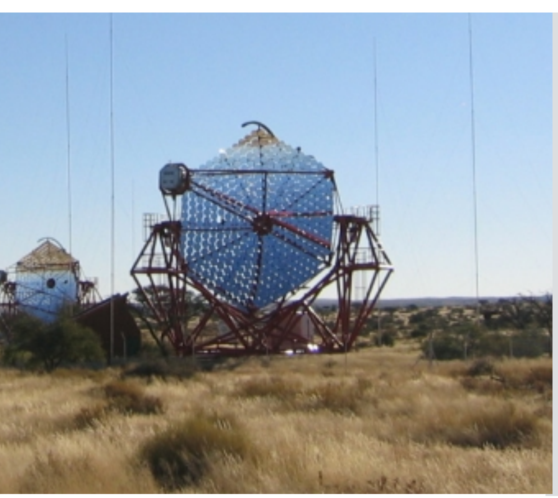
Cosmic (Particle) Accelerators I

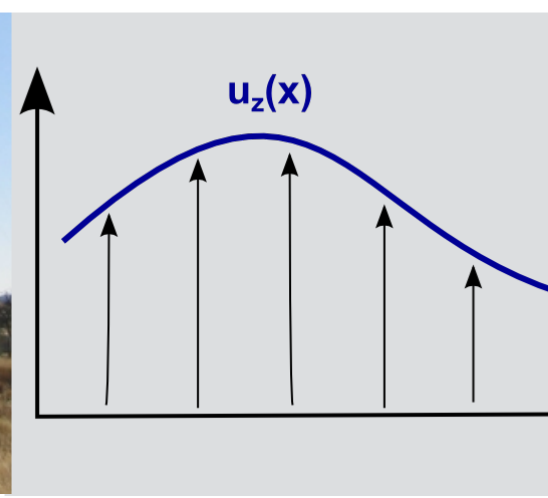
- **Sources** & Mechanisms -

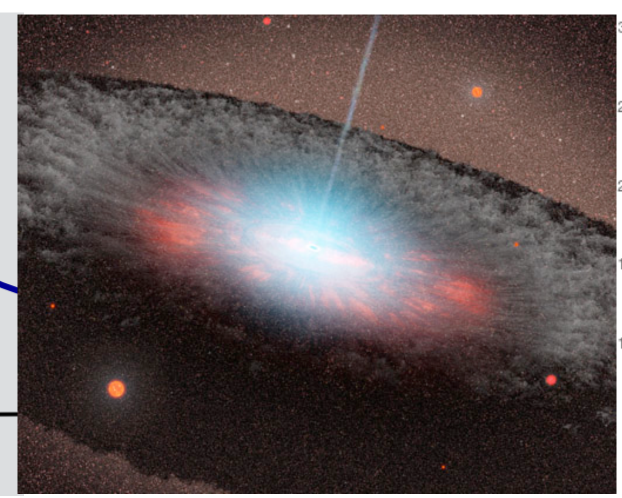
Frank M. Rieger

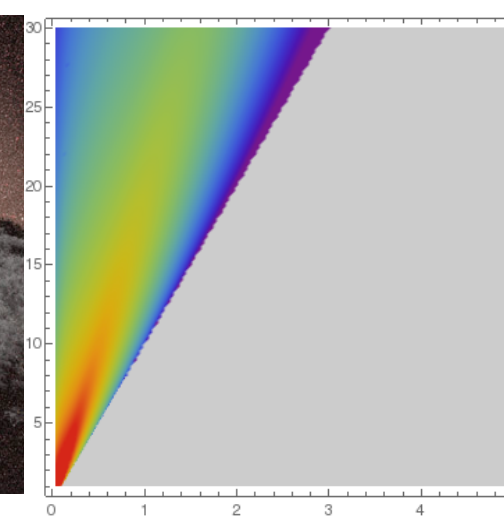
ISAPP School

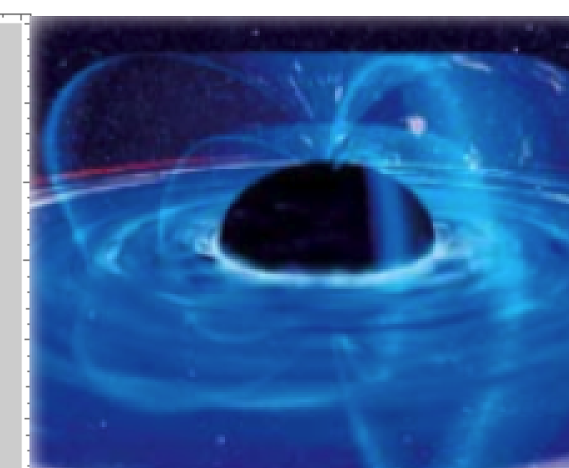
Heidelberg, May 28, 2019











ITA Univ. Heidelberg

Heisenberg-Programm
DFG Deutsche Forschungsgemeinschaft

Max Planck Institut für Kernphysik
Heidelberg, Germany

Outline

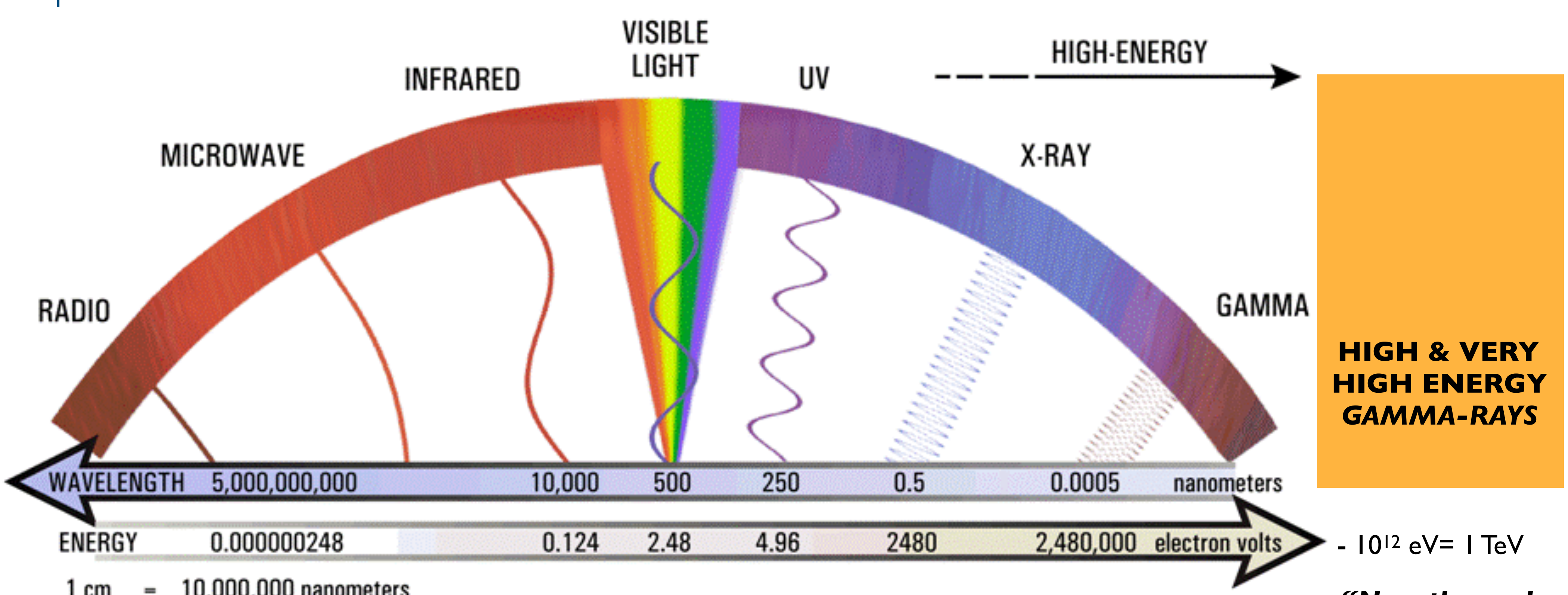
- Introduction & Generalities
- Progress in Gamma-Ray Astronomy
- Cosmic Particle Accelerators
  - Astrophysical VHE sources (classes)
  - Prototypical experimental results
  - Basics Physics
- Summary

Generalities

High Energy Particles & Radiation

- *Non-thermal Universe* regime: $\varepsilon \gg kT \sim 2 \times 10^5$ (T / 10^9 K) eV (thermal black body, Planck), particle distributions not Maxwellian, but e.g. power-laws (no characteristic scale)…
- Electromagnetic spectrum: Photon energies from X- up to γ-ray energies.
- Charged particles with energies up to $\sim 10^{20}$ eV (Cosmic Ray Spectrum).
- X-rays: 0.1-100 keV, *HE* γ-rays $\geqq$ 50 MeV, *VHE* γ-rays $\geqq$ 100 GeV.
- Note: 1 eV [SI]= 1.6 x 10^{12} erg [cgs]; 1 eV = h = h (2.4 x 10^{14} Hz).

  1 pc $\simeq 3 \times 10^{18}$ cm



Electromagnetic Spectrum - Photon Energies

"Non-thermal Universe"

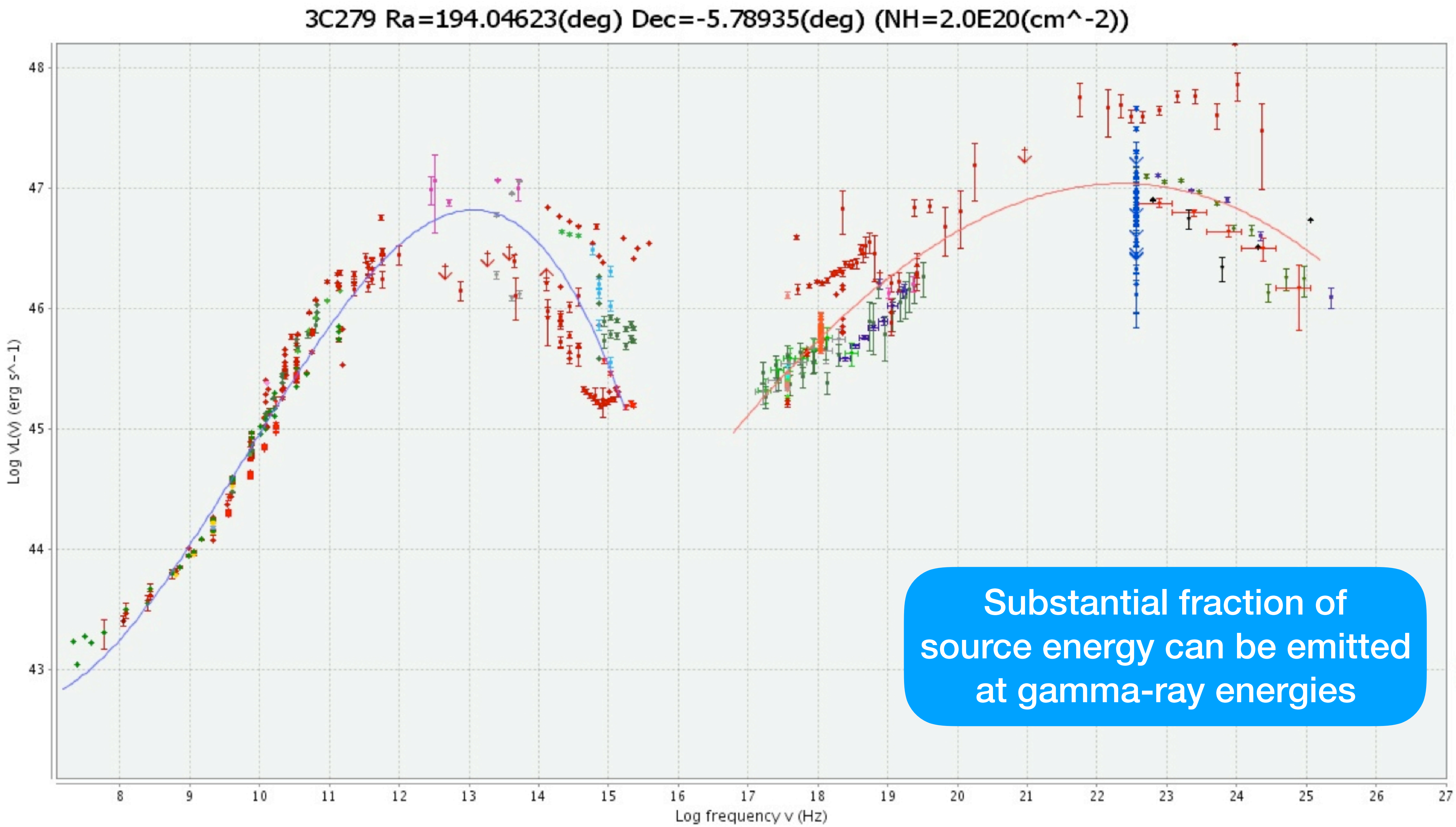
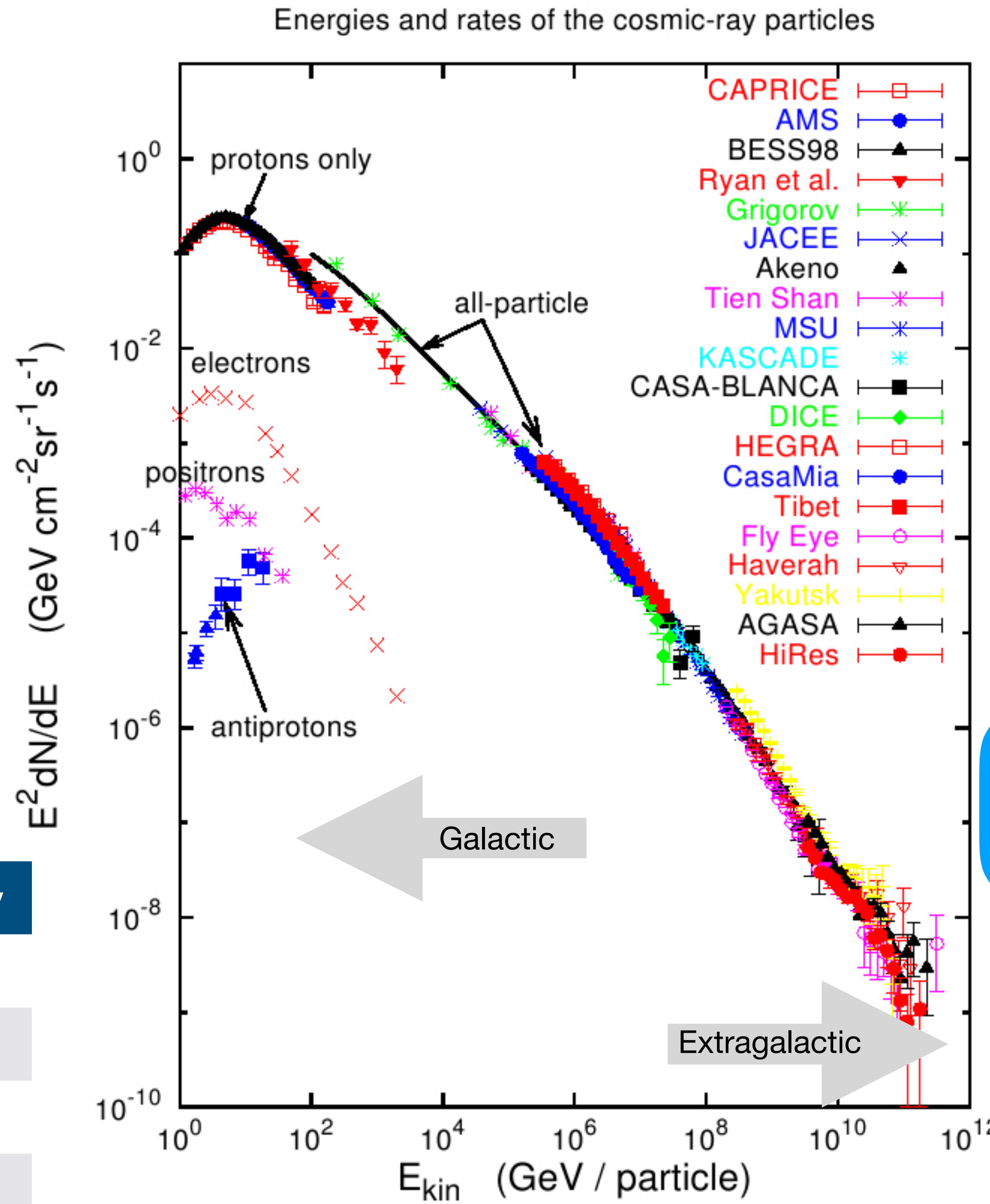


Figure 2: Example: Electromagnetic radiation (photon energy distribution) seen from an Active Galaxy (3C279, $z = 0.54$) as a function of frequency [Credits: ASDC].

Cosmic Ray Spectrum

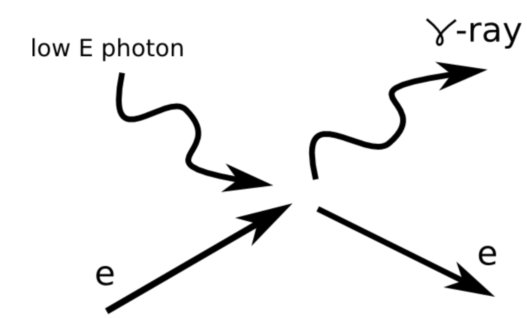


	Energy density
Cosmic Rays	1 eV / cm^3
CMB	0.3 eV / cm^3
Starlight	0.1 eV / cm^3
Magnetic fields	1 eV / cm^3

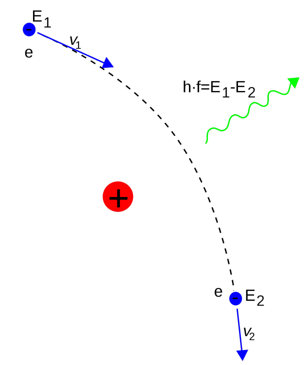
Charged particles accelerated to >10^{20} eV

Gamma-Ray Production Mechanisms

- ***electron** inverse-Compton (soft photon field):*
  - $h\nu \sim \gamma^2 h\nu_s$ (Thomson), $h\nu \sim \gamma_e m_e c^2$ (KN)

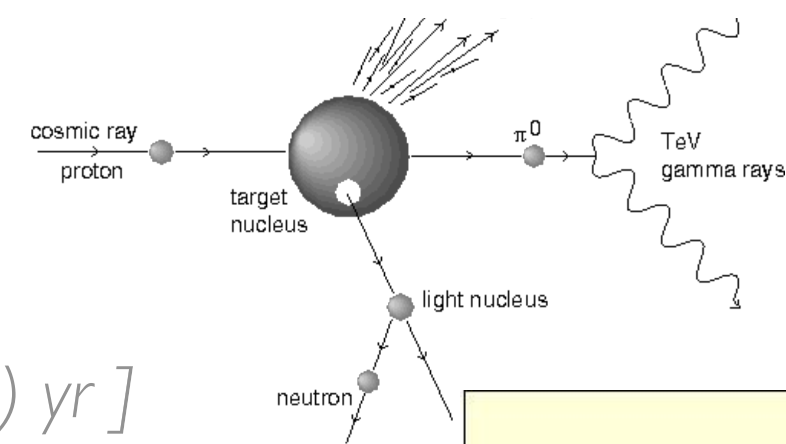


- ***relativistic electron bremsstrahlung:***
  - $h\nu \sim (1/3)\,\gamma_e m_e c^2$, *[$t_{br} \sim 10^7$ ($1\ cm^{-3}$ / n) yr]*



- ***proton synchrotron:***
  - $\nu_c \sim 10^6\,(m_e/m)\,\gamma^2\,B$ [Hz] , *[$t_{syn} \sim 10^{11}$ / ($\gamma\ B^2$) yr]*

- ***proton-proton interactions*** (ambient matter):
  - e.g., $p + p \rightarrow p + p + \pi^0$, $\pi^0 \rightarrow 2\gamma$
  - mean energy $\varepsilon_\gamma \sim 0.1\ E_p$, *[$t_{pp} \sim 10^8$ ($1\ cm^{-3}$ / n) yr]*



- ***proton-photon interaction*** (soft photon field):
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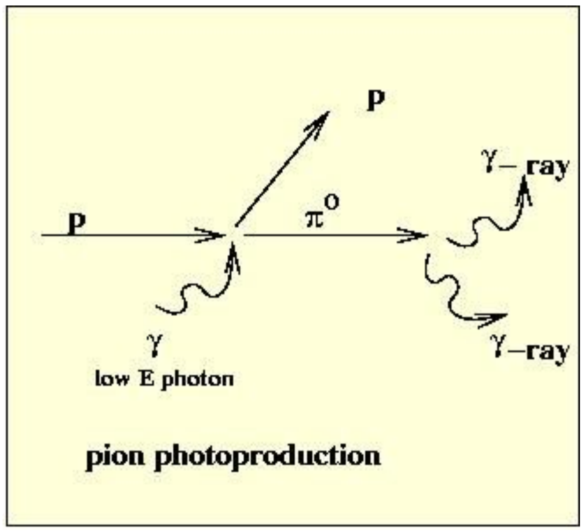


In "summary"

Need sources & acceleration mechanisms facilitating production of

- ultra-high energy (UHE) CRs, e.g. up to $\gamma_p \sim 10^{11}$ (proton $E_p = 10^{20}$ eV),
- $>$ 10 TeV gamma-rays, e.g. up to $\gamma_e \gtrsim 10\,\text{TeV} / m_e c^2 \sim 10^7$ (IC-KN)

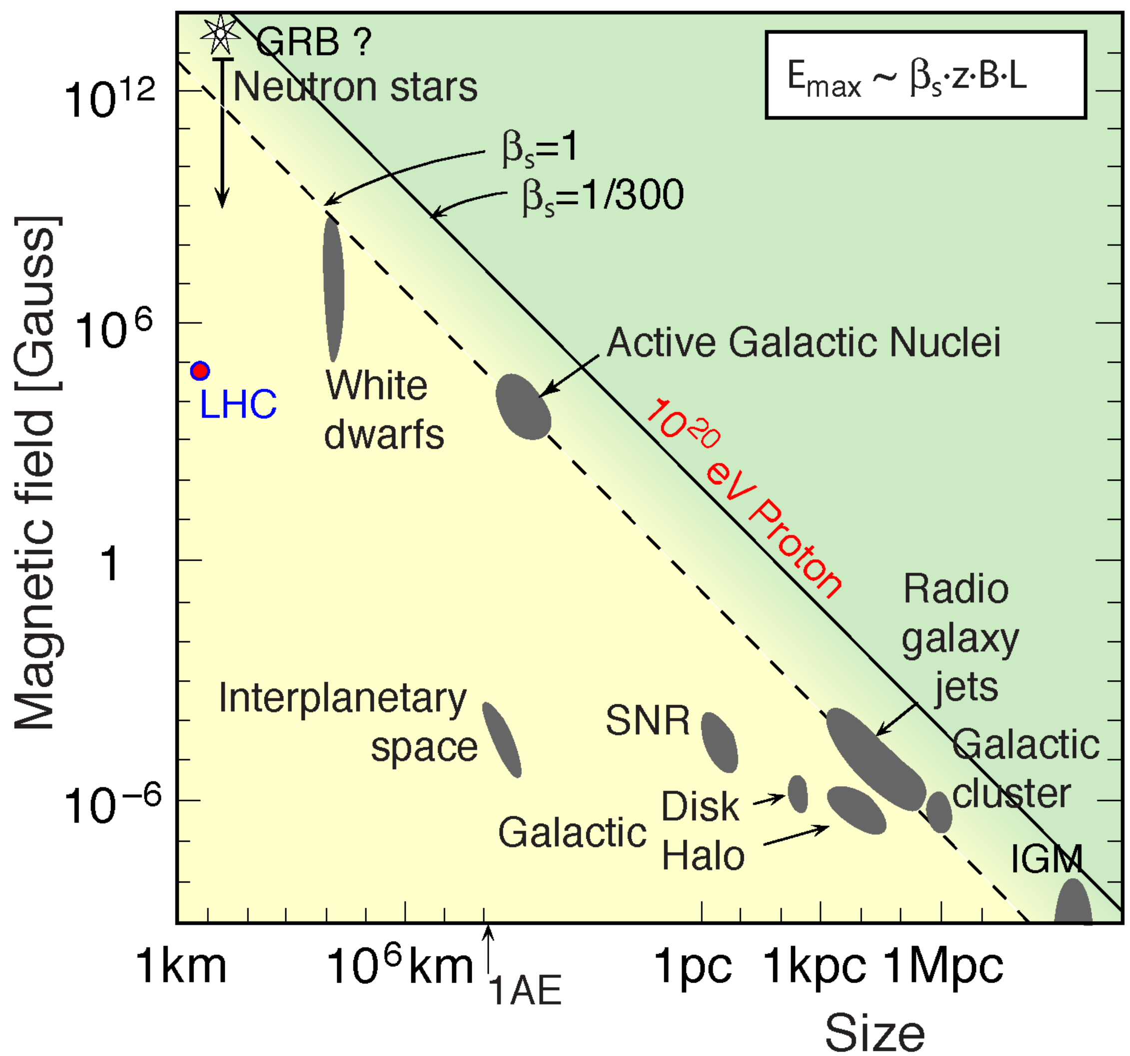
Confinement limit for UHE protons ("Hillas plot"): $E_{,CR} \sim \underbrace{(v \times B)}_{\text{E-field}}\, q\, L$:

Hillas (1984)

UHE cosmic ray acceleration requires:

* very large magnetic fields,

* or very large sizes



Progress in Gamma-Ray Astronomy

Example: How to measure HE and VHE gamma-rays?

Fermi/LAT (2008-)

*High energy (**HE**) photons > 50 MeV*

- Direct detection in space ("small" area), always active
- Pair production in detector (gamma-ray conversion in thin lead foils) & calorimeter

IACT/HE.S.S., MAGIC… (2004-)

*very high energy (**VHE**) photons > 100 GeV*

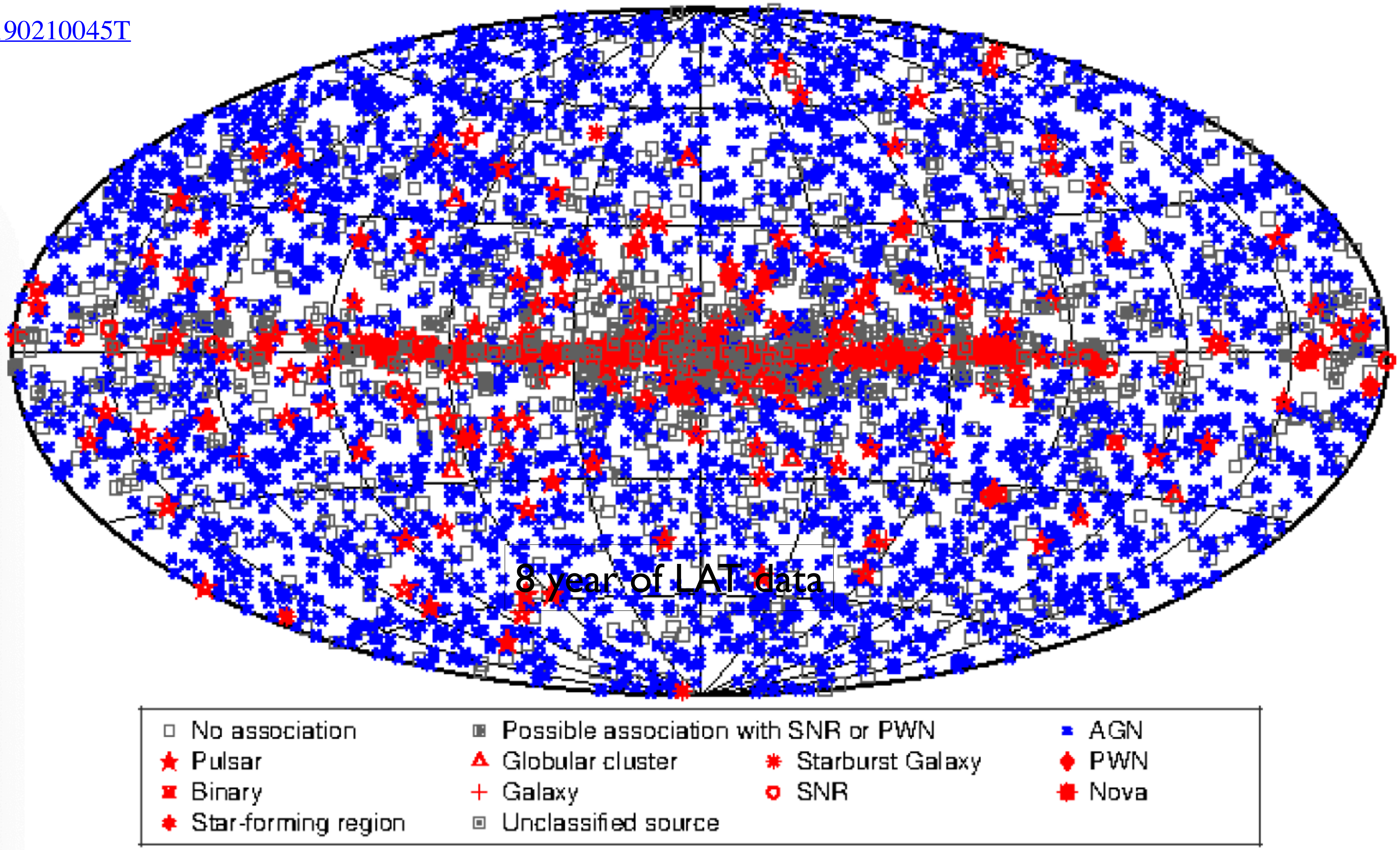
- Need huge collection areas as flux is weak, so ground-based strategy
- indirect (Cherenkov) technique: Particle cascade created by a VHE photon in atmosphere, with blue Cherenkov light beamed towards telescopes

Developments in **HE** Gamma-Ray Astronomy

4th Fermi LAT catalog (4FGL) > 50 MeV

Fermi-LAT Collab 2019

2019arXiv190210045T



Developments in **HE** Gamma-Ray Astronomy

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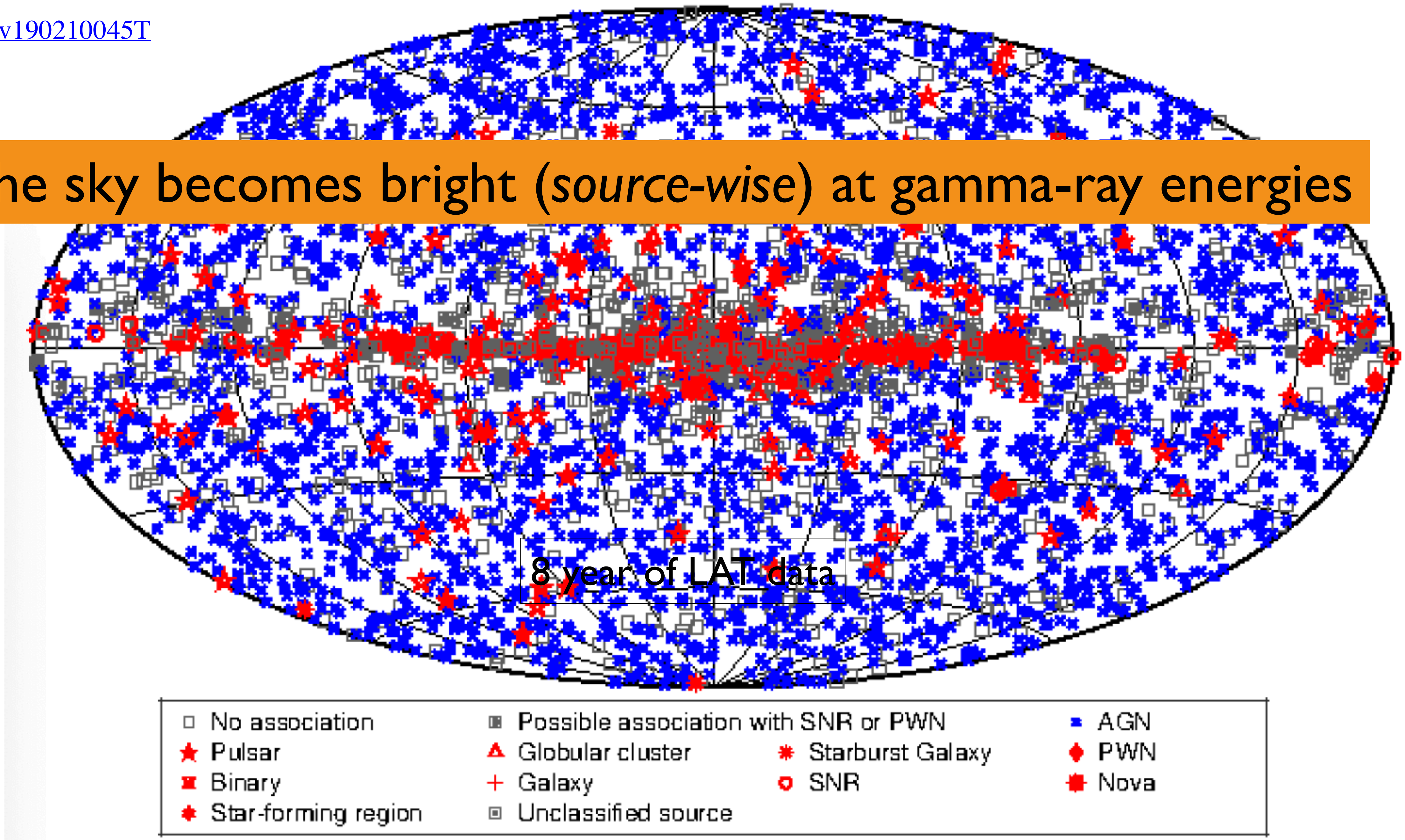
Fermi-LAT Collab 2019
2019arXiv190210045T

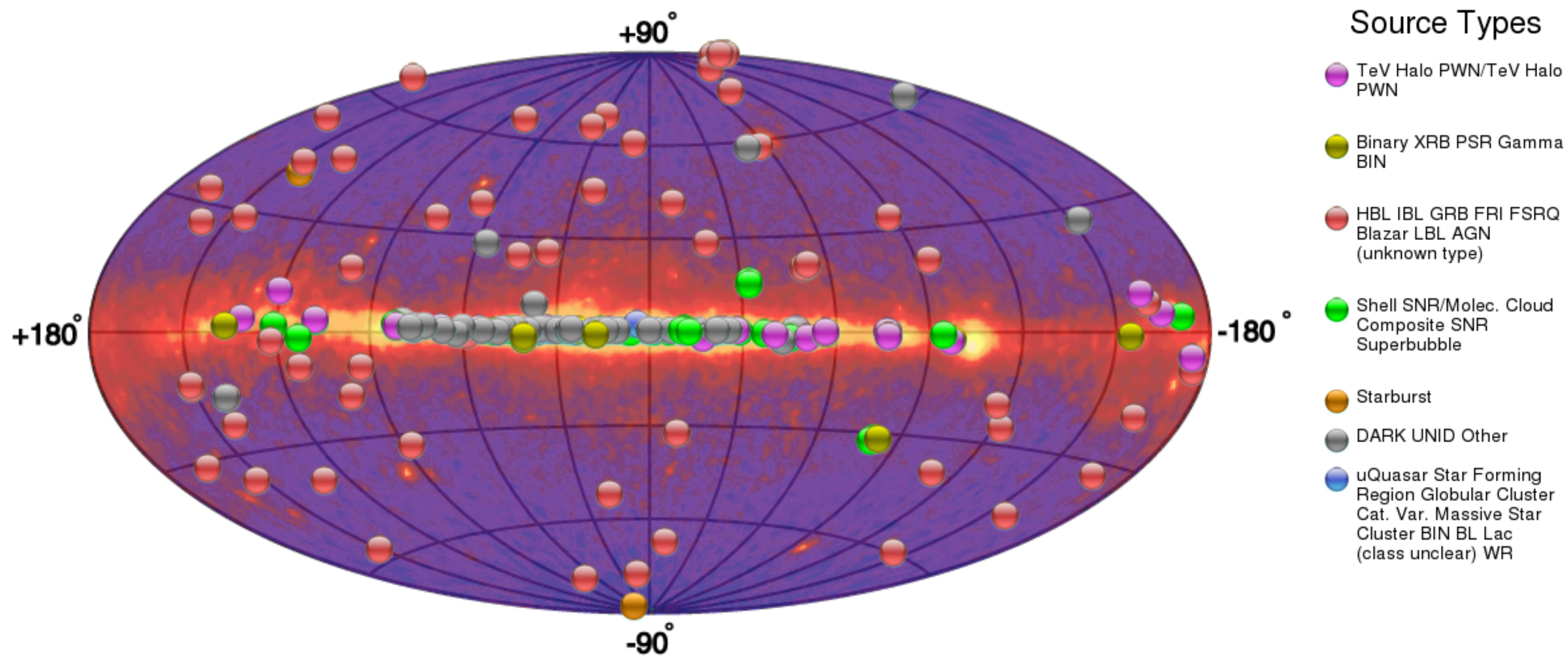
The sky becomes bright (*source-wise*) at gamma-ray energies



