CSIC Institute of Space Sciences EXCELENCIA MARÍA DE MAEZTU

GAMMA-RAY ASTROPHYSICS EXTRA-GALACTIC SOURCES

1

Daniela Hadasch

SOURCE CLASSES

The same physical engines operate in our Galaxy and beyond, but on different scales and in different environments.

Engine / Environment	Galactic examples	Extragalactic counterparts
Rotation-powered	**Pulsars** (rotation-powered neutron stars)	No major steady rotation-powered extragalactic population established*
Accretion onto compact object	**Microquasars** (accreting stellar-mass black holes / neutron stars)	**AGN** (accretion onto supermassive black holes)
Relativistic jets	Microquasar jets	**Blazars** (jet pointed toward us, a subclass of AGN), **Radio galaxies** (jet at larger angles)
Explosive transients	SNRs, novae, stellar flares	**GRBs** (gamma-ray bursts), superluminous supernovae, TDEs
Dense environments (cosmic-ray targets)	Galactic Centre, molecular clouds	**Starburst galaxies, galaxy clusters**, AGN environments

Galactic sources:

- Closer laboratories
- Resolved spatially
- We can study the building blocks in detail

Galactic example:
Supernova Remnant (Crab Nebula)

Same physics

Different scales and environments

Extragalactic example:
Blazar (jet from an AGN)

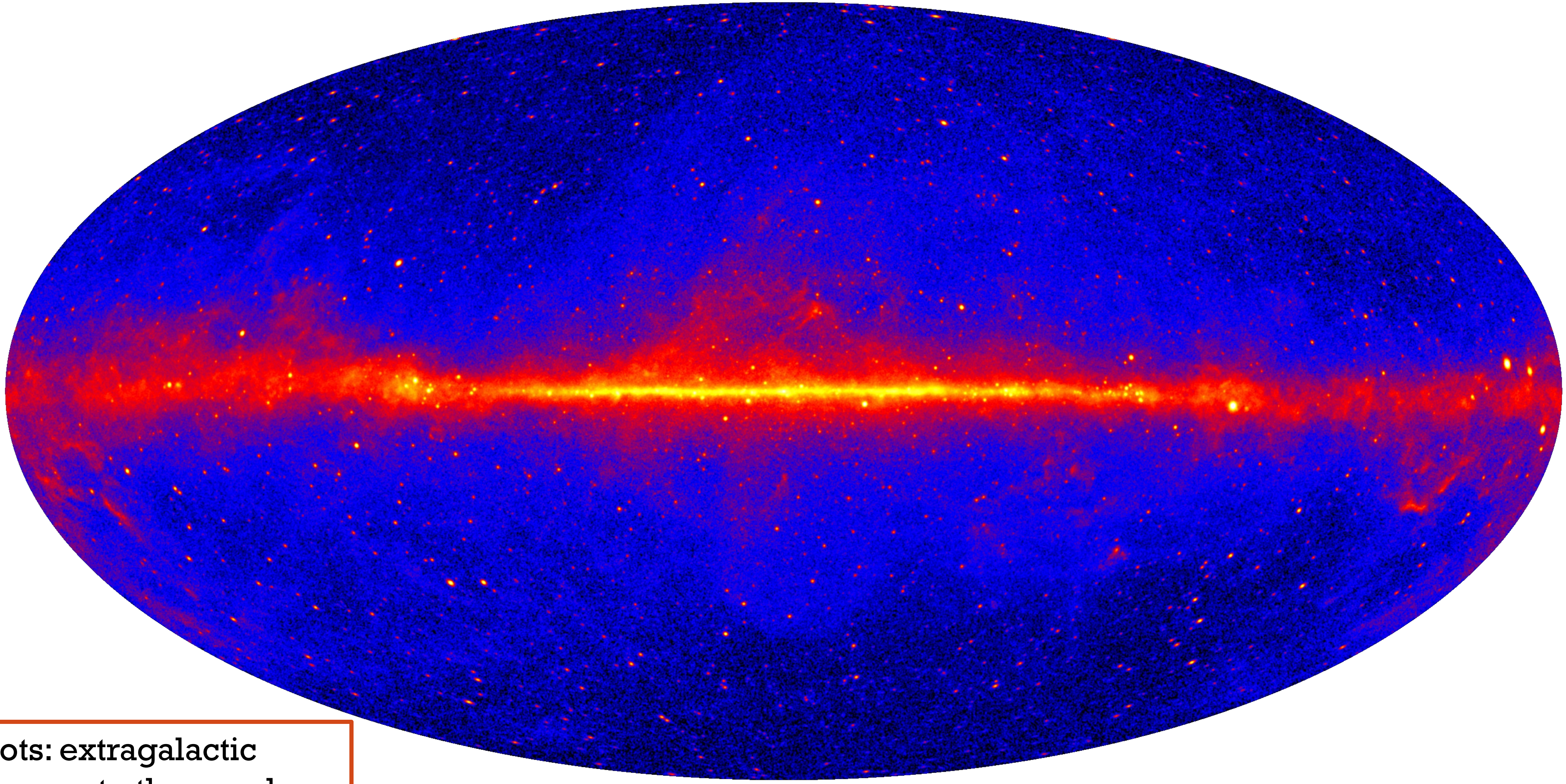
Extragalactic sources:

- Same physical processes on much larger scales
- Often more extreme conditions
- Access to cosmological distances and times

By studying Galactic sources we learn the physics. By studying extragalactic sources we push it to extremes.
Together they give a complete picture of high-energy astrophysics.

*Isolated rotation-powered gamma-ray sources have not been established outside the Local Group (magnetars in external galaxies are an open area of study).

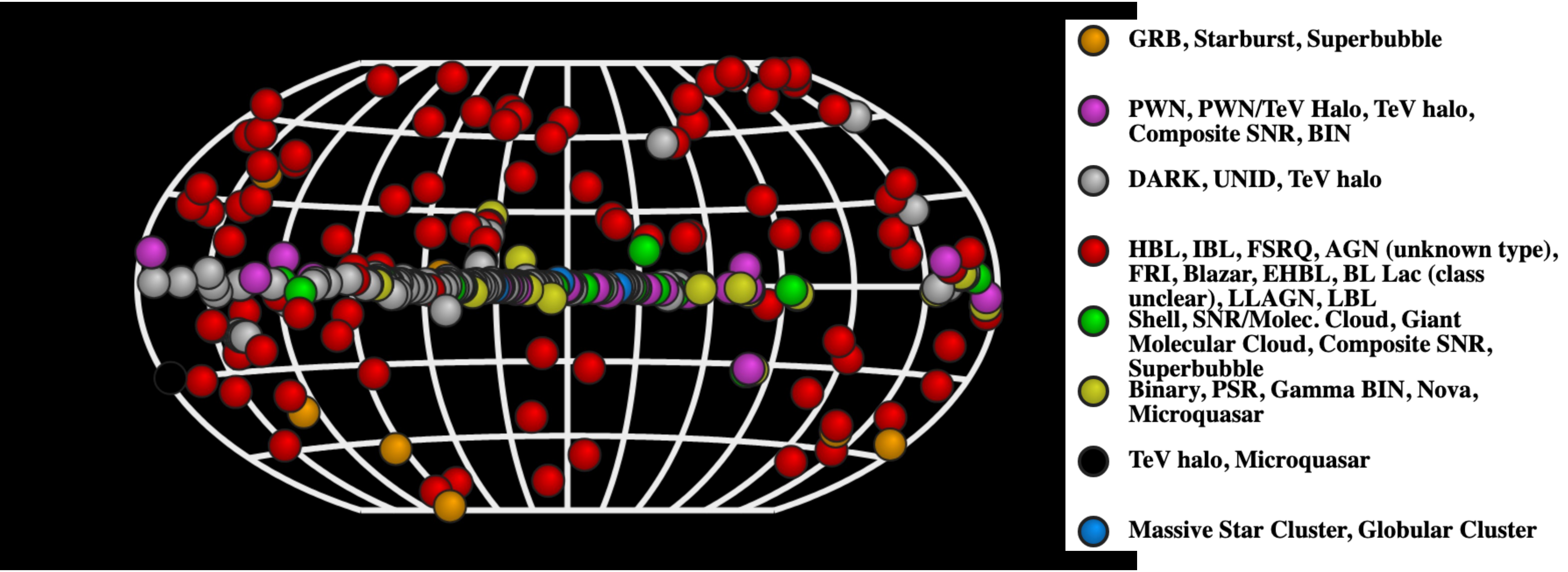
GAMMA-RAY SKY SEEN BY FERMI-LAT



Red dots: extragalactic
Source count ~thousands

Fermi LAT, Energy > 1 GeV, 12 years of data (7,464,664 photons)

VERY HIGH ENERGY SOURCES



- 323 sources of VHE gamma rays (June 2026)
  - Unidentified sources are the largest population (126)
  - Followed by blazars (88)
  - And by supernova remnants and pulsar wind nebulae (66)

http://tevcat2.uchicago.edu/

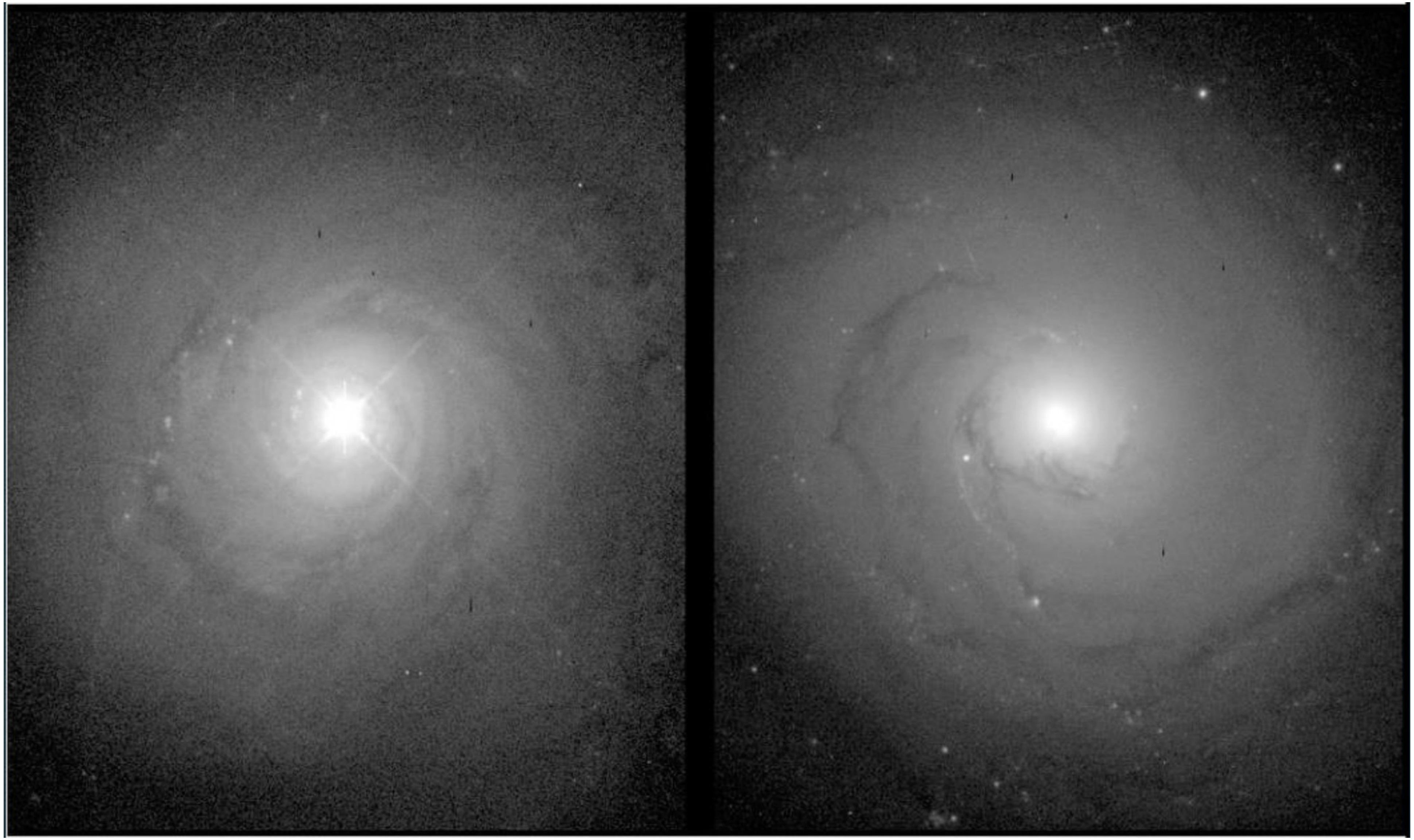
ACTIVE GALACTIC NUCLEI (AGN)

- Blazars
- Radio Galaxies
- FSRQs
- BL Lacs

ACTIVE GALACTIC NUCLEI

- Exceptionally bright compared to normal galaxies.
- The luminosity originates from the very central region from matter accreting to supermassive black hole in the center of galaxies.
- The luminosity of the nucleus outshines the thermal emission produced by the stars of the galaxy.

WHICH ONE OF THIS IS AGN?



Slide: Elina Lindfors

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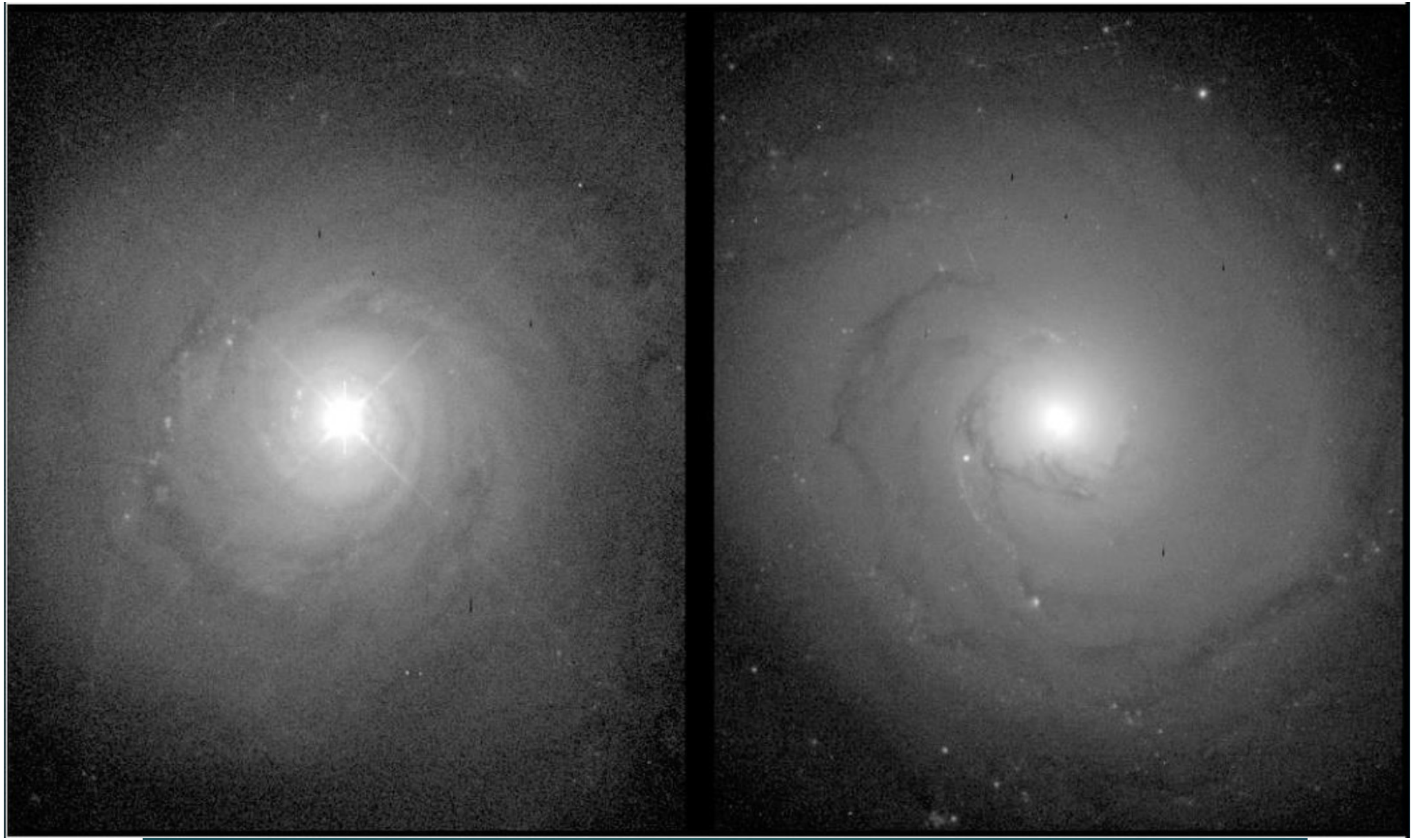
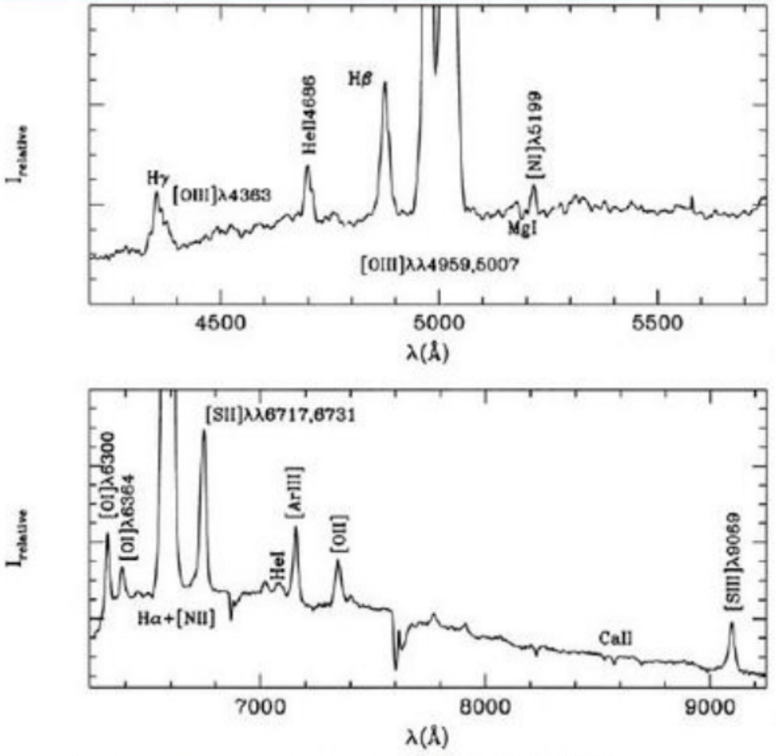


NGC5548 (Seyfert1) NGC3277 (Normal Spiral)

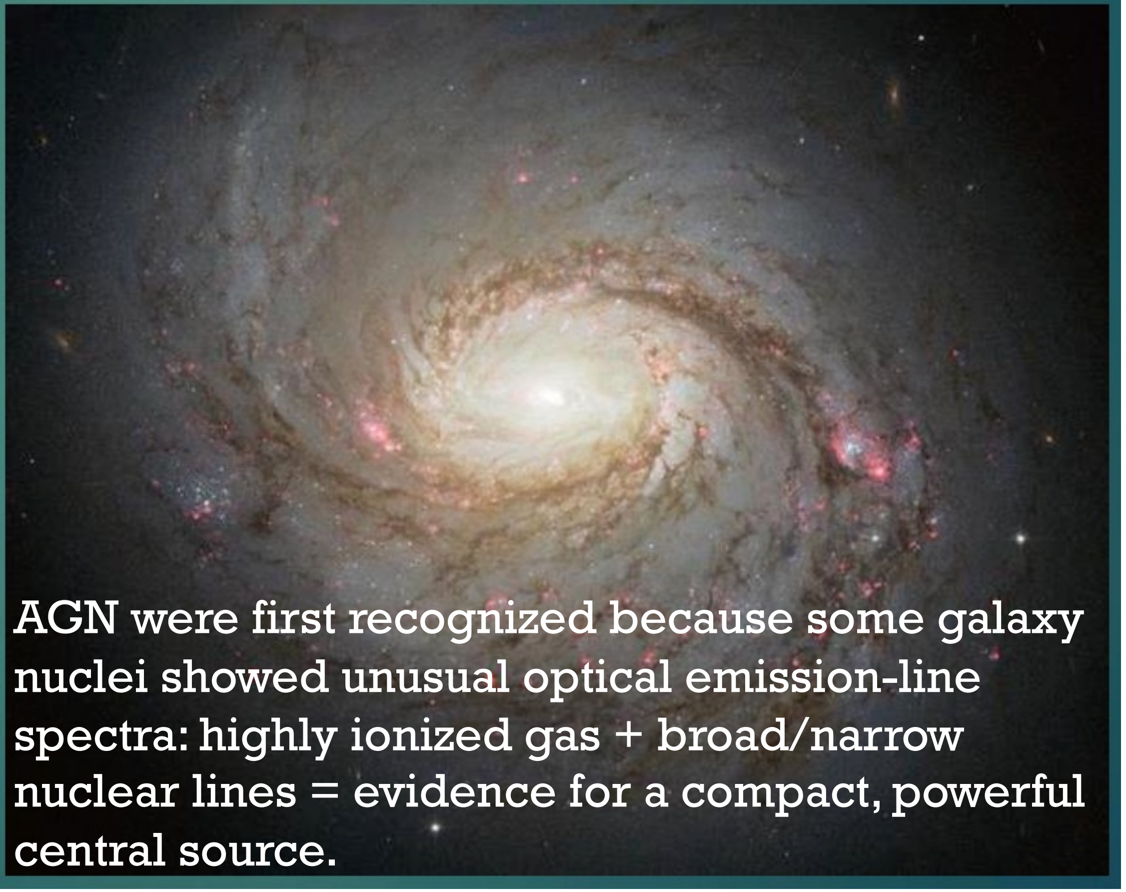
Slide: Elina Lindfors

AGN FIRST REVEALED BY OPTICAL SPECTROSCOPY

- Optical emission: **1908 – Fath & Slipher** detect strong emission lines (from H, O, Ne) similar to planetary nebulae with high ionization levels and line-width of several hundred km/s in spiral nebulae, including NGC 1068.



Optical spectrum of NGC1068 (Garcia-Lorenzo et al. 1999)

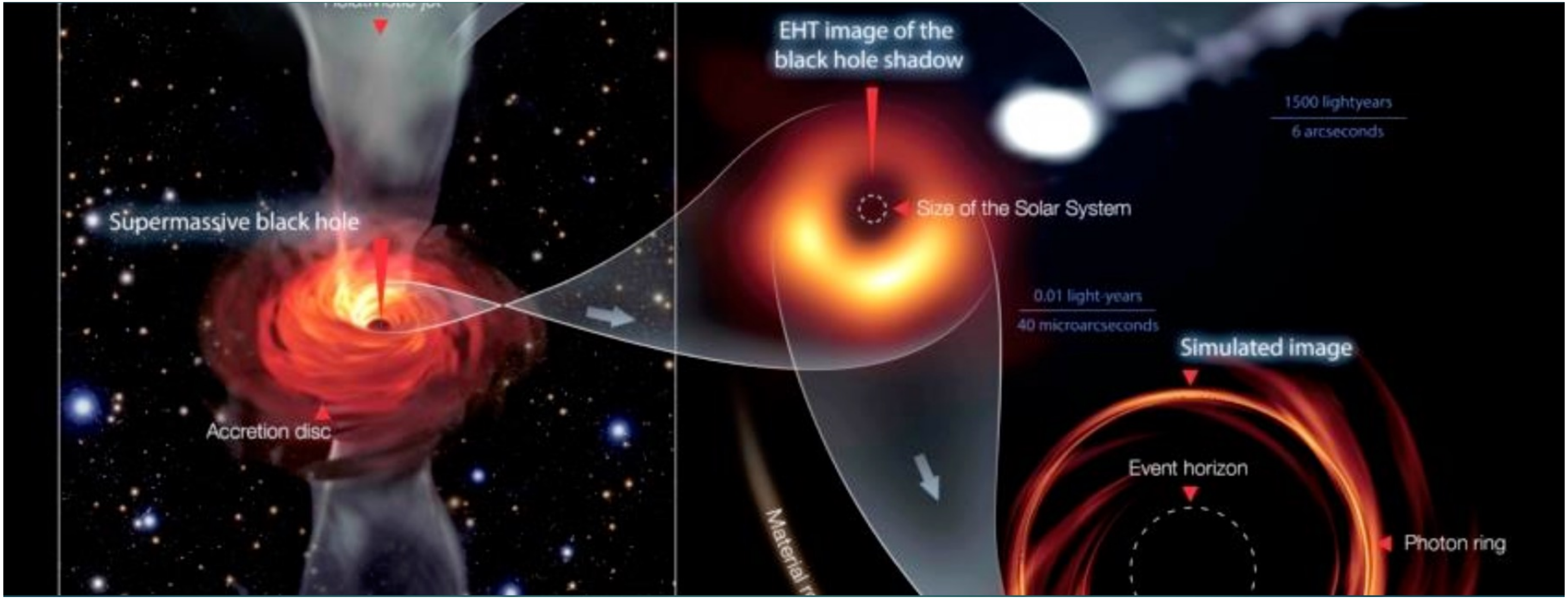


Slide: Elina Lindfors

M87: ONE OF THE EARLIEST JET OBSERVATIONS

Slide: Elina Lindfors

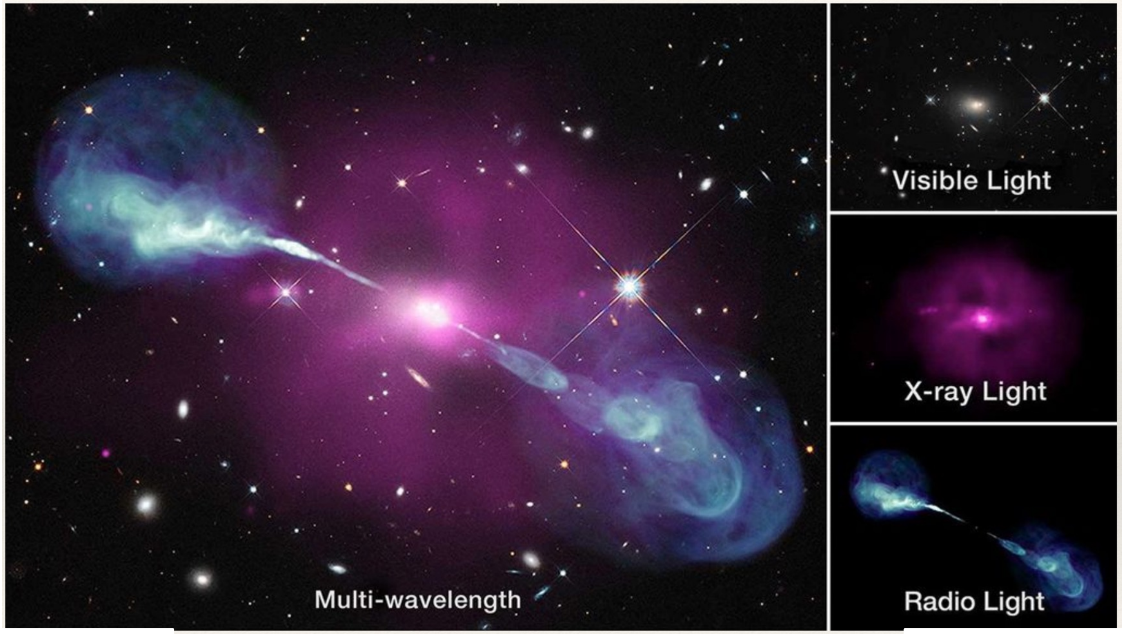
M87: CENTER OF VIRGO CLUSTER, AGN



Slide: Elina Lindfors

WHY SHOULD WE STUDY AGN?

- AGN form **the largest population** of known sources in the Fermi Catalog and among TeV sources.
- These sources have major **emission across all wavebands** along with major **multi-messenger emission.**
- **AGN feedback:** jets and winds launched by an AGN interact with the gas in the host galaxy, thereby influencing the galaxy's evolution.
- A promising class of ultra-high-energy cosmic ray (**UHECR**) accelerators (depending on distance).
- Can be used to study **diffuse emission**.
- If you are not looking at AGN as a source, its very likely you might look at it as a background (Fermi analysis).



Credit: X-ray: NASA/CXC/SAO; visual: NASA/STScI; radio: NSF/NRAO/VLA.

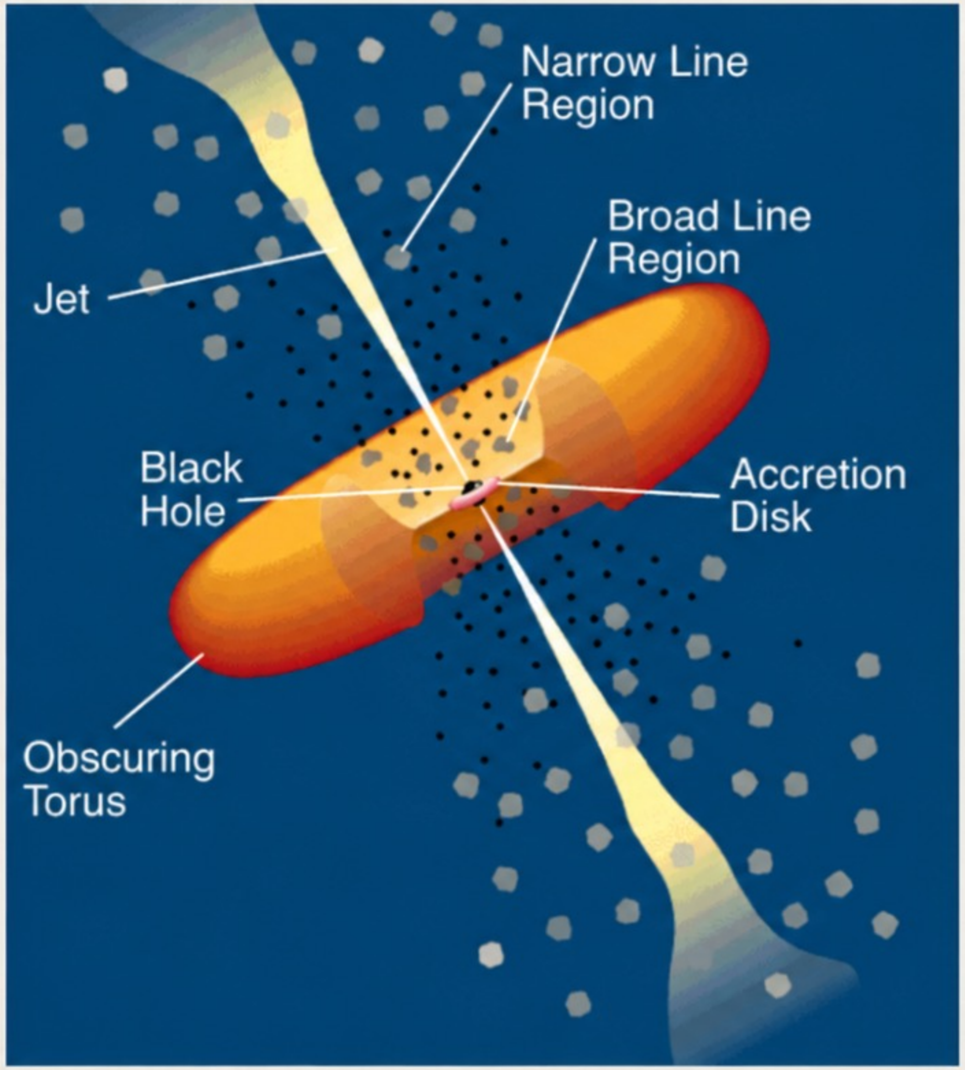
Slide: Abhishek Desai

AGN UNIFIED MODEL

This is the standard "unified model" of an AGN.

