Astroparticle Physics

A syllabus for using astroparticle observations to delve deeper in our universe

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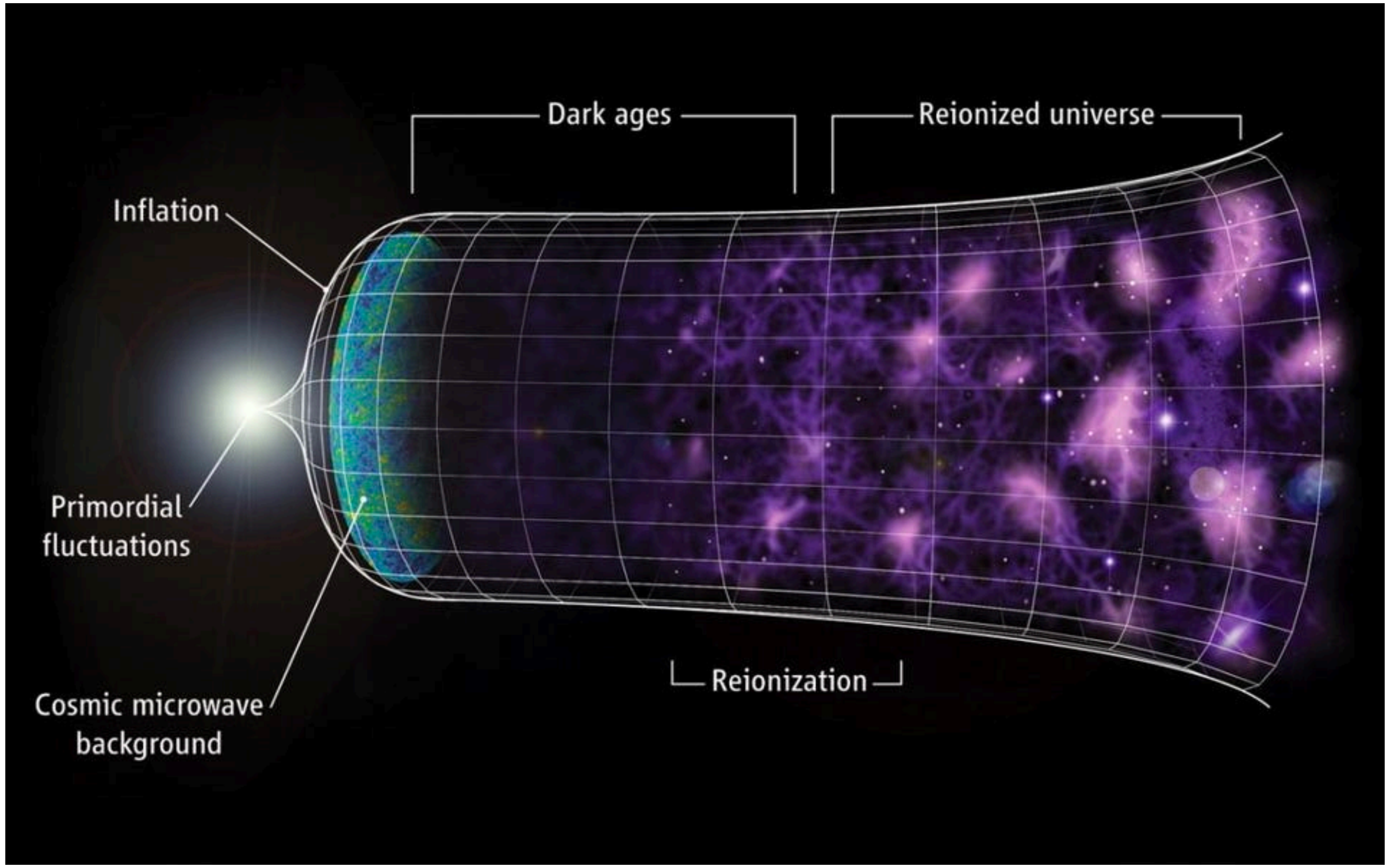
Who am I?

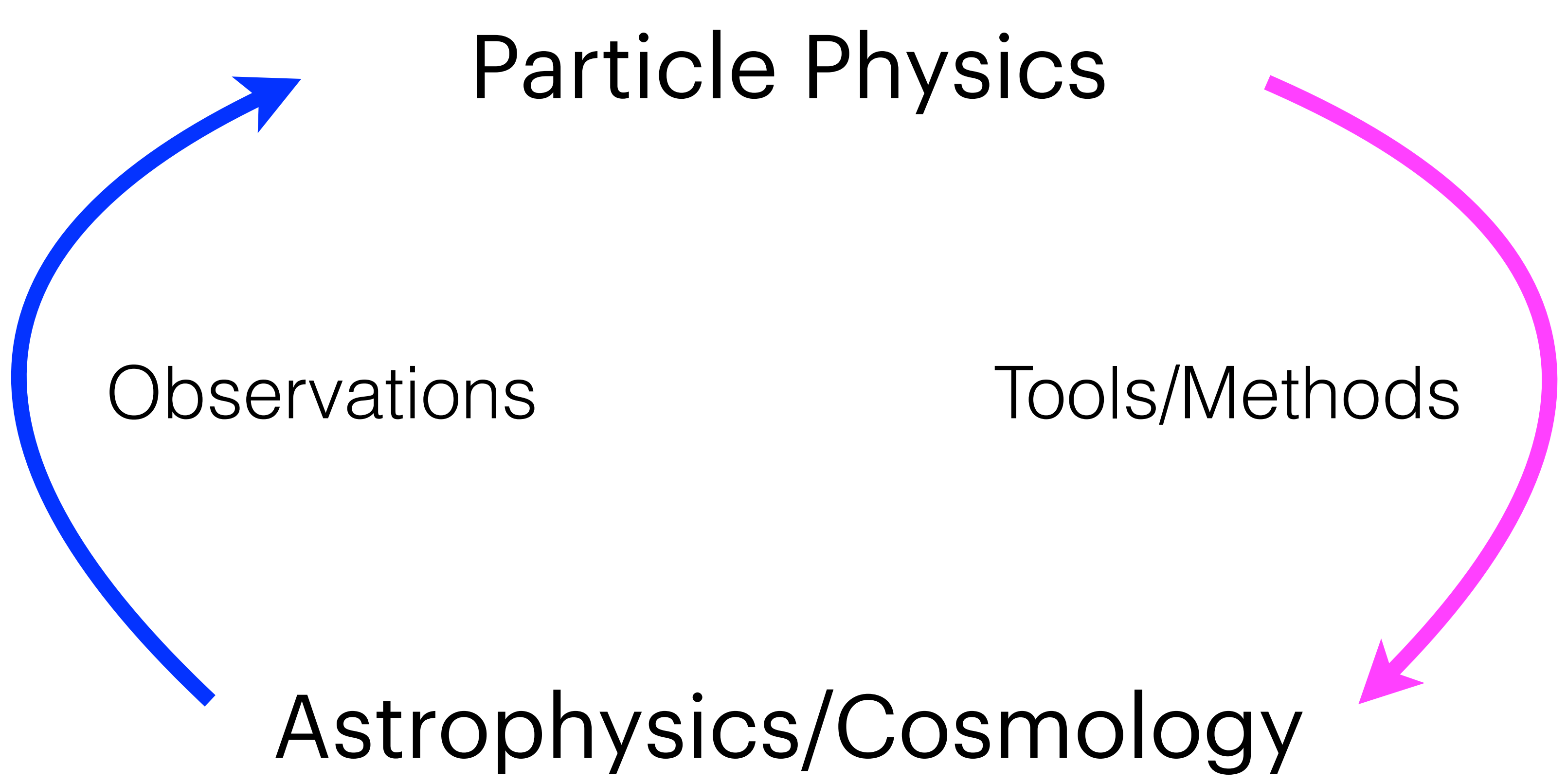
Francesca Calore is a staff researcher at the French National Center for Scientific Research (CNRS) at the Annecy-le-Vieux Theoretical Physics Laboratory (LAPTh). After completing a joint Ph.D. at the University of Hamburg, Germany, and the University of Turin, Italy, she has held a postdoctoral position at the Center of Excellence for Gravitation and Astroparticle Physics (GRAPPA) at the University of Amsterdam, Netherlands. She is an expert in dark matter searches with astroparticle experiments and high-energy astrophysics.

APS Physics

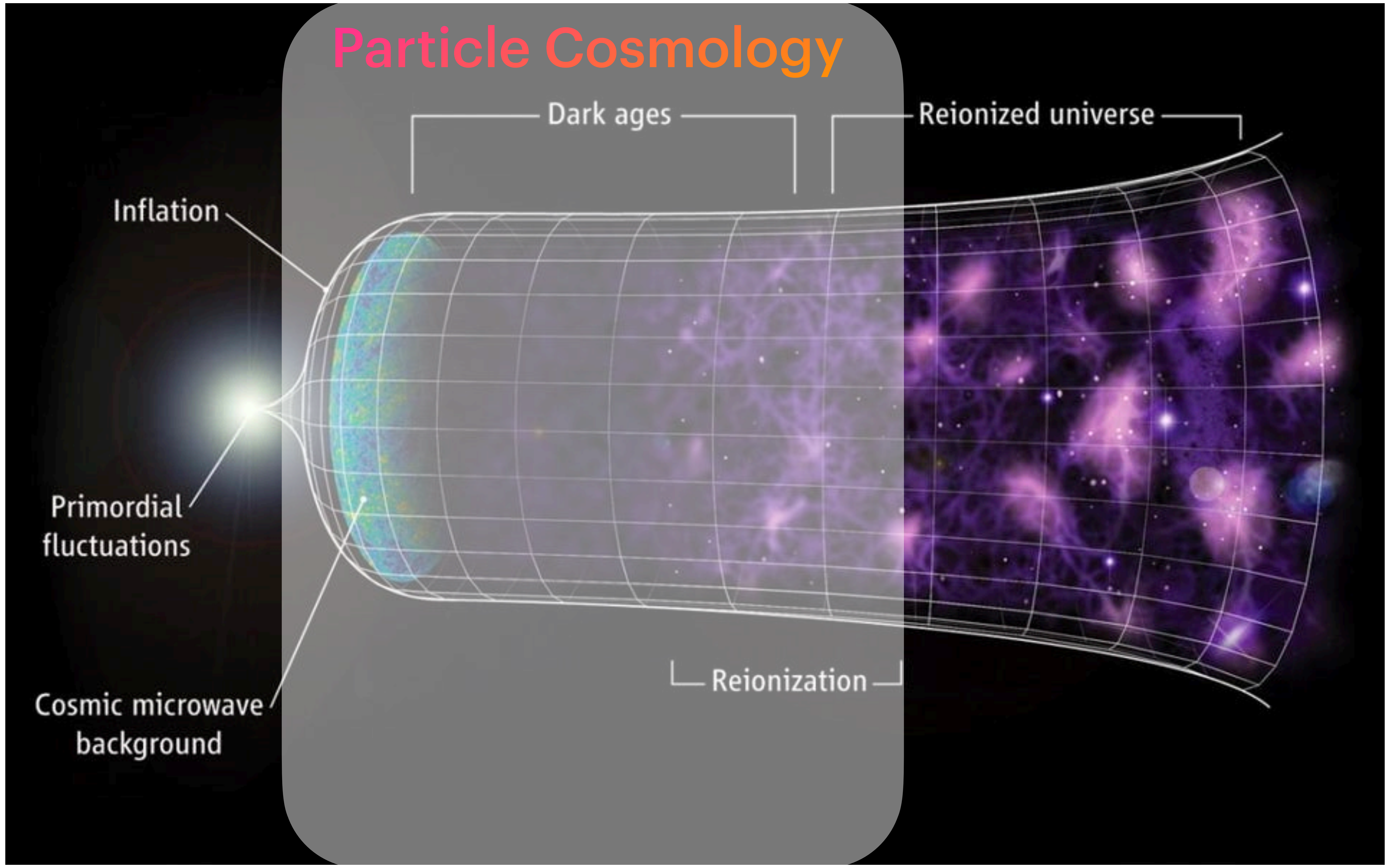
What is astroparticle physics?



C. FAUCHER-GIGUÈRE, A. LIDZ, AND L. HERNQUIST, SCIENCE 319, 5859 (47)



What is astroparticle physics?



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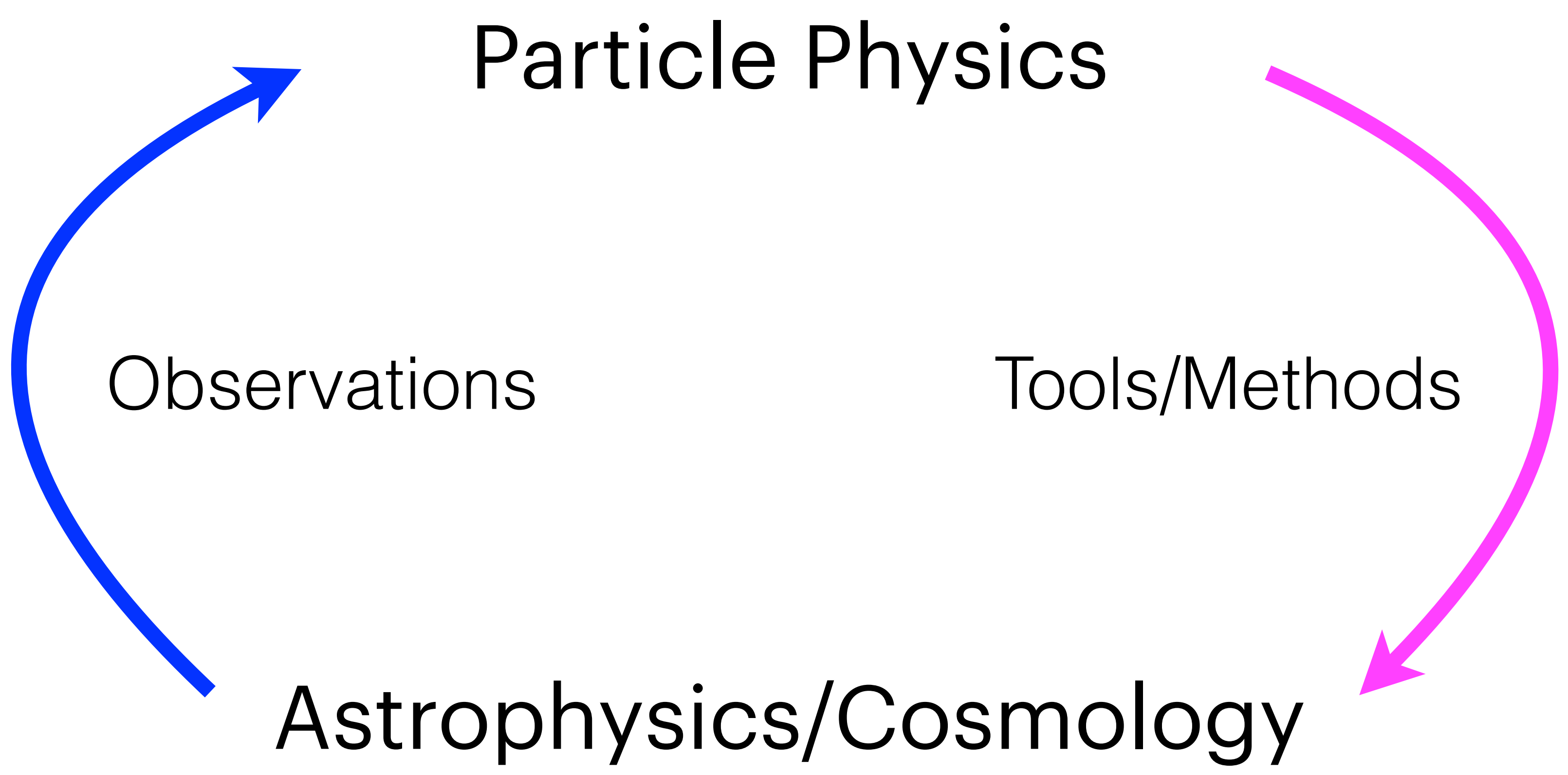
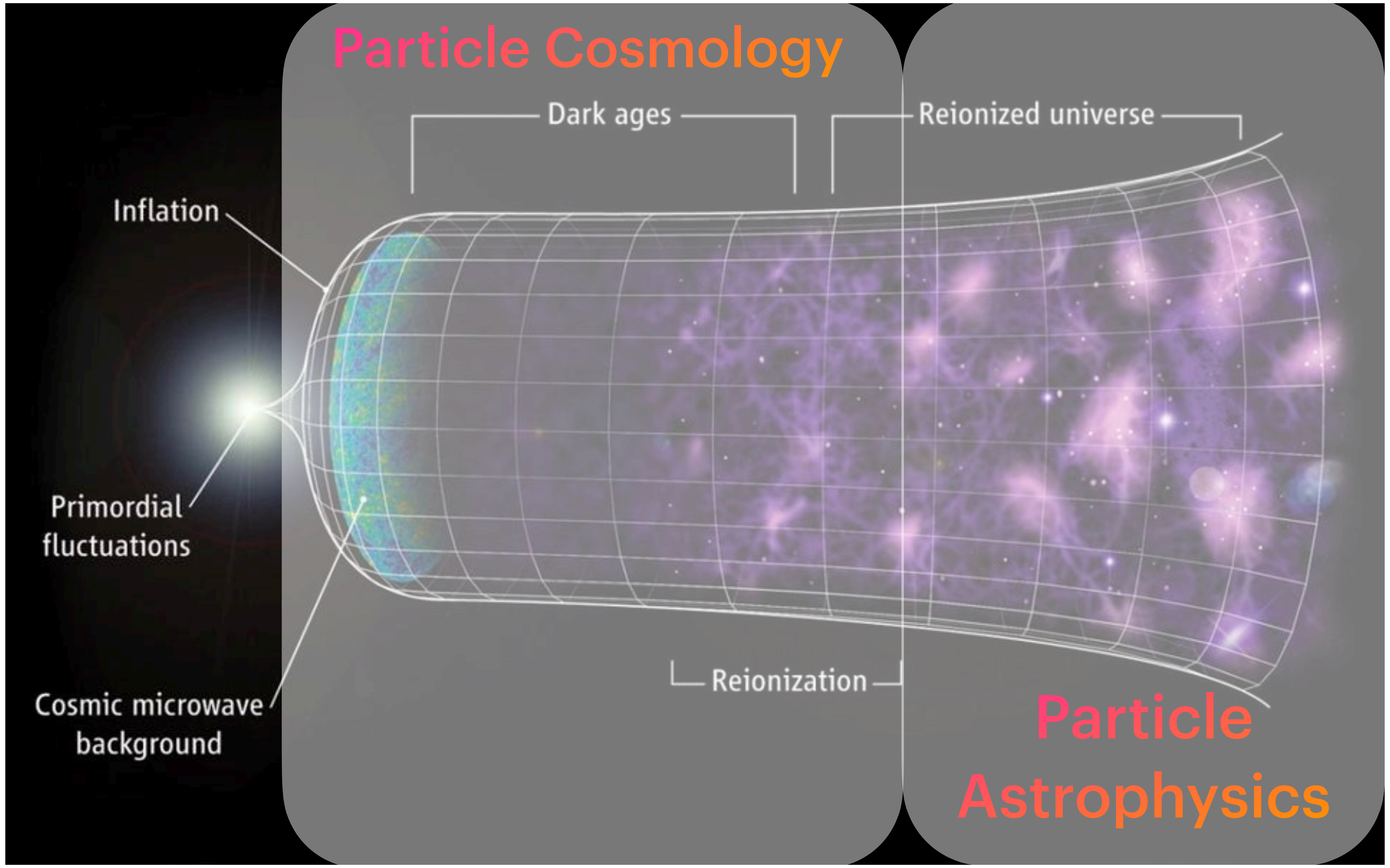


What is astroparticle physics?



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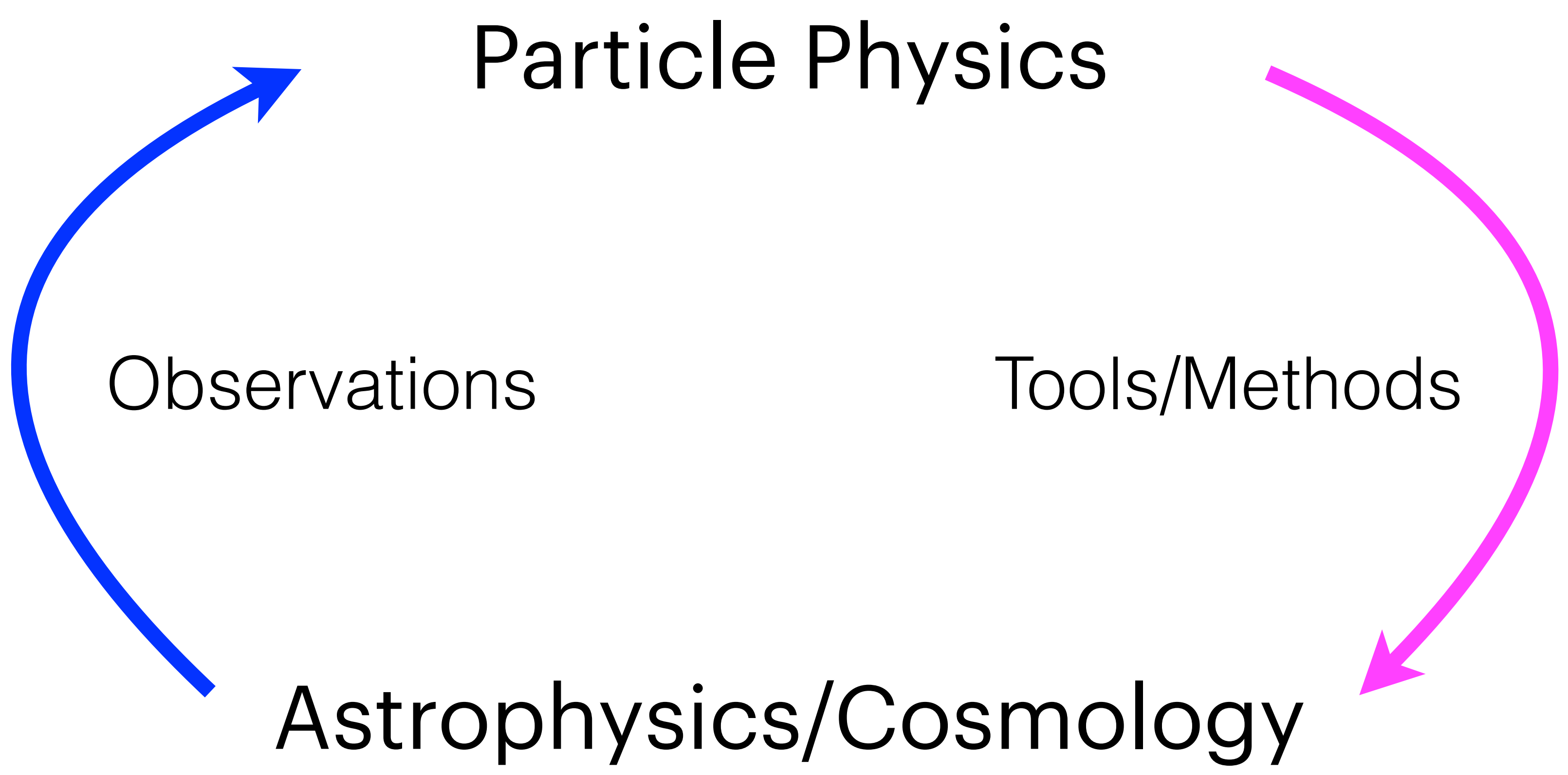


Particle Astrophysics

Plan of the lectures

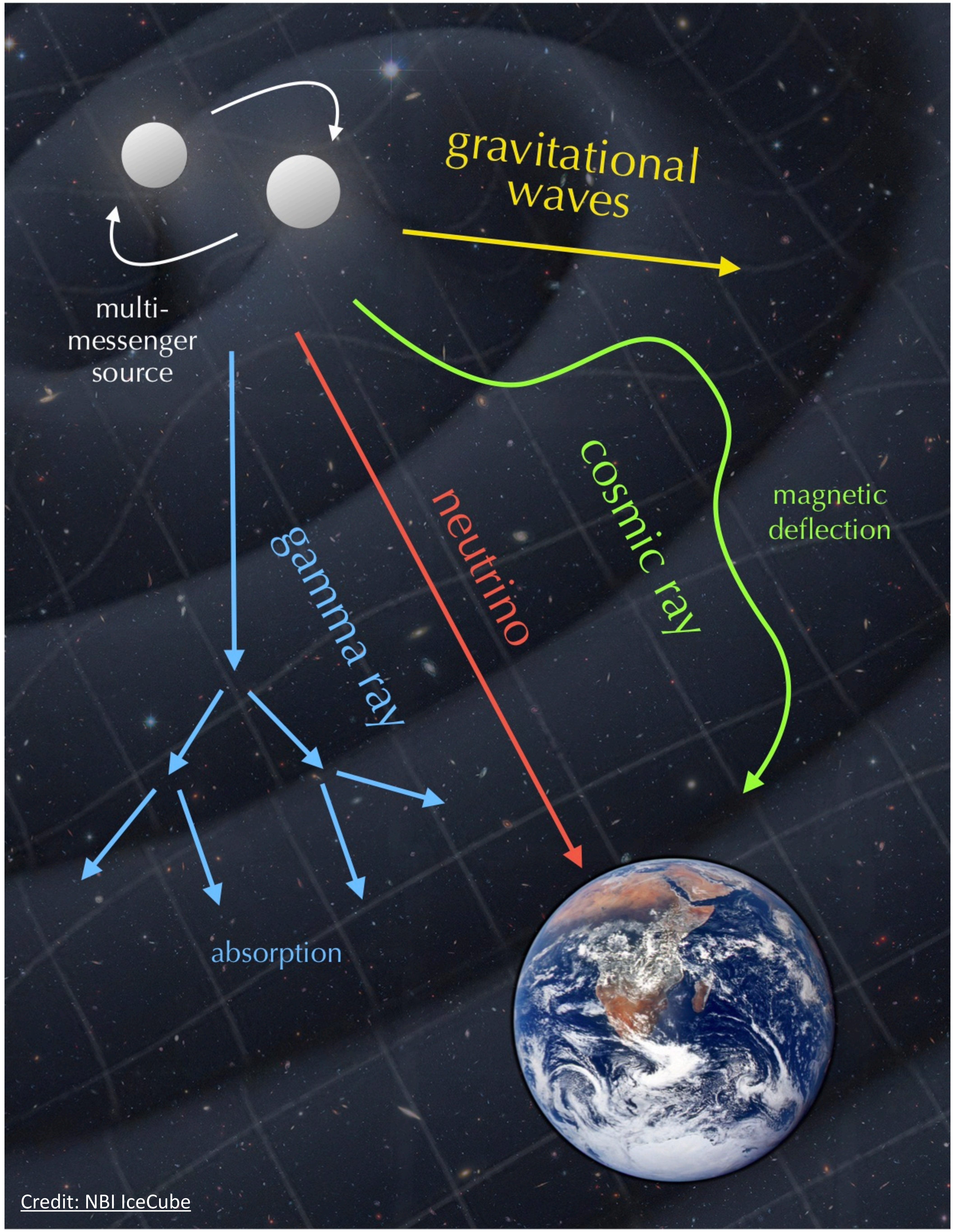
Today

- Particles from the sky: Detection techniques and observations
- **Charged cosmic rays**: production and origin
- **Gamma rays** and **neutrinos**

Tomorrow

- The multi-messenger connection
- Probing exotic physics with astroparticle observations

Complemented by *Cosmology* (D. Alonso), *Dark Matter* (A. Green), *BSM Physics* (V. Sanz) and *Gravitational Waves* (C. Sopuerta) lectures



Some reading material

M. Longair, *High energy astrophysics*, Cambridge Univ. Press (2012)
V. S. Berezinskii et al., *Astrophysics of cosmic rays*, Amsterdam: North-Hollans (1990)
G. Sigl, *Astroparticle Physics: Theory and Phenomenology*, Atlantis Press Paris (2017)
Very good lectures notes: *Foundations of cosmic-ray astrophysics*, Varenna (2022)

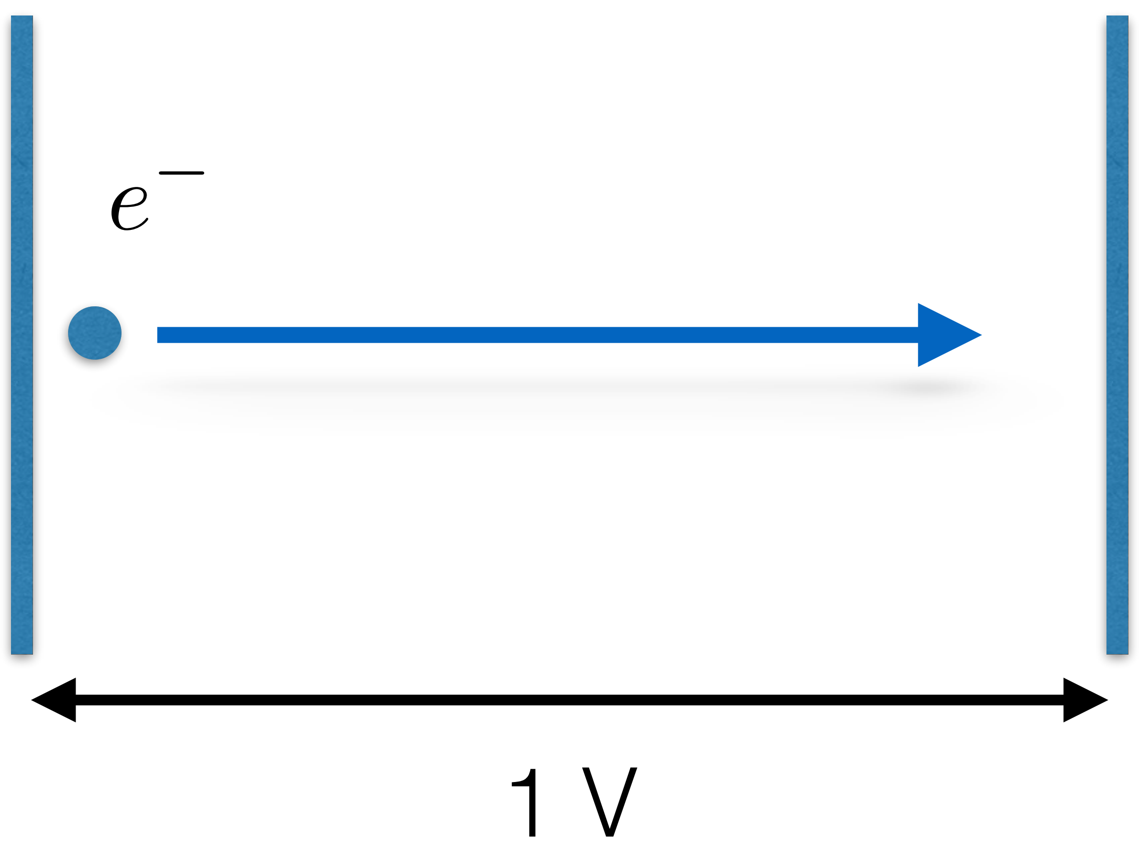
EuCAPT White Paper, *Opportunities and Challenges for Theoretical Astroparticle Physics in the Next Decade*, arXiv:2110.10074

EuCAPT

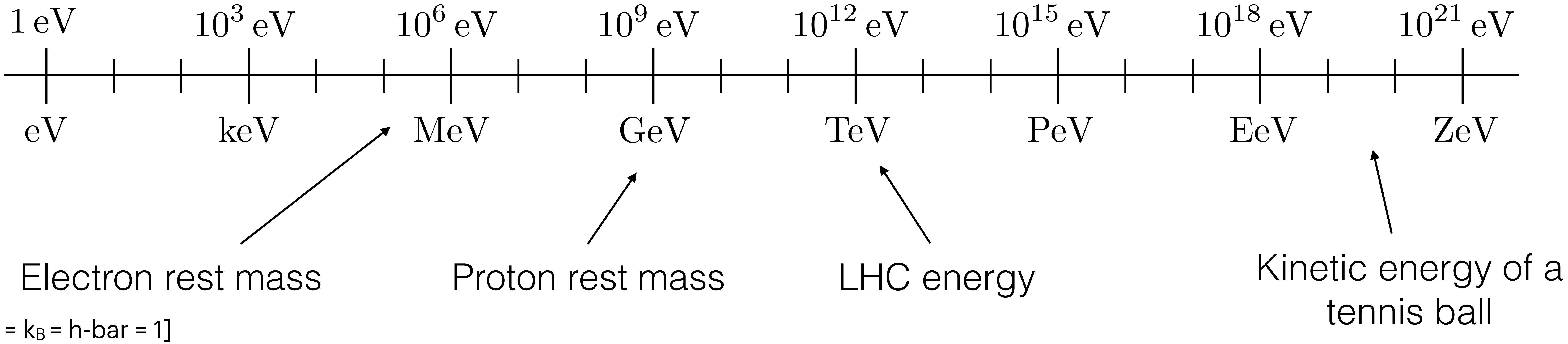
Feel free to email me at calore@lapth.cnrs.fr!

Energy scales

1 eV is the kinetic energy an electron gains from being accelerated across a potential of 1 V



$$
\begin{aligned}
1\,\text{eV} &\approx 1.6 \times 10^{-19}\,\text{J} \\
&\approx 1.8 \times 10^{-36}\,\text{kg} \\
&\approx 1.2 \times 10^{4}\,\text{K}
\end{aligned}
$$



[Natural units: $c = k_B =$ h-bar = 1]

Galactic and extragalactic environments

$\lesssim 1\,\mathrm{cm}^{-3}$

Several kpc

~230 Myr
one solar orbit

$1 - 10\,\mu\mathrm{G}$

Extremely rarefied densities of matter

Very large distances and spatial scales

Very long timescales

Magnetised environment

$\lesssim 10^{-6}\,\mathrm{cm}^{-3}$

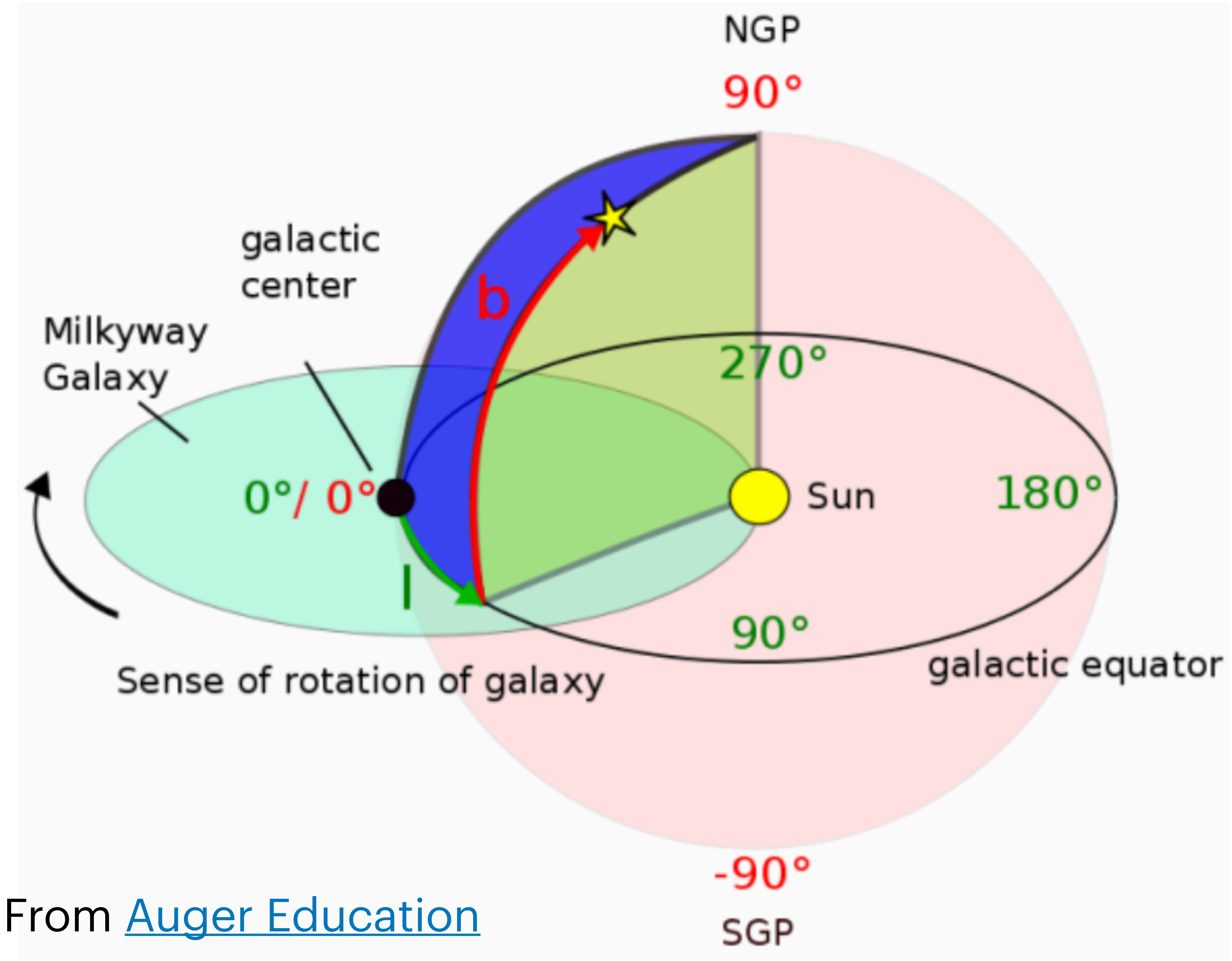
100s Mpc or Gpc

~14 Gyr
age of the universe

$2 - 4\,\mathrm{nG}$

$$1\,\mathrm{pc} \simeq 3.26\,\mathrm{lyr} \simeq 3.086 \times 10^{16}\,\mathrm{m}$$

Galactic coordinate system



From [Auger Education]

MIKY WAY ID:

Stars ~ 10^{11} => ~5 x 10^{10} M_{Sun}

Gas ~10% => ~5 x 10^{9} M_{Sun}

Total Mass => ~2 x 10^{12} M_{Sun}

D_{GC} ~8.5 kpc

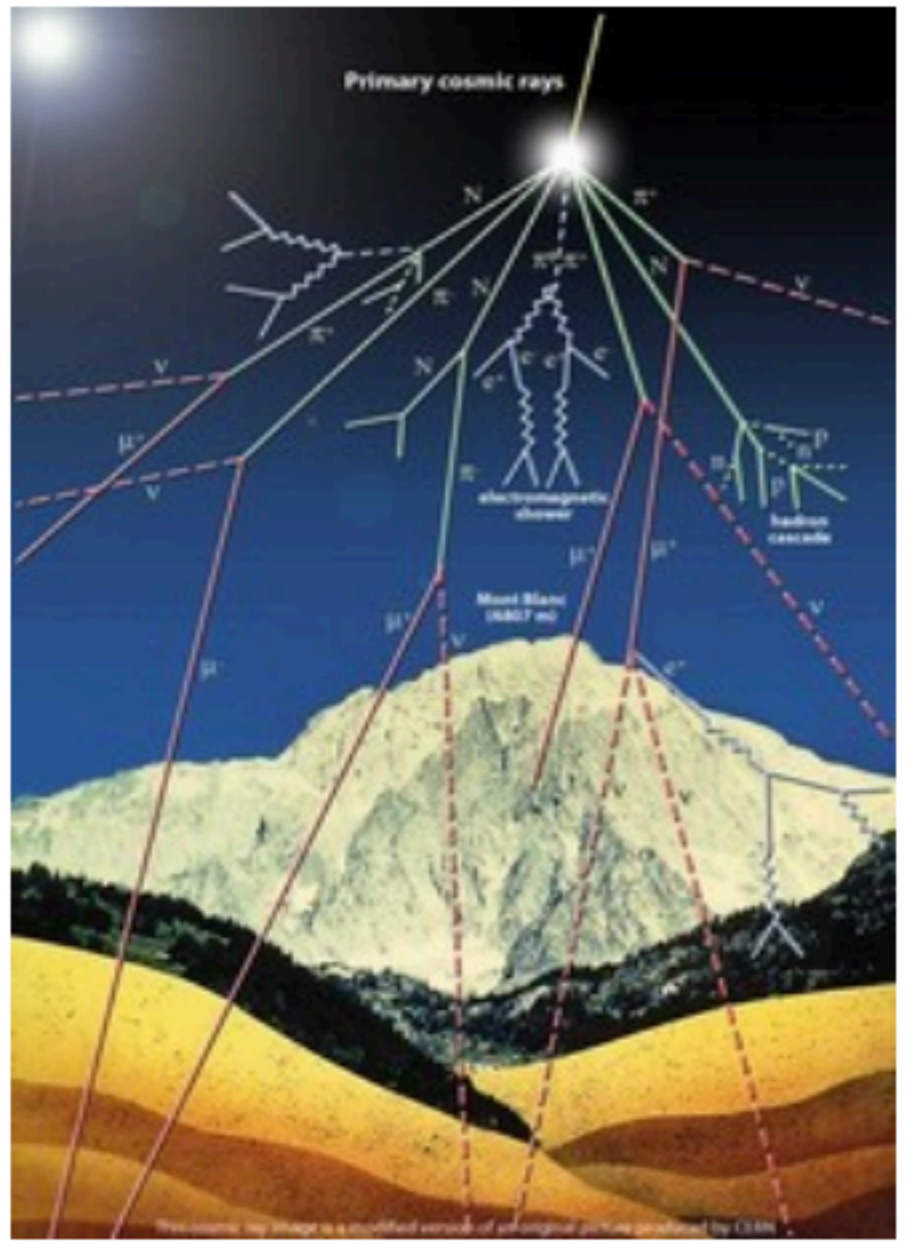
R_{MW} ~15 kpc

R_{DM} ~300 kpc

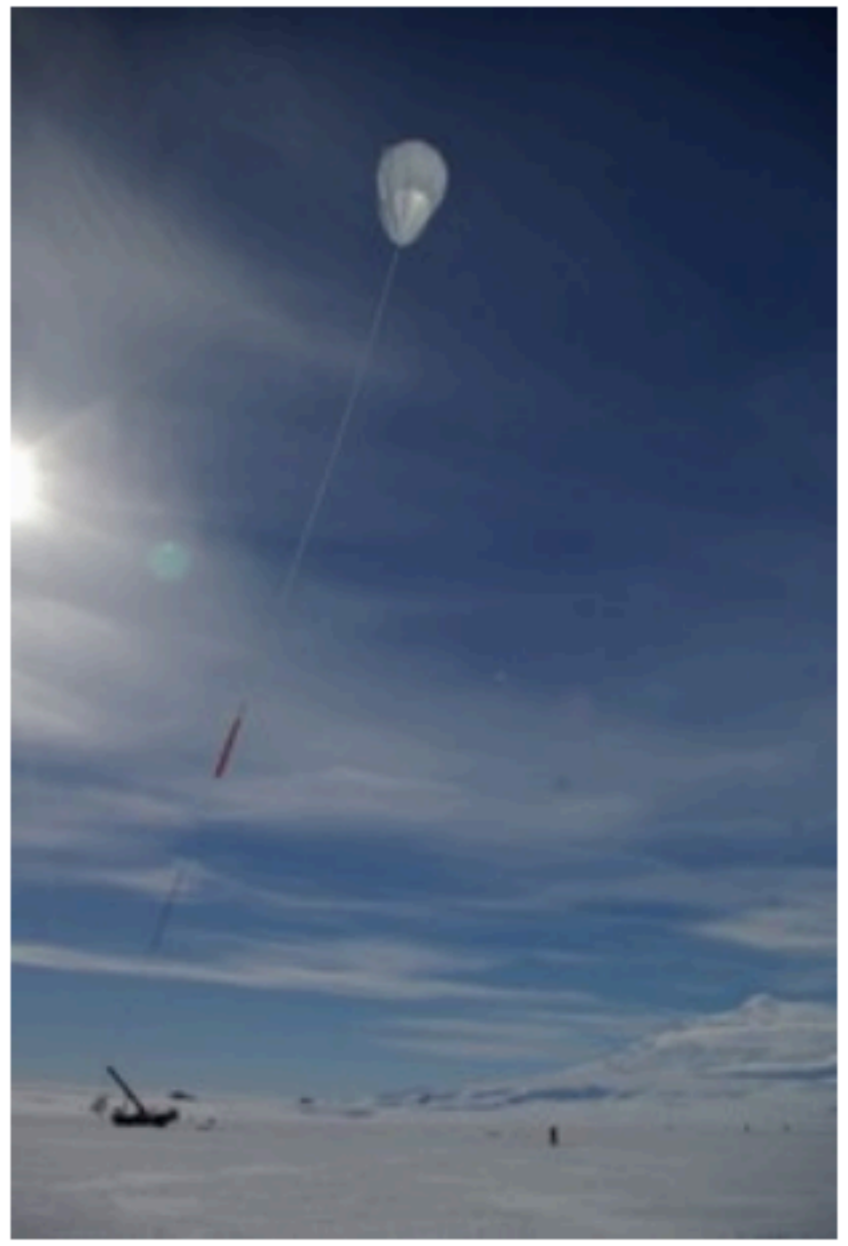
[Conversion algorithms in Astropy]

Cosmic rays: Experimental milestones

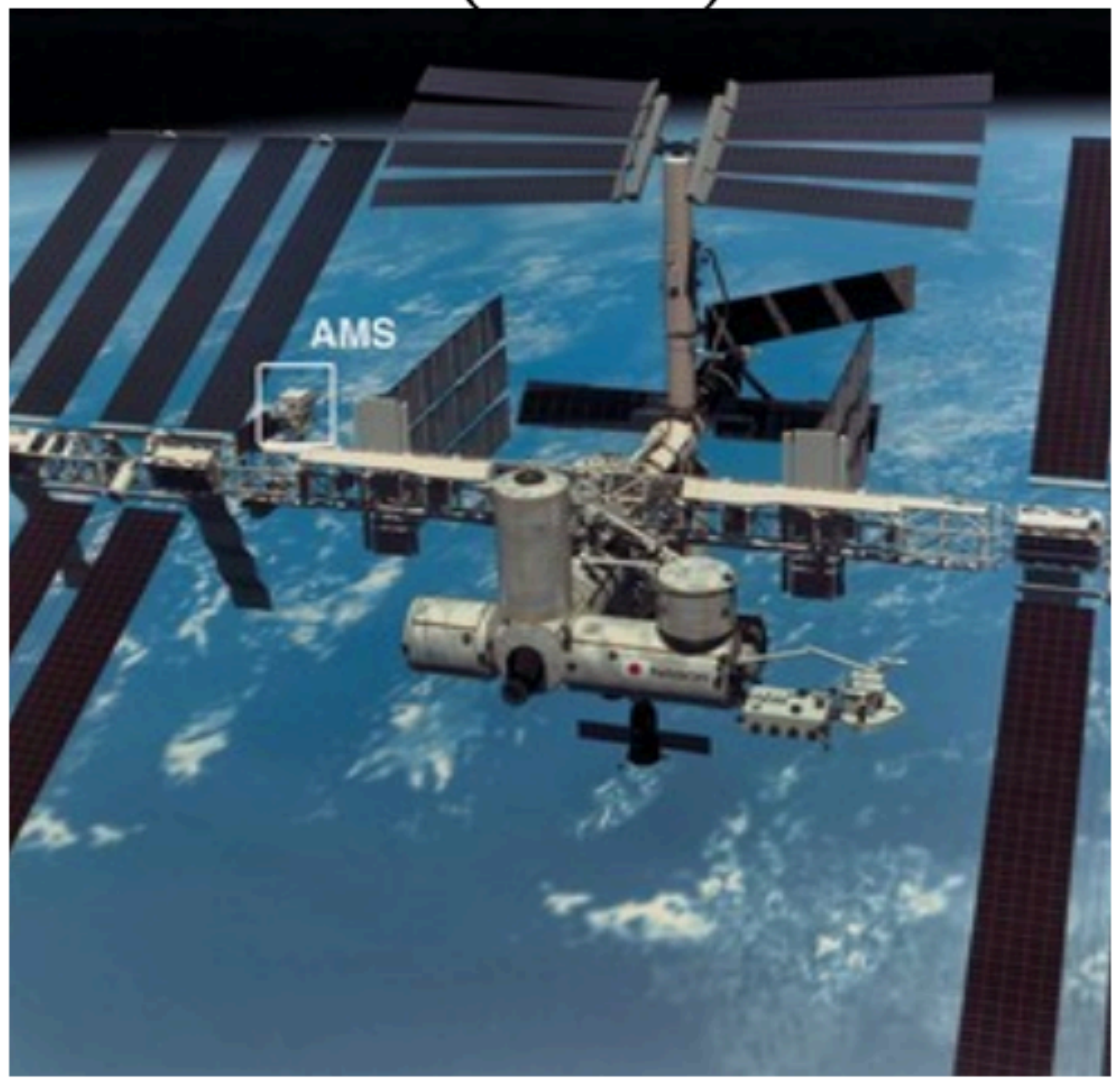
Mountain altitude < 5 km

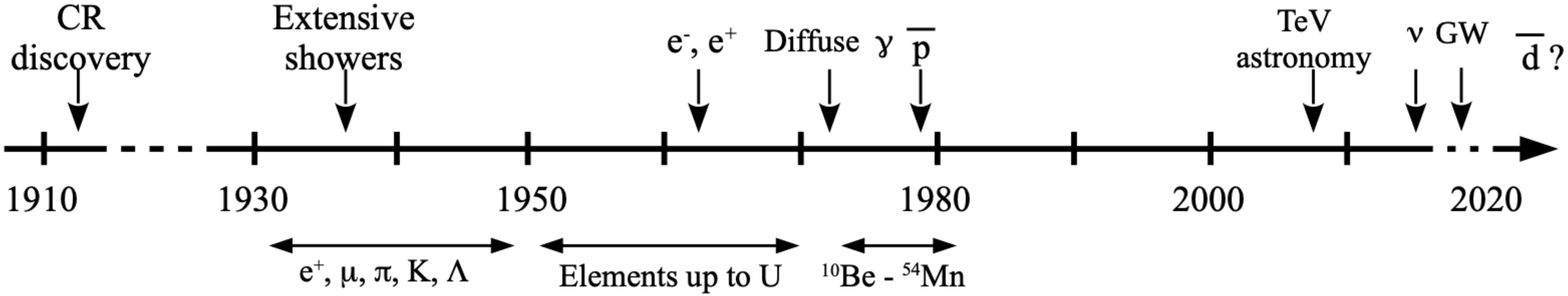


CREAM balloon ~ 40 km



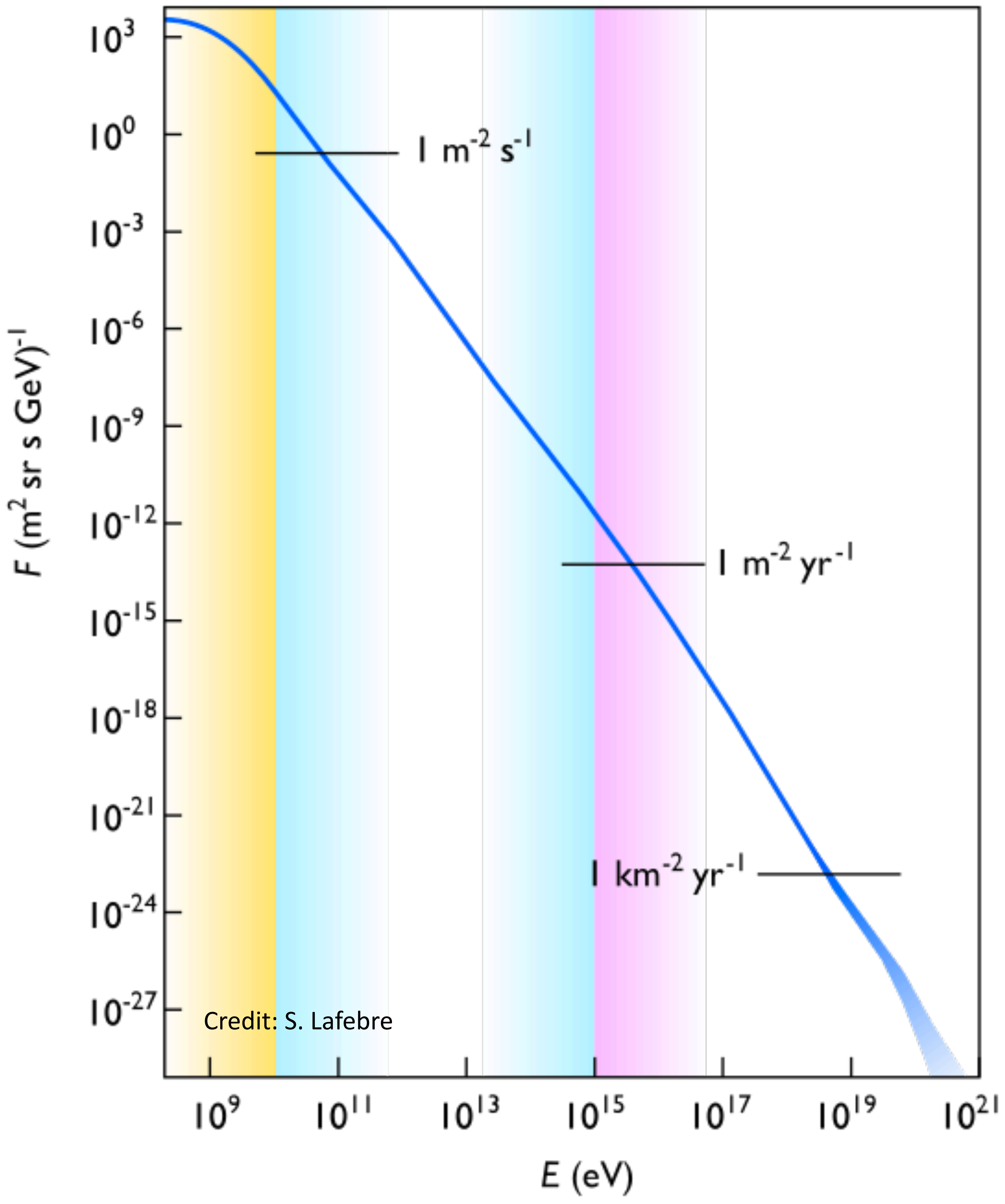
AMS-02 (on ISS) ~ 300 km





Cosmic rays: The all-particle flux

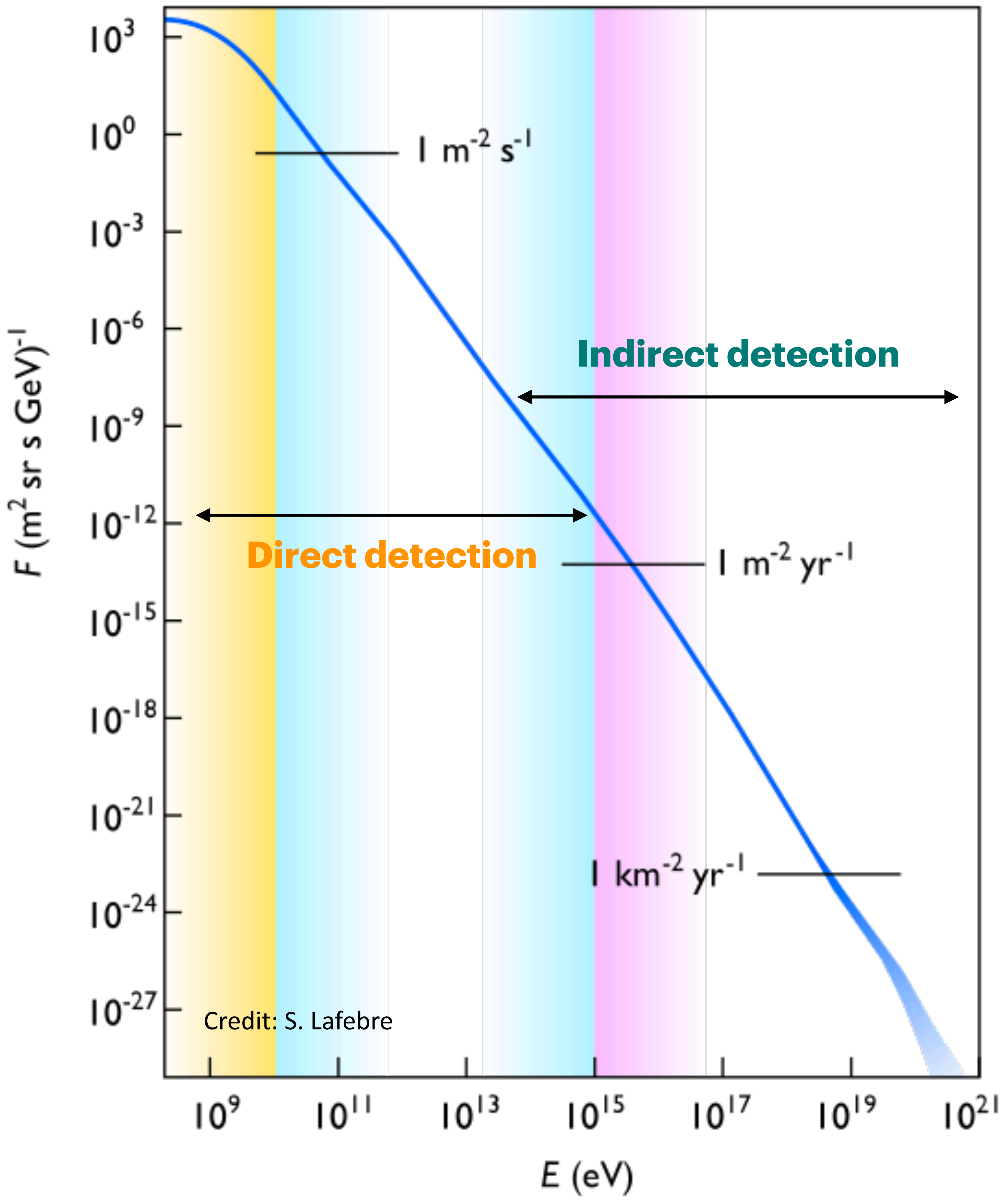
The all-particle flux of cosmic rays



- 13 decades in energy; 30 decades in flux!
- Quite featureless spectrum, almost perfect power-law with index about -3
- Two main features, i.e. softening at 3 x10^{15}eV (*knee*) and hardening at 5x10^{18} eV (*ankle*) reflect changes in CR behaviour (sources, propagation, etc)
- Rather isotropic distribution in arrival directions (< 0.1%)

Cosmic rays: The all-particle flux

The all-particle flux of cosmic rays



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How do we measure them?

