Galactic sources

Astrophysical sources of cosmic rays
Paris-Saclay ISAPP school

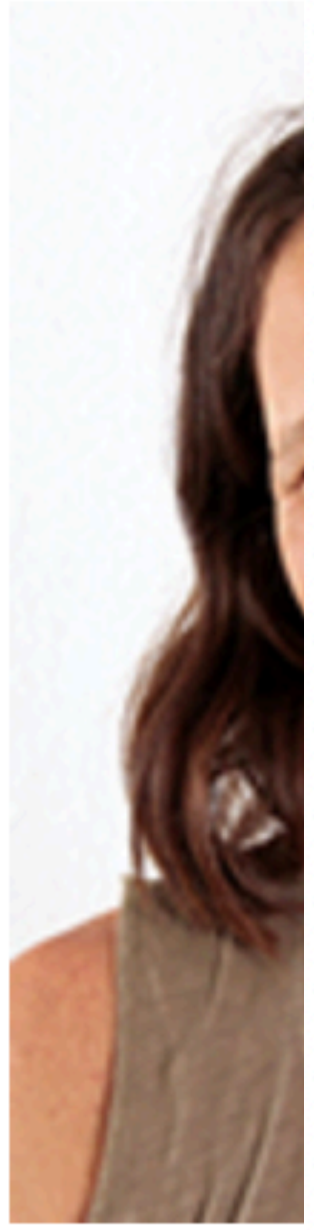
Emma de Oña Wilhelmi - DESY-Zeuthen, Germany

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Who am I?

Presentation



	9:00 - 10:45	11:15 - 13:00		14:15 - 16:00	16:30 - 18:00	19:00 - 20:00
Monday 28/03	Arrival	Arrival		Astrophysics introductory course (H. Dole)		
Tuesday 29/03	Particle physics introductory course (N. Besson)	Radiation mechanisms (R. Aloisio)		Multimessenger astroparticle introductory course (K. Kotera)	Student presentations	
Wednesday 30/03	Physics of high-energy showers (R. Engel)	Statistical methods (G. Mention)		Radiation mechanisms (R. Aloisio)	Student presentations	Public lecture, in Fre La quête de nos origi cosmiques avec le télescope spatial Jan Webb (D. Elbaz)
Thursday 31/03	Particle acceleration and transport (P. Blasi)	Extensive air showers detection (P. Ghia)		Physics of high-energy showers (R. Engel)	Hands-on: high-energy shower modelling (T. Pierog)	
Friday 01/04	Particle acceleration and transport (P. Blasi)	The Cherenkov Telescope Array and its science (W. Hofmann)		Visit to NectarCAM		
Saturday 02/04						
Sunday 03/04						
Monday 04/04	Neutrino Telescopes and Results (M. Ahlers)	Advanced statistical methods (J. Bobin)		Galactic sources (E. de Oña Wilhelmi)	Seminar: SVOM and gamma-ray bursts (F. Daigne)	
Tuesday 05/04	CR probes of fundamental physics (P. Serpico)	Galactic sources (E. de Oña Wilhelmi)		Extragalactic sources (E. Lindfors)	Student presentations	
Wednesday 06/04	CR probes of fundamental physics (P. Serpico)	Cosmic ray and gamma ray detection, space based (M. Tavani)		Gamma ray detection, ground based (K. Kosack)	Hands-on: VHE gamma ray data analysis (R. Terrier)	
Thursday 07/04	Extragalactic sources (E. Lindfors)			Multimessenger approach (M. Santander)	Student presentations	
Friday 08/04	Gravitational wave detectors and results (N. Leroy)	Hands-on: Multimessenger approach (M. Santander)		Departure	Departure	

Emma de

CTA, H.E.

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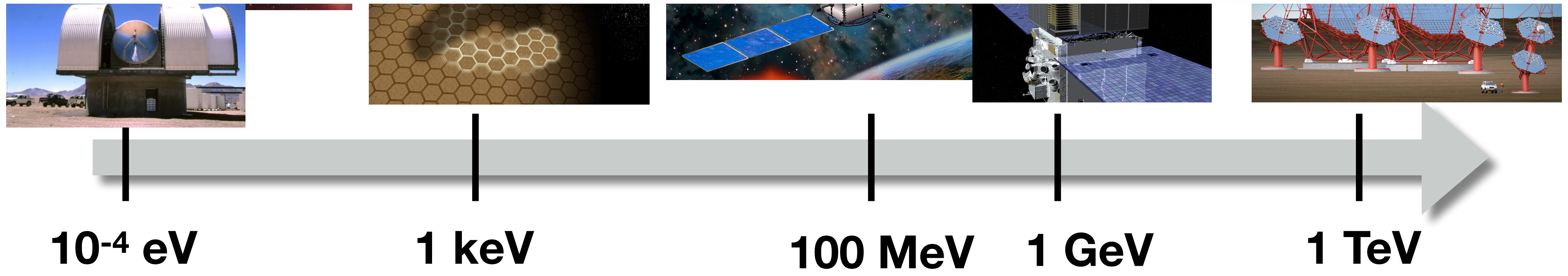


High energy astrophysics

To radiate high-energy gamma-ray, particles (electrons and hadrons) have to be accelerated to TeV energies or more:

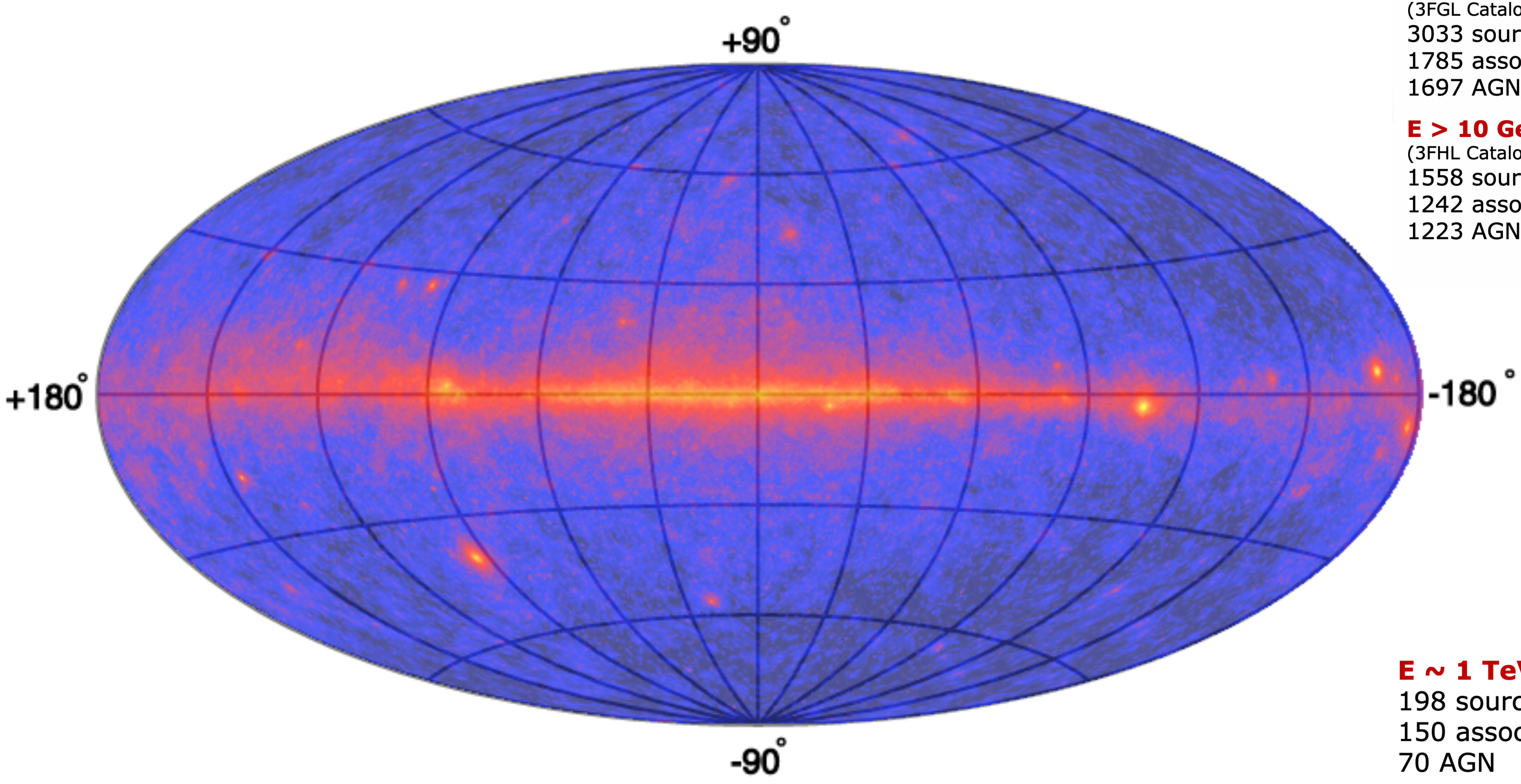
- huge gravitational, magnetic and electric fields
- very dense background radiation
- relativistic bulk motions (black hole jets and pulsar winds) shock waves (SNRs), highly excited (turbulent) media, etc…
- Involves rich interdisciplinary teams
- Generates new statistical problems (very large and very small number of events)
- Is one of the most attractive topics to reach the general public

Includes: X-ray astronomy, g-ray astronomy (MeV-TeV), neutrino astronomy, gravitational wave astronomy, cosmic ray astrophysics, and cosmology.

Research topics in VHE (Galactic science)

Content of the course

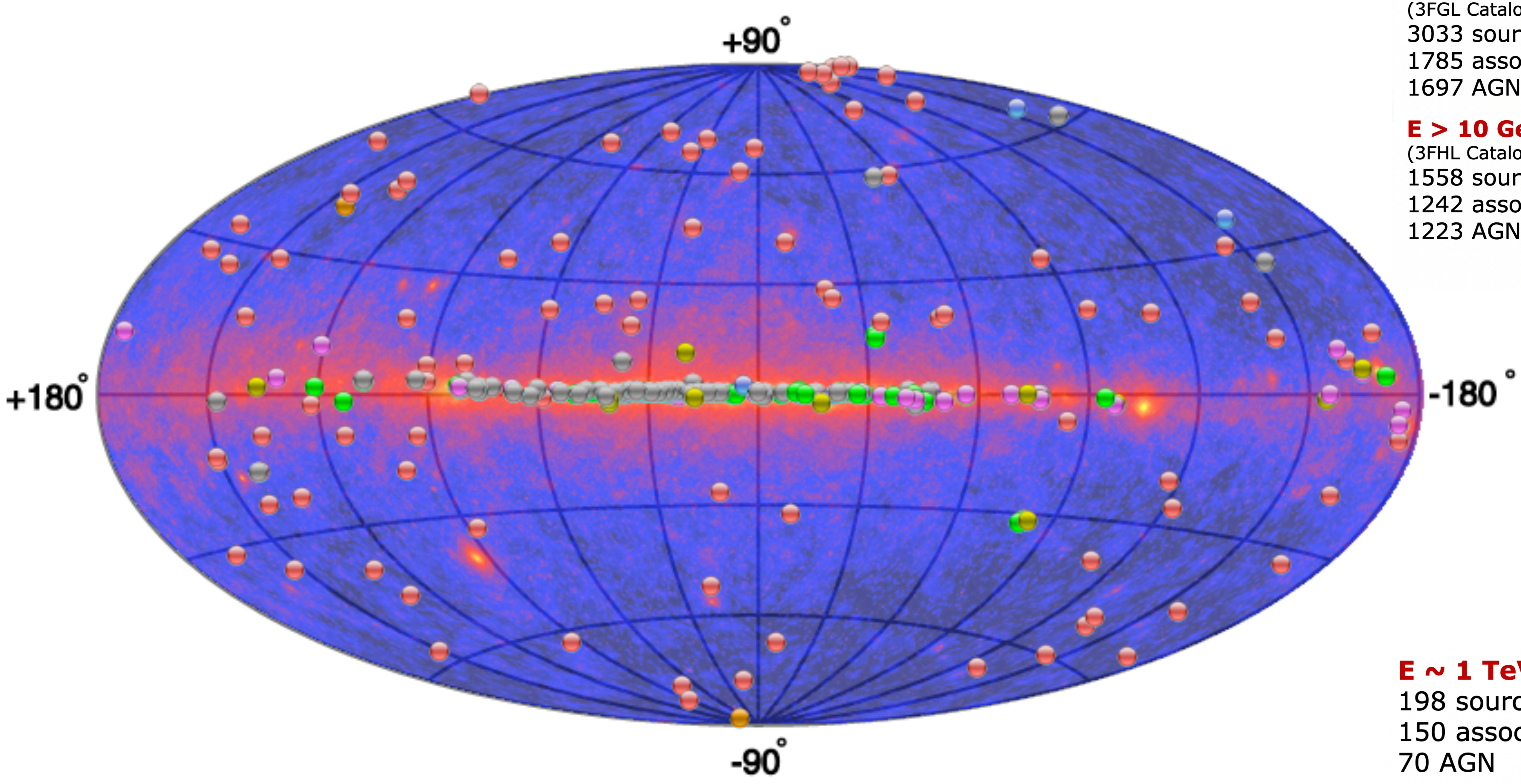
- **Acceleration and propagation of CRs**
    - Galactic CRs : Luminosity, maximum energy, propagation
      Hadronic accelerator
      Leptonic accelerators
- **Understanding the media in which CRs propagate**
    - Targets: Clouds and photon fields
- **Prospects in Galactic physics**



E > 100 MeV
(3FGL Catalog)
3033 sources
1785 associated
1697 AGN

E > 10 GeV
(3FHL Catalog)
1558 sources
1242 associated
1223 AGN

E ~ 1 TeV
198 sources
150 associated
70 AGN



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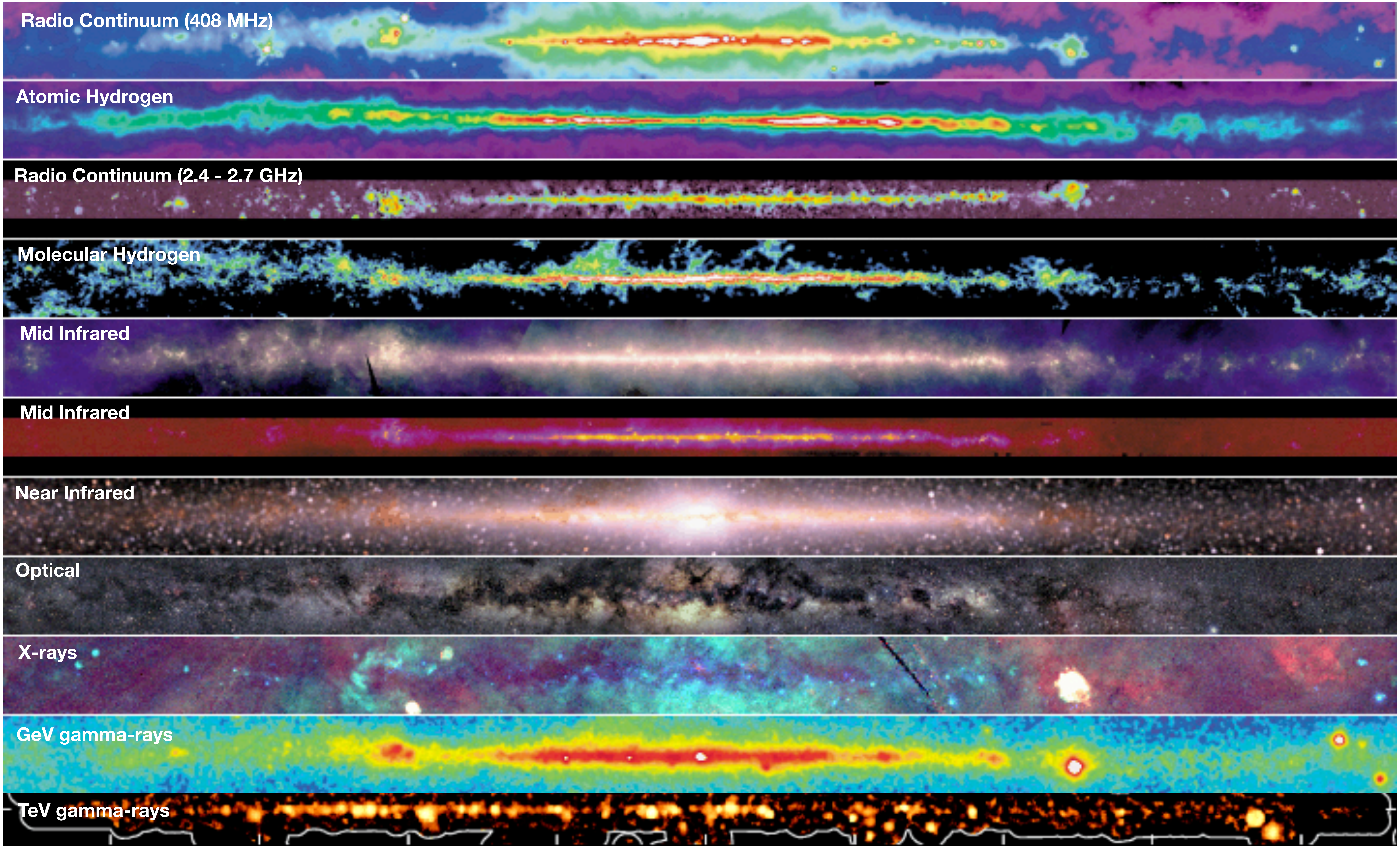
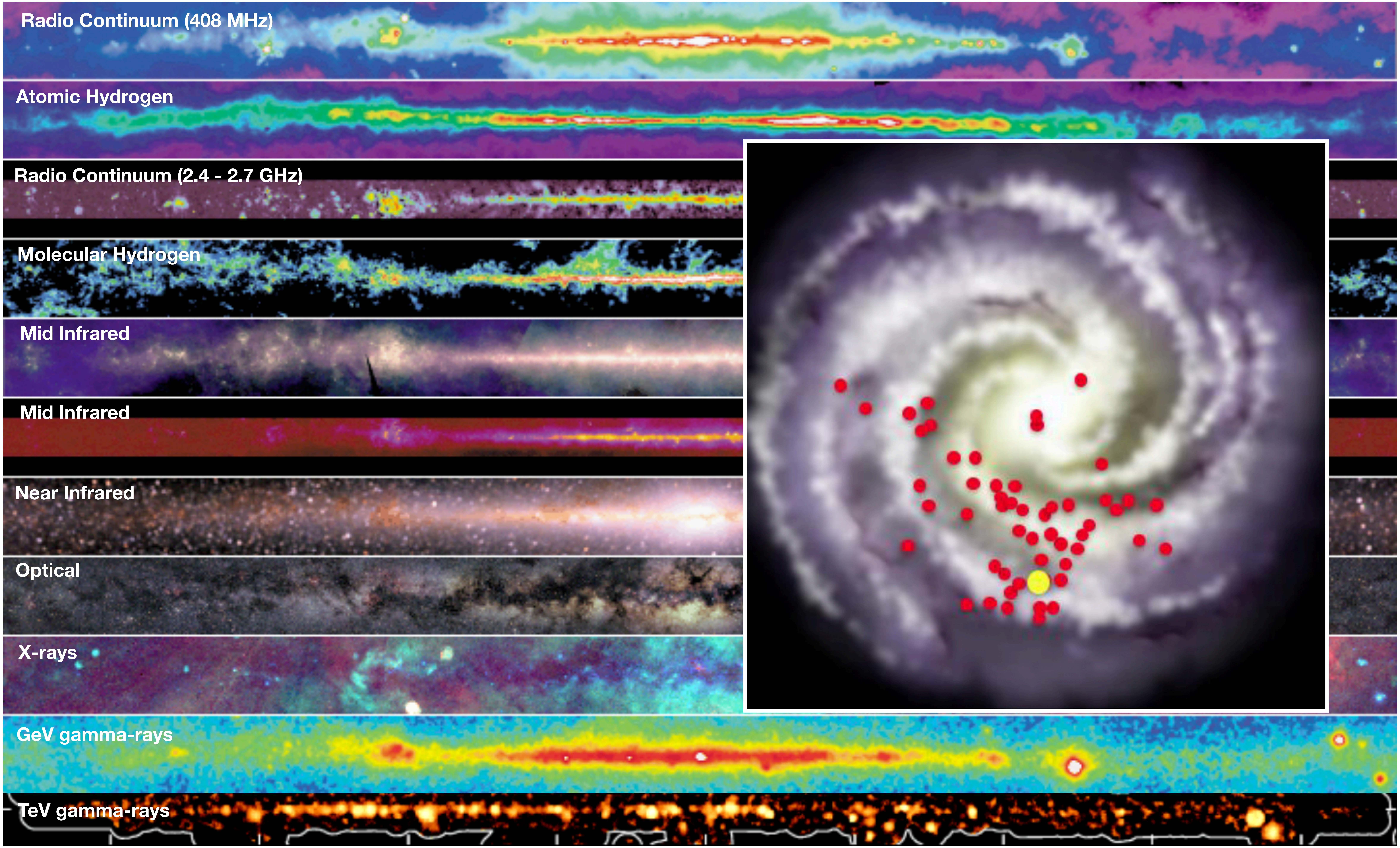

Radio Continuum (408 MHz)
Atomic Hydrogen
Radio Continuum (2.4 - 2.7 GHz)
Molecular Hydrogen
Mid Infrared
Mid Infrared
Near Infrared
Optical
X-rays
GeV gamma-rays
TeV gamma-rays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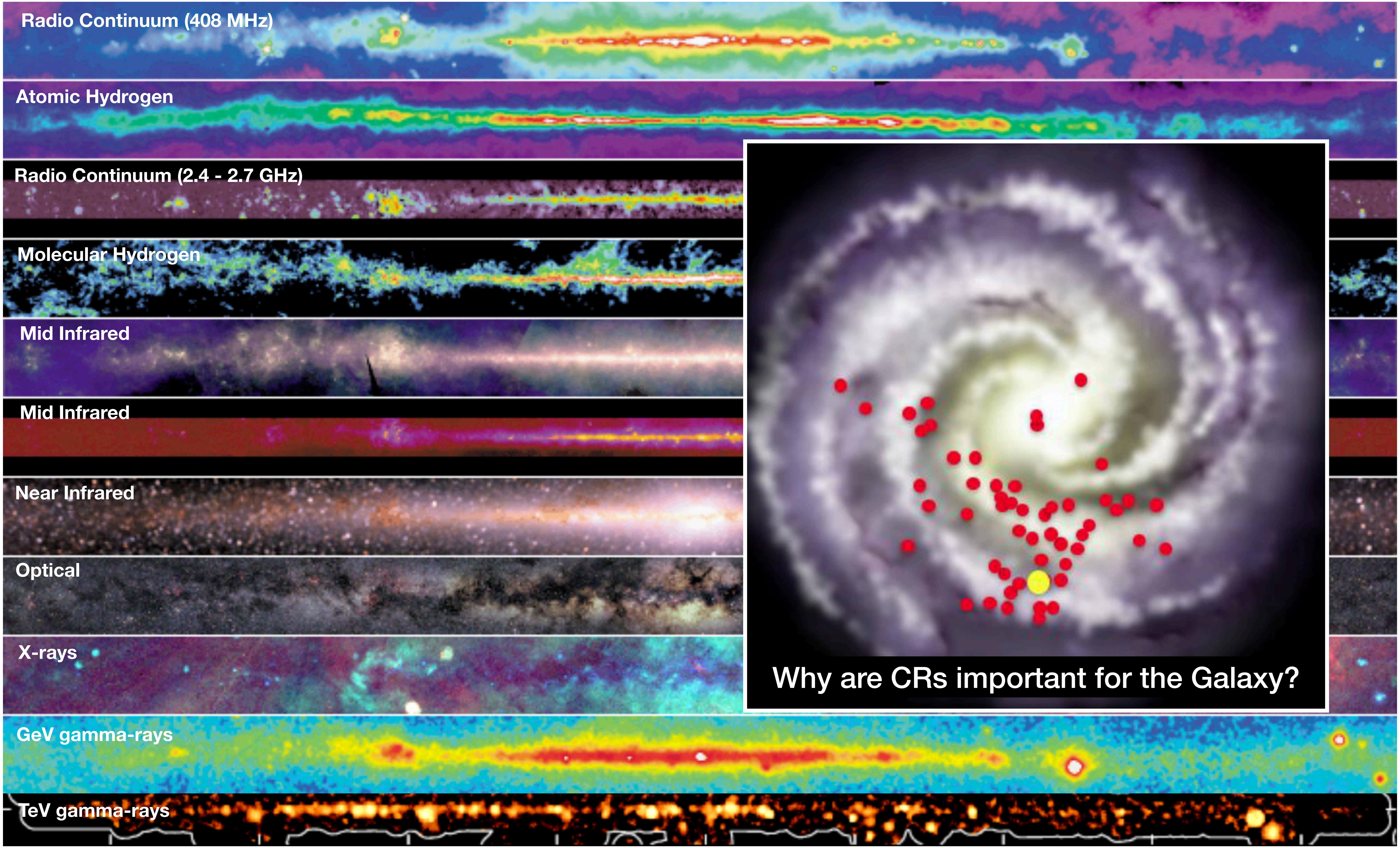
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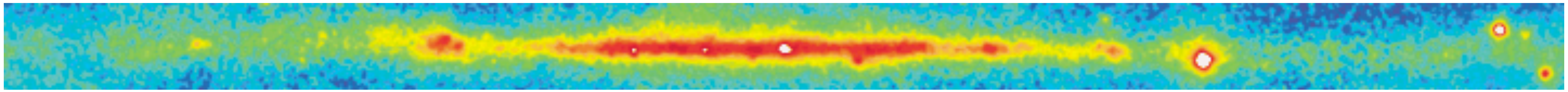
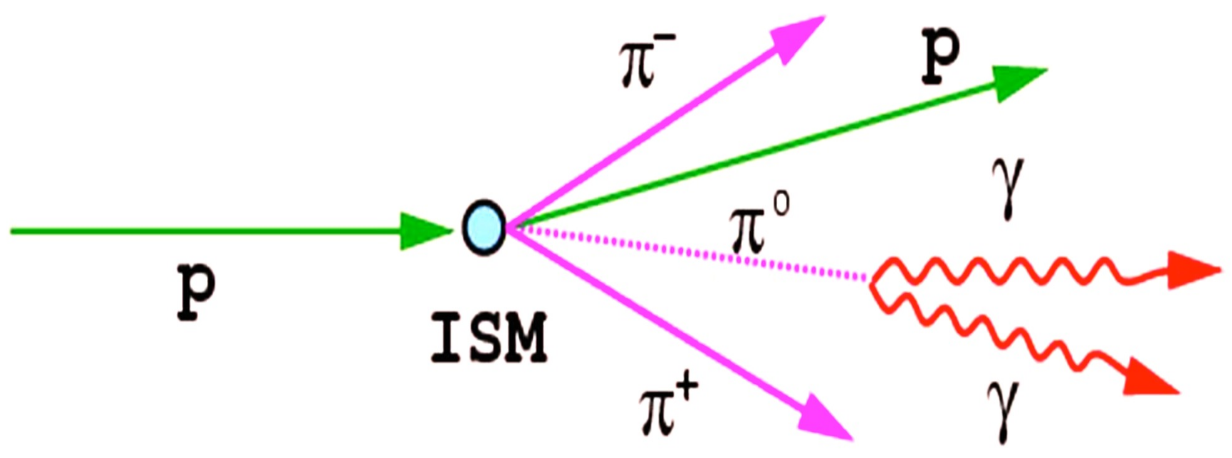
Why are CRs important for the Galaxy?



Galactic gamma-ray disk: not only due to the presence of many (relatively) nearby *discrete* sources, but also due to diffuse emission resulting from the interaction of cosmic rays (mostly p's) with the interstellar medium (ISM), e.g. atomic H, molecular clouds



Basic Component of the ISM:

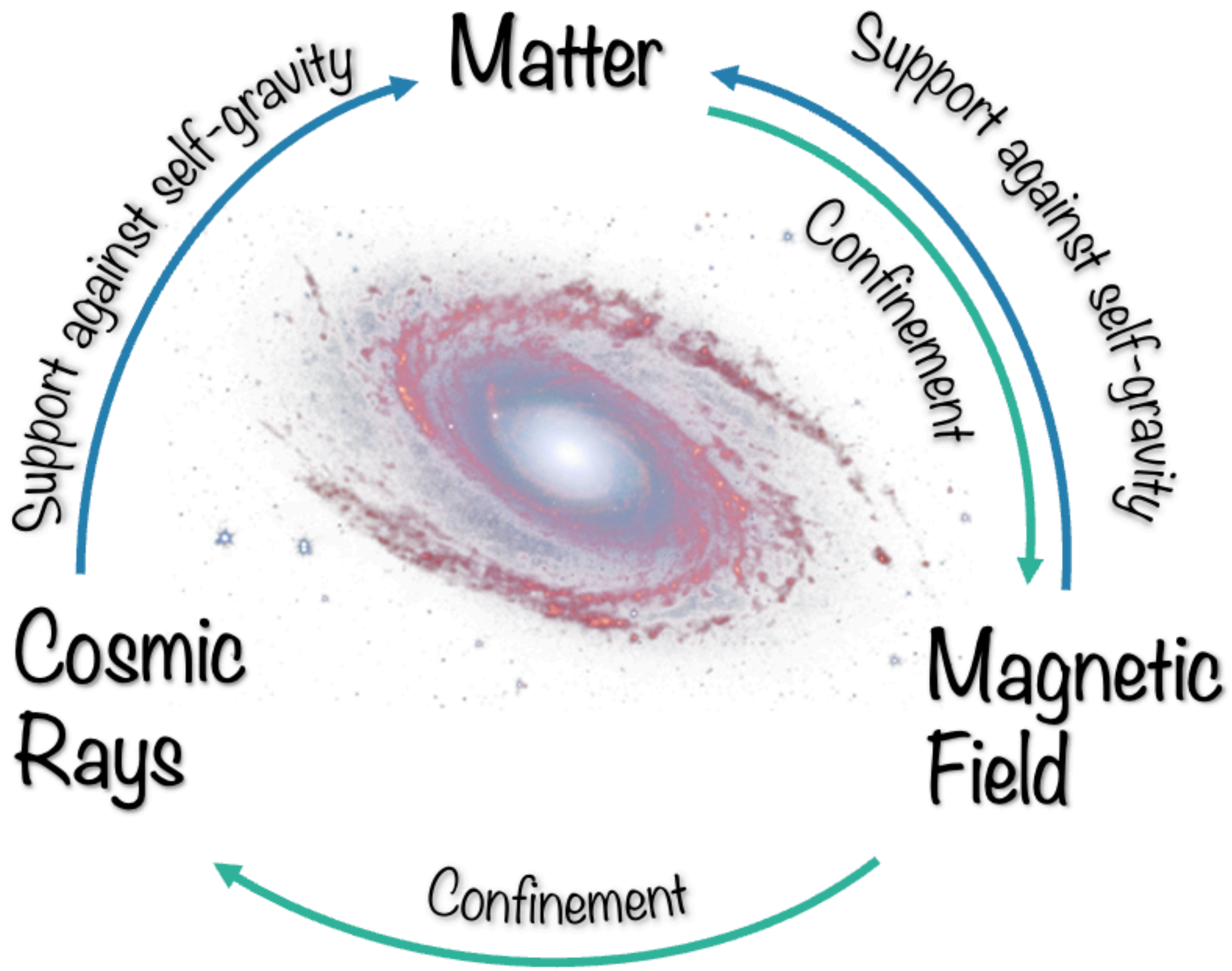
Matter, GCRs and GMF

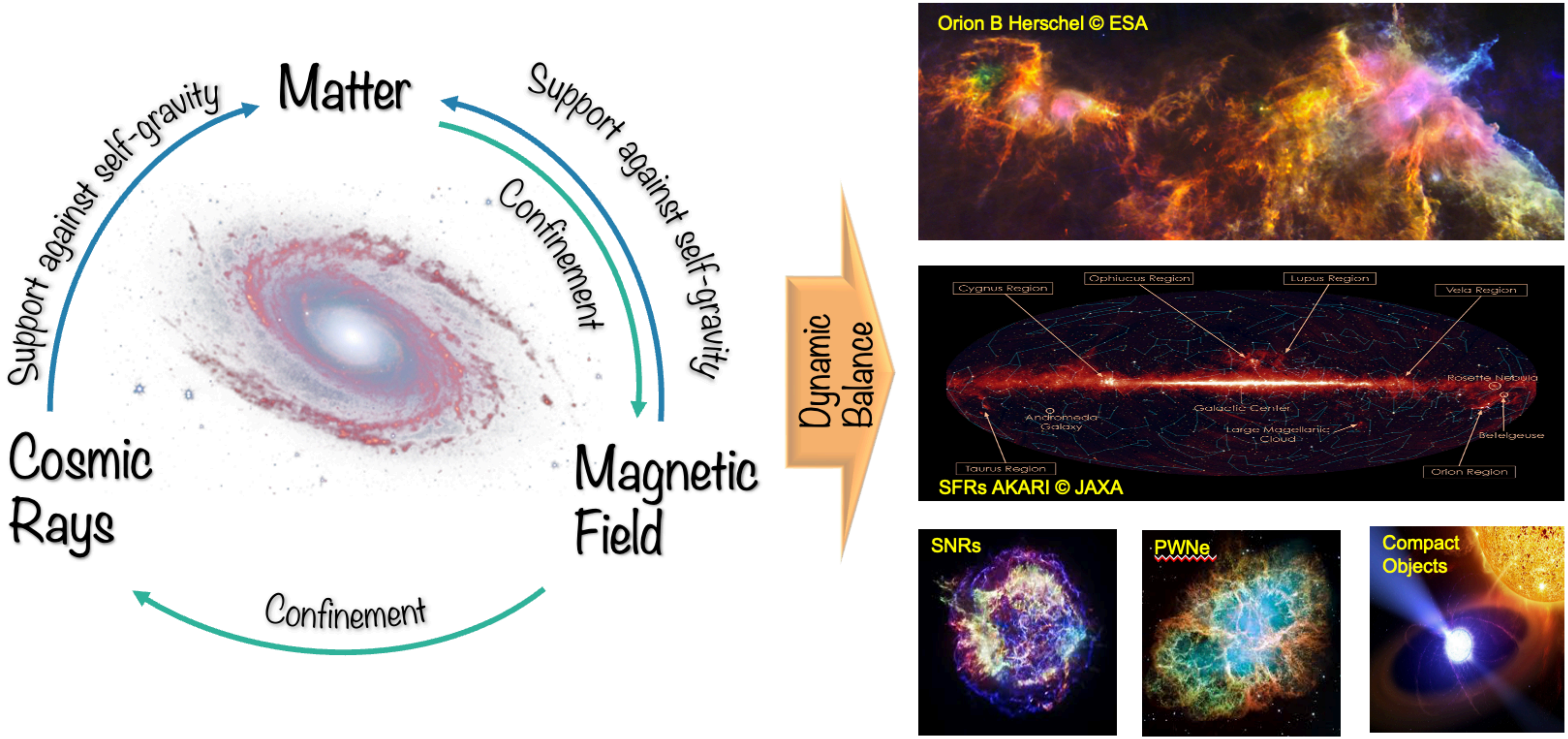
Dynamic balance processes triggers instabilities in the Galaxy structure

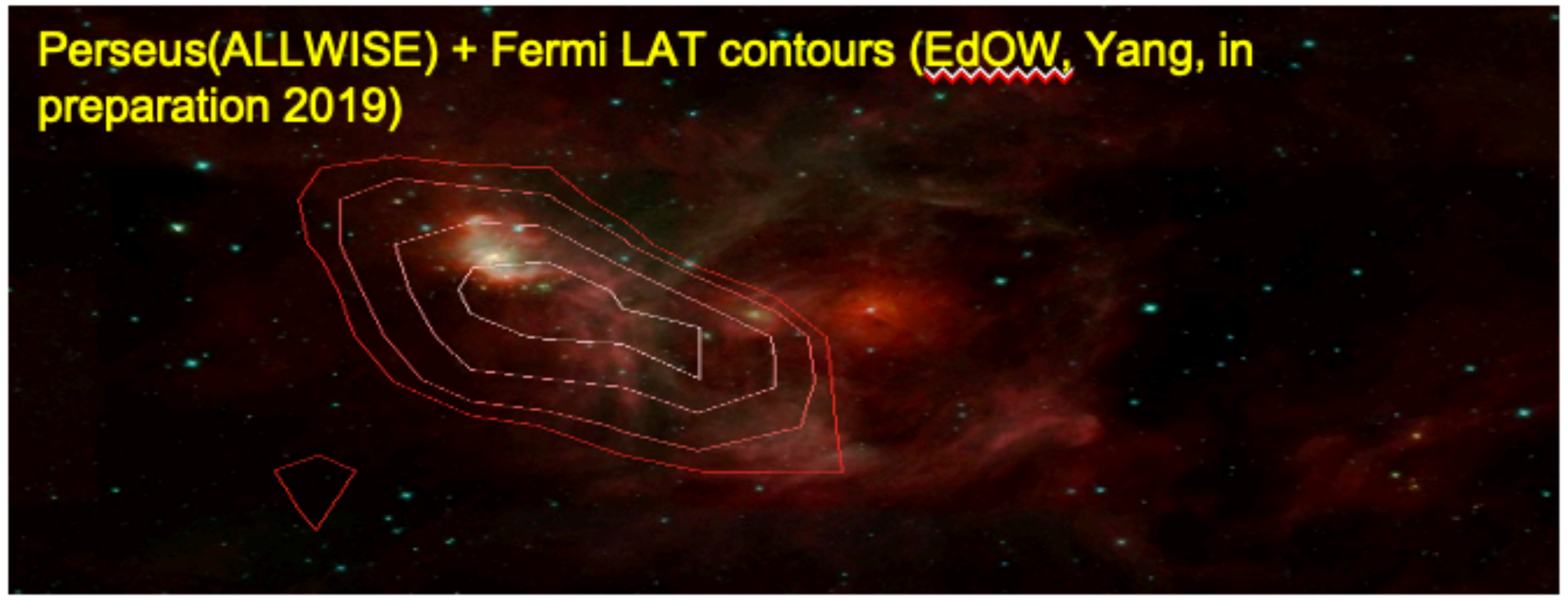
ω_{CR} ~1 eV/cm^3

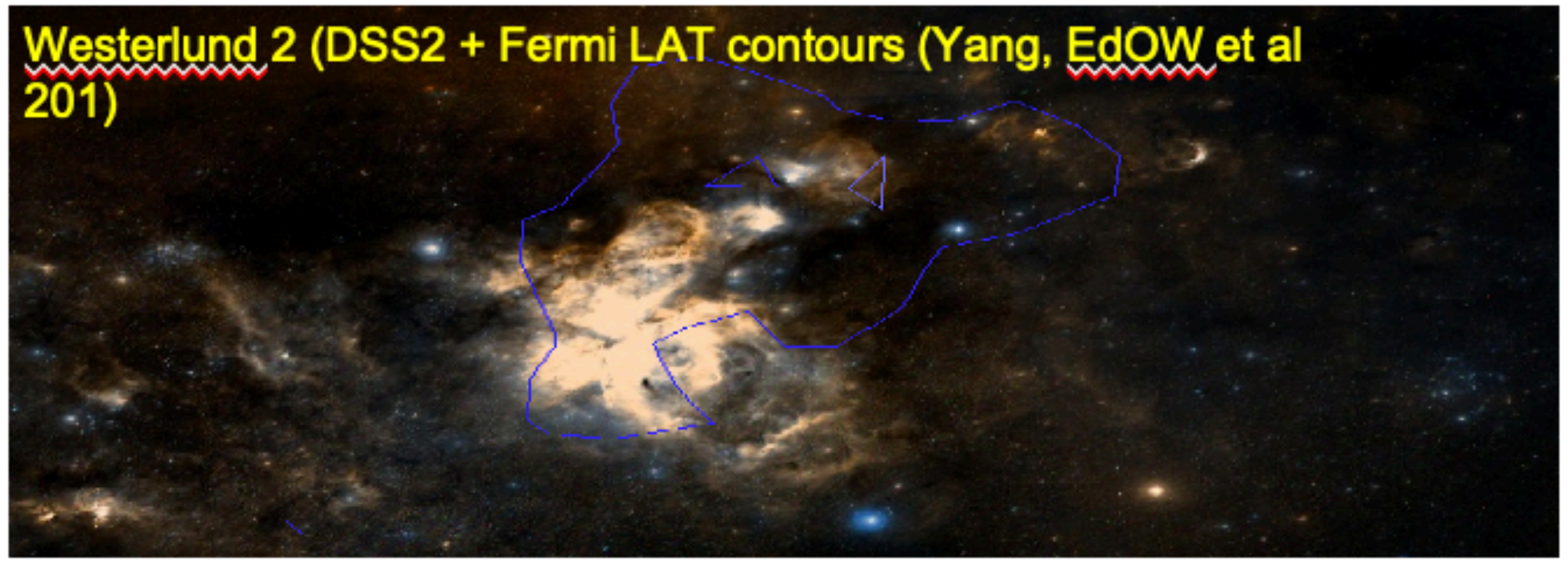
$\omega_B = B^2/8\pi$ ~1 eV/cm^3

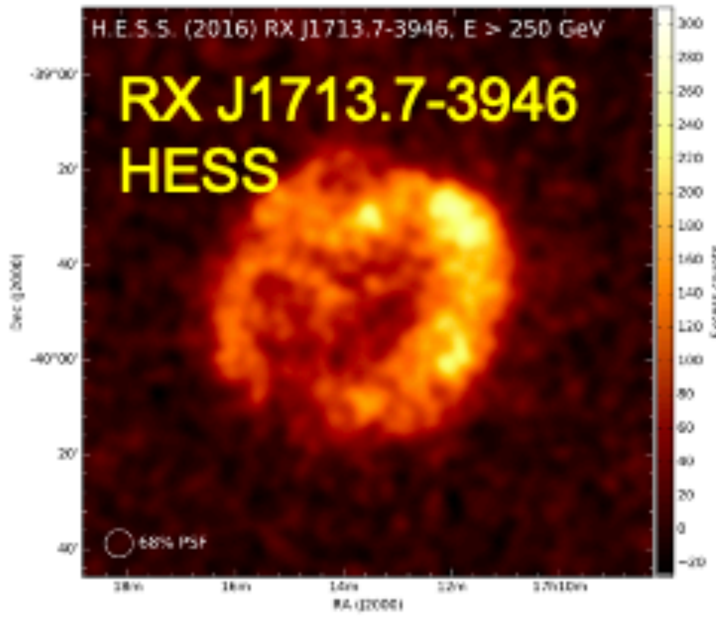
$\omega^{turb}_{gas} = \rho_{gas} v^2_{turb}$ ~1 eV/cm^3

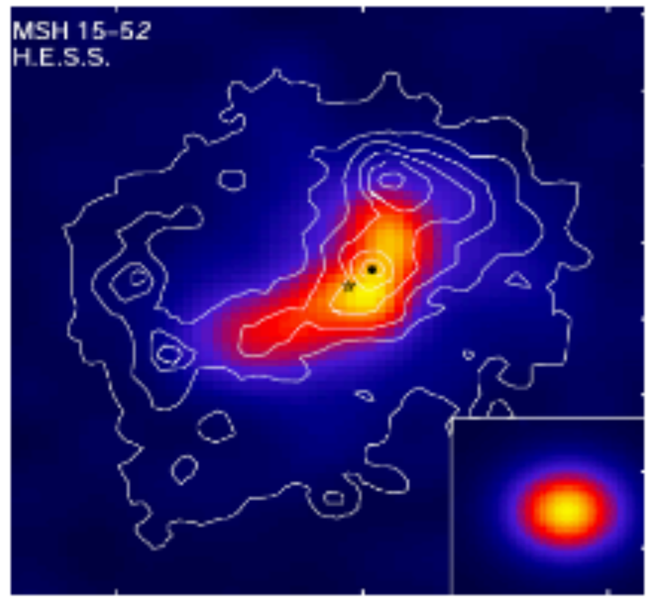


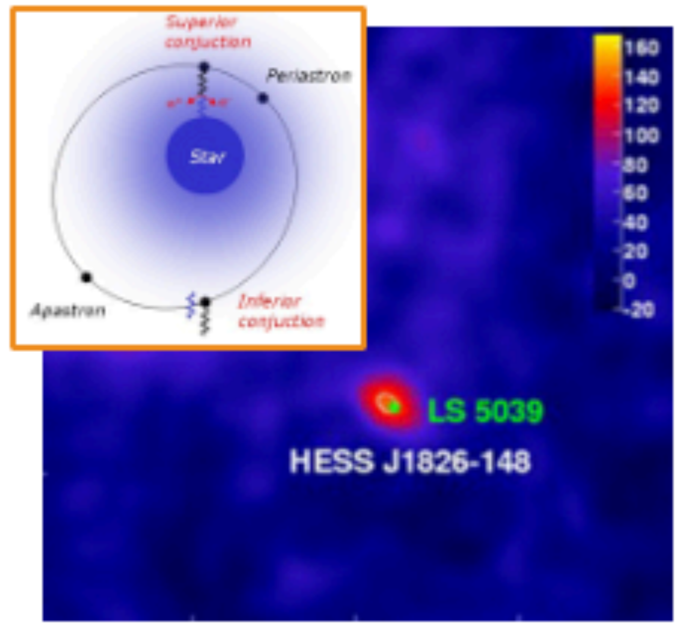

Matter
Support against self-gravity
Support against self-gravity
Confinement
Cosmic Rays
Magnetic Field
Confinement
Dynamic Balance
Orion B Herschel © ESA
Cygnus Region
Ophiucus Region
Lupus Region
Vela Region
Rosette Nebula
Galactic Center
Andromeda Galaxy
Large Magellanic Cloud
Betelgeuse
Taurus Region
Orion Region
SFRs AKARI © JAXA
SNRs
PWNe
Compact Objects


Perseus(ALLWISE) + Fermi LAT contours (EdOW, Yang, in preparation 2019)

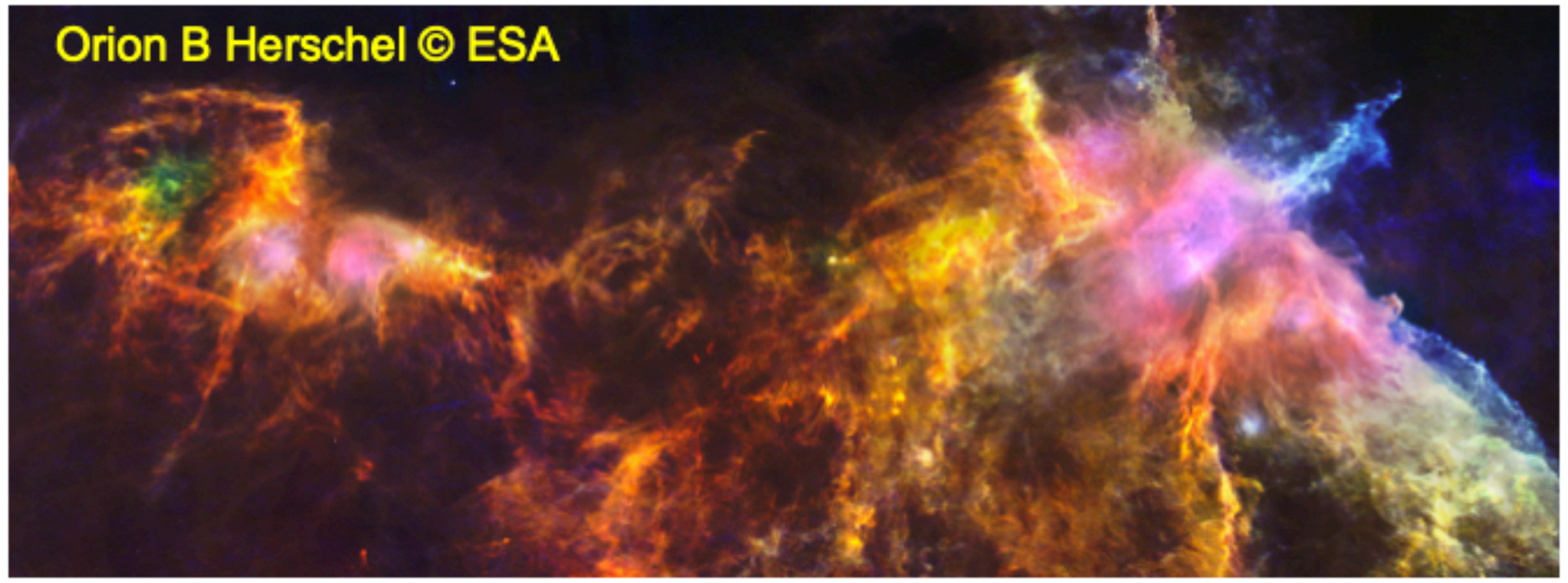

Westerlund 2 (DSS2 + Fermi LAT contours (Yang, EdOW et al 201)

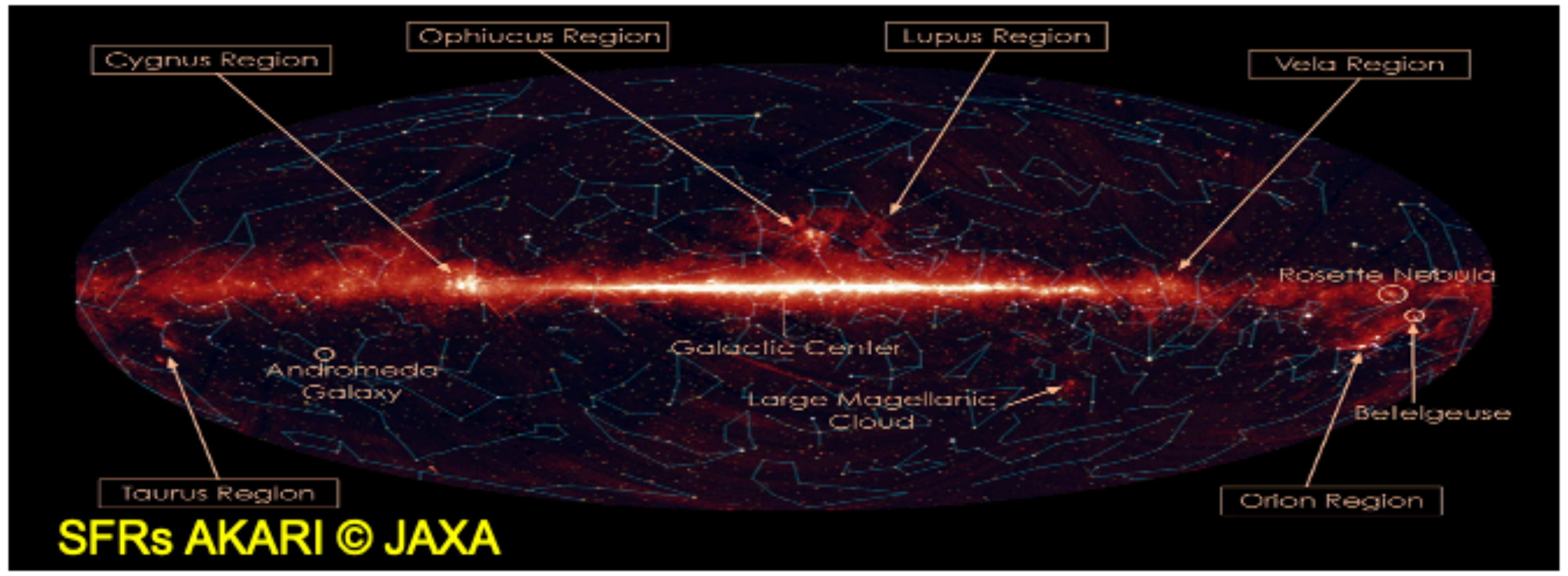

H.E.S.S. (2016) RX J1713.7-3946, E > 250 GeV
RX J1713.7-3946
HESS


MSH 15-52
H.E.S.S.


Superior conjunction
Periastron
Star
Apastron
Inferior conjunction
LS 5039
HESS J1826-148

Gamma-ray


Orion B Herschel © ESA


Cygnus Region
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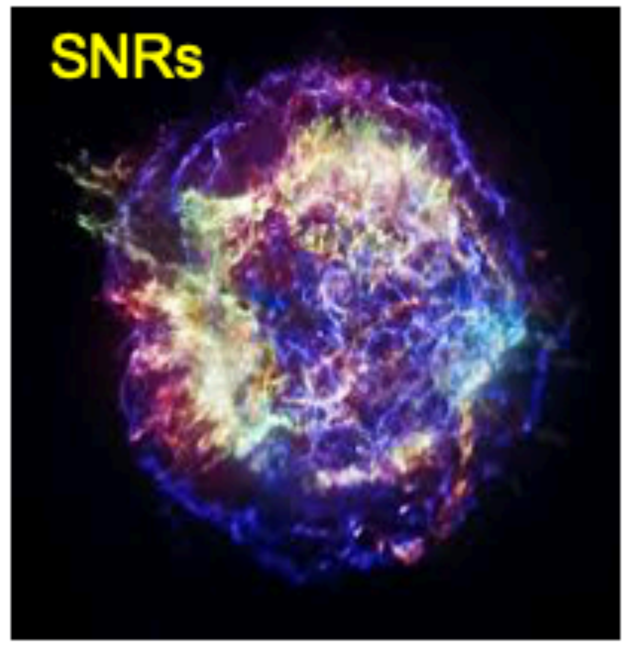
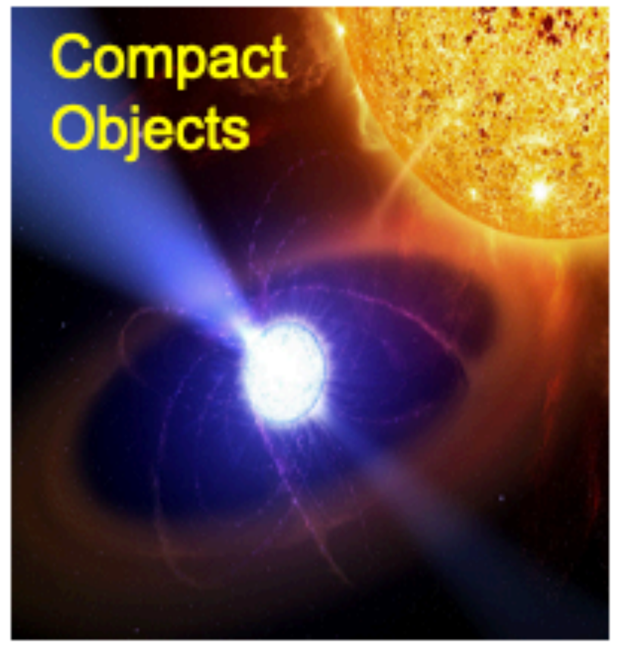
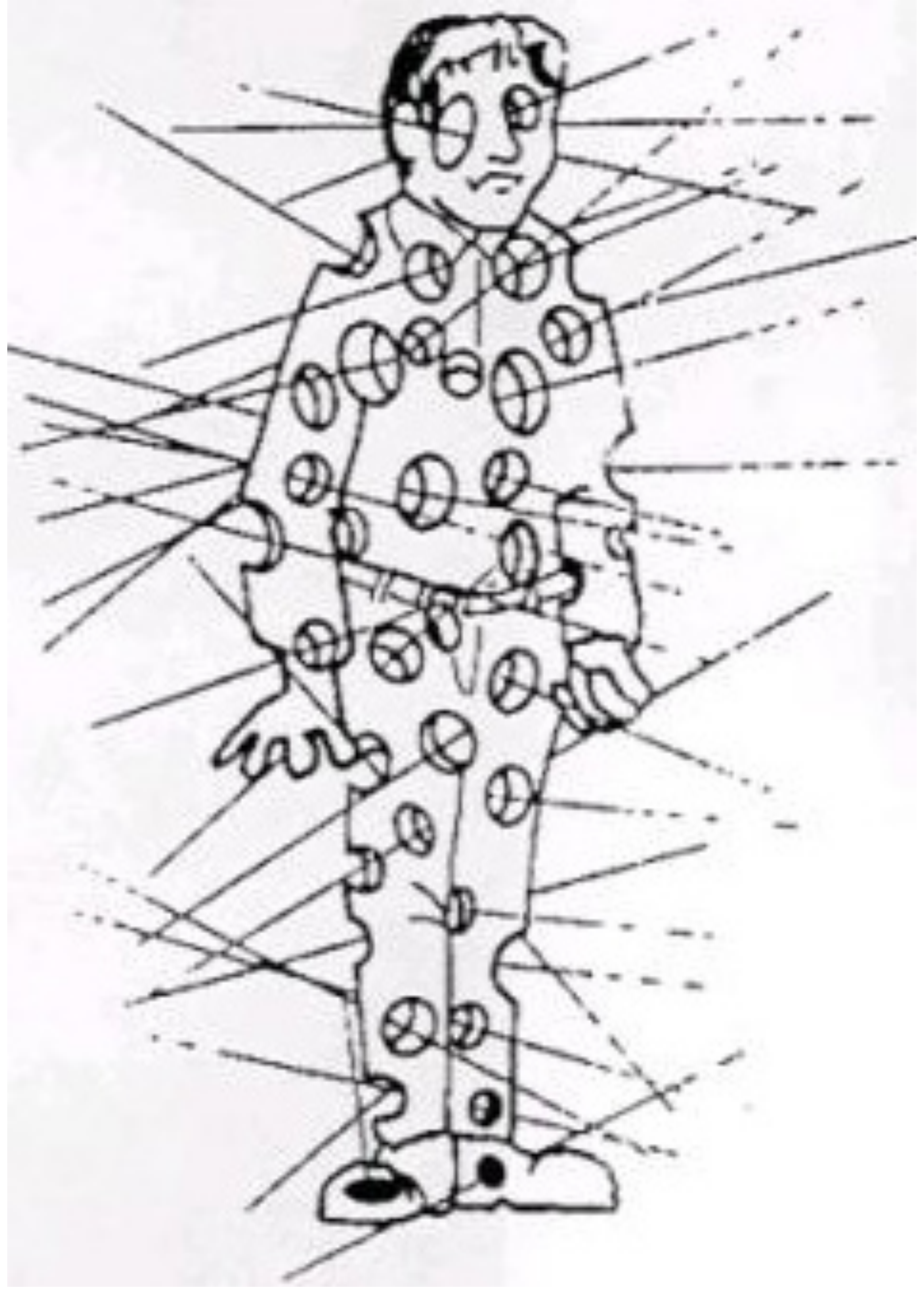

SNRs


PWNe


Compact Objects

The Quest Cosmic Rays: a driver for the high energy domiain

More than 100,000 cosmic rays will hit each of you during this lecture



In 1912, after 9 balloon ascents to record ionisation levels,Victor Hess concluded that

"A radiation of very high penetrating power enters our atmosphere from above".

The newly discovered radiation was dubbed "cosmic" by Robert A. Millikan in 1925.

In 1936, Victor Hess was awarded with the Nobel Prize for his discovery.

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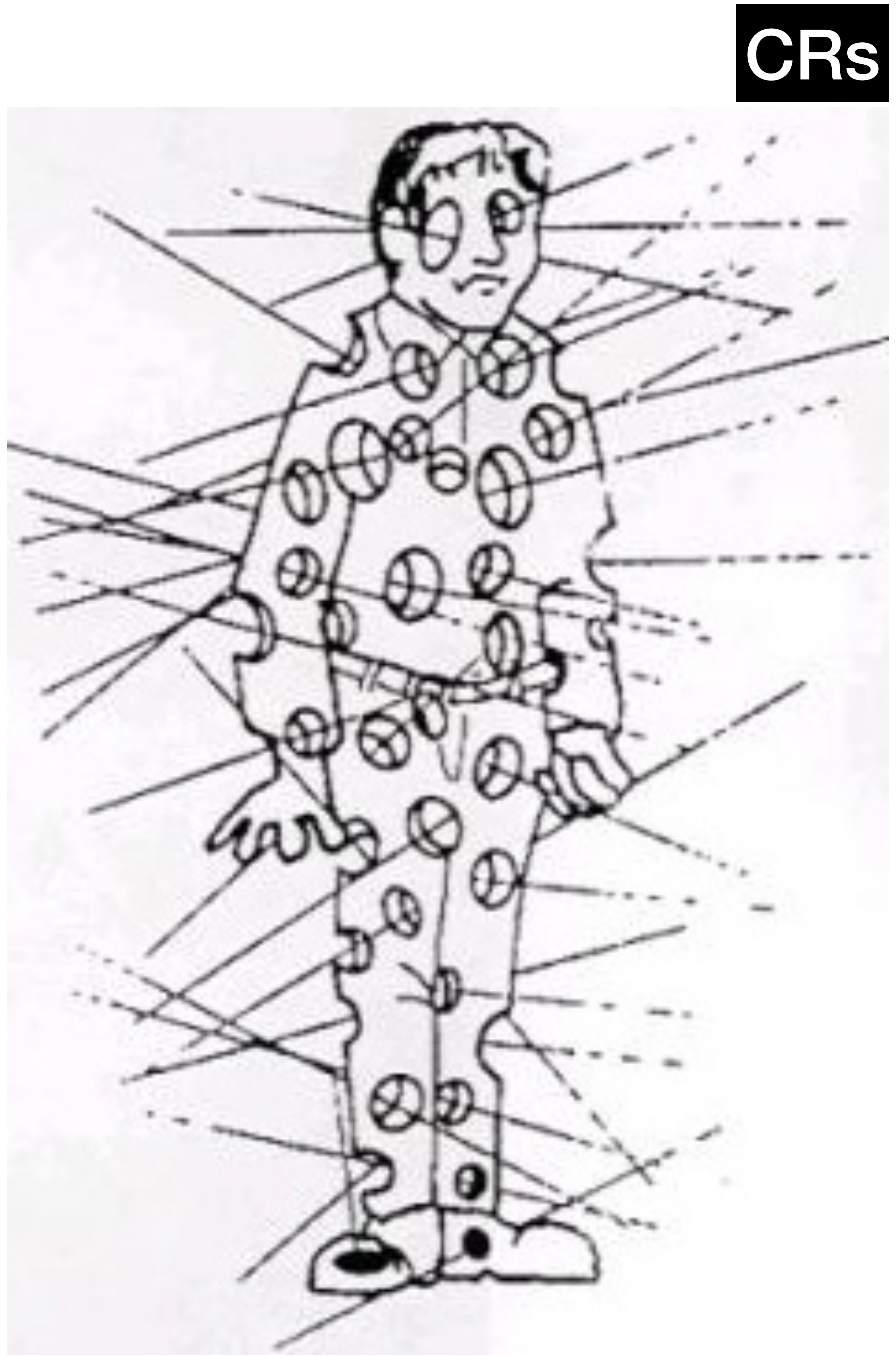

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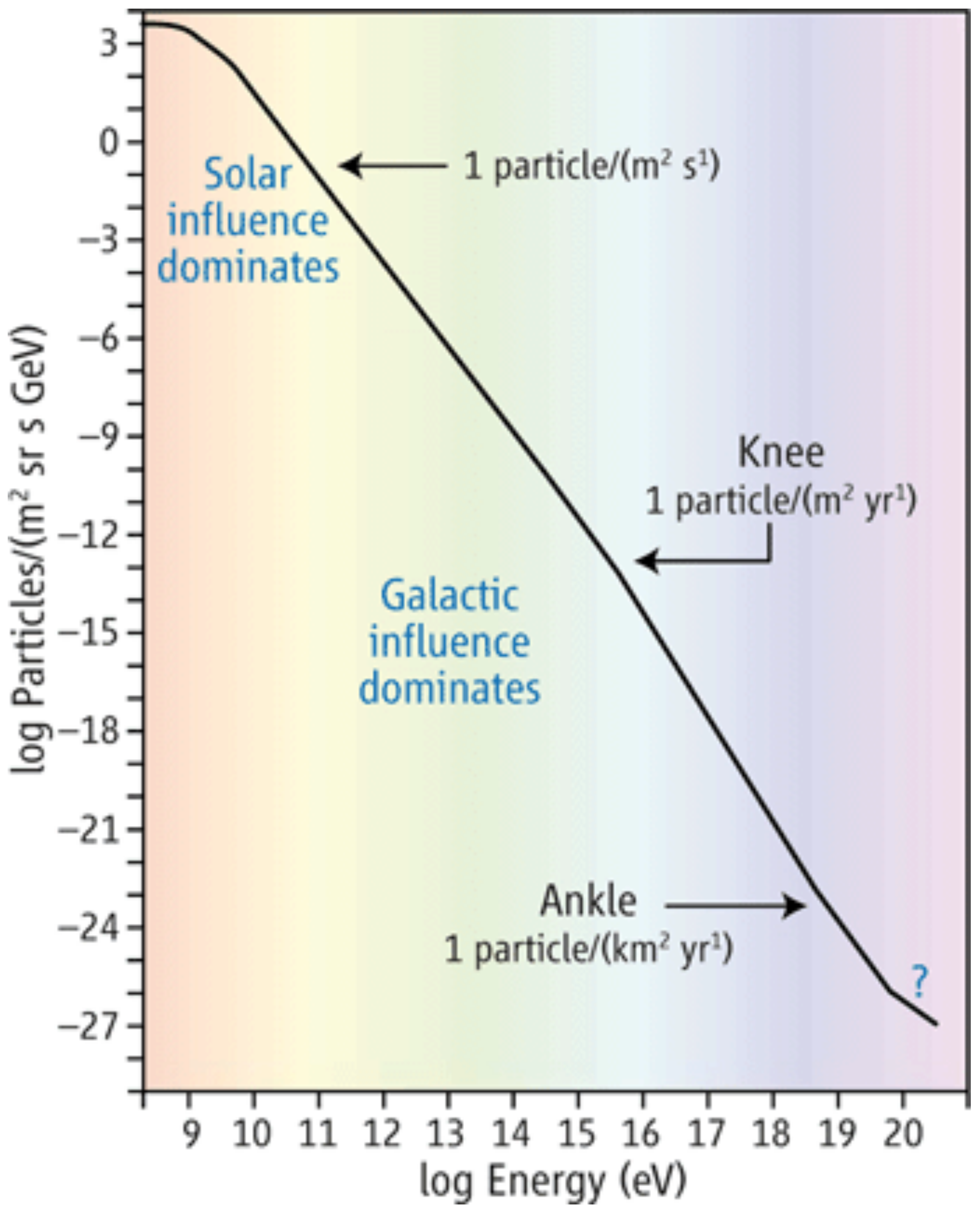
Cosmic ray Spectrum



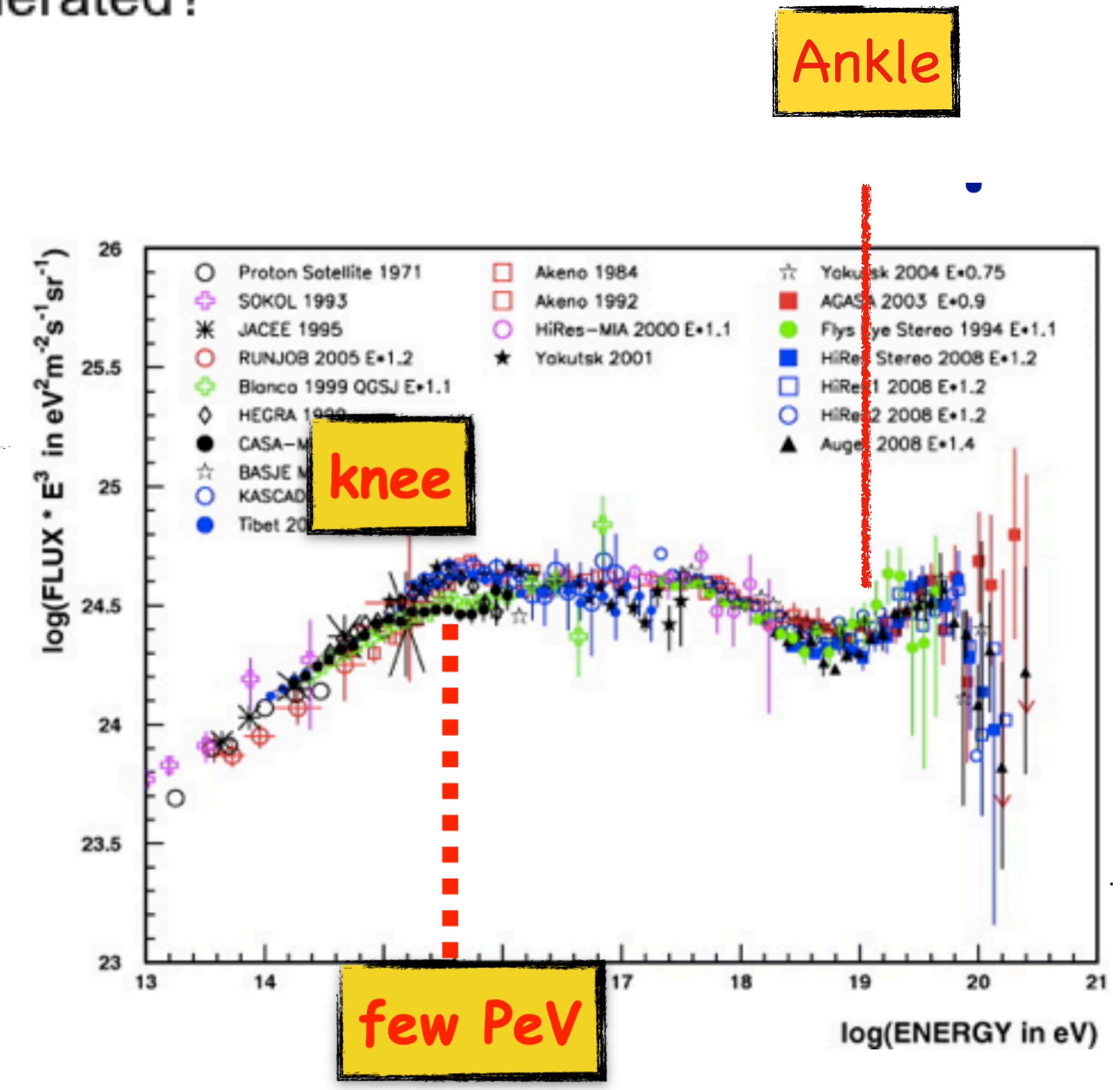
Question since 1912: what is the origin of Cosmic Rays?

Spectrum of CRs

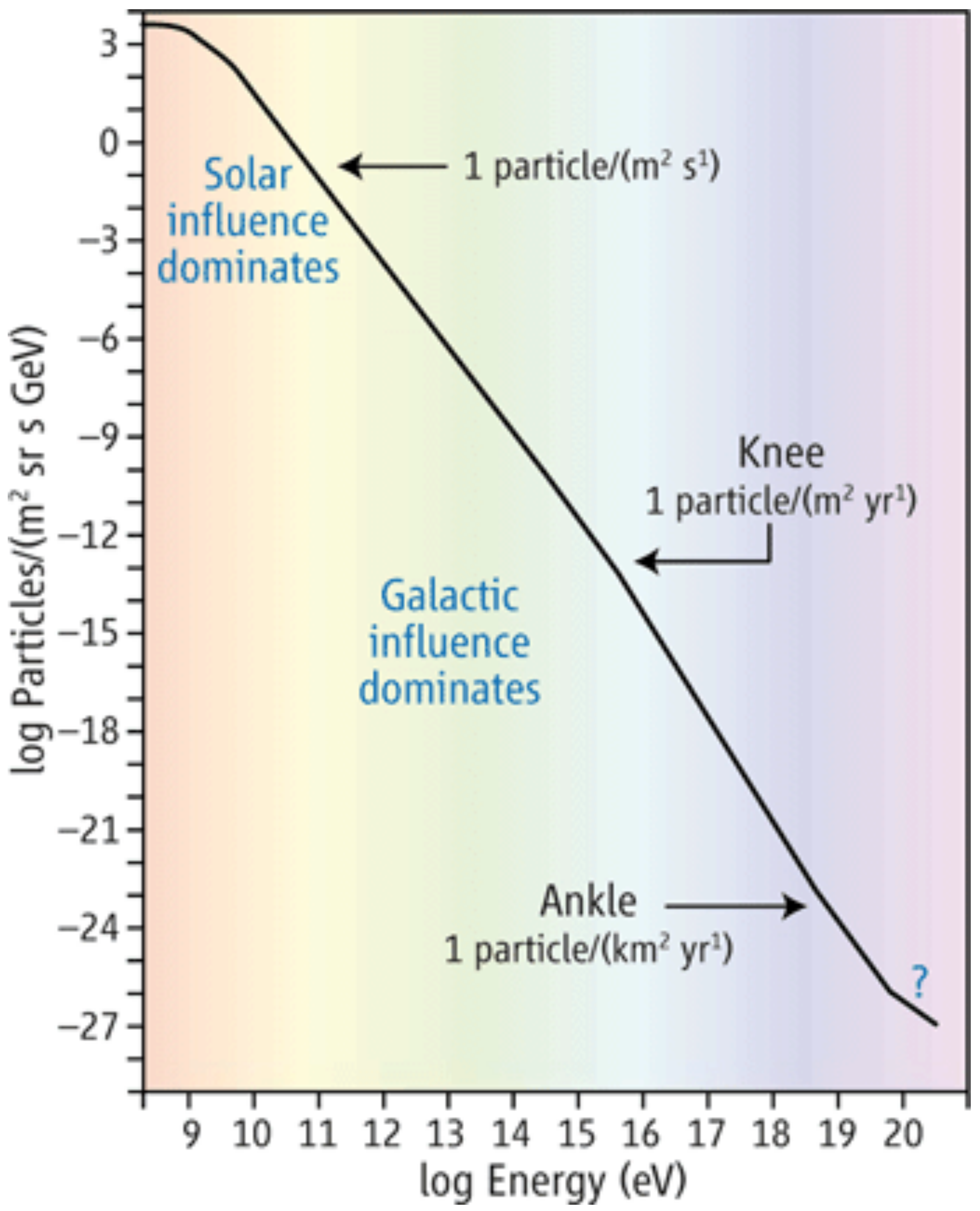
- Extends over 32 orders of magnitude
- Below ~3 PeV CRs are believed to be of Galactic origin
- Luminosity of Galactic CRs $L_{CR} \sim 10^{41}$ erg/s
- Where are PeV CRs accelerated?

same plot x E^3

The presence of a knee and the change of chemical composition around it have stimulated the idea that the bulk of CRs originates within our Galaxy.



Cosmic ray Spectrum



Source population that can provide the correct **luminosity** ~ 1eV/cm^3

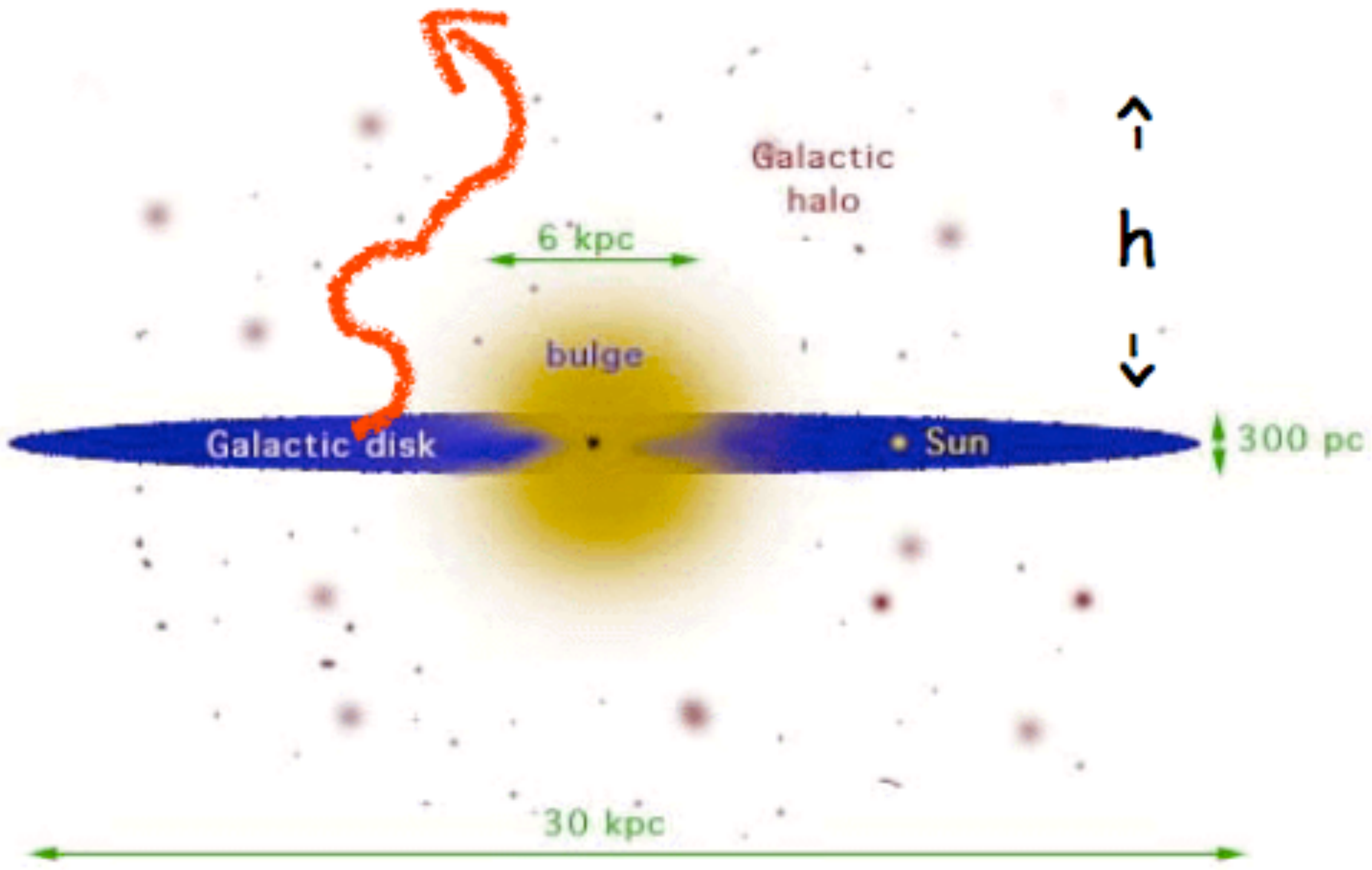
Acceleration of particles up to knee (~**3 PeV** ~3x10^{15} eV)

Diffusion in the Galaxy

CRs Luminosity

CR Energetics

- Energy Density of CRs u_{CR}~1 eV/cm^3
- Volume of the Galaxy $V_{gal} = \pi R_{disk}^2(2h) \sim 3\times10^{11}$ pc^3 ~10^7 cm^3
- Luminosity $L=u_{CR}*V_{gal}/t_{CR}$
- Isotropic in the Galaxy



- If we measure the CR confinement time (nuclear abundance) t_{CR}~10^7 yrs:

  $L=u_{CR}*V_{gal}/t_{CR} = 5\times10^{40}$ erg/s

We need Galactic accelerators that can provide the right energy budget, up to PeV energies, at the required rate to make the distribution homogeneous.

- ✓ $L=u_{CR}*V_{gal}/t_{CR} = 5\times10^{40}$ erg/s
- ✓ Homogeneity
- ✓ Up to PeV energies

CRs Maximum energy

Hillas criterium

What is the maximum energy a particle can reach in a Galactic source?

- Acceleration is always (expect for non-ideal cases) carried out by an electric field
- For a particle with charge q, moving a distance L

$$E = q\,|\vec{E}|\,L$$

- We can define the acceleration efficiency as:

$$\eta = \vec{B}/\vec{E}$$

then:

$$E = q\eta BL$$

L = Size of the source

B = Magnetic field in the source

This two value will define the maximum energy

CRs Maximum energy

Hillas criterium

We can derive the same condition considering confinement:
the Larmour radius should be smaller than the size of the accelerator

necessary condition but not determining

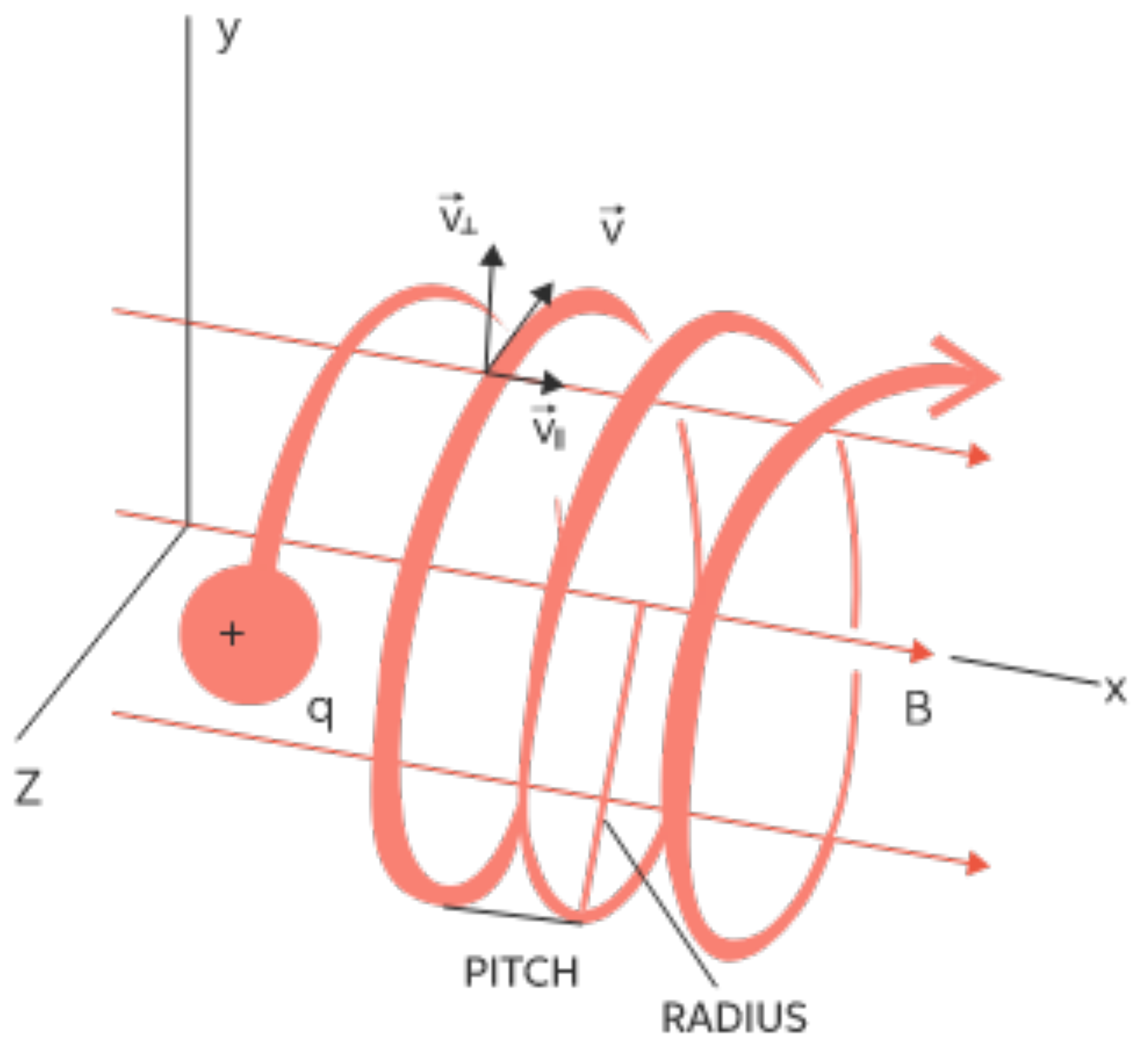
R_L (=E/qB) < R => $E_{max} = \Gamma qBR$

$$E_{max} \propto u \; R \; B$$

Magnetic Field

Radius

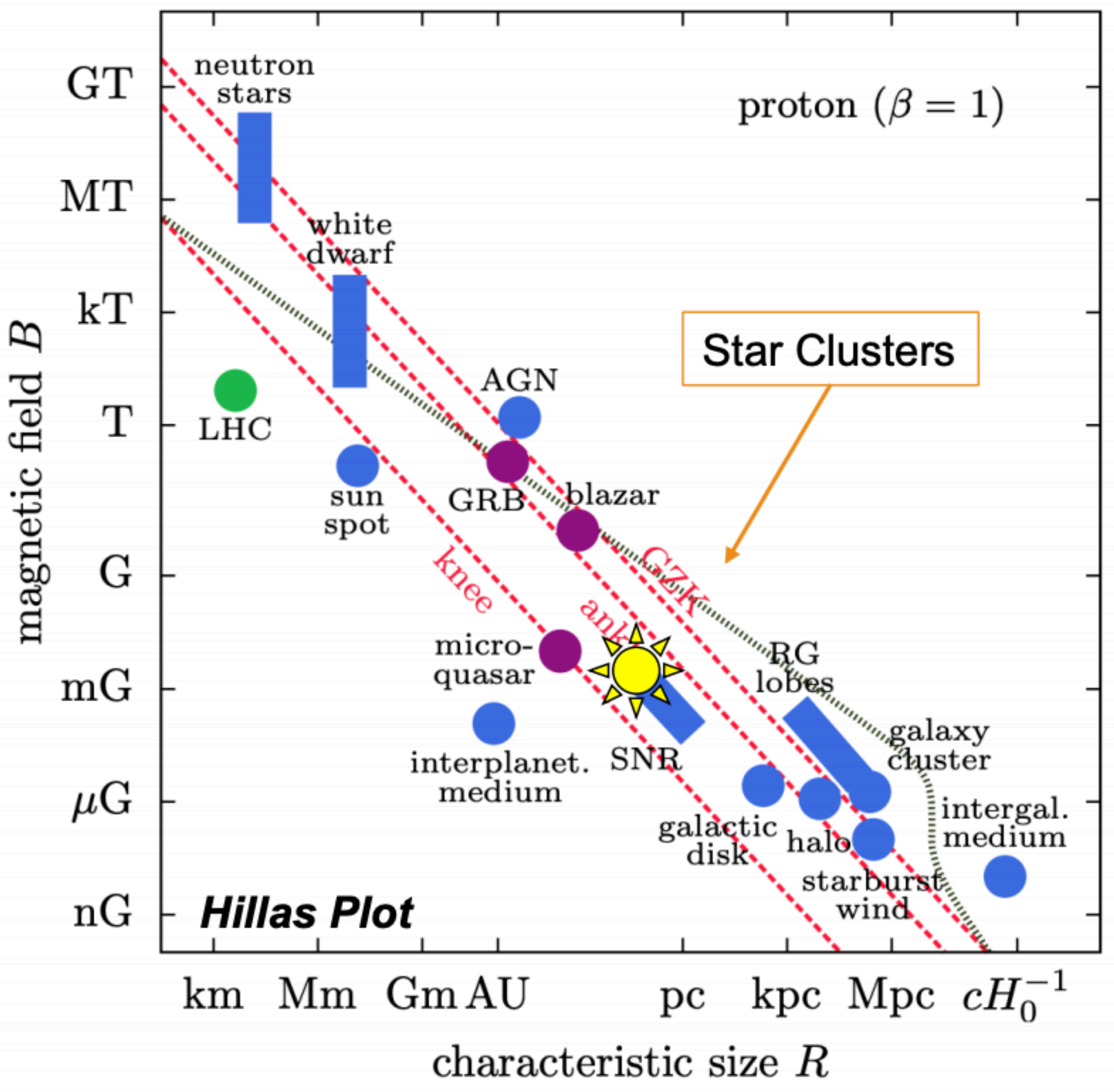
Velocity



CRs Maximum energy

Hillas criterium

Aartsen et al (IceCUBE) 2017

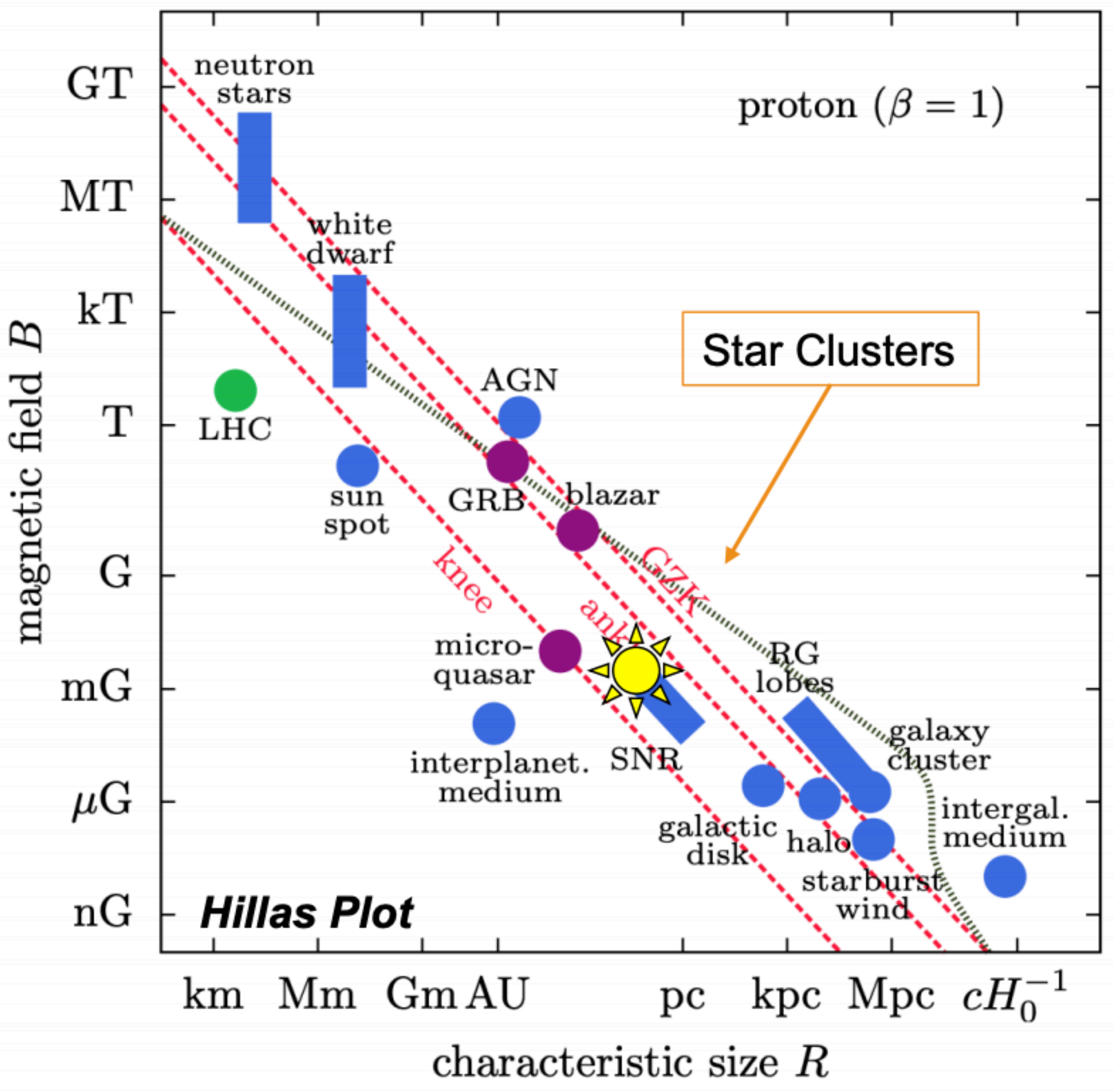


$$E_{max} \approx 1 \left(\frac{u}{10^3\ \mathrm{km/s}}\right)\left(\frac{R}{\mathrm{pc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right) \mathrm{TeV}$$

R_L (=E/qB) < R => $E_{max} = \Gamma qBR$

CRs Maximum energy
Hillas criterium

Aartsen et al (IceCUBE) 2017



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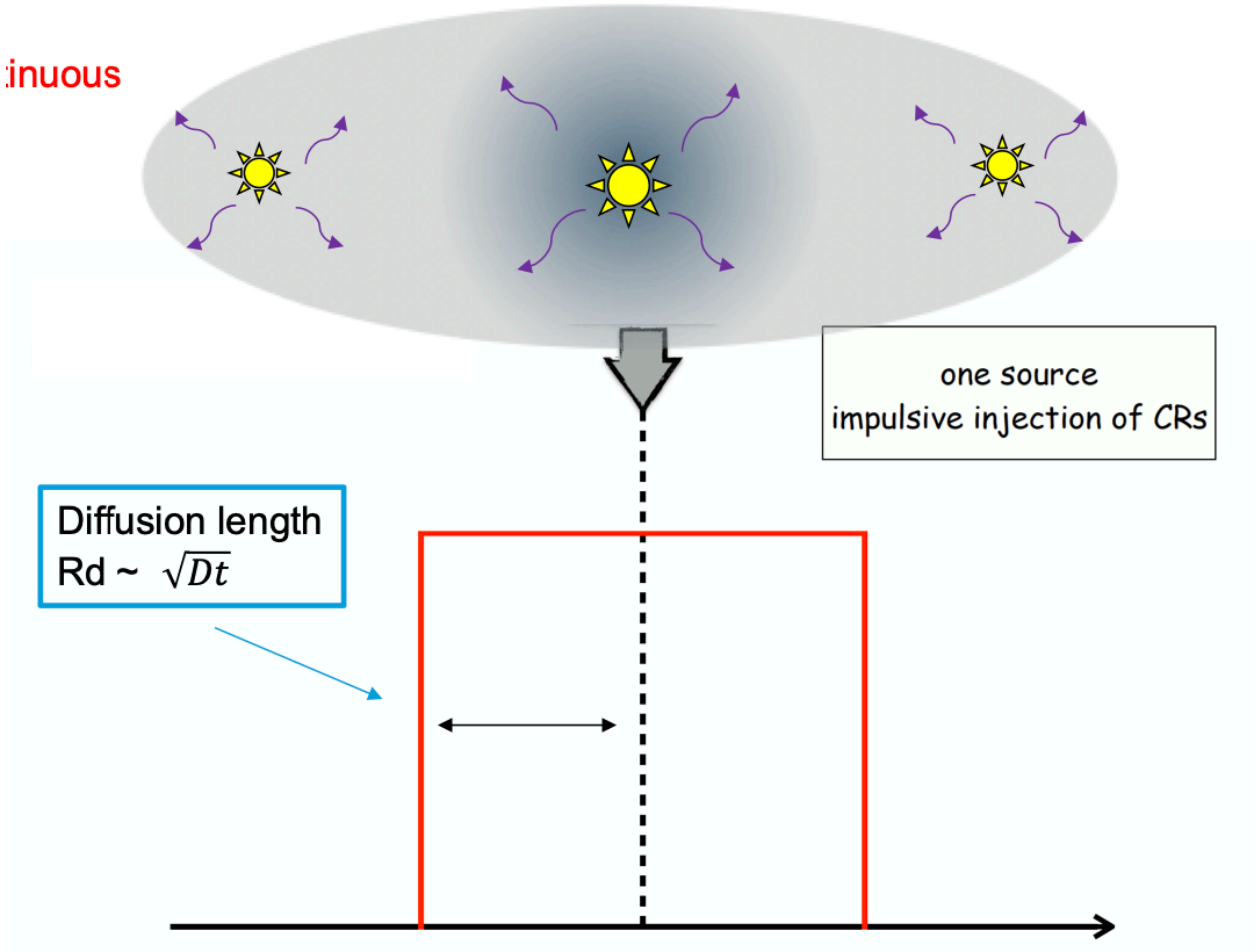
R_L (=E/qB) < R => $E_{max} = \Gamma qBR$

Does this solve the problem then?

Diffusion in the Galaxy

$dN/dE \sim \dot{Q}/D(E) \sim E^{-(\alpha + k\delta)}$ k=3/2, 1

$D(E) = D_o(E/E_o)^{\delta}$, $D_o \sim 10^{28\text{-}30}$ $cm^2 s^{-1}$



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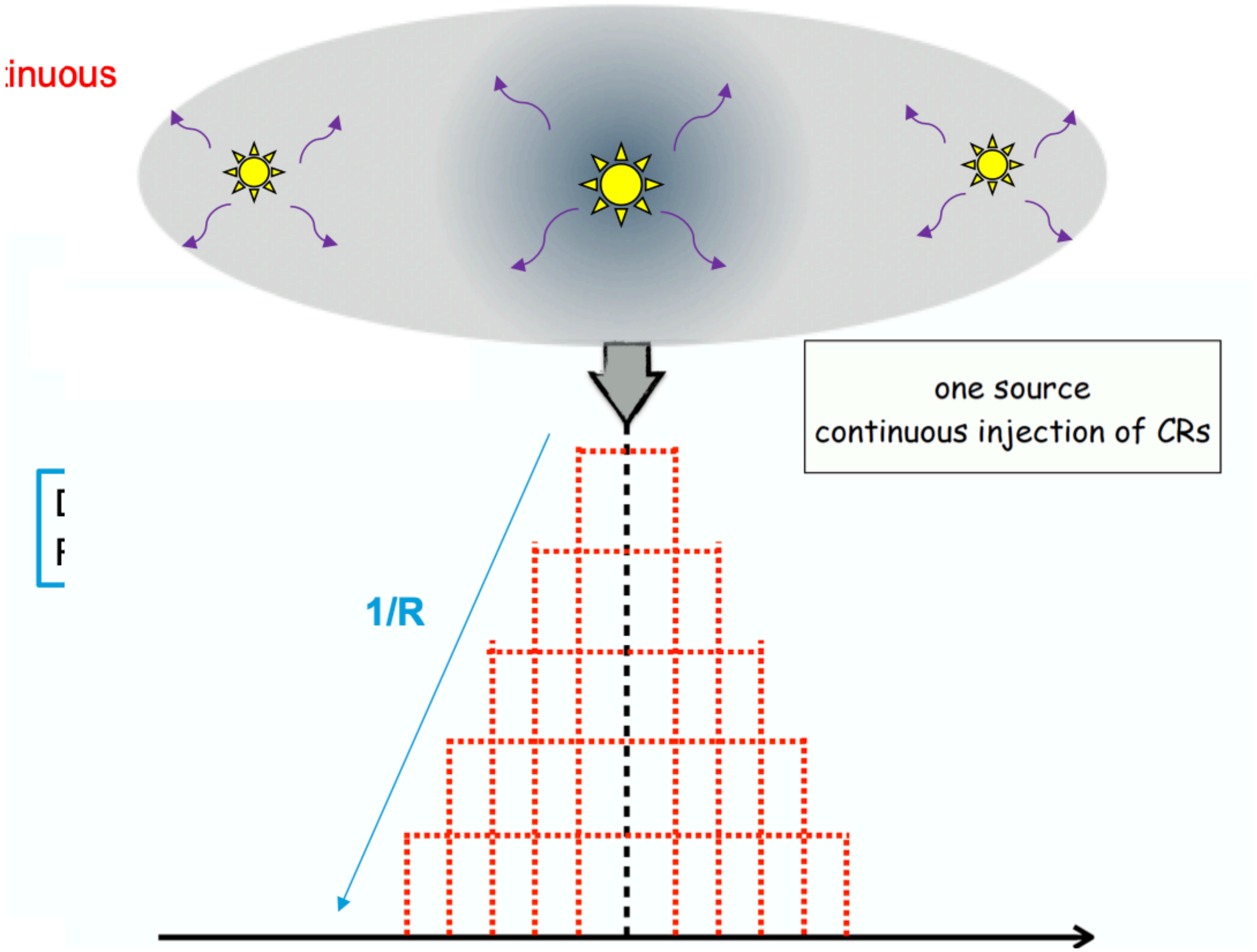
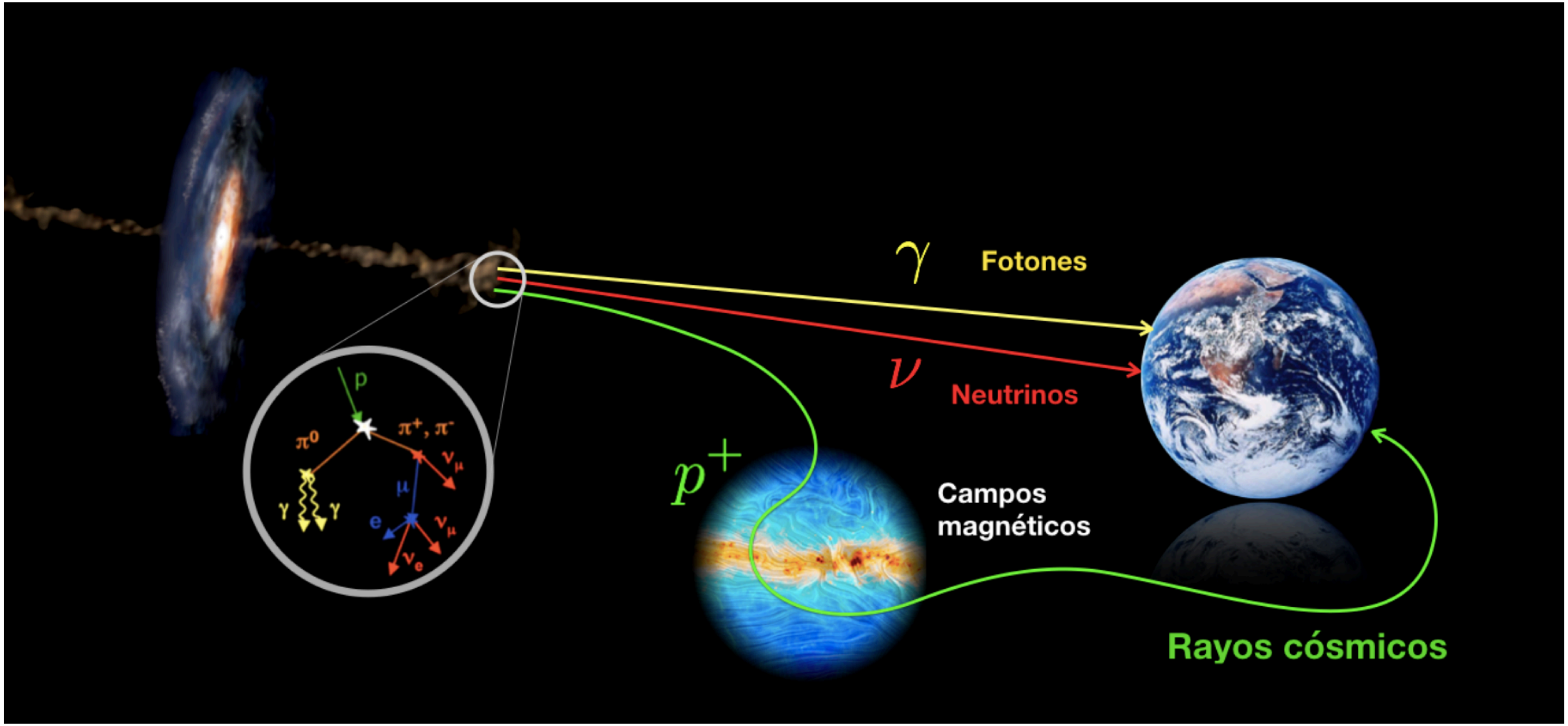
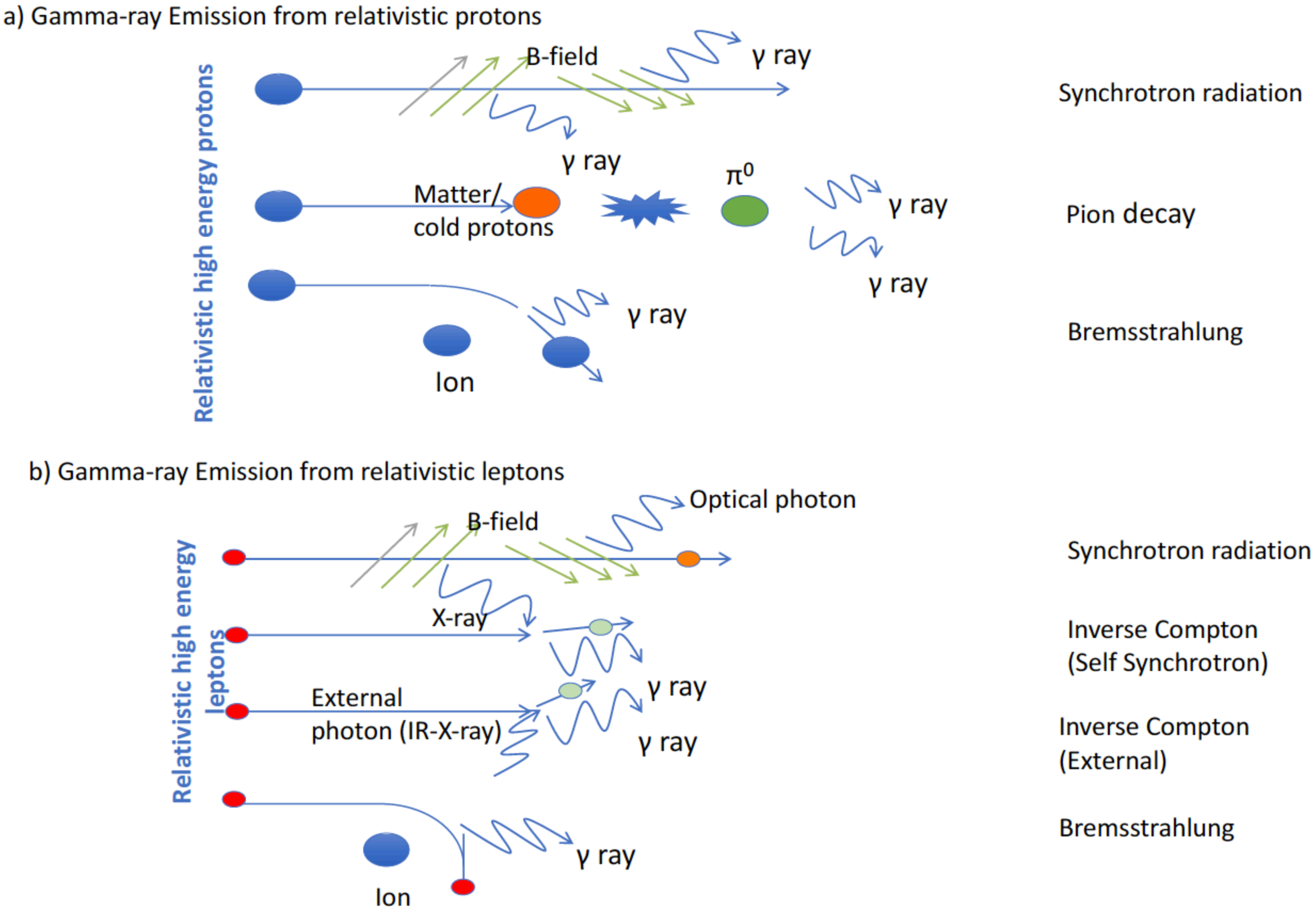


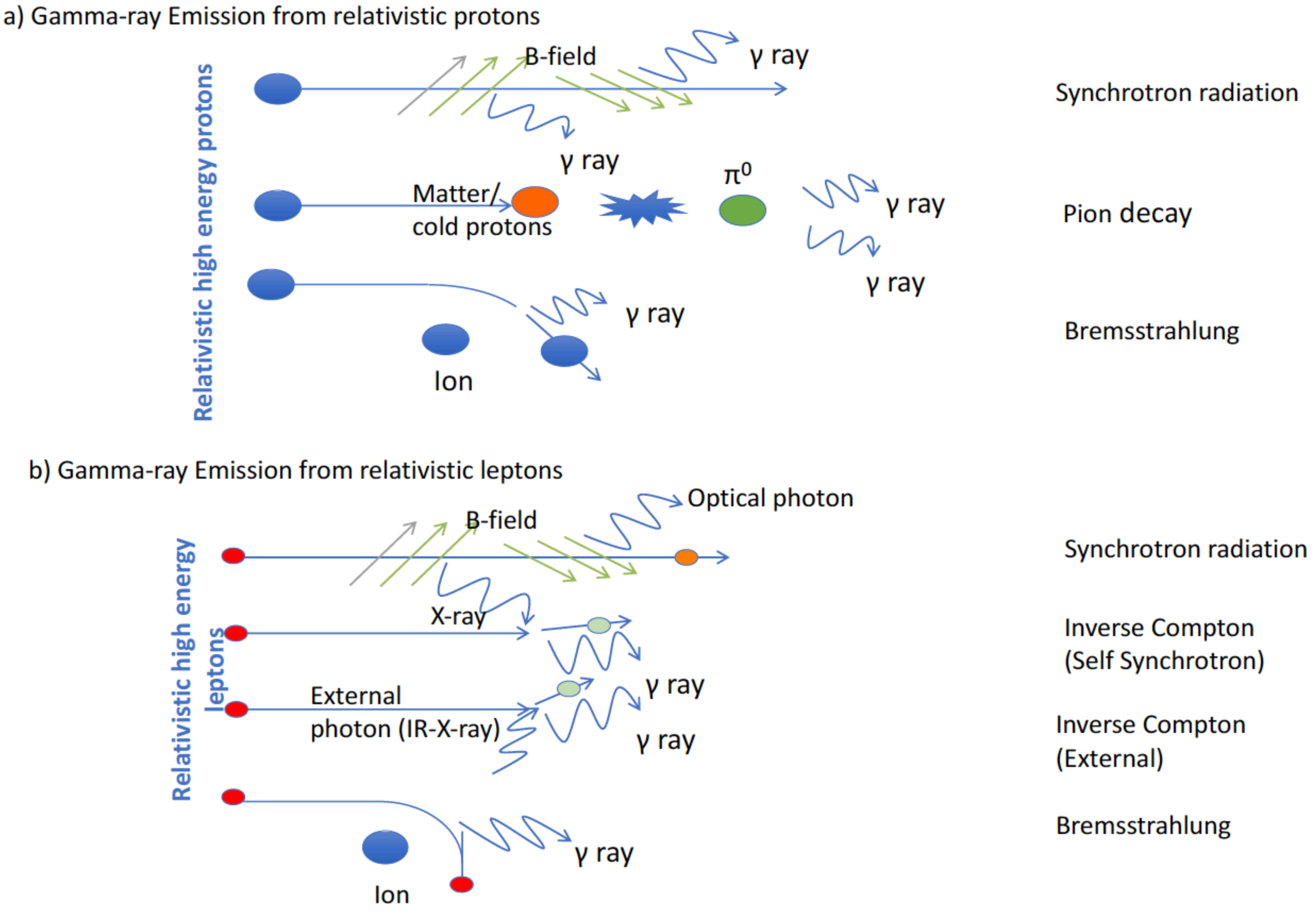
wait but, CRs are charged particles!