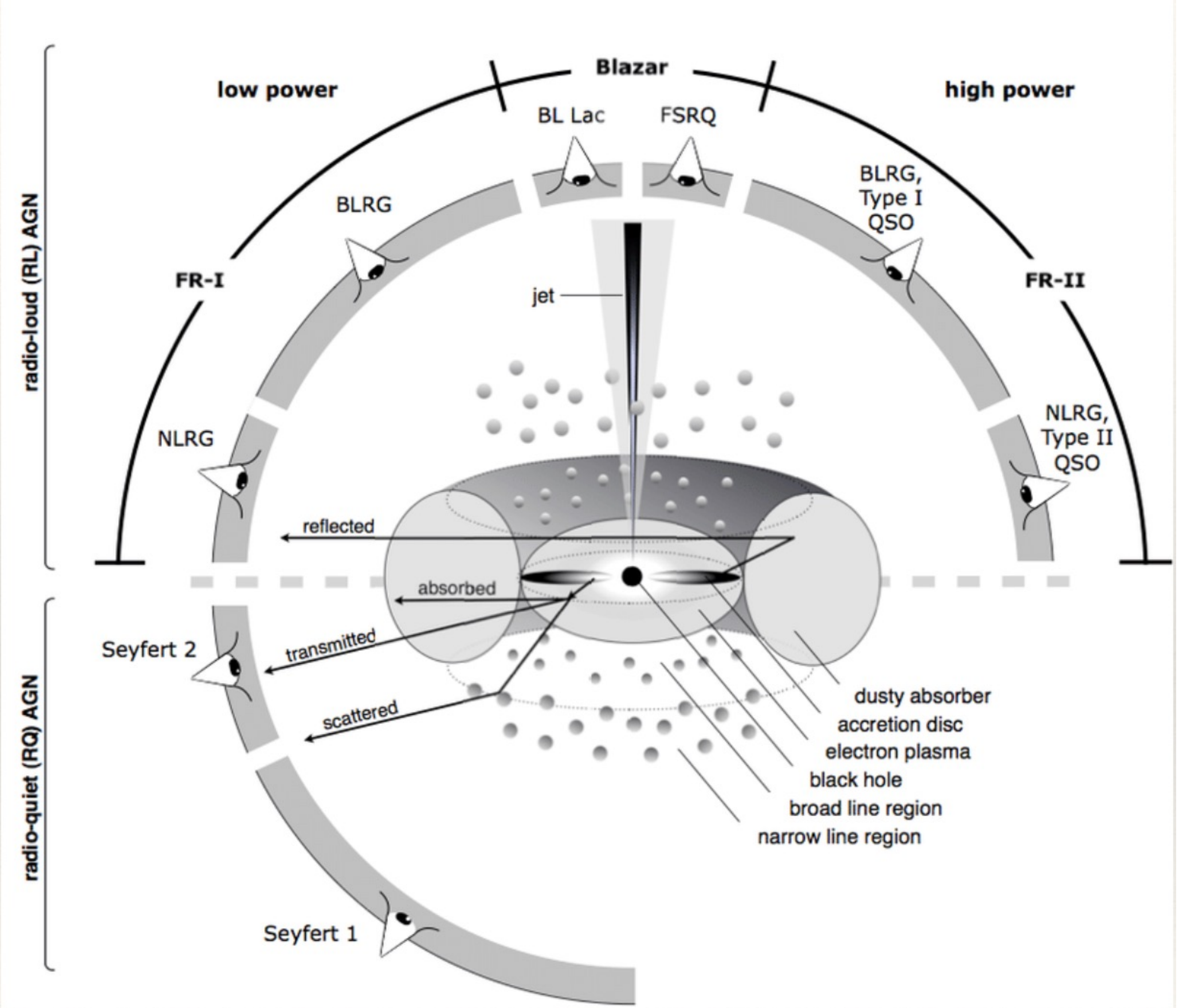
- **Black hole:** a supermassive black hole (10^6–10^{10} $M_\odot$) at the center.
- **Accretion disk:** gas spirals in and heats up, radiating across the electromagnetic spectrum.
- **Obscuring torus:** a thick doughnut-shaped structure of dust and gas that can hide the central engine depending on our viewing angle.
- **Broad line region (BLR):** fast-moving gas close to the black hole produces broad emission lines.
- **Narrow line region (NLR):** slower gas farther out produces narrow emission lines.
- **Jets:** powerful, collimated outflows of relativistic particles launched along the rotation axis.

Key idea: AGN look different mainly because of orientation and obscuration, not because the engines are fundamentally different.



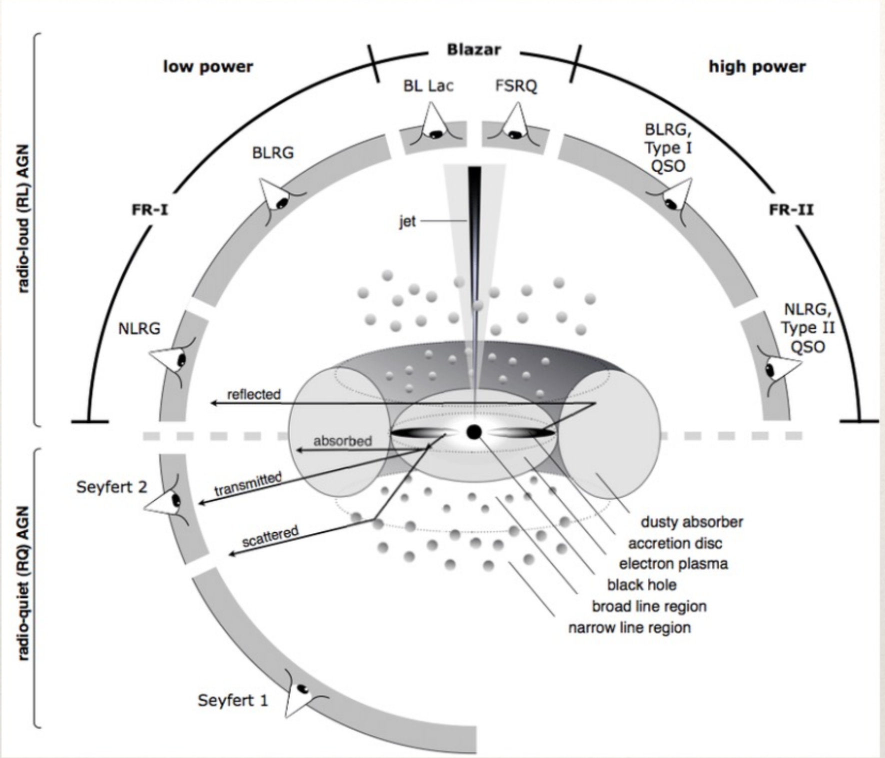
Credit: C.M. Urry and P. Padovani

AGN CLASSIFICATION



Unified model of AGN. Beckmann & Shrader (2012).

AGN CLASSIFICATION



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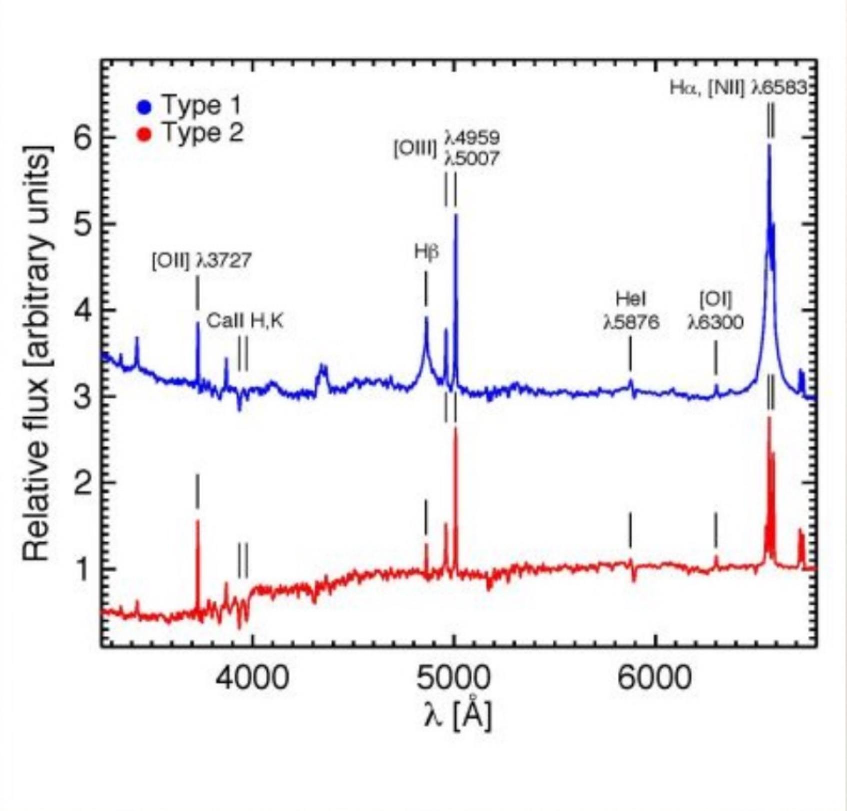


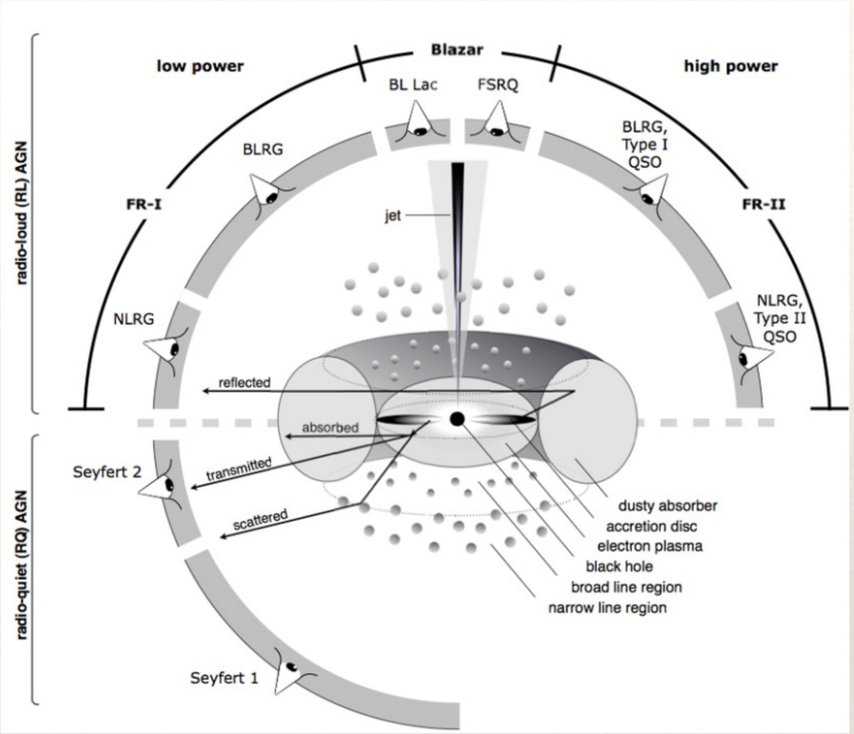
DiPompeo et al. (2018)

Type 1: direct view of BLR → broad Balmer lines

Type 2: BLR obscured by dusty torus → only narrow lines

Supports AGN unification: same engine, different line of sight

AGN CLASSIFICATION



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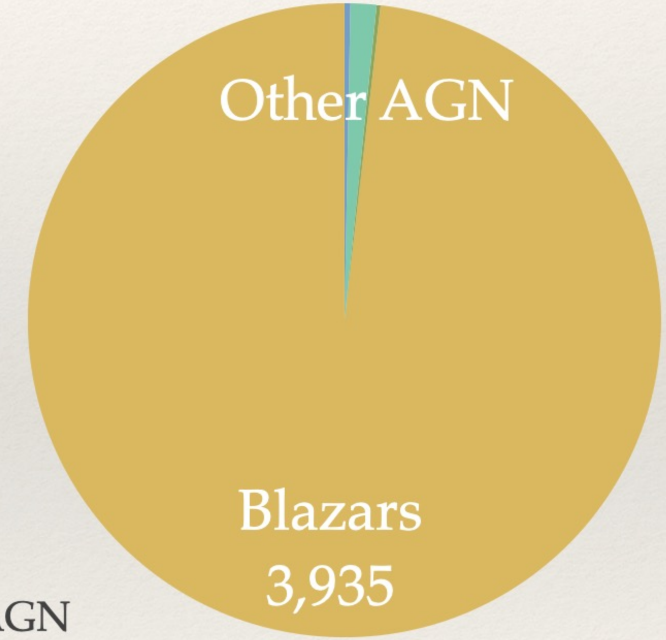
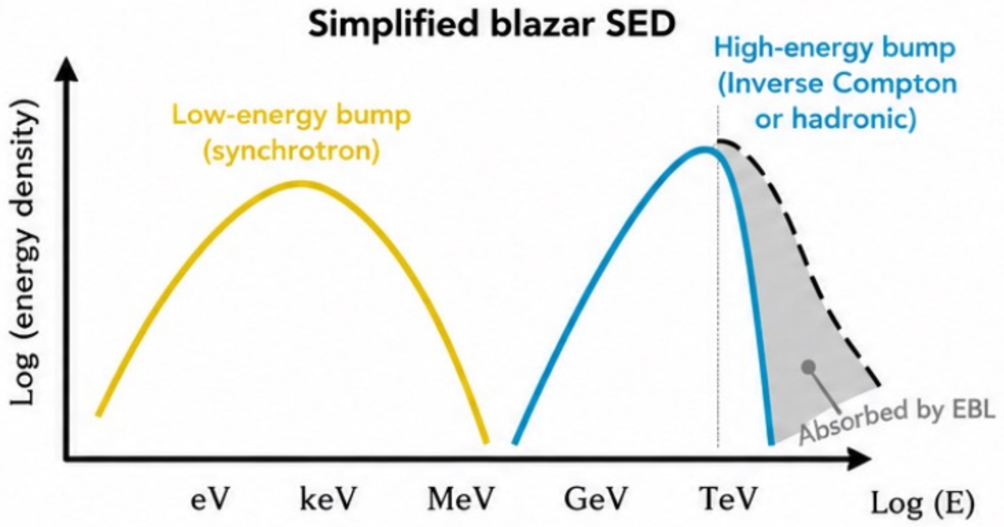
What does Fermi "see"?



ALL AGN
4,008

Blazar SED Basics

Blazars are AGN whose relativistic jet is pointed close to our line of sight.

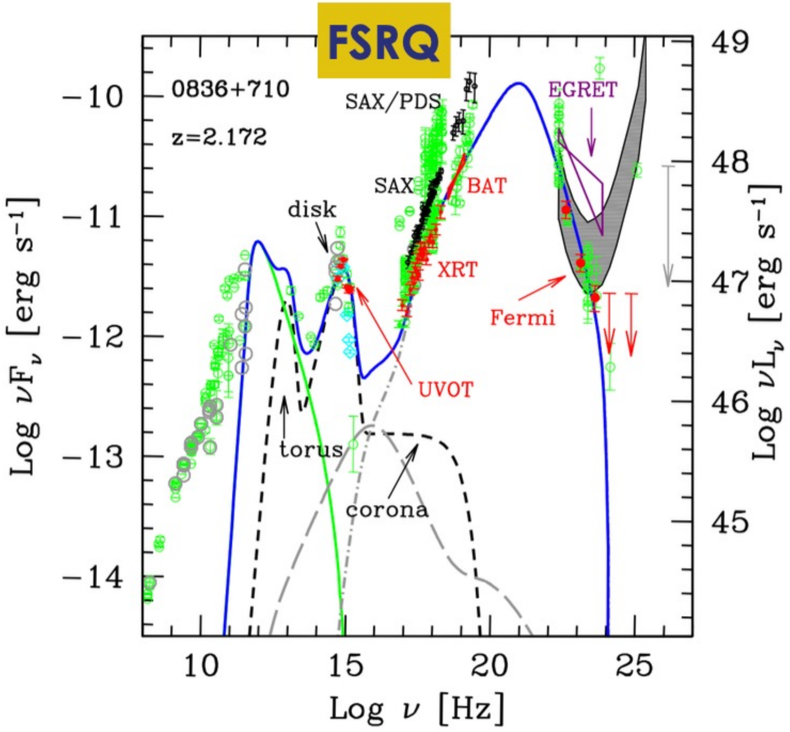


Blazars are classified into two main observational classes:

- **Flat Spectrum Radio Quasars (FSRQs):** strong broad emission lines, generally more luminous; significant external photon fields (disk, BLR, torus).
- **BL Lac objects:** weak or absent emission lines; jet emission dominates the observed radiation.

The two bumps are commonly interpreted with: leptonic models (electron synchrotron + inverse Compton) or hadronic models (proton-induced emission).

Example: FSRQ SED (z = 2.17)



- Strong thermal components from the accretion disk, broad-line region, and dusty torus.
- High-energy bump peaks in the MeV–GeV range, well covered by **Fermi-LAT**.
- FSRQs are typically more luminous than BL Lacs.

Data: Abdo et al. (2009); Ghisellini et al. (2013)

Blazar Subclasses and Gamma-ray Windows

BL Lac objects span a sequence in which the synchrotron peak frequency shifts to higher energies.

- LBL (Low-frequency-peaked BL Lacs): Synchrotron peak in IR–optical.
- IBL (Intermediate): Synchrotron peak in optical–UV.
- HBL (High-frequency-peaked BL Lacs): Synchrotron peak in UV–X-ray.

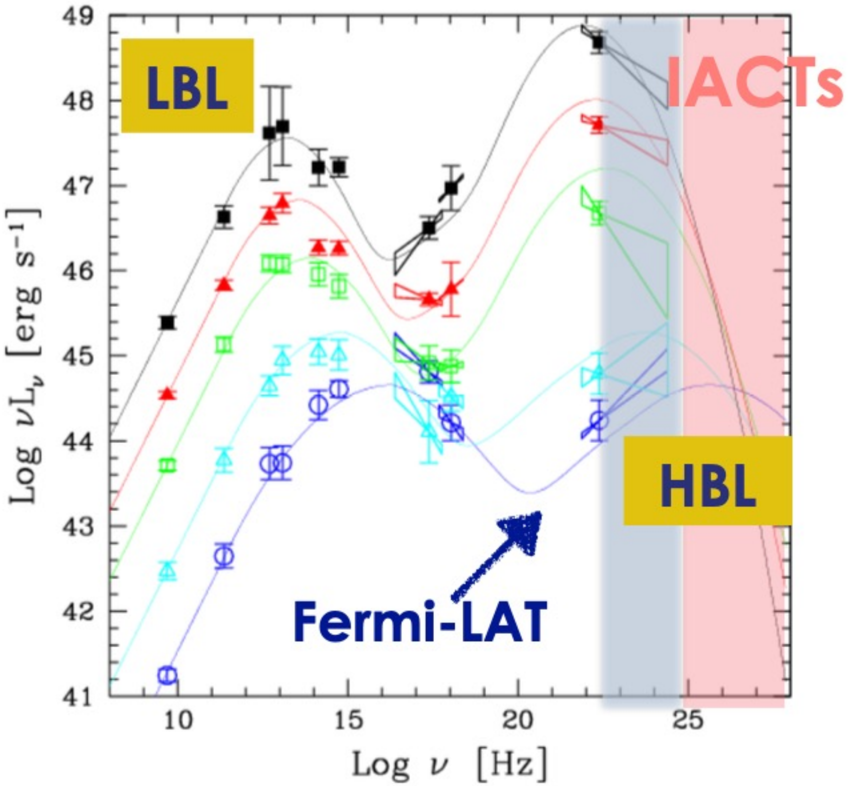
As the synchrotron peak moves to higher frequency, the inverse Compton peak also moves to higher energies.

Why this matters for gamma rays

- Fermi-LAT (100 MeV – 1 TeV) detects all types of blazars.
- IACTs (≥ 50 GeV) are most sensitive to HBLs, whose high-energy peak extends to TeV energies.
- HBLs are therefore the primary blazar population in TeV catalogs.

Blazar sequence ≠ pure luminosity sequence. It reflects intrinsic differences in electron energies, magnetic fields, and jet environment.

The BL Lac sequence (blazar sequence)



Typical properties

- LBLs: lower ν_{peak}, lower peak luminosity in gamma rays.
- IBLs: intermediate ν_{peak} and gamma-ray peak.
- HBLs: highest ν_{peak} (UV–X), gamma-ray peak in GeV–TeV.

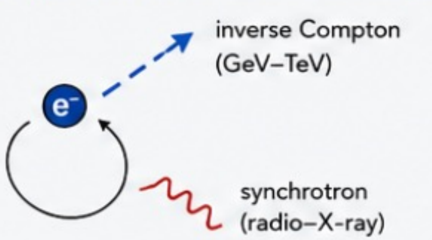
Fossati et al. 1998; Ghisellini et al. 2010

Extreme HBLs: The TeV End of the Blazar Population

A small subset of HBLs has synchrotron peaks at very high frequencies and high-energy peaks that extend to TeV energies.

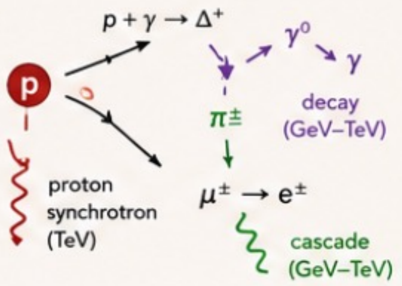
These "extreme TeV blazars" are key targets for Cherenkov telescopes (IACTs) and probe extreme jet physics.

Leptonic scenario: one-zone SSC



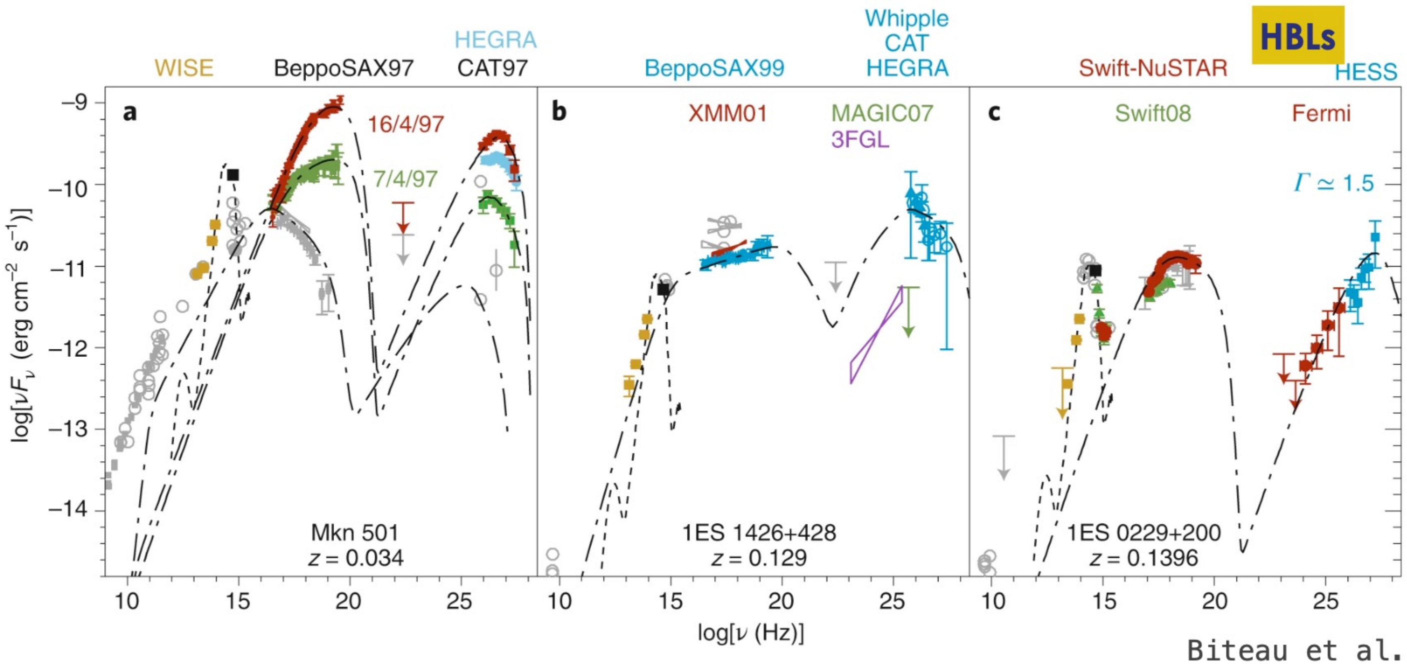
- Electrons emit synchrotron radiation.
- The same electrons upscatter synchrotron photons to gamma-ray energies.
- Fits often require high γ_{min} (>> 1), hard spectra ($p < 2$) and low B (below equipartition).

Hadronic scenario



- Protons are co-accelerated with electrons.
- TeV emission from proton synchrotron...
- ...or from pion production ($p\gamma$ interactions) and subsequent decay/cascades.
- Can reproduce hard TeV spectra and rapid variability.

Example extreme HBL



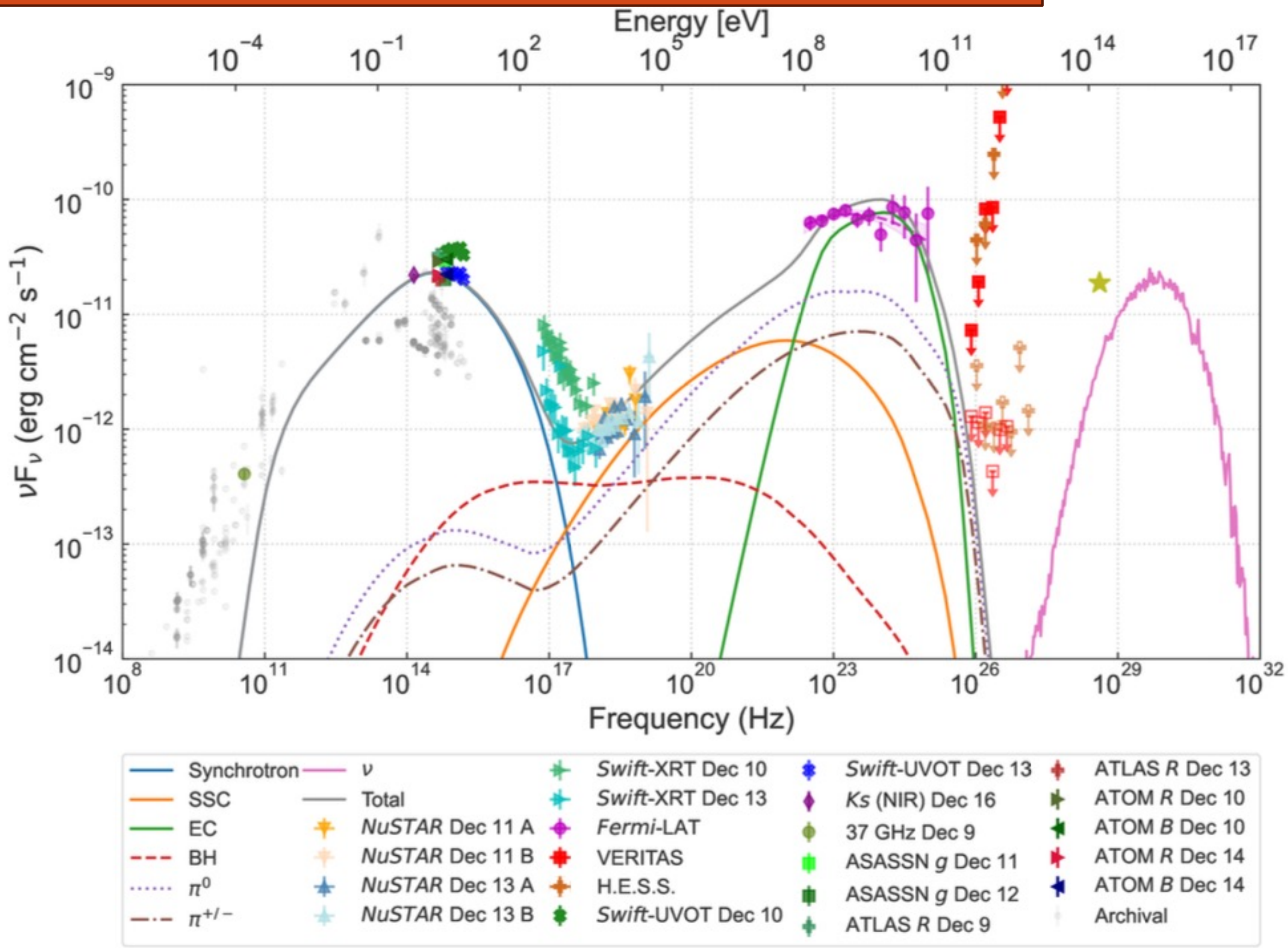
Biteau et al. 2020

- Synchrotron peak at UV–X-ray frequencies.
- High-energy component extends to multi-TeV energies.
- Extreme HBLs **test the limits of emission models and jet physics.**

PKS 0735+178: WHAT DOES THE SED TELL US?

- Possible association with IceCube-211208A (Eν=171 TeV; Dec 2021).
- Swift, NuSTAR, LAT and optical show historically high flux and daily variability.