4FGL (preliminary): 5098 sources out of which
> 2940 identified as AGN / blazars, 241 as pulsars, 40 SNR…

Developments in **VHE** Gamma-Ray Astronomy

TeVCat (2019):
>200 sources
(~ 75 AGN)



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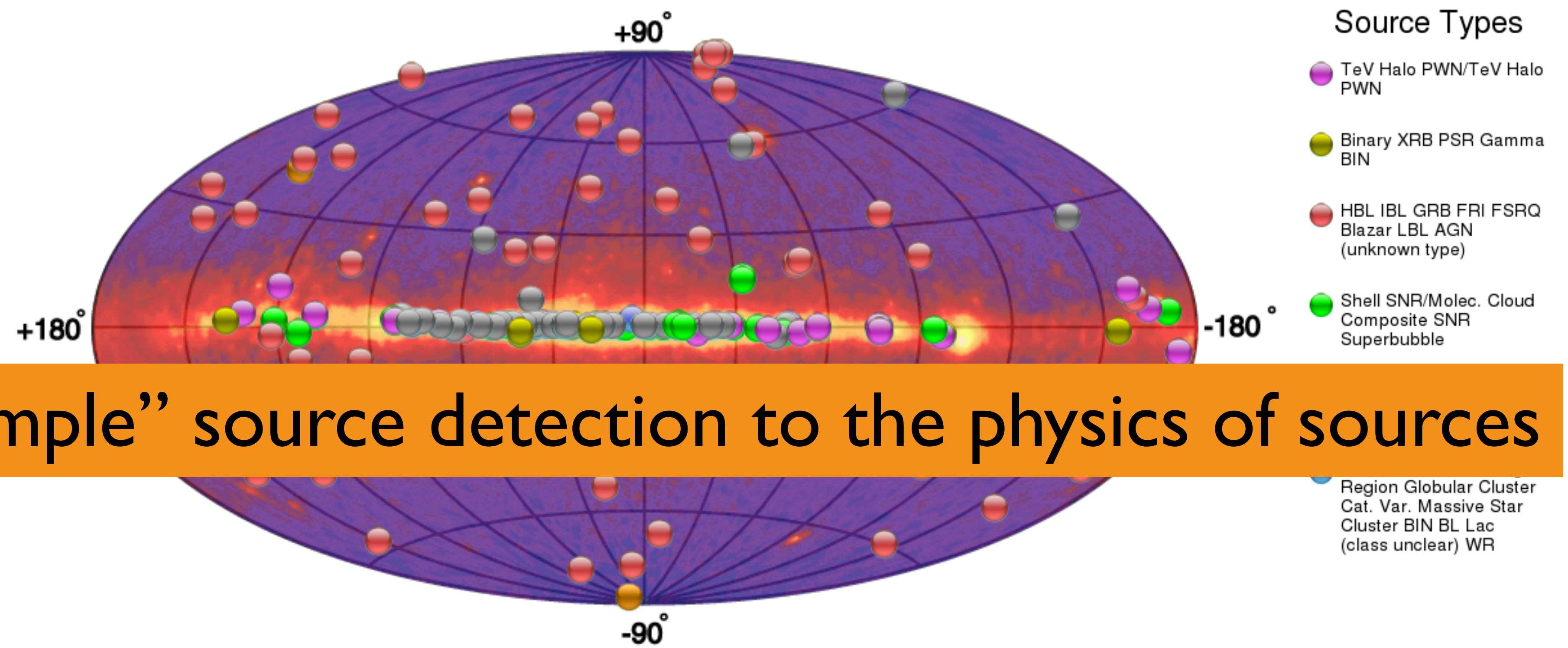

From “simple” source detection to the physics of sources

Developments in **VHE** Gamma-Ray Astronomy

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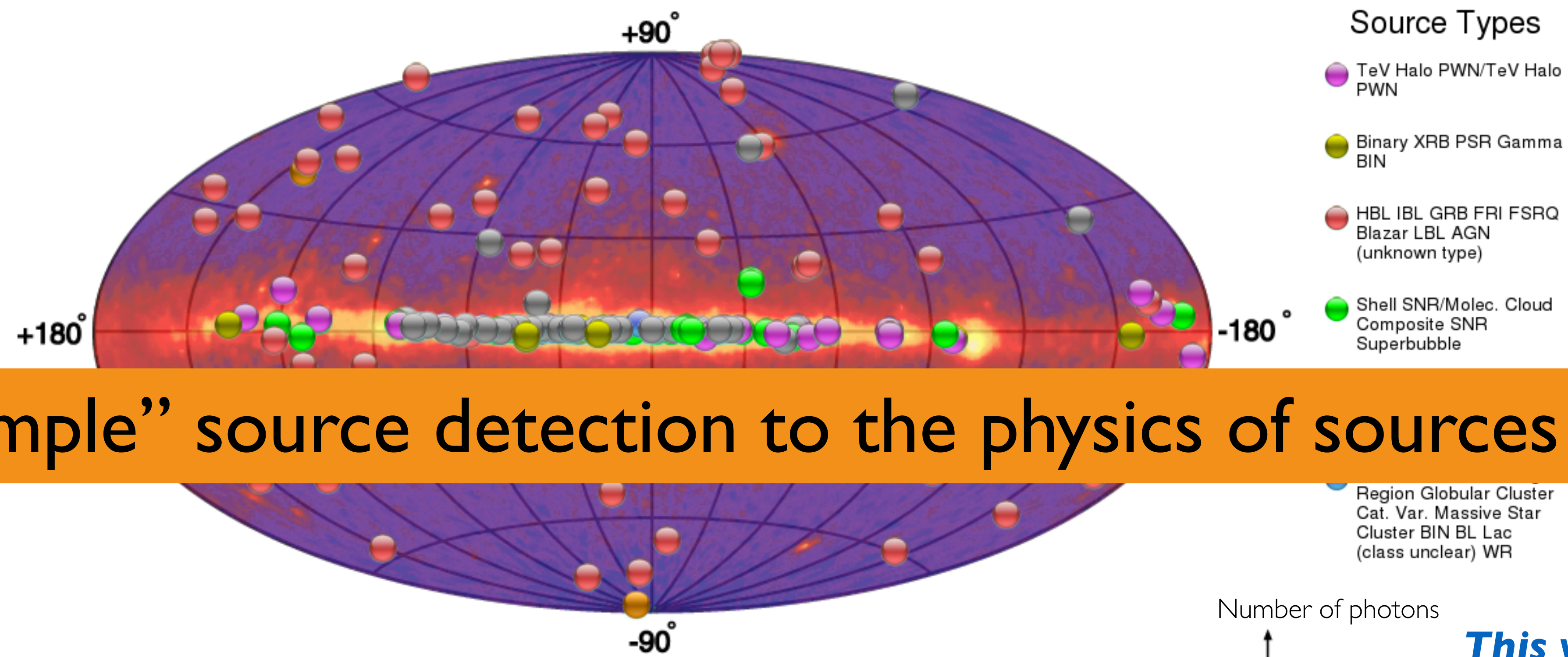

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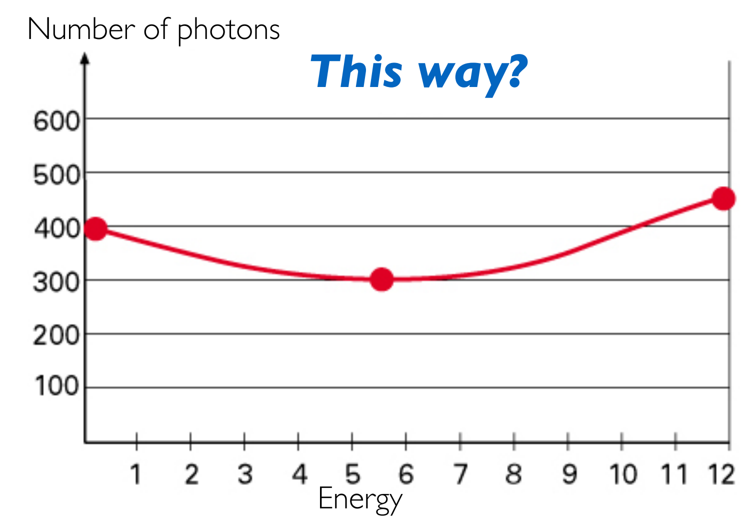

Spectral (photon) distribution

smoothness, curvature, breaks, measurement precision….

⇨ maximum particle energy, emission process…

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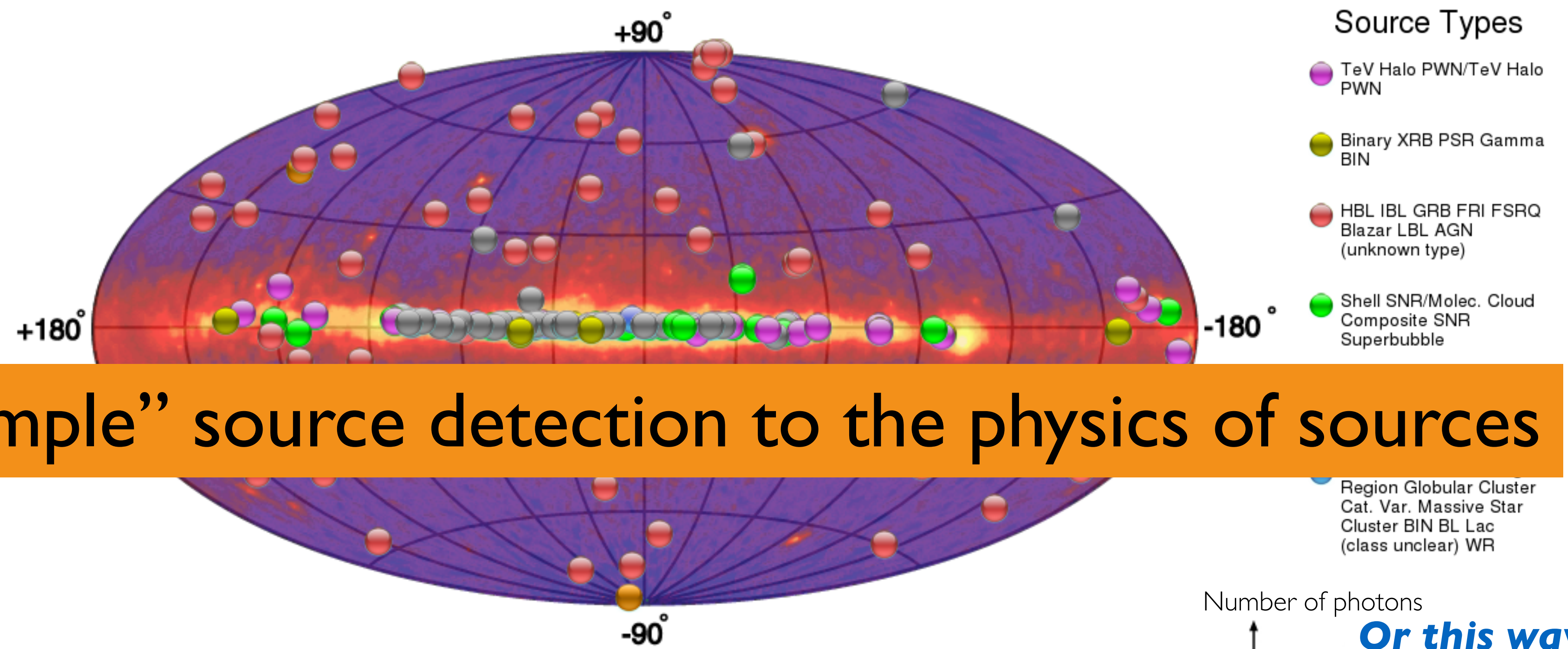

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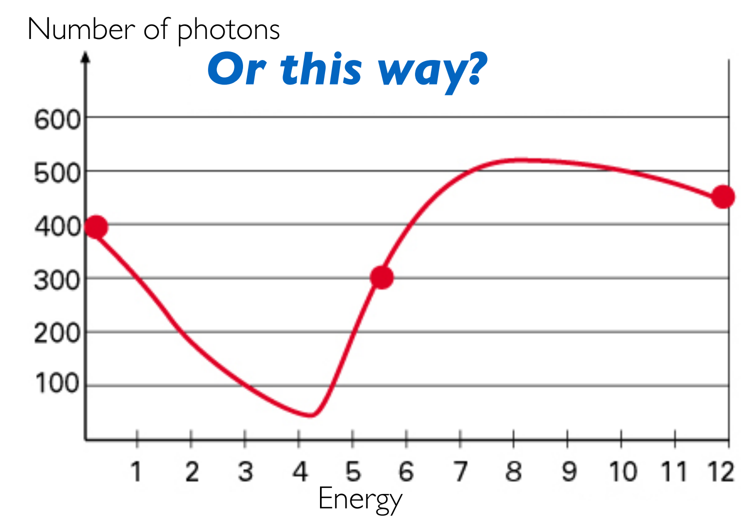

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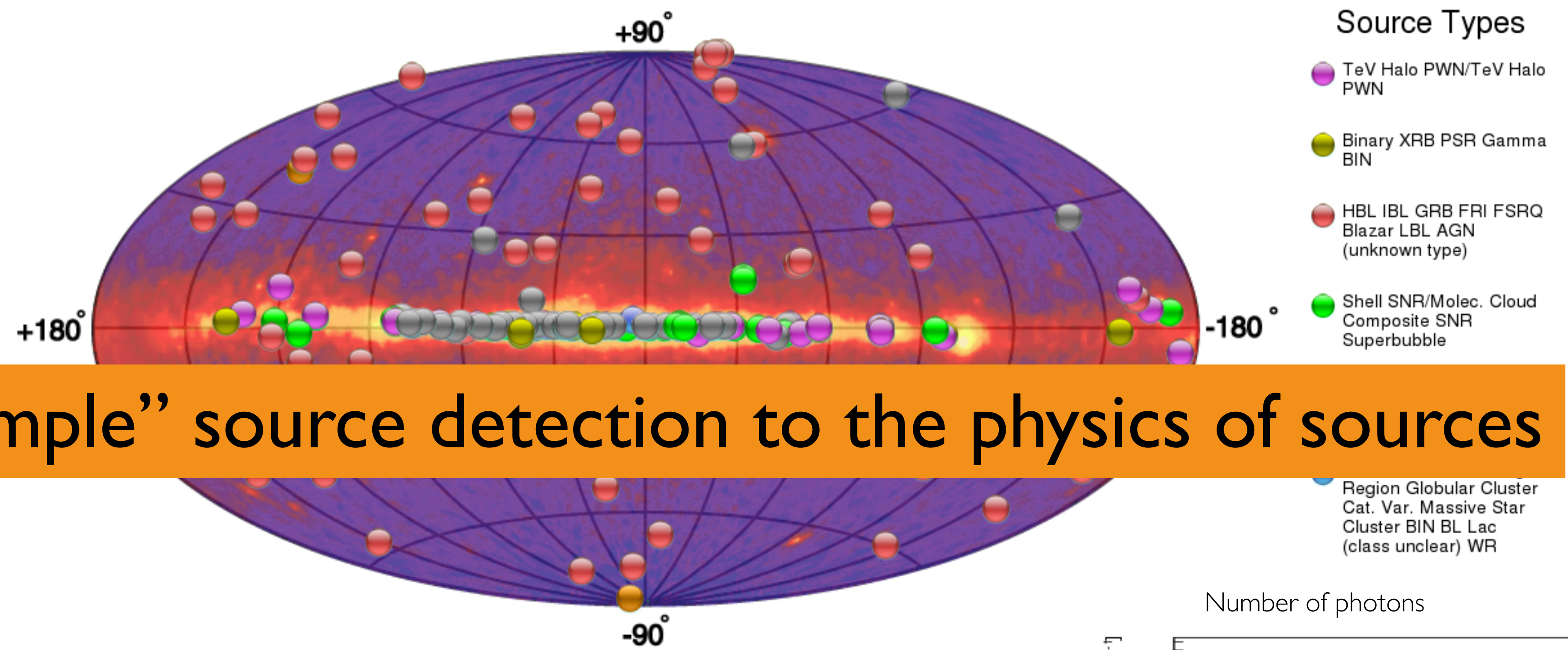

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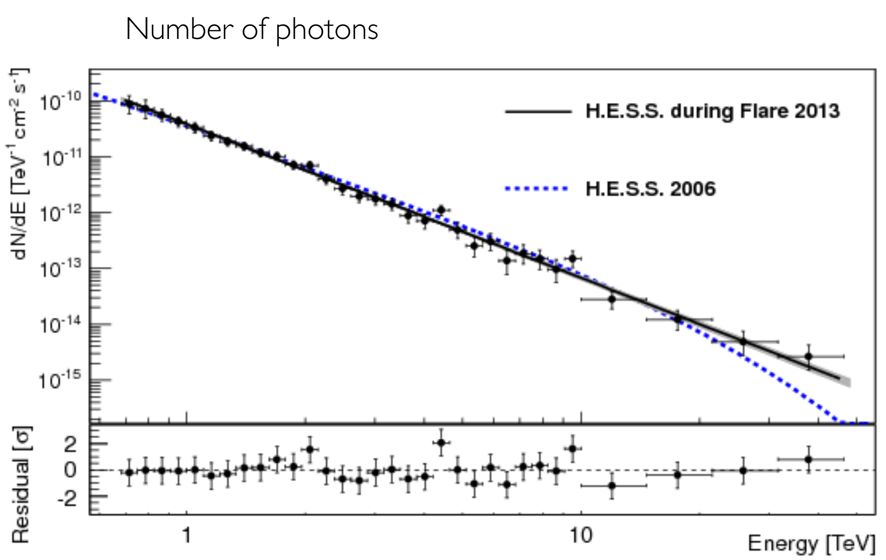

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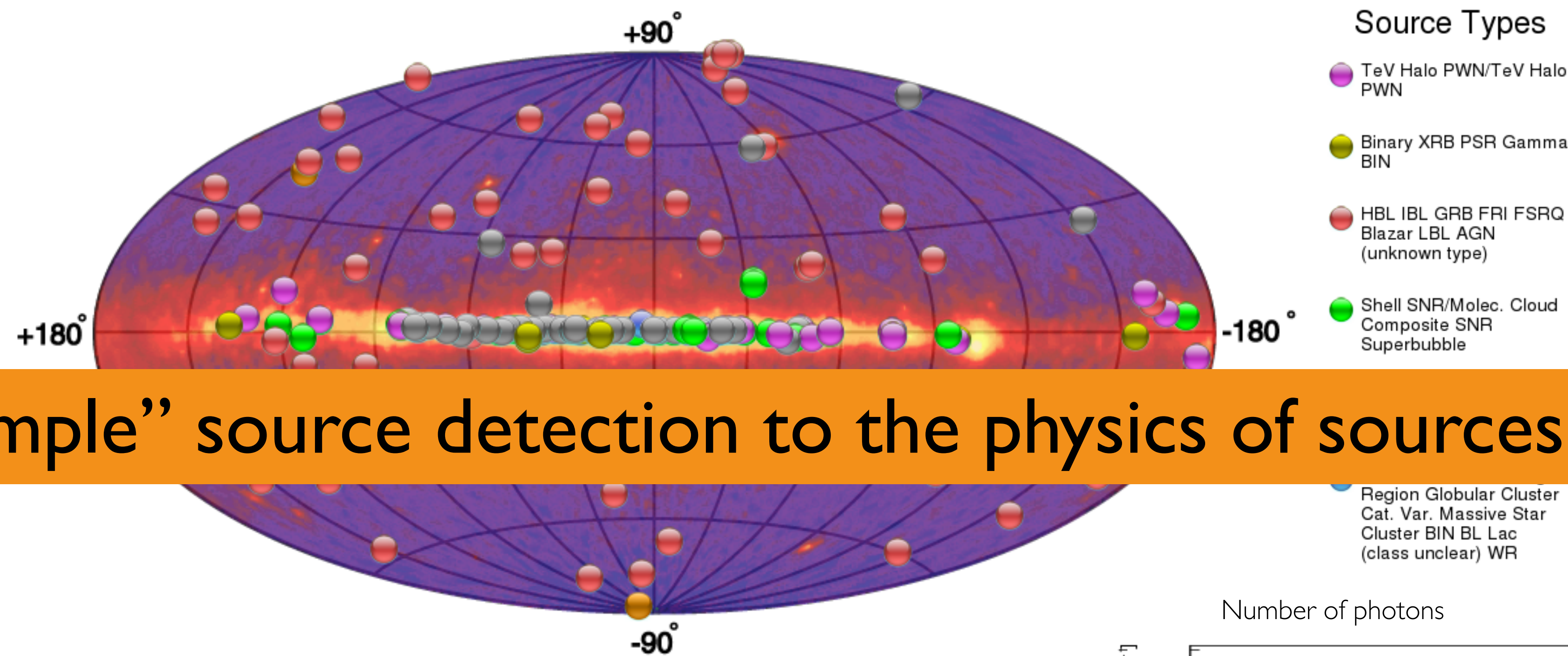

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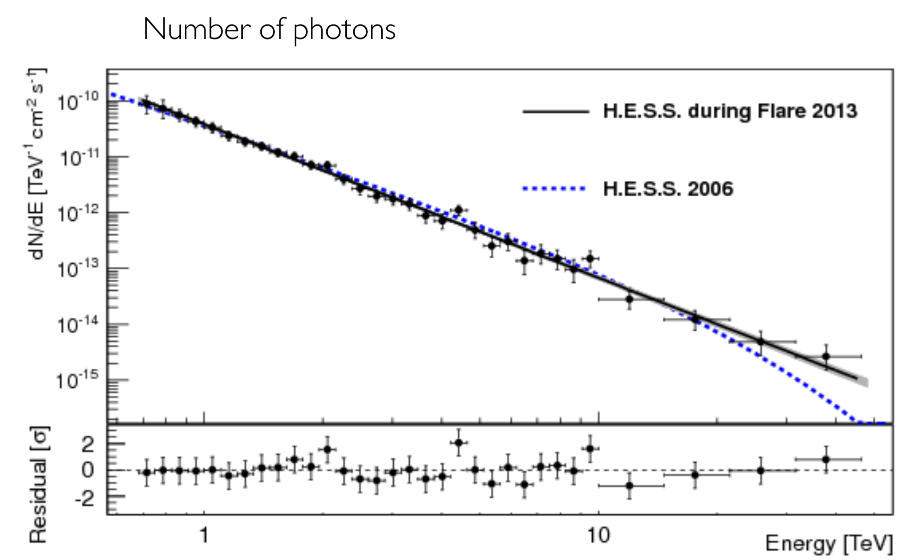


Spectral (photon) distribution

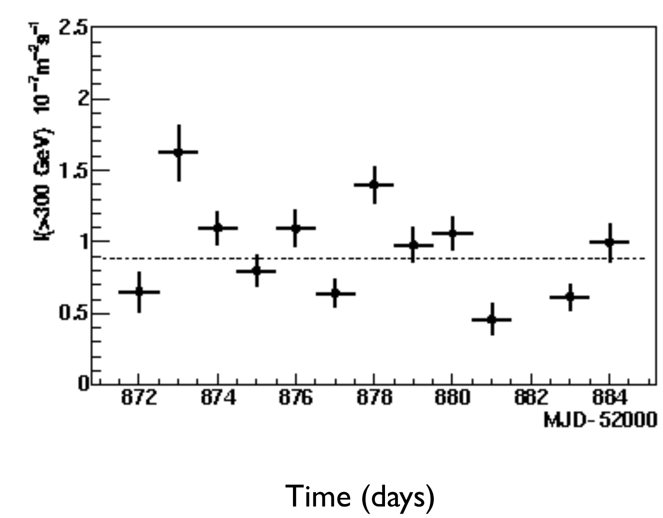
smoothness, curvature, breaks, measurement precision....

⇨ maximum particle energy, emission process...

Timing capabilities (light curves)

Variability, outbursts/active states, regularities....

⇨ timescales, physical triggers, location, geometry...



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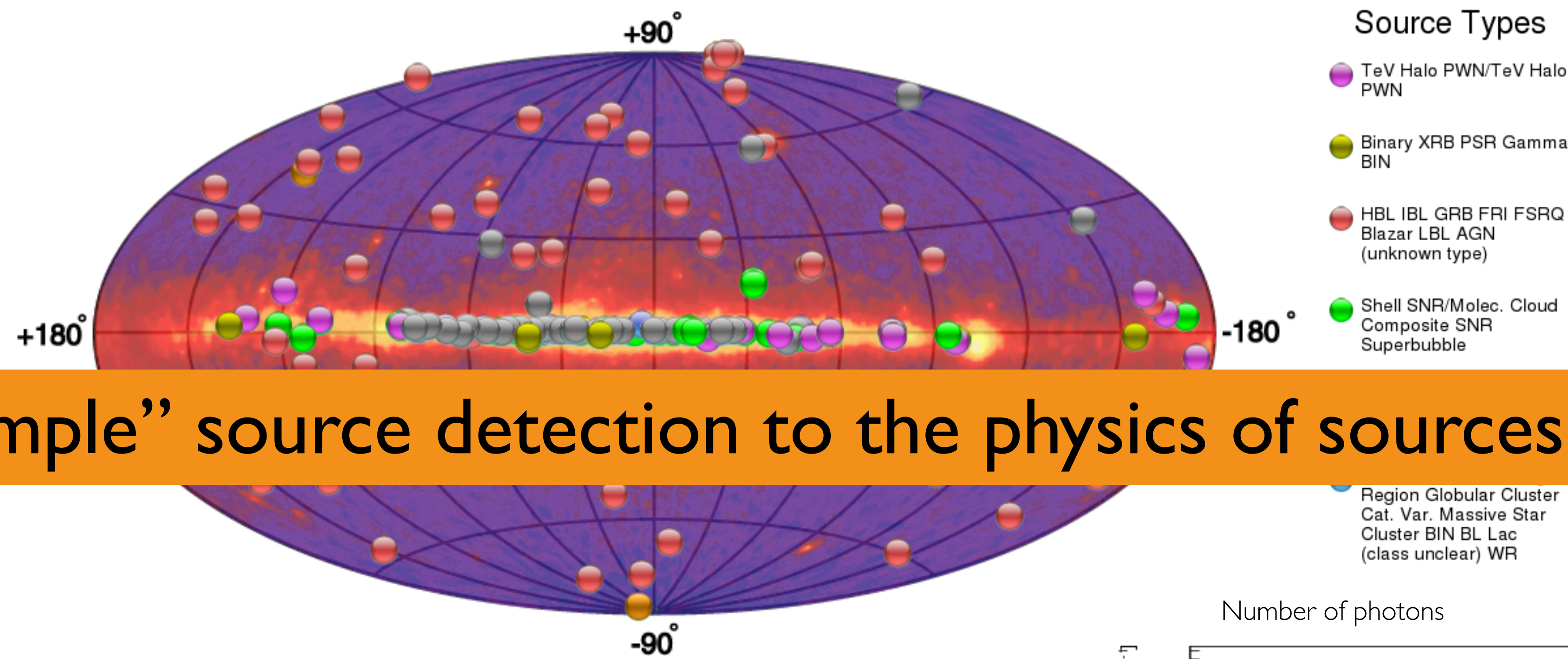
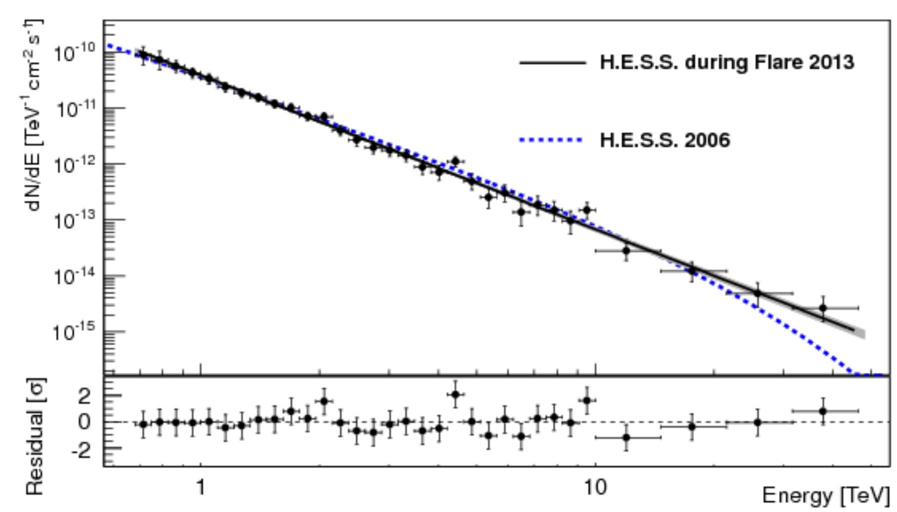


From "simple" source detection to the physics of sources

Number of photons



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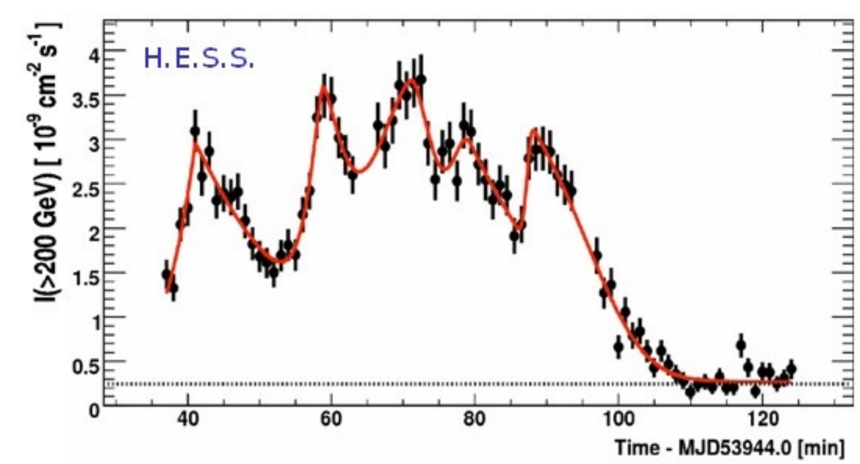
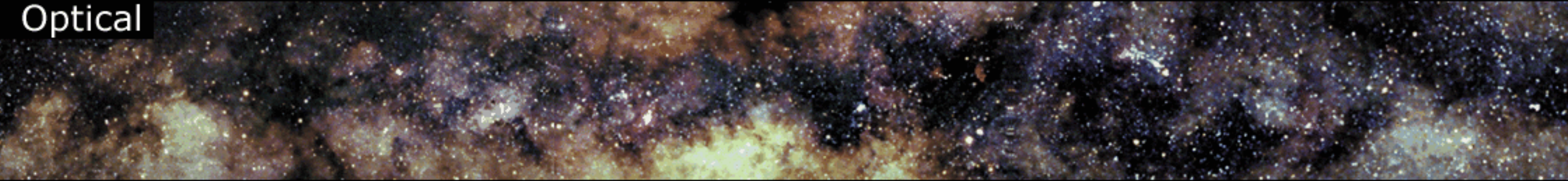
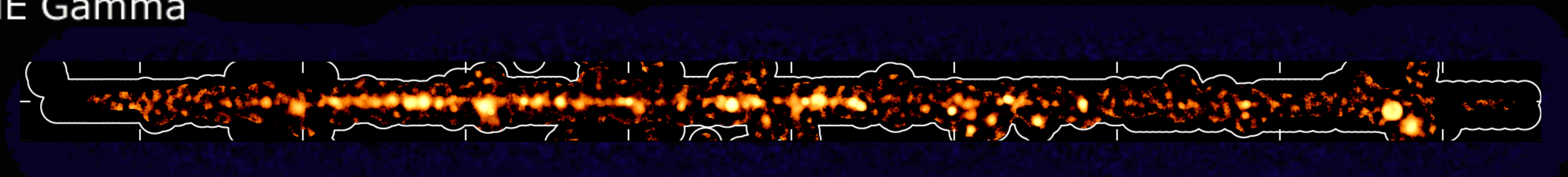


Time (minutes)



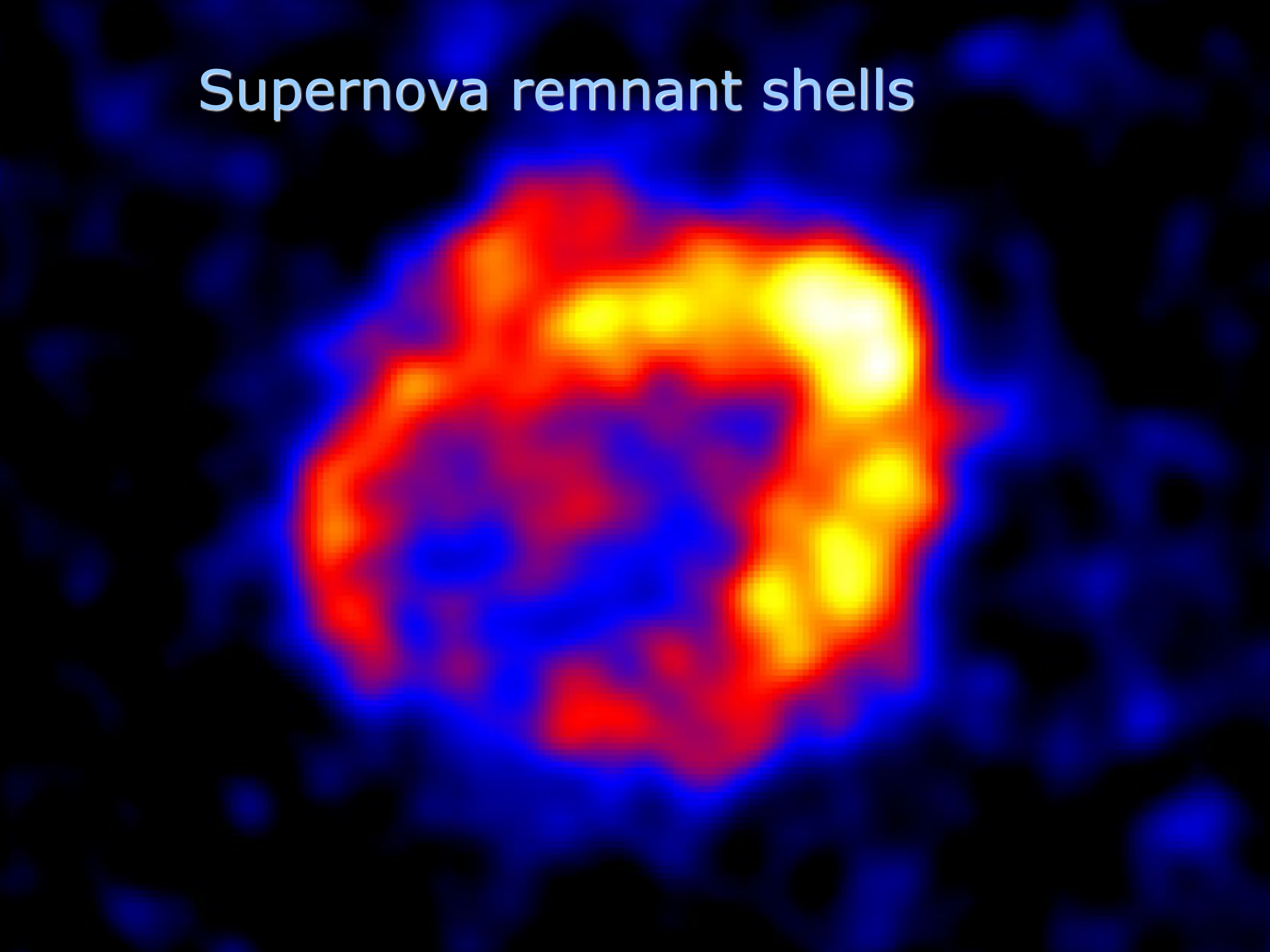


H.E.S.S. Galactic Plane Survey (flux > 1 TeV)