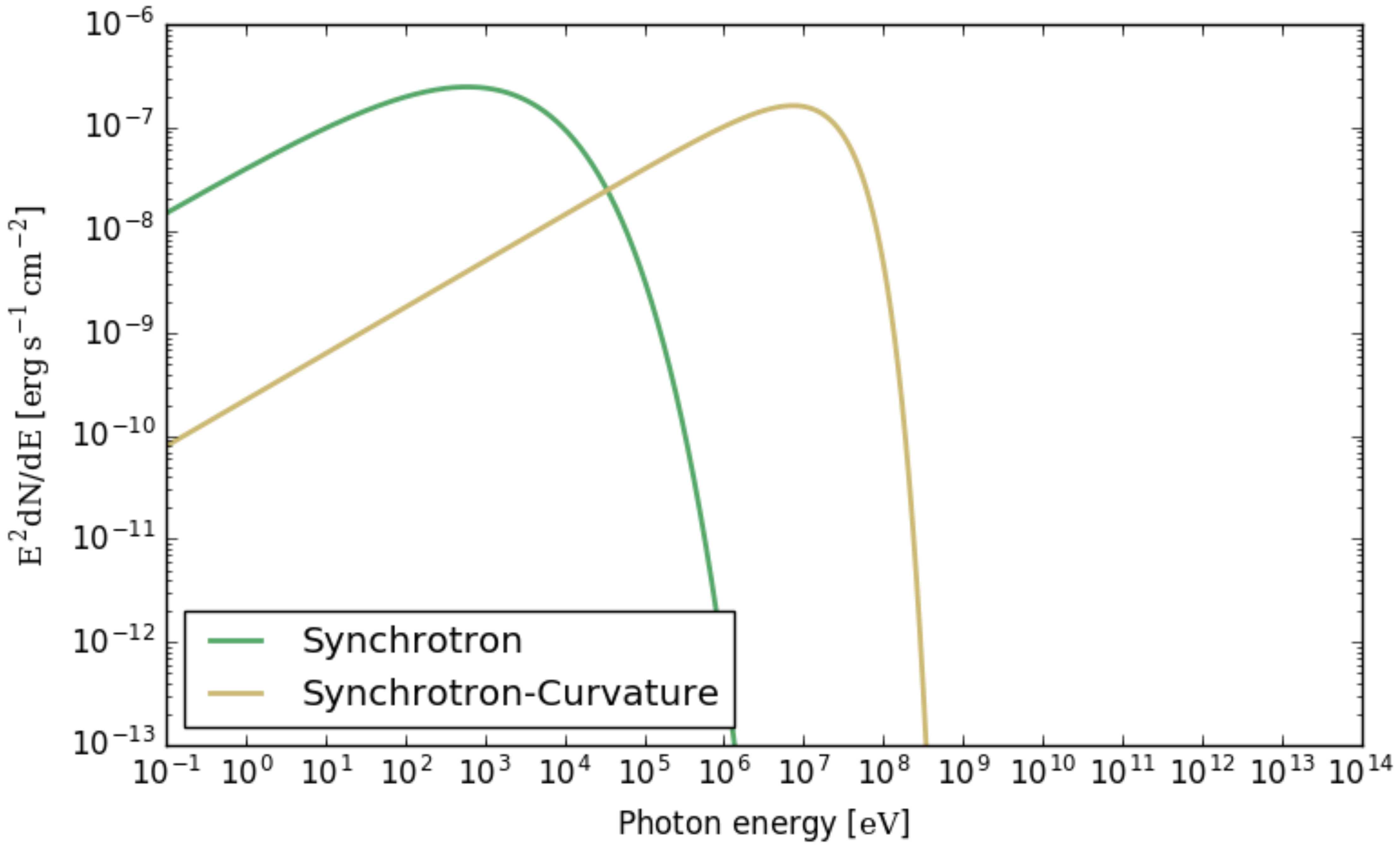


a) Gamma-ray Emission from relativistic protons
Relativistic high energy protons
B-field
γ ray
γ ray
Synchrotron radiation
Matter/
cold protons
π0
γ ray
γ ray
Pion decay
γ ray
Ion
Bremsstrahlung
b) Gamma-ray Emission from relativistic leptons
Relativistic high energy leptons
B-field
Optical photon
Synchrotron radiation
X-ray
Inverse Compton
(Self Synchrotron)
External
photon (IR-X-ray)
γ ray
γ ray
Inverse Compton
(External)
γ ray
Ion
Bremsstrahlung

Non-thermal high-energy radiation processes



Radiation Mechanisms

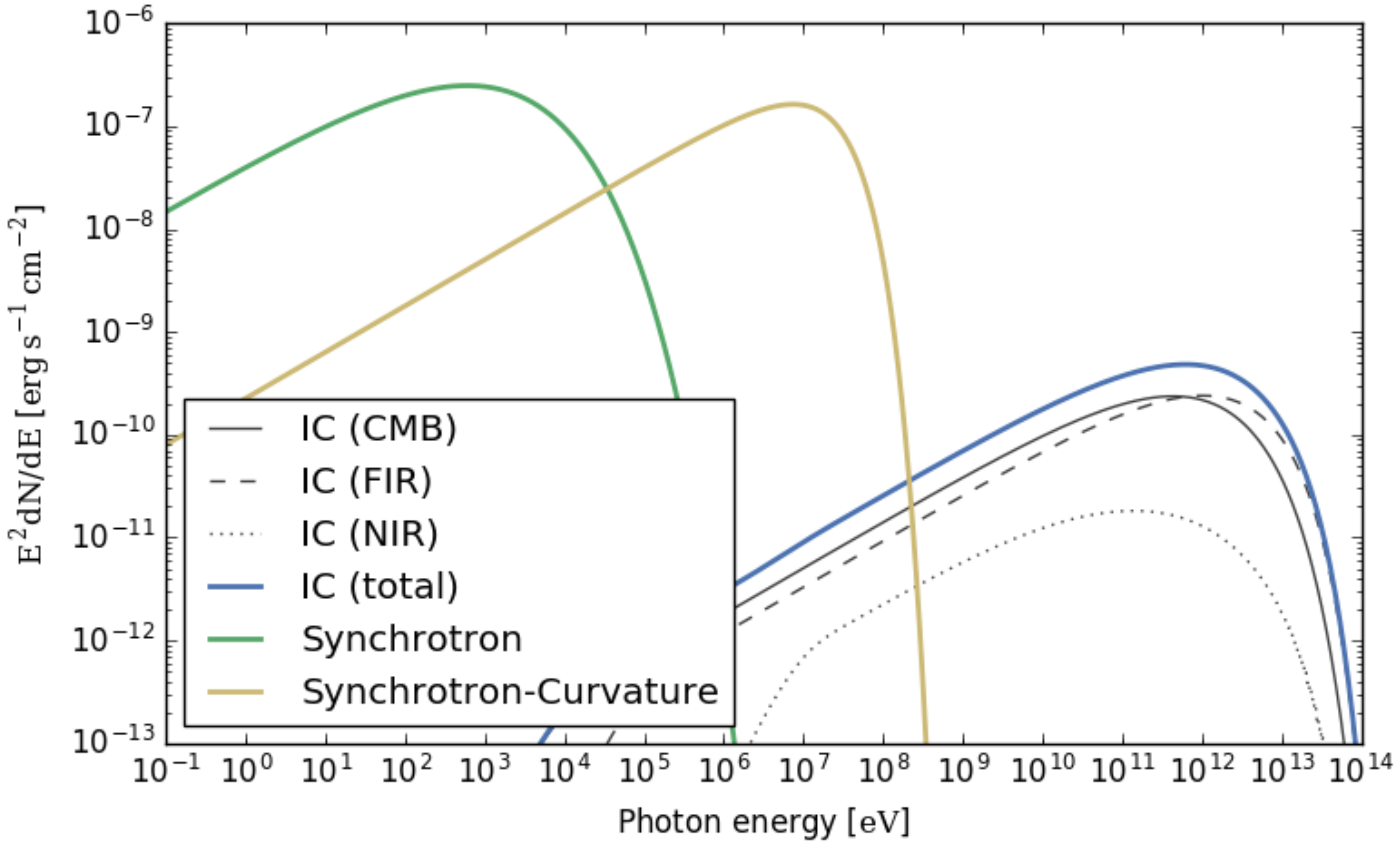


Synchrotron-Curvature

$e^{\pm} + \mathbf{B} \Rightarrow \gamma + e^{\pm}_{lowerE}$

$$dN/dE \propto Q(E)t_{\rm loss}(E) \propto E^{-(s+1)}$$

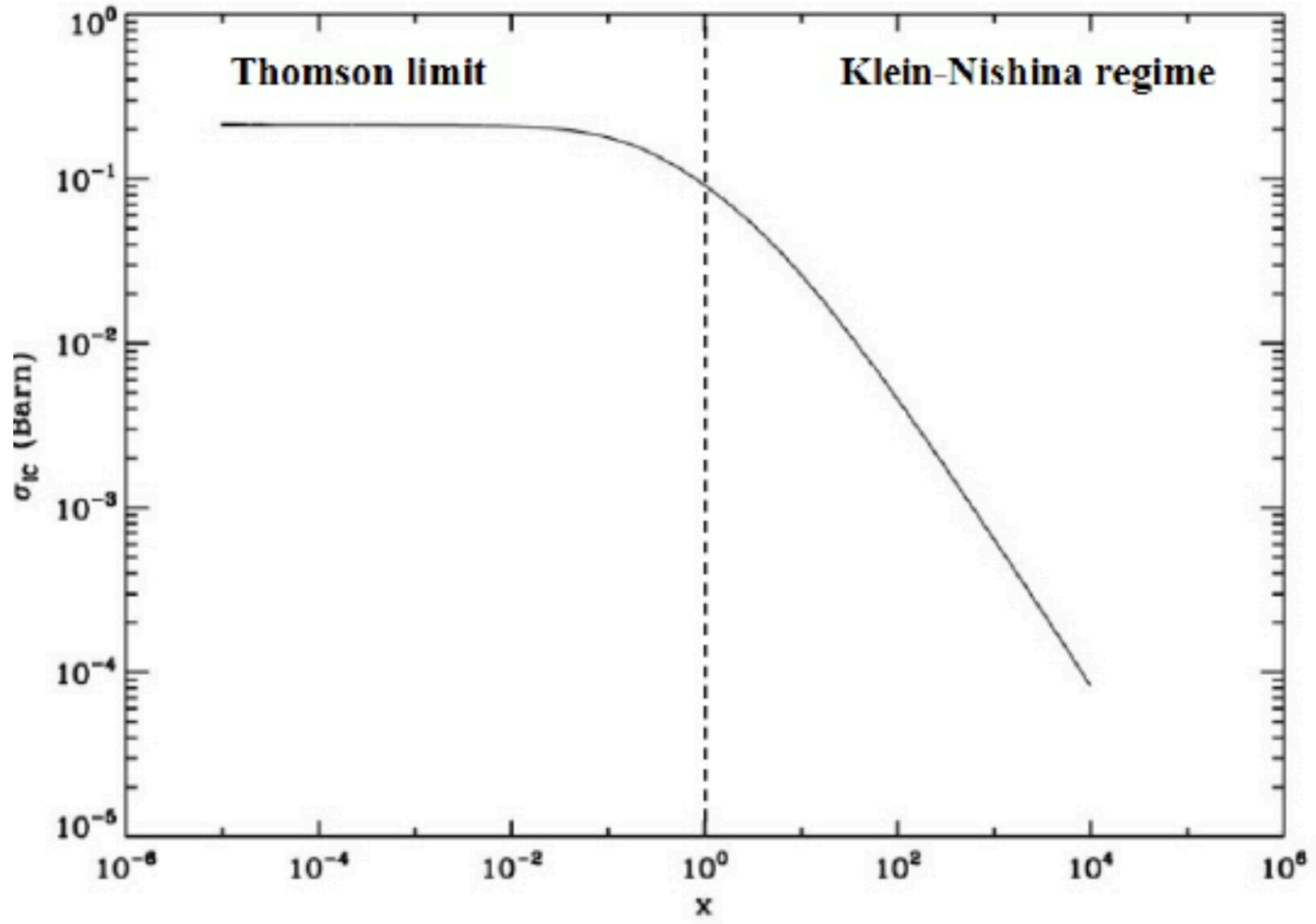
Radiation Mechanisms



Inverse Compton

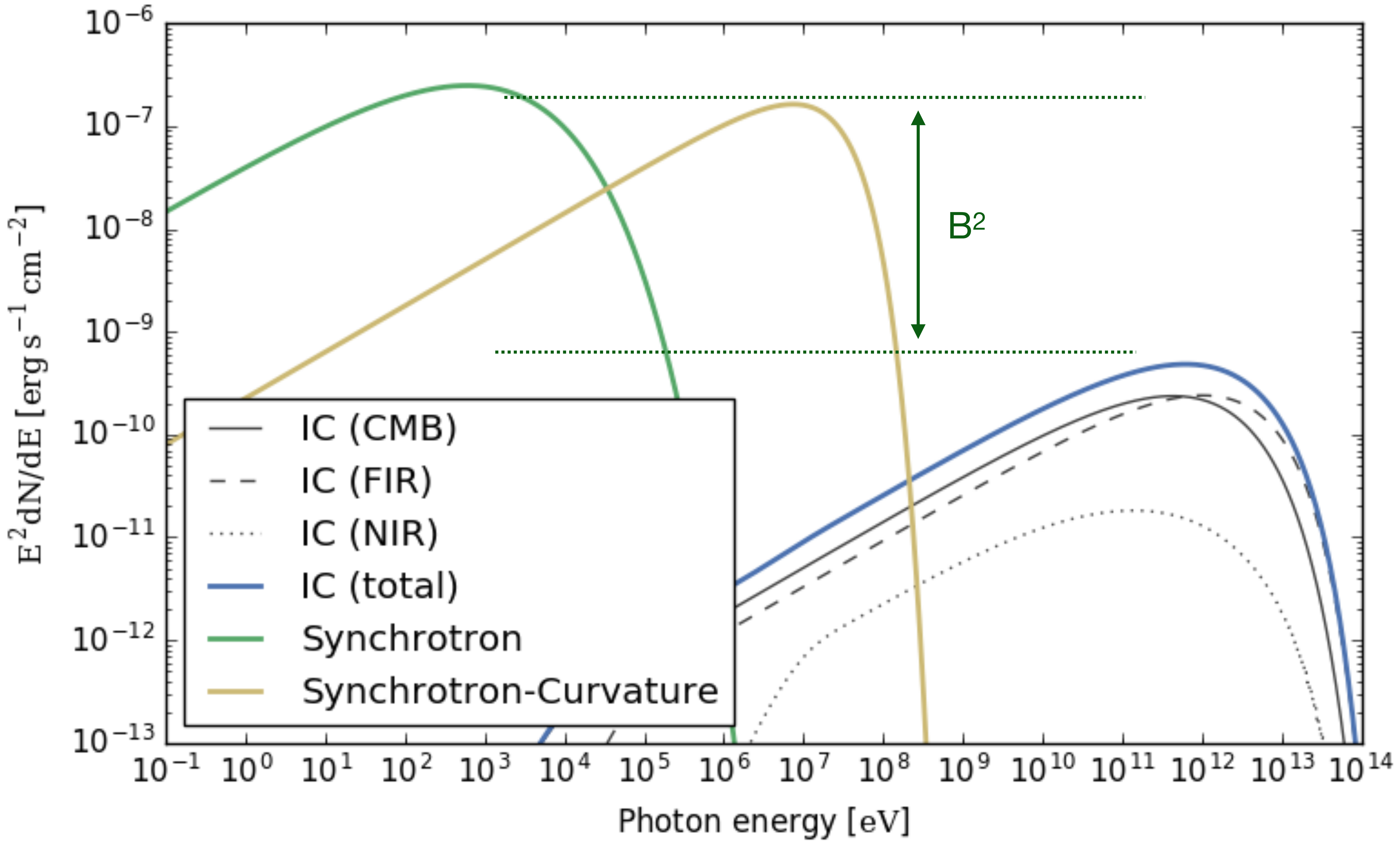
$e^{\pm}_{HE} + Y_{LE} \Rightarrow e^{\pm}_{lowerE} + Y_{LE}$

$b = 4EeE_T/m^2c^4$
b<<1 Thompson Regime
b~1 Klein-Nishina Regime



- Thompson approximation (no relativistic): $\phi \sim E^{-(s+1)/2}$
- Klein-Nishina approximation (relativistic): $\phi \sim E^{-(s+1)}$

Radiation Mechanisms



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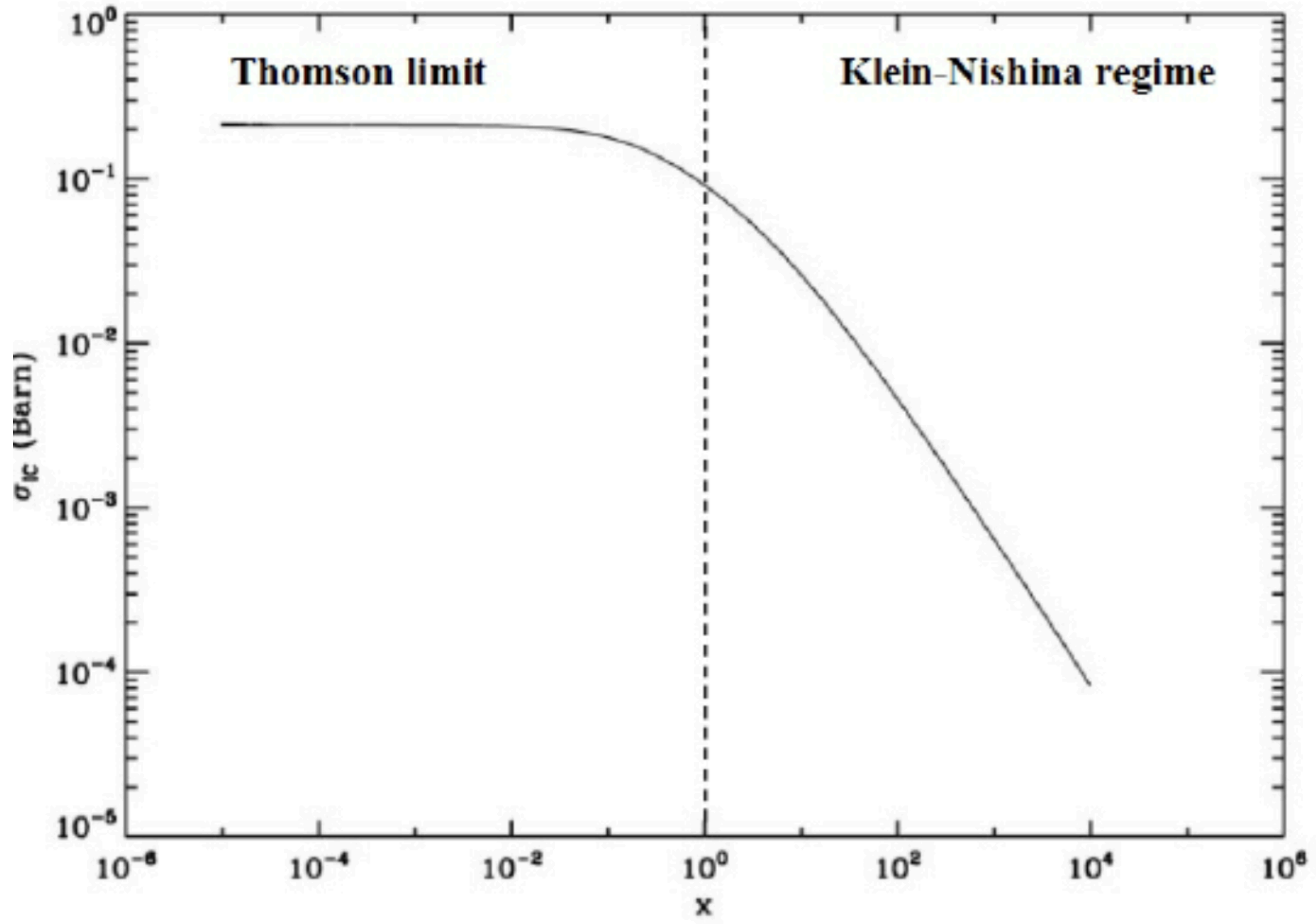

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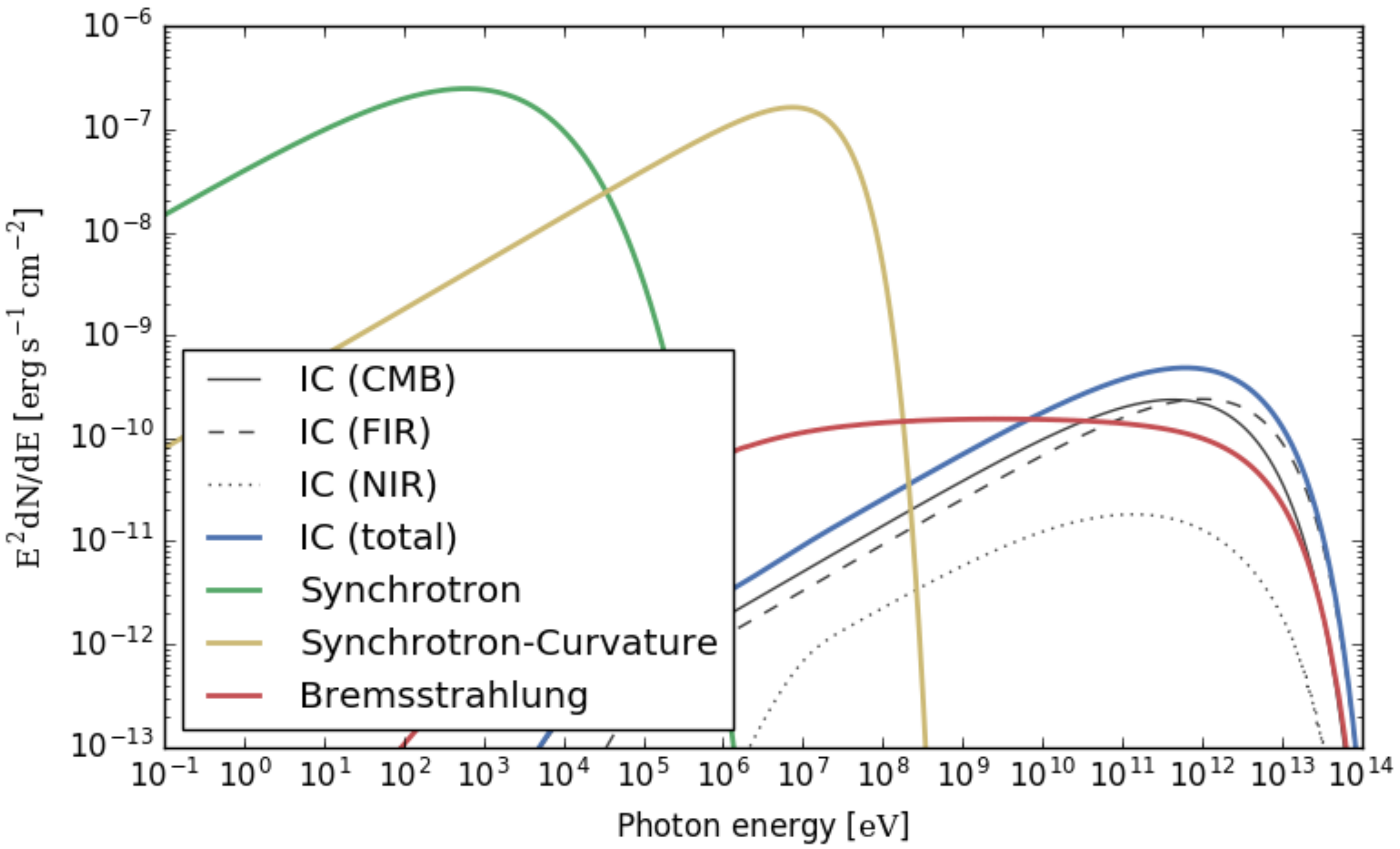
Radiation Mechanisms



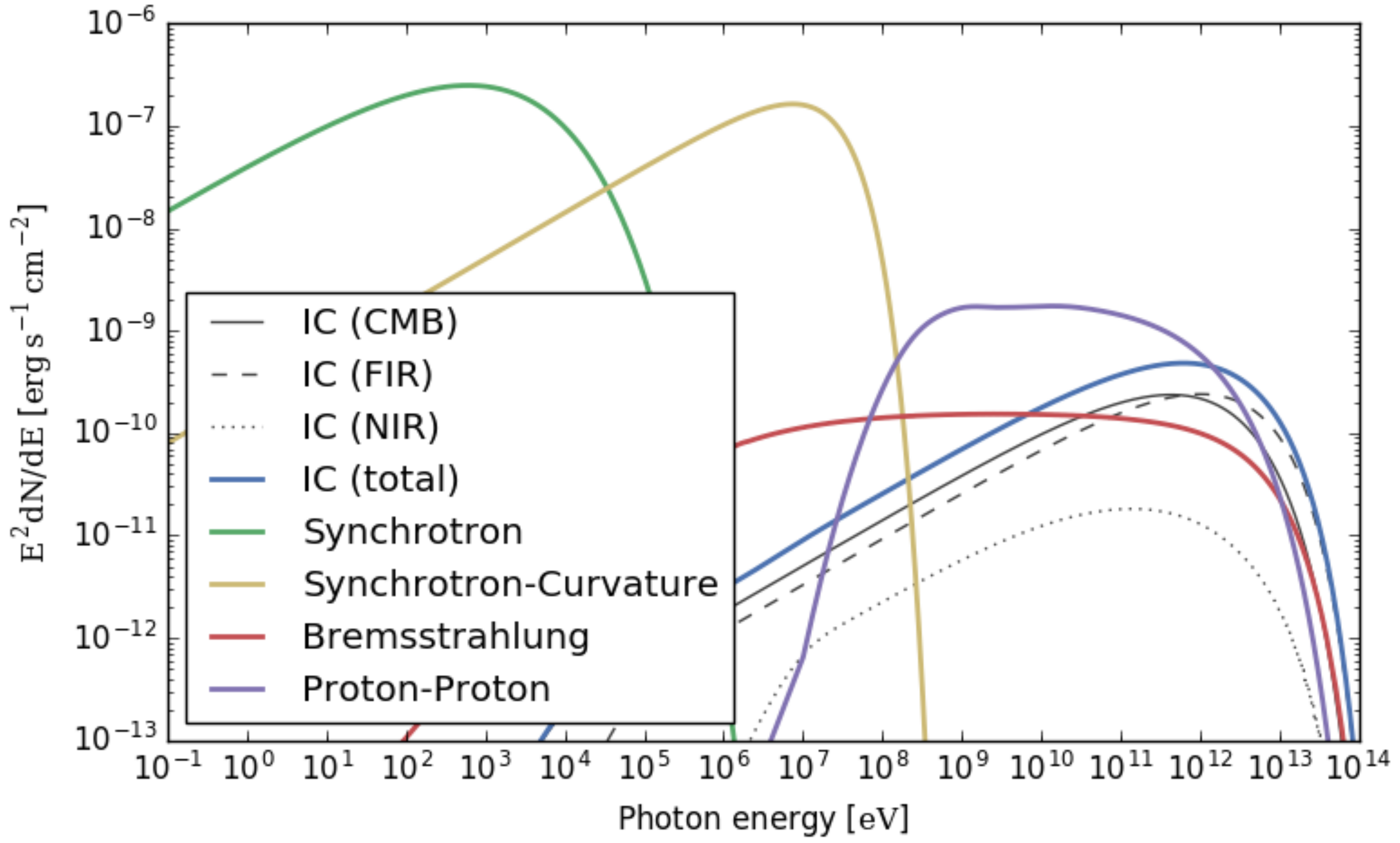
Bremsstrahlung

$e^{\pm}$ + N(e) ⇒ e' γN(e) , Eγ~1/2 Ee

Regions of high density:
Galactic Center, dense clouds, SNRs

Pair Production: γN(e) → e+e- N(e)
e+e- annihilations: e+e- → **γ γ** (511 keV line)

Radiation Mechanisms



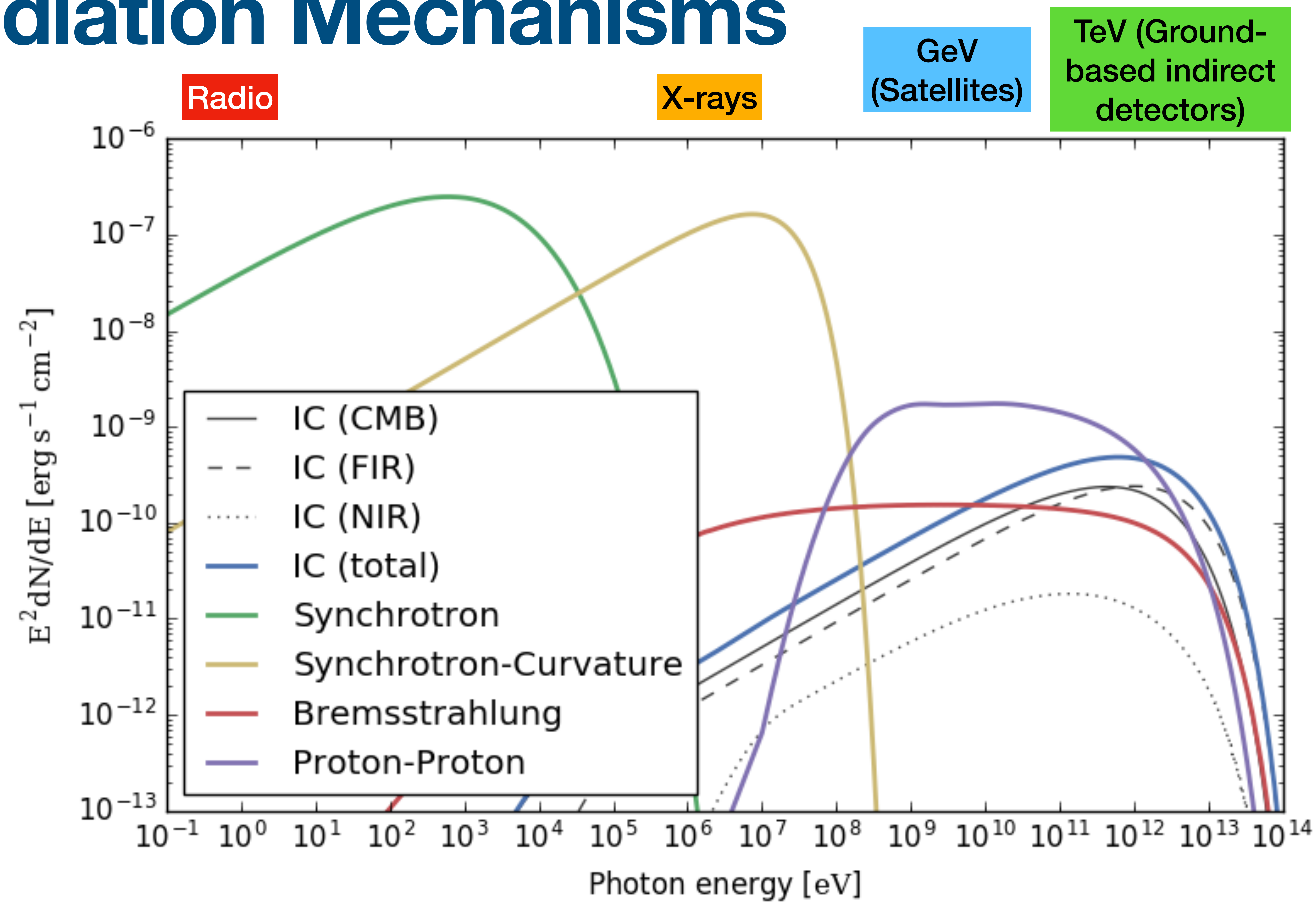
Proton-Proton

$p + p \rightarrow \pi^0 + \chi + \ldots + \pi^{\pm}$

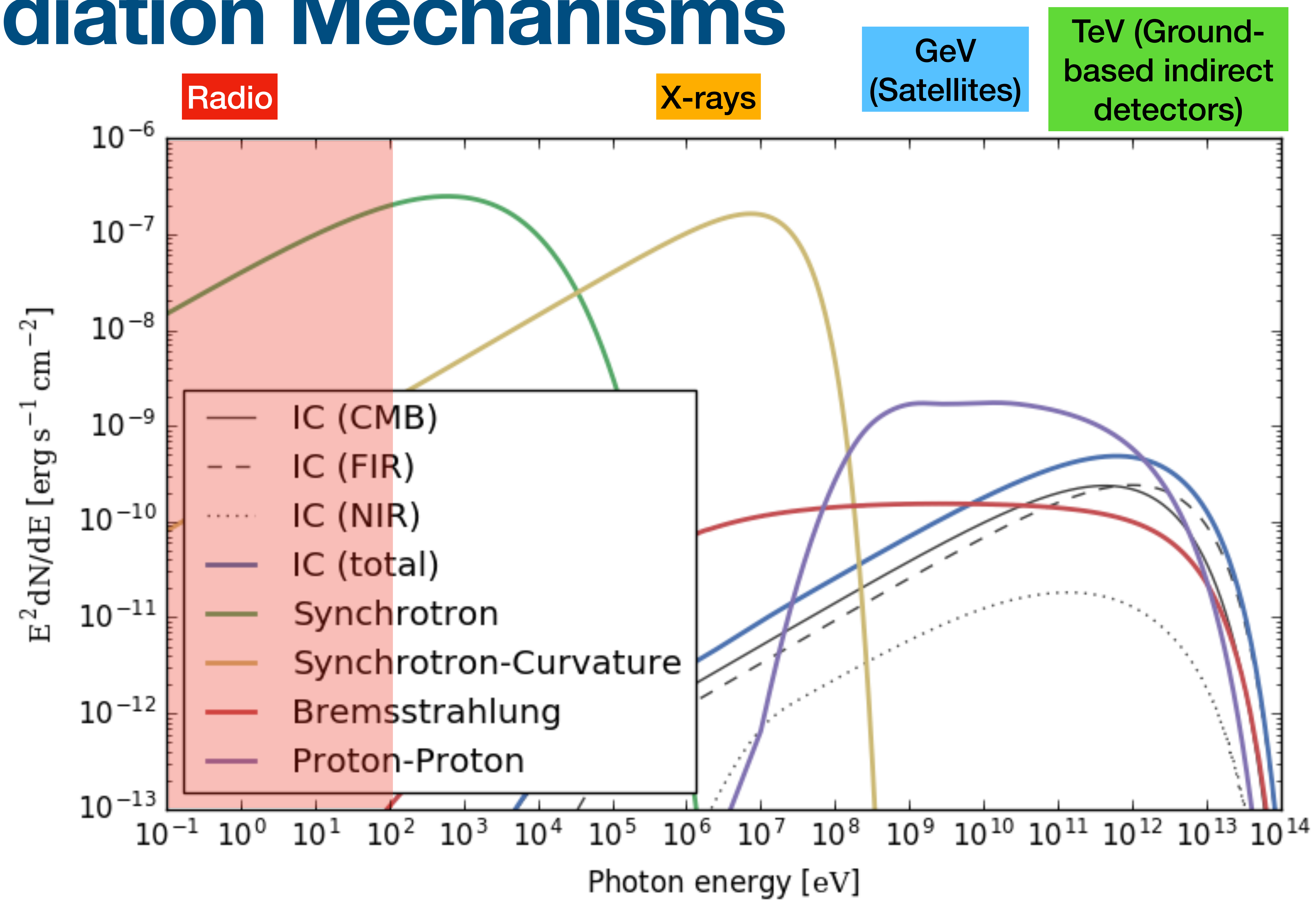
↳ $\gamma + \gamma$ ↳ $\nu_\tau + \nu_e$

↳ e+, e-

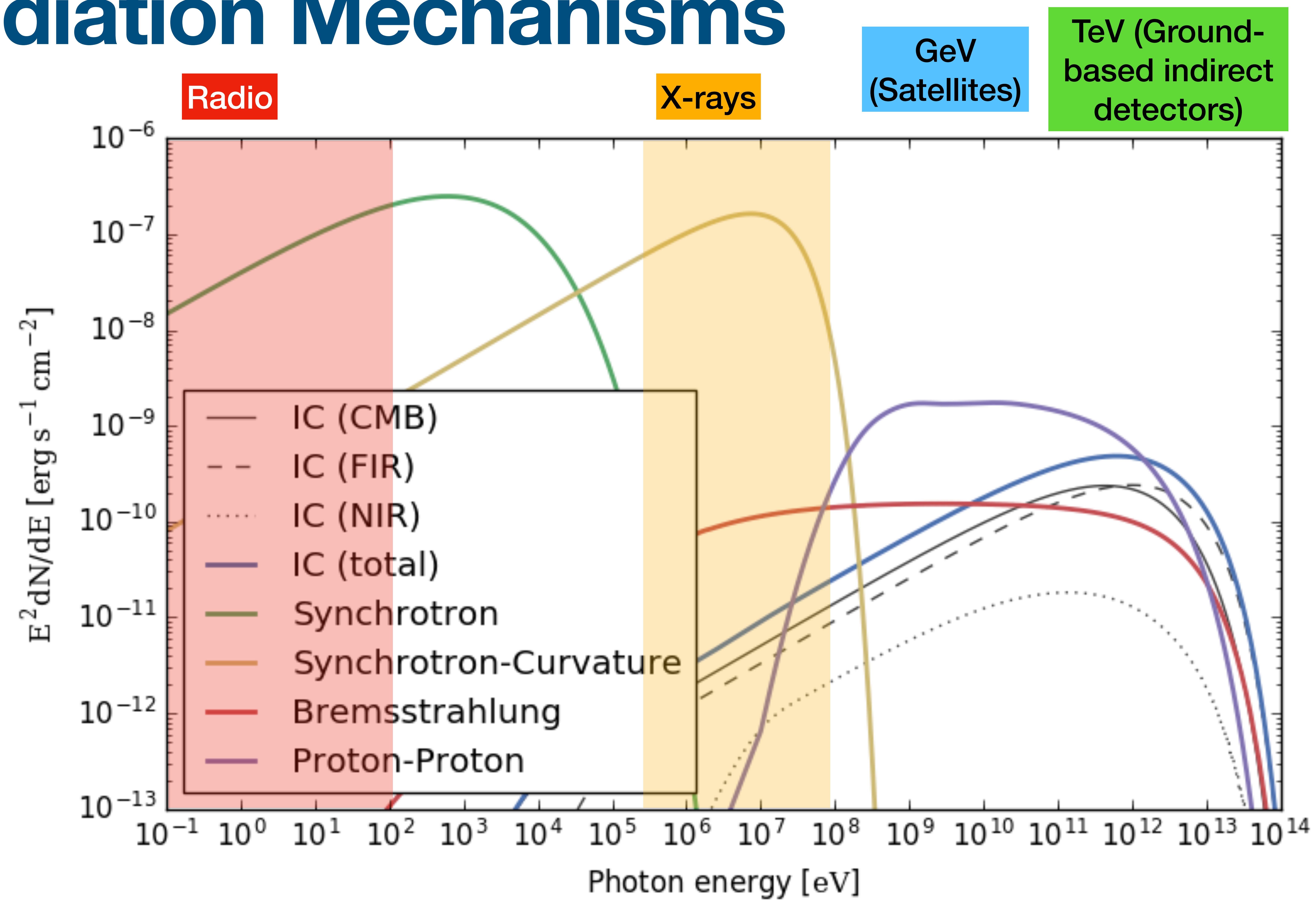
Radiation Mechanisms



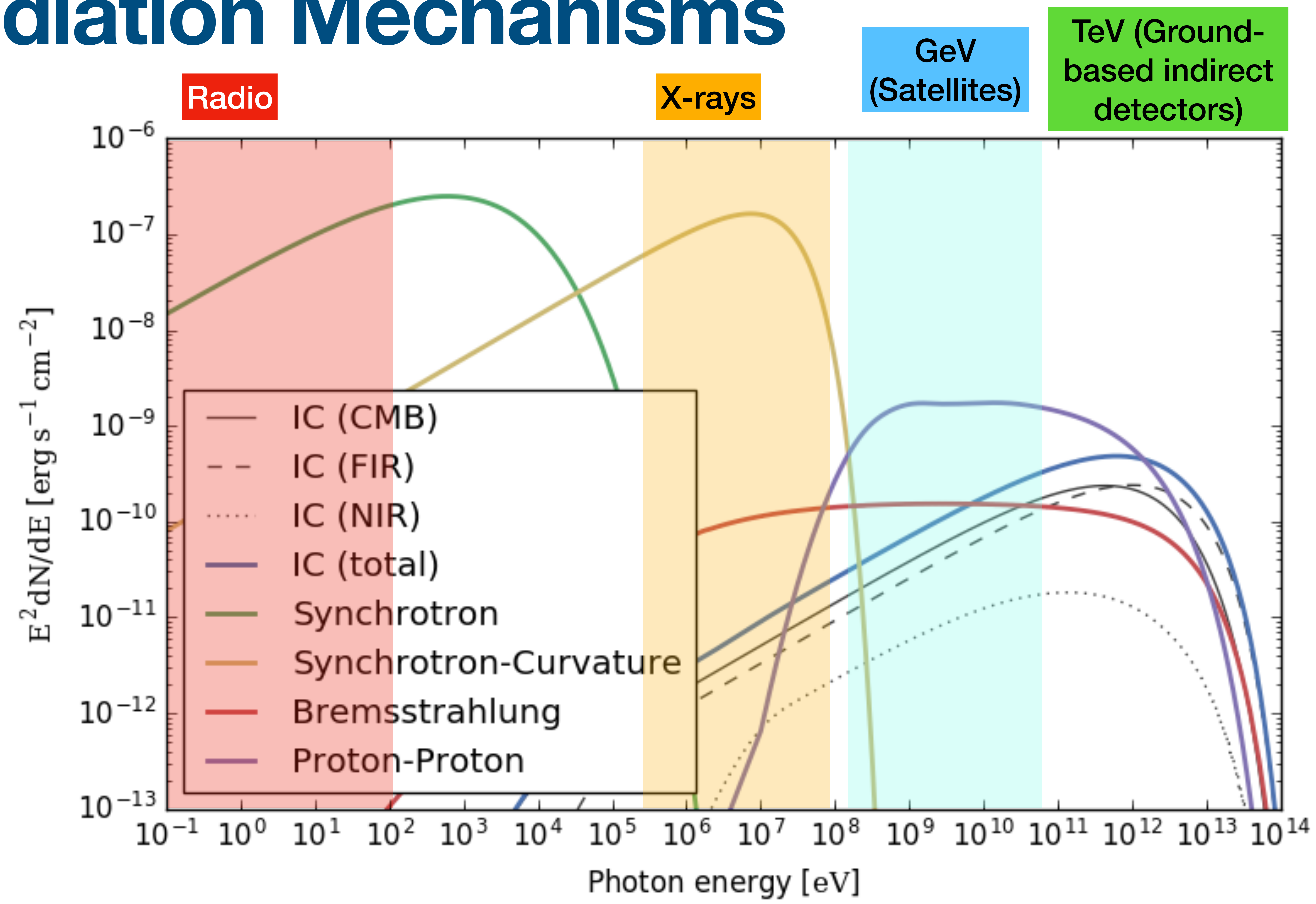
Radiation Mechanisms



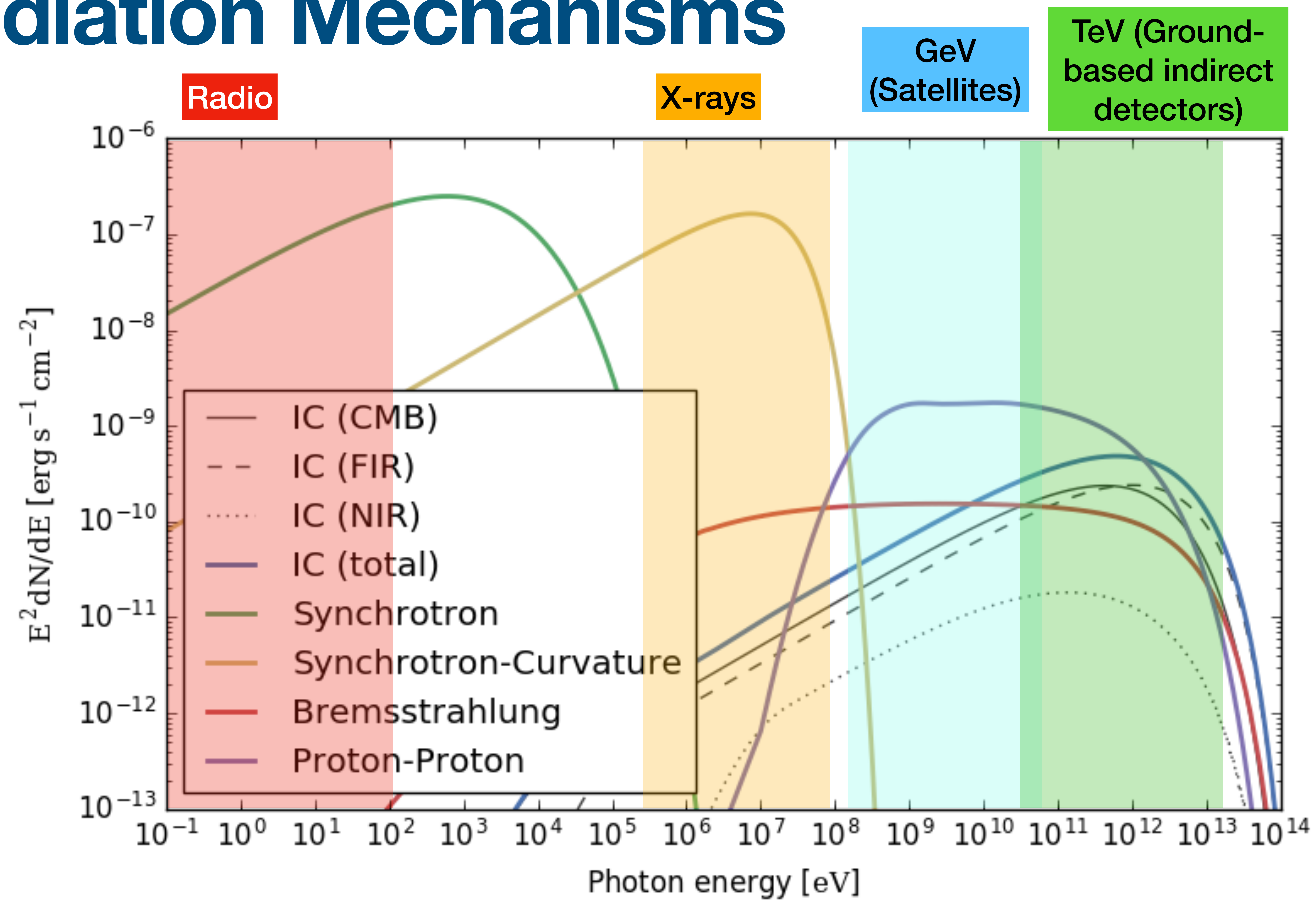
Radiation Mechanisms



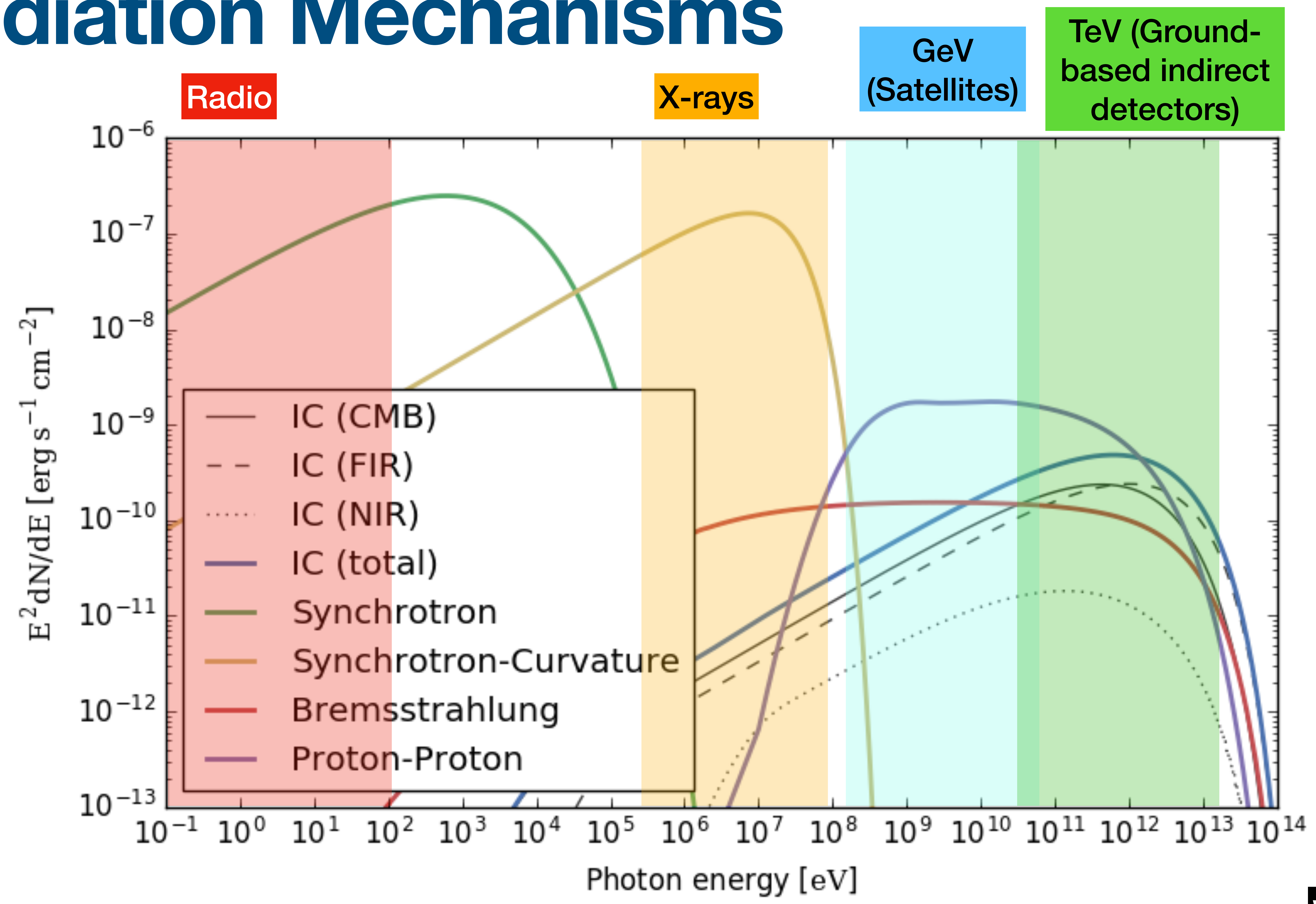
Radiation Mechanisms



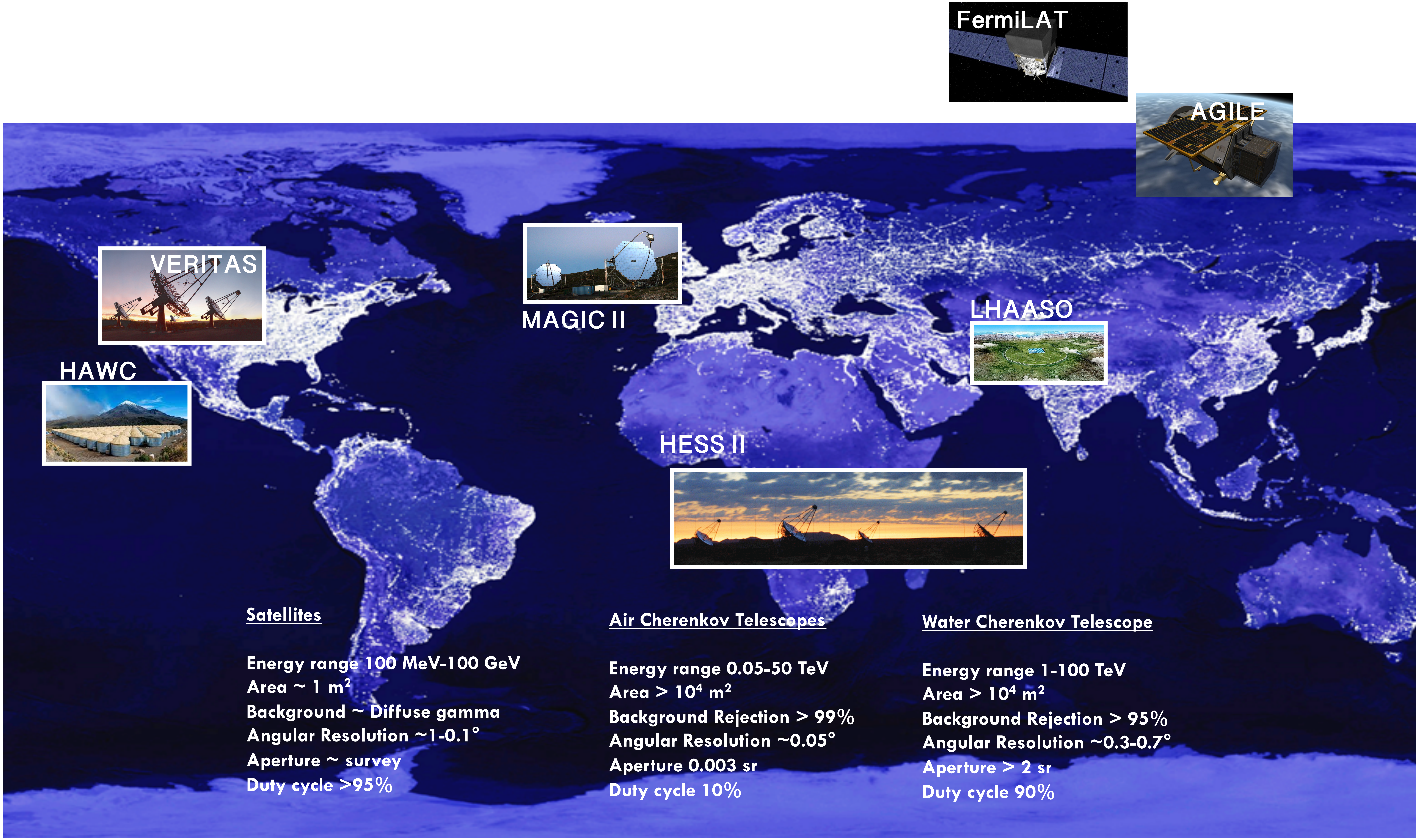
Radiation Mechanisms

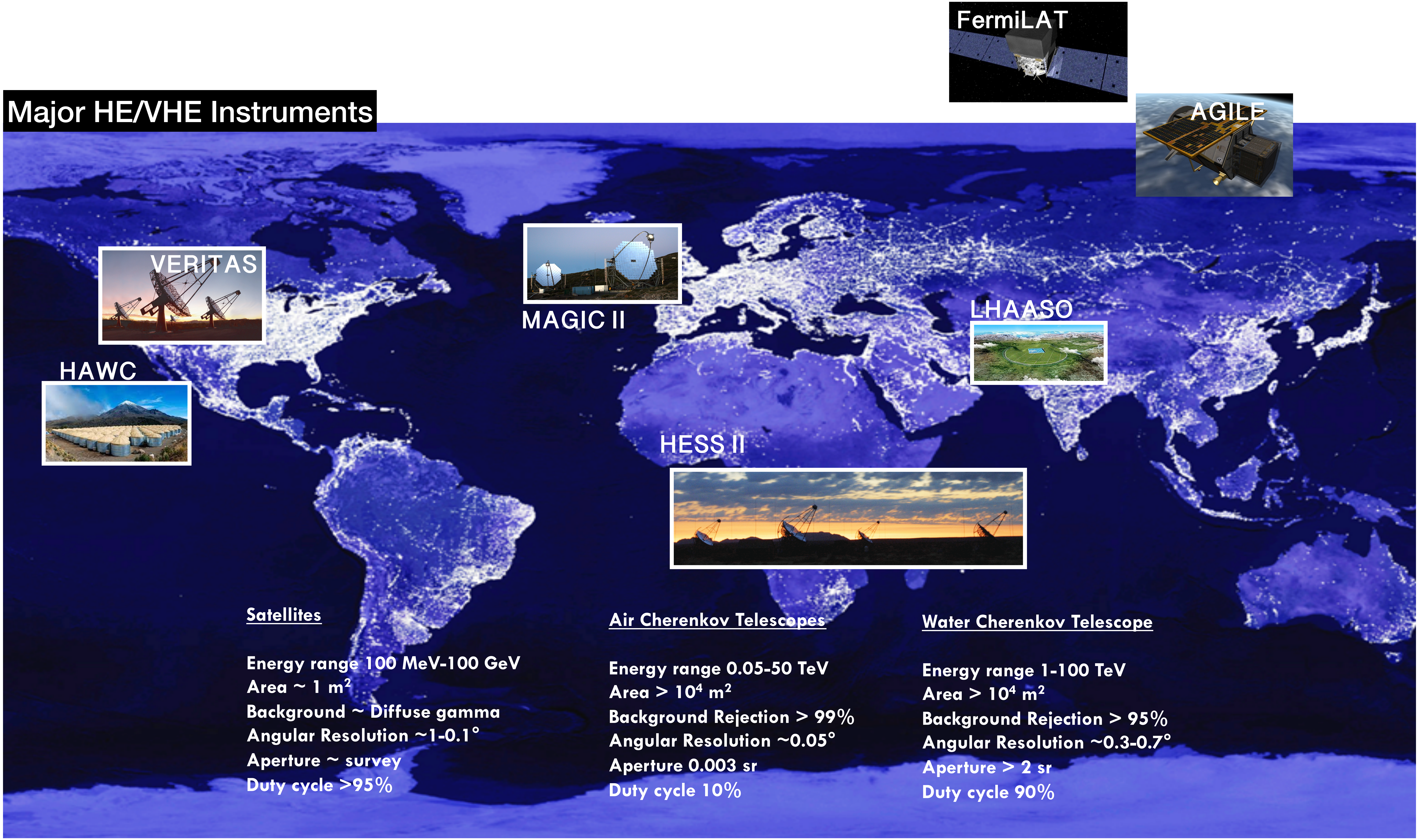


Radiation Mechanisms



Which Instruments?


FermiLAT
AGILE
VERITAS
MAGIC II
LHAASO
HAWC
HESS II
Satellites
Energy range 100 MeV-100 GeV
Area ~ 1 m^2
Background ~ Diffuse gamma
Angular Resolution ~1-0.1°
Aperture ~ survey
Duty cycle >95%
Air Cherenkov Telescopes
Energy range 0.05-50 TeV
Area > 10^4 m^2
Background Rejection > 99%
Angular Resolution ~0.05°
Aperture 0.003 sr
Duty cycle 10%
Water Cherenkov Telescope
Energy range 1-100 TeV
Area > 10^4 m^2
Background Rejection > 95%
Angular Resolution ~0.3-0.7°
Aperture > 2 sr
Duty cycle 90%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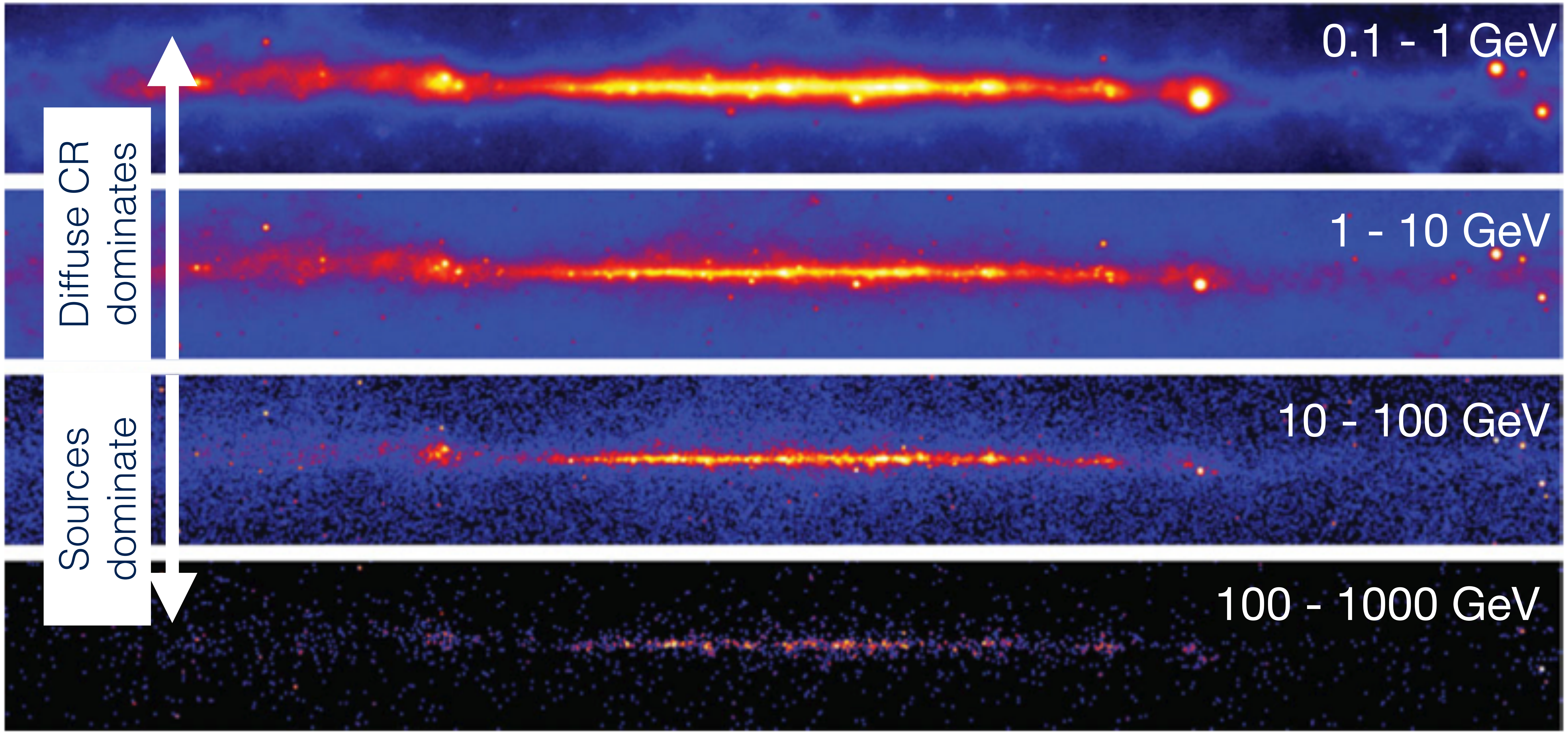
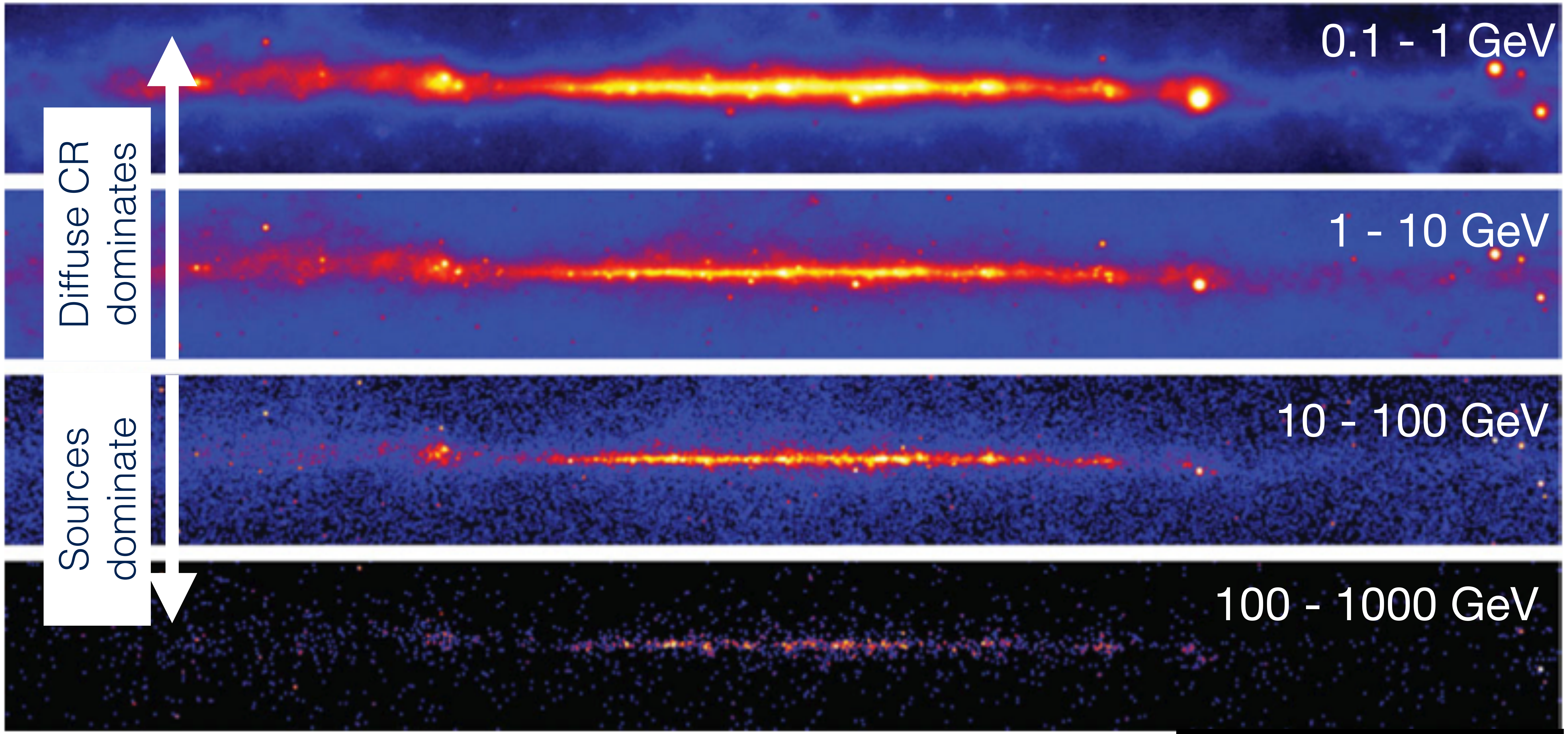
CR Accelerators - hadronic

Hadronic CRs



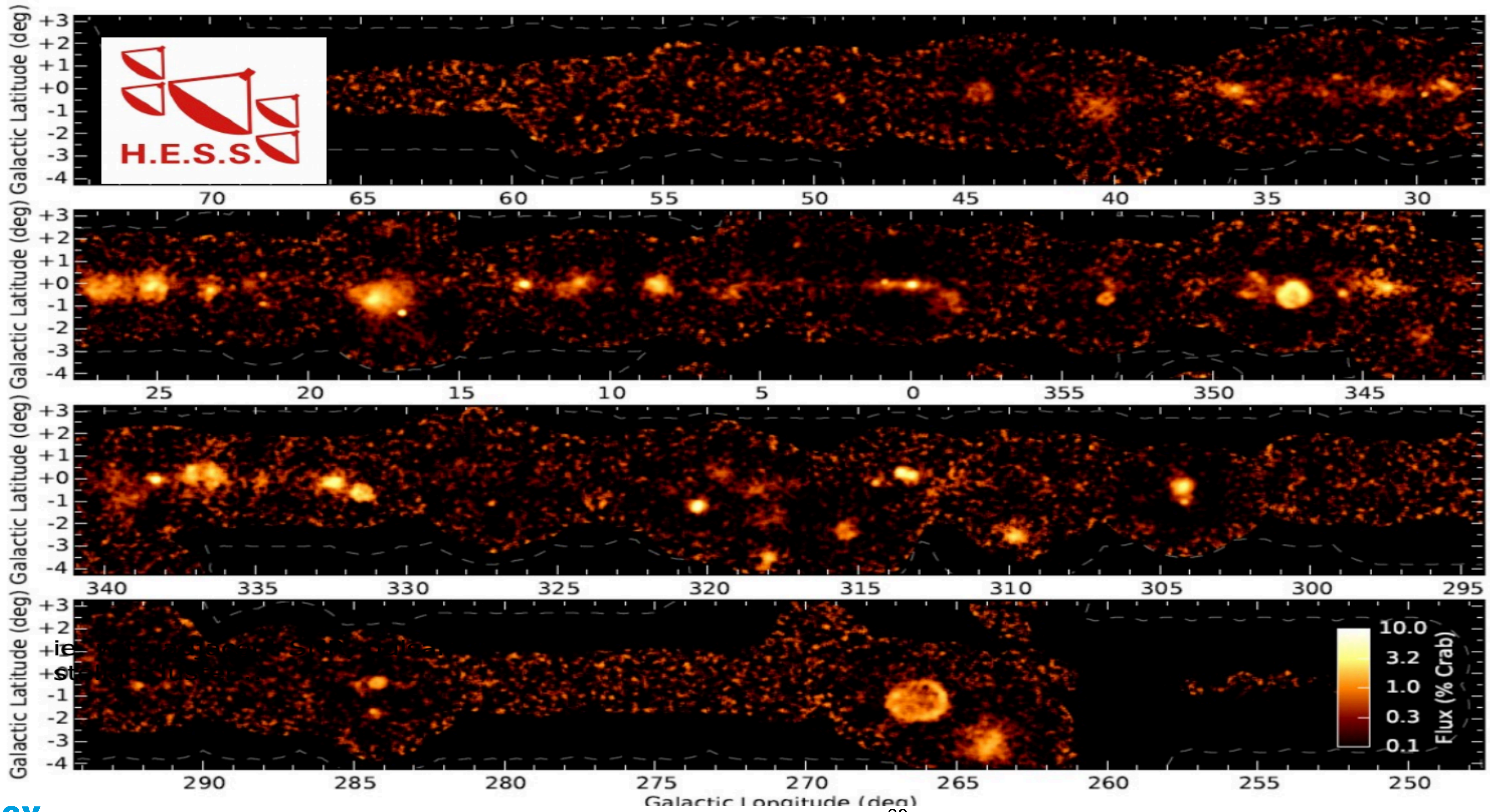
Hadronic CRs



Dominant process?

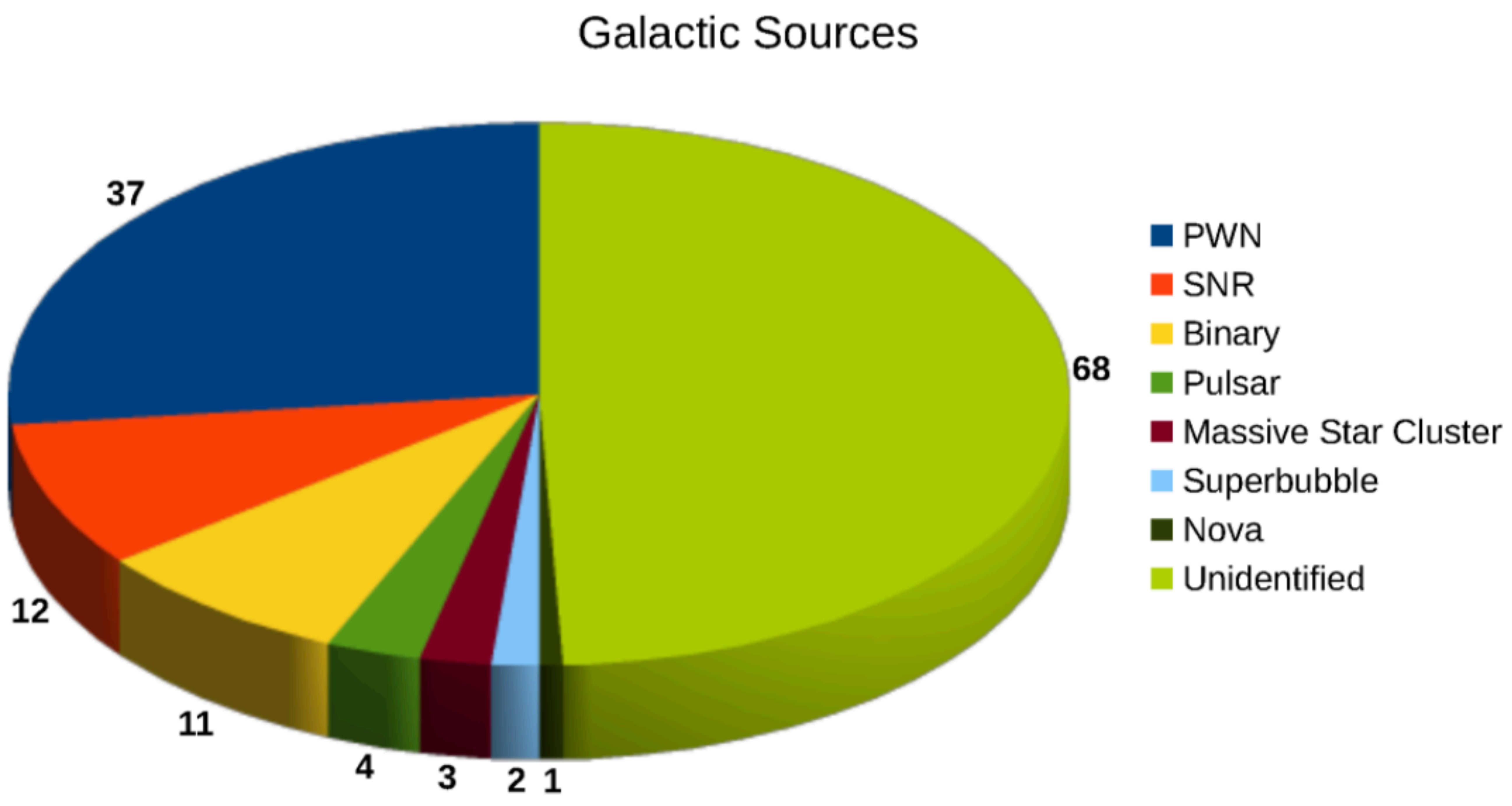
The Galactic Plane in Gamma-rays

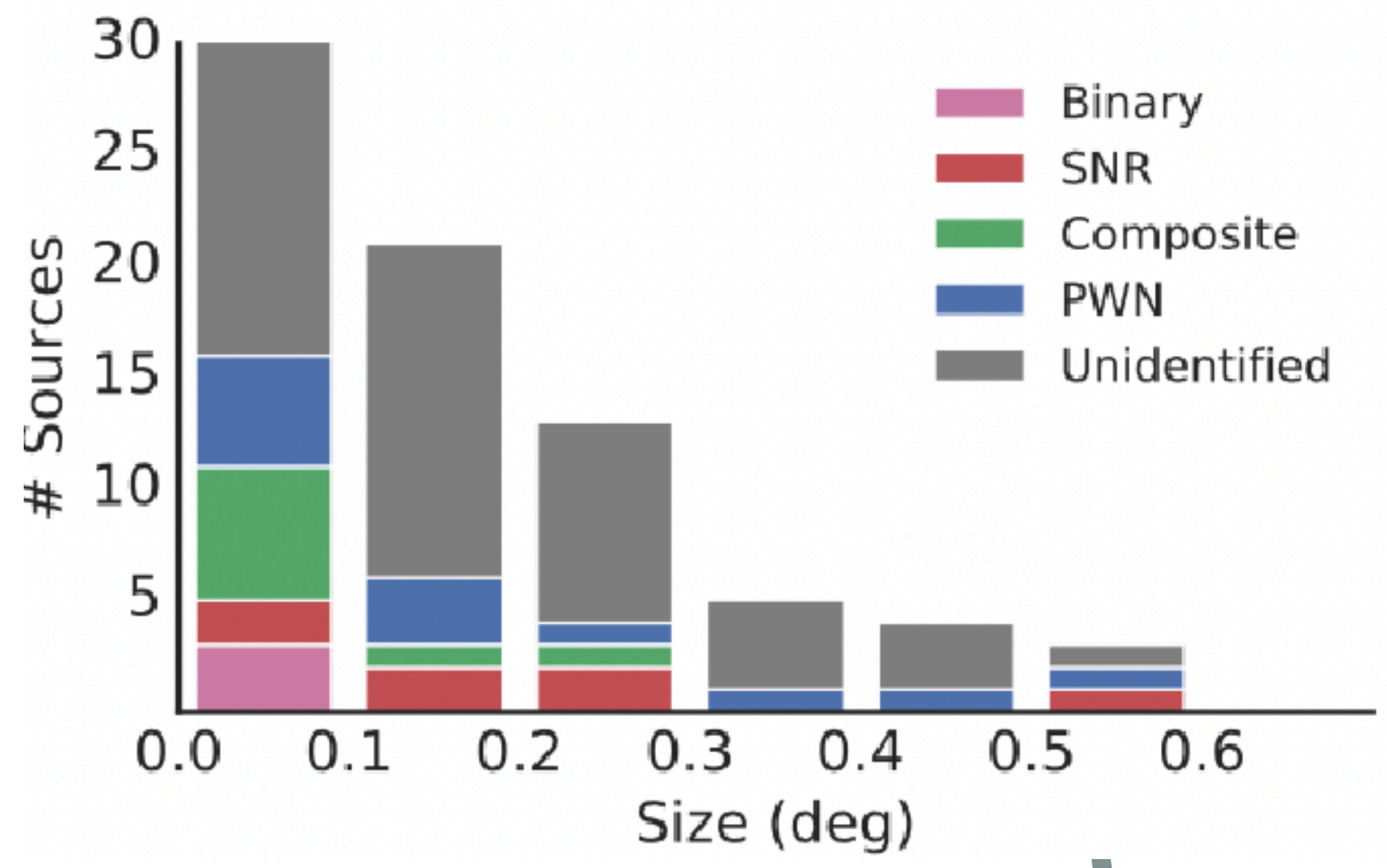
H.E.S.S. Galactic Plane Survey (HGPS)

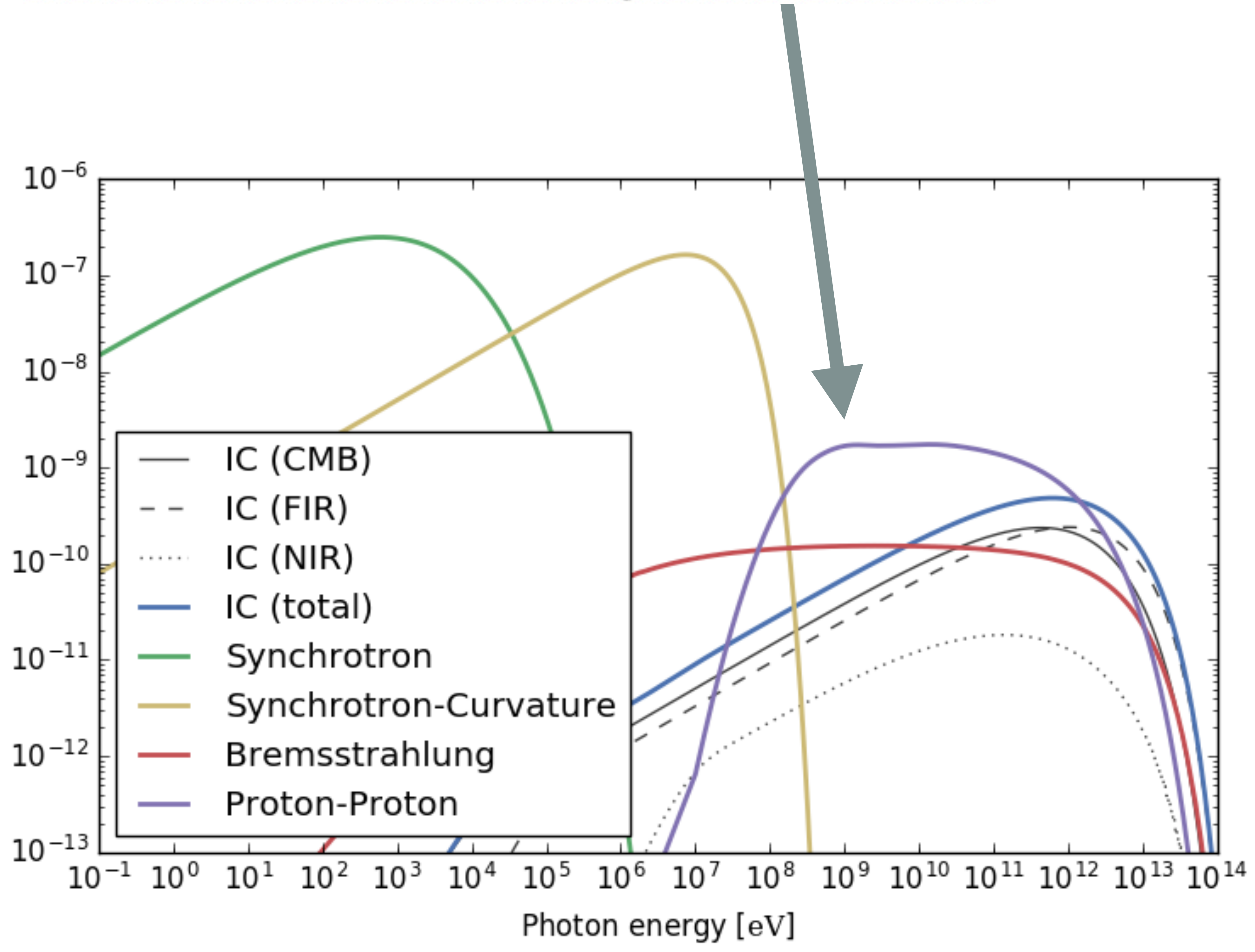


The H.E.S.S. GPS

Galactic Population







The standard paradigm: SNRs

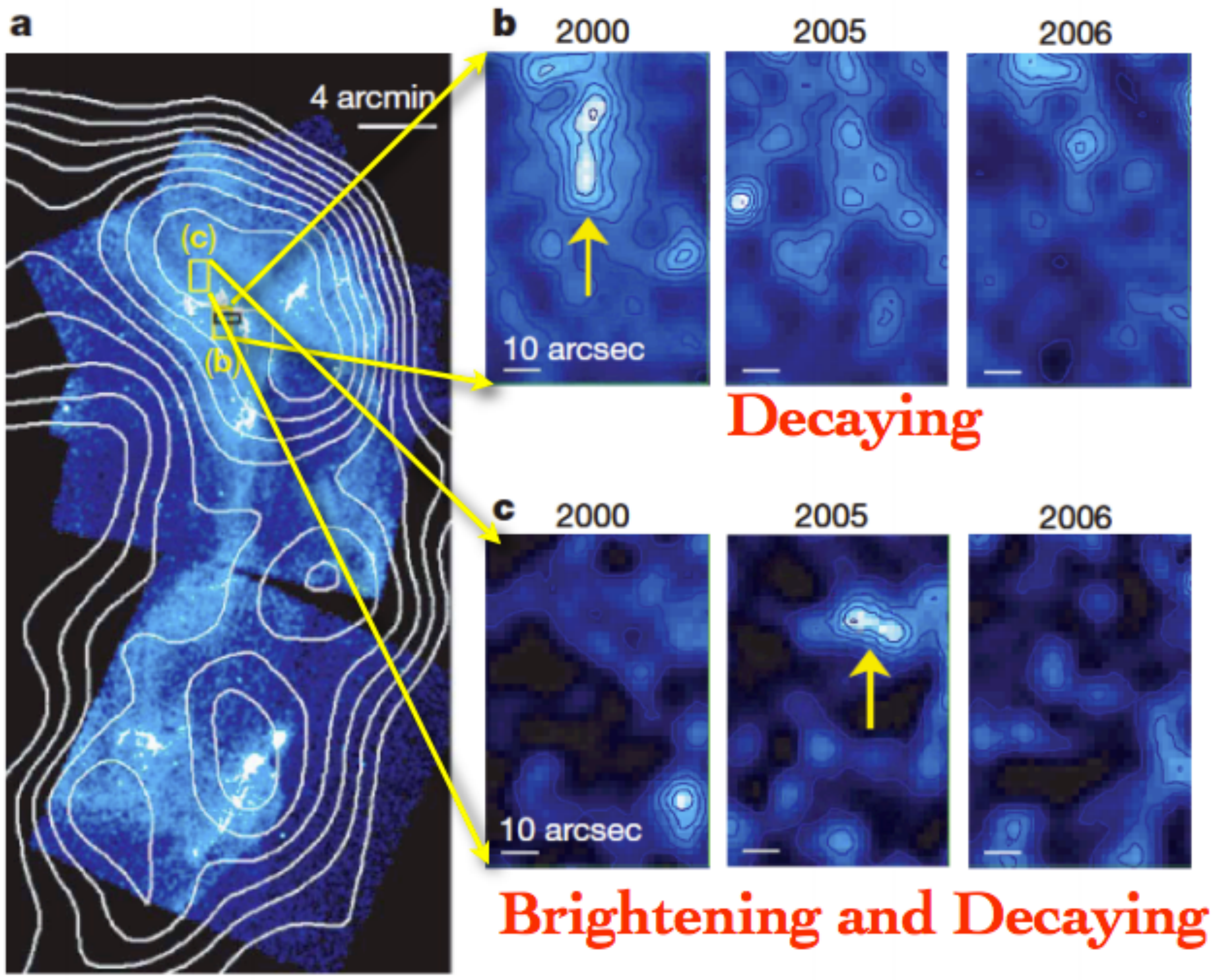
CR Accelerators

- ✓ $L=u_{CR}*V_{gal}/t_{CR} = 5x10^{40}$ erg/s
- ✓ Homogeneity
- ✓ Up to PeV energies

- **Energetics**
  $E_{kin} = 10^{51}$ erg
  $\tau \sim$ 2-3 year
  $L_{SN} = 10^{51} / \tau = 6x10^{41}$erg/s => 10% into CRs should be sufficient

- **Maximum energy**
  $v_{sh} \sim 10^3$ km/s, B ~few mG => Emax ~ 10^{17} eV

Uchiyama et al, 2017



Chandra (color)
HESS (contours)

Decaying = Synchrotron Cooling

$t_{syn} \sim 1/5\ B_{mG}^{-1.5} E_{KeV}^{-0.5}$ years

$B \sim 1$ mG

Brightening = Electrons Acceleration

$t_{acc} \sim \eta B_{mG}^{-1.5} E^{0.5} V_{3000}$ years

$B \sim 1$ mG ($\eta \sim 1$)

The standard paradigm: SNRs

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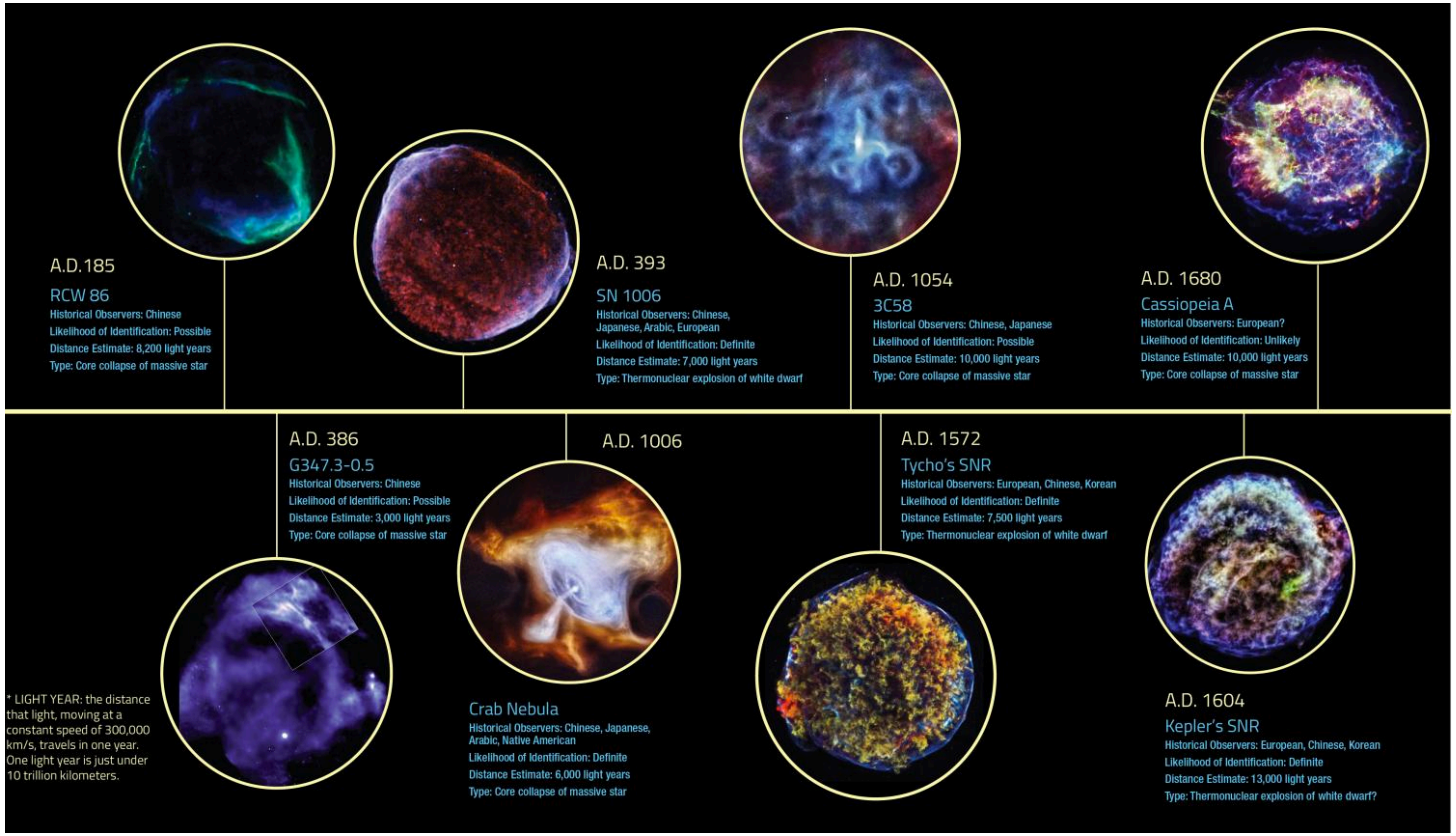
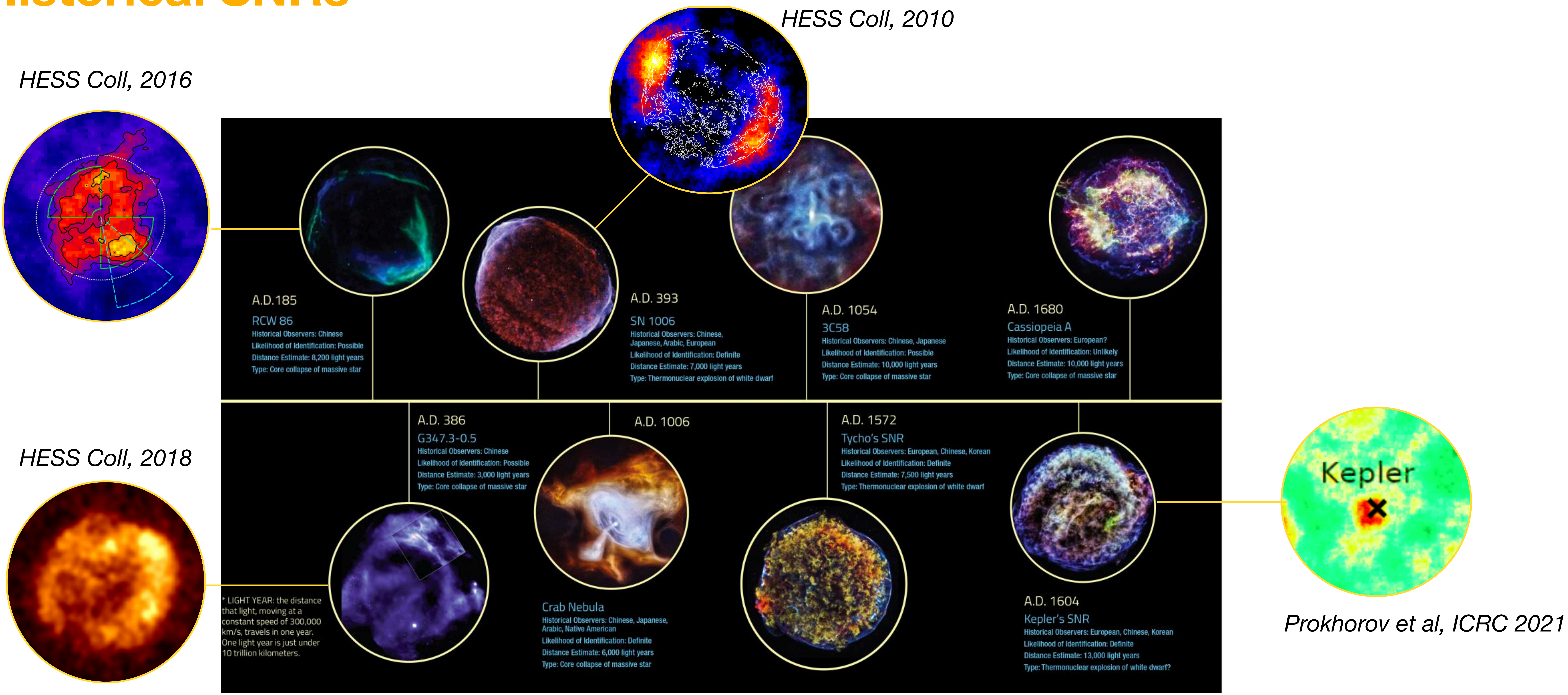
CRs accelerators: SNRs

Historical SNRs



CRs accelerators: SNRs

Historical SNRs



DESY.

CRs accelerators: SNRs

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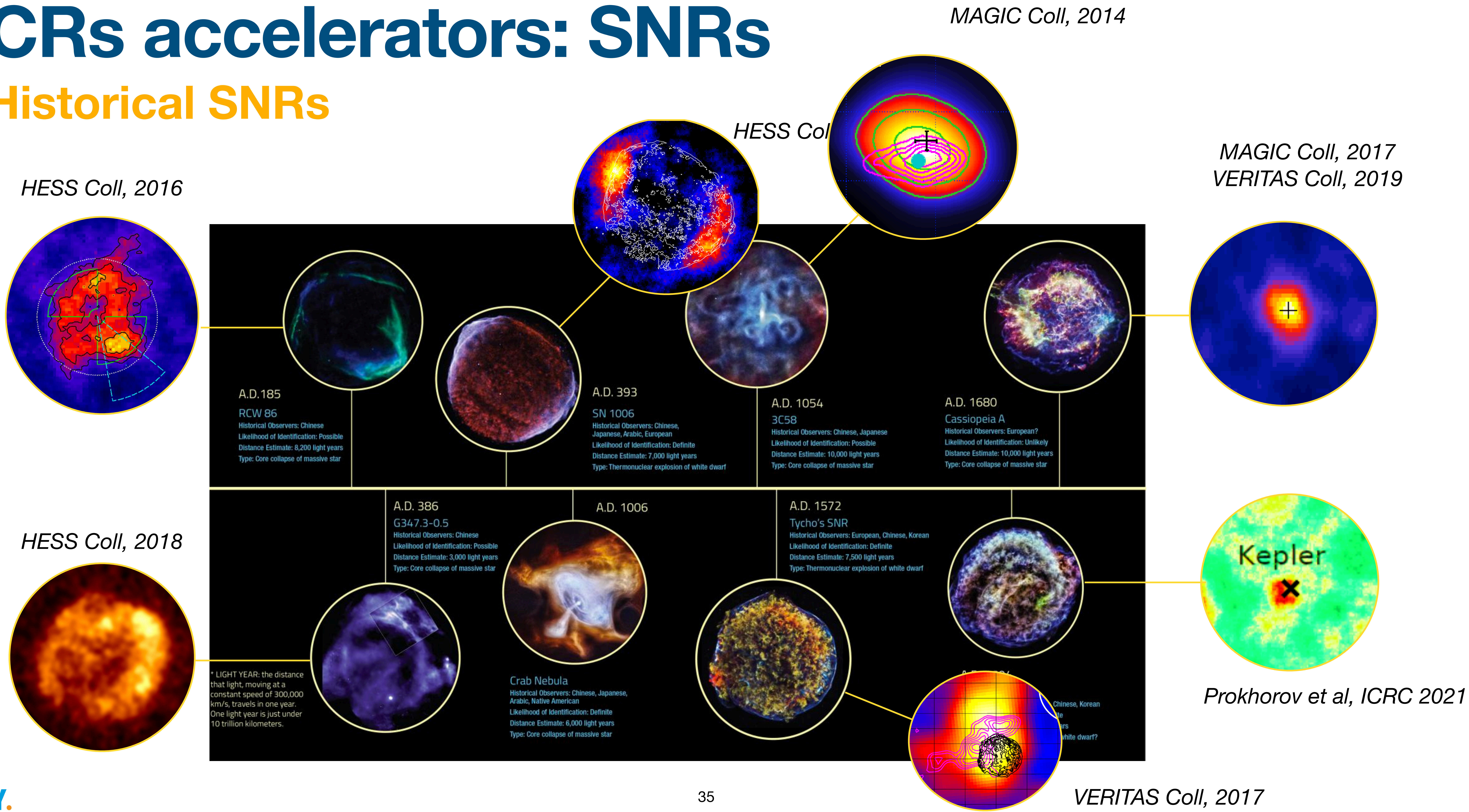

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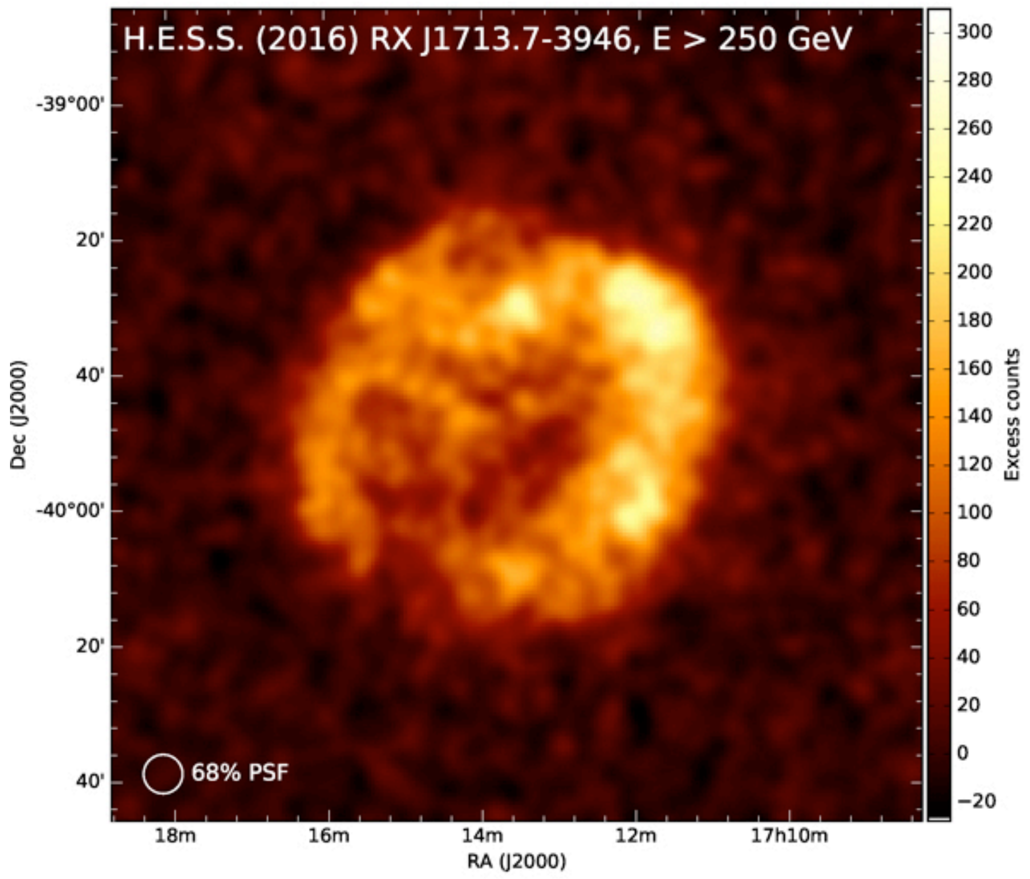
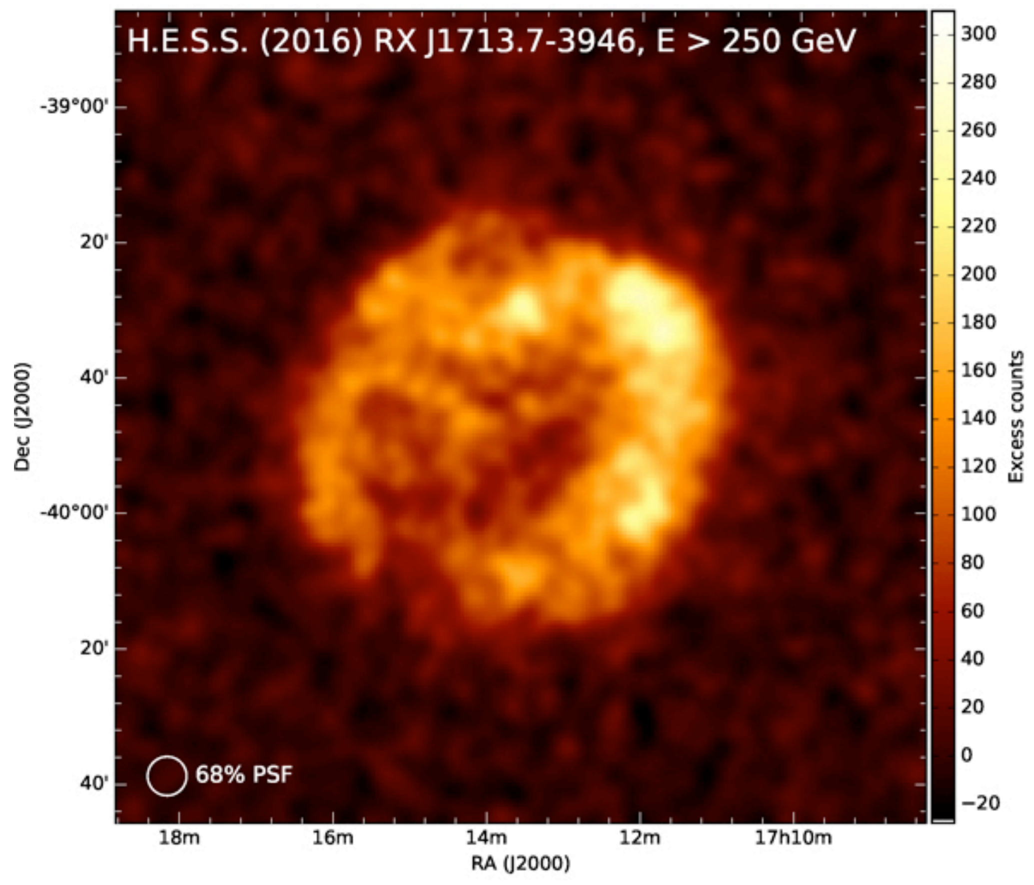


We see TeV gamma-ray shells

But energy cutoff at a few tens of TeV, where are the PeV CRs?

CRs accelerators: SNRs



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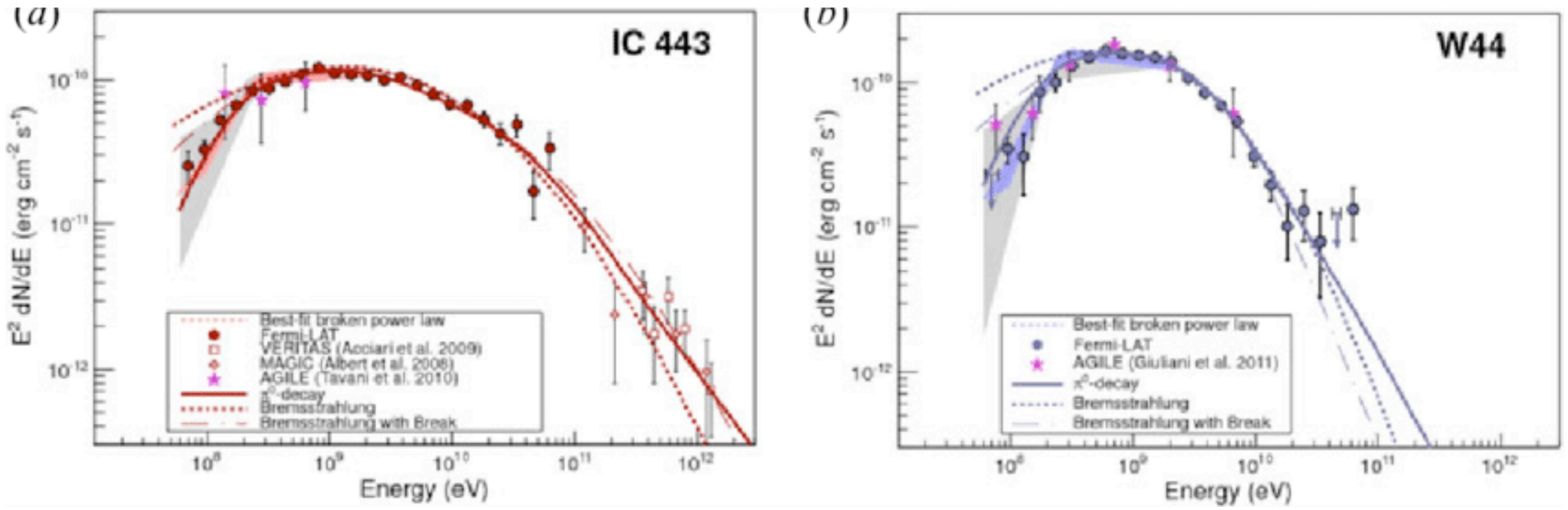

We see GeV gamma-ray shells & pion-peak shape

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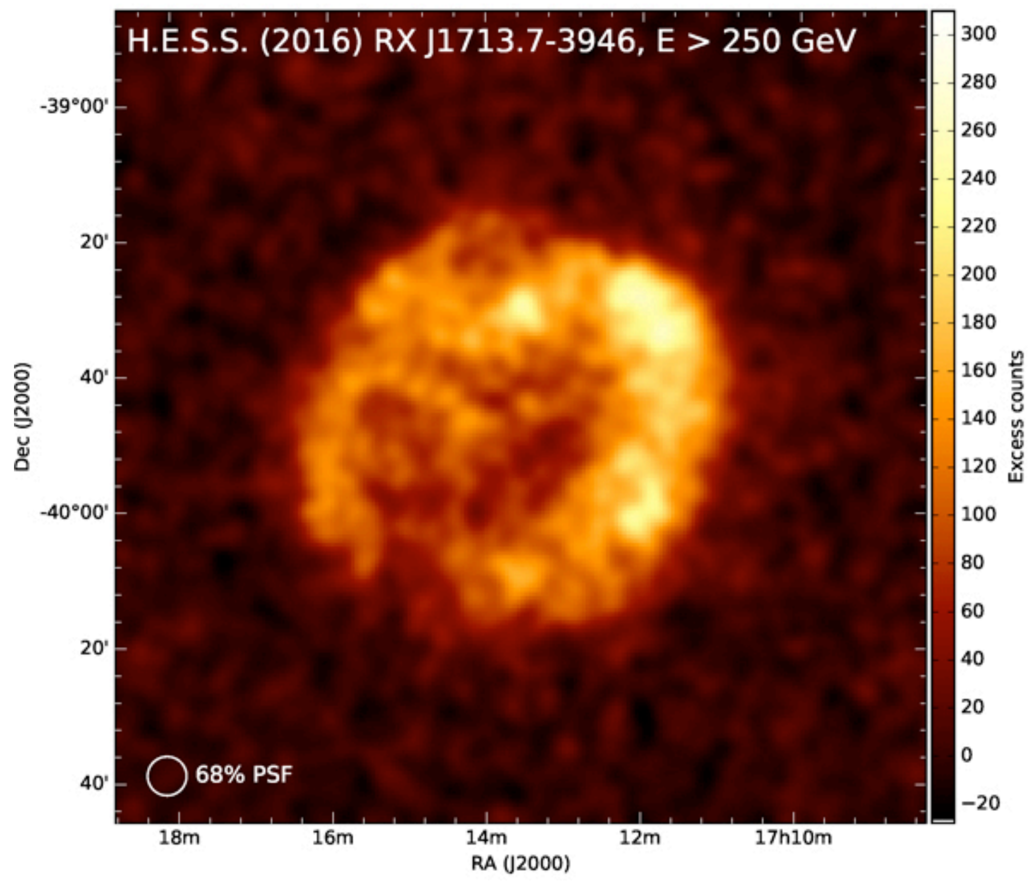

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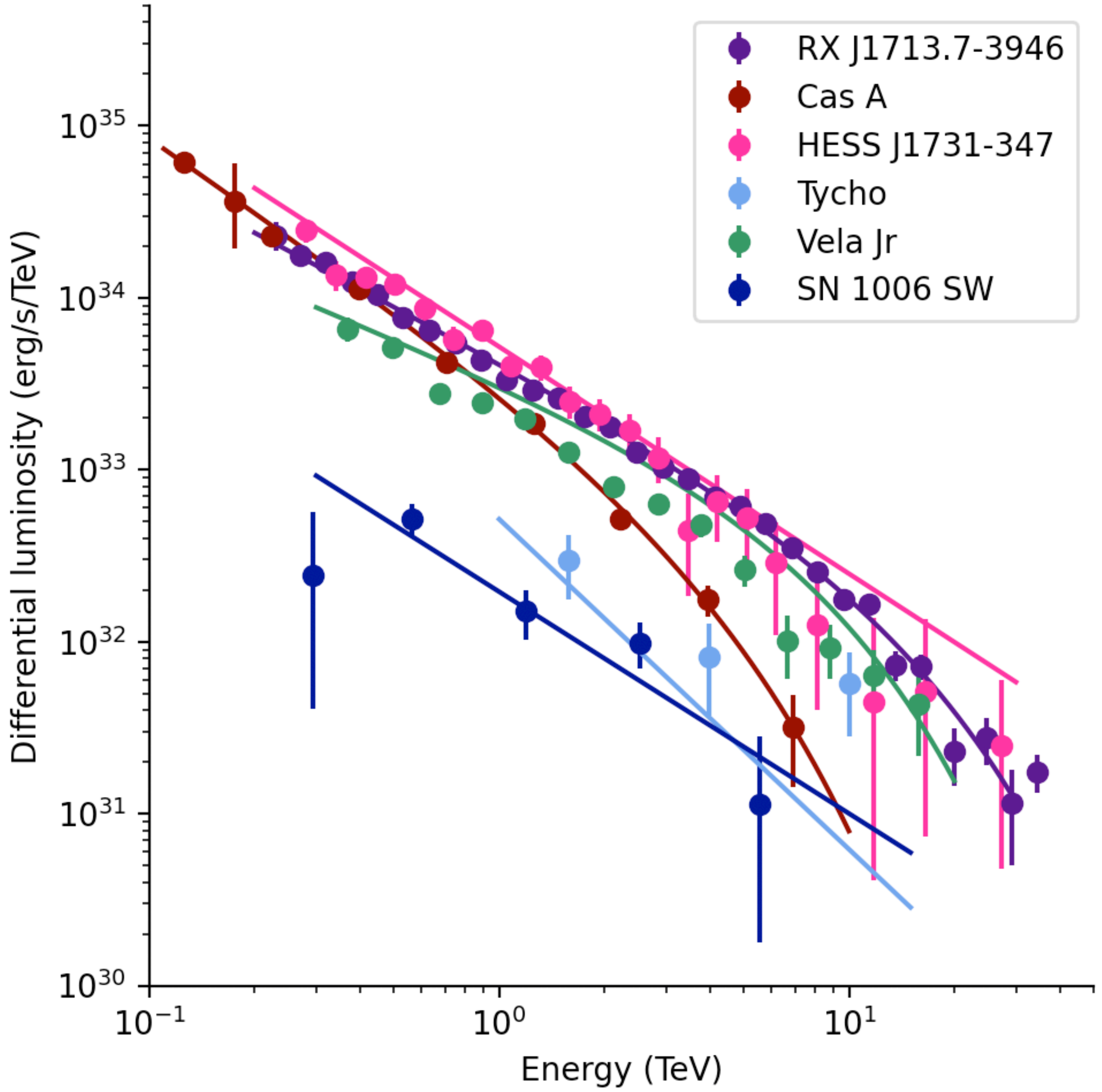

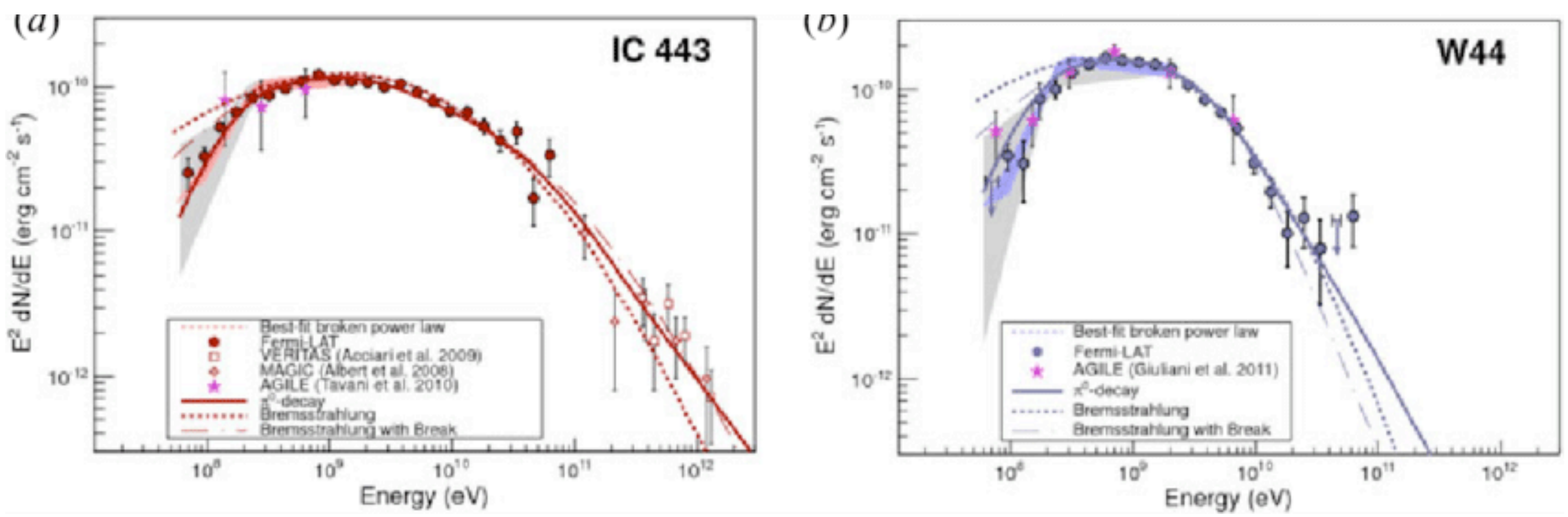

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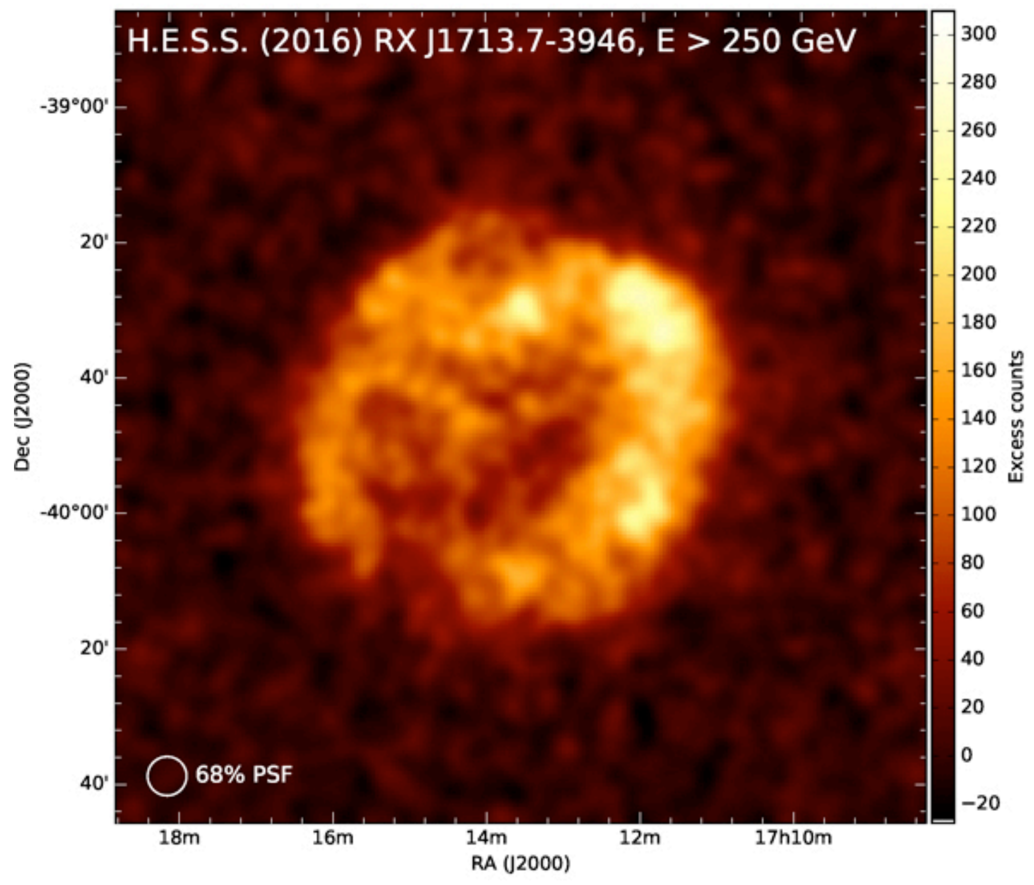

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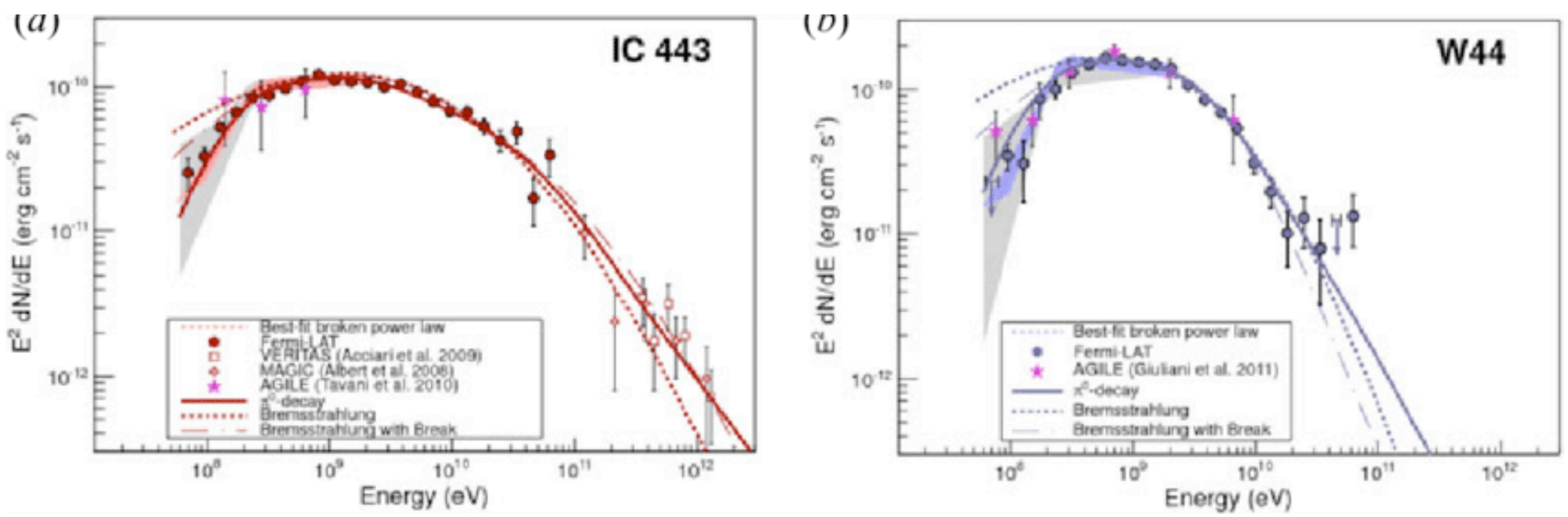

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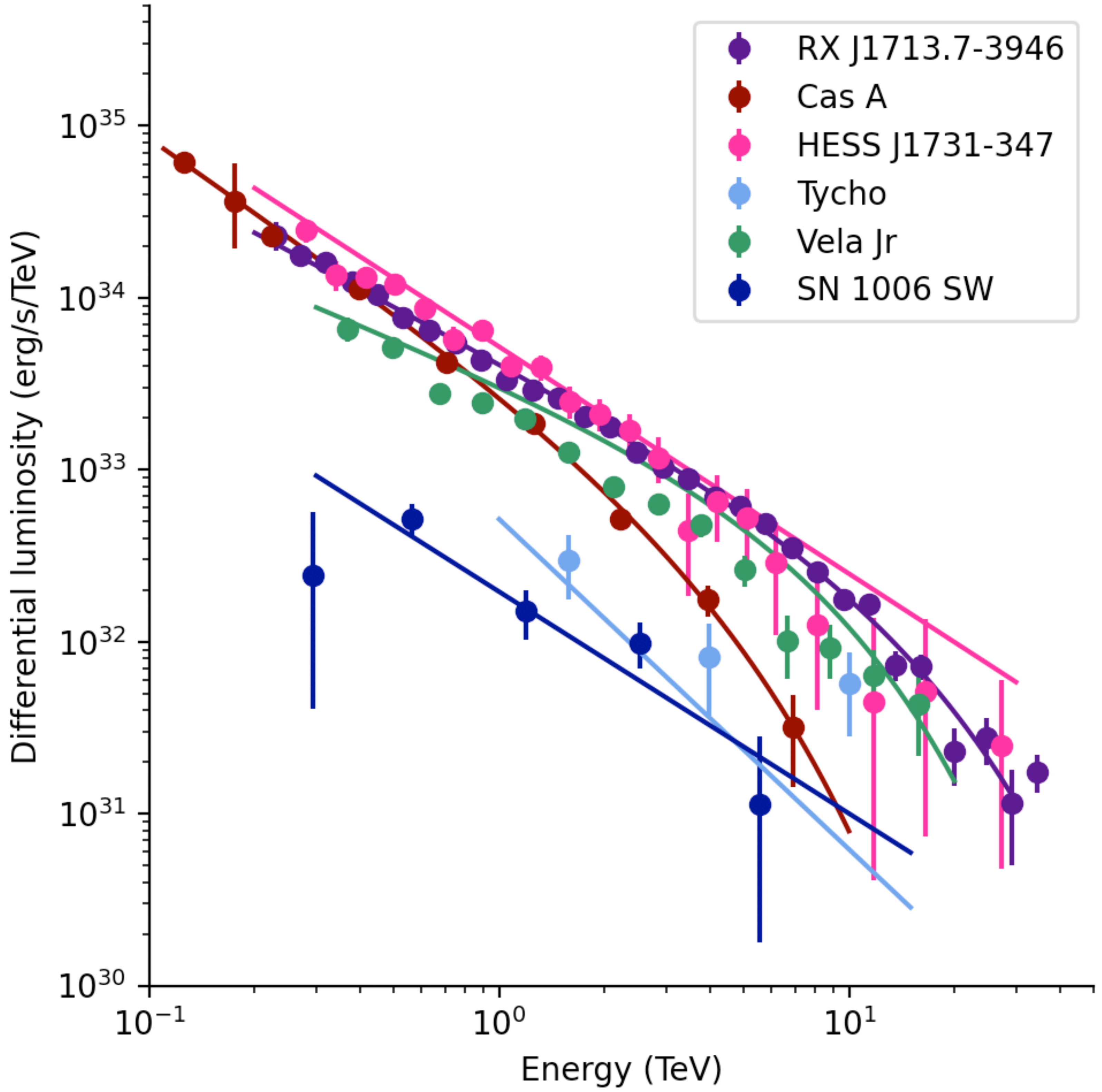


CRs accelerators: SNRs

Evolution

Free Expansion

R ~ t, M_{ej} >> M_{ISM}, < 200-300 yrs
v ~ 5000 km/s - 10000 km/s
M_{ej} ~ few $M_\odot$ - 1 $M_\odot$

PeVatron Phase

Adiabatic (Sedov-Taylor)

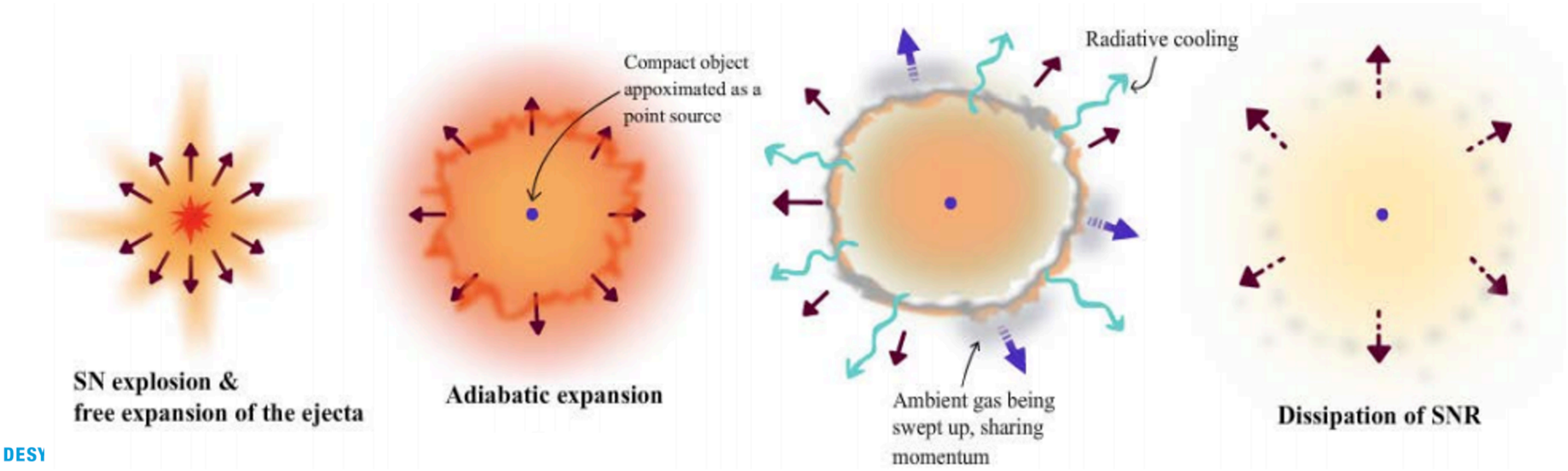
R ~ $t^{2/5}$, M_{ej} ~ M_{ISM}, 10^4yrs
t_{cool} >> t_{dyn} ⇒Adiabatic Expansion

Highest Gamma-ray Luminosity

Radiative

Dissipation into ISM v_{sh} ~200 km/s

CR Propagation



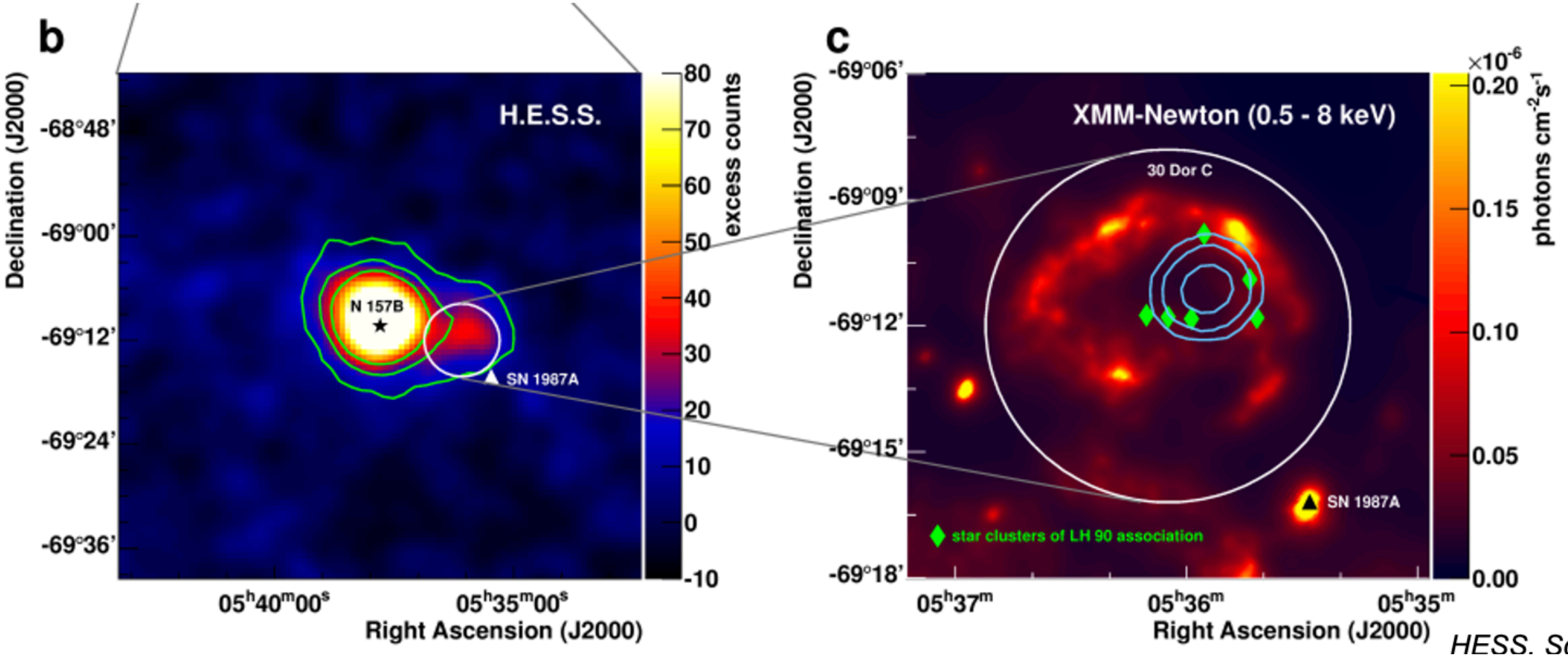
CRs accelerators: SNRs

Free Expansion: PeVatron Phase ?

SN 1987A

L (>1 TeV) < 2.2×10^{34} erg/s => W_{pp}(n ~10^3-10^4 cm^{-3}) < $1.4 \times 10^{48} f^{-1}$ erg

For f ~ 0.2 (spherical symmetric distribution) => W_{pp} < 9×10^{48}erg (1% to nuclei)



HESS, Science 2015

CRs accelerators: SNRs

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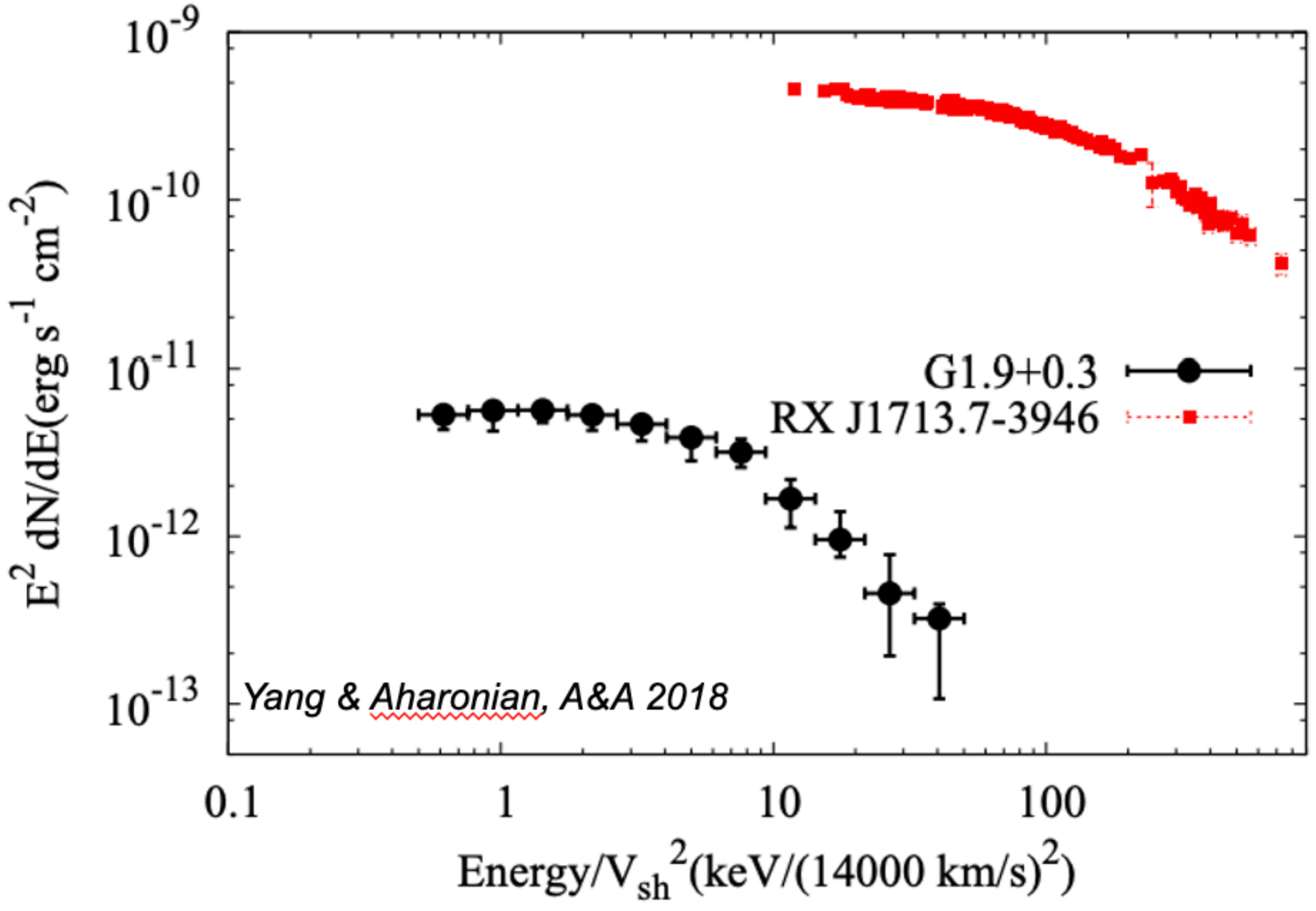
$t_{acc} \sim \eta B_{mG}^{-1.5} E^{0.5} V_{3000}$ years

Free Expansion: PeVatron Phase ?

In strong fields, the maximum Eo results from $t_{cool} = t_{acc} \Rightarrow E_o \propto B^{-1/2} v_{sh} \Rightarrow E_m \propto E_o B^{1/2} \propto v_{sh}$

SNR G1.9+0.3

- Youngest SN in our Galaxy (age ~150 yrs)
- Fast shock $v_{sh} \sim 14000$ km/s (=> $E_o \sim 10$ keV)
- Chandra+nuStar: Cutoff at 1.5 keV
  => Not an efficient accelerator
- Was it a PeVatron?



CRs accelerators: SNRs

Free Expansion: PeVatron Phase ?

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SNR G1.9+0.3

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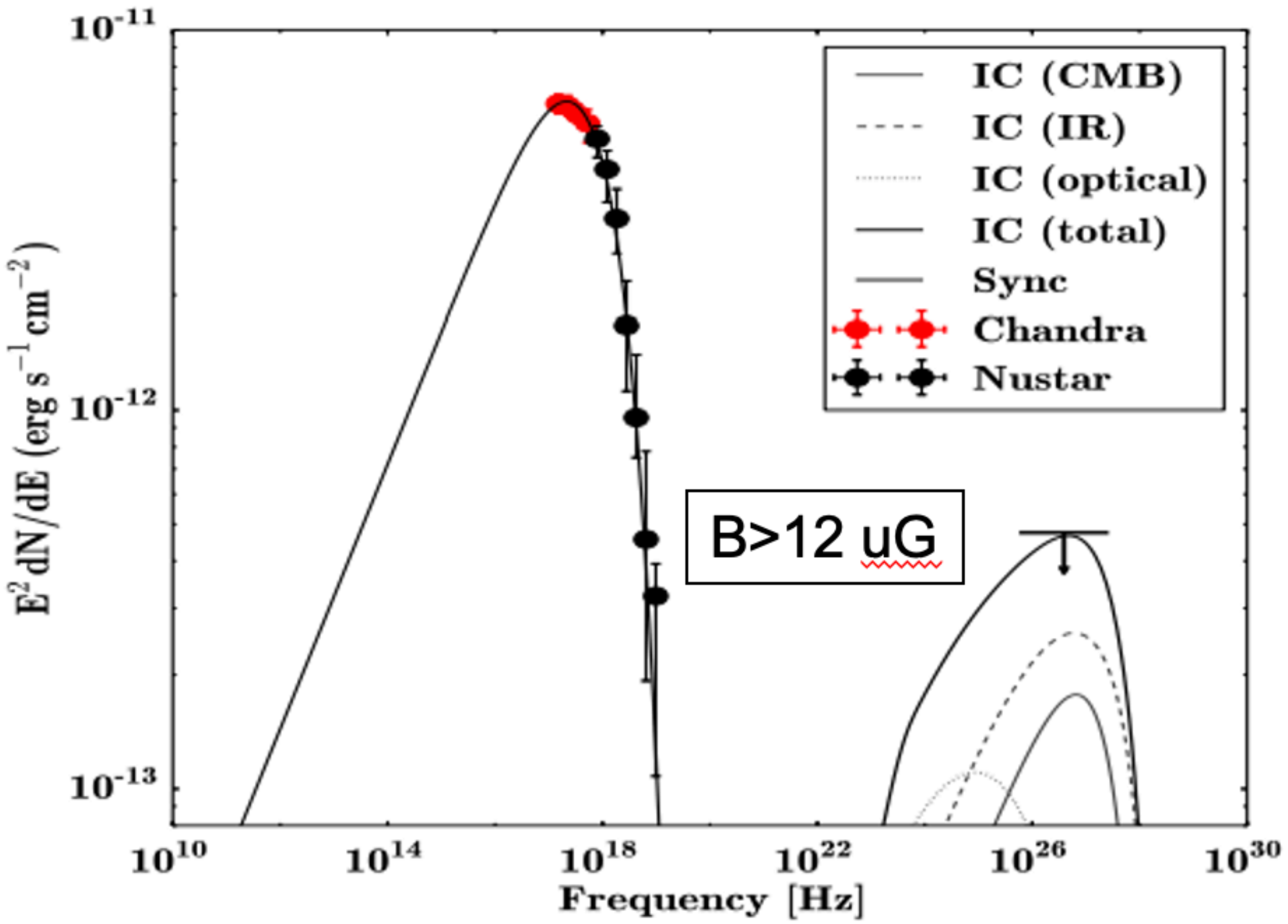
- Fast shock v_{sh} ~ 14000 km/s (=> E_o ~ 10 keV)
- Chandra+nuStar: Cutoff at 1.5 keV
  => Not an efficient accelerator
- Was it a PeVatron?
  Run-away protons R(D=10^{30}cm2/s) <~30pc => 10 arcmin
- W_p(n~100 cm^{-3})<10^{45} erg/s

$R = \sqrt{2Dt_{cool}}$



Yang & Aharonian, A&A 2018

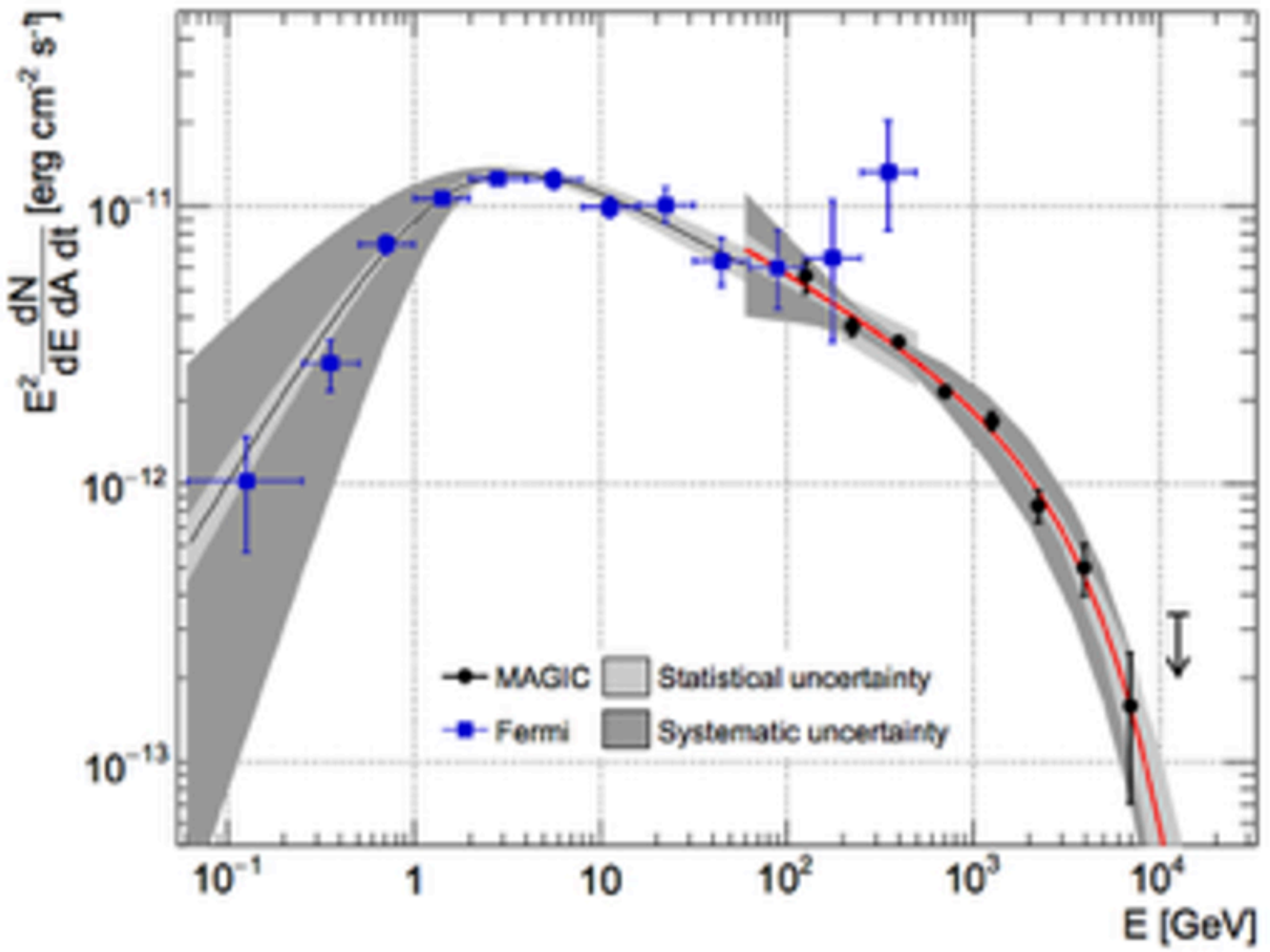
CRs accelerators: SNRs

Sedov-Taylor phase: Maximum of the gamma-ray emission?

Cassiopeia A

- Age ~ 340 yrs
- Fast shock v_{sh} ~ 5000 km/s
- Highly turbulent Bfield ~ 0.2-0.3 mG
- Ecut = 3.5 TeV
  - Composition: can reduce gamma efficiency by factor 2(
  - Spectrum dominated by plateau, shell higher cut off?

