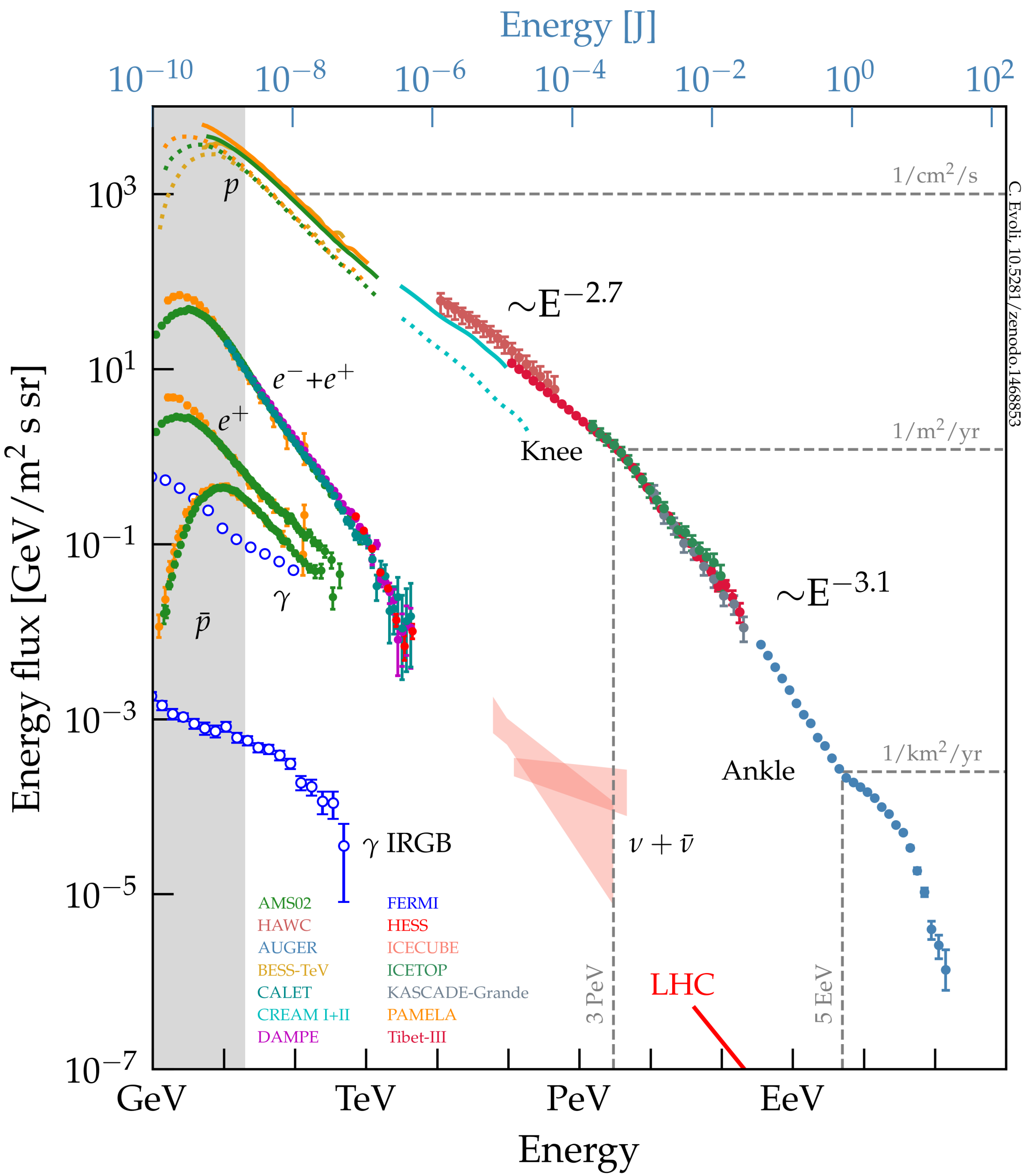
2.5 Gamma ray astrophysics

- Kenny CY Ng
- kcyng@cuhk.edu.hk
- Sci Cen North Black 345
- CUHK

- Course webpage: https://blackboard.cuhk.edu.hk

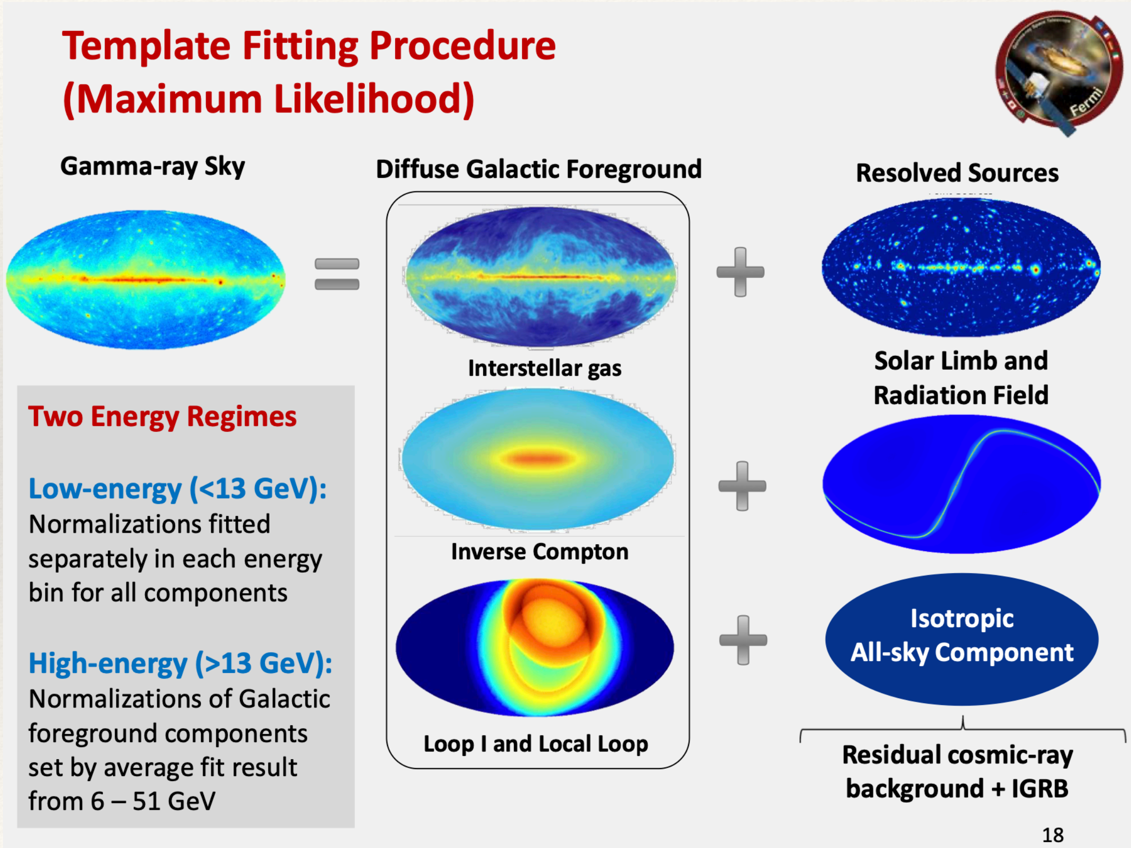
Gamma rays



Energy [J]
10−10 10−8 10−6 10−4 10−2 100 102
1/cm2/s
1/m2/yr
1/km2/yr
p
e−+e+
e+
γ
p̄
~E−2.7
Knee
~E−3.1
Ankle
γ IRGB
ν + ν̄
LHC
3 PeV
5 EeV
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASCADE-Grande
PAMELA
Tibet-III
Energy flux [GeV/m2 s sr]
GeV TeV PeV EeV
Energy
C. Evoli, 10.5281/zenodo.1468853

Cosmic-ray gamma rays

- What are gamma ray sources
- What are the gamma-ray production mechanisms
- What we care about gamma rays



How to detect gamma rays?

How to detect gamma rays?

- Detection means interaction
- Interaction means energy loss

- One of the most useful chapter in PDG
  - Mostly on electromagnetic processes

34. Passage of Particles Through Matter

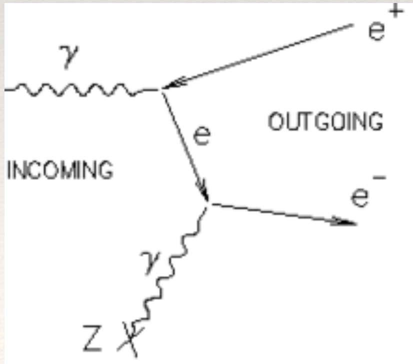
Revised August 2021 by D.E. Groom (LBNL) and S.R. Klein (NSD LBNL; UC Berkeley).

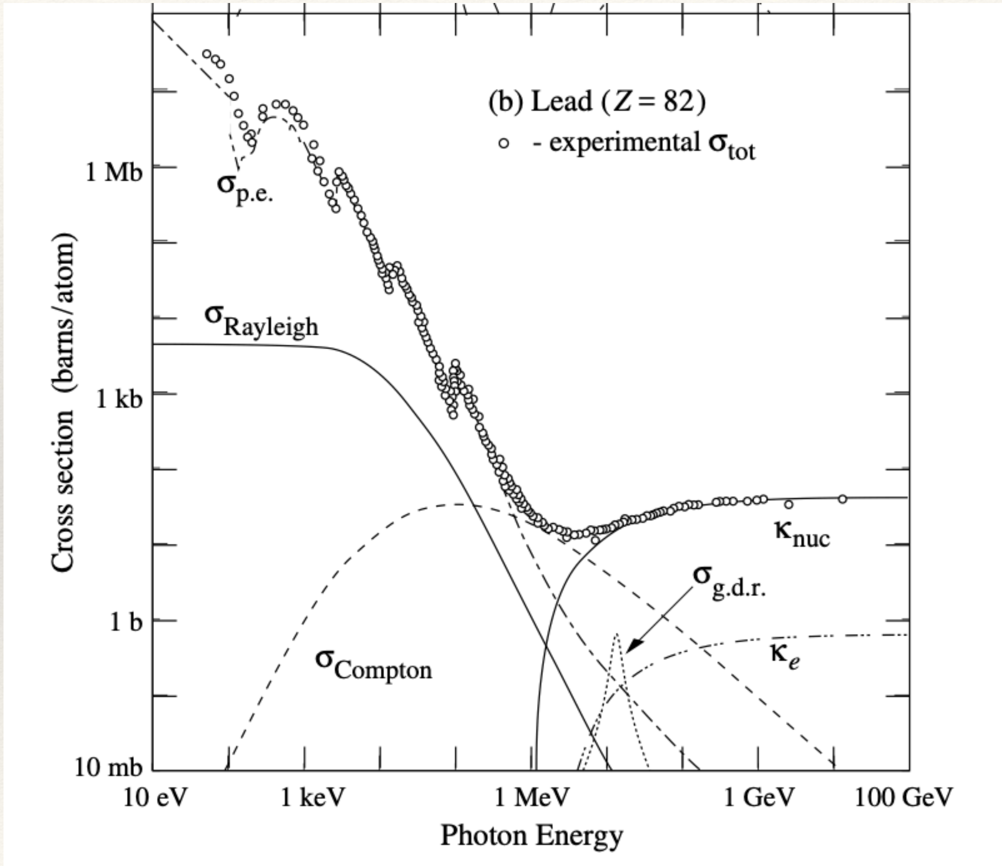
How to detect gamma rays?