- **SED constraints**
  - **Swift-XRT** constrains the transition between the **synchrotron** and **high-energy** components
  - **H.E.S.S. / VERITAS** upper limits indicate a **cutoff around ~100 GeV**
- **Photon interpretation**
  - The broadband SED can be reproduced with a **leptonic inverse-Compton scenario**
  - An **external soft-photon field** improves the description of the gamma-ray component
- **Neutrino connection**
  - **Lepto-hadronic scenarios** remain viable in the context of **IceCube-211208A**
  - **Photon data alone do not uniquely determine the particle content**



Feng, VERITAS + HESS 2023ApJ...954...70A

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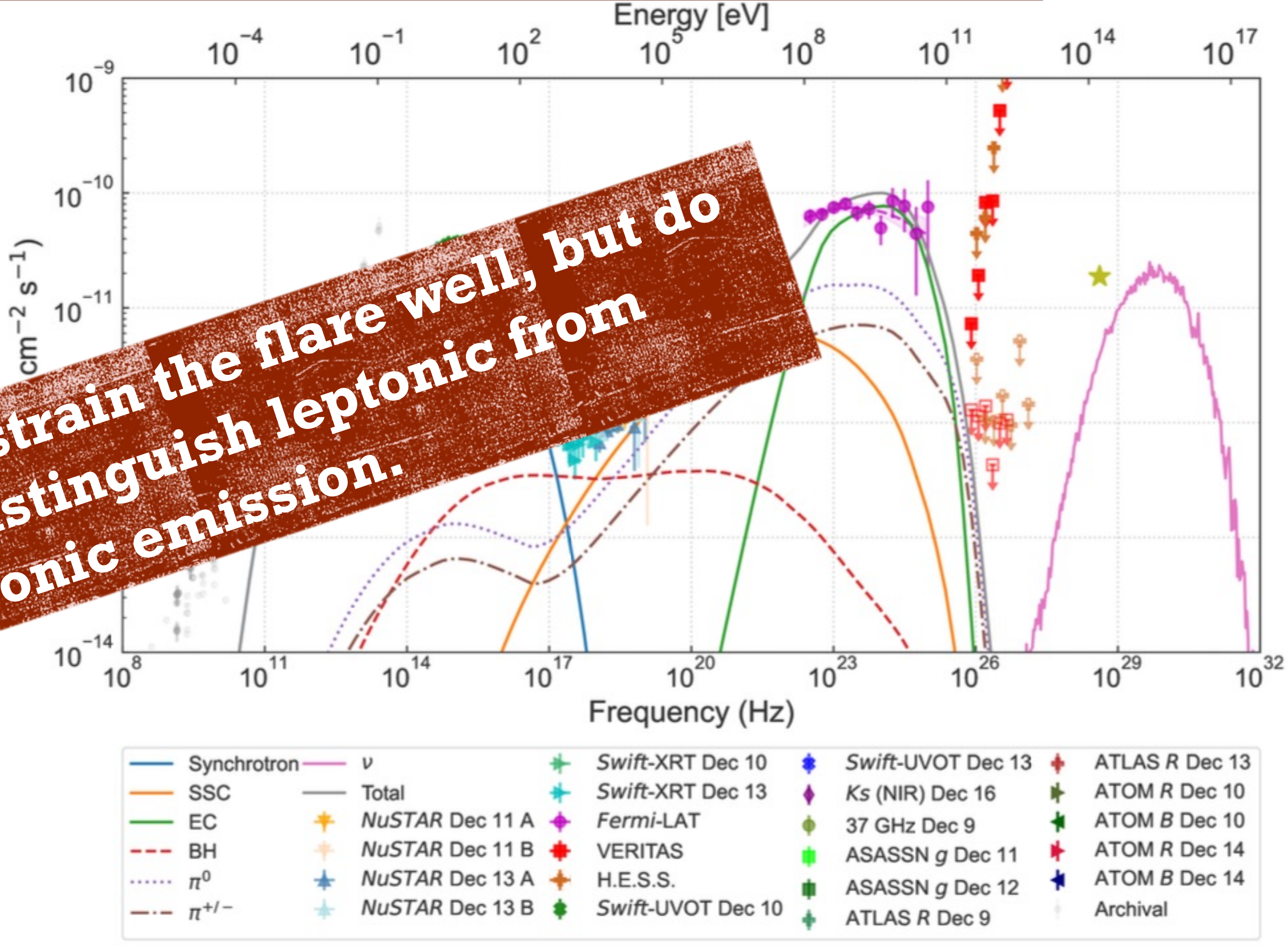
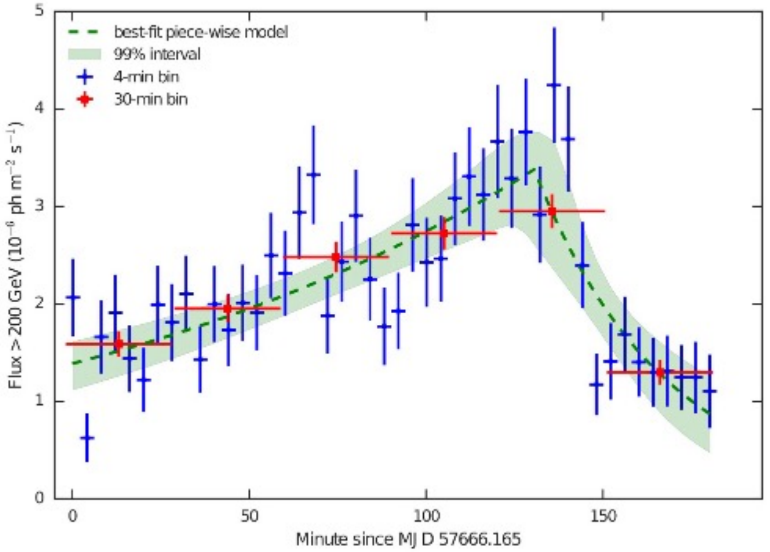
The MWL data constrain the flare well, but do not uniquely distinguish leptonic from hadronic emission.



Feng, VERITAS + HESS 2023ApJ...954...70A

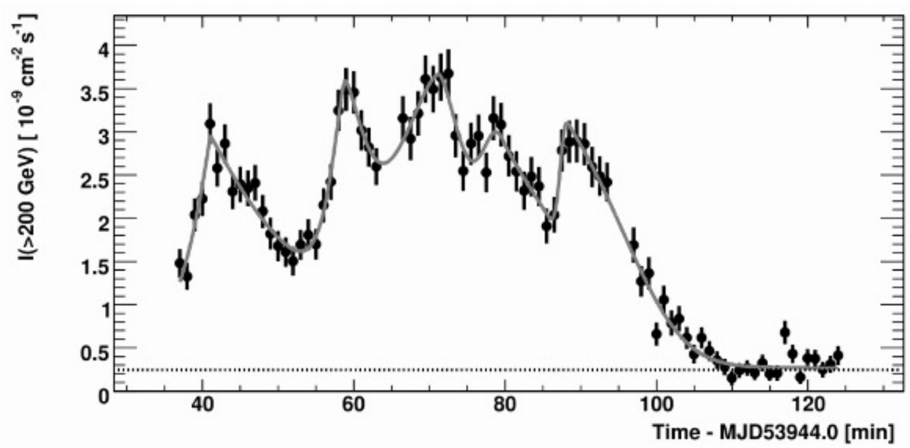
MINUTE-SCALE VARIABILITY IN BLAZARS

BL Lac



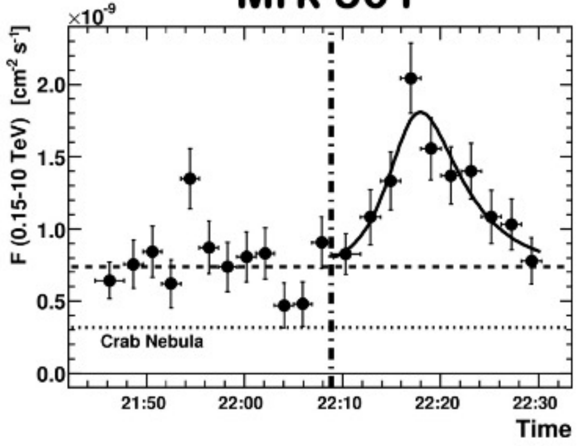
VERITAS Collaboration, 2018

PKS 2155-304



HESS Collaboration, 2007

Mrk 501



MAGIC Collaboration, 2007

Physical constraint:

- the emitting region cannot be larger than the distance light can travel during the observed variability time, once relativistic boosting and redshift are taken into account.

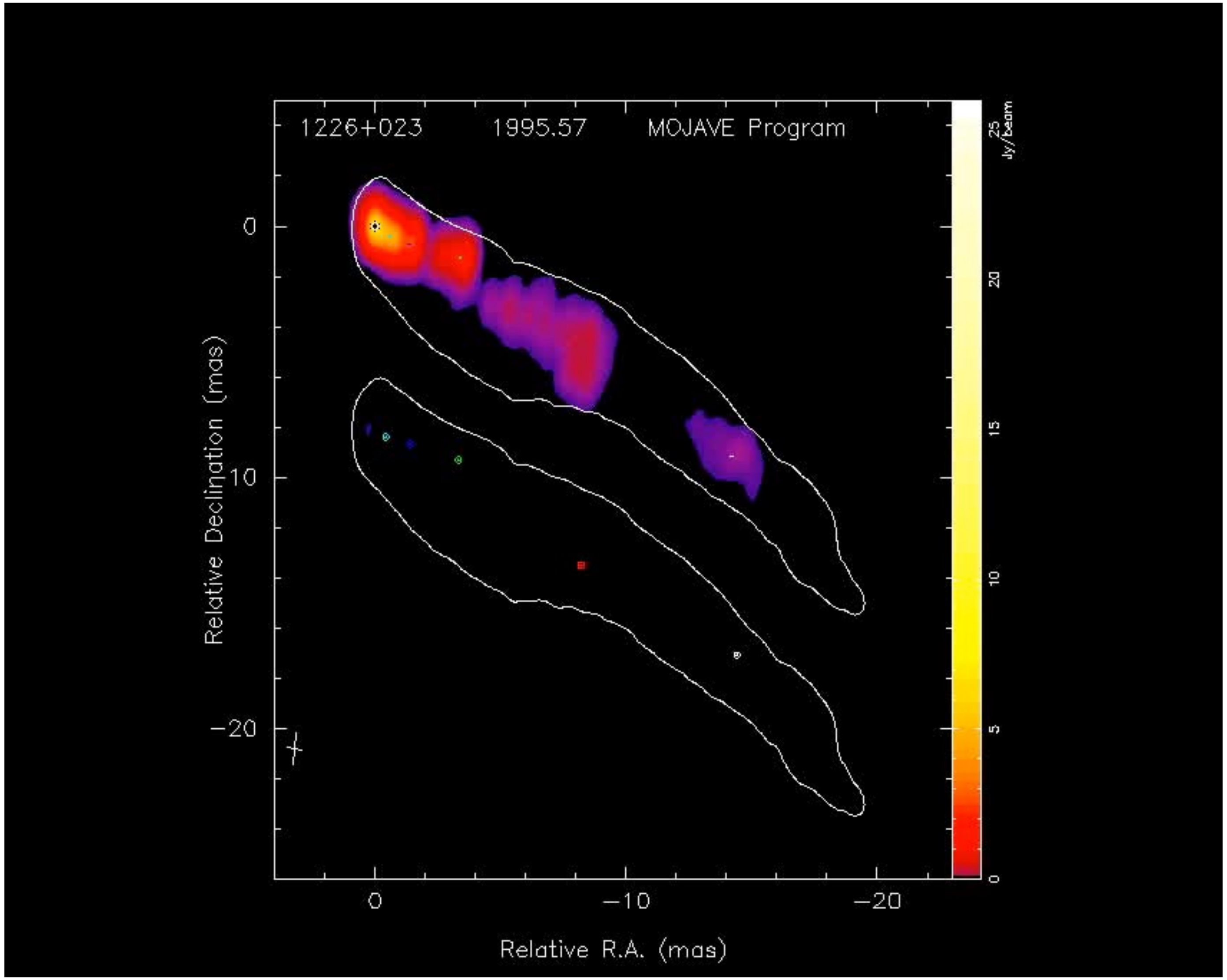
$$R \leq \frac{c t_{\mathrm{var}} \delta}{1+z}$$

- **Fast variability imposes strong constraints on the size and Doppler factor of the emission zone**

Minute-scale TeV variability implies a compact, relativistically boosted emission region

Slide: adapted Amy Furniss

RELATIVISTIC JETS IN ACTION: 3C 273

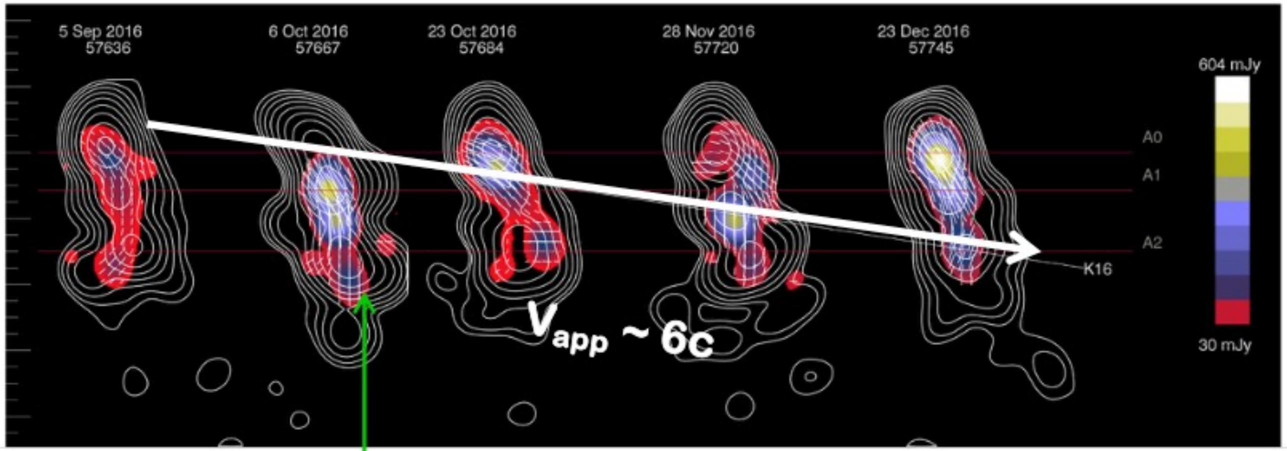


VLBI monitoring of the parsec-scale radio jet
https://www.cv.nrao.edu/MOJAVE/movies.html

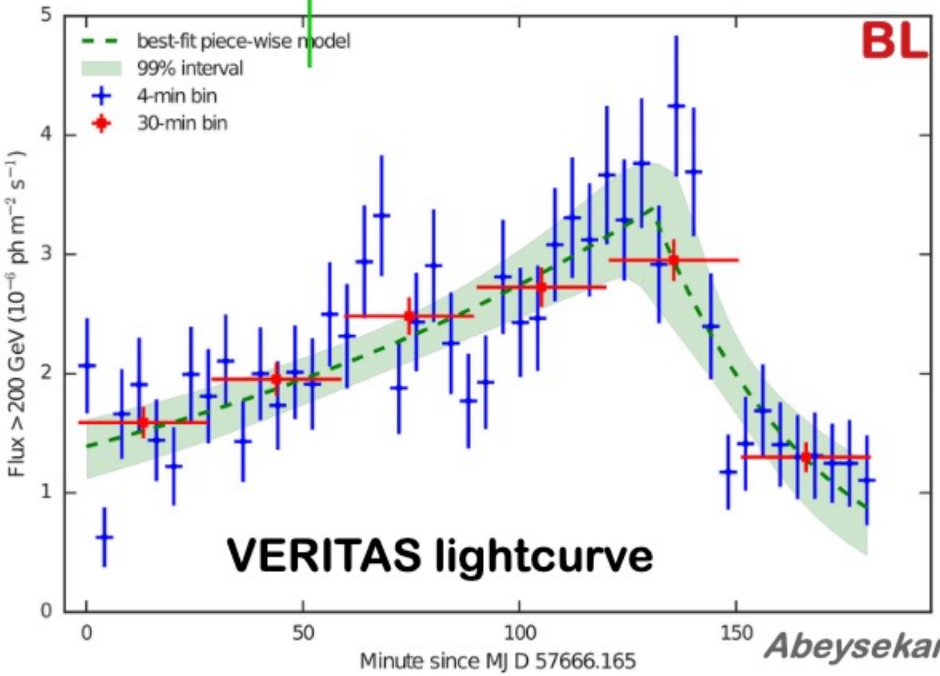
- **What the movie shows**
  - **Bright radio core** = apparent base of the jet
  - VLBI resolves **ejected knots** moving away from the **radio core**
  - **Apparent superluminal motion ⇒ relativistic jet + small viewing angle**

AGN jets are dynamic, relativistic outflows; when aligned with us, they appear as blazars.

Gamma / VLBI events – *Gamma-ray flare simultaneous with an ejecta close to the core*



BL Lacertae (2016)



Abeysekara et al. 2018

The gamma-ray flare and the ejection of a new radio knot happen at about the same time.

Also seen in:

- **3C 120 in 2012-2014** *(Casadio et al. 2015)*
- **S4 0954+658 in 2011** *(Morozova et al. 2014)*
- **BL Lacertae 2011** *(Arlen et al. 2013)*
- **3C 454.3 in 2010** *(Wehrle et al. 2012)*
- **OJ 287 in 2009, 2017** *(Agudo et al. 2010, VERITAS 2024)*
- **PKS1510-089 in 2009** *(Marscher et al 2010)*
- **BL Lacertae in 2005** *(Marscher et al. 2008)*
- **...**

Reminder: We need an emission zone…

I. relatively small

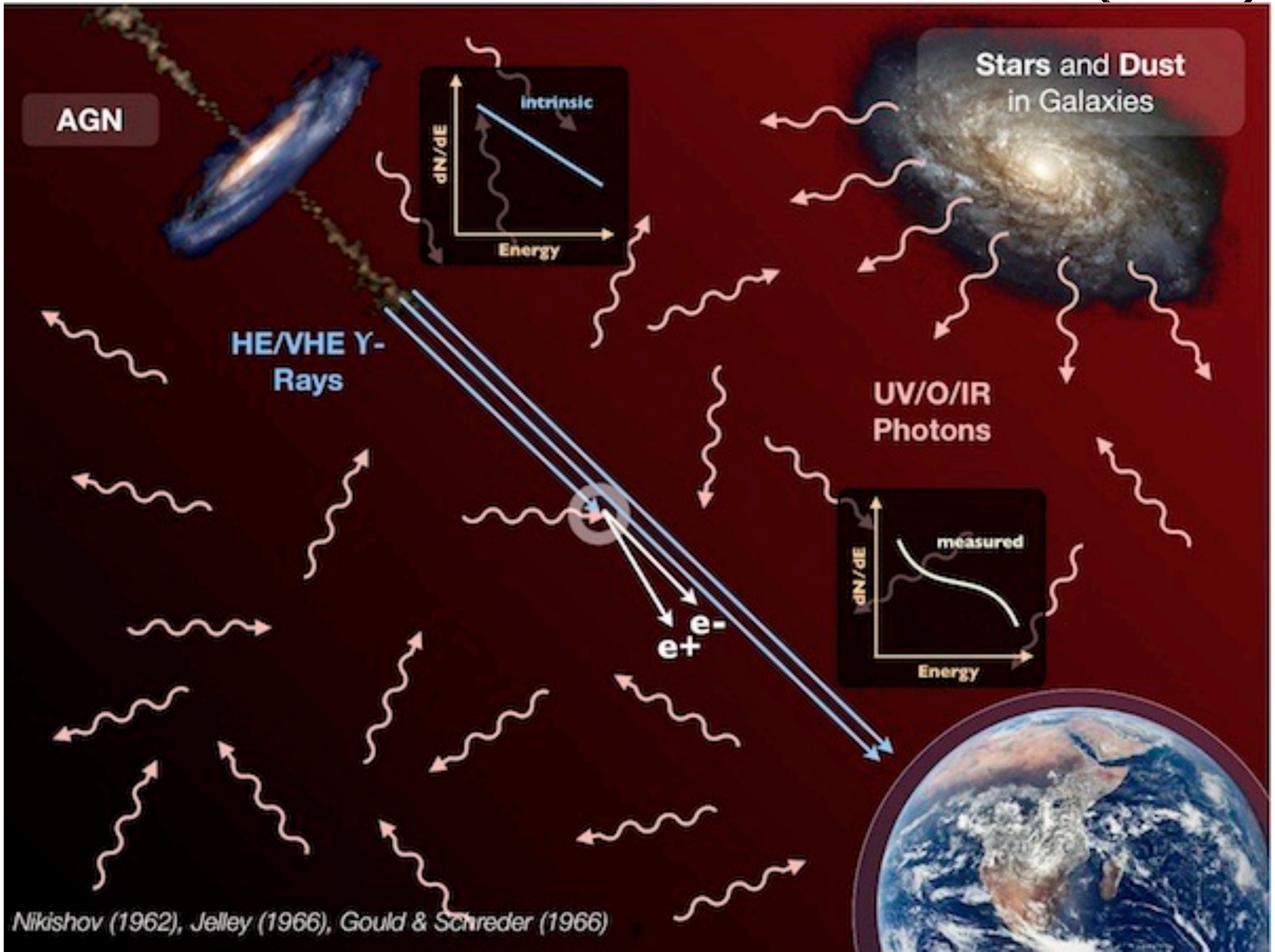
II. highly Doppler-boosted

III. not too close to the nucleus

IV. In or outside the radio core

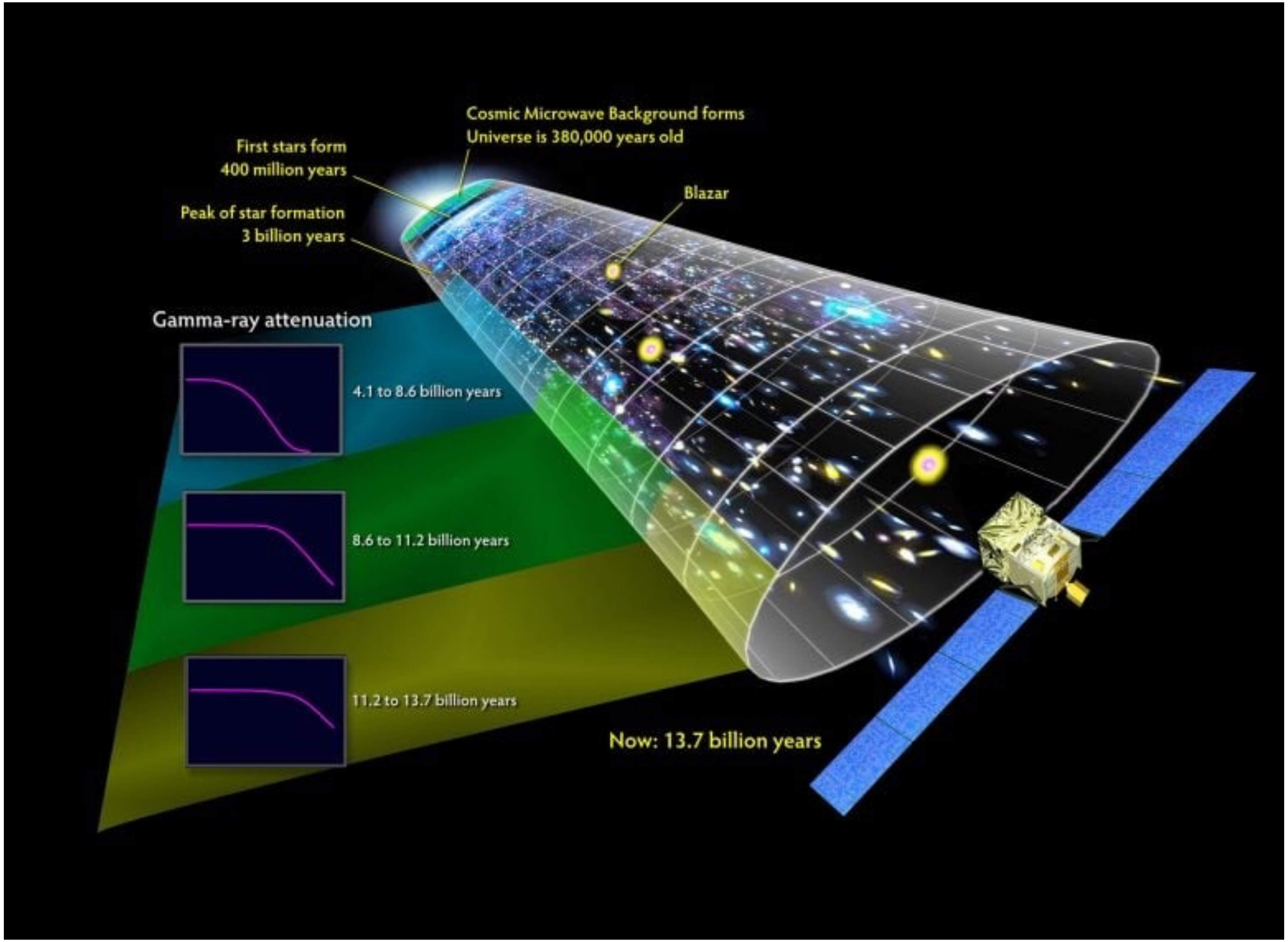
Slide: Amy Furniss

EXTRAGALACTIC BACKGROUND LIGHT (EBL)



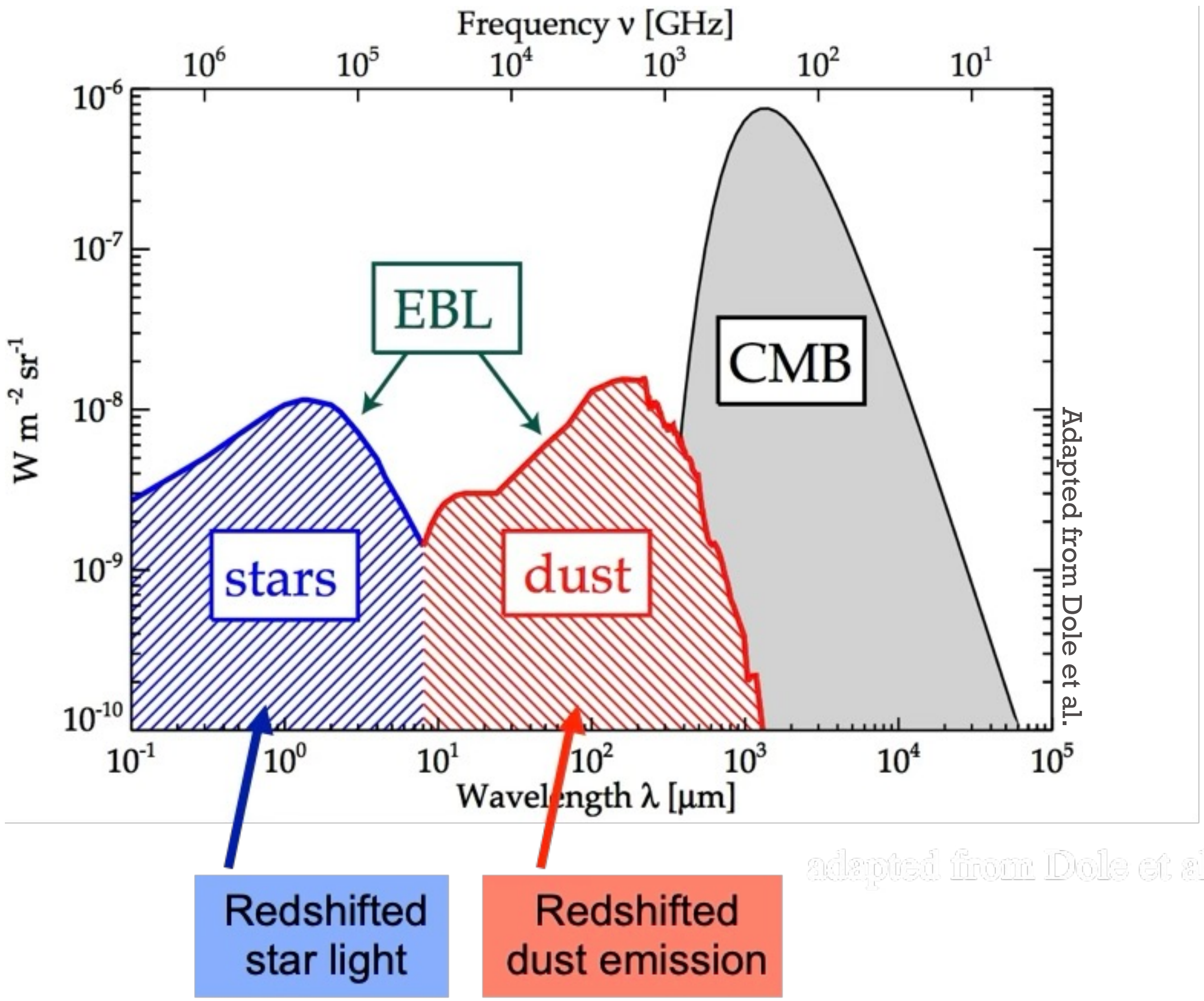
$\gamma_{VHE} + \gamma_{EBL} \rightarrow e^{+} + e^{-}$

BLAZARS AS PROBES OF COSMIC HISTORY



Credit: NASA's Goddard Space Flight Center

SPECTRAL ENERGY DISTRIBUTION OF THE EBL



adapted from Dole et al.

- **EBL** = integrated starlight + dust-reprocessed infrared light from galaxy evolution
- Unique imprint of the history of the universe
- Test of star formation and galaxy evolution models
- Cosmological evolution models have to explain current EBL
- **TeV gamma rays** are strongly affected by **optical/IR EBL photons**
- The higher the gamma-ray energy and the larger the redshift, the stronger the attenuation
- Optical and infrared light can interact with > 100 GeV extragalactic photons.
- Difficult to observe directly due to strong foreground sources.

