

Neutrinos

Anna Franckowiak
Ruhr-University Bochum

Summer School 2026



Bochum – Deep in the West



Bochum – Deep in the West

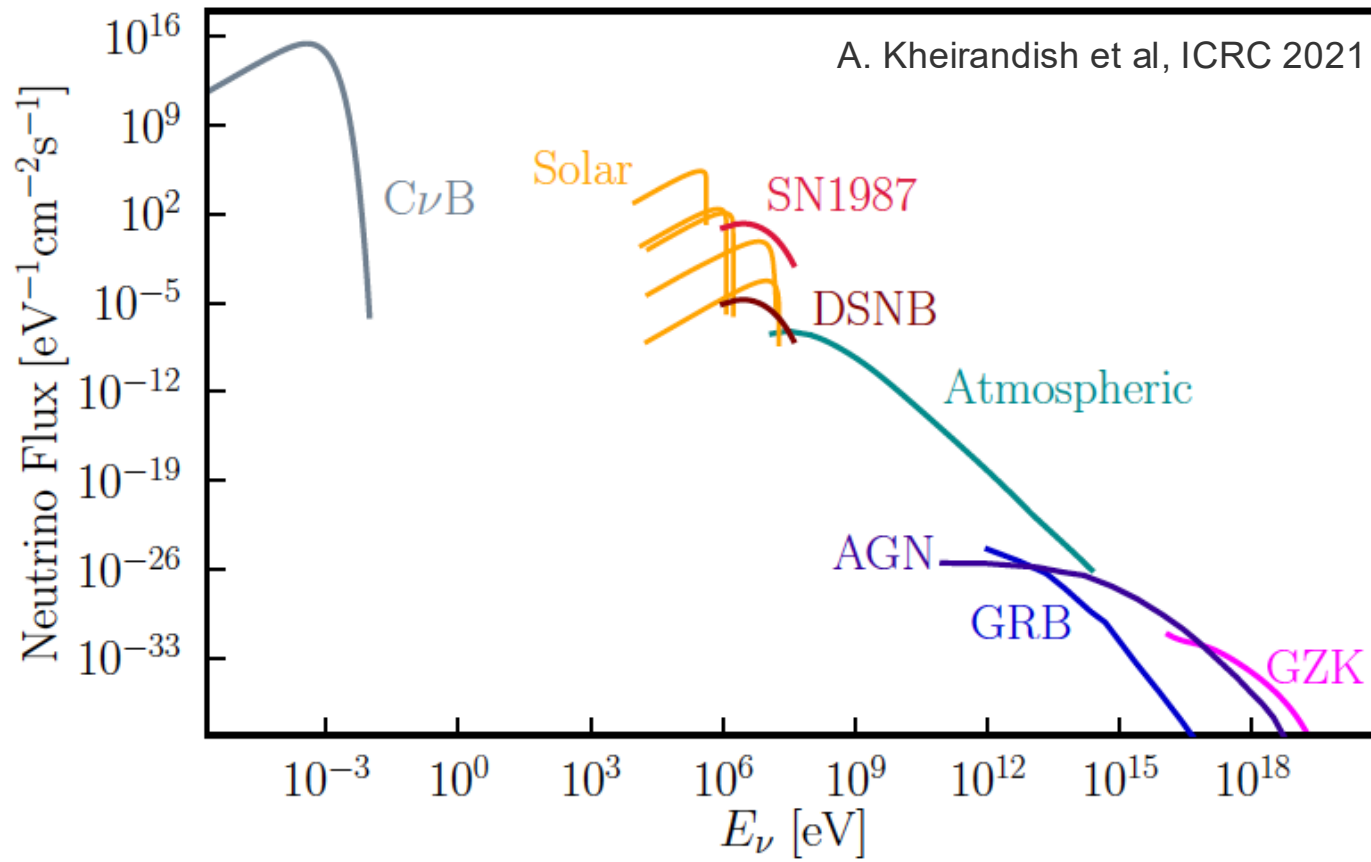


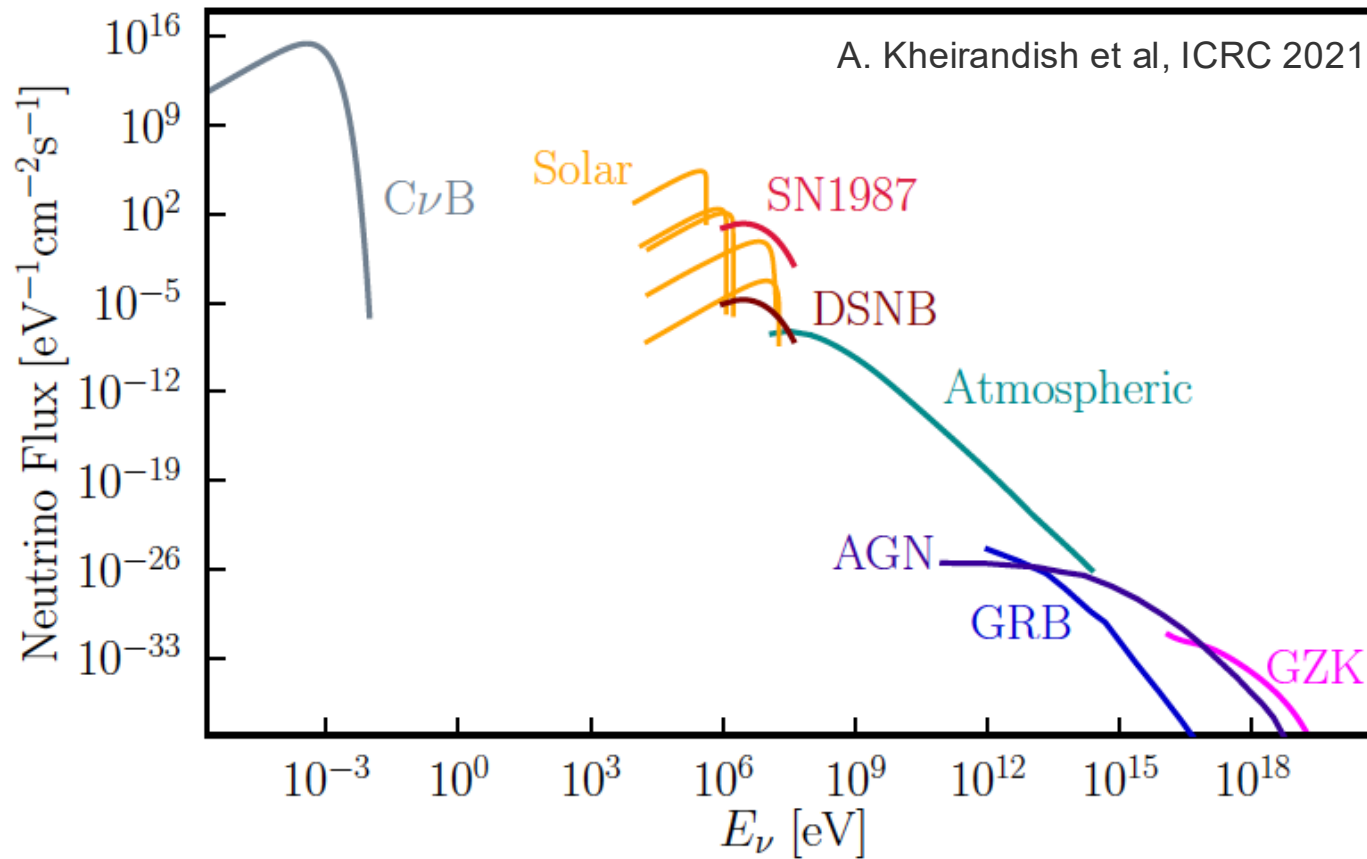
Bochum – Deep in the West



**Which neutrino sources do
you know?**

Mentimeter





↔

Ideas: neutrino capture
on unstable nucleus
(e.g. tritium)

↔

↔

Neutrino capture on
stable nucleus
(Chlorine, Gallium)

↔

Water / ice
Cherenkov
detectors

↔

Radio arrays,
cosmic-ray
detectors

Content of the 3 lectures

- Discovery of the neutrino
- Low-energy (MeV) neutrinos
 - Sun
 - Supernovae
- High-energy (TeV-PeV) neutrinos
 - Astrophysics
 - Particle physics
- Even higher energies
 - 220 PeV neutrino detected by KM3NeT
 - New detector concepts

Content of the 3 lectures

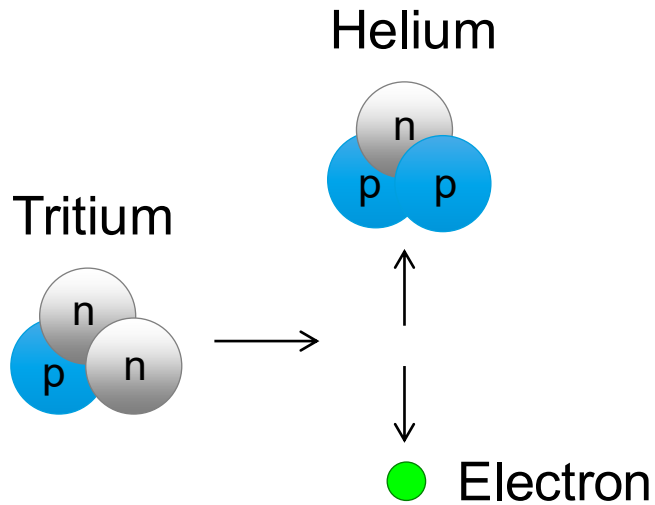
- **Discovery of the neutrino**
- Low-energy (MeV) neutrinos
 - Sun
 - Supernovae
- High-energy (TeV-PeV) neutrinos
 - Astrophysics
 - Particle physics
- Even higher energies
 - 220 PeV neutrino detected by KM3NeT
 - New detector concepts

Learning Objectives

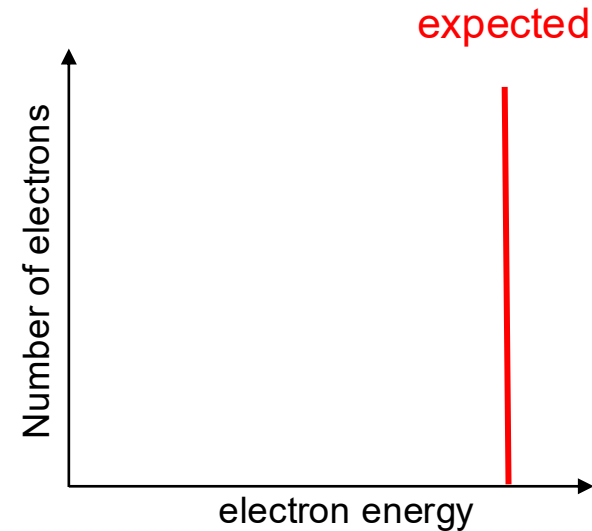
- Why was the neutrino predicted before it was detected?
- What did it take to detect neutrinos for the first time?

Beta decay spectrum

Two-body final state

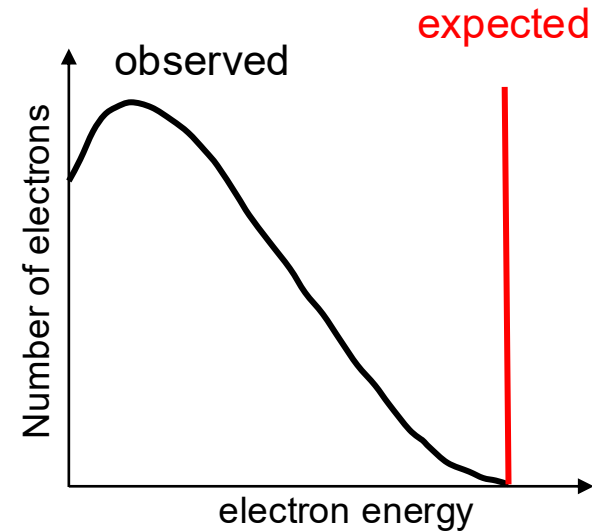
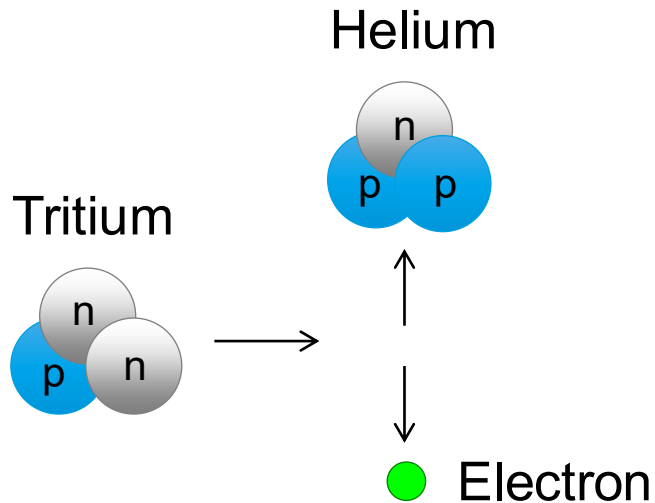


Recoil nucleus and electron separate with equal and opposite momentum



Beta decay spectrum

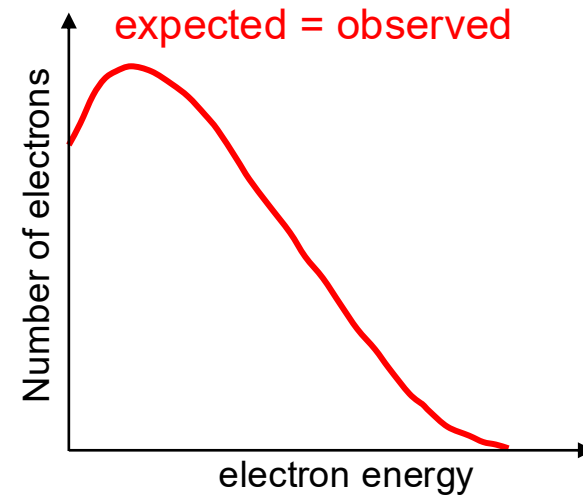
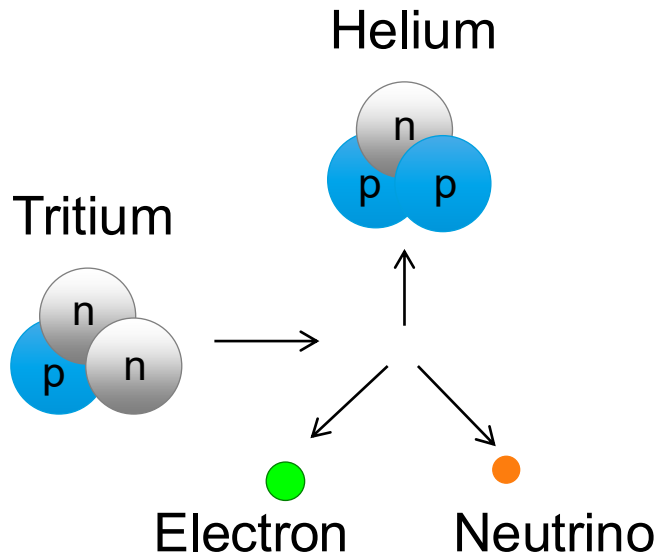
Two-body final state



Recoil nucleus and electron
separate with equal and
opposite momentum

Beta decay spectrum

Three-body final state



Electron and neutrino share the available energy.

Pauli had a desperate remedy

4 December 1930
Gloriastr.
Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and

As the bearer of these lip

raciously, will explain mo

false' statistics of N-14

continuous β -spectrum, I have

save the "exchange theorem"

theorem. Namely [there is] the pos.

exist in the nuclei electrically neutral pairs of the 1

sh to call neutrons,** which have spin $1/2$ and obey the

conclusion principle, and additionally differ from light quan-

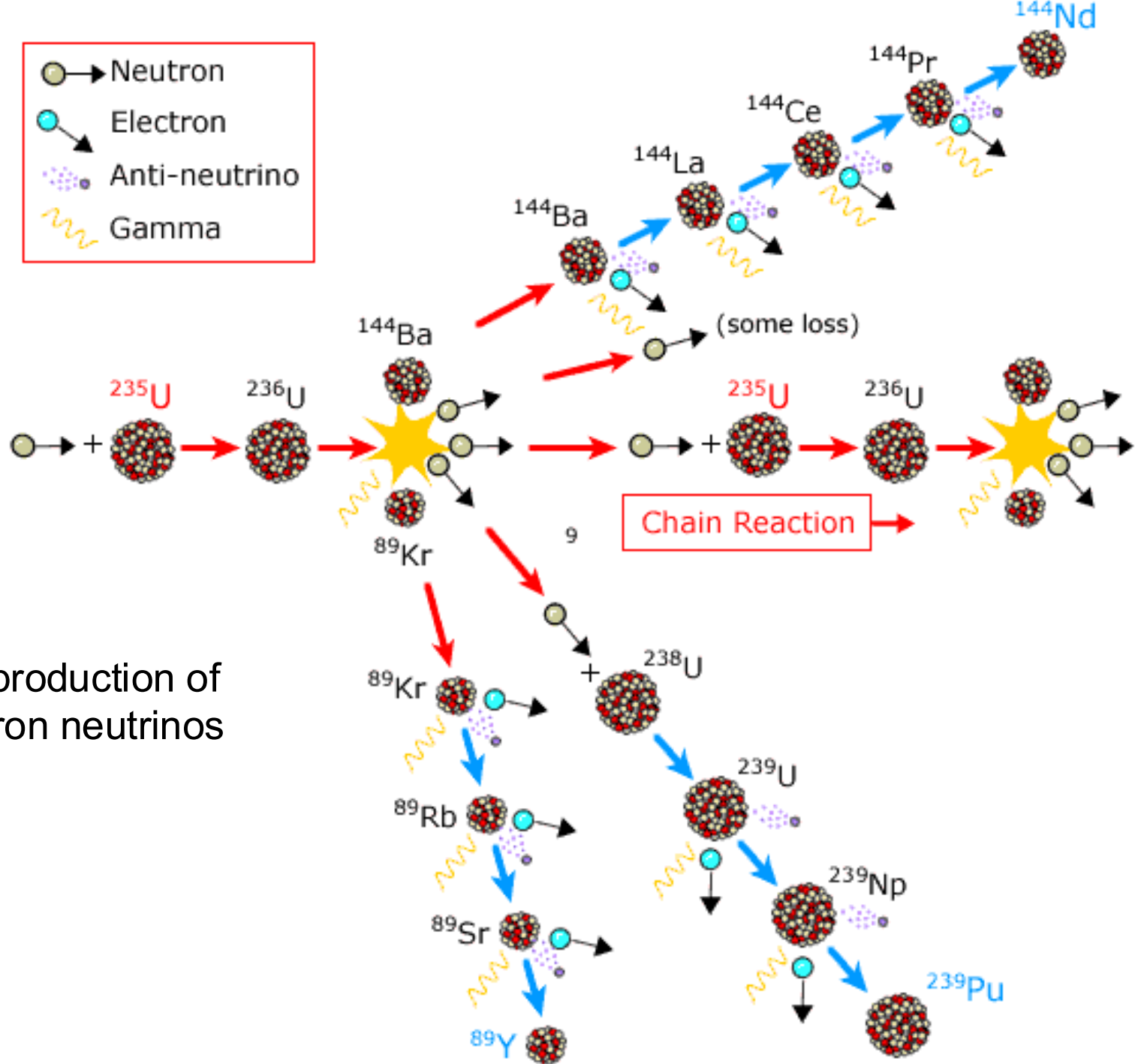
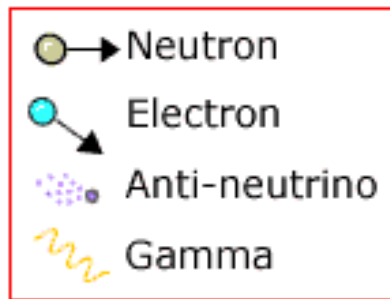
in that they do not travel with the velocity of light:

I admit that my remedy may appear to have a small a priori probability because neutrons, if they exist, would probably have long ago been seen. However, only those who never can win, and the seriousness of the situation of the continuous β -spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." Thus one should earnestly discuss every way of salvation.—So, dear radioactives, put it to test and set it right.—Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December.—With many greetings to you, also to Mrs. Back, your devoted servant,

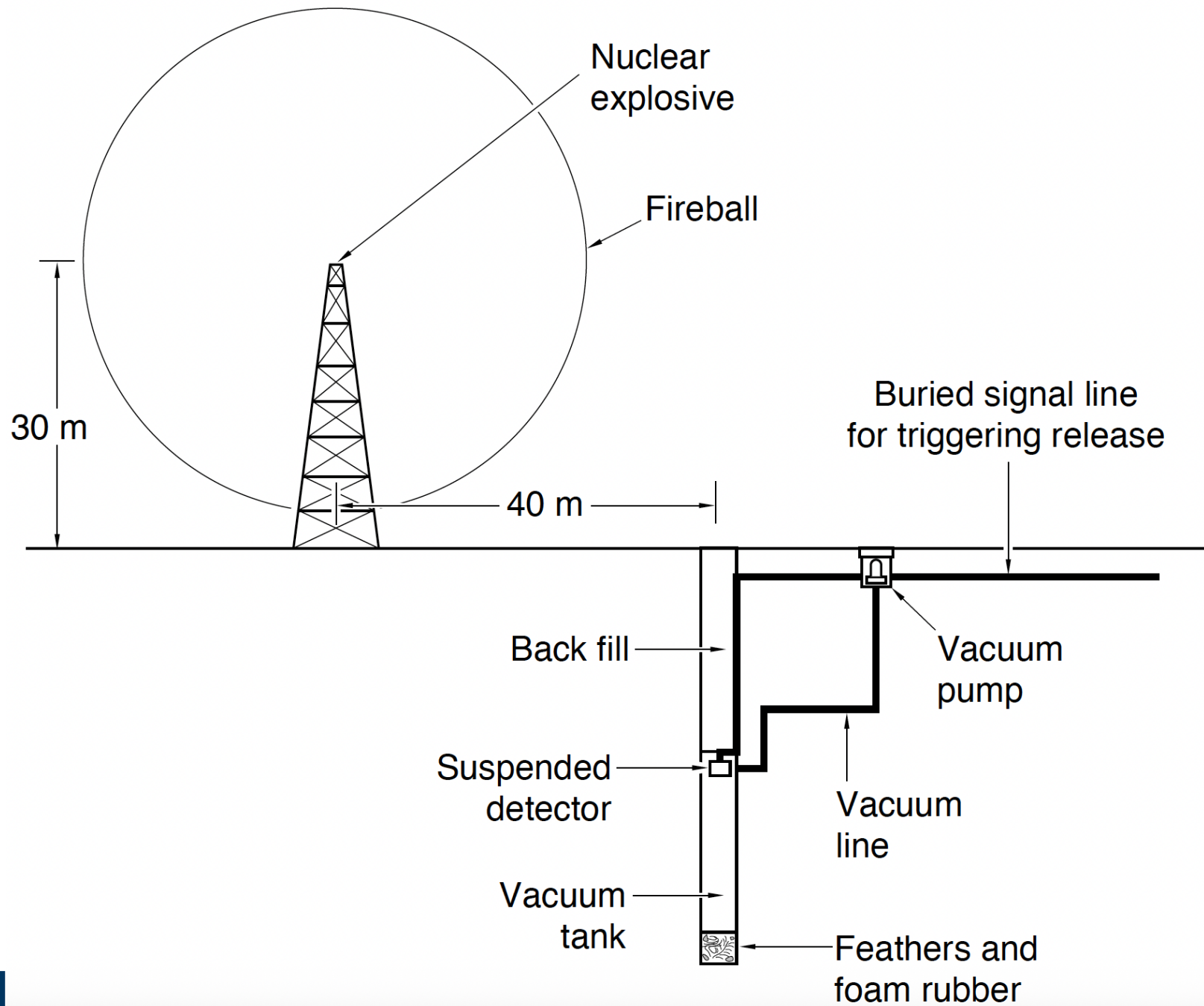
I have done a terrible thing, I have postulated a particle that cannot be detected.



Nuclear Fission



Efficient production of
anti electron neutrinos



Detecting neutrinos at a nuclear reactor

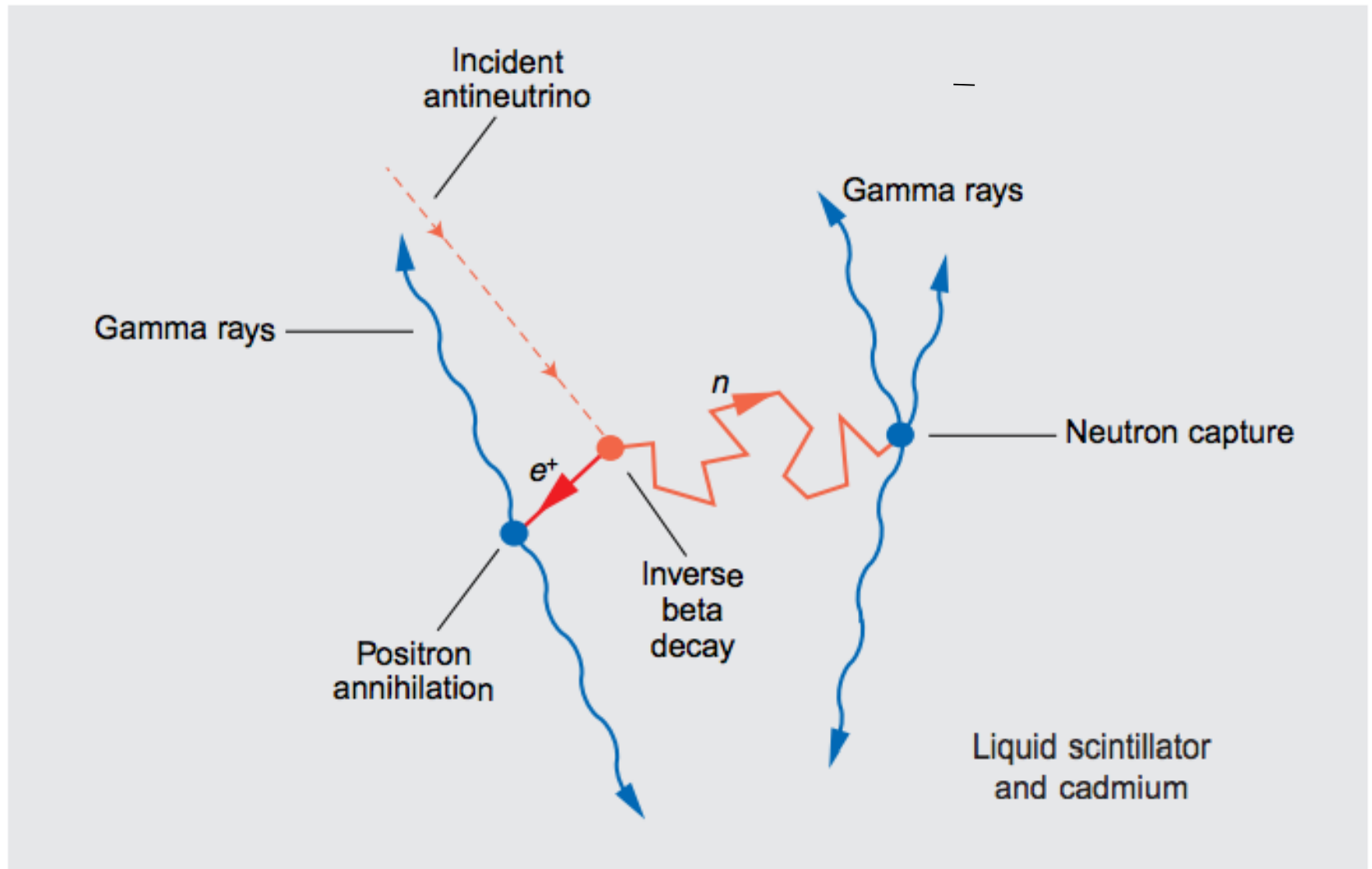


Inverse beta-decay as
detection mechanism:



2×10^{20} anti electron neutrinos / s per GW of thermal power

Double Signature of Inverse Beta Decay



1956 Cowen-Reines Neutrino experiment → Nobel price in 1995

The Neutrino as a particle

- Part of the standard model
 - Three flavors
- Spin: 1/2

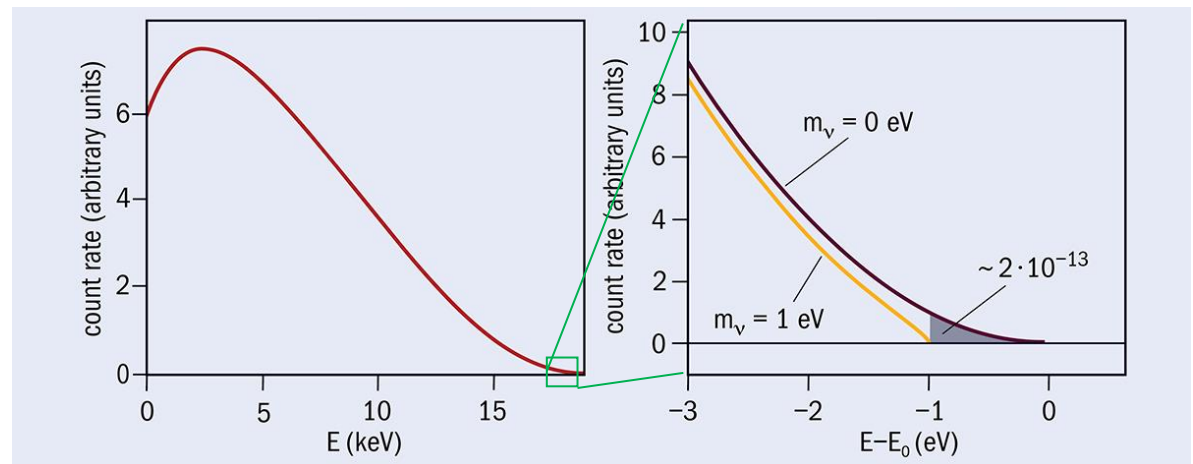
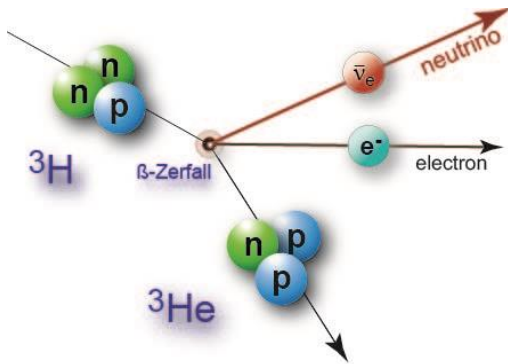
	I	II	III		
Masse →	2,3 MeV	1,275 GeV	173,07 GeV		125,9 GeV
Ladung →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{e}{p}$	0
Spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$		0
Name →	u up	c charm	t top	q e/p-Quant	H Higgs Boson
Quarks	4,8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	95 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4,18 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g Gluon	
	<2 eV 0 $\frac{1}{2}$ ν_e Elektron-Neutrino	<0,19 MeV 0 $\frac{1}{2}$ ν_μ Myon-Neutrino	<18,2 MeV 0 $\frac{1}{2}$ ν_τ Tau-Neutrino	91,2 GeV 0 1 Z^0 Z Boson	
	0,511 MeV -1 $\frac{1}{2}$ e Elektron	105,7 MeV -1 $\frac{1}{2}$ μ Myon	1,777 GeV -1 $\frac{1}{2}$ τ Tau	80,4 GeV ± 1 1 $W^\pm$ W Boson	
Leptonen					Eichbosonen

Neutrino Mass



KATRIN
(Karlsruhe Tritium
Neutrino Experiment)

$$m_\nu < 0.45 \text{ eV c}^{-2}$$





Take home message

Pauli predicted the neutrino to save energy conservation in beta decay.

Anti-neutrinos from nuclear fission were first detected next to a nuclear power plant.

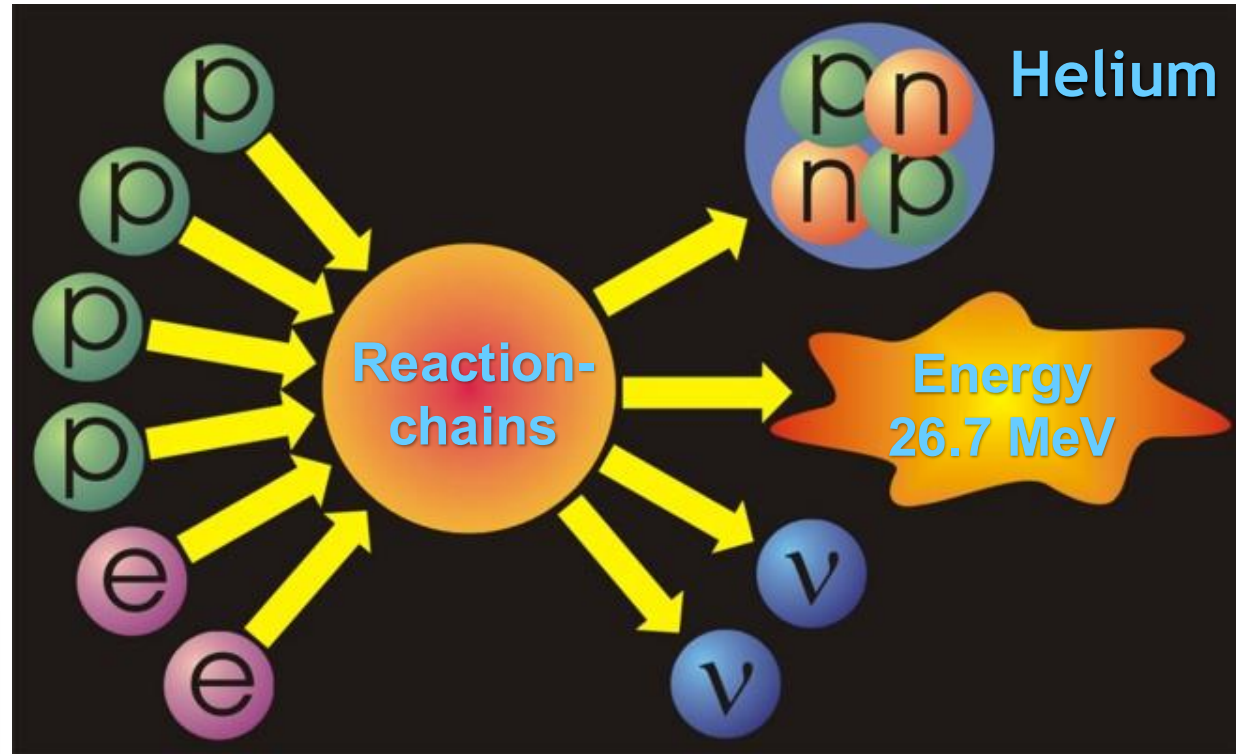
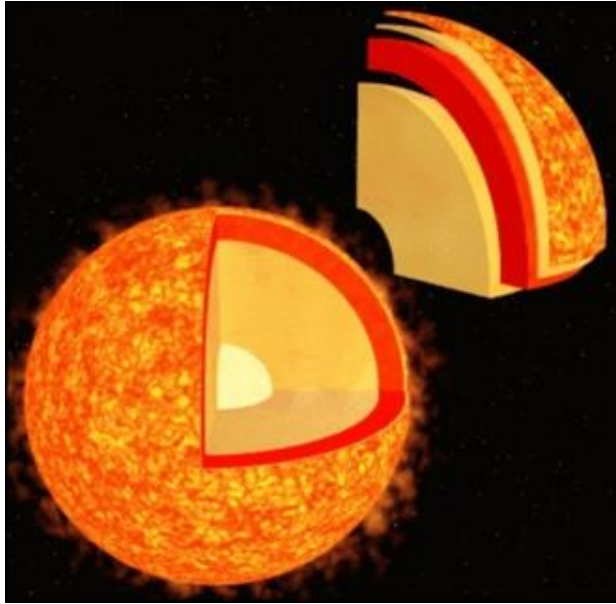
Content of the 3 lectures

- Discovery of the neutrino
- **Low-energy (MeV) neutrinos**
 - **Sun**
 - **Supernovae**
- High-energy (TeV-PeV) neutrinos
 - Astrophysics
 - Particle physics
- Even higher energies
 - 220 PeV neutrino detected by KM3NeT
 - New detector concepts

Learning Objectives

- What have we learned from MeV solar and supernova neutrinos?
- Are we ready for the next Galactic supernova?!

Solar Neutrinos



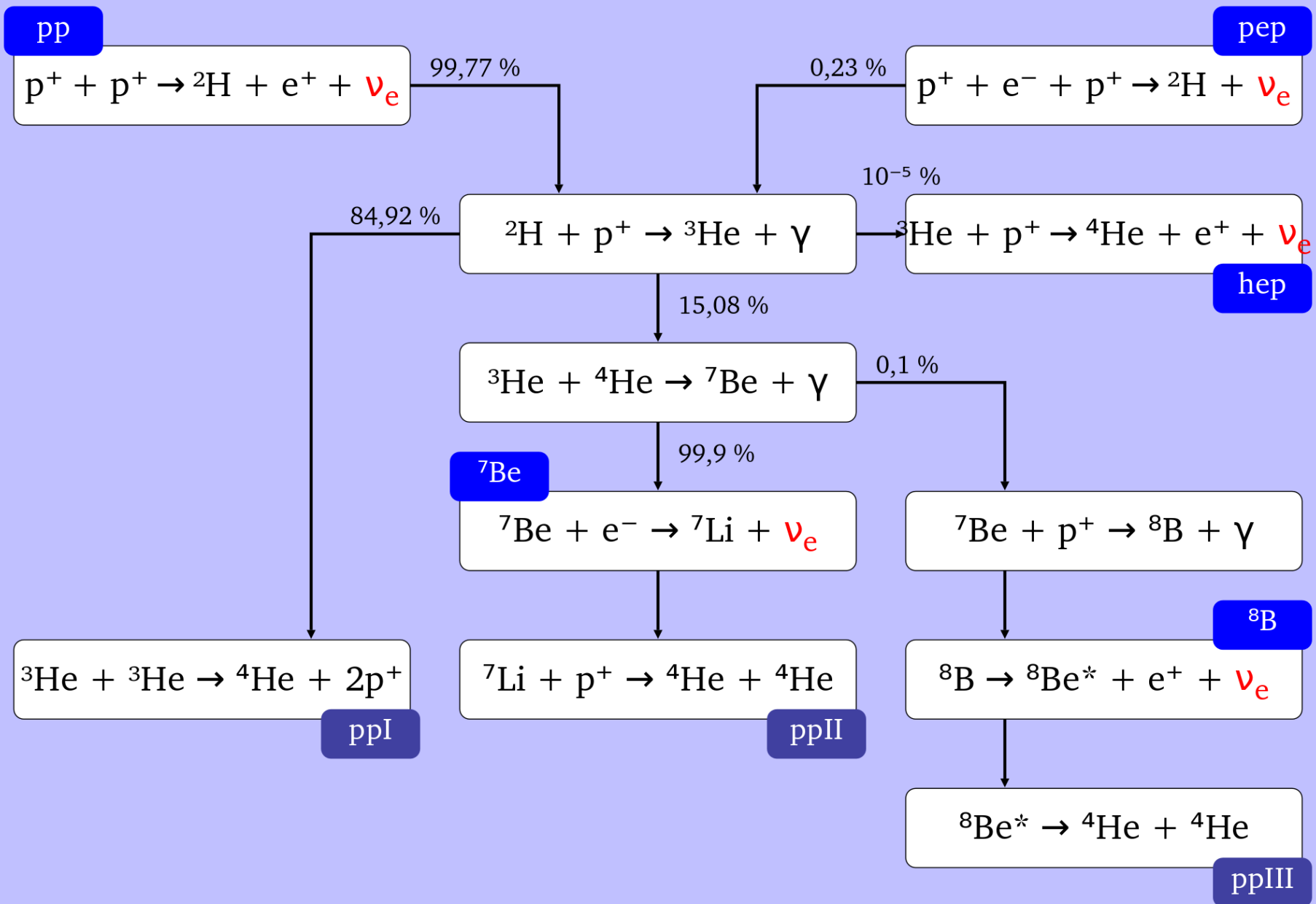
1967

Solar radiation:

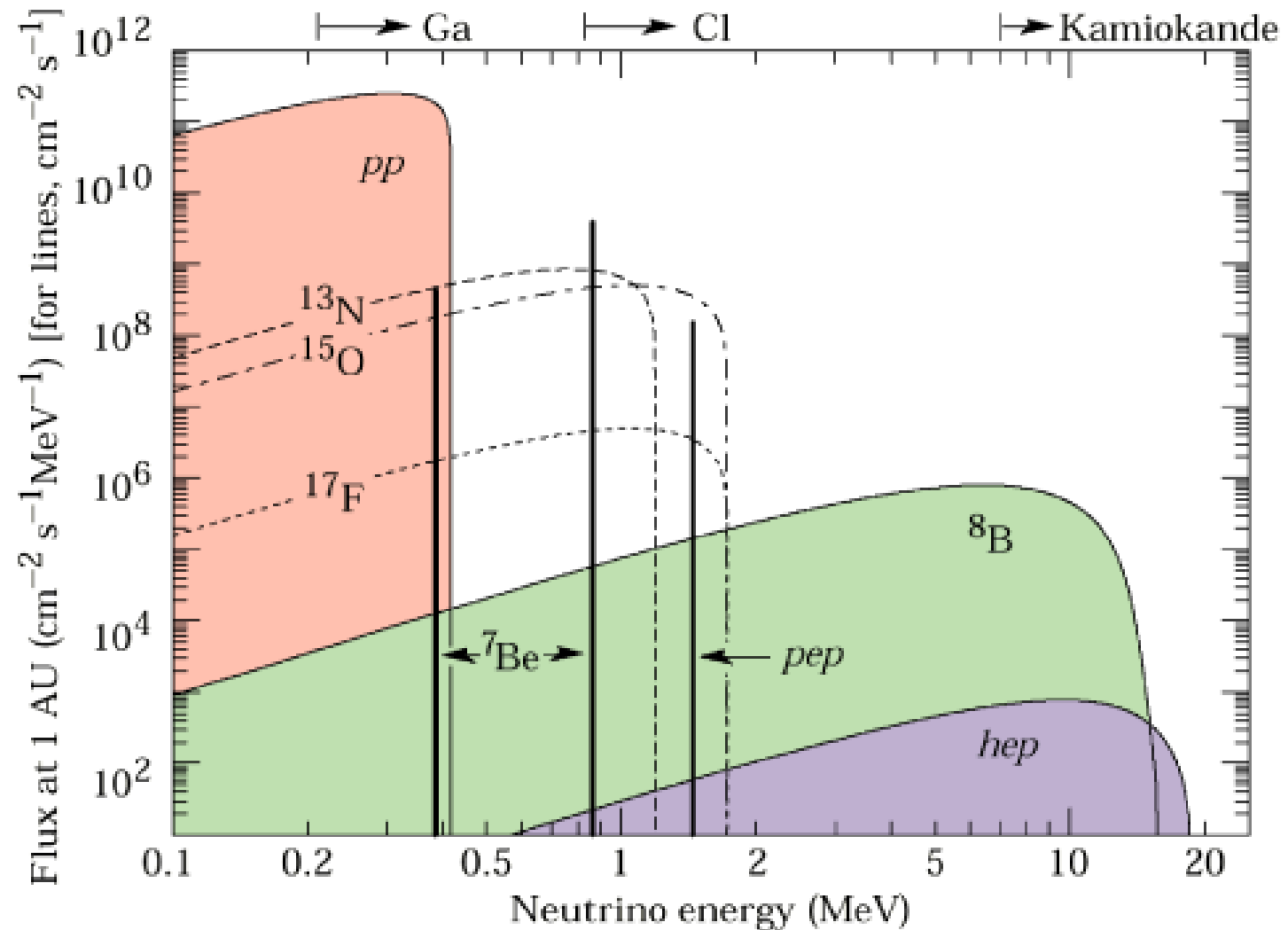
- 98% light
- 2% **electron-neutrinos**

→ at Earth: 66 billion neutrinos / cm^2 / s

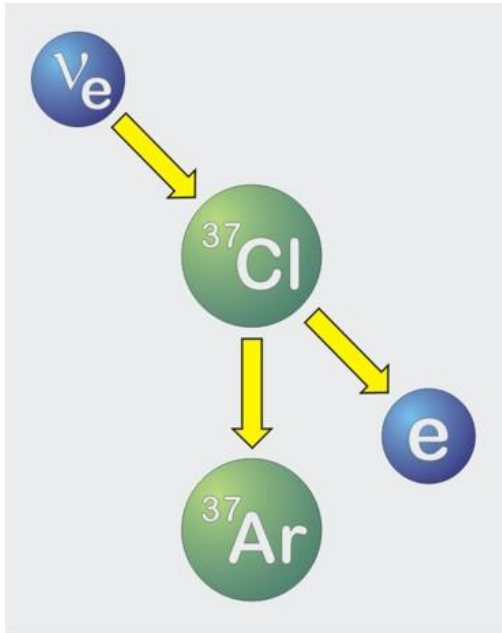
Neutrino Production in the Sun



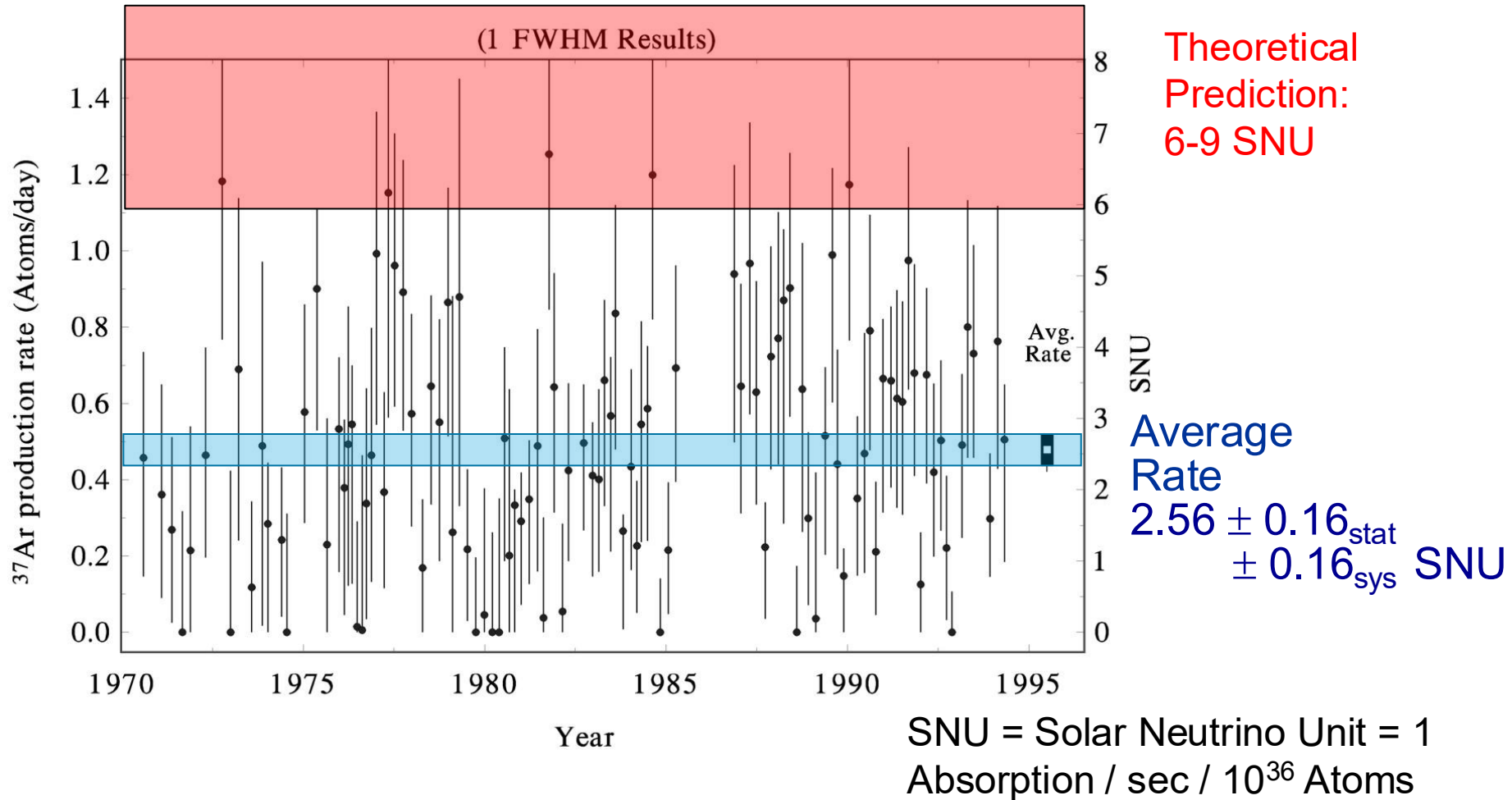
Solar Neutrino Spectrum



The Homestake Experiment



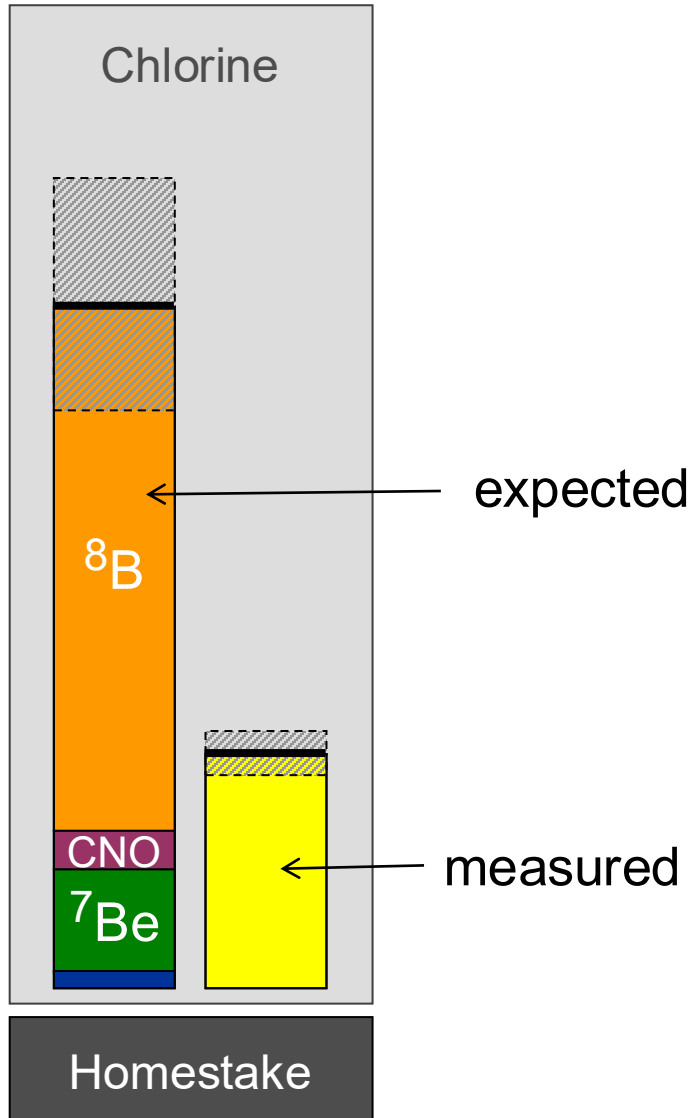
Homestake: Results



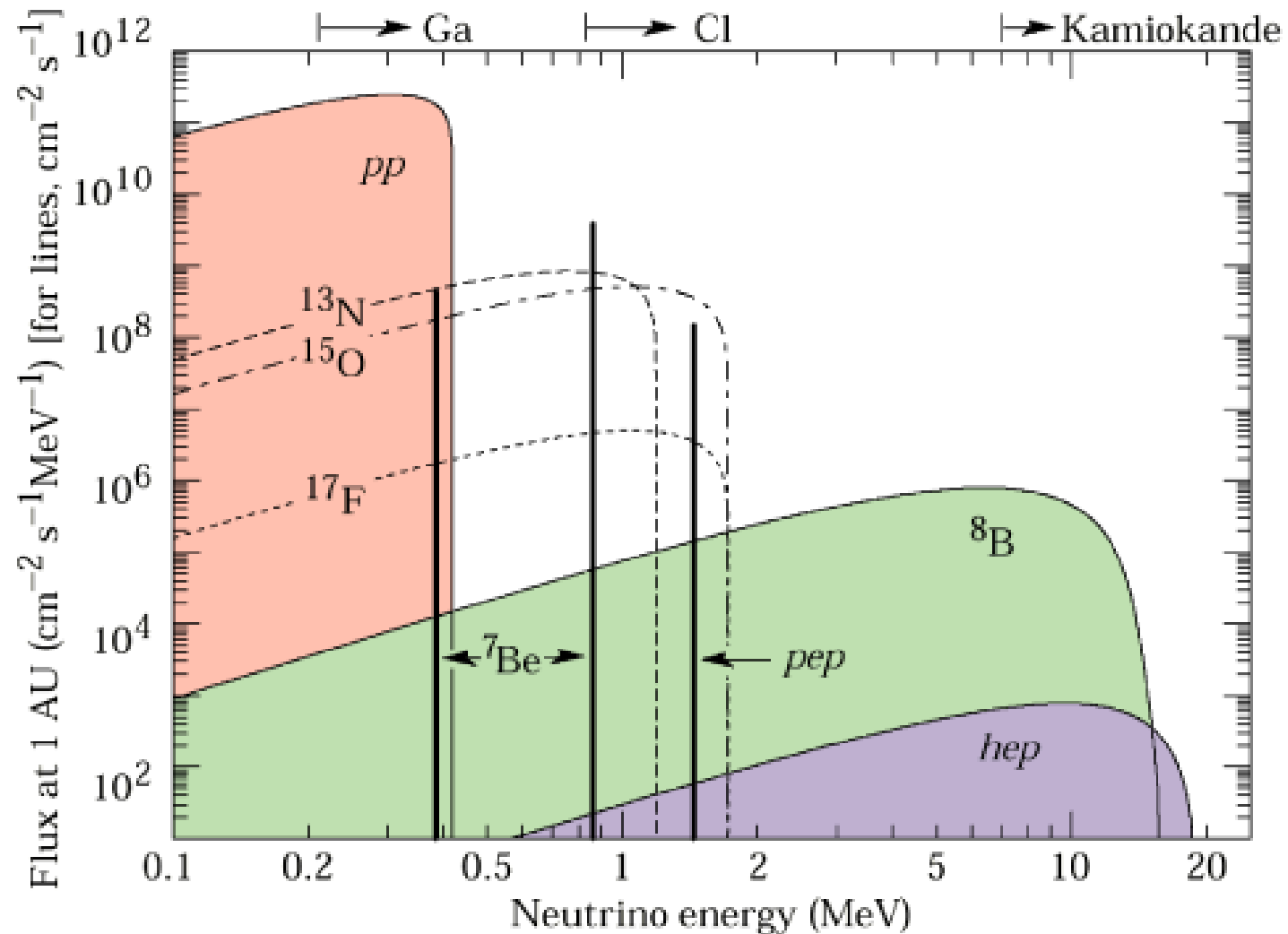
→ **Solar neutrino problem**

Solution to the solar neutrino problem

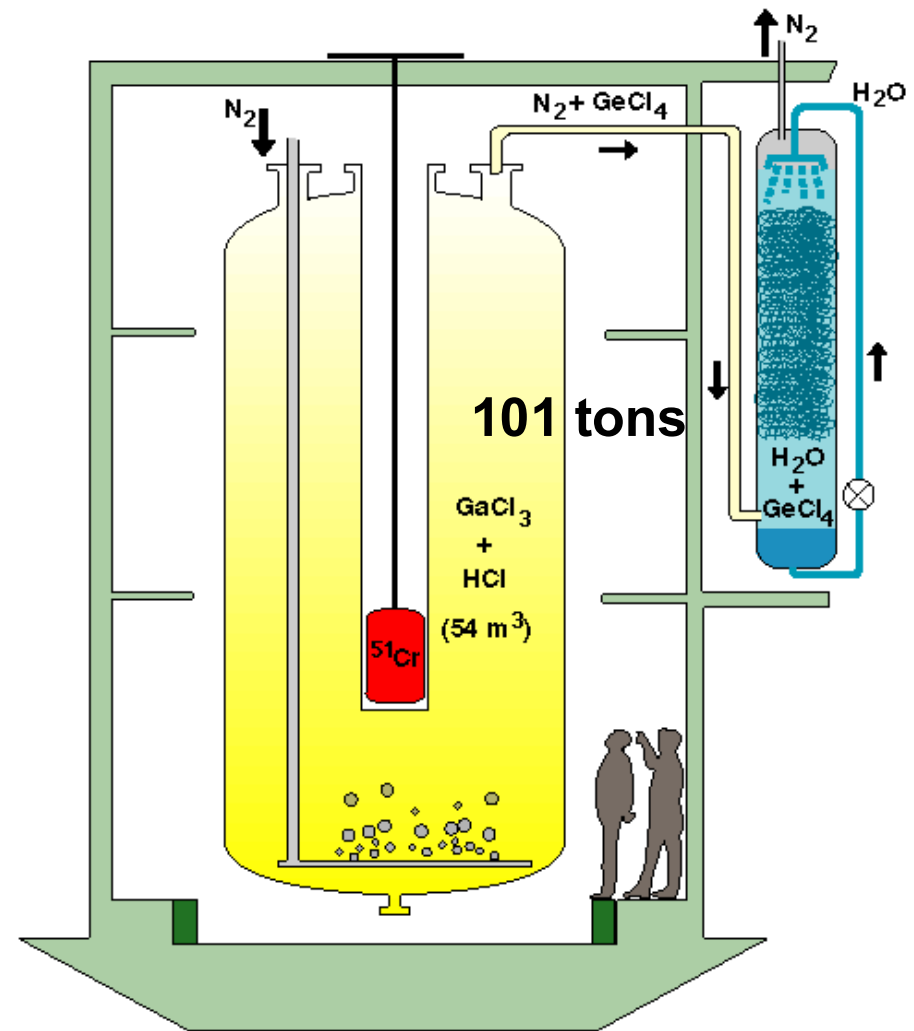
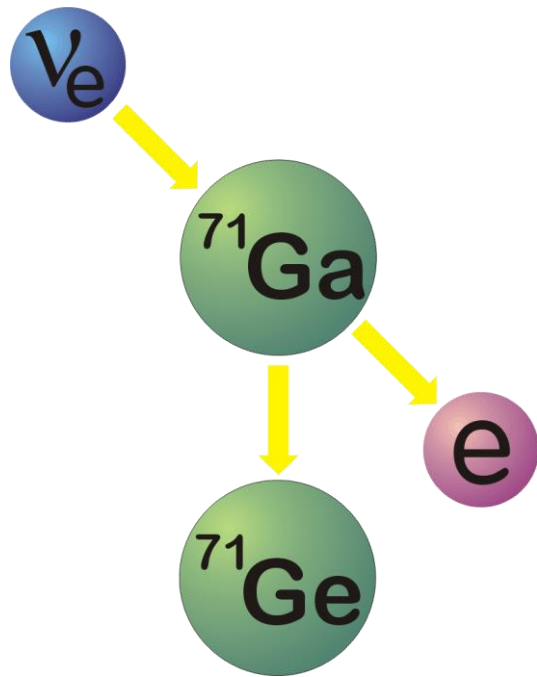
Electron-Neutrino Detectors



Solar Neutrino Spectrum

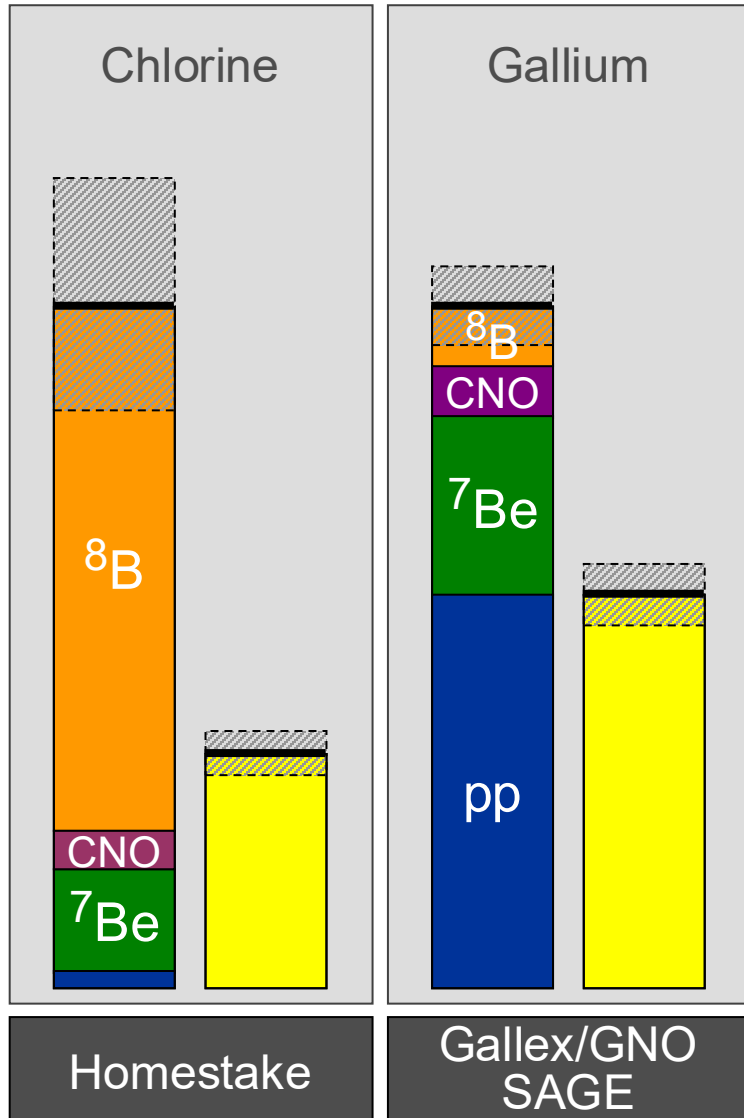


GALLEX / SAGE (1991-2003)



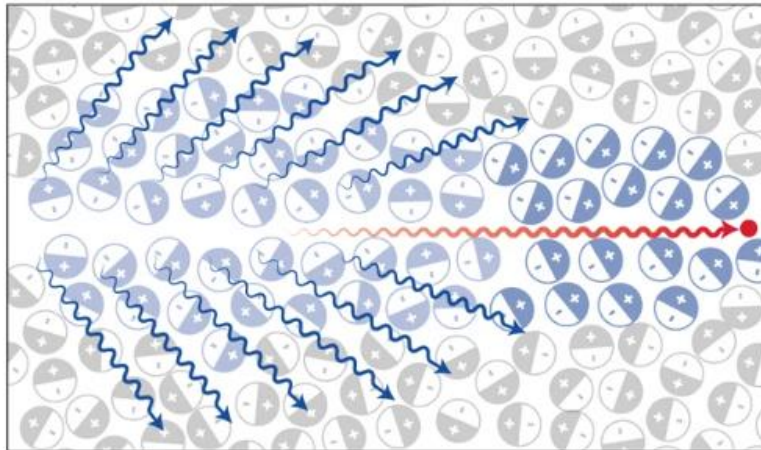
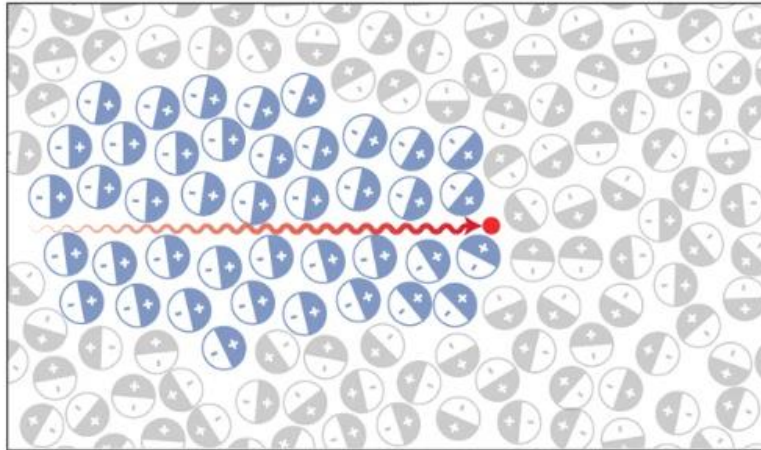
Solution to the solar neutrino problem

Electron-Neutrino Detectors

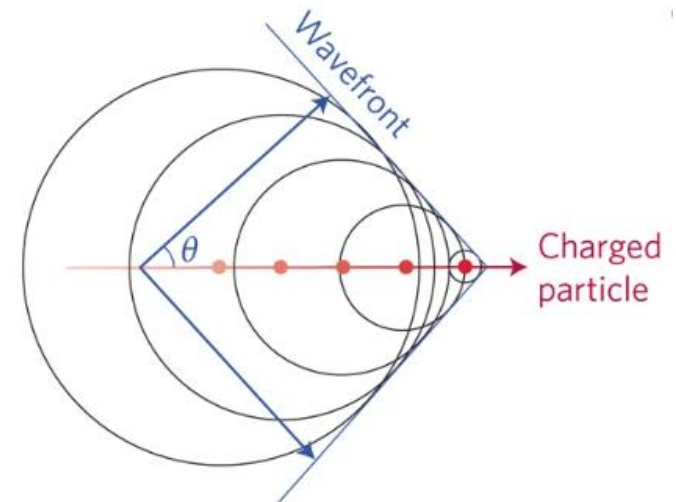
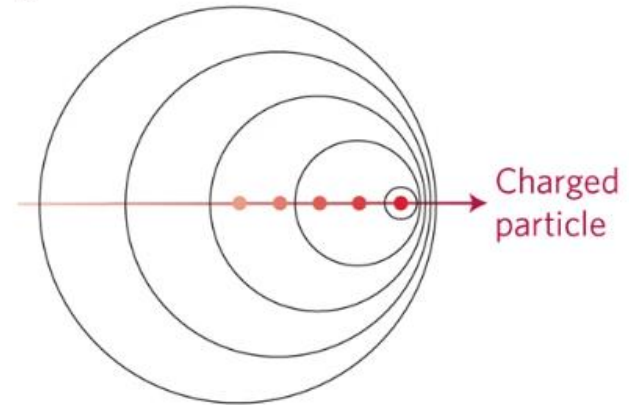


Different detection technique: Cherenkov Effect

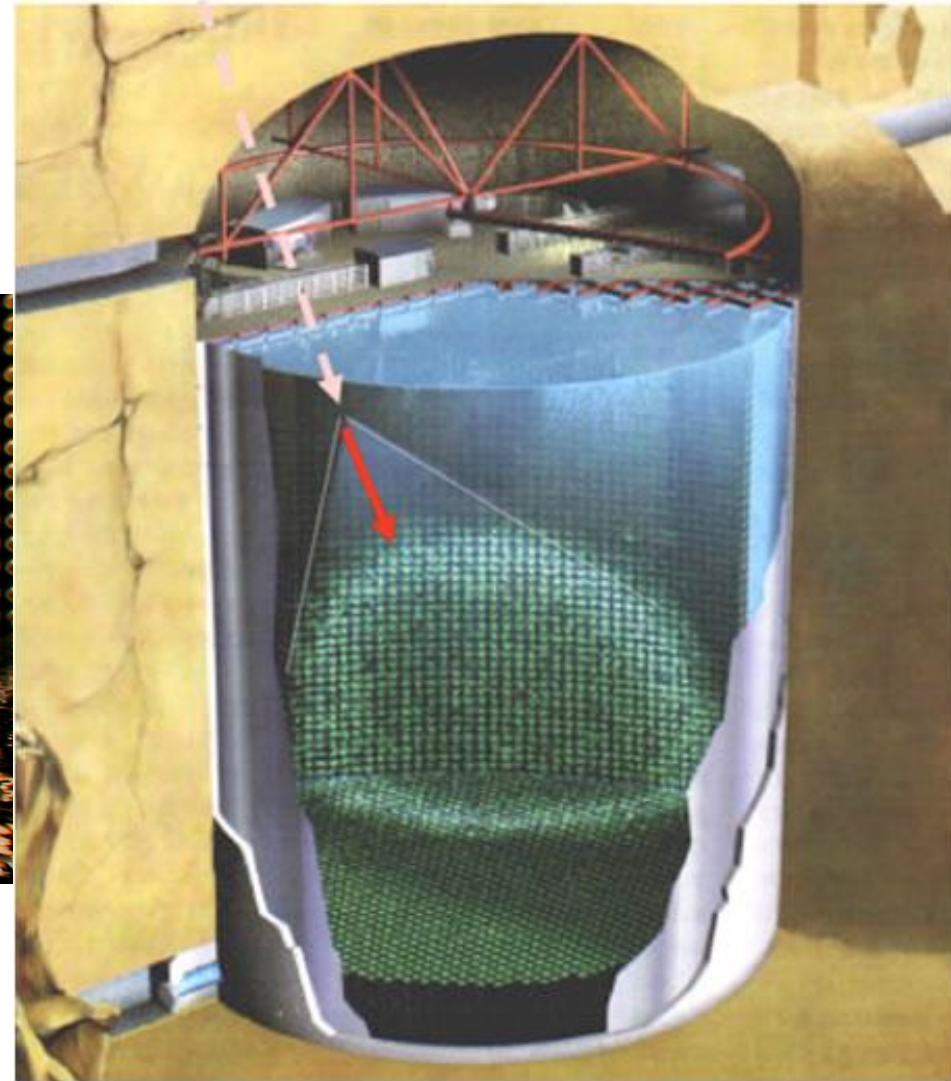
a



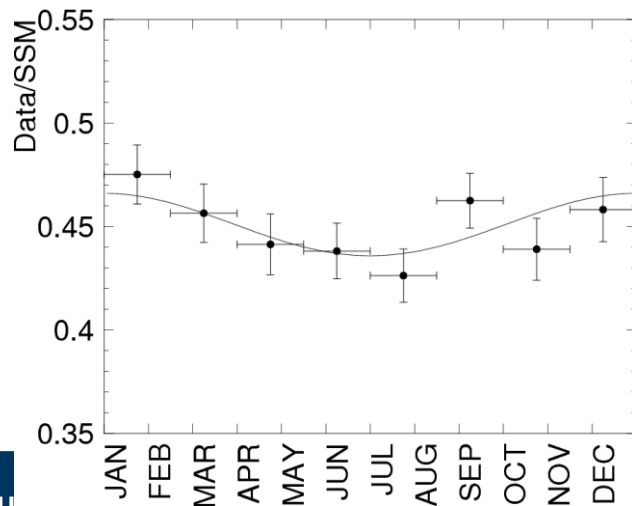
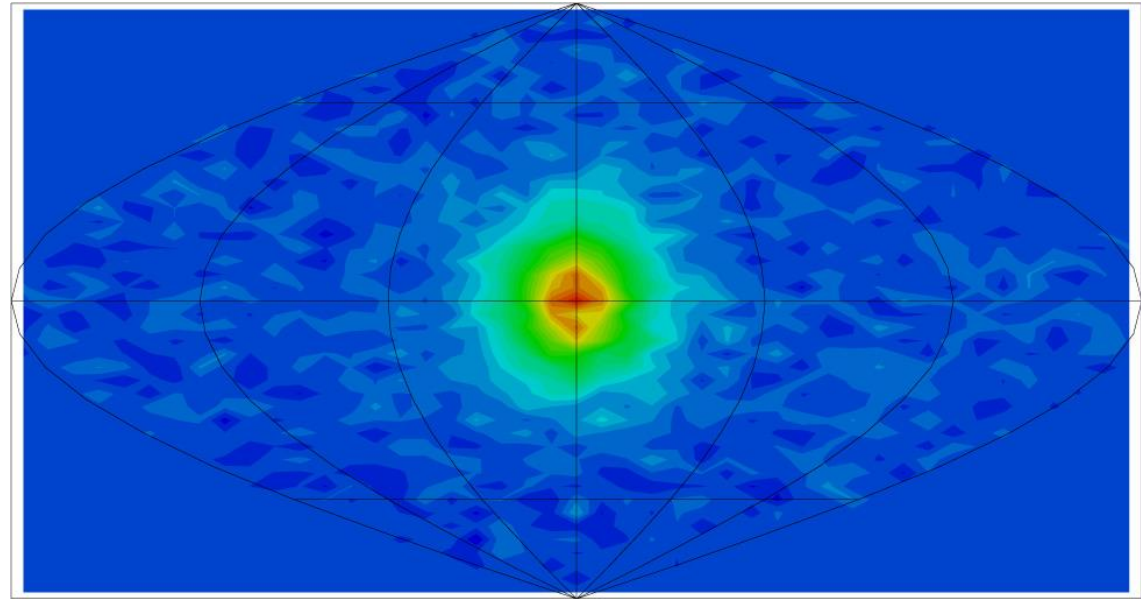
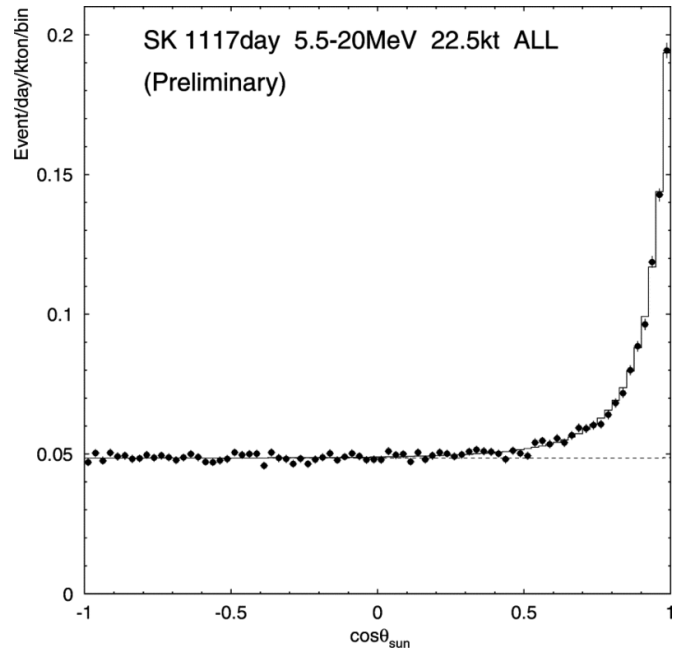
b



Super Kamiokande



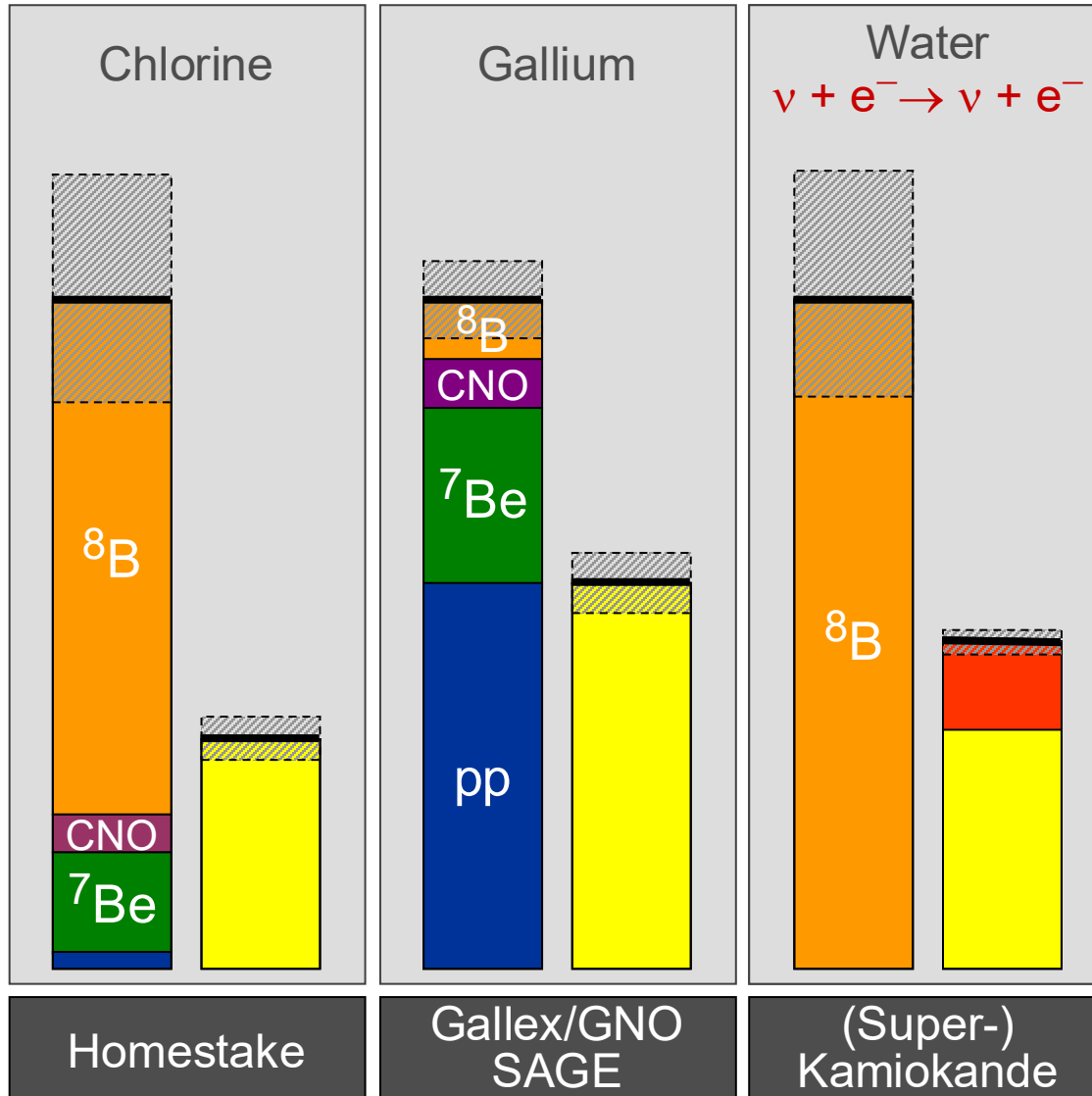
Super-Kamiokande – “Image” of the Sun



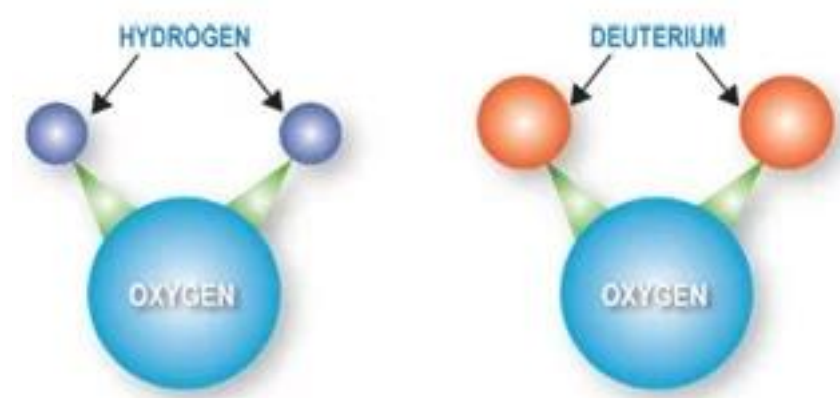
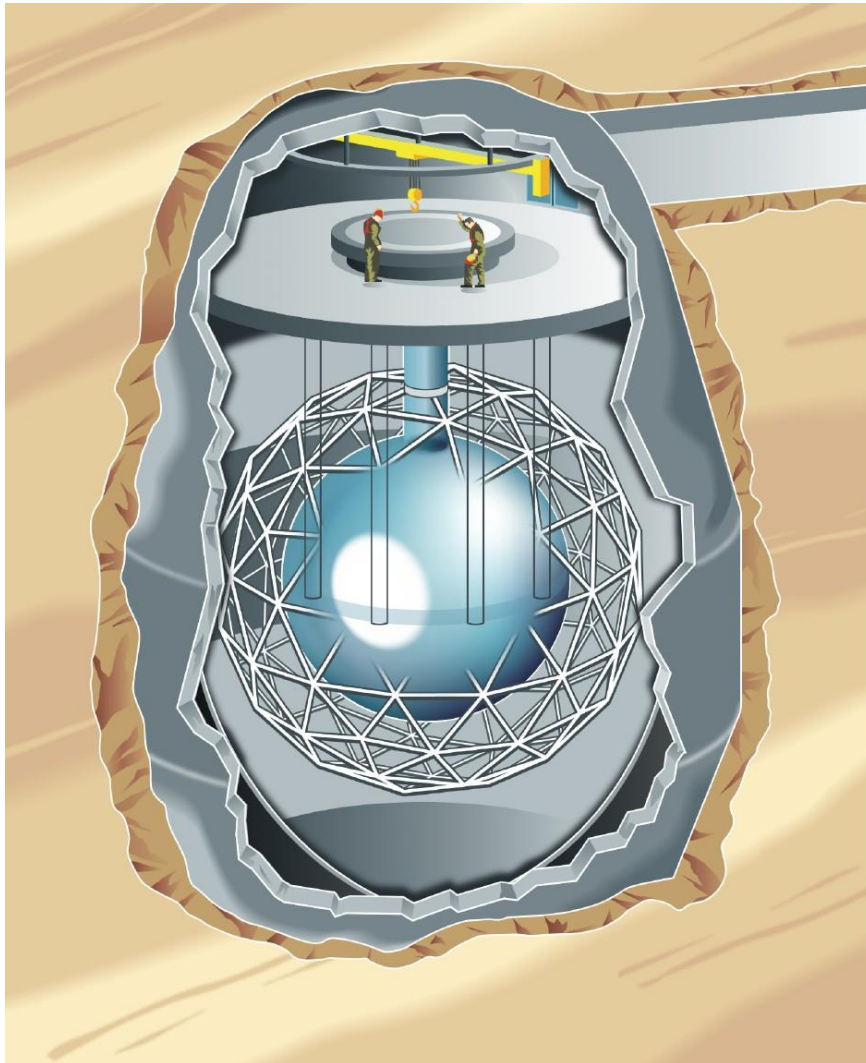
Seasonal variation
due to elliptic orbit of
Earth around sun

Solution to the solar neutrino problem

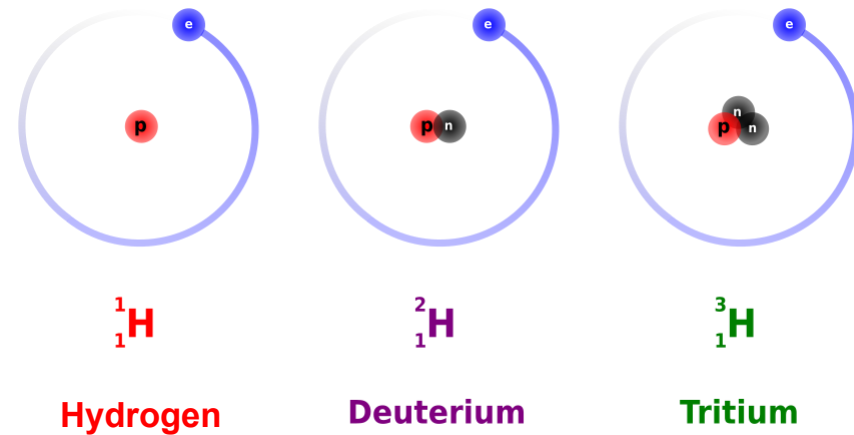
Electron-Neutrino Detectors



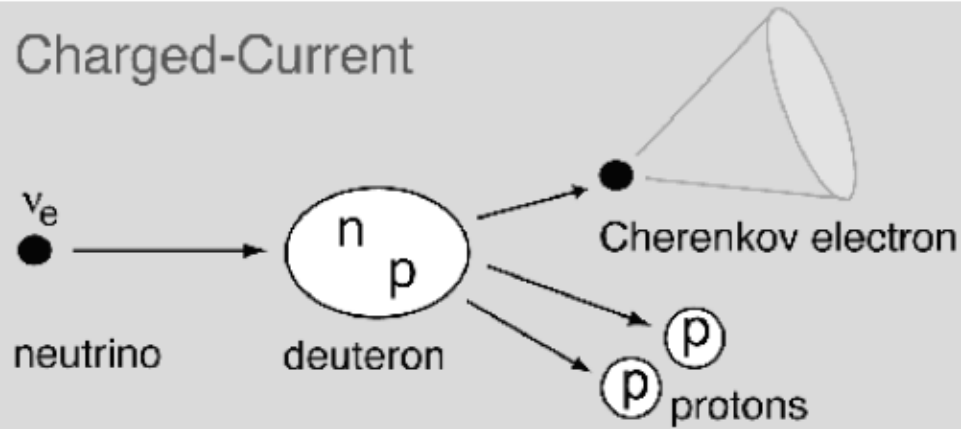
Sudbery Neutrino Observatory (SNO)



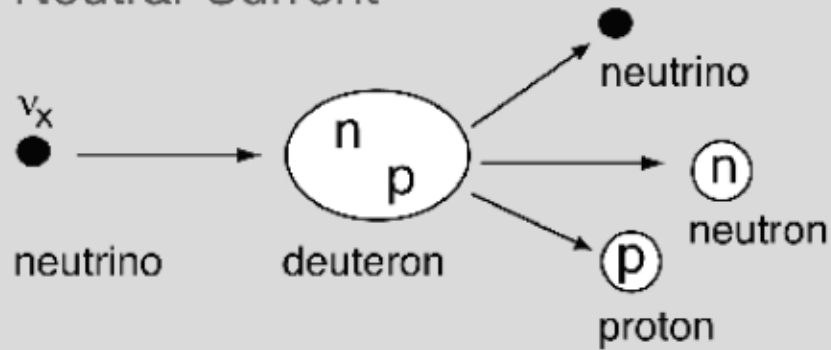
Isotopes of hydrogen



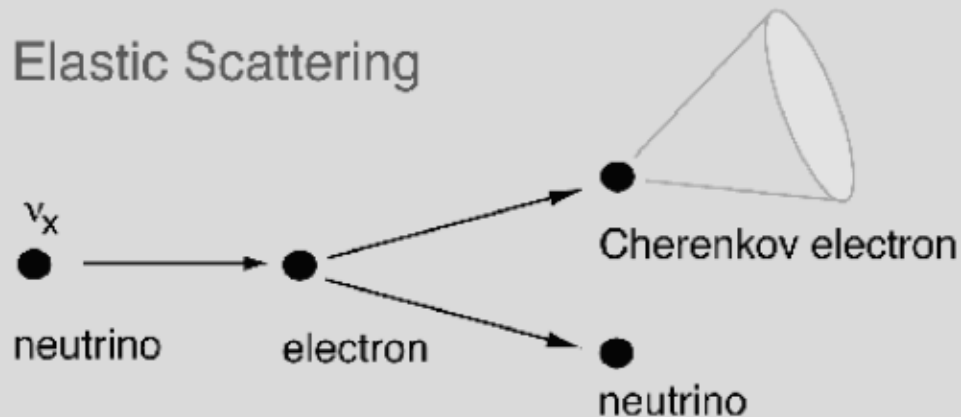
Charged-Current



Neutral-Current



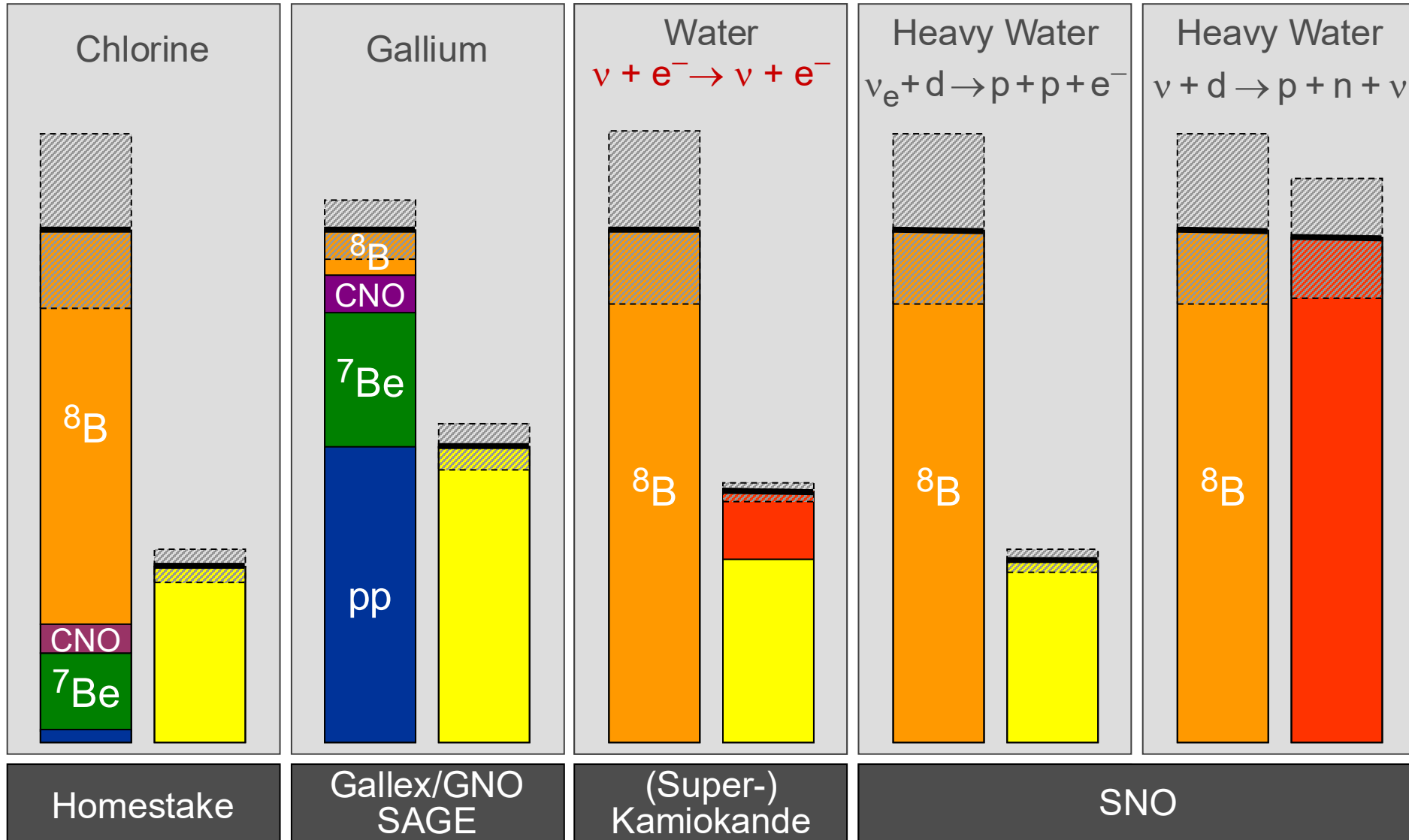
Elastic Scattering



Solution to the solar neutrino problem

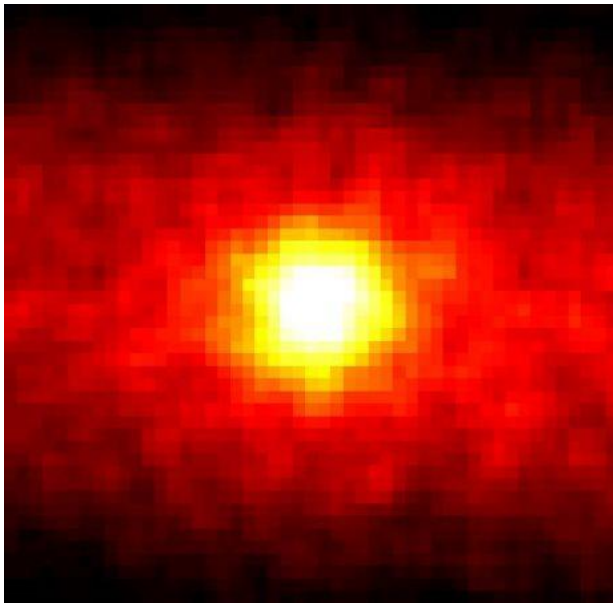
Electron-Neutrino Detectors

All Flavors



Solar Neutrinos

Astronomy Picture of the Day
June 5, 1998



The Sun in Neutrinos seen
by Super-Kamiokande

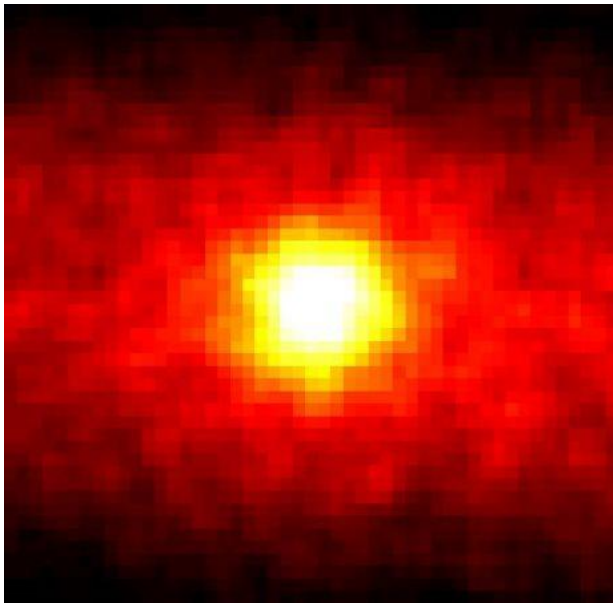
Combining neutrinos and electromagnetic information led to:

- **The solar neutrino problem**



Solar Neutrinos

Astronomy Picture of the Day
June 5, 1998



The Sun in Neutrinos seen
by Super-Kamiokande

Combining neutrinos and electromagnetic information led to:

- Confirmation of model of fusion
- New understanding of the standard model of particle physics
→ neutrinos oscillate → have mass!