Figure 34.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [50]:

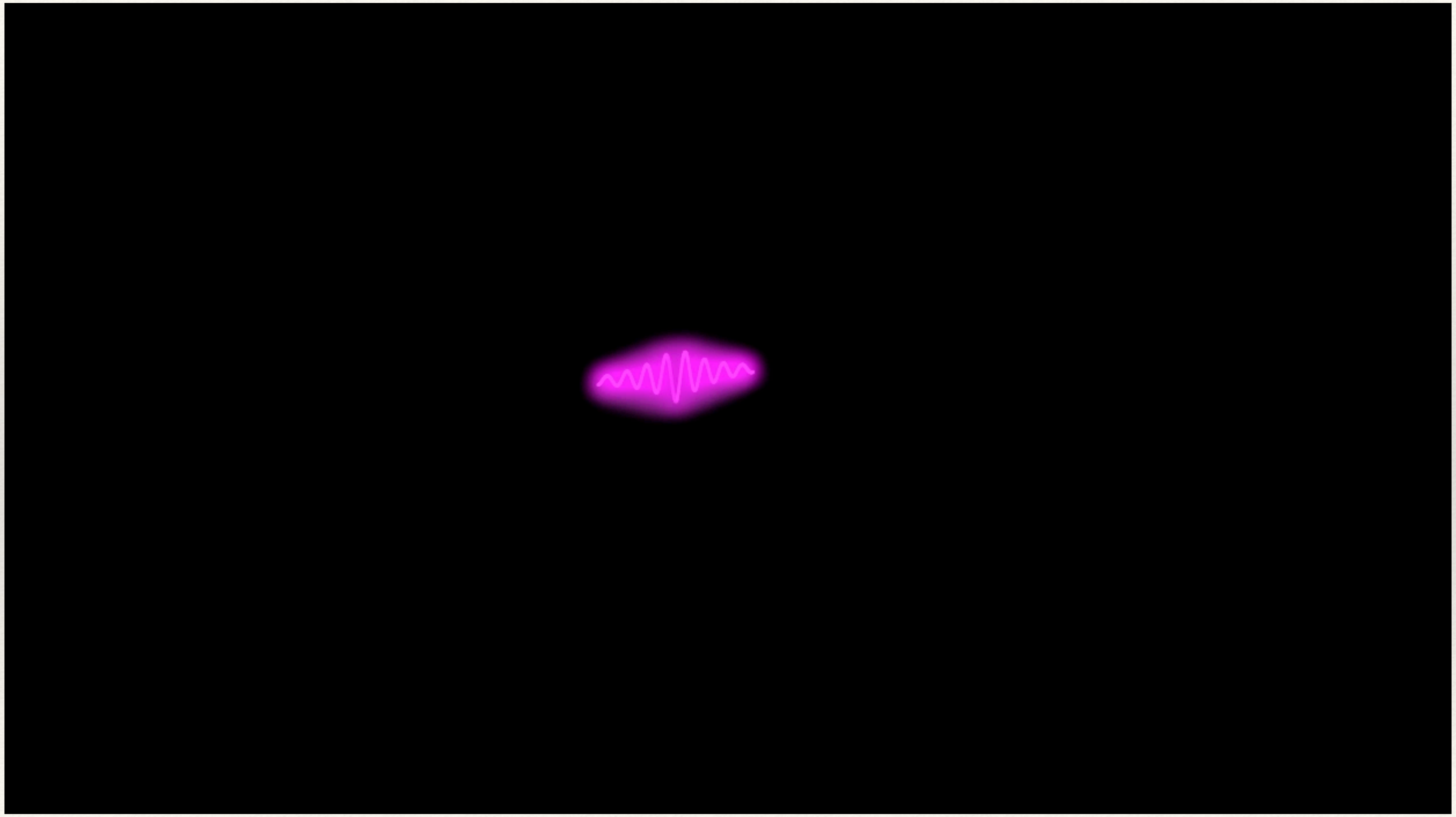
$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [51]. In these interactions, the target nucleus is usually broken up.

- Photon cross section with matter
- At high energy, pair creation dominates the cross section.
- $\gamma + A \rightarrow A + e^+ + e^-$





Pair production

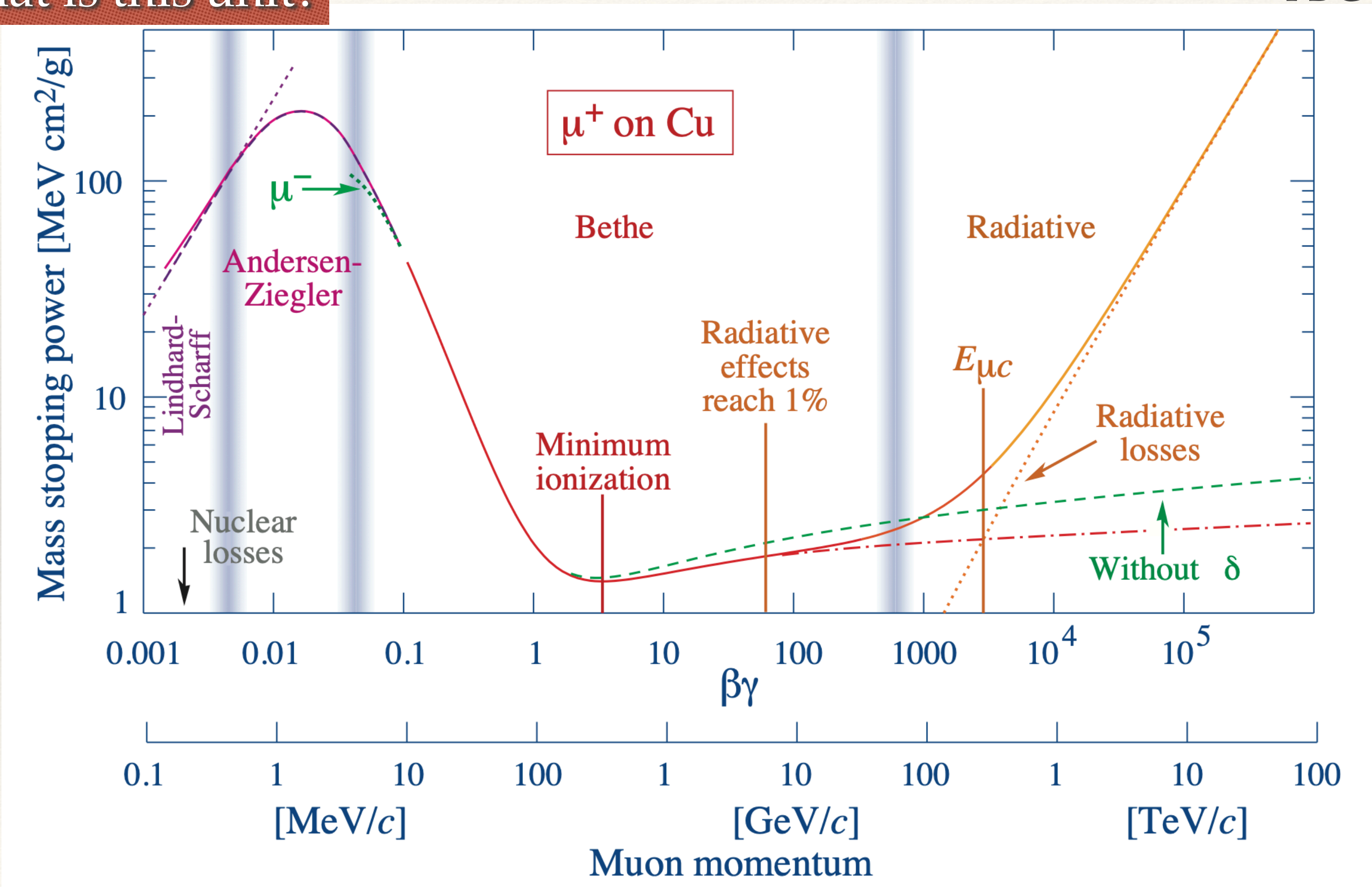


How to detect charged particles (e.g., Muons)
Charged (Leptons) particle interaction with Matter

What is this unit?

PDG

- Charged particle energy loss
- For the energy range we care about (> GeV)
- Ionization $\frac{dE}{dx} \simeq$ constant
- Radiative energy loss
  - Aka Bremsstrahlung
- $\frac{dE}{dx} \propto E$
- What is plotted in the y-axis?