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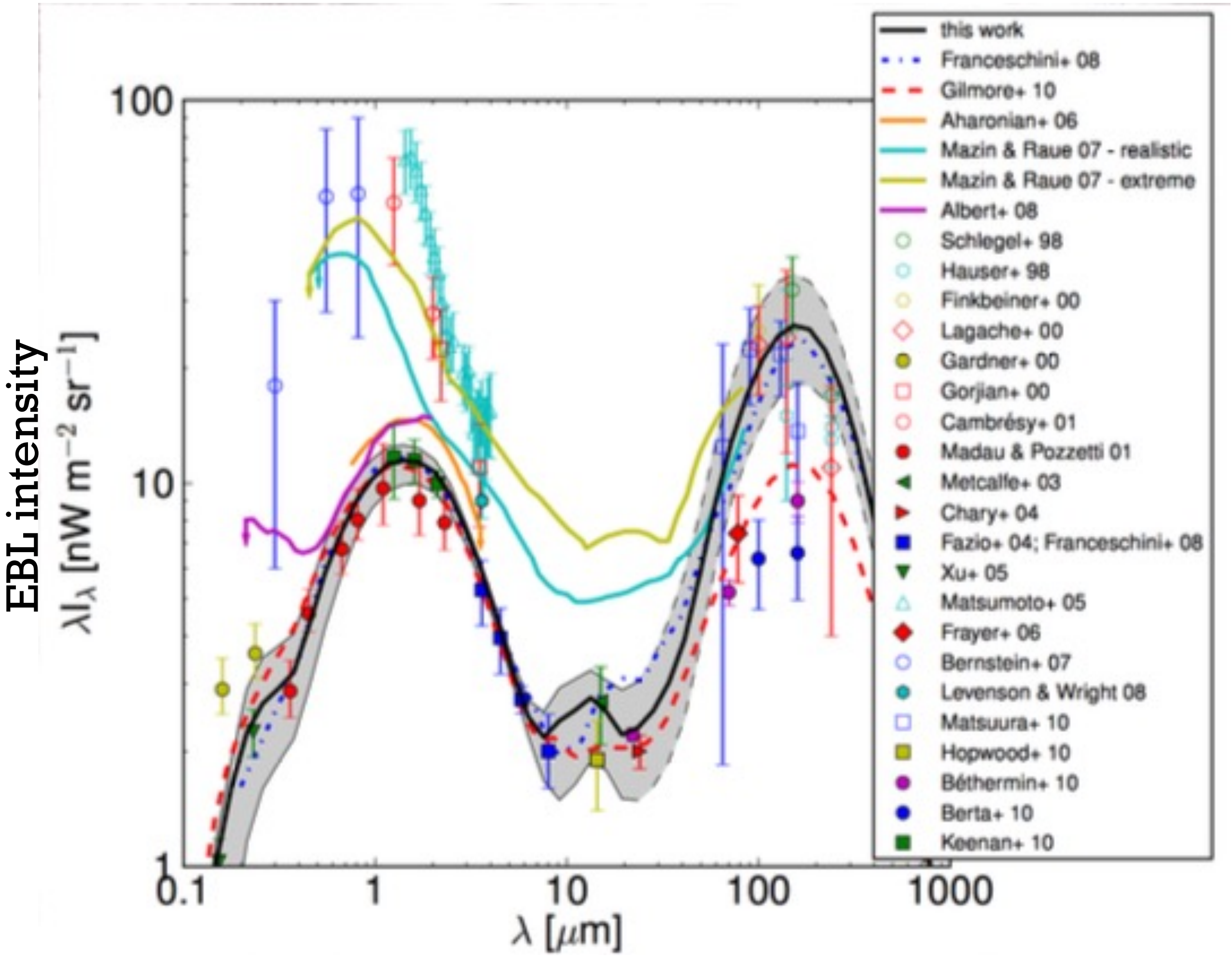

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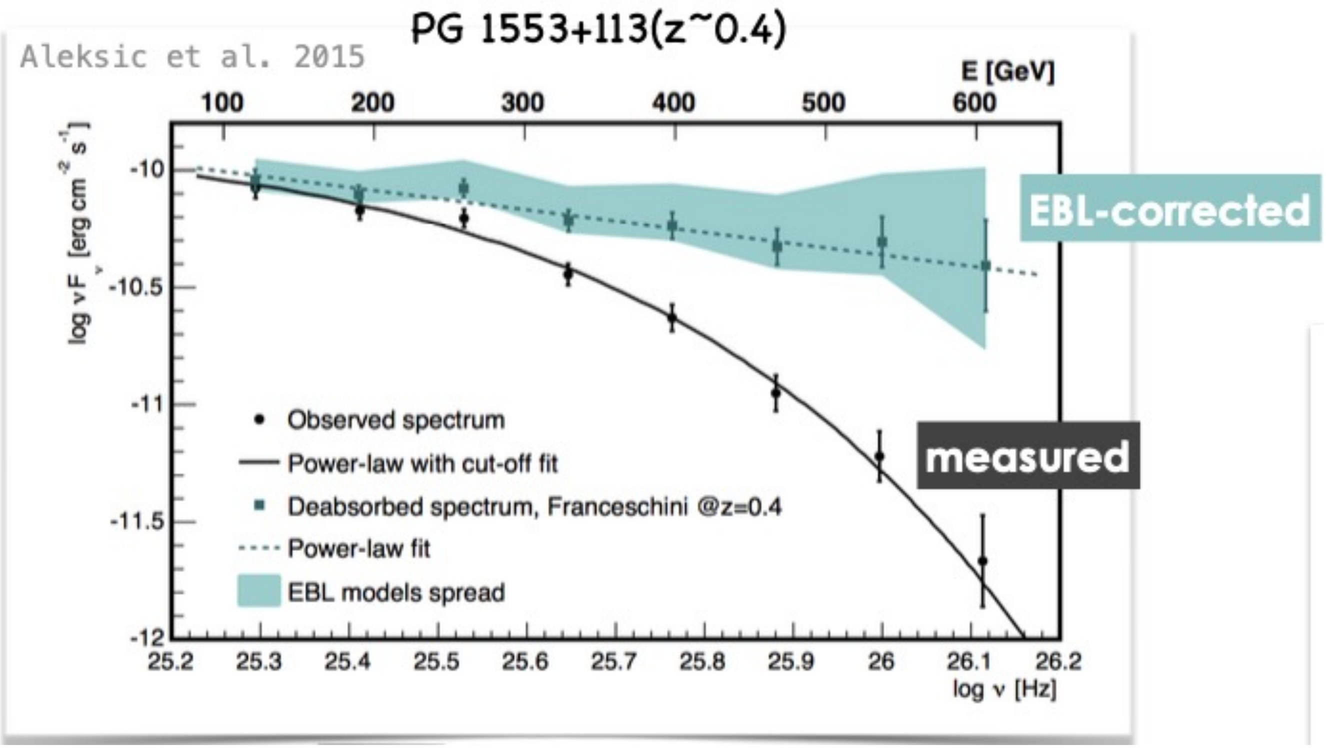
BLAZAR SPECTRA AS PROBES OF THE EBL



$\mathbf{F_{obs}(E,z)=F_{int}(E)e^{-\tau(E,z)}}$

F_{obs}: observed spectrum

F_{int}: intrinsic source spectrum

$\tau(E, z)$: optical depth due to the EBL

E: gamma-ray energy

z: source redshift

Gamma-ray attenuation by the EBL

- **VHE gamma rays from distant blazars interact with EBL photons**

$$\gamma_{\mathrm{VHE}} + \gamma_{\mathrm{EBL}} \rightarrow e^{+}e^{-}$$

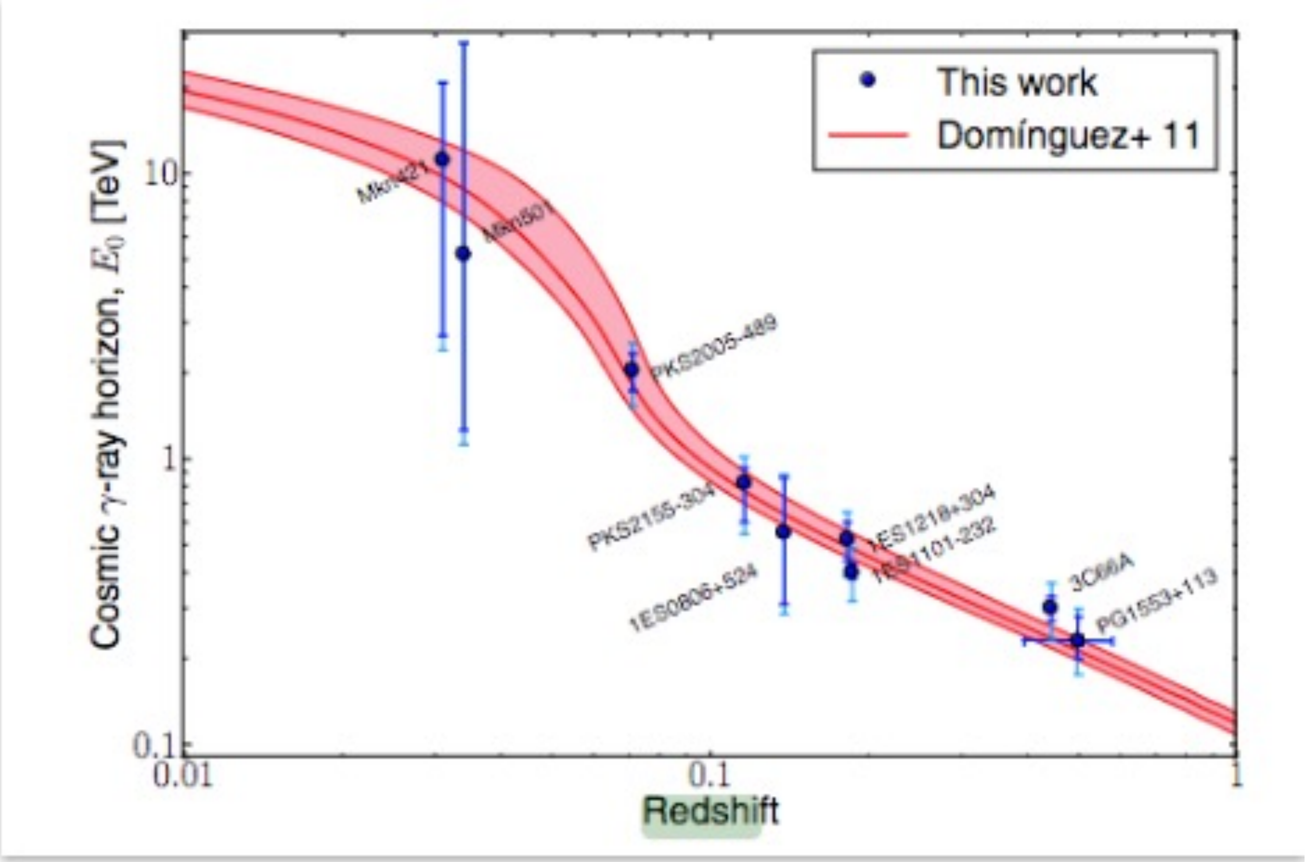
- This produces an **energy- and redshift-dependent suppression** of the observed spectrum:

$$F_{\mathrm{obs}} = F_{\mathrm{int}}\, e^{-\tau(E, z)}$$

- By fitting the **intrinsic blazar spectrum** and measuring the attenuation, we constrain the **EBL optical depth** $\tau(E, z)$and therefore the **EBL intensity / gamma-ray horizon**.

Blazars act as cosmic backlights:
the EBL is measured from the attenuation imprinted on their GeV–TeV spectra.

GAMMA-RAY HORIZON: WHAT DO WE LEARN FROM EBL ATTENUATION?

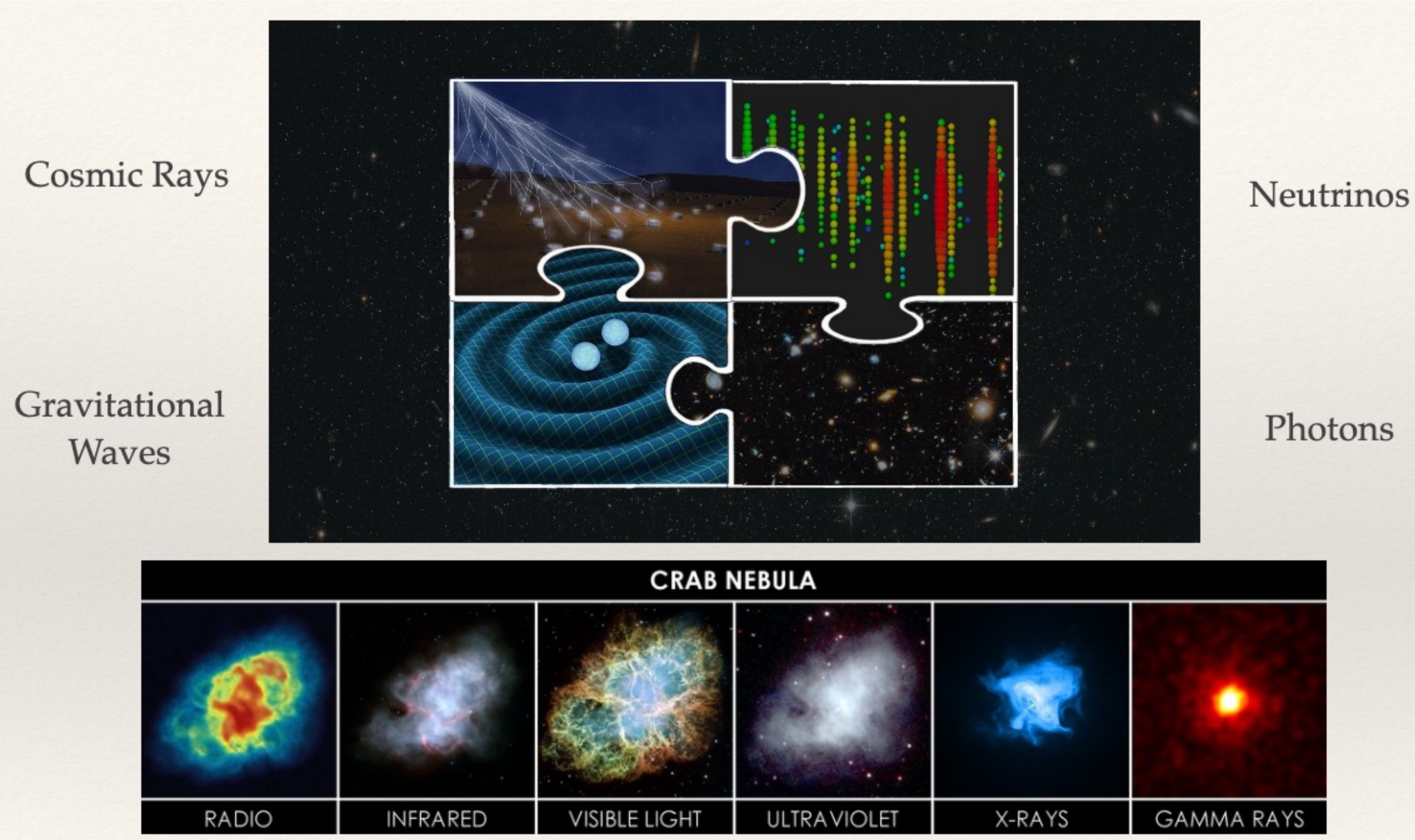


Dominguez et al. 2011

- **EBL absorption defines a gamma-ray horizon:** the farther the source, the lower the maximum energy we can observe.
- **Blazars and GRBs act as backlights:** comparing observed and intrinsic spectra measures the optical depth $\tau(E, z)$.
- **Therefore gamma-ray spectra probe cosmic light production:** the EBL encodes the history of **star formation, dust reprocessing, and galaxy evolution**.

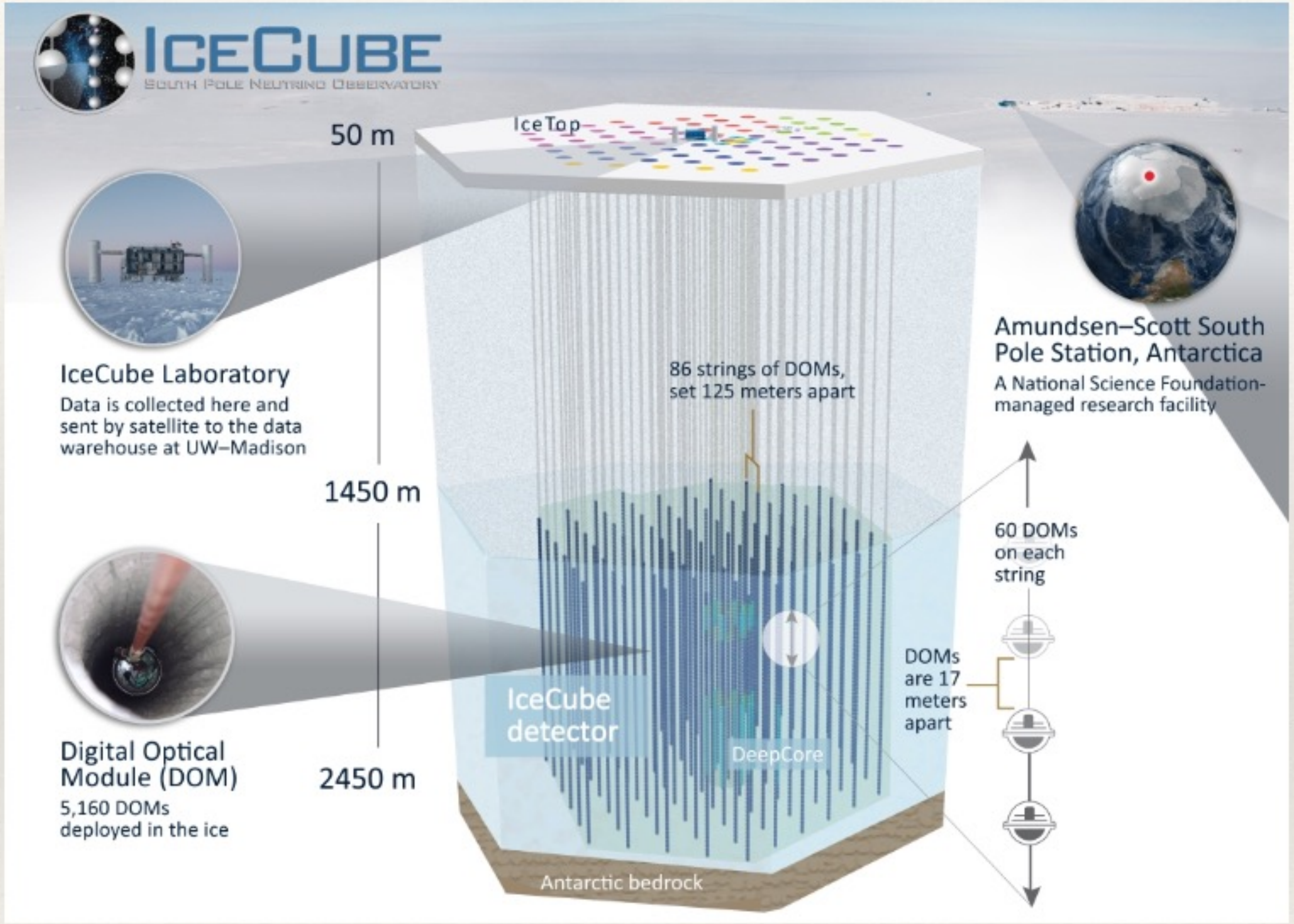
The Universe is transparent to GeV photons, but increasingly opaque to TeV photons at high redshift.

