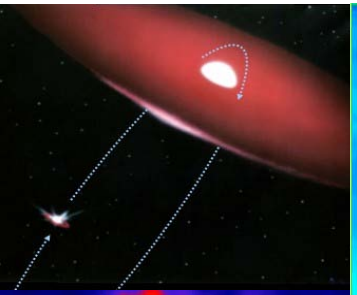
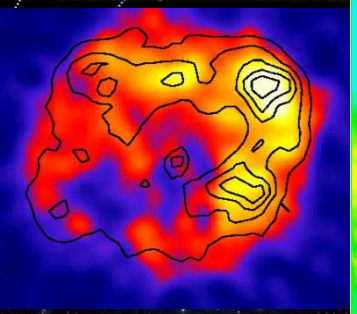
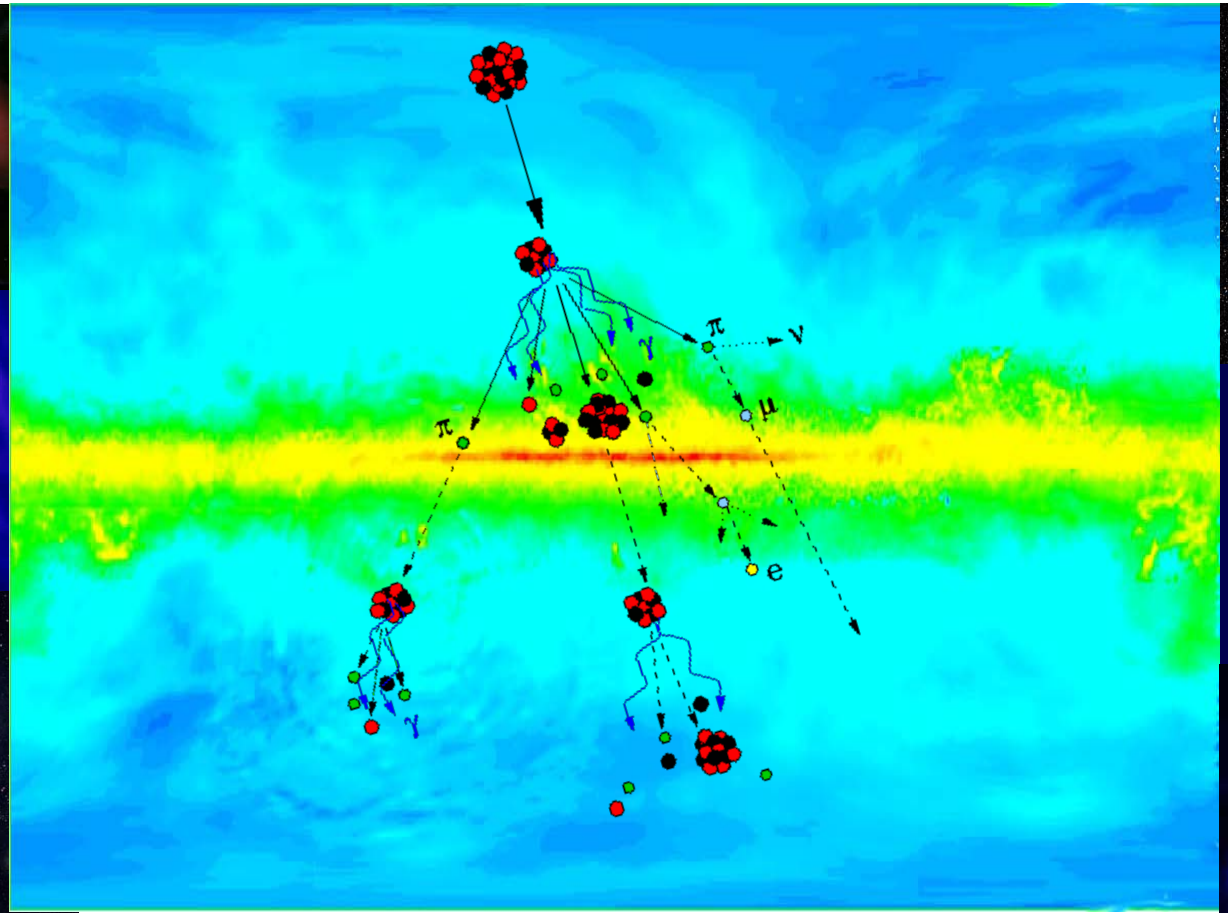
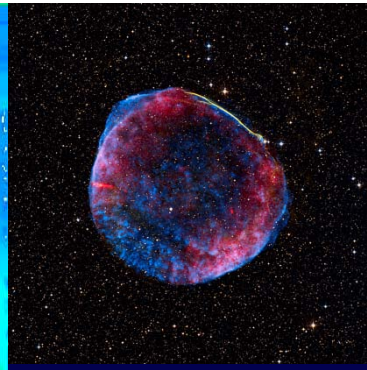
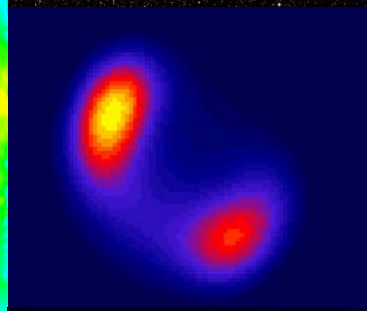
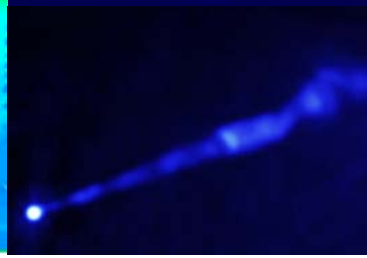
Observing signatures of Cosmic Rays using high-energy gamma-ray telescopes

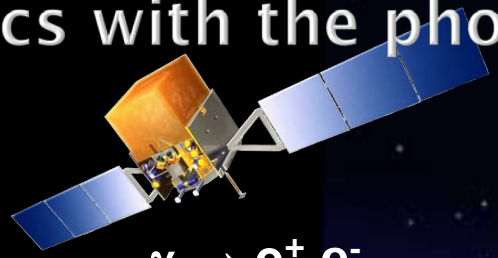


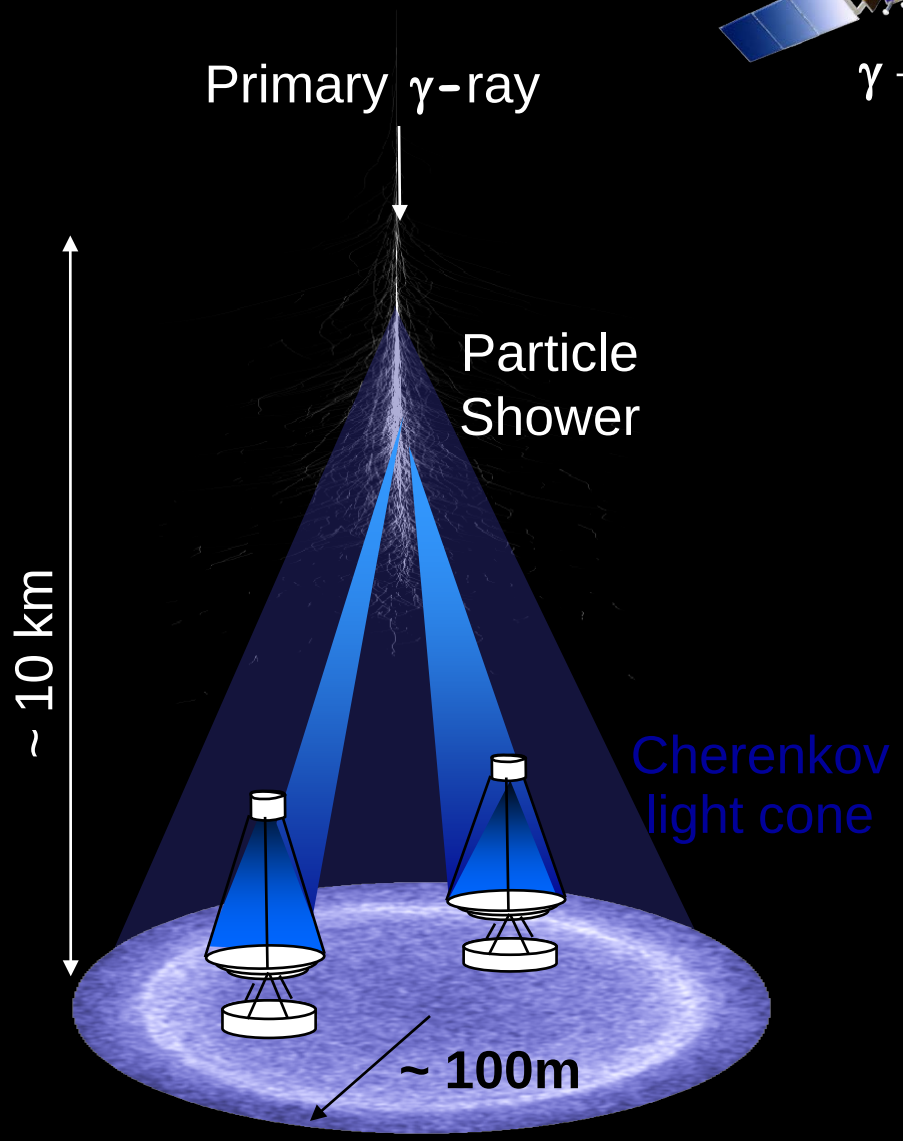
Olaf Reimer

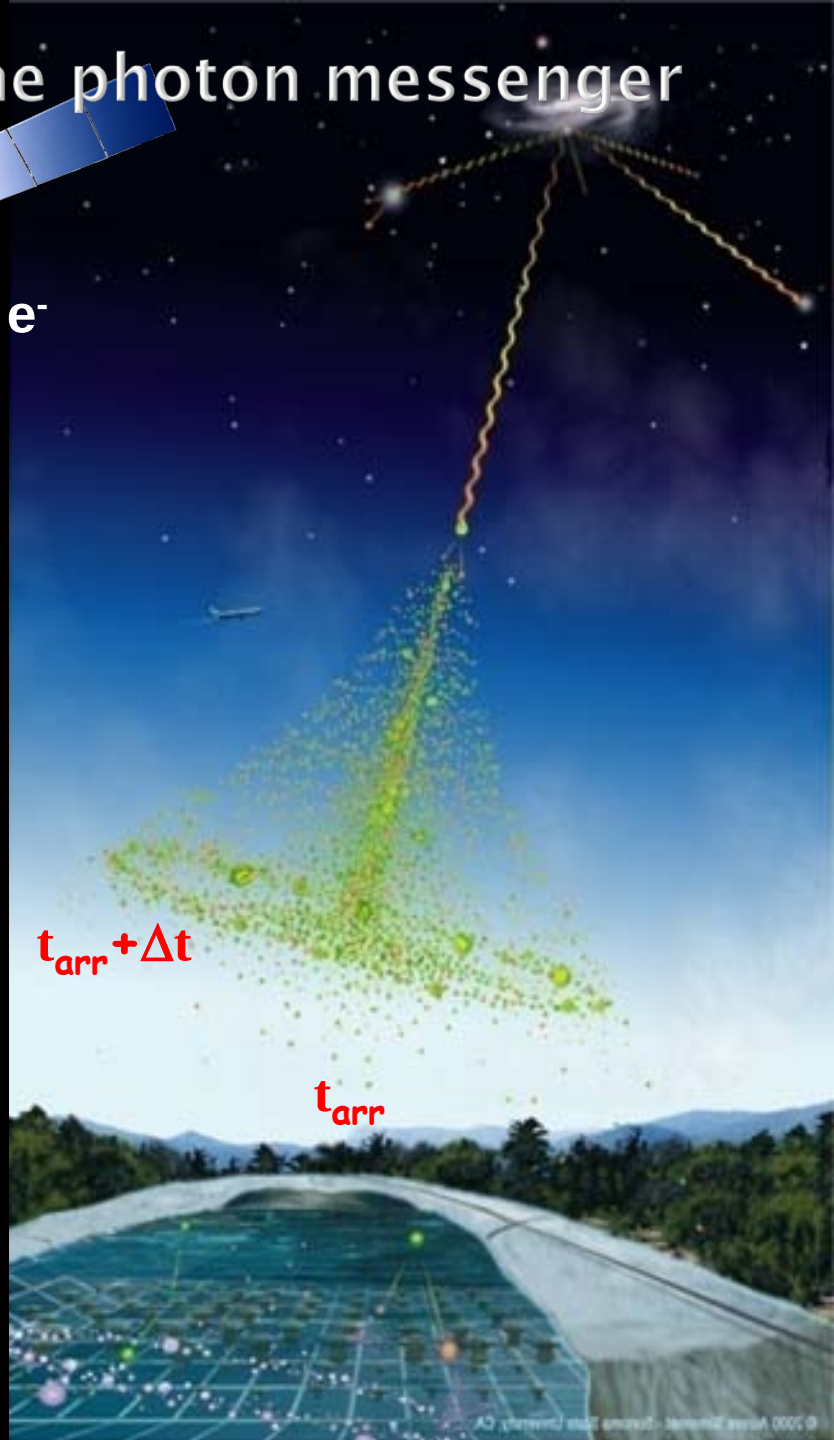
Institute for Astro- and Particle Physics
Leopold-Franzens-Universität Innsbruck
&
Kavli Institute for Astroparticle Physics and Cosmology
Stanford University