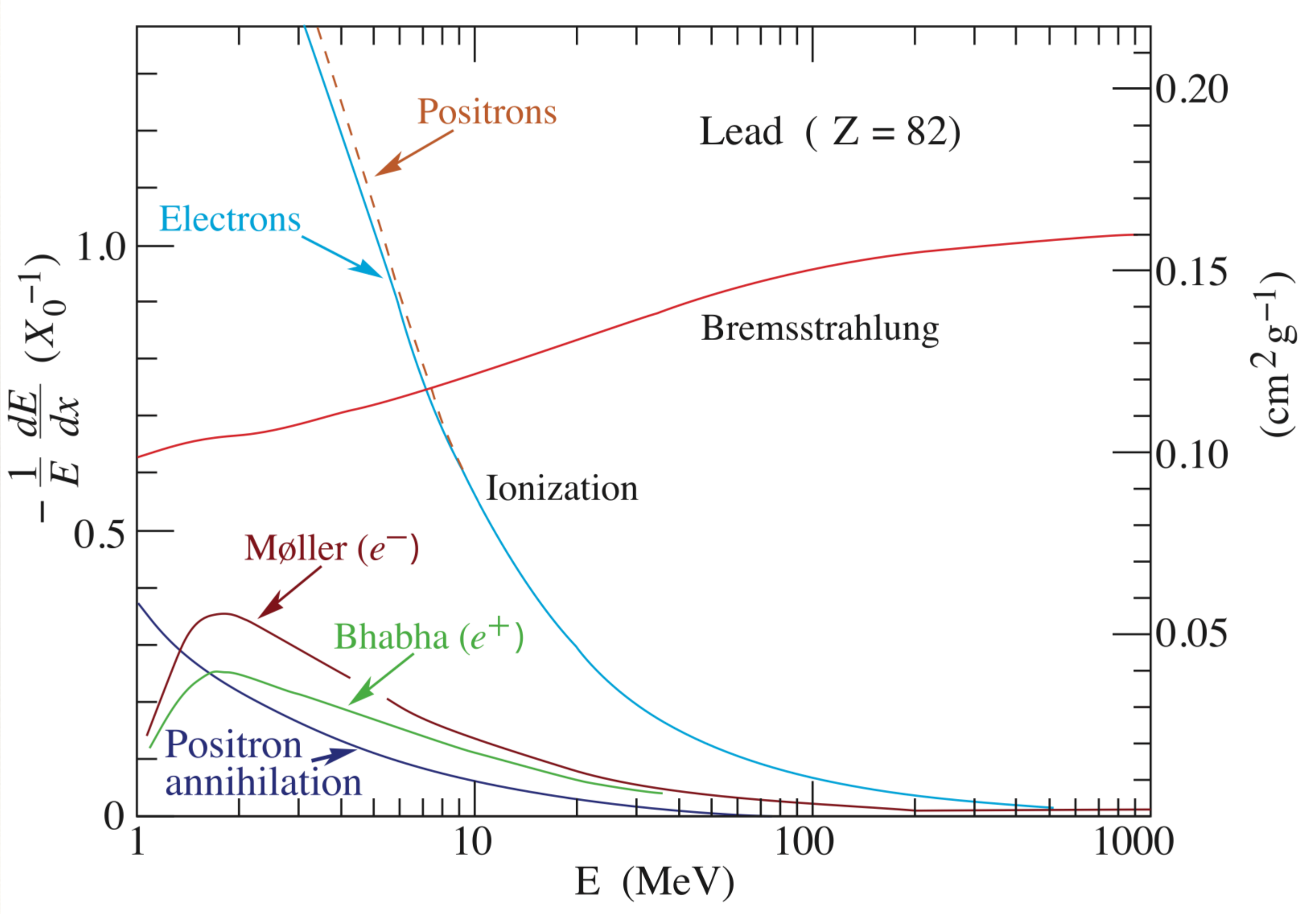


Electrons

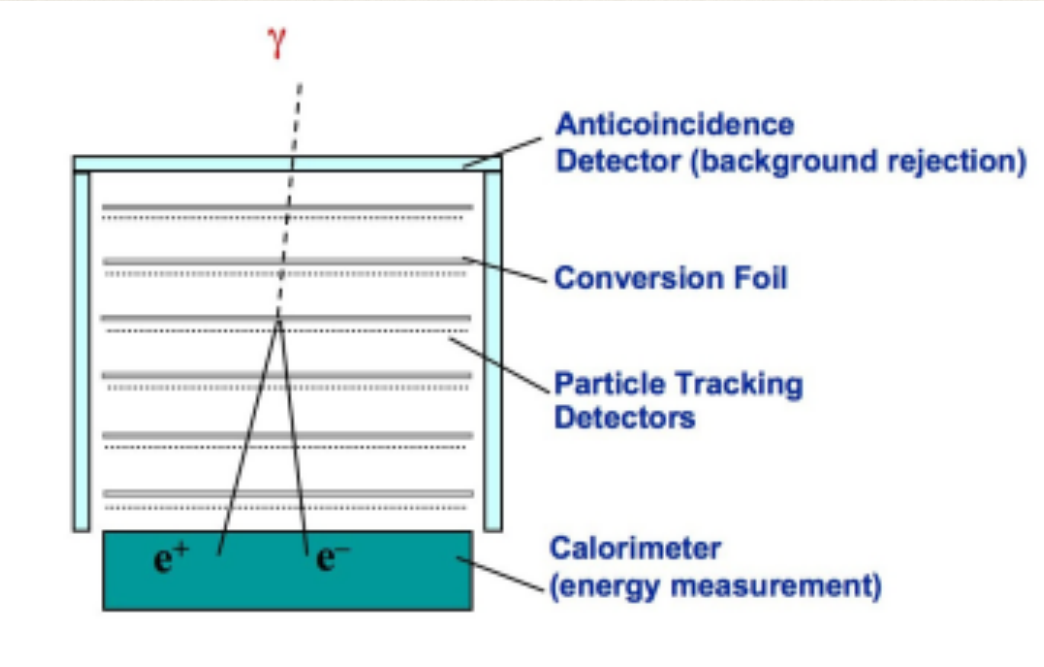
PDG

- Vs Muons?

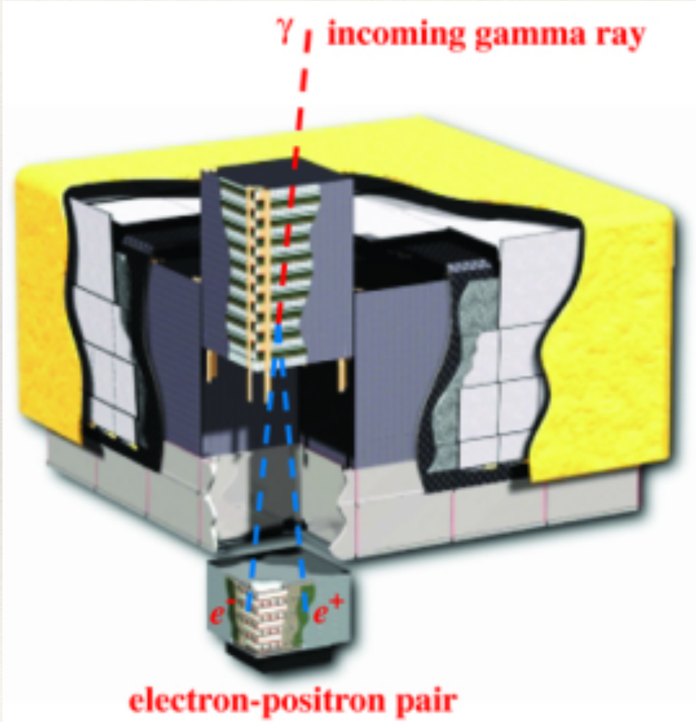
- What do you see?
- Does it make sense?



Fermi-LAT

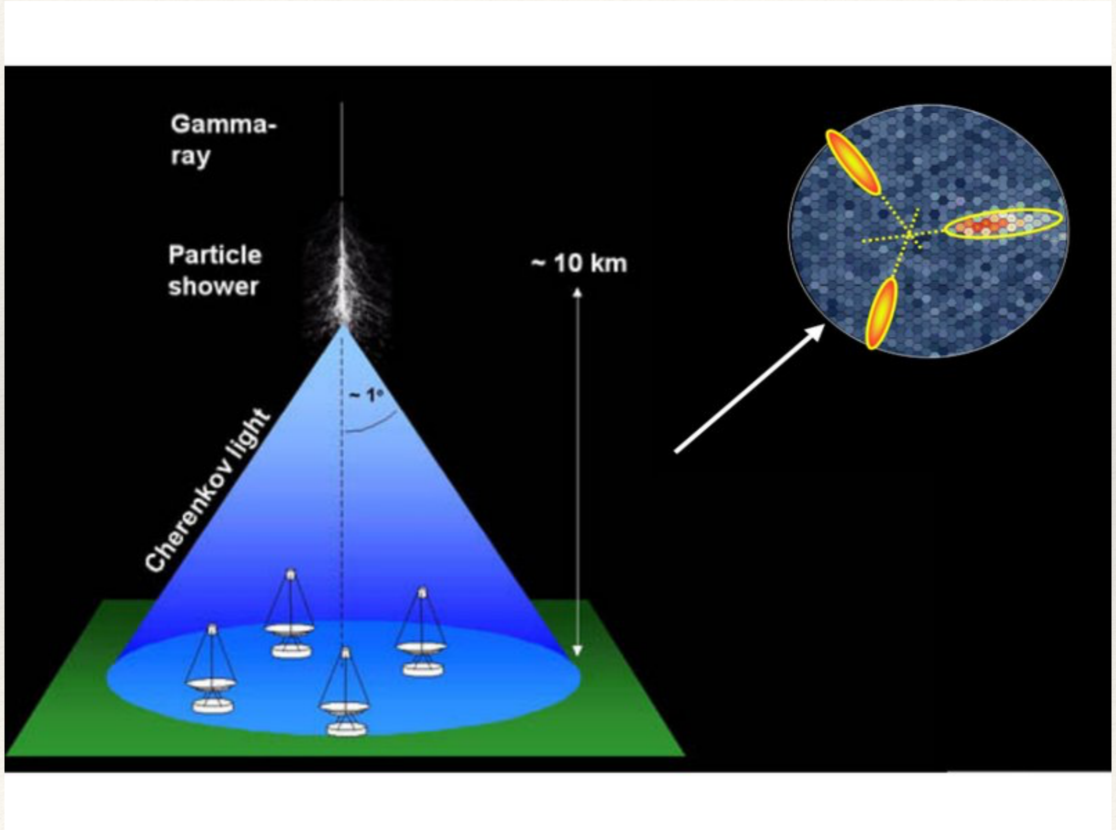


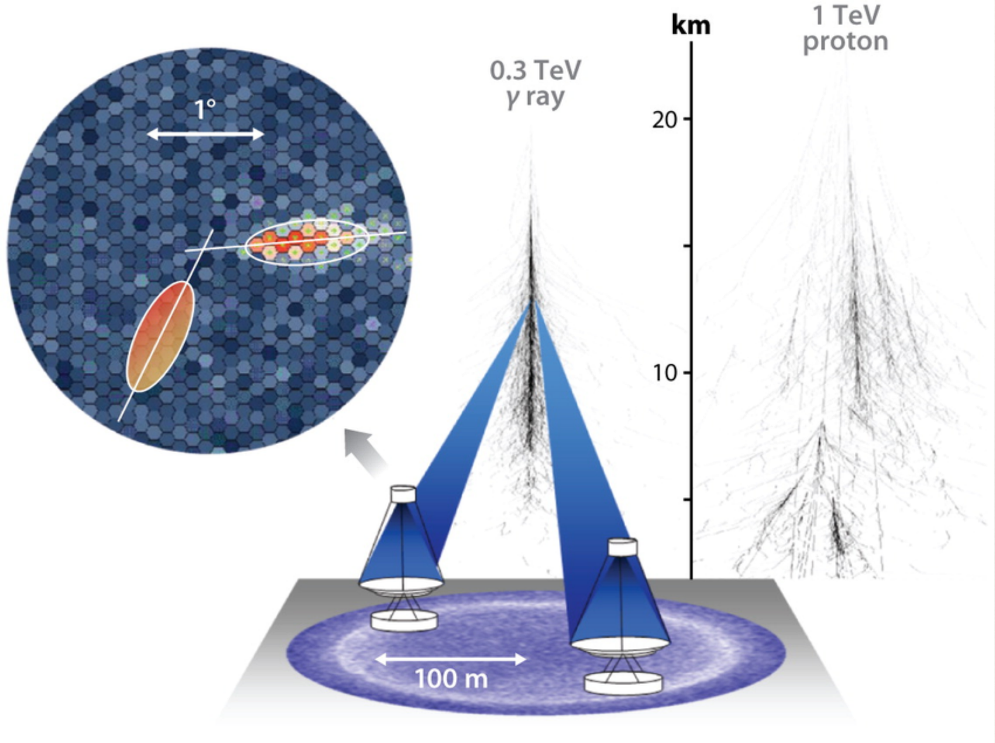
γ
Anticoincidence
Detector (background rejection)
Conversion Foil
Particle Tracking
Detectors
e+
e−
Calorimeter
(energy measurement)