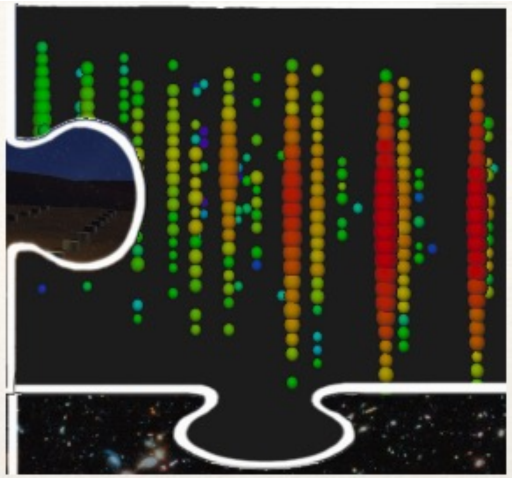
LET'S GET A DIFFERENT LOOK



Slide: Abhishek Desai

THE MULTI MESSENGER PICTURE



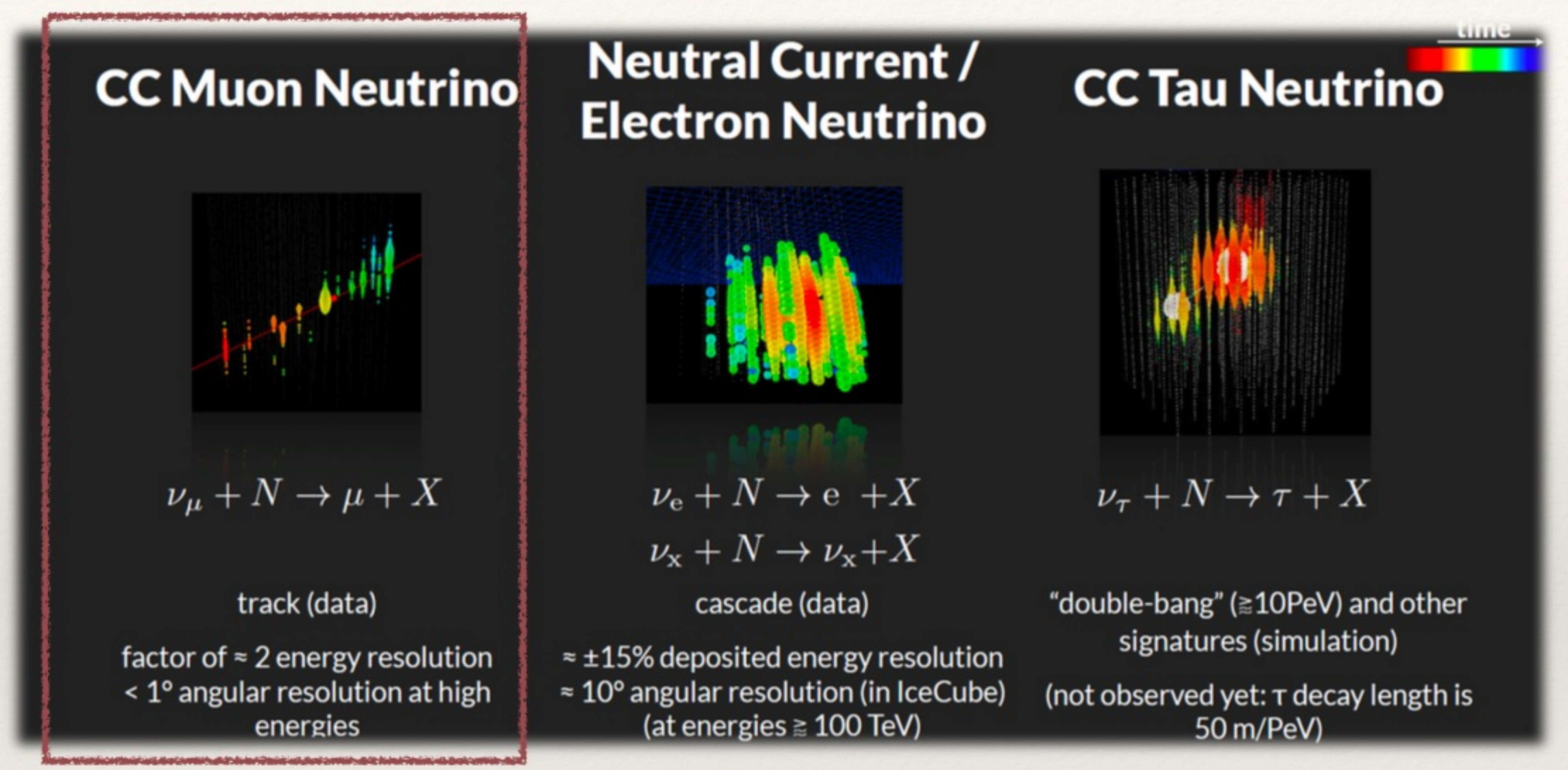


Neutrinos

AGNs are the only Confirmed Extragalactic IceCube Neutrino Sources… till now

Slide: Abhishek Desai

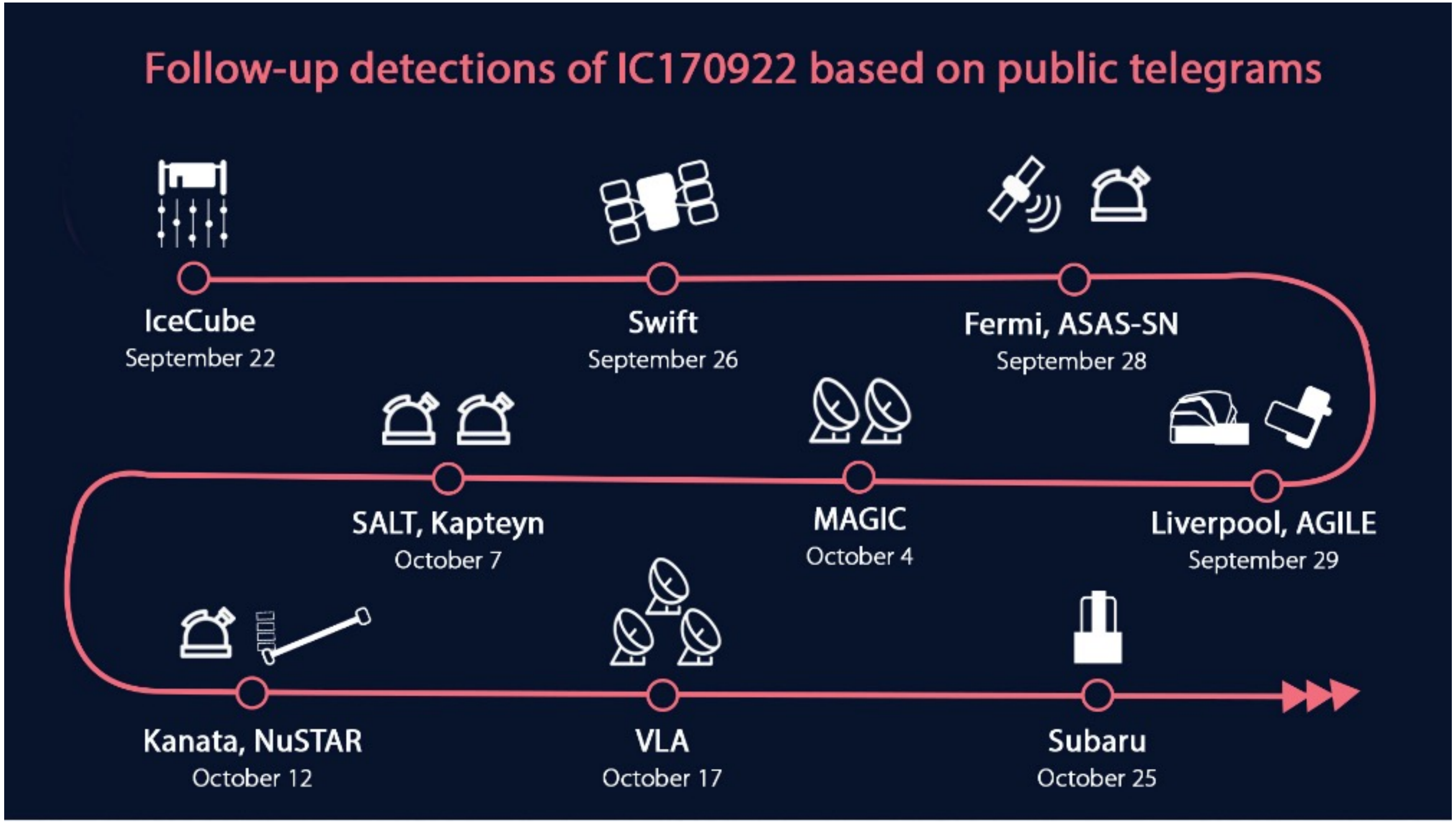
HOW AGN BECAME INTERESTING FOR NEUTRINO STUDIES



The IceCube Collaboration. Science 2018, 361

Slide: Abhishek Desai

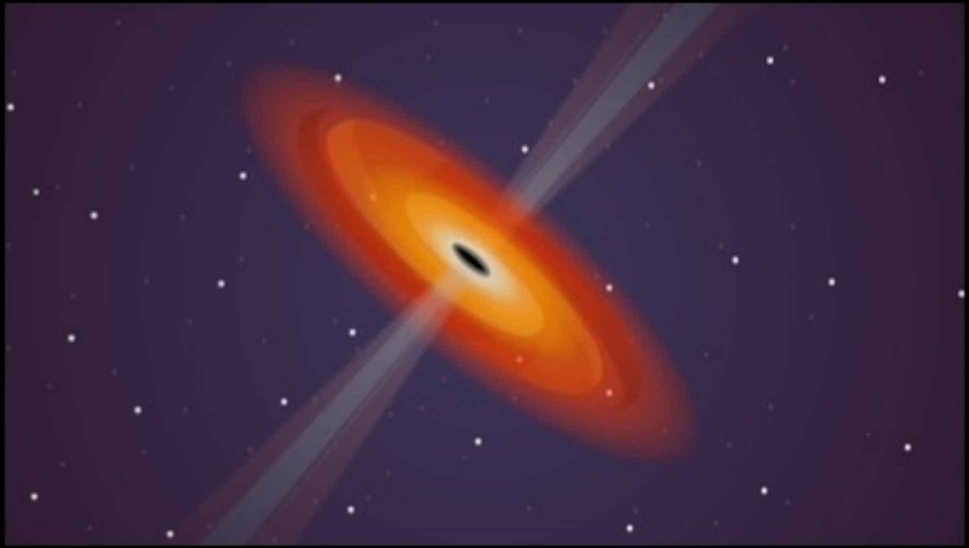
ICECUBE DETECTS A ~290 TEV NEUTRINO AND SENDS AN ALERT



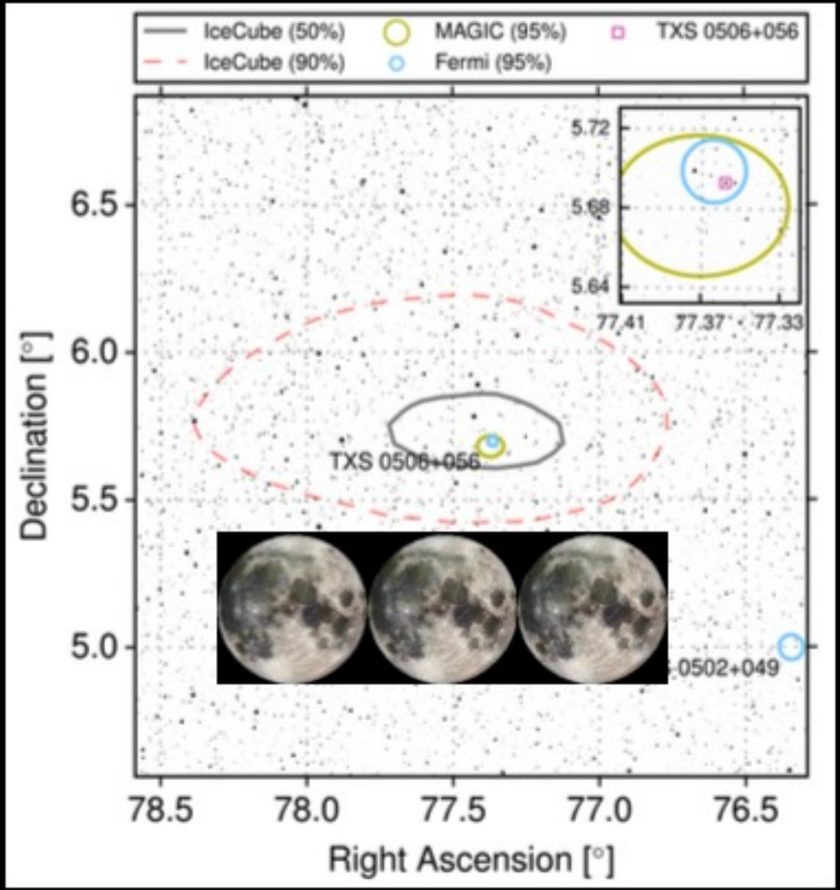
Slide: Abhishek Desai

First confirmed cosmic/extragalactic neutrino

Galaxy **TXS 0506+056** : a blazar in Orion



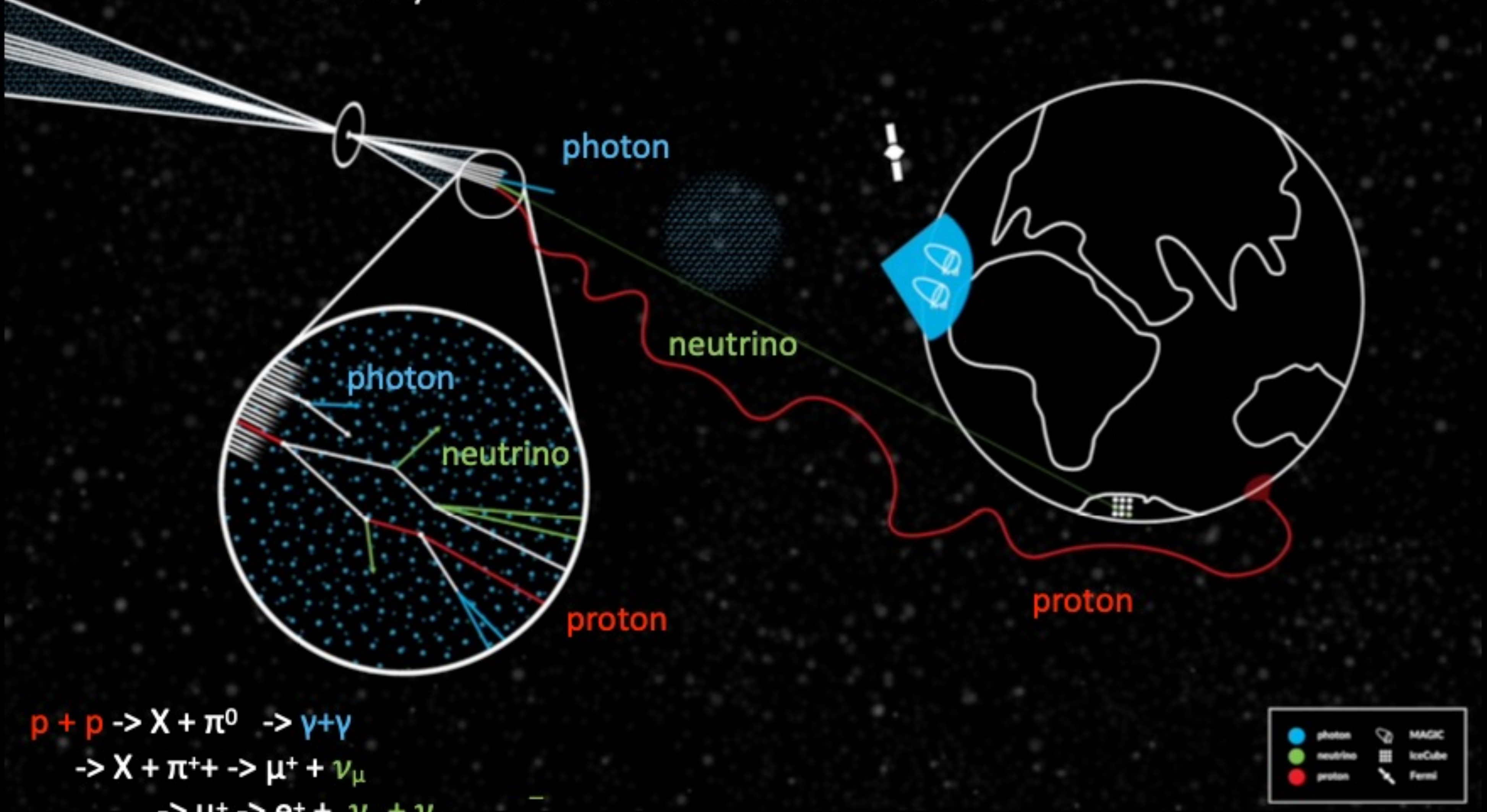
z = 0.34 (Paiano et al. 2018)



Slide: Alicia López

First confirmed cosmic/extragalactic neutrino

Galaxy **TXS 0506+056** : a blazar in Orion



$p + p \rightarrow X + \pi^0 \rightarrow \gamma+\gamma$

$\rightarrow X + \pi^{+}+ \rightarrow \mu^+ + \nu_\mu$

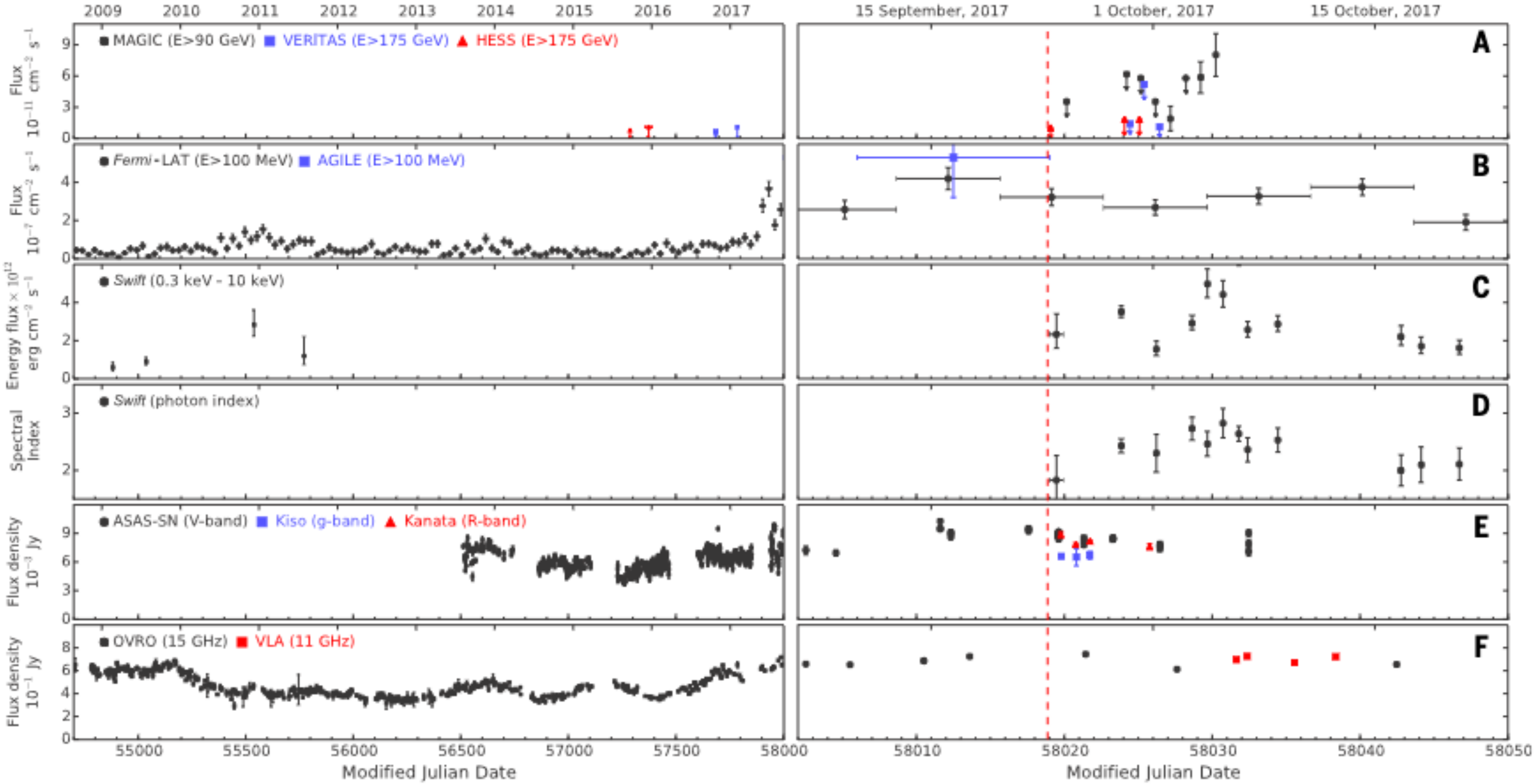
$\rightarrow \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Aartsen et al. (ICECUBE, Fermi, MAGIC+), Science, 2018

Slide: Alicia López

WHAT'S THE ROLE OF FERMI LAT HERE?

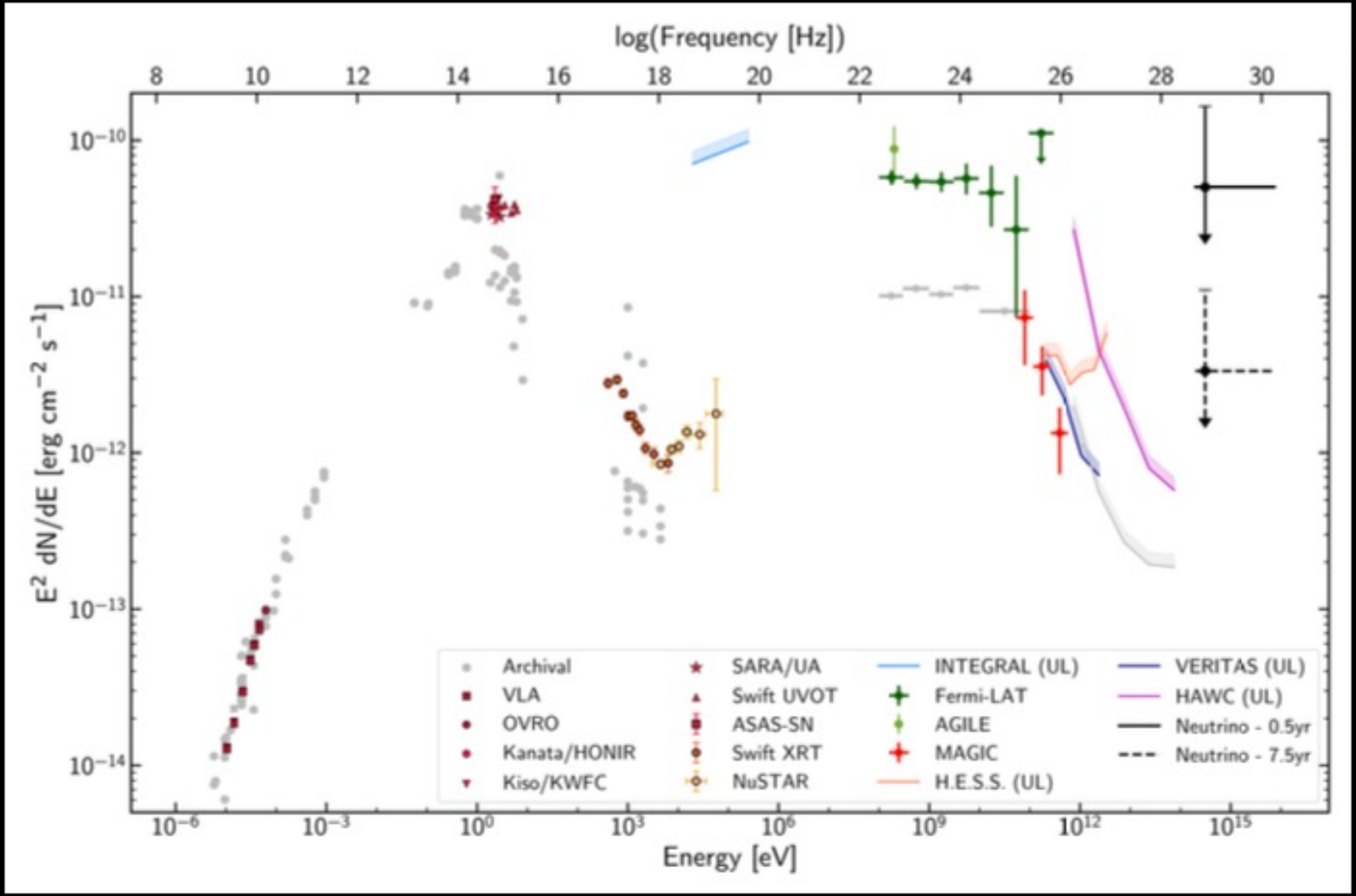
- Neutrino Alert: IC-170922A (Red dashed line); Blazar: **TXS 0506+056**
- TXS 0506+056 was in an enhanced GeV gamma-ray state around the neutrino alert, as seen by Fermi-LAT.
- LAT identified it as the most plausible active blazar counterpart and motivated VHE follow-up.



The IceCube Collaboration. Science 2018, 361

Slide: adapted from Abhishek Desai

First confirmed extragalactic neutrino of identified origin



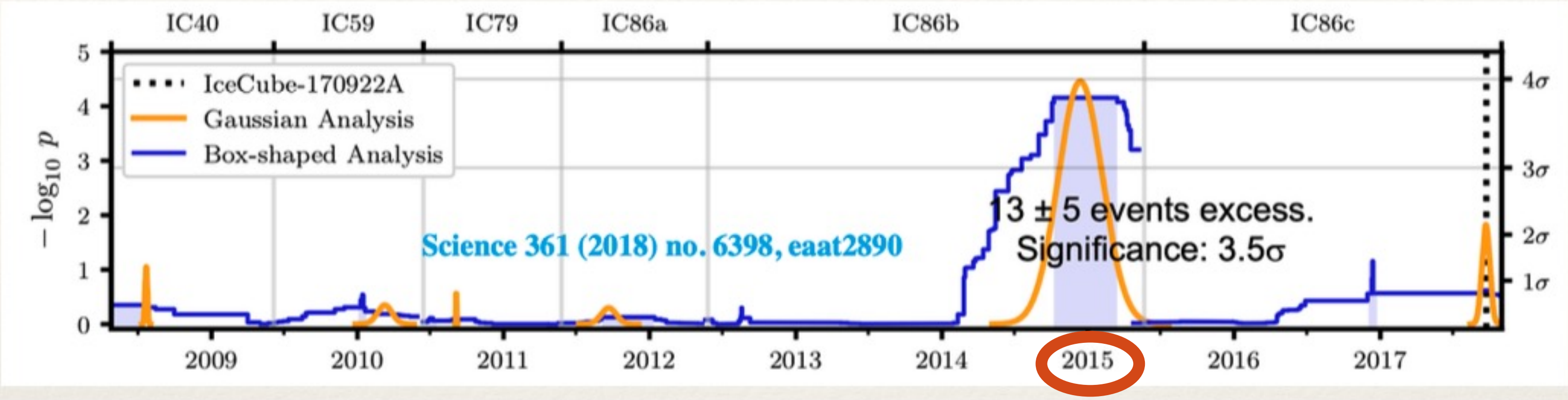
Aartsen et al. (ICECUBE, Fermi, MAGIC+), Science, 2018

More interesting results released by ICECUBE in the past years

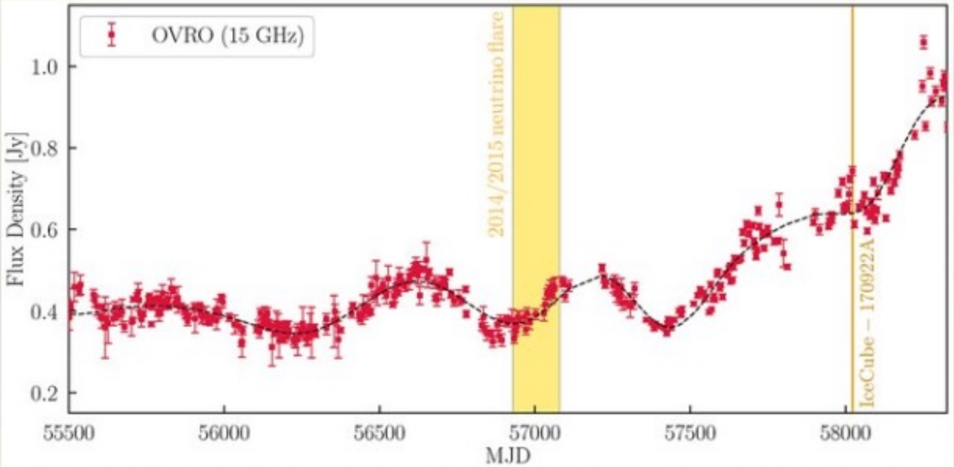
Science Magazine 2018 Breakthrough:
2º Editor's Choice
3º People's choice

Slide: Alicia López

GAMMA-RAYS OR NO GAMMA-RAYS?



- More significant flare detected from same direction!!!
- But no Gamma-ray flaring activity during that time from Fermi-LAT



Halzen 2021, adp

TXS 0506+056 gave us both a neutrino+gamma-ray coincidence in 2017 and a neutrino flare without a clear gamma-ray counterpart in 2014–15, which means the neutrino–gamma-ray connection in blazars is real but not straightforward.

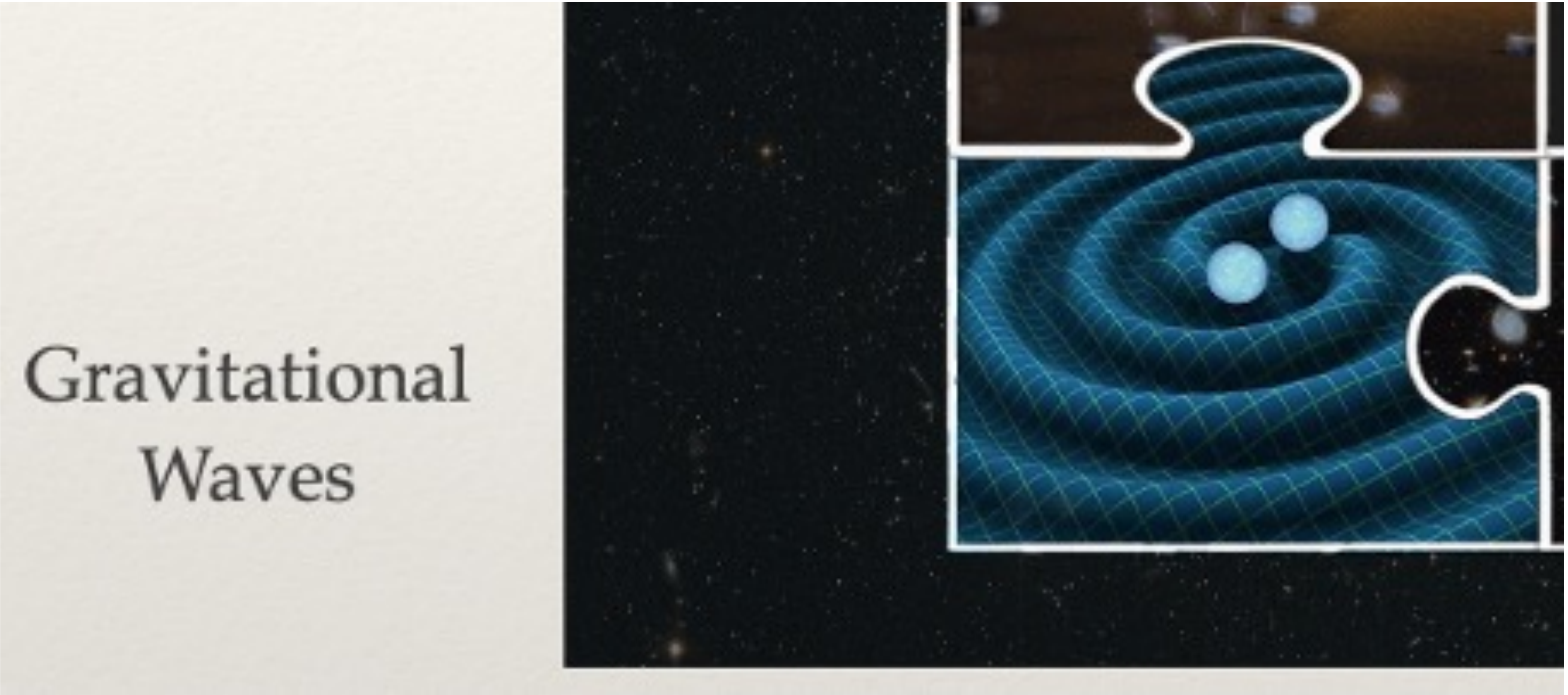
Slide: Abhishek Desai

AGN & NEUTRINOS: WHAT DID WE LEARN?

- **IceCube + Fermi-LAT + MWL follow-up** turned TXS 0506+056 into the first convincing **extragalactic neutrino source association**.
- The source shows **two behaviors**:
  - **2017:** neutrino + gamma-ray flare
  - **2014–15:** neutrino flare without a strong GeV counterpart
- This suggests **hadronic activity in AGN jets**, but likely in a **complex environment** rather than a simple one-zone picture.
- AGN are therefore a **prime target for multi-messenger astronomy**, linking **photons, neutrinos, and cosmic-ray acceleration**.

Neutrinos show that at least some blazar jets accelerate hadrons — but how that connects to the observed gamma rays is still an open question.

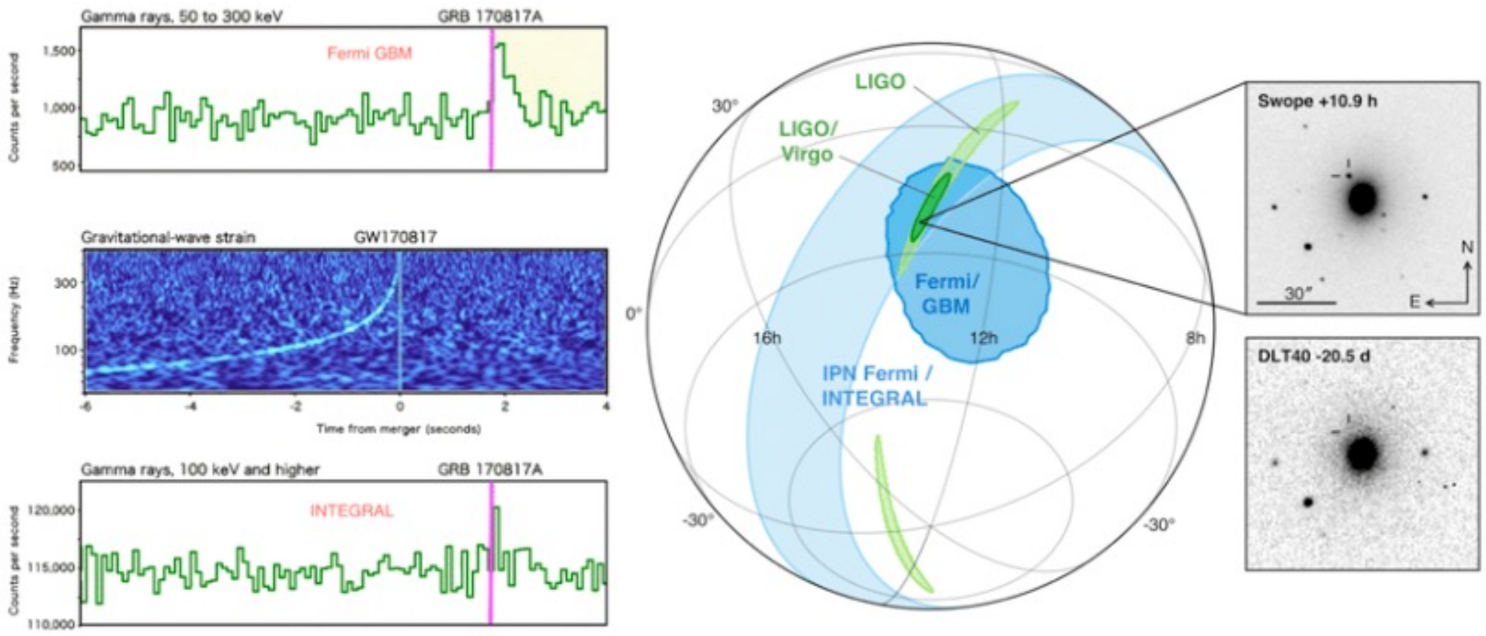
GRAVITATIONAL WAVE COUNTERPARTS



SHORT GRBS: BINARY NEUTRON STAR (BNS) MERGERS

- **GW 170817 (On 2017 August 17, at 17:54:51 UTC): binary NS merger** detected by **LIGO/VIRGO** (Abbot et al. 2017)
  - **EM counterpart GRB170817: kilonova**
  - Result: BH (2.73 - 3.29 M⊙)

Birth of multi-messenger astronomy with GW
First evidence of BNS mergers as progenitors for sGRB



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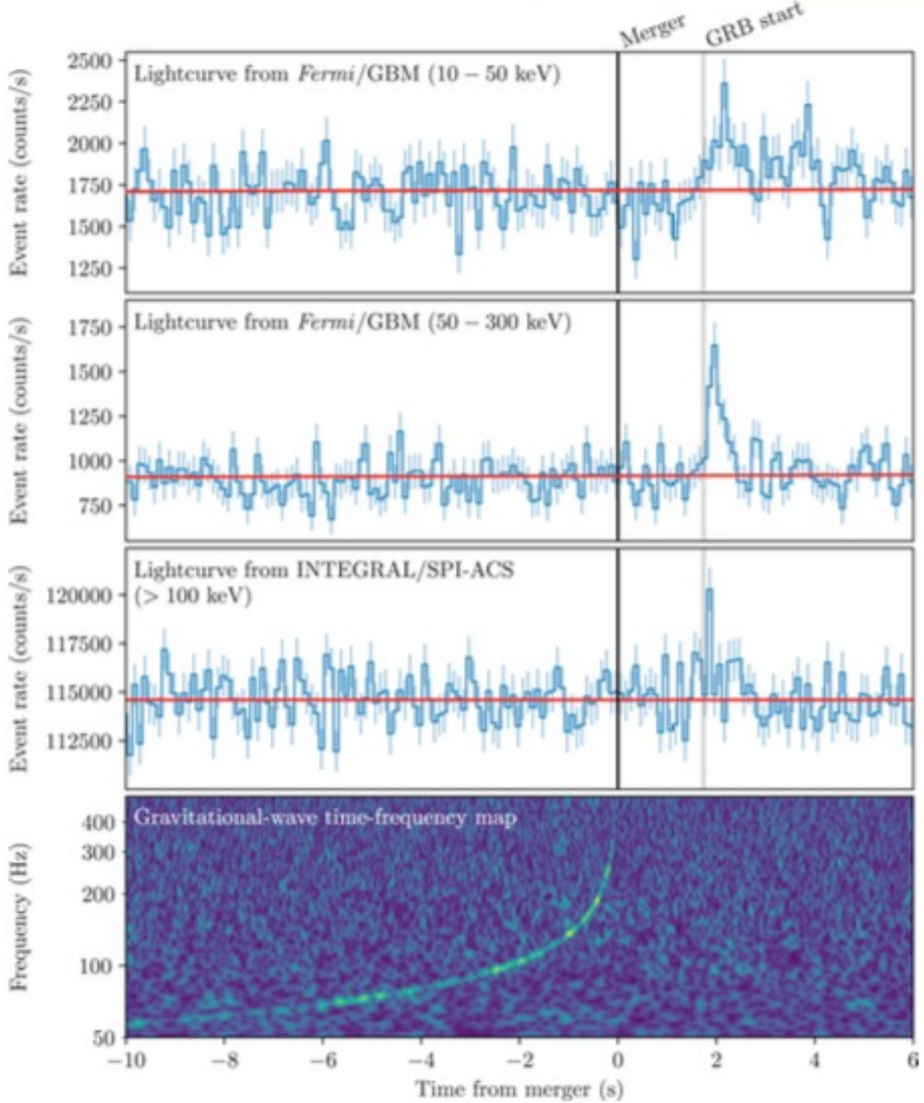
LIGO/VIRGO