What is neutrino oscillation?

- Three neutrino flavor states: one per lepton flavor
- Mixing between these flavor states and the neutrino mass states



- Characterised by the PMNS matrix

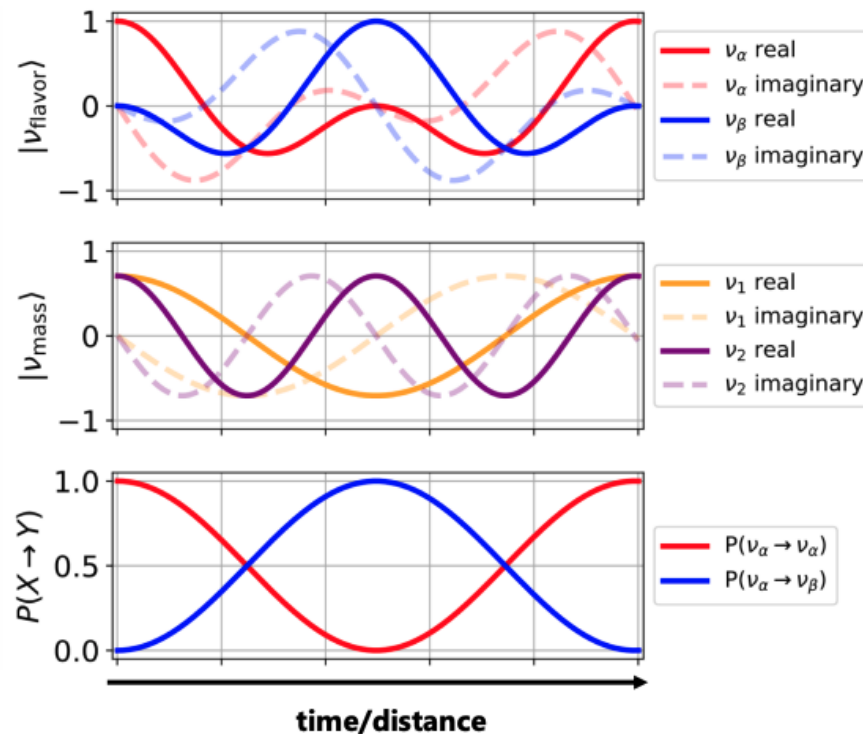
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- A neutrino produced as a given flavor is thus a superposition of all three mass states
- The wavefunction of each mass state evolves with a different frequency (defined by its mass) as they propagate
- The superposition of the flavor states therefore changes over time → time-dependent flavour composition
- A neutrino produced as one flavor can therefore be detected later as another → this is neutrino oscillations

A simple example (credit: T. Stuttard)

Visualise the superposition effects and resulting oscillations using simplified model...

- 2 neutrino states (flavour = ν_α, ν_β , mass = ν_1, ν_2) $\rightarrow$ flavor states are 50:50 mix of mass states ($\theta = 45^\circ$)
- $m_2 = \sqrt{2} m_1$



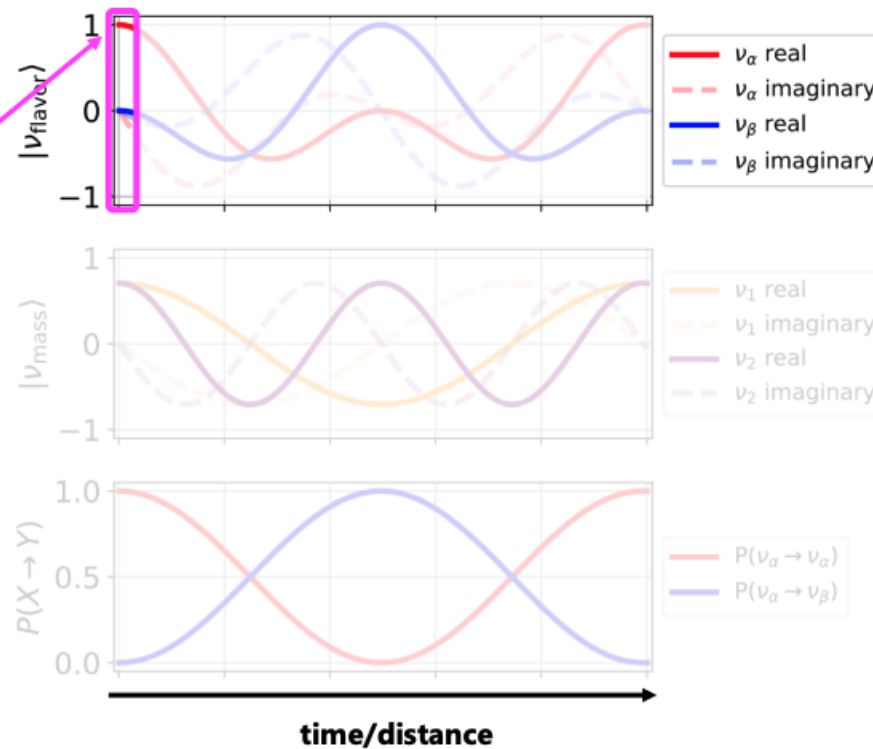
$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\} |\nu_j(0)\rangle$$

A simple example (credit: T. Stuttard)

Visualise the superposition effects and resulting oscillations using simplified model...

- 2 neutrino states (flavour = ν_α, ν_β , mass = ν_1, ν_2) $\rightarrow$ flavor states are 50:50 mix of mass states ($\theta = 45^\circ$)
- $m_2 = \sqrt{2} m_1$

1) Neutrino produced in pure (single) flavor state
In this case ν_α

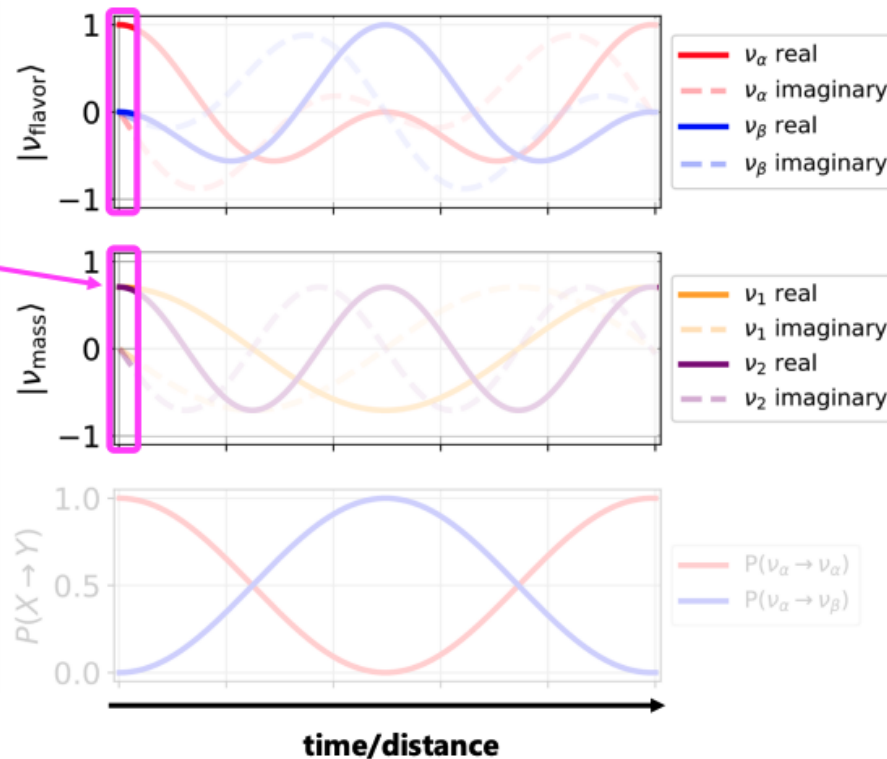


A simple example (credit: T. Stuttard)

Visualise the superposition effects and resulting oscillations using simplified model...

- 2 neutrino states (flavour = ν_α, ν_β , mass = ν_1, ν_2) $\rightarrow$ flavor states are 50:50 mix of mass states ($\theta = 45^\circ$)
- $m_2 = \sqrt{2} m_1$

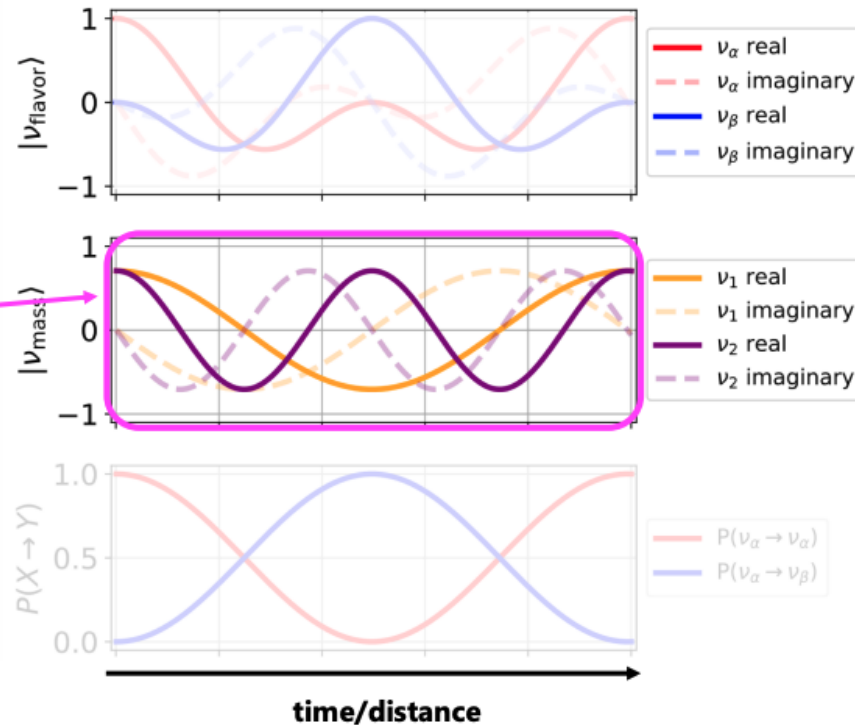
2) This means the neutrino is initially an equal mix of the two mass states
Because of 50:50 mixing in this example



A simple example (credit: T. Stuttard)

Visualise the superposition effects and resulting oscillations using simplified model...

- 2 neutrino states (flavour = ν_α, ν_β , mass = ν_1, ν_2) $\rightarrow$ flavor states are 50:50 mix of mass states ($\theta = 45^\circ$)
- $m_2 = \sqrt{2} m_1$



$$|\nu_j(L)\rangle = \exp\left\{-i \frac{m_j^2 L}{2E}\right\} |\nu_j(0)\rangle$$

Mass state evolution
(Plane wave)

3) The wavefunctions of the mass states evolve over time

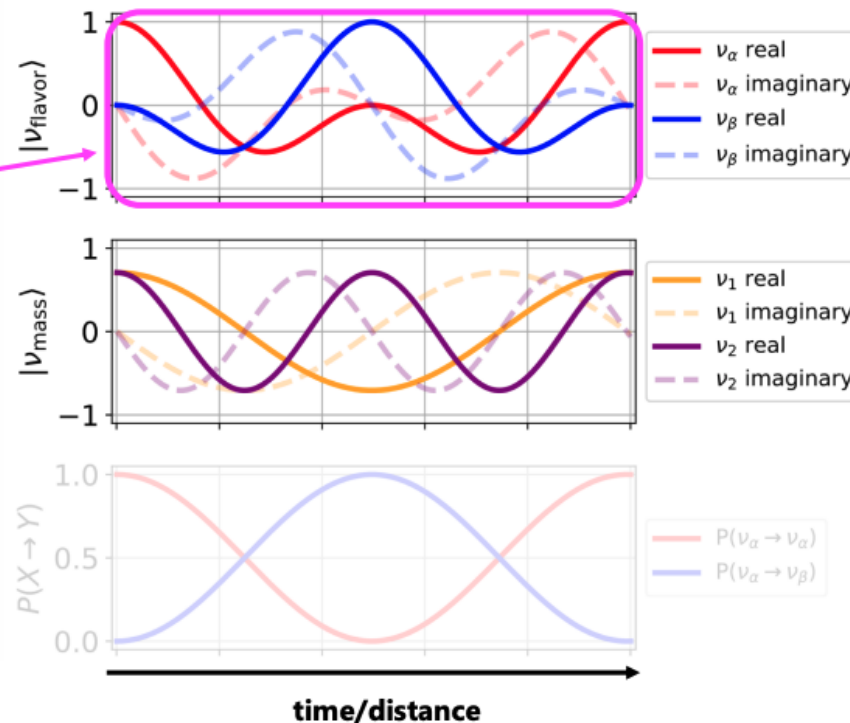
The frequency of this evolution depends on the mass state mass
The frequency of ν_2 is 2x ν_1 in this example

A simple example (credit: T. Stuttard)

Visualise the superposition effects and resulting oscillations using simplified model...

- 2 neutrino states (flavour = ν_α, ν_β , mass = ν_1, ν_2) $\rightarrow$ flavor states are 50:50 mix of mass states ($\theta = 45^\circ$)
- $m_2 = \sqrt{2} m_1$

4) The evolution of the mass states modified the flavor state superposition over time



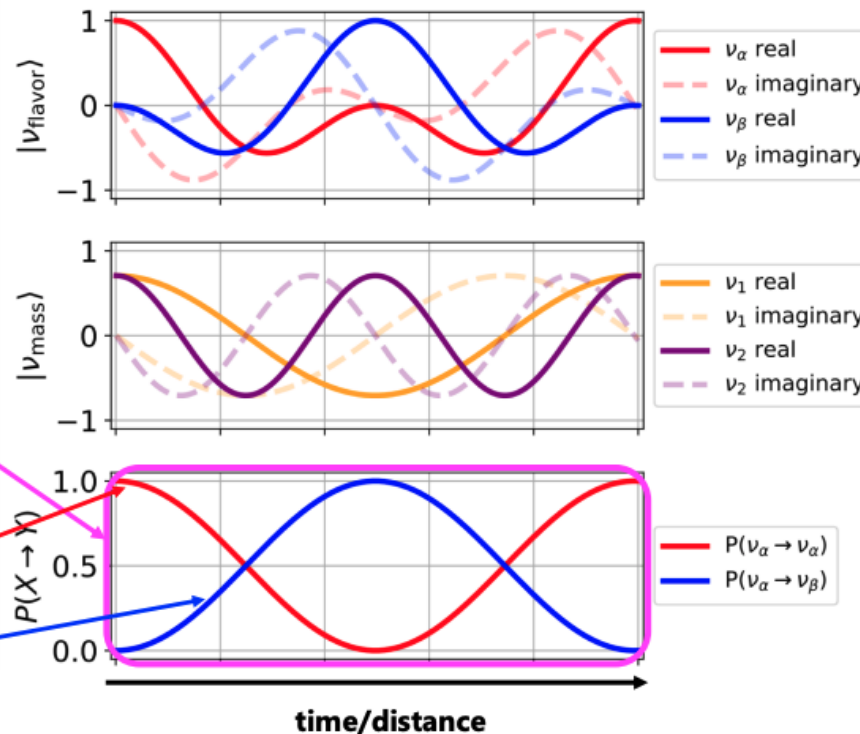
$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\} |\nu_j(0)\rangle$$

Mass state evolution
(Plane wave)

A simple example (credit: T. Stuttard)

Visualise the superposition effects and resulting oscillations using simplified model...

- 2 neutrino states (flavour = ν_α, ν_β , mass = ν_1, ν_2) $\rightarrow$ flavor states are 50:50 mix of mass states ($\theta = 45^\circ$)
- $m_2 = \sqrt{2} m_1$



$$|\nu_j(L)\rangle = \exp\left\{-i\frac{m_j^2 L}{2E}\right\} |\nu_j(0)\rangle$$

Mass state evolution
(Plane wave)

5) The probability to be detected as a given flavor thus changes over time

Initially the probability to detect as the production flavor is 100%

Probability to detect as another flavor (*oscillate*) rises and falls over time

How can we access those parameters?

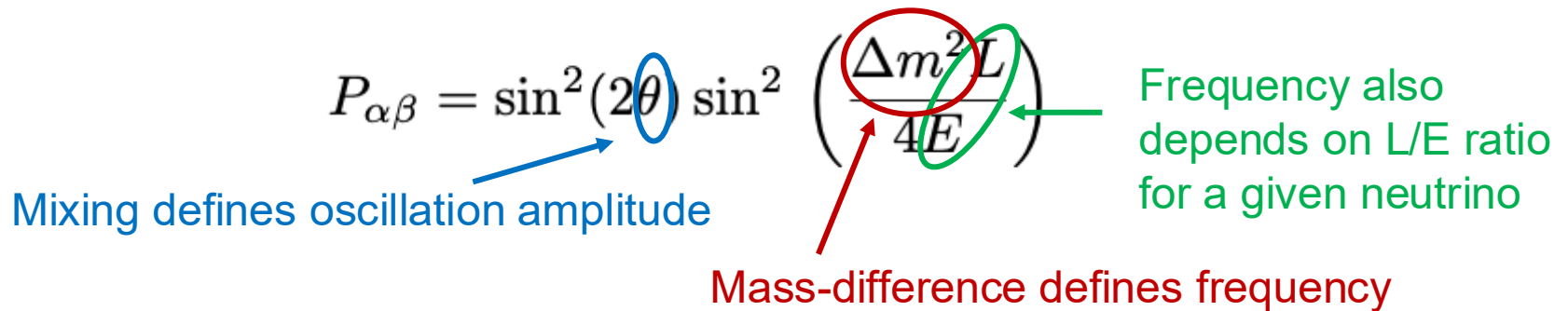
- Probability of oscillating between flavors (for simplified 2-flavour case)

$$P_{\alpha\beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Mixing defines oscillation amplitude

Mass-difference defines frequency

Frequency also depends on L/E ratio for a given neutrino

The diagram shows the neutrino oscillation probability formula $P_{\alpha\beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$. A blue arrow points from the text 'Mixing defines oscillation amplitude' to the 2θ term, which is circled in blue. A red arrow points from the text 'Mass-difference defines frequency' to the Δm^2 term, which is circled in red. A green arrow points from the text 'Frequency also depends on L/E ratio for a given neutrino' to the L/E ratio inside the second sine function, which is circled in green.

How can we access those parameters?

- Probability of oscillating between flavors (for simplified 2-flavour case)

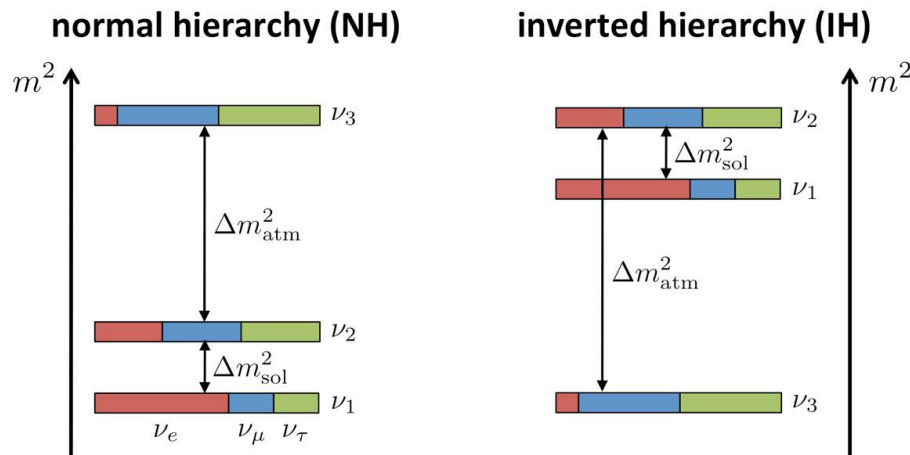
$$P_{\alpha\beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Mixing defines oscillation amplitude

Mass-difference defines frequency

Frequency also depends on L/E ratio for a given neutrino

- Insensitive to the sign of $\Delta m^2 \rightarrow$ neutrino mass ordering problem



How can we access those parameters?

- Probability of oscillating between flavors (for simplified 2-flavour case)

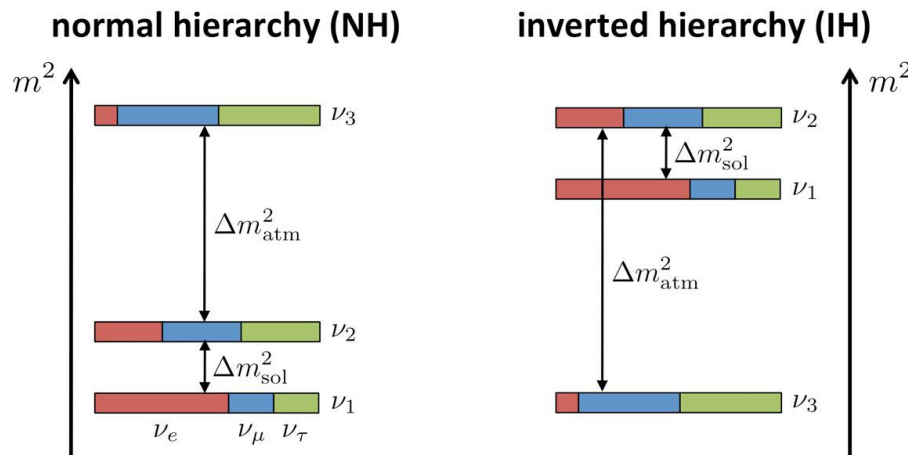
$$P_{\alpha\beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Mixing defines oscillation amplitude

Mass-difference defines frequency

Frequency also depends on L/E ratio for a given neutrino

- Insensitive to the sign of $\Delta m^2 \rightarrow$ neutrino mass ordering problem



Modified oscillation effects for neutrinos passing through matter

Neutrino Oscillations

- Neutrino mixing characterised by the (complex) PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- If unitary, can be parameterised as 3 mixing angles and a CP-violating phase

$$\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$$

- Oscillation frequency depends on the mass-difference between mass states

$$\Delta m_{21}^2, \Delta m_{31}^2$$

→ 6 oscillation parameters to measure in experiments

Experiments

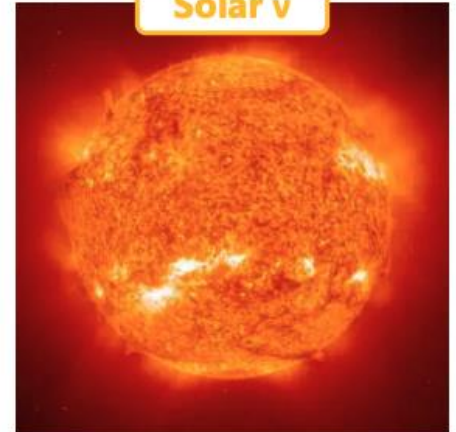
Accelerators



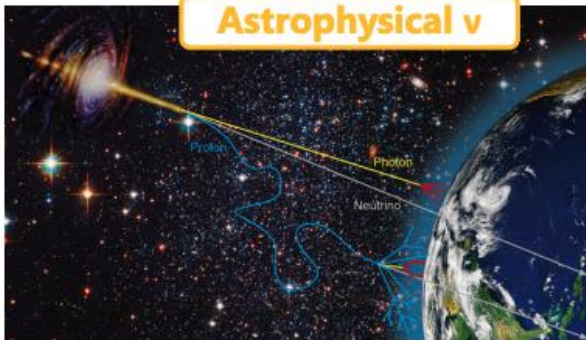
Nuclear reactors



Solar ν



Astrophysical ν



Atmospheric ν

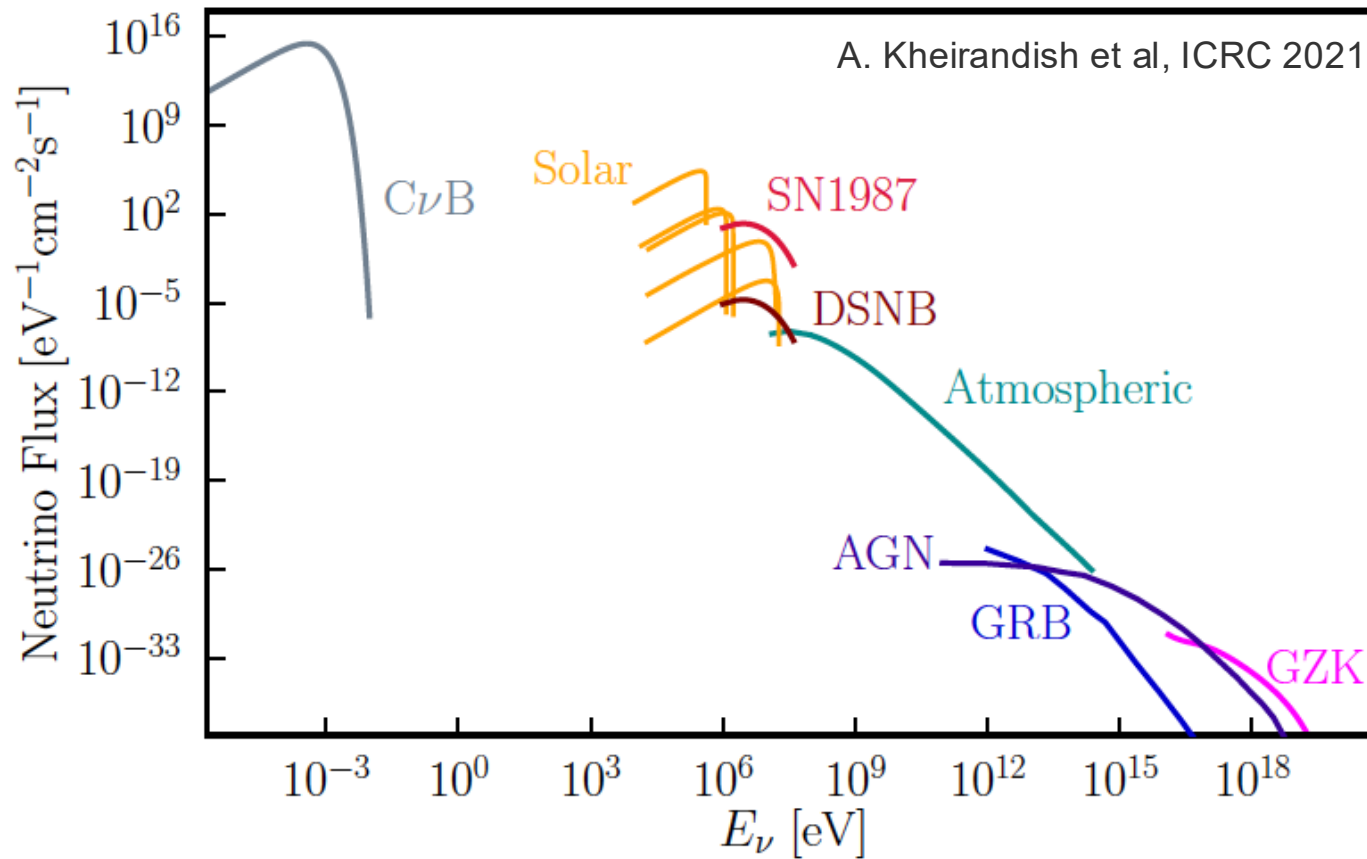




Take home message

Too few electron neutrinos have been detected from the sun, but the number matches expectations if all flavors are considered.

This is explained by neutrino oscillation, which only works when neutrinos have mass.



↔

Ideas: neutrino capture
on unstable nucleus
(e.g. tritium)

↔

Neutrino capture on
stable nucleus
(Chlorine, Gallium)

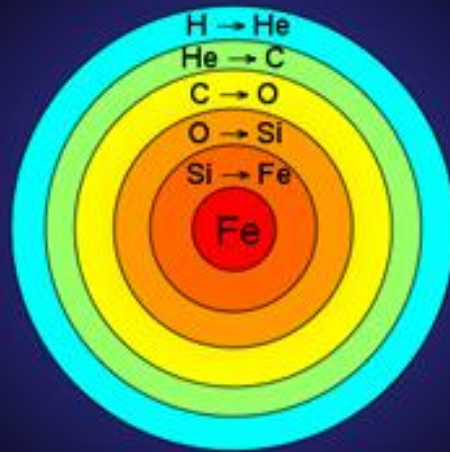
↔

Water / ice
Cherenkov
detectors

↔

Radio arrays,
cosmic-ray
detectors

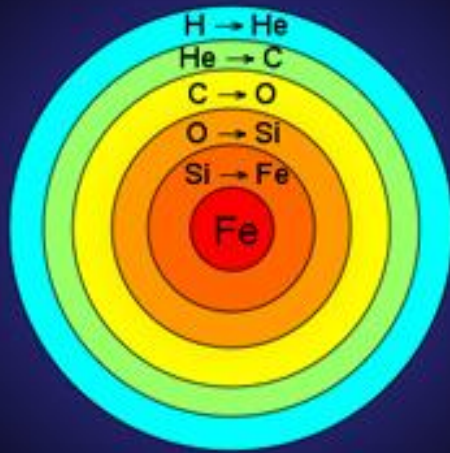
Supernova Neutrinos



For a 25 solar mass star:

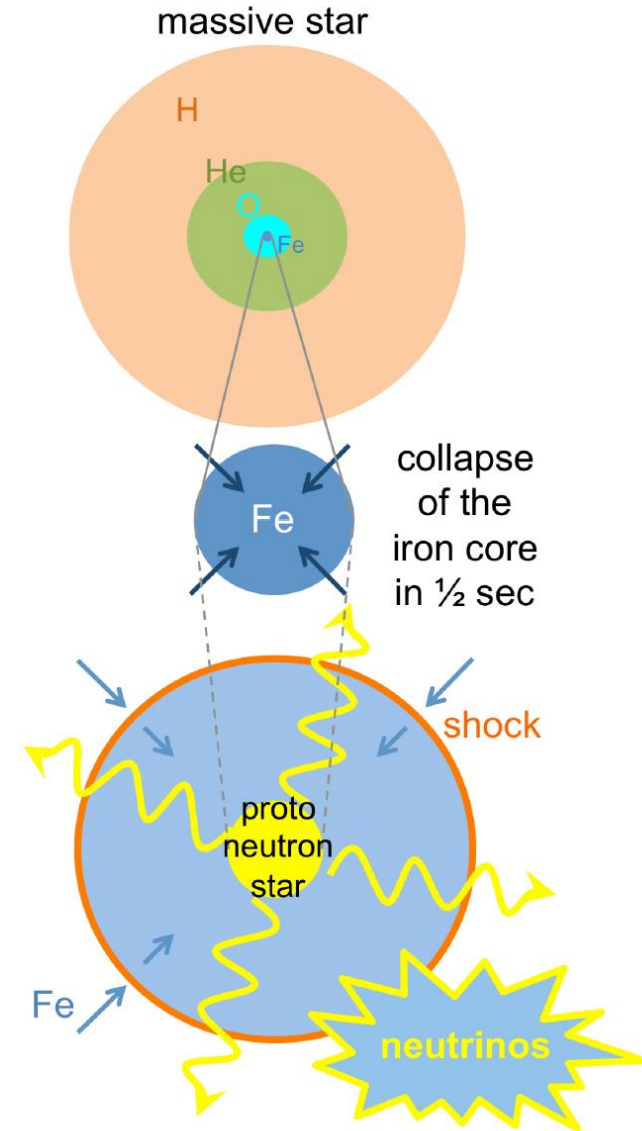
Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Supernova Neutrinos

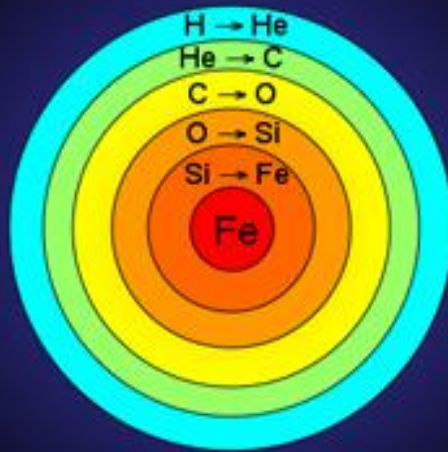


For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second



Supernova Neutrinos

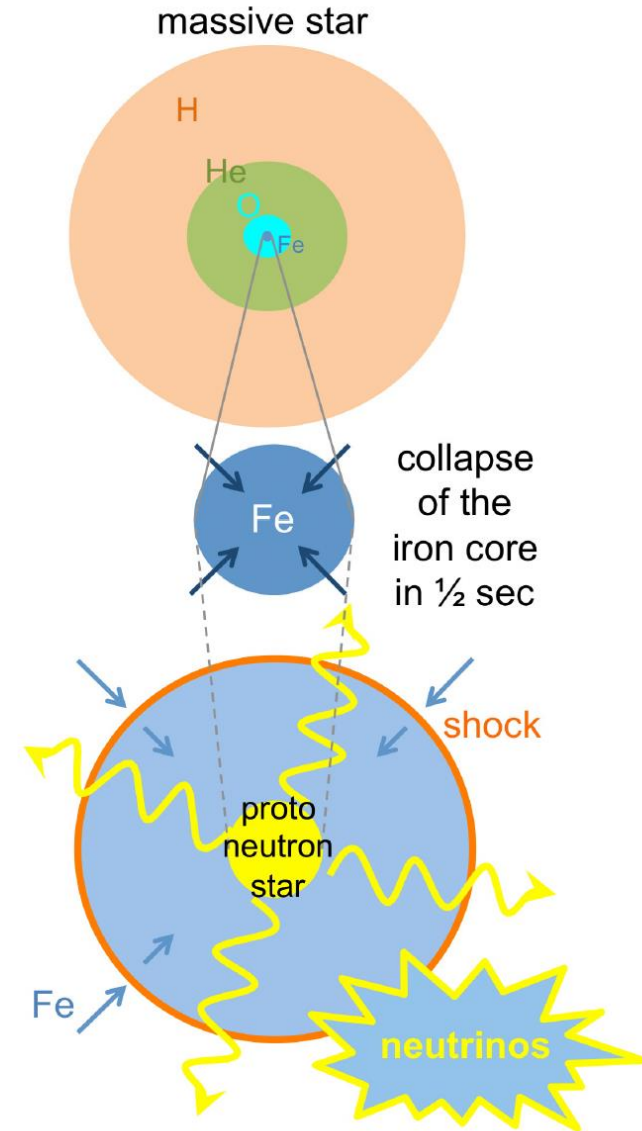


For a 25 solar mass star:

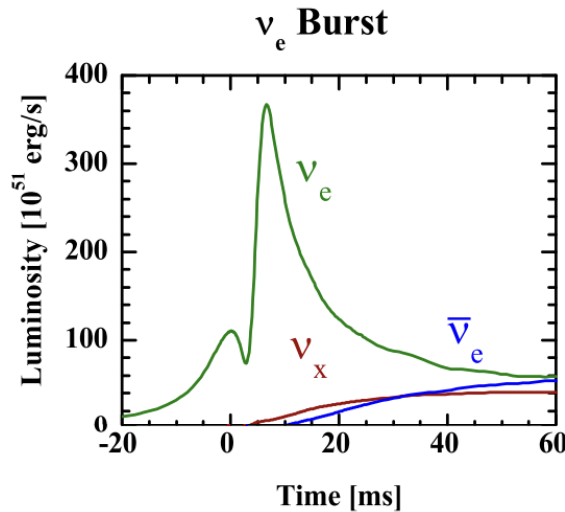
Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Neutronization burst: $e^- + p \rightarrow n + \nu_e$
 Thermal neutrinos of all flavors

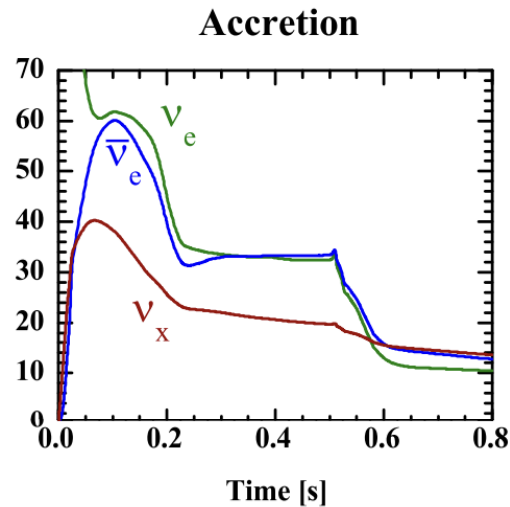
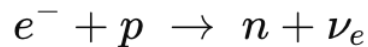
- $\sim 10^{58}$ neutrinos in ~ 10 s
- 99% of gravitational energy
- typical energy: 10-20 MeV



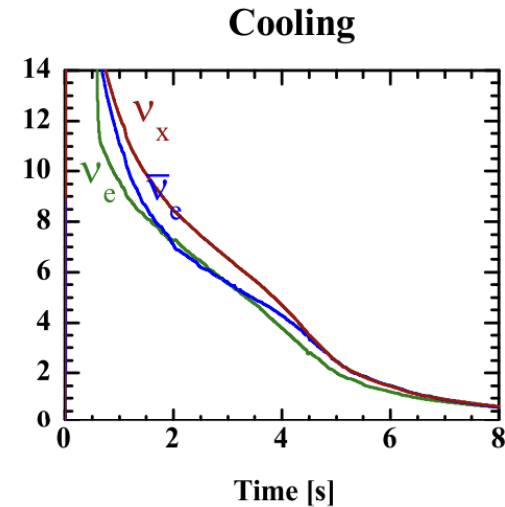
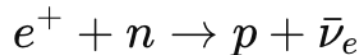
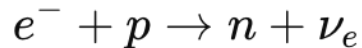
Expected neutrino signal



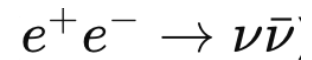
Initial neutronization burst



Material falls onto the proto-neutron star, e^- and e^+ in hot plasma



proto-neutron star loses trapped thermal energy mainly by neutrino emission of all flavors

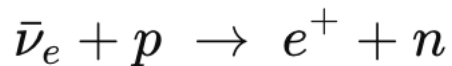


(Super) Kamiokande

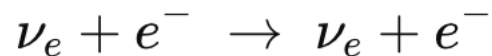


Detection channels:

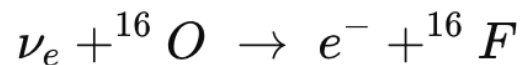
Inverse beta decay:



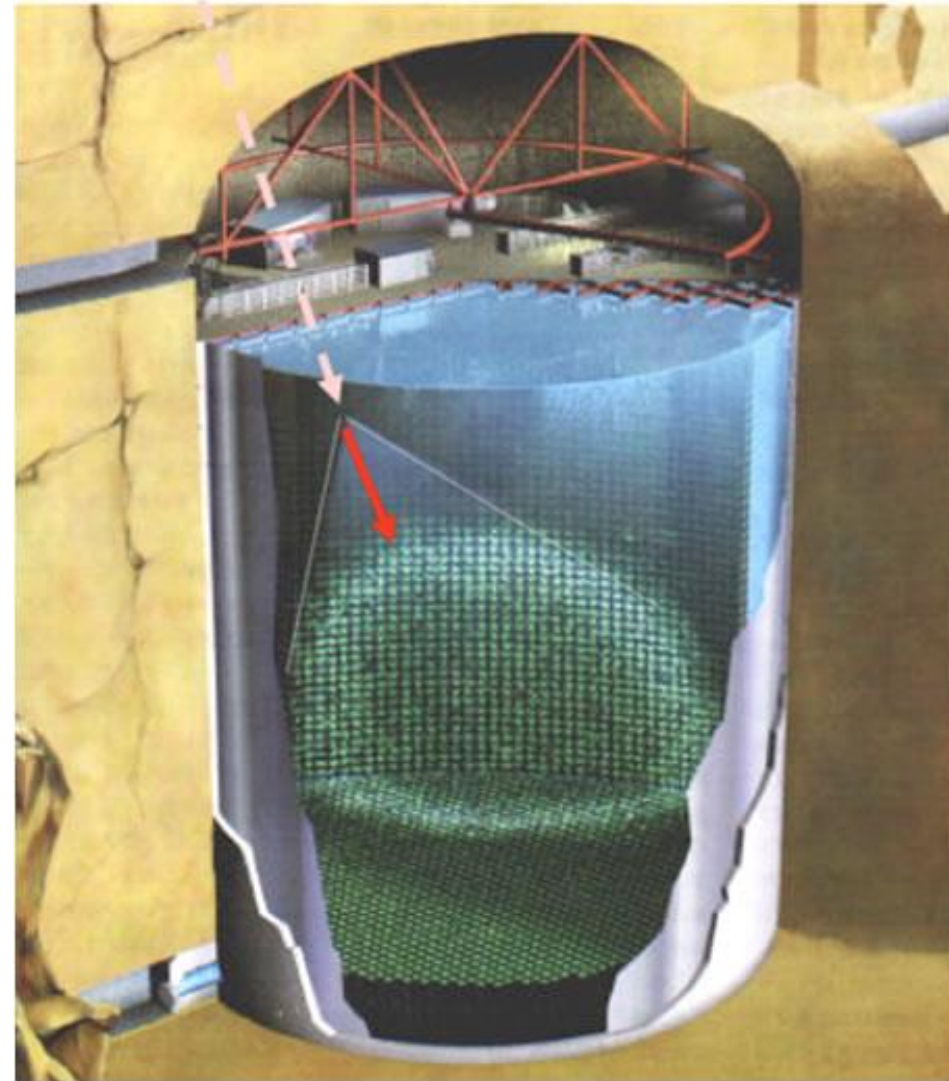
Elastic scattering:



Charged current absorption on oxygen:



Volume: 3kT (50kT)

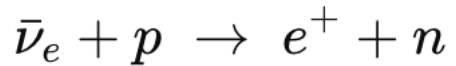


(Super) Kamiokande



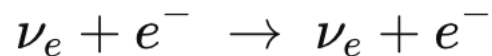
Detection channels:

Inverse beta decay:

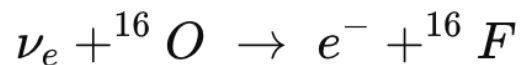


Most
efficient

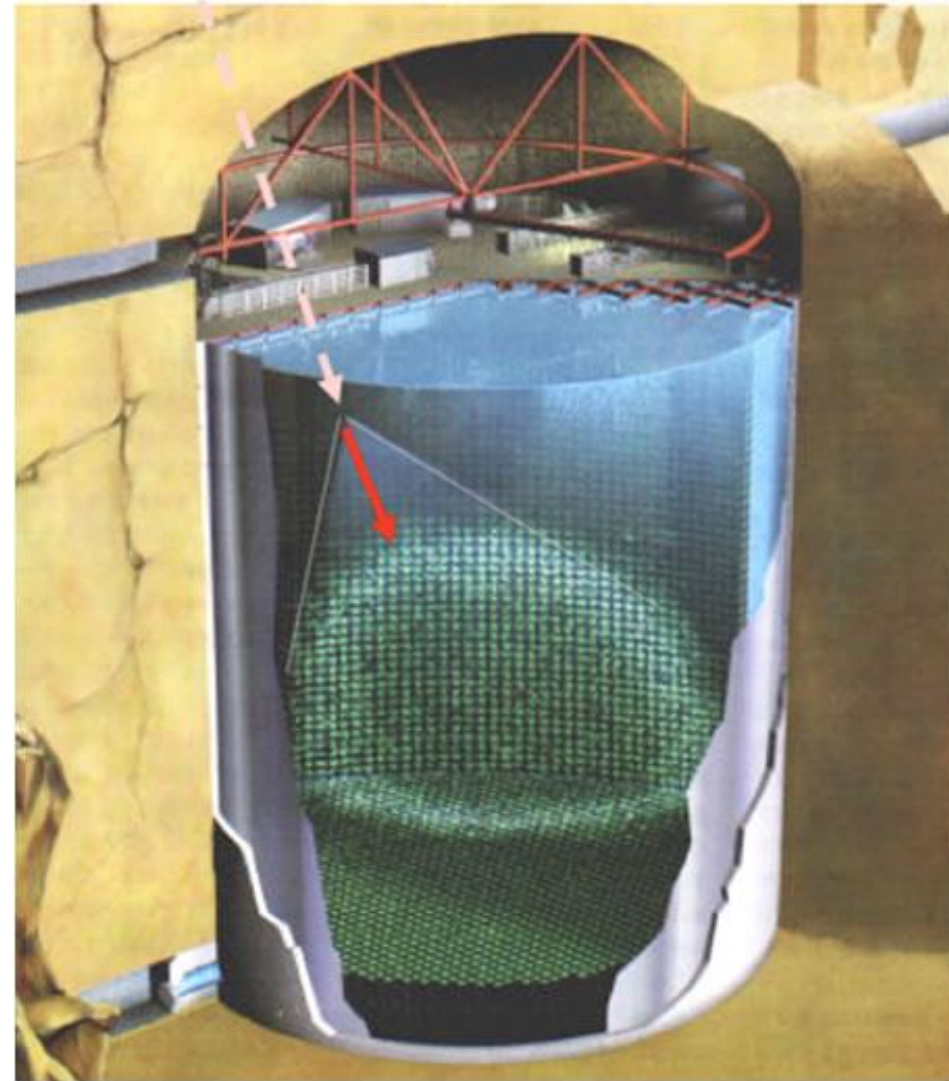
Elastic scattering:



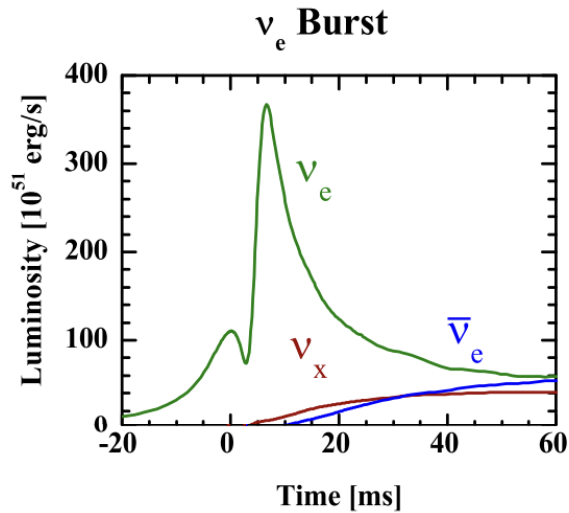
Charged current absorption on
oxygen:



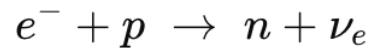
Volume: 3kT (50kT)



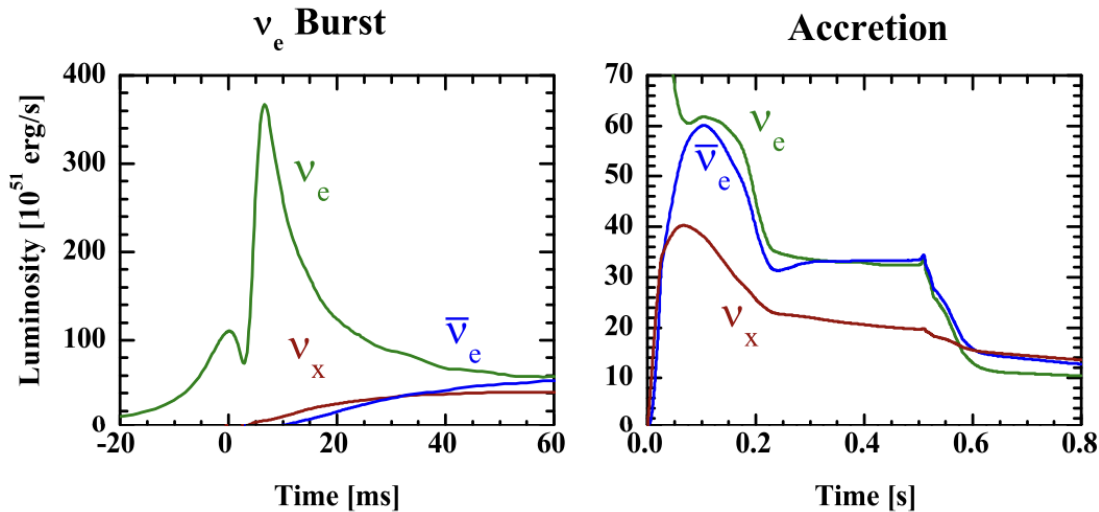
Expected neutrino signal



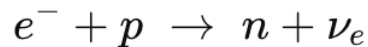
Initial neutronization
burst



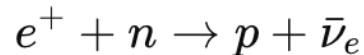
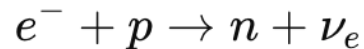
Expected neutrino signal



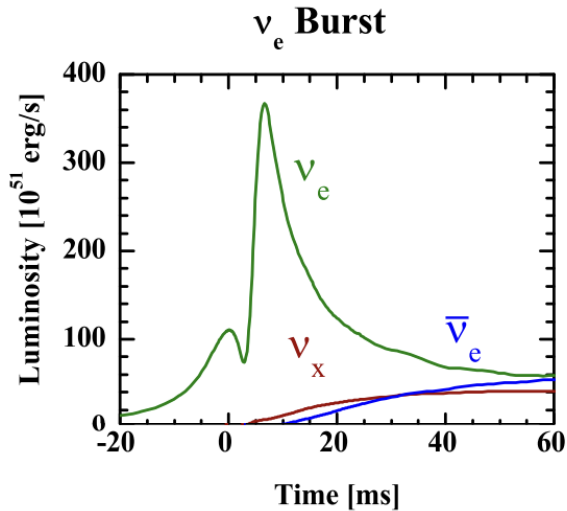
Initial neutronization
burst



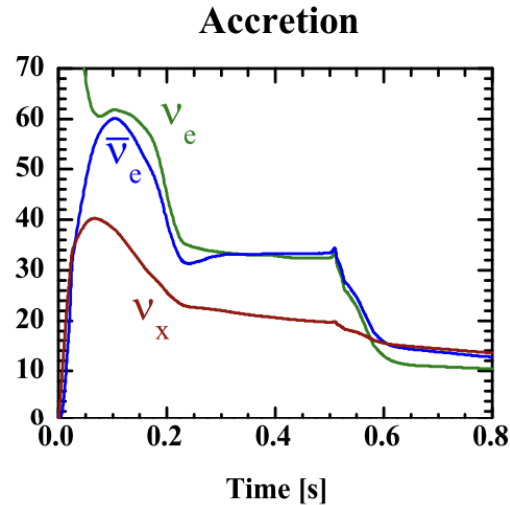
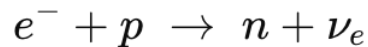
Material falls onto the
proto-neutron star,
 e^{-} and e^{+} in hot plasma



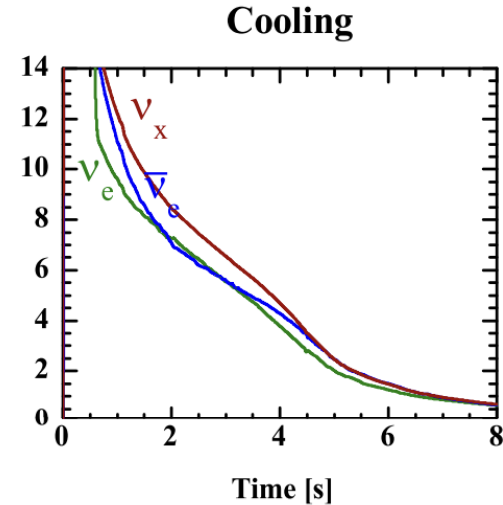
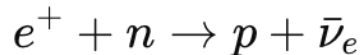
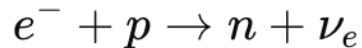
Expected neutrino signal



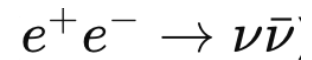
Initial neutronization burst



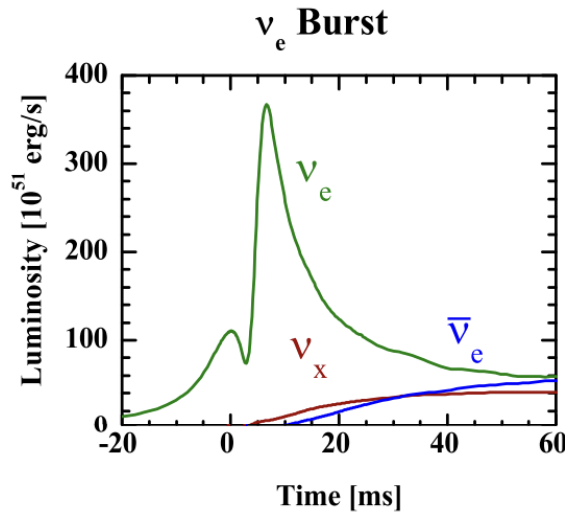
Material falls onto the proto-neutron star, e^- and e^+ in hot plasma



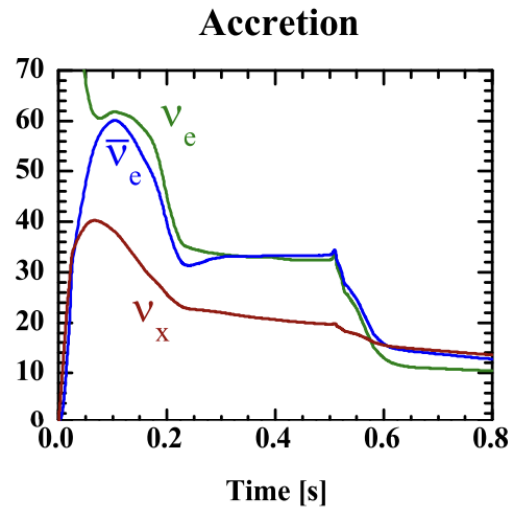
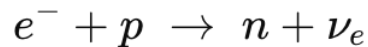
proto-neutron star loses trapped thermal energy mainly by neutrino emission of all flavors



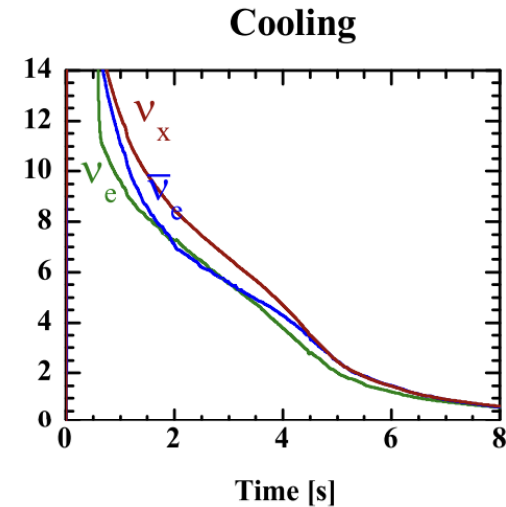
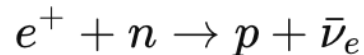
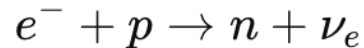
Expected neutrino signal



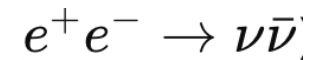
Initial neutronization burst



Material falls onto the proto-neutron star, e^- and e^+ in hot plasma



proto-neutron star loses trapped thermal energy mainly by neutrino emission of all flavors



Expected signal in Super-K dominated by **anti-electron neutrinos**

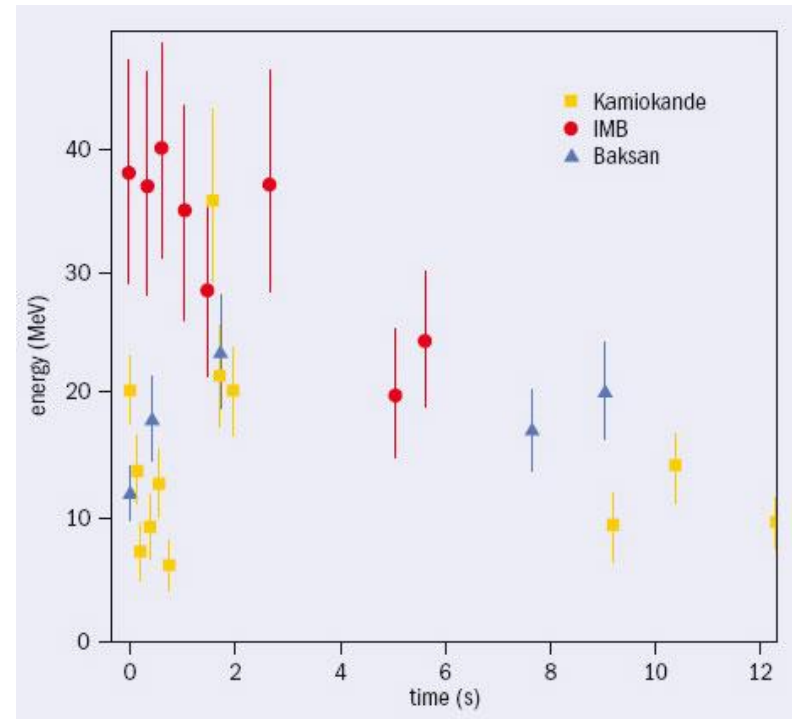
First and only Supernova neutrino detection

Optical detection of SN1987A in LMC



Neutrinos arrived 2-3h earlier

MeV neutrino burst



Location of Magellanic Clouds

Distance: 50kpc = 160000 Ly

NGC 2419

300 000 l.y.

160 000 l.y.

200 000 l.y.

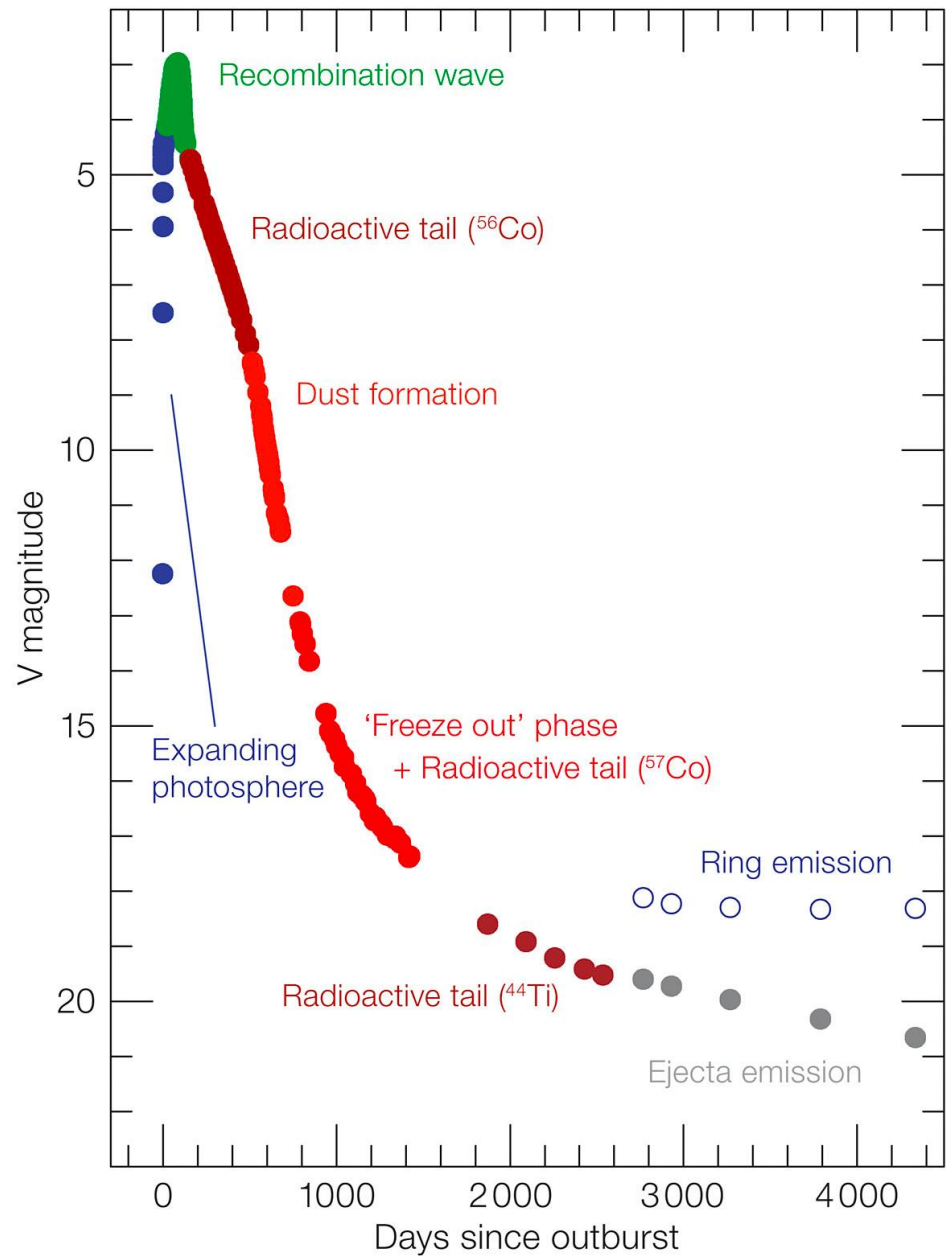
LARGE MAGELLANIC CLOUD

SMALL MAGELLANIC CLOUD

MILKY WAY

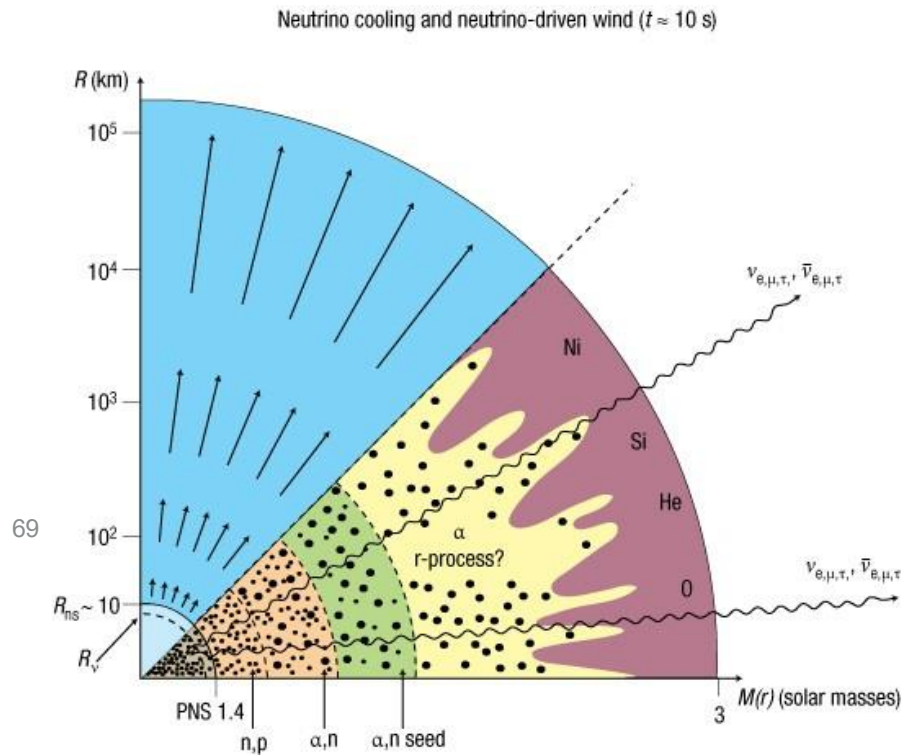


SN1987A light curve



First (and only) detection of a Supernova

First direct confirmation of our
basic picture of a stellar collapse

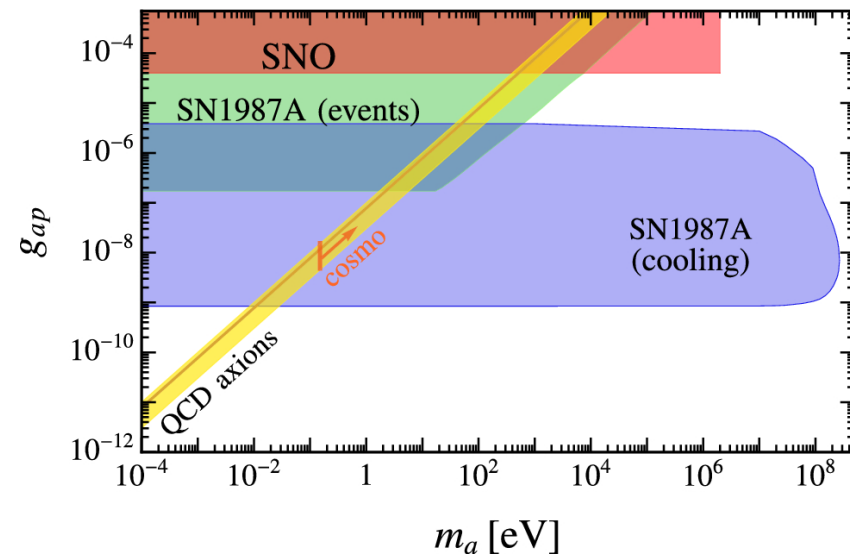
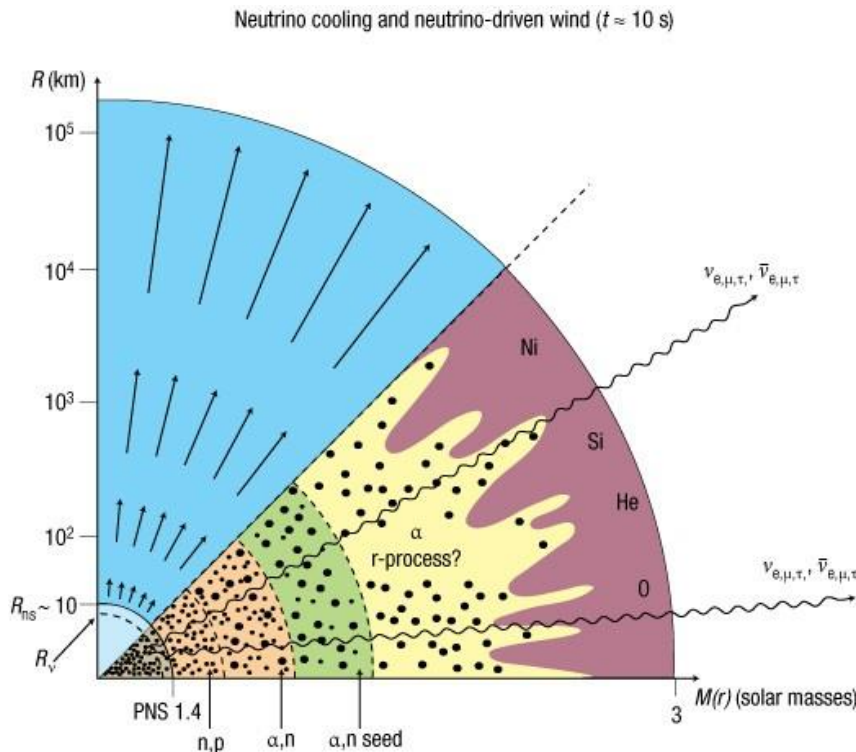


Woosely & Janka,
Nature Physics 2005

First (and only) detection of a Supernova

First direct confirmation of our basic picture of a stellar collapse

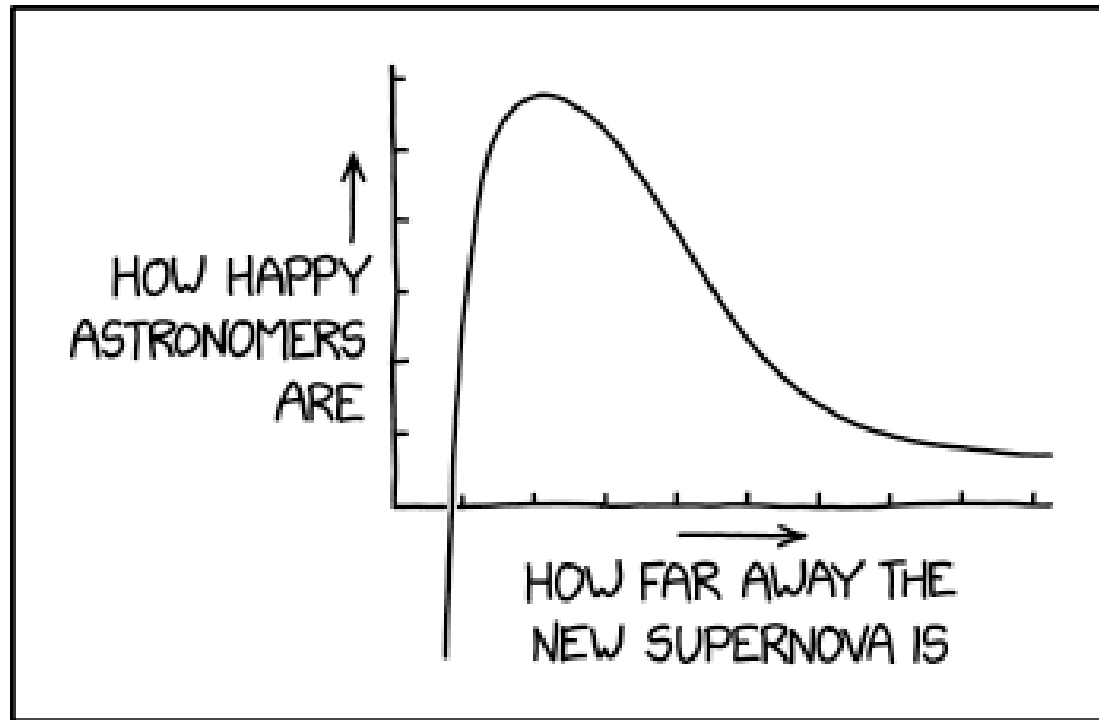
Constraints on exotic physics (e.g. axions)



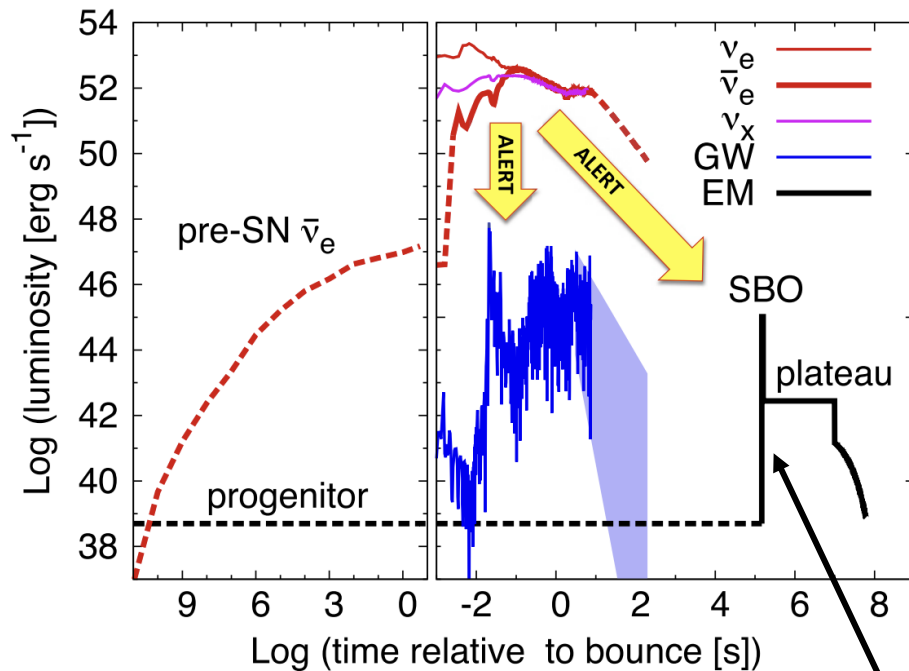
Lella et al. PRD 109 (2024)

Woosely & Janka,
Nature Physics 2005

Are we ready for the next Galactic Supernova?!

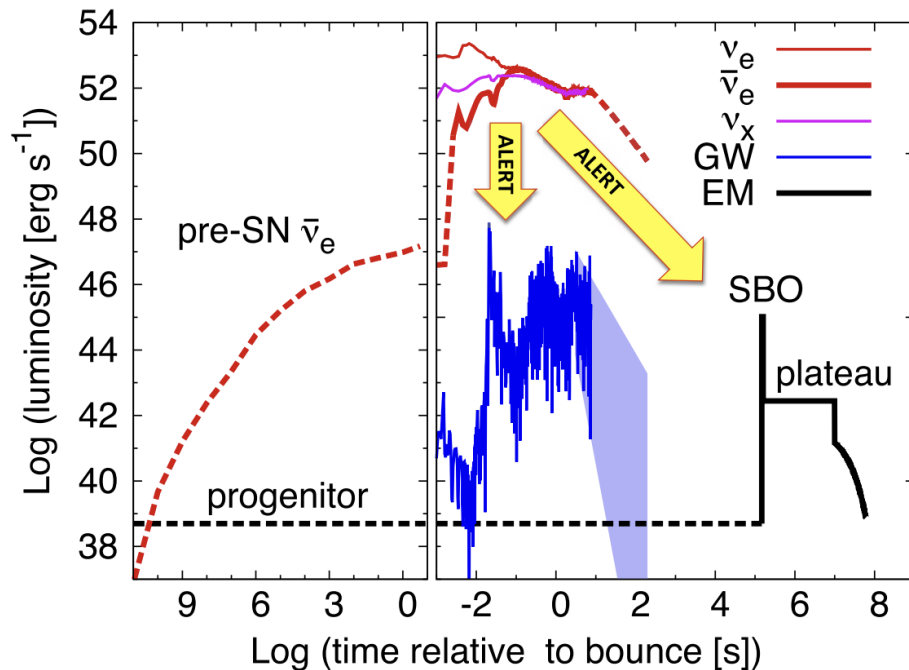


Supernova early warning system



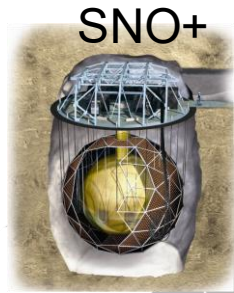
Shock breakout in X-ray
and UV emission

Supernova early warning system

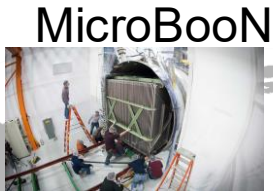


MeV neutrino burst as trigger for electromagnetic supernovae observations

Detectors participating in SNEWS

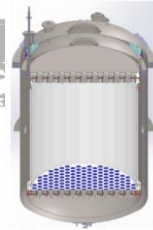


SNO+



MicroBooN

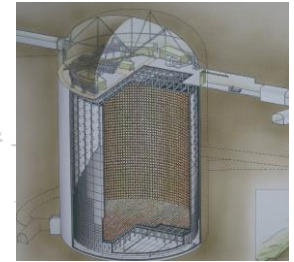
XENONnT



Baksan



Super-K



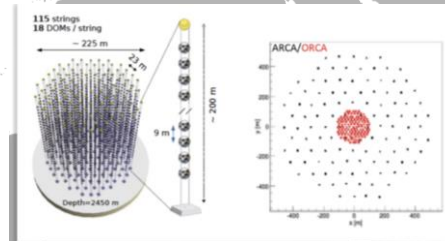
SBND



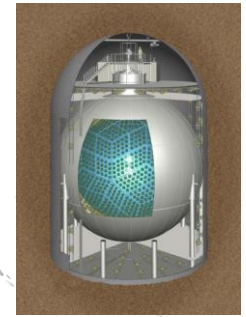
LVD



NOvA



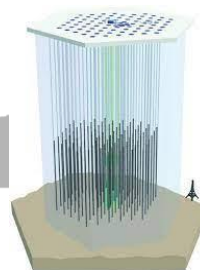
KM3NeT



KamLAND

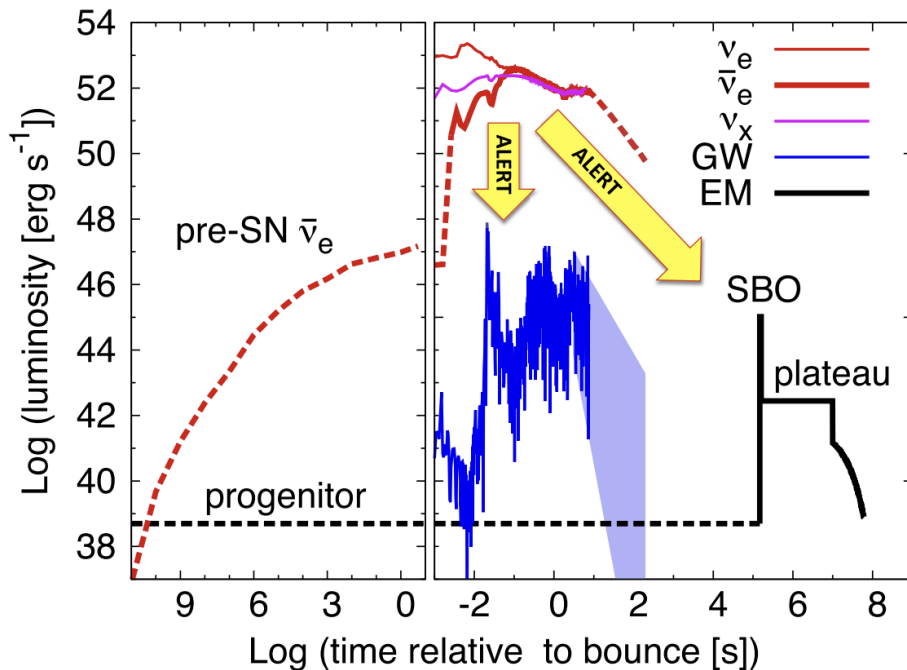


HALO



IceCube

Supernova early warning system

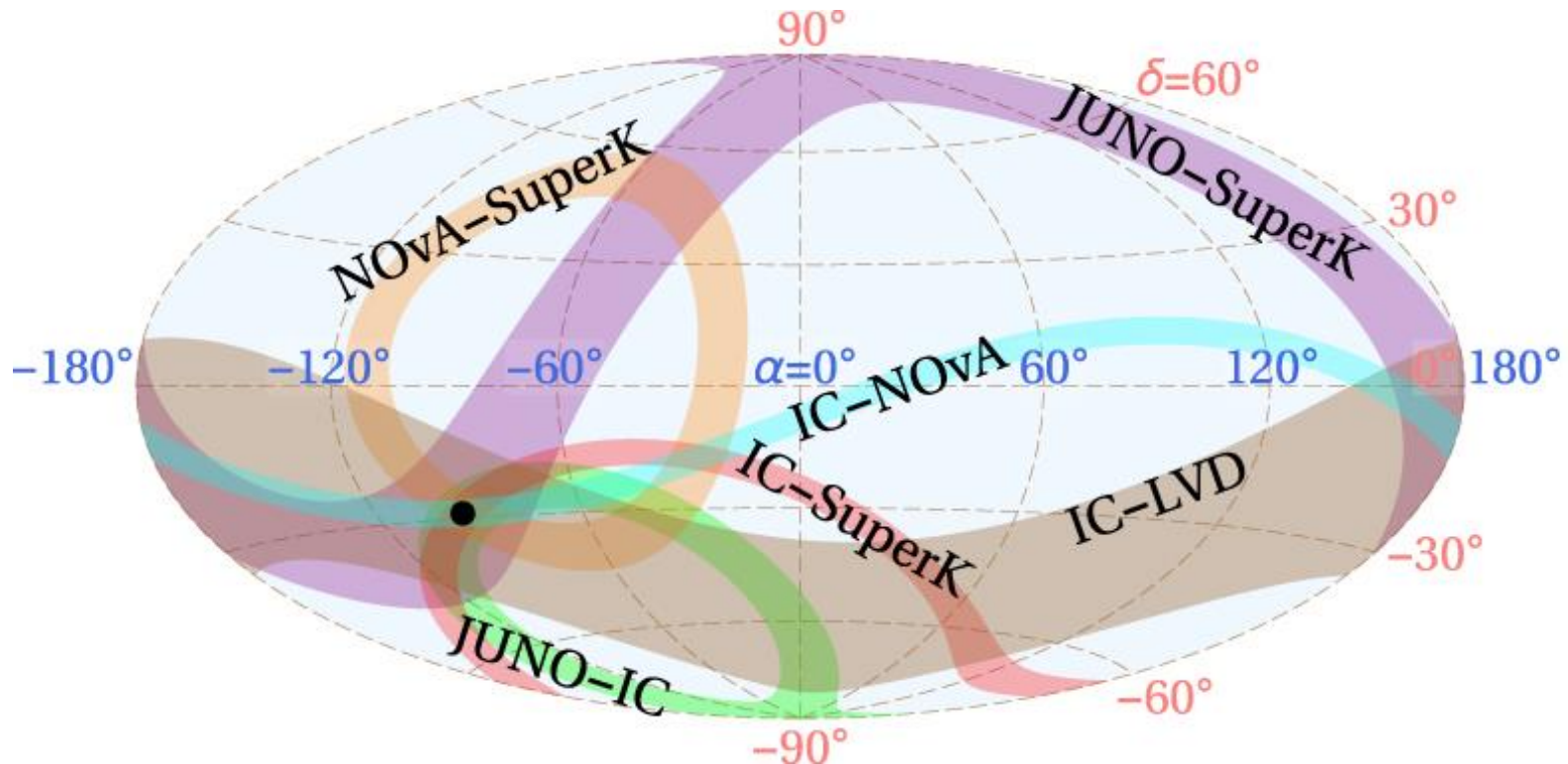


MeV neutrino burst as trigger for electromagnetic supernovae observations

SNEWS 2.0:

- new infrastructure
- public sub-threshold alerts
- pointing using inter-experiment triangulation
- searches for pre-supernova neutrinos

Supernova localization



Coordinated follow-up observations with wide-field-of-view instruments are necessary

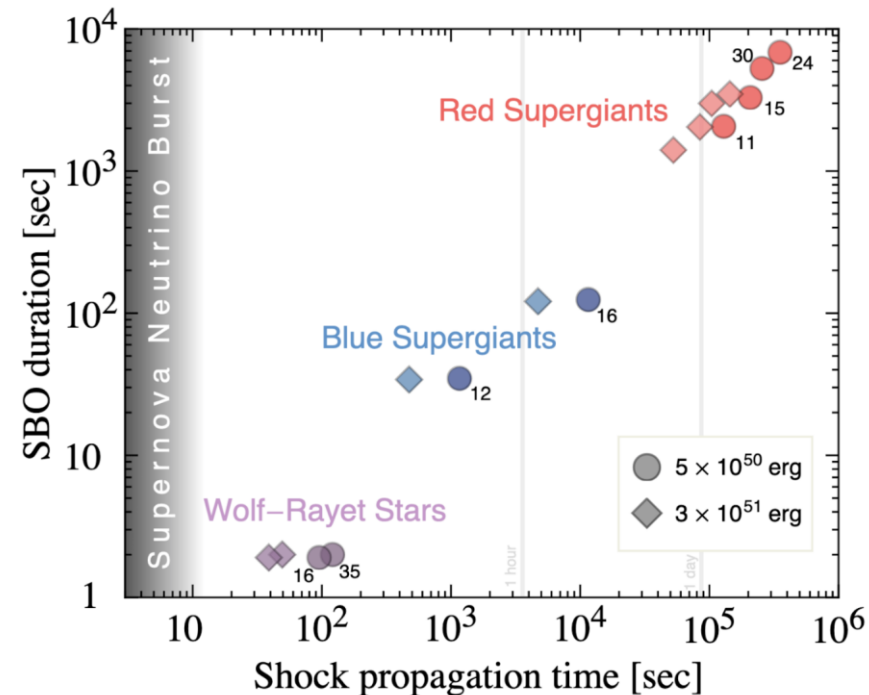
Catching the next Galactic Neutrino Supernova

- Unprecedented insights into the explosion mechanism
- Information about surrounding material
- Spatially resolved imaging of early phases of explosion

Catching the next Galactic Neutrino Supernova

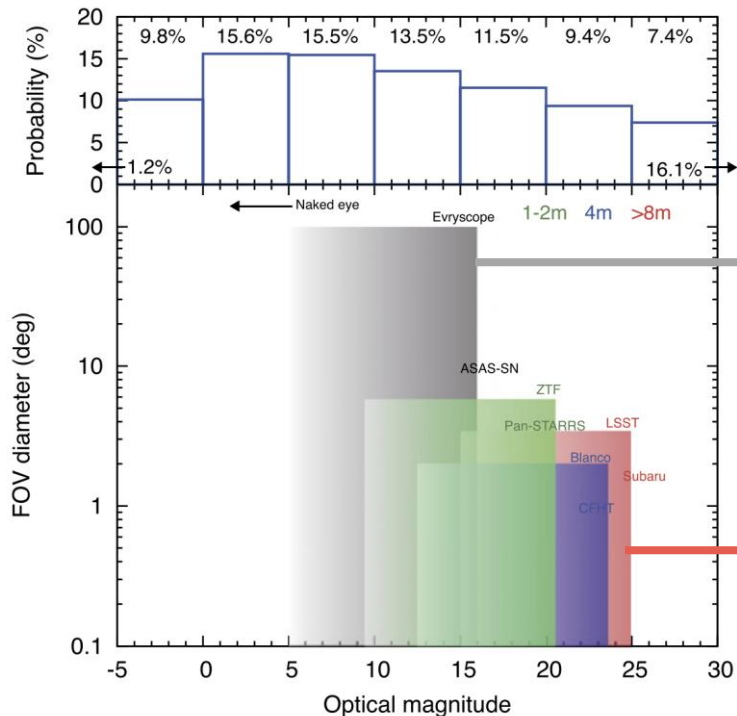
- Unprecedented insights into the explosion mechanism
- Information about surrounding material
- Spatially resolved imaging of early phases of explosion

Delay between neutrino burst and optical signal: 2 min to 2 days

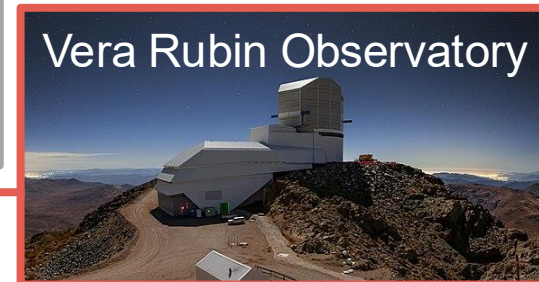


Catching the next Galactic Neutrino Supernova

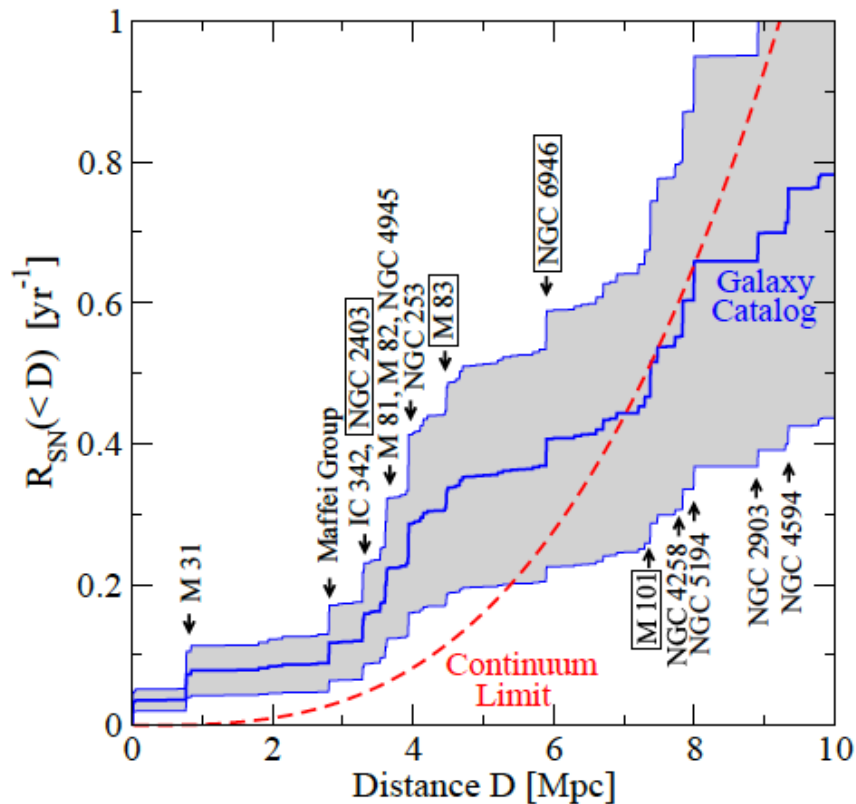
Detectability of shock breakout



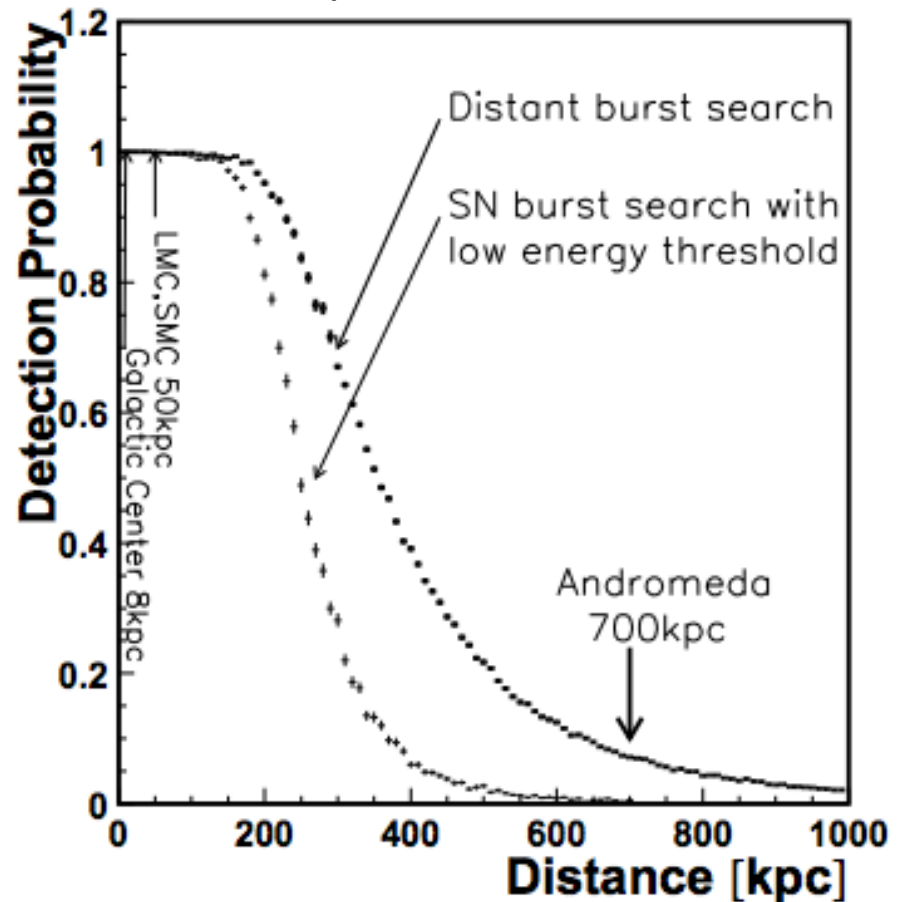
Optical counterpart can appear within minutes of neutrino alert → take full advantage of once-in-a-lifetime event



