Of photons and protons

Chasing galactic cosmic rays with HESS

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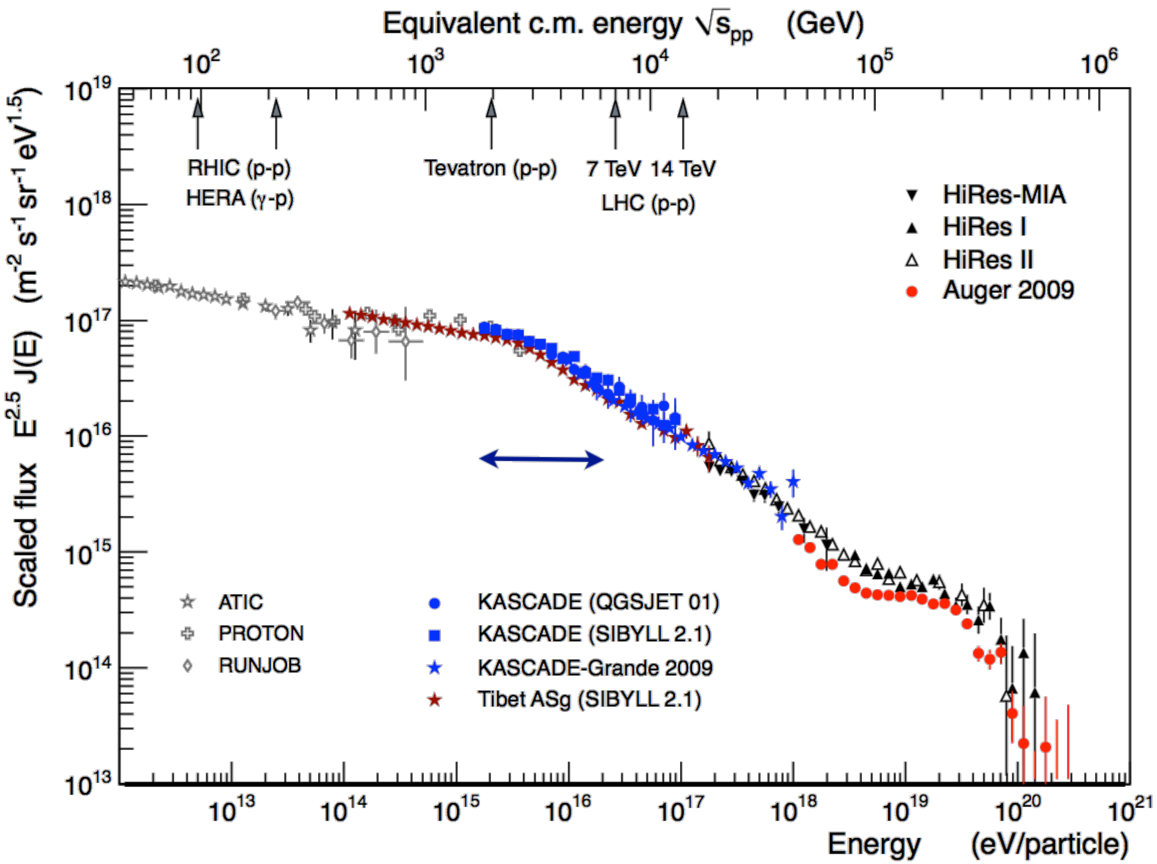
GRAPPA INSTITUTE
Gravitation AstroParticle Physics Amsterdam

Charged Cosmic Rays



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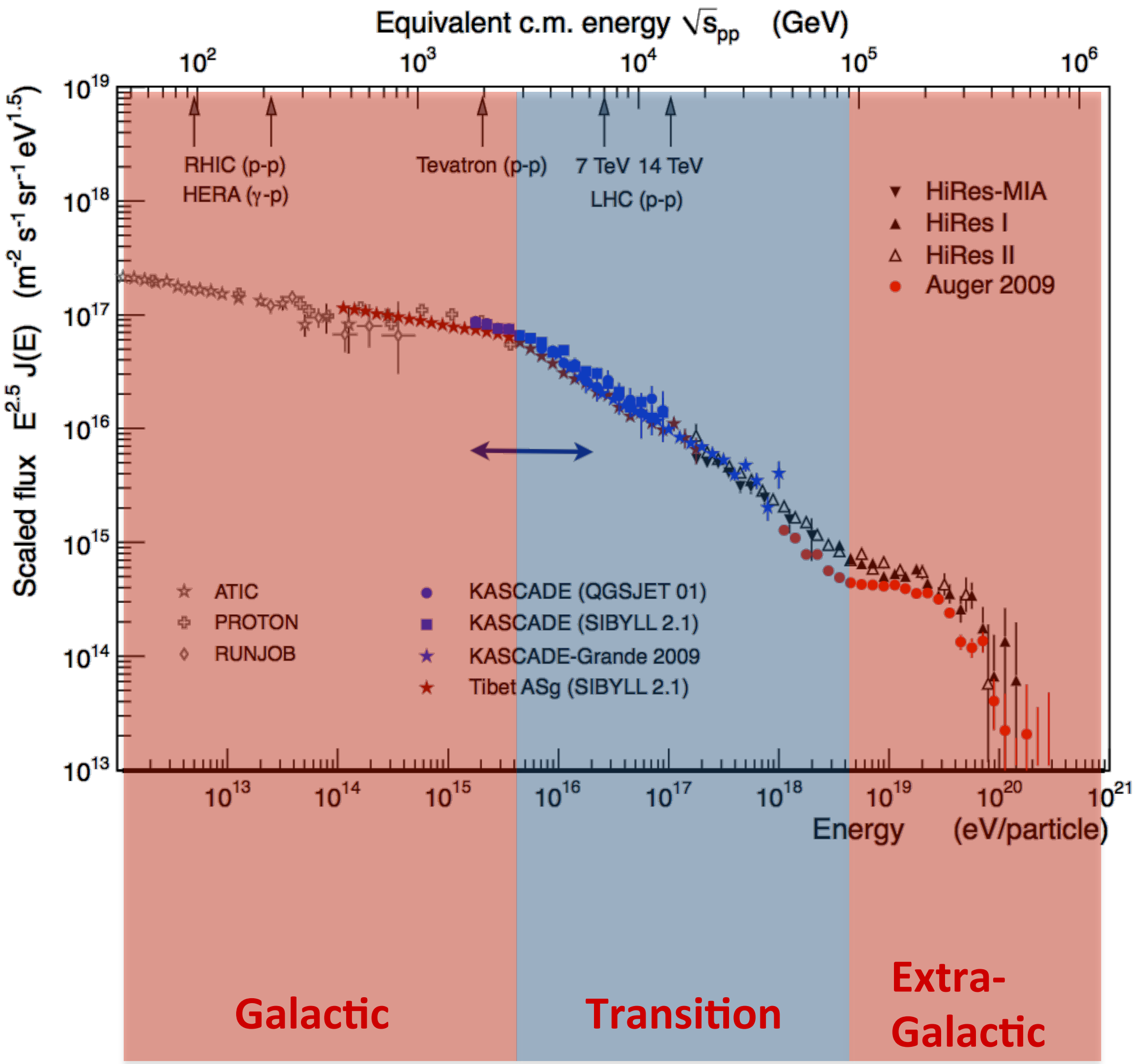
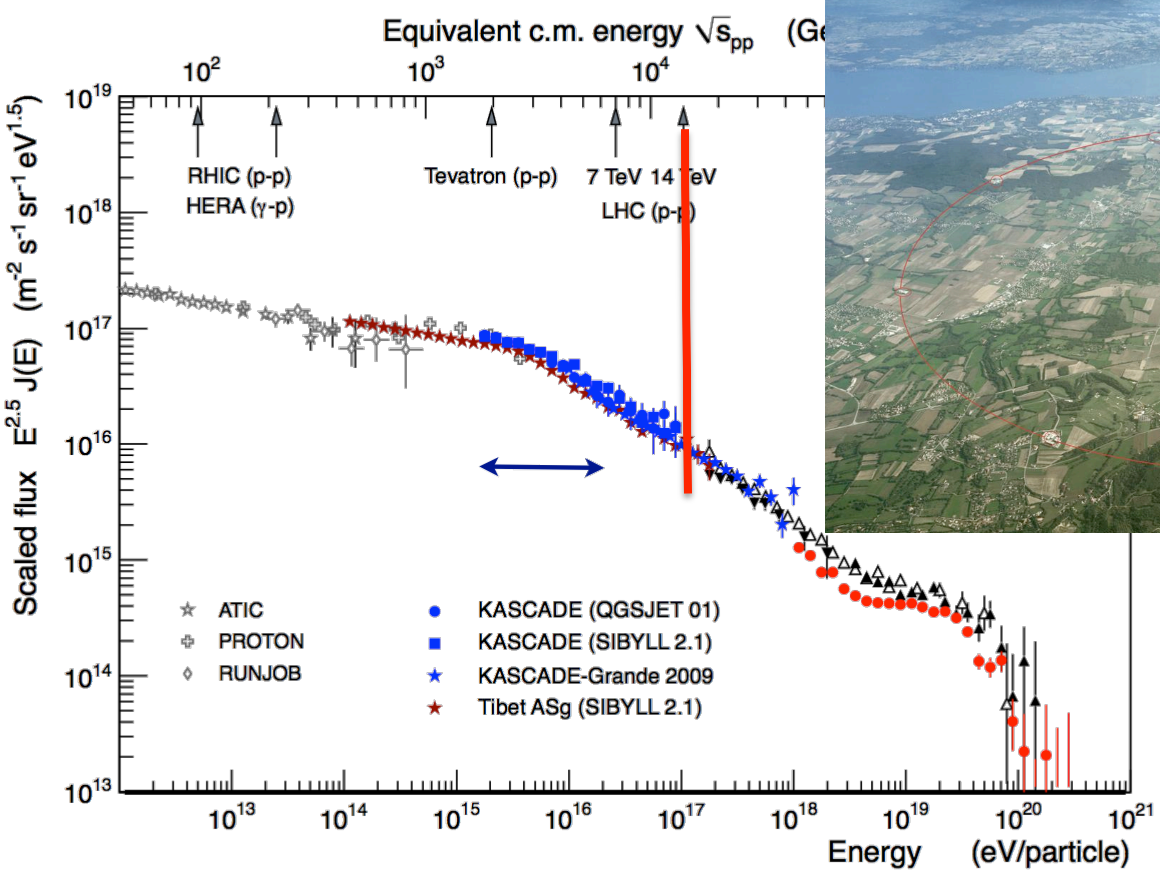


Why bother?

1. Nature's most powerful accelerators!



2. Huge energy density

In the Milky Way, in each of Cosmic Rays, magnetic fields, thermal gas, have about:

$1\ \mathrm{eV\ cm^{-3}}$

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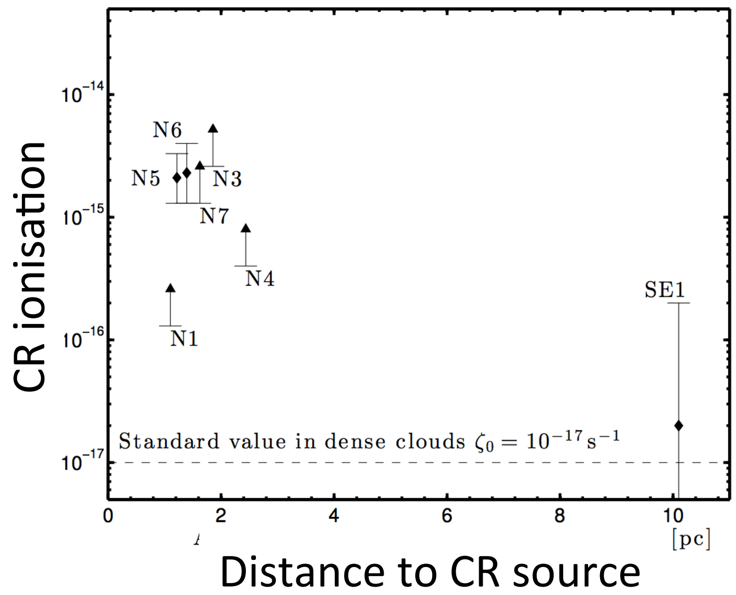
Example: ionisation of interstellar medium (ISM)

- Dense molecular clouds are opaque to ionising UV light
- Cosmic Rays can penetrate into gas and ionise
  - ISM chemistry
- Potentially trigger star formation
- Exploding stars (very likely) feed back and accelerate Cosmic Rays again



Vaupre et al (2014)

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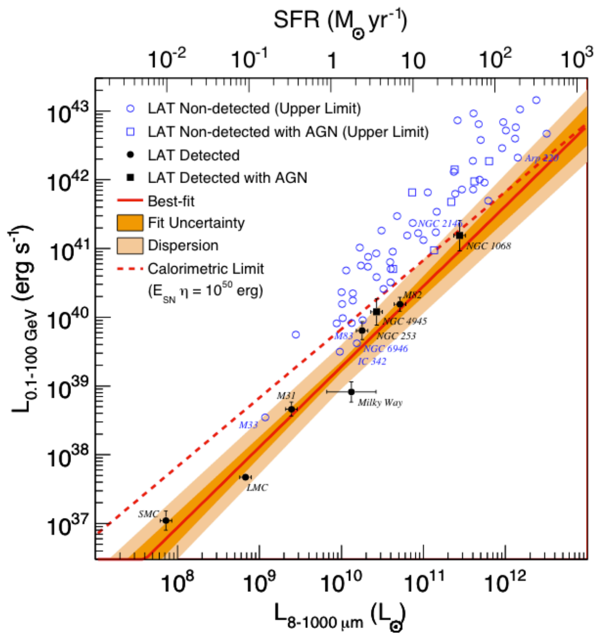
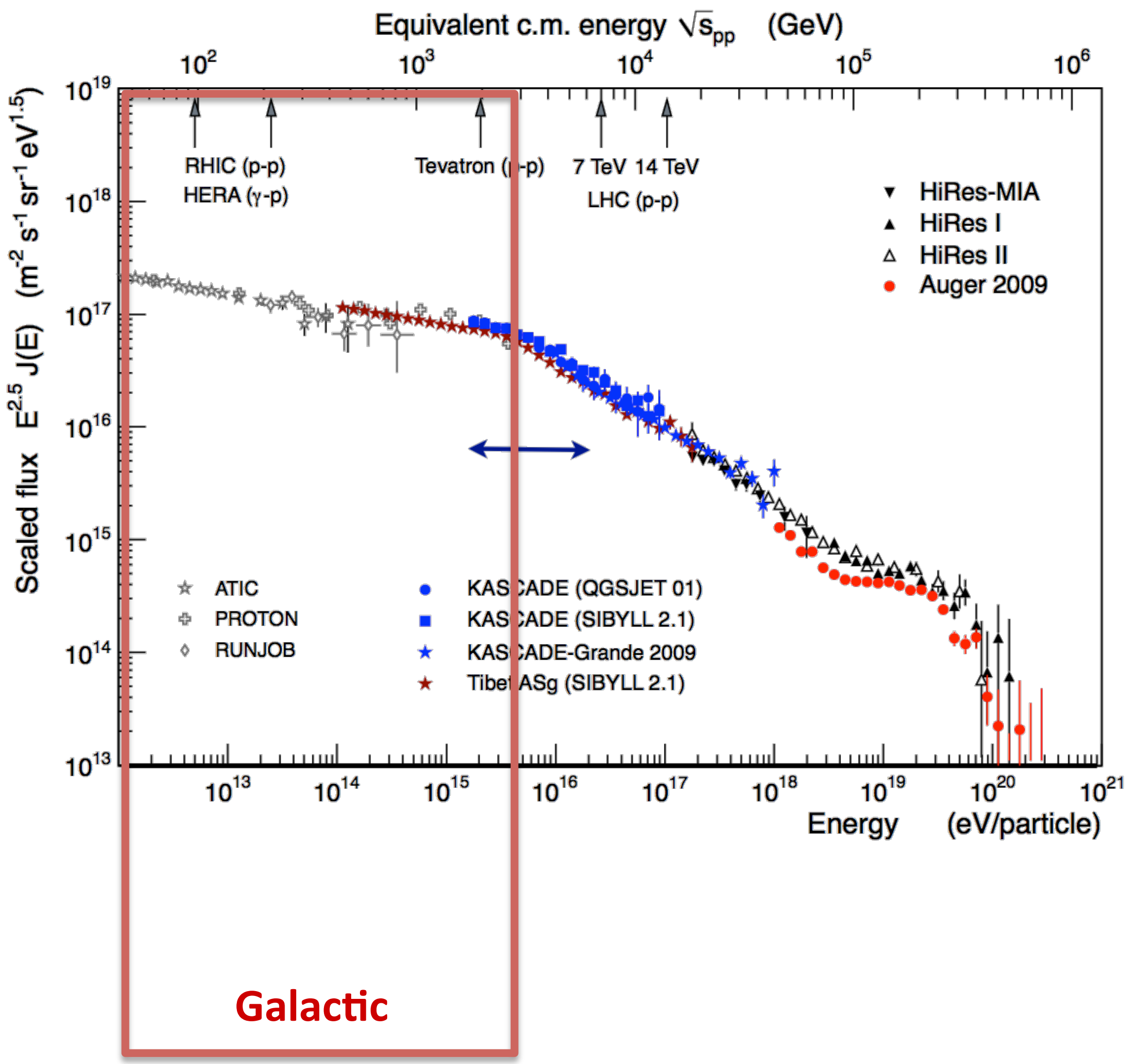


Fermi-LAT, ApJ 755 (2012)

Galactic Cosmic Rays – Facts



There are PeVatrons in the Milky Way!

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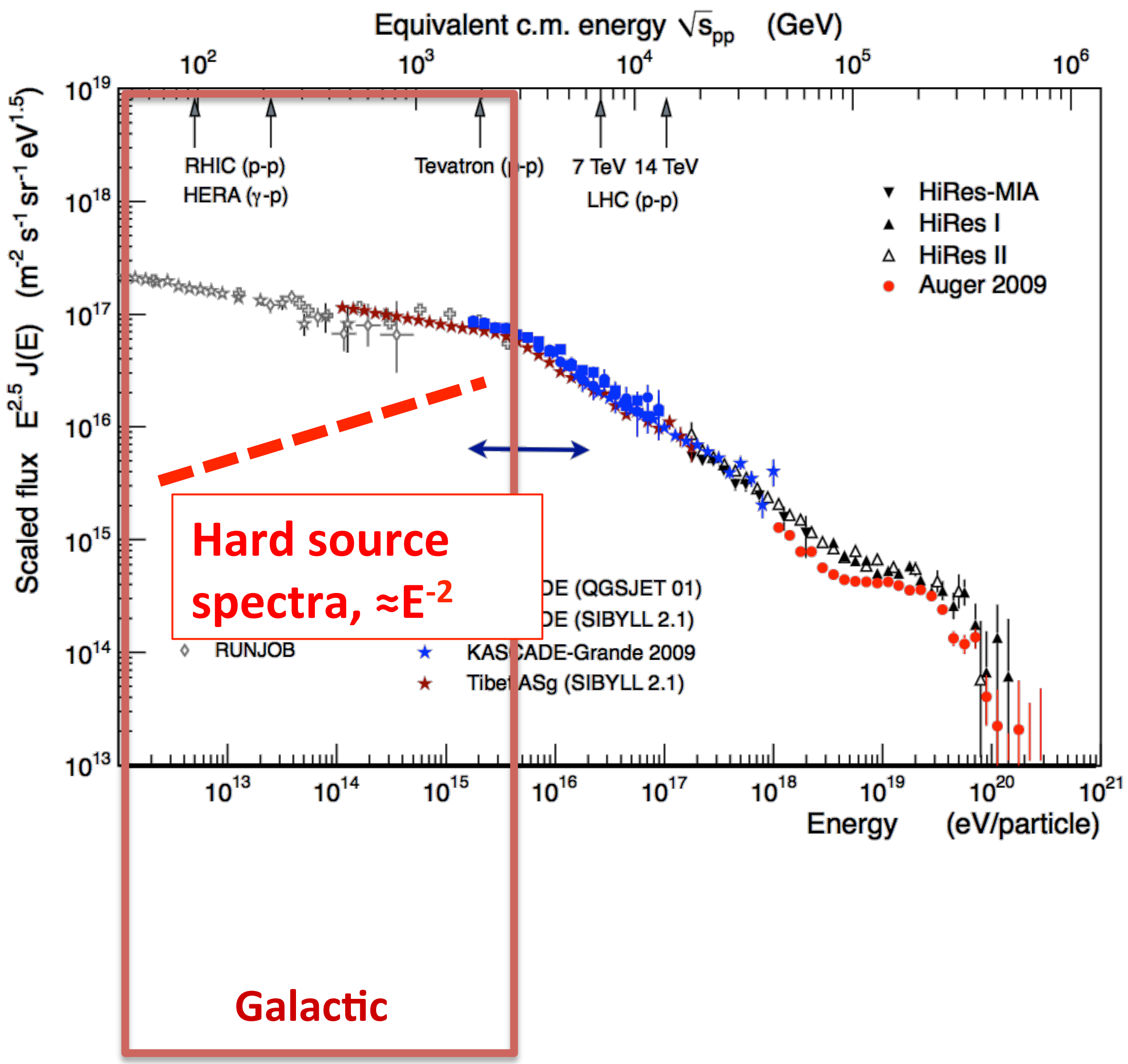

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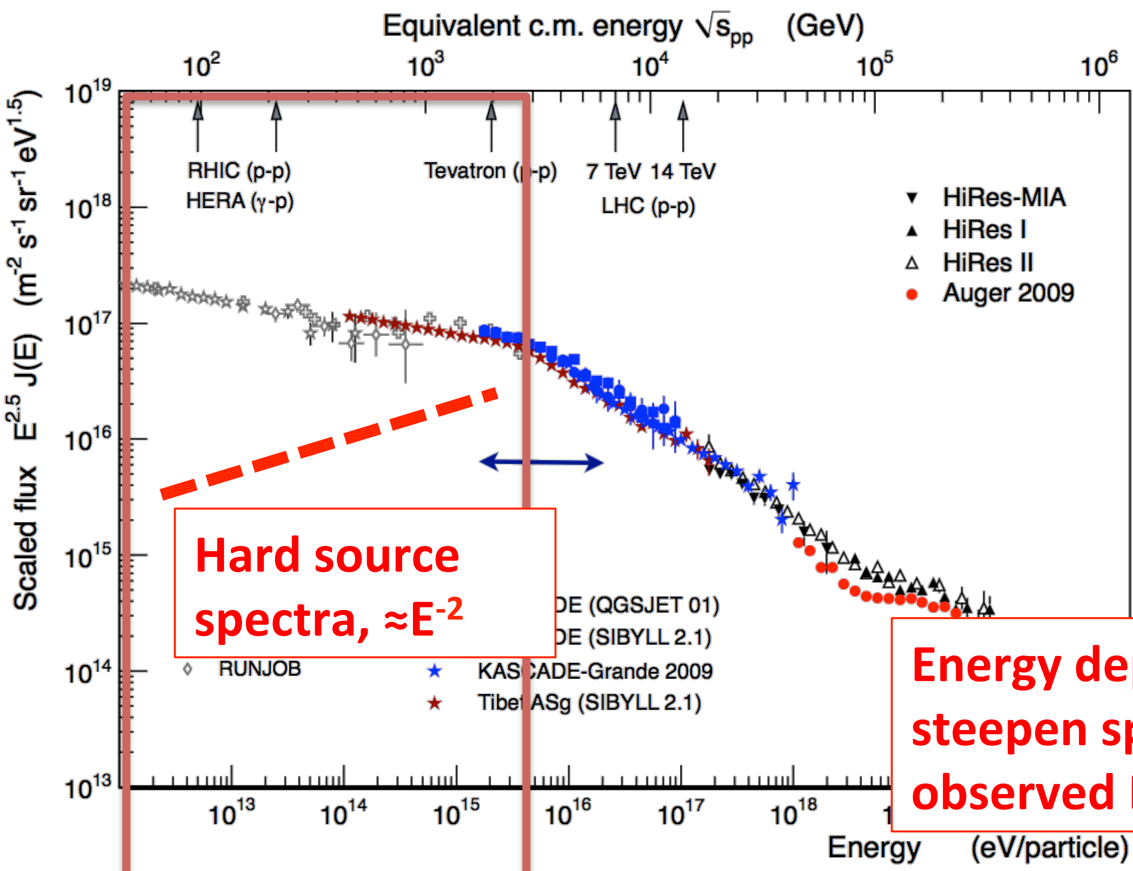


Hard source spectra, $\approx E^{-2}$

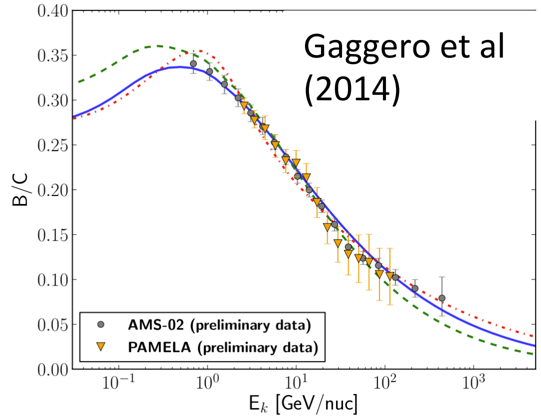
Galactic

Energy dependent losses steepen spectrum to observed $E^{-2.7}$

There are PeVatrons in the Milky Way!