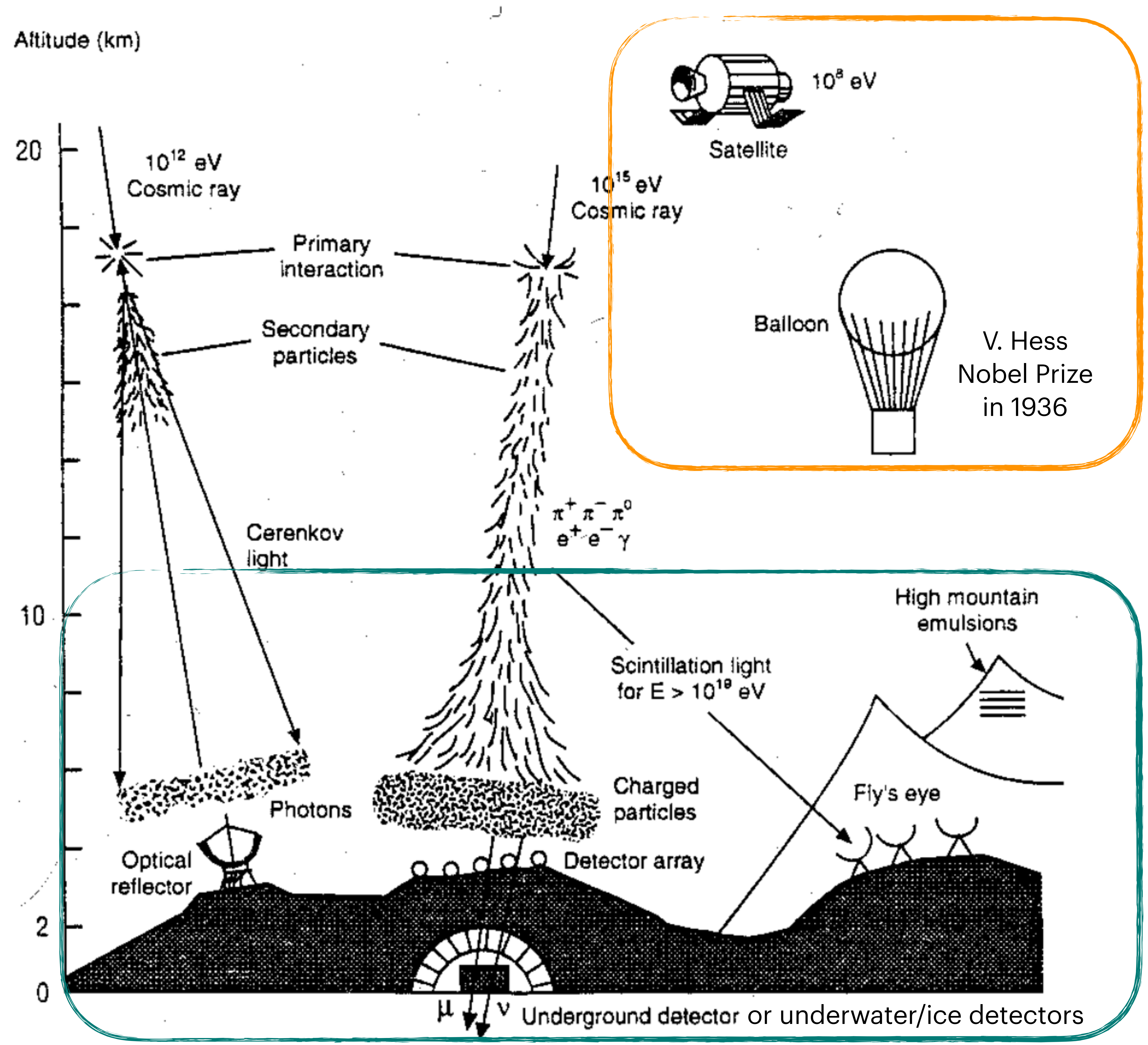
Cosmic-ray direct and indirect measurements

Direct detection

- Below few tens of TeV
- High statistics
- CRs absorbed in the upper atmosphere
- Direct measurements in space possible with magnetic spectrometers (Q and **p**) and/or calorimeters (E)

Indirect detection

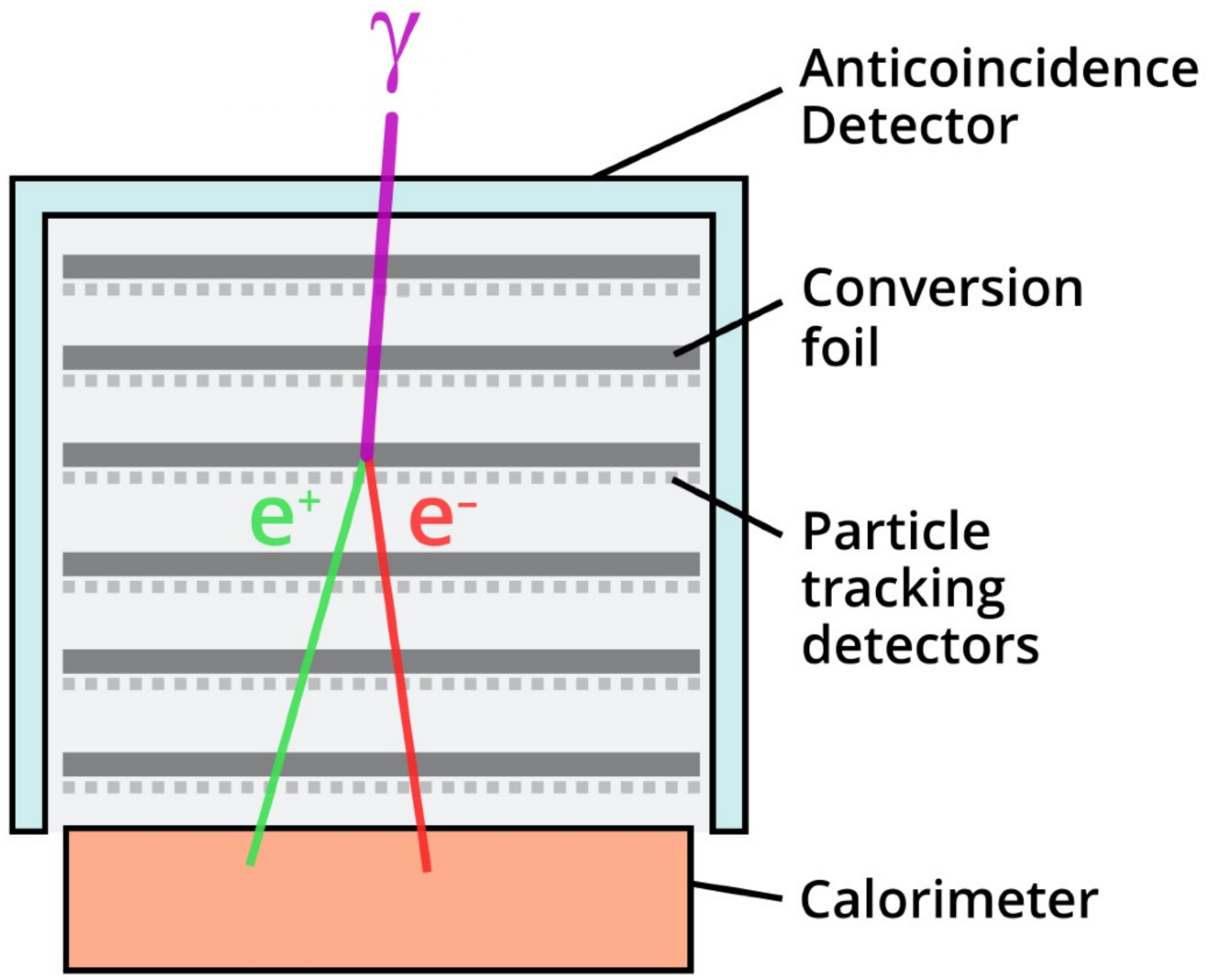
- Above tens of TeV
- Very much reduced statistics
- CRs penetrating to the ground thanks to extensive air showers
- Indirect measurements with long-lived large instruments deployed at Earth



Spiro, Auburn & Palanque-Delabrouille, Survey in High-energy Physics (2000)

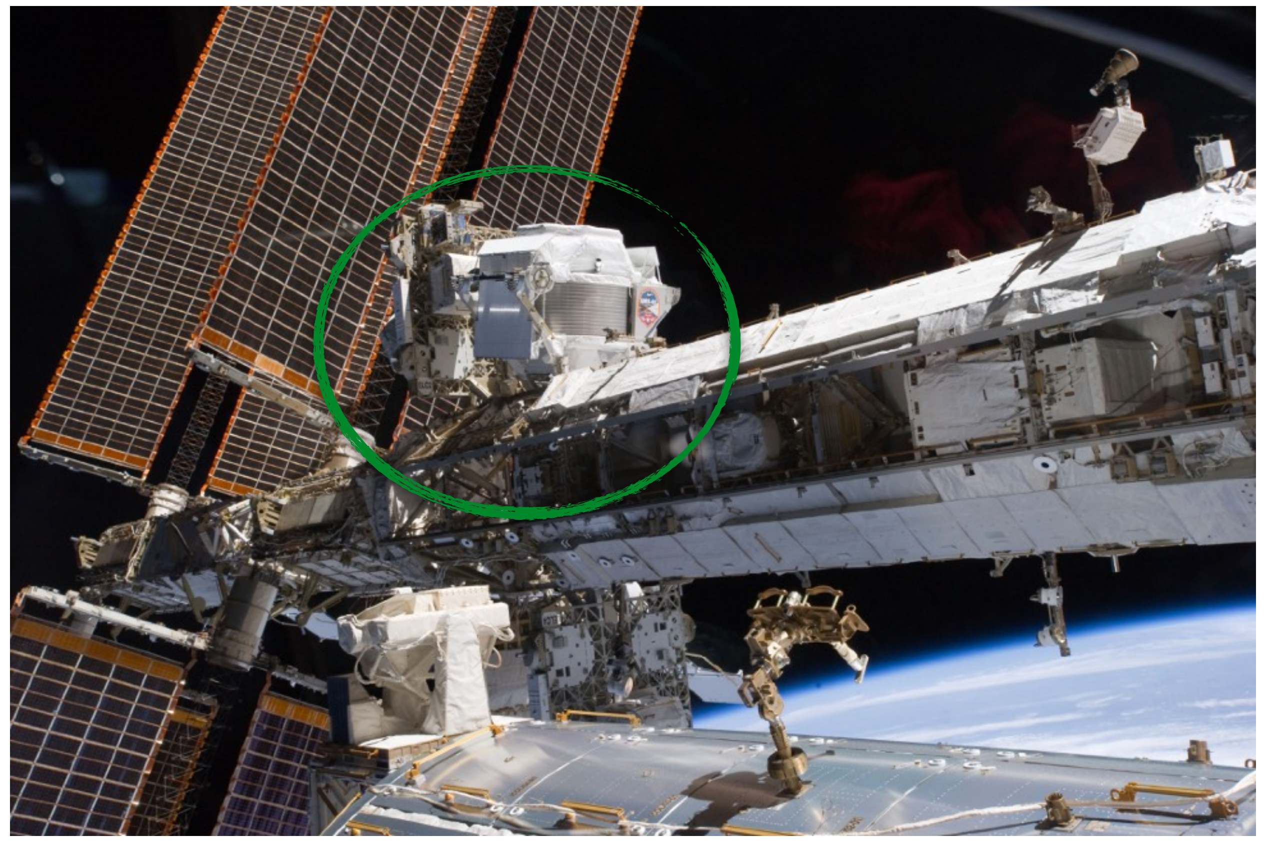
Cosmic-ray detection in space

Fermi-LAT (2008-)

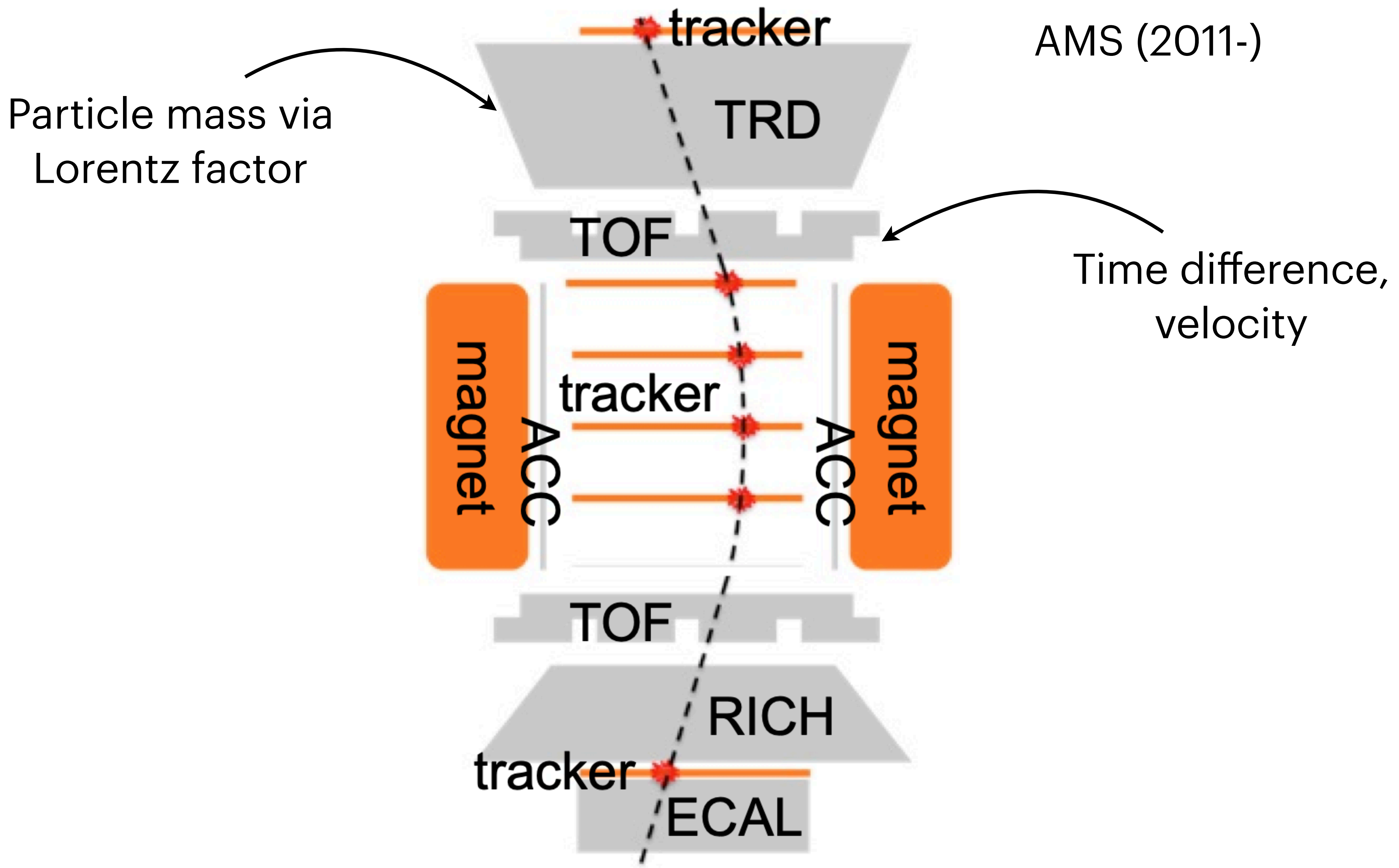


Credit: NASA's Goddard Space Flight Center

Detection of gamma-rays
in the range 20 MeV - 300 GeV

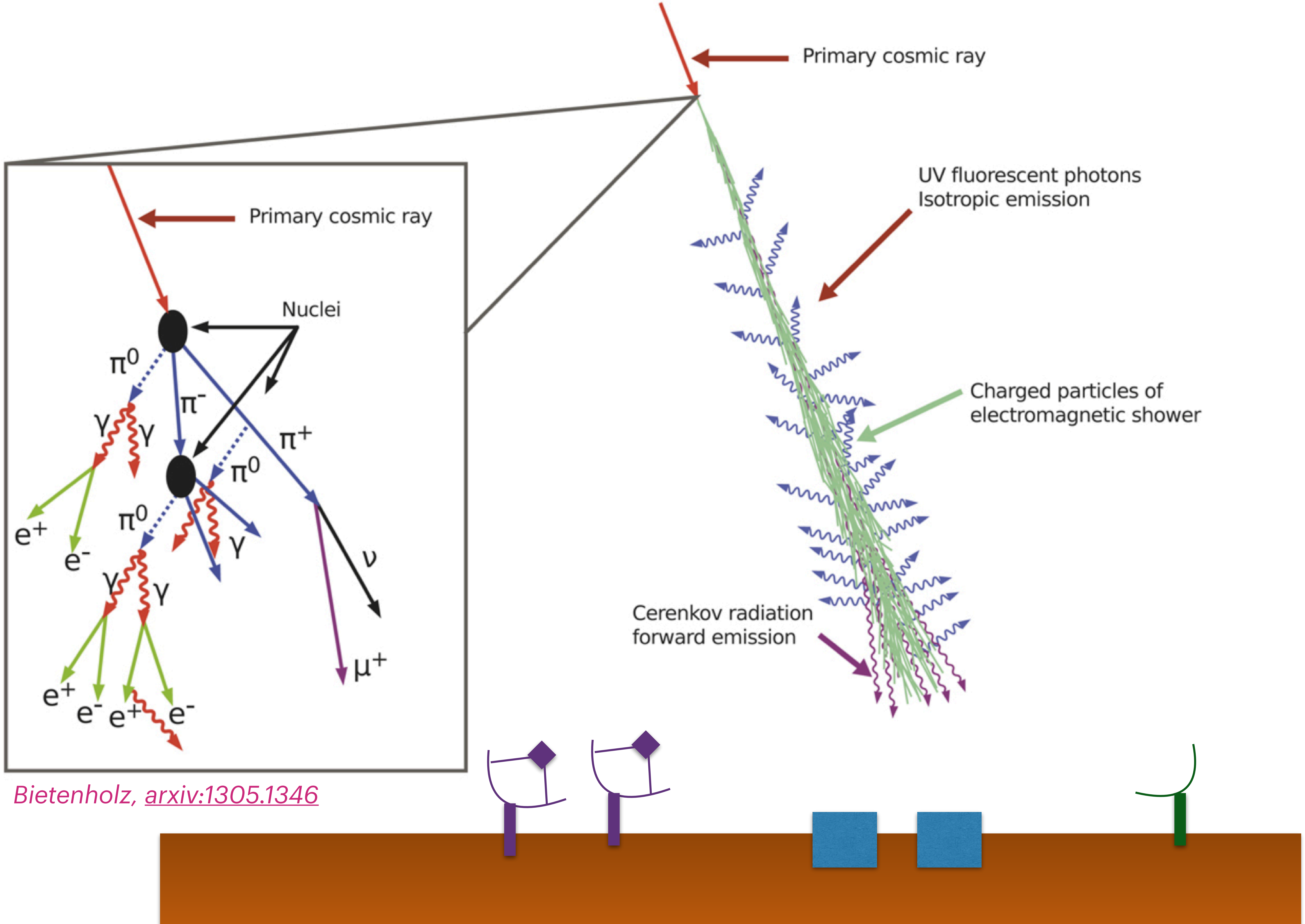


AMS (2011-)



Detection of $e^{\pm}$, $p^{\pm}$ and heavier nuclei
in the range 1 GeV - 2 TeV

Cosmic-ray detection on the ground



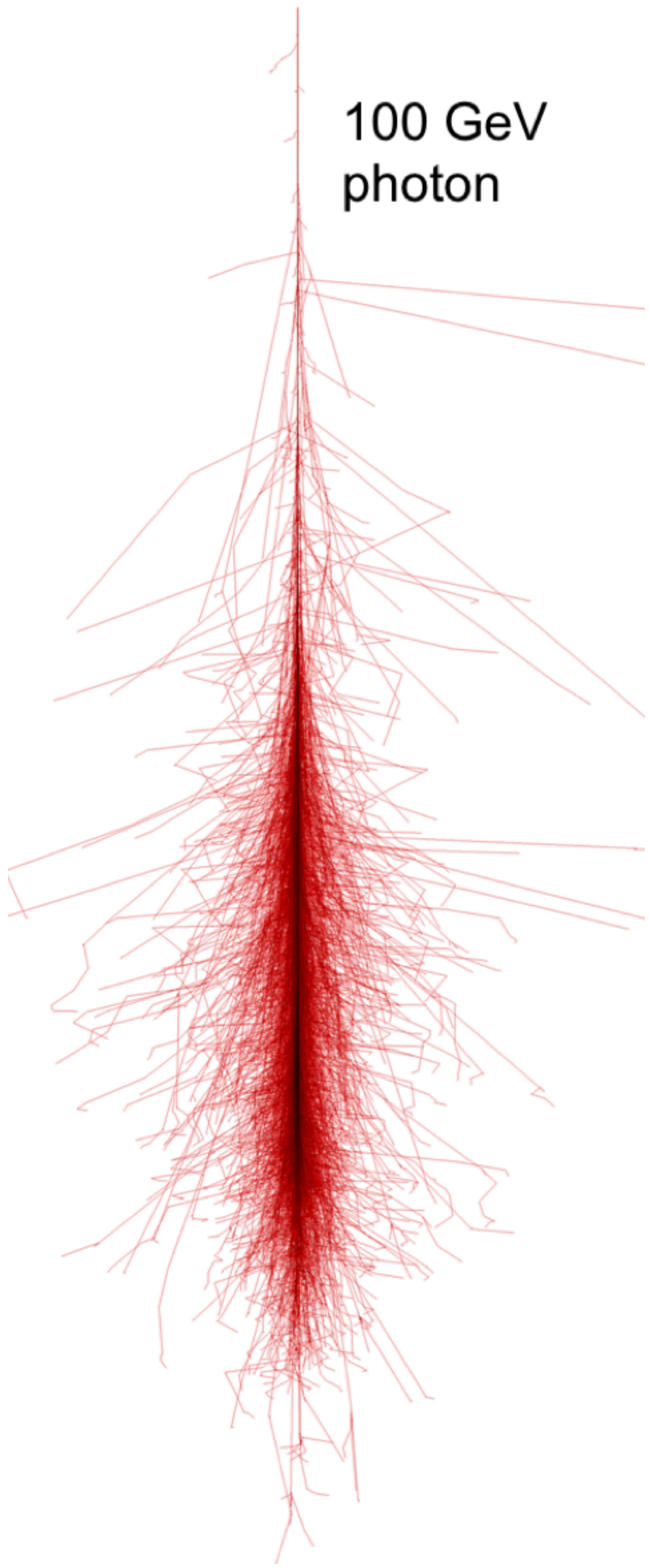
Bietenholz, [arxiv:1305.1346]

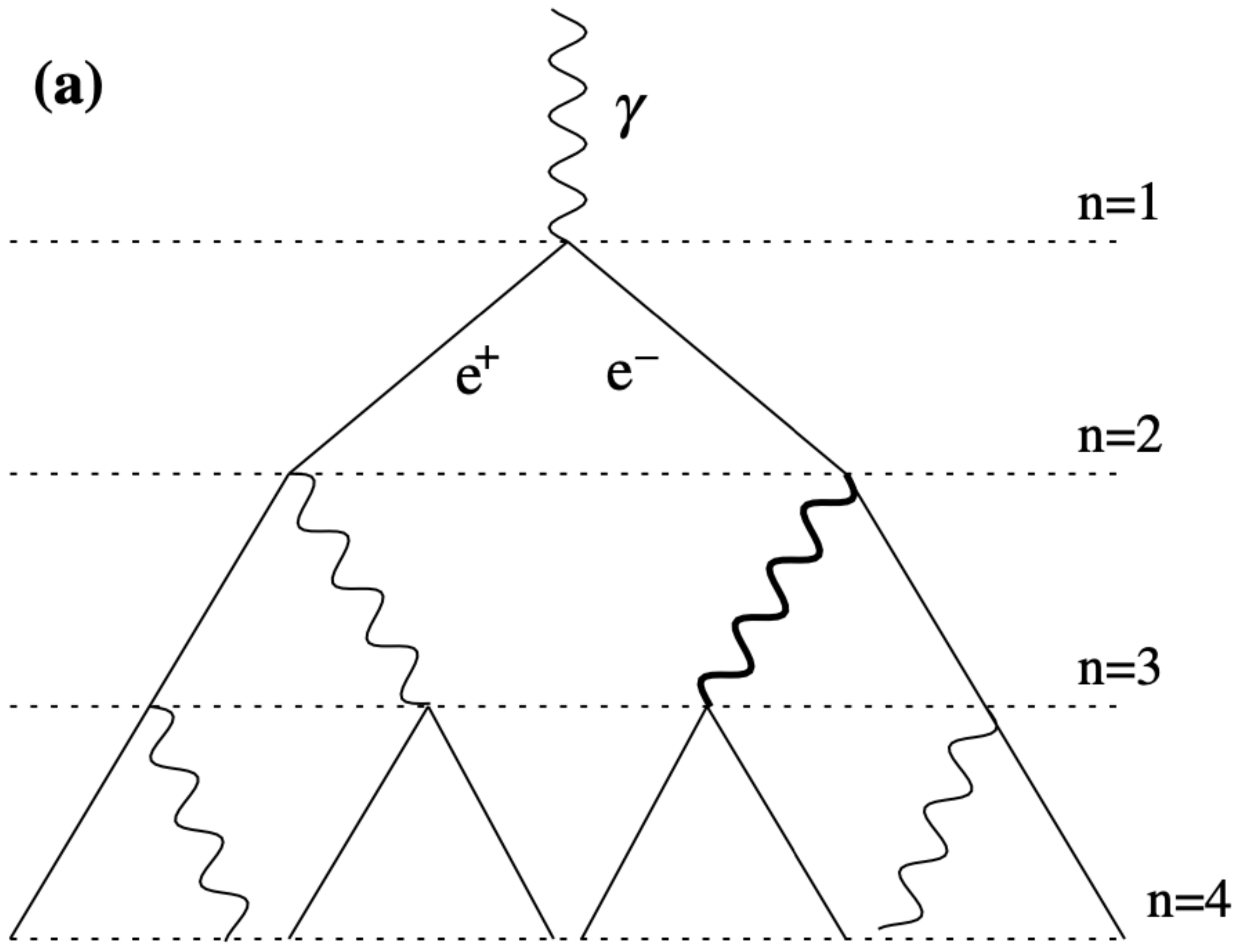
Fluorescence
(e.g. Fly's Eye, Auger observatory)

Imaging Air Cherenkov Telescope (IACT)
(e.g. MAGIC, VERITAS, HESS, planned CTA)

Ground array and Water Cherenkov detectors
(e.g. KASCADE-GRANDE, MILAGRO, HAWC)

Gamma rays vs charged cosmic rays





Matthews, Astrop. Phys'05

Semi-analytical model for QED showers (Heitler model)

$$\lambda \equiv \int \rho(\ell)\mathrm{d}\ell \sim 35\,\mathrm{g/cm^2}$$

Grammage: characteristic depth to produce pair

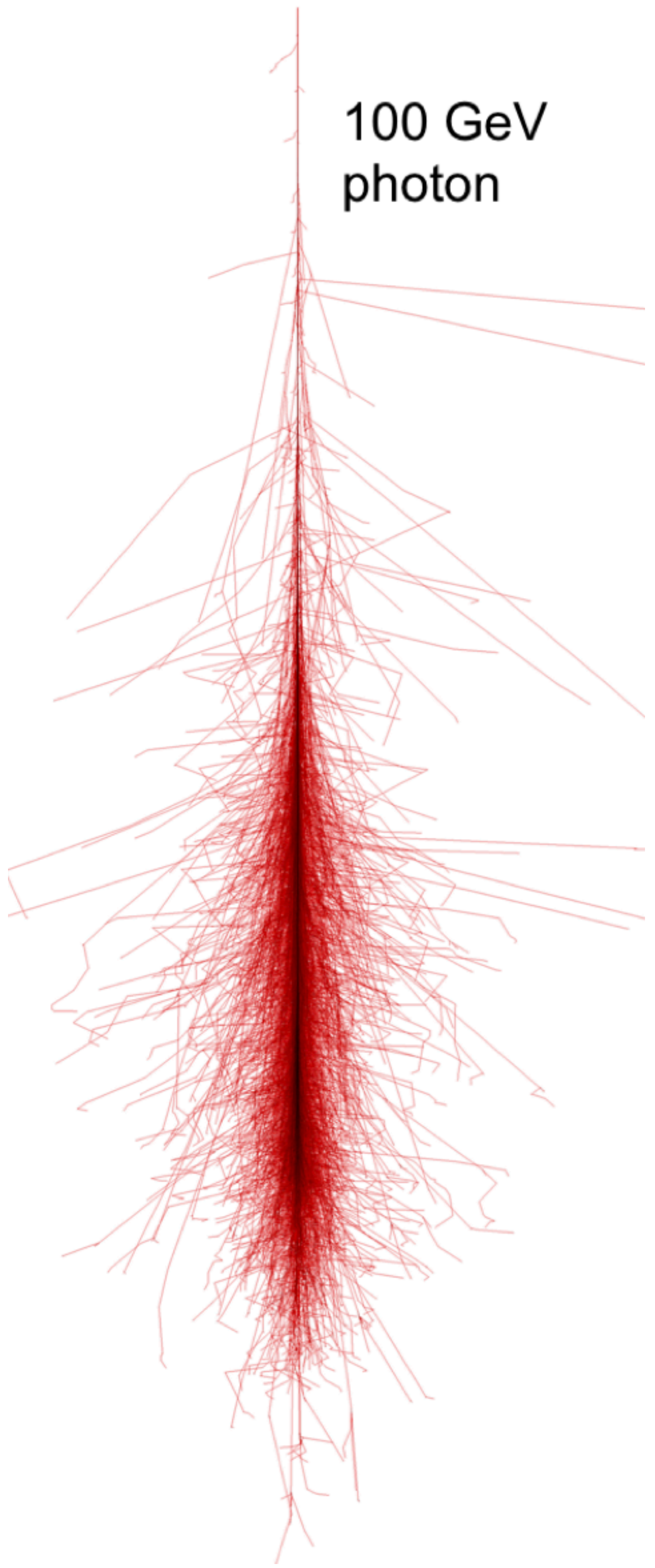
$$X = n\lambda$$

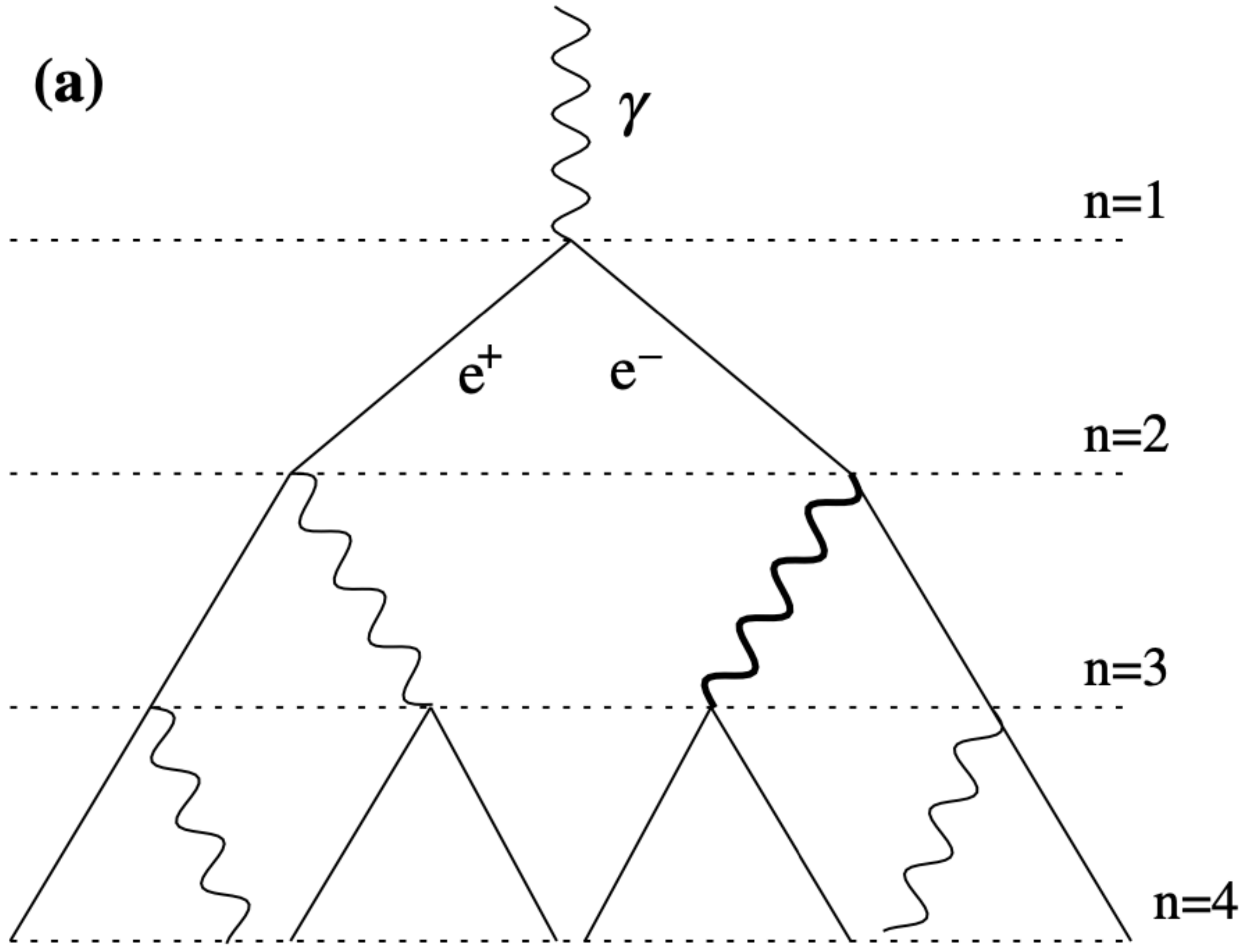
$$N(X) = 2^n = 2^{X/\lambda}$$

$$\langle E \rangle = E_0/2^n$$

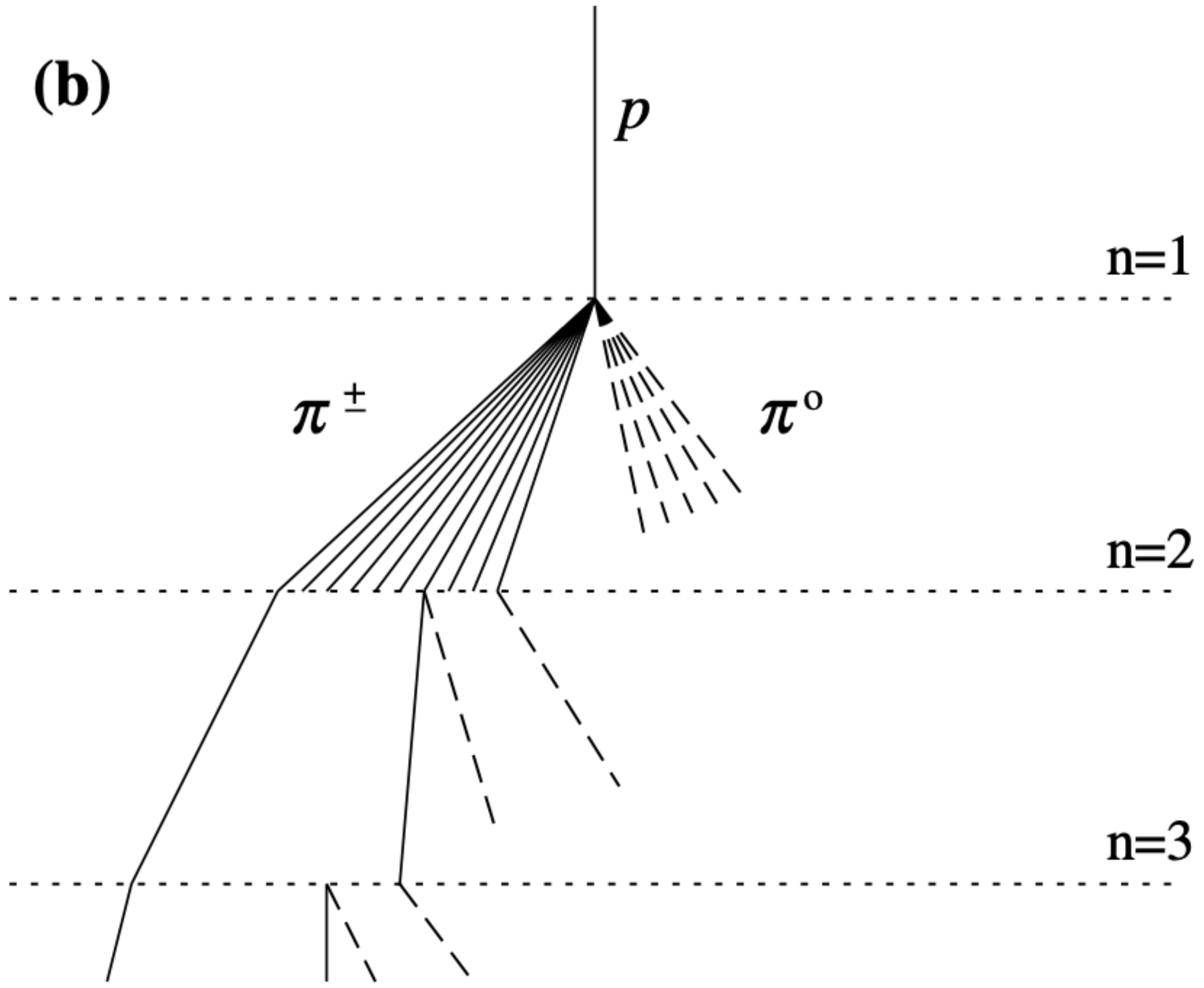
$E_c \sim 80\,\mathrm{MeV}$ $\quad N_{\mathrm{max}} = E_0/E_c$ @ X_{max}

Gamma rays vs charged cosmic rays



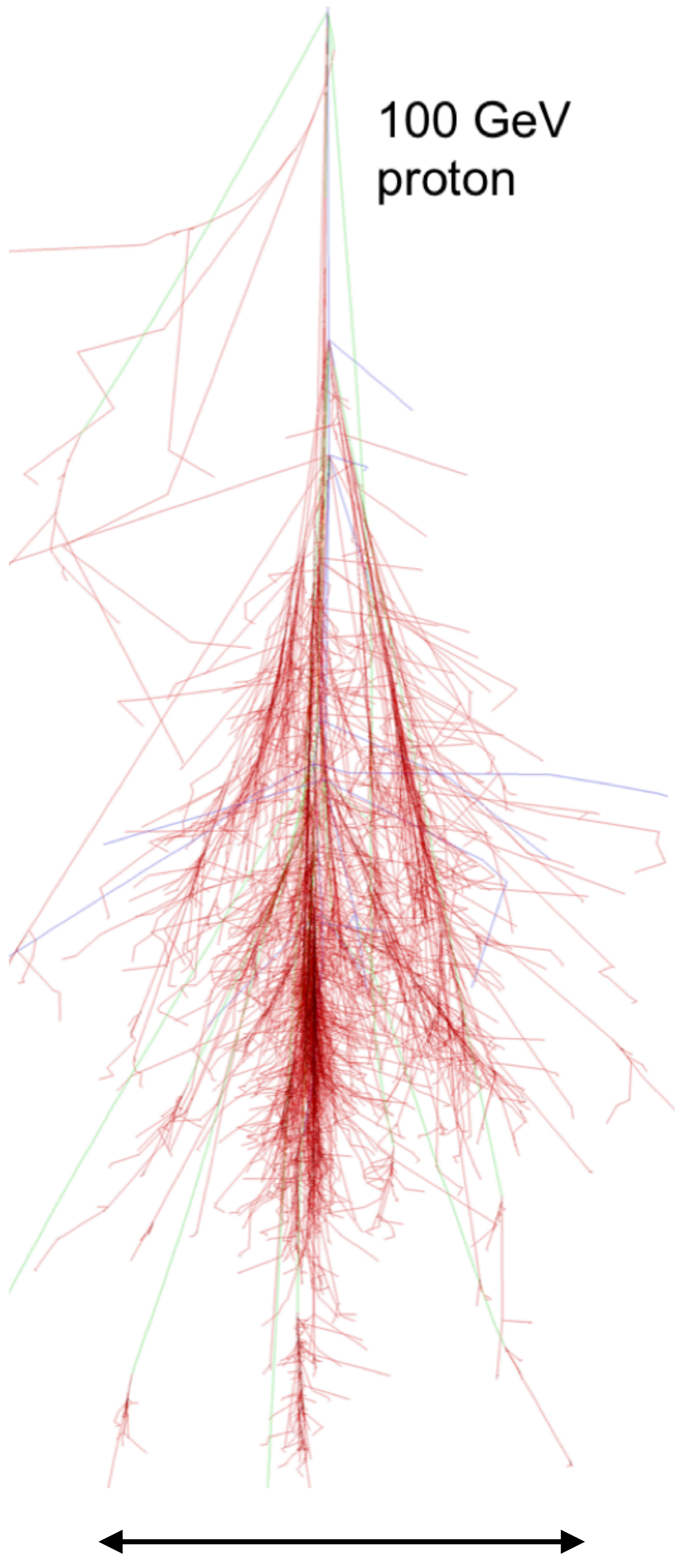


$$\langle E \rangle = E_0 / 2^n$$



$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0^p$$

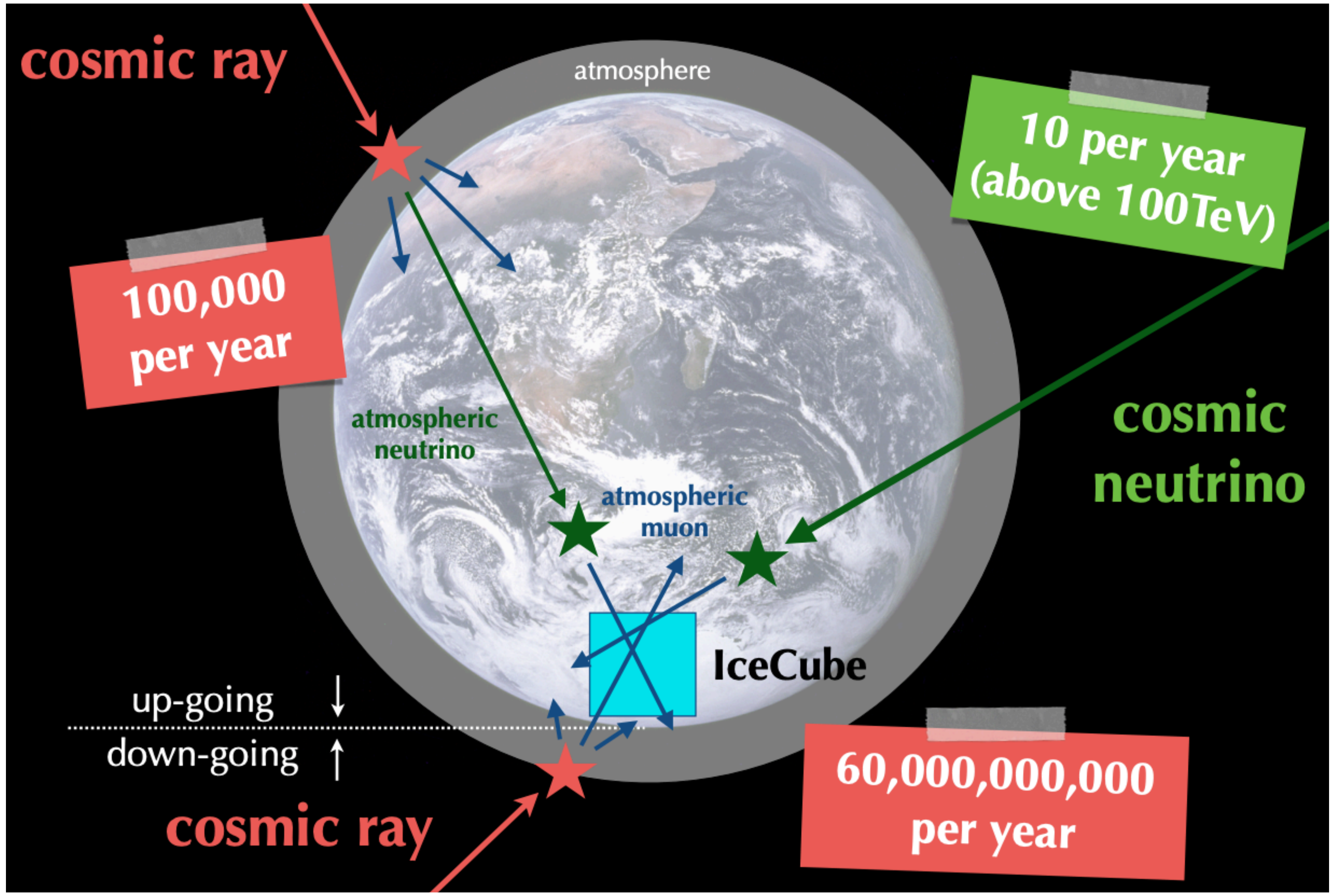
$$E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0^p$$

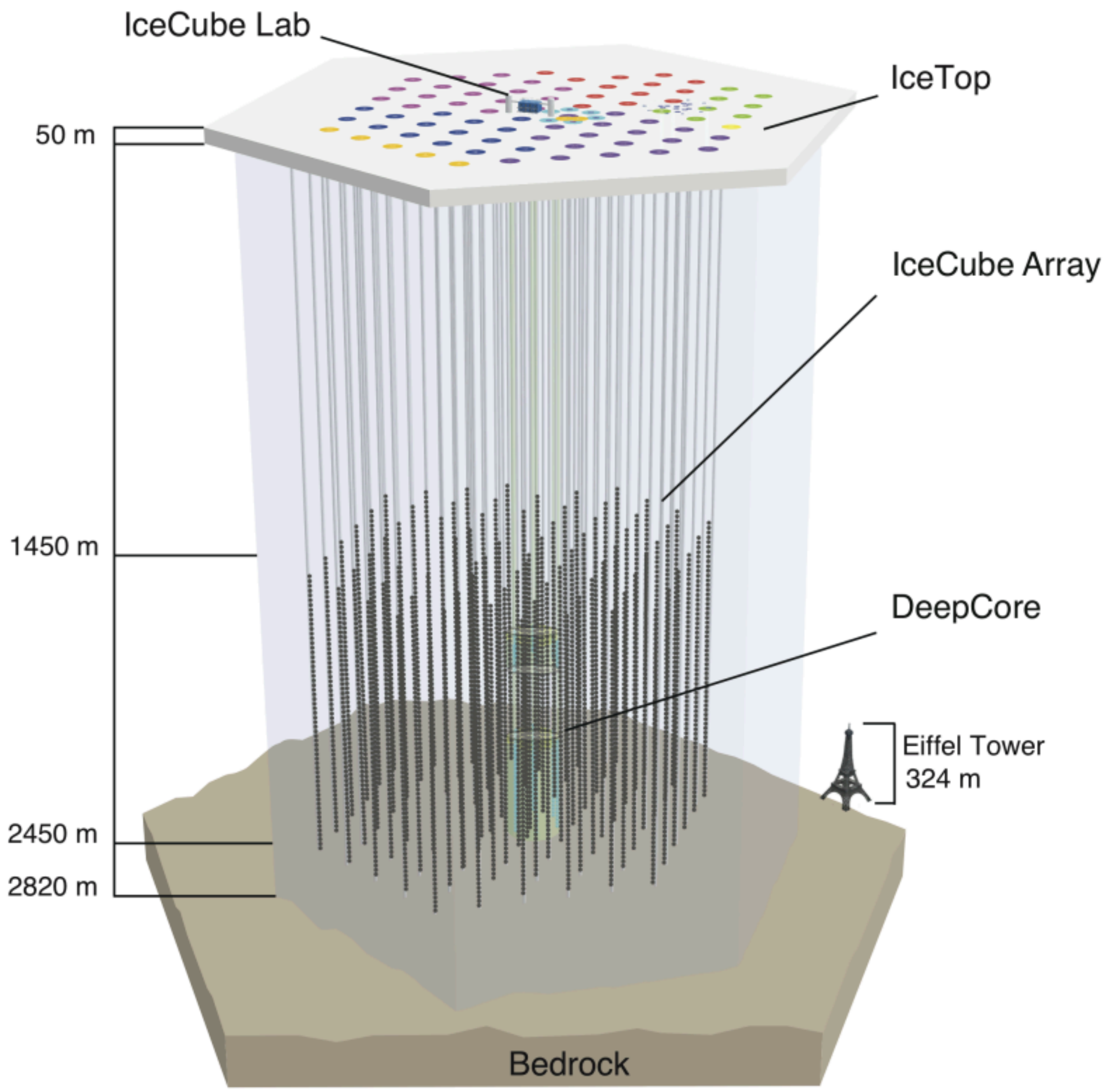


Matthews, Astrop. Phys'05

Neutrino detection on the ground

Optical Cherenkov Telescopes: Separate charged particles directions through Cherenkov light (Markov, 1960)





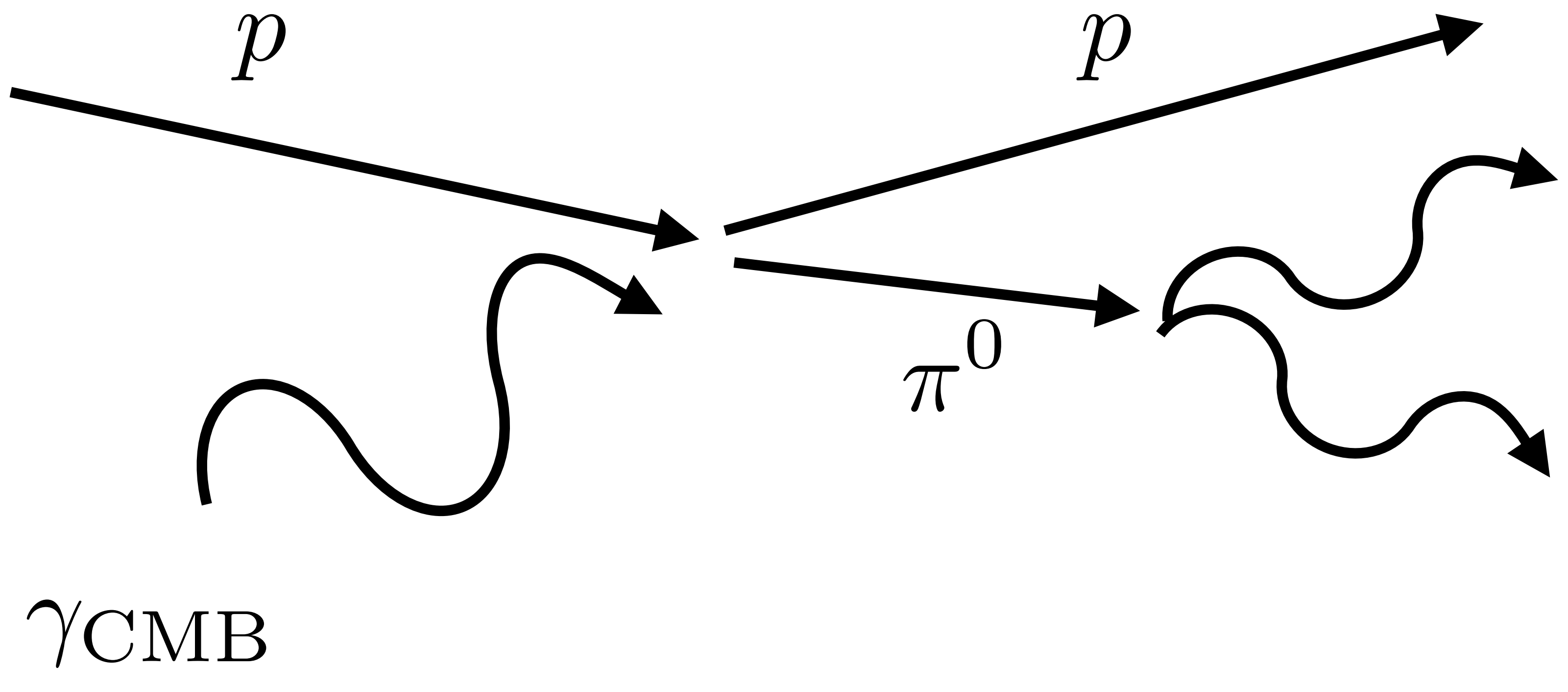
- **Giga-ton optical Cherenkov telescope at the South Pole**
- Collaboration of about 300 scientists at more than 50 international institutions
- 60 digital optical modules (DOMs) attached to strings
- 86 IceCube strings **instrumenting 1 km³ of clear glacial ice**
- 81 IceTop stations for cosmic ray shower detections

