



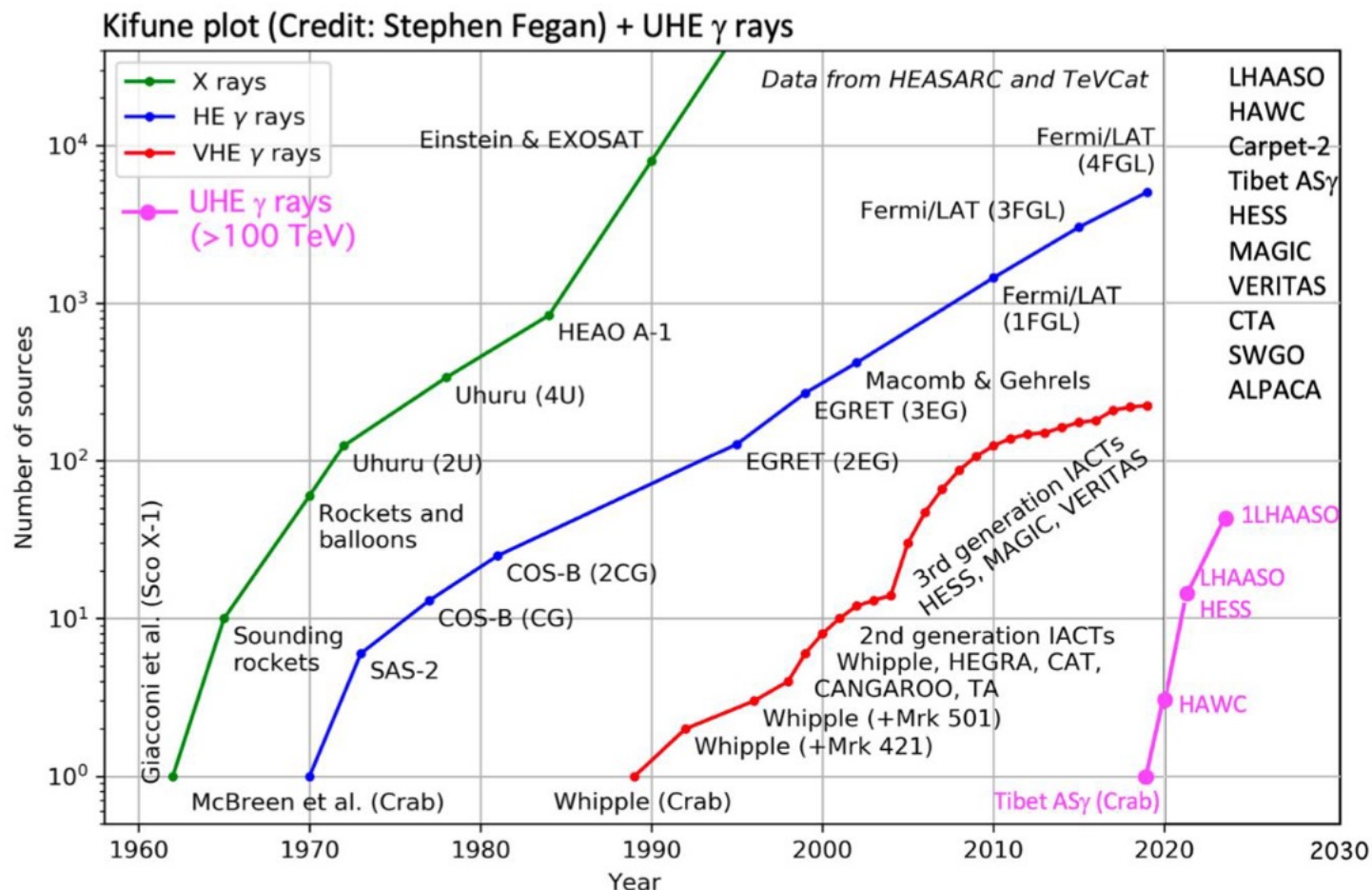
GAMMA-RAY ASTROPHYSICS GALACTIC SOURCES

Daniela Hadasch

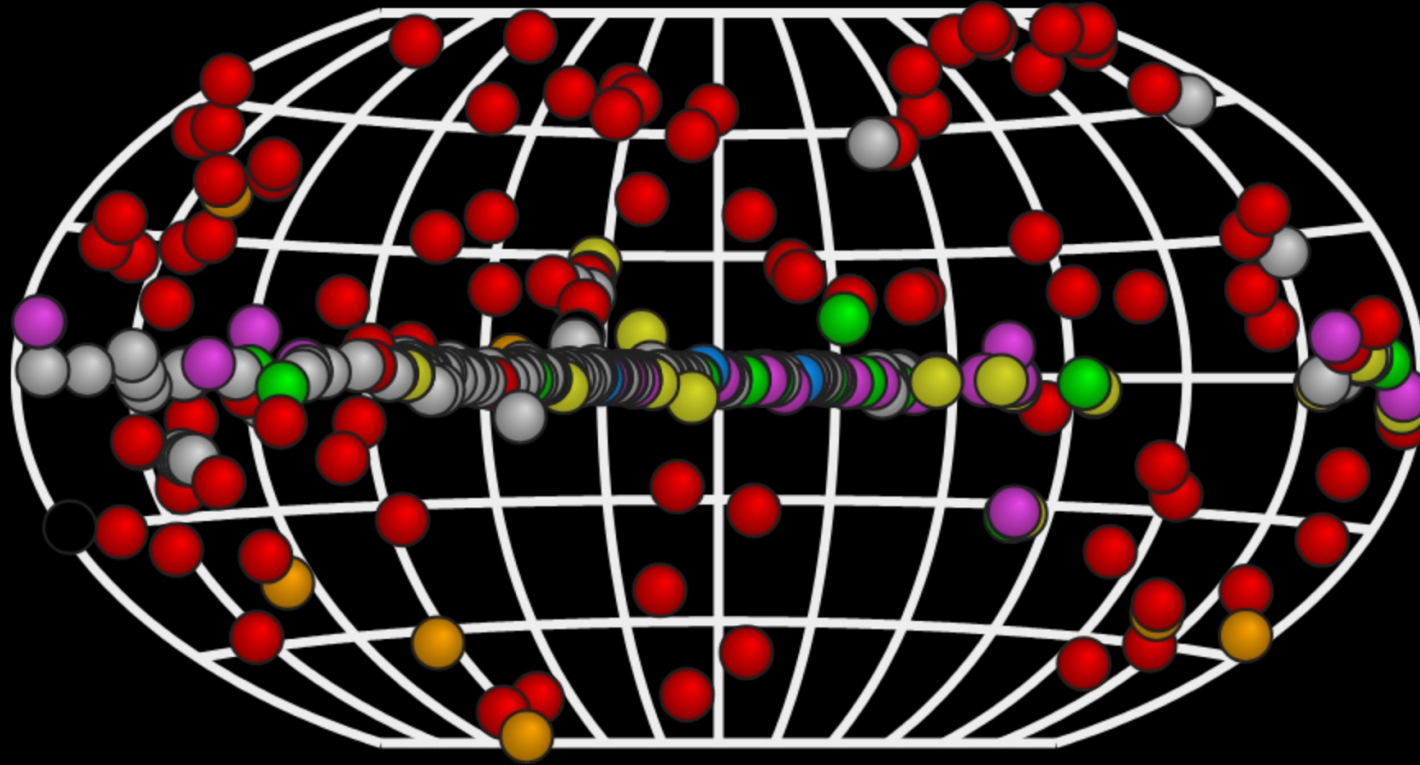
1

KIFUNE PLOT

- "Kifune" plot - the integral number of high energy sources detected as a function of year - in the style of a plot developped by Tadashi Kifune.
- In high-energy astrophysics, new technology almost always leads to new discoveries.



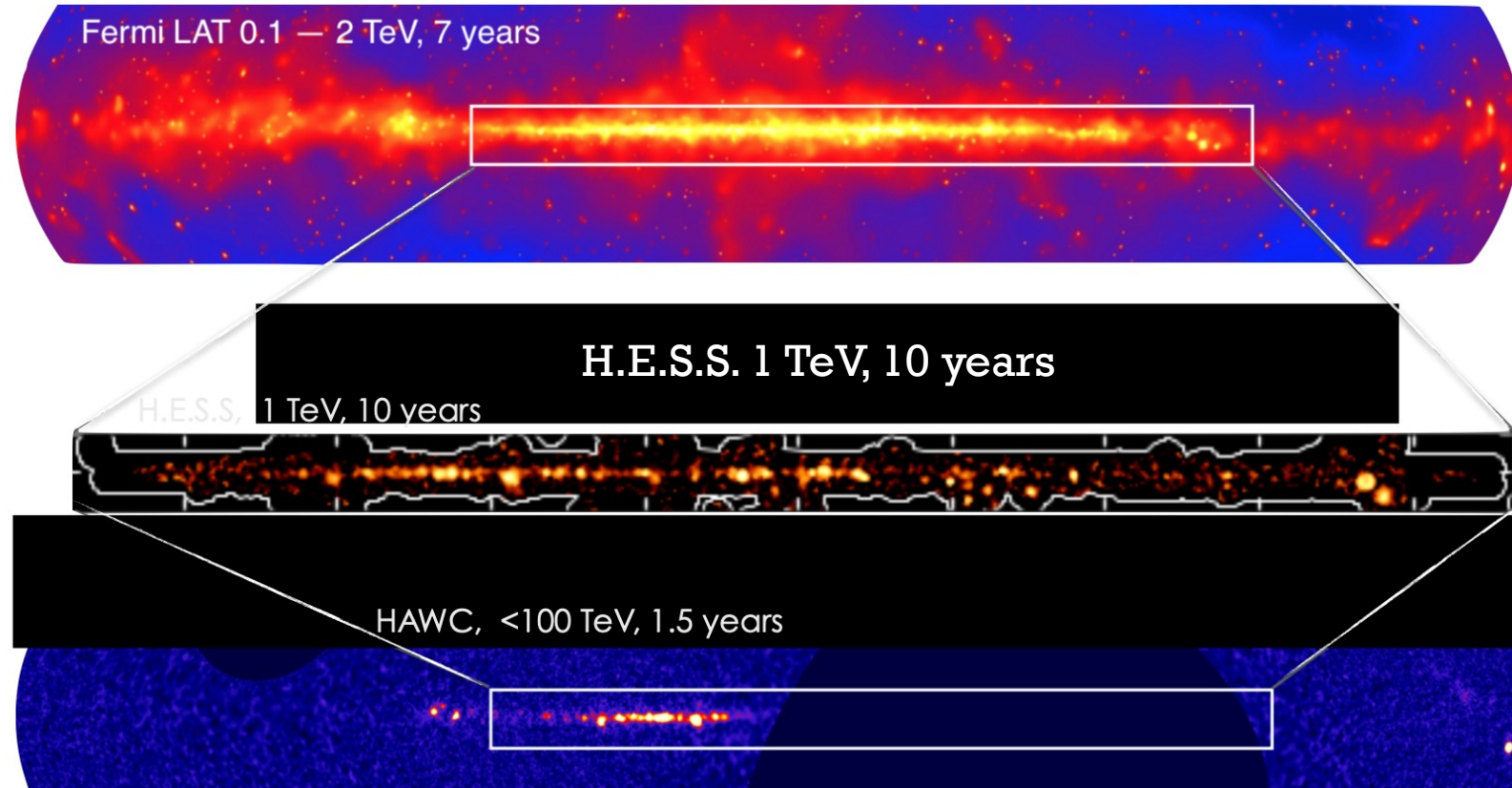
VERY HIGH ENERGY SOURCES



- GRB, Starburst, Superbubble
- PWN, PWN/TeV Halo, TeV halo, Composite SNR, BIN
- DARK, UNID, TeV halo
- HBL, IBL, FSRQ, AGN (unknown type), FRI, Blazar, EHBL, BL Lac (class unclear), LLAGN, LBL
- Shell, SNR/Molec. Cloud, Giant Molecular Cloud, Composite SNR, Superbubble
- Binary, PSR, Gamma BIN, Nova, Microquasar
- TeV halo, Microquasar
- Massive Star Cluster, Globular Cluster

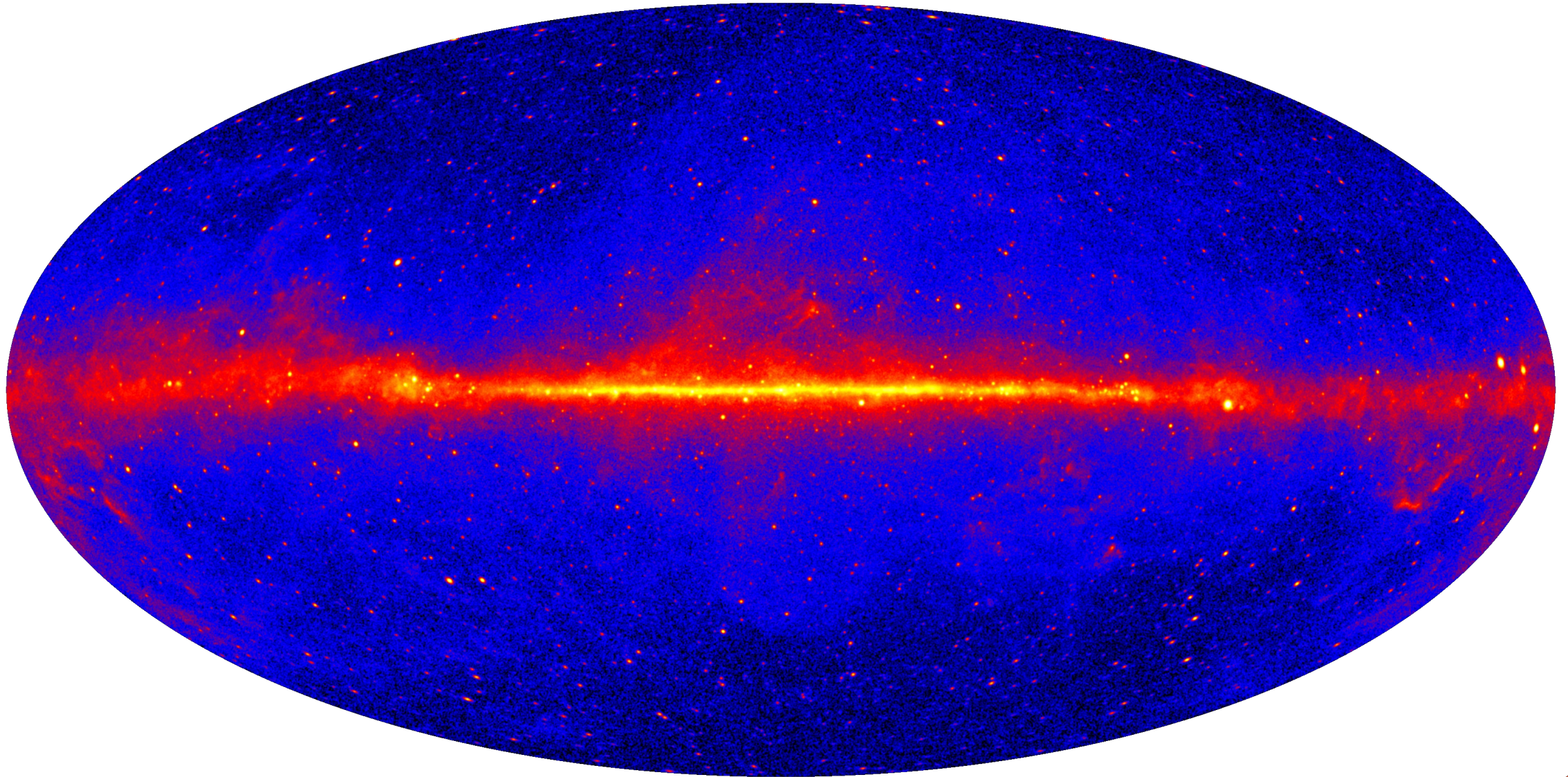
- 323 sources of VHE gamma rays (June 2026)
 - Unidentified sources are the largest population (126)
 - Followed by blazars (88)
 - And by supernova remnants and pulsar wind nebulae (66)

VIEW ON THE GALACTIC PLANE



As you go from GeV to TeV to tens of TeV, the Galactic plane remains bright, but the sky becomes increasingly dominated by a smaller number of hard, extreme accelerators.

THE FERMI SKY

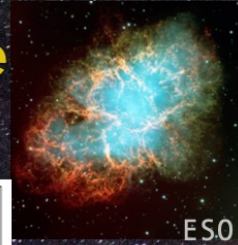
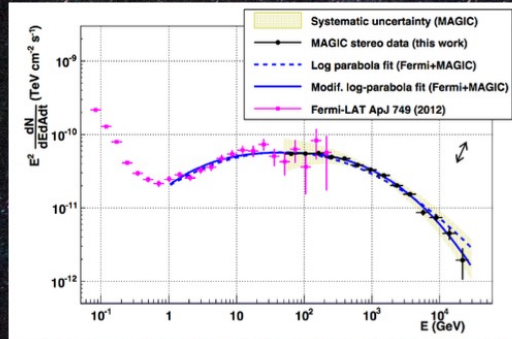


Fermi LAT, Energy > 1 GeV, 12 years of data (7,464,664 photons)

VHE Galactic Sources

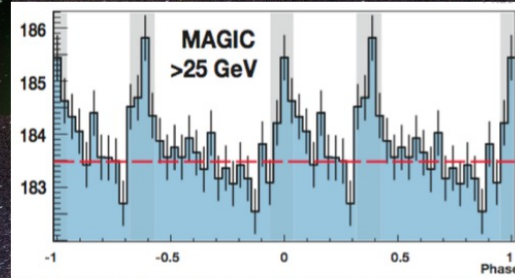
~100 VHE Galactic sources
(TeVCat)

Pulsar-wind nebulae & Crab Nebula

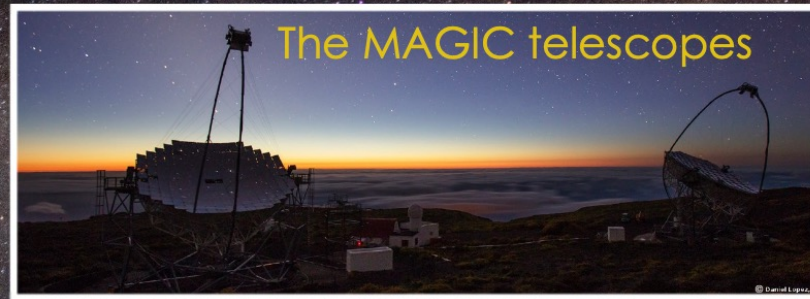
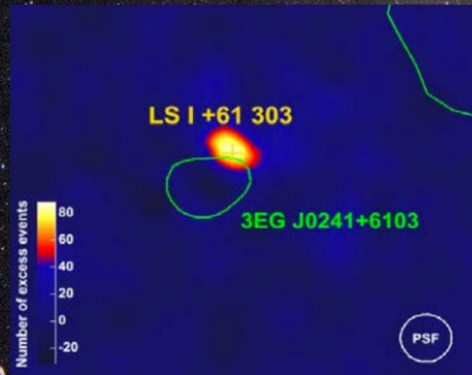


ESO

Pulsars

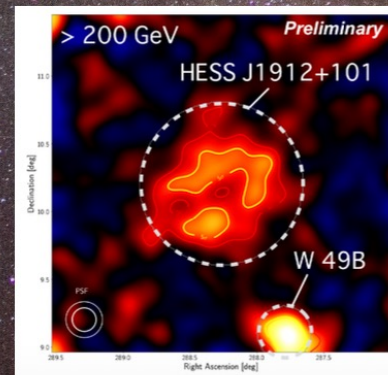


Binaries

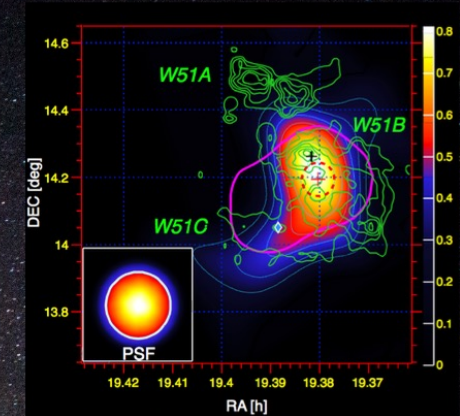


The MAGIC telescopes

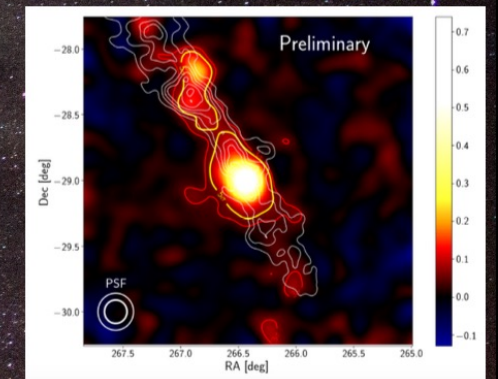
Extended/unidentified sources



SNRs



Galactic Center



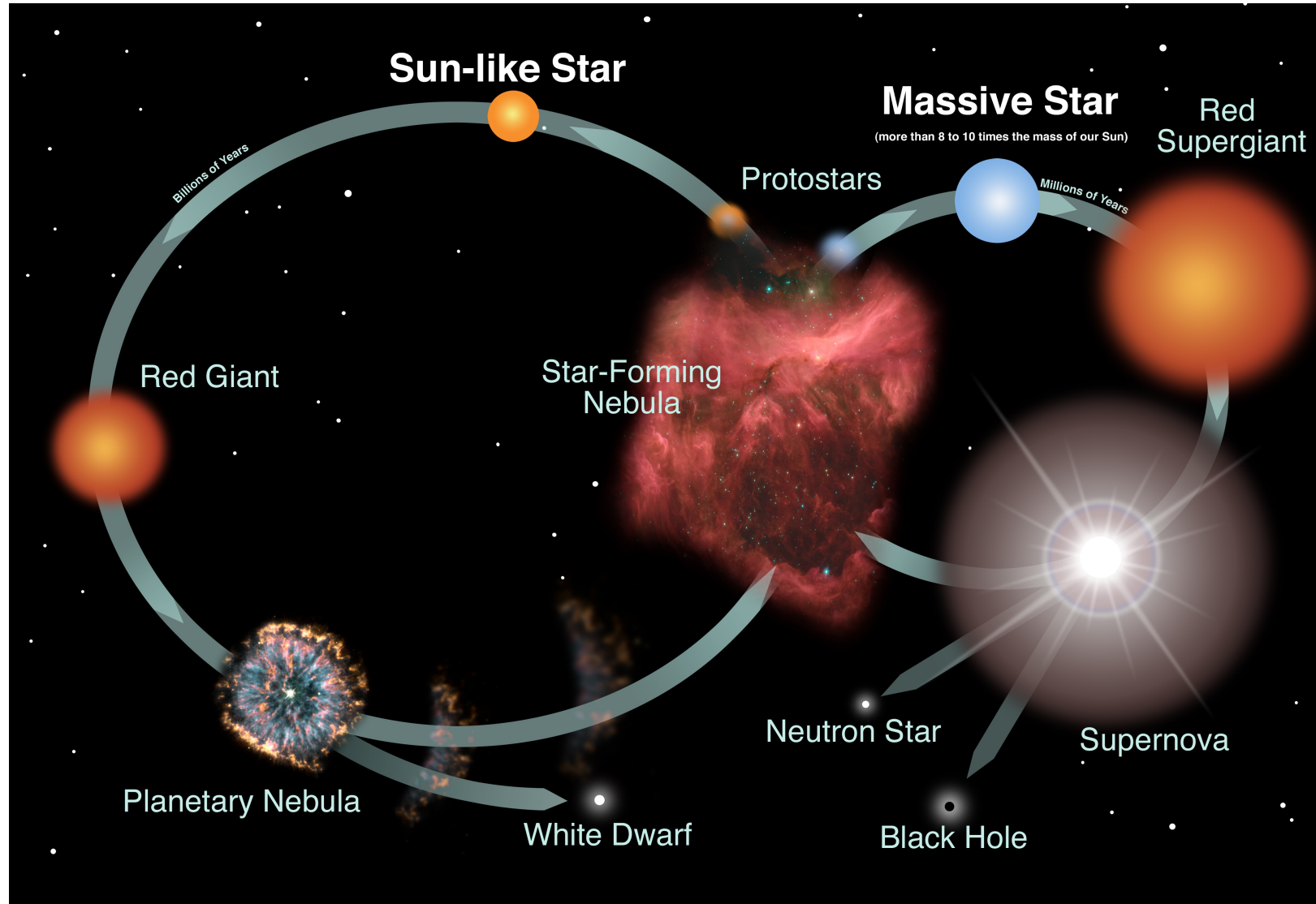
Transient phenomena



Star-forming regions



LIFE CYCLE OF A STAR



POWERING THE GALACTIC GAMMA-RAY SKY

Engine	Examples
Rotation-powered	Pulsars, Pulsar Wind Nebulae (PWNe)
Accretion-powered	Microquasars, X-ray binaries
Wind-Interaction-powered	Gamma-ray binaries
Explosion-powered	Novae, Supernova remnants (SNRs), PeVatrons
Magnetic-powered	Magnetars
Complex environments	Galactic Centre

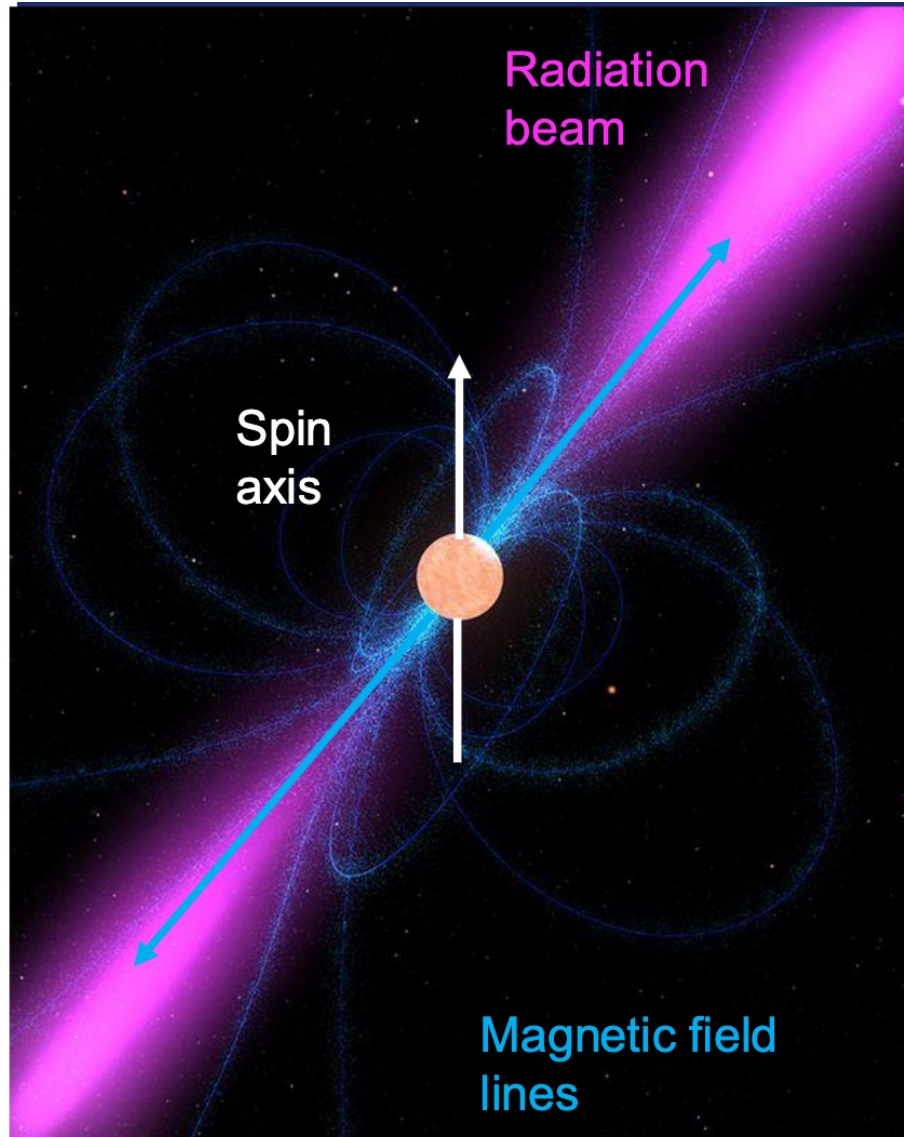


ROTATION POWERED SYSTEMS

Pulsars

Pulsar Wind Nebulae

WHAT ARE PULSARS?

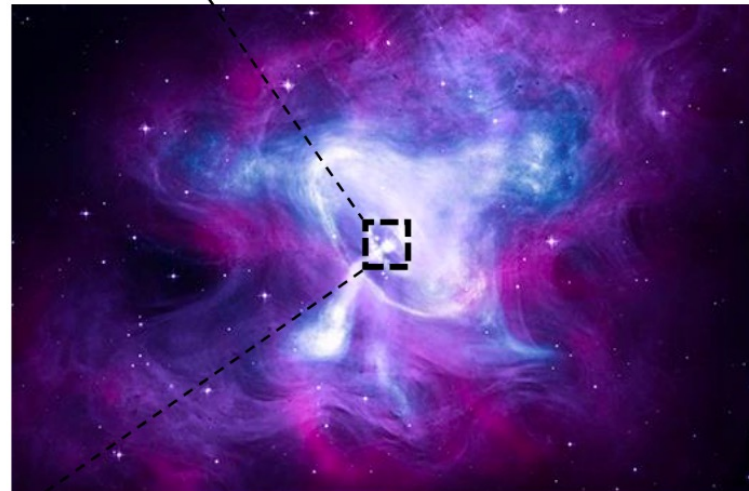


Pulsar: Rotating neutron star

Formed during collapse of a stellar core, sustained against gravity via neutron degeneracy pressure

Angular momentum conserved → very rapid rotation

Magnetic flux conserved → very strong and variable B field $\sim 10^{11} - 10^{14}$ Gauss (Earth's magnetic field = 0.5 G)



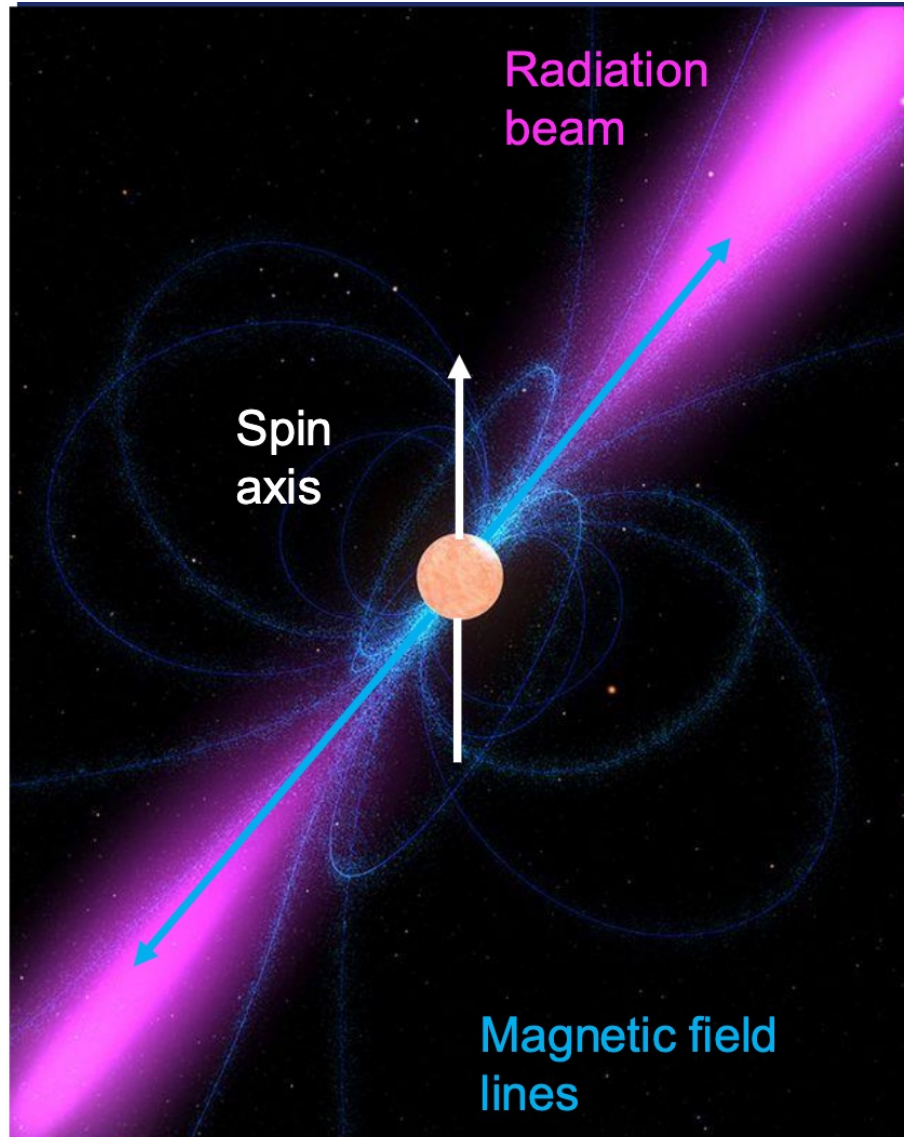
Crab pulsar: X-ray, infrared & optical
Credit: NASA/CXC/SAO/STScI

$$L = I\omega = \frac{2}{5}MR^2\omega \propto \frac{MR^2}{P}$$

$$\Phi = BR^2$$

$$B_{NS} = B_* \left(\frac{R_*}{R_{NS}} \right)^2$$

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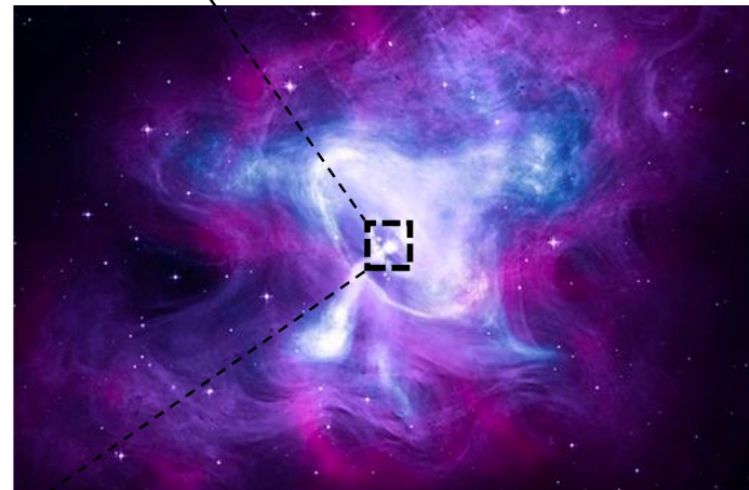
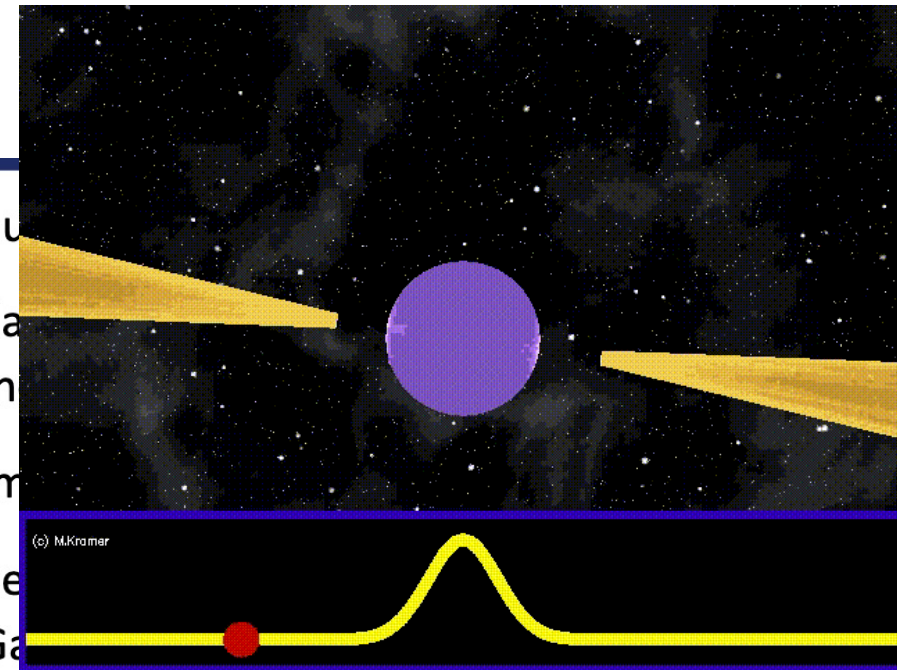


Pulsar: Rotating neu

Formed during colla
against gravity via n

Angular momentum

Magnetic flux conse
field $\sim 10^{11} - 10^{14}$ Ga



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PULSARS

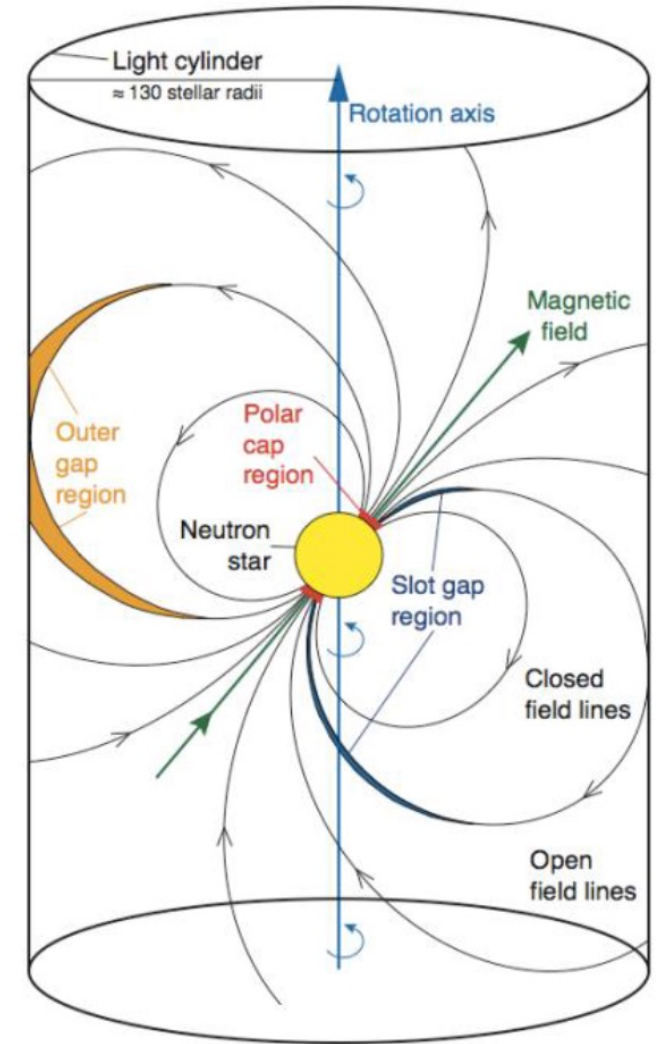
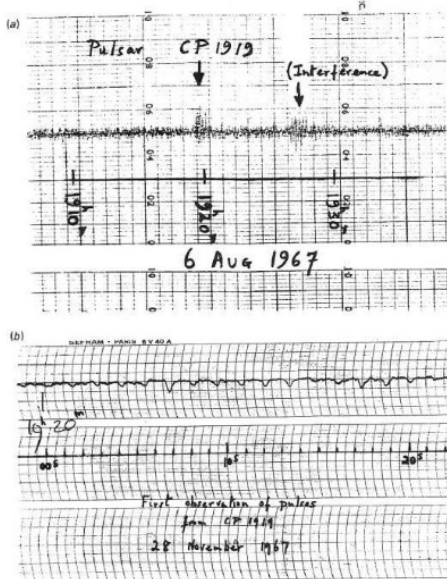
Discovered in 1967 – astrophysical signal with very short periods

Typical size $R \sim 10$ km

Rotation velocity at surface must be less than the speed of light, c: $R < \frac{Pc}{2\pi}$

“Light cylinder” = radius at which particles would have to travel at c to co-rotate $R_{LC} = \frac{Pc}{2\pi}$

Jocelyn Bell Burnell



PULSAR POPULATION

Consider the known pulsar population

Typically shown on a “p-pdot” diagram,
i.e. period vs period derivative

Blue lines = characteristic timescale

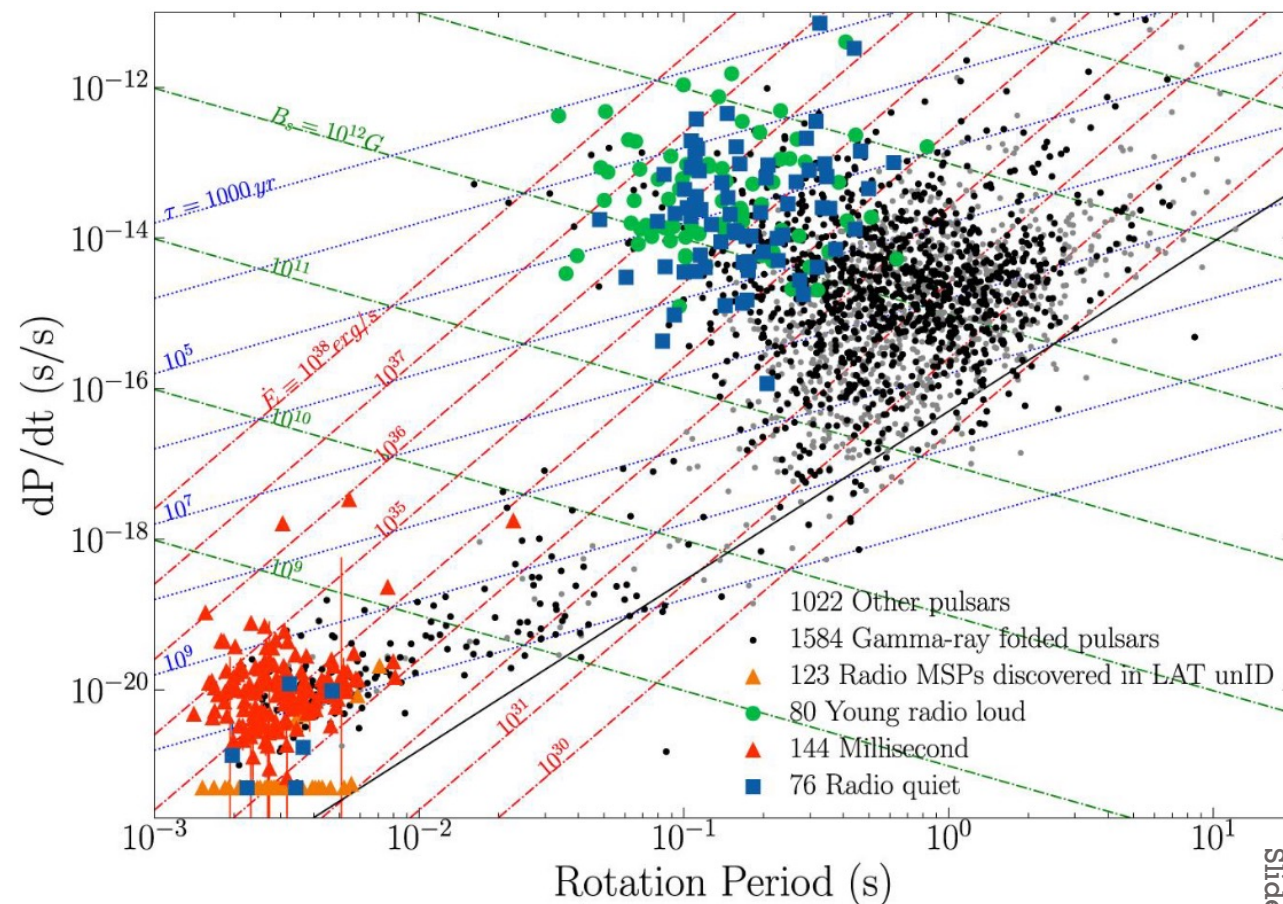
Red lines = spin-down luminosity

Green lines = magnetic field

Lower left = millisecond pulsars

Black line = “death line” → pulsed signals are typically not
observed beyond this line.