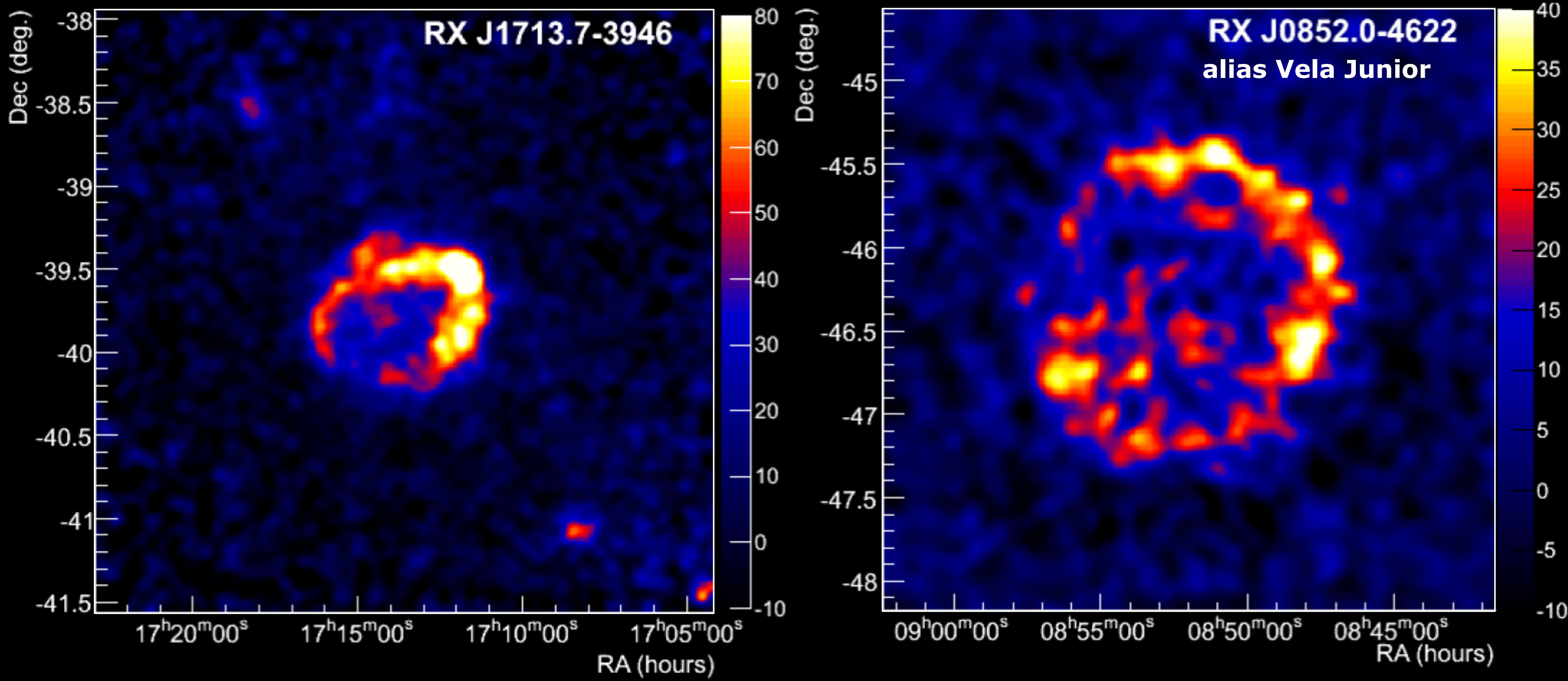
Galactic particle accelerators:

- Supernova remnants
- Pulsars
- Pulsar Wind Nebulae
- Binaries
- Galactic center (BH?)

Supernova remnant shells



Supernova remnant shells

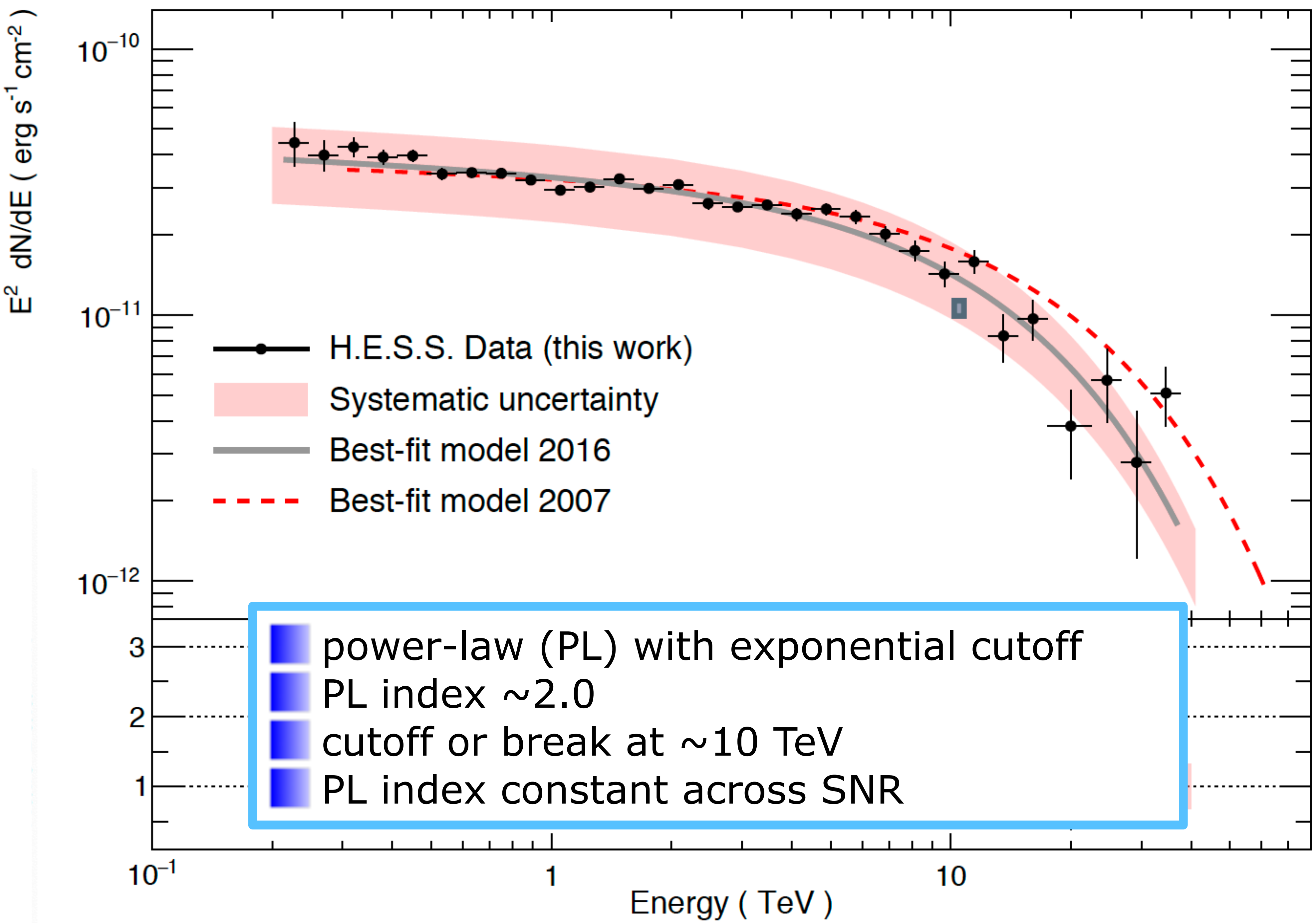


HESS Collab., 2007a,b

SNR - RXJ 1713.7-3946

(distance ~ 1 kpc, size ≃ 20 pc , age ~ 1 kyr)

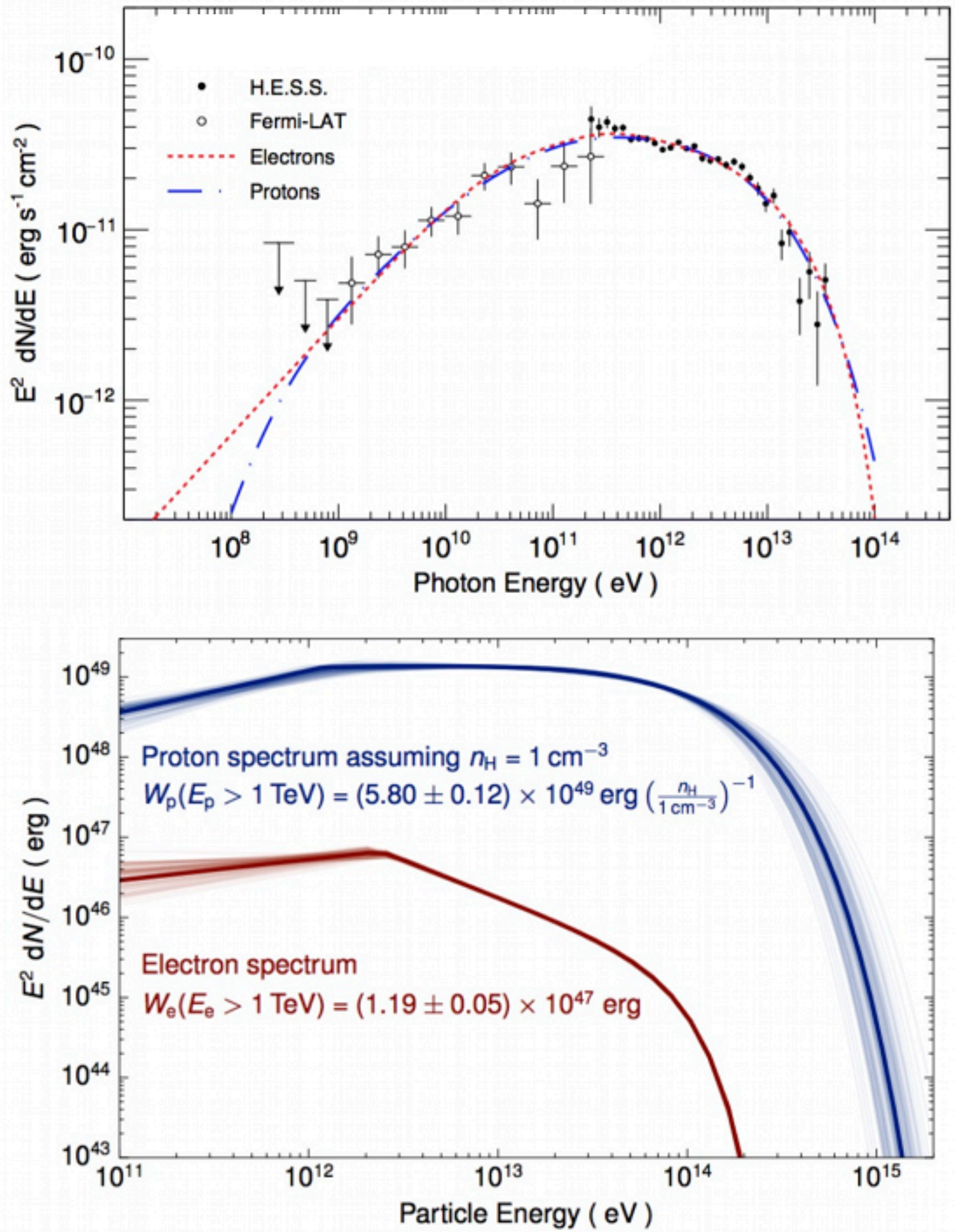
Particle acceleration to beyond ~100 TeV



- power-law (PL) with exponential cutoff
- PL index ~2.0
- cutoff or break at ~10 TeV
- PL index constant across SNR

HESS Collab., 2018

Could see emission from accelerated **electrons** (IC), and/or **protons** (pp).

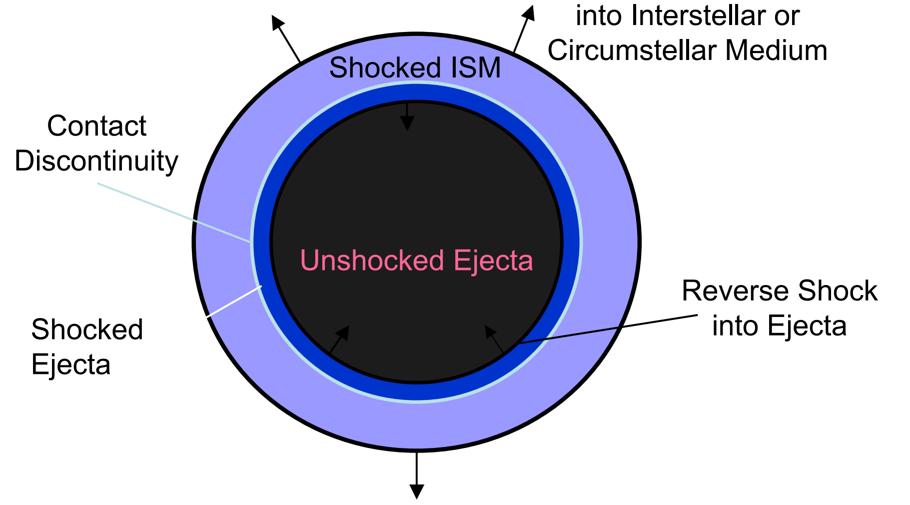


HESS Collab., 2018

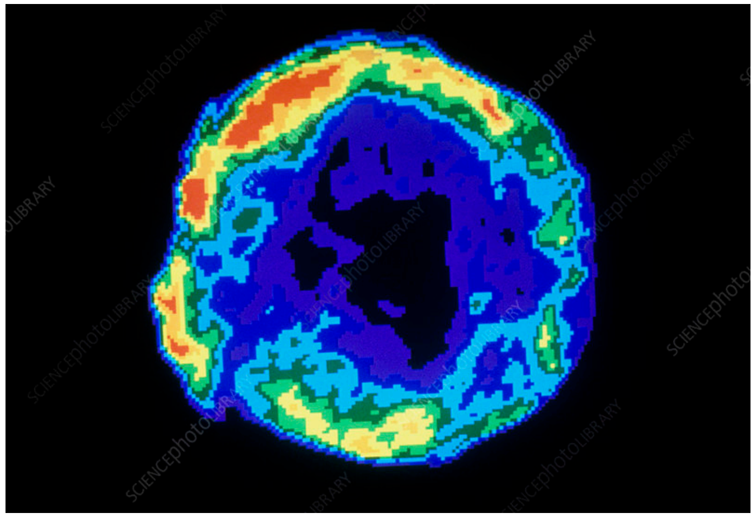
Basic Physics Sheet - Supernova (SN)

- Core-collapse or thermonuclear explosion of star
- kinetic energy of SN ejecta $E_{kin} \sim 10^{51}$ erg
- ejected mass $M_{ej} \sim (1\text{-}10)\ M_\odot$
- initial (free) expansion speed of ejecta:
  - $v_{ej} \sim (2\ E_{kin} / M_{ej})^{1/2} \sim 10^4\ (E_{kin} / 10^{51}\ \mathrm{erg})^{1/2}\ (M_\odot / M_{ej})^{1/2}$ km/s
  - free expansion $R_s(t) = v_{ej}\ t$
  - radio synchrotron radiation (GeV electrons, $B \sim 10^{-4}$ G)…
- free expansion ends when swept-up mass = ejected mass
  - $(4\pi/3)\ R_{SW}^3\ \rho_{ISM} = M_{ej}$, $t_{sw} = R_{SW}/v_{ej} \sim$ few 100 yr
  - reverse shocks forms & propagates inwards, heating ejecta…
  - thermal-pressure driven (adiabatic) expansion:
- Sedov-Taylor phase (lasting ~10^4 yr): $R_s(t) \propto t^{2/5}$, $v_s(t) \propto t^{-3/5}$

Supernova Remnant Cartoon



Forward shock moves supersonically into interstellar/circumstellar medium
Reverse shock propagates into ejecta, starting from outside



Tycho SNR (1572) as seen by the VLA (22 cm)
Credit: NRAO et

Galactic Particle Accelerators

- Supernova remnants
- Pulsars
- Pulsar Wind nebulae
- Binaries
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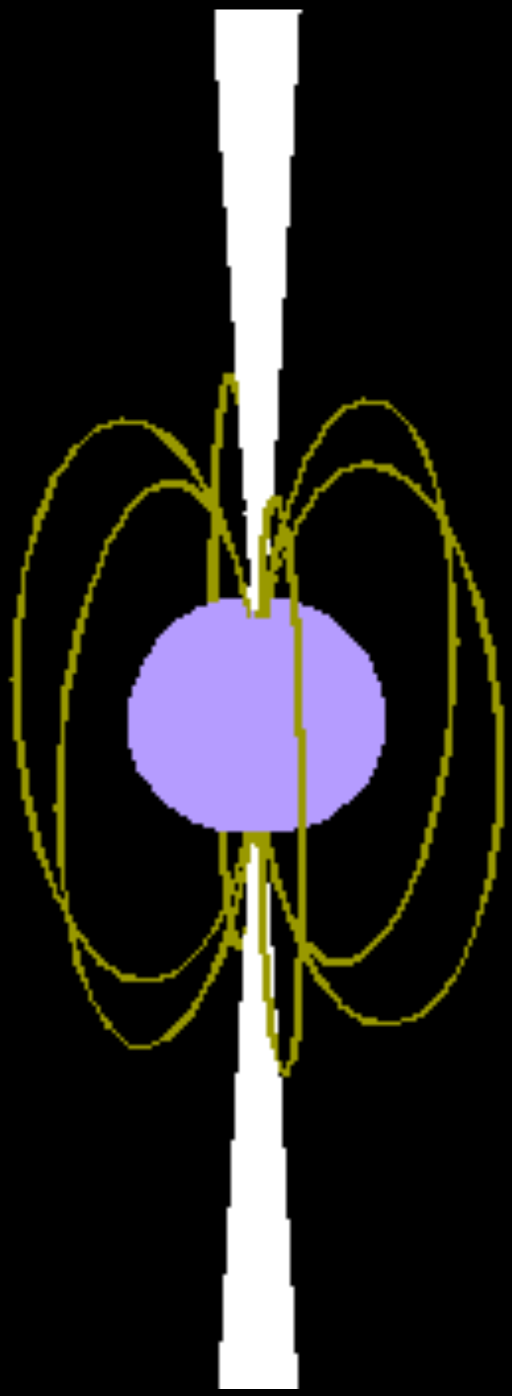
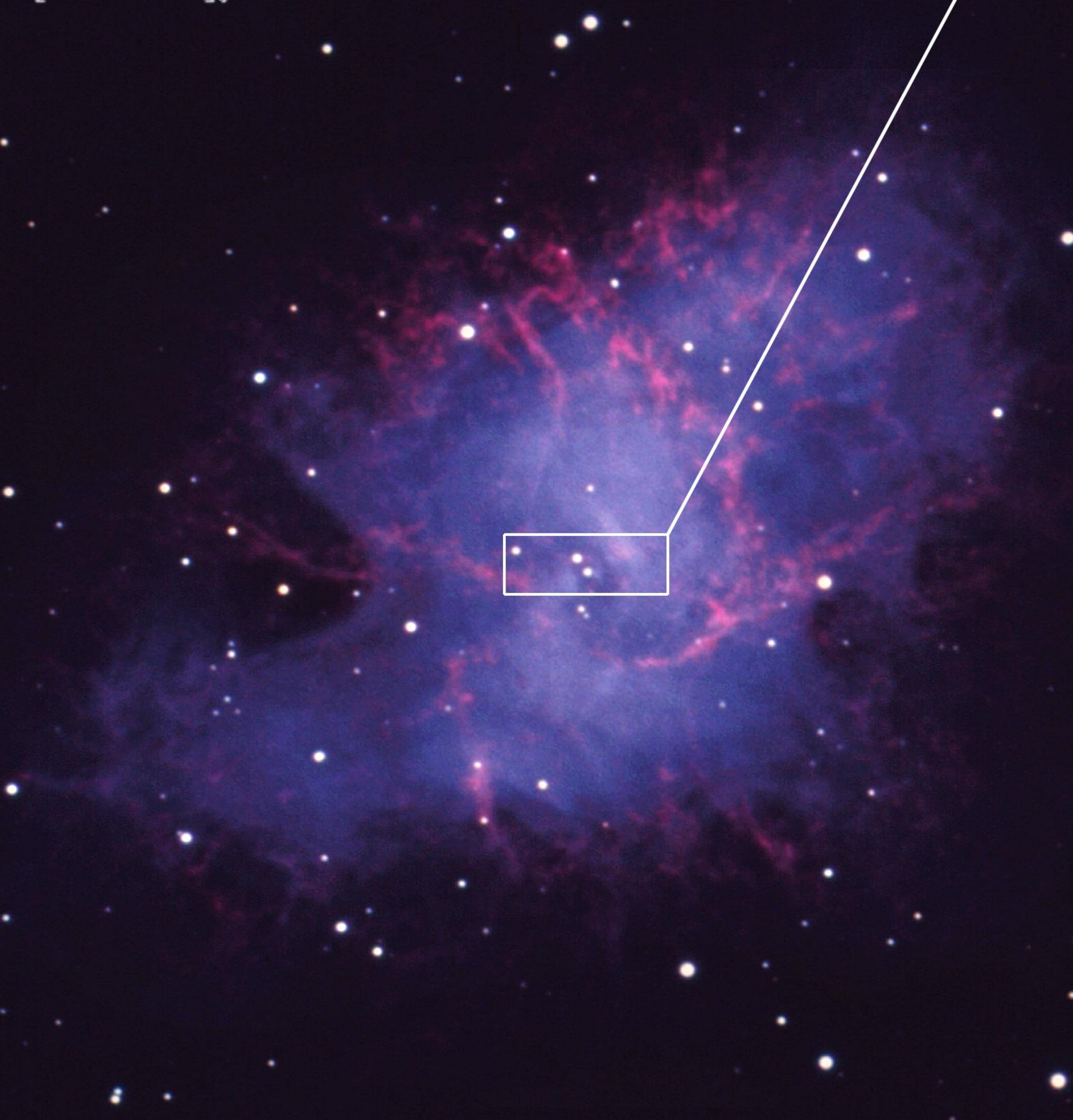
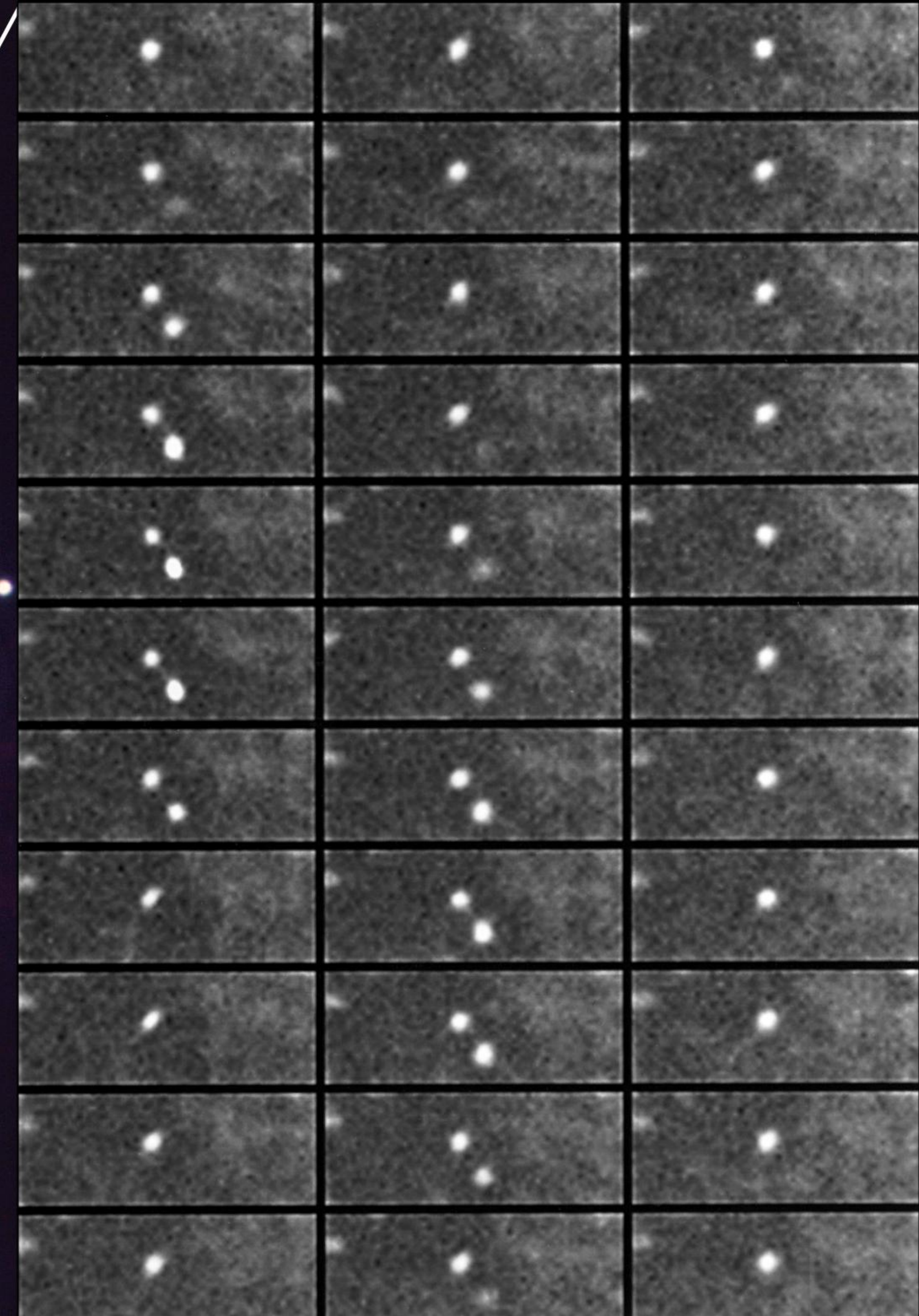


Crab Pulsar in the Crab Nebula

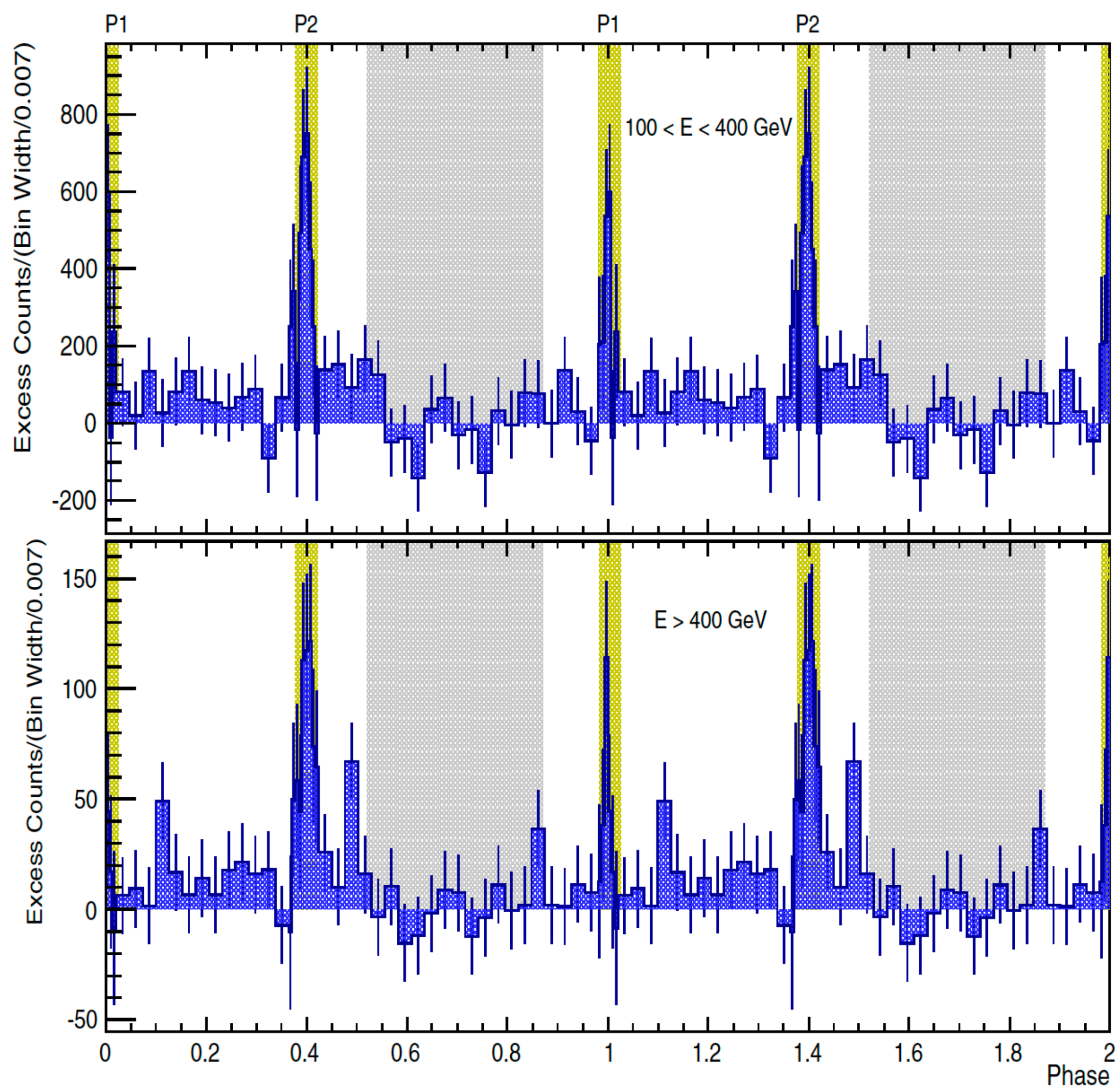
(distance ~ 2 kpc, period = 33 ms, age ~ 1 kyr [AD 1054])

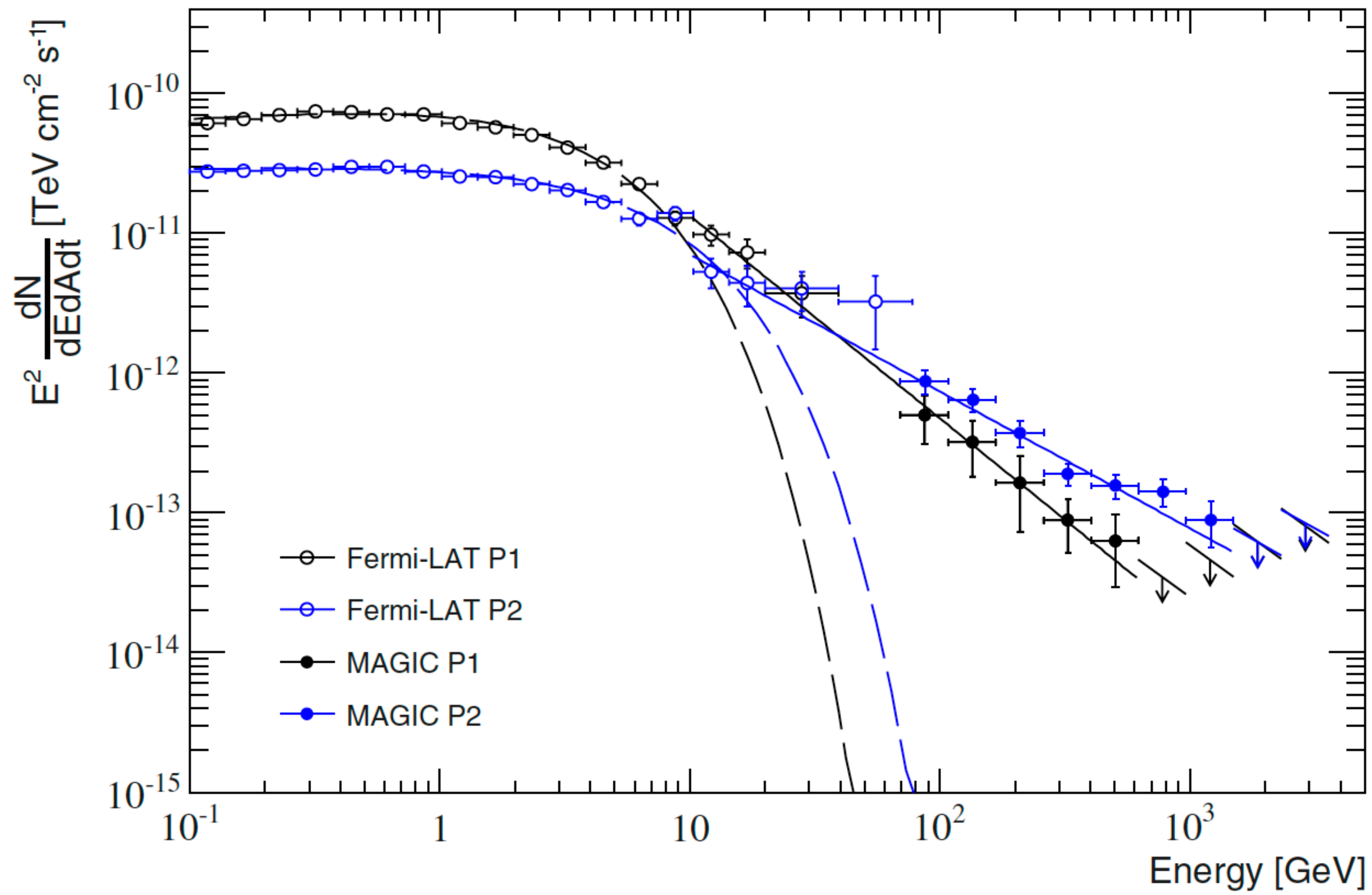




Crab Pulsar (optical sequence)
(credit: NOAO)

Pulsed VHE gamma-ray emission from the **Crab Pulsar**





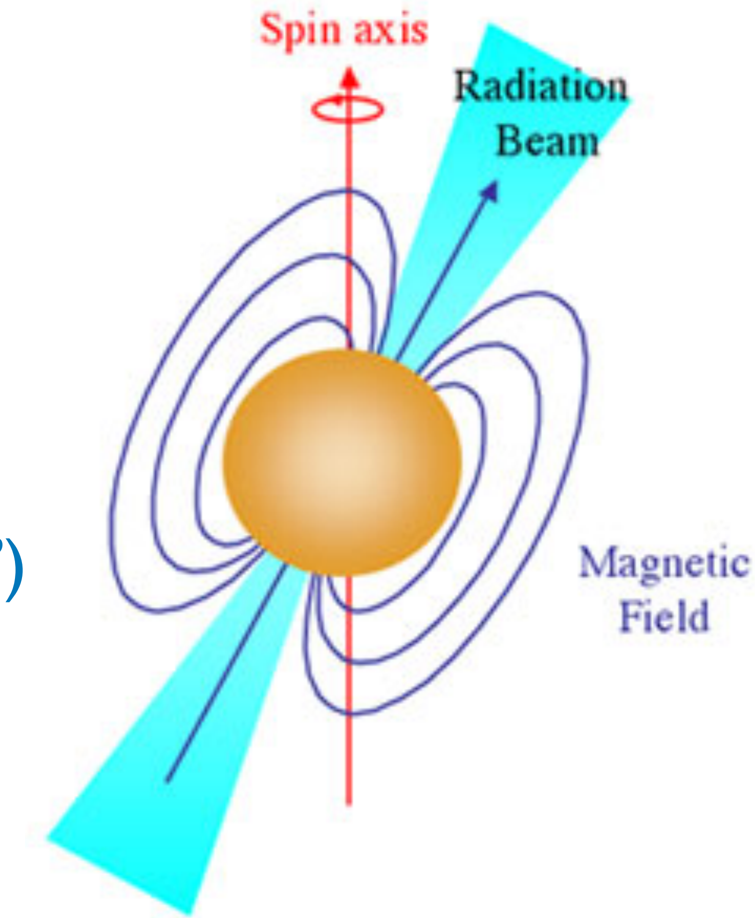
- power-law with extension up to TeV
- PL index ~ -3.5 (P1), -3 (P2)
- extension or new component?