γ incoming gamma ray
e−
e+
electron-positron pair

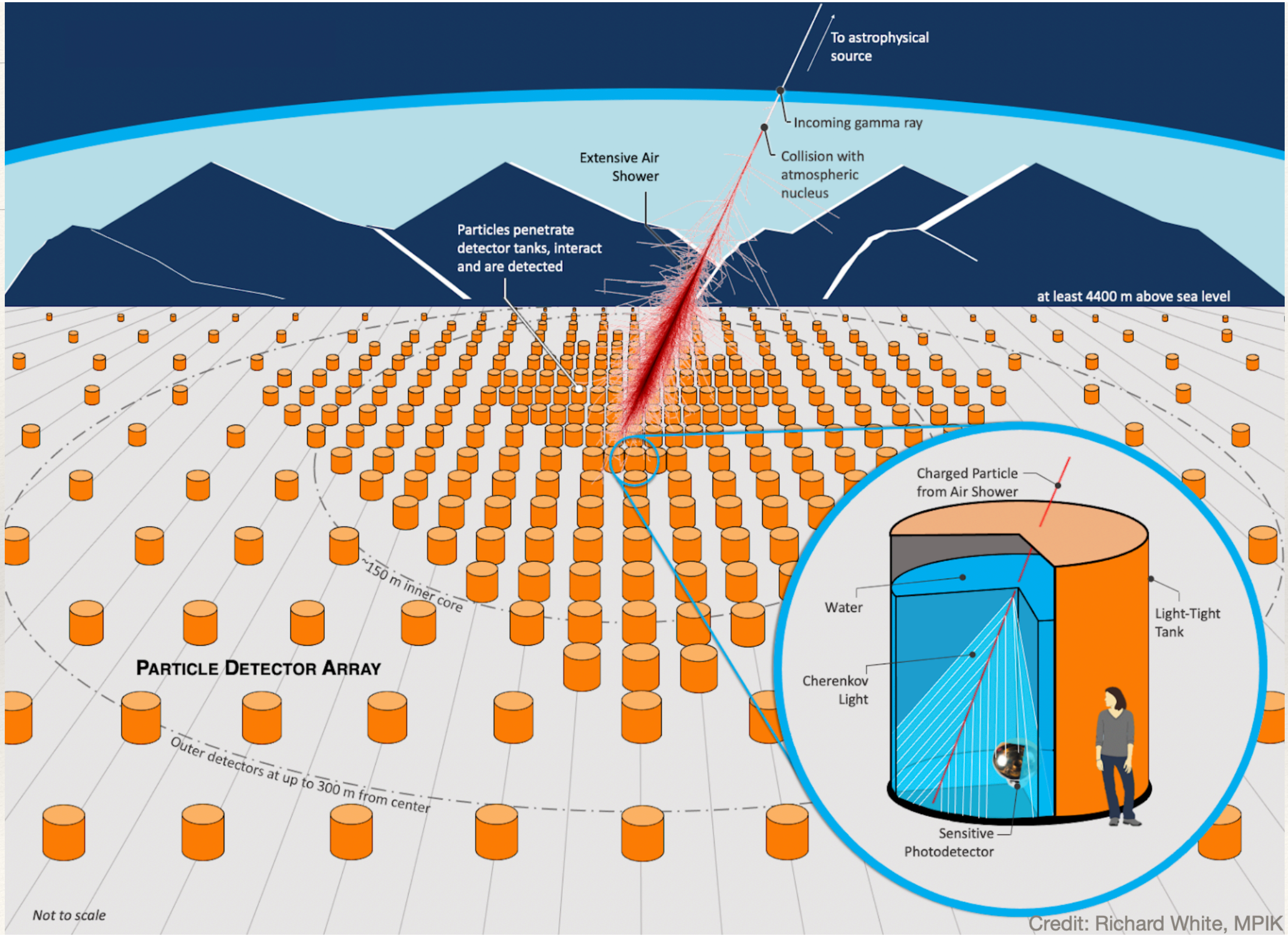
Air Cherenkov Telescopes





Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

Air Shower arrays

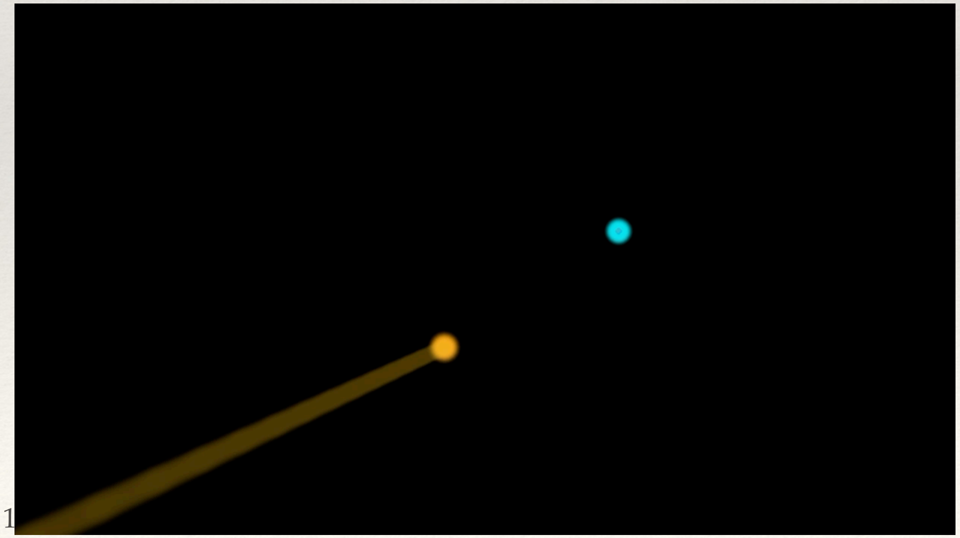


Gamma-ray production

Leptonic gamma-ray production

- You already see examples gamma ray production from Leptons
- The most abundant charged leptons are electrons

- Electron interaction with matter
  - Bremsstrahlung gamma rays
- Electron interaction with radiation
  - Inverse Compton gamma rays



IC emission

- $$\frac{dn}{dE_\gamma dt} = \int \frac{dn_e}{dE_e d\Omega_e} \frac{dN}{dE_\gamma dt} dE_e d\Omega_e$$

  Electron number density X Gamma-ray production rate per electron

- Can be analytically done assuming isotropic electron and photons

- $$P = E_\gamma \frac{dN}{dE_\gamma dt}$$

  $$\mathcal{P}(\epsilon_1, E, r) = \frac{3\sigma_T}{4\gamma^2}\epsilon_1 \int_0^1 dy \frac{n(\epsilon(y), r)}{y} \left[2y \ln y + y + 1 - 2y^2\right] \qquad [\text{Thomson limit}].$$

  $\epsilon_1 = E_\gamma$

- Or in KN

  $$\mathcal{P}(\epsilon_1, E, r) = \frac{3\sigma_T}{4\gamma^2}\epsilon_1 \int_{1/4\gamma^2}^1 dq \left(1 - \frac{1}{4q\gamma^2(1-\tilde{\epsilon}_1)}\right) \frac{n(\epsilon(q), r)}{q} \left[2q \ln q + q + 1 - 2q^2 + \frac{1}{2}\frac{\tilde{\epsilon}_1^2}{1-\tilde{\epsilon}_1}(1-q)\right]$$

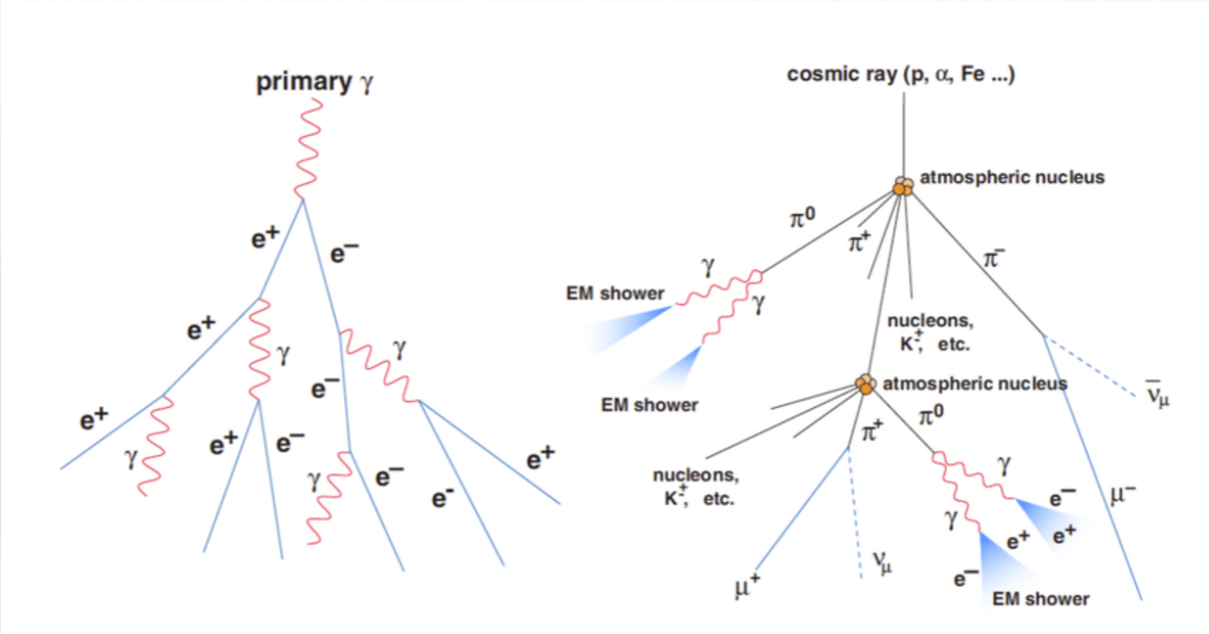
- More work to take into account the angular distributions.

Hadronic Gamma-ray production

- Most of the cosmic rays are protons
    - The underlying physics for nuclei is the same, just likely more complicated.
- So proton-proton interactions are another major gamma-ray production methods

Proton-proton interactions

- Proton-proton interactions
  - The lightest hadronic states are pions, so they are the primary products from proton-proton interactions
    - (The next ones are kaons)



Pions

- Charged pion decay into muon+neutrinos
  - Weak interactions
- Neutral pion decay into two photons
  - EM interactions, much stronger, much faster

Electrons are much lighter than muons
Why dont pions decay into them?

Pions

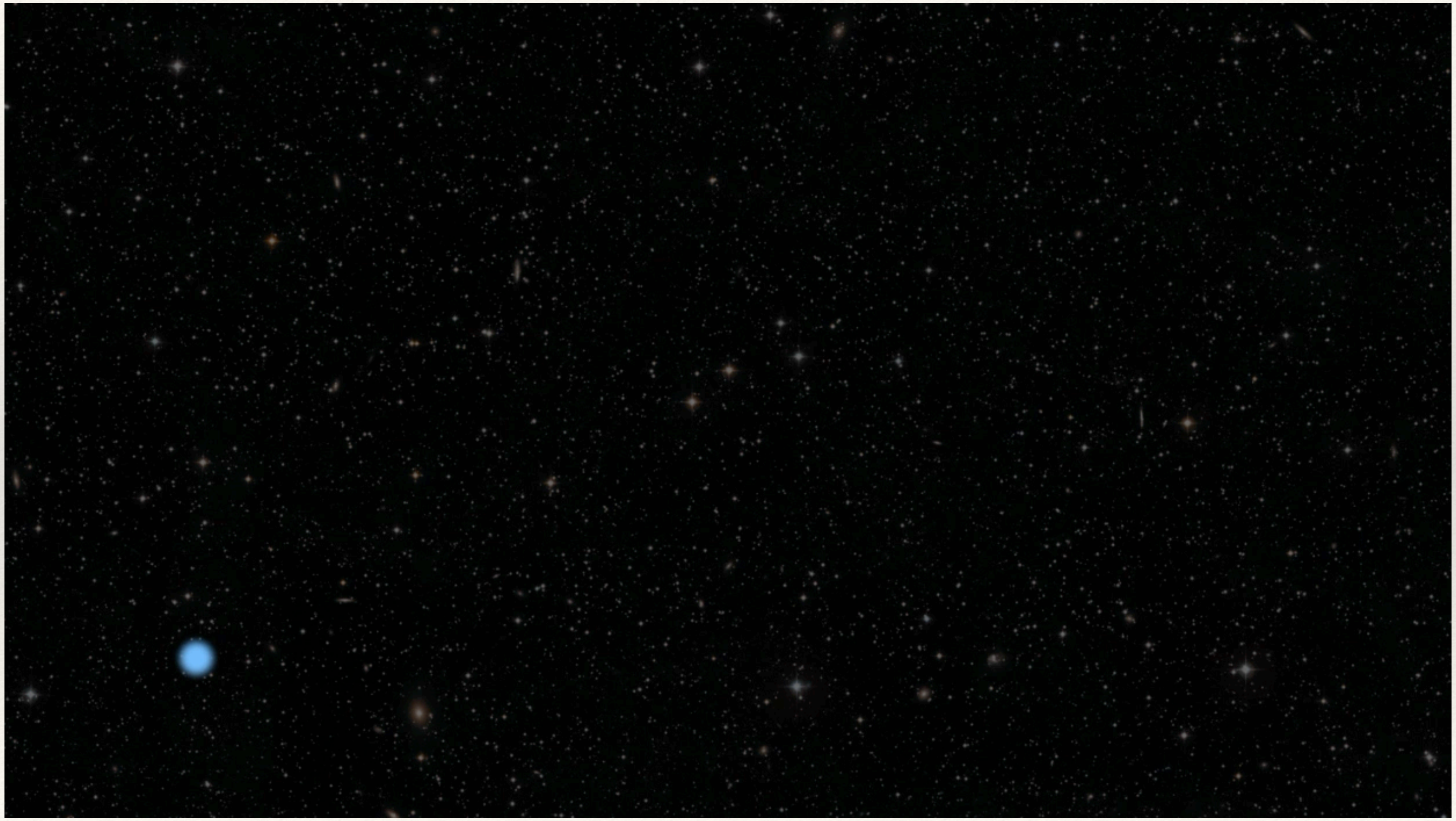
Particle name	Particle symbol	Antiparticle symbol	Quark content[15]	Rest mass [MeV/c^2]	I^G	J^{PC}	S	C	B'	Mean lifetime [s]	Commonly decays to (> 5% of decays)
Pion[1]	π^+	π^-	$u\bar{d}$	139.570 39 ± 0.000 18	1^-	0^-	0	0	0	$(2.6033 \pm 0.0005) \times 10^{-8}$	$\mu^+ + \nu_\mu$
Pion[1]	π^0	Self	$\frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$ [a]	134.9768 ± 0.0005	1^-	0^{-+}	0	0	0	$(8.5 \pm 0.2) \times 10^{-17}$	$\gamma + \gamma$