Secondary Boron over primary Carbon ratio driven by retention time:

$$\tau_d(E) \propto E^{-0.3\ldots0.5}$$



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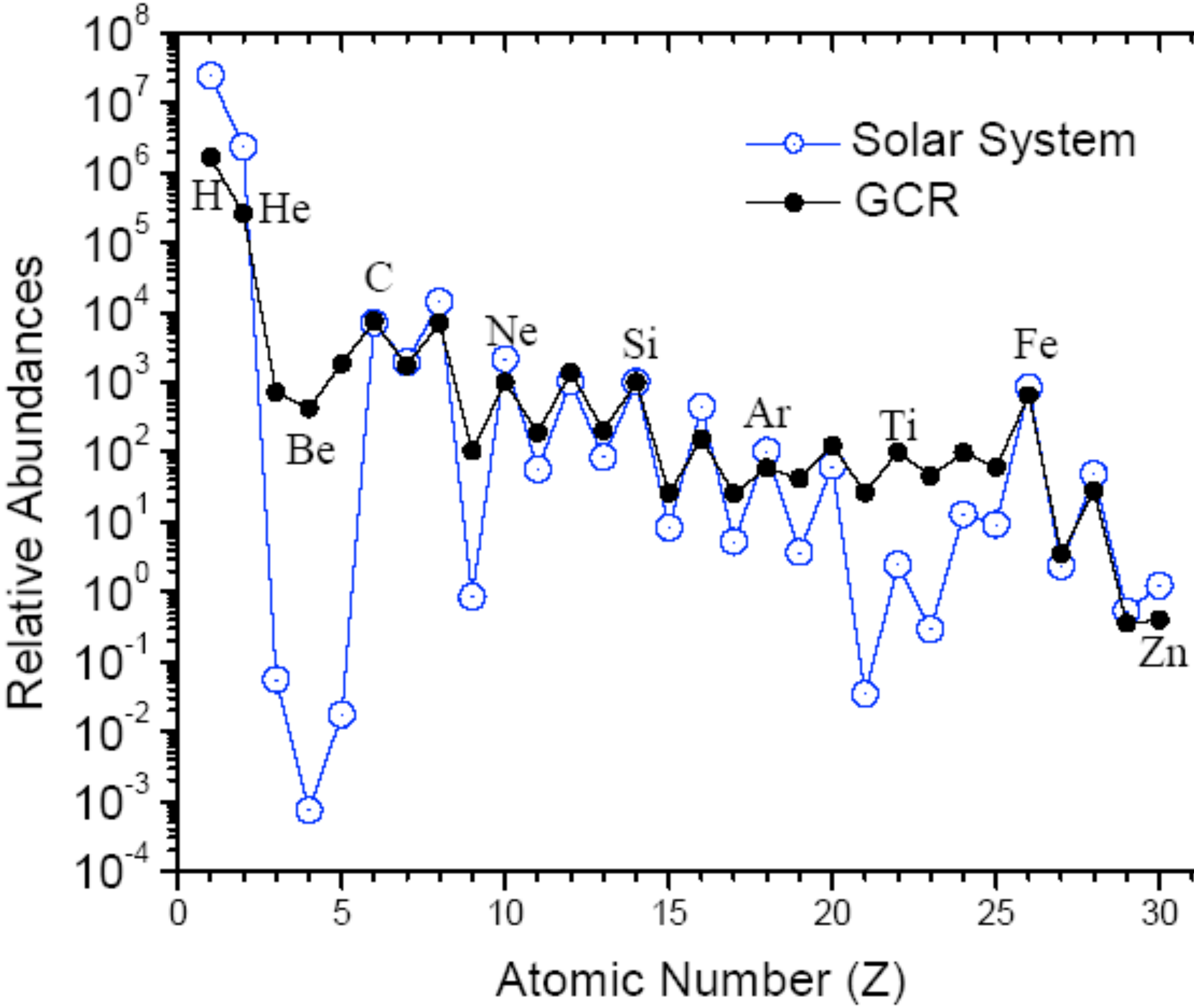

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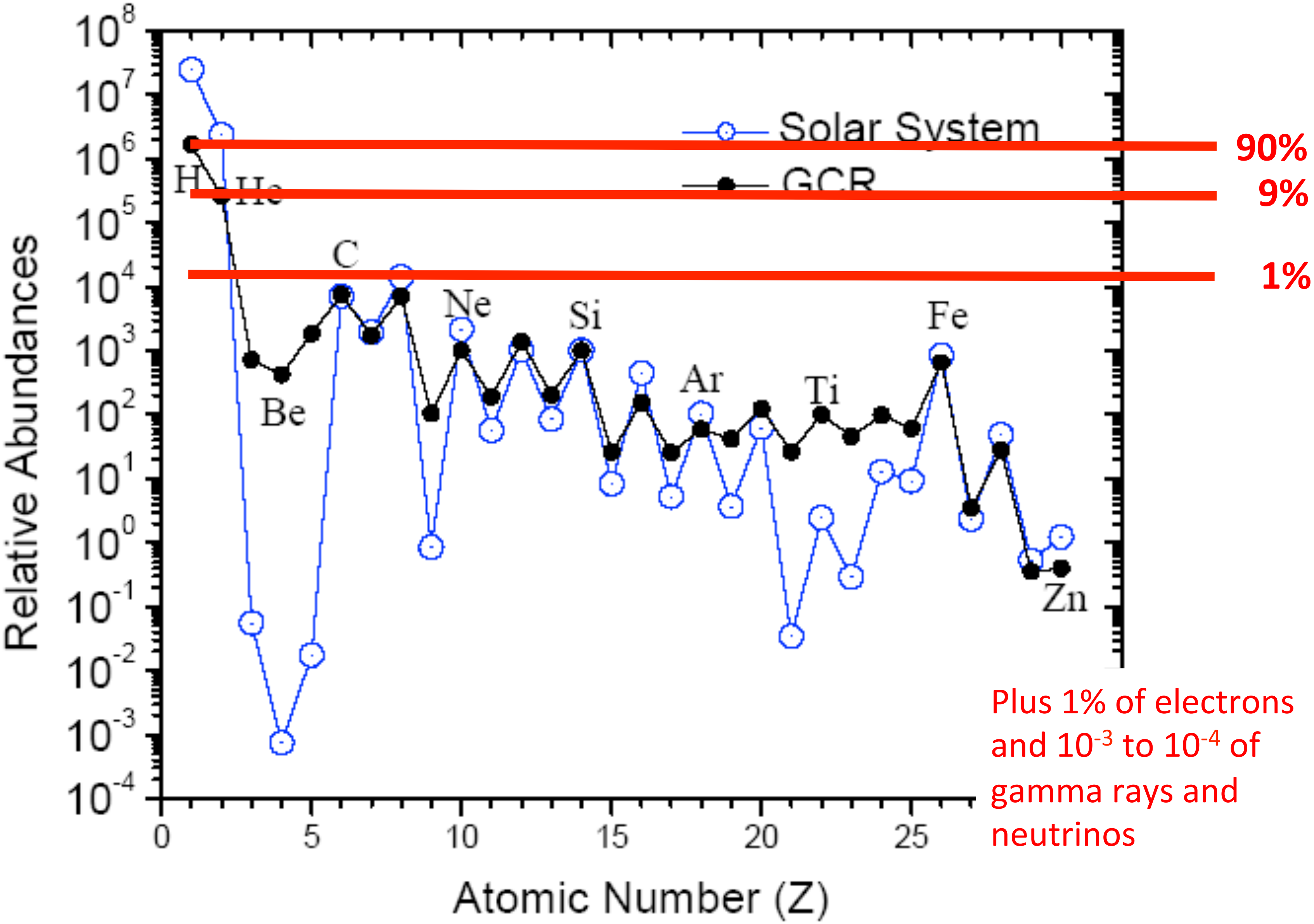
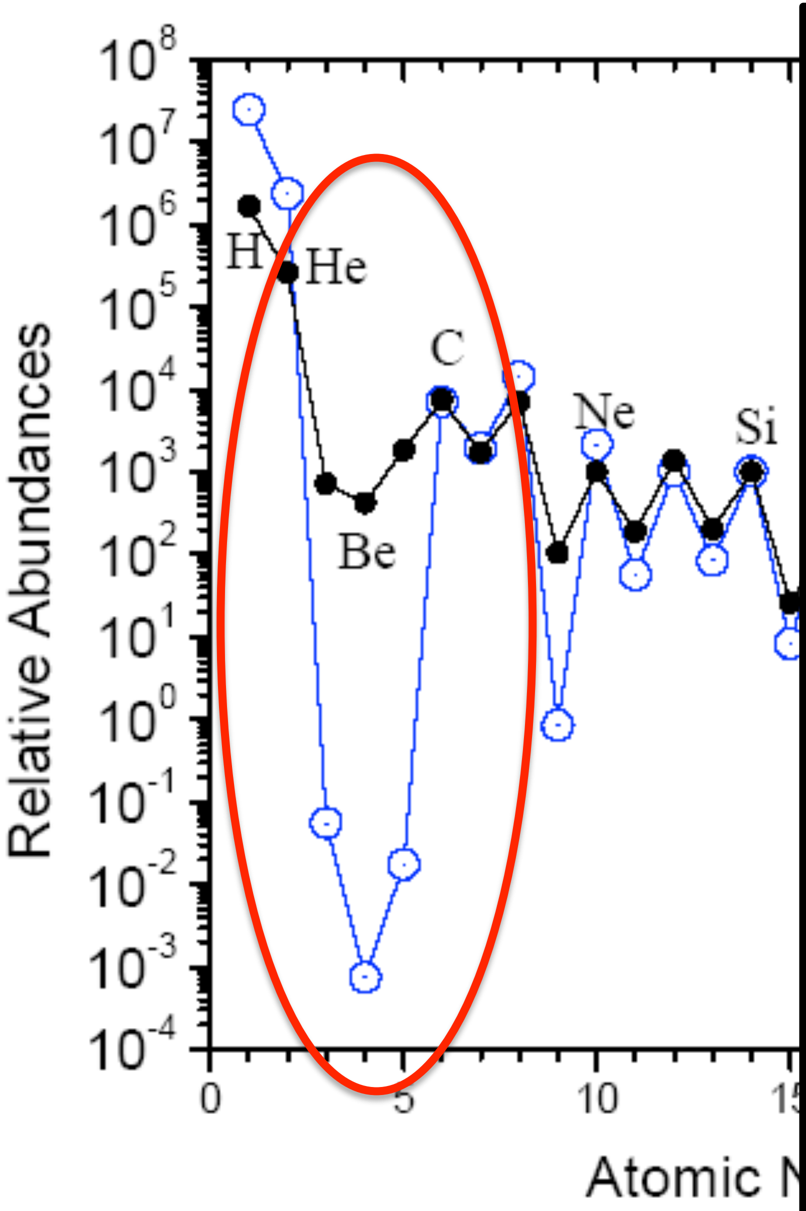
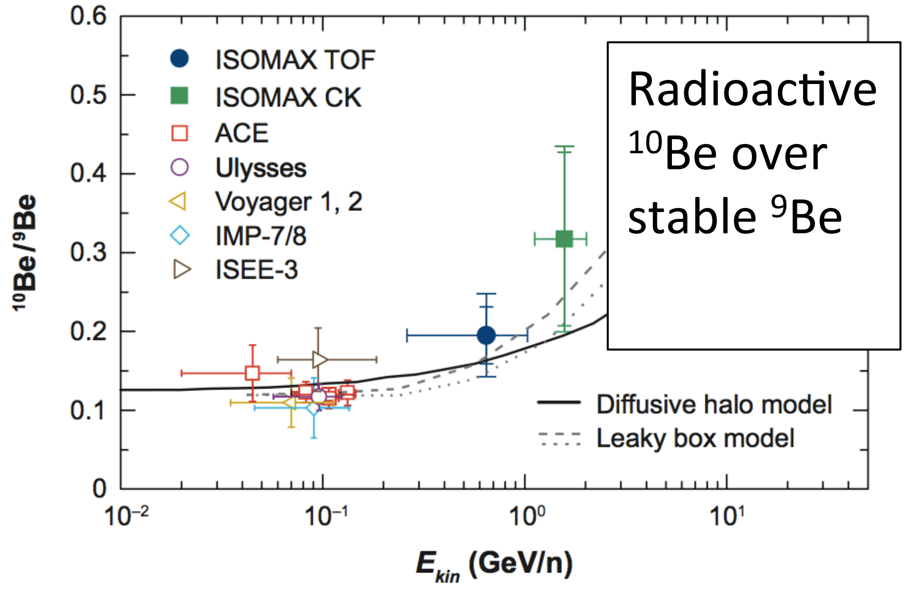


Plus 1% of electrons and 10^{-3} to 10^{-4} of gamma rays and neutrinos

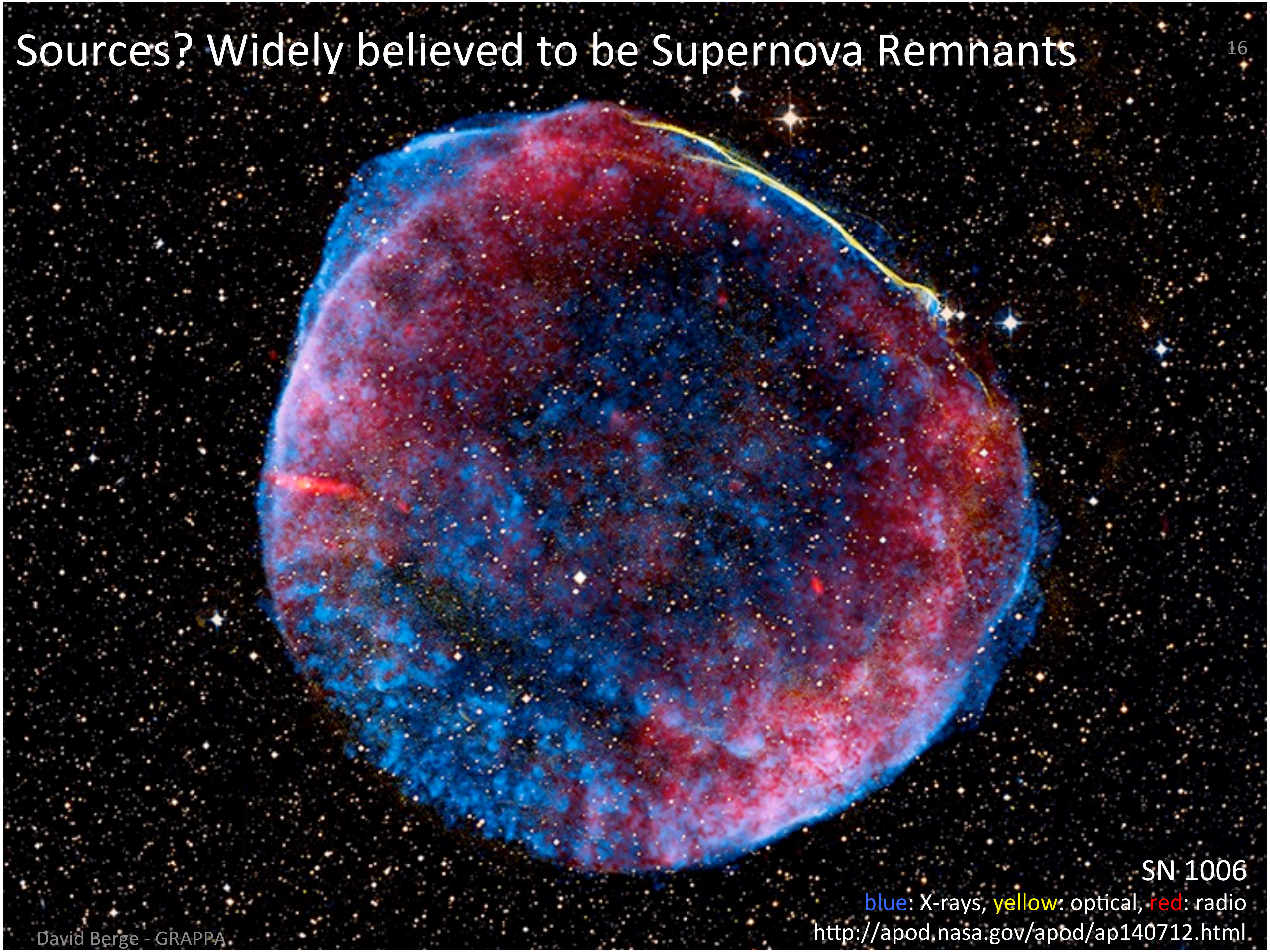
Galactic Cosmic Rays – Facts





- Radioactive secondary cosmic rays can be used as clocks
- Isotope ratio fixed by retention time, 10^7 years in the Galaxy!
- Need 10^{41} erg/s = 10^{34} W to sustain Cosmic Ray flux
- Which source object can provide this?