Electron acceleration to beyond $\gamma_e \sim 5 \times 10^6$

MAGIC Collab., 2016

Basic Physics Sheet - Pulsars

- rotating & strongly magnetized neutron star ($B_N \sim 10^{10-15}$ G at surface)
- typical mass: 1.4-3.2 $M_\odot$ (Chandrasekhar limit), radius $R_N \simeq$ 10 km
- rotation/pulse periods $P = 2\pi/\Omega$ between 1 ms - 10 sec:
  - *Crab: P = 33.5 ms =0.033 sec (age ≃ 950 yr)*
  - *Vela: P = 89 ms (age ~ 10^4 yr)*
  - *Geminga: P = 237 ms (age ~ 3 x10^5 yr; nearest to us ~ 250 pc)*



- pulsar is living off its rotational energy (”spin-down luminosity”)
  - $E_{rot} = \frac{1}{2} I \Omega^2 = \frac{2\pi^2 I}{P^2}$
  - $I = (2/5)\, MR^2$ momentum of inertia; for the Crab: $I \simeq 10^{45}$ erg s^2
  - decrease in rotational energy: $\frac{dE_{rot}}{dt} = -\frac{4\pi^2 I\dot{P}}{P^3} \sim 4 \times 10^{38} \frac{\text{erg}}{\text{sec}}$ (for Crab)

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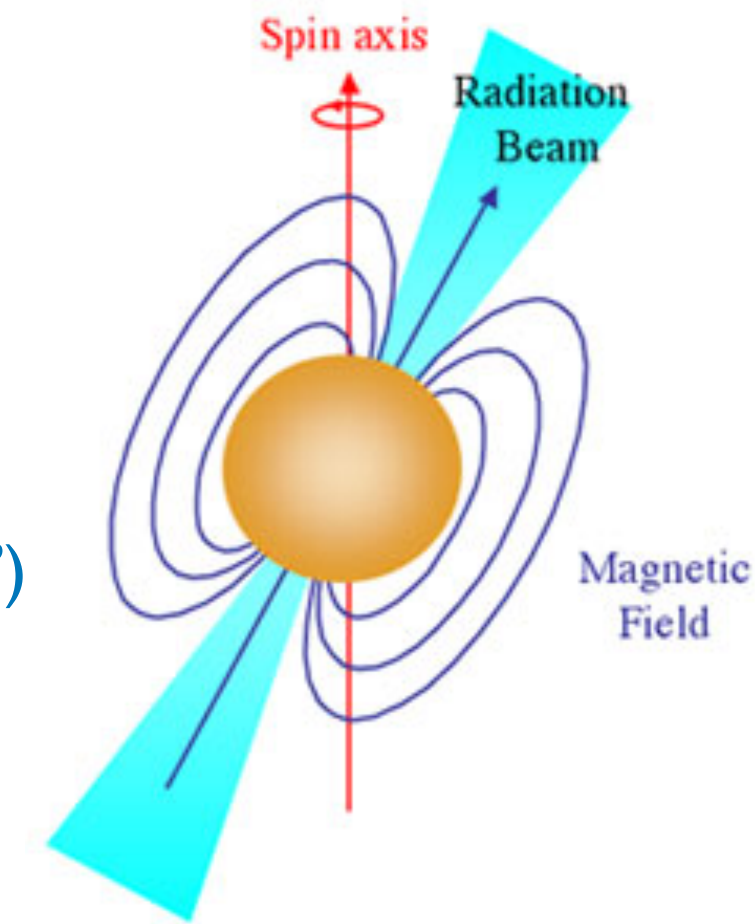

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- Magnetic dipole radiation (elm radiation of a varying magnetic moment):
  - magnitude of mag. moment: $m = B\,R^3$
  - radiated power (Larmor formula) : $P_{rad} = \frac{2}{3}\frac{\ddot{m}_\perp^2}{c^3} = \frac{2}{3}\frac{(\Omega^2 m_\perp)^2}{c^3} = \frac{2}{3c^3}(B\,R^3 \sin\alpha)^2 \left(\frac{2\pi}{P}\right)^4$
  - B-field estimate via $dE_{rot}/dt = P_{rad}$ $\Rightarrow$ $B > 3 \times 10^{12}$ G (Crab)

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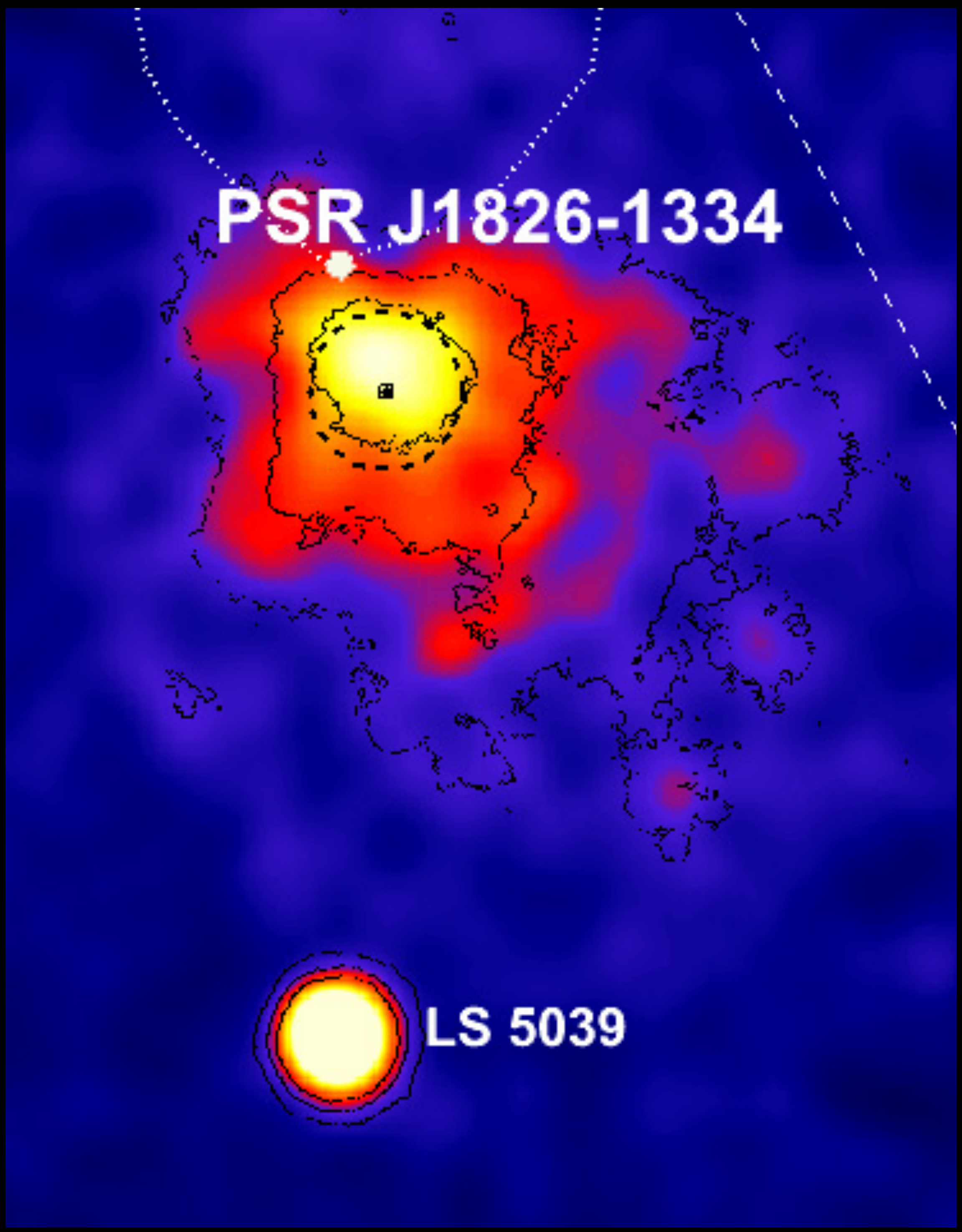
G21.5-0.9 in X-rays
Chandra / H.Matheson & S.Safi-Harb

HESS J1825-137 - energy-dependent morphology

(d ~ 4 kpc, size ~ tens of pc)



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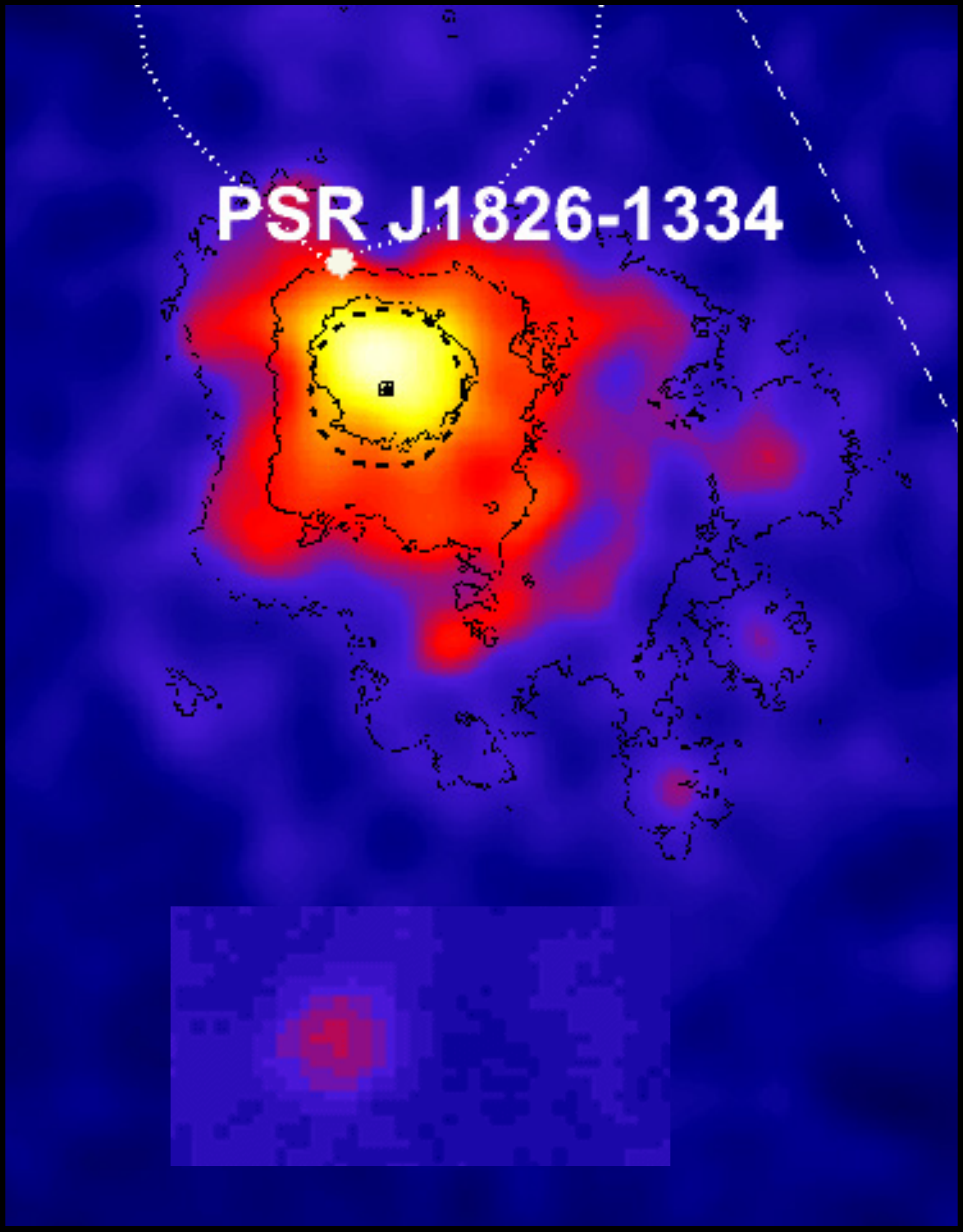

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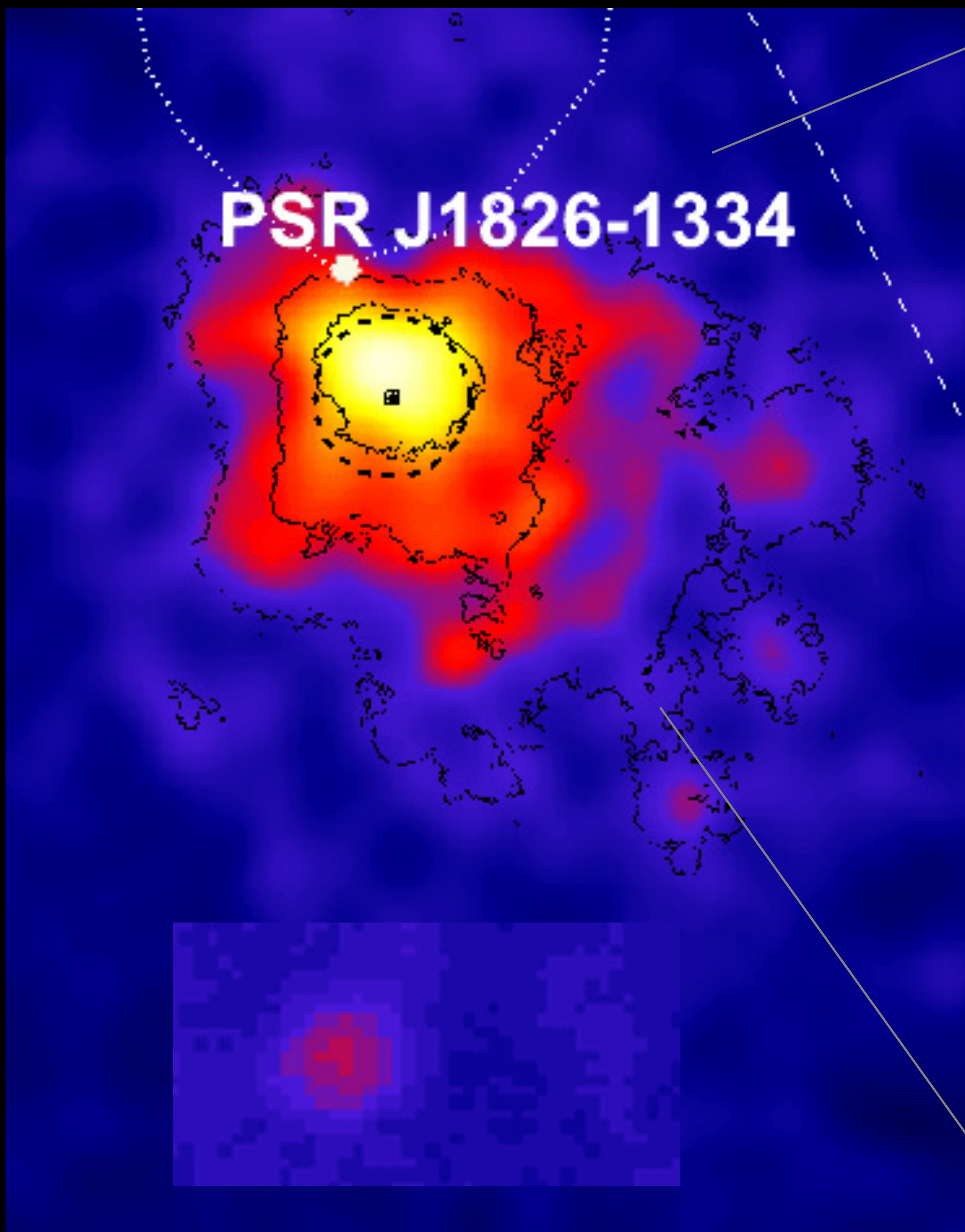

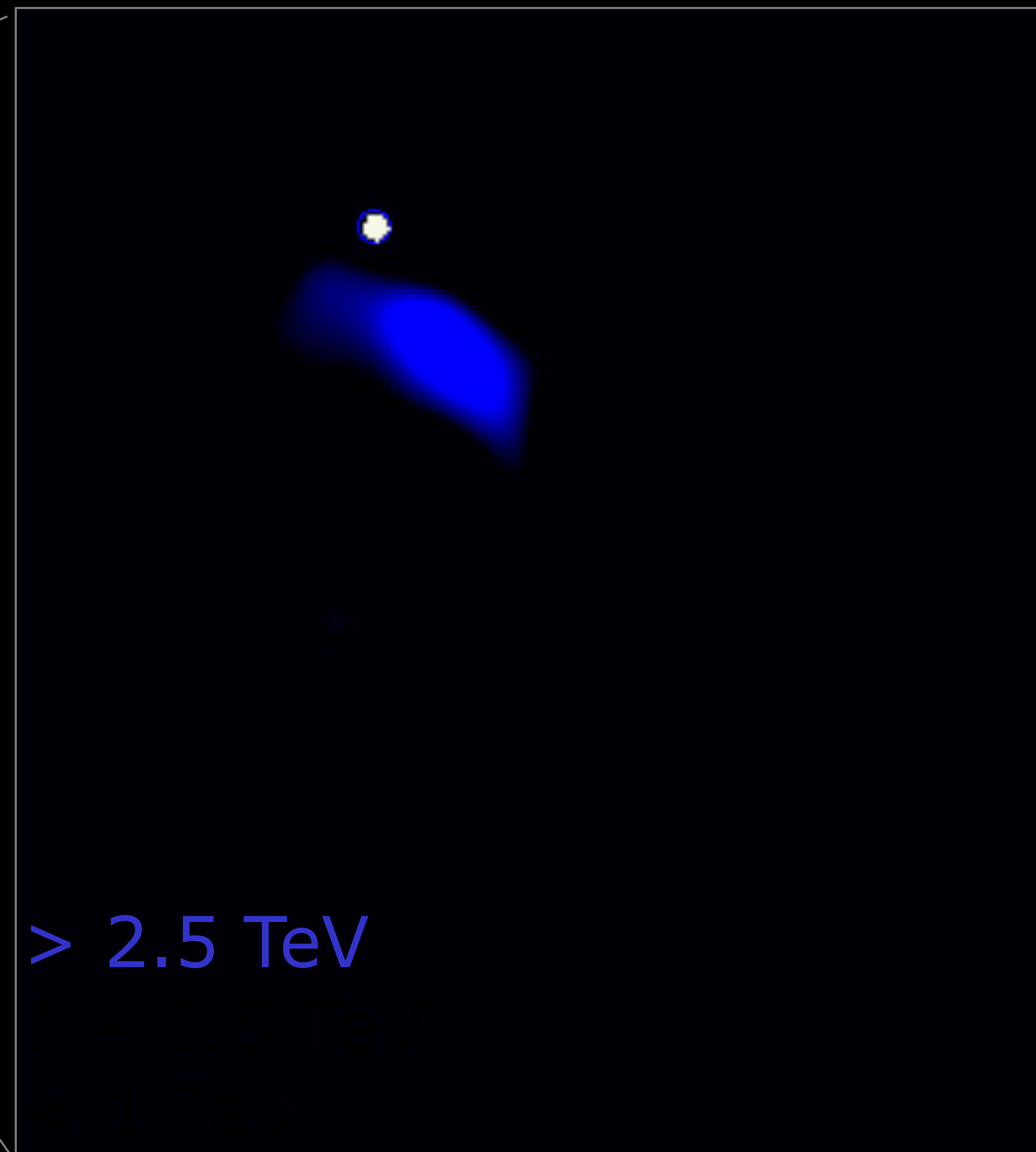

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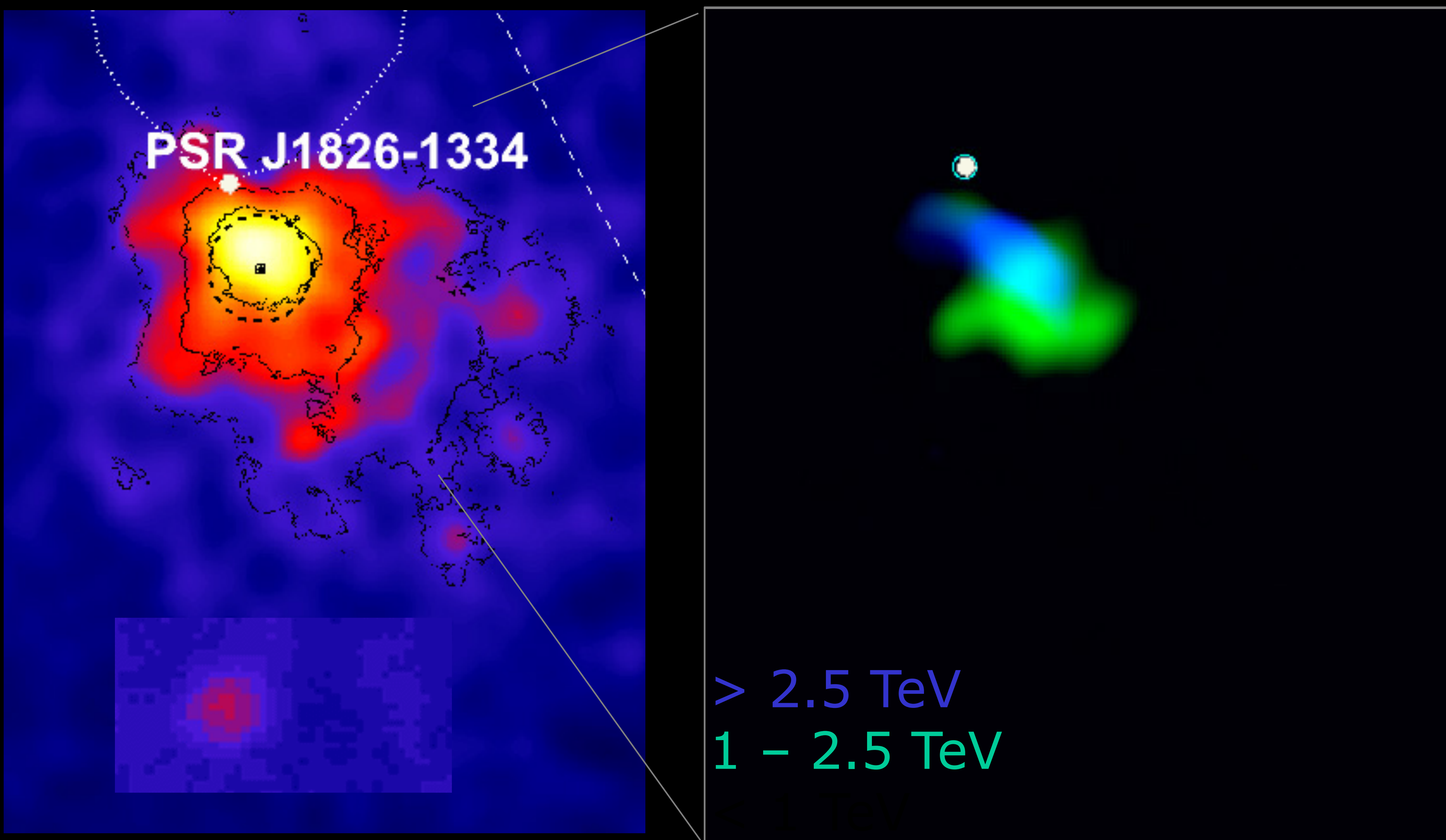

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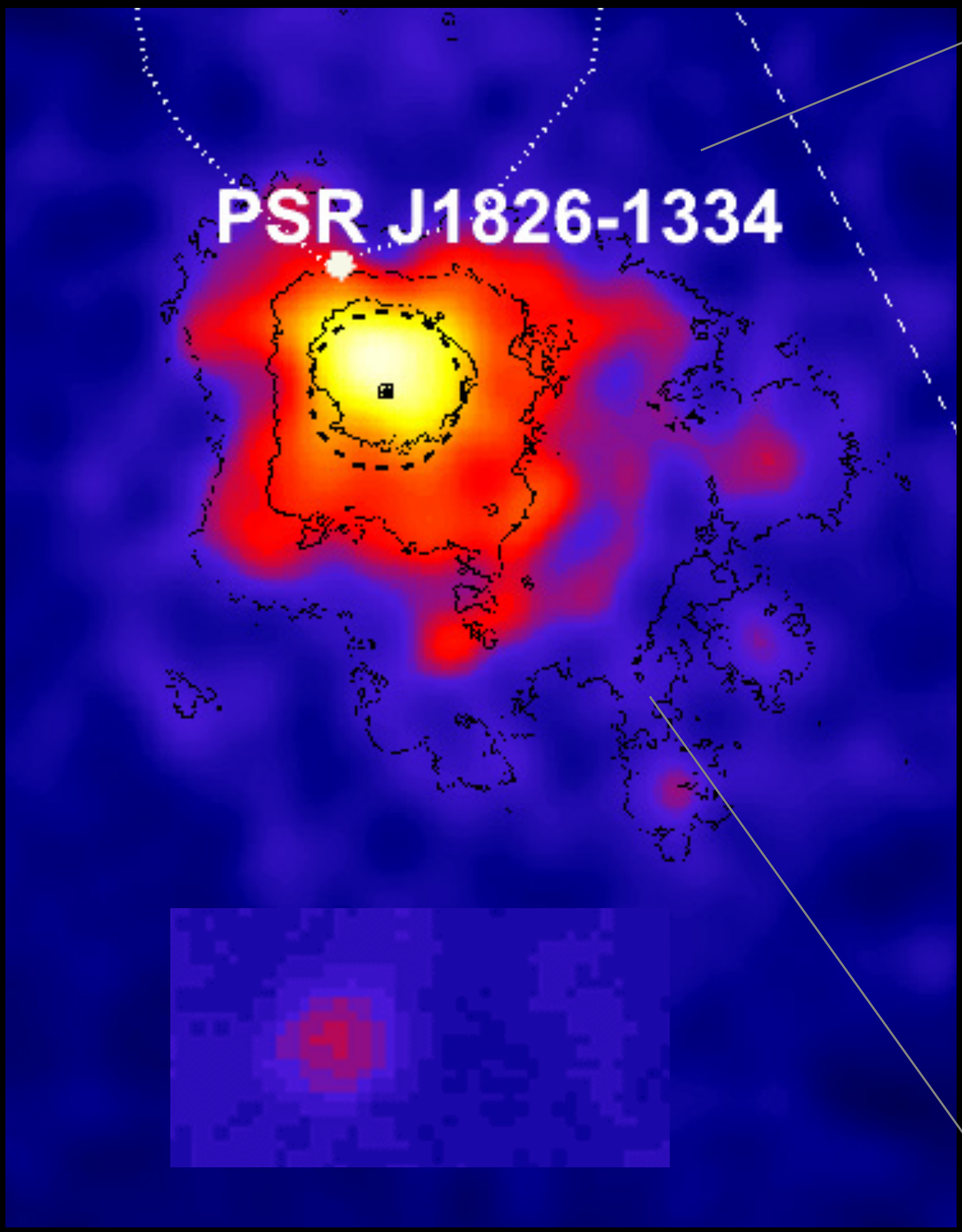
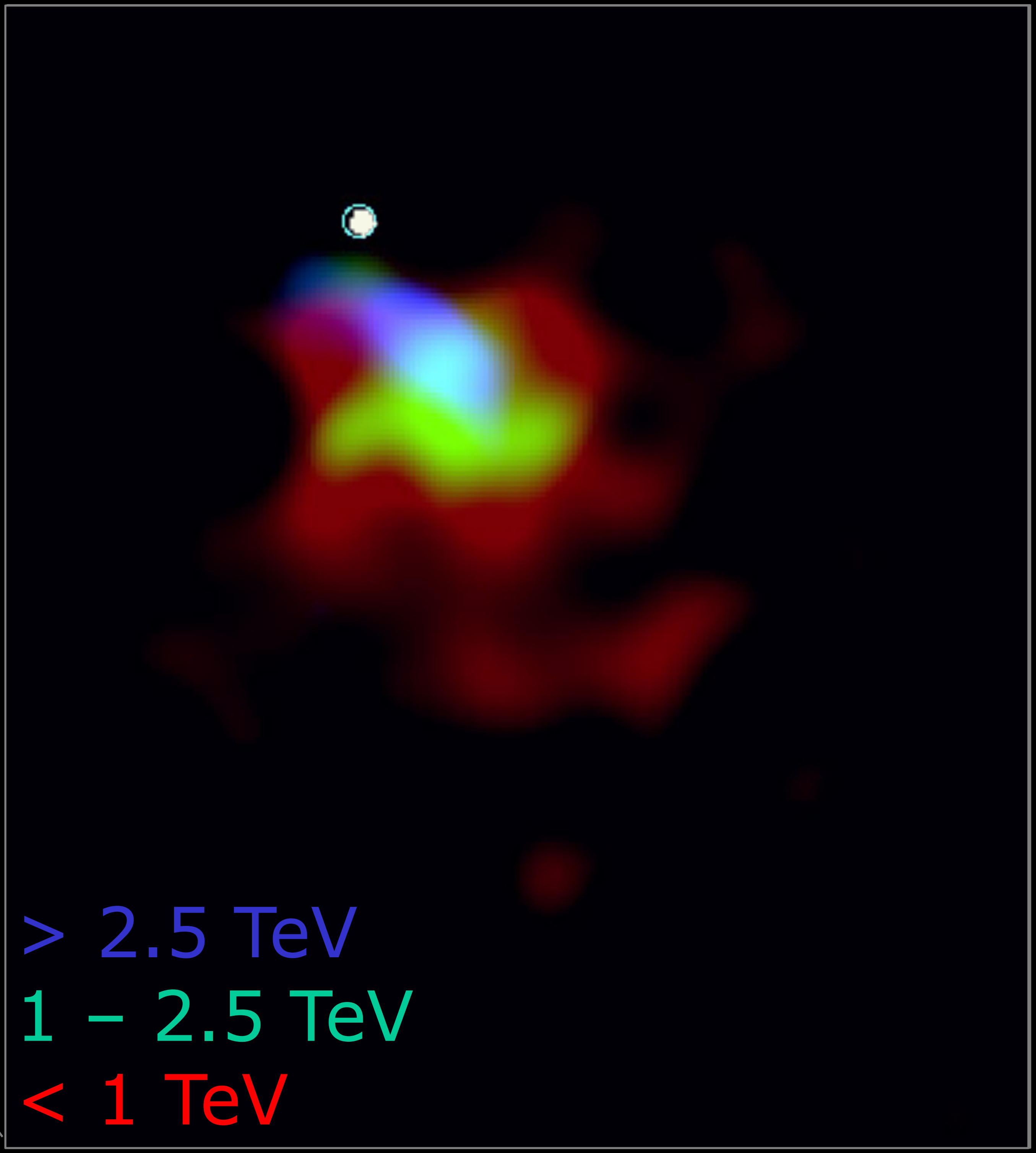
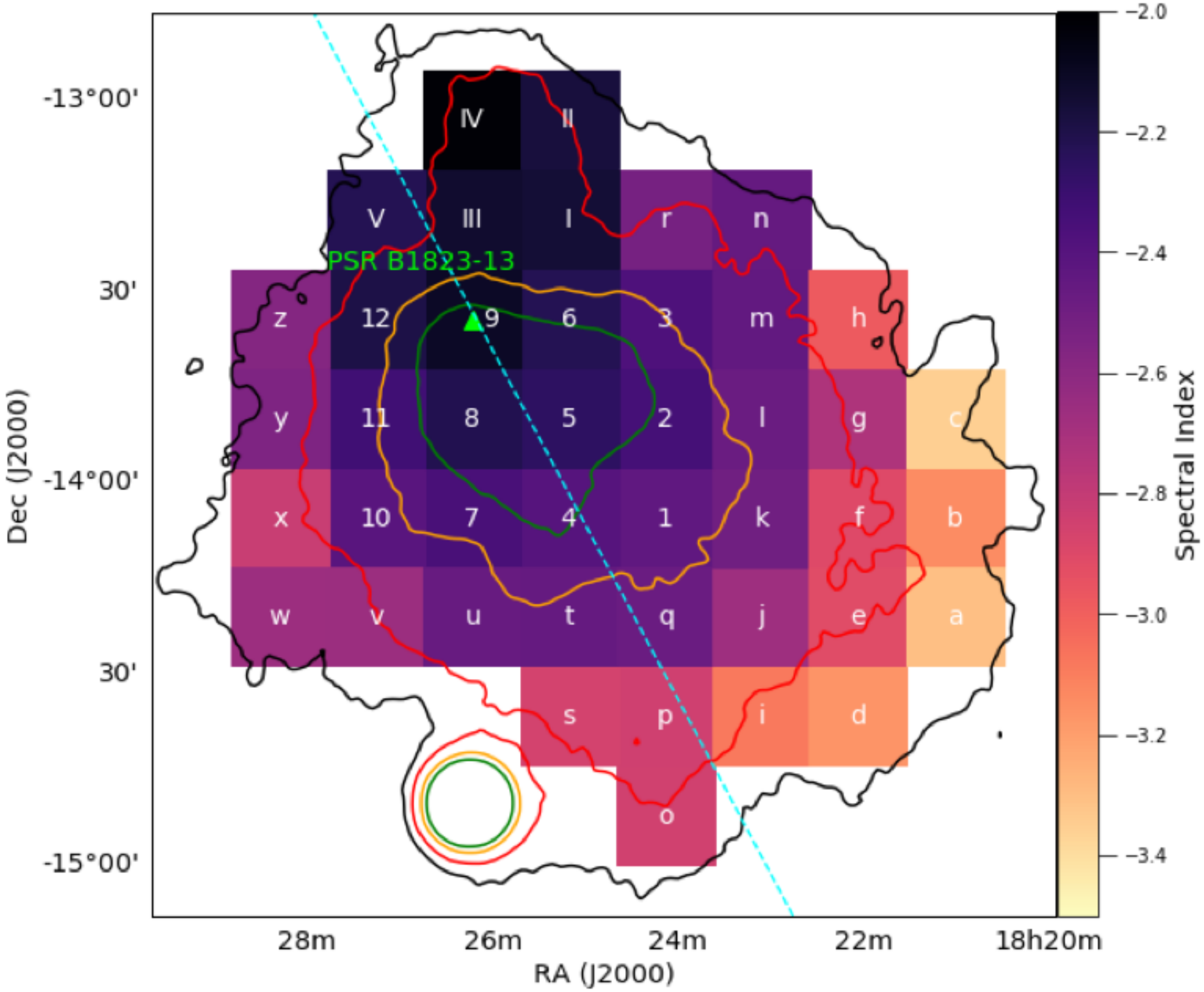




Spectral Map of Nebula (HESS J1825-137)



- extension up to ~75 pc
- emission up to > 30 TeV
- spectrum becomes softer with distance
- result of particle transport (advective?) & cooling

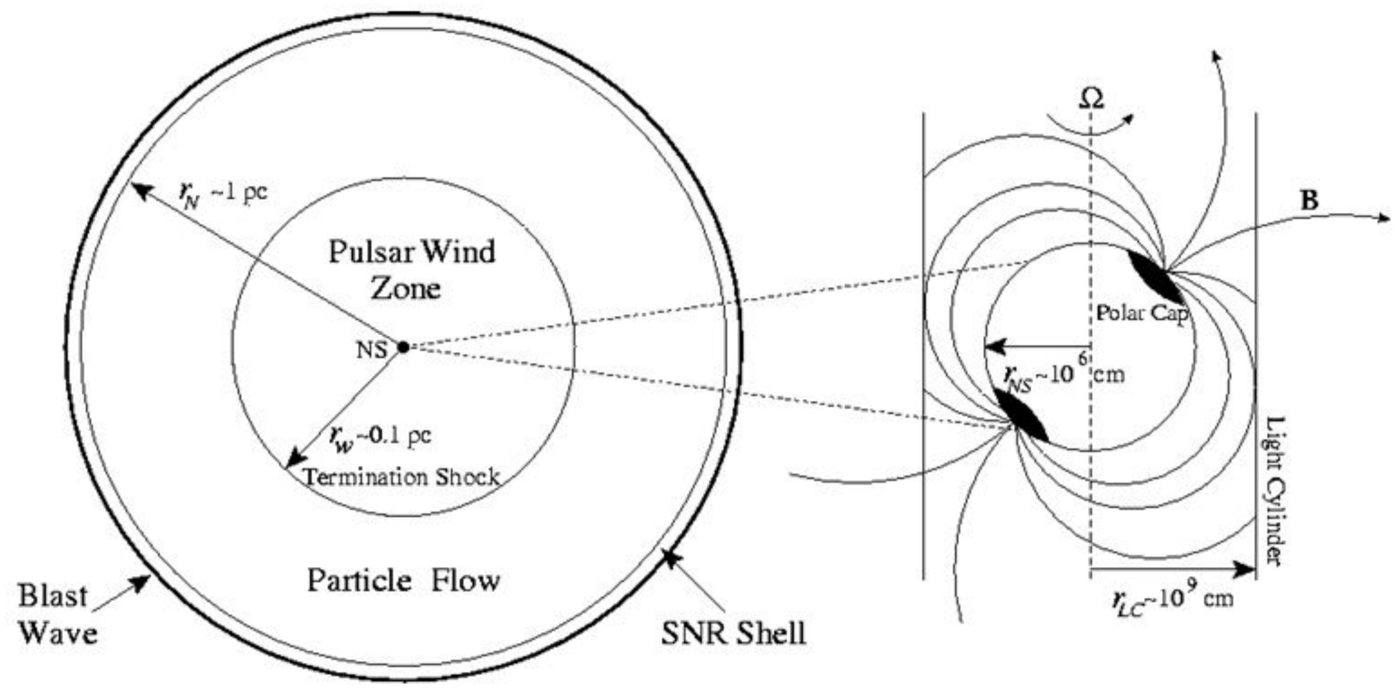
Electron acceleration to beyond $\gamma_e \sim 10^7$

H.E.S.S. Collab., 2019

Basic Physics Sheet - Pulsar Wind Nebula (PWN)

- ***PWN*** = bubble of radiating, shocked relativistic electrons produced when pulsar wind interacts with environment.