Hadronic gamma rays

- Proton-proton into pions
- Neutral pions into gamma rays

Hadronic gamma-ray production

❖ $$p + p \to \pi^{\pm,0} + X$$



How to model pionic gamma-ray production?

- $pp \to \pi^0 - > \gamma,$ how to model this ??

- Zeroth step. The photon spectrum from a pion with energy E_π is given by $\frac{dN_{\pi\to\gamma}}{dE_\gamma}(E_\pi)$

-

- Now, consider that there is some density energy distribution of pion. $\frac{dn}{dE_\pi}$, the photon density energy distribution is

- $$\frac{dn}{dE_\gamma} = \int_{E_{min}(E_\gamma)} \frac{dn_\pi}{dE_\pi}\frac{dN_{\pi\to\gamma}}{dE_\gamma}(E_\pi)dE_\pi$$

E_{min} is the minimum pion energy to produce a photon with energy E_γ

(How to show this?)

$$E_{min} = E_\gamma + \frac{m_\pi^2}{4E_\gamma}$$

How to model pionic gamma-ray production?

- $pp \rightarrow \pi^0 -> \gamma,$ how to model this ??

- Zeroth step. The photon spectrum from a pion with energy E_π is given by
  $\frac{dN_{\pi\rightarrow\gamma}}{dE_\gamma}(E_\pi)$

- Now, consider that there is some density energy distribution of pion. $\frac{dn}{dE_\pi}$, the photon density energy distribution is

- $$\frac{dn}{dE_\gamma} = \int_{E_{min}(E_\gamma)} \frac{dn_\pi}{dE_\pi} \frac{dN_{\pi\rightarrow\gamma}}{dE_\gamma}(E_\pi) dE_\pi$$

- Pion density energy distribution obtained from proton-proton interaction
  $$\frac{dn_\pi}{dE_\pi} = \int_{E_{p,min}} \frac{dn_p}{dE_p} \frac{d\sigma_{pp\rightarrow\pi}}{dE_\pi} n_{ISM} c \, dE_p$$

Gamma-ray emissivity (photons per volume per time per energy)

$$\frac{dn}{dE_\gamma} = \int\int \frac{dn_p}{dE_p} \frac{d\sigma_{pp\rightarrow\pi}}{dE_\pi} n_{ISM} c \frac{dN_{\pi\rightarrow\gamma}}{dE_\gamma} dE_\pi dE_p$$

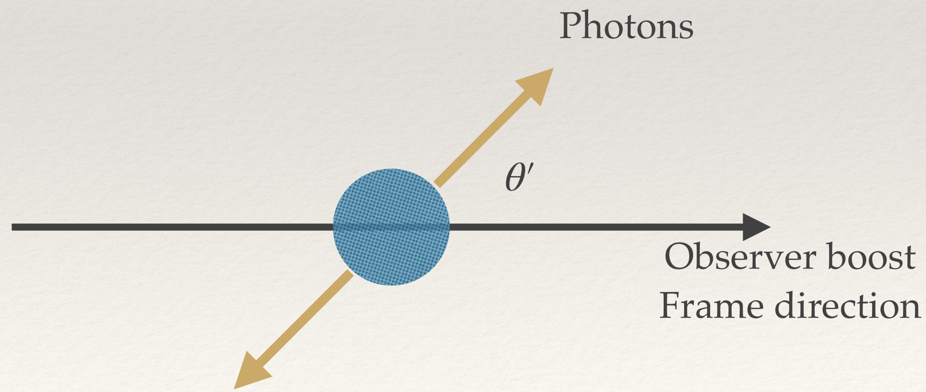
How to model pionic gamma-ray production?

- $pp \to \pi^0 -> \gamma,$ how to model this ??

- Zeroth step. The photon spectrum from a pion with energy E_π is given by
$$\frac{dN_{\pi\to\gamma}}{dE_\gamma}(E_\pi)$$

- We already know that
- $$\frac{m_\pi}{2}\gamma(1-\beta) < E_\gamma < \frac{m_\pi}{2}\gamma(1+\beta)$$

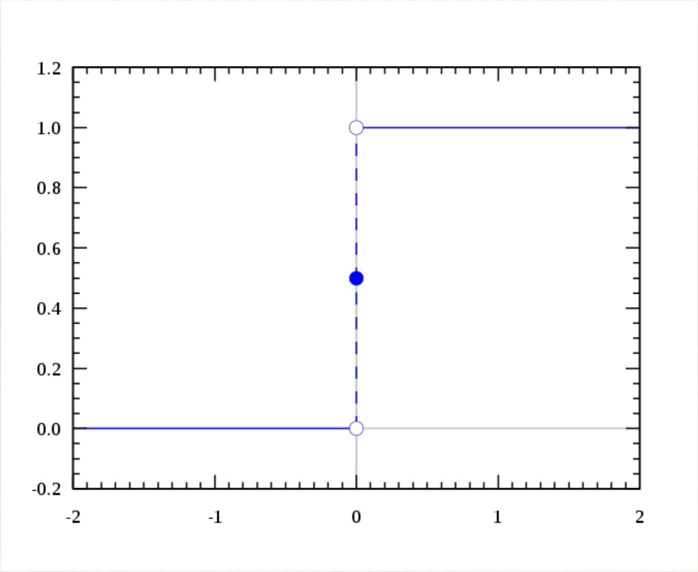
- We also know that in the rest frame of the pion, the photon decays isotropically
- $$\frac{dN}{d\cos\theta'} = \text{constant.}$$
- As usual, we define CM frame (= pion rest frame here with ')



How to model pionic gamma-ray production?

- $E_\gamma = \frac{m_\pi}{2}\gamma(1 + \beta\cos\theta')$
- $\frac{dN}{dE_\gamma} = \frac{dN}{d\cos\theta'}(\frac{dE_\gamma}{d\cos\theta'})^{-1} = \frac{dN}{d\cos\theta'}\frac{1}{\frac{m_\pi}{2}\gamma\beta}$
- RHS is independent of gamma-ray energy, only the electron energy
- $\frac{dN}{dE_\gamma} = \text{ constant}$
- $\frac{dN}{dE_\gamma} = \frac{2}{\mathrm{E_{max}} - \mathrm{E_{min}}}$
- $\frac{dN}{dE_\gamma} = \frac{2}{m_\pi\gamma\beta}.$ $, \; E_{min}(\beta) < E_\gamma < E_{max}(\beta),$ or
- $\frac{dN}{dE_\gamma} = \frac{2}{m_\pi\gamma\beta}\Theta(E_\gamma - E_{min})\Theta(E_{max} - E_\gamma)$

Heaviside Theta function

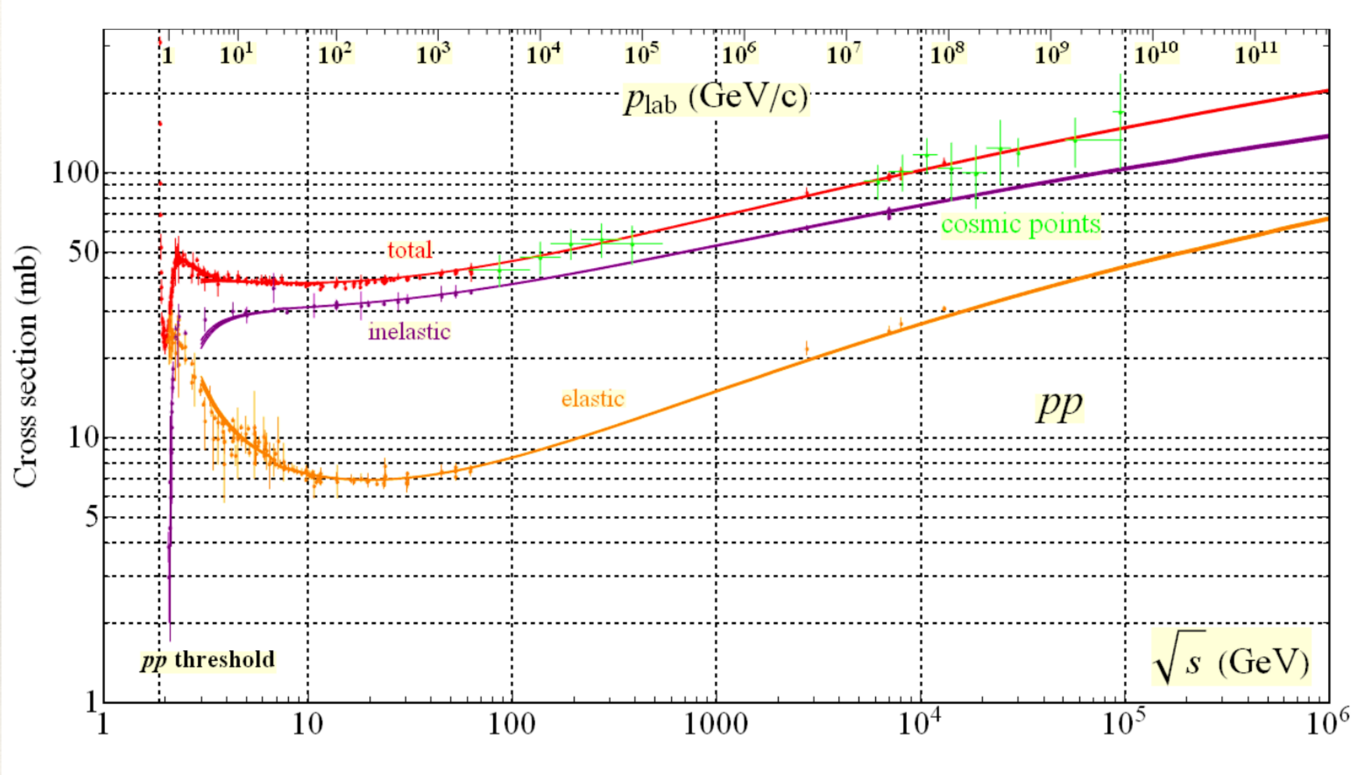


How to model pionic gamma-ray production?