Pulsars with detected GeV pulsed emission



3PC Fermi-LAT Collaboration, Smith et al. ApJ **958** (2023) 191

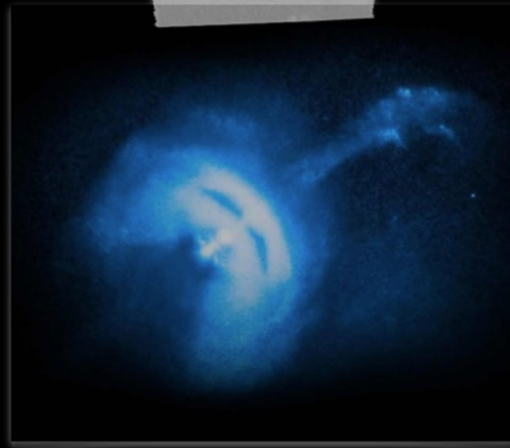
Famous pulsars at VHE

Crab



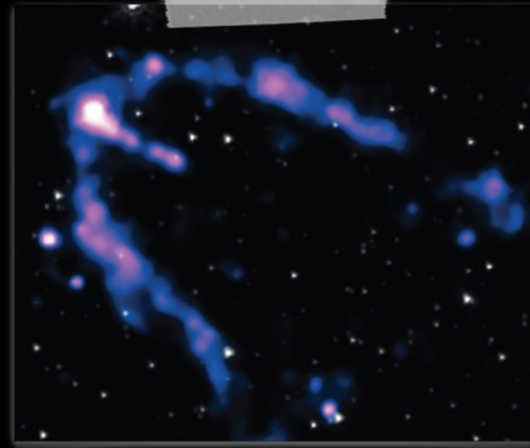
SN explosion:
1054 AC
Pulsar rotation:
30 times per second
33 msec

Vela



SN explosion:
110 000 - 123 000 years ago
Pulsar rotation:
12 times per second
83 msec

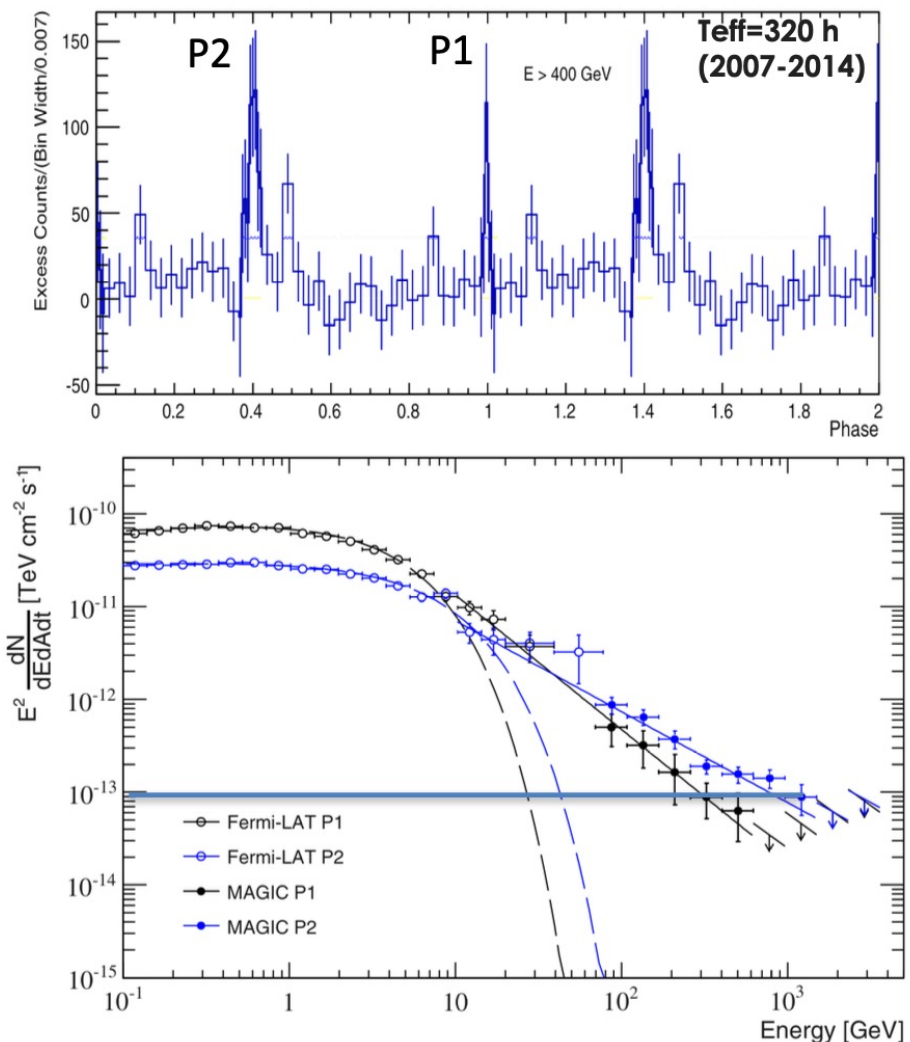
Geminga



SN explosion:
300 000 years ago
Pulsar rotation:
4.2 times per second
238 msec

CRAB PULSAR AT TEV ENERGIES

MAGIC, 2016, A&A, 585, A33



MAGIC discovery of pulsed TeV emission

- MAGIC detected pulsed emission from the Crab pulsar up to 1.5 TeV.
- Pulsed signal remains clearly visible above **400 GeV**
 - P1 detected up to ~ 0.6 TeV
 - P2 detected up to 1.5 TeV

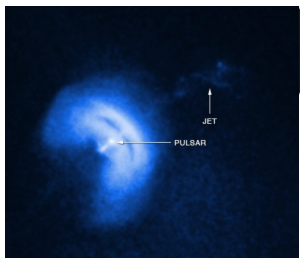
Why was this surprising?

- Fermi-LAT spectra suggested an **exponential cutoff** at a few GeV.
- MAGIC found a **power-law extension** beyond the cutoff.
- The pulsed emission therefore extends **two orders of magnitude higher in energy** than expected.

Implications

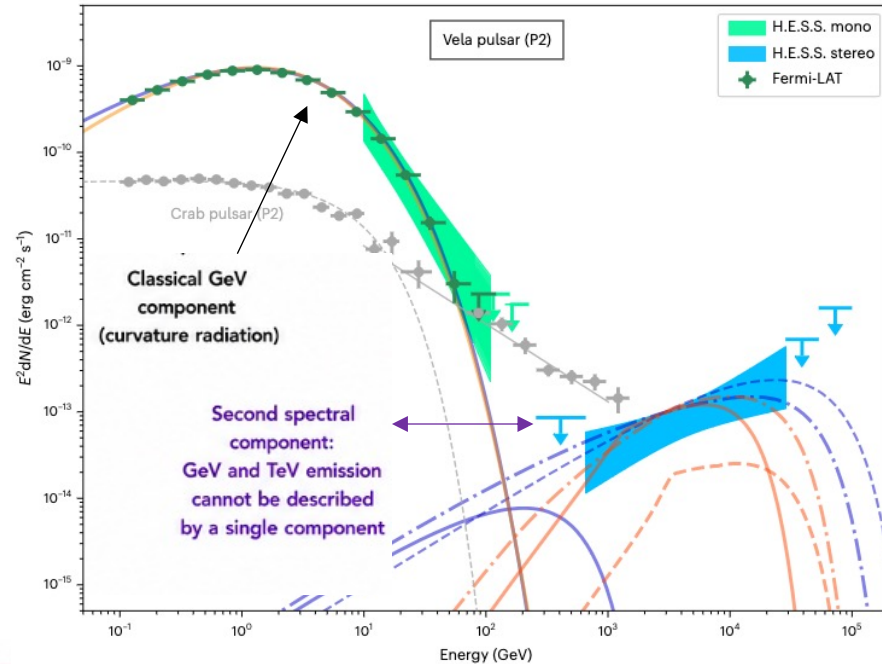
- Curvature radiation alone cannot explain the TeV photons
- Additional emission mechanism required $\rightarrow$ **likely inverse Compton scattering**
- Possible emission region:
 - Outer magnetosphere
 - Near / beyond the light cylinder (striped wind or current sheet)
- No single model currently explains all observations.

FROM A GEV CUTOFF TO A SECOND COMPONENT



Vela pulsar (PSR B0833-45)
(H.E.S.S. Collaboration, Nature Astronomy 7, 1341-1350, 2023)

Figure 3: Spectral energy distribution of the P2 pulse



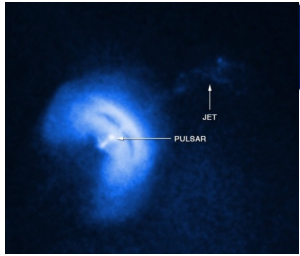
OBSERVATION

- Pulsed γ -rays detected up to 20 TeV.
- A new hard TeV spectral component emerges above the Fermi-LAT cutoff.
- GeV and TeV emission cannot be explained by a single spectral component.

IMPLICATION

- Requires an additional radiation mechanism.
- Strong evidence for inverse Compton (IC) scattering.
- Emission likely produced near or beyond the light cylinder (outer gap / current sheet scenarios favored).

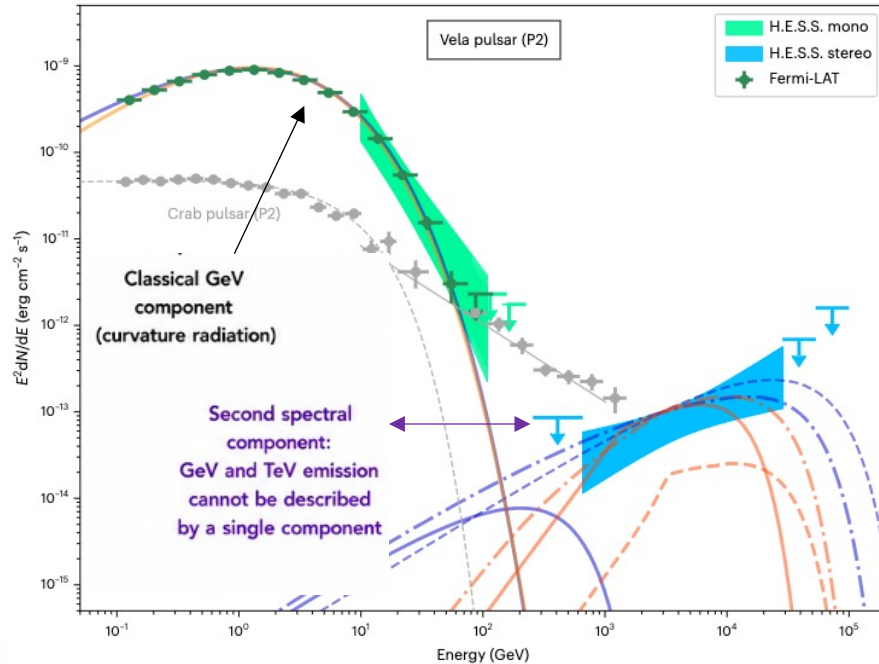
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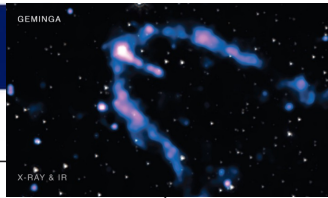


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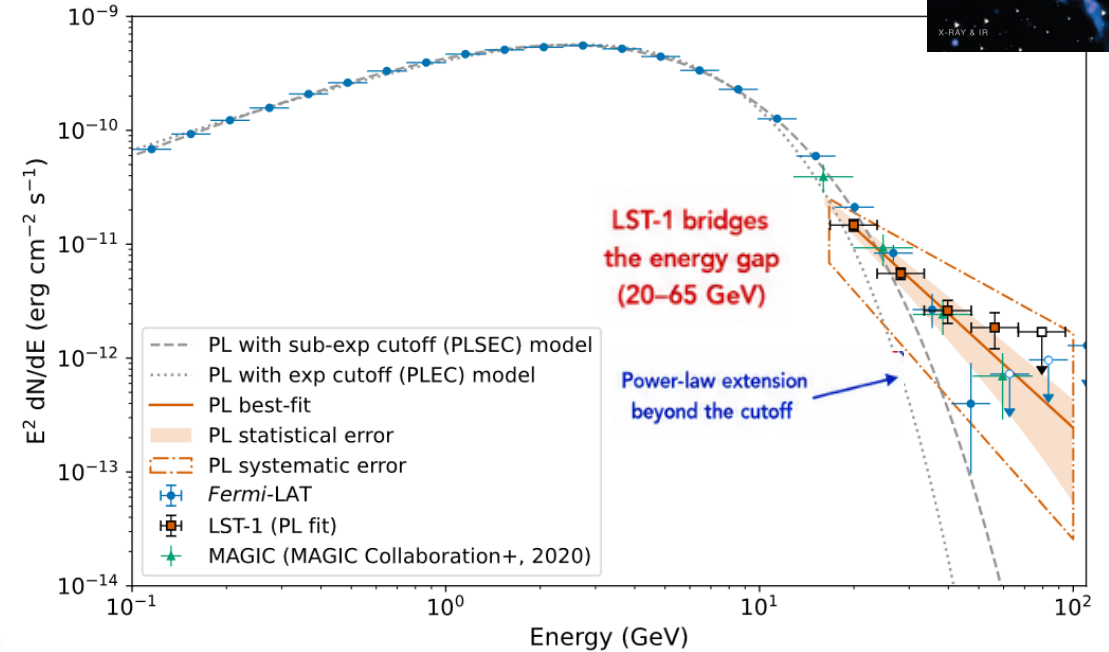
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Geminga pulsar (PSR J0633+1746)

(LST-1 Collaboration, A&A 698, A283, 2025)

Figure 4: Spectral energy distribution of the P2 pulse



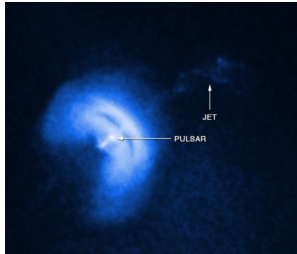
OBSERVATION

- LST-1 detects pulsed emission between 20–65 GeV.
- Bridges the gap between Fermi-LAT and IACTs.
- Spectrum extends beyond the classical cutoff.

IMPLICATION

- Consistent with a power-law tail rather than an exponential cutoff.
- Indicates the transition toward the high-energy (IC) component.
- No pulsed TeV emission detected so far (only upper limits).

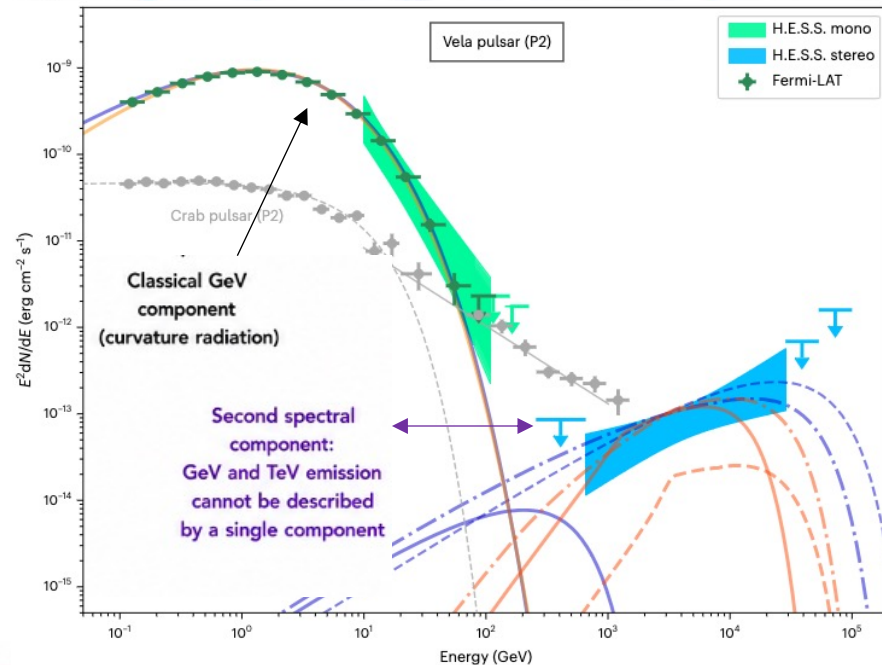
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Figure 3: Spectral energy distribution of the P2 pulse



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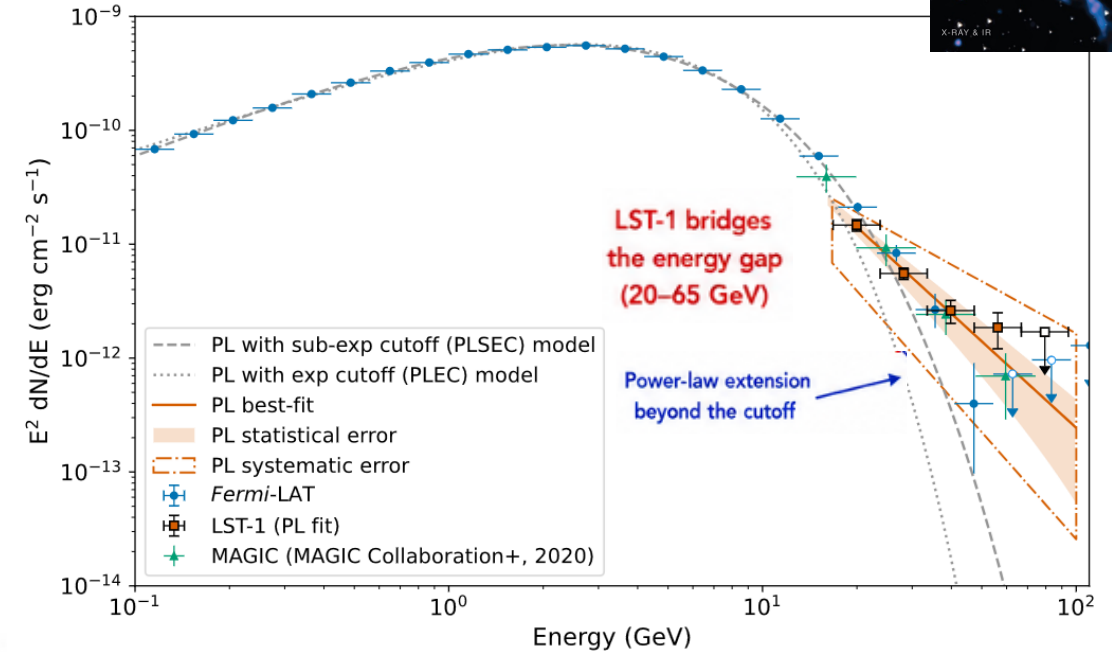
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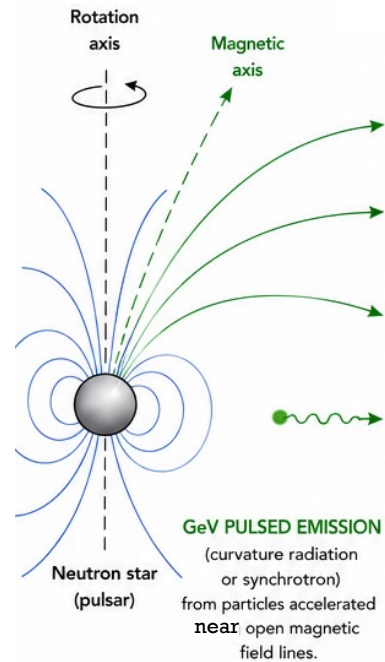
Crab, Vela and Geminga demonstrate that pulsar emission **above the classical GeV cutoff** is more complex than predicted by standard curvature-radiation models. The highest-energy photons likely require an **additional emission mechanism**, but its location and nature remain **open questions**.

Pulsar geometry and high-energy emission

Two sites of TeV gamma-ray production

1. MAGNETOSPHERE

(inside the light cylinder)



Di

— Closed field lines — Open field lines — Magnetic field (one direction) — Magnetic field (opposite direction) - - - Current sheet — Gamma rays (TeV)

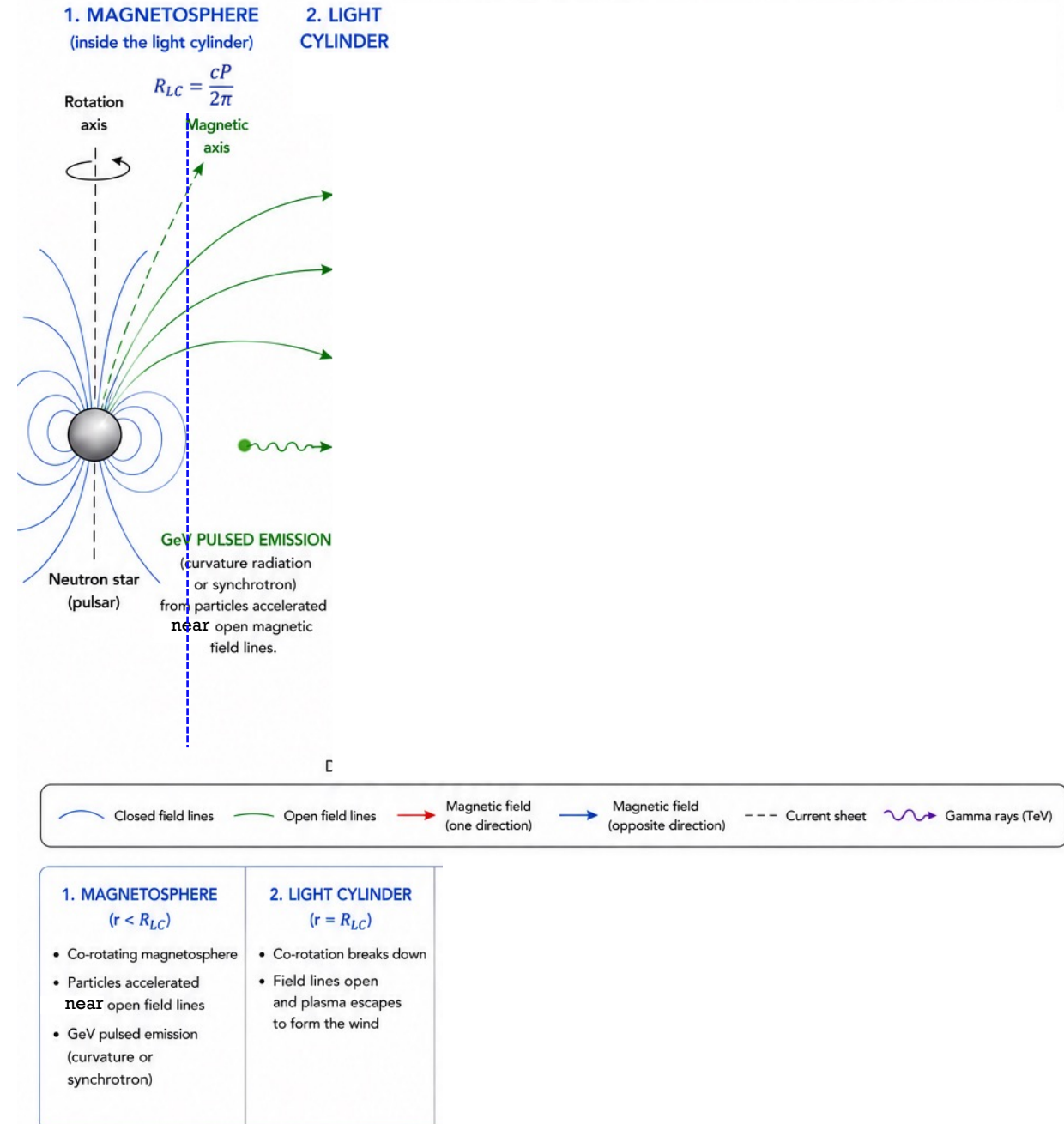
1. MAGNETOSPHERE

($r < R_{LC}$)

- Co-rotating magnetosphere
- Particles accelerated open field lines
- GeV pulsed emission (curvature or synchrotron)

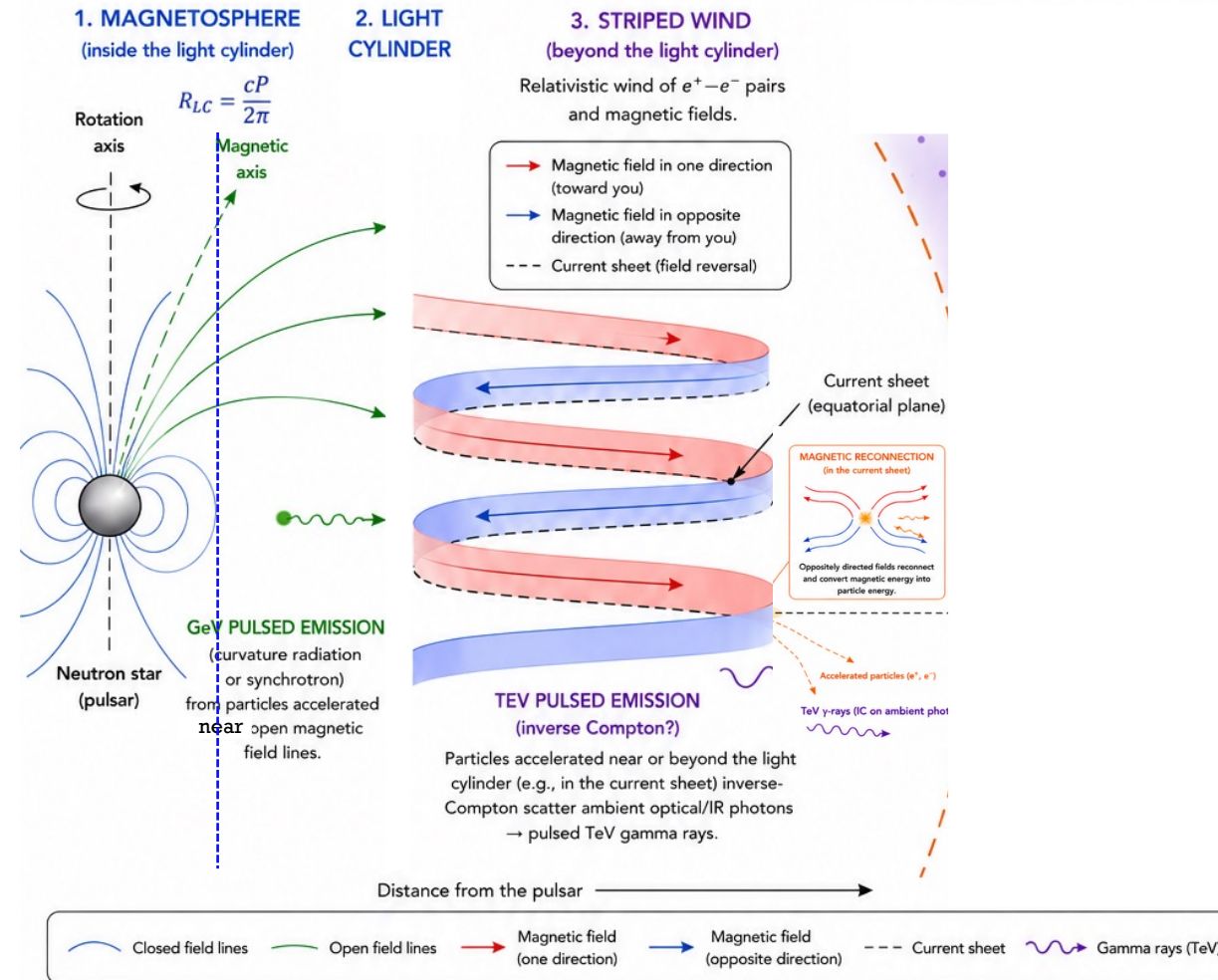
Pulsar geometry and high-energy emission

Two sites of TeV gamma-ray production



Pulsar geometry and high-energy emission

Two sites of TeV gamma-ray production



1. MAGNETOSPHERE ($r < R_{LC}$)

- Co-rotating magnetosphere
- Particles accelerated near open field lines
- GeV pulsed emission (curvature or synchrotron)

2. LIGHT CYLINDER ($r = R_{LC}$)

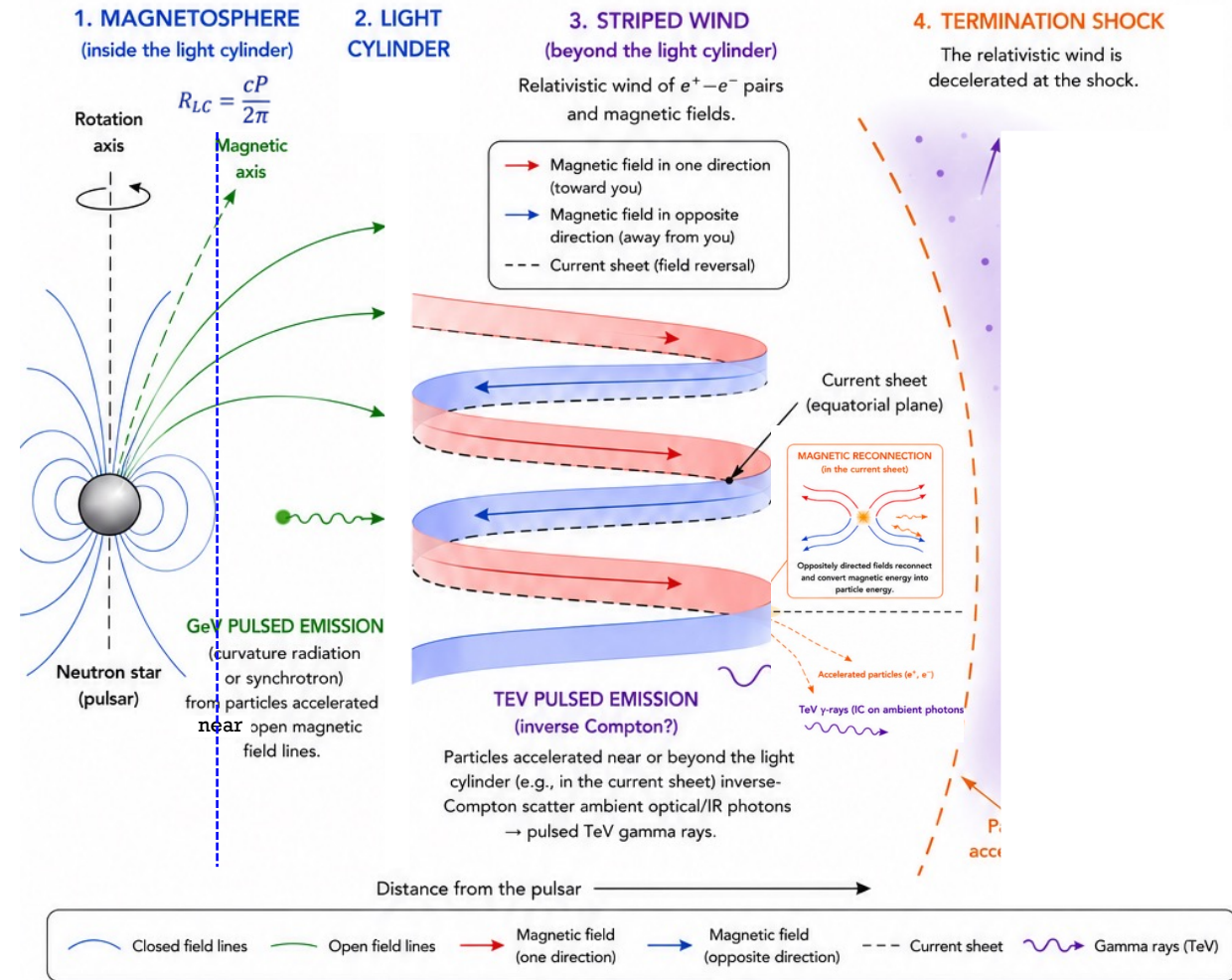
- Co-rotation breaks down
- Field lines open and plasma escapes to form the wind

3. STRIPED WIND ($r > R_{LC}$)

- Toroidal magnetic field reverses every half rotation
- Alternating stripes of opposite polarity
- Current sheet between stripes
- Possible particle acceleration → pulsed TeV emission

Pulsar geometry and high-energy emission

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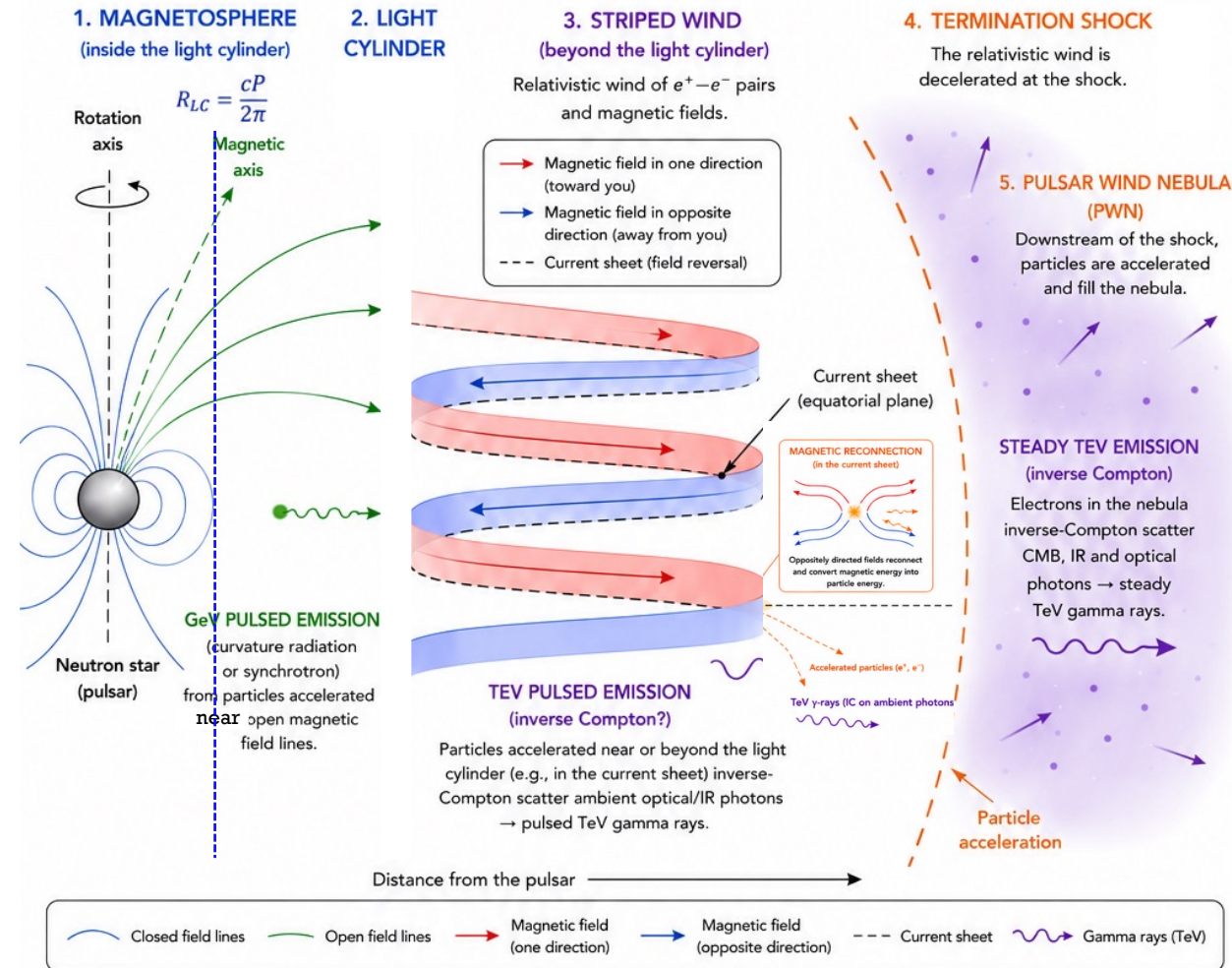
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4. TERMINATION SHOCK

- Wind is decelerated abruptly
- Site of particle acceleration

Pulsar geometry and high-energy emission

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5. PWN

- Relativistic particles fill the nebula
- Synchrotron emission (radio to X-rays)
- Inverse Compton emission → steady TeV gamma rays

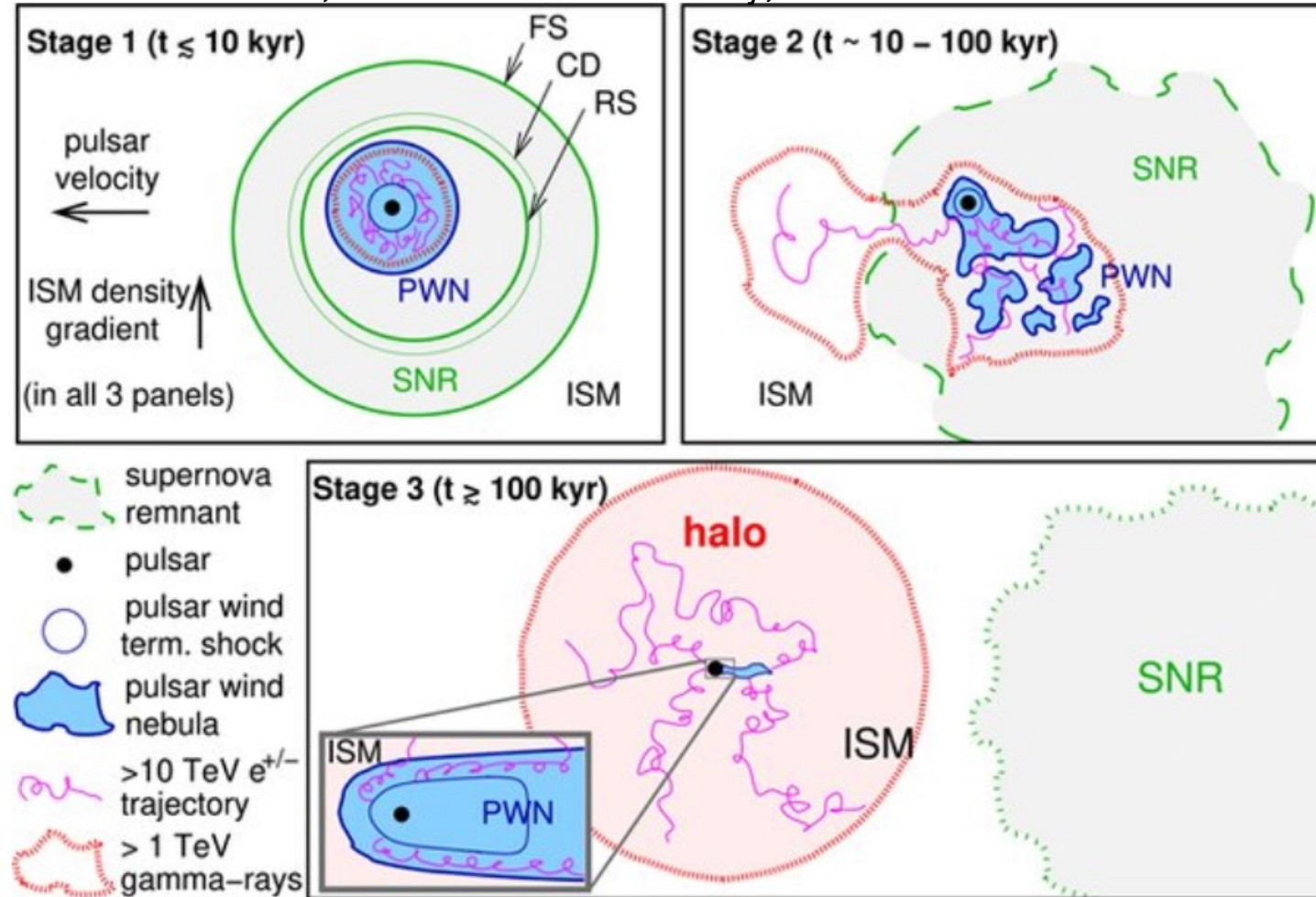
PULSAR SUMMARY

Region	Main process	Target photon field	Gamma rays	Pulsed?	Status
Magnetosphere (inside R_{LC})	Curvature / synchrotron radiation	Magnetic field	GeV (up to ≈ 100 GeV)	Yes	Well established
Striped wind / current sheet ($\approx$ beyond R_{LC})	Inverse Compton (IC)	Ambient optical / infrared photons	TeV (up to ≈ 20 TeV)	Yes (pulsed)	Active research (Vela, Crab, ...)
PWN (downstream of termination shock)	Inverse Compton (IC)	CMB, IR, optical photons	TeV ($\approx 0.1 - 100$ TeV+)	No (steady)	Well established (Crab, Vela X, ...)