- fast e^+e^- - pulsar wind ($\Gamma \gtrsim 10^4$) efficiently confined by surrounding SNR



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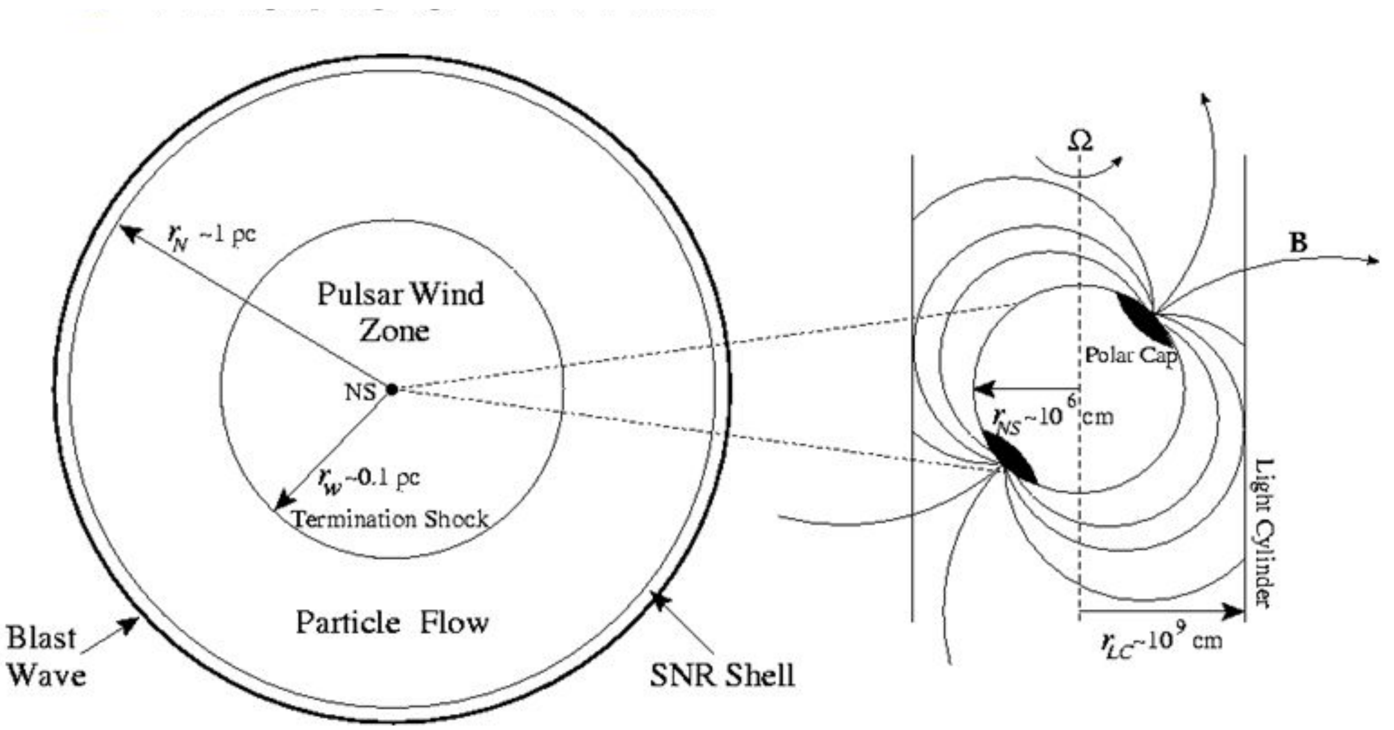


- **pulsar wind expands until its ram pressure is balance by surrounding nebula**
  - formation of a pulsar wind **termination shock** at which particle acceleration occurs.
  - rough estimate for ***location*** (Rees & Gunn 1974): balance ram pressure of wind with energy reservoir in nebula accumulated steadily over its lifetime:

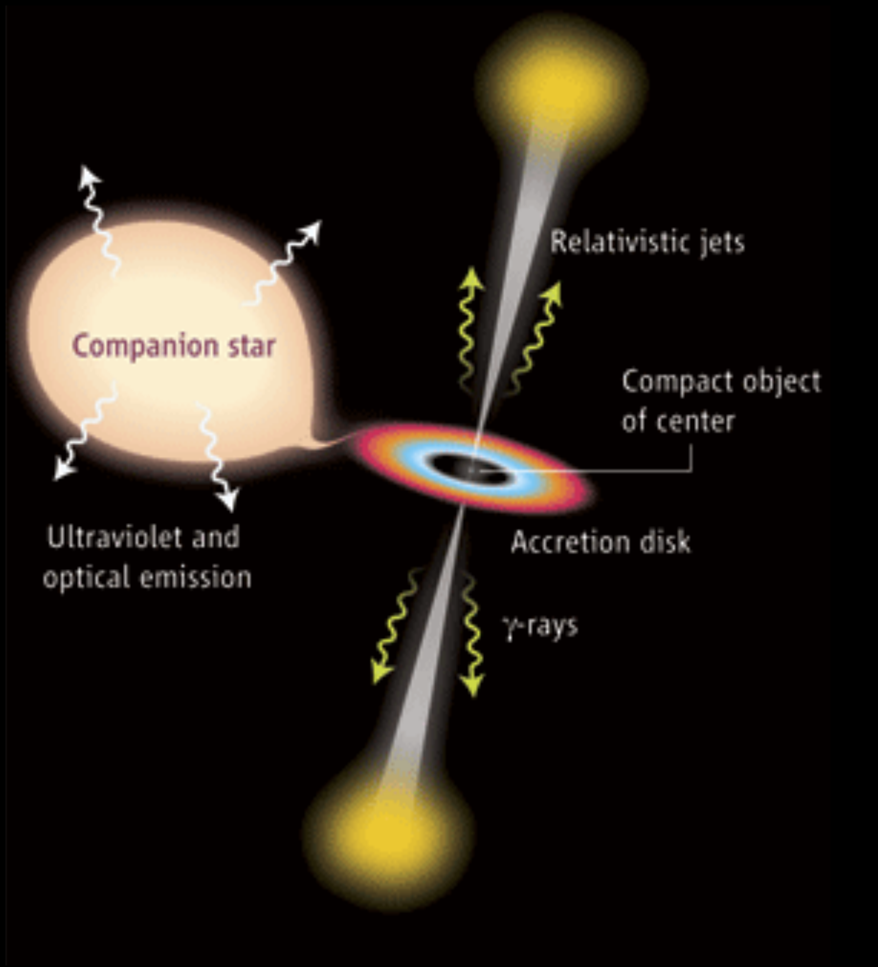
$$\frac{\dot{E}_{sd}\, t_{TS}}{\frac{4\pi}{3} R_{TS}^3} = \frac{\dot{E}_{sd}\, t_{age}}{\frac{4\pi}{3} R_{PWN}^3} \Rightarrow R_{TS} \simeq R_{PWN} \left(\frac{V_{PWN}}{c} \right)^{1/2}$$

using that $t_{age} = R_{PWN} / V_{PWN}$ and $t_{TS} = R_{TS} / c$; $\dot{E}_{sd}$ = spin-down luminosity

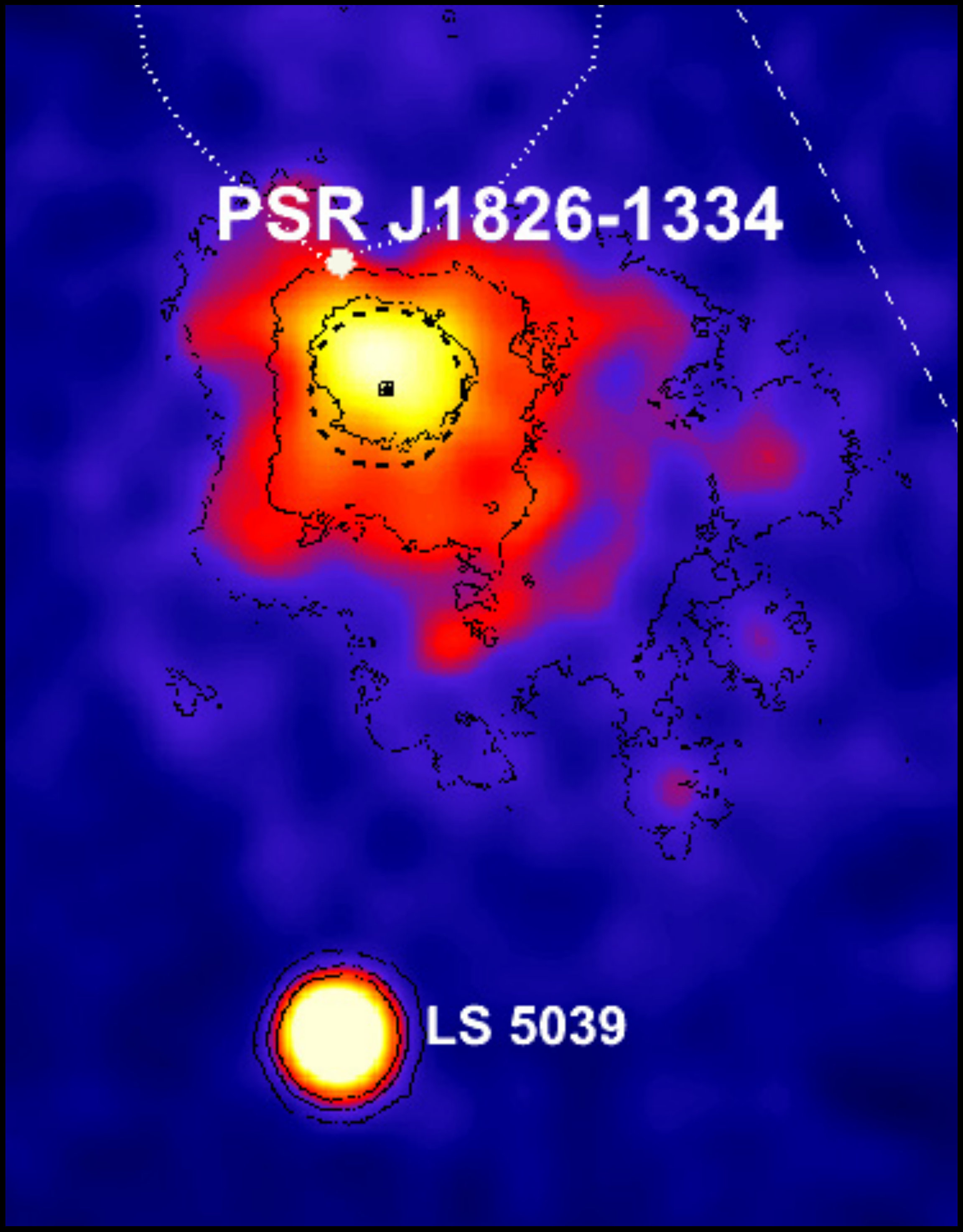
  - for the Crab: R_{PWN} ~ 1.5 pc, V_{PWN} ~1000 km/s ⇒ **R_{TS} ~ 0.1 pc**

Galactic Particle Accelerators

- Supernova remnants
- Pulsars
- Pulsar Wind nebulae
- Binaries
- Galactic center (BH?)



LS 5039 - periodic VHE emission



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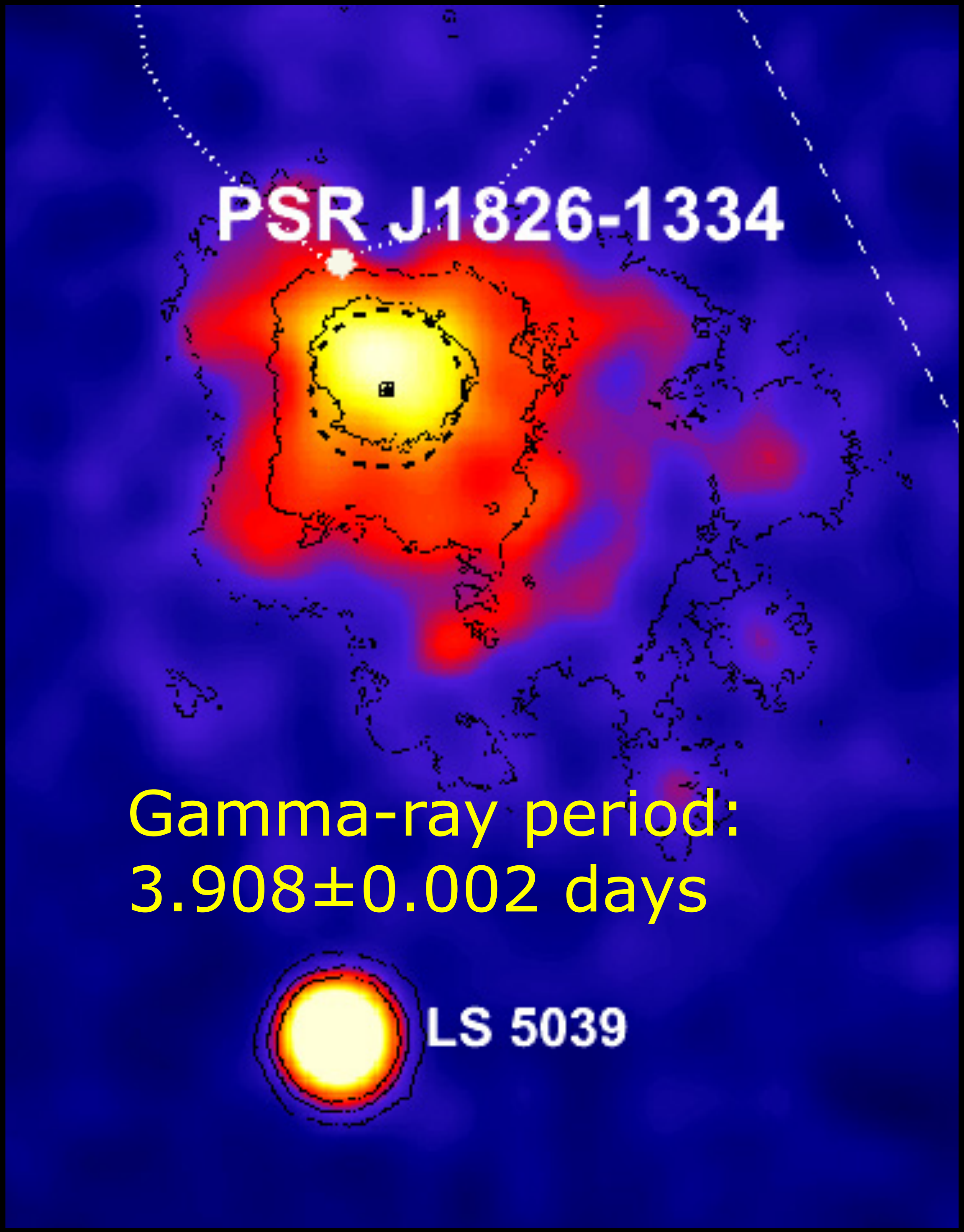

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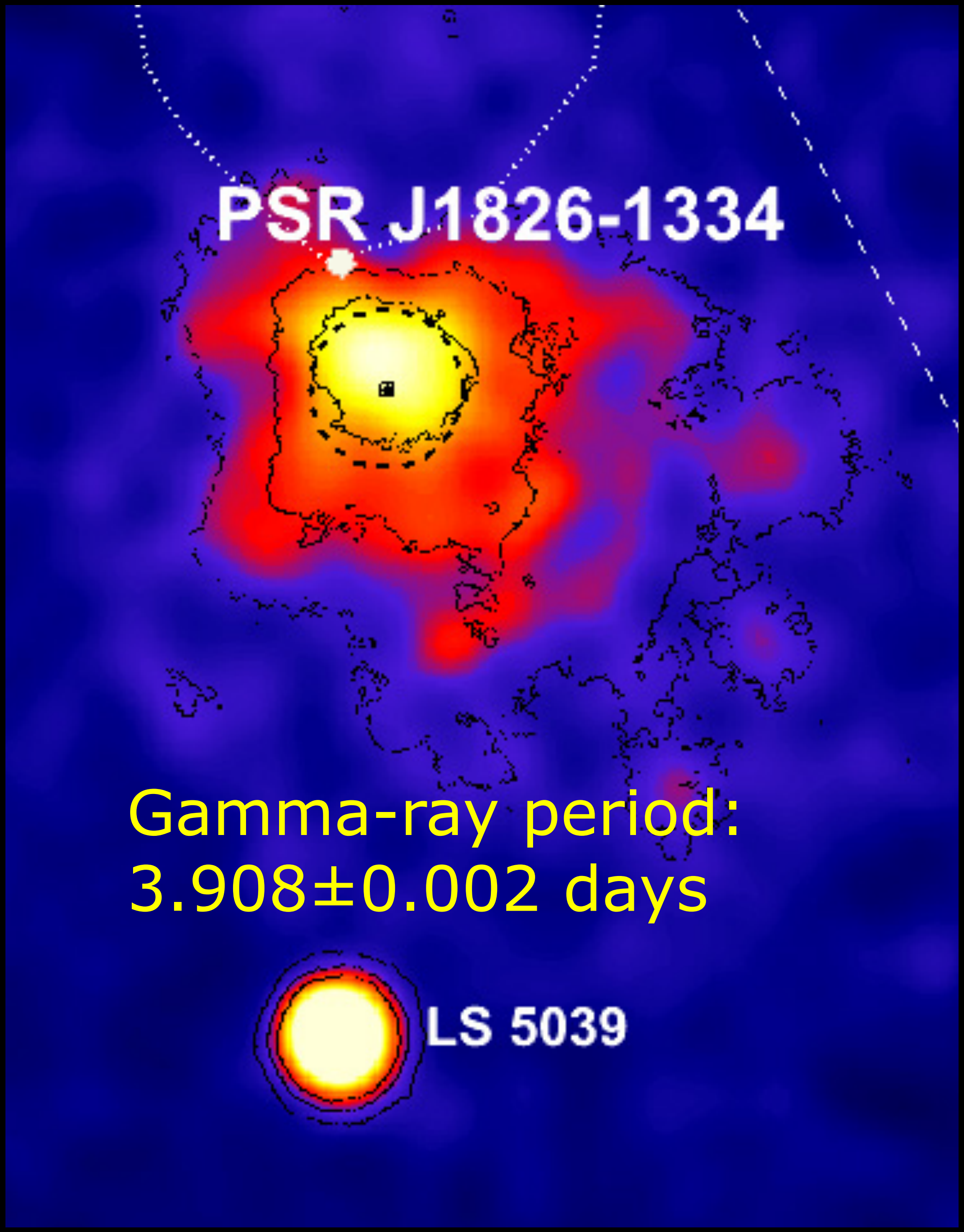
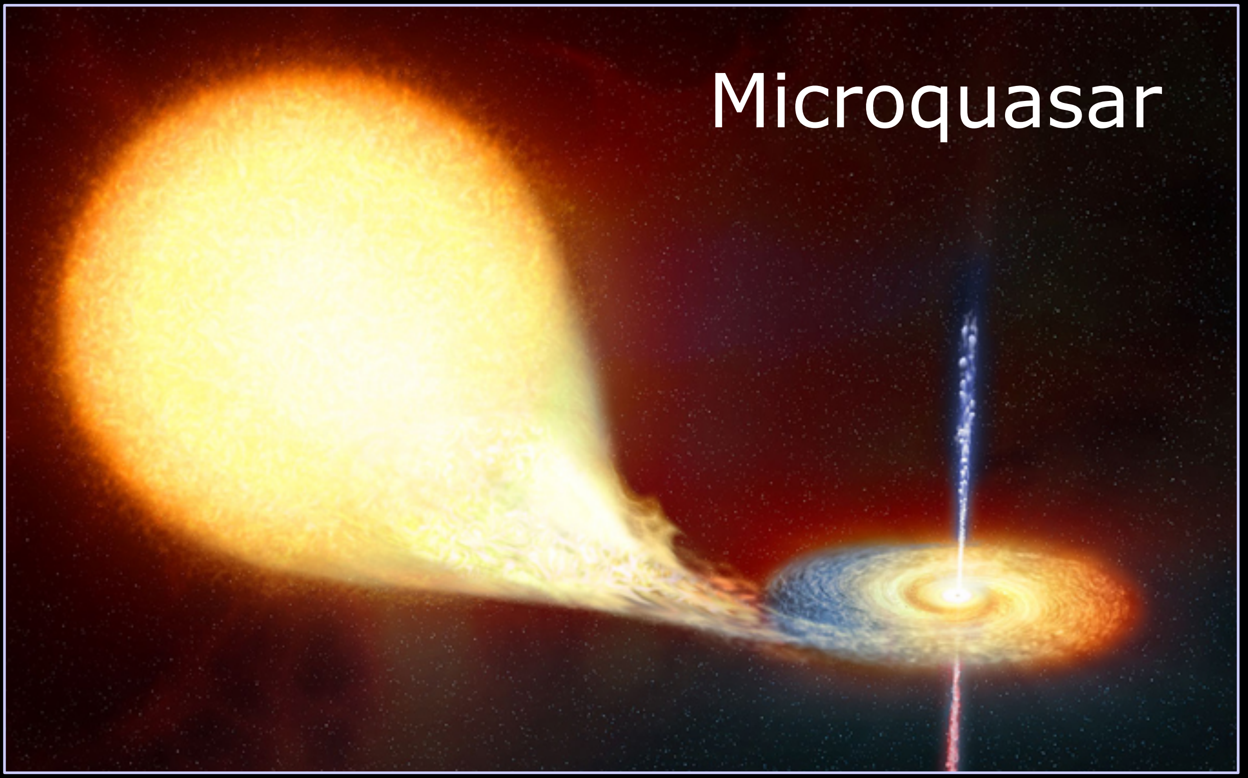




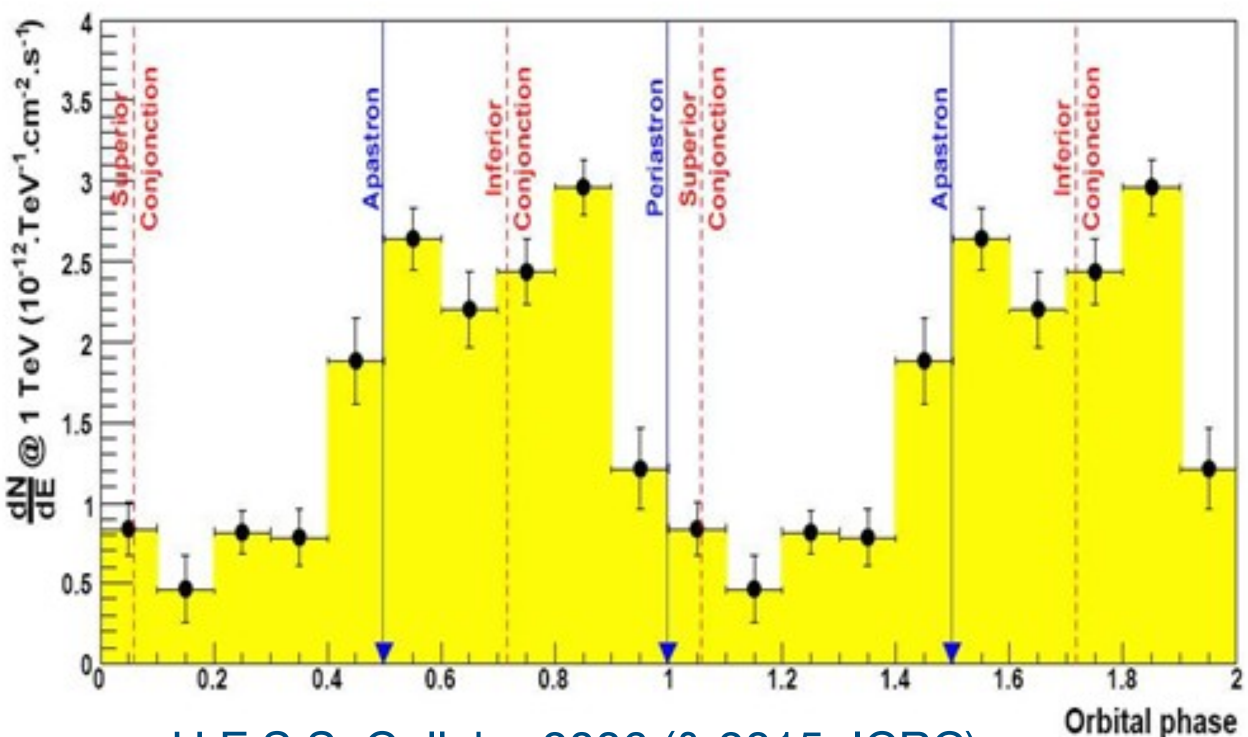
LS 5039 (distance ~2.5 kpc)**:**

- binary system:

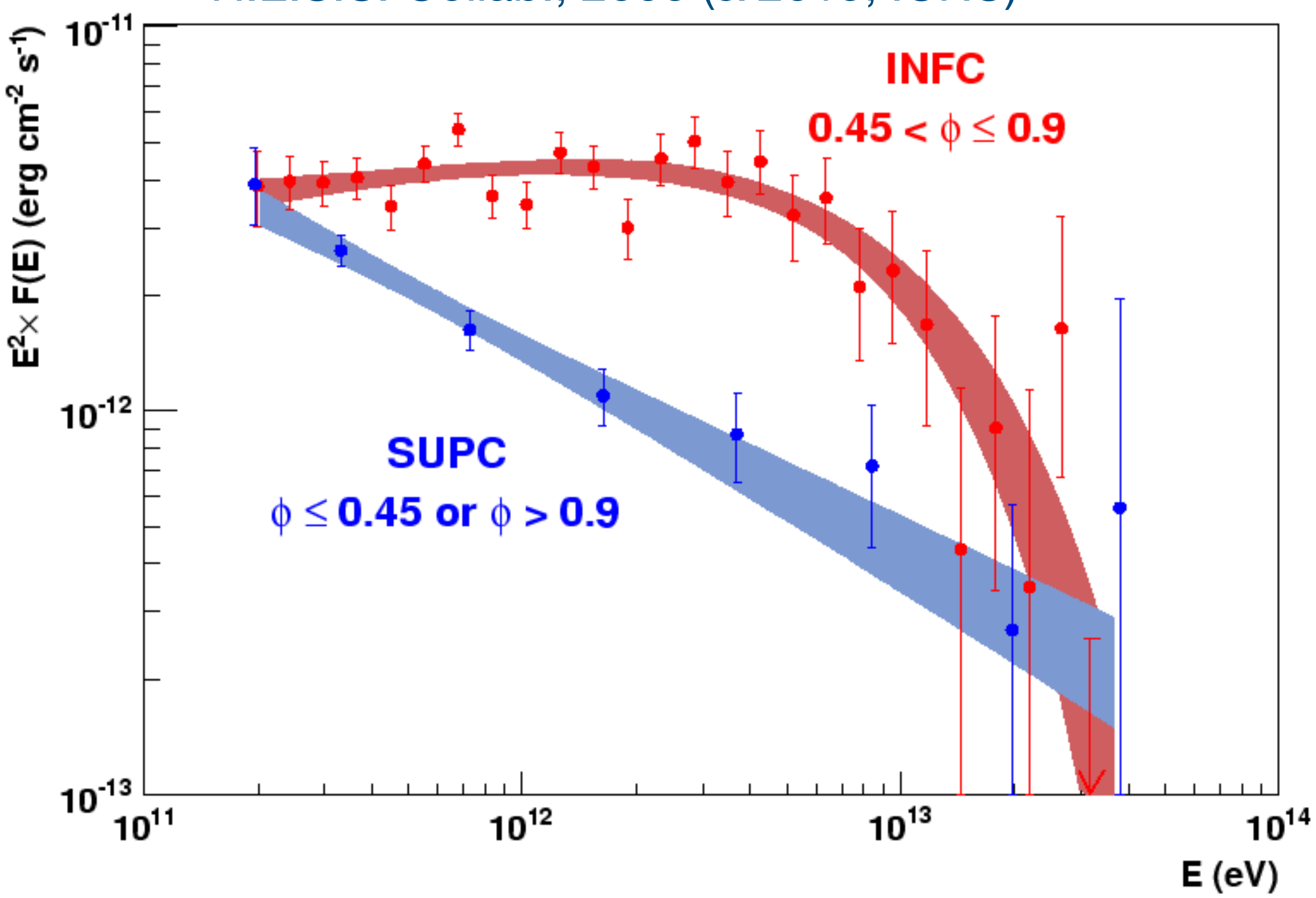
  compact object (~4 $M_\odot$ black hole?) in eccentric 3.906-day orbit around 20-30 $M_\odot$ star

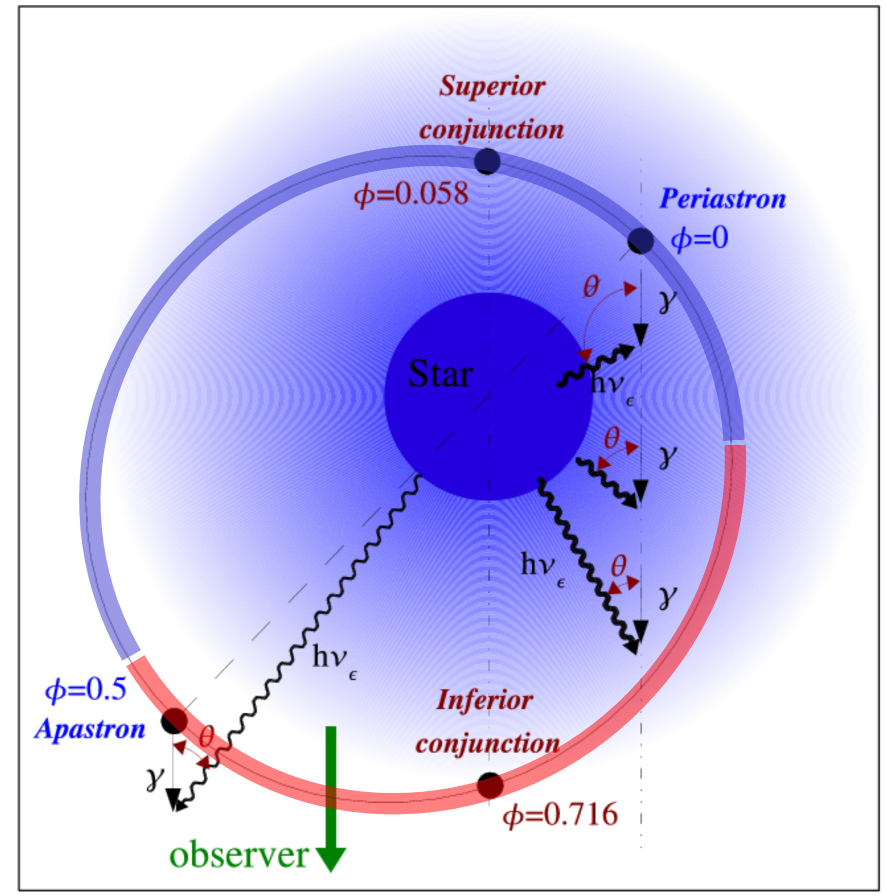
- closest approach ~ 10^{12} cm or about ~2 stellar radii