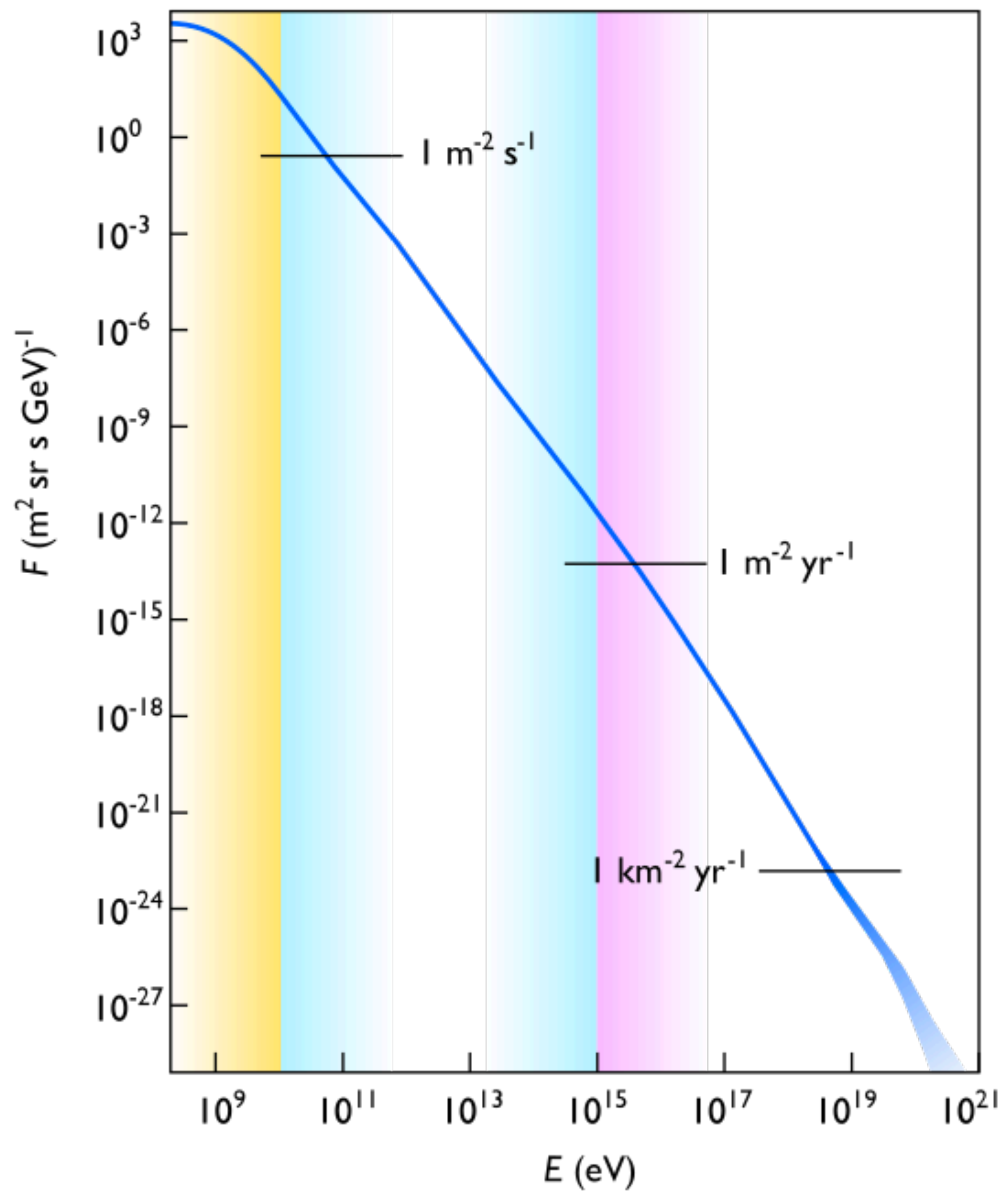
New idea: Giant Radio Array for Neutrino Detection, GRAND, look for coherent radio emission of air showers produced by Earth-skimming tau neutrinos with horizontal-shower optimised antennas. *Martineau-Huynh et al., EPJ Web of Conference 116 (2016) 03005*

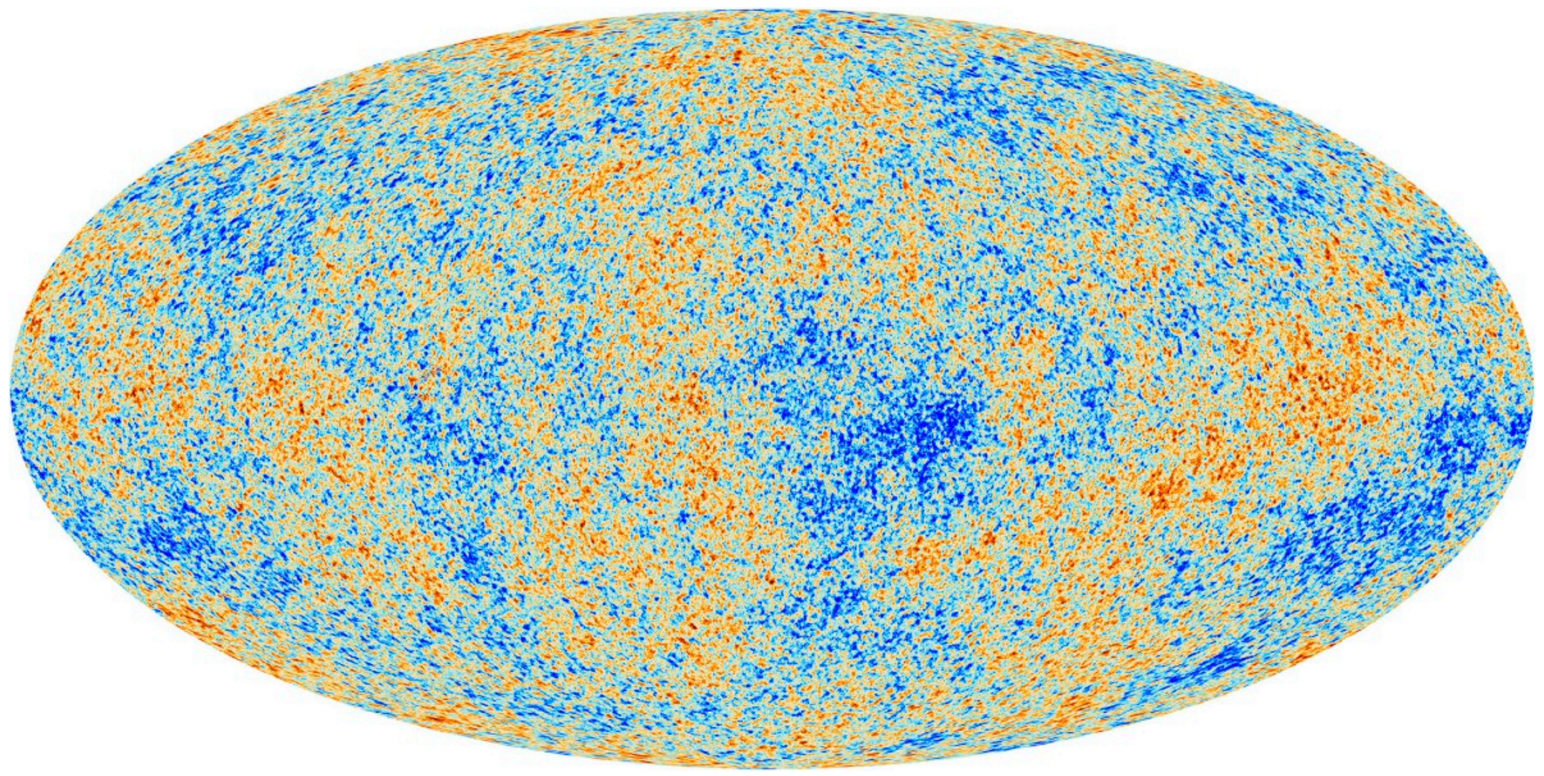
GRAND

Cosmic-ray horizon: proton-pion production

Very high energy cosmic rays will be destroyed by interactions with background photons:







Credit: ESA/Planck

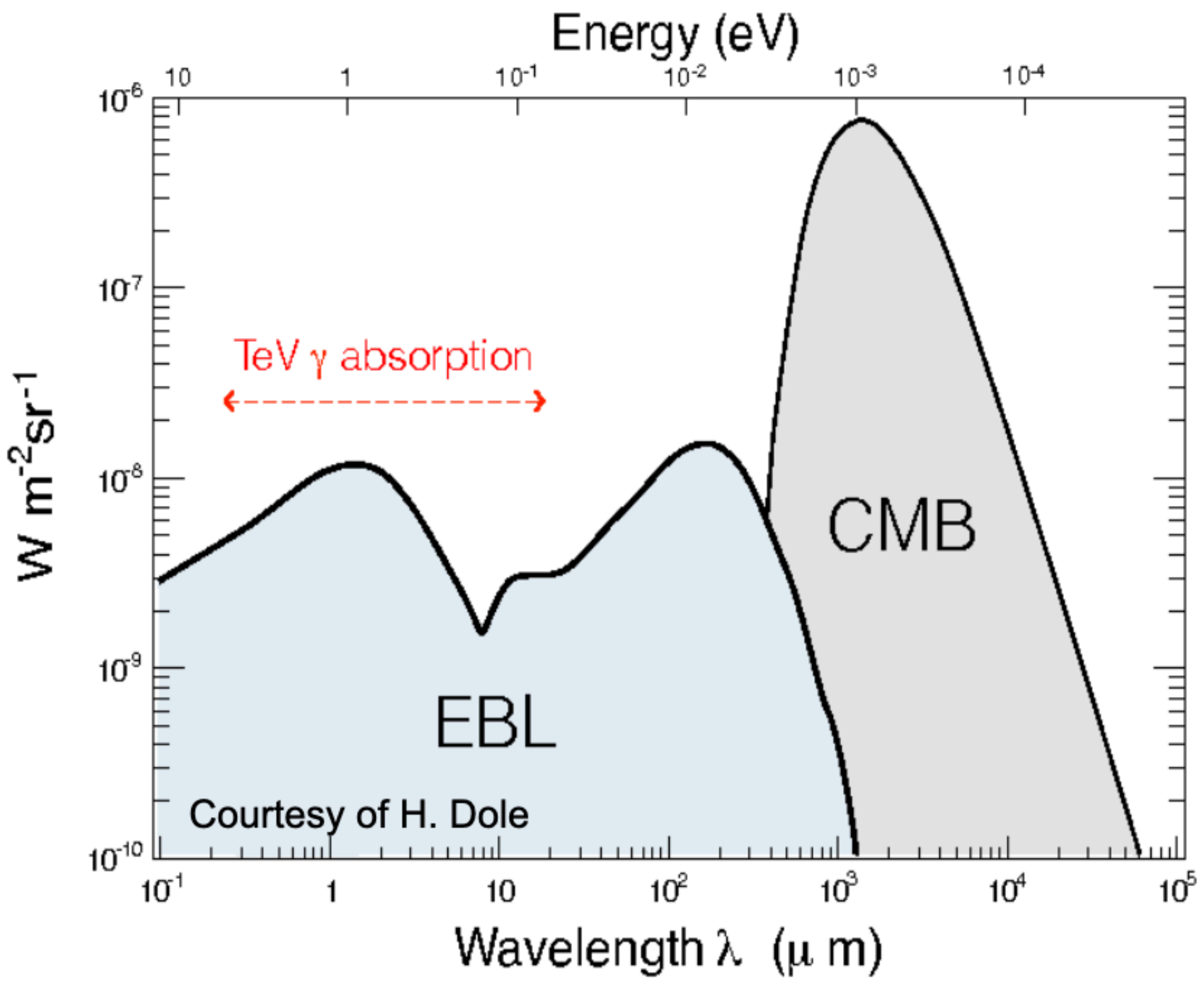
$$\mathrm{p} + \gamma_{\mathrm{CMB}} \rightarrow \mathrm{p} + \pi_0$$

Threshold energy for this process gives rise to the Greisen–Zatsepin–Kuzmin (GZK) cut-off:

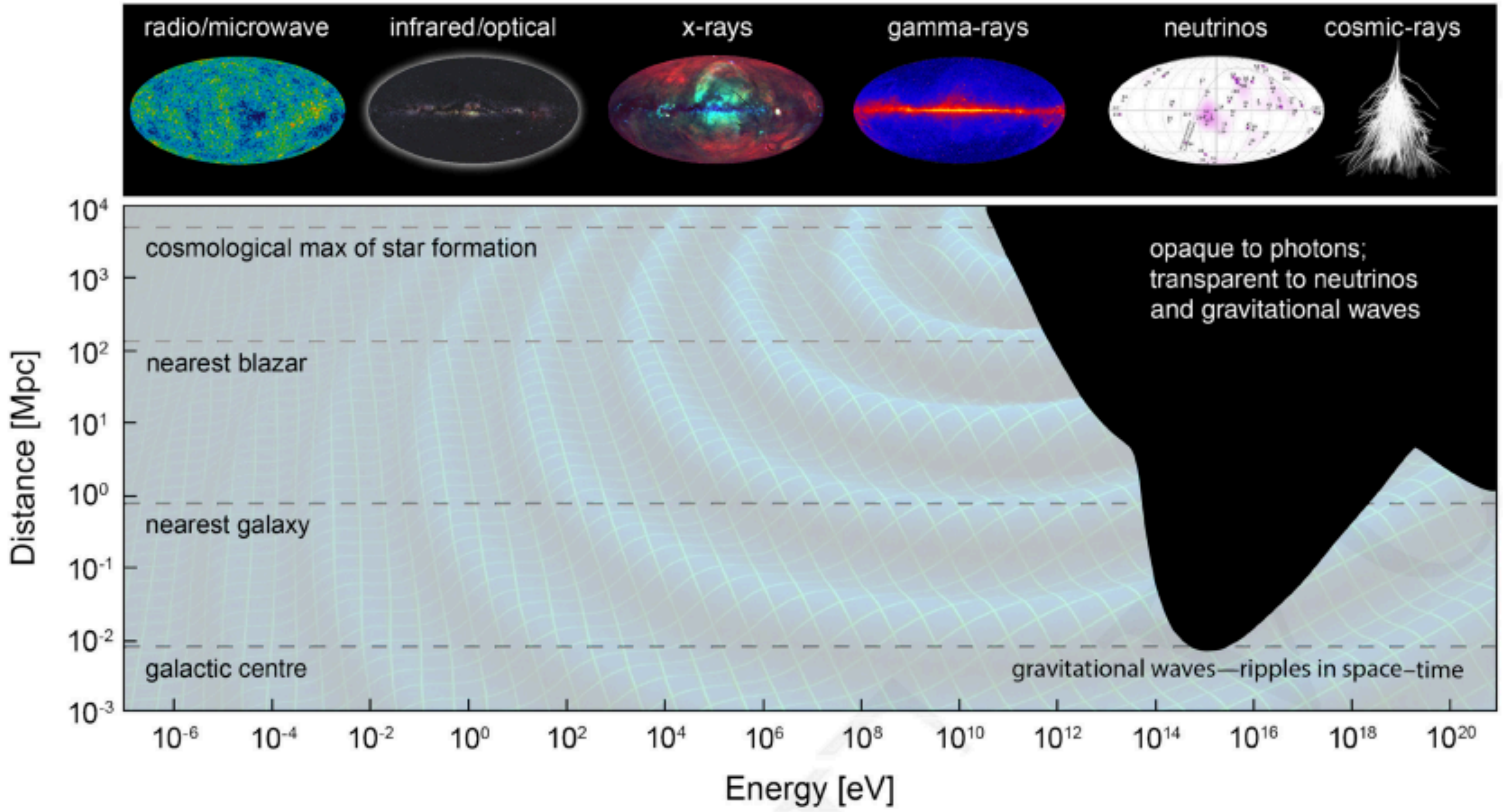
$$E_{\mathrm{p}\gamma} \approx 3.4 \times 10^{19} \left(\frac{\epsilon}{10^{-3}\mathrm{eV}} \right)^{-1} \mathrm{eV}$$

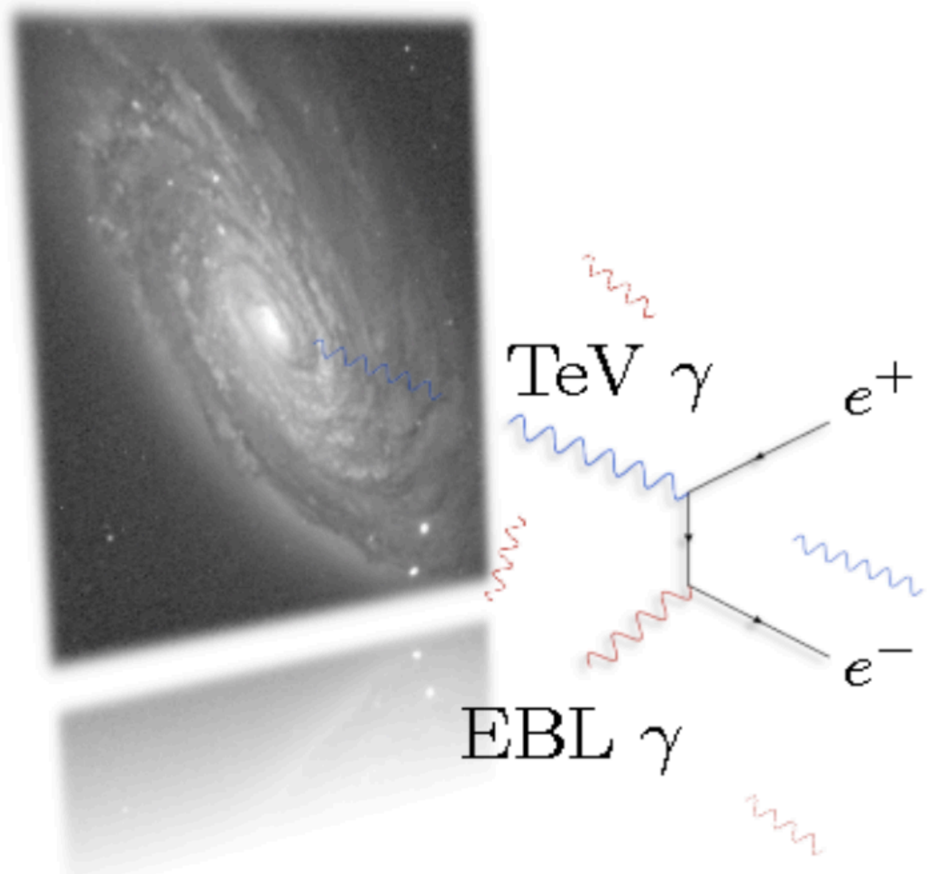
Ultra high energy CRs cannot propagate more than around $\ell_{\mathrm{GZK}} \sim 50\,\mathrm{Mpc}$ before being destroyed.

Cosmic-ray horizon: pair production



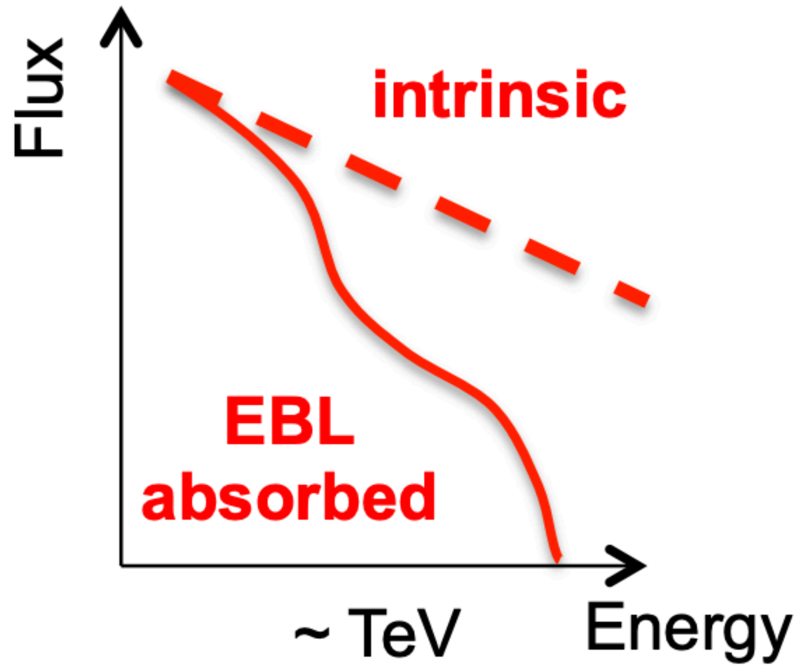
Bartos&Kowalski, Mutimessenger Astronomy





Nikishow'62,
Gould&Shreder'67,
Stecker+ '92

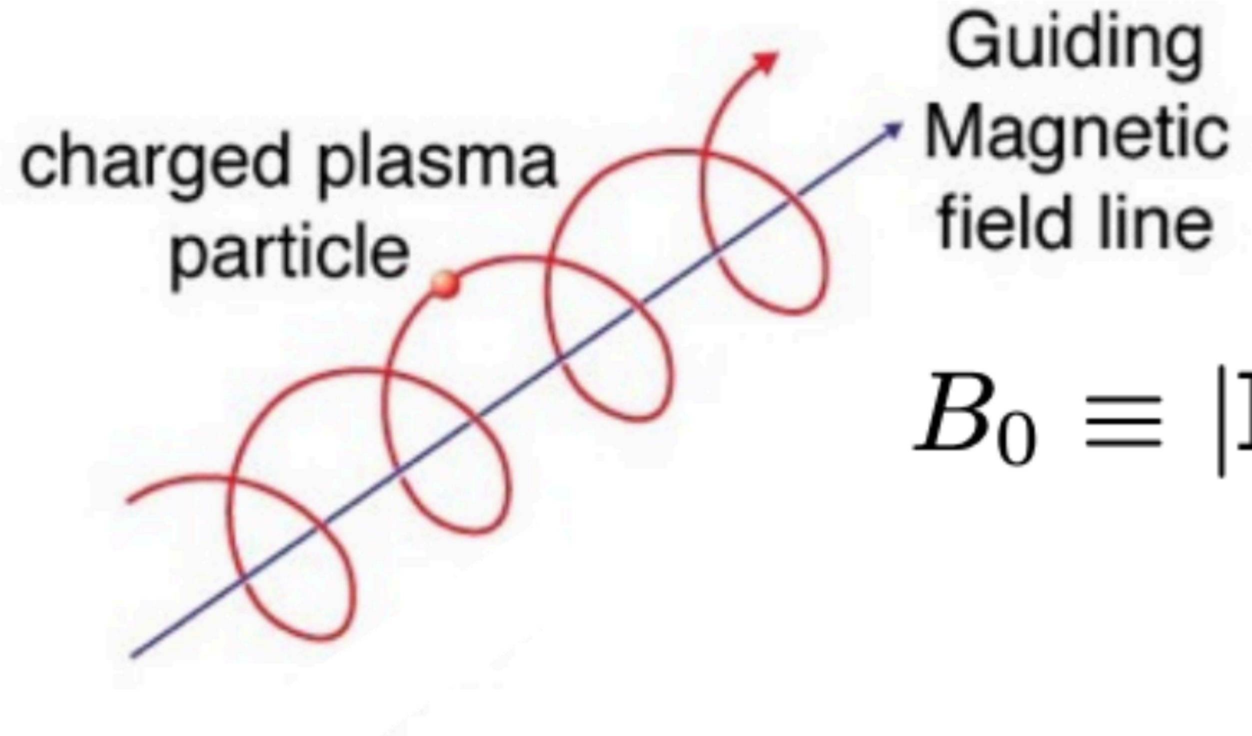
$$\Phi_{obs}(E_\gamma) = \Phi_{int}(E_\gamma)e^{-\tau(E_\gamma, z_s)}$$



Cosmic-ray sources and transport

Cosmic-ray in regular B-field

$$\frac{d\mathbf{p}}{dt} = q\mathbf{E} + q\frac{\mathbf{v}}{c} \times \mathbf{B}$$



$$B_0 \equiv |\mathbf{B}_0|$$

Solutions (no electric field):

$$p_z = \mathrm{const}$$
$$v_x = v_0 \cos(\Omega \mathrm{t})$$
$$v_y = v_0 \sin(\Omega \mathrm{t})$$

$$r_L = \gamma r_g = \sqrt{1-\mu^2}\frac{\mathcal{R}}{B_0} \simeq 10^{-6}\sqrt{1-\mu^2}\frac{\mathcal{R}}{\mathrm{GV}}\frac{\mu\mathrm{G}}{B_0}\mathrm{pc}$$

Larmor radius

$$\Omega = \frac{qB_0}{E} \simeq 10^{-2}\frac{B_0}{\mu\mathrm{G}}\frac{\mathrm{GeV}}{E}\,\mathrm{rad/s}$$

Larmor frequency

$\mu = p_z/p$ $\mathcal{R} = p/q\,[\mathrm{GV}]$

Cosmic-ray in perturbed B-field

Small-scale stochastic perturbations

$|\delta\mathbf{B}| \ll |\mathbf{B}_0|$ and $\delta\mathbf{B} \perp \mathbf{B}_0$

$$\frac{\mathrm{d}\mathbf{p}}{dt} = q\frac{\mathbf{v}}{c} \times (\mathbf{B} + \delta\mathbf{B})$$

Changes x and y component of the momentum

Changes only the direction of p_z

$$\mu = p_z/p$$

Cosmic-ray in perturbed B-field

Small-scale stochastic perturbations

$$|\delta \mathbf{B}| \ll |\mathbf{B}_0| \text{ and } \delta \mathbf{B} \perp \mathbf{B}_0$$

$$\left\langle \frac{\mathrm{d}\mu}{\mathrm{d}t} \right\rangle_\psi = 0$$

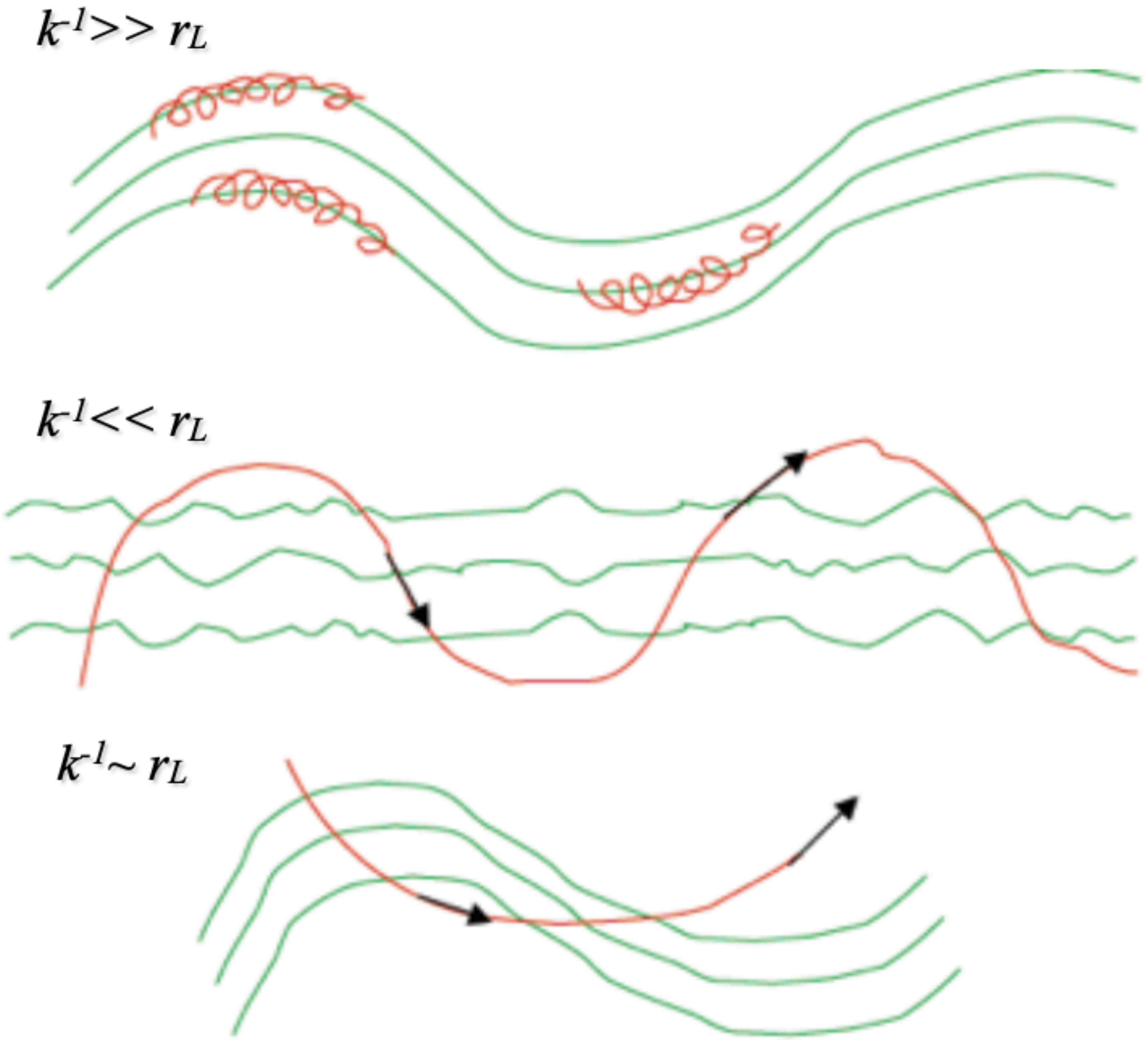
Diffusive process

$$\frac{\mathrm{d}\left\langle \Delta\mu^2 \right\rangle}{\mathrm{d}t} \underset{\Delta t \gg \Omega^{-1}}{\rightarrow} \pi C^2 \delta(w) = \pi\,(1-\mu^2)\Omega \frac{|\delta \mathbf{B}|^2}{B_0^2} k_{\mathrm{res}} \delta\left(k - k_{\mathrm{res}}\right)\,, \qquad k_{\mathrm{res}} \equiv \frac{\Omega}{v\mu}$$

Cosmic-ray in perturbed B-field

Small-scale stochastic perturbations

$$|\delta \mathbf{B}| \ll |\mathbf{B}_0| \text{ and } \delta \mathbf{B} \perp \mathbf{B}_0$$



Credit: P.D.Serpico

Collisionless Diffusion
[i.e. scattering on inhomogeneities of the magnetic field]

Diffusion coefficient
Describes the random change of the pitch angle

CR propagation in phase space

Phase-space density of CR

$$f_\alpha = \frac{\mathrm{d}N_\alpha}{\mathrm{d}\Pi}$$

$$f = f(t, \mathbf{x}, \mathbf{p}),$$
$$\mathrm{d}\Pi \equiv \mathrm{d}^3\mathbf{x}\mathrm{d}^3\mathbf{p}$$

$$\left[\frac{\partial}{\partial t} + \dot{\mathbf{x}} \cdot \nabla_{\mathbf{x}} + \dot{\mathbf{p}} \cdot \nabla_{\mathbf{p}}\right] f = 0$$

Similar to Liouville equation

Describes the **collisionless** aspects of CR acceleration and transport

CR propagation in phase space

Phase-space density of CR $\quad f_\alpha = \frac{\mathrm{d}N_\alpha}{\mathrm{d}\Pi}$

$$f = f(t, \mathbf{x}, \mathbf{p}),$$
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Similar to Liouville equation
Describes the **collisionless** aspects of CR acceleration and transport

Collisional aspects account for particle generation/absorption, secondary particle production, etc

CR propagation in phase space

Phase-space density of CR

$$f_\alpha = \frac{\mathrm{d}N_\alpha}{\mathrm{d}\Pi}$$

$$f = f(t, \mathbf{x}, \mathbf{p}),$$
$$\mathrm{d}\Pi \equiv \mathrm{d}^3\mathbf{x}\mathrm{d}^3\mathbf{p}$$

$$\mathrm{d}^3\mathbf{p} = p^2\mathrm{d}p\mathrm{d}\Omega$$

$$\phi(t, \mathbf{x}, p) \equiv \frac{1}{4\pi}\int \mathrm{d}\Omega f(t, \mathbf{x}, \mathbf{p})$$

$$\mathbf{\Phi}(t, \mathbf{x}, p) \equiv \frac{1}{4\pi}\int \mathrm{d}\Omega\, \hat{\mathbf{p}}\, f(t, \mathbf{x}, \mathbf{p})$$

$$\mathrm{d}^3\mathbf{x} = \beta \mathrm{d}t\mathrm{d}A_\perp$$

$$F(t, \mathbf{x}, E, \Omega) = \frac{\mathrm{d}N}{\mathrm{d}t\mathrm{d}A_\perp\mathrm{d}E\mathrm{d}\Omega} = \frac{f\mathrm{d}^3\mathbf{x}\mathrm{d}^3\mathbf{p}}{\mathrm{d}t\mathrm{d}A_\perp\mathrm{d}E\mathrm{d}\Omega} = \beta p^2\frac{\mathrm{d}p}{\mathrm{d}E}f = p^2 f$$

$$n(t, \mathbf{x}, E) = \frac{1}{\beta}\int \mathrm{d}\Omega F = \frac{4\pi p^2}{\beta}\phi$$

Spectral intensity and density

CR diffusion in phase space

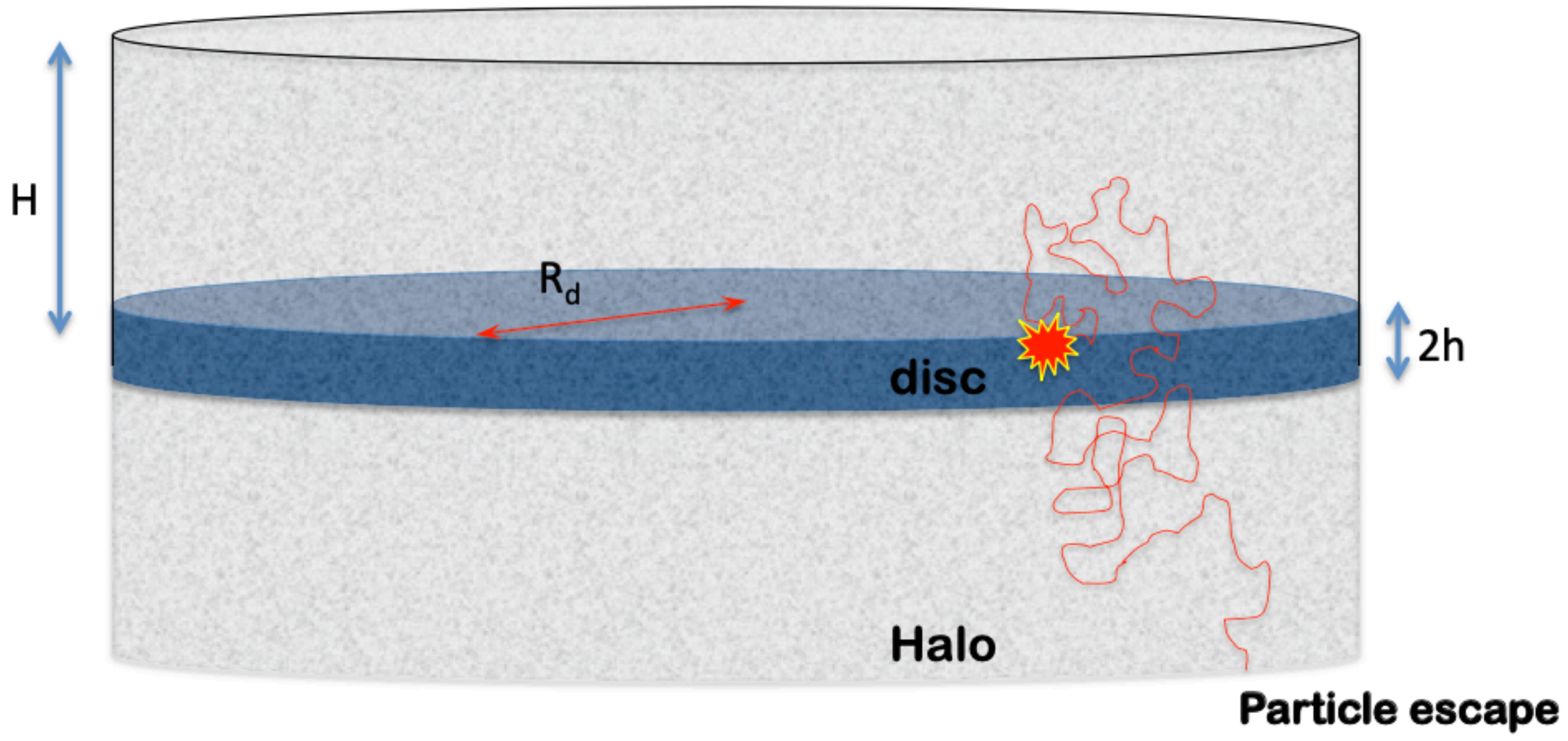
$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_{\mathbf{x}} f + q \frac{(\mathbf{p} \times \mathbf{B})}{E} \cdot \nabla_{\mathbf{p}} f = 0$$

$$\frac{\partial \langle \phi \rangle}{\partial t} = \frac{\partial}{\partial x_i} \left(K_{ij} \frac{\partial}{\partial x_j} \langle \phi \rangle \right)$$

K_{ij} spatial diffusion tensor

Adding a source term Q (1D)

$$\frac{\partial \varphi}{\partial t} - \frac{\partial}{\partial z} \left(K \frac{\partial \varphi}{\partial z} \right) = Q$$



E.g. “Leaky box” model for Galactic propagation

$$Q = 2 q_0(p) h \delta(z)$$

CR transport equation in 1D

$$\frac{\partial \varphi}{\partial t} - \frac{\partial}{\partial z}\left(K \frac{\partial \varphi}{\partial z}\right) + u \frac{\partial \varphi}{\partial z} - \frac{1}{3}\frac{\mathrm{d}u}{\mathrm{d}z} p \frac{\partial \varphi}{\partial p} = Q$$

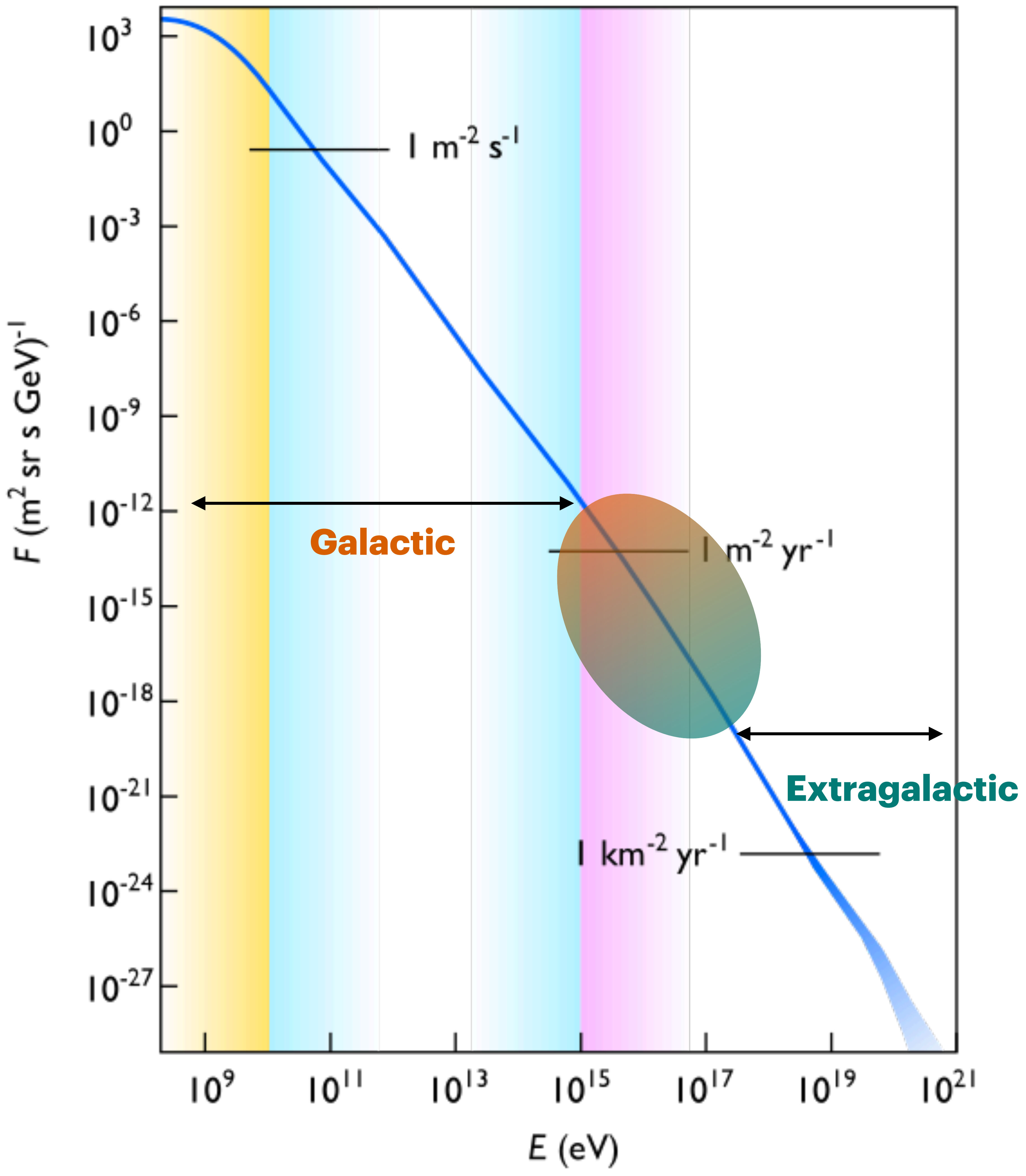
Diffusion: The diffusion coefficient is typically energy (rigidity) dependent

Convection/Advection: Spatial transport due to large scale movements like Galactic winds. Typically relevant at GeV energies for wind speeds ~10 km/s

Adiabatic energy losses/gains: Particularly crucial for particles acceleration

Re-acceleration (not shown): Due to the residual velocity distribution of the waves even in the plasma frame, generating a diffusion term in momentum space => Relevant only below a few GeV

Cosmic-ray sources: Galactic or extragal?



In the Galaxy we **observe** CR factories up to
1 TeV = 10^{12} eV (HESS, VERITAS, MAGIC)
1 PeV = 10^{15} eV(LHAASO)

SNR, pulsars & neutron stars, binary, stellar clusters, PWN

AGN & jets, galaxy clusters, galaxies

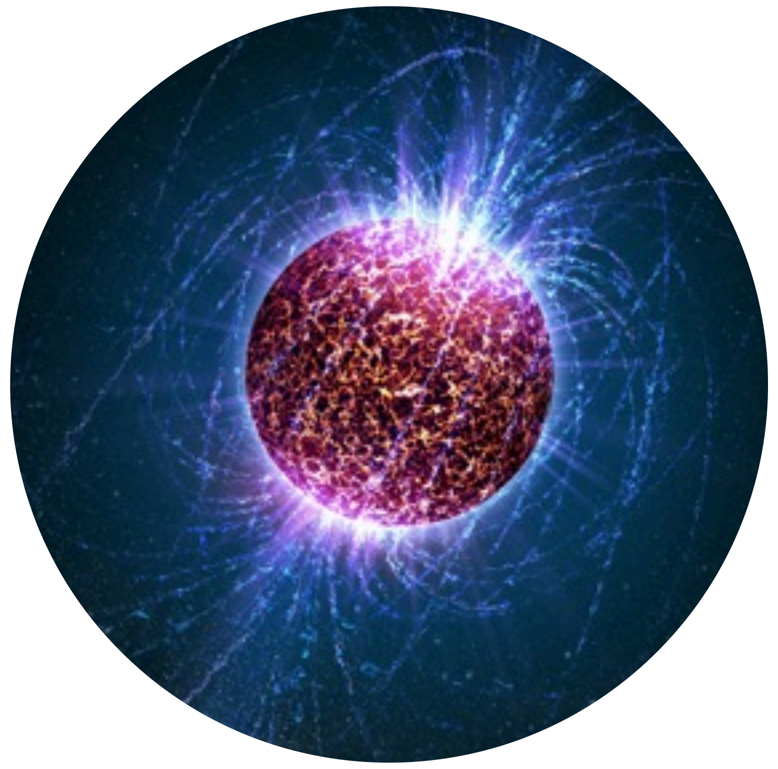
Open questions:

1. What is the maximal energy CR are accelerated?
2. Where does the Gal-extragal transition occur?

How to accelerate CRs?

Some **requirements**:

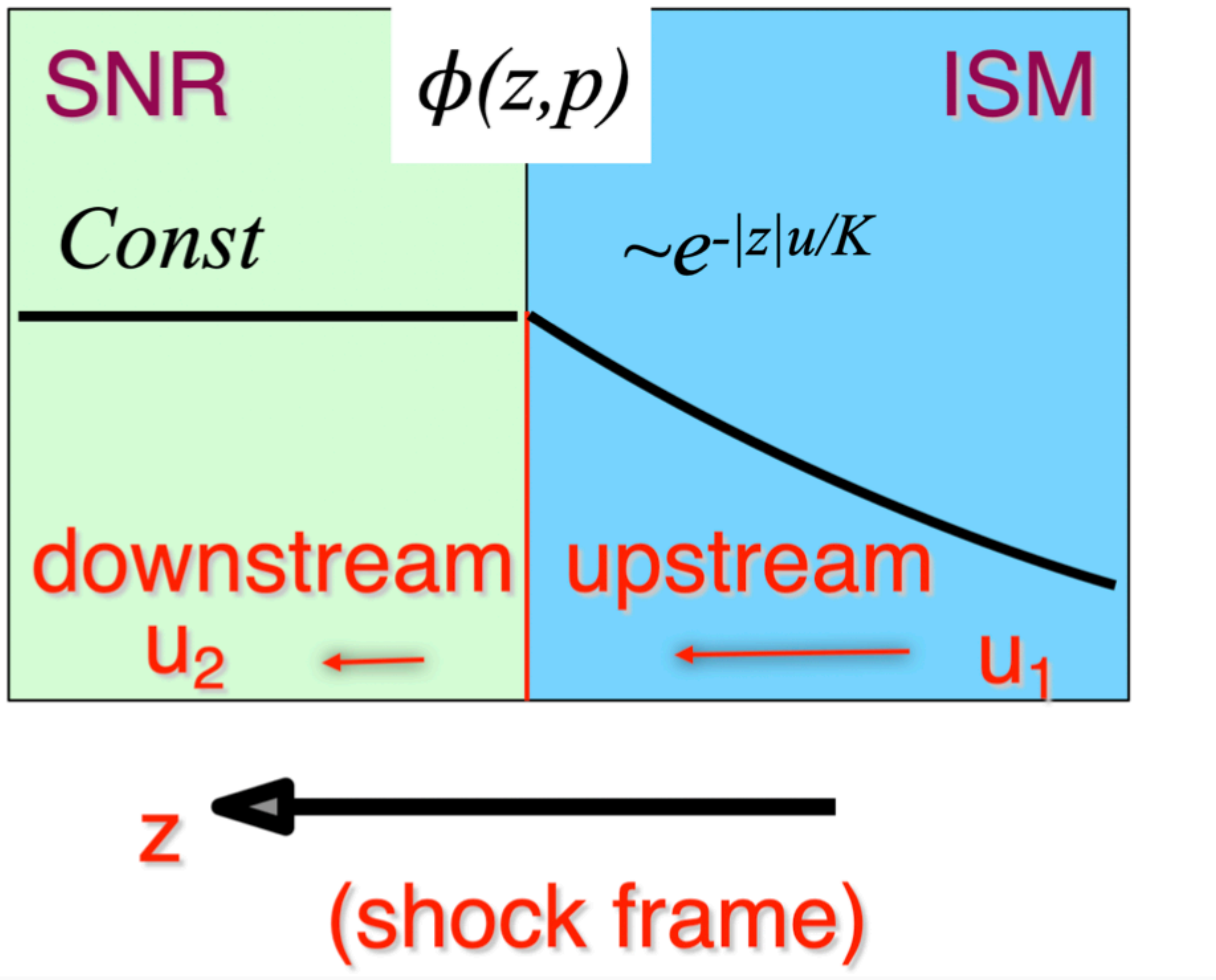
1. Energetics:
   - Kinetic Energy (translational in SNRs, rotational in pulsars)
   - Gravitational Energy (accretion disks)
   - Magnetic (solar flares)
2. Mechanism for Energy Transfer: how to transfer energy from macroscopic objects into the (microscopic) acceleration of particles? (electromagnetic)
3. Confinement: particles must stay in the accelerator for the time needed to accelerate them
4. No significant E-losses



We need electric fields to accelerate particles!
They are generated by moving magnetic fields in the plasma
e.g. fast rotating B-field in pulsars, shock waves

Shock acceleration: 1st order Fermi

A **shock wave** is a propagating disturbance in a medium that moves faster than the local speed of sound in the medium, i.e. a mathematical discontinuity



Shock front at z = 0

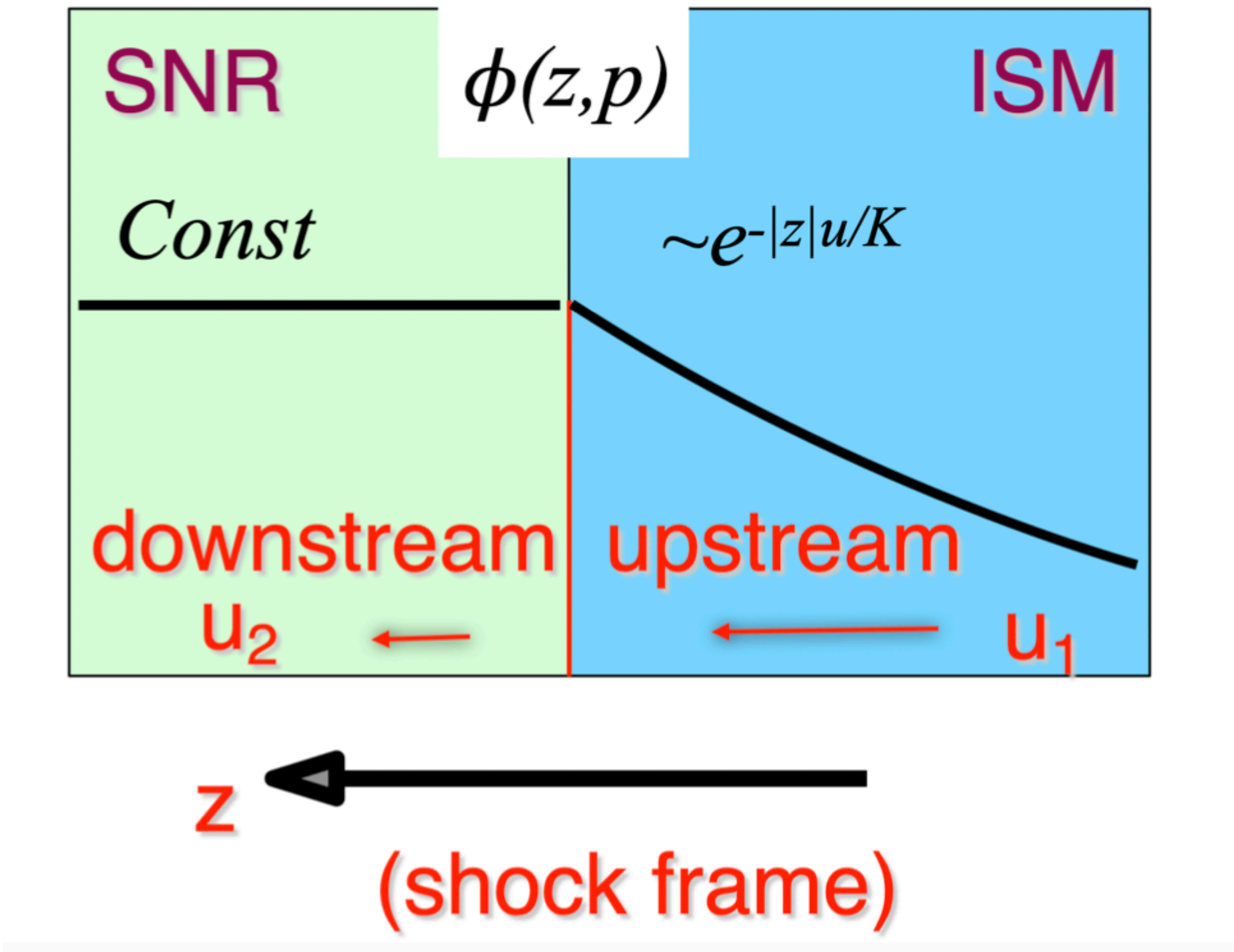
Particles injected only at the shock

Far from the discontinuity, steady state condition in each side of the shock

$$u\frac{\partial \varphi}{\partial z} = \frac{\partial}{\partial z}\left(K\frac{\partial \varphi}{\partial z}\right)$$

Shock acceleration: 1st order Fermi

A **shock wave** is a propagating disturbance in a medium that moves faster than the local speed of sound in the medium, i.e. a mathematical discontinuity



Shock front at z = 0

Particles injected only at the shock

Far from the discontinuity, steady state condition in each side of the shock

Upstream: Vanishing profile

Downstream: Constant

$$\phi_0(p) \simeq p^{-4}$$

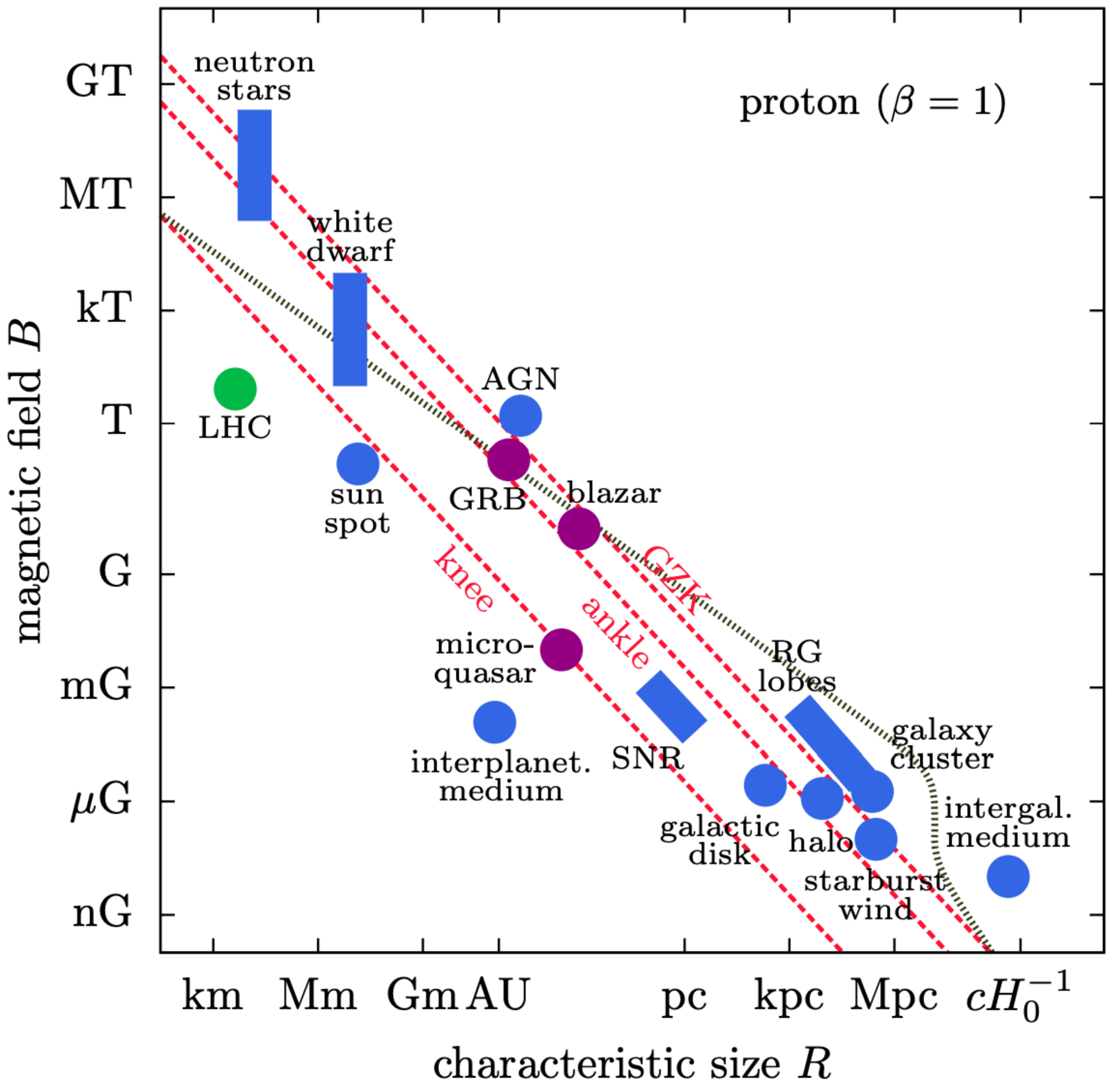
Fermi spectrum (in-situ)