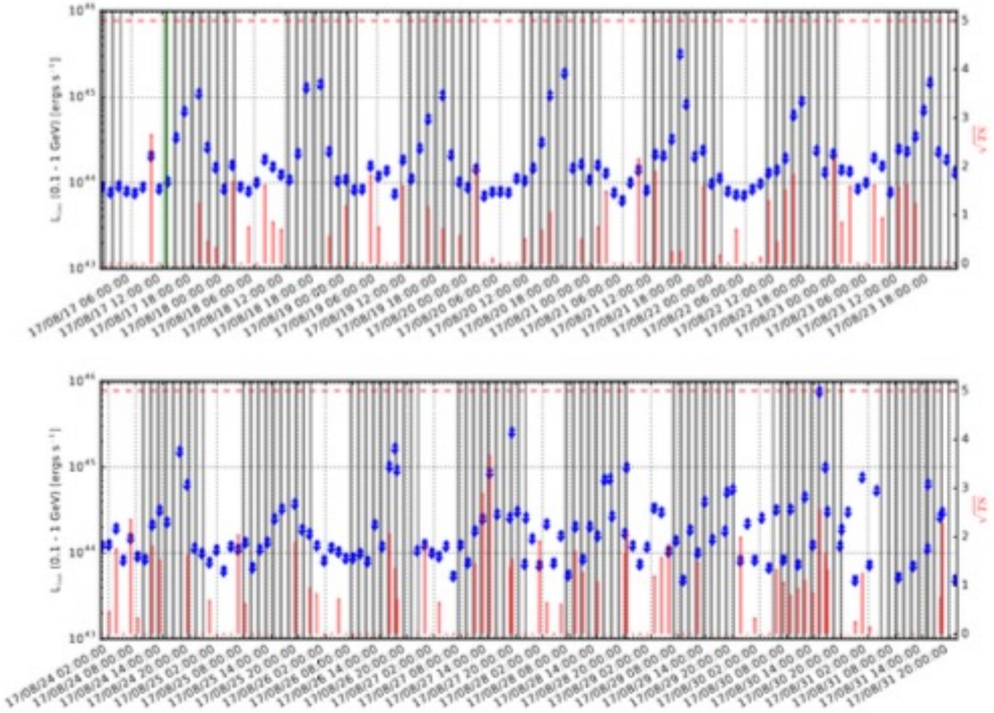
Slide: Alicia López

GW 170817 AT HIGH ENERGIES



Abbot et al. 2017

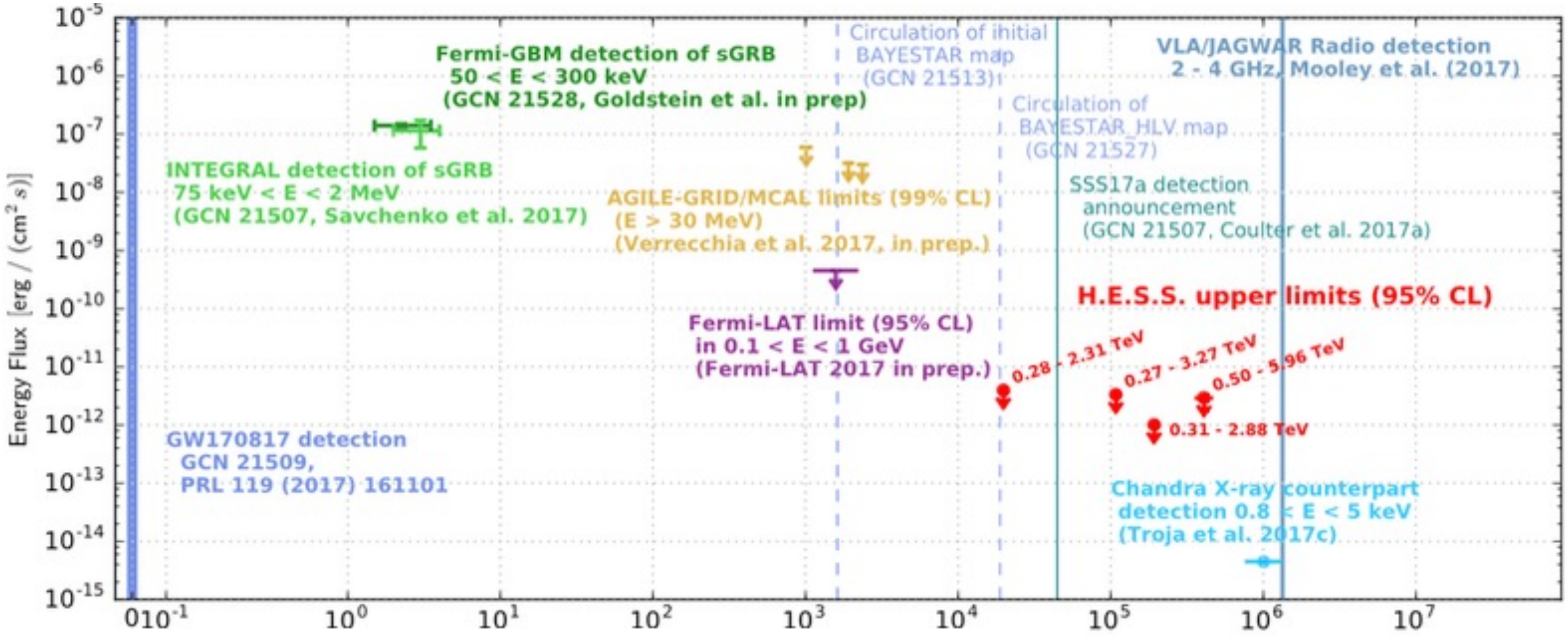
- **Fermi-GBM detected** the GRB right after the merger
- **No detection by Fermi-LAT**
  - LAT was not collecting data due to a passage through the South Atlantic Anomaly (SAA), and was thus unable to observe the prompt emission phase of the GRB
  - The LAT resumed collecting science data ~ 103 seconds later



Fermi-LAT 2017

Slide: Alicia López

GW 170817 AT VERY HIGH ENERGIES



- HESS Observations between Aug 17 - Aug 22
- No VHE detection (Abdalla et al. 2017)

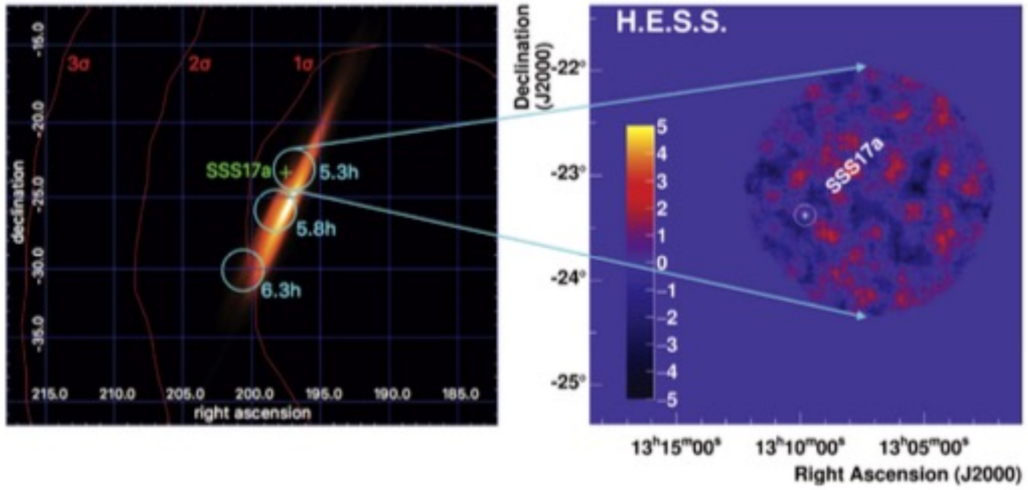


Table 2
Limits on the High-energy Gamma-Ray Flux at 95% C.L. and Assuming a E^{-2} Energy Spectrum Obtained During the Monitoring of SSS17a with H.E.S.S.

Pointings (See Table 1)	Time since GW170817 (days)	f_γ (erg cm^{-2} s^{-1})	Energy Band (TeV)
1a	0.22	$<3.9 \times 10^{-12}$	0.28–2.31
2a+2b	1.22	$<3.3 \times 10^{-12}$	0.27–3.27
3a+3b	2.22	$<1.0 \times 10^{-12}$	0.31–2.88
5a+6a	4.23, 5.23	$<2.9 \times 10^{-12}$	0.50–5.96
all	0.22—5.23	$<1.5 \times 10^{-12}$	0.27–8.55

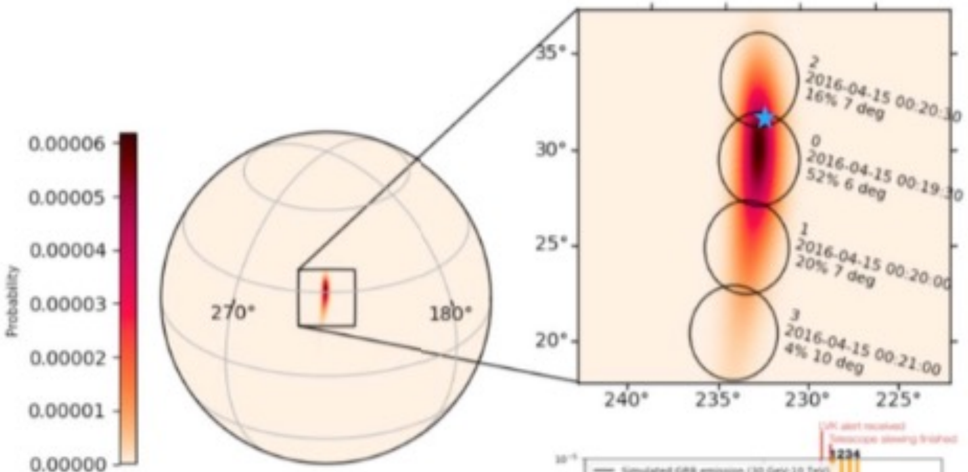
Abdalla et al. 2017

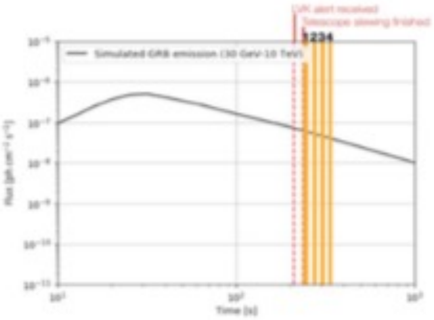
Slide: Alicia López

GW/SGRBS AT VERY HIGH ENERGIES

We now know that GRBs are possible VHE emitter and we also have a good hint that sGRB can be too. However, few differences have to be considered wrt "standard" GRB case:

- ❑ GW emission is isotropic while GRB em emission is collimated within a jet → the viewing angle plays an important role
- ❑ The uncertainty in the sky location of the GW event requires the definition of an observational strategy for the search of the EM counterpart with pointed instruments through a scan of the sky map provided by the GW event.





Patricelli+2021, Searching for very-high-energy electromagnetic counterparts to gravitational-wave events with the Cherenkov Telescope Array, ICRC 2021

Slide from A. Carosi

GW/SGRBS: WHAT DID WE LEARN?

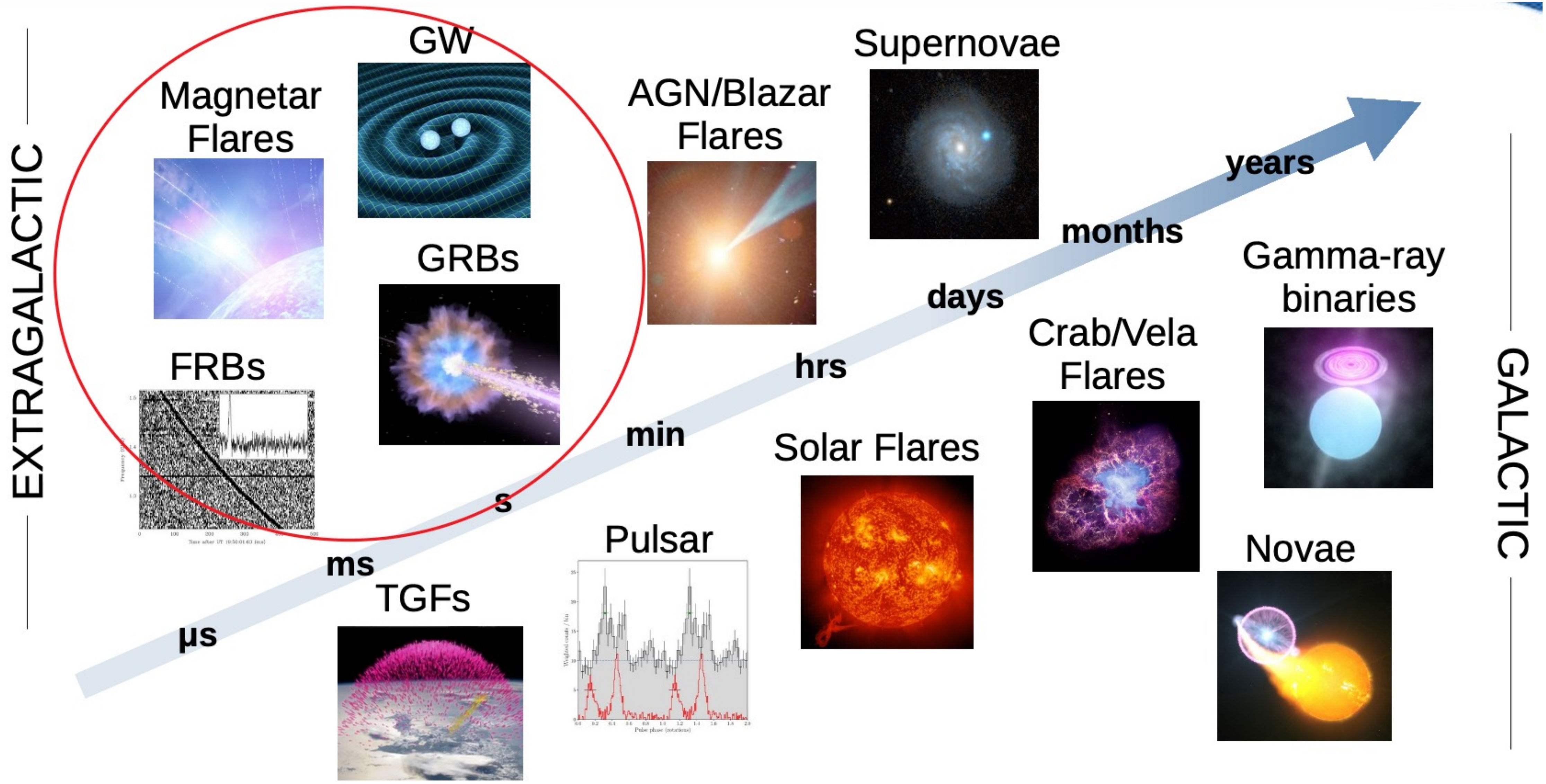
- **GW170817 + GRB 170817A + kilonova** provided the first direct proof that **binary neutron-star mergers produce short GRBs**.
- **Prompt emission** was seen in the **keV–MeV band**, but the GeV/TeV behavior was harder to constrain because of **instrument coverage and viewing-angle effects**.
- **H.E.S.S. non-detection at VHE** set the first TeV constraints on a GW counterpart and defined the roadmap for future GW-triggered gamma-ray follow-up.

TRANSIENT GAMMA RAY SKY

Gamma-ray bursts

Fast radio bursts

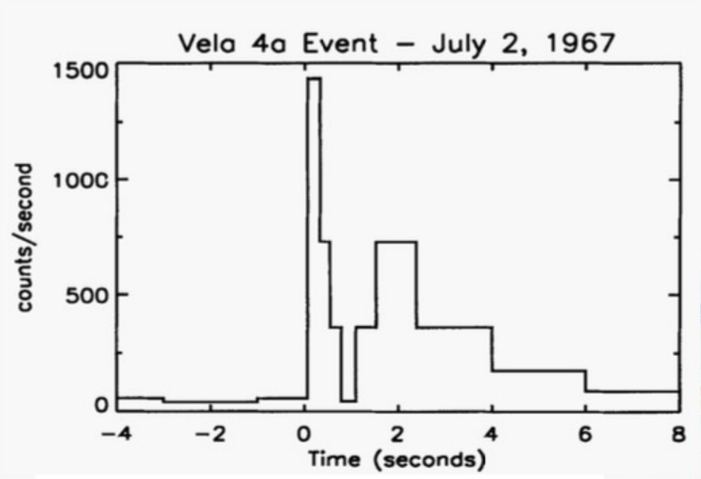
THE TRANSIENT GAMMA-RAY SKY



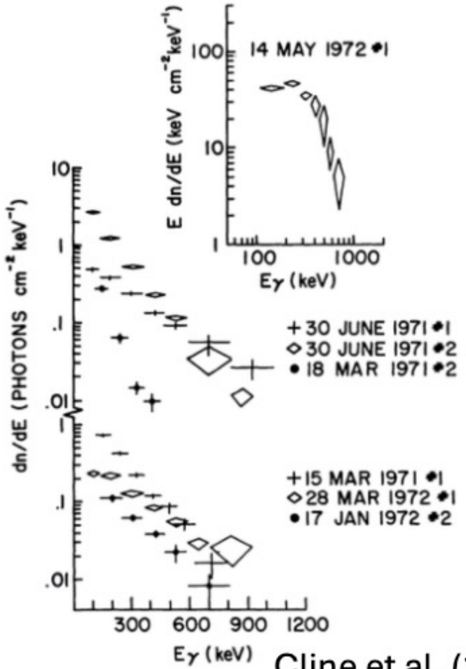
Slide: Niccolò Di Lalla

DISCOVERY OF GAMMA-RAY BURSTS

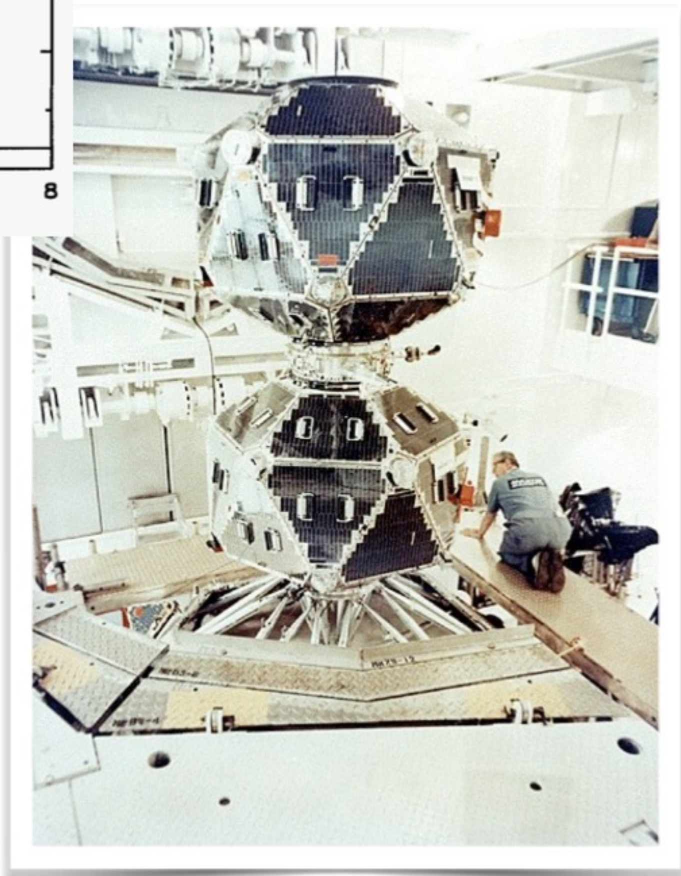
- Vela satellites program - launched by US military starting in 1963 to monitor the nuclear test ban treaty
    - 6 satellites launched between 1963-1970
- First detected burst of cosmic γ-rays in 1967
    - last seconds to minutes and then fade away
    - occur randomly
- Eventually determined that origin was neither terrestrial nor solar
- De-classified and published (Klebesadel et al. 1973)
- Confirmed by on IMP-6 and provided first spectral information showing gamma-ray peak (Cline et al. 1973)



First GRB
Strong & Klebesadel (1976)



Cline et al. (1973)

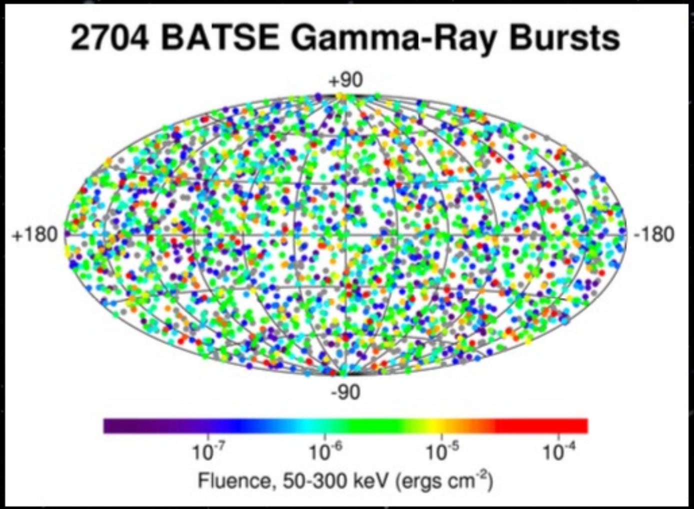


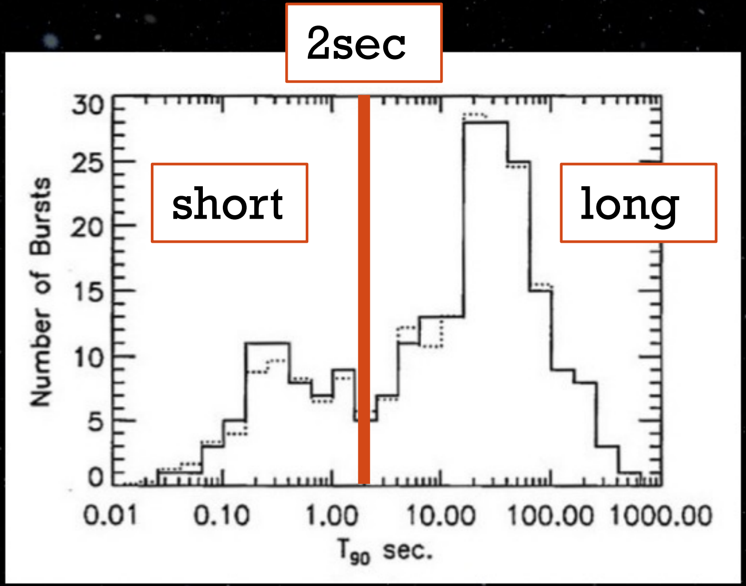
Vela Satellites

Slide: Judy Racusin

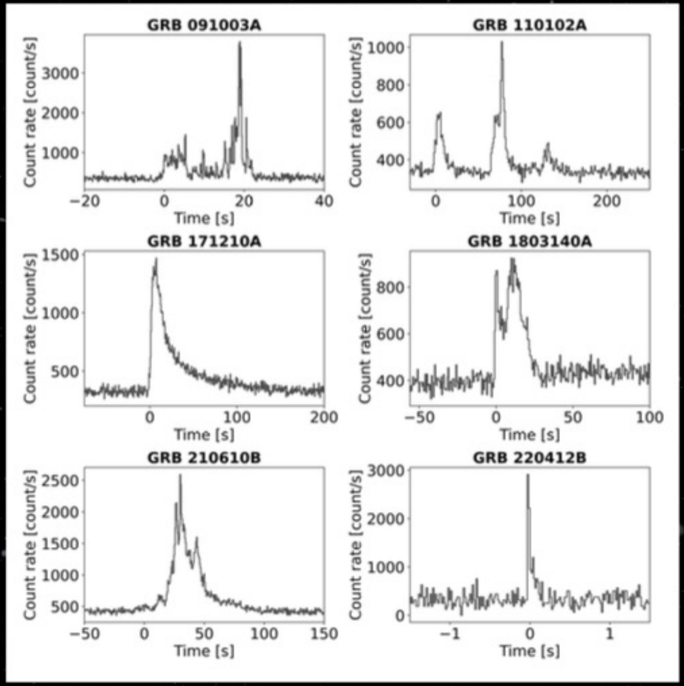
BATSE OBSERVATIONS

- Onboard Compton Gamma Ray Observatory, 1991–2000
- 8 NaI scintillation detectors (20 in diameter)
- Isotropic distribution, supporting extragalactic origin
- Bimodal duration distribution → long and short GRBs
- Unique lightcurves





Kouveliotou et al 1993



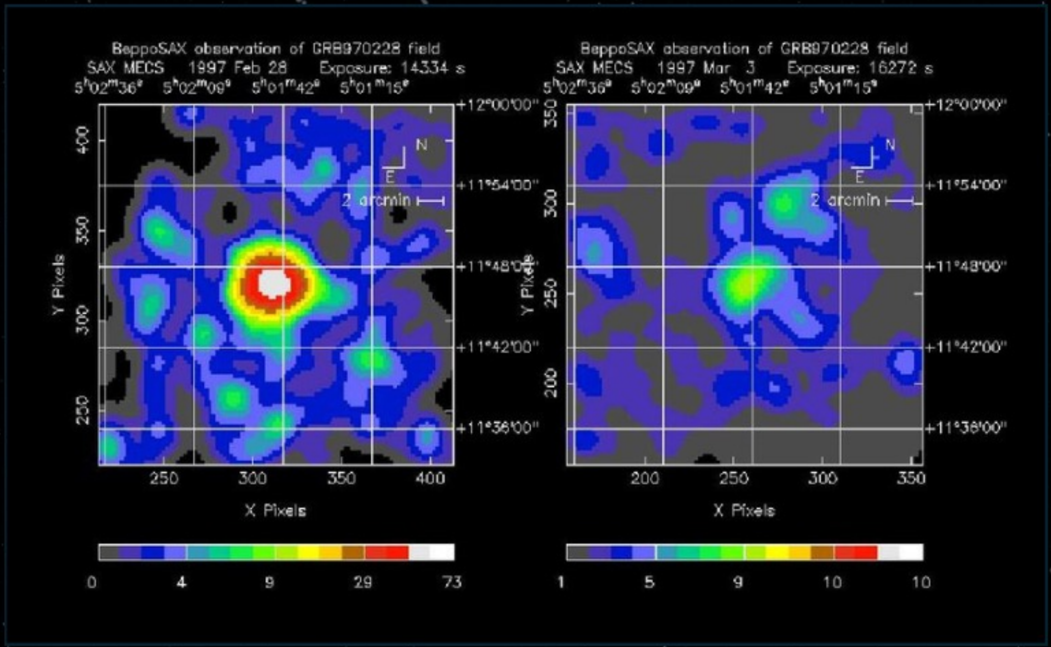
Slide: adapted Judy Racusin

EARLY BREAKTHROUGHS

- 1997: First afterglow detection by BeppoSAX → first redshift = 0.695
- Confirmed GRBs are among the most energetic events in the universe
- More energy in 1 s than Sun will emit in its entire lifetime (3e51 ergs)

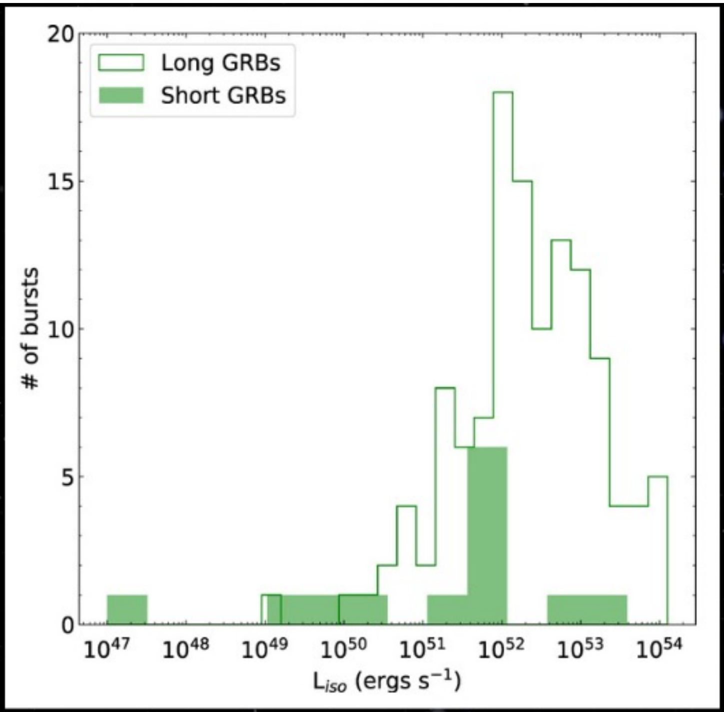
→ enabling arcminute localization and follow-up
--> first GRB redshift, proving a cosmological origi

GRB 970228
T0+8 hr / T0+3 days



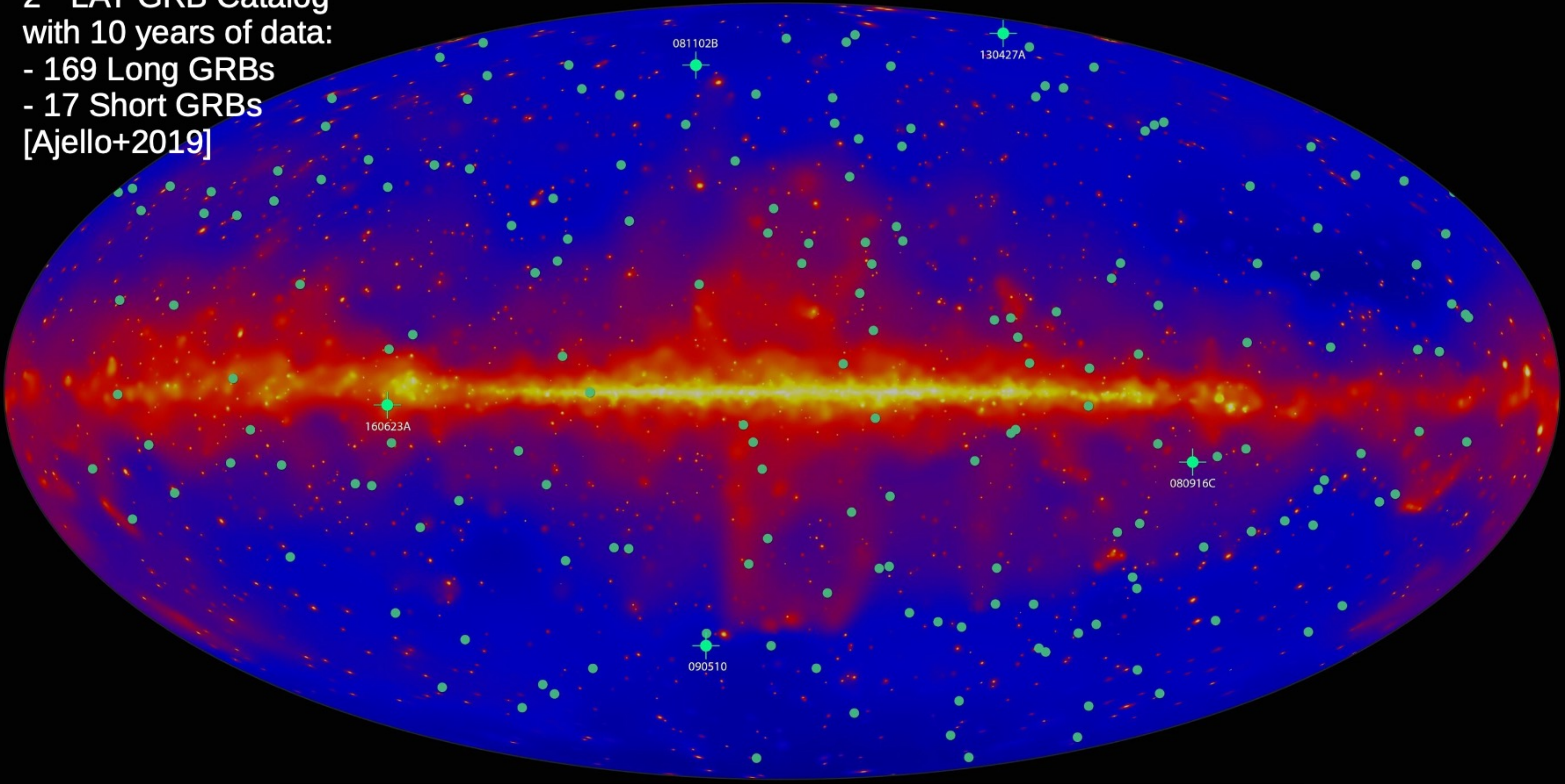
Costa et al 1997

- Transient events with **10^{52} - 10^{54} erg** energy release



Slide: adapted Judy Racusin

2nd LAT GRB Catalog
with 10 years of data:
- 169 Long GRBs
- 17 Short GRBs
[Ajello+2019]



https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilgrb.html

Fermi to TeV: GRBs across the high-energy sky

Fermi transformed GRB studies at high energies: between 2008–2018, **GBM detected 2356 GRBs** and **LAT detected 186.**

TeV detections are **rare but decisive**: five GRBs have been detected at very-high energies: **GRB 180720B, GRB 190114C, GRB 190829A, GRB 201216C, GRB 221009A.**

These events extend the GRB spectrum to **GeV–TeV energies** and directly test the physics of relativistic jets, afterglow emission, and particle acceleration.