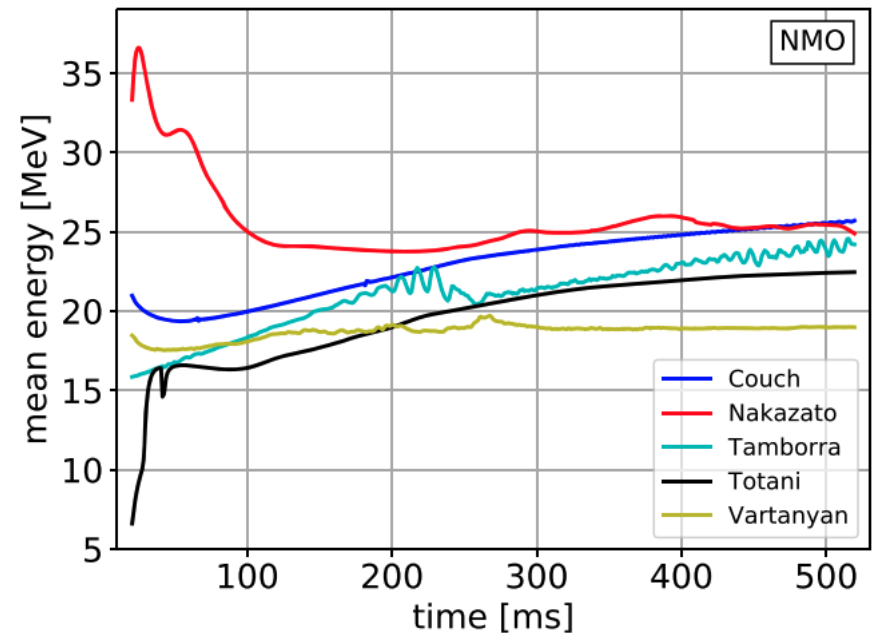
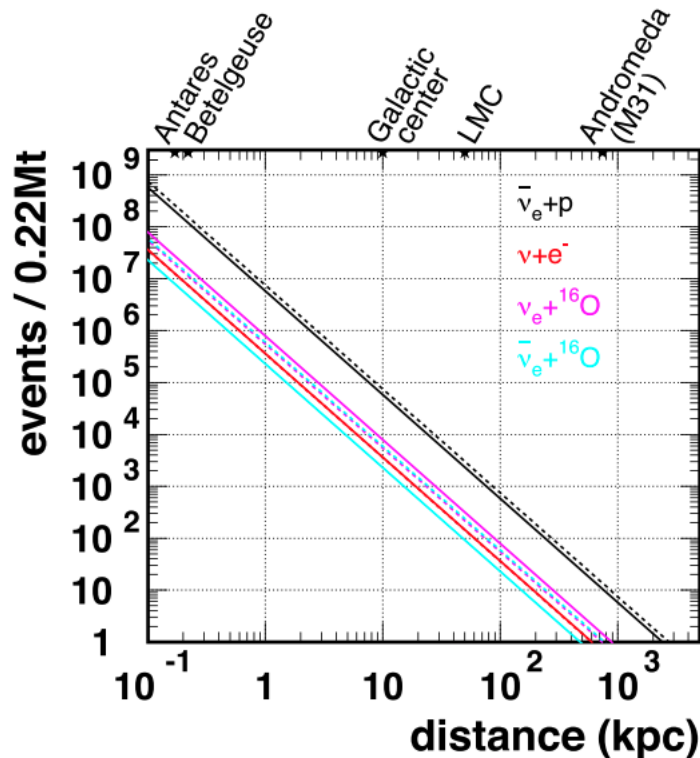
Sensitivity to Supernovae today



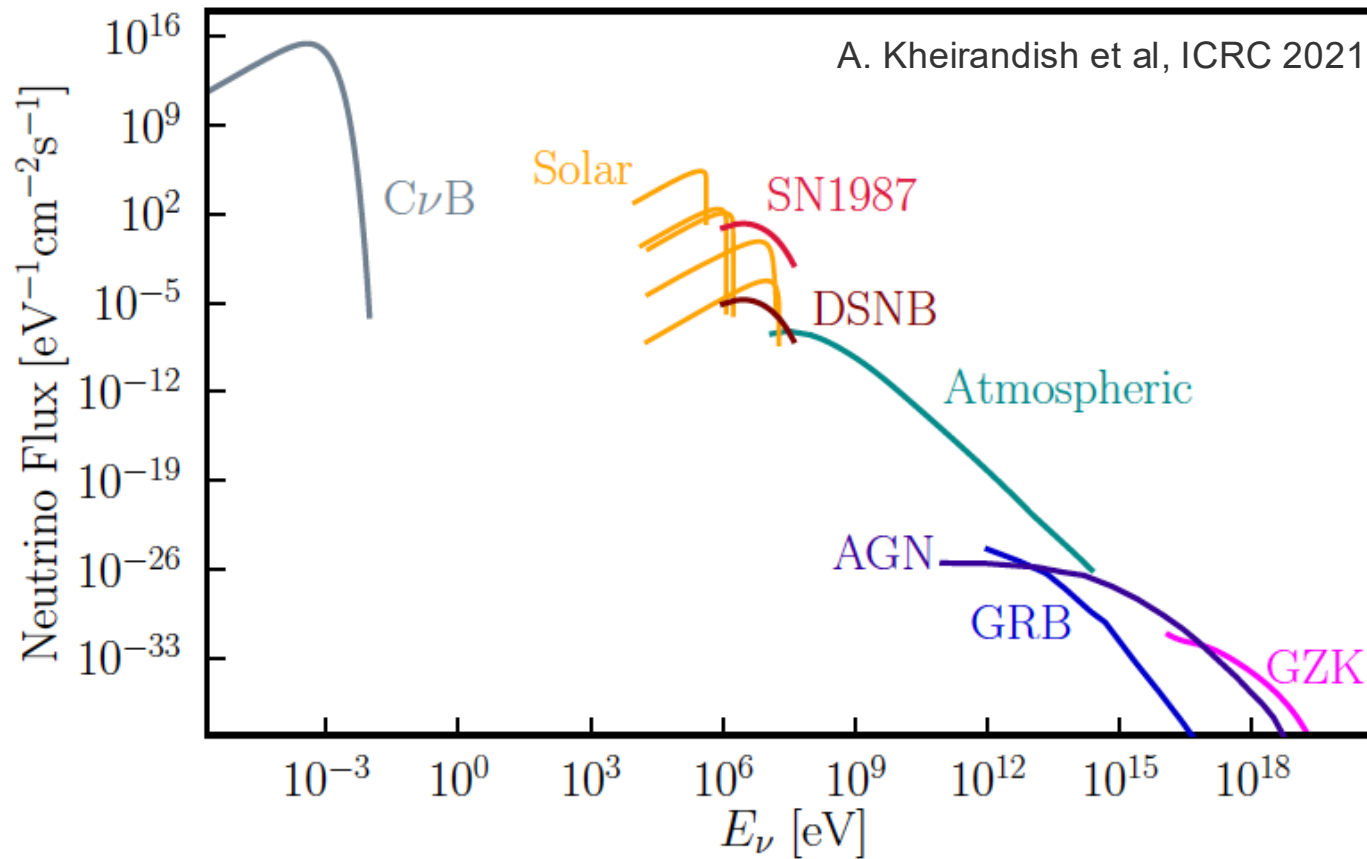
Super-Kamiokande



In the future: Hyper-Kamiokande (~2030)



Distinguish different supernova models



↔

Ideas: neutrino capture
on unstable nucleus
(e.g. tritium)

↔

Neutrino capture on
stable nucleus
(Chlorine, Gallium)

↔

Water / ice
Cherenkov
detectors

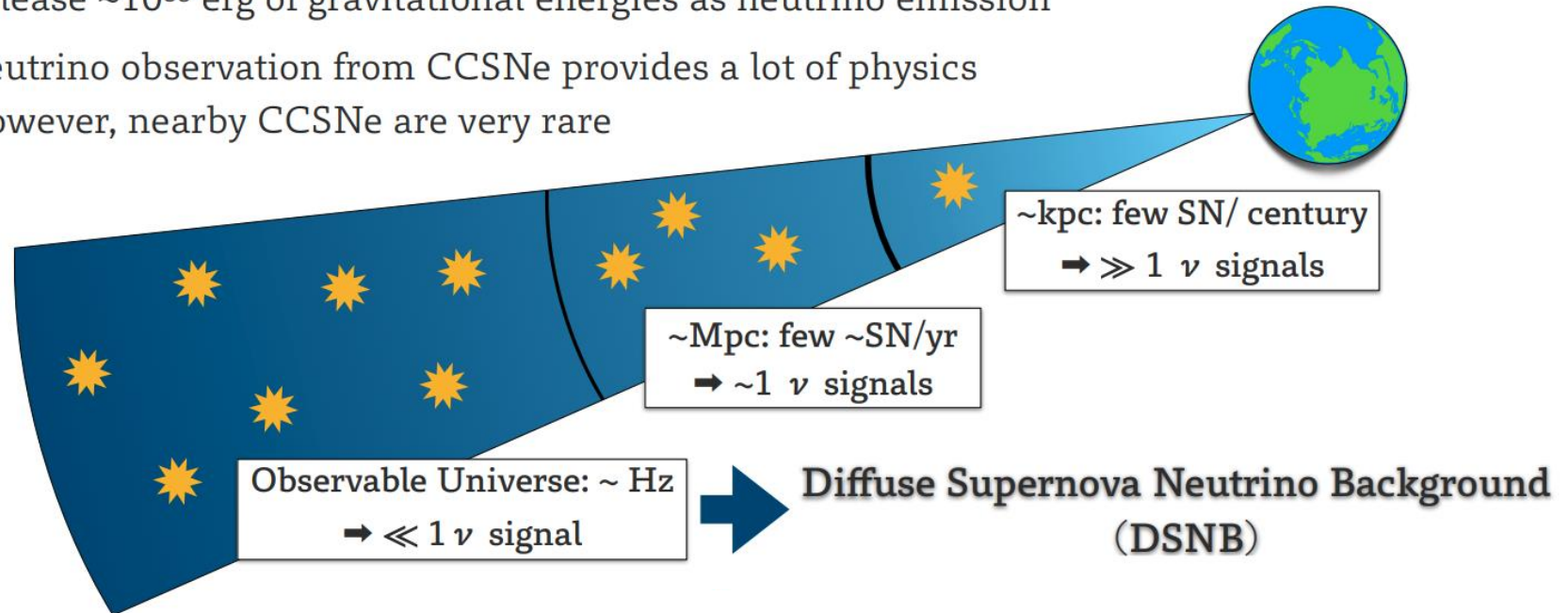
↔

Radio arrays,
cosmic-ray
detectors

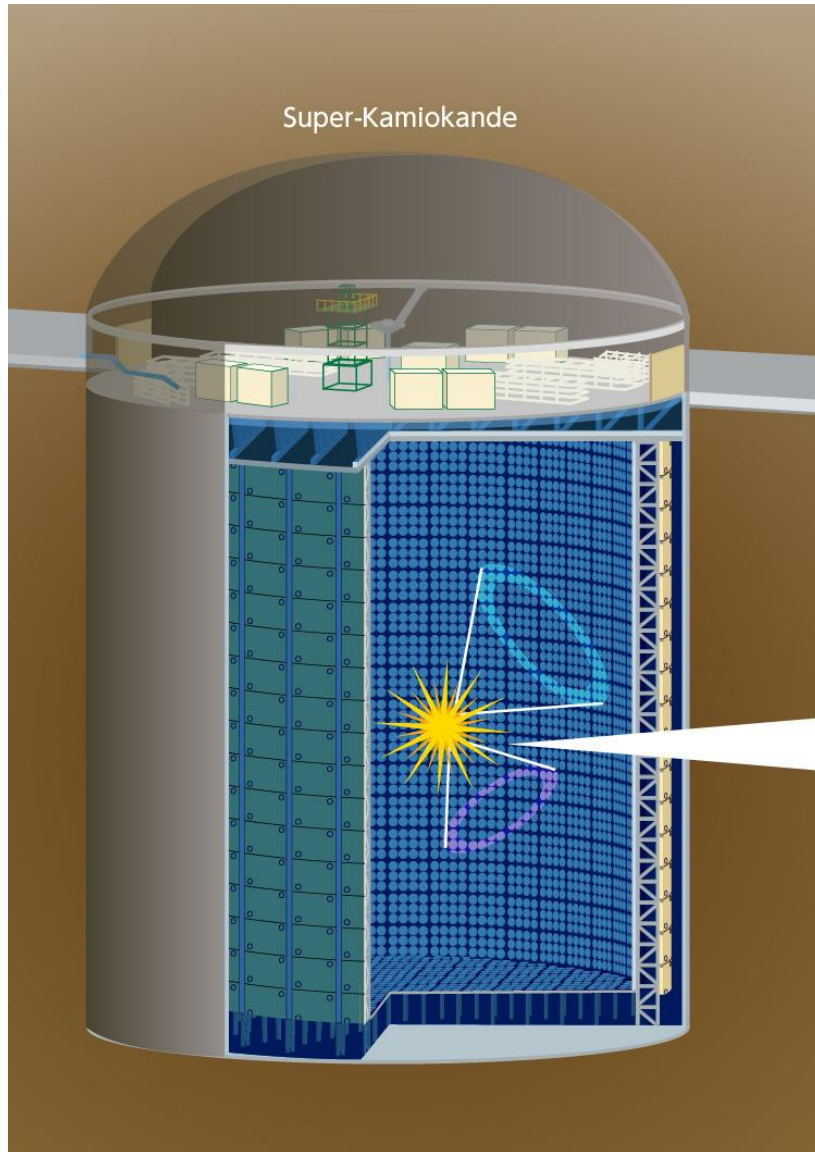
Diffuse Supernova Background (DSNB)

Core-Collapse Supernova (CCSN)

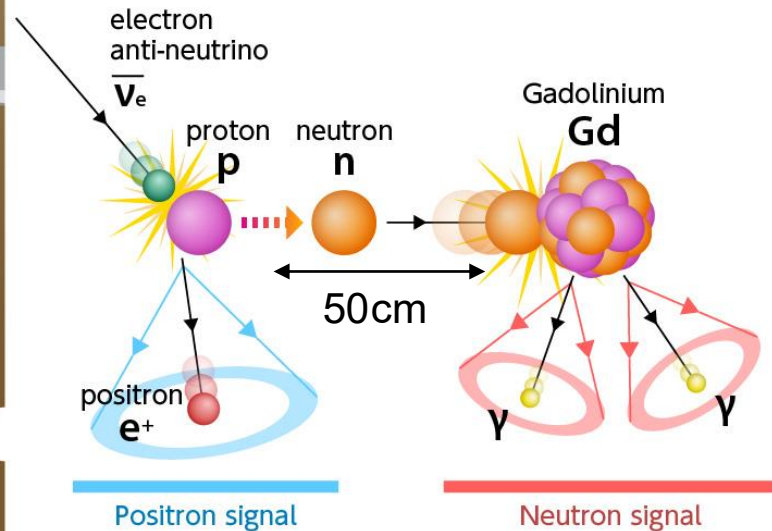
- Release $\sim 10^{53}$ erg of gravitational energies as neutrino emission
 - Neutrino observation from CCSNe provides a lot of physics
- However, nearby CCSNe are very rare



Super Kamiokande with Gadolinium



Gadolinium: highest affinity for capturing neutrons among all elements in nature.

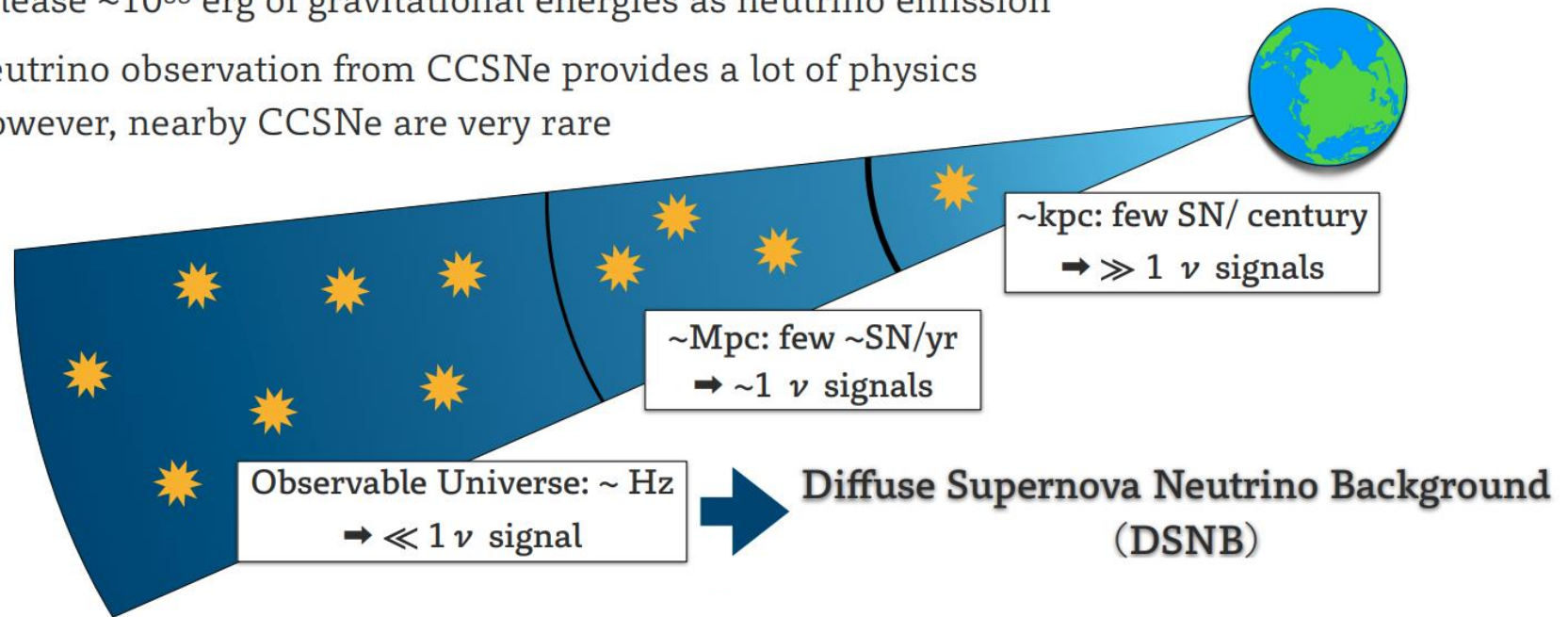


0.1% concentration of Gd: 90% of neutrons will be captured
→ highly efficient background suppression

Diffuse Supernova Background (DSNB)

Core-Collapse Supernova (CCSN)

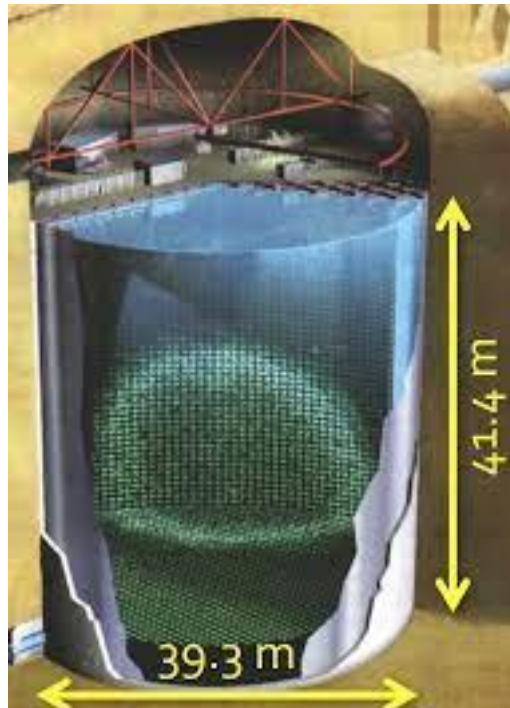
- Release $\sim 10^{53}$ erg of gravitational energies as neutrino emission
 - Neutrino observation from CCSNe provides a lot of physics
- However, nearby CCSNe are very rare



- Also, the latest update of DSNB search in SK-Gd using additional more condensed Gd-water data are exhibited
 - $\rightarrow$ There is no significant DSNB signal, however, some excess appears to be visible in the signal region, which is **2.3 σ tension from non-DSNB hypothesis**
- Looking forward to discovery of DSNB in the next decade !!

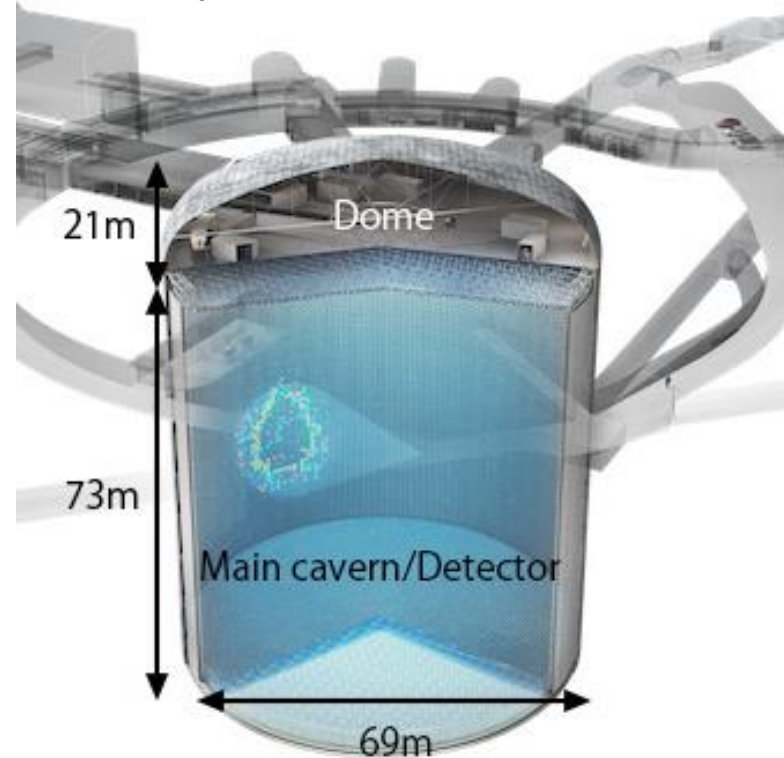
Next Generation Detector: Hyper Kamiokande

Super Kamiokande



Volume: 50kT

Hyper Kamiokande



Volume: 260kT

Data taking start in 2027



Take home message

A short burst of $\sim 10\text{MeV}$ neutrinos is expected from a core-collapse supernova and can be detected for Galactic source, expected only 1-3 times per 100 years.

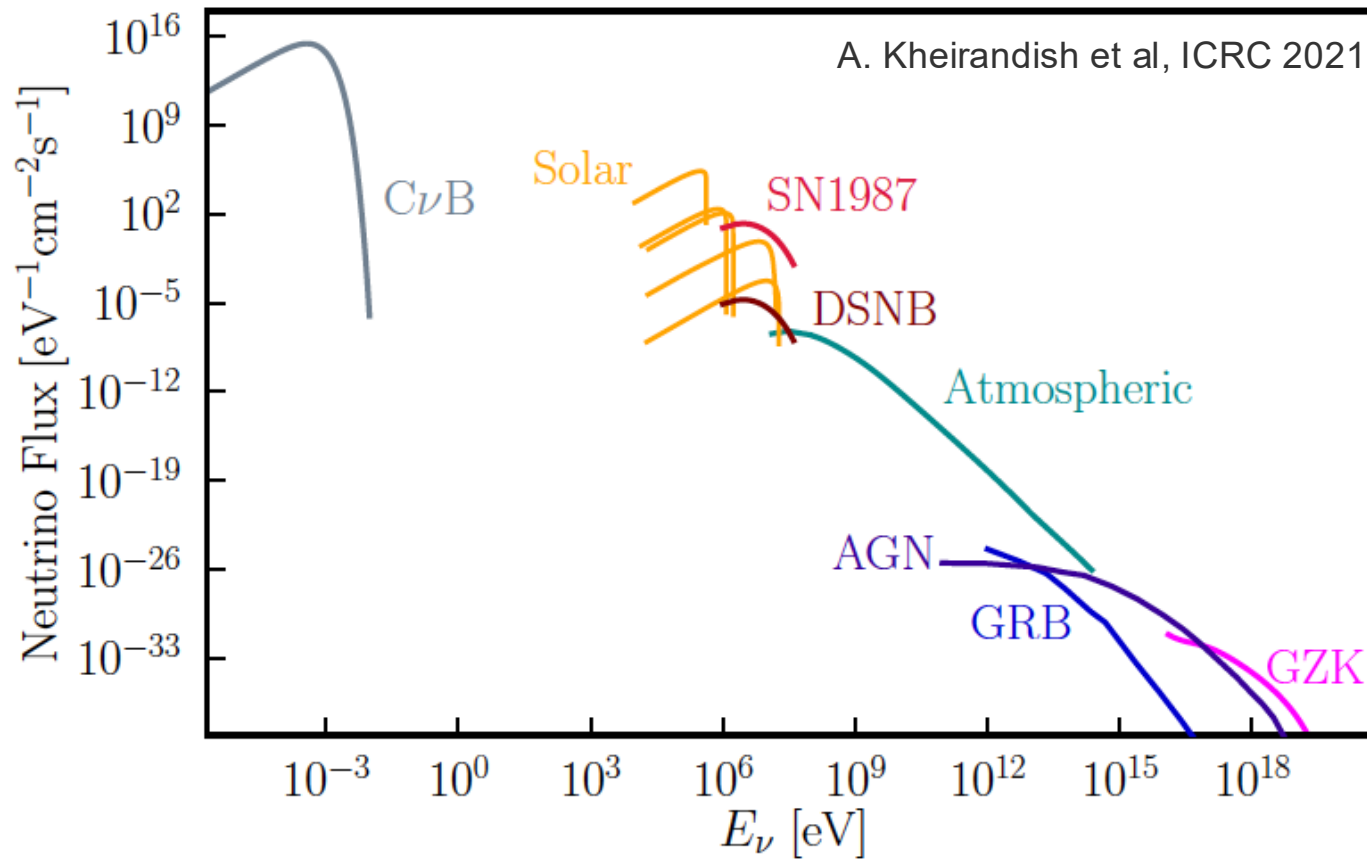
SNEWS connects many instruments and will send an alert to trigger observations.

Questions?!

Quiz 1 – MeV Neutrinos



<https://forms.gle/uHCYKcGDBP2bGRsC6>



↔

Ideas: neutrino capture
on unstable nucleus
(e.g. tritium)

↔

Neutrino capture on
stable nucleus
(Chlorine, Gallium)

↔

Water / ice
Cherenkov
detectors

↔

Radio arrays,
cosmic-ray
detectors

Content of the 3 lectures

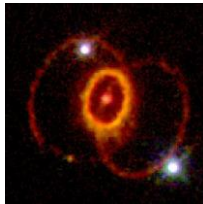
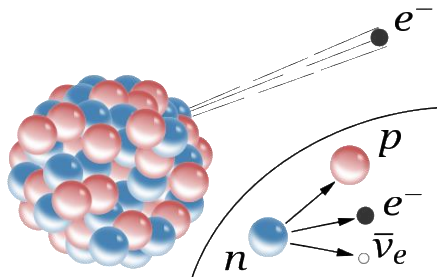
- Discovery of the neutrino
- Low-energy (MeV) neutrinos
 - Sun
 - Supernovae
- **High-energy (TeV-PeV) neutrinos**
 - **Astrophysics**
 - **Particle physics**
- Even higher energies
 - 220 PeV neutrino detected by KM3NeT
 - New detector concepts

Learning Objectives

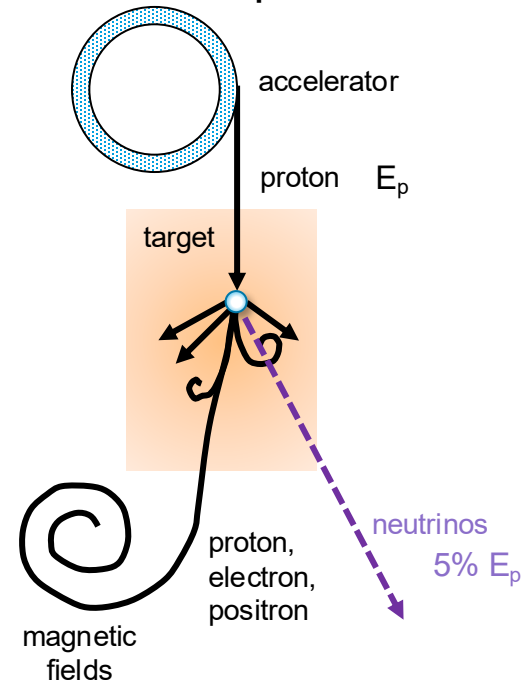
- How can we detect high-energy astrophysical neutrinos?
- What is the background in the search for high-energy cosmic neutrinos and how can we disentangle it from the signal?
- What have we learned so far from high-energy neutrino detections?
- How can we improve in the future?

How are high-energy neutrinos produced?

MeV neutrinos from nuclear processes, (inverse) beta decay



TeV-PeV neutrinos from cosmic-ray “beam dumps”



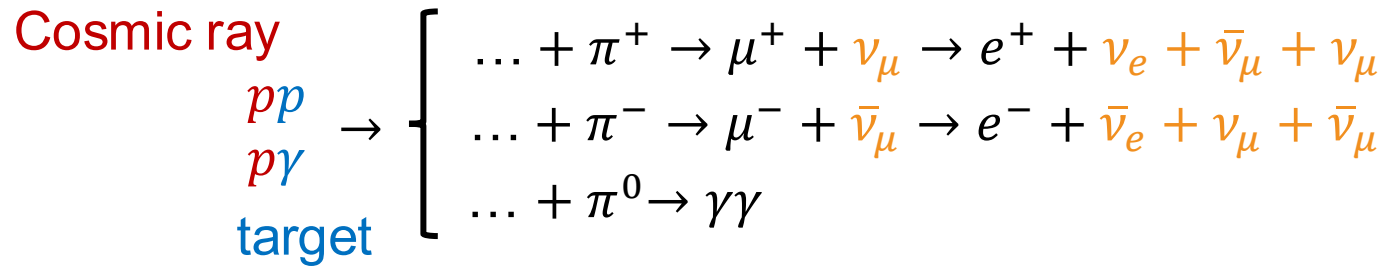
Two ingredients:

- Proton acceleration
- Target for interaction

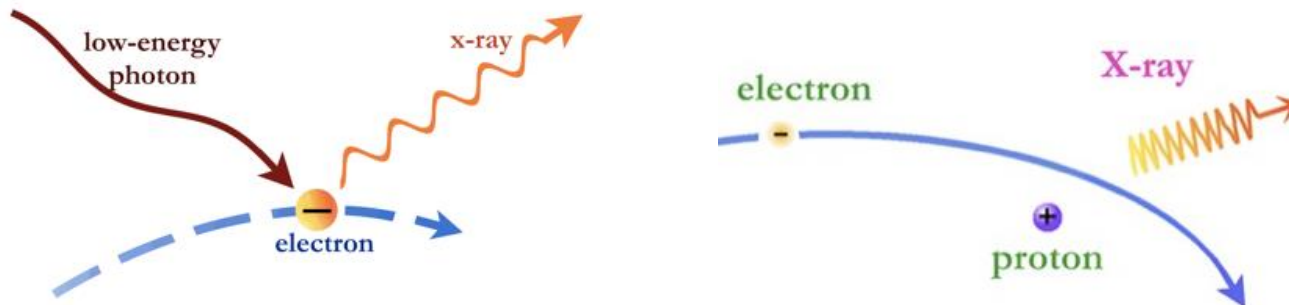
Neutrino Production Processes

$$\begin{array}{l}
 \text{Cosmic ray} \\
 \text{ } pp \\
 \text{ } p\gamma \\
 \text{target}
 \end{array}
 \rightarrow \left\{ \begin{array}{l}
 \dots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \\
 \dots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \\
 \dots + \pi^0 \rightarrow \gamma\gamma
 \end{array} \right.$$

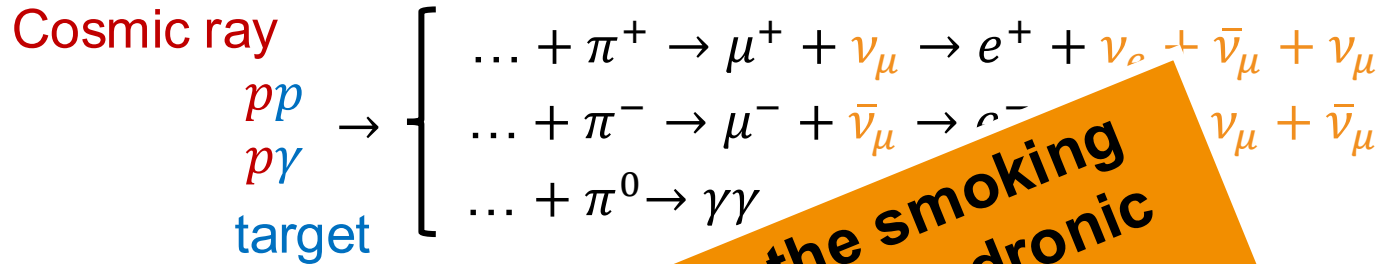
Neutrino Production Processes



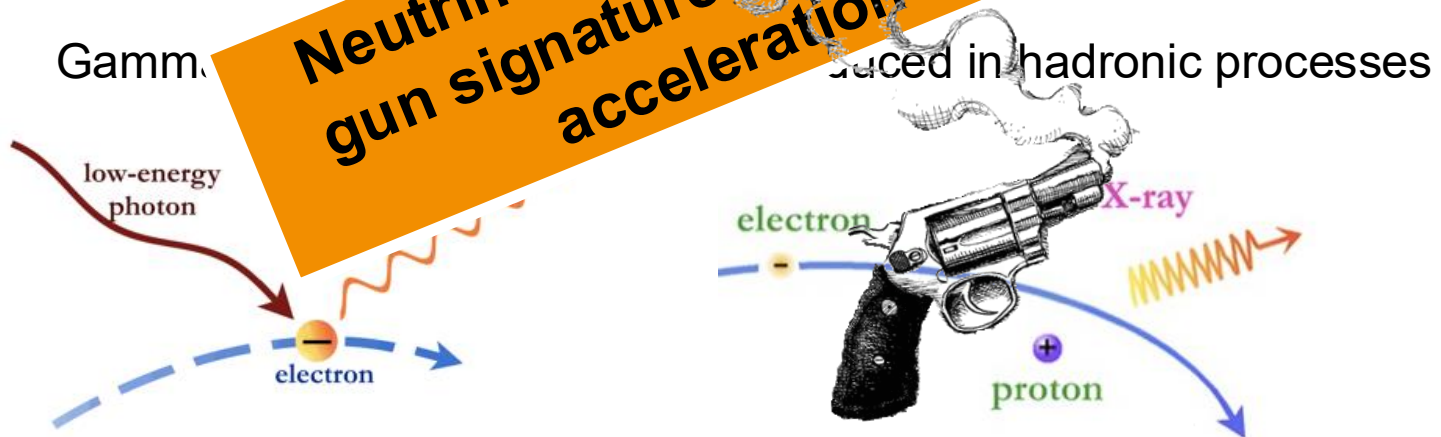
Gamma-rays are not exclusively produced in hadronic processes



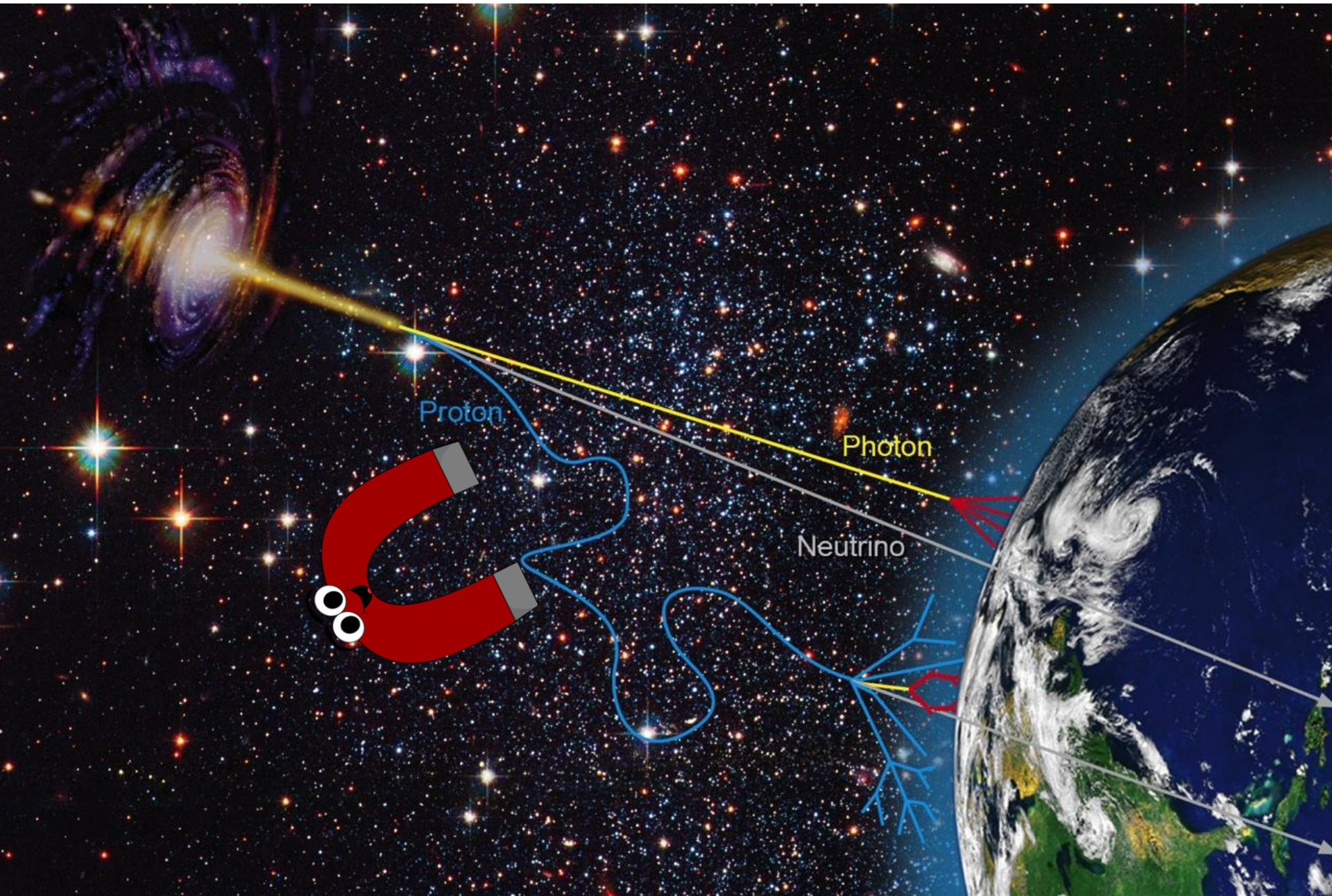
Neutrino Production Processes



**Neutrinos are the smoking
gun signature for hadronic
acceleration**



What are the Cosmic-Ray Sources?



High-energy Neutrino Detectors

- Huge volumes necessary: $\sim 1\text{km}^3 \rightarrow$ need to use natural medium
- Transparent medium (Cherenkov emission of secondary charged particles)

Waxman-Bahcall Bound

- Protons are accelerated in the sources with an energy spectrum proportional to $dN_{\text{CR}}/dE_{\text{CR}} \propto E^{-2}$
- Energy production rate in CRs between 10^{19}eV and 10^{21}eV is $5 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$
- All protons undergo photohadronic interactions ($p\gamma$), producing **neutrons**, **gamma rays** and **neutrinos**

$$p\gamma \rightarrow \Delta^+ \left\{ \begin{array}{l} n + \pi^+ \\ p + \pi^0 \end{array} \right.$$

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu \\ \pi^0 &\rightarrow \gamma\gamma \end{aligned}$$

Waxman-Bahcall Bound

- Protons are accelerated in the sources with an energy spectrum proportional to $dN_{\text{CR}}/dE_{\text{CR}} \propto E^{-2}$
- Energy production rate in CRs between 10^{19}eV and 10^{21}eV is $5 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$
- All protons undergo photohadronic interactions (py), producing neutrons, gamma rays and neutrinos
- The sources are optically thin to neutrons, which leave the sources and subsequently decay into protons, accounting for the UHECR flux observed at the Earth
- Energy flux of neutrinos cannot be greater than that of CR

$$E^2 \Phi < 3 \times 10^{-8} \text{ GeV s}^{-1} \text{ sr}^{-1} \text{ cm}^{-2}$$

1km³ volume needed to probe this flux



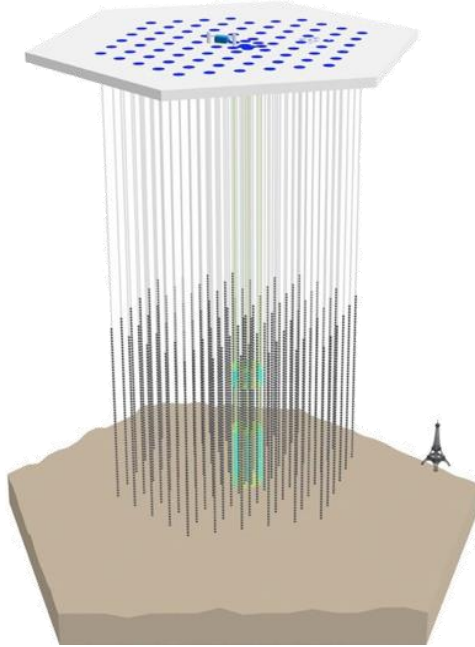
Take home message

Kubic-kilometer sized neutrino detectors are needed to detect cosmic neutrinos.

Those could reveal the sources of cosmic rays and deliver information from dense environments

High-energy Neutrino Detectors

IceCube (1 km³)

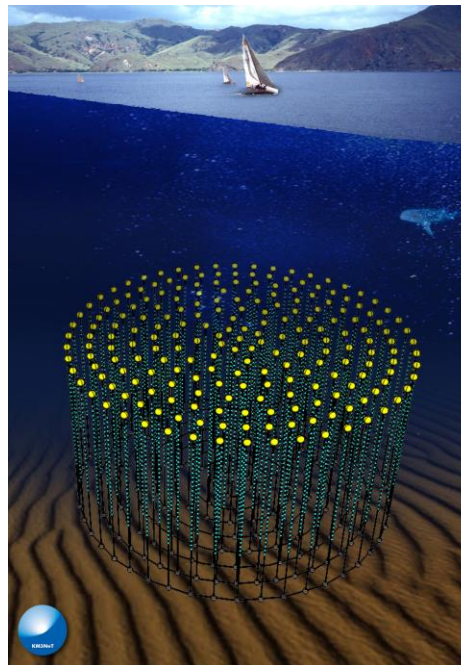


IceCube-Gen2 (8km³) planned

M.G. Aartsen *et al* 2017 *JINST* **12** P03012
 M.G. Aartsen *et al* *J.Phys.G*
 48 (2021) 6, 060501

KM3NeT (2 x 0.5 km³)

Under construction
 Predecessor ANTARES
 decommissioned after 14y

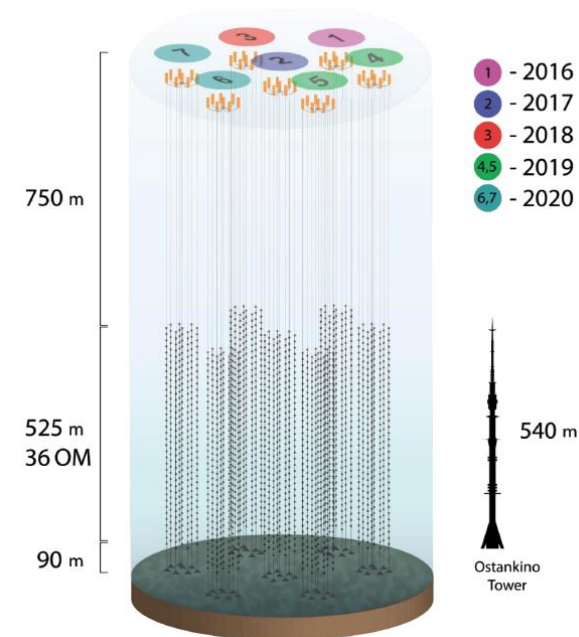


Two sites: ARCA for HE and
 ORCA for LE, roughly ~20-
 35% complete

S. Adrián-Martínez et al. arXiv:1601.07459

Baikal-GVD (1 km³)

Under construction



2022: 10 clusters
 2026: 18 clusters

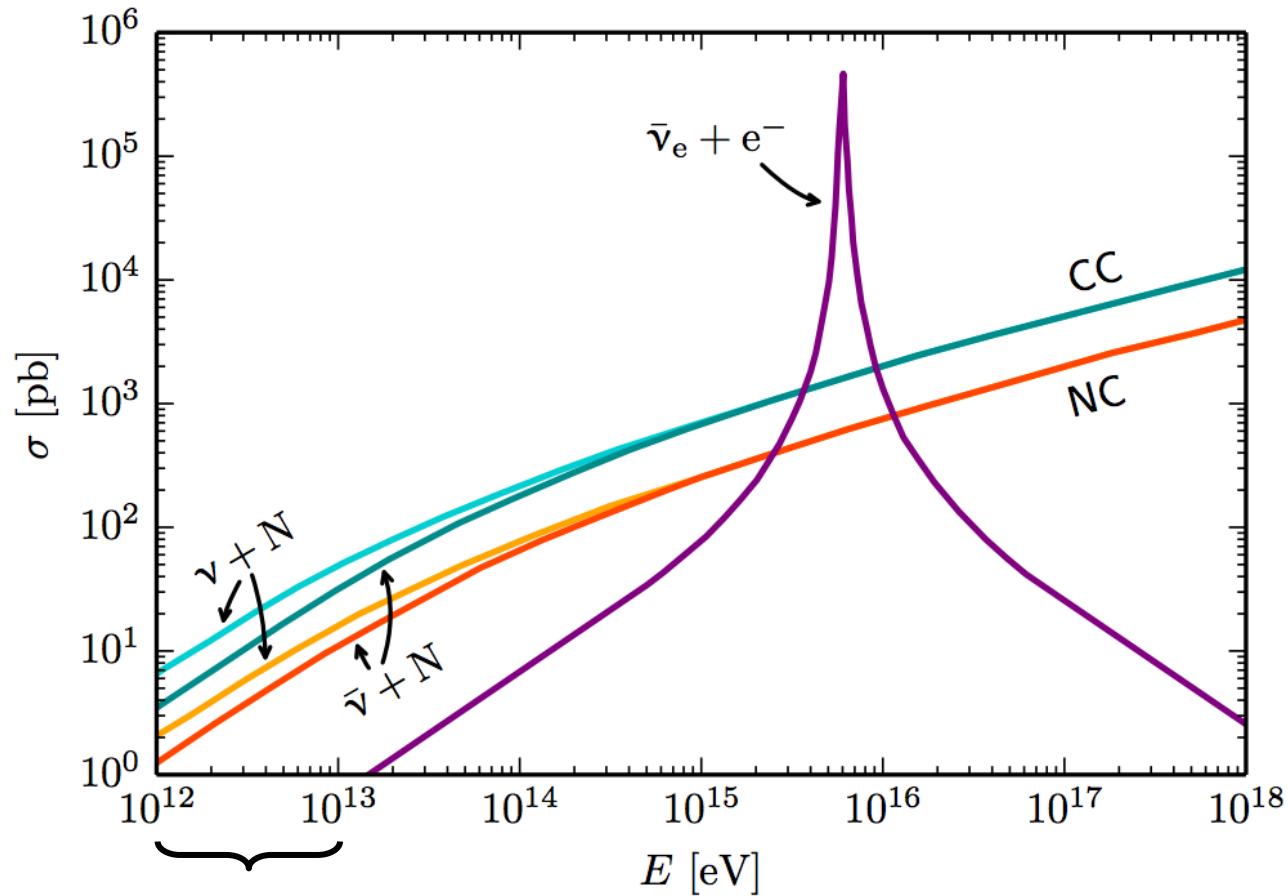
A.D. Avrorin et al.
 arXiv:2011.09209

Differences between ice and water detectors

Property	Lake Baikal	Mediterranean (ANTARES)	Antarctic Ice
Absorption length (m)	22	60	100
Effective Scattering (m)	480	265	25
Depth	1370	2475	2450
Noise	Quiet	^{40}K , bioluminescence	Quiet
Retrieve/redeploy	Yes	Yes	No

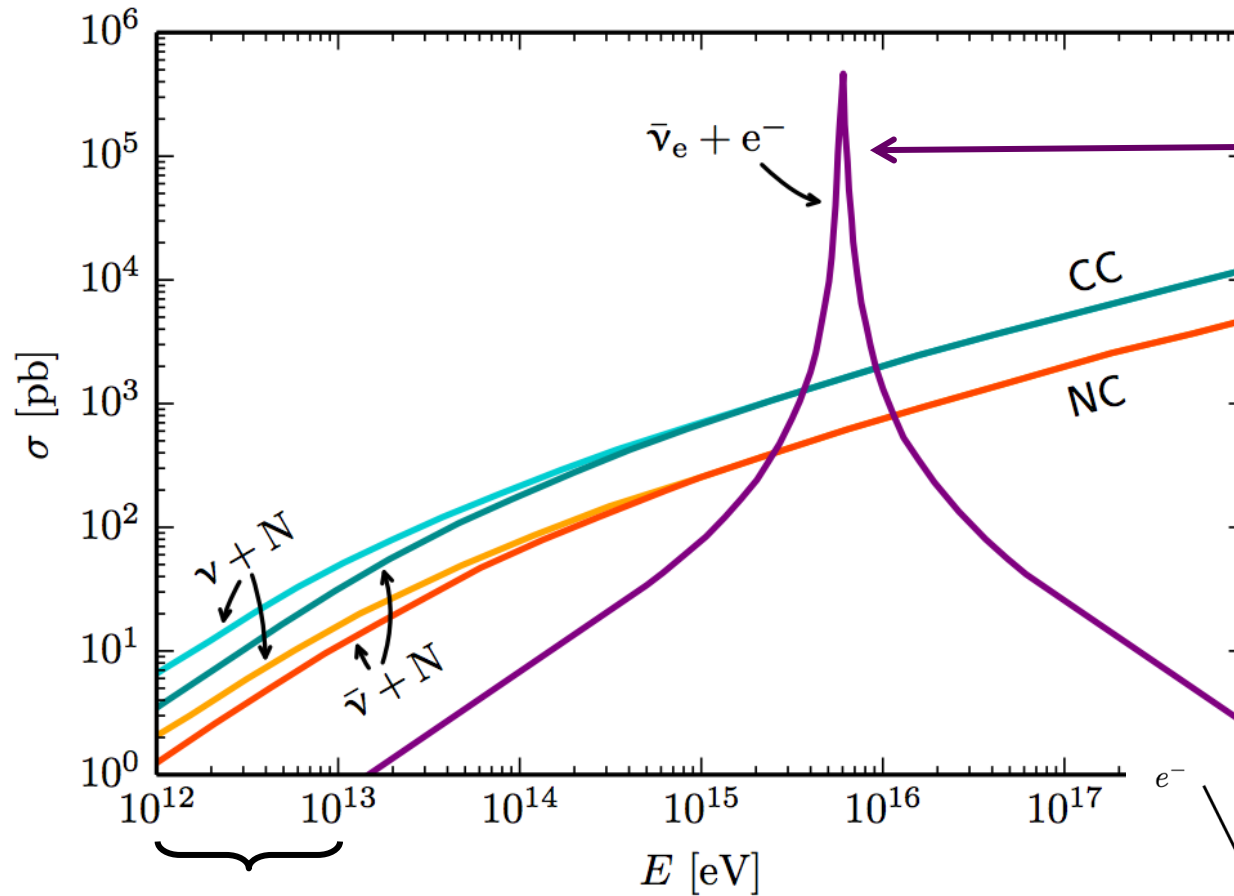
Long scattering length in Mediterranean implies better angular resolution; long absorption length for IceCube allows sparser instrumentation. Smaller depth implies larger atmospheric muon background.

Neutrino Cross-Sections



Neutrino cross sections are very small and they increase with energy

Neutrino Cross-Sections

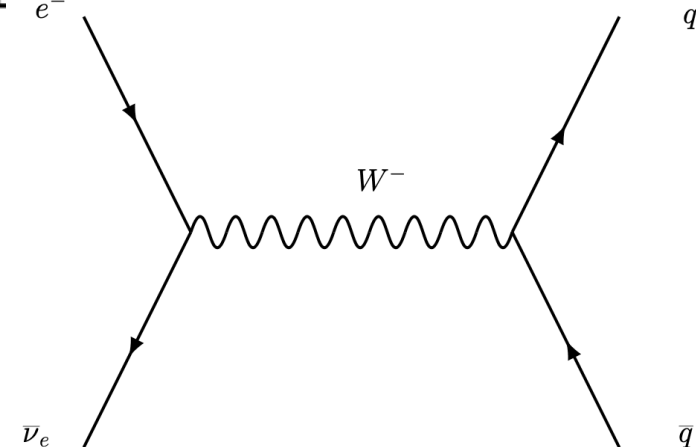


Linear with E ,
Smaller for
anti-neutrinos
due to helicity

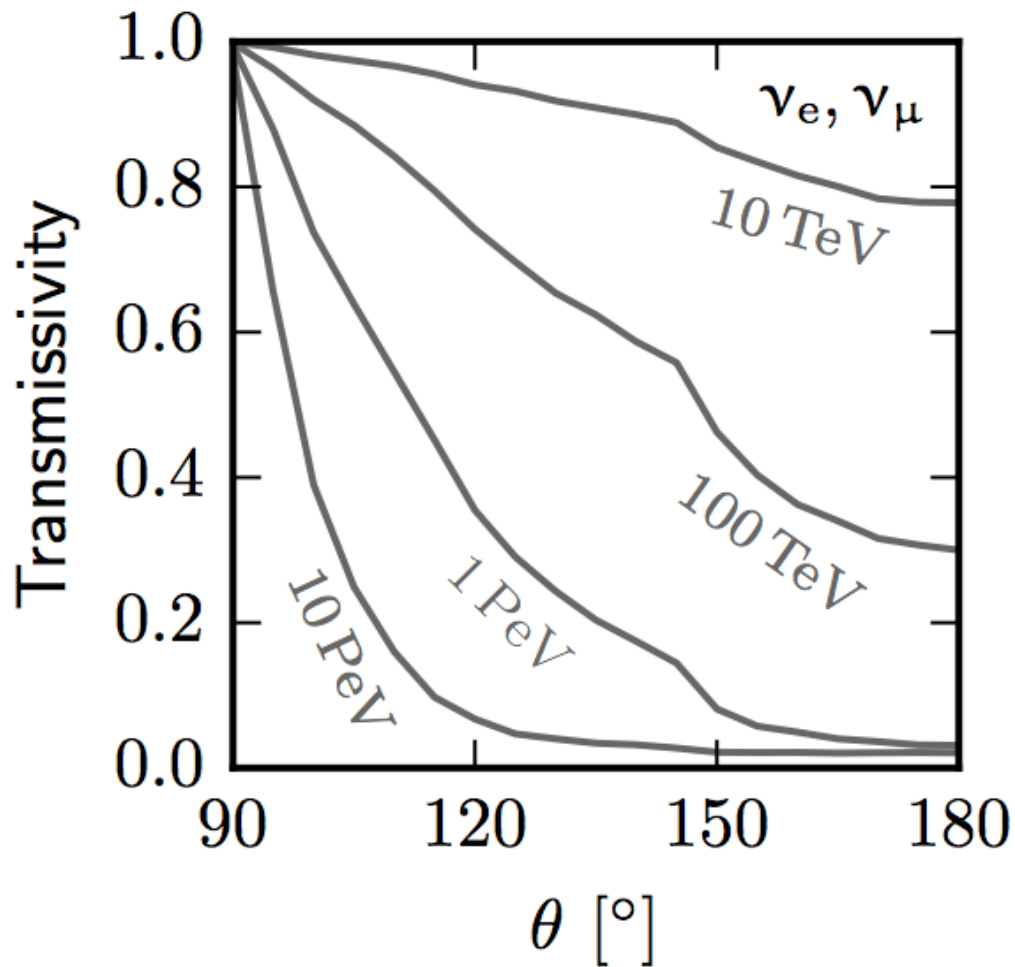
damped by the W -
boson propagator

Glashow resonance:

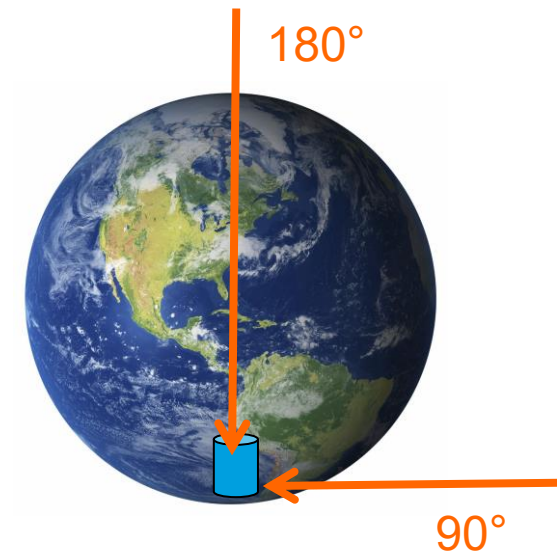
resonance when the
center-of-mass
energy of the
system reaches the
mass of the
mediating boson.
For electrons at rest
and the mass of the
 $W^\pm$ boson (80 GeV),
the Glashow
resonance occurs at
a neutrino energy of
 6.3×10^{15} eV



Absorption of High-Energy Neutrinos in the Earth



For high-energies Earth becomes opaque to neutrinos





ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY



The South Pole

Elevation: 2,835 m

Average temperature: -28°C (summer), -60°C (winter)





ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY



IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW-Madison



Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

50 m

IceTop

1450 m

2450 m

IceCube detector

86 strings of DOMs,
set 125 meters apart

DeepCore

Antarctic bedrock

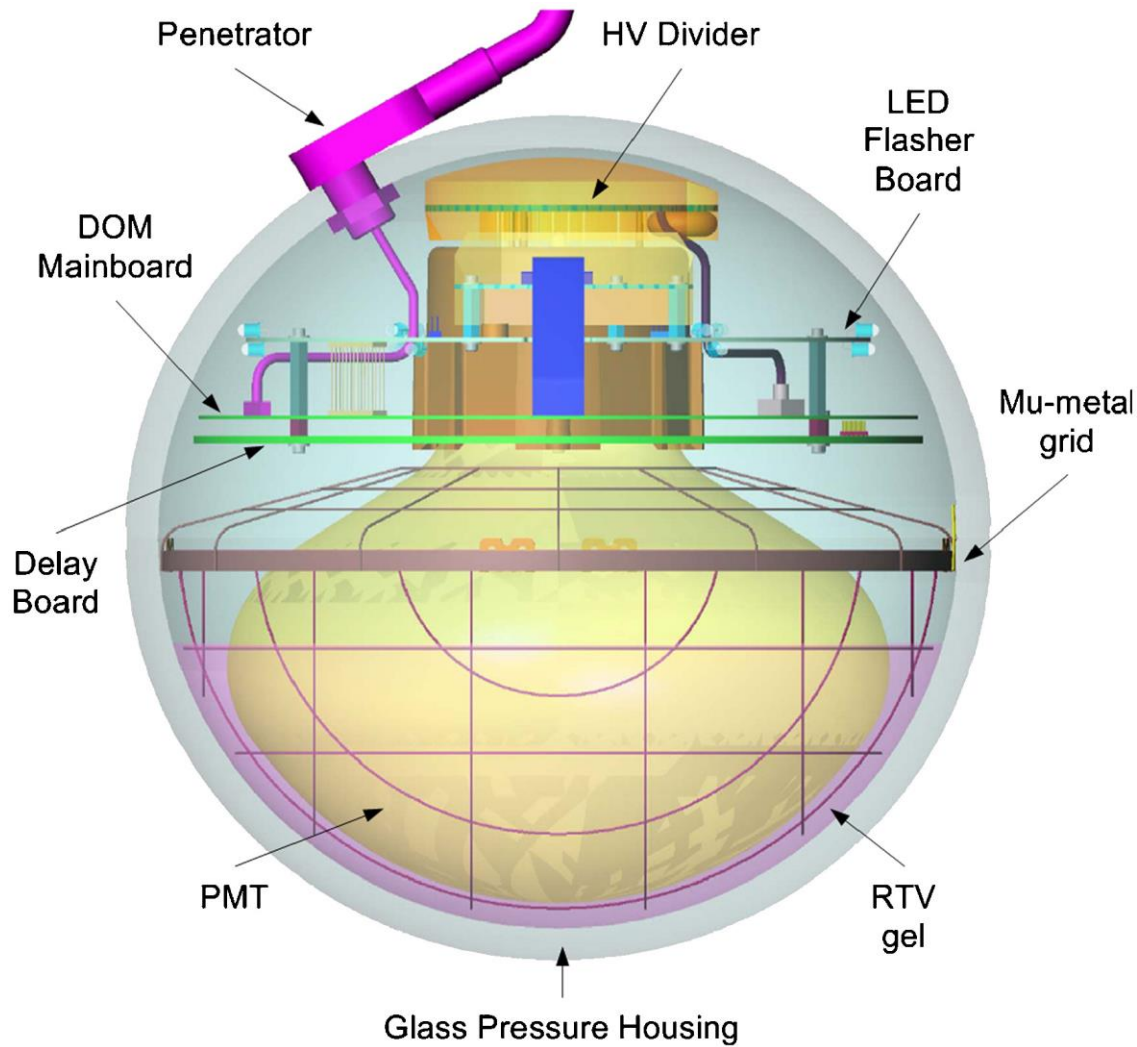
Amundsen-Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

60 DOMs
on each
string

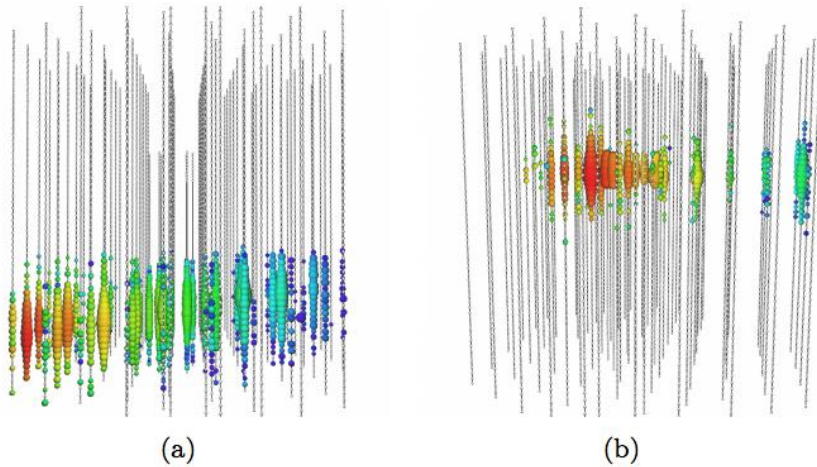
DOMs
are 17
meters
apart





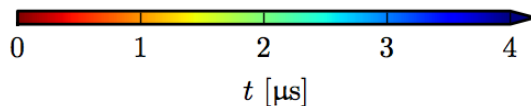
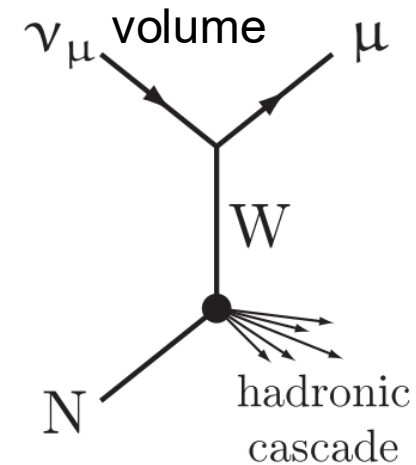
5160 DOMs
deployed
Failure rate: $<0.3\%$

Event Signatures

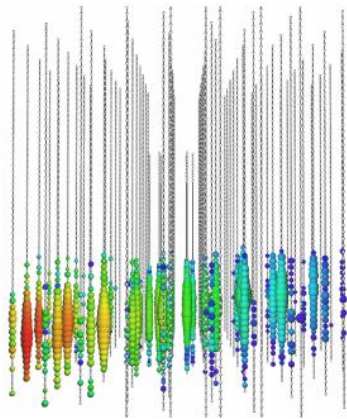


- a) through-going muon track $E \sim 140$ TeV
- b) Starting muon track $E \sim 70$ TeV

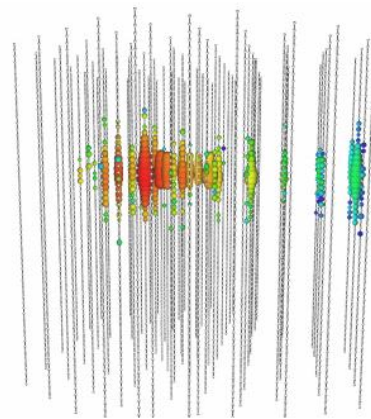
Charged current interaction of muon neutrino outside / inside the detector



Event Signatures

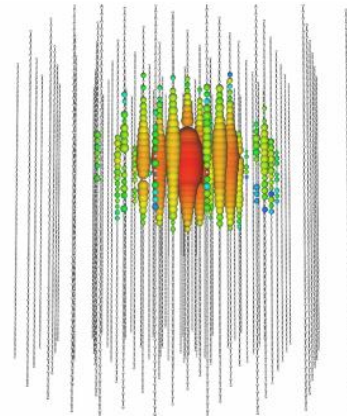


(a)



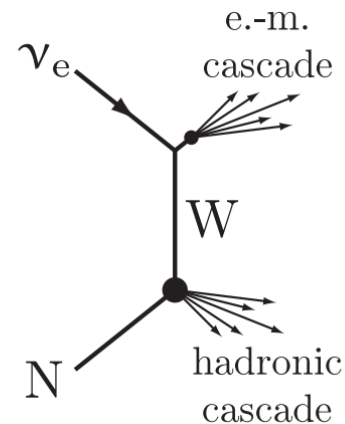
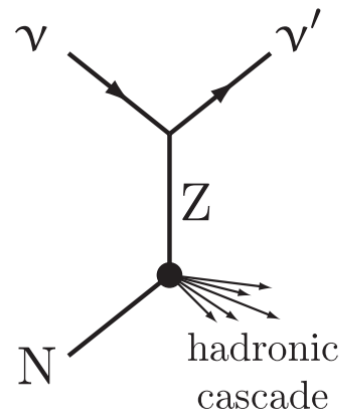
(b)

- a) through-going muon track $E \sim 140 \text{ TeV}$
- b) Starting muon track $E \sim 70 \text{ TeV}$
- c) **Shower event $E \sim 1 \text{ PeV}$**

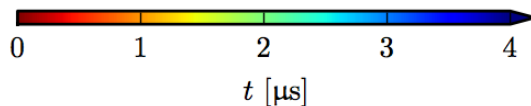


(c)

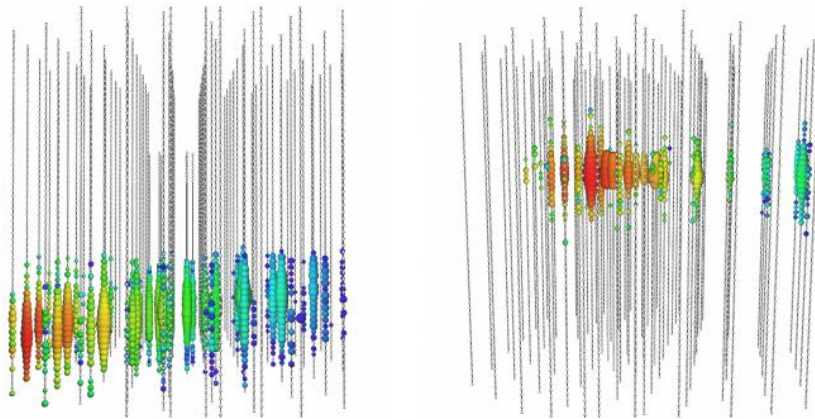
Neutral current or electron neutrino
charged current interaction



Cannot
distinguish
between
showers (size
few meters)



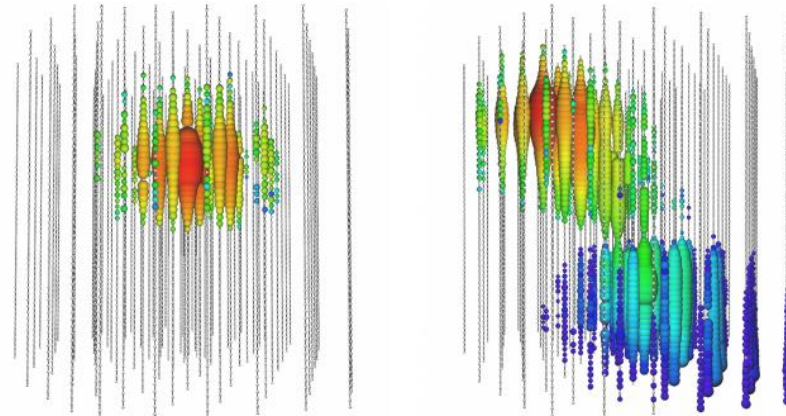
Event Signatures



(a)

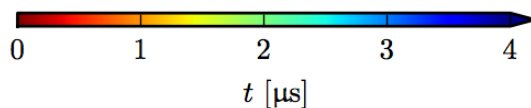
(b)

- a) through-going muon track $E \sim 140$ TeV
- b) Starting muon track $E \sim 70$ TeV
- c) Shower event $E \sim 1$ PeV
- d) **“double bang” event $E \sim 200$ PeV**

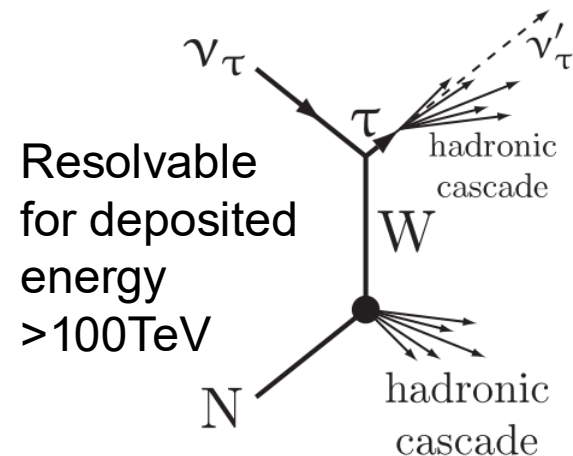


(c)

(d)

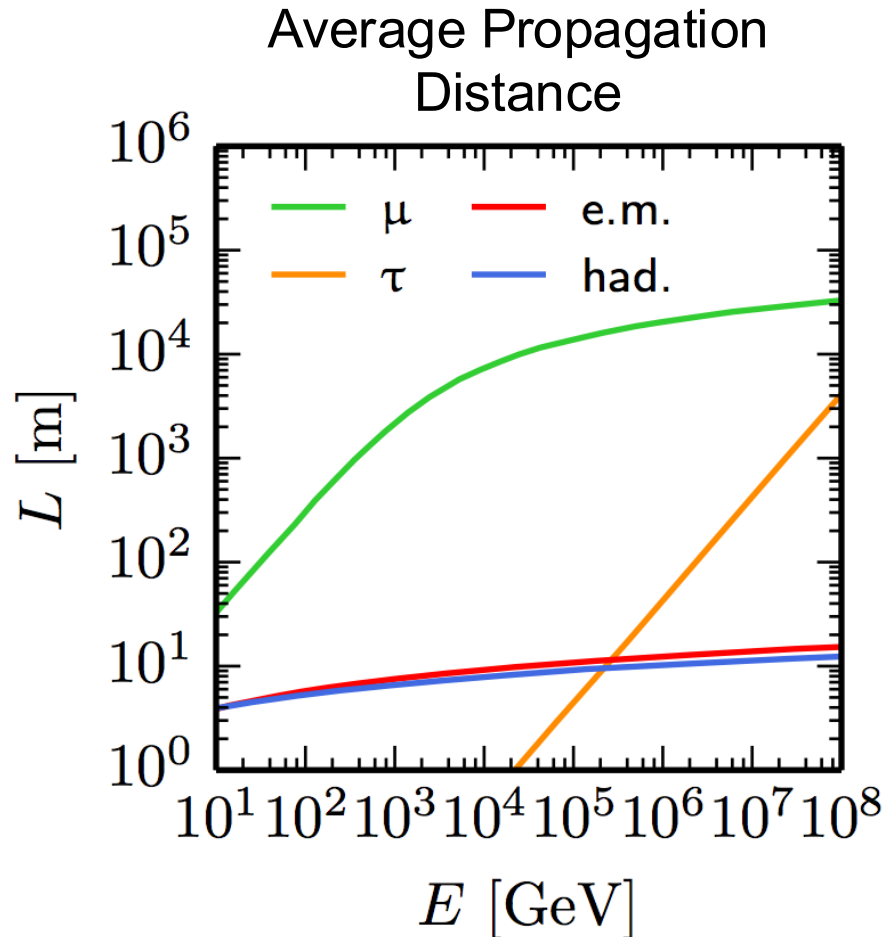


Tau neutrino charged current interaction



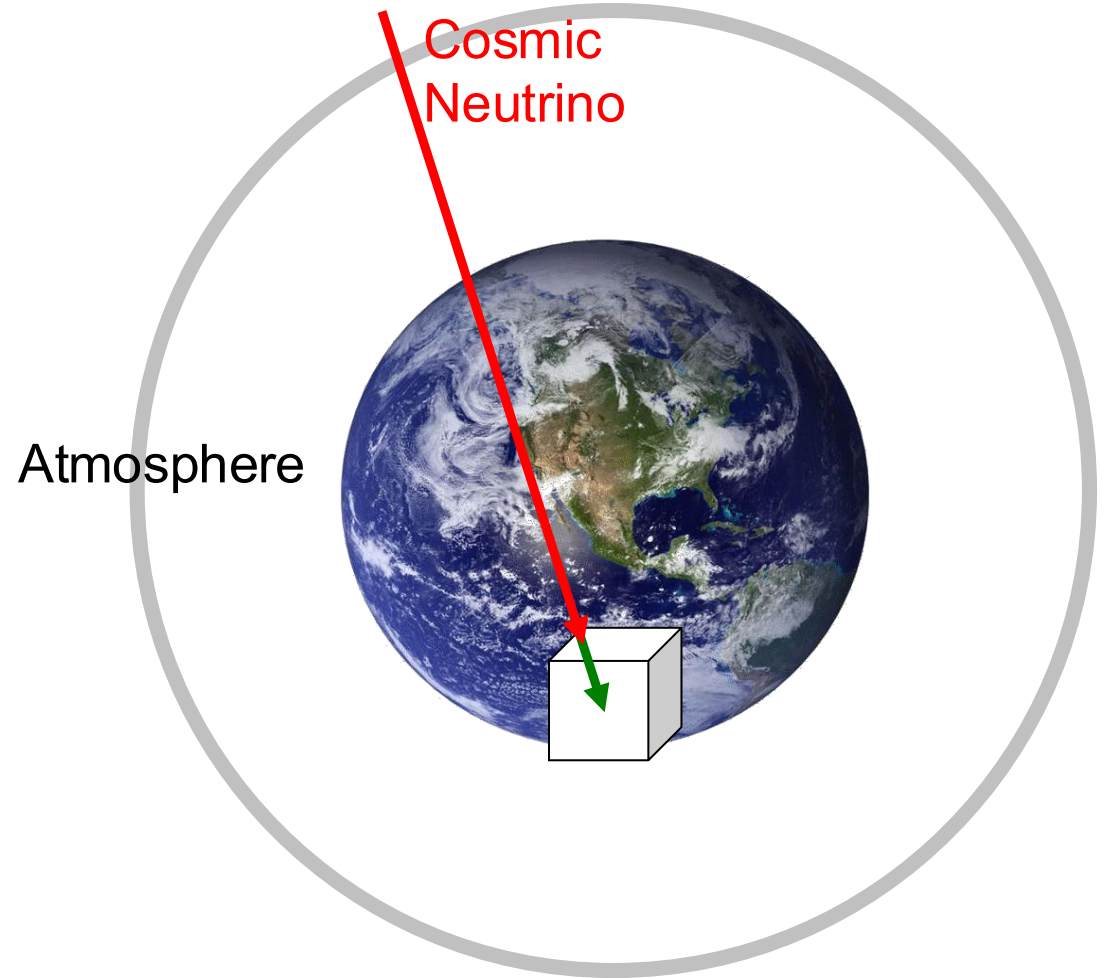
Only for very large energies the two showers can be separated (otherwise signature c)

Secondary Particle Interactions in Ice

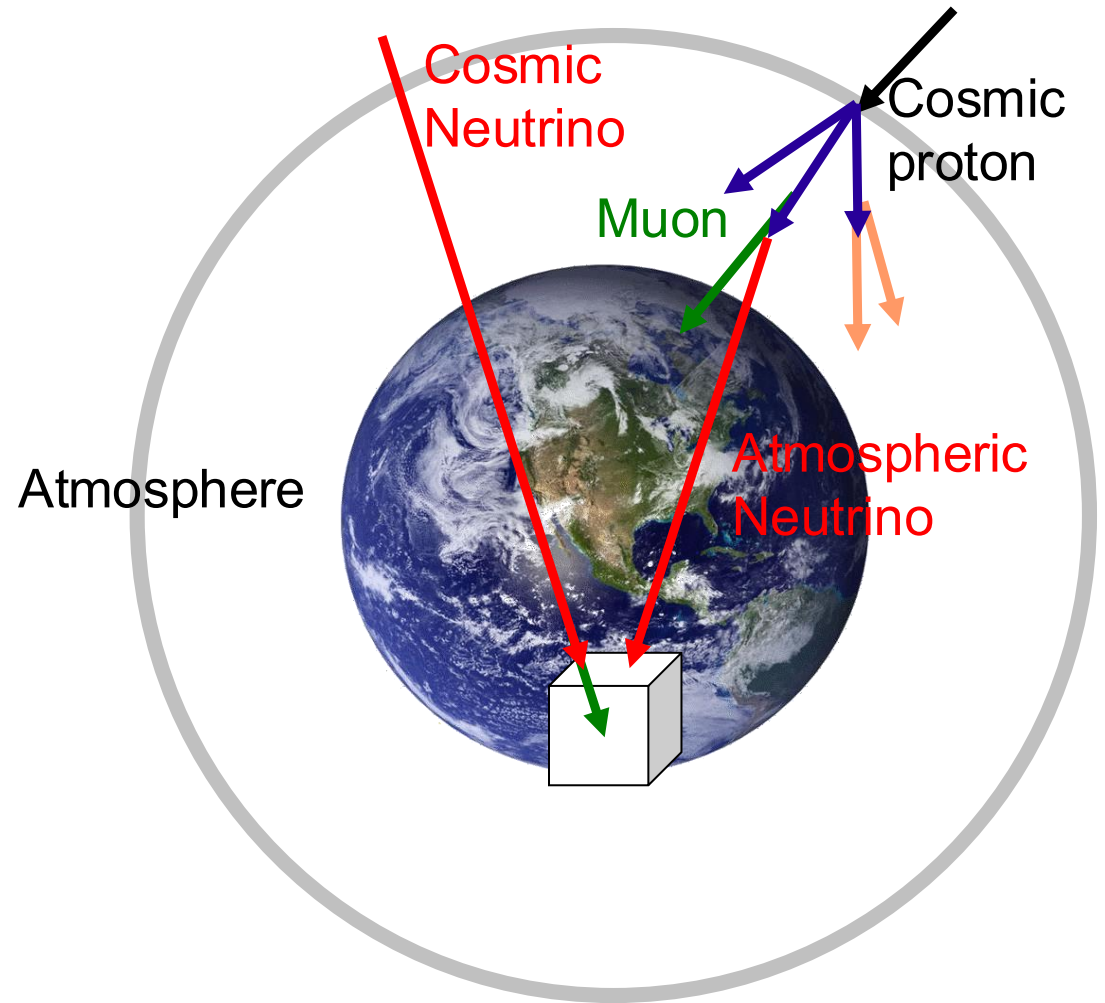


In the TeV range muons travel 1-10km, while showers have a small extension of few meters. Tau needs to reach >100TeV energies to reach detectable length of >10 meters.