Periodic TeV emission & spectral variations



H.E.S.S. Collab., 2006 (& 2015, ICRC)

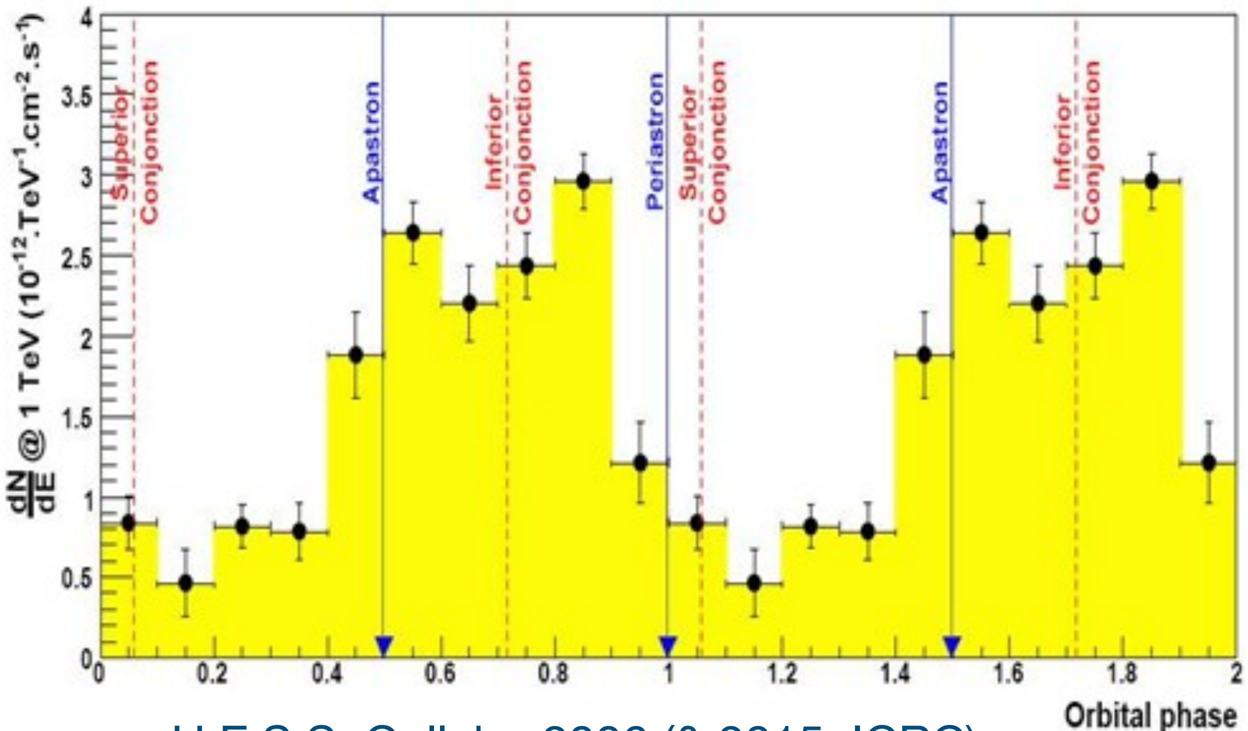




- VHE gamma-rays beyond 10 TeV
- SUPC spectrum: compatible with pure PL (index 2.4)
- INFC: softer PL with exp. cutoff
- modulation induced by variation in γγ-absorption, IC (anisotropic), plus possibly particle acceleration

IC scattering (KN) needs > 10 TeV electrons

Periodic TeV emission & spectral variations



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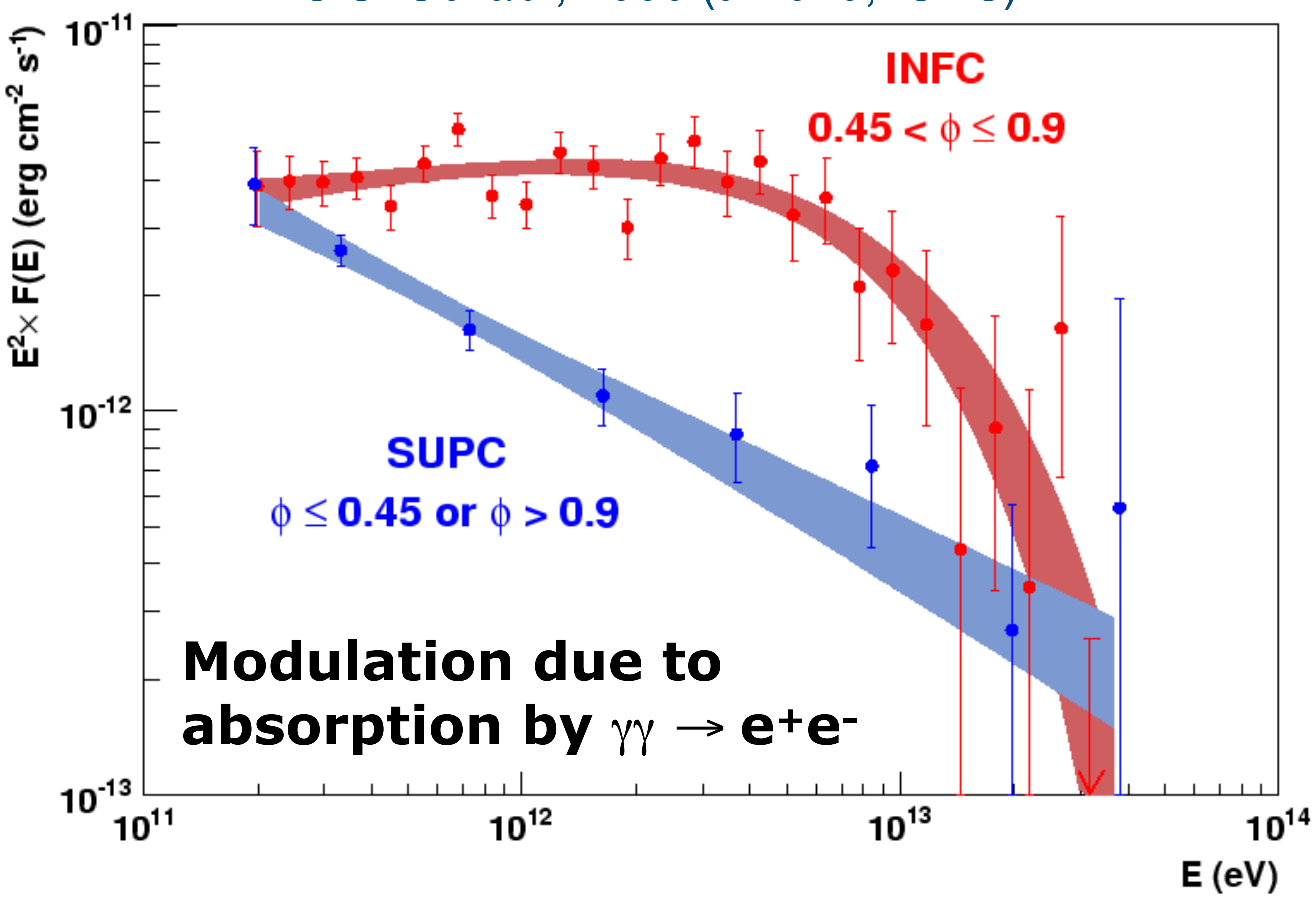

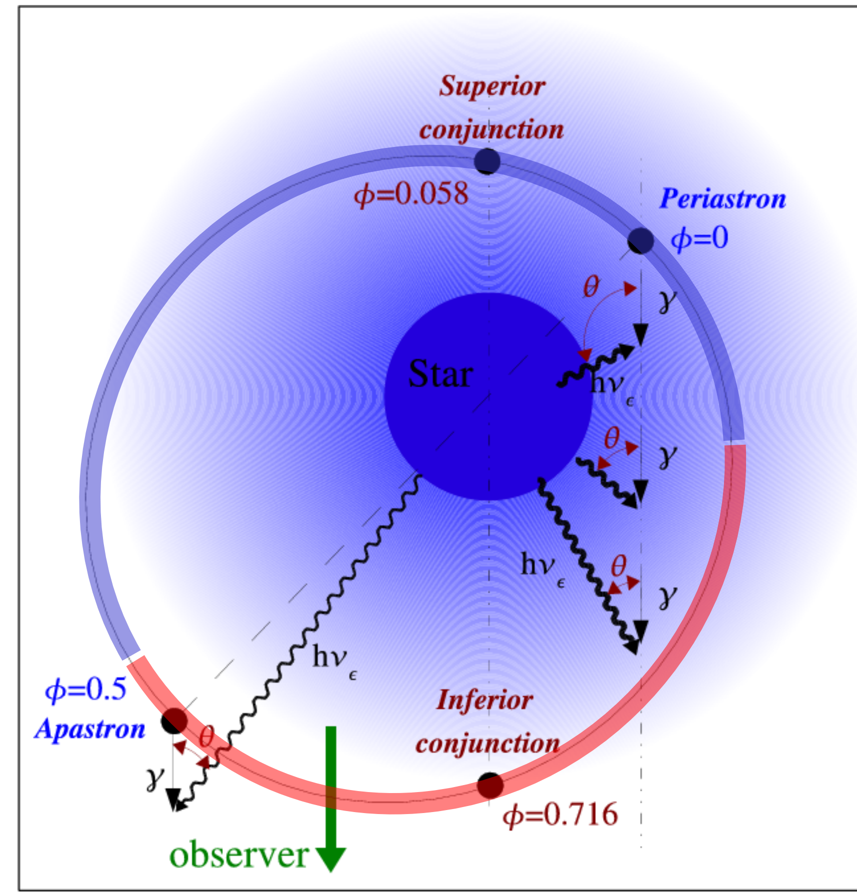

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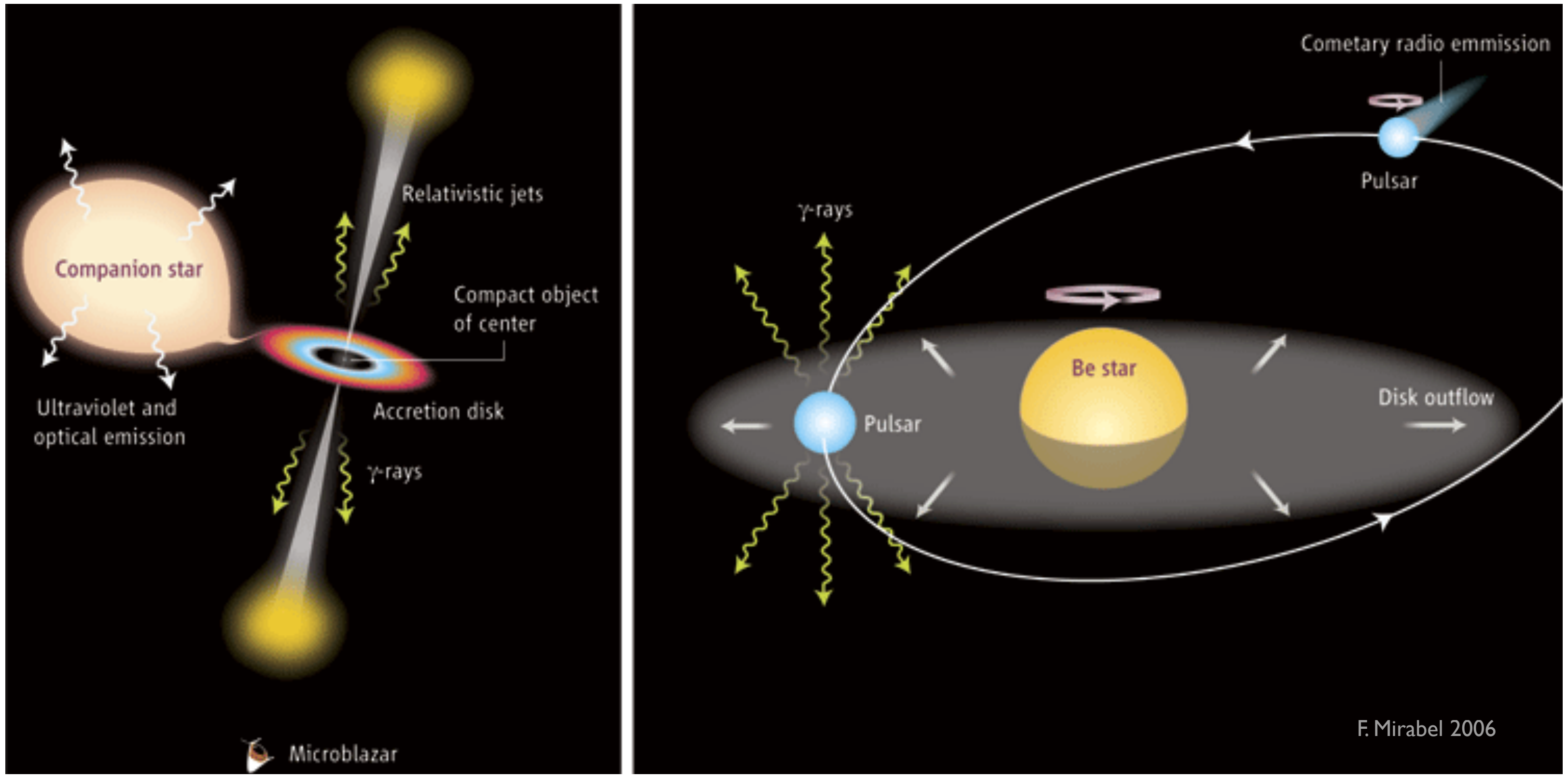
Basic Physics Sheet - Gamma-Ray Binaries

- compact object - either pulsar (neutron star) or a black hole (*micro-quasar*)
- VHE modulation induced by orbital varying absorption and anisotropic IC scattering
- VHE produced inside or very close to system (LS 5039)



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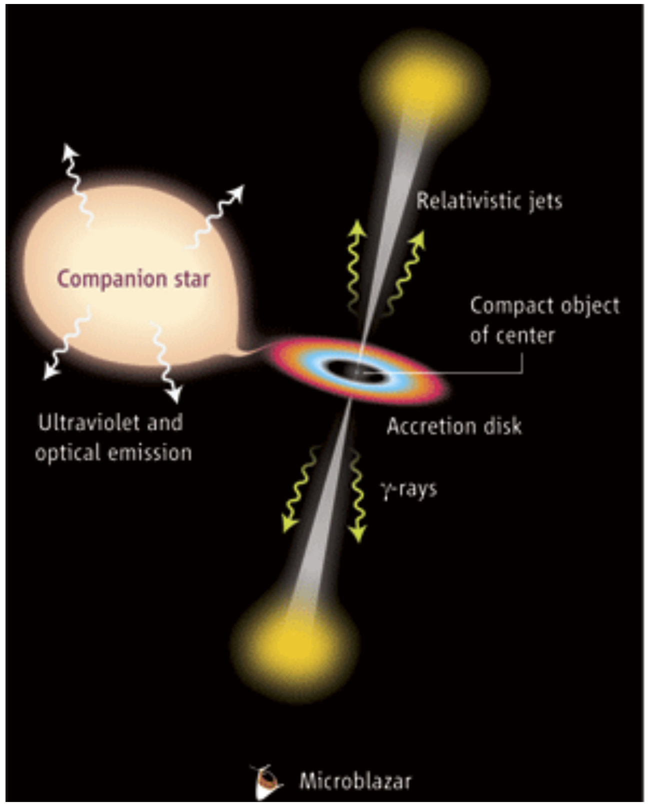
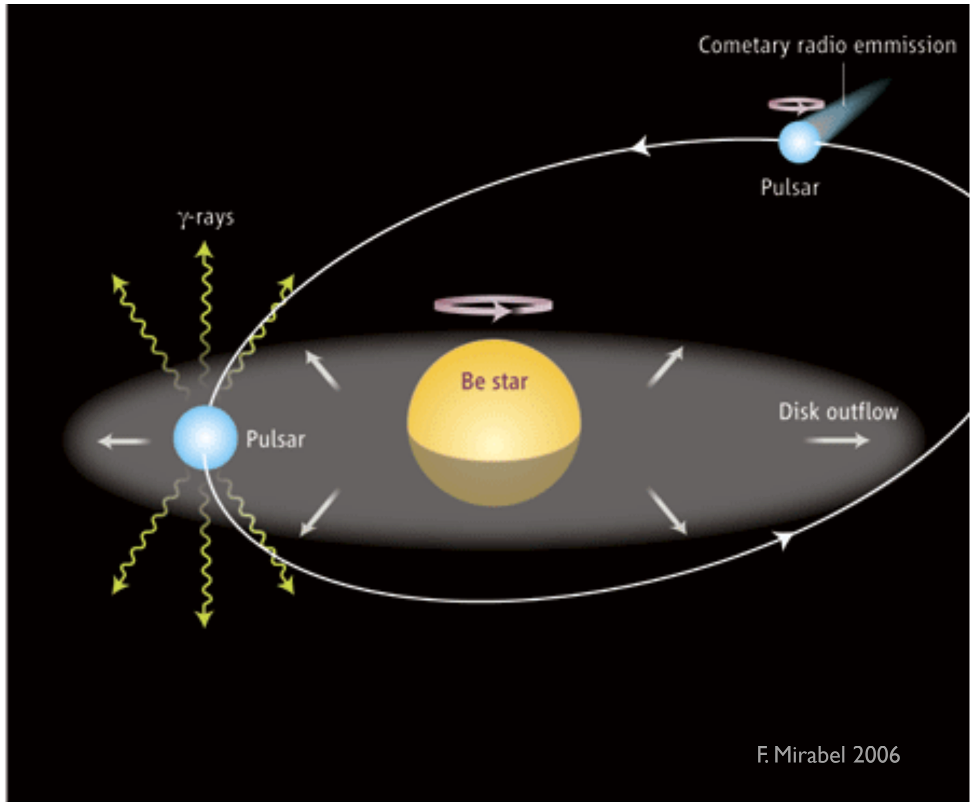




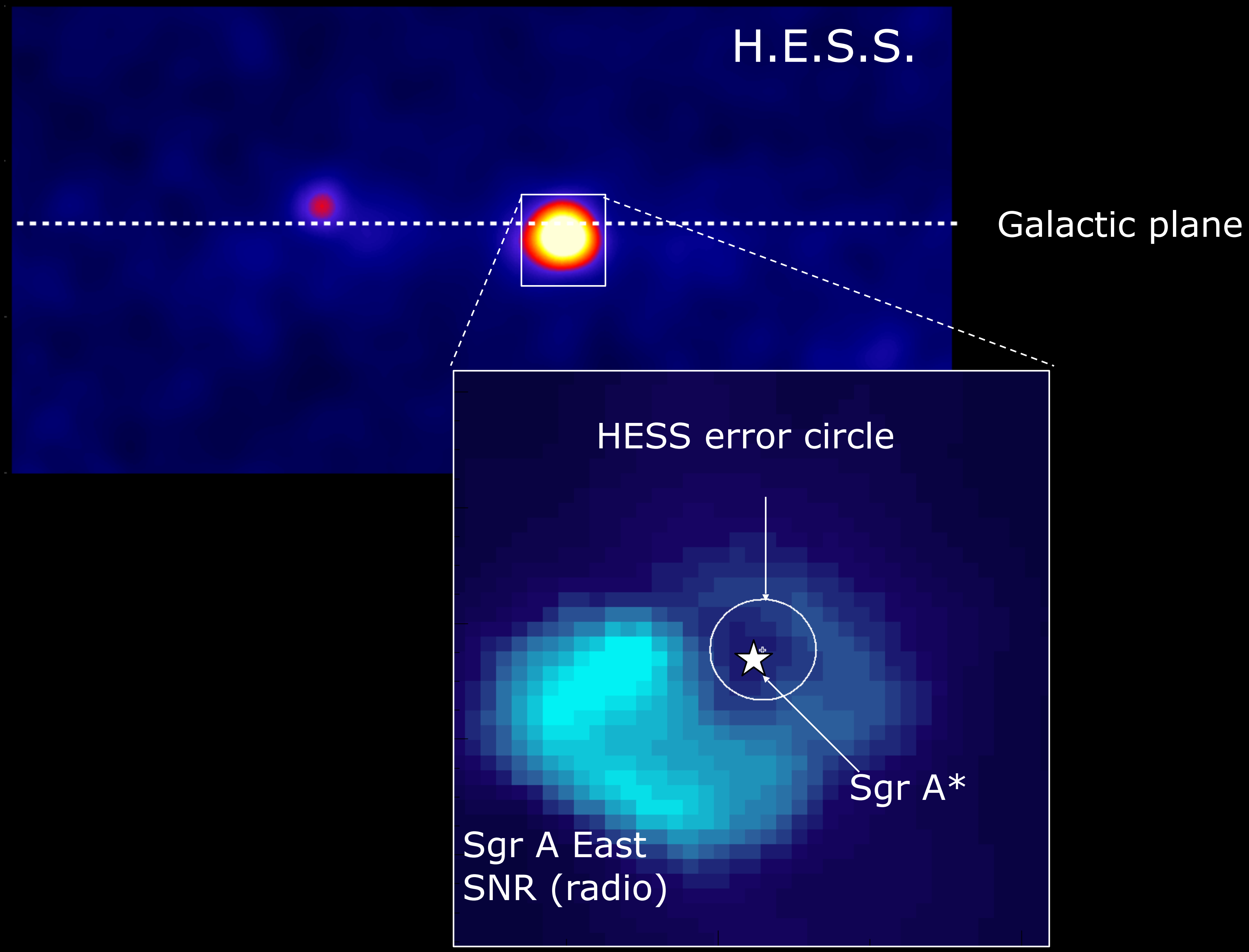
- varying absorption via pair-production ($\gamma\gamma \rightarrow e^+e^-$):
  - threshold-dependence on interaction angle (θ=π head on): $\epsilon_\gamma \, \epsilon_{soft} \, (1 - \cos\theta) = 2 m_e^2 c^4$
  - optical depth (describing absorption ∝ $e^{-\tau}$) dependent on interaction probability

$$\tau(\epsilon_\gamma) \sim (1 - \cos\theta) \; \sigma_{\gamma\gamma} \; n_{soft}(\epsilon \geq \epsilon_{soft}) \; s$$

  - at SUPC, compact object is behind star: close to head-on collision (θ=π head on) with stellar photons (point-like source of soft photons), increased absorption….

Khangulyan+ 2007

The center of our Galaxy



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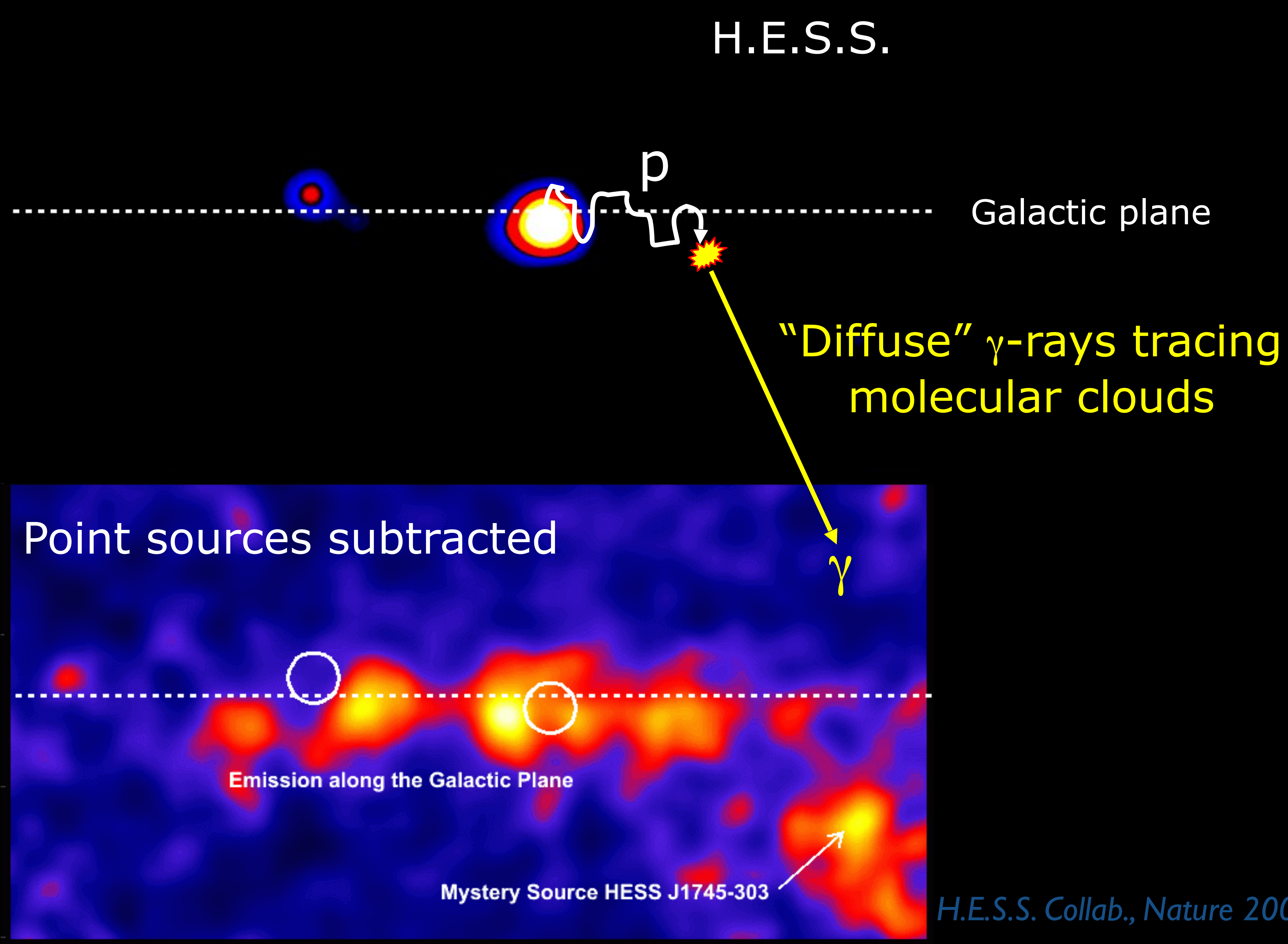
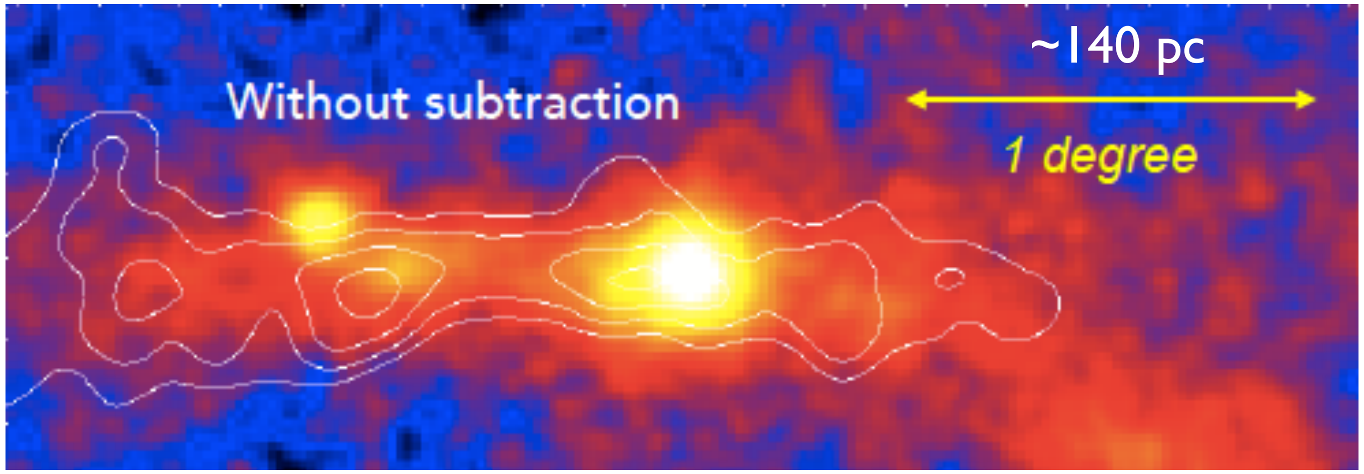


H.E.S.S. Collab., Nature 2006

Evidence for a PeVatron in the Galactic Center I



H.E.S.S. Collab., Nature 2016

- diffuse VHE emission evident (level $L_{TeV} \sim 10^{33\text{-}34}$ erg/s)
- hadronic origin (pp with clouds - correlation)
- estimate CR density in different regions from ratio of TeV flux to target material via: $L_{\gamma,i}(> E_\gamma) \sim W_{CR,i}(>10\ E_\gamma) / t_{pp,i}$
- distribution compatible with continuous injection in central 10 pc & diffusion for > 1 kyr

(Assumption: Diffusion coeff. does not vary significantly within CMZ)

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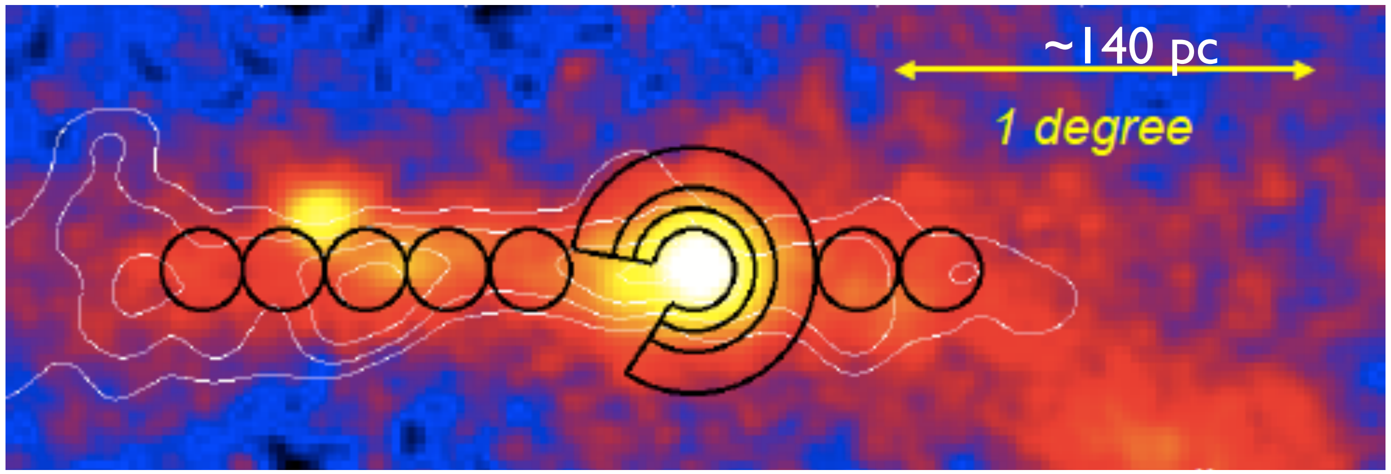

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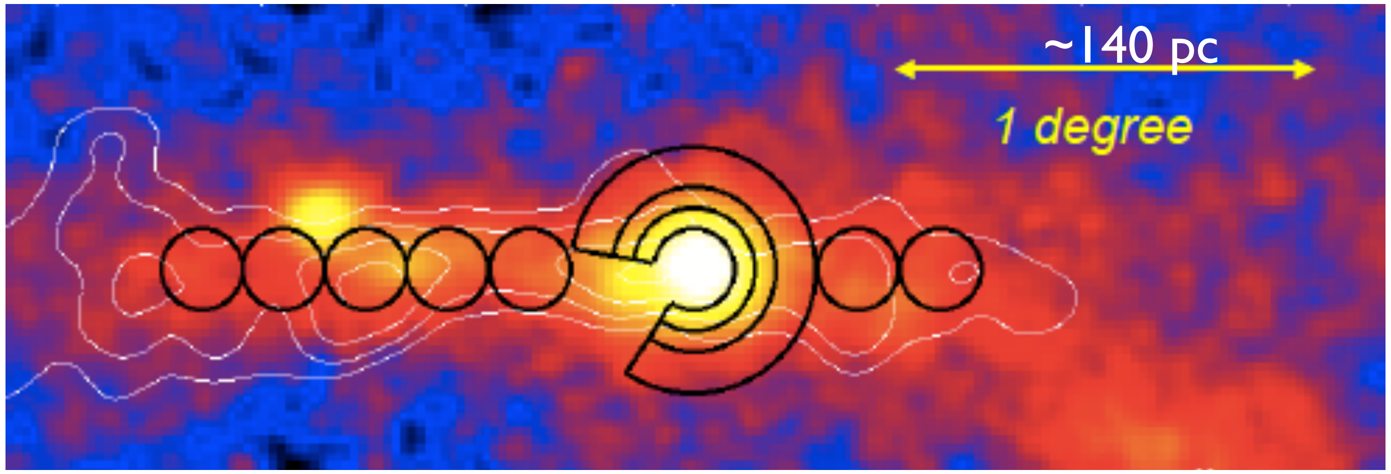

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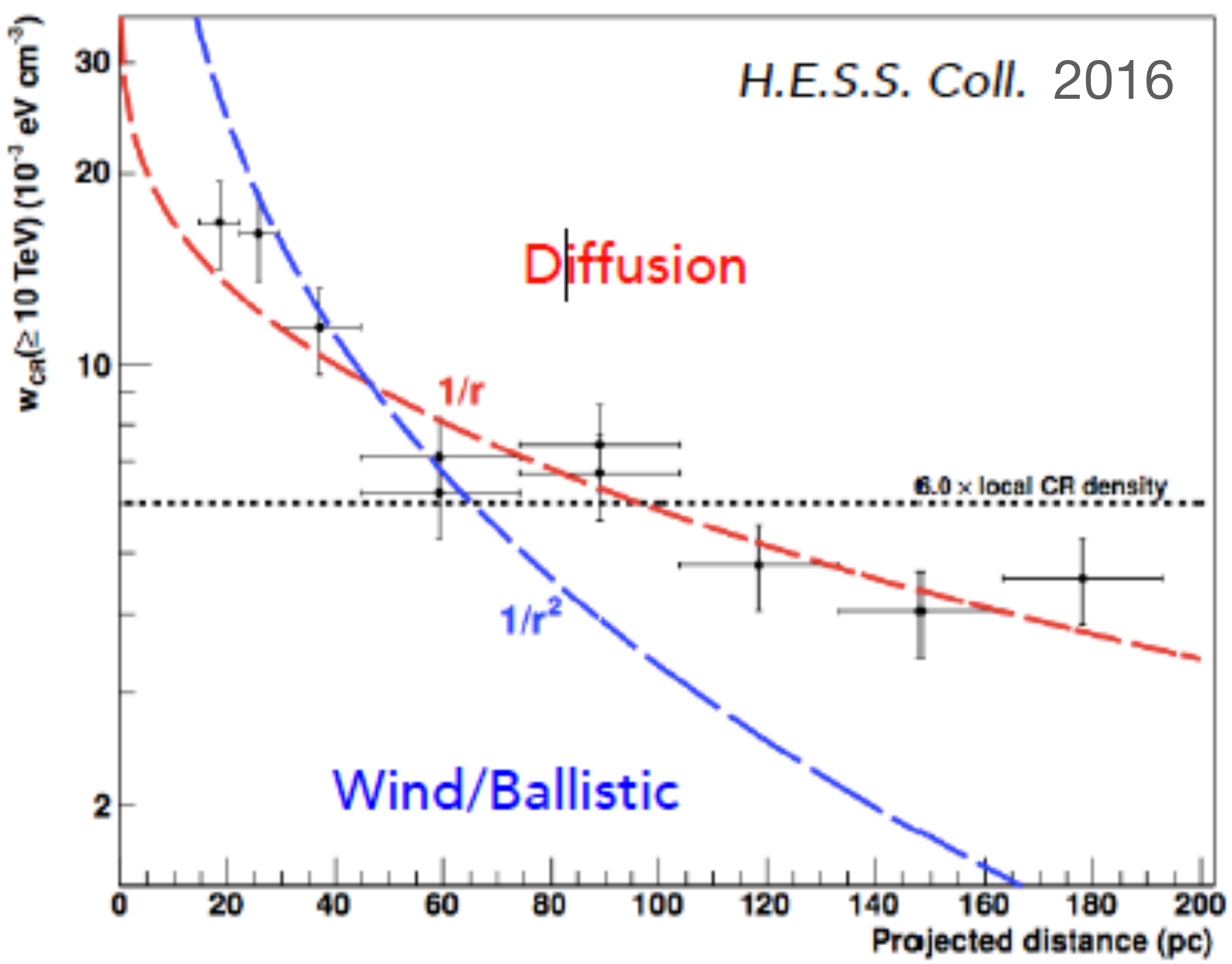