- $$\frac{dN}{dE_\gamma} = \frac{2}{m_\pi \gamma\beta}\ ,\ E_{min}(\beta) < E_\gamma < E_{max}(\beta),$$
  or
- $$\frac{dN}{dE_\gamma} = \frac{2}{m_\pi \gamma\beta}\Theta(E_\gamma - E_{min})\Theta(E_{max} - E_\gamma)$$
- How does the spectrum look like?

Proton-proton cross section

- What is your observation?



Hadronic gamma-ray production (pi0 decay)

Gamma-ray emissivity (photons per volume per time per energy)

$$\frac{dn}{dE_\gamma} = \int\int \frac{dn_p}{dE_p} \frac{d\sigma_{pp\to\pi}}{dE_\pi} n_{ISM} c \frac{dN_{\pi\to\gamma}}{dE_\gamma} dE_\pi dE_p$$

- $\frac{dn}{dE_p}$
- $\frac{d\sigma}{dE_{pi}} = \sigma_{pp} \frac{dN_\pi}{dE_\pi} \simeq \sigma_{pp} \delta(E_\pi - K_\pi T_p)$
- Below 100GeV, is a good approximation that the outgoing pion has energy $K_\pi \simeq 0.17$ of the proton kinetic energy T_p

Shape of pion spectrum

- Pion bump!
  - Quite characteristic

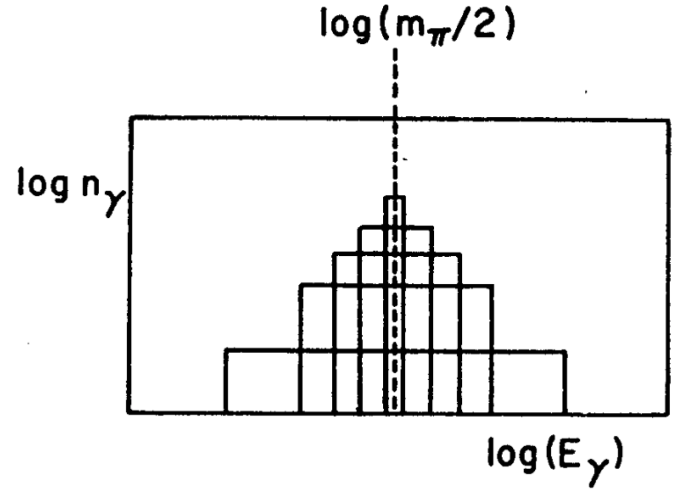


Figure 10.1: Schematic construction of the photon spectrum produced by decay of a spectrum of neutral pions. (After Stecker, 1971.)

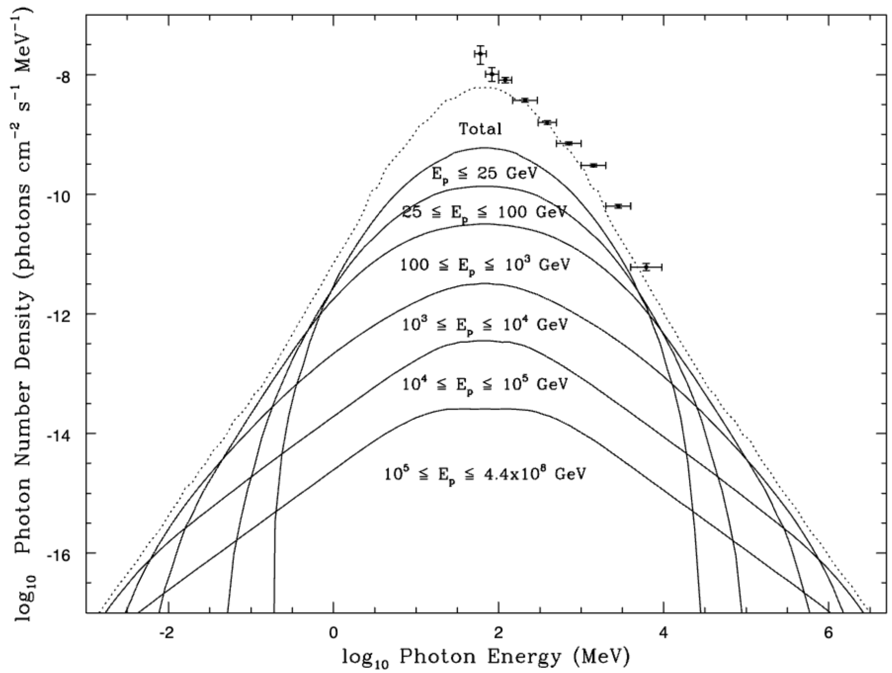


FIG. 3.—Contributions to the overall pion decay spectrum from the various proton energy ranges.

Fermi Highlights

Detection of pion bumps by Fermi-LAT

Detection of the Characteristic Pion-Decay Signature in Supernova Remnants

Fermi-LAT Collaboration • M. Ackermann (DESY) Show All(169)

Feb 13, 2013

21 pages
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DOI: 10.1126/science.1231160
Experiments: FERMI-LAT
View in: OSTI Information Bridge Server, ADS Abstract Service

Cosmic rays are particles (mostly protons) accelerated to relativistic speeds. Despite wide agreement that supernova remnants (SNRs) are the sources of galactic cosmic rays, unequivocal evidence for the acceleration of protons in these objects is still lacking. When accelerated protons encounter interstellar material, they produce neutral pions, which in turn decay into gamma rays. This offers a compelling way to detect the acceleration sites of protons. The identification of pion-decay gamma rays has been difficult because high-energy electrons also produce gamma rays via bremsstrahlung and inverse Compton scattering. We detected the characteristic pion-decay feature in the gamma-ray spectra of two SNRs, IC 443 and W44, with the Fermi Large Area Telescope. This detection provides direct evidence that cosmic-ray protons are accelerated in SNRs.

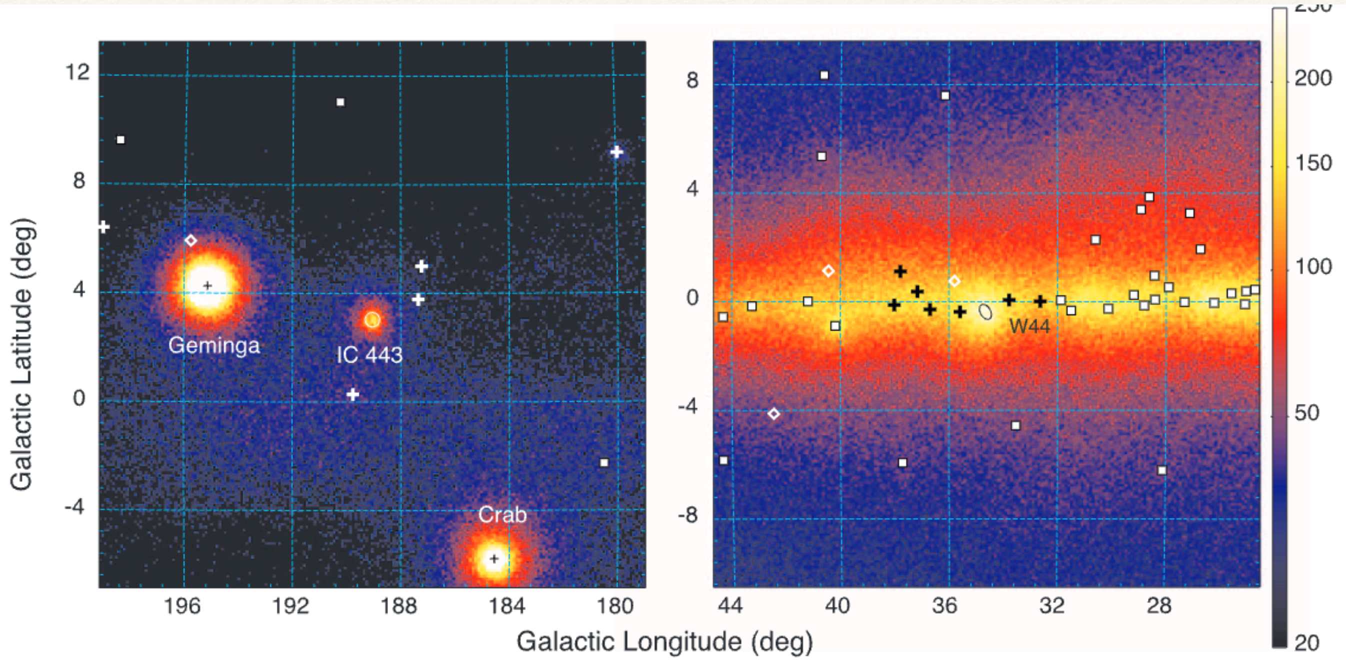
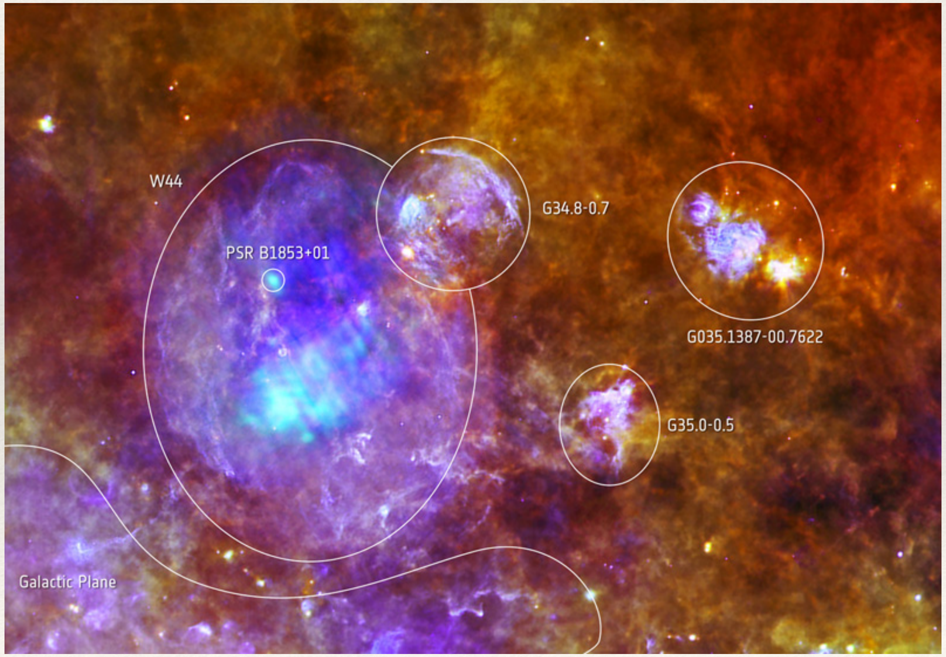


Fig. 1. Gamma-ray count maps of the 20° × 20° fields around IC 443 (**left**) and W44 (**right**) in the energy range 60 MeV to 2 GeV. Nearby gamma-ray sources are marked as crosses and squares. Diamonds denote previously undetected sources. For sources indicated by crosses and diamonds, the fluxes were left as free parameters in the analysis. Events were spatially binned in regions of side length 0.1°, the color scale units represent the square root of count density, and the colors have been clipped at 20 counts per pixel to make the galactic diffuse emission less prominent. Given the spectra of the sources and the effective area of the LAT instrument, the bulk of the photons seen in this plot have energies between 300 and 500 MeV. IC 443 is located in the galactic anti-center region, where the background gamma-ray emission produced by the pool of galactic cosmic rays interacting with interstellar gas is rather weak relative to the region around W44. The two dominant sources in the IC 443 field are the Geminga pulsar (2FGL J0633.9+1746) and the Crab (2FGL J0534.5+2201). For the W44 count map, W44 is the dominant source (subdominant, however, to the galactic diffuse emission).