Astroparticle Physics with the photon messenger



$\gamma \rightarrow e^+ e^-$

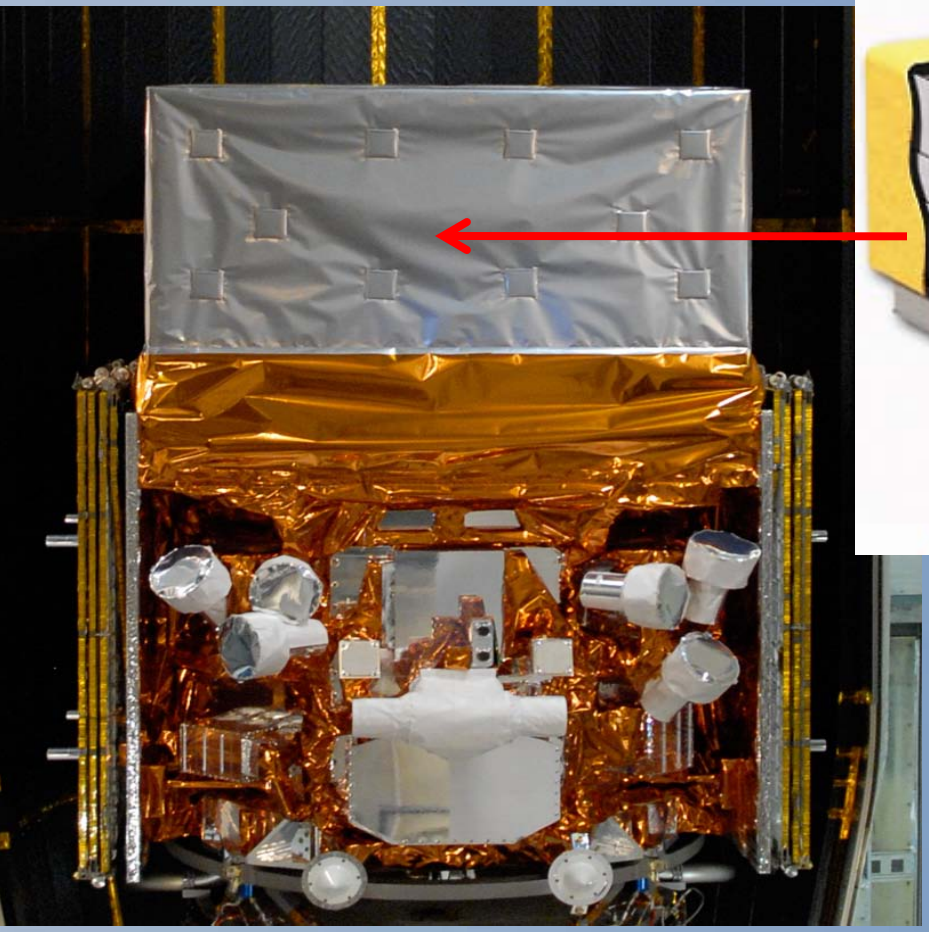


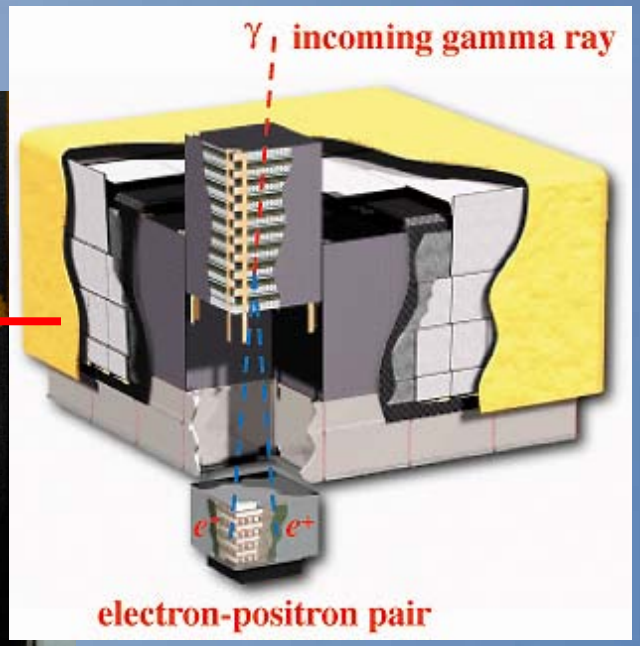


The Fermi Gamma-Ray Space Telescope

June 11, 2008 12:05 PM EDT; Cape Canaveral

Large Area Telescope (LAT)



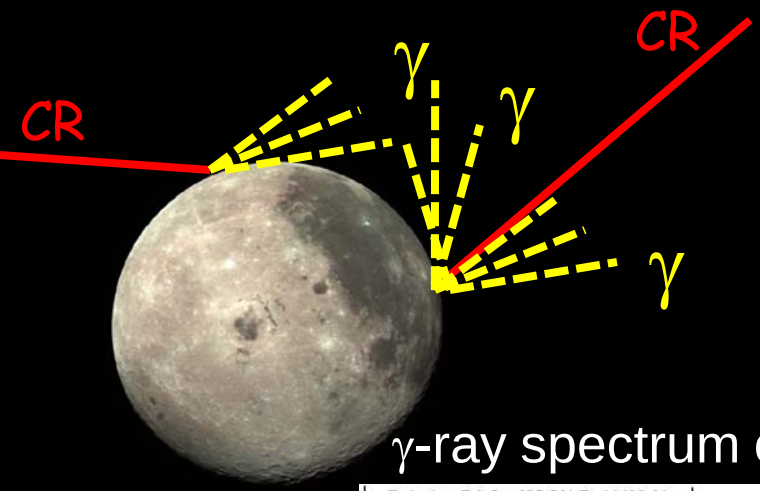


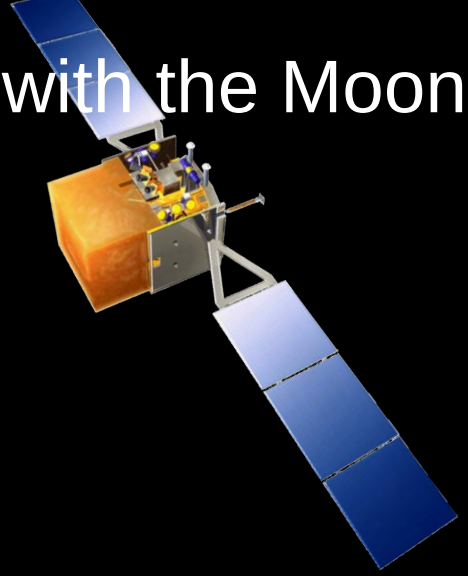
LAT images the sky one photon at a time: γ-ray converts in LAT to an electron and a positron; direction and energy of these particles tell us the direction and energy of the photon

1xx GeV to ~100 TeV – Imaging atmospheric Cherenkov telescopes

TeV-scale EAS arrays with γ-hadron separation capability

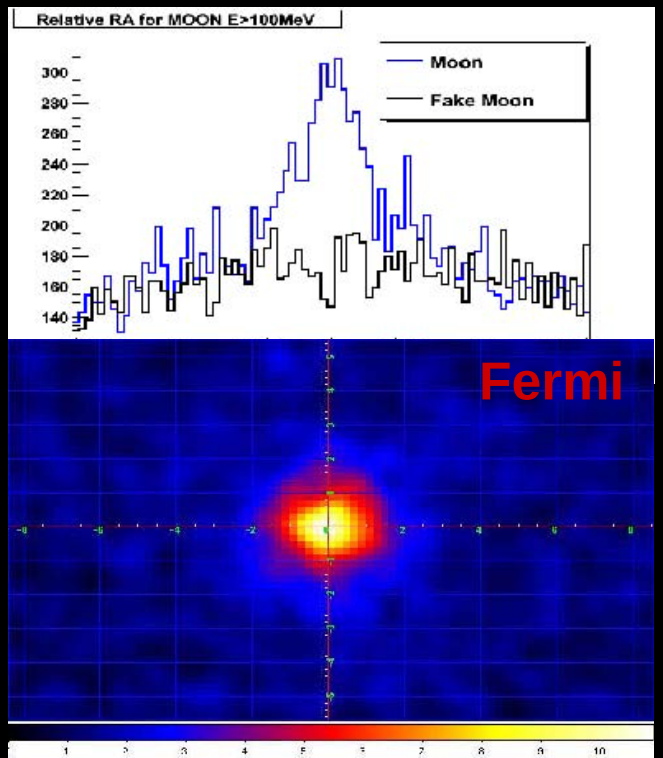
Cosmic Ray Interactions with the Moon surface