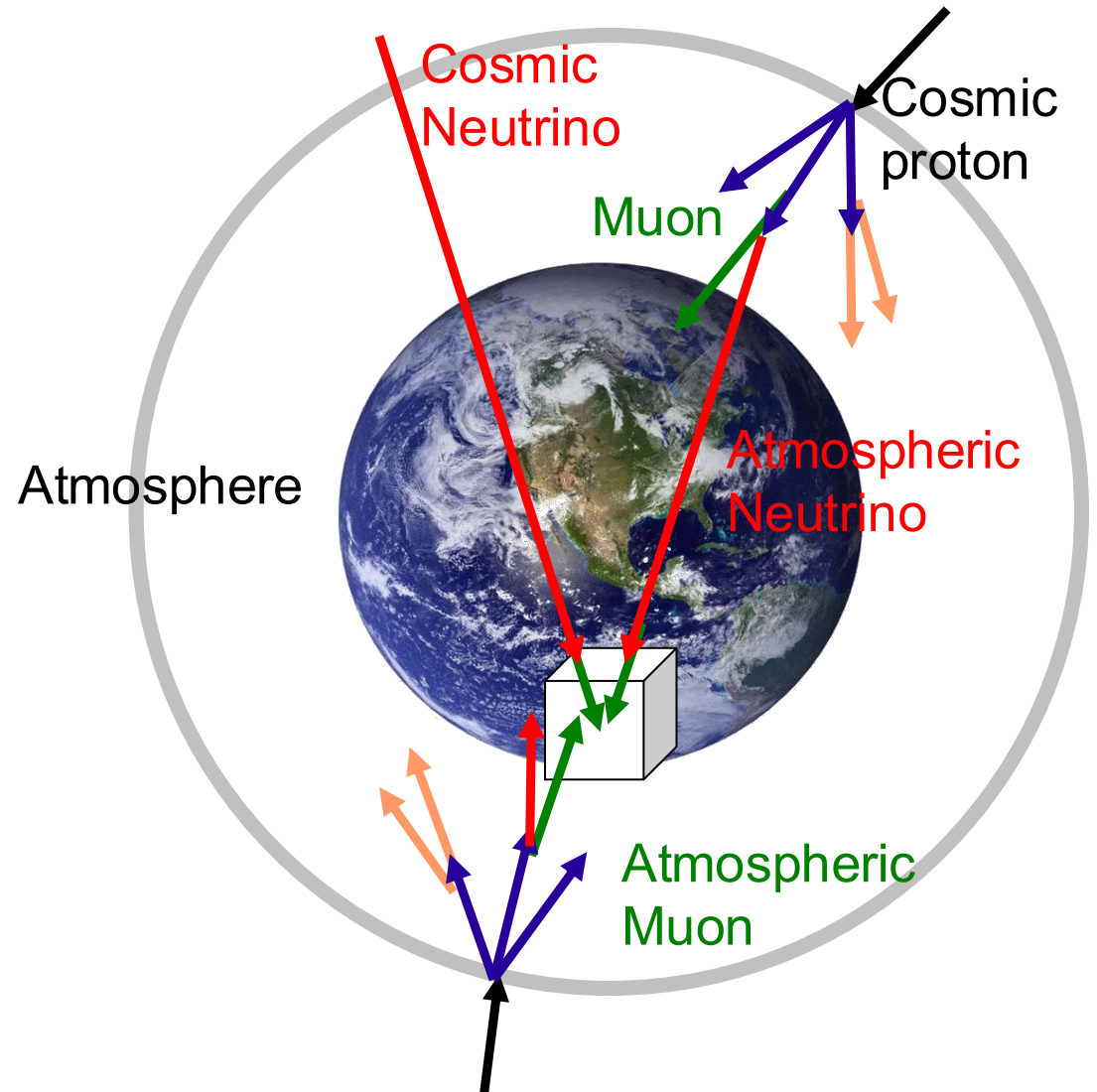
Background in Search for Cosmic Neutrinos



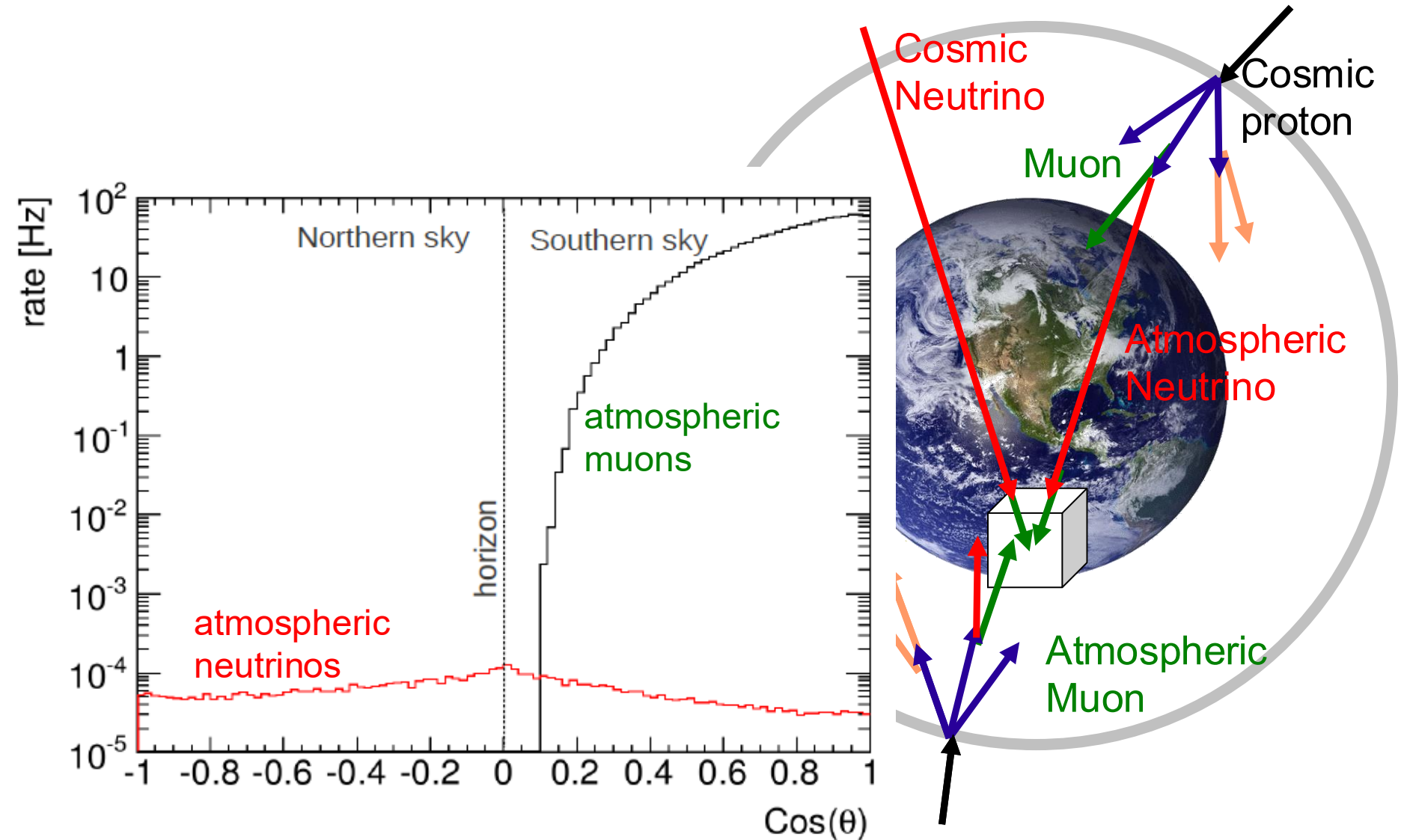
Background in Search for Cosmic Neutrinos



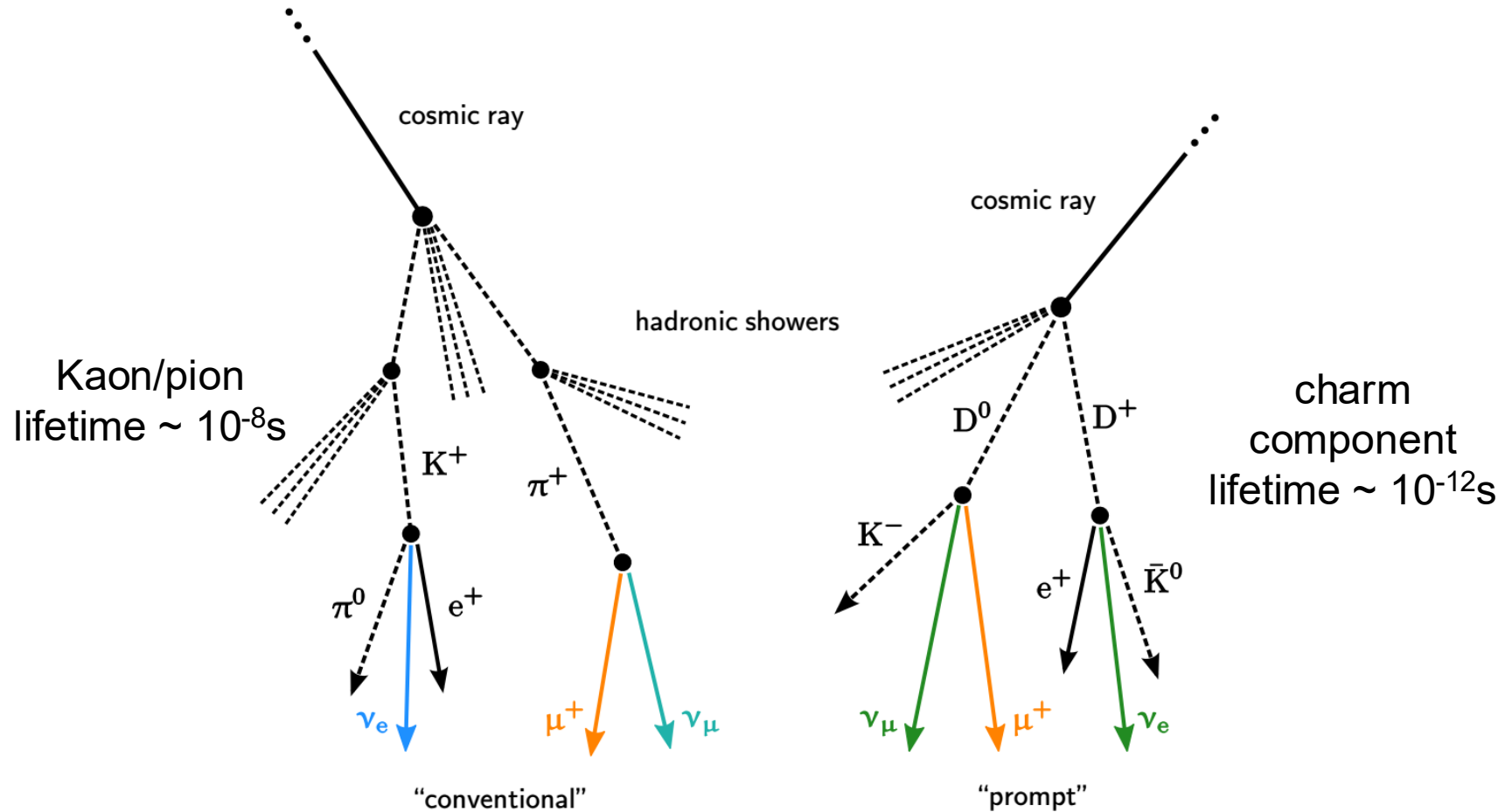
Background in Search for Cosmic Neutrinos



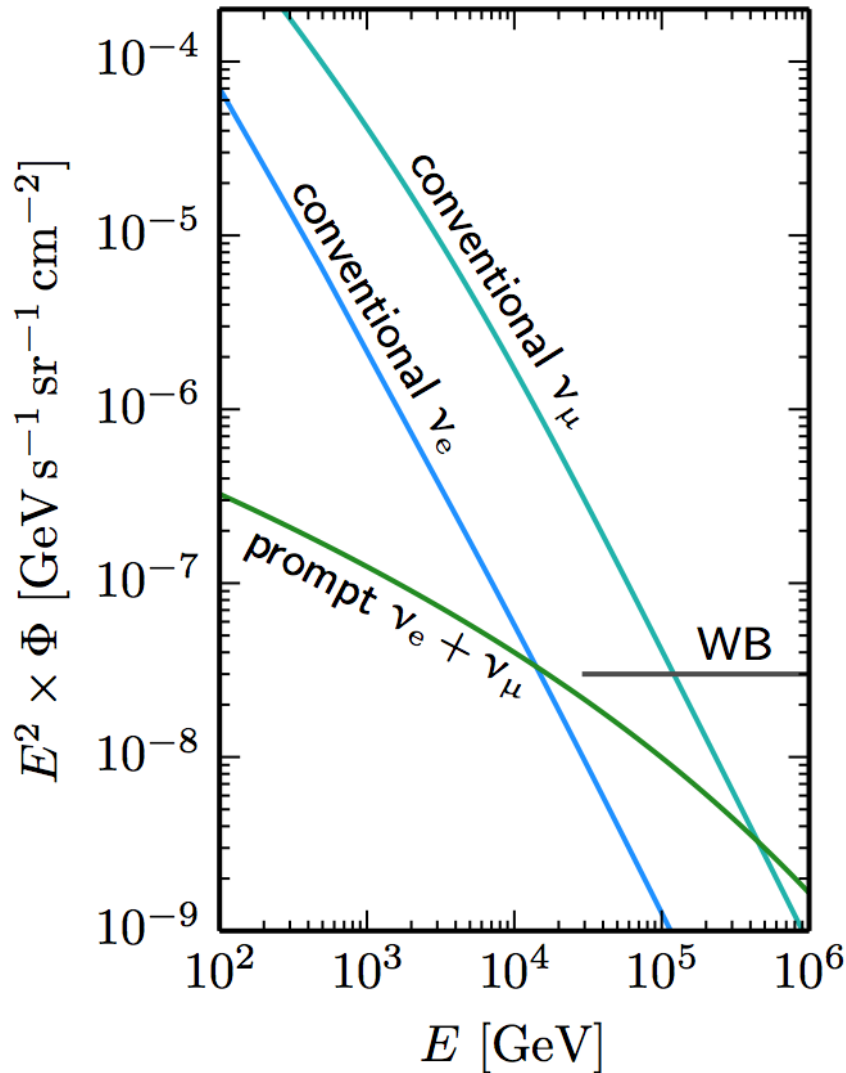
Background in Search for Cosmic Neutrinos



Atmospheric Neutrinos - Production



Atmospheric Neutrinos - Spectrum



Kaons and pions (conventional)

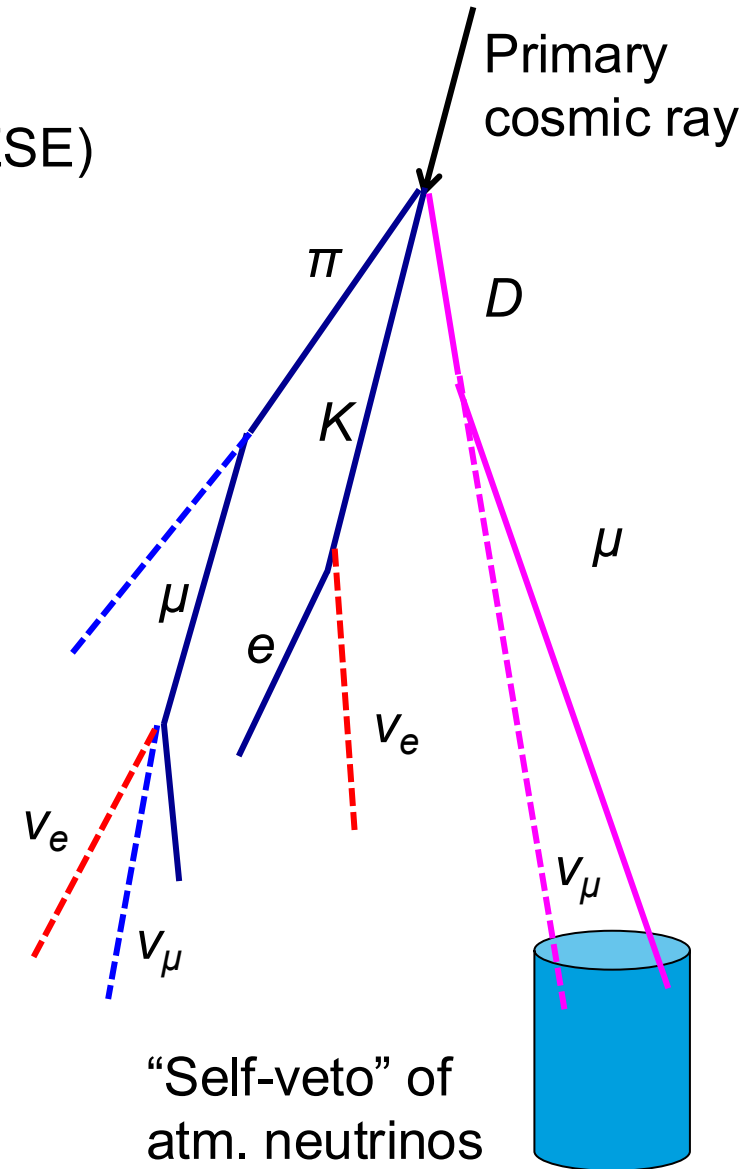
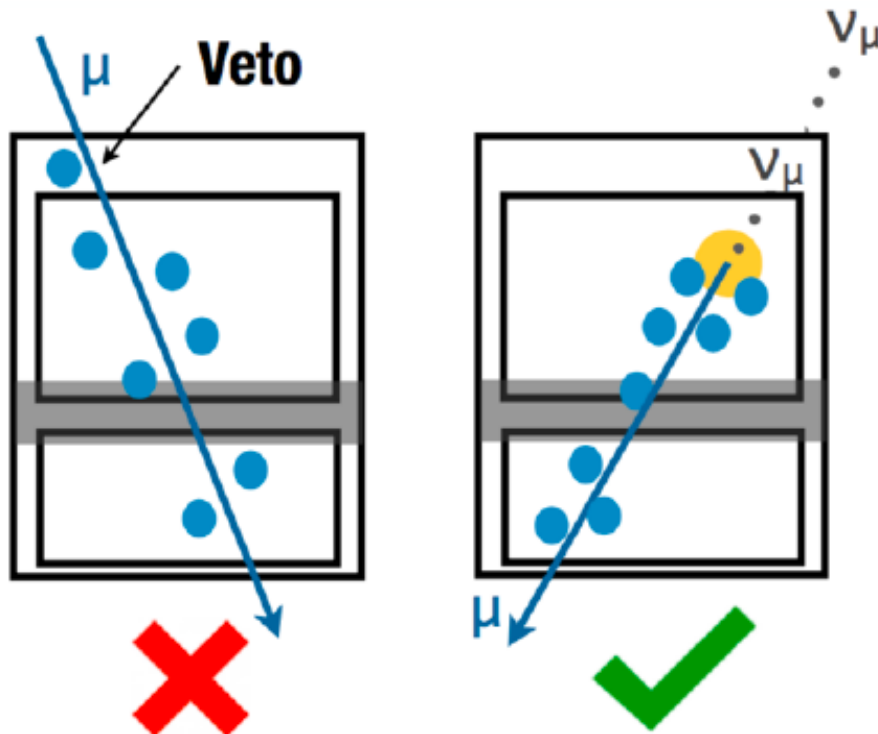
- predominantly decay into muon neutrinos rather than electron neutrinos
- are more likely to interact in the atmosphere rather than to decay into neutrinos if the atmosphere is denser

Charm (prompt)

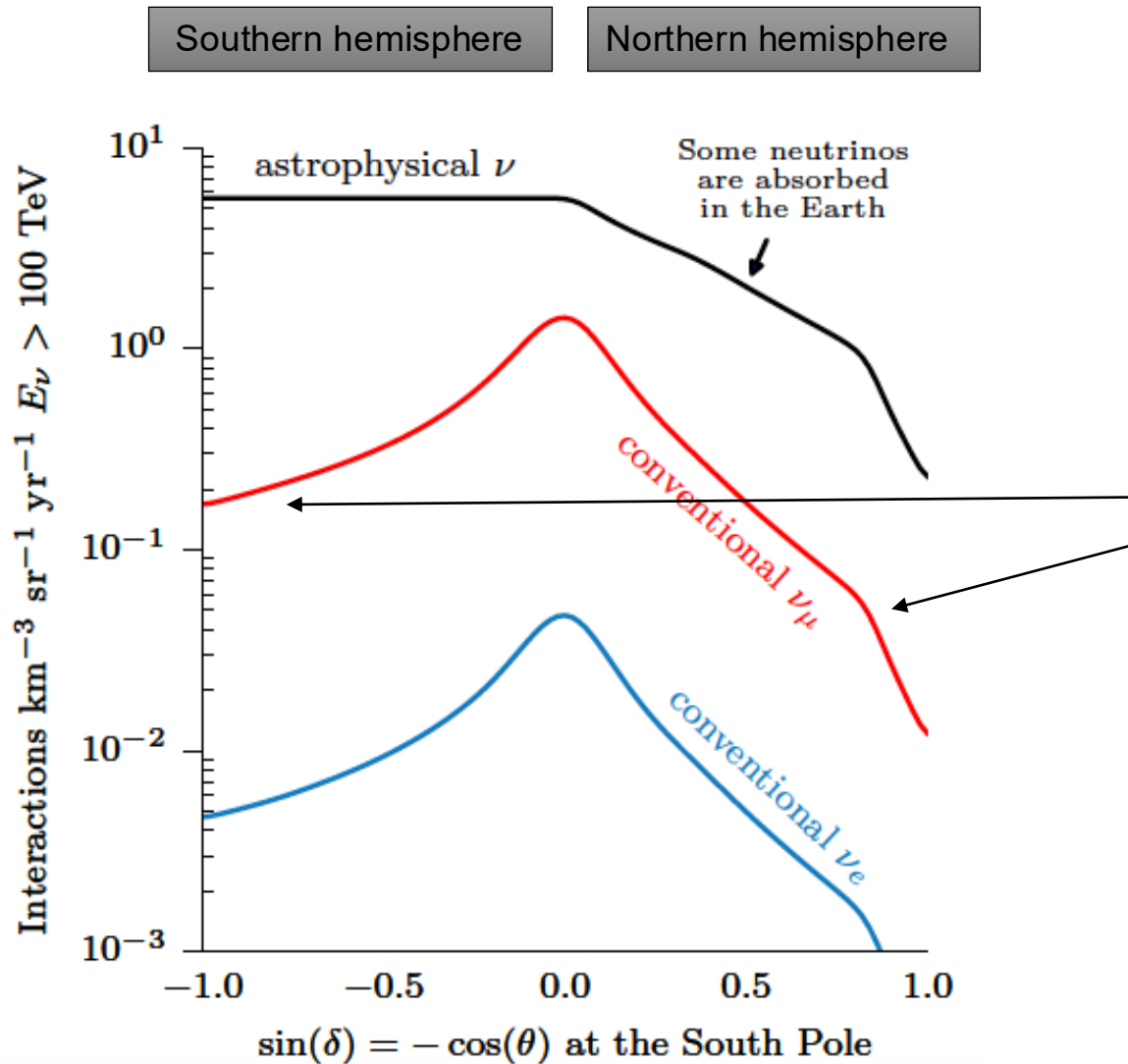
- Decay before interacting

Vetoing Atmospheric Muons and Neutrinos

Selection of high-energy starting events (HESE)



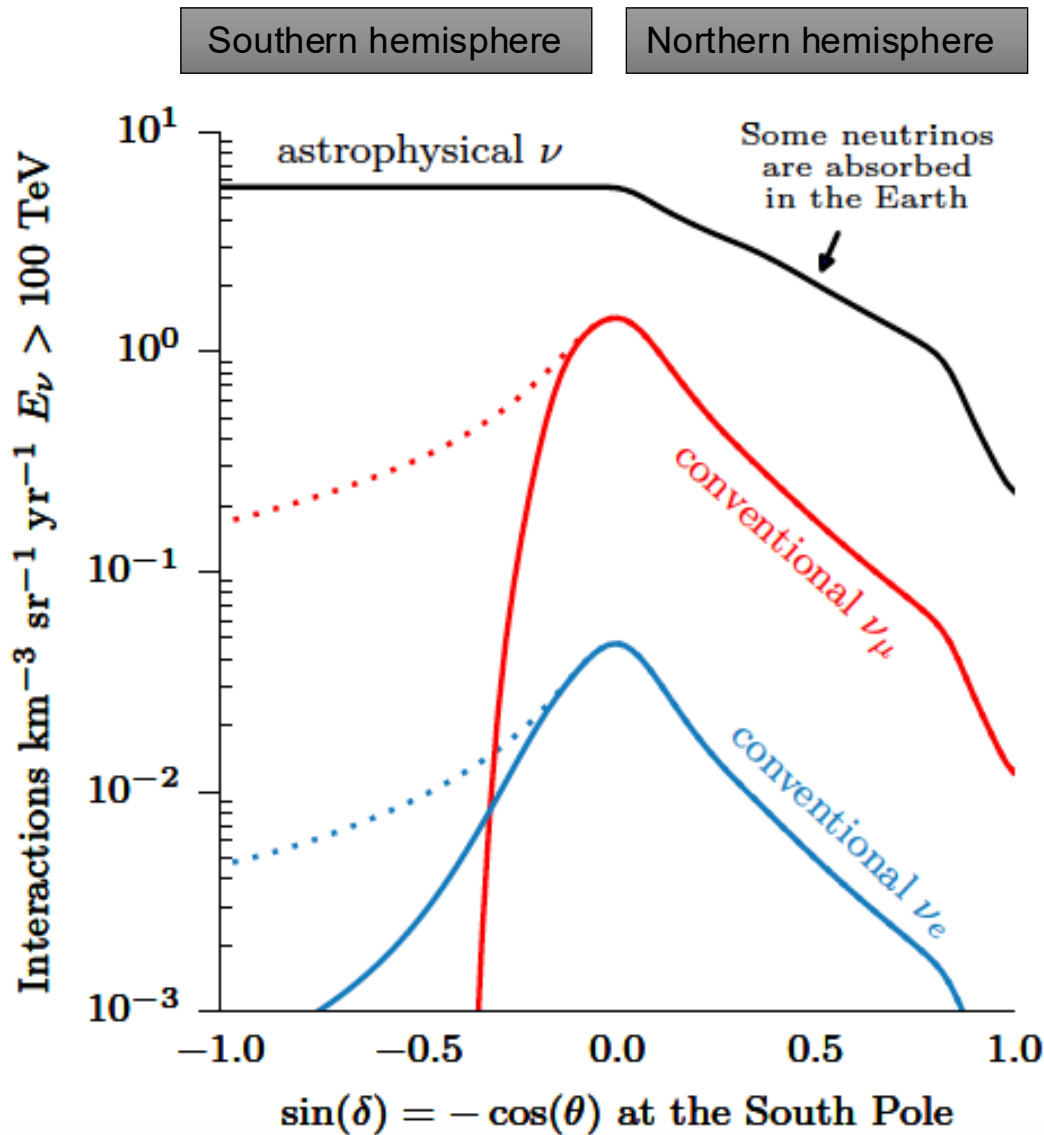
Zenith Distribution



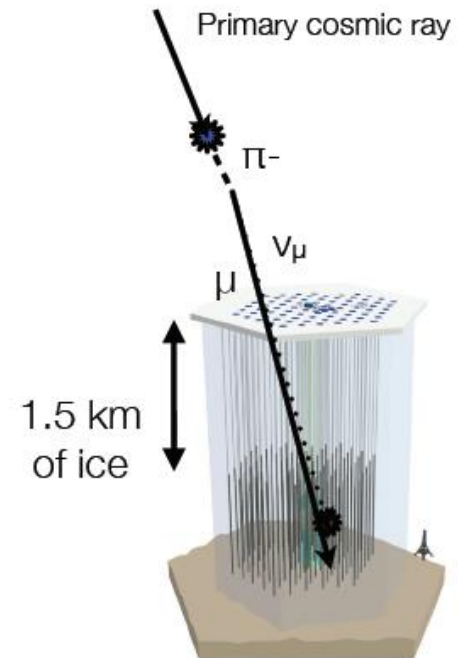
from vertical directions denser parts of the atmosphere are reached more quickly, leading to a suppression of the neutrino flux

Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Zenith Distribution

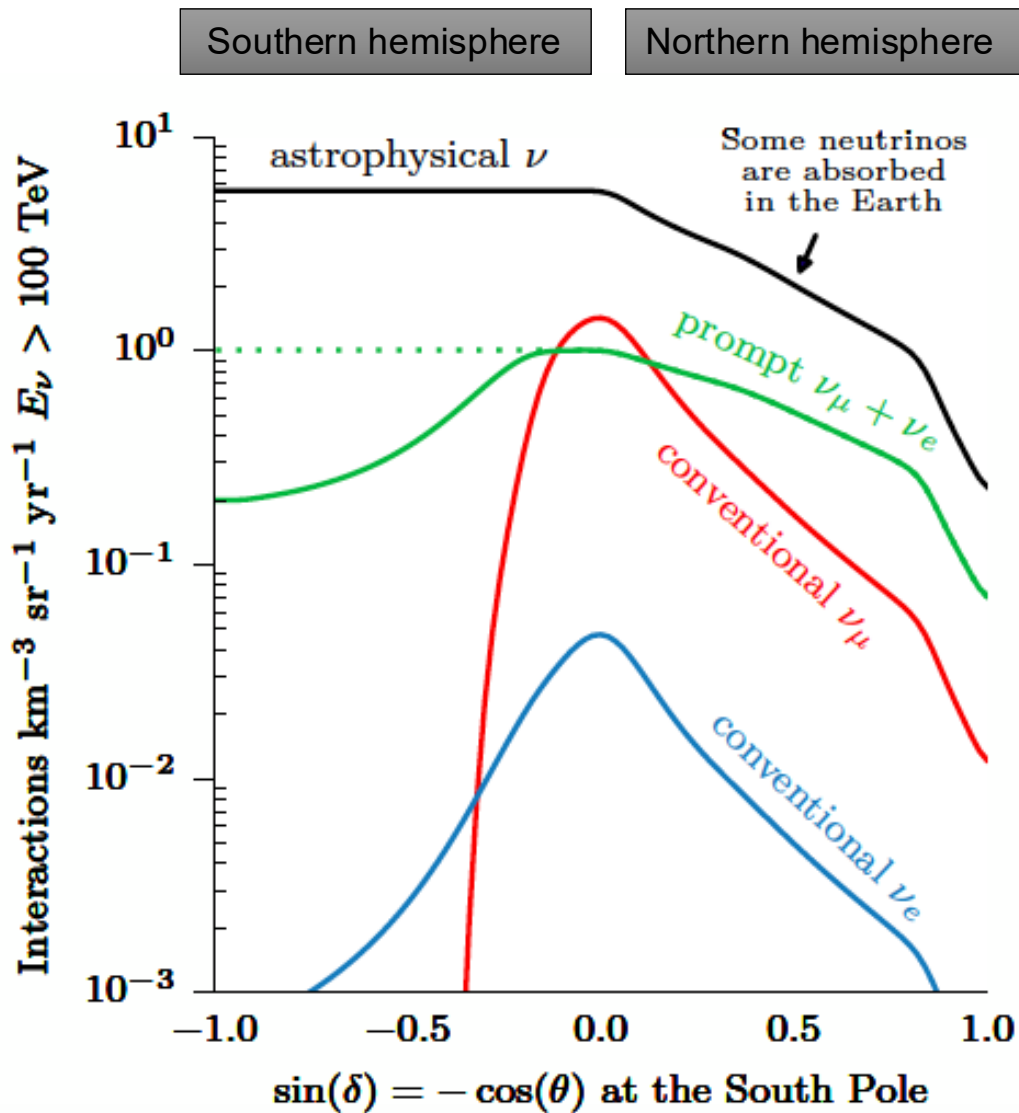


active muon veto
removes down-going
atmospheric neutrinos

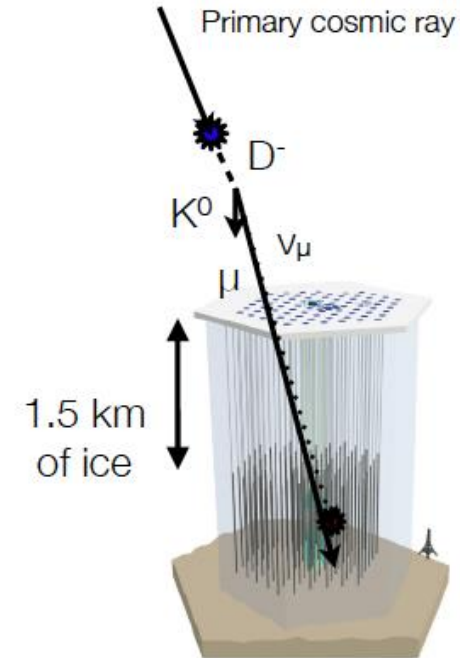


Schönert, Gaisser, Resconi,
Schulz, Phys. Rev. D,
79:043009 (2009)
Gaisser, Jero, Karle, van Santen,
Phys. Rev. D, 90:023009 (2014)

Zenith Distribution

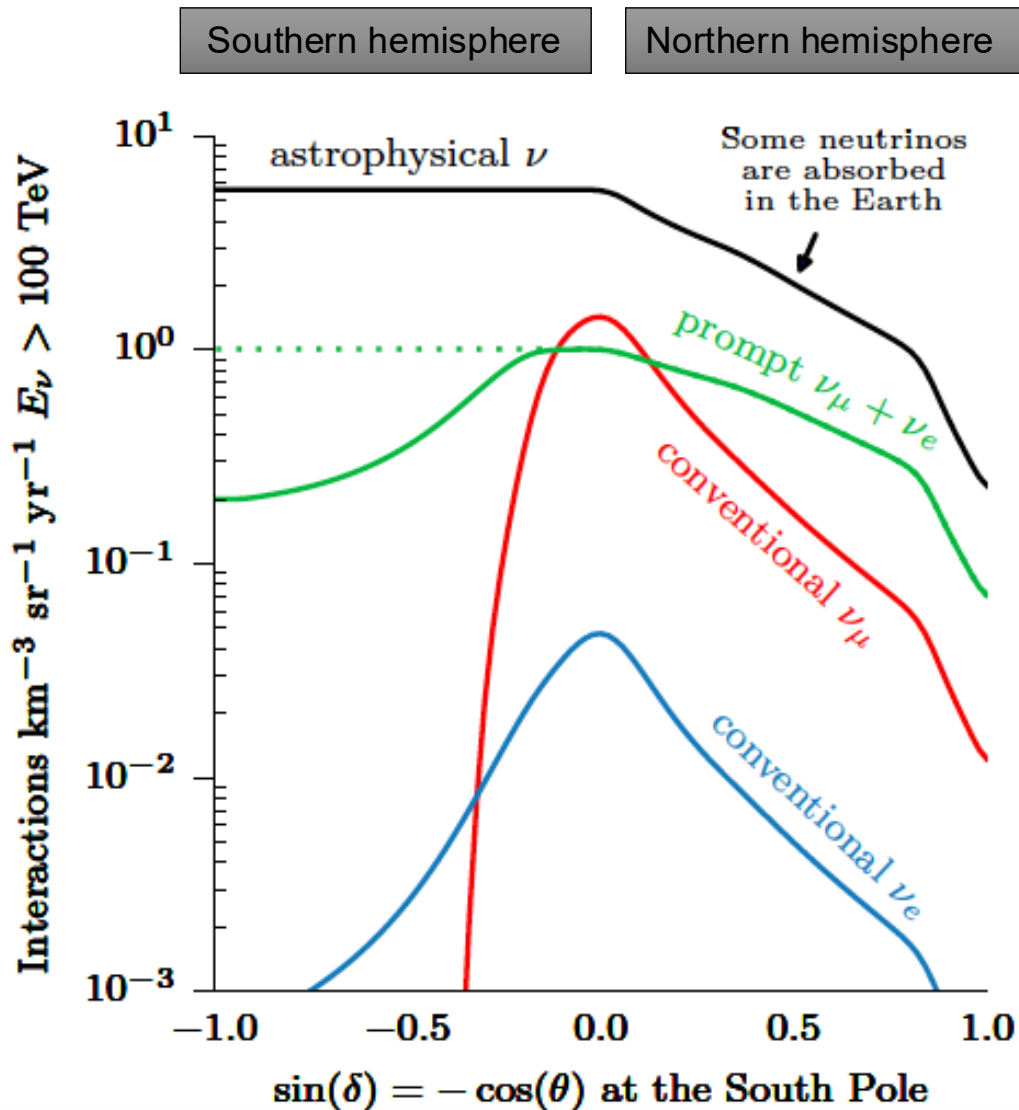


Prompt atmospheric neutrinos are vetoed too



Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

Zenith Distribution



The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

Schönert, Gaisser, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)



Take home message

Water or ice Cherenkov detectors can reach km^3 size.

Atmospheric muons and neutrinos are a background for the search of cosmic neutrinos
→ using outer detector layers as veto can reduce this background

Quiz 2 – High-energy neutrino detection



<https://forms.gle/2hueqB5K25446cY16>

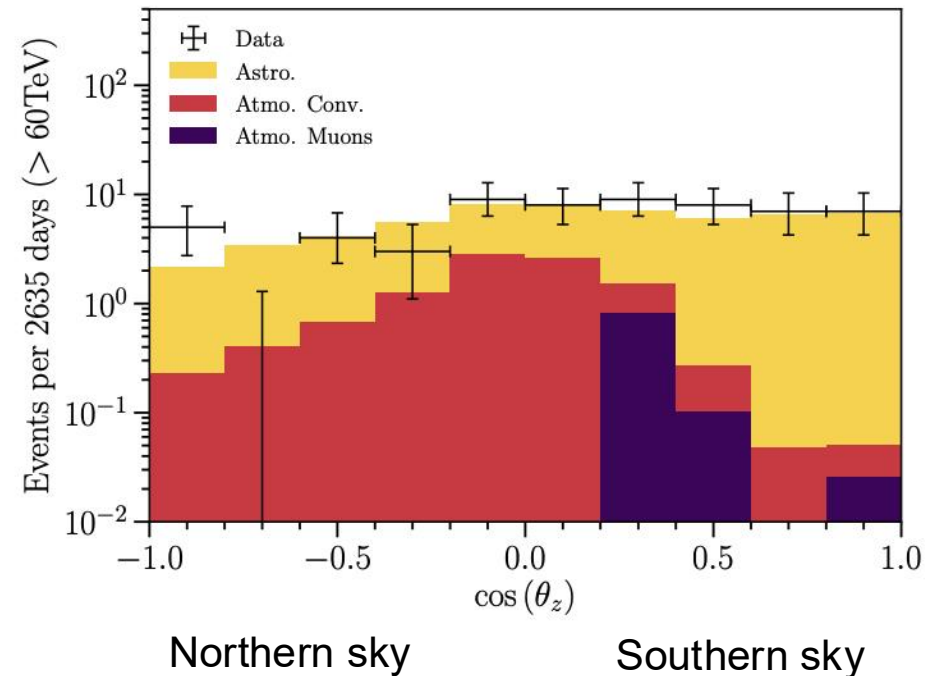
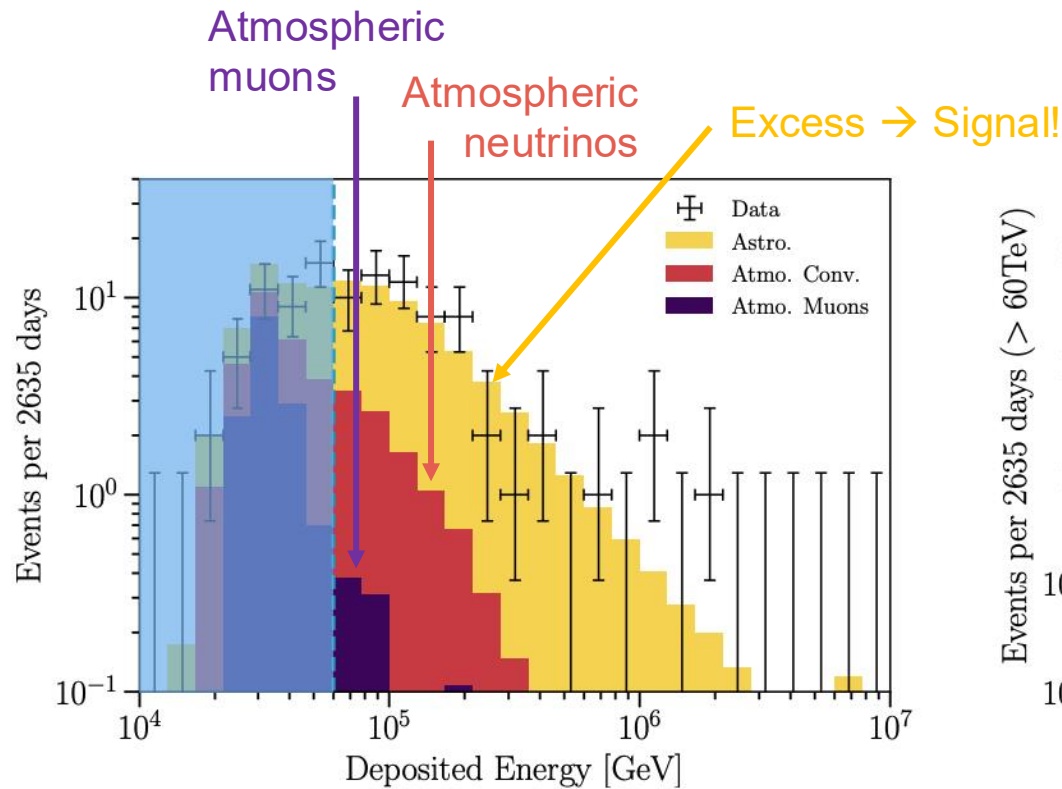
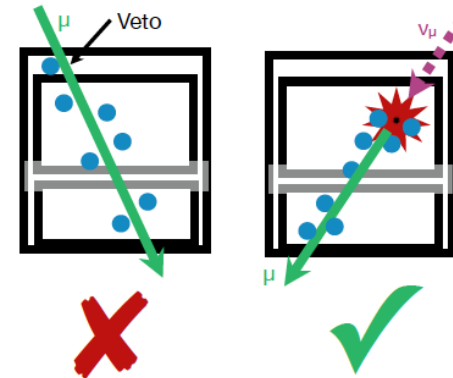
Results from water / ice Cherenkov Telescopes

- Astronomy
 - Diffuse Flux
 - Milky Way
 - Source Candidates
- Neutrino as a particle
 - Neutrino Oscillations
 - Neutrino Cross Section
- New physics
 - Sterile Neutrinos
 - Dark Matter

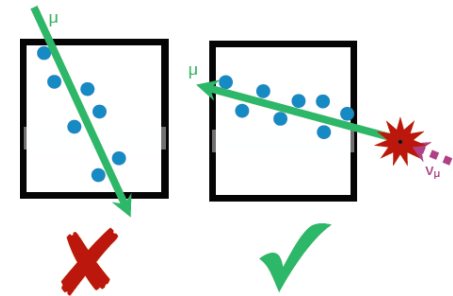
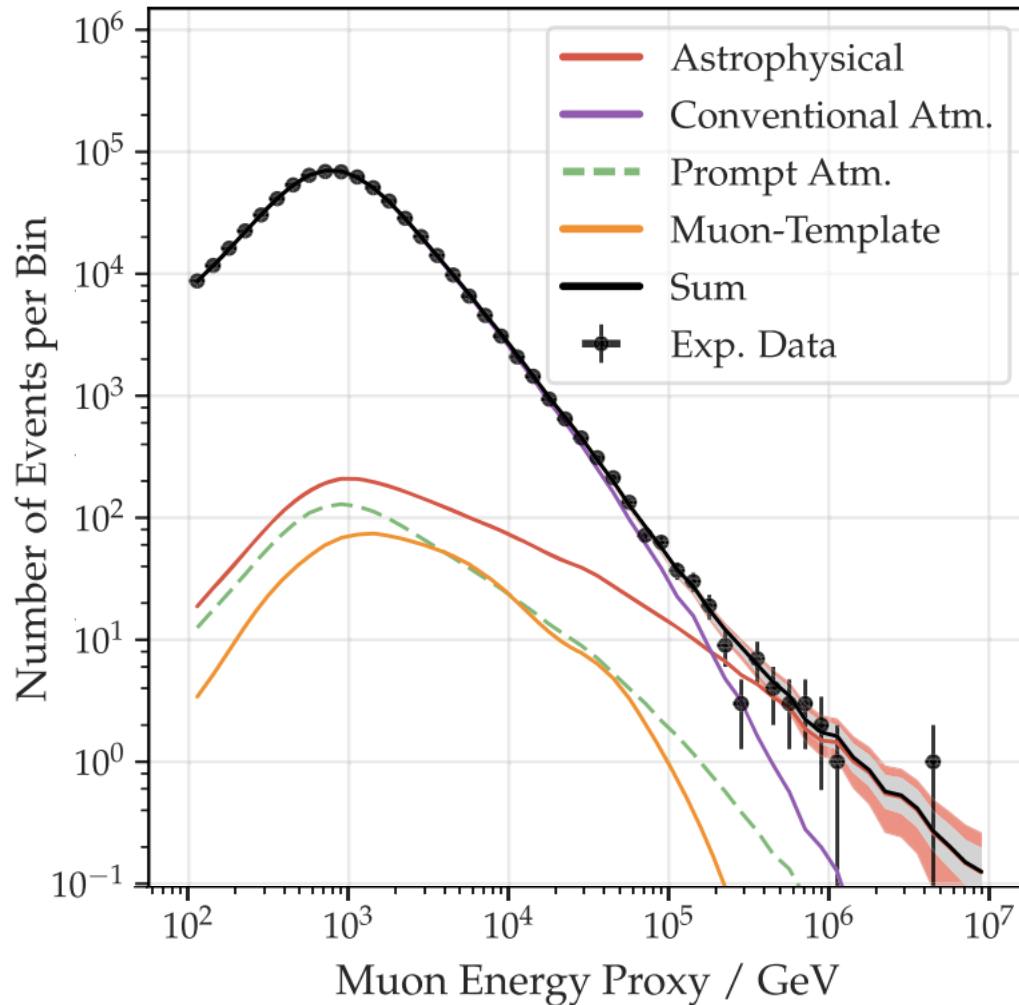
Results from water / ice Cherenkov Telescopes

- Astronomy
 - **Diffuse Flux**
 - Milky Way
 - Source Candidates
- Neutrino as a particle
 - Neutrino Oscillations
 - Neutrino Cross Section
- New physics
 - Sterile Neutrinos
 - Dark Matter

Discovery of High-Energy Astrophysical Neutrinos

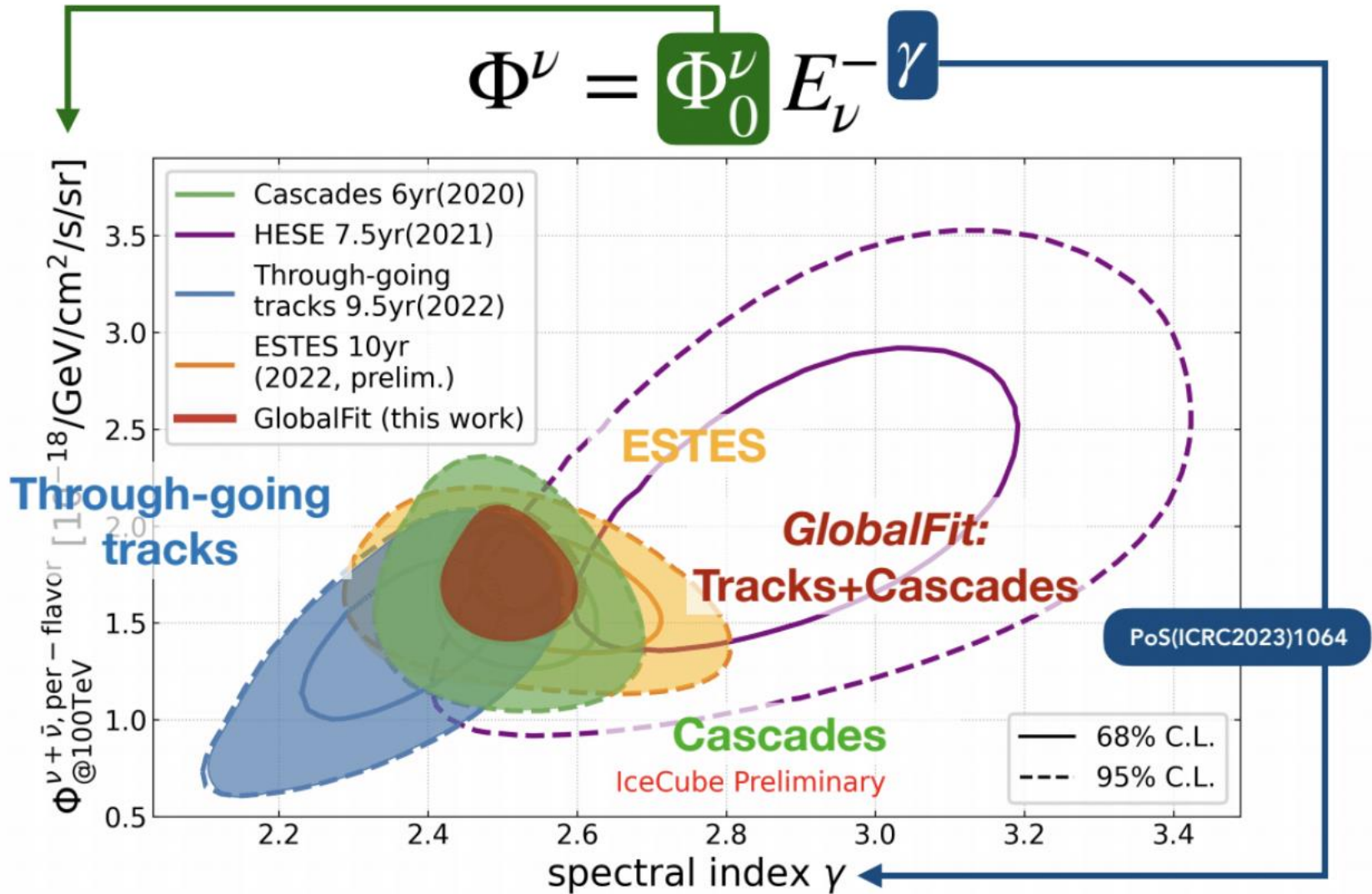


Diffuse flux seen in different channels

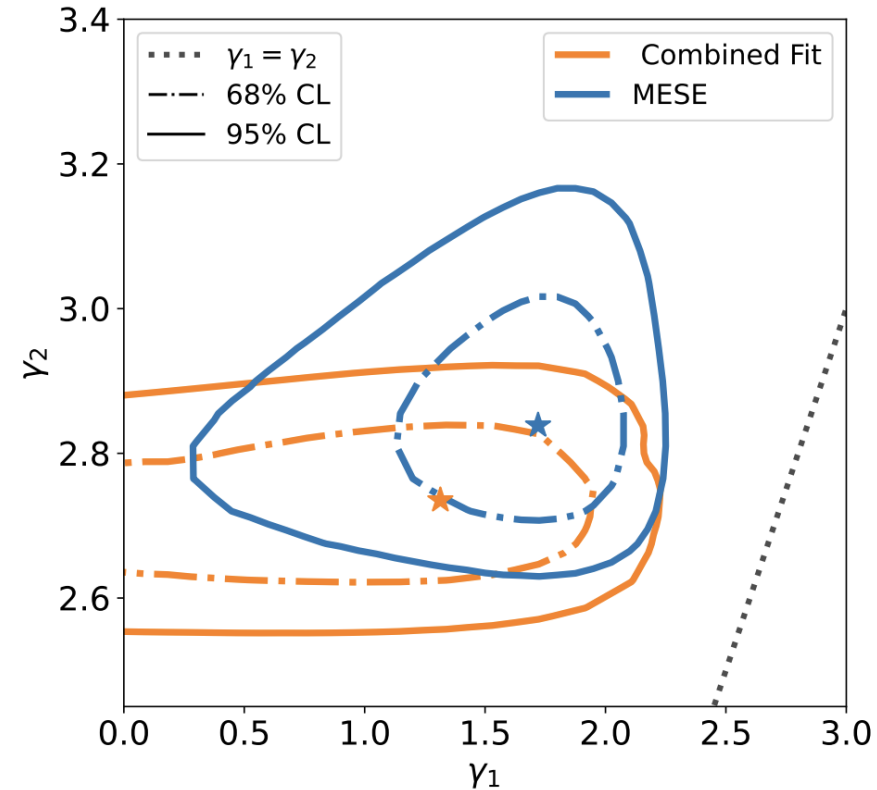
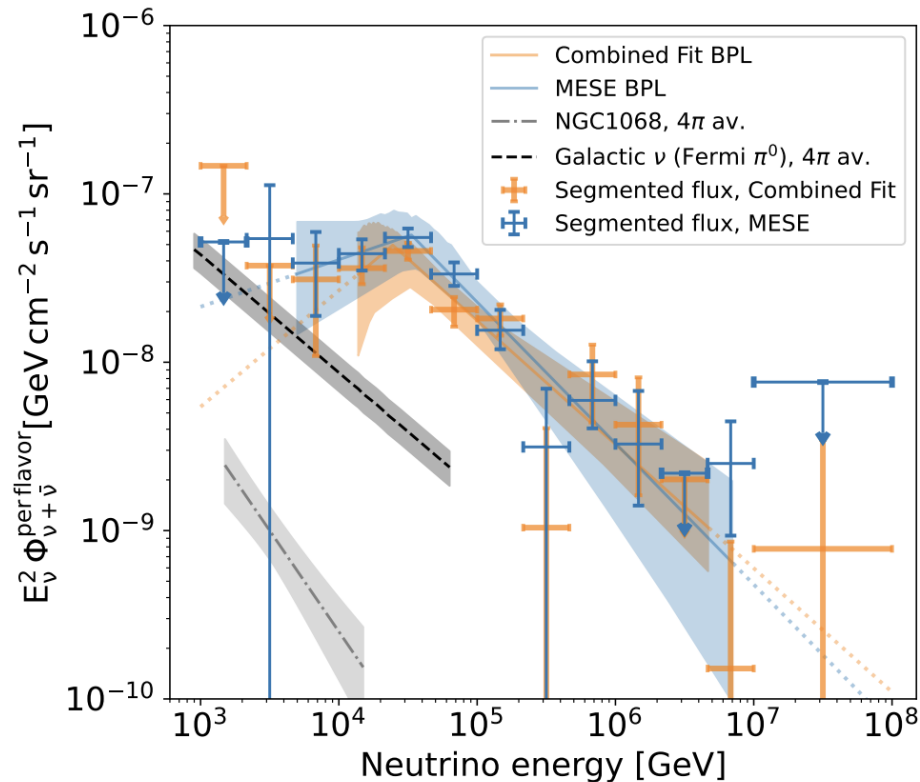


- Selected horizontal and up-going muon tracks
- Sensitive to astrophysical neutrinos above ~ 100 TeV

Spectrum of diffuse flux



Spectrum of diffuse flux: not a power law?

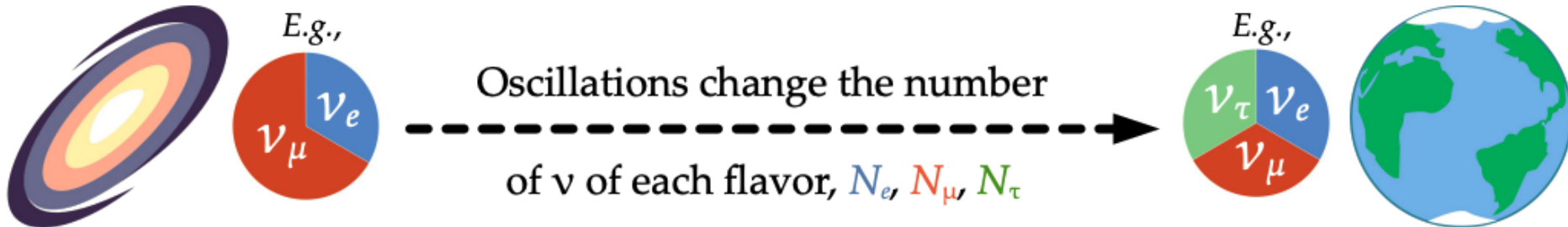


Flavor Composition (slides credit: M. Bustamante)

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{\text{tot}}$$

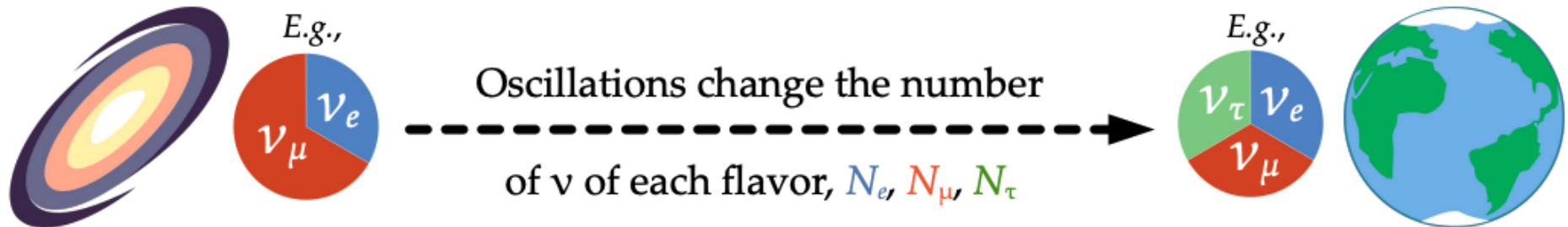
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S}$$

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{\text{tot}}$$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S}$$

Standard oscillations
or
new physics

From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$

Sources



$(f_{e,S}, f_{\mu,S}, f_{\tau,S})$

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

Earth



$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

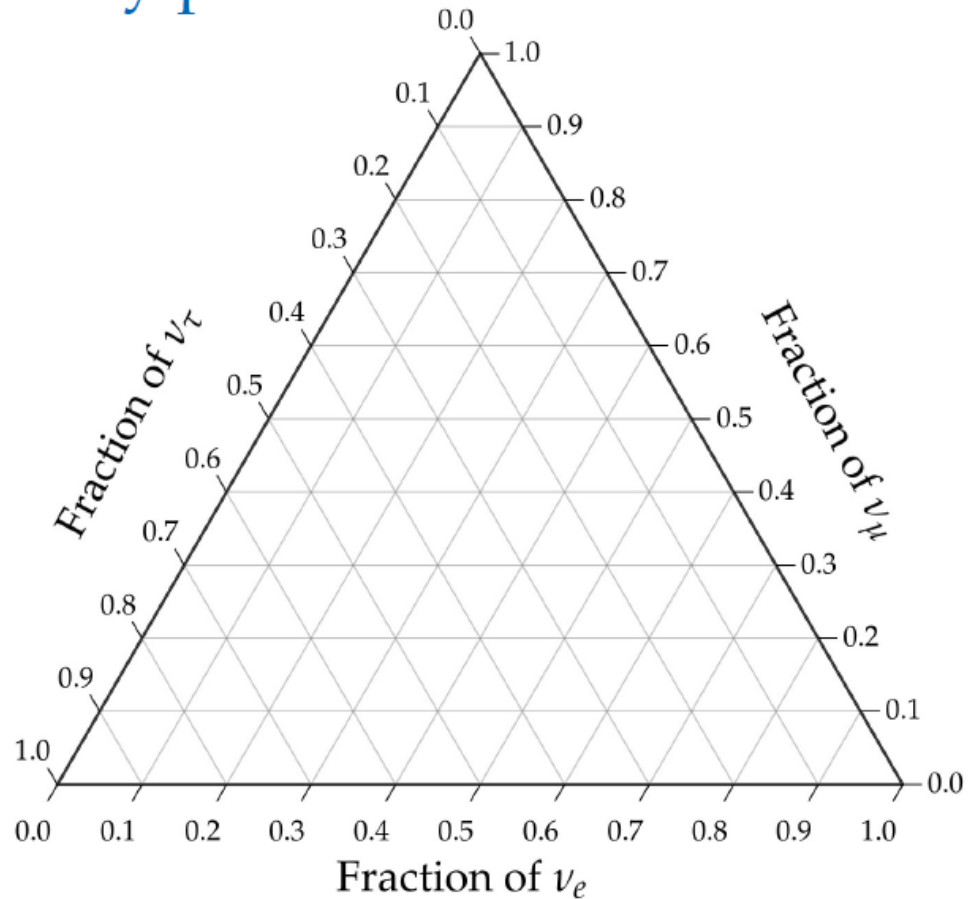
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



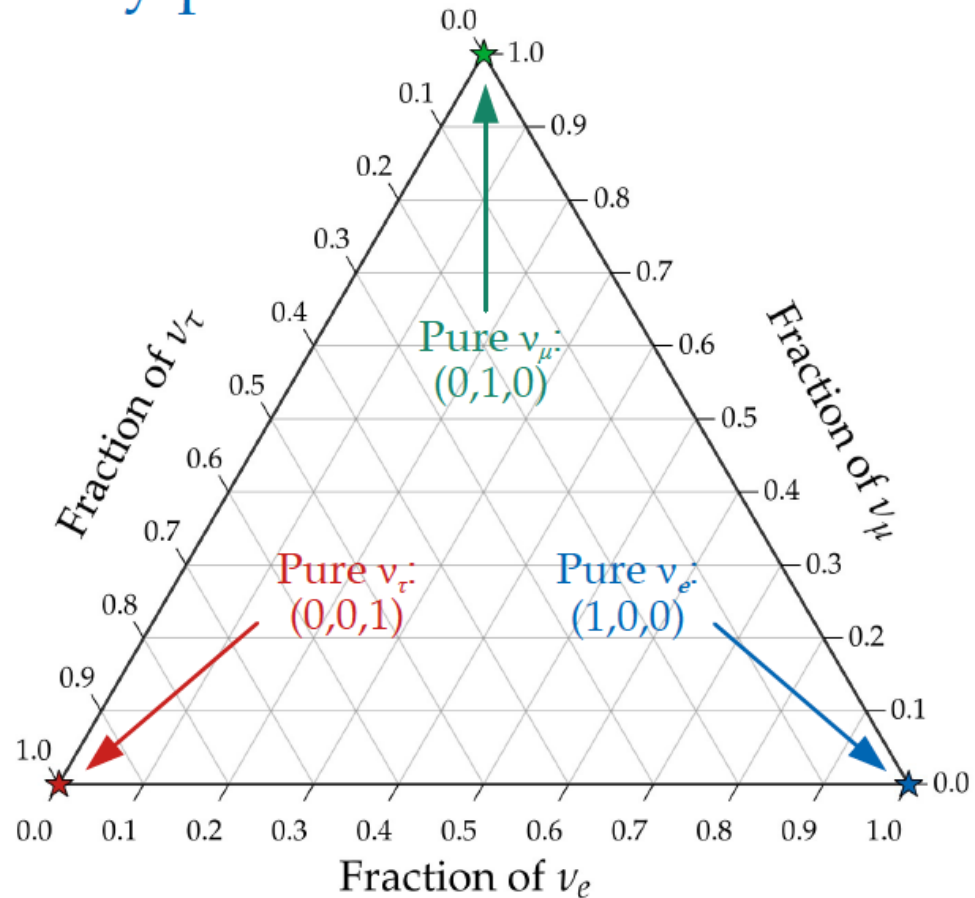
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



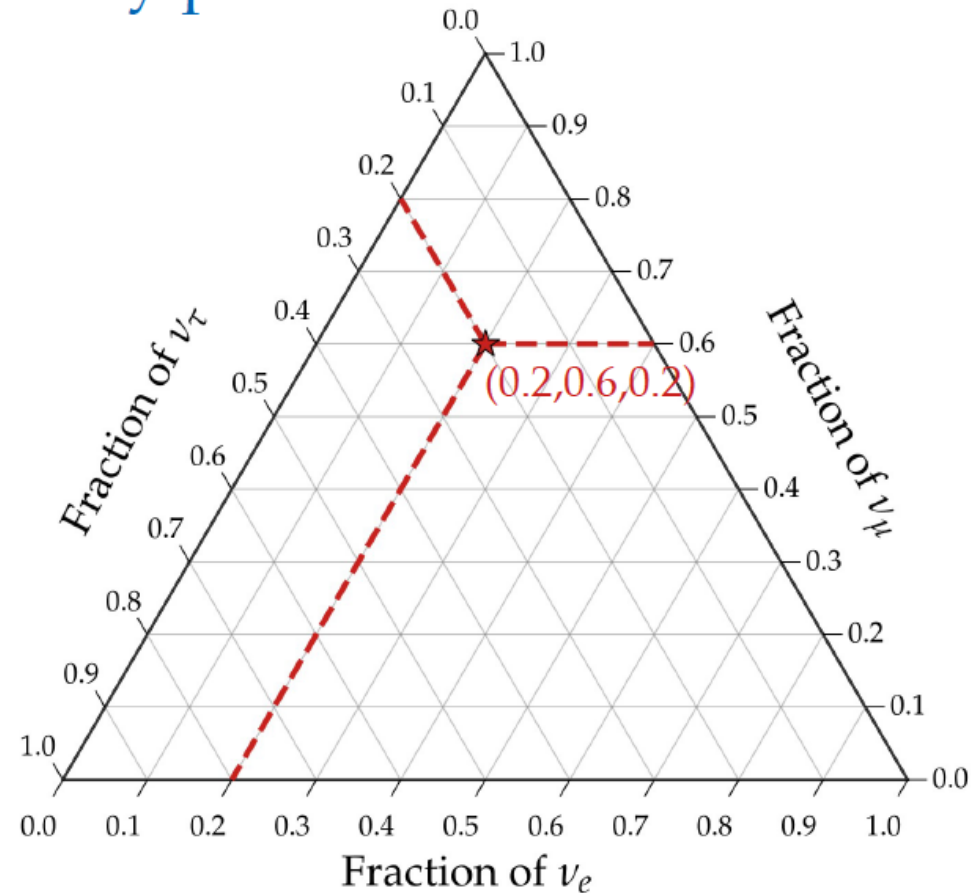
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



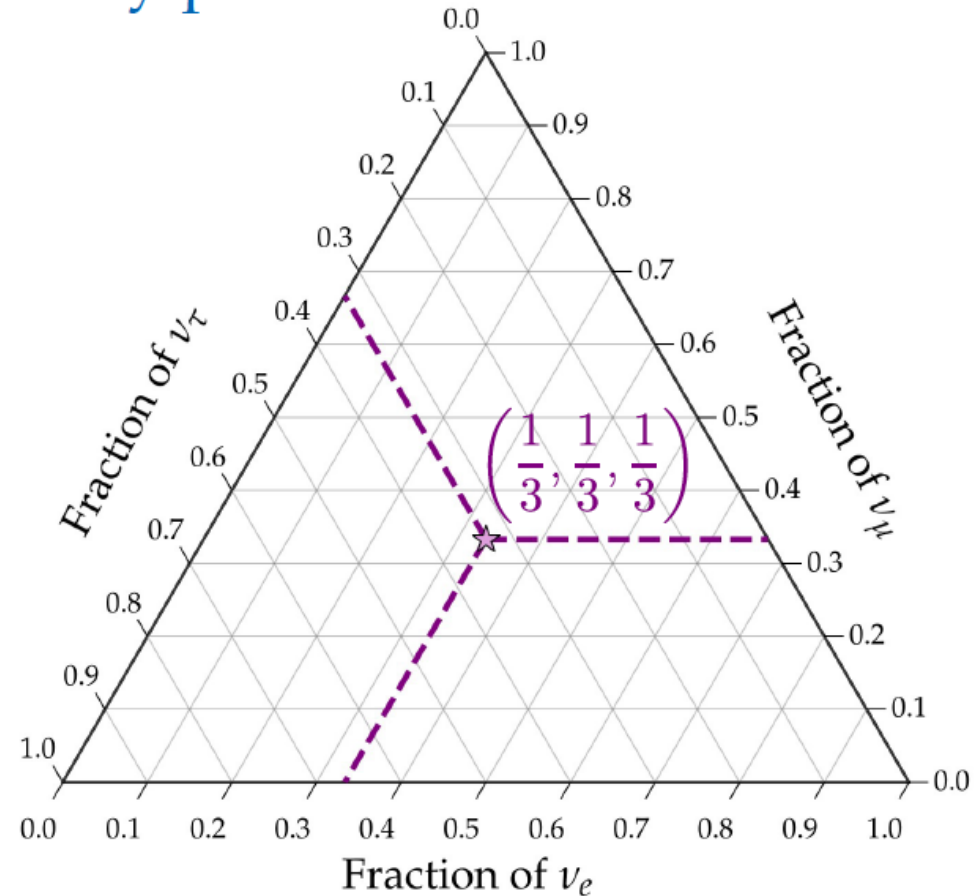
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



One likely TeV–PeV ν production scenario:

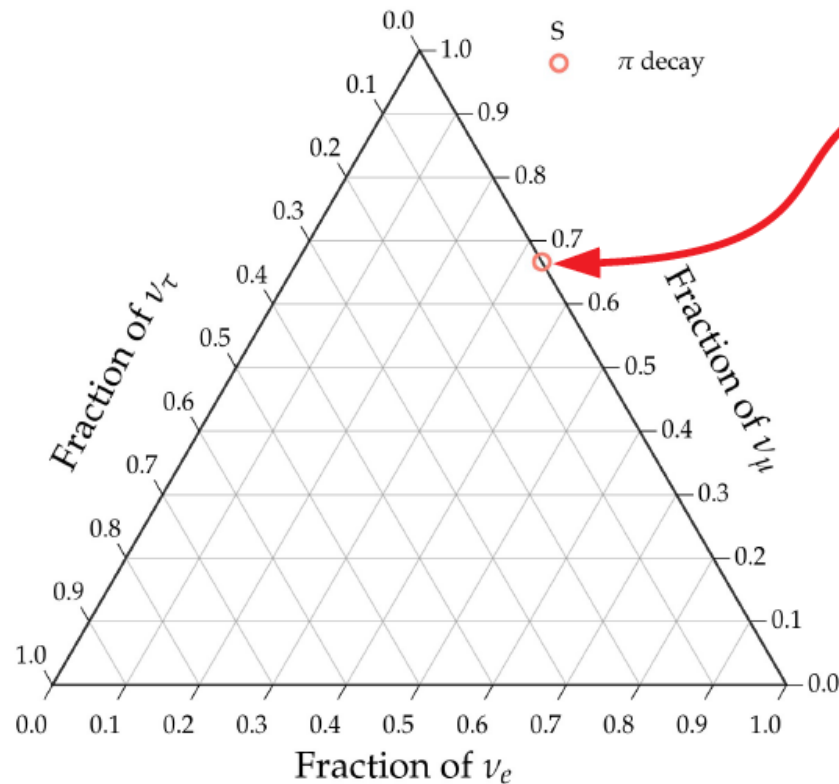
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Full π decay chain

$$(1/3:2/3:0)_S$$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable
in neutrino telescopes

One likely TeV–PeV ν production scenario:

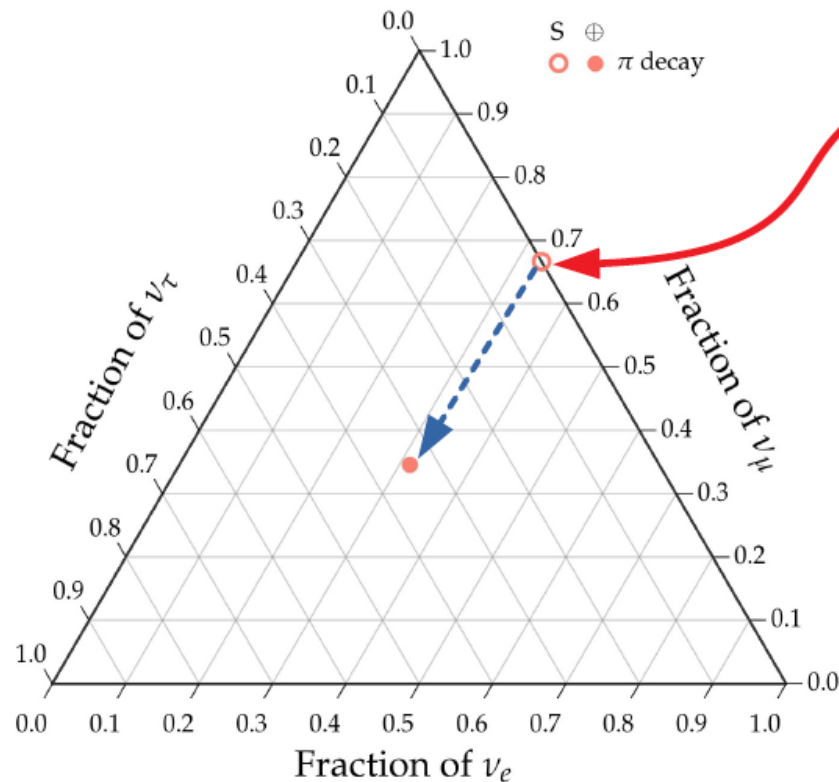


Full π decay chain

$(1/3:2/3:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

One likely TeV–PeV ν production scenario:

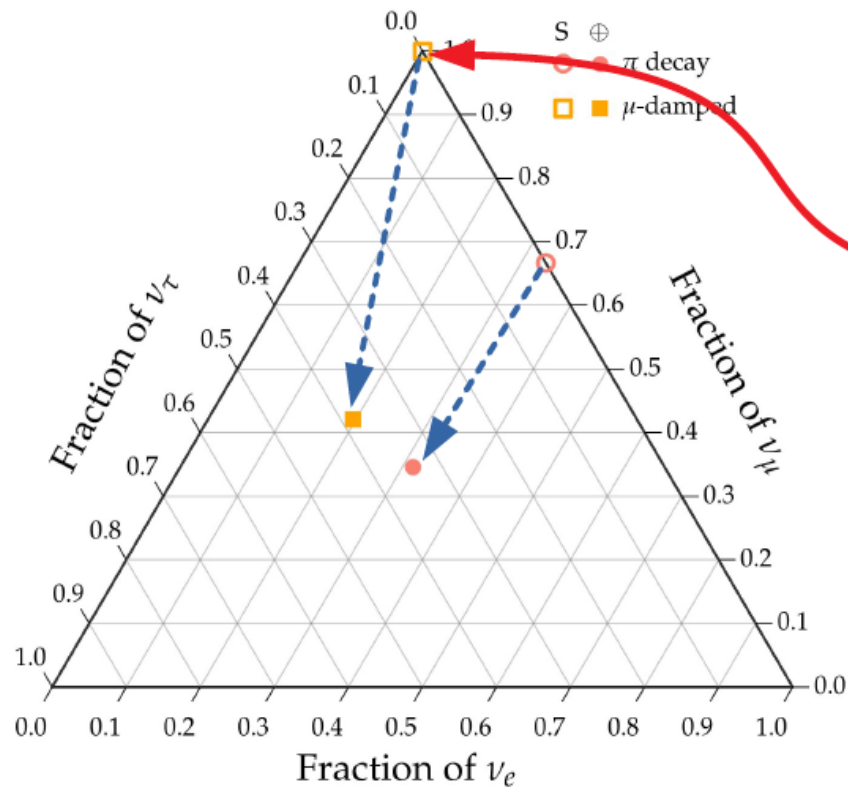
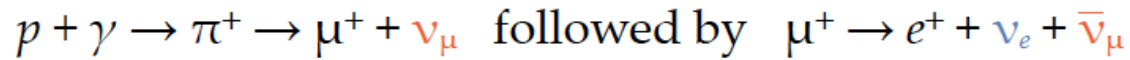


Full π decay chain

$(1/3:2/3:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

One likely TeV–PeV ν production scenario:



Full π decay chain

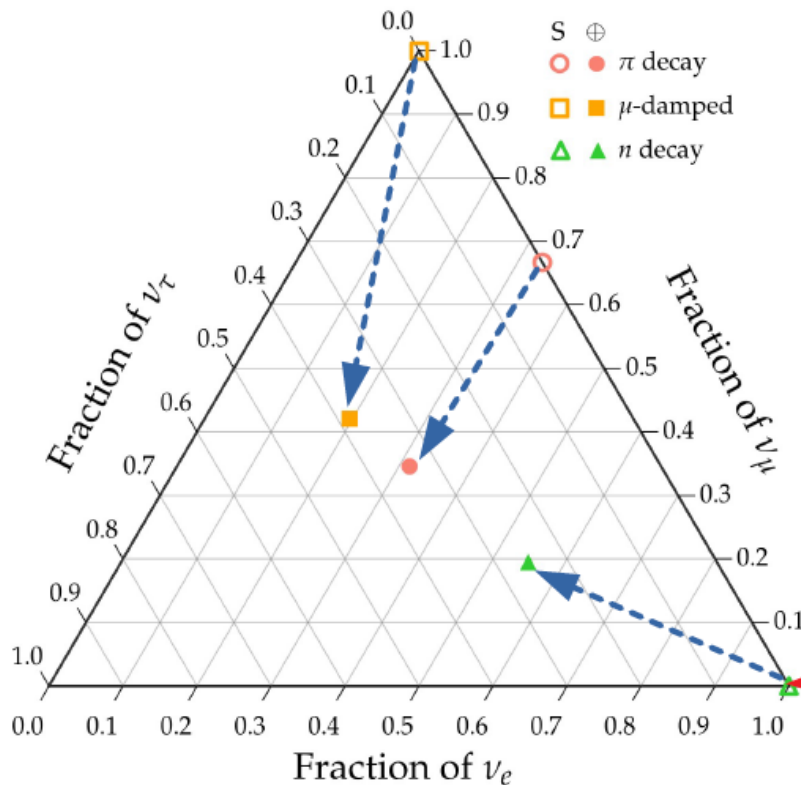
$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

One likely TeV–PeV ν production scenario:



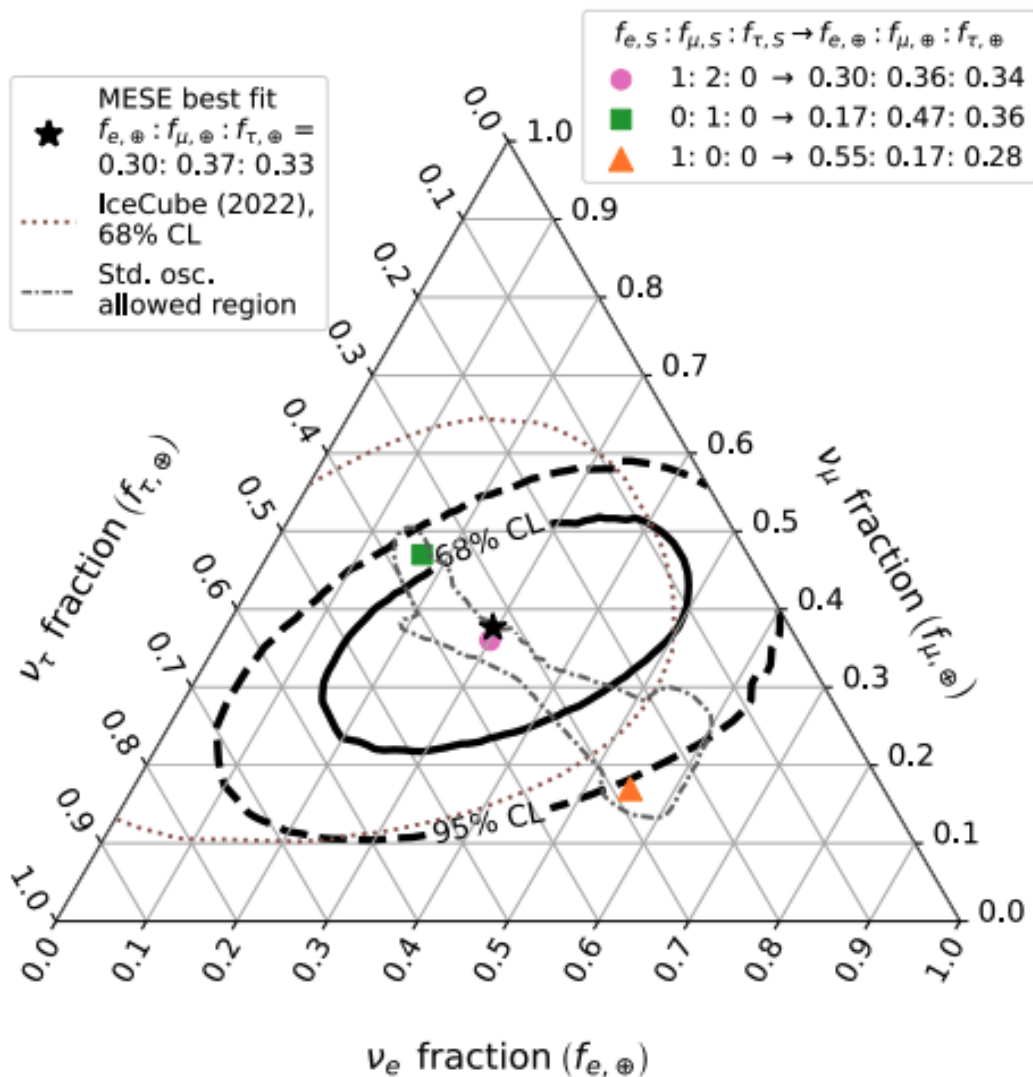
Full π decay chain
(1/3:2/3:0)_S

Muon damped
(0:1:0)_S

Neutron decay
(1:0:0)_S

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

Latest measurement



Pion decay
 Muon damped
 Neutron decay

Neutron decay
 scenario disfavored



Take home message

A diffuse flux of high-energy neutrinos was measured above atmospheric background.

The flavor ratio can tell us something about the neutrino production mechanism in the source.

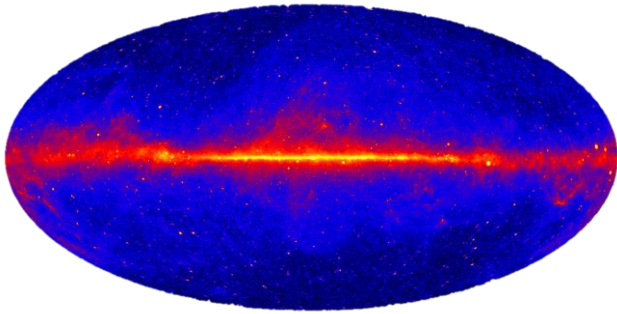
**What is the origin of the
diffuse flux?**

Results from water / ice Cherenkov Telescopes

- Astronomy
 - Diffuse Flux
 - **Milky Way**
 - Source Candidates
- Neutrino as a particle
 - Neutrino Oscillations
 - Neutrino Cross Section
- New physics
 - Sterile Neutrinos
 - Dark Matter

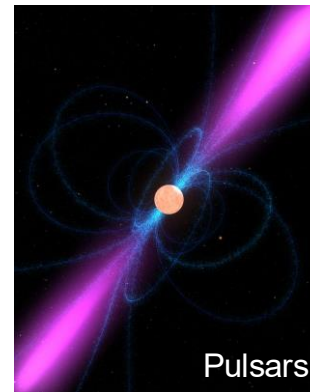
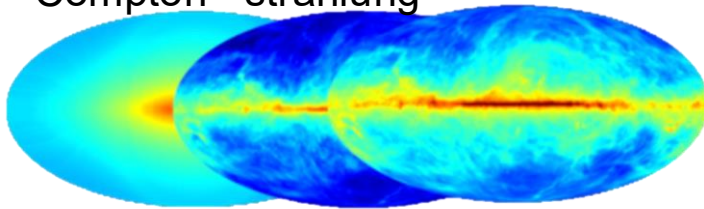
Galactic Contribution

GeV gamma-ray sky by Fermi-LAT

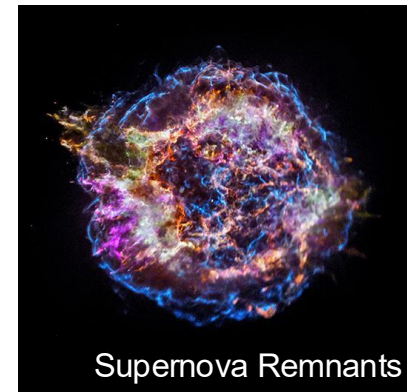


Cosmic rays propagate through the Galaxy and interact with photons and gas

Inverse Compton Bremsstrahlung π^0 decay



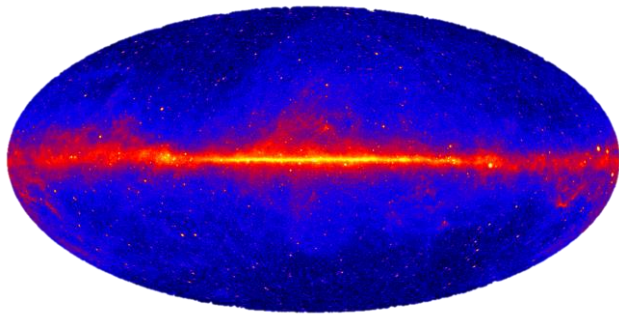
Pulsars



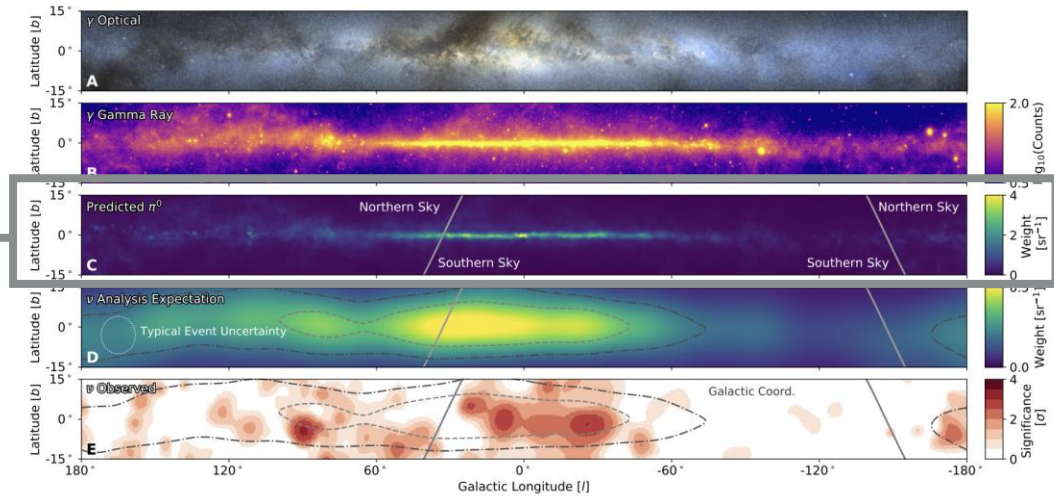
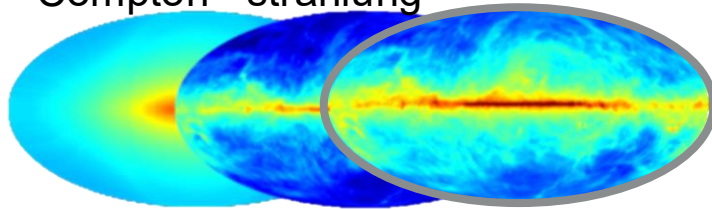
Supernova Remnants

Galactic Contribution

GeV gamma-ray sky by Fermi-LAT

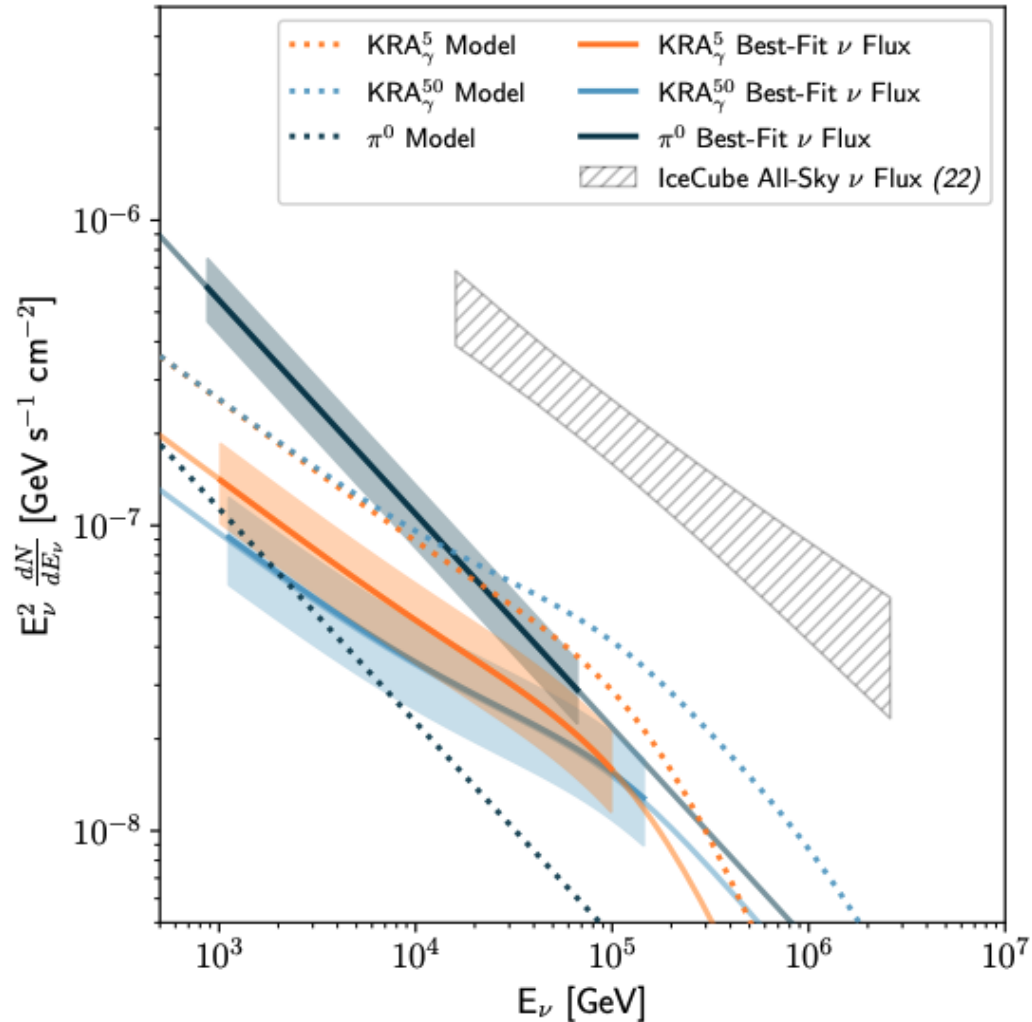


Inverse Compton Bremsstrahlung π^0 decay



First detection of galactic plane neutrino flux thanks to gamma-ray template fit

Galactic Neutrinos



Galactic neutrinos
make up ~10% of
diffuse neutrinos



Take home message

Neutrino emission from the Galactic plane has been detected.

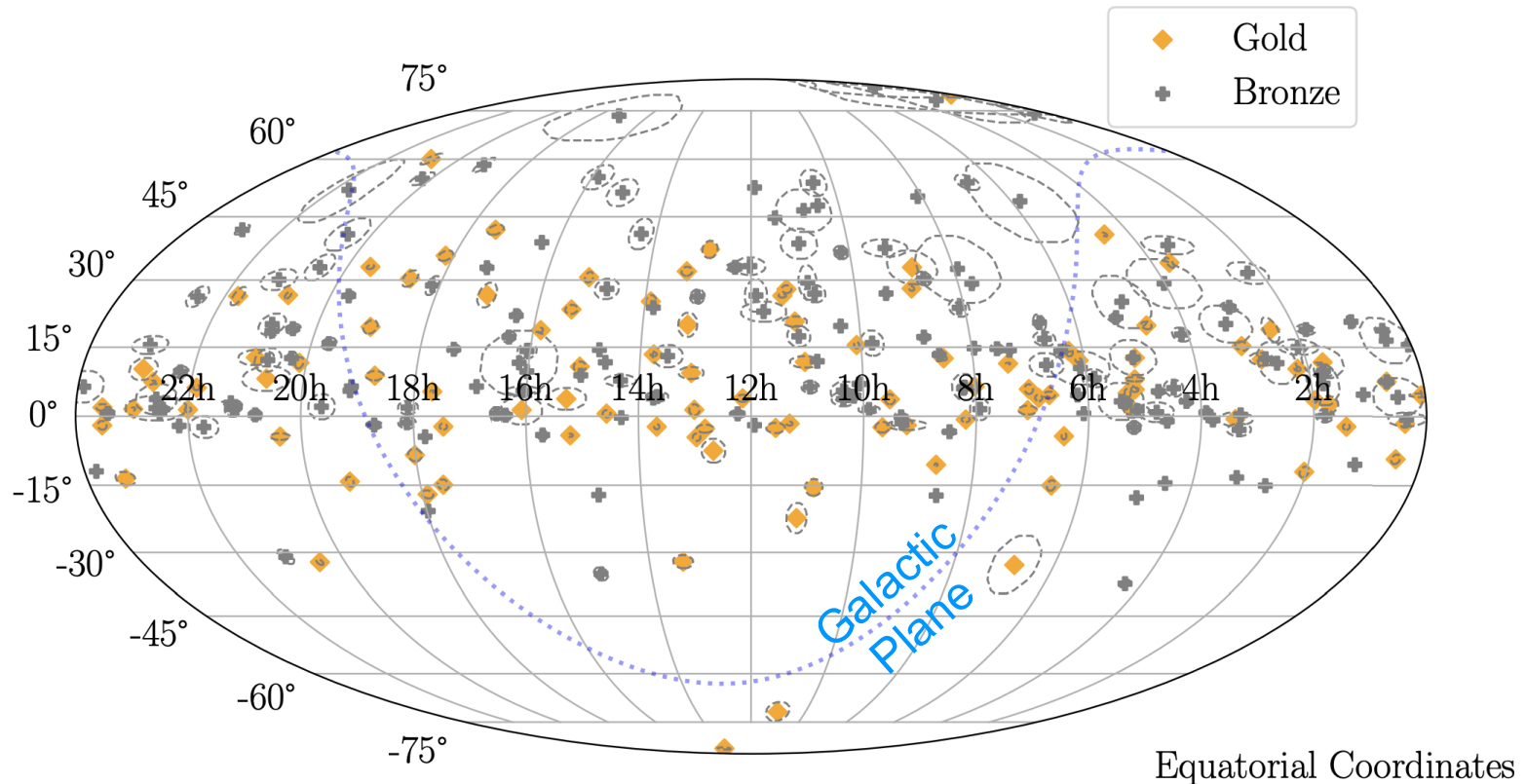
It is currently not possible to distinguish between a signal from Galactic point sources and a diffuse signal.