Sources? Widely believed to be Supernova Remnants



SN 1006

blue: X-rays, yellow: optical, red: radio

http://apod.nasa.gov/apod/ap140712.html

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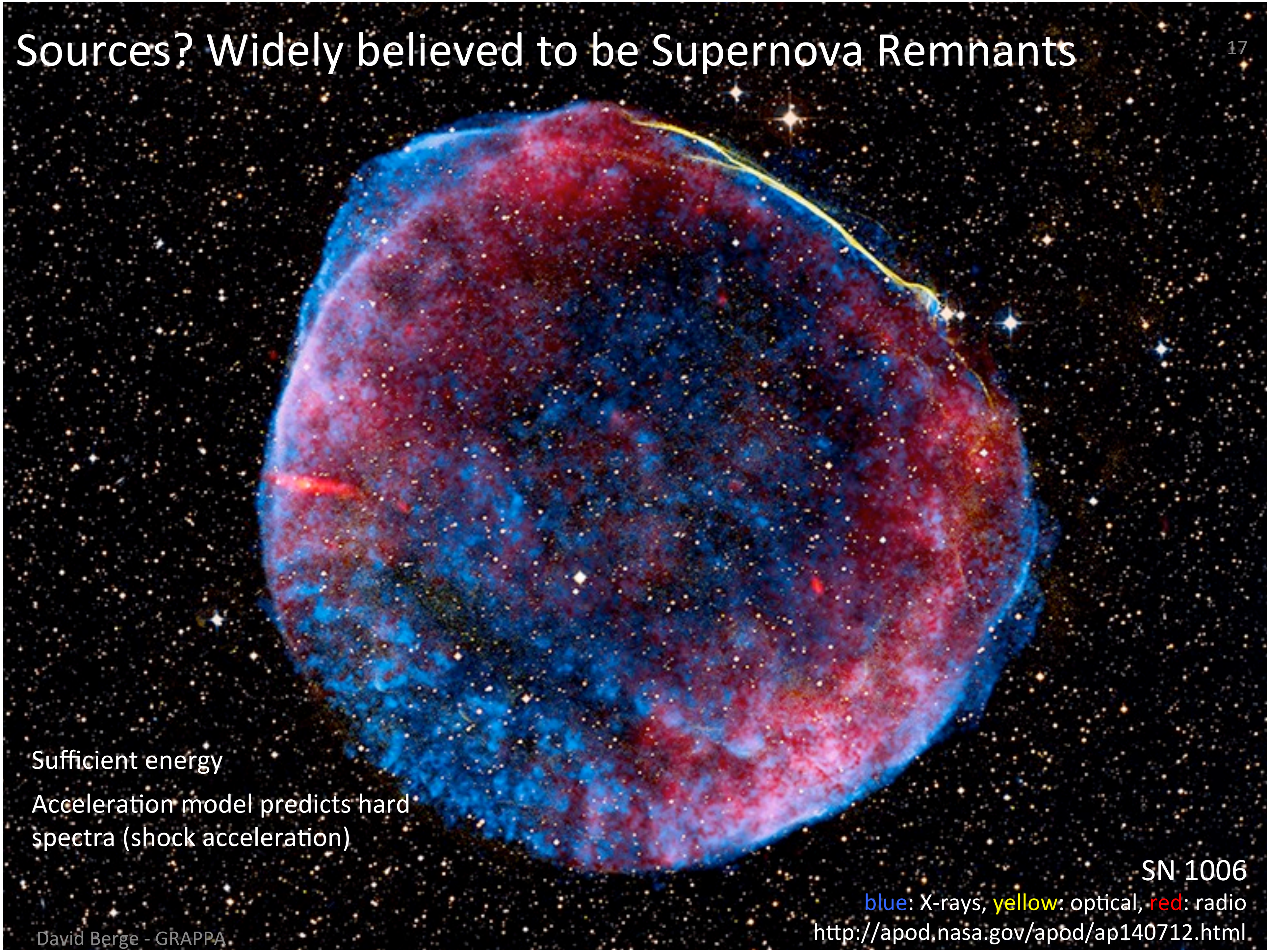


Sufficient energy

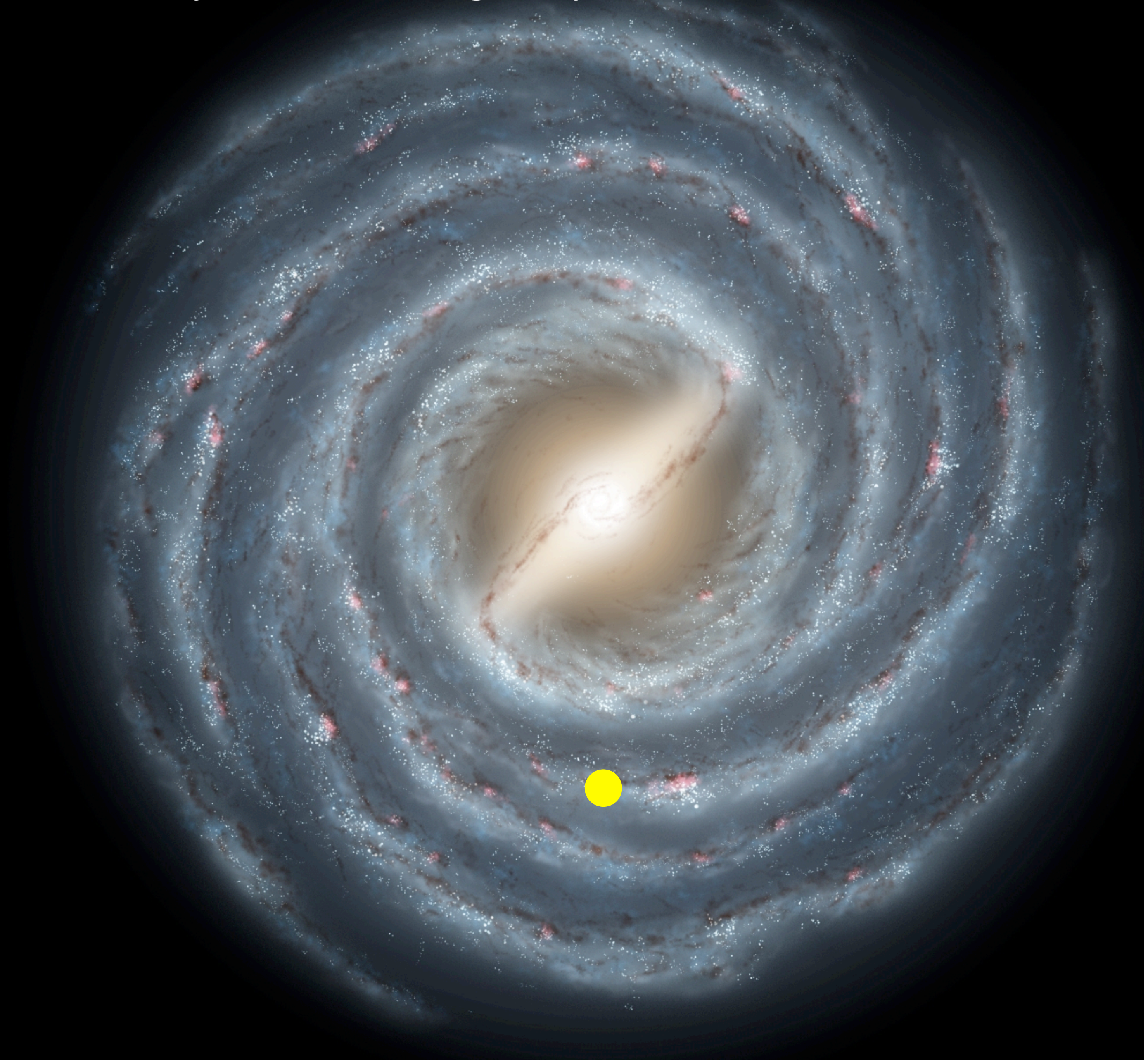
Acceleration model predicts hard spectra (shock acceleration)

SN 1006

blue: X-rays, yellow: optical, red: radio

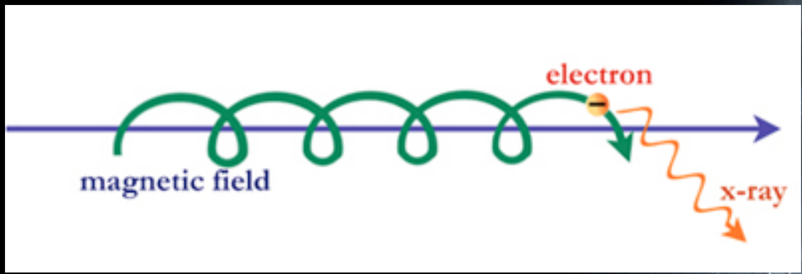
http://apod.nasa.gov/apod/ap140712.html

But how to do astronomy with charged particles?

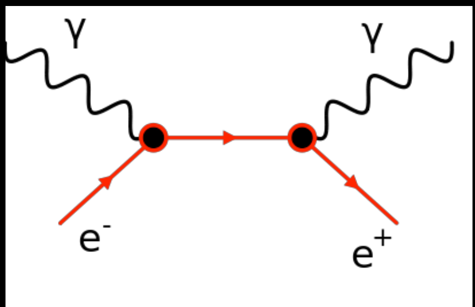


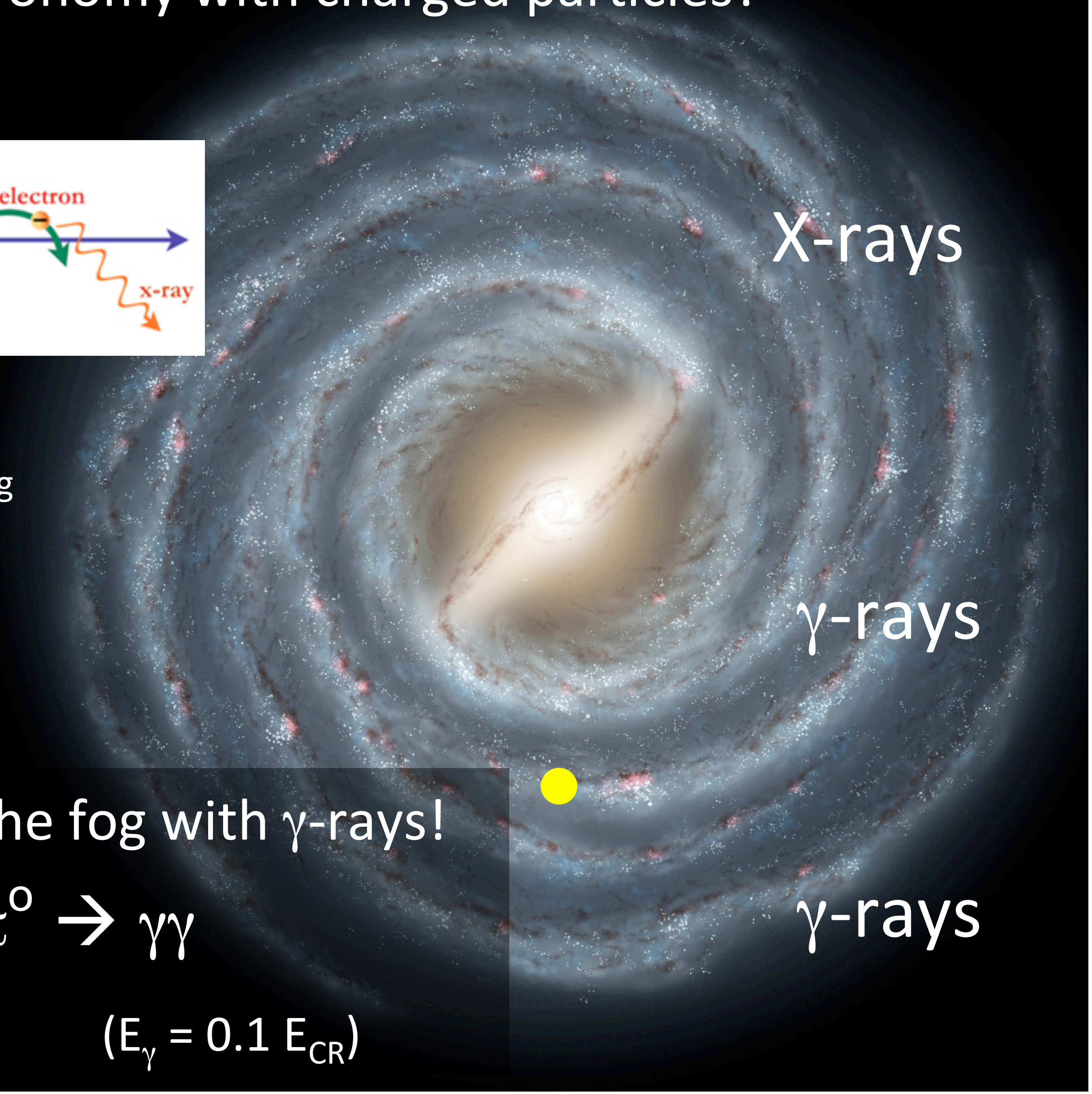
But how to do astronomy with charged particles?

Synchrotron Radiation



Inverse Compton Scattering



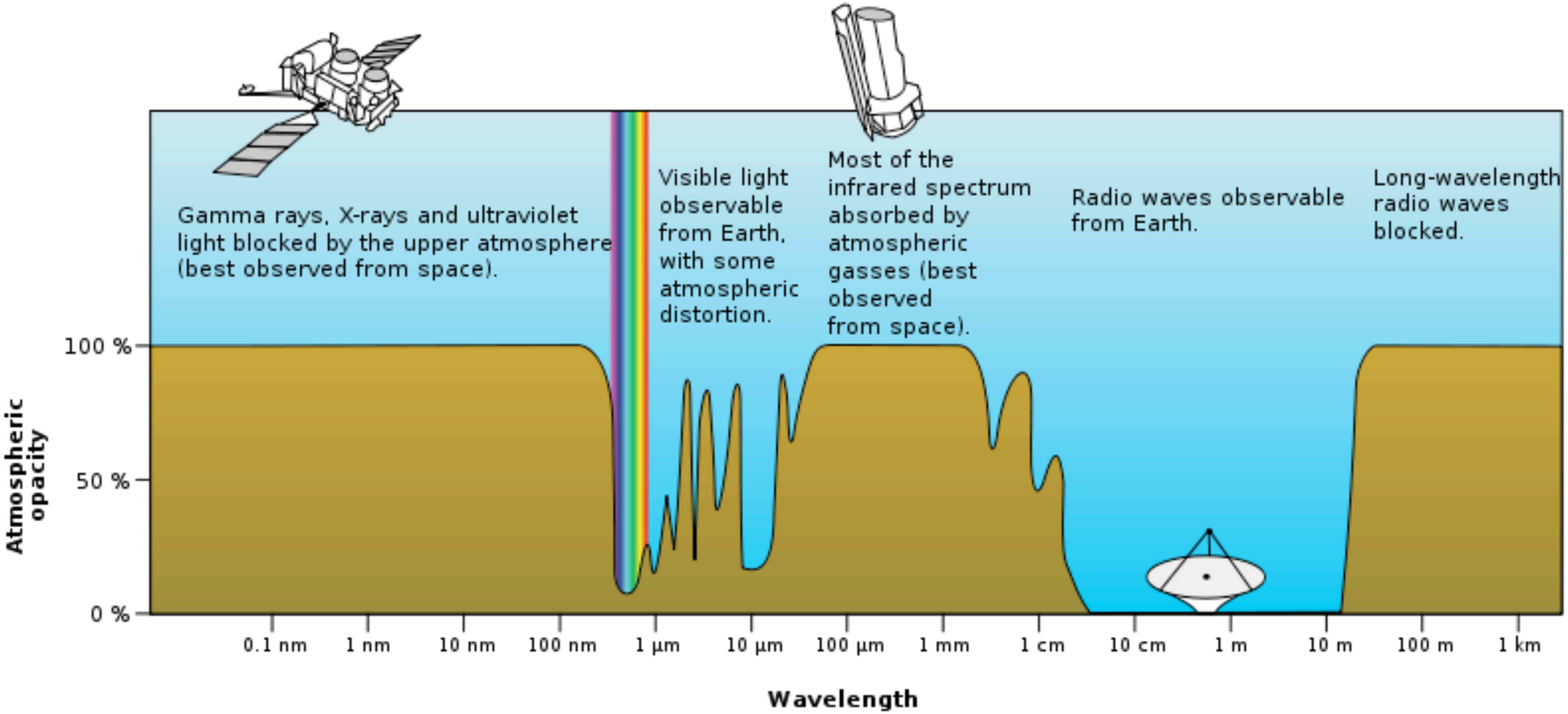


Looking through the fog with γ-rays!

$$p_{CR} + ISM \rightarrow \pi^{o} \rightarrow \gamma\gamma$$

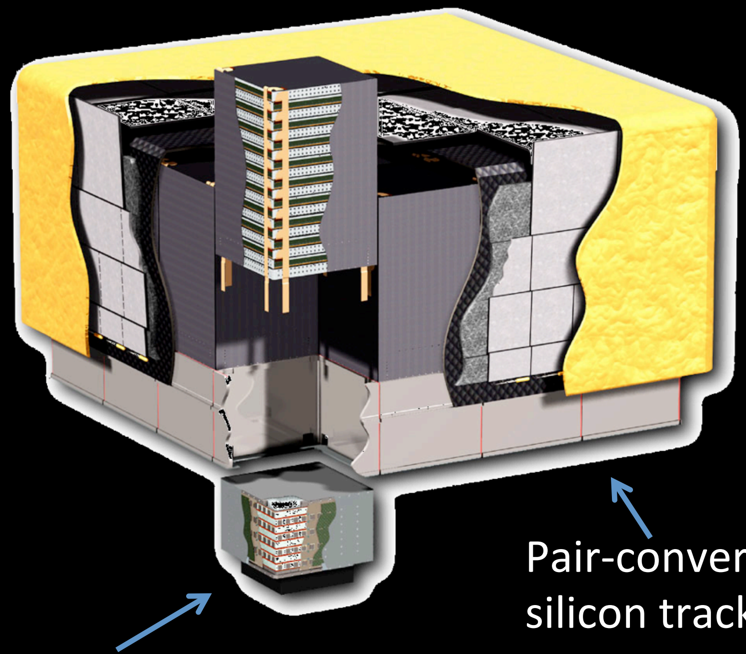
$(E_{\gamma} = 0.1\ E_{CR})$

γ-ray Astronomy



100 MeV – 100 GeV γ-rays:

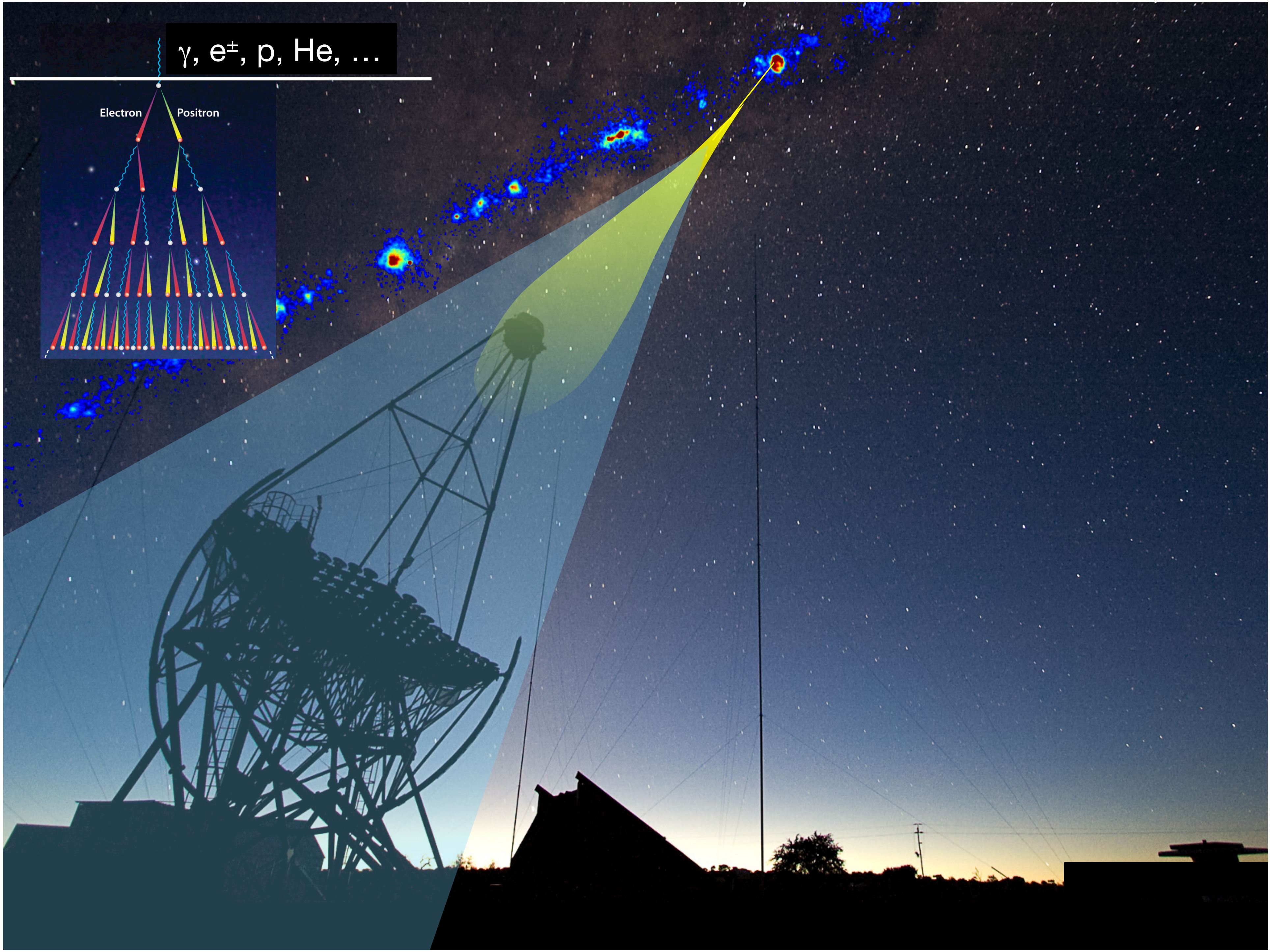
Fermi-LAT

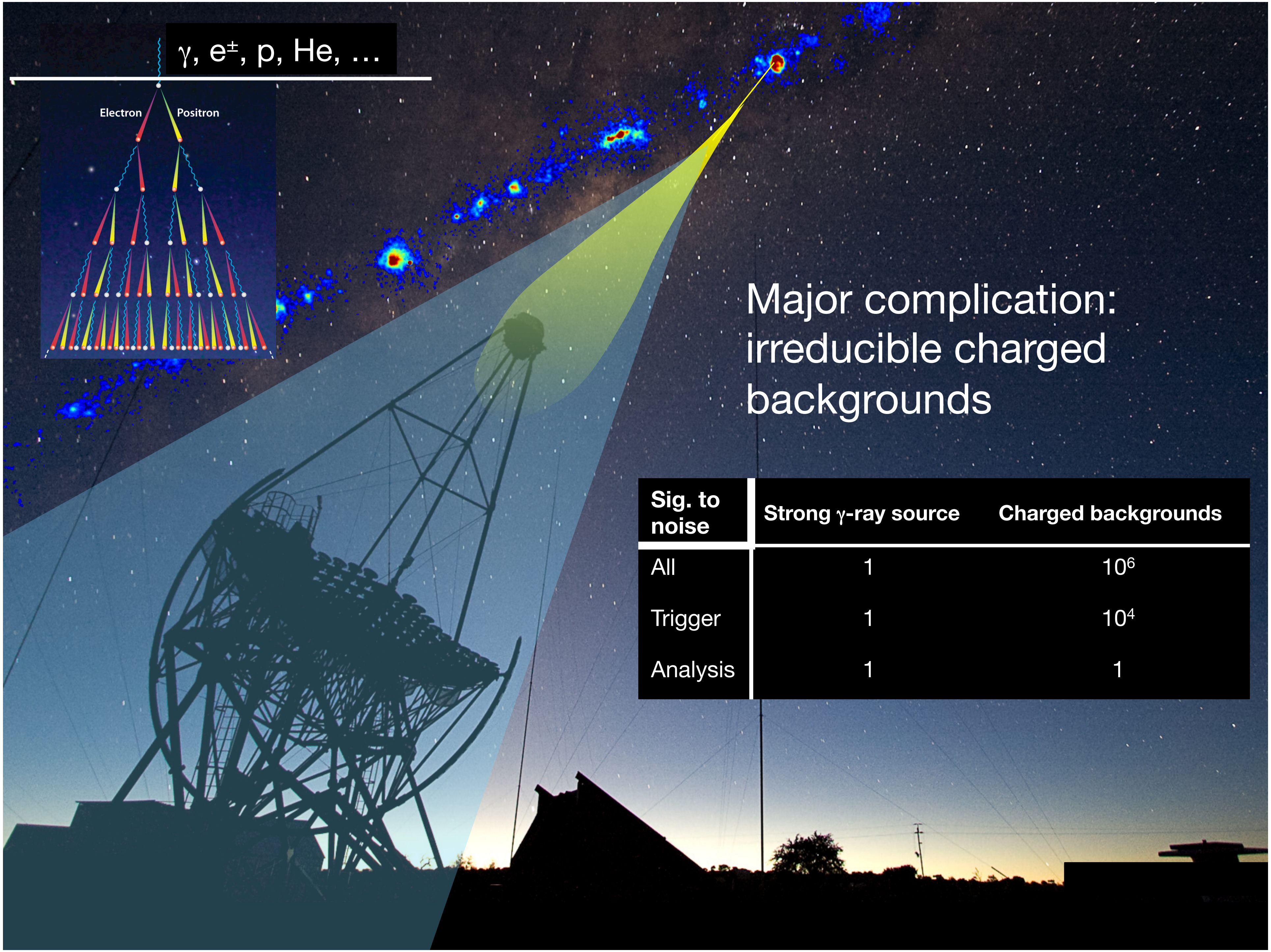


Pair-conversion
silicon tracker

Calorimeter

30 MeV – 300 GeV
1 m^2 2.5 sr
Near perfect charged
particle rejection


γ, e±, p, He, ...
Electron
Positron



Major complication: irreducible charged backgrounds

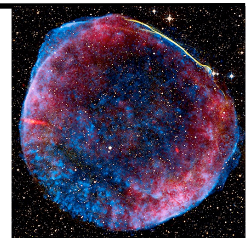
Sig. to noise	Strong γ-ray source	Charged backgrounds
All	1	10^6
Trigger	1	10^4
Analysis	1	1

The Question

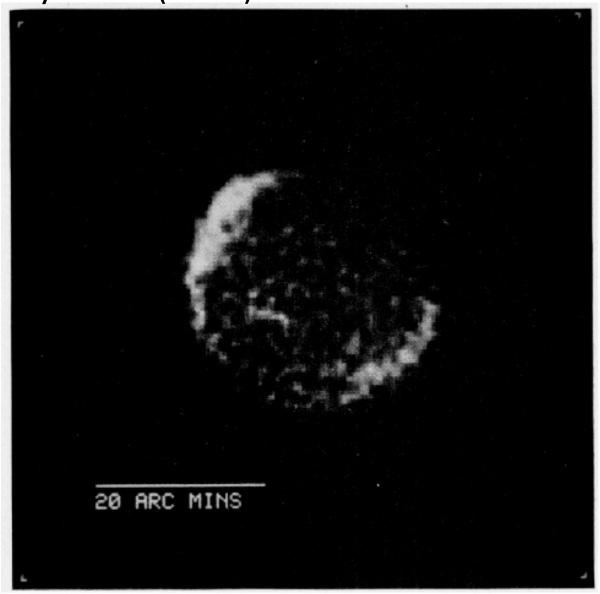
- Are charged particles accelerated at SN shocks?