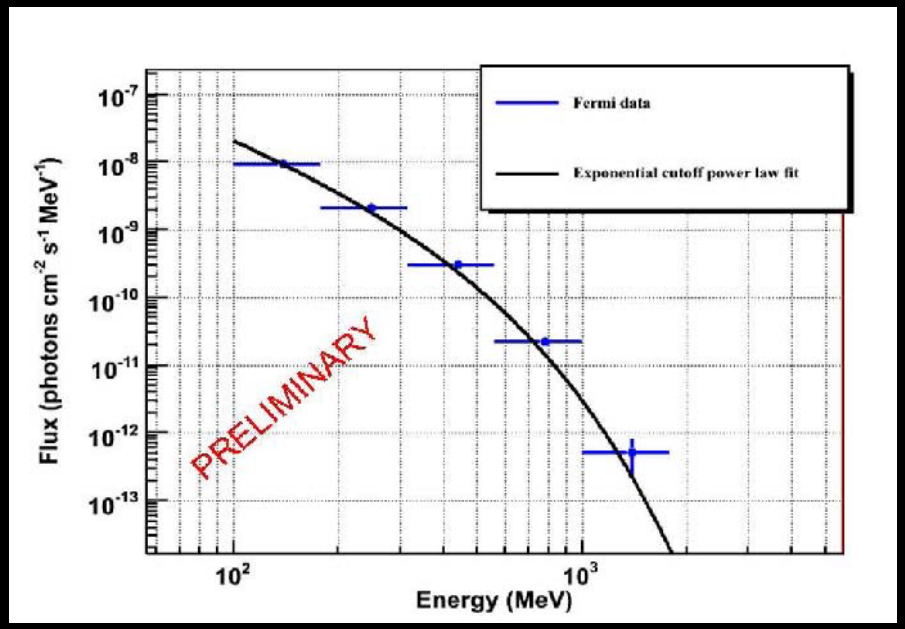




γ-ray spectrum characteristic for *moon limb or center interactions*

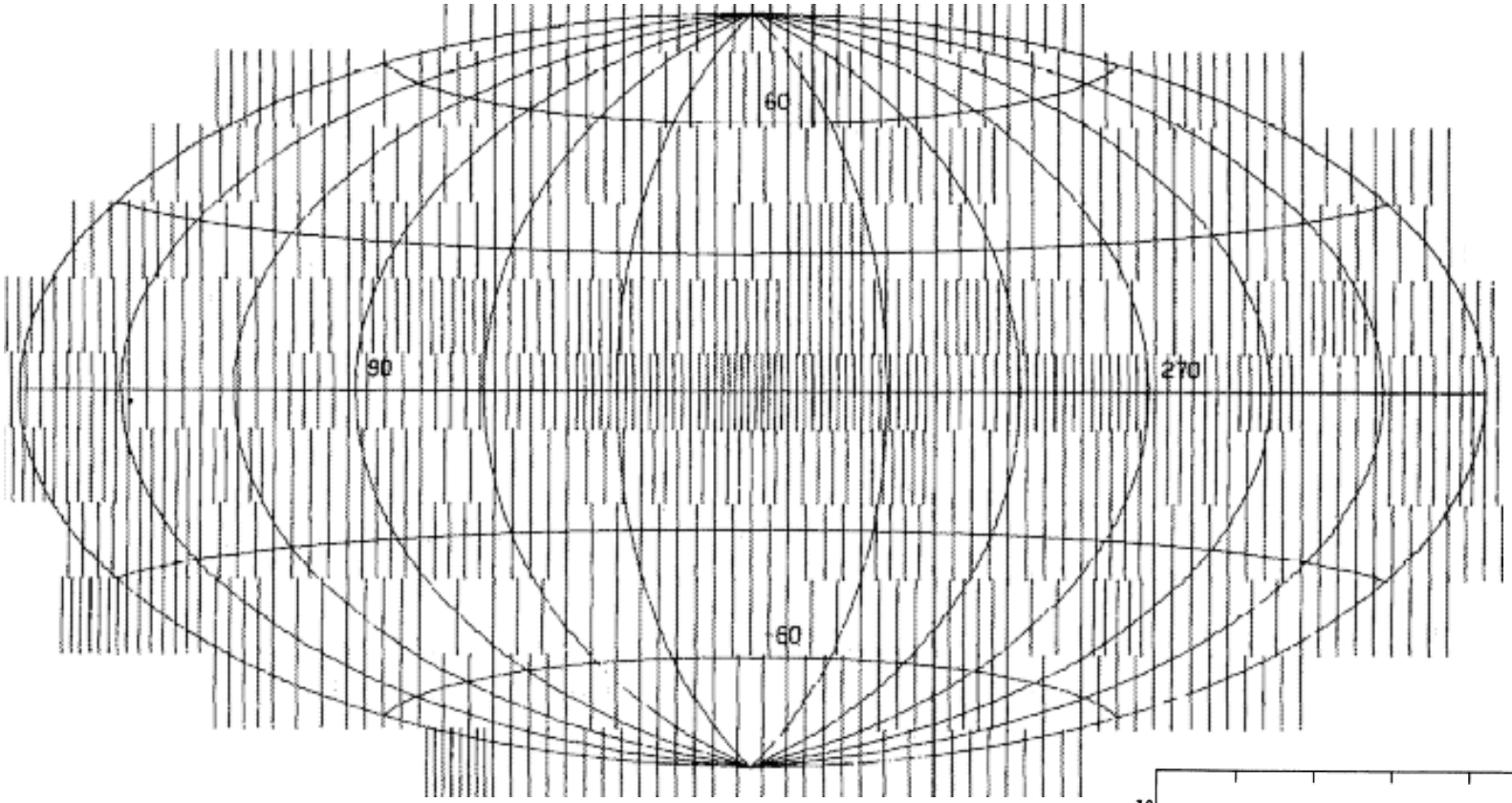
E > 100 MeV
0.2º/bin

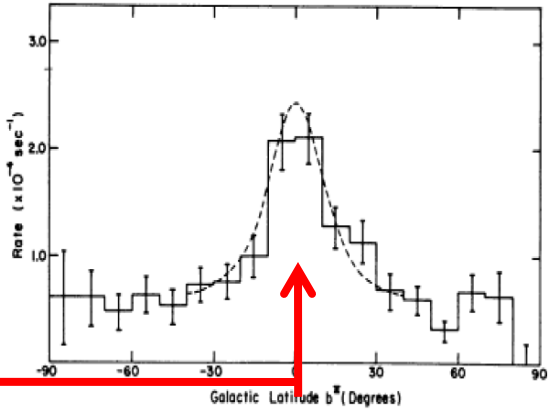




$f_{>100\ \mathrm{MeV}}$ = (1.06 0.2) x10^{-6} ph cm^{-2}s^{-1}

OSO-III 1967-1968

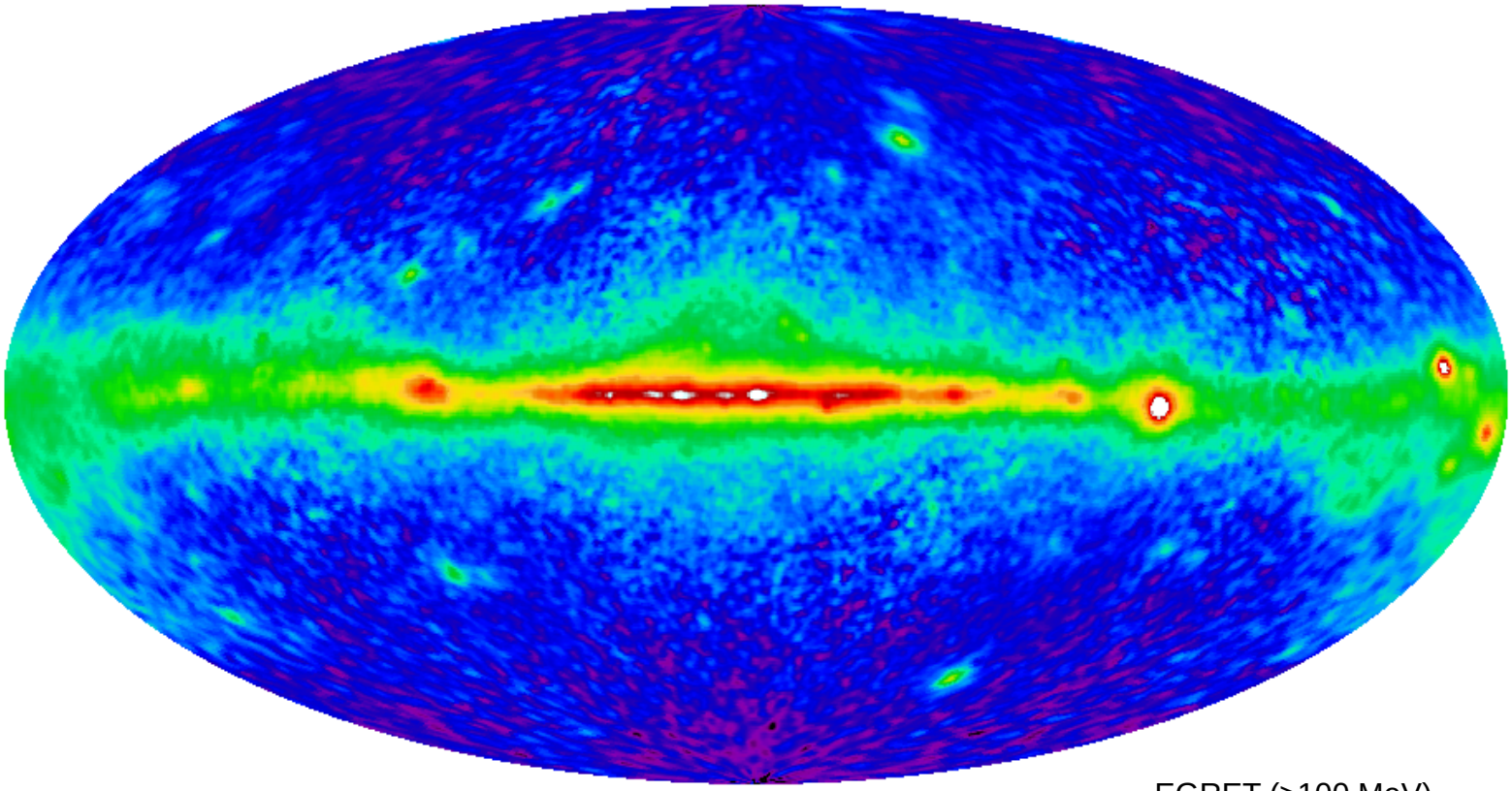




The begin of galactic γ-ray astronomy:

Galactic Plane Excess: **Milkyway**

EGRET – 1991-2000

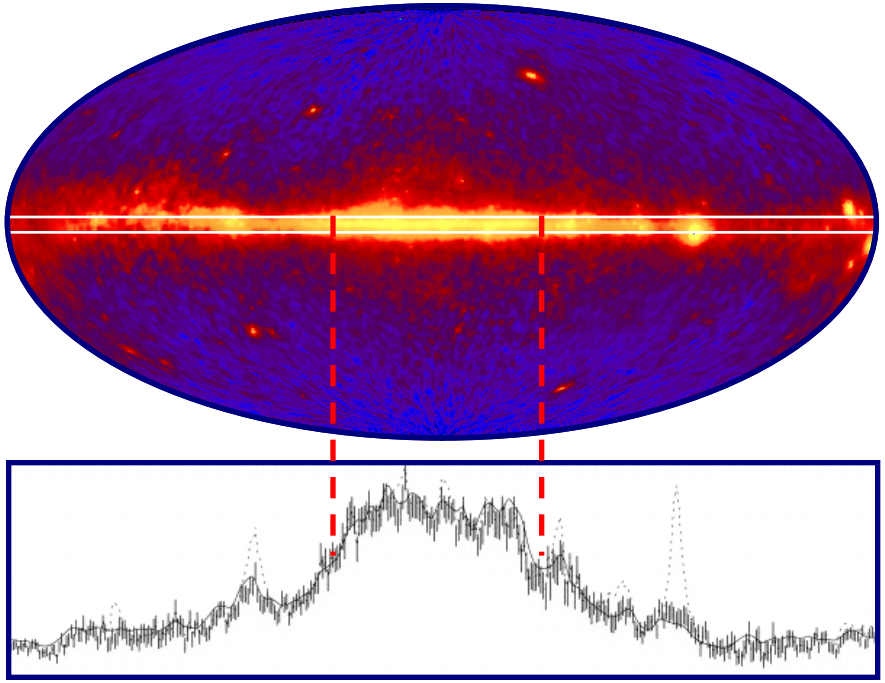


EGRET (>100 MeV)

- ~1.4x10^6 γ, ~65% interstellar emission from the Milkyway
- ~15% in resolved sources

large scale spatial agreement o.k.

- assumption of **dynamic balance*** resonably correct
- fraction of unresolved sources is small (unless distributed like the interstellar gas and uniform on a scale smaller than the instrumental PSF)



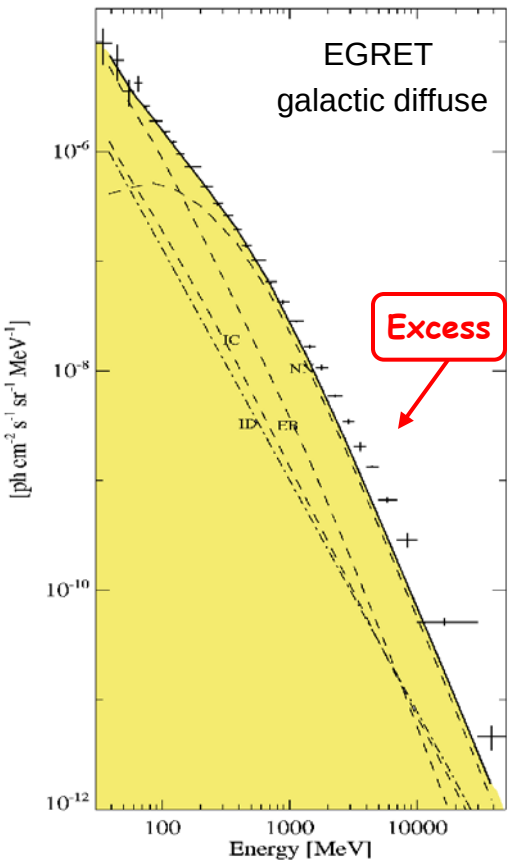
*dynamic balance between the binding forces of cosmic rays, kinetic motion & content of interstellar medium, and galactic magnetic fields.
→ the cosmic ray surface density is assumed to be proportional to that of the interstellar gas

A different approach:
Solving the CR transport equation
Cosmic Ray propagation model
(e.g. GALPROP)

large scale spectral agreement only *somewhat* o.k.

- IC, electron bremsstrahlung, and nucleon-nucleon interaction (π^0-decay) components confirmed: "pion bump" seen
- strong correlation of γ-emission with Galactic structural features

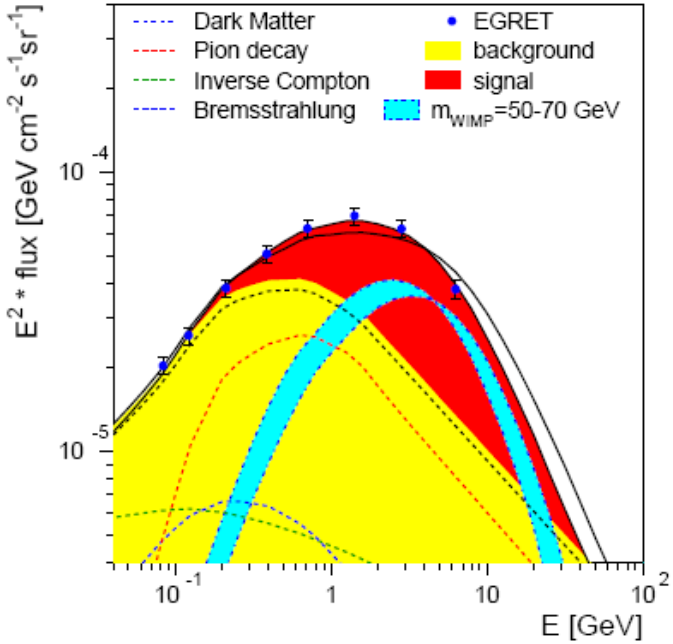
HOWEVER:



GeV excess left room for interpretation & speculation!

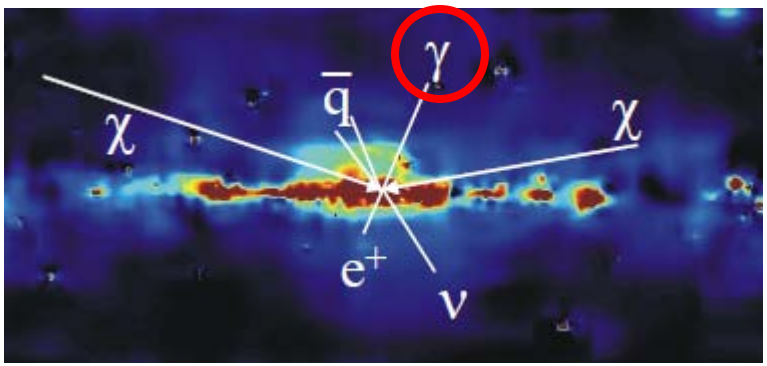
1. Hard *nucleon* injection spectrum?
2. Hard *electron* injection spectrum?
3. Atypical local p and e spectra?
4. Imperfect knowledge of π^o production
5. Unresolved GeV γ - ray sources
6. Prosaic: Instrumental effect
7. Exiting: Manifestation of dark matter!

When you have eliminated the impossible, whatever remains, however improbable, must be the truth. Sherlock Holmes



Signature of DM annihilation

(de Boer et al. 2005)



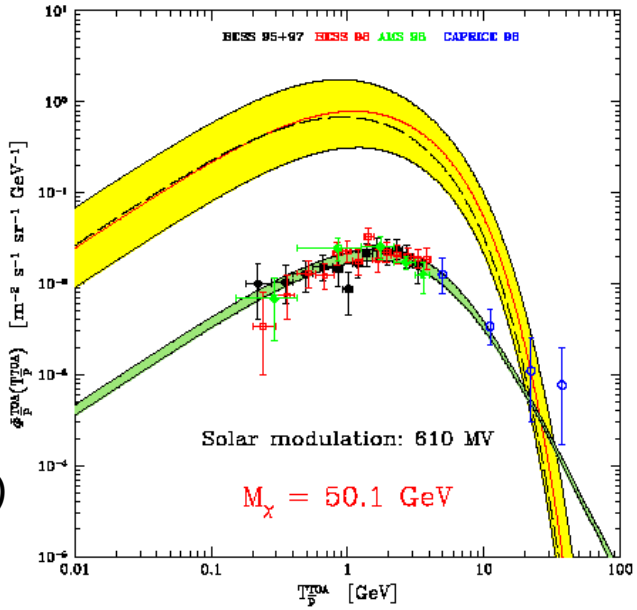
... but met criticism early on:

B. Moore:

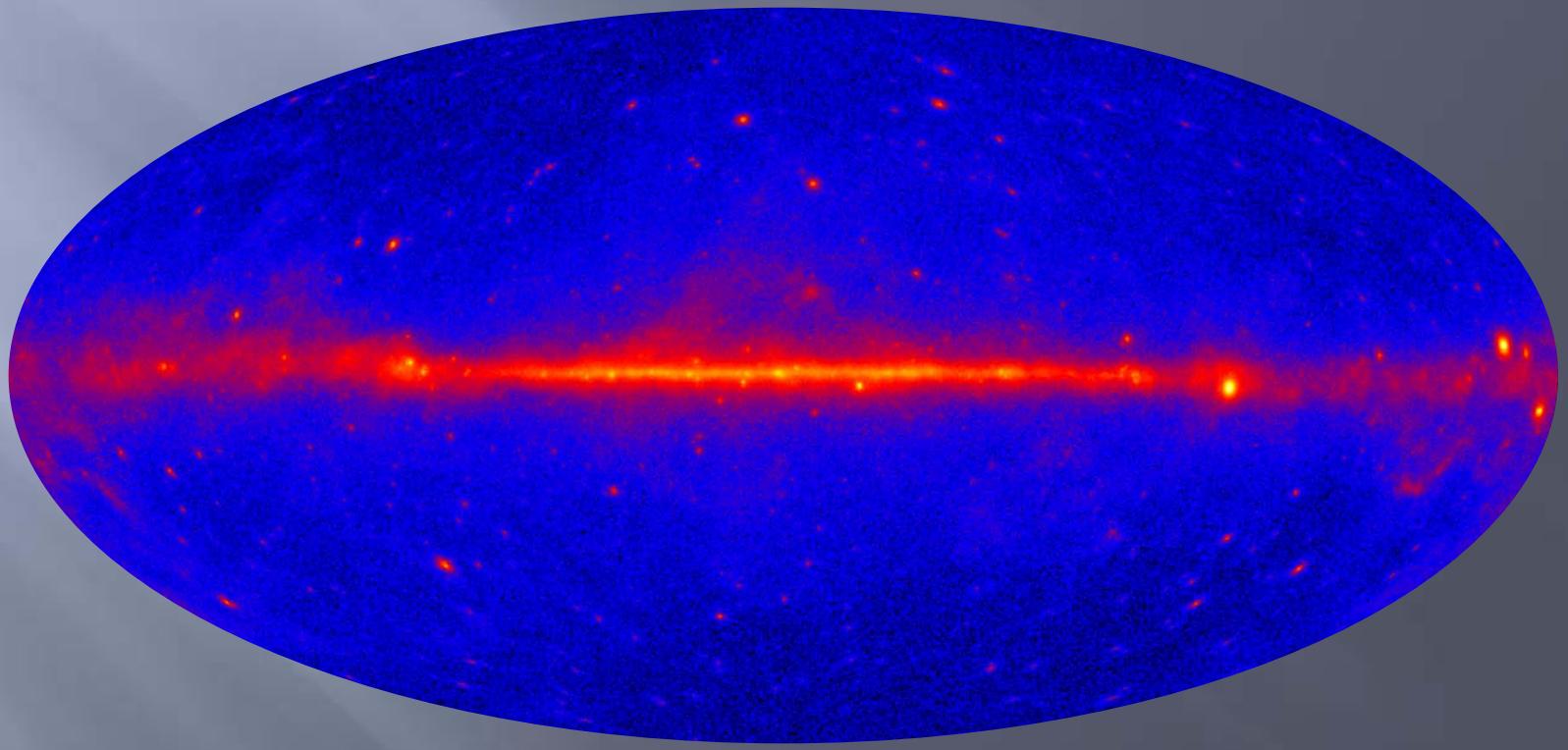
Proposed DM profile is ***unstable*** *for considered timescales.*