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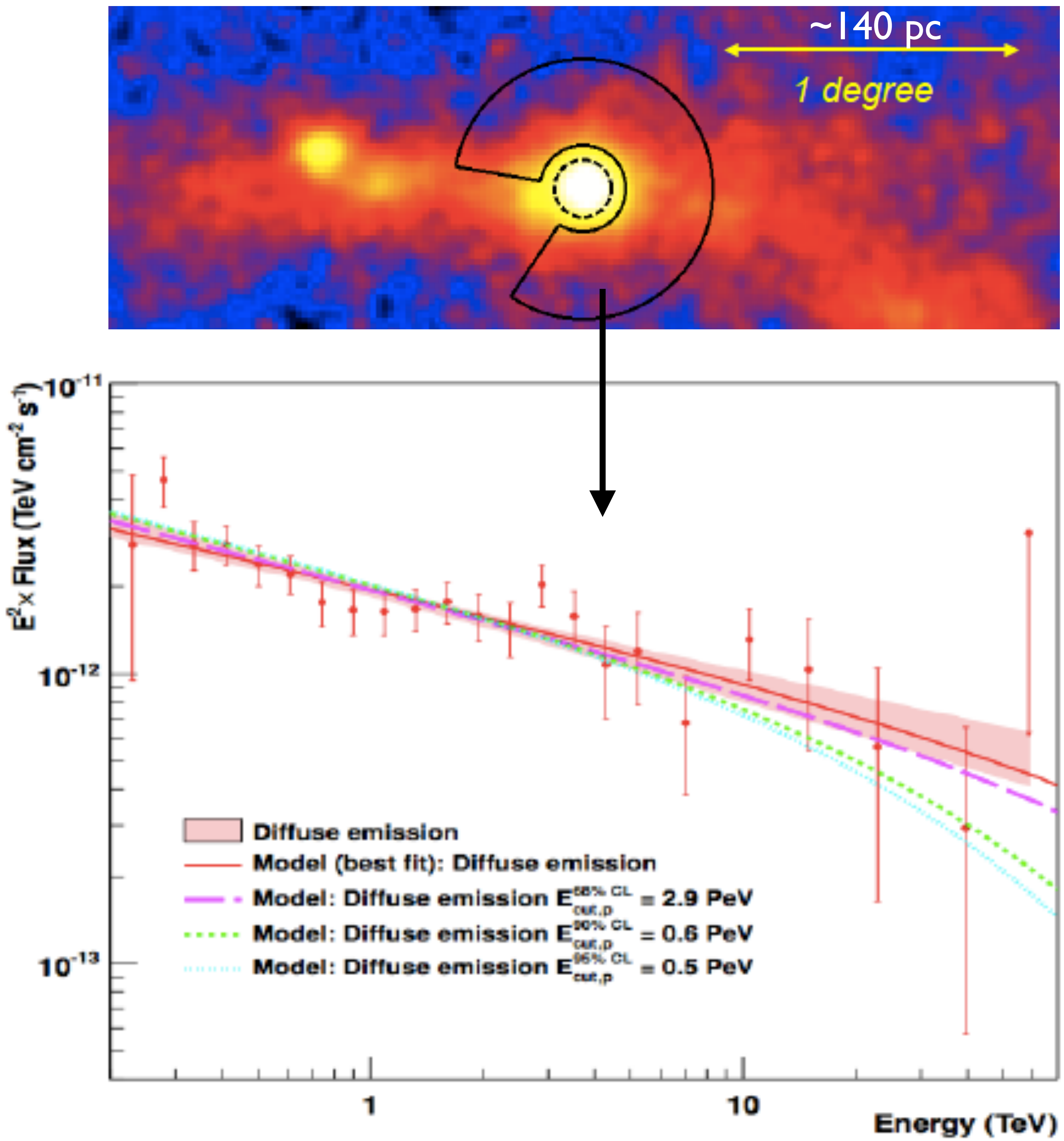
Evidence for a PeVatron in the Galactic Center II



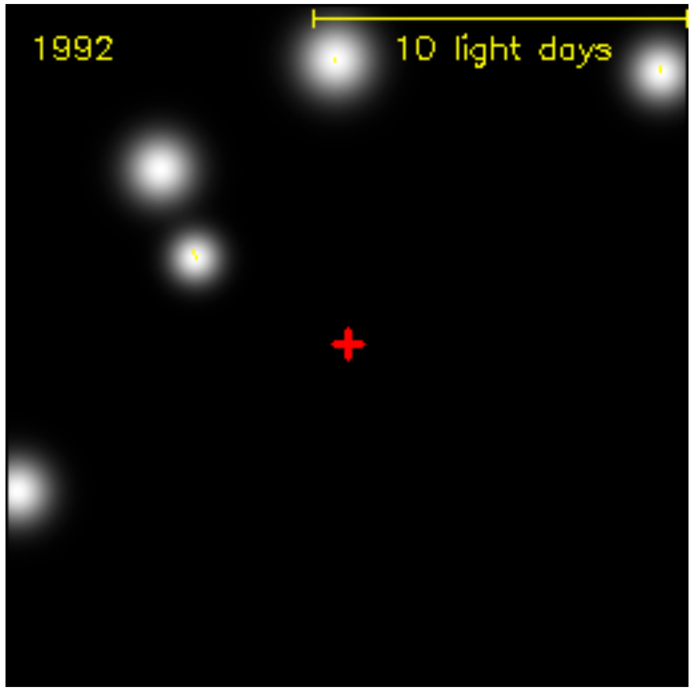
H.E.S.S. Collab., Nature 2016

- Diffuse emission shows no cut-off, spectrum implies acceleration of protons to ~PeV (10^{15}eV) energies;
- VHE CMZ emission possibly due to CR propagation from central source (black hole);
- energetically plausible (average injection rate ~few x 10^{37} erg/s)
- if more active in past, Sgr A* might have played significant role for flux of PeV cosmic rays in our galaxy (~$5x10^{38}$ erg/s)

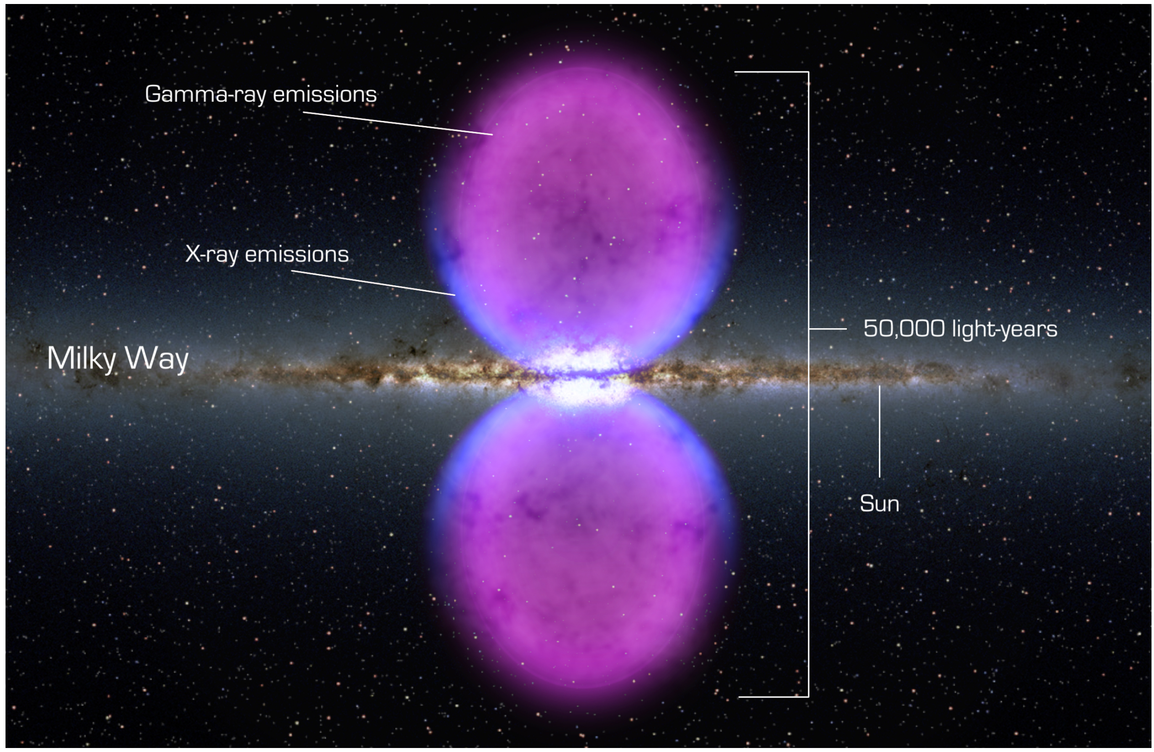
Evidence for proton acceleration up to 10^{15} eV

Basic Physics Sheet - Galactic Center Black Hole

- black hole mass inferred from infrared observations of stars on close orbits: $M_{BH} \simeq 4 \times 10^6 M_\odot$
  - Schwarzschild radius $r_s = 2\,GM_{BH} / c^2 = 1.8 \times 10^{12}$ cm
- current bolometric luminosity $L_{bol} \sim$ few $\times 10^{36}$ erg/s $\ll L_{Edd} \sim 5 \times 10^{44}$ erg/s $\Rightarrow$ very low accretion rates
- *"non-active" black hole - but could have been more active in the past (driving jets in the environment?)*
- possibly related to origin of "Fermi bubble" ?
  - gamma-ray lobes up to beyond 100 GeV (expon. cut-off?) with radio/microwave counterparts
  - sharp edges, spatially uniform (hard, $\sim E^{-2}$) spectra
  - origin: increased jet activity of Sgr A* ?
  - need $\sim 10^{52}$ erg (electrons) or $\sim 10^{55}$ erg (protons)



Gillessen 2019, MPE Garching



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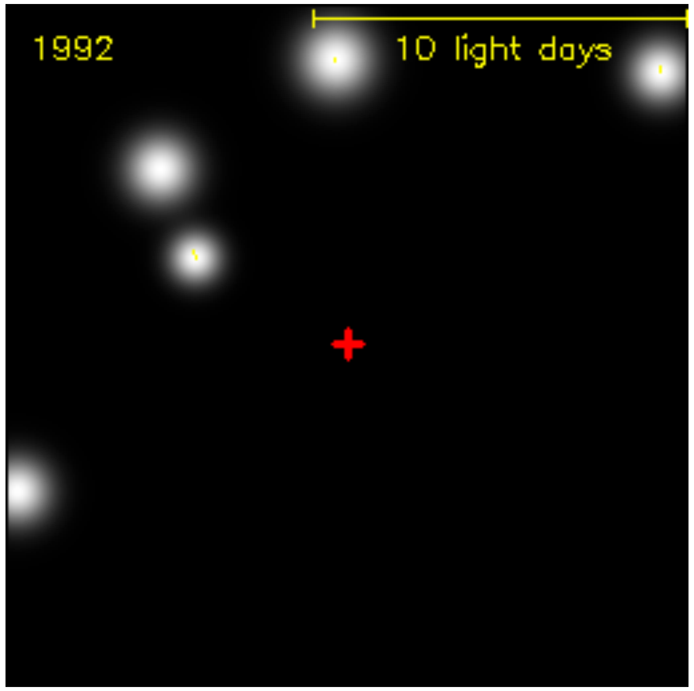

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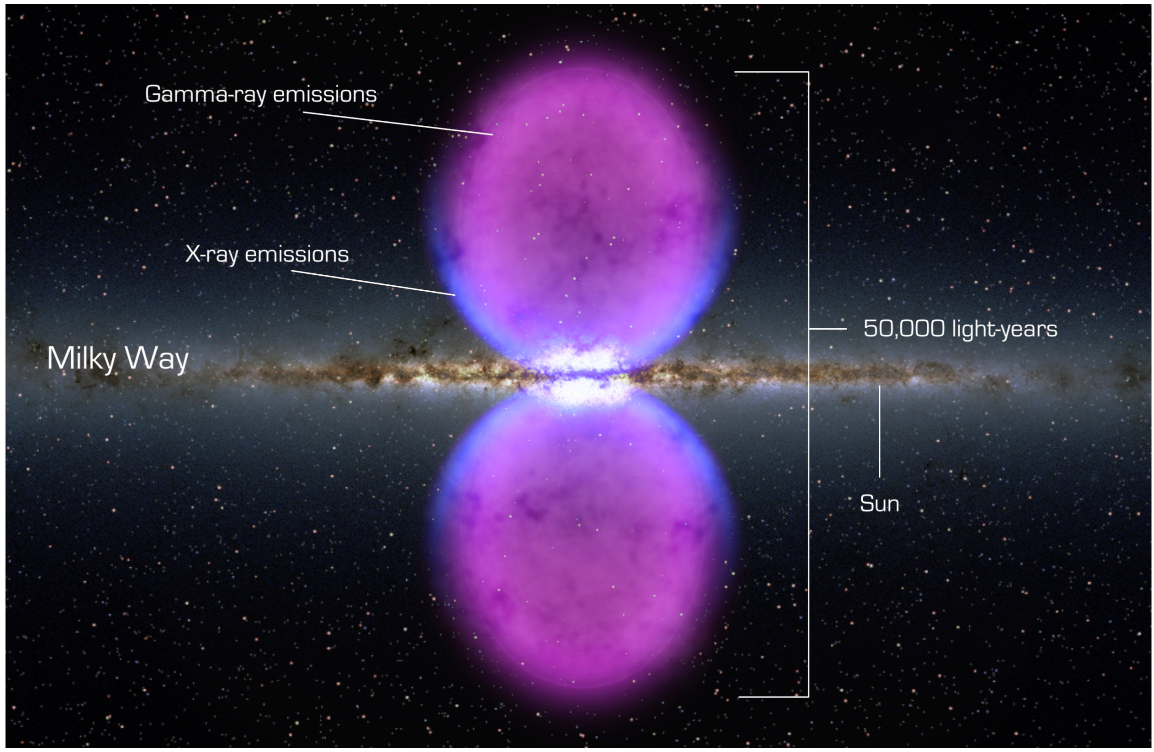
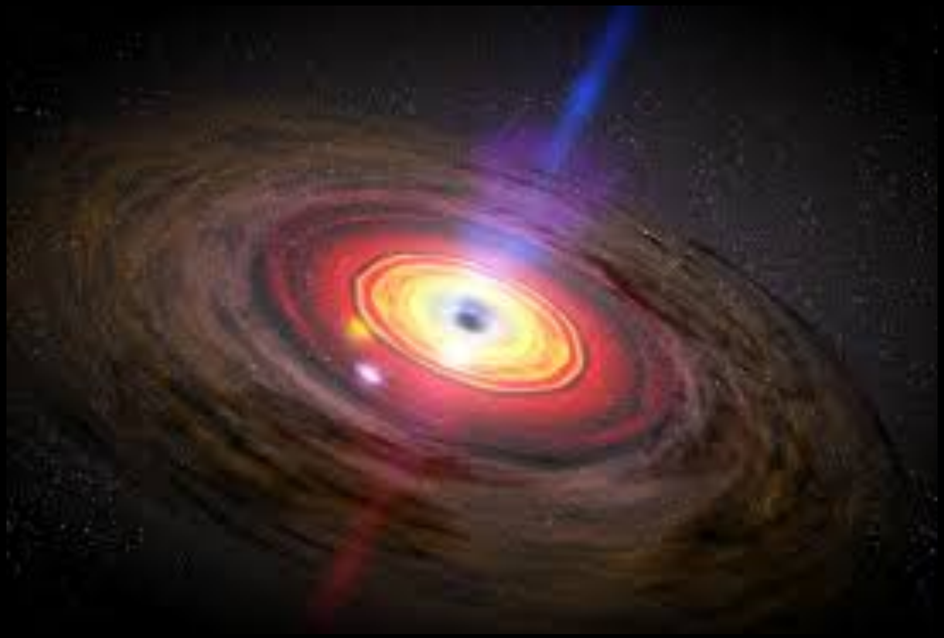
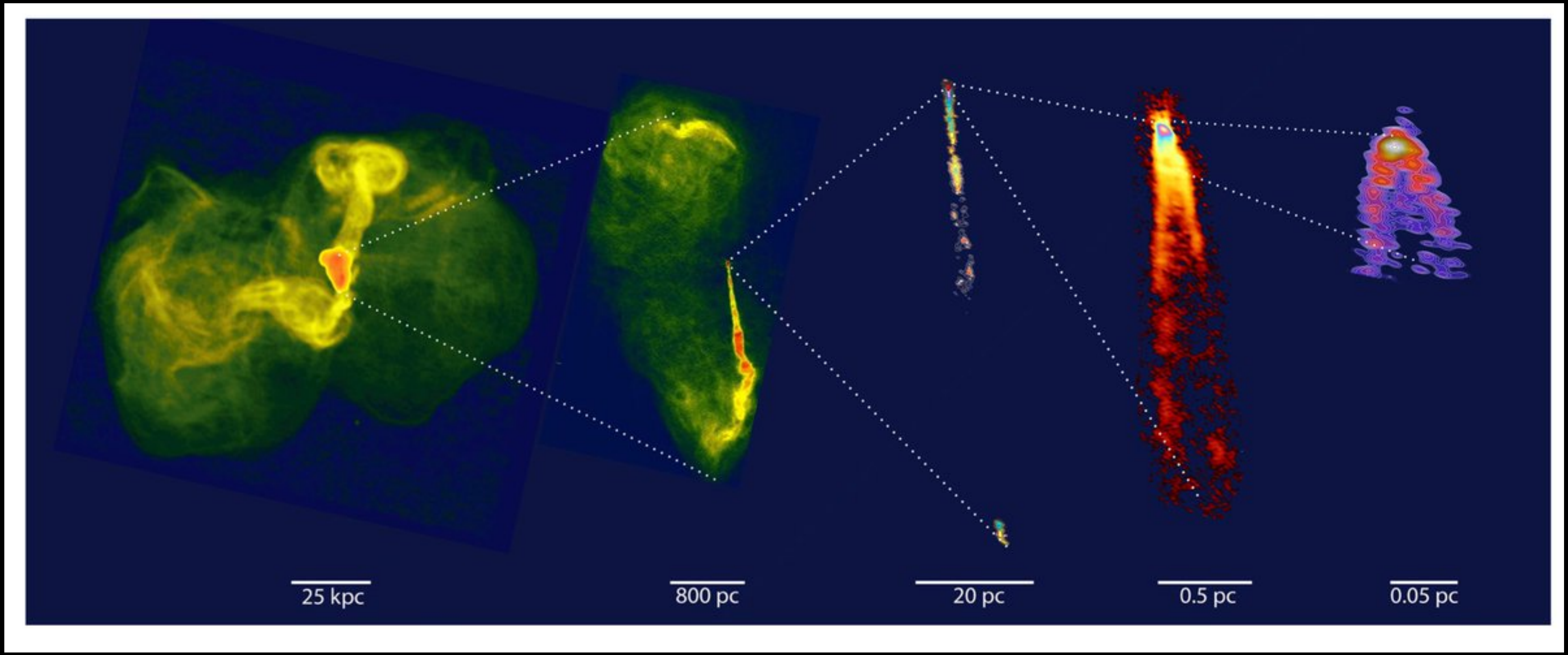




Extragalactic particle accelerators:

- Active Galactic Nuclei
- Gamma-Ray Bursts

M87 - 1st detected extragalactic VHE source

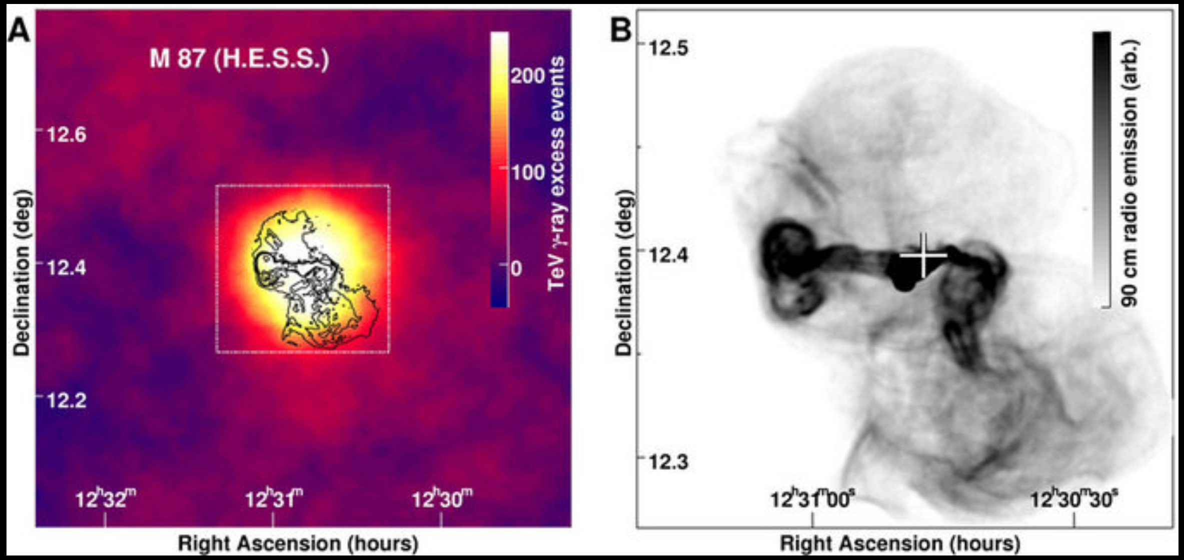


Radio Structure (credit: Blandford+ 2018)

distance ≃ 17 Mpc

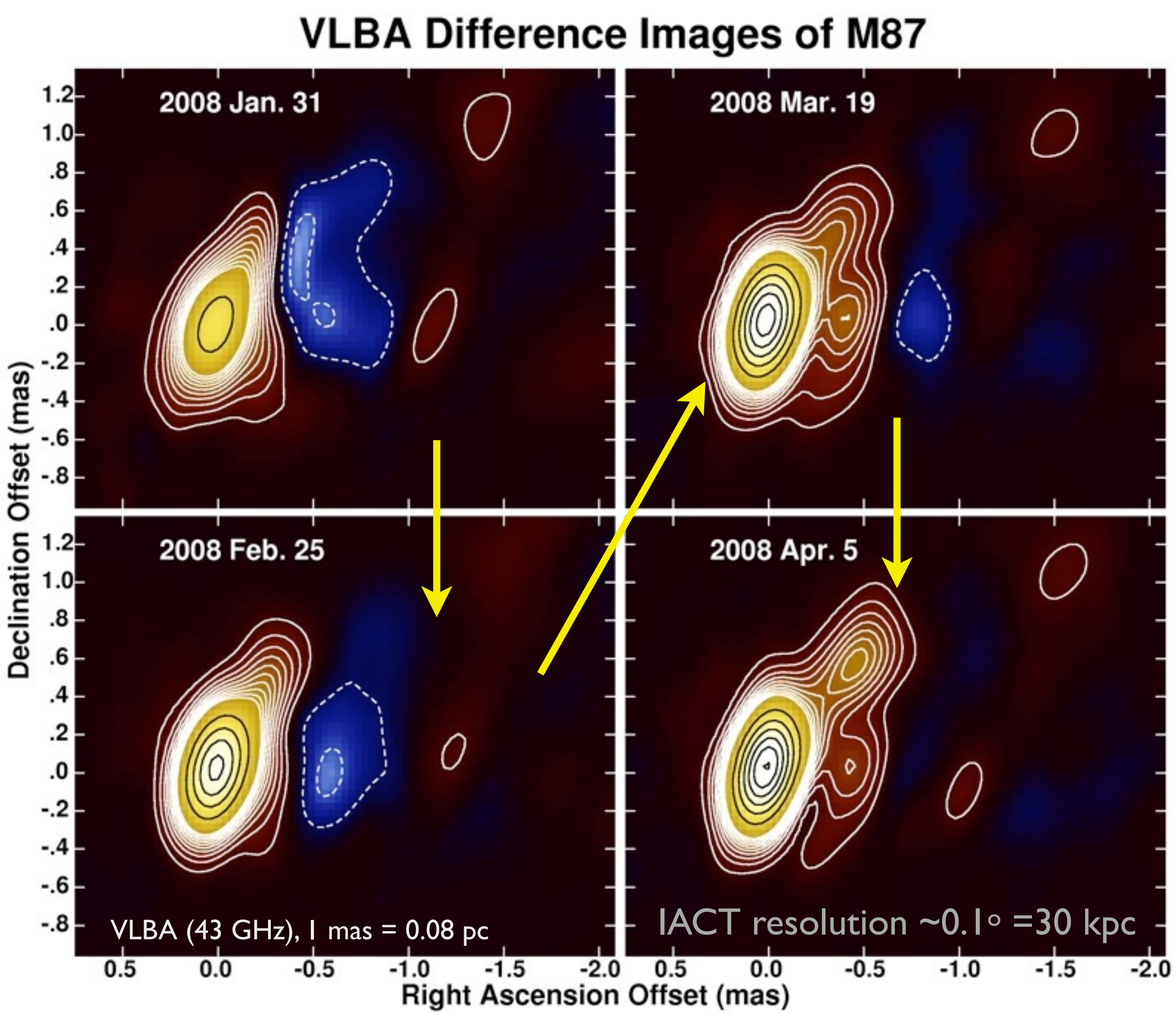
BH mass (EHT) ≃ 6.5 x 10^9 $M_\odot$

EHT Collab. 2019

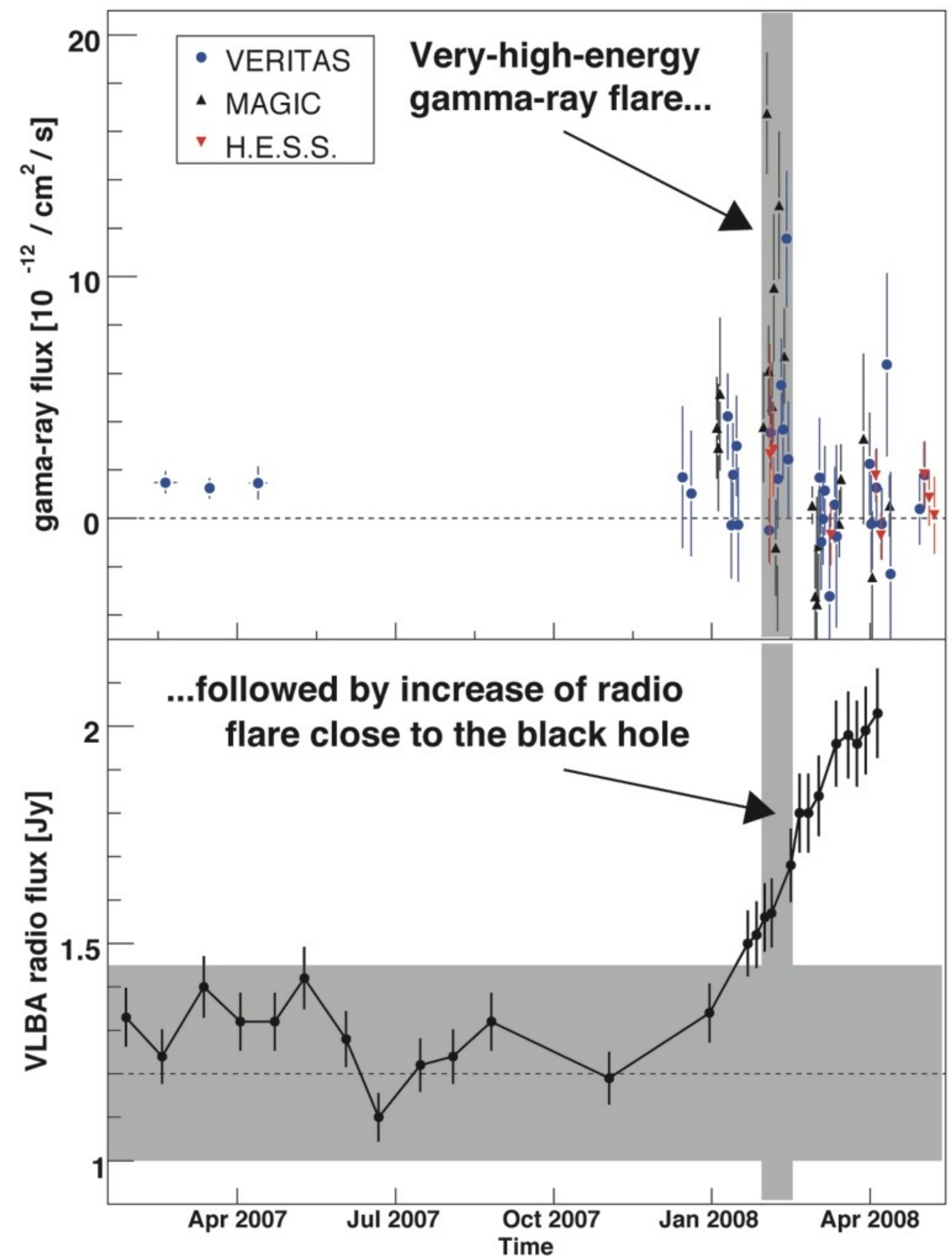


HESS Collab., 2006

M87 - towards locating the site of the VHE emission



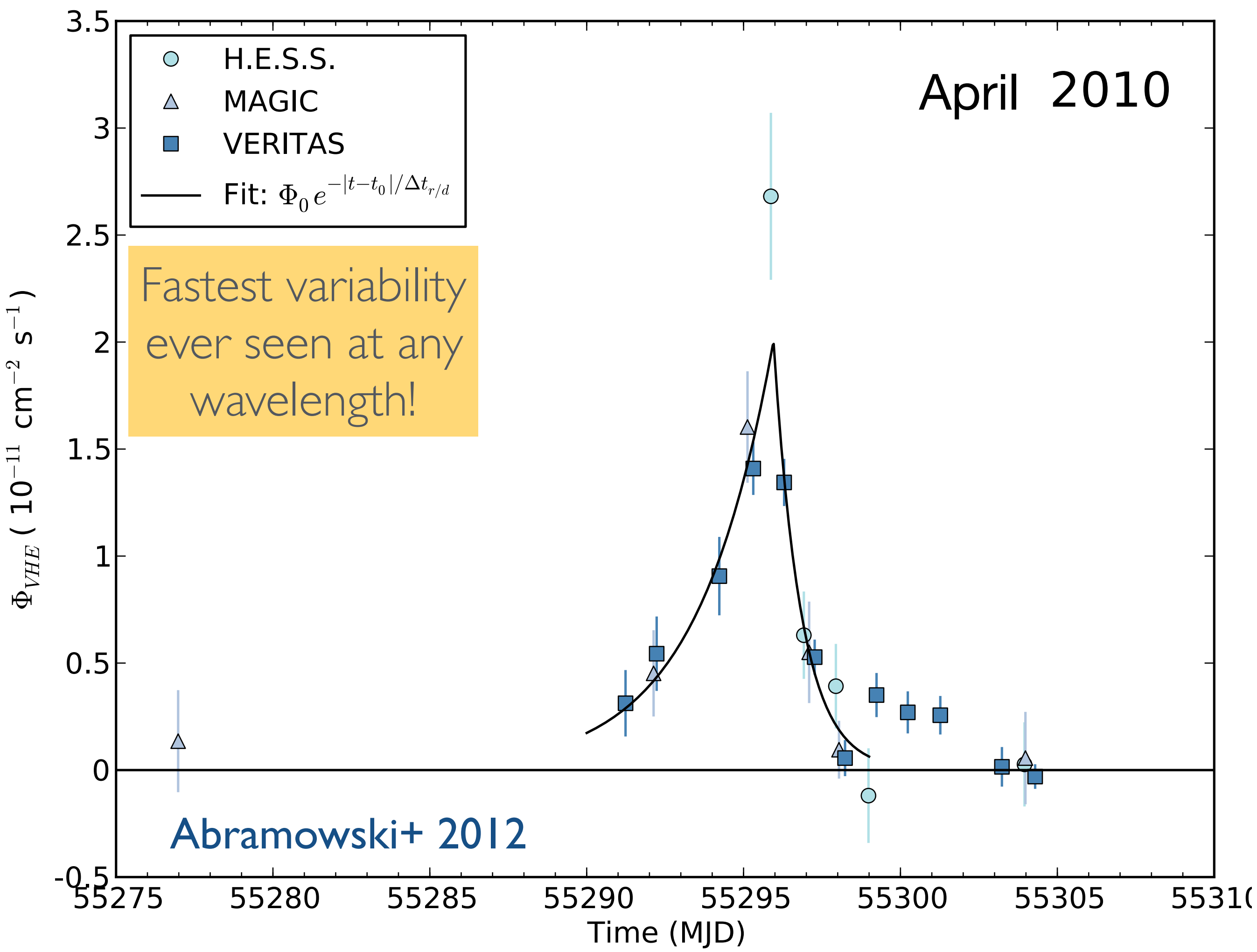
Feb. 2008 VHE flare

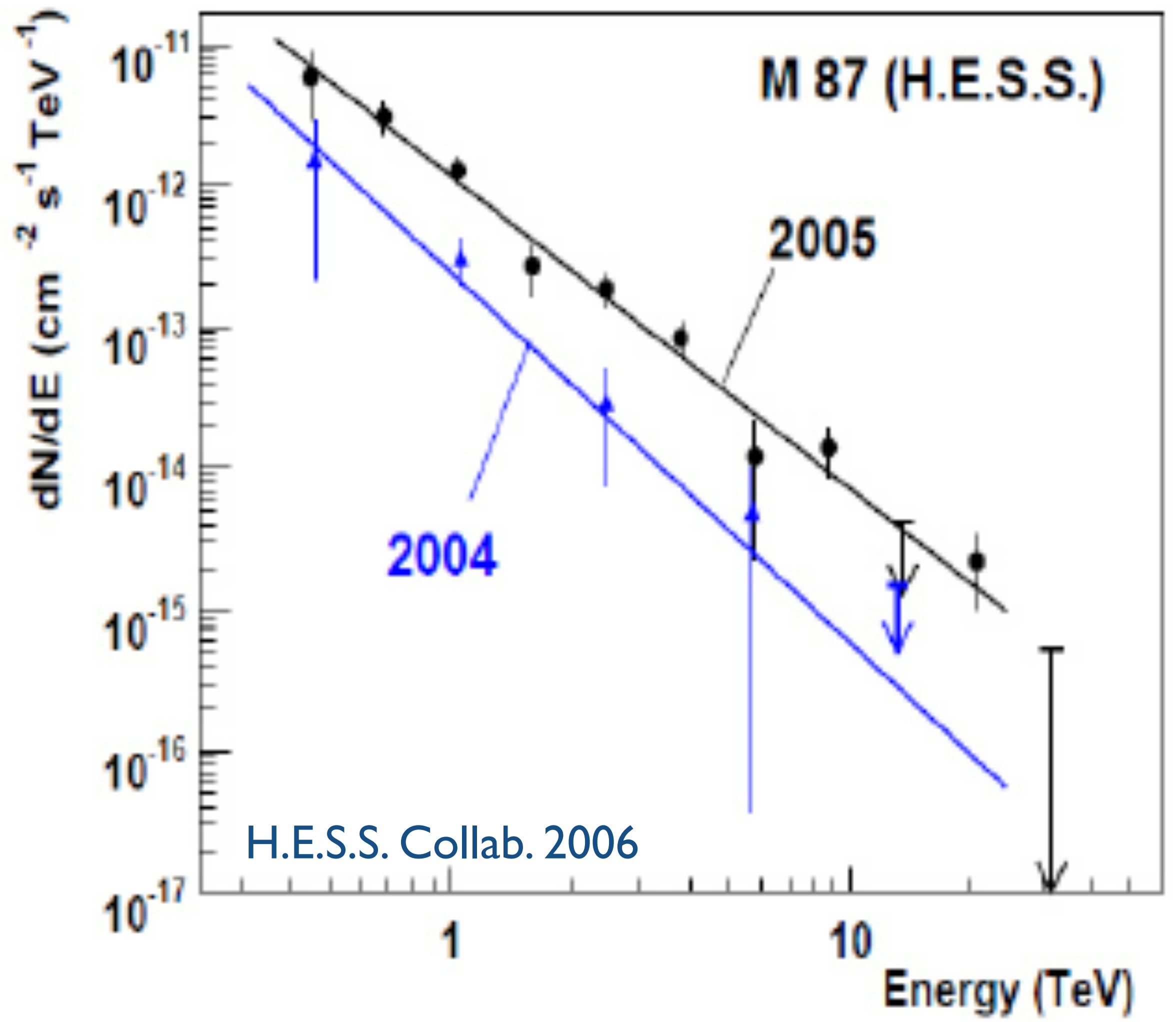


Acciari+ 2009, Science

- VHE day-scale variability implies size ~ r_s
- radio nucleus progressively brightened
- energetic particle injection close to BH ($<10^2\ r_s$)