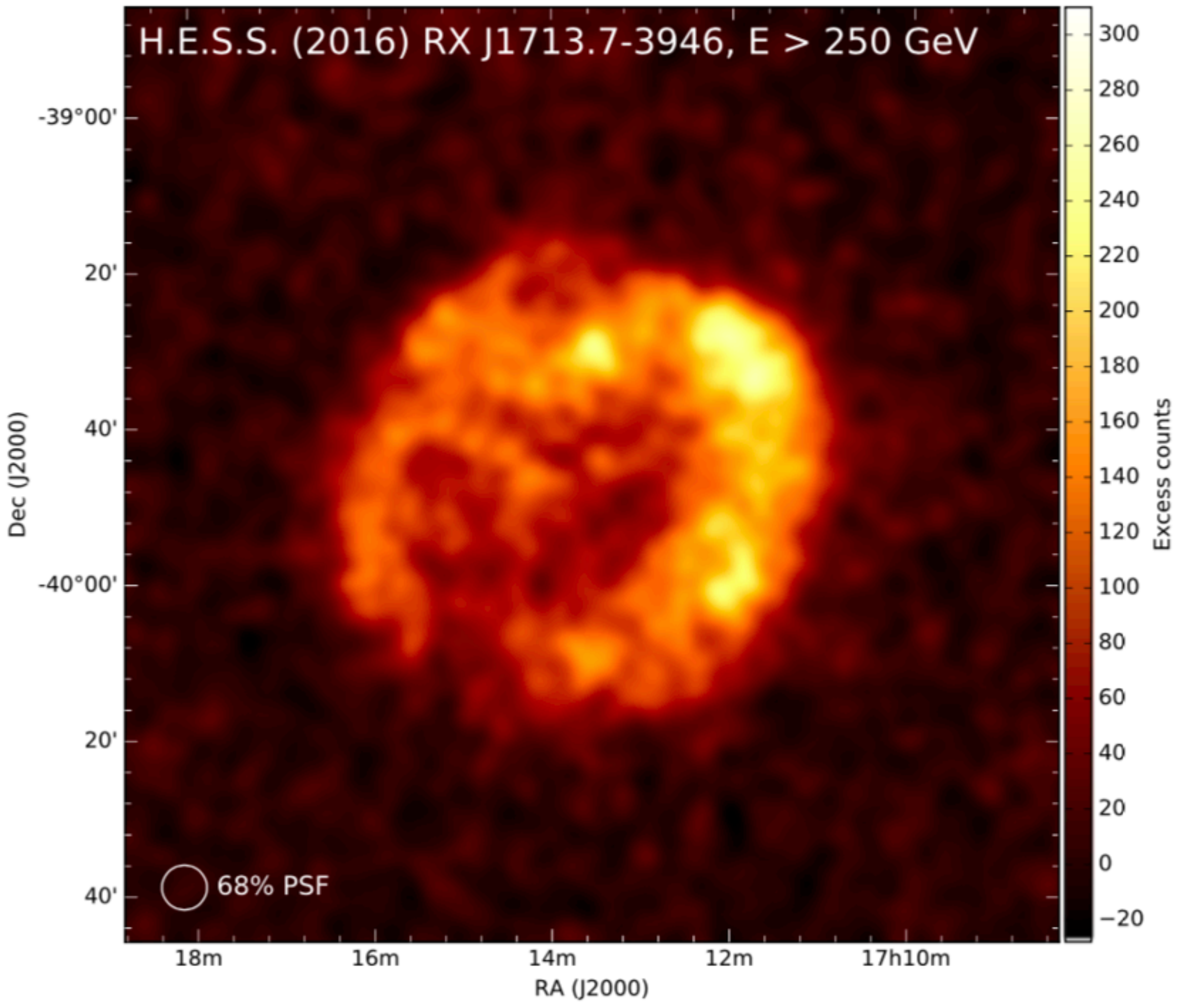
MAGIC, A&A 2018

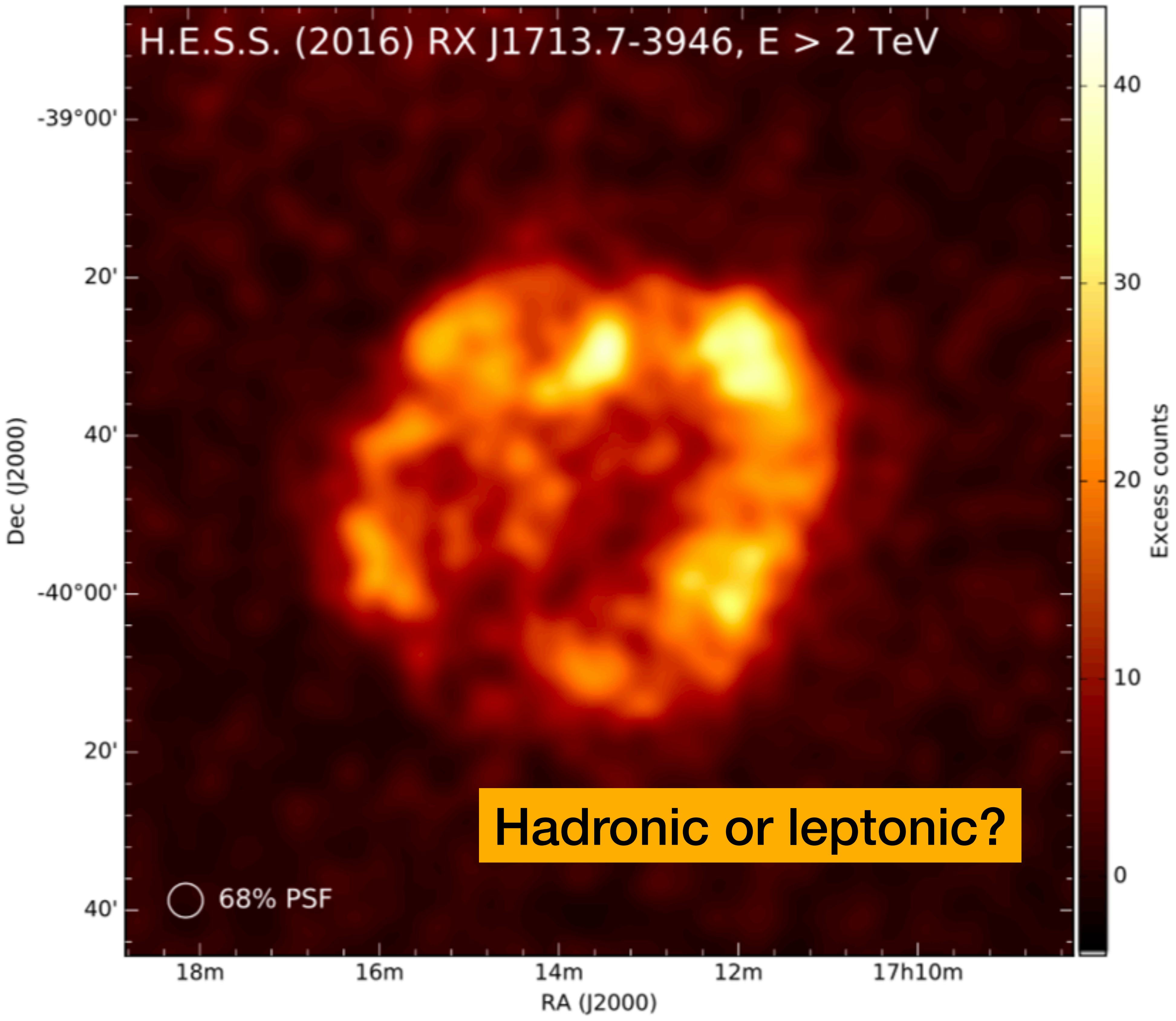


CRs accelerators: SNRs

Sedov-Taylor phase: Maximum of the gamma-ray emission?

HESS, A&A 2018



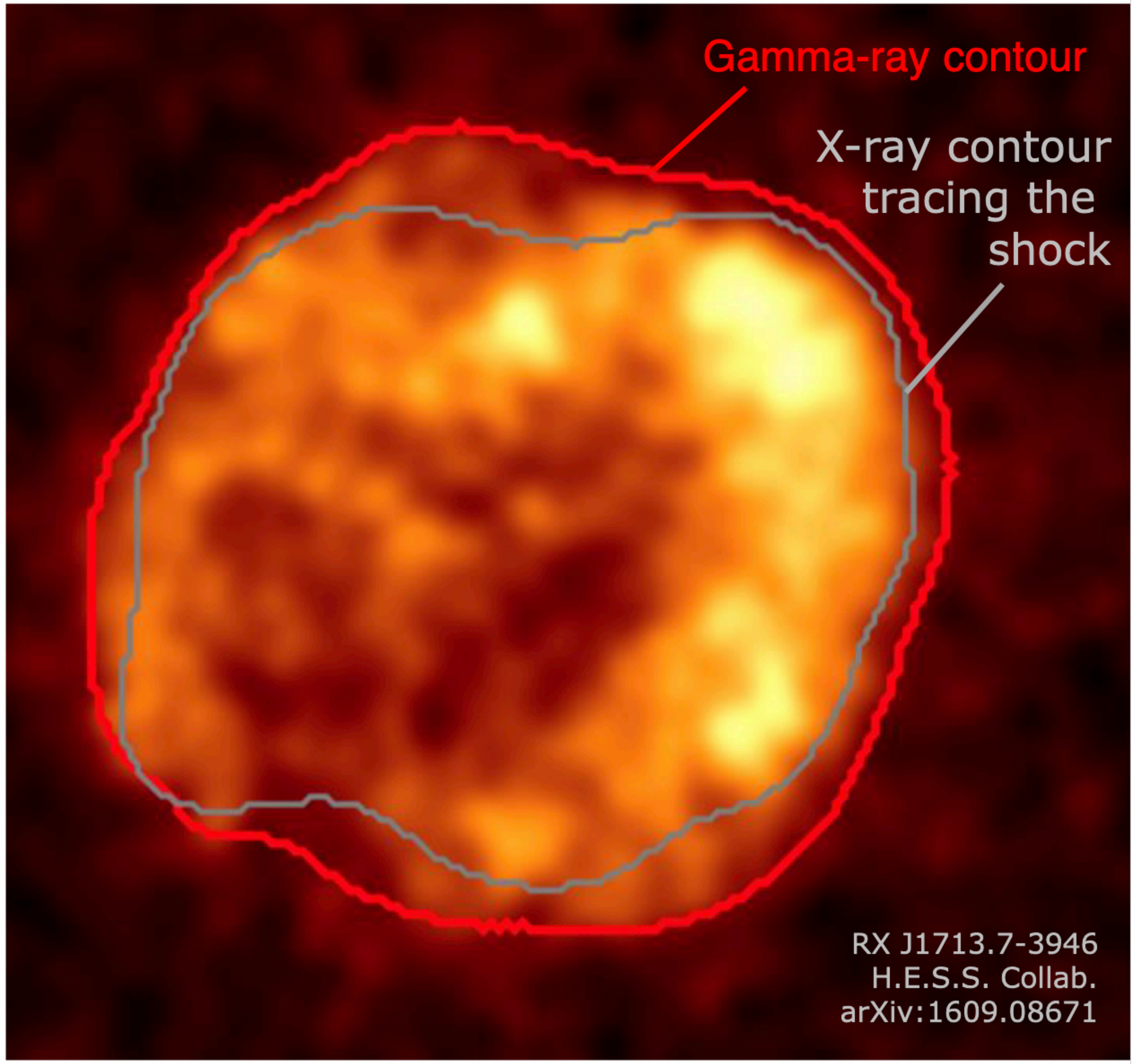


CRs accelerators: SNRs

Recognized as essential feature: CR escape from remnants
e.g. Malkov et al., arXiv:1207.4728

→ CR current generates turbulent magnetic fields that are crucial for the acceleration

→ PeV cosmic rays only contained during the first O(100) years (?)

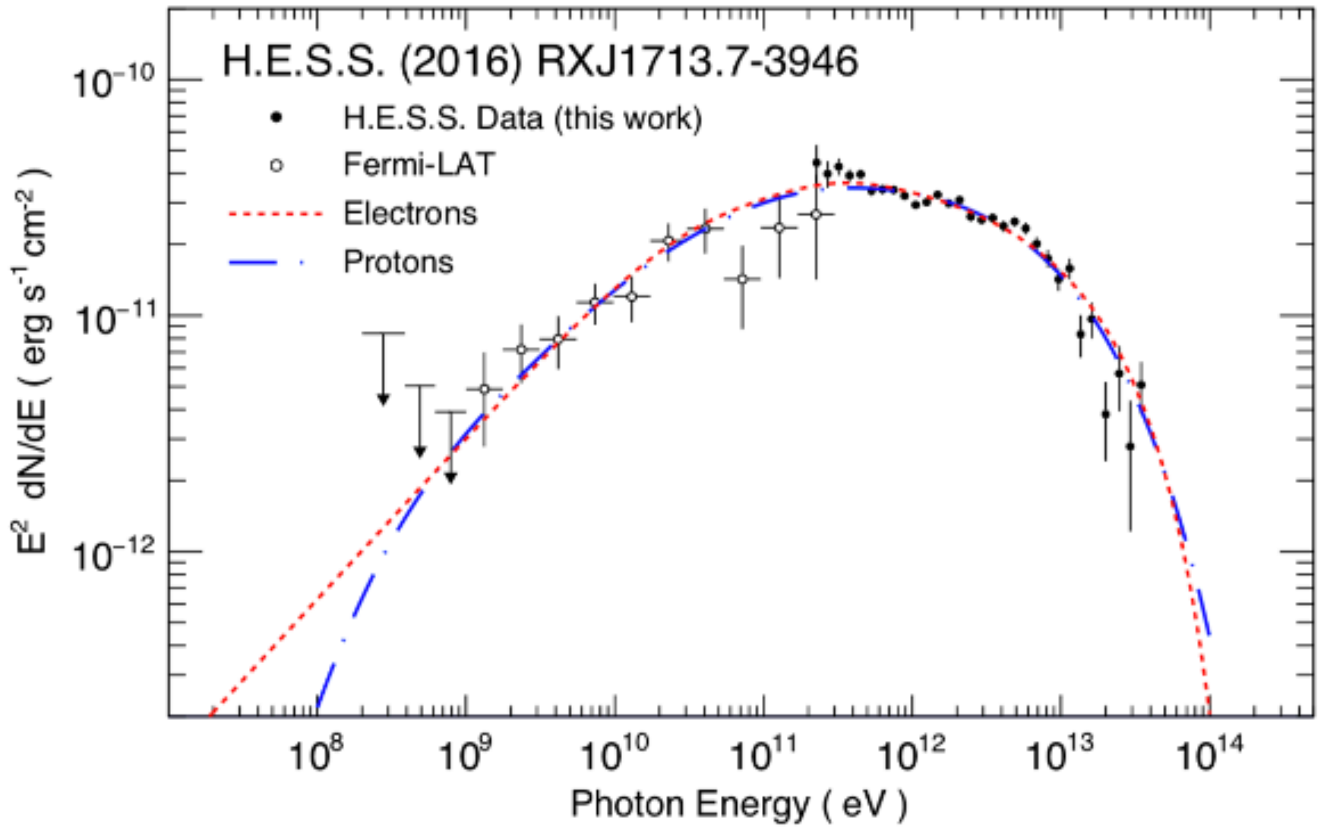


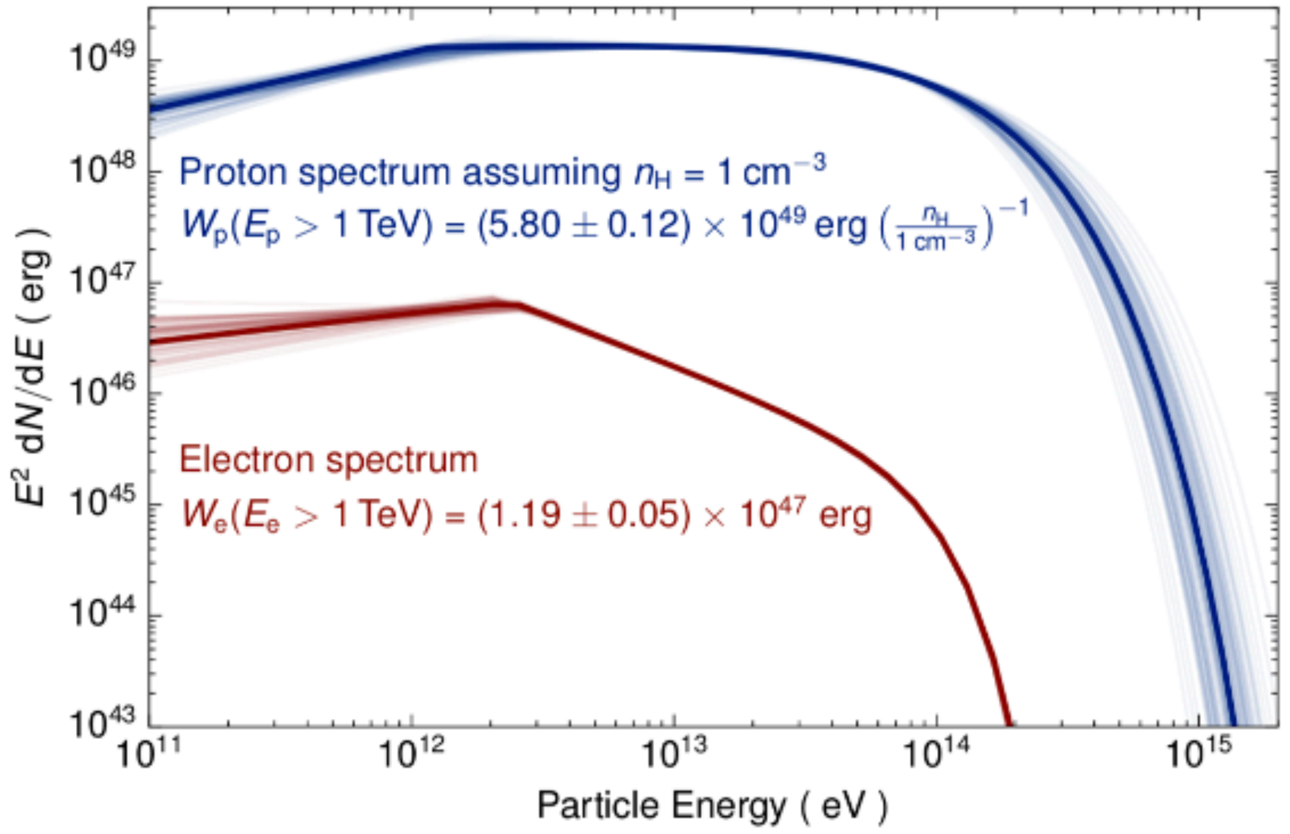
CRs accelerators: SNRs

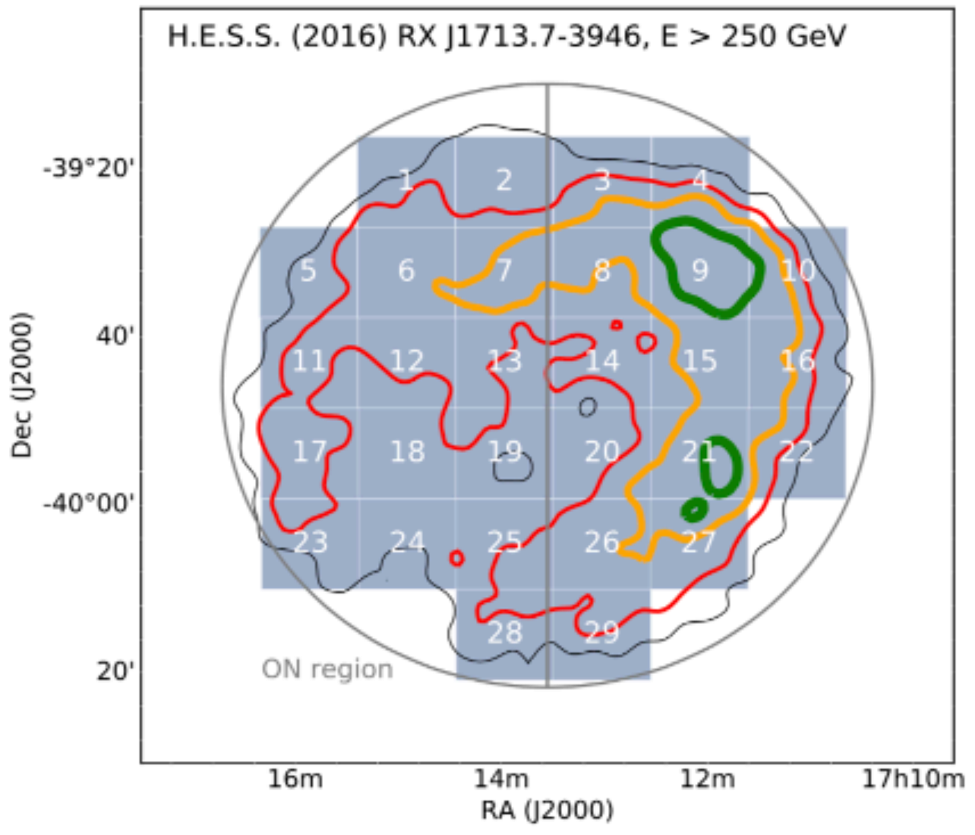
HESS, A&A 2018

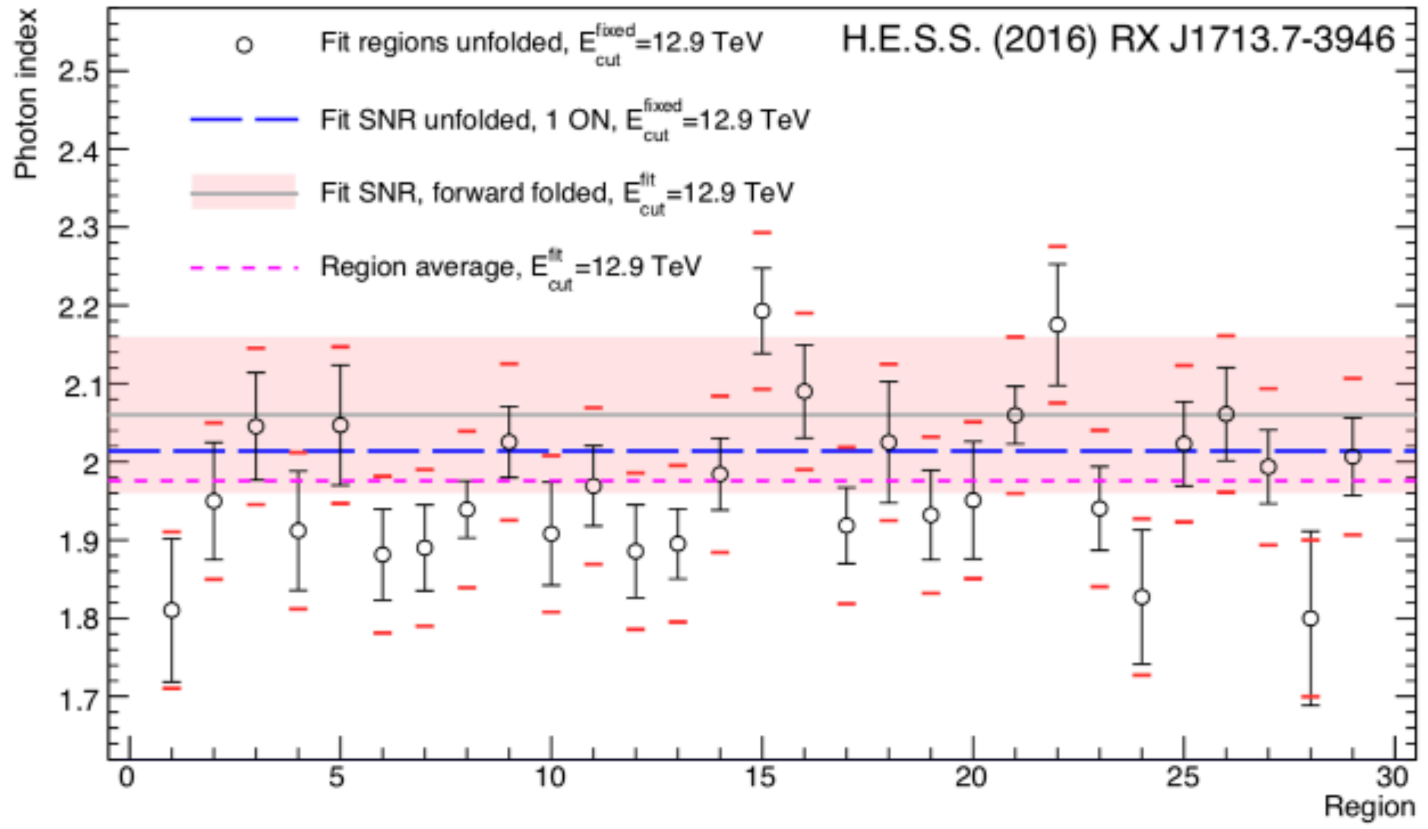
Sedov-Taylor phase: Maximum of the gamma-ray emission?

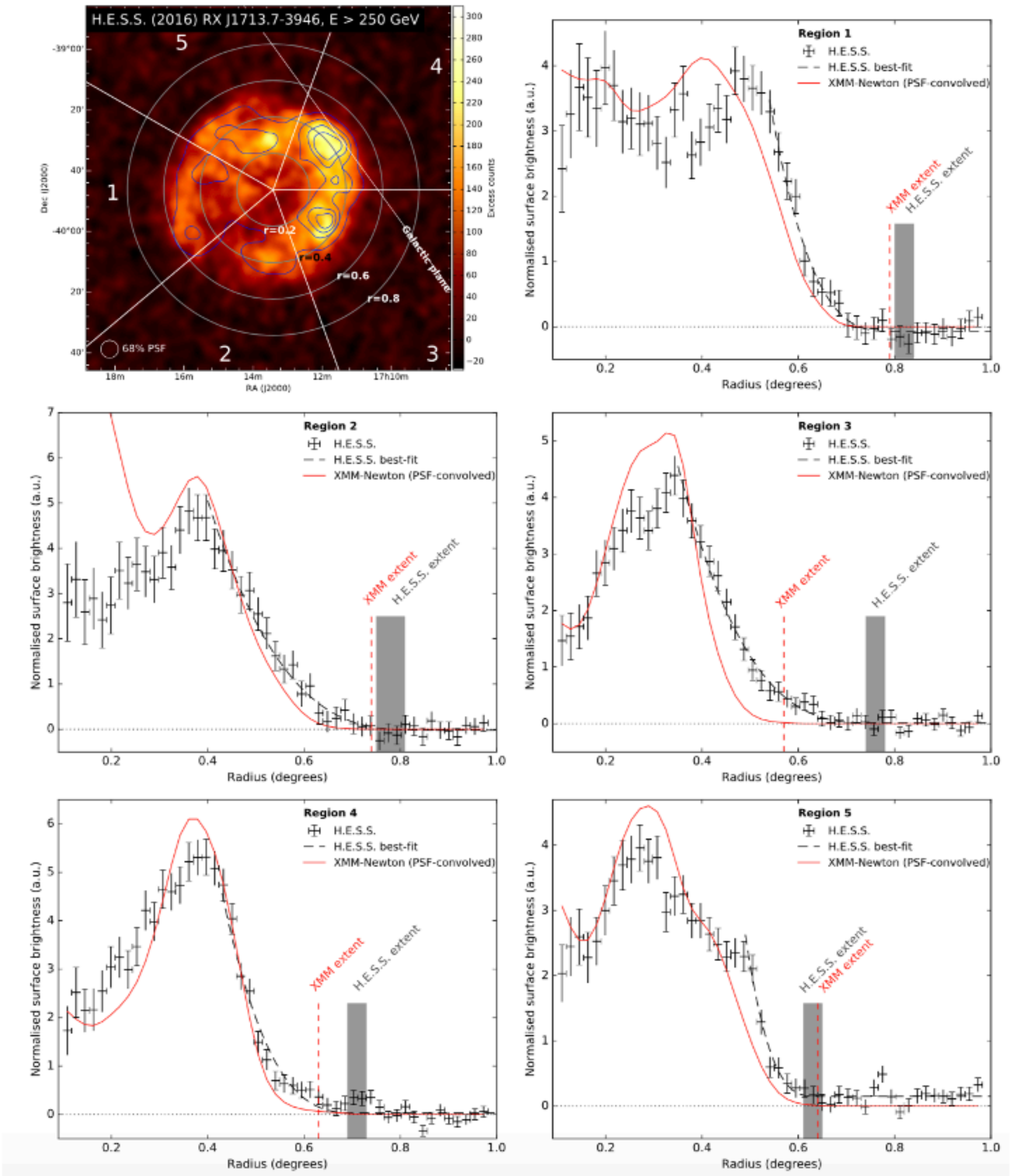
Did particles run-away?







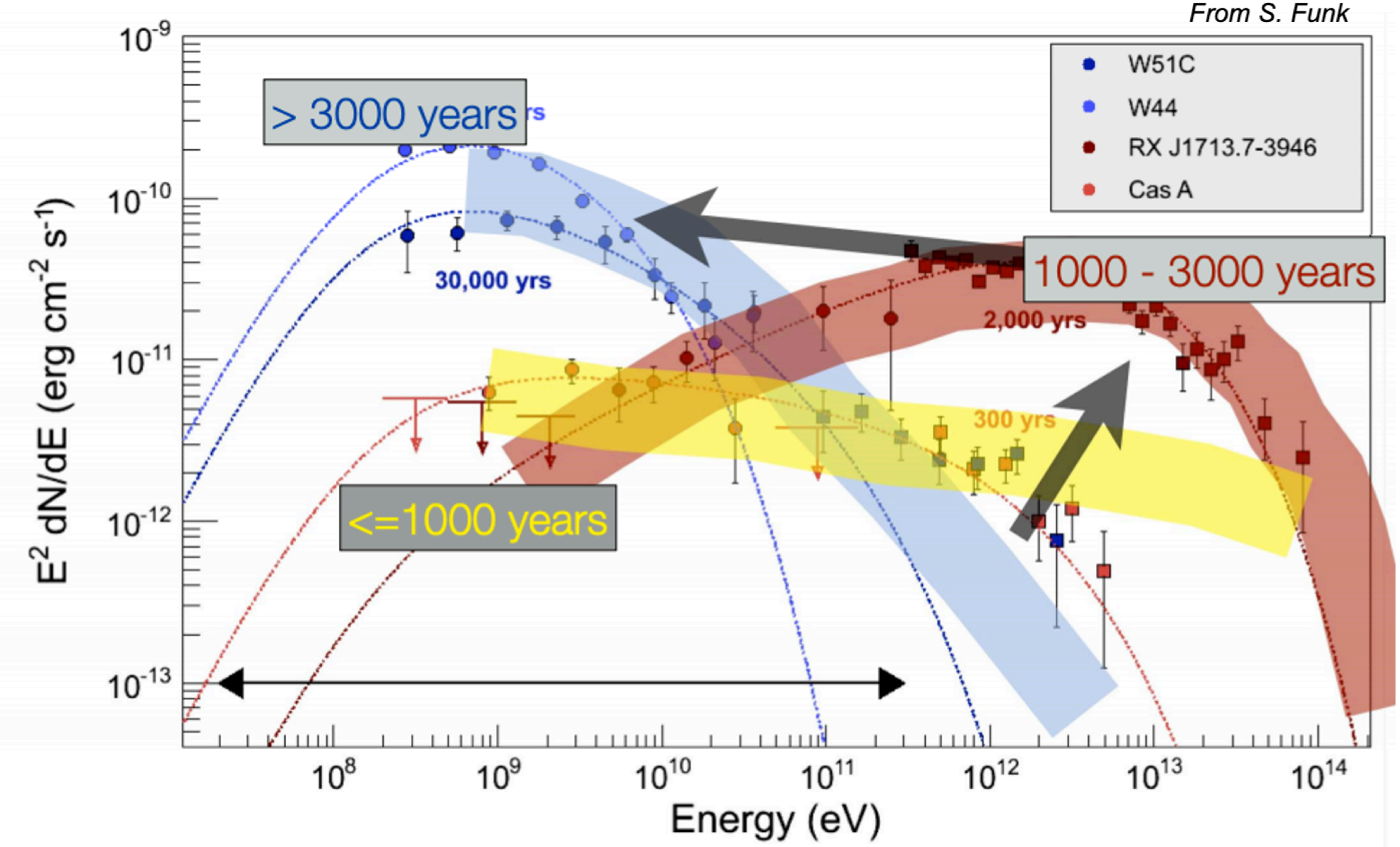




CRs accelerators: SNRs

Radiative phase: Old CRs reservoirs? Observations of the CR pion peak

From S. Funk



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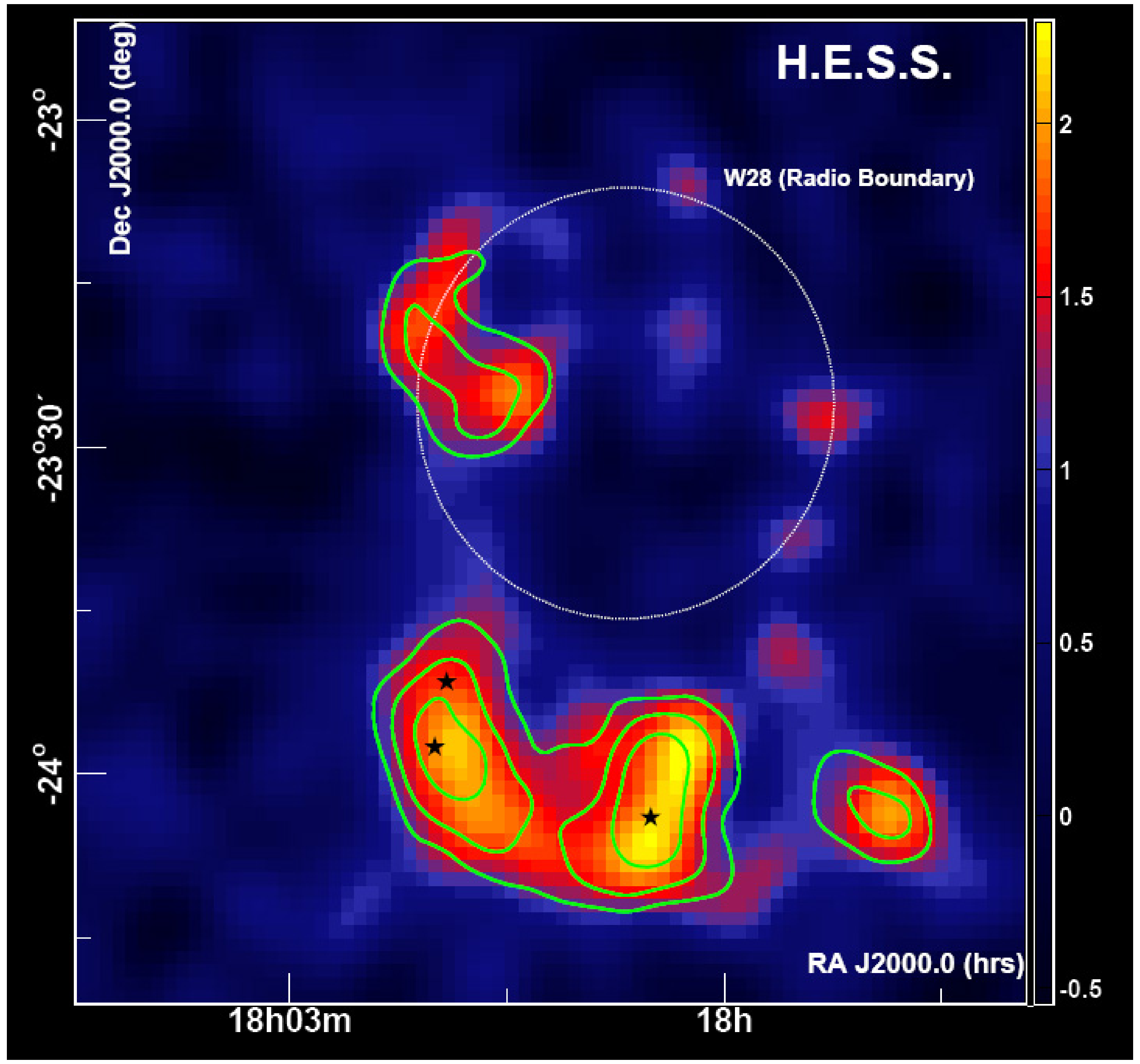
Morphological and High resolution spectroscopic Studies



Looks like it in some old SNRs at low energies, but still, no trace of PeV energies

CRs accelerators: SNRs

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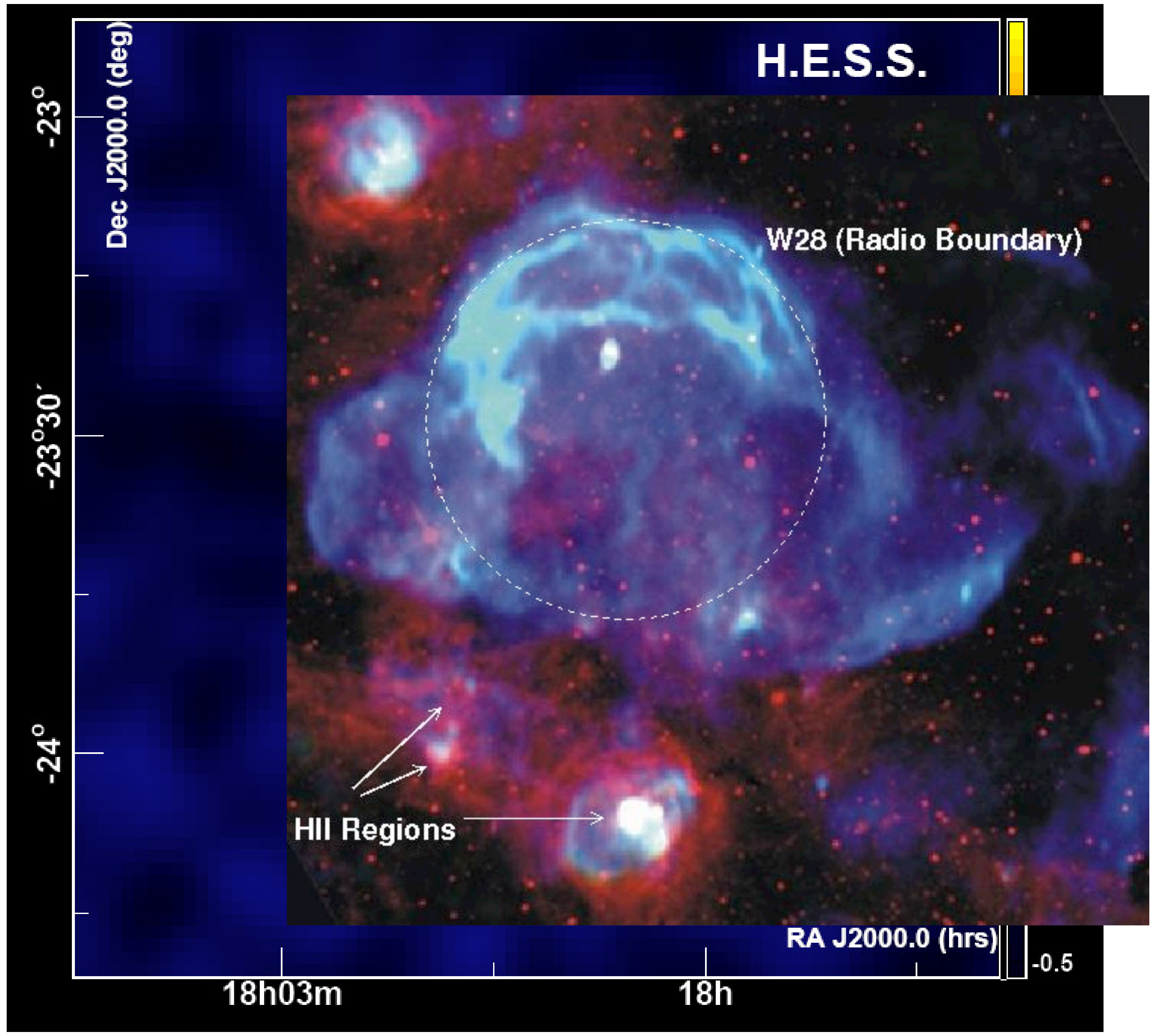

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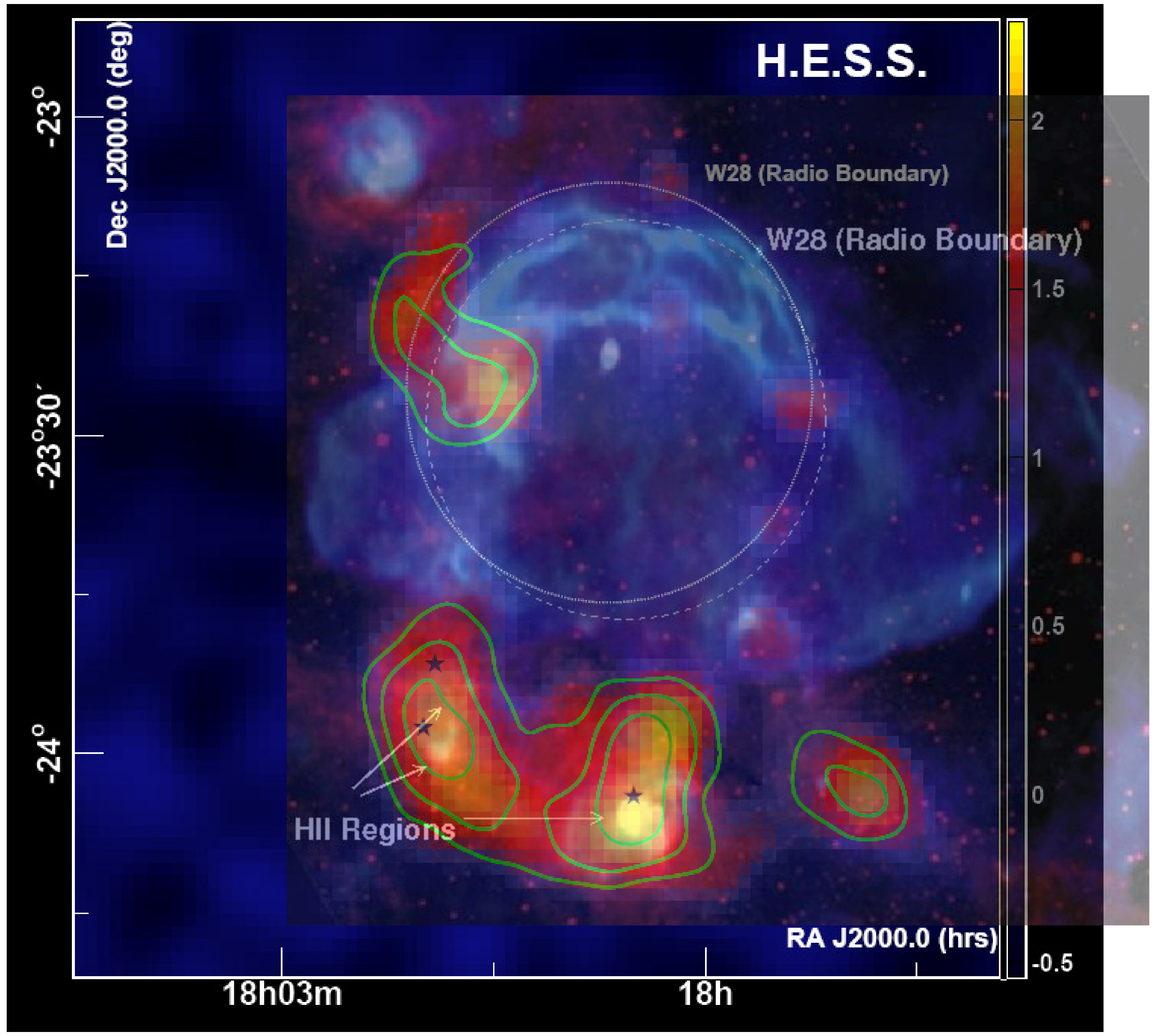

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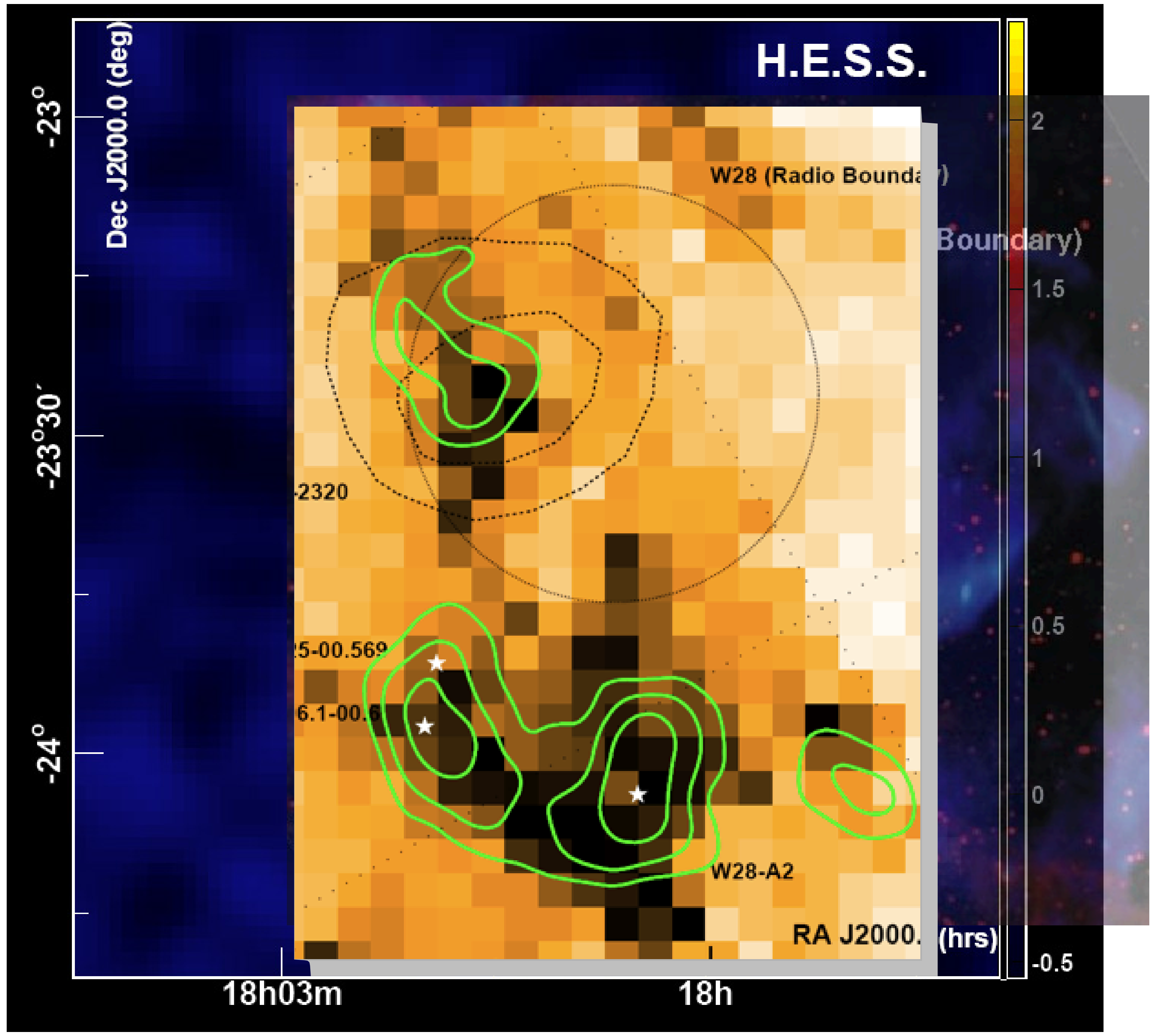

NANTEN CO
10-20 km/s

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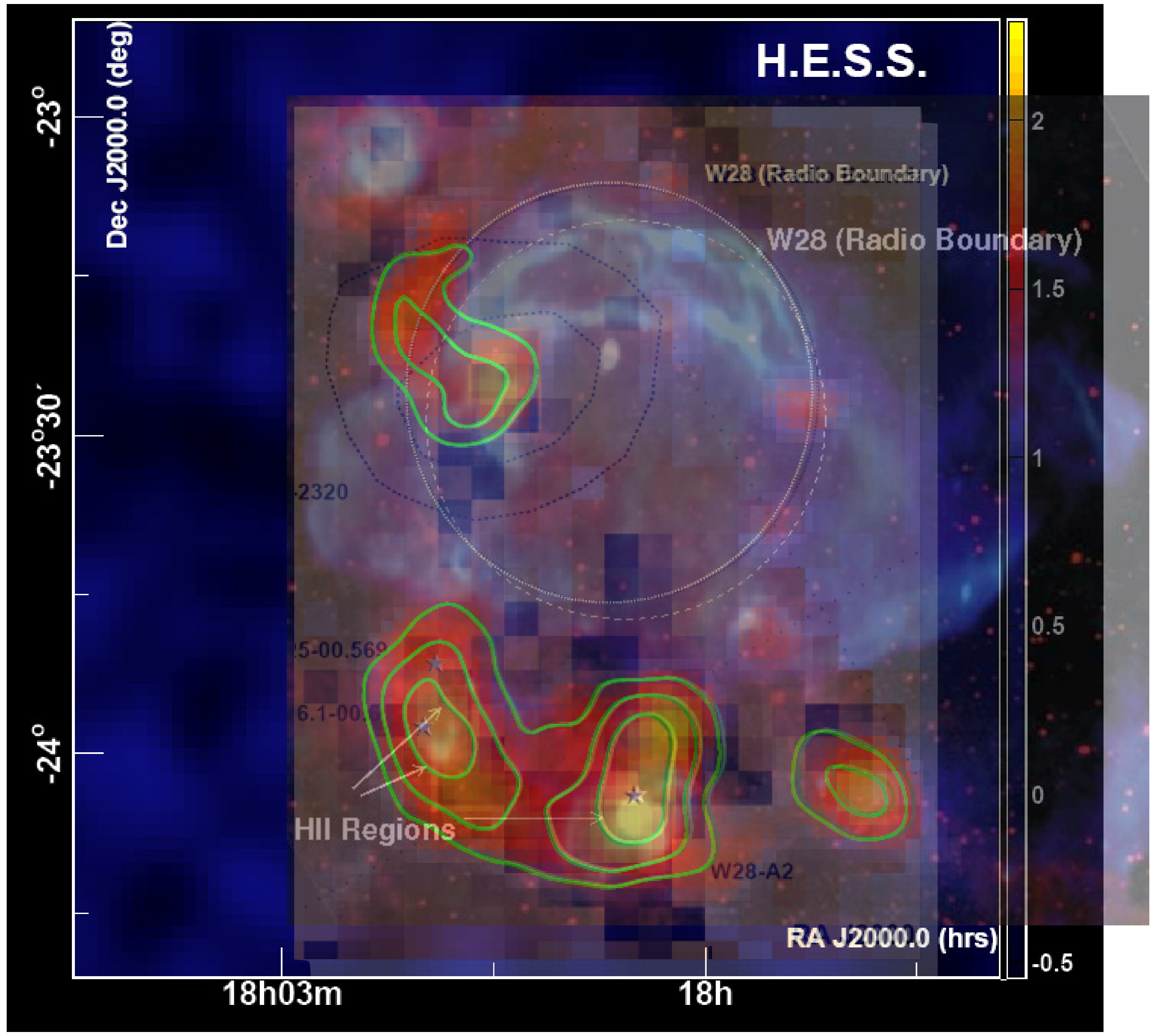

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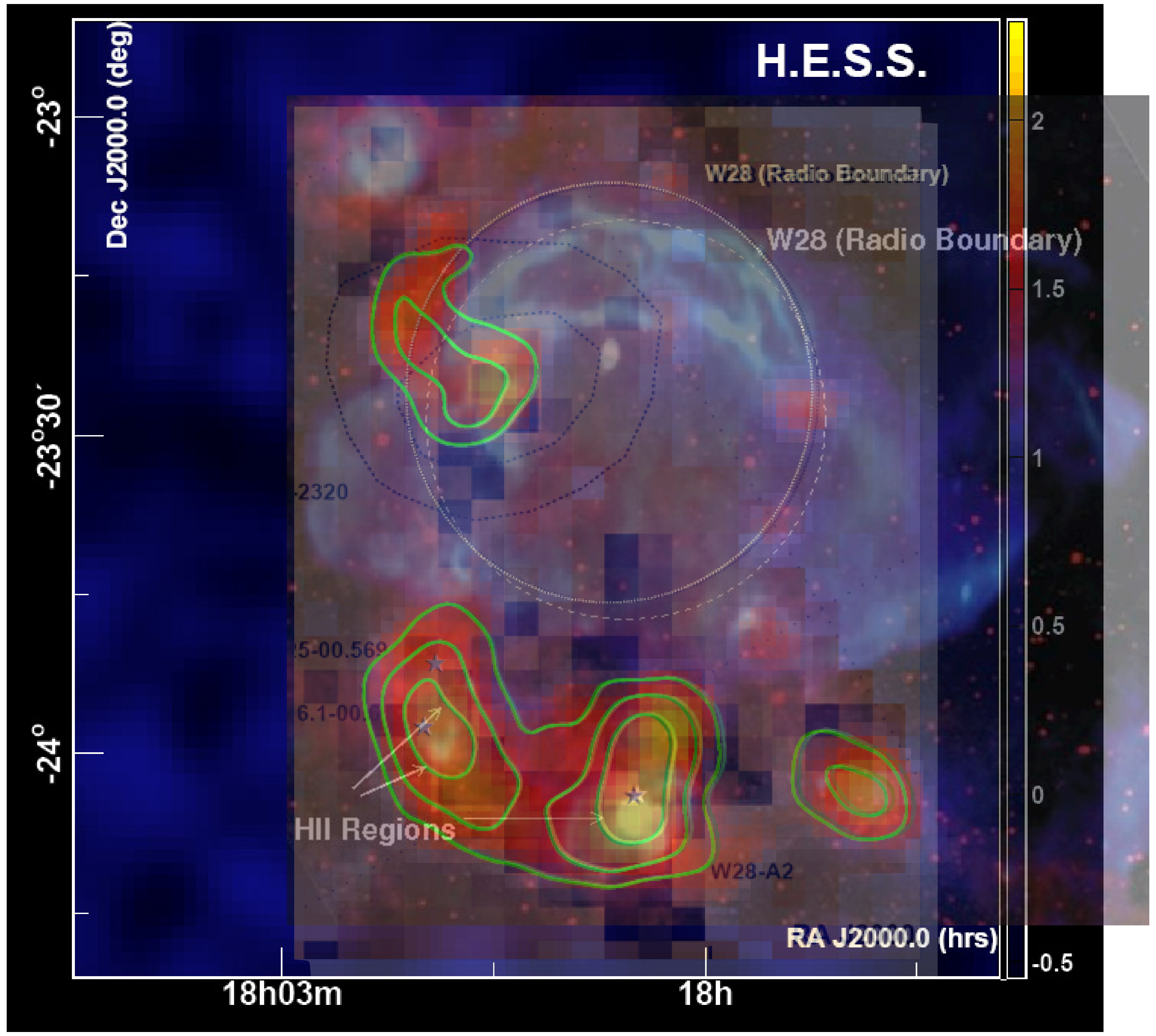

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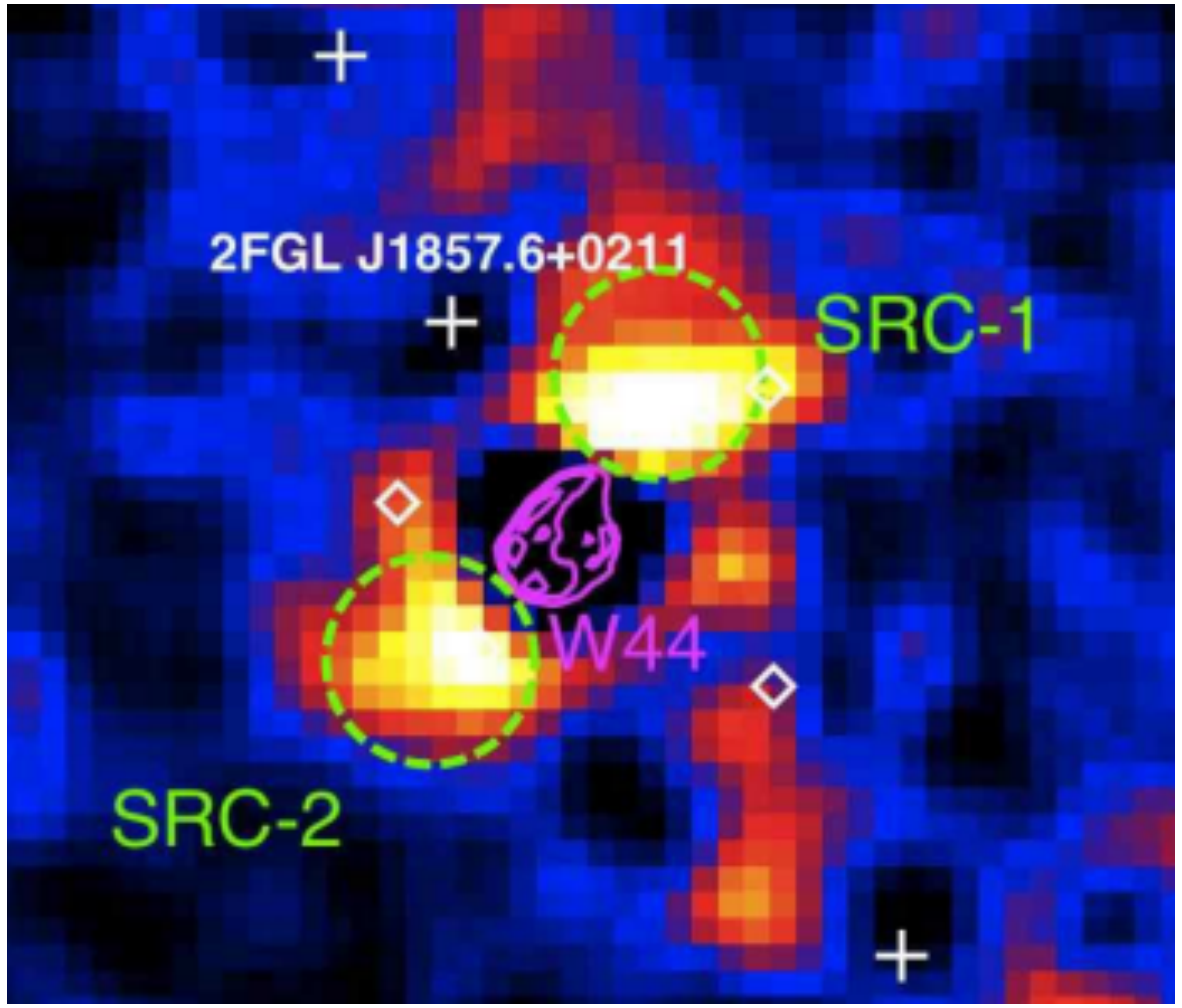

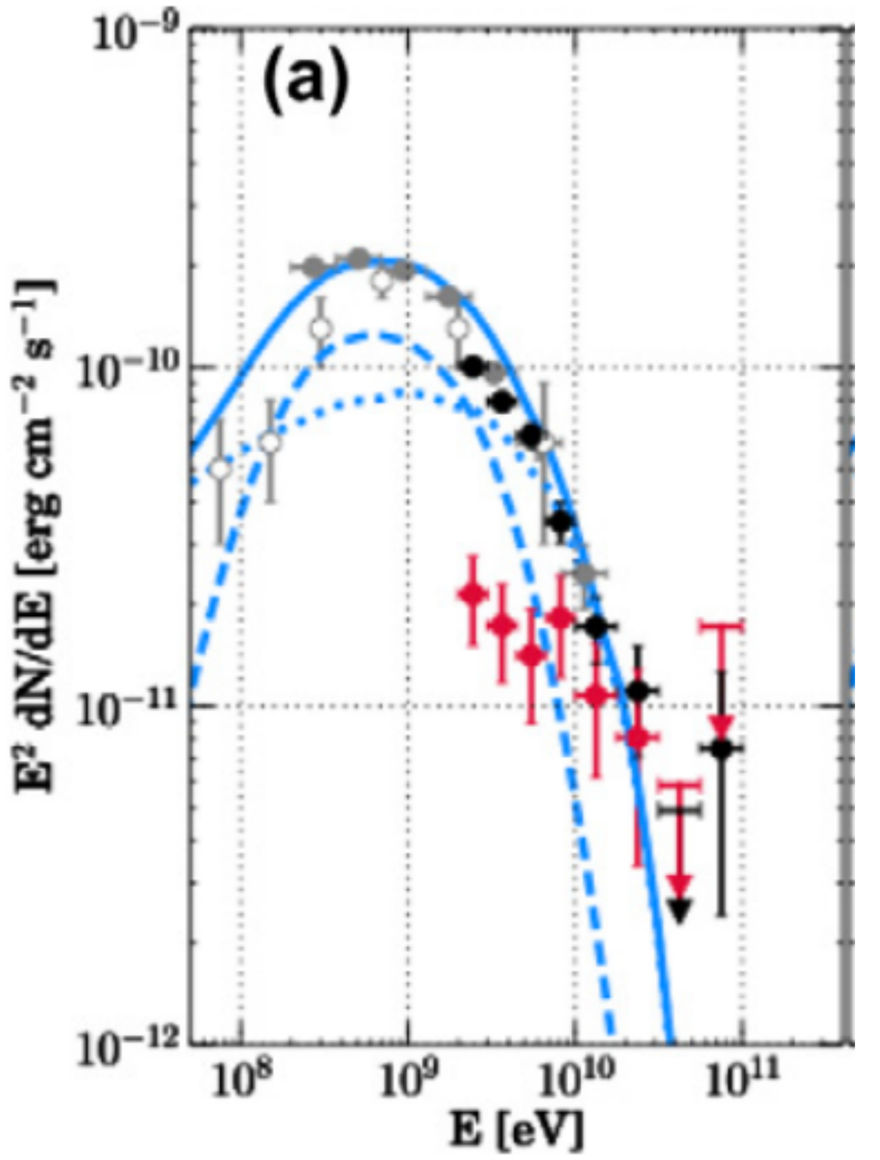

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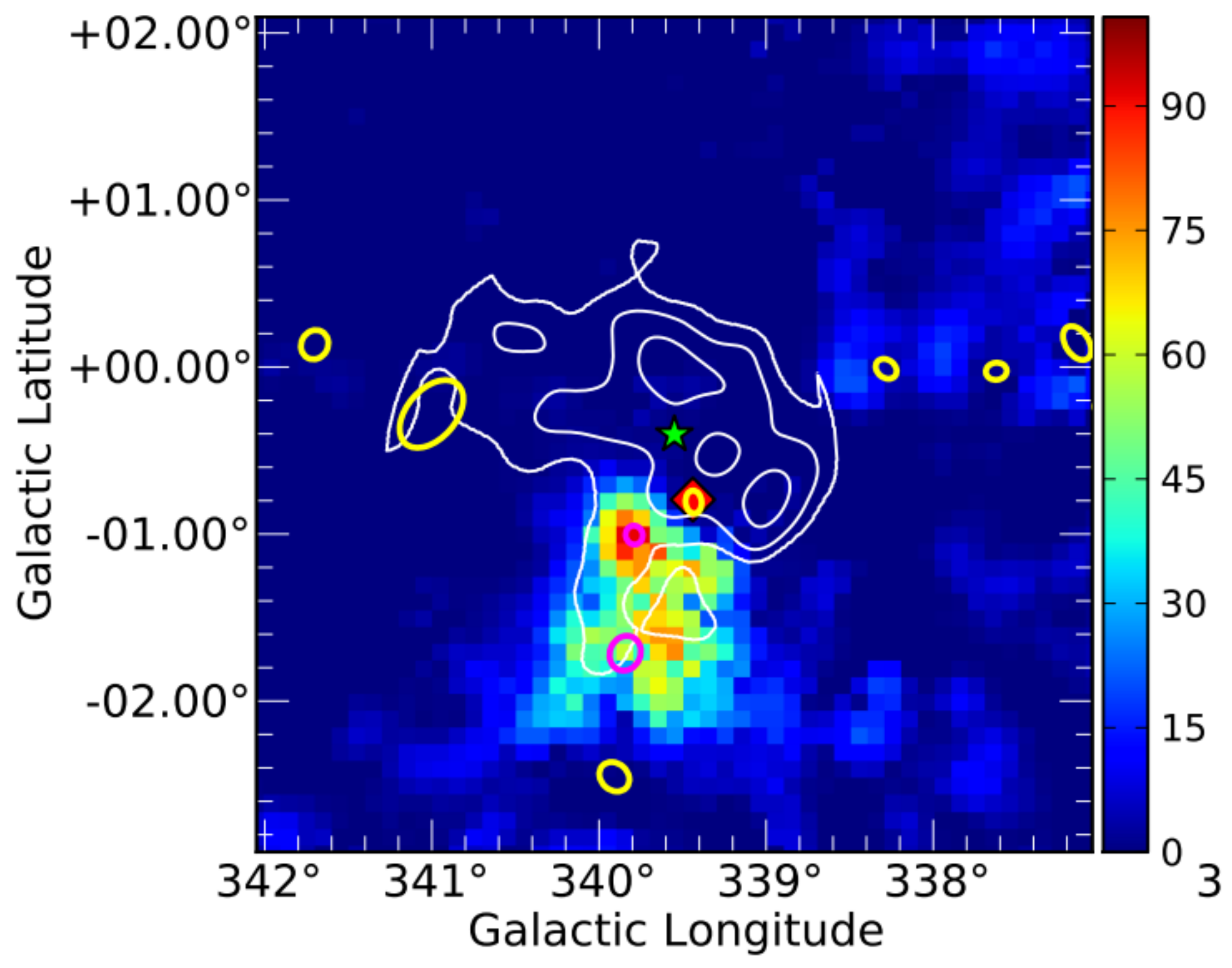
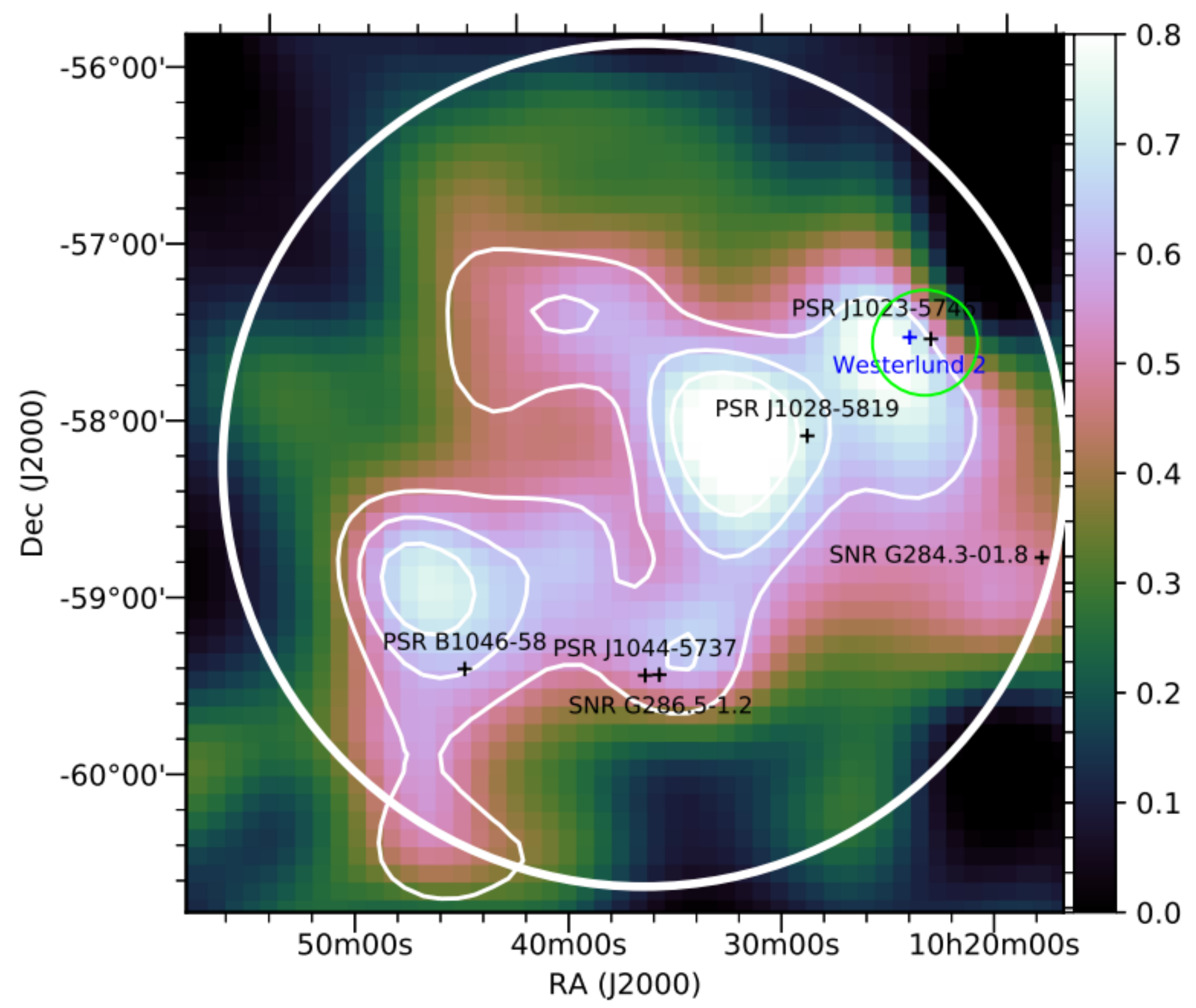
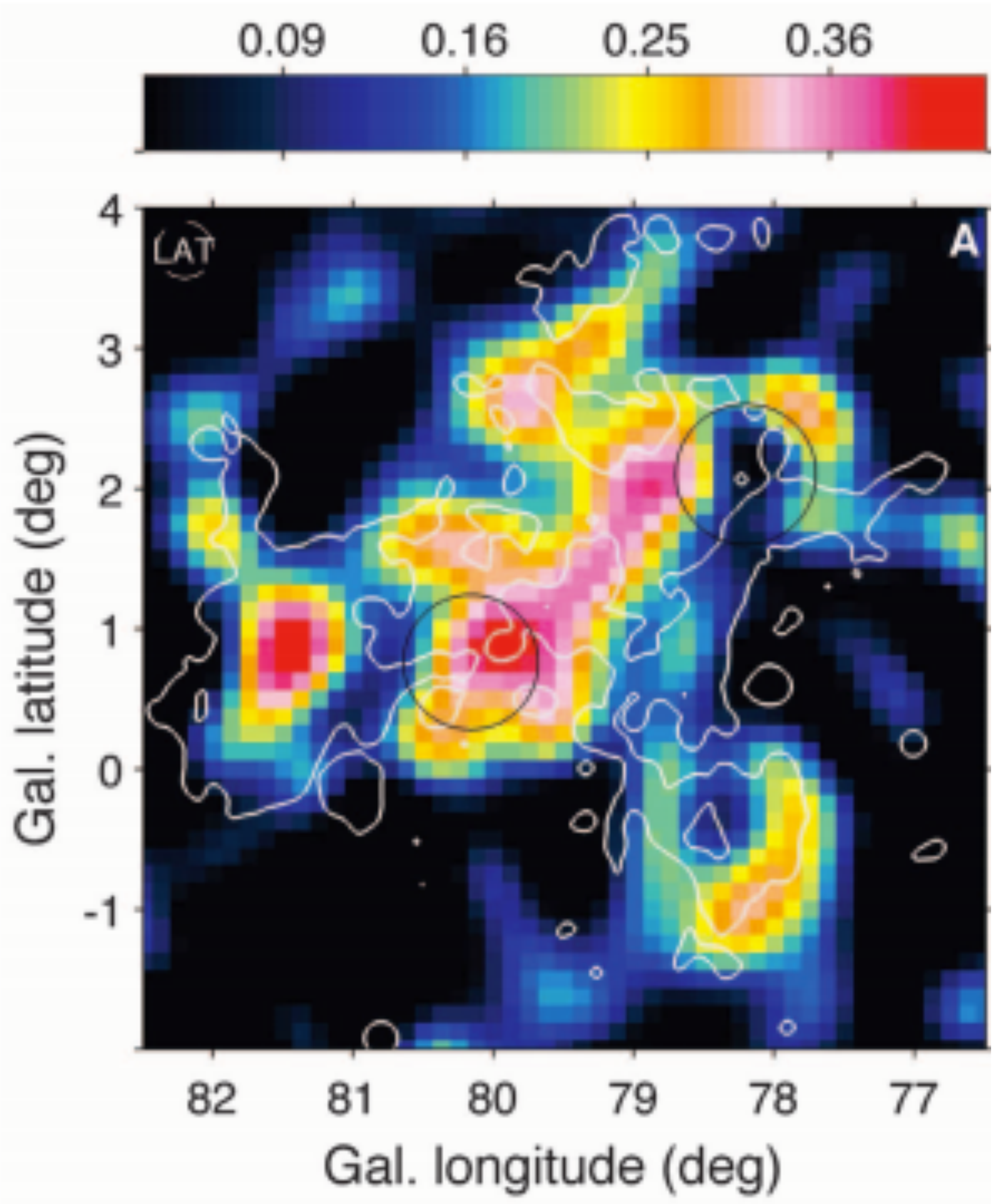
CRs accelerators: Stellar clusters

- Other accelerators - Old massive Stars (wind-wind, clusters, collective effects)
- Energy reservoir ~$10^{38\text{-}39}$ erg over ages of T≥10^6 years
- In the GeV range: huge structures covering few degree



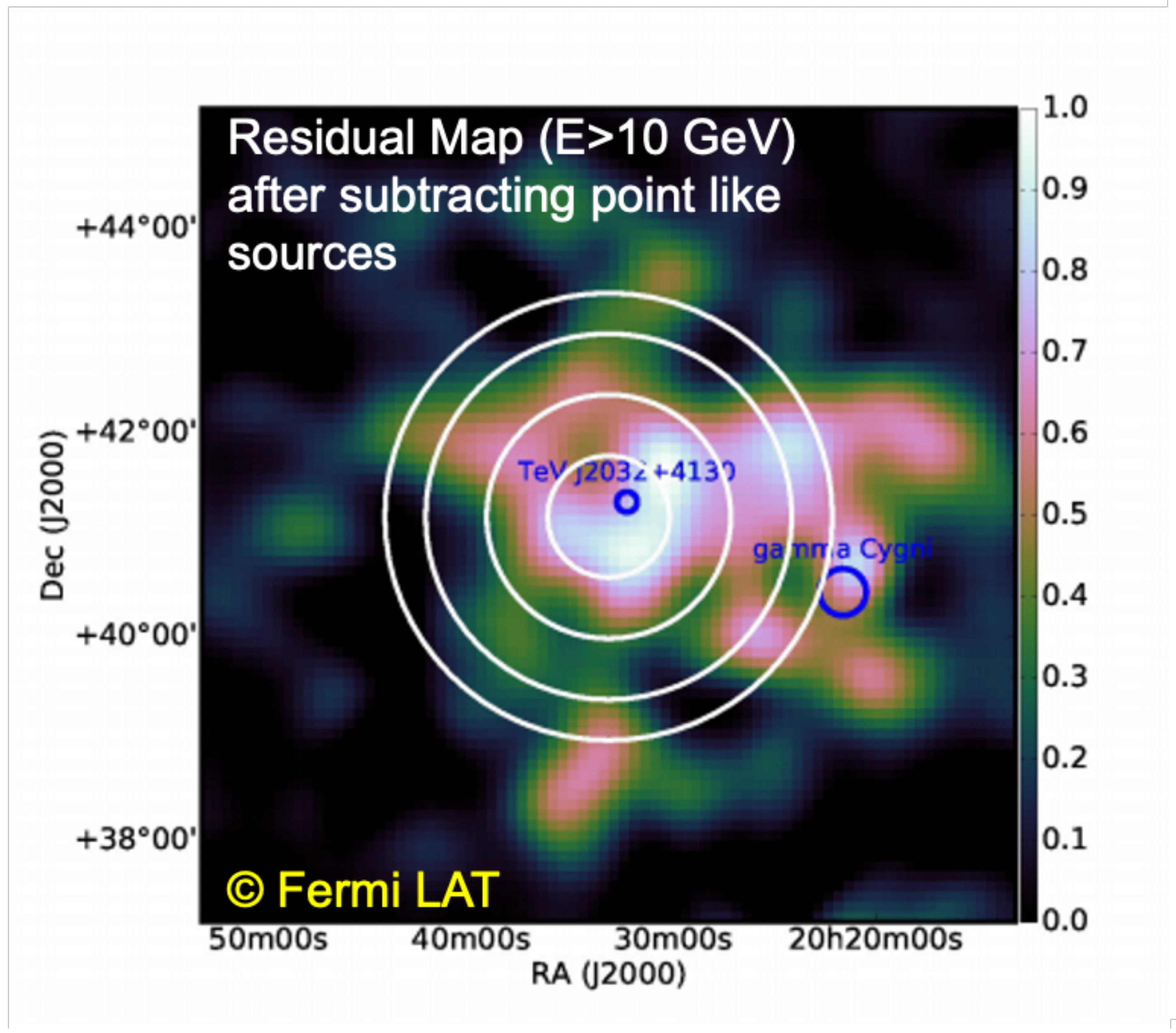


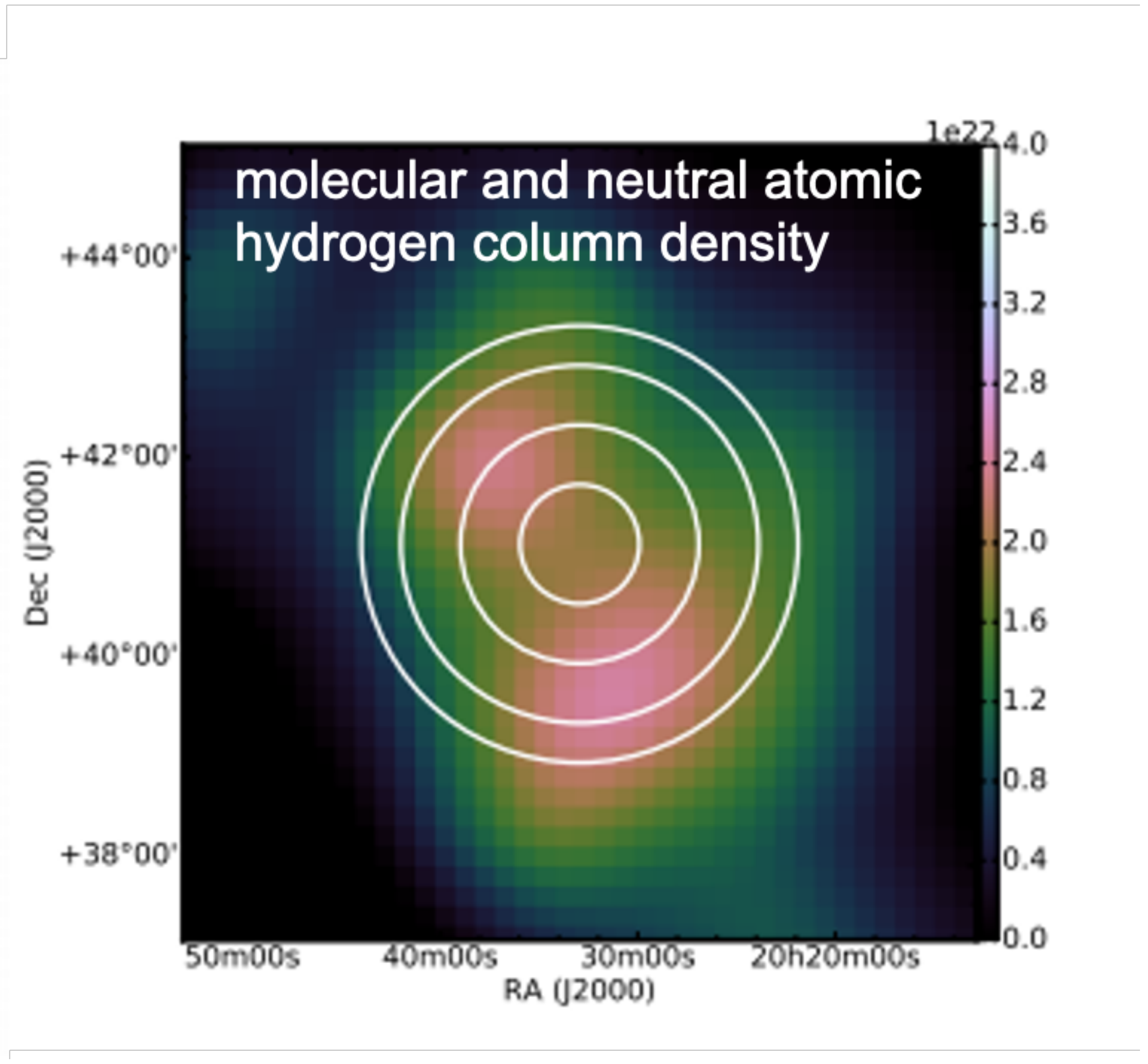


Knowing the matter, we can derive the CR image:
Planck free-free (HII) and CfA (CO) maps in the [-11,21] km/s.

CRs accelerators: Stellar clusters

- Other accelerators - Old massive Stars (wind-wind, clusters, collective effects)
- Energy reservoir ~$10^{38\text{-}39}$ erg over ages of $T \geq 10^6$ years
- In the GeV range: huge structures covering few degree - too large for leptonic emission





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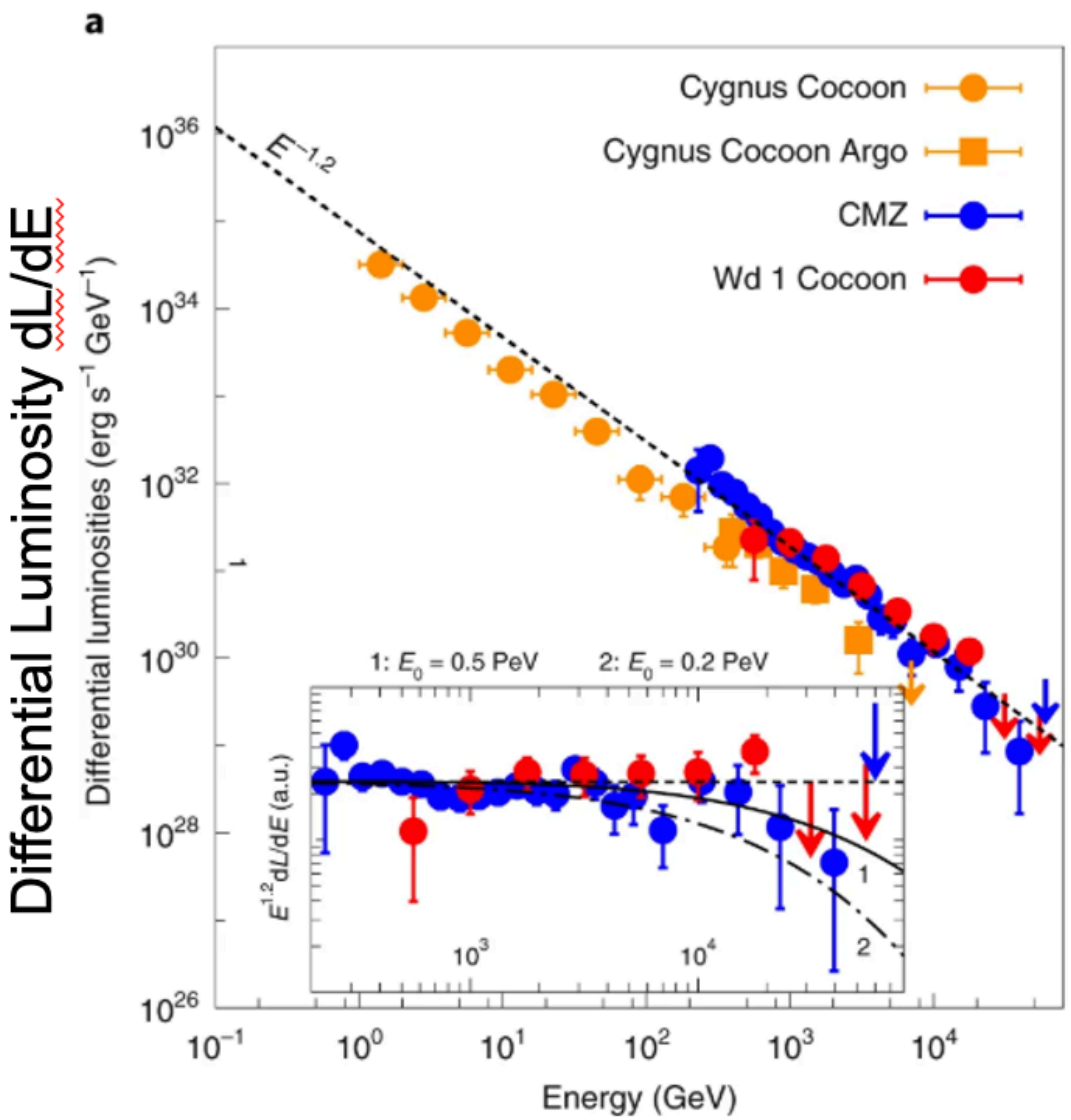
CRs accelerators: Stellar clusters



The spectra (of some of them) extends to high energies

With remarkably similar shape and spectral index (2.2)

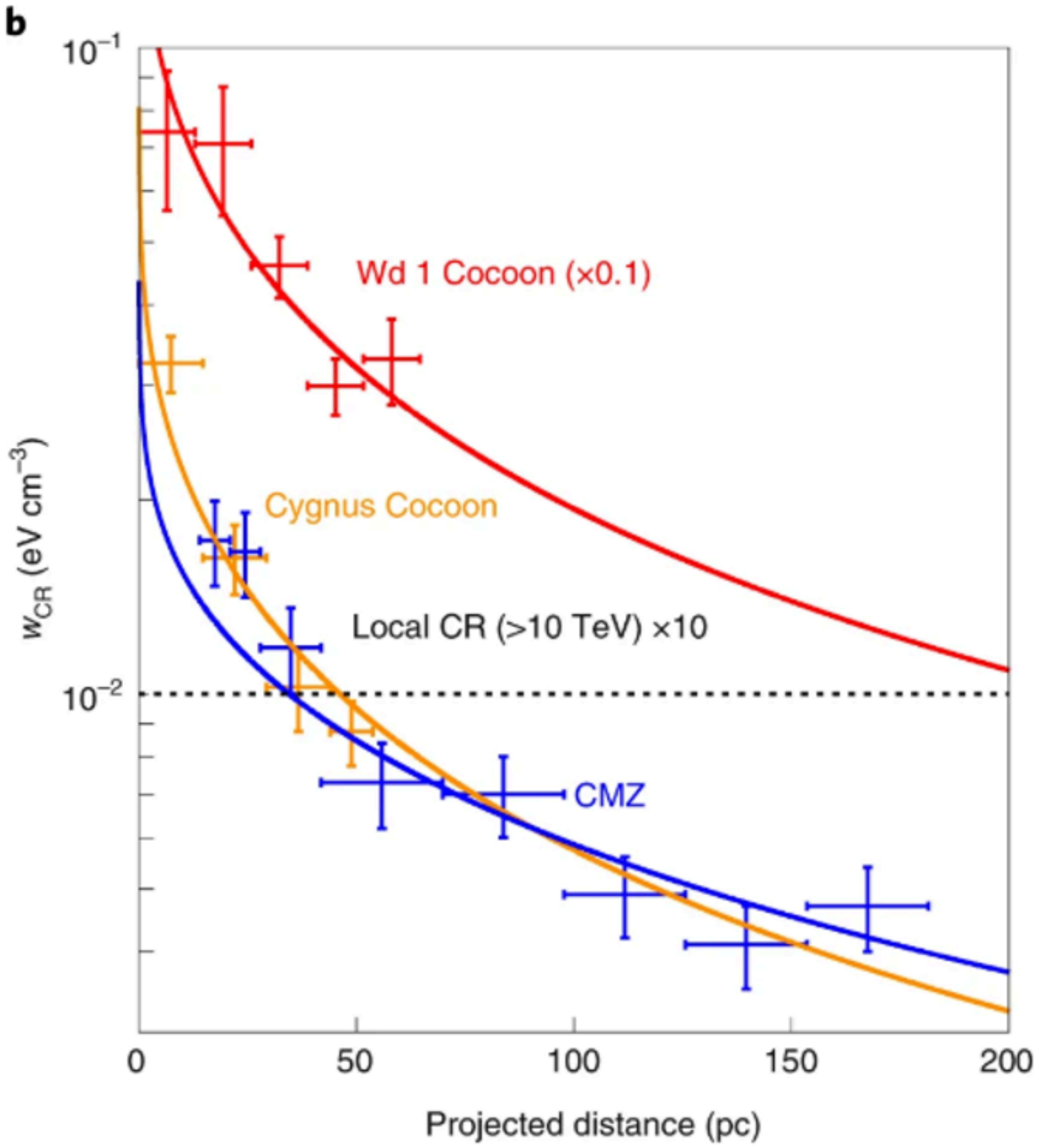
No indication of energy cutoff (with the available statistics)

Proton spectrum described with:

$E^{-2.3}\exp(-E/E_o)$ with E_o = 0.2 (1), 0.5 (2) PeV

=> For Kolmogorov-type turbulence, $D(E) \propto E^{1/3}$, we arrive at a 'classical' E^{-2}-type acceleration spectrum.

CRs accelerators: Stellar clusters



The CR proton radial distribution follows a 1/r line (>10 TeV)
(for the Cygnus Cocoon we extrapolated from LAT energies)

Exceeding the local CR by a factor of 10 (from AMS)

We parametrized the CR density as:

$$w(r) = w_0 (r/r_0)^{-1}$$

$$\begin{aligned} W_p &= 4\pi \int_0^{R_0} w(r) r^2 \, dr \\ &\approx 2.7 \times 10^{47} (w_0 / 1 \text{ eV cm}^{-3})(R_0 / 10 \text{ pc})^2 \text{ erg} \end{aligned}$$

CRs accelerators: Stellar clusters

We define R as the extension of the source (50 and 300 pc), or more conservatively, the maximum given by the diffusion condition:

$$R_{\rm D} = 2\sqrt{T_0 D(E)} \approx 3.6 \times 10^3 (D_{30} T_6)^{1/2} \text{ pc}$$

Since W_{CR} cannot be larger than W_{tot} => $f(\geq 10 \text{ TeV}) \approx 1 w_0 D_{30} L_{39}^{-1}$

$$W_{\rm tot} = f L_0 T_0 = 3 \times 10^{52} f L_{39} T_6 \text{ erg}$$

Measuring the Local diffuse coefficient:
if f=10% => D ~10^{28} cm^{-2} s^{-1}

Halos as large as 300 pc and with a density still 2 order of magnitude larger than the local CR density

$$W_{\rm p} = 4\pi \int_0^{R_0} w(r) r^2 \, dr \approx 2.7 \times 10^{47} (w_0/1 \text{ eV cm}^{-3})(R_0/10 \text{ pc})^2 \text{ erg}$$

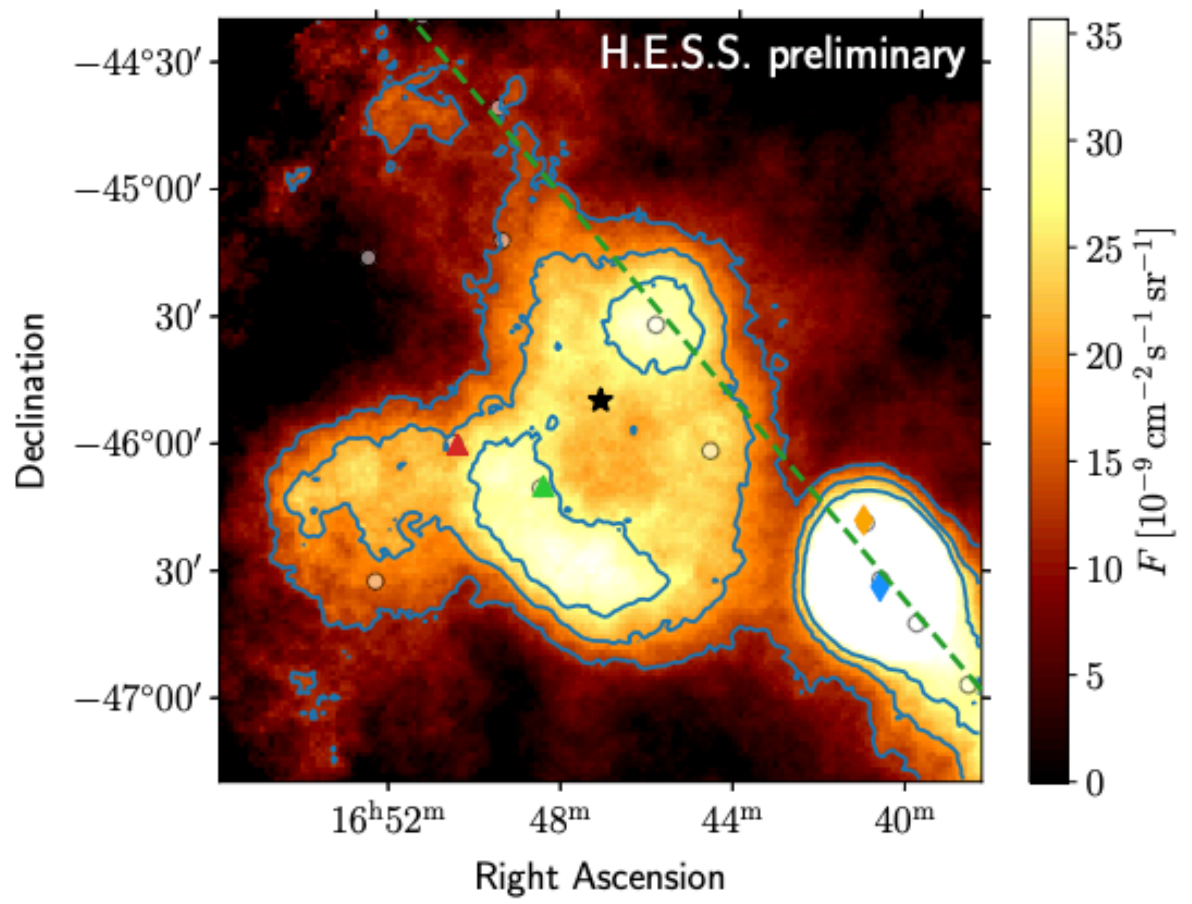
Source	Cygnus Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
Age of cluster (Myr)[39]	3–6	2–7	4–6
Kinetic luminosity, L_{kin}, of cluster (erg s^{-1})	2×10^{38} (ref. [17])	1×10^{39} (ref. [40])	1×10^{39} (ref. [41])
Distance (kpc)	1.4	8.5	4
ω_0 (>10 TeV) (eV cm^{-3})	0.05	0.07	1.2

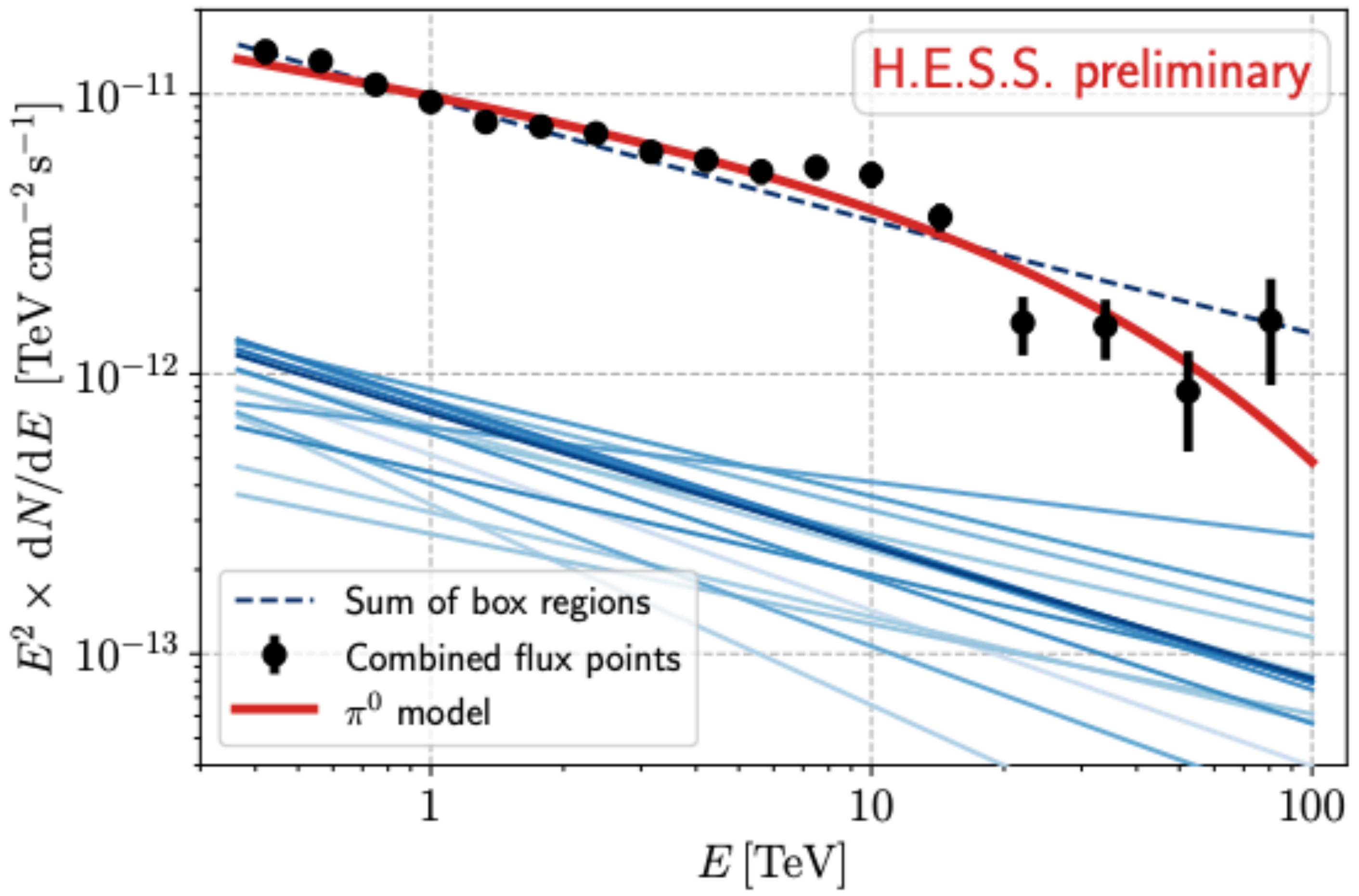
CRs accelerators: Stellar clusters

- What do we see in the VHE with Cherenkov instruments? Look at the most massive SC

Westerlund 1

Mohrmann et al, ICRC 2021





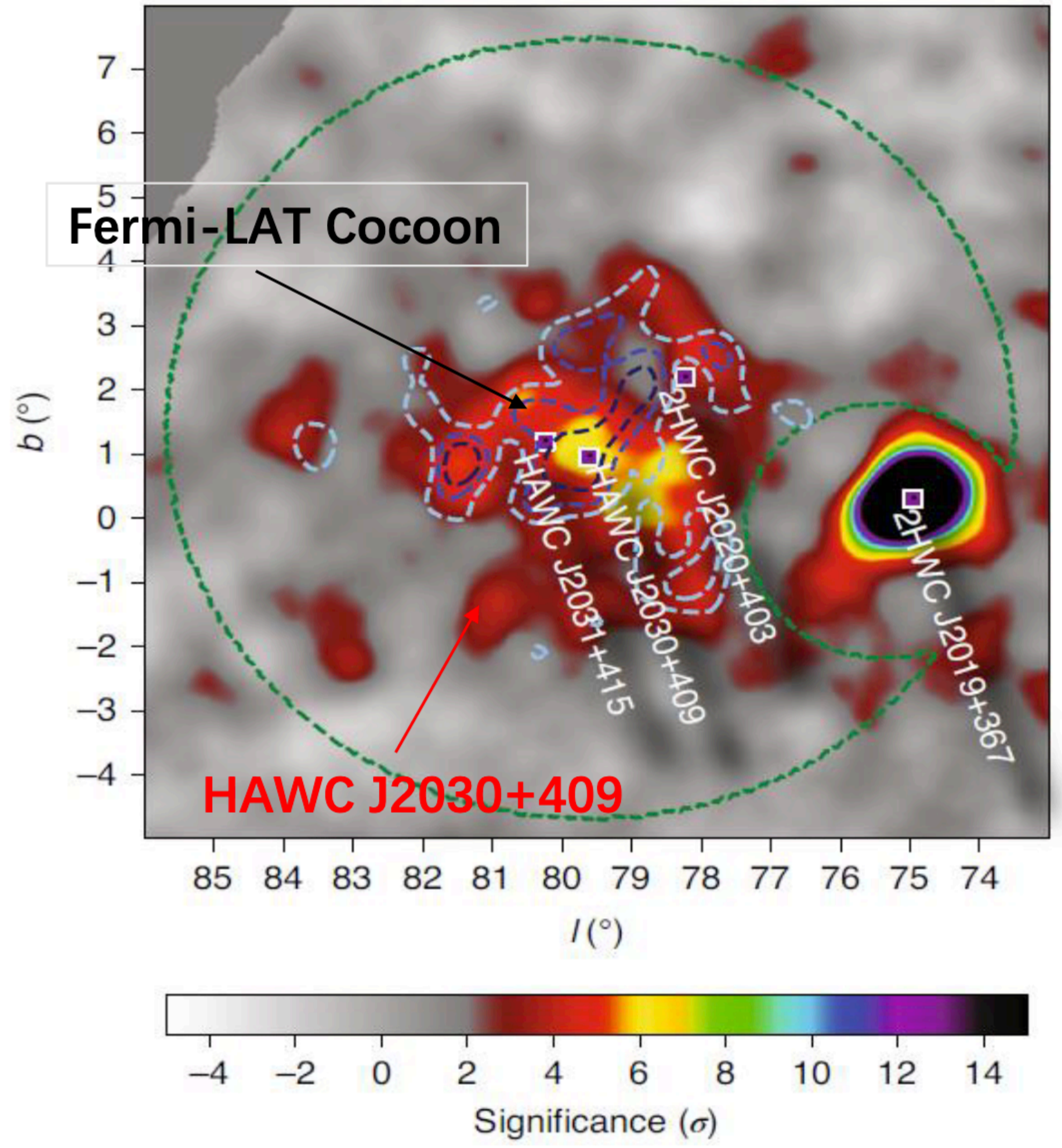
$E_c = 400(^{+250}_{-130})$ TeV
$W_p \sim 5\times10^{49}\,(n/10\,cm^{-3})(d/3.9\,kpc)^2$ erg

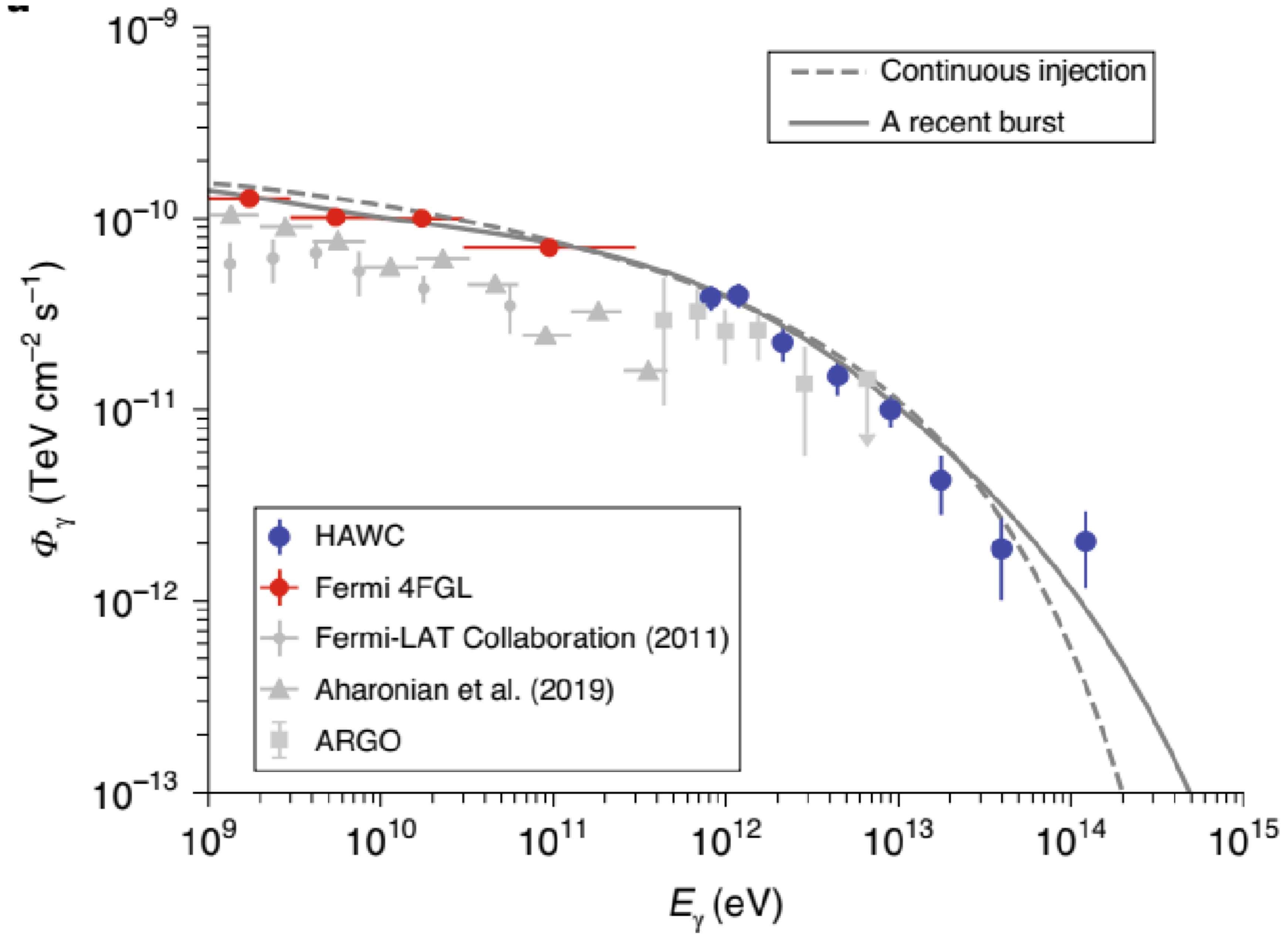
- Complex morphology
- Similar spectra along the 1^{o} (70 pc at 3.9 kpc) source & similar radial profile at different energies
- Dip in the surrounding of Westerlund 1
- Spectrum extends to 100 TeV

CRs accelerators: Stellar clusters

- What do we see in the VHE with Cherenkov instruments?

  Cygnus Region





HAWC 2021 result

CRs accelerators: Stellar clusters

- If PeVatrons: where are particles accelerated and how?
- LHAASO results >> 100 TeV!
- To be continue…

CRs accelerators: Galactic Center

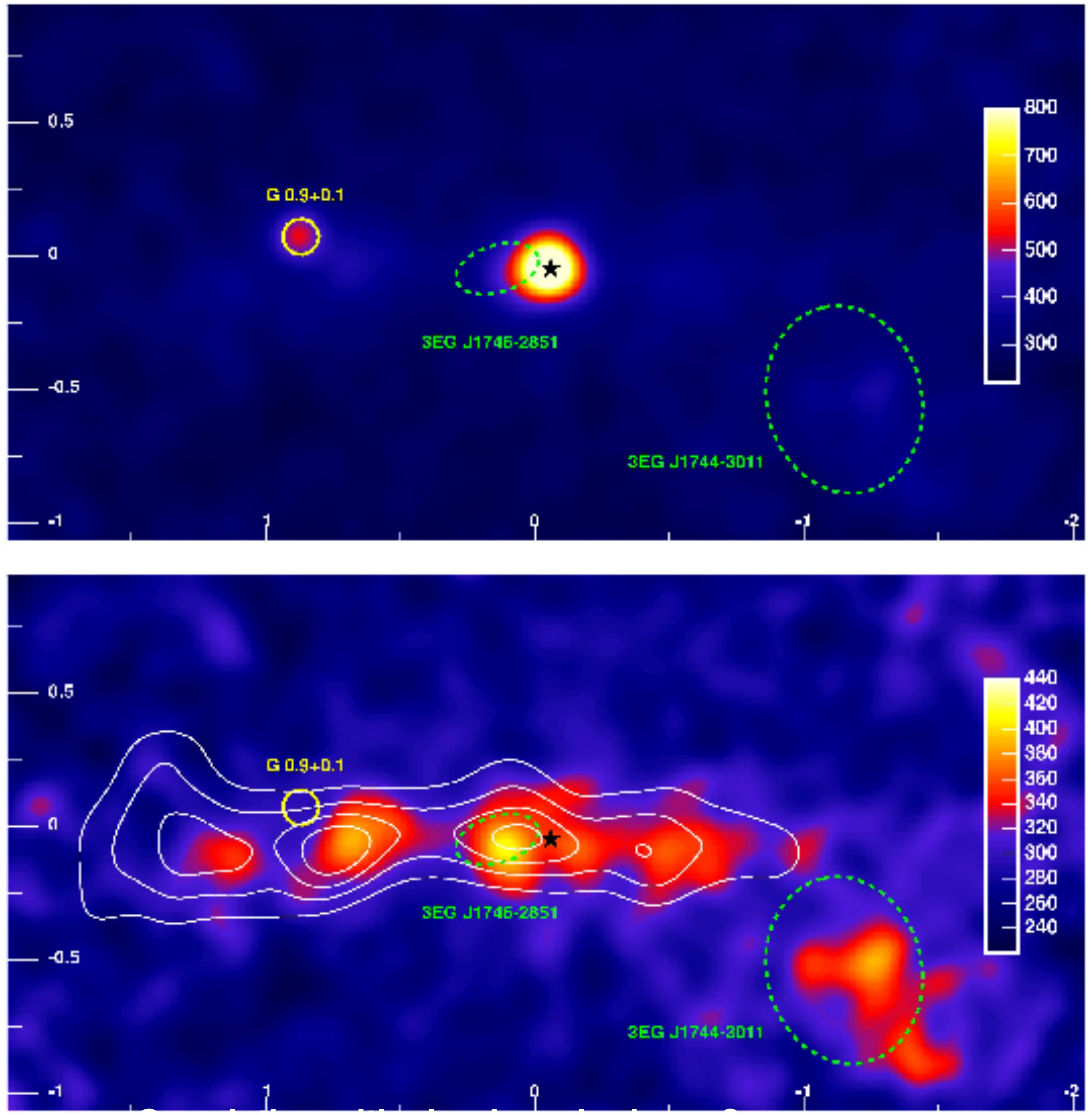
- **Energetics** - Outburst-like event /slow outflows

  $E_{kin} = 3x10^{54}$ erg
  $L_{IR} \sim 1.6x10^{42}$ erg/s

- Is there any indication of such behaviour?

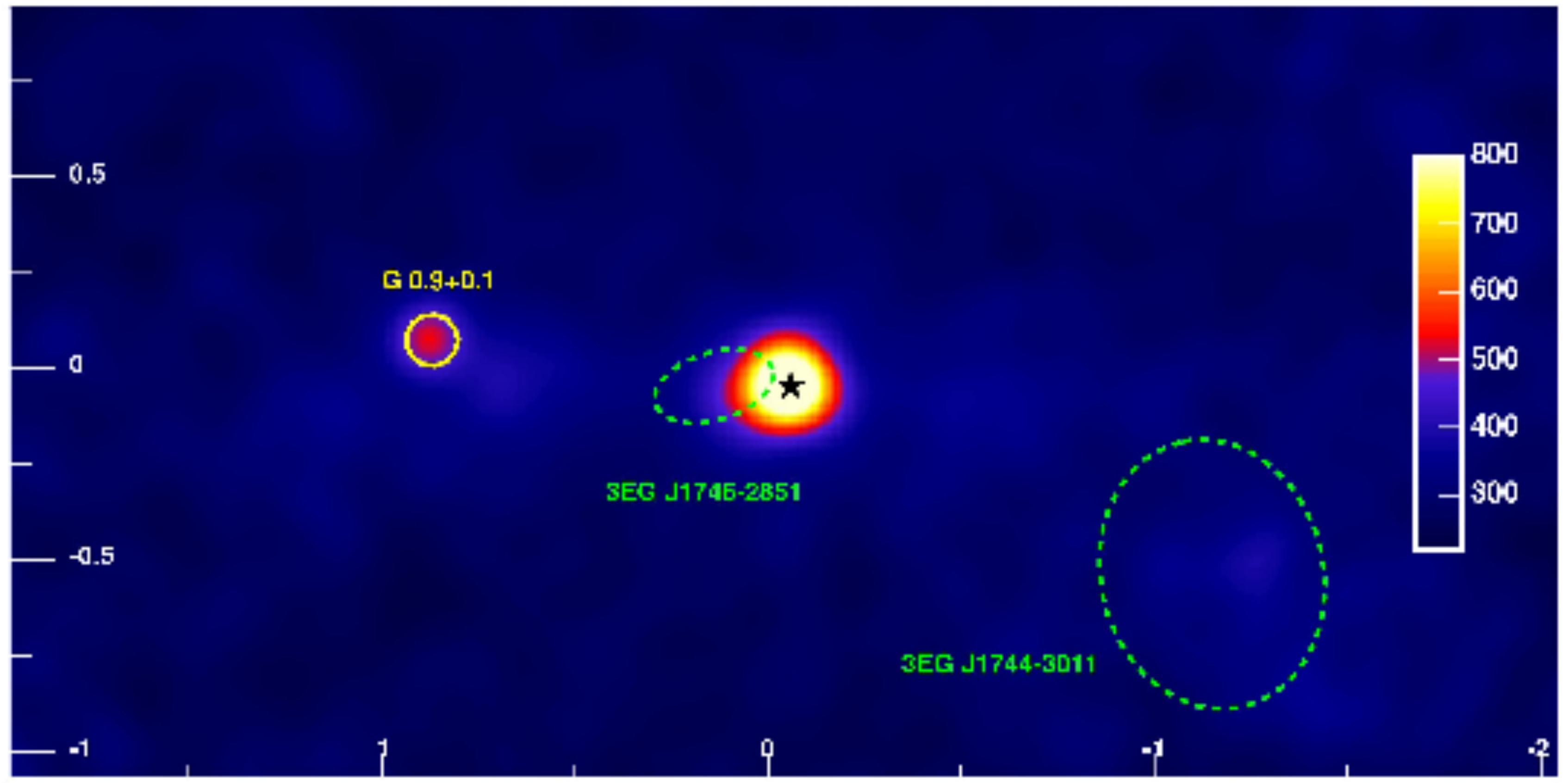
CRs accelerators: Galactic Center

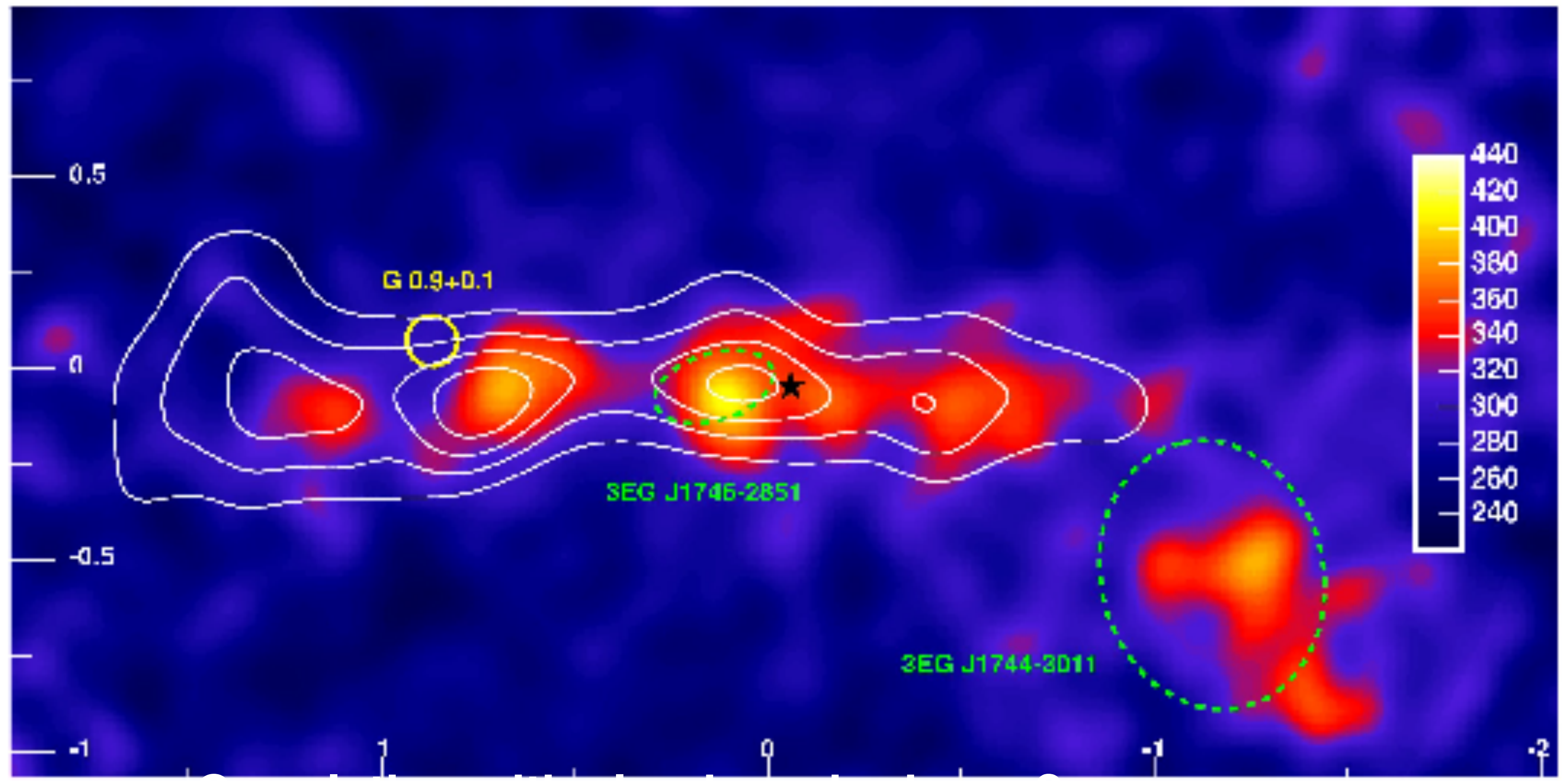
- In the TeV regime:



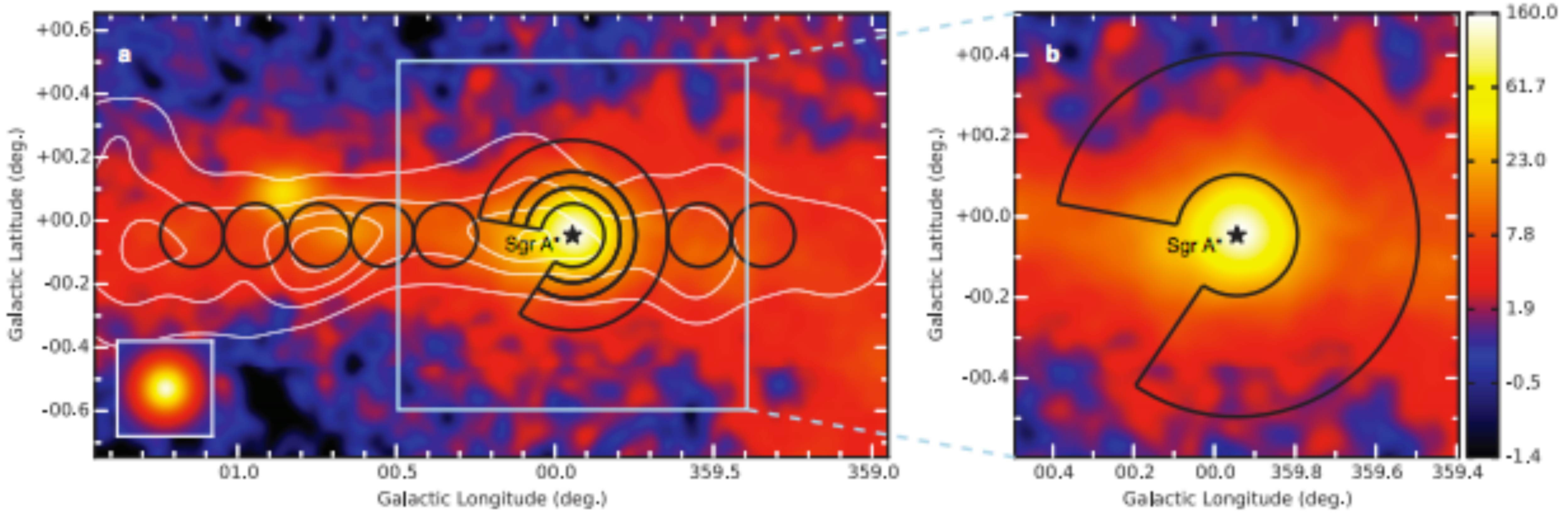
CRs accelerators: Galactic Center

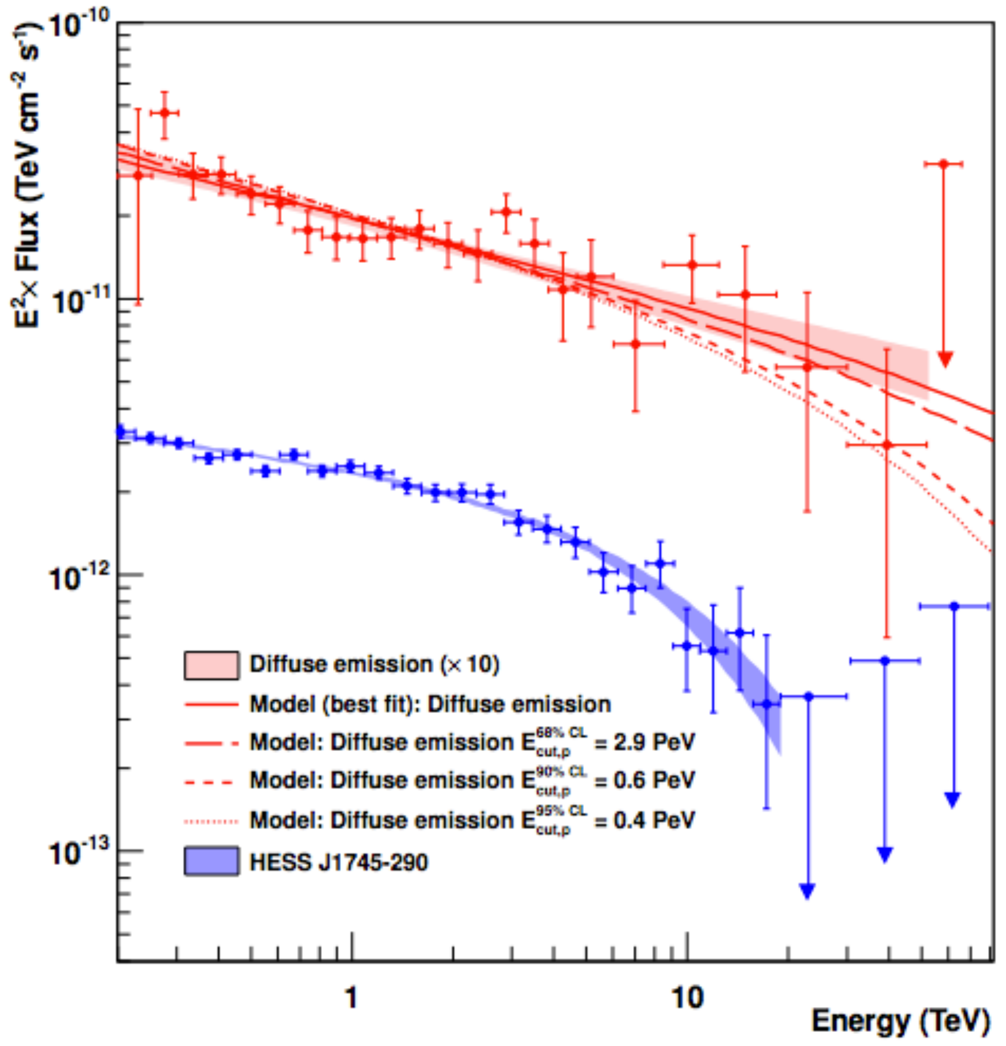
- In the TeV regime:

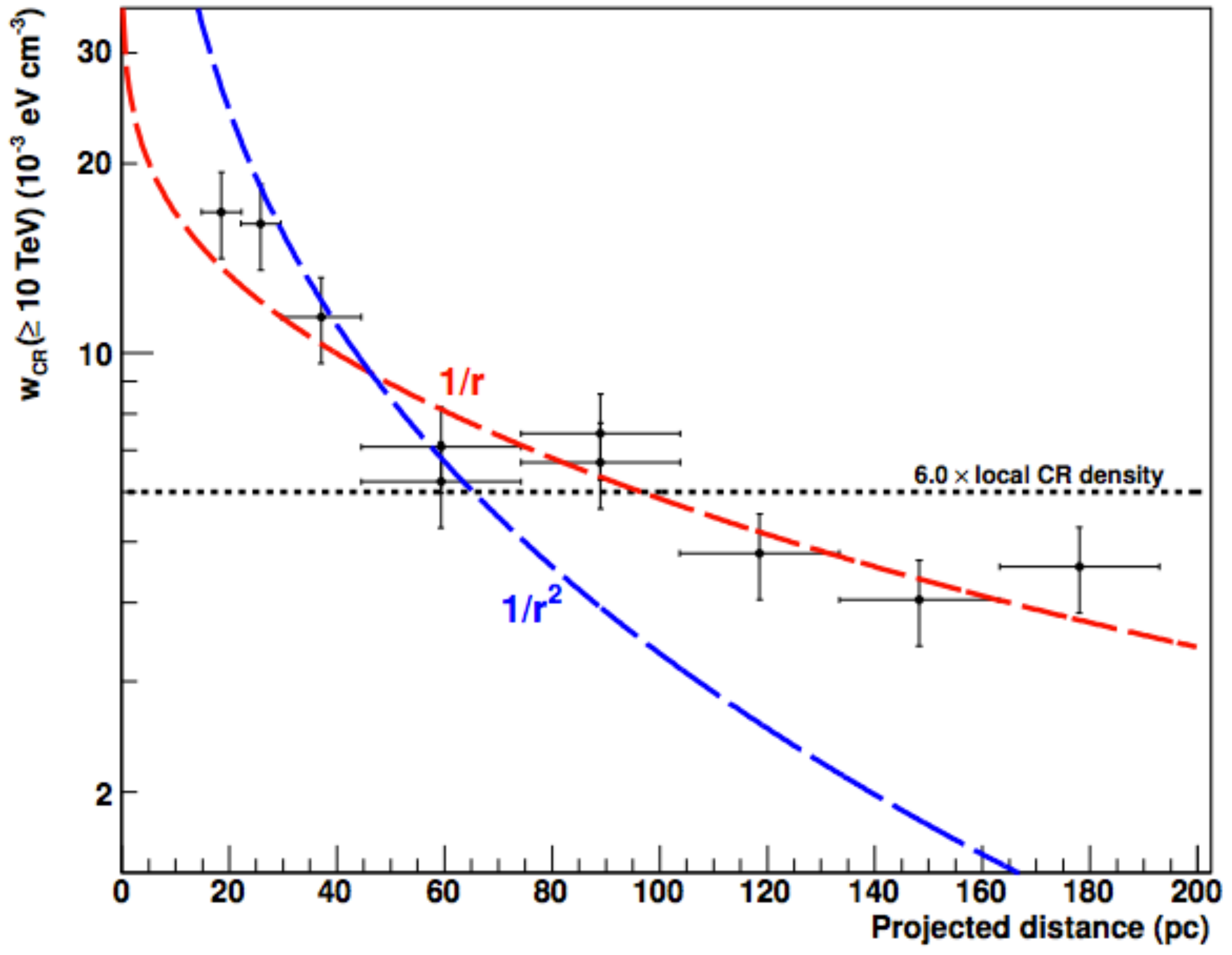




- Parent proton population up to 1 PeV: first detection of a PeVatron
- Constant injection and diffusion for > 1 kyrs







CRs accelerators: Galactic Center

The injection time should be larger than the escape one:

$$\Delta t \geq t_{\rm diff} \approx R^2/6D \approx 2\times10^3 (D/10^{30}\ {\rm cm^2 s^{-1}})^{-1}\ {\rm yr},$$

$$Q_p(\geq 10\ {\rm TeV}) \approx 4\times10^{37} ({\rm D}/10^{30}\ {\rm cm^2 s^{-1}})\ {\rm erg/s}.$$

Rather modest injection for thousands of years:
- Galactic center?
- Stellar clusters in the inner region?