Bergstrøm et al. (JCAP 0605 (2006) :

Proposed DM ***overproduces antiproton flux*** *(by factor 50-100!)*

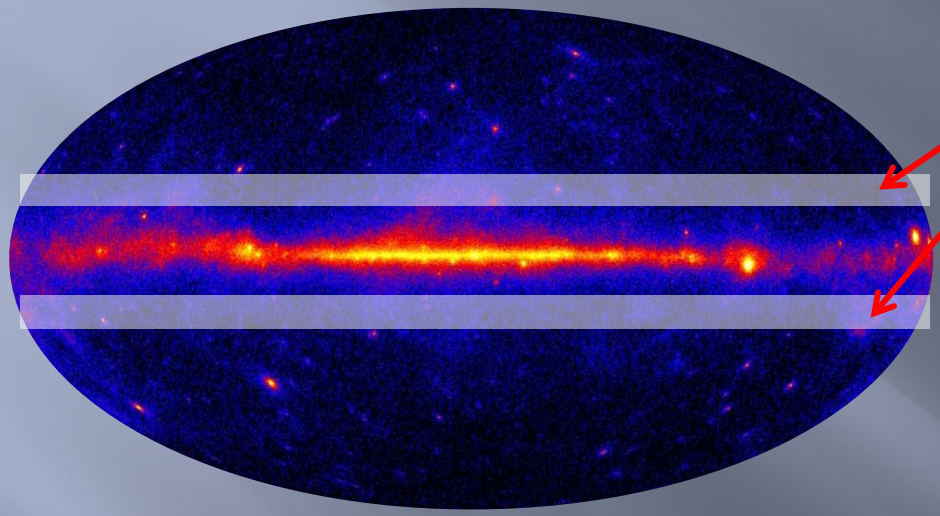


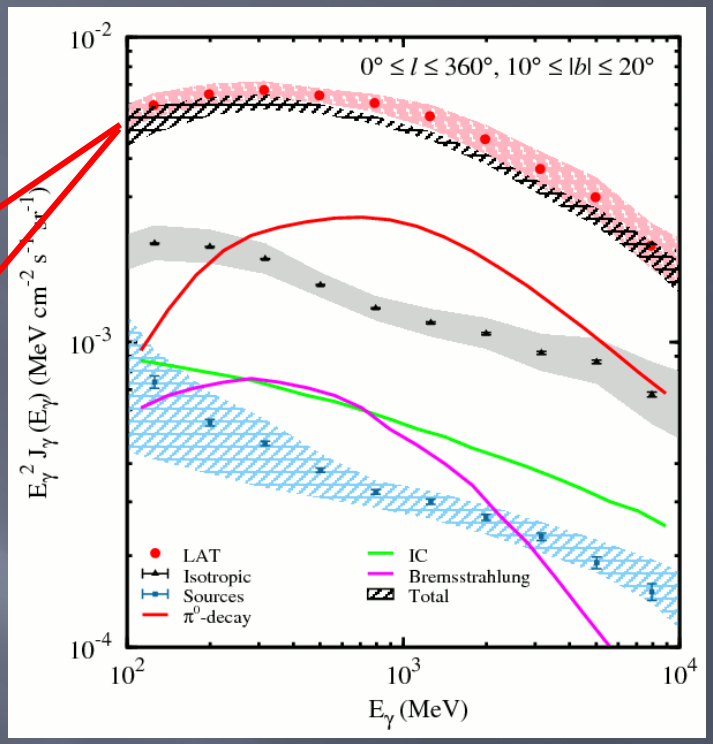
The Fermi sky after 9 month



Fermi: Galactic diffuse emission

100 MeV – 10 GeV





EGRET GeV excess is not seen in 10º ≤ |b| ≤ 20º, thus not an universal feature at gamma-ray sky

→ standard CR interaction models adequate (which do justice to locally measured CR abundances, sec/prim ratios)

→ Fermi/LAT errors are systematics dominated, estimated to ~10%

So we're left with conventional CR interaction physics!

1. ~~Hard *nucleon* injection spectrum~~

2. ~~Hard *electron* injection spectrum~~

3. Atypical local ~~p and~~ e spectra
   affects diffuse g-ray sky only mildly

4. ~~Imperfect knowledge of pp $\rightarrow \pi^o$ prod.~~

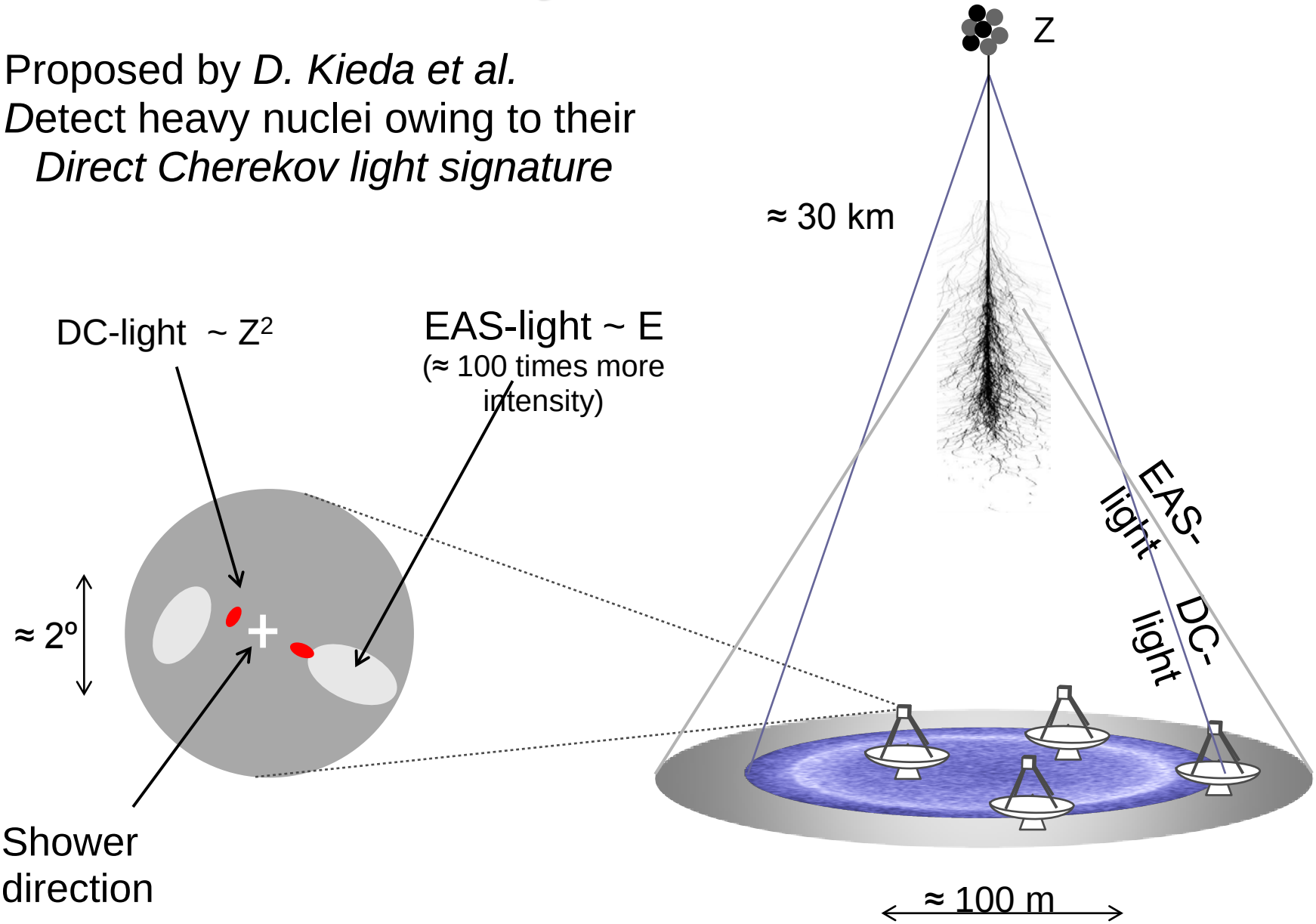
5. Unresolved GeV γ - ray sources

6. Instrumental effect
   charged particle background f(E)
   self-veto due to monolithic cal $\rightarrow A_{eff}$

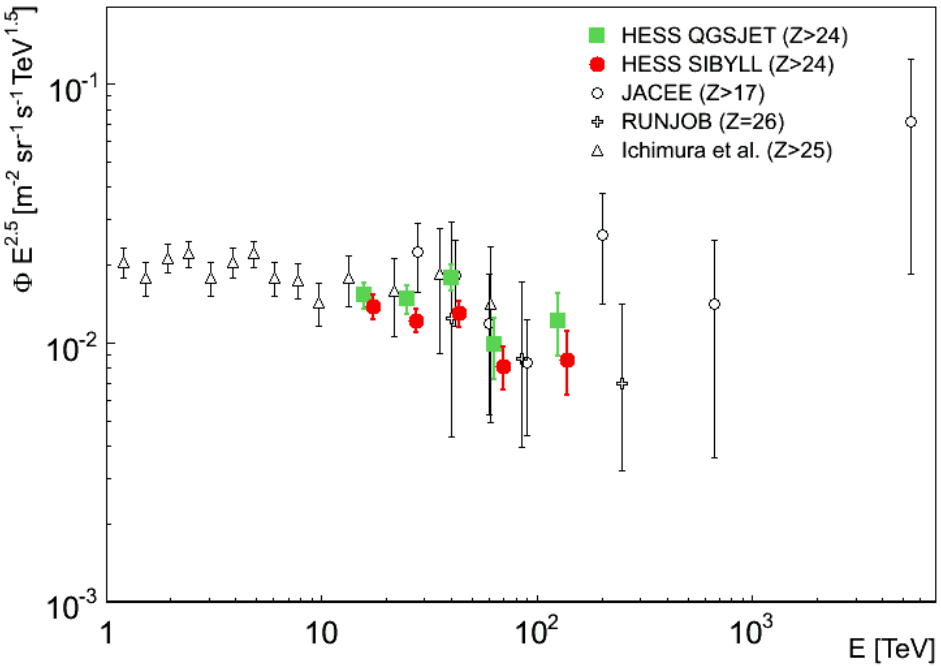
7. ~~Manifestation of dark matter~~

Gamma-ray instruments hunting in CR territory: CR Iron abundance by H.E.S.S.

Proposed by *D. Kieda et al.*
*D*etect heavy nuclei owing to their
Direct Cherekov light signature



Gamma-ray instruments hunting in CR territory: CR Iron abundance by H.E.S.S.



particle interaction model dependent

→ Estimate uncertainty by using SIBYLL 2.1 and QGSJET

- Good agreement with other experimental results
- Most precise measurement of the Z > 24 spectrum at 13…200 TeV
- Future extension to 1PeV and composition measurements possible
- ***Direct Cherenkov light* detection works!**

Gamma-ray instruments hunting in CR territory: $e^+ + e^-$ spectrum by H.E.S.S.

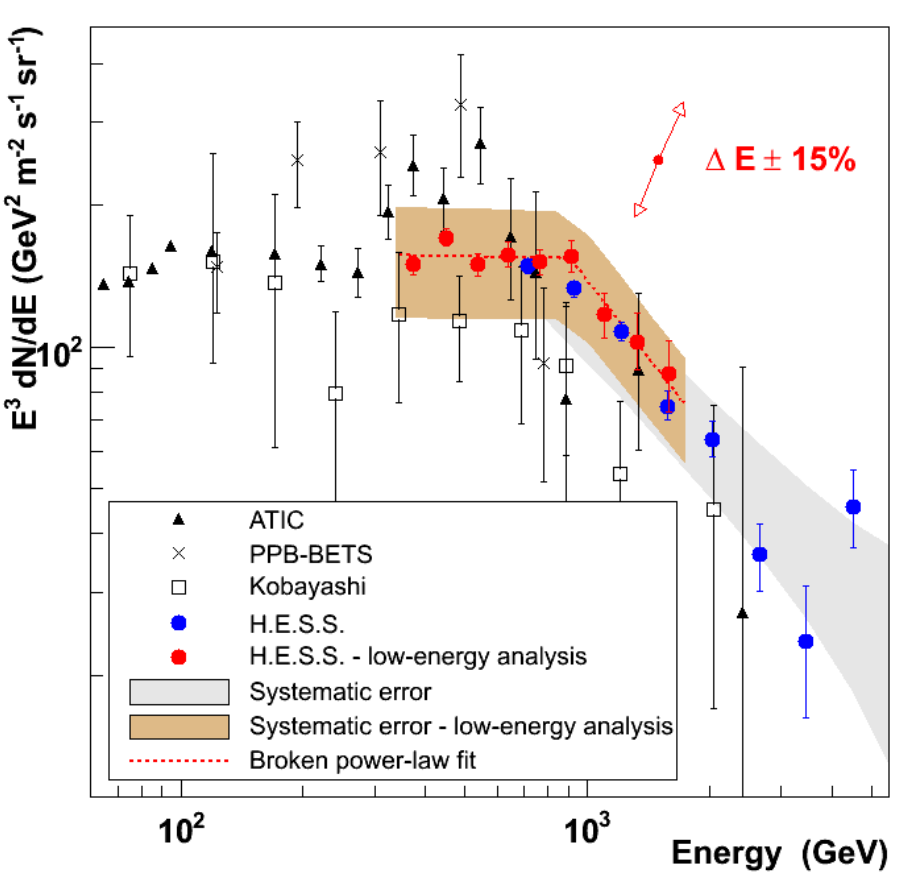
H.E.S.S. has measured cosmic-ray electrons between 340 GeV and 5 TeV

Systematic uncertainties include atmospheric variations, uncertainties in hadronic interaction models and H.E.S.S. energy scale uncertainty