M87 - characteristics of the VHE emission





- VHE variability down to day-scale (2005, 2008, 2010)
- VHE emission extends beyond 10 TeV

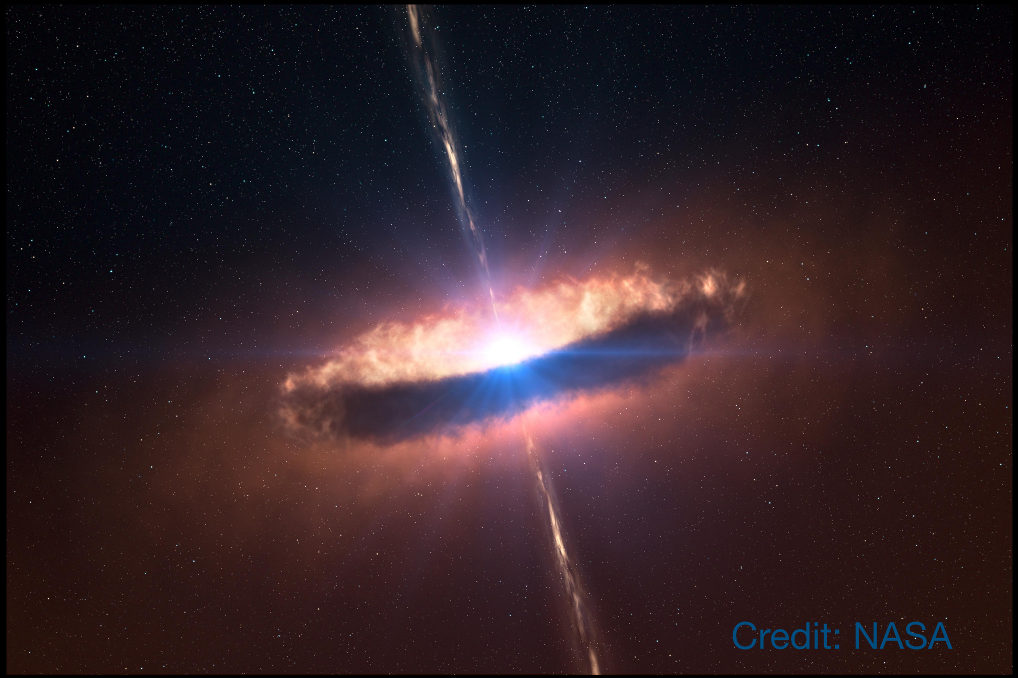
IC scattering needs > 10 TeV electrons (misaligned AGN)

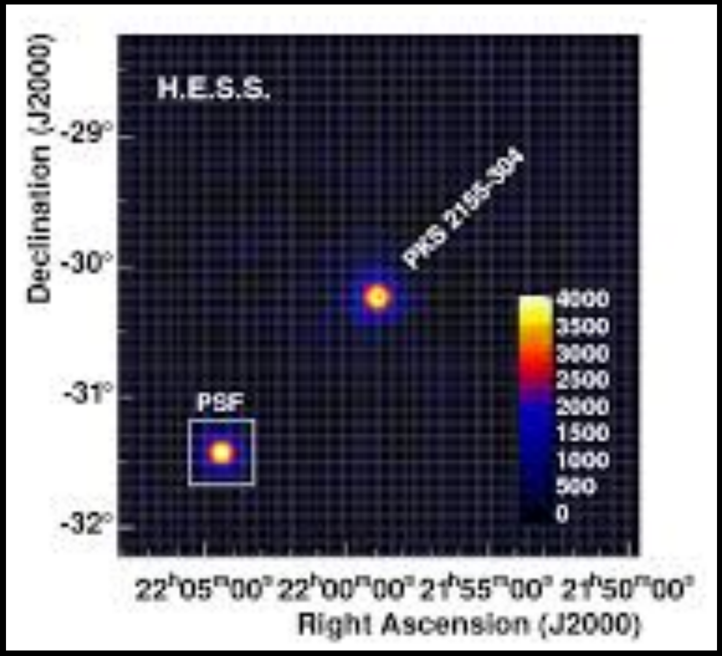
PKS 2155-304 - extreme VHE emitting source

Blazar-type AGN

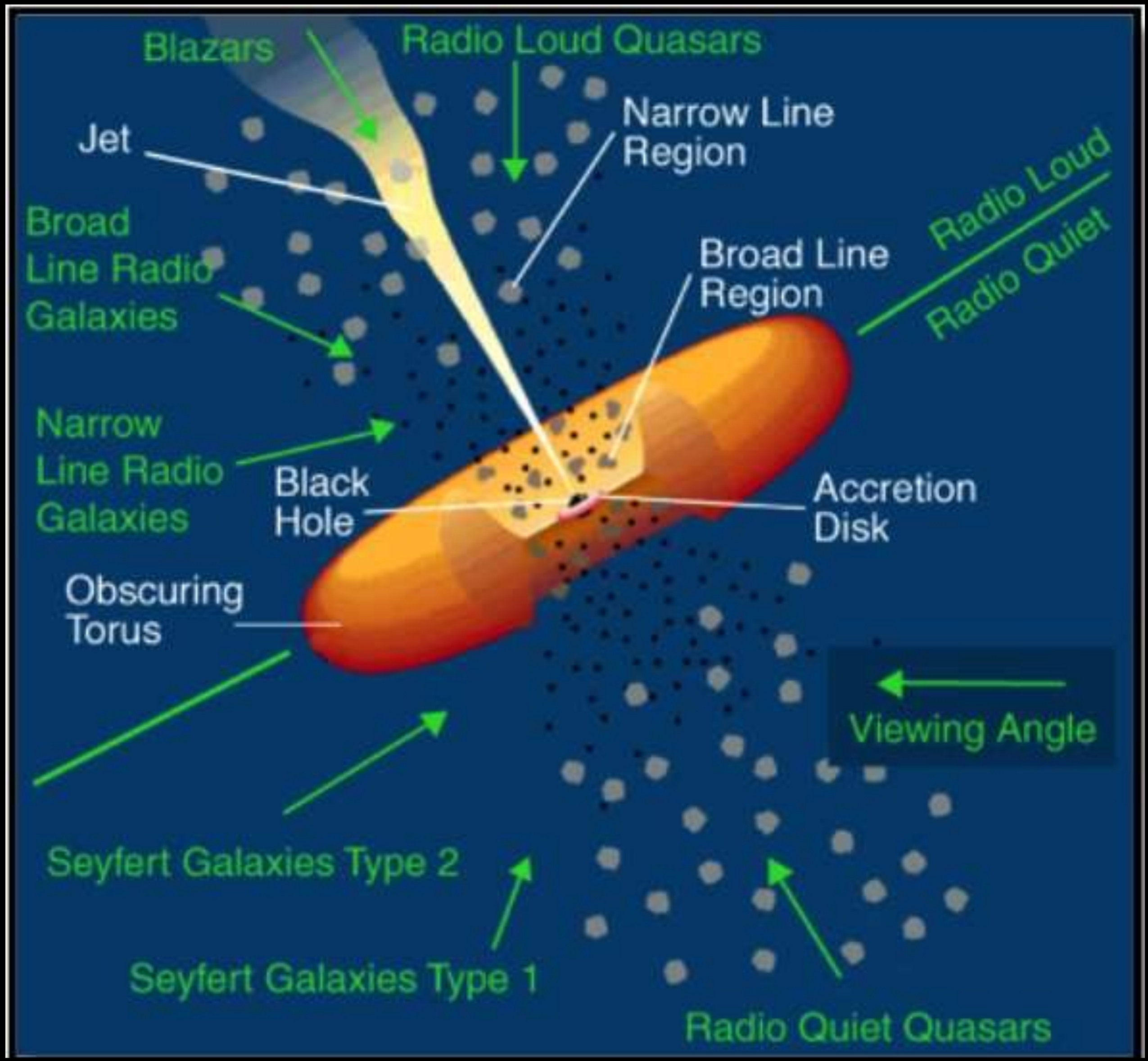
distance ≃ 540 Mpc

BH mass ~ few 10^8 $M_\odot$



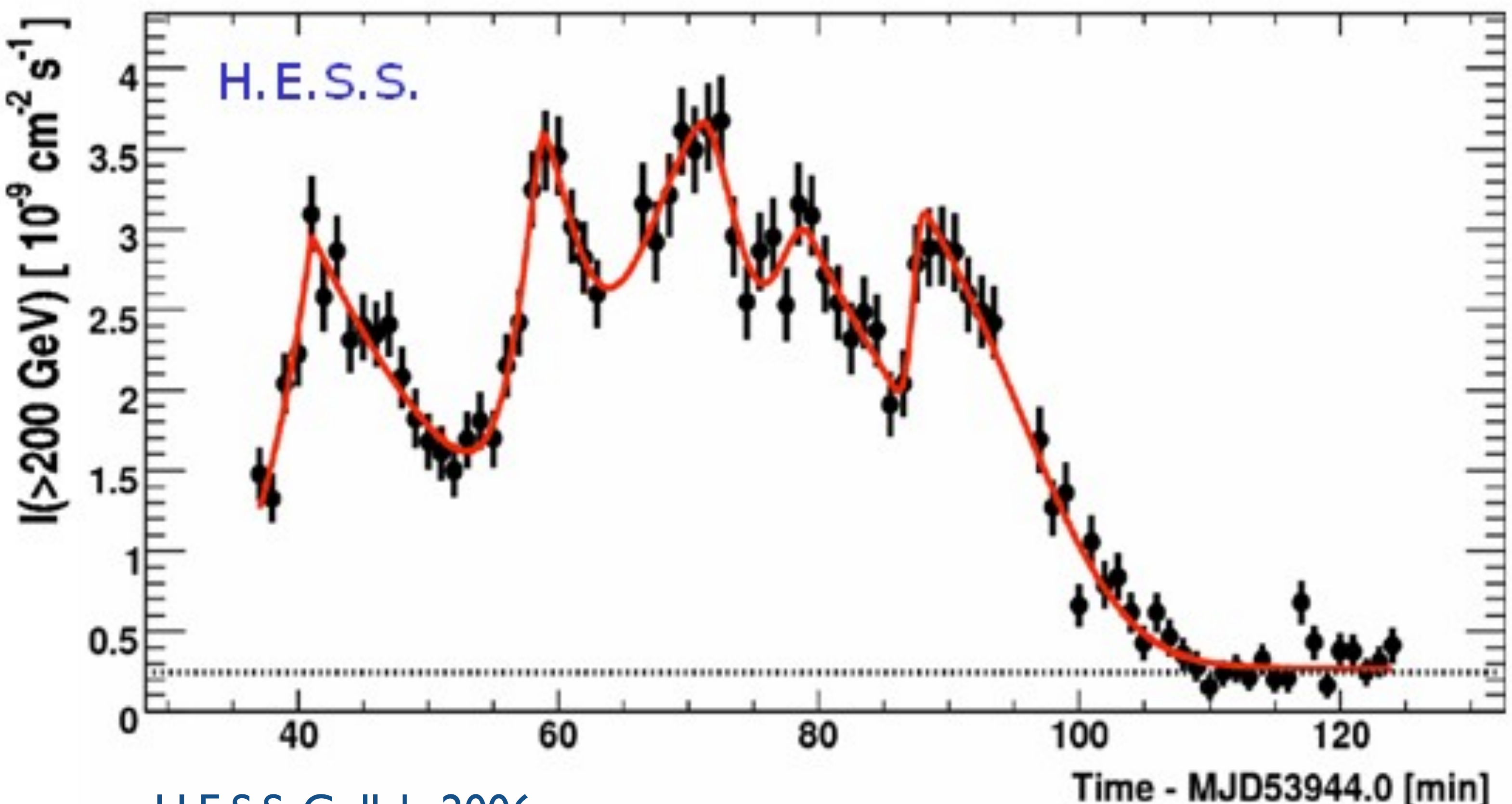


H.E.S.S. Collab. 2017

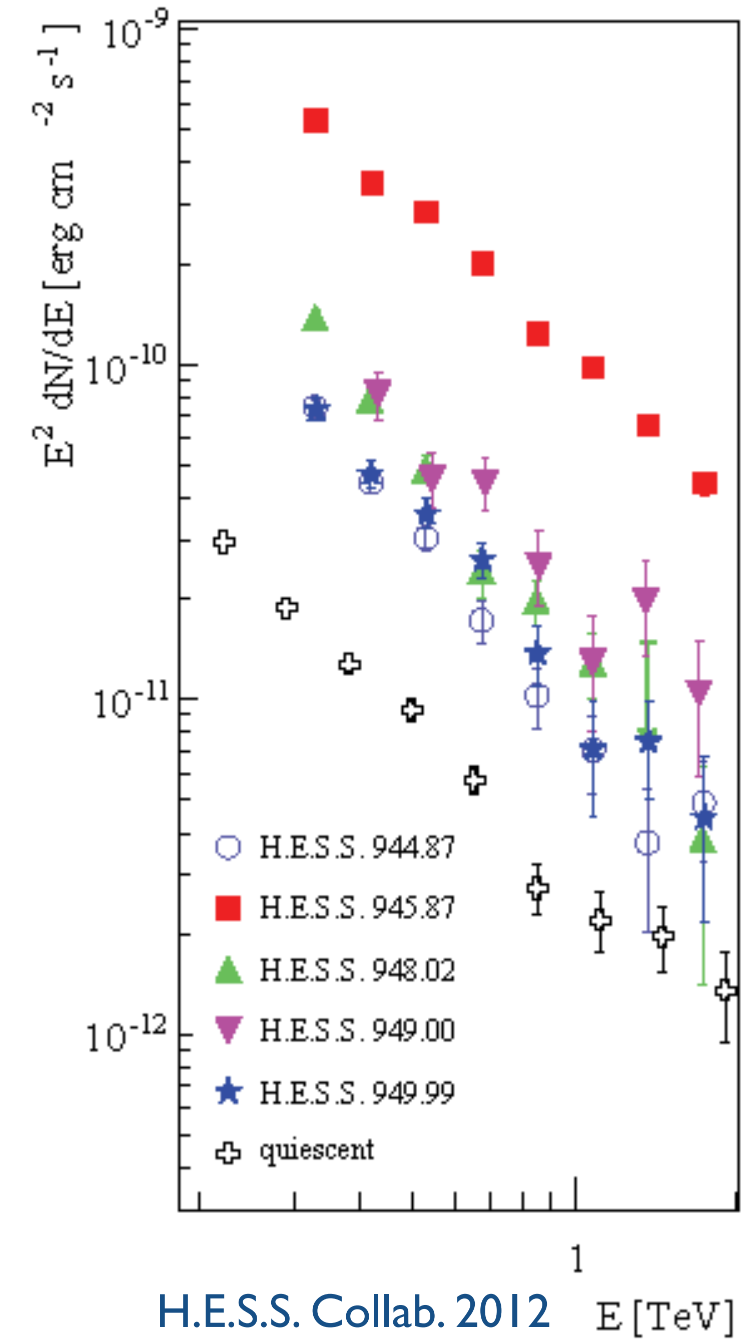


Observed emission modified by relativistic beaming

PKS 2155-304 - extreme VHE variability



H.E.S.S. Collab. 2006



H.E.S.S. Collab. 2012

- VHE variability down to a few minutes !
- VHE emission extends beyond 10 TeV

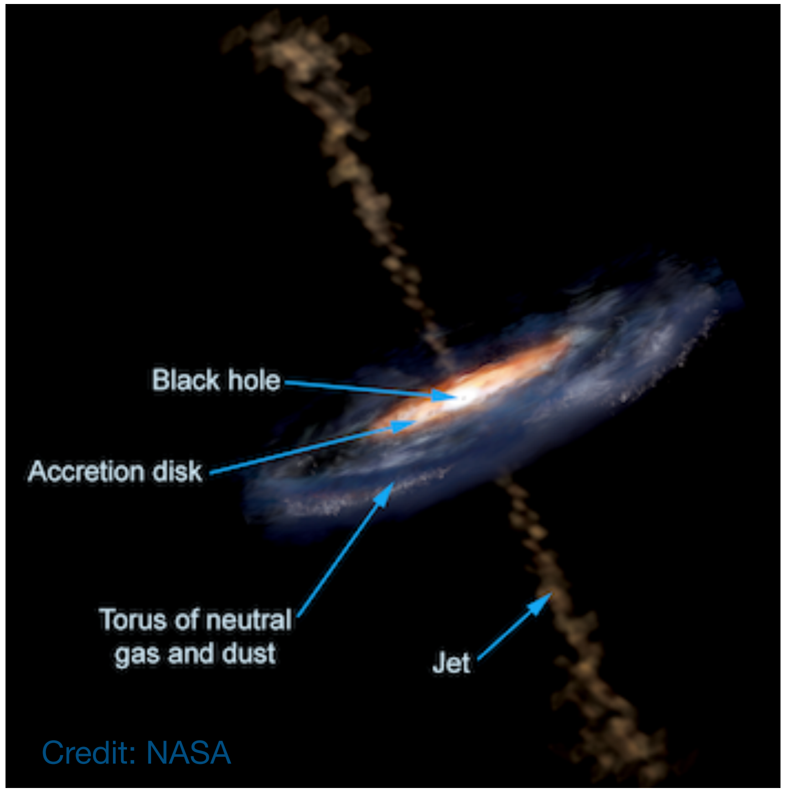
IC scattering needs > 10 TeV / Γ electrons (blazar)

Basic Physics Sheet - Active Galaxies - Active Galactic Nuclei

- only few % of all galaxies (e.g., very bright, variable, non-thermal emission, jets….)
- central engine: black hole - accretion disk - jet
- powered by accretion onto black hole: $L = \eta \dfrac{dM}{dt} c^2$
- maximum *Eddington* luminosity ($F_{rad} < F_{grav}$):

$$\sigma_T \, (L/4\pi r^2 c) \leq G M_{BH} m_p / r^2$$

$$\Rightarrow L_{\mathrm{Edd}} = 1.3 \times 10^{46} \, (M_{BH}/10^8 M_\odot) \text{ erg/sec}$$



BH mass $10^6 < M_{BH}/M_\odot < 10^{10}$
outflow speeds (jets) $\Gamma \lesssim 50$

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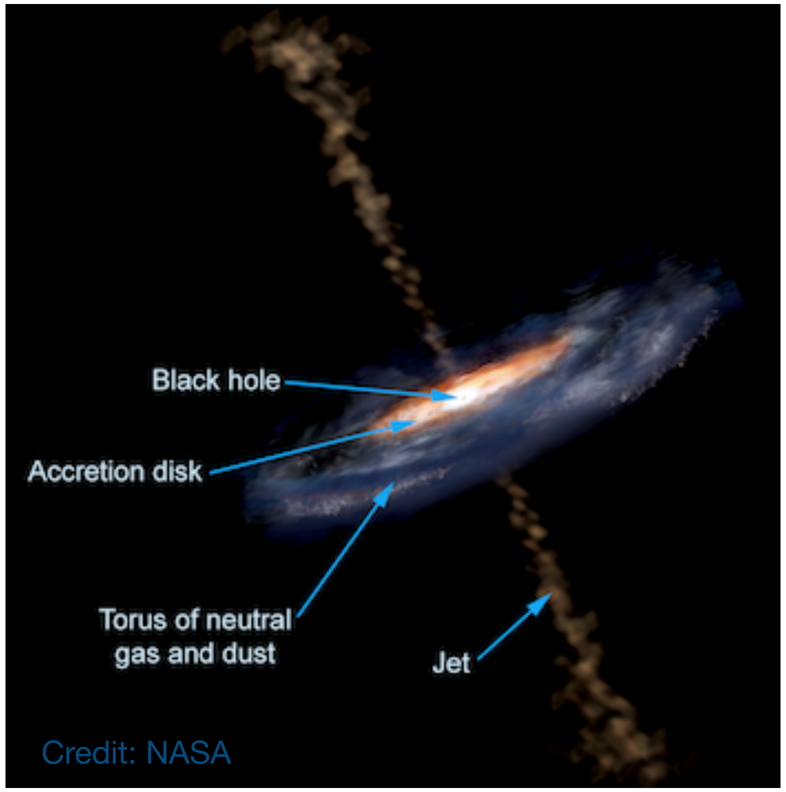
- powered by accretion onto black hole: $L = \eta \dfrac{dM}{dt} c^2$
- **maximum *Eddington* luminosity ($F_{rad} < F_{grav}$):**

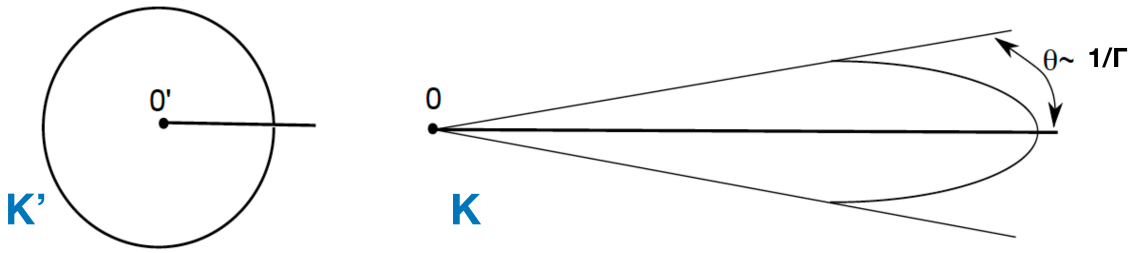
$$\sigma_T \, (L/4\pi r^2 c) \leq G M_{BH} m_p / r^2$$

$$\Rightarrow L_{\mathrm{Edd}} = 1.3 \times 10^{46} \, (M_{BH}/10^8 M_\odot) \text{ erg/sec}$$



BH mass $10^6 < M_{BH}/M_\odot < 10^{10}$
outflow speeds (jets) $\Gamma \lesssim 50$

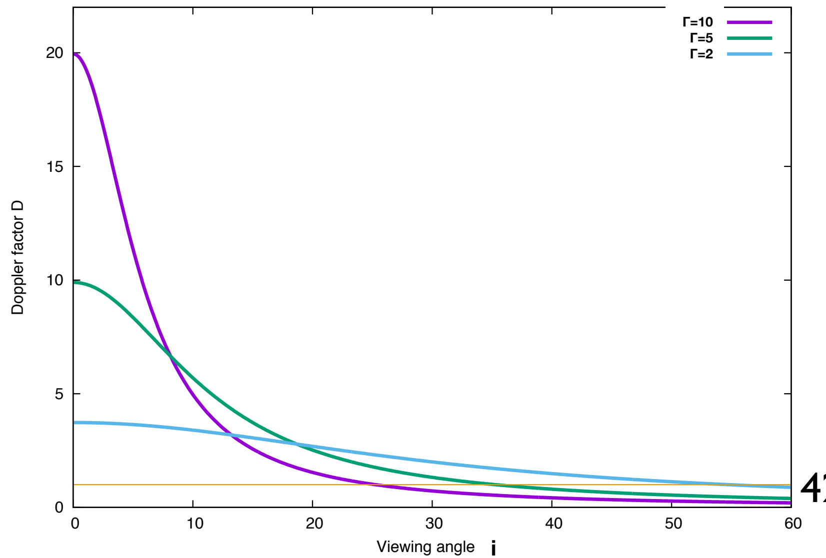
- *relativistic effects important* for $\Gamma = 1/(1-\beta^2)^{1/2} >> 1$:

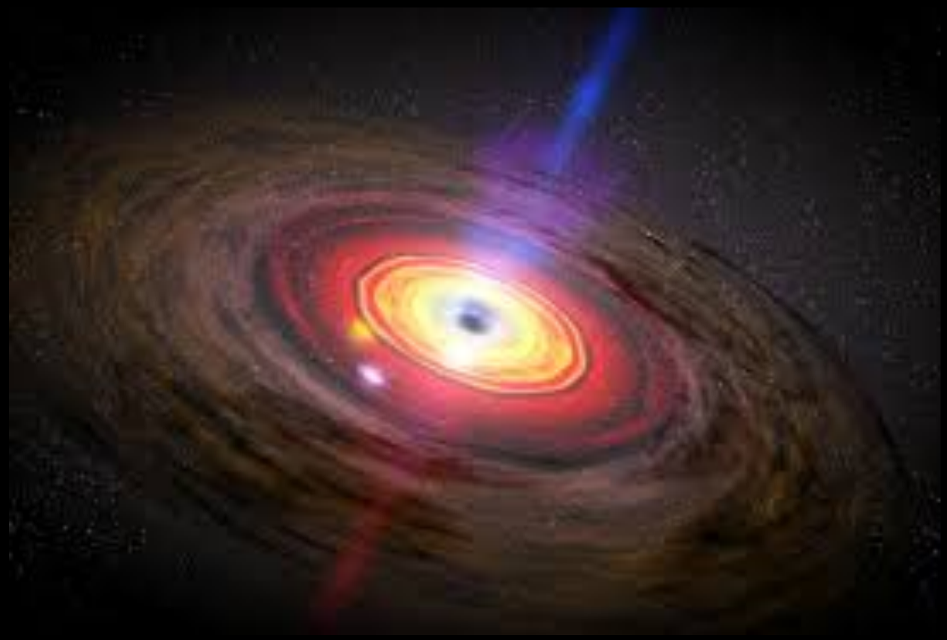


  - relativistic aberration: $\theta' \sim \pi/2 \;\; \Rightarrow \;\; \theta \sim 1/\Gamma$ (**beaming**)
  - relativistic Doppler effect: $h\nu_{obs} = D \, h\nu'$

$$D := \frac{1}{\Gamma \, (1 - \beta \cos i)} \;\leq\; 2\Gamma$$

  - **$L = D^4 L'$, $F_\nu(\nu) = D^3 F_{\nu'}(\nu')$ …**

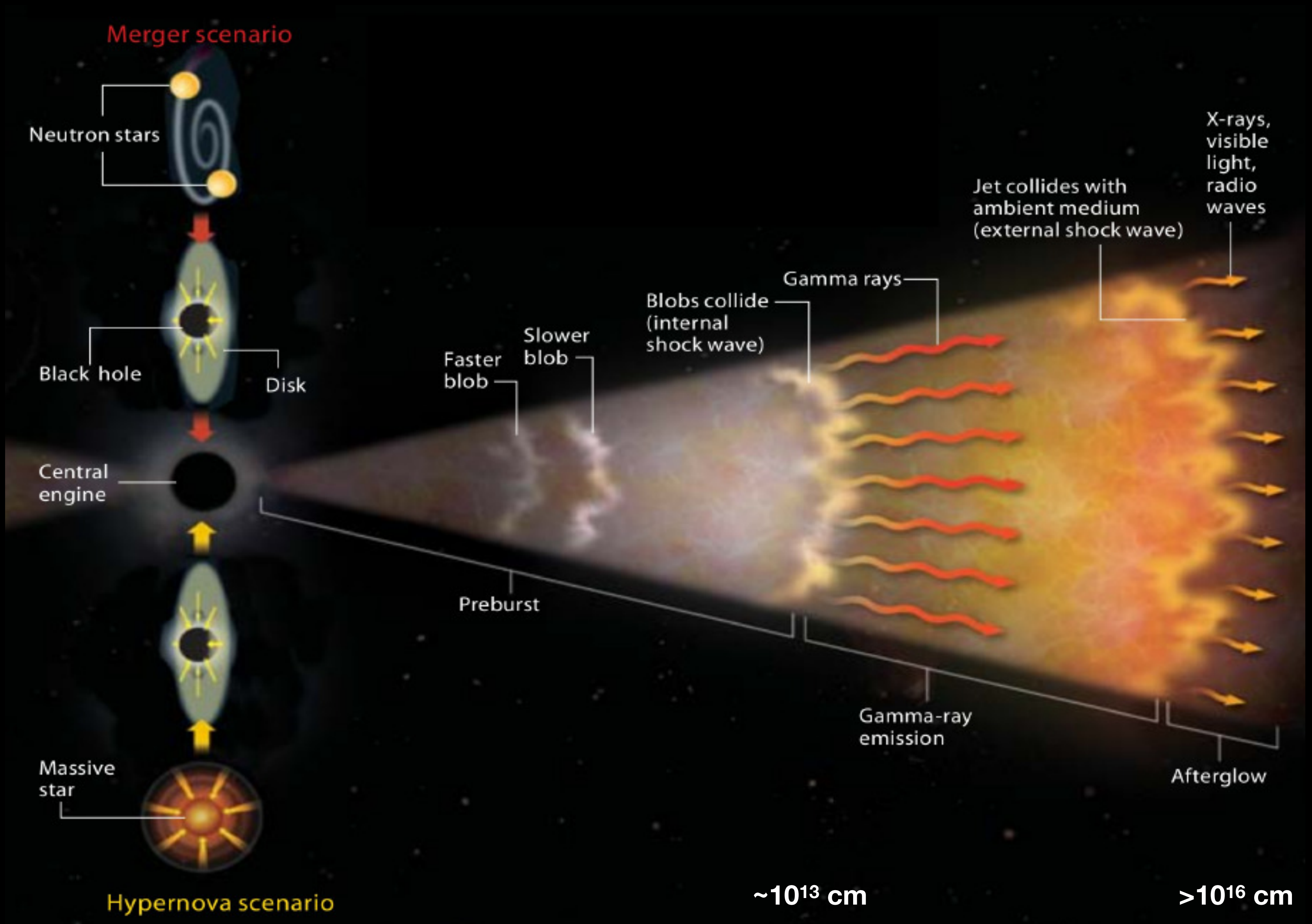




Extragalactic particle accelerators:

- Active Galactic Nuclei
- Gamma-Ray Bursts

GRB 190114C - first VHE detection (Jan 2019)



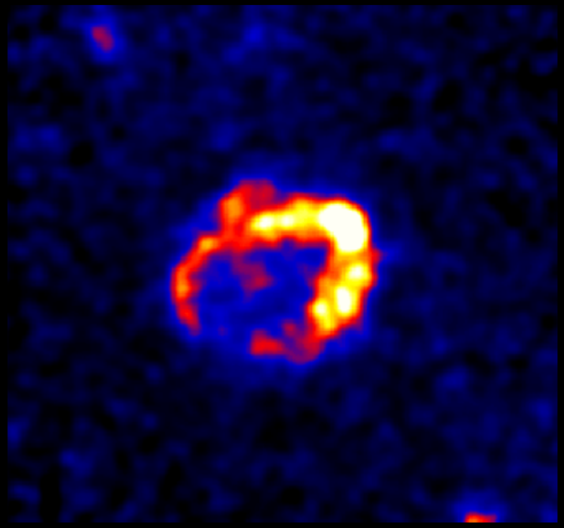
Credit: NASA

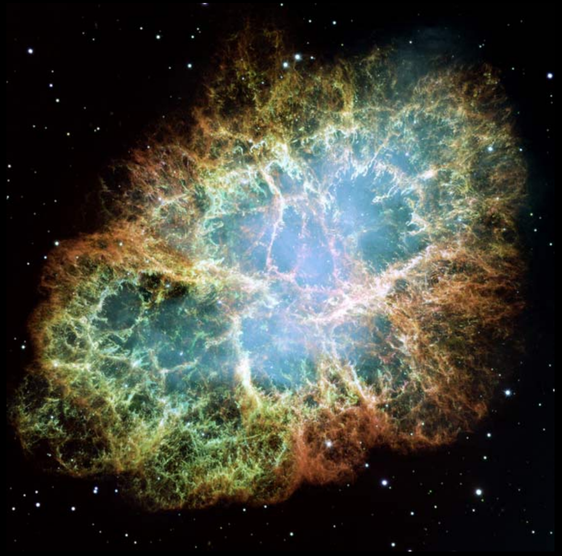
- distance z=0.4245 (d~2000 Mpc).
- VHE emission >300 GeV detected (~50 sec after Swift alert at ~100 keV).
- prompt (~4 sec) phase seen by Fermi-GBM (10 keV-40 MeV).
- initial bulk flow Lorentz factor Γ_0~ 500.
- Inverse Compton (optical-infrared) or SSC (prompt) by shock-accelerated e^-?
- KN energy limit = $\Gamma \chi_c m_e c^2$

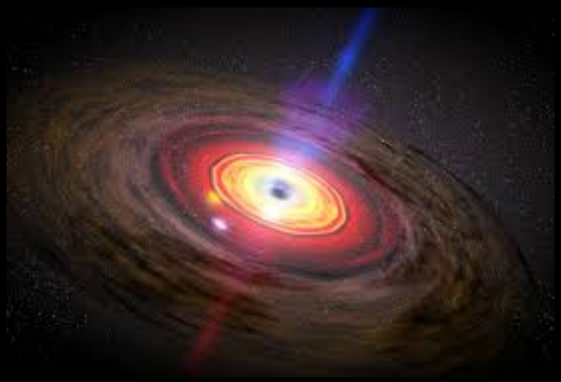
MAGIC Collab 2019 (ATtel)

Ravasio+ 2019

Cosmic (Particle) Accelerators I







- Supernova Remnants
- Pulsars
- Pulsar Wind Nebulae
- Binaries
- Black Holes & AGNs
- Gamma-Ray Bursts
- ....

- cosmic-rays from $10^{15\text{-}16}$ (galactic) to 10^{20} eV
- > 10 TeV gamma-rays, e.g. $\gamma_e \gtrsim 10^7$ (IC-KN)