Pulsed TeV emission comes from the inner system ($\leq \text{few} \times R_{LC}$),
while **steady** TeV emission comes from the extended pulsar wind nebula.

EVOLUTIONARY STAGES OF PULSAR ENVIRONMENTS

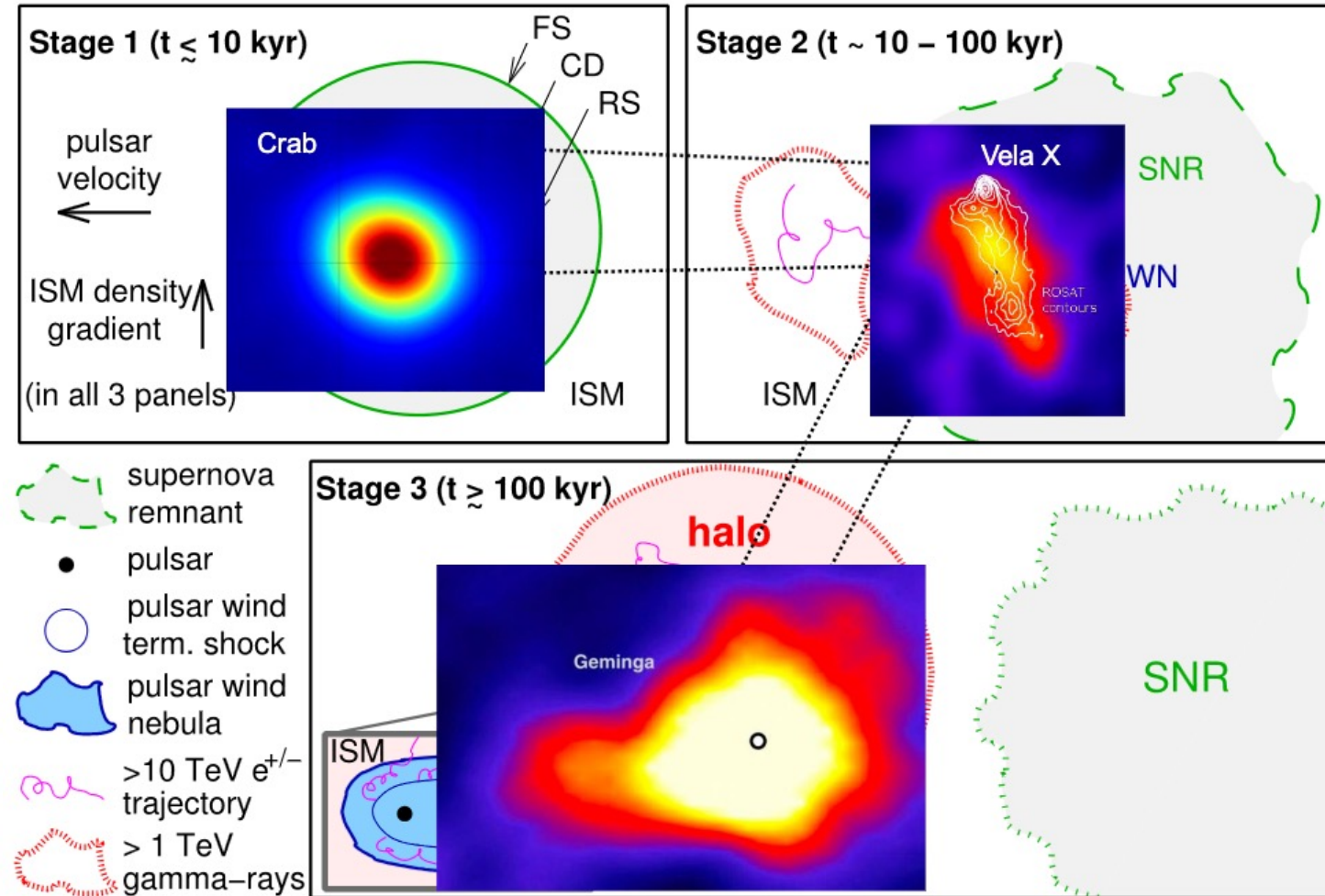
FS = forward shock; CD = Contact Discontinuity; RS = reverse shock



- **Stage 1 (< 10 kyr): Young PWN** Pulsar wind is confined inside the supernova remnant (SNR).
 - Most relativistic $e^{\pm}$ remain trapped and radiate inside the PWN.
- **Stage 2 (10–100 kyr): Transitional phase** Reverse shock disrupts the PWN.
 - High-energy particles begin escaping into the SNR and surrounding ISM.
 - Emission comes from both the PWN and escaping particles.
- **Stage 3 (> 100 kyr): Pulsar halo** Pulsar has left (or outlived) the SNR.
 - Escaping $e^{\pm}$ diffuse through the interstellar medium.
 - Inverse Compton scattering produces an extended TeV halo.

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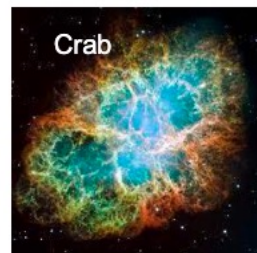
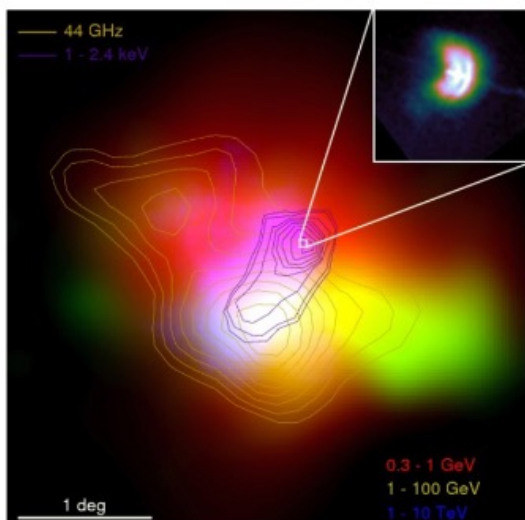


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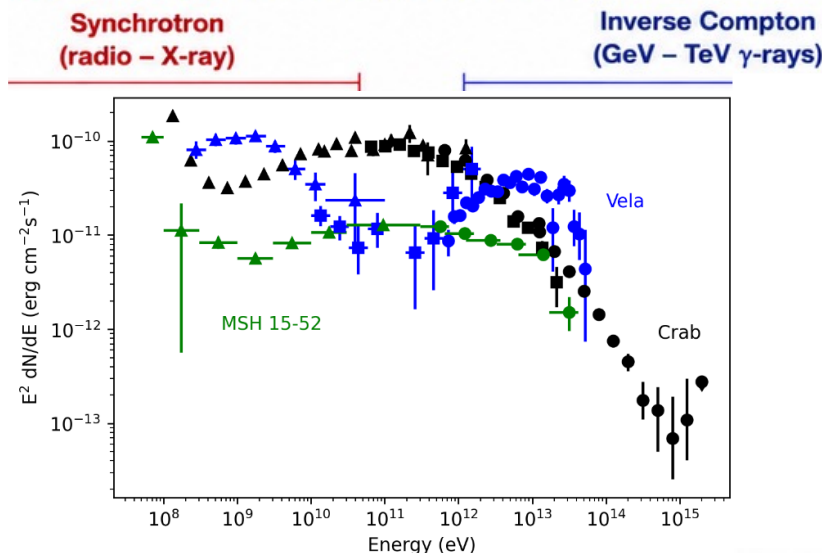
PULSAR WIND NEBULAE

Example: Vela X (X-ray + radio)

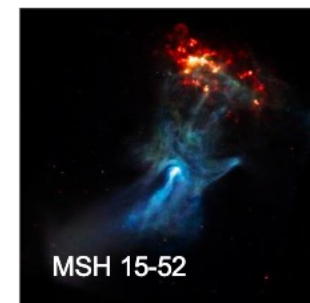
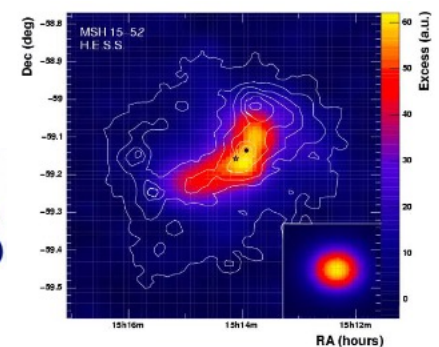
Yellow contours:
radio (44 GHz)
Purple contours:
X-rays (1–2.4 keV)
Red: 0.3–1 GeV
Green: 1–100 GeV
Blue: 1–10 TeV



Broadband spectral energy distributions



A&A 435, L17-L20 (2005)



Observational properties

- Powered by the spin-down energy of a young pulsar
- Bright non-thermal nebulae emitting from radio to >100 TeV
- **Synchrotron emission:** radio → X-rays
- **Inverse Compton emission:** GeV → TeV γ-rays

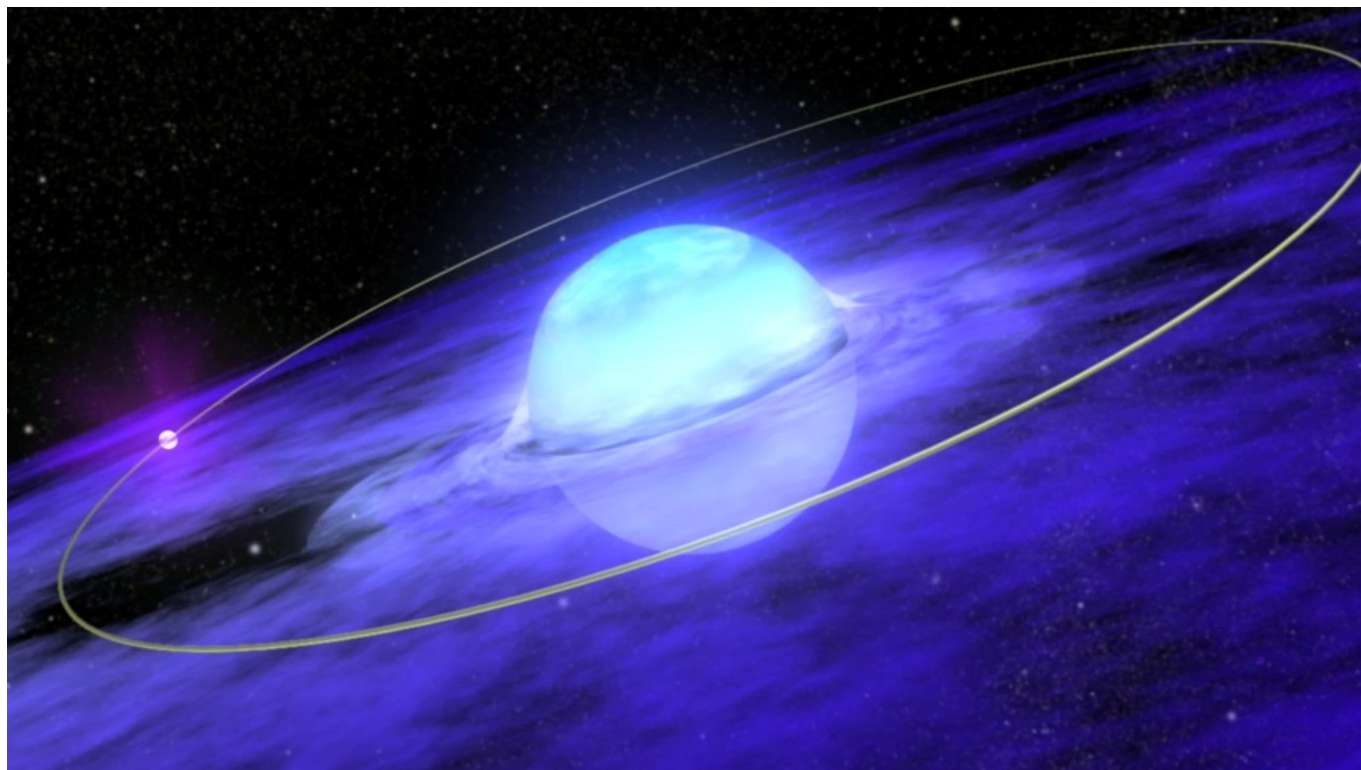
What do observations tell us?

- Electrons are accelerated up to hundreds of TeV
- PWNe are among the brightest Galactic TeV sources
- Morphology evolves with age and environment (e.g. Crab → Vela X → relic PWNe)

Current challenges

- Where are the highest-energy particles accelerated?
 - Termination shock? Magnetic reconnection?
- How do particles escape to form TeV halos?

PWNe trace where particles are accelerated. TeV halos trace what happens after they escape into the ISM.

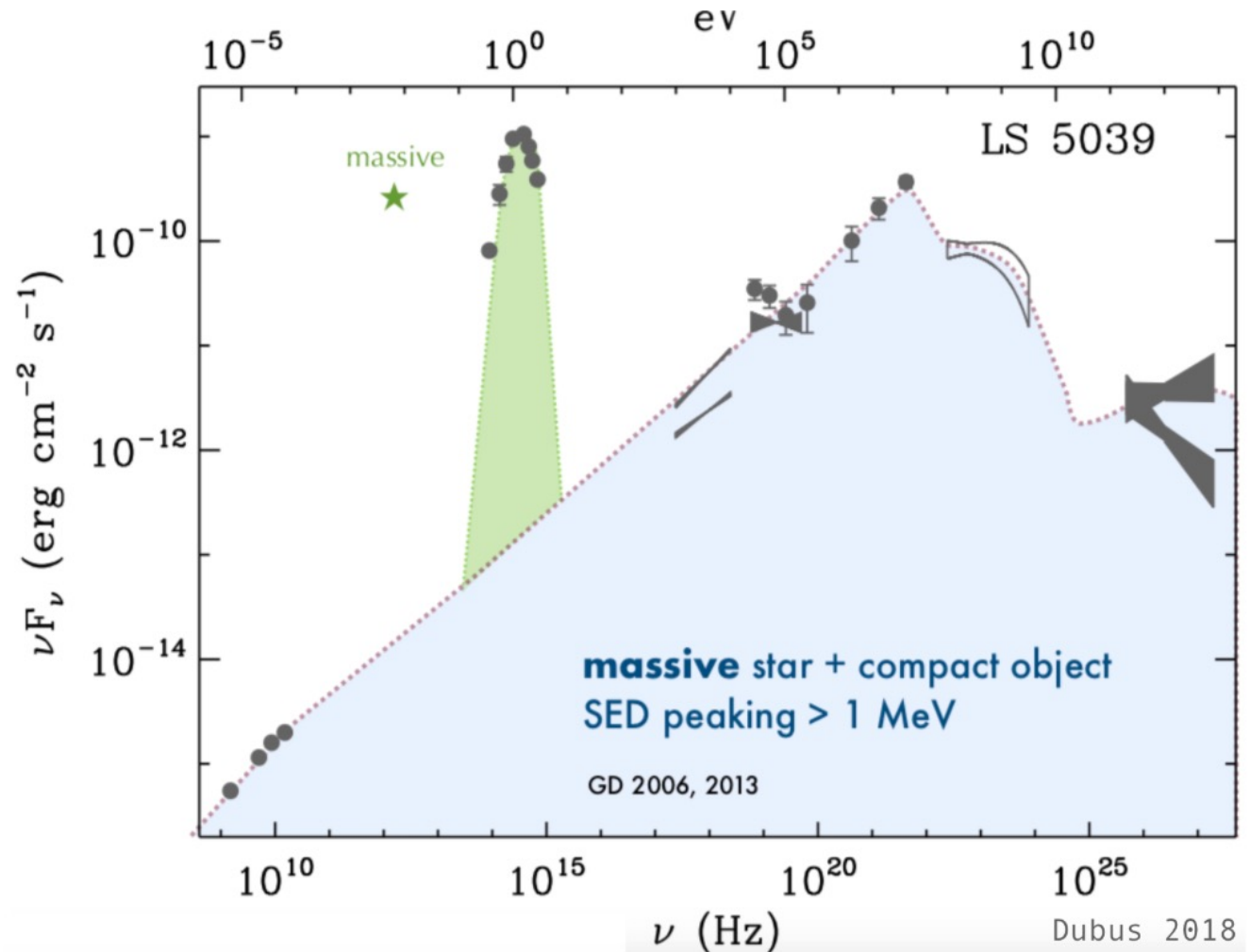


WIND-INTERACTION POWERED SYSTEMS

Gamma-ray binaries

DEFINITION OF GAMMA-RAY BINARIES

- Show periodic emission.
- Gamma-ray emission above 1 MeV “dominates” the SED output.
- Only 9 known systems (out of ~300 X-ray binaries) -> progenitors of HMXBs? (Dubus 2013)
 - 8 HMGBs have been identified in the Milky Way
 - 1 in the Large Magellanic Cloud
- Non-thermal radio emission
- Moderate X-ray emission
- HE and VHE not necessarily correlated
- GeV spectra can be fitted with a power law + exponential cutoff, like for pulsar magnetospheres, but the emission is variable(!) and periodic.



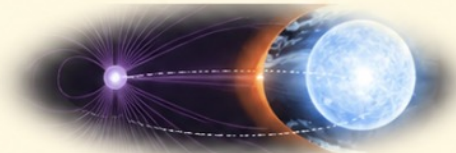
GAMMA-LOUD BINARIES: STATE-OF-THE-ART

Gamma-ray binaries

System	Star spectral type	Compact object	Porb [days]	HE emission	VHE emission	UHE emission
PSR B1259-63	O9.5Ve	48ms pulsar	1236.72	yes	yes	
LS 5039	O	pulsar?	3.91	yes	yes	yes
LS I +61 303	Be	pulsar	26.49	yes	yes	yes
HESS J0632+057	Be	-	315.50	yes	yes	
FGL J1018.6-5856	O	-	16.58	yes	yes	
LMC P-3	O	-	10.2	yes	yes	
HESS J1832-093	O	-	82	yes	yes	
PSR J2032+4127	Be	143 ms pulsar	50 years	yes	yes	
4FGL J1405.1-6119	O	-		yes	?	



Gamma-ray binaries are **rare**, but **extreme laboratories** for studying particle acceleration and the interaction between compact objects and massive stars.



PULSAR-WIND GAMMA-RAY BINARIES

PHYSICAL PICTURE



Rotation-powered pulsar launches a relativistic wind.



Pulsar wind collides with the stellar wind of the massive companion.



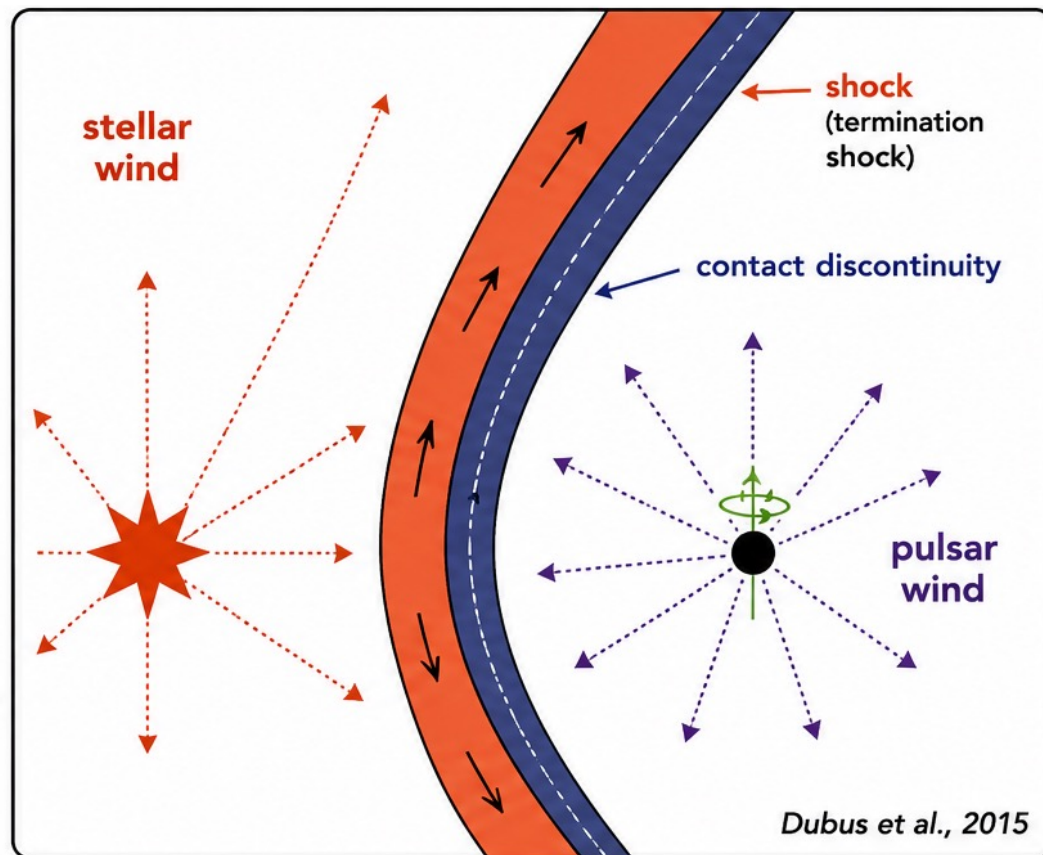
A **termination shock** forms where the wind pressures balance.



The shock **accelerates particles** to relativistic energies.



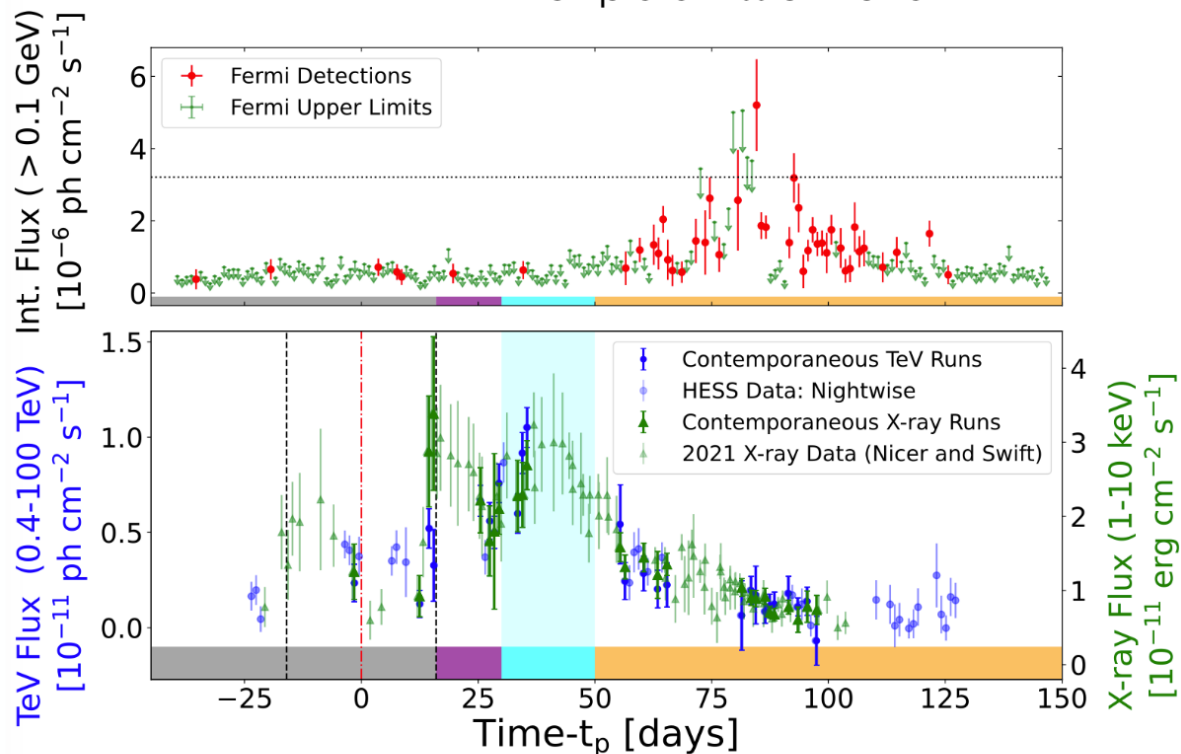
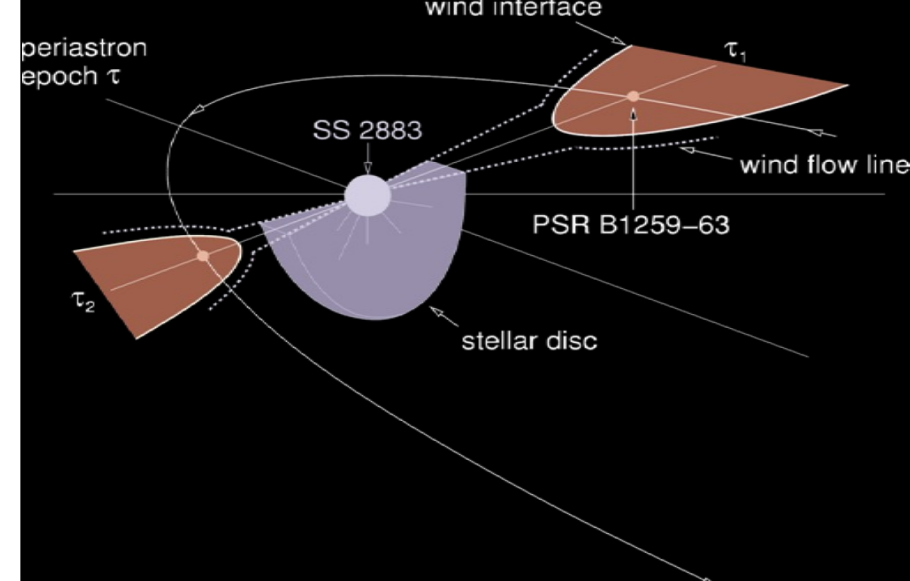
Electrons produce **γ -rays** mainly through **Inverse Compton scattering** on stellar UV photons.



Unlike PWNe, the shock is **not stationary**—it **moves** throughout the orbit as the stellar and pulsar winds change their relative pressure.

PSR B1259-63

- 48 ms pulsar orbiting a B2e companion with inclined disk.
- Orbital period: 3.4 year, highly eccentric orbit.
- ~ 0.7 A.U separation at periastron (10 AU at apastron).



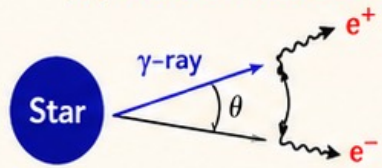
H.E.S.S. Coll (2024)

- **TeV**: double-peaked lightcurve, with a sharp dip shortly after periastron.
- **TeV** emission corresponds to $\sim 1\%$ of the pulsar spin-down energy.
- **GeV**: bright flares, 30 – 70 days after periastron. Flares show rapid variability
- **Apparent GeV luminosity $\gtrsim$ pulsar spin-down power (assuming isotropic emission).**
- **$\Rightarrow$ Relativistic Doppler boosting is a leading explanation**
- $\rightarrow$ GeV and TeV produced by a different electron population or in a different emission region.

LS 5039: ORBITAL MODULATION & γ - γ ABSORPTION

- **Variable TeV emission** with the orbital phase (Aharonian et al. 2006).
- Flux maximum at inferior conjunction (compact object between star and observer).
- **γ - γ absorption** (e^+e^- pair production on stellar UV photons) has an angle-dependent cross-section, **plays a major role**.

γ - γ ABSORPTION: ANGLE DEPENDENCE

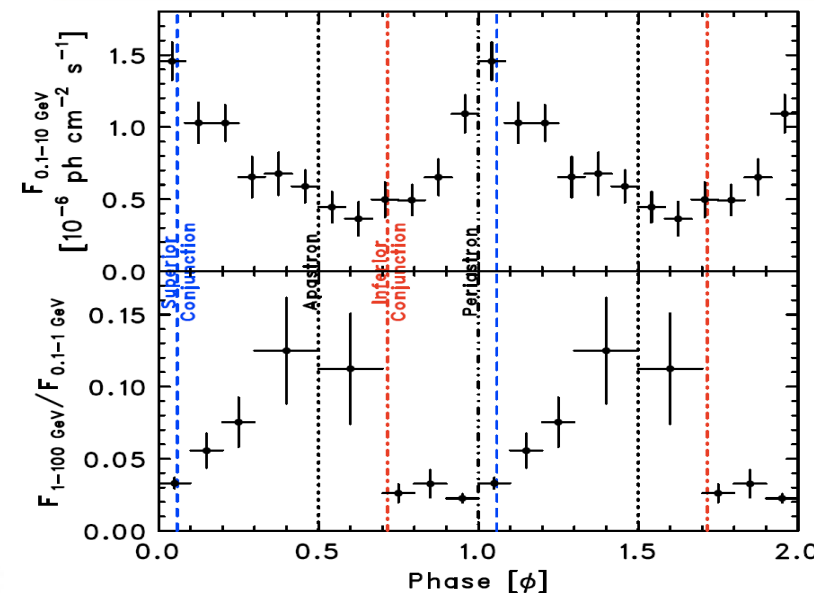
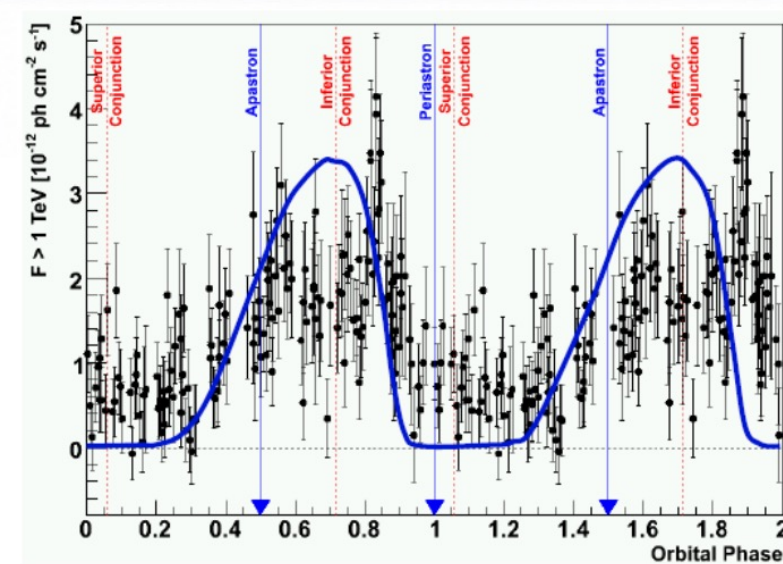
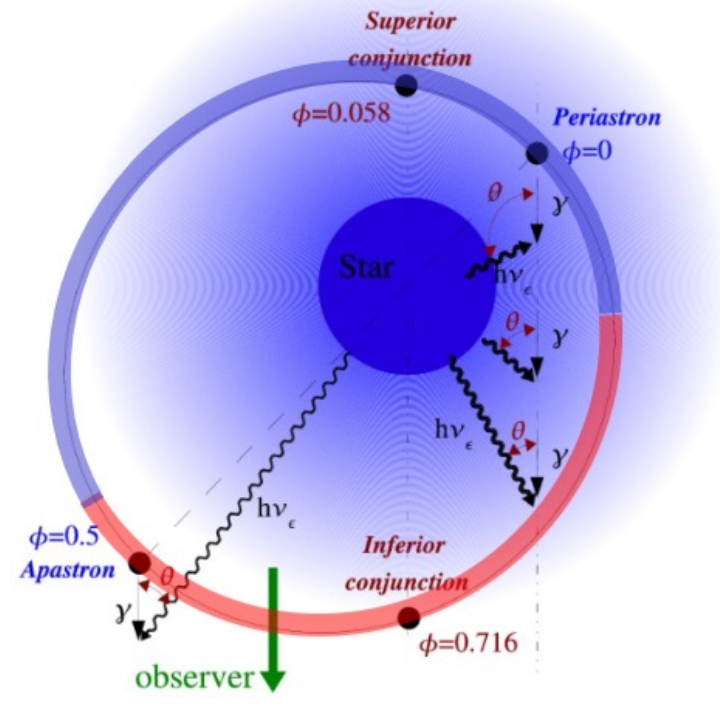


Cross-section peaks for $\theta \sim 180^\circ$ (head-on) and is minimal for $\theta \sim 0^\circ$ (tail-on).

θ = angle between γ -ray and target photon

- γ - γ absorption depends on the angle between the γ ray and stellar UV photons.
- Absorption is strongest near superior conjunction, but it does not explain all the observed variability.
- The spectrum shows strong variability, but not at 200 GeV as predicted by absorption models (Dubus 2006, Böttcher 2007). Cascading has to be modeled in detail (Khangulyan+ 2008, Cerutti+ 2010).

Phase-dependent e^- acceleration? TeV emission produced away from CO?



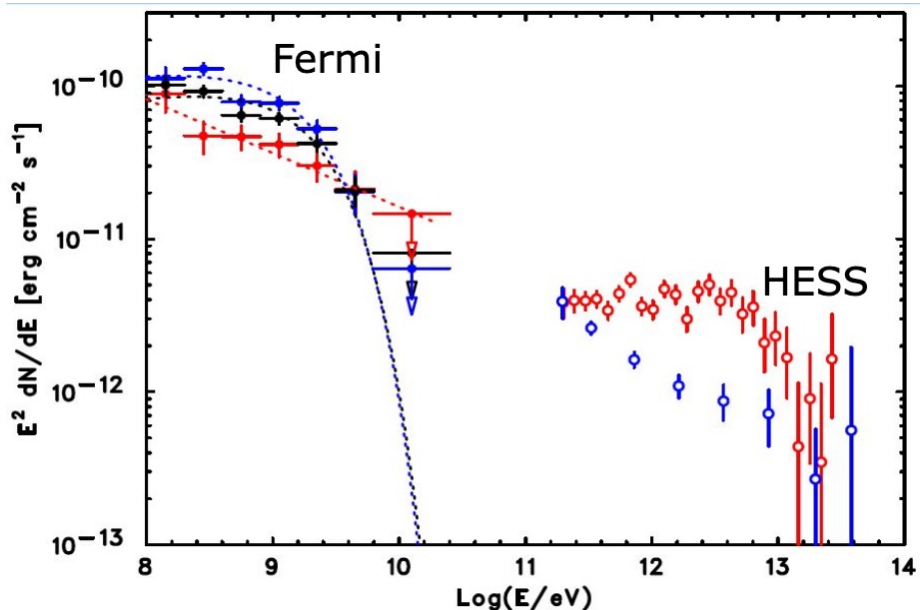
GeV and TeV light curves are **anti-correlated**.