Results from water / ice Cherenkov Telescopes

- Astronomy
 - Diffuse Flux
 - Milky Way
 - **Source Candidates**
- Neutrino as a particle
 - Neutrino Oscillations
 - Neutrino Cross Section
- New physics
 - Sterile Neutrinos
 - Dark Matter

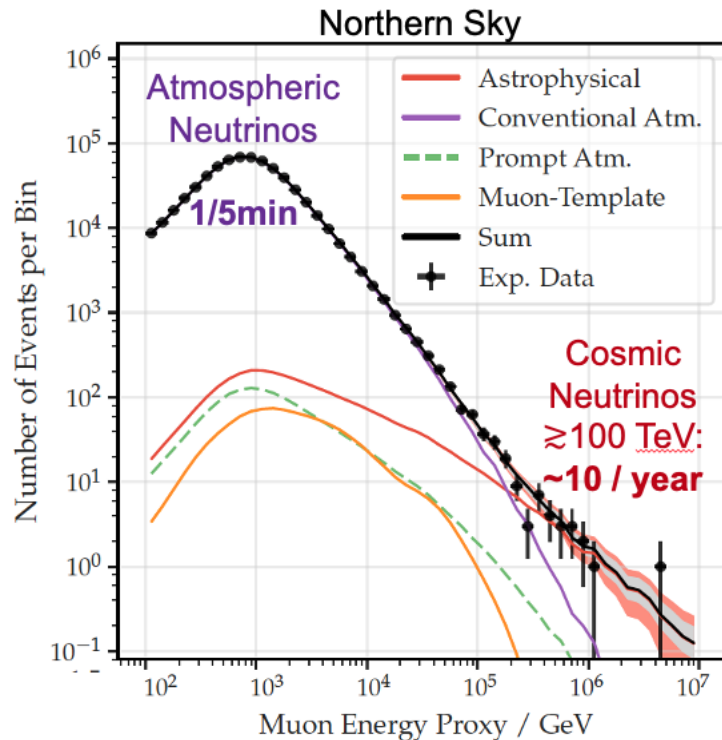
Neutrino Sky Map

IceCube neutrinos with high ($>30\%$) probability to be of cosmic origin



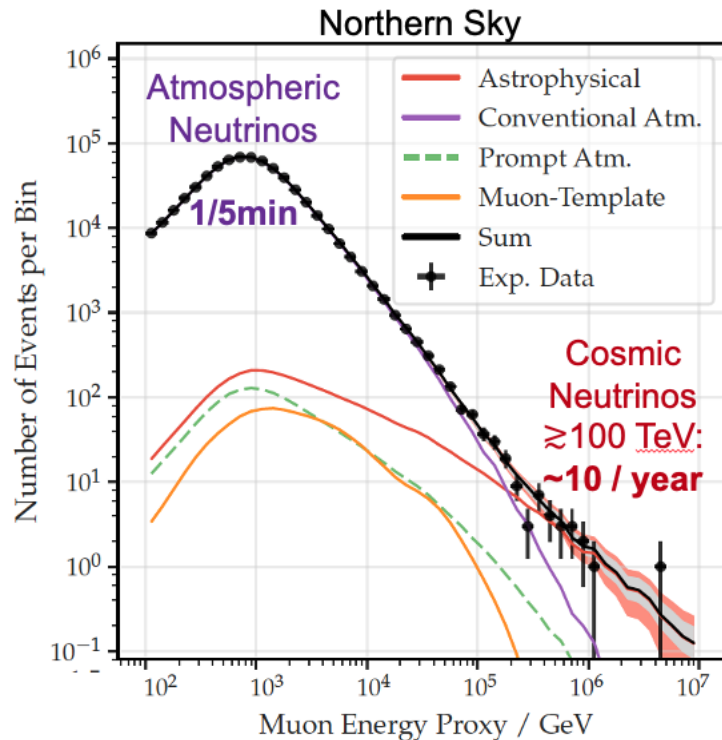
Neutrinos alone do not reveal the sources (yet)

Search for Extragalactic Sources: Strategies



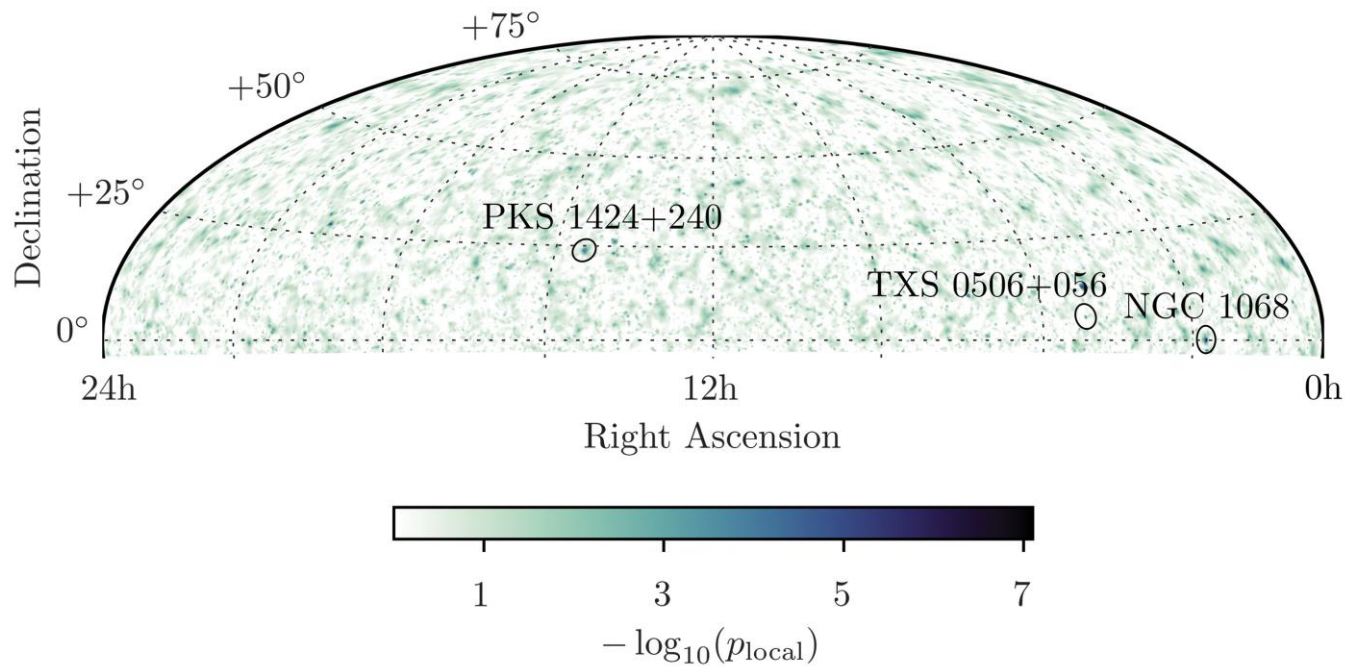
1. Look for hotspots in the neutrino sky → identify source candidates
2. Start from EM source catalog → look for neutrinos from source population
3. Focus on high-energy neutrinos with high signal probability → look for EM counterparts

Search for Extragalactic Sources: Strategies

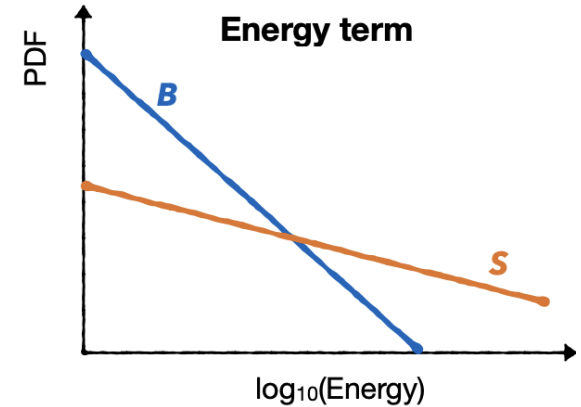
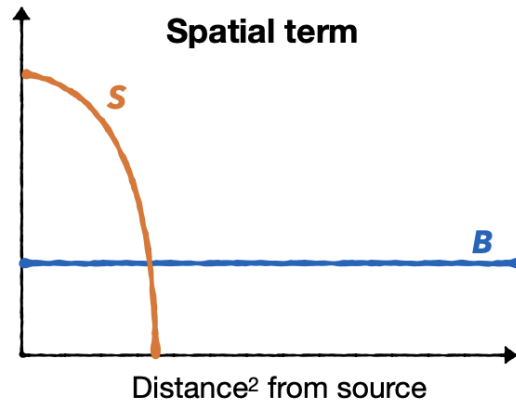
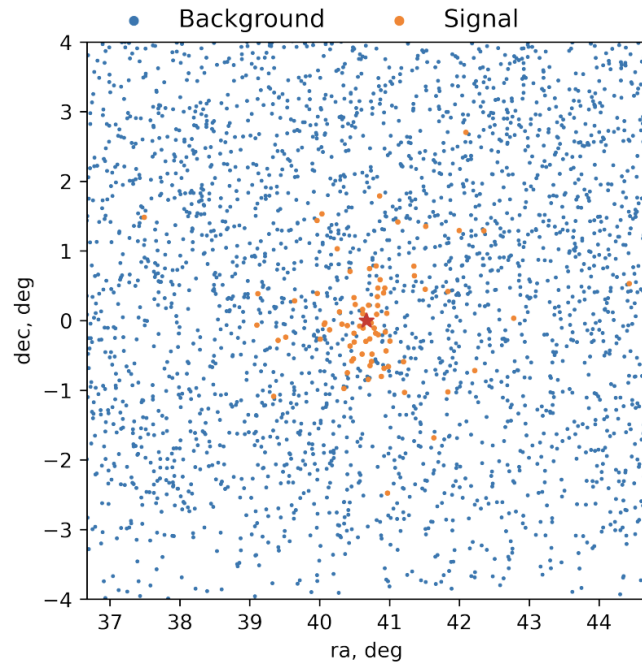


1. Look for hotspots in the neutrino sky
→ identify source candidates
2. Start from EM source catalog → look for neutrinos from source population
3. Focus on high-energy neutrinos with high signal probability → look for EM counterparts

Search for hotspots in the neutrino sky



Maximum Likelihood Technique



Maximum Likelihood Technique

$$\mathcal{L}(n_S, \gamma) = \prod_{\substack{i \\ \text{Neutrino event } i}} \left(\overbrace{\frac{n_S}{N} \mathcal{S}(|\mathbf{x}_S - \mathbf{x}_i|, E_i; \gamma)}^{\text{Signal probability}} + \left(1 - \frac{n_S}{N}\right) \underbrace{\mathcal{B}(\sin \delta_i, E_i)}_{\text{background probability}} \right)$$

Test Statistic:

$$\mathcal{TS} = 2 \log (\mathcal{L}(\hat{n}_S, \hat{\gamma}) / \mathcal{L}(n_S = 0))$$

Maximum Likelihood Technique

$$\mathcal{S} = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\mathbf{x}_S - \mathbf{x}_i|^2}{2\sigma_i^2}} \times \mathcal{E}_S(E_i, \sin \delta_i; \gamma)$$

Signal probability

$$\mathcal{L}(n_S, \gamma) = \prod_i \left(\frac{n_S}{N} \overbrace{\mathcal{S}(|\mathbf{x}_S - \mathbf{x}_i|, E_i; \gamma)}^{\text{Signal probability}} + \left(1 - \frac{n_S}{N}\right) \mathcal{B}(\sin \delta_i, E_i) \right)$$

$\mathbf{x}_S$: source position

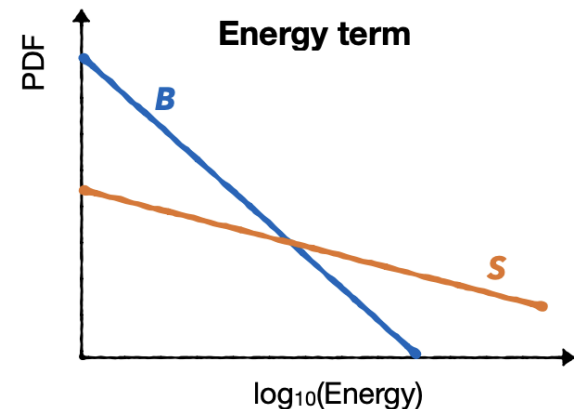
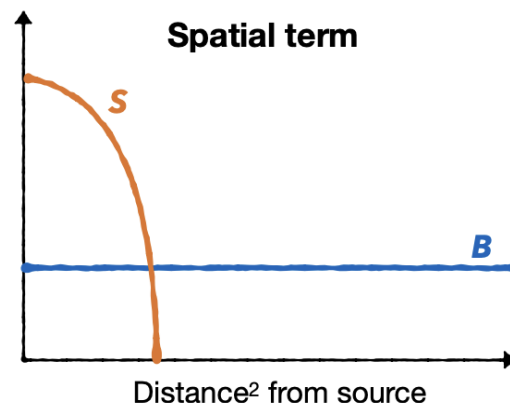
$\mathbf{x}_i$: nu direction

δ_i : nu declination

σ_i : nu declination

E_i : nu energy

γ : spectral index



Maximum Likelihood Technique

$$\mathcal{S} = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\mathbf{x}_S - \mathbf{x}_i|^2}{2\sigma_i^2}} \times \mathcal{E}_S(E_i, \sin \delta_i, \gamma)$$

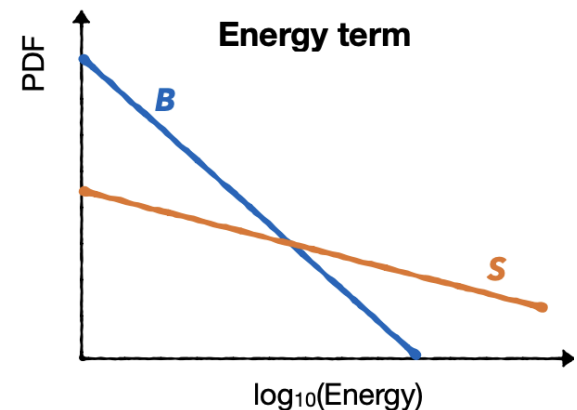
Signal probability

Spectral index
(free parameter
in fit)

$$\mathcal{L}(n_S, \gamma) = \prod_i \left(\frac{n_S}{N} \mathcal{S}(|\mathbf{x}_S - \mathbf{x}_i|, E_i; \gamma) + \left(1 - \frac{n_S}{N}\right) \mathcal{B}(\sin \delta_i, E_i) \right)$$

number of events
from source (**free
parameter in fit**)

$\mathbf{x}_S$: source position
 $\mathbf{x}_i$: neutrino direction
 δ_i : neutrino declination
 σ_i : neutrino declination
 E_i : neutrino energy
 γ : spectral index



Maximum Likelihood Technique

$$\mathcal{S} = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\mathbf{x}_S - \mathbf{x}_i|^2}{2\sigma_i^2}} \times \mathcal{E}_S(E_i, \sin \delta_i, \gamma)$$

Spectral index
(free parameter
in fit)

$$\mathcal{L}(n_S, \gamma) = \prod_i \left(\frac{n_S}{N} \mathcal{S}(|\mathbf{x}_S - \mathbf{x}_i|, E_i; \gamma) + \left(1 - \frac{n_S}{N}\right) \mathcal{B}(\sin \delta_i, E_i) \right)$$

number of events
from source (**free
parameter in fit**)

background
probability

$$\mathcal{B} = \frac{\mathcal{P}_B(\sin \delta_i)}{2\pi} \times \mathcal{E}_B(E_i, \sin \delta_i)$$

$\mathbf{x}_S$: source position
 $\mathbf{x}_i$: nu direction
 δ_i : nu declination
 σ_i : nu declination
 E_i : nu energy
 γ : spectral index

Maximum Likelihood Technique

$$\mathcal{S} = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|\mathbf{x}_S - \mathbf{x}_i|^2}{2\sigma_i^2}} \times \mathcal{E}_S(E_i, \sin \delta_i, \gamma)$$

Signal probability

Spectral index (free parameter in fit)

$$\mathcal{L}(n_S, \gamma) = \prod_i \left(\frac{n_S}{N} \mathcal{S}(|\mathbf{x}_S - \mathbf{x}_i|, E_i; \gamma) + \left(1 - \frac{n_S}{N}\right) \mathcal{B}(\sin \delta_i, E_i) \right)$$

number of events from source (free parameter in fit)

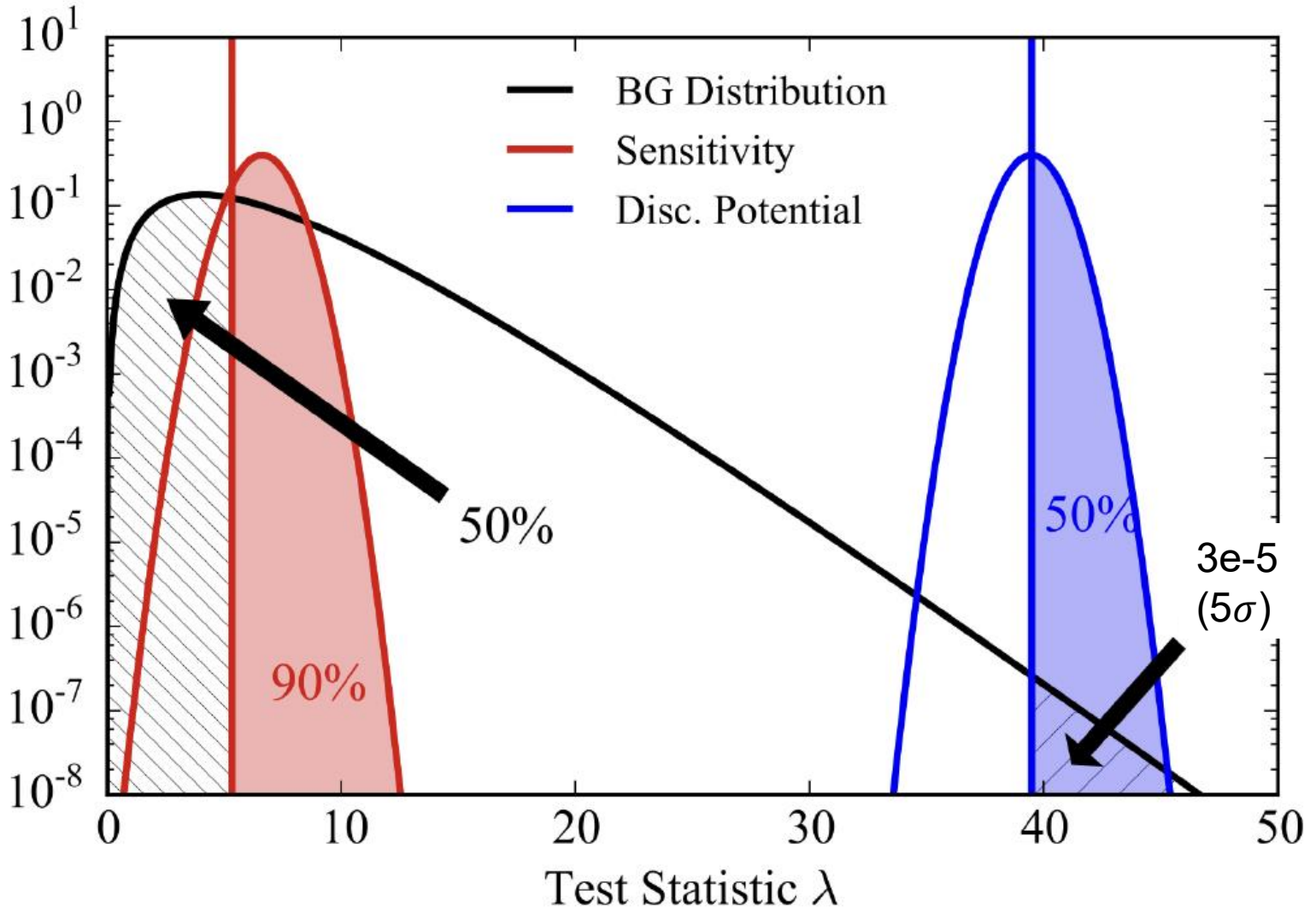
background probability

$$\mathcal{B} = \frac{\mathcal{P}_B(\sin \delta_i)}{2\pi} \times \mathcal{E}_B(E_i, \sin \delta_i)$$

Test Statistic:

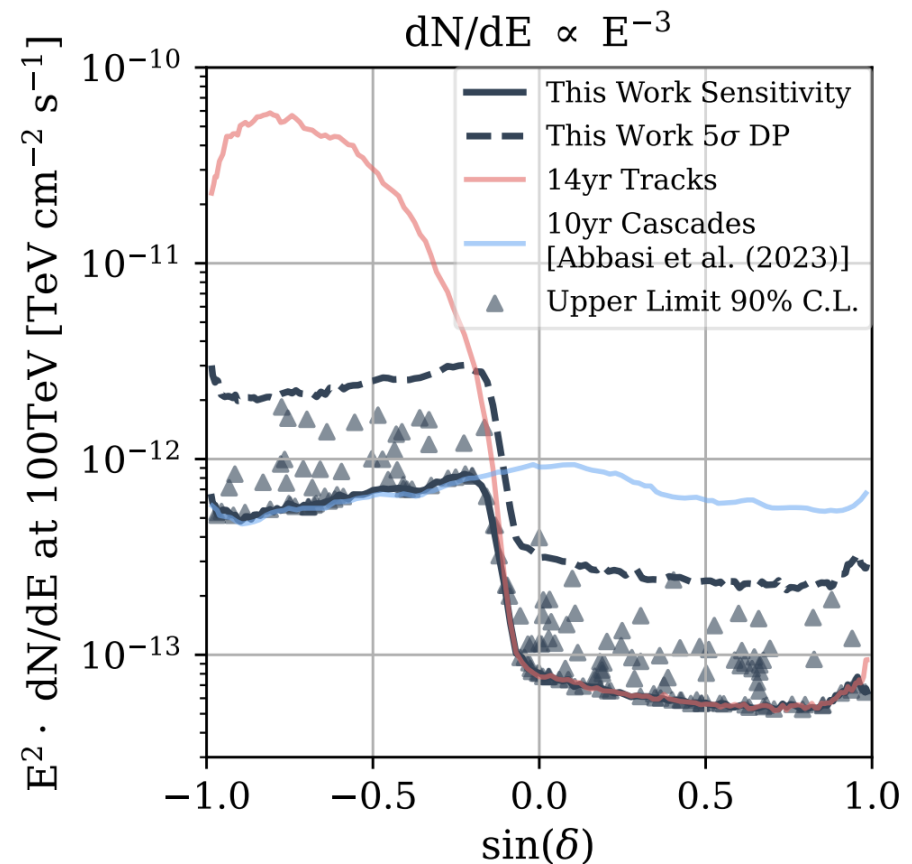
$$\mathcal{TS} = 2 \log (\mathcal{L}(\hat{n}_S, \hat{\gamma}) / \mathcal{L}(n_S = 0))$$

Definition of Sensitivity



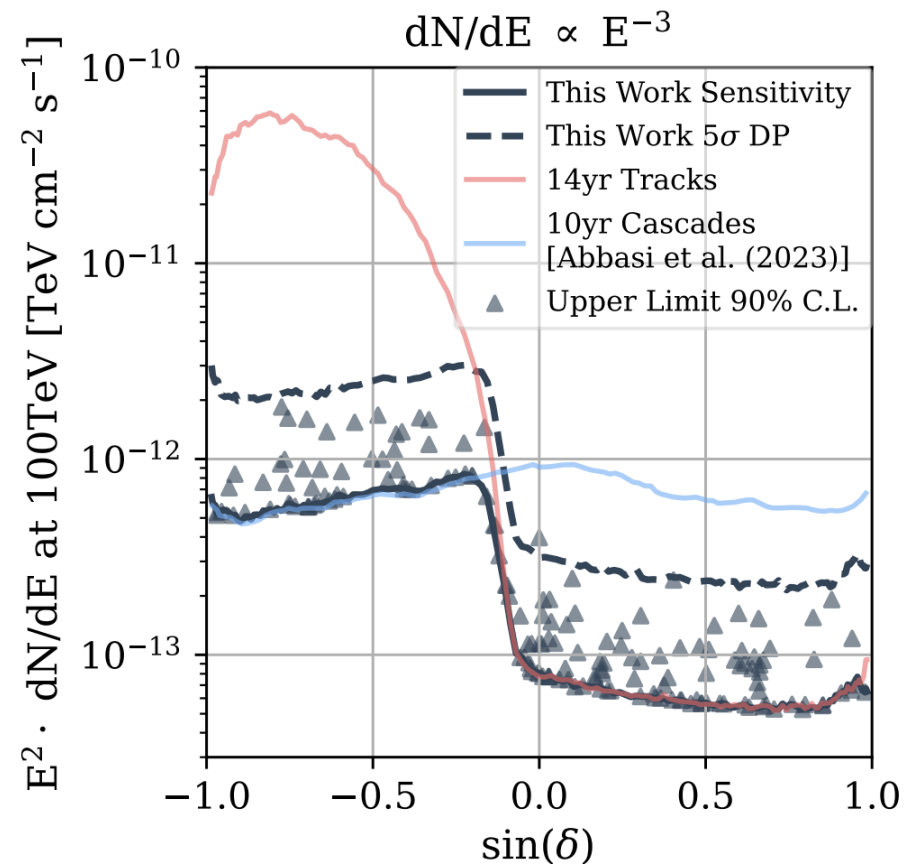
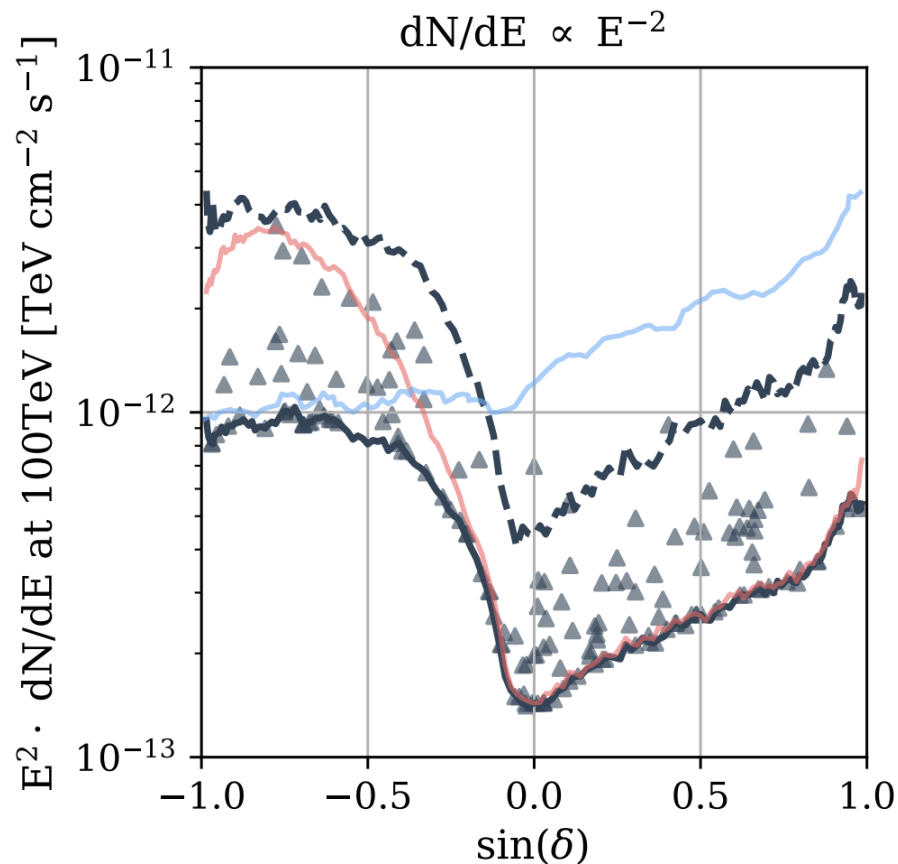
Point Source Sensitivity

Signal trials: determine how much signal needs to be injected to have 90% of the signal trials yield a TS greater than the median TS derived from background trials

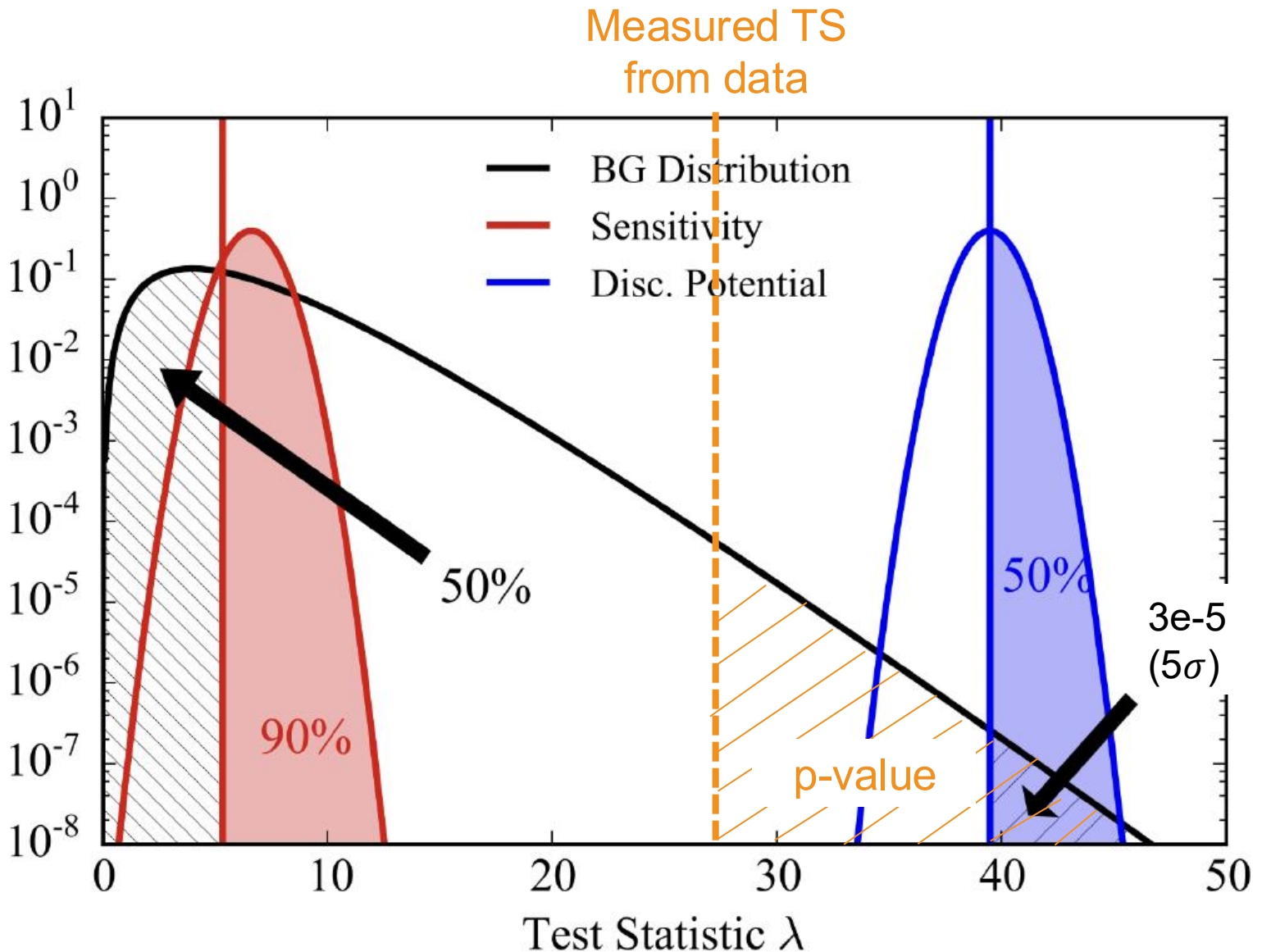


Point Source Sensitivity

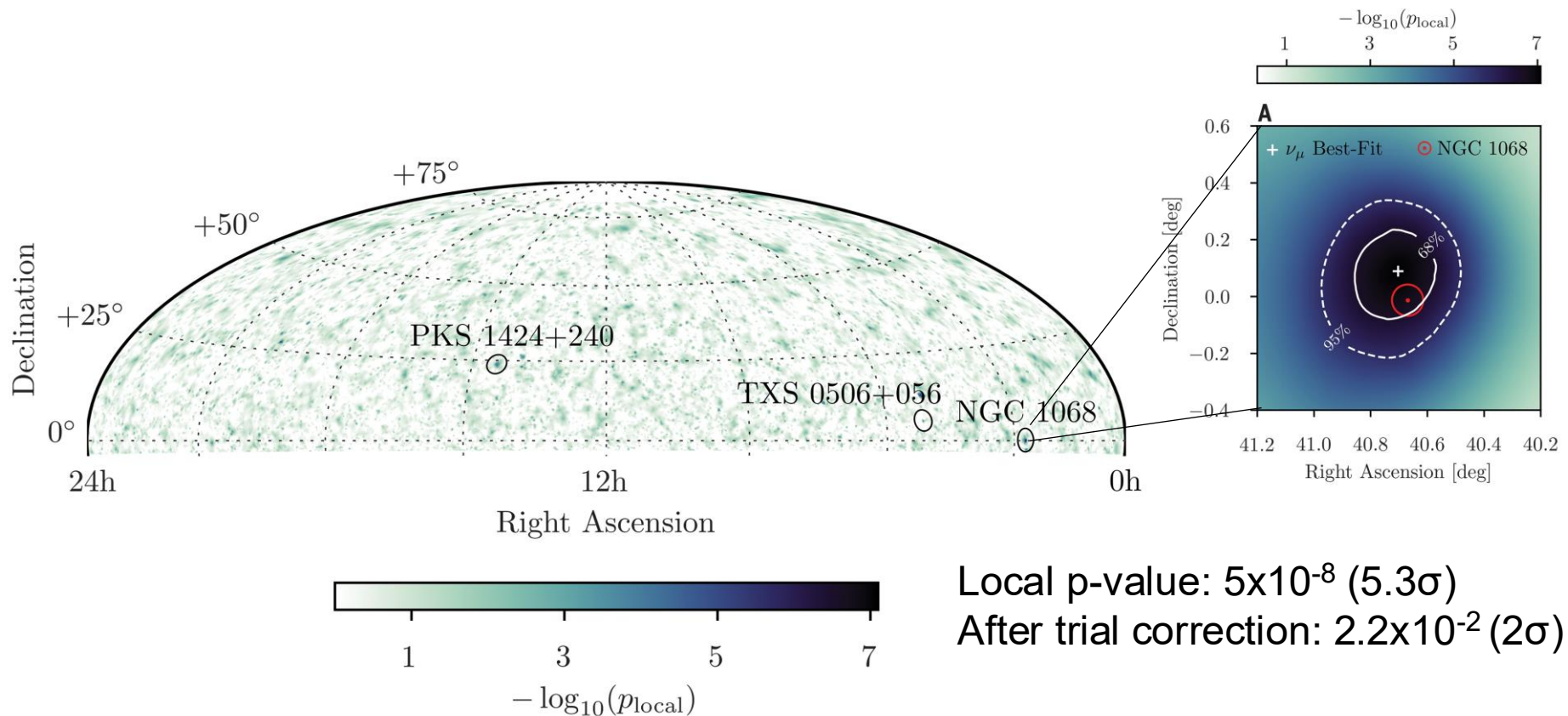
Signal trials: determine how much signal needs to be injected to have 90% of the signal trials yield a TS greater than the median TS derived from background trials



Definition of p-value

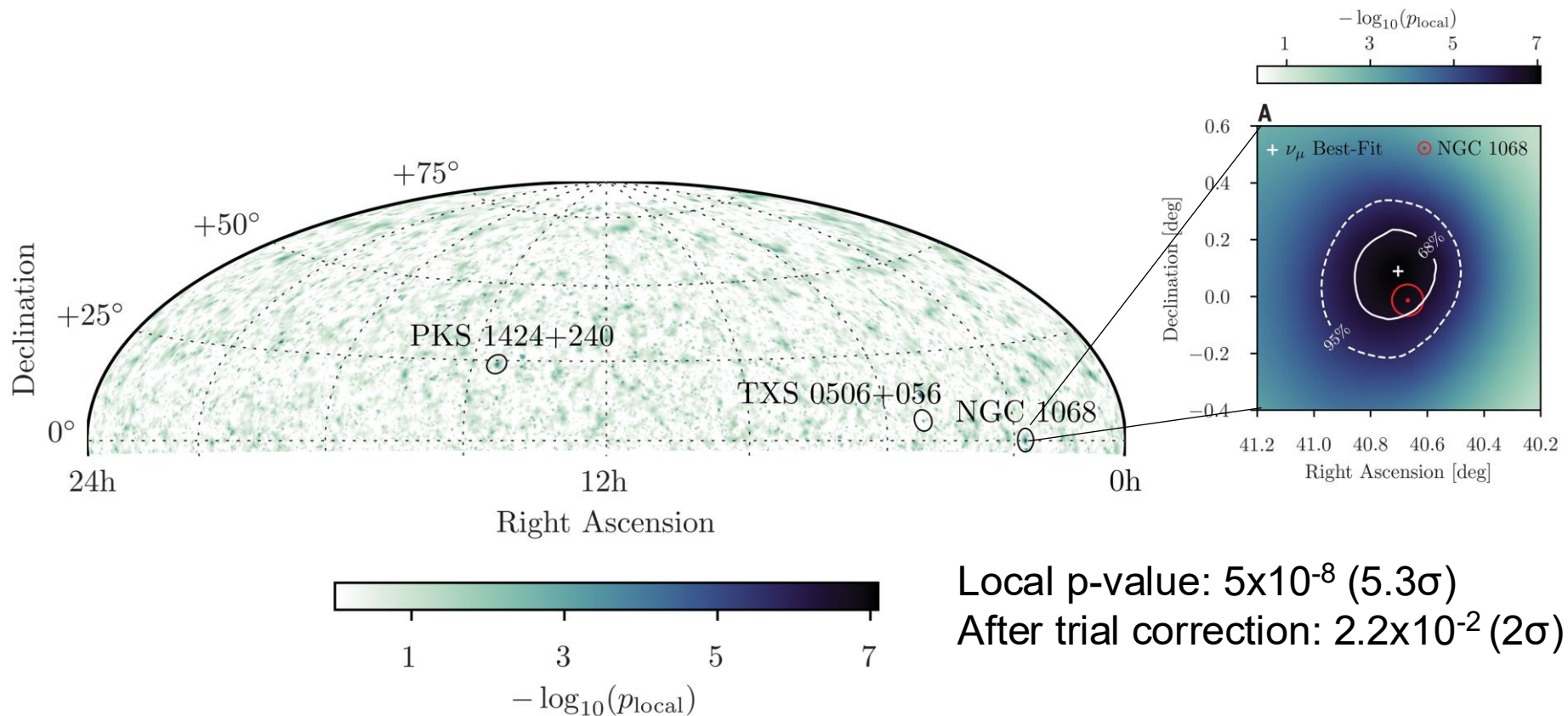


Search for hotspots in the neutrino sky



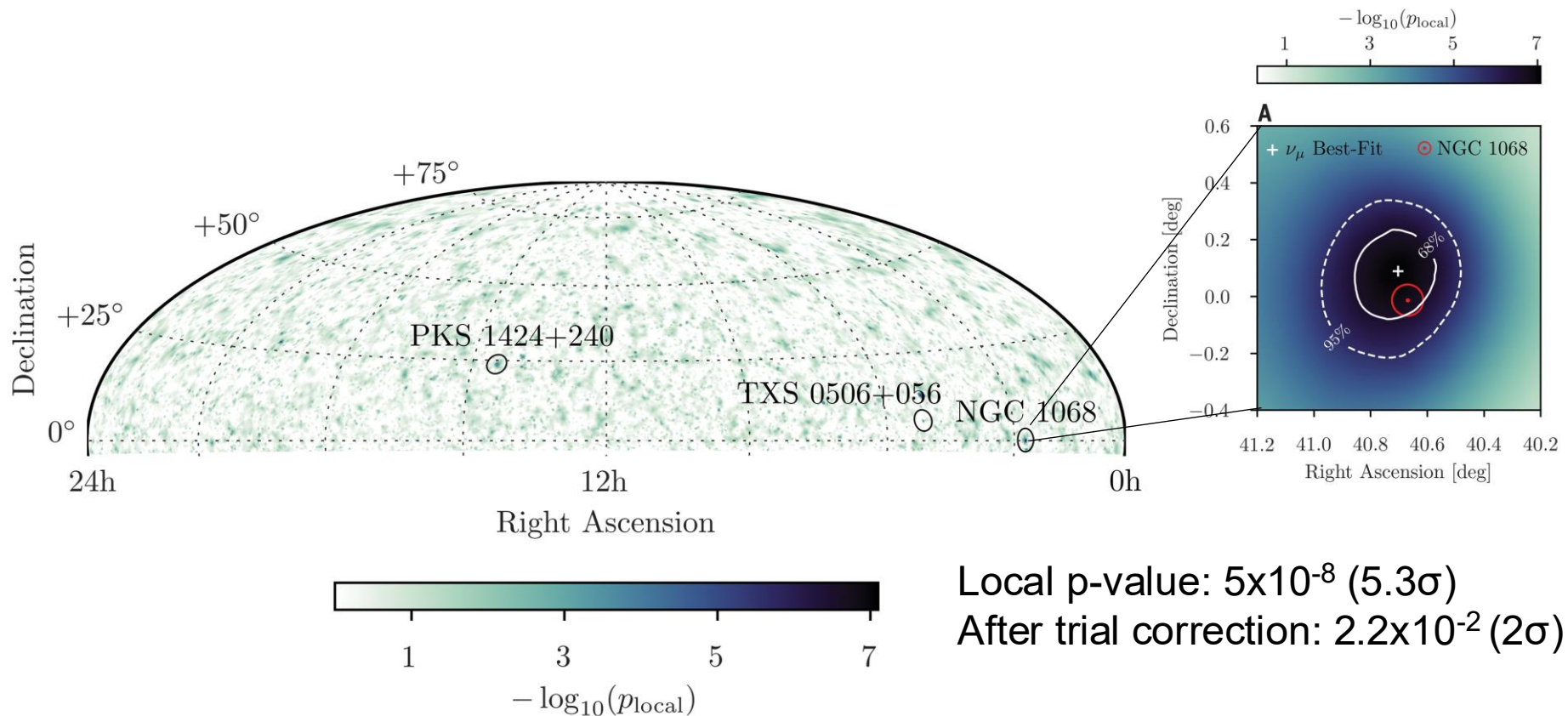
The post-trial probability is estimated by comparing the p-value of the hottest spot in the data with a distribution of hottest spots in a large number of background trials.

Search for hotspots in the neutrino sky



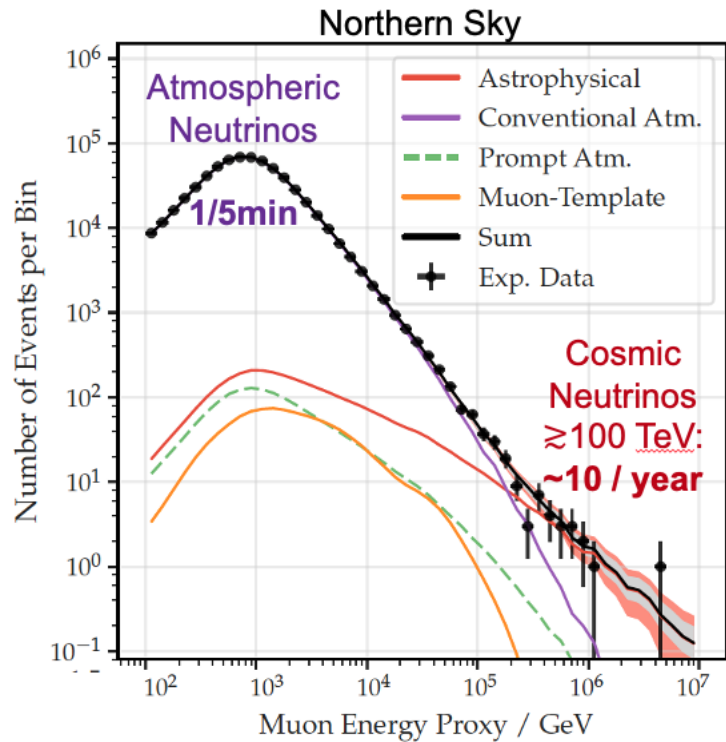
Challenge: Atmospheric background, large trial factor

Search for hotspots in the neutrino sky



Solution: Use predefined source lists to reduce trials

Search for Extragalactic Sources: Strategies



1. Look for hotspots in the neutrino sky → identify source candidates
2. Start from EM source catalog → look for neutrinos from source population
3. Focus on high-energy neutrinos with high signal probability → look for EM counterparts

Predefined source list

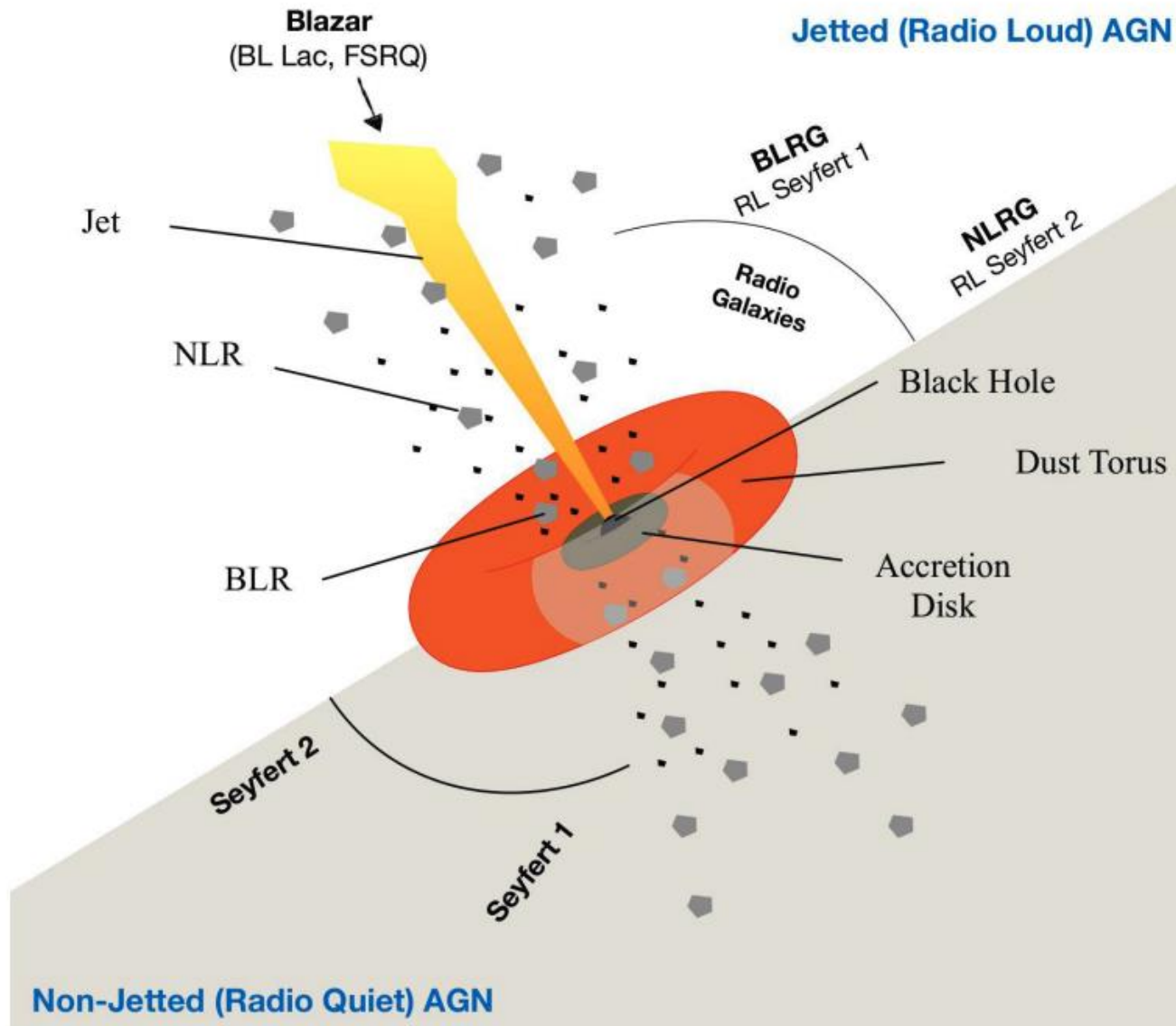
110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

Why 110 sources: 5σ p-value before trials would remain above 4σ after trials

Extragal. Sources:

1. 4FGL sources weighted according to the integral gamma-ray flux > 1 GeV divided by the sensitivity neutrino flux for this analysis at the respective source declination
 2. 5% highest-weighted BL Lacs and flat spectrum radio quasars (FSRQs) are each selected
 3. minimum weighted integral flux from the combined selection of BL Lac and FSRQs is used as a flux threshold to include unidentified blazars and AGN
 4. Starburst galaxies in 4FGL (8 sources) are included in addition
- **87 extragalactic gamma-ray sources**

Unified AGN Model



Predefined source list

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

Why 110 sources: 5 σ p-value before trials would remain above 4 σ after trials

Galactic Sources:

1. VHE gamma-ray sources from TeVCat and gammaCat
 2. Convert gamma-ray spectra to equivalent neutrino fluxes, assuming a purely hadronic origin: $E_\gamma = 2E_\nu$
 3. Keep sources with predicted energy fluxes $> 50\%$ of neutrino sensitivity (assuming E^{-2} spectrum)
- **12 Galactic gamma-ray sources**

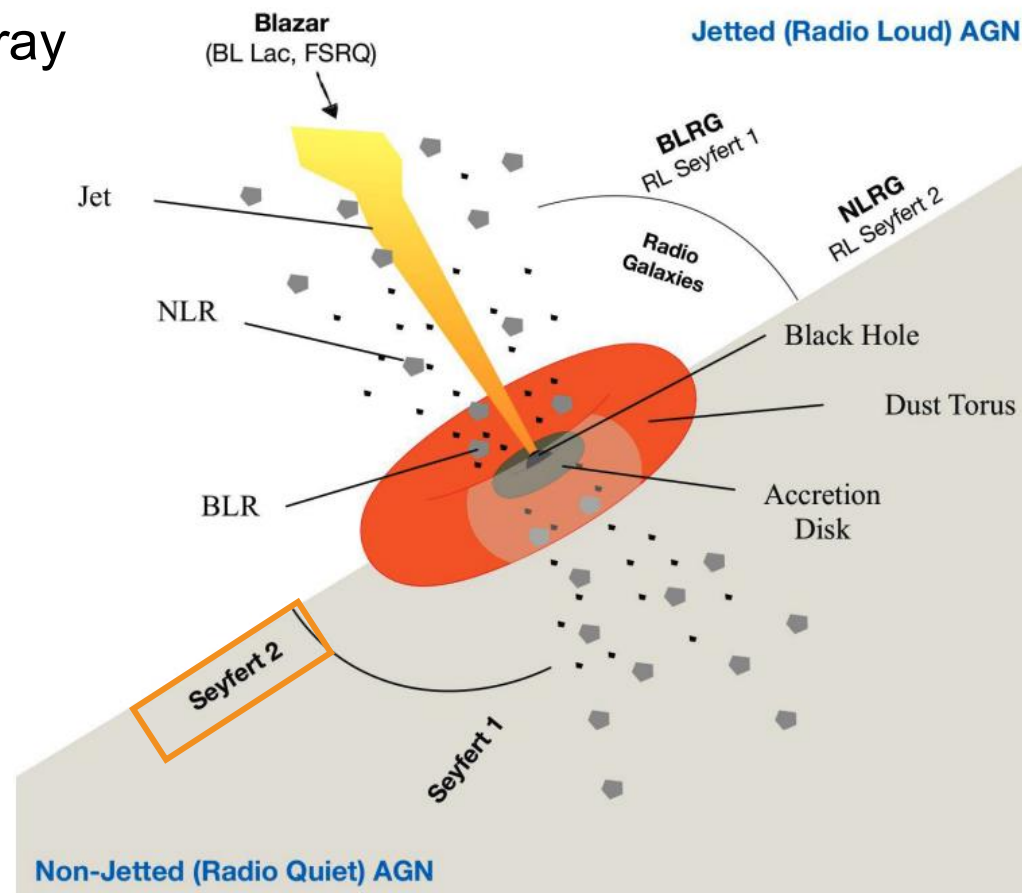
Predefined source list: Results

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

Most significant candidate:

NGC 1068 (M77), 4.2σ

- Nearby ($M=14\text{Mpc}$) Seyfert 2 galaxy
- AGN and star-forming activity



Combining gamma-ray source list with neutrino data
allowed neutrino source detection

Predefined source list: Results

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

Most significant candidate:

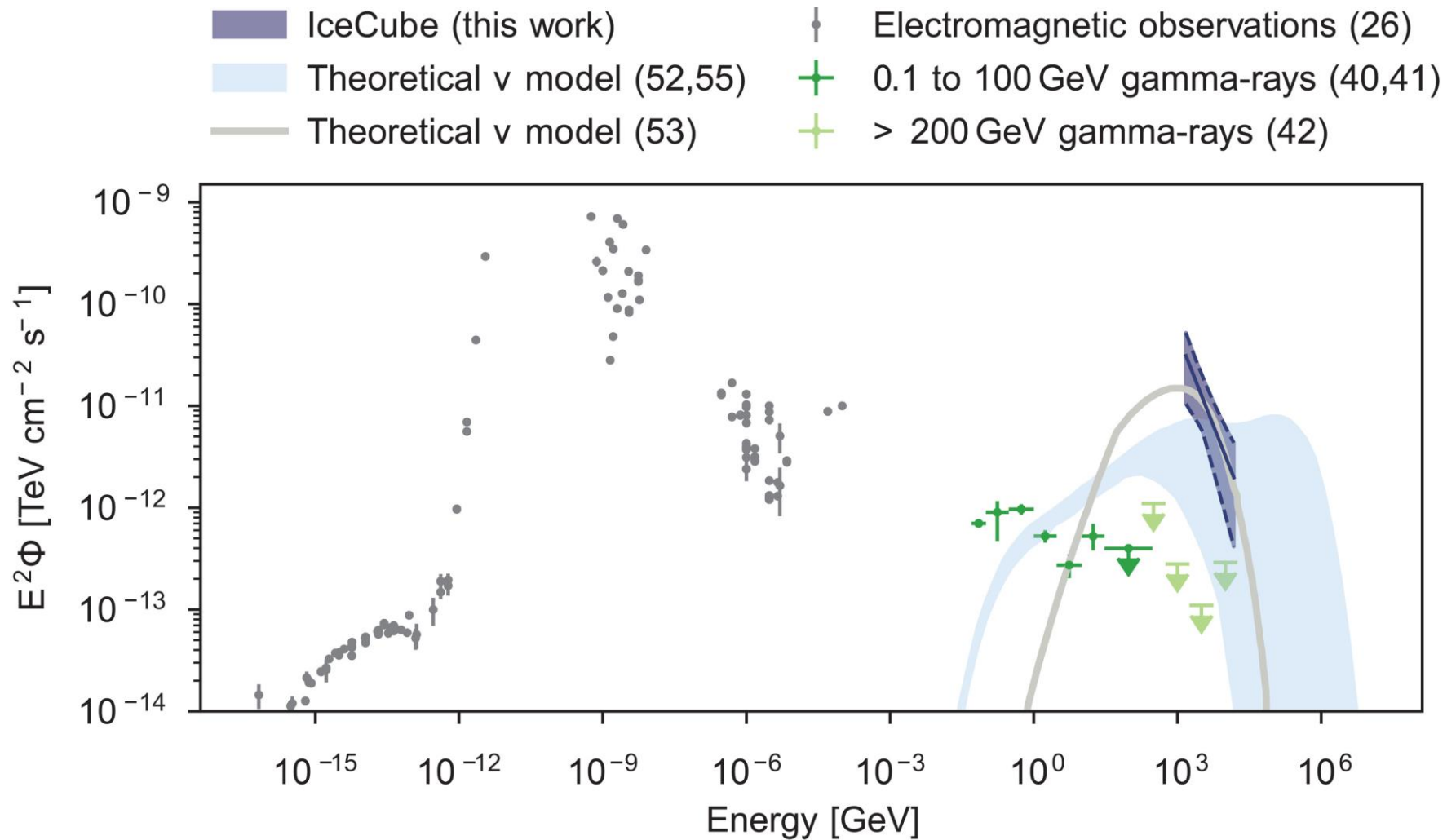
NGC 1068 (M77), 4.2σ

- Nearby ($M=14\text{Mpc}$)
Seyfert 2 galaxy
- AGN and star-forming activity



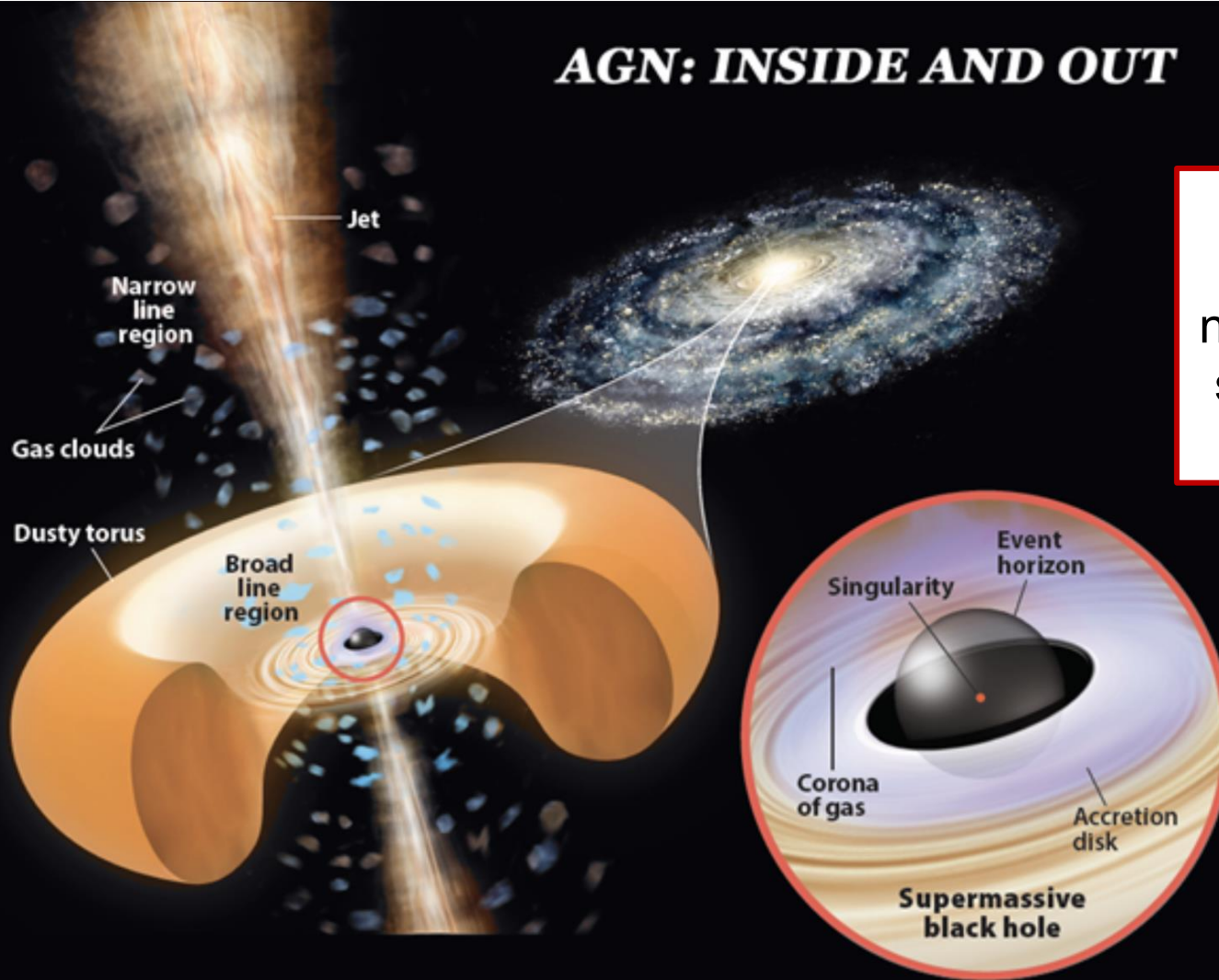
Combining gamma-ray source list with neutrino data
allowed neutrino source detection

Complete Multi-wavelength data of NGC 1068



Gamma rays need to be absorbed

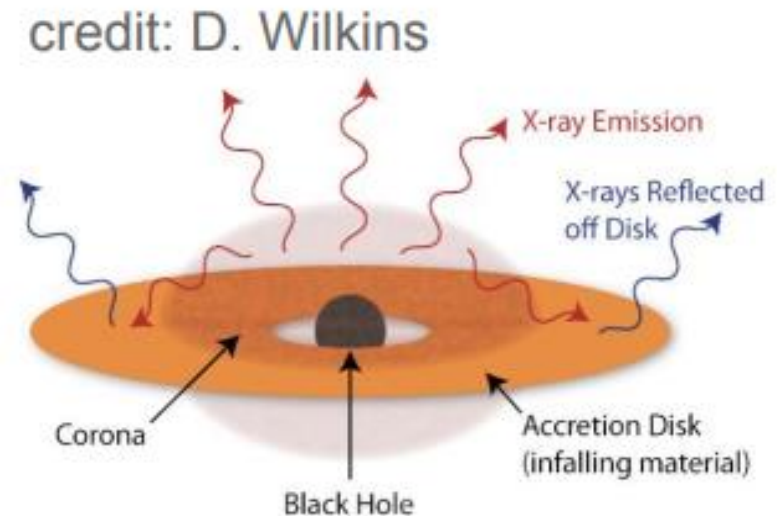
AGN: INSIDE AND OUT



Lack of gamma rays places neutrino production site in the heart of the galaxy

What is the corona?

- region of very **hot plasma** (10^8 – 10^9 K) close to accretion disk (few **gravitational radii**)
- Accretion disk emits thermal **optical/UV photons**.
- In the corona: low-energy photons undergo **inverse Compton scattering** with energetic electrons → **X-rays**
- X-ray emission is observed in AGN spectra (**power-law component**)
- X-ray flux changes on timescales of hours to days → consistent with a **very compact region**

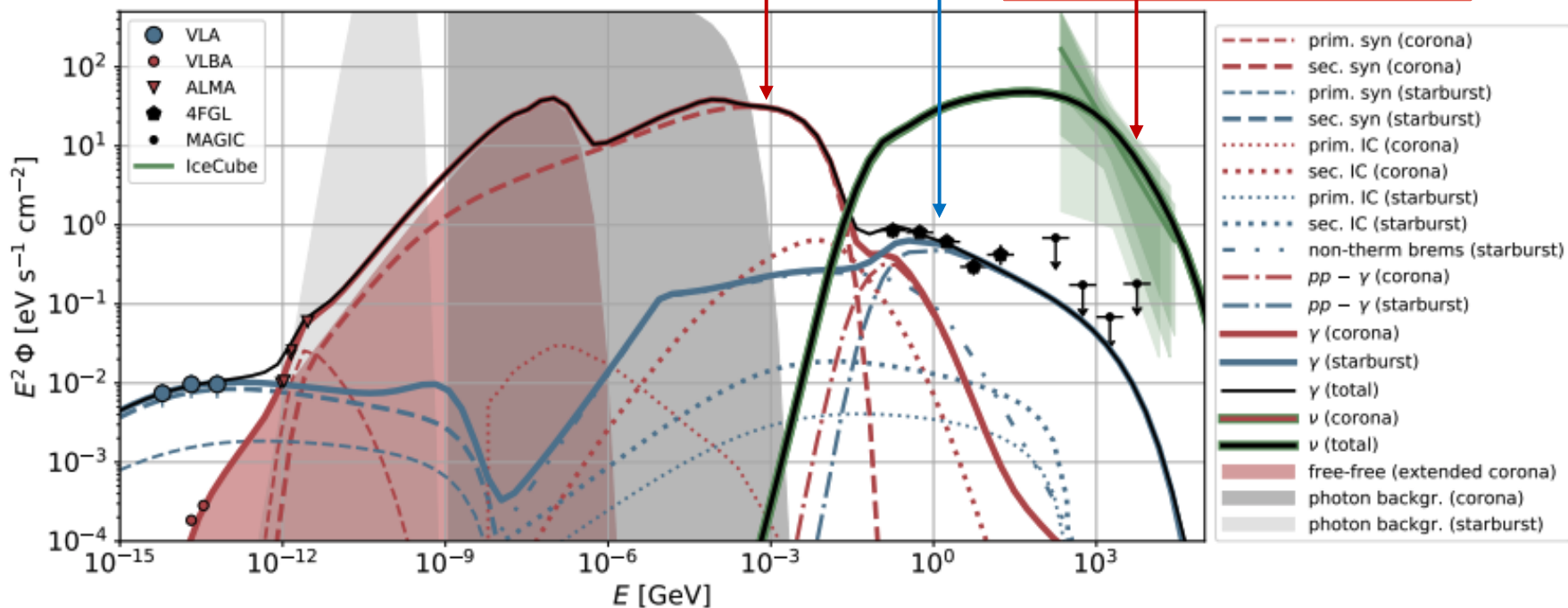


Detailed Modeling of Starburst-AGN Composite

Gamma-ray emission dominated by starburst

X-ray emission dominated by corona

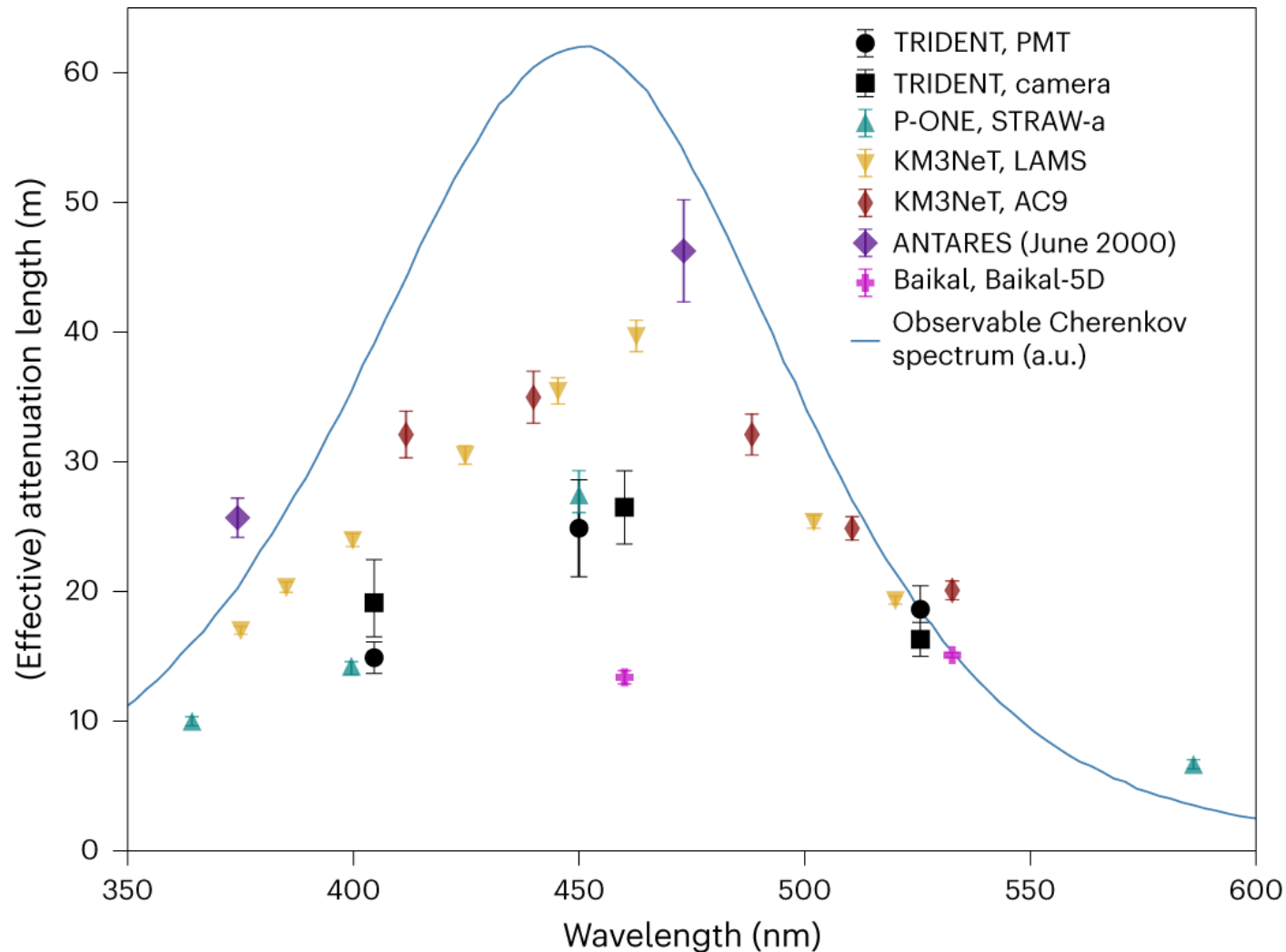
Neutrinos dominated by corona



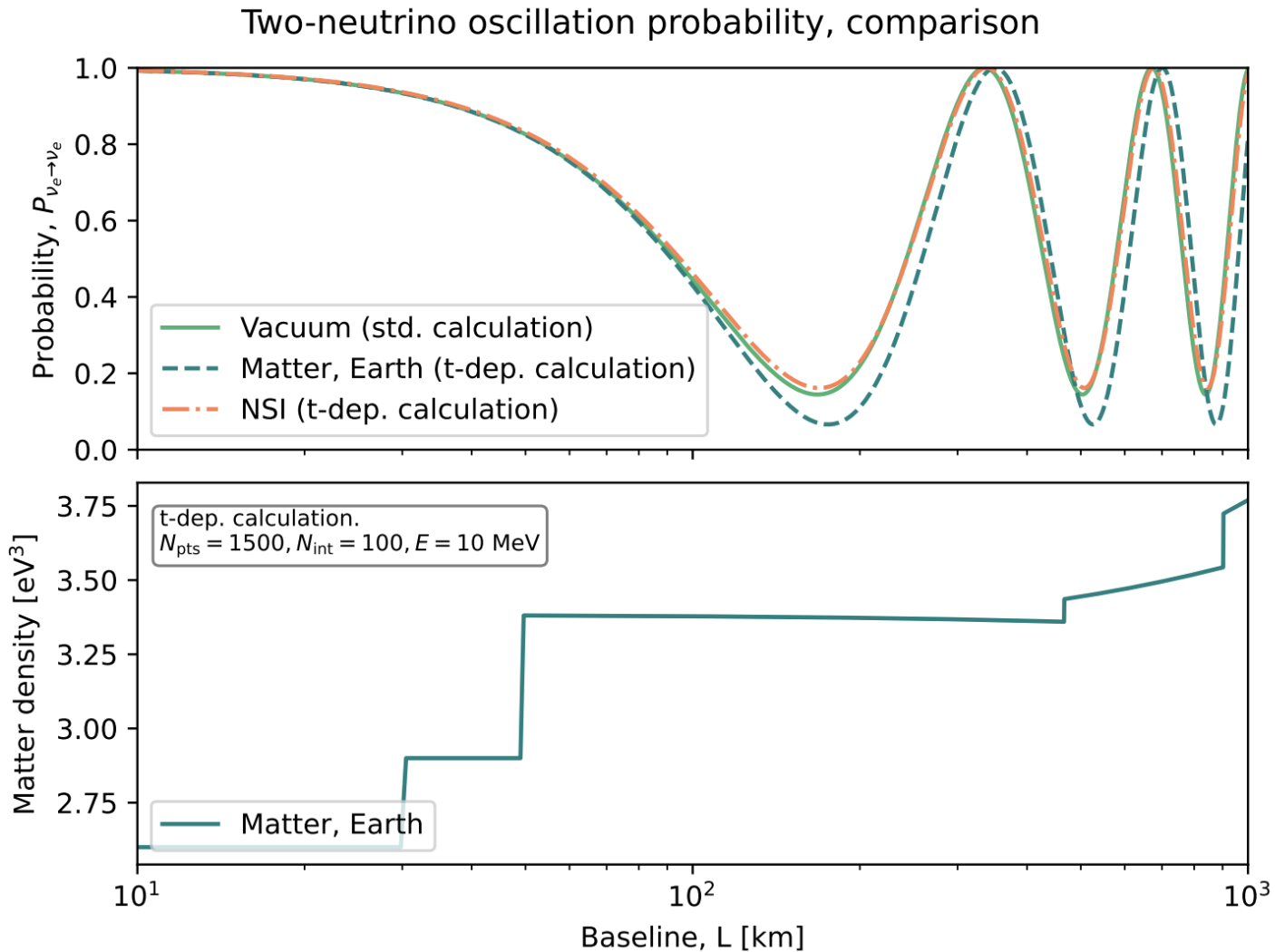
Day 2

Optical properties of water / ice

- Minerals and salts, organic material

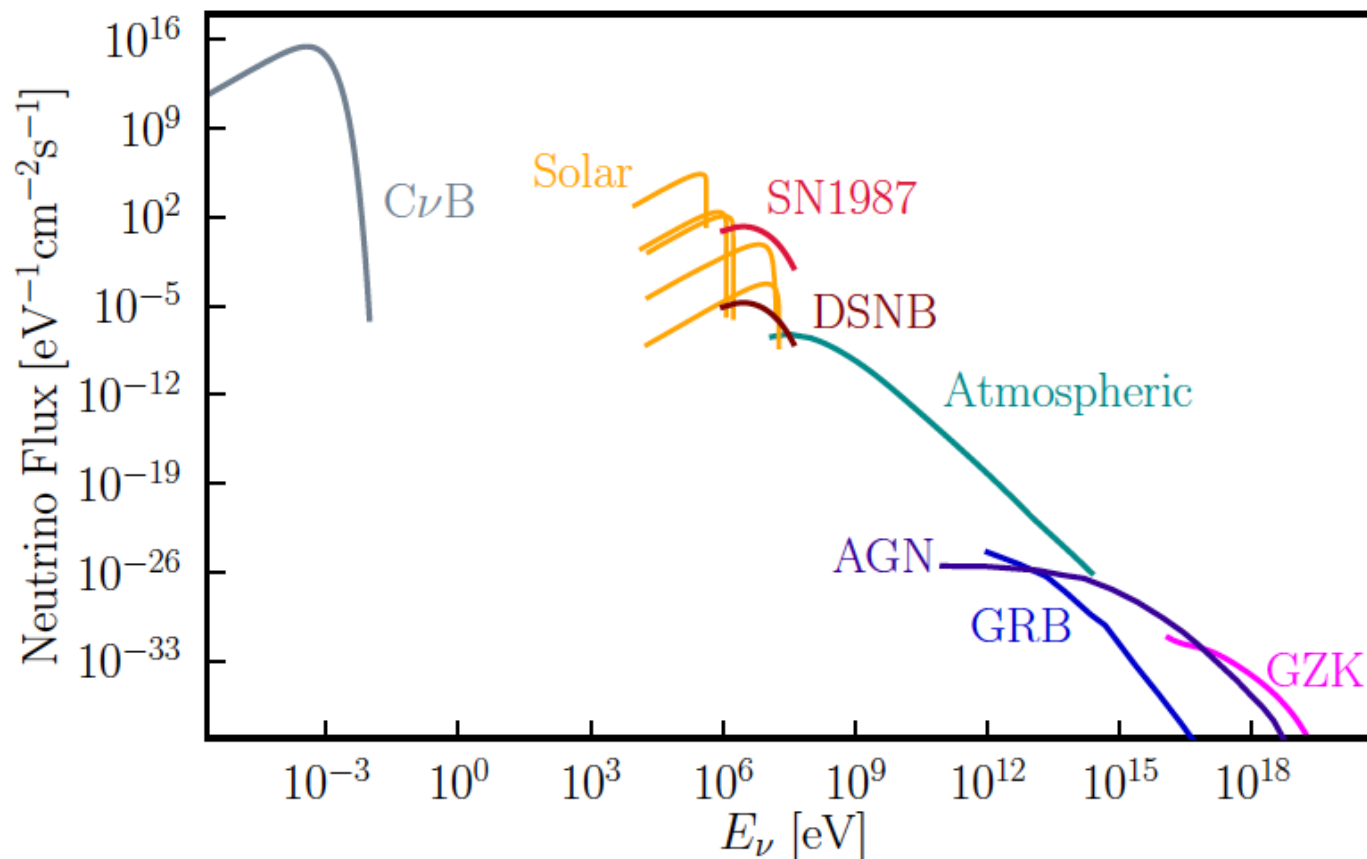


How mass effects neutrino oscillations



Recap Day 1

A. Kheirandish et al, ICRC 2021



↔
Ideas: neutrino capture
on unstable nucleus
(e.g. tritium)

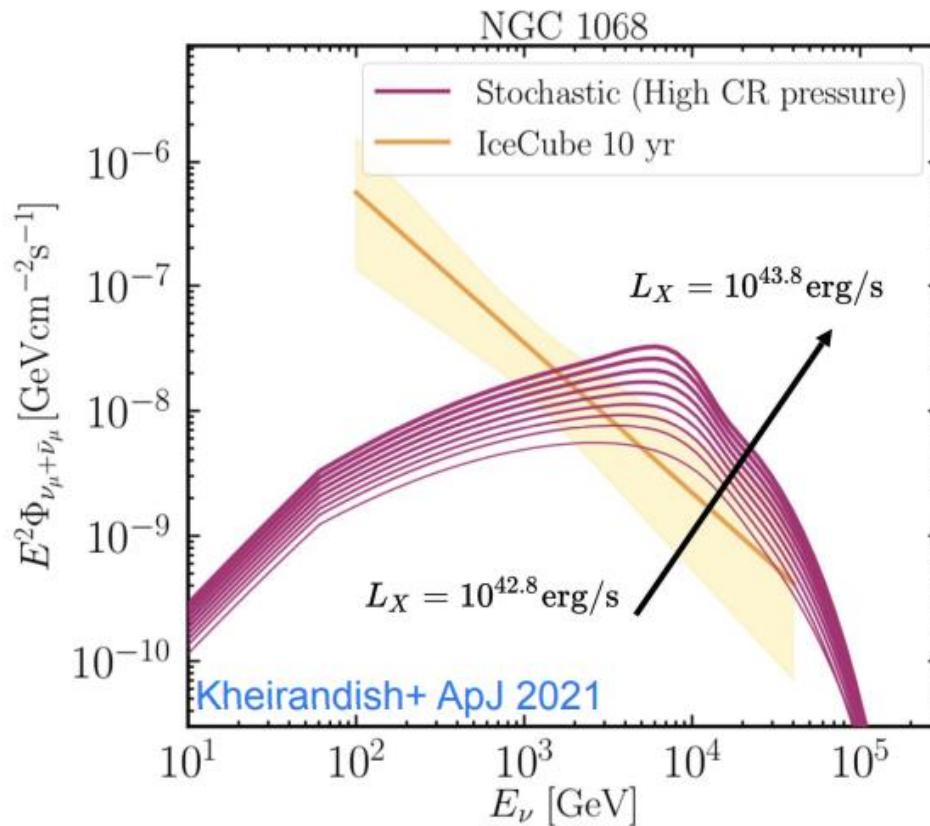
↔
Neutrino capture on
stable nucleus
(Chlorine, Gallium)

↔
Water / ice
Cherenkov
detectors

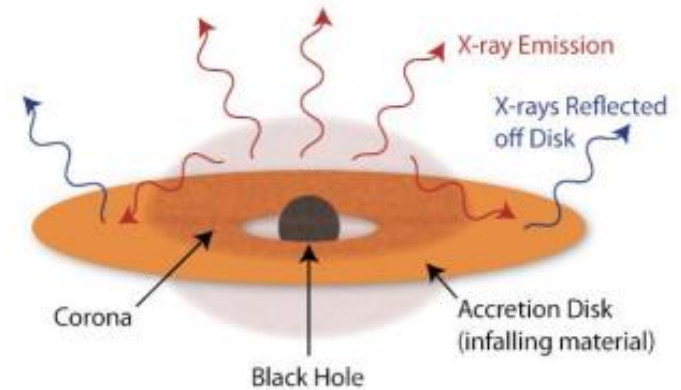
↔
Radio arrays,
cosmic-ray
detectors

More Seyferts?

Assumption: Neutrino flux scales with intrinsic X-ray flux (2–10 keV)



credit: D. Wilkins



Stacking Search

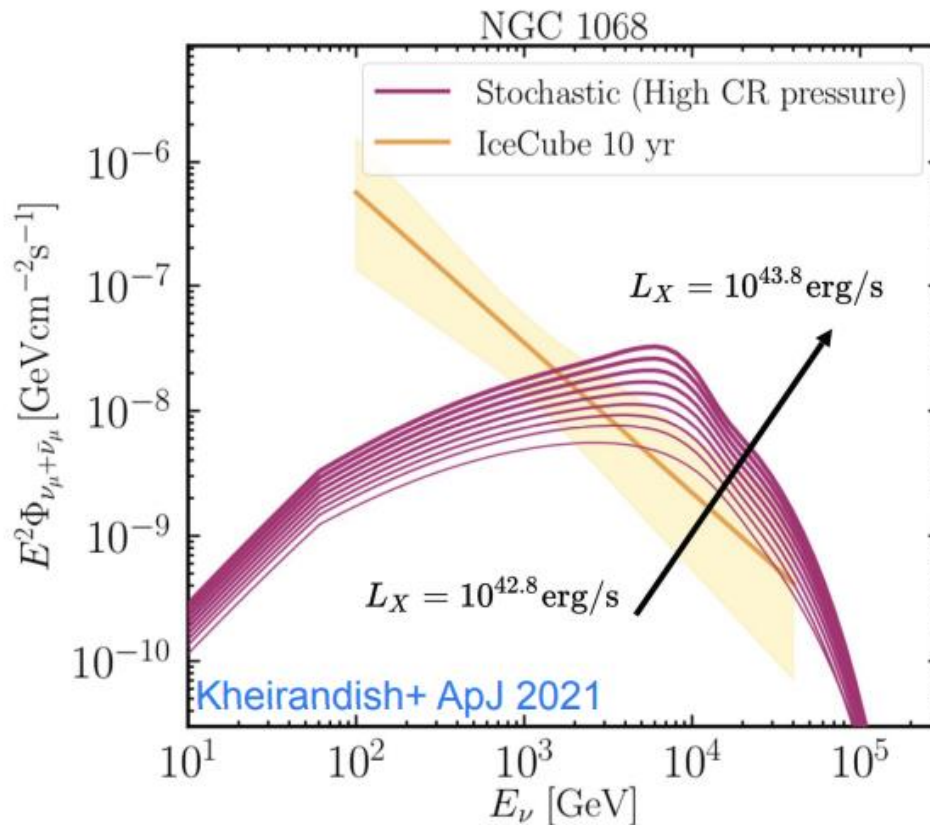
- Use **catalog of sources** (here: Seyferts)
 - Assume neutrino spectral shape (often power-law, here: disk corona model prediction)
 - Assume weighting scheme between neutrino sources (here: neutrino flux follows X-ray flux)
- only one fit parameter for entire population: overall normalization

Potential problem: if assumption (weighting) does not hold, sensitivity is reduced

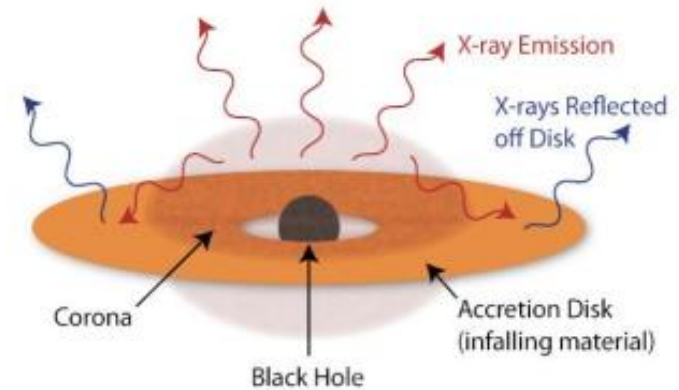
Alternative: fit each individually and combine results with binomial test

More Seyferts: Stacking results

Assumption: Neutrino production in disk corona, intrinsic X-ray flux (2–10 keV) as proxy for neutrino emission



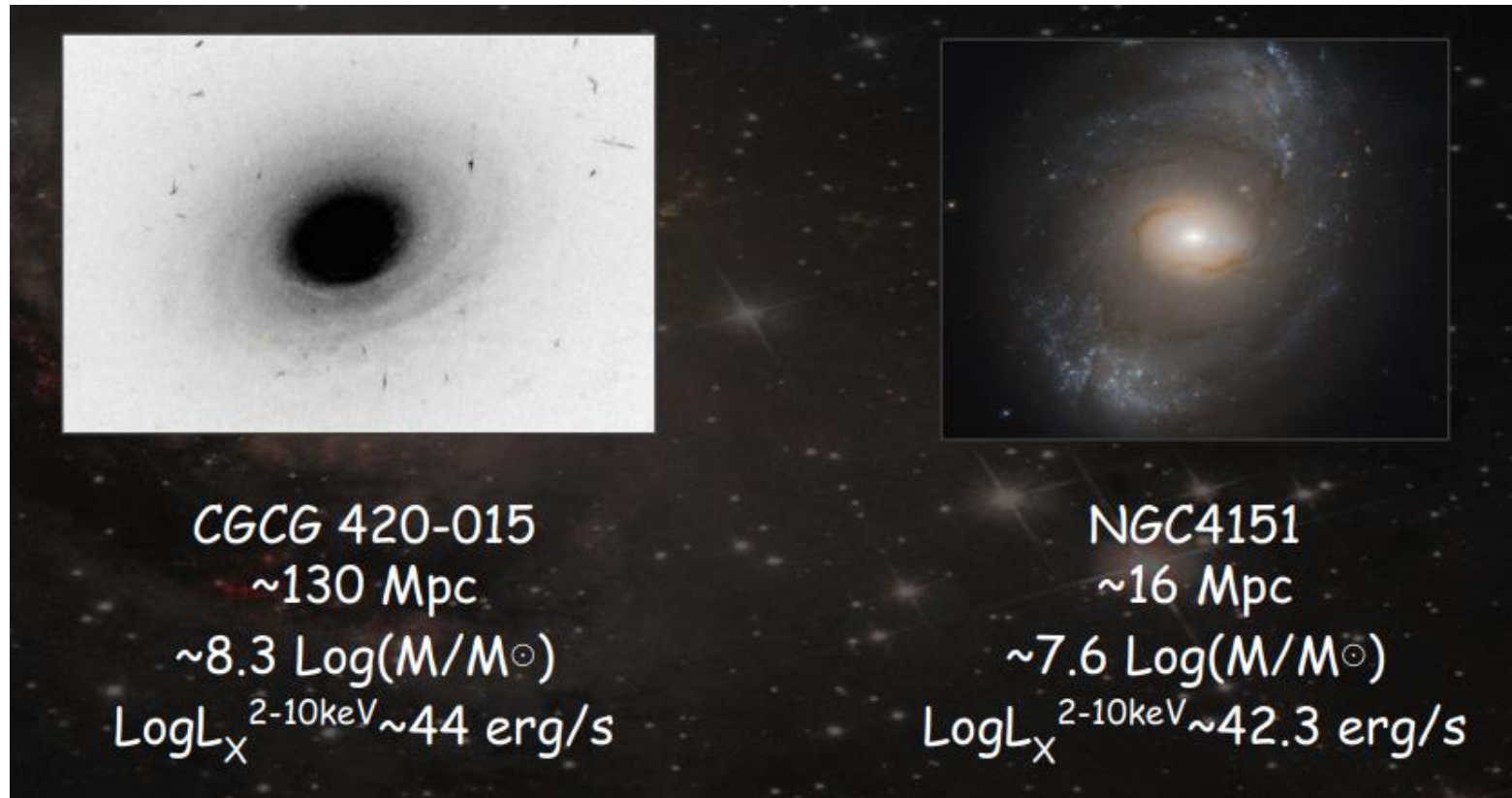
credit: D. Wilkins



No significant emission is found in the stacking search excluding NGC 1068.

More Seyferts: Individual sources

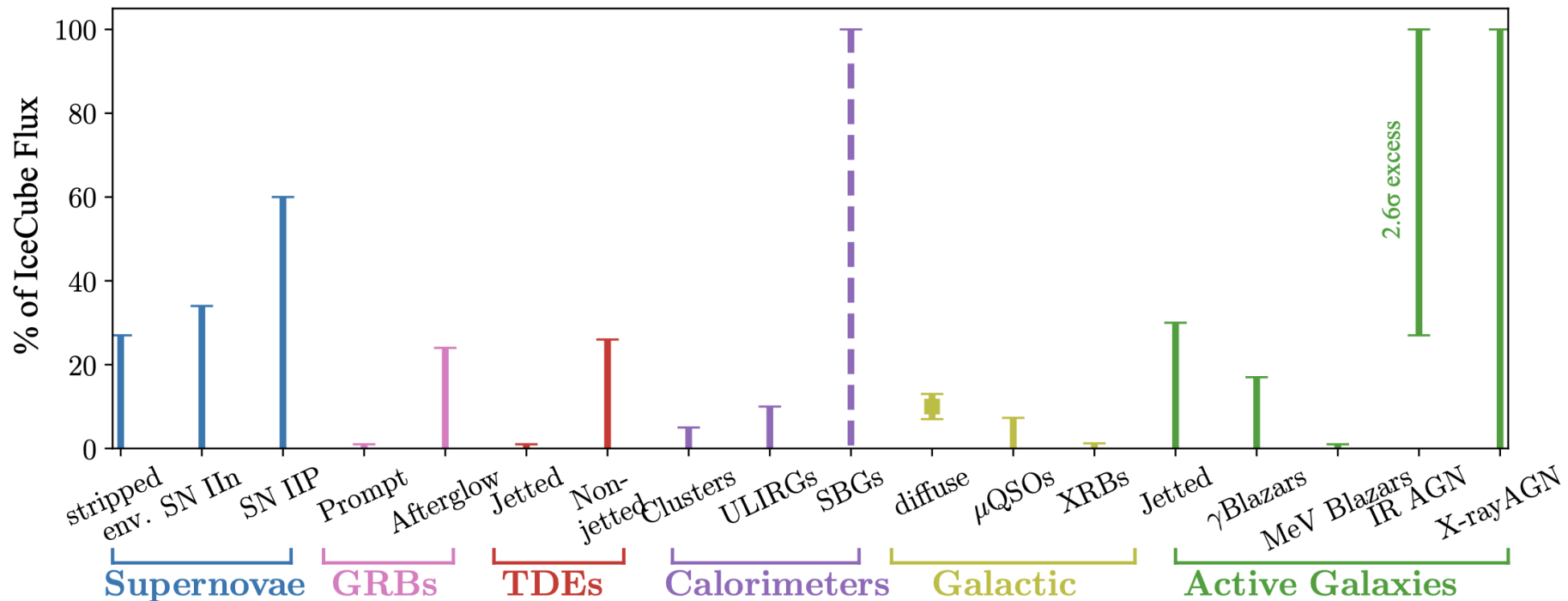
No assumption about neutrino emission model



Two more source candidates at 2.5σ and 2.1σ level

Results of other stacking searches

plot from FO PoS ICRC2021 (2022) 030, based on numerous IceCube analyses, see [arXiv:2201.05623](https://arxiv.org/abs/2201.05623) for references



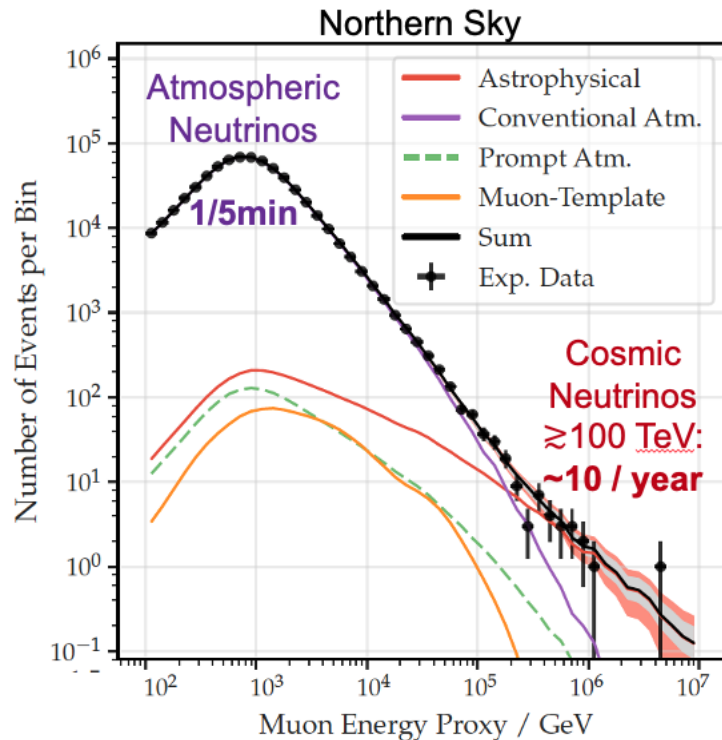


Take home message

Seyferts are currently the most promising neutrino source class.

Neutrinos from corona region, not starburst, but neutrino production not fully understood.

Search for Extragalactic Sources: Strategies



1. Look for hotspots in the neutrino sky → identify source candidates
2. Start from EM source catalog → look for neutrinos from source population
3. **Focus on high-energy neutrinos with high signal probability → look for EM counterparts**

Neutrinos as Triggers

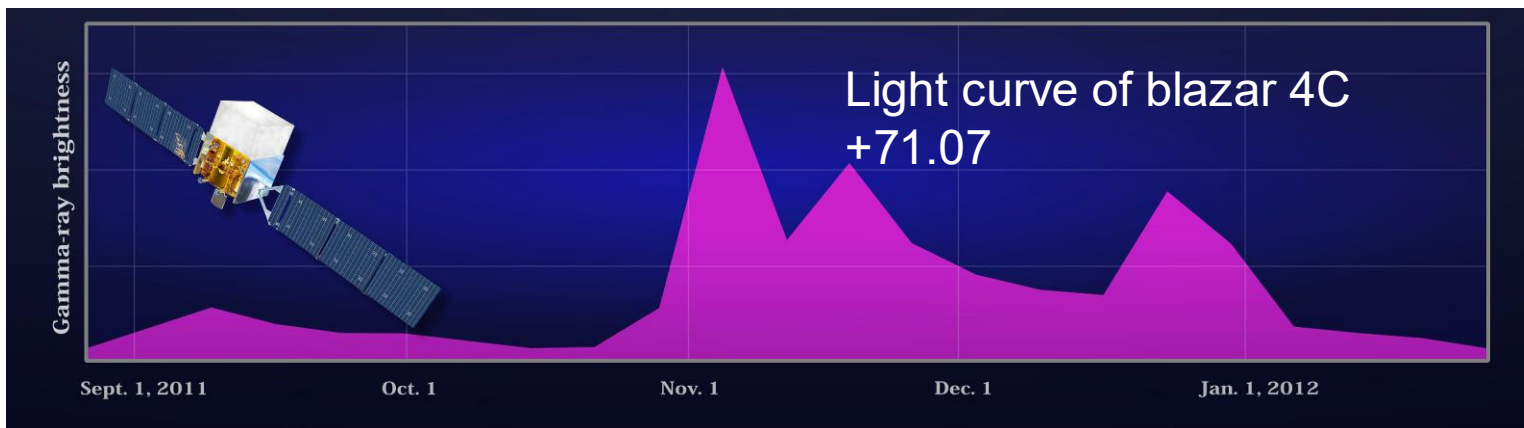
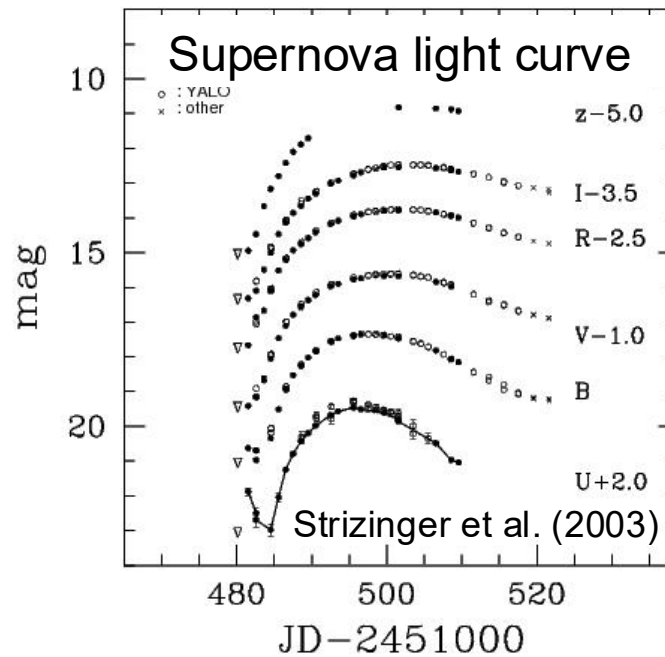
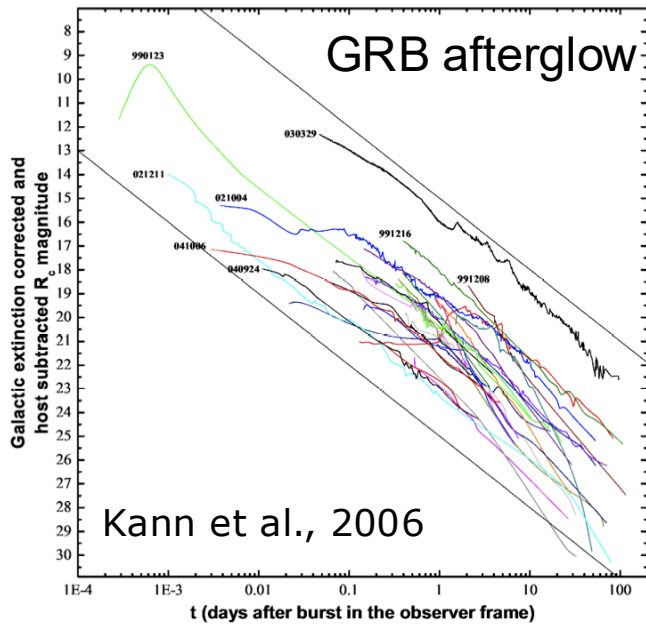
Public alerts since April 2016

- Single high-energy muon track events ($> \sim 100\text{TeV}$)
- “Gold” alert stream: 10 / yr, ~ 5 / yr of cosmic origin
- Median latency: 30 sec

Goal: Find electromagnetic counterpart



Expected EM Counterparts



```
////////////////////////////////////  
TITLE:          GCN/AMON NOTICE  
NOTICE_DATE:    Wed 08 Jul 26 17:19:44 UT  
NOTICE_TYPE:    ICECUBE Astrotrack Gold  
STREAM:        24  
RUN_NUM:       142827  
EVENT_NUM:     7869742  
SRC_RA:        293.1463d {+19h 32m 35s} (J2000),  
                293.5222d {+19h 34m 05s} (current),  
                292.4370d {+19h 29m 45s} (1950)  
SRC_DEC:       -14.9547d {-14d 57' 16"} (J2000),  
                -14.8962d {-14d 53' 45"} (current),  
                -15.0625d {-15d 03' 44"} (1950)  
SRC_ERROR:     30.80 [arcmin radius, stat-only, 90% containment]  
SRC_ERROR50:   12.00 [arcmin radius, stat-only, 50% containment]  
DISCOVERY_DATE: 21229 TJD;   189 DOY;   26/07/08 (yy/mm/dd)  
DISCOVERY_TIME: 62262 SOD {17:17:42.55} UT  
REVISION:      0  
ENERGY:        2.2930e+03 [TeV]  
SIGNALNESS:    8.2509e-01 [dn]  
FAR:          0.1472 [yr^-1]  
SUN_POSTN:    107.96d {+07h 11m 51s} +22.41d {+22d 24' 29"}  
SUN_DIST:     170.83 [deg]   Sun_angle= 11.6 [hr] (West of Sun)  
MOON_POSTN:   24.42d {+01h 37m 40s} +14.92d {+14d 55' 10"}  
MOON_DIST:    94.63 [deg]  
GAL_COORDS:   23.91,-15.74 [deg] galactic lon,lat of the event  
ECL_COORDS:   292.48, 6.70 [deg] ecliptic lon,lat of the event  
COMMENTS:     IceCube Gold event.  
COMMENTS:     The position error is statistical only, there is no systematic added.
```



GCN Circular 45125

Subject IceCube-260708A: One candidate from the Zwicky Transient Facility
Event [IceCube-260708A](#)
Date 2026-07-09T16:21:49Z (15 hours ago)
From Robert David Stein at JSI <rdstein@umd.edu>
Via Web form

Robert Stein (JSI), Tomas Ahumada (Noirlab), Mansi Kasliwal (Caltech), Jesper Sollerman (Stockholm), Cristobal Zilleruelo Cañas (DESY), Jannis Necker (Leiden University), Akshay Eranhalodi (DESY), and Anna Franckowiak (Ruhr University Bochum) report,

On behalf of the Zwicky Transient Facility (ZTF) and Global Relay of Observatories Watching Transients Happen (GROWTH) collaborations:

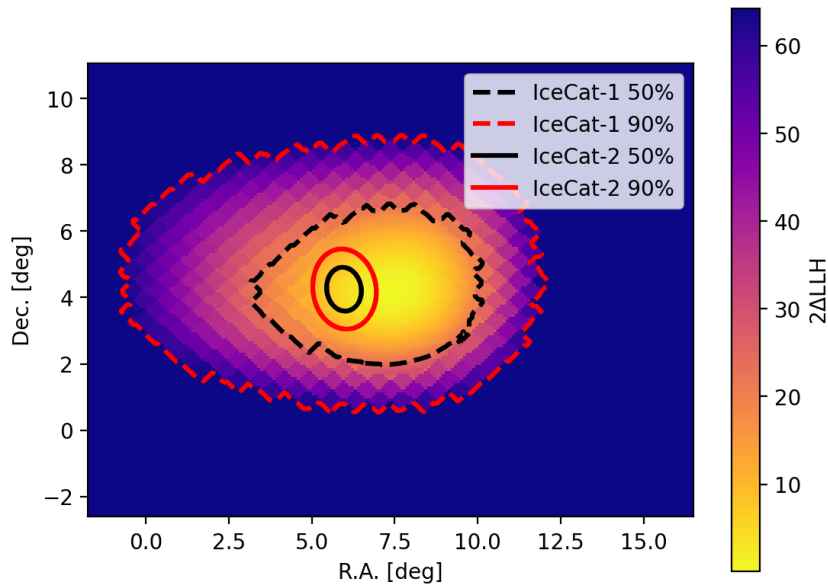
[...]