FERMI-GRB DETECTIONS (2008–2018)

Fermi–GBM	Fermi–LAT
2356	**186**
GRBs detected	GRBs detected

THE 5 GRBs DETECTED AT TeV ENERGIES

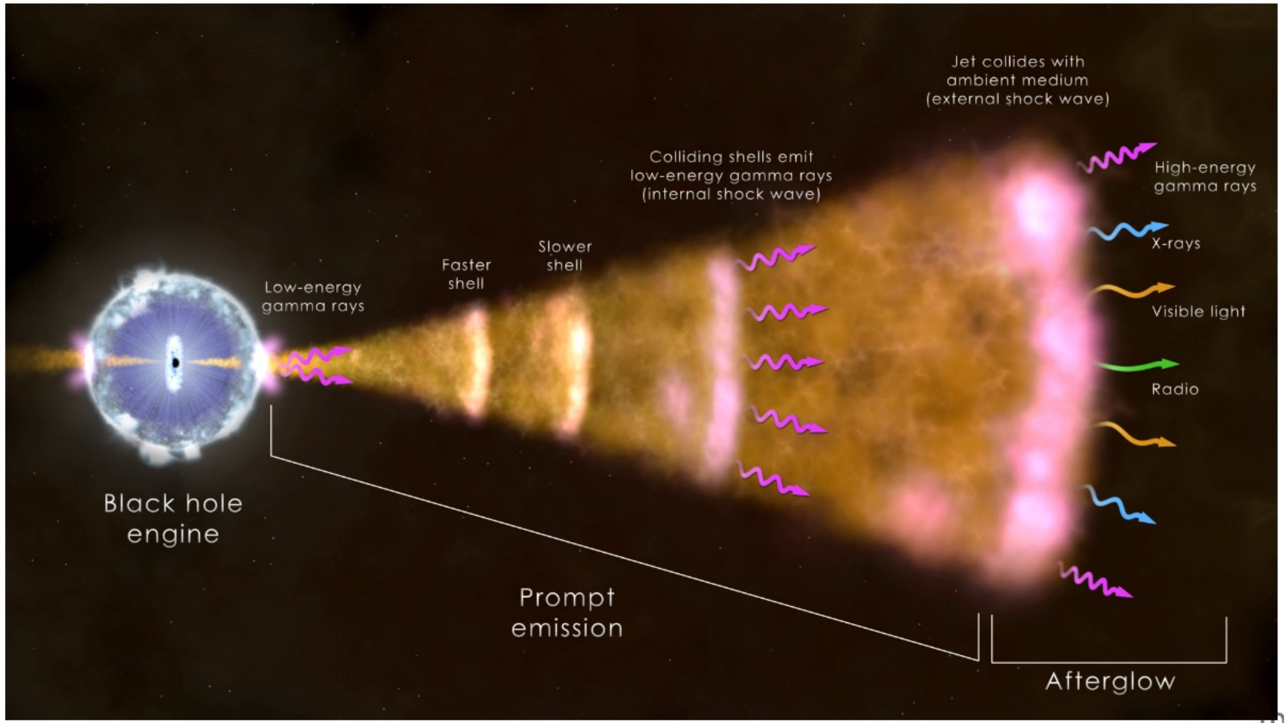
GRB	INSTRUMENT	DETECTION TYPE	REFERENCE
GRB 180720B	H.E.S.S.	Delayed (~10 hr)	H.E.S.S. Collab. 2018
GRB 190114C	MAGIC	Prompt (~57 s)	MAGIC Collab. 2019
GRB 190829A	H.E.S.S.	Prompt (~4–5 hr)	H.E.S.S. Collab. 2021
GRB 201216C	MAGIC	Prompt (~56 s)	MAGIC Collab. 2021
GRB 221009A	LHAASO	Prompt (~200–2000 s)	LHAASO Collab. 2023

From MeV to TeV, GRBs probe the most extreme environments in the Universe and remain **key targets** for multi-messenger and next-generation observations.

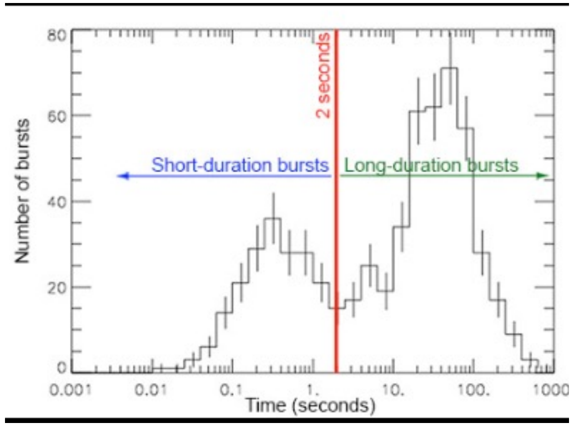
WHAT ARE GAMMA-RAY BURSTS?

- A powerful central engine accelerates particles to relativistic speeds in bipolar jets
- Two phases
  - prompt emission - material moving at slightly different speeds crashes into each other producing gamma rays
  - afterglow - the shock wave interacts with the environment around the star producing the long-lived multiwavelength afterglow

- Distances - $0.01 \lesssim z \lesssim 9.4$
- Gamma-ray energies ~ $M_{\odot}c^2 \sim 2\times10^{54}$ erg
- Jetted outflow ~10° half opening angle (reduces energy by ~ 1/100)

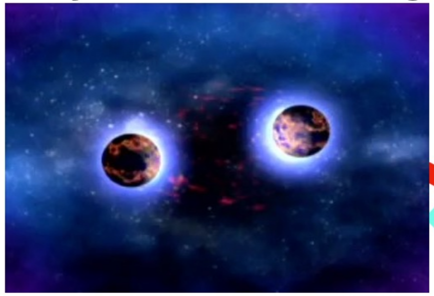


GRB FORMATION

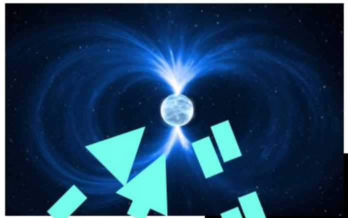


Short GRB

Binary Neutron Star Merger

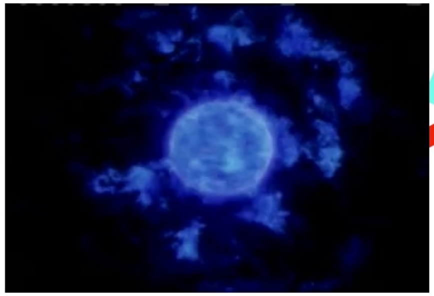


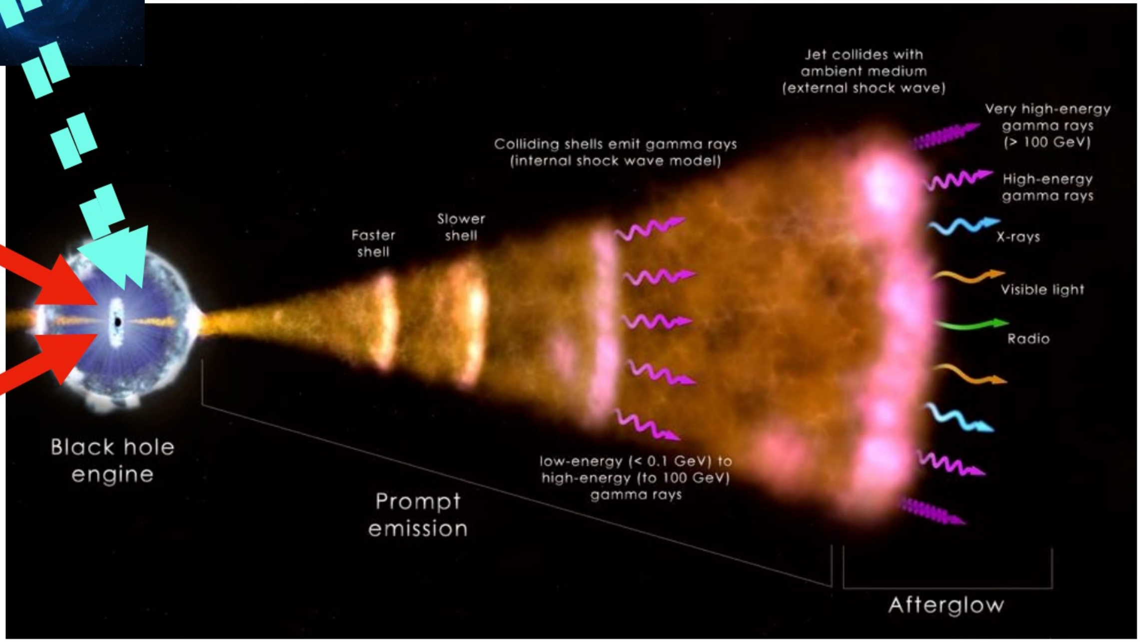
Newly-formed short-lived magnetar?



Long GRB

Massive Star Collapse



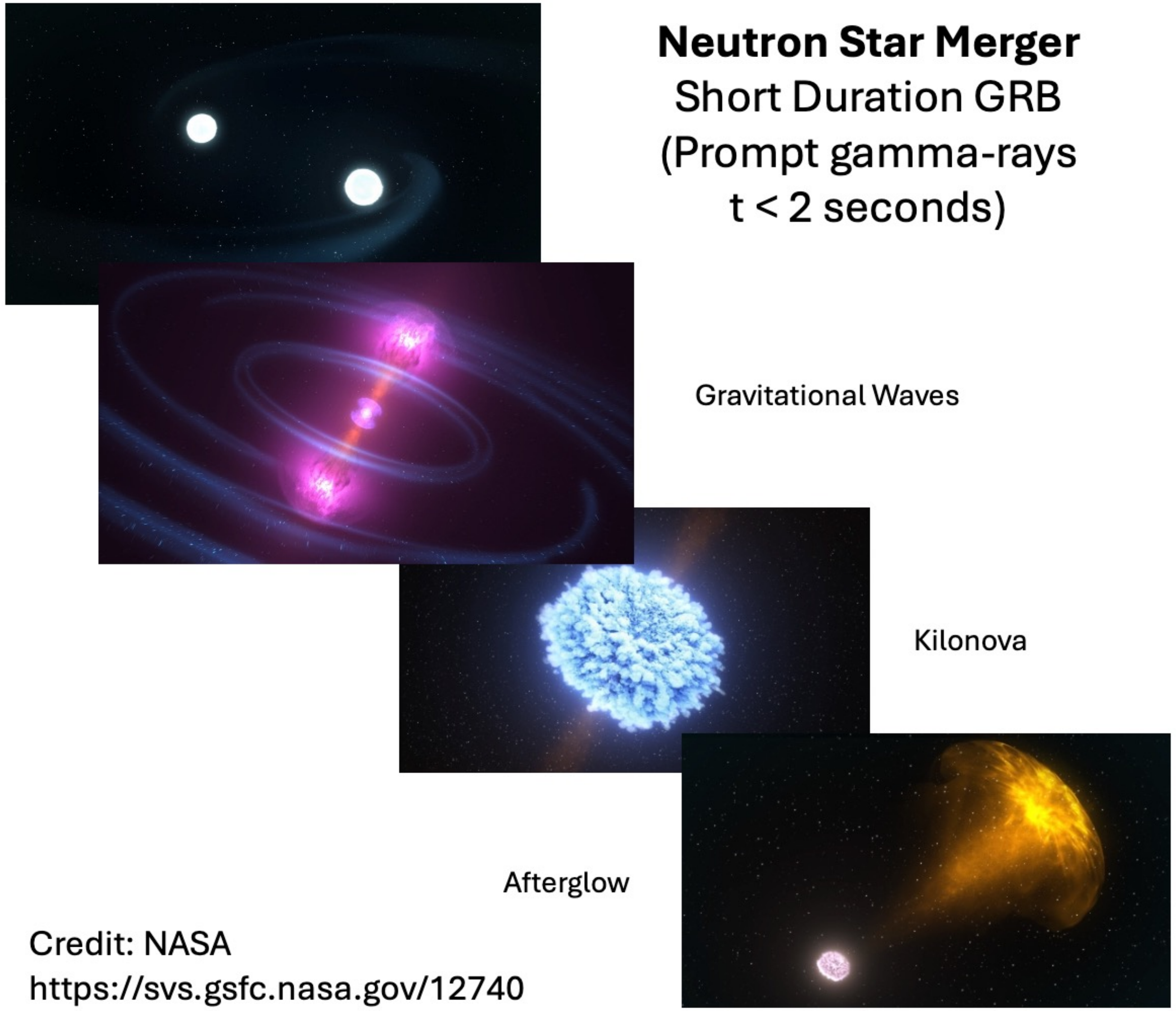


Prompt emission
internal shocks / magnetic dissipation / photosphere?

Afterglow
External Shocks

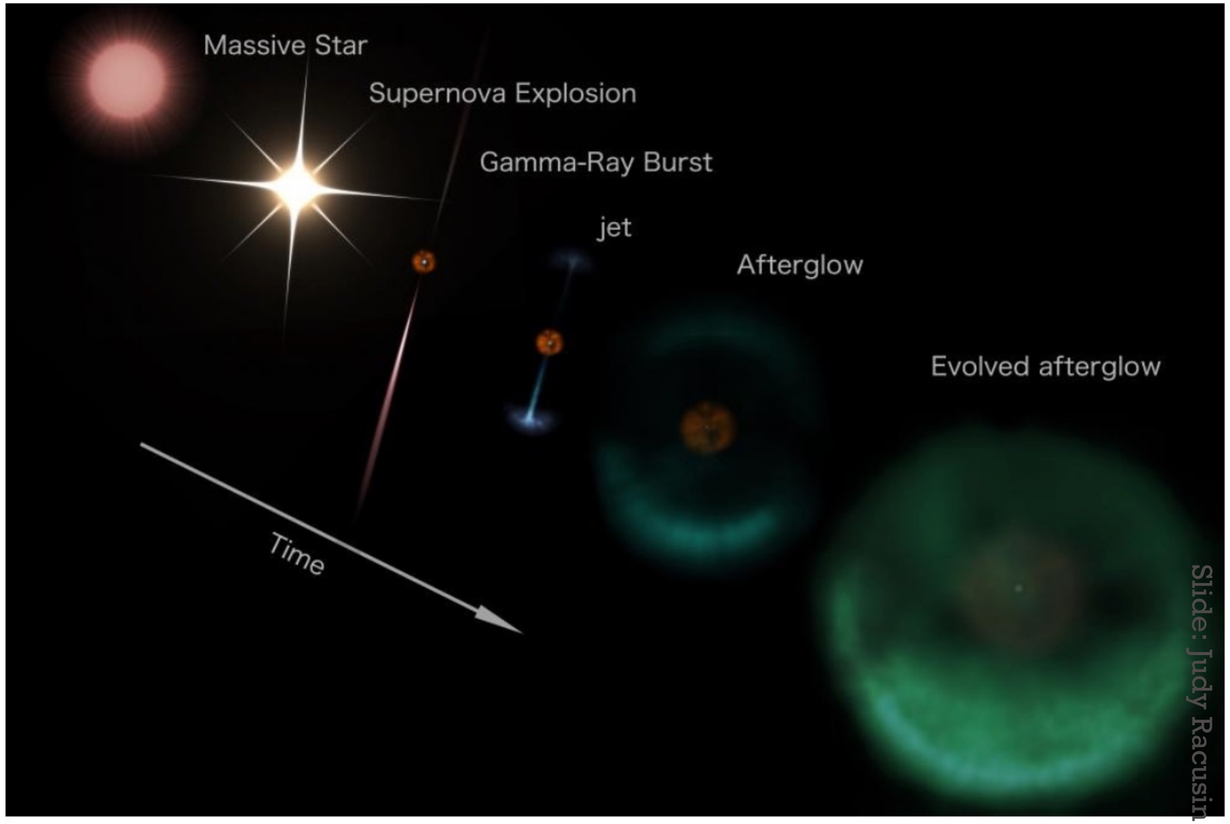
PROGENITOR SYSTEMS

Neutron Star Merger
Short Duration GRB
(Prompt gamma-rays
t < 2 seconds)



Credit: NASA
https://svs.gsfc.nasa.gov/12740

Massive Stars Collapse
Long Duration GRB
(Prompt gamma-rays
t > 2 seconds)

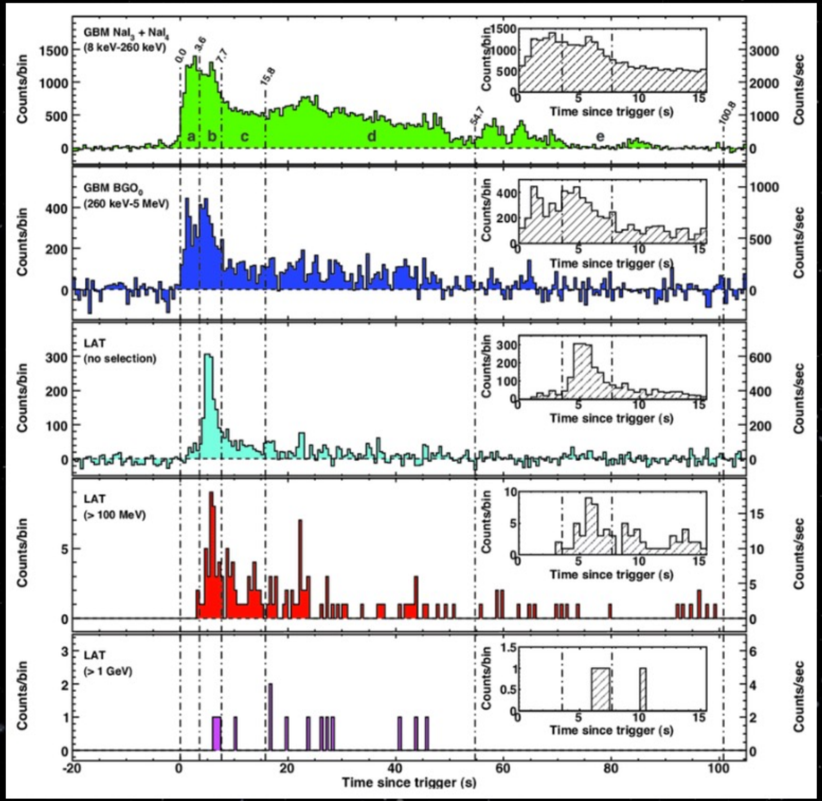


Credit: ASTRON/ Benito Marcote (JIVE)
https://www.astron.nl/news-and-events/news/astronomers-observe-smoking-gun-orphan-gamma-ray-burst-afterglow

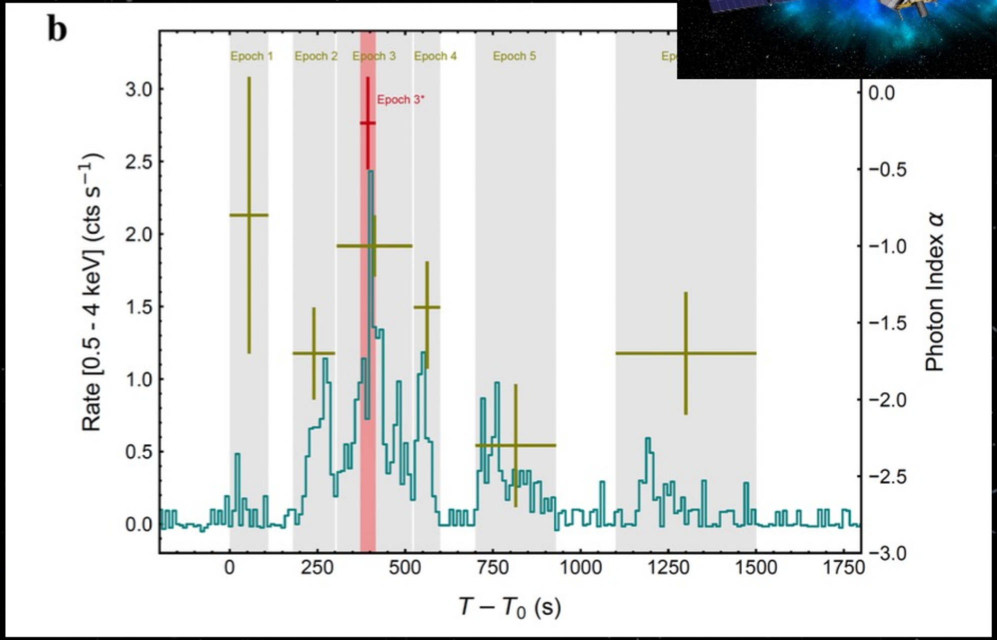
Slide: Judy Racusin

PROMPT EMISSION

- Initial flash of gamma-rays (keV-MeV) lasting from ms-min that defines the trigger time
- Typically observed in keV–MeV range (up to GeV for some)



GRB 080916C (2nd LAT GRB)
Abdo et al 2009



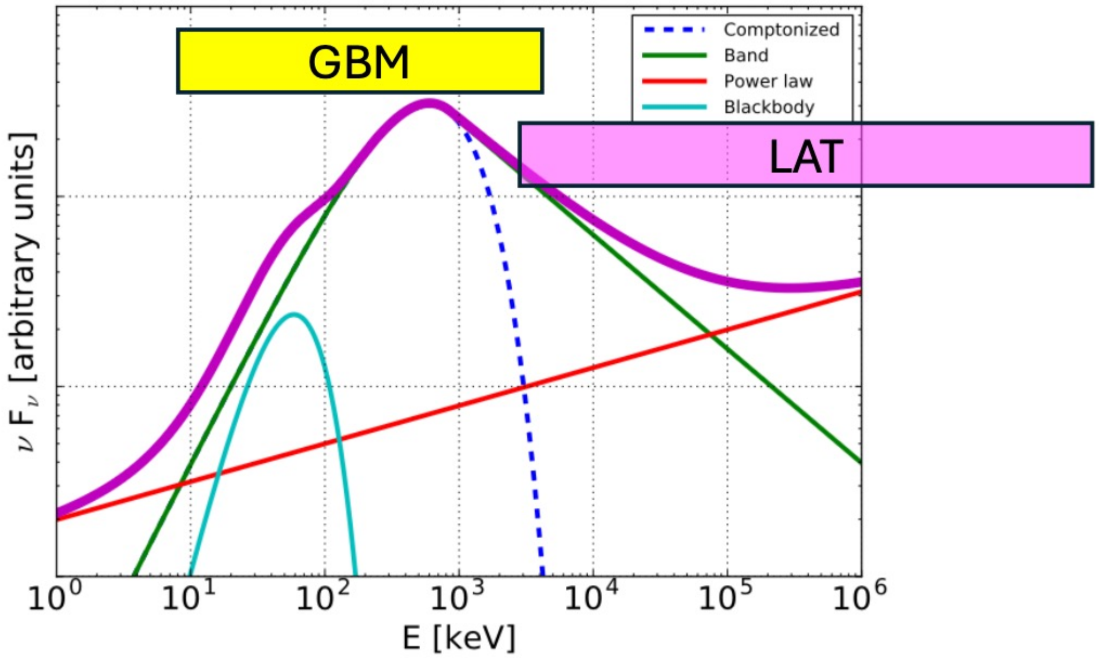
EP 240315a
Liu et al 2024

Slide: Judy Racusin

GRB SPECTRA

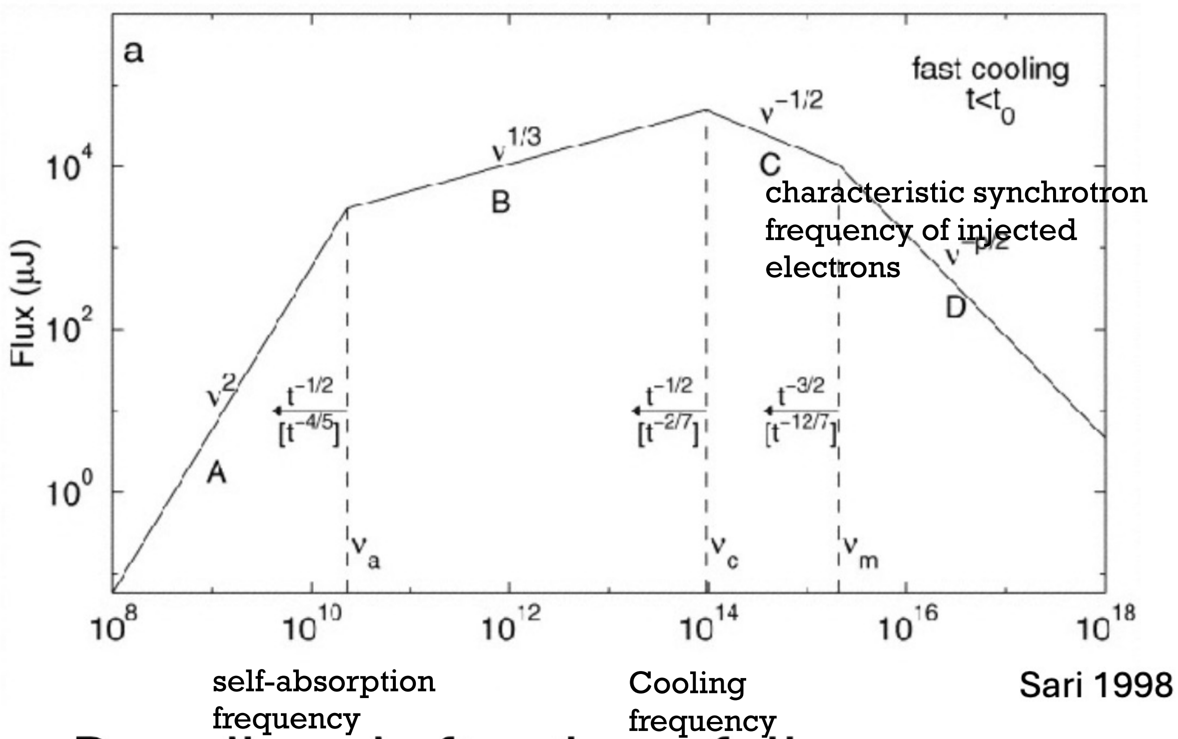
Prompt: phenomenologically fit, emission mechanism still debated
Afterglow: broadly consistent with **external-shock synchrotron**

Prompt Empirical Spectra



- Smoothly connected power laws
- Slower variation than light curves
- Sometimes additional components (black body, extra power law)
- Synchrotron doesn't usually work

Afterglow Synchrotron Spectra



- Broadband afterglows follow synchrotron evolution
- Light curve behavior depend on relative position on spectrum