H.E.S.S.: Aharonian et al. 2006, A&A 460, 743

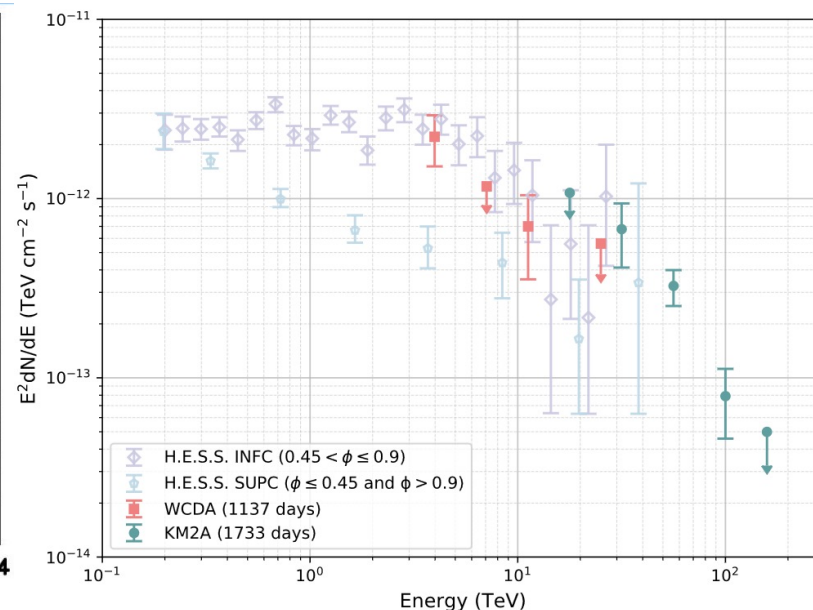
Fermi-LAT: Abdo et al. 2009, ApJ 706, L56

LS 5039: SPECTRAL PROPERTIES & OPEN QUESTIONS

BROADBAND SPECTRAL ENERGY DISTRIBUTION



SPECTRA IN DIFFERENT PHASES



KEY PHYSICS POINTS

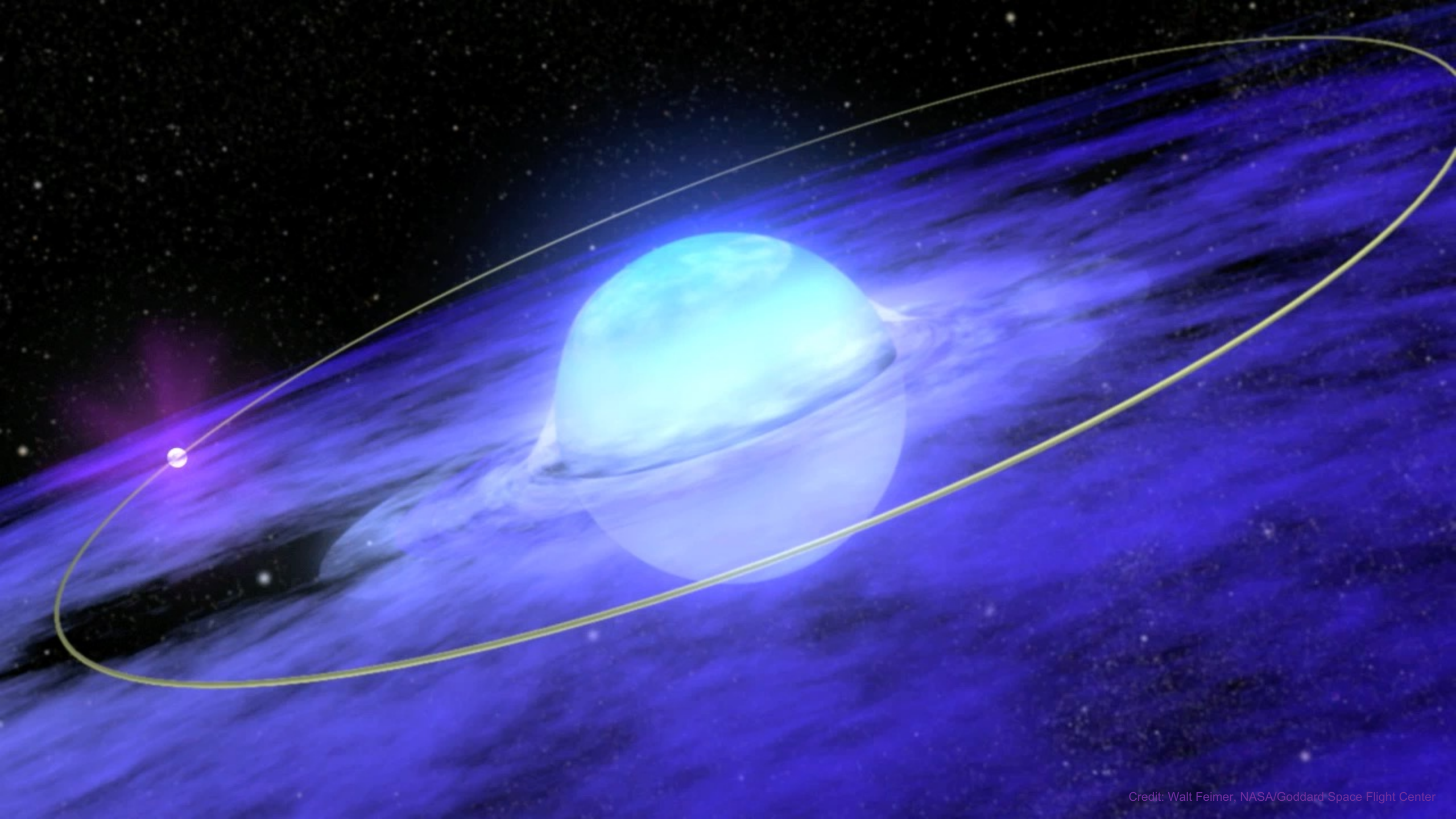
- γ - γ absorption on stellar UV photons is important (angle dependent).
- Absorption alone cannot explain all observations.
- Strong spectral variability with orbital phase.
- GeV spectrum shows a cut-off around a few GeV.
- GeV and TeV spectra do not connect smoothly.
- **TeV emission extends beyond 100 TeV with no cutoff.**

OPEN QUESTIONS

- Nature of the compact object still unknown (pulsar or black hole?).
- Tentative 9 s X-ray periodicity reported (Yoneda et al. 2020) → possible magnetar? (not yet confirmed)
- Hints of a triple system? (Zeng et al. 2024)
- Where and how are particles accelerated?
- Why do GeV and TeV emissions behave differently?
- Does orbital modulation persist above 10–100 TeV? (HAWC reports hints of orbital modulation above 10 TeV; Wang PoS(ICRC2023))
- Can LS 5039 accelerate particles to PeV energies?

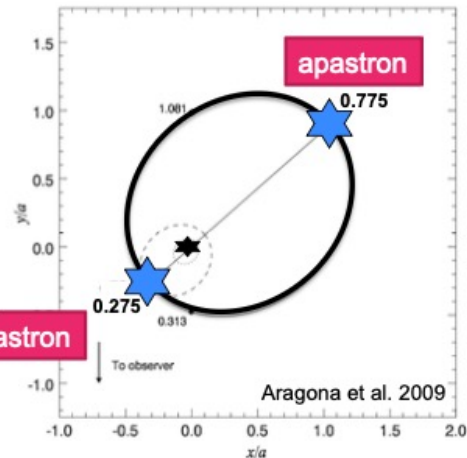


LHAASO detects γ -rays up to **~ 100 TeV** with no spectral cutoff →
LS 5039 is a **strong Galactic PeVatron candidate**.



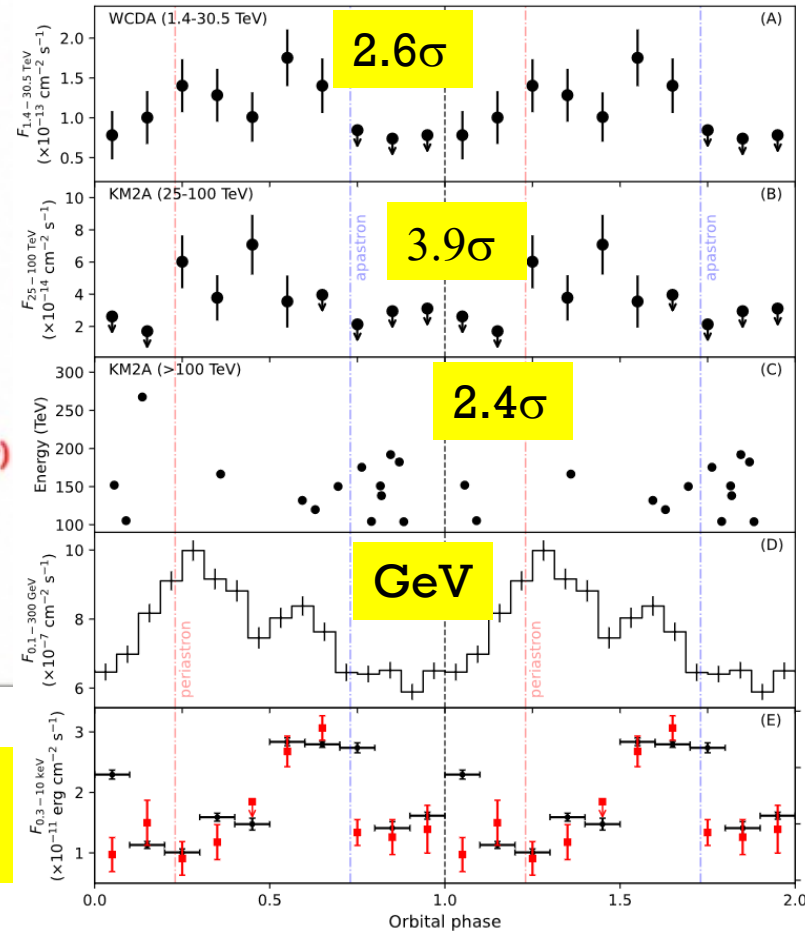
LS I +61 303: MULTI-TIMESCALE VARIABILITY

- Be star + compact object
- Magnetar-like short burst (0.31 s) detected by Swift/BAT (Barthelmy et al. 2008)
- Orbit: 26.496 days
 - Periastron ($\phi \approx 0.23$): compact object near the Be star
 - Apastron ($\phi \approx 0.6-0.8$): compact object far from the Be star
- Orbital modulation at all γ -ray bands
 - GeV peak near periastron
 - TeV peak near apastron
- Super-orbital modulation: $P \approx 1660$ d (~ 4.6 yr)
 - Radio/optical/GeV: $P = 1667 \pm 8$ d (Gregory 2002; Ackermann et al. 2013)
 - TeV: $P = 1610 \pm 58$ d (Ahnen et al. 2016)
- LHAASO detects emission up to ~ 100 TeV without cutoff (Cao et al. 2026)

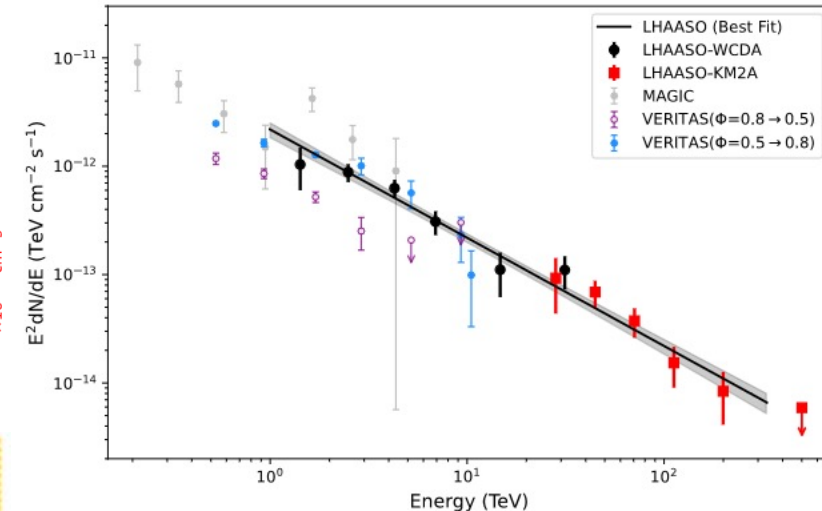
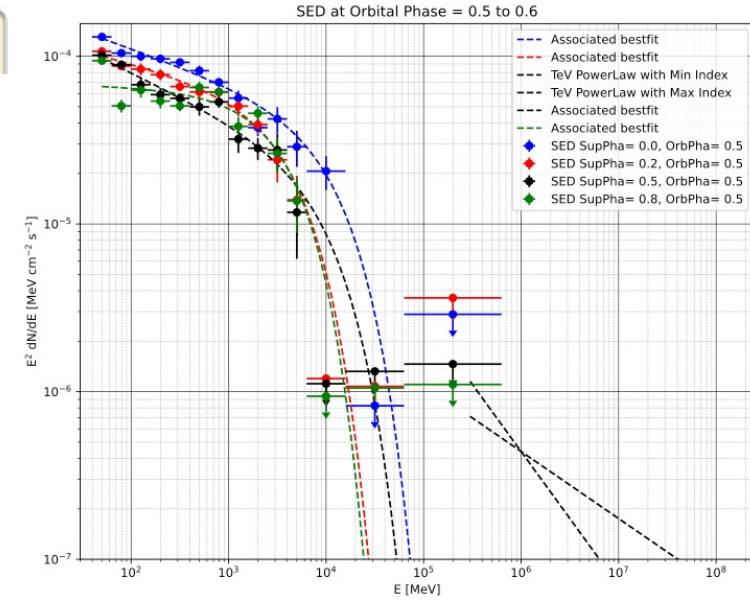


X-ray
TeV

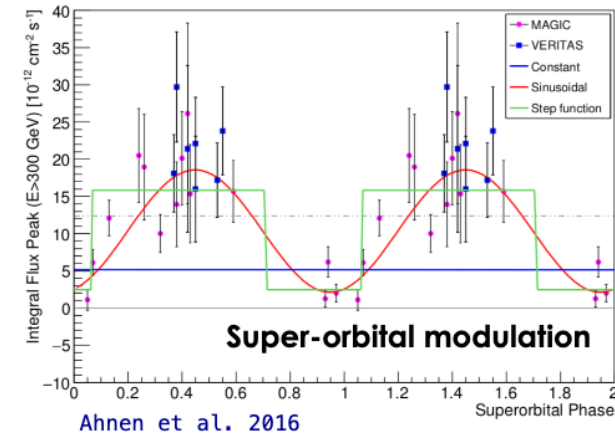
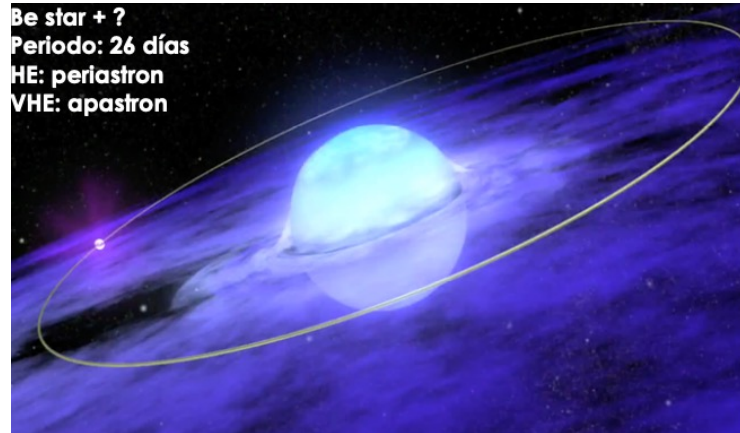
UHE MODULATION WITH ENERGY (LHAASO)



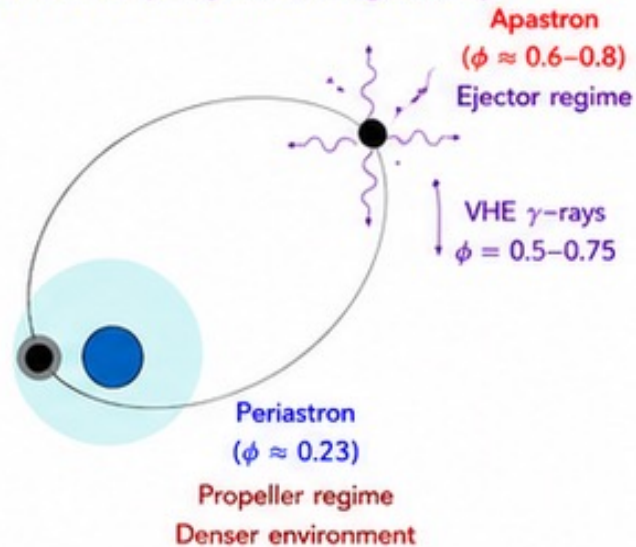
Orbital modulation persists up to 25–100 TeV.
Hints of emission above 100 TeV.
Indicates ongoing acceleration up to PeV energies.



LS I +61 303: BE DISK REGULATES EMISSION

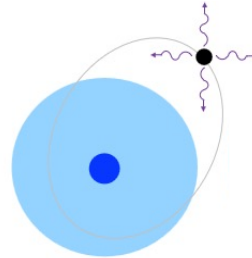


Orbit and γ -ray emission geometry



Torres et al. 2012

Small disk
 (low density)

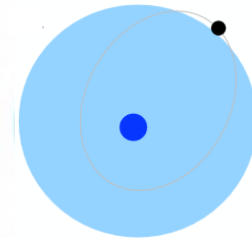


- Ejector regime
- Lower mass-loss rate
- Weaker absorption



Efficient
 particle acceleration
 → Strong TeV emission

Large disk
 (high density)



- Propeller regime
- Higher mass-loss rate
- Stronger absorption



Less efficient
 acceleration
 → Suppressed
 TeV emission

The Be star's disk evolves on the **super-orbital timescale** (~ 4.6 yr),
modifying the interaction conditions and the γ -ray output.

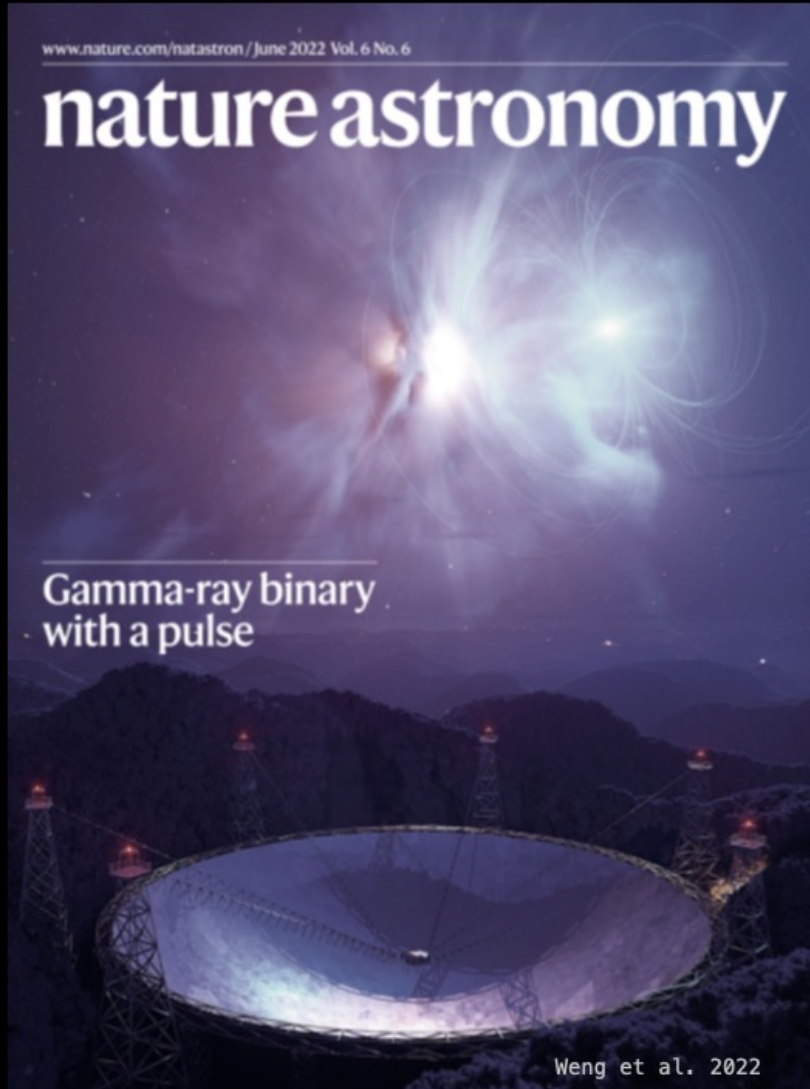
Open questions

- Nature of the compact object?
 Pulsar or magnetar?
 Black hole?
- Where and how are particles accelerated up to PeV energies?
- How do disk evolution, orbital geometry, and particle acceleration combine?

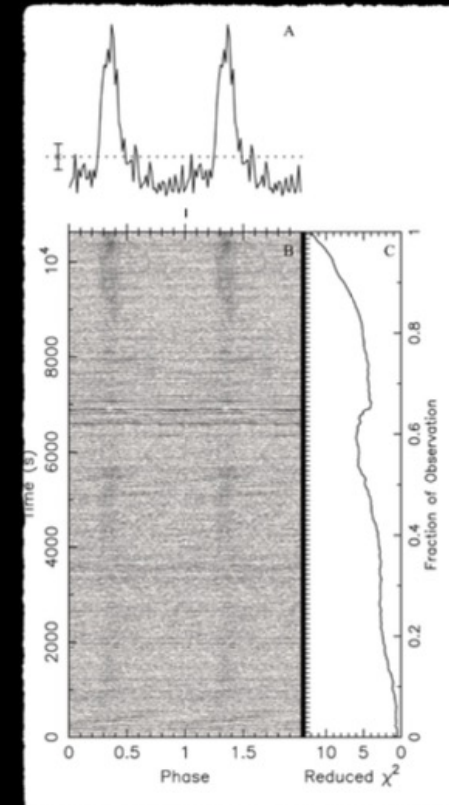


LS I +61°303 is the prototype of an **environment-driven** gamma-ray binary: the Be disk regulates the accelerator, producing complex variability on **orbital, super-orbital, and energy-dependent timescales** up to ~ 100 TeV.

A pulsar in LS I +61° 303



- Pulsations 0.27 seg detected with FAST (Weng et al. 2022)
- No periodicity in the signal
- “LS I 61 303 is the **first binary system containing a pulsar behaving as a magnetar**, probably one of the low-field magnetars class”



- “We find that 5–10% of the galactic magnetar population could plausibly have a bound companion” (Crimes et al. 2022)

GAMMA-RAY BINARIES

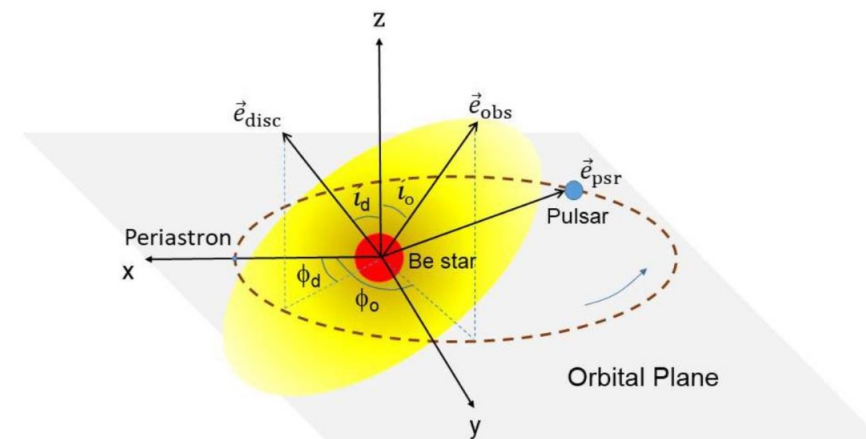
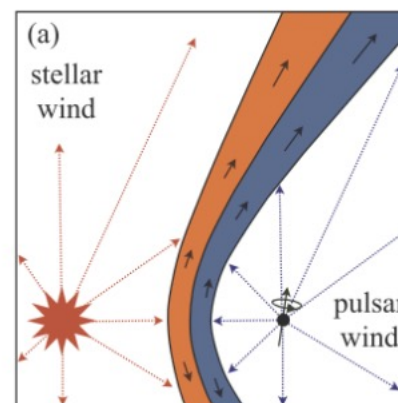
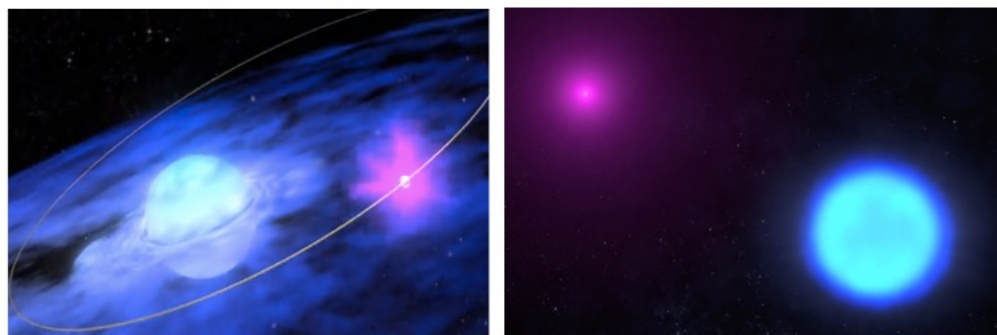
- Massive stars with compact object -> likely non-accreting pulsars
- Emission up to even 100 TeV without cutoff
- Real population **at least x10** current one (Dubus 2015)
- Many unknown parameters

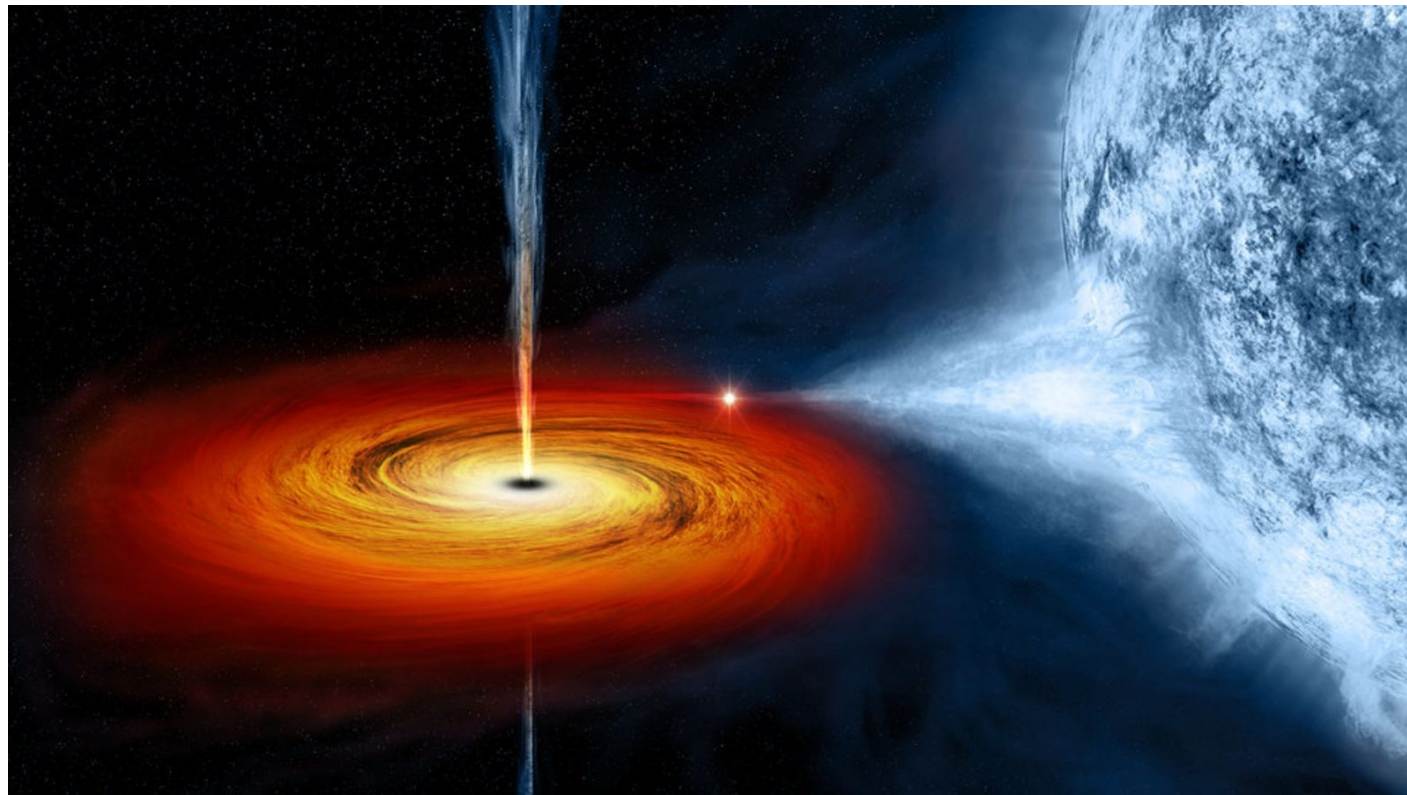
A FEW KEY QUESTIONS (far from exhaustive)

Power source?	⇒	Pulsar wind
Particle acceleration?	⇒	Wind shocks, magnetic reconnection, ...
Dominant particles?	⇒	Hadronic or leptonic?
Gamma-ray production?	⇒	Pion decay, inverse Compton, curvature radiation
Where produced?	⇒	Pulsar wind zone, wind collision region, circumstellar environment, ...
What modulates the flux?	⇒	Geometry, photon fields, matter density, B-fields, ...

Many of these are not mutually exclusive!

(Likely) Non-accreting pulsars





ACCRETION POWERED SYSTEMS

Microquasars

MICROQUASARS: CANDIDATE γ -RAY PRODUCTION REGIONS

We do not yet know which region dominates the observed GeV–TeV emission.

1 Jet base / corona

- Close to the compact object.
- Dense photon fields from the disk and corona.
- Particle acceleration possible.
- $\gamma\gamma$ absorption may be important for TeV photons.

2 Internal shocks

- Variability in the jet (changes in velocity or direction) can produce collisions within the flow.
- These shocks may accelerate particles.

3 Magnetic reconnection

- In the jet or in the disk corona.
- Dissipation of magnetic energy can efficiently accelerate particles.

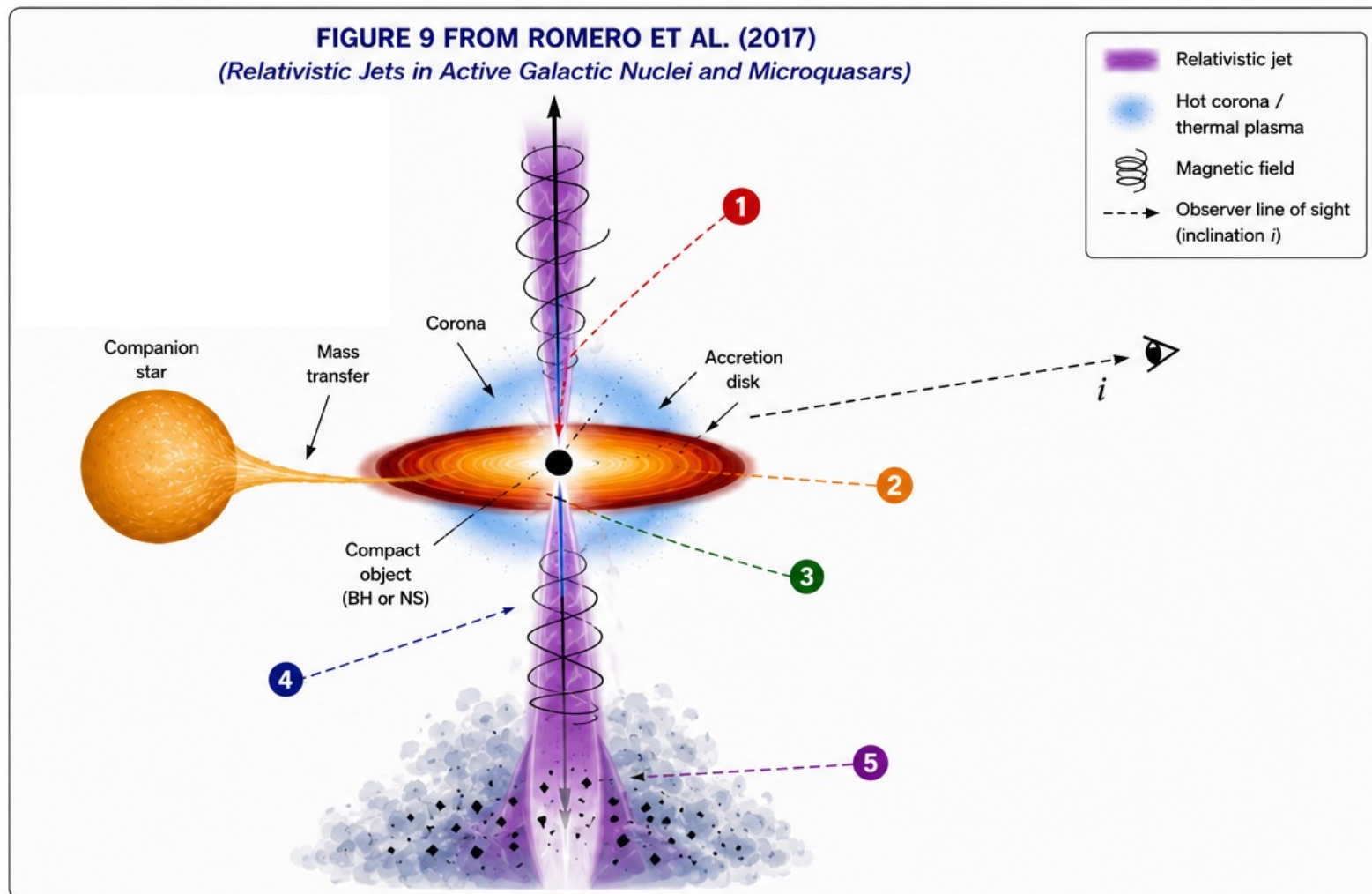
4 Jet–stellar wind interaction (HMXBs)

- Jet interacts with the dense stellar wind.
- Shocks and inverse Compton scattering on stellar photons.

5 Jet termination region

- Jet impacts the interstellar medium (ISM).
- Formation of termination shocks, turbulence, and particle acceleration on large scales.

FIGURE 9 FROM ROMERO ET AL. (2017)
(Relativistic Jets in Active Galactic Nuclei and Microquasars)



RADIATION MECHANISMS

Synchrotron

- Relativistic electrons in magnetic fields.
- Radio $\rightarrow$ IR $\rightarrow$ X-rays.

Inverse Compton

- Up-scattering of low-energy photons (synchrotron, stellar, disk, CMB).
- GeV–TeV γ -rays.

Hadronic interactions

- (if relativistic protons are present)
- pp collisions $\rightarrow \pi^0 \rightarrow 2\gamma$
 - $p\gamma$ interactions $\rightarrow \pi^0/\pi^\pm$
 - Neutrinos from $\pi^\pm \rightarrow \nu$

OPEN QUESTION

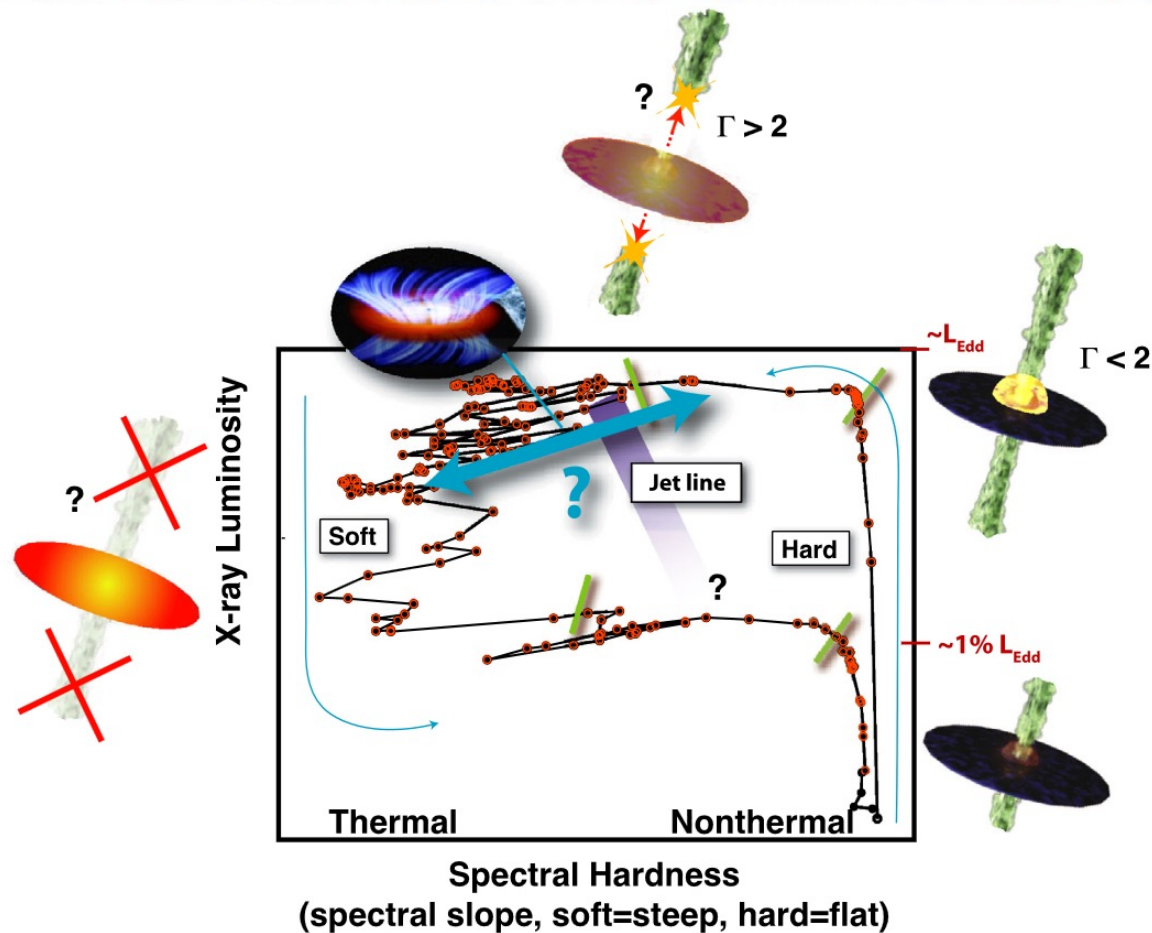


Which of these regions dominates the observed GeV–TeV γ -ray emission?

Current observations do not yet identify the dominant site.

Disk-jet coupling in X-ray binaries (from Romero et al. 2017)

Disk-jet coupling in X-ray binaries (from Romero et al. 2017)



WHAT FIGURE 9 SHOWS

The coupling between the accretion flow and relativistic jets in X-ray binaries as a function of the accretion state.

HARD STATE

- Radiatively inefficient inner flow / hot corona
- Hard X-ray spectrum
- Compact, steady radio jet
- Site of persistent (possibly steady) particle acceleration

STATE TRANSITION

- The steady compact jet is suppressed
- Discrete, relativistic ejecta are launched
- Strong radio flares are observed
- Transient ejections may be efficient particle accelerators

SOFT STATE

- Thin accretion disk extends to the ISCO
- Jet is strongly suppressed (“jet quenching”)
- Thermal X-ray spectrum dominates
- Very little radio emission

TAKE-HOME MESSAGE



The production (and suppression) of relativistic jets in microquasars is closely linked to the **accretion state**.

IMPLICATION FOR γ -RAYS

Since **γ -ray emission** is believed to originate in jets, the **accretion state** controls when high-energy (GeV–TeV) emission is expected.

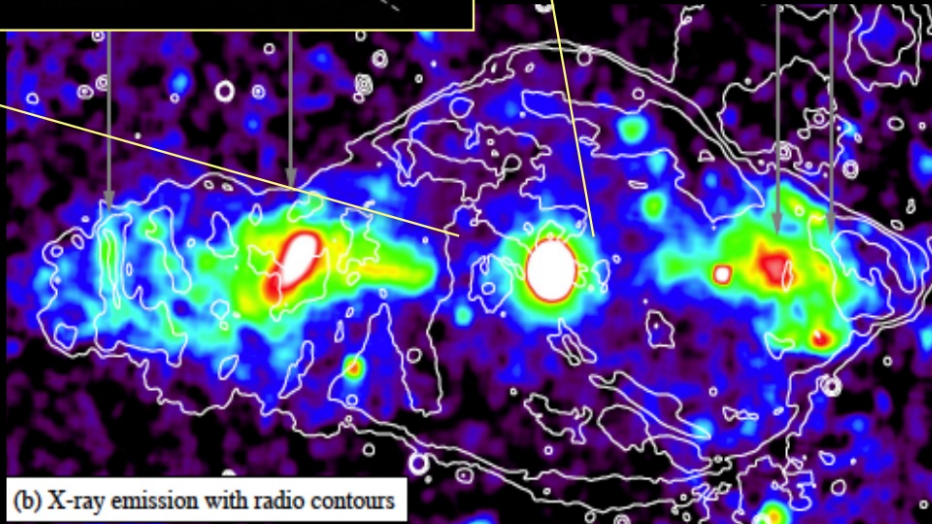
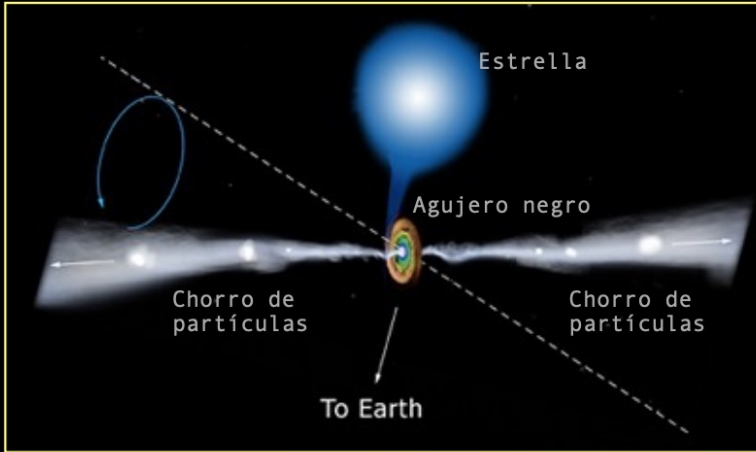


Open question: Which regions within the jet are responsible for accelerating particles up to GeV–TeV energies?