+-----+						
ZTF Name	IAU Name	RA (deg)	DEC (deg)	Filter	Mag	MagErr
+-----+						
ZTF26abfurzw	AT2026kuv 	292.8653948	-15.1344488	r	20.11	0.07
+-----+						

[...]

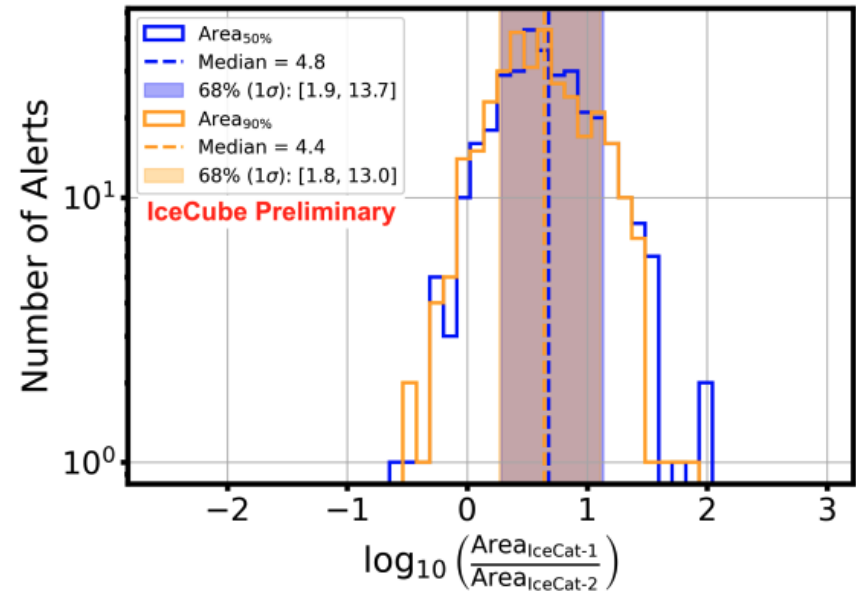
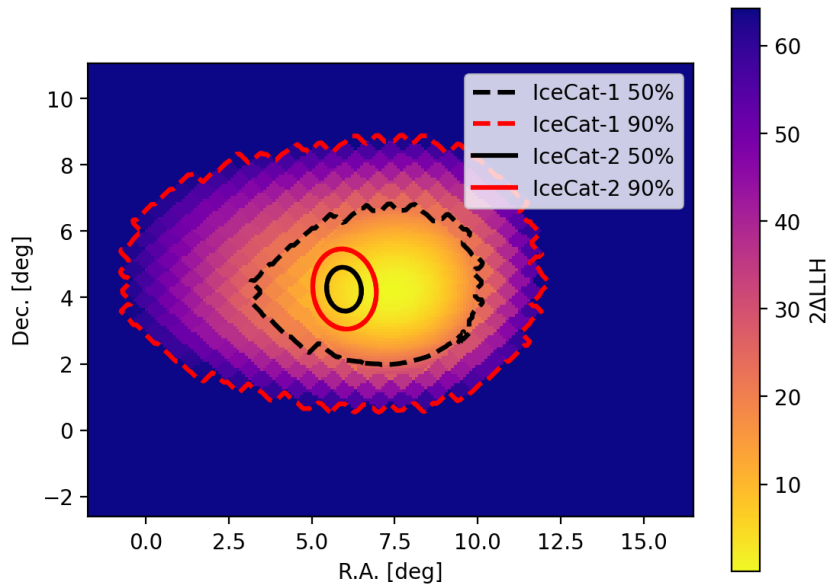
The photometric properties (rise, fade, and late-time colour) of [AT 2026kuv](#)  appear consistent with a supernova. Neutrino emission in a post-peak supernova would be plausible if there were CSM interaction in the source. We encourage spectroscopic observations of this source to confirm its nature, and to search for evidence of CSM interaction.

Neutrino Angular Uncertainty



Probability maps indicate best fit position and 50%/90% uncertainty regions

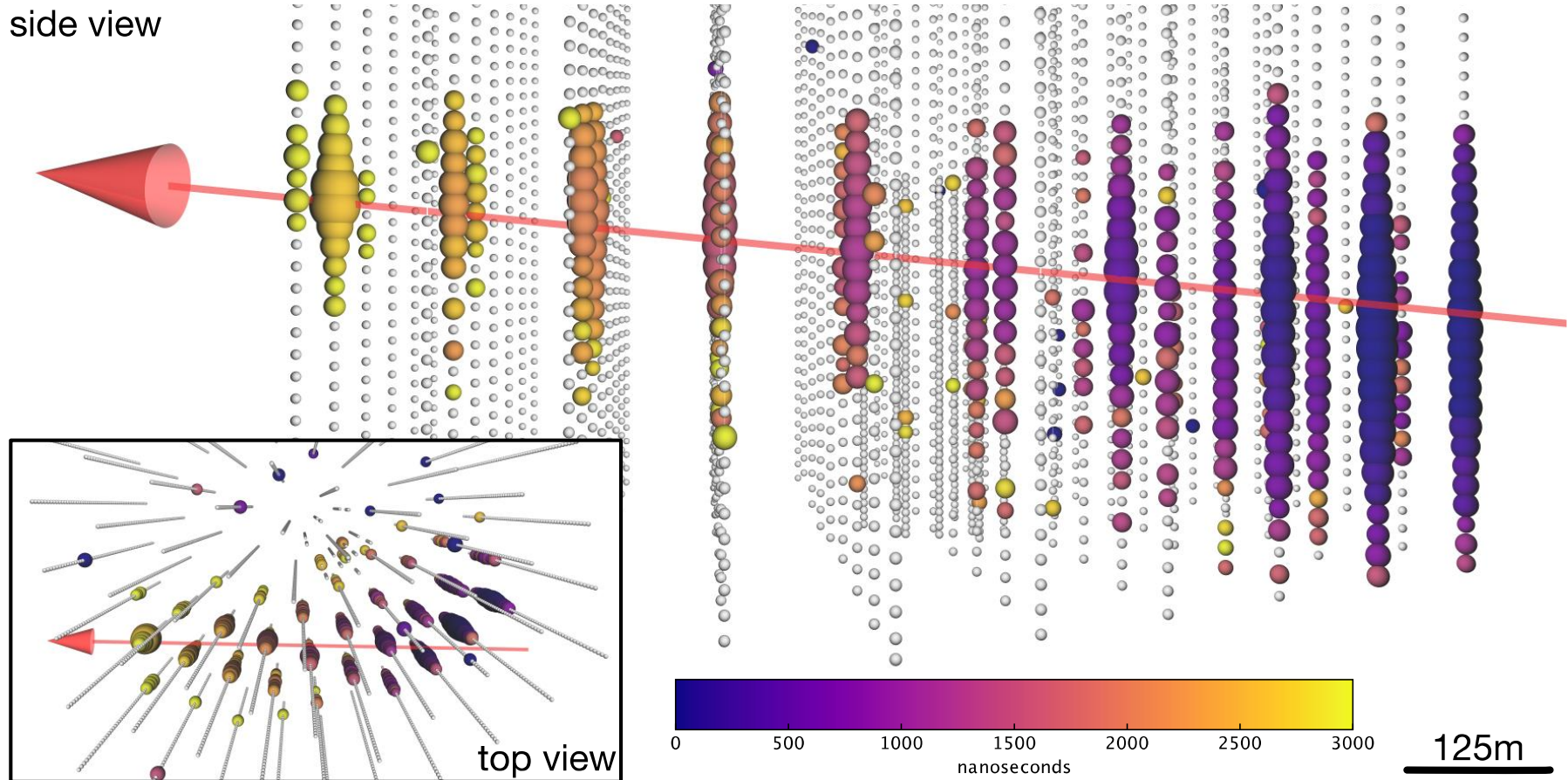
IceCube alert track catalog (IceCat-2)



Improvement in 90% uncertainty area of factor 4.4

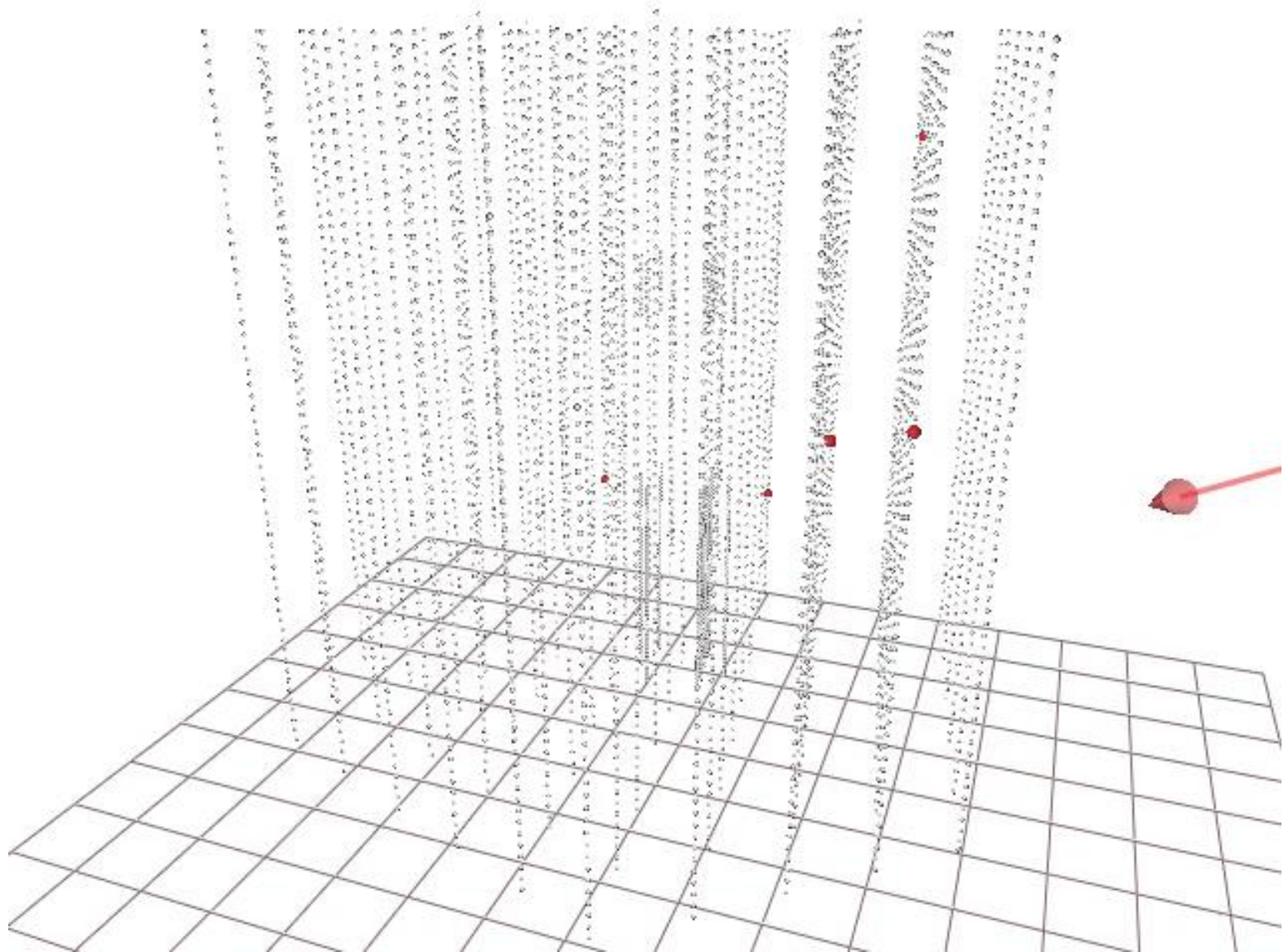
Archival alert catalog (IceCat-2) under development

First example: IC-170922A – a 290 TeV Neutrino

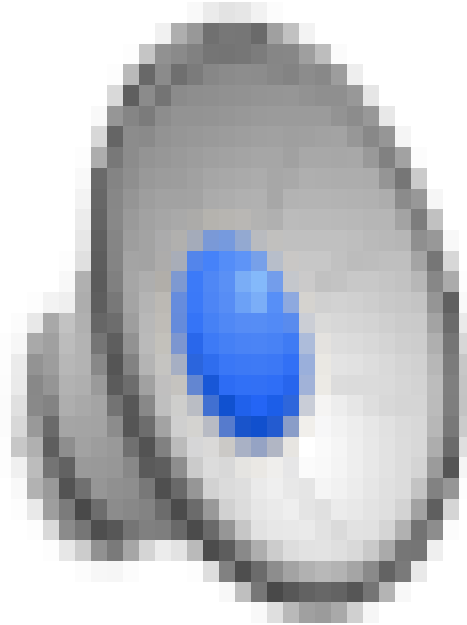


Signalness: 56.5%

IC-170922A – a 290 TeV Neutrino

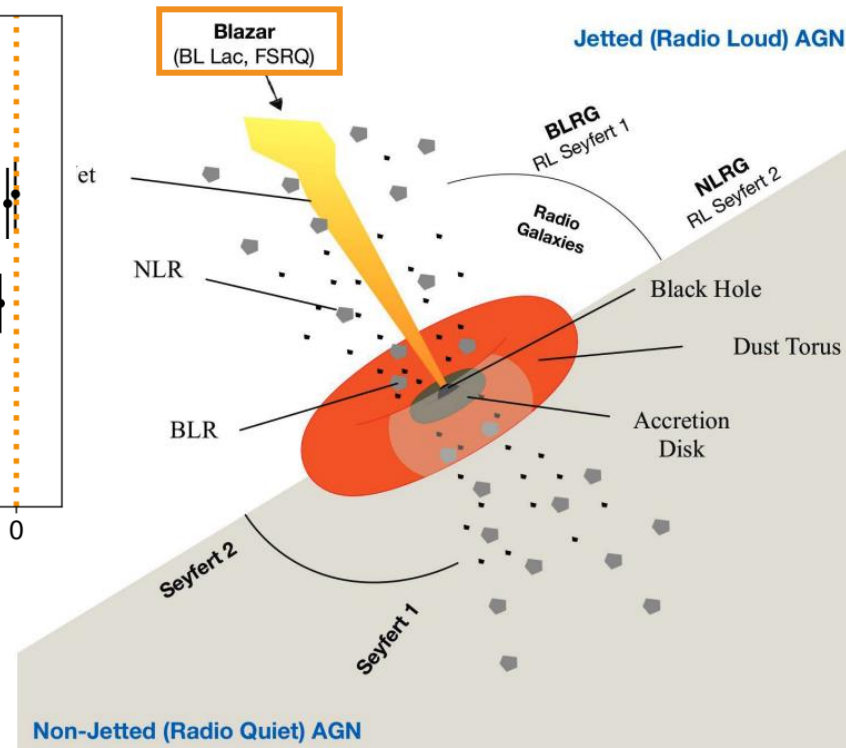
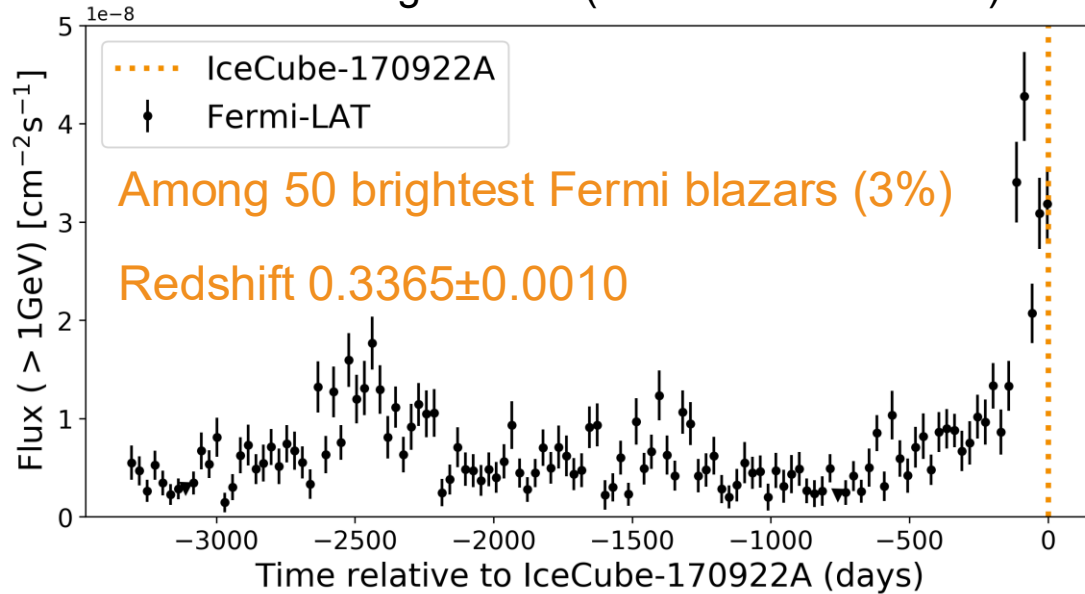


Fermi-LAT finds Flaring Source



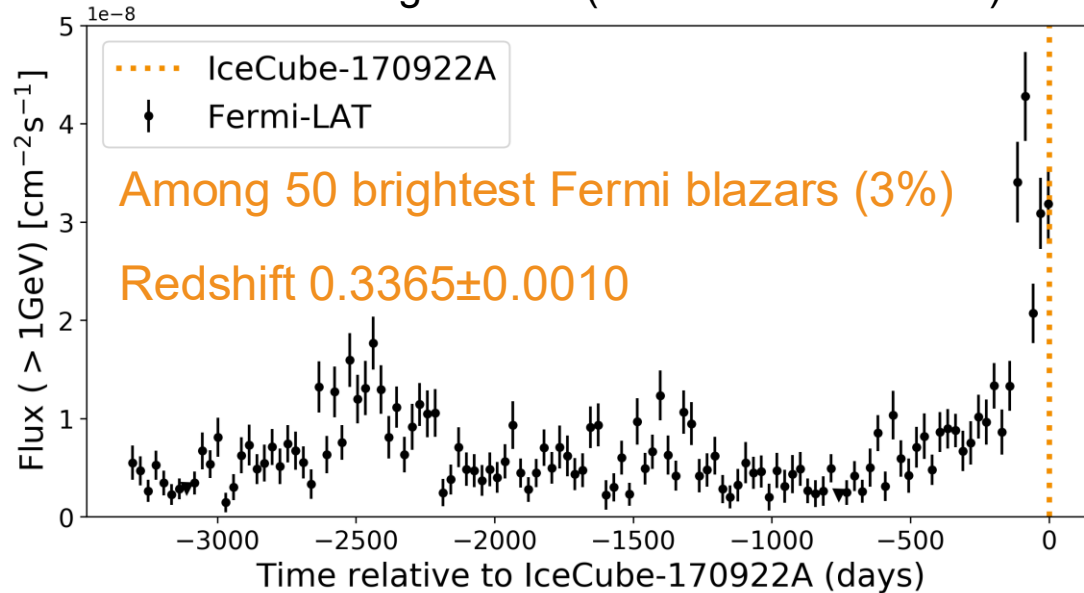
Fermi-LAT finds Flaring Blazar, TXS 0506+056

Fermi-LAT light curve (100 MeV – 300 GeV)

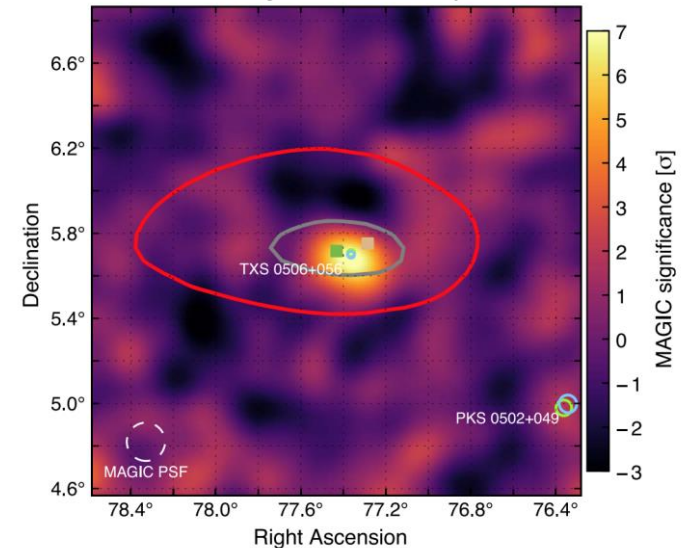


Fermi-LAT finds Flaring Blazar, TXS 0506+056

Fermi-LAT light curve (100 MeV – 300 GeV)

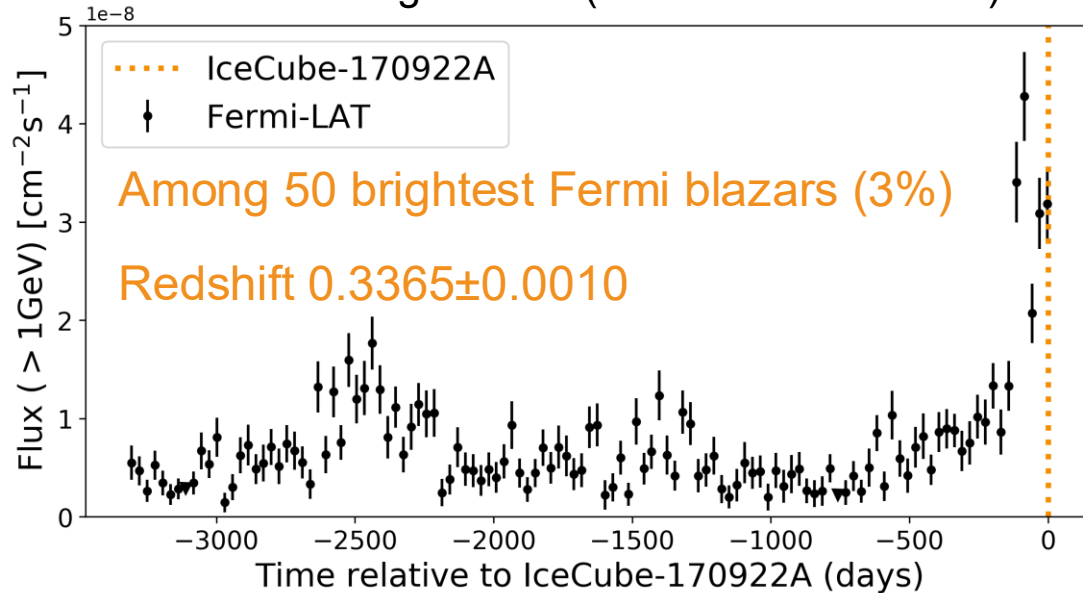


MAGIC Significance map:
TeV gamma rays

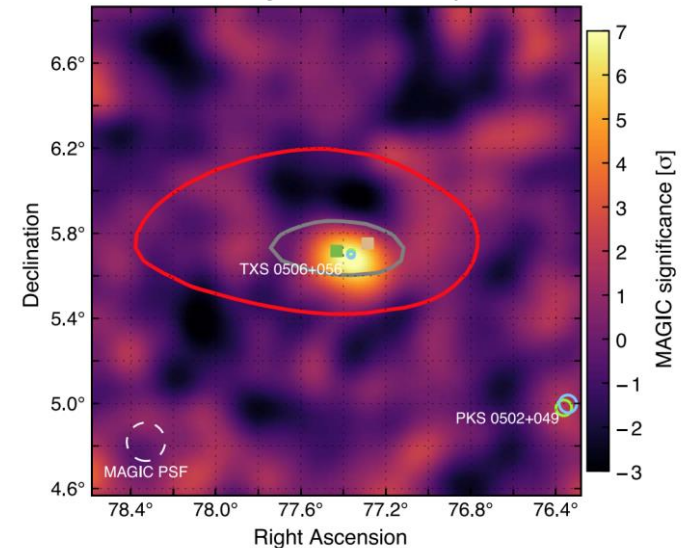


Fermi-LAT finds Flaring Blazar, TXS 0506+056

Fermi-LAT light curve (100 MeV – 300 GeV)

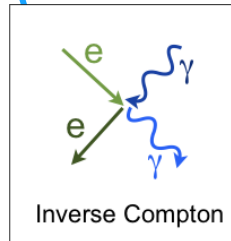
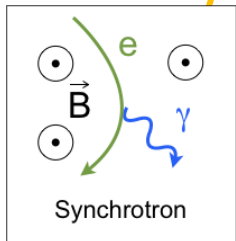
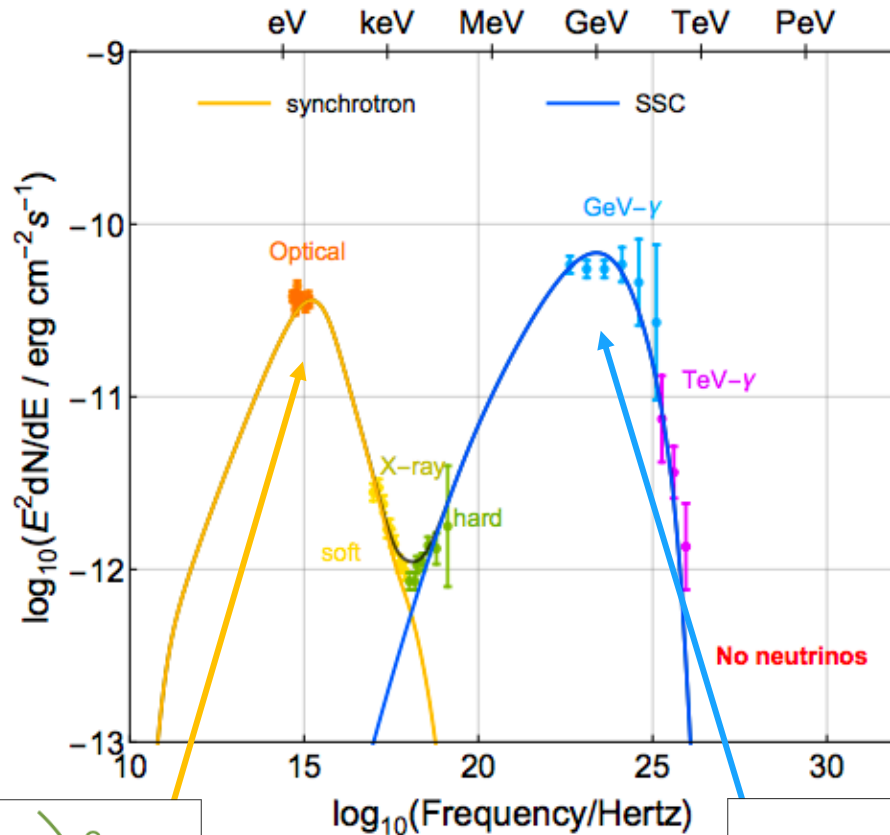


MAGIC Significance map:
TeV gamma rays



3 sigma significance including trials
> 6 PeV protons accelerated in the source

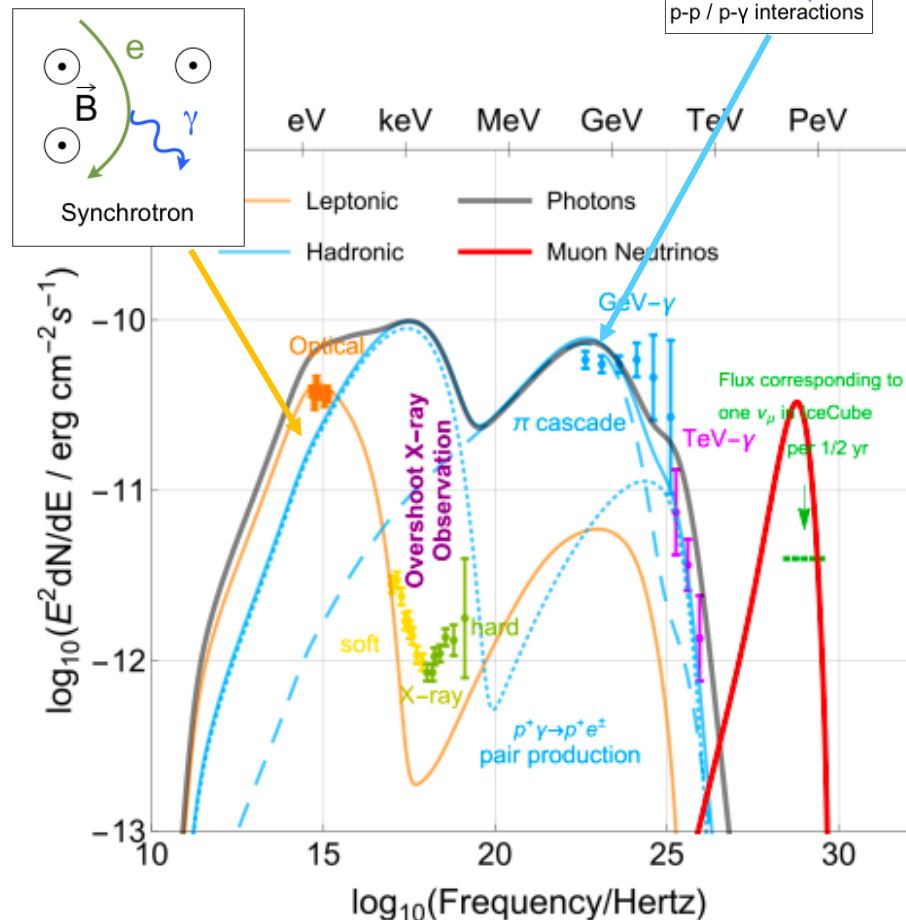
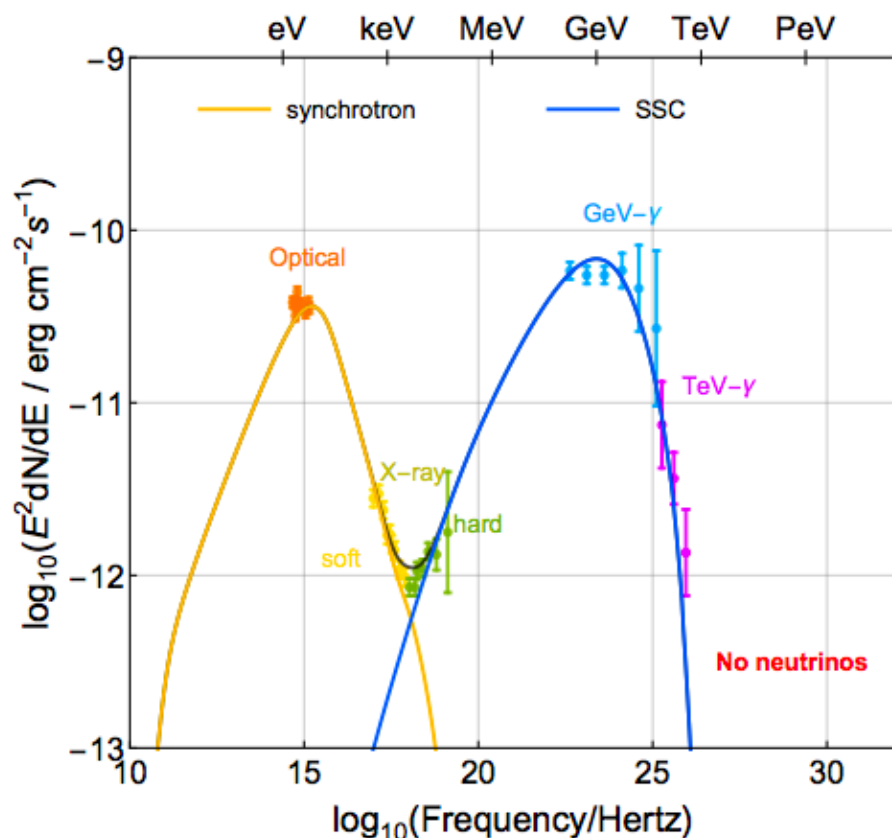
Modeling – leptonic



Gao et al., Nature Astronomy 2018,

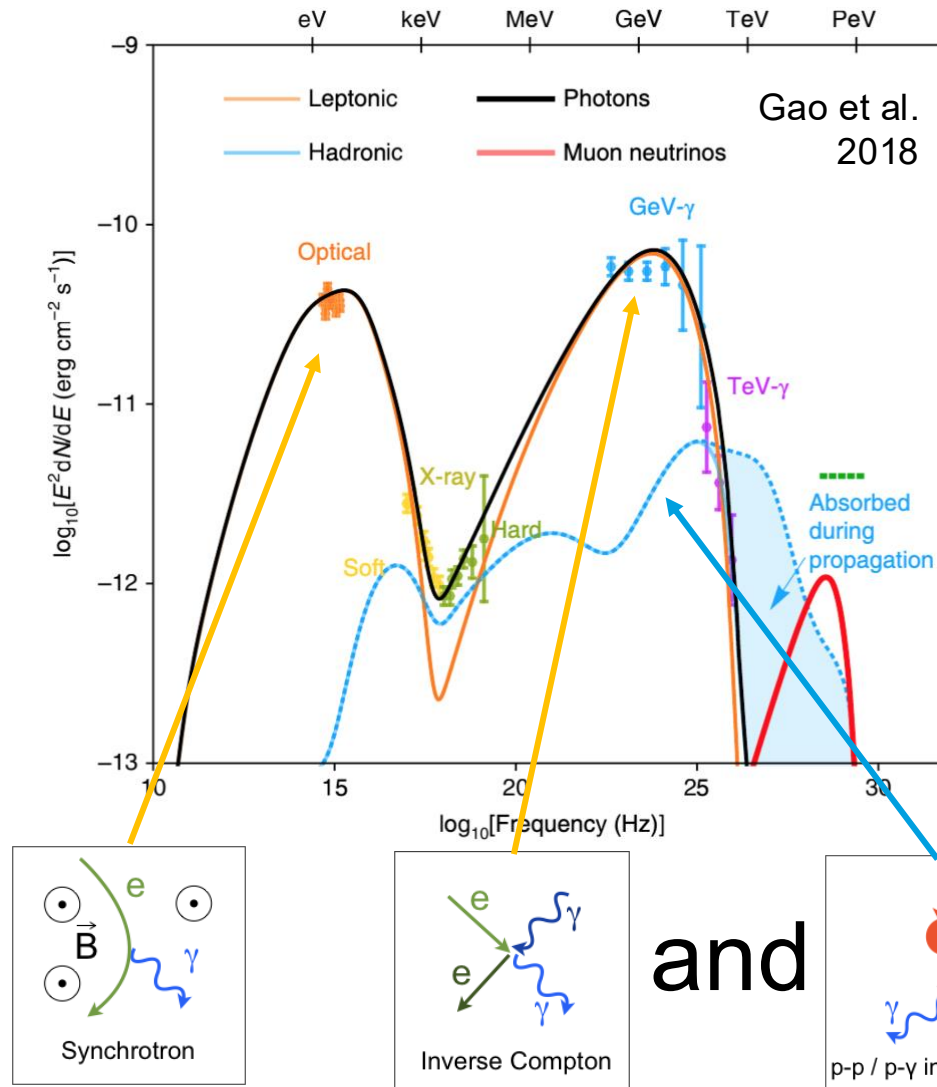
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, ...

Modeling – leptonic, hadronic



**Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed**

Modeling – lepto-hadronic

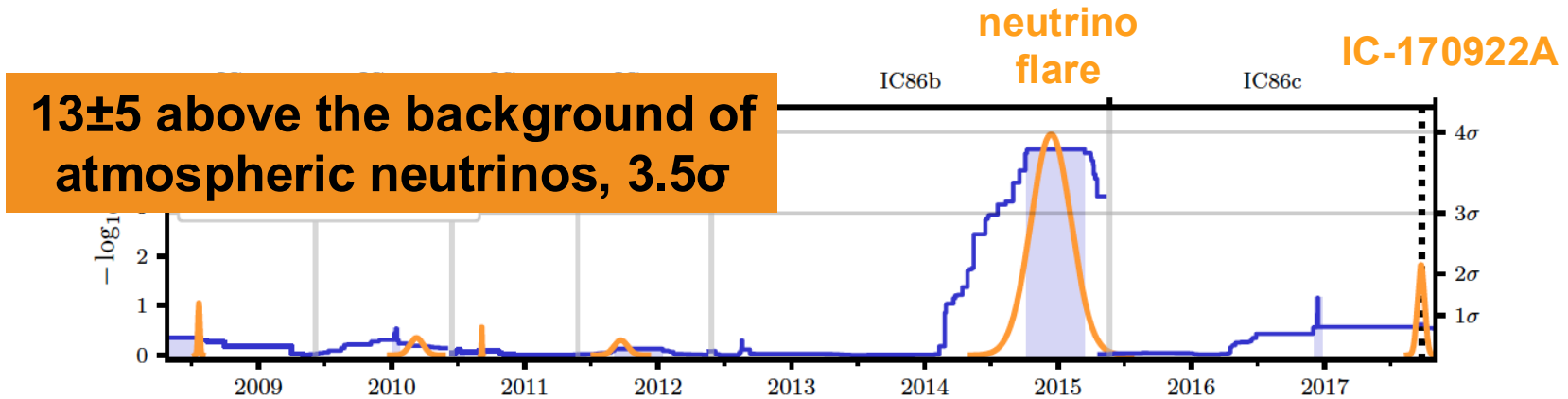


Neutrino prediction
~0.01-0.1 events in
6 months
(Eddington bias!)
Strohjohann et al. 2019

Gao et al., Nature Astronomy 2018,

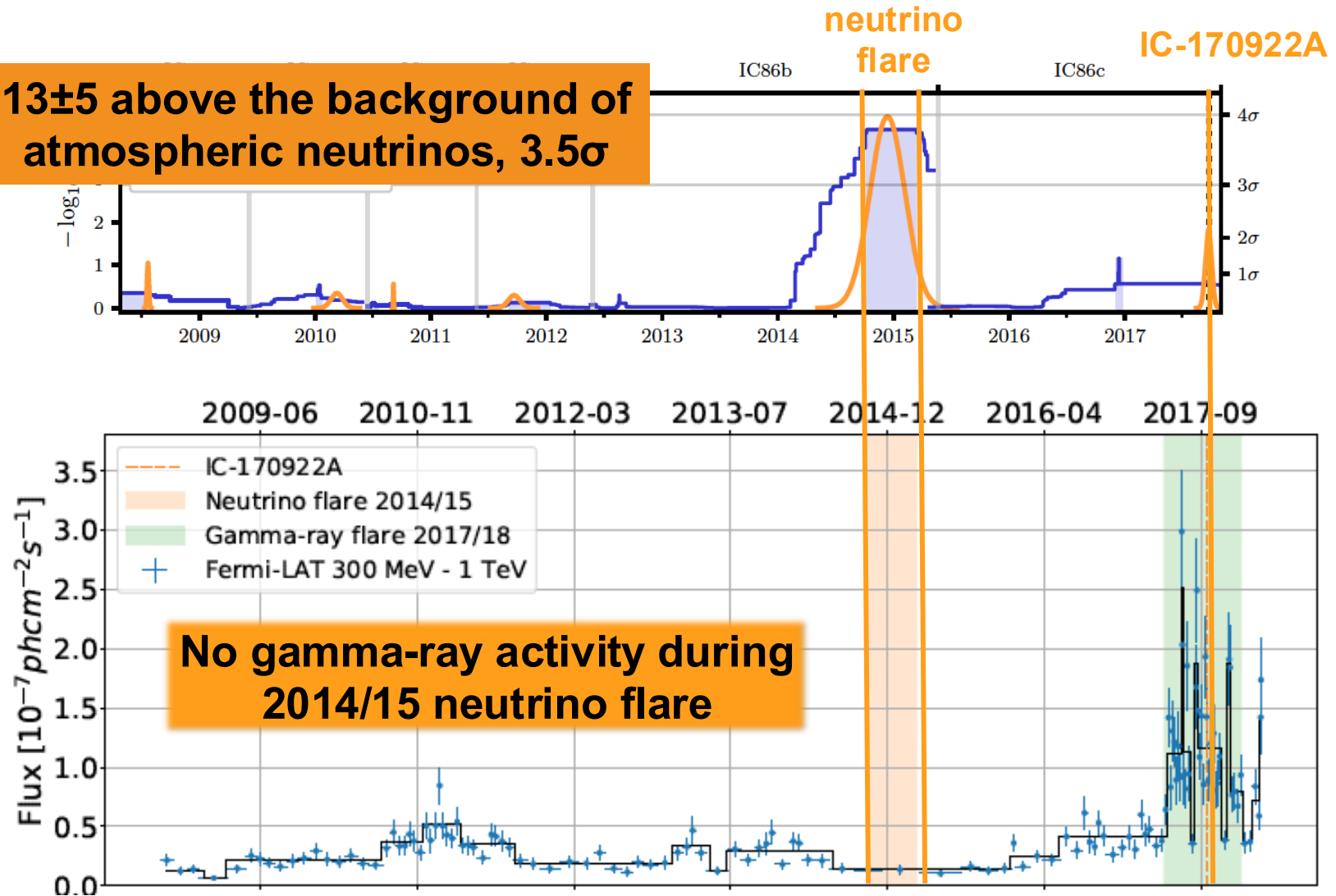
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, ...

Are there more Neutrinos from this Source?



Is there also a Gamma-ray Flare?

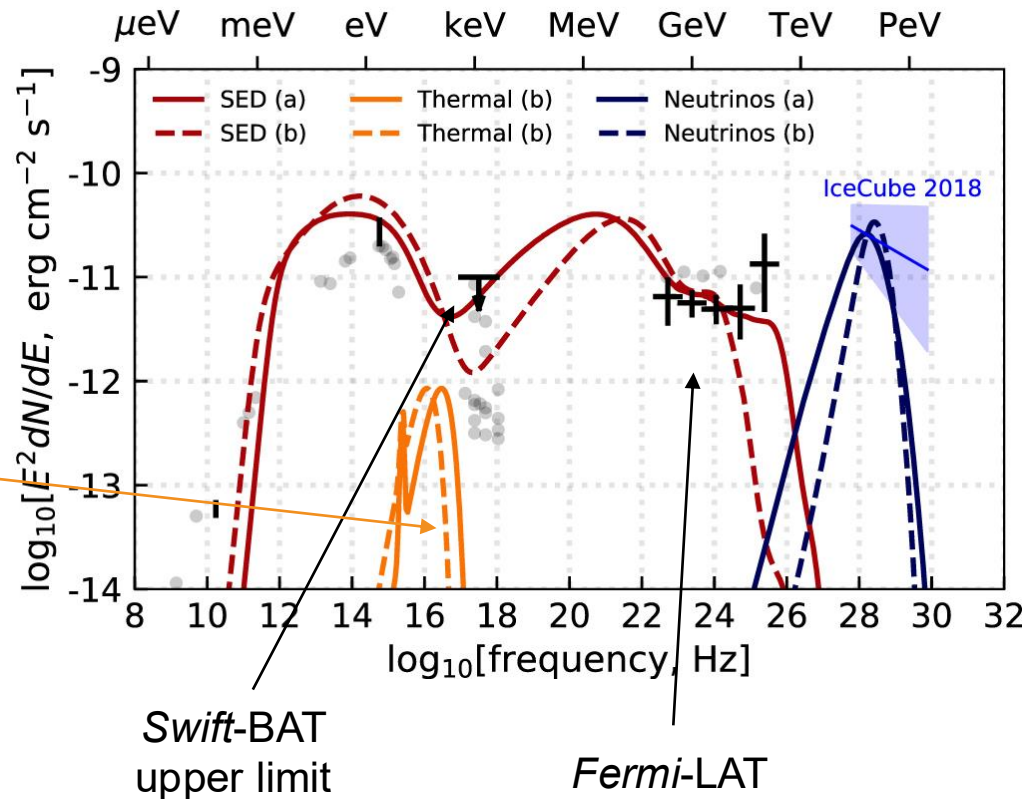
13 ± 5 above the background of atmospheric neutrinos, 3.5σ



Modeling of 2014/15 neutrino flare

neutrino luminosity is ~ 4 times higher than gamma-ray luminosity
 $\rightarrow$ **challenge for models**

BLR photons
boosted into
the jet



see e.g. Rodrigues et al. ApJL 874 2019, A. Reimer et al. ApJ 881 2019,
F. Halzen et al. ApJL 874 2019



Take home message

High-energy neutrinos can be used to search for electromagnetic counterparts

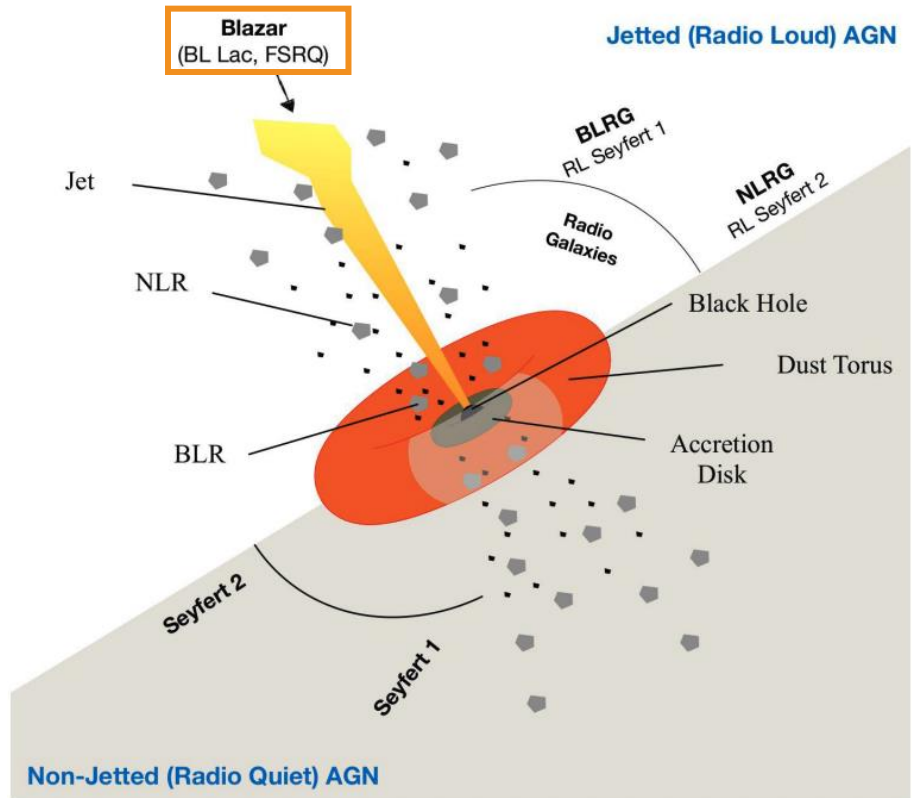
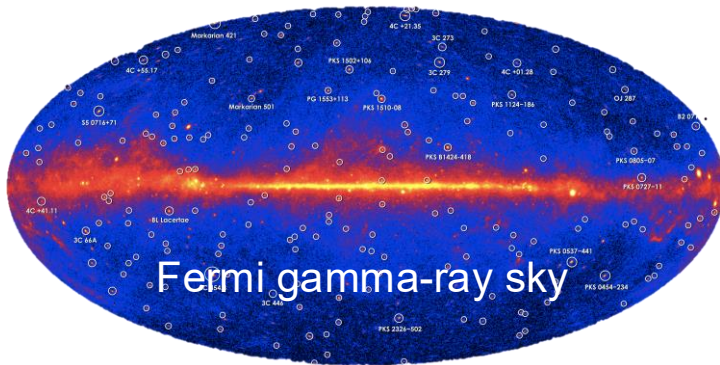
The blazar TXS 0506+056 was flaring in gamma rays in temporal coincidence with a 290TeV neutrino.

An orphan flare or 1-10TeV neutrinos was found and is difficult to explain with simple models.

**Do gamma-ray blazars
produce all diffuse neutrinos?**

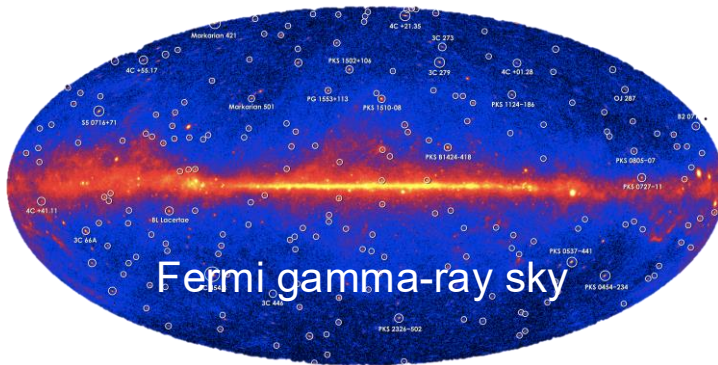
Fermi Blazars

Gamma rays tell us **where** to look for neutrinos

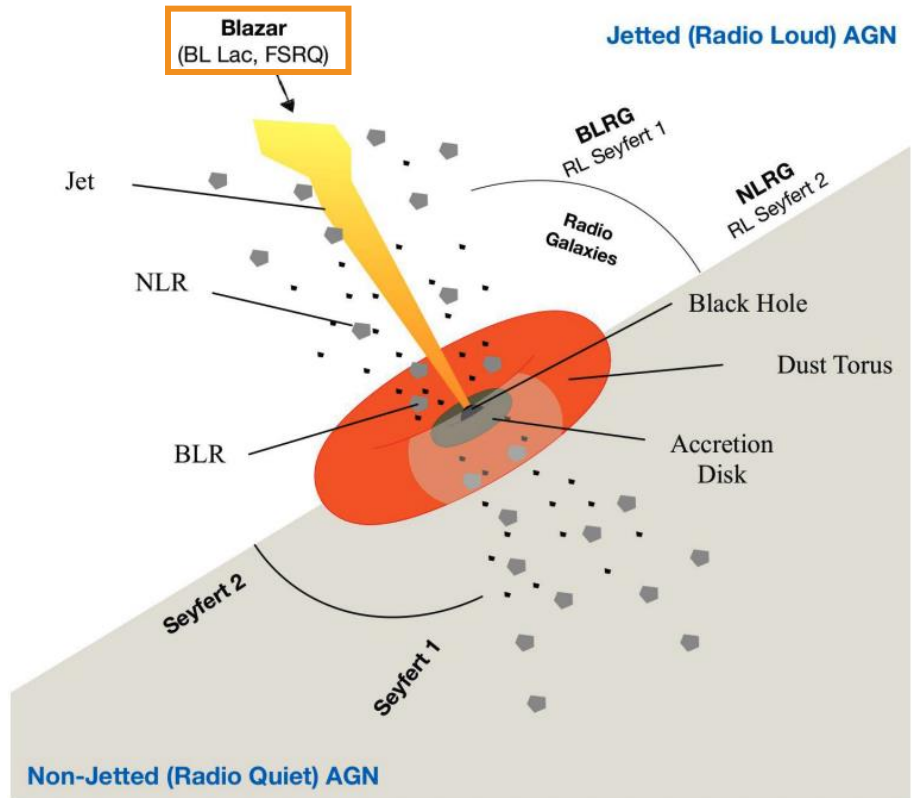


Fermi Blazars

Gamma rays tell us **where** to look for neutrinos



Correlation study of 12 years of IceCube data and 2089 *Fermi*-LAT blazars

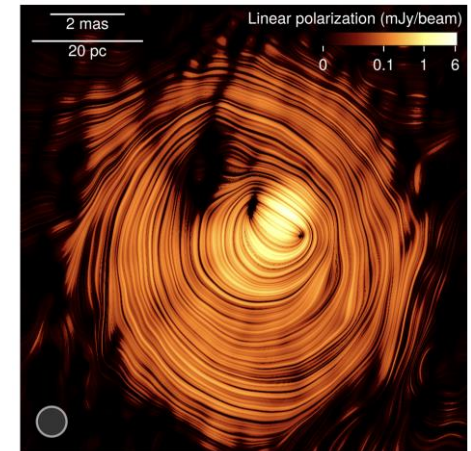
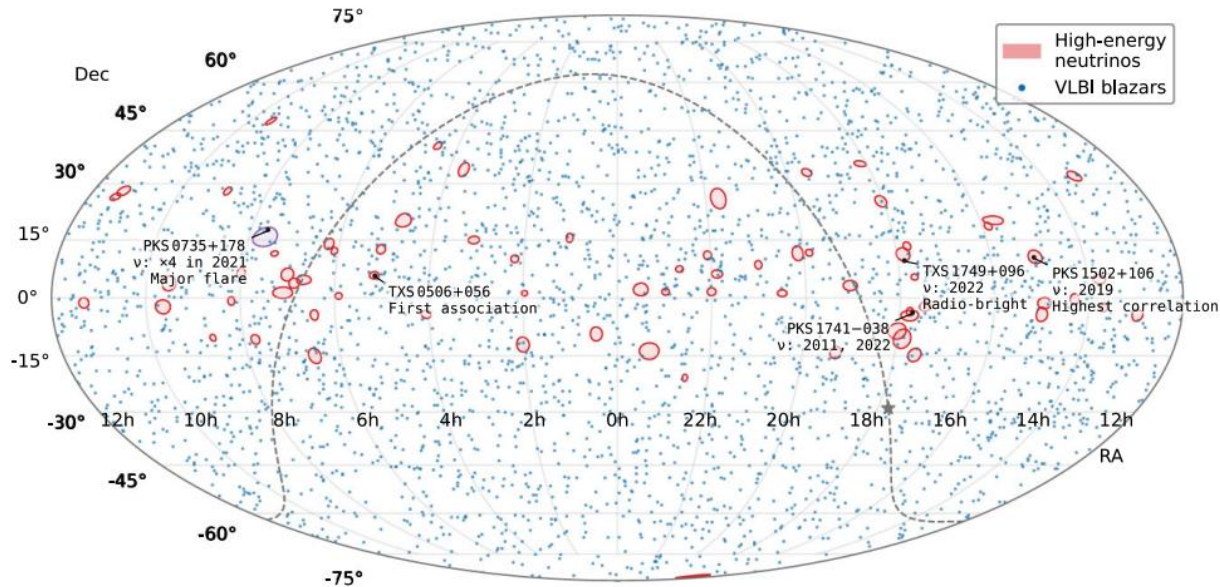


***Fermi*-LAT blazars can only be responsible for a small fraction of the observed ν 's.**

**Other wavelength as tracer for
neutrinos from blazars?**

Radio Core Brightness as Tracer

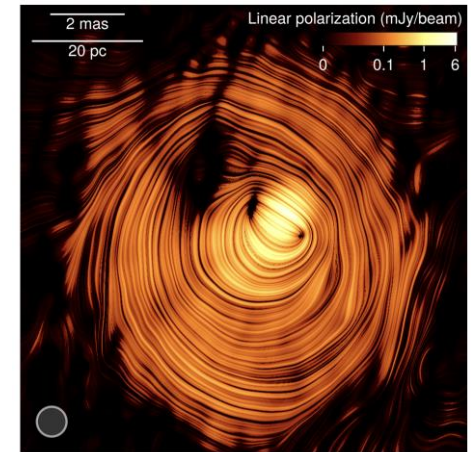
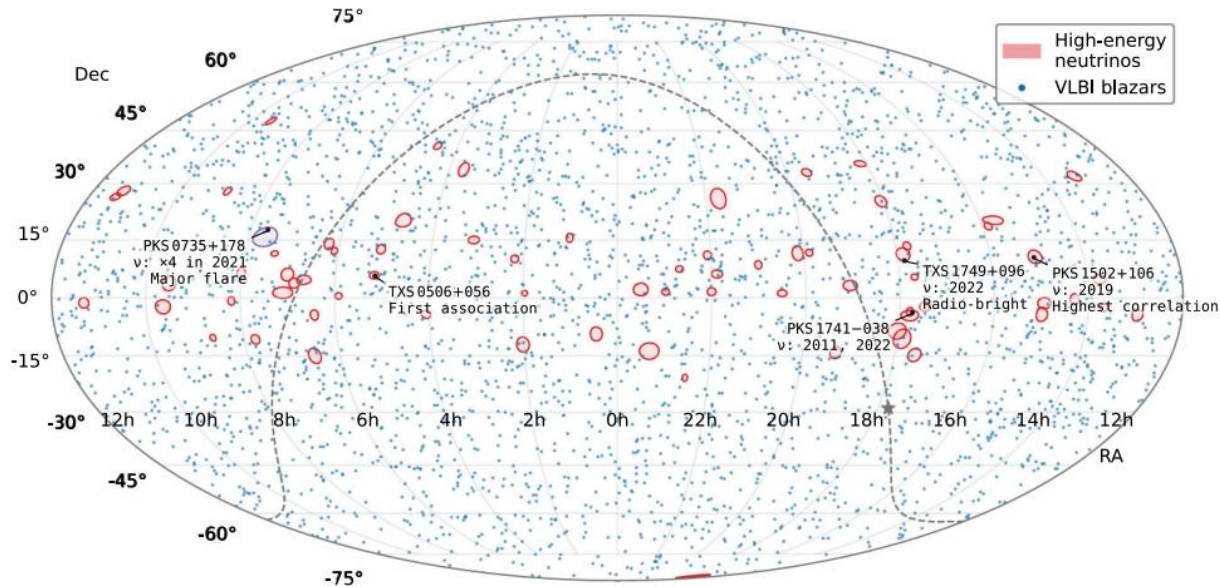
Correlation with VLBI-flux-density limited sample of blazars



Correlation of radio-bright blazars with
IceCube neutrino alerts at chance
coincidence of $3 \cdot 10^{-4}$

Radio Core Brightness as Tracer

Correlation with VLBI-flux-density limited sample of blazars



Correlation of radio-bright blazars with IceCube neutrino alerts at chance coincidence of $3 \cdot 10^{-4}$

Correlation not confirmed by slightly different analyses

Zhou et al. 2021 PRD 103 (2021),
IceCube ApJ 954 (2023)

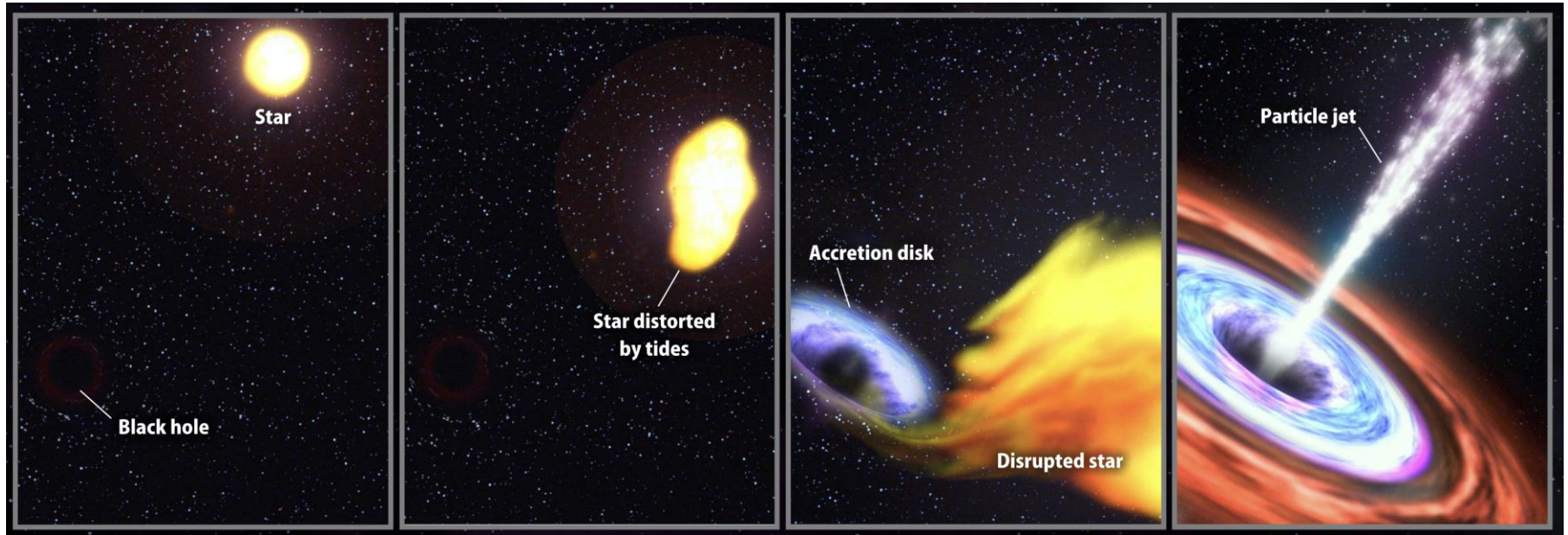


Take home message

Gamma-ray emission in blazars could not be established as a universal tracer for neutrino emission, but blazars are not ruled out as neutrino sources.

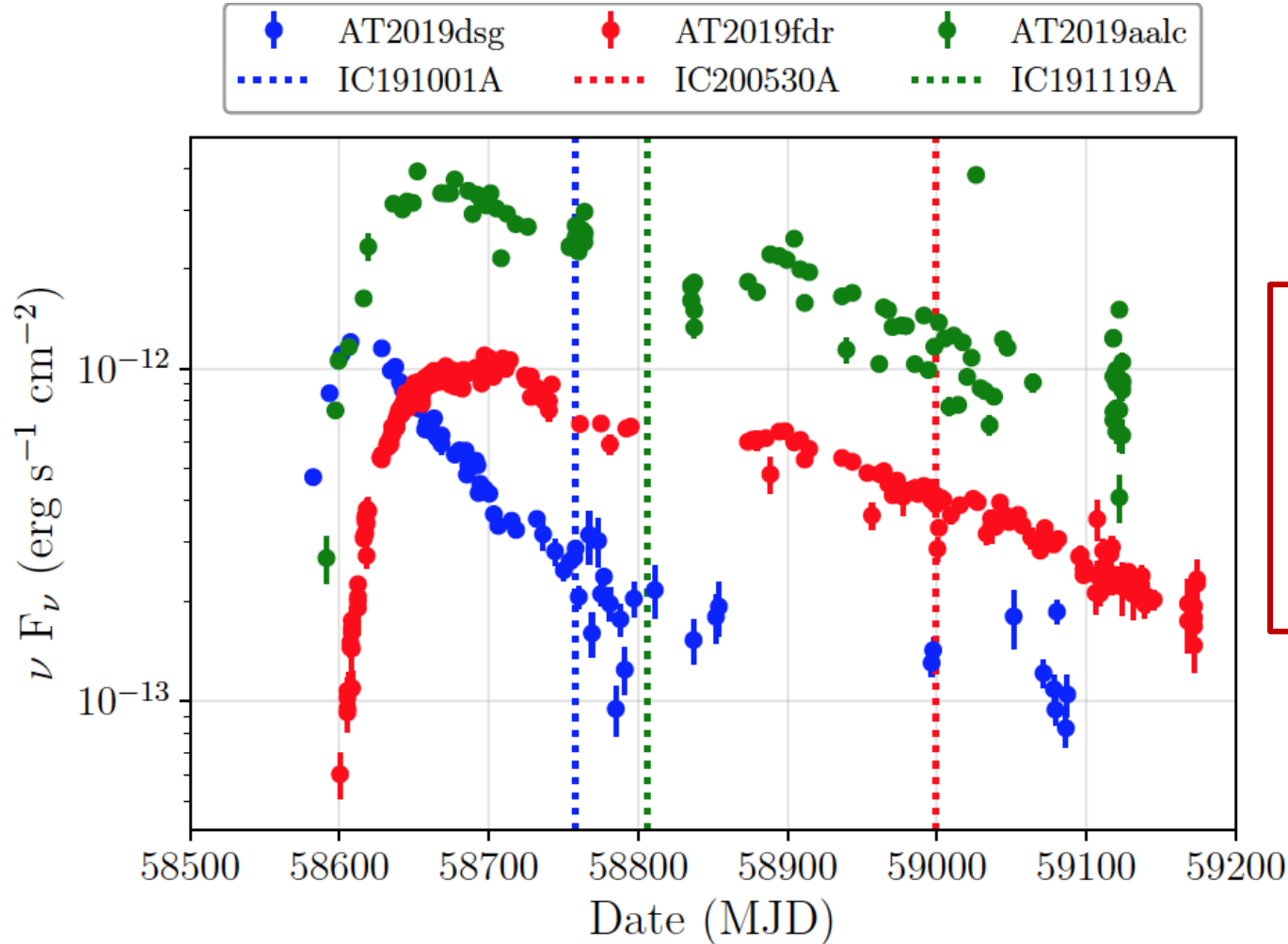
Other Sources?

What about quiet black holes? Tidal Disruption Events



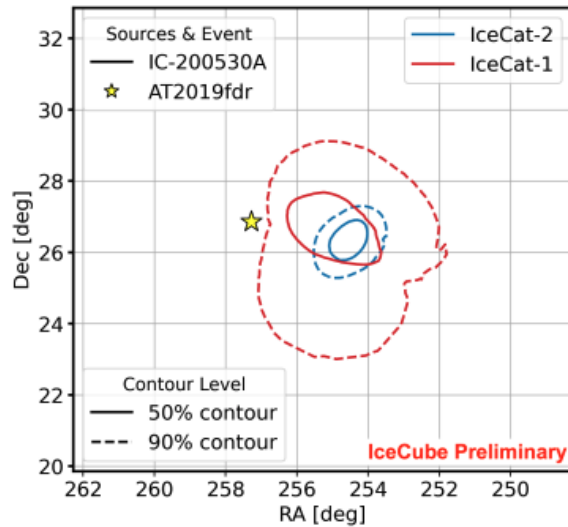
~50 TDEs identified, 4 jetted TDEs
bright in optical

Tidal Disruption Events as Neutrino Candidates

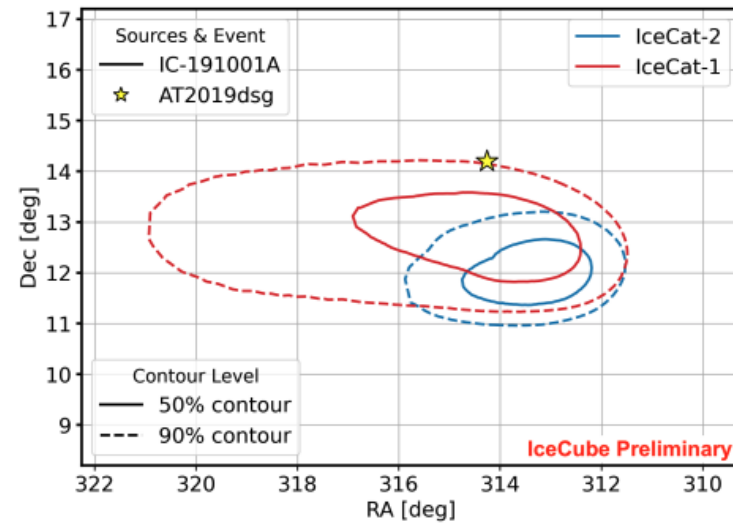


First hint of neutrino production in TDEs
→ **Very efficient** neutrino production in TDEs compared to AGN?

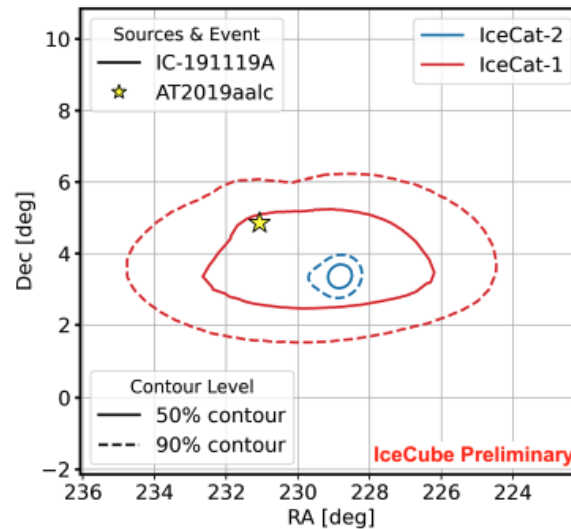
Neutrino TDEs disfavored with IceCat-2



(a) AT2019fdr

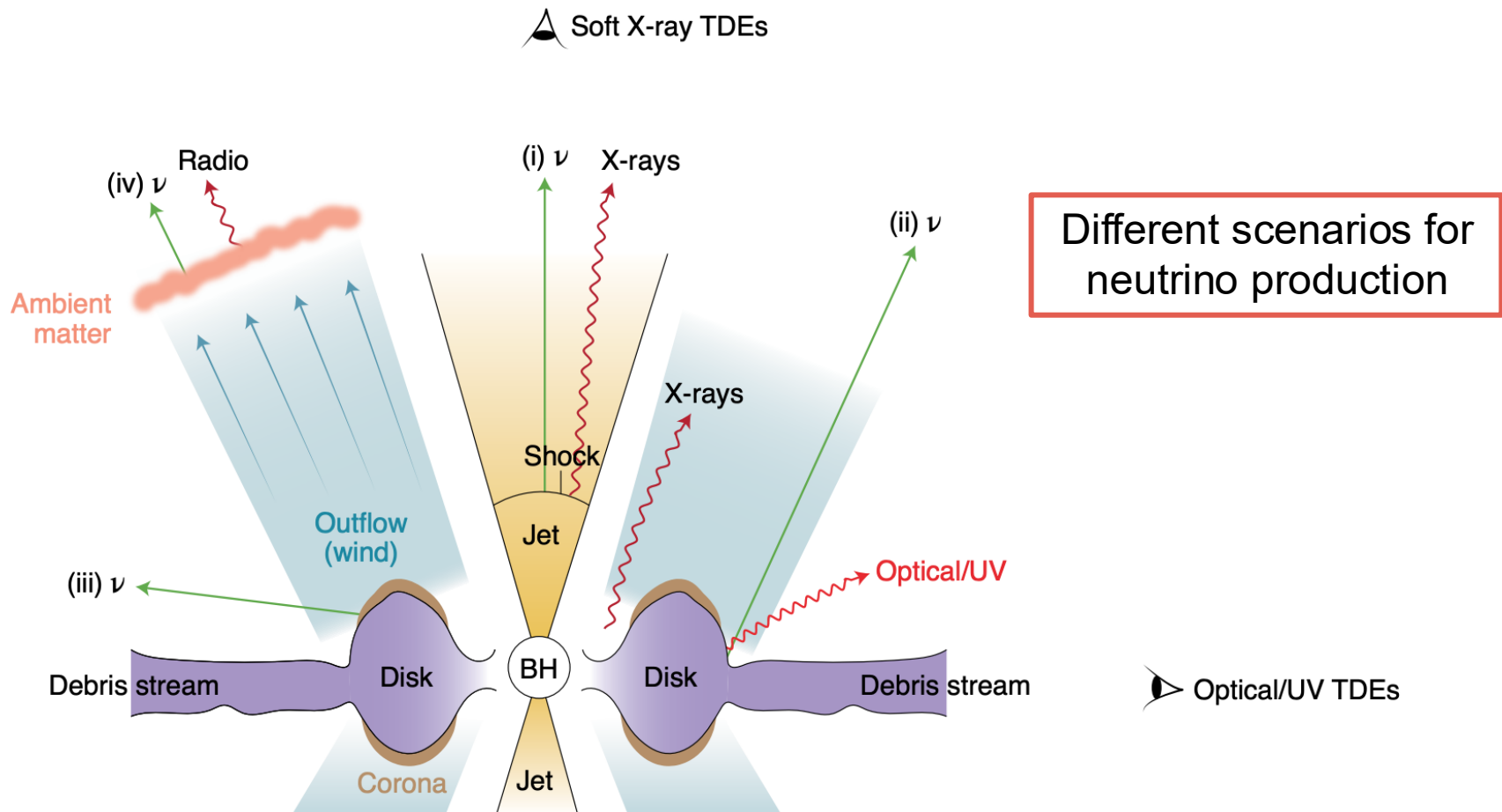


(b) AT2019dsg



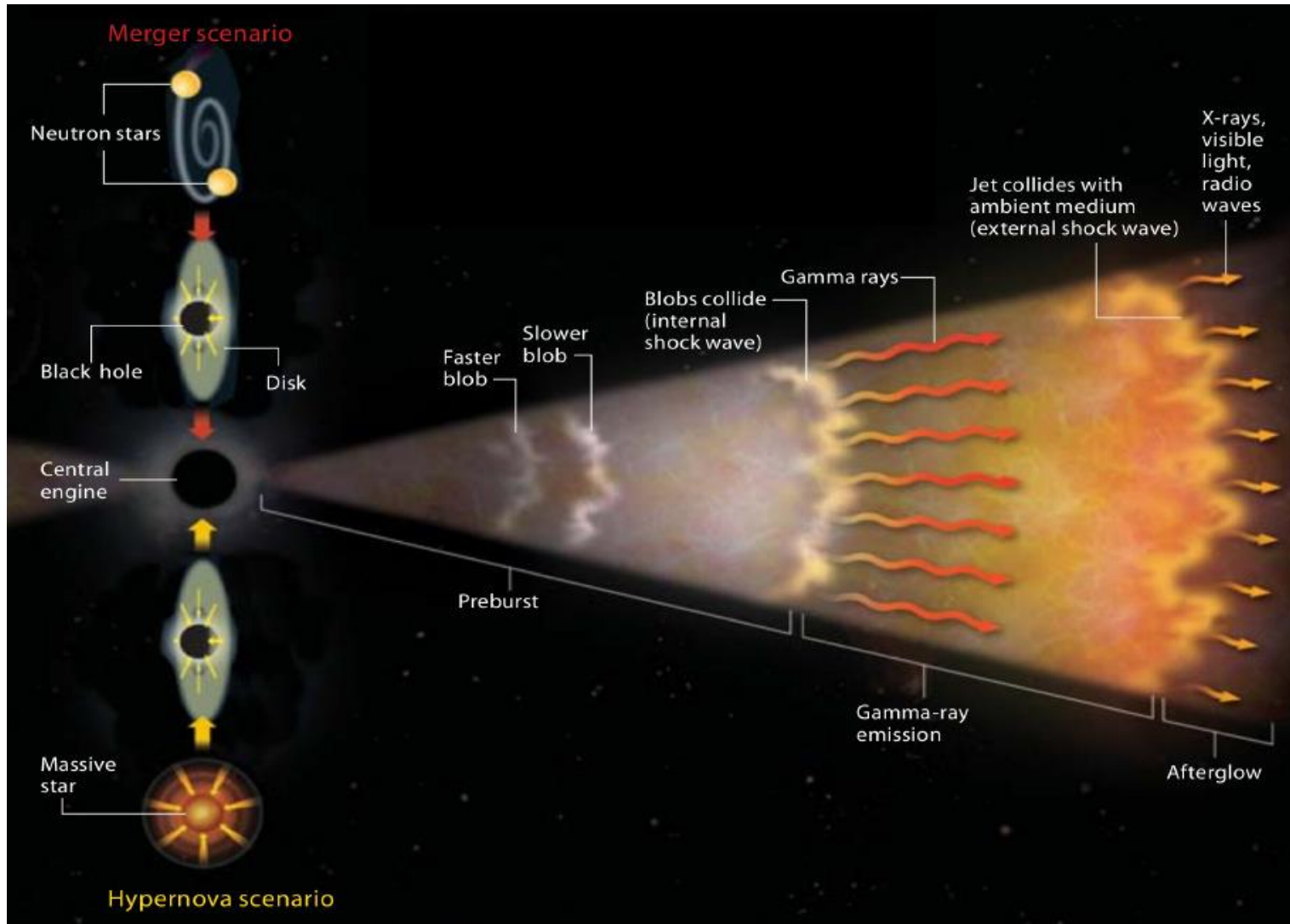
(c) AT2019aalc

Neutrino Production in TDEs

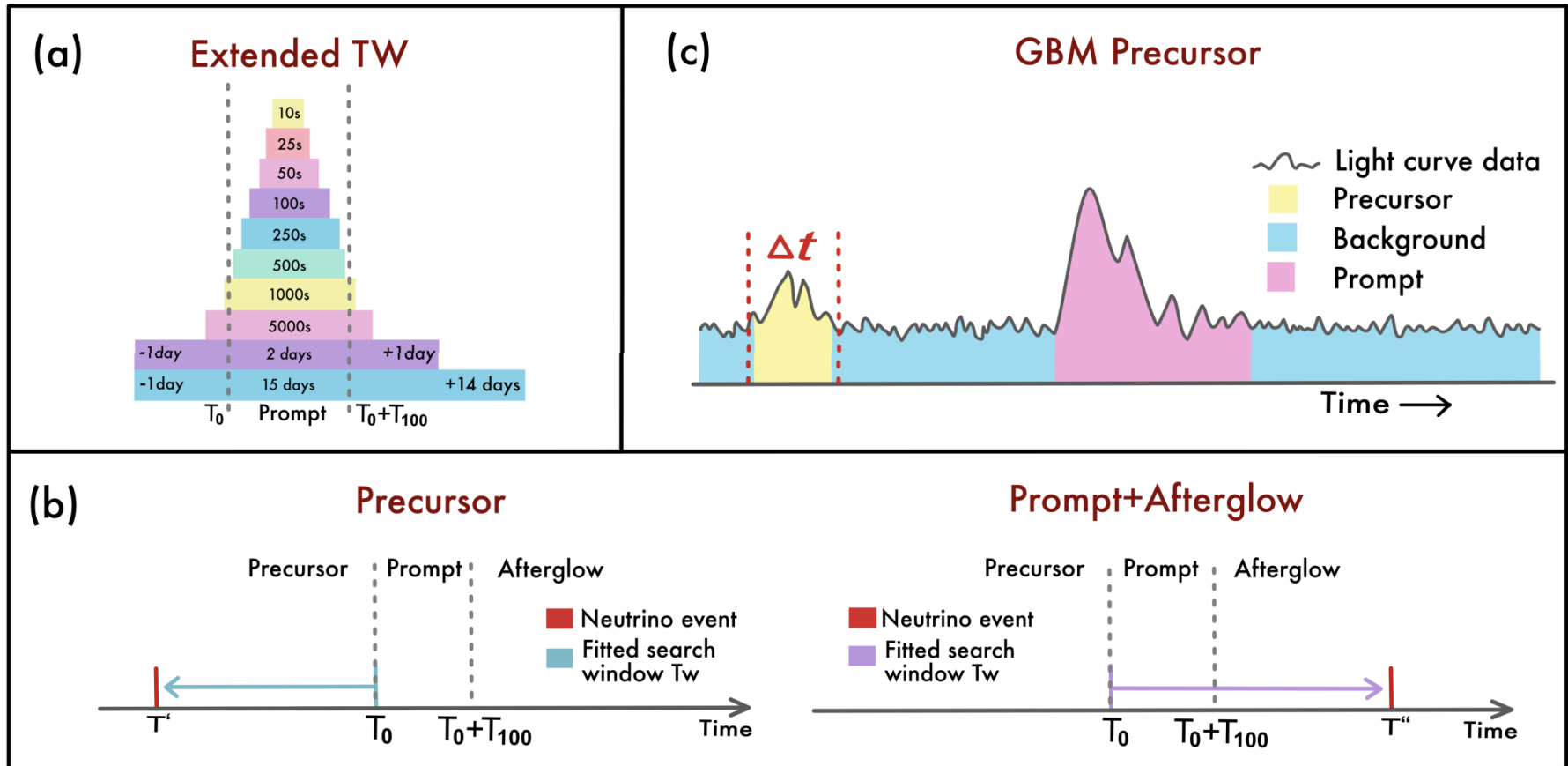


Stellar collapse as neutrino sources?

Gamma-ray Bursts

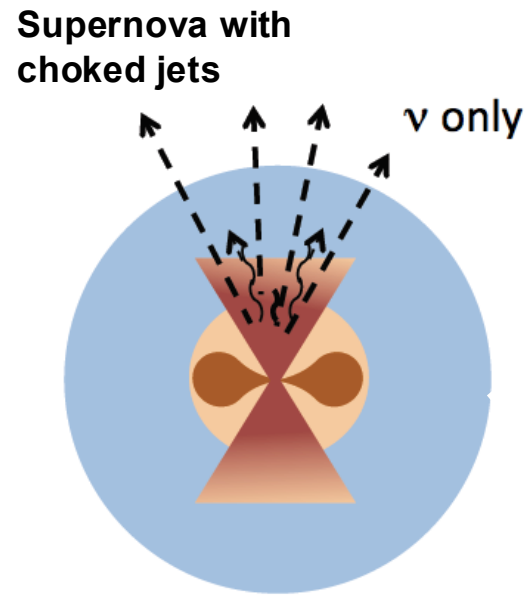
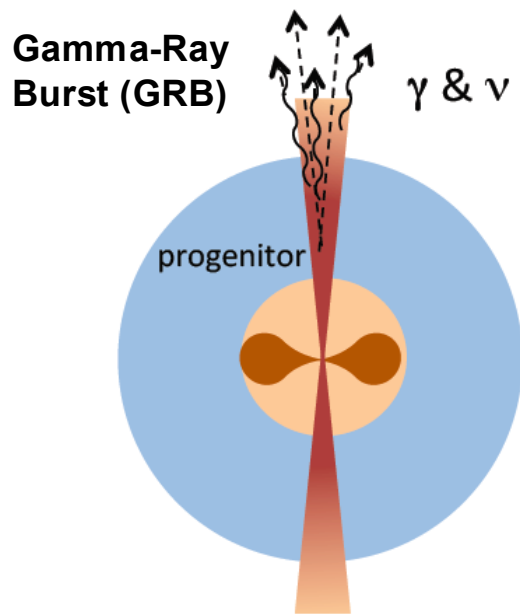


Gamma-ray Bursts: Neutrino Searches

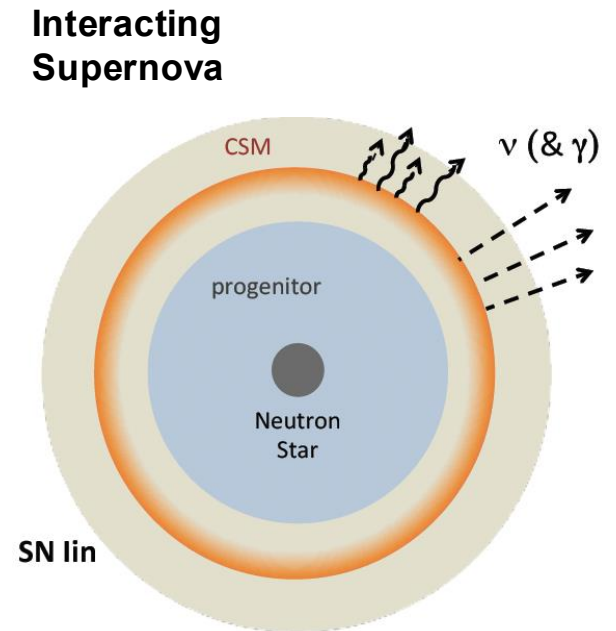
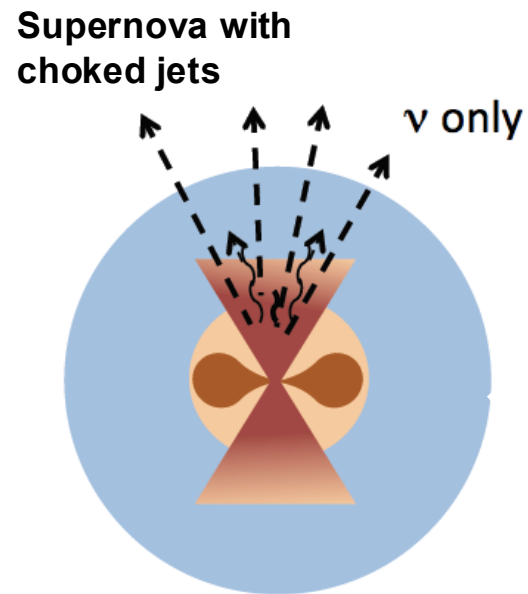
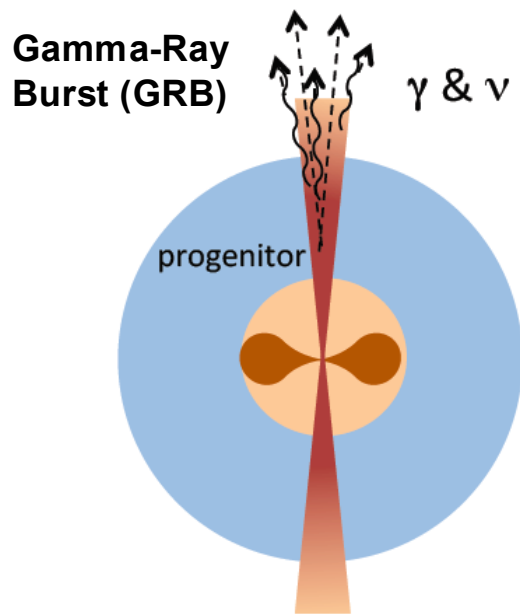


No excess found $\rightarrow$ Prompt neutrinos contribute $<1\%$ to diffuse neutrino flux

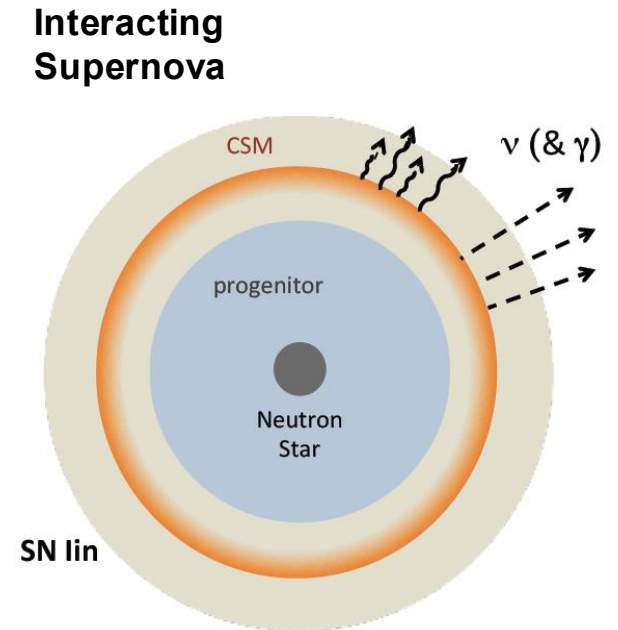
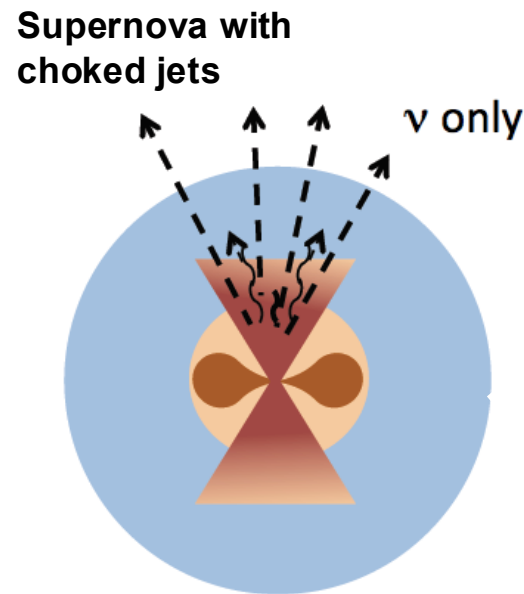
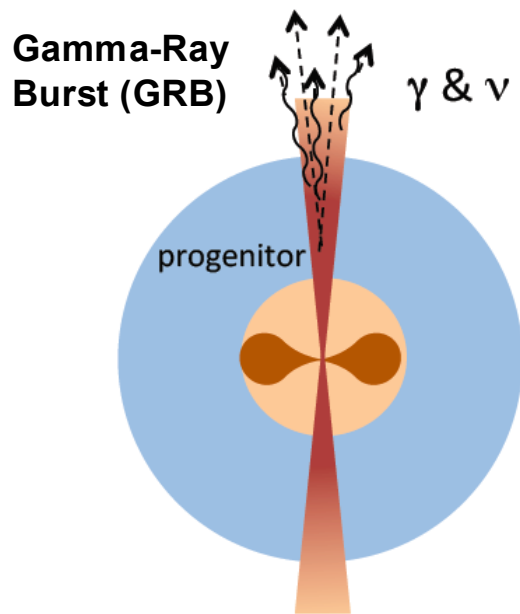
Alternatives to GRBs



Alternatives to GRBs



Alternatives to GRBs



“hidden” sources, best discovered in the optical

Optical Counterpart to a high-energy neutrino: SN2023uqf

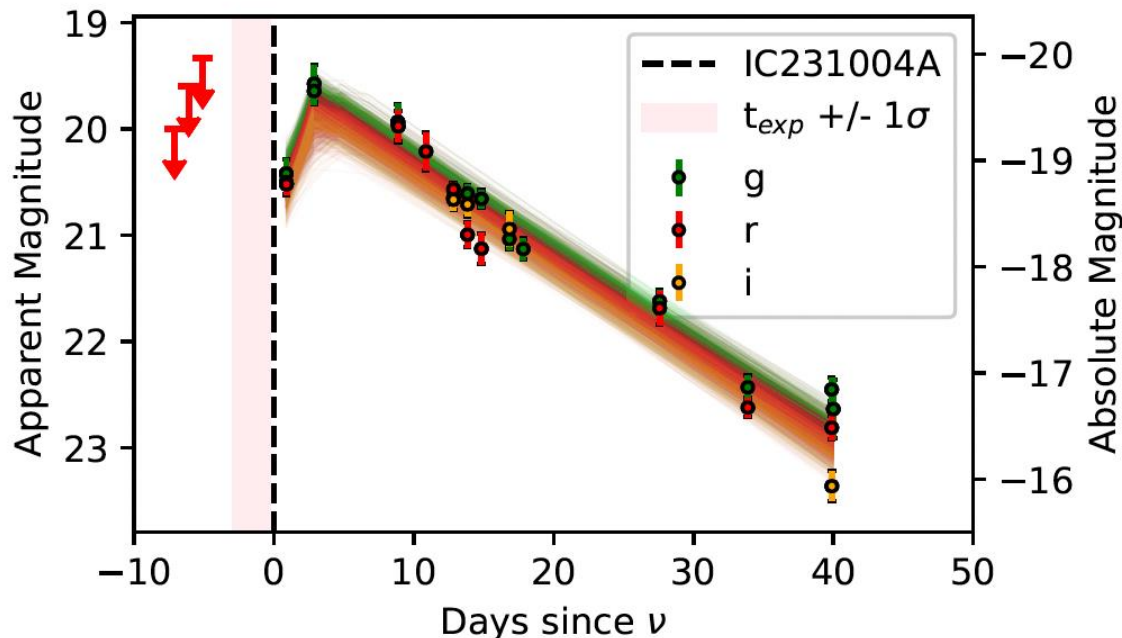
IC-231004A

440 TeV Neutrino

84% signalness

3σ association

Distance: 700 Mpc



Optical Counterpart to a high-energy neutrino: SN2023uqf

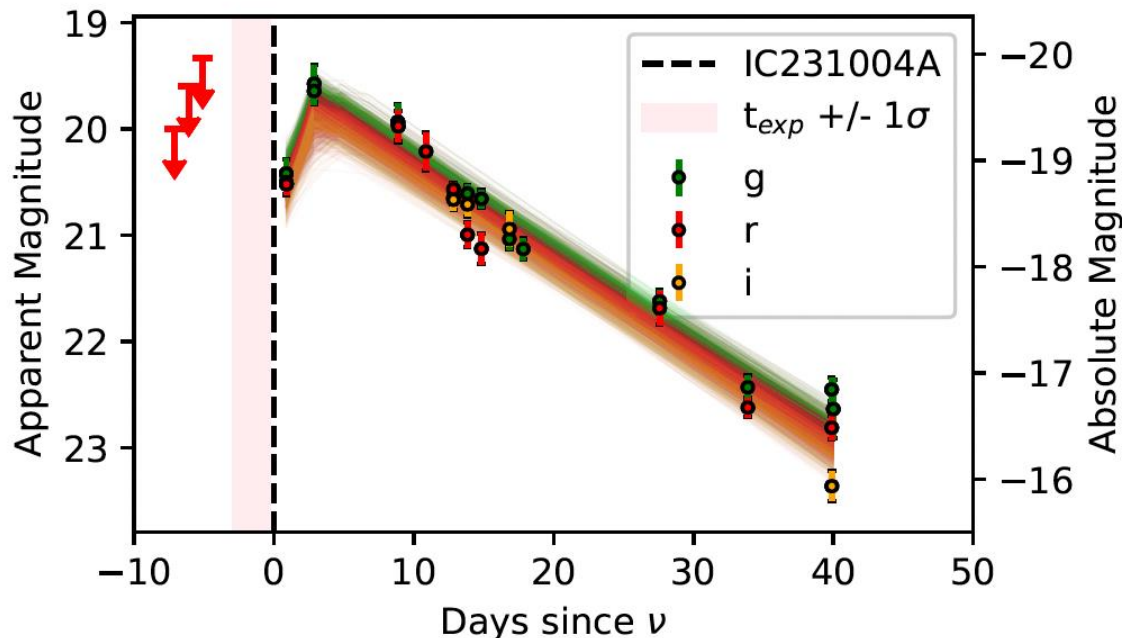
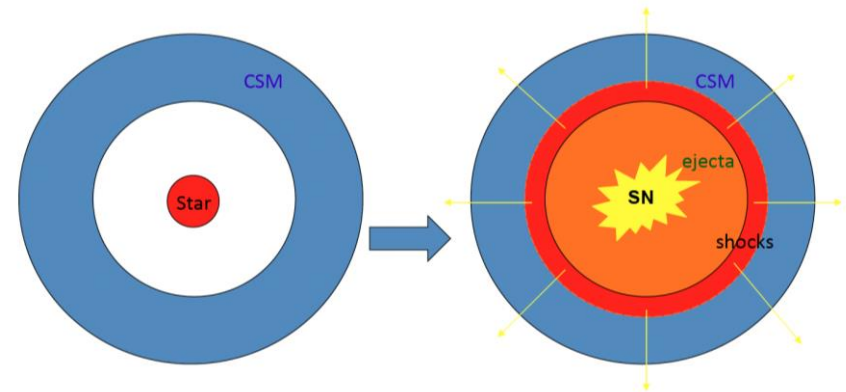
IC-231004A

440 TeV Neutrino

84% signalness

3σ association

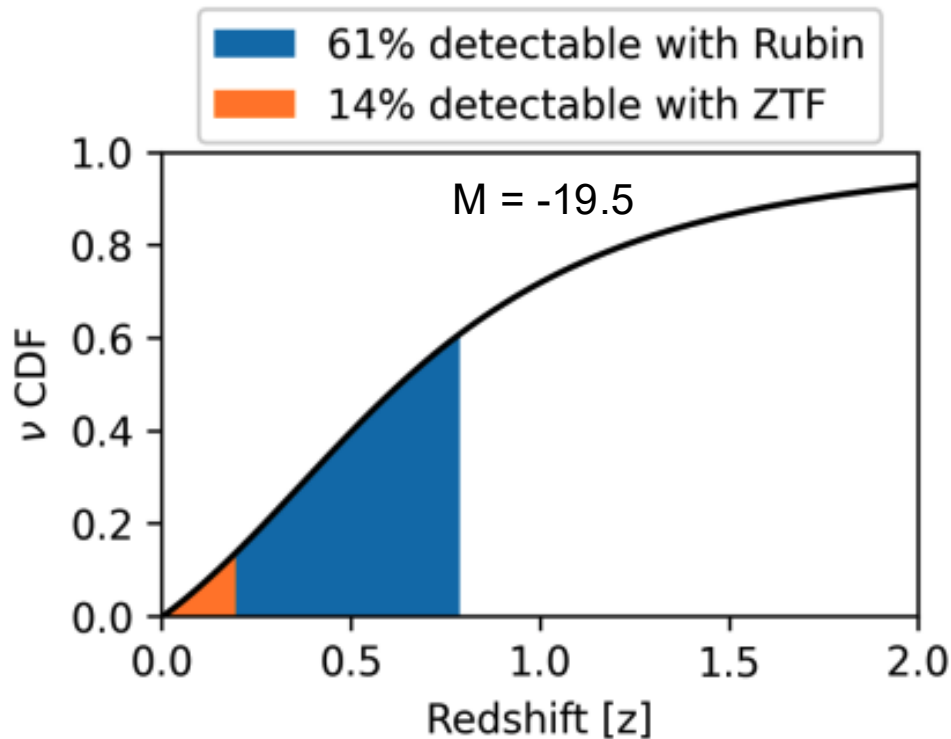
Distance: 700 Mpc



Murase MNRAS 440 (2013)

Evidence for hadronic acceleration in core-collapse supernova explosions

Improved follow-up



First light: July 2025, Alert stream 4-7 months later
Rubin ToO report: 2-12 triggers/year

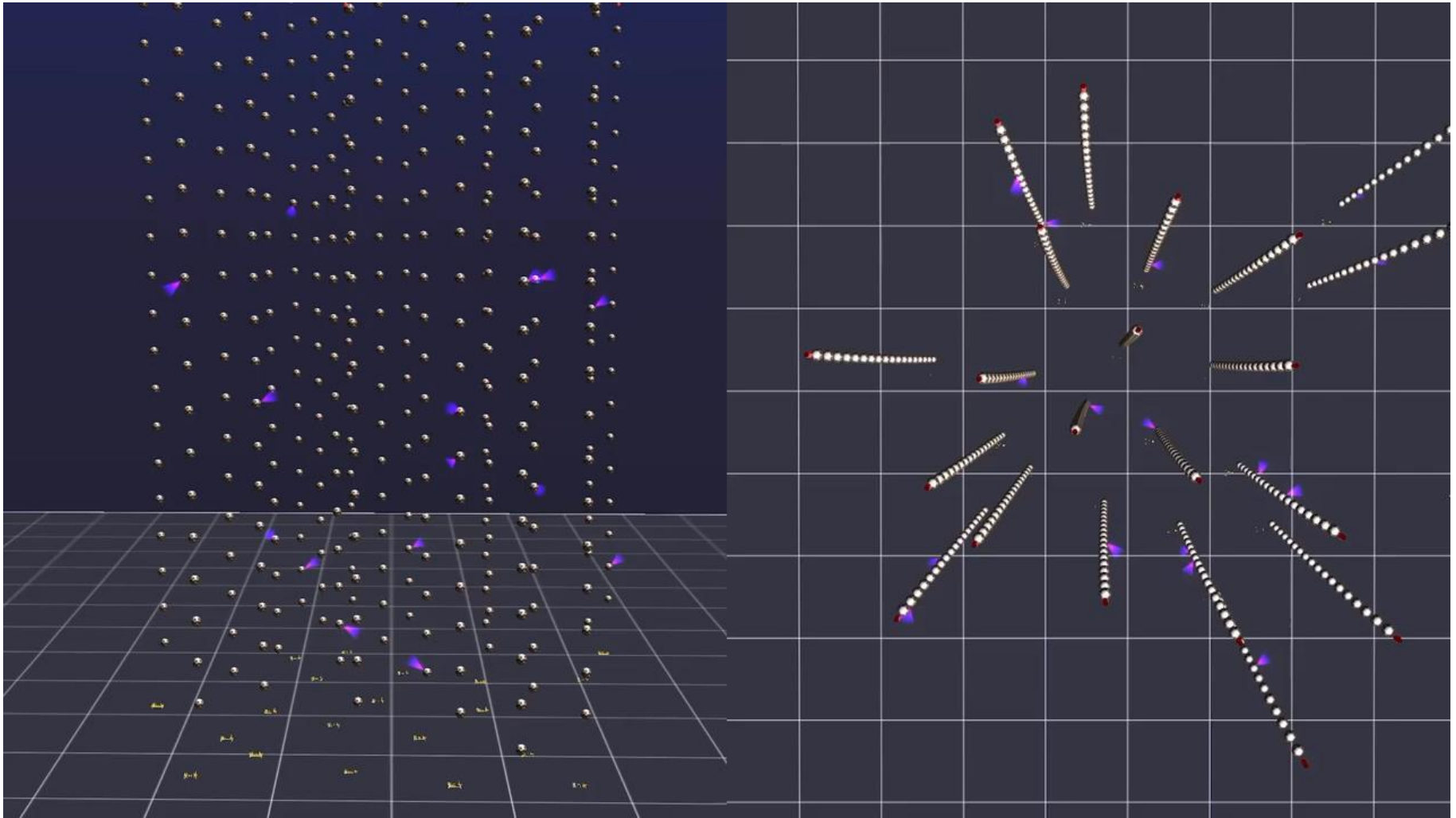


Take home message

While GRBs are disfavored, choked-jet or interacting Supernovae are promising source classes, which can be probed with up-coming instruments.