CRs accelerators: Galactic Center

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- Constant injection and diffusion for > 1 kyrs

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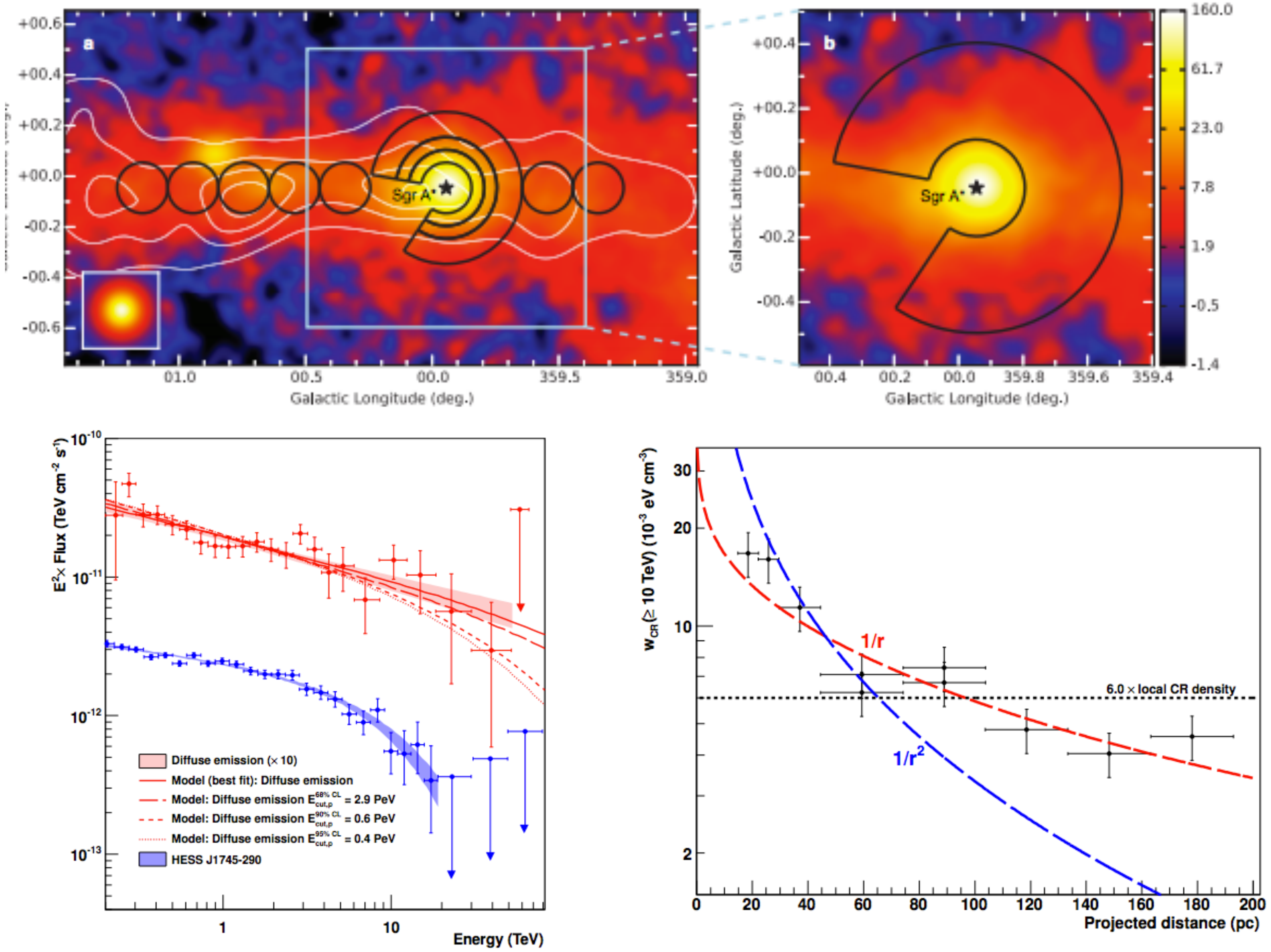
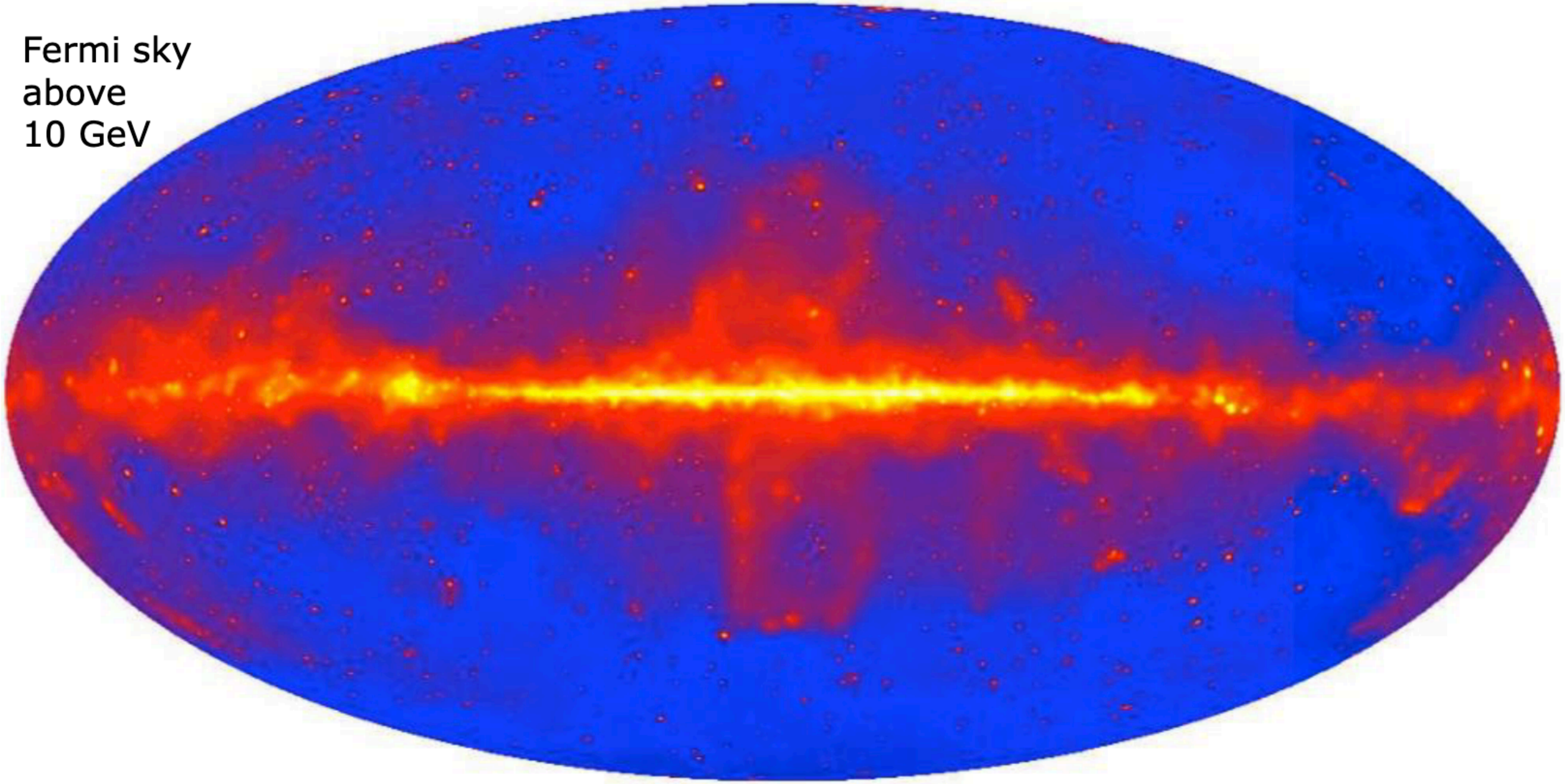
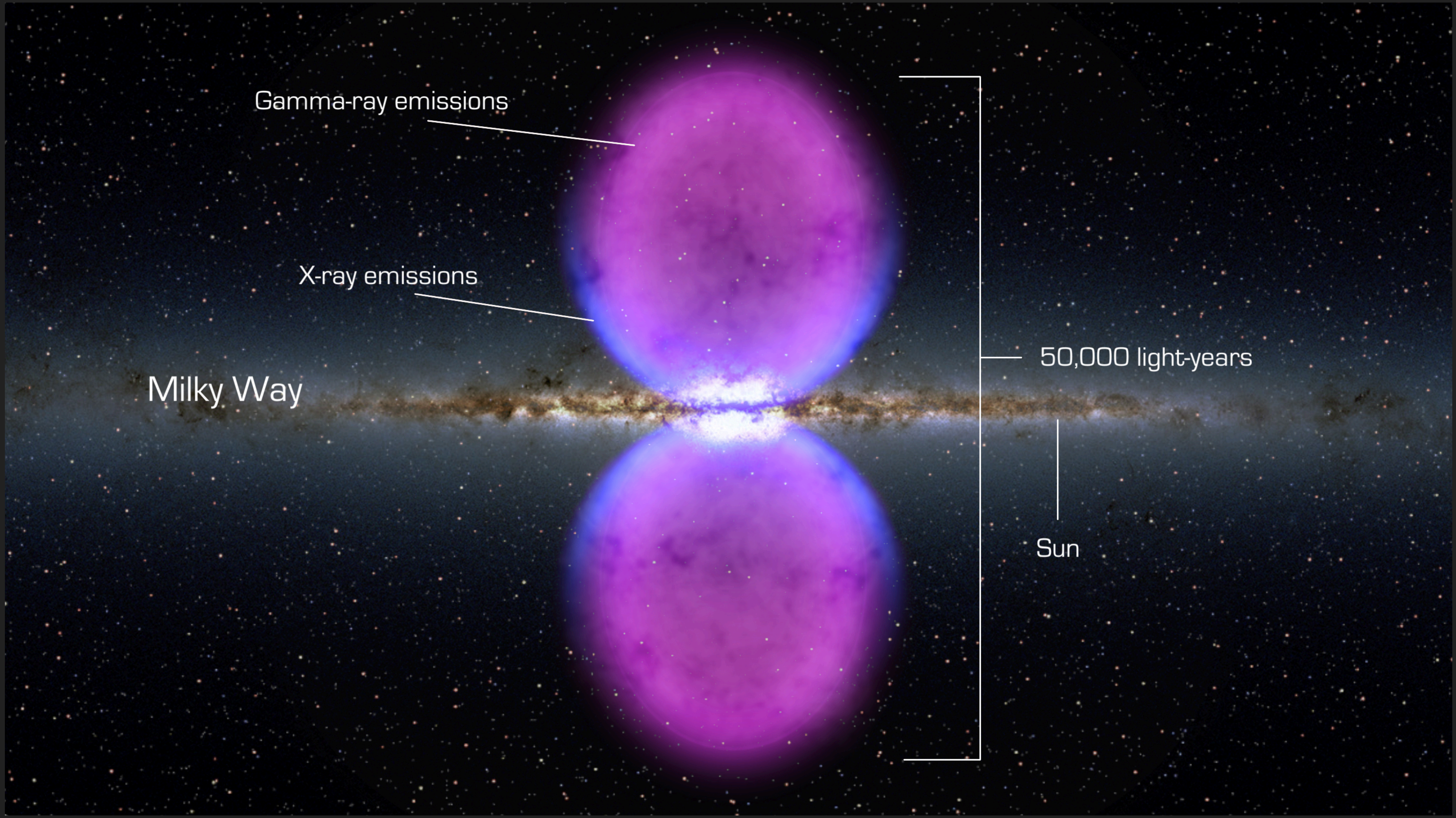


CRs accelerators: Galactic Center

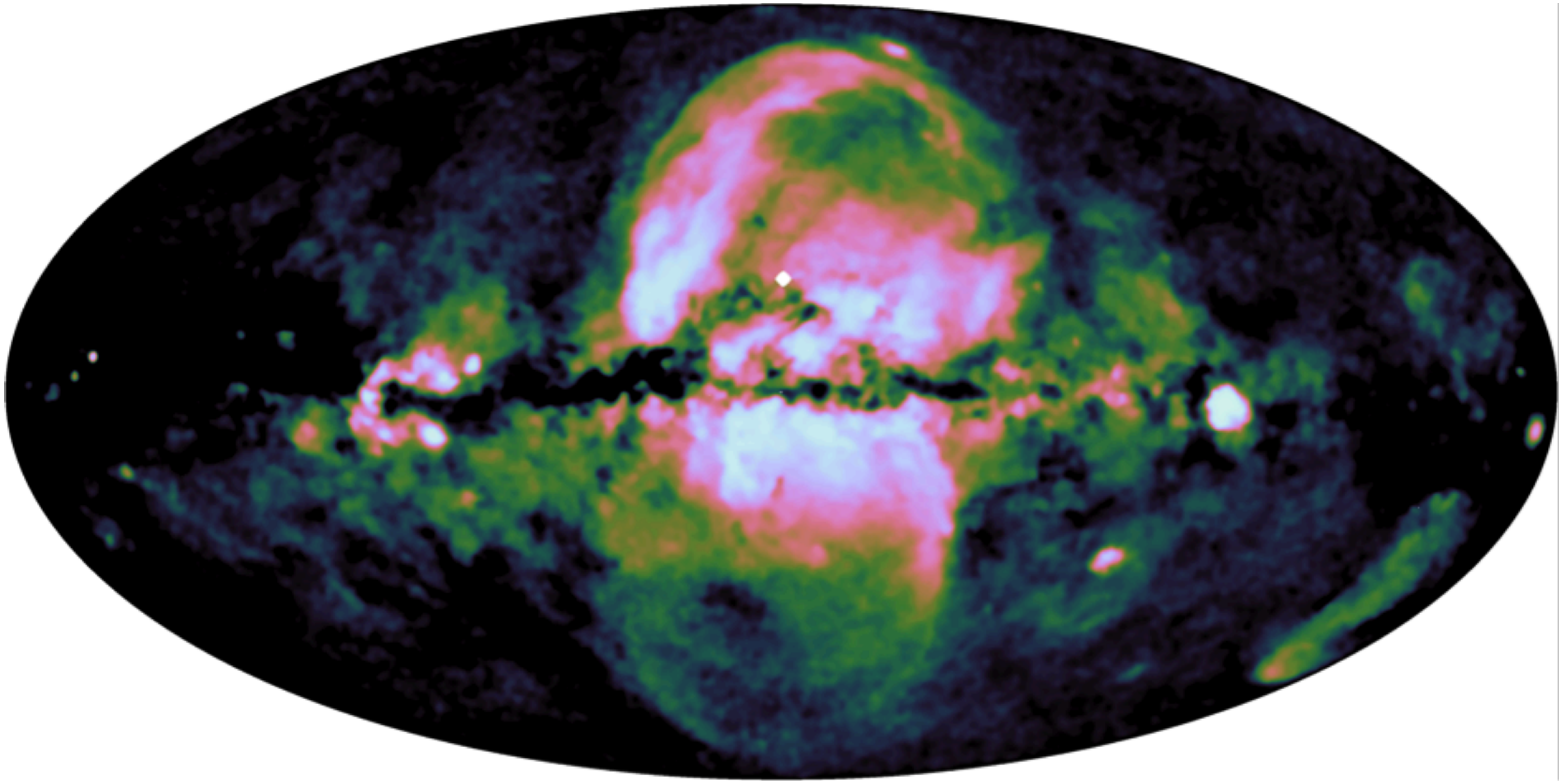
- In the GeV regime:

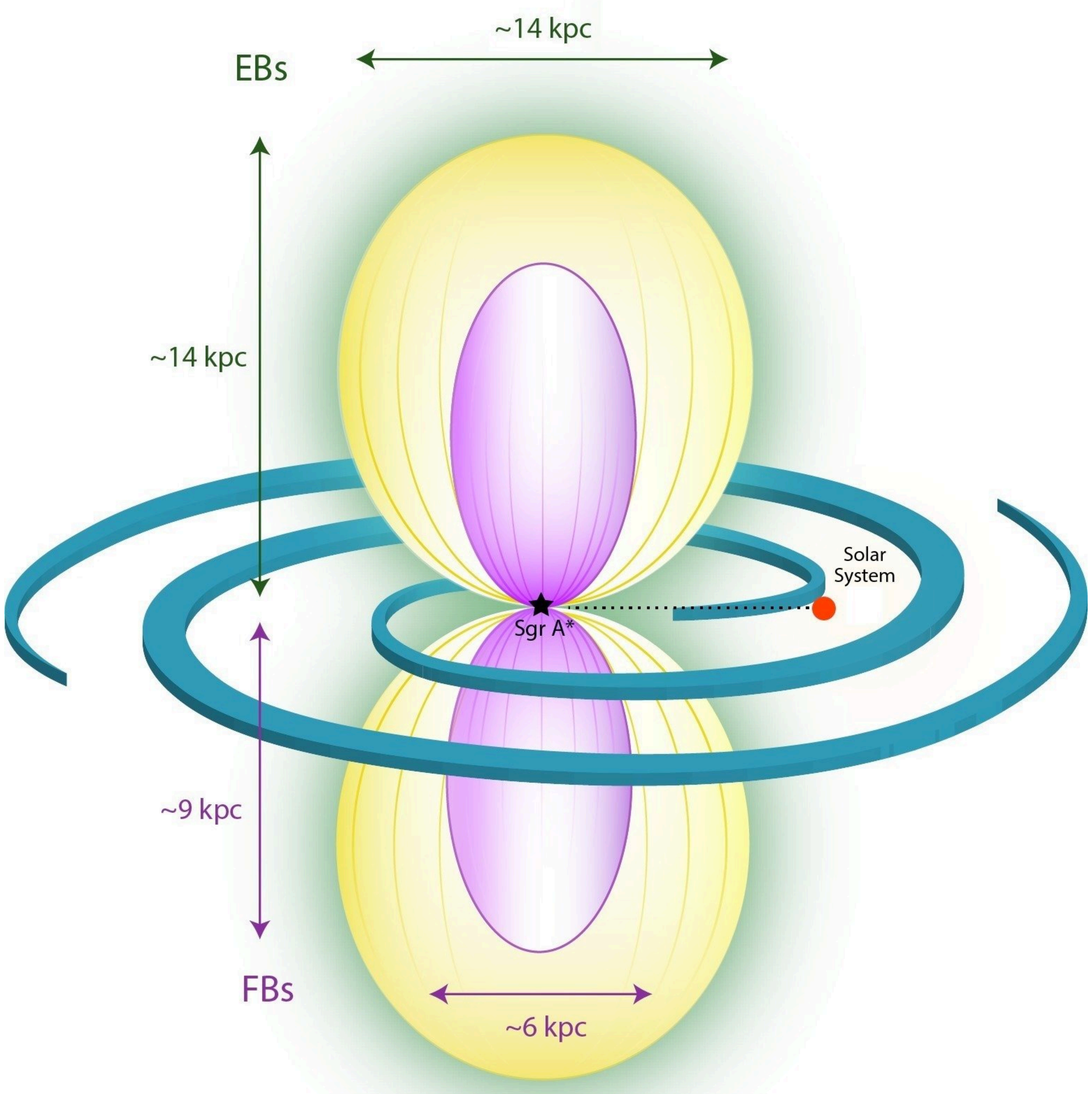


Scale of the Fermi bubbles



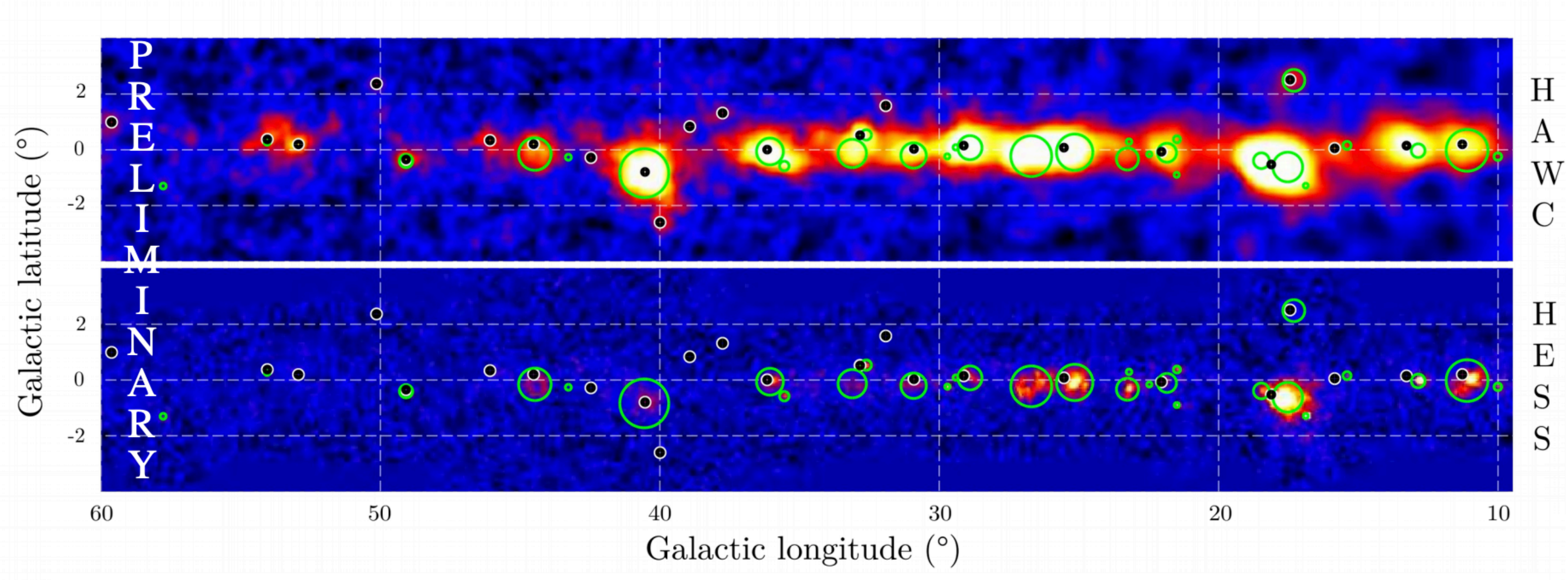
eROSITA (0.6-1 keV)




~14 kpc
EBs
~14 kpc
Solar
System
Sgr A*
~9 kpc
FBs
~6 kpc

CRs accelerators - other hadronic accelerators?

- We see a large number of unidentified sources



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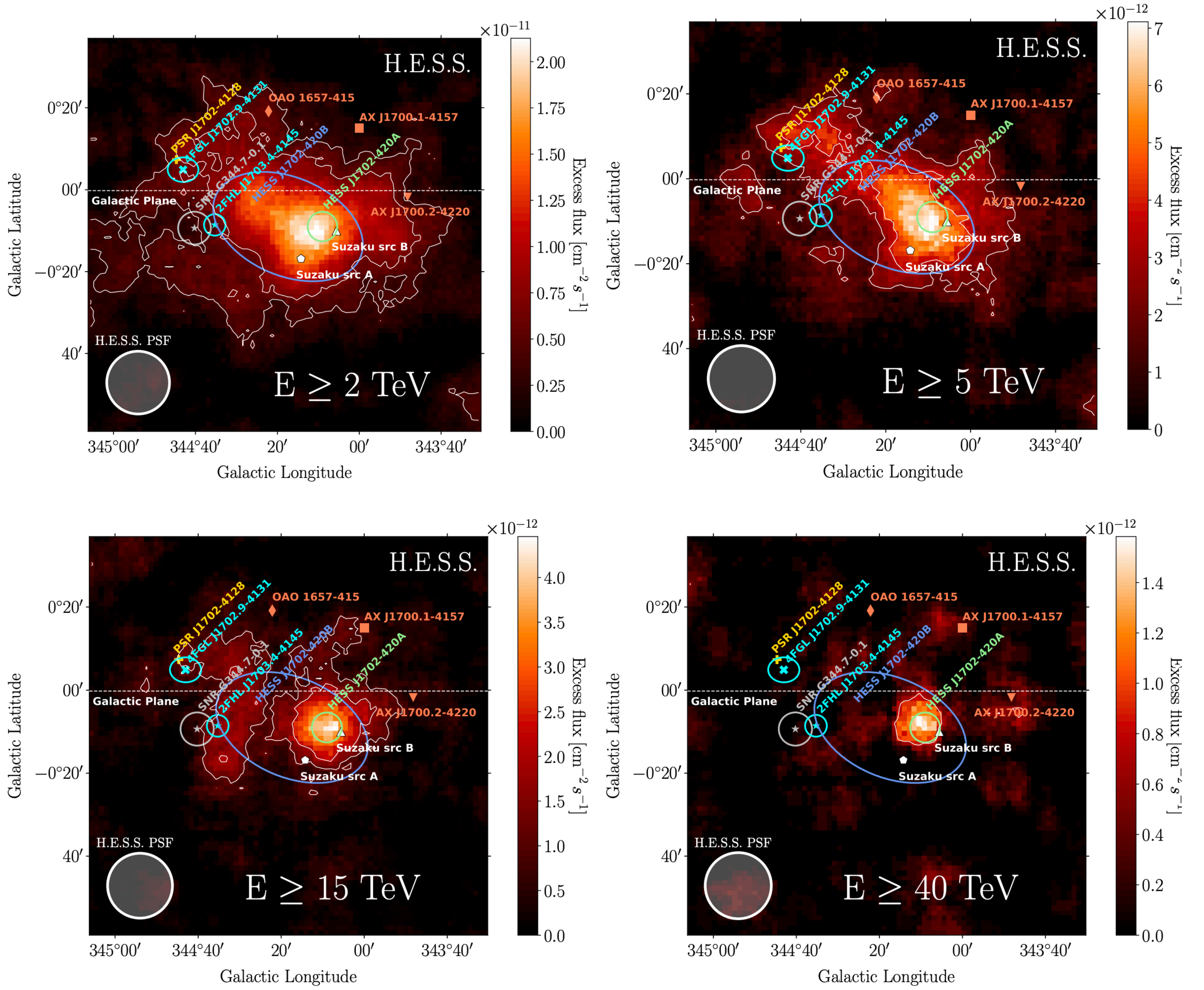
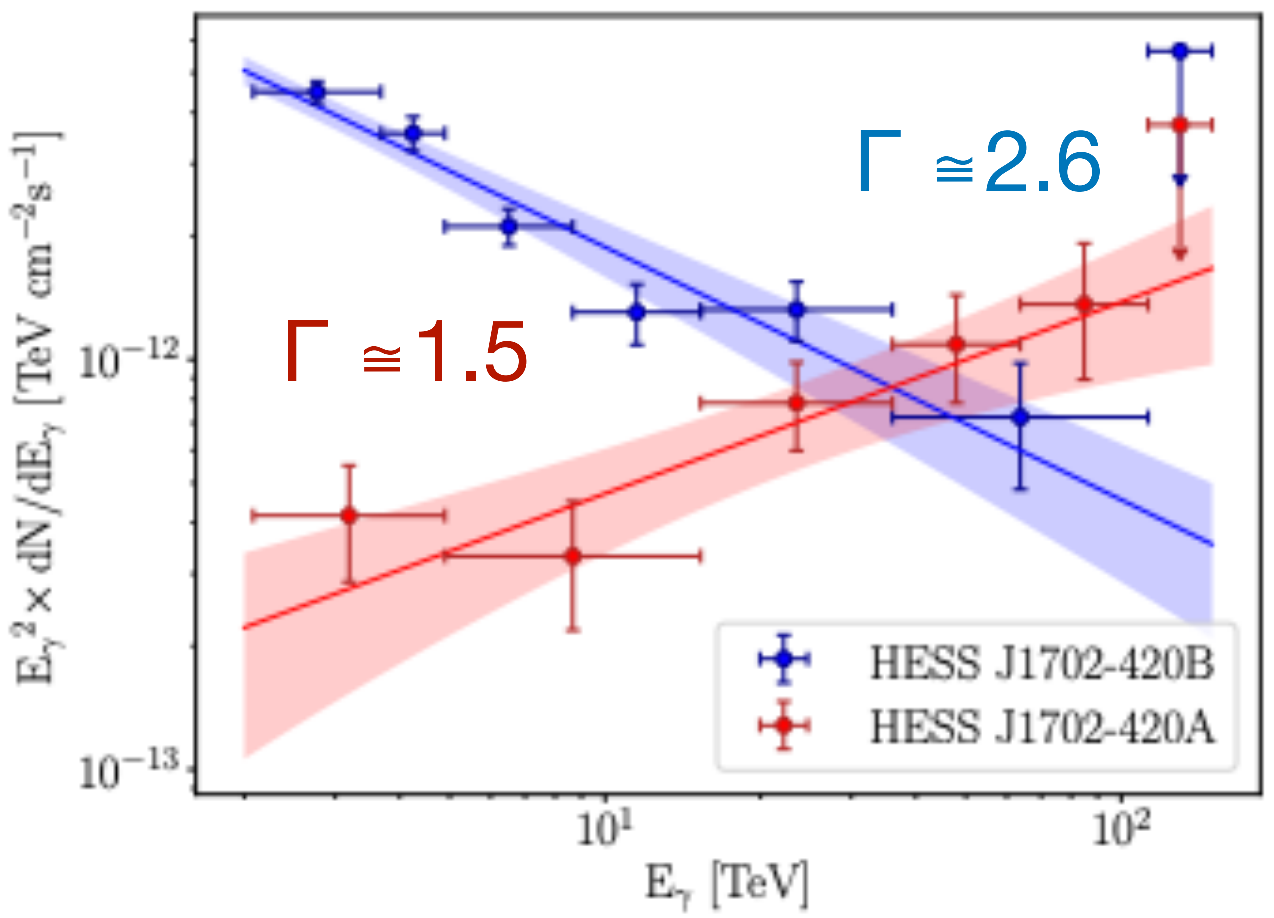
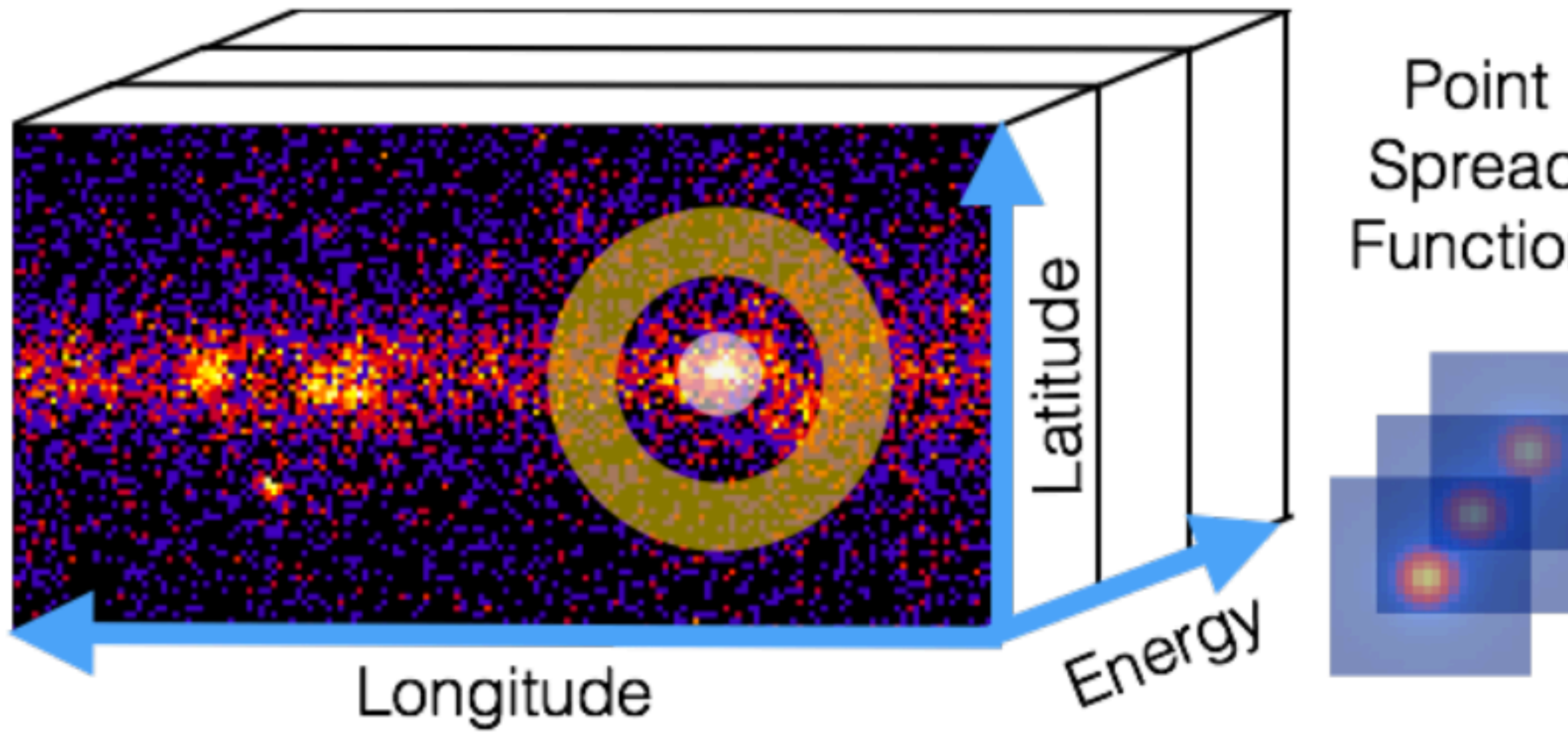






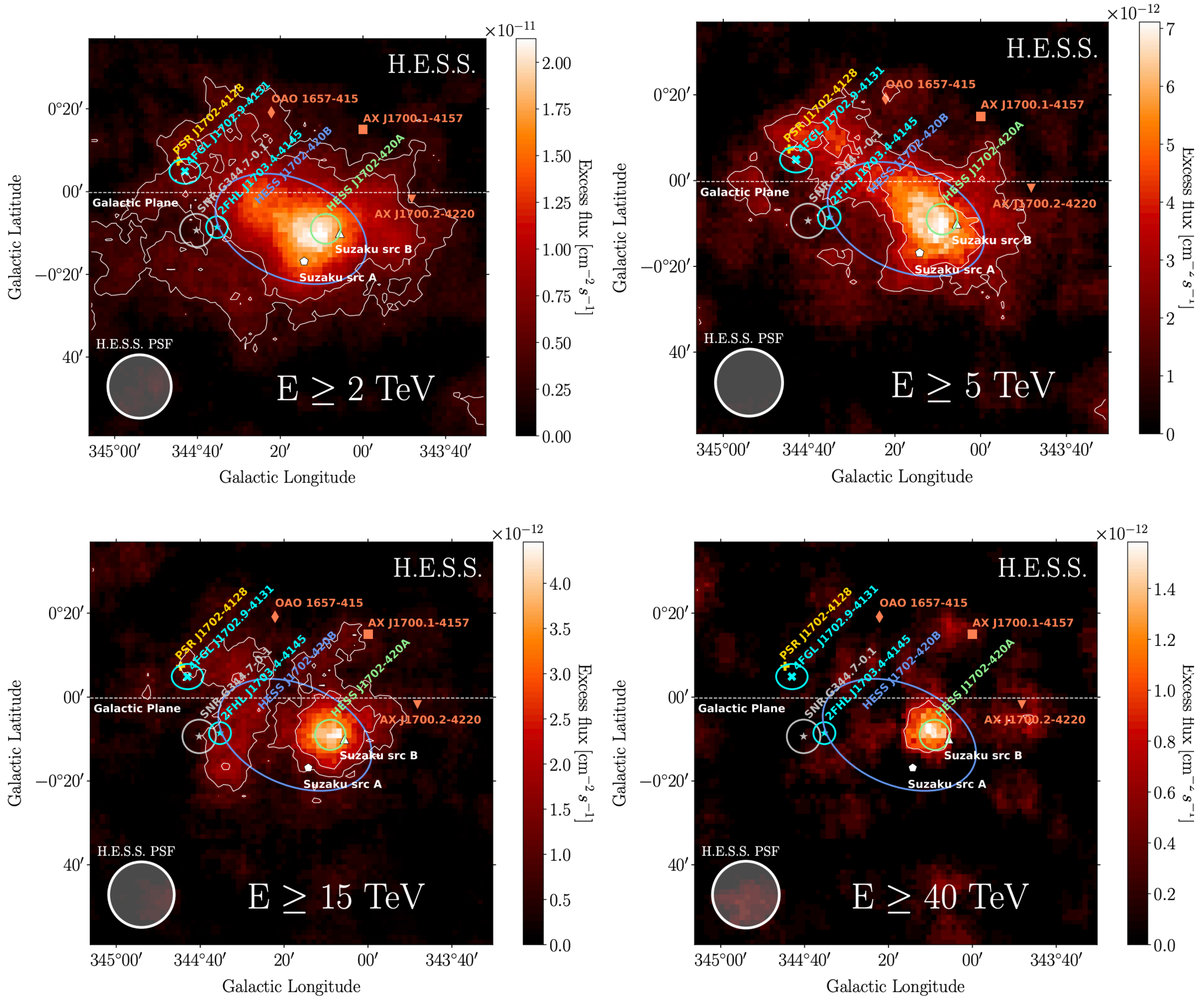
If hadronic => E_c (Γ_p=2) > 0.83 PeV ((1.7)0.55 PeV, (2.3)1.16 PeV)
=> W_p (E_p>1 TeV) > 1.8x10^{47} erg

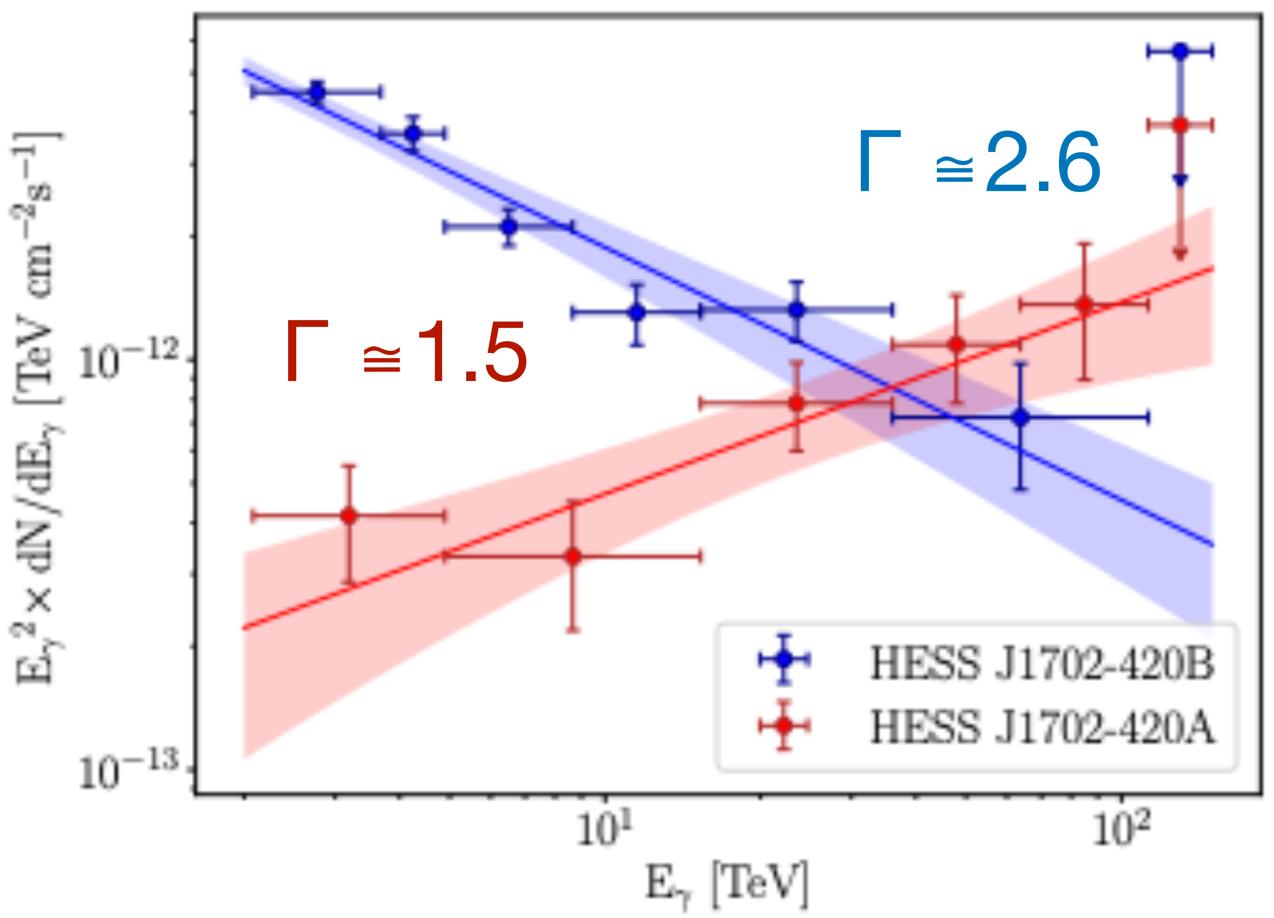
If leptonic => E_c (Γ_e=2) > 0.12 PeV ((1.5)0.06 PeV, (2.5)0.52 PeV)
=> W_e (E_p>1 TeV) > 8.1x10^{45} erg

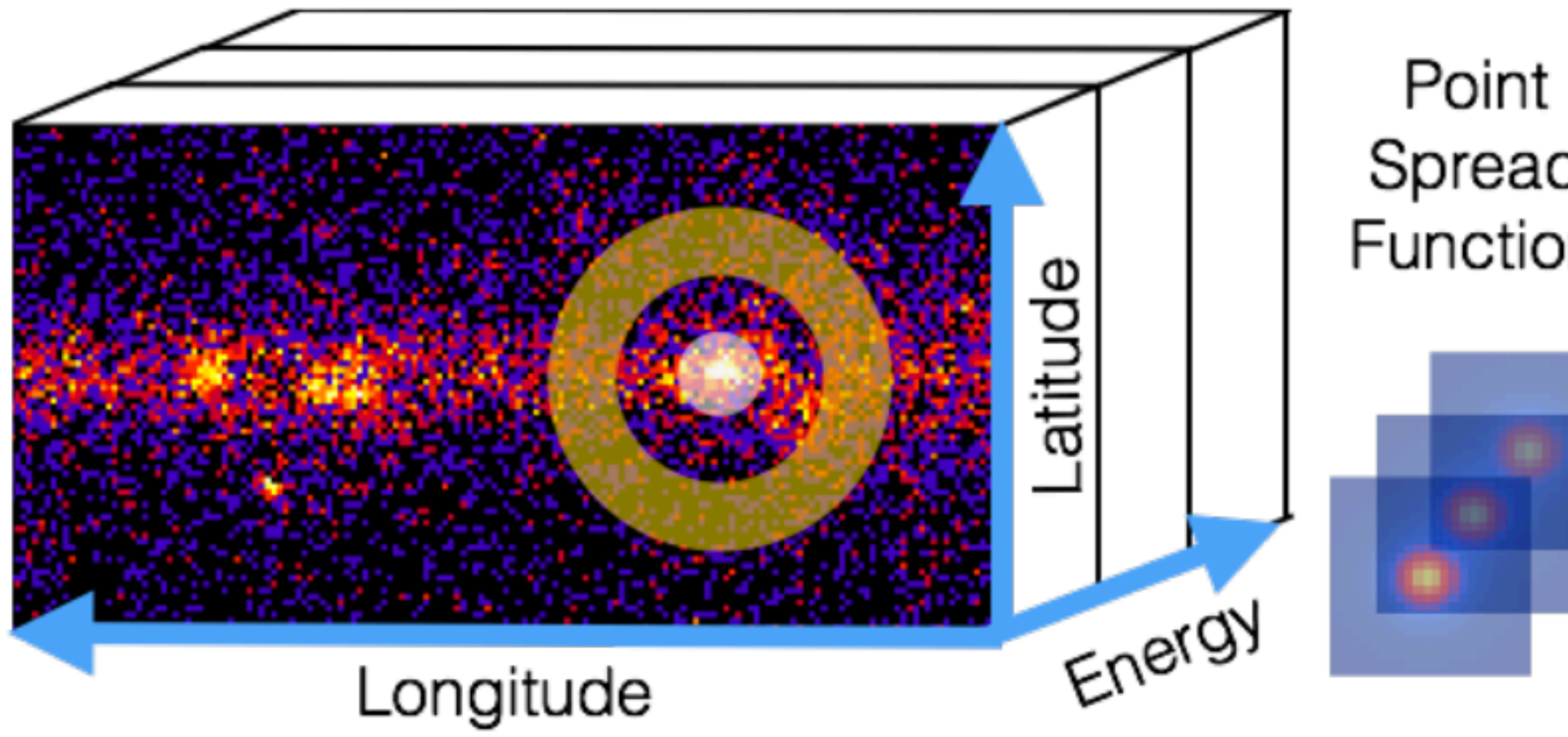
CRs accelerators - other hadronic accelerators?

- We see a large number of unidentified sources

Any other population that can accelerate protons?







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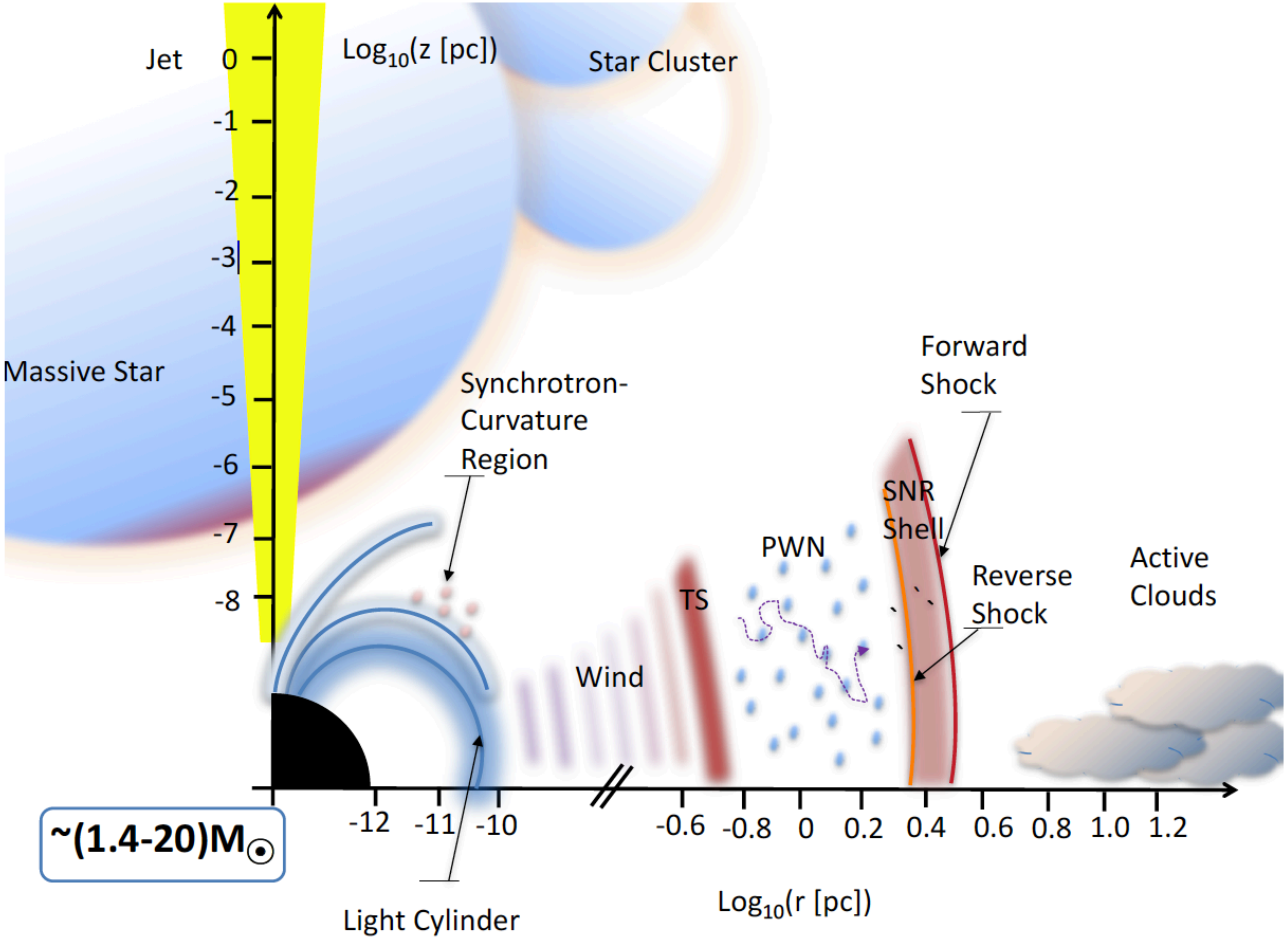
CR Accelerators - leptonic

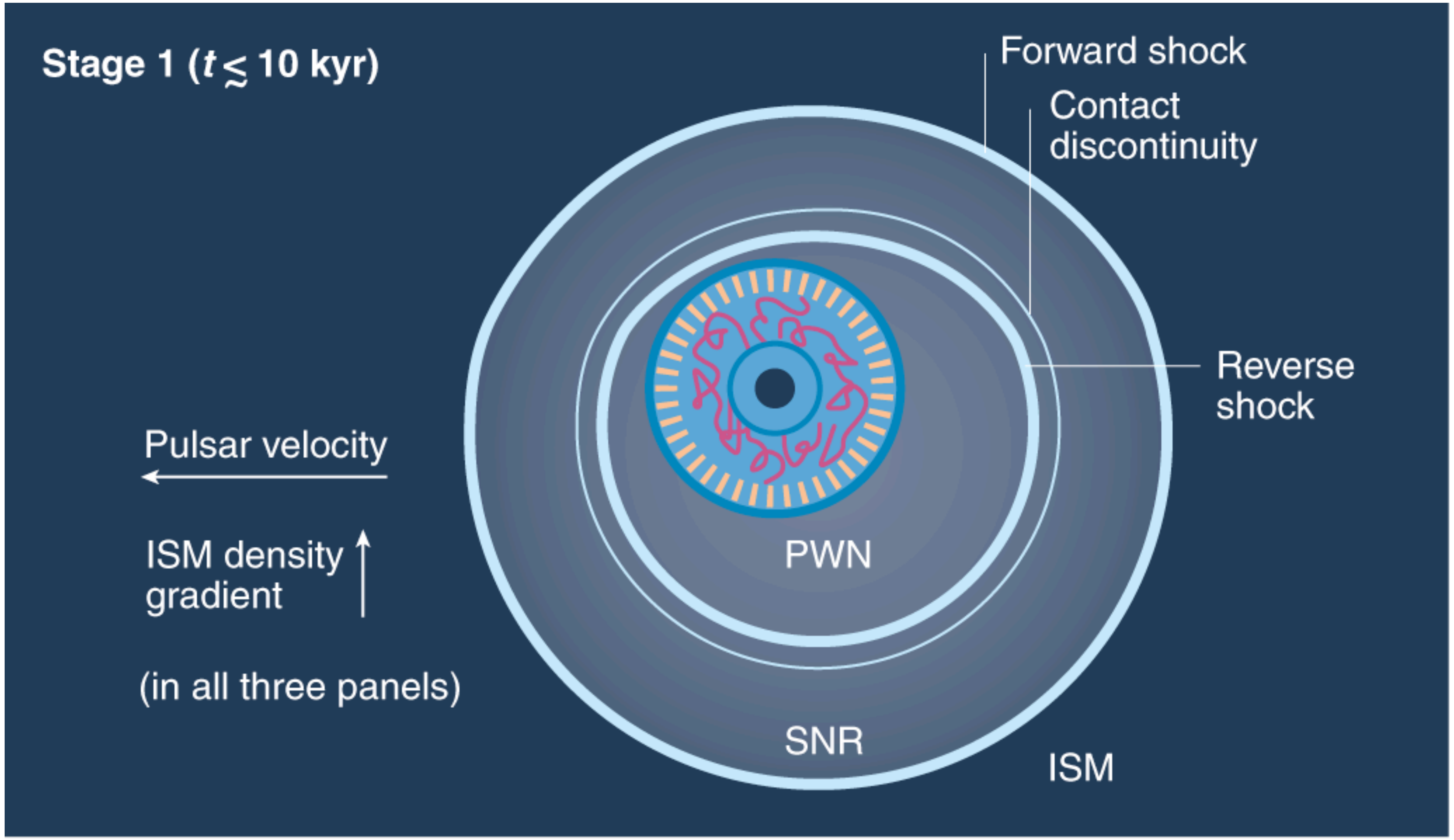
CRs accelerators - leptonic accelerators

Physic of Compact objets

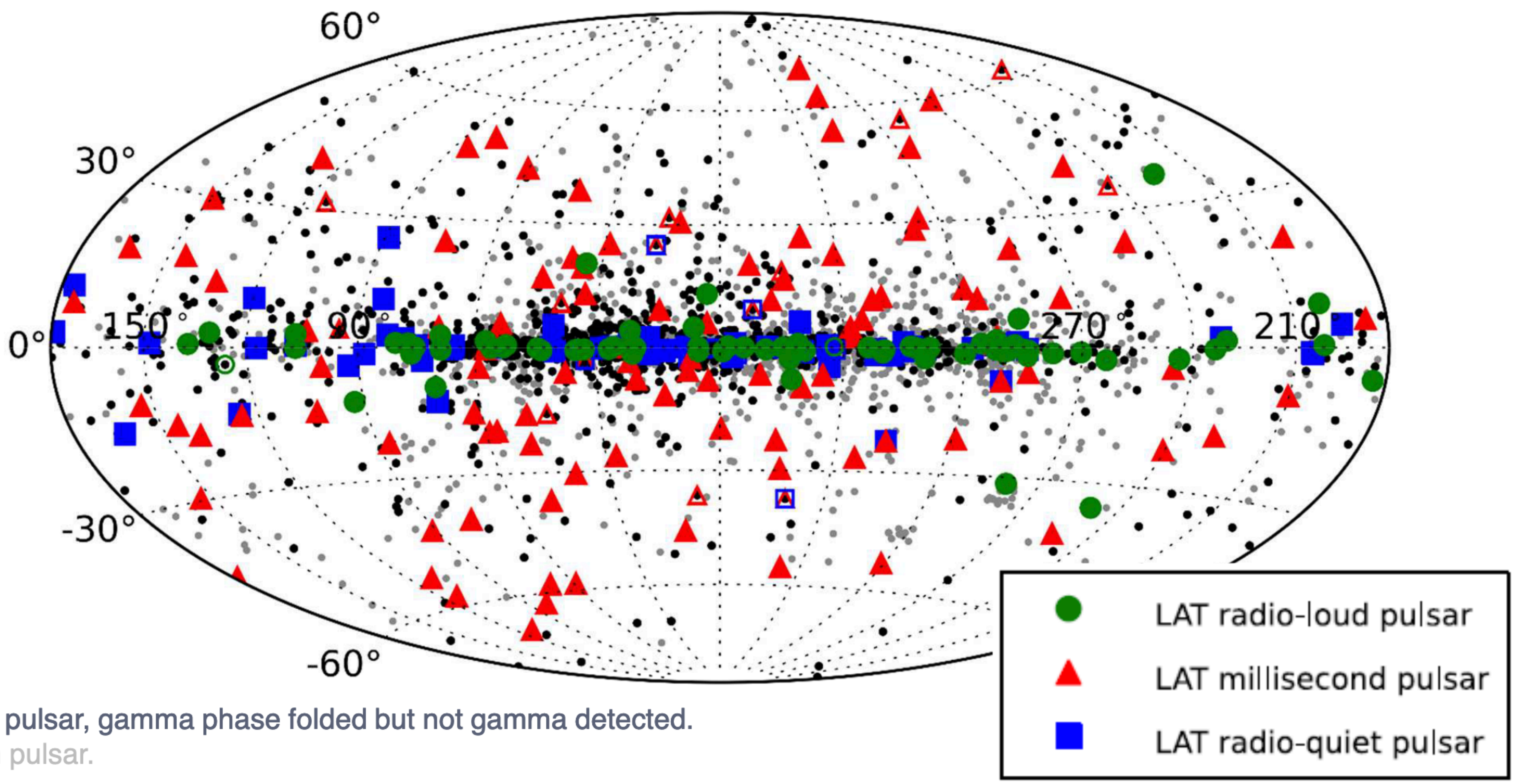


CRs accelerators - leptonic accelerators

Pulsars and Compact Objects

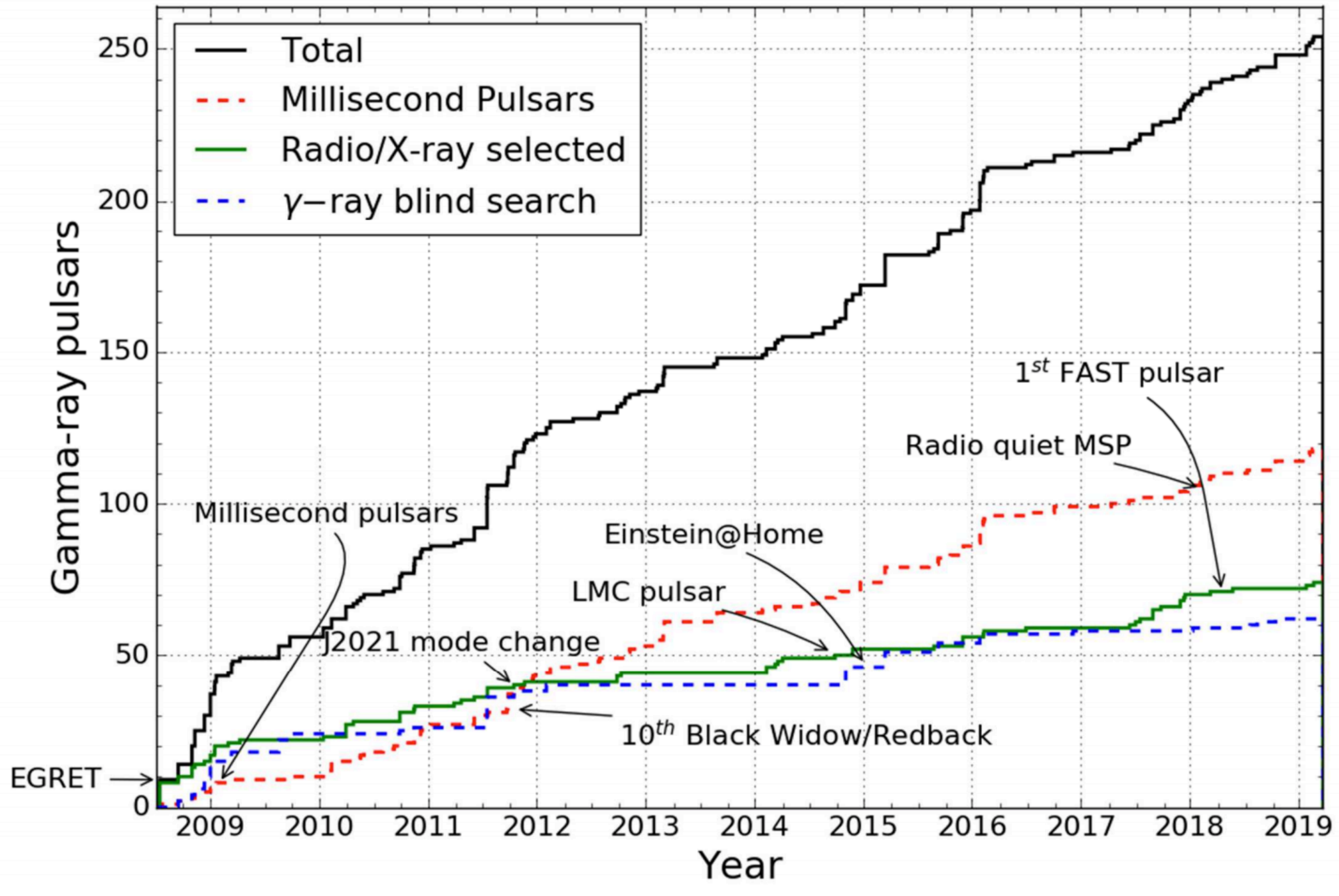


Compact objects: GeV and TeV Pulsars



• known pulsar, gamma phase folded but not gamma detected.
• known pulsar.

Fermi LAT still detecting ~25 gamma pulsars per year.



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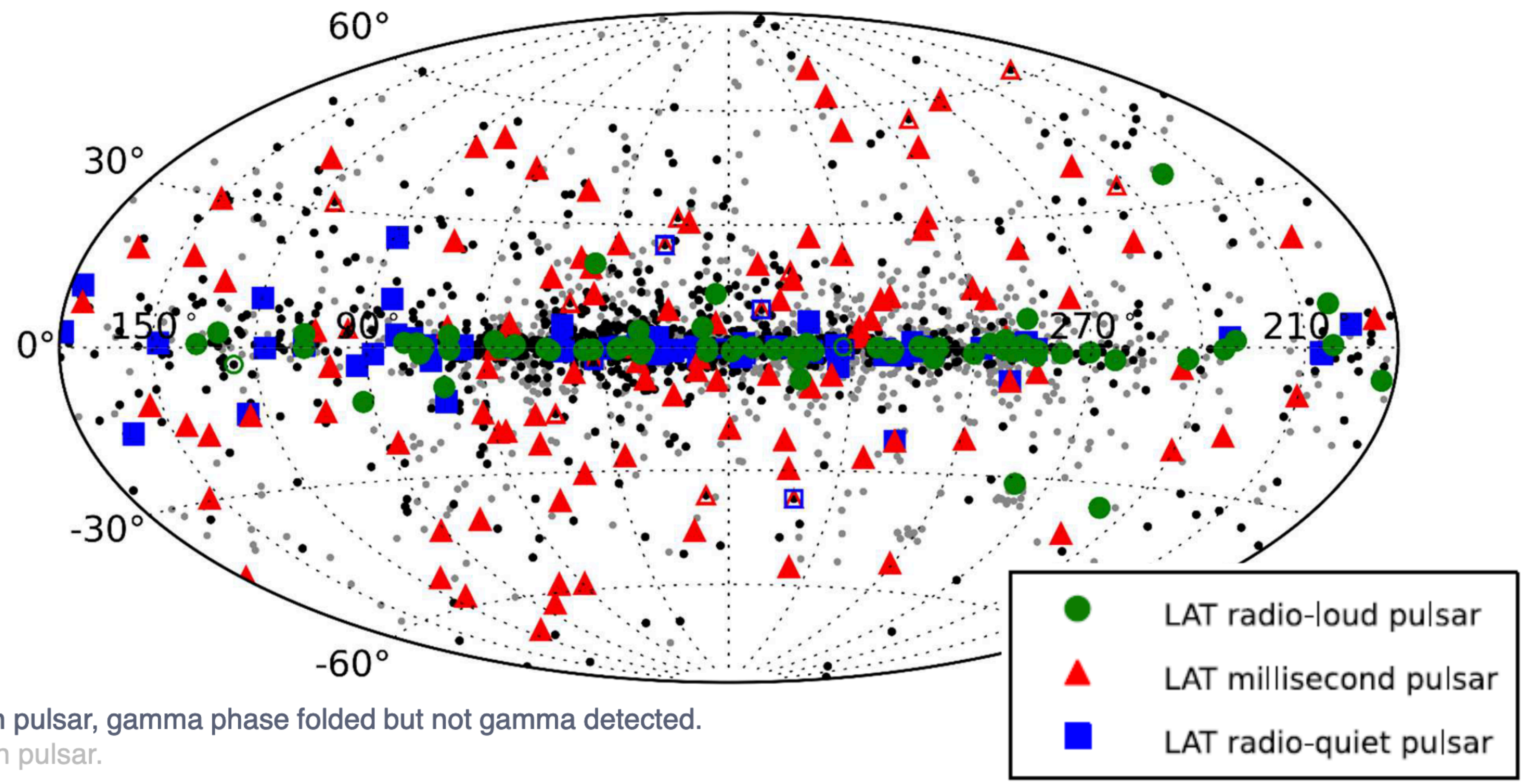

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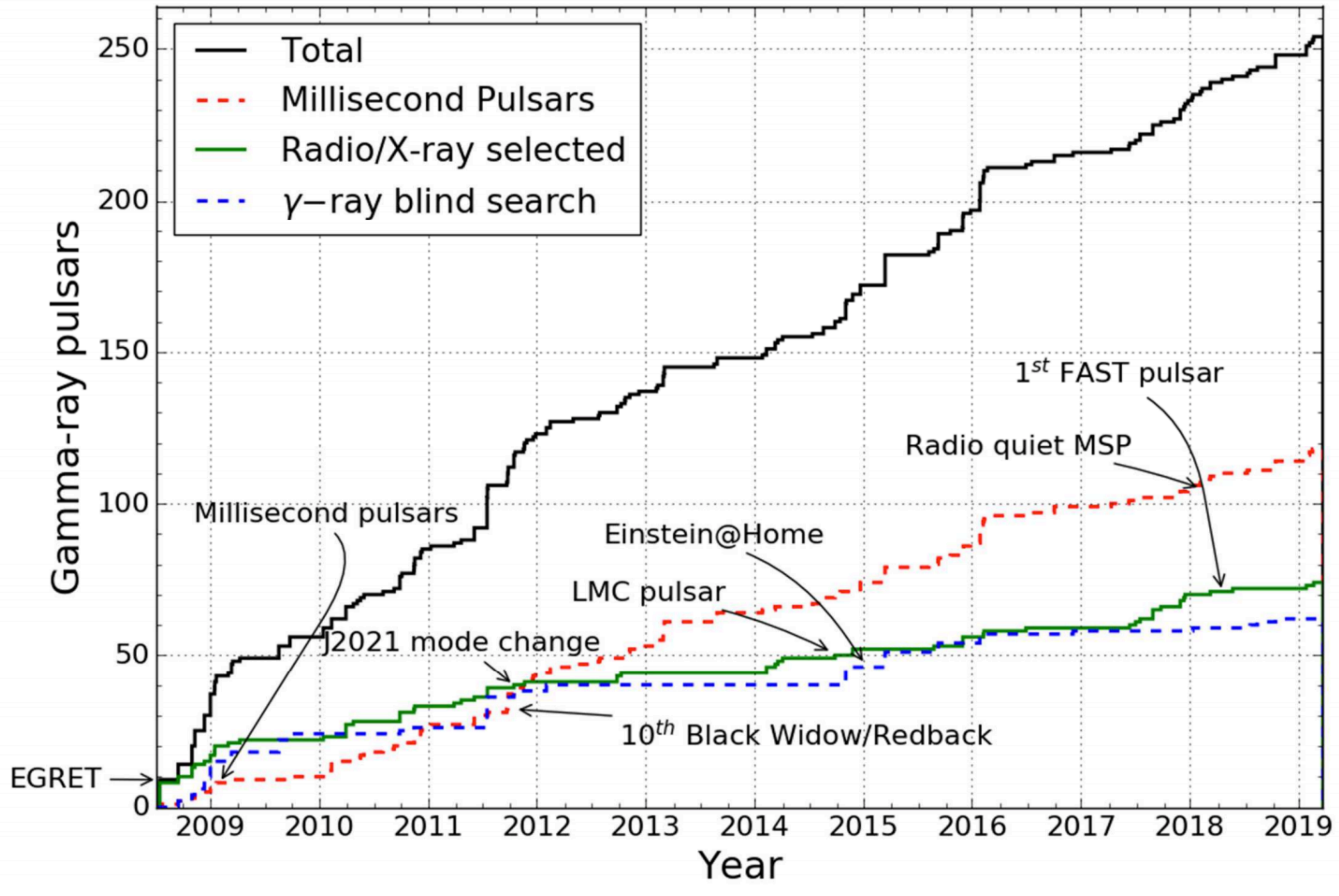


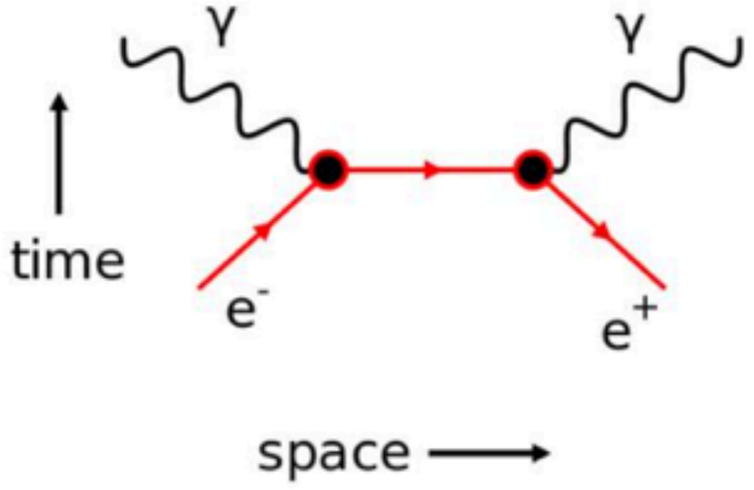
How do we identify pulsars?

High energy radiation from pulsars

Radiation mechanisms

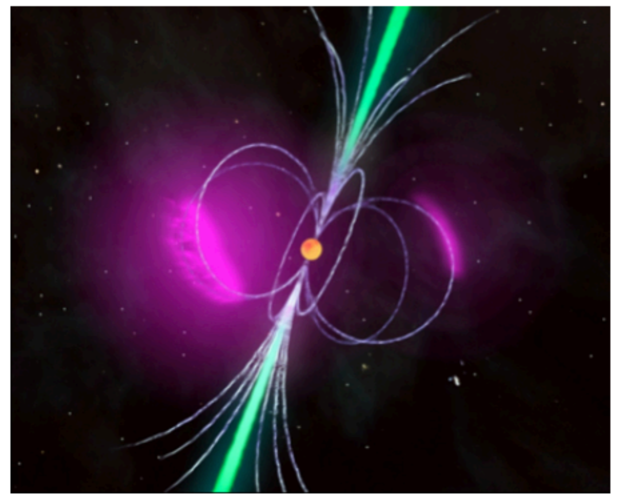
Energy source

Acceleration mechanism

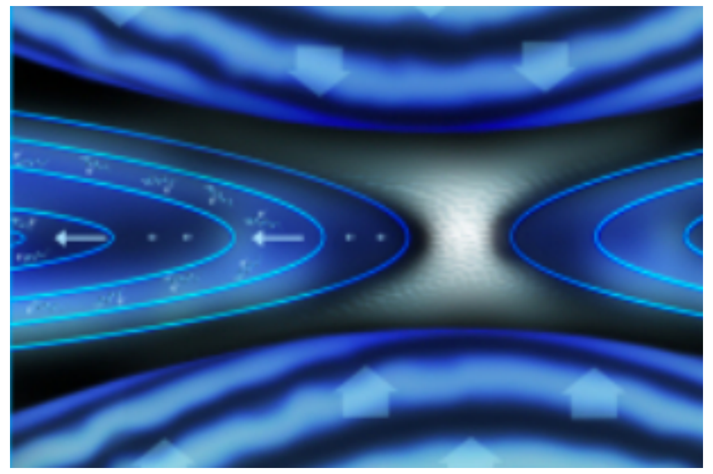


γ-ray production mechanism

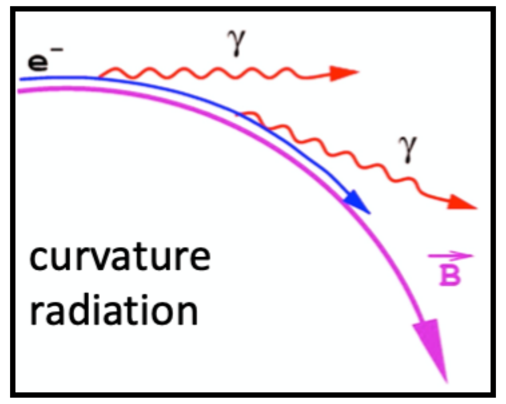
γ rays

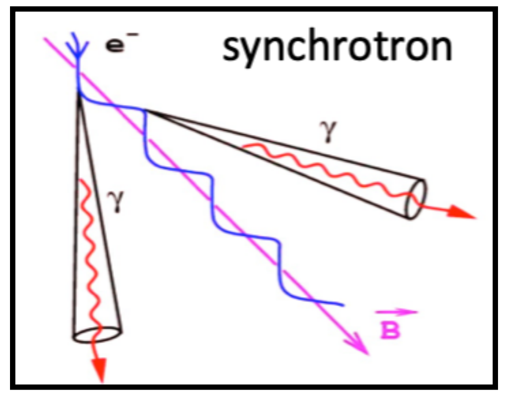


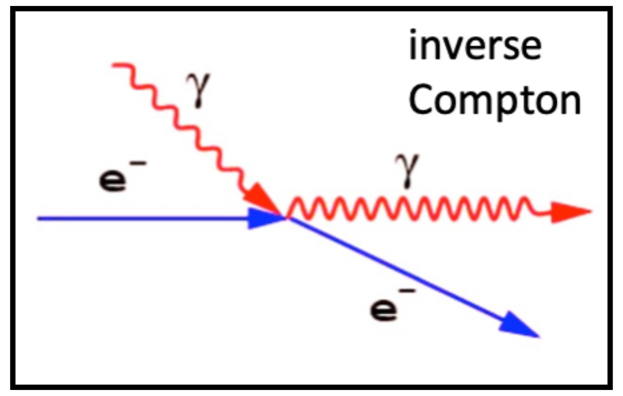
Pulsars

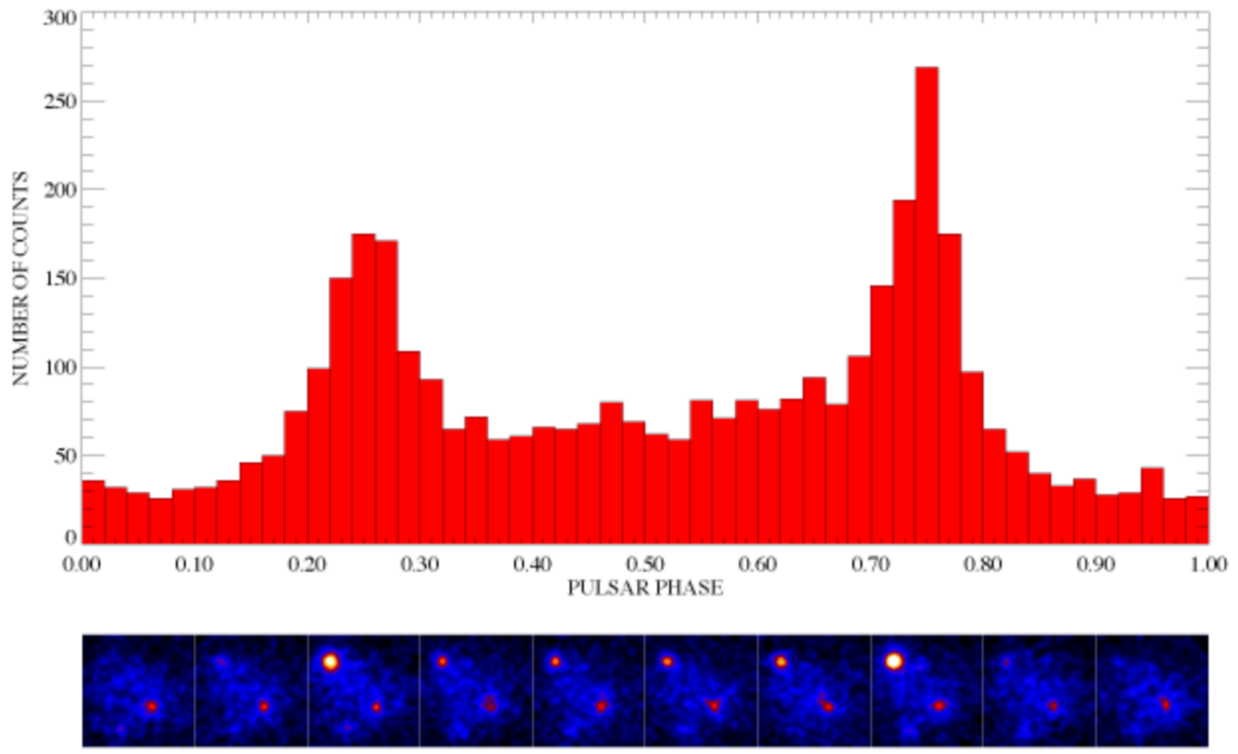


Rotating B-field
Magnetic reconnection
Poynting fluxes



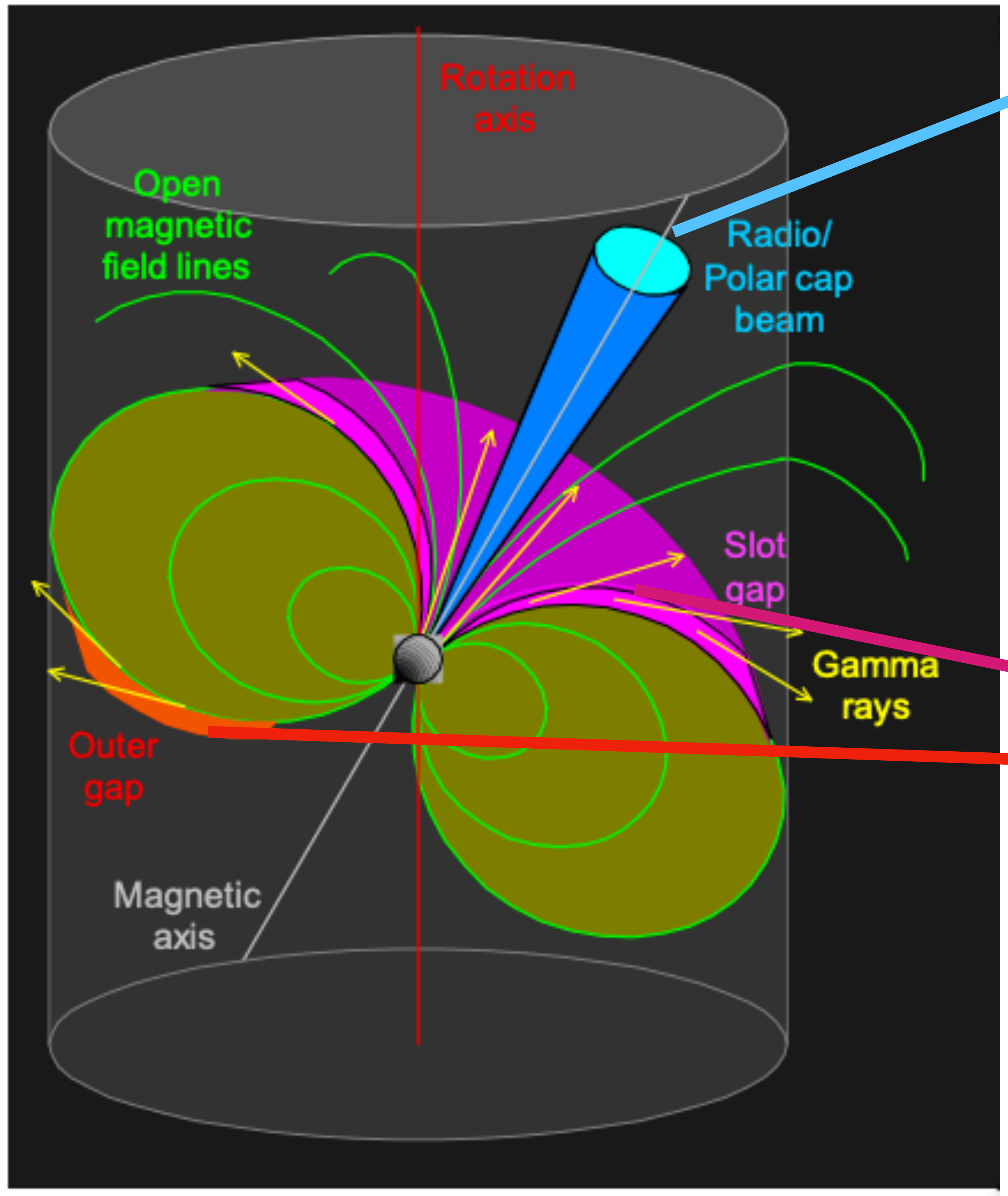






High energy radiation from pulsars

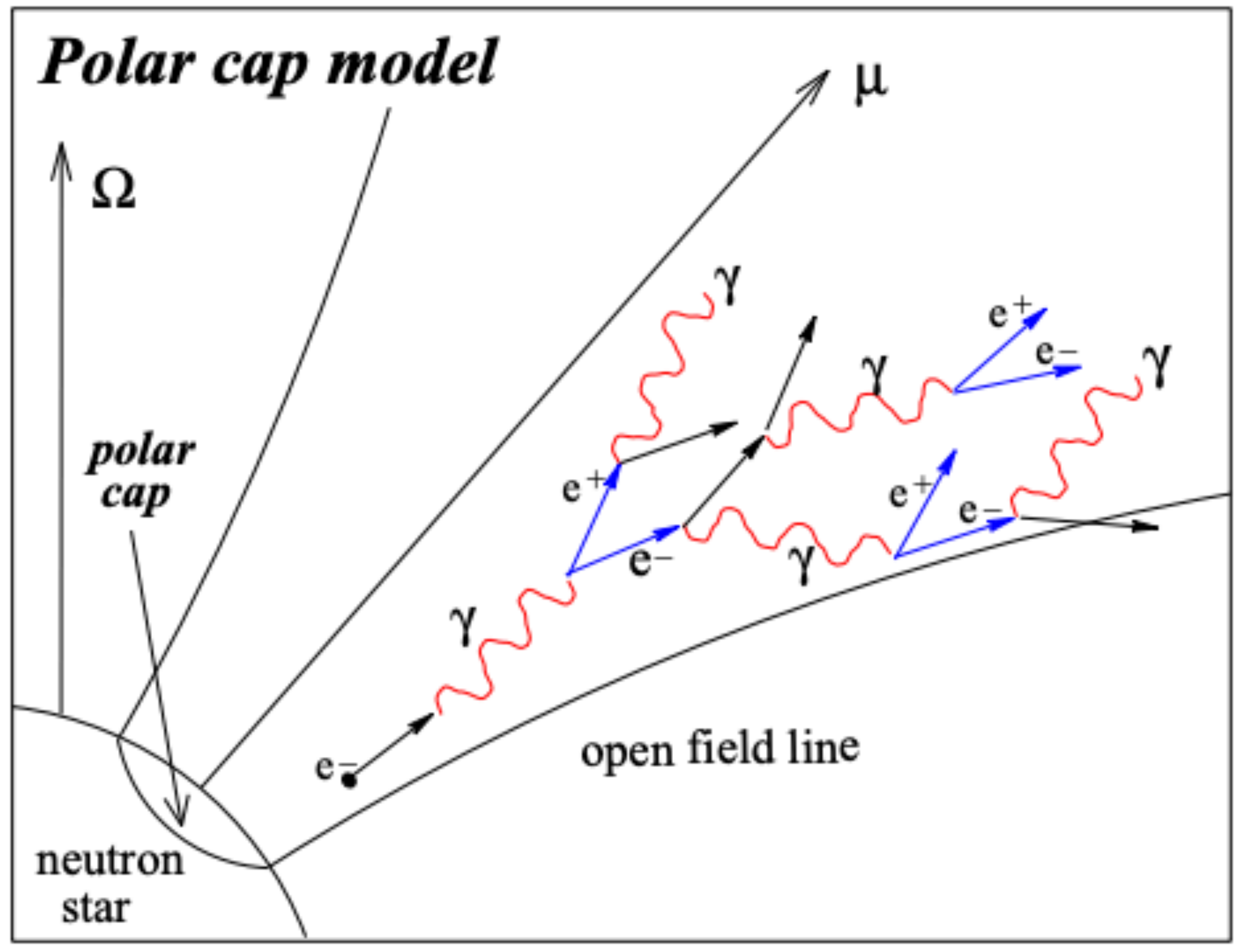
What have we learnt?

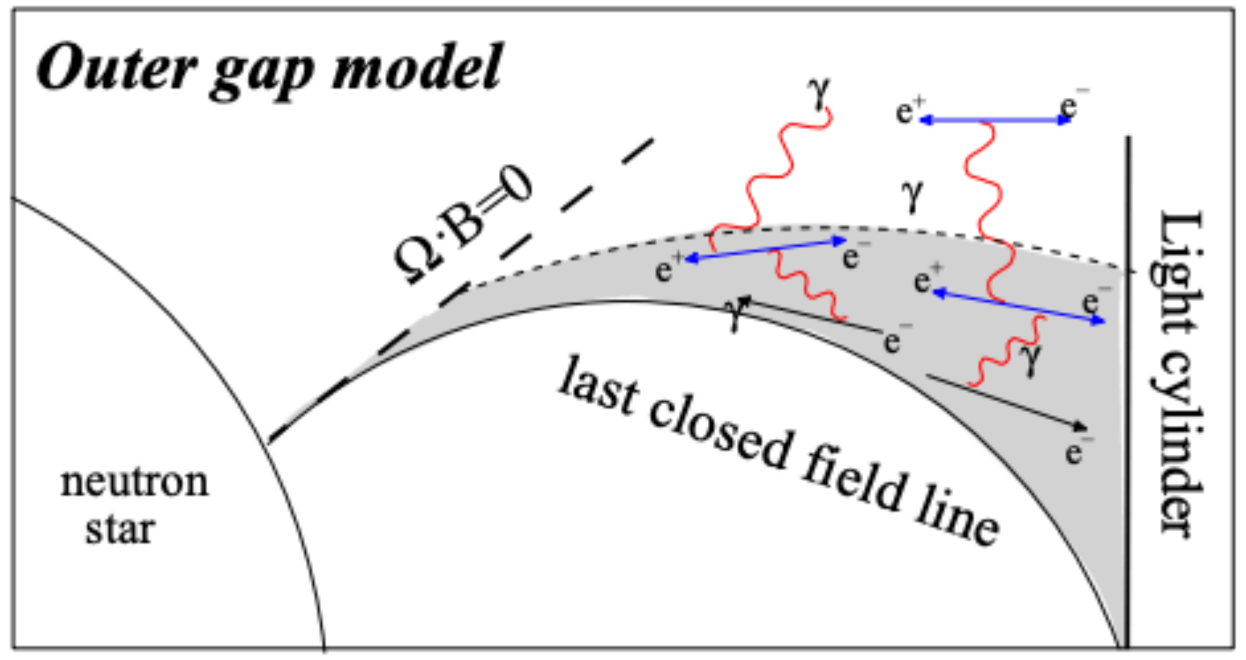


[Many !]

Super-exponential cutoff (magnetic absorption)

Exponential cutoff (photon-photon absorption)





DESY.

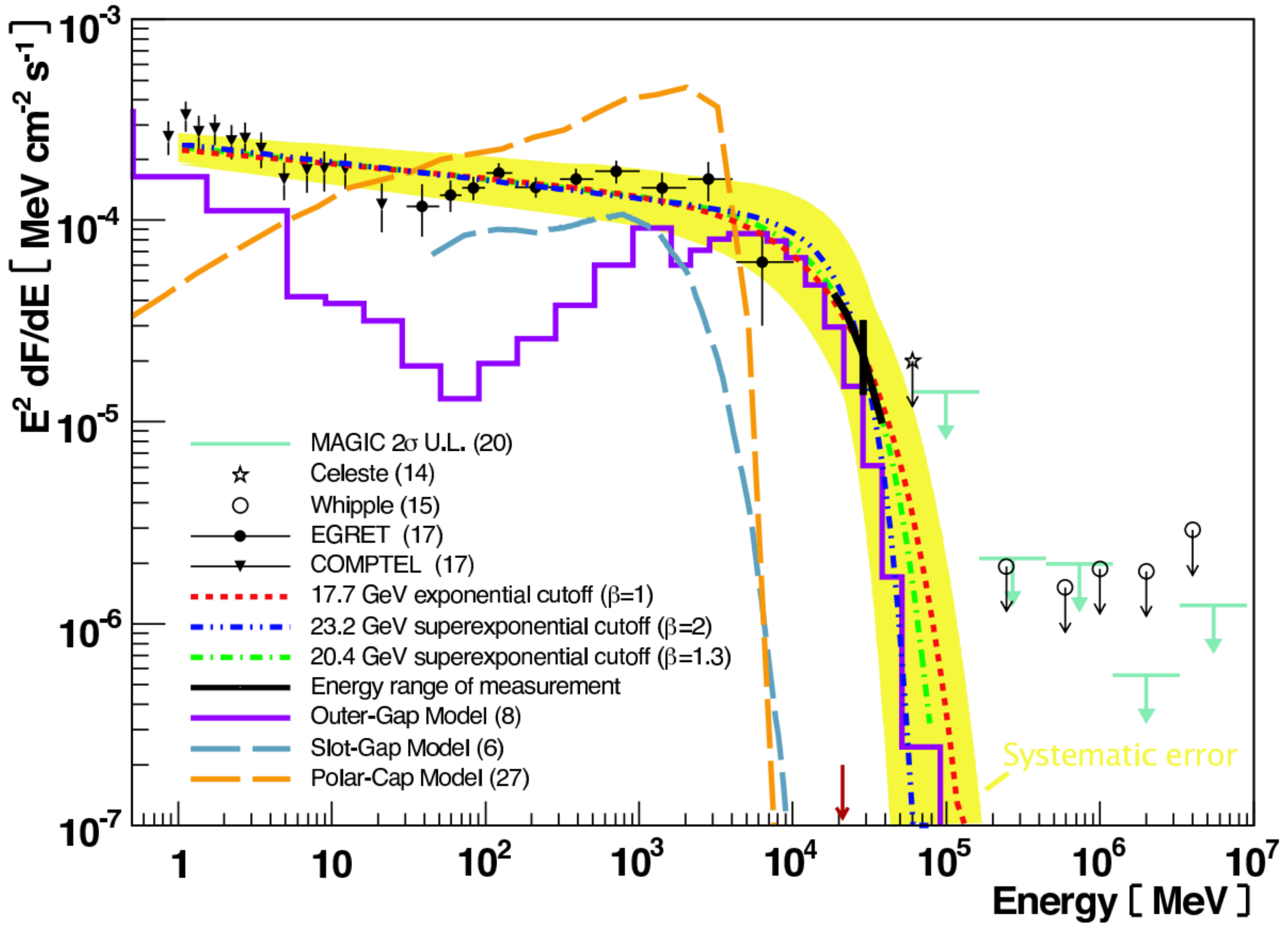
High energy radiation from pulsars

What have we learnt?

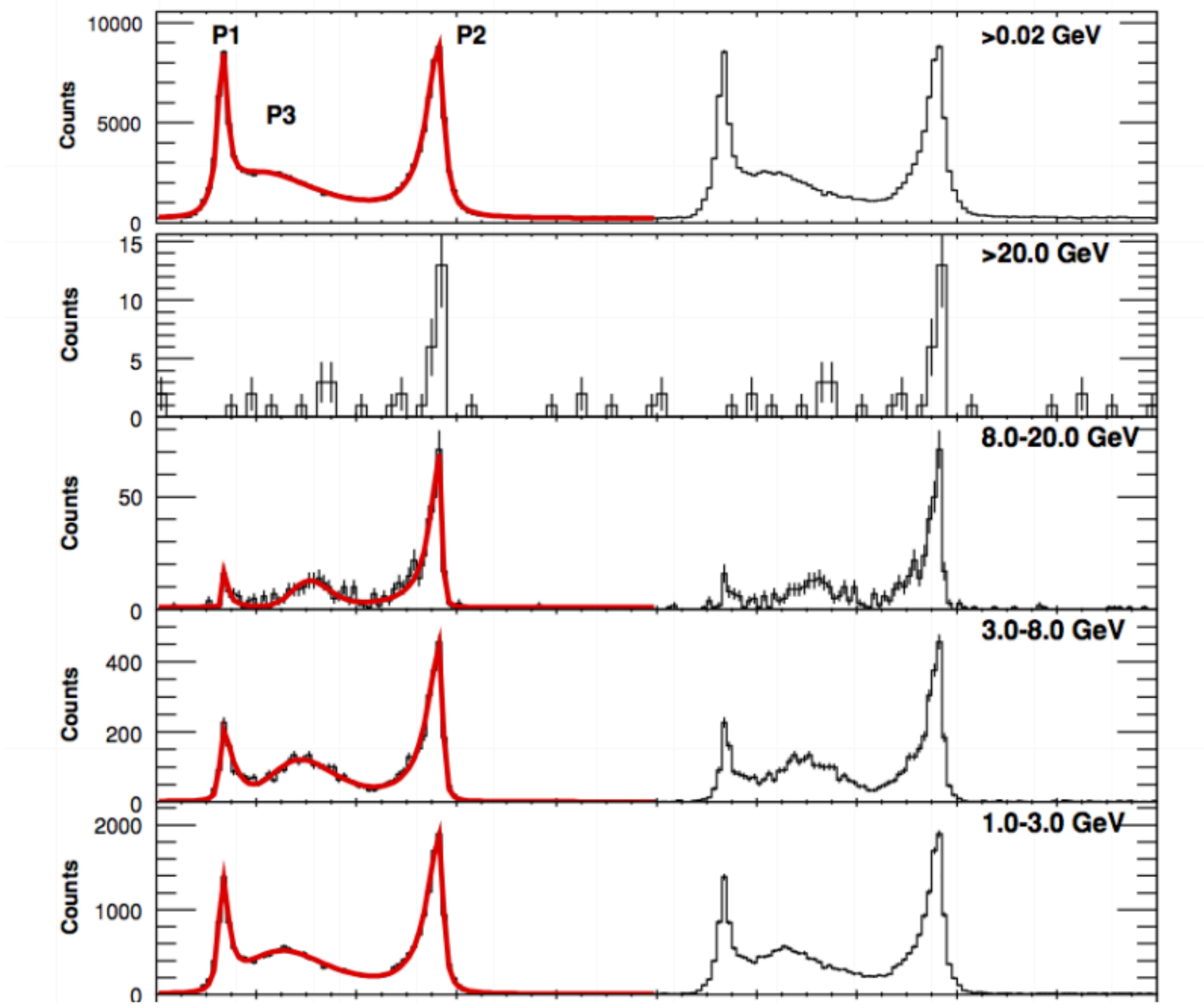
- Not super-exponential
- Not large differences for different magnetic fields

=> Up in the magnetosphere

MAGIC Collaboration 2008

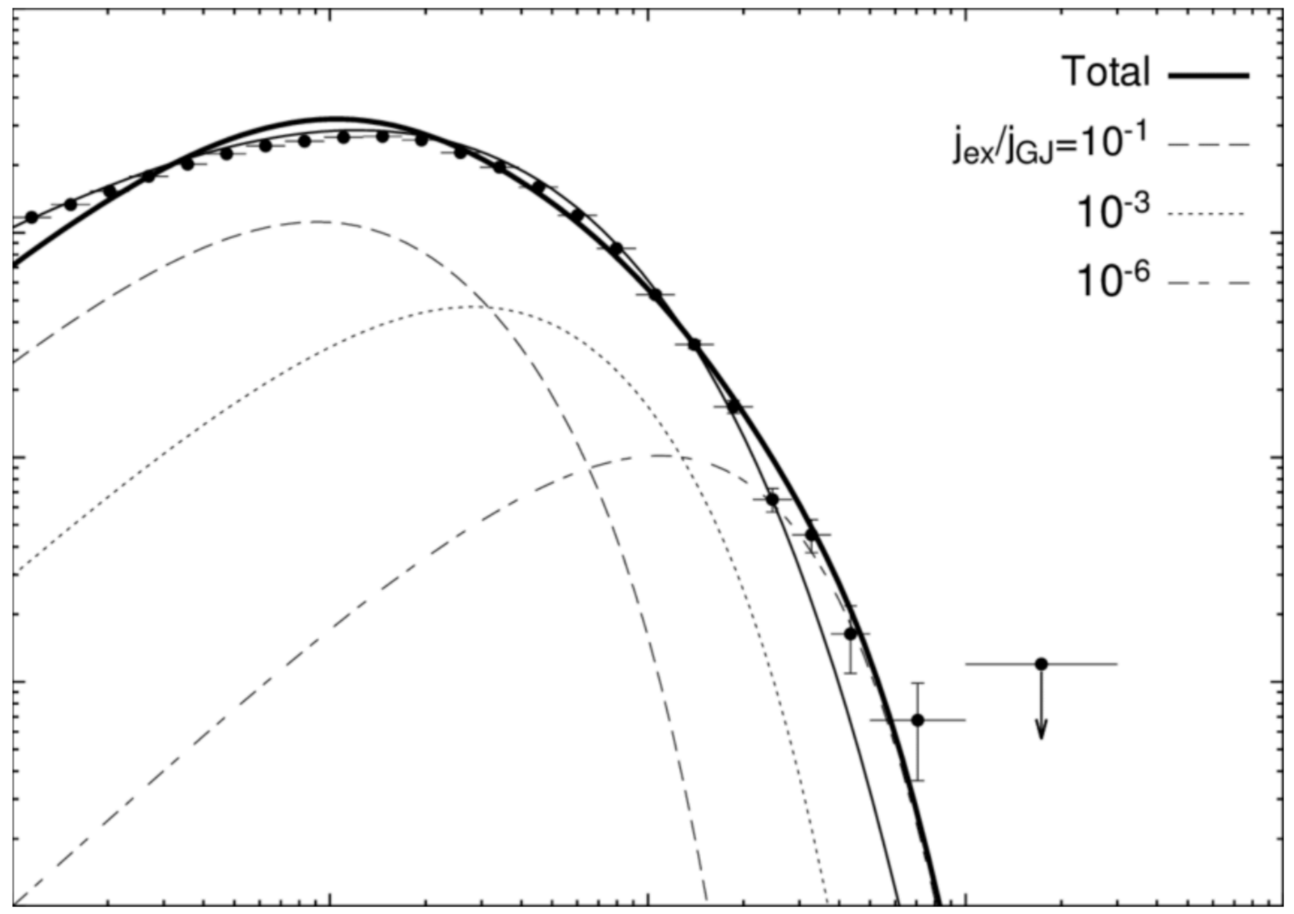


- Evolution of the peaks
  => *Caustic* of different size?



LAT Collaboration 2008

- Deficit at <1 GeV when assuming pure curvature radiation
  => synchrotron contribution?



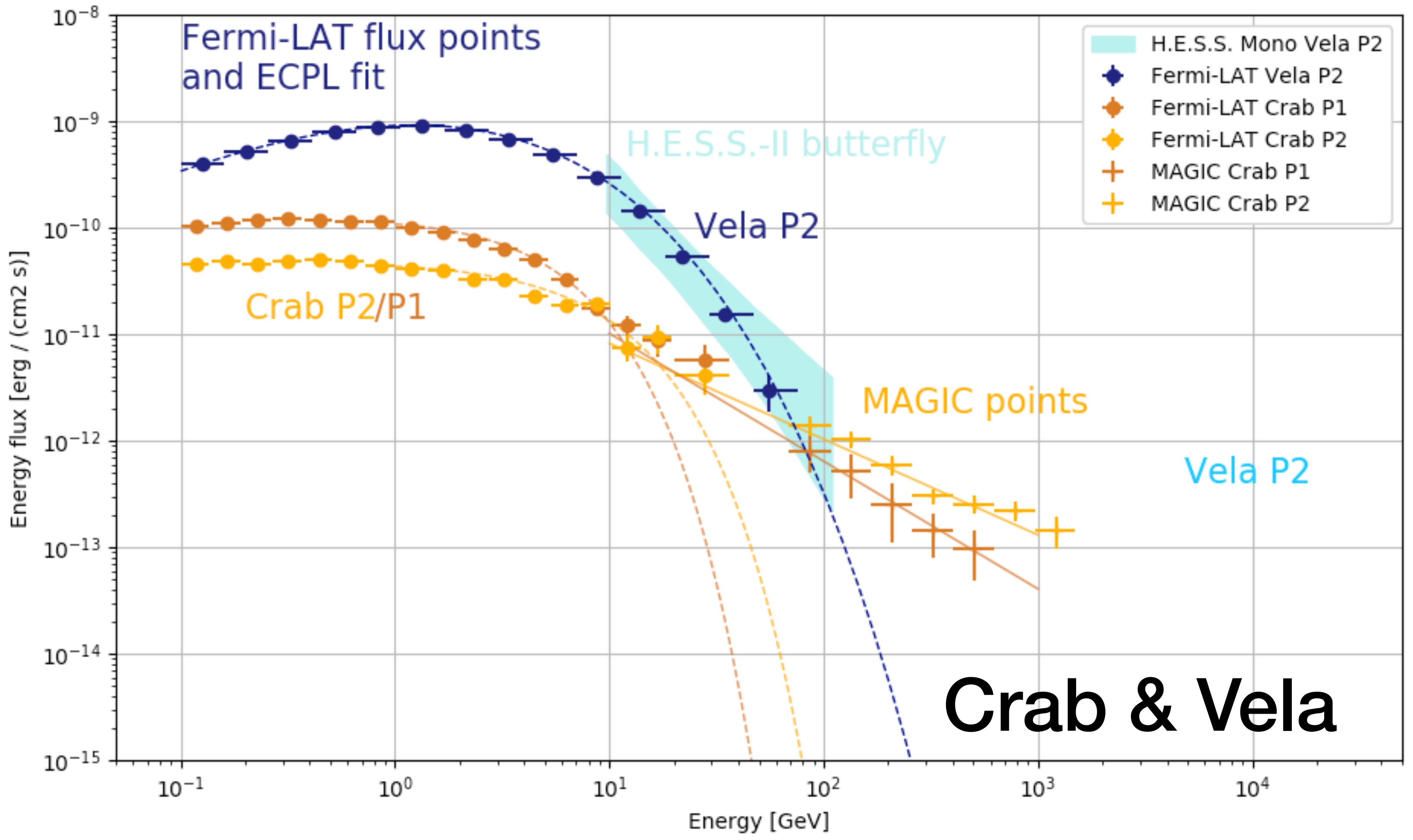
Leung et al 2014

and much more about LCs and transitional behaviour…

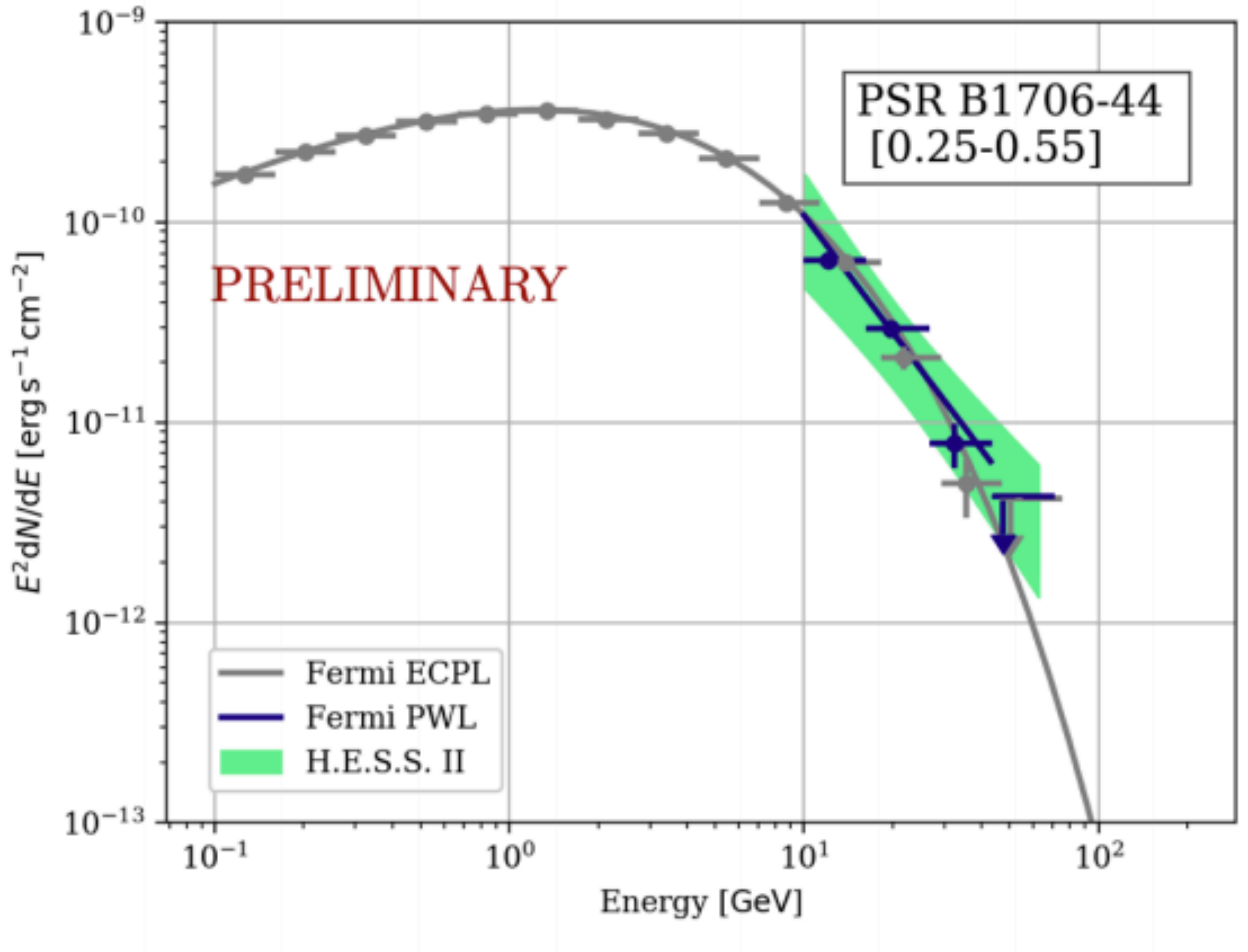
High energy radiation from pulsars

Surprises at TeV energies

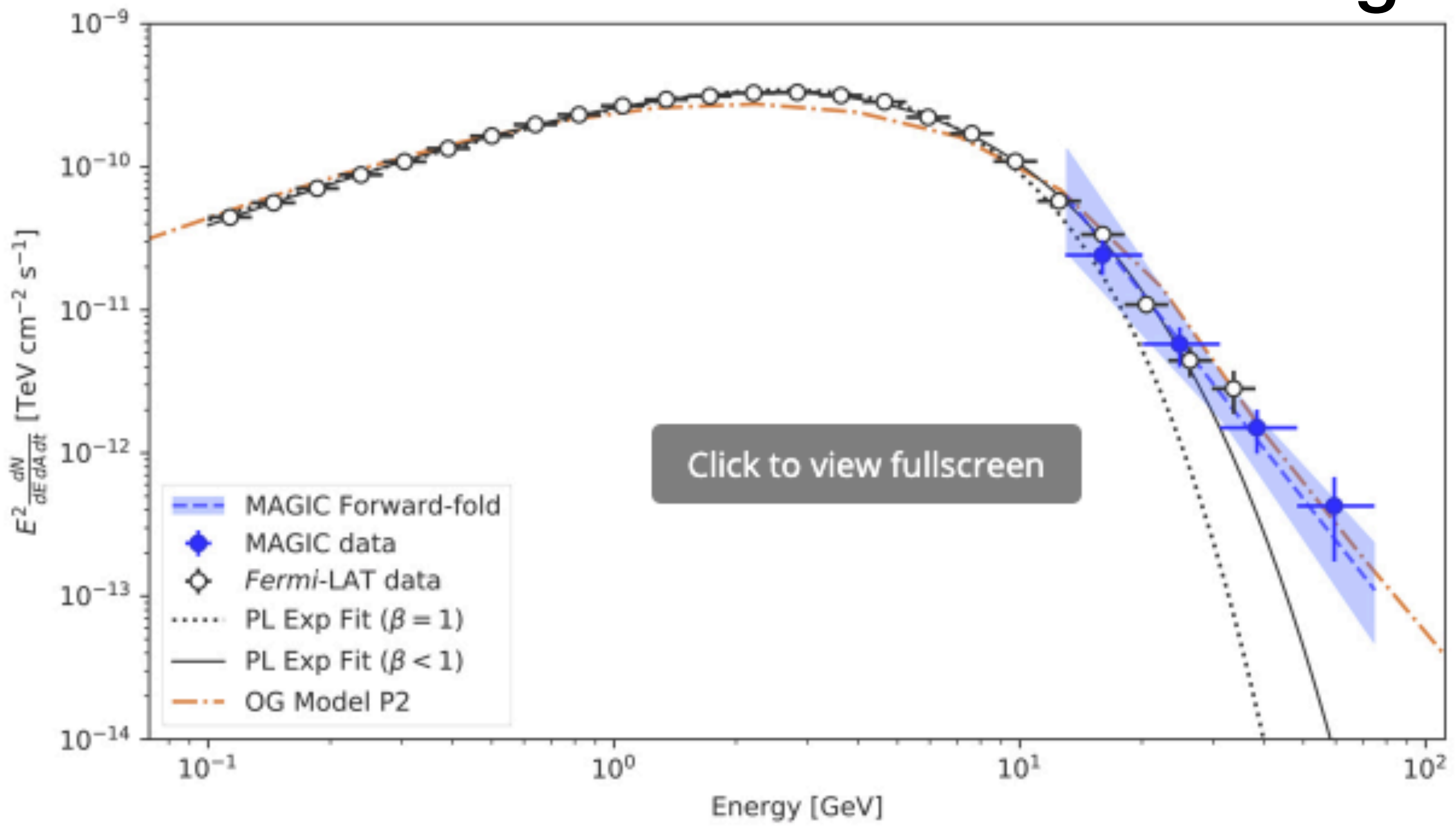
- A number of bright pulsars detected in the TeV regime



PSR B1706-44



Geminga



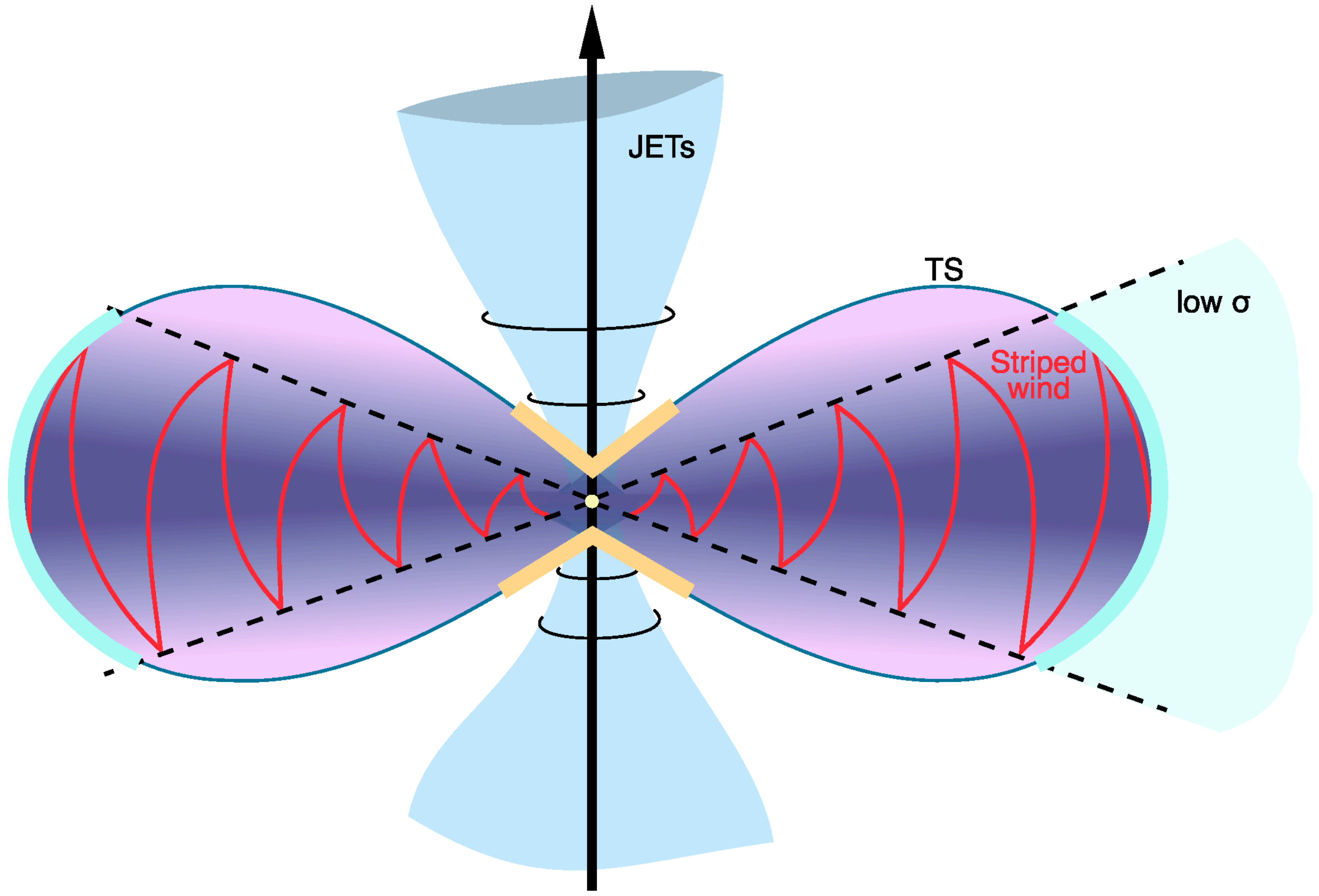
Young, bright GeV pulsar (~10^3 yrs)
High magnetic field (~$5x10^{6-9}$ G @ LC)
Large low-energy photon field (FIR)
Simultaneous light curve across the em spectrum

Old, bright GeV pulsar (~10^4 yrs)
Low(er) magnetic field (~$5x10^5$ G @LC)
Large low-energy photon field (FIR)

High energy radiation from pulsars

Surprises at TeV energies

- A number of bright pulsars detected in the TeV regime
  - Where is the emission produced?
  - How much can pulsars accelerate?



DESY.

High energy radiation from pulsars

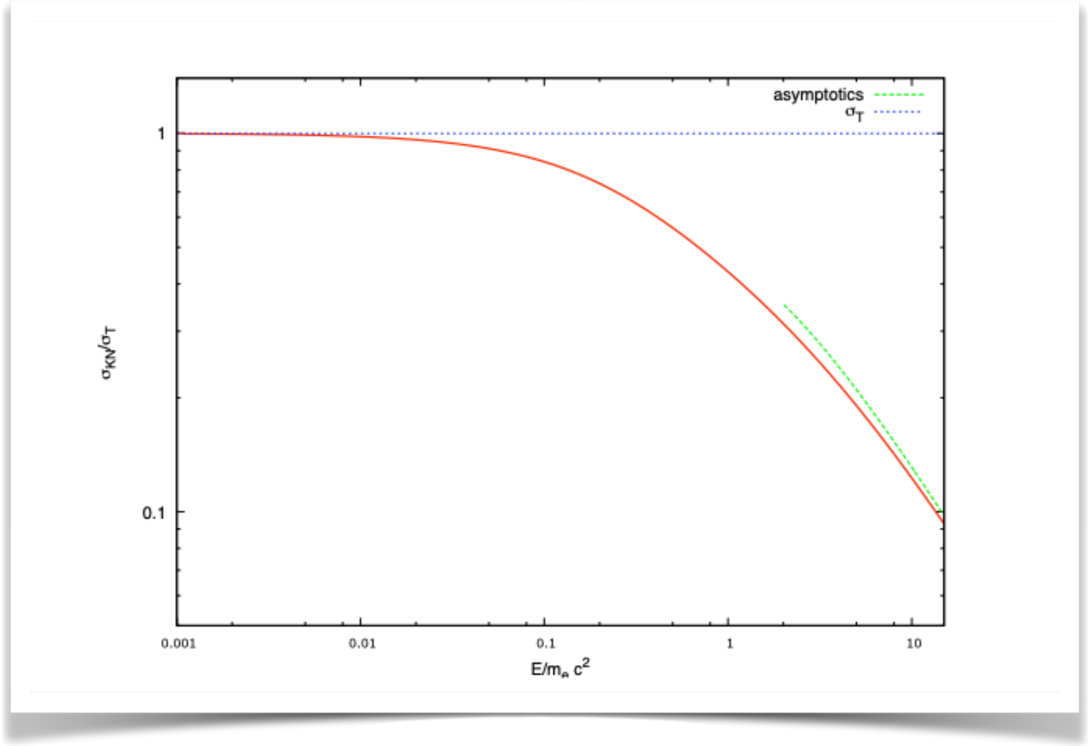
Is there any common trend?

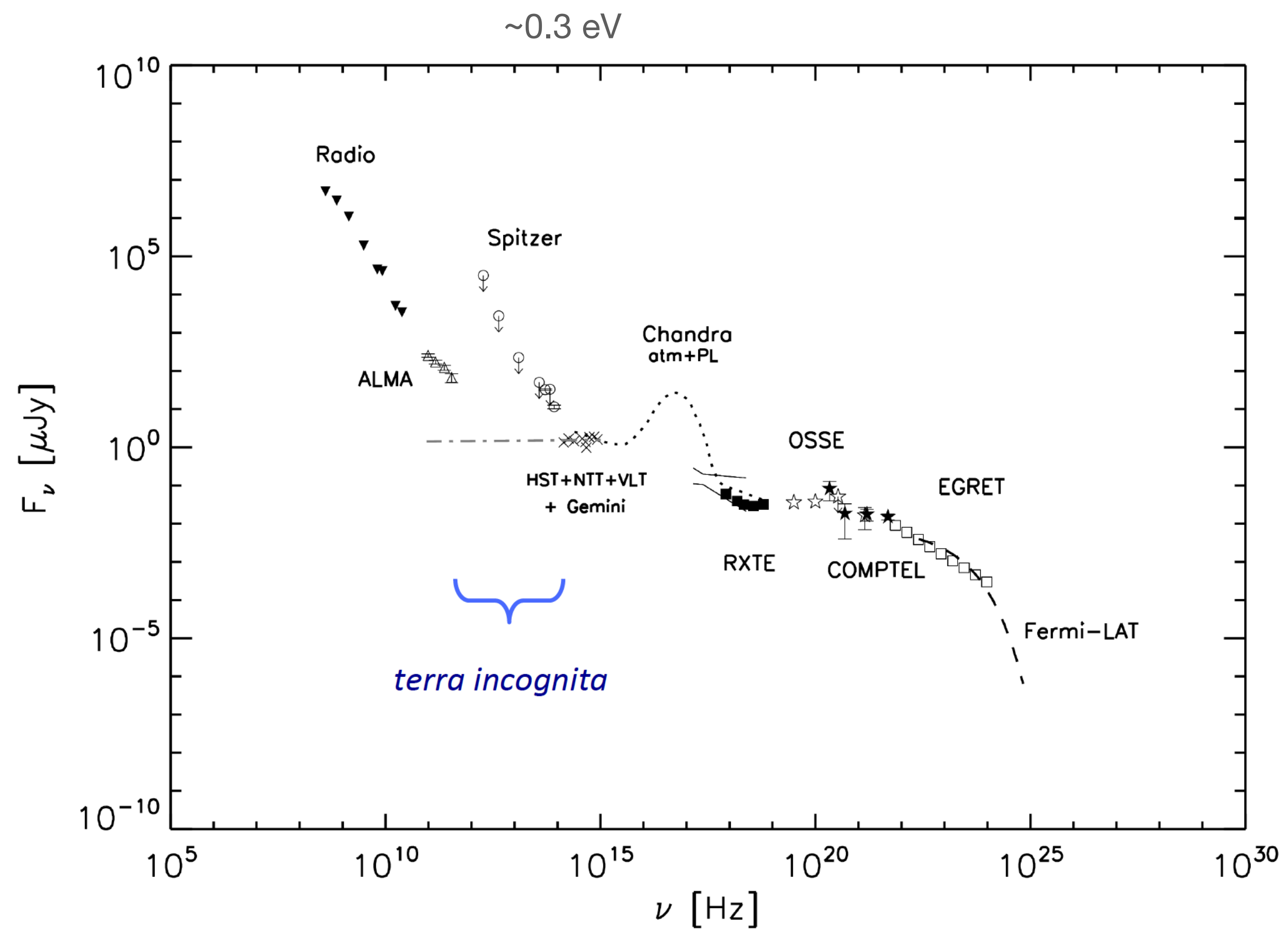
- The light curve in the GeV and TeV agree and we observe the same tendency (i.e. peak ratio, width evolution)
  => Same electron (e±) population
- Sizeable low energy photon fields
  => susceptible of being up-scattered to high energies
- The exponential cutoff seems to be favoured
  => A clear second component = Inverse Compton on soft photon fields

High energy radiation from pulsars

Is there any common trend?

- The light curve in the GeV and TeV agree and we observe the same tendency (i.e. peak ratio, width evolution)
  => Same electron (e±) population
- Sizeable low energy photon fields
  => susceptible of being up-scattered to high energies
- The exponential cutoff seems to be favoured
  => A clear second component = Inverse Compton on soft photon fields





- Inverse Compton in Thomson regime if b<<1
  $b \approx 15\, E_{e,TeV} E_{target\_ph,eV}$
  => Klein-Nishina regime dominant (1-20 TeV)

  Two implications for the electron spectrum
  $E = \Gamma m_e c^2$

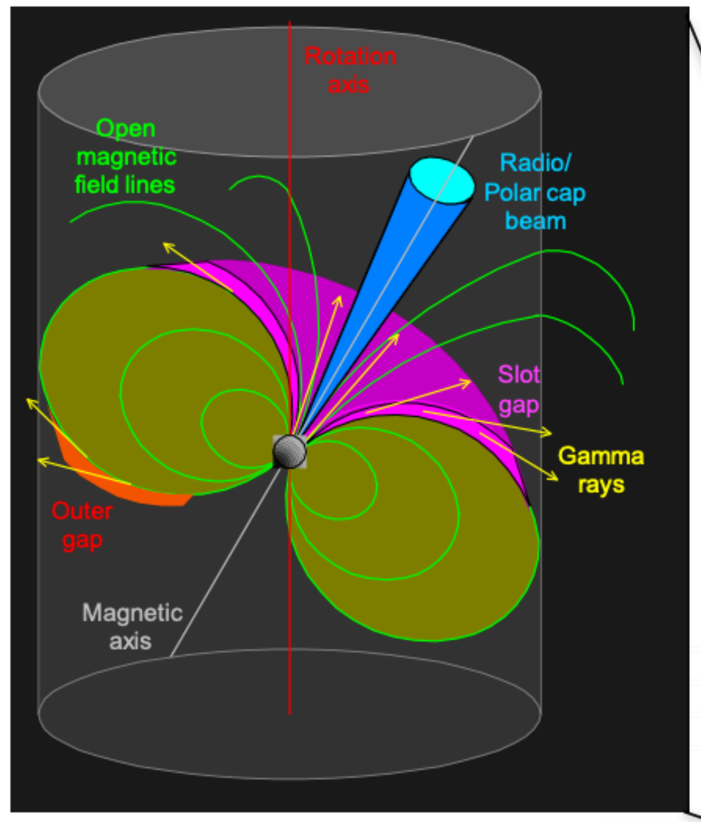
  => $\Gamma = 4 \times 10^7$ (20 TeV)
  => $\Gamma = 2 \times 10^6$ (TeV)

High energy radiation from pulsars

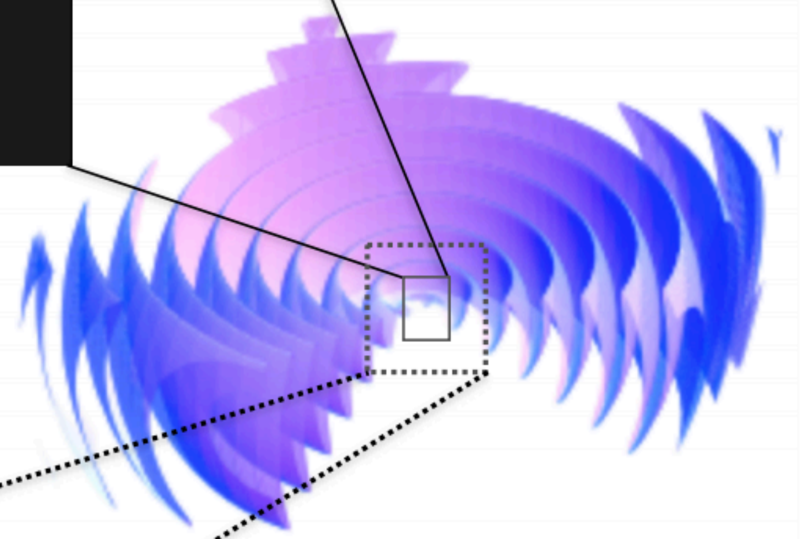
The underlying electron population

- Inverse Compton: only depends on the photon field (known) and electron population
- Same electron population produces GeV (same light curve)
- GeV emission can be attributed to:

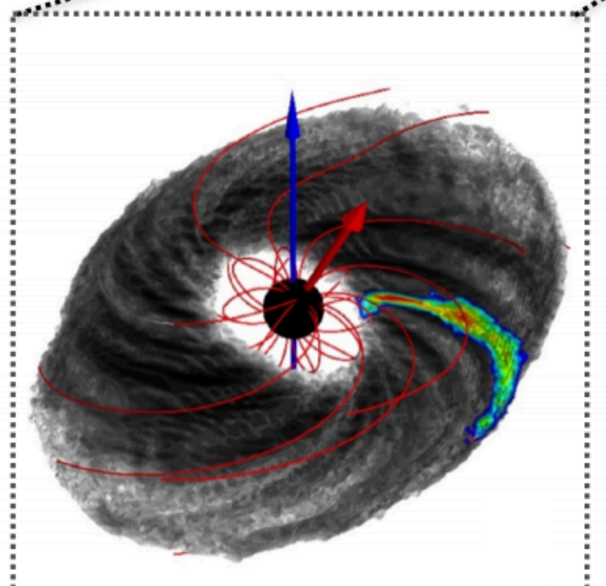
Curvature radiation (CR)
Synchrotron emission (SYN)
non-ideal MHD plasma to go beyond ~160 MeV!



[Many !]



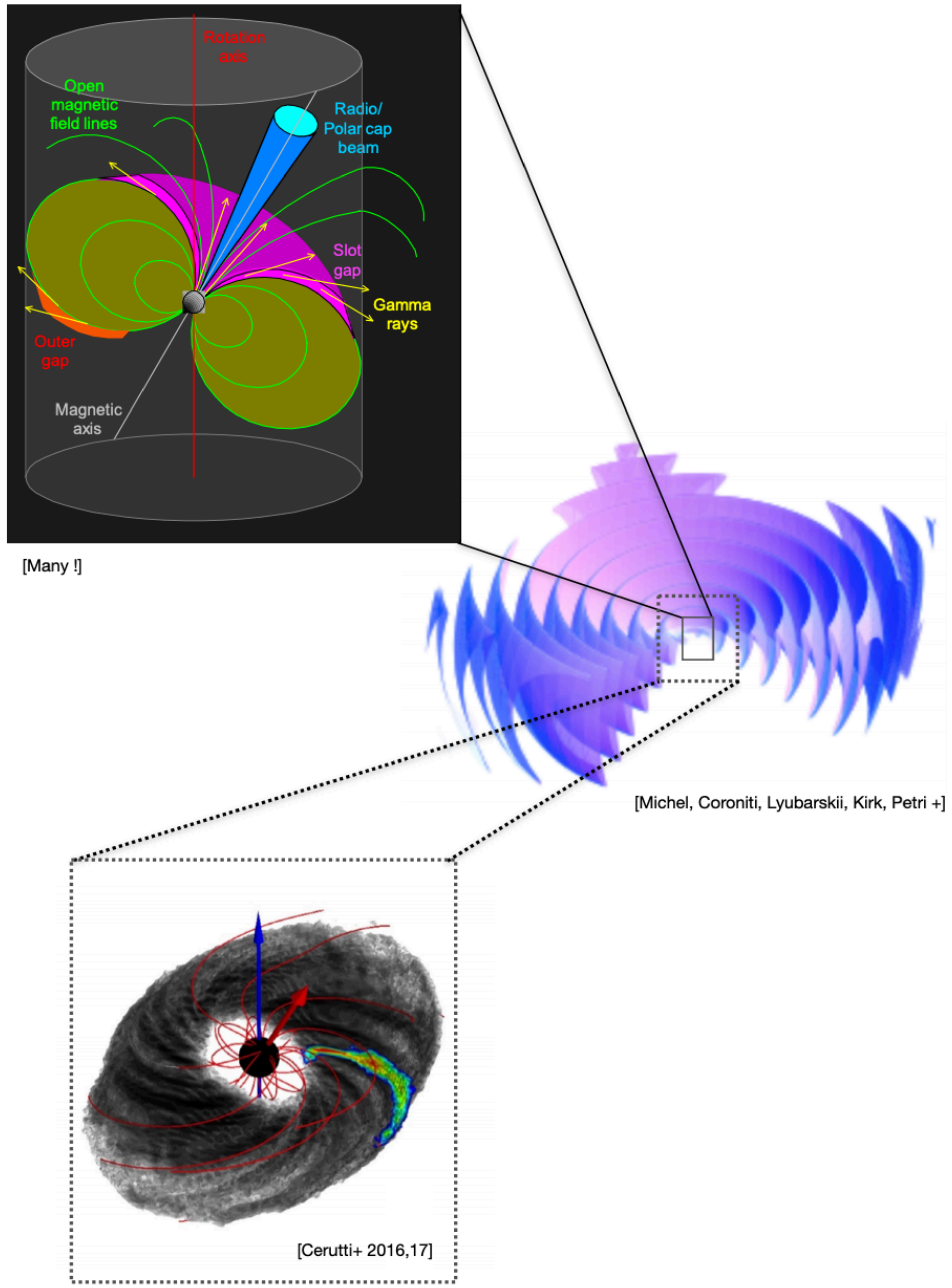
[Michel, Coroniti, Lyubarskii, Kirk, Petri +]



[Cerutti+ 2016,17]

High energy radiation from pulsars
magnetospheric models

- Within the magnetosphere (or rather within the gaps):
  Electrons are accelerated in gaps through $E_{||} = \eta B$
  HE => CR radiation
  VHE => IC on low-energy photon target



[Many !]