H.E.S.S.: Smooth spectrum that steepens at 0.9 TeV

$\Gamma_1 = 3.0$ $0.1_{stat.}$ $0.3_{syst.}$

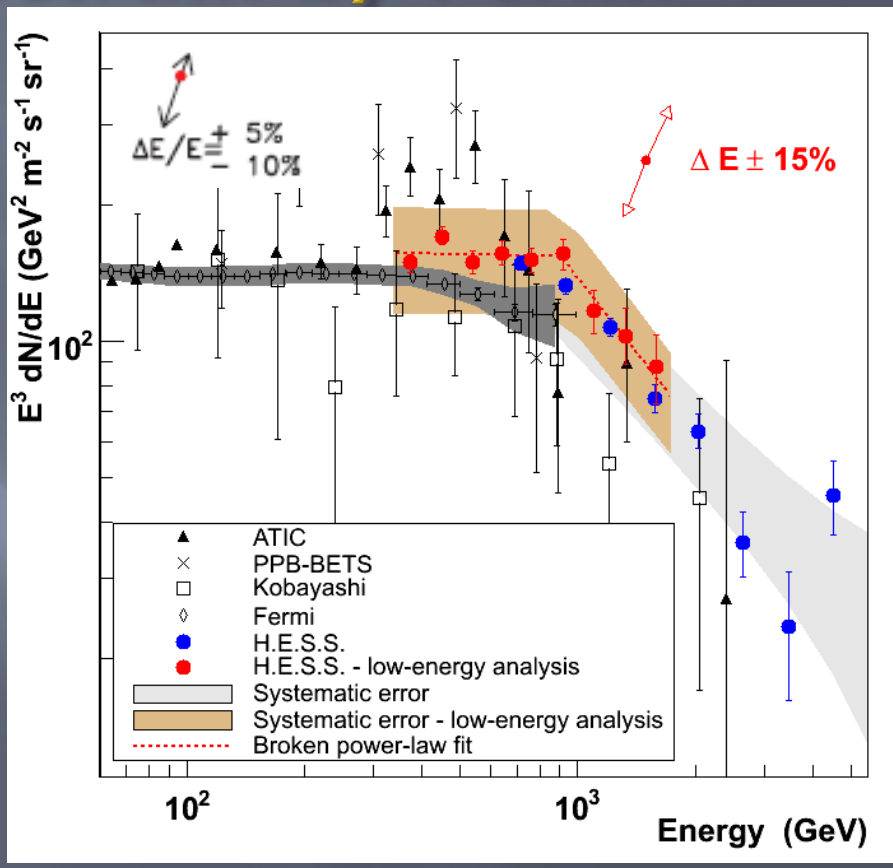
$\Gamma_2 = 4.1$ $0.3_{stat.}$ $0.3_{syst.}$



Gamma-ray instruments hunting in CR territory: $e^+ + e^-$ spectrum by Fermi

- events for e^+ e^- analysis required to fail ACD vetoes for selecting γ events; resulting γ contamination < 1%
- further cuts distinguish EM and hadron events; rejection 1:10^3 up to 200 GeV; ~1:10^4 at 1 TeV

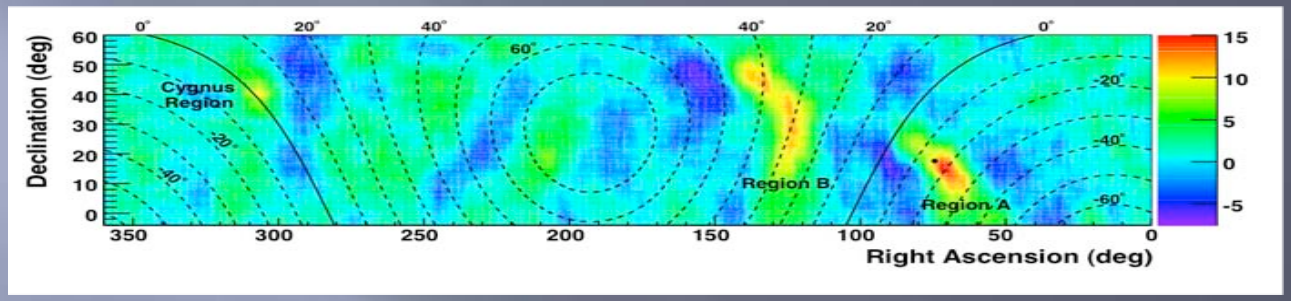
No prominent spectral features between 20 GeV and 1 TeV.



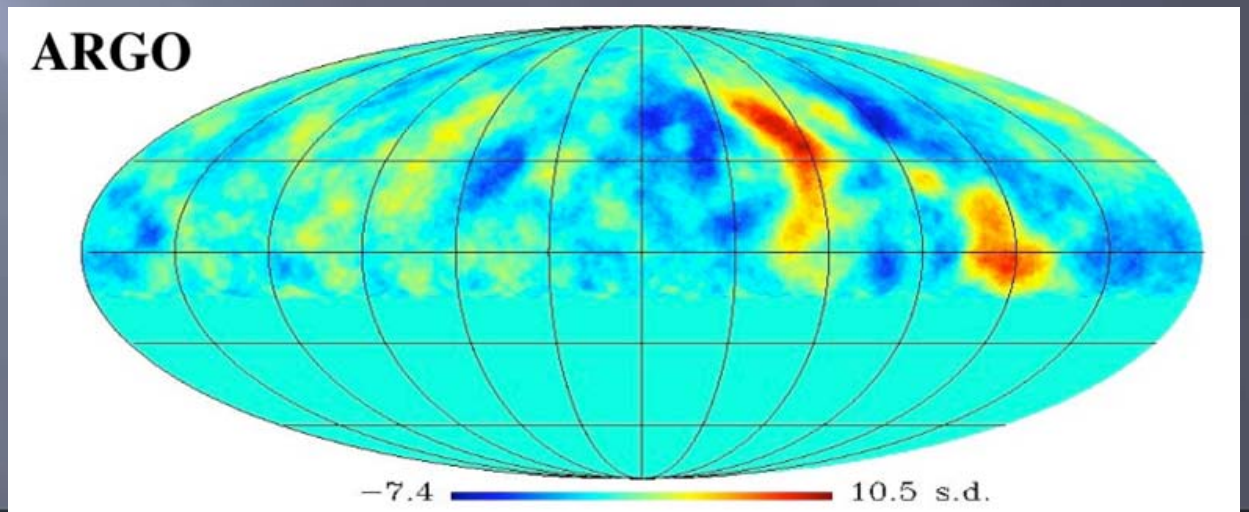
Fermi and *PAMELA* $e^+/(e^+ + e^-)$ data might require a new high-energy positron source

- ***Nearby conventional astrophysical sources*** (e.g. pulsars) injecting required amounts of e^+ and e^-, injected spectrum & efficiency are very uncertain
- even standard ***TeV electron propagation*** can have many stochastic realizations
- ***Dark matter?***
  - annihilation; requires boost factors (either density or σv)
  - decays;

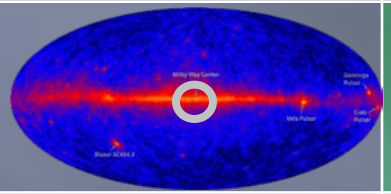
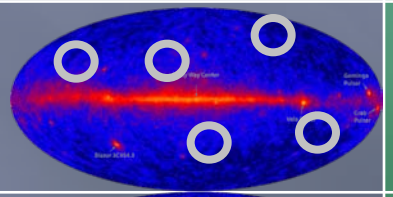
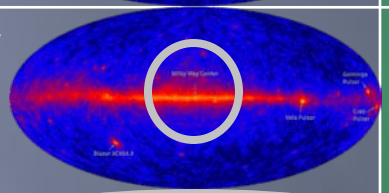
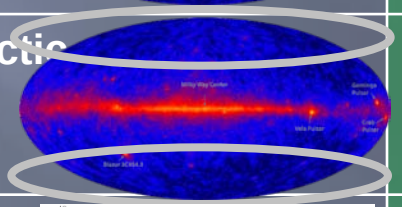
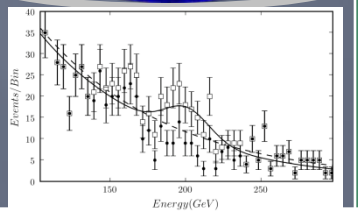
Milagro's Surprising Cosmic Ray Anisotropy



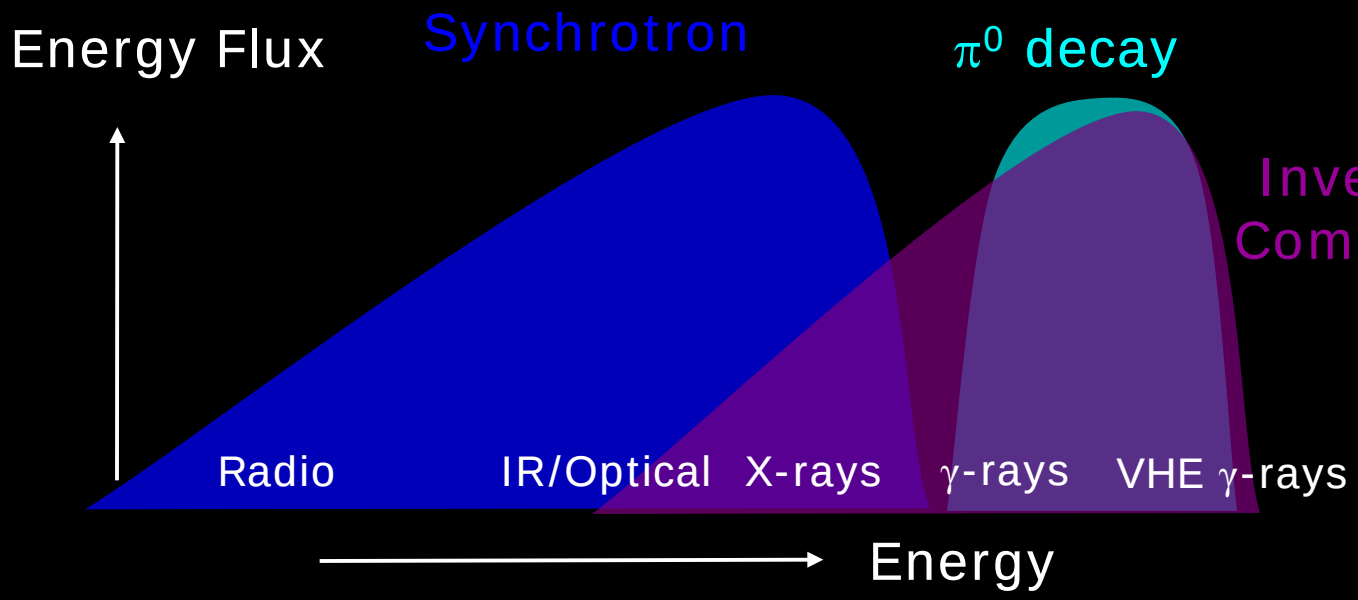
- Localized anisotropy on 5-10 deg size scale with a fractional excess up to 7e-4 above the cosmic ray background (15 σ)
- Excess is not gamma rays, but hadronic cosmic rays (7 σ)
- Different spectrum than cosmic rays (4 σ) that is harder up to ~10 TeV
- **Cosmic Ray Propagation and/or Nearby source ?**

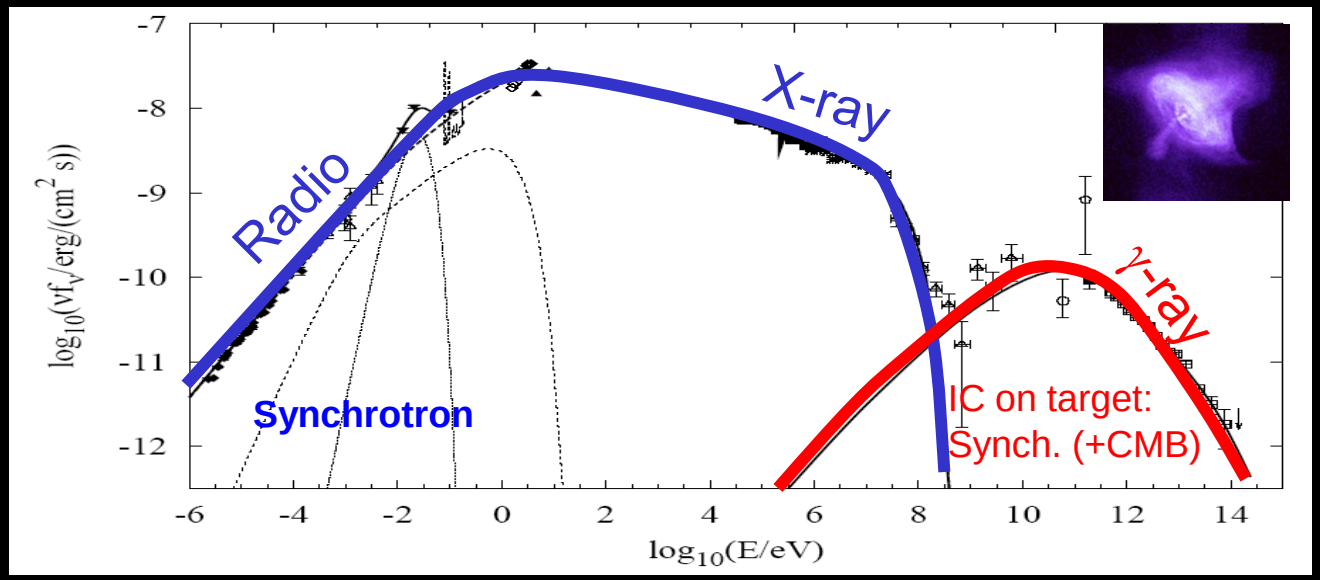


Complementary dark matter search techniques in Fermi

Search Technique	advantages	challenges
Galactic center 	Good statistics Uniquely studies location	Source confusion Non-DM astrophysics Diffuse galactic emission
Satellites, Subhalos 	Low background Chance for unique ID	Low statistics Accomplish ID
Milky Way Halo 	Large statistics	Diffuse galactic emission
Extragalactic diffuse 	Large Statistics	Non-DM astrophysics, Diffuse galactic emission as foreground
Lines 	No astrophysical uncertainties Unique source id	Low statistics Parameter space

Photons as the messenger of cosmic rays





Synchrotron:

$E_x(\mathrm{keV}) = 4\,(B/1\mathrm{mG})(E_e/10\mathrm{TeV})^2$

IC (on CMB):