Confinement condition

The system must be able to contain the particle

$$r_L \lesssim R$$

Aartsen+ Advances Space Research '17



Hillas Plot

Upper limits on the reachable CR energy dependent on the size of the acceleration region and magnetic field strength

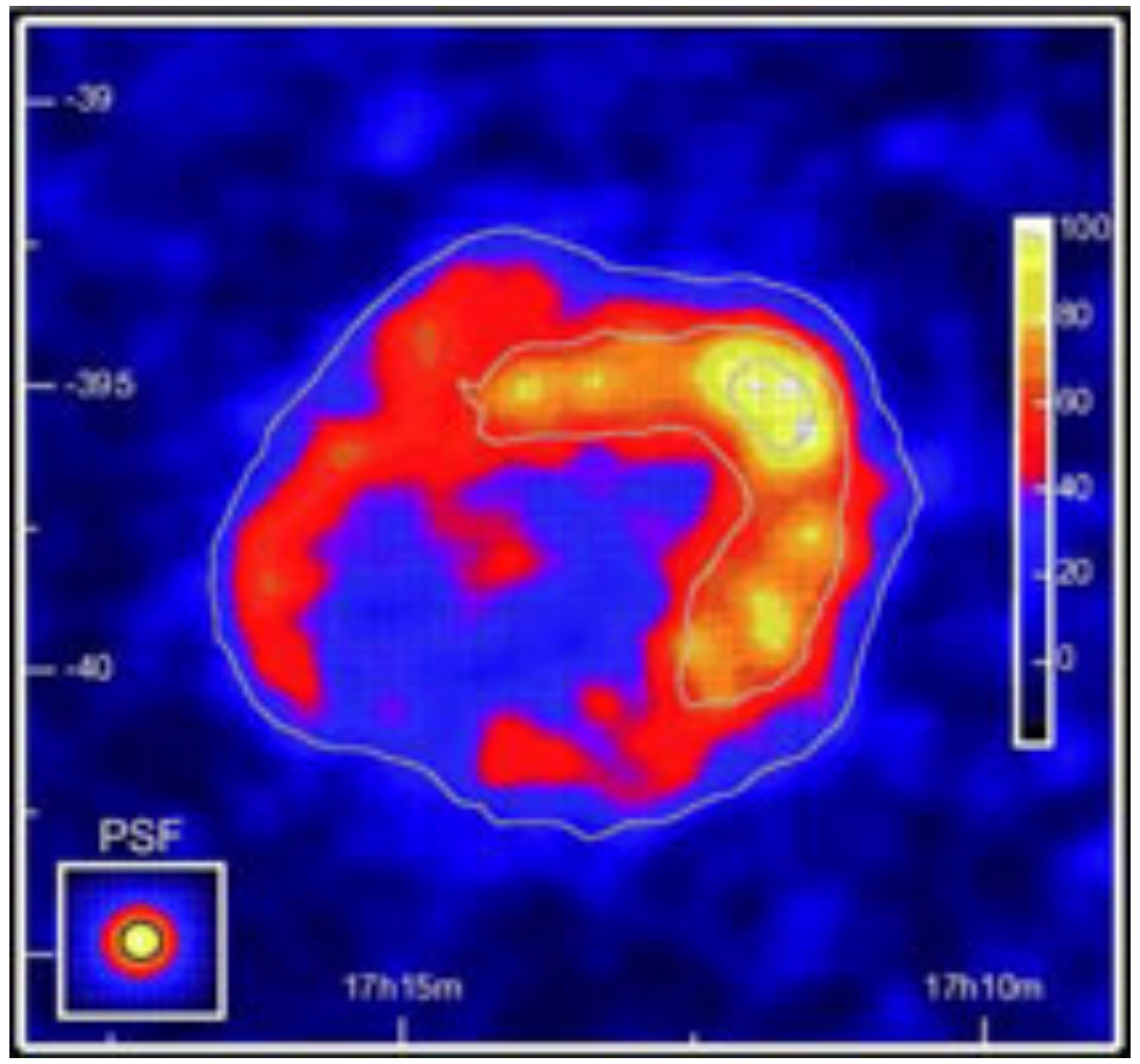
$$E_{\max} \lesssim RB_0$$

$$r_L = \gamma r_g = \sqrt{1-\mu^2}\frac{\mathcal{R}}{B_0} \simeq 10^{-6}\sqrt{1-\mu^2}\frac{\mathcal{R}}{\mathrm{GV}}\frac{\mu\mathrm{G}}{B_0}\mathrm{pc}$$

CR accelerators: Supernova remnants

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

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

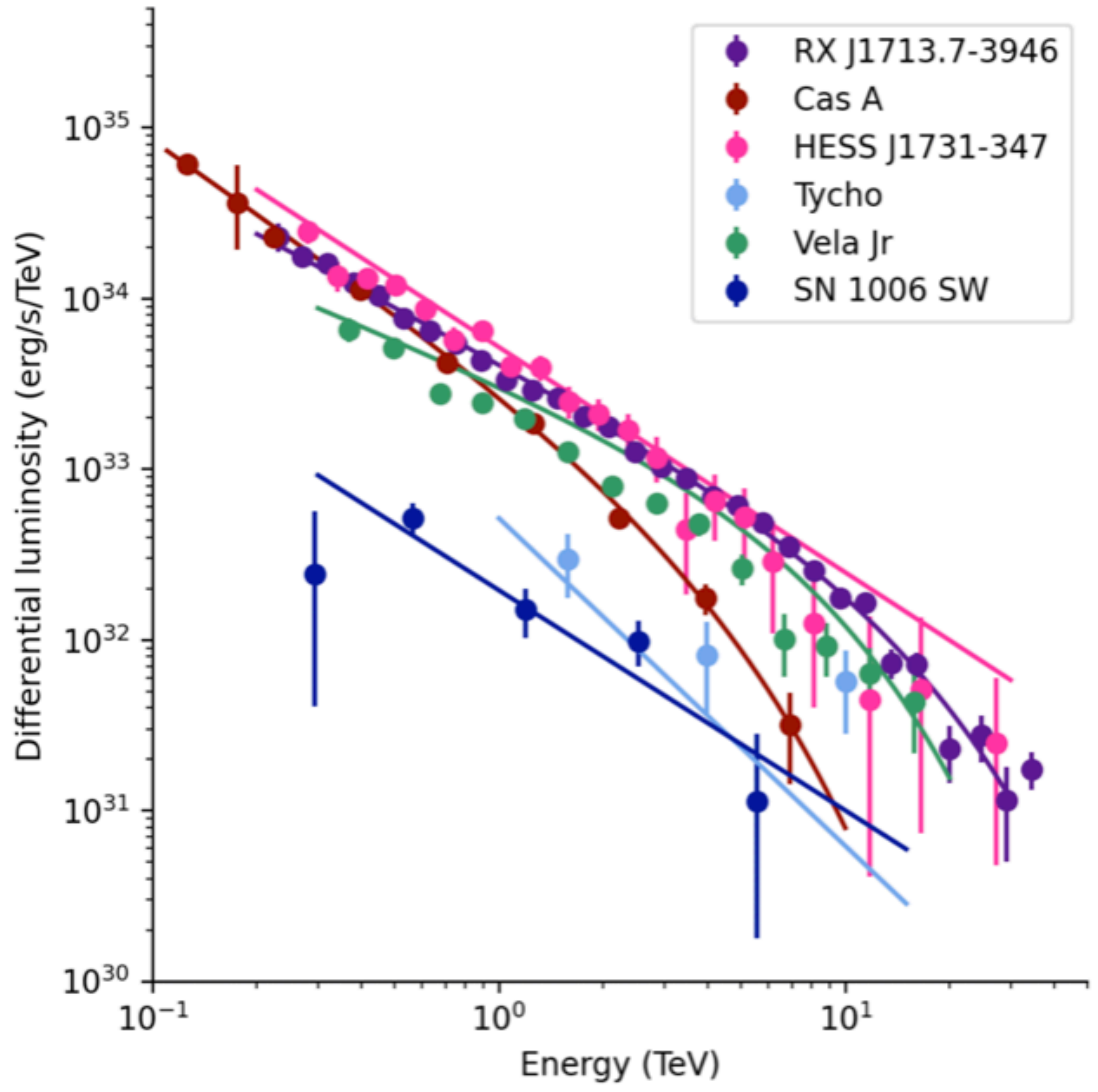


Aharonian+ A&A'07

We see pion bump at GeV energies (proton acceleration)

We see TeV shells (e.g. HESS)

We do not see PeV accelerated particles from SNR



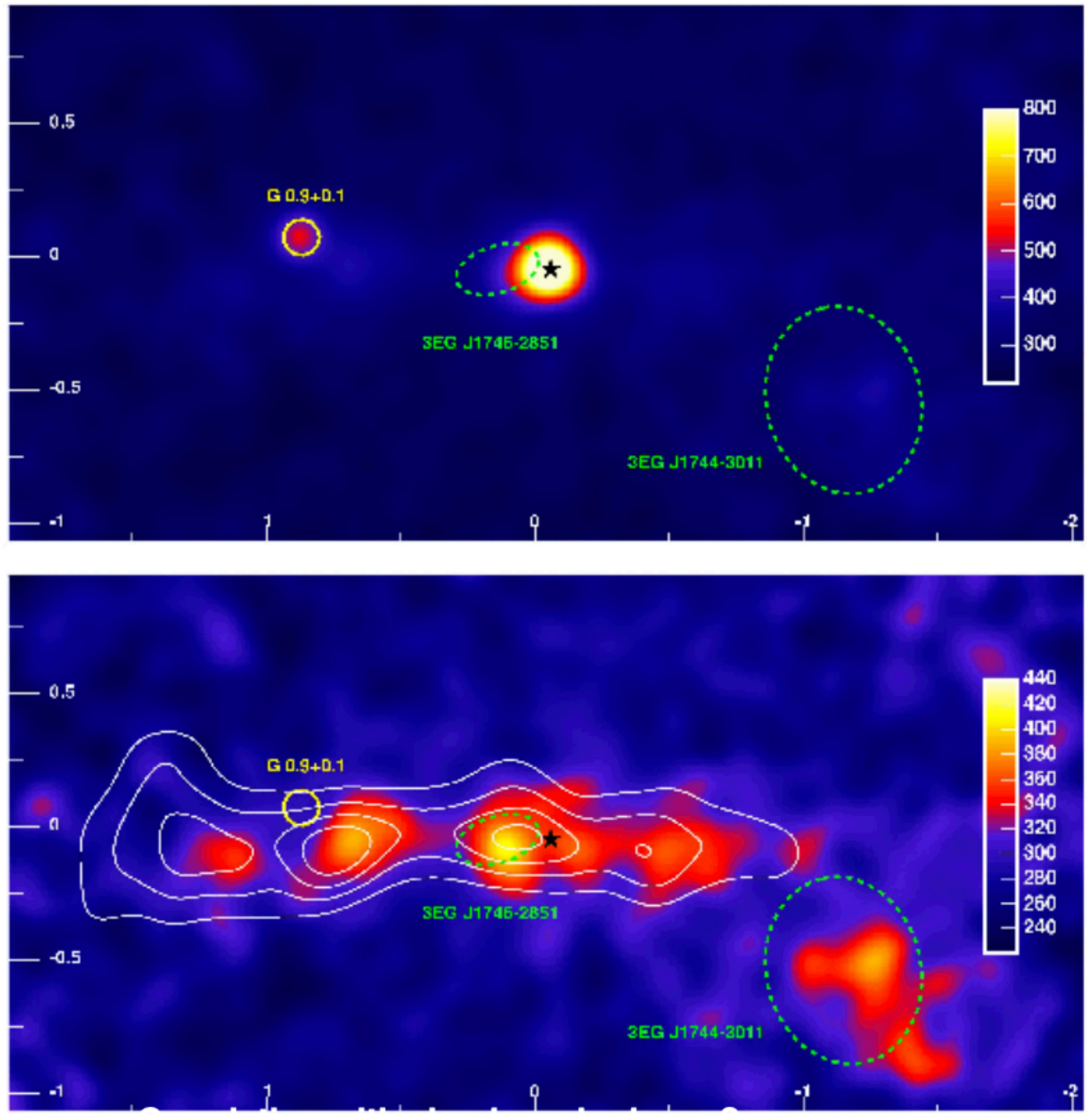
[Others: stellar clusters, no indication of a TeV cutoff so far]

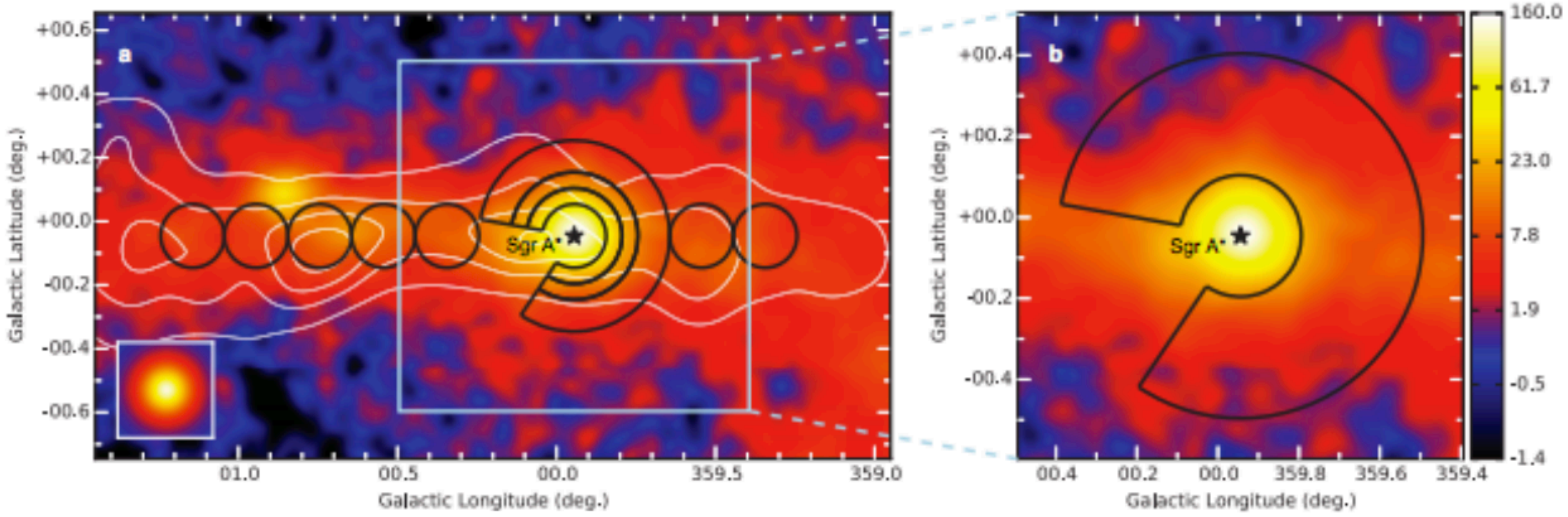
CR accelerators: Supernova remnants

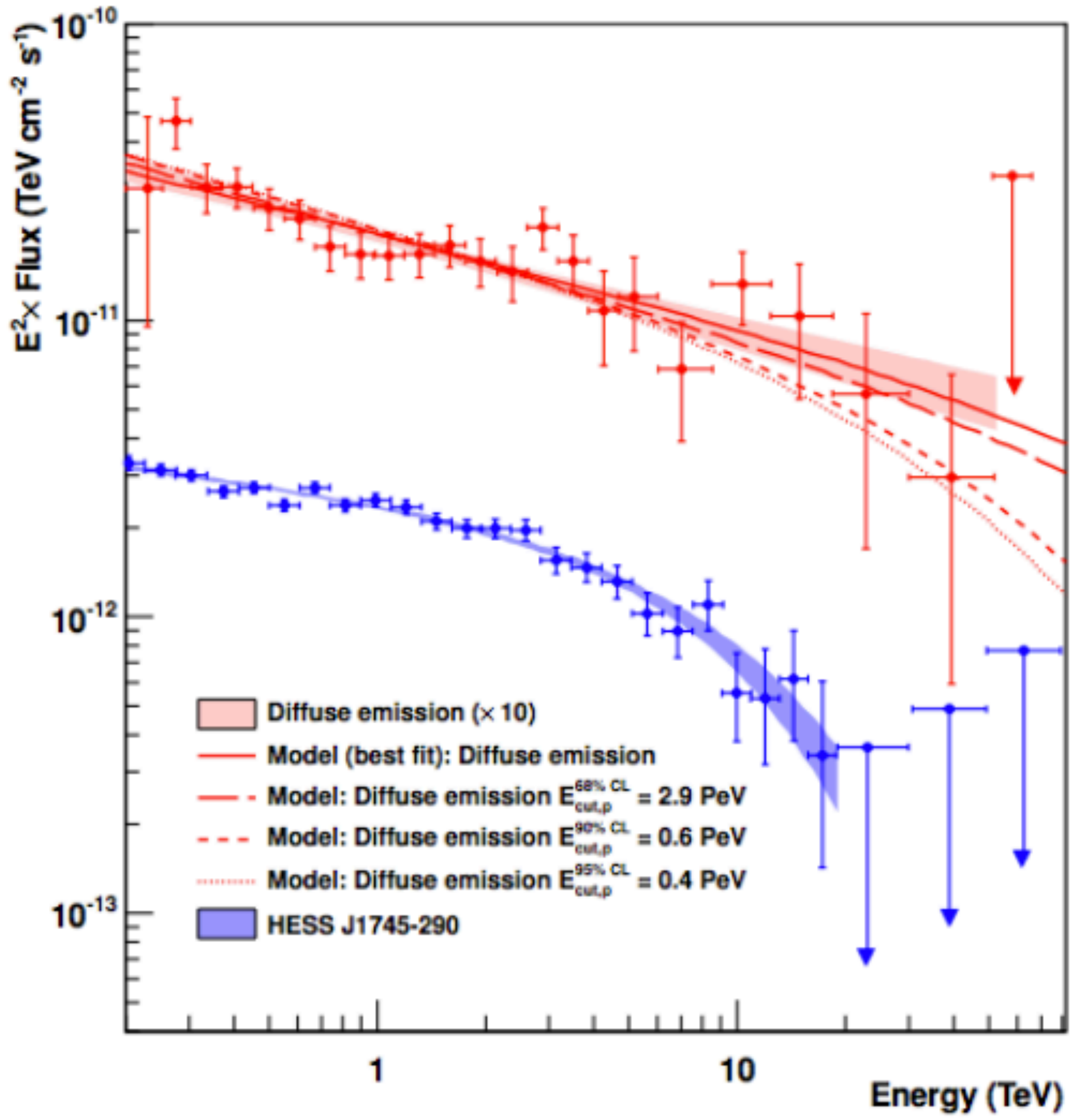
- **Energetics** - Outburst-like event /slow outflows

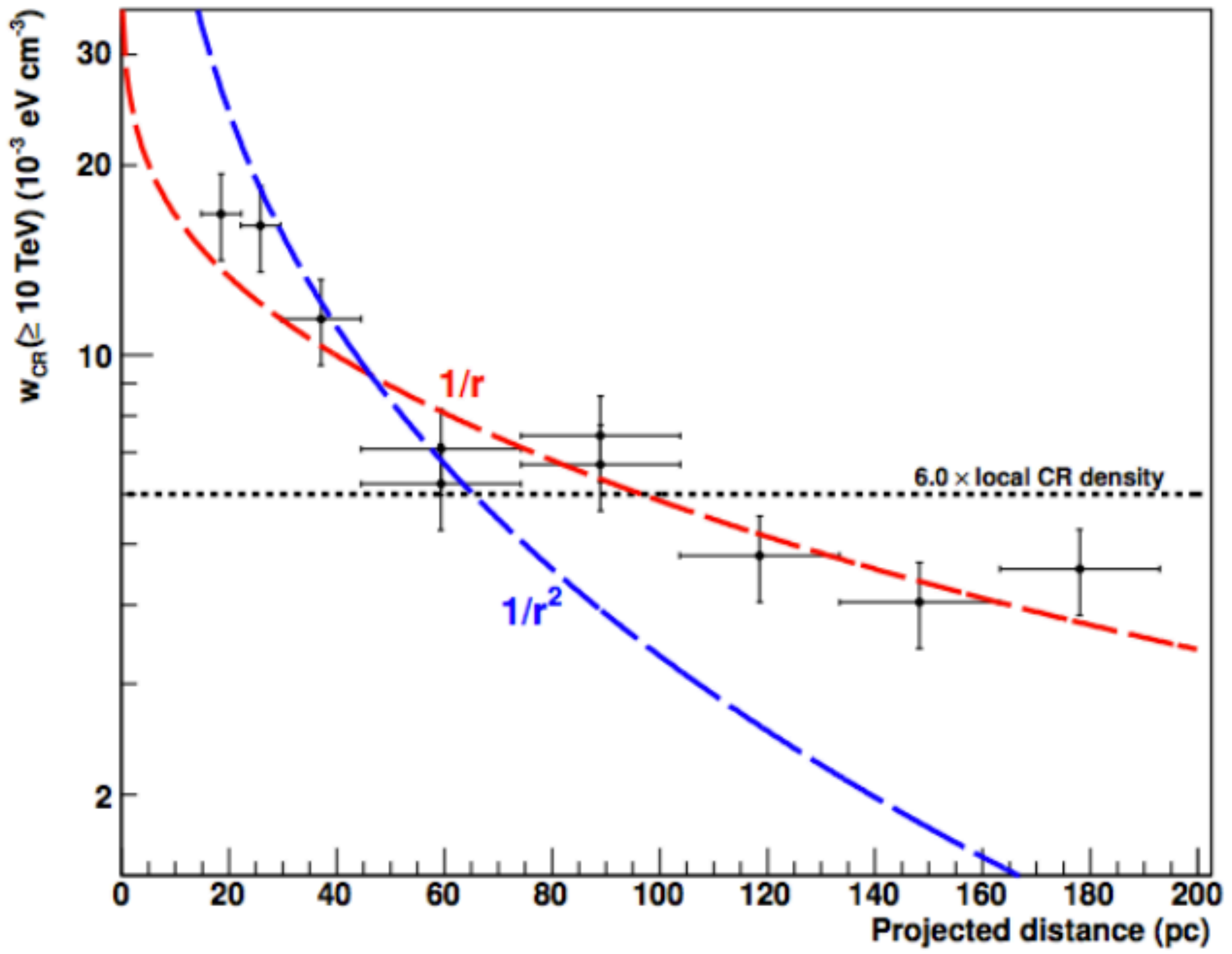
  $E_{kin} = 3 \times 10^{54}$ erg
  $L_{IR} \sim 1.6 \times 10^{42}$ erg/s

- Is there any indication of such behaviour?









CR collisional effects

A collision is associated to a **catastrophic loss**

$$\ell = \frac{1}{\sigma\, n}, \quad \Gamma = \sigma\, \beta\, n = \frac{\beta}{\ell}$$

Mean-free path
Avg distance travelled in the medium of density *n* before interacting

Cross-section of the interaction process

Collision rate

Particle **velocity**

Optical depth $\tau = \frac{R}{\ell}$

CR collisional effects

If losses are **continuous**

$$\tau_{\rm loss} \equiv \frac{E}{-{\rm d}E/{\rm d}t}$$

Loss timescale
Avg distance travelled in the medium of density *n* before interacting

Loss rate per unit time

G. Ghisellini, *Radiative processes in high-energy astrophysics*, Lect. Notes Phys. (2013)

Synchrotron radiation

A rotating charge is accelerated => An accelerate charge radiates

$$P_s = \frac{2q^4\gamma^2}{3\,m^2} v^2 B^2 \sin^2\theta$$

Relativistic acceleration

Synchrotron power

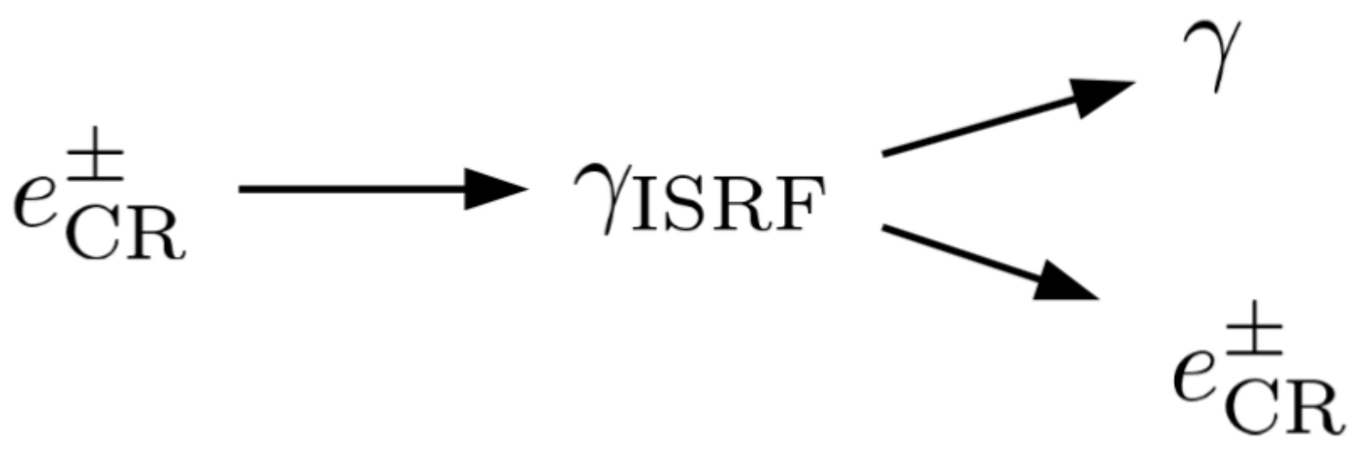
$$E_s \simeq 500\,\mu\text{eV}\,\frac{B}{\mu G}\left(\frac{E_e}{\text{GeV}}\right)^2$$

Energy of radiation for a electron CR

$$\epsilon(\nu)\mathrm{d}\nu = \frac{1}{4\pi} P_s n(E)\mathrm{d}E \propto E^2 B^2 E^{-\alpha}\mathrm{d}E \propto \nu^{\frac{1-\alpha}{2}} B^{\frac{1+\alpha}{2}}\mathrm{d}\nu\,.$$

Spectrum of an electron population

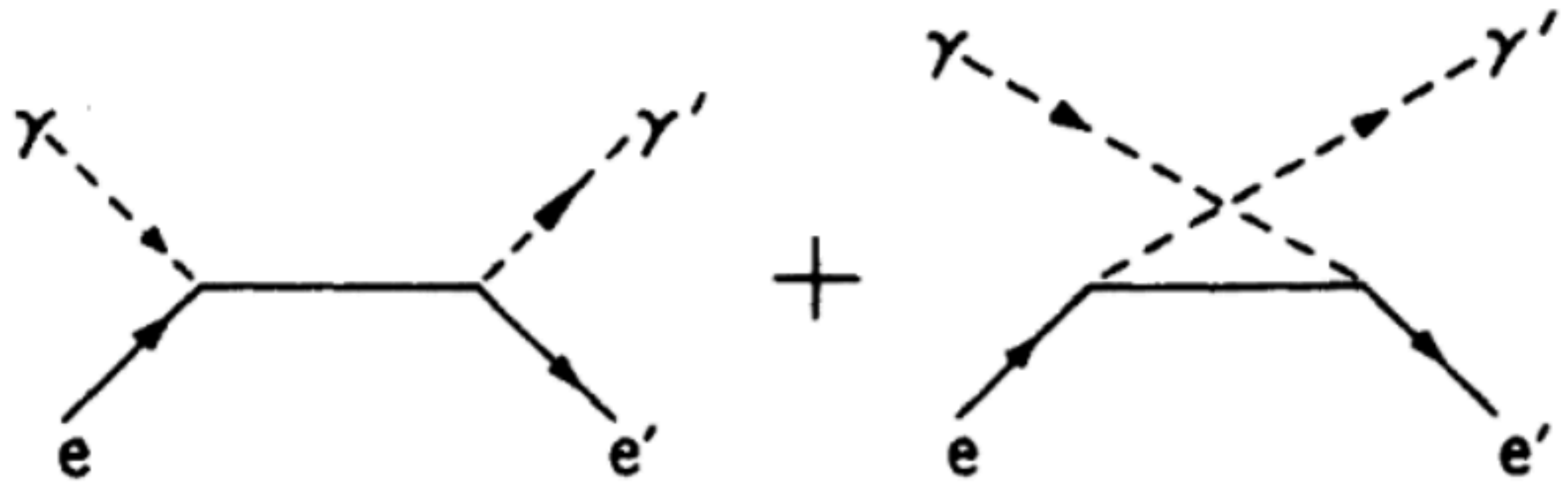
Inverse Compton emission



$$-\frac{\mathrm{d}E}{\mathrm{d}t} = \sigma_T\, u \left[\gamma^2 \left(1 + \frac{\beta^2}{3}\right) - 1\right] = \frac{4}{3}\gamma^2\beta^2\, u\sigma_T \simeq \frac{4}{3}\gamma^2\, u\sigma_T$$

Thomson regime

$\epsilon_i/m_e \ll 1$

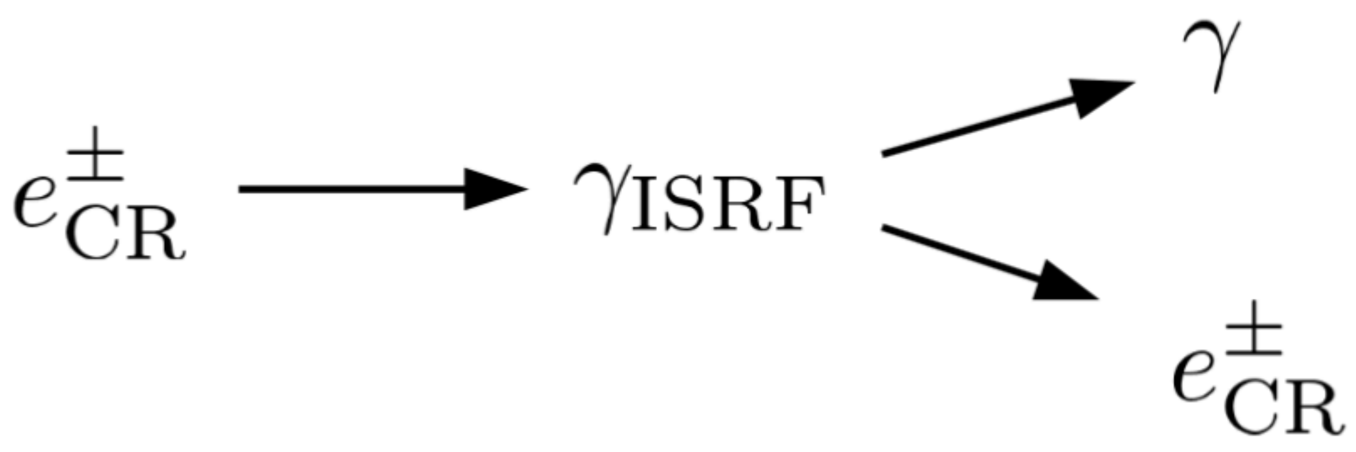


Klein-Nishina process: tree-level electron photon scattering in QED

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3}{16\pi}\sigma_T \left(\frac{\epsilon_f}{\epsilon_i}\right)^2 \left(\frac{\epsilon_i}{\epsilon_f} + \frac{\epsilon_f}{\epsilon_i} - \sin^2\theta\right)$$

$$\sigma = 2\pi \int_0^\pi \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \sin\theta d\theta = \frac{3}{4}\sigma_T \left[\frac{1+x}{x^3}\left(\frac{2x(1+x)}{1+2x} - \ln(1+2x)\right) + \frac{1}{2x}\ln(1+2x) - \frac{1+3x}{(1+2x)^2}\right]$$

Inverse Compton emission



$$-\frac{\mathrm{d}E}{\mathrm{d}t} = \sigma_T\, u \left[\gamma^2\left(1+\frac{\beta^2}{3}\right)-1\right] = \frac{4}{3}\gamma^2\beta^2\, u\sigma_T \simeq \frac{4}{3}\gamma^2\, u\sigma_T$$

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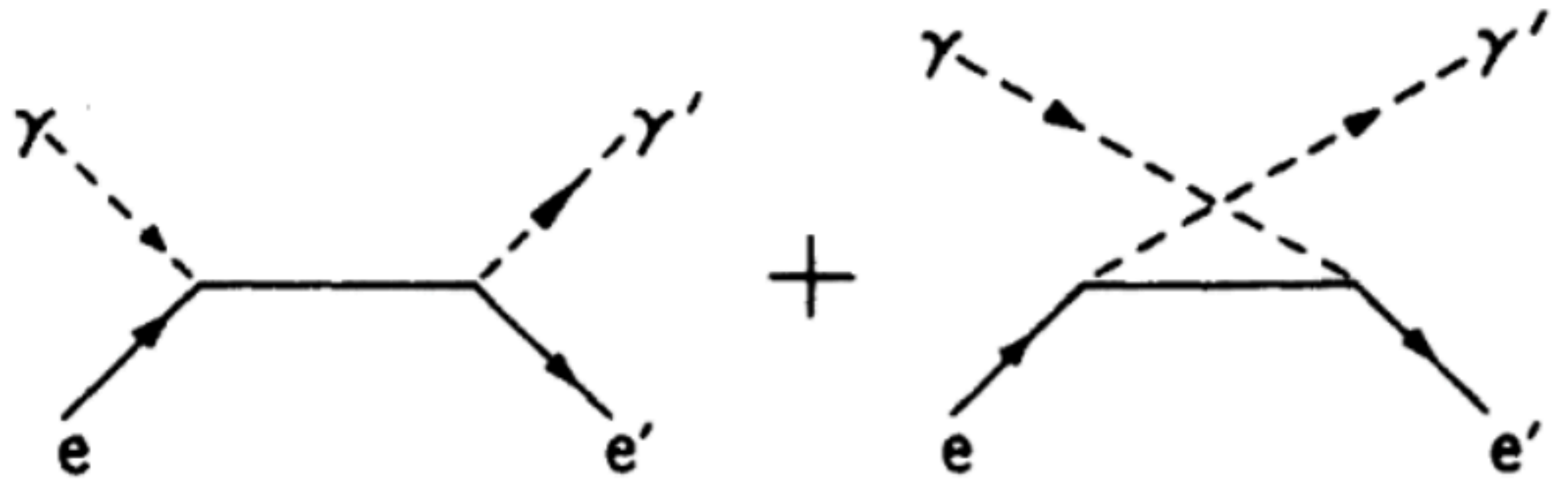
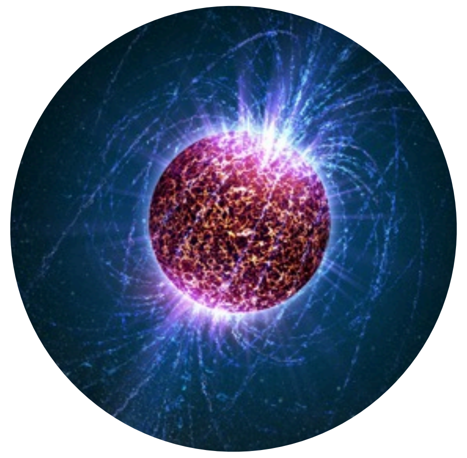


Klein-Nishina process: tree-level electron photon scattering in QED

$$\epsilon_f \simeq \gamma^2\epsilon_i = 30\left(\frac{\epsilon_i}{\mathrm{eV}}\right)\left(\frac{E_e}{\mathrm{GeV}}\right)^2\ \mathrm{MeV}$$

$$\epsilon_i E_e \ll m_e^2$$

Leptonic accelerators: Pulsars



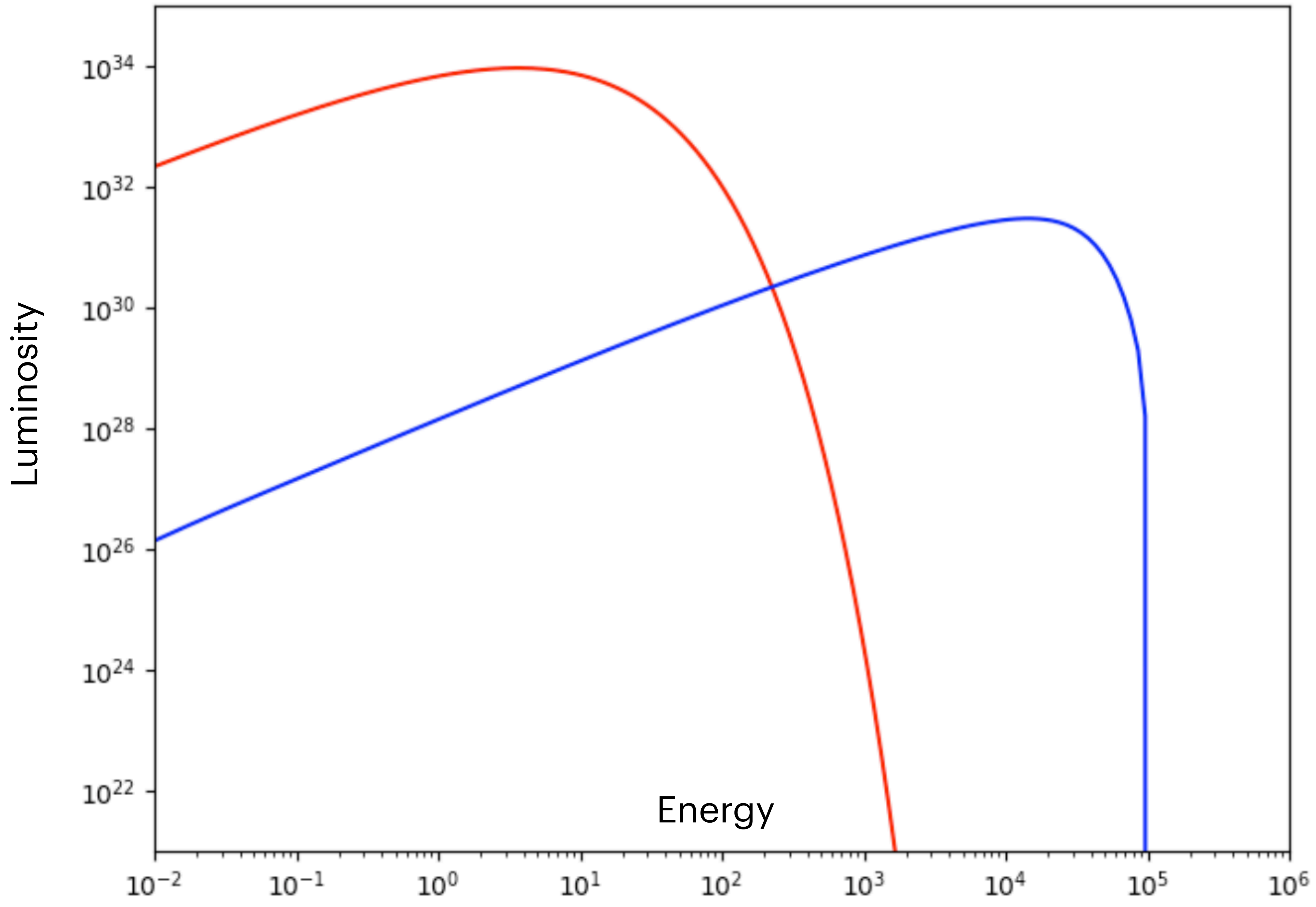
GeV — TeV emitters

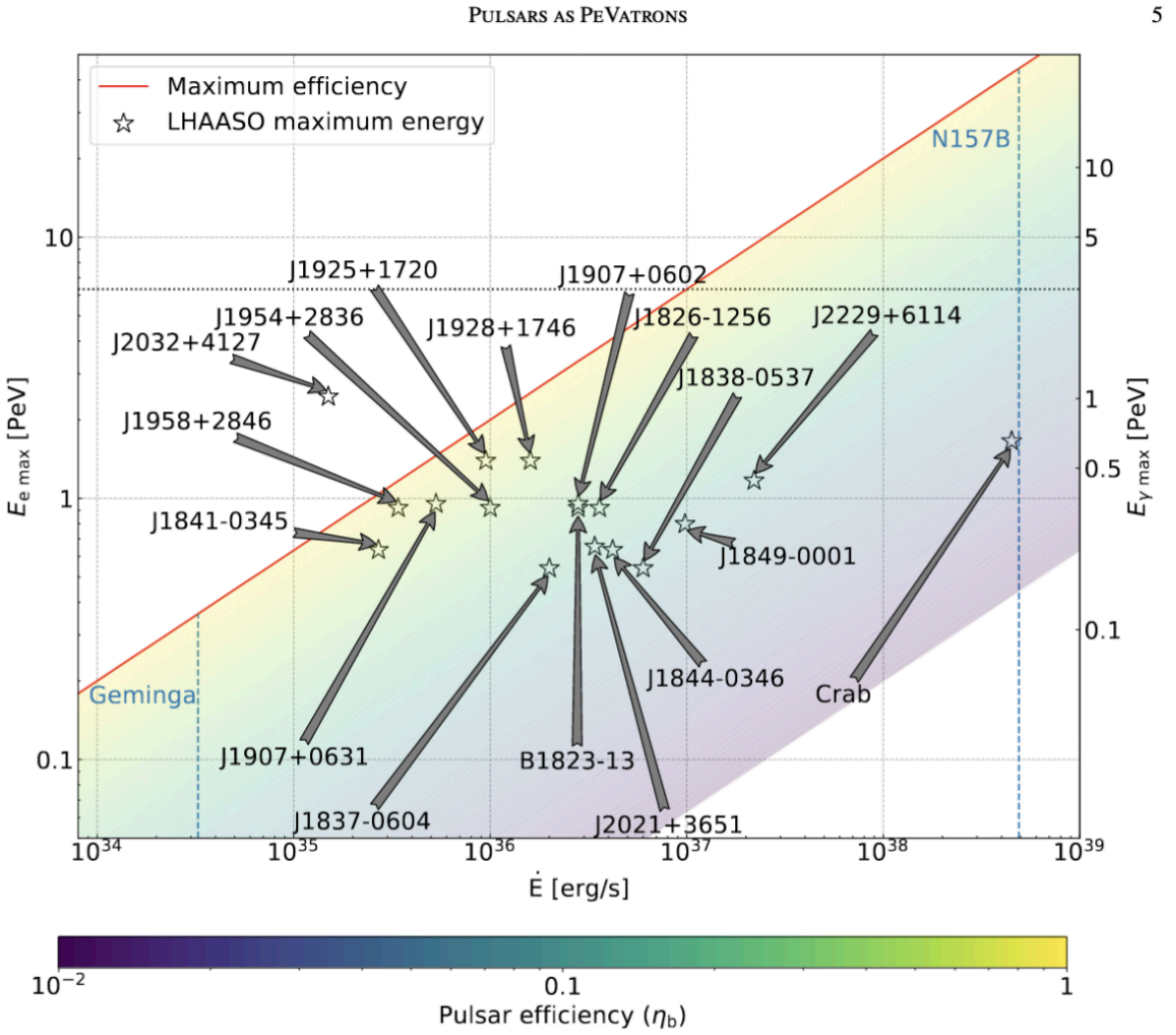
HE: curvature radiation from acceleration in magnetosphere

VHE: IC on low-energy target photons

LHAASO Observed ~10 PeVatrons

9 have a bright pulsars associated





[Others: compact objects in binary systems (high-energy binaries, novae, micro quasars)]

The diffusion-loss equation (full 3D)

$$\frac{\partial \phi_\alpha}{\partial t} - \frac{\partial}{\partial x_i} K_{ij} \frac{\partial \phi_\alpha}{\partial x_j} + u_i \frac{\partial \phi_\alpha}{\partial x_i} - \frac{1}{3}\frac{\partial u_i}{\partial x_i}\left(p \frac{\partial \phi_\alpha}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_\ell \phi_\alpha\right] - \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 K_{pp} \frac{\partial \phi_\alpha}{\partial p}\right) = q - \Gamma \phi_\alpha + \sum_\beta \phi_\beta \Gamma_{\beta \to \alpha}$$

Continuous energy losses

Catastrophic losses

Energy-loss dominated propagation
Energy-loss timescales are the shortest ones

$$-\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 \left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_\ell \phi_\alpha\right] = q \implies \phi(p) \propto -\frac{1}{p^2 (\mathrm{d}p/\mathrm{d}t)_\ell} \int^p \mathrm{d}p' q(p')\, p'^2$$

for $q \propto p^{-s}$ and $(\mathrm{d}p/\mathrm{d}t)_\ell \propto -p^\ell$

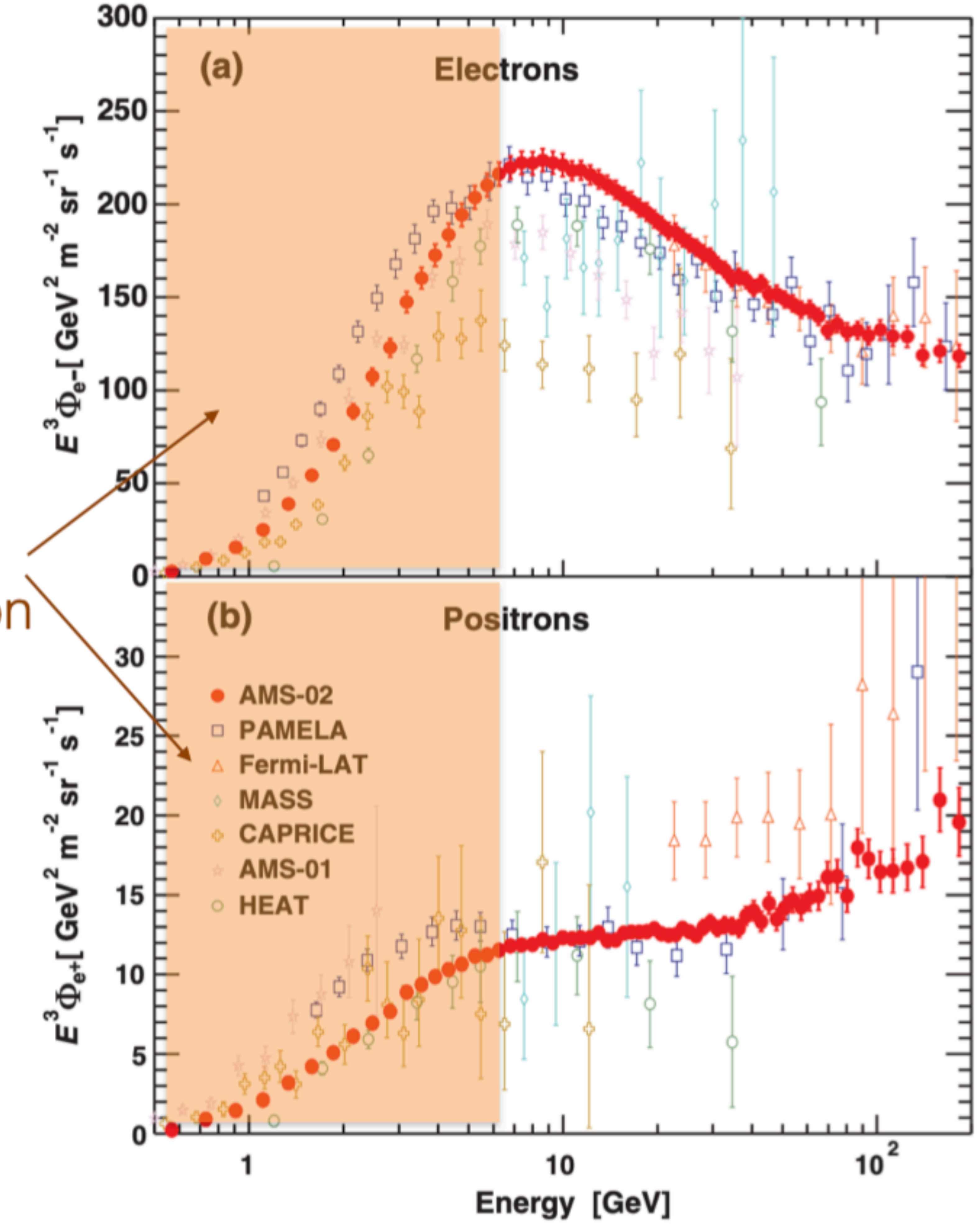
$$\phi(p) \propto p^{-s-\ell+1}$$

Charged cosmic rays

Galactic cosmic rays

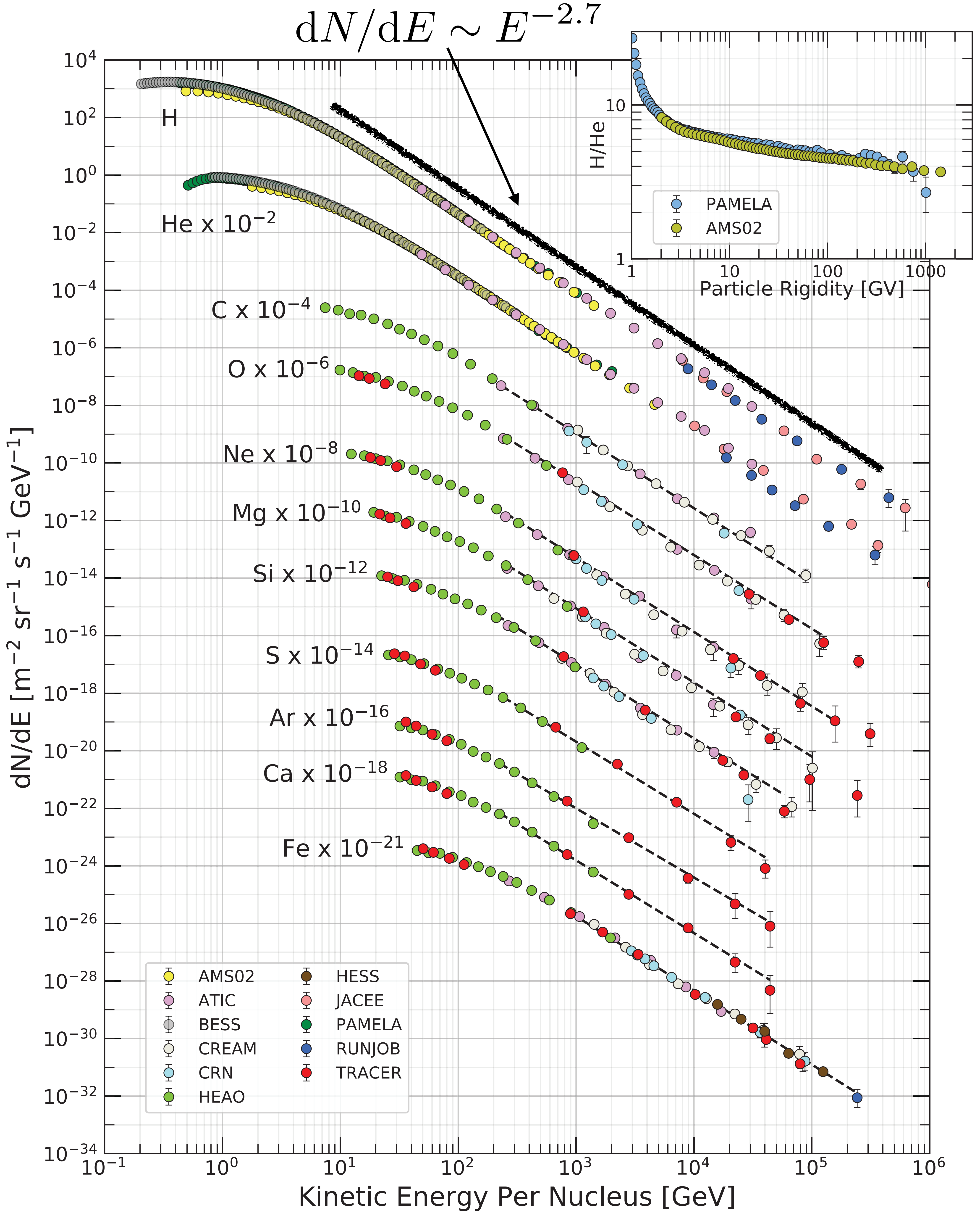
E ~ 10^8 — 10^{15} eV

Solar modulation



Credit: M. Aguilar et al. (AMS Collaboration), 2014

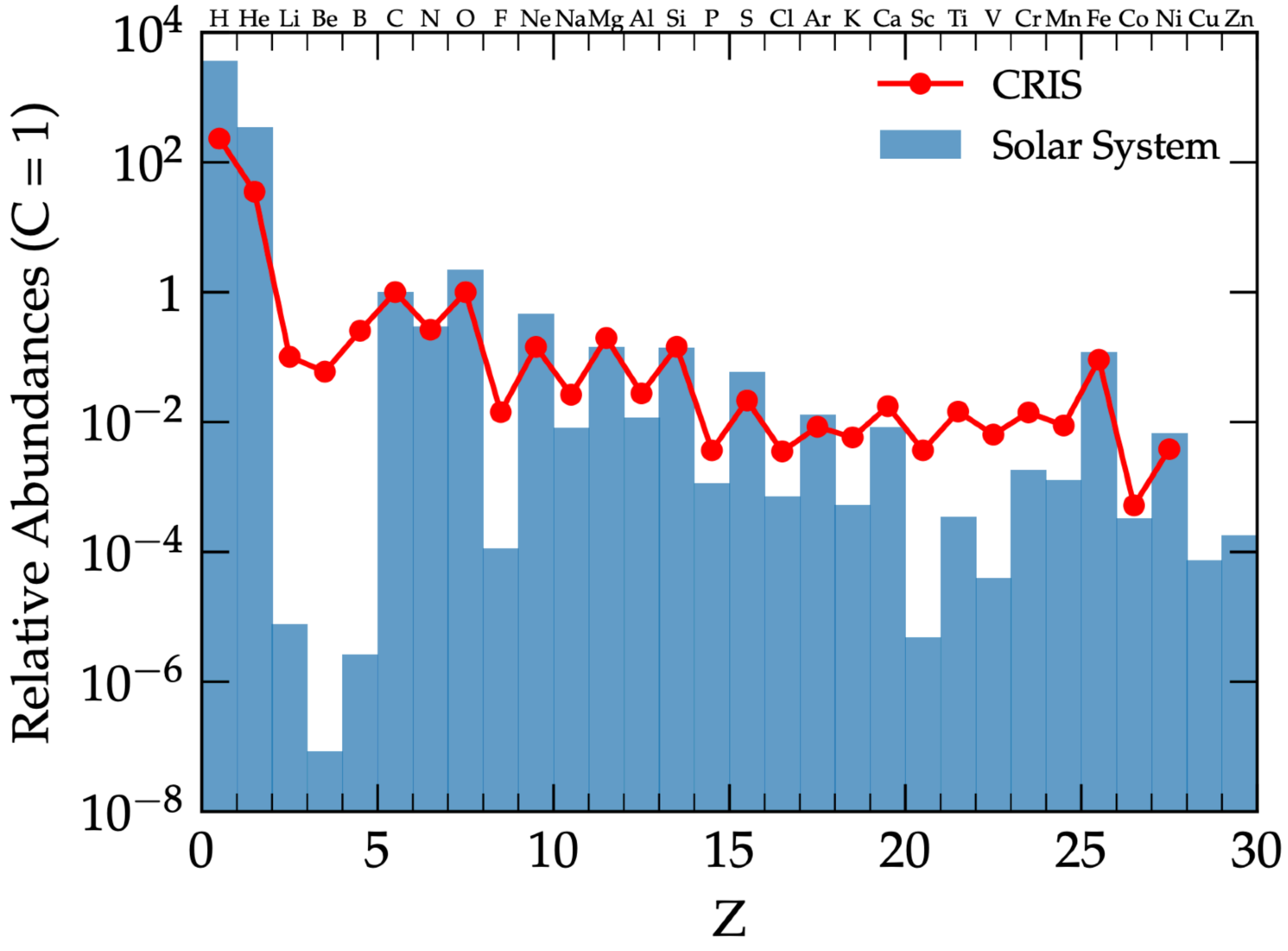
Flux, per unit area, unit time and unit energy