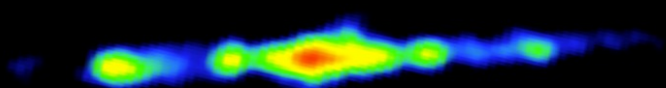
SS 433 / W50

A precessing microquasar whose jets feed the giant lobes ~25 pc away

- Supercritical microquasar
- Persistent relativistic jets ($v_{\text{jet}} \approx 0.26 c$)
- Jets precess with period $P_{\text{prec}} \approx 162$ days
- Jets interact with the ISM to inflate the W50 lobes
- γ -ray emission up to >100 TeV



← Total extent of W50 ~100 pc →



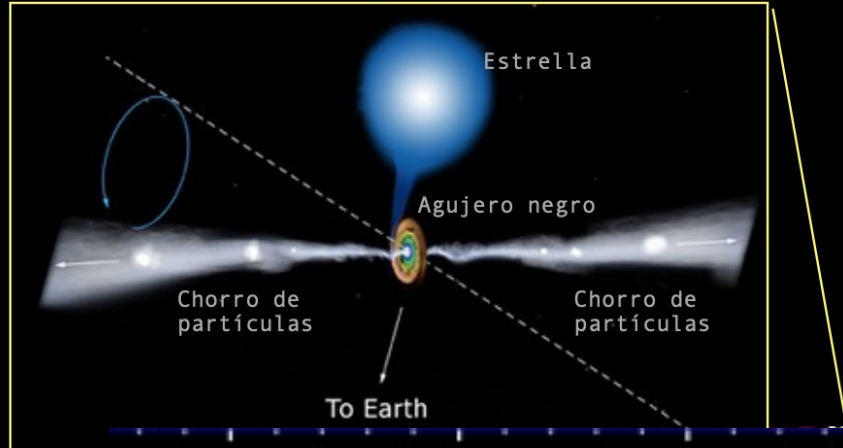
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NASA/CXC/U.Amsterdam/S.Migliari et al // Goodall et al. 2011 /// NRAO

SS 433 / W50 @GeV

A precessing microquasar whose jets feed the giant lobes ~25 pc away

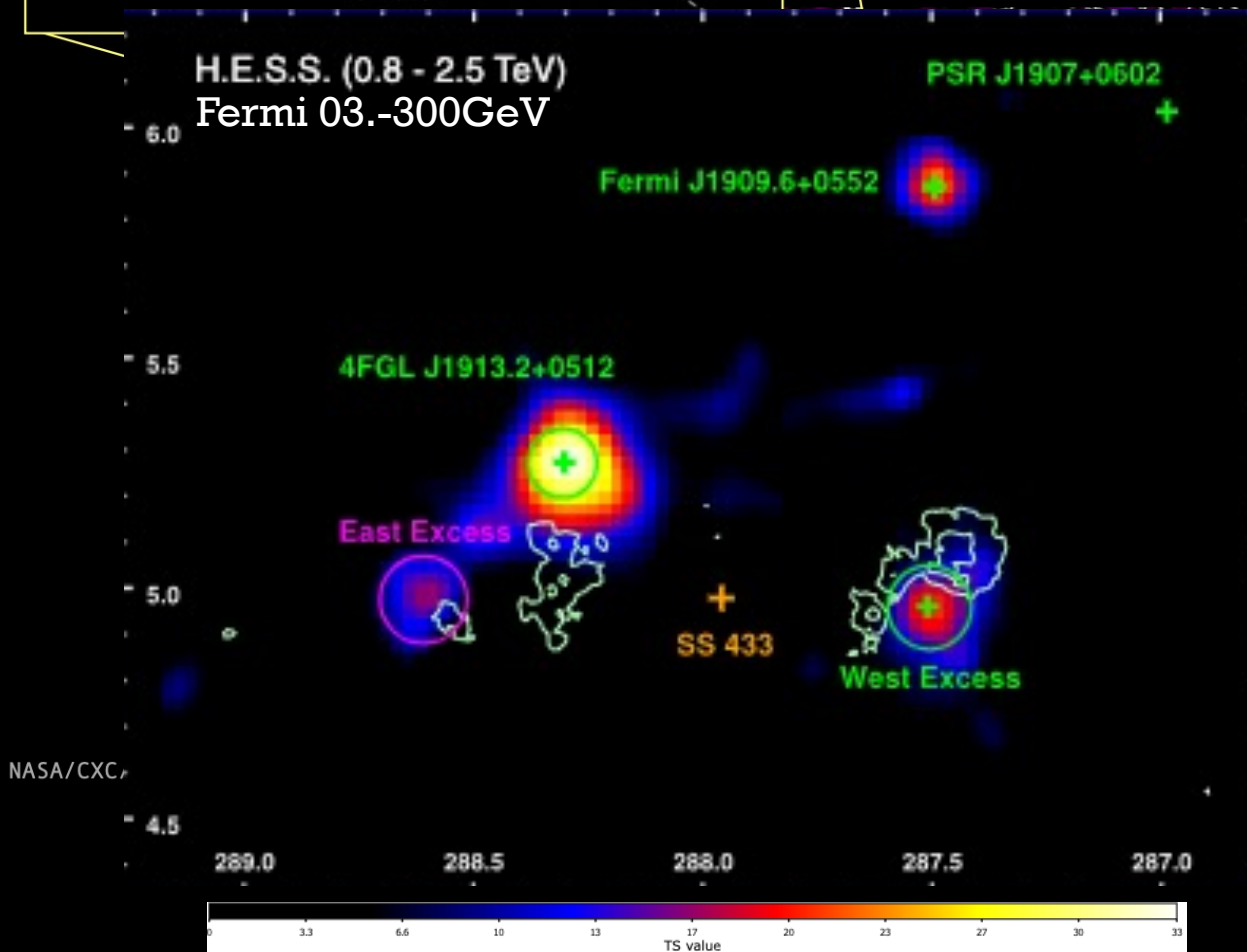
- Supercritical microquasar
- Persistent relativistic jets ($v_{\text{jet}} \approx 0.26 c$)
- Jets precess with period $P_{\text{prec}} \approx 162$ days
- Jets interact with the ISM to inflate the W50 lobes
- γ -ray emission up to >100 TeV



GeV components in the SS433/W50 field:

4FGL J1913.2+0512: significantly detected
West Excess: $\sim 4\sigma$ consistent with Western lobe
East Excess: hint of excess, only few photons.
 No emission from inner binary.

Periodicity consistent with jet precession of 162 days only in 4FGL J1913.2, but absent in last 6 years.

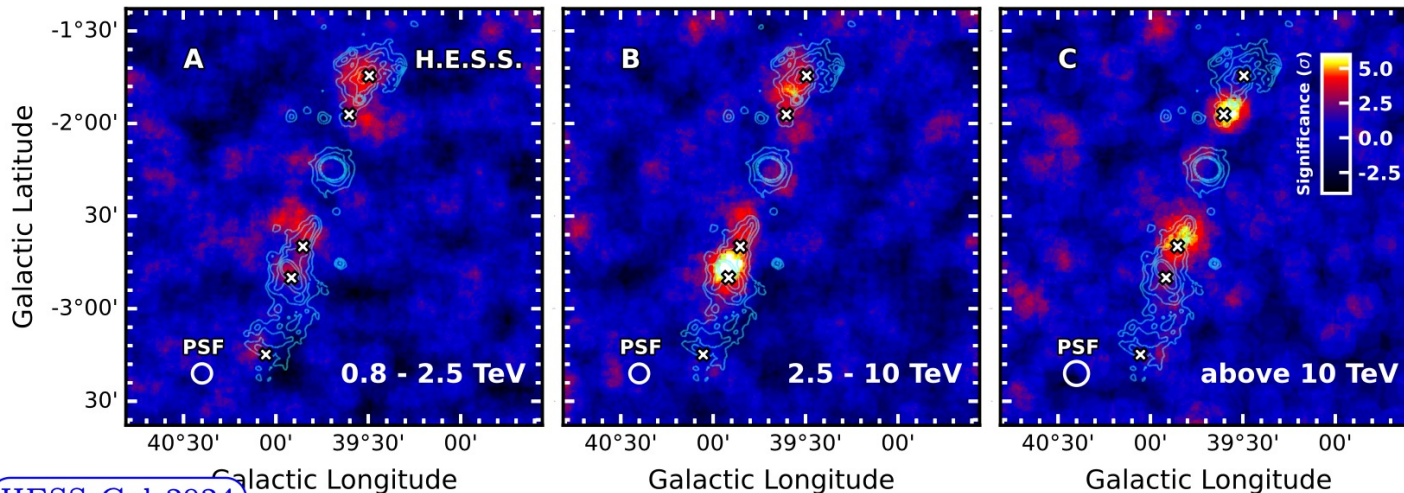
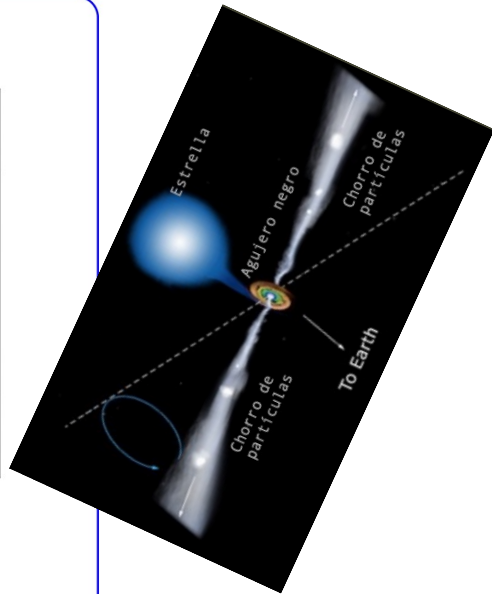
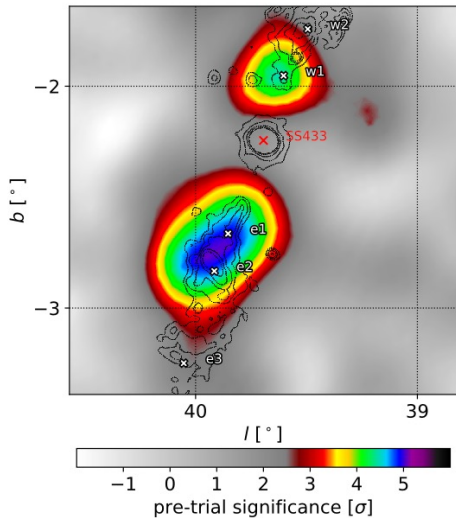


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SS 433 / W50 @ TeV

- Resolved TeV emission from both outer jets / lobes of SS 433; no significant TeV emission from the central binary.
- Splitting the data by energy reveals **energy-dependent morphology**:
 > 10 TeV emission is concentrated at the base of the outer X-ray jets, while lower-energy TeV emission extends farther downstream.
- This strongly favors a **leptonic scenario**: TeV γ rays are produced by **inverse-Compton scattering of relativistic electrons**.
- The data imply **particle acceleration at shocks** $\sim 25 - 30$ pc from the binary, where the precessing jets are **re-collimated and abruptly decelerated**.

HAWC Col 2018

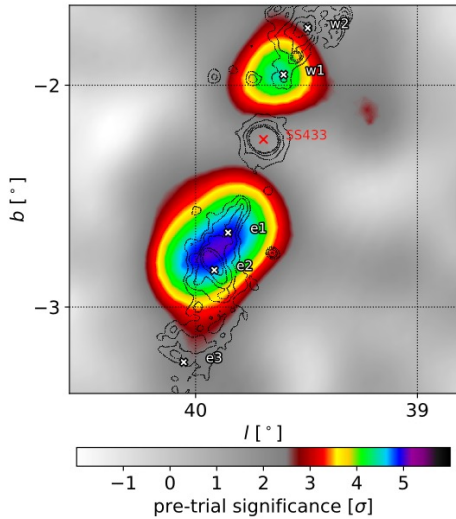


HESS Col 2024

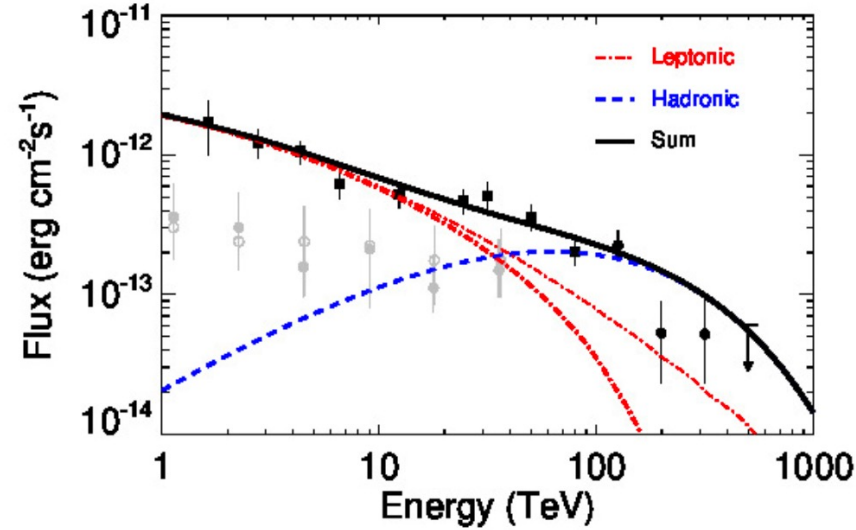
Takeaway:
H.E.S.S. turns SS 433 into a **resolved TeV jet-acceleration laboratory**.

SS 433/ W50 @ UHE

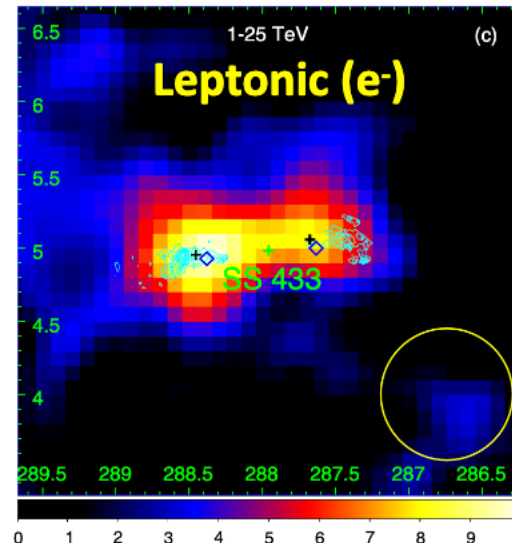
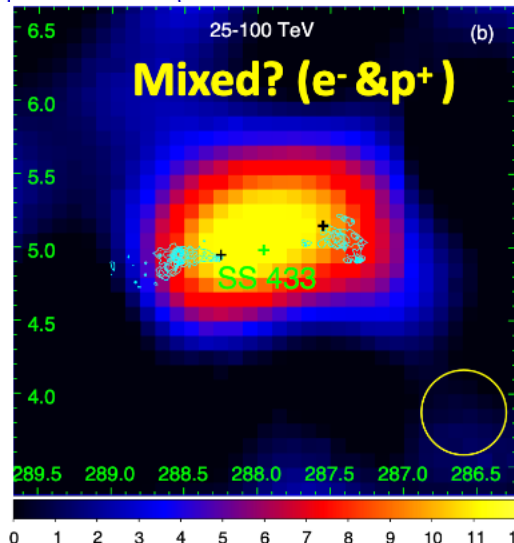
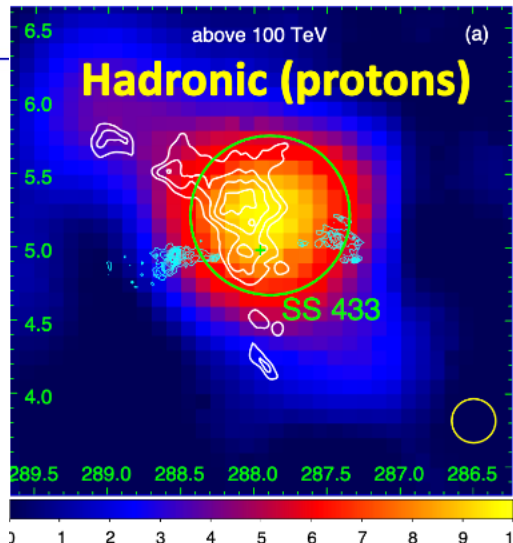
HAWC Col 2018



LHAASO Col 2024



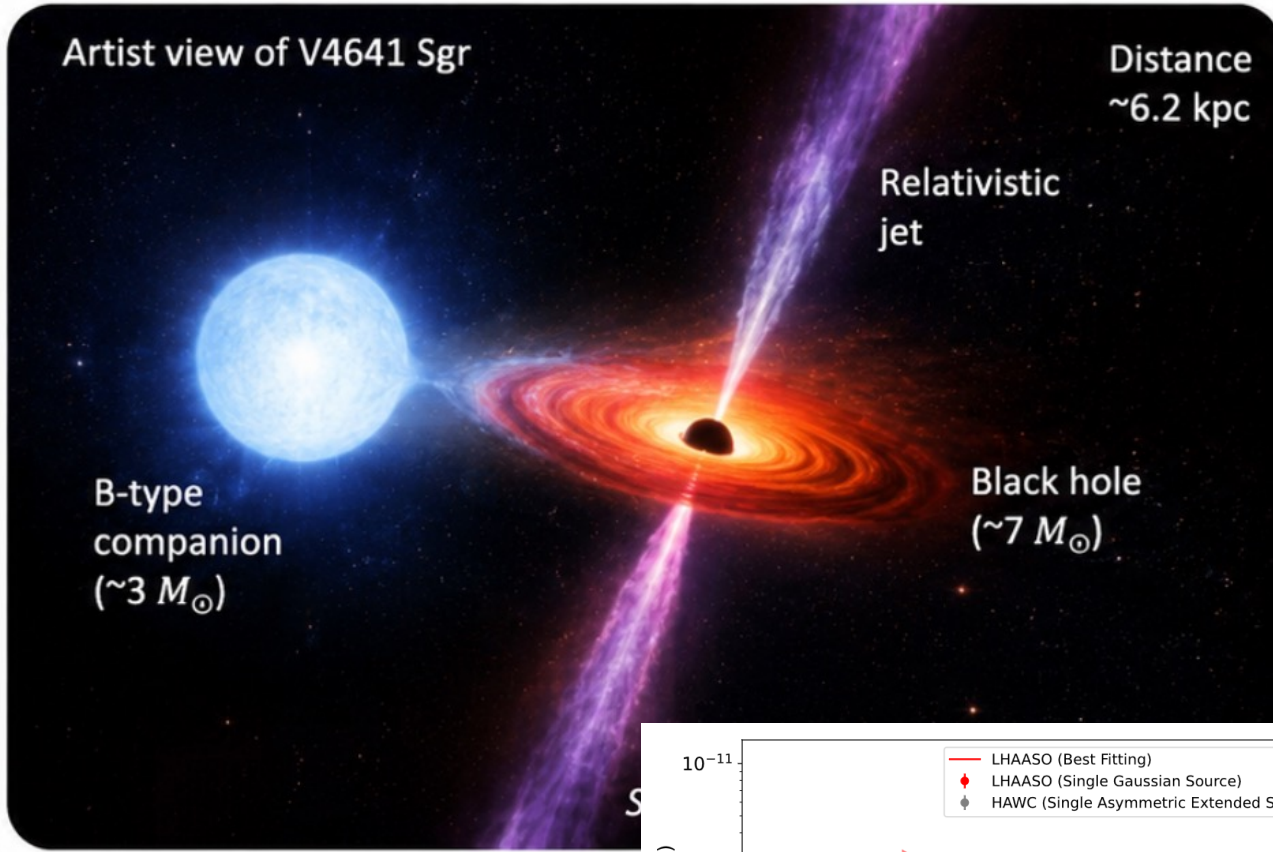
- LHAASO detects the **east/west lobe emission below 100 TeV** and an extended component in the central region **above 100 TeV**.
- The **> 100 TeV morphology differs** from the H.E.S.S.-like TeV lobe picture.
- A single **leptonic IC component** struggles at these energies because of **Klein-Nishina suppression**.
- A plausible explanation is a **hadronic component** from **PeV protons** interacting with a nearby **H I cloud**



Takeaway:

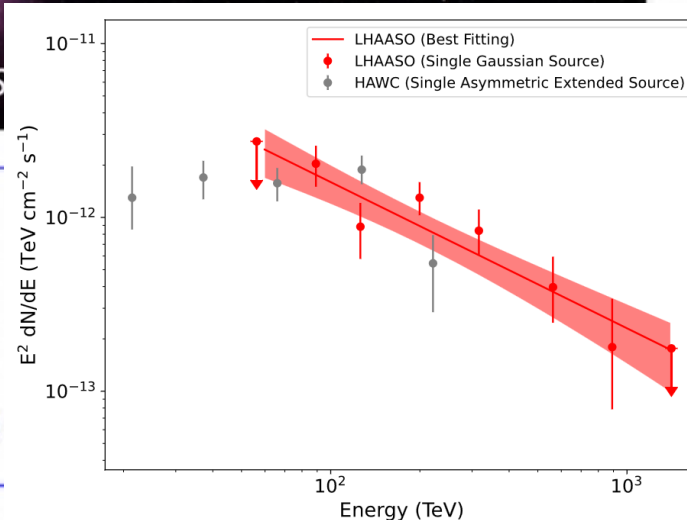
LHAASO suggests SS 433 may be a **microquasar PeVatron candidate**.

V4641 Sgr: a microquasar with extended TeV–PeV emission



- **Black-hole X-ray binary / microquasar** with orbital period $P_{\text{orb}} = 2.8$ days.
- Famous for the **1999 giant outburst**, showing apparent **superluminal** motion in its radio jet.
- The jet is thought to be oriented within a few degrees of our line of sight → **microblazar-like system**.
- Now detected by **HAWC**, **H.E.S.S.**, and **LHAASO** as a persistent, **extended gamma-ray source**.
- The emission extends from **TeV** energies up to **0.8 PeV**, making V4641 Sgr one of the strongest microquasar **PeVatron / super-PeVatron** candidates.

- Orbital period: 2.8 d
- Black hole mass: $\sim 7 M_{\odot}$
- Companion: B-type ($\sim 3 M_{\odot}$)



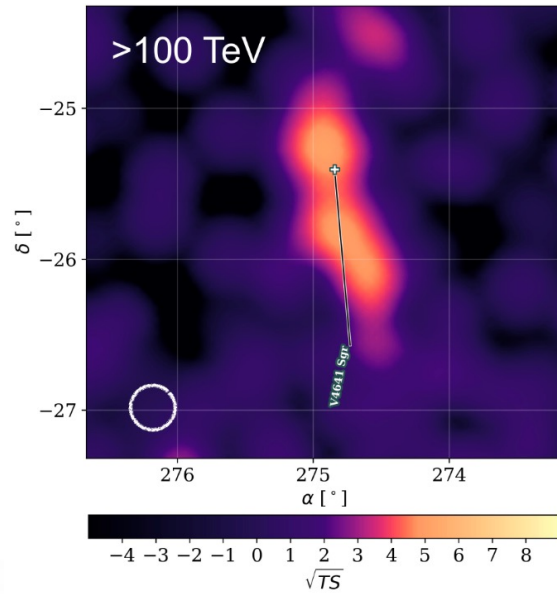
Takeaway:

V4641 Sgr is not just a flaring X-ray binary: it may host a large-scale accelerator reaching nearly PeV energies.

V4641 Sgr: the HAWC – H.E.S.S. – LHAASO picture

HAWC (Alfaro et al. 2024)

Discovery of extended TeV emission



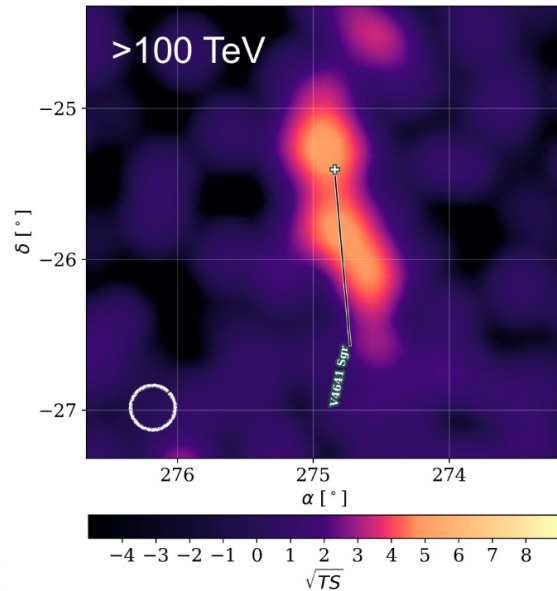
Morphology consistent with either
one elongated source or two components
~30 pc and ~60 pc from the binary.

- **HAWC** first revealed extended TeV emission around V4641 Sgr, inconsistent with a simple central point source.

V4641 Sgr: the HAWC – H.E.S.S. – LHAASO picture

HAWC (Alfaro et al. 2024)

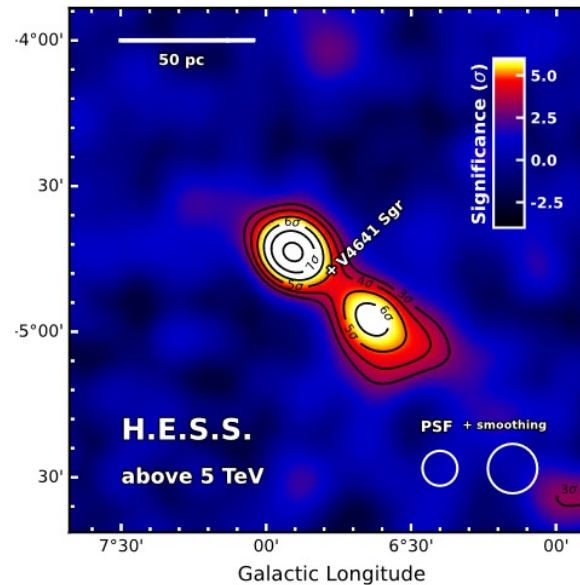
Discovery of extended TeV emission



Morphology consistent with either one elongated source or two components ~ 30 pc and ~ 60 pc from the binary.

H.E.S.S. (Acharyya et al. 2026)

Resolved elongated TeV source



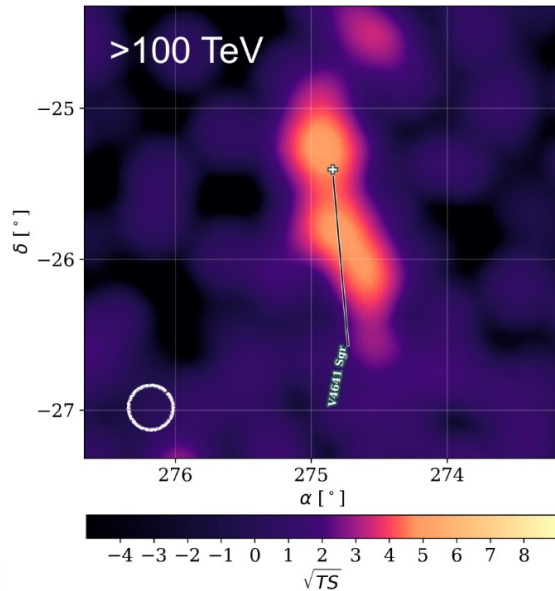
Highly elongated source:
 $\sim 0.34^\circ \times 0.06^\circ$ ($\approx 110 \times 20$ pc at 6.2 kpc).
Only weak ($\sim 3\sigma$) evidence for two components.

- **HAWC** first revealed extended TeV emission around V4641 Sgr, inconsistent with a simple central point source.
- **H.E.S.S.** resolved the emission as a highly elongated TeV structure ($\sim 0.34^\circ \times 0.06^\circ$, about 110×20 pc at 6.2 kpc).

V4641 Sgr: the HAWC – H.E.S.S. – LHAASO picture

HAWC (Alfaro et al. 2024)

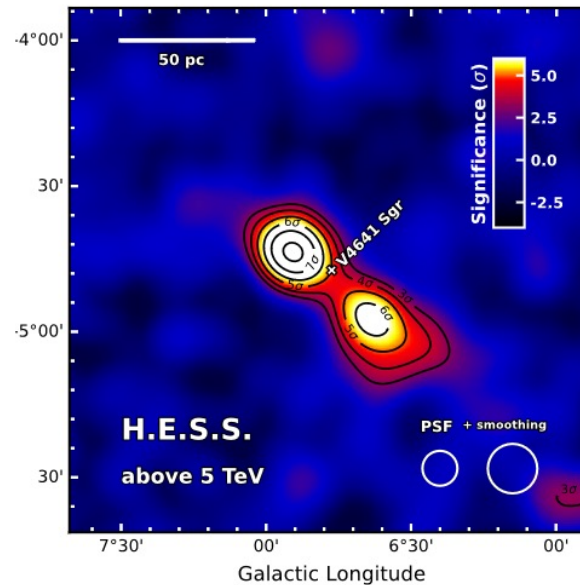
Discovery of extended TeV emission



Morphology consistent with either one elongated source or two components ~ 30 pc and ~ 60 pc from the binary.

H.E.S.S. (Acharyya et al. 2026)

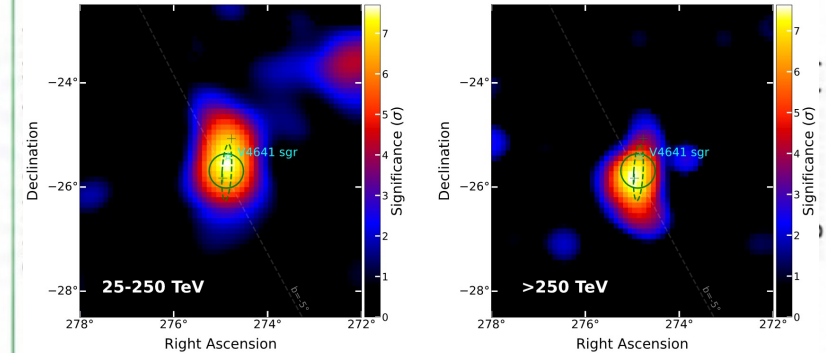
Resolved elongated TeV source



Highly elongated source: $\sim 0.34^\circ \times 0.06^\circ$ ($\approx 110 \times 20$ pc at 6.2 kpc). Only weak ($\sim 3\sigma$) evidence for two components.

LHAASO (Cao et al. 2024)

Extended emission up to 0.8 PeV



LHAASO J1819~2541 is spatially associated with V4641 Sgr. The spectrum extends to ~ 0.8 PeV.

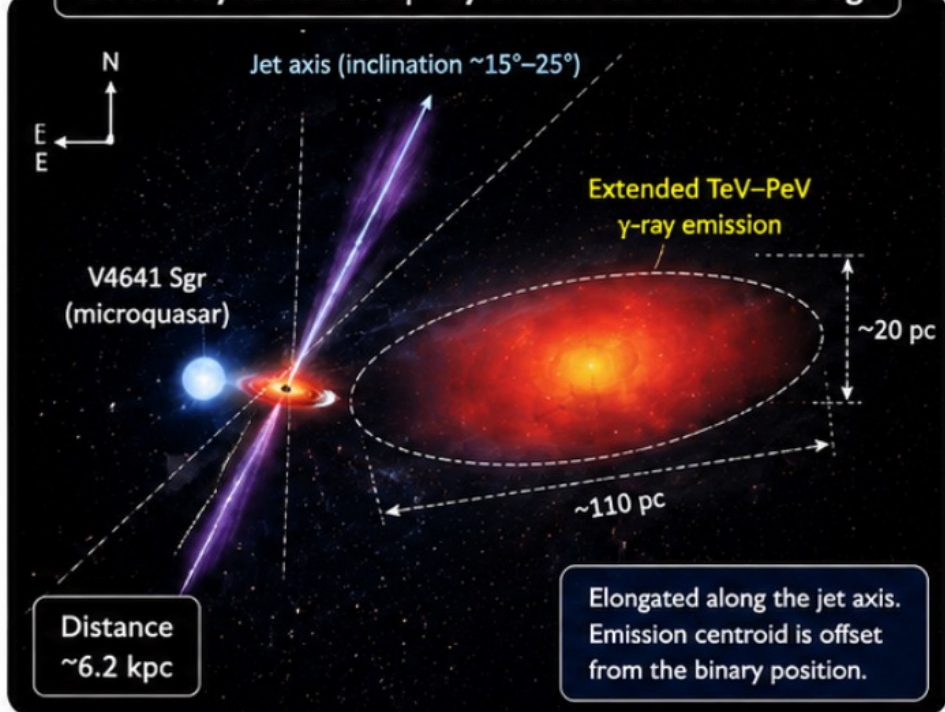
- **HAWC** first revealed extended TeV emission around V4641 Sgr, inconsistent with a simple central point source.
- **H.E.S.S.** resolved the emission as a highly elongated TeV structure ($\sim 0.34^\circ \times 0.06^\circ$, about 110×20 pc at 6.2 kpc).
- The 1–20 TeV spectrum is very hard ($\Gamma \approx 1.8$); the combined SED peaks around ~ 100 TeV.
- **LHAASO** extends the source to ~ 0.8 PeV, making V4641 Sgr one of the strongest microquasar PeVatron candidates.

Takeaway: three instruments now show a consistent picture of an extended microquasar-powered TeV–PeV source.

V4641 Sgr: a microquasar PeVatron — but where is the accelerator?

V4641 Sgr is now one of the best microquasar PeVatron candidates: extended γ -ray emission peaks around **~ 100 TeV** and reaches **~ 0.8 PeV**, implying **multi-PeV** particle acceleration.

Geometry: extended γ -ray emitter around V4641 Sgr



What the data require

- **Extended emission:** H.E.S.S. rules out a dominant point-like source at the binary.
- **Very hard TeV spectrum:** combined data peak around ~ 100 TeV.
- **No significant energy-dependent morphology** in H.E.S.S. between 0.8 – 5 TeV and 5 – 22 TeV.
- **No clear dense molecular cloud target** in the TeV-emitting region (H.E.S.S. gas study).

Interpretation tension

Hadronic scenario

- π^0 -decay from pp interactions can naturally explain γ -rays up to hundreds of TeV.
- Lack of dense target gas near the source makes this energetically demanding.
- H.E.S.S. modeling shows that very hard proton spectra ($\Gamma_p \leq 1.5$) or special conditions are required.

Possible, but energetically challenging.

Leptonic scenario

- Inverse Compton from relativistic electrons can reproduce the TeV emission with fewer energetic difficulties.
- Requires efficient transport of TeV electrons throughout the extended region.
- Weak X-ray constraints imply a low magnetic field, $B \leq \text{few } \mu\text{G}$.

Currently favored by H.E.S.S., but needs efficient transport and low B -field.

Key implications



Particles are accelerated beyond the knee, likely to multi-PeV energies.



Acceleration and/or transport occurs on > 100 pc scales along the jet axis.



Unclear whether we see a jet-powered electron population or hadrons in the environment.



Firm association, far from the Galactic plane, and reaches near-PeV energies.

Takeaway: V4641 Sgr is likely accelerating particles beyond the knee, but unlike SS 433 we still do not know whether the emission is produced by a jet-powered electron population or by hadrons in the extended environment.

Cygnus X-3: a compact Wolf–Rayet microquasar with transient high-energy emission

★ **Cygnus X-3** is a high-mass microquasar / X-ray binary with a Wolf–Rayet (WR) companion and a compact object (BH or NS).

Orbital period: $P_{\text{orb}} = 4.8 \text{ h}$.



The source shows **recurrent GeV flares** and strong multiwavelength variability. The GeV emission is orbitally modulated and is usually interpreted as **inverse-Compton emission from jet electrons**.

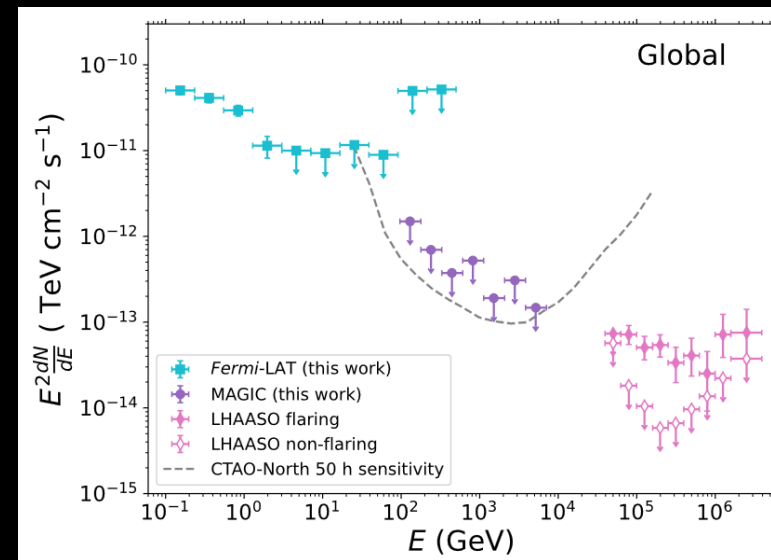
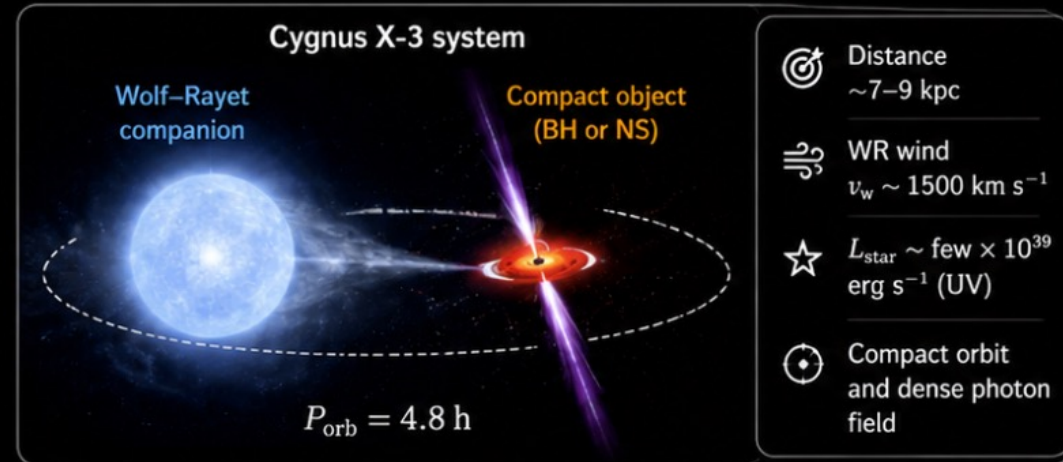


A 12-year MAGIC campaign (2013–2024, ~130 h after quality cuts) finds **no significant emission between ~0.1 and 7 TeV**, even when selecting GeV flaring states and favorable orbital phases.



This suggests that binary-scale TeV emission is weak or **strongly absorbed** by $\gamma\gamma$ pair production on the intense radiation field of the WR star.

$$\gamma + \gamma_{\text{star}} \rightarrow e^+ + e^-$$



Takeaway: Cygnus X-3 is not a steady TeV microquasar: it is bright at GeV, but the 0.1–few TeV band appears suppressed by compact-system geometry and absorption.

Cygnus X-3 @ PeV: LHAASO reveals a transient microquasar PeVatron

LHAASO detects γ -rays from **~ 60 TeV to 3.7 PeV** from Cygnus X-3 with **$\sim 10\sigma$** significance. The emission is **variable**, coincides with **GeV high states**, and shows a hint of **orbital modulation**.



PeV emission detected from **~ 60 TeV to 3.7 PeV** with **$\sim 10\sigma$** significance. The spectrum hardens above ~ 1 PeV.