X-rays: SN shells are particle accelerators!

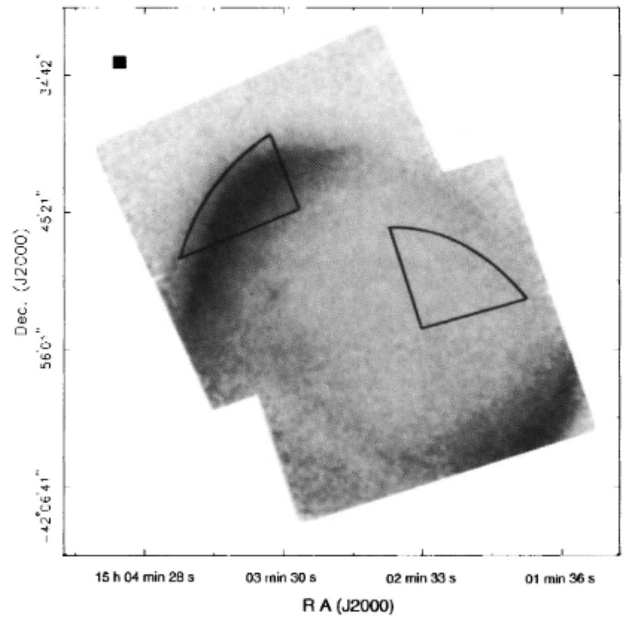
SN 1006

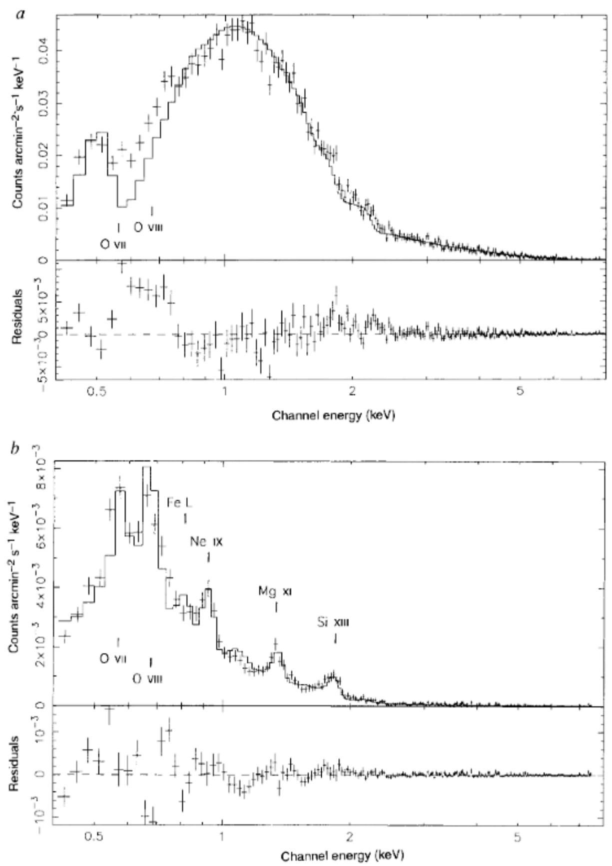


1.2-4 keV, Einstein observatory, Pye et al (1981)



0.4-8 keV, ASCA, Koyama et al (1995)



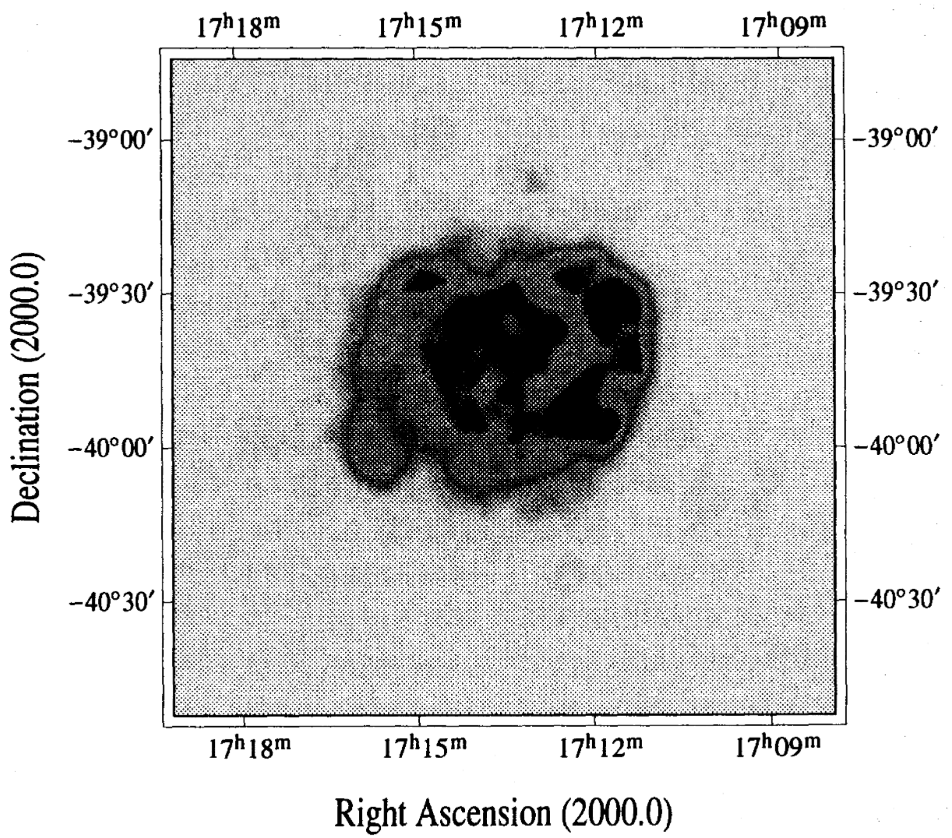


Proof of 100 TeV electrons accelerated at shock!

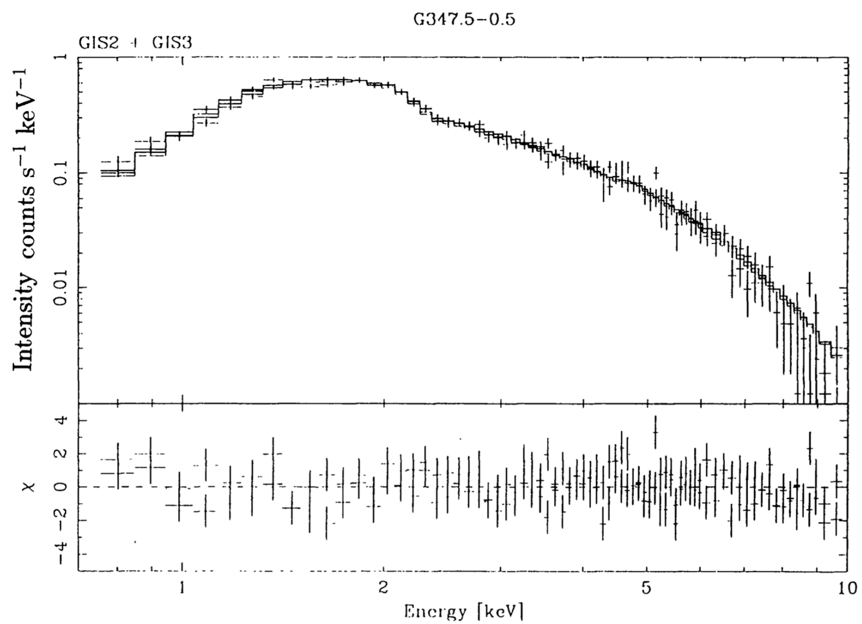
X-rays: SN shells are particle accelerators!

<u>RX J1713.7-3946</u>

1.2-4 keV, ROSAT, Pfeffermann, Aschenbach (1996)



1-10 keV, ASCA, Koyama et al (1997)



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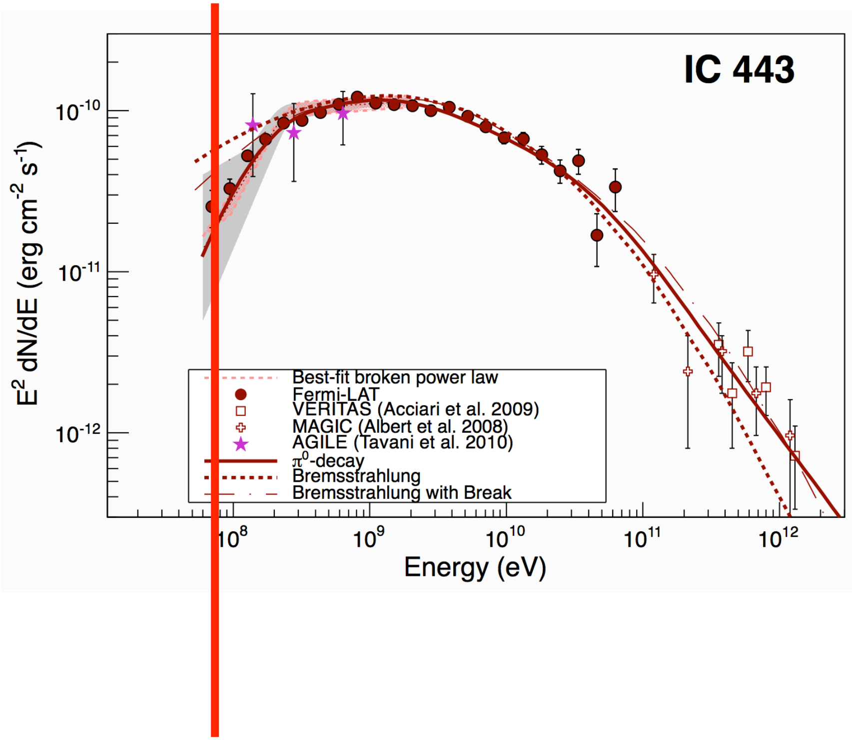
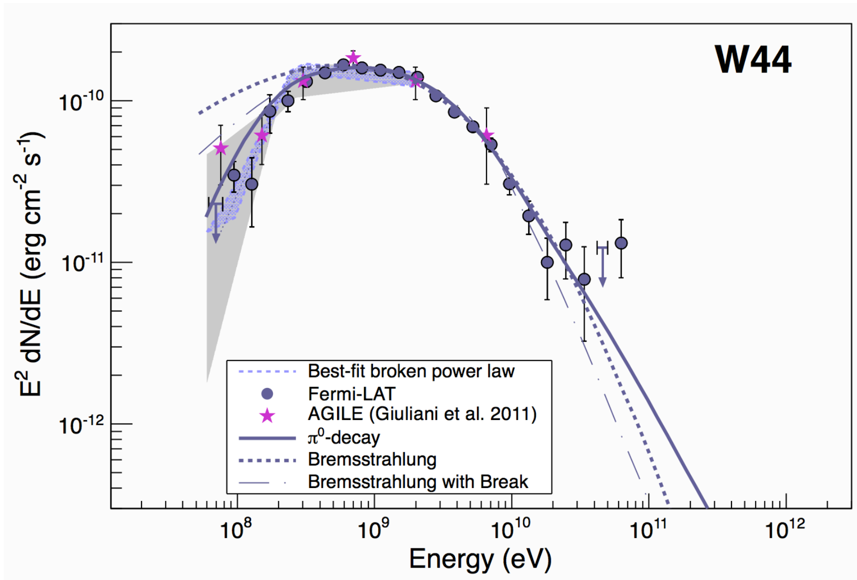
Fermi-LAT discovery of the "pion bump"

Ackermann et al (2013)





$$\frac{m_{\pi^0}}{2}$$

p_{CR} + ISM → π^o → $\gamma\gamma$

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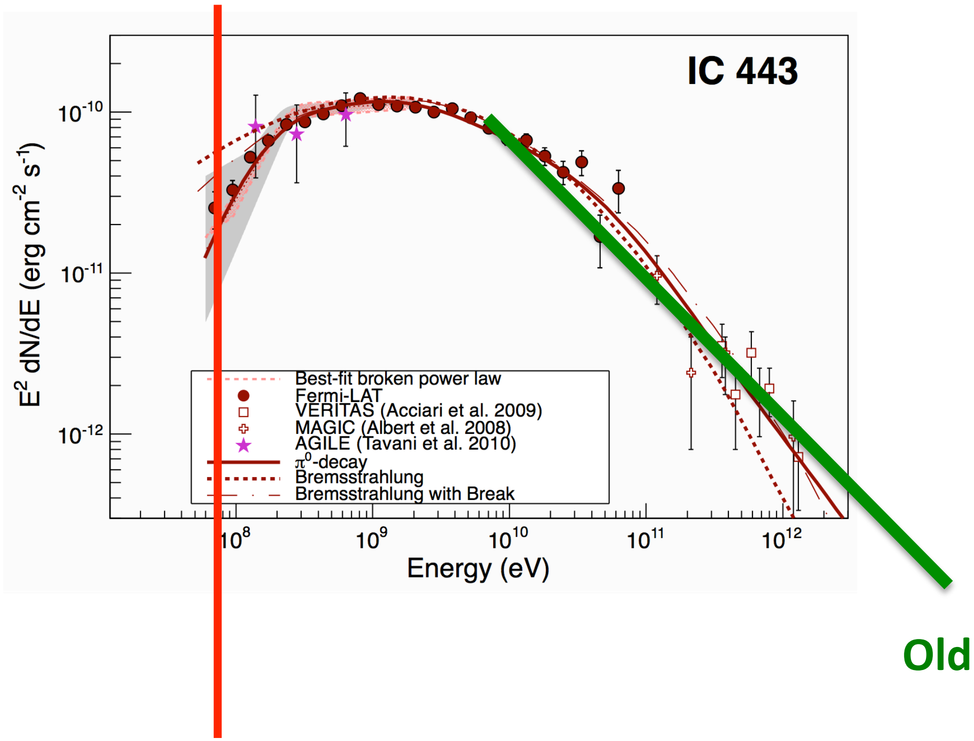

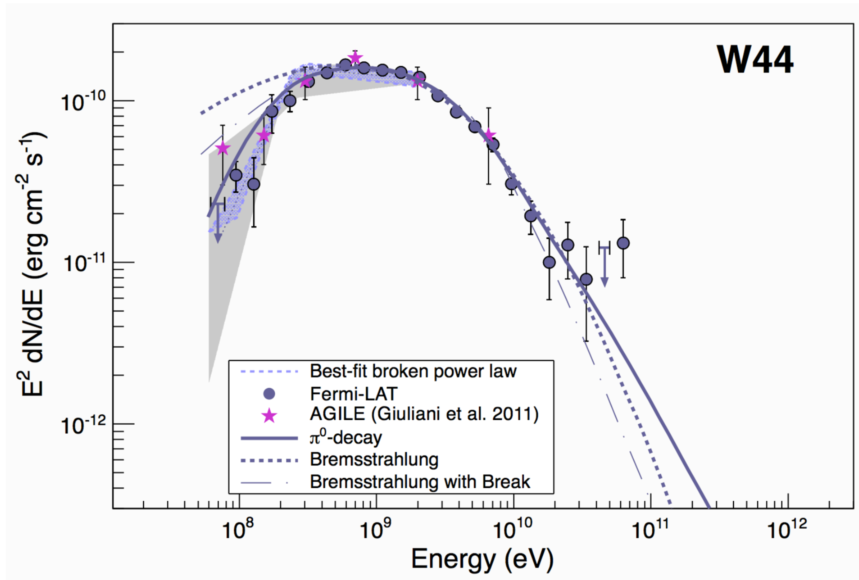

Old remnants, steep spectra…

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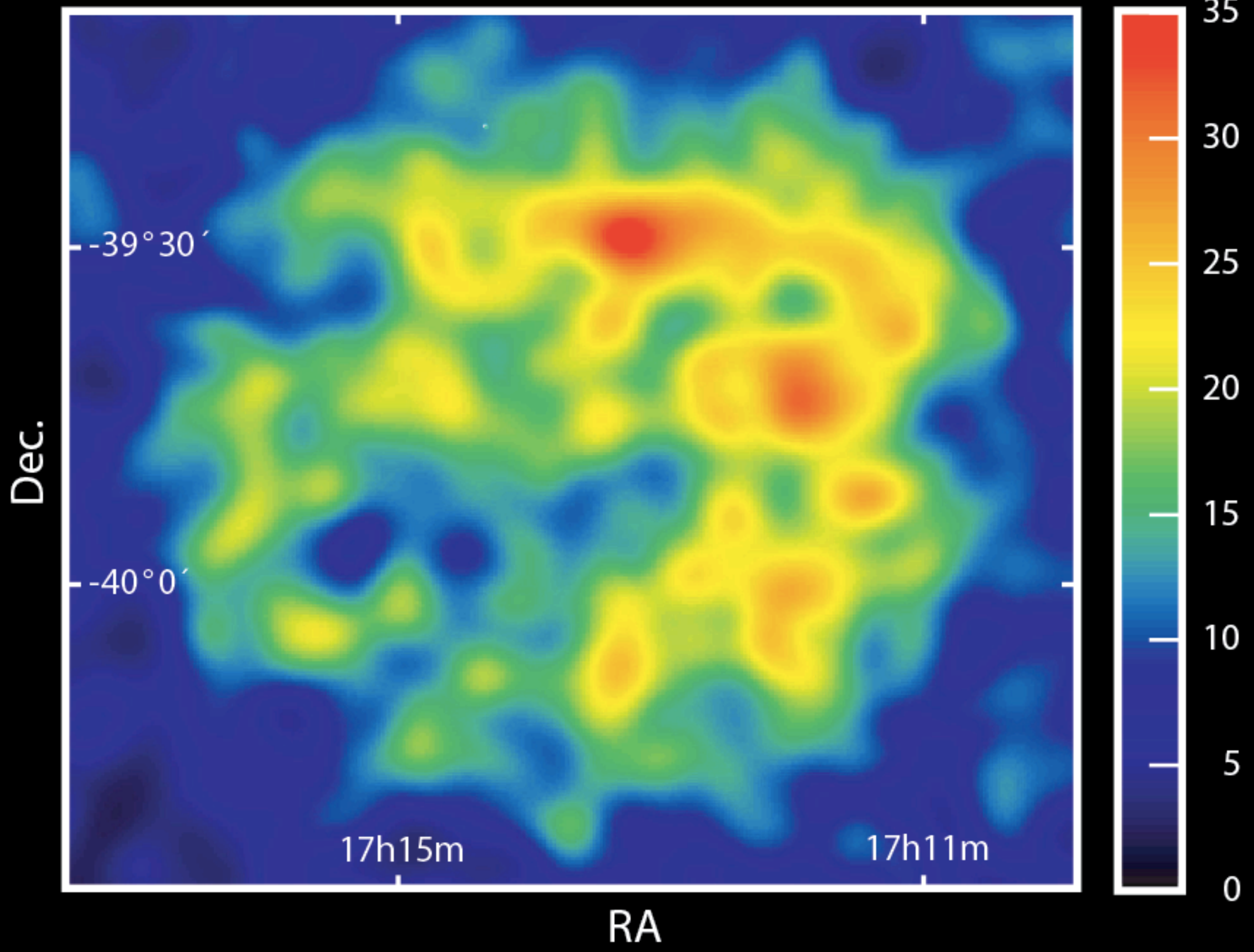
- Are TeV protons accelerated at SN shocks?