[Michel, Coroniti, Lyubarskii, Kirk, Petri +]

[Cerutti+ 2016,17]

High energy radiation from pulsars

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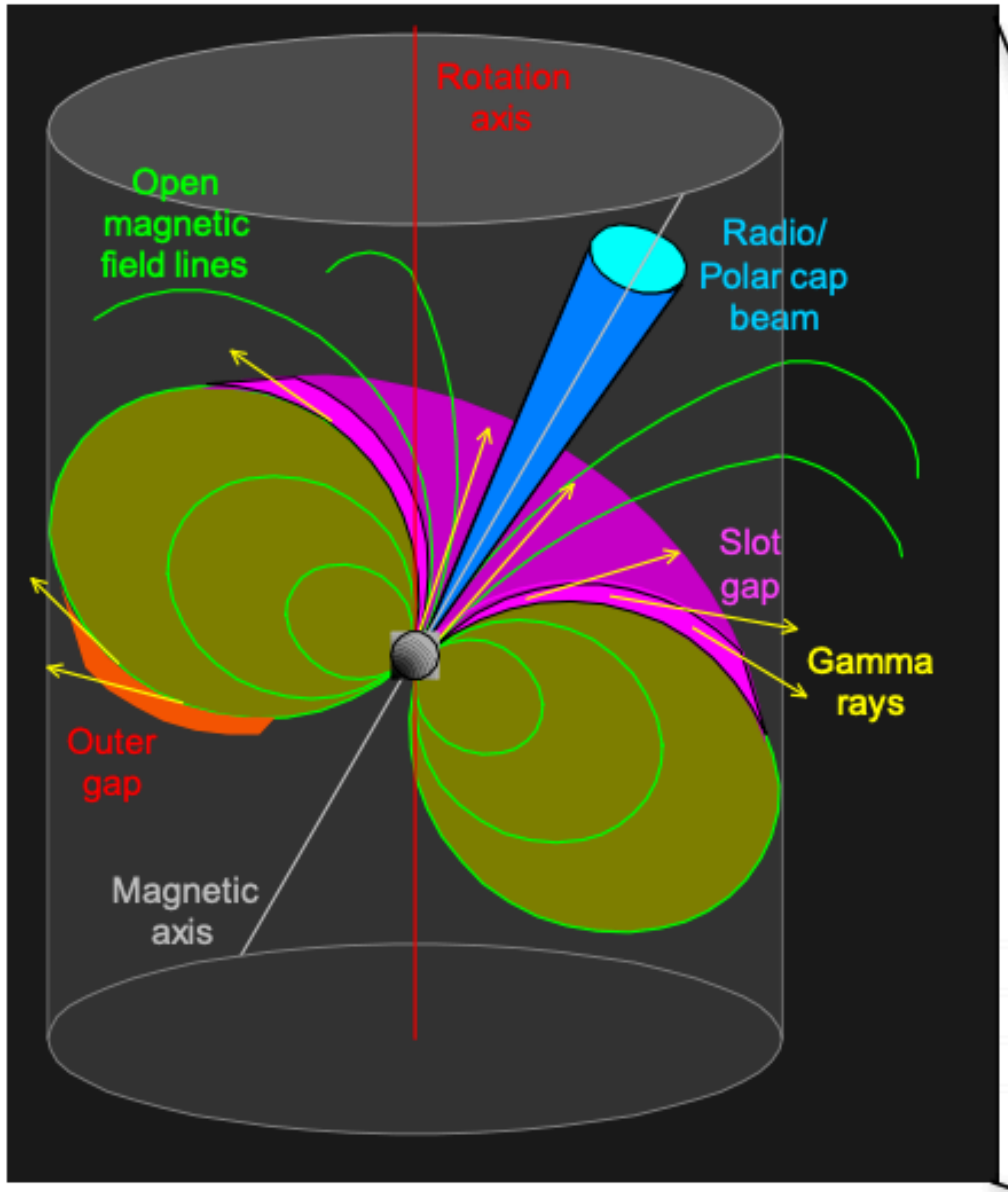

[Many !]

High energy radiation from pulsars

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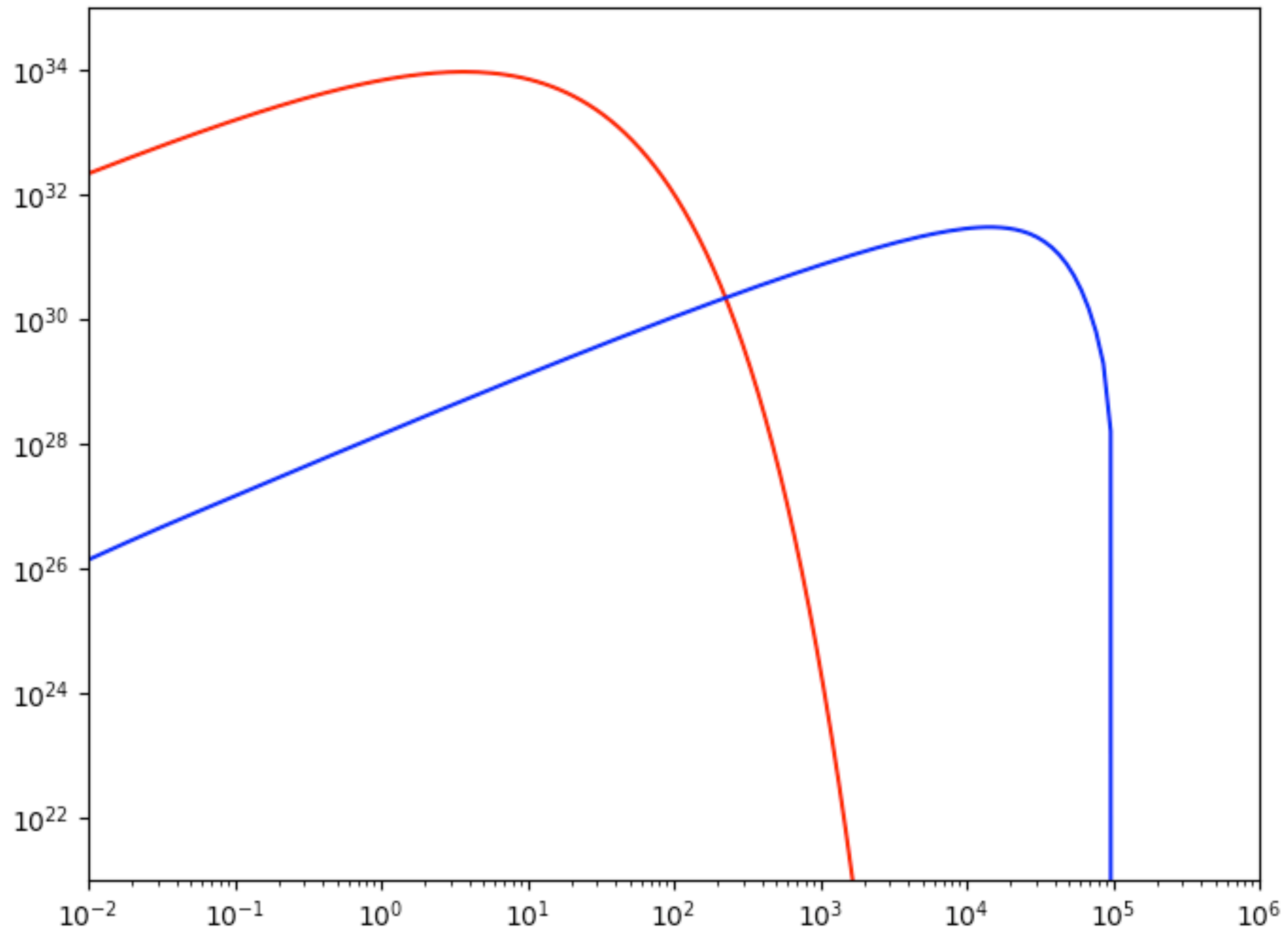

High energy radiation from pulsars

magnetospheric models

- Within the magnetosphere (or rather within the gaps):
  Electrons are accelerated in gaps through $E_{\parallel} = \eta B$
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  VHE => IC on low-energy photon target

$\eta \lessapprox 10\,\%$

gain rates

$$-\frac{dE}{dt} = e\,c\,\eta\,B$$

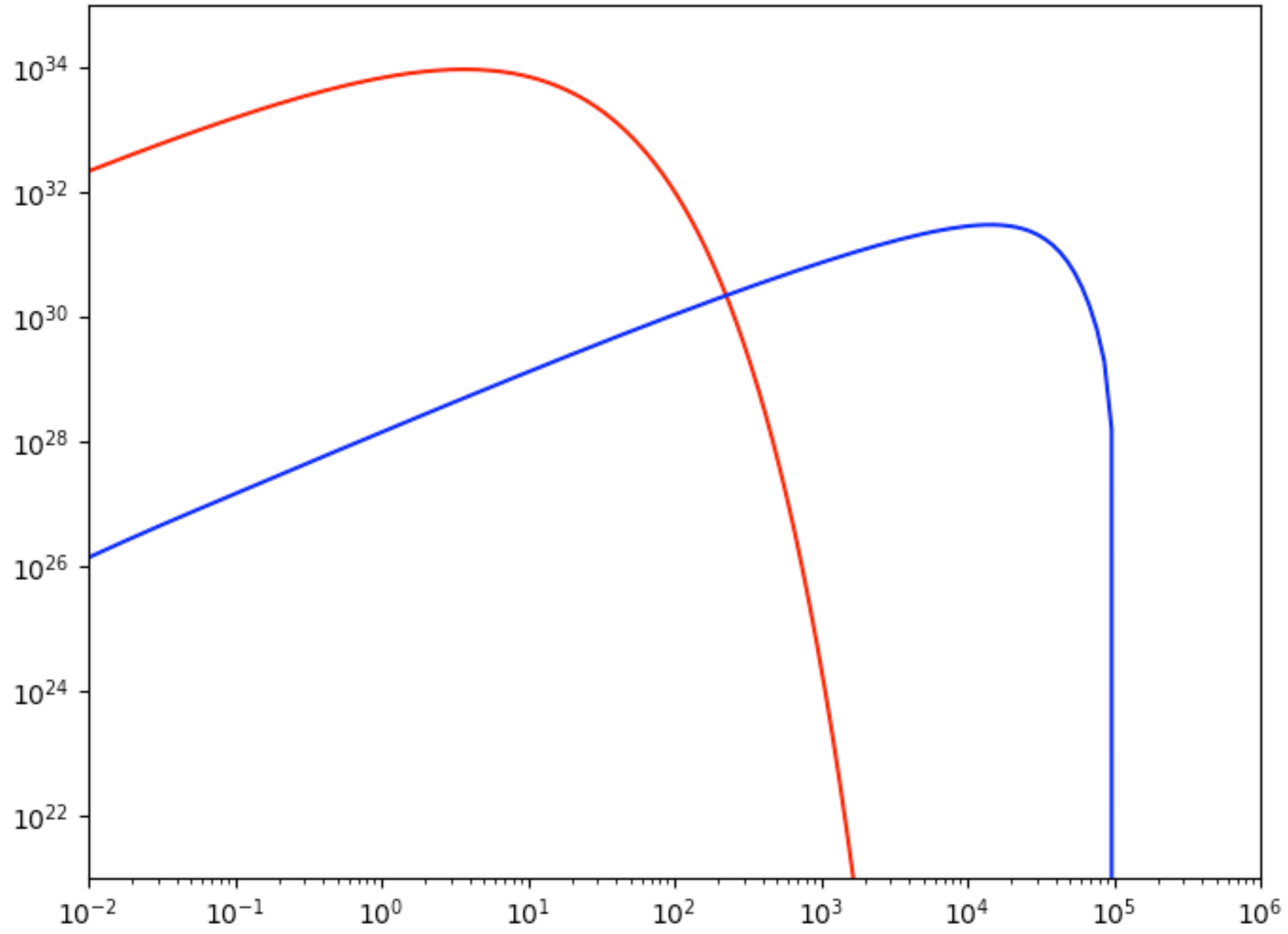
energy loss

$$-\frac{dE}{dt} = \frac{2}{3}\frac{e^2 c}{R_c^2}\Gamma_e^4$$

Using Vela values

$$\Gamma_e \approx 4.2 \times 10^7\,\xi^{1/2}\eta_{-1}^{1/4}$$

$\Gamma_e = 4 \times 10^7$ (20 TeV) from TeV



$R_C = \xi R_{LC} = \xi(cP/2\pi)$ => $\xi > 1$

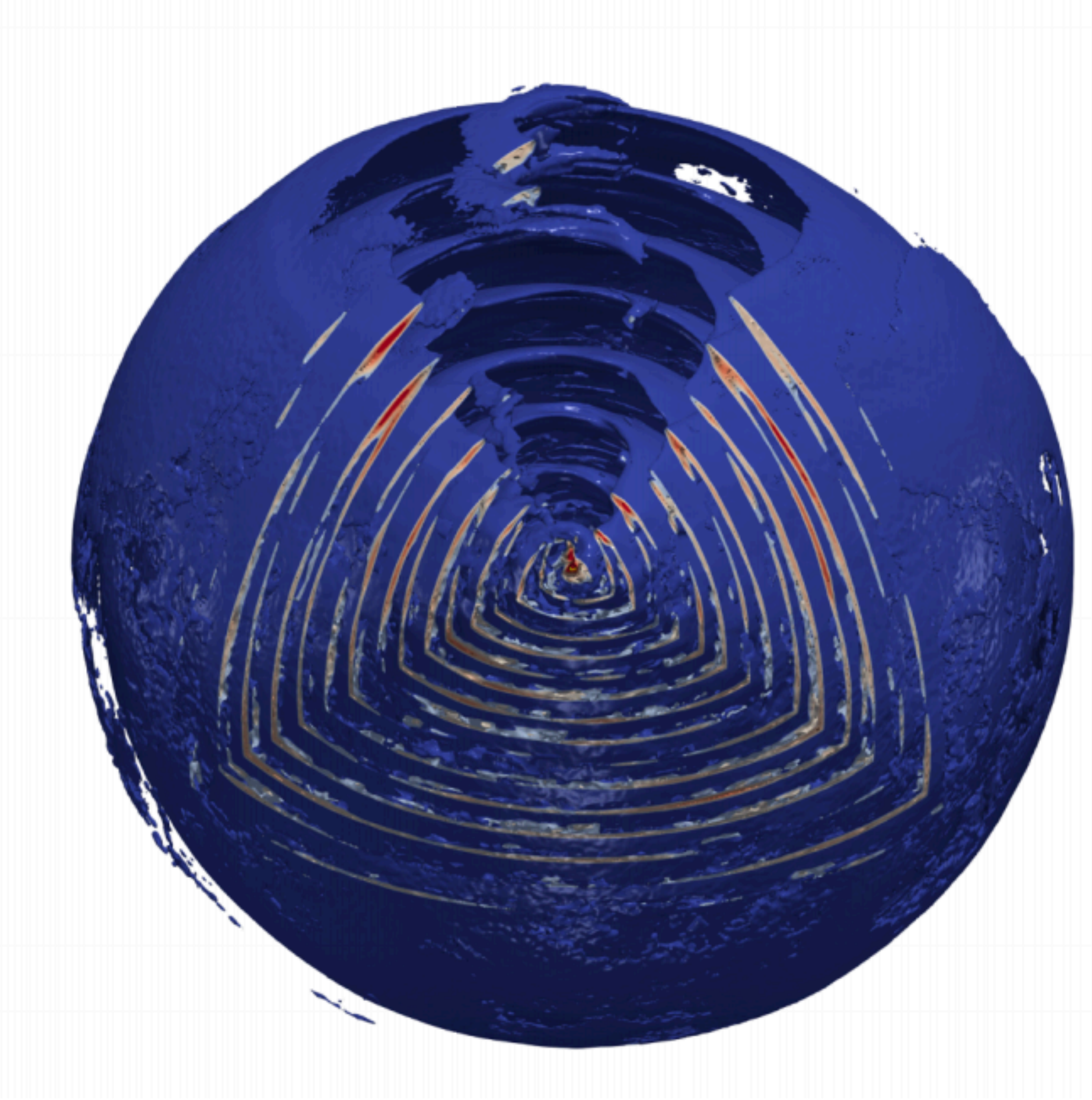
Acceleration & Emission beyond the magnetosphere

DESY.

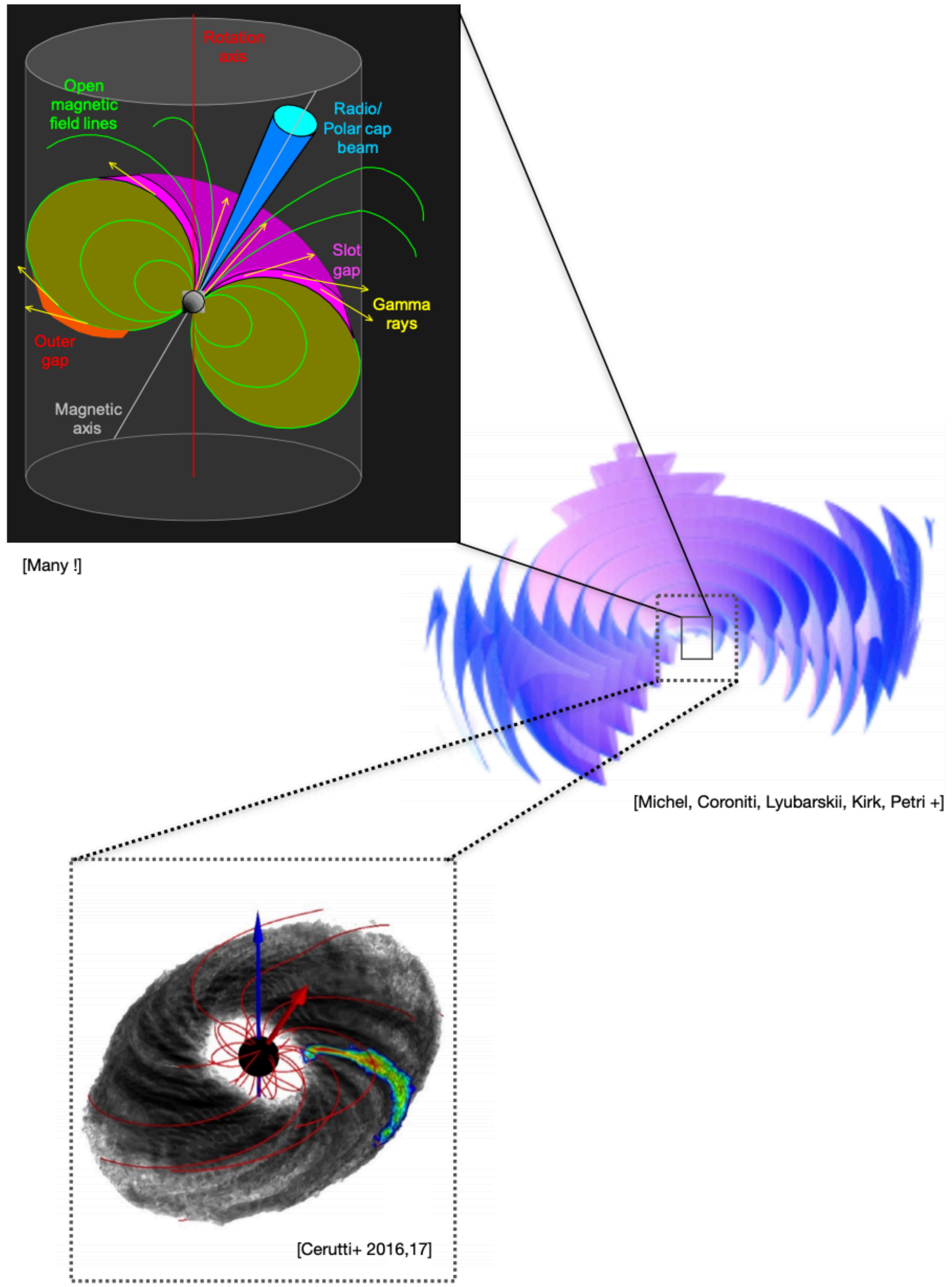
High energy radiation from pulsars

striped wind models

- Beyond the magnetosphere:
  Electrons are accelerated in the wind through magnetic reconnection in the current sheet (CS)
  HE => SYN emission on the CS
  VHE => IC emission on the CS



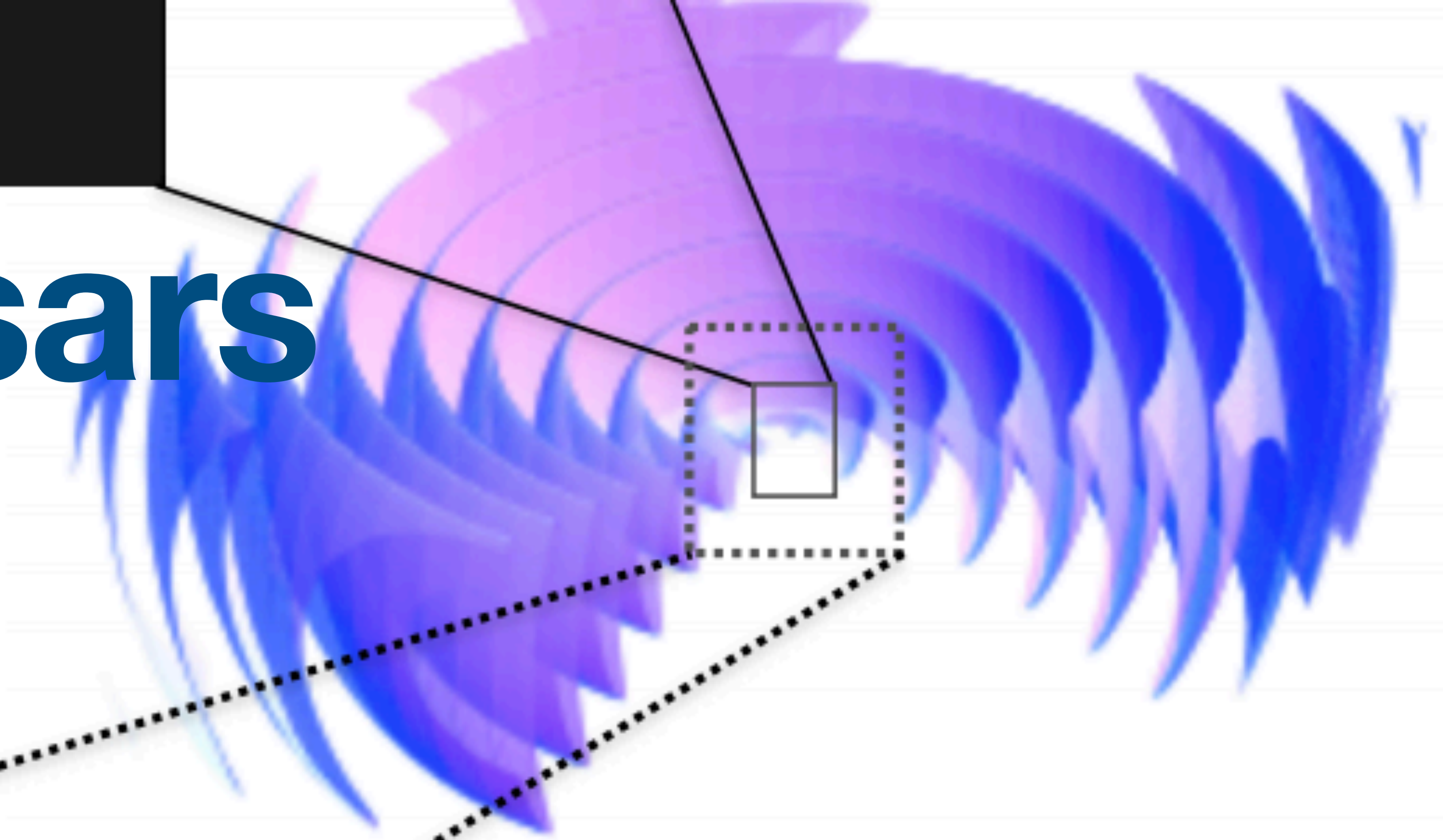
Simulations by Cerruti et al 2020



[Many !]

High energy radiation from pulsars

striped wind models



[Michel, Coroniti, Lyubarskii, Kirk, Petri +]

- Beyond the magnetosphere:
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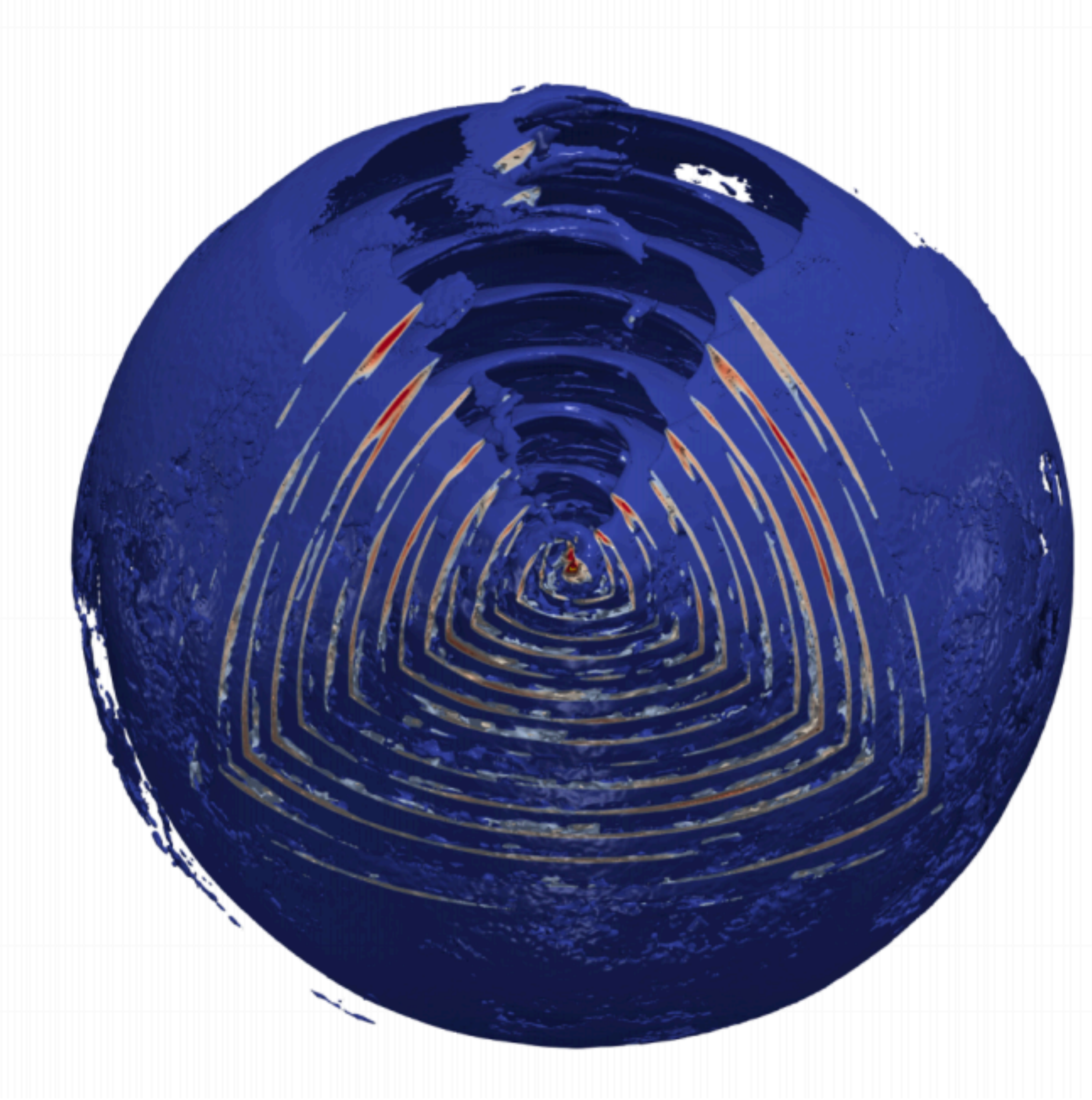

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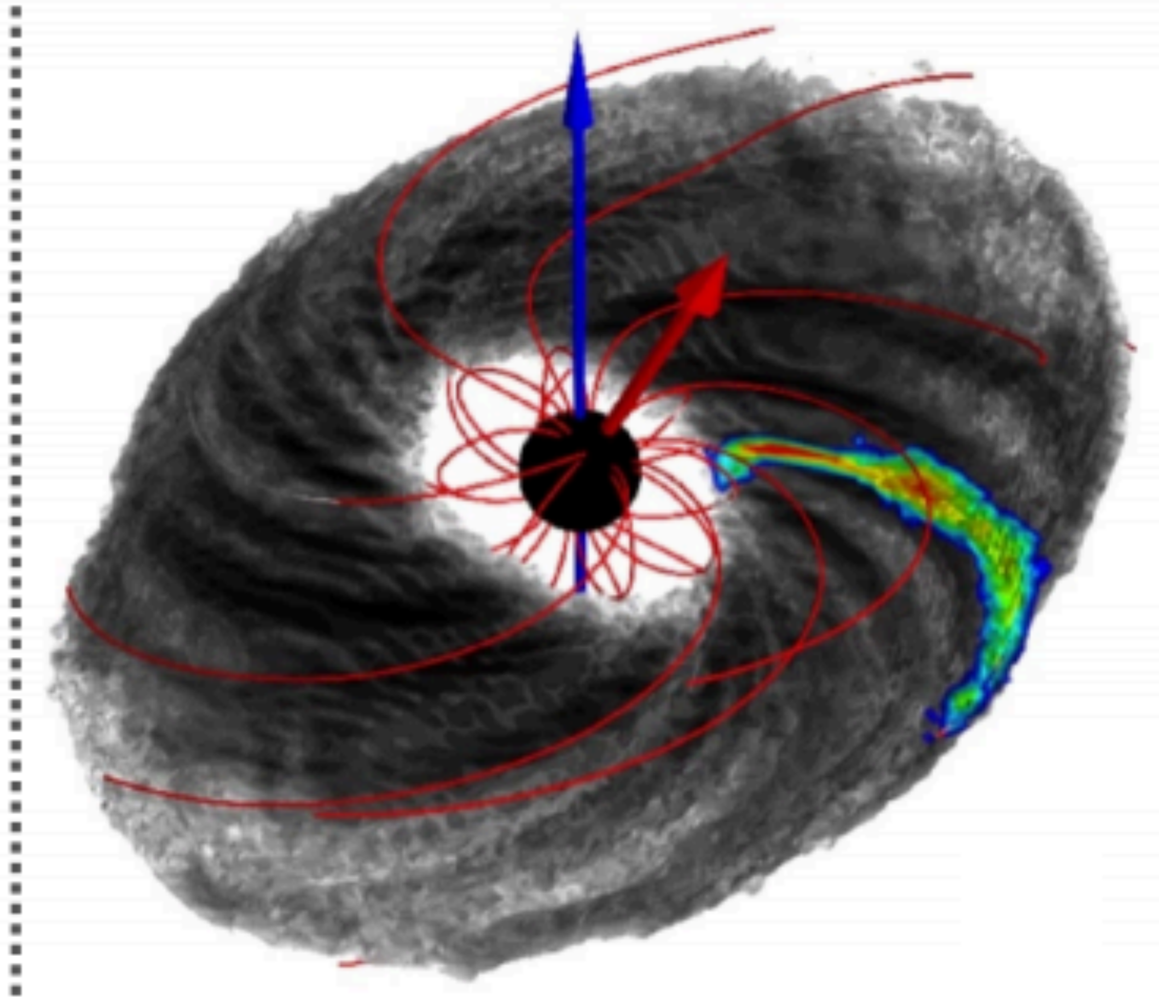
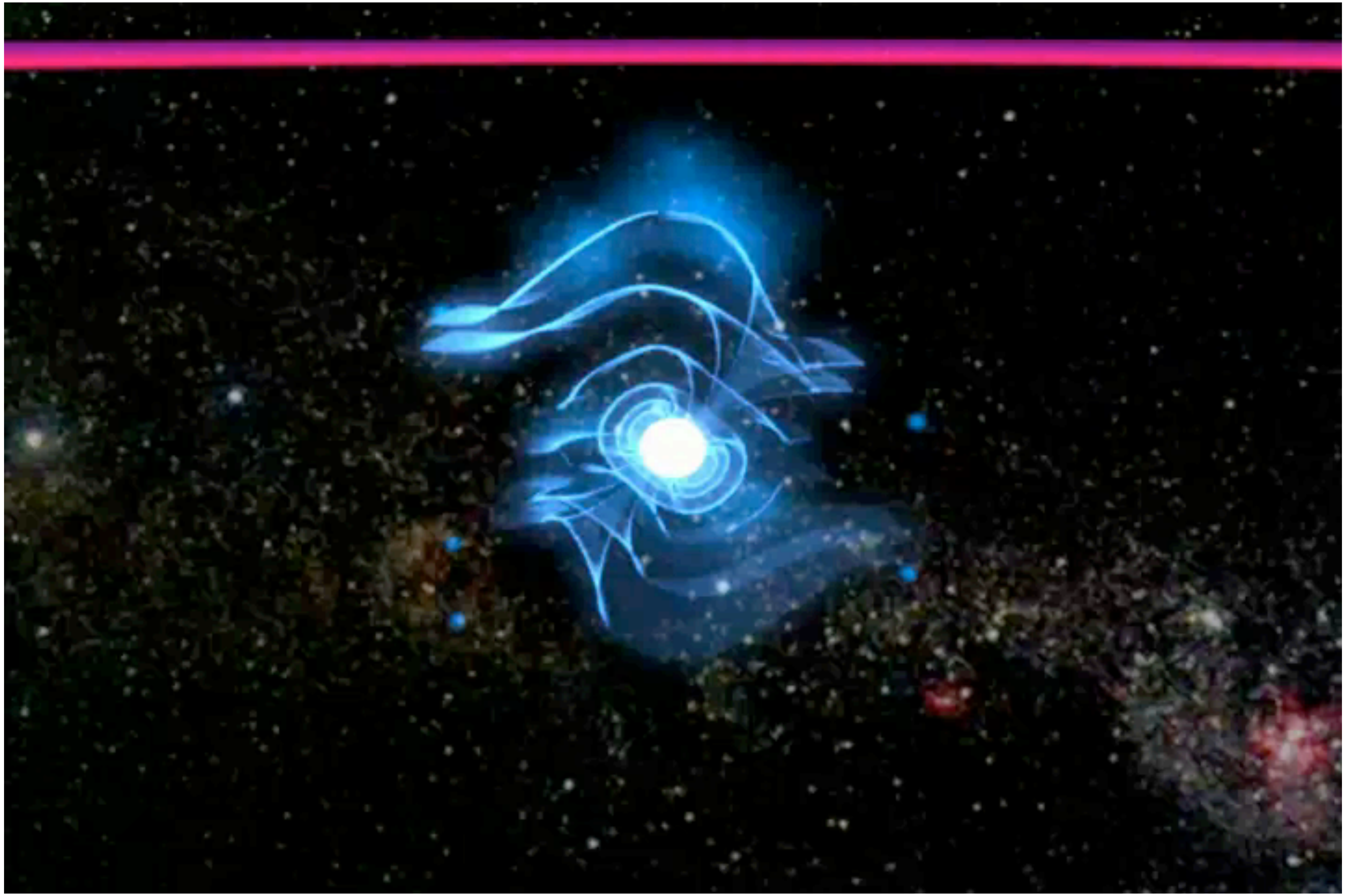
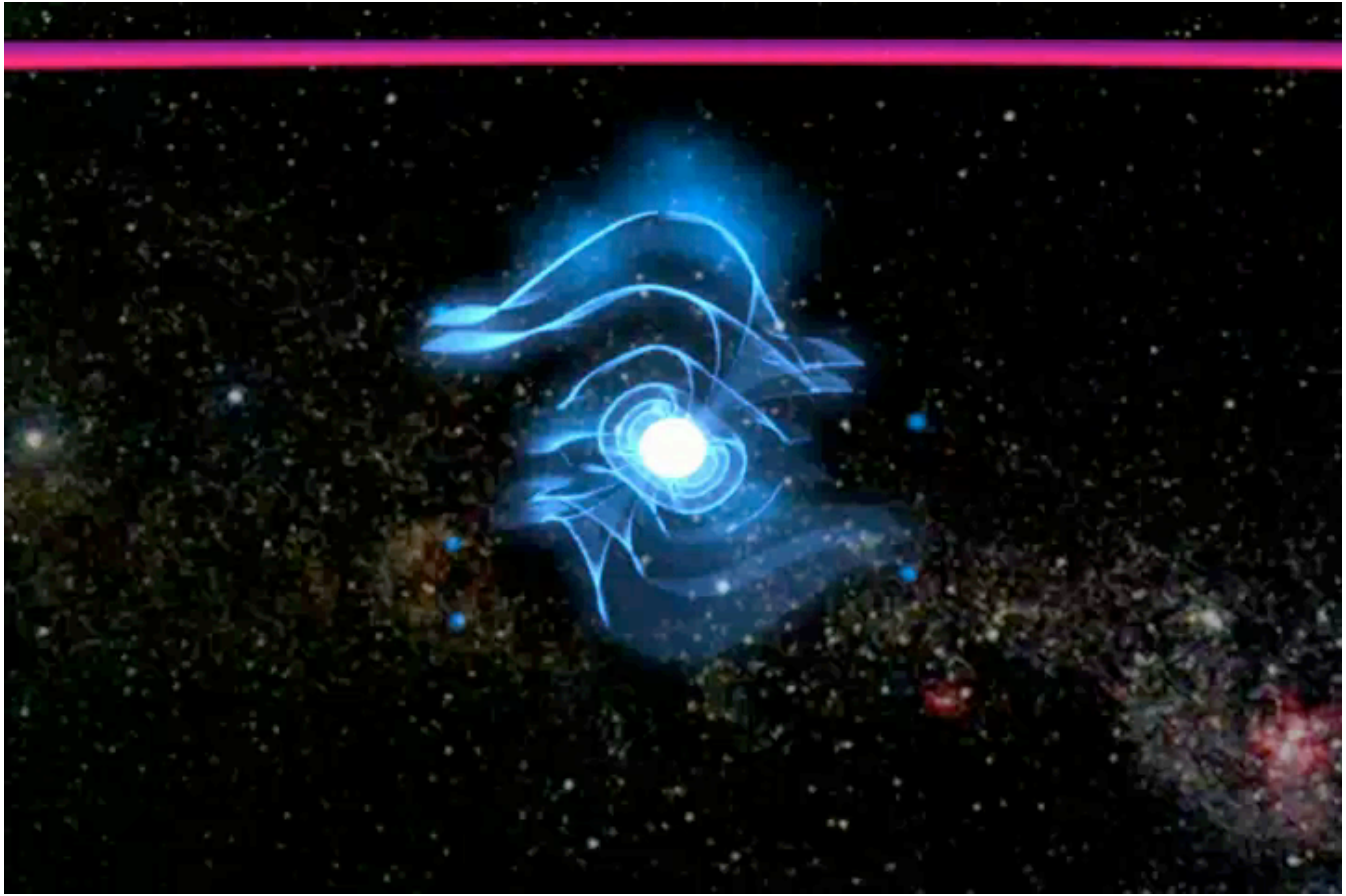


[Cerutti+ 2016,17]



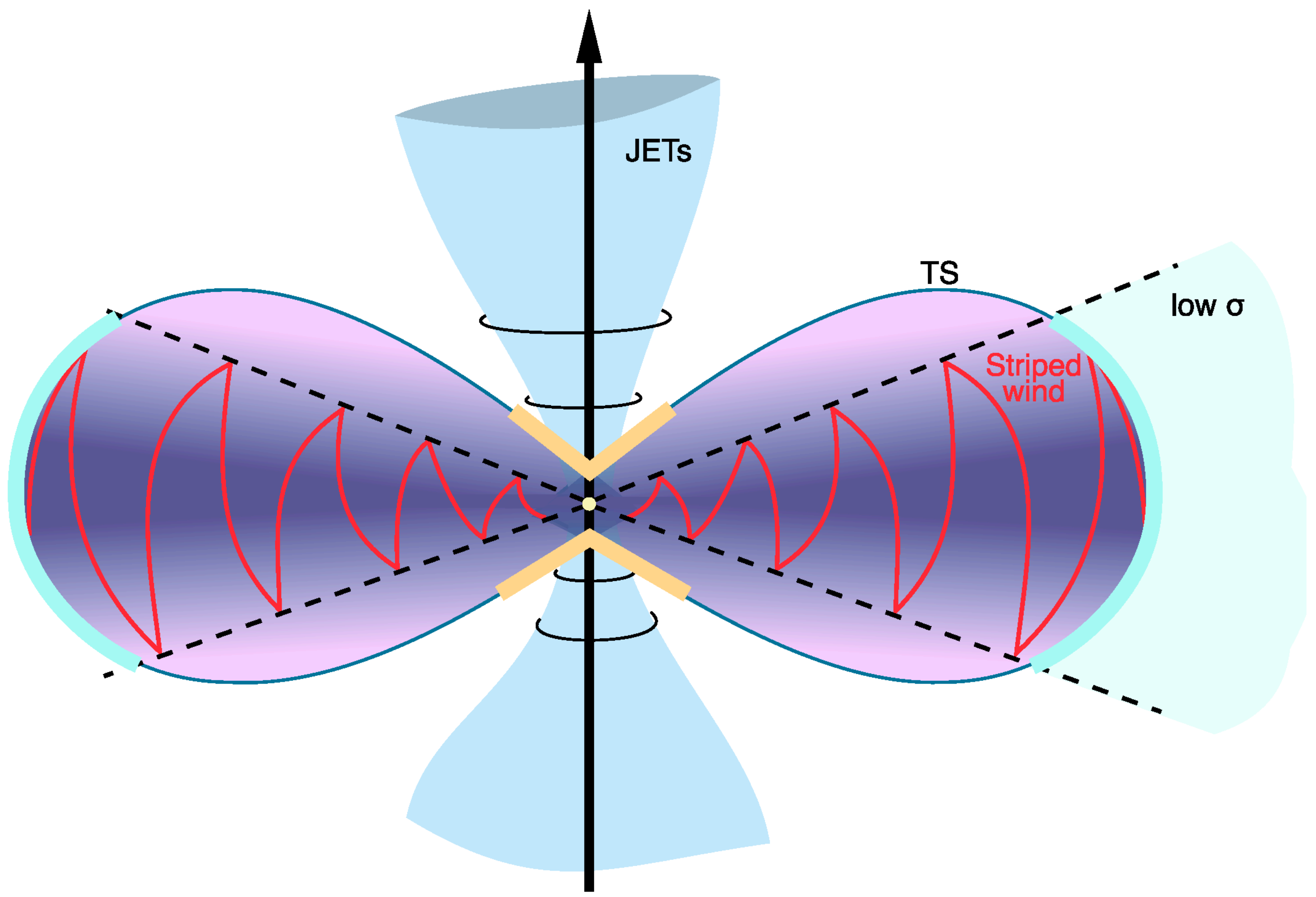


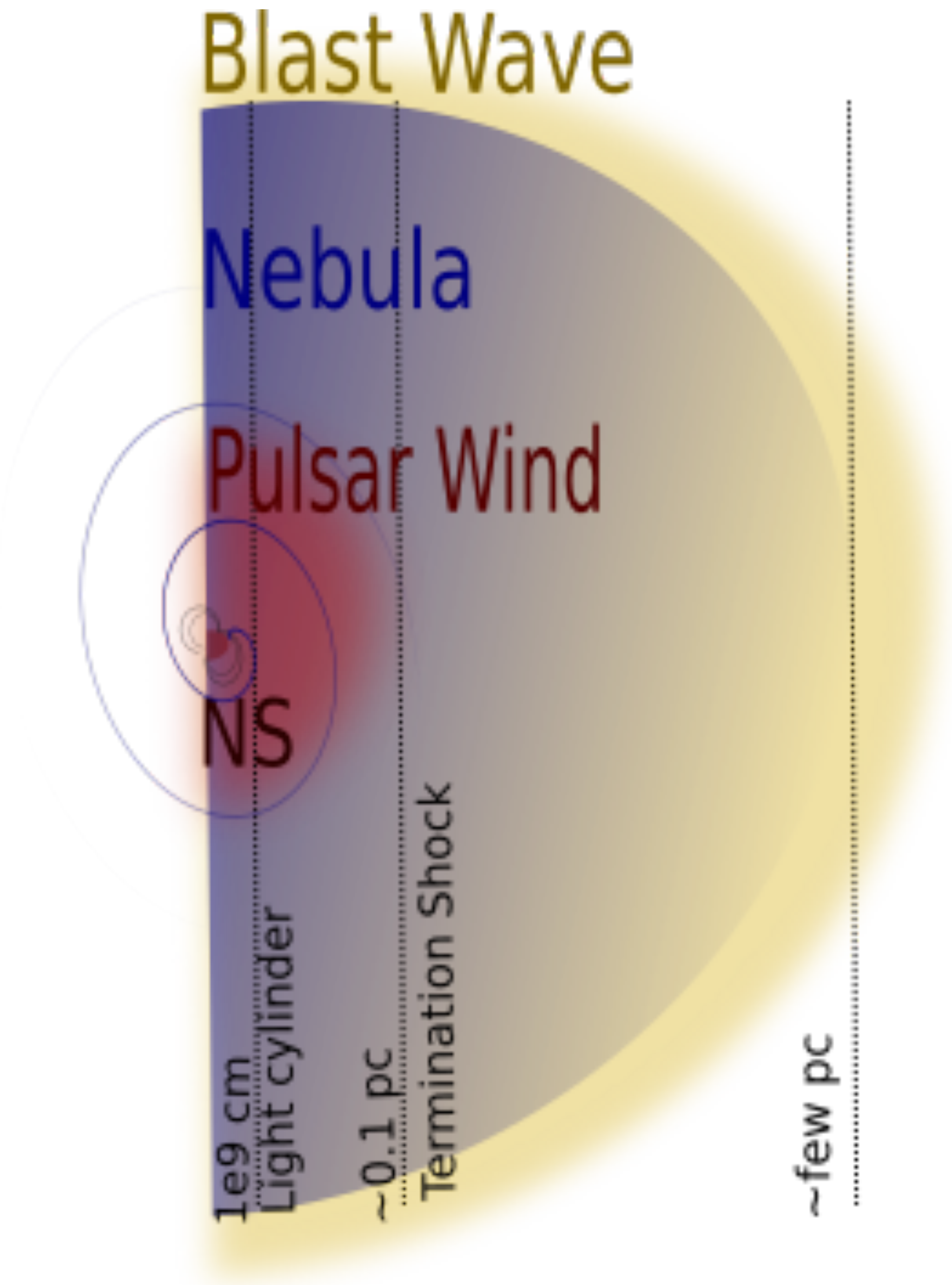
High energy radiation from pulsars

Surprises at TeV energies

A number of bright pulsars detected in the TeV regime

- Where is the emission produced?
- How much can pulsars accelerate?





The maximum energy:

$$E_{\rm max} = q\eta_e {\rm B_{TS} R_{TS}},$$

The magnetic density is a fraction of the pulsar wind energy flux:

$$\frac{B_{\rm TS}^2}{8\pi} = \eta_{\rm B} \frac{\dot{E}}{(4\pi R_{\rm TS}^2 c)}$$

Then the Emax:

$$E_{\rm max} \approx 2\, \eta_e\, \eta_{\rm B}^{1/2}\, \dot{E}_{36}^{1/2} \ \ {\rm PeV}$$

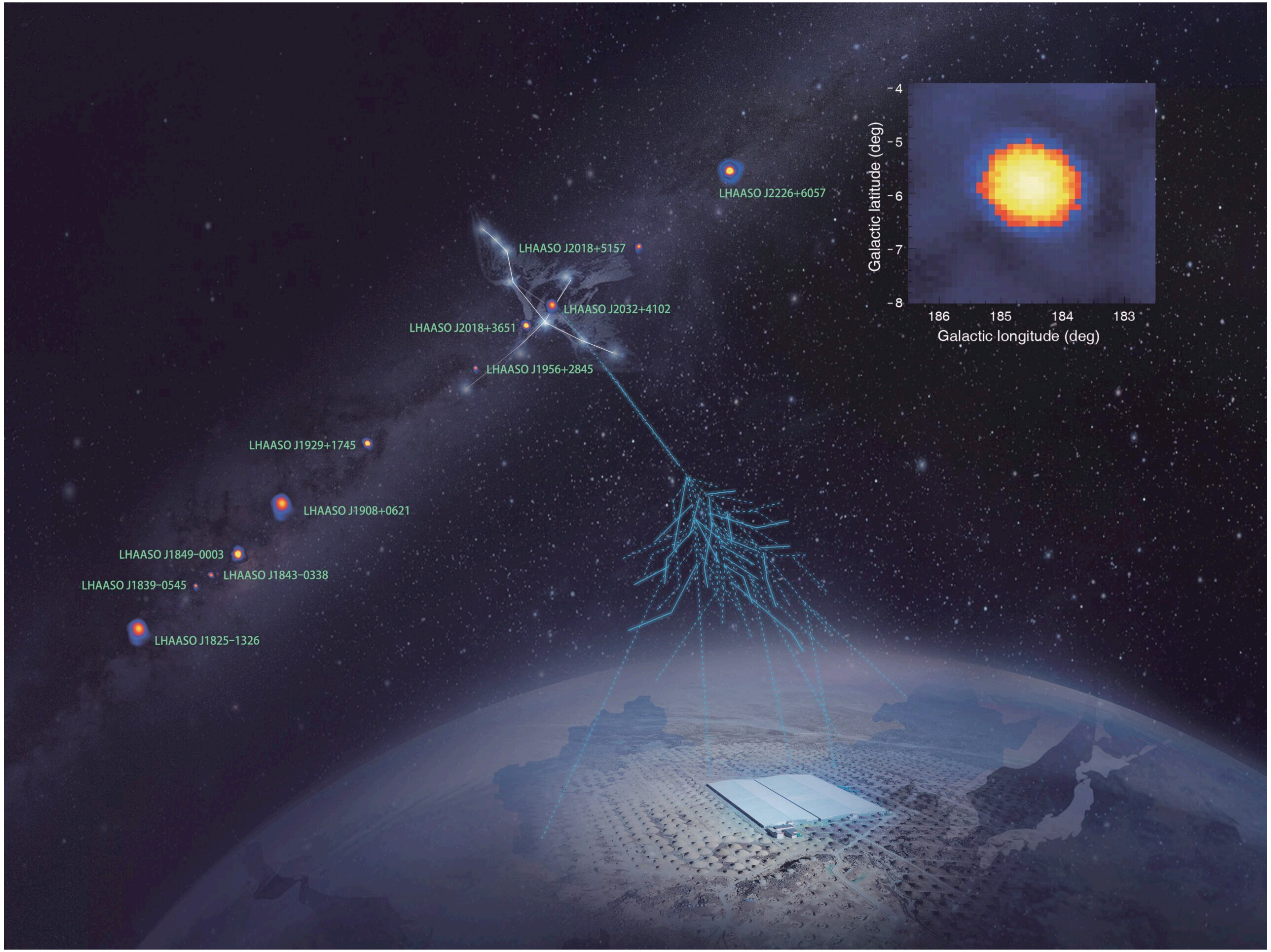
and if CMB (only target >100 TeV)

$$E_{\rm e} \simeq 2.15 E_{\gamma,15}^{0.77} \ {\rm PeV}$$

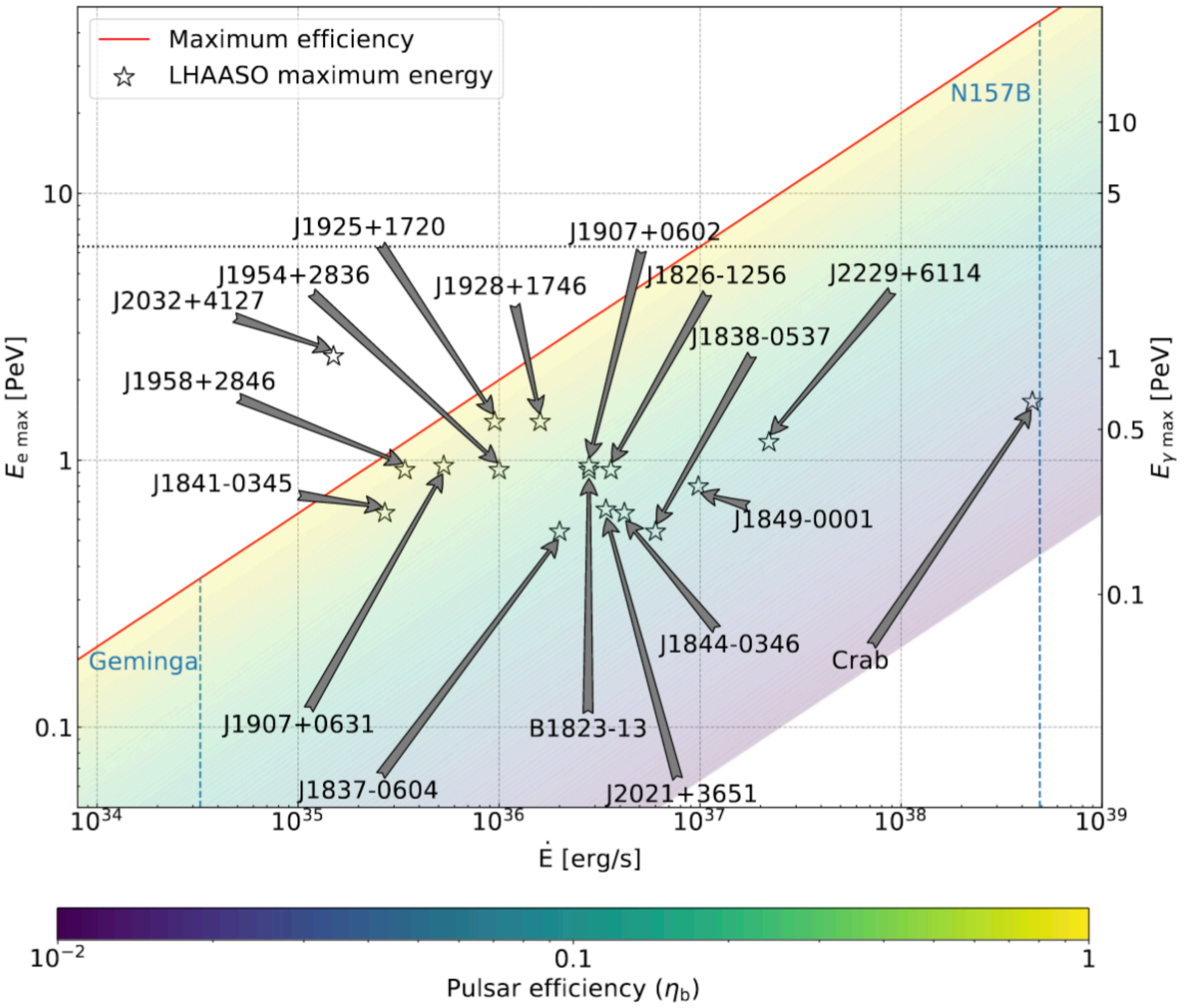
$$E_{\gamma\ \rm max} \approx 0.9\, \eta_e^{1.3}\, \eta_B^{0.65}\, \dot{E}_{36}^{0.65} \ \ {\rm PeV}$$

Cao et al, 2021

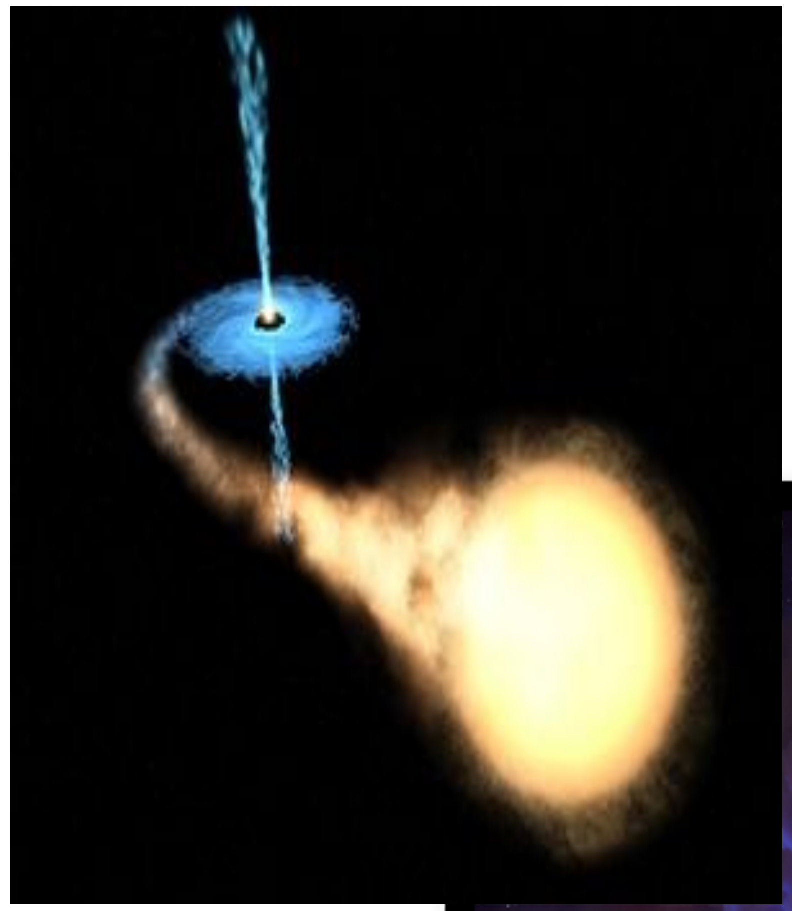
LHAASO Observed ~10 PeVatrons - 9 have a bright pulsars associated



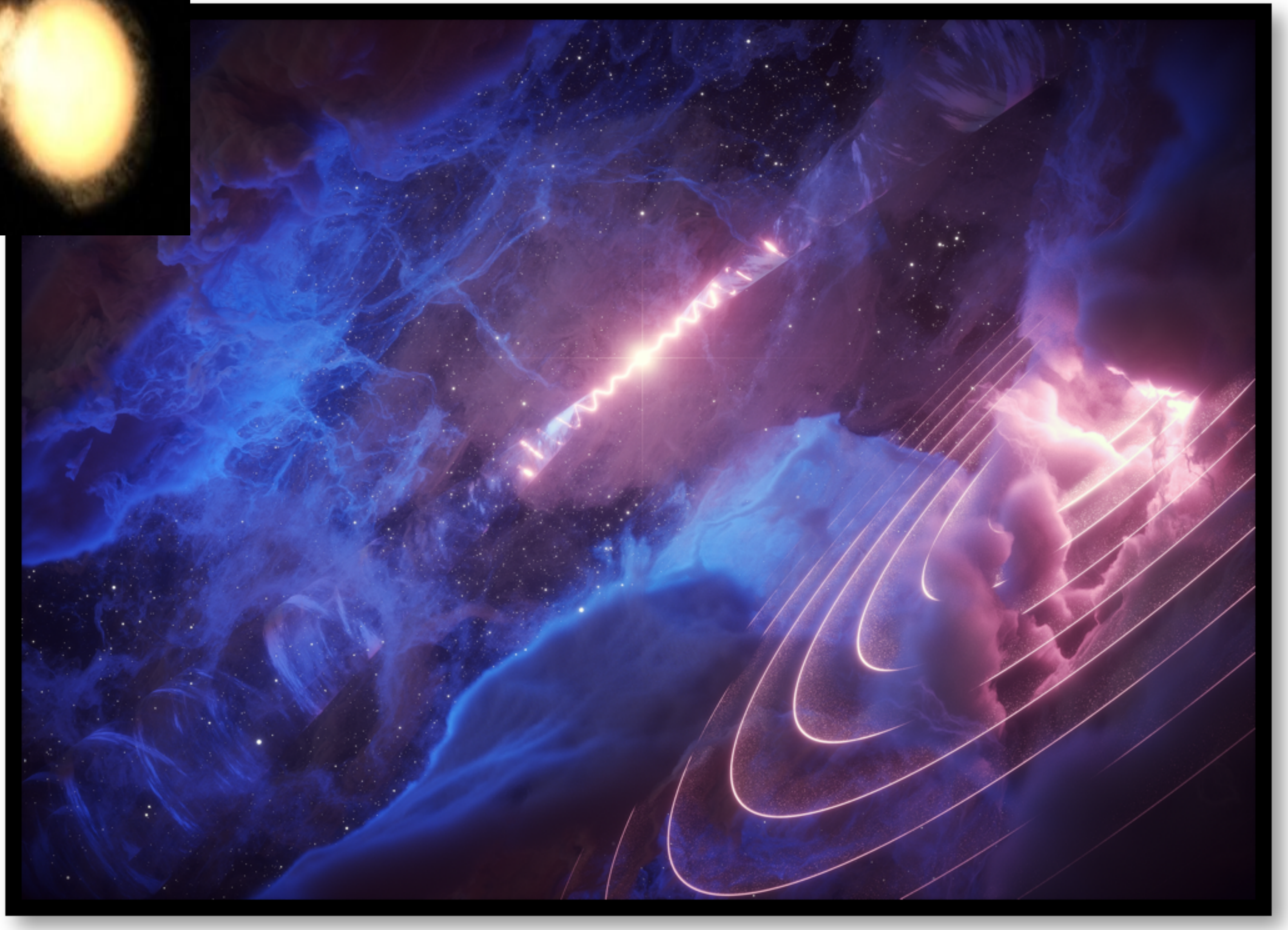
LHAASO Source	Pulsar	$E_{\gamma\ max}$ [PeV]	E_{max} [PeV]
J1825-1326	J1826-1256	2.06	3.79
	B1823-13	1.77	3.35
J1839-0545	J1837-0604	1.44	2.83
	J1838-0537	2.78	4.90
J1843-0338	J1841-0345	0.41	1.04
	J1844-0346	2.25	4.10
J1849-0003	J1849-0001	3.71	6.26
J1908+0621	J1907+0602	1.77	3.35
	J1907+0631	0.63	1.46
J1929+1745	J1925+1720	0.91	1.95
	J1928+1746	1.26	2.53
J1956+2845	J1954+2836	0.94	2.00
	J1958+2846	0.47	1.17
J2018+3651	J2021+3651	1.99	3.69
J2032+4102	J2032+4127	0.28	0.77
J2108+5157			
J2226+6057	J2229+6114	5.89	9.38



Compact in binary systems



Photon field enhanced by the massive companion - modulated emission!

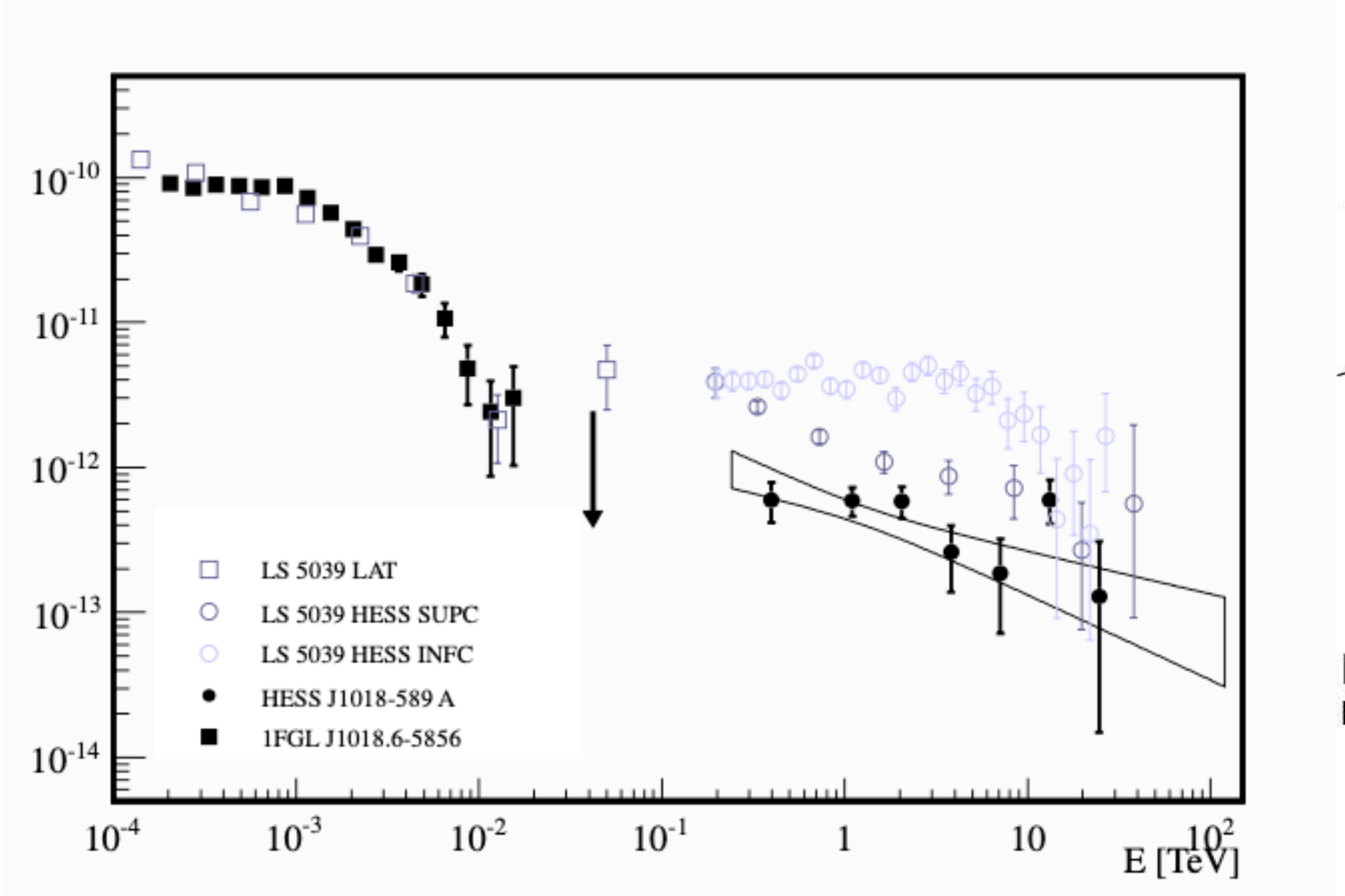


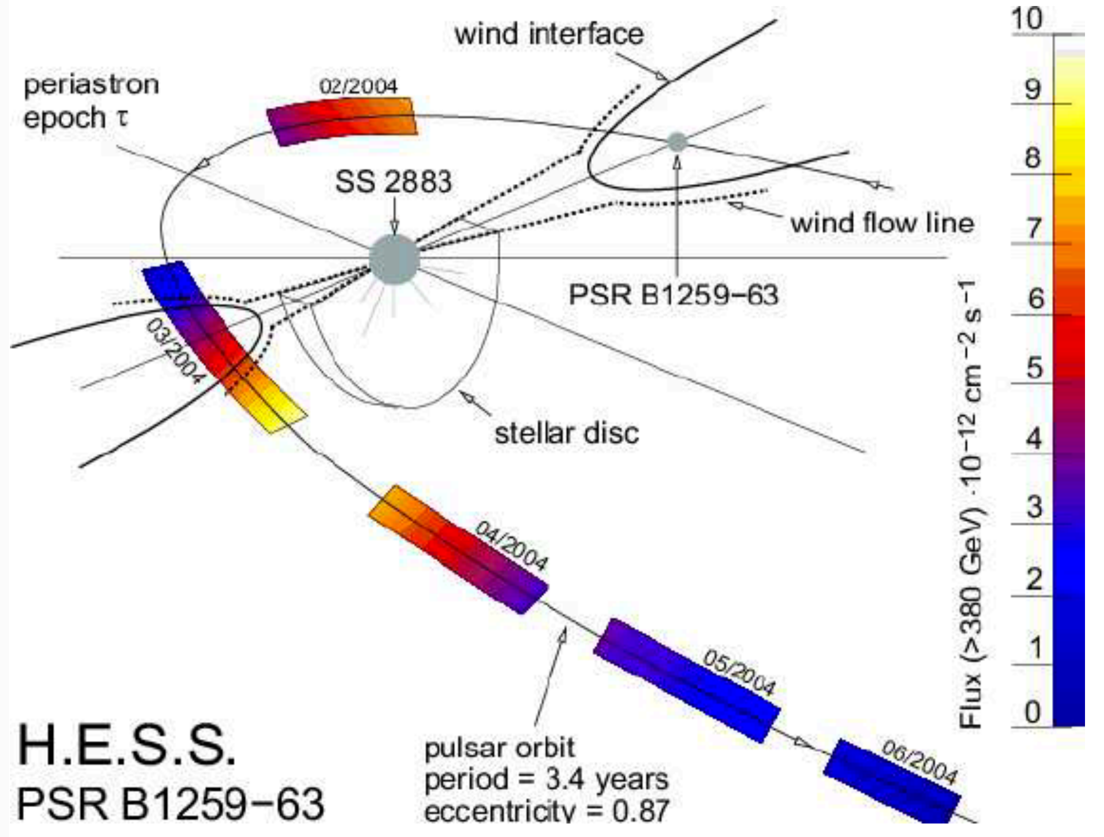
Compact object in binary systems

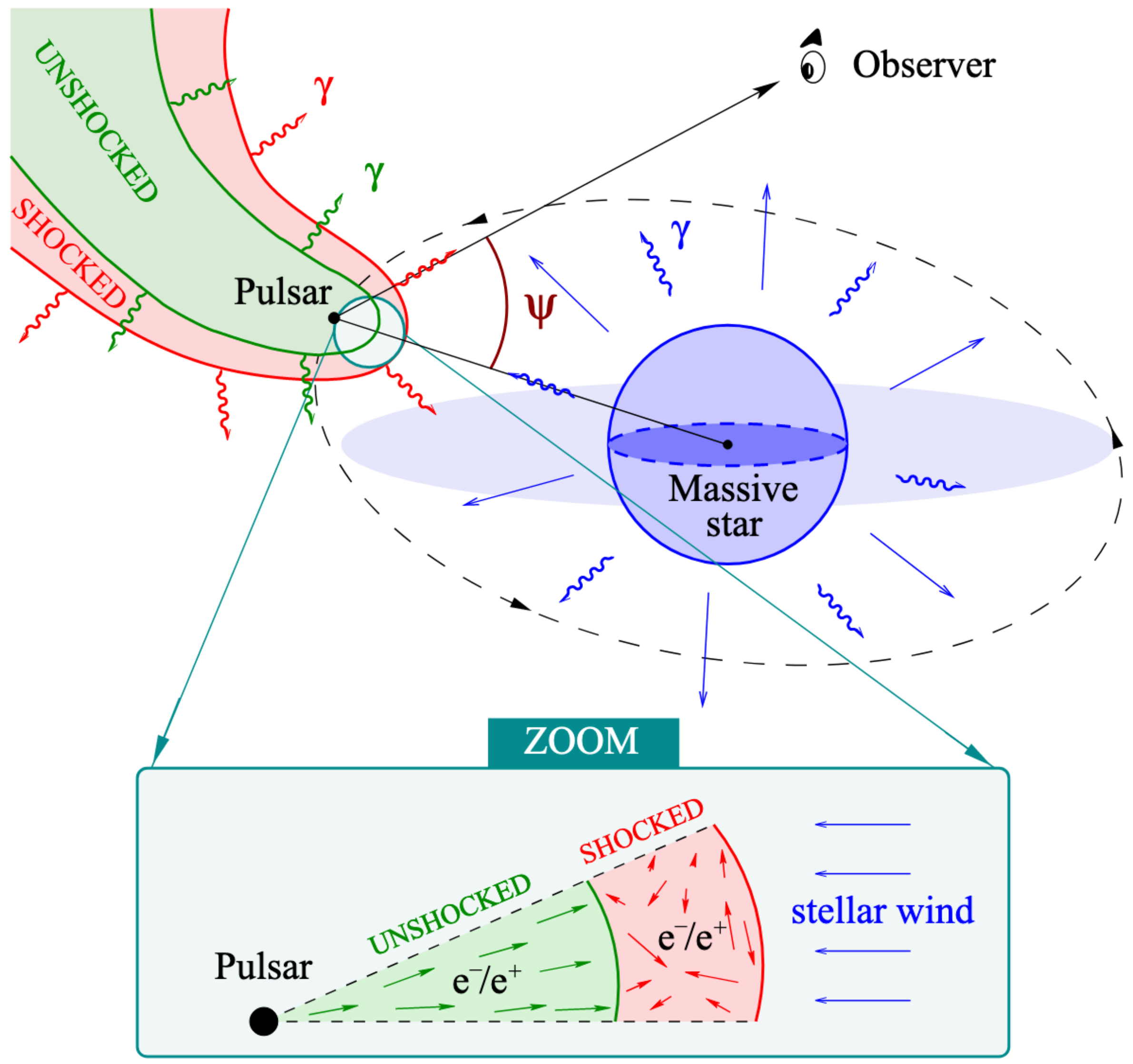
High Energy Binary

GeV and TeV often uncorrelated:

- Max of orbital light curve
- Two spectral components
- Flares and rich phenomenology

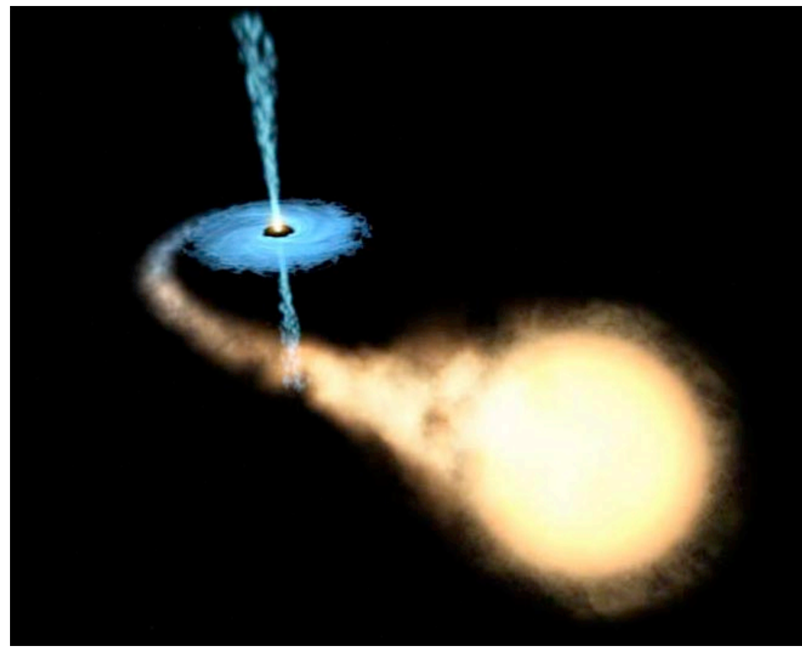






	Flux (% Crab)	D (Kpc)	Flux variability (HE/VHE)	Periodic
LSI +61 303	0-15	2	yes/yes	yes (~1 month)
LS 5039	5-15	2.5	yes/yes	yes (~4 days)
PSR B1259-63	0-10	1.5	yes/yes	yes (~3.4 years)
HESS J0632+057	0-3	1.5	no/yes	yes (~300 days)
Cyg X-1	0-10	2.2	yes/yes(?)	no
1FGL J1018.6-589	5-15	5	yes/?	yes (~16 days)

Compact object in binary systems



High Energy Binary

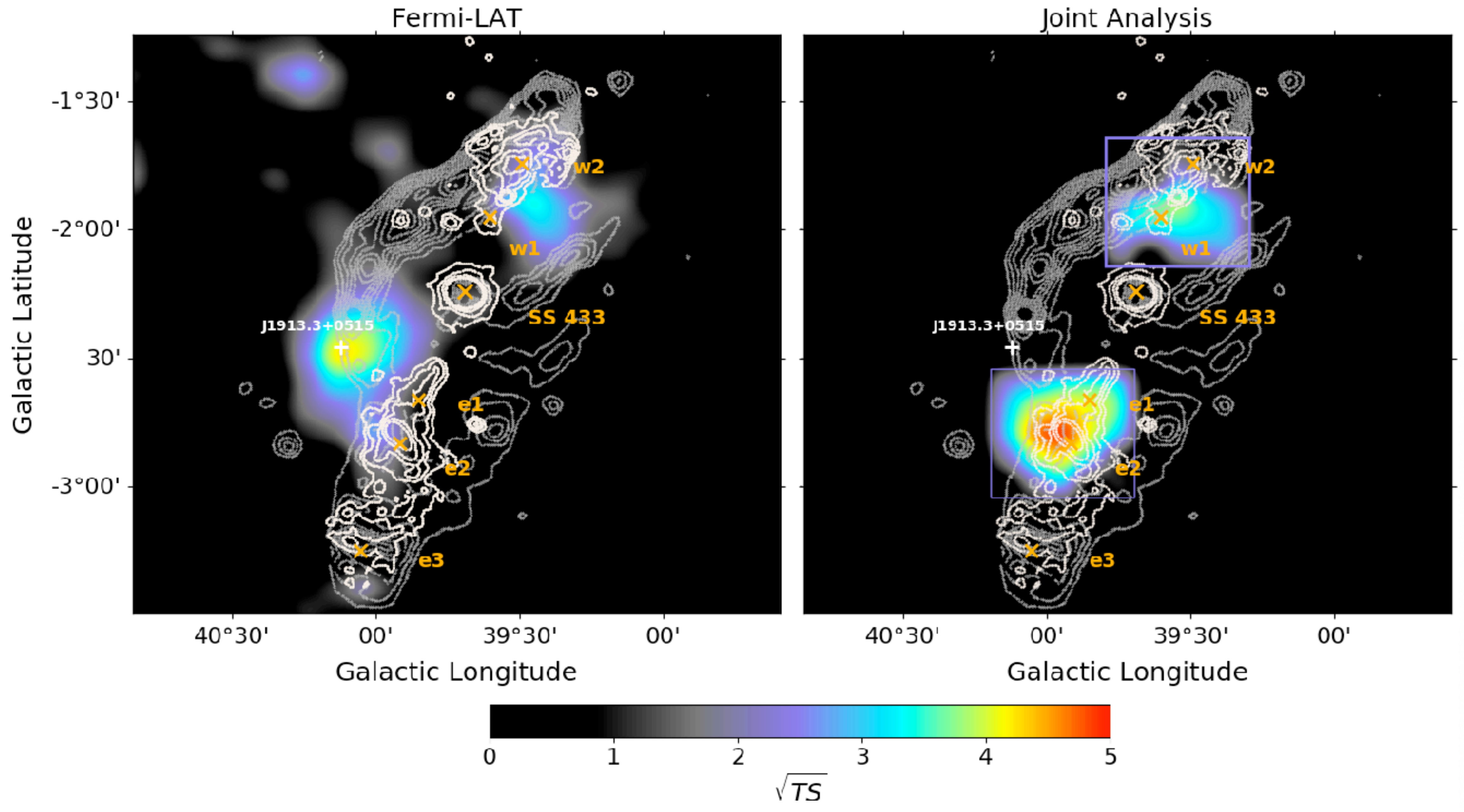
GeV and TeV often uncorrelated:
* Max of orbital light curve
* Two spectral components
* Flares and rich phenomenology

Microquasars

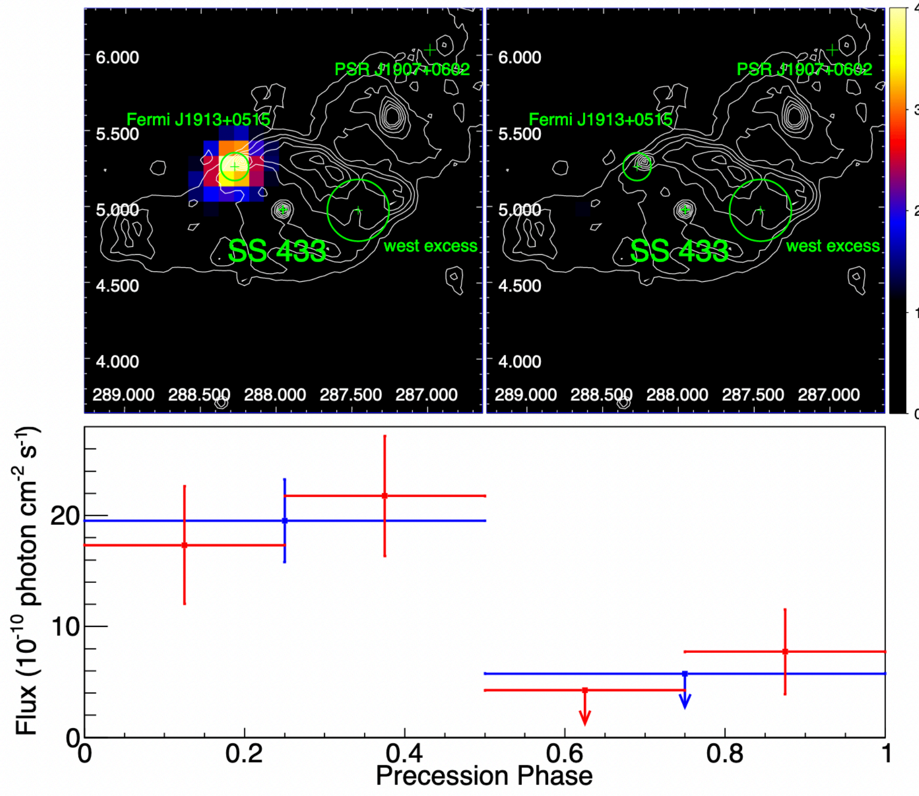
Black hole + massive companion

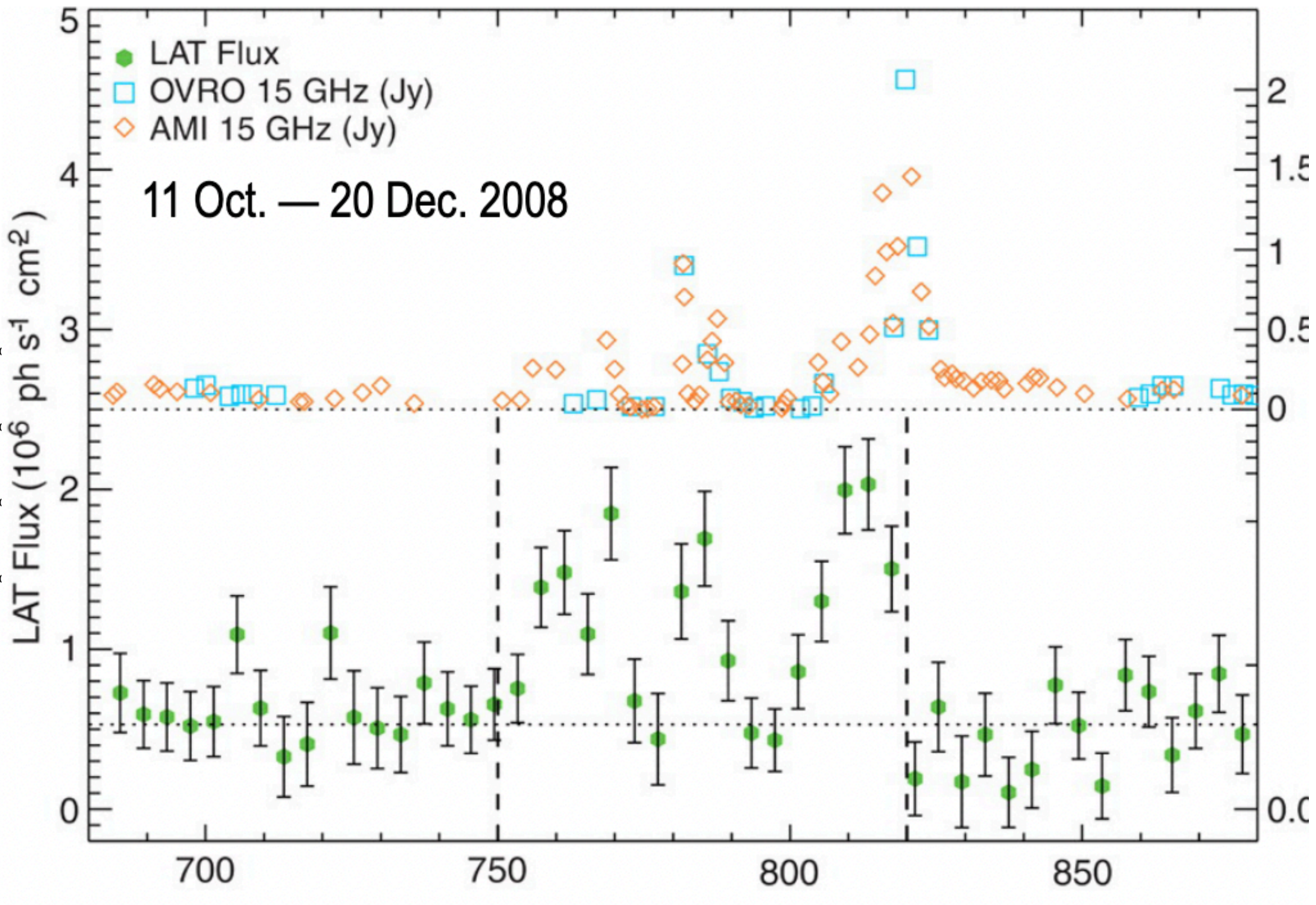
GeV detection associated to X-ray activities

GeV/TeV detection associated to jets



Li et al, 2020





precessing with a period of 162.250 days

Compact object in binary systems

High Energy Binary

GeV and TeV often uncorrelated:
* Max of orbital light curve
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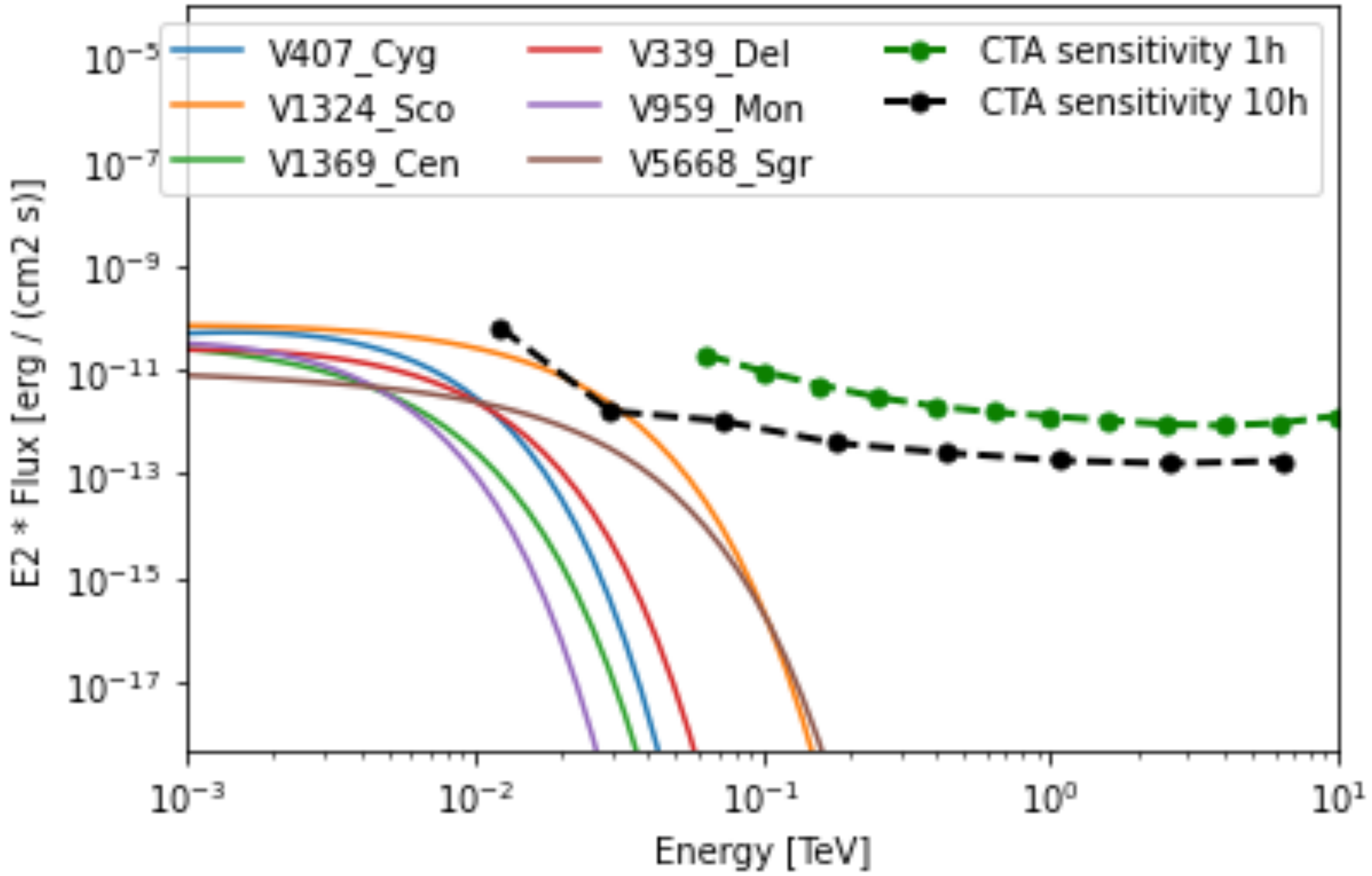
GeV/TeV detection associated to jets

Novae

GeV Detection of a few

First TeV detection of RS Oph



Compact object in binary systems

Novae

What are novae? lots of different kind of novae

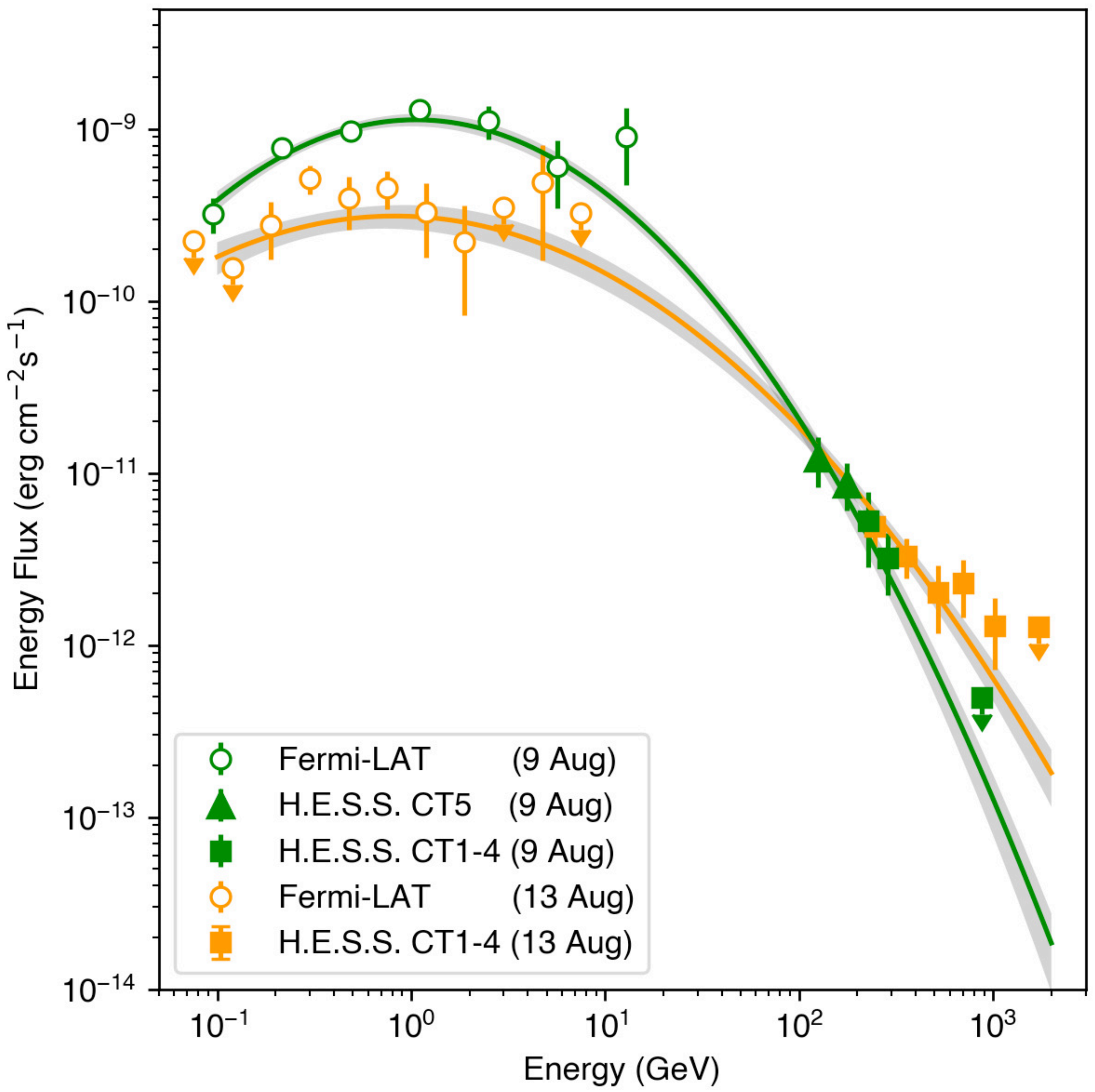
- Luminous red novae - probably stellar mergers
- Dwarf novae - eruption on accretion disks in cataclysmic variables
- Kilonova - neutron star mergers
- Classical novae - thermo-nuclear explosions from outer layers of accreting white dwarfs WD
- Massive WD => fast ejecta with low ejecta mass
- Low-mass WD => opposite

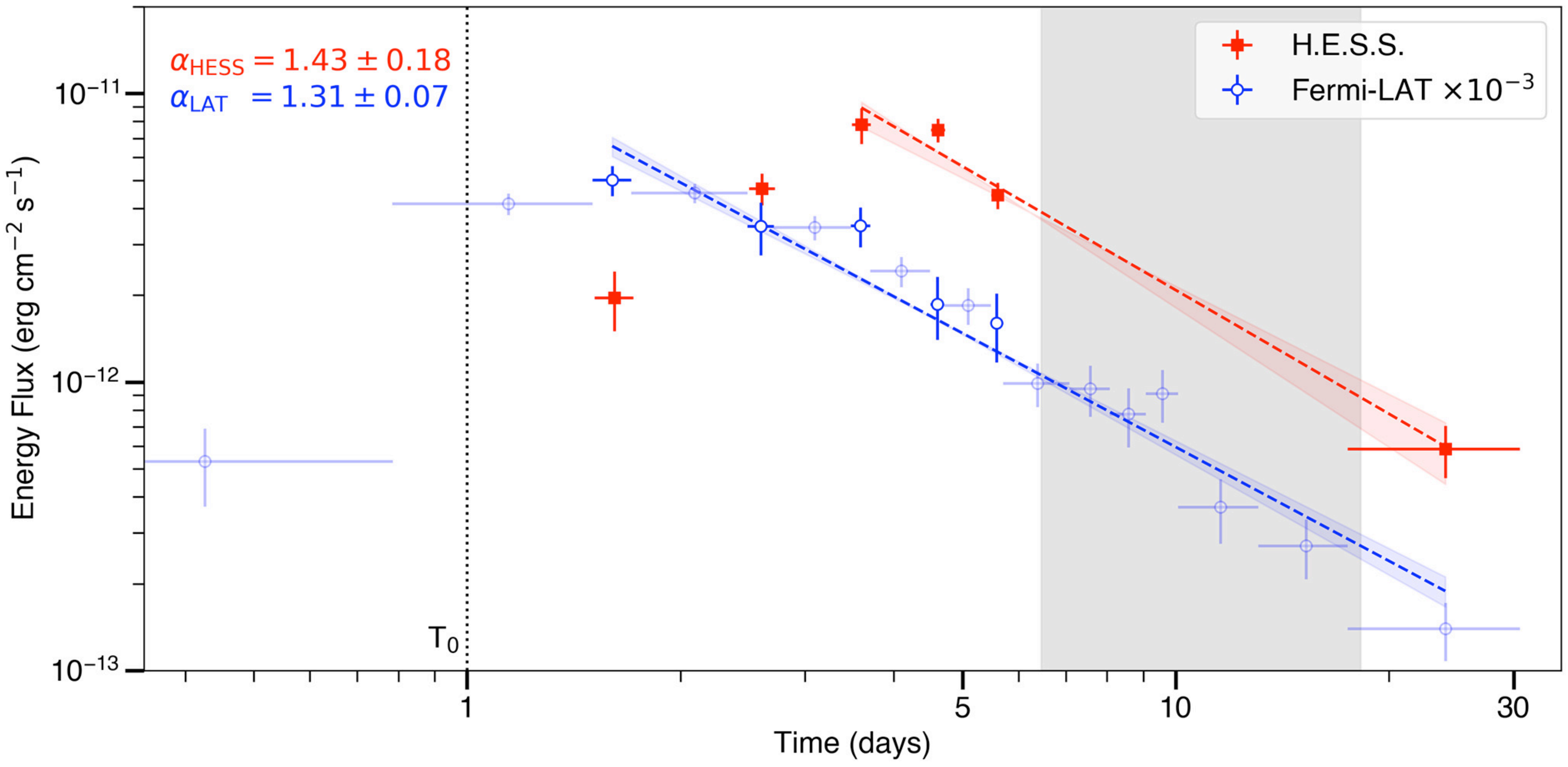
<table>
<tr><th>"Classical Novae"</th><th>Helium Novae</th><th>Symbiotic Novae*</th></tr>
<tr><td>Main-sequence companion star (weak and fast wind)</td><td>Companion is a Helium star, e.g. V445 Puppis</td><td>Companion is a Red Giant → symbiotic binary system, e.g. RS Oph</td></tr>
<tr><td>Most common type of nova, few recurring</td><td>Rare</td><td>Less common overall, but more often recurring</td></tr>
<tr><td colspan="2">Short period binary (few days)</td><td>Long period (~1 year)</td></tr>
<tr><td colspan="2">Low-density, fast wind from companion</td><td>Dense slow wind from RG</td></tr>
<tr><td colspan="2">High-energy (FERMI-LAT) emission thought to arise from internal shocks</td><td>External shock for GeV/TeV emission (we argue)</td></tr>
<tr><td>FERMI detections</td><td>?</td><td>FERMI and HESS</td></tr>
</table>

Compact object in binary systems

Novae

$$E_{\rm max} = 1.5|Z| \left(\frac{\xi_{\rm esc}}{0.01}\right) \left(\frac{\dot{M}/v_{\rm wind}}{10^{11}\ {\rm kg\ m^{-1}}}\right)^{1/2} \left(\frac{u_{\rm sh}}{5000\ {\rm km\ s^{-1}}}\right)^{2}\ {\rm TeV}$$

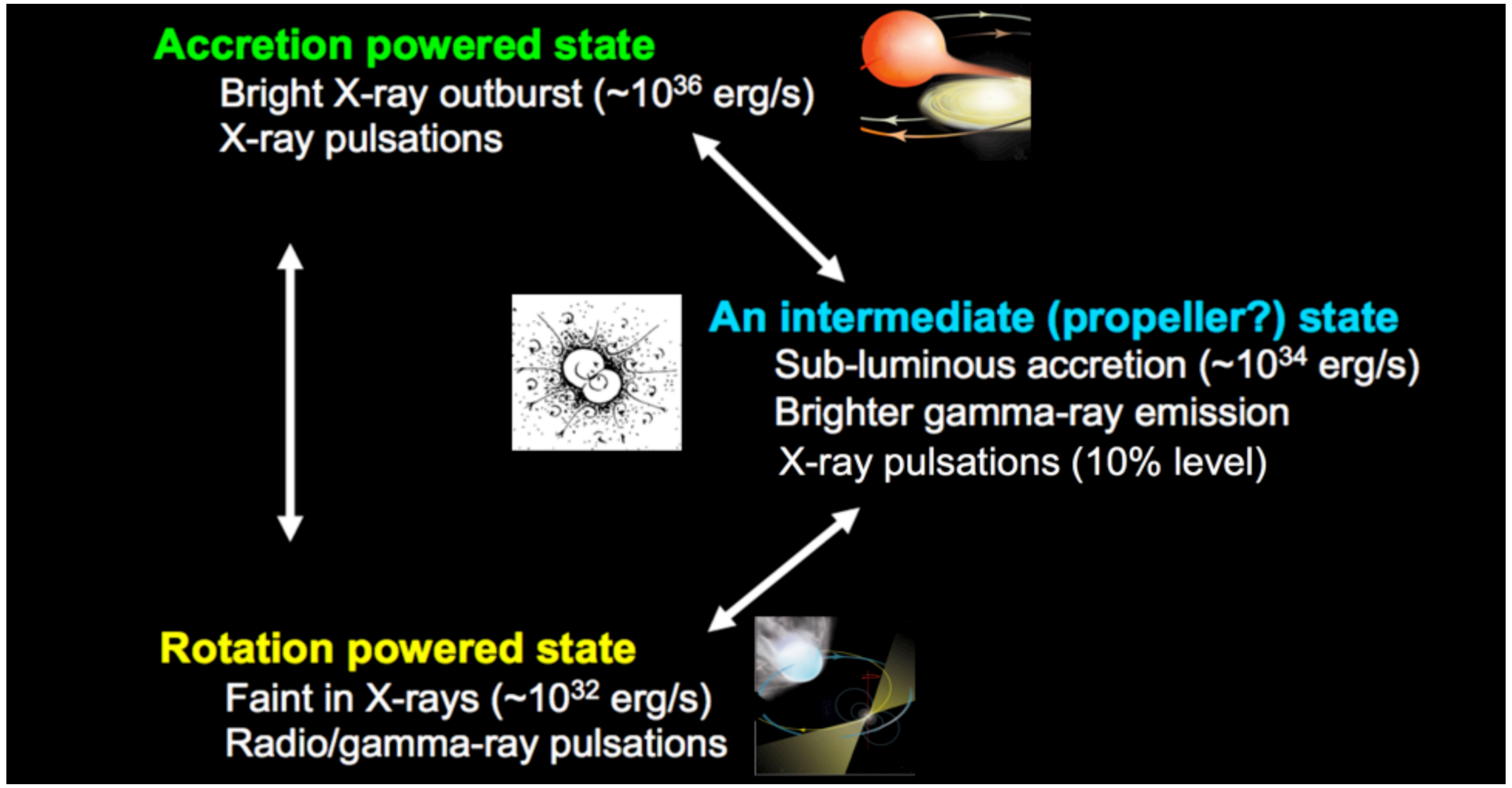


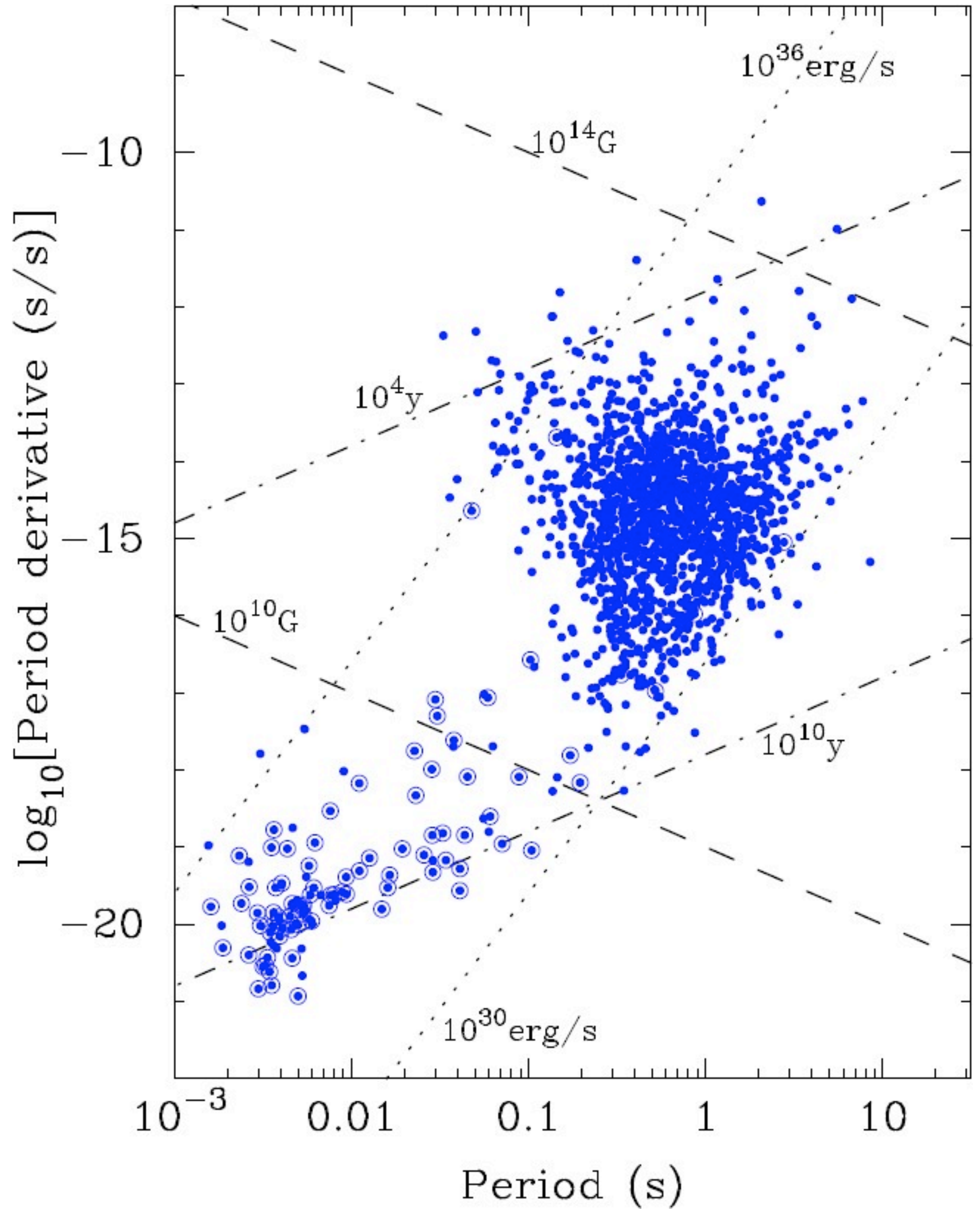


Compact object in binary systems

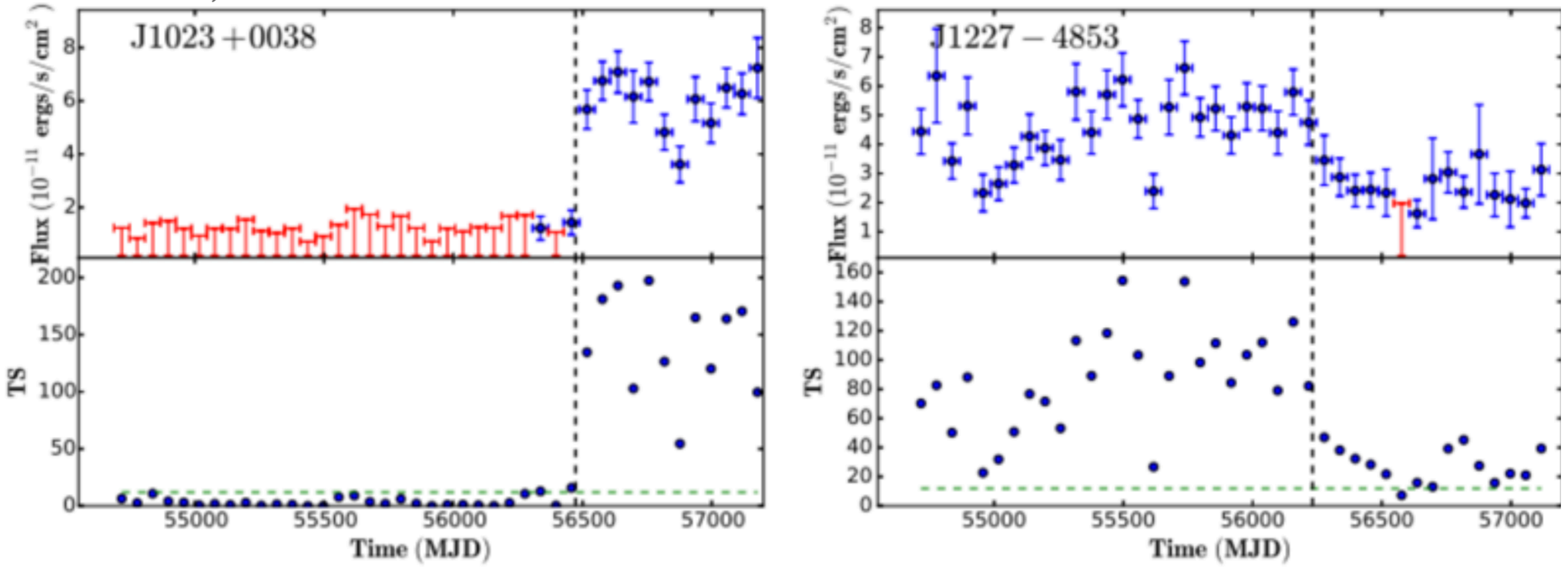
In the GeV band:

- Transitional ms-pulsar: a game between rotational <=> accretion





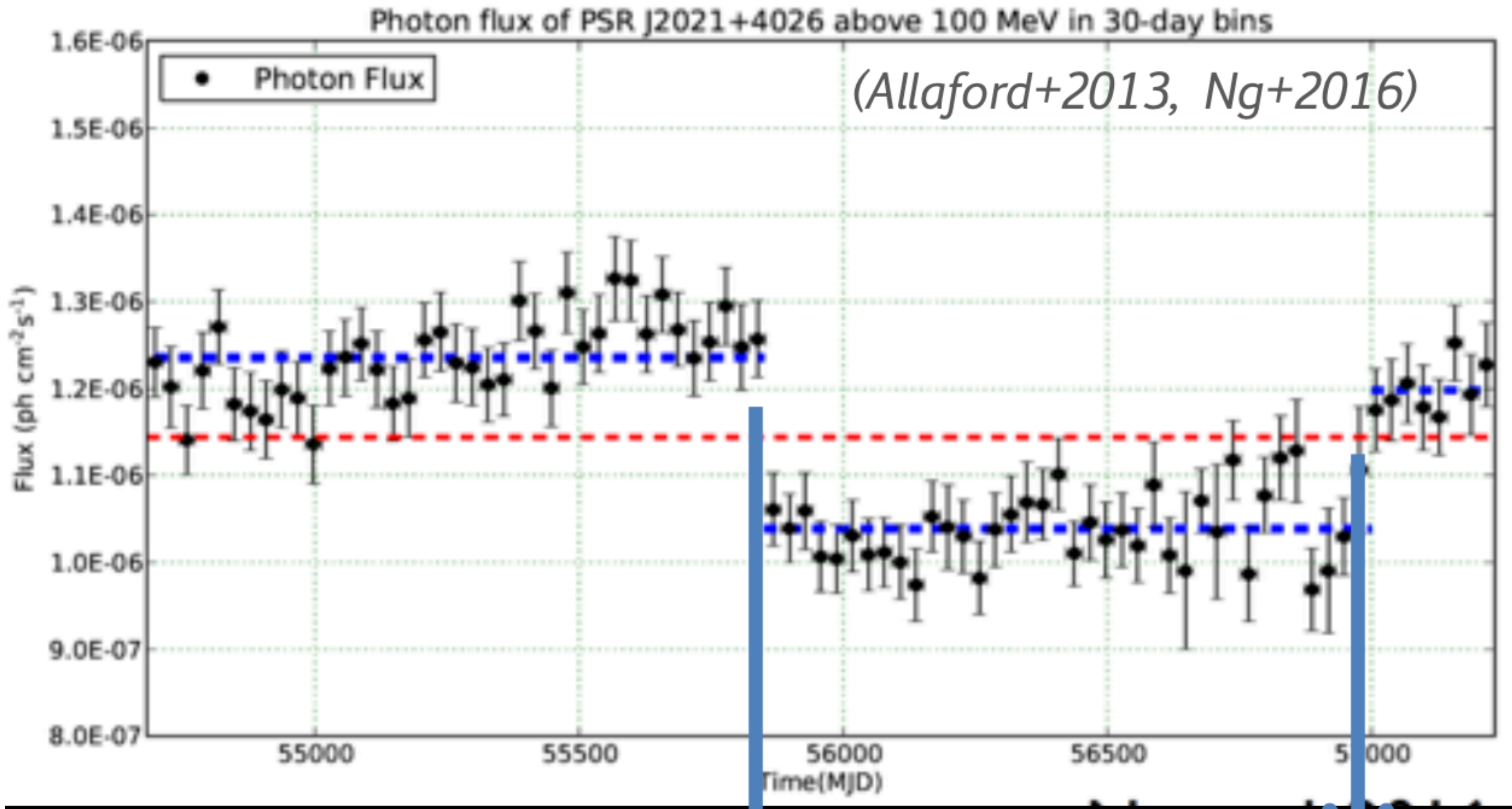
Torres et al, 2016



Compact object in binary systems

In the GeV band:

- Transitional ms-pulsar
- Glitching pulsars



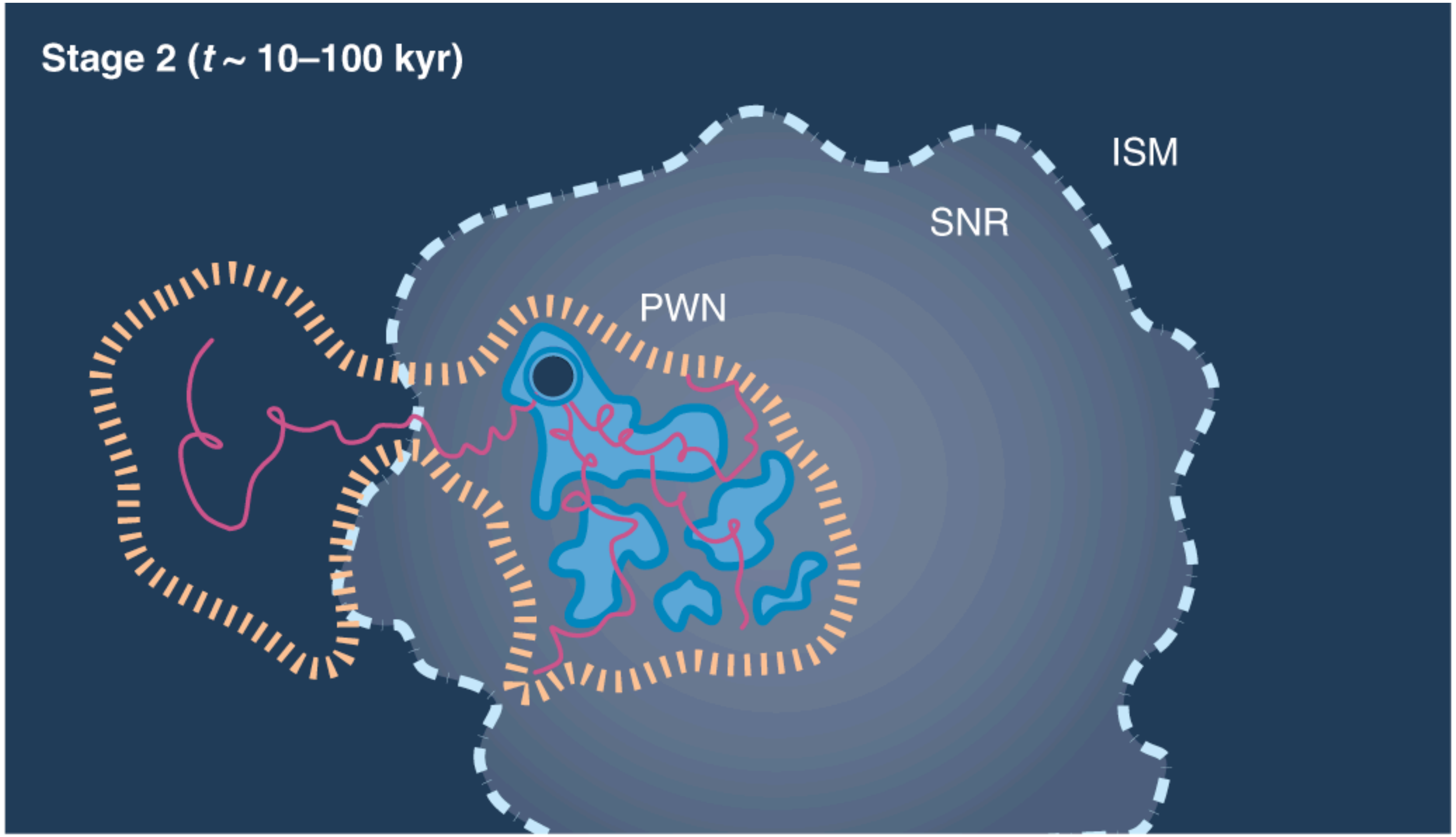
- **20% flux drop**
- **Increase in spin down rate**
- **Change in the pulsar profile**
- **Decrease energy cutoff**

Glitch!