$E_\gamma(\mathrm{TeV}) \sim (0.05E_e)^2$

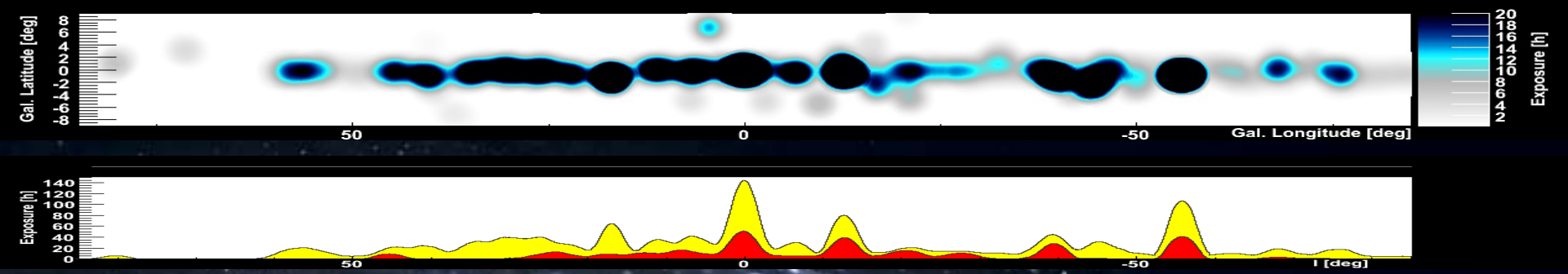
Neutral pion decay:

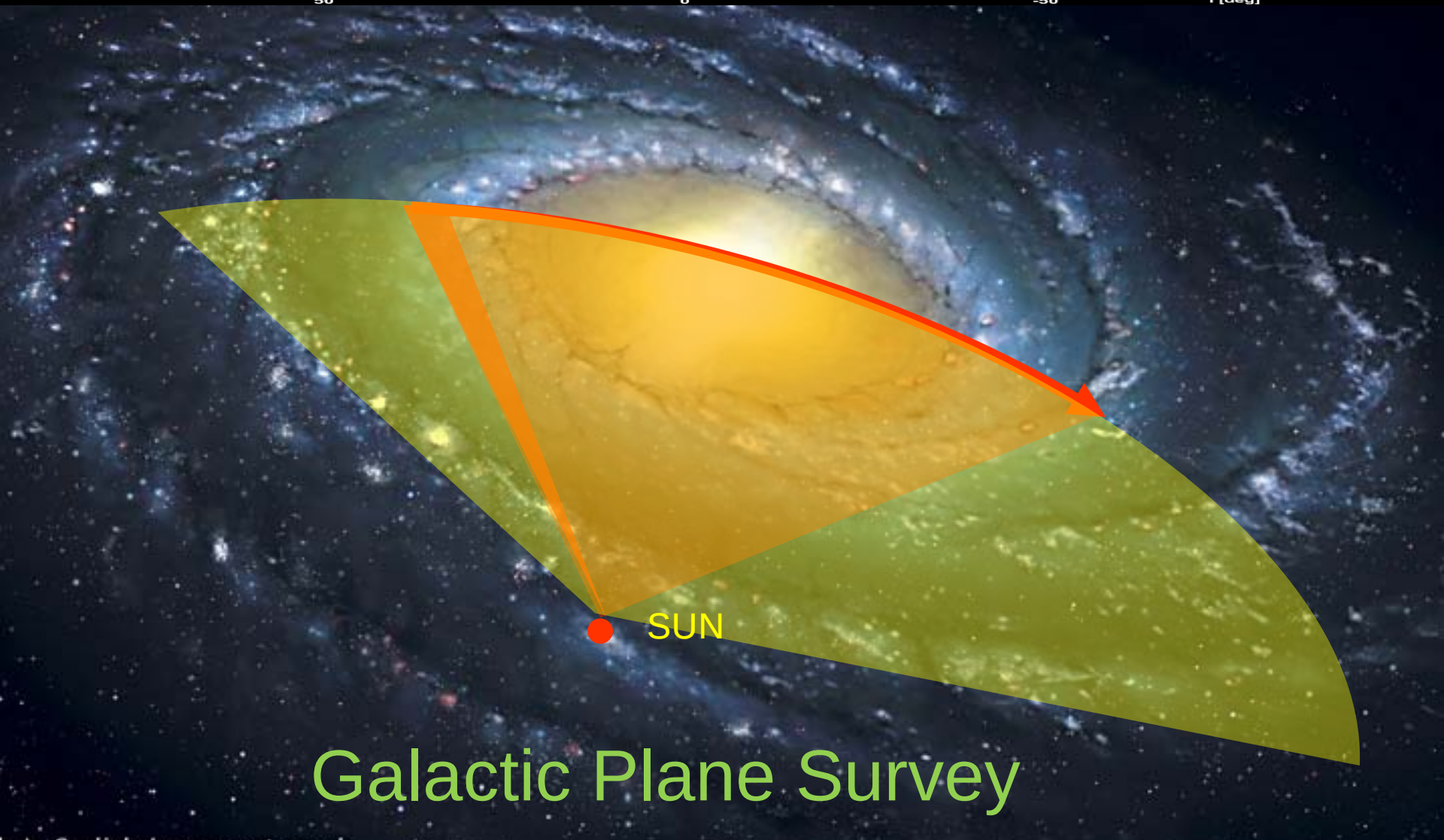
$\langle E_{\gamma\gamma}\rangle \sim 0.15\,E_p$

10 keV X-ray → **10 TeV e^-**

1 TeV γ-ray → **20 TeV e^-**

→ **6 TeV p**

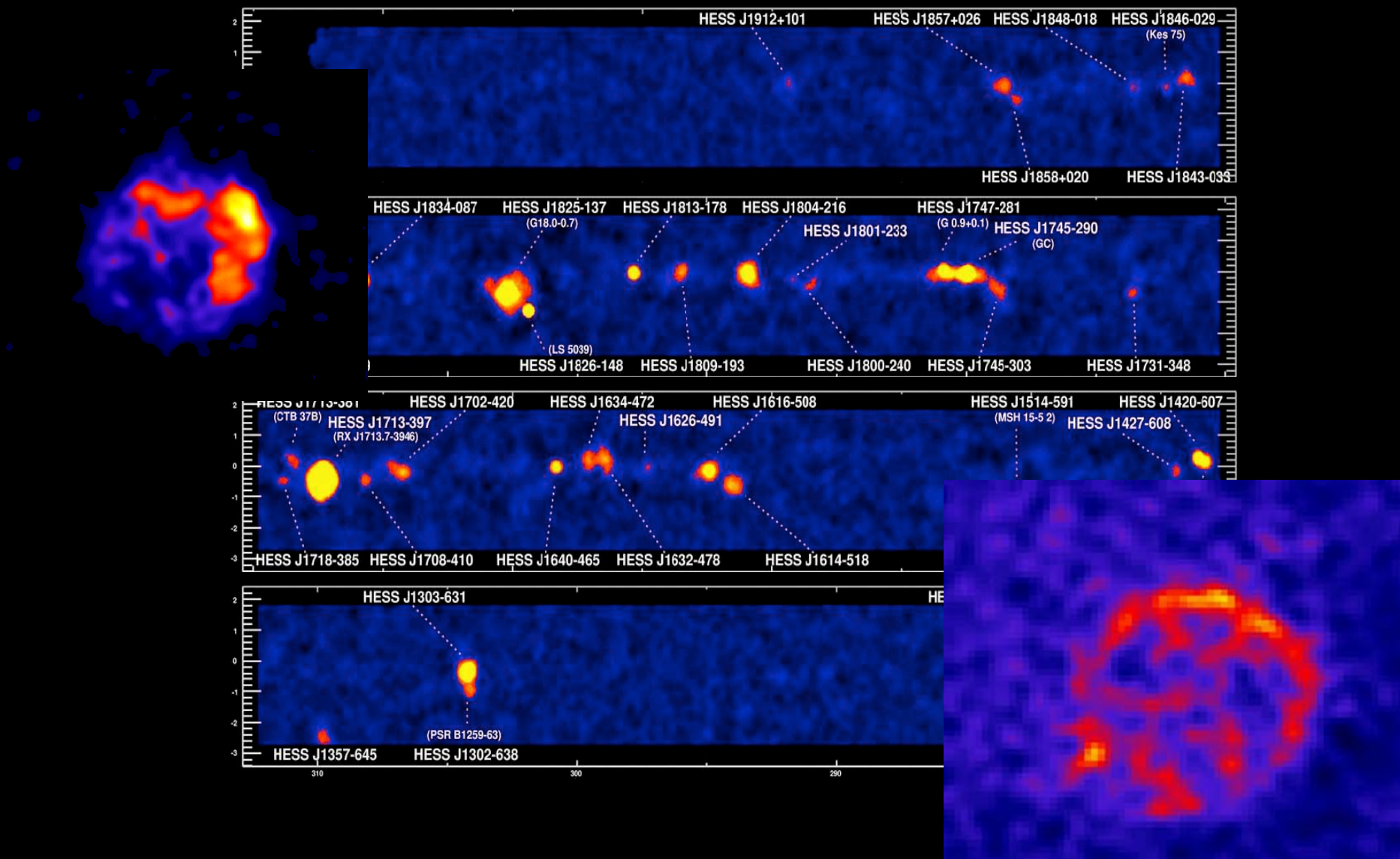




Galactic Plane Survey

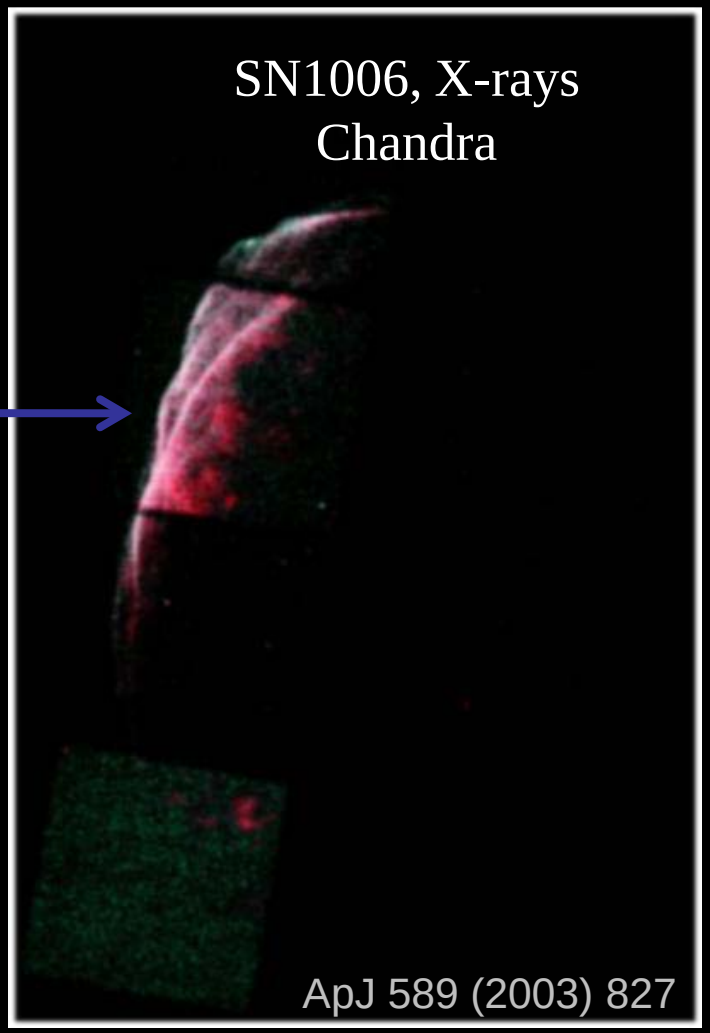
Cosmic particle accelerators: ground-based Cherenkov astronomy

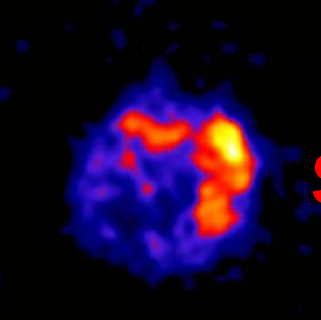
Stunning diversity of γ-ray sources between 150 GeV and 50 TeV !



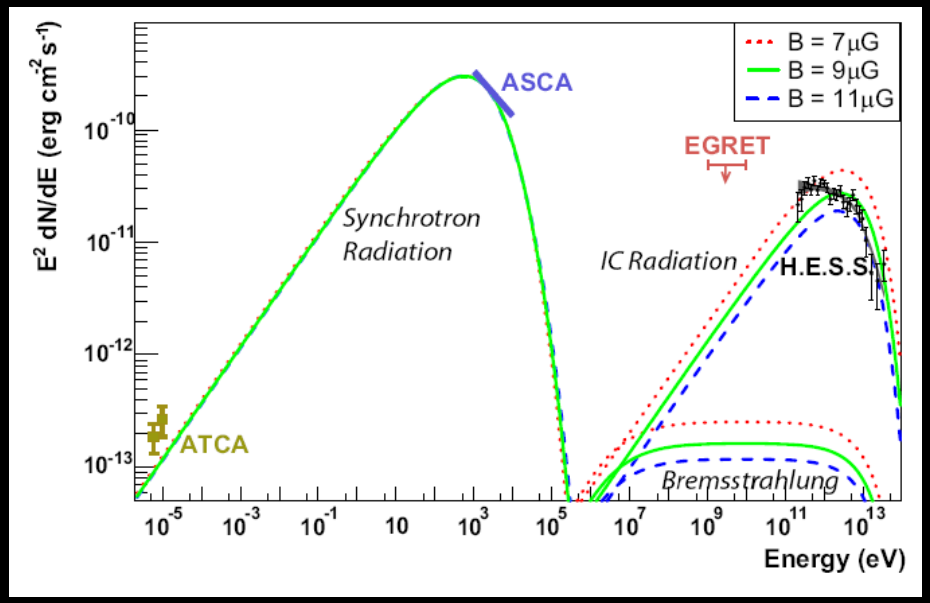
Shell-type supernova remnants

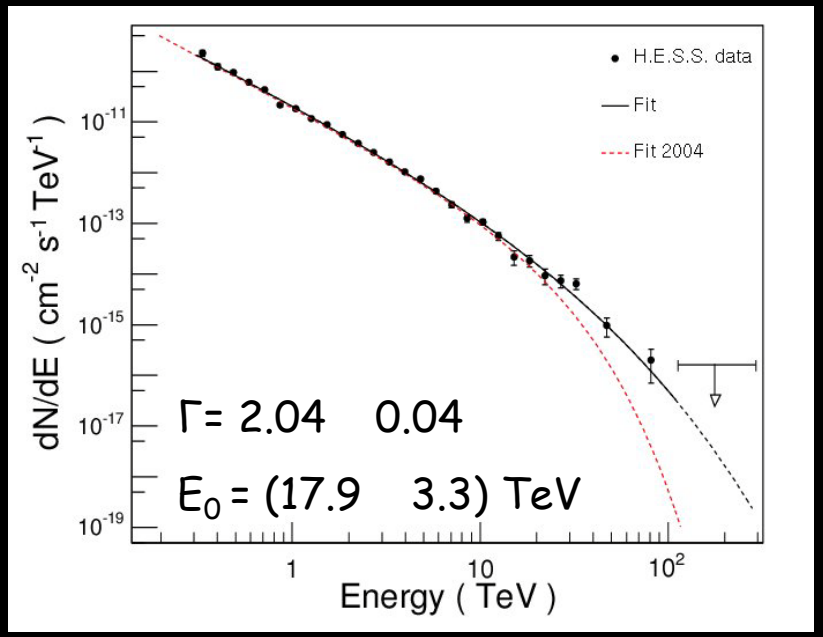
- Supernova remnants (SNR's) are suspected to be the main accelerators of galactic cosmic-rays up to the knee
  - Diffusive shock acceleration
  - 10% of the mechanical energy of supernovae can account for the injection of CR's in the Galaxy.
- Thin filaments seen in non-thermal (synchrotron) X-rays prove that electrons are accelerated up to 100 TeV and indicate the shock position.
- SNR's are often extended sources → no clear detection at GeV sky (they do not readily stand out over the diffuse γ-ray flux)
- Ground-based Cherekov telescopes provided resolved images of several prominent shell-type SNR's