The highest energy neutrino event ever detected

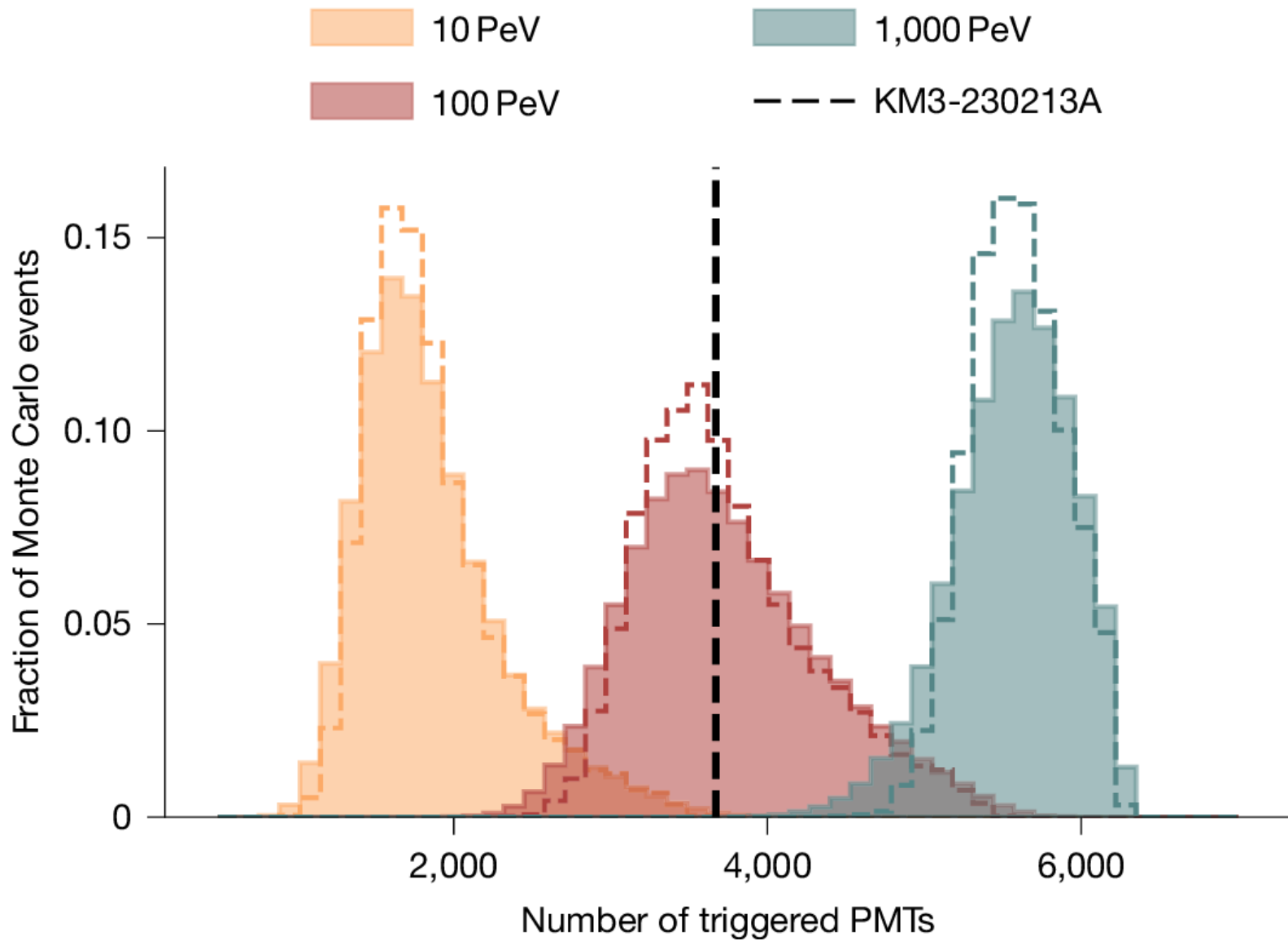
220 PeV Event from KM3NeT



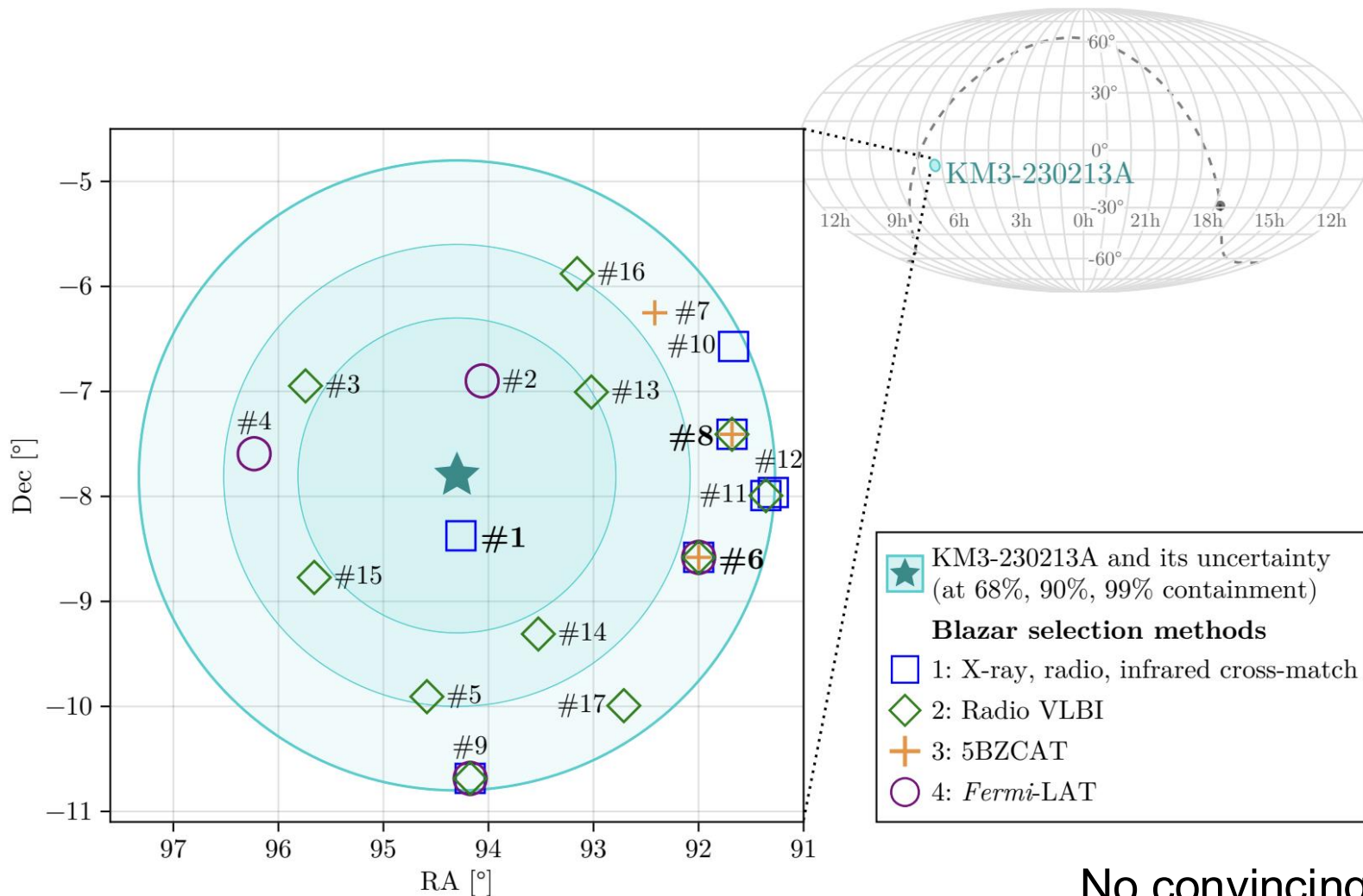
220 PeV Event from KM3NeT

- Huge amount of light seen in the ARCA detector
- Horizontal event (1deg above horizon) as expected since Earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered
- Muon simulation indicates that 100 PeV muons are needed to reproduce this signature

Muon energy

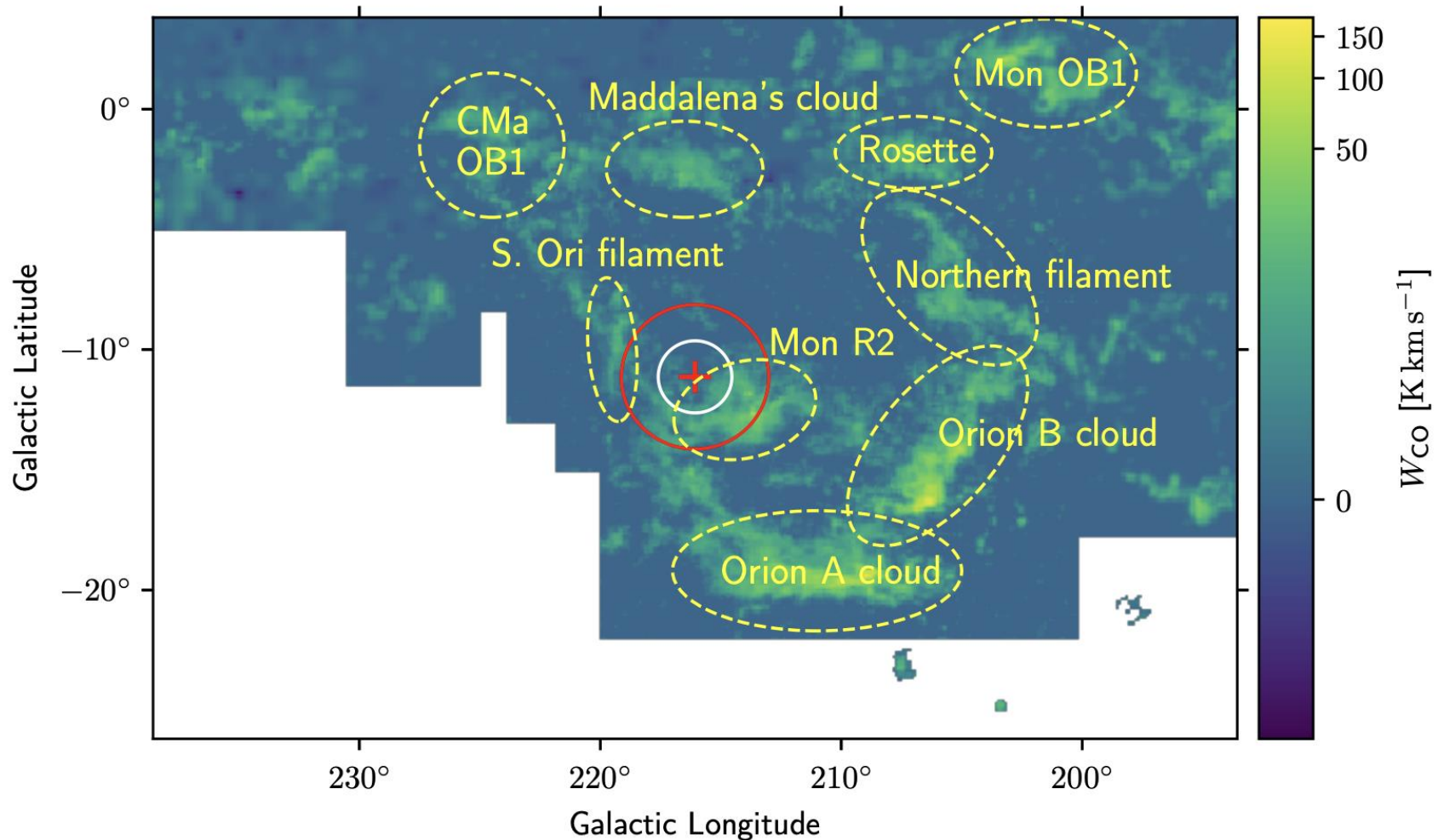


Potential sources?



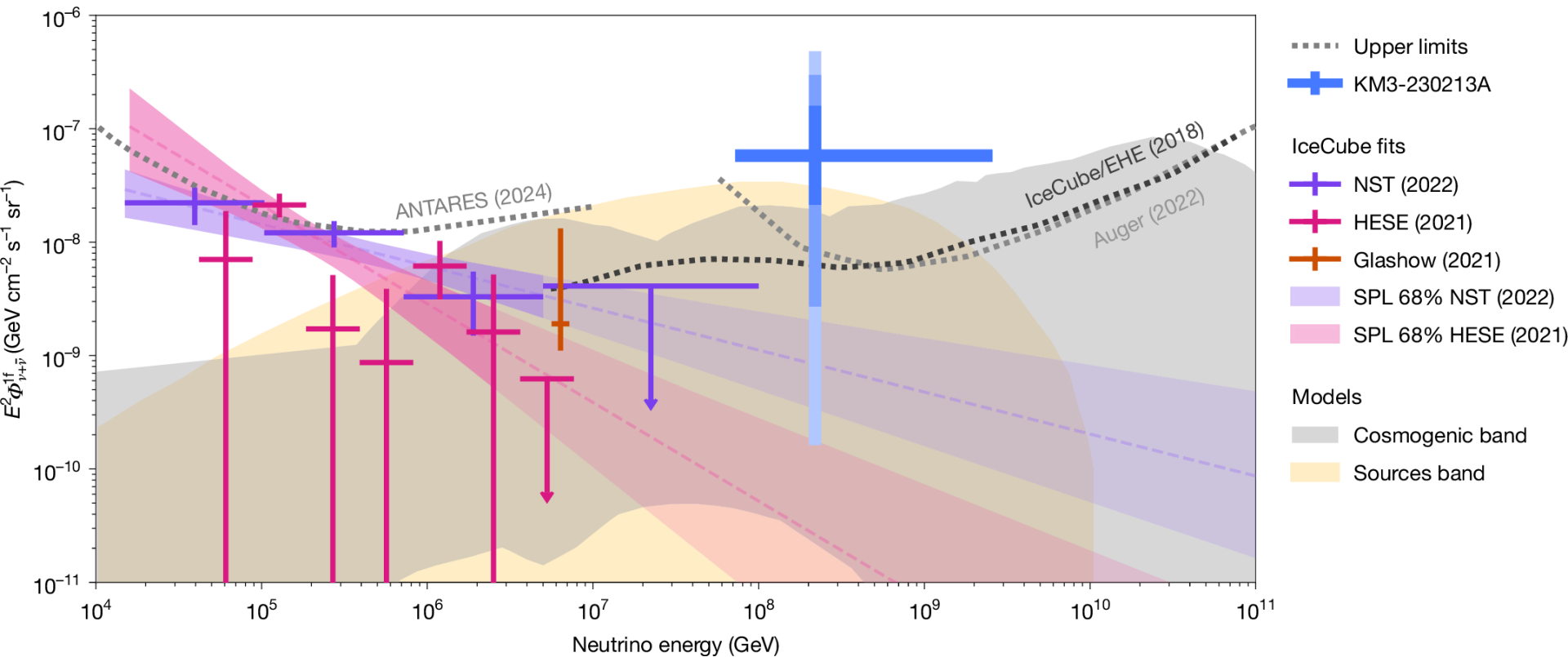
No convincing blazar counterpart found

Potential sources?



Galactic origin unlikely

Tension with IceCube and Auger upper limits?





Take home message

KM3NeT detected the highest energy neutrino event with $\sim 220\text{PeV}$.

This is in mild tension with IceCube upper limits.

It's origin is unknown.

Results from water / ice Cherenkov Telescopes

- **Astronomy Summary**

- Diffuse Flux
 - First detected in 2013, now deviation from simple power law
- Milky Way: $\sim 10\%$ of diffuse flux
- Source Candidates
 - Neutrino map alone does not reveal sources
 - Using electromagnetic information
 - Seyfert galaxy NGC 1068 at 4 sigma in 10 year data + other potential Seyfert candidates
 - Blazar TXS 0506+056 at 3 sigma through realtime observations
 - Interacting Supernova SN2023uqf ?

Astro Quiz

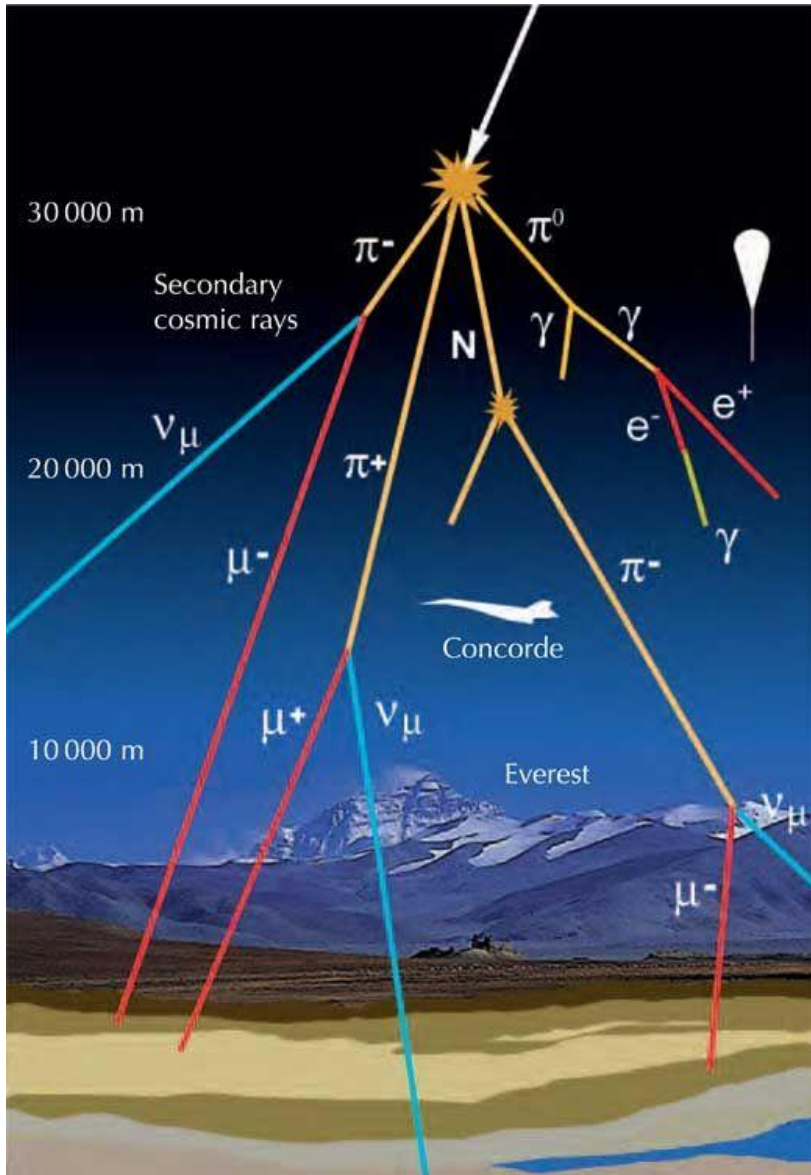


<https://forms.gle/UHKjRUvZPEJZqJqy5>

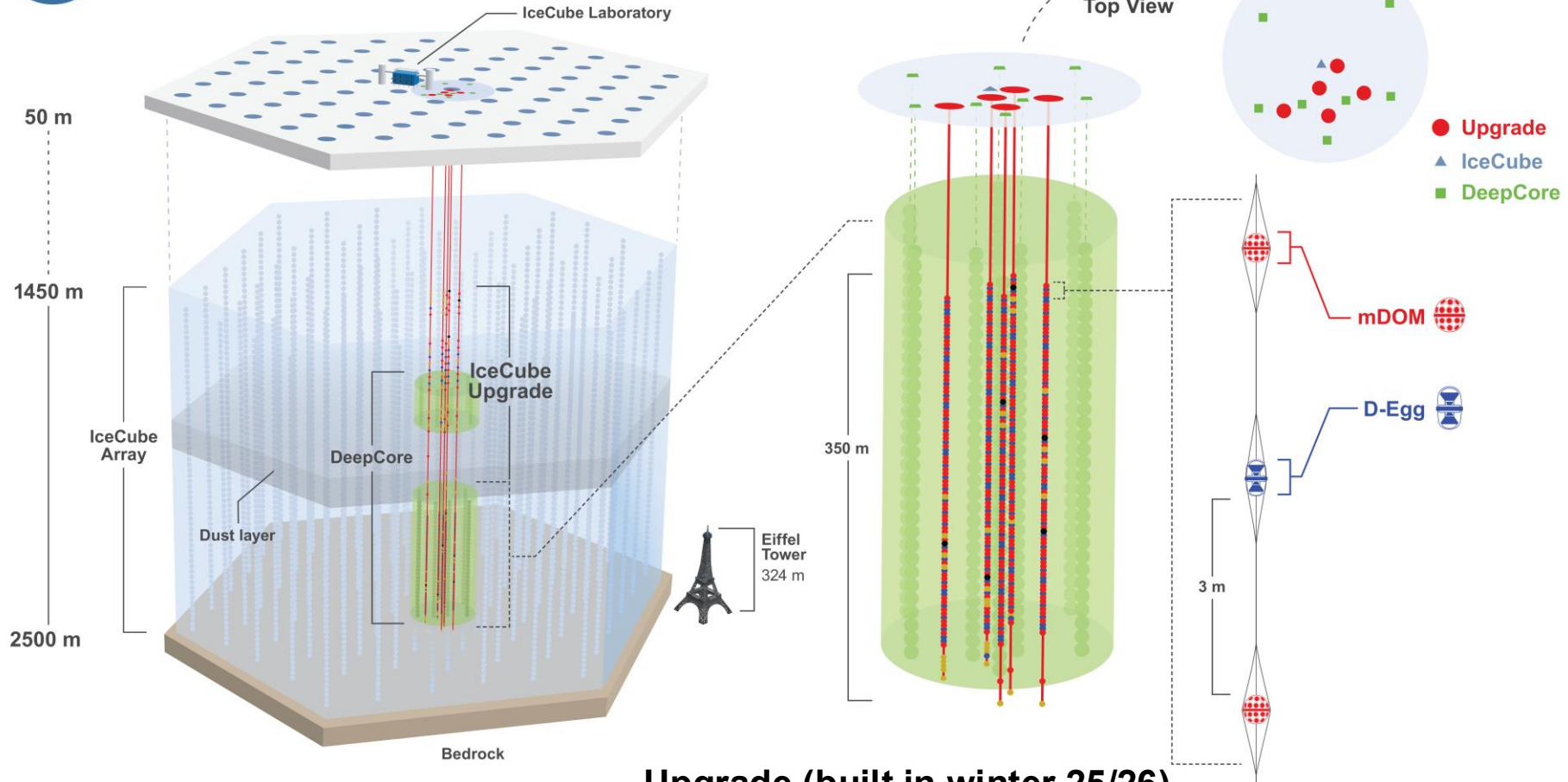
Results from water / ice Cherenkov Telescopes

- Astronomy
 - Diffuse Flux
 - Milky Way
 - Source Candidates
- **Neutrino as a particle**
 - Neutrino Oscillations
 - Neutrino Cross Section
- New physics
 - Sterile Neutrinos
 - Dark Matter

Atmospheric Neutrinos



IceCube DeepCore and Upgrade



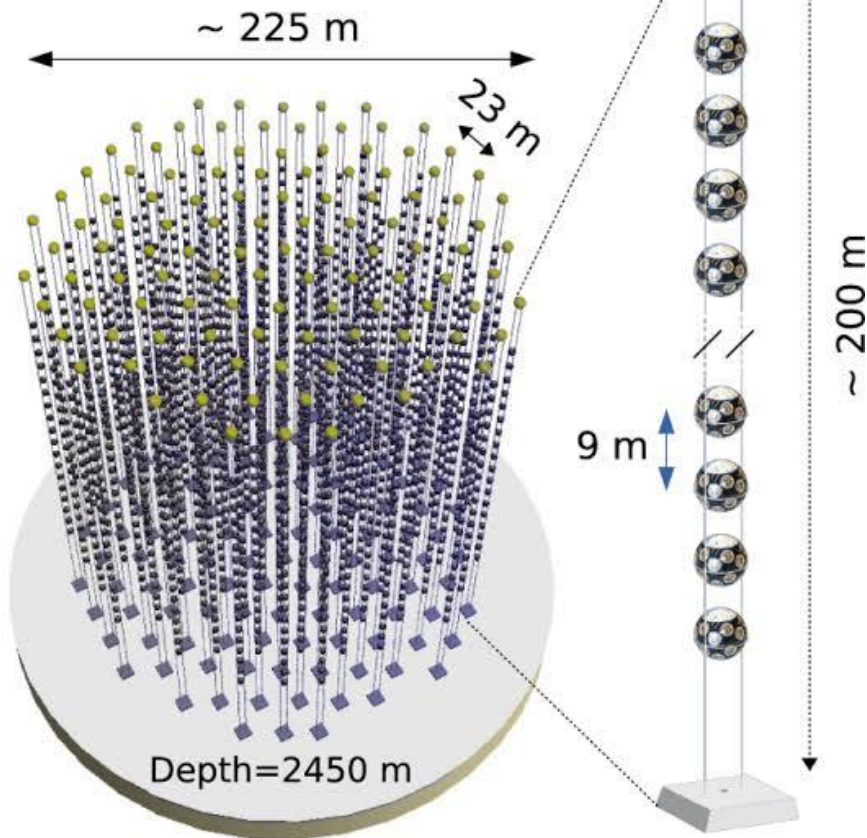
Upgrade (built in winter 25/26)

Additional 5 strings and
calibration devices

KM3NeT ORCA

115 strings

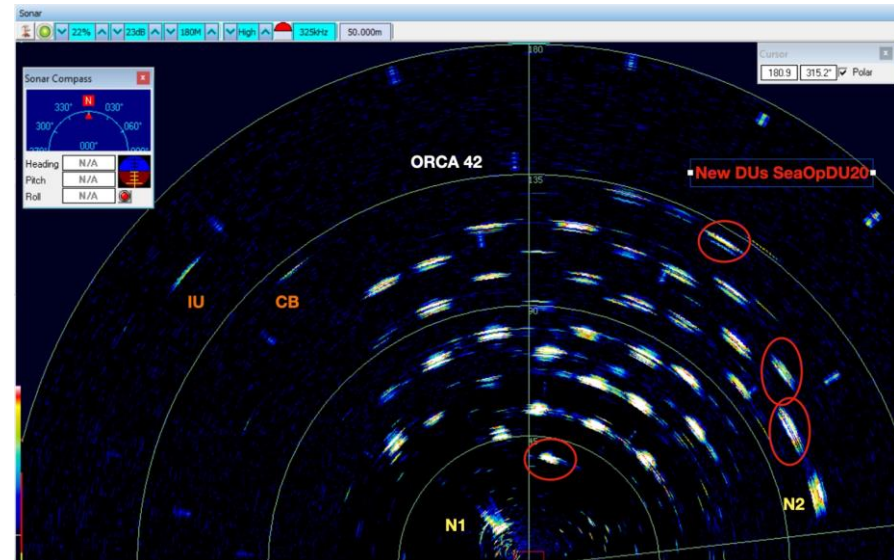
18 DOMs / string



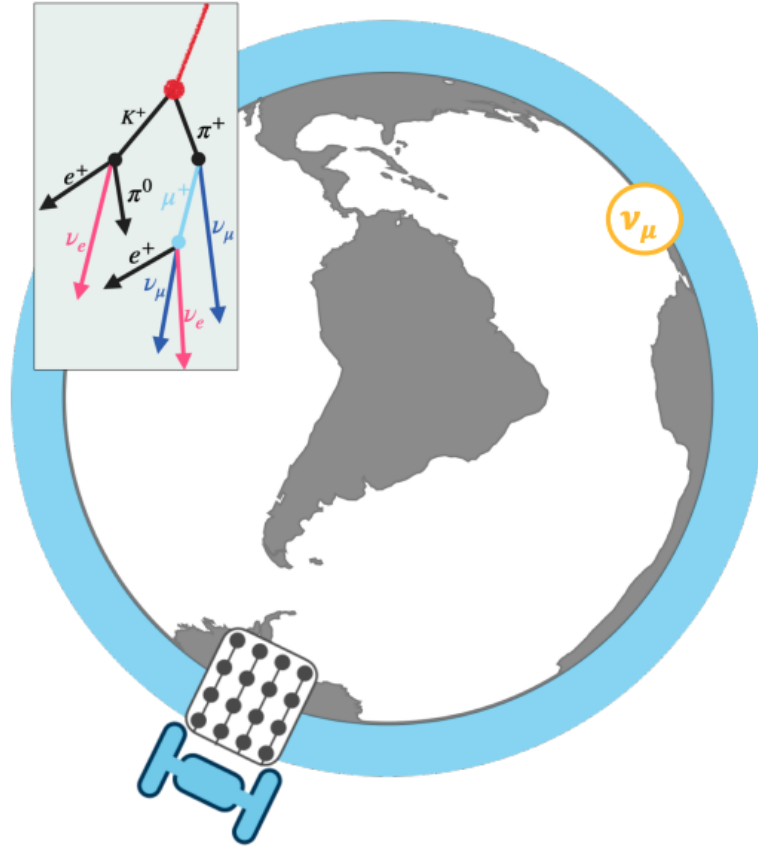
Welcome, ORCA-42!

8 July 2026 – **A very successful sea operation** took place during last week-end, leading to a new extension of the ORCA submarine telescope off the coast of Toulon, France.

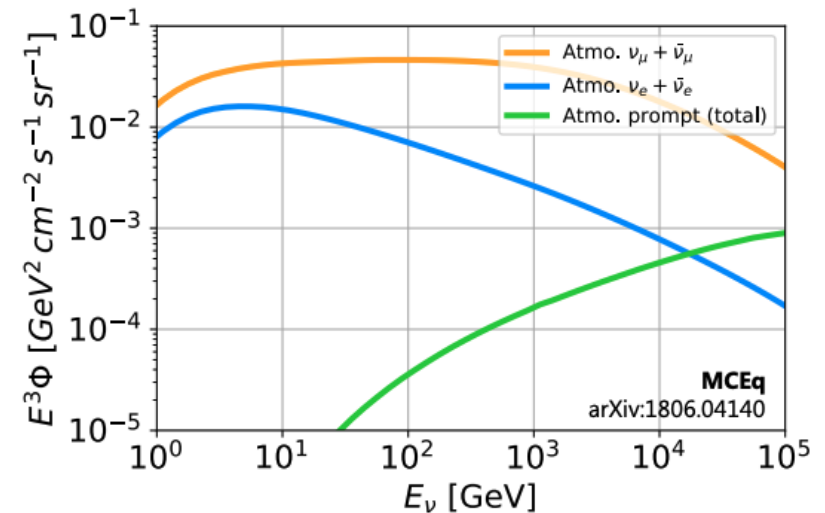
During the operation, four new detection units were installed in the deep sea and connected to the detector in a record time of an average 8.5 hours of operation per unit.



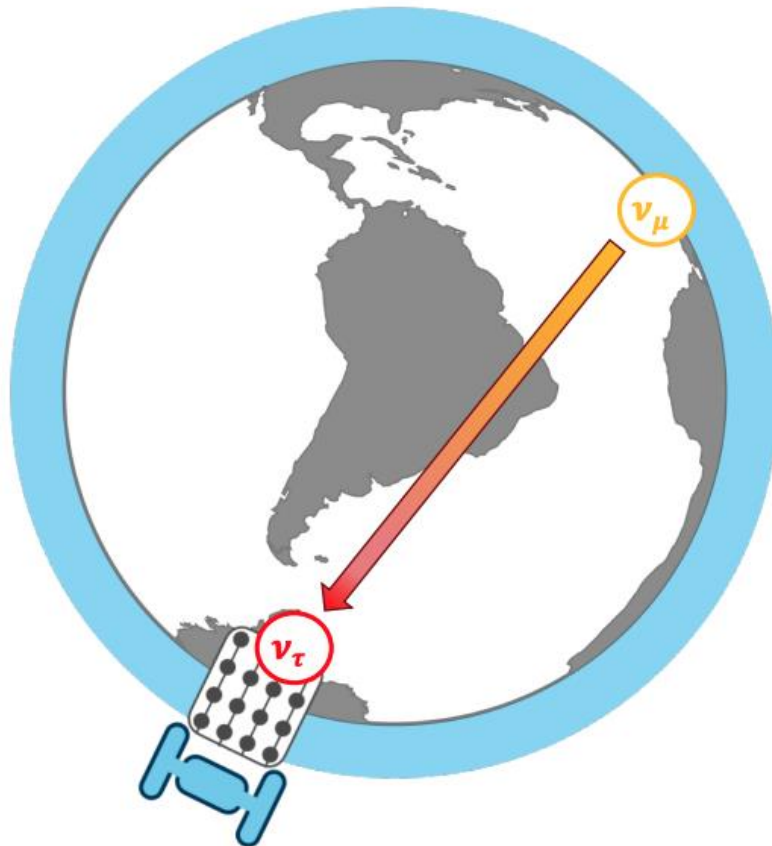
Atmospheric Neutrinos: Background to one, signal to another (credit: T. Stuttard)



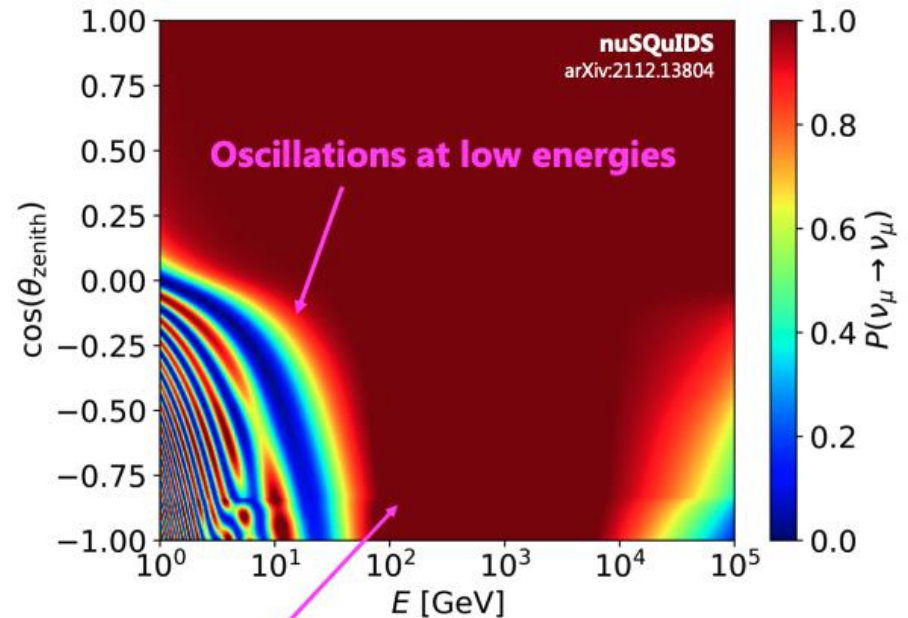
(1) Cosmic rays interact in the atmosphere and produce air showers
→ Large flux of high energy neutrinos



Atmospheric Neutrinos - Oscillations

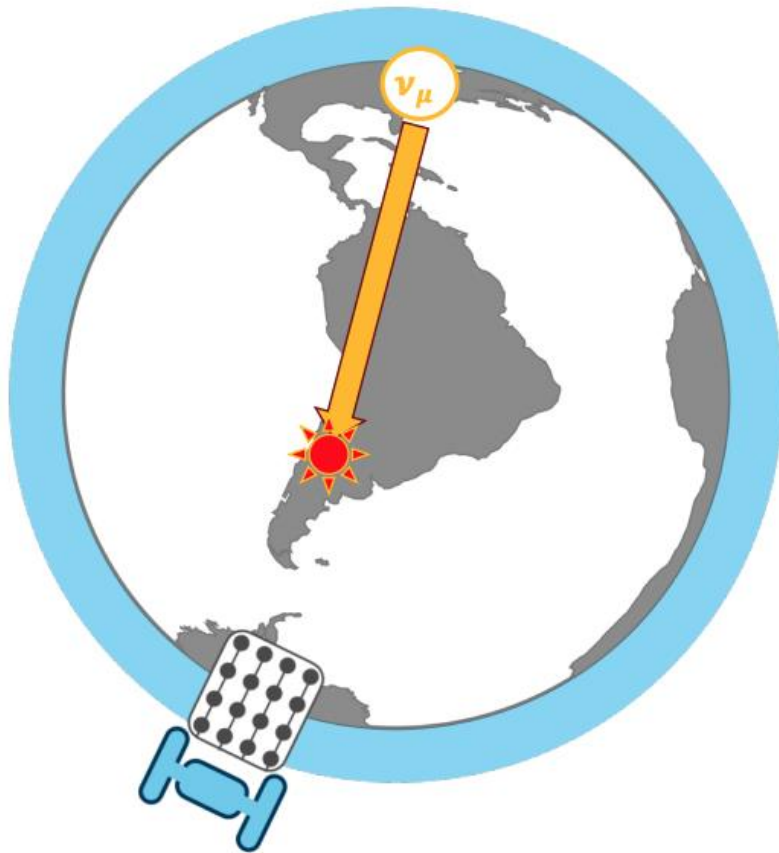


(2) Neutrinos propagate across the Earth

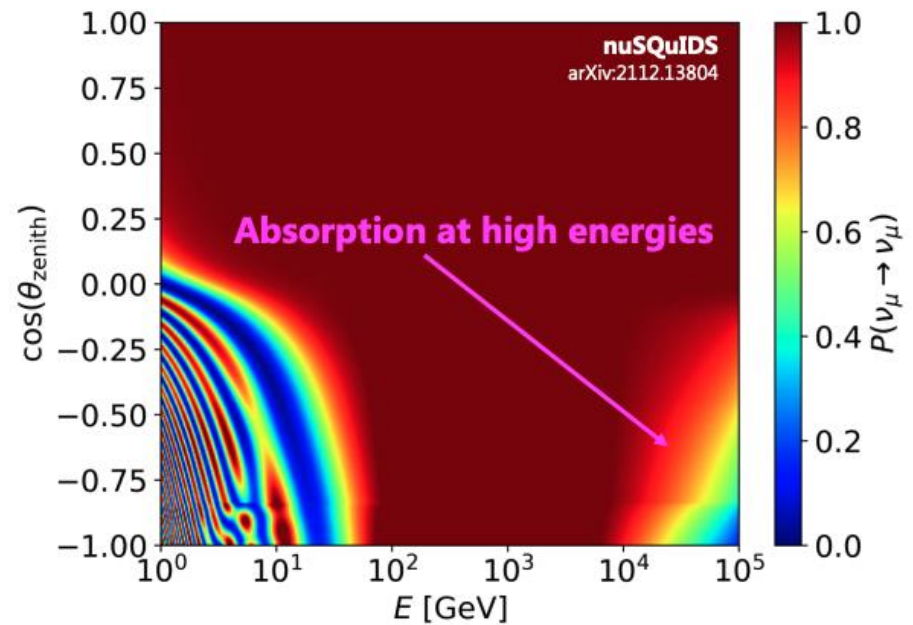


When E is $\gtrsim 100$ GeV, oscillation baseline is larger than the Earth's diameter

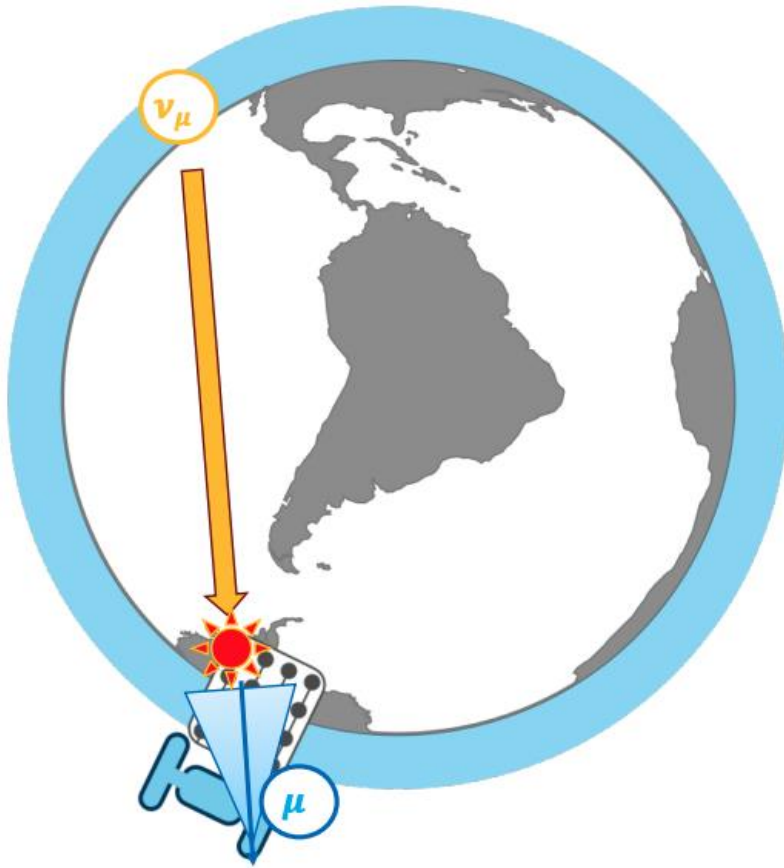
Atmospheric Neutrinos - Oscillations



(2) Neutrinos propagate across the Earth



Atmospheric Neutrinos - Oscillations

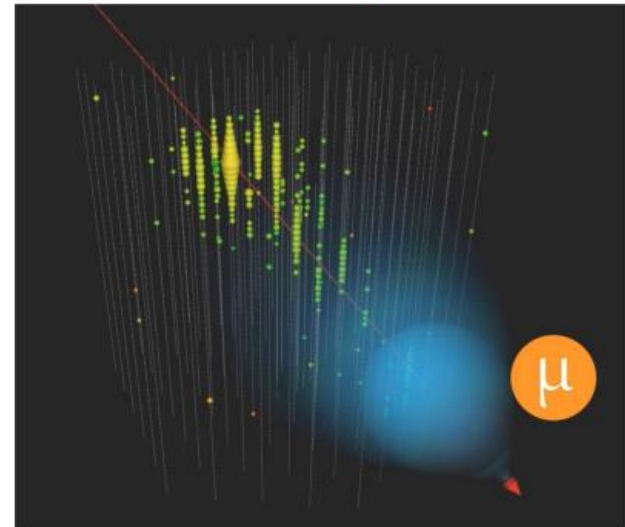


(3) Detection via Cherenkov emission from products of $\nu - N$ interactions

Predominantly Deep Inelastic Scattering (DIS)

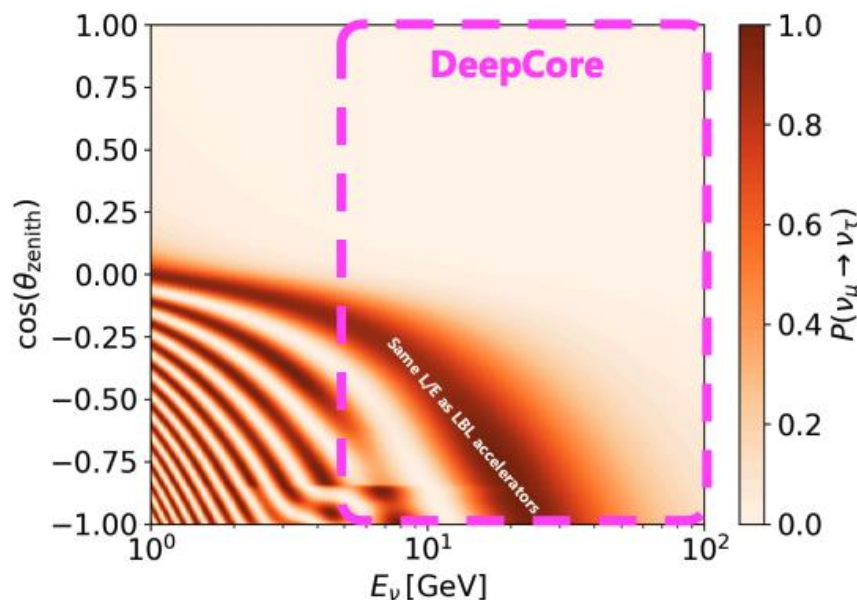
“Tracks” from secondary μ

“Cascades” from secondary e , τ and hadrons



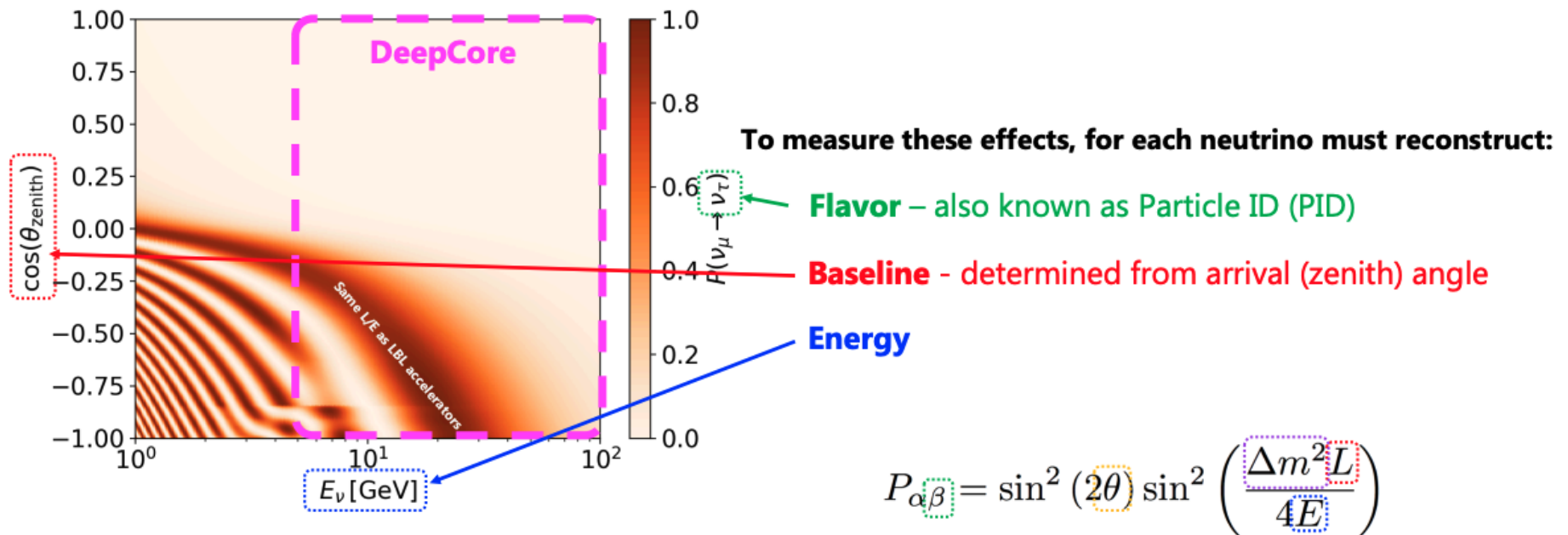
Measuring Neutrino Oscillations

- The DeepCore sub-array of IceCube can measure atmospheric neutrino oscillations in the 5 – 100 GeV energy range
- Earth-crossing ν_μ **near maximally oscillate to ν_τ** $\rightarrow$ measures θ_{23} and Δm_{32}^2



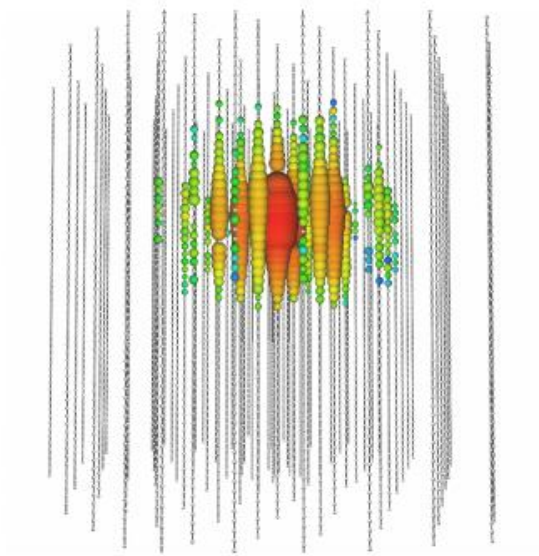
$$P_{\alpha\beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Measuring Neutrino Oscillations

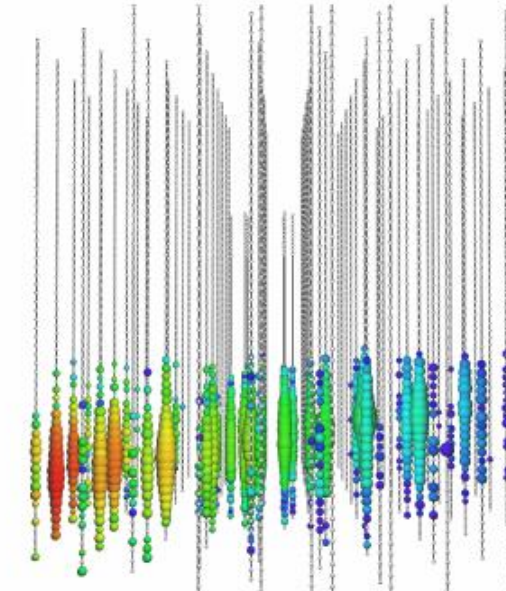


Measuring Neutrino Oscillations

- Two event topologies at high energies



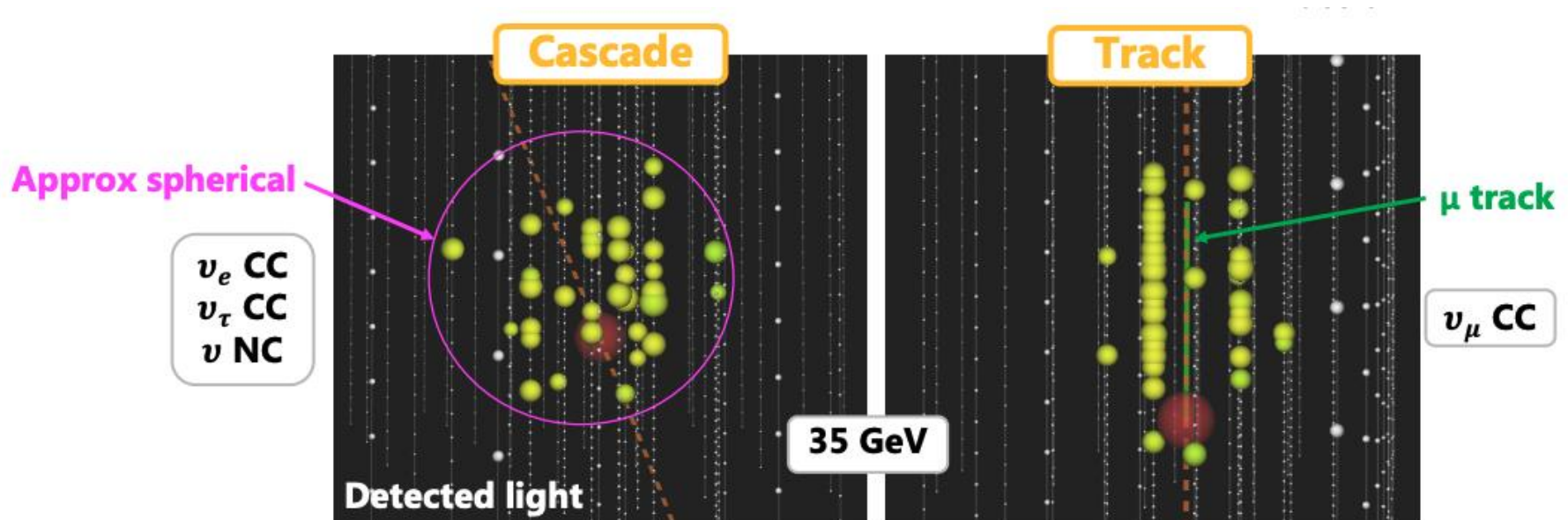
Cascade
 $E \sim 1 \text{ PeV}$



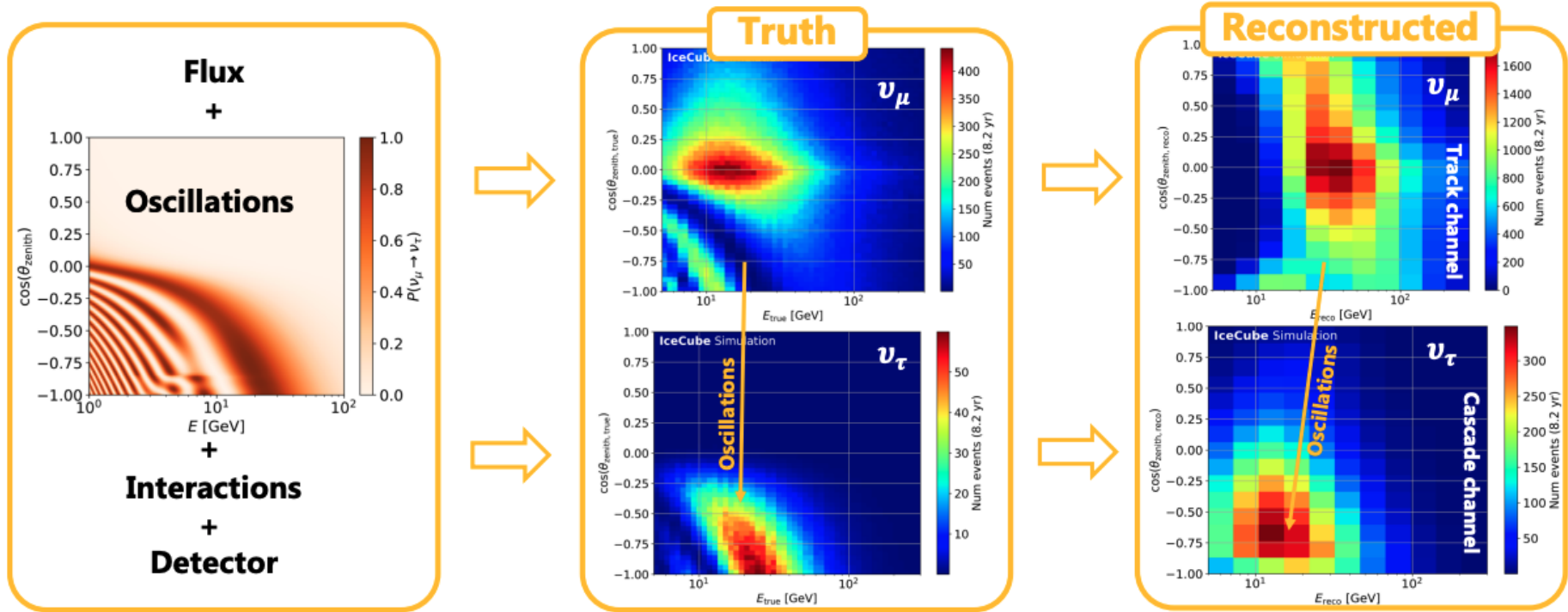
Muon track
 $E \sim 140 \text{ TeV}$

Measuring Neutrino Oscillations

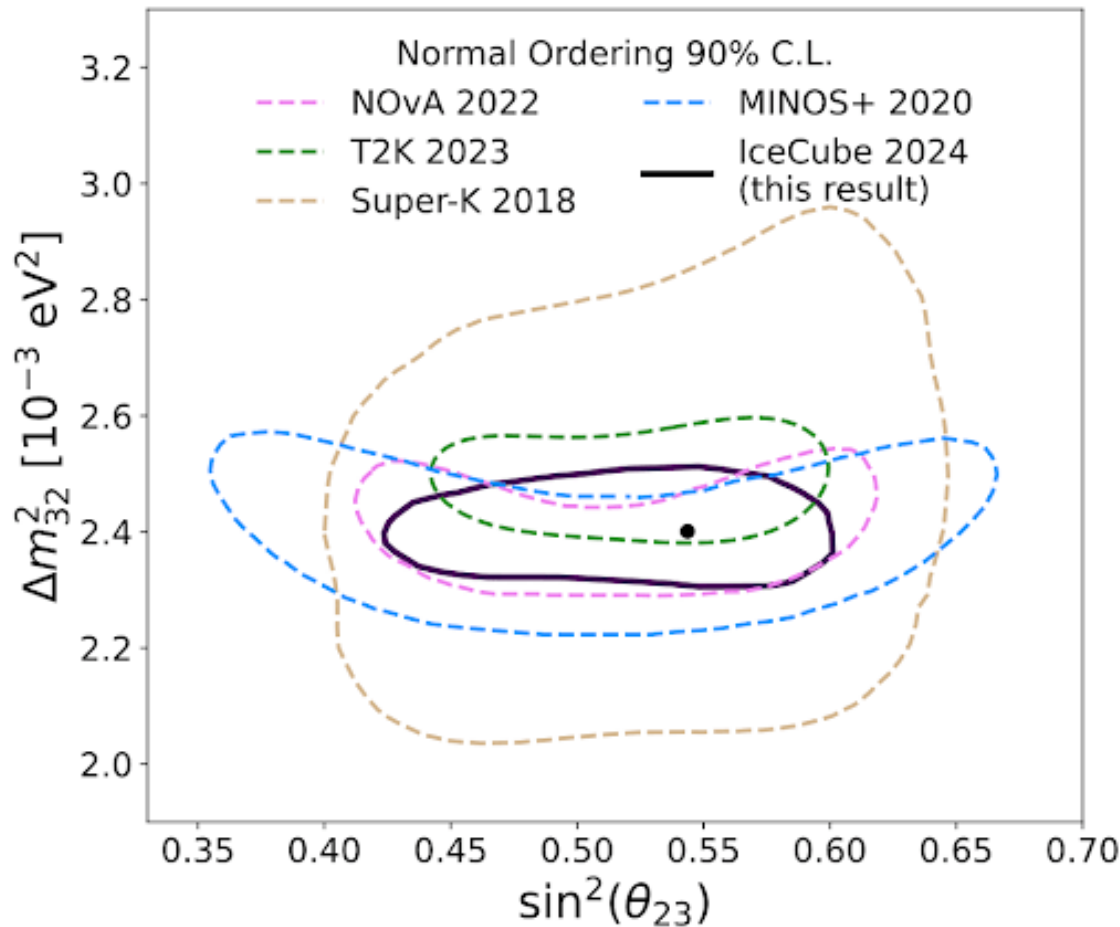
- Two event topologies at oscillation energies:



Measuring Neutrino Oscillations



Neutrino Oscillations: Results



DeepCore data taken between 2012-2021

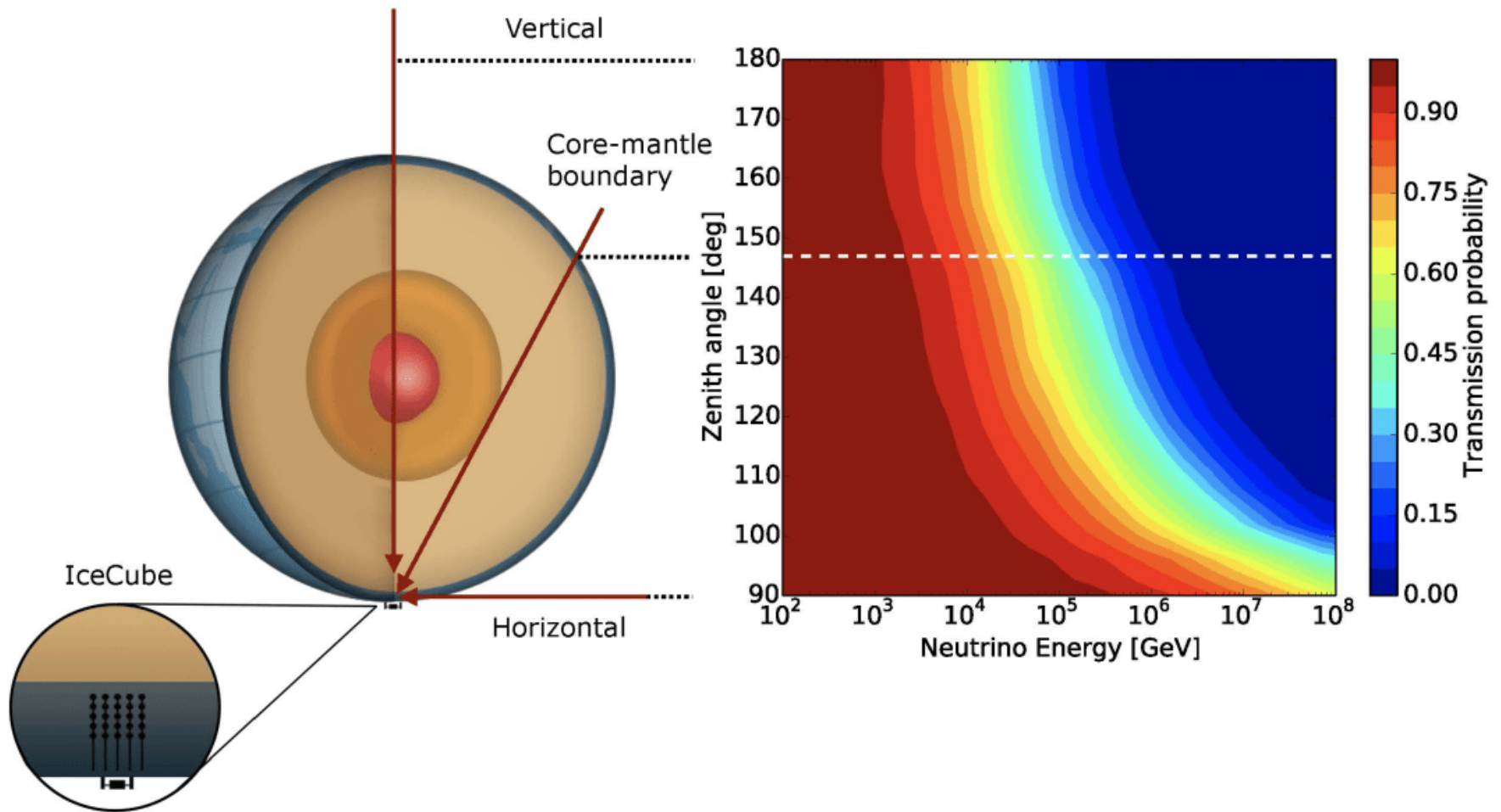
150,000 candidate neutrino events between 5 GeV and 100 GeV



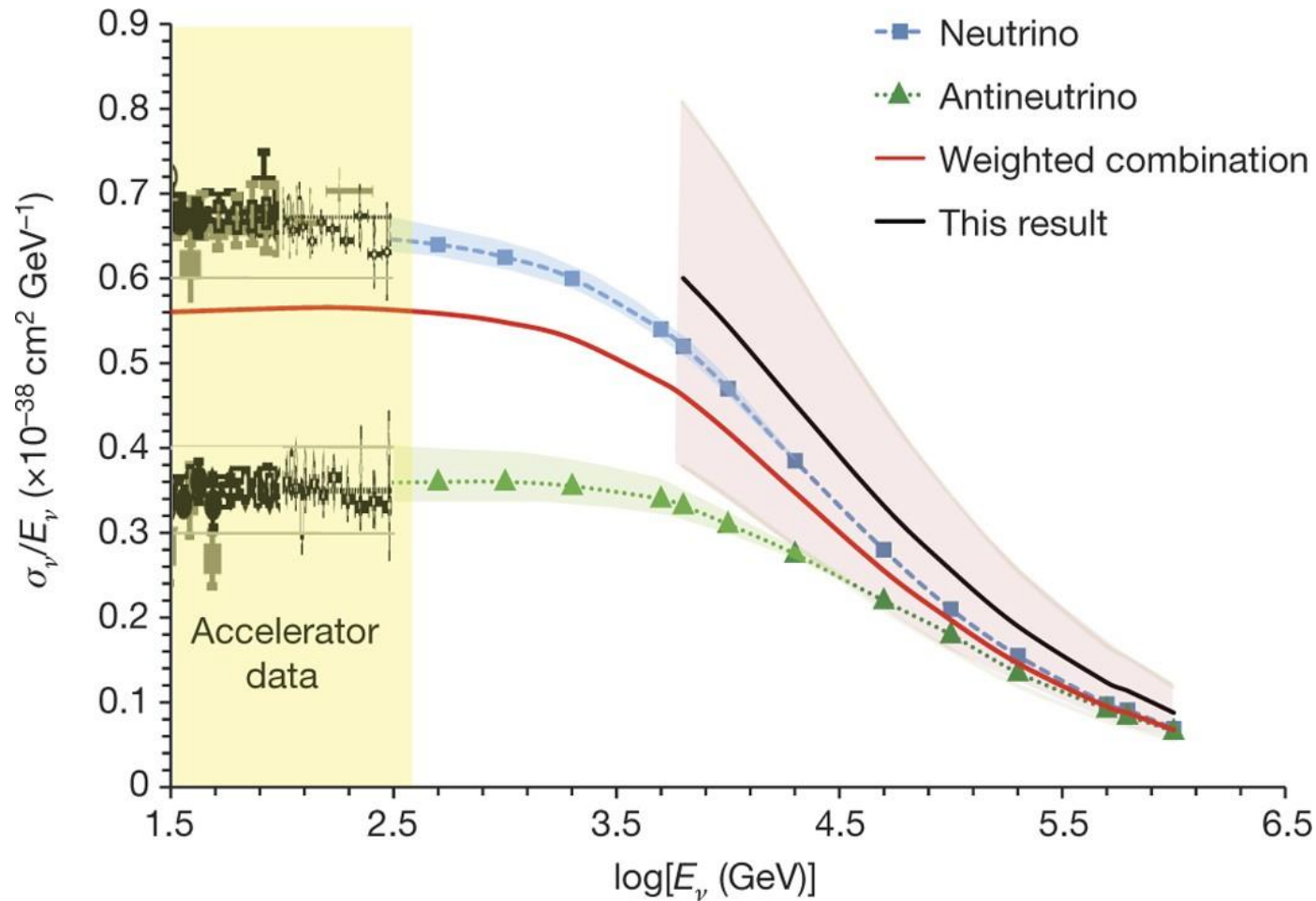
Take home message

Neutrino telescopes can do competitive measurements of neutrino oscillation parameters. The $O(10\text{GeV})$ range is crucial.

Neutrino Cross Section Measurement

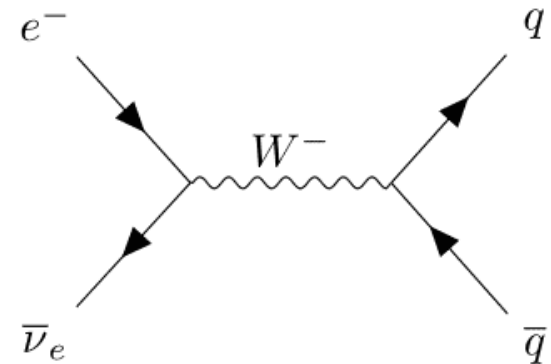
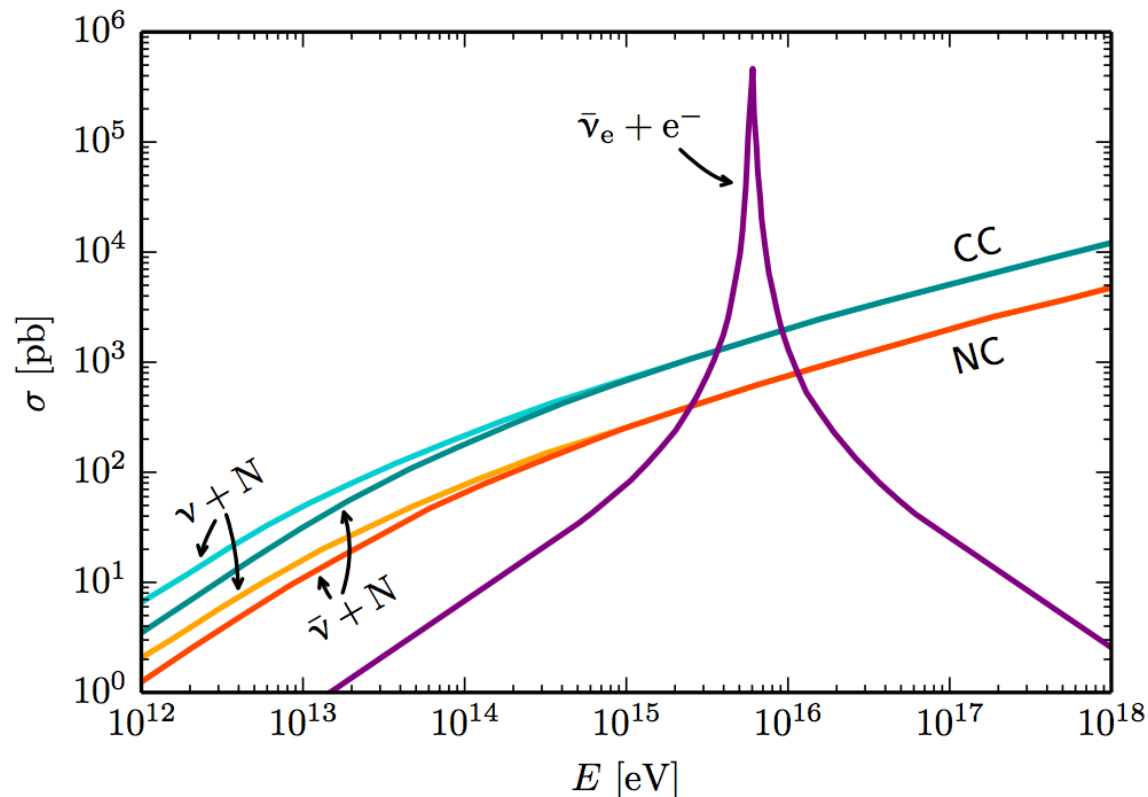


Neutrino Cross Section Measurement

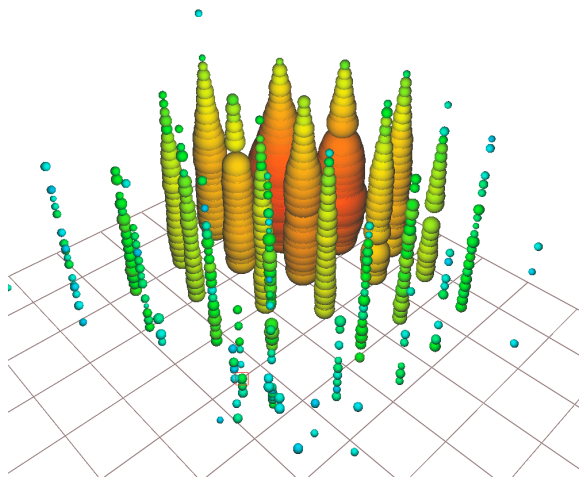


Glashow Resonance

Glashow resonance: resonant formation of a W^- boson during the interaction of a high-energy electron antineutrino with an electron, peaking at an antineutrino energy of 6.3 PeV in the rest frame of the electron.



Glashow Resonance



$$E = 6.05 \pm 0.72 \text{ PeV}$$

- astrophysical neutrino at the 5σ level
 - consistent with the hadronic decay of a W^- boson produced on the Glashow resonance
 - probability that the event is produced off-resonance by deep inelastic scattering is 0.01
-
- Confirms standard model
 - Measurement of the diffuse flux
 - Opens a way to distinguish ν_e and $\bar{\nu}_e$
 - identify hadronuclear or photohadronic interactions, with or without strong magnetic fields

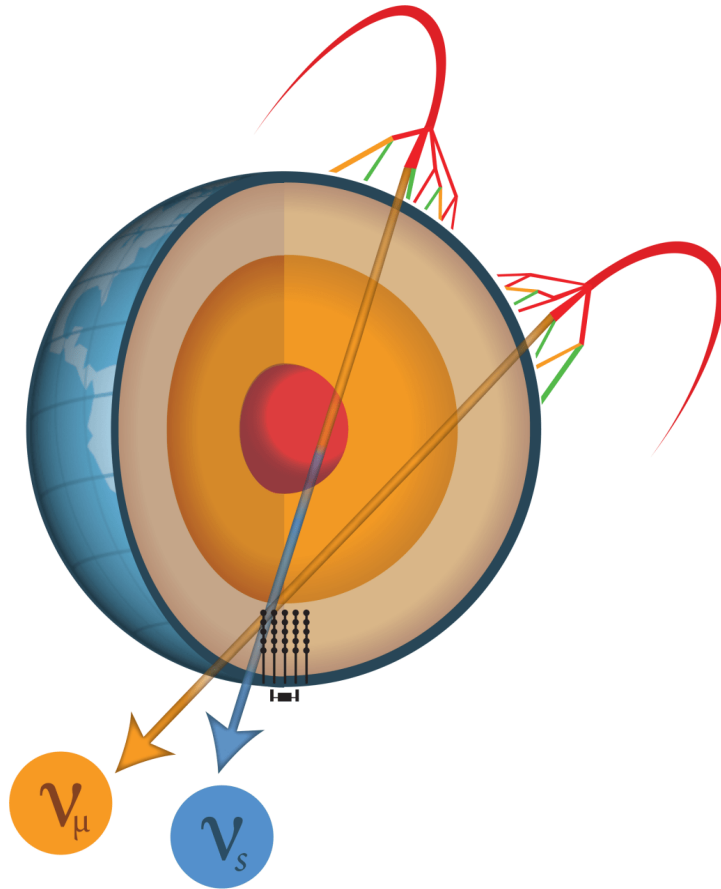


Take home message

Earth absorption can be used to measure the neutrino cross section.

One event consistent with the Glashow resonance was found.