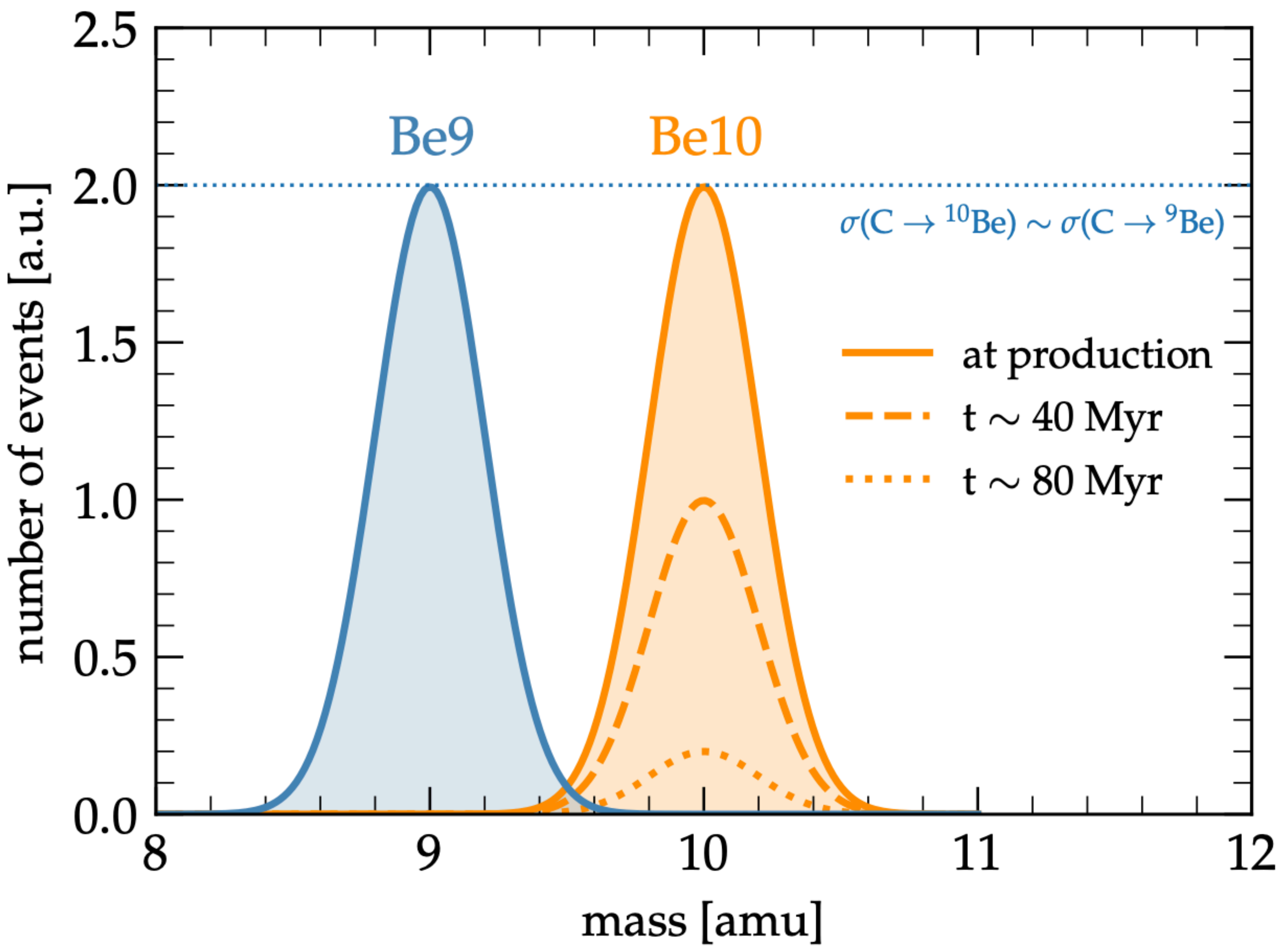


Credit: Particle Data Group (2020)

GCR: Composition

Basic indicators of diffuse transport





STABLE ELEMENTS

Besides primary species, produced in stellar nucleosynthesis, the average interstellar medium hosts a population of secondary particles produced by primary fragmentation during propagation

UNSTABLE ELEMENTS

^{10}B is beta unstable with half-life time of 1.5 Myr
Production rate similar to other stable nuclei (^{9}Be)
The ratio ^{9}Be/^{10}Be can be used as a CR clock => residence time in the Galaxy of O(100) Myr => **DIFFUSIVE** propagation

GCR: Propagation and diffusion

Secondary-to-primary ratio

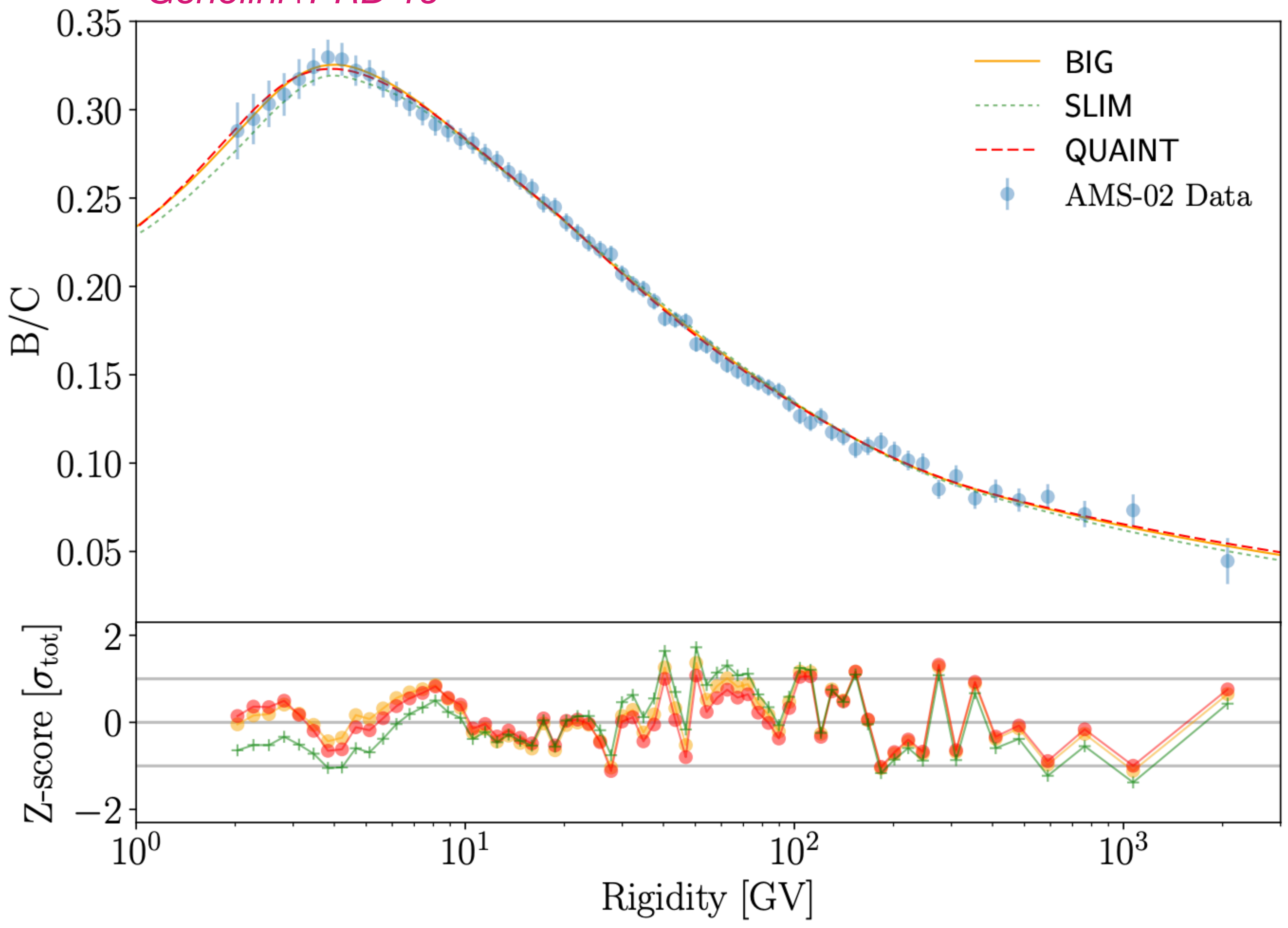
Primaries: Produced in source term Q

Secondaries: Nuclei only produced by spallation during propagation

$$q_0(p) \rightarrow \phi_P \Gamma_{P\rightarrow S}$$

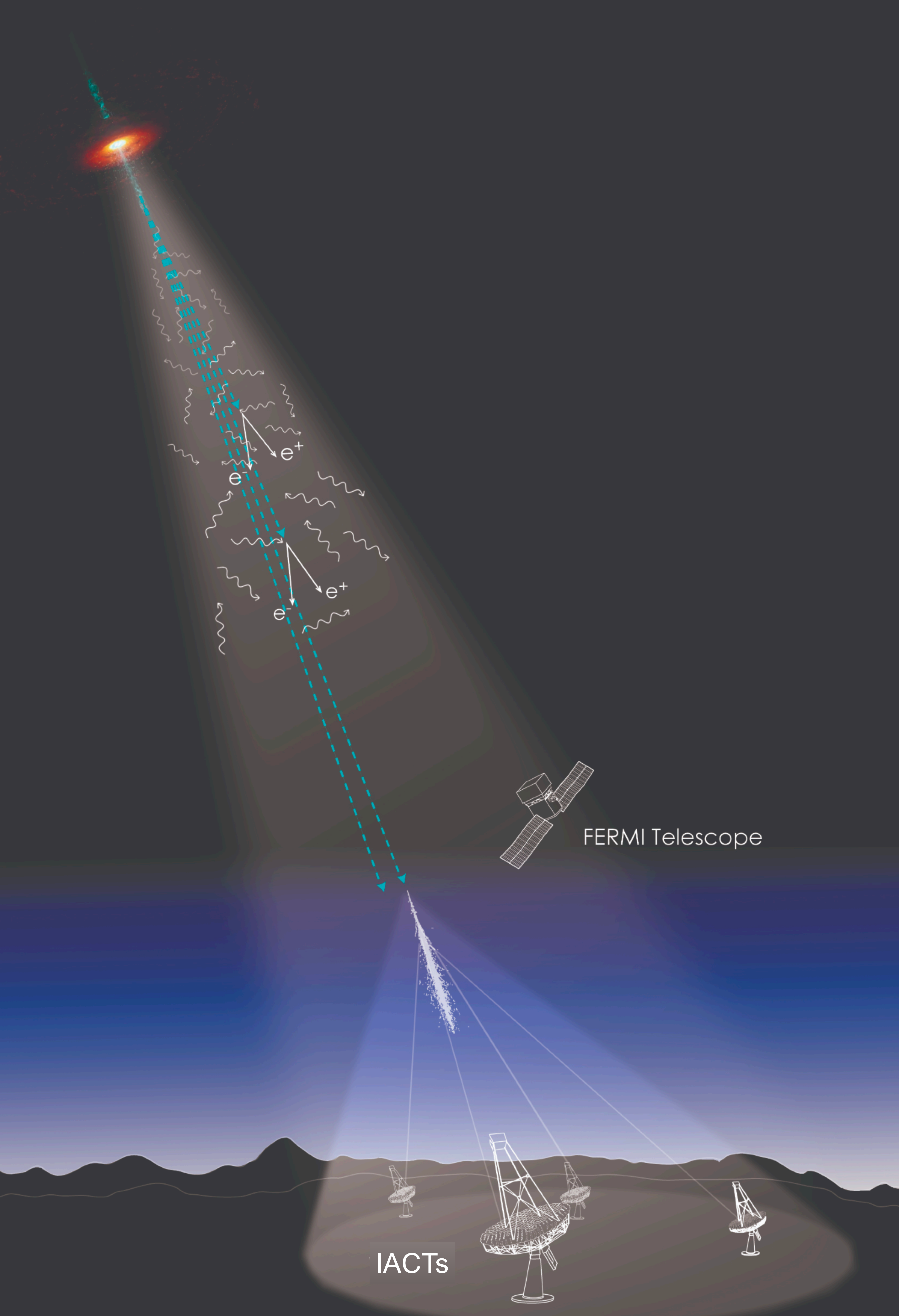
$$\frac{\phi_S(p)}{\phi_P(p)} \simeq \Gamma_{P\rightarrow S}\tau_{\mathrm{eff},P} \simeq \Gamma_{P\rightarrow S}\frac{H\,h}{K(p)}$$

Genolini+PRD'19



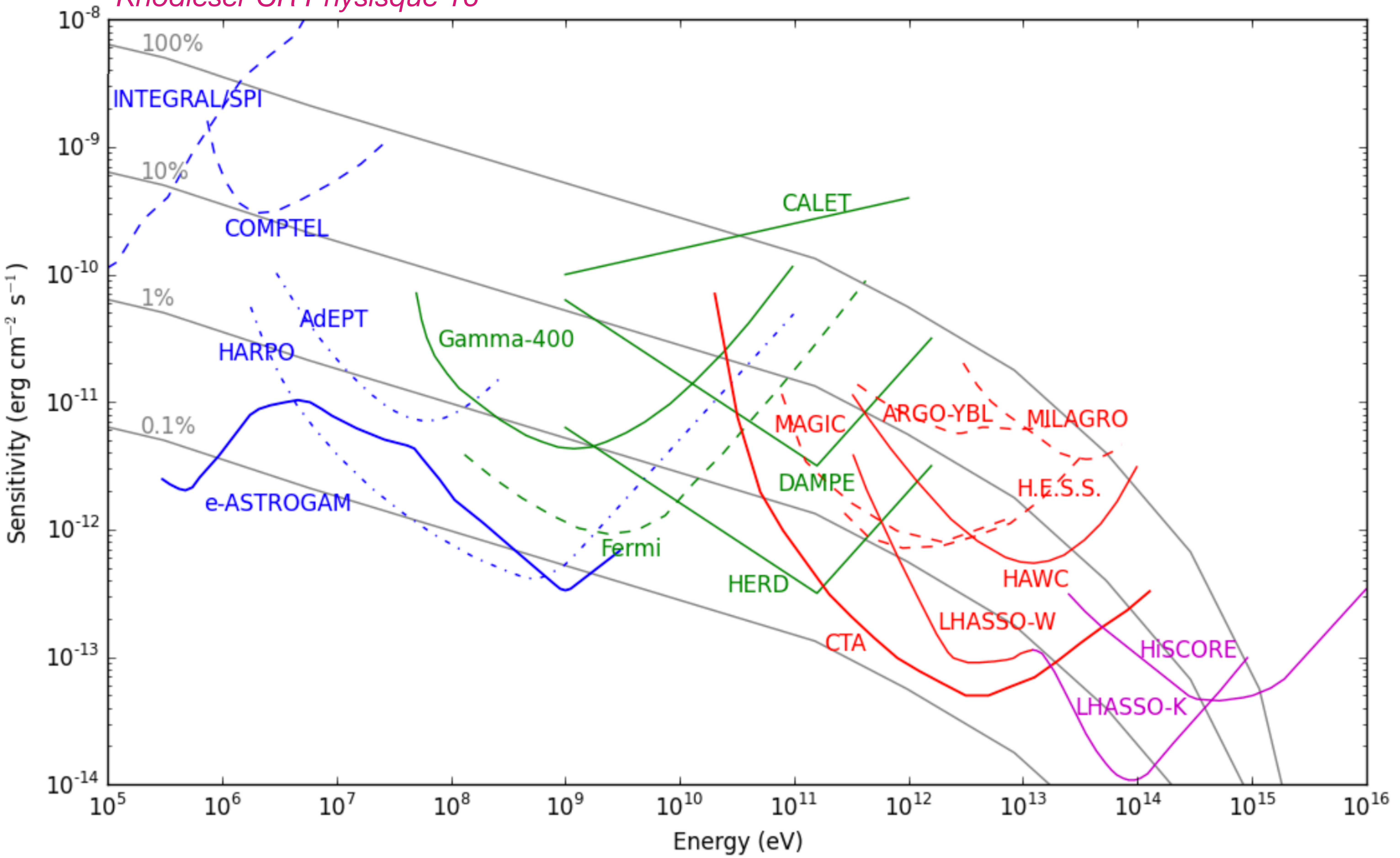
Gamma rays

Gamma-ray instruments

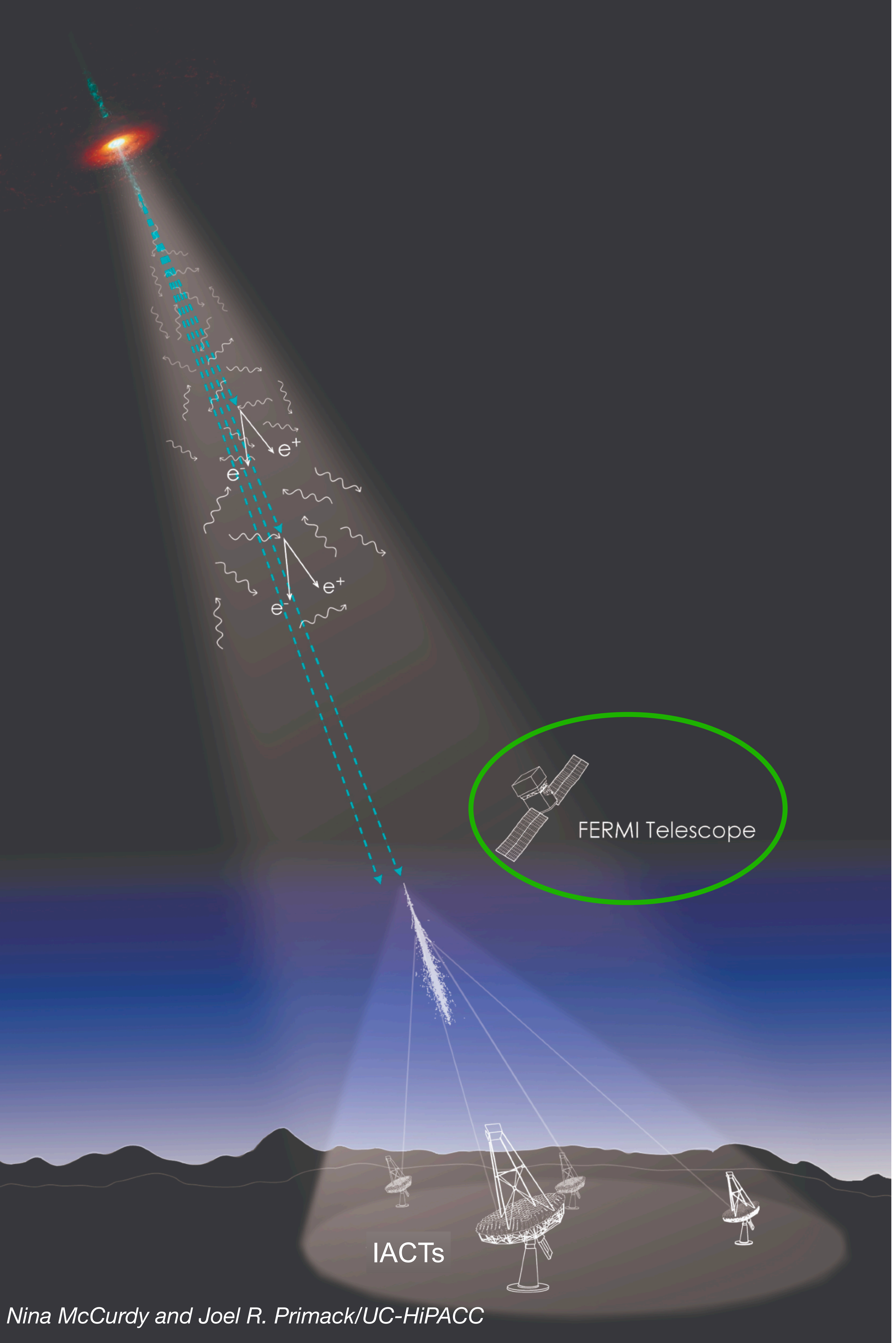


Nina McCurdy and Joel R. Primack/UC-HiPACC

Knödleser CR Physisque'16

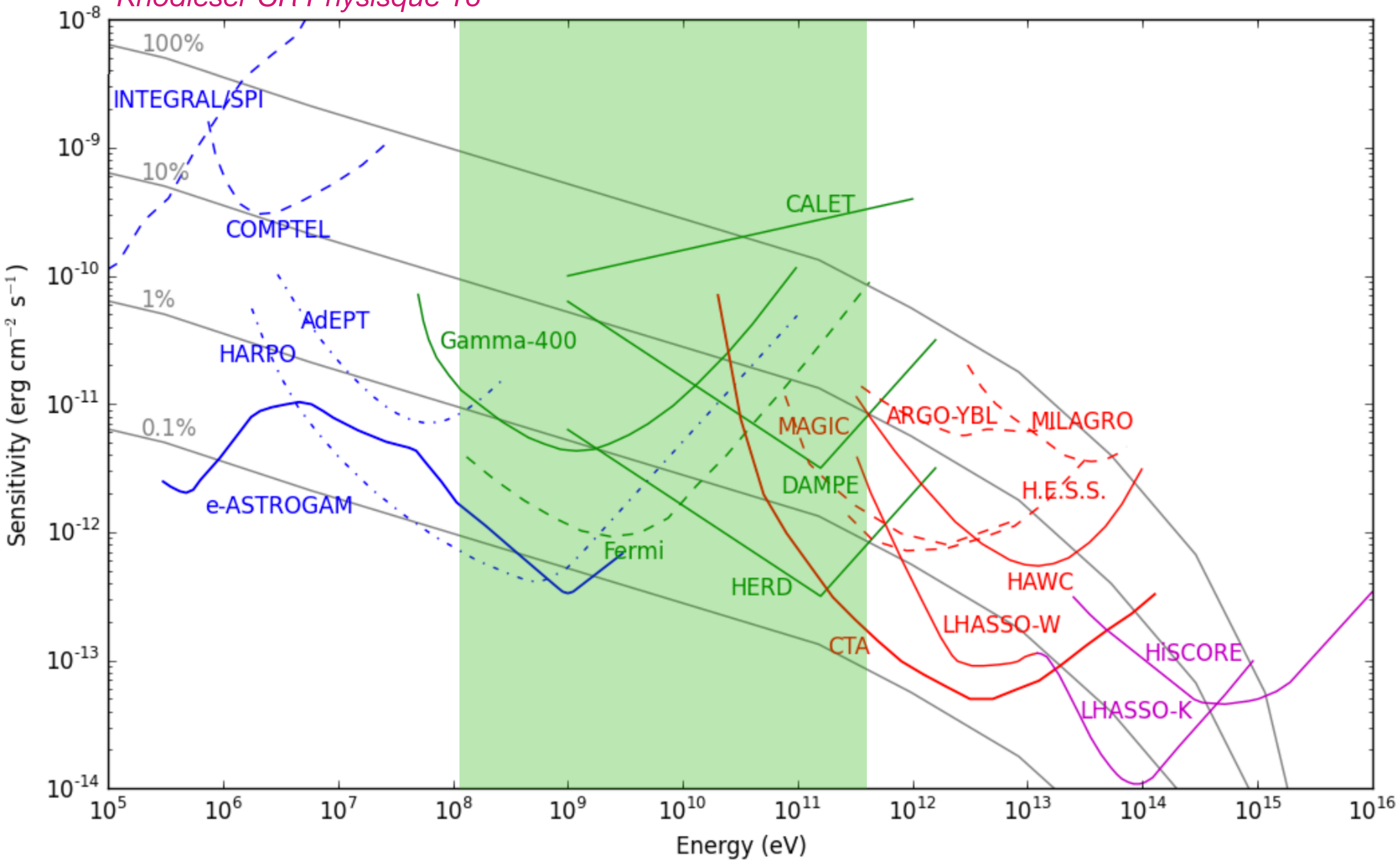


Differential 5σ point source sensitivities of present and future gamma-ray instruments

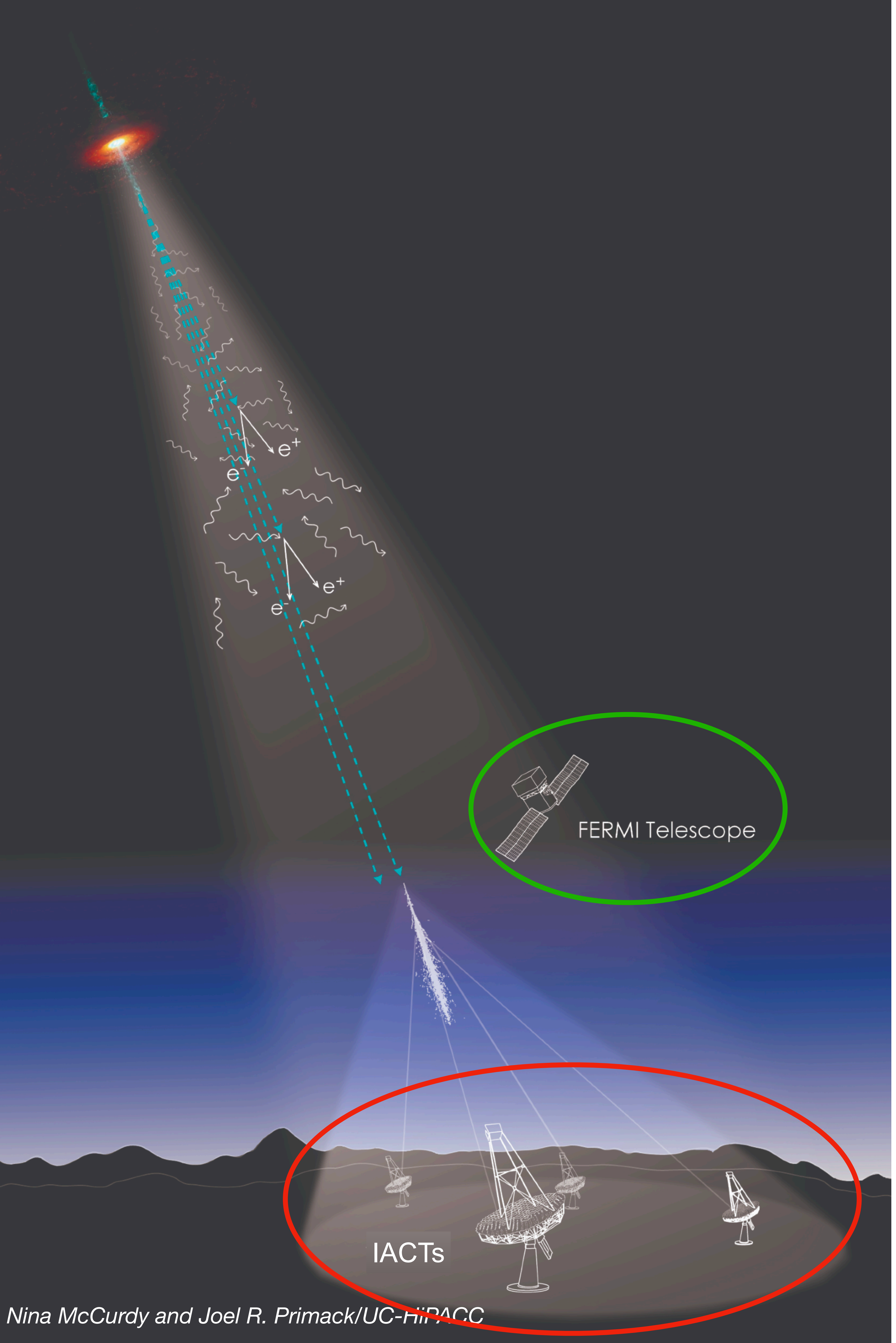


Gamma-ray instruments

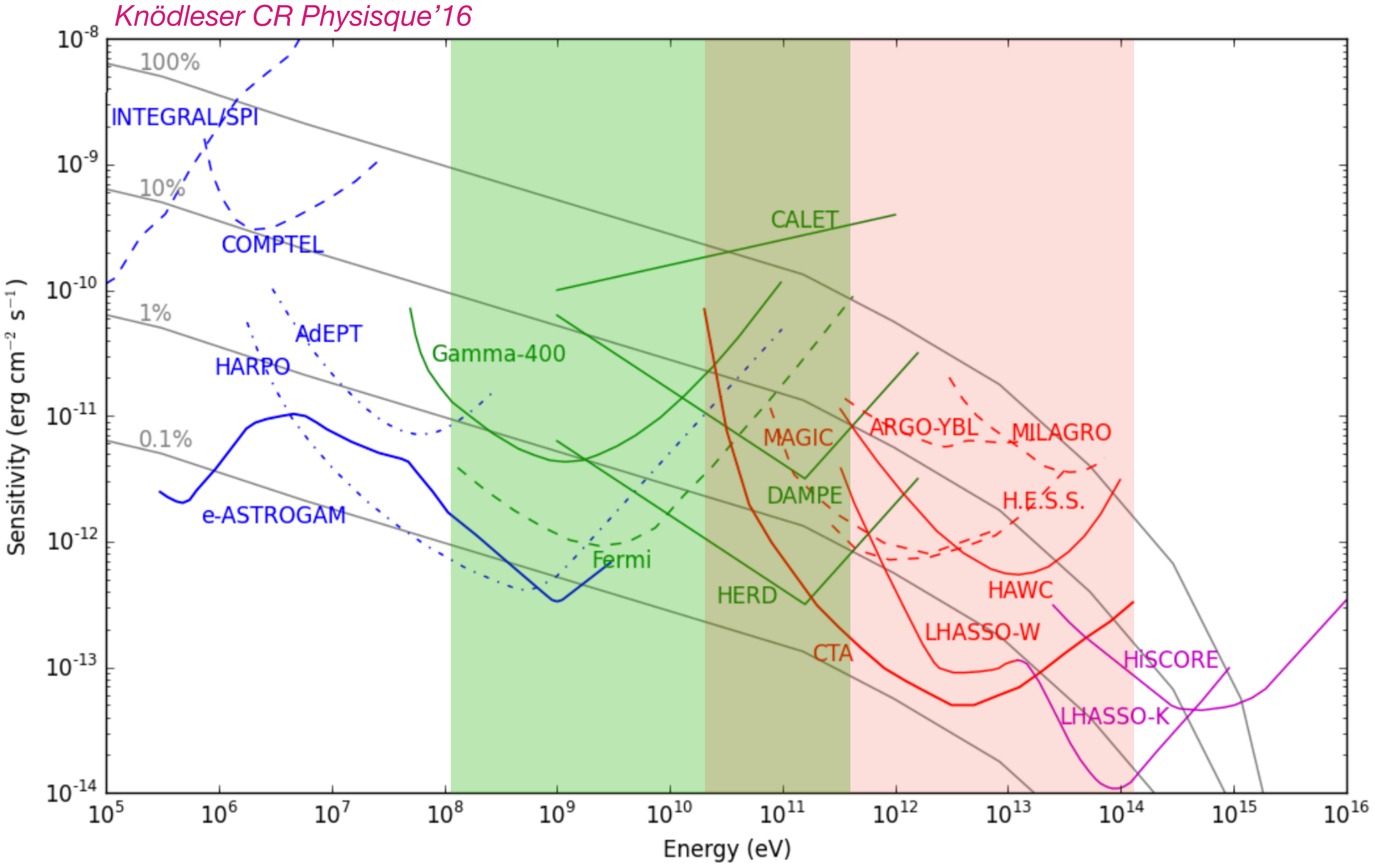
Knödleser CR Physisque'16



Differential 5σ point source sensitivities of present and future gamma-ray instruments



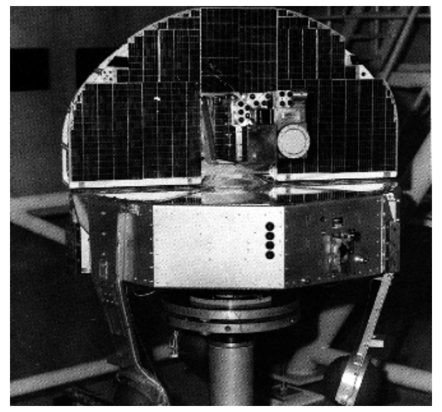
Gamma-ray instruments



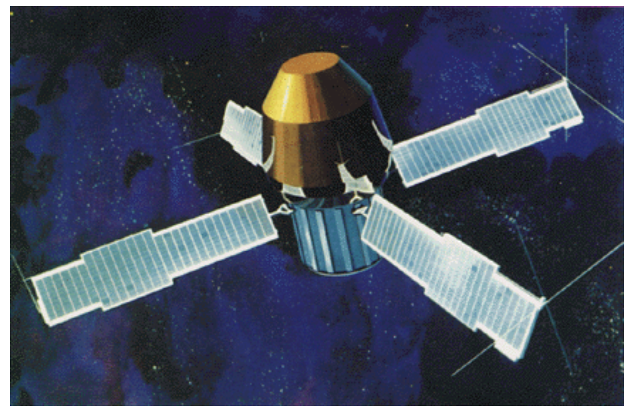
Differential 5σ point source sensitivities of present and future gamma-ray instruments

Cosmic gamma rays: a short history

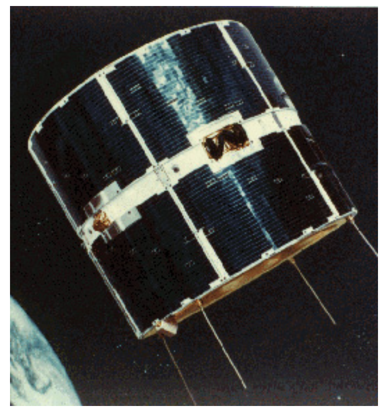
1967-1969
OSO-3 satellite



1972-1973
SAS-2



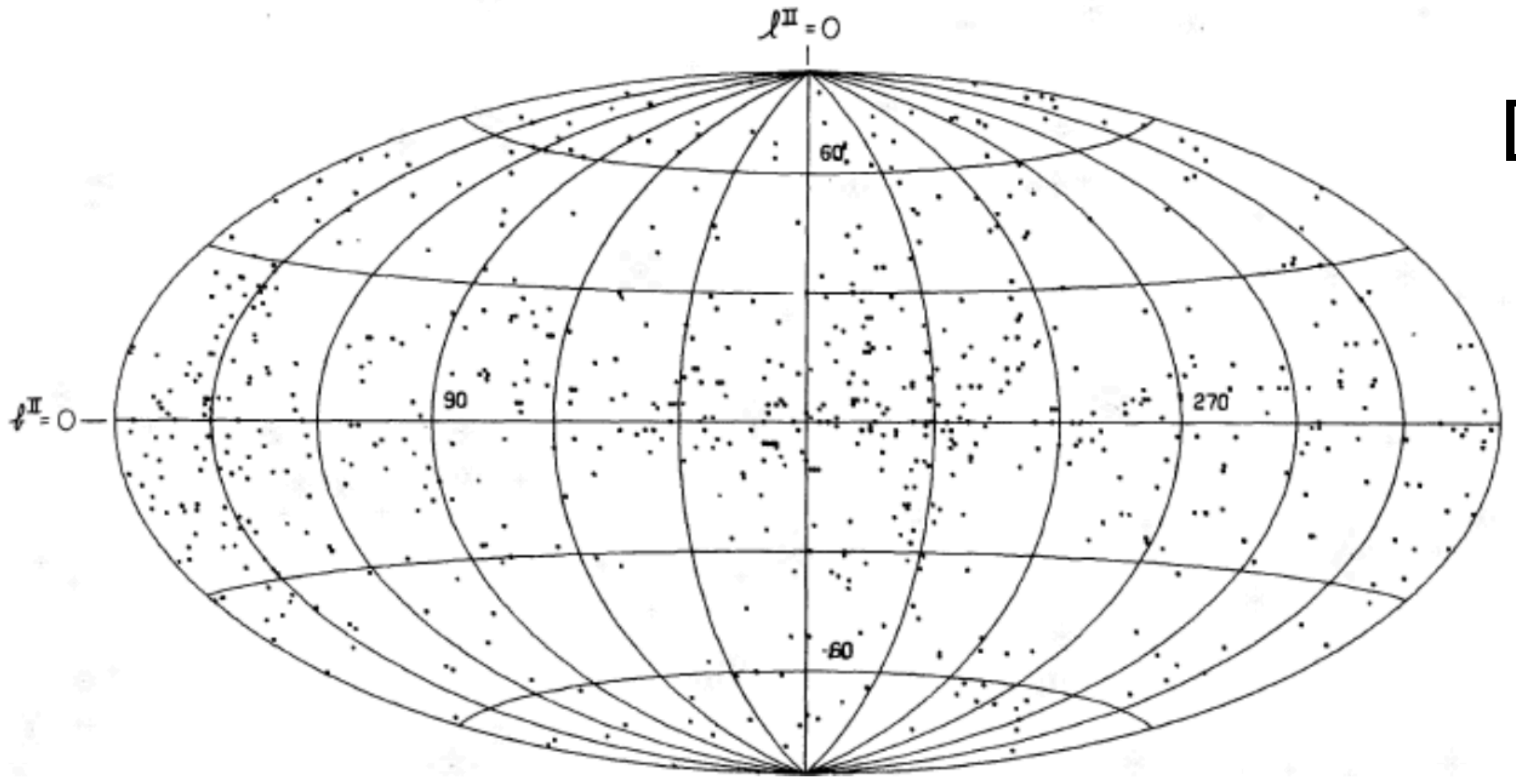
1975-1982
COS-B



1991-2000
EGRET

2008-present
Fermi-LAT

First sky-map of gamma rays



Kraushaar+ ApJ 1972

50 MeV - 10 GeV
Catalog of 25 Galactic sources
Discovery of Crab and Vela PSR

Swanenburg+ ApJL 1981

30 MeV - 30 GeV
271 sources in 3rd catalog

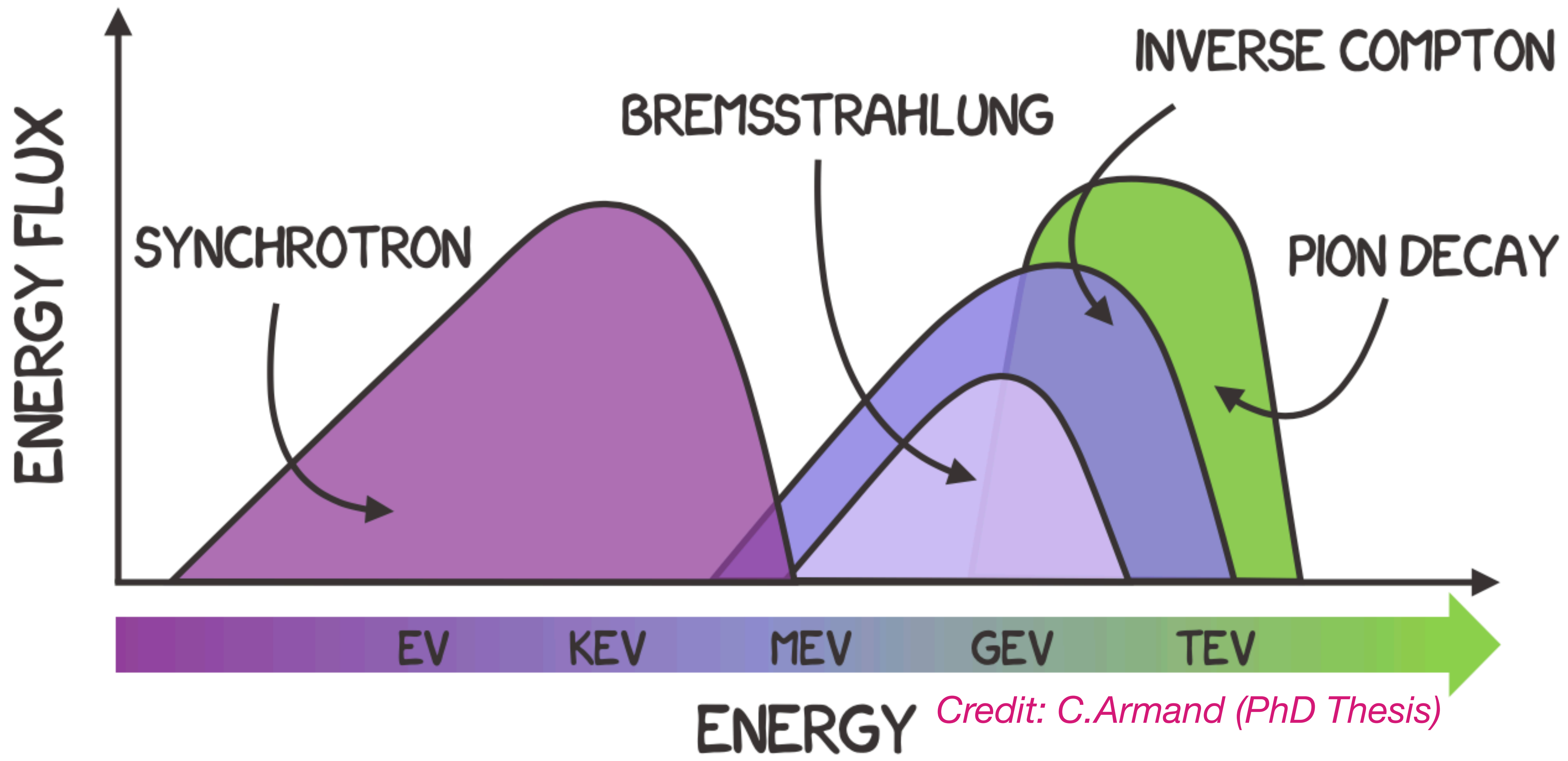
Hartman+ ApJS 1999

20 MeV - 300 GeV
Large FoV (2.4 sr)
Excellent angular res.
(0.1 deg@10 GeV)

Atwood+ ApJ'09


20 years of cosmic gamma rays
pre-Fermi
9yr Fermi
EGRET (1991-2000)
30 MeV - 30 GeV
Fermi-LAT (2008-2017)
20 MeV - 500 GeV

Gamma-ray production mechanisms



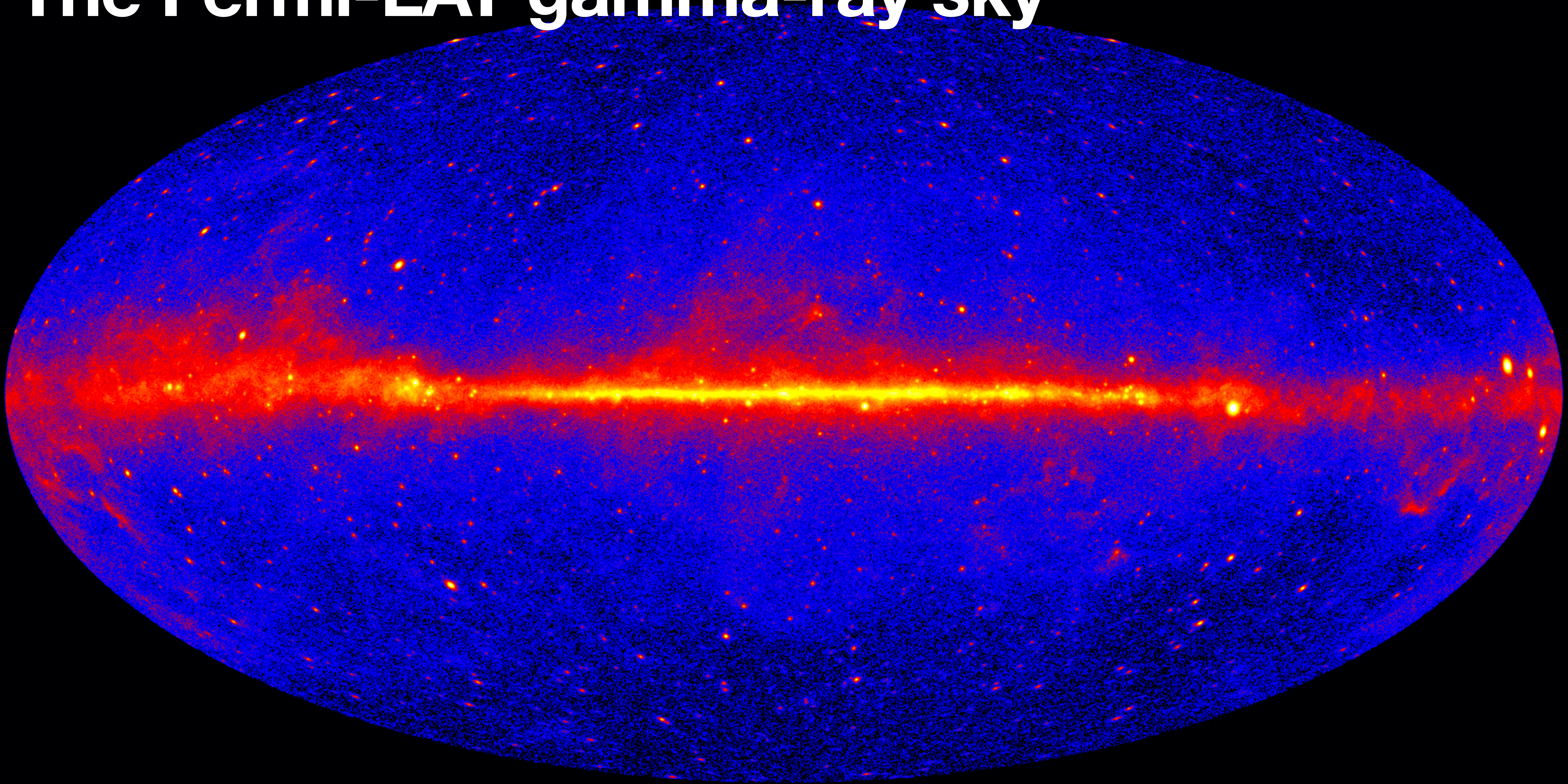
Credit: C.Armand (PhD Thesis)

Multi-wavelength emission spectrum

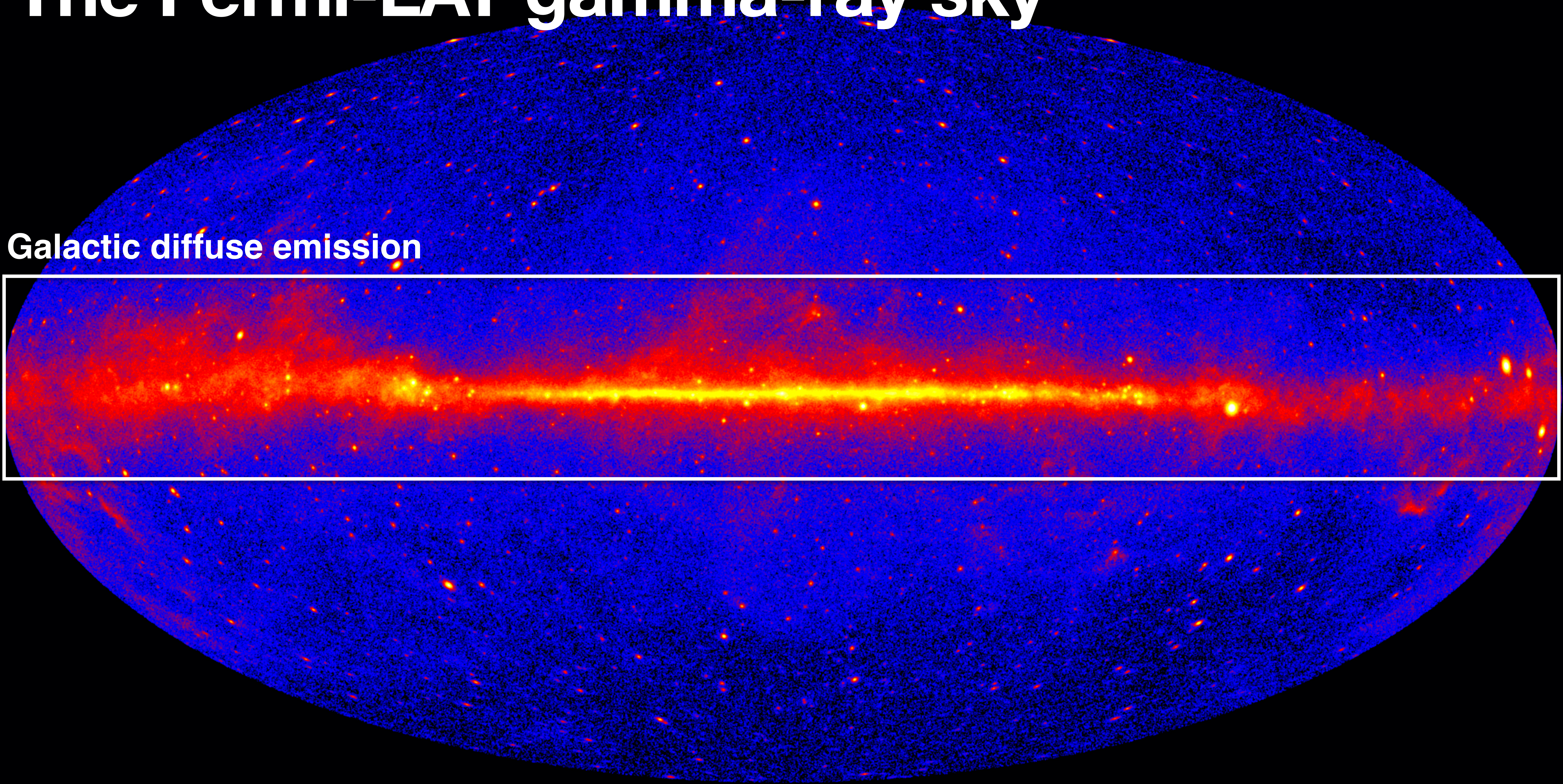
- Gamma-ray production follows the **acceleration of charged particles**, or the **decay of exotic particles** (e.g. dark matter)
- A population of accelerated charged particles in astrophysical sources is required
- **Leptonic gamma rays** trace the cosmic-ray electron density and the radiation fields
- **Hadronic gamma rays** trace the cosmic-ray hadrons, as well as the target gas densities

G. Rybicki and A.P. Lightman, 1979, 'Radiative Processes in Astrophysics'; John Wiley & Sons Inc. M. S. Longair, 2011, 'High Energy Astrophysics', Cambridge University Press