✓ glitch cause a re-arrangement of the B structure
→ α change *(Ng+2016)*

Accelerators: Pulsar Wind Nebulae

The most numerous population in the Galaxy

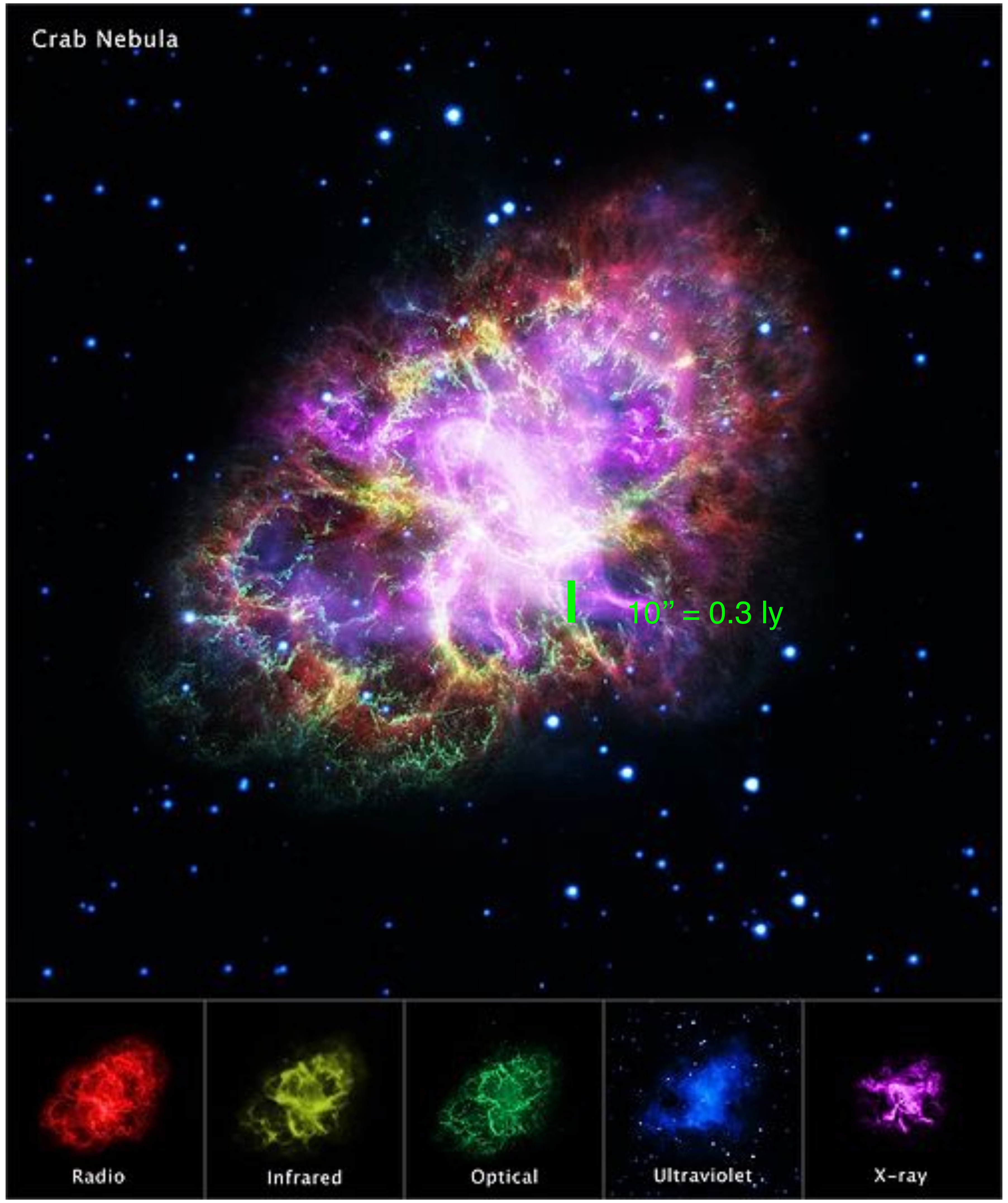


Accelerators: Pulsar Wind Nebulae

The archetype: the Crab nebula

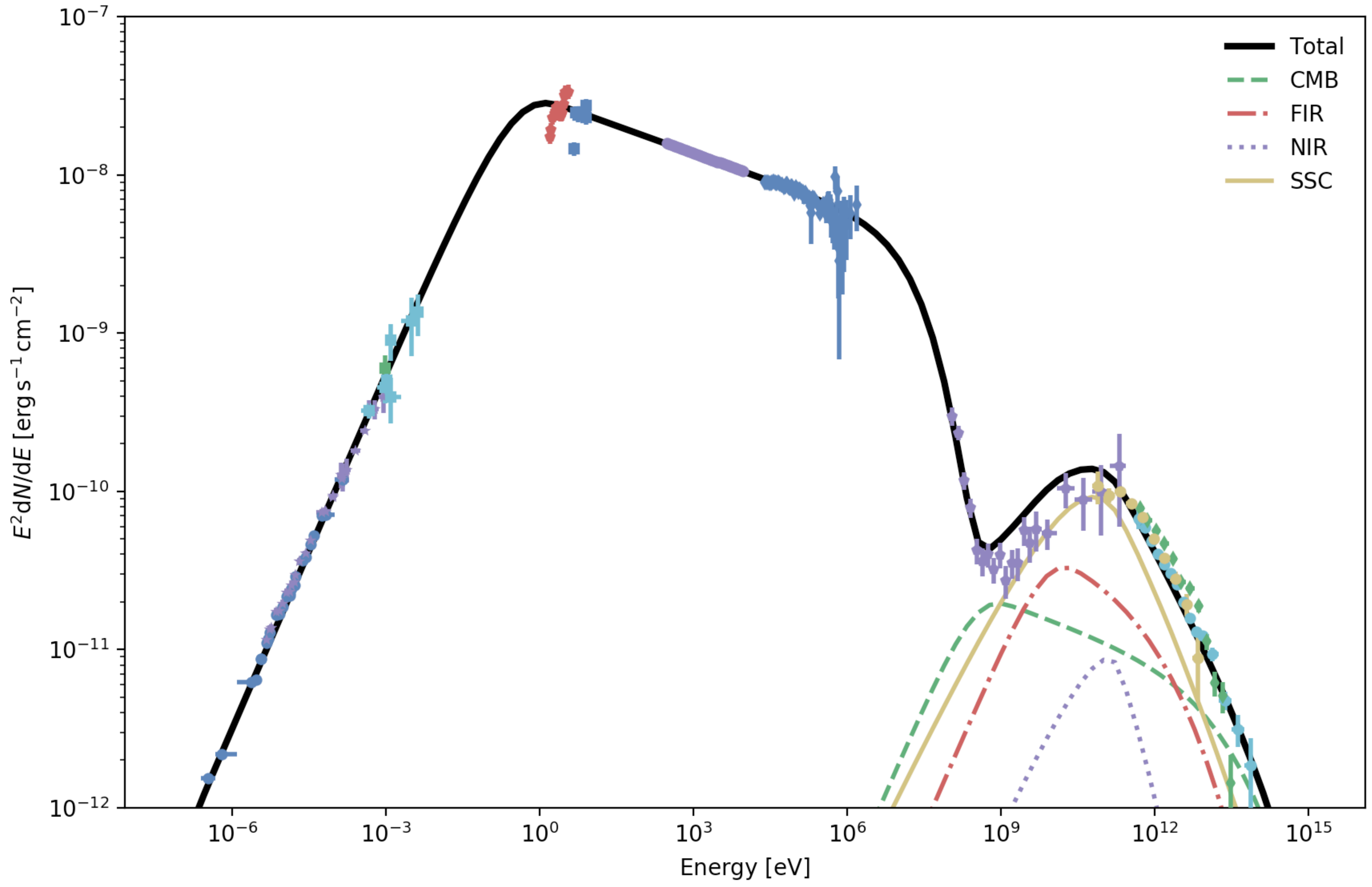
Bright in many wavelength

Different size <=> Different electron population



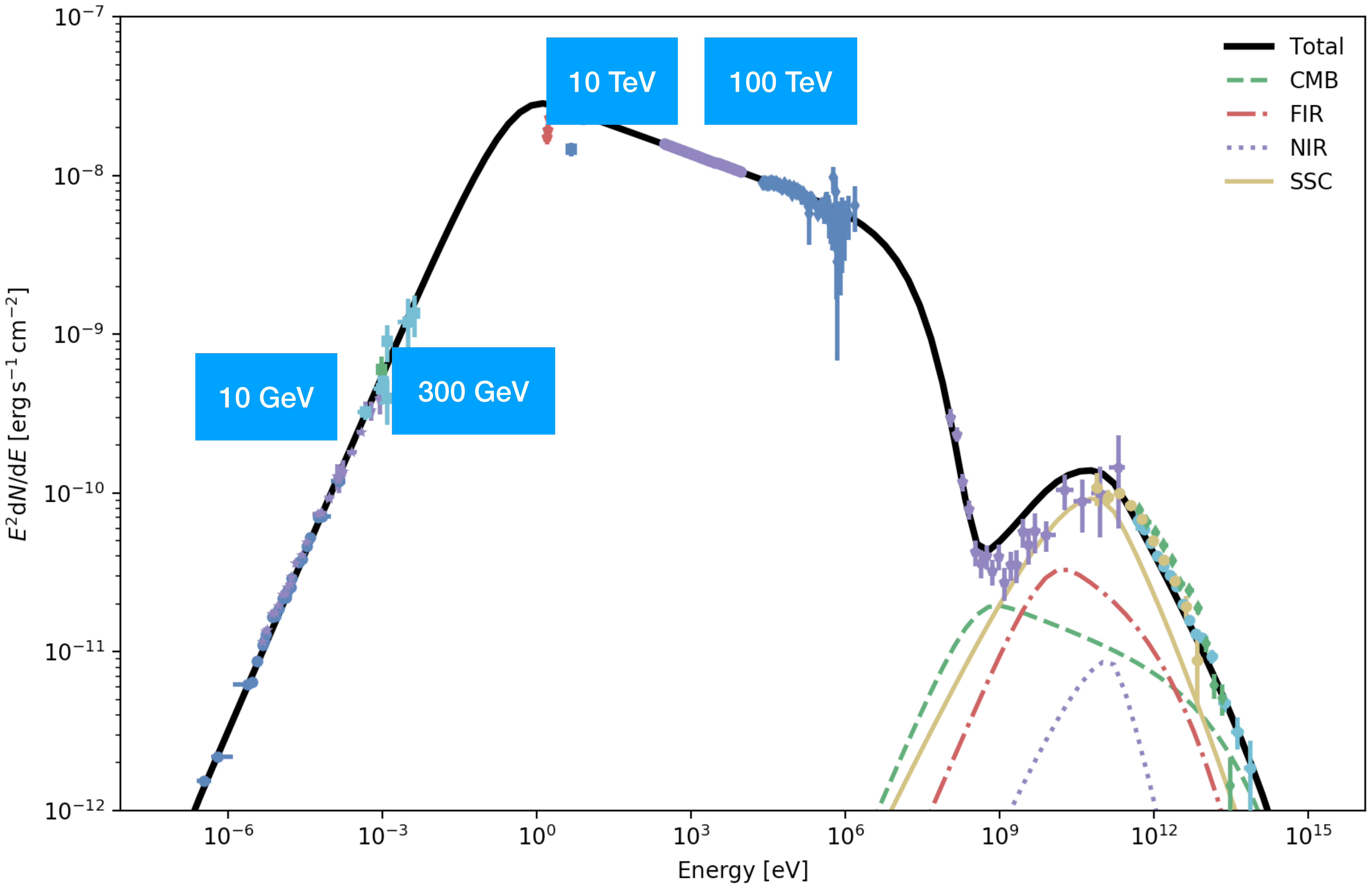
Accelerators: Pulsar Wind Nebulae

Physic of Compact objets



Accelerators: Pulsar Wind Nebulae

Physic of Compact objets



Accelerators: Pulsar Wind Nebulae

Young PWNe

- Energetics:

  Syn => Depends on the magnetic field $\dot{E}_{syn} = -\frac{4}{3}U_B c\gamma^4$

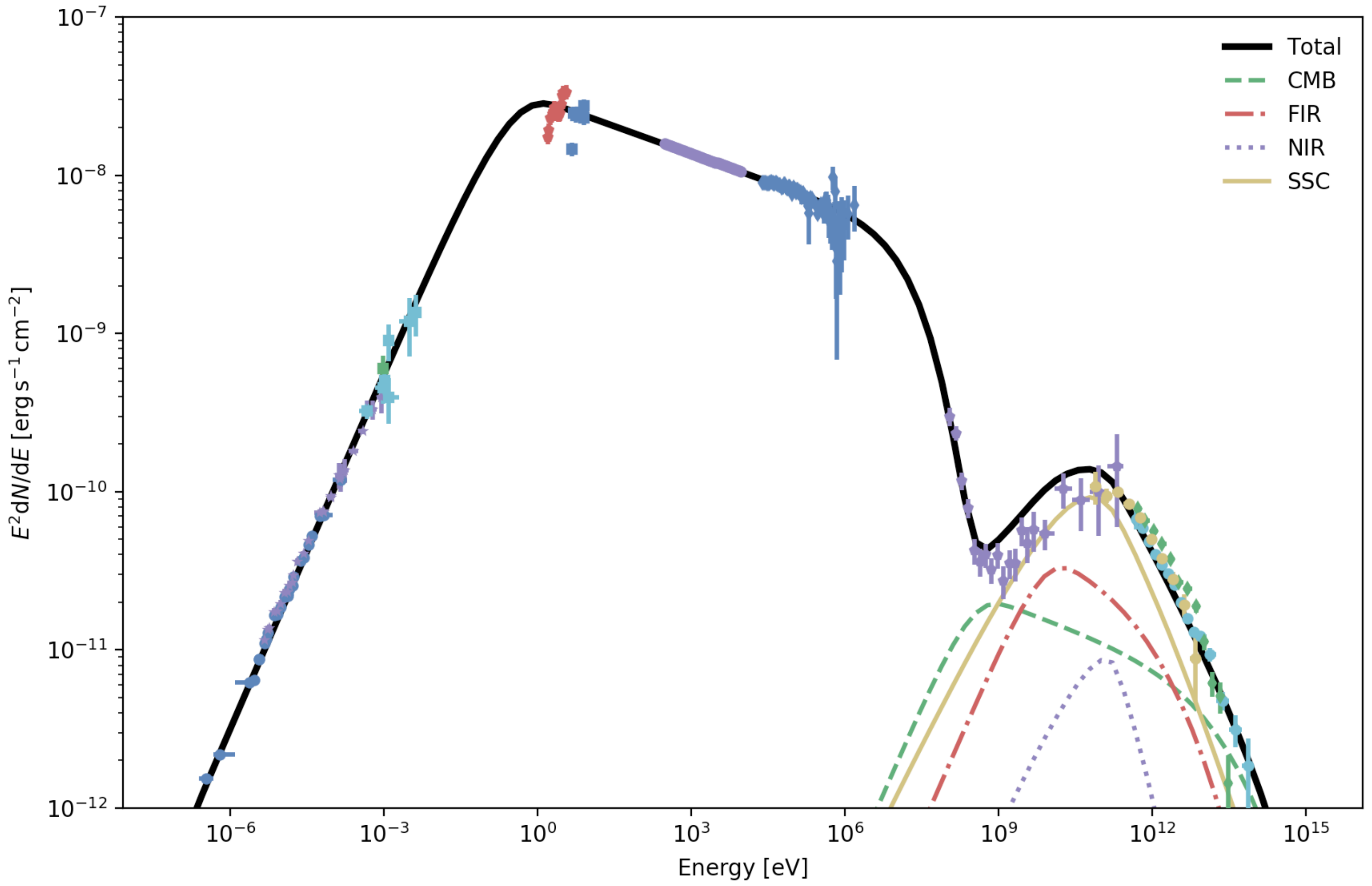
  IC => Depends on the photon field $\dot{E}_{IC} = -\frac{4}{3}U_{ph} c\gamma^2$

Sum of the electric fields of the incident waves

Motion of an electron in a Bfield

$$\frac{L_1}{L_2} = \frac{\dot{E}_1}{\dot{E}_2}$$

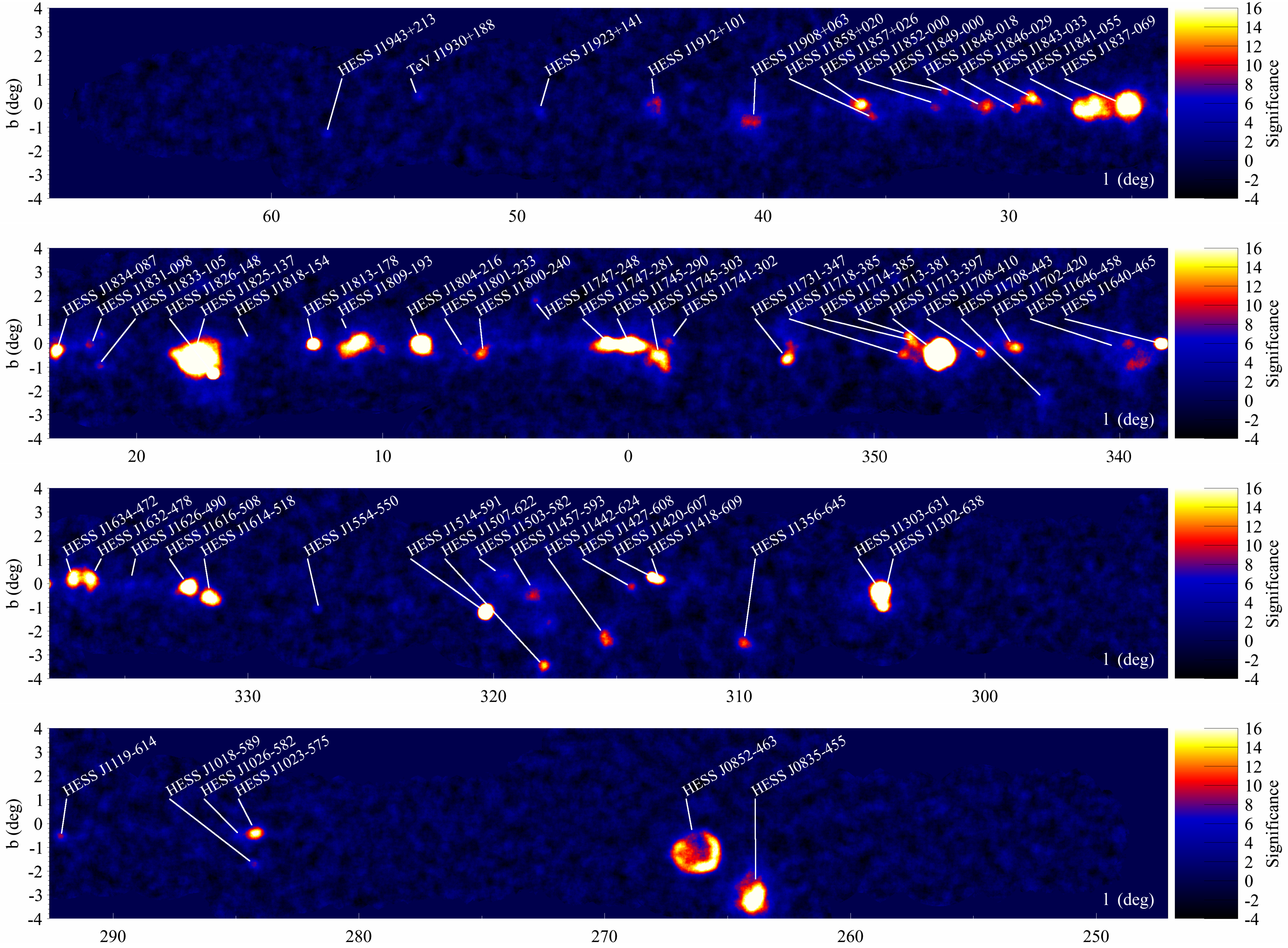
$$\frac{L_1}{L_2} = \frac{U_B}{U_{ph}} = \frac{\frac{B^2}{8\pi}}{\omega_{CMB} + \omega_{FIR} + \omega_{NIR} + \omega_{SYN}}$$

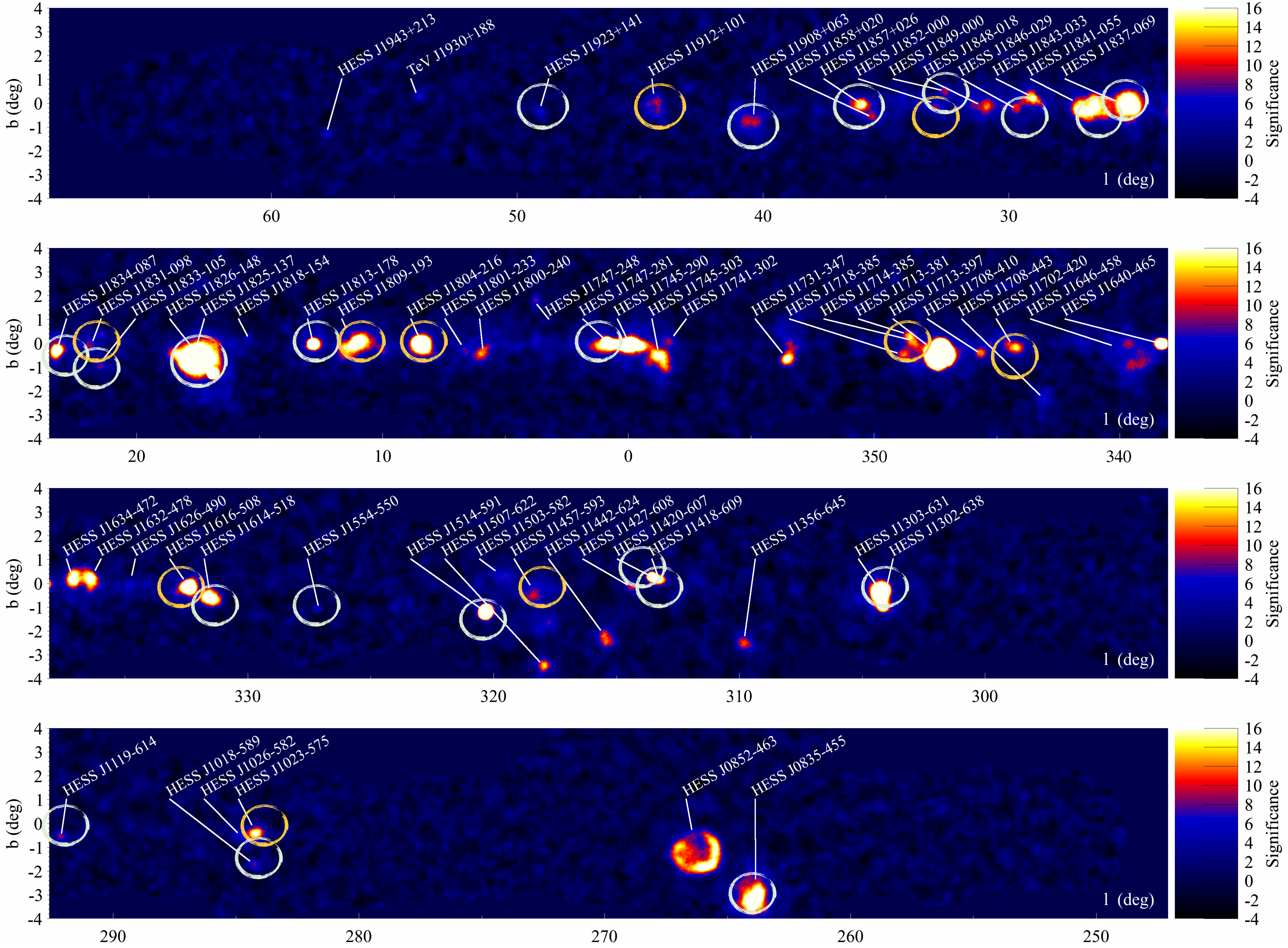


$$\frac{L_{IC}}{L_{syn}} \approx \left(\frac{B}{3\mu G}\right)^{-2}$$

For CMB

B~ 100 uG


b (deg)
l (deg)
Significance
60
50
40
30
20
10
0
350
340
330
320
310
300
290
280
270
260
250
HESS J1943+213
TeV J1930+188
HESS J1923+141
HESS J1912+101
HESS J1908+063
HESS J1858+020
HESS J1857+026
HESS J1852-000
HESS J1849-000
HESS J1848-018
HESS J1846-029
HESS J1843-033
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1831-098
HESS J1833-105
HESS J1826-148
HESS J1825-137
HESS J1818-154
HESS J1813-178
HESS J1809-193
HESS J1804-216
HESS J1801-233
HESS J1800-240
HESS J1747-248
HESS J1747-281
HESS J1745-290
HESS J1745-303
HESS J1741-302
HESS J1731-347
HESS J1718-385
HESS J1714-385
HESS J1713-381
HESS J1713-397
HESS J1708-410
HESS J1708-443
HESS J1702-420
HESS J1646-458
HESS J1640-465
HESS J1634-472
HESS J1632-478
HESS J1626-490
HESS J1616-508
HESS J1614-518
HESS J1554-550
HESS J1514-591
HESS J1507-622
HESS J1503-582
HESS J1457-593
HESS J1442-624
HESS J1427-608
HESS J1420-607
HESS J1418-609
HESS J1356-645
HESS J1303-631
HESS J1302-638
HESS J1119-614
HESS J1018-589
HESS J1026-582
HESS J1023-575
HESS J0852-463
HESS J0835-455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HESS J1849-000
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HESS J1846-029
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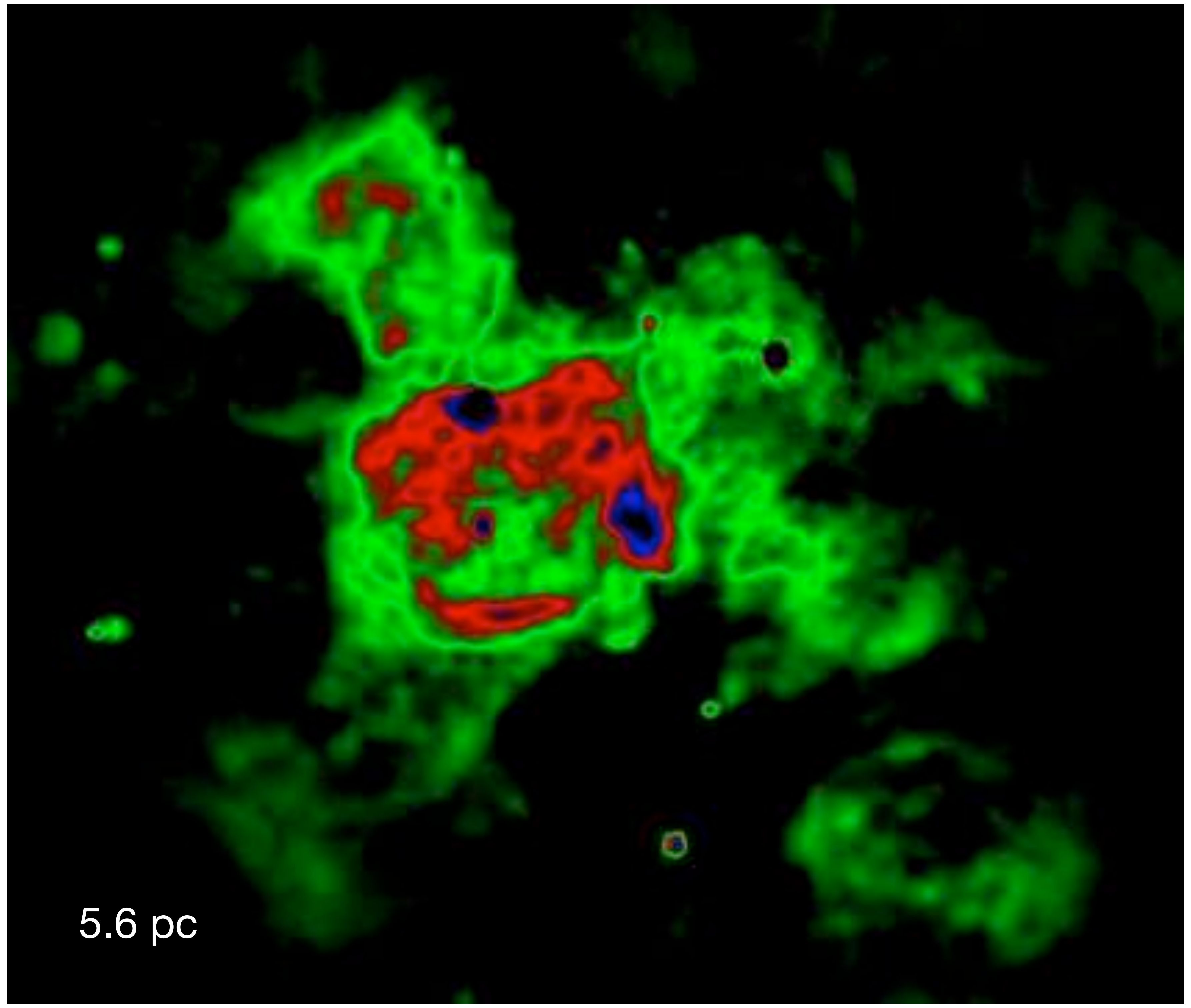
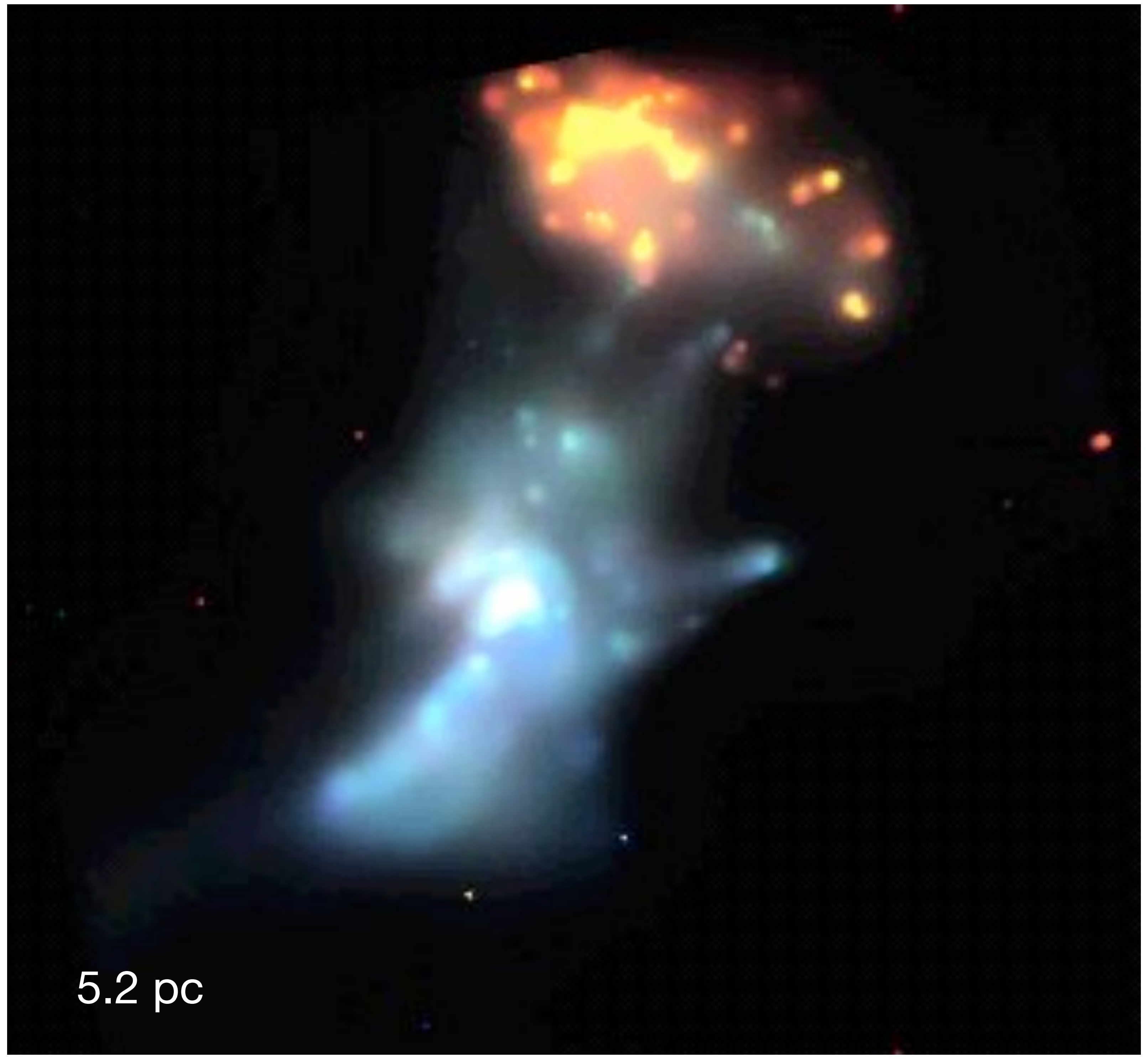
HESS J1418-609
HESS J1356-645
HESS J1303-631
HESS J1302-638
HESS J1119-614
HESS J1018-589
HESS J1026-582
HESS J1023-575
HESS J0852-463
HESS J0835-455
b (deg)
l (deg)
Significance

Accelerators: Pulsar Wind Nebulae

Young PWNe

Excellent correlation with X-rays (large size compensates sometimes the relatively poor angular resolution ~0.1deg





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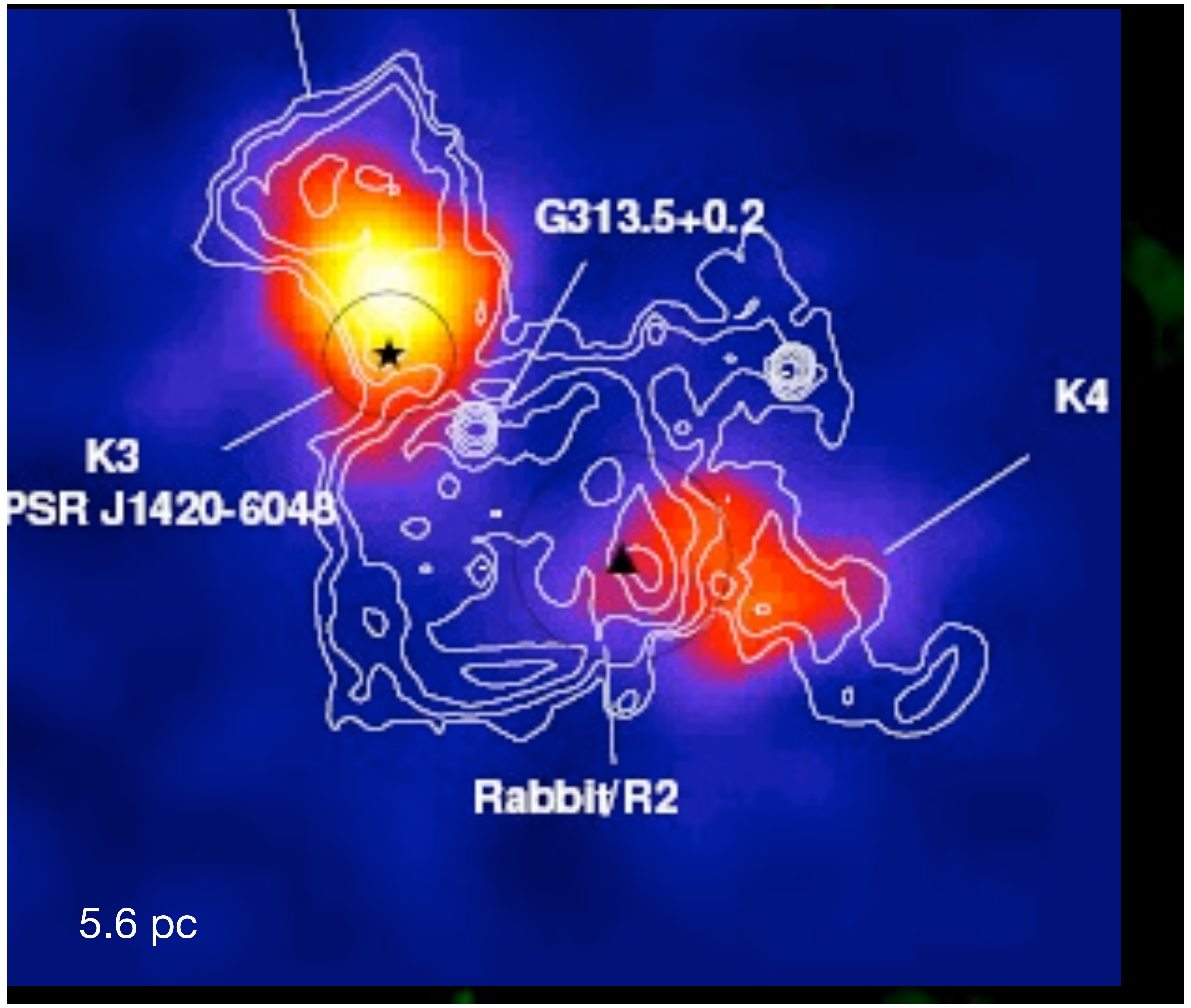

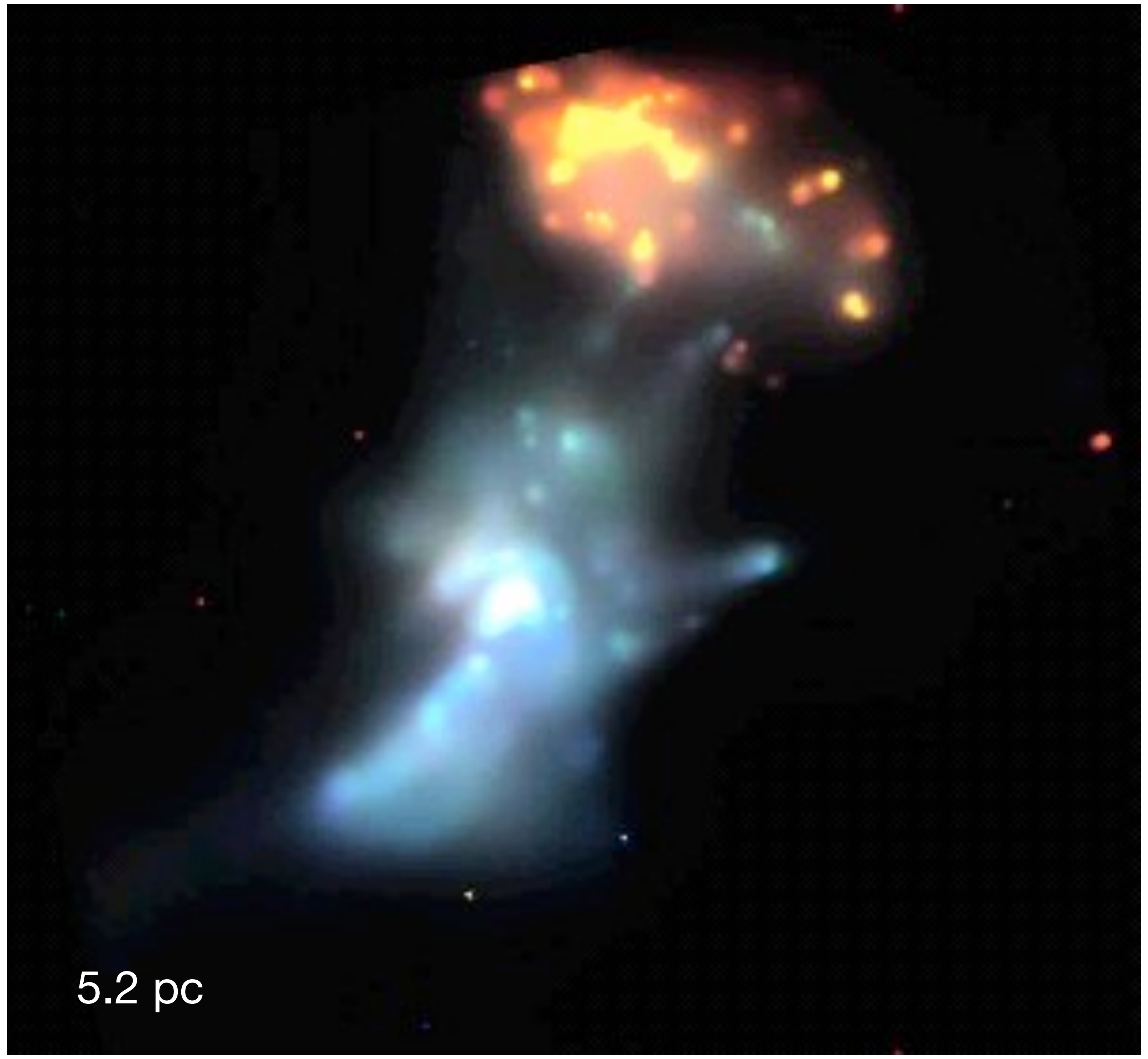

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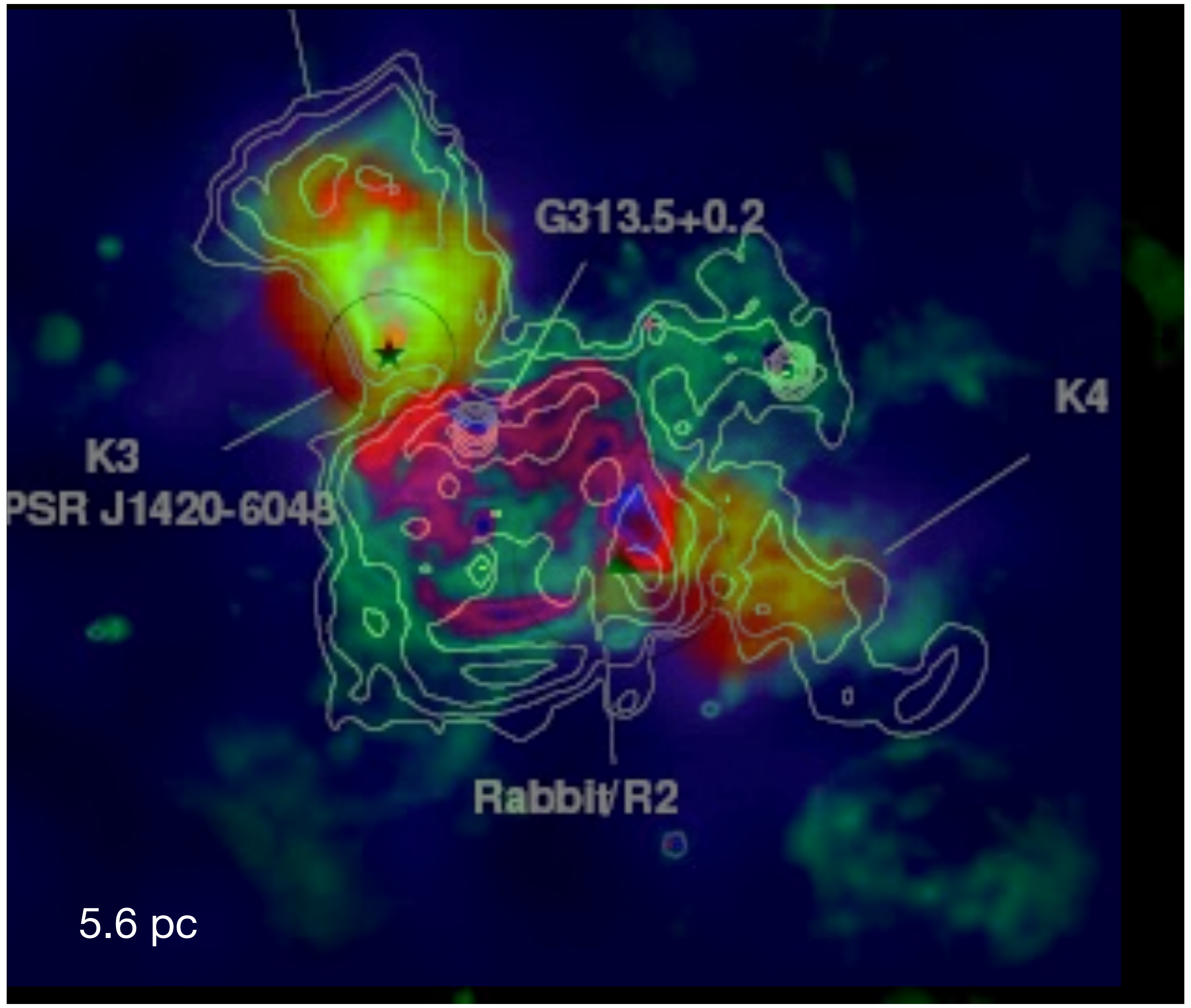

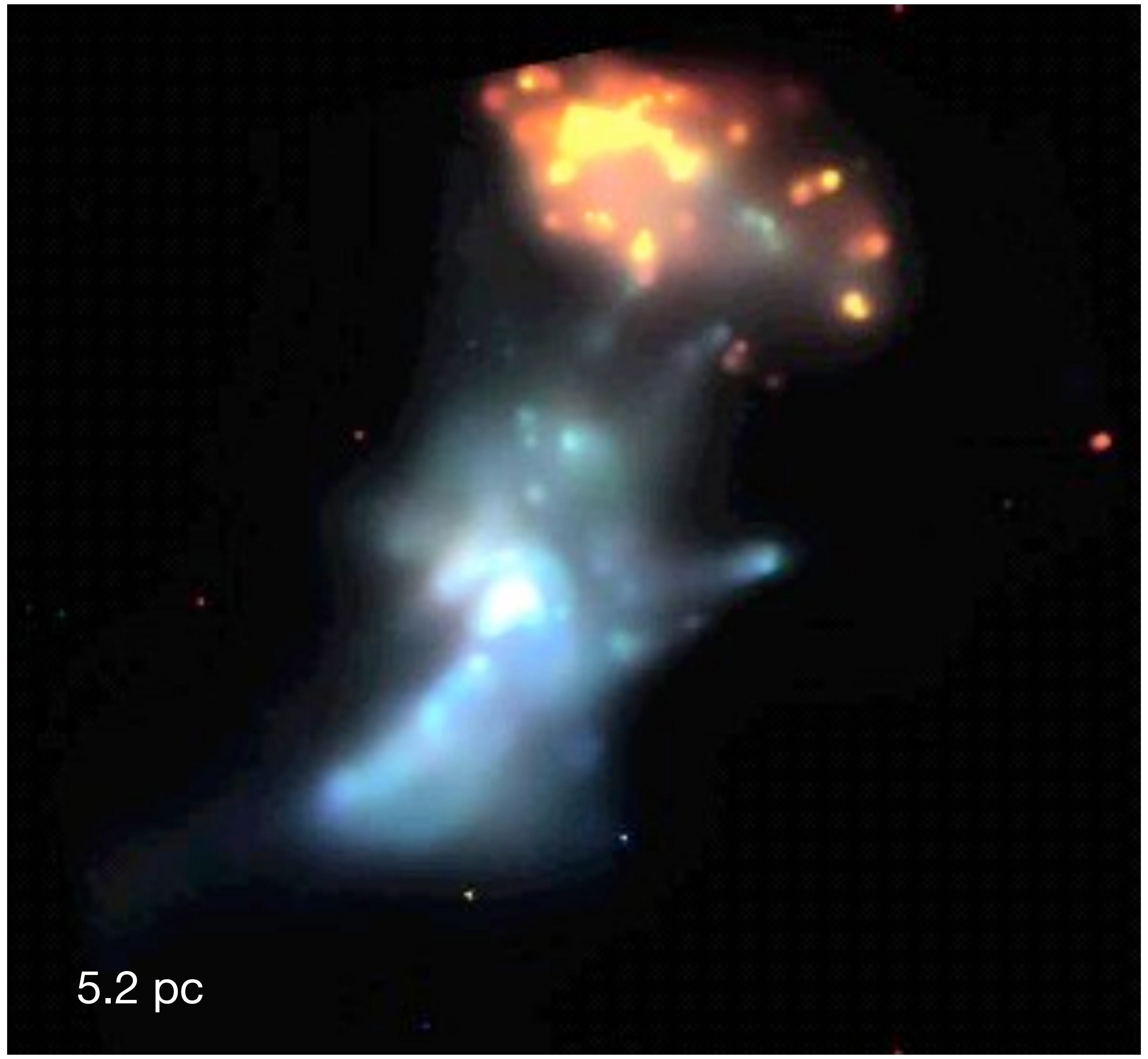

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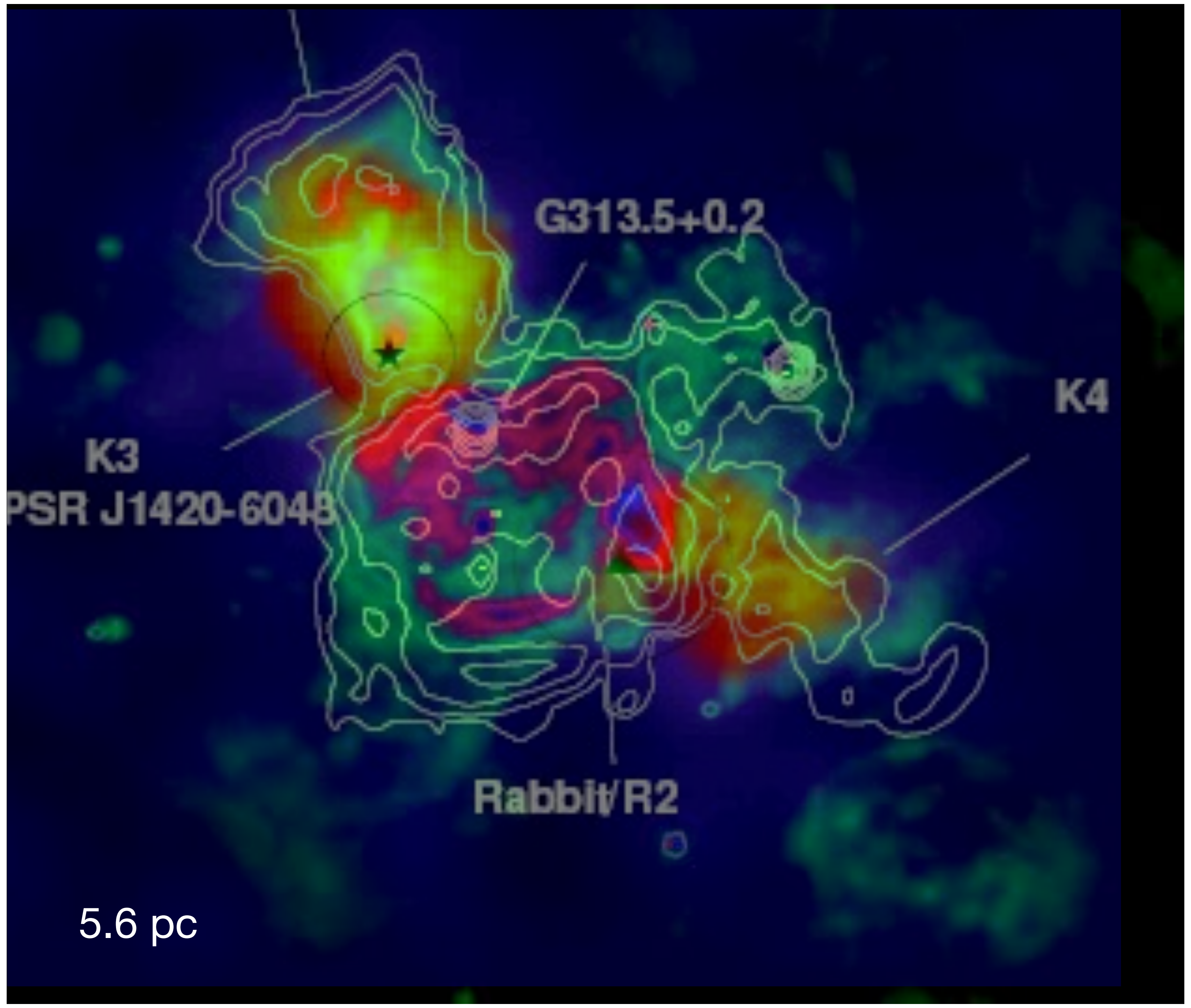

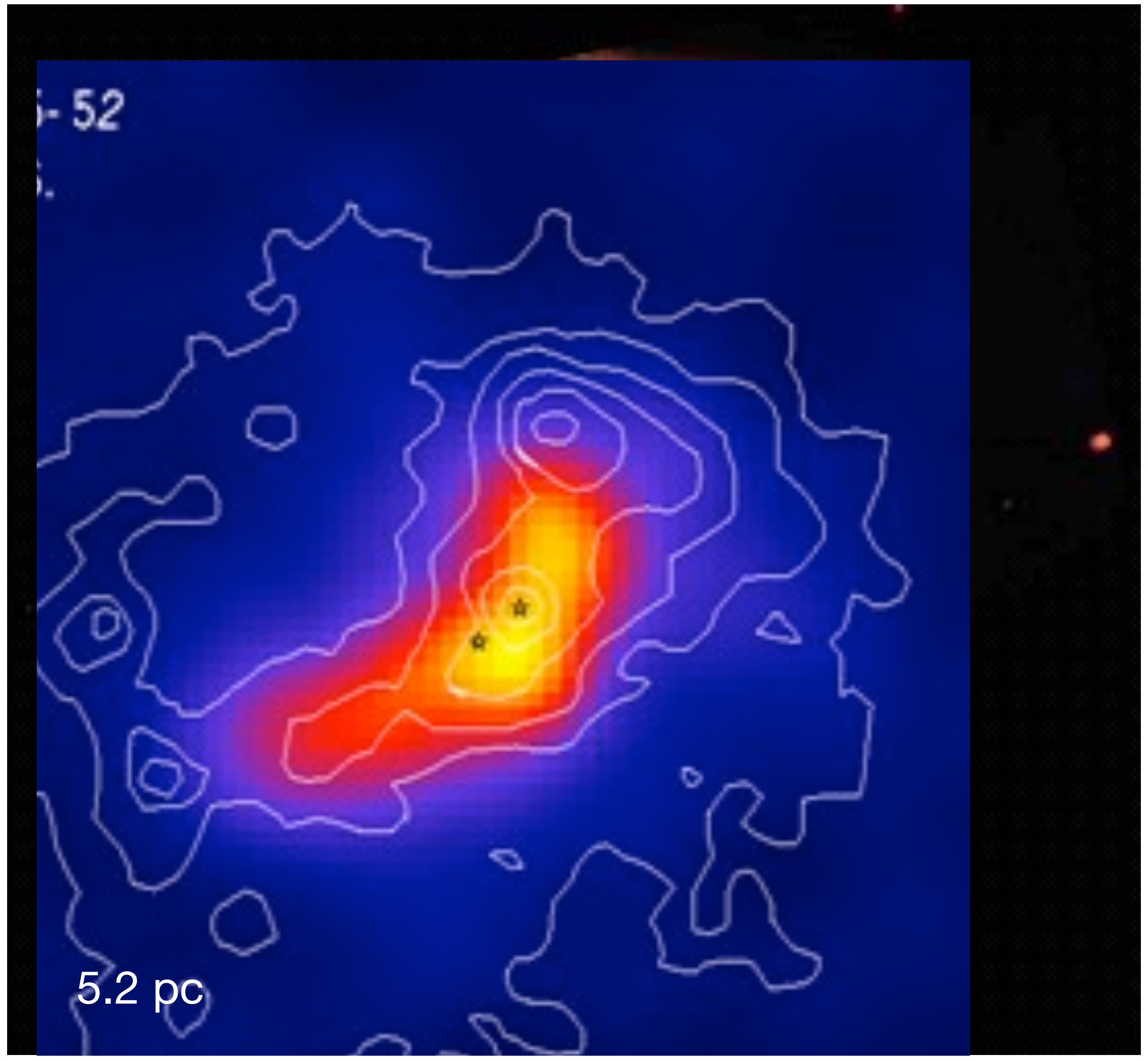

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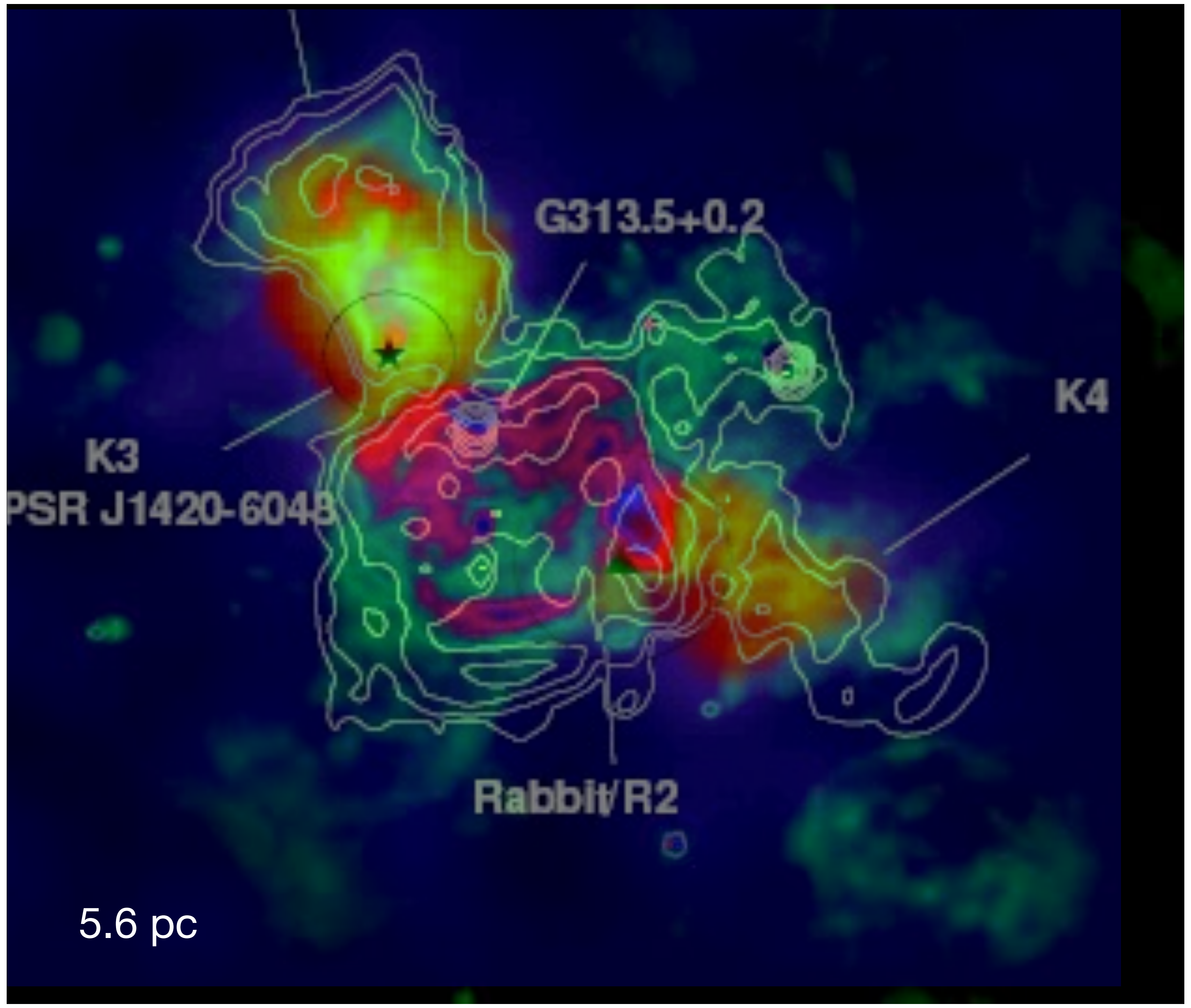
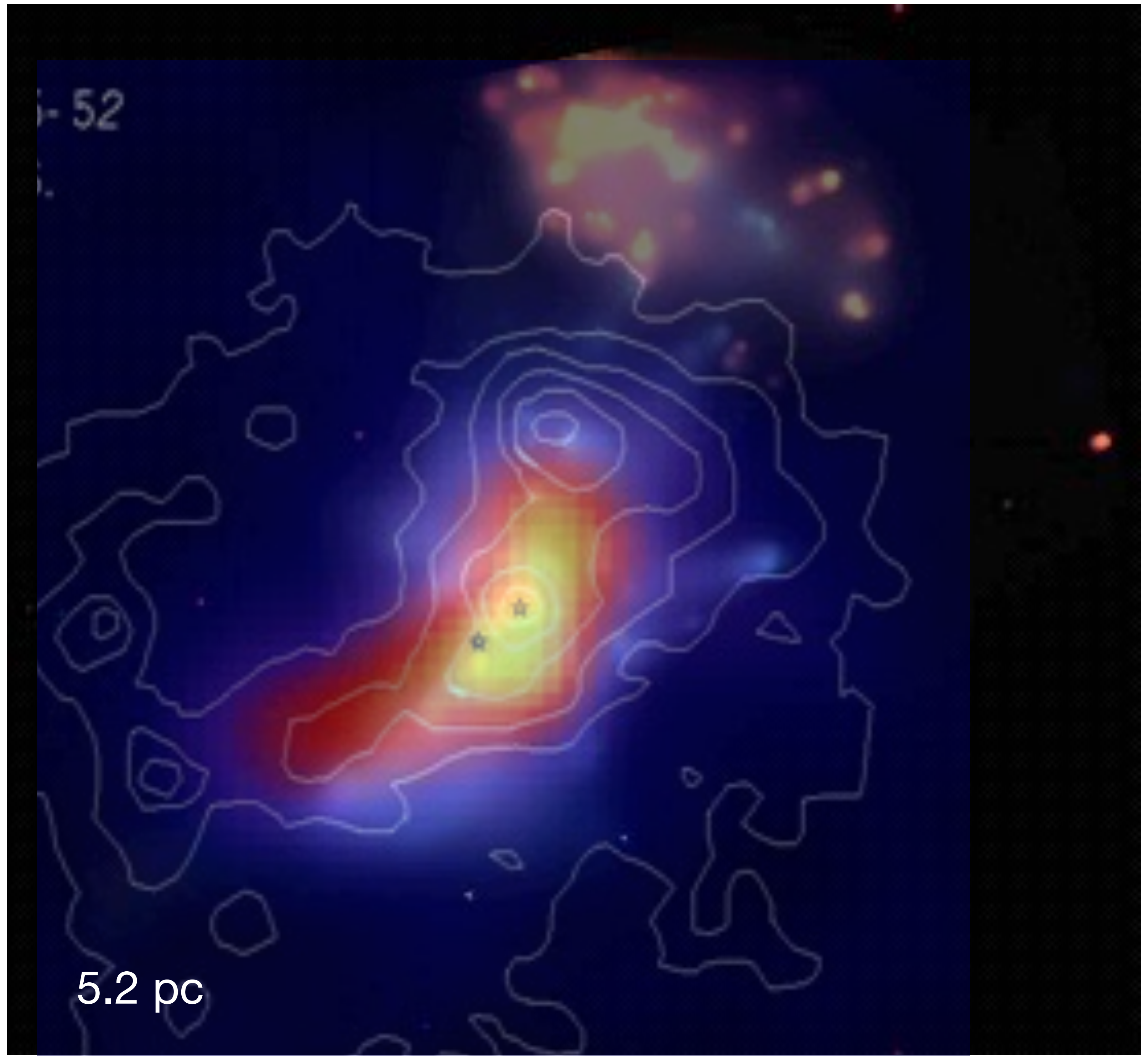
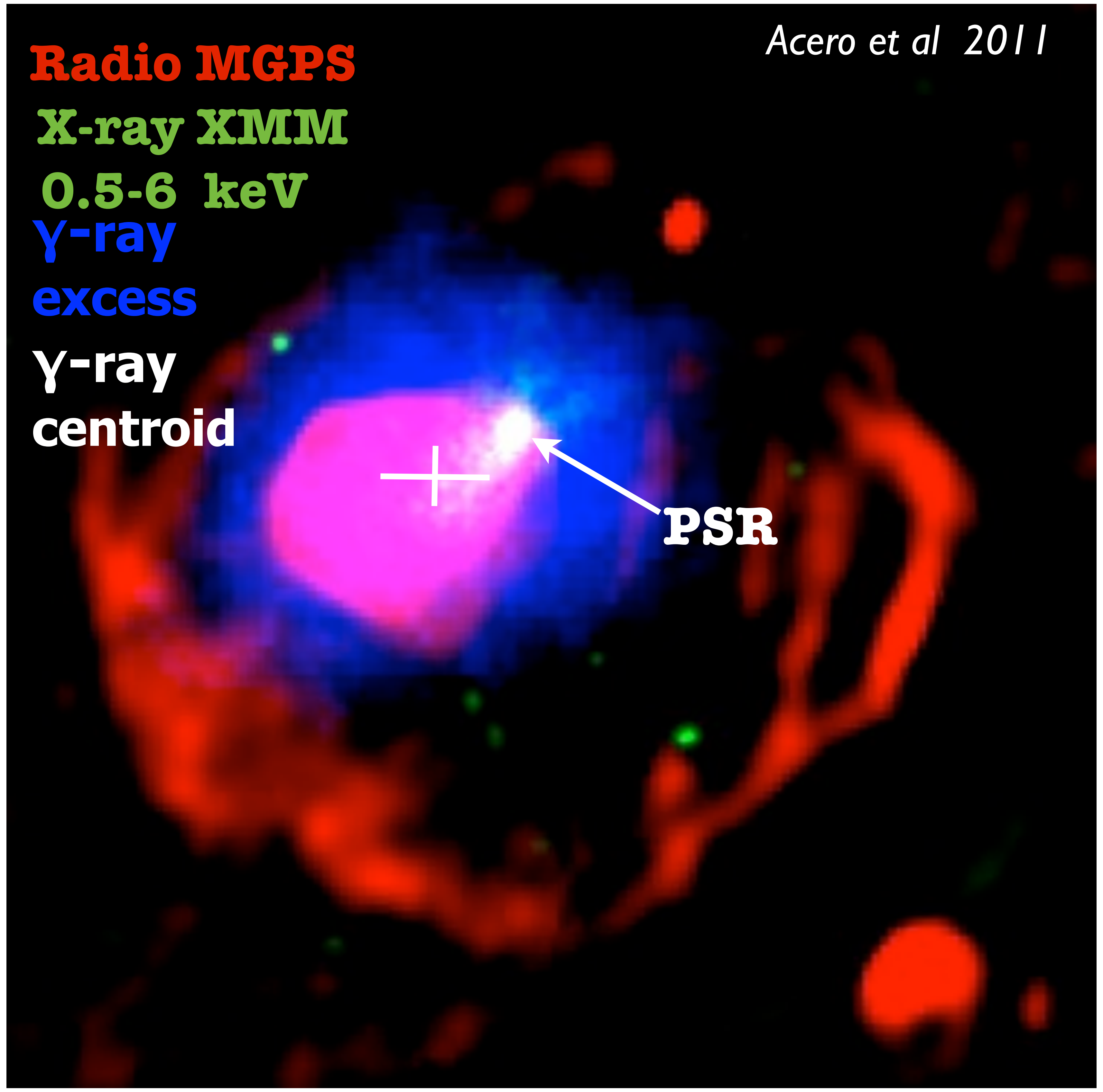


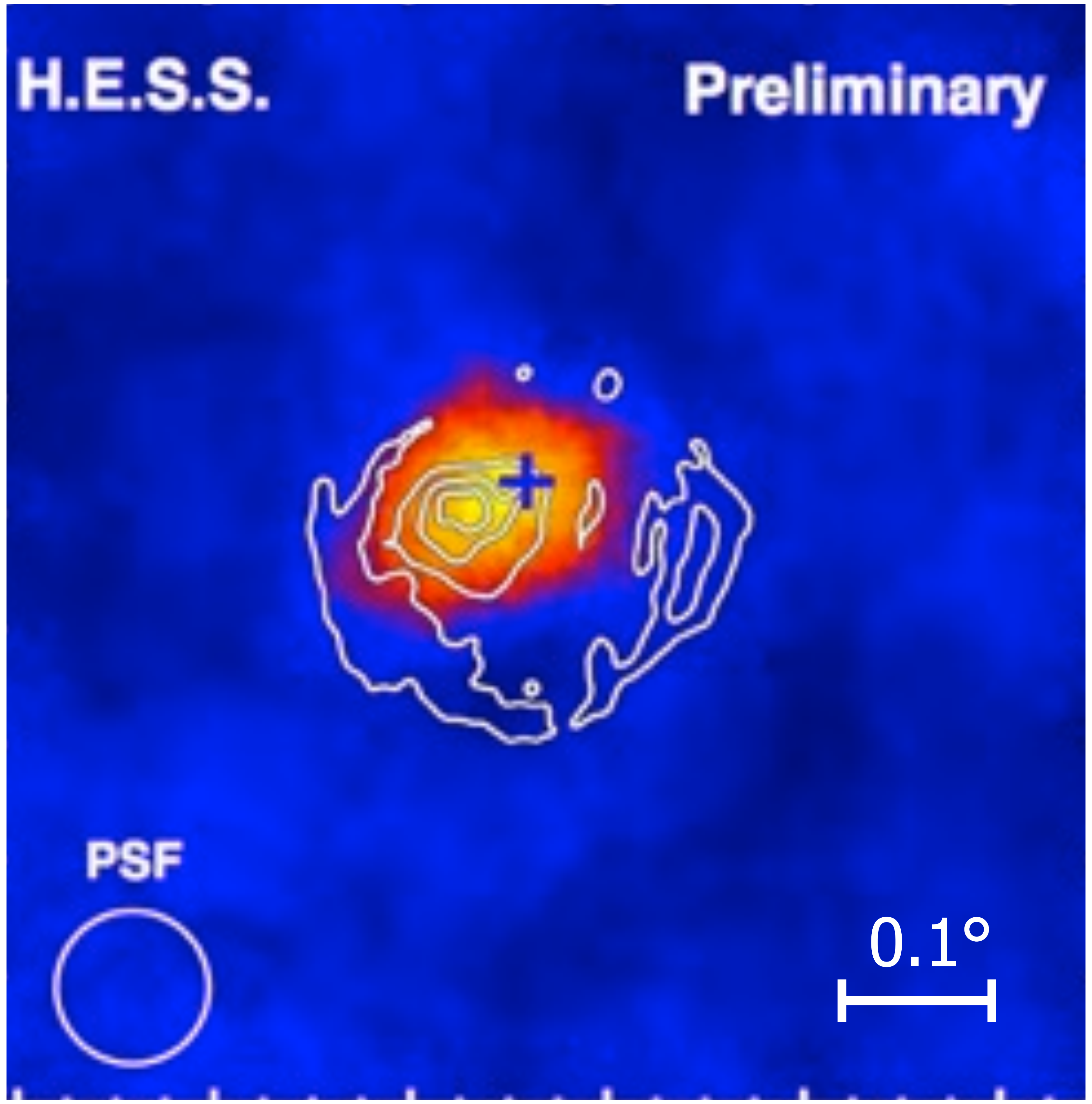


Accelerators: Pulsar Wind Nebulae

Young PWNe

Very low magnetic fields when comparing with Lx ~ few uG => Far from equipartition

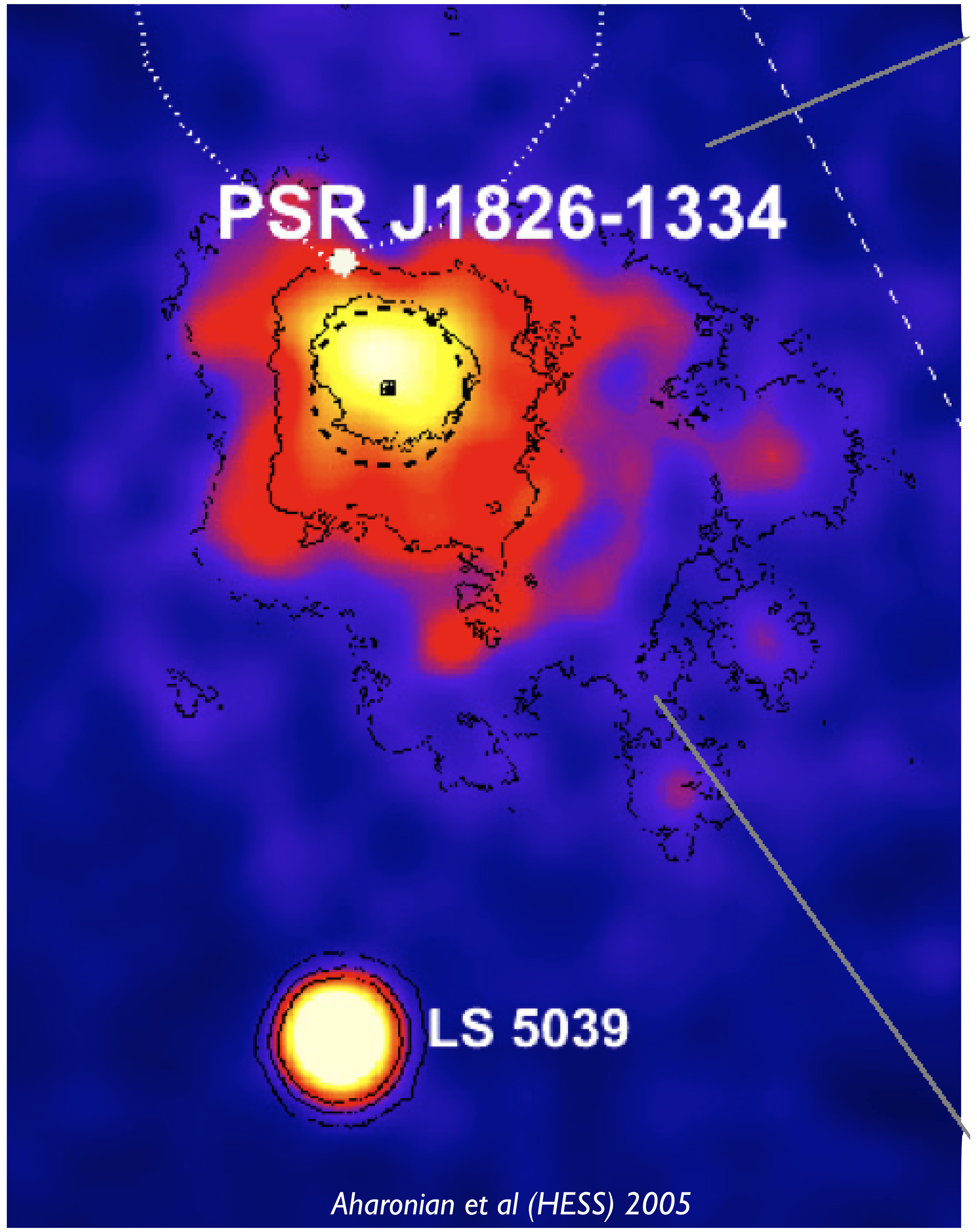




Accelerators: Pulsar Wind Nebulae

Evolved PWNe

21 kys



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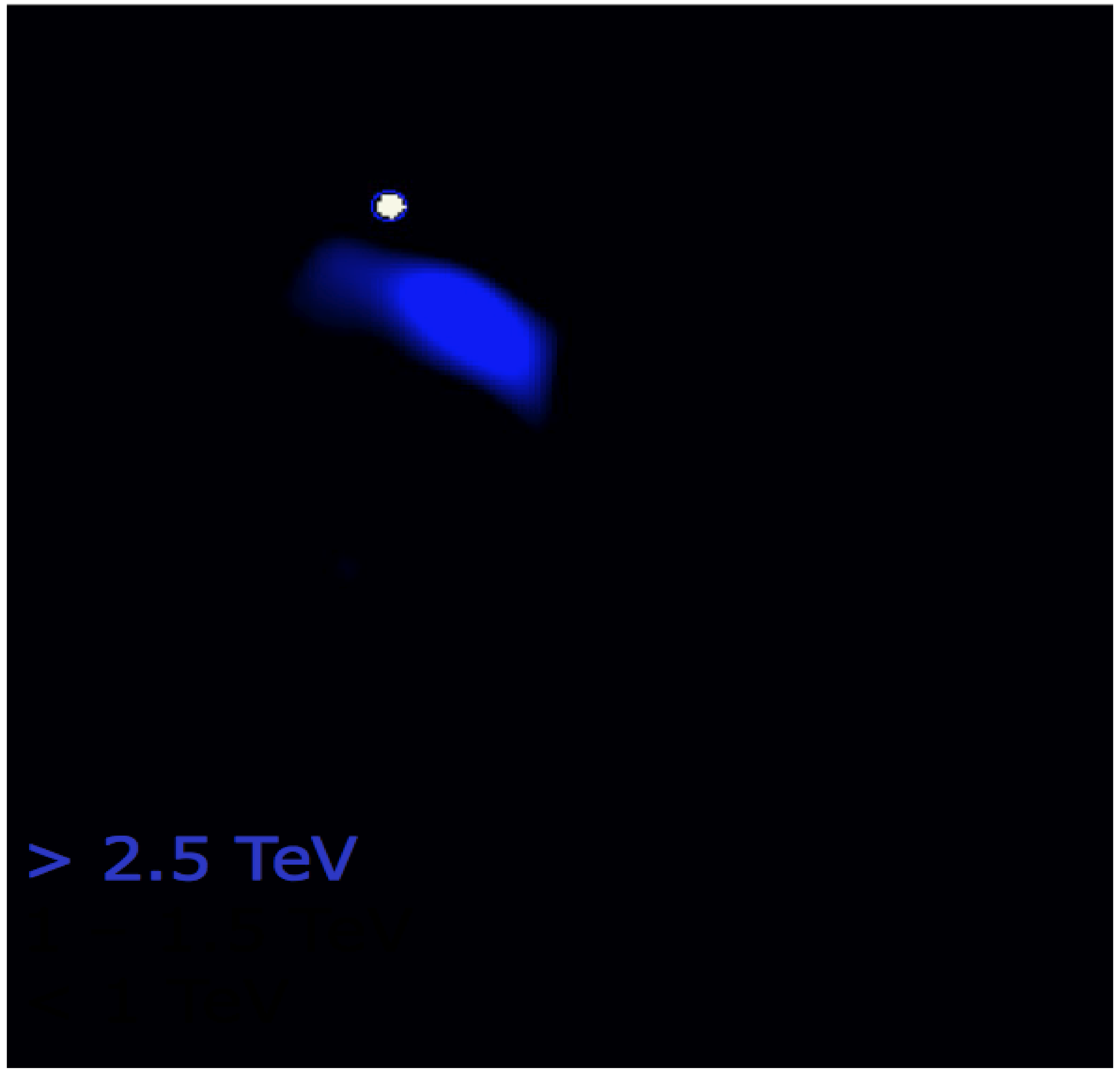

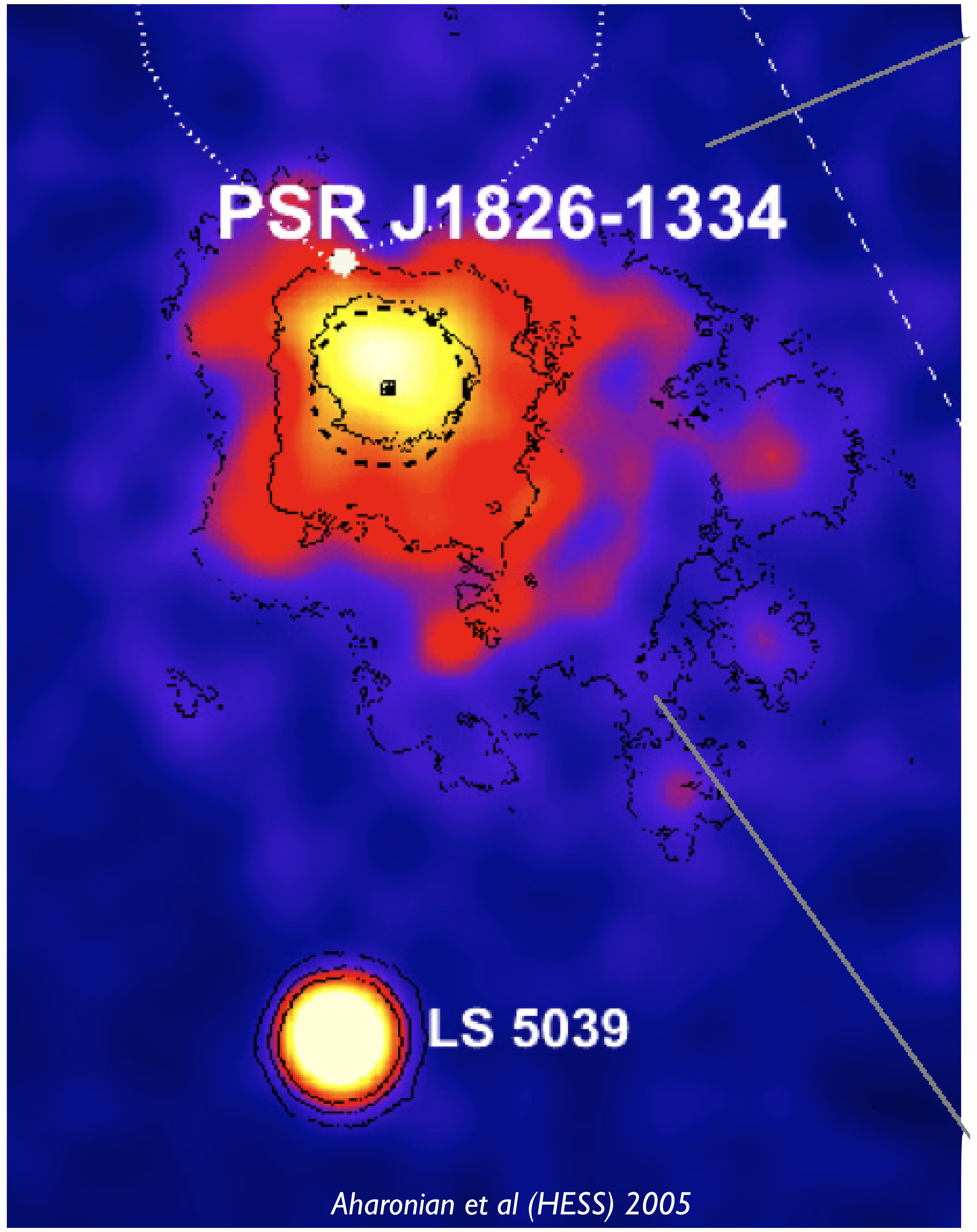

Aharonian et al (HESS) 2005

Accelerators: Pulsar Wind Nebulae

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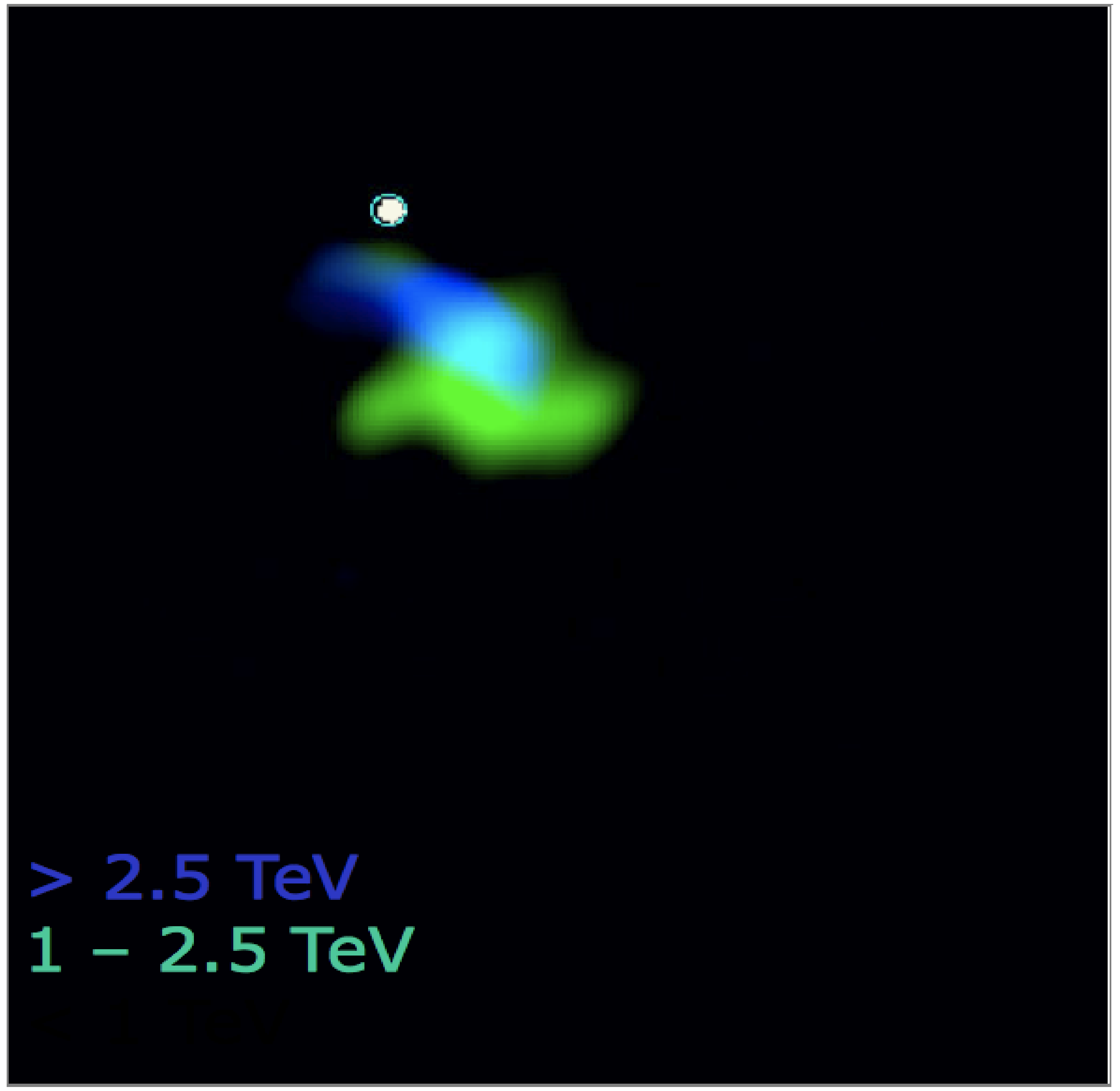

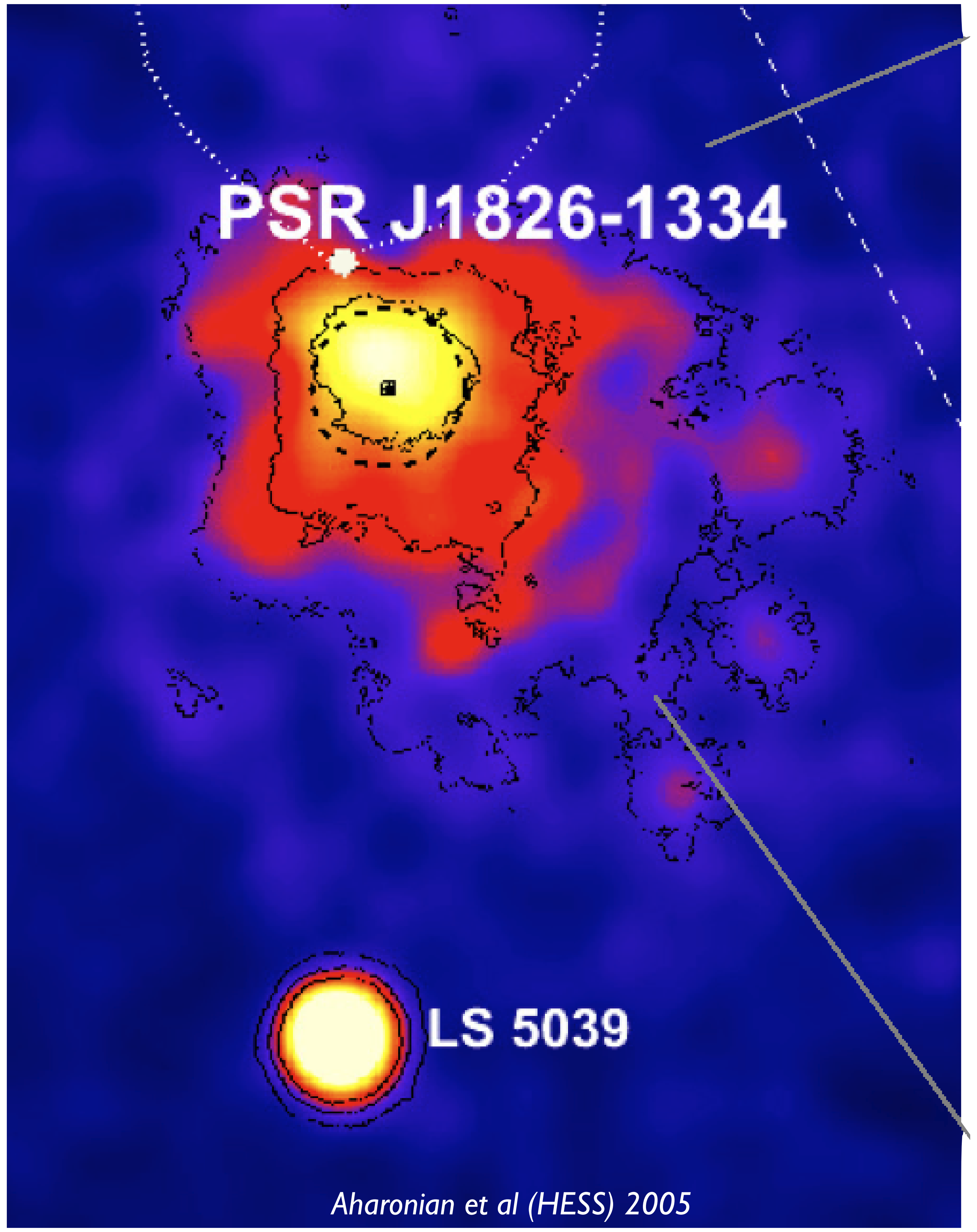

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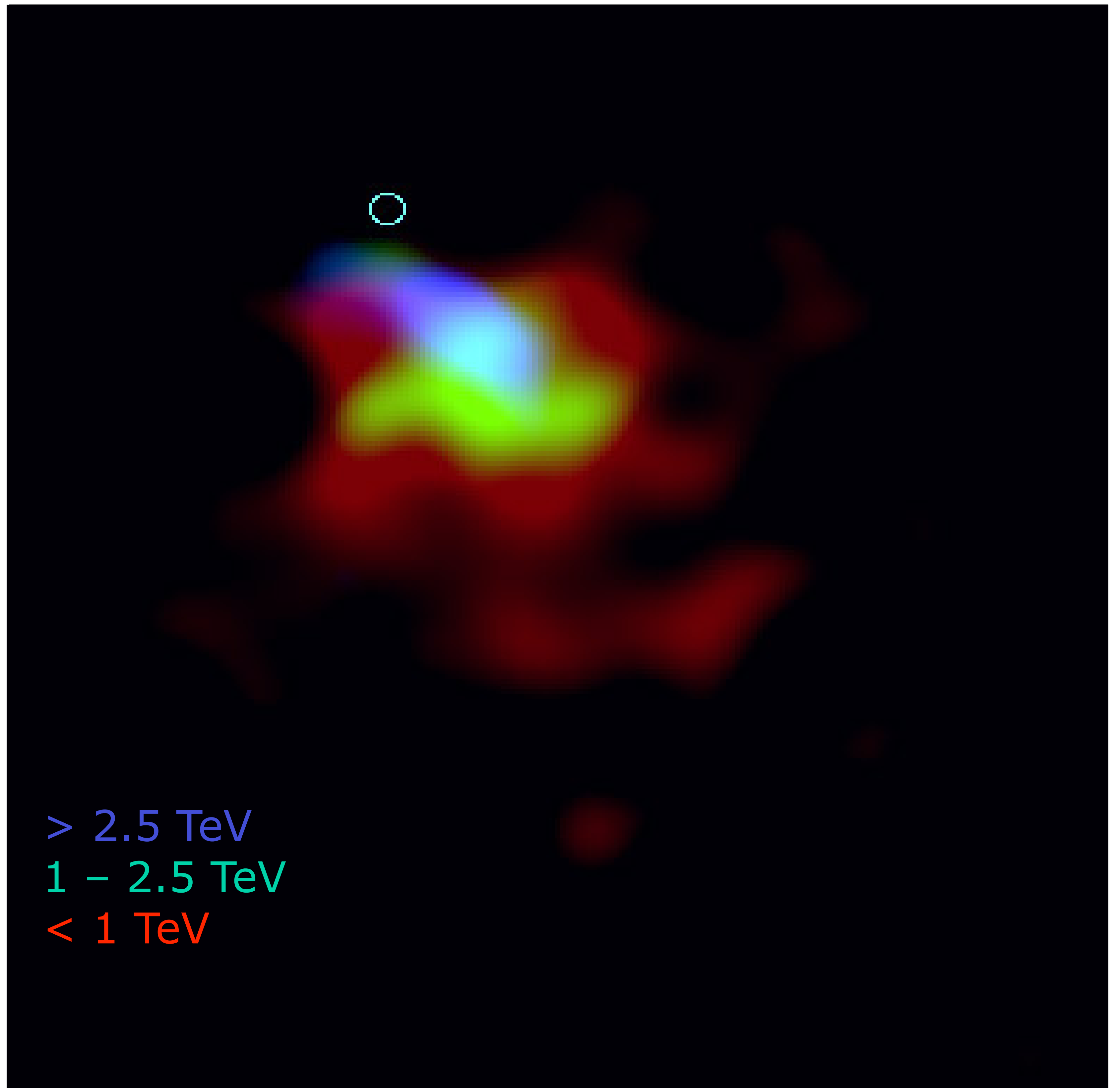

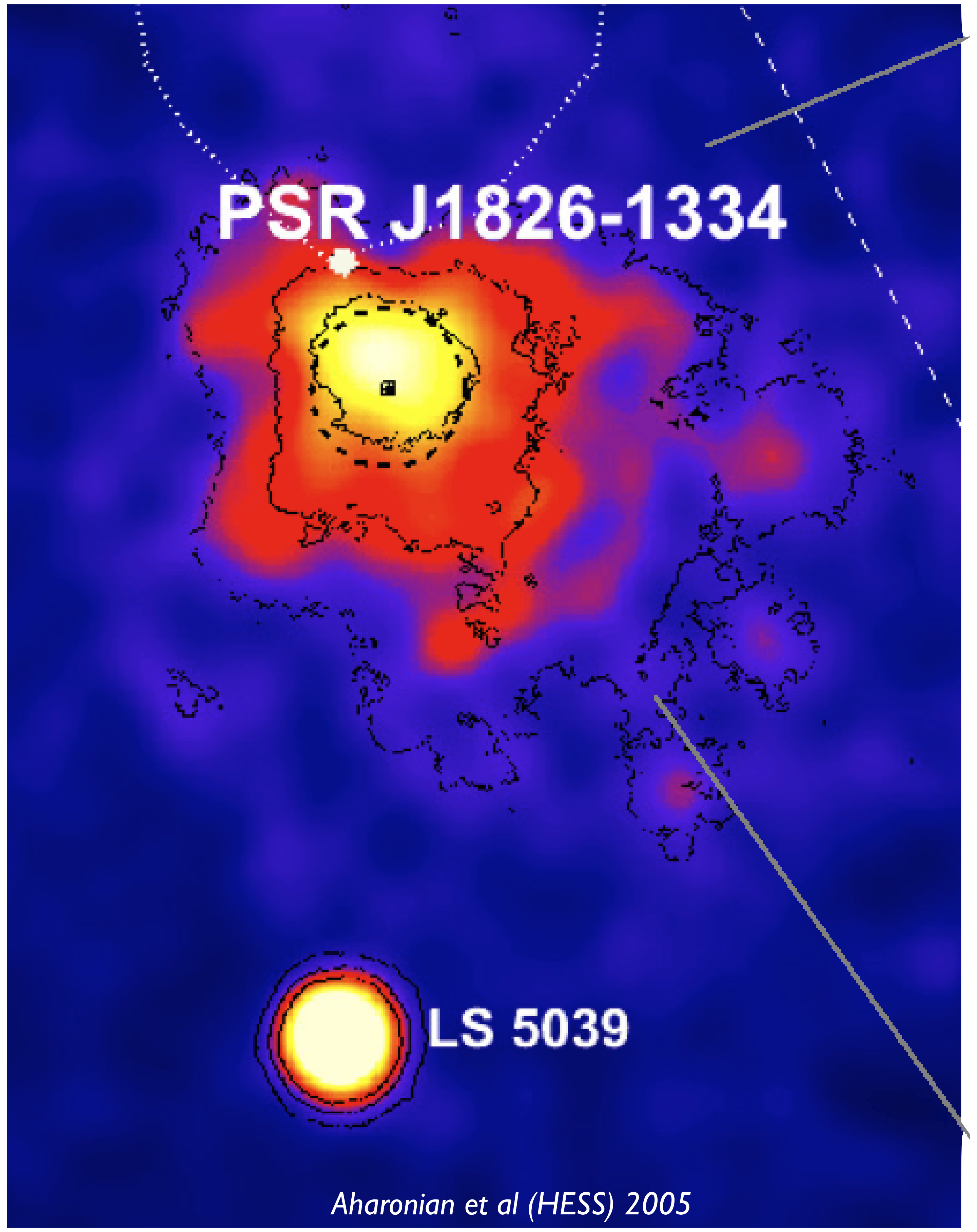

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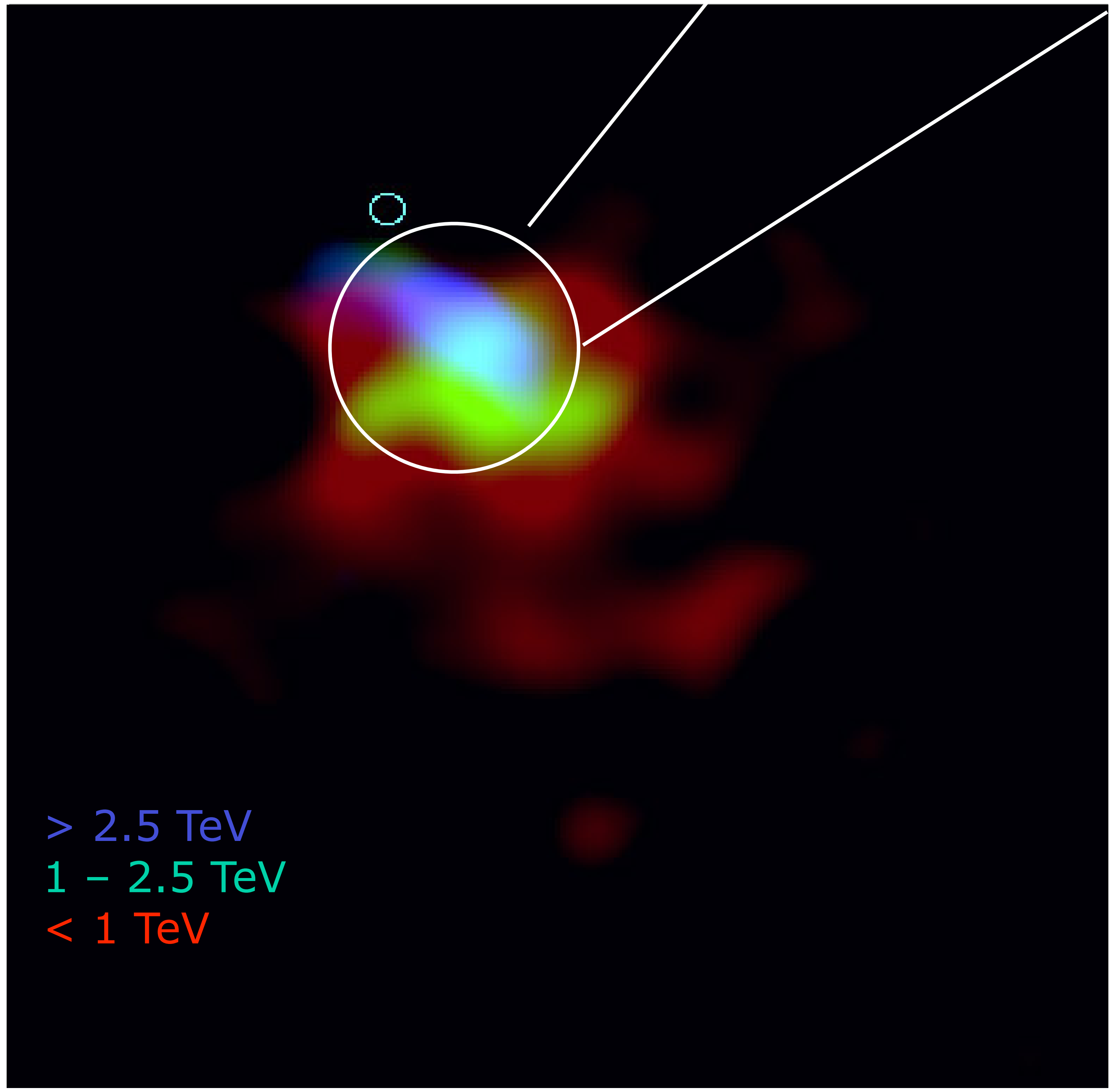

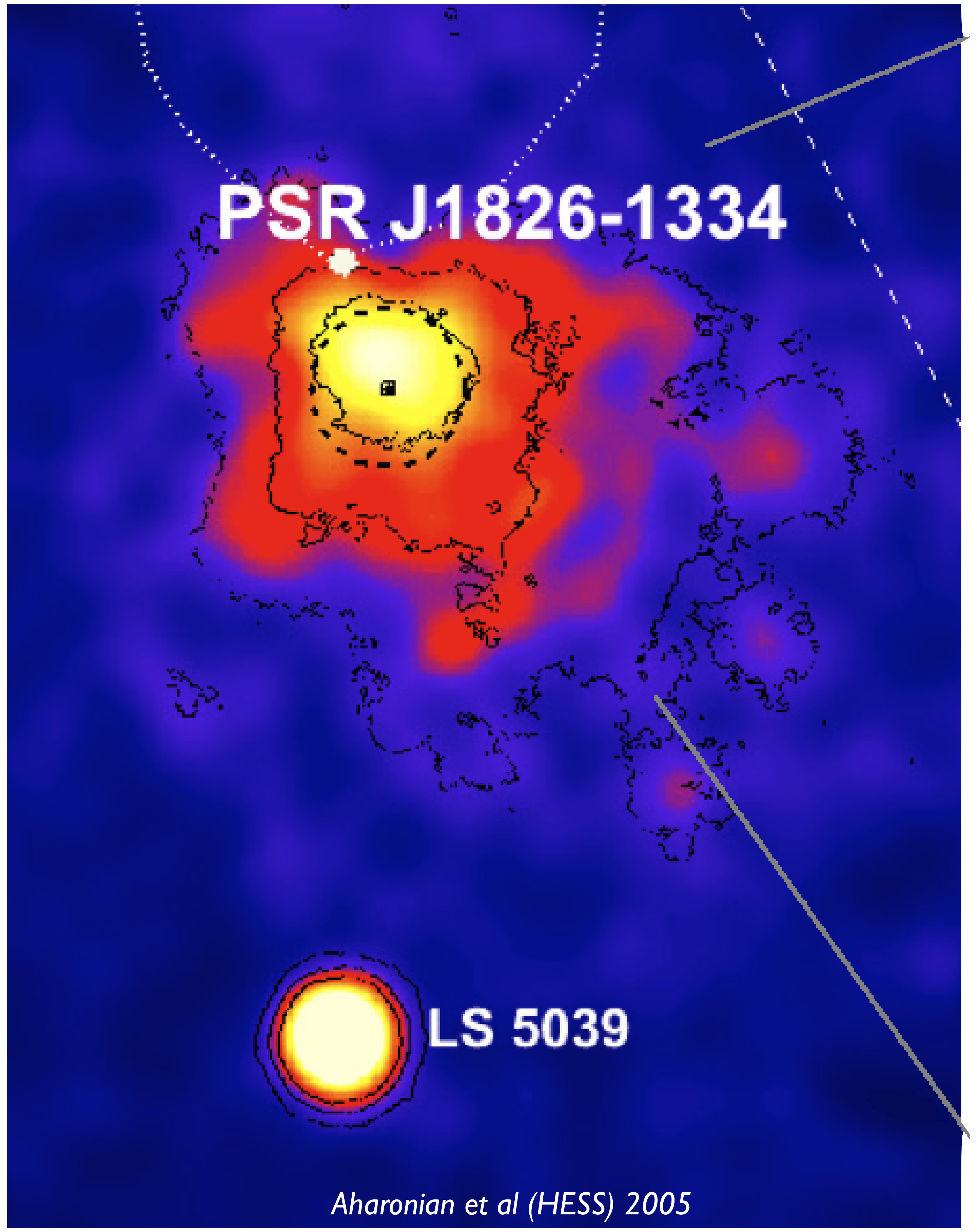

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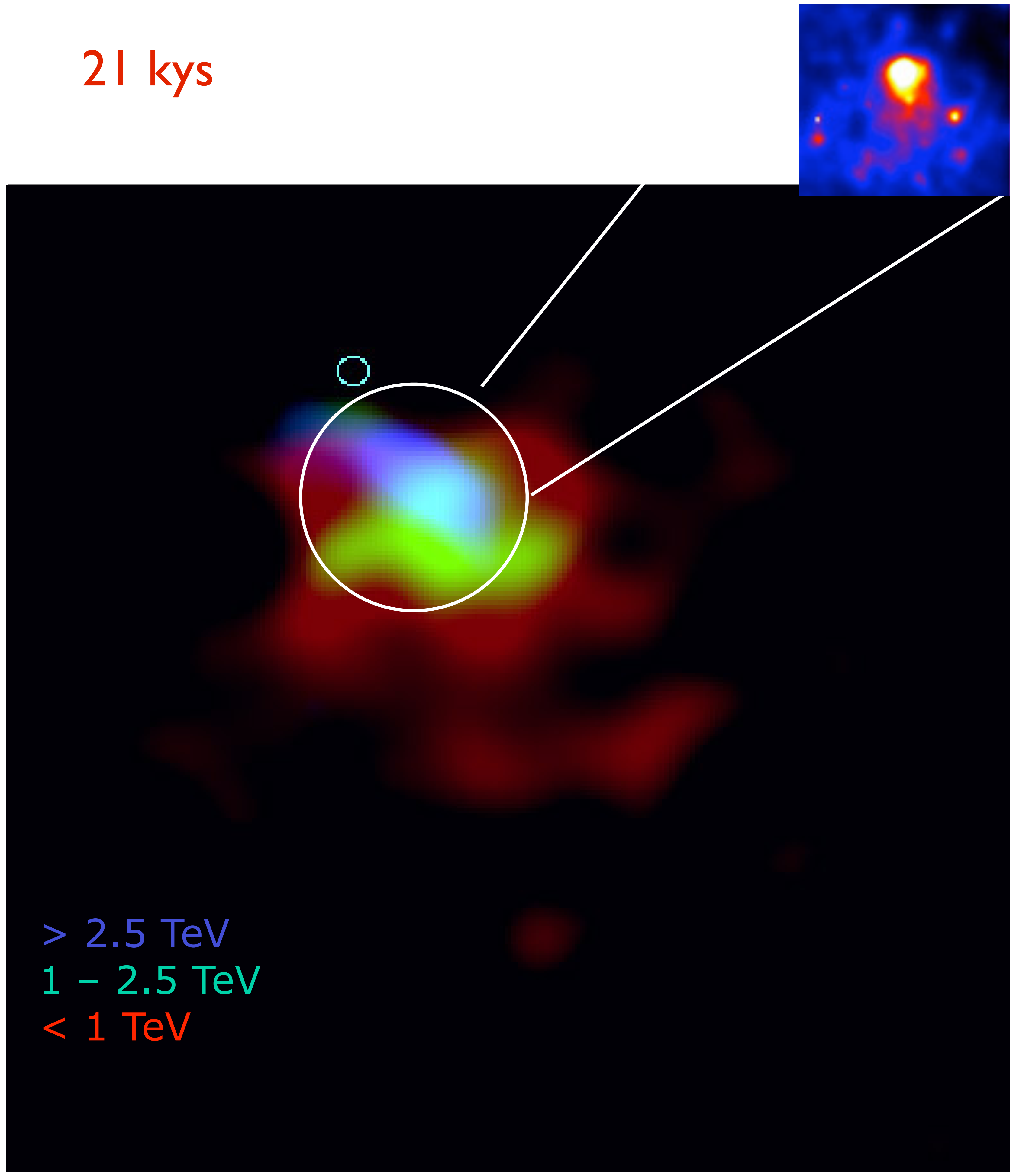

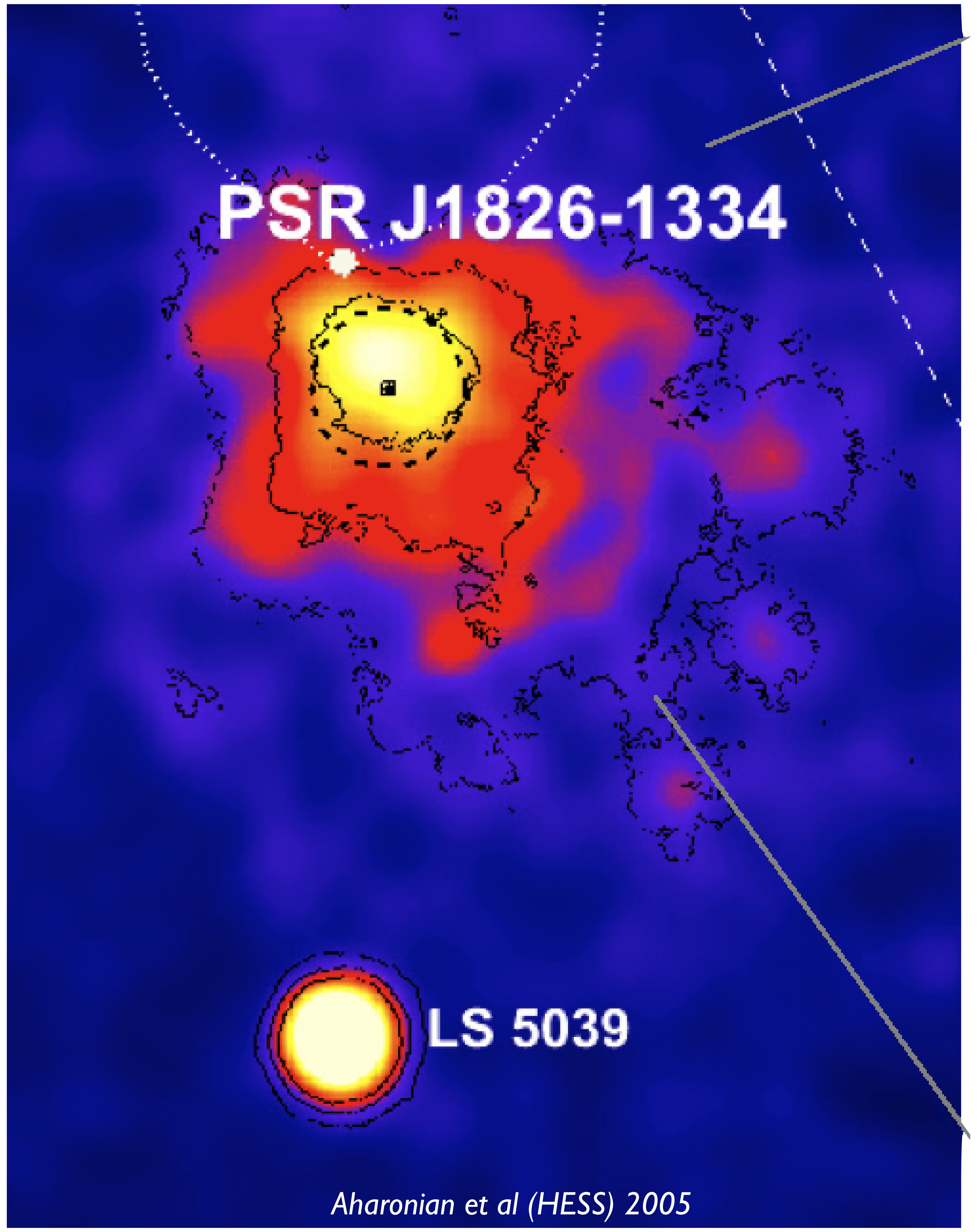

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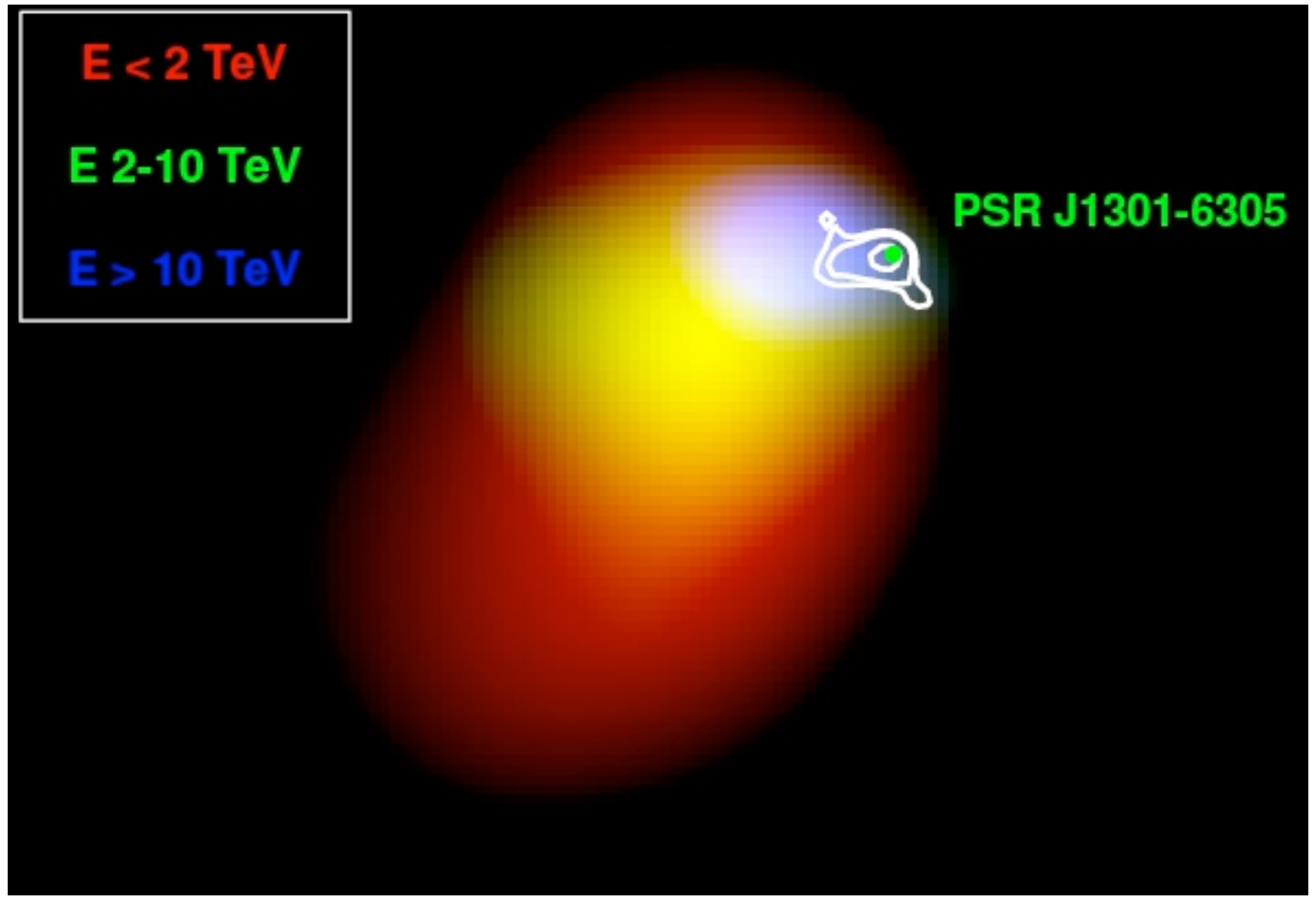

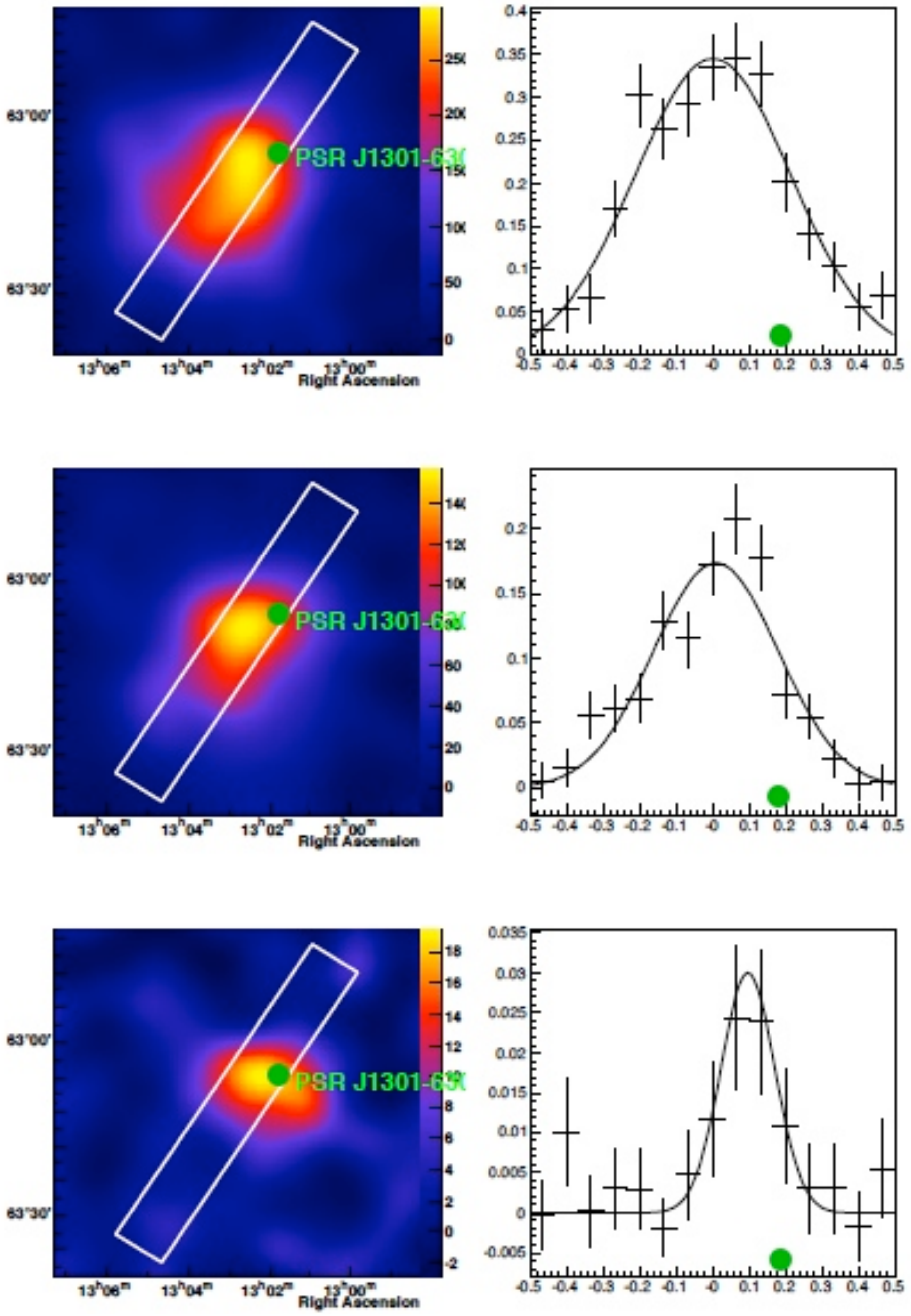

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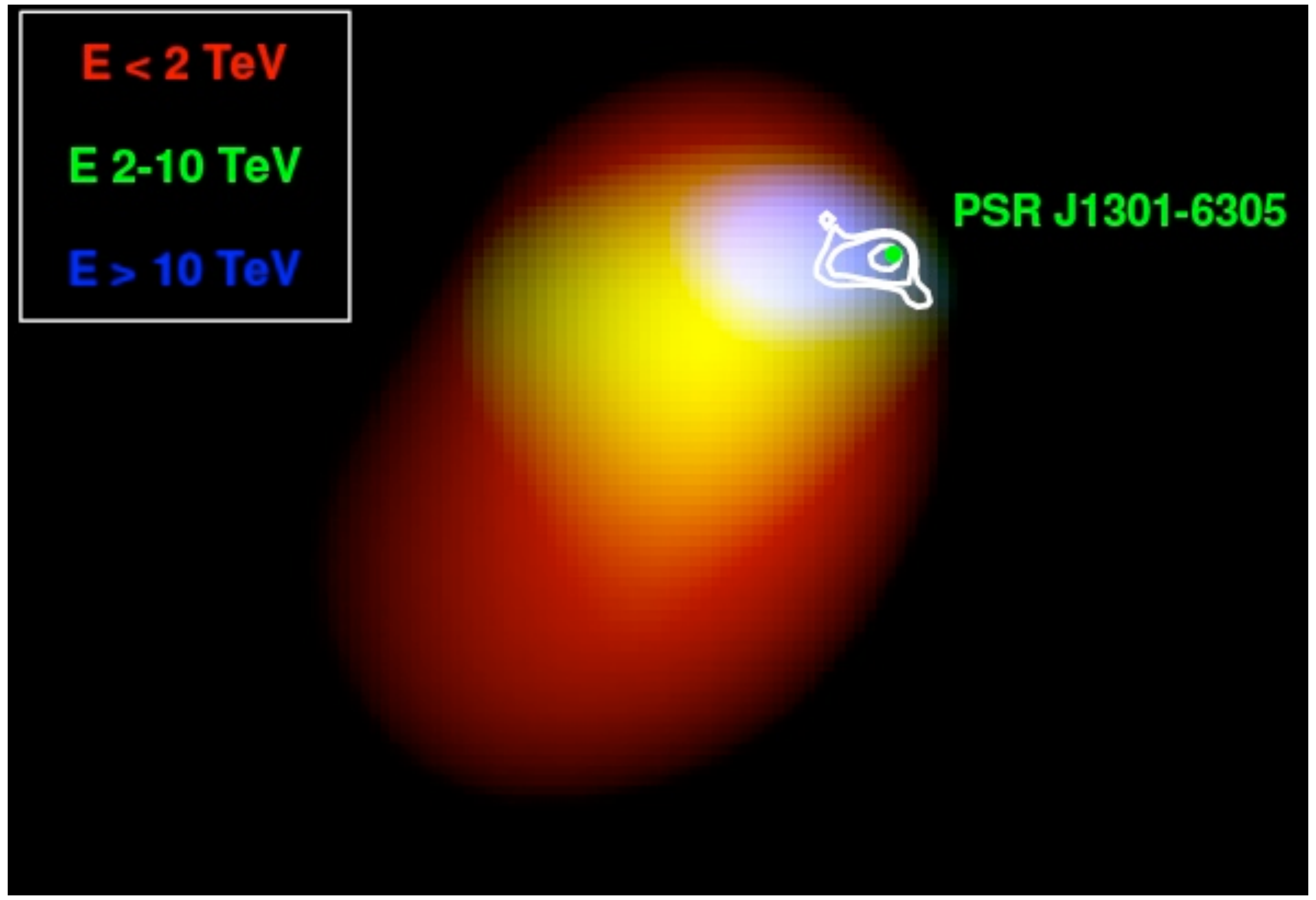

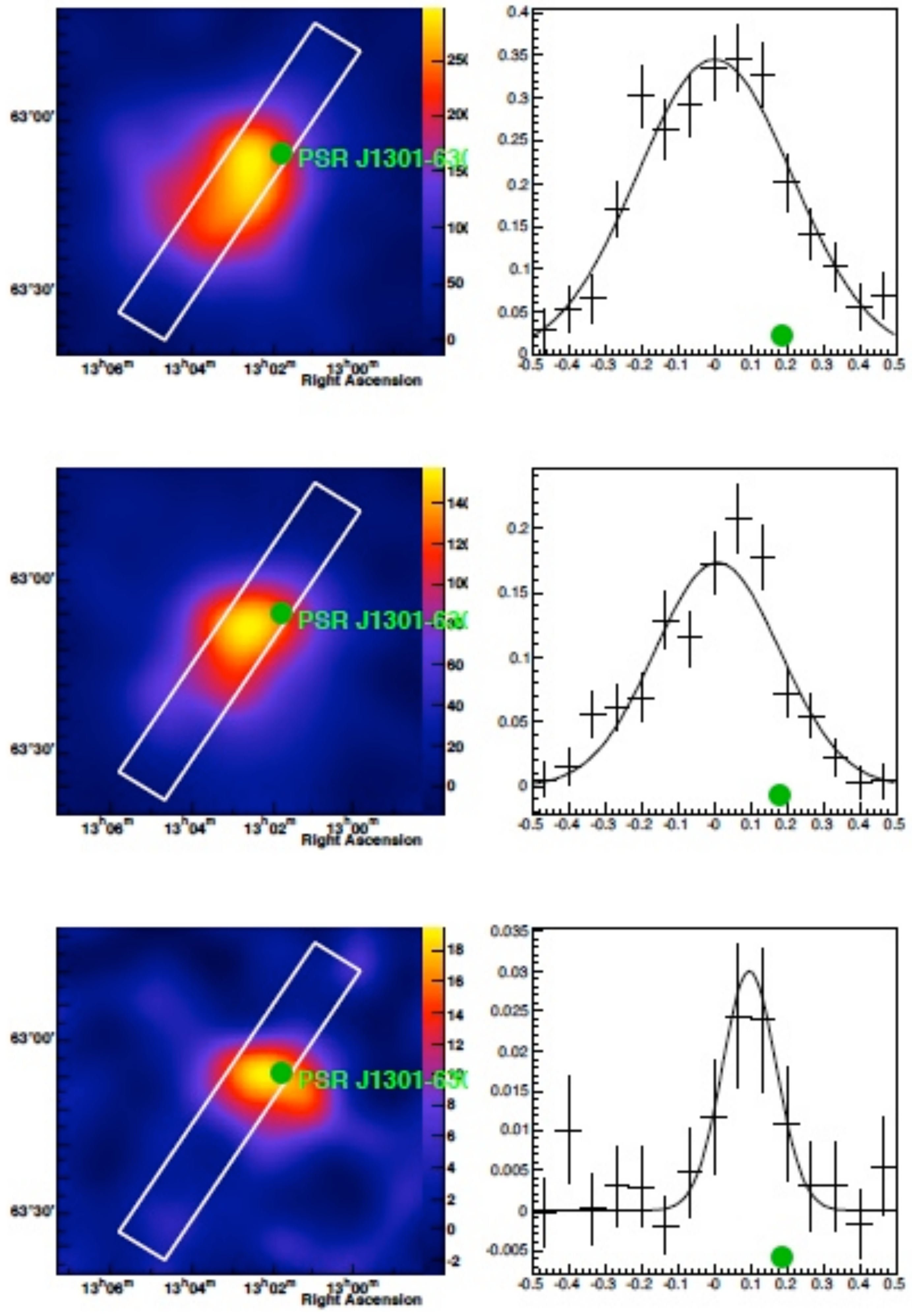

Shrinking towards high energies

But keep in mind for old systems we mixed:
Inverse Compton cooling time
Diffusion

Accelerators: Pulsar Wind Nebulae

Evolved PWNe

Spectral variation with distance from the pulsar could result from:

* energy loss of particles during propagation, with radiative cooling of electrons propagating outward from the pulsar termination shock

* energy dependent diffusion or convection speeds

* variation of the shape of the injection spectrum with age of the pulsar which, after propagation, translates into a spatial variation of spectra.