Exotic Physics – Sterile Neutrinos



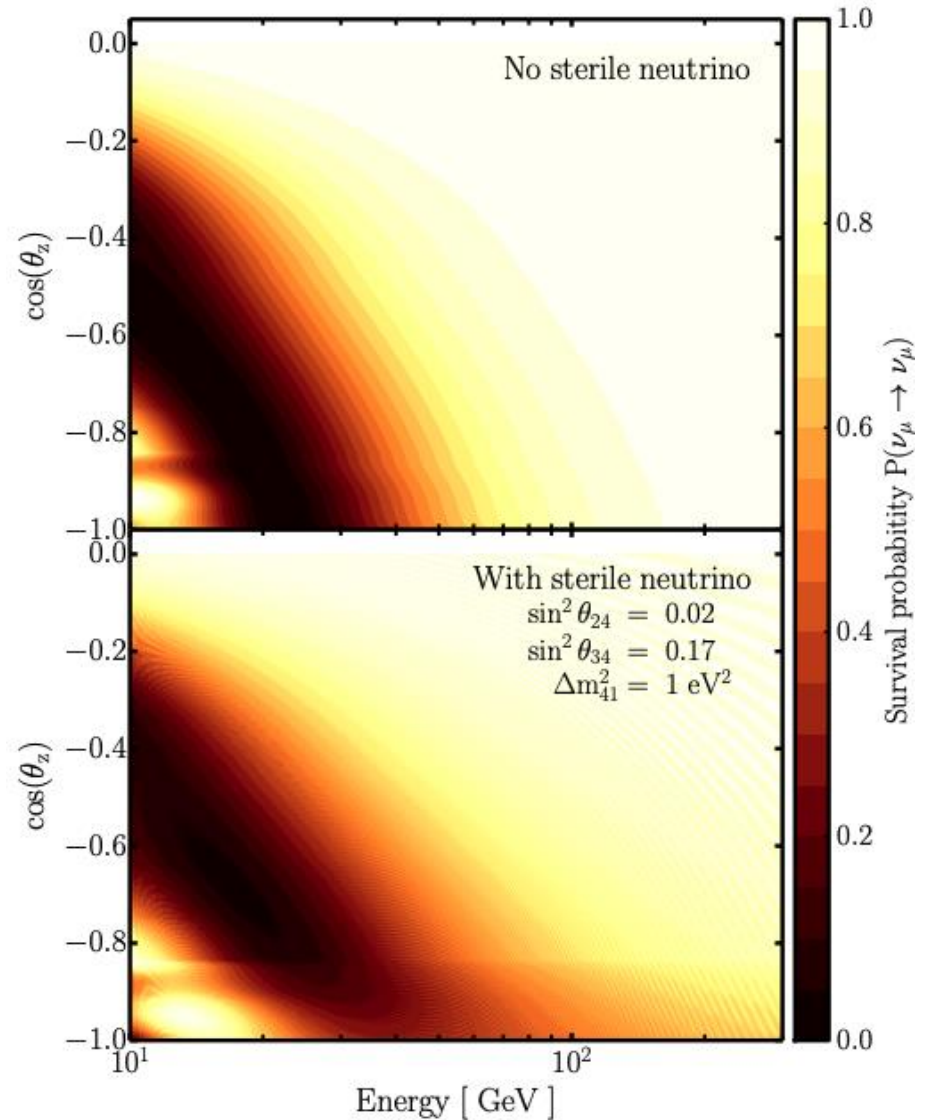
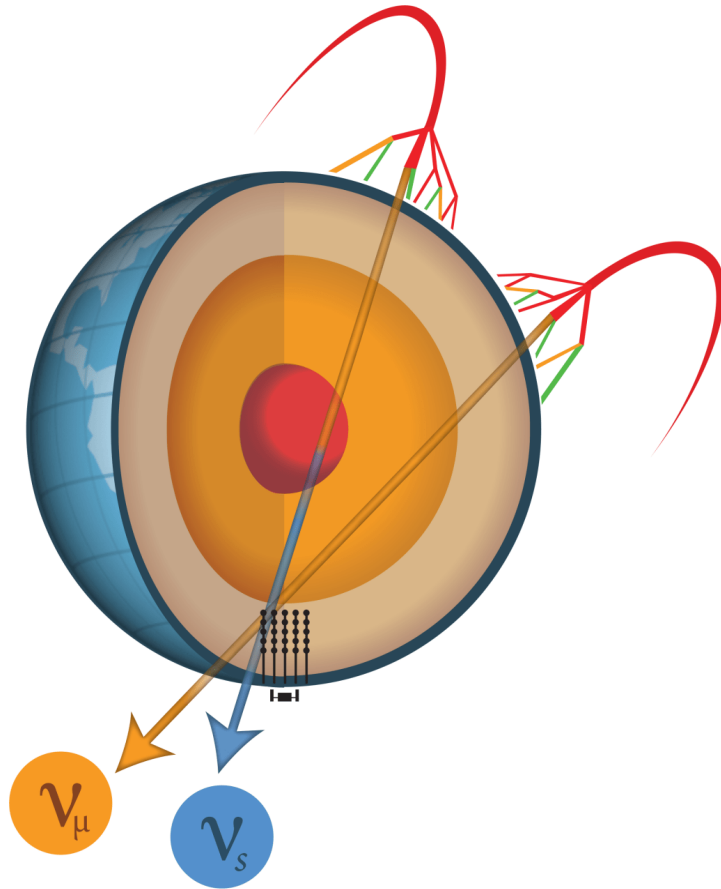
Sterile neutrino: A fourth neutrino, that does not interact weakly, but can mix with other neutrinos

Motivation:

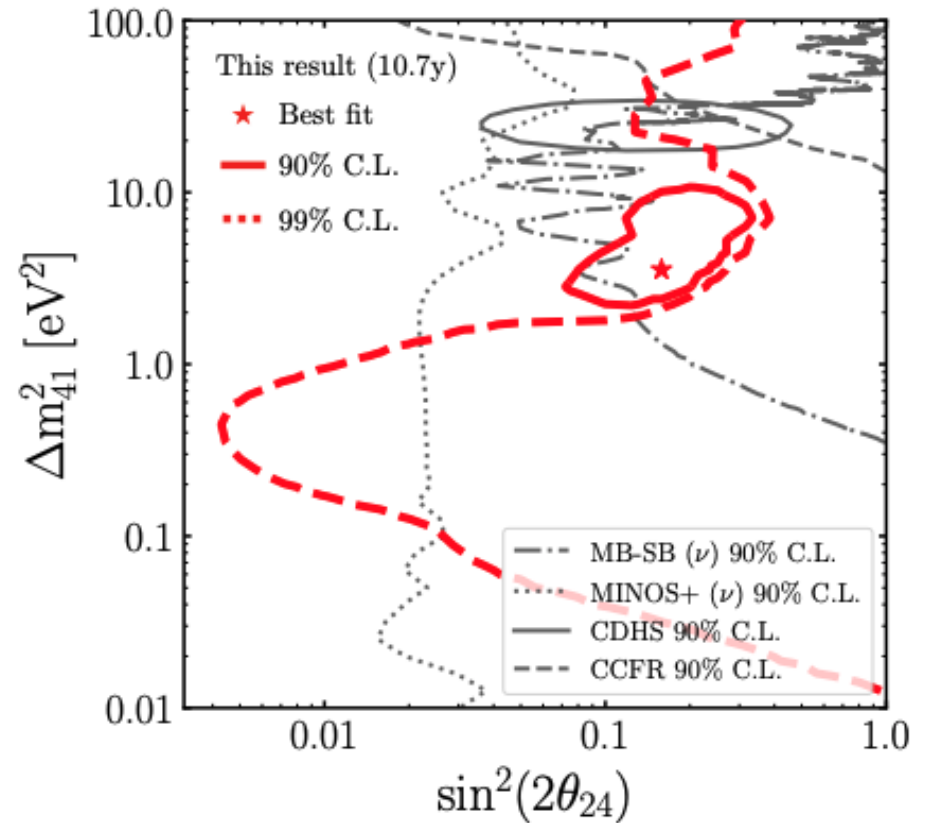
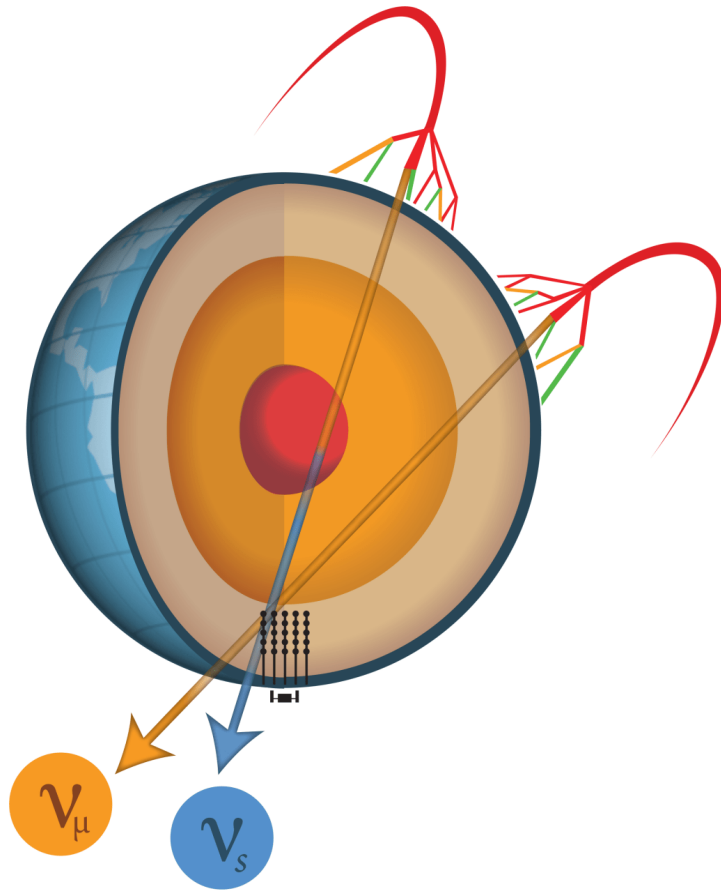
- Dark matter candidate
- Anomalies seen by reactor and accelerator neutrino experiments
- In the see-saw mechanism, heavy sterile neutrinos explain small neutrino mass

Search: Look for modifications in oscillation pattern

Exotic Physics – Sterile Neutrinos



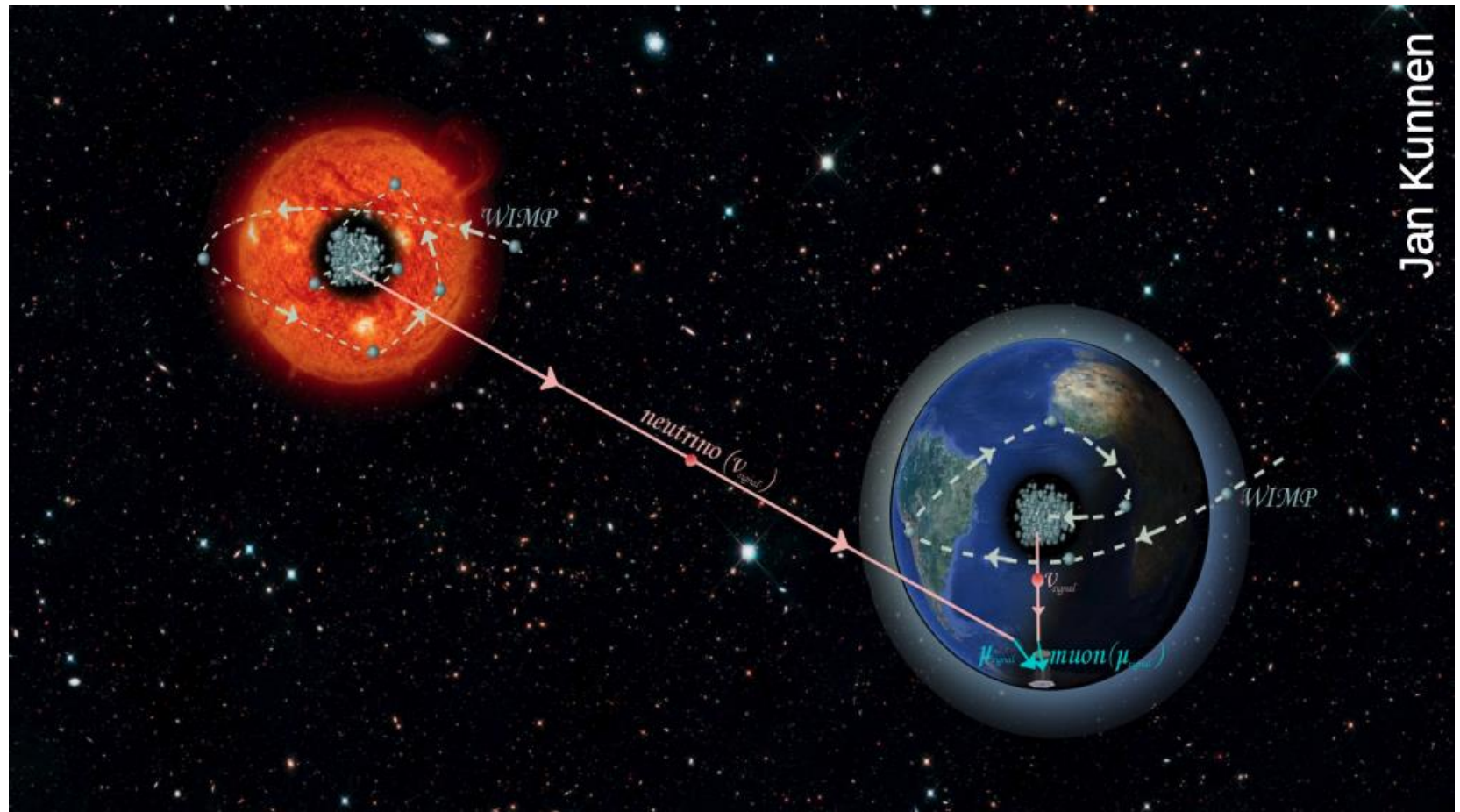
Exotic Physics – Sterile Neutrinos



Results: no significant excess found
→ anomalies largely excluded

Exotic Physics – Searches for WIMP Dark Matter

WIMP dark matter particles can be captured by celestial bodies like the Sun or Earth



Jan Kunnen

Exotic Physics – Searches for WIMP Dark Matter

WIMP dark matter particles can be captured by celestial bodies like the Sun or Earth → enhanced self-annihilation into Standard Model particles including neutrinos

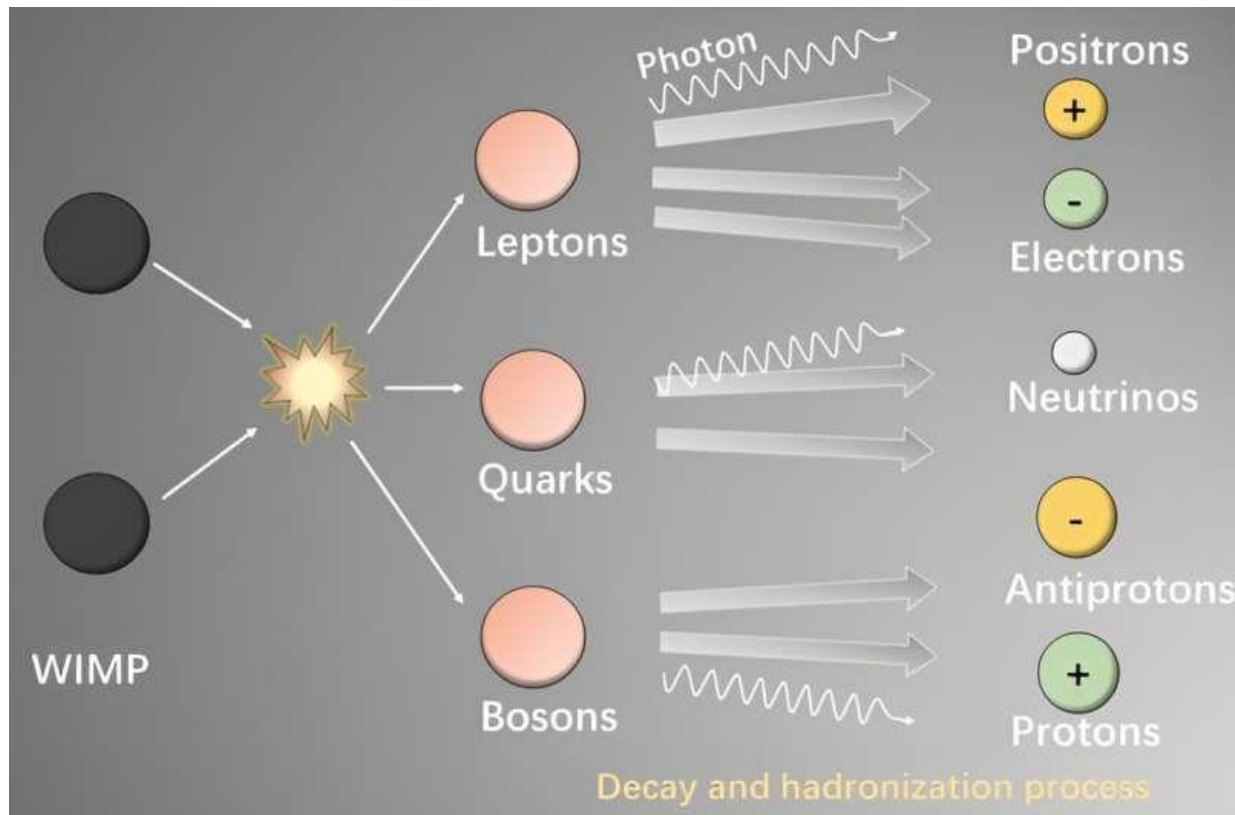


Image Credit: Gao Linqing and Lin Sujie



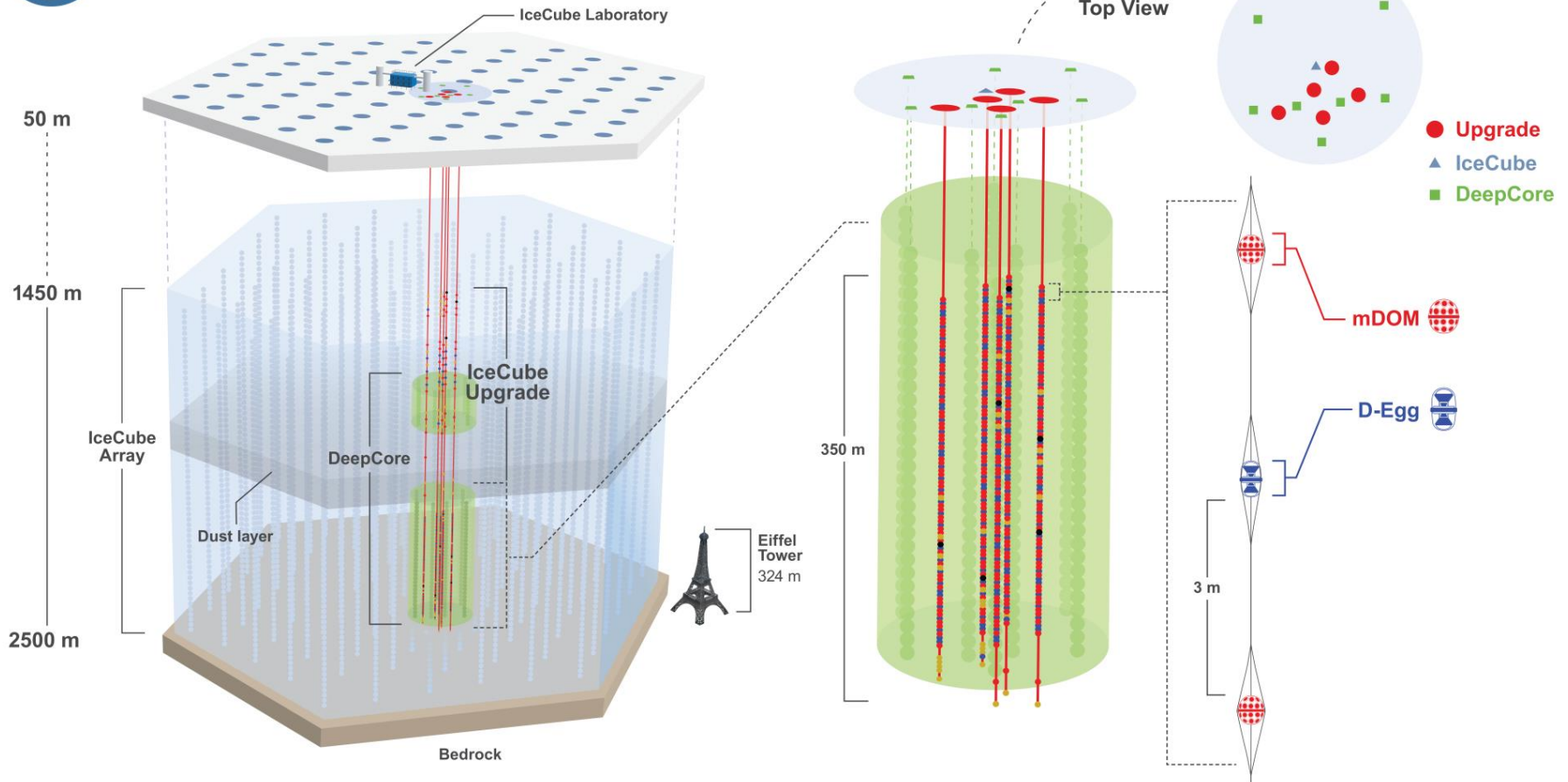
Take home message

Deviations from the expected neutrino oscillation pattern could be caused by sterile neutrinos.

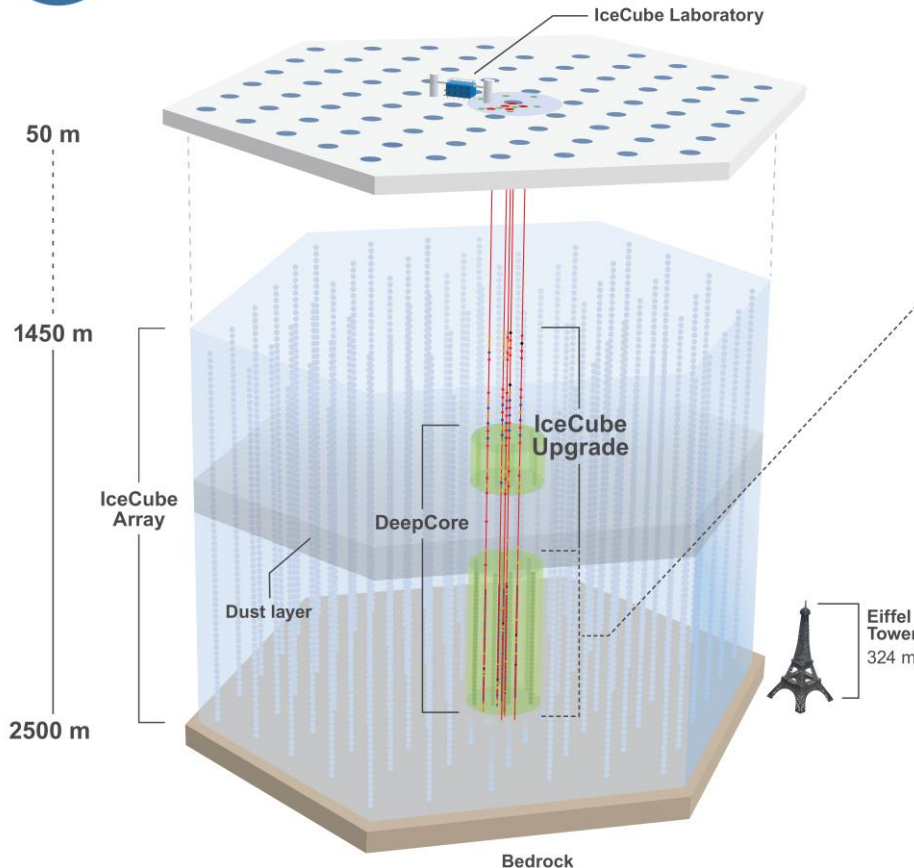
WIMPs can accumulate in the Earth and Sun and produce an excess of neutrinos when annihilating.

Future Detectors

IceCube-Upgrade: Low-energy Extension and Calibration



IceCube-Upgrade: Low-energy Extension and Calibration



- First step towards IceCube-Gen2 (8 km³)
- 5 new strings in the center of IceCube
- **New calibration devices**
- Science focus:
Neutrino properties



ICECUBE GEN2

DETECTORS

SURFACE • RADIO • OPTICAL



Cosmic Ray Surface Array

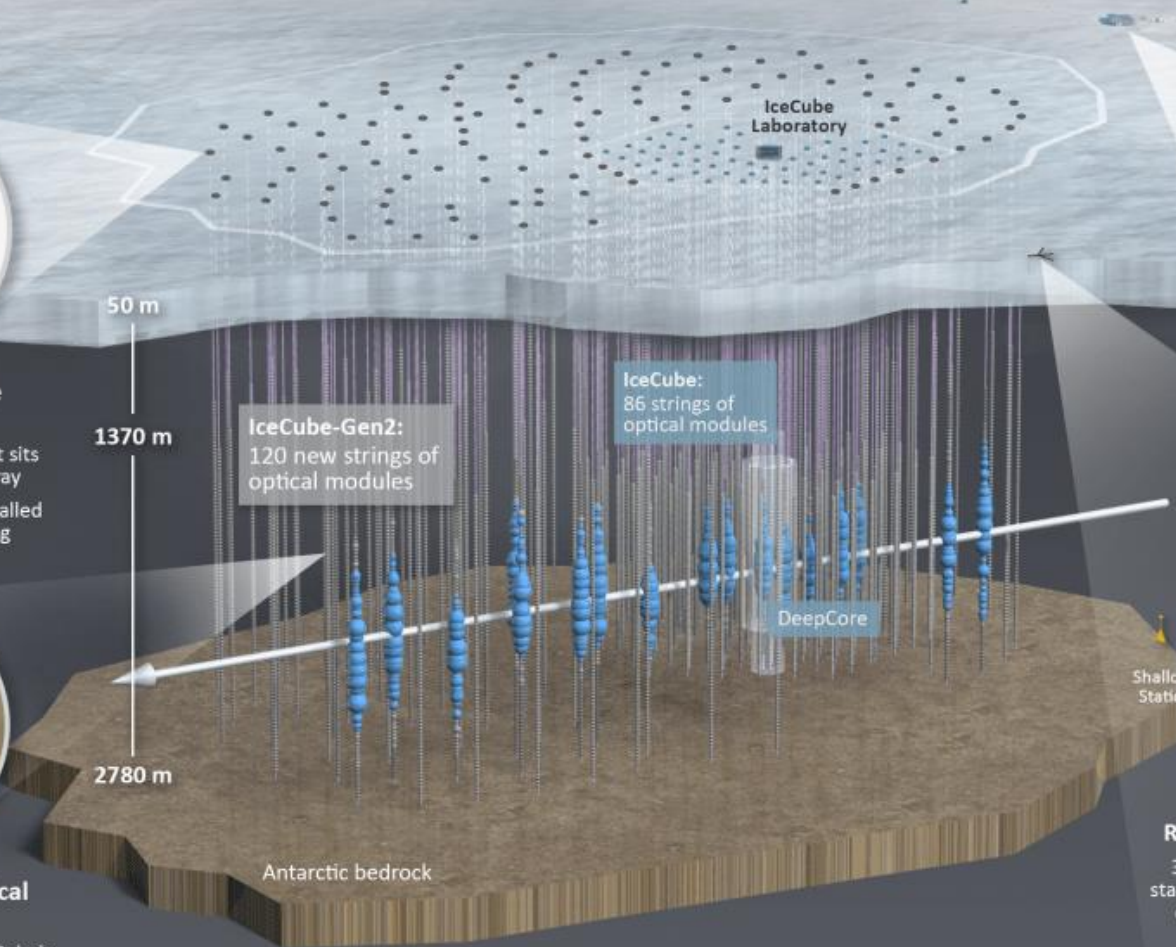
An air shower array that sits on top of the optical array
One surface station installed above each optical string



IceCube-Gen2 Optical Module

4x the sensitivity of IceCube's modules
9,600 new optical modules in total to be deployed in the ice

80 modules on each string, spaced 17 meters apart



IceCube Laboratory

IceCube:
86 strings of optical modules

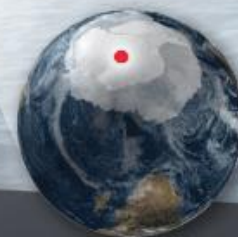
IceCube-Gen2:
120 new strings of optical modules

DeepCore

Antarctic bedrock

IceCube
(1 km)

IceCube-Gen2
(5 km)



Amundsen-Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

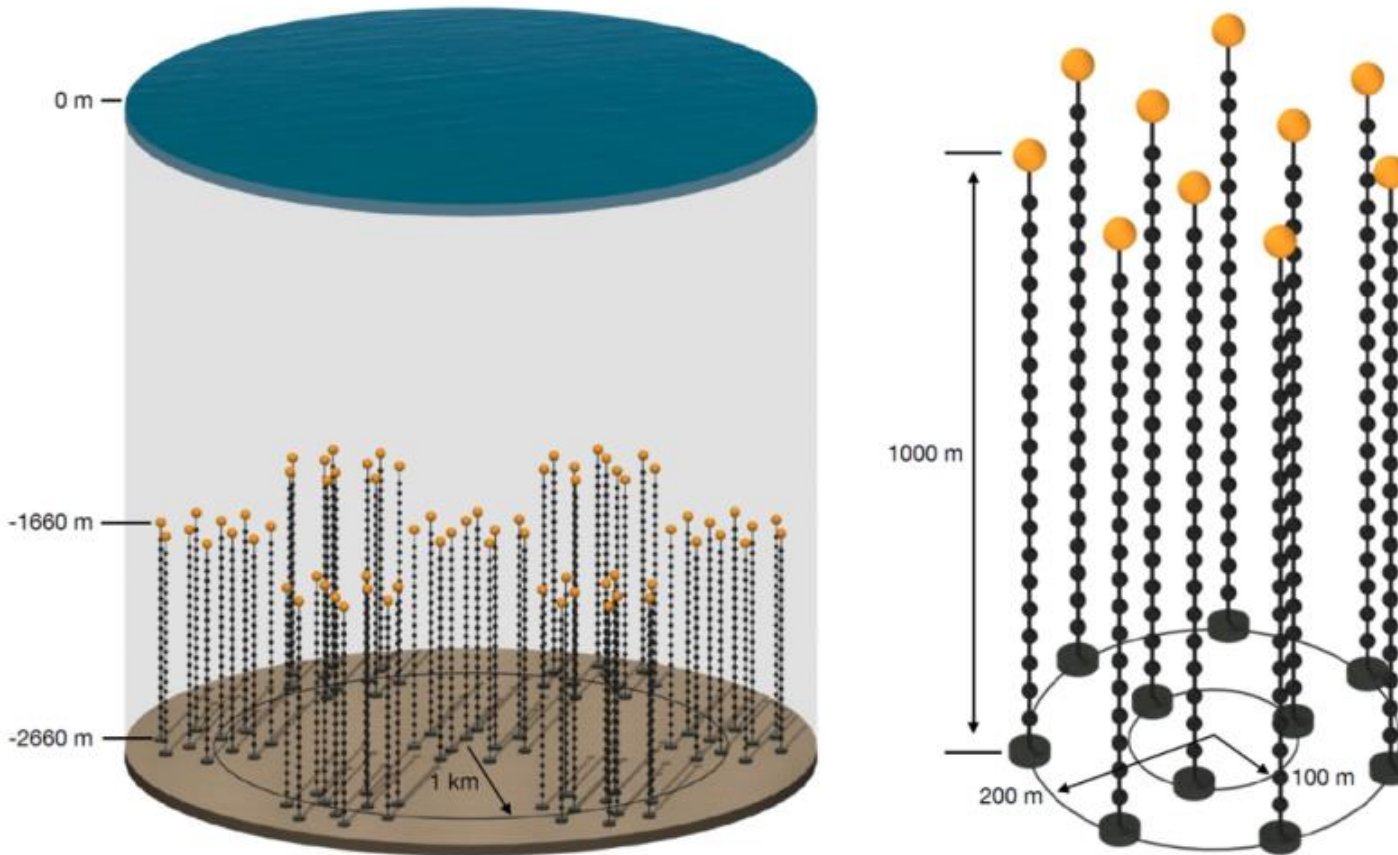


Below-Ice Radio Array

361 detector stations spread over an area of 500 km²

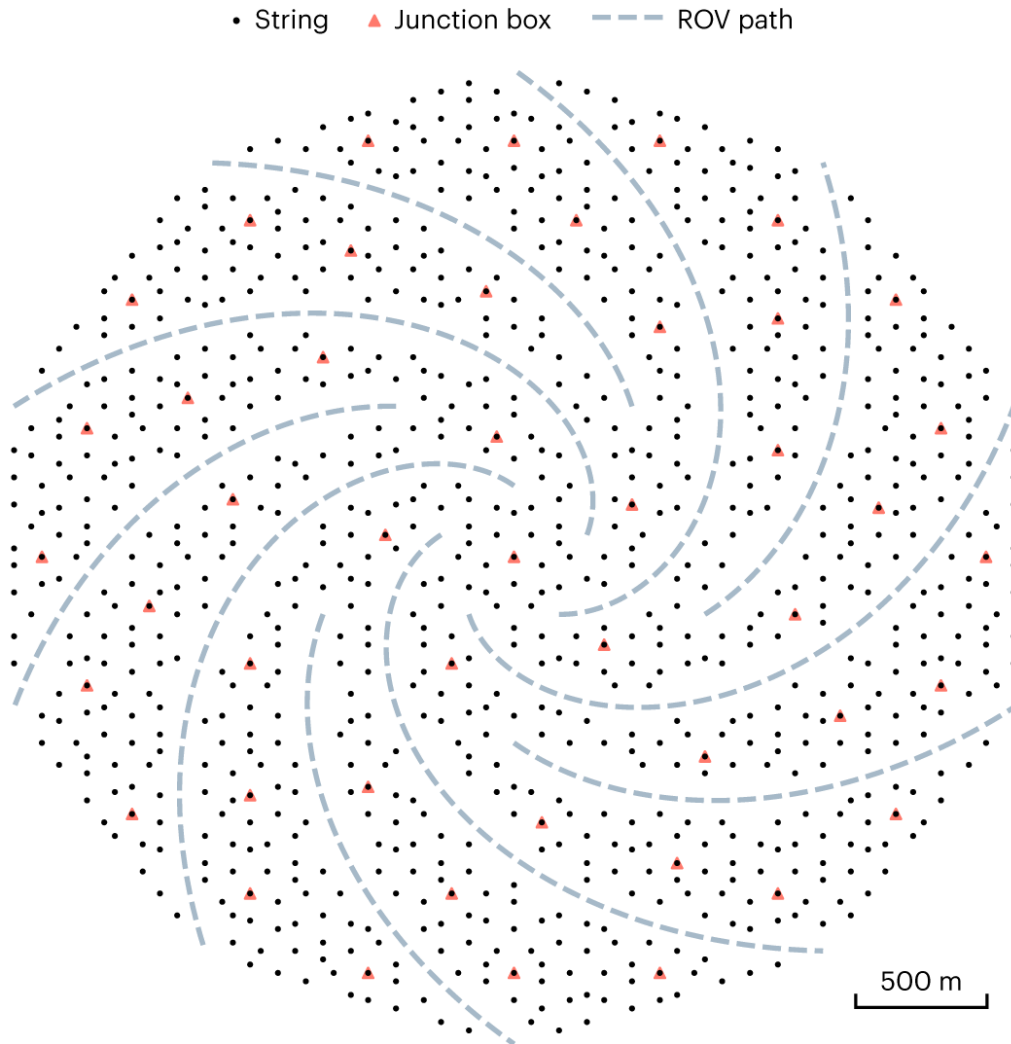
High-energy Neutrino Detectors

P-ONE



planned deployment of 10 strings explorer in 2025-2026
70 strings between 2028-2030

High-energy Neutrino Detectors



Tropical Deep-sea
Neutrino Telescope
(TRIDENT), South
Chinese Sea

depth of ~ 3.5 km

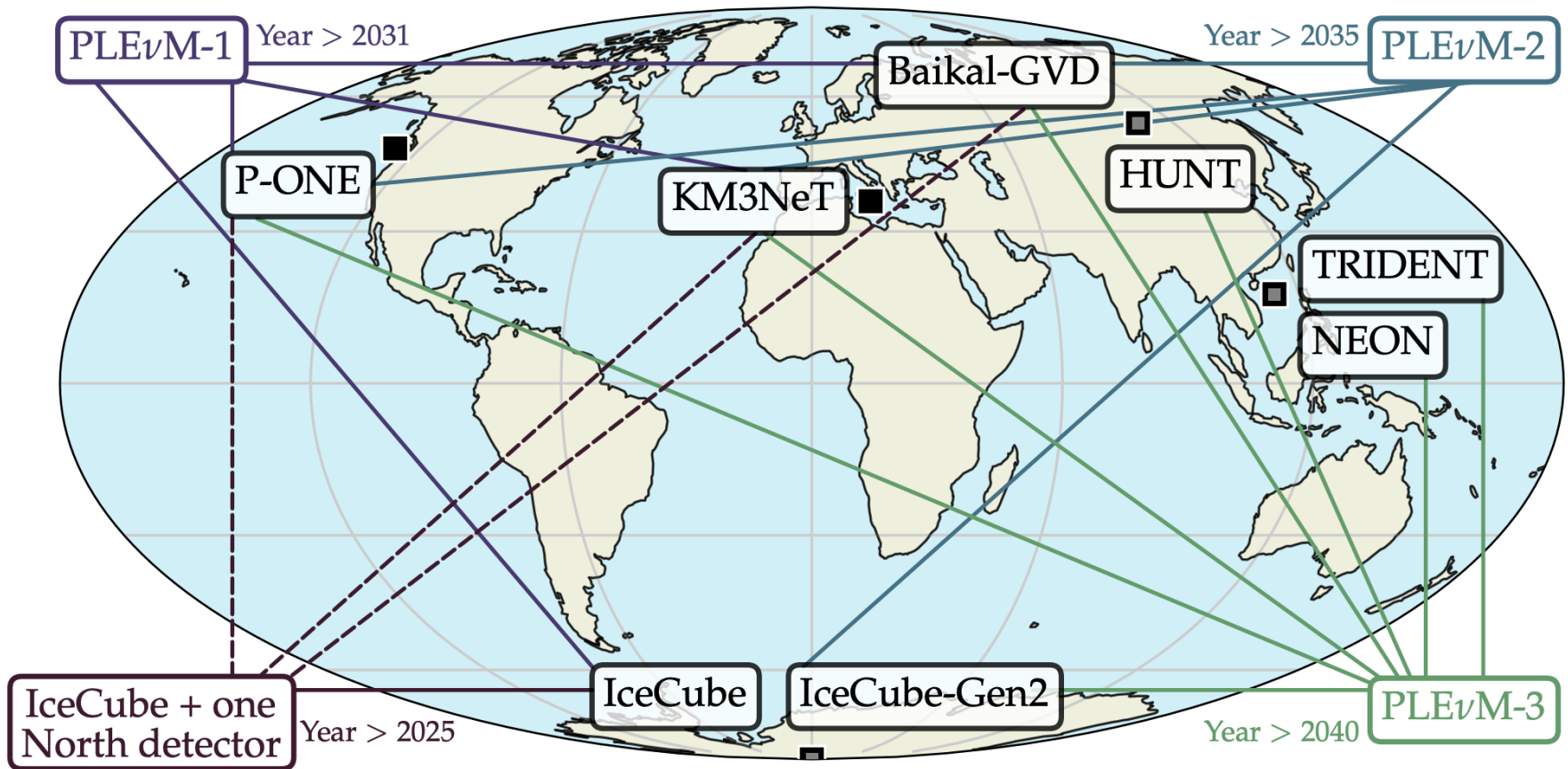
Volume: 7.5 km^3

2021: water quality
measurements

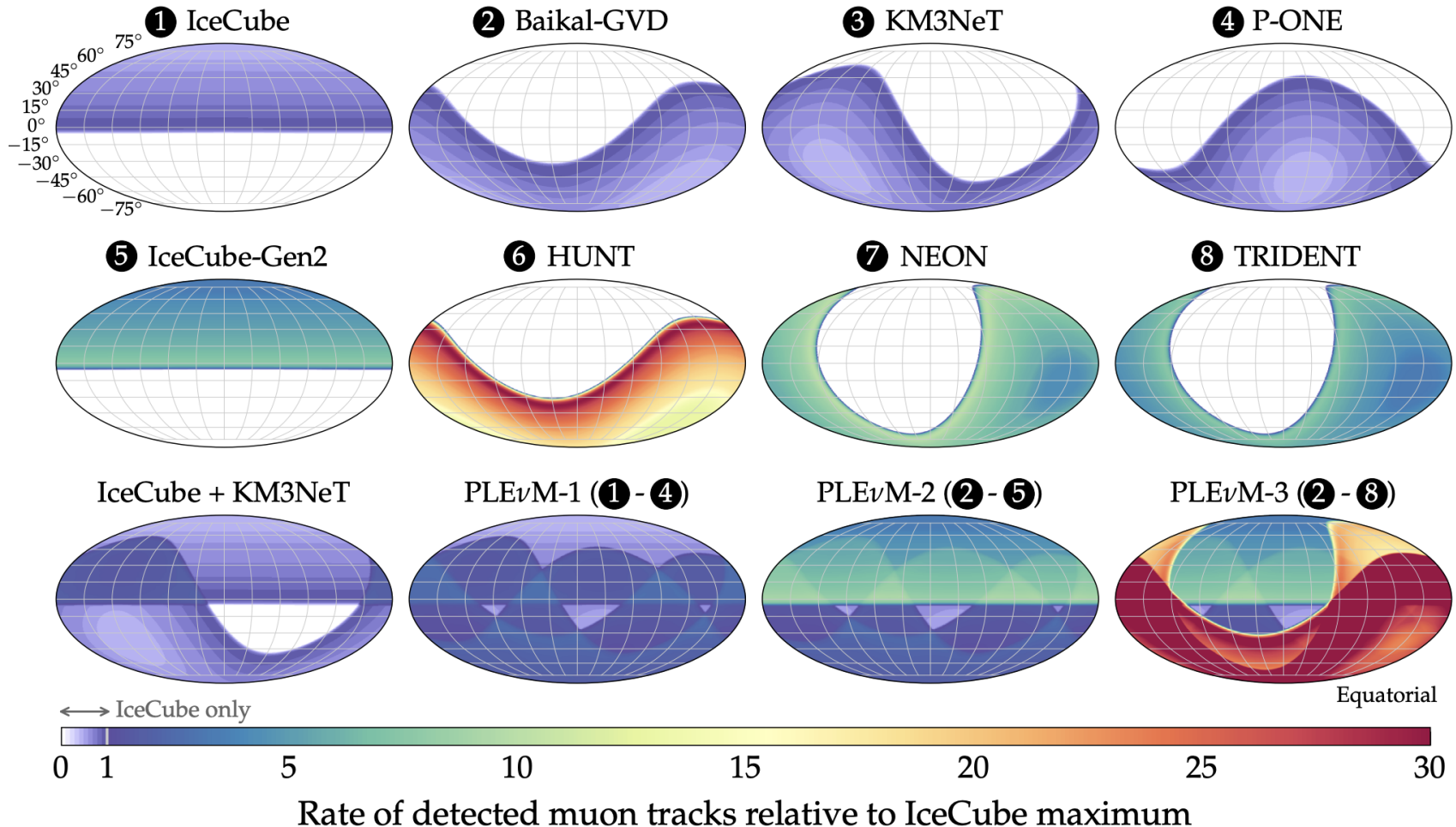
Full deployment in 2030

Planetary Neutrino Monitoring network (PLEnuM)

Idea: combined analysis of global data will expedite source discovery



Planetary Neutrino Monitoring network (PLEnuM)

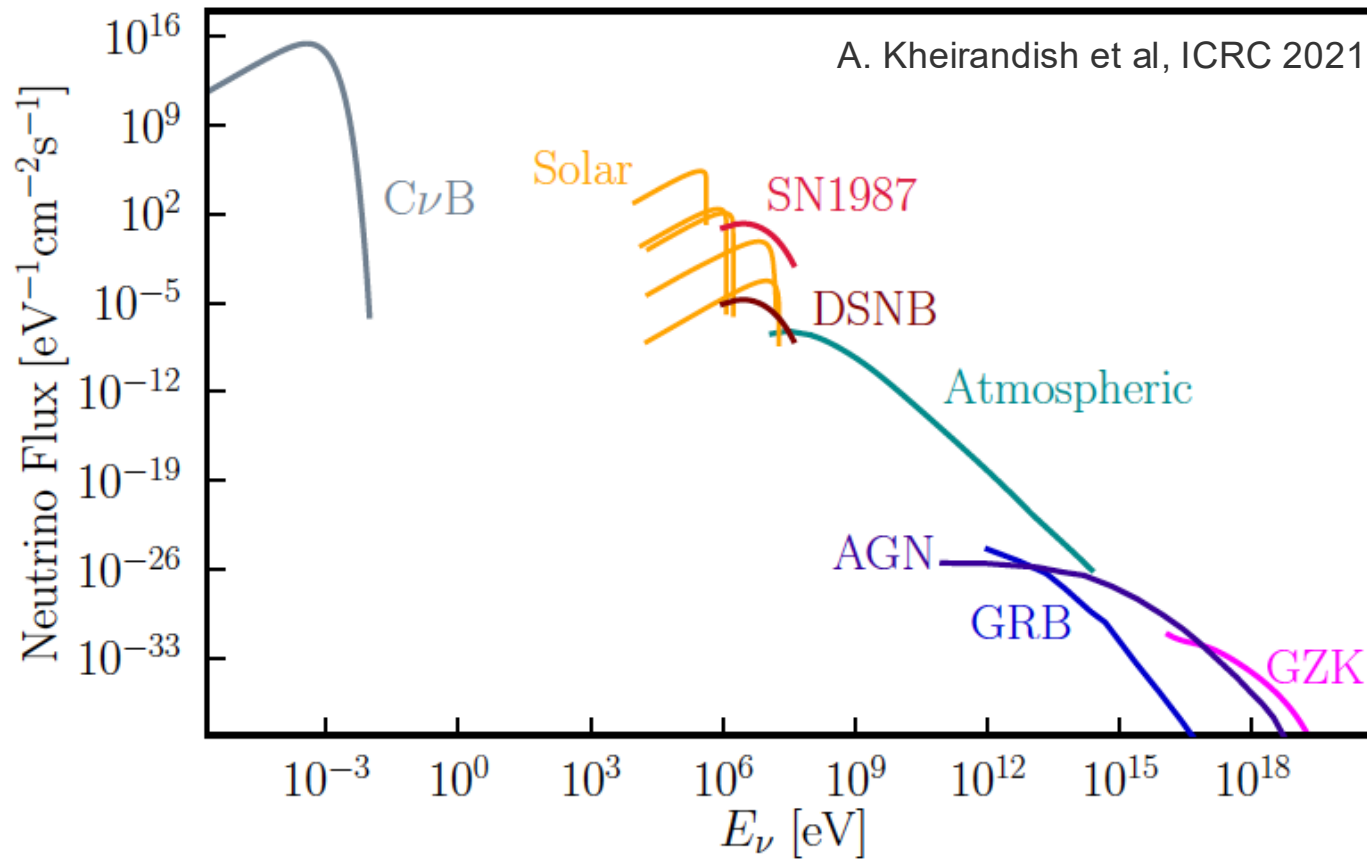




Take home message

New high-energy neutrino telescopes are currently under construction / planned.

Combining their data increases the sky coverage and sensitivity.



↔

Ideas: neutrino capture
on unstable nucleus
(e.g. tritium)

↔

Neutrino capture on
stable nucleus
(Chlorine, Gallium)

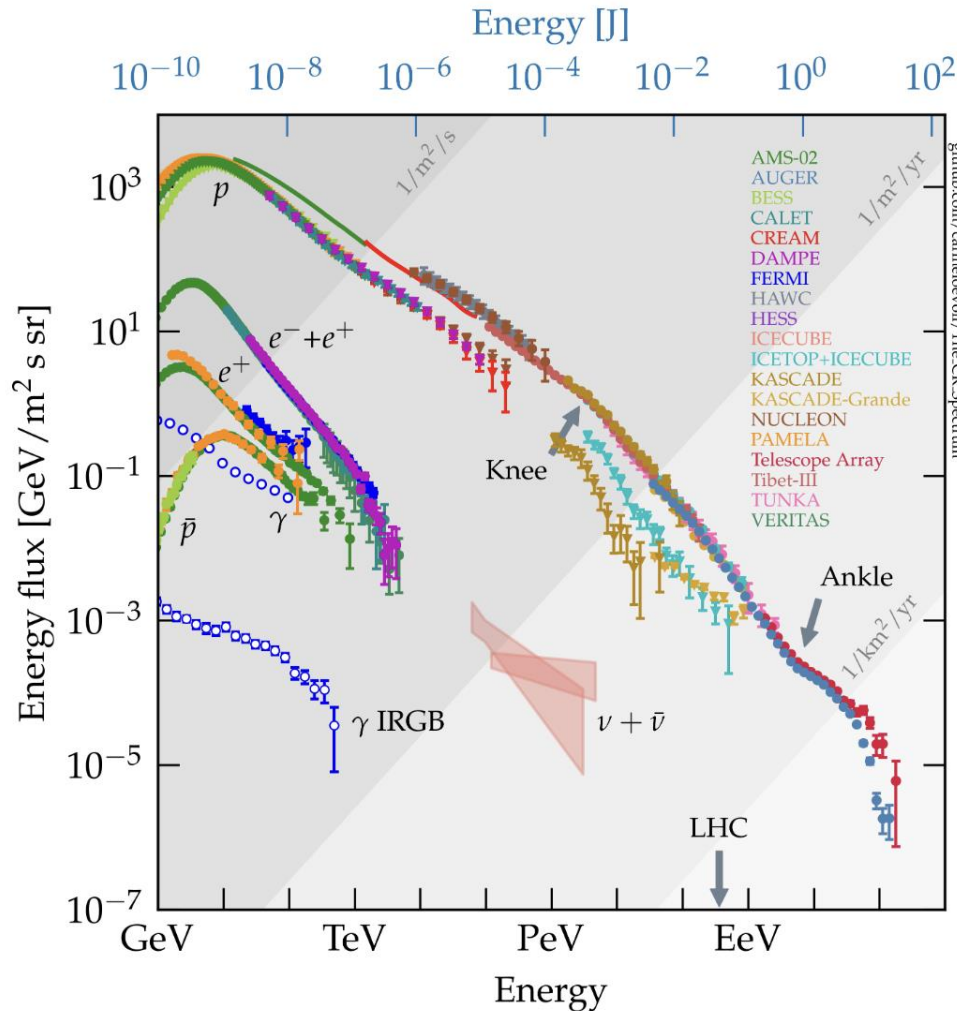
↔

Water / ice
Cherenkov
detectors

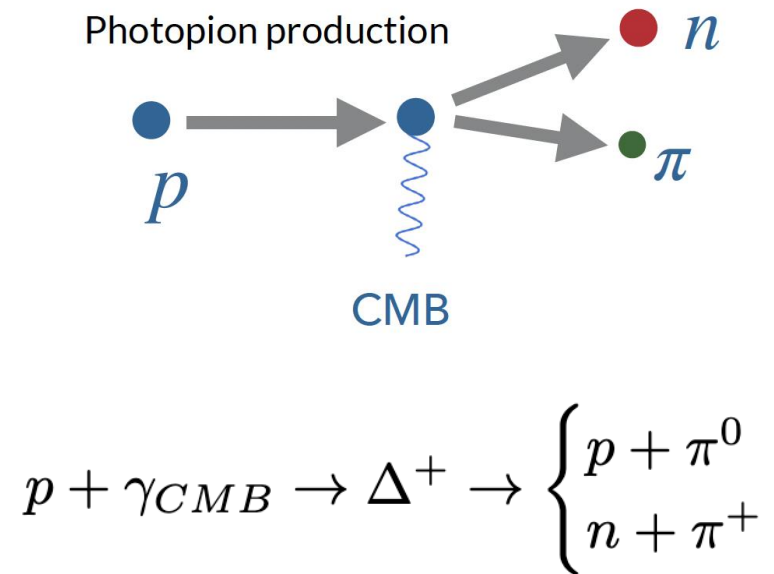
↔

**Radio arrays,
cosmic-ray
detectors**

Cosmogenic Neutrinos

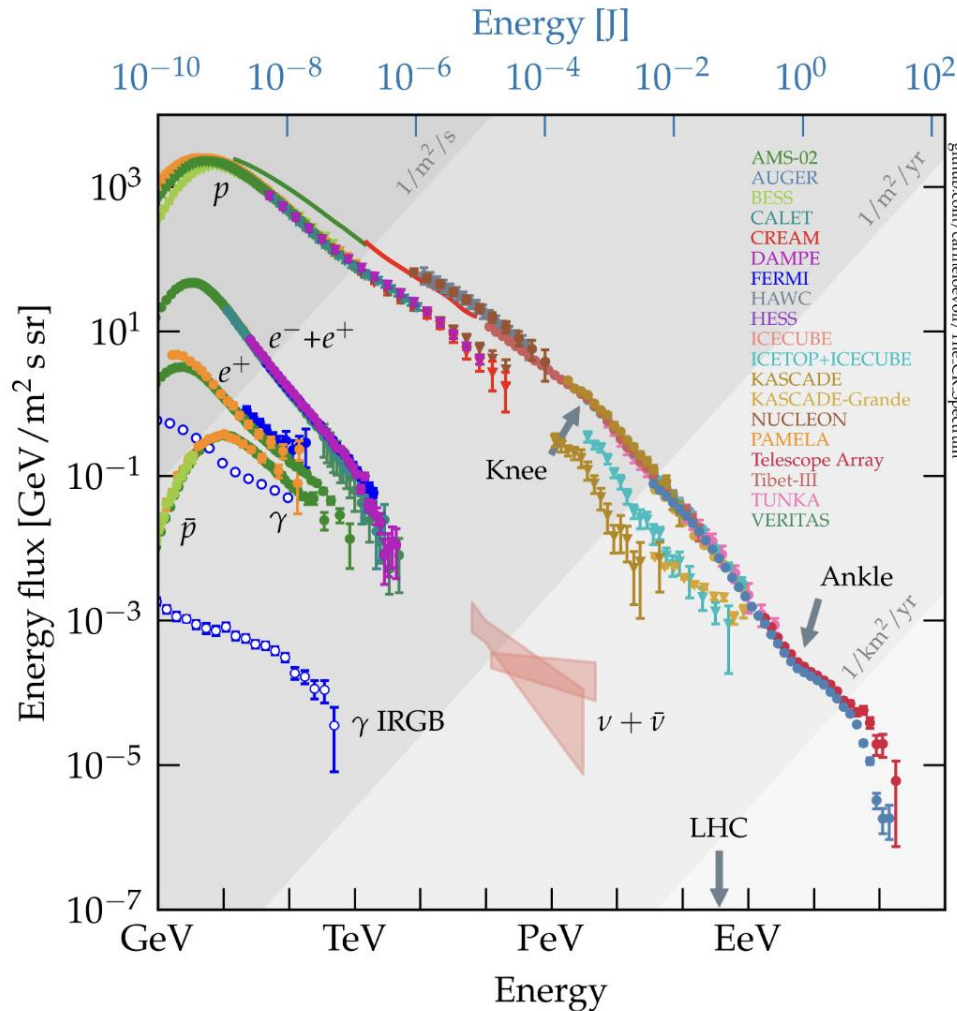


For Protons:



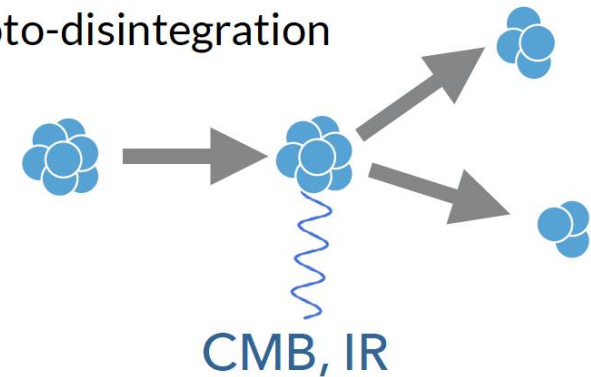
Energy Threshold: $5 \cdot 10^{19} \text{ eV}$

Cosmogenic Neutrinos



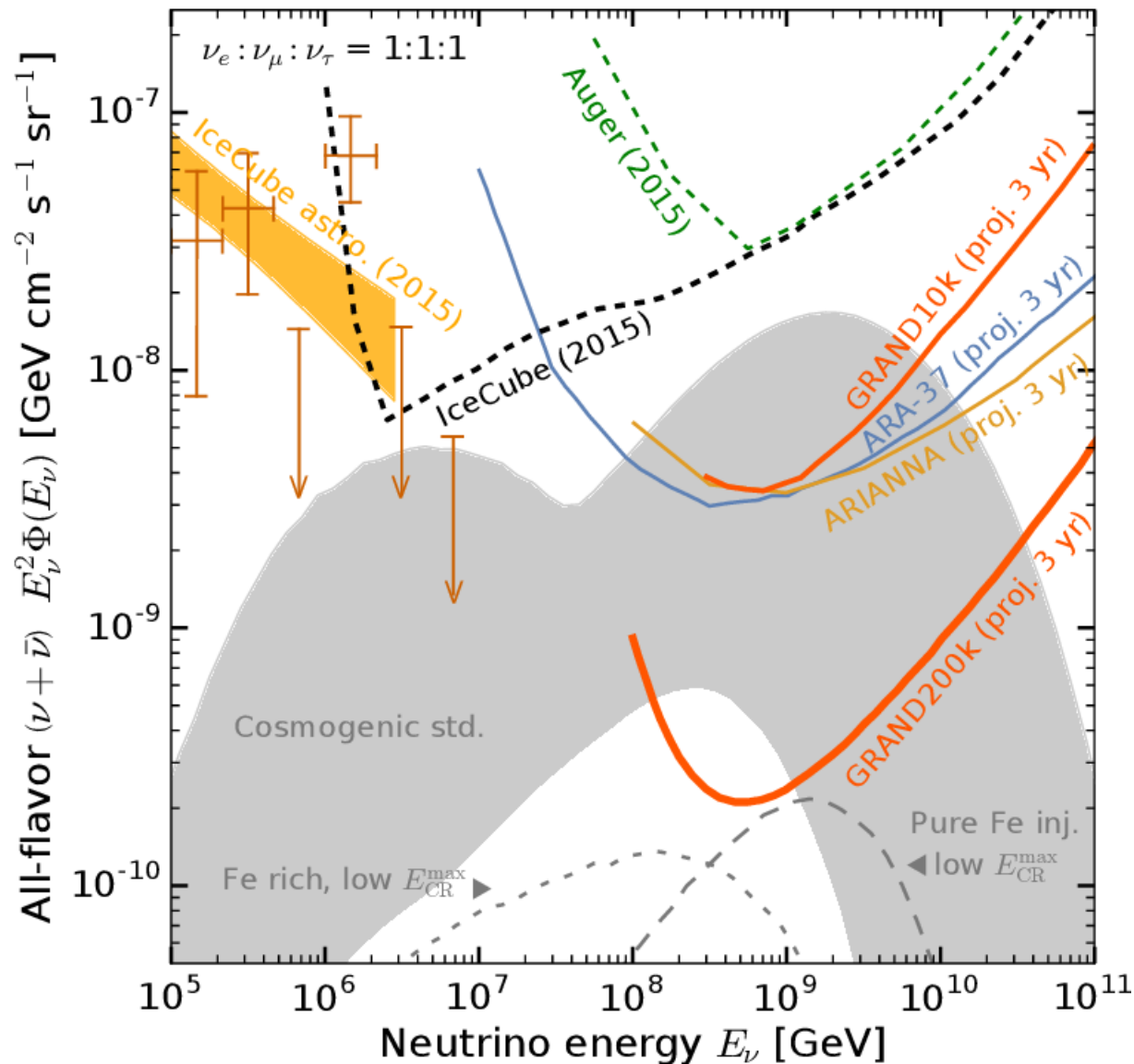
For heavier elements:

Photo-disintegration

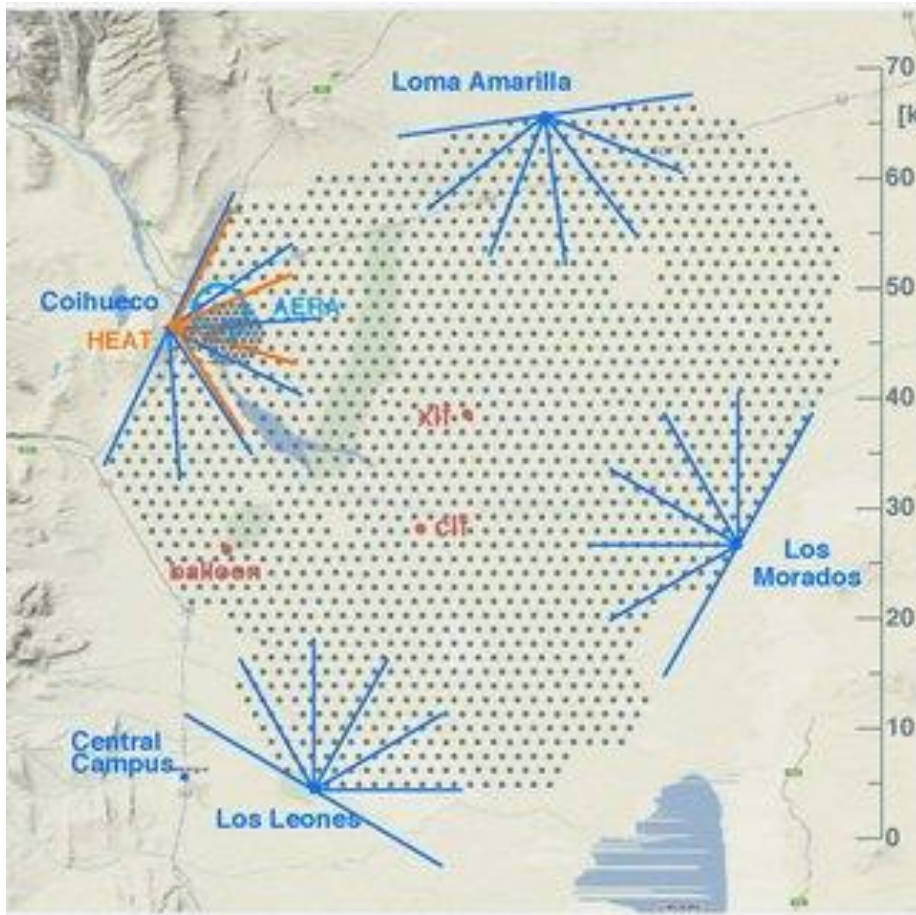


→ Neutrinos can help to infer the composition

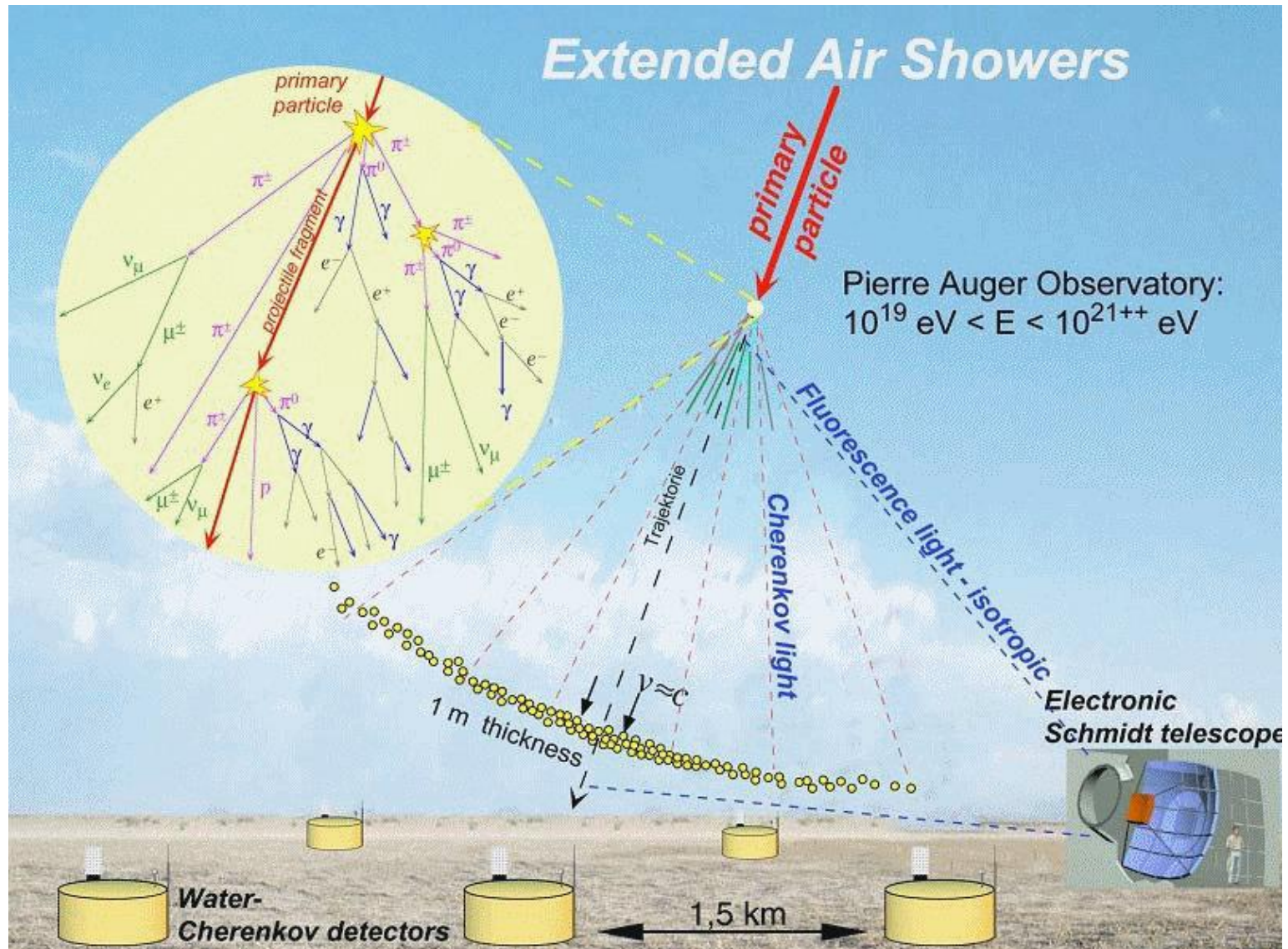
Cosmogenic Neutrinos



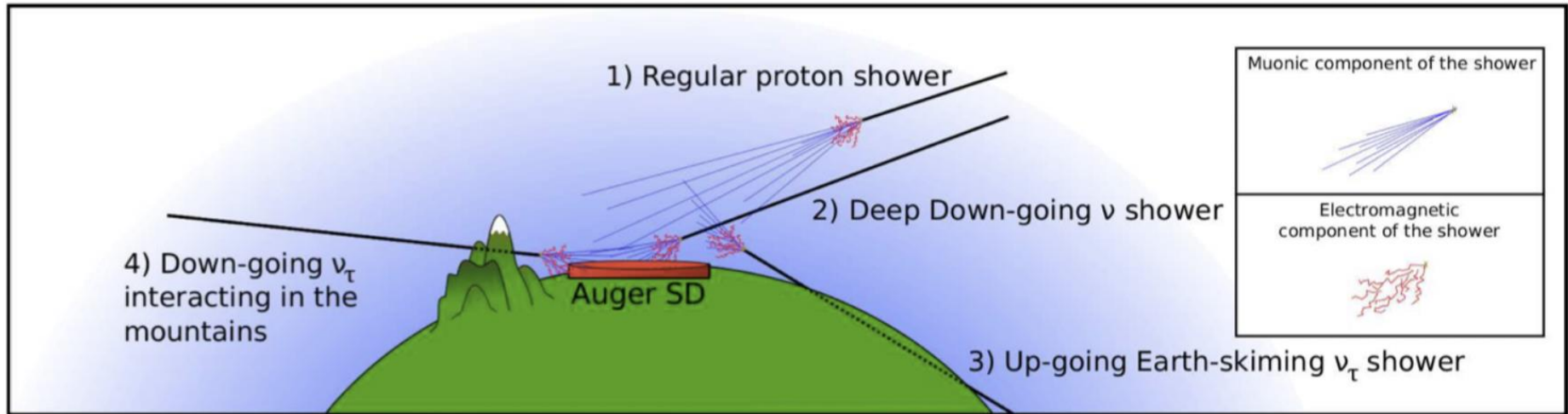
Neutrinos with the Pierre Auger Observatory



Neutrinos with the Pierre Auger Observatory



Neutrinos with the Pierre Auger Observatory



Decay of tau:

$$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau \quad \sim 18\%$$

$$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau \quad \sim 17\%$$

$$\tau^- \rightarrow \text{hadrons} + \nu_\tau \quad \sim 65\%$$

Mostly (25%)

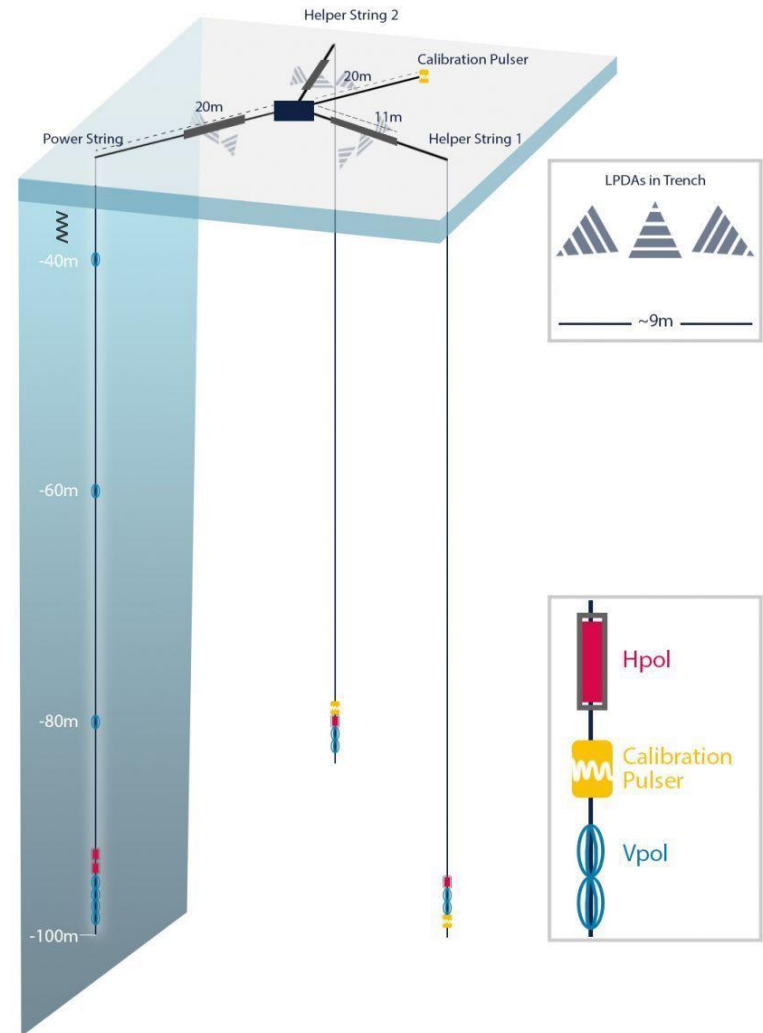
$$\tau^- \rightarrow \pi^- + \pi^0 + \nu_\tau$$

RNO-G



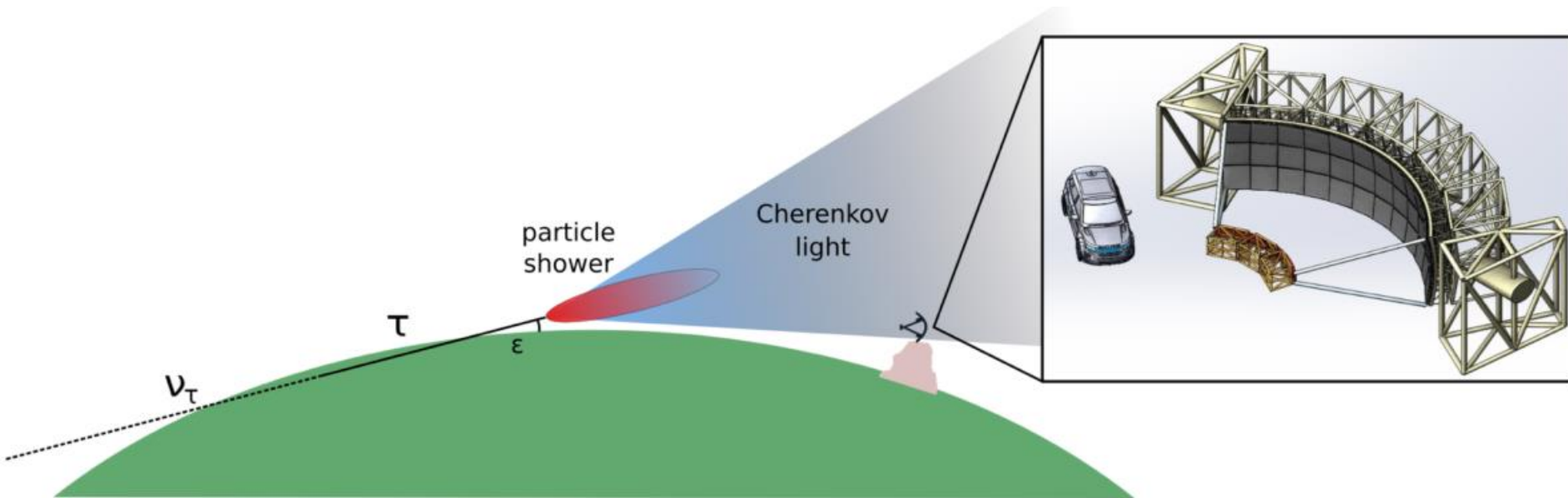
Askaryan effect:

- Negative charge accumulation in the shower front gives rise to a changing current, which gives rise to radio emission
- Emission is coherent at frequencies corresponding to the size of the shower



Trinity

One of 18 planned Trinity telescopes



Trinity demonstrator

Deployed: Oct 2023

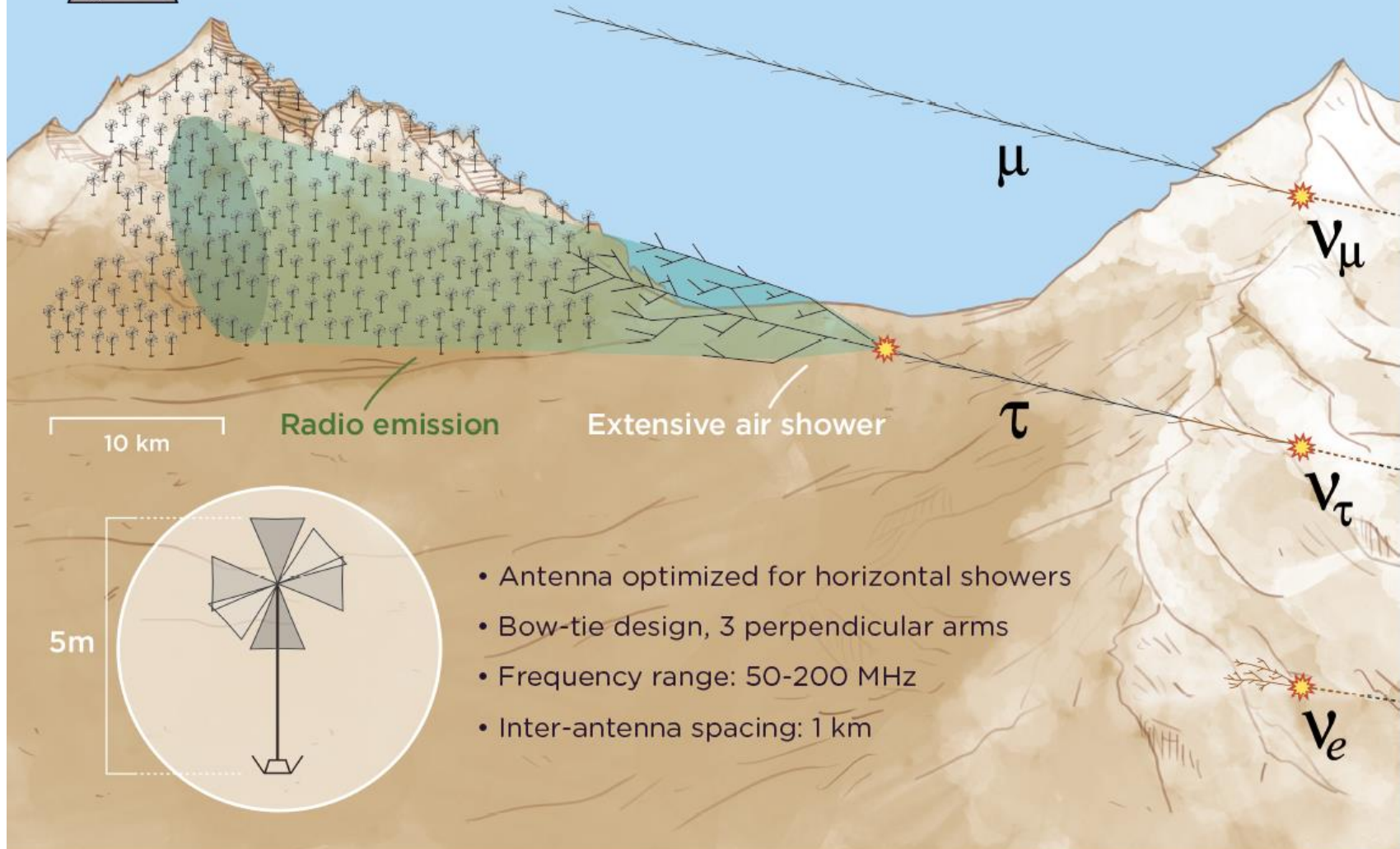
Frisco Peak, UT



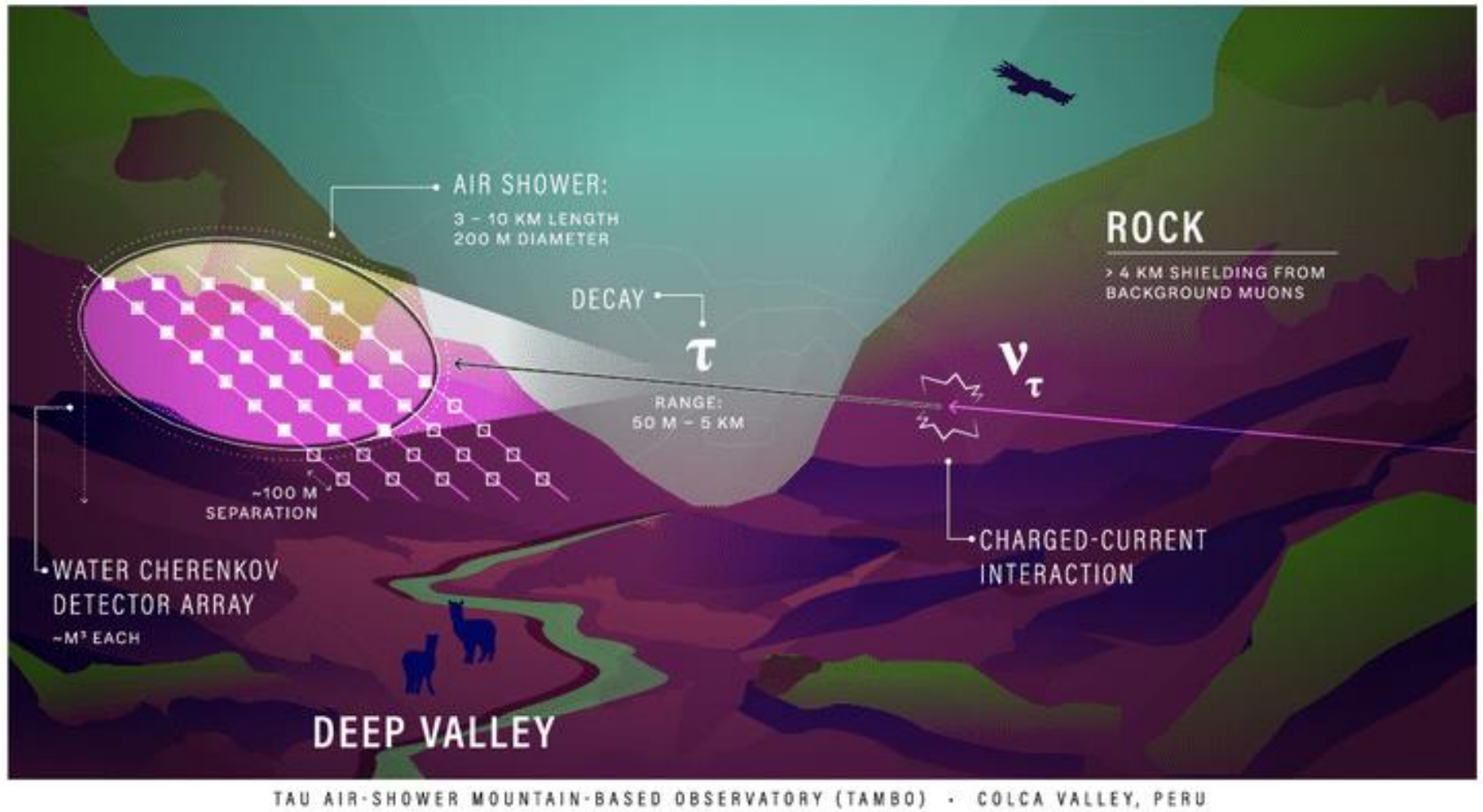
GRAND



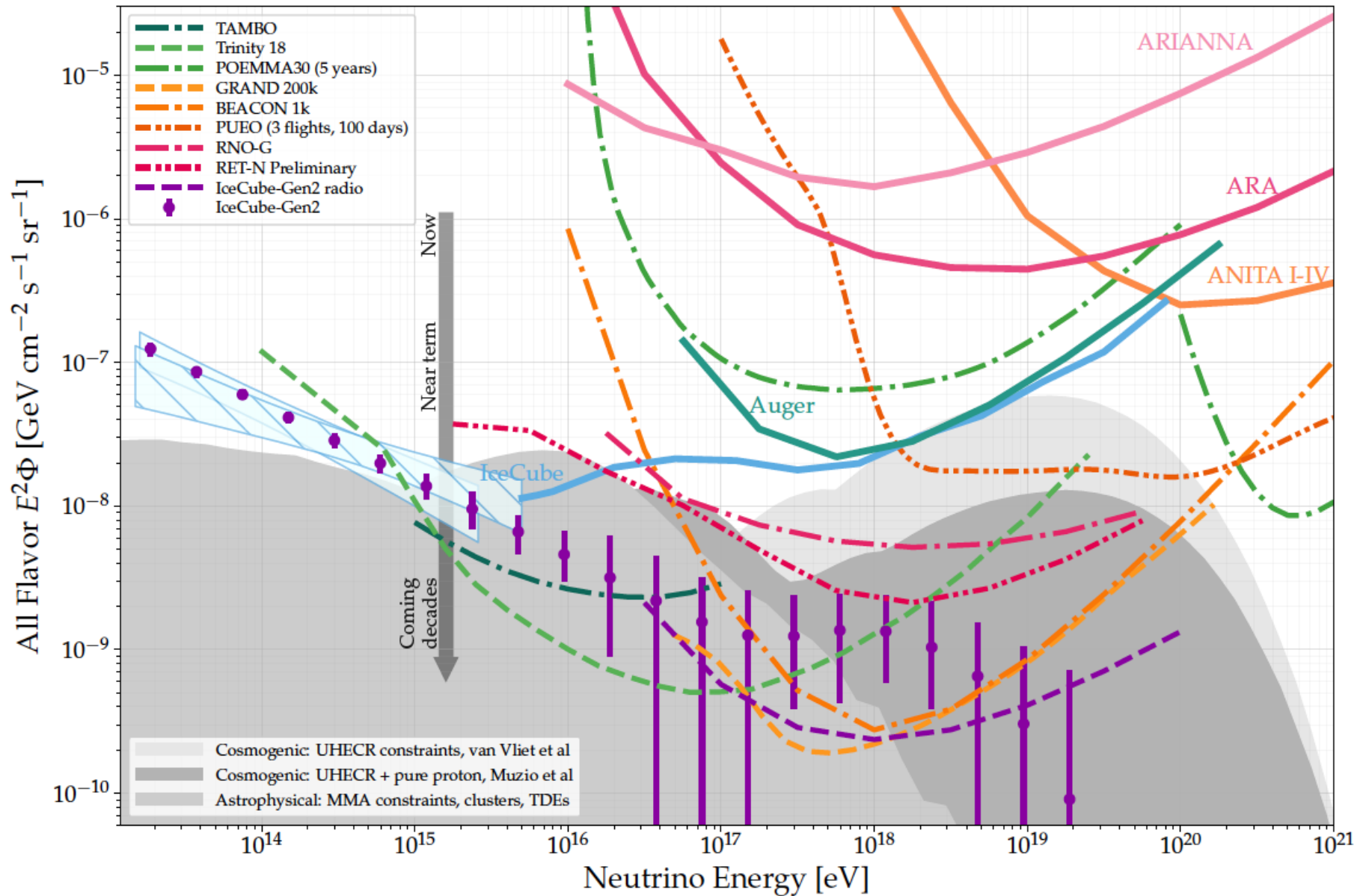
Giant Radio Array for Neutrino Detection



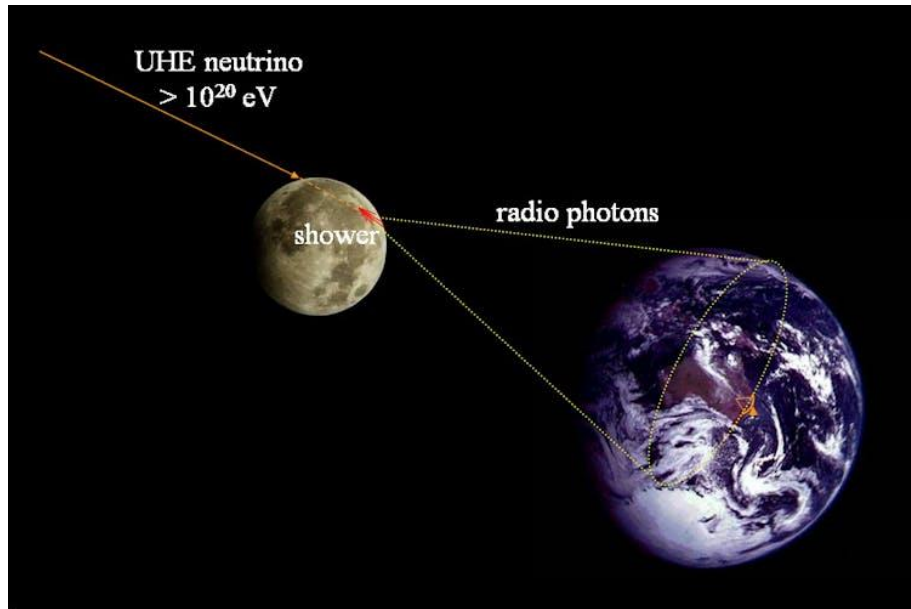
TAMBO



Diffuse Flux, 1:1:1 Flavor Ratio



Other detector Concepts



O. Scholten 2011

trees are efficient broadband antennas

S. Prohira 2024, arXiv:2401.14454





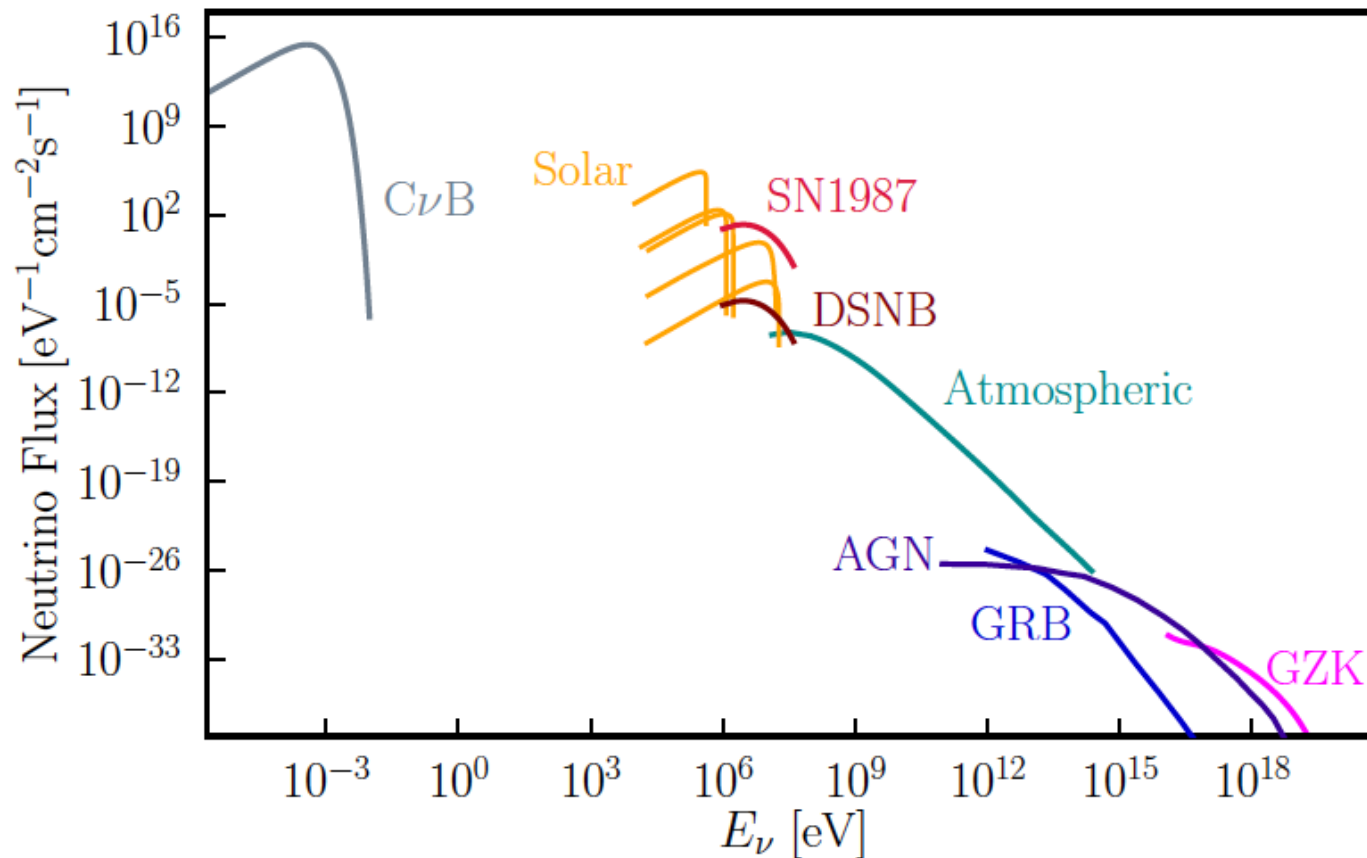
Take home message

Cosmogenic neutrinos are produced in interactions of UHECR during propagation.

New detector technologies target this energy range.

Summary Day 2

A. Kheirandish et al, ICRC 2021



↔
Ideas: neutrino capture
on unstable nucleus
(e.g. tritium)

↔
Neutrino capture on
stable nucleus
(Chlorine, Gallium)

↔
Water / ice
Cherenkov
detectors

↔
Radio arrays,
cosmic-ray
detectors

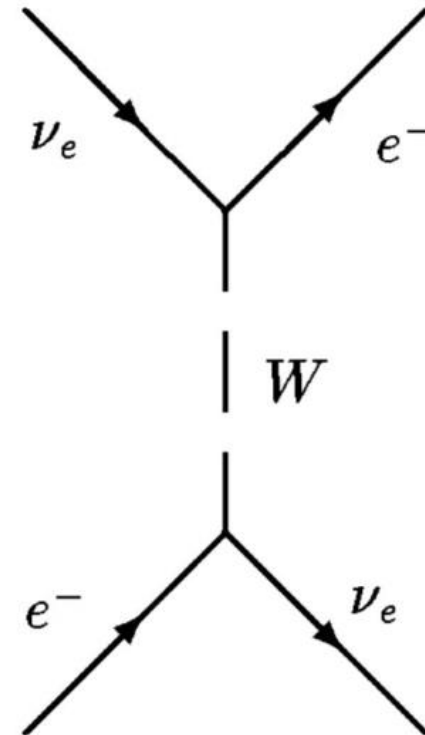
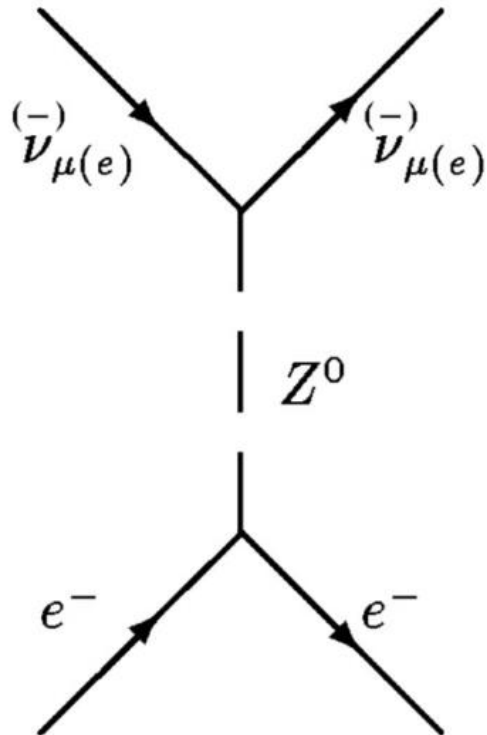


Take home message

Neutrinos are awesome for astronomy and particle physics!

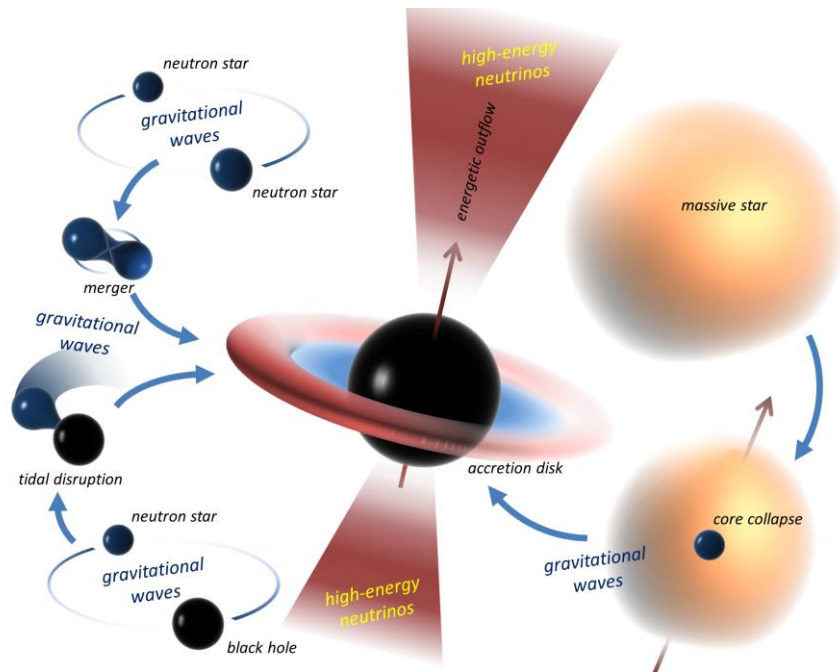
Backup

Elastic scattering



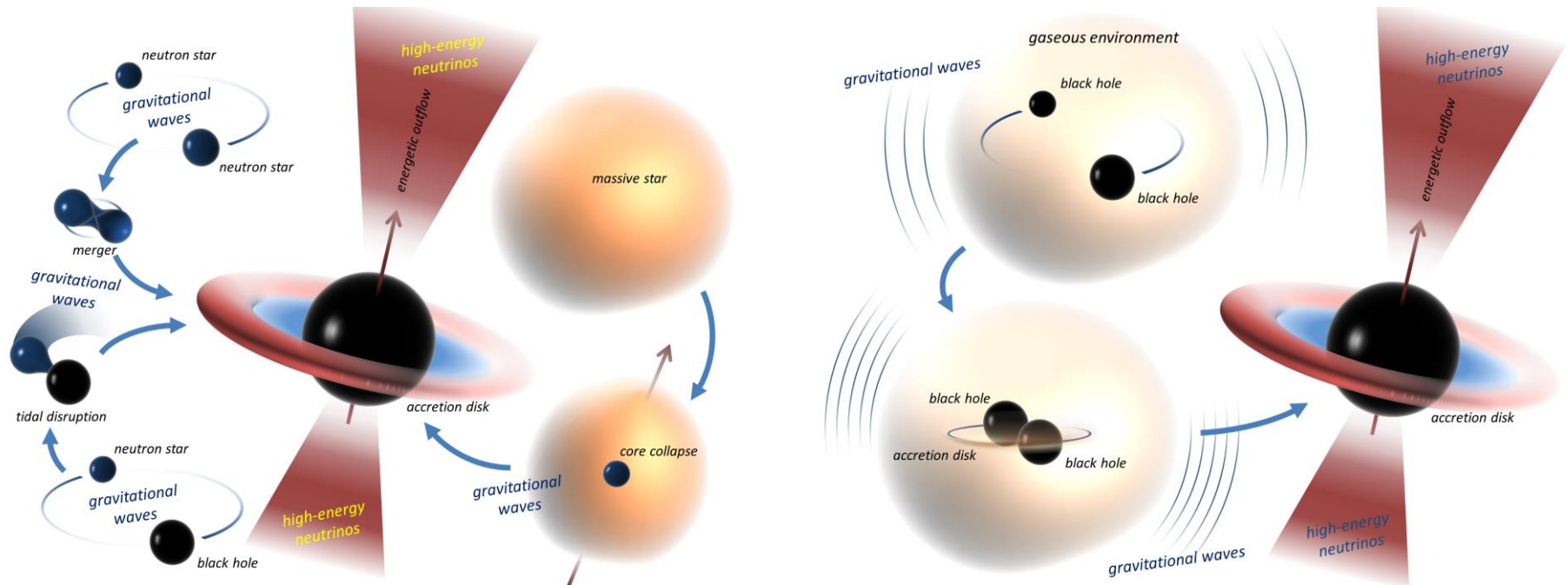
Cross-section is larger for electron neutrinos, because they can interact via Z AND W boson exchange. Other flavors only via Z exchange

Neutrinos and Gravitational Waves



Credit: I. Bartos

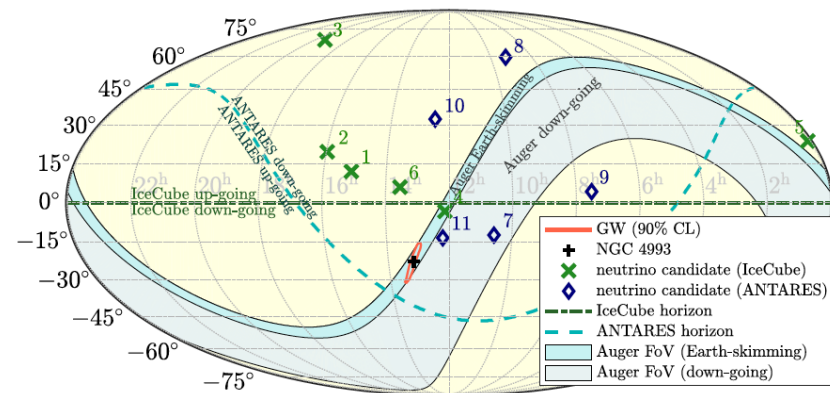
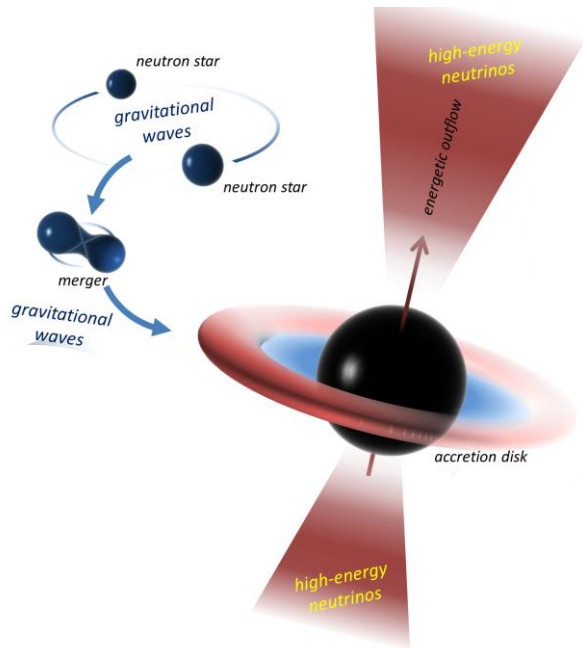
Neutrinos and Gravitational Waves



Credit: I. Bartos

TeV Neutrinos and Gravitational Waves: BNS merger

GW170817: Search for neutrinos in ANTARES, Auger and IceCube data in ± 500 sec



Neutrino could help to constrain direction and teach us about the GW source environment

LIGO, Virgo, Auger, ANTARES, IceCube, ApJ 850 (2017)