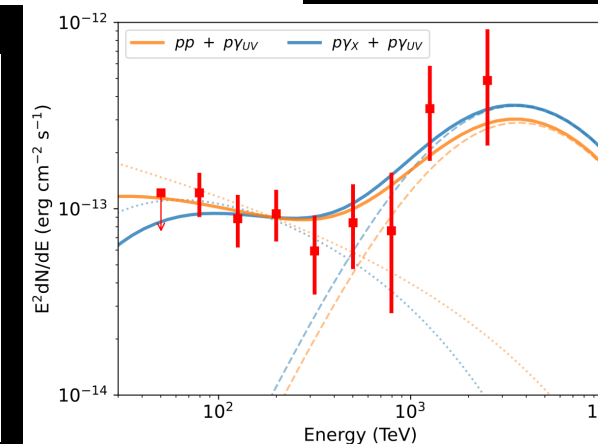
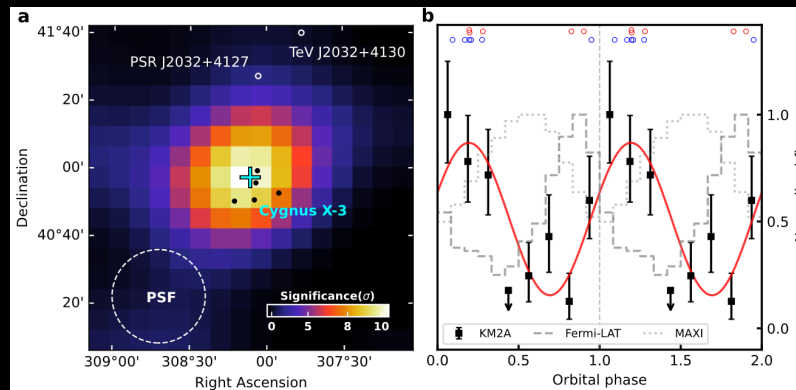
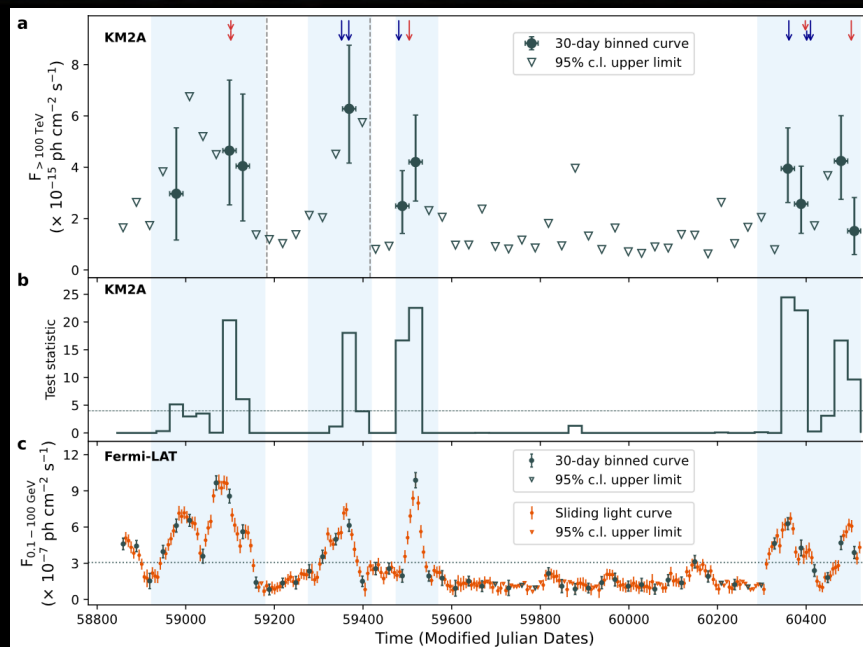
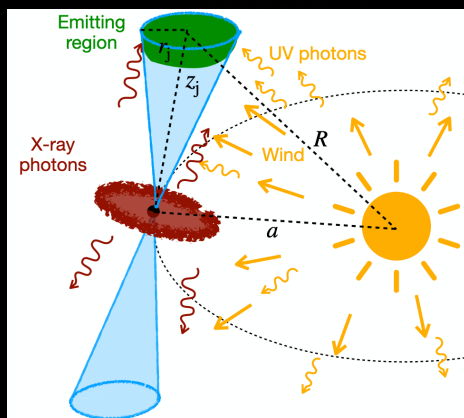
Strong variability on month timescales. Detected only during **GeV high states**; significance increases to 11.5σ in those periods.



3.2σ hint of **orbital modulation** at the 4.8 h binary period.



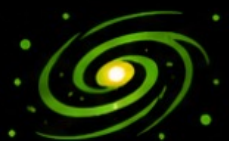
The hard spectrum and temporal behaviour favor **hadronic photomeson** ($p\gamma$) emission in the inner jet, implying proton acceleration up to **tens of PeV**.



Takeaway: Cygnus X-3 shows transient PeV emission linked to GeV high states, likely produced close to the binary / inner jet.

Microquasars: Galactic accelerators up to PeV energies

Microquasars host **relativistic jets** that accelerate **electrons** and **protons** to extreme energies, producing γ -rays from **GeV** to **PeV** on a wide range of spatial and temporal scales.



Multi-messenger

- Detected across the **electromagnetic spectrum** with **Fermi-LAT**, **HESS**, **MAGIC** and **LHAASO**.



Jets on many scales

- From **compact** binary environments to **extended** jets and lobes over **parsec** scales.



Particle acceleration

- Electrons** accelerated to multi-TeV.
- Protons** accelerated to at least tens of **PeV**, possibly beyond.



Hadronic γ -ray production

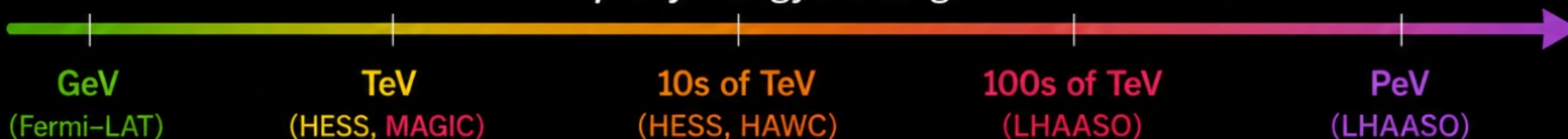
- γ -rays produced via hadronic processes (**pp** or **p γ**) in gas and photon fields.



Diverse behaviours

- Emissions can be **persistent** (lobes) or **transient** and state-dependent (binary scale).

γ -ray energy coverage



Takeaway:

- Microquasars are established Galactic accelerators, reaching at least tens of PeV.
- They operate on a wide range of spatial scales and show both steady and transient high-energy activity.

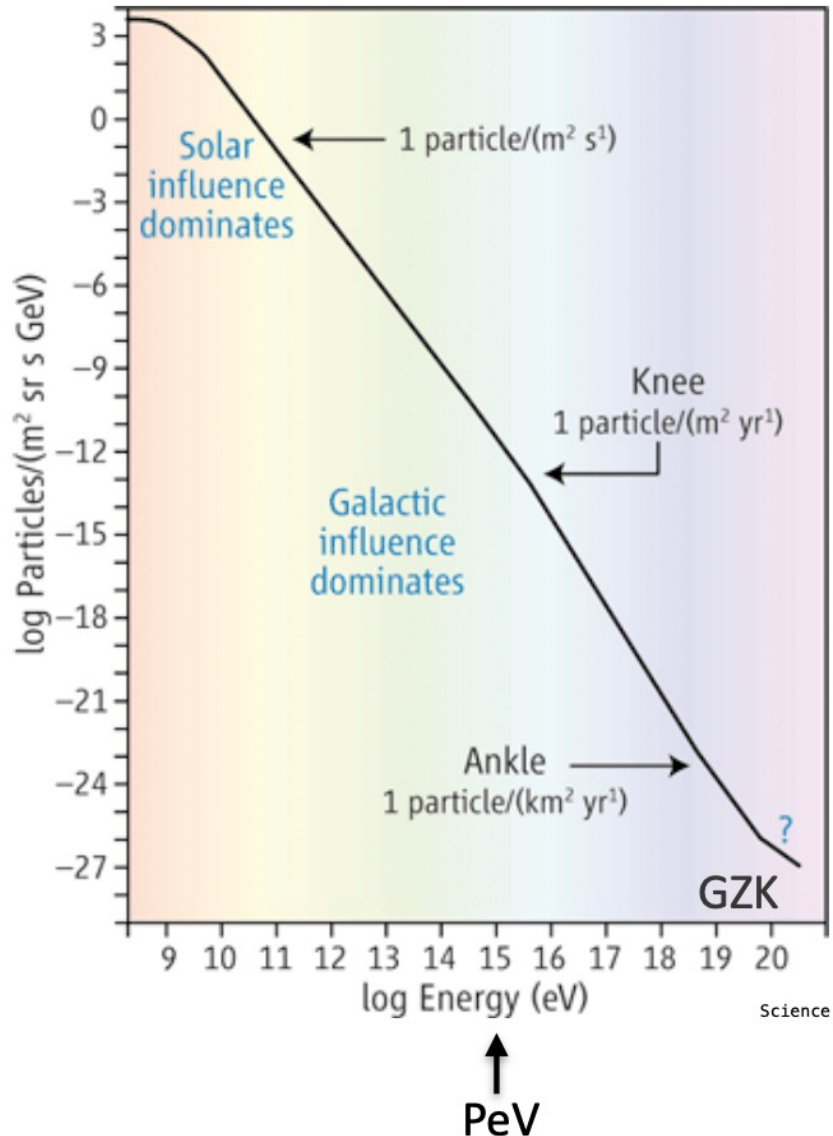


EXPLOSION POWERED SYSTEMS

Supernova remnants

Novae

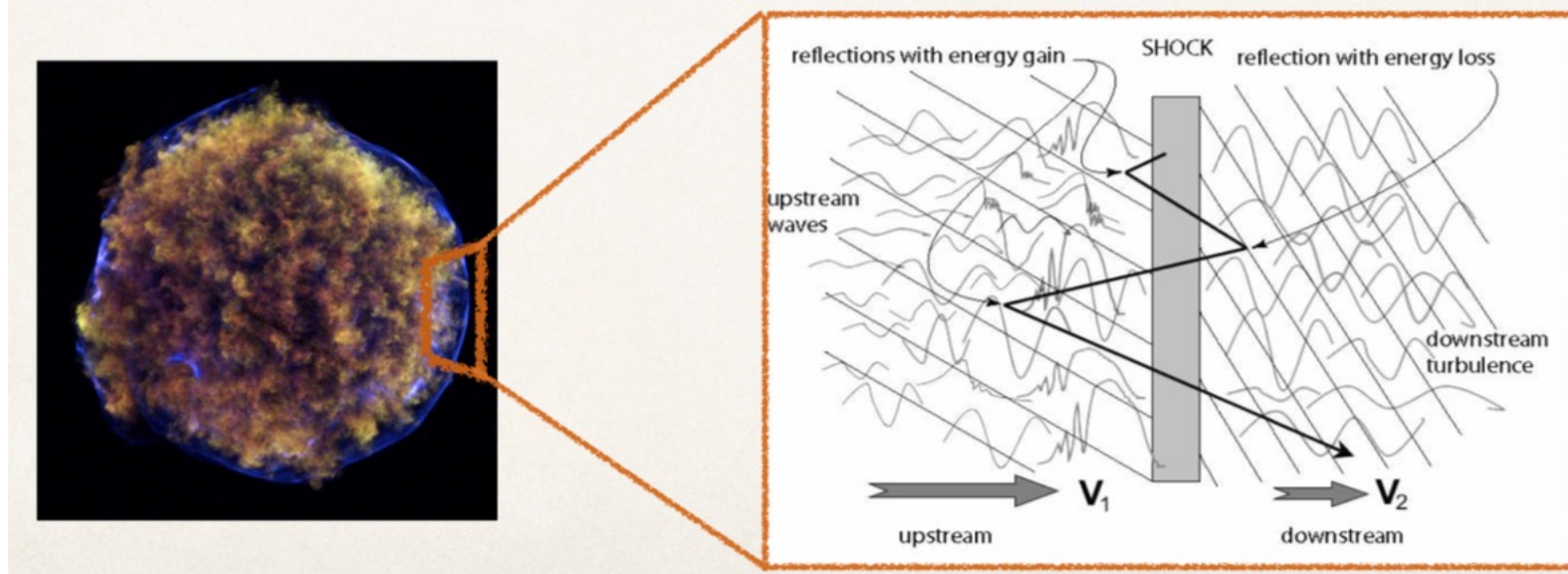
SNRS: COSMIC ACCELERATORS



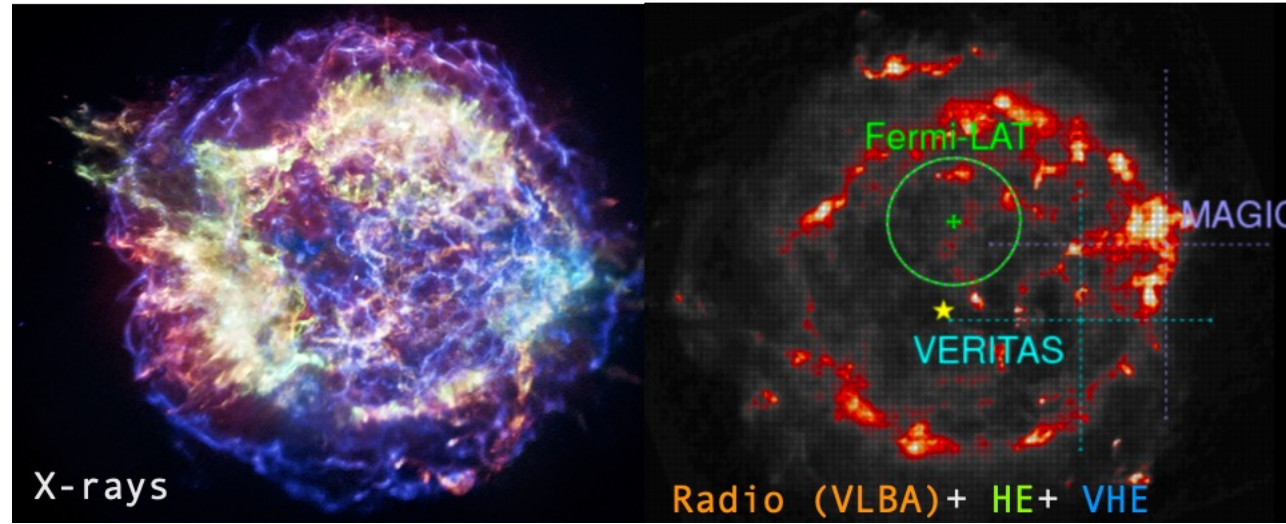
- Galactic CR knee at $E_{\text{knee}} \sim 1 - 3 \text{ PeV}$
- If SNRs power Galactic CRs, they must reach PeV proton energies
- γ -rays above $\sim 100 \text{ TeV}$ are a key signpost of PeV particle acceleration
- Requires efficient diffusive shock acceleration + magnetic-field amplification

SNRS: COSMIC ACCELERATORS

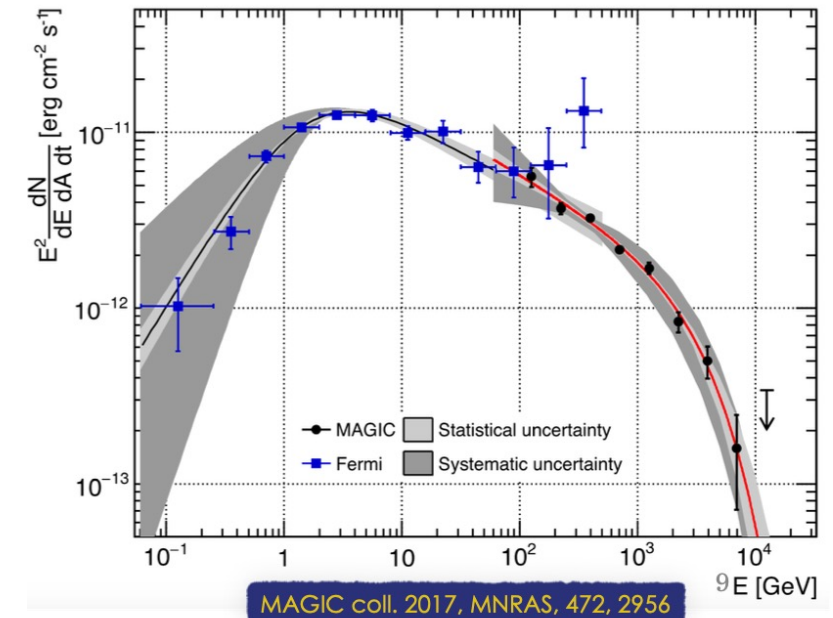
- **Diffusive shock acceleration at SNR blast waves**
- Particles gain energy by repeated shock crossings (**1st-order Fermi acceleration**)
- Two key gamma-ray signatures of hadronic acceleration in SNRs:
 - **GeV:** π^0 -decay “pion bump”
 - **UHE:** γ -rays above $\sim 100\text{TeV}$



CASSIOPEA A: A HADRONIC PEVATRON?



- Young shell SNR (~ 300 yr), detected from GeV to TeV
- GeV/TeV point-like emission: Fermi, HEGRA, VERITAS and MAGIC
- Broadband emission cannot be explained by a single electron or proton population
- TeV emission is likely hadronic-dominated
- MAGIC cutoff at ~ 3.5 TeV $\rightarrow$ Cas A is not a present-day PeVatron



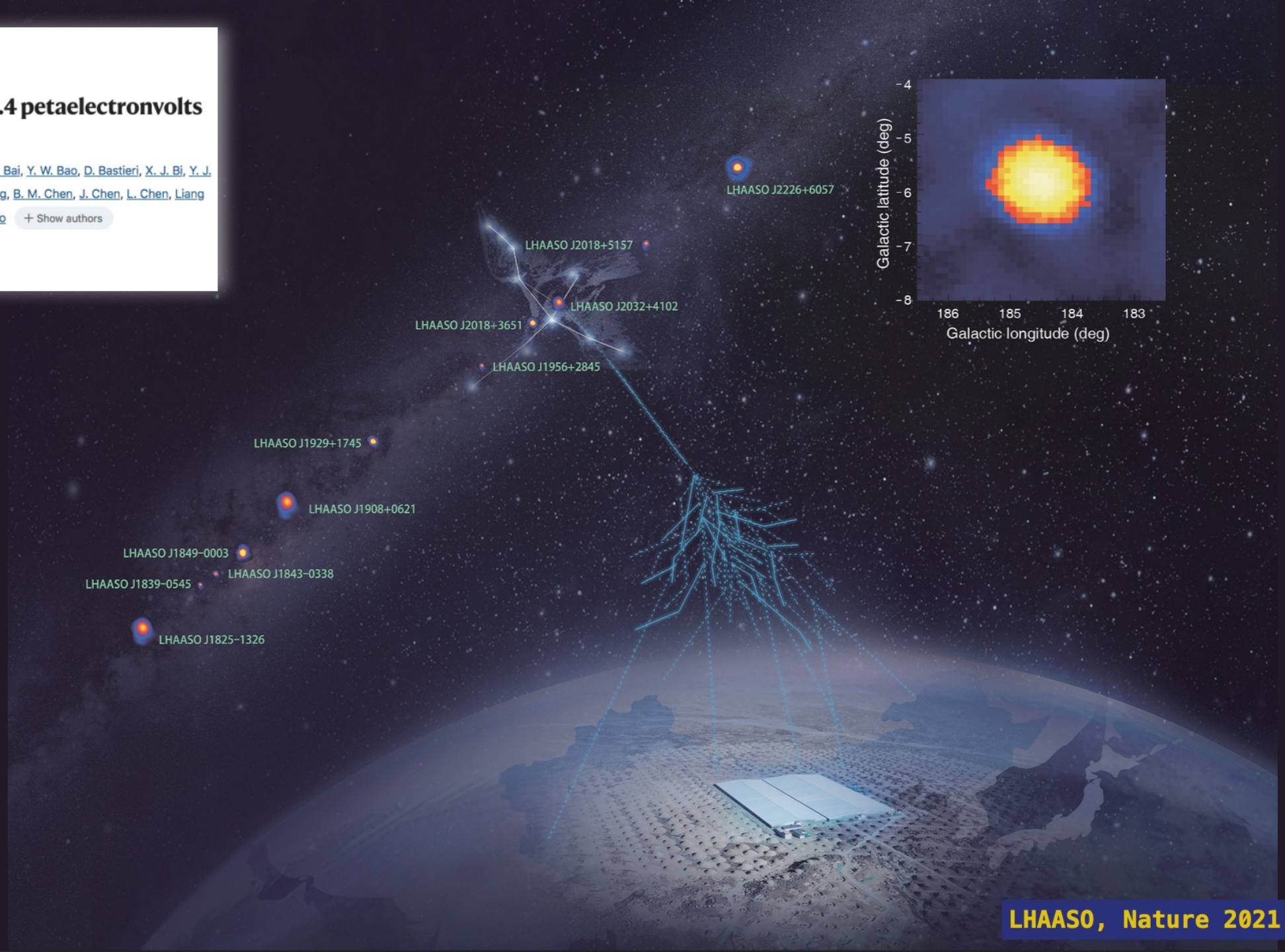
MAGIC coll. 2017, MNRAS, 472, 2956

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources

Zhen Cao , F. A. Aharonian , Q. An, Axikegu, L. X. Bai, Y. X. Bai, Y. W. Bao, D. Bastieri, X. J. Bi, Y. J. Bi, H. Cai, J. T. Cai, Zhe Cao, J. Chang, J. F. Chang, X. C. Chang, B. M. Chen, J. Chen, L. Chen, Liang Chen, Long Chen, M. J. Chen, M. L. Chen, Q. H. Chen, ... X. Zuo [+ Show authors](#)

Nature **594**, 33–36 (2021) | [Cite this article](#)

22k Accesses | 164 Citations | 686 Altmetric | [Metrics](#)



HIGHEST ENERGY GAMMA-RAY SKY

- LHAASO, Tibet-AS γ and HAWCat $E_\gamma > 100$ TeV ($E_p \sim 1$ PeV; $E_e \sim 183$ TeV)

→ ~12 sources in **2021**

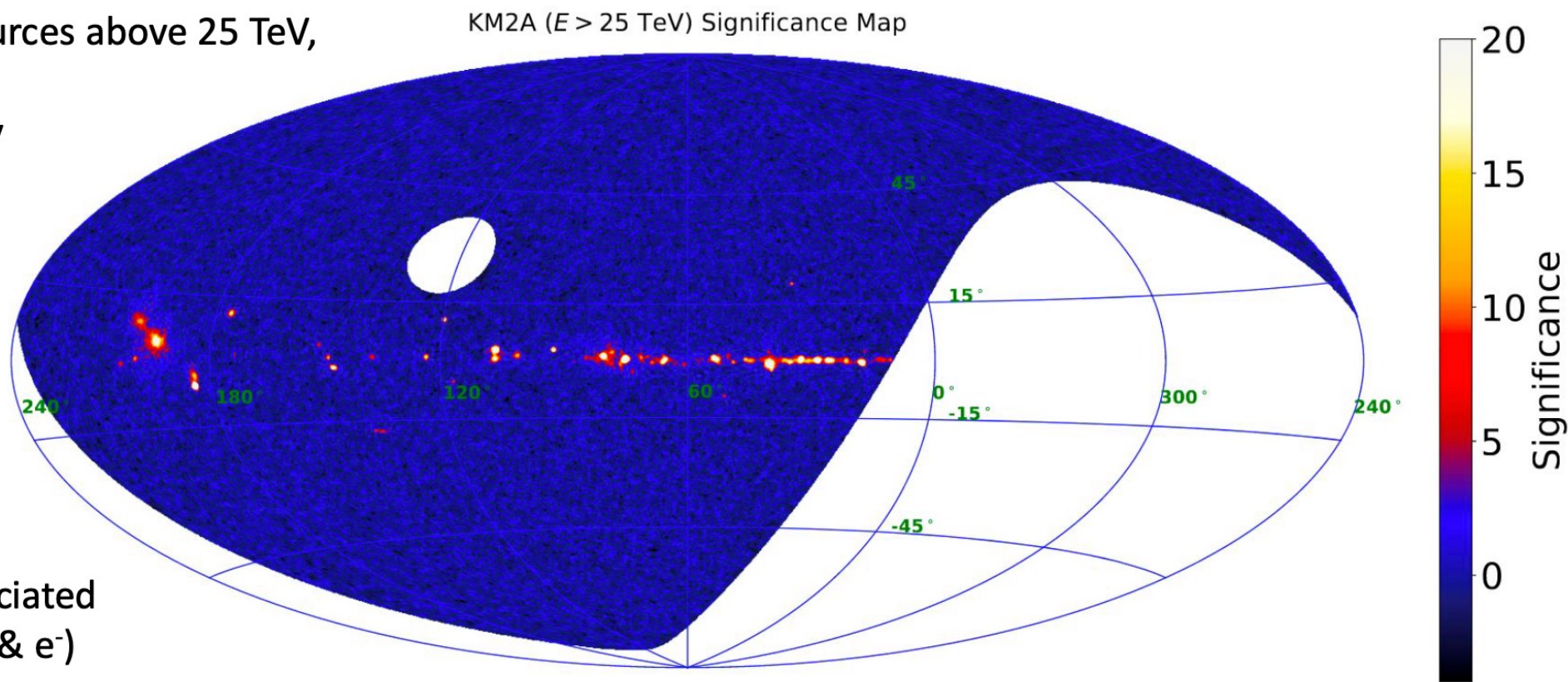
Cao et al. Nature **594** (2021) 33-36

- **2023:** ~ 75 gamma-ray sources above 25 TeV,
43 above 100 TeV

→ all located in our Galaxy

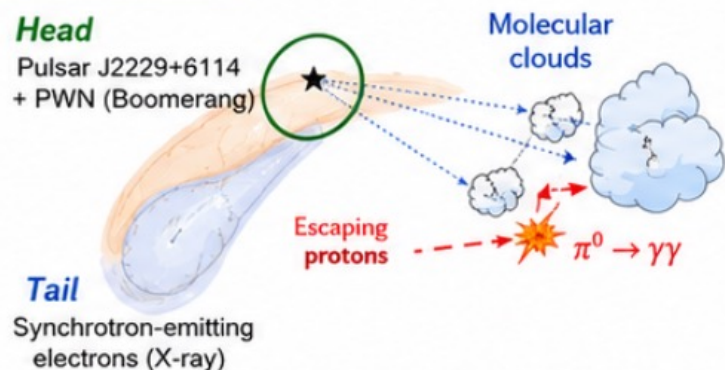
1st LHAASO Catalogue,
Cao et. al. arXiv:2305.17030v1

- Many unassociated
– no known counterpart
- Most common identified counterparts are pulsars
- Generally, pulsars are associated with leptonic emission (e^+ & e^-)



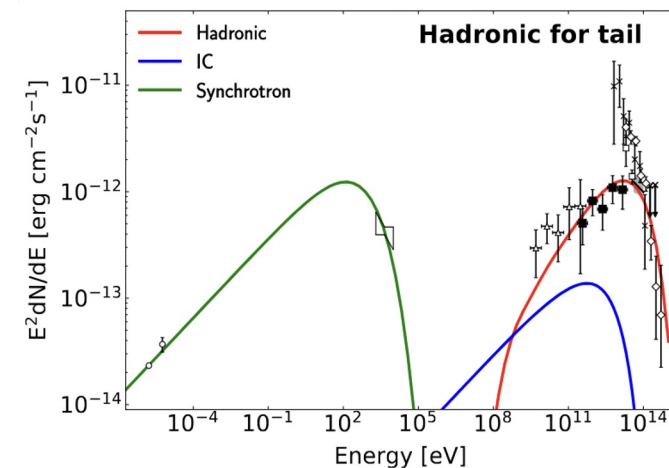
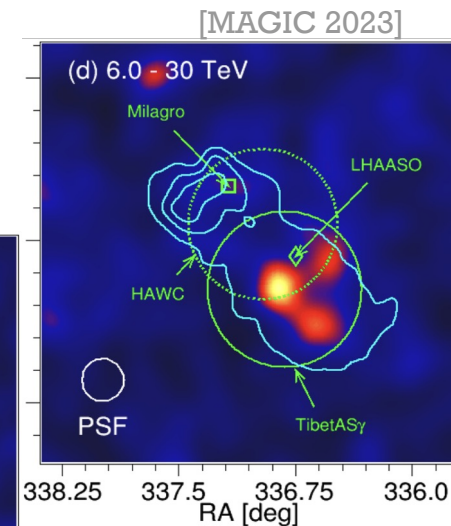
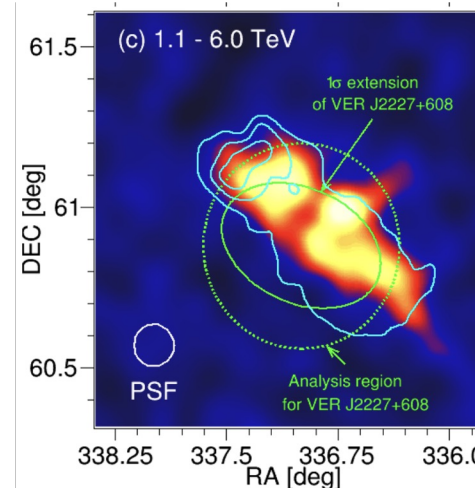
G106.3+2.7/BOOMERANG: SNR PEVATRON CANDIDATE

- **“LHAASO makes G106 a PeVatron candidate”**
→ photons above 100 TeV, up to 1.4 PeV
- **“MAGIC resolves the source”**
→ emission in **head + tail**, but **highest-energy TeV** emission sits in the **tail**
- **“Tail emission looks hadronic”**
→ difficult to explain with electrons alone; hadrons are favored
- **“HAWC links the UHE emission to molecular clouds”**
→ supports **escaping CR protons + cloud interaction**



Boomerang: a strong PeVatron candidate

- ✓ Multi-wavelength detections from radio to >100 TeV
- ✓ Extended γ -ray emission bridging head & tail regions
- ✓ Hadronic origin favored, with escaping protons interacting with nearby molecular clouds
- ✓ Candidate PeVatron accelerating protons up to PeV energies



Tail spectrum can be modeled with a hard proton population extending to ~PeV energies.

SNR SUMMARY

SNRs: where do we stand as Galactic CR accelerators?

- **SNR shocks remain prime candidates for Galactic CR acceleration up to the knee**
- **GeV evidence:**
 - π^0 -decay “pion bump” in interacting SNRs proves hadronic acceleration
- **TeV evidence:**
 - shell-type SNRs show particle acceleration to multi-TeV energies
- **UHE evidence (>100 TeV):**
 - only a few SNR systems are strong **PeVatron candidates**
- **But not all UHE emission is from the shell itself:**
 - escaping CRs interacting with nearby clouds may dominate
- **Current picture:**
 - SNRs likely power a major fraction of Galactic CRs, but whether they alone reach the knee is still open

Examples

- **Cas A:** young shell SNR, hadronic TeV emitter, not a present-day PeVatron
- **G106.3+2.7 / Boomerang:** one of the best current **SNR PeVatron candidates**, likely via **escaping hadrons + molecular clouds**

Takeaway

- **Gamma rays show that SNRs accelerate hadrons efficiently, but the origin of Galactic PeV cosmic rays is still not fully settled.**

Novae



Novae: accreting white dwarfs and explosive outbursts



Novae are **thermonuclear explosions** on the surface of an **accreting white dwarf (WD)** in a **binary system**. The WD accumulates hydrogen-rich material from a companion star until a thermonuclear runaway occurs, ejecting part of the accreted envelope at high velocity.



Two main classes

- **Classical novae**: donor is usually a low-mass main-sequence star.
- **Symbiotic novae**: donor is a red giant (RG); the WD is embedded in a dense stellar wind.



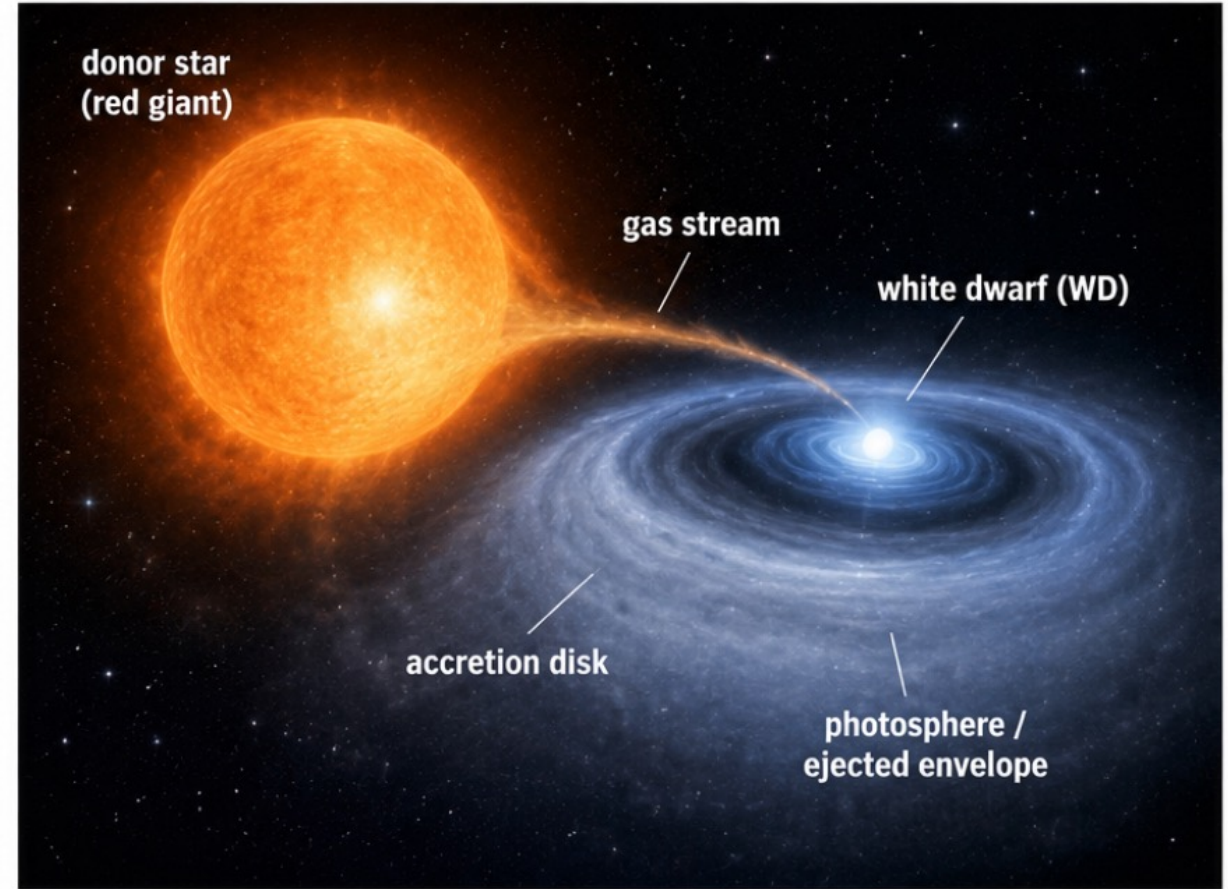
Relevant for high-energy emission

- The eruption drives fast outflows and shocks that propagate into the surrounding medium.
- These shocks can accelerate particles and produce **GeV–TeV gamma rays**.



Timescales

- Optical outburst: weeks to months
- Some systems repeat on human timescales: **recurrent novae (RN)**



Take-home message: Novae are powerful, but relatively short-lived explosions on accreting white dwarfs. Their shocks can accelerate particles and produce **gamma rays** from **GeV** up to (and possibly beyond) **TeV** energies.

NOVAE AS SHOCK-POWERED TRANSIENTS

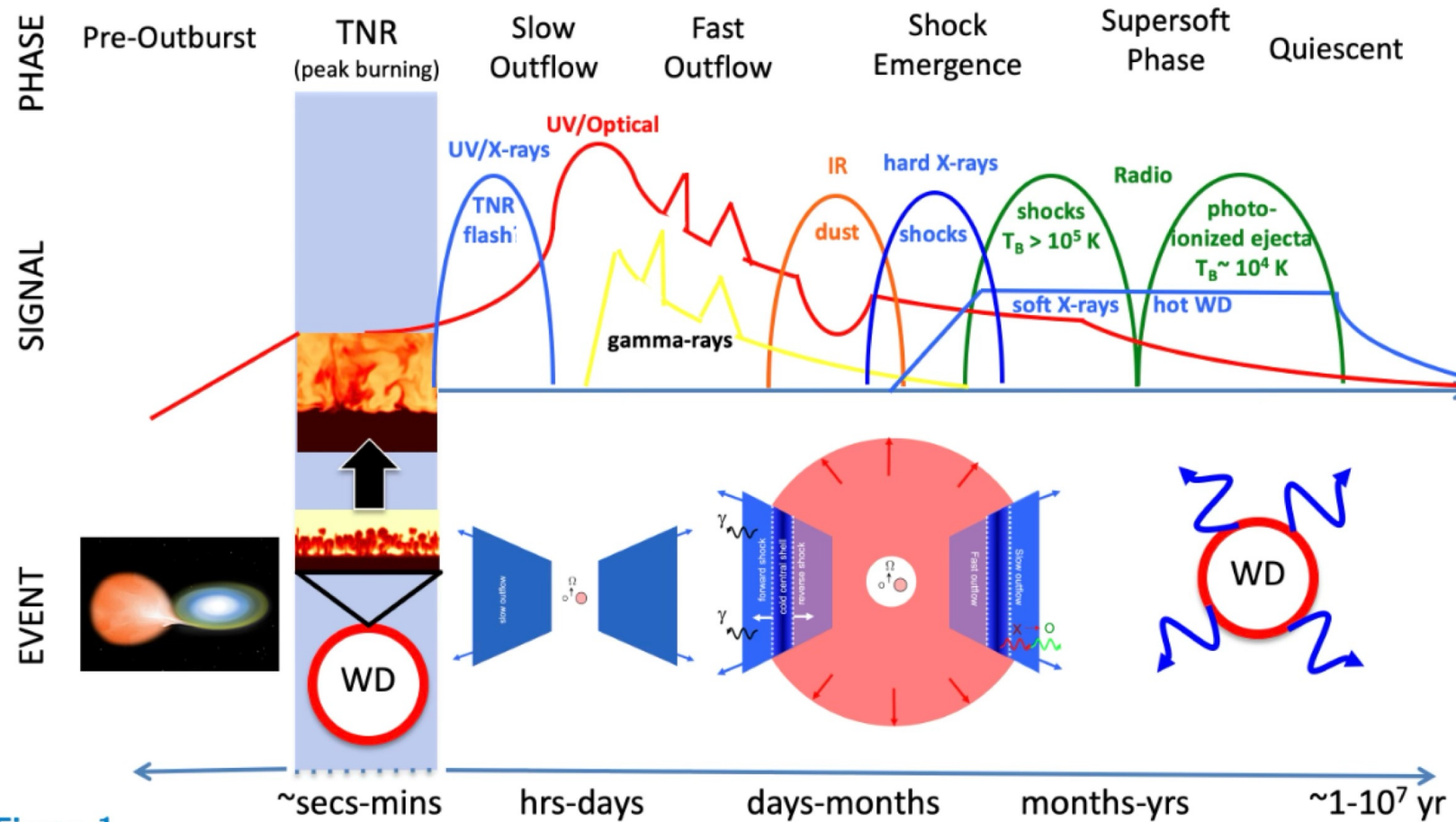


Figure 1

Schematic timeline of the physical processes and electromagnetic signals from novae. The figure includes modified images of convection/mixing during the thermonuclear runaway from Casanova et al. (2016), reproduced with permission ©ESO) and internal shocks from Metzger et al. (2015).