Supernova Remnants

IC 443 Jellyfish Nebula

W44



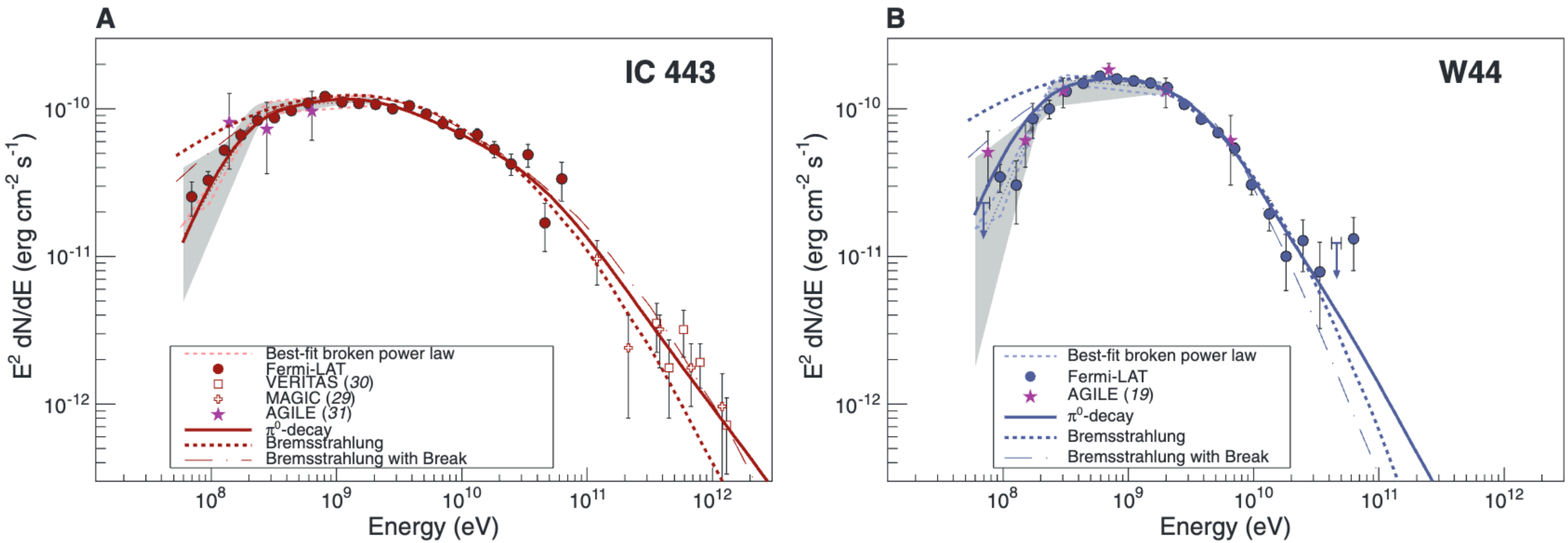


Fig. 2. (**A** and **B**) Gamma-ray spectra of IC 443 (A) and W44 (B) as measured with the Fermi LAT. Color-shaded areas bound by dashed lines denote the best-fit broadband smooth broken power law (60 MeV to 2 GeV); gray-shaded bands show systematic errors below 2 GeV due mainly to imperfect modeling of the galactic diffuse emission. At the high-energy end, TeV spectral data points for IC 443 from MAGIC (*29*) and VERITAS (*30*) are shown. Solid lines denote the best-fit pion-decay gamma-ray spectra, dashed lines denote the best-fit bremsstrahlung spectra, and dash-dotted lines denote the best-fit bremsstrahlung spectra when including an ad hoc low-energy break at 300 MeV c^{-1} in the electron spectrum. These fits were done to the Fermi LAT data alone (not taking the TeV data points into account). Magenta stars denote measurements from the AGILE satellite for these two SNRs, taken from (*31*) and (*19*), respectively.

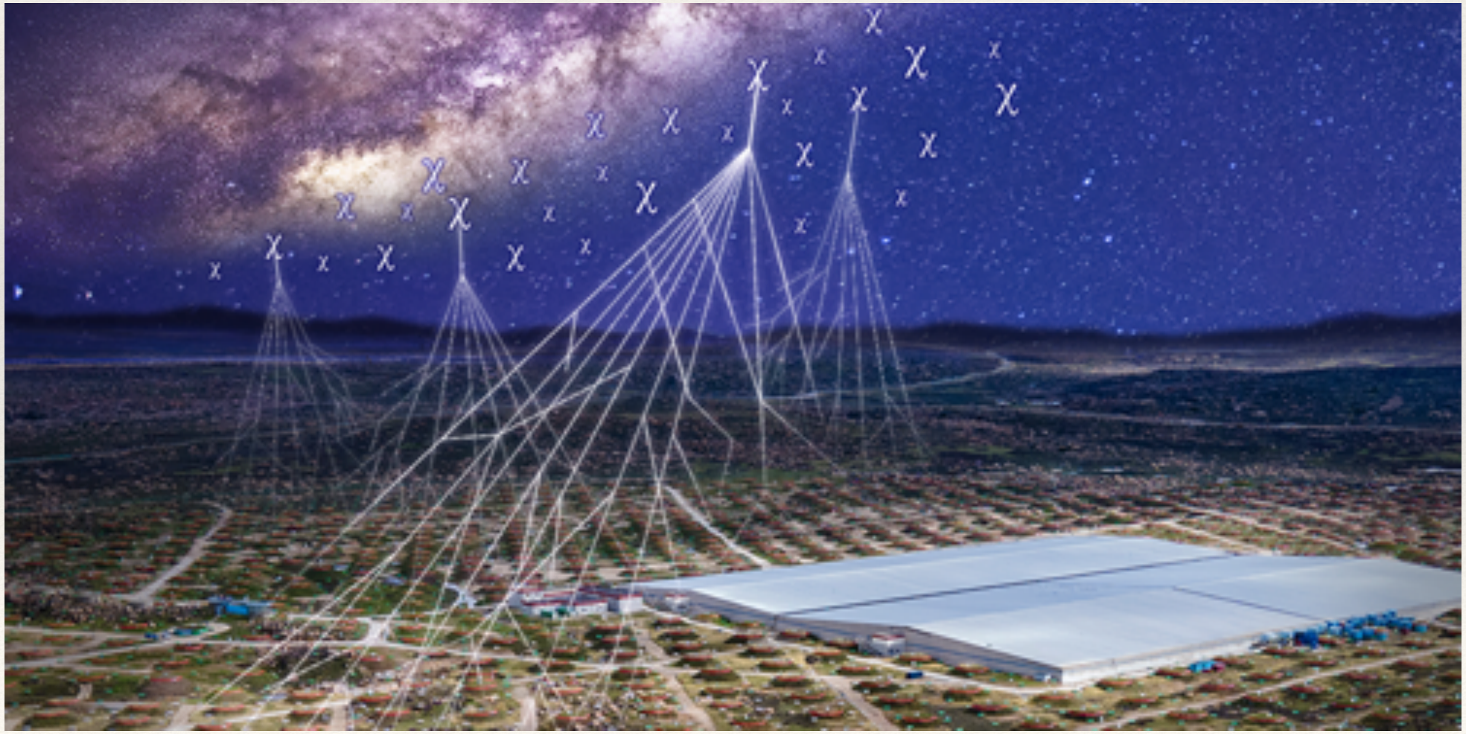
Cosmic ray sources

- SNR are at last a site for hadronic cosmic ray accelerations
  - If you believe Fermi results.
  - At low energies
-

LHAASO highlights

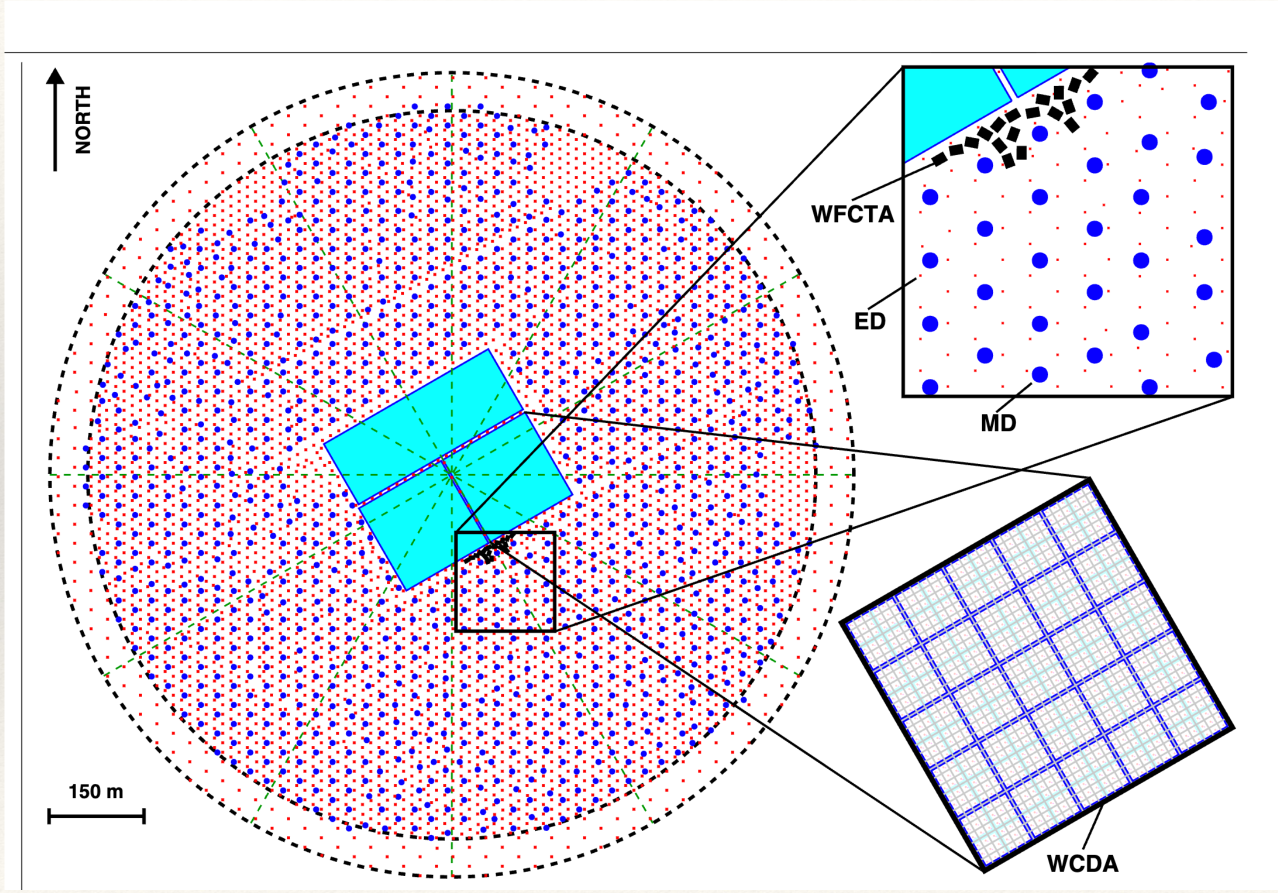
Large High Altitude Air Shower Array (LHAASO)