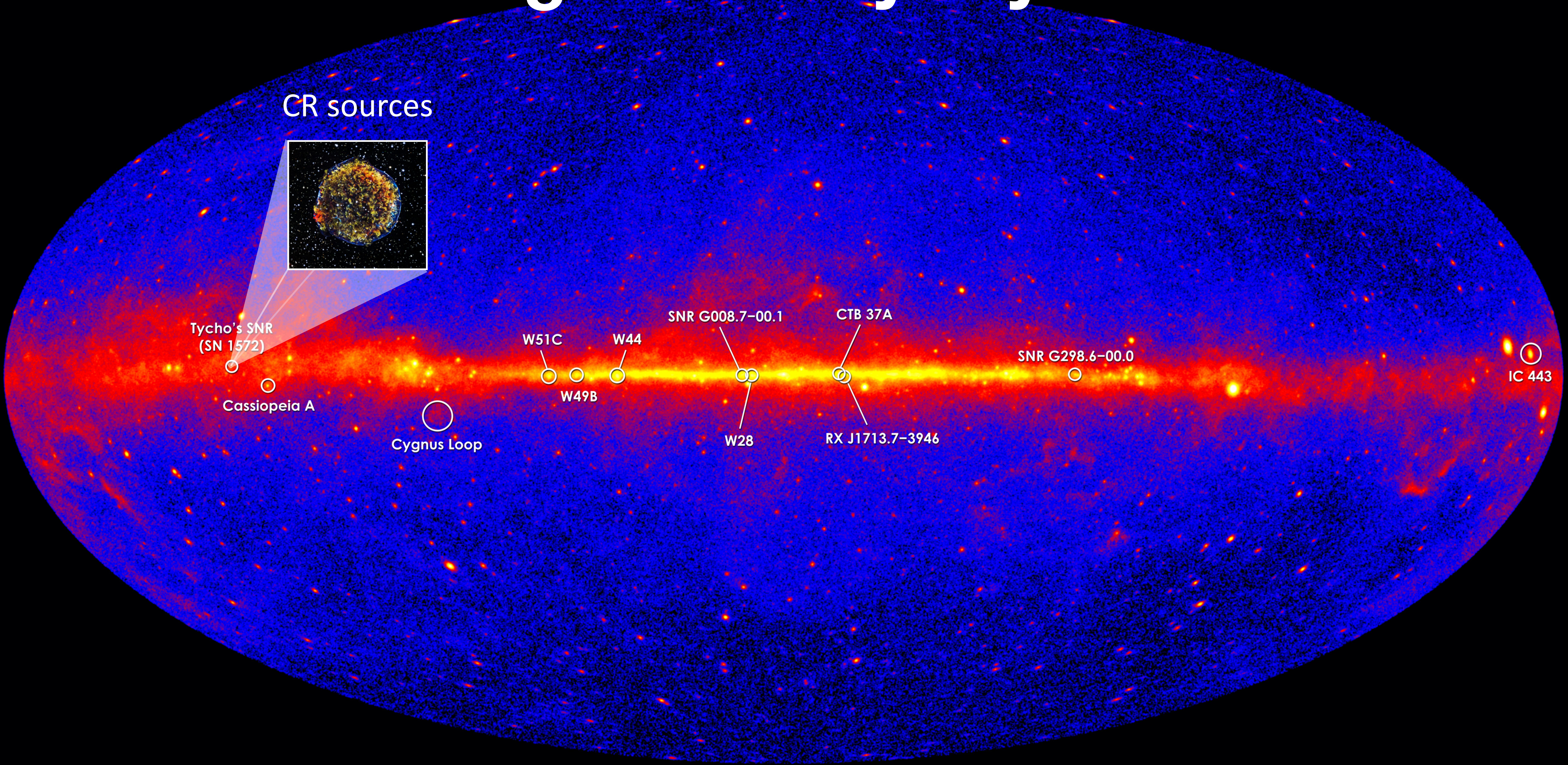
The Fermi-LAT gamma-ray sky



The Fermi-LAT gamma-ray sky



The Fermi-LAT gamma-ray sky



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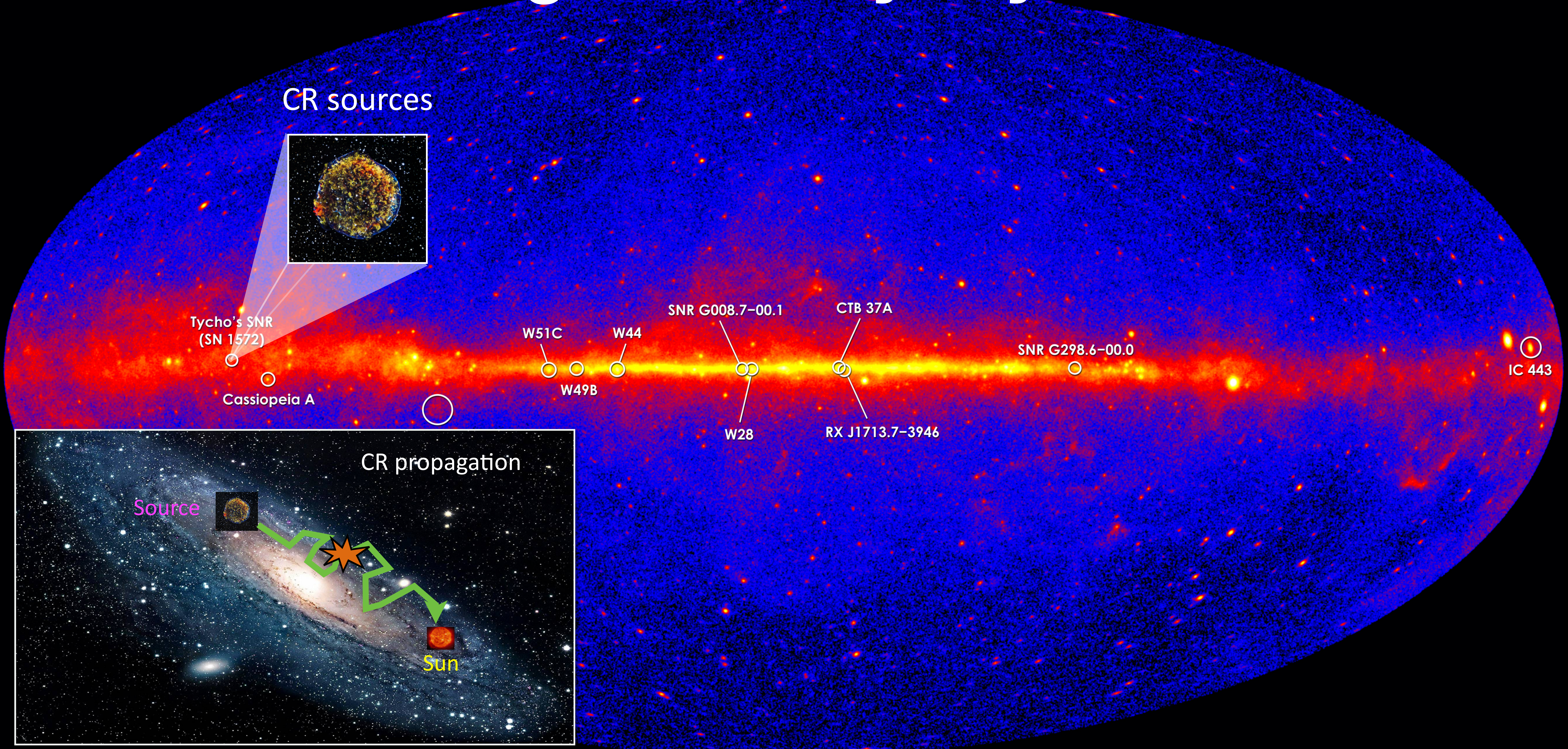
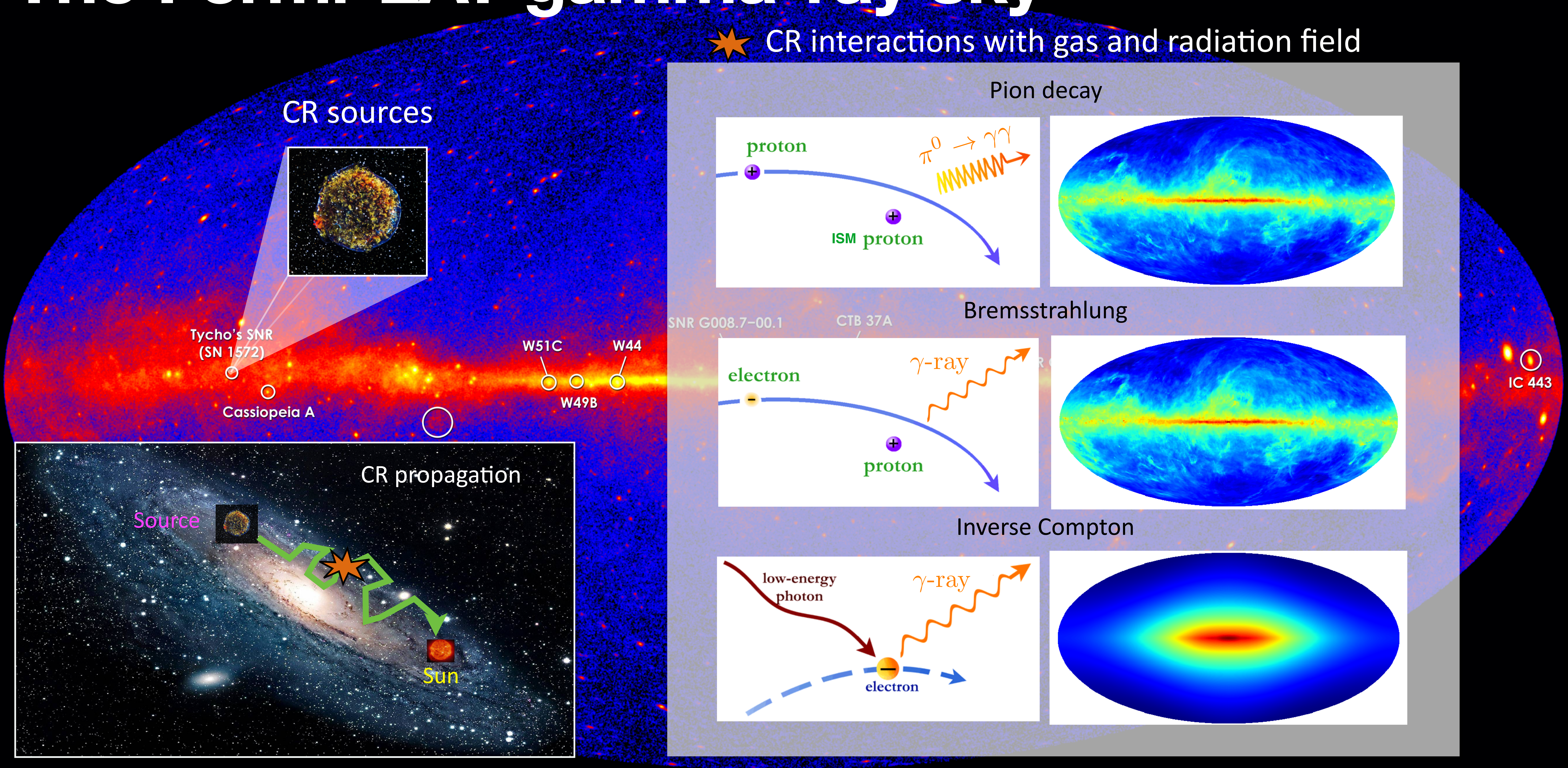
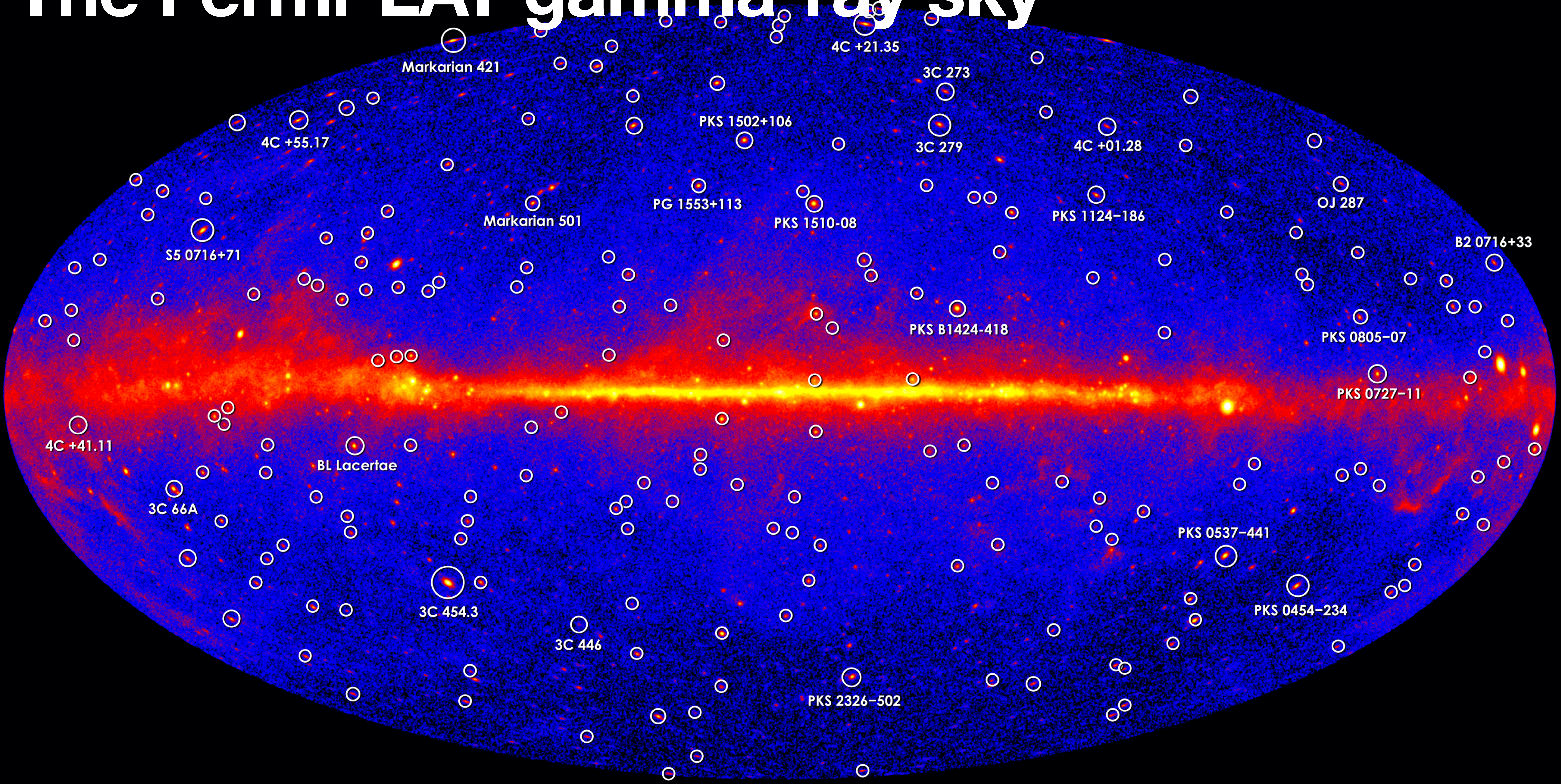


The Fermi-LAT gamma-ray sky

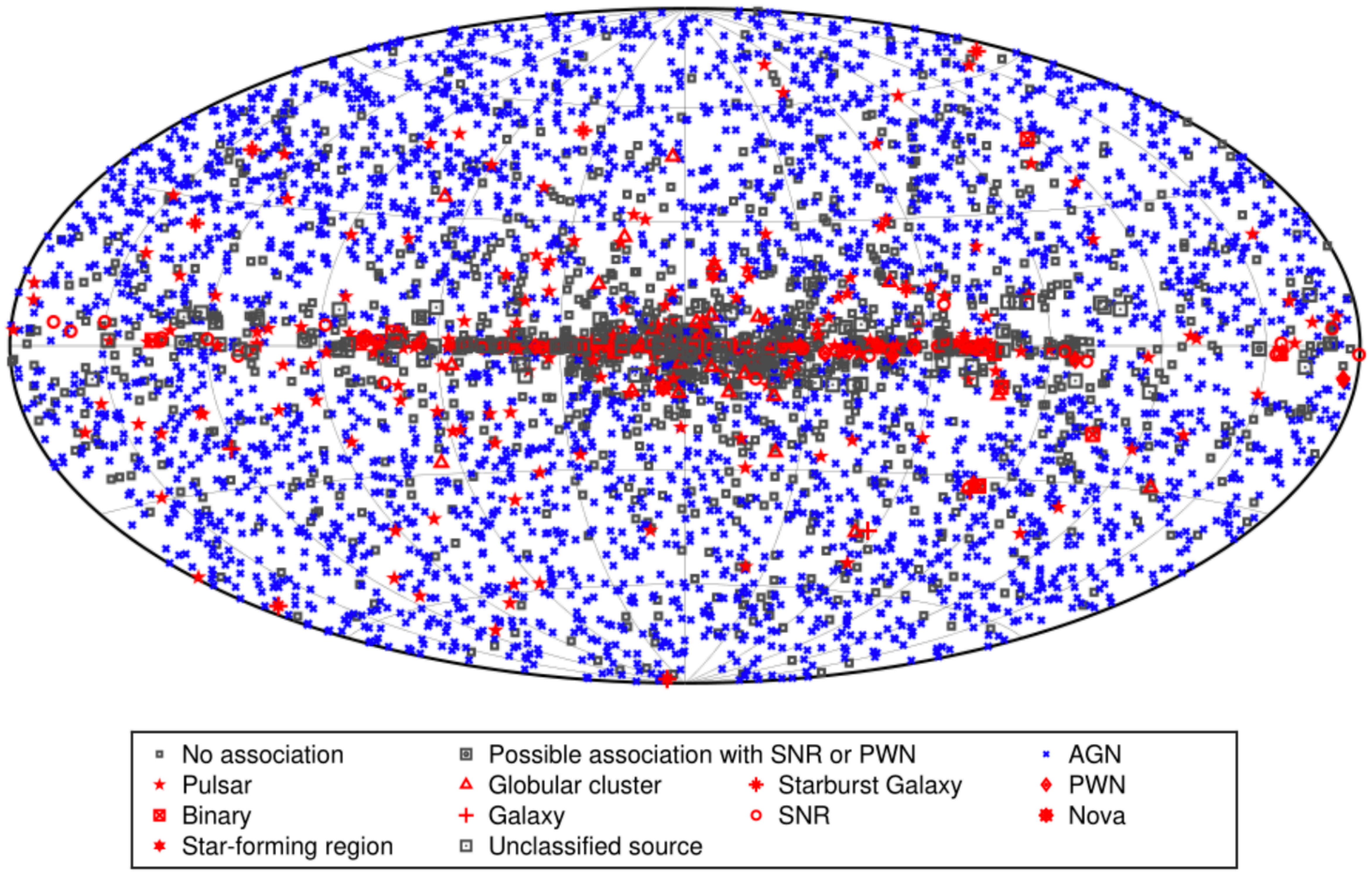


Galactic diffuse gamma-ray emission (GDE)

The Fermi-LAT gamma-ray sky



Fermi-LAT gamma-ray sources

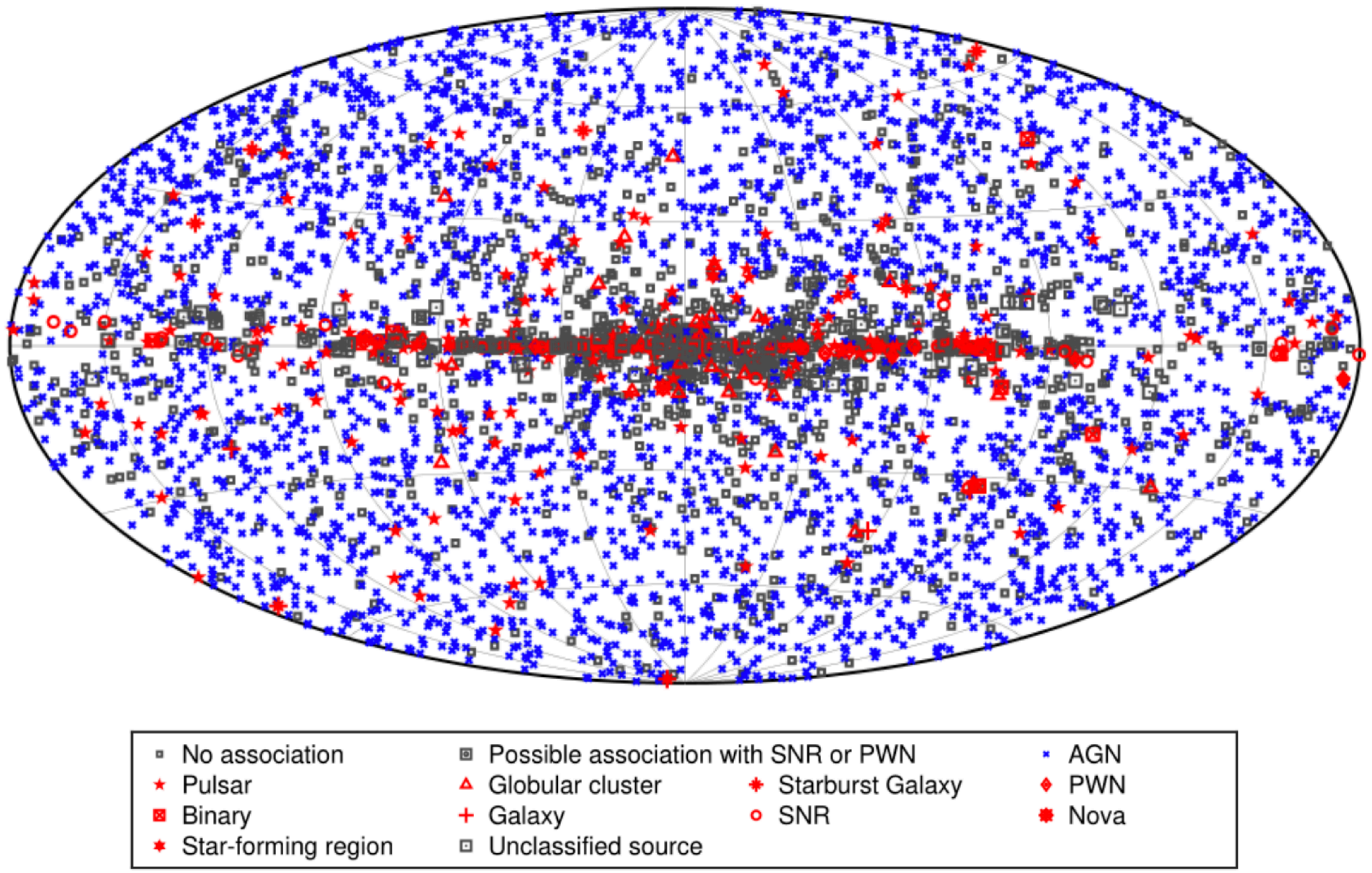


FERMI-LAT FOURTH SOURCE CATALOG (4FGL)

Fermi-LAT Collab. ApJS'20

- 8yr data-set
- **5064** sources above 4σ significance
- **3130** AGN; **239** pulsars

Fermi-LAT gamma-ray sources



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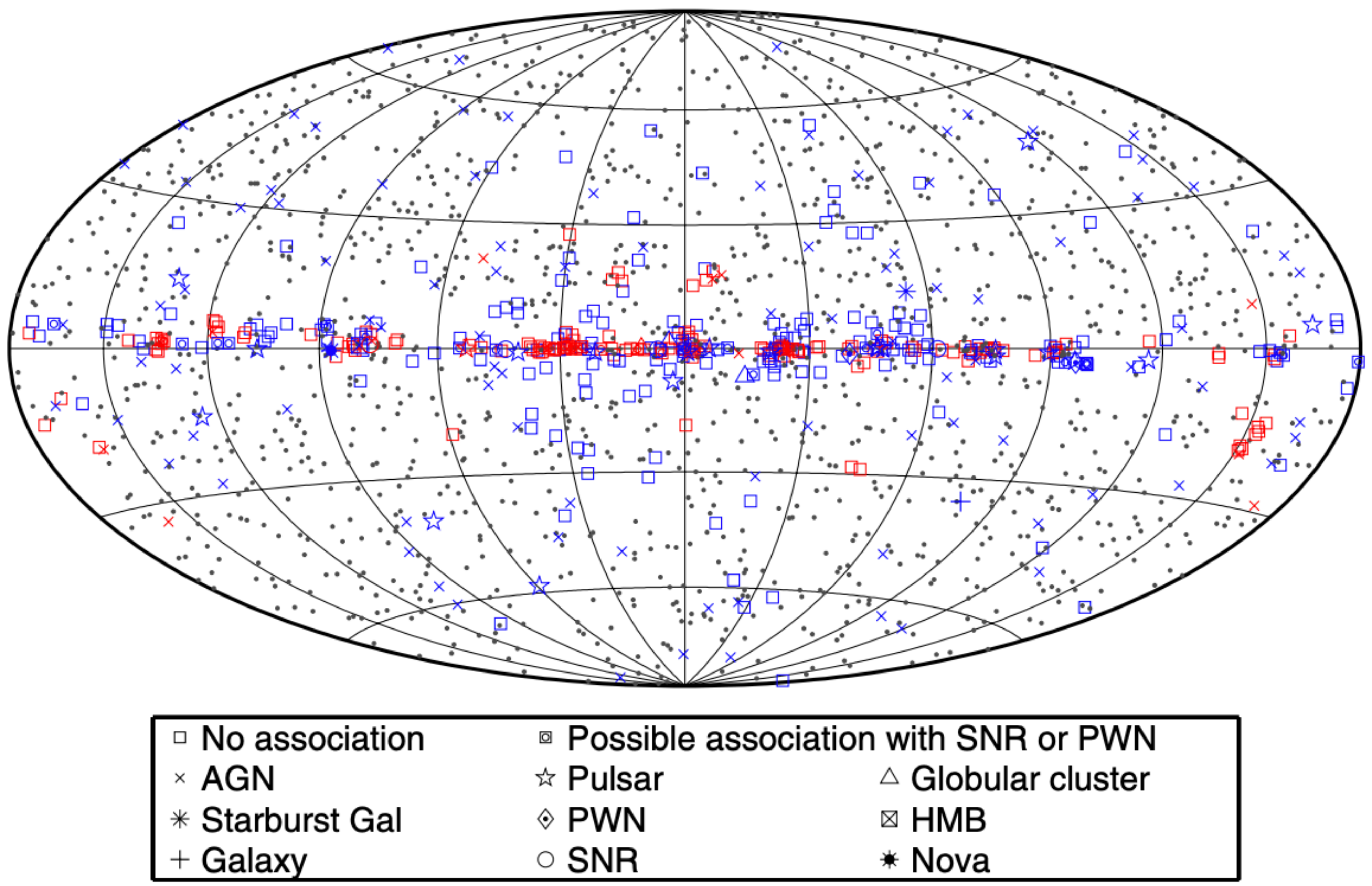
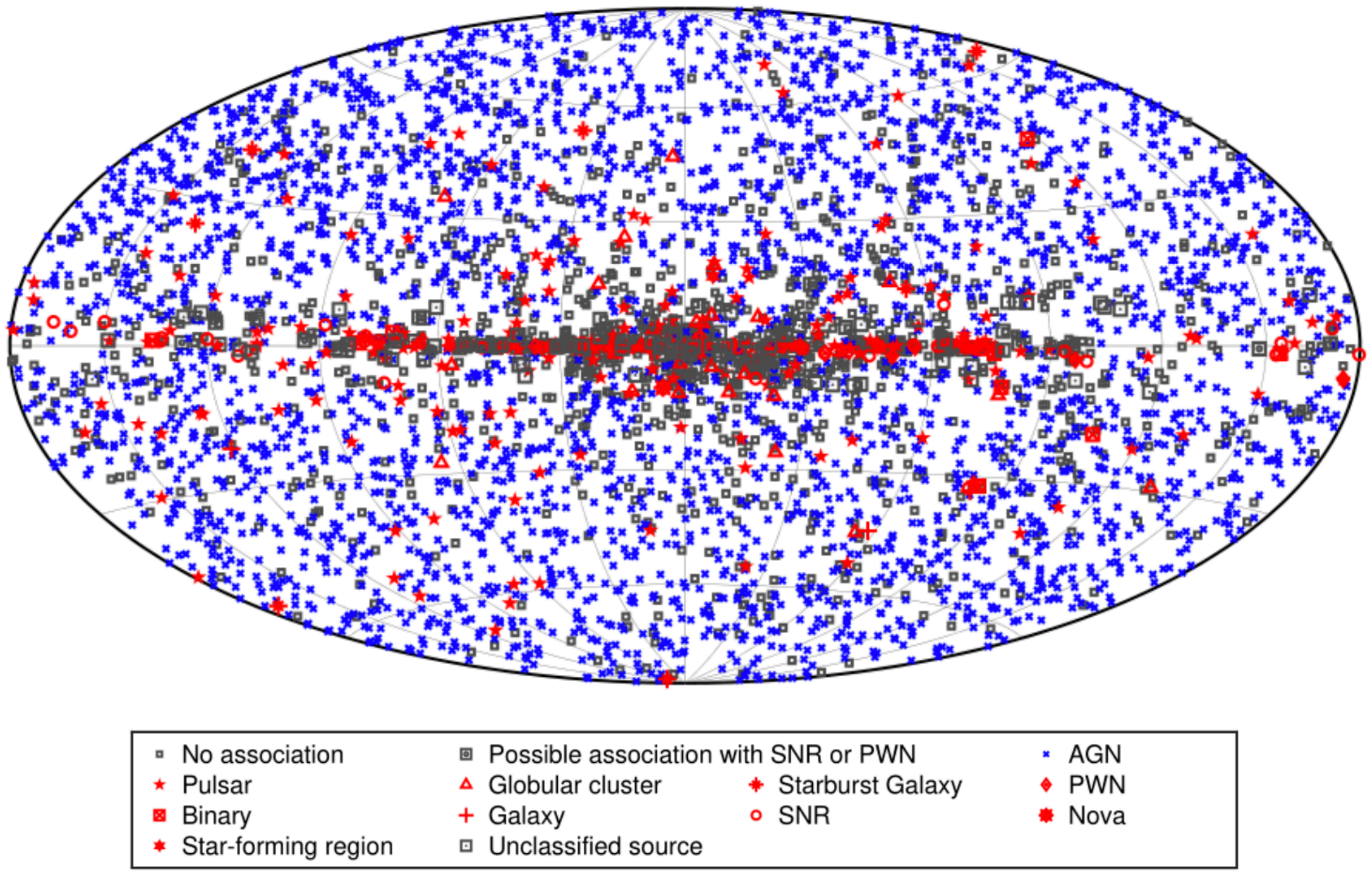


Nolan+ ApJS'12

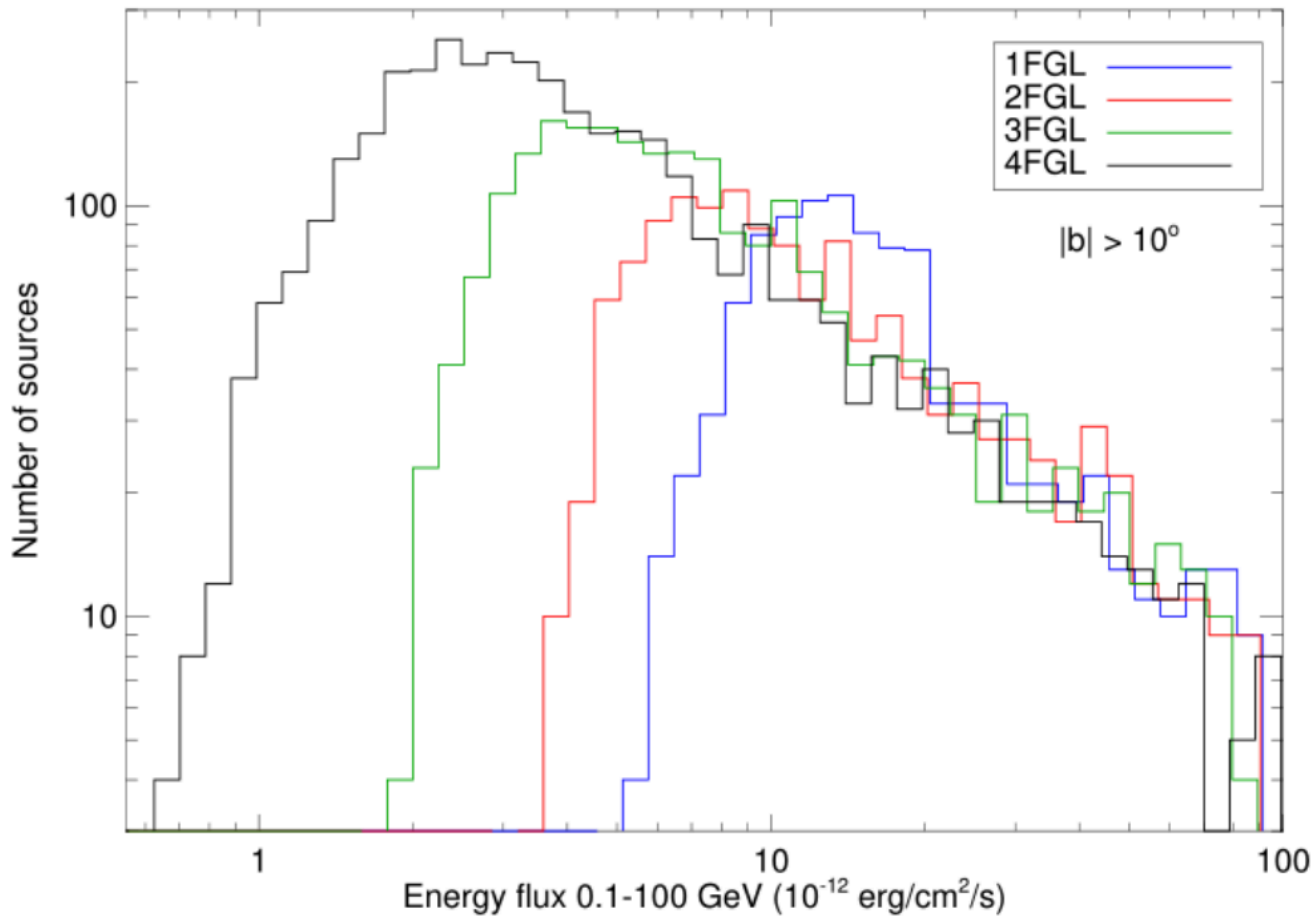
Fermi-LAT gamma-ray sources



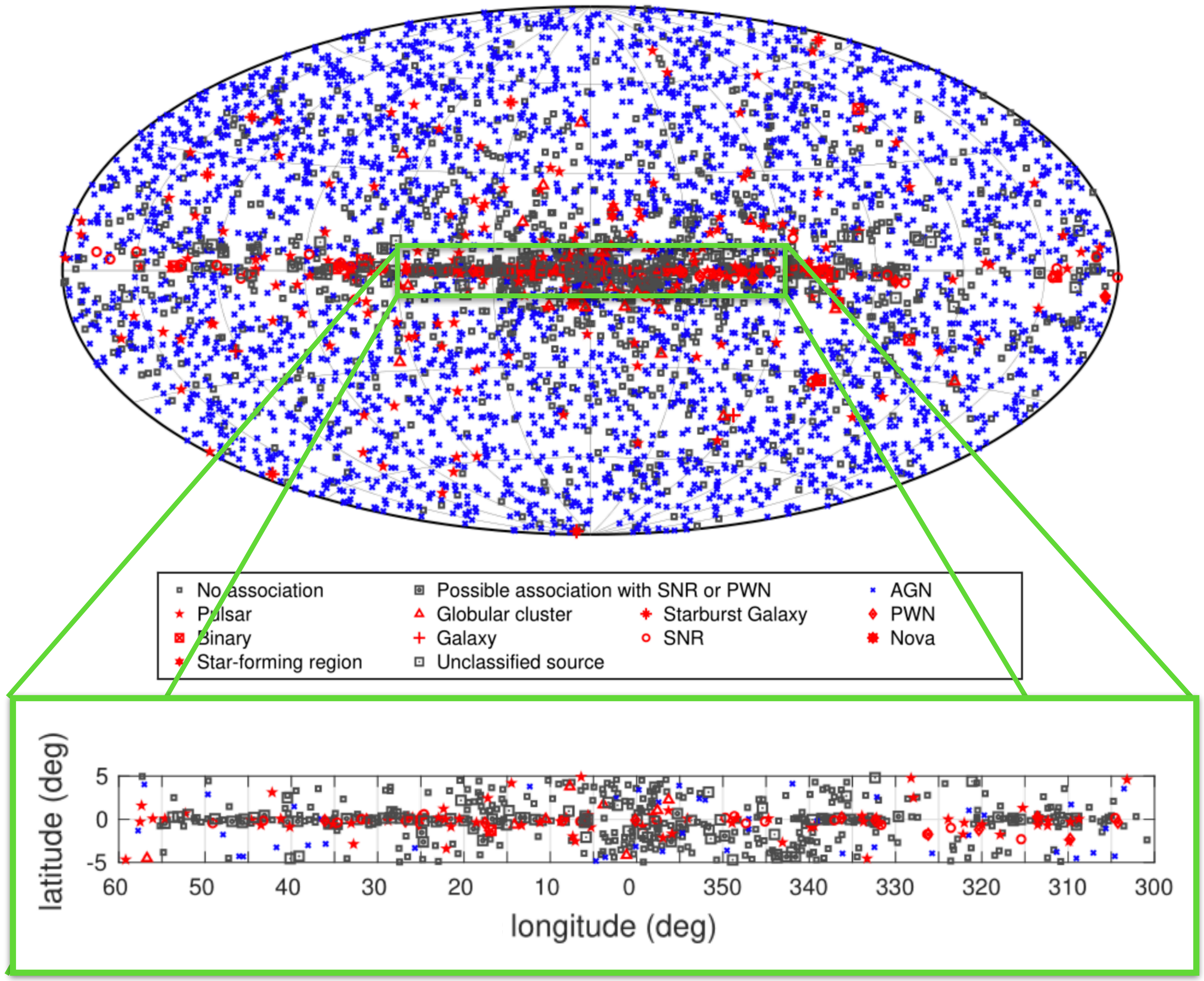
FERMI-LAT FOURTH SOURCE CATALOG (4FGL)

Fermi-LAT Collab. ApJS'20

- 8yr data-set
- **5064** sources above 4σ significance
- **3130** AGN; **239** pulsars



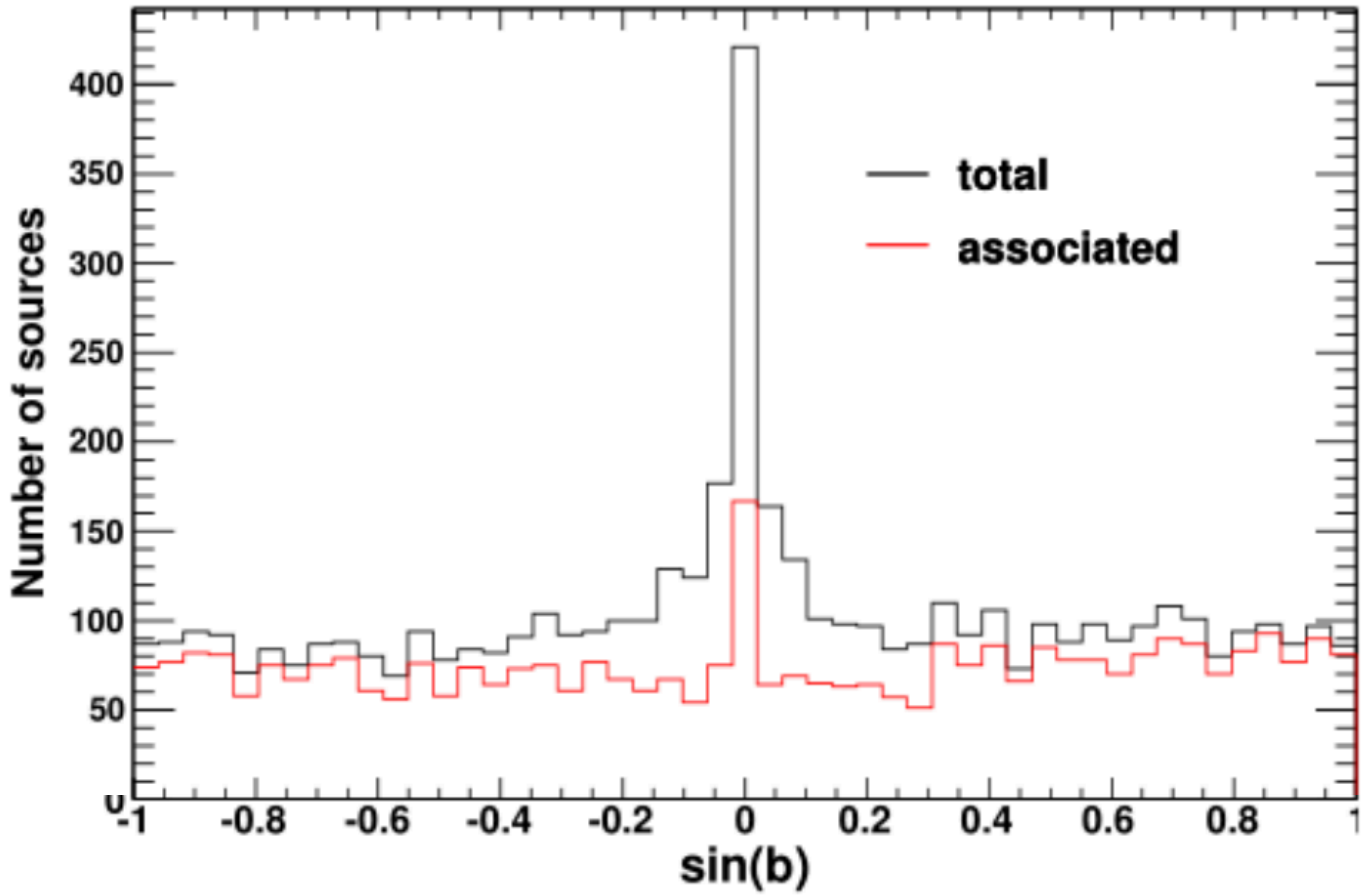
Fermi-LAT gamma-ray sources



FERMI-LAT FOURTH SOURCE CATALOG (4FGL)

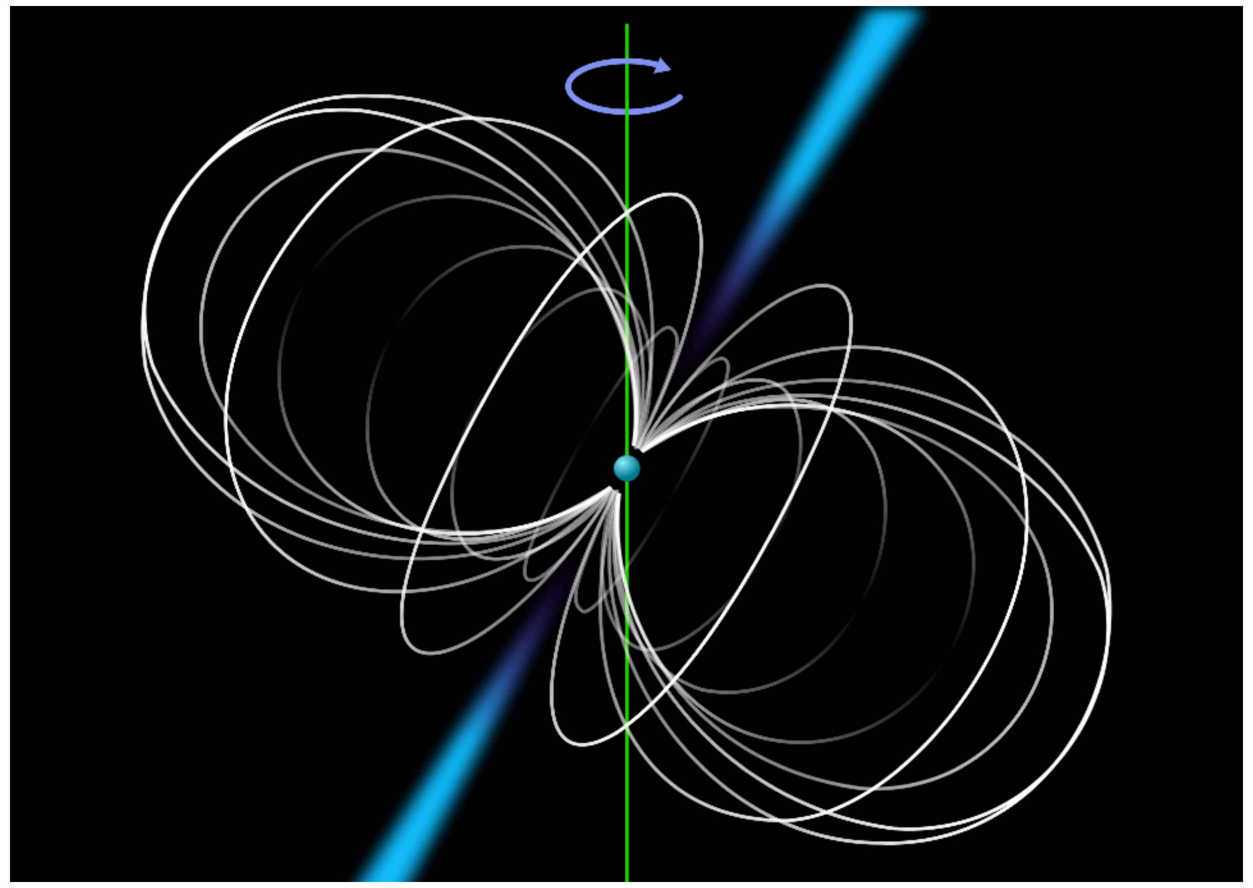
Fermi-LAT Collab. ApJS'20

- 8yr data-set
- **5064** sources above 4σ significance
- **3130** AGN; **239** pulsars
- **1336** sources w/o counterparts at other wavelengths

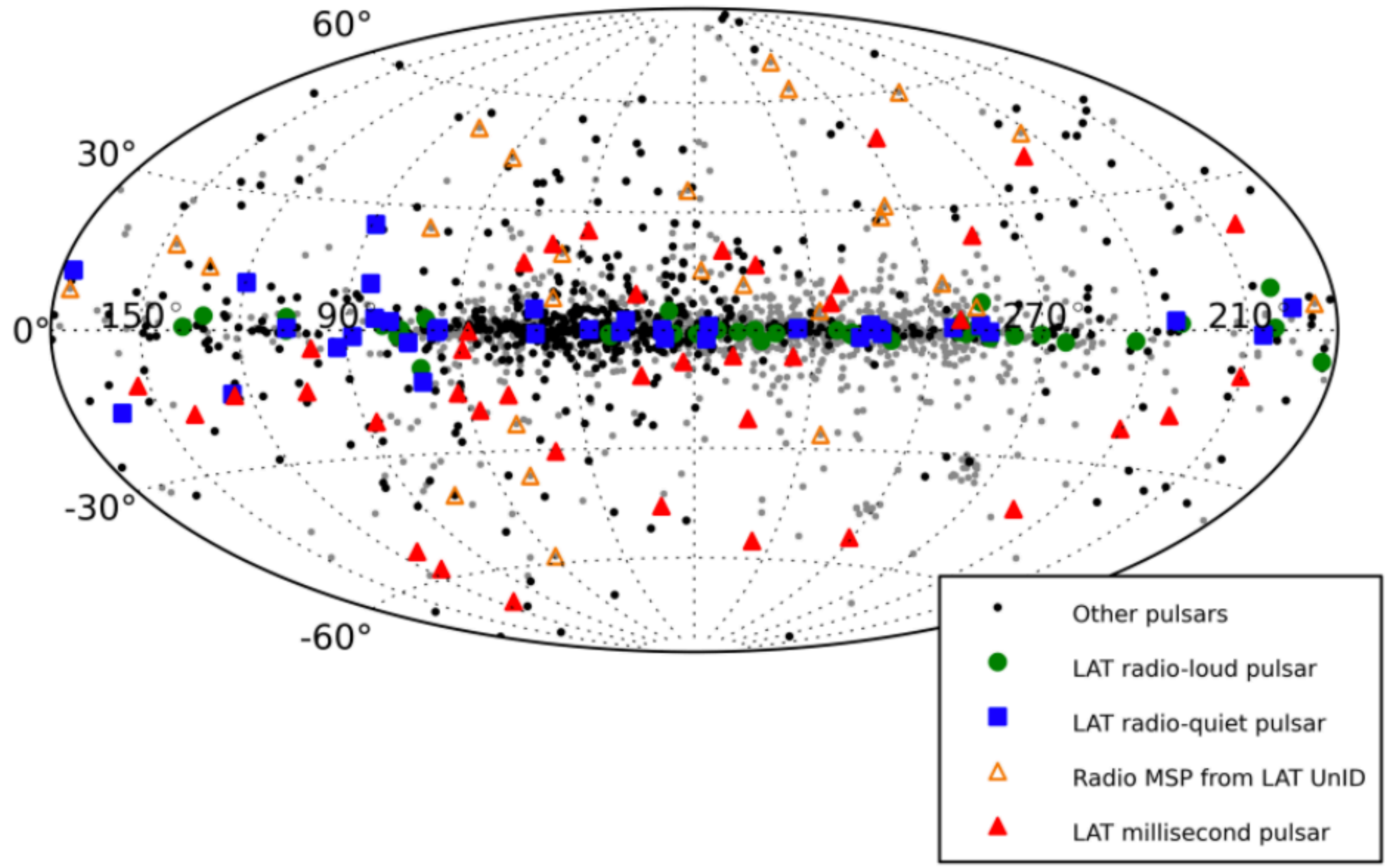


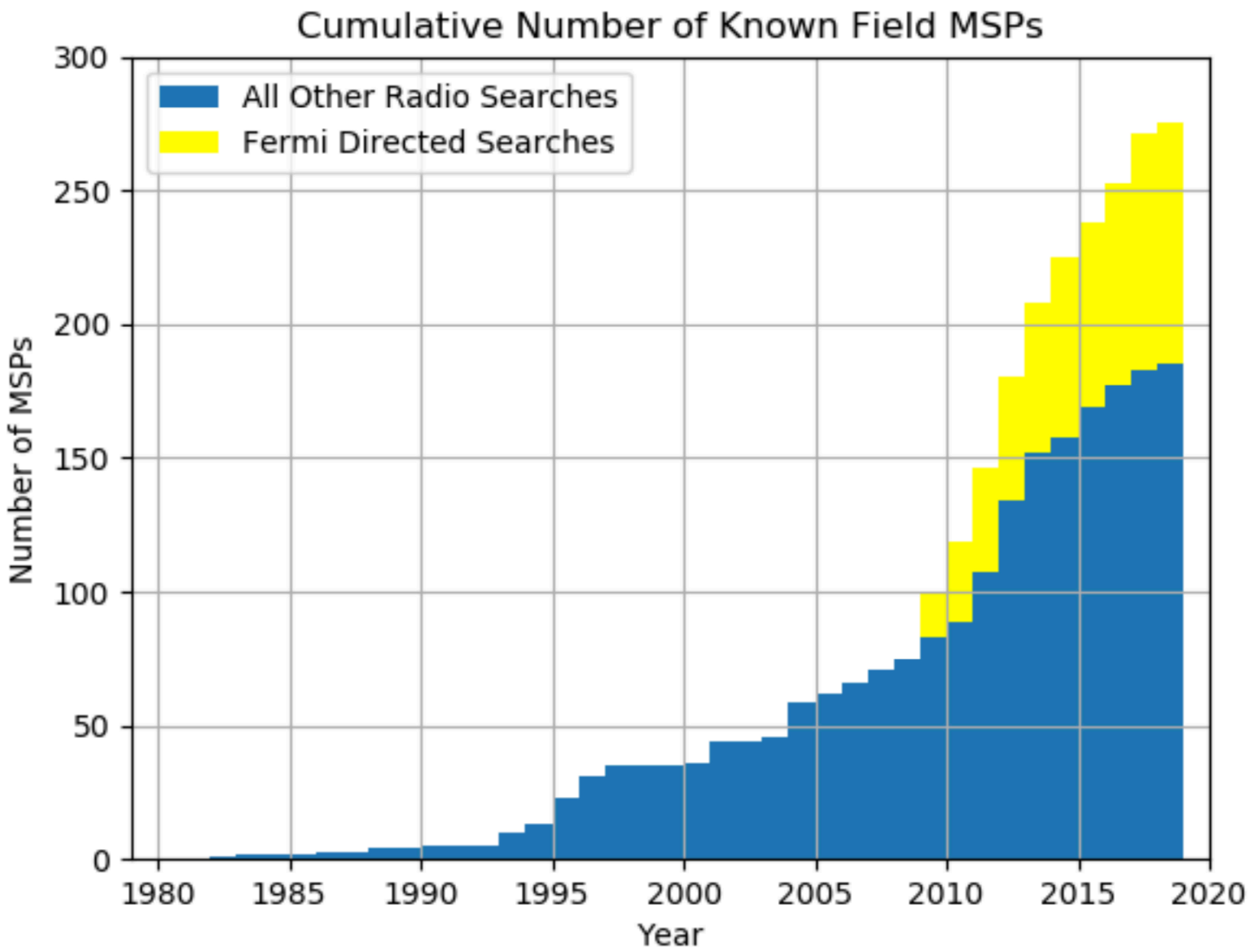
The pulsars' revolution

Caraveo Ann.Rev.Astron.Astrophys. 52 (2014) 211-250



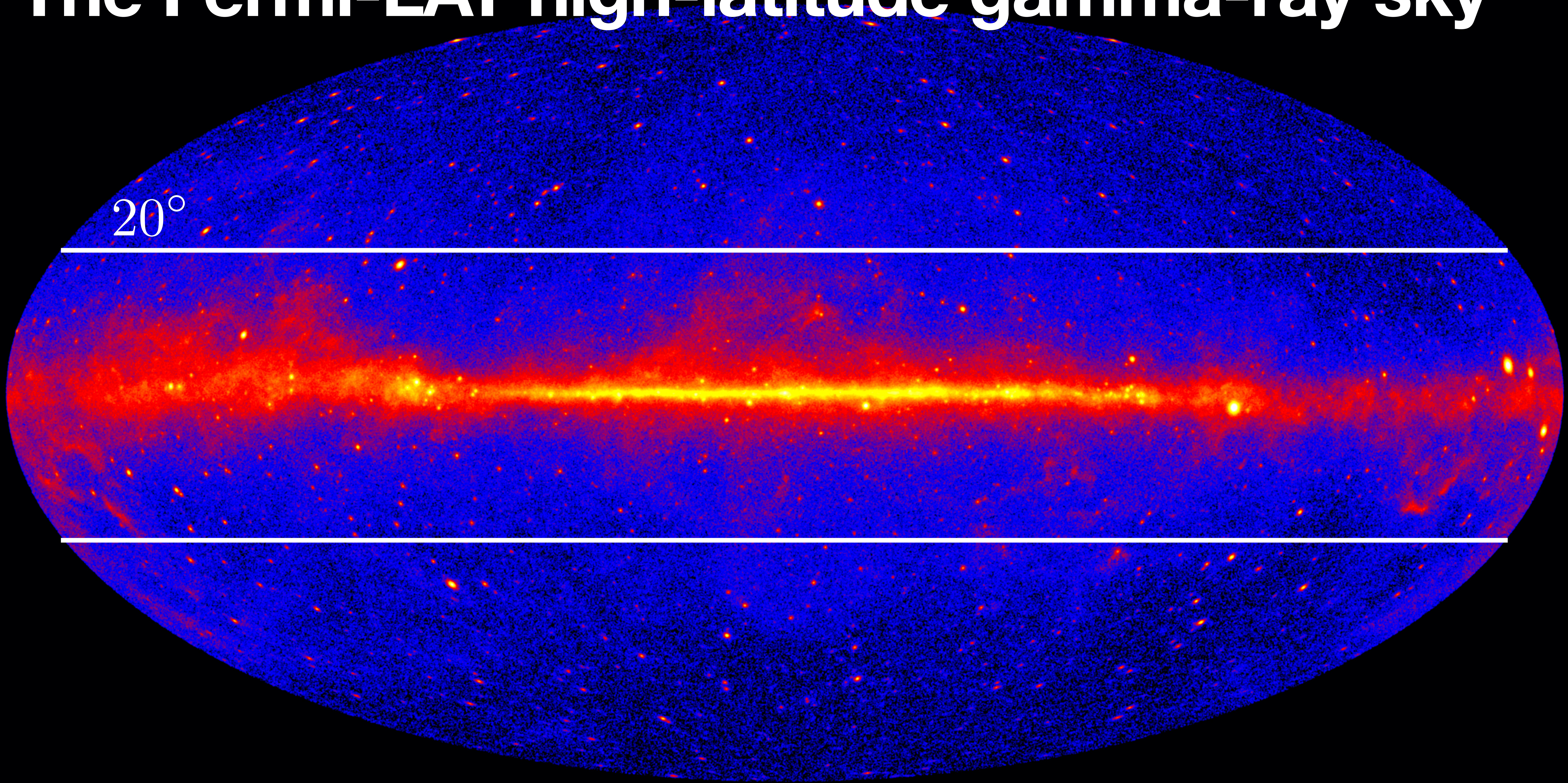
- Highly magnetised, rotating, compact stars originating from the collapse of massive stars
- First sources identified in high-energy gamma-ray astronomy, '70
- Primarily identified in radio, but **radio-quiet** gamma-ray pulsars exist
- Rapid growth of the number of isolated and binary **millisecond pulsars** (MSPs)



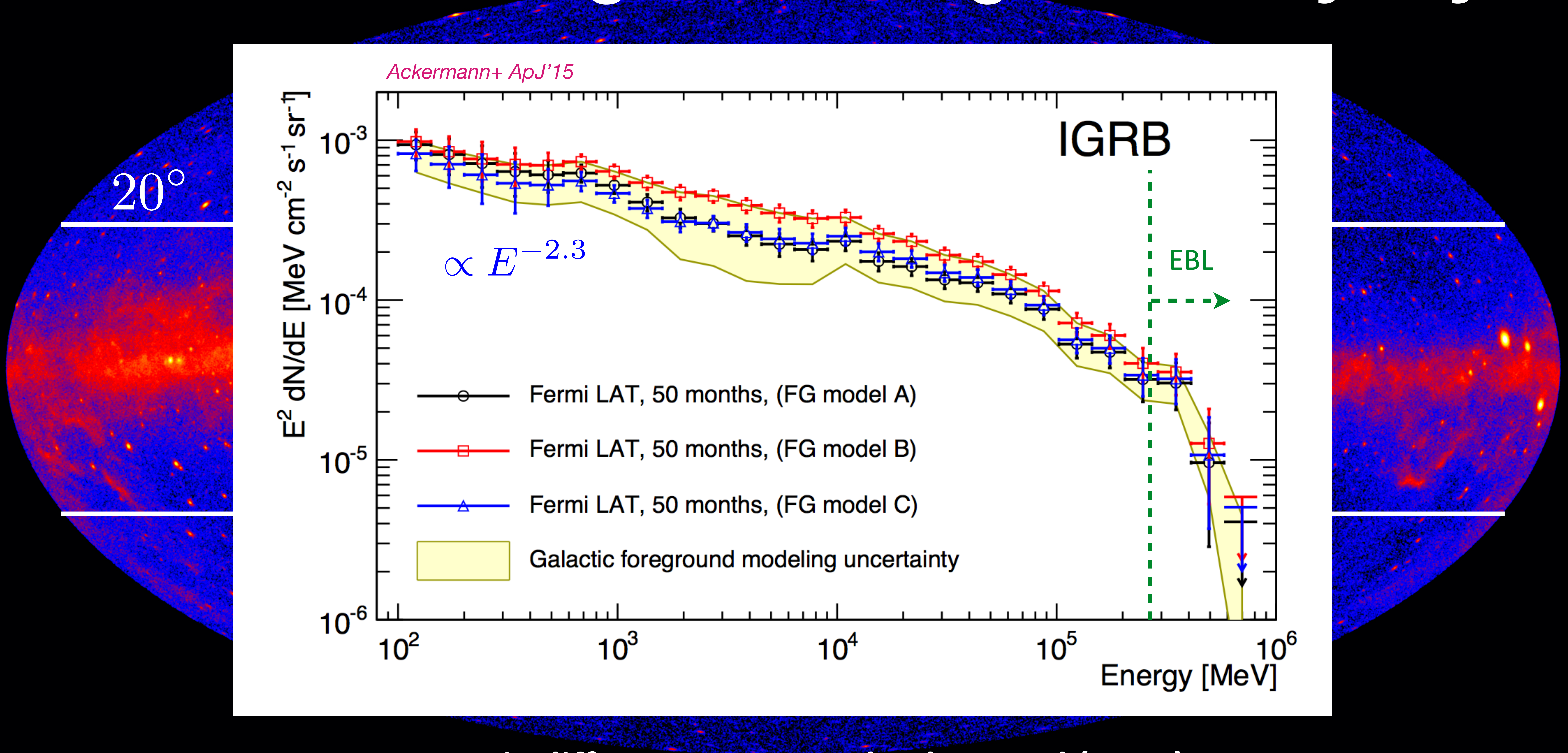


P. Ray 8th Fermi Symposium 2019

The Fermi-LAT high-latitude gamma-ray sky

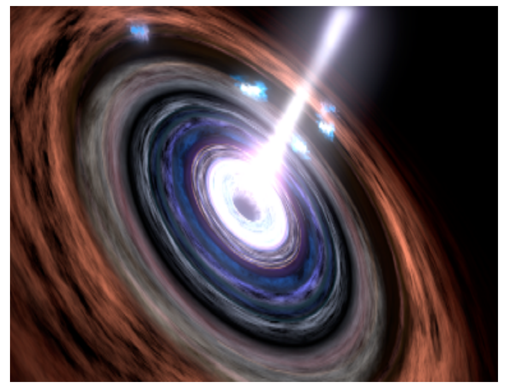


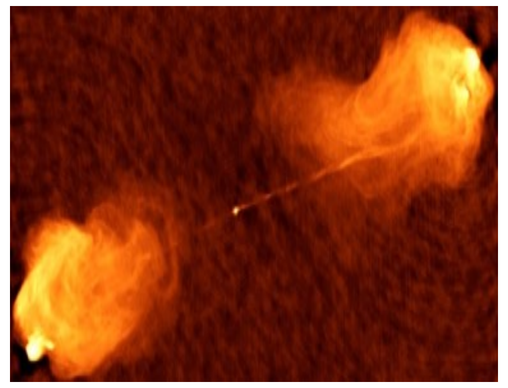
The Fermi-LAT high-latitude gamma-ray sky