If α = electron index -> synchrotron cooling ($\tau_{syn} \sim 400\ B^{-2}_{G} E^{-1}_{TeV}$ s)

$\Delta\alpha = 1 \quad \rightarrow \Delta\Gamma = 1/2$

Hofmann 2009

Accelerators: Pulsar Wind Nebulae

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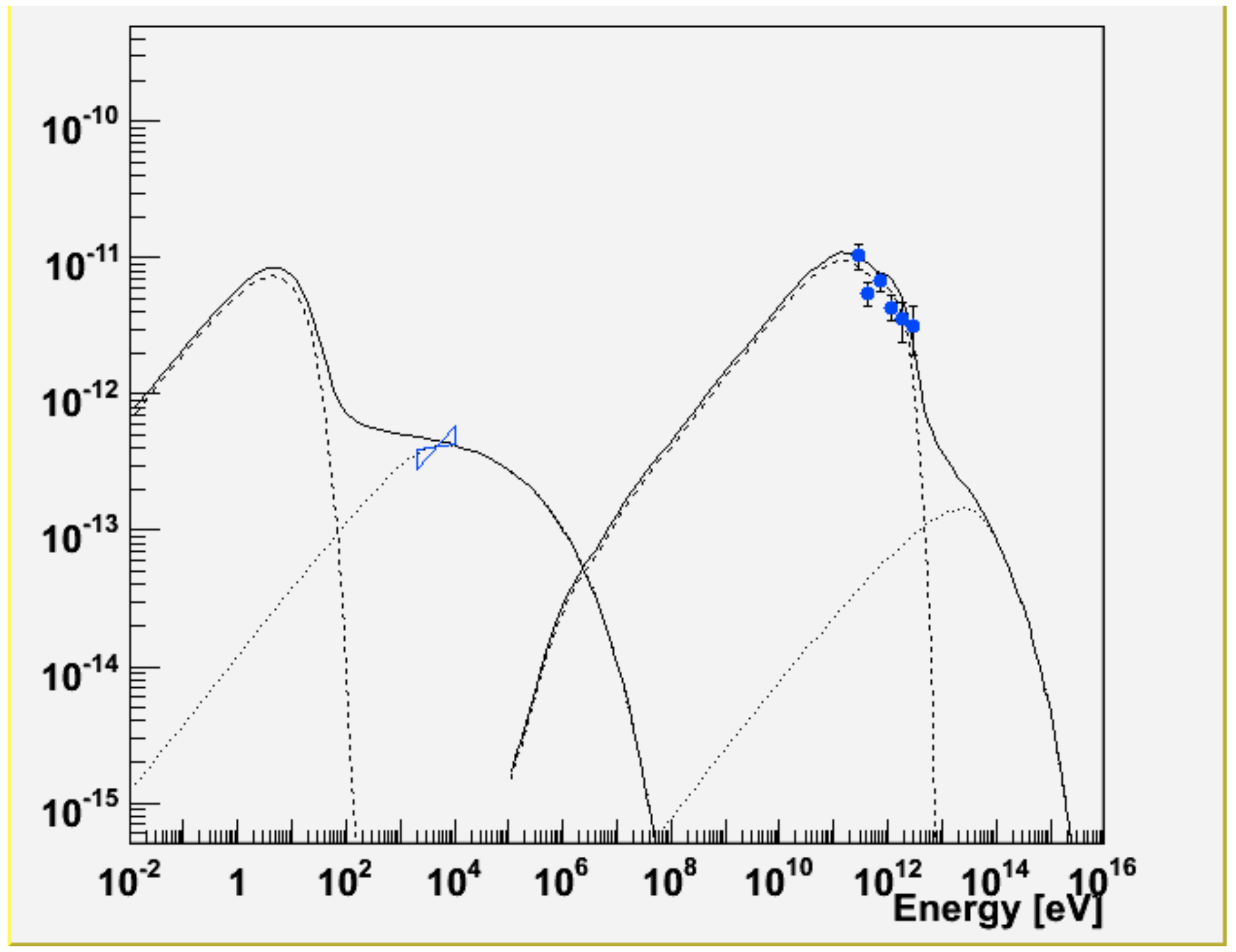

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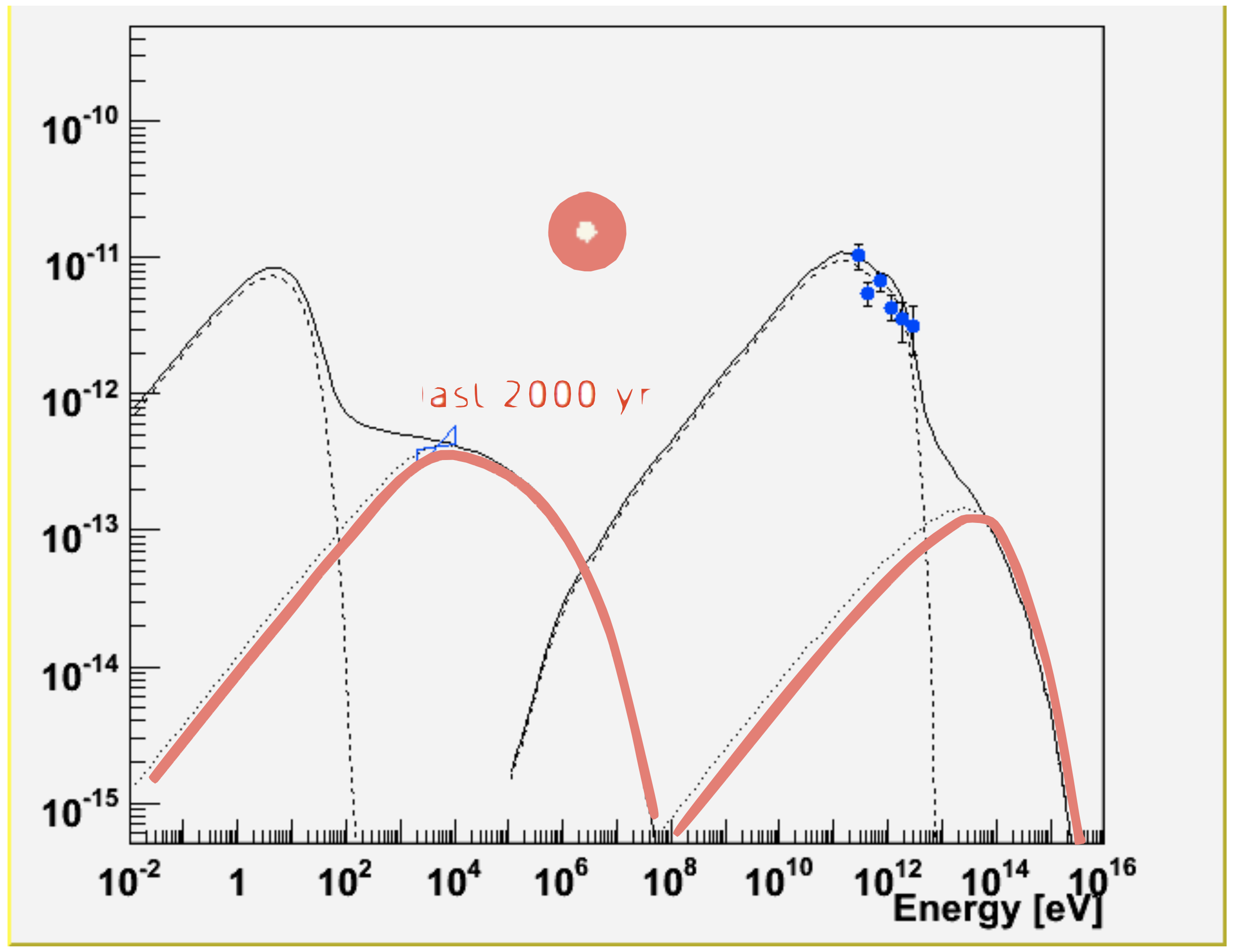

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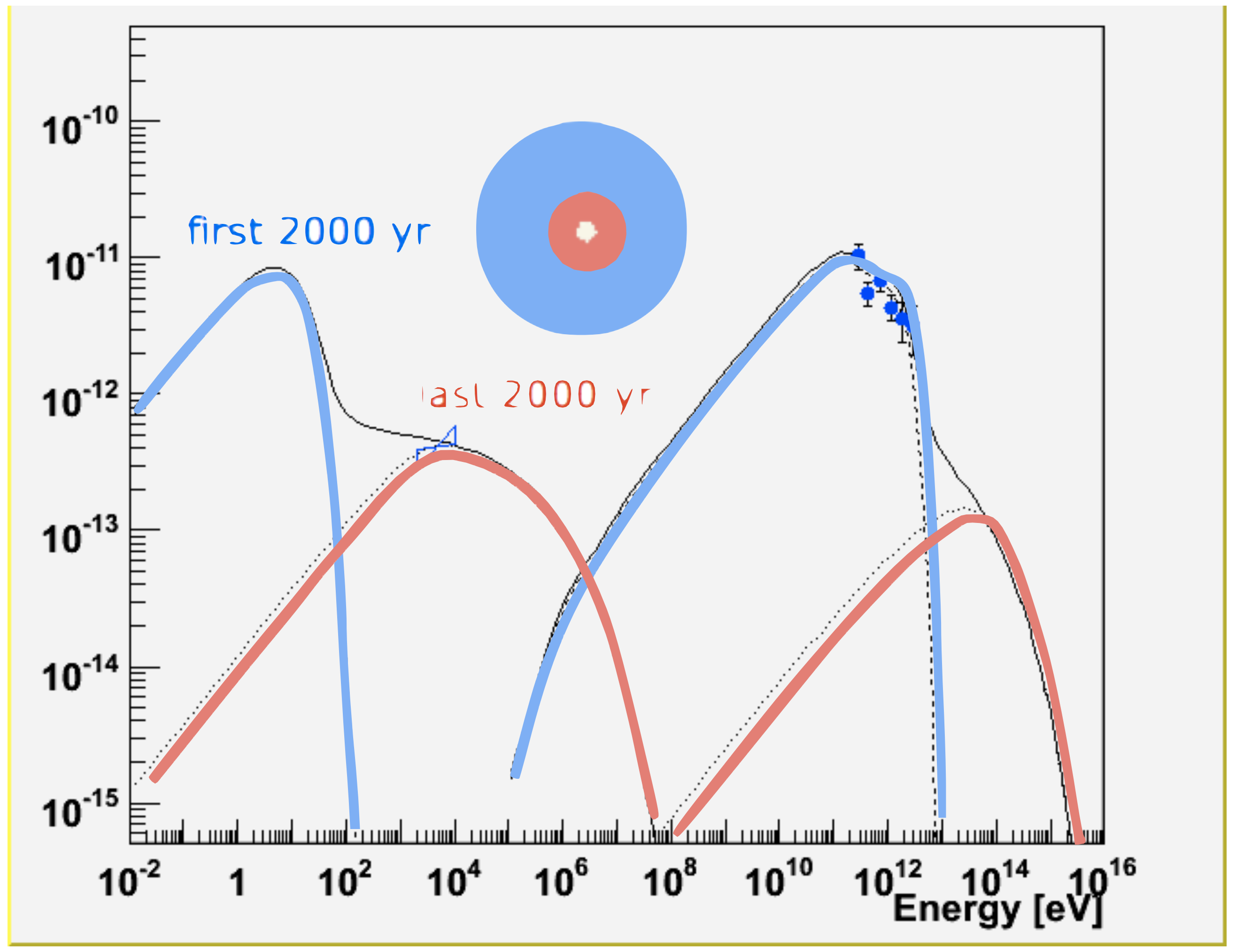
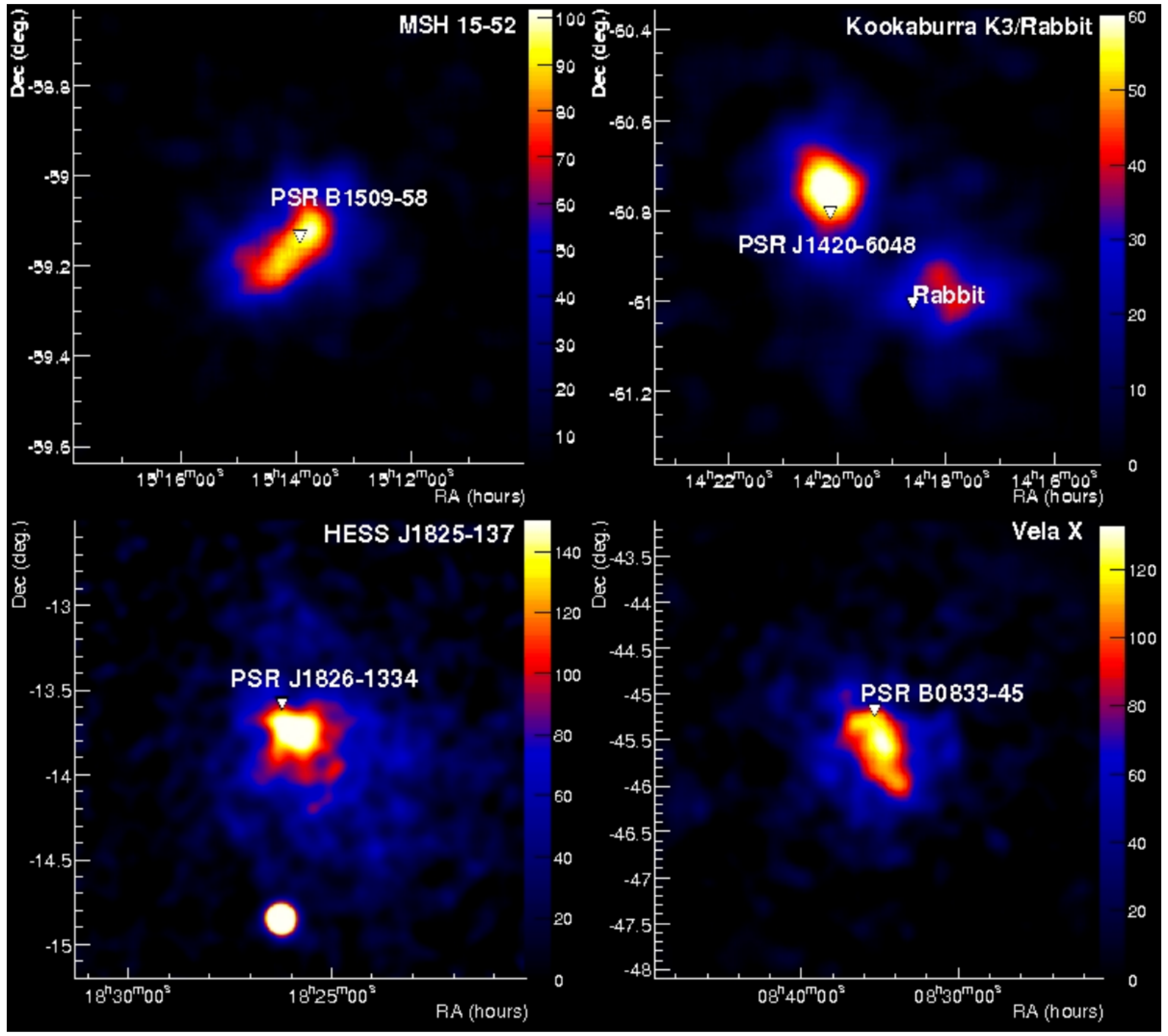


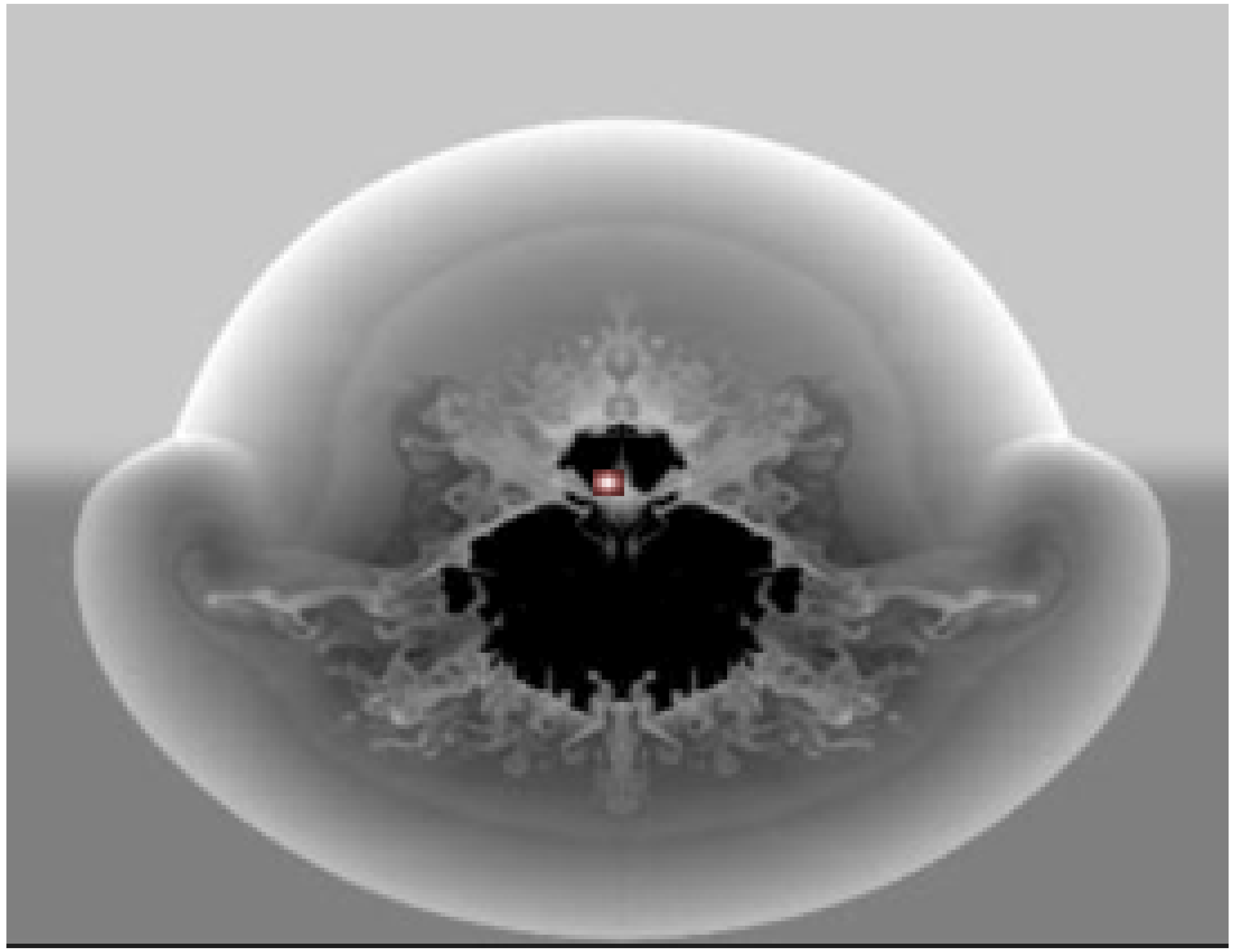
Hofmann 2009

Accelerators: Pulsar Wind Nebulae

Evolved PWNe

In comparison with other sources of relativistic magnetised plasma, PWNe can be resolved in great detail





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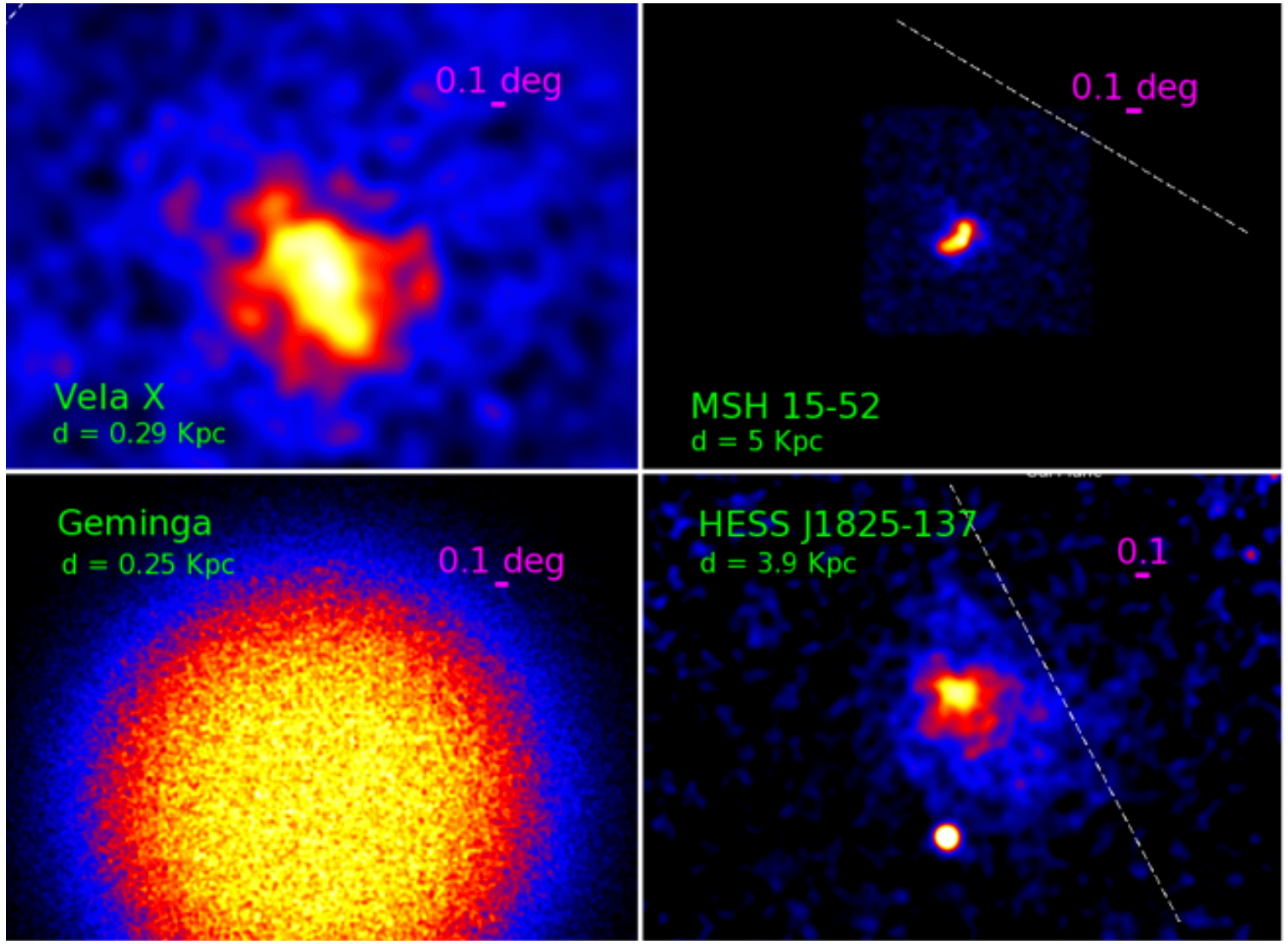


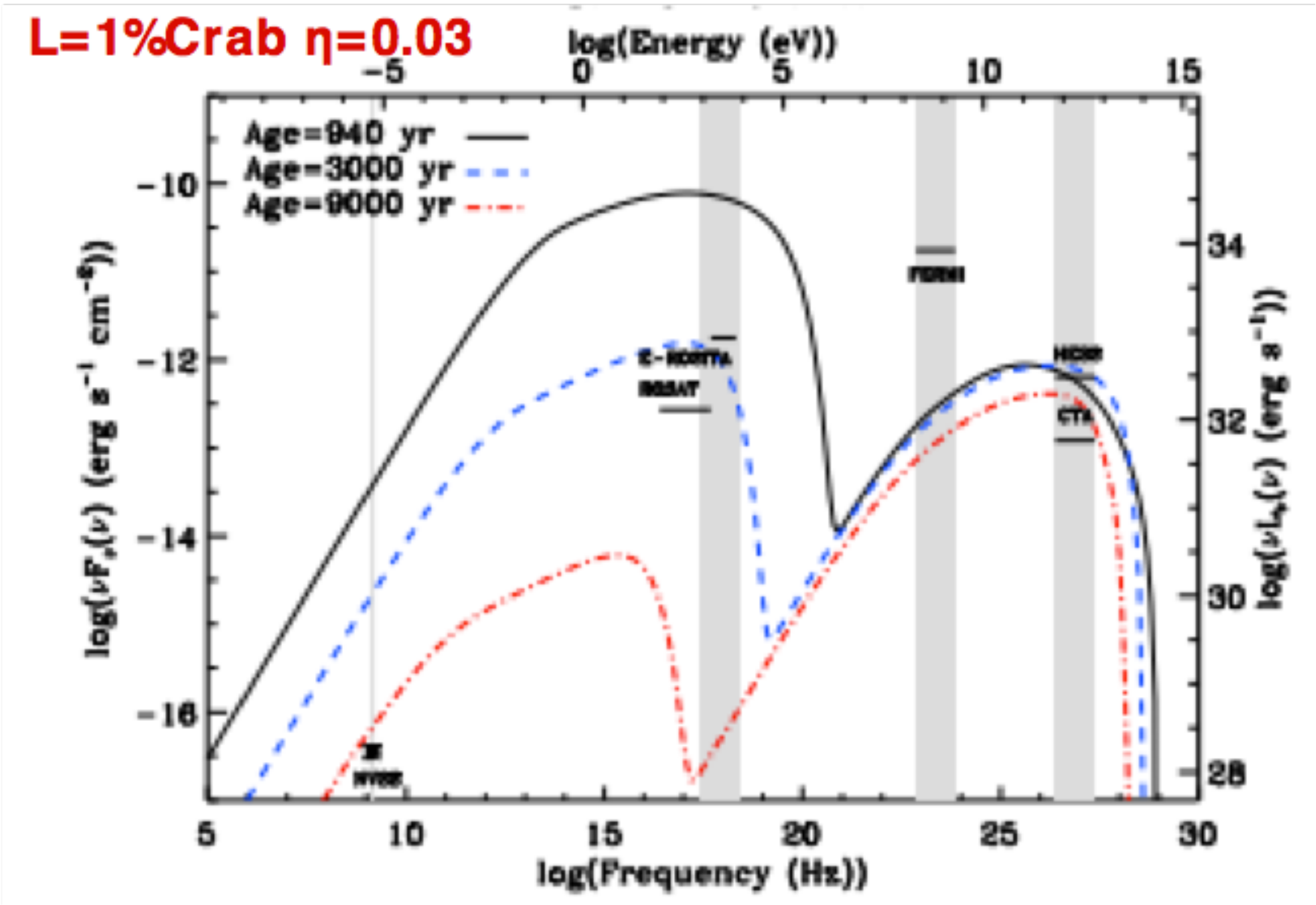
SED depends on:

Pulsar

The age of the pulsar/pwn
The initial spin-down energy
The magnetization fraction (or fraction of energy shared in particles and in magnetic field)

Wind

Injection Spectrum
Radiation Field



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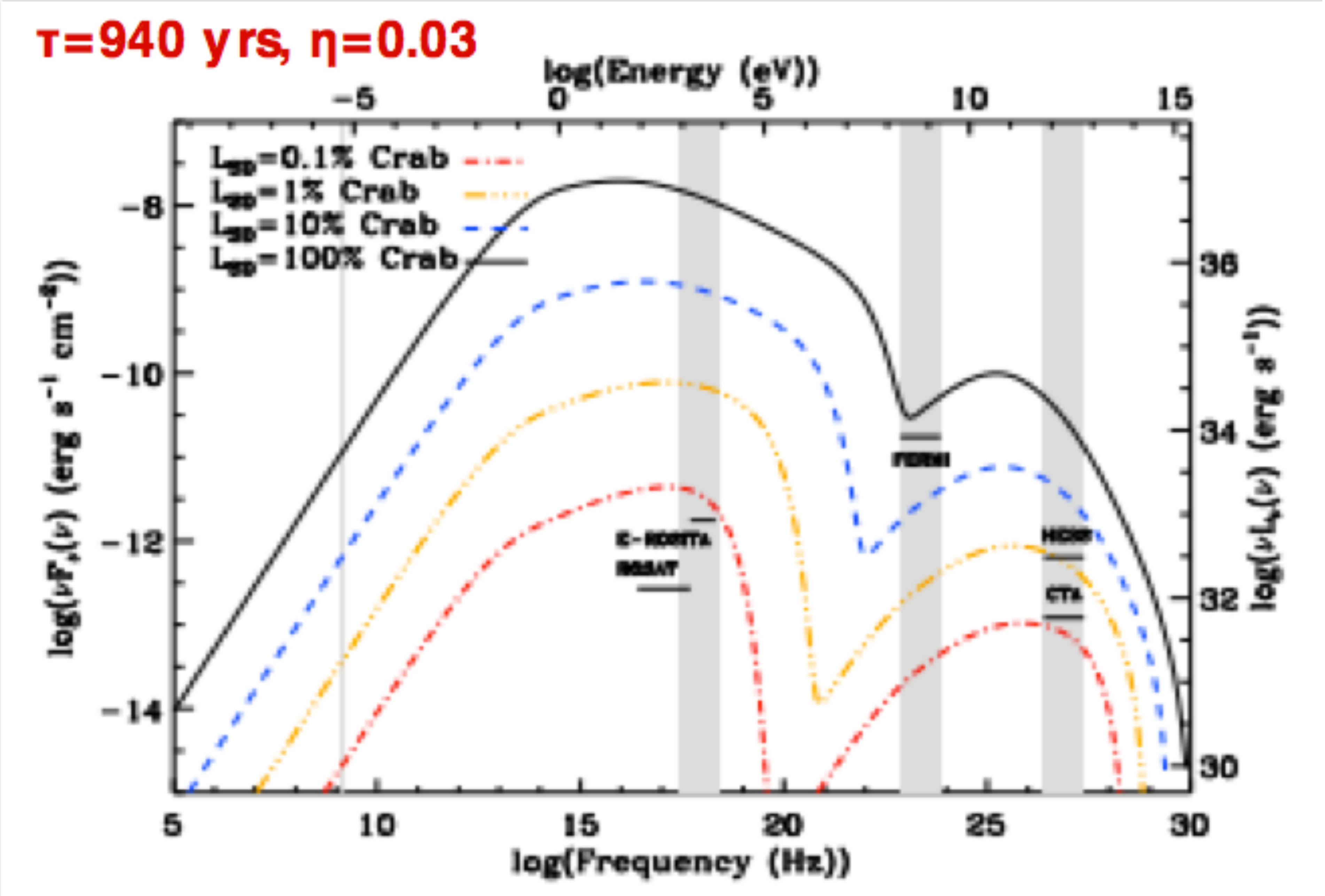

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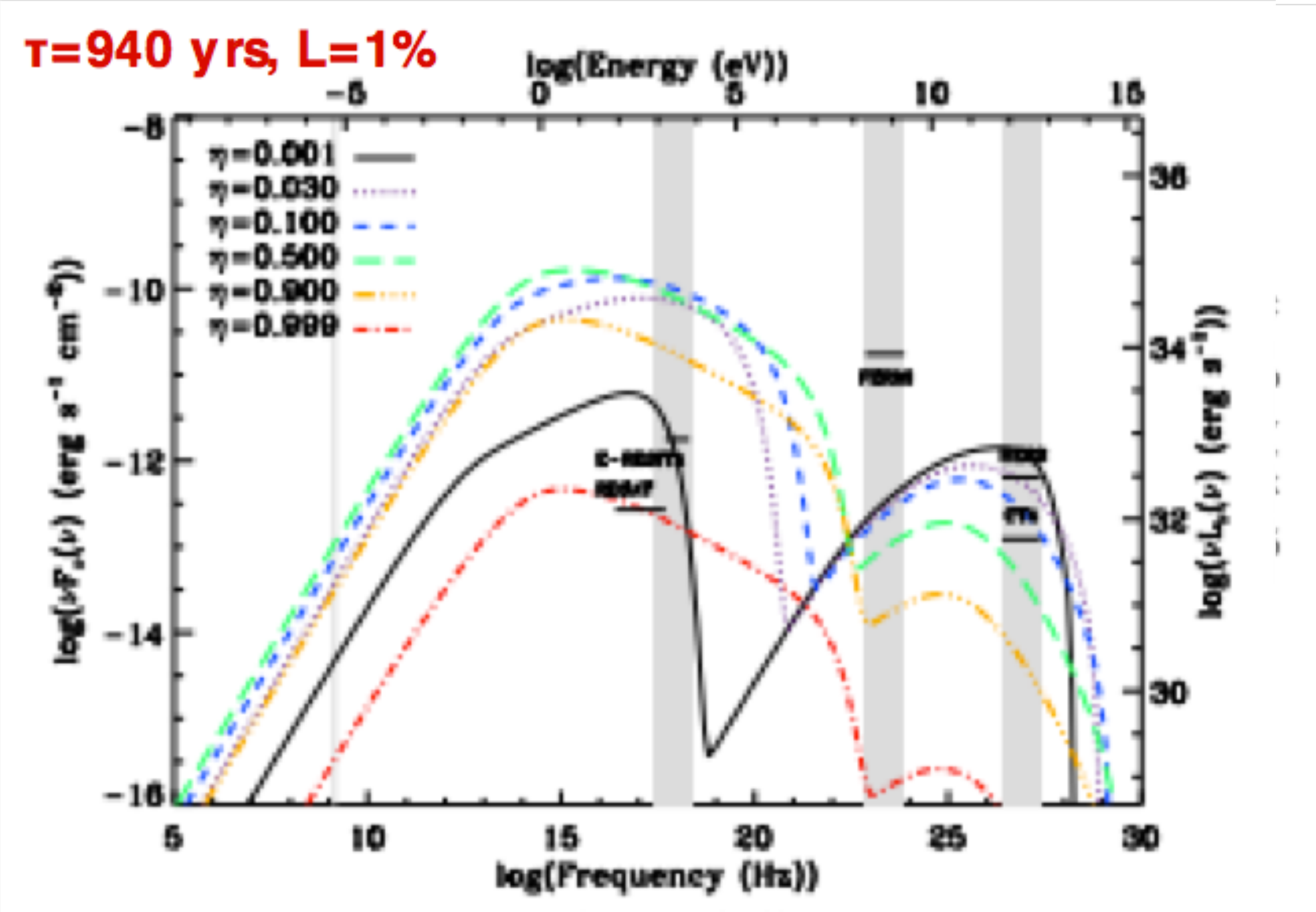

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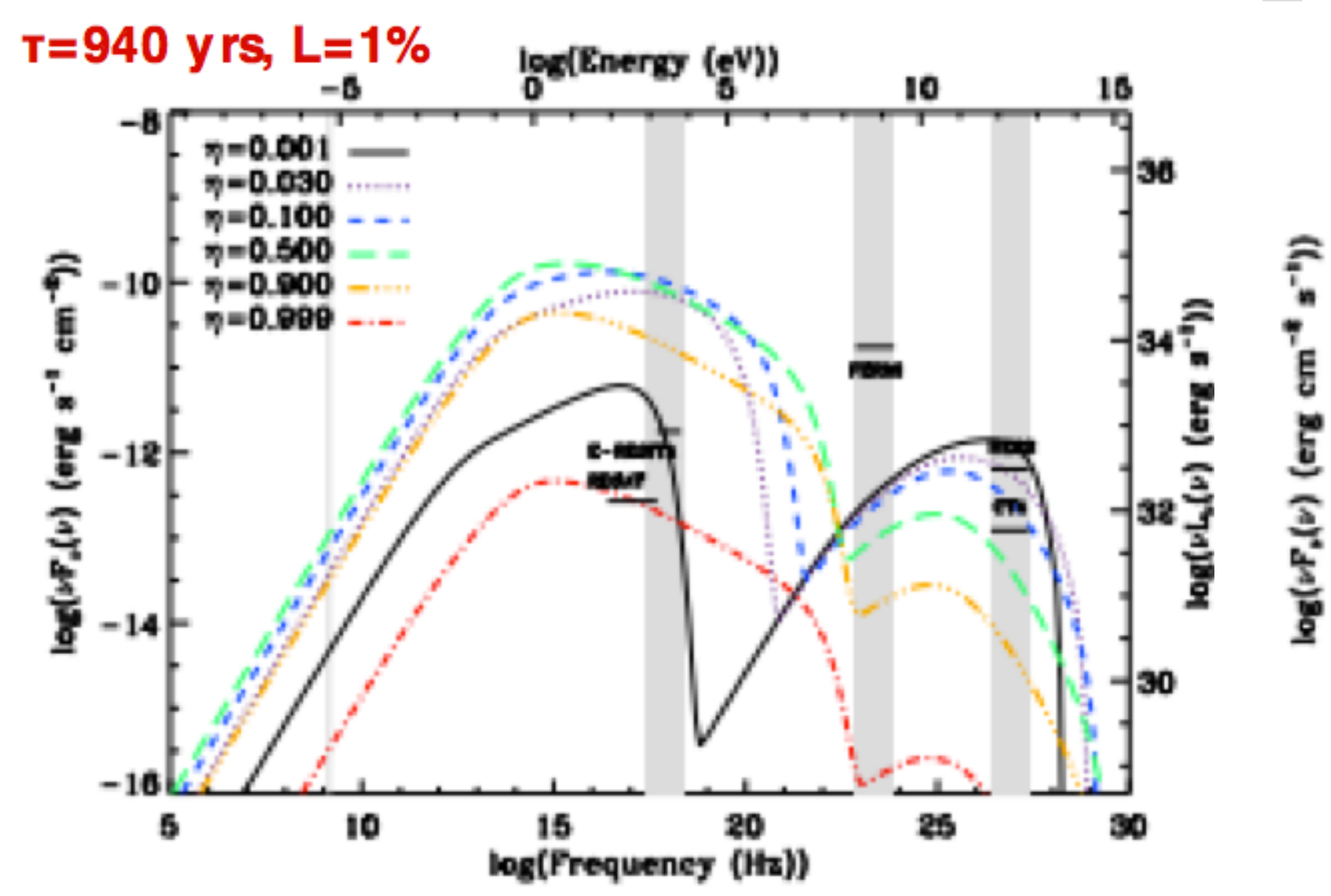

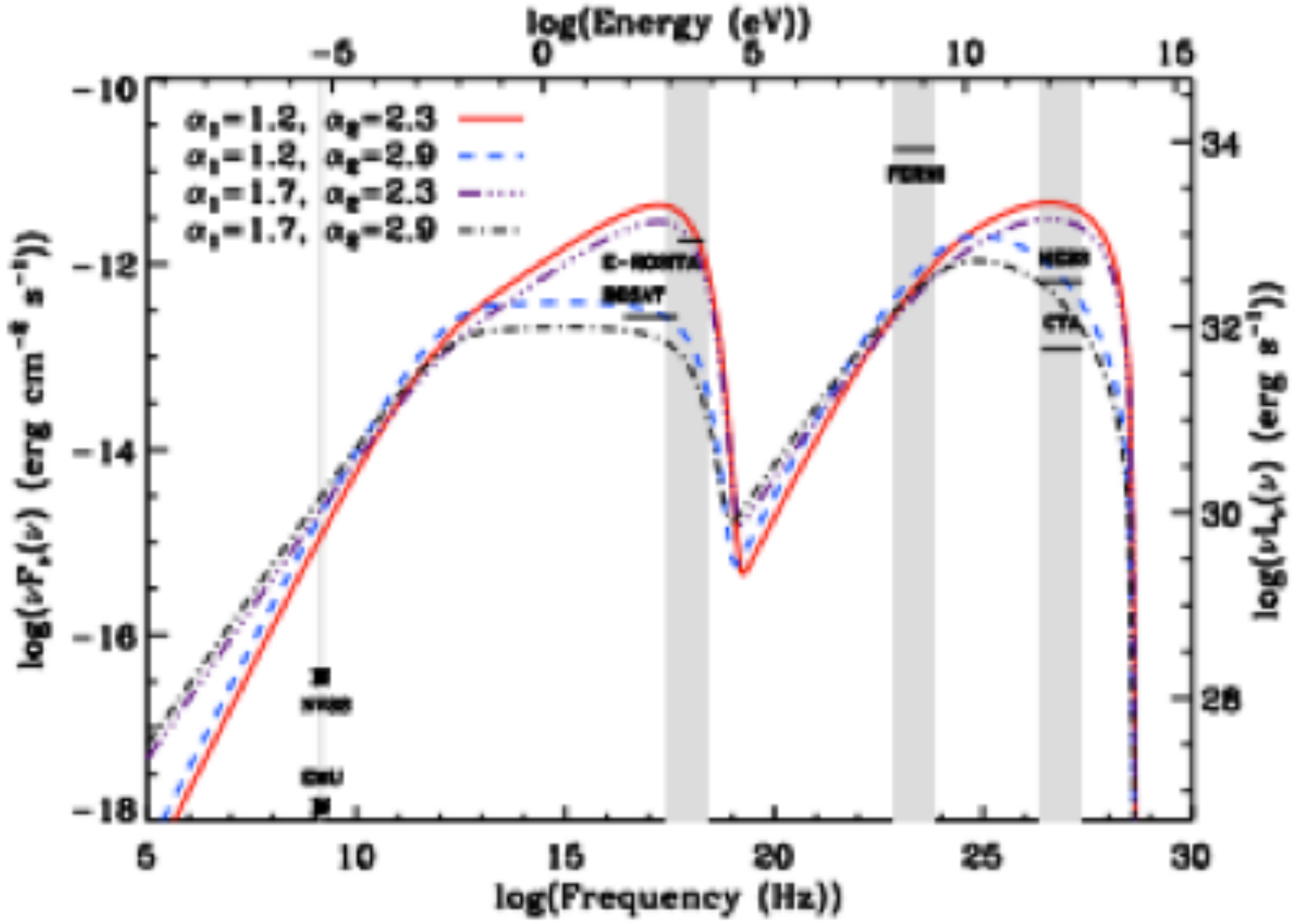

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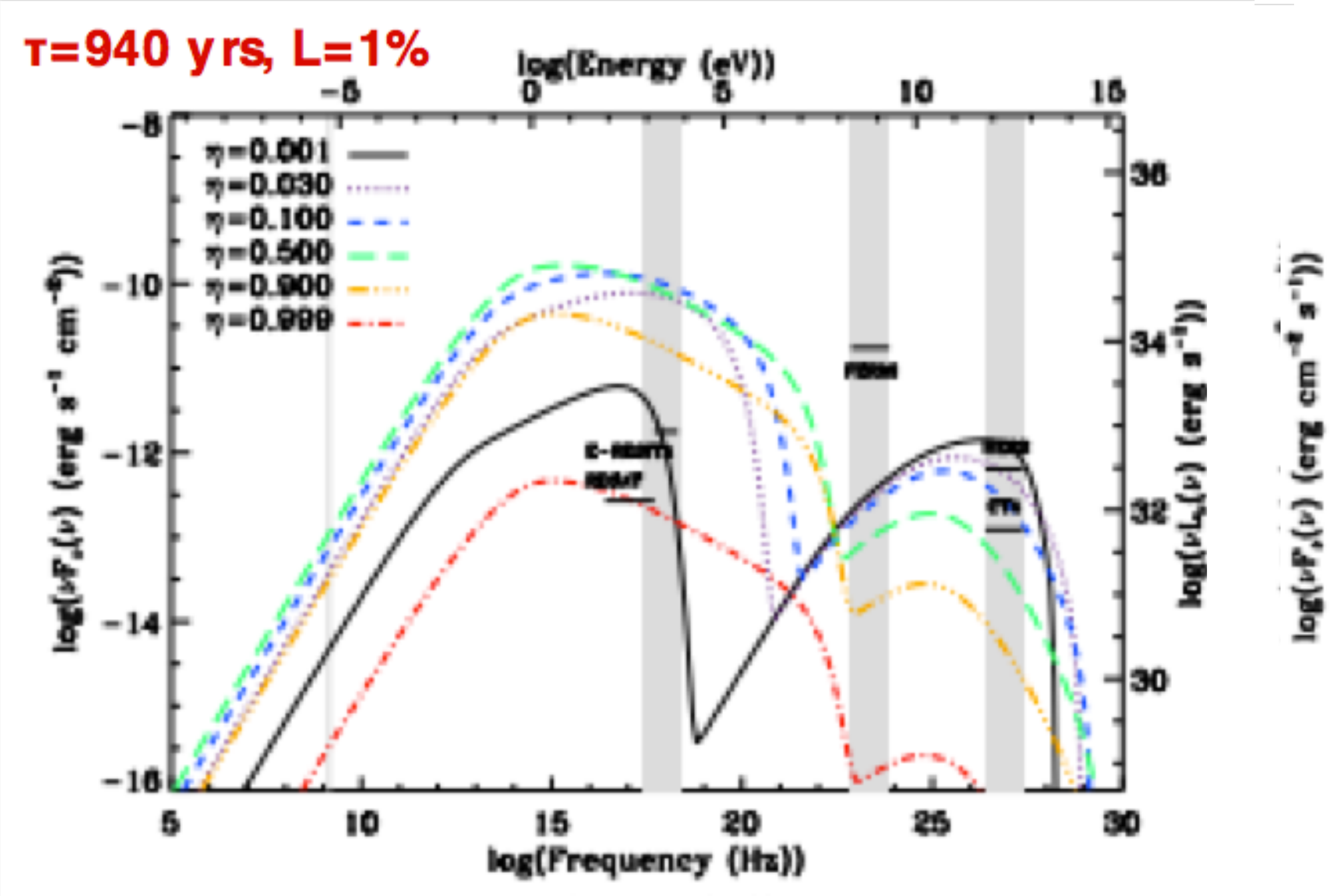
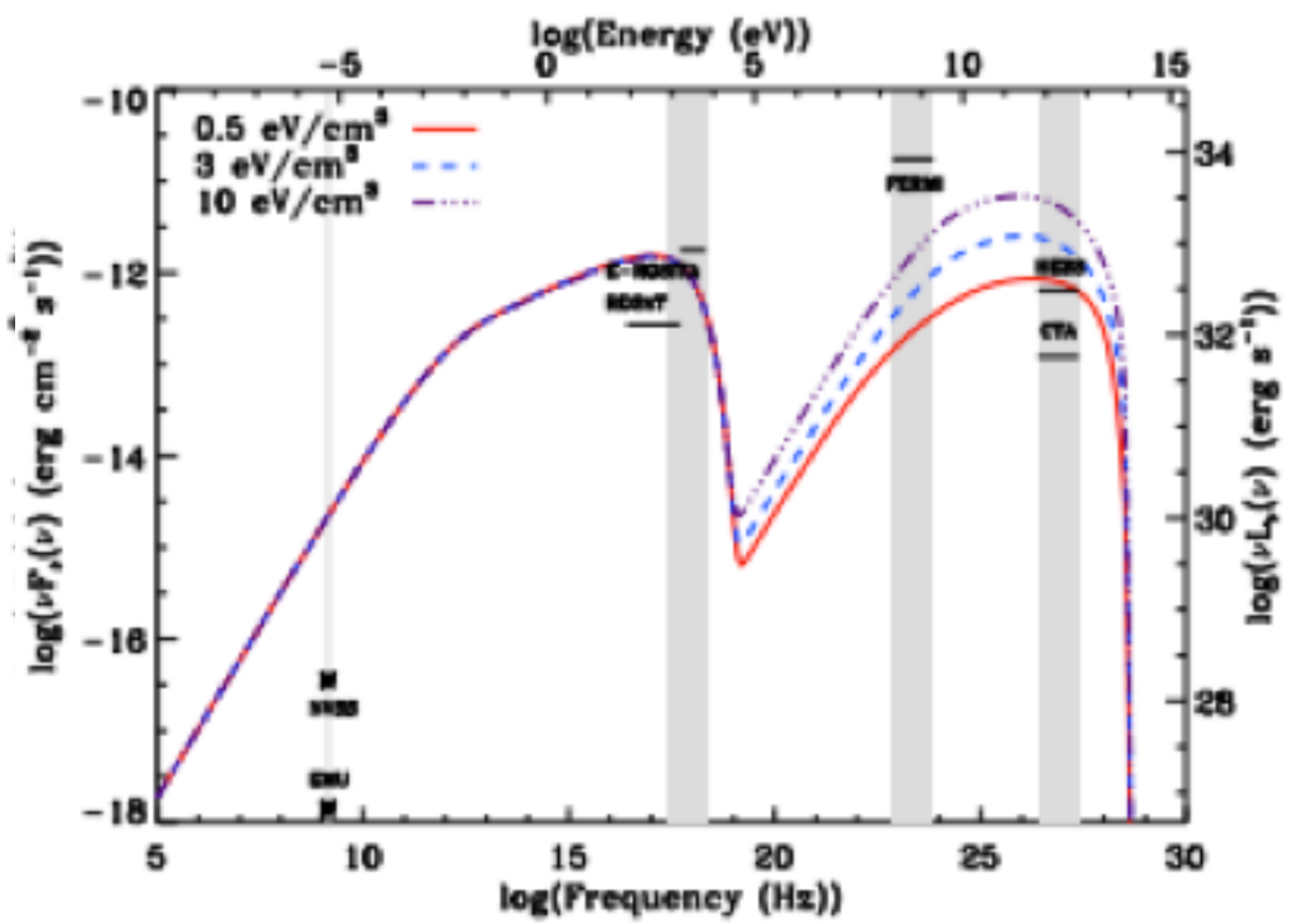
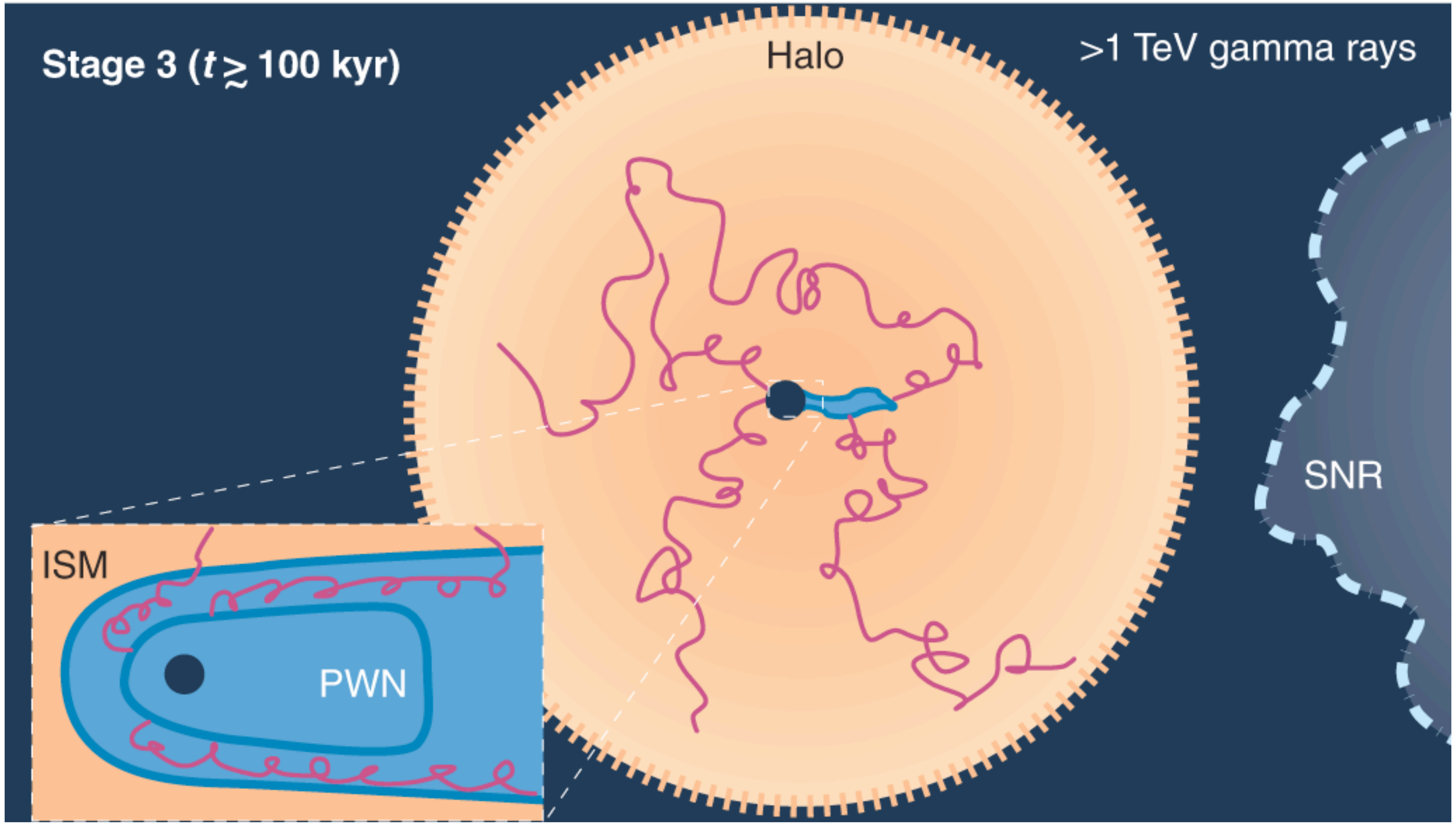




Understanding the Galactic ISM

Accelerators: Haloes

Halo - Studying the diffusion of particles in the Galaxy



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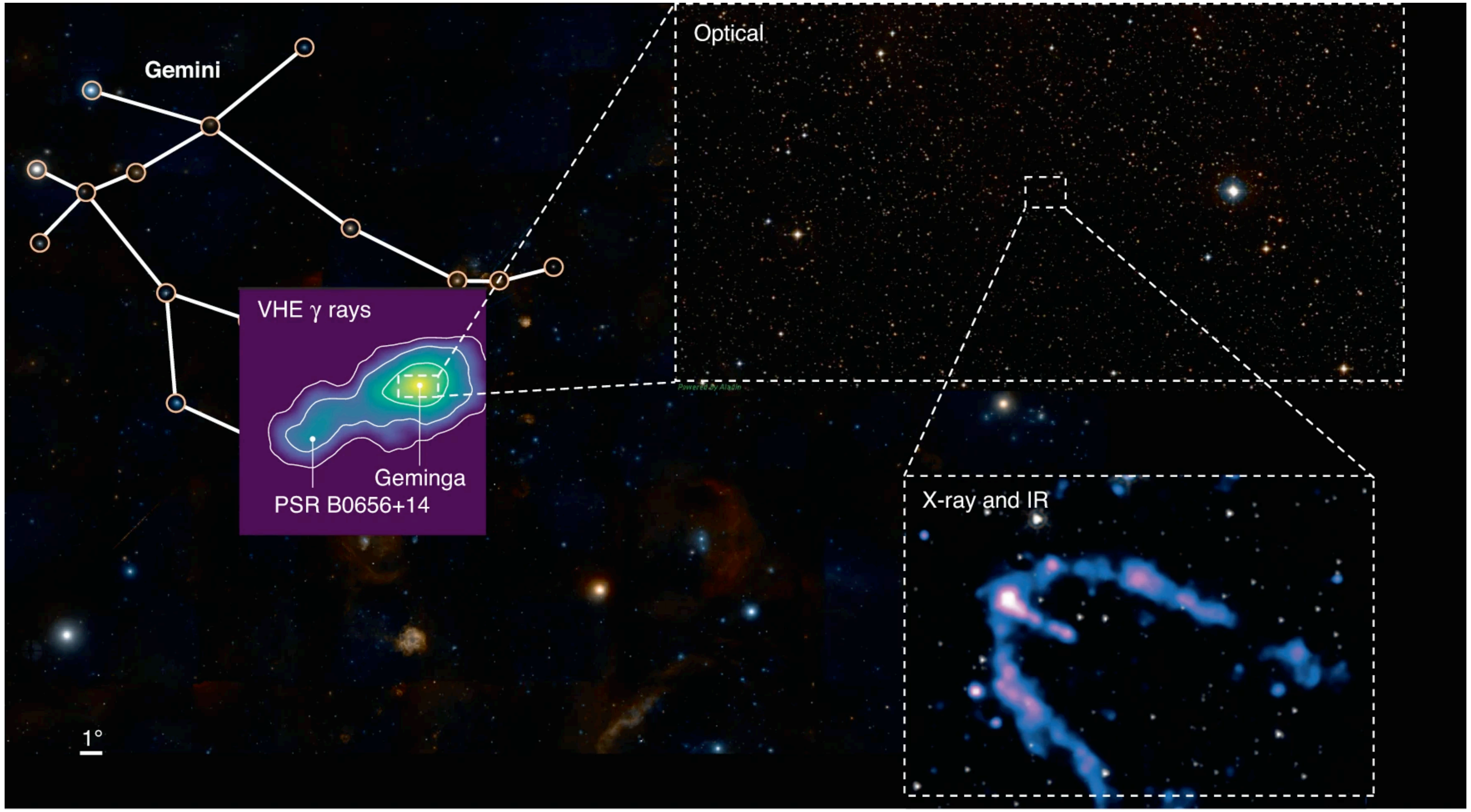

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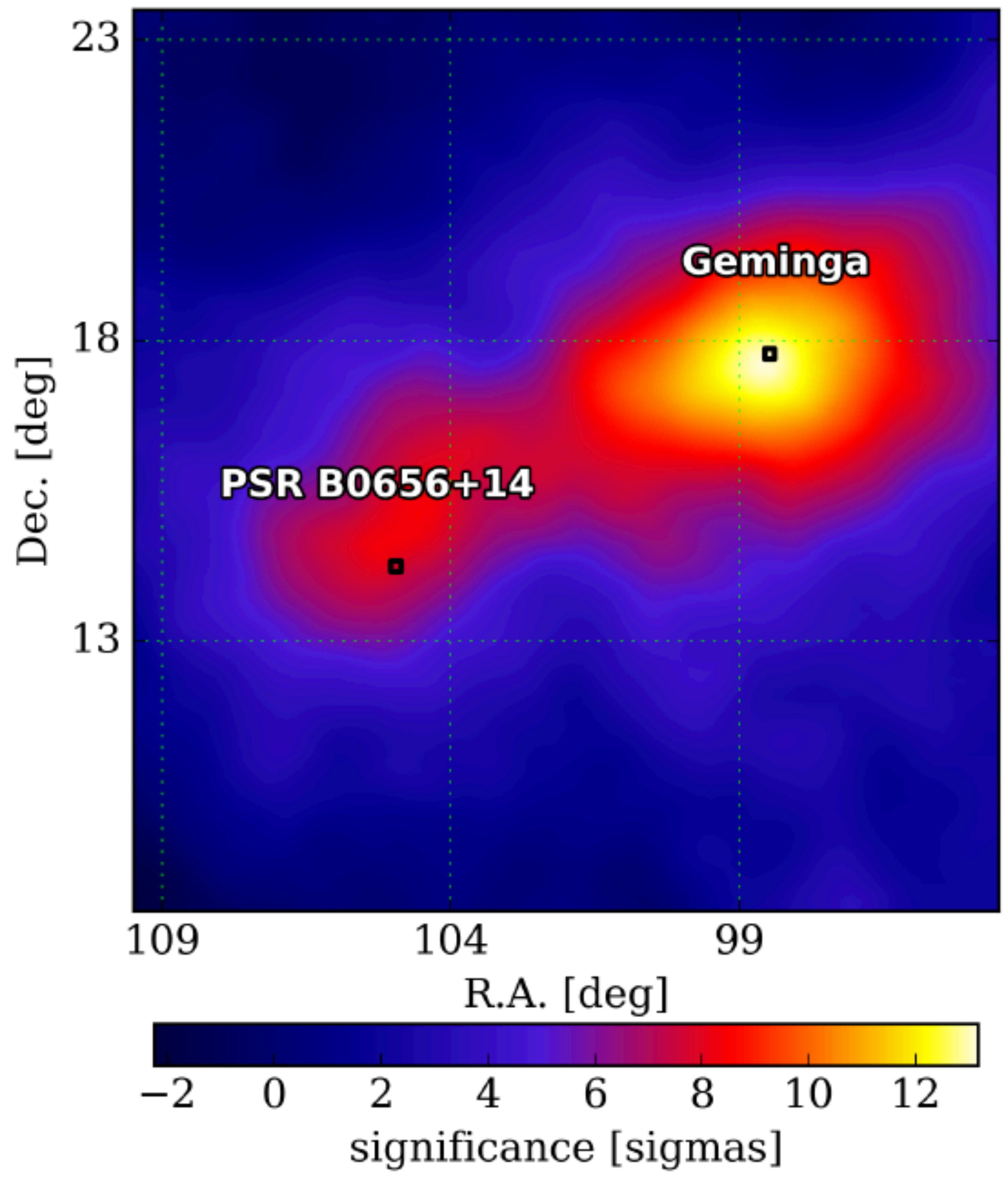

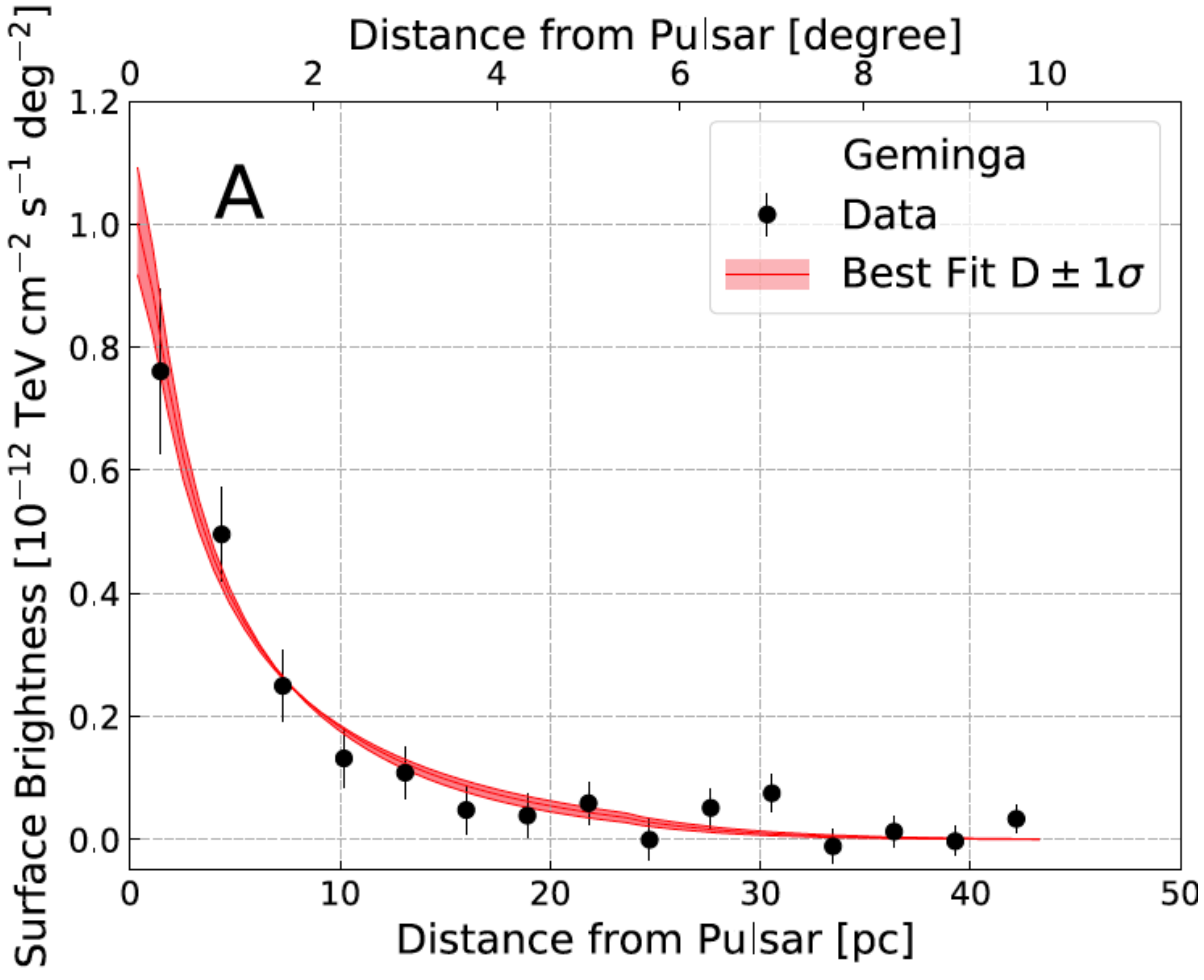

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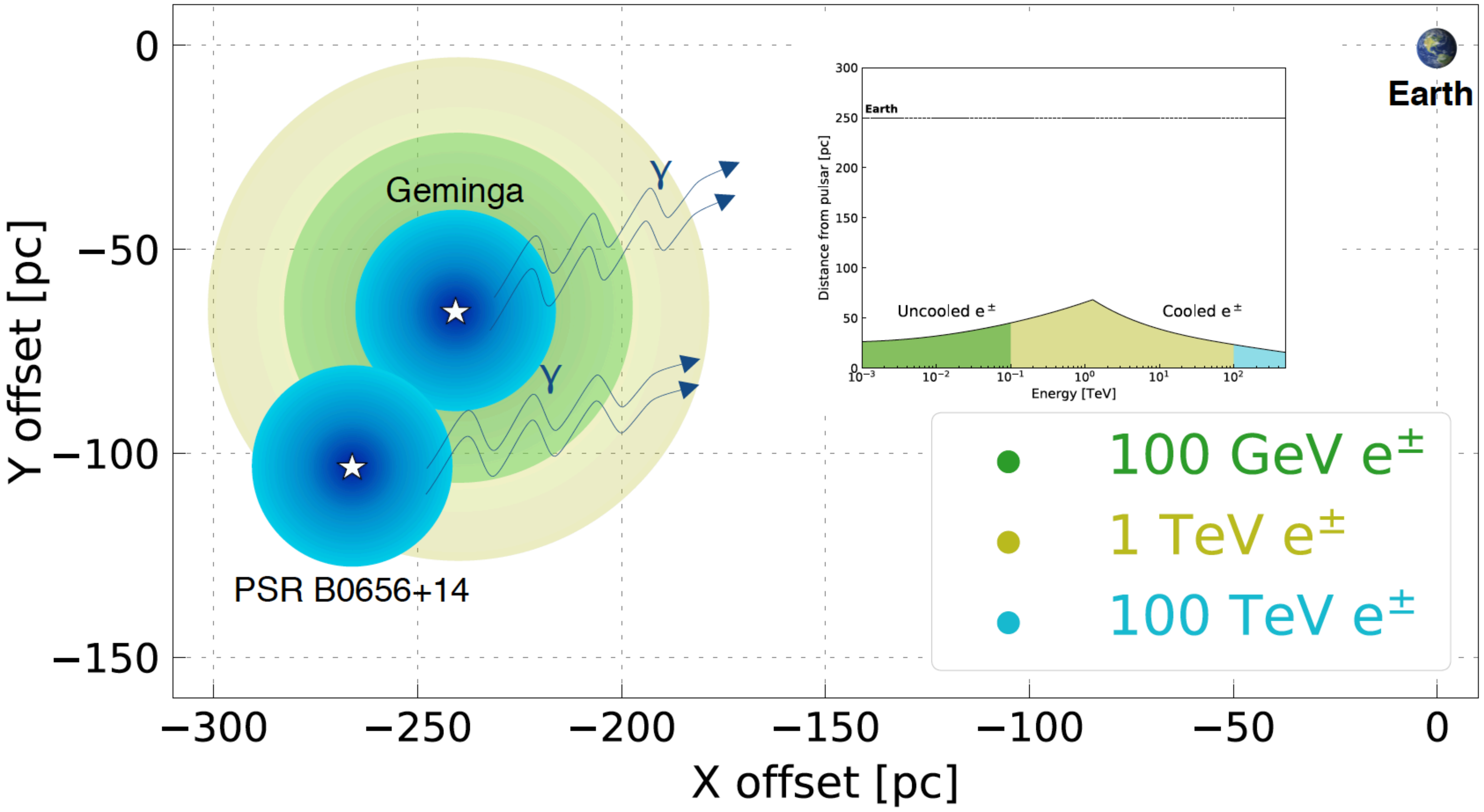

$$D(E) \approx 2 \times 10^{28}\ \mathrm{cm}^2\ \mathrm{s}^{-1}\ \xi_{B,0.1}^{-1} \left(\frac{\lambda_{\mathrm{pc}}}{E_{\mathrm{TeV}}} \right)^{\alpha-1} B_\mu^{\alpha-2}$$

D ~ 4.5 x 10^{27} cm^2/s
(mean value in the ISM is ~10^{30} cm^2/s)

Accelerators: Haloes

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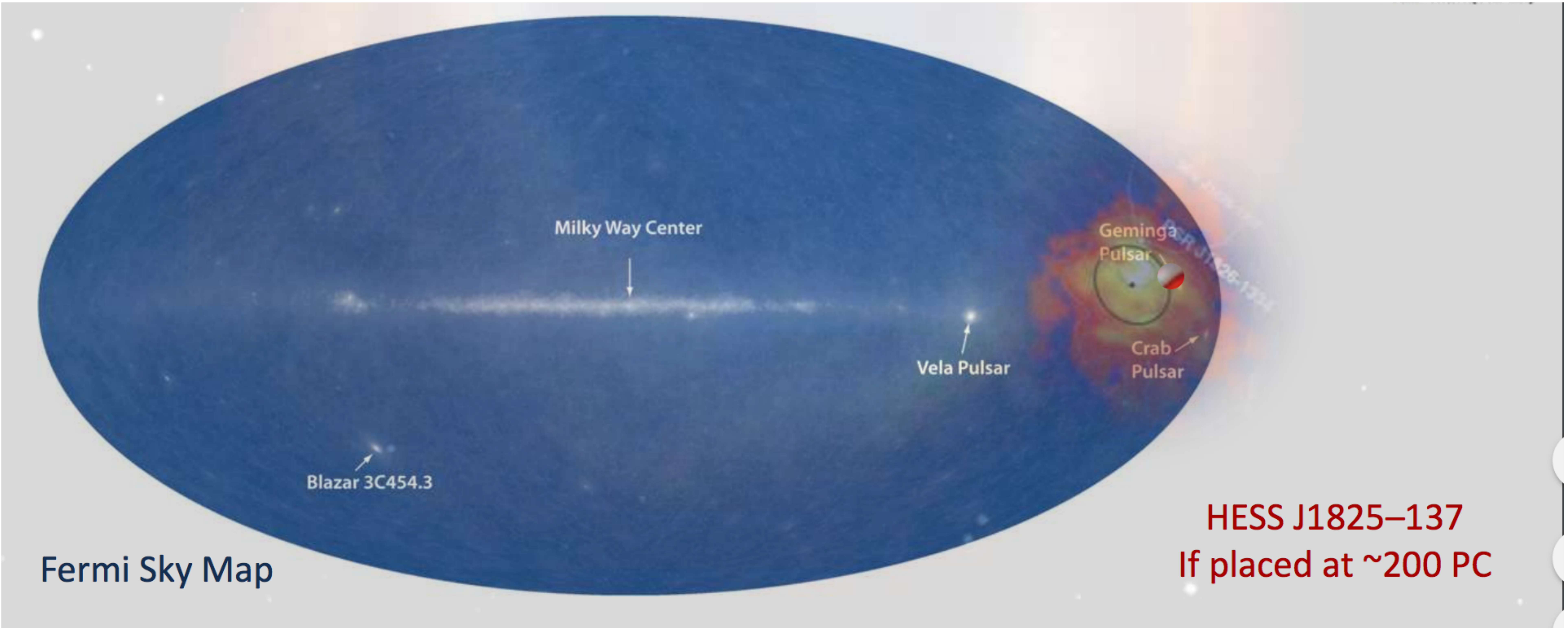

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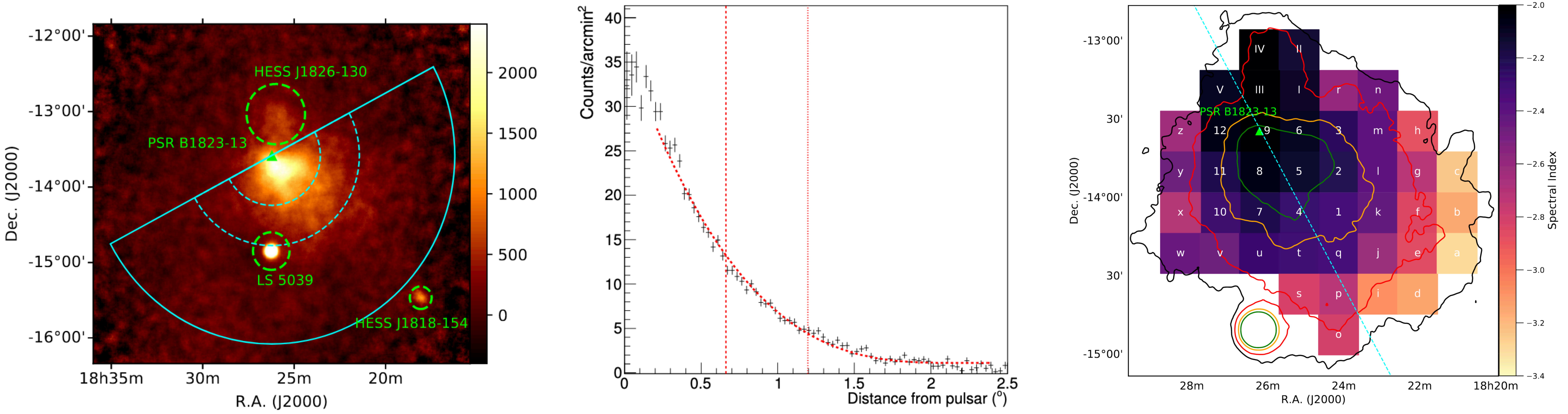
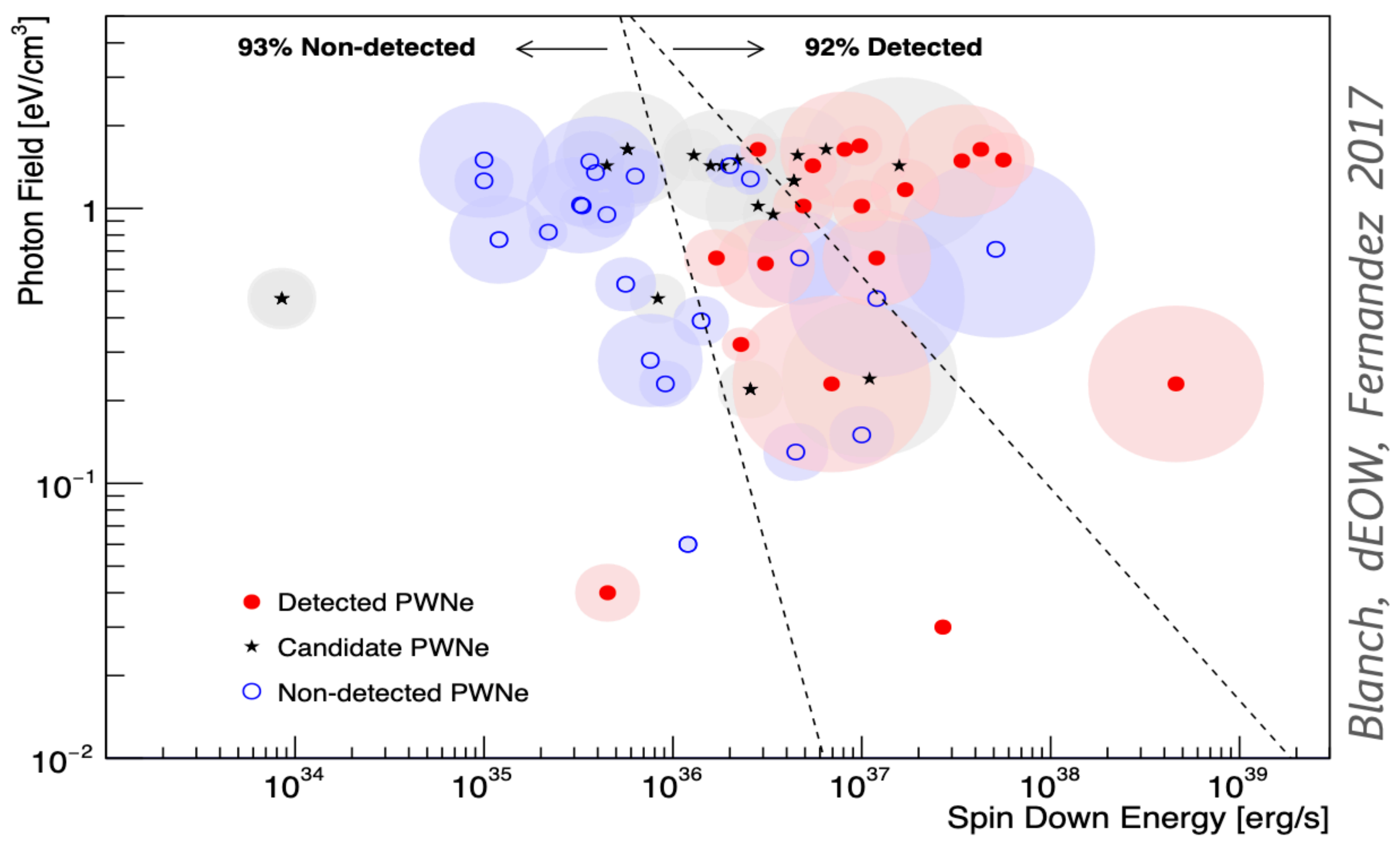
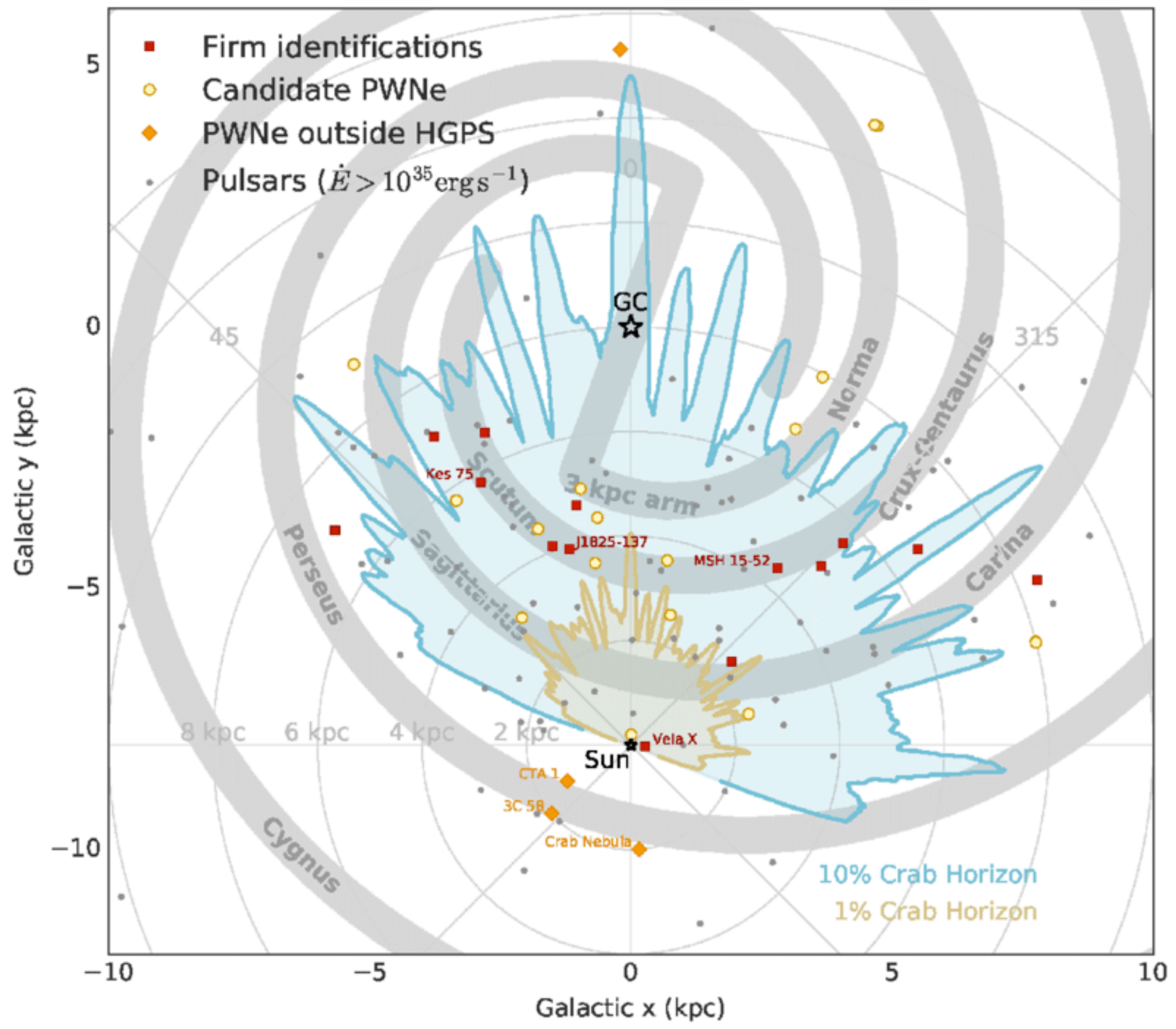
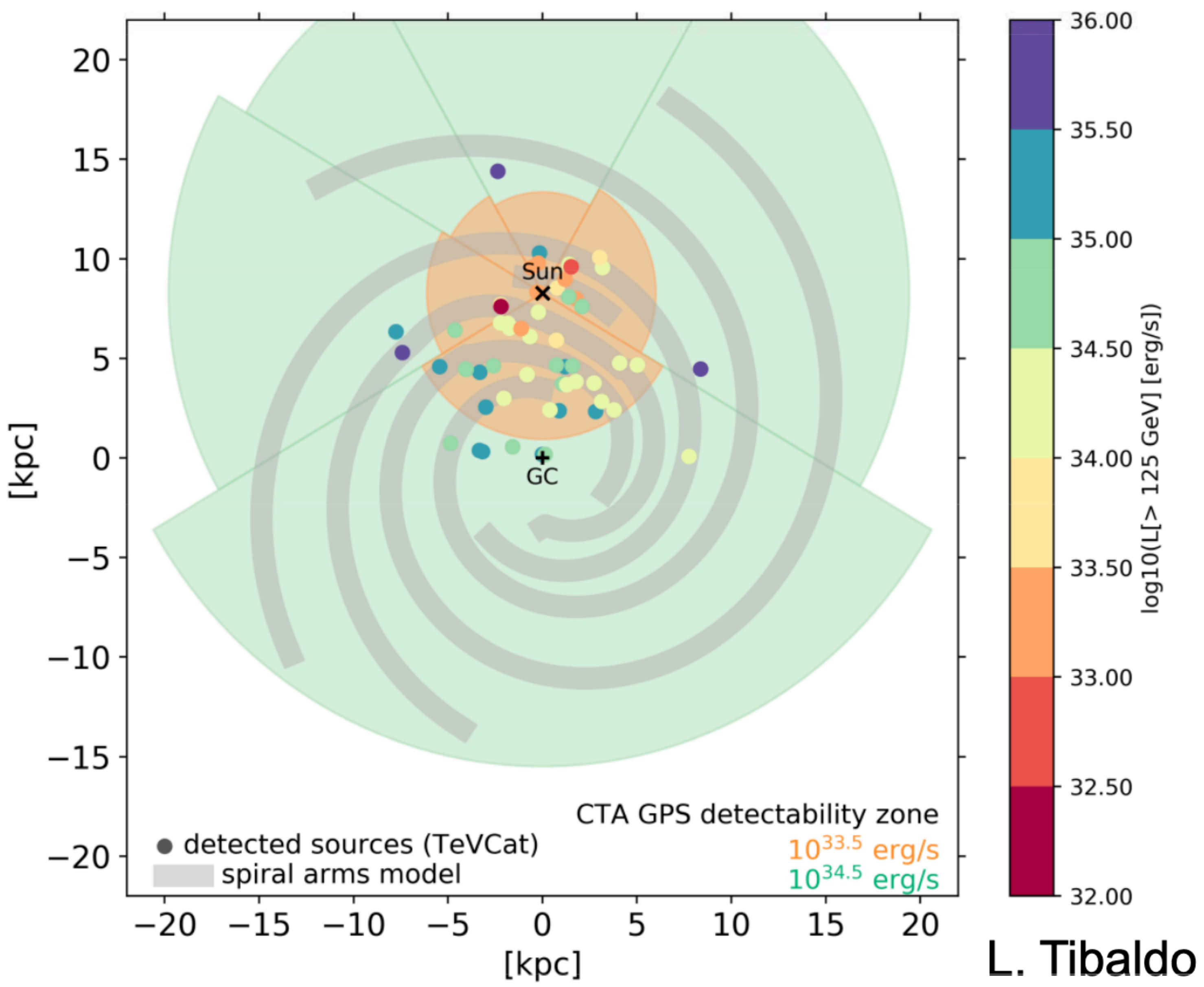


Accelerators: Haloes

Understanding the ISM / photon fields



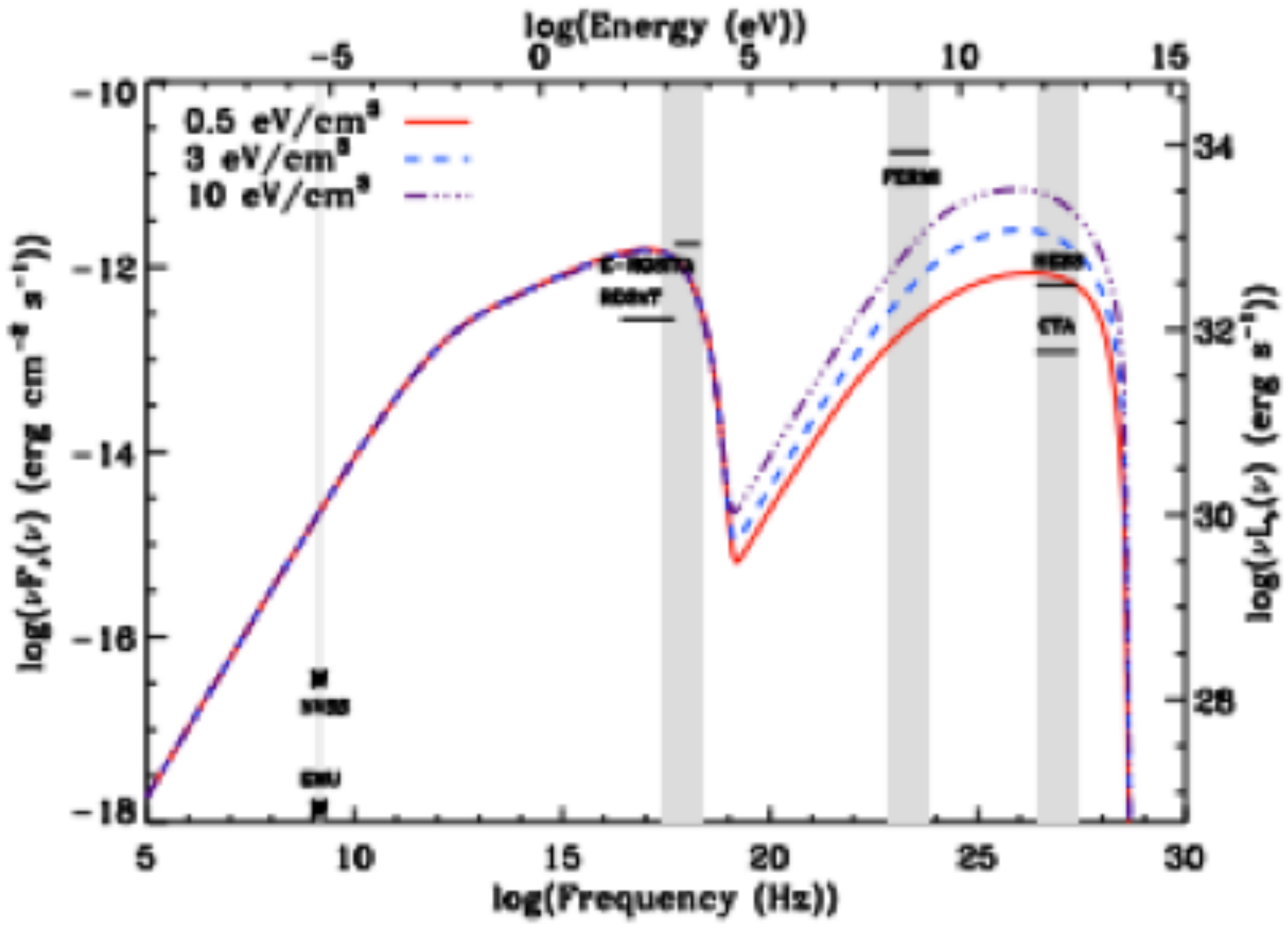


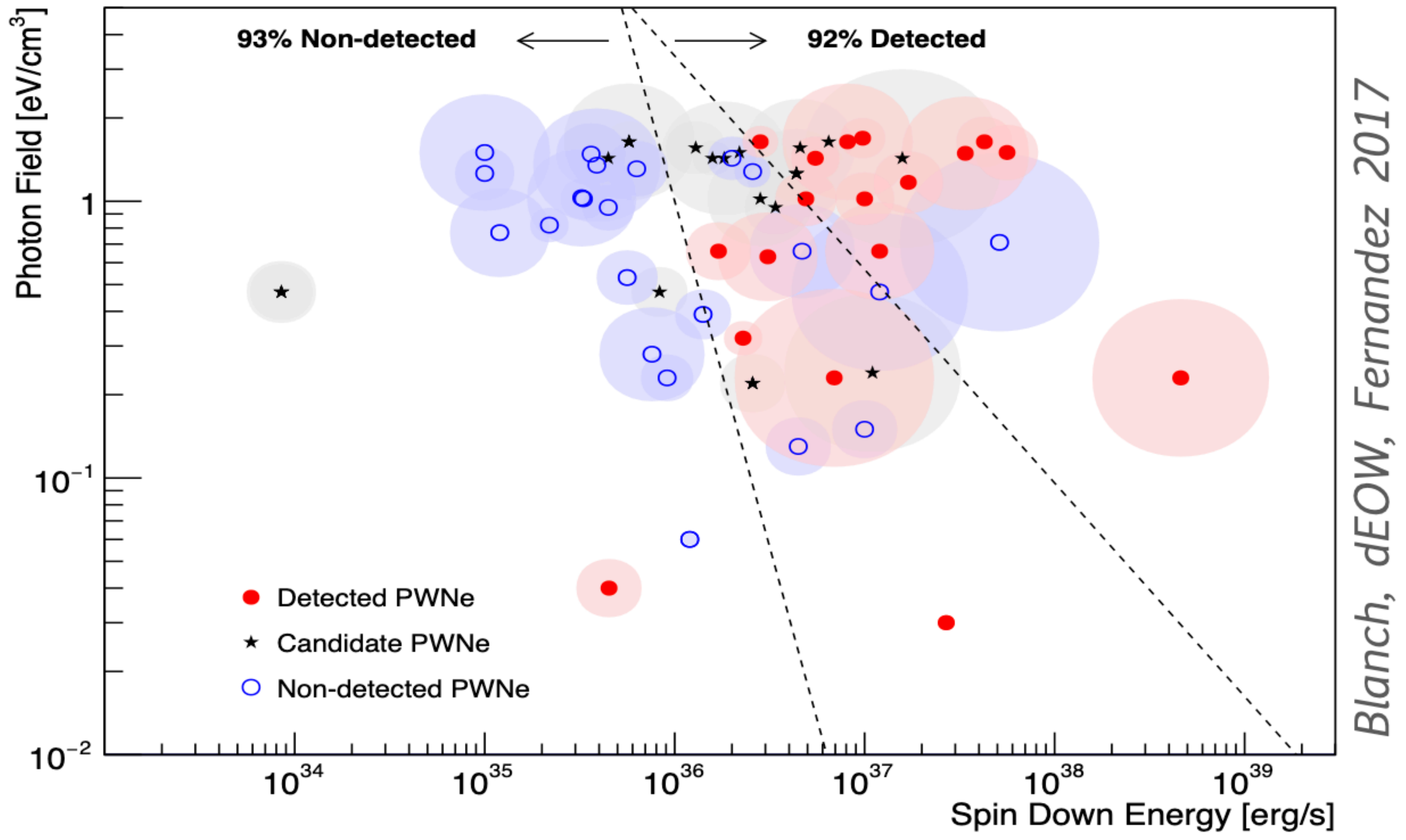


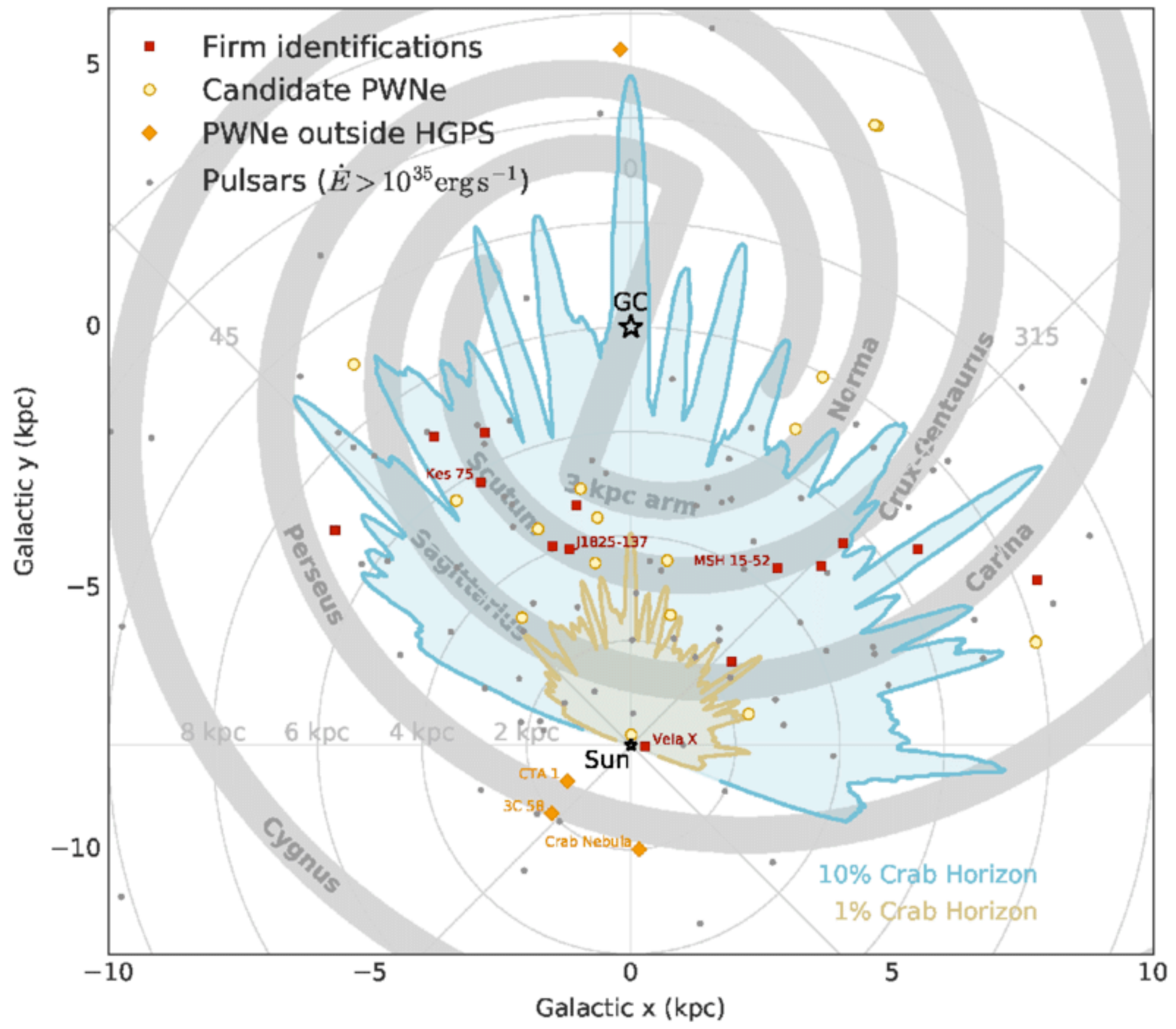
L. Tibaldo

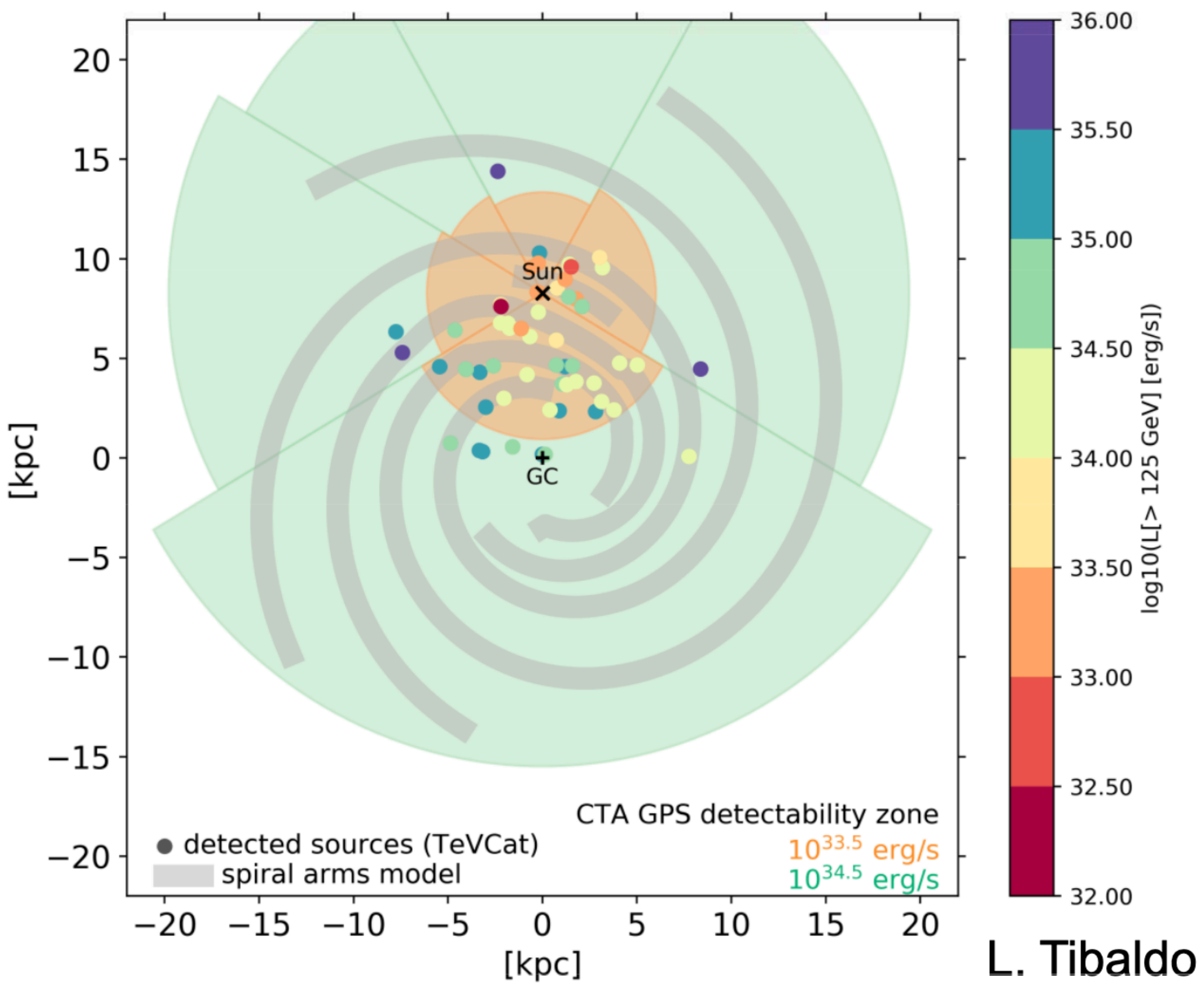
Accelerators: Haloes

Understanding the ISM / photon fields



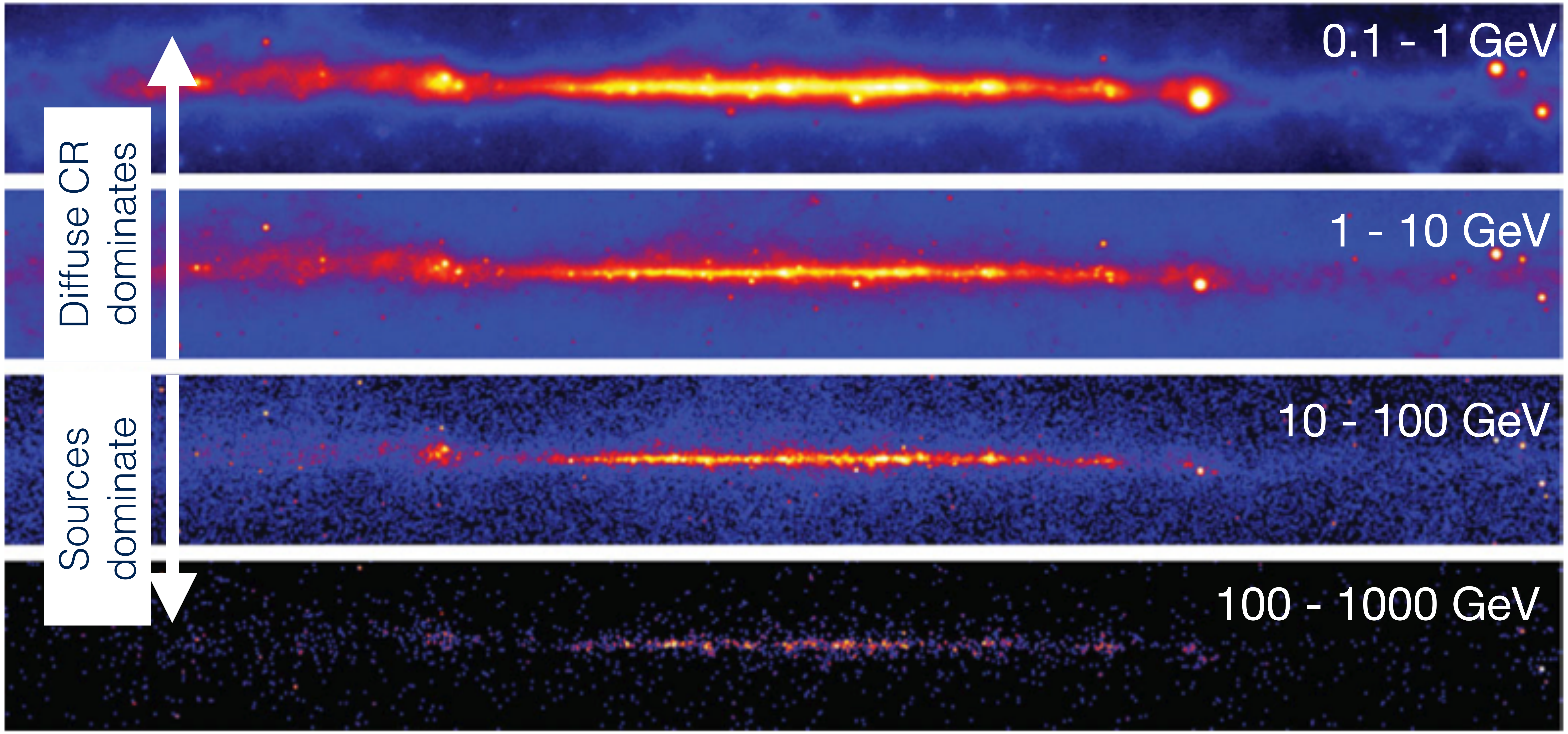






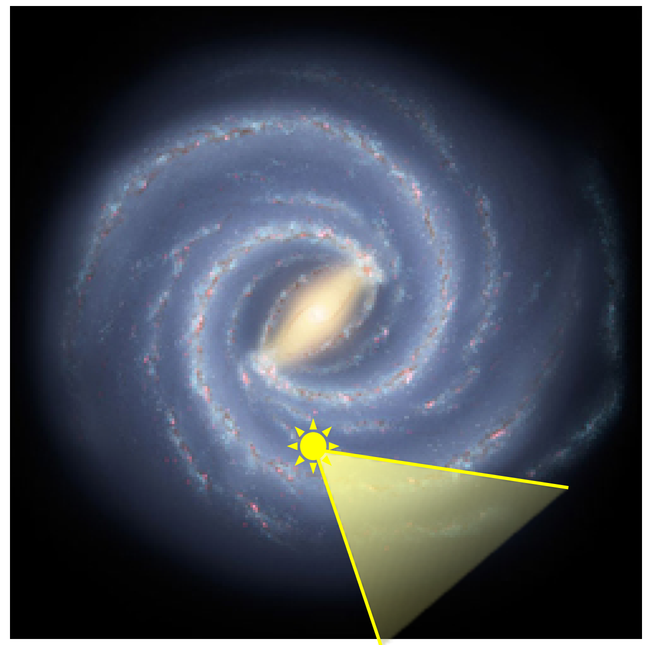
L. Tibaldo

Propagation of CRs

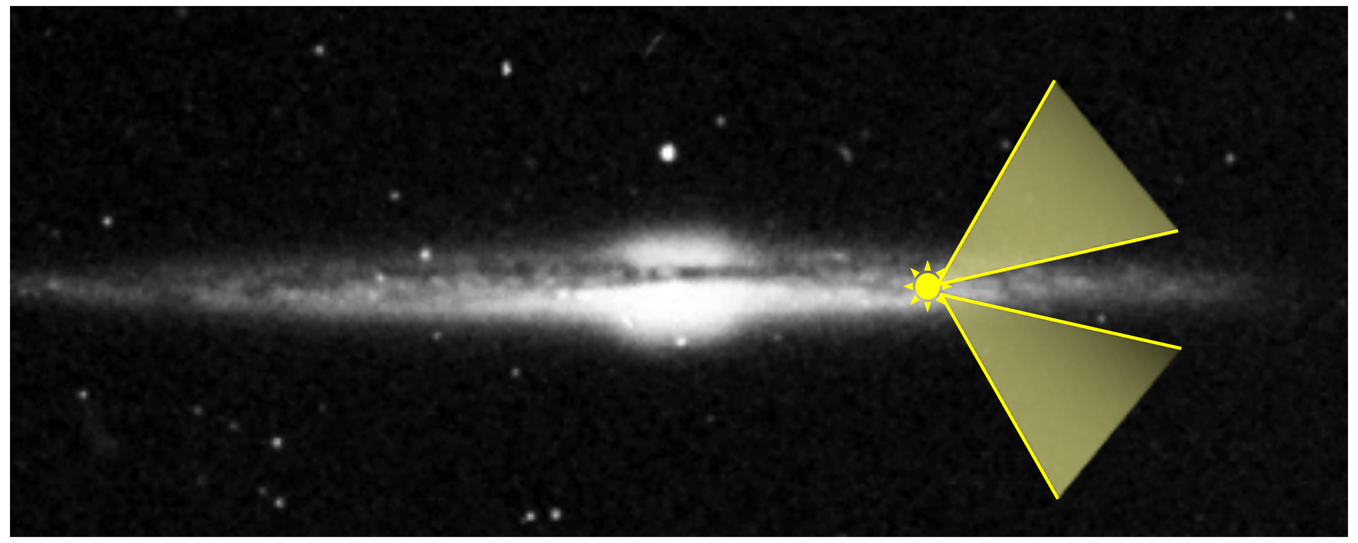


Propagation of CRs

Understanding the ISM / photon fields & the molecular content

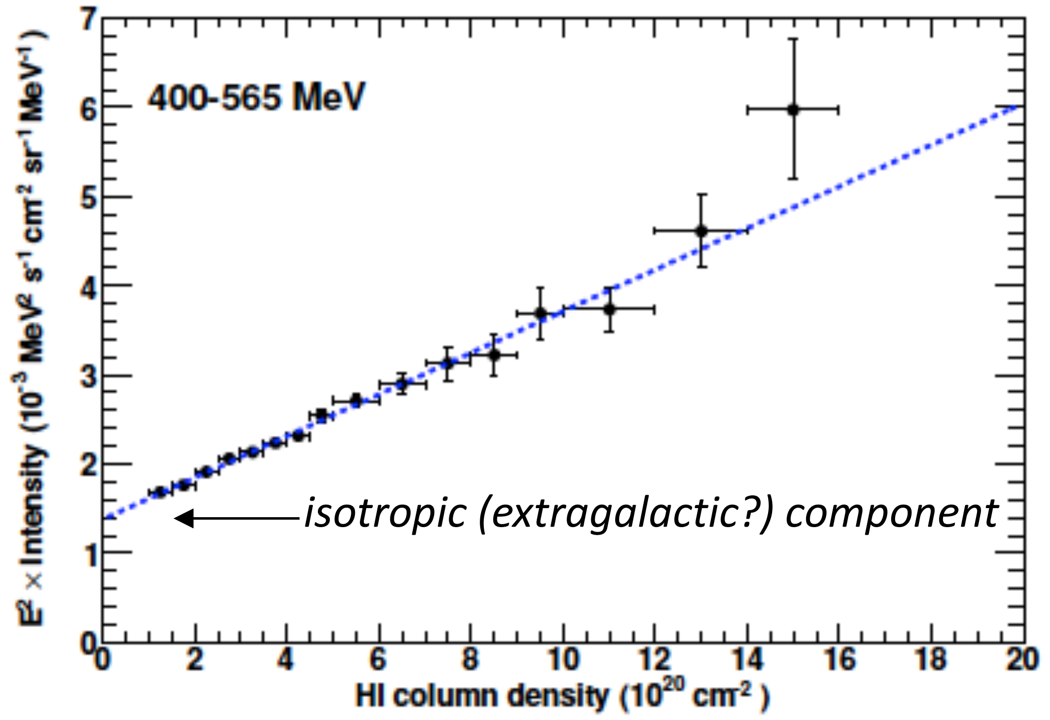


longitude: 200º to 260º

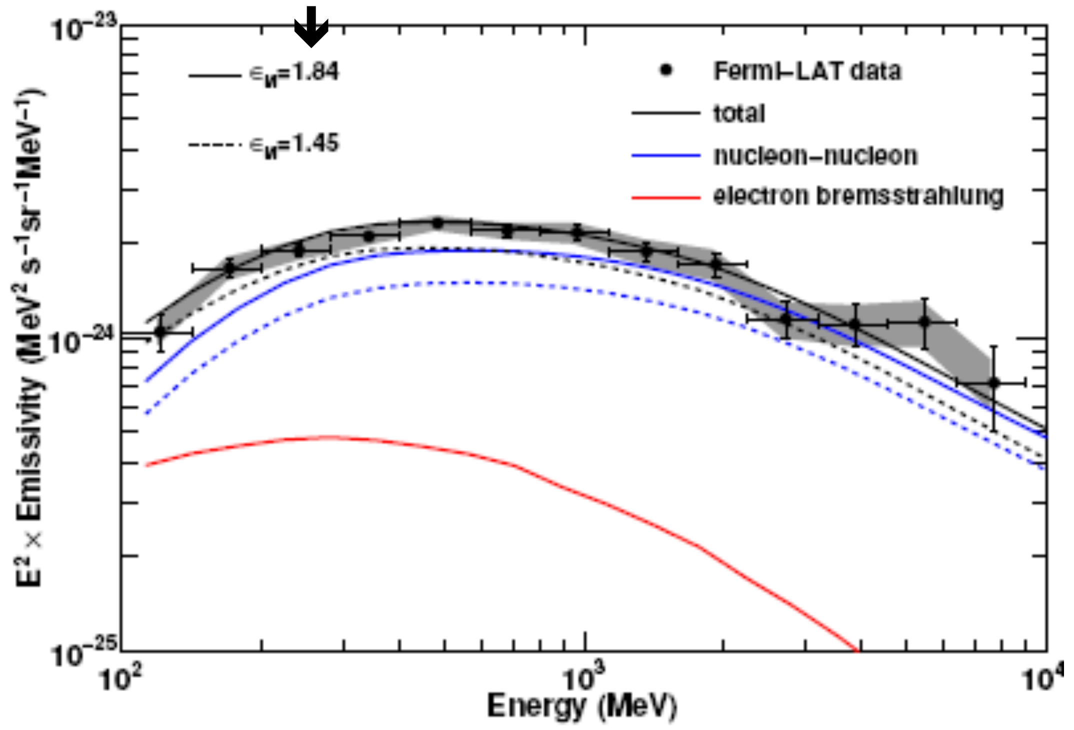


latitude: 22º to 60º (+ & -)

Abdo et al., ApJ, 703, 1249, 2009



enhancement factor from CRs heavier than p



The gamma-ray intensity exhibits a linear correlation with the atomic gas column density
The flux of CR nuclei is consistent (10%) with 1 kpc with the one measured locally at the Earth

Propagation of CRs

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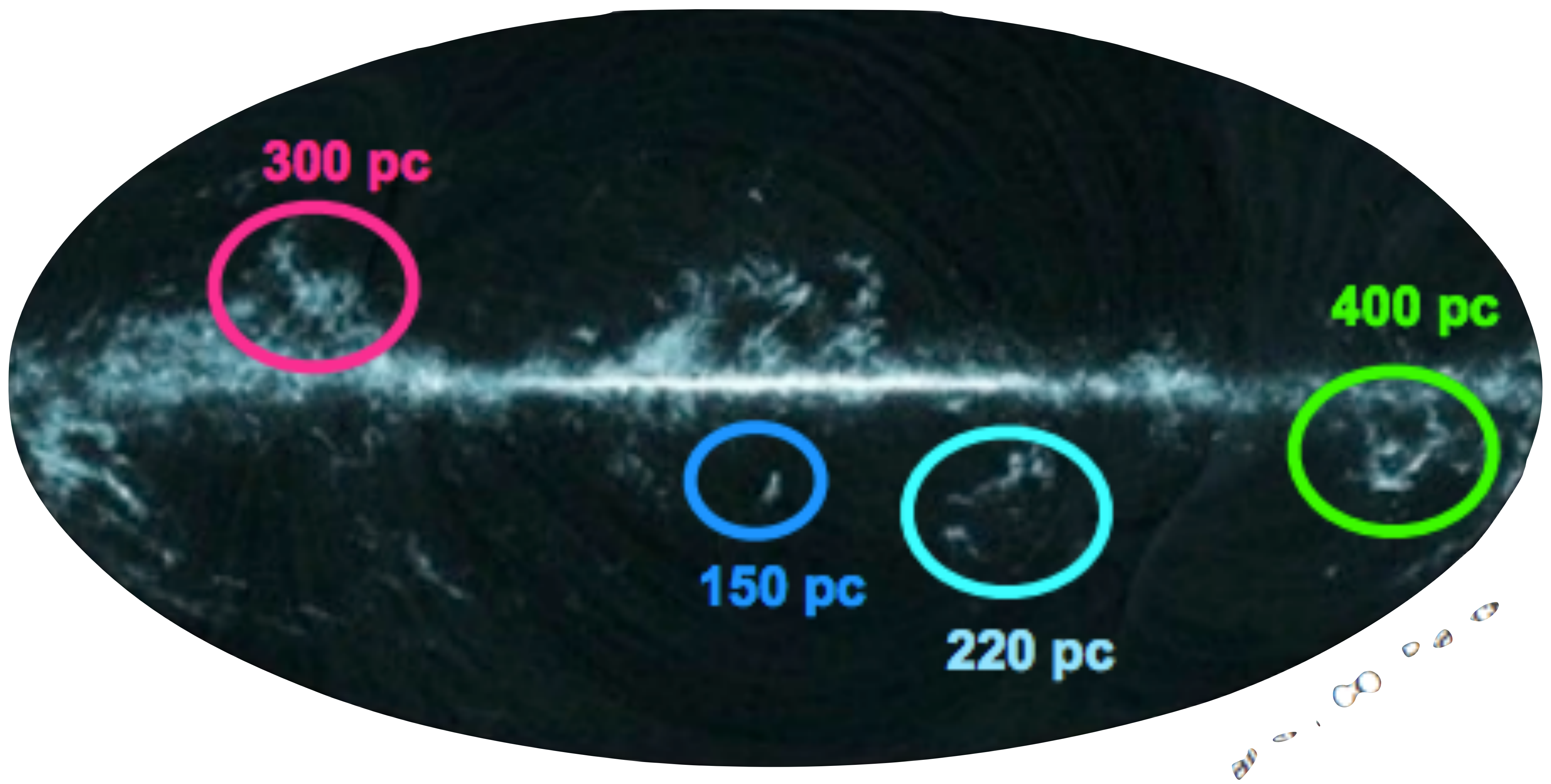
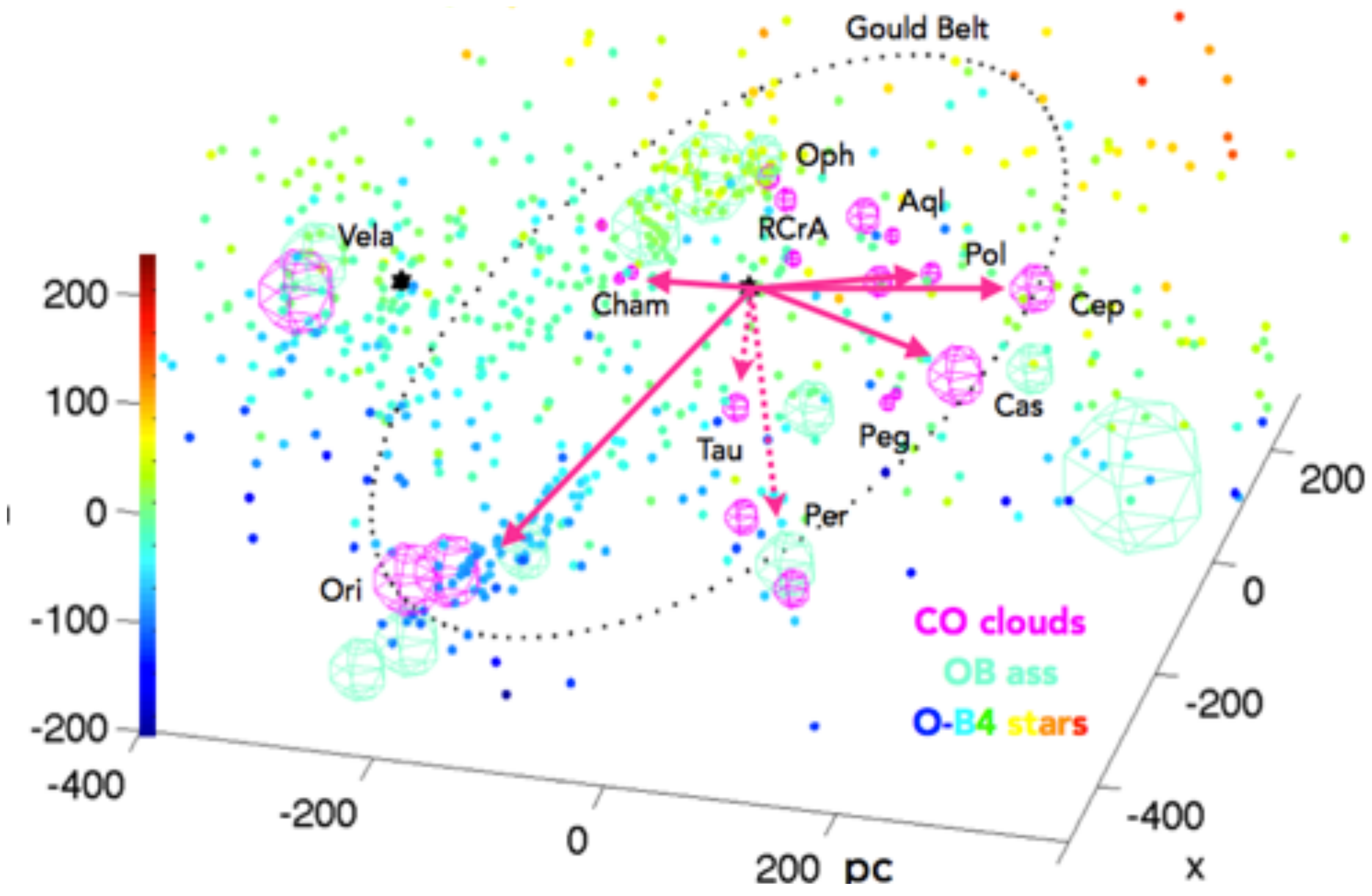




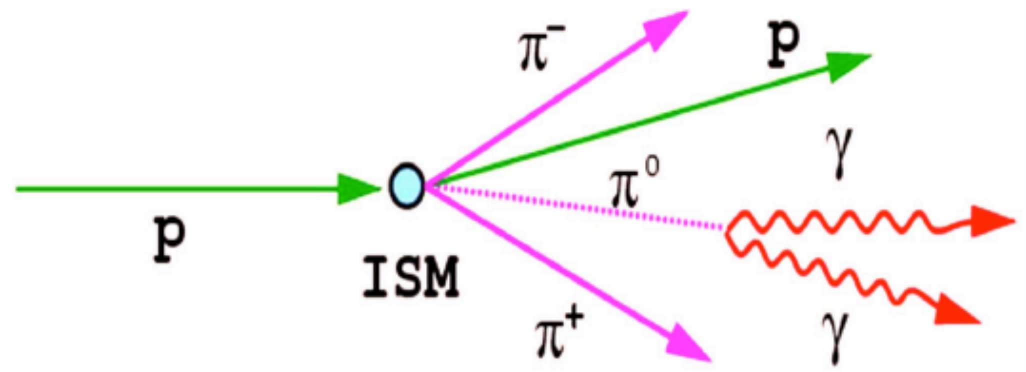
Using massive clouds are barometers for determine the pressure (energy density) of CRs

Large number of photons to determine the spectrum with accuracy

Nearby and dense clouds

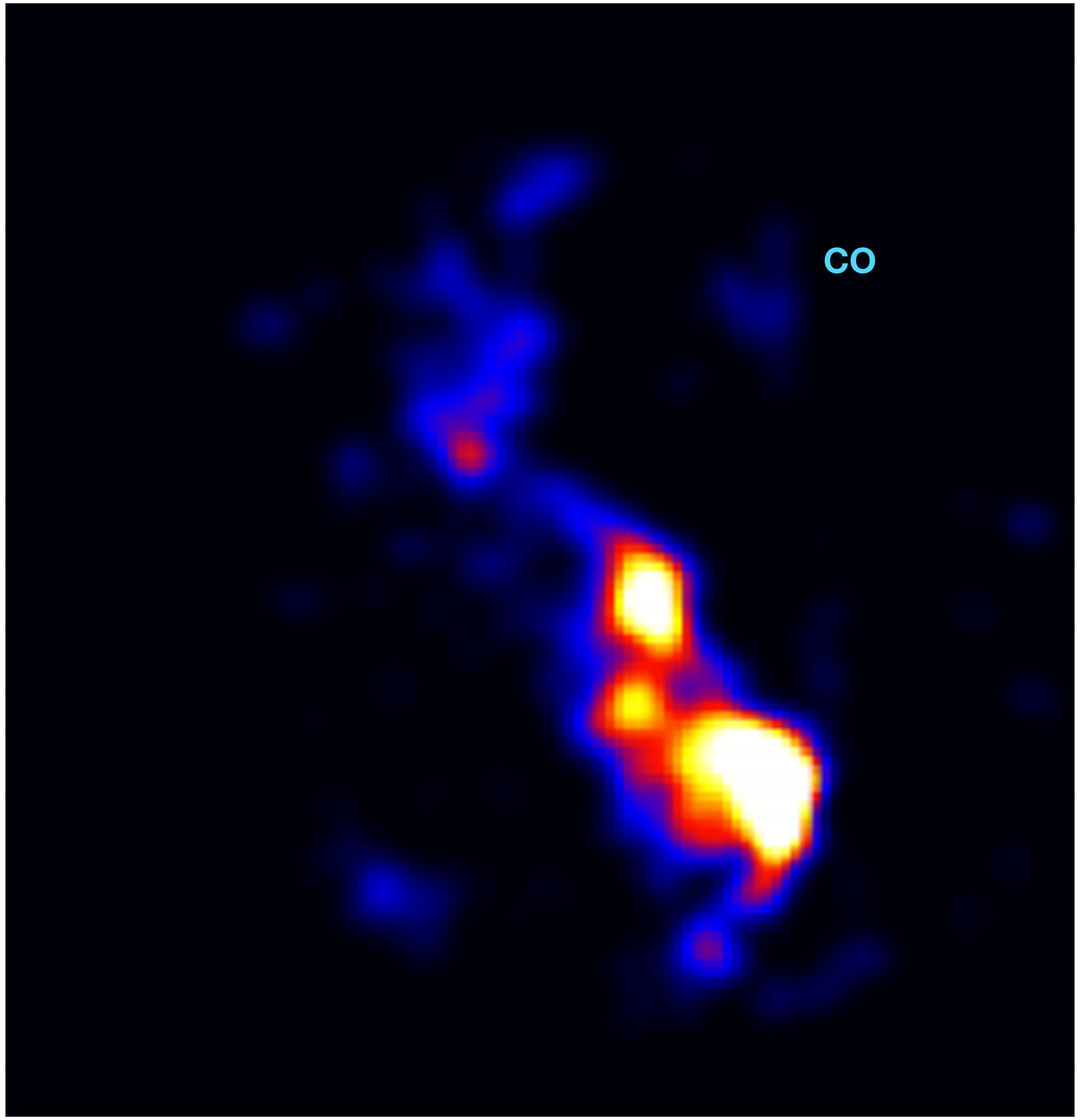
Propagation of CRs

Understanding the ISM / photon fields & the molecular content



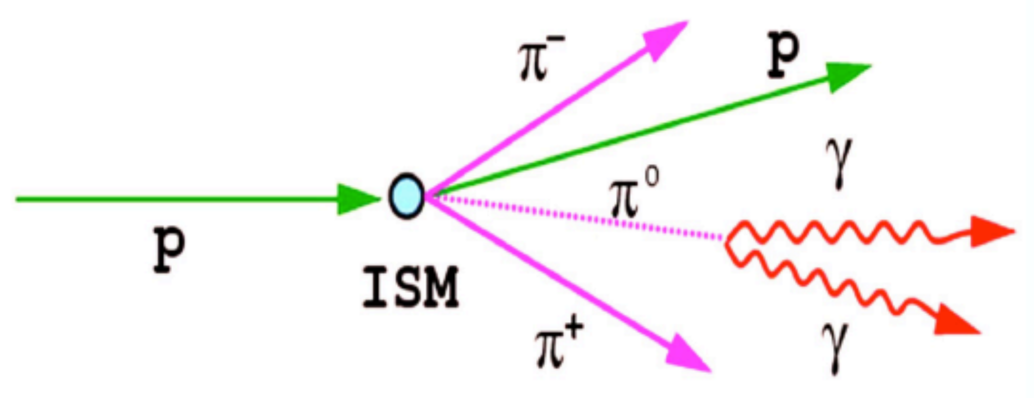
Target [p]

CRs [p]

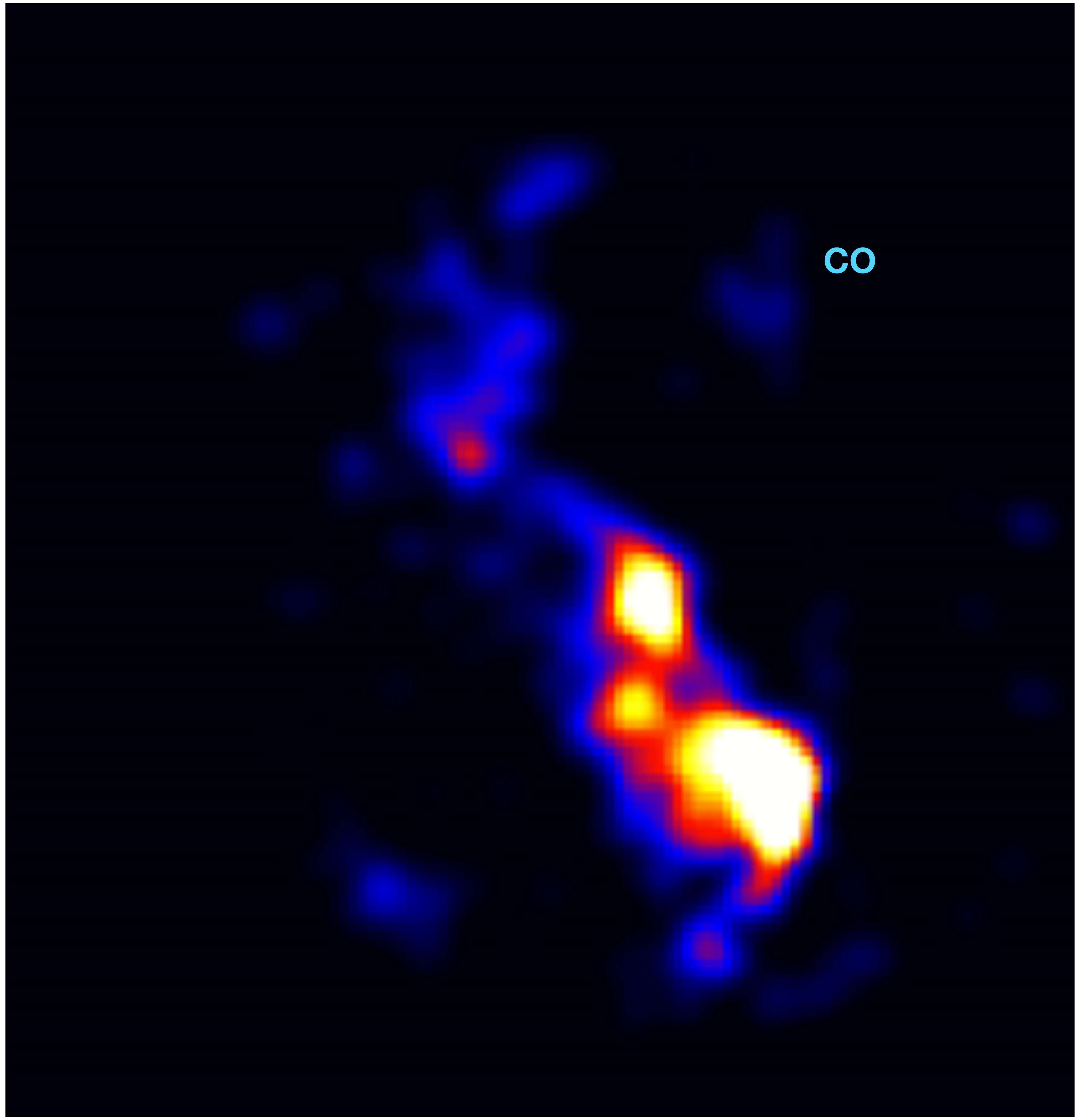


Propagation of CRs

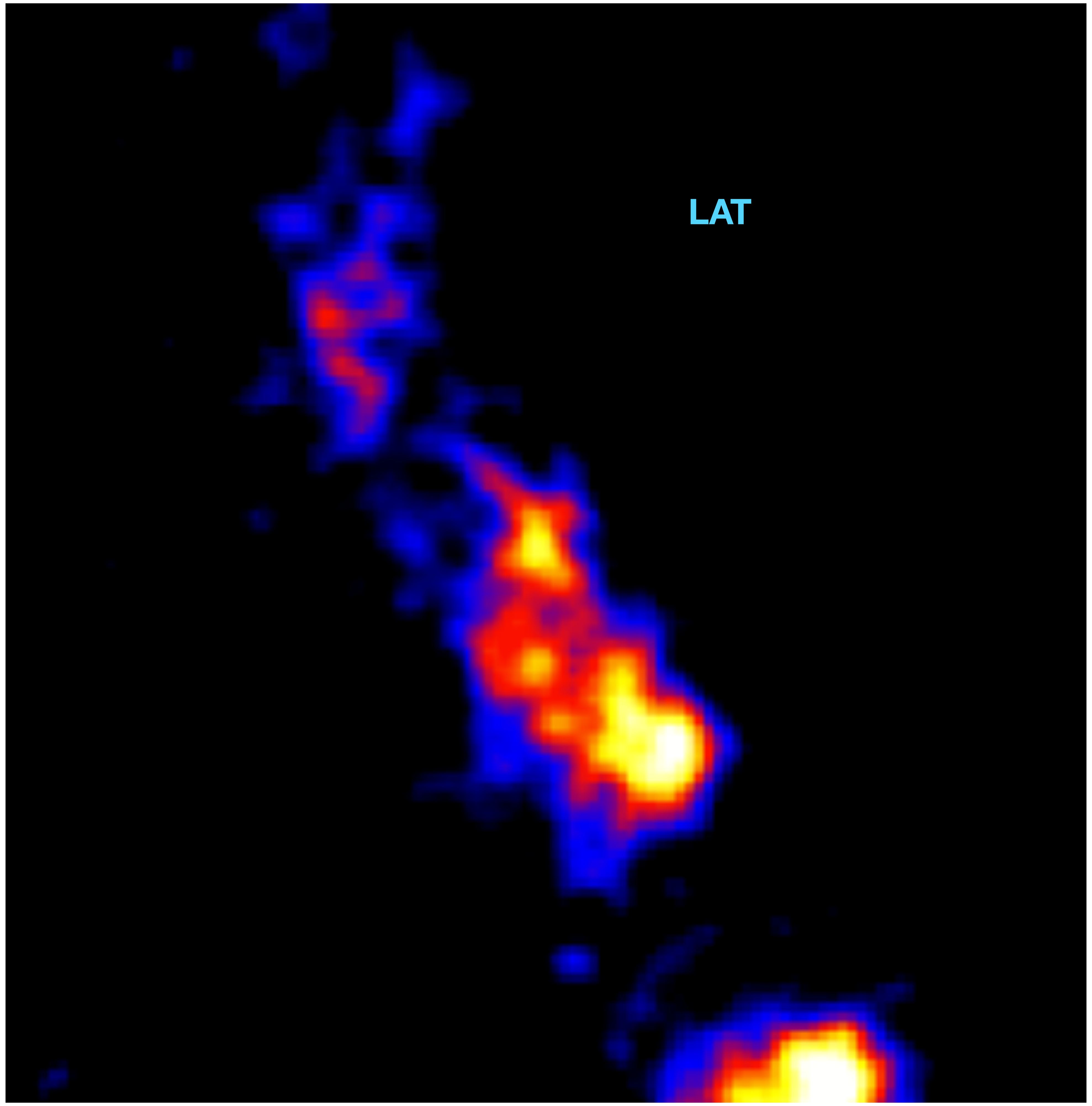
Understanding the ISM / photon fields & the molecular content



Target [p]



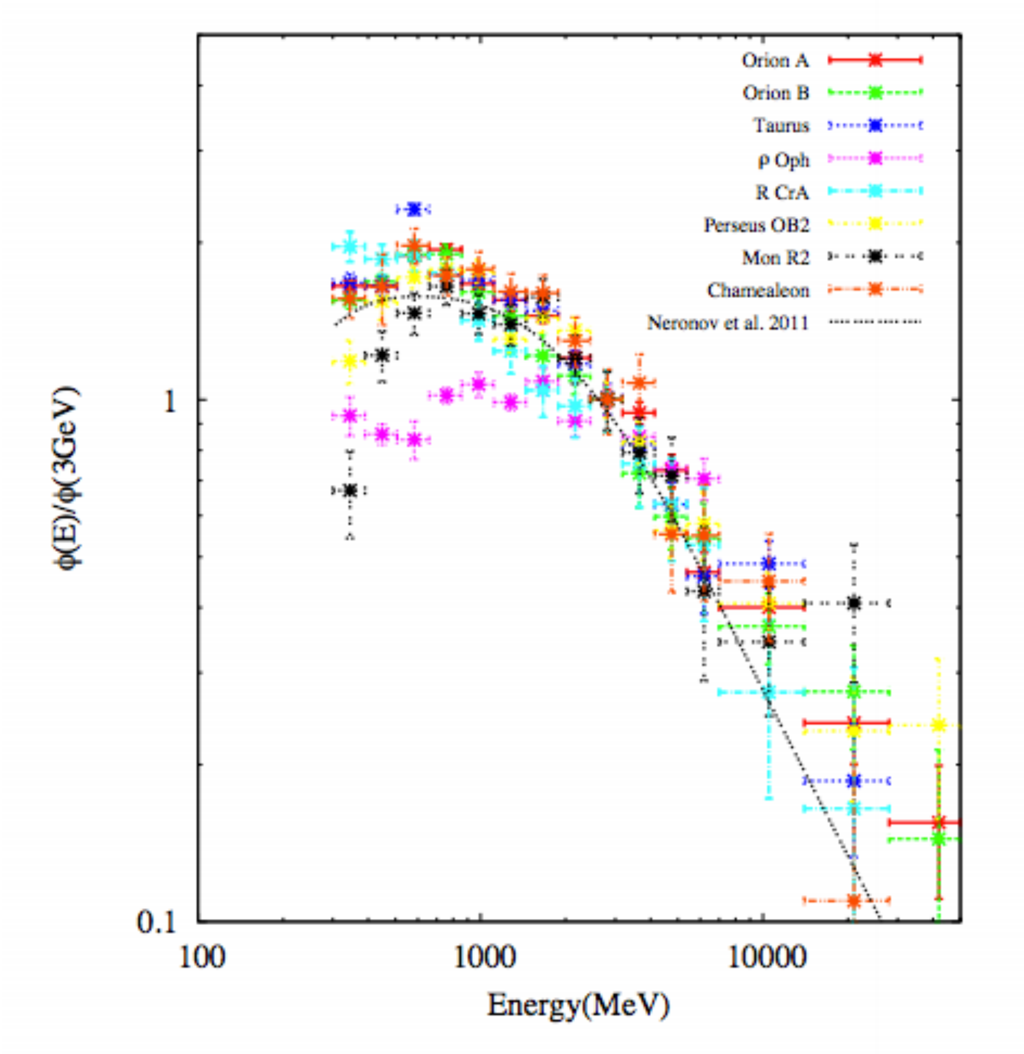
CRs [p]

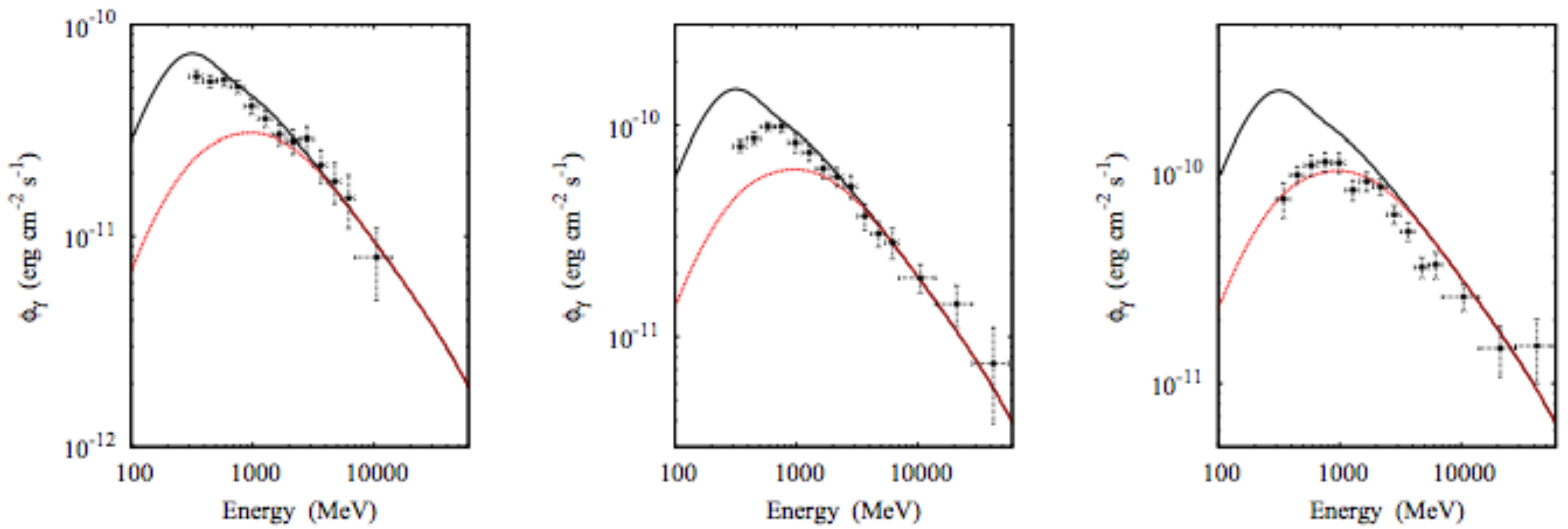


Propagation of CRs

Understanding the ISM / photon fields & the molecular content

Yang, EOW, Aharonian 2014



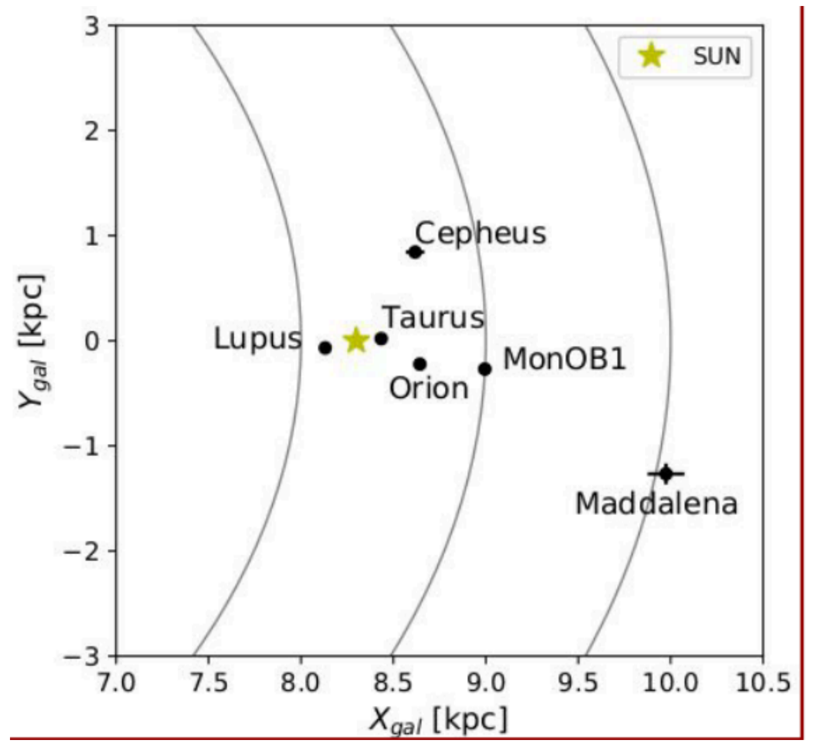


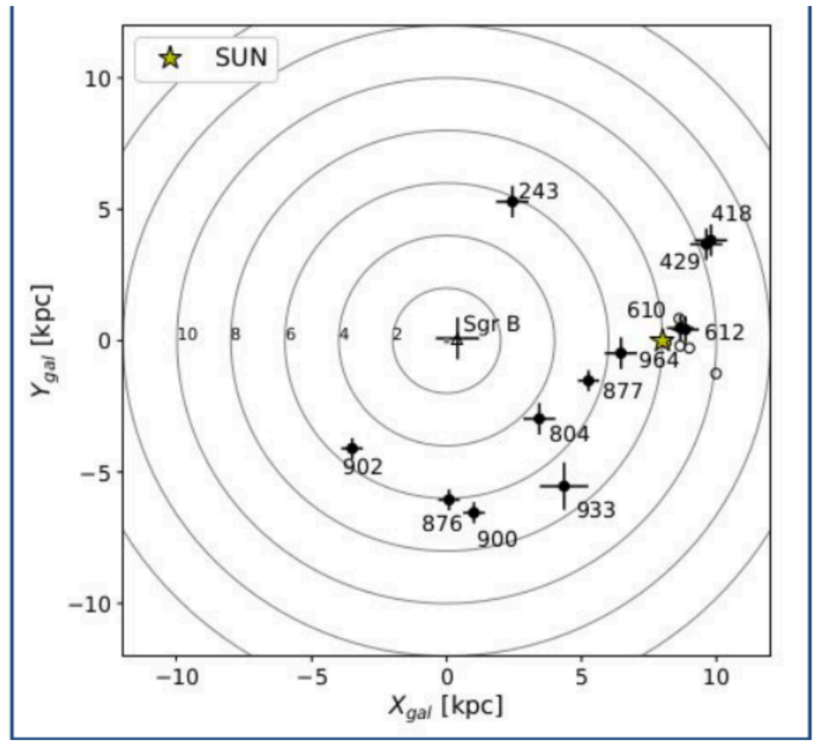
(a) R CrA (b) Orion B (c) Perseus OB2

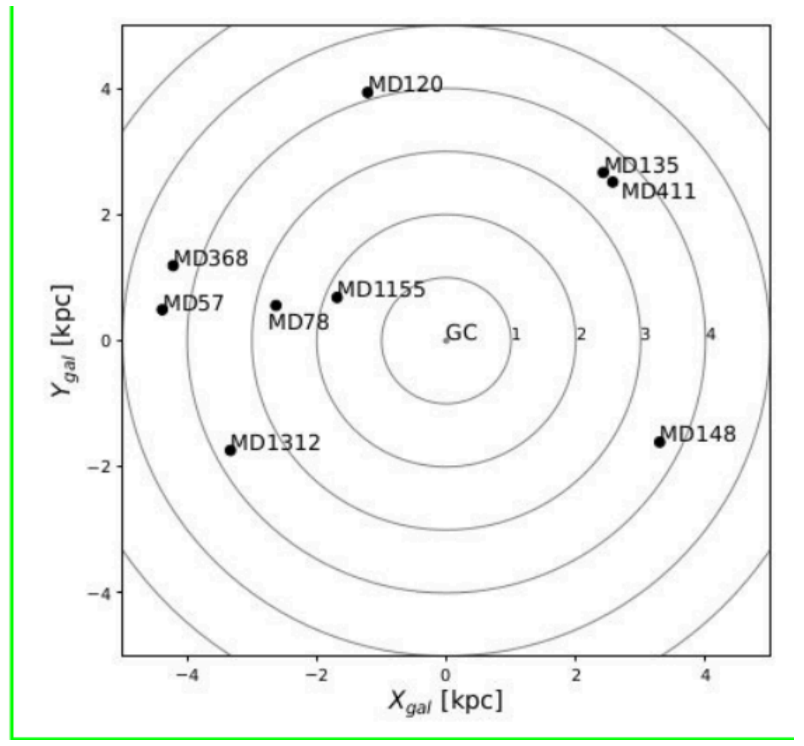
- > 20 GeV: good agreement with CR spectrum measured at Earth
- Low energy part shows differs from cloud to cloud (deviating for pure power law)
- Related to different environment (local acceleration, low CR penetration effects, modulation effects?)