H.E.S.S. Observations of RX J1713

H.E.S.S. 2004 (Nature)



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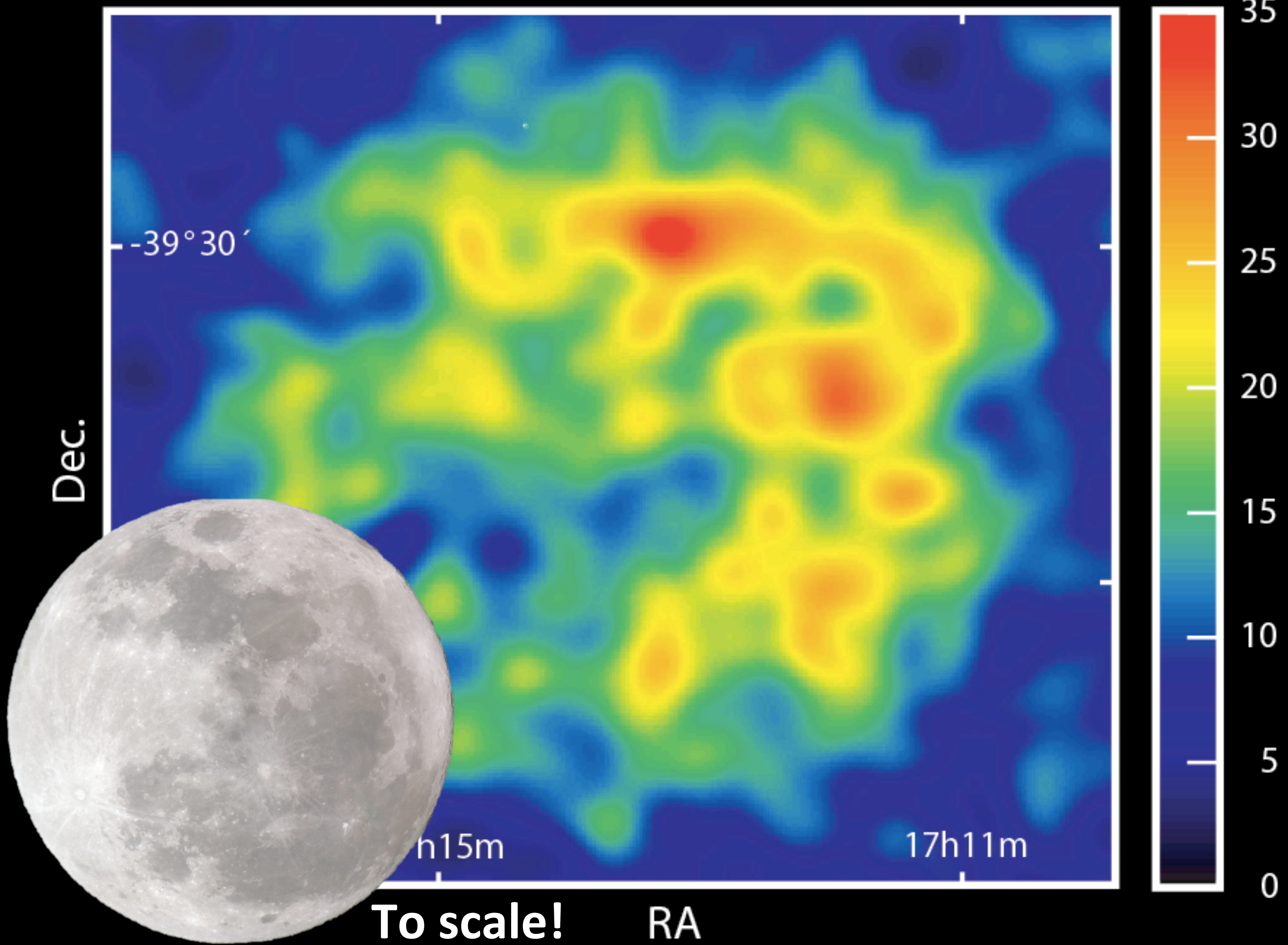

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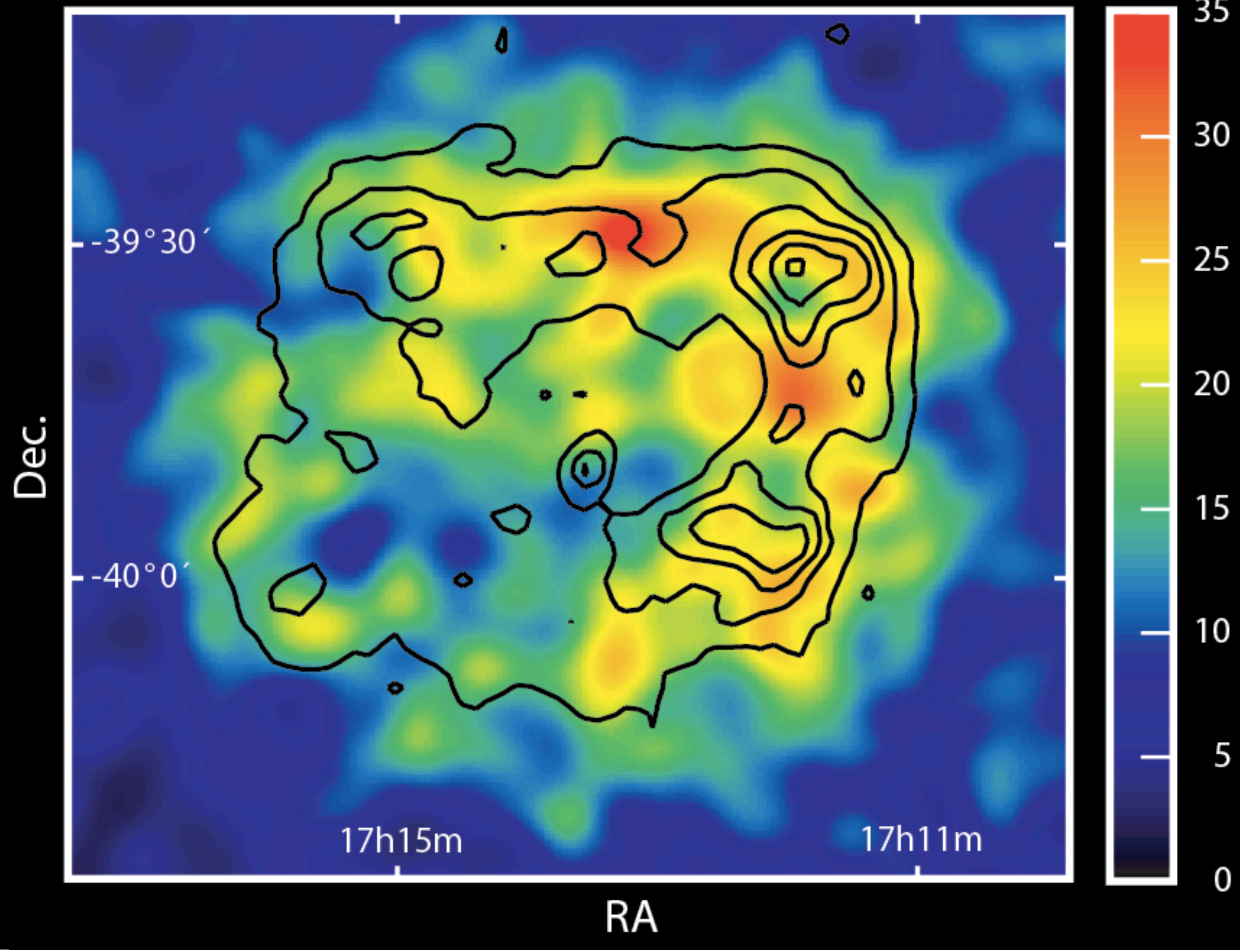
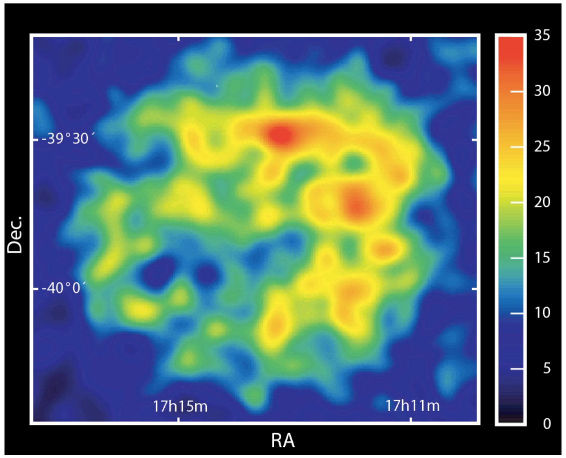
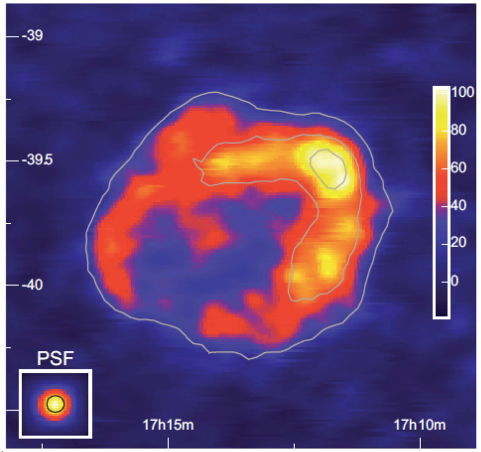


A decade of RX J1713 observations

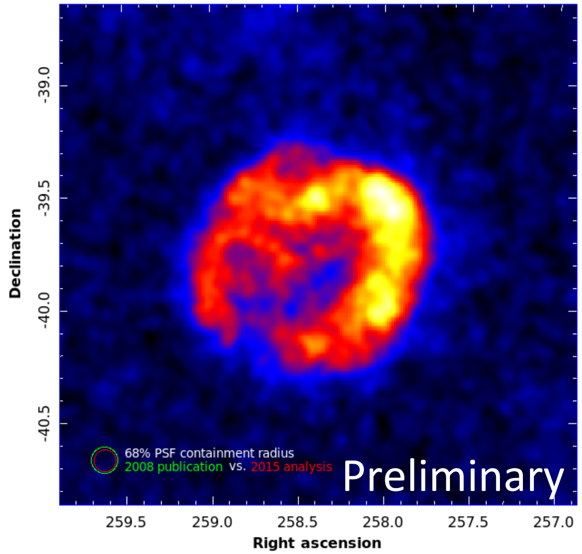
H.E.S.S. 2004



H.E.S.S. 2008



H.E.S.S. 2015



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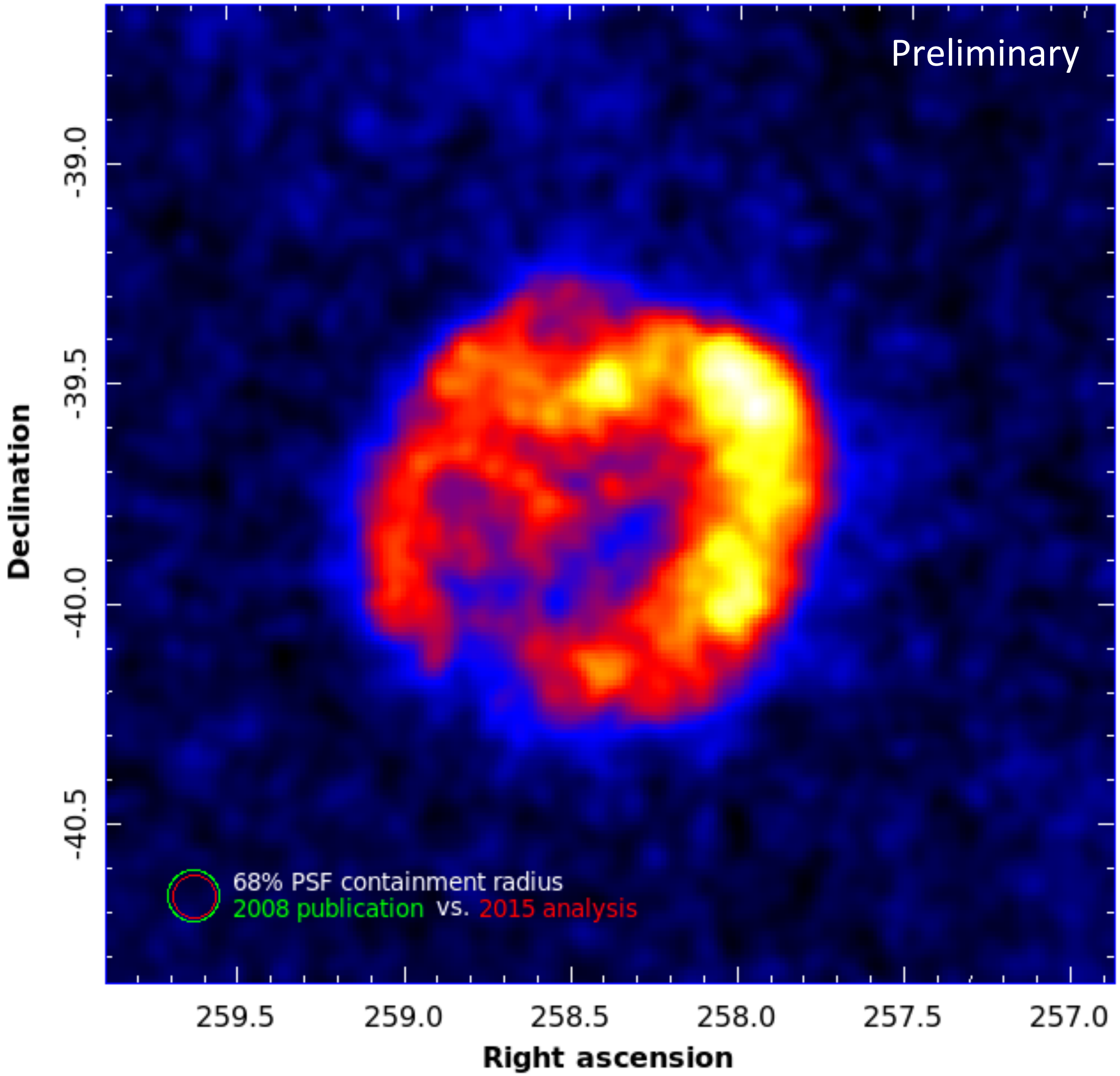
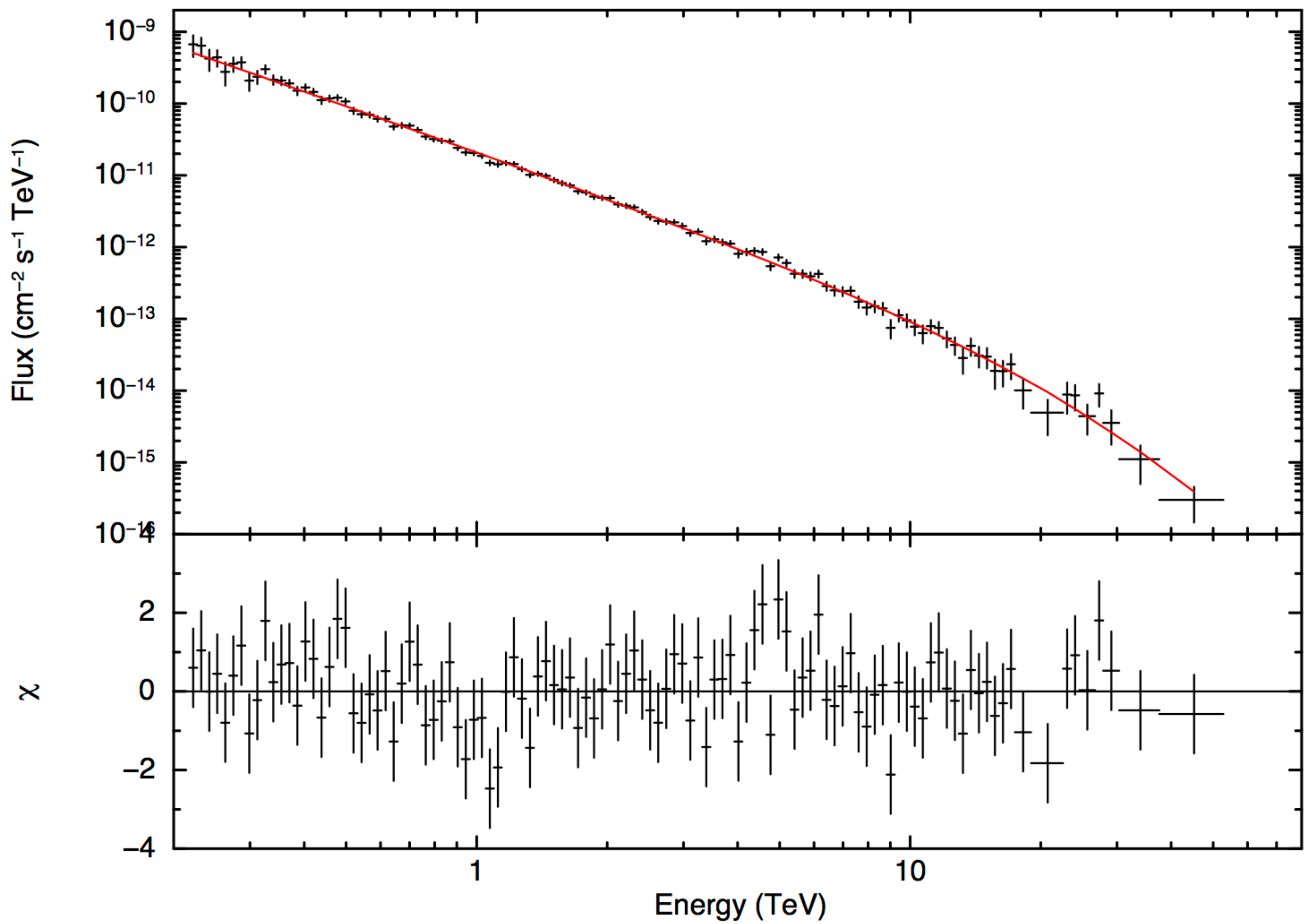


Spectral shape analysis

H.E.S.S. Preliminary (2015)

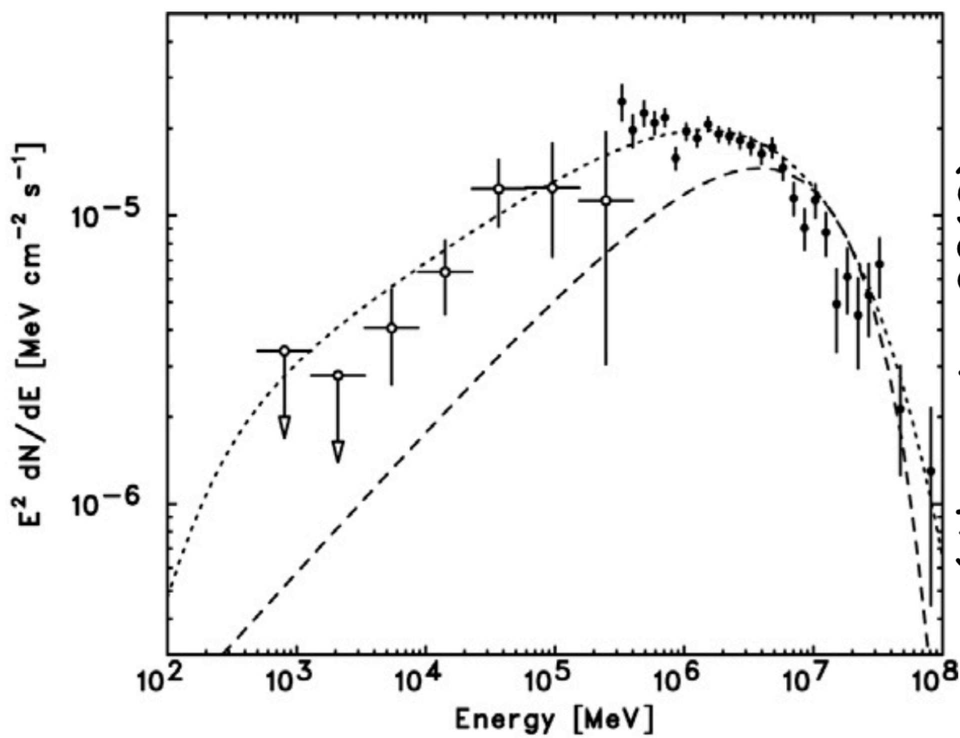


Spectral shape analysis

Gabici, Aharonian (2015)

Ratio of leptonic to hadronic γ-ray flux at 1 TeV:

$$\phi_{\mathrm{IC/pp}}(1\ \mathrm{TeV}) \approx 0.5 \left(\frac{n_{gas}}{\mathrm{cm}^{-3}}\right)^{-1} \left(\frac{K_{ep}}{10^{-3}}\right)$$



(Aharonian 2013)

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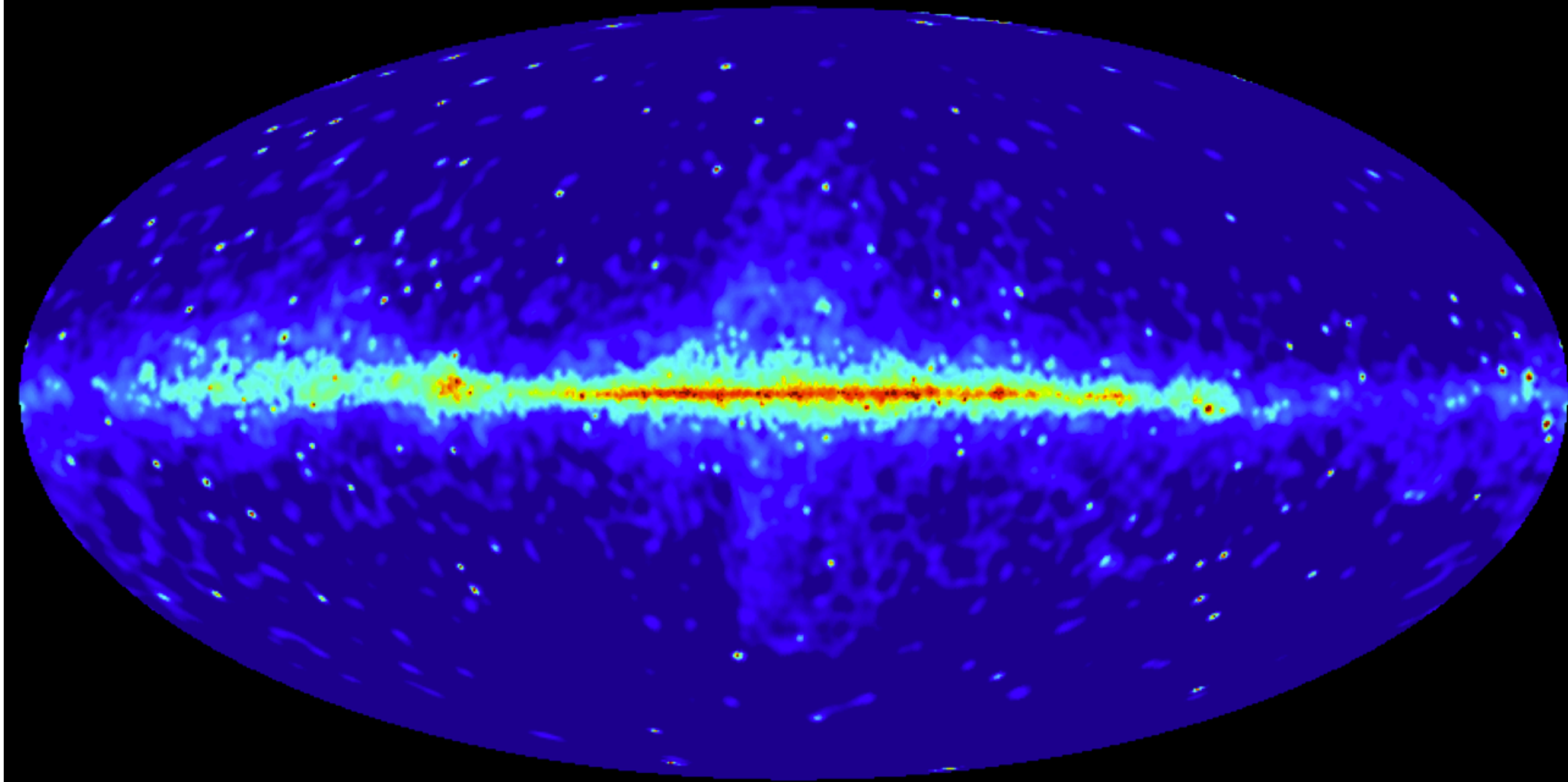
- Are charged particles accelerated at SN shocks? **YES, electrons!**
- Are protons accelerated at SN shocks? **Yes, for MeV – GeV energies!**
- Are TeV protons accelerated at SN shocks? **Hard to exclude electrons!**
- Is the local “sea of cosmic rays” a good proxy for the whole Galaxy?