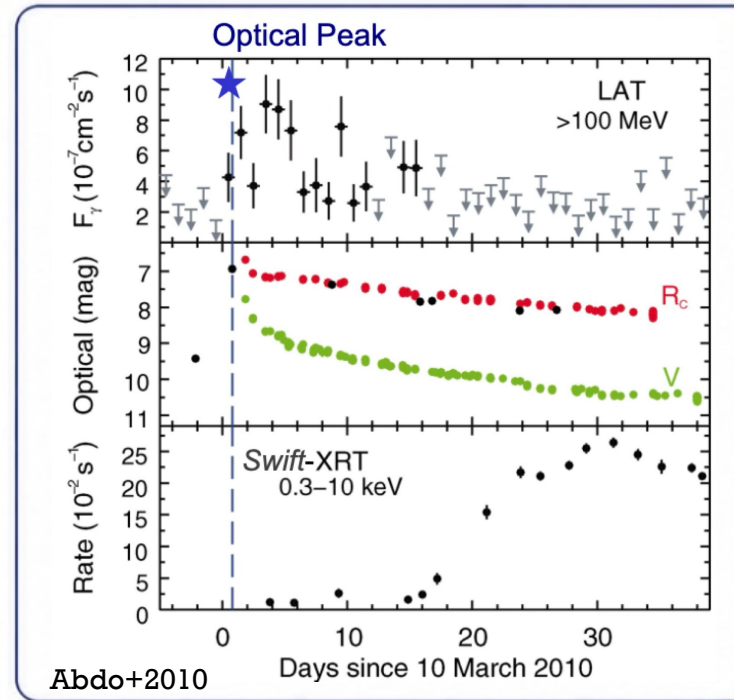
Chomiuk+2021

Fermi DISCOVERY OF GAMMA-RAY NOVAE

Fermi-LAT revealed novae as a new class of transient GeV gamma-ray sources

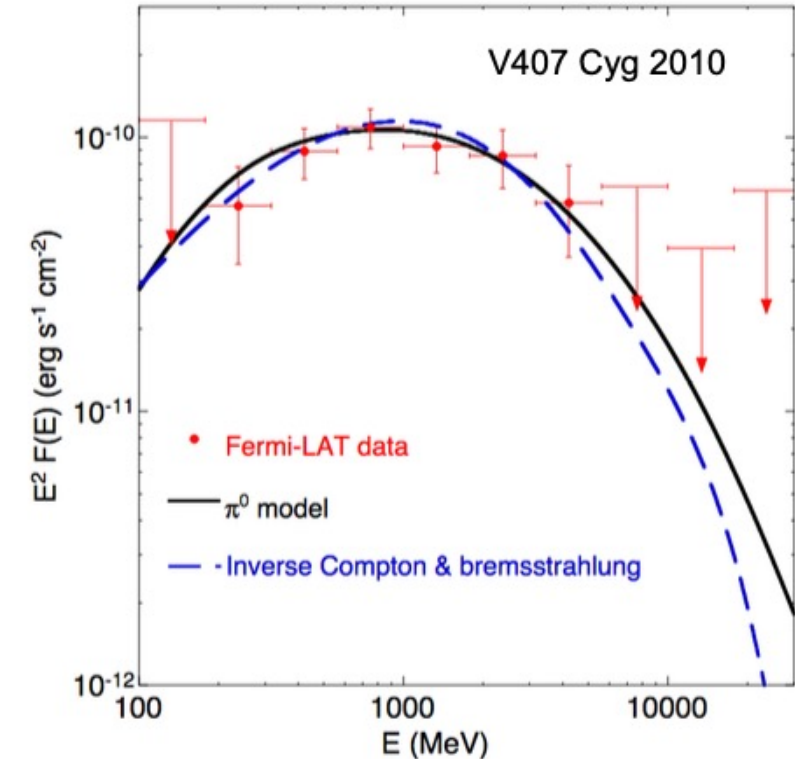
- 2010: *Fermi*-LAT detected **V407 Cyg**, the first nova seen in gamma rays.
- The GeV flare appeared **near optical maximum** and lasted days to weeks.
- This established novae as **transient HE sources** ($E > 100$ MeV).
- Later *Fermi* detections showed that both **symbiotic** and **classical novae** emit GeV gamma rays.
- The GeV spectra typically extend to **a few-10 GeV** and can be explained by **hadronic** or **leptonic** shock models.

V407 Cyg (2010): multiwavelength light curves



Example GeV spectrum

V407 Cyg (2010)



TAKEAWAY: Fermi-LAT turned novae from purely optical transients into a new class of shock-powered **GeV** gamma-ray sources.



Gamma-ray emission arises from **shocks** in nova ejecta accelerating particles.

Gamma-ray properties of novae

Fermi-LAT view of GeV novae



Transient GeV emission (days–weeks)

- Typically lasts ~5–55 days
- Gamma-ray activity occurs around **optical maximum**, often with delays of a few days



GeV-peaked spectra with cutoffs

- Spectra well described by a power law with exponential cutoff
- Photon index $\Gamma \sim 1.3\text{--}2.3$; cutoff energies $E_c \sim \text{a few GeV}$ ($\lesssim 10$ GeV)



Seen in both symbiotic and classical novae

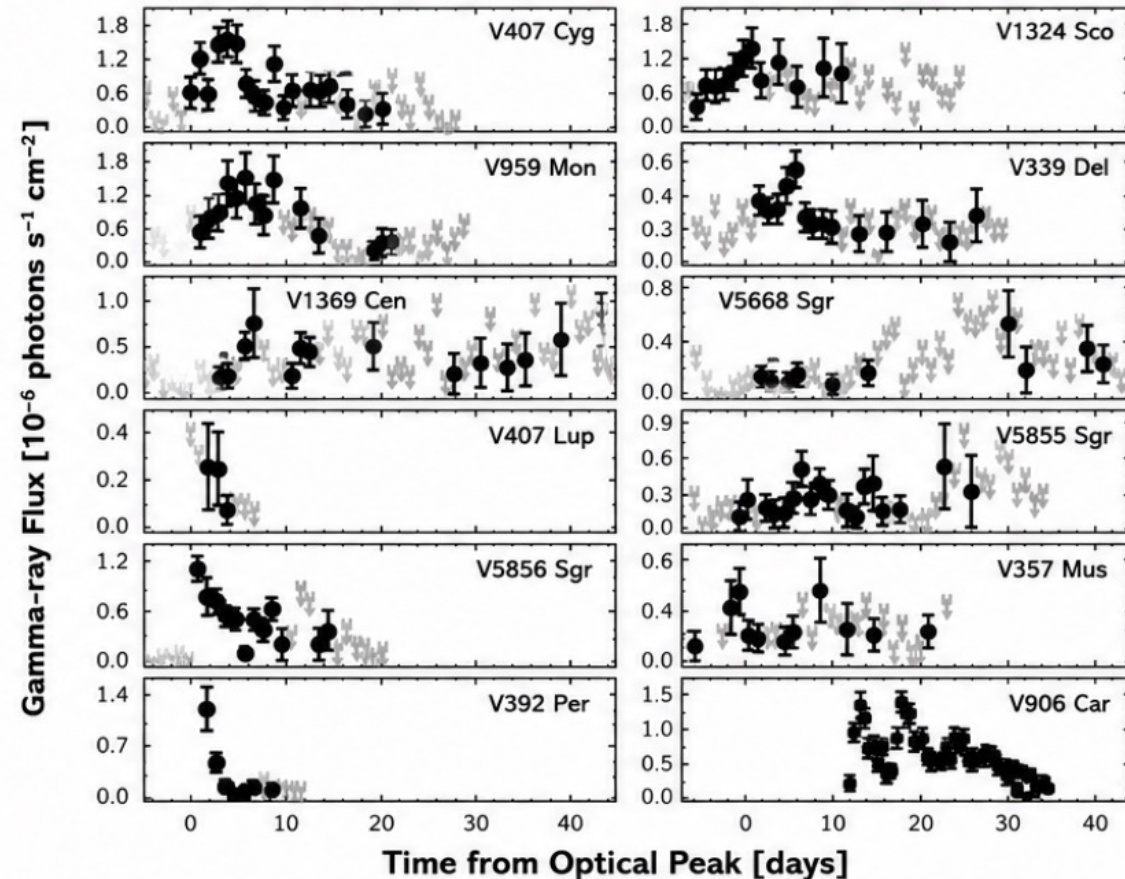
- Gamma-ray novae include systems with red-giant companions (**symbiotic**) and main-sequence companions (**classical**)
- Dense red-giant wind is not required



Shock-powered emission

- Internal shocks in the nova ejecta accelerate particles
- Gamma rays trace non-thermal processes in the outflows (hadronic or leptonic)

Examples of Fermi-LAT light curves (>100 MeV)



Diverse temporal behavior, but emission is generally confined to the first few weeks after eruption.

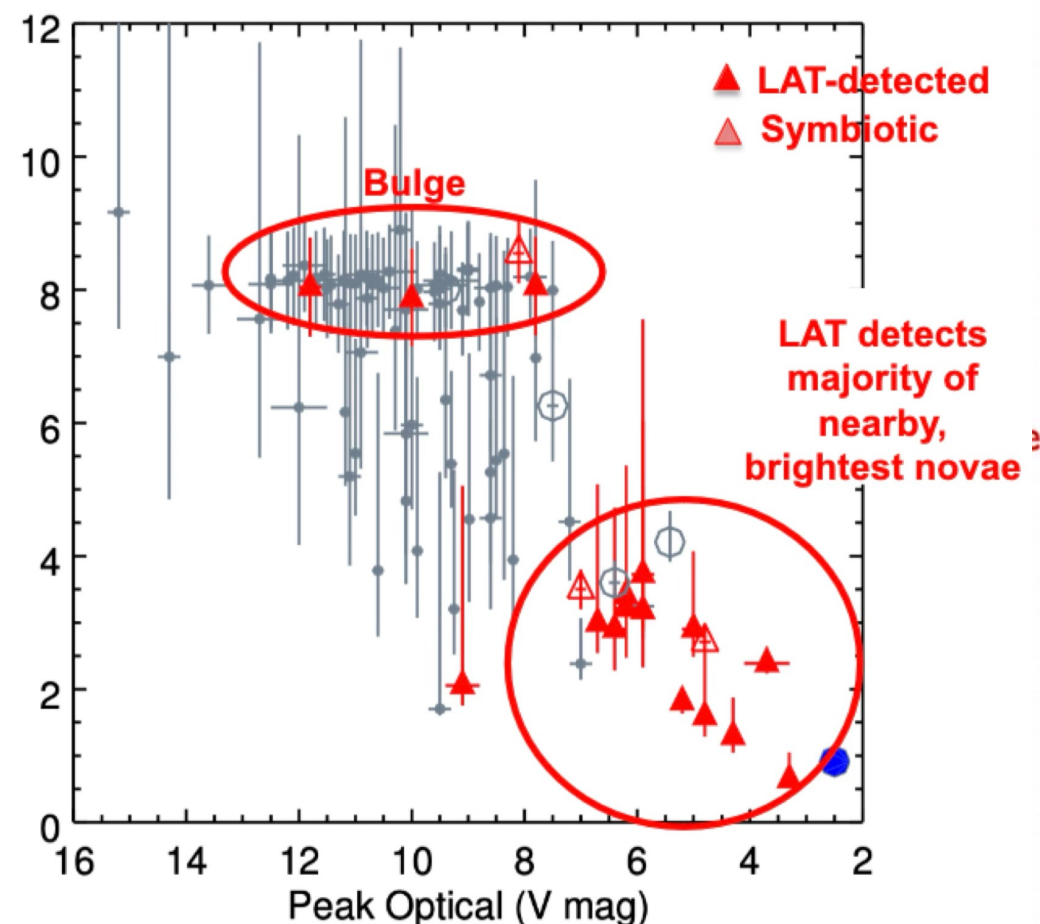


Takeaway: Gamma-ray novae are short-lived GeV transients produced by shocks, with broadly similar spectral shapes but a wide range of luminosities and temporal behavior.

Fermi-LAT GeV Novae: 2008 – 2023

LAT detects the nearest and optically brightest novae

- Total of 19 GeV novae detected by **Fermi-LAT** (2008–2023)
- **LAT-detected novae are biased toward nearby, optically bright systems**
 - LAT novae in the Galactic disk tend to be the closest and brightest
- **Most detections in the Galactic disk**
 - N = 15 disk novae (2 of them seen through the bulge line of sight)
- Only 4 detections in the **Galactic bulge**
 - Including the symbiotic recurrent nova V3890 Sgr
- Many distant and faint novae remain below current LAT sensitivity



Takeaway: Fermi-LAT novae are a biased subset of the full Galactic nova population. LAT preferentially detects nearby, optically bright novae in the disk, while many bulge novae remain undetected.

SEARCHING FOR VERY HIGH ENERGY EMISSION



- GeV data alone do not uniquely distinguish leptonic and hadronic emission models.



- Nova shocks accelerate non-thermal particles.
 - Electrons and protons can both reproduce the observed GeV component.



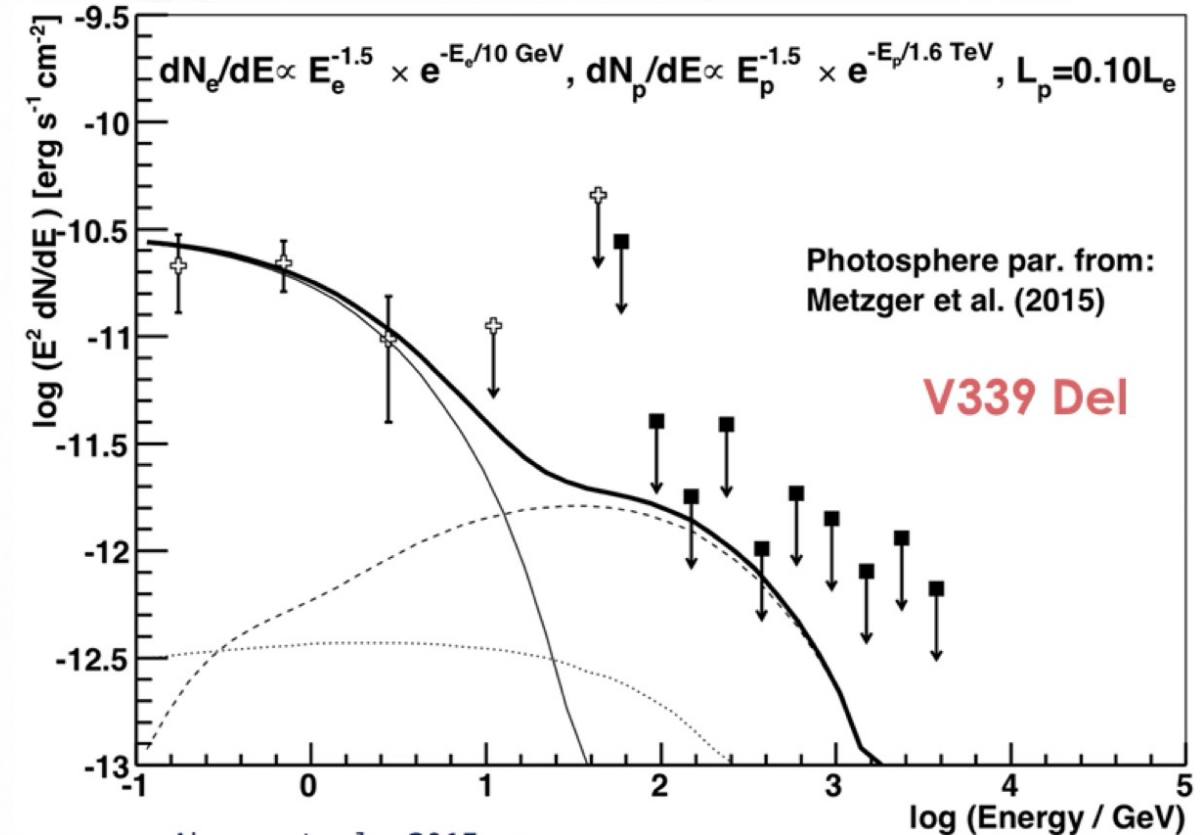
- Protons may reach higher energies than electrons.
 - They suffer lower radiative losses and can potentially produce a second, harder component
 - This component could extend into the VHE band (>100 GeV) detectable by Cherenkov telescopes.



This motivated more than a decade of VHE searches for novae with IACTs.

- VERITAS, MAGIC, H.E.S.S. and others

Example: V339 Del – possible hadronic extension



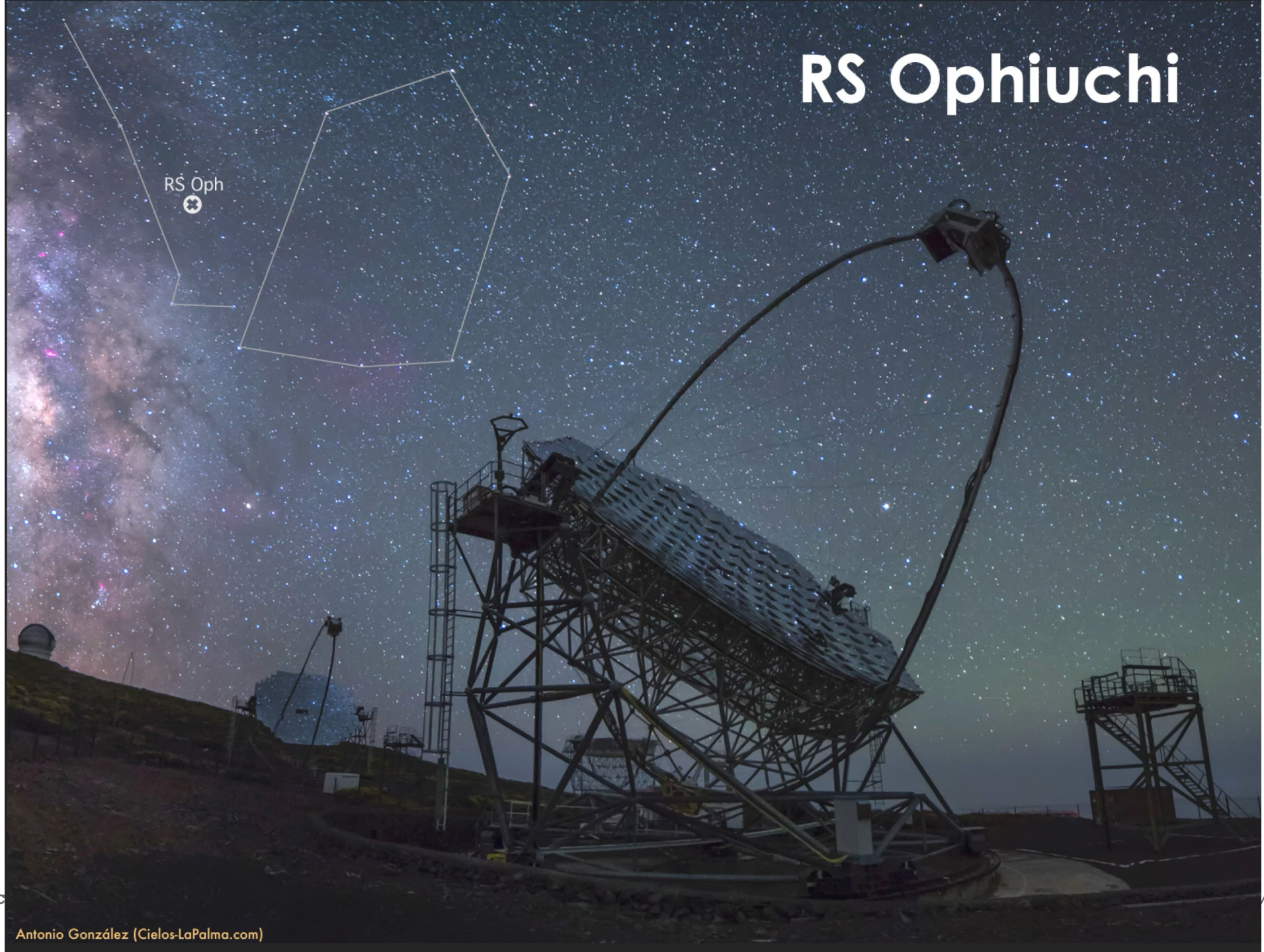
Hadronic models predict emission extending to higher energies and possibly a detectable VHE component.



TAKEAWAY: While GeV data do not yet reveal the dominant emission channel, protons may produce an additional VHE component—motivating dedicated searches with Cherenkov telescopes.

Aliu et al. 2012, Ahnén et al. 2015,
Metzger et al. 2015

RS Ophiuchi



FIRST DETECTION OF NOVA AT VHE: RS OPHIUCHI



- **Recurrent symbiotic nova**

- WD + red giant companion
- Major outbursts every ~15 years



- **Strong shocks from nova–wind interaction**

- Nova ejecta collide with the dense wind of the red giant
- Efficient particle acceleration expected



- **Early high–energy indication (2006 outburst)**

- Detected by Swift/BAT
- Could not be accounted for by the decay of radioactive isotopes
- Emission could be explained **via the production of non-thermal particles by diffuse shock acceleration**
(Tatischeff et al. 2007)



KEY POINT: RS Oph is a nearby recurrent symbiotic nova where nova ejecta collide with a dense red-giant wind, producing strong shocks and accelerating particles—already showing high-energy emission in the 2006 outburst.

FIRST DETECTION OF NOVA AT VERY HIGH ENERGIES

- **First nova detected at VHE (≥ 100 GeV)**

(H.E.S.S. Science 2022; MAGIC Nat Astron 2022)

Novae established as a new source class at VHE gamma rays

- **VHE emission appeared during the optical/GeV outburst**

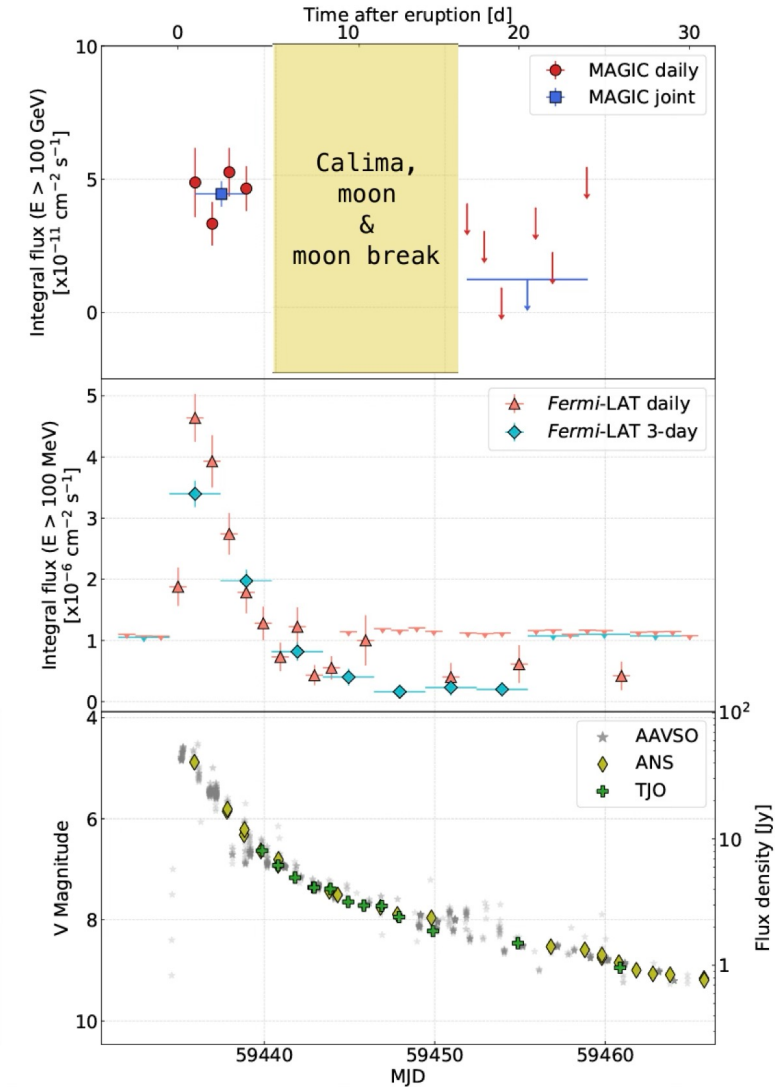
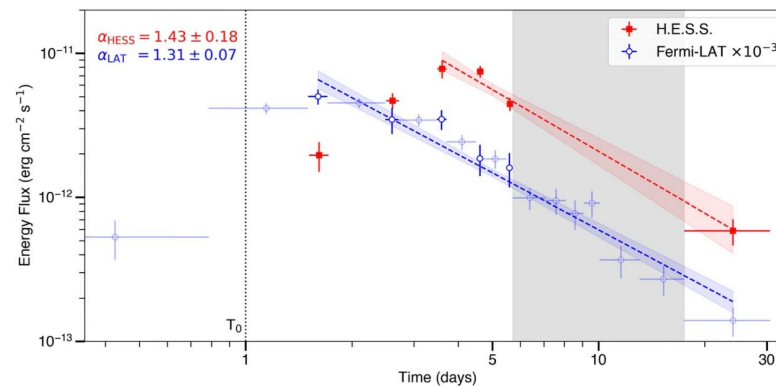
- MAGIC saw VHE emission during the first few days
- H.E.S.S. detected a delayed peak by ~ 2 days relative to Fermi-LAT

- **Rapid fading at high energies**

- Decay timescale ~ 2.2 days

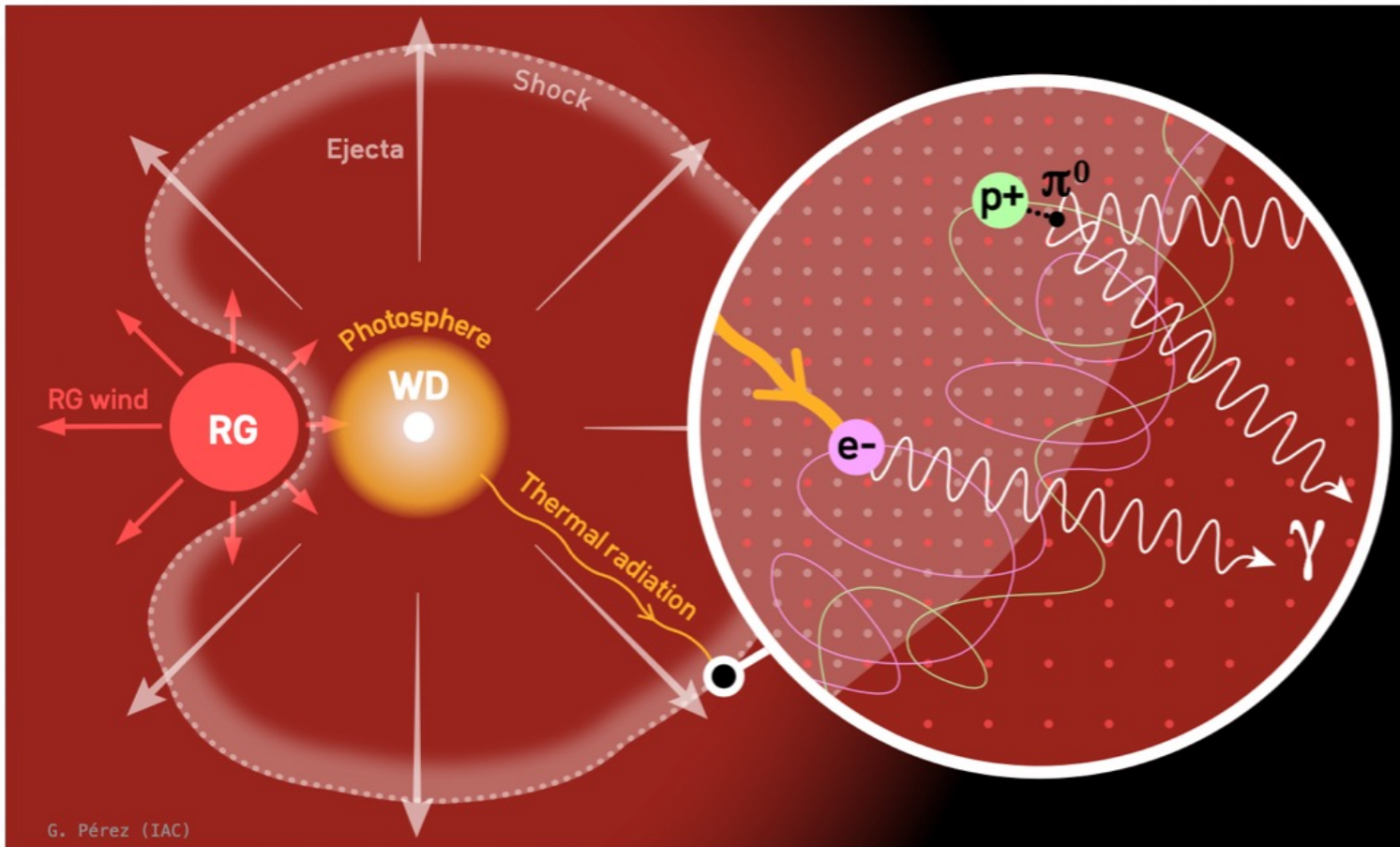
- **Dominant radiation field**

- Photospheric emission dominates during the nova outburst



KEY TAKEAWAY: In 2021, RS Ophiuchi became the first nova detected at very high energies (≥ 100 GeV). The VHE emission peaked shortly after the GeV/optical maximum and then decayed rapidly.

PARTICLE ACCELERATION IN RS OPHIUCHI



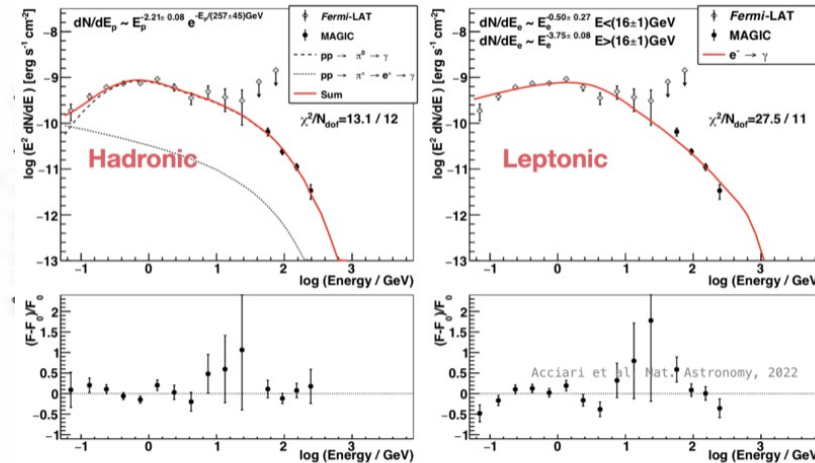
- Nova ejecta drive a **shock** into the dense red-giant wind and surrounding circumstellar material.
- The shock accelerates both **electrons** and **protons** via diffusive shock acceleration (Fermi acceleration).
- **Electrons**: produce γ -rays mainly through **inverse Compton (IC)** scattering of the nova photosphere radiation field.
- **Protons**: produce γ -rays through **pp interactions** in the ejecta / shocked ambient gas, followed by $\pi^0 \rightarrow \gamma\gamma$.
- In RS Oph, electron cooling is very fast while protons cool much more slowly, making the **hadronic scenario favored** for the VHE emission.

- p^+ Proton (**hadronic channel**): **pp interaction** on nova ejecta (with some contribution from RG wind) $\rightarrow \pi^0 \rightarrow \gamma\gamma$
- e^- Electron (**leptonic channel**): **IC scattering** on the thermal radiation of the WD photosphere

WHY IS THE HADRONIC SCENARIO FAVORED IN RS OPHIUCHI?

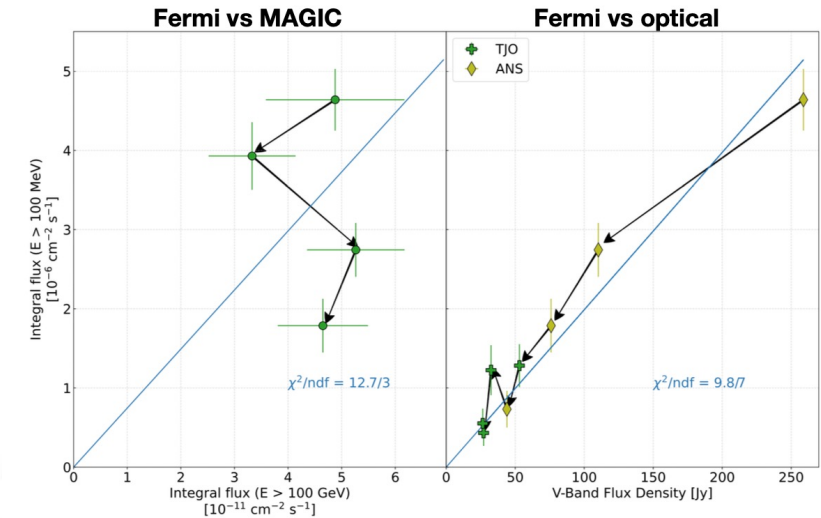
- **SED fits favor hadrons:** proton models reproduce the LAT+VHE spectrum more naturally than leptonic models.
- **Electrons cool too fast:** a purely leptonic interpretation requires an *ad hoc* strong spectral break in the electron distribution.
- **Temporal evolution supports hadrons:** VHE flux is roughly flat, while HE (GeV) and optical decay faster—hard to reconcile with simple IC expectations.
- **Cutoff energy increases with time:** spectral hardening is consistent with proton acceleration and slower cooling timescales.

1. SED fits: hadronic vs leptonic



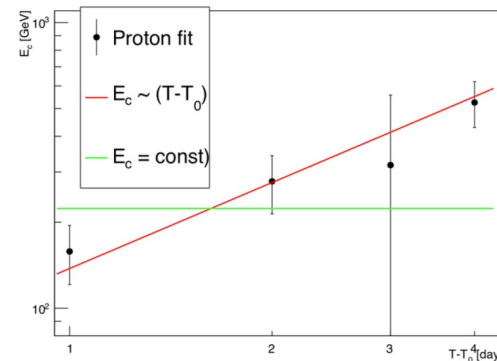
Acciari et al. 2022

2. MWL flux evolution



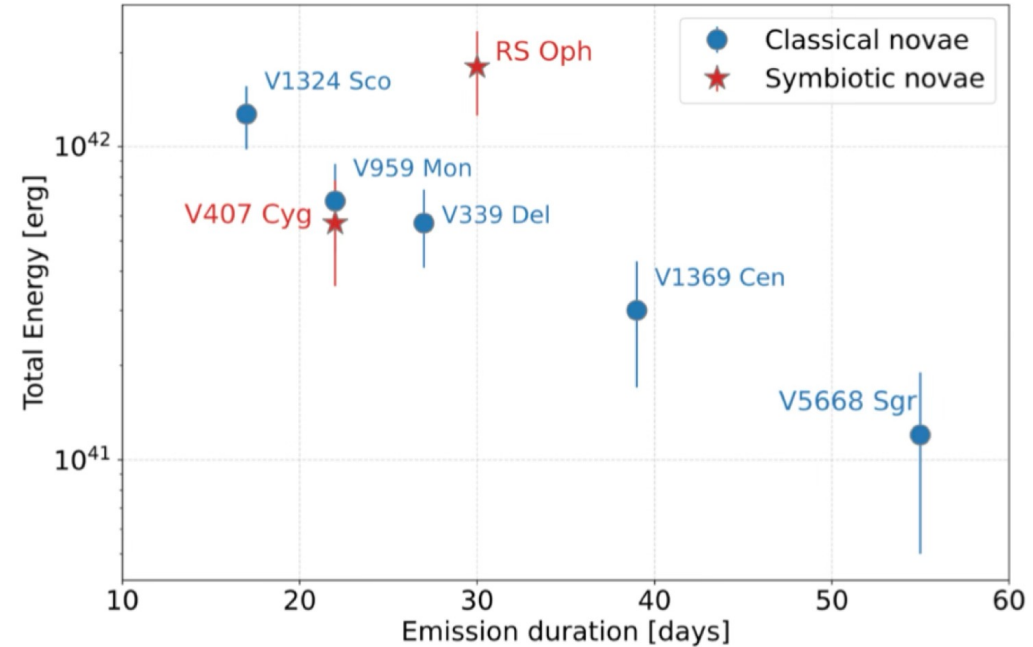
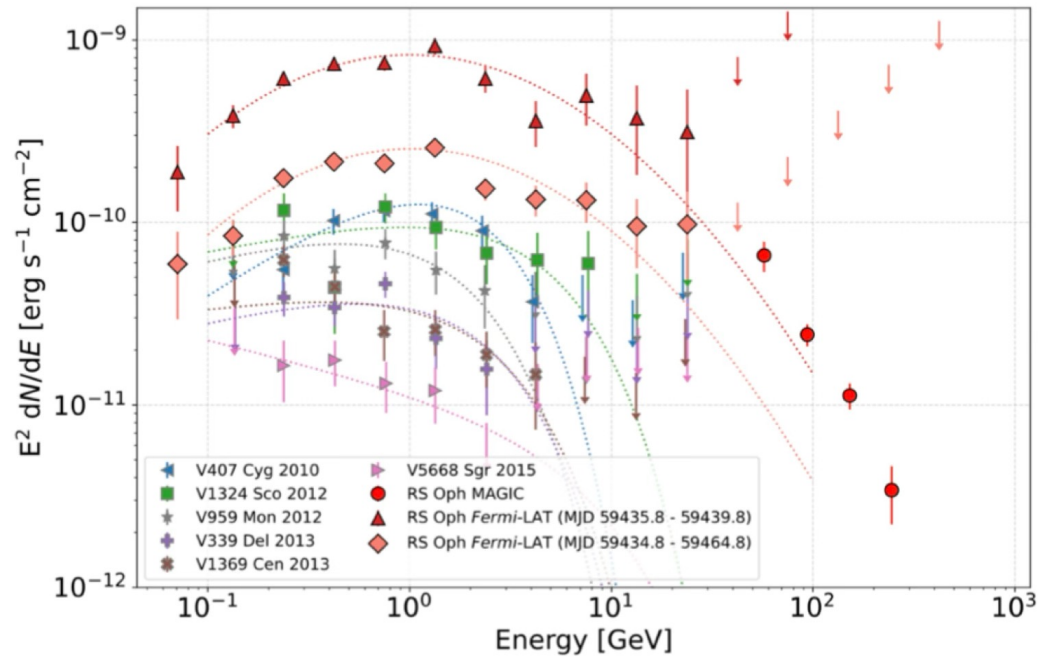
Acciari et al. Nat. Astronomy, 2022

3. Cutoff energy evolution (spectral hardening)



TAKEAWAY: RS Ophiuchi's spectrum and multiwavelength evolution are best explained by shock-accelerated **protons (hadronic scenario)**. Electrons cool too fast and struggle to account for the VHE emission.