MAGIC: designed for GRB hunting

MAGIC: 17 m de diámetro
64 T de peso
25 segundos

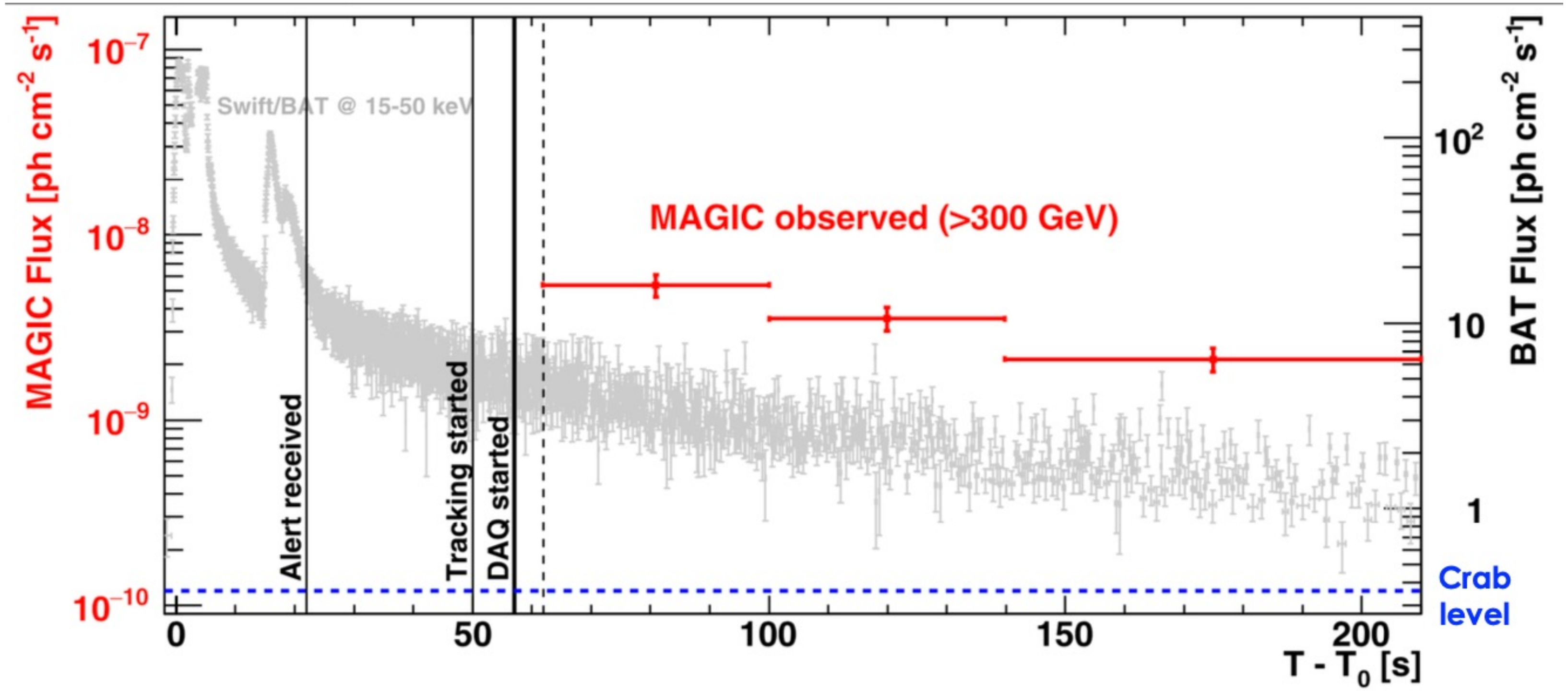
GTC: 10.4 m de diámetro
400 T de peso

Slide: Alicia López

LST-3 FULL SPEED FULL ACCELERATION

GRB 190114C: FIRST GRB DETECTED AT TEV

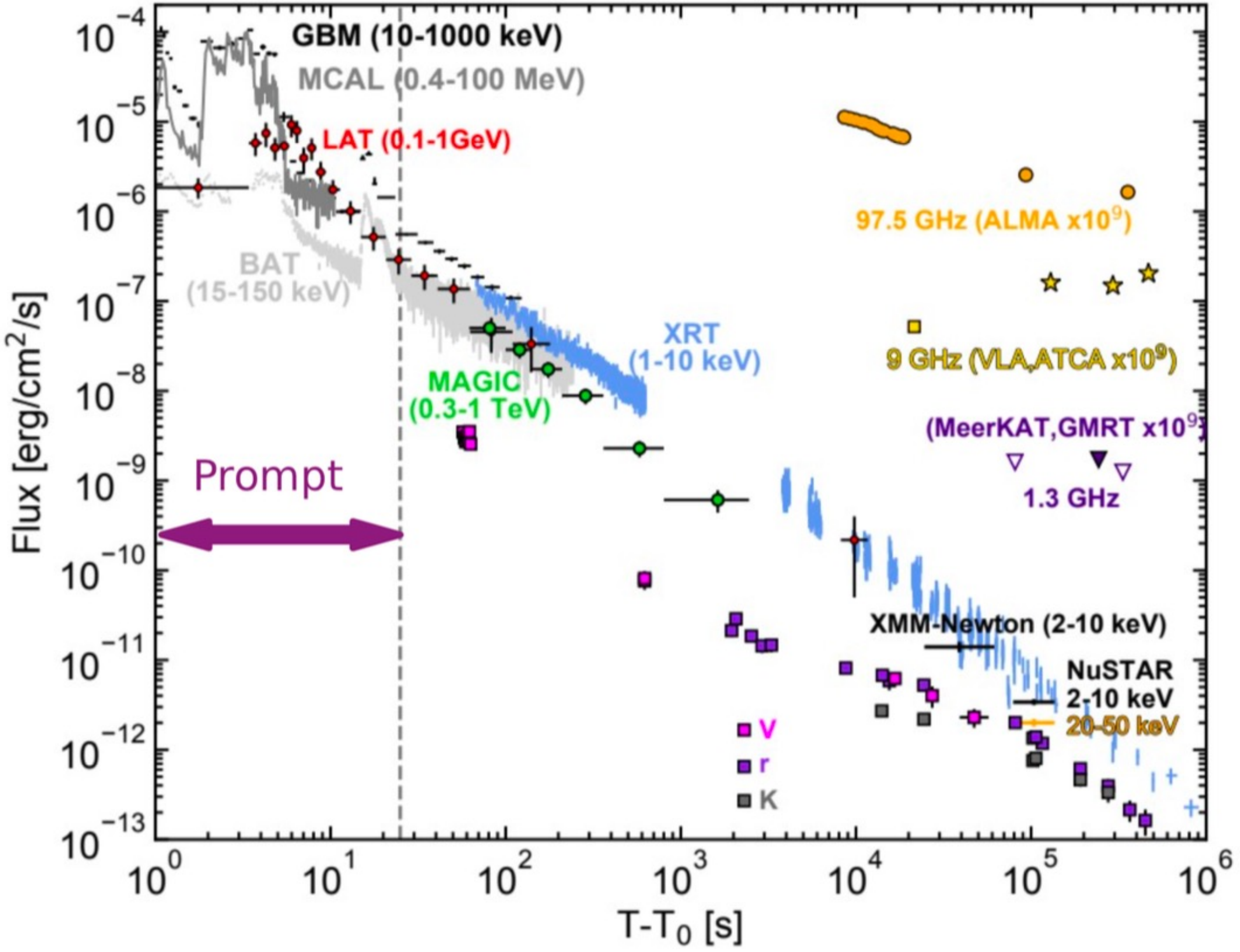
The MAGIC Collaboration, Nature 575, 455–458(2019) / Nature 575, 459–463 (2019)



- MAGIC detected **0.2–1 TeV γ-rays** from **GRB 190114C**, beginning **~57 s after trigger**.
- The detection was extremely significant: **>50σ in the first 20 min**.

1st GRB in the VHE domain (200 GeV-1 TeV)
It took MAGIC only **28 seg to repositing and start datataking**
VHE emission **vanished after 20min**
New era starts!

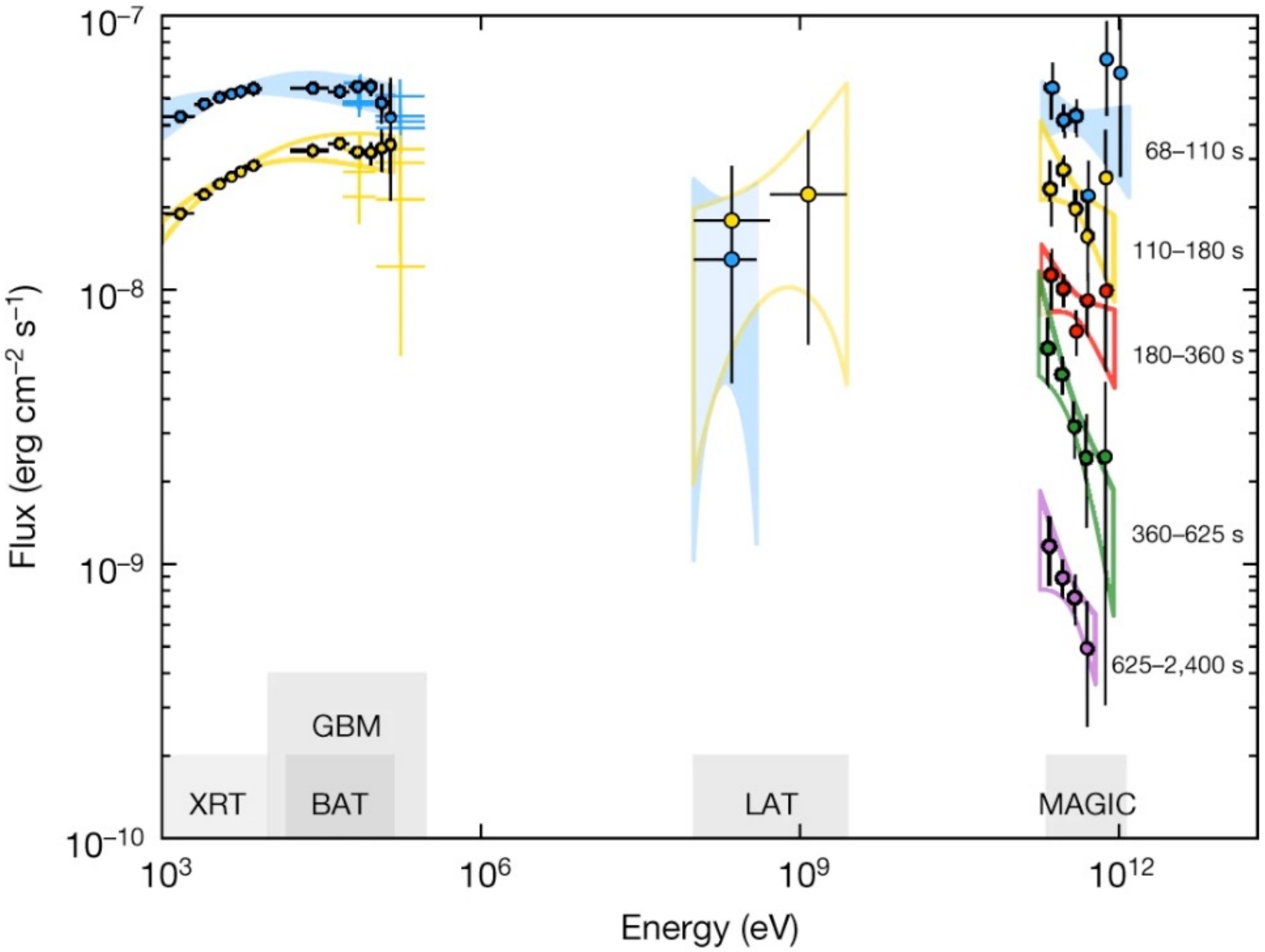
GRB 190114C: THE FIRST CLEAR TEV GRB AFTERGLOW



- The TeV flux decayed smoothly as a **power law**, unlike the rapidly variable prompt phase.
- This showed that **GRB afterglows can emit into the TeV band.**

Key point:
The TeV emission behaves like the **afterglow**, not the prompt burst, pointing to an origin in the external shock.

BROADBAND SED OF GRB 190114C

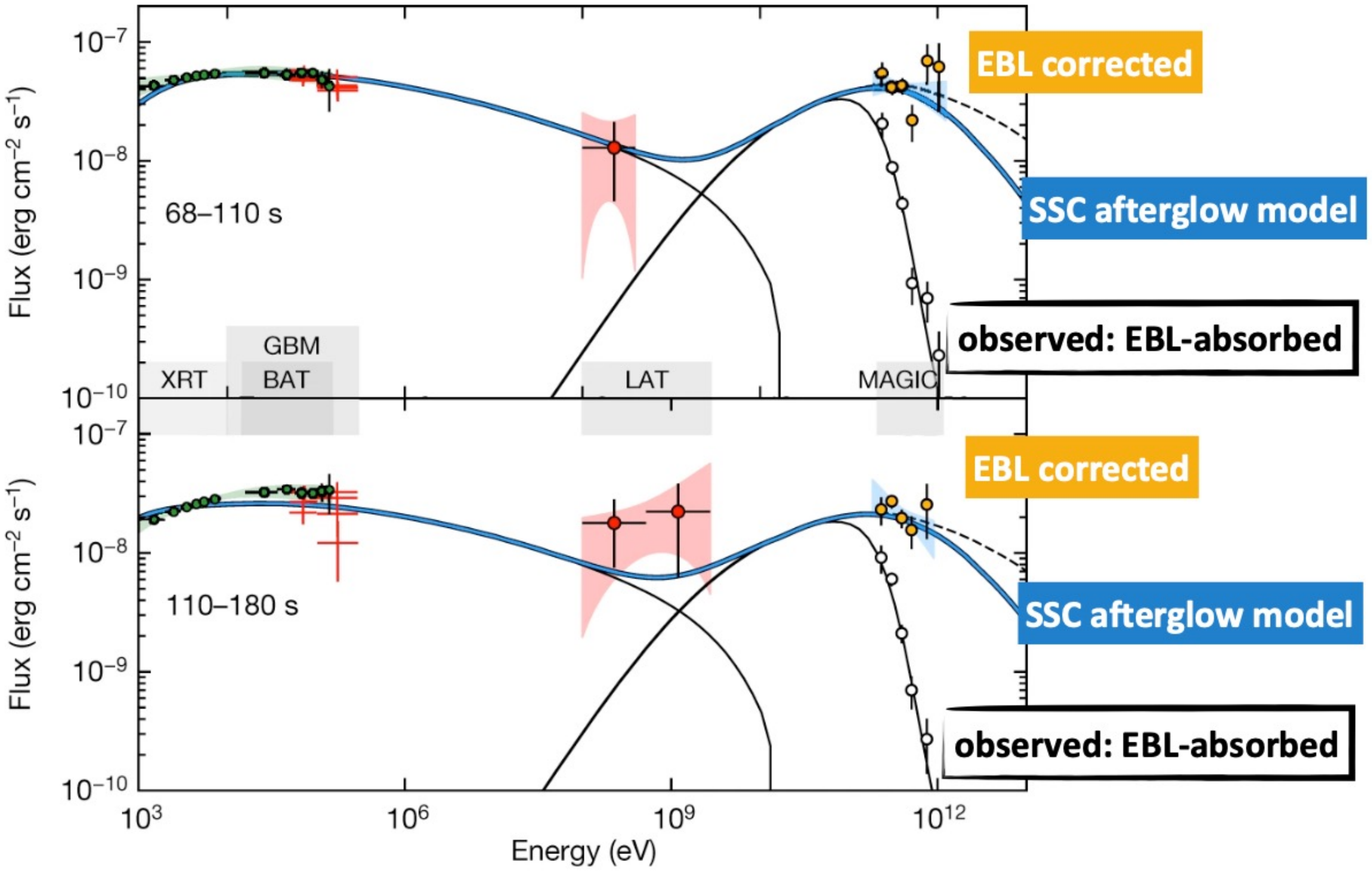


The MAGIC Collaboration, Nature 575, 455–458(2019) / Nature 575, 459–463 (2019)

- **Broadband, time-resolved SED:** simultaneous coverage from **Swift/Fermi** to **MAGIC**.
- **Key implication:** the TeV component is strong enough that it likely requires **more than a simple synchrotron extrapolation**.

GRB 190114C was the first GRB with a clear, time-resolved TeV detection, opening the TeV GRB era.

GRB 190114C: EVIDENCE FOR SECOND COMPONENT



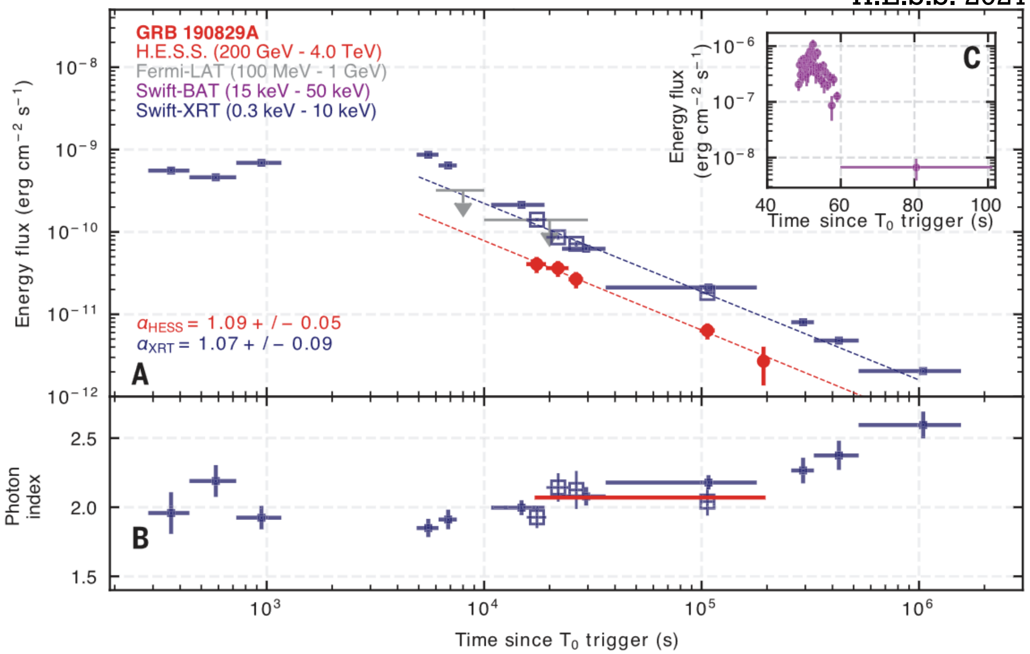
First clear evidence of a second emission component (SSC - blazar-like)

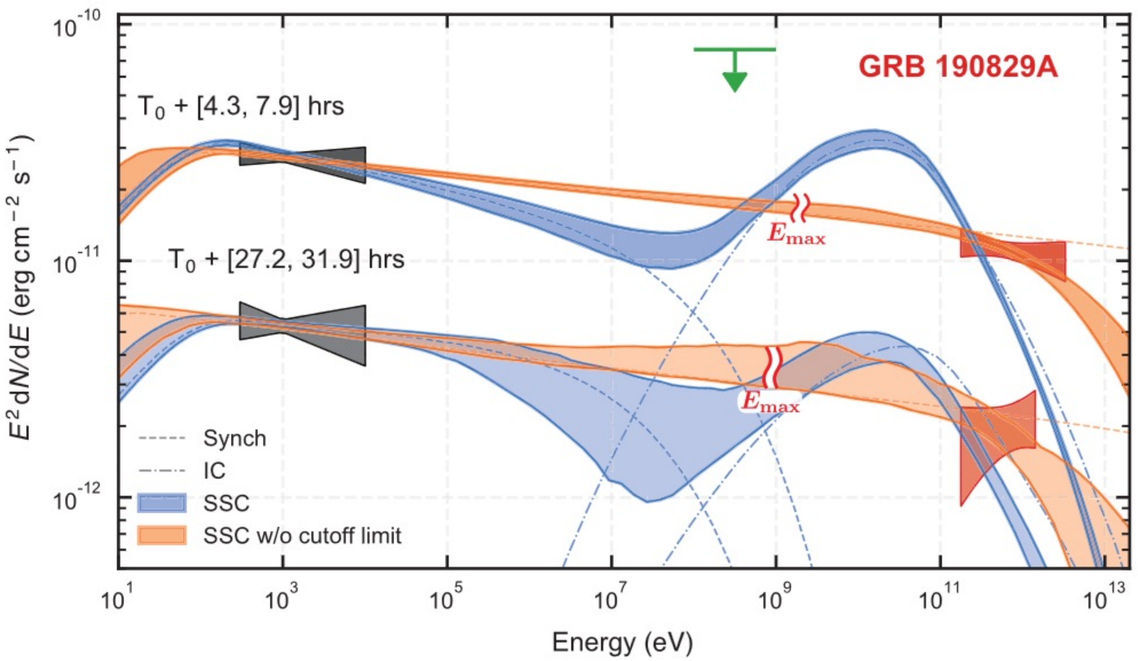
- Observed MAGIC spectrum is strongly attenuated by the EBL at TeV energies.
- After EBL correction, the intrinsic spectrum shows a second high-energy hump.
- That component is well explained by afterglow SSC: synchrotron photons upscattered by the same relativistic electrons.

The MAGIC Collaboration, Nature 575, 455–458(2019) / Nature 575, 459–463 (2019)

GRB 190829A: A TEV AFTERGLOW

H.E.S.S. 2021



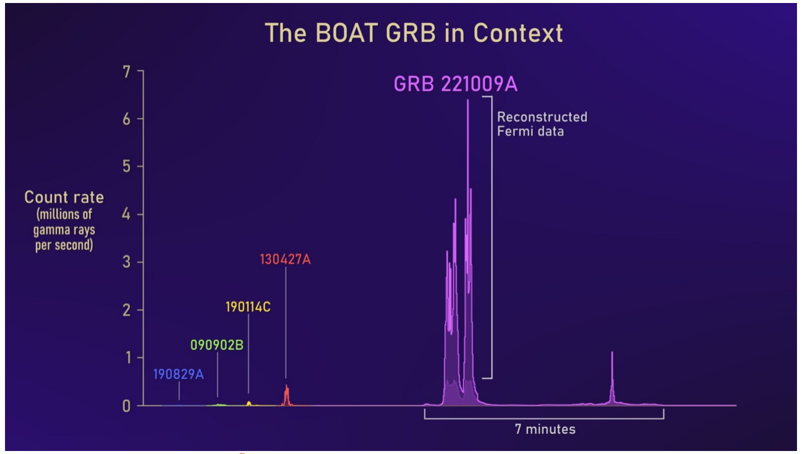


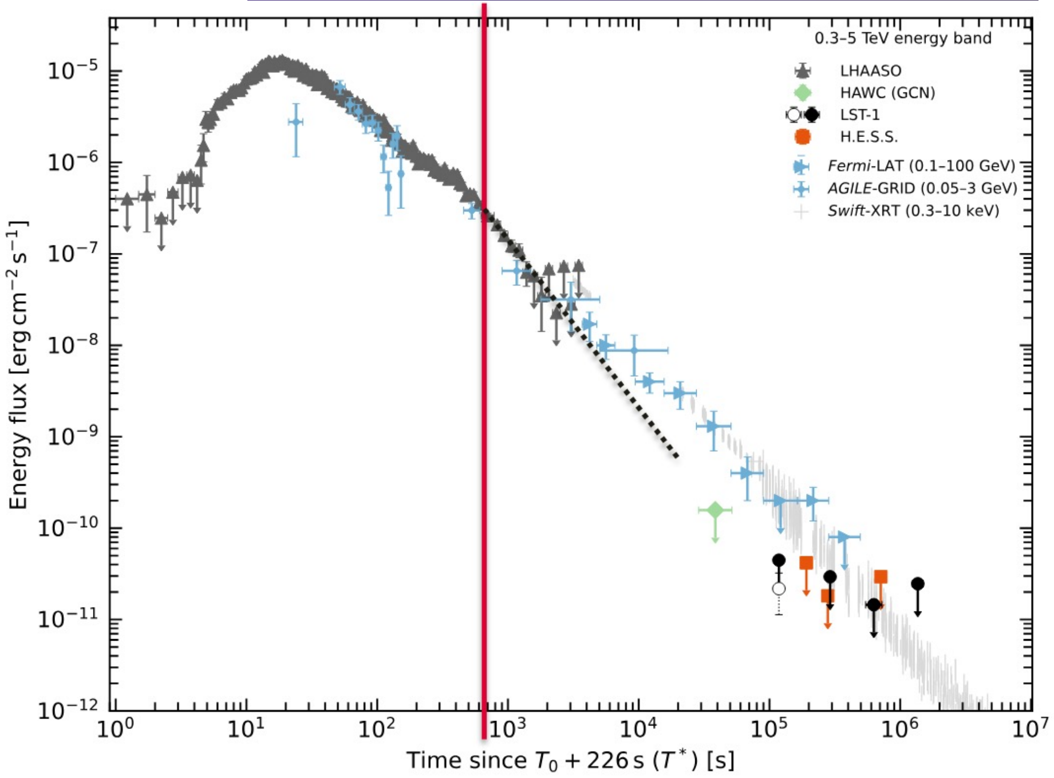
- **Nearby, low-luminosity long GRB** at $z \approx 0.0785$
- **Observed by H.E.S.S. from 4 to 56 h after trigger**
- Low redshift →**reduced EBL absorption**, so TeV afterglow could be measured

- TeV spectrum extends from **0.18–3.3 TeV**
- Intrinsic TeV slope $\Gamma_{\mathrm{VHE}} \approx 2.1$
- X-ray and TeV spectra + decay are remarkably similar
- **Standard one-zone SSC is not an easy explanation**

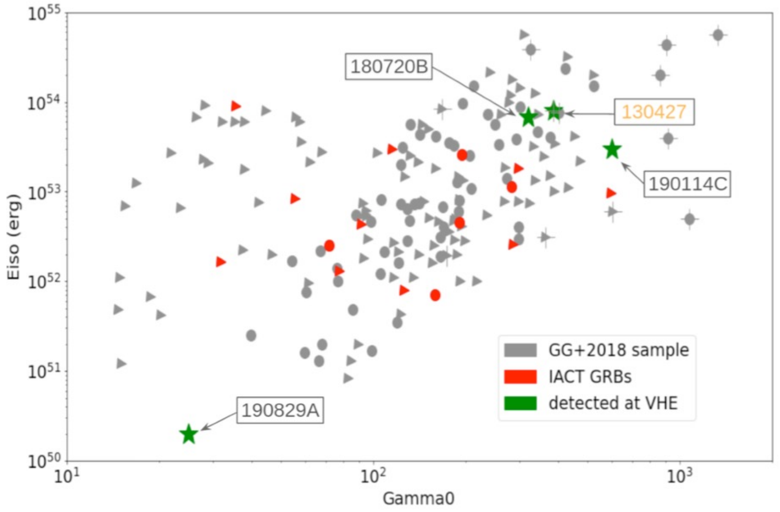
GRB 221009A (BOAT): BRIGHTEST GRB EVER

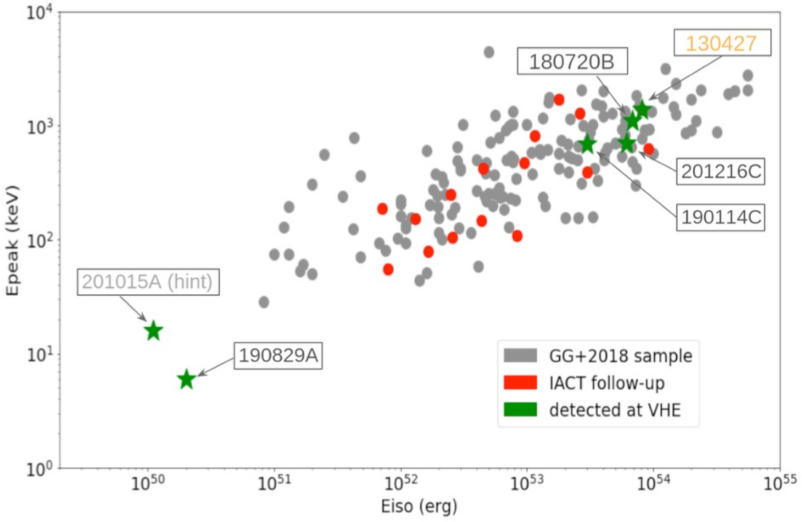
- "Brightest of all time" (BOAT) GRB: ≤ 1 event every 1000 years [Williams et al. (2023)]
  - $E_{iso} \sim 2x10^{54}$ erg; z = 0.151
- LHAASO detected an exceptionally bright early TeV afterglow, extending beyond 10 TeV
- The VHE light curve shows a slope change, consistent with a structured-jet afterglow rather than a simple single-component decay
  - The emission at later times likely origins from a separated region surrounding the inner 0.6 deg jet
- The hard TeV spectrum challenges simple one-zone electron SSC models and may require more complex afterglow physics.





GRBS AT VHE: SUMMARY

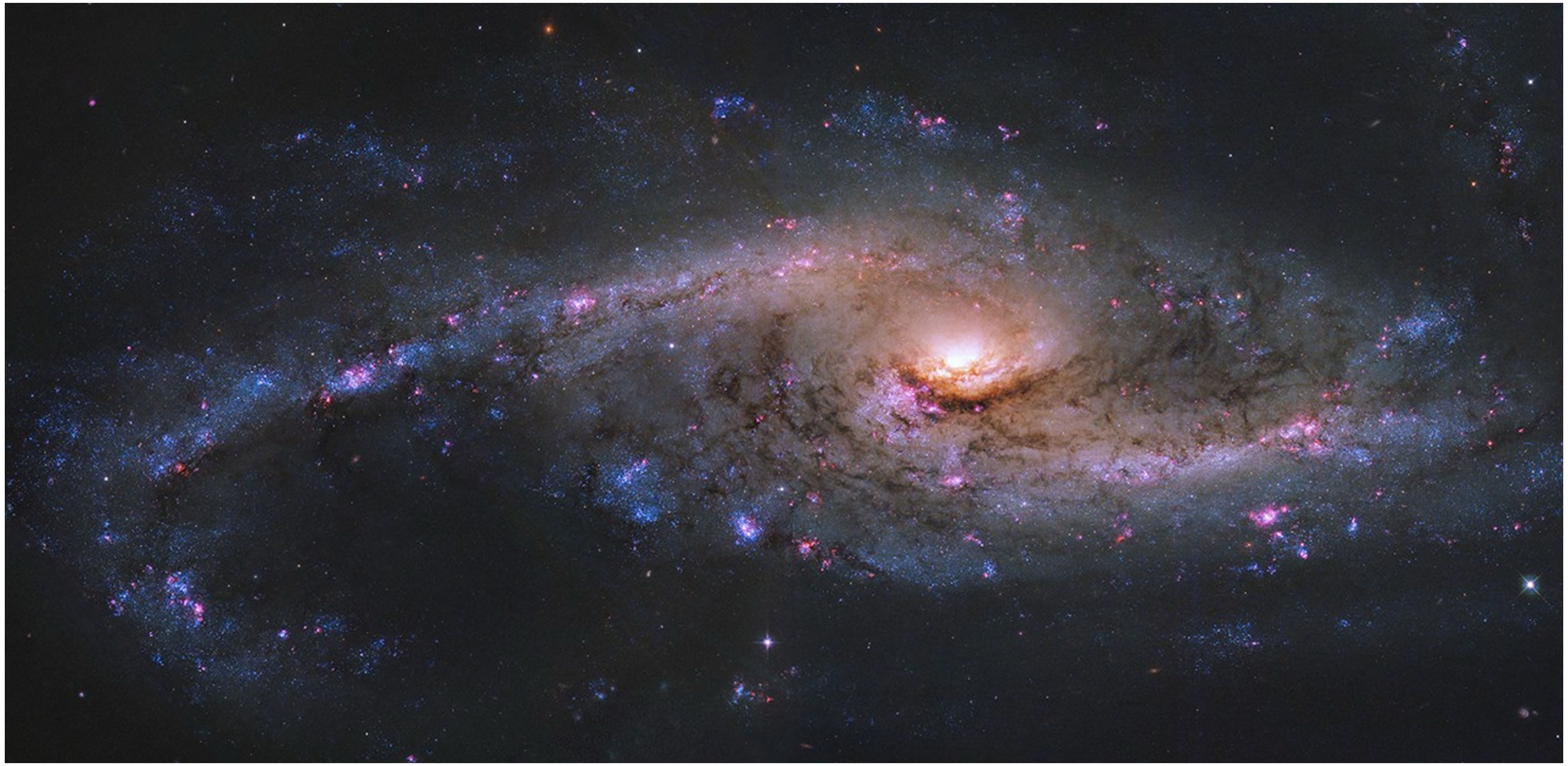




Berti & Carosi 2022

- **A new phase:** the question is no longer *whether* GRBs emit at VHE, but **when, how, and how often.**
- **A diverse sample:**
  GRB 180720B / 190114C are bright, energetic long GRBs;
  GRB 190829A shows that **nearby, low-luminosity bursts can also reach TeV energies.**
- **Emission mechanism still debated:**
  afterglow SSC is plausible in some cases, but **simple one-zone models struggle for others.**
- **Open questions:**
  prompt or afterglow?
  universal VHE component or selection effect?
  one population or multiple channels to TeV emission?

STAR BURST GALAXIES & GALAXY CLUSTERS



THANK YOU

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