Diffuse Galactic γ-rays

GeV sky dominantly diffuse emission



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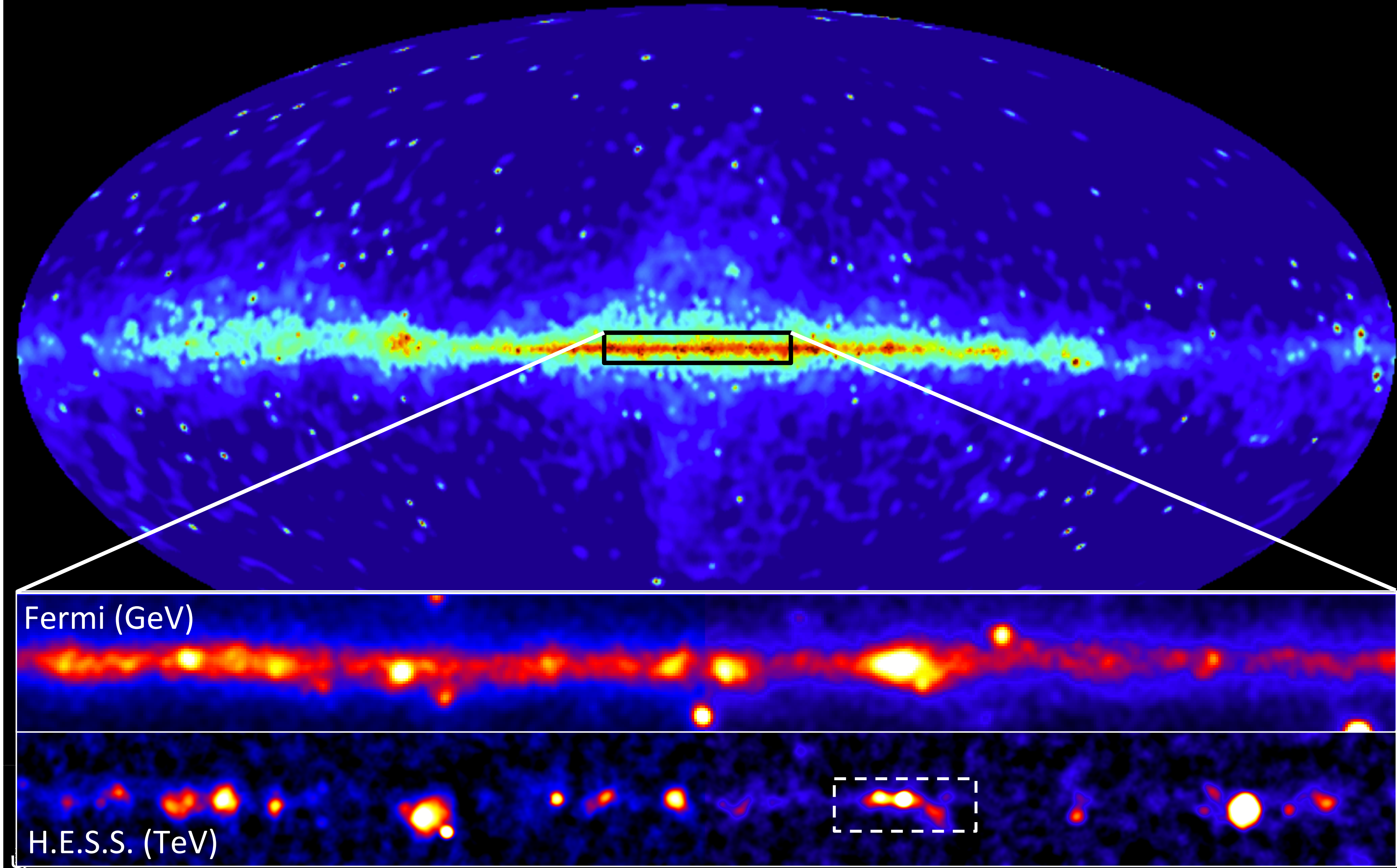
TeV sky dominantly sources



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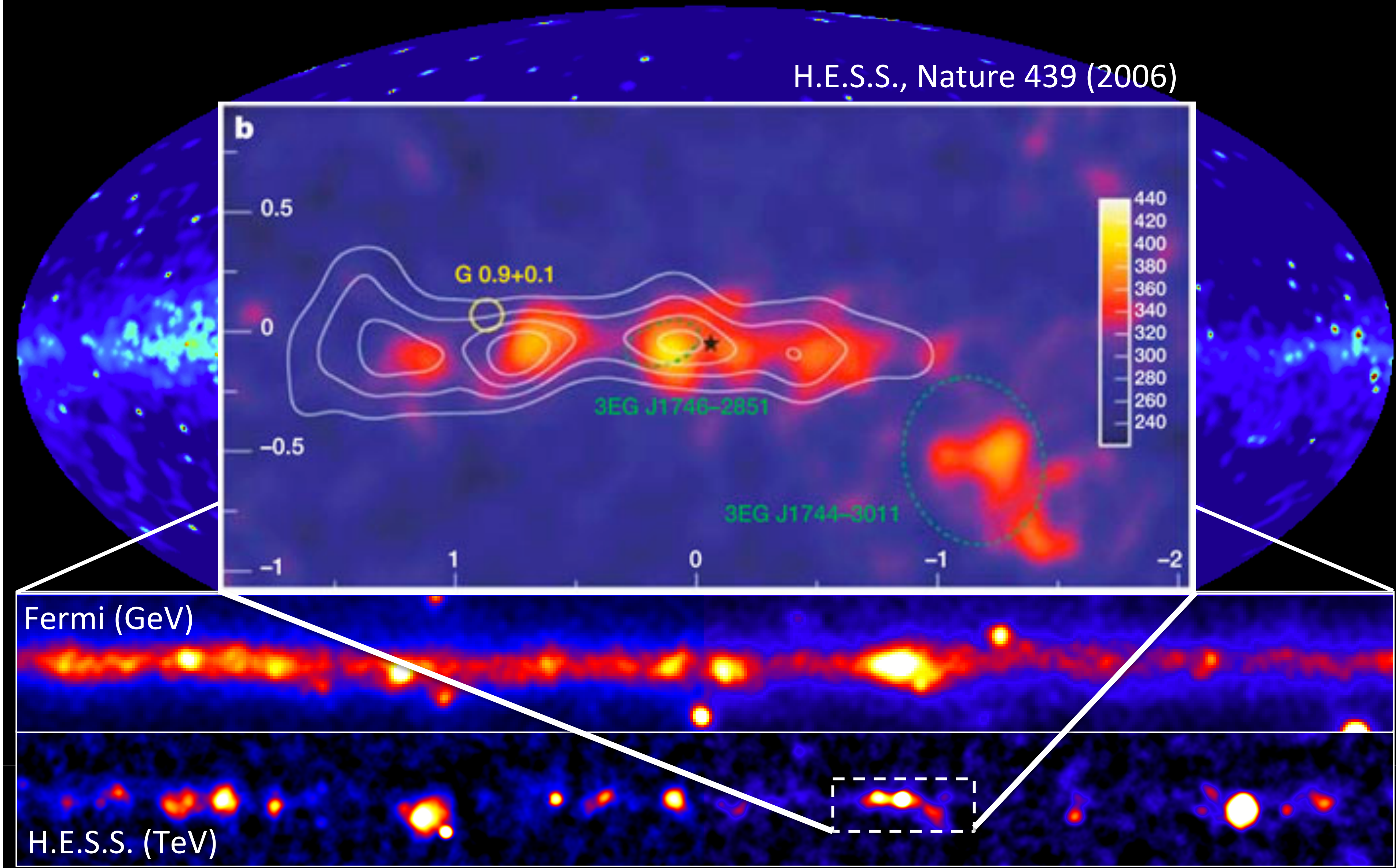
H.E.S.S., Nature 439 (2006)



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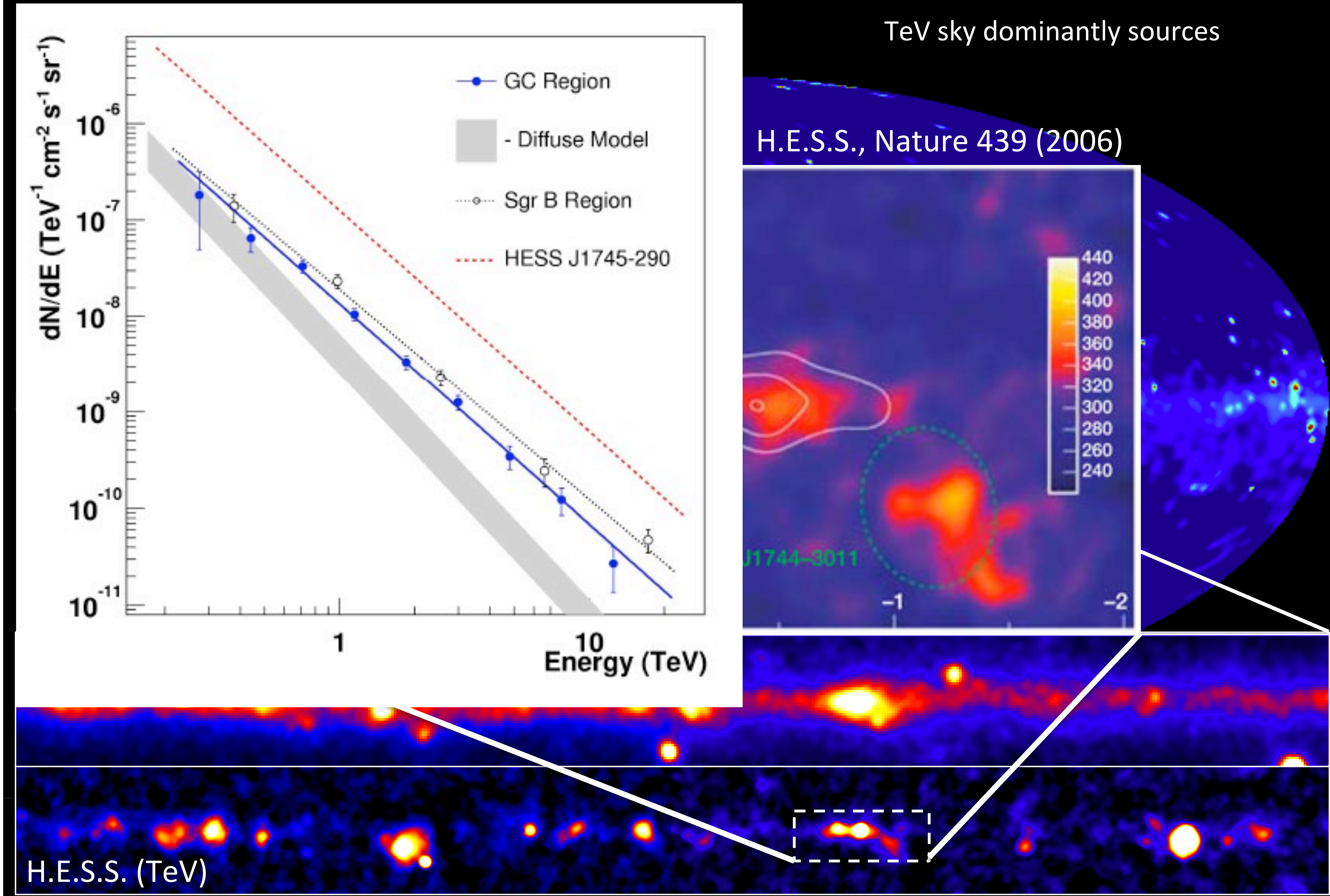

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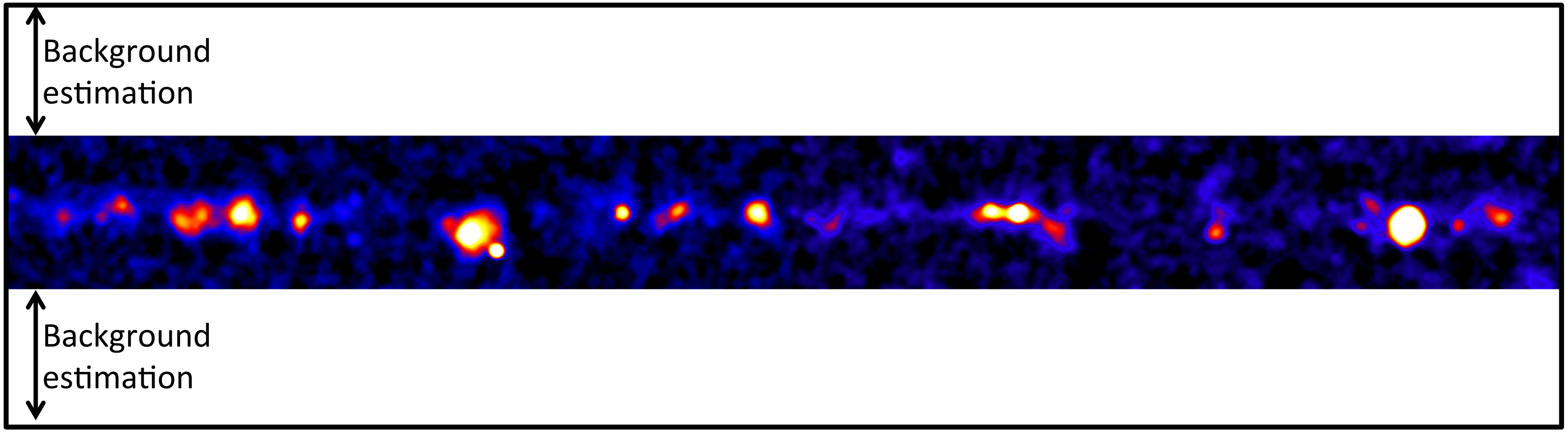
The background challenge

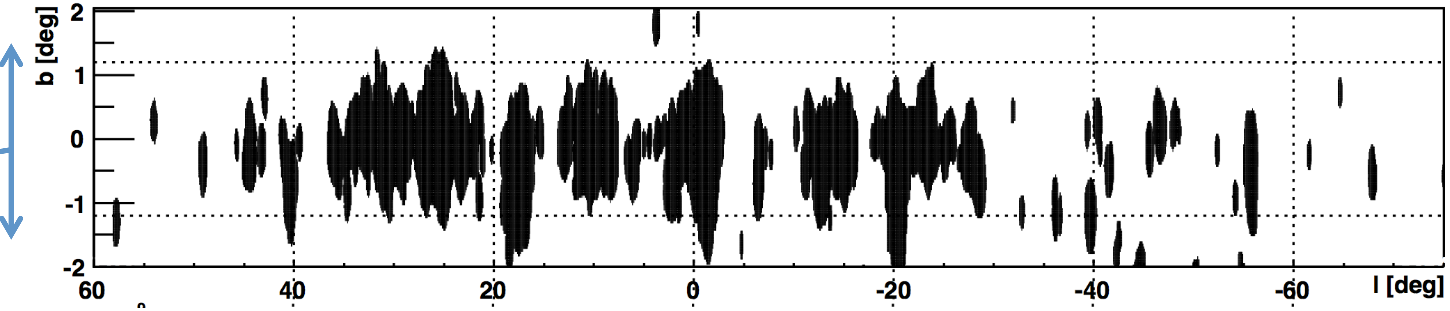


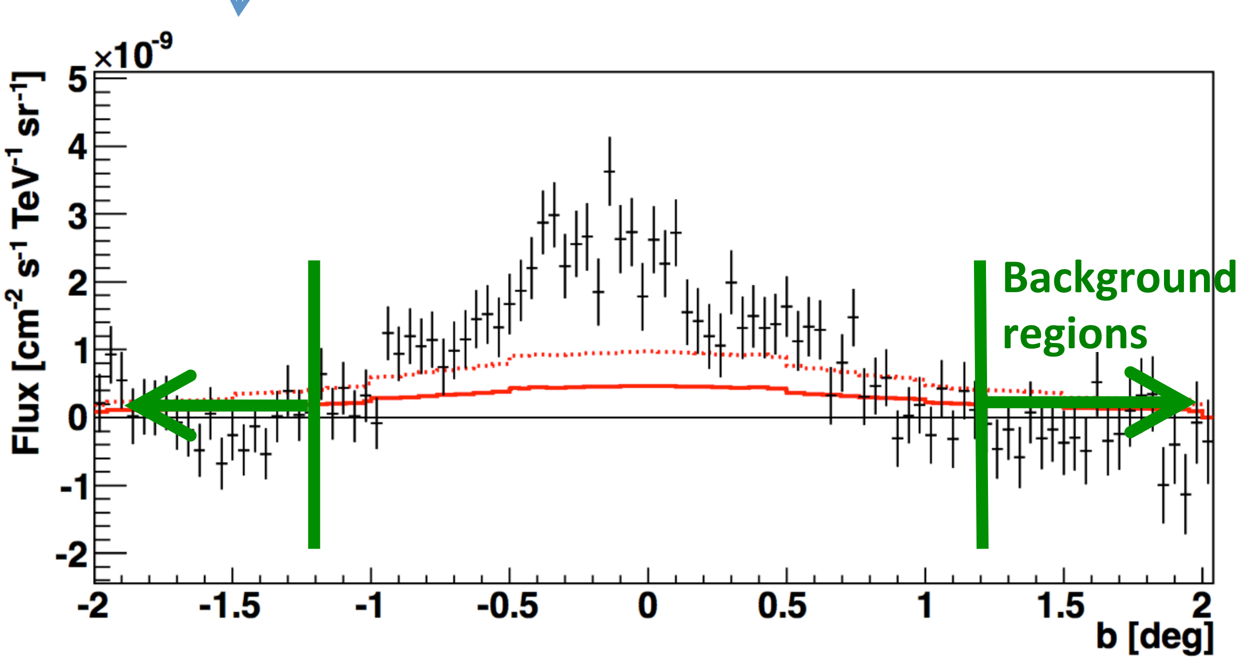
Background modeling in γ-ray astronomy,
Berge, Hinton, Funk (A&A 2007)

Diffuse TeV emission

H.E.S.S. Phys.Rev.D (2014)

All sources masked:





Indications for a diffuse tail in 10 years of H.E.S.S. data, first step only...

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- Are TeV protons accelerated at SN shocks? **Hard to exclude electrons!**
- Is the local "sea of cosmic rays" a good proxy for the whole Galaxy? **Galactic centre apparently special, hosts a powerful cosmic-ray accelerator! What about the Galactic plane? Absolute flux level within a factor of a few!**
- Do we see a PeVatron at work?

PeVatrons with H.E.S.S.