- 4400m
- CUHK is part of the collaboration!
-

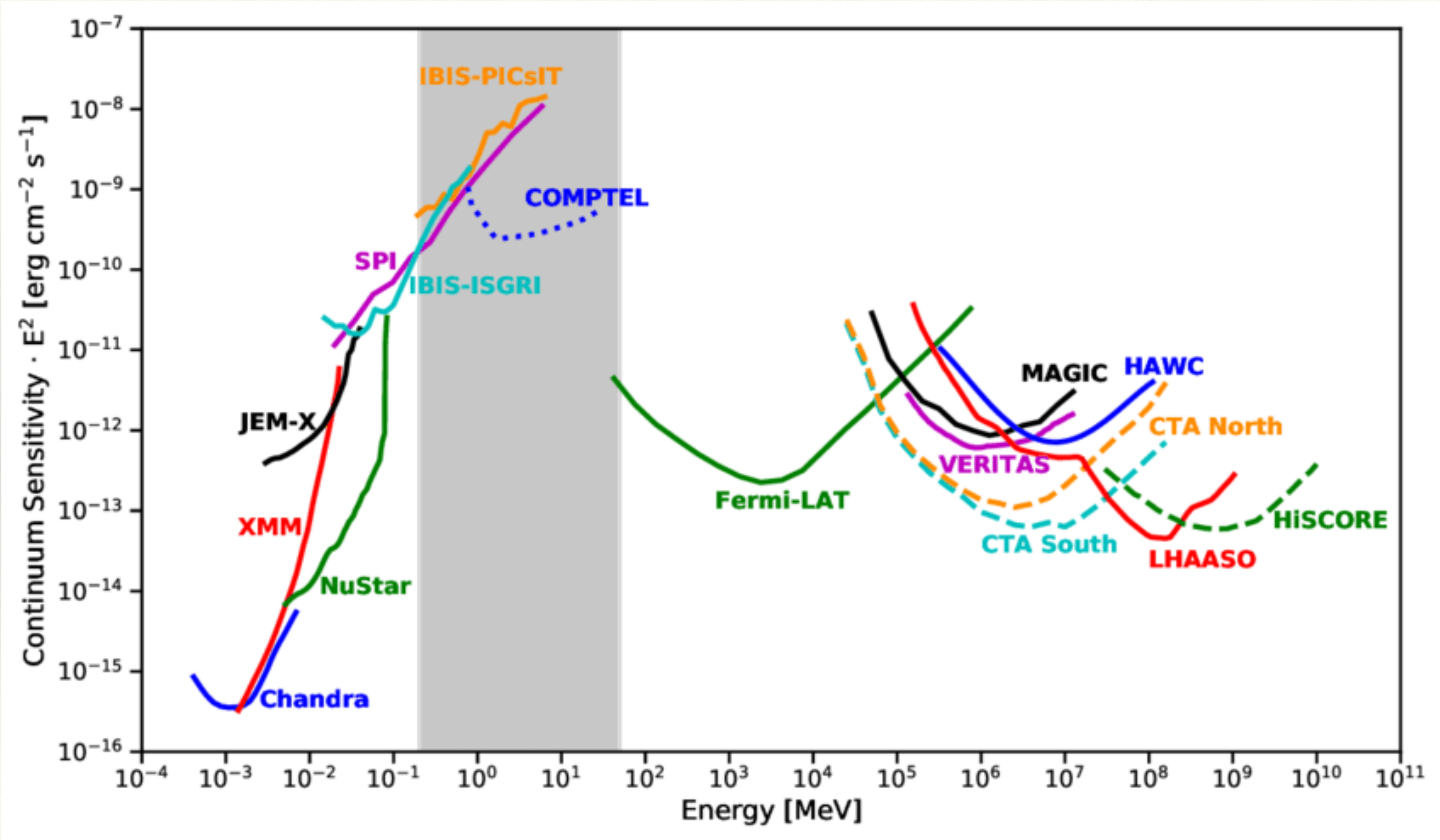


LHAASO

- KM2A
  - Electronic detector ED
  - Muon detector MD
    - MD to reject hadrons
  - EM shower has no muons
- WCDA
  - Water Cherenkov telescope



Best gamma-ray telescope at PeV



Article

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

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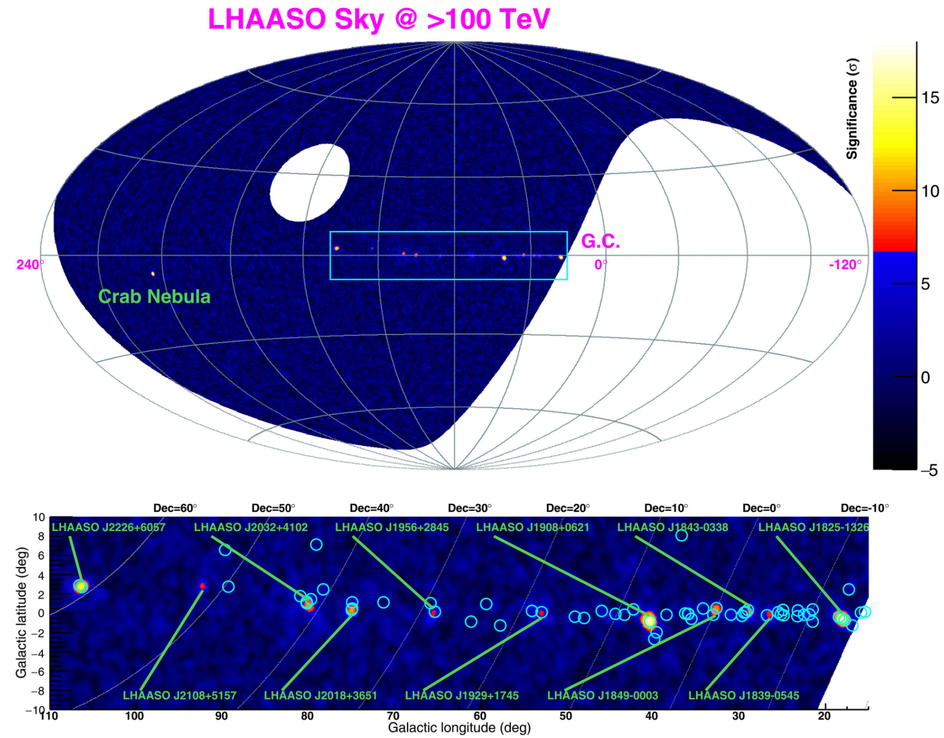
Check for updates

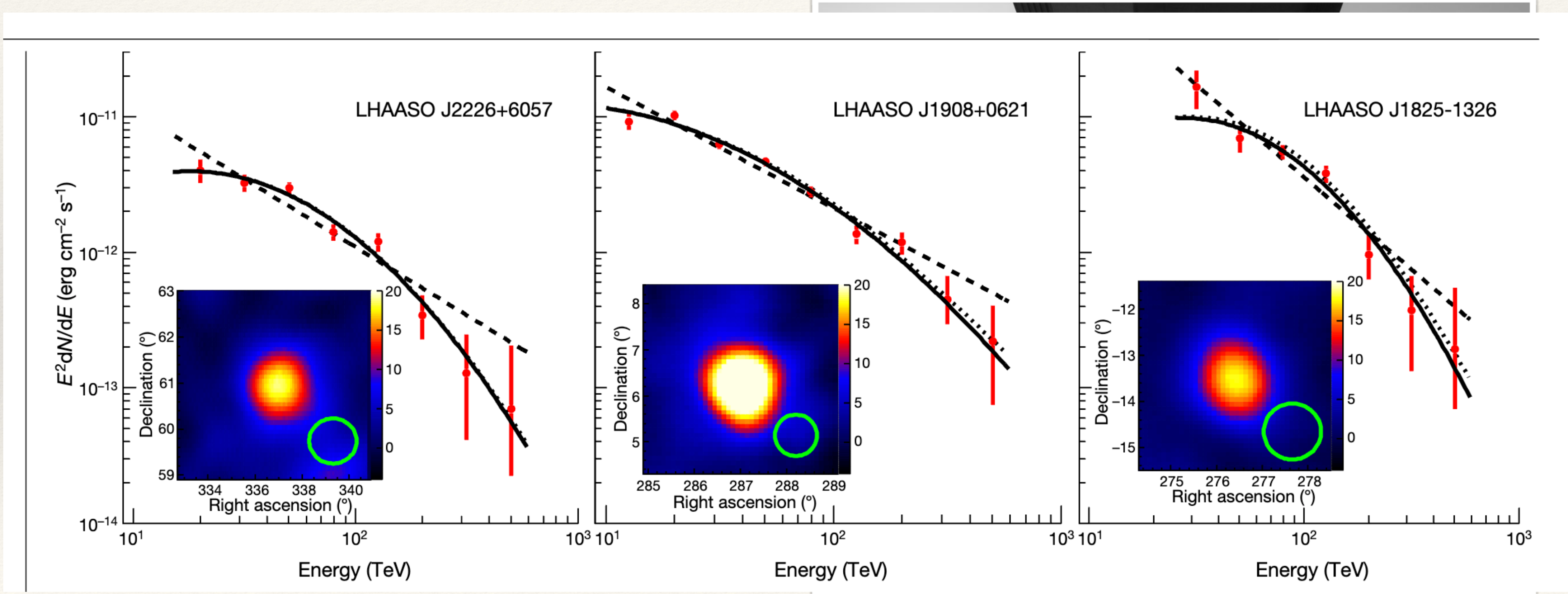
A list of authors and affiliations appears at the end of the paper.

The extension of the cosmic-ray spectrum beyond 1 petaelectronvolt (PeV; 10^{15} electronvolts) indicates the existence of the so-called PeVatrons—cosmic-ray factories that accelerate particles to PeV energies. We need to locate and identify such objects to find the origin of Galactic cosmic rays[1]. The principal signature of both electron and proton PeVatrons is ultrahigh-energy (exceeding 100 TeV) γ radiation. Evidence of the presence of a proton PeVatron has been found in the Galactic Centre, according to the detection of a hard-spectrum radiation extending to 0.04 PeV (ref. [2]). Although γ-rays with energies slightly higher than 0.1 PeV have been reported from a few objects in the Galactic plane[3–6], unbiased identification and in-depth exploration of PeVatrons requires detection of γ-rays with energies well above 0.1 PeV. Here we report the detection of more than 530 photons at energies above 100 teraelectronvolts and up to 1.4 PeV from 12 ultrahigh-energy γ-ray sources with a statistical significance greater than seven standard deviations. Despite having several potential counterparts in their proximity, including pulsar wind nebulae, supernova remnants and star-forming regions, the PeVatrons responsible for the ultrahigh-energy γ-rays have not yet been firmly localized and identified (except for the Crab Nebula), leaving open the origin of these extreme accelerators.

Article



Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.


LHAASO J2226+6057
LHAASO J1908+0621
LHAASO J1825-1326
E^2dN/dE (erg cm^{-2} s^{-1})
Energy (TeV)
Declination (°)
Right ascension (°)