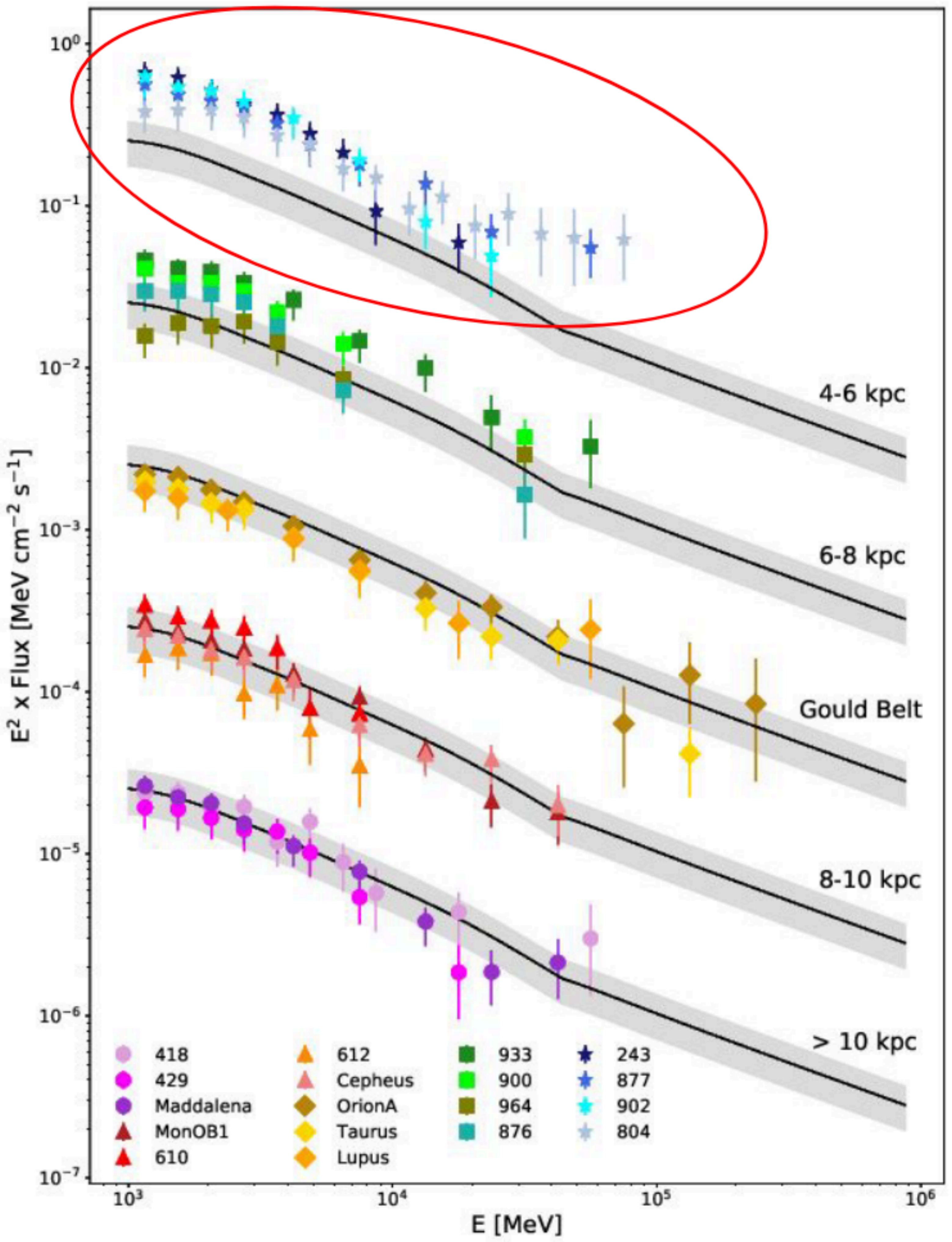
Using molecular clouds as barometers

Peron et al 2021







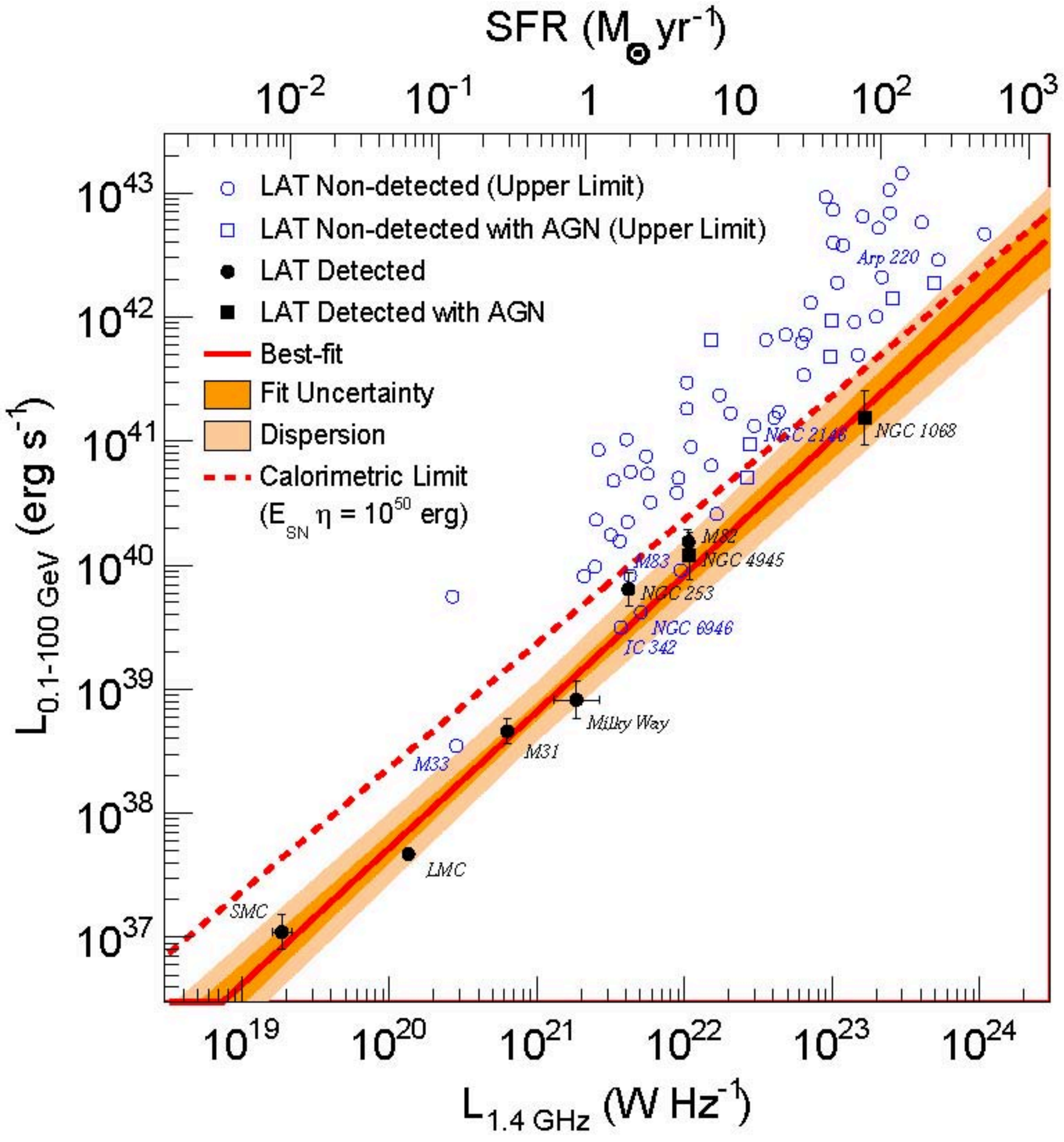


- Probing the CRs at different location far for us
- Analysis of molecular clouds provide localized information on the CR spectrum far from Earth
- Results from GMCs show deviations from the local emissivity only in the inner Galaxy, around 4-6 kpc. The deviations are fluctuating, discouraging a global variation

Galactic science in extragalactic objects

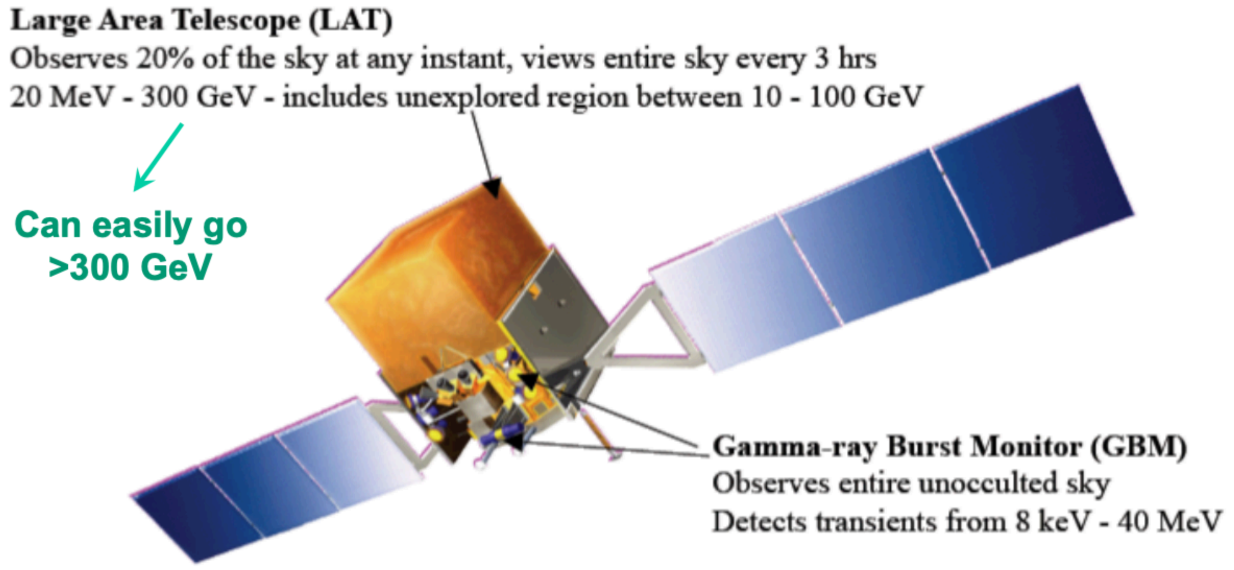
- HE gamma-ray emission from star burst Galaxies SBGs and nearby ordinary galaxies (Magellanic clouds, M31) scales quasi-linearly with Star Formation Rates (SFR) derived from IR observations

- Also correlates with radio continuum (from CR electrons)

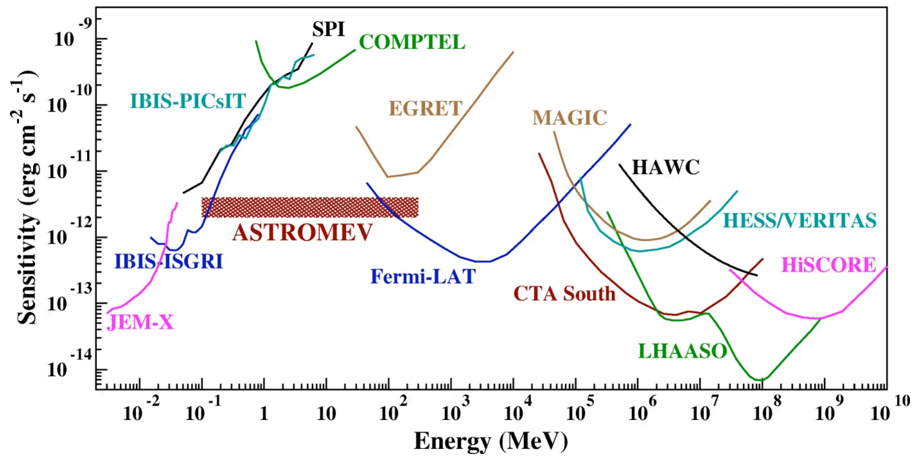


Prospects for the upcoming years

The Multi-wavelength approach to astrophysics



eASTROGAM
DAMPE
AdePT
HERD
....



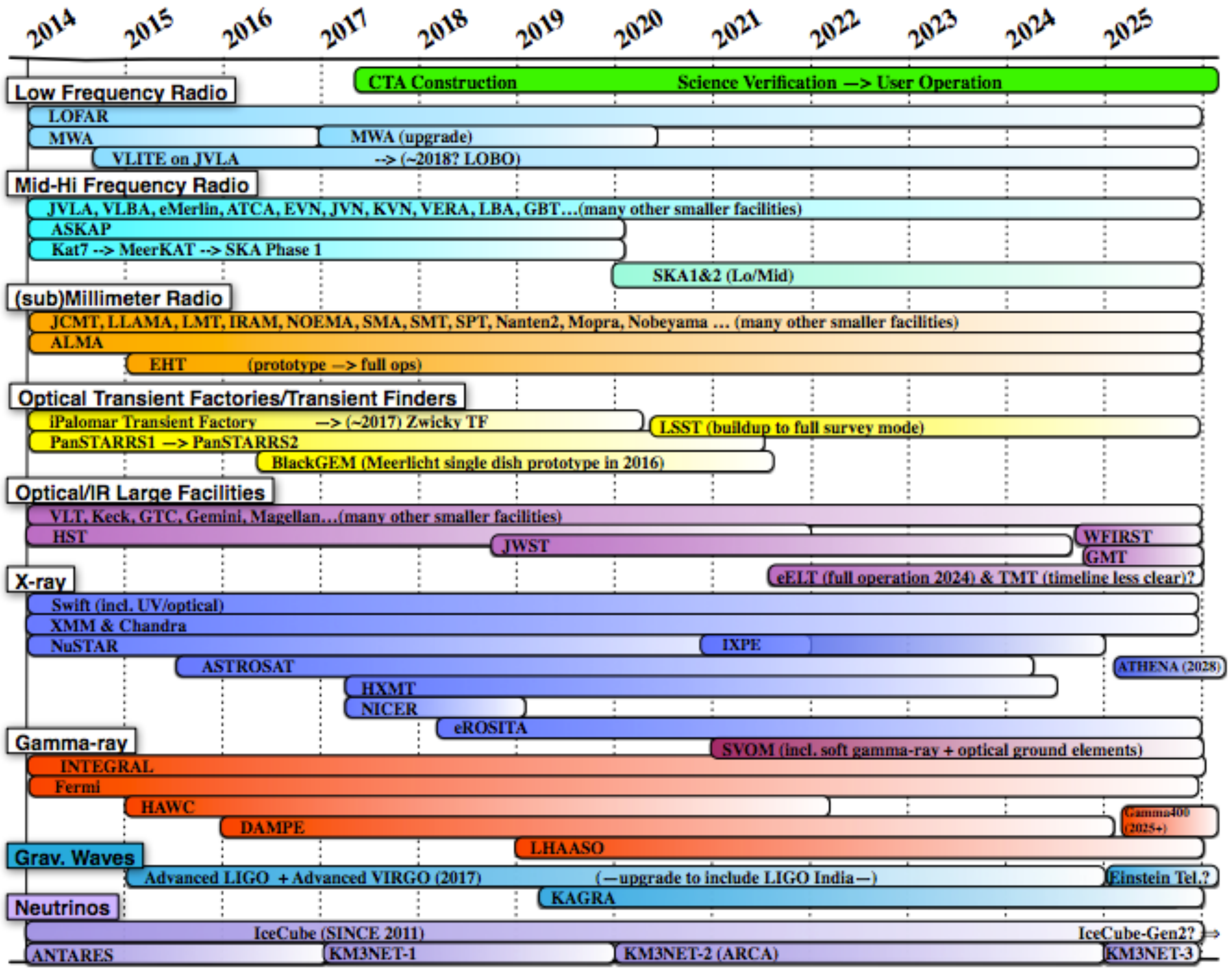
cta cherenkov telescope array

SWGO
LHAASO++

MeV - GeV **GeV - > 100 TeV** **PeV**

The Multi-wavelength approach to astrophysics

The Multi-wavelength approach to astrophysics



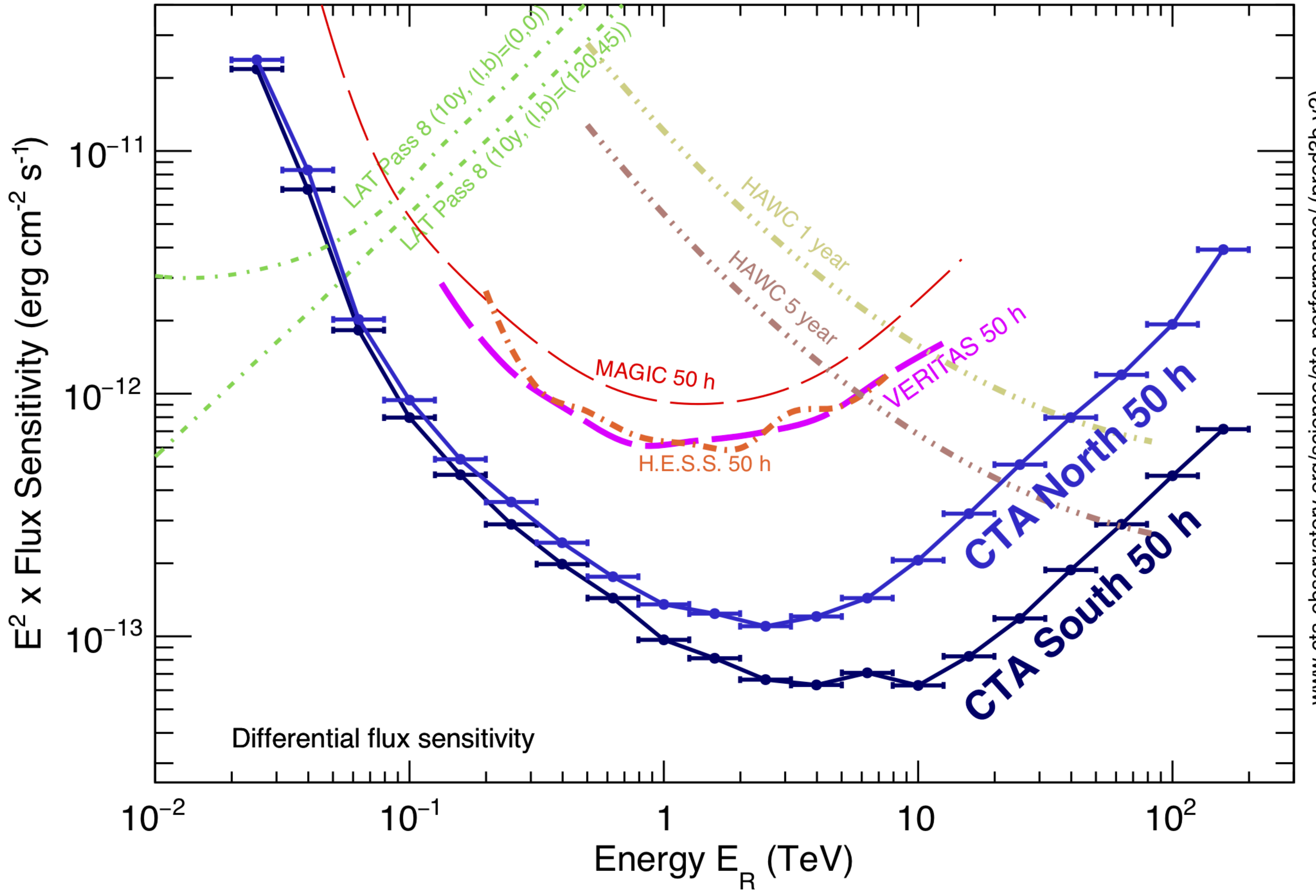
Galactic Physics with CTA

Boosting:

- Increase sensitivity by up to a factor ~6 at 1 TeV
- Increase the detection area for transients and at the highest energies
- Increase the angular resolution/maintaining a large FoV

New:

- Energy coverage: tens of GeV => >100 TeV (~300 TeV)
- 2 Sites, flexibility of operation, allowing for sub-arrays and multi-mode
- Operate as an observatory



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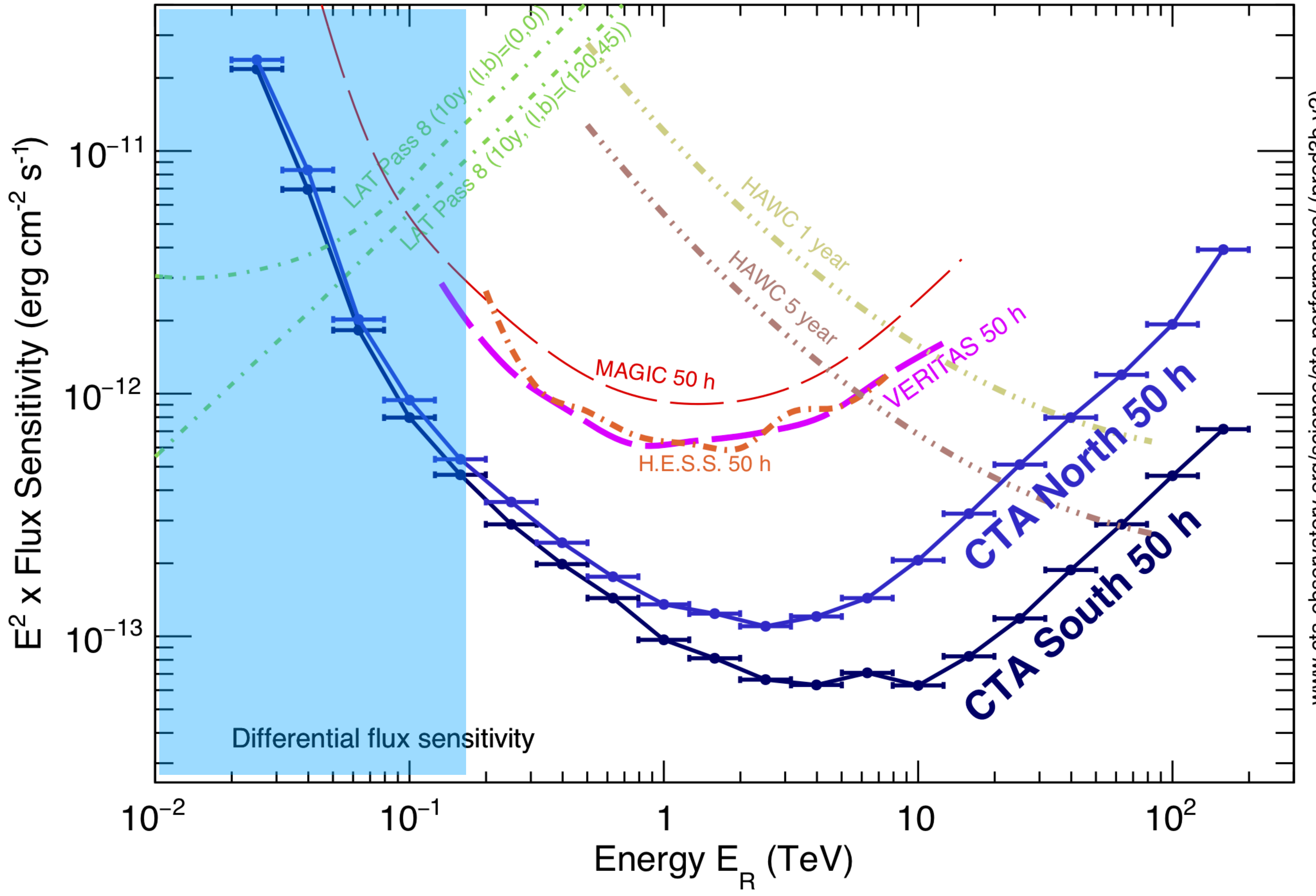

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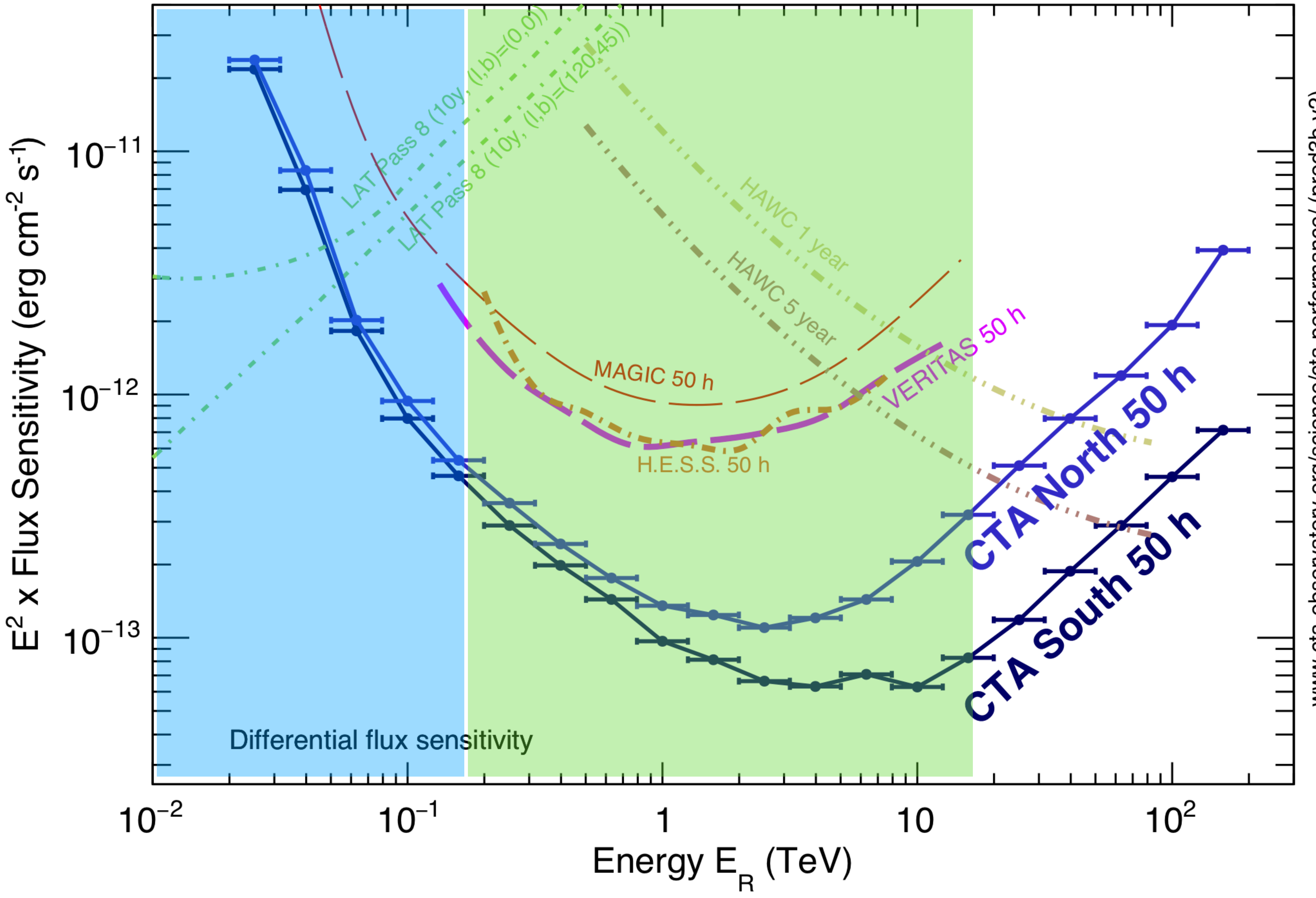

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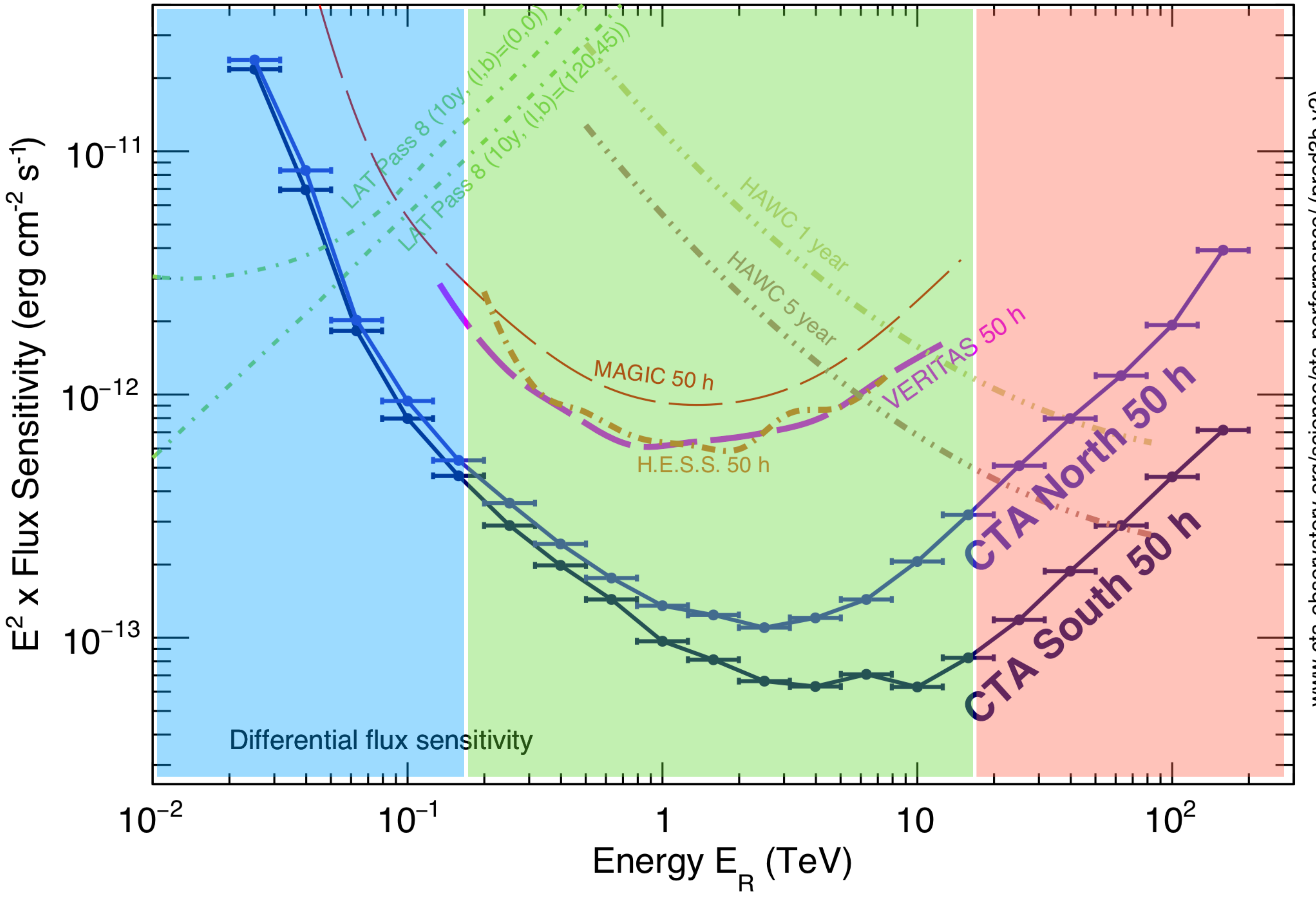

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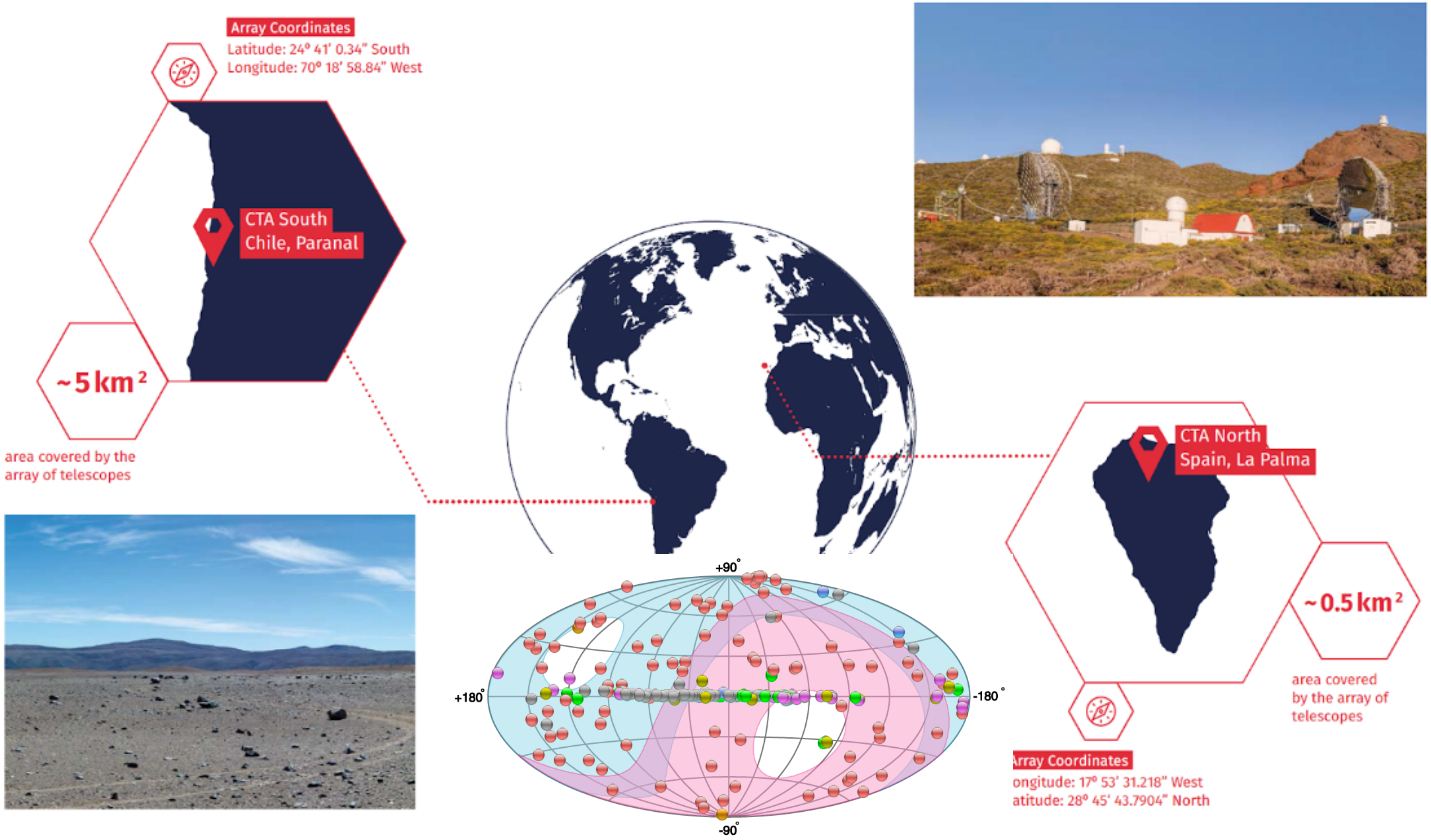
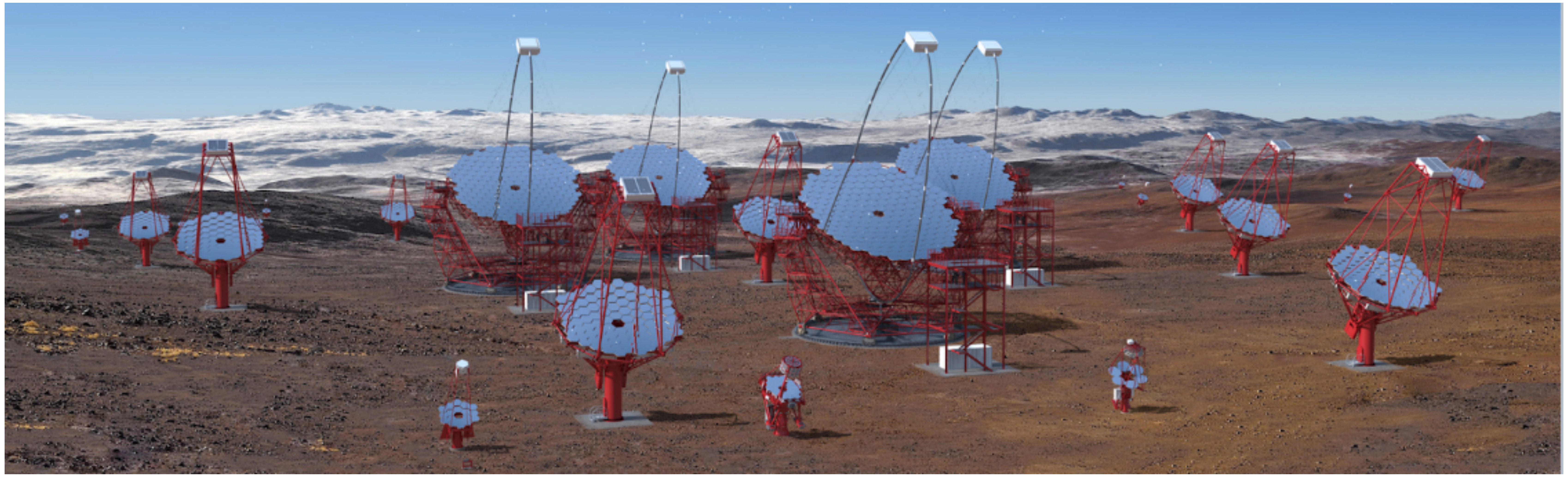


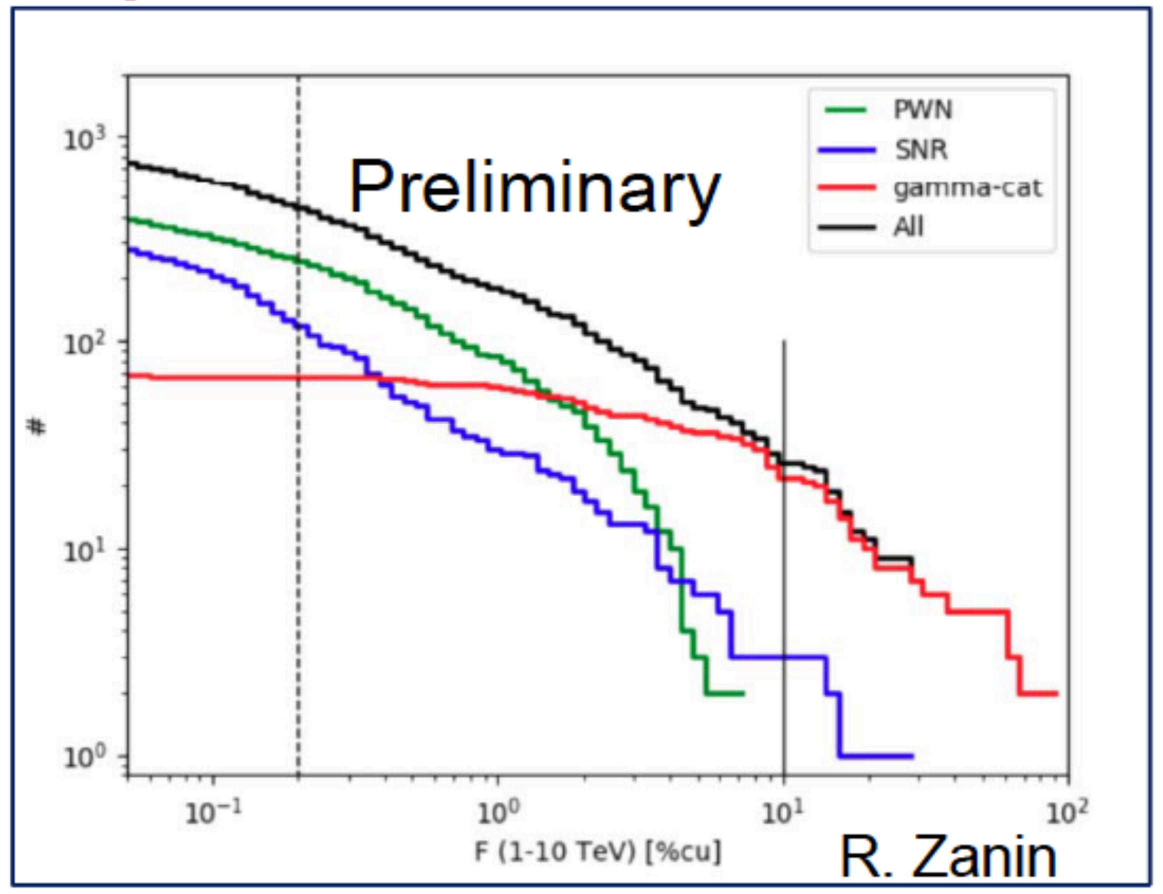
Galactic Physics with CTA

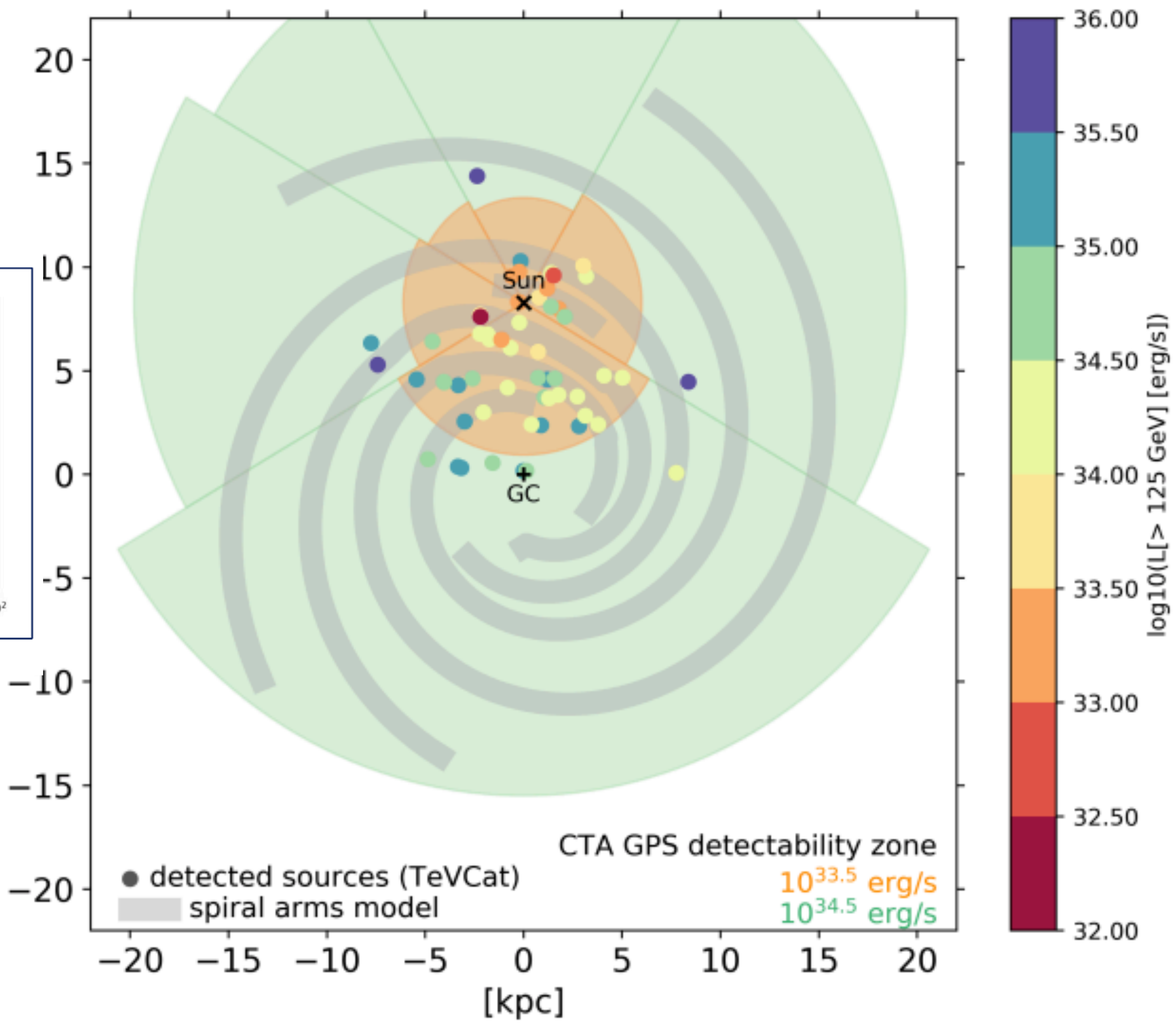
South: 99 telescopes spread out over ~5 km2 (70 SSTs, 25 MSTs, 4 LSTs)



North: 19 telescopes spread out over ~1 km2 (15 MSTs, 4 LSTs)

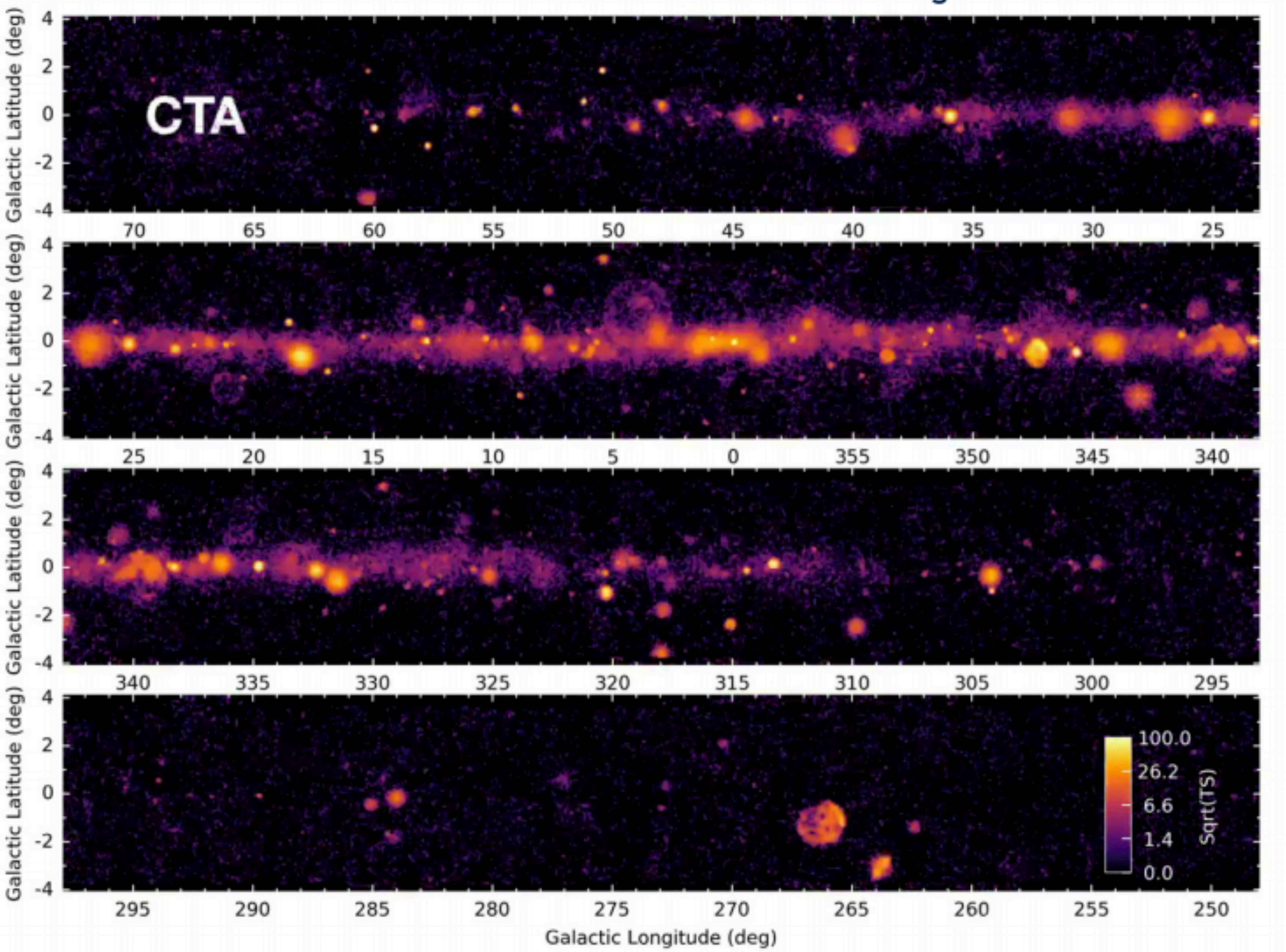
Population Studies





Full galactic plane (1020 h) ~2 mCrab (now ~1-2%Crab)
Deep survey of the Galactic Centre region (300 h on 10°x10° region, 525 h on GC)
The Large Magellanic Cloud (340 h in 6 pointings)

Cutout of CTA GPS from first Data Challenge



Plot credits: Christoph Deil, Roberta Zanin

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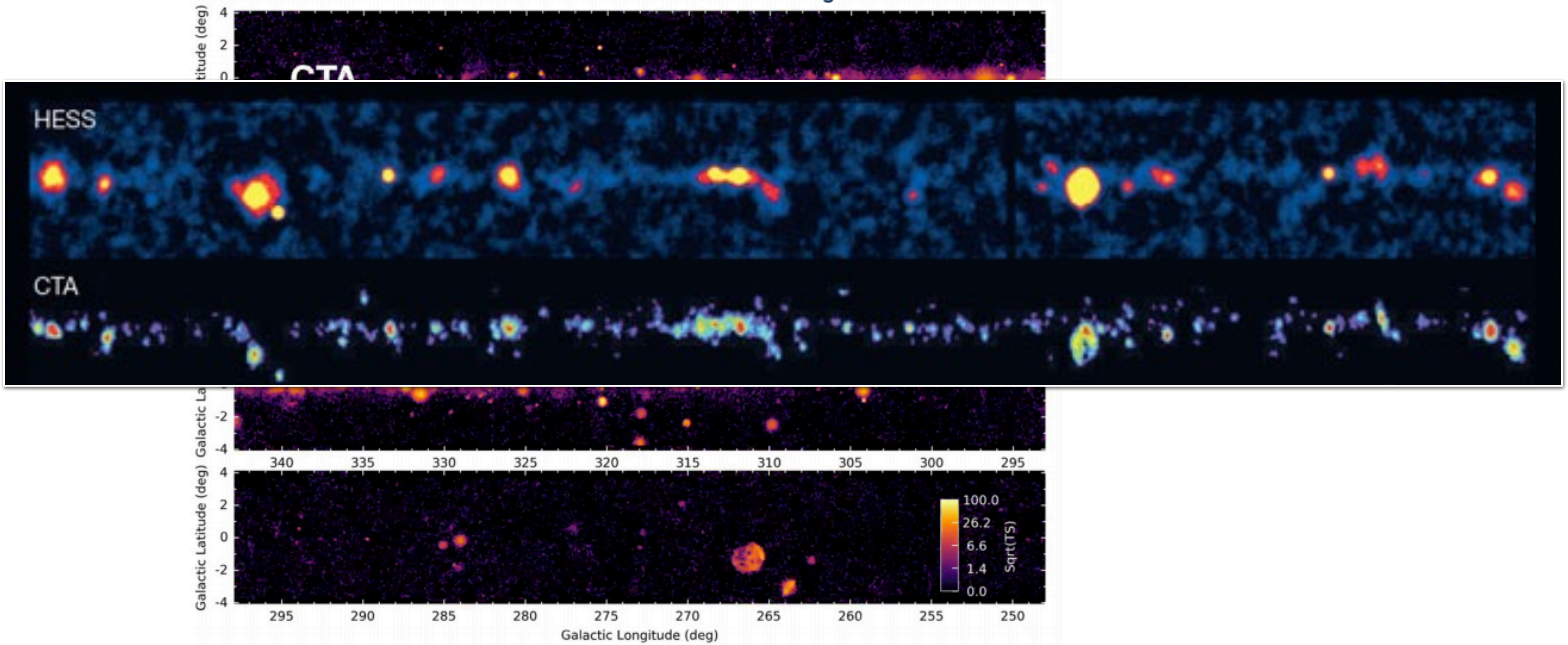

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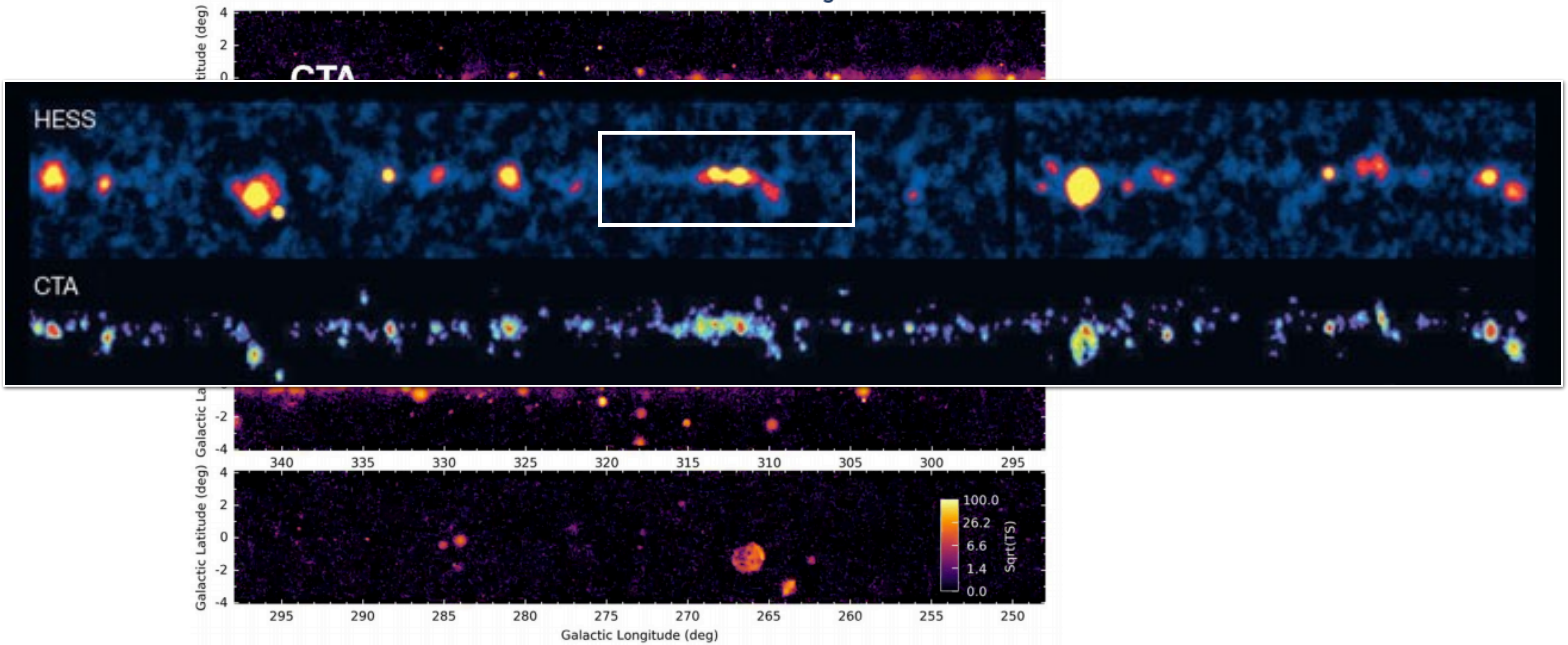

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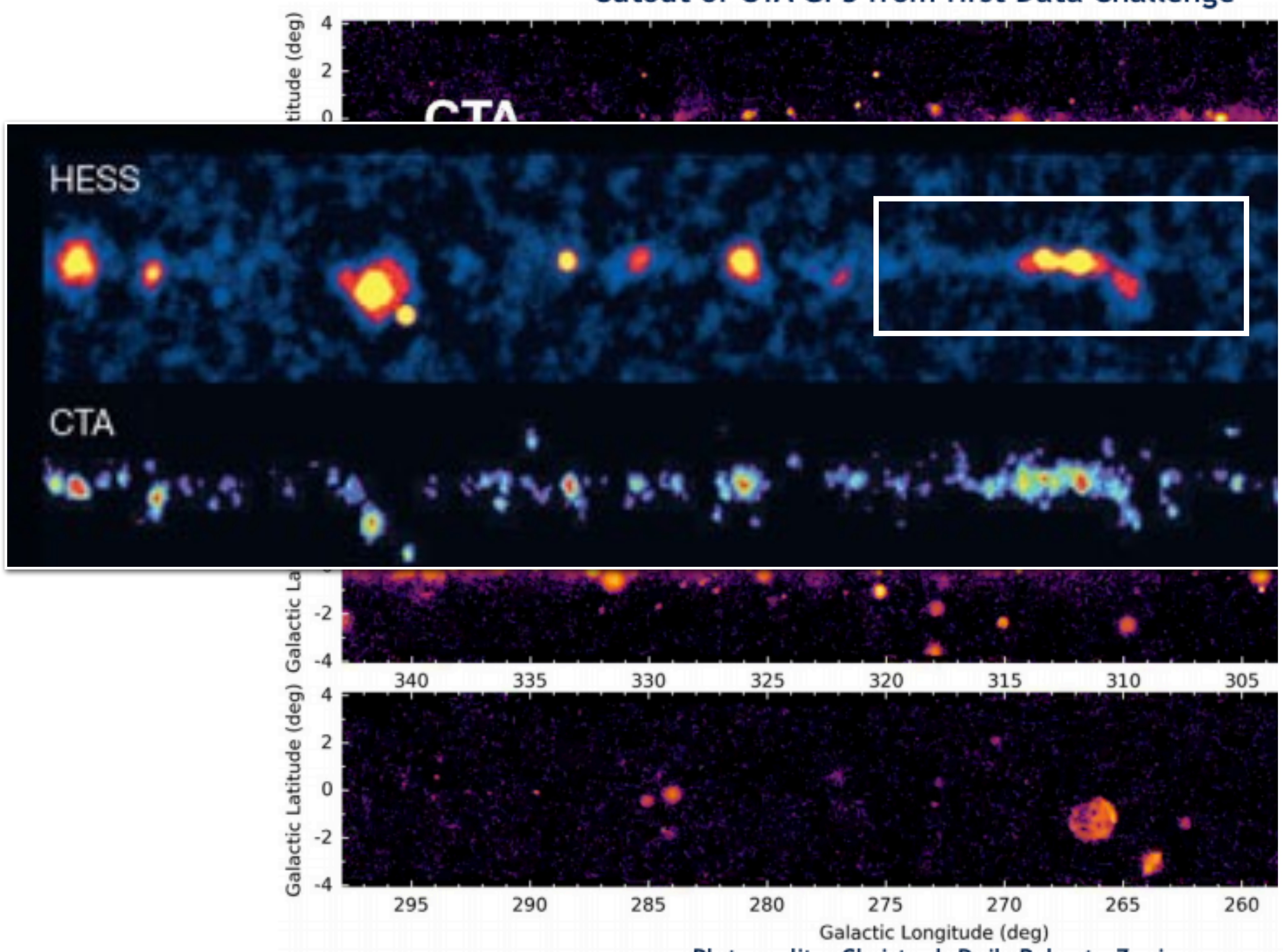

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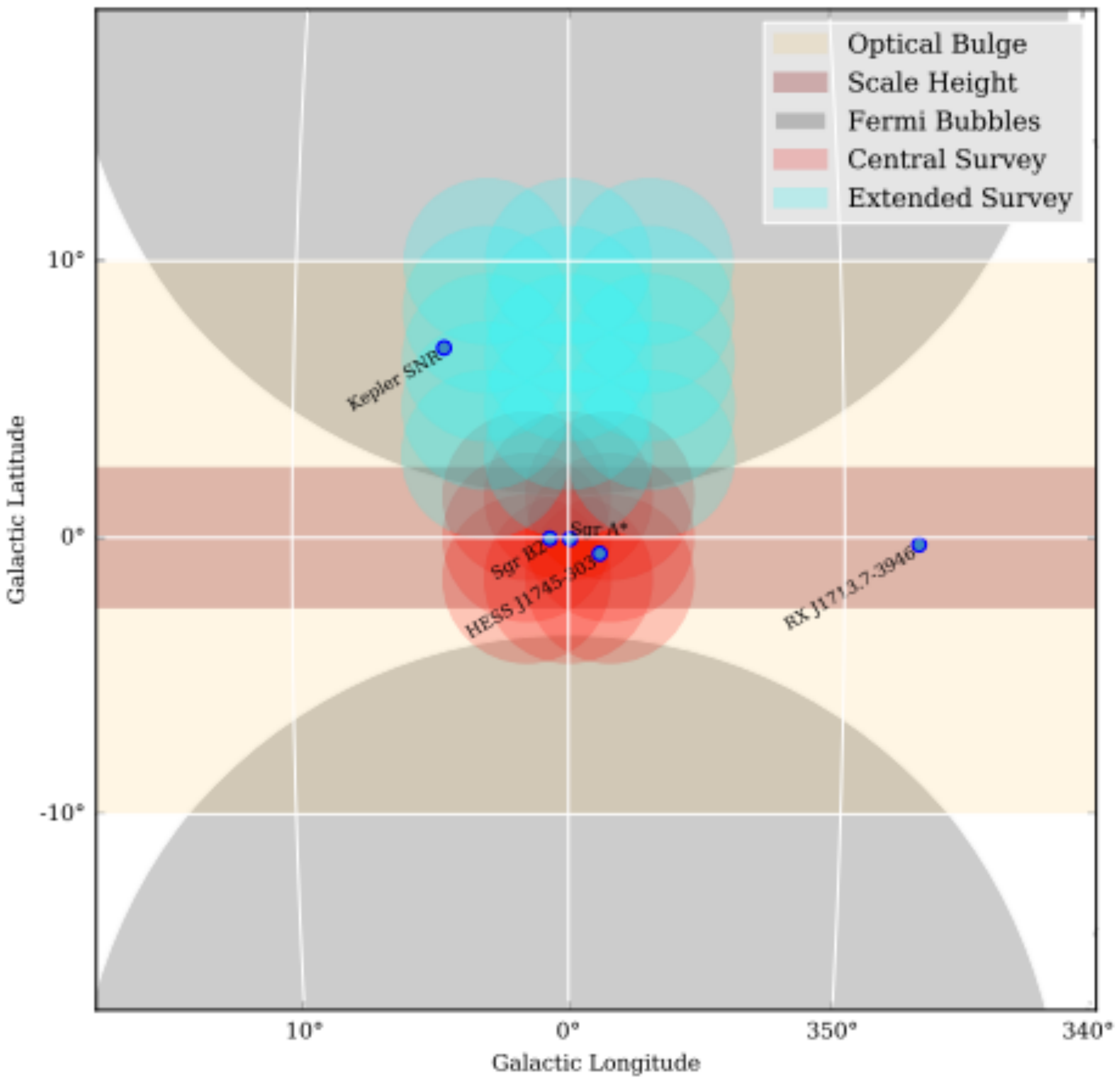
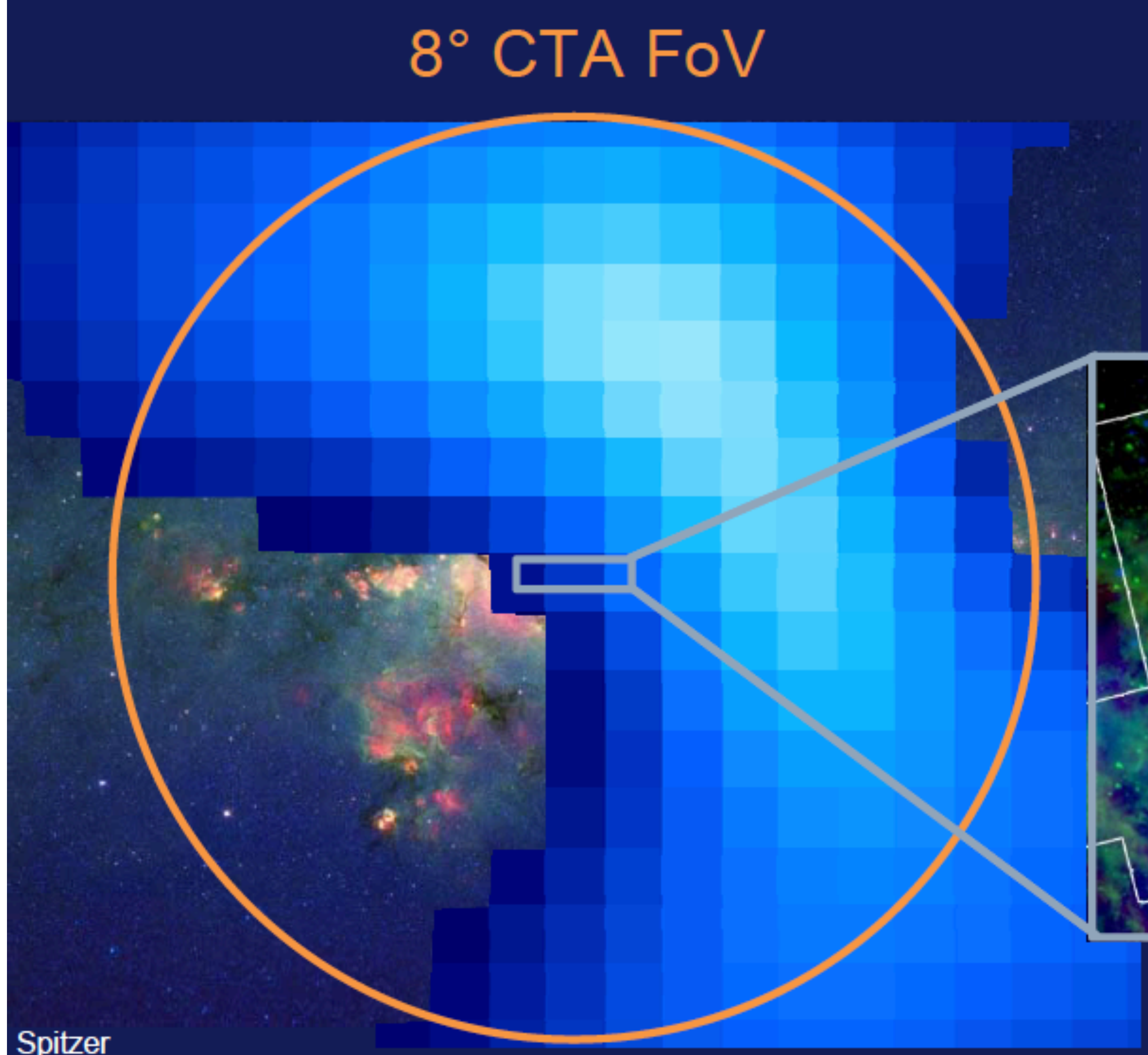
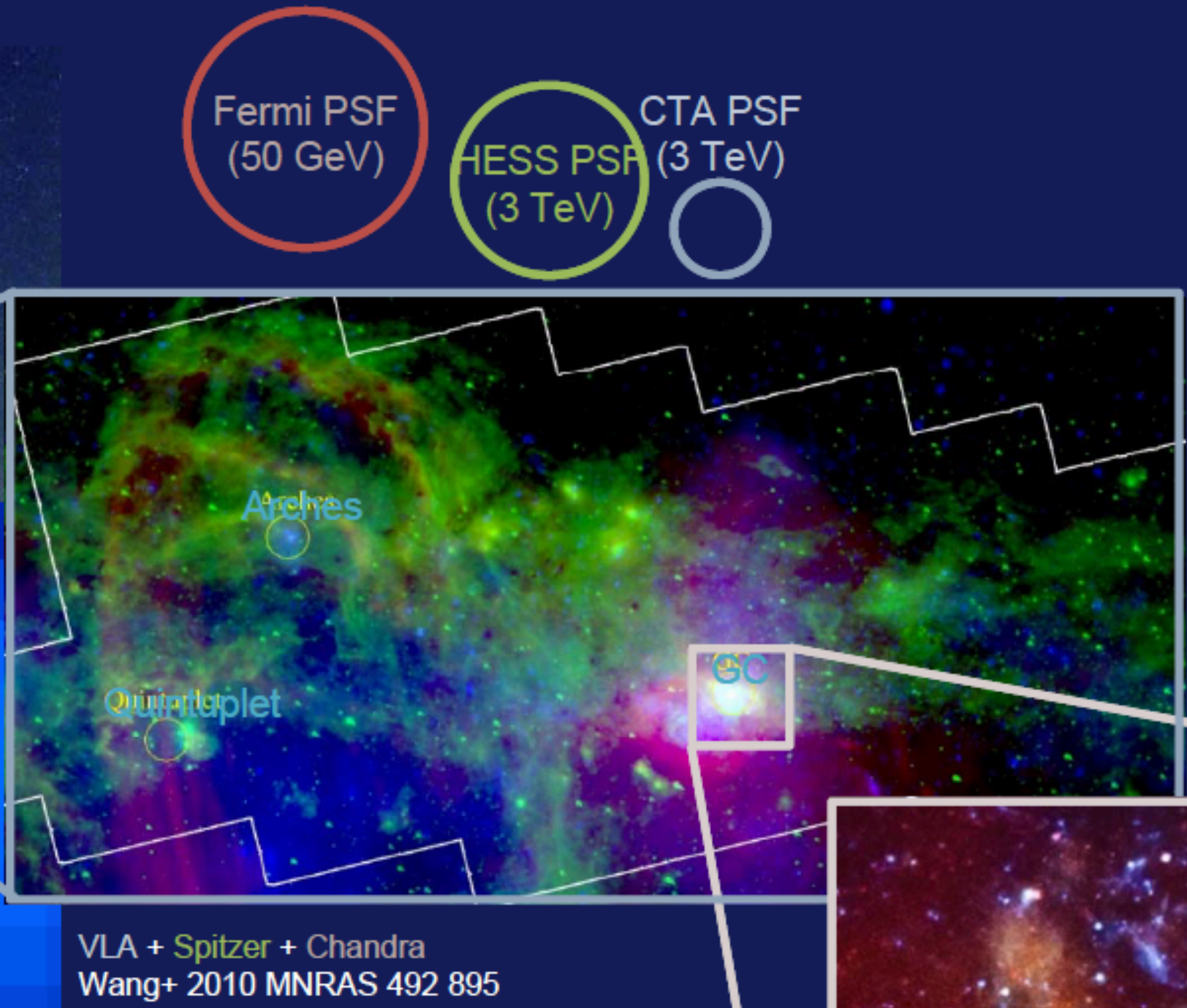
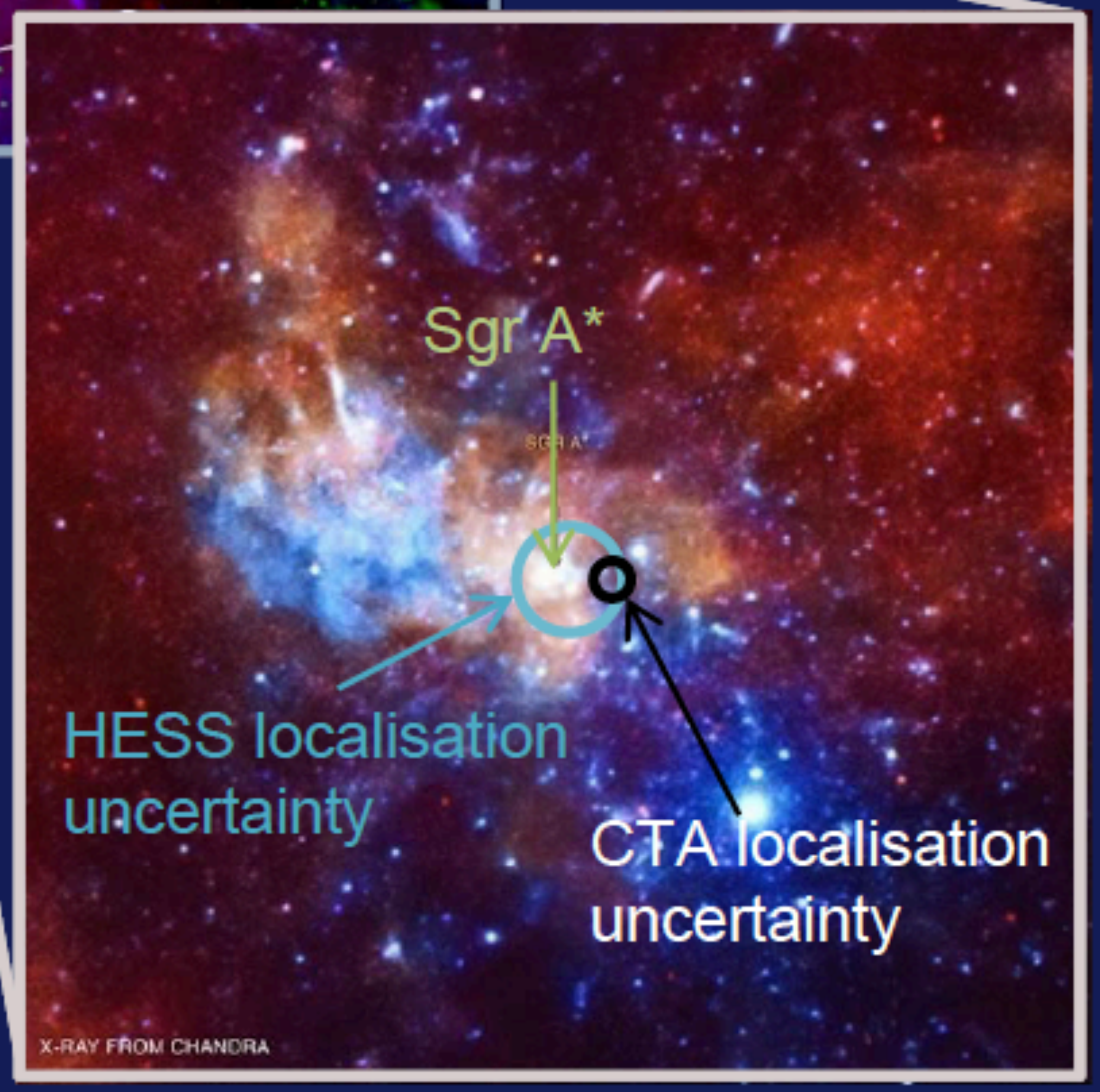


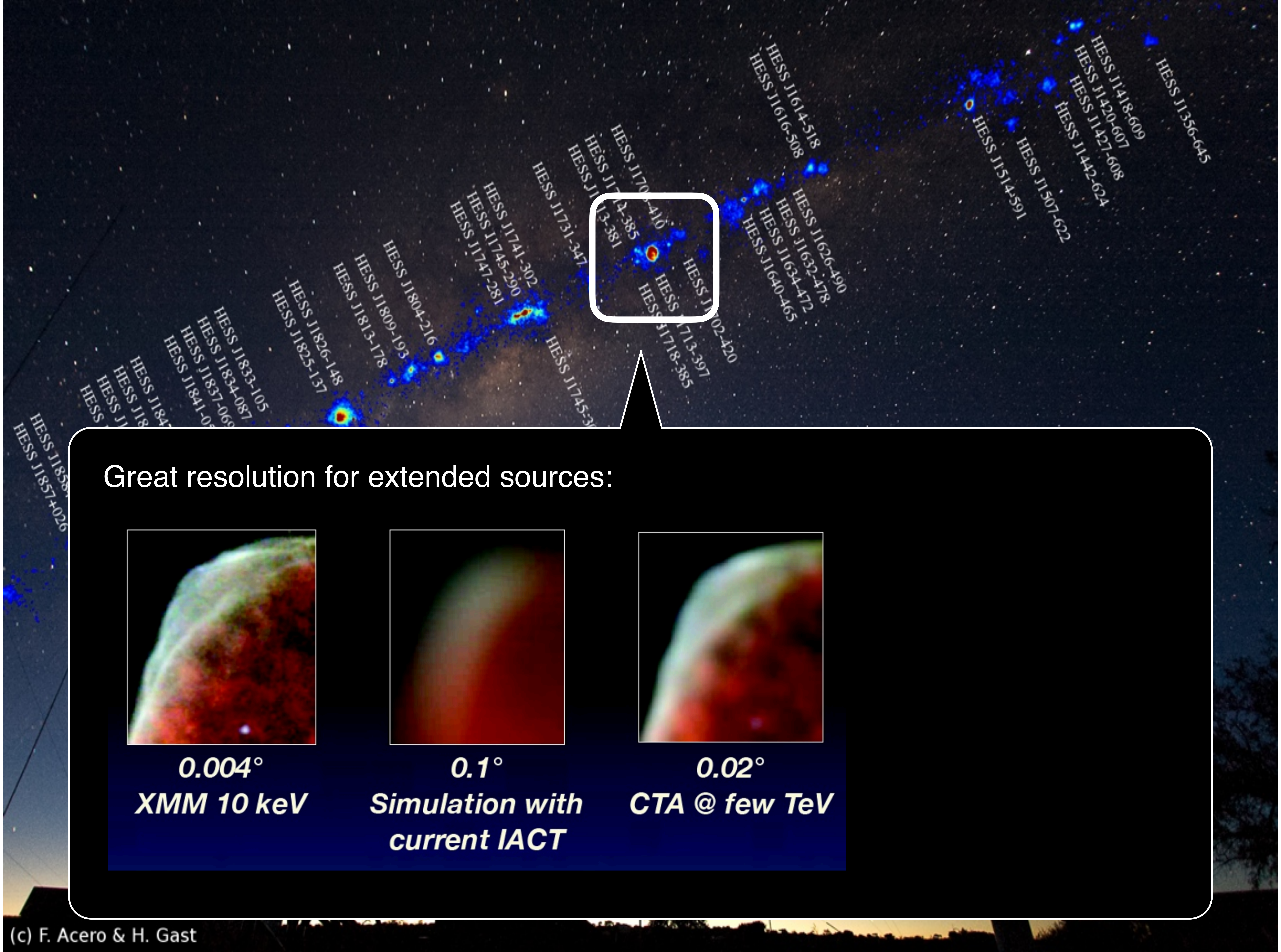
Slide courtesy of L. Tibaldo

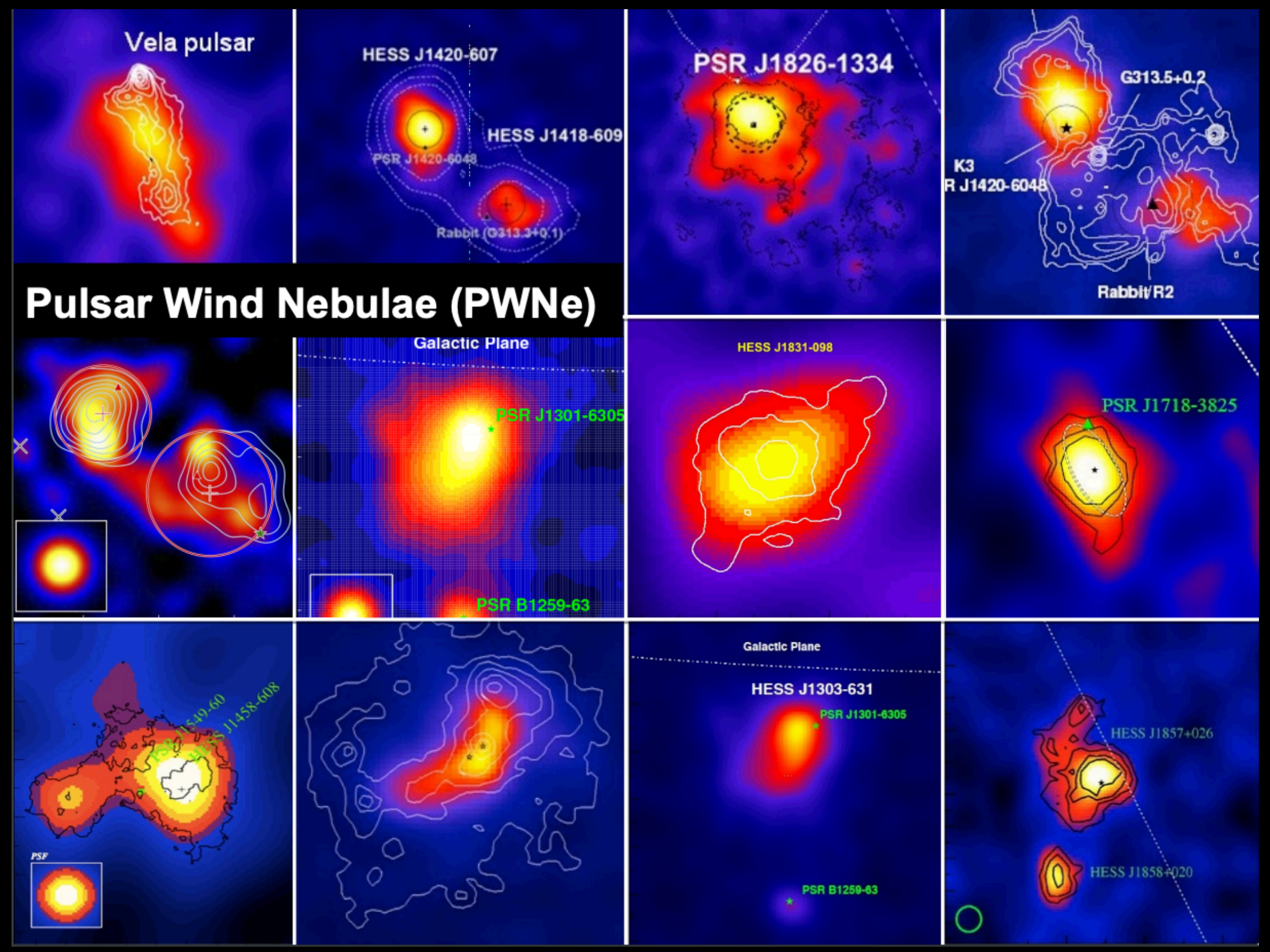






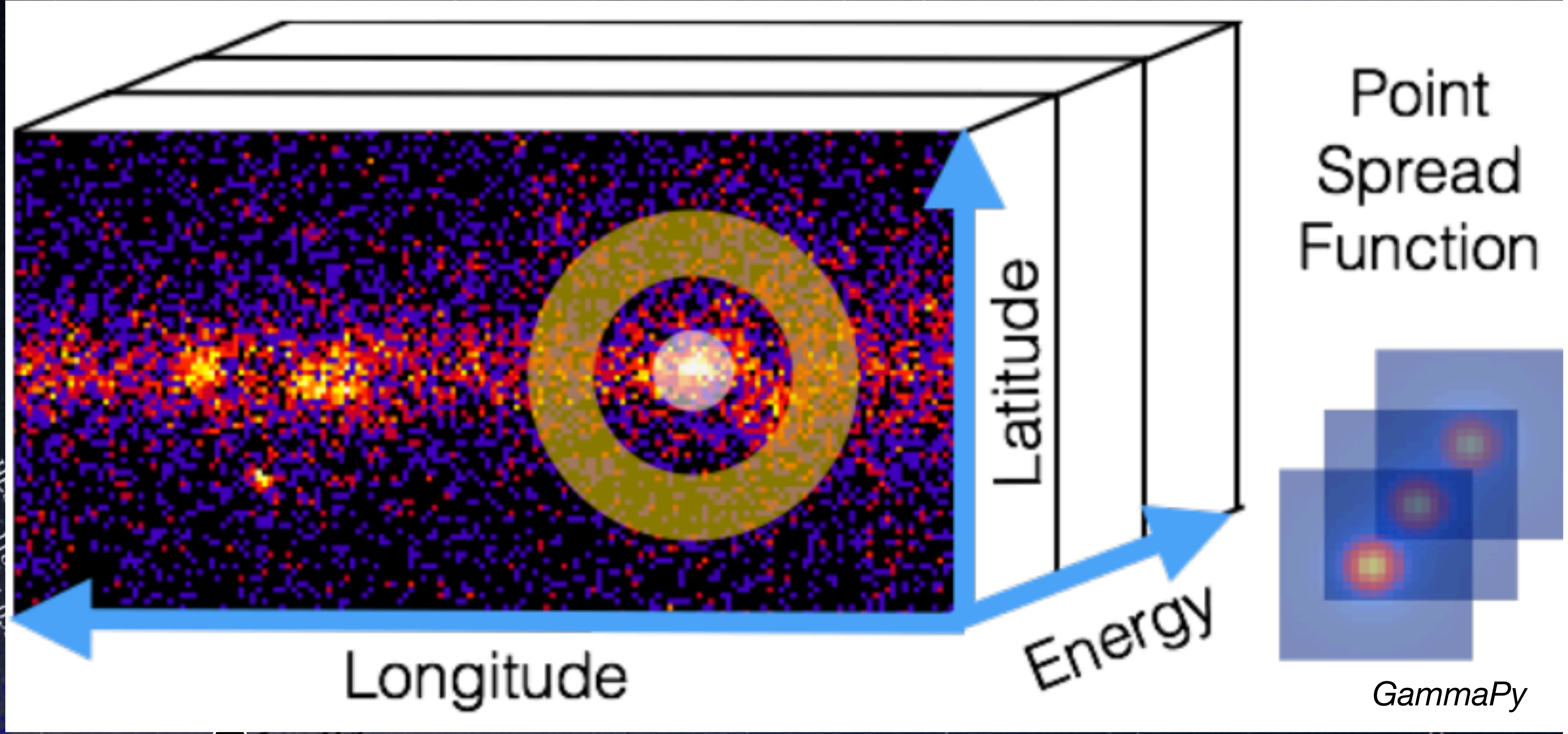
- wealth of VHE diffuse emission & sources, including the only known PeVatron
- giant particle outflow (*Fermi* bubbles)
- ideal region for dark matter searches

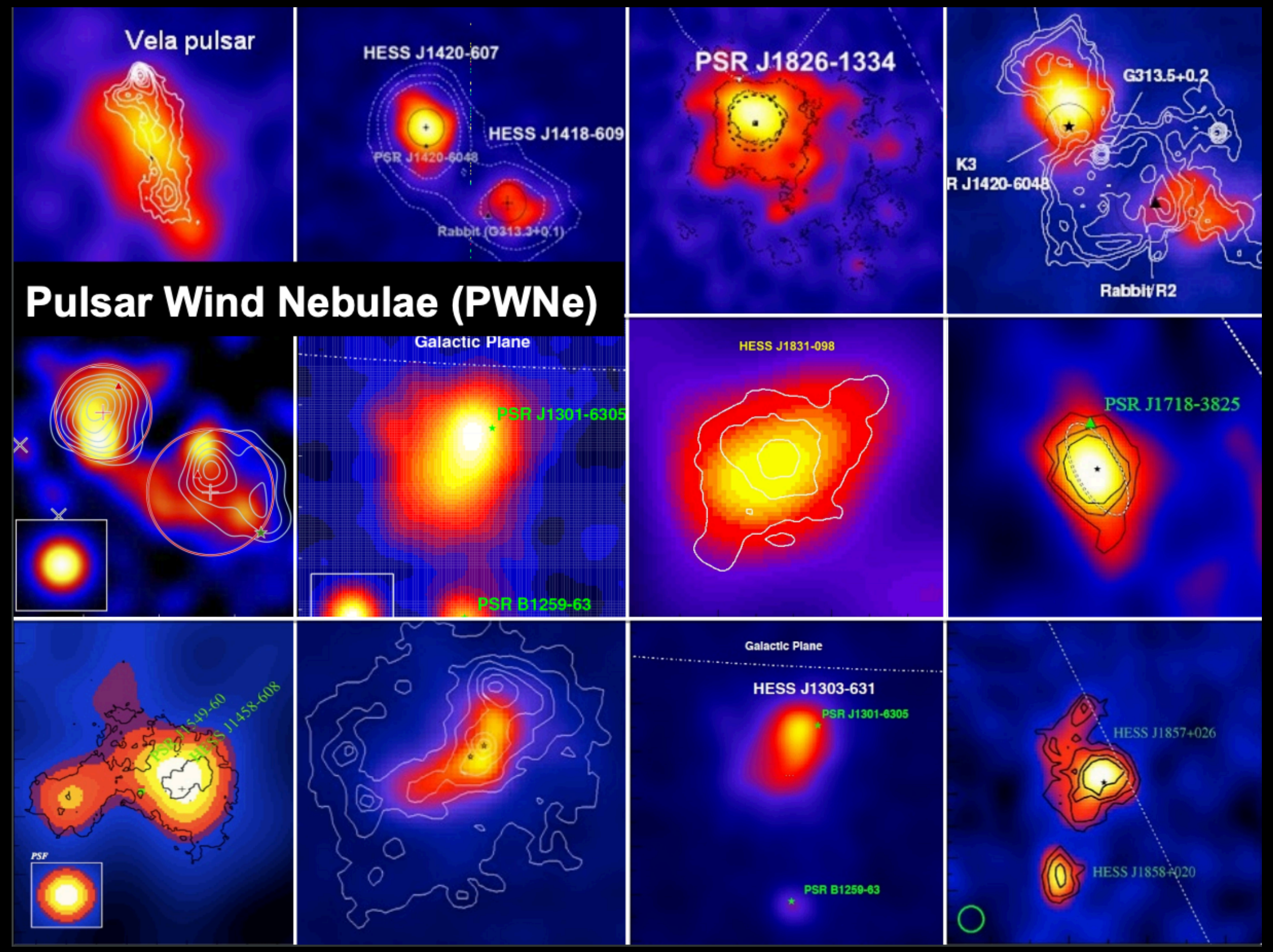

Great resolution for extended sources:
0.004°
XMM 10 keV
0.1°
Simulation with
current IACT
0.02°
CTA @ few TeV
HESS J1356-645
HESS J1418-609
HESS J1420-607
HESS J1427-608
HESS J1442-624
HESS J1507-622
HESS J1514-591
HESS J1614-518
HESS J1616-508
HESS J1626-490
HESS J1632-478
HESS J1634-472
HESS J1640-465
HESS J1731-347
HESS J1741-302
HESS J1745-290
HESS J1747-281
HESS J1804-216
HESS J1809-193
HESS J1813-178
HESS J1826-148
HESS J1825-137
HESS J1833-105
HESS J1834-087
HESS J1857+026
(c) F. Acero & H. Gast



Better resolution, but also better sensitivity
=> More extended sources!

GeV / TeV/ PeV analysis





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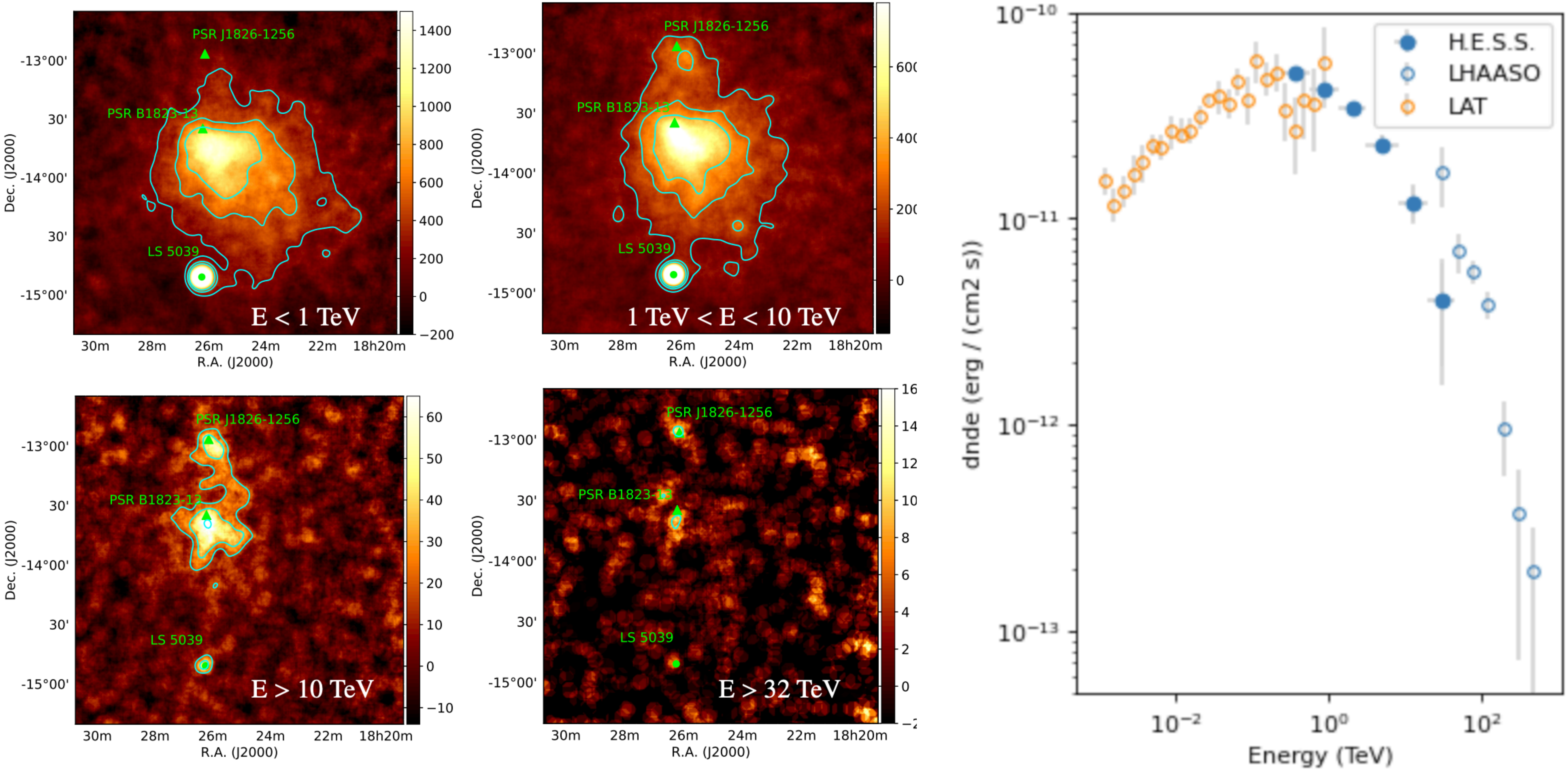
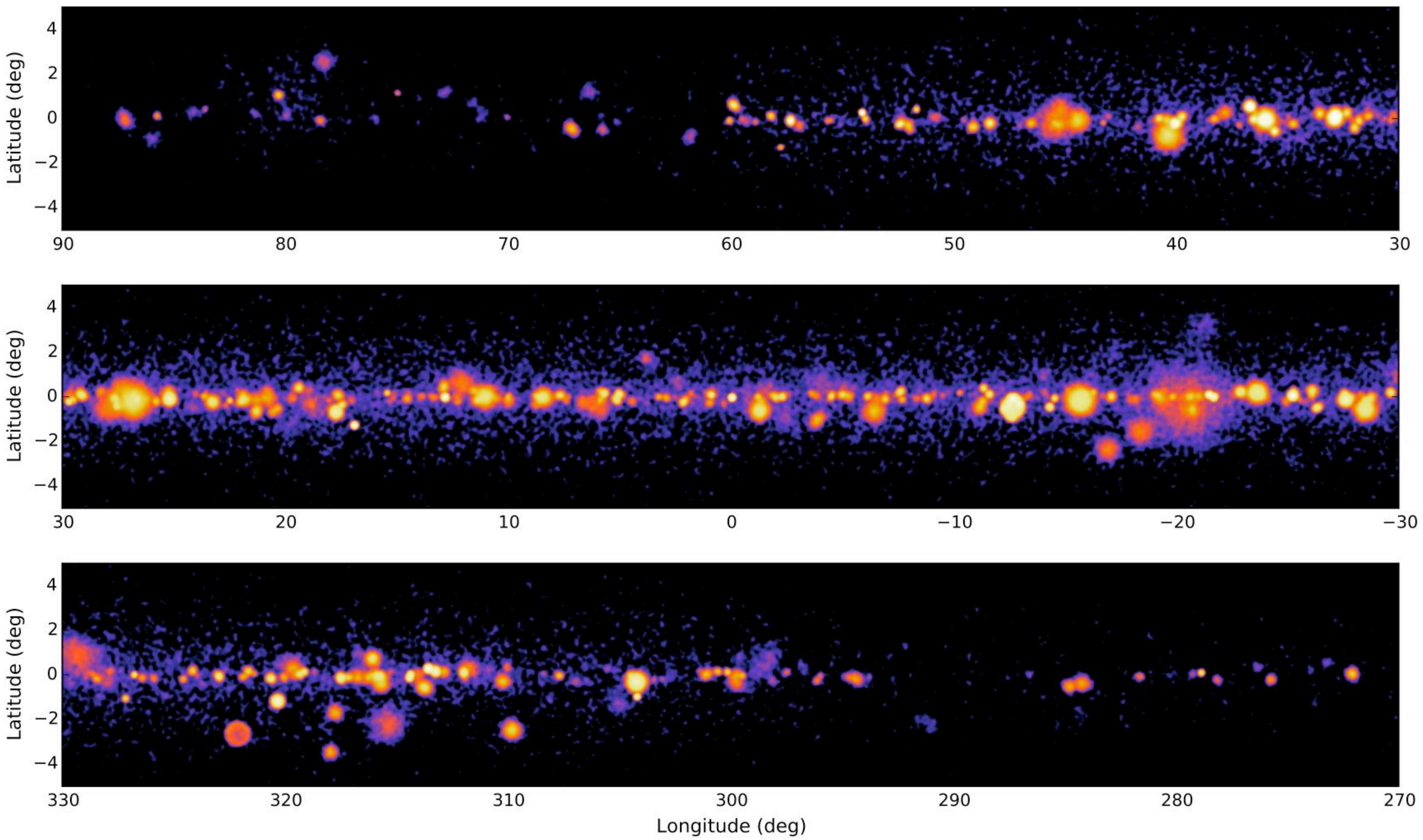
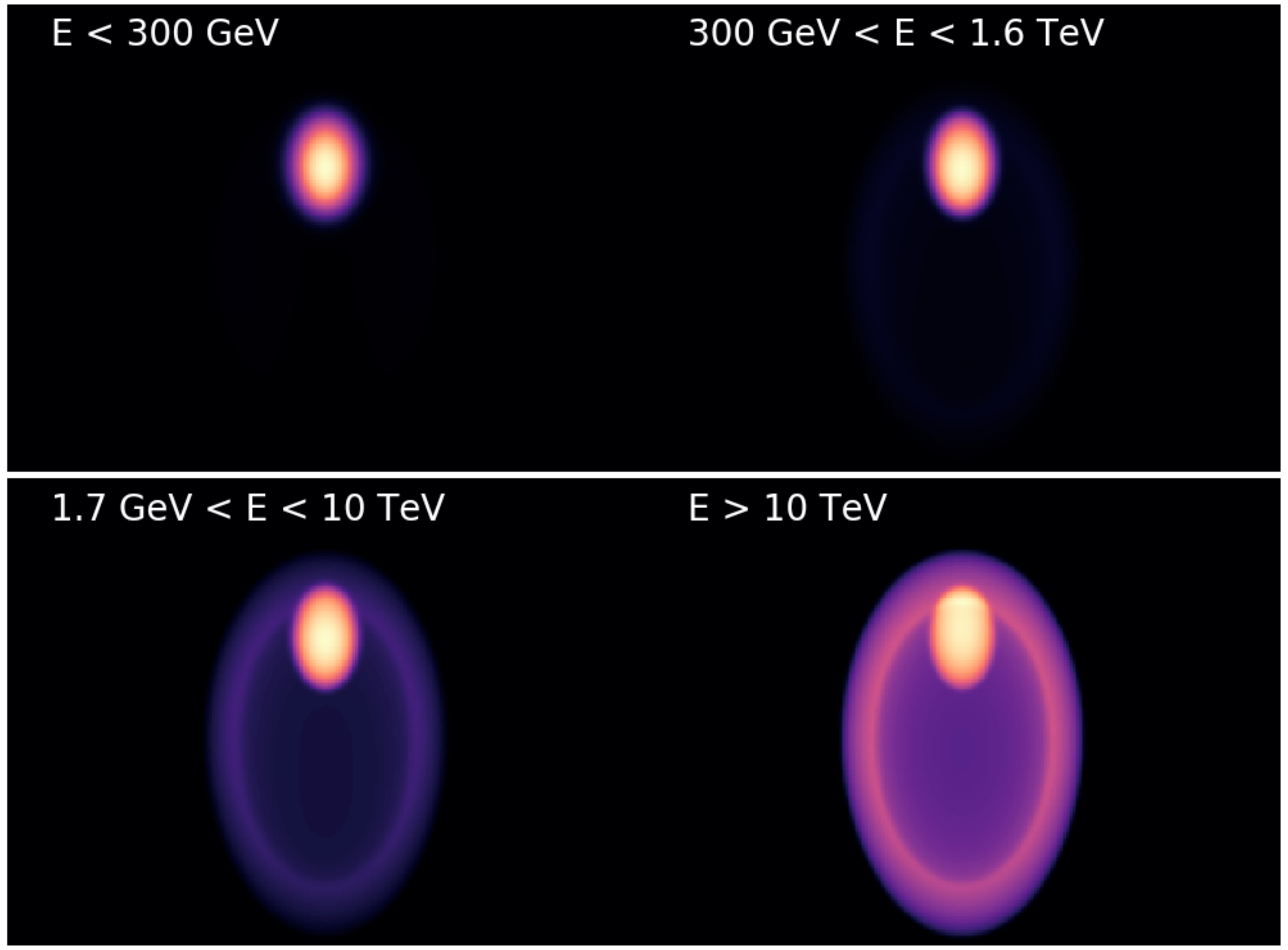


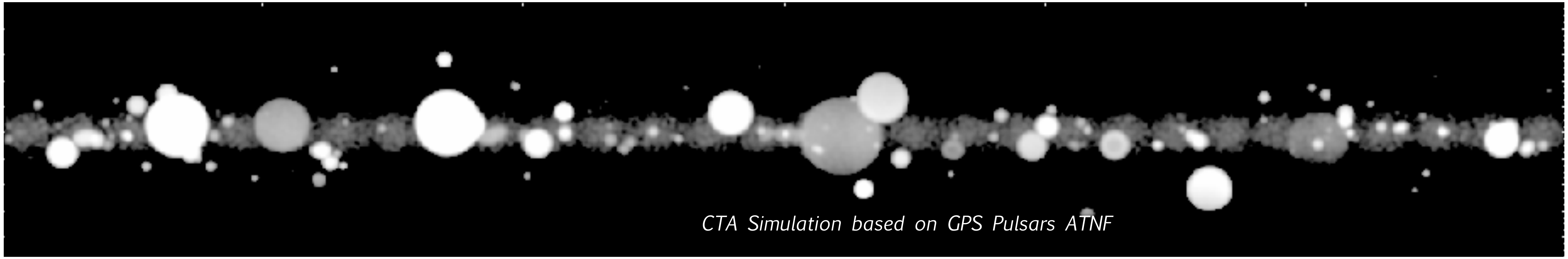
PSR J1826-1256
PSR B1823-13
LS 5039
E < 1 TeV
1 TeV < E < 10 TeV
E > 10 TeV
E > 32 TeV
Dec. (J2000)
R.A. (J2000)
H.E.S.S.
LHAASO
LAT
dnde (erg / (cm2 s))
Energy (TeV)

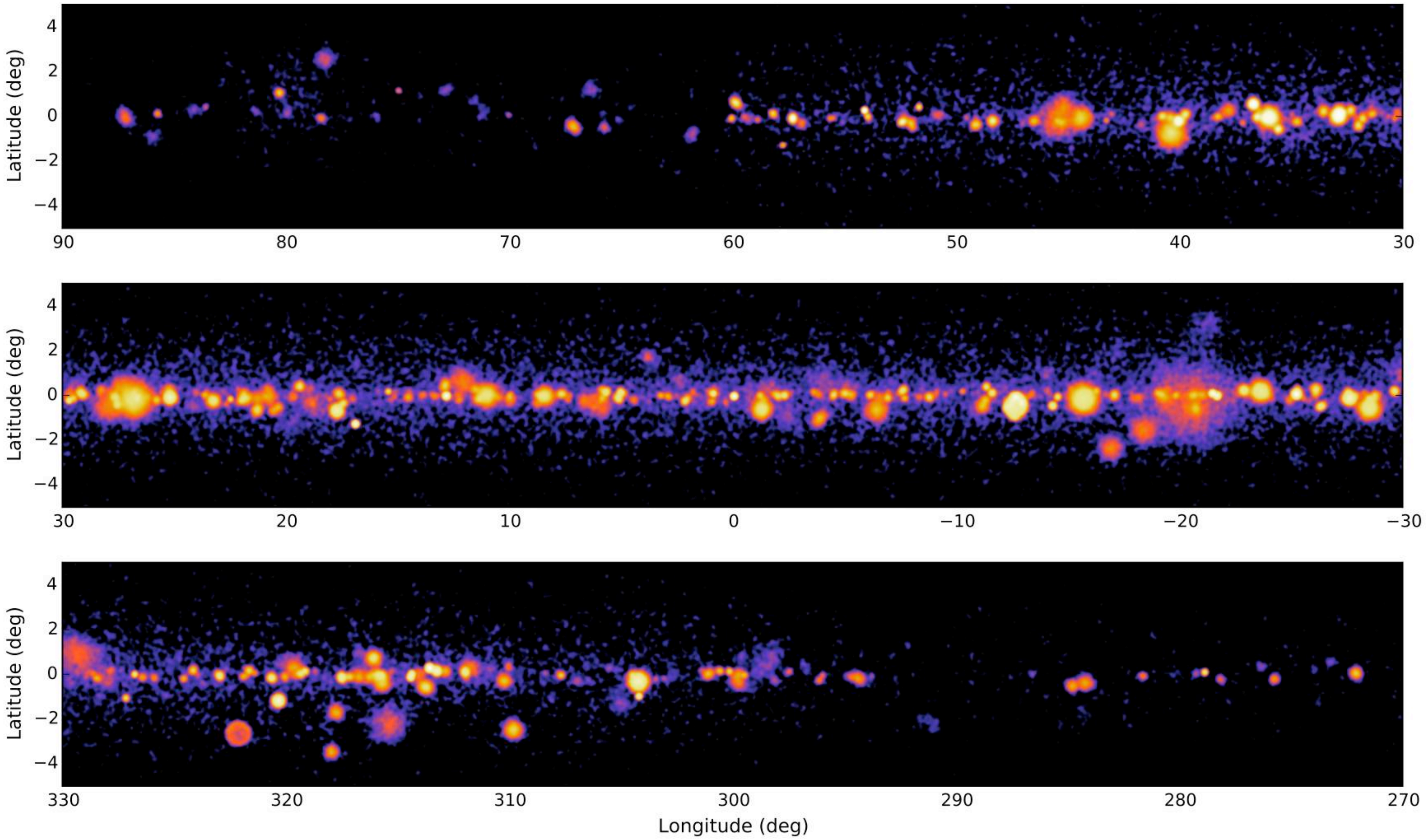
Source Confusion

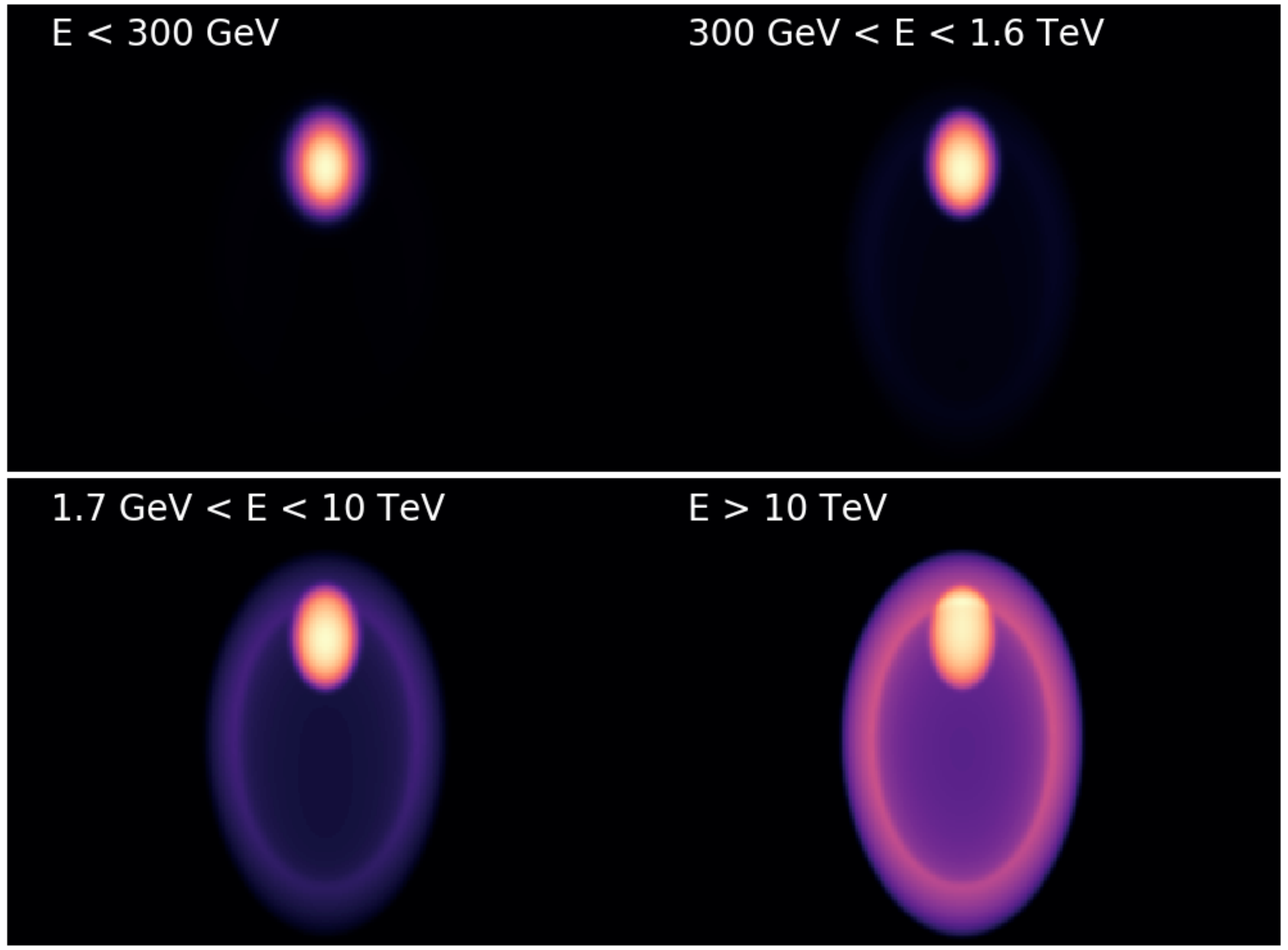




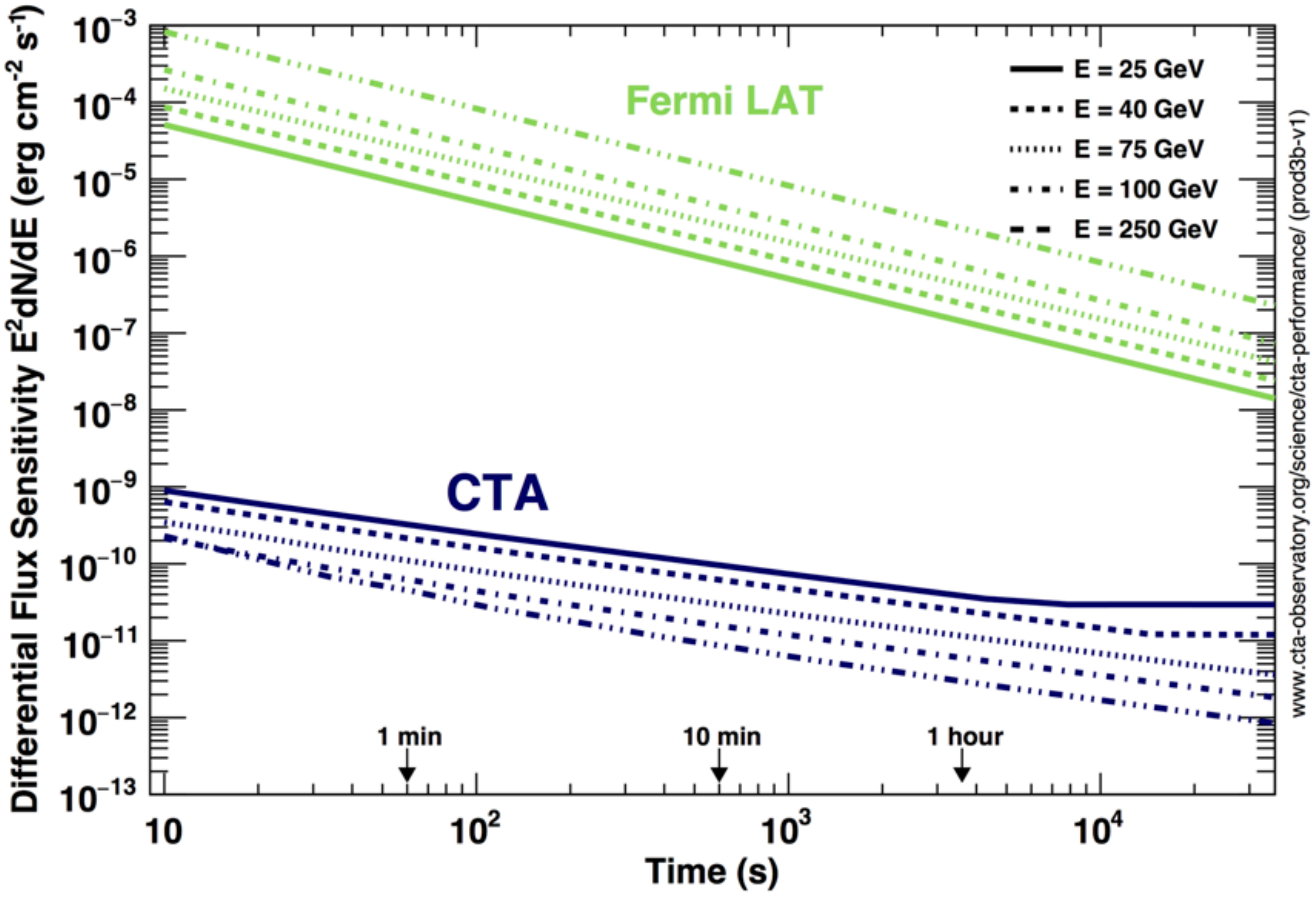
Source Confusion





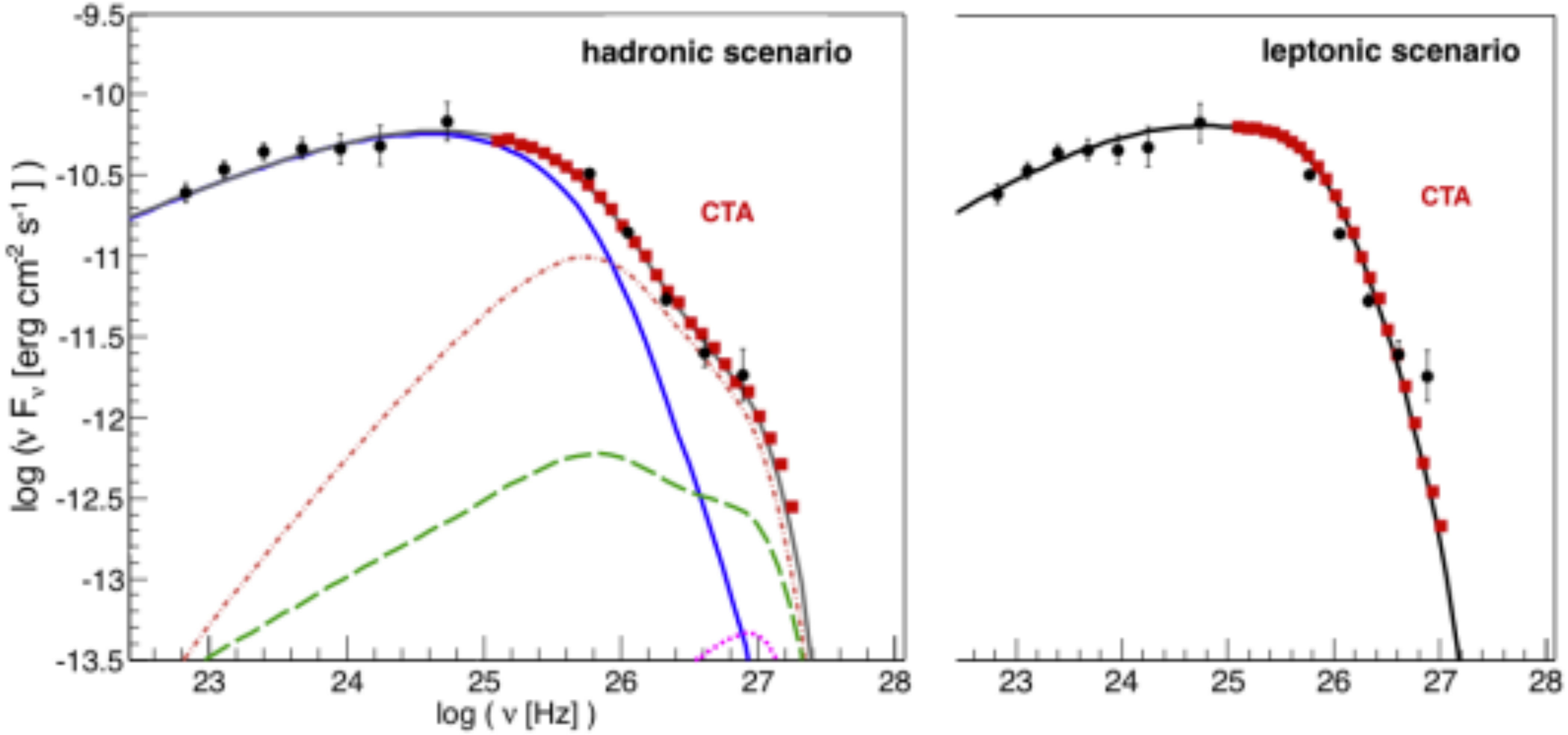


Short-time Scale Capabilities



Short-time Scale Capabilities

Distinguish between leptonic and hadronic models



Summary

- Cosmic particle acceleration, as traced by Galactic gamma rays, is a crucial component of our Galaxy

- We are starting to understand where CRs are accelerated and how do they distribute in our Galaxy, but still lacking lots of knowledg

- New analysis techniques + Large dataset + New instrument improves: exciting new results

- However the future is bright! many fantastic instruments to the rescue