SNR RXJ1713.7-3946 became archetypal



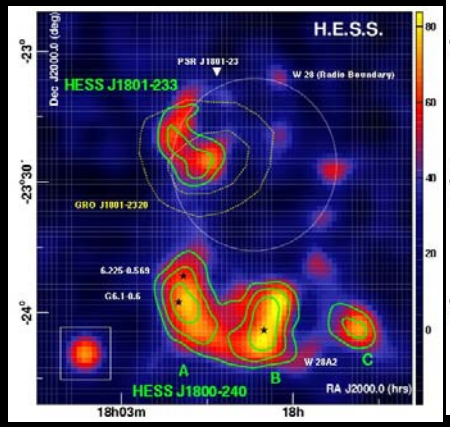


- Tight keV-TeV correlation [+electrons]
- No tight correlation with molecular material [+electrons]
- Inverse Compton implies (too?) low B-Field [+protons]
- Spectral shape [+protons]

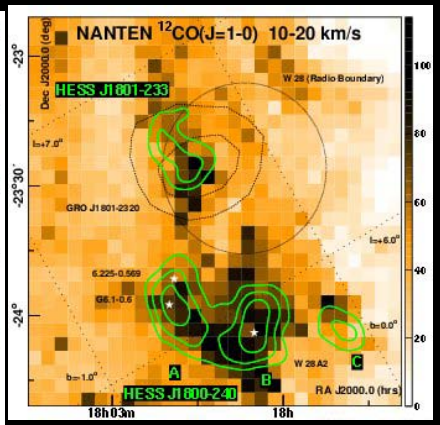
In the hadronic scenario, efficient proton acceleration up to 200 TeV is implied

Some older (T>10^4 years) supernova remnants are detected by their interaction with a nearby molecular cloud

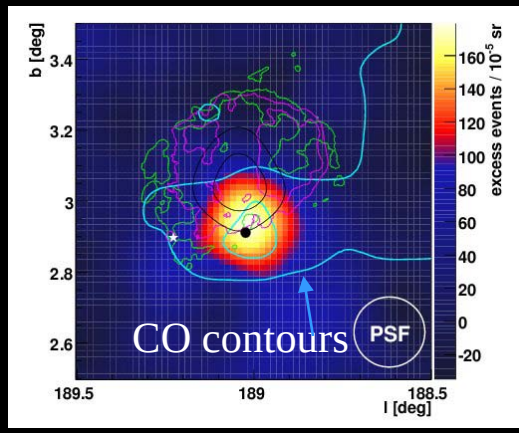
- The VHE γ-ray signal coincides with the molecular cloud (CO map), not with the radio shell.
  - W28 by H.E.S.S.
  - IC 443 by MAGIC/VERITAS
- In the preceding cases, OH masers show that molecular clouds are perturbed by SNR shocks
- Hadronic origin of γ-rays likely



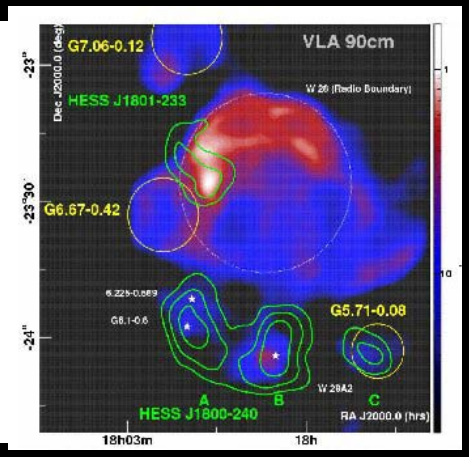
W28 (H.E.S.S.)



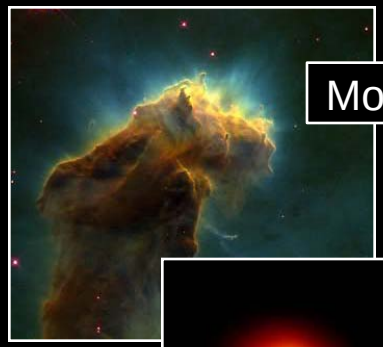
W28 (CO map)



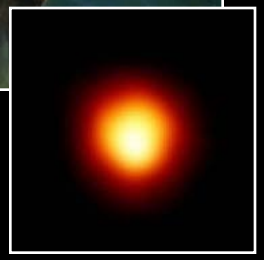
IC443 (MAGIC)



W28 (radio)