Recall: p_{CR} + ISM → π^{o} → $\gamma\gamma$ **(E_{γ} = 0.1 E_{CR})**

Need 100 TeV (10^{14} eV) γ-ray sensitivity for 1 PeV CR's

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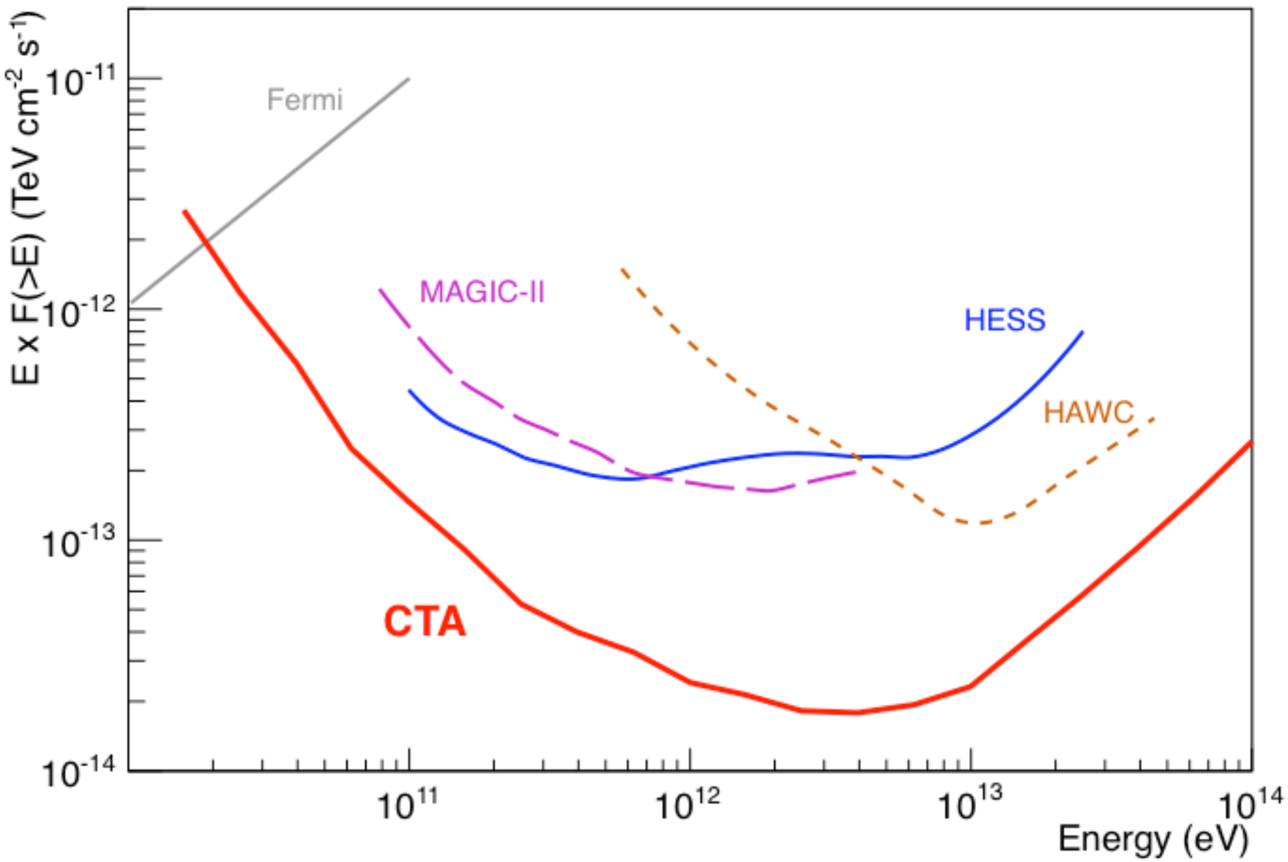
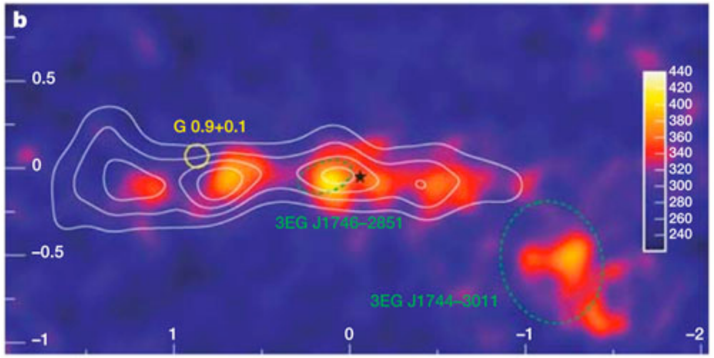
Integral sensitivities

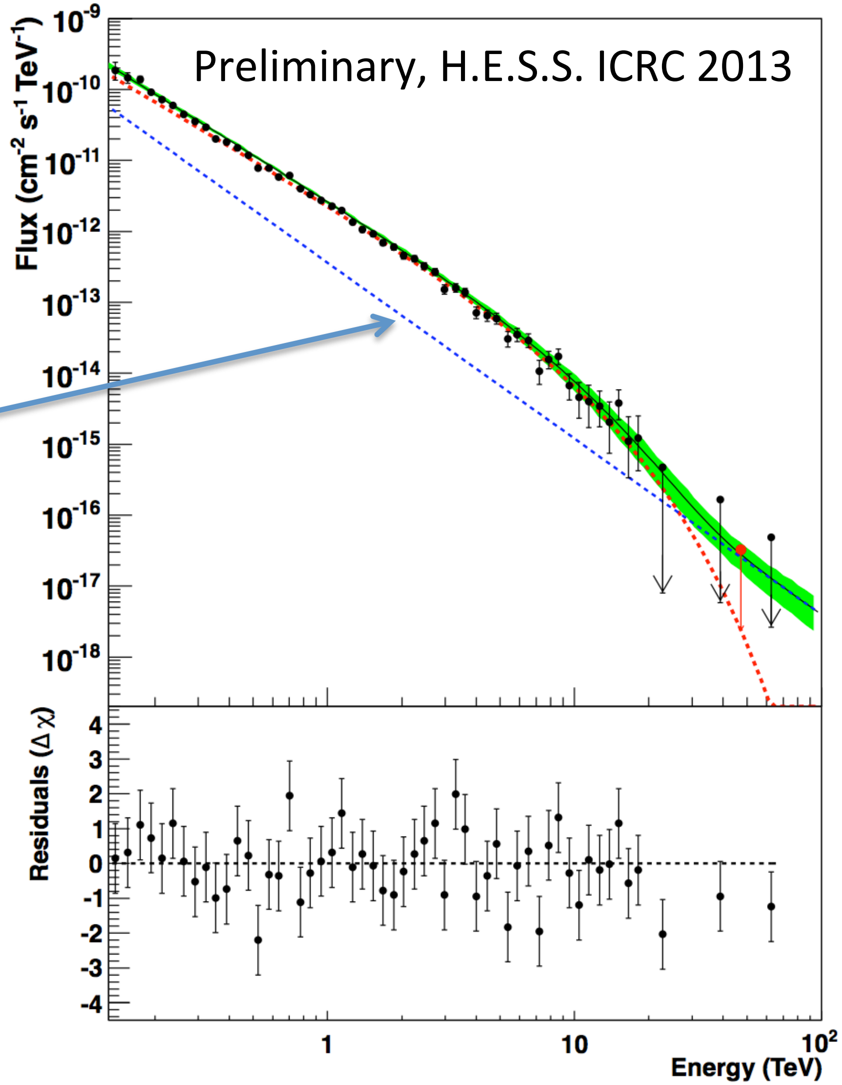


PeVatrons with H.E.S.S.

Can still look for candidates, search energy spectra w/o indication of a cutoff

H.E.S.S., Nature 439 (2006)



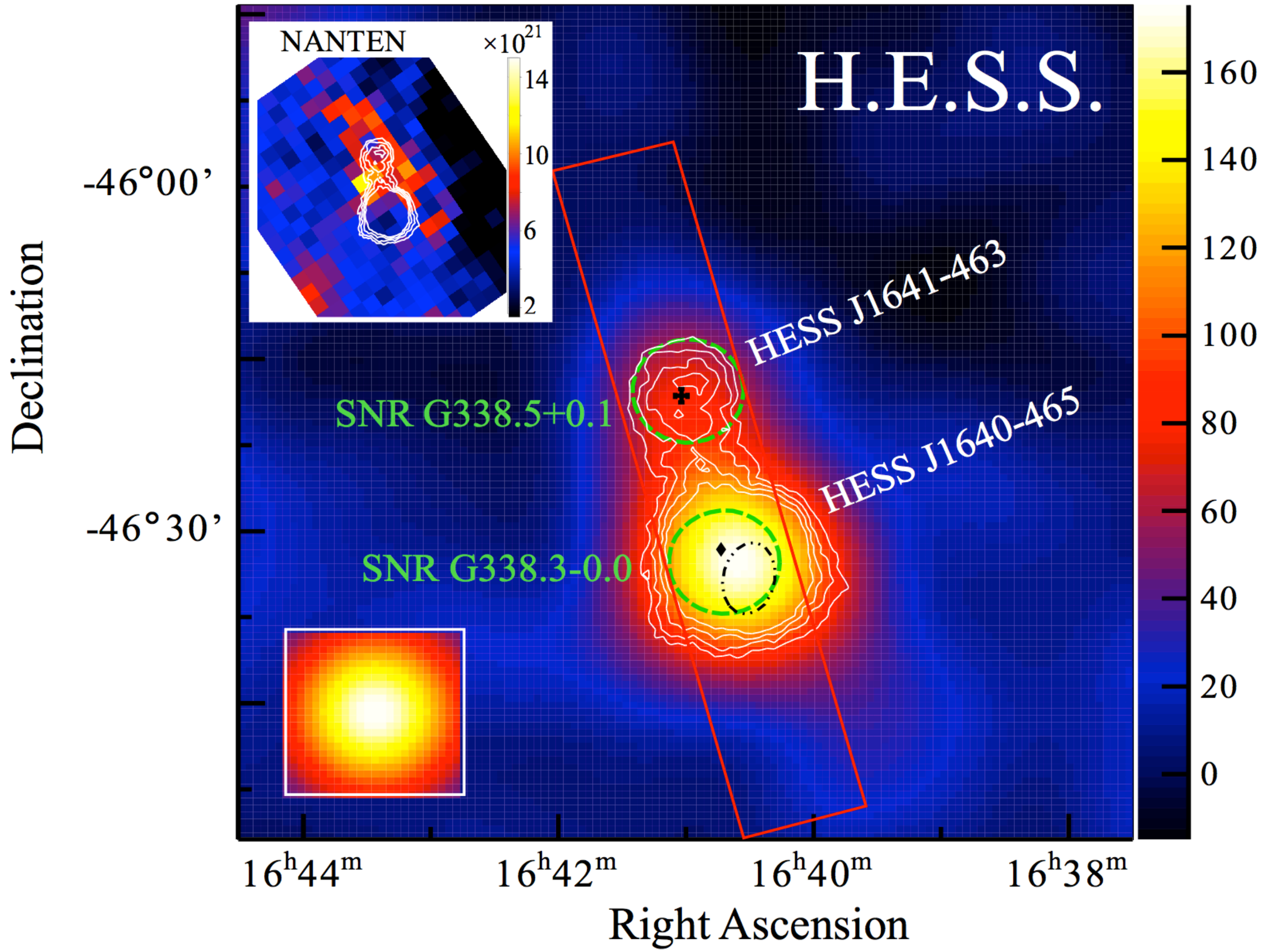


Diffuse component around Galactic centre, no apparent sign of spectral cutoff

PeVatrons with H.E.S.S.

HESS J1641-463 (ApJL 2014)

A point-like source, coincident with a supernova remnant



PeVatrons with H.E.S.S.

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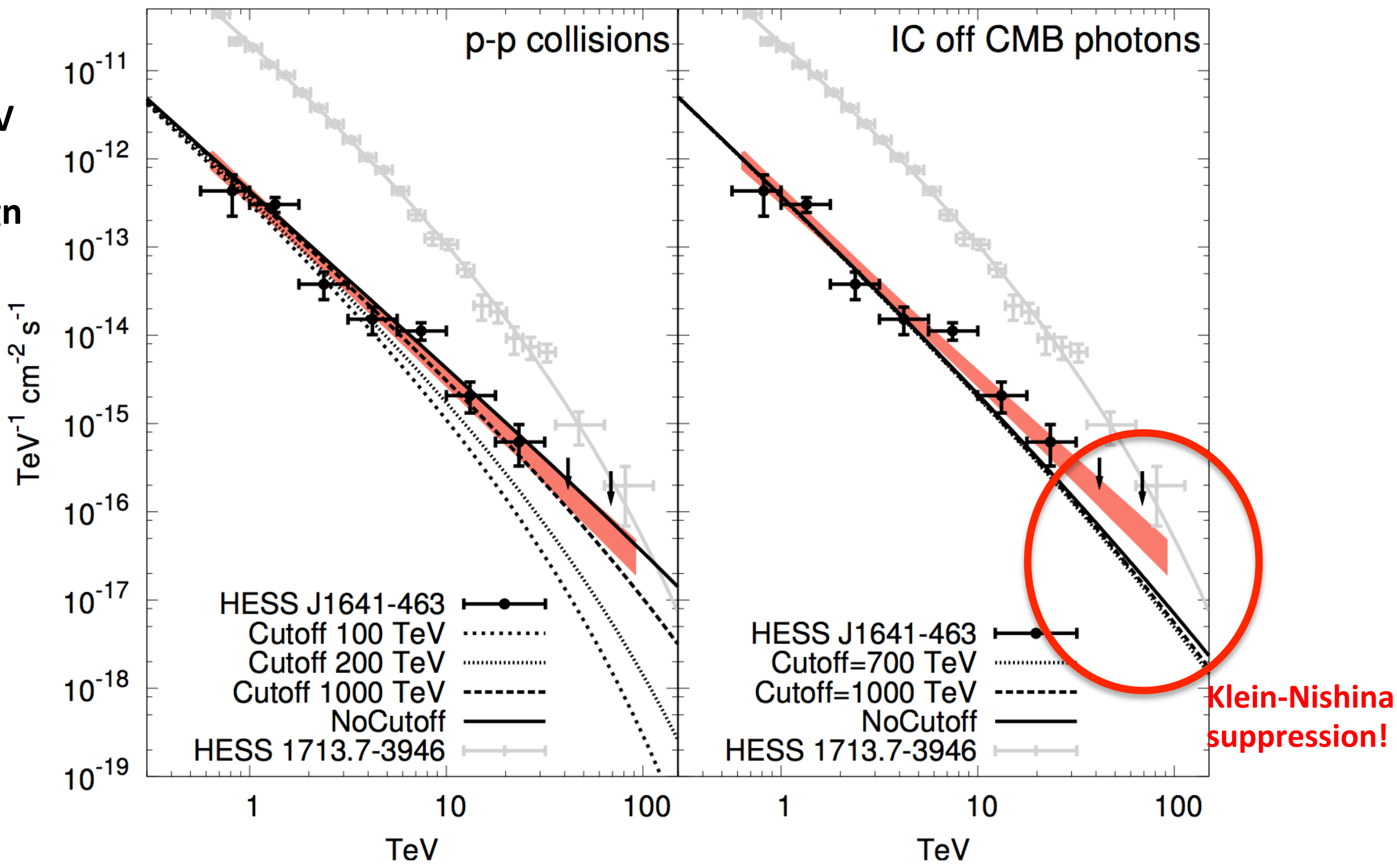
A point-like source, coincident with a supernova remnant

99% CL lower limit on proton cutoff: 100 TeV

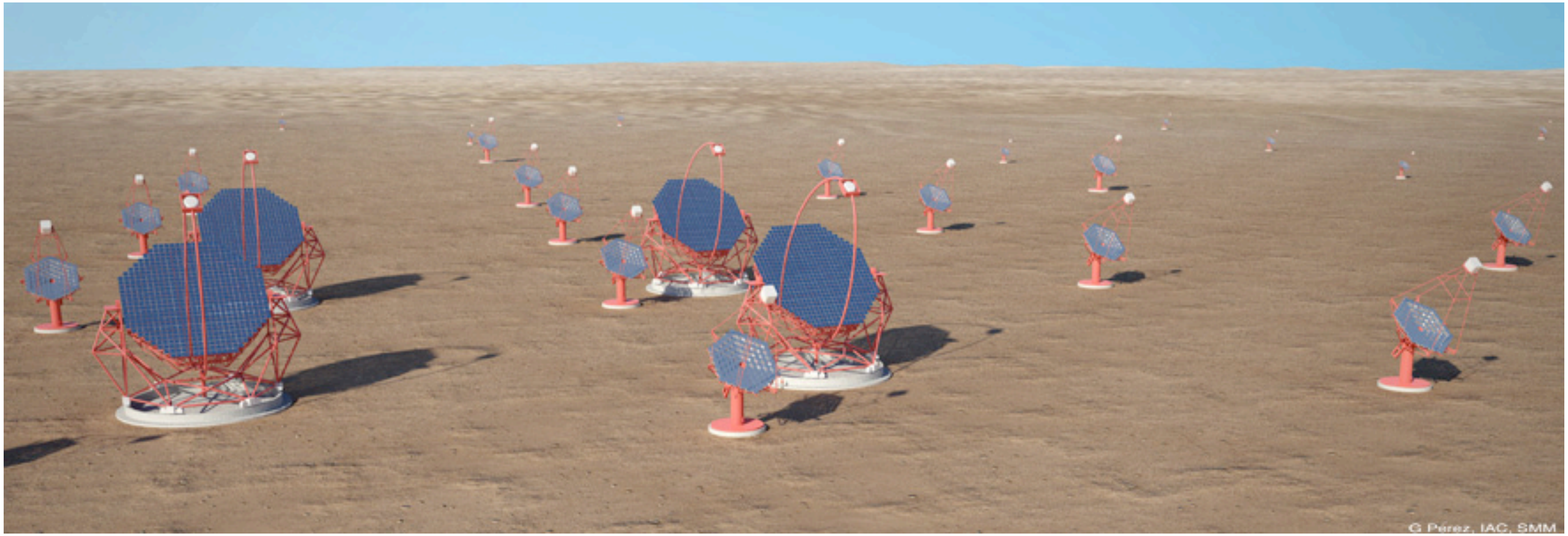
Again no apparent sign of spectral cutoff



The Question

- Are charged particles accelerated at SN shocks? **YES, electrons!**
- Are protons accelerated at SN shocks? **Yes, for MeV – GeV energies!**
- Are TeV protons accelerated at SN shocks? **Hard to exclude electrons!**
- Is the local "sea of cosmic rays" a good proxy for the whole Galaxy? **Galactic centre apparently special, hosts a powerful cosmic-ray accelerator! What about the Galactic plane? Absolute flux level within a factor of a few!**
- Do we see a PeVatron at work? **Maybe…**

On to the next one: CTA!

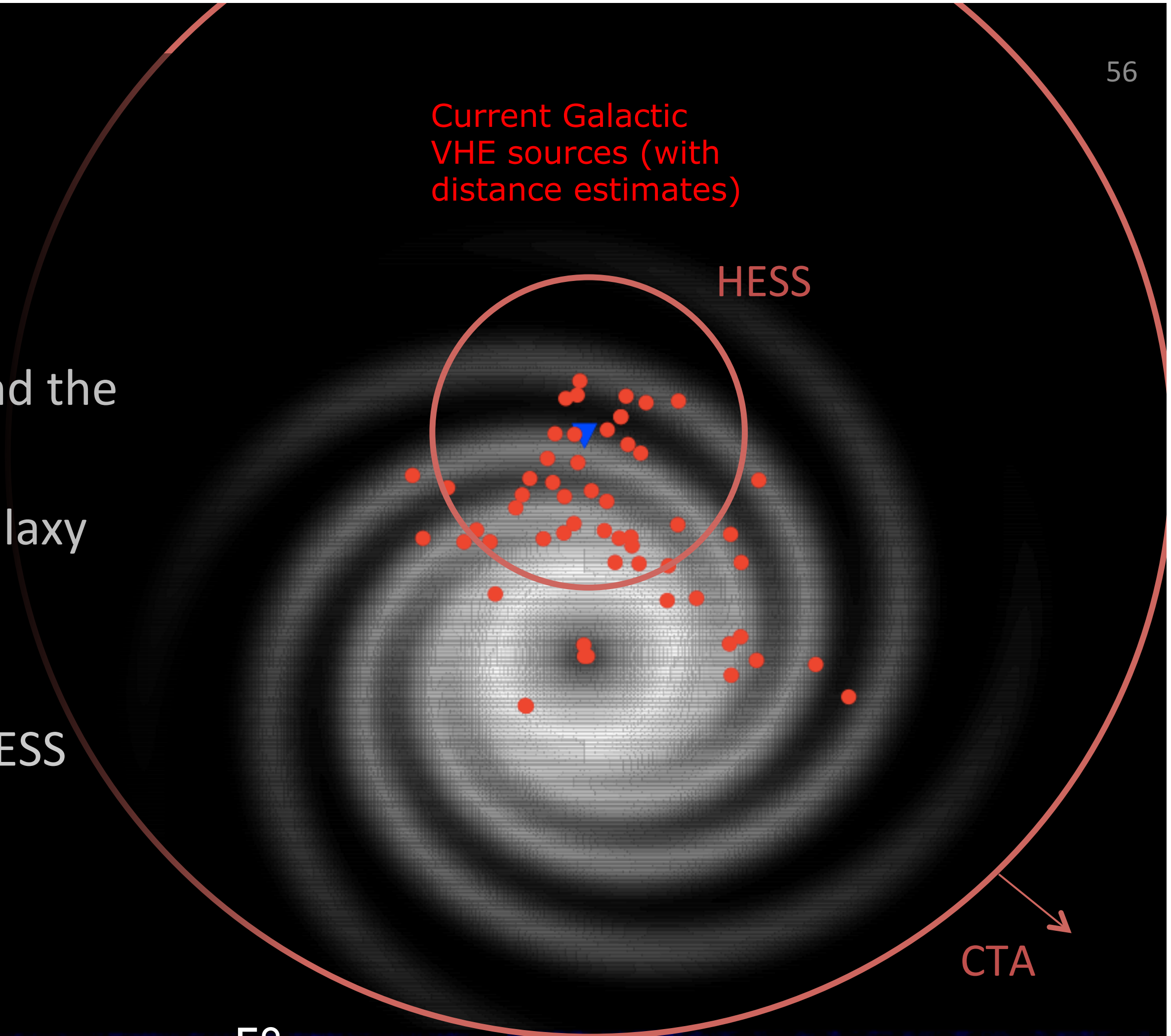


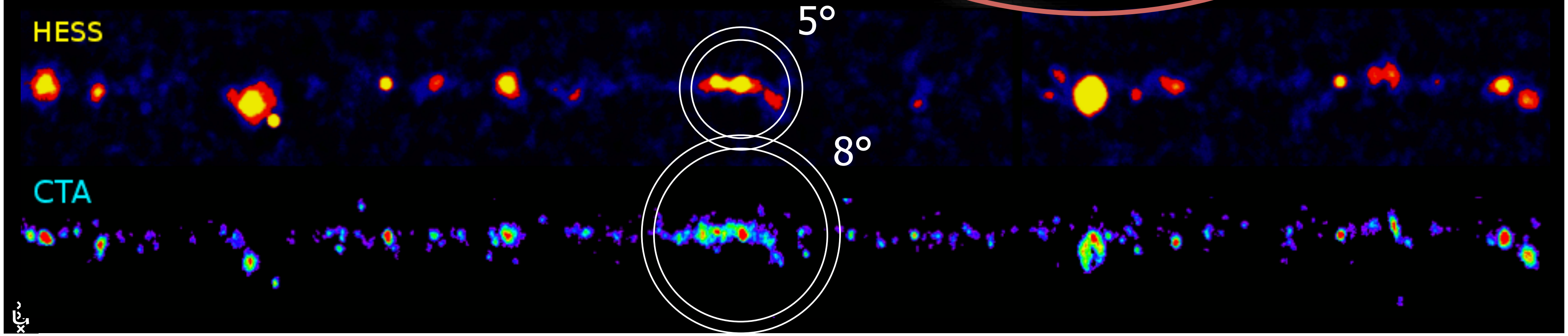
- 1000 scientists from 27 countries
- 2 sites, up to 100 telescopes per site
- Small, Medium, Large telescope types for high, medium, low energies
- 200 M€ investment costs
- Science from 2020 onwards