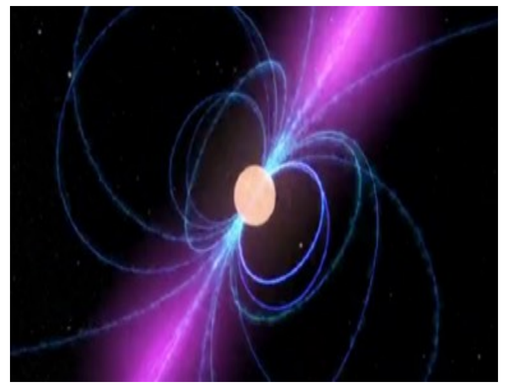
Isotropic diffuse gamma-ray background (IGRB)

The origin of the IGRB

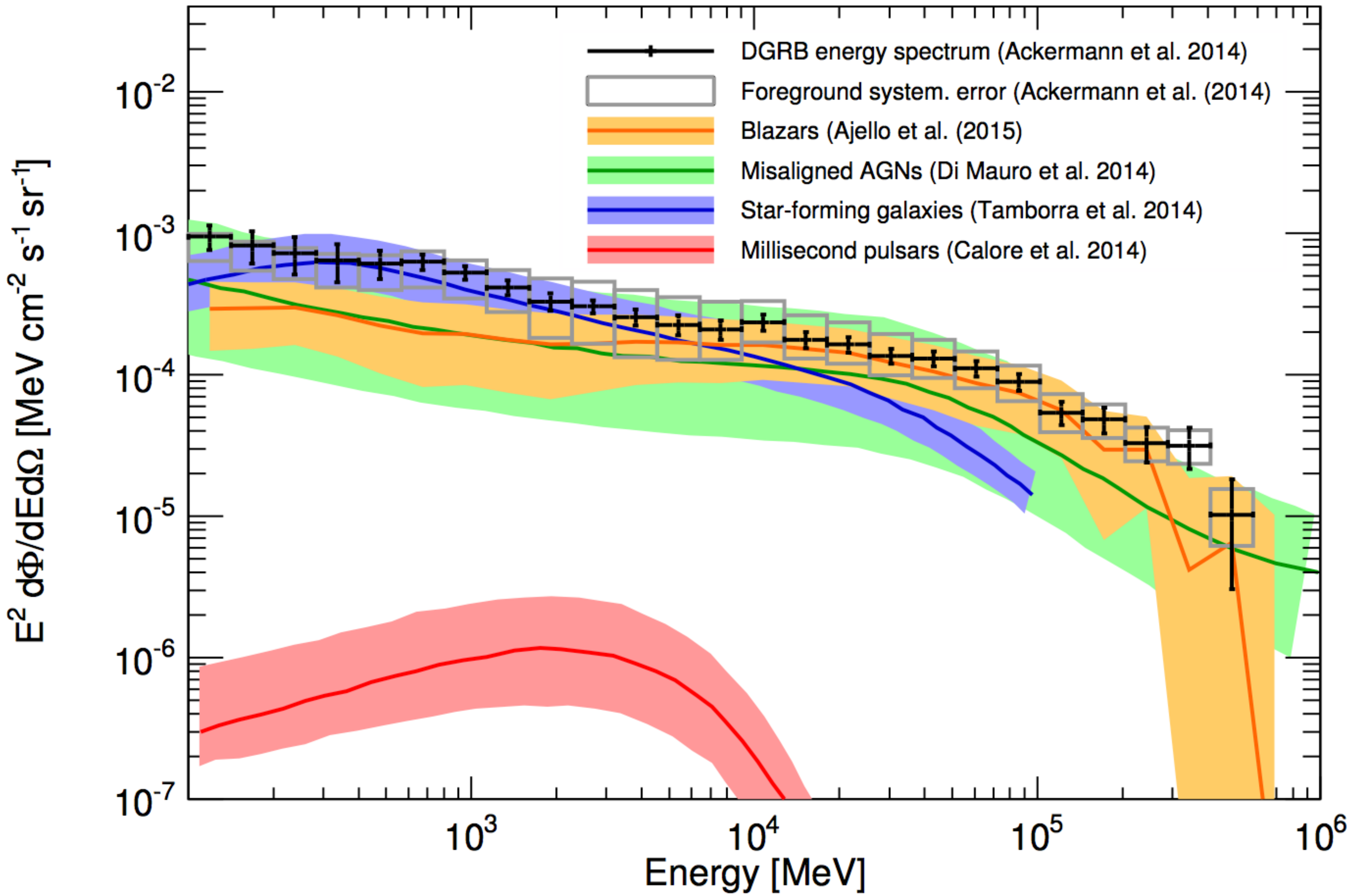

Blazars

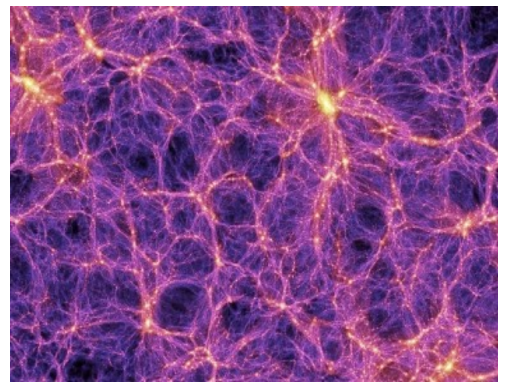

MAGN

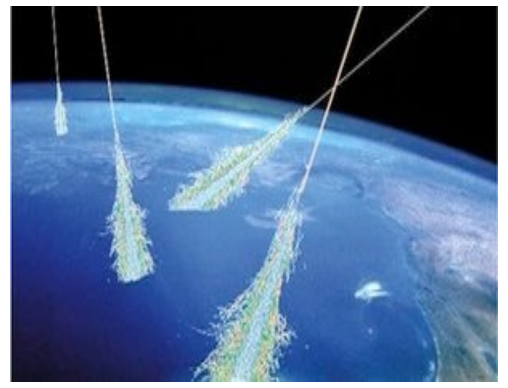

SF galaxies


PSR

Fornasa & Sanchez-Conde Phys. Rep.'15




Dark matter

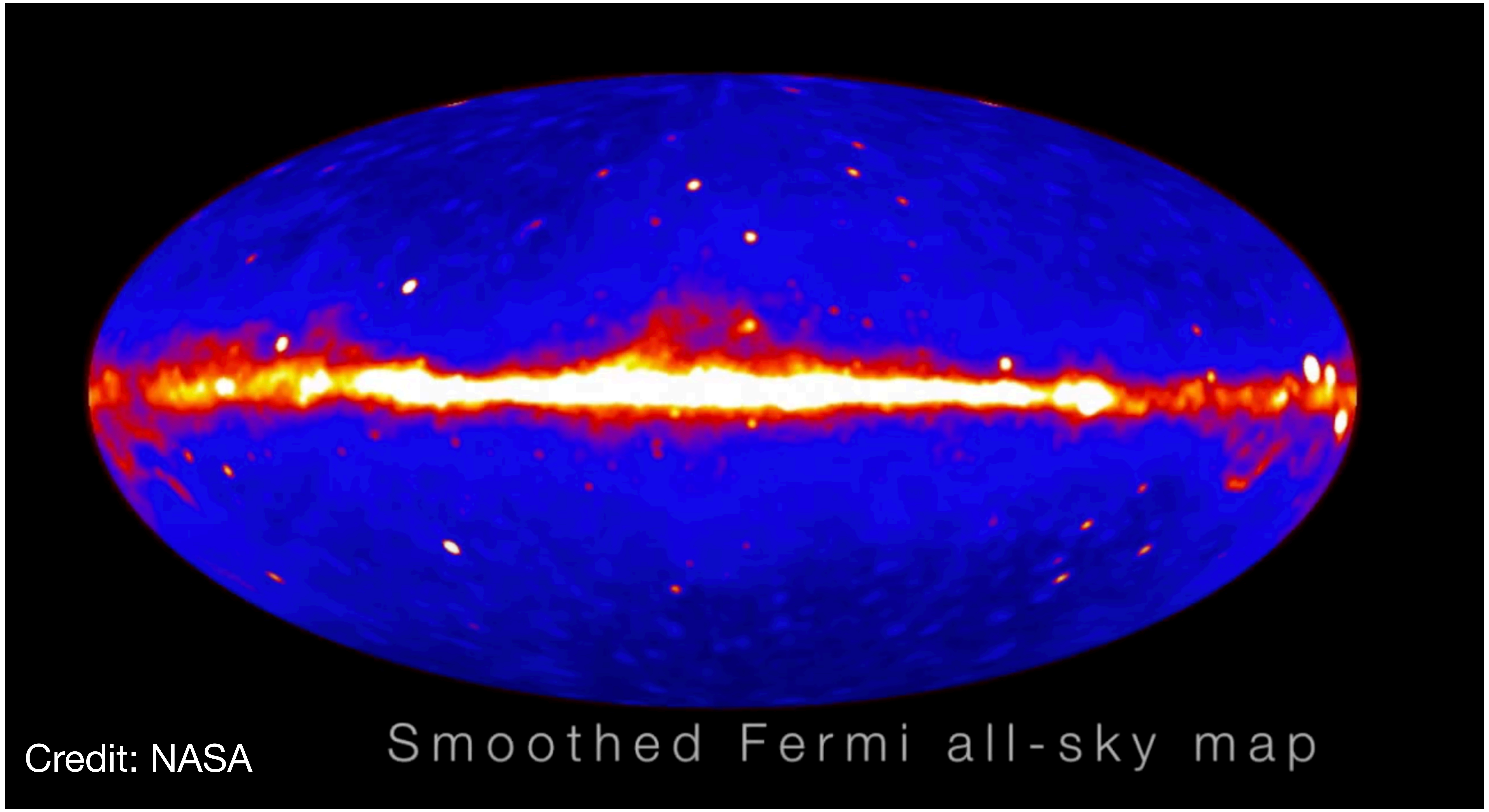

UHECR


Galaxy clusters

[Degeneracy can be broken by combining anisotropy and X-correlation measurements, e.g. *Ammazzalorso+PRD'18*]

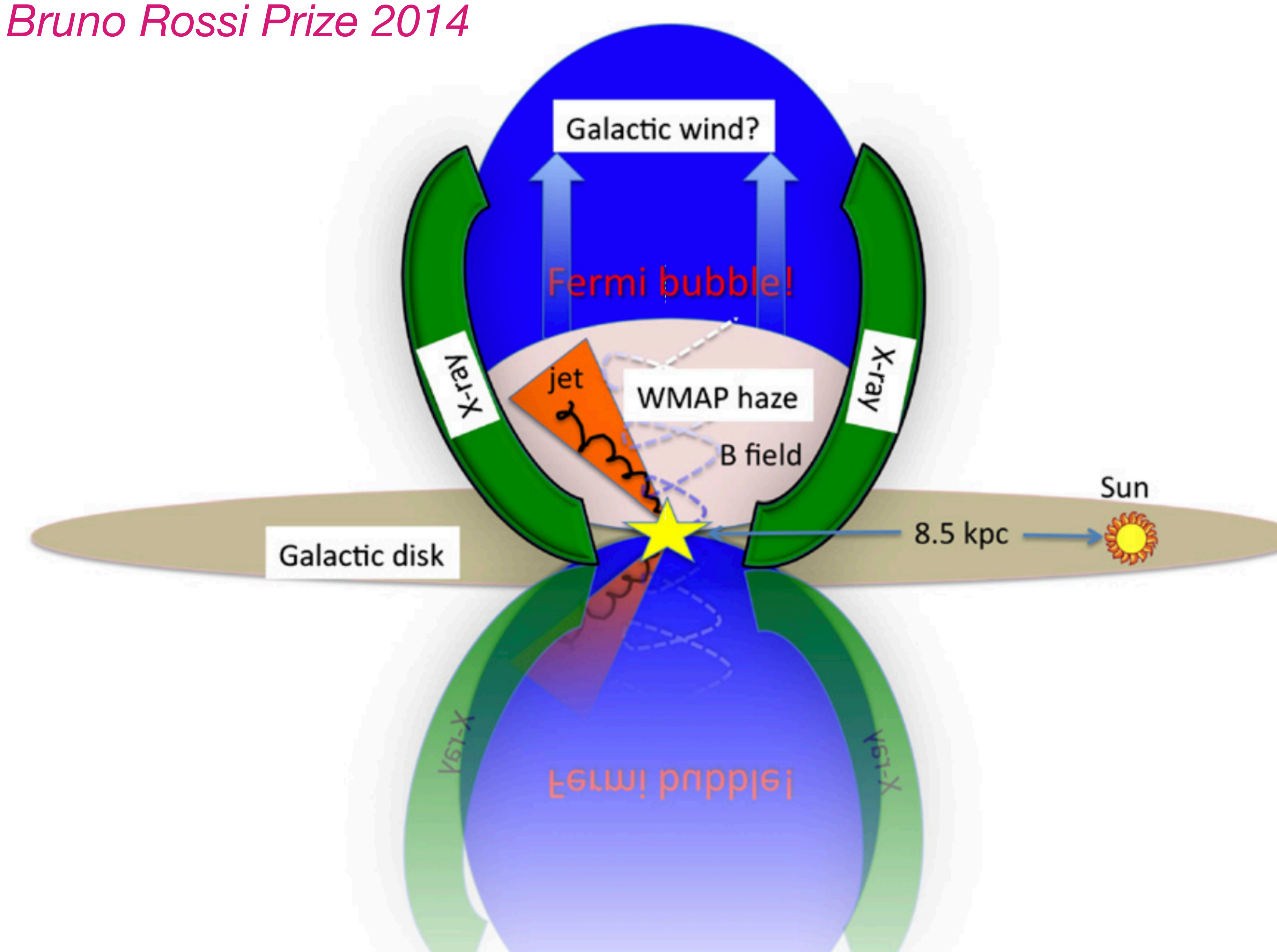
Two transformative discoveries

1. Fermi Bubbles



Su+ ApJ'10

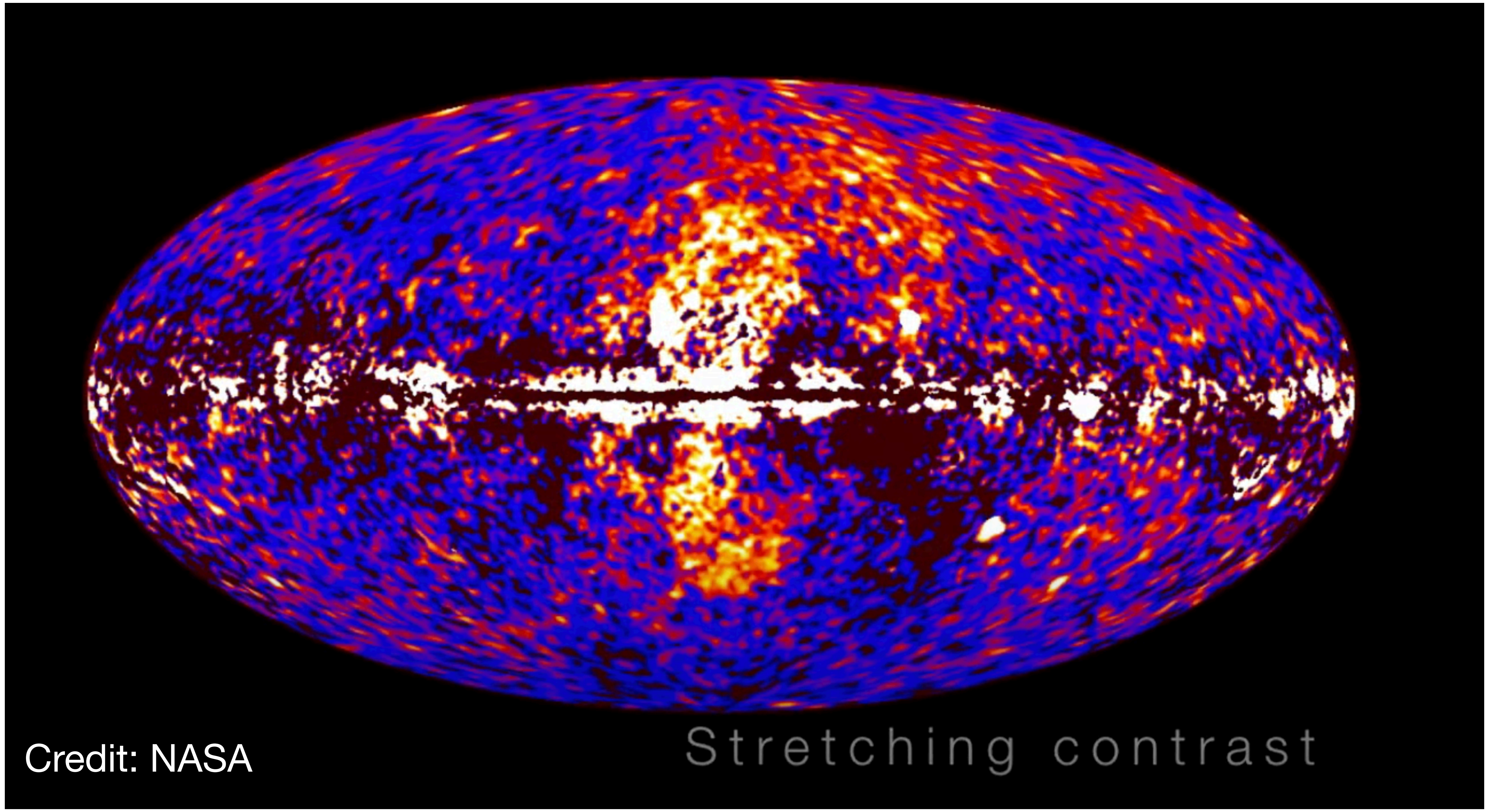
Bruno Rossi Prize 2014



- Discovery of previously unseen structure centered in the Galactic center
- Multi-wavelength counterparts (radio, microwave, X rays)
- **Yet of unknown origin**: fuelled by past AGN activities and/or nuclear starbursts?

Two transformative discoveries

1. Fermi Bubbles



Su+ ApJ'10

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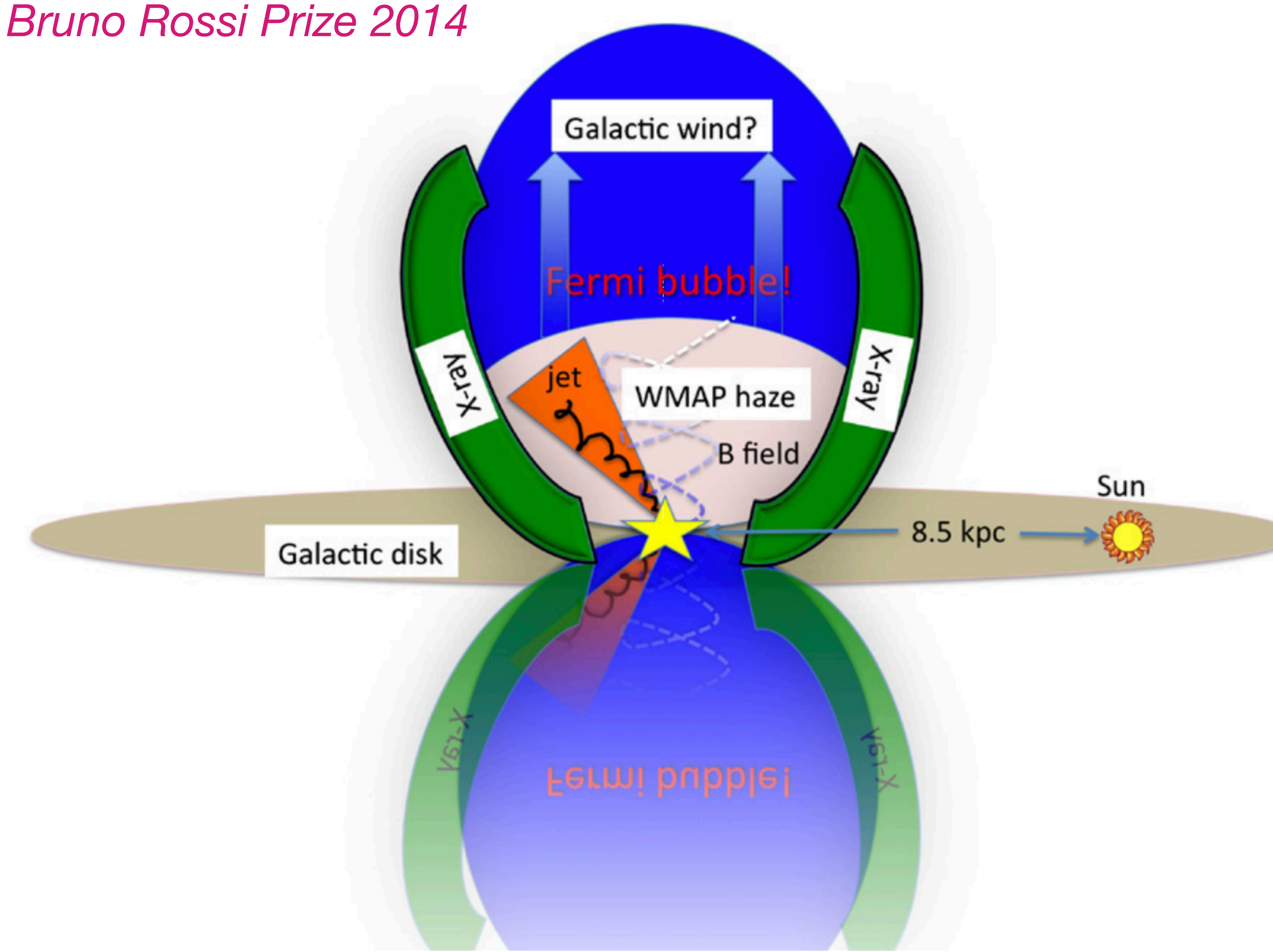
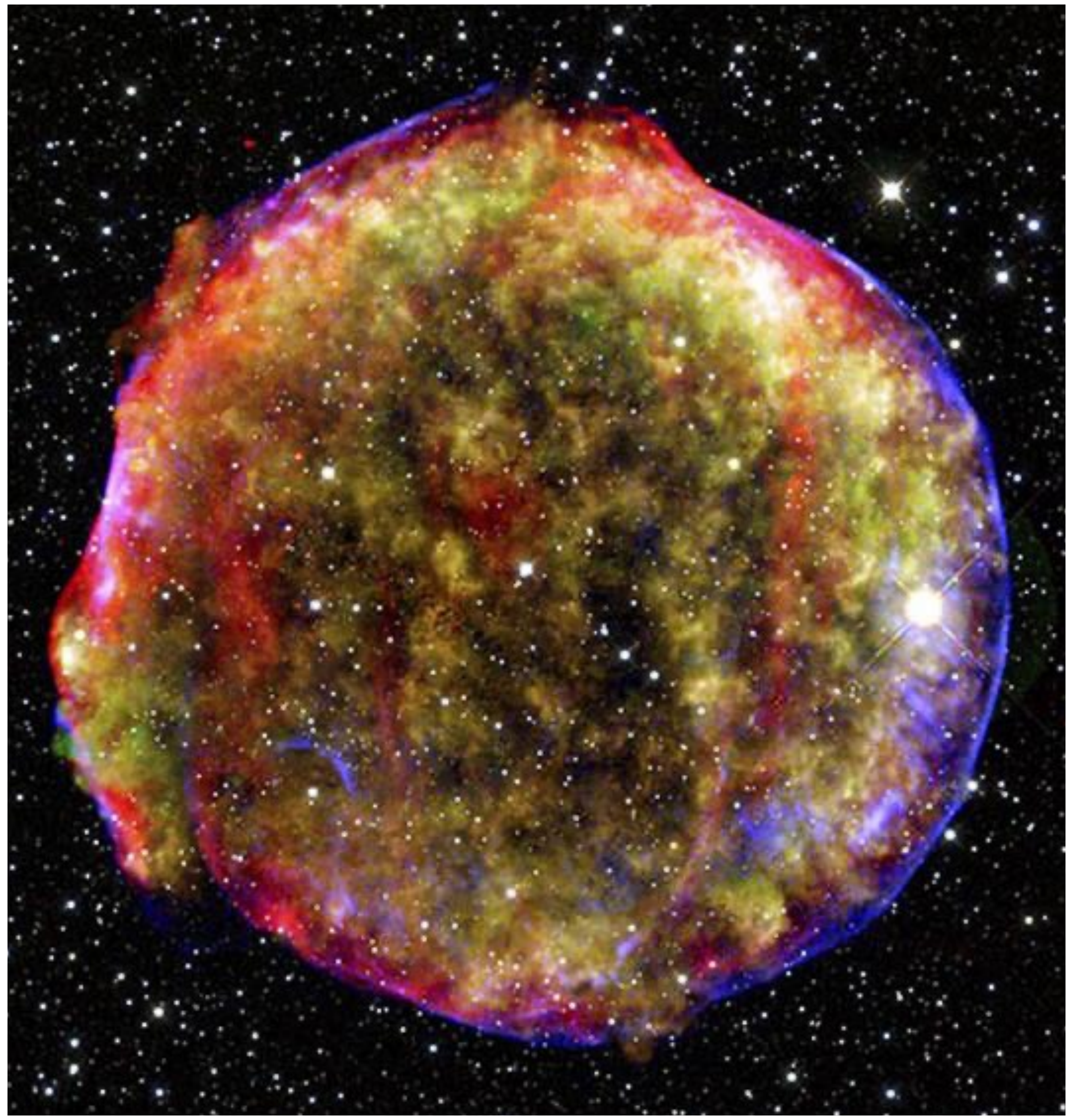
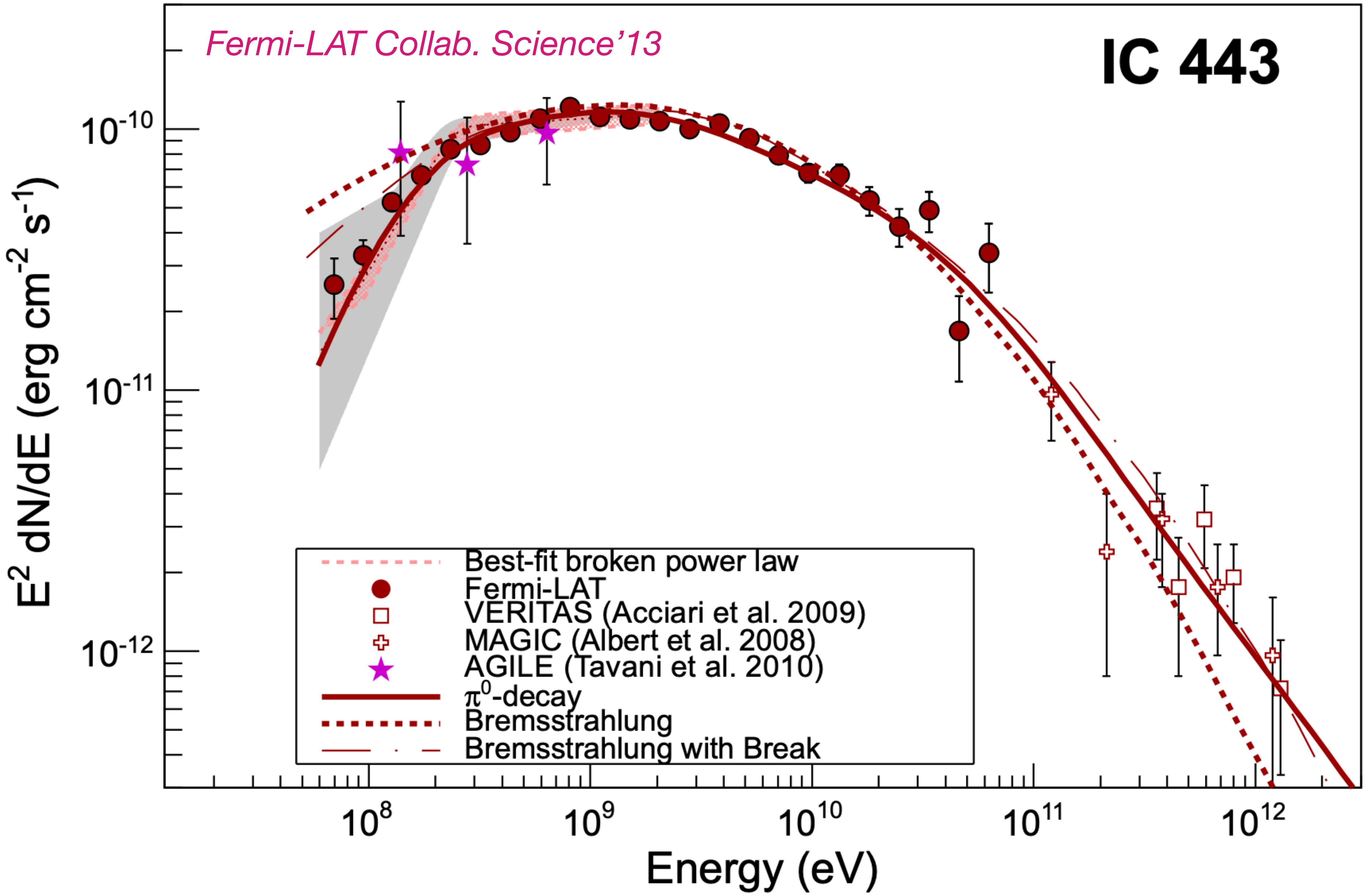


- Discovery of previously unseen structure centered in the Galactic center
- Multi-wavelength counterparts (radio, microwave, X rays)
- **Yet of unknown origin**: fuelled by past AGN activities and/or nuclear starbursts?

Two transformative discoveries

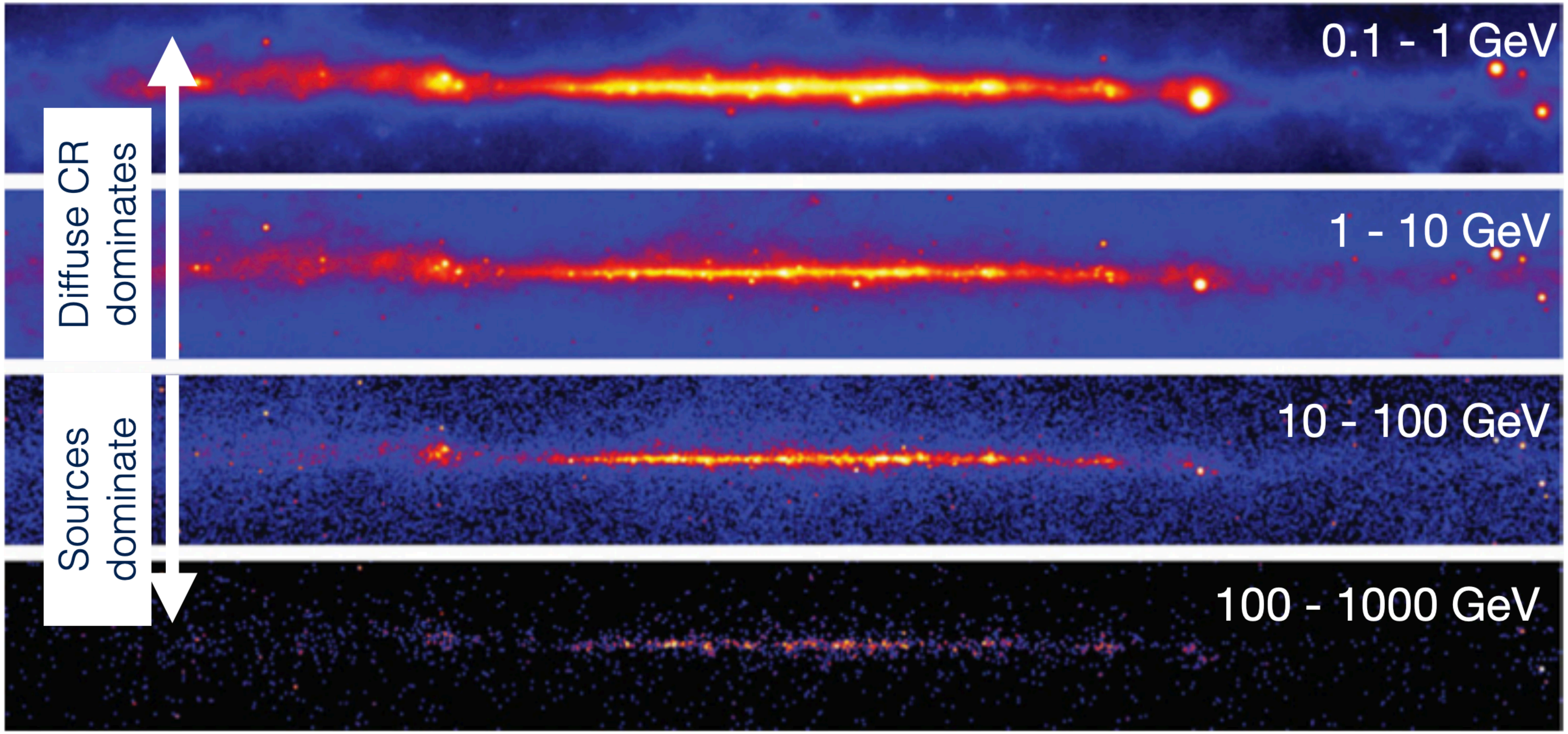
2. Evidence for proton acceleration in SNR





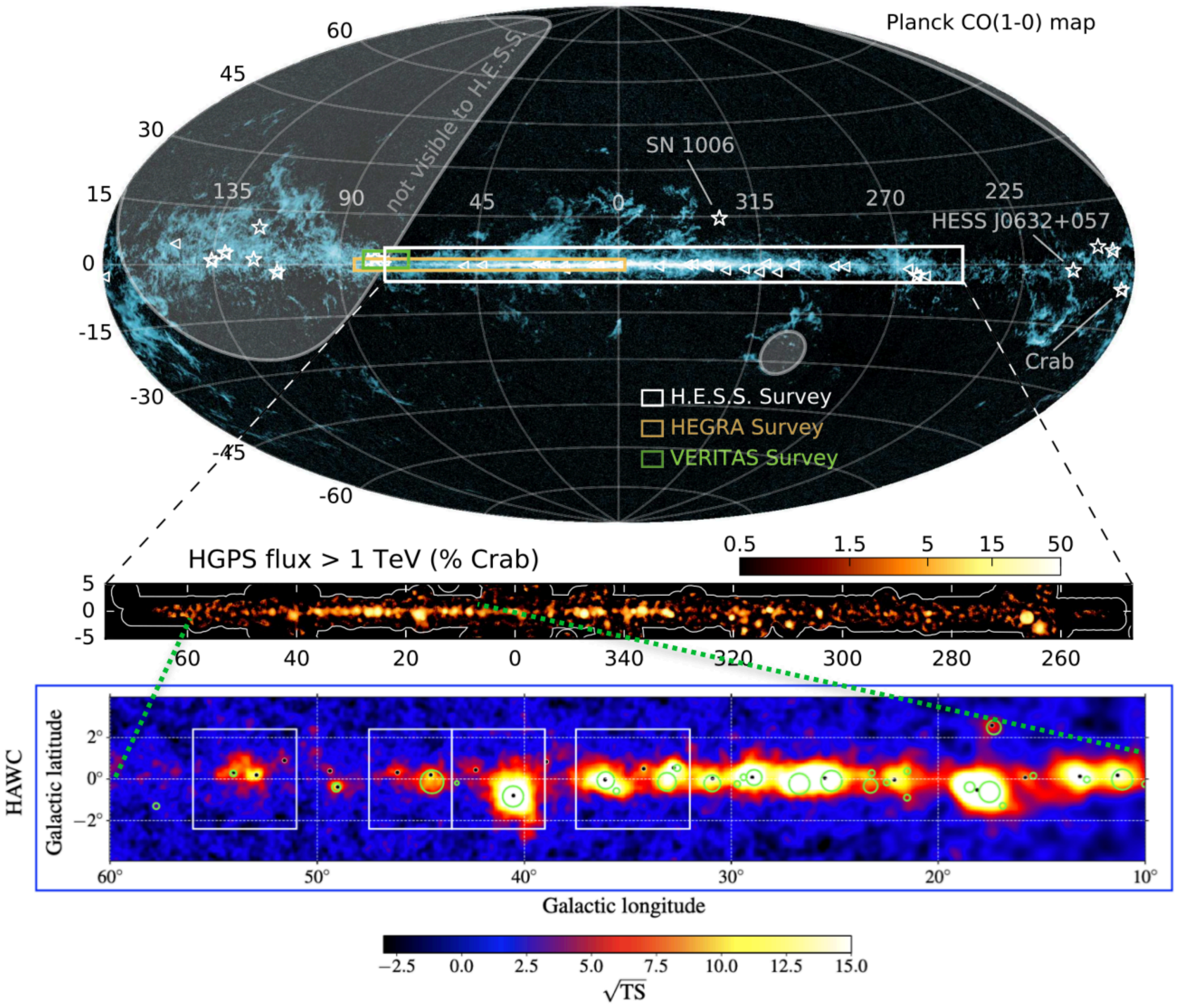
- Detection of the characteristic gamma-ray pion-decay signature in SNRs
- Leptonic models are disfavoured
- Direct evidence that cosmic-ray protons accelerated in SNR W44 & IC443

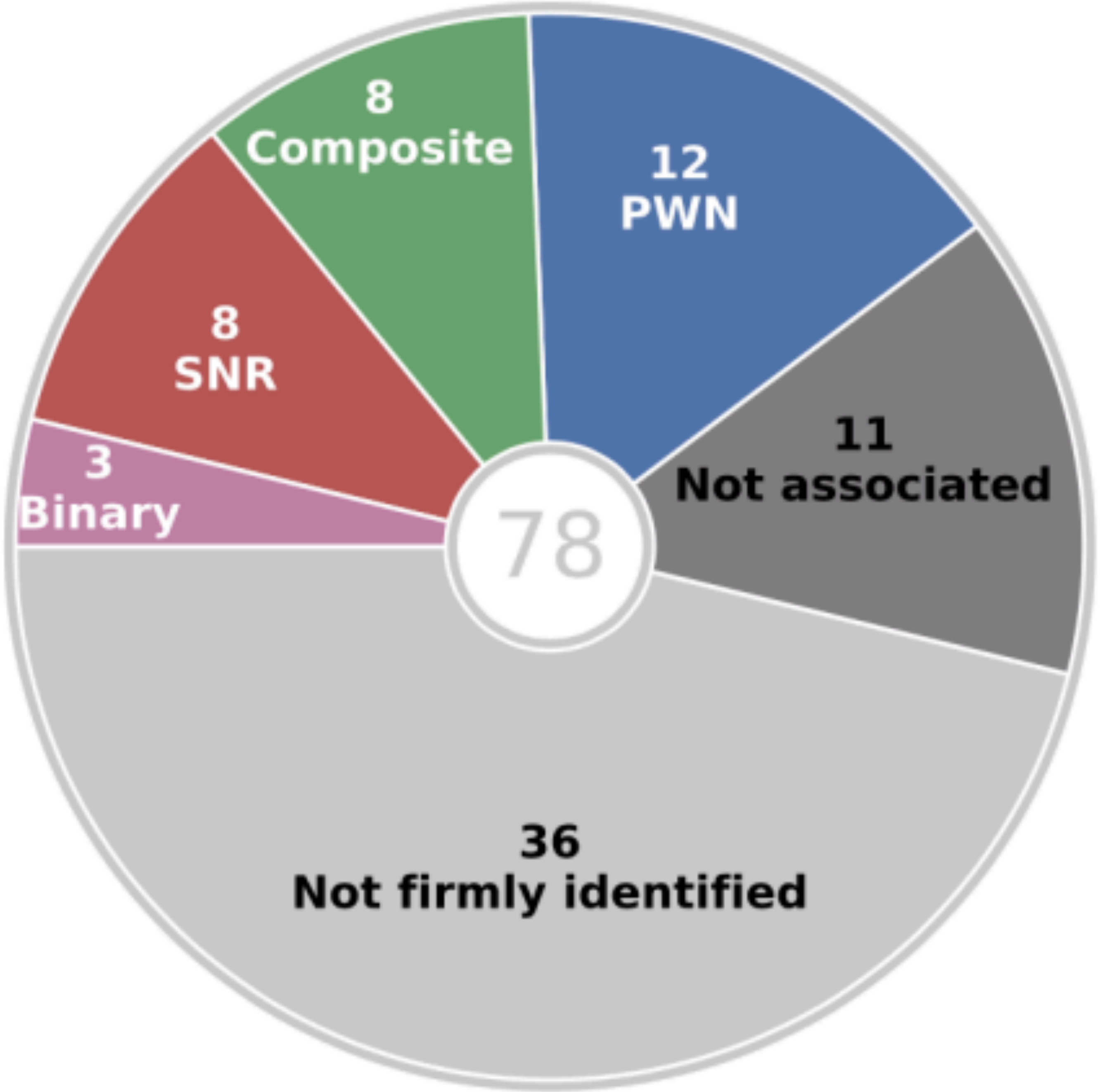
Diffuse emission from TeV to sub-PeV



Point sources at TeV energies

Despite small FoV IACTs can perform effective surveys

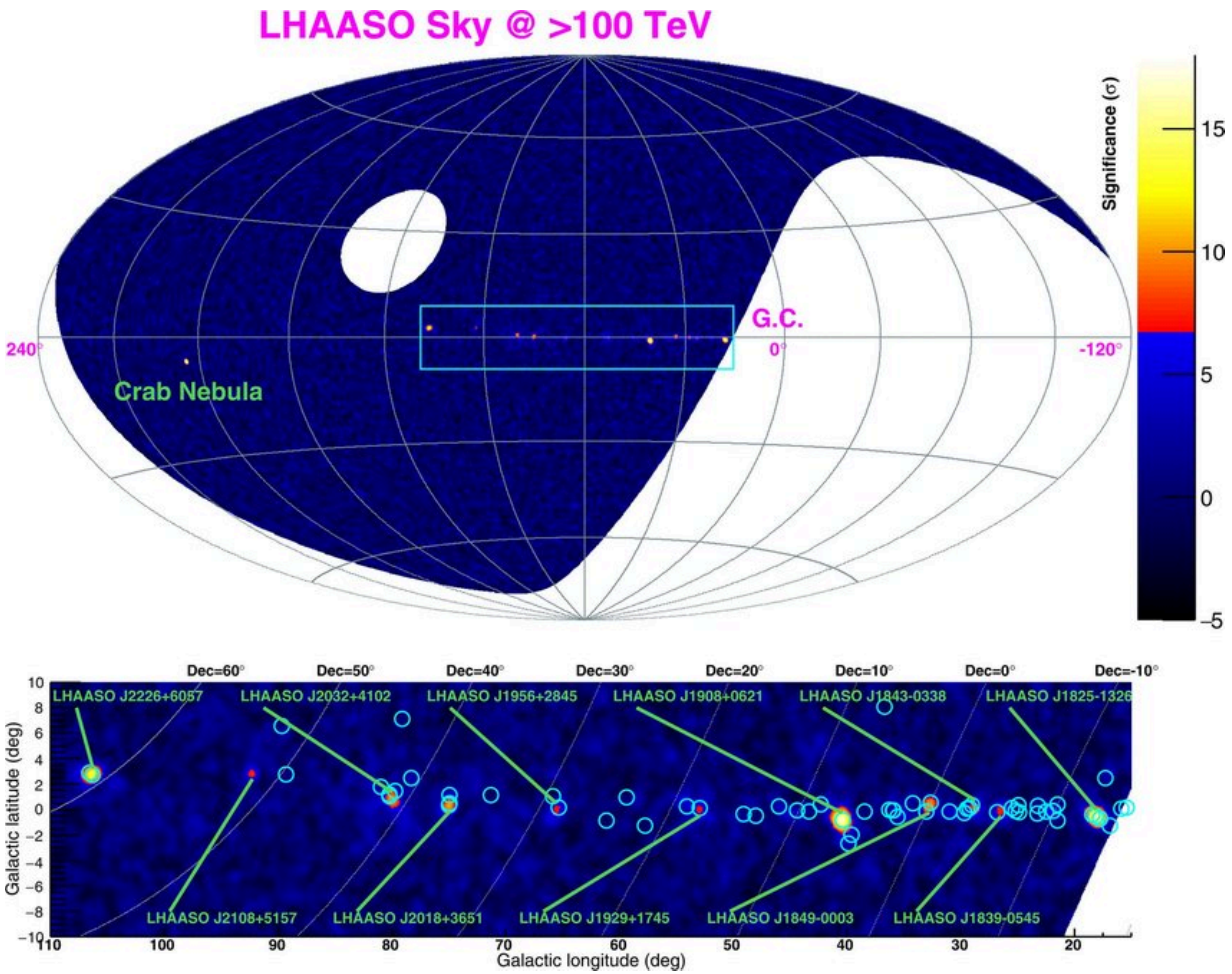


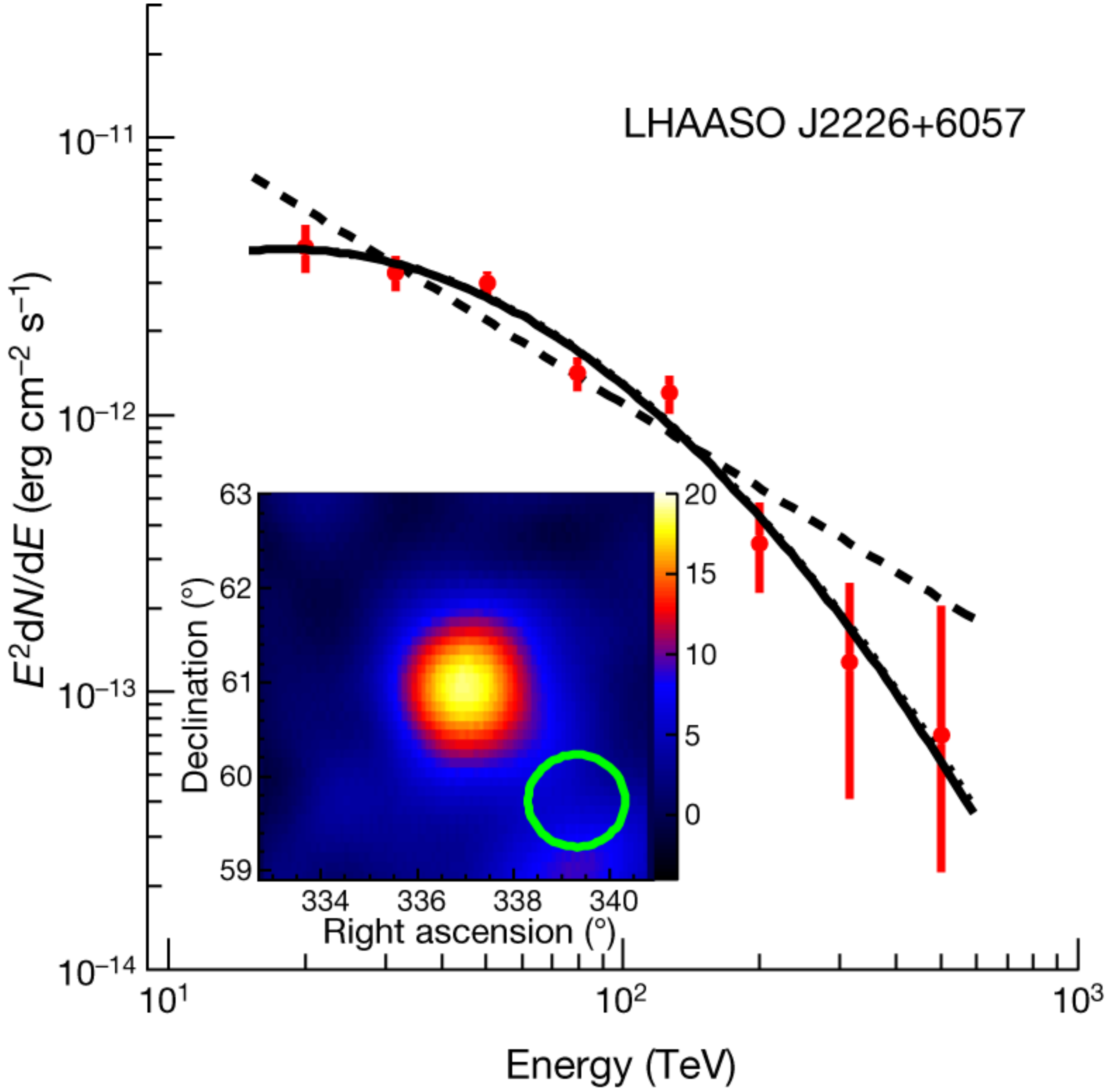


Galactic plane full of TeVatrons!

HAWC: Sources up to 100 TeV!