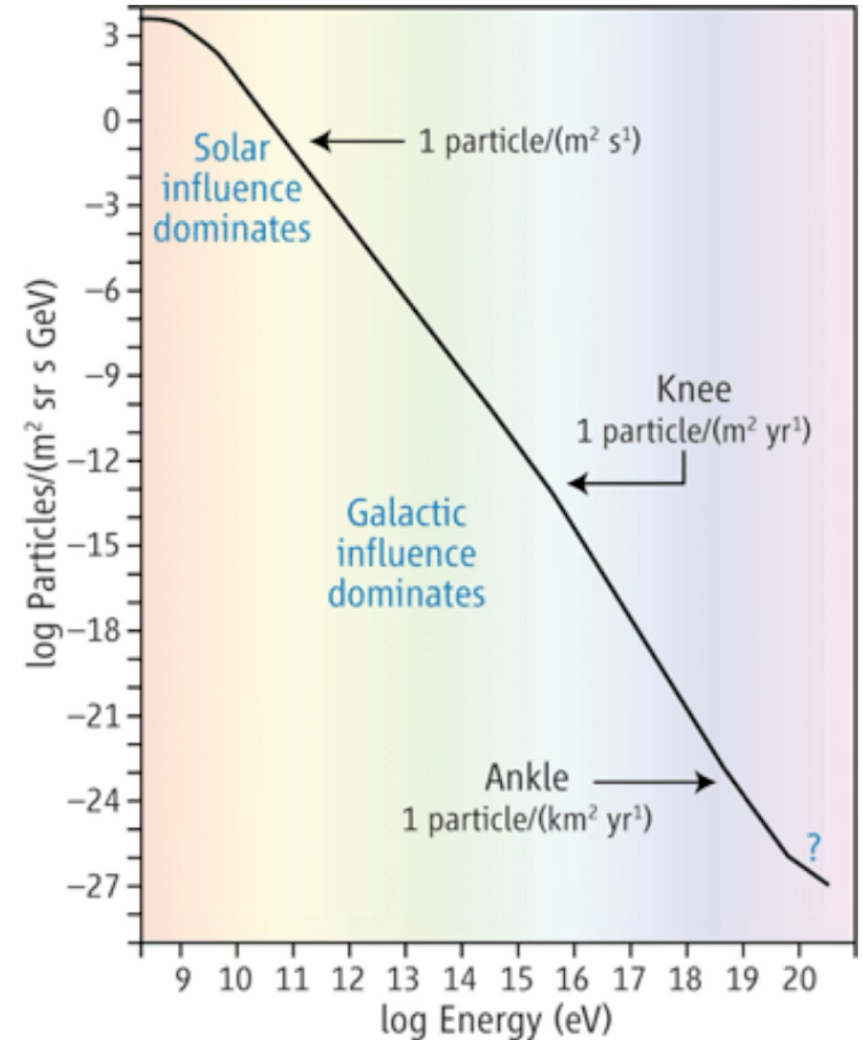
COMPARISON WITH OTHER NOVAE

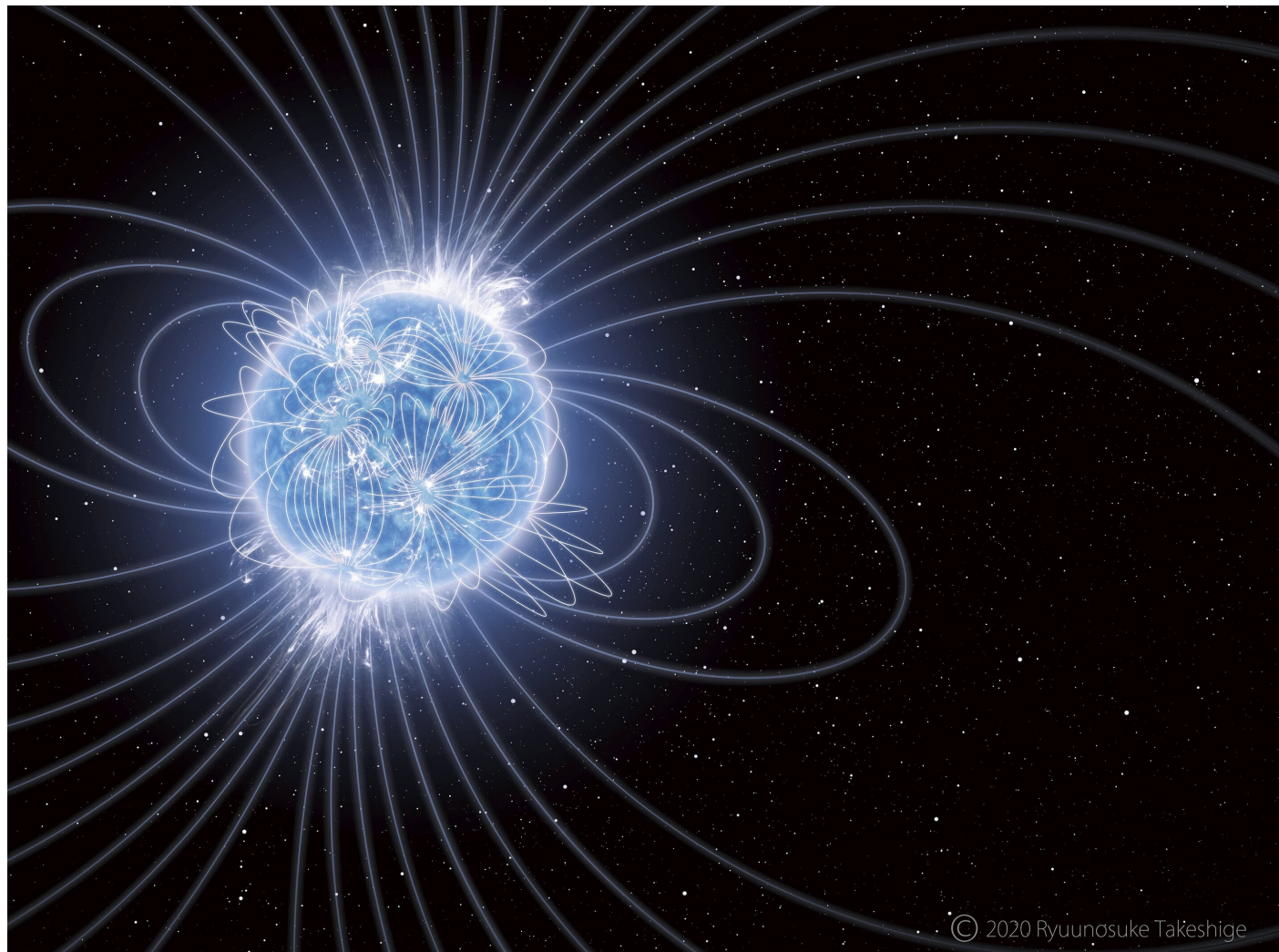


- RS Oph is the nova with the **highest flux** and **brightest nova**
 - Almost two orders of magnitude larger than previously-detected eruptions
- **Comparison does not reveal any peculiarity** in the emission of RS Oph, except for its brightness

GALACTIC NOVAE AND COSMIC RAYS

- Accelerated protons will eventually escape the nova shock carrying away most of their obtained energy. Such protons can **contribute to the Galactic Cosmic Ray sea**
- Using the CR energetic derived for RS Oph ($\sim 4.4 \times 10^{43}$ erg): **<0.2% of the contribution from supernovae**
- Despite the small contribution to the overall CR sea, **novae would significantly increase the CR density in its close environment:**
 $E_{\text{density}}(\text{nova}) > E_{\text{density}}(\text{CR})$
- In the case of **recurrent novae**, protons will accumulate in a **~ 10 pc bubble with enhanced CR density**



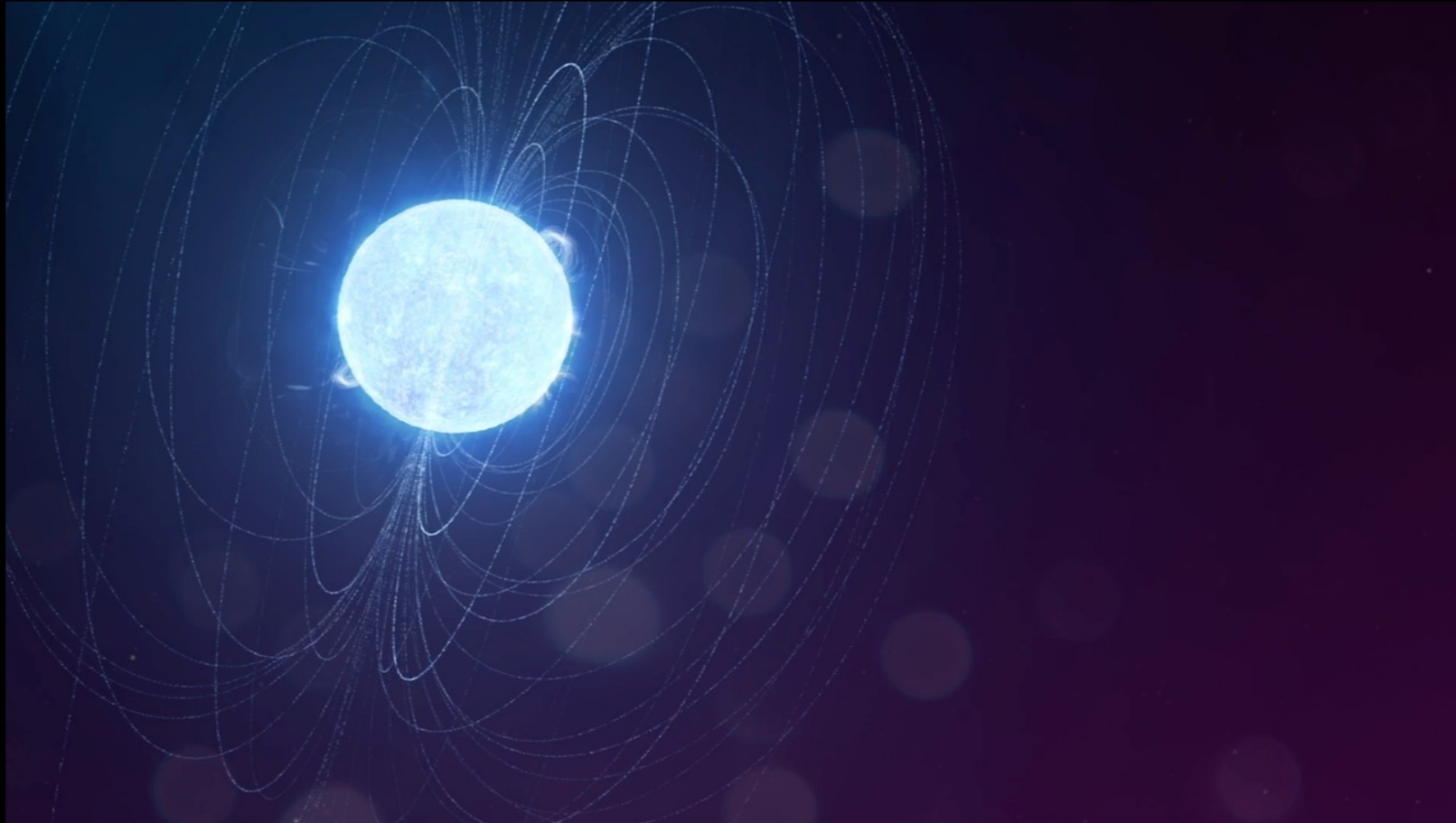


MAGNETIC POWERED SYSTEMS

Magnetars

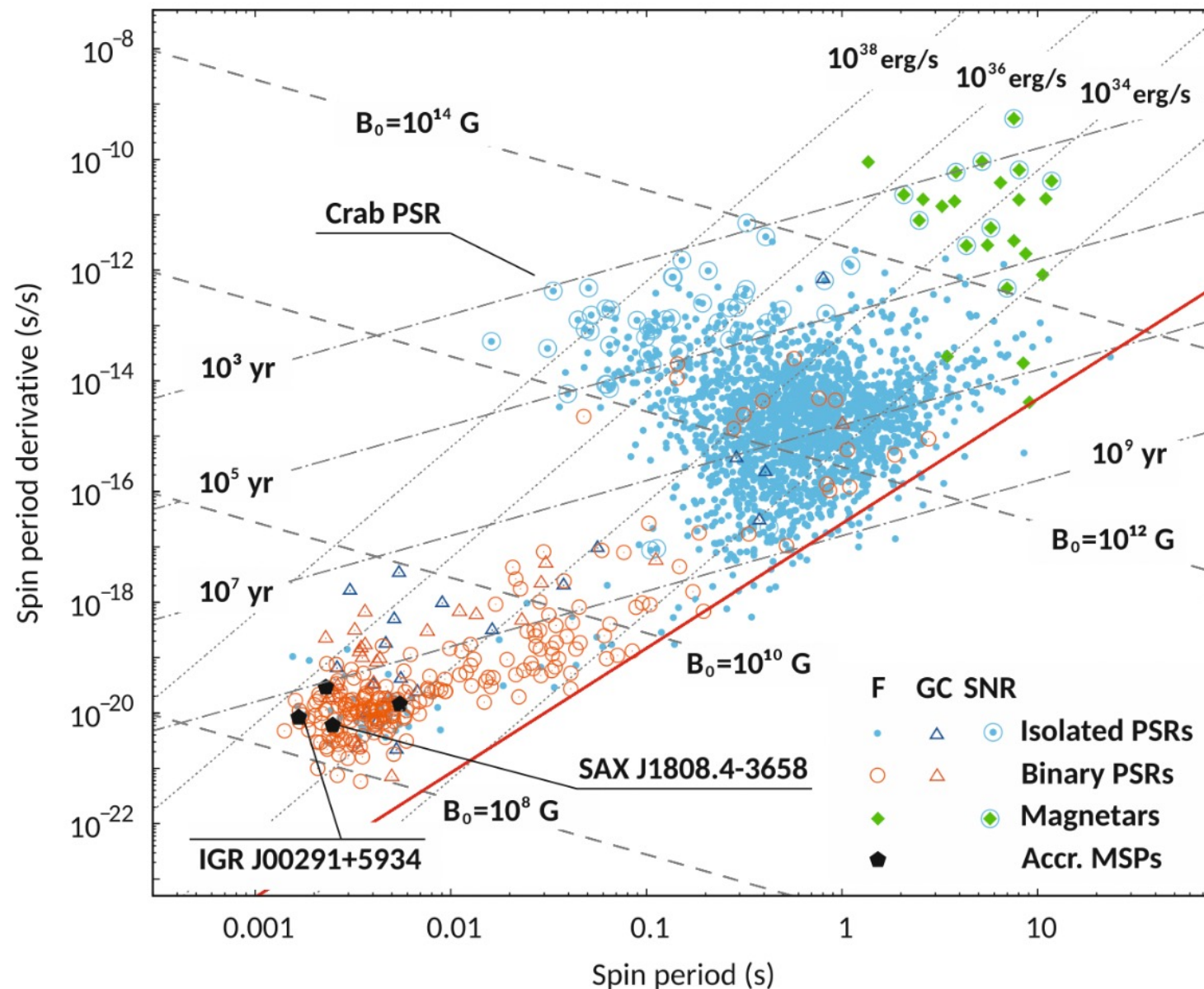
- Extreme magnetic fields -> $\sim 10^{14}$ - 10^{15} G ; Pulsar: $\sim 10^{12}$ G; Earth magnetic field ~ 0.5 G
- 10% SN explosions-> magnetars (Popov & Prokhorov 2006)
- **Slower rotation than pulsars:** 0.3-10 segundos
- **~ 30 known magnetars** in the Milky Way

STRONGEST
MAGNETIC FIELDS IN
THE UNIVERSE



PULSAR EVOLUTION

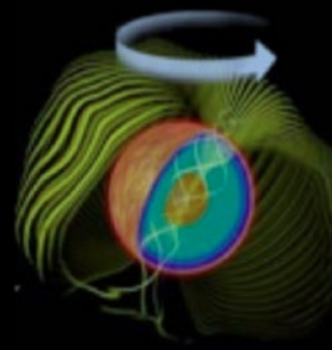
- **P- $\dot{P}$ diagram** (spin period vs. period derivative) summarizes the evolutionary states of neutron stars.
- **Magnetars** (green diamonds) occupy the top-right region: longer periods and high $\dot{P}$ (strong B-field $\sim 10^{14-15}$ G).
- Isolated and binary radio pulsars lie in the central and lower regions.
- Accreting millisecond pulsars (black pentagons) and Gamma-ray binary PSR J1808.4-3658 (SAX J1808) are in the bottom-left.
- Diagonal lines: characteristic ages (yr) and surface dipole magnetic fields (G).



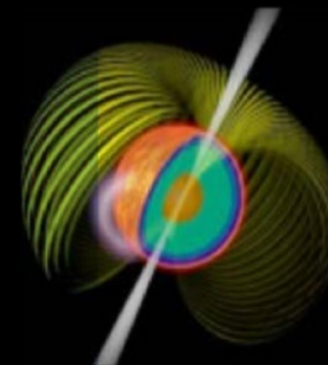
- Magnetars have highly twisted and complex magnetic field morphologies, both inside and outside the star. The surface of young magnetars are so hot that they are bright in X-rays.
- Magnetar magnetospheres are filled by charged particles trapped in the twisted field lines, interacting with the surface thermal emission through resonant cyclotron scattering.
- Twisted magnetic fields might locally (or globally) stress the crust (either from the inside or from the outside). Plastic motions and/or returning currents convert into crustal heating causing the outburst onset and evolution.



Magnetars



Normal Pulsars

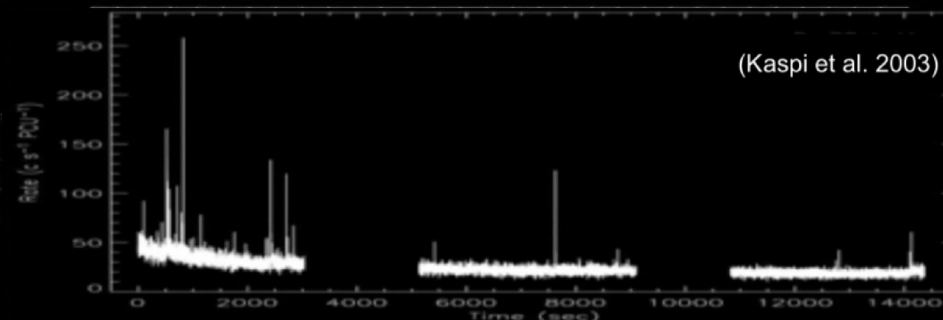


(Thompson & Duncan 1993; Thompson, Lyutikov & Kulkarni 2002; Fernandez & Thompson 2008; Nobili, Turolla & Zane 2008a,b)

TYPE OF BURSTS KNOWN FROM X-RAYS

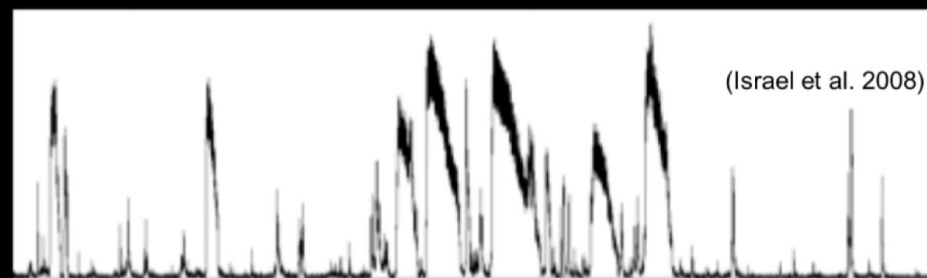
Short bursts

- the most common
- they last ~ 0.1 s
- peak $\sim 10^{41}$ ergs/s
- soft γ -rays thermal spectra



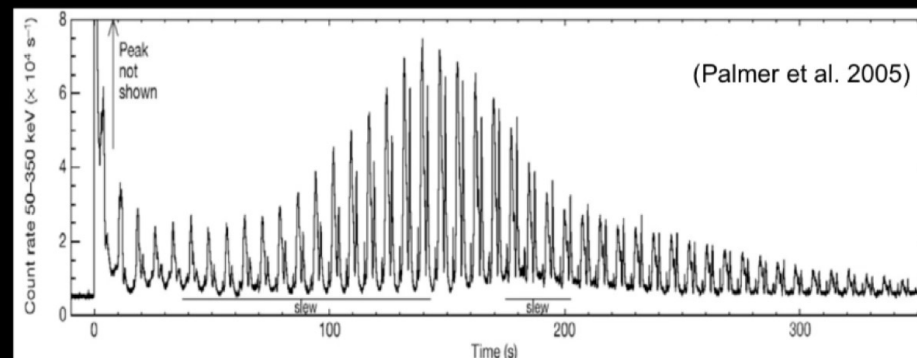
Intermediate bursts

- they last 1-40 s
- peak $\sim 10^{41}$ - 10^{43} ergs/s
- abrupt on-set
- usually soft γ -rays thermal spectra

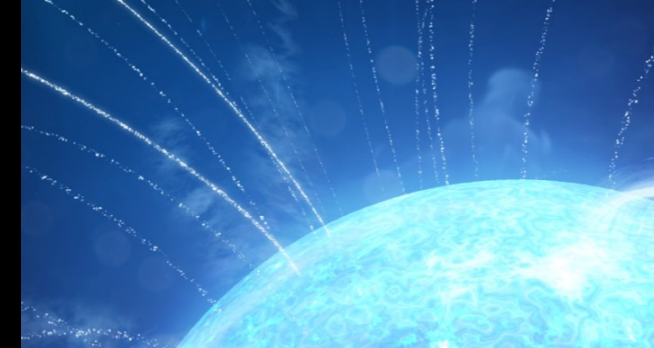


Giant Flares

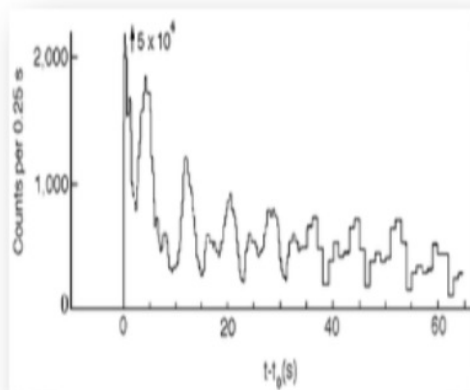
- Output of high energy is exceeded only by blazars and GRBs
- peak energy $> 3 \times 10^{46}$ ergs/s
- burst tail can last > 500 s, showing the NS spin



GIANT FLARES

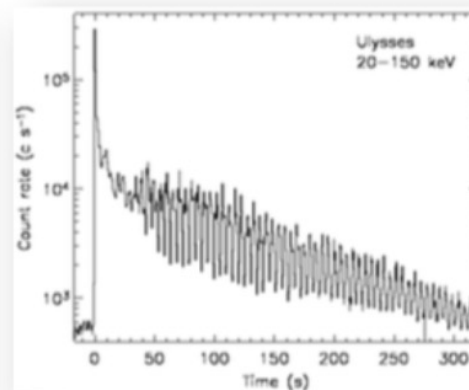


- **Most energetic explosions** ($\sim 10^{44} - 10^{47} \text{ erg s}^{-1}$)
- **3 detected in the last 40 years in the Galaxy:**
 - **Very luminous hard peak, lasting about a second** and with a luminosity of $\sim 10^{47} \text{ erg s}^{-1}$
 - **Rapid decay into a softer tail lasting hundreds of seconds**
 - **Thermal afterglow** of $< 1 \text{ h}$ at hard x-rays



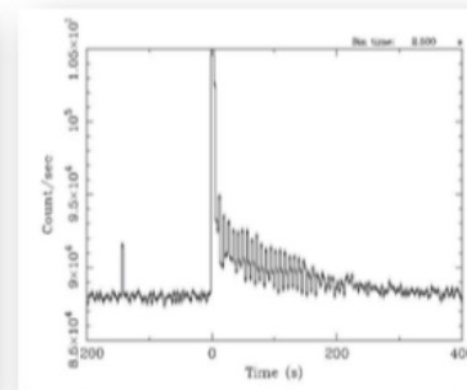
1979 March 5 SGR 0626-66

Initial spike $L_{\text{peak}} : 4 \cdot 10^{44} \text{ erg/s}$
 Tail energy: $4 \cdot 10^{44} \text{ erg}$



1998 Aug 27 SGR 1900+14

$> 8 \cdot 10^{44} \text{ erg/s}$
 10^{44} erg



2004 Dec 27 SGR 1806-20

$\approx 10^{47} \text{ erg/s}$
 10^{44} erg

Rare (1/decade) short (few min-1 h) transient events

GIANT FLARES

Also Giant Flares?



April 15, 2020

NGC 253 (Sculptor)



11.4 Mly

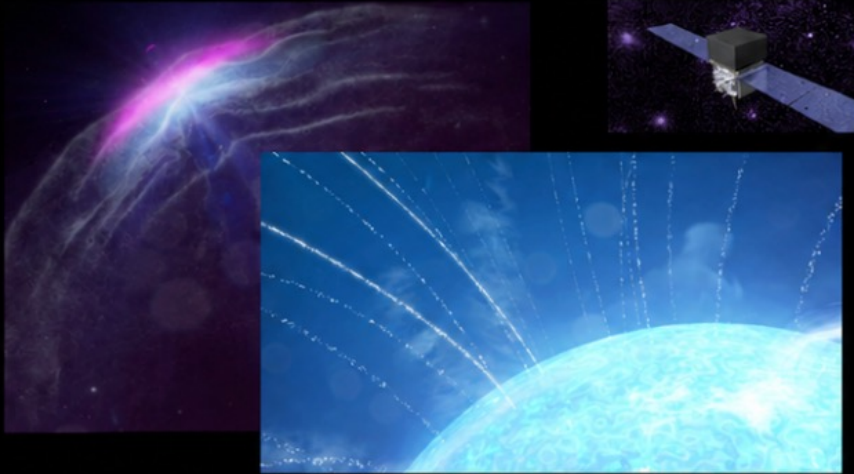
1.3×10^{46} erg*

GIANT FLARE IN NGC 253

Fermi-LAT: first GeV detection of a magnetar giant flare

WHAT IS A MAGNETAR GIANT FLARE?

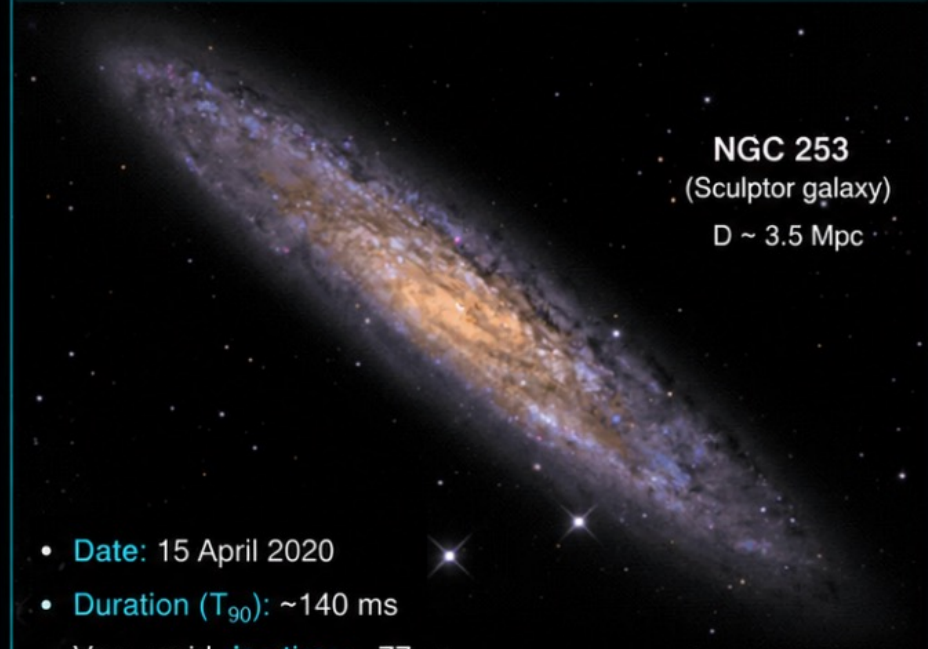
An ultra-magnetized neutron star releases a huge amount of energy in a very short time.



A **relativistic outflow** launched during the flare collides with material around the magnetar, forming **shocks** that accelerate electrons. These electrons emit **GeV γ rays** via synchrotron radiation as the outflow decelerates.

Only 3 HE photons detected: 480 MeV, 1.3 GeV and 1.7 GeV
(Fermi-LAT coll. 2021)

THE EVENT: 15 APRIL 2020



NGC 253
(Sculptor galaxy)
D ~ 3.5 Mpc

- **Date:** 15 April 2020
- **Duration (T_{90}):** ~140 ms
- Very rapid **rise time:** ~77 μ s
(Fermi-GBM coll. 2021)
- Localized to **NGC 253** with high confidence (LR analysis, $P \sim 10^{-3}$) $\rightarrow$ unlikely to be a cosmological GRB
- First detection of **GeV emission** from a magnetar giant flare



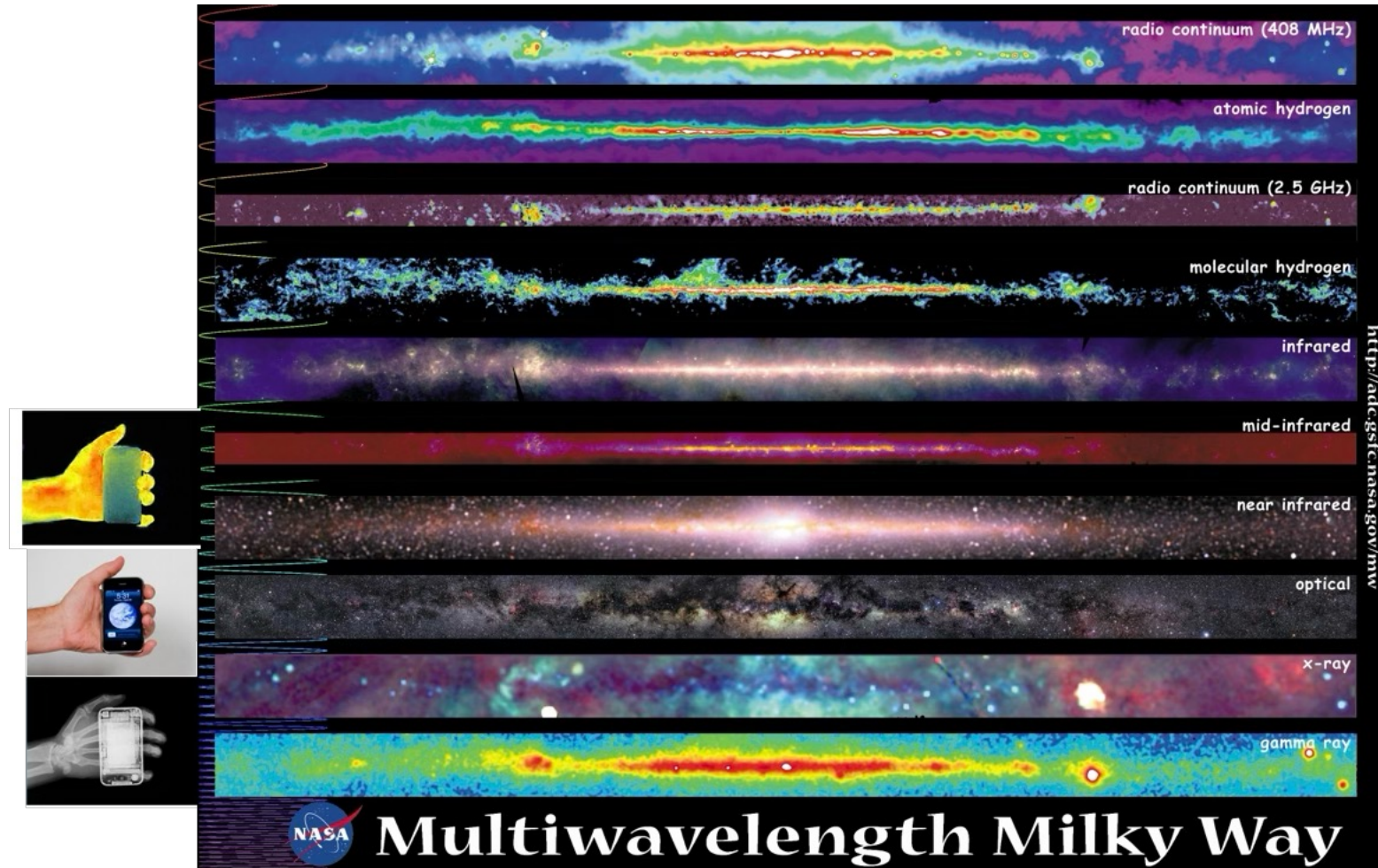
KEY MESSAGE: A magnetar giant flare in NGC 253 produced prompt hard X-/ γ -ray emission and subsequent **GeV γ rays** detected by *Fermi-LAT*. The GeV photons are produced when a **relativistic outflow** from the flare interacts with the surrounding medium and drives **shocks**.



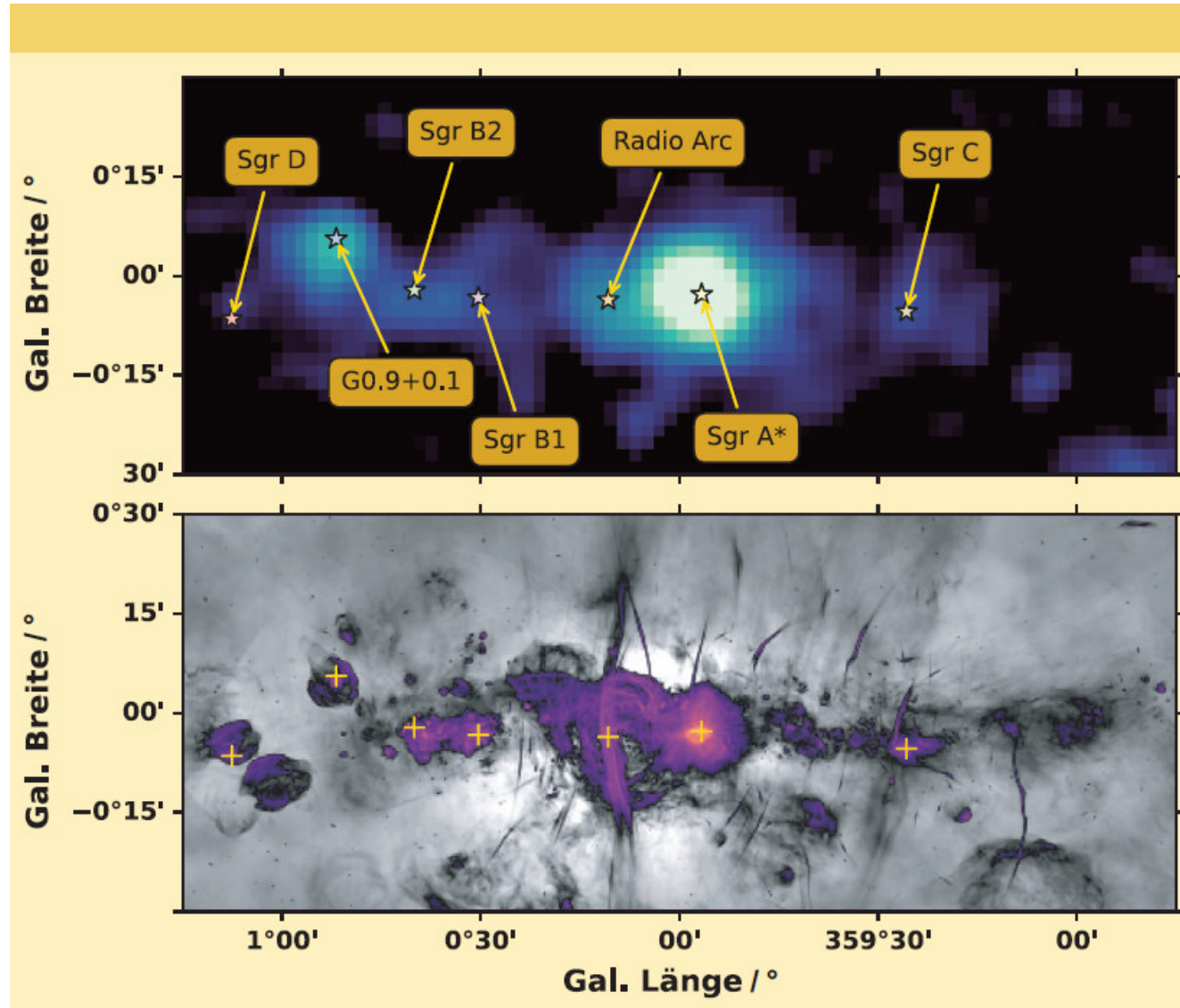
COMPLEX ENVIRONMENTS

Galactic Center

GALACTIC PLANE AT DIFFERENT WAVE LENGTHS



GALACTIC CENTER



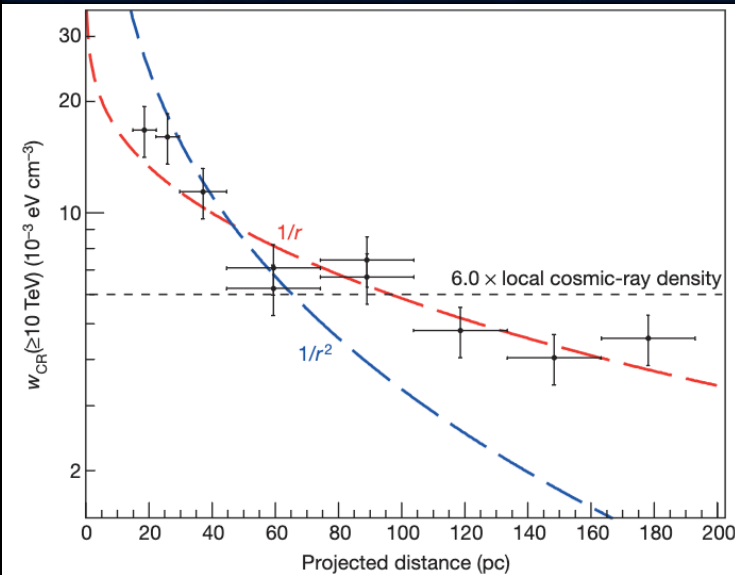
LST-1 γ -rays

MeerKAT radio

Galactic Center ridge: evidence for centrally injected hadronic cosmic rays

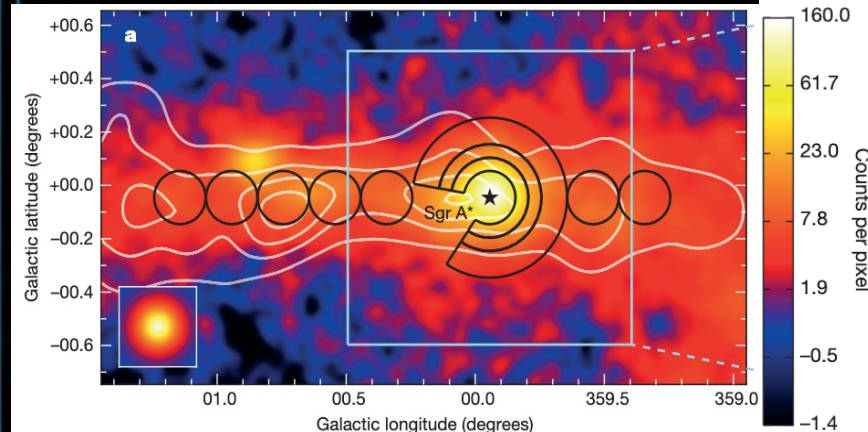
- **Diffuse TeV γ -rays** trace dense molecular gas in the central molecular zone (CMZ) $\rightarrow$ hadronic origin via pp interactions.
- **Inferred CR density profile** is centrally peaked and consistent with $w_{CR}(r) \propto 1/r$ $\rightarrow$ quasi-continuous injection from a source near Sgr A*.
- **Open question:** H.E.S.S. supports a PeVatron extending to $\sim$ PeV energies, while MAGIC and LST-1 report **hints of a cutoff/curvature at $\sim$ 20–30 TeV**.

1) CR density profile peaks toward GC (from H.E.S.S. 2016 Nature)



Best fit: $w_{CR}(r) \propto 1/r$
Consistent with continuous injection from a central source (e.g., Sgr A*)

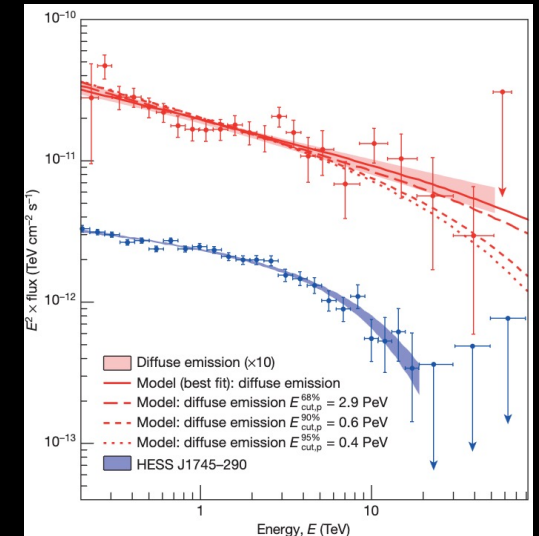
2) TeV γ -ray map follows molecular gas (H.E.S.S. 2016 Nature)



Diffuse TeV emission correlates with the distribution of dense molecular gas in the CMZ
 $\rightarrow$ strong evidence for a hadronic origin

CMZ = Central Molecular Zone

3) Diffuse γ -ray spectrum and cutoff (H.E.S.S. 2016; MAGIC 2020; LST-1 2025)



Status of the PeVatron claim

- **H.E.S.S.:** no clear cutoff $\rightarrow$ protons up to $\sim$ PeV
- **MAGIC:** $\sim 2\sigma$ cutoff hint at $\sim 20 \text{ TeV}$
- **LST-1:** 2.8σ cutoff hint at $\sim 30 \text{ TeV}$



Takeaway: All three studies support a **hadronic CR population** injected from the inner GC, with a **central $1/r$ profile**. The main debate now is whether the spectrum **extends unbroken to PeV energies**.

SUMMARY: GALACTIC GAMMA-RAY ASTROPHYSICS

The Milky Way is a laboratory of extreme particle acceleration and non-thermal processes.

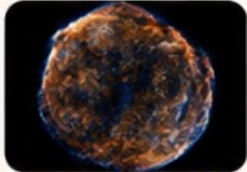
GALACTIC GAMMA-RAY SOURCES: THE MAIN ENGINES



ROTATION-POWERED

Pulsars, Pulsar Wind Nebulae (PWNe),
TeV halos

► Magnetospheric emission and relativistic winds



EXPLOSION-POWERED

Supernova Remnants (SNRs), PeVatrons

► Shocks accelerate protons to very high energies;
hadronic and leptonic gamma rays



ACCRETION / WIND-INTERACTION

Gamma-ray binaries, Microquasars, X-ray binaries

► Particle acceleration in jets, coronae and colliding winds



MAGNETIC-POWERED

Magnetars, Giant flares

► Magnetic energy release powering high-energy
transients



COMPLEX ENVIRONMENTS

Galactic Centre (CMZ), Diffuse Galactic emission

► Dense gas and radiation fields reveal cosmic-ray
interactions on large scales

WHAT DO GAMMA RAYS TELL US?



WHERE ARE PARTICLES ACCELERATED?

Magnetospheres, winds, shocks, binary
interactions, or extreme environments.



WHAT IS THE DOMINANT RADIATION PROCESS?

Synchrotron and inverse Compton (leptons) vs.
hadronic interactions and π^0 -decay (hadrons).



PULSED OR STEADY EMISSION?

Probing magnetospheric gaps, pulsar winds,
and long-term particle acceleration.



HOW DO PARTICLES ESCAPE AND PROPAGATE?

From sources to the interstellar medium,
forming halos and diffuse emission.



WHAT IS THE MAXIMUM ENERGY?

From GeV to TeV and up to PeV energies –
clues to the origin of Galactic cosmic rays.



Galactic gamma-ray astronomy connects compact objects, stellar explosions, magnetic activity and cosmic-ray origin in our own Galaxy.



THANK YOU

95