As you know, lead effort by MPI-K

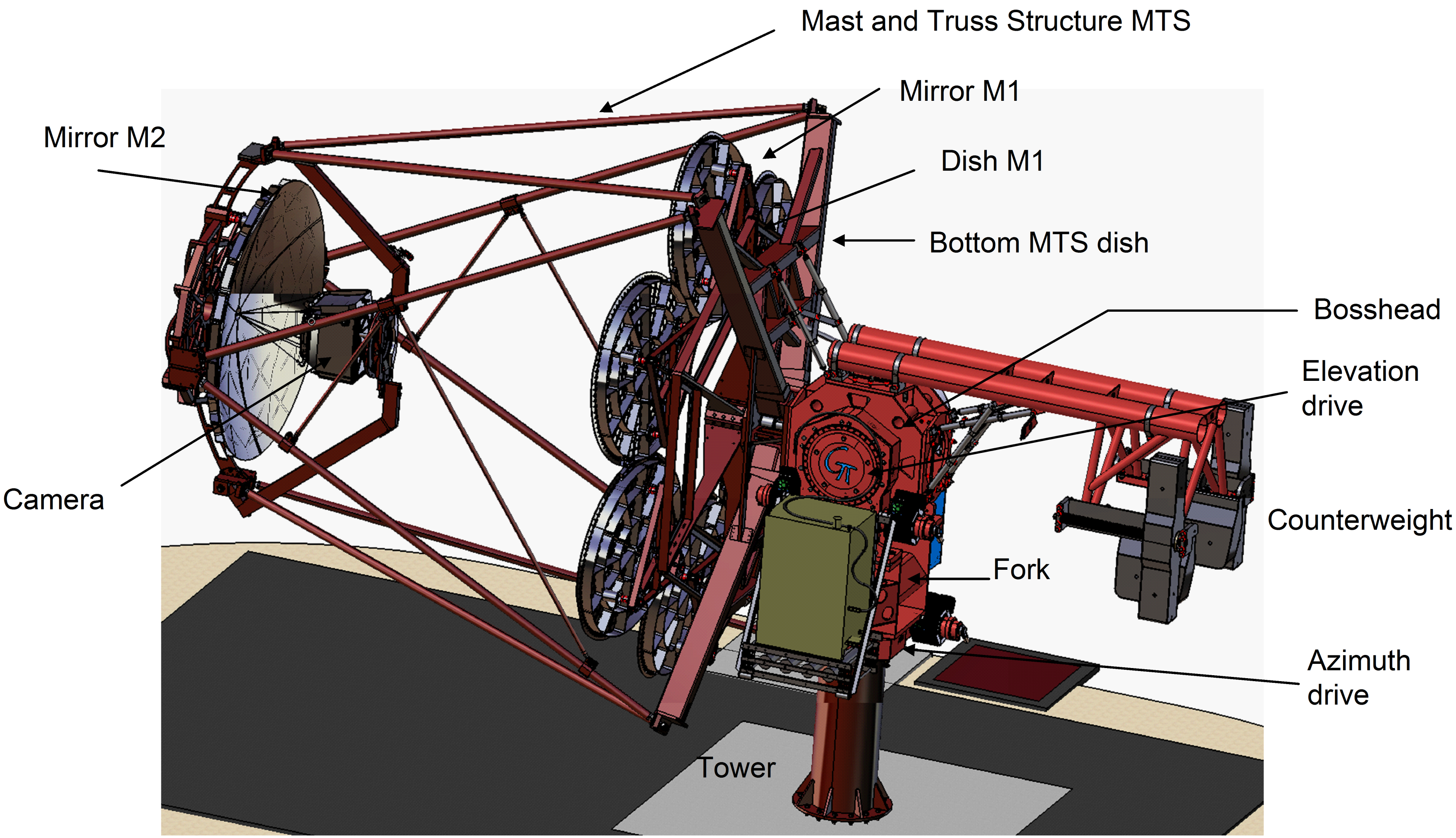
The bright future: CTA

- Galactic objects
  - Newly born pulsars and the supernova remnants
  - CTA will see **whole** Galaxy
- Field of view + Sens.
  - Survey speed ~300×HESS



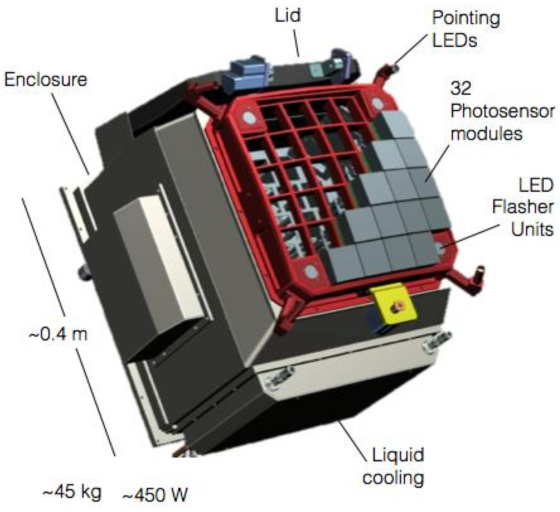


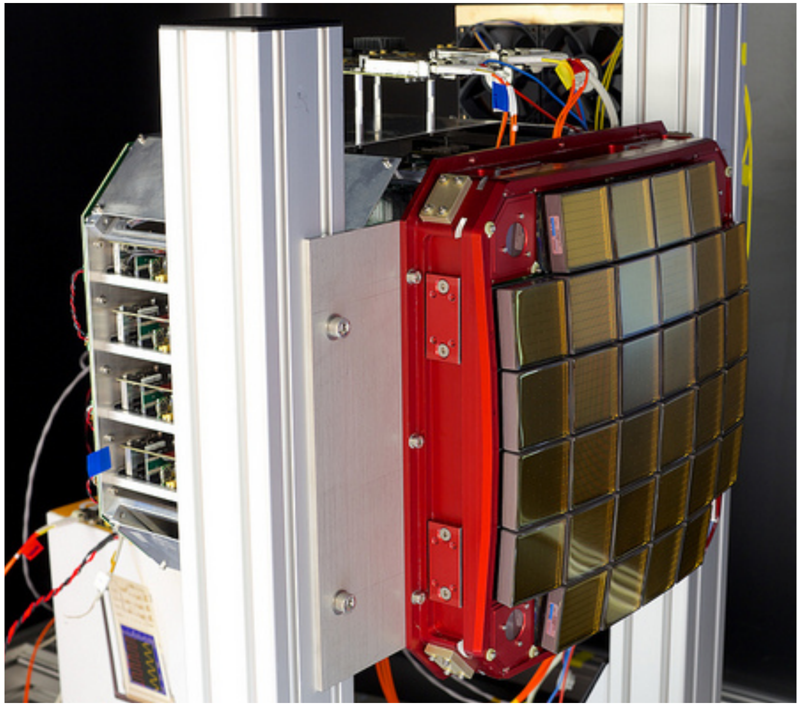
Small-Size Telescopes



<u>GCT:</u>
Includes Amsterdam and MPI-K
Dual-mirror design, reduces camera size and costs!

Small-Size Telescopes





Summary

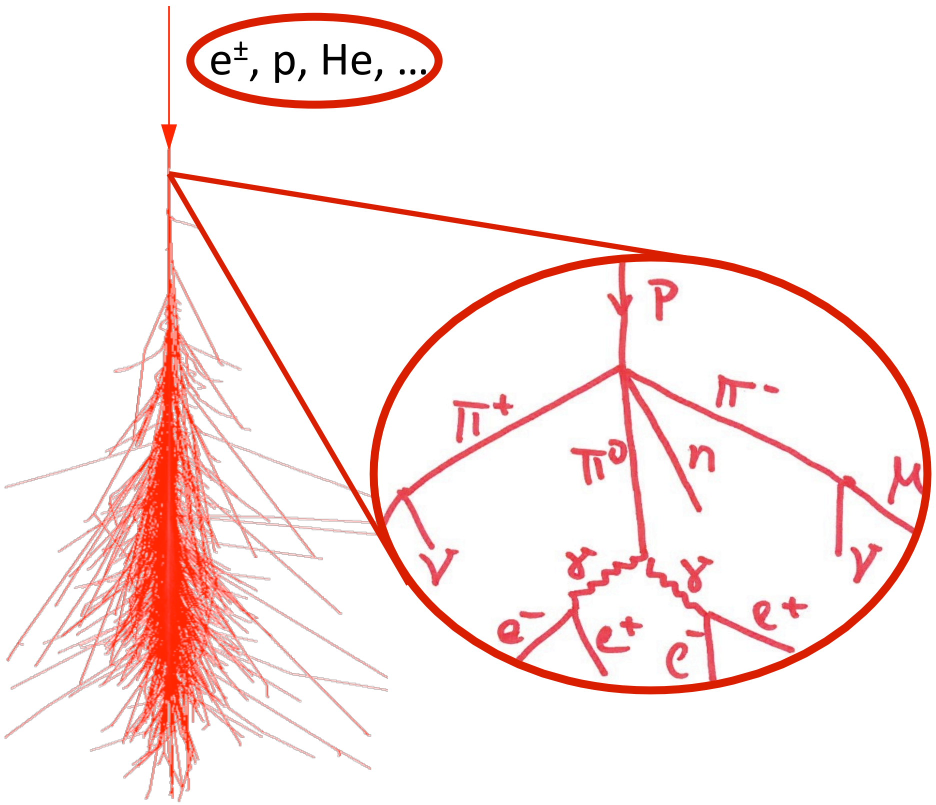
- Huge progress in Galactic cosmic-ray puzzle since the advent of imaging very-high-energy γ-ray astronomy

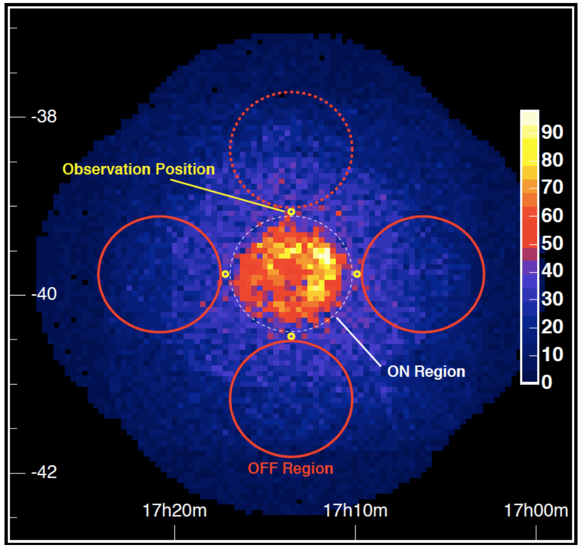
- But: ruling out leptonic emission remains a challenge
  - And I have only really discussed the easier questions
  - Some of the harder ones: how do CR's escape from their accelerator, how do they propagate through the turbulent Galactic B fields, how exactly are the Knee and the Ankle formed, …

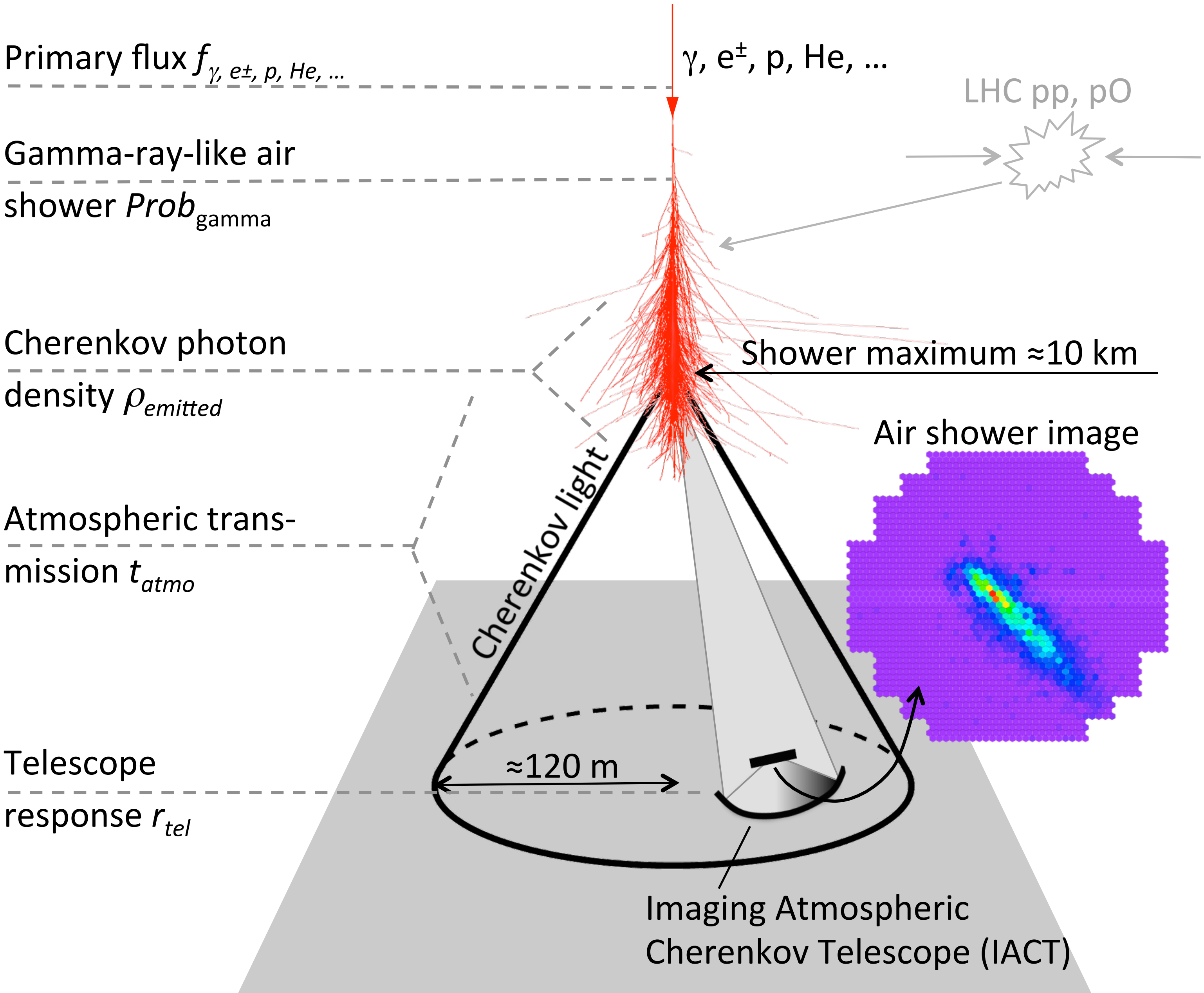
- One (obvious) improvement: a better instrument

- One not so obvious improvement: master the backgrounds…

The background challenge

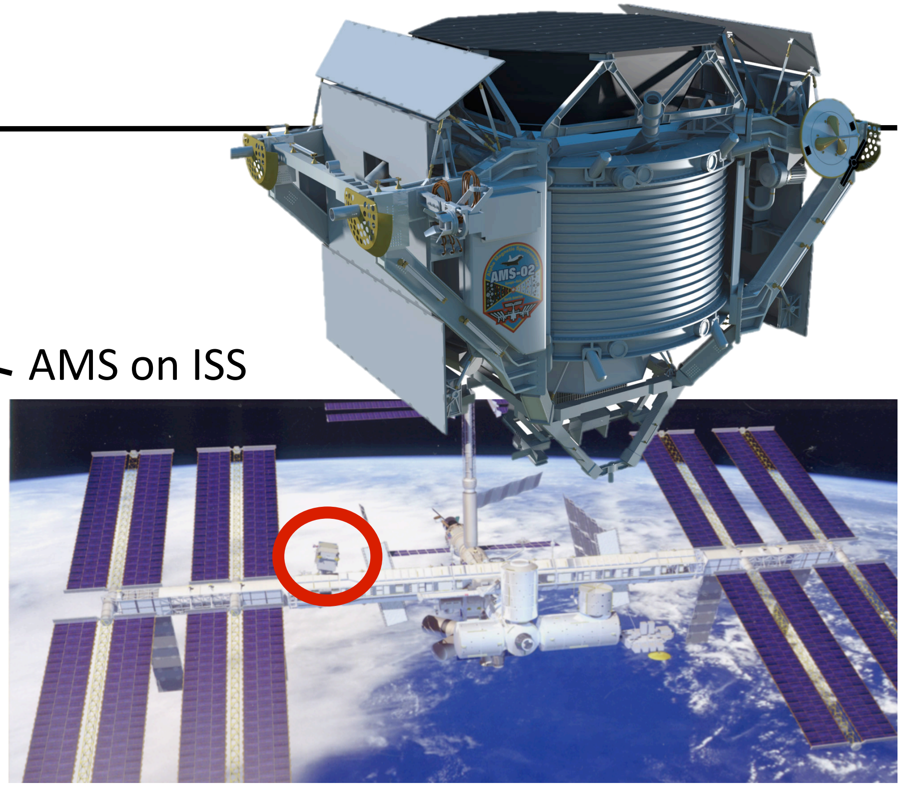




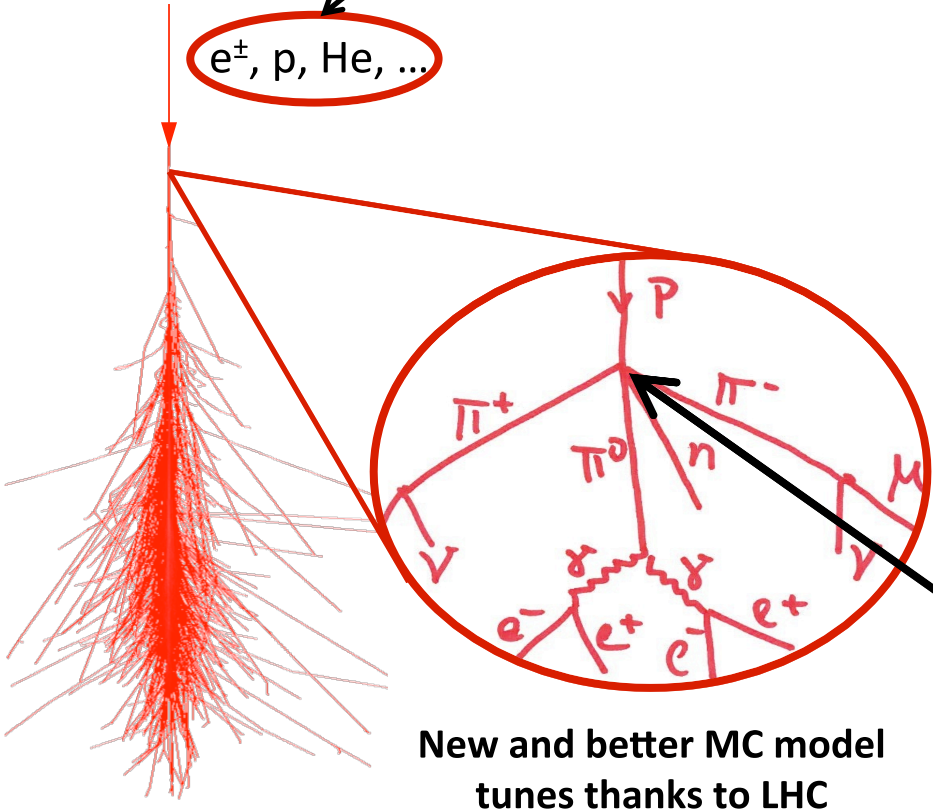


Primary flux $f_{\gamma, e\pm, p, He, ...}$
γ, e±, p, He, ...
LHC pp, pO
Gamma-ray-like air shower $Prob_{gamma}$
Cherenkov photon density $\rho_{emitted}$
Shower maximum ≈10 km
Air shower image
Cherenkov light
Atmospheric trans-mission t_{atmo}
Telescope response r_{tel}
≈120 m
Imaging Atmospheric Cherenkov Telescope (IACT)

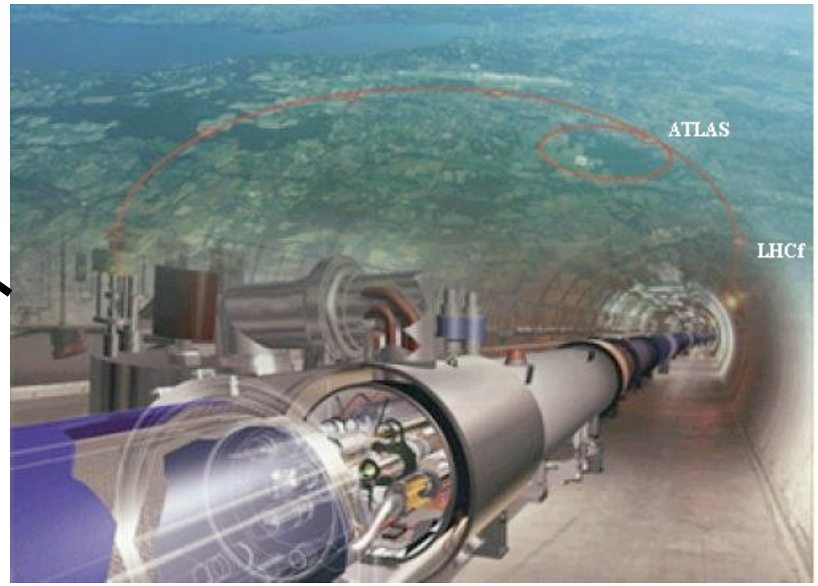
The background challenge



AMS on ISS



New and better MC model tunes thanks to LHC Oxygen-proton run…



LHCf