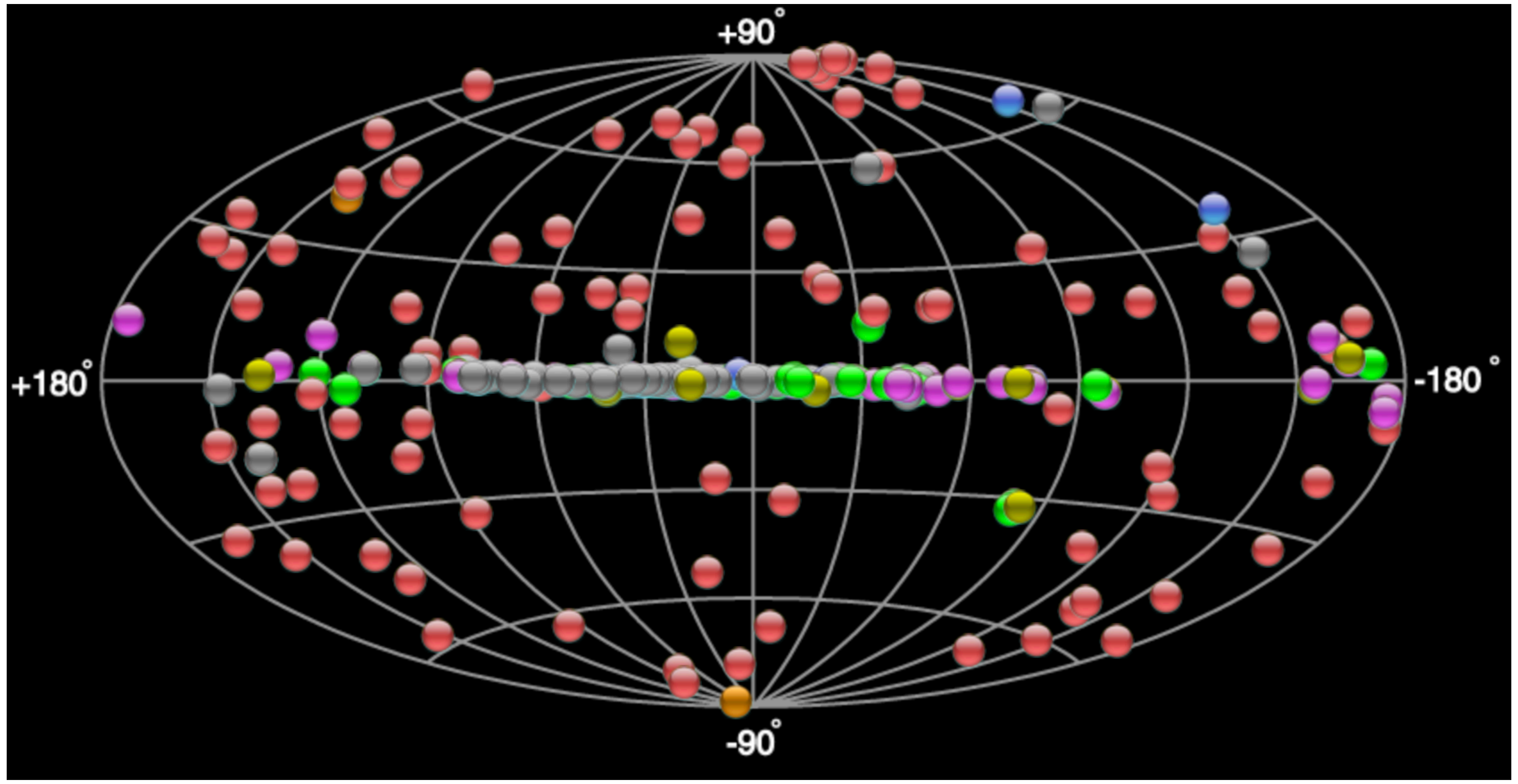
Point sources at sub-PeV energies



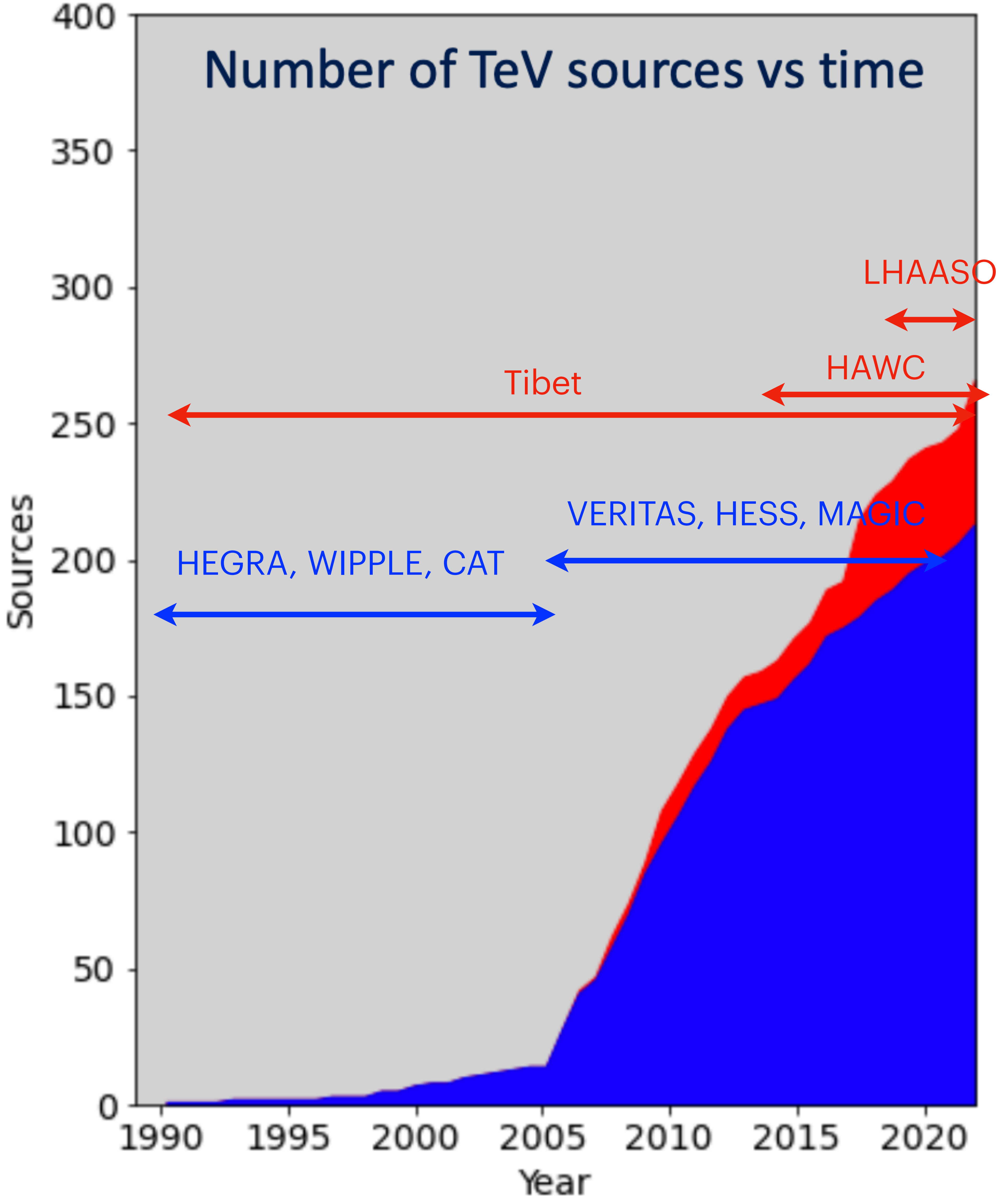


12 PeVatrons

Sources: from TeV to sub-PeV



[TeVCAT Catalog]

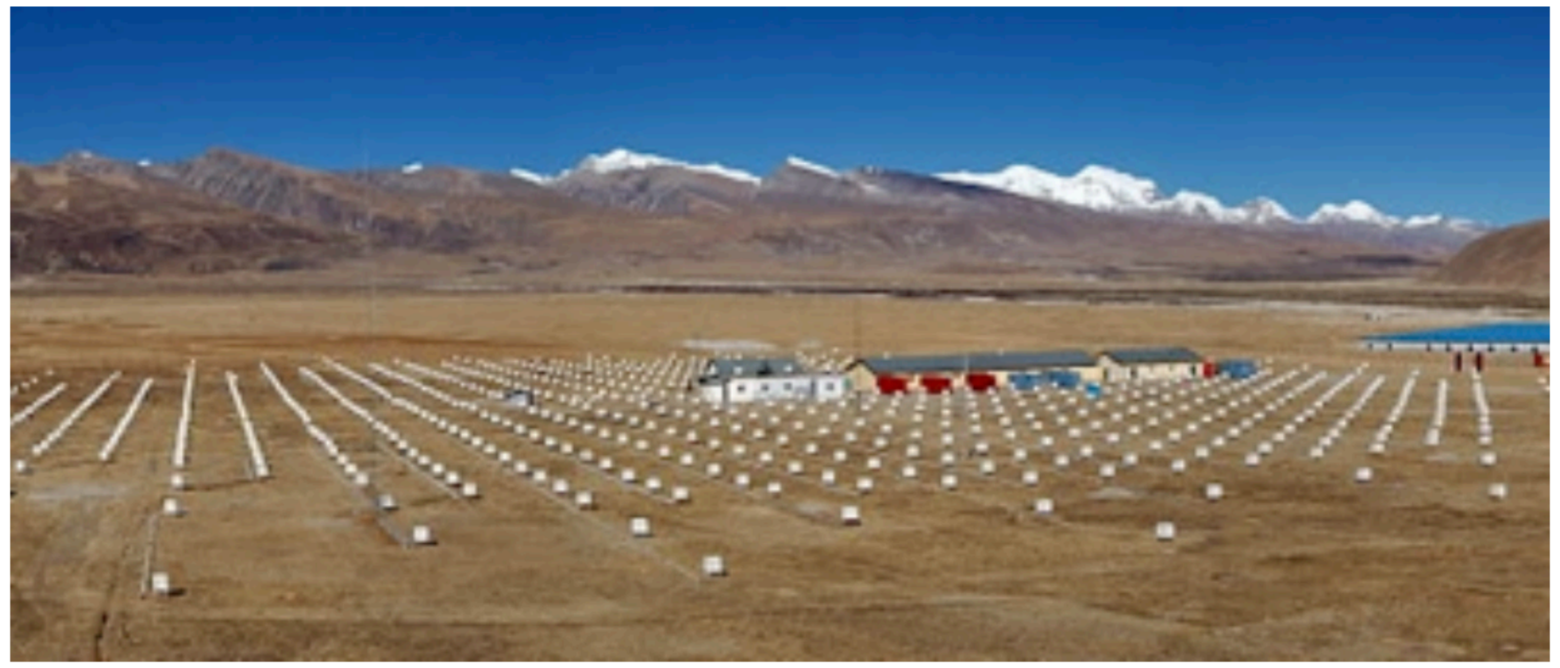


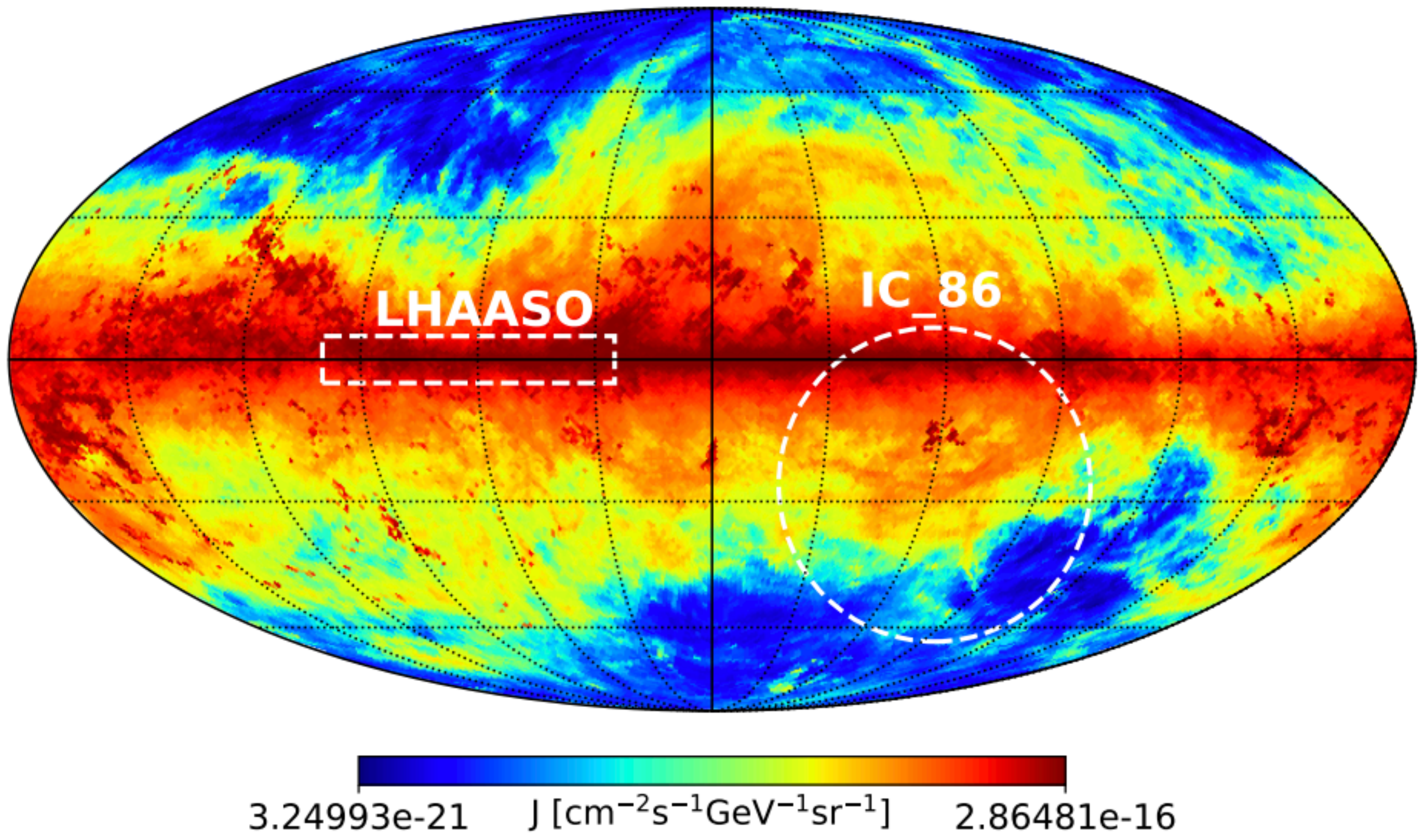
Diffuse emission: from TeV to sub-PeV

First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies

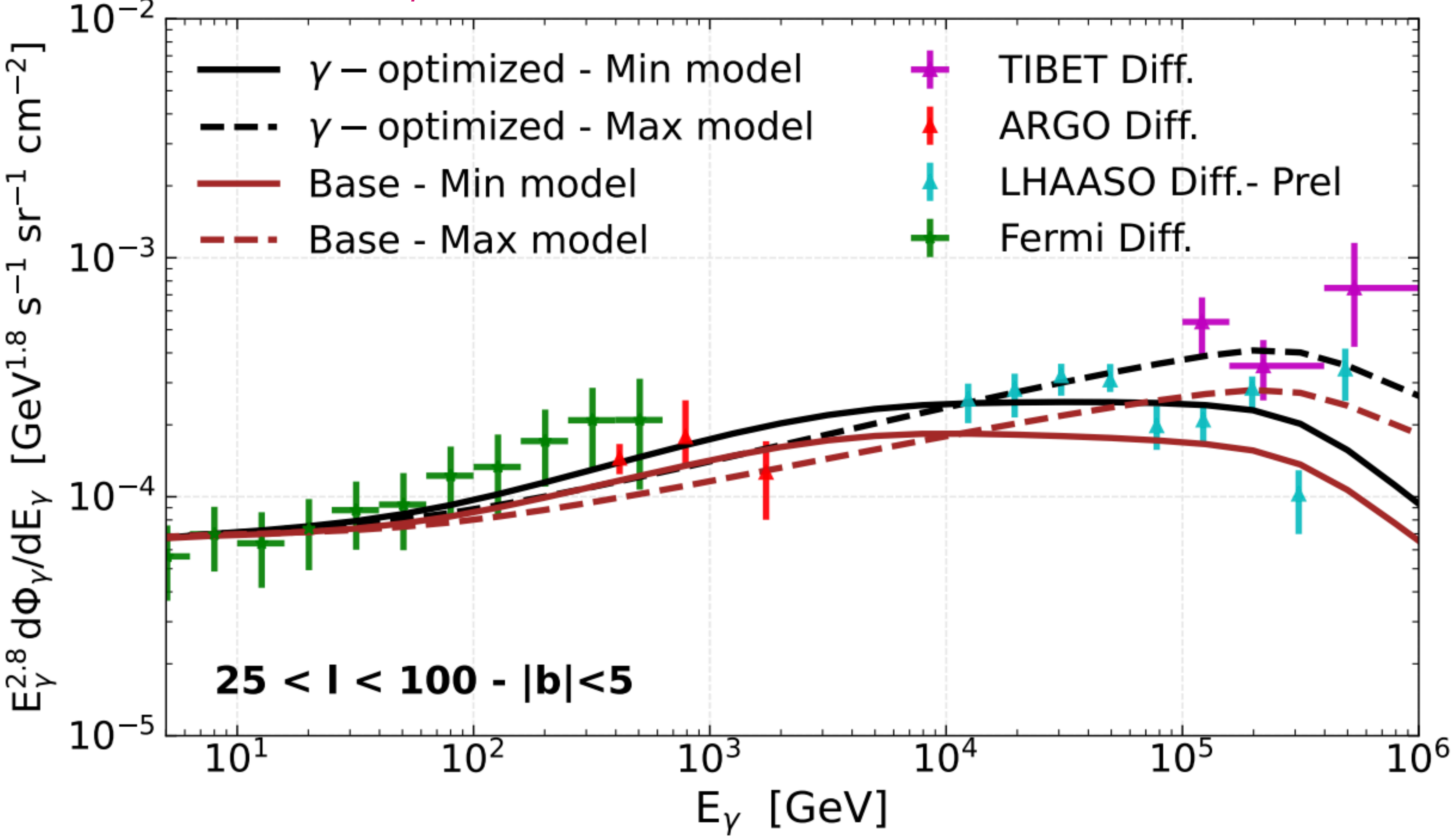
M. Amenomori *et al.* (Tibet AS_γ Collaboration)

Phys. Rev. Lett. **126**, 141101 – Published 5 April 2021

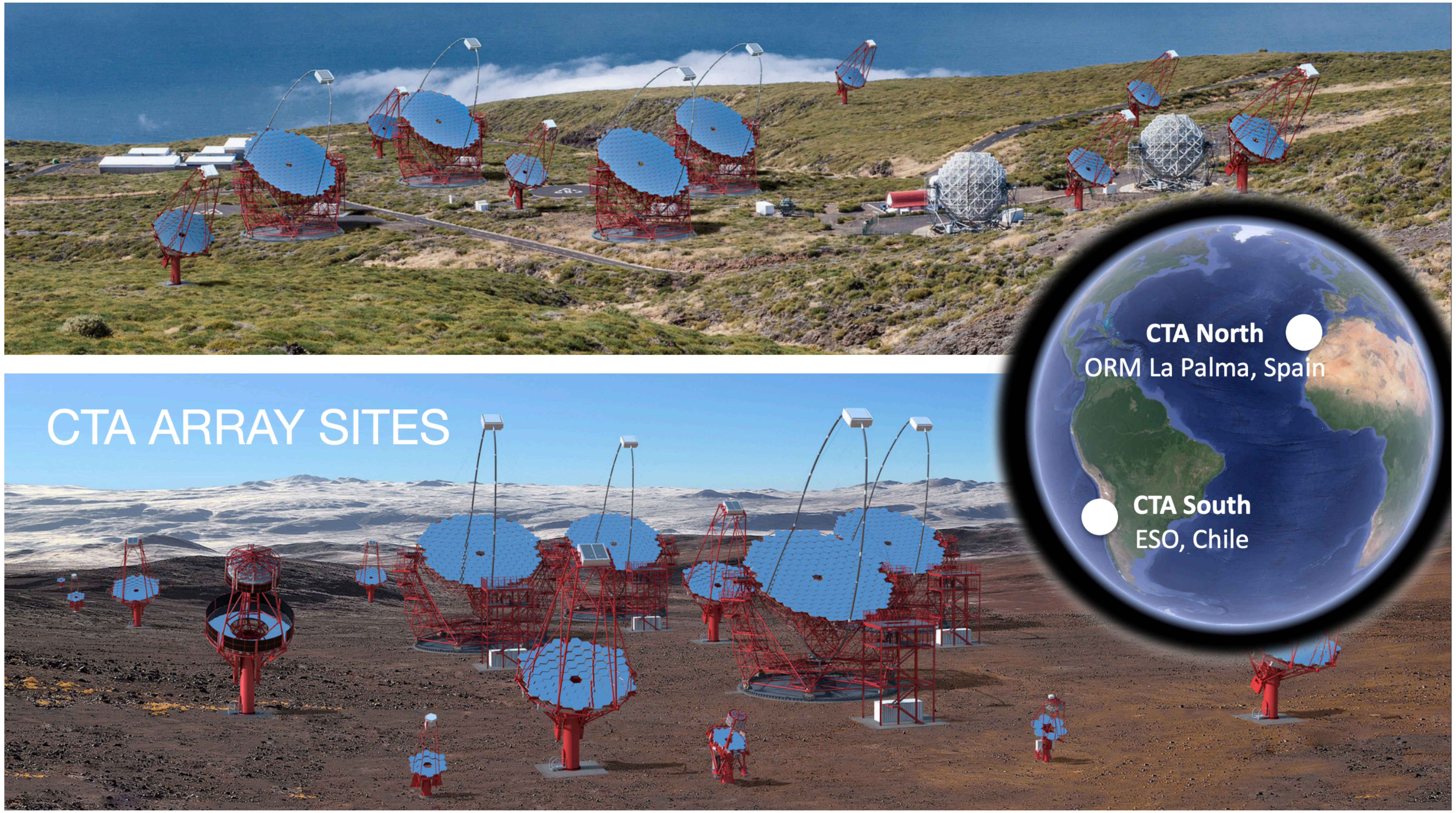




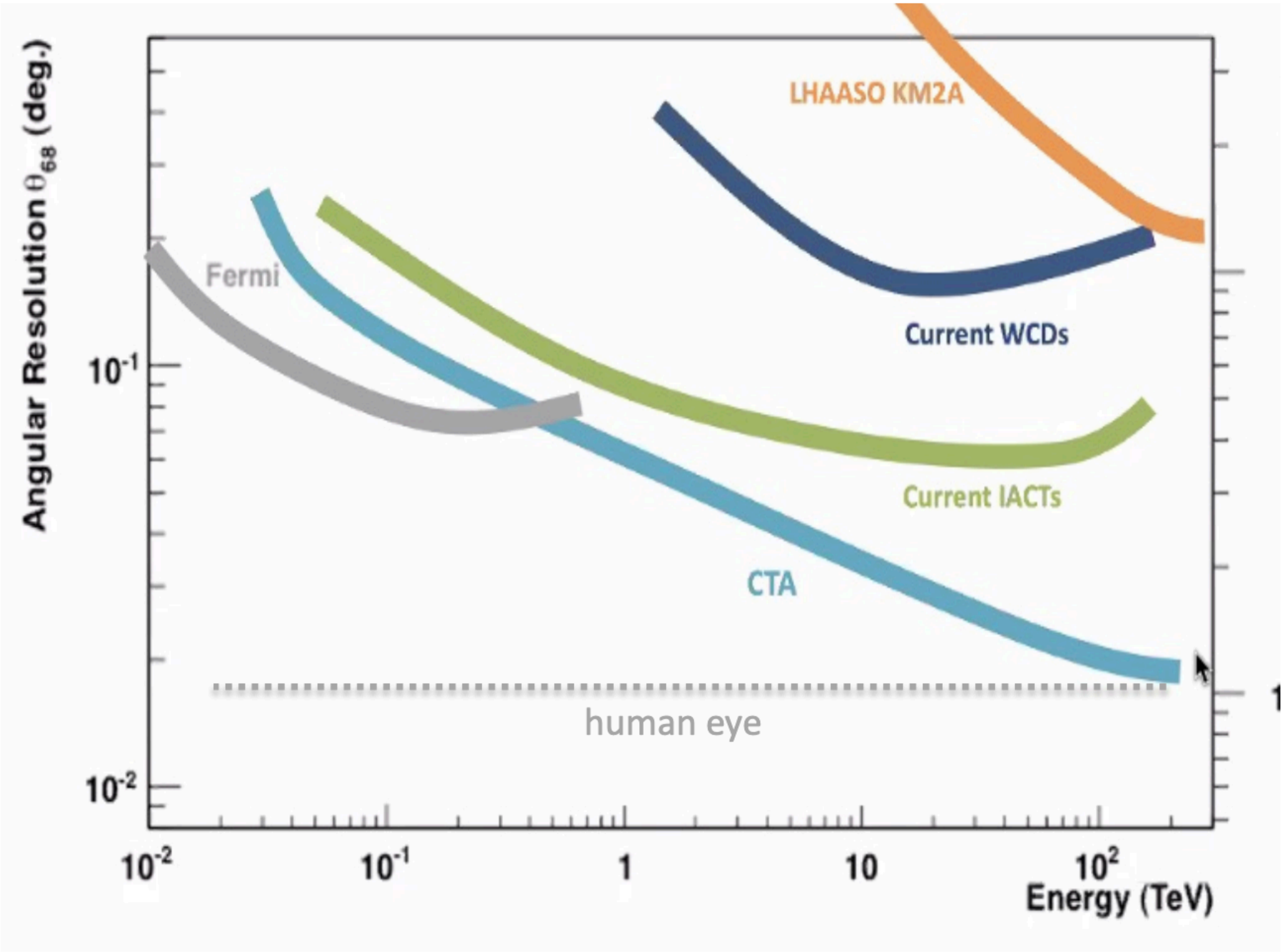
De la Torre Luque+ arXiv:2203.15759

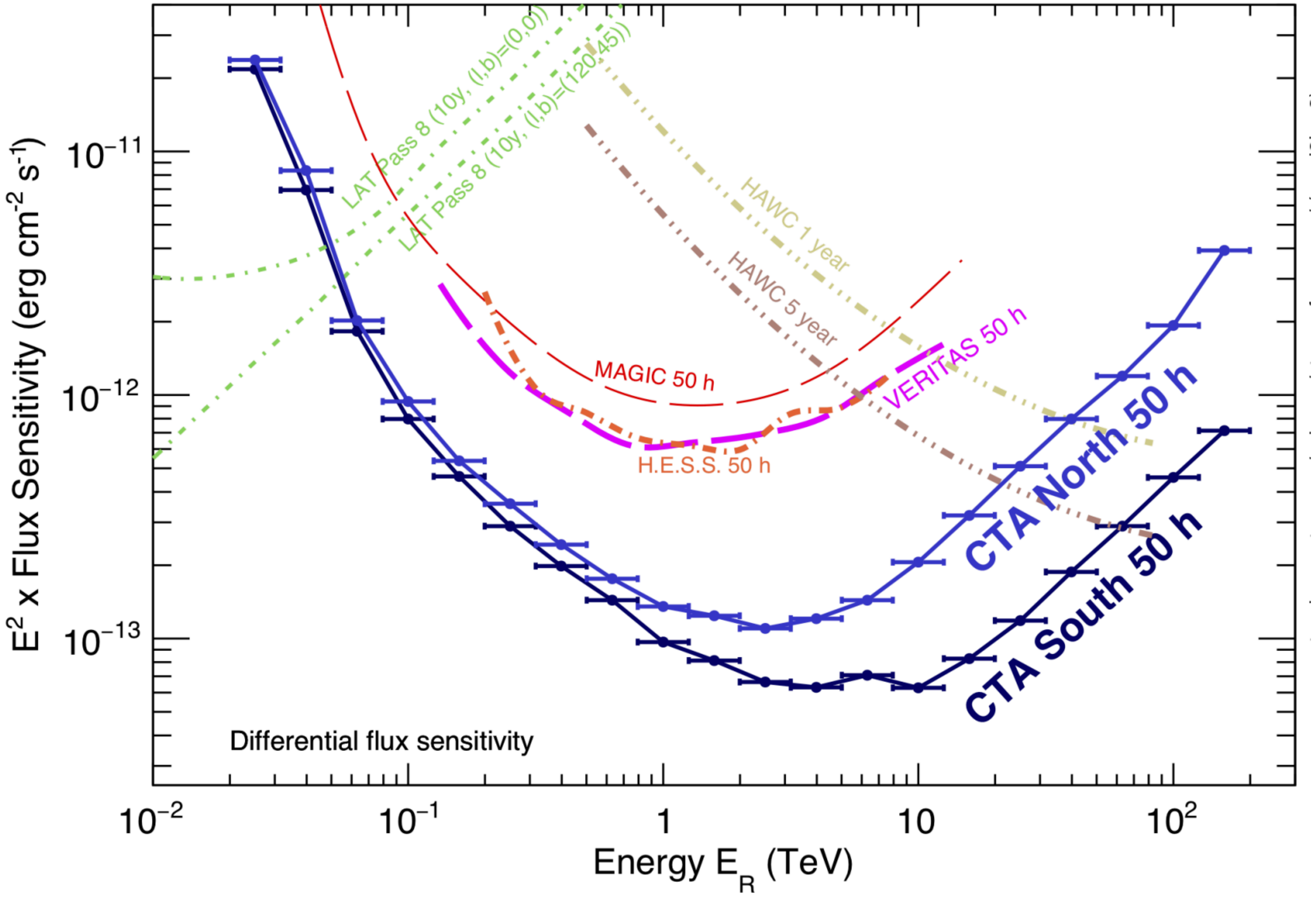


Future: Cherenkov Telescope Array

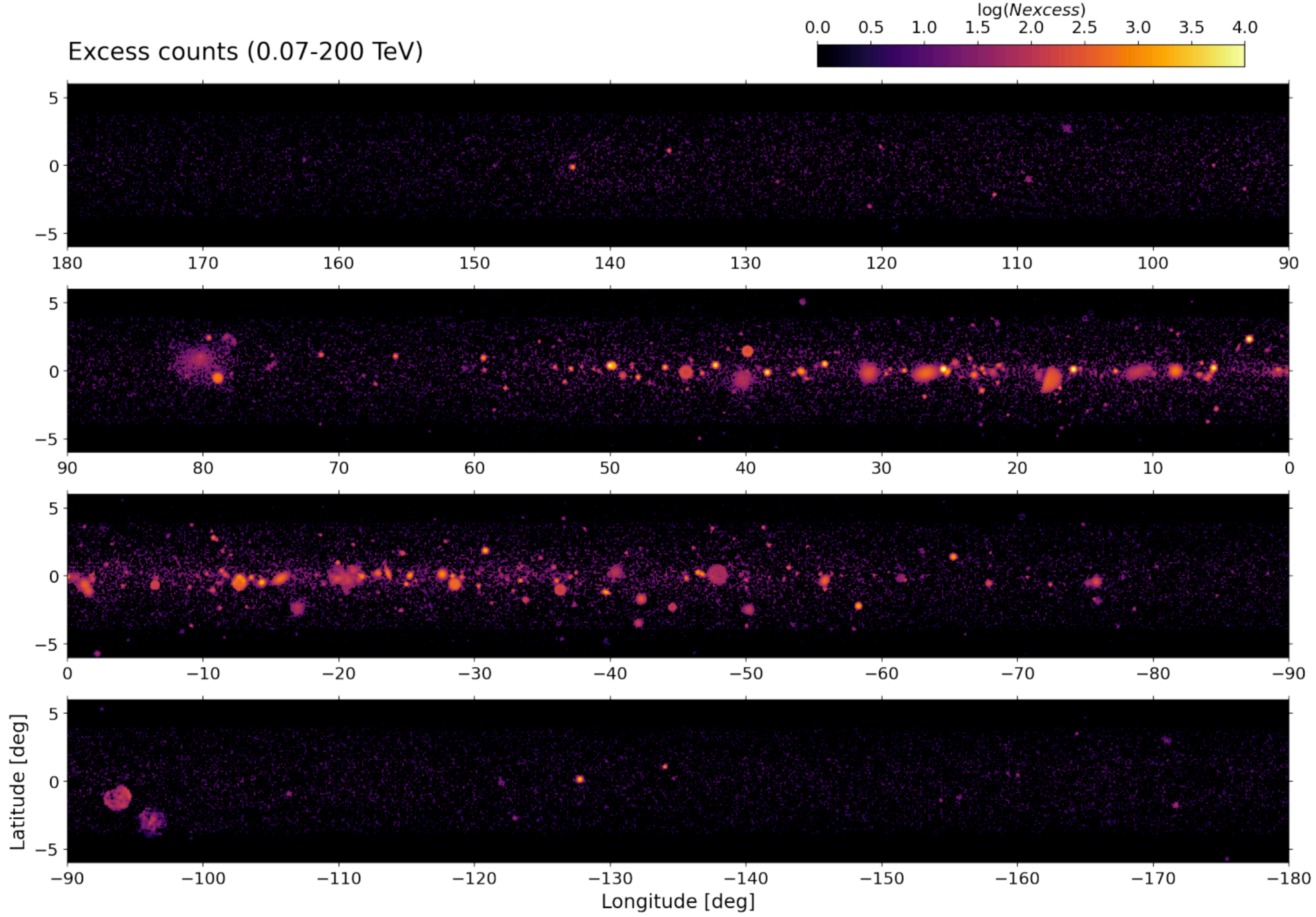


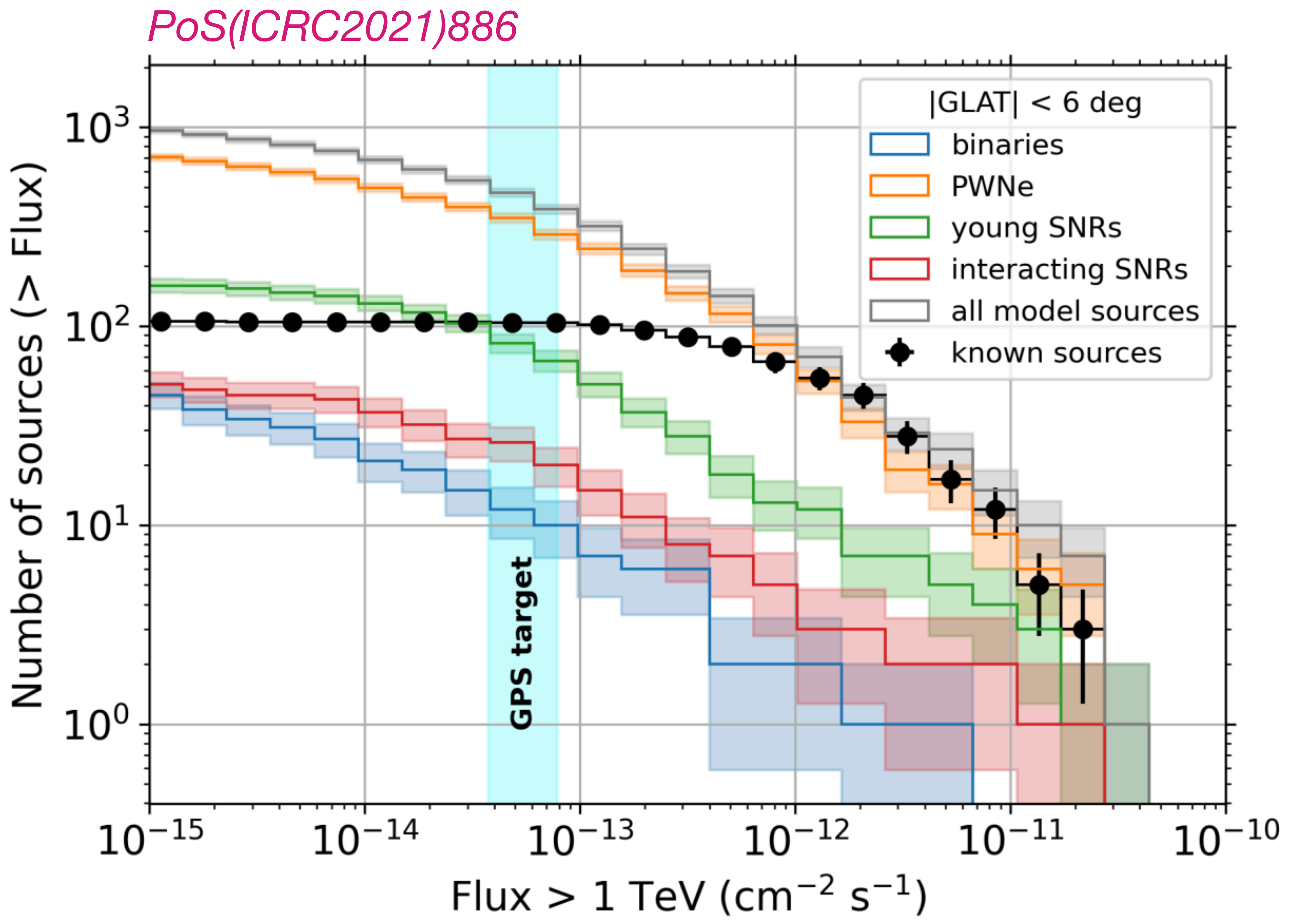
Future: Cherenkov Telescope Array





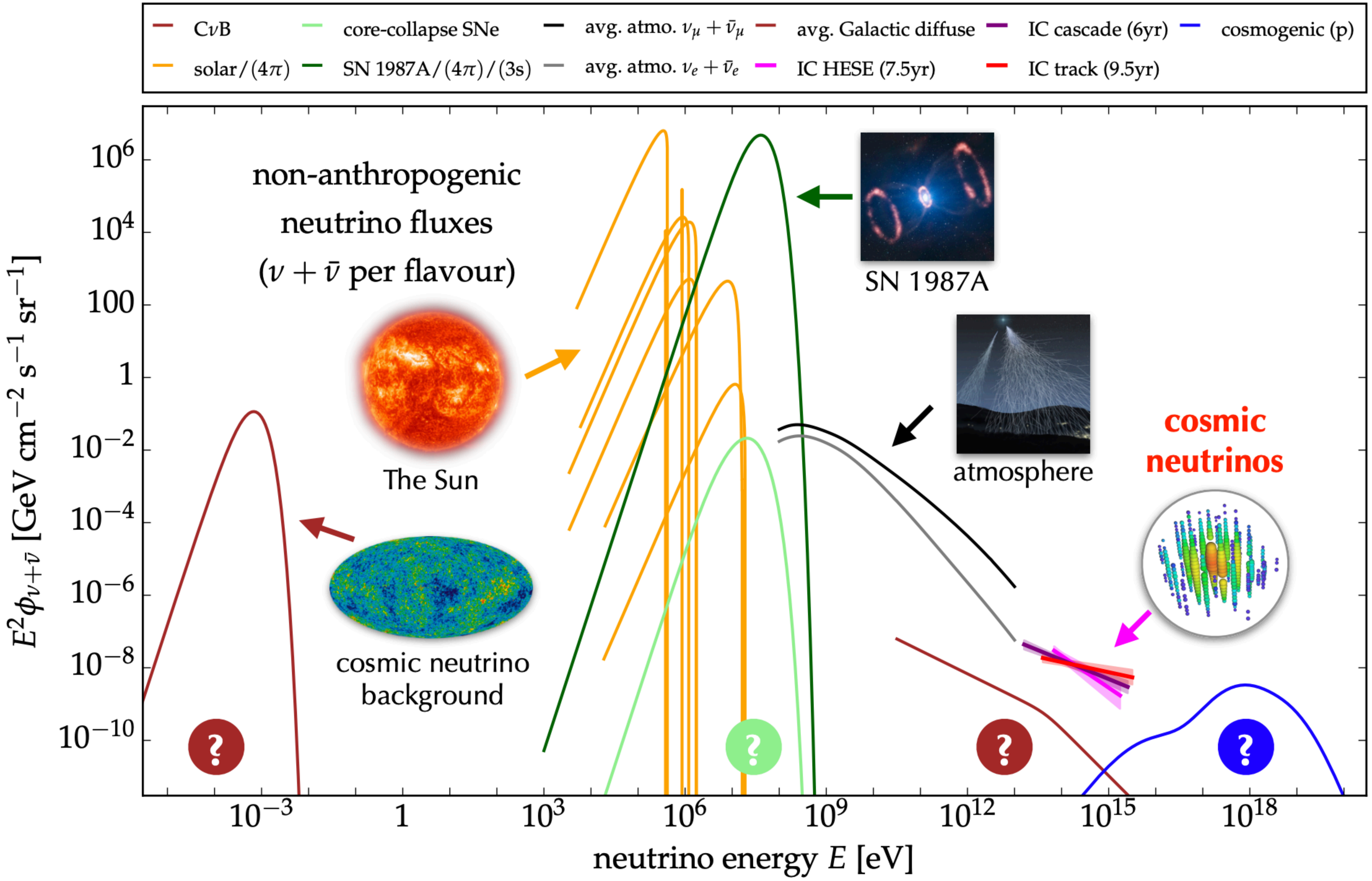
CTA Sources: Galactic Plane Survey





Neutrinos

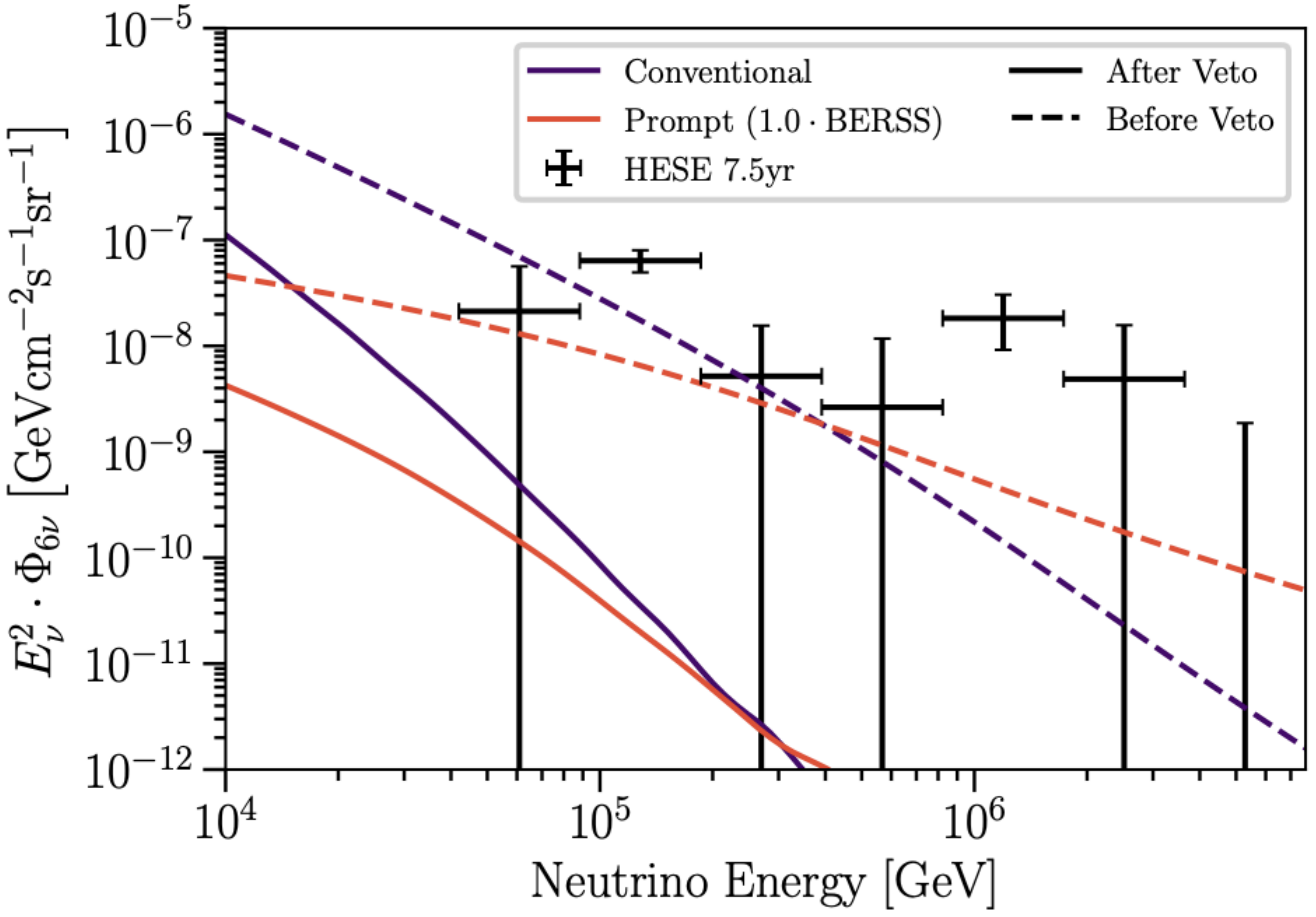
Neutrino sources

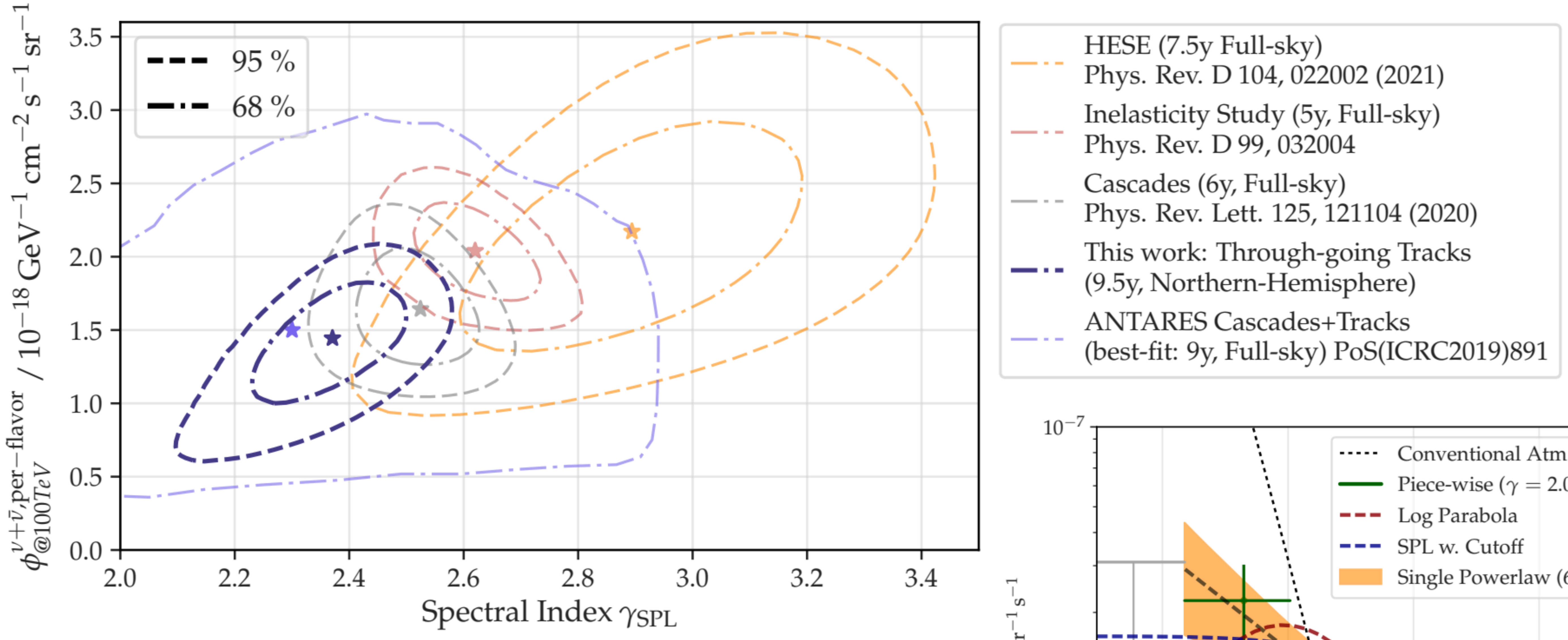


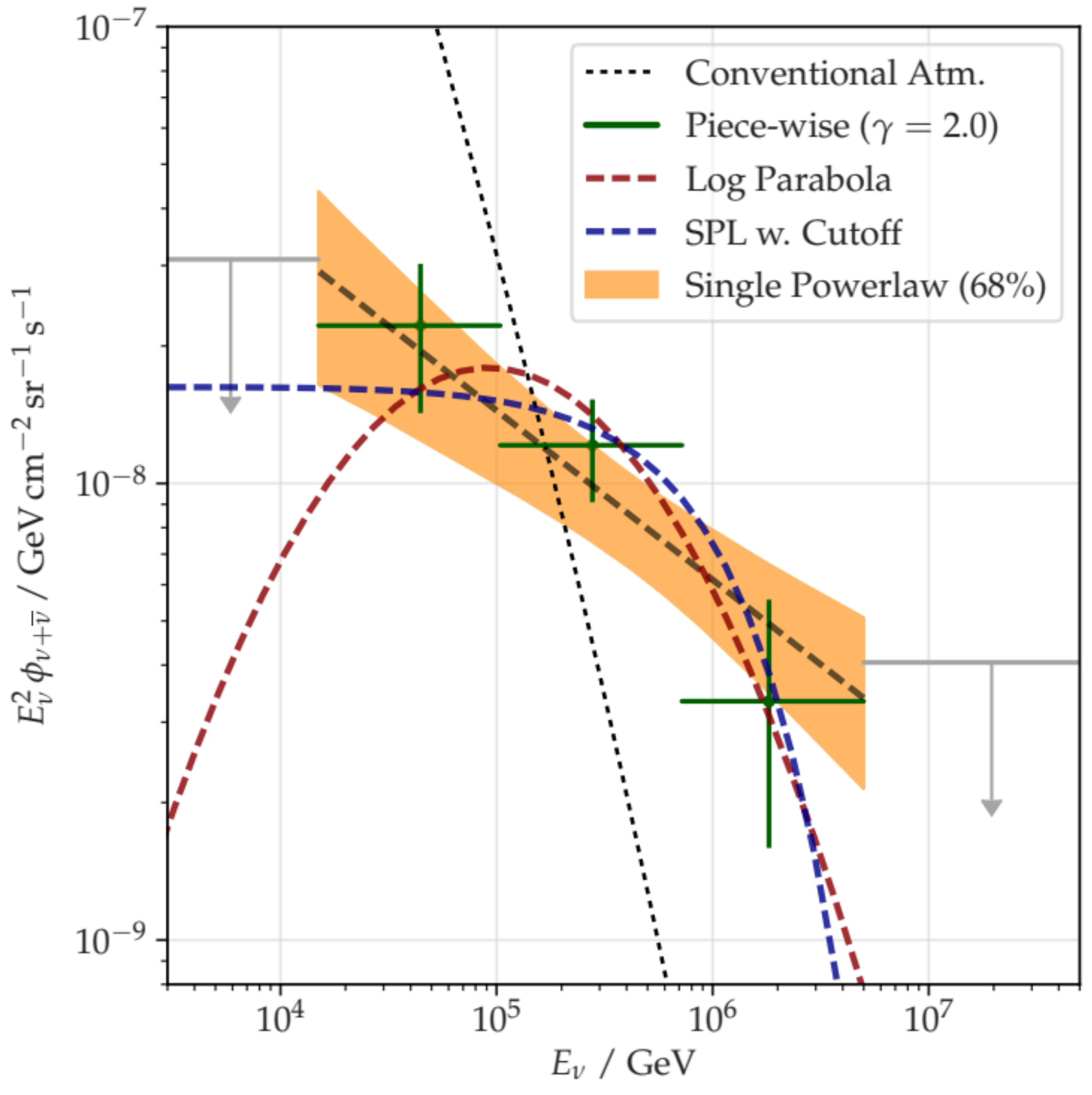
High-energy neutrinos

TeV — PeV neutrinos (discovered by IceCube)

IceCube Collab. PRD'21







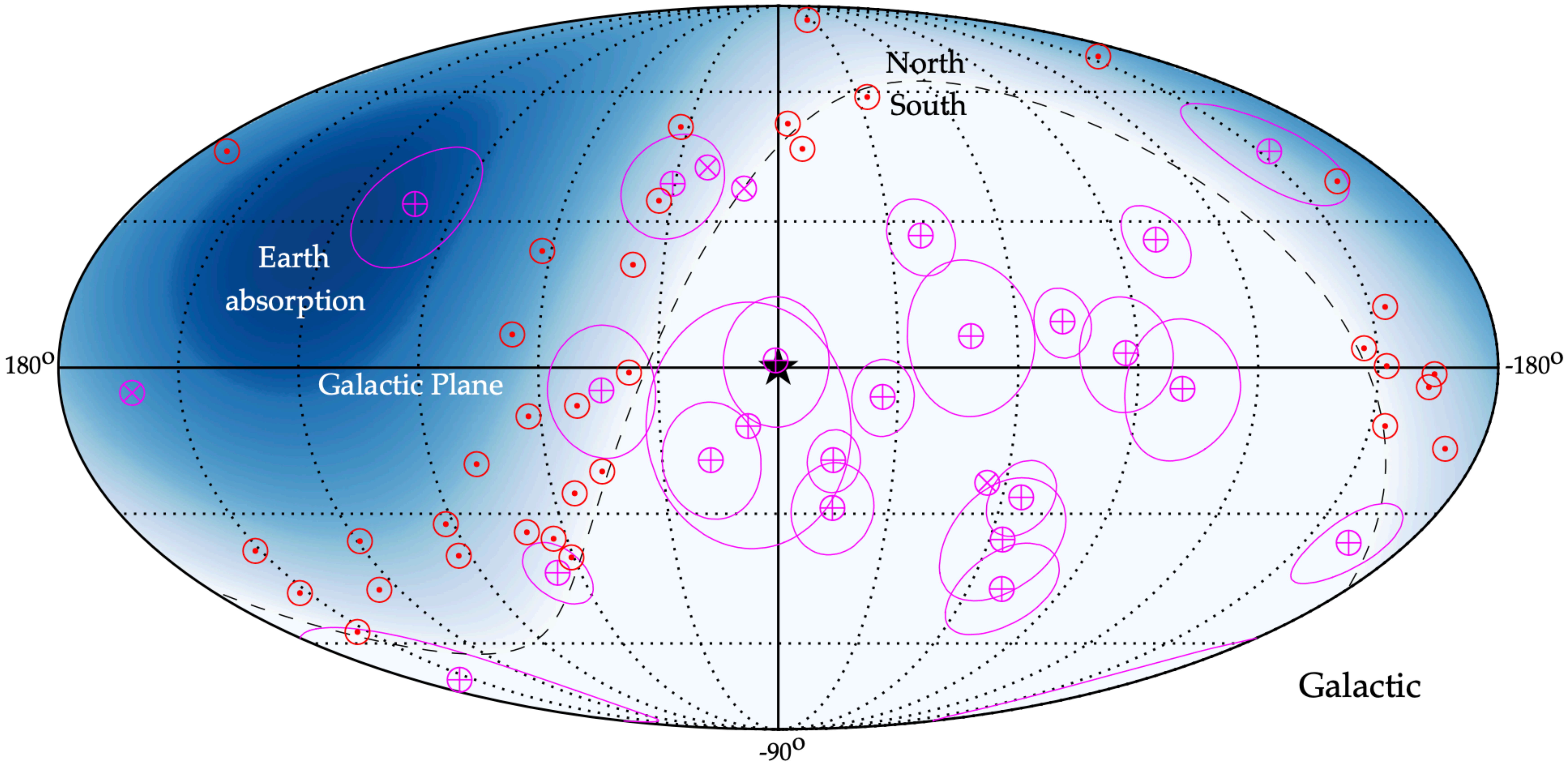
- Diffuse **flux level agrees** across analyses (*within their overlapping energy regions*).
- However, **mild tension between spectral index** for a "vanilla" single power-law flux.

IceCube Collab. ApJ'22

High-energy neutrinos

TeV — PeV neutrinos (discovered by IceCube)

Most energetic neutrino events (HESE 6yr (magenta) & $\nu_\mu + \bar{\nu}_\mu$ 8yr (red))



No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Neutrino production and gamma rays

Photo-hadronic interactions (pγ)

$$p + \gamma_{\rm target} \rightarrow n + \pi^+$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

BR = 1/3 — Neutrino energy = Proton energy / 20

$$p + \gamma_{\rm target} \rightarrow p + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

BR = 2/3 — Gamma-ray energy = Proton energy / 10

Hadronic interactions (pp)

$$A + A_{\rm target} \rightarrow N(\pi^0 + \pi^+ + \pi^-) + X$$

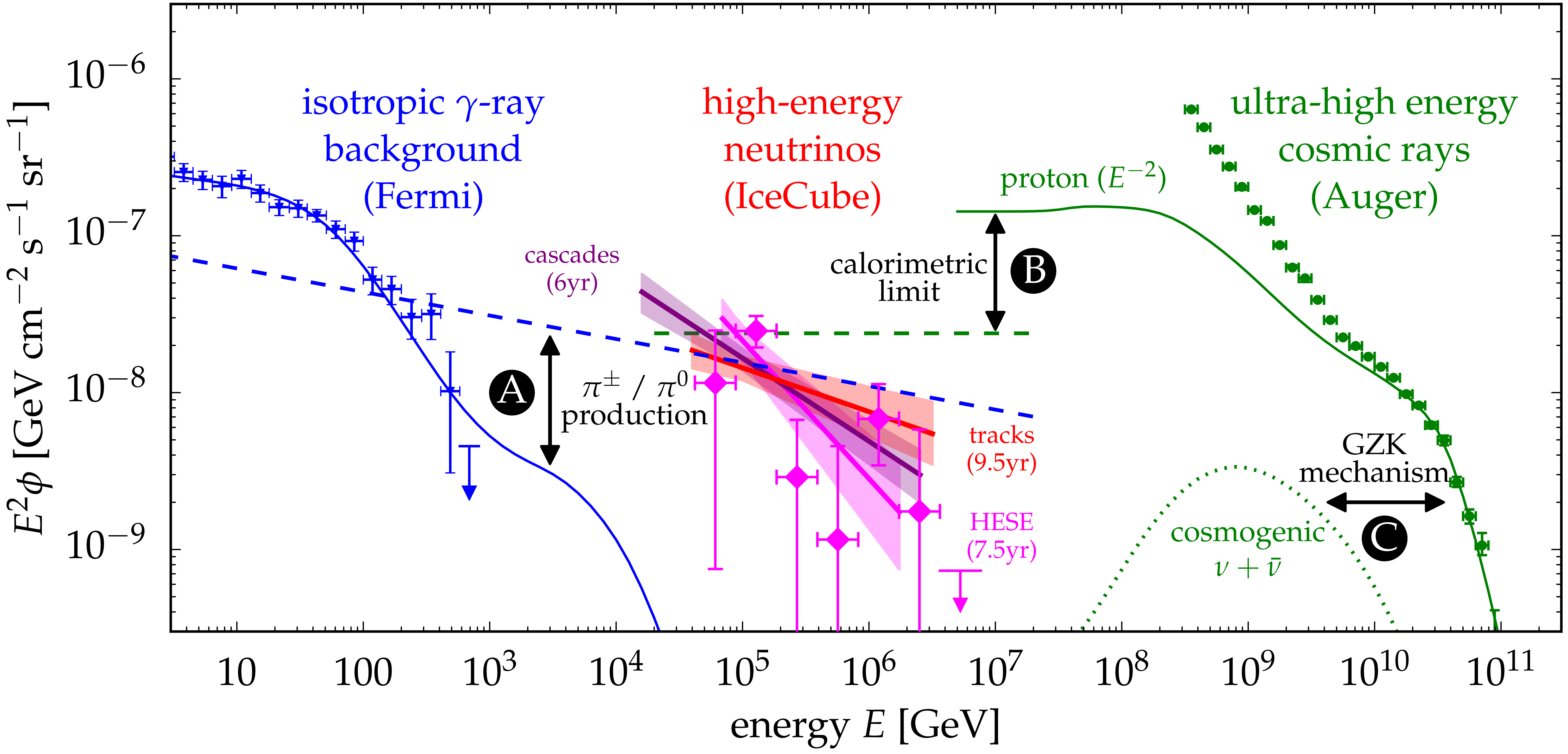
$$\varepsilon_\gamma \frac{\mathrm{d}N_\gamma}{\mathrm{d}\varepsilon_\gamma} = \frac{4}{3\kappa} \left[\varepsilon_\nu \frac{\mathrm{d}N_\nu}{\mathrm{d}\varepsilon_\nu} \right]_{\varepsilon_\nu = \varepsilon_\gamma/2}$$

Neutral to charged pion ratio

$\kappa \sim 1$ (pγ)

$\kappa \sim 2$ (pp)

The multi-messenger connection



The high intensity of the neutrino flux compared to that of γ-rays and cosmic rays offers many interesting multi-messenger interfaces.