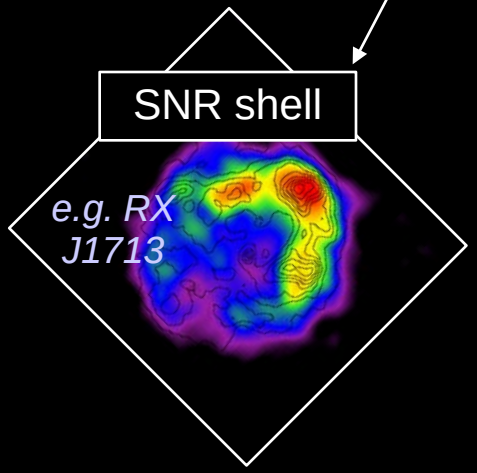
Molecular cloud

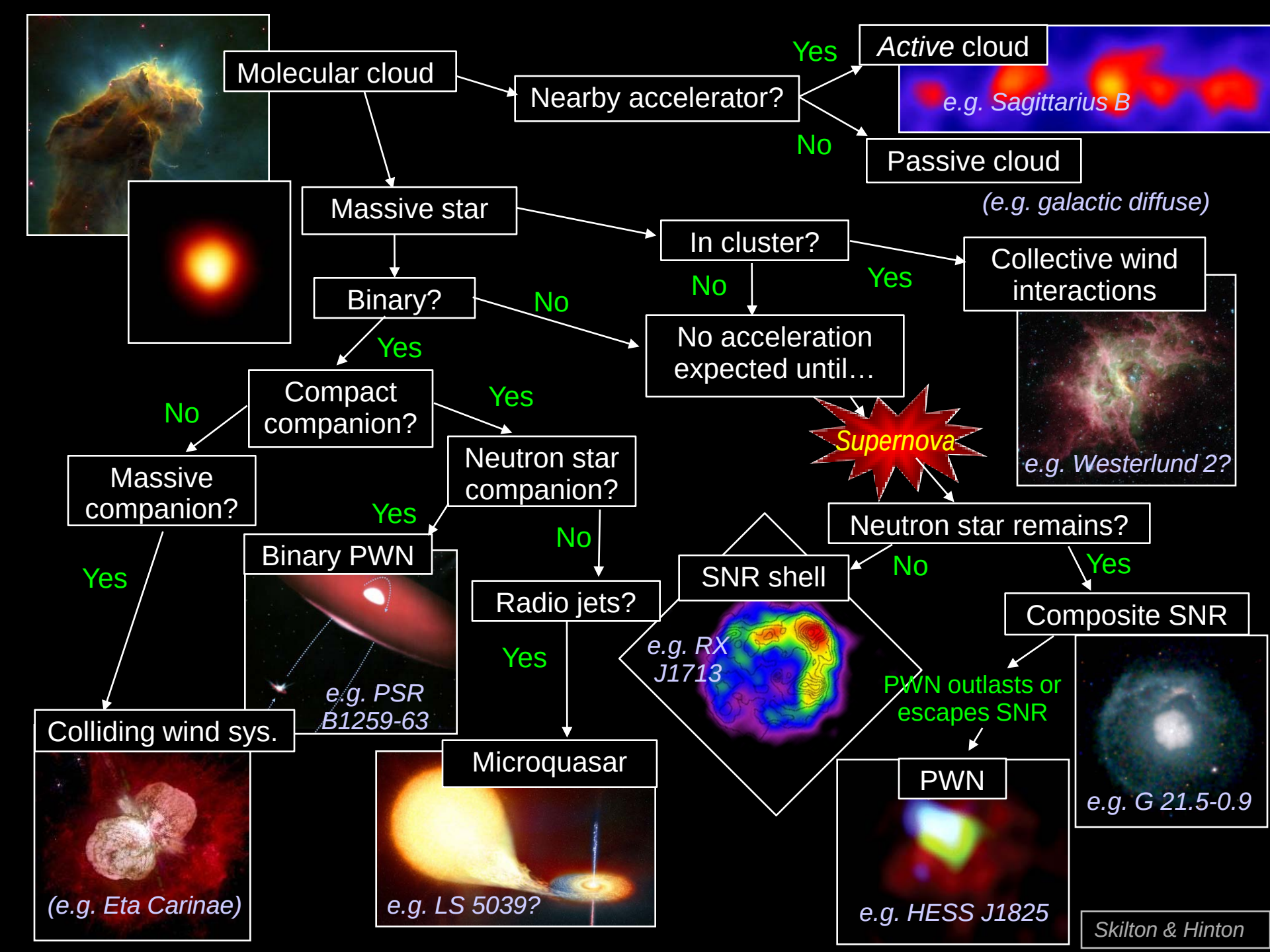


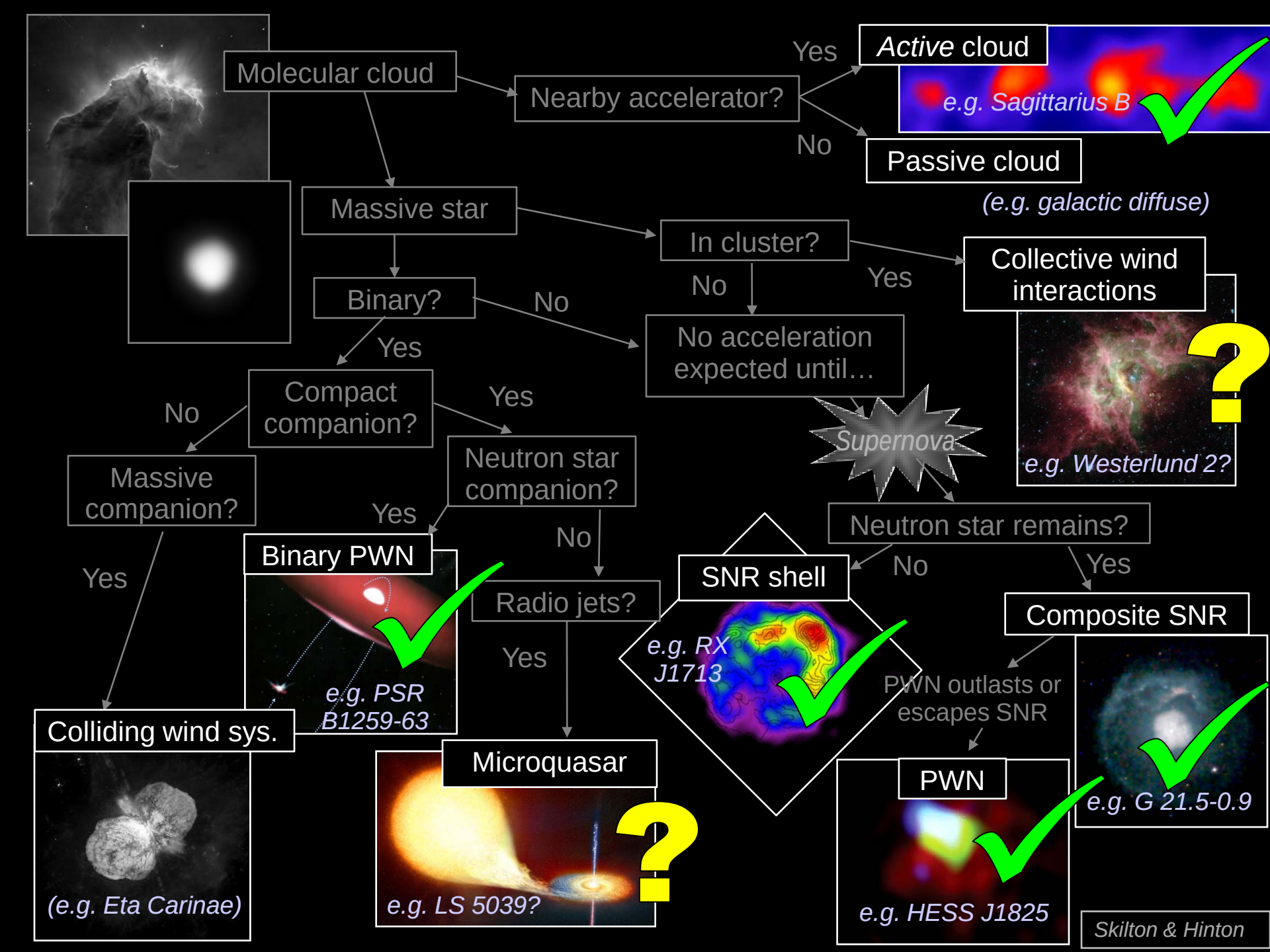
Massive star

No acceleration expected until…

SNR shell




Molecular cloud
Nearby accelerator?
Yes
Active cloud
e.g. Sagittarius B
No
Passive cloud
(e.g. galactic diffuse)
Massive star
In cluster?
No
Yes
Collective wind interactions
e.g. Westerlund 2?
Binary?
No
No acceleration expected until…
Yes
Compact companion?
No
Yes
Supernova
Massive companion?
Neutron star companion?
Neutron star remains?
Yes
Binary PWN
e.g. PSR B1259-63
No
Yes
SNR shell
No
Yes
Radio jets?
Composite SNR
e.g. RX J1713
Yes
PWN outlasts or escapes SNR
e.g. G 21.5-0.9
Colliding wind sys.
(e.g. Eta Carinae)
Microquasar
e.g. LS 5039?
PWN
e.g. HESS J1825
Skilton & Hinton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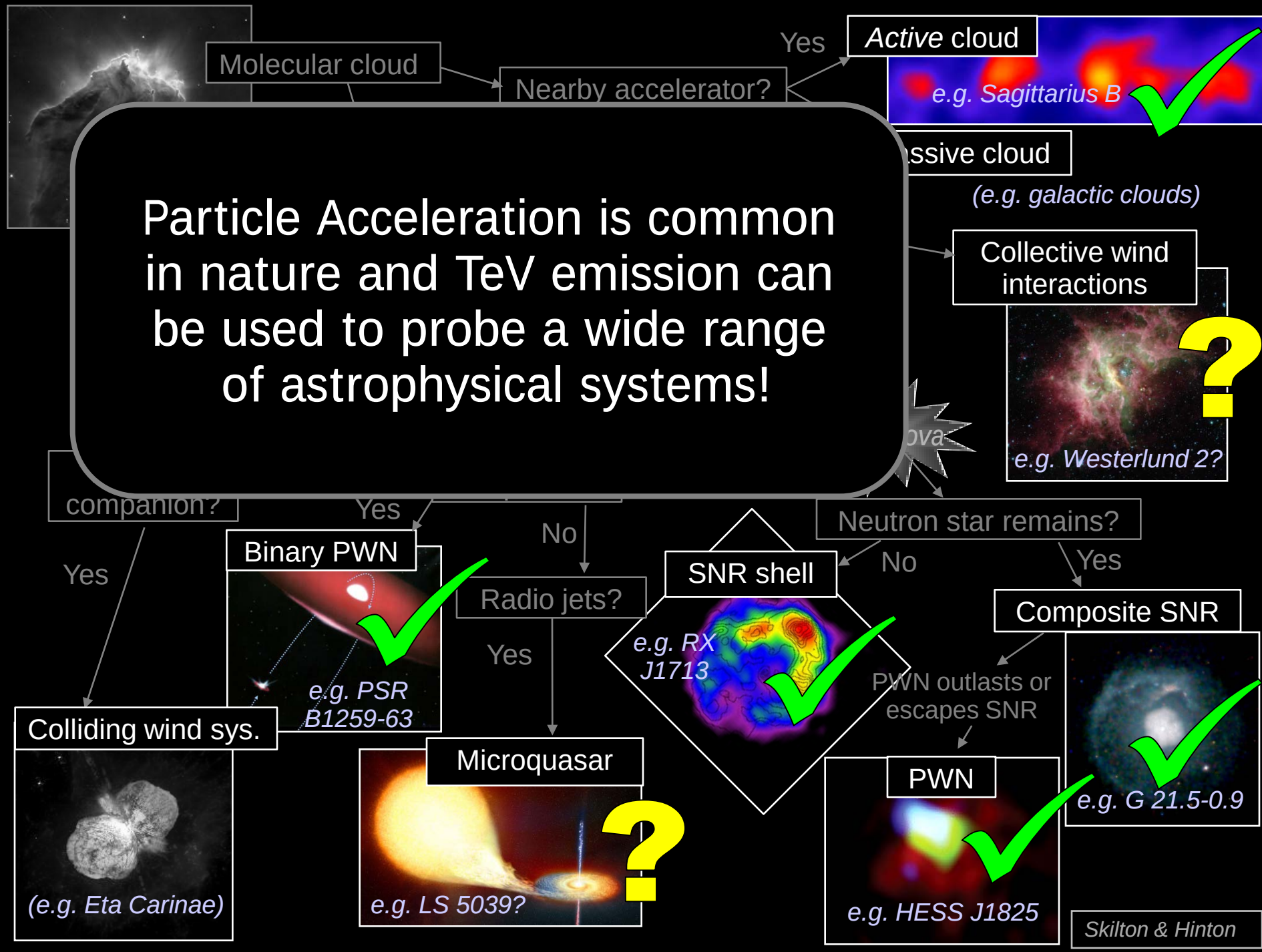
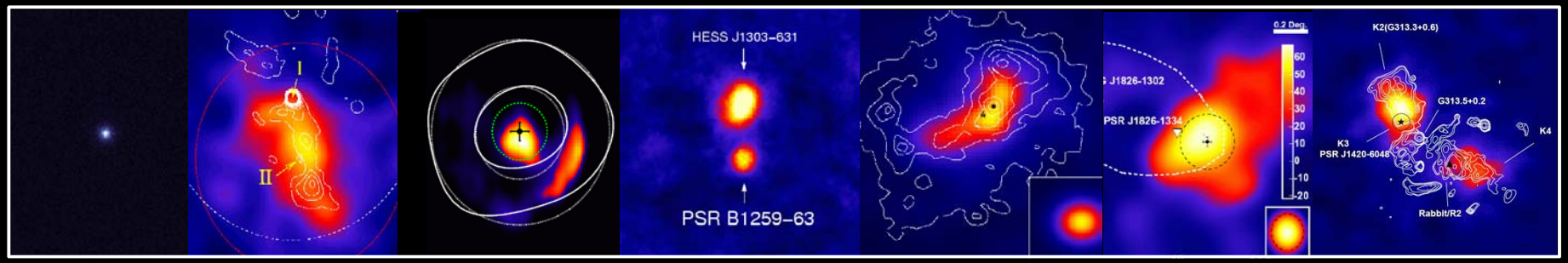


Particle Acceleration is common in nature and TeV emission can be used to probe a wide range of astrophysical systems!

TeV Pulsar Wind Nebulae



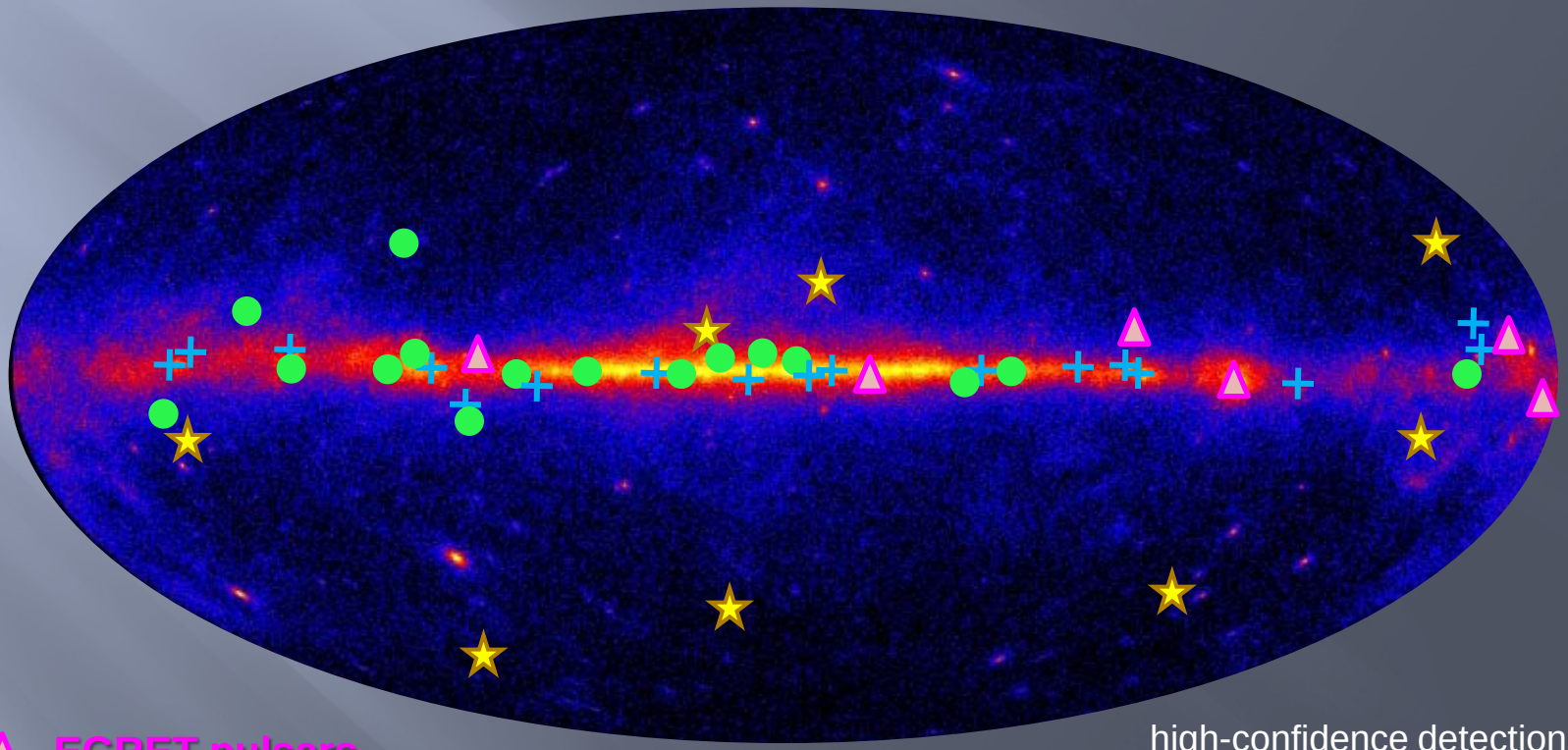
- **Many known X-ray PWN now identified as TeV emitters and almost all of the highest spin-down power radio pulsars have associated TeV emission**
  - **Efficient particle accelerators**
- **May be easier to detect in TeV than keV ?**
  - **Integration over pulsar lifetime for TeV electrons (less cooling)**
  - **TeV instruments sensitive to more extended objects**
  - **no confusion with thermal emission**
  - **Many of our unidentified sources may be PWN**

What powers TeV PWN? Fermi Pulsars!

31 gamma-ray and radio pulsars (including 8 msPSRs)

16 gamma-ray only pulsars

Pulses at ~1/10th real rate



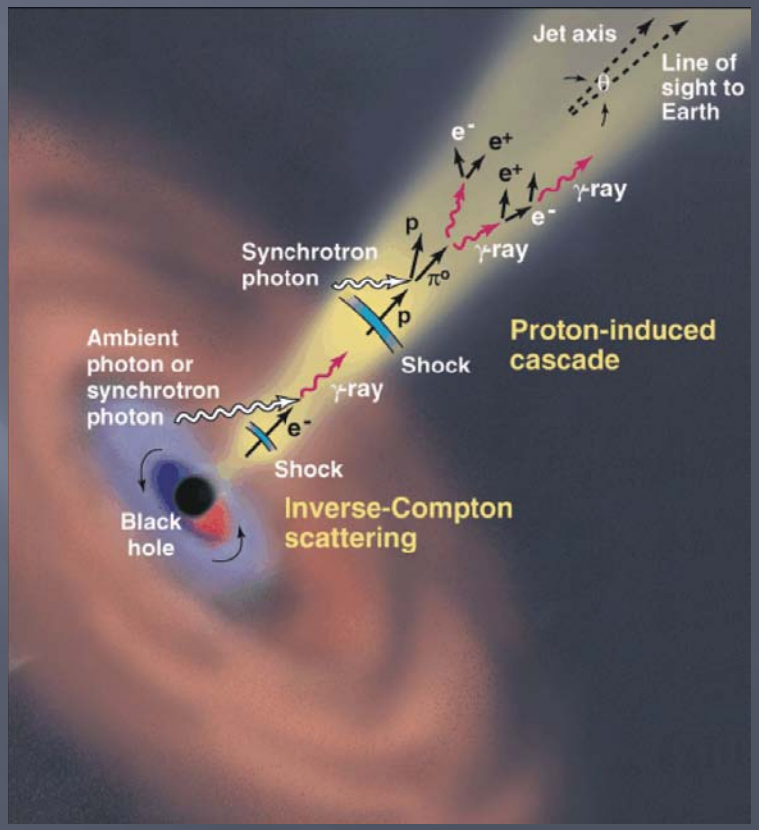
high-confidence detections from 1st six month Fermi operations

- ▲ **EGRET pulsars**
- + **young pulsars discovered using radio ephemeris**
- ● **pulsars discovered in blind search**
- ★ **millisecond pulsars discovered using radio ephemeris**

Blazars: Key Questions

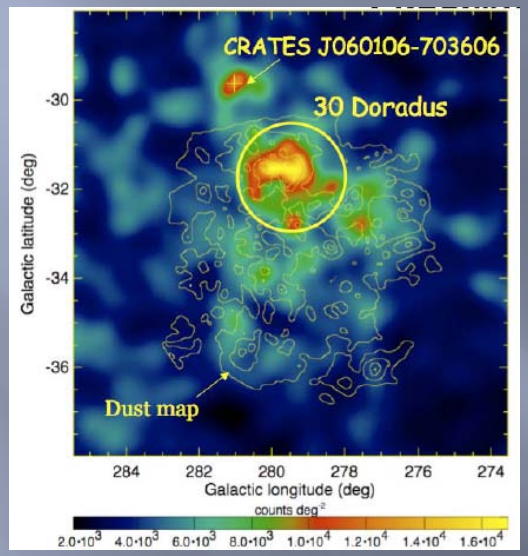
Fermi's dominant source class, but regarding CRs…

- Emission mechanisms unclear (particularly for high energy component)
  - leptonic (IC of synchrotron or external photons)
  - hadronic ($\pi_0 \rightarrow \gamma\gamma$, proton synchrotron)
- Emission location unclear
  - Single zone for all wavebands (completely constraining for simplest leptonic models)
  - Opacity effects and energy-dependent photospheres
- Jet composition unclear
  - Poynting flux, leptonic, ions
- Jet confinement unclear
  - External pressure, magnetic stresses
- Effect of blazar emission on host galaxies and galaxy clusters



Starformation & Cosmic Rays – YES!

30 Dor in LMC by Fermi



M82 by VERITAS

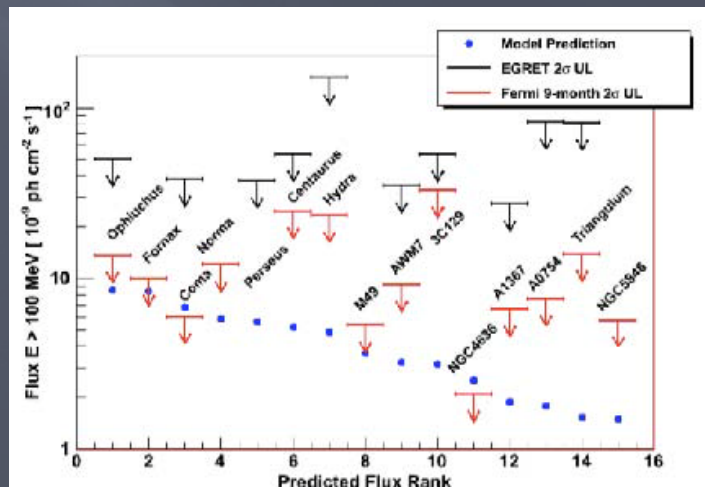
NGC253 By HESS

Galaxy clusters – CR calorimeter?

- CR storage over cosmological time scales;
- CRs, AGN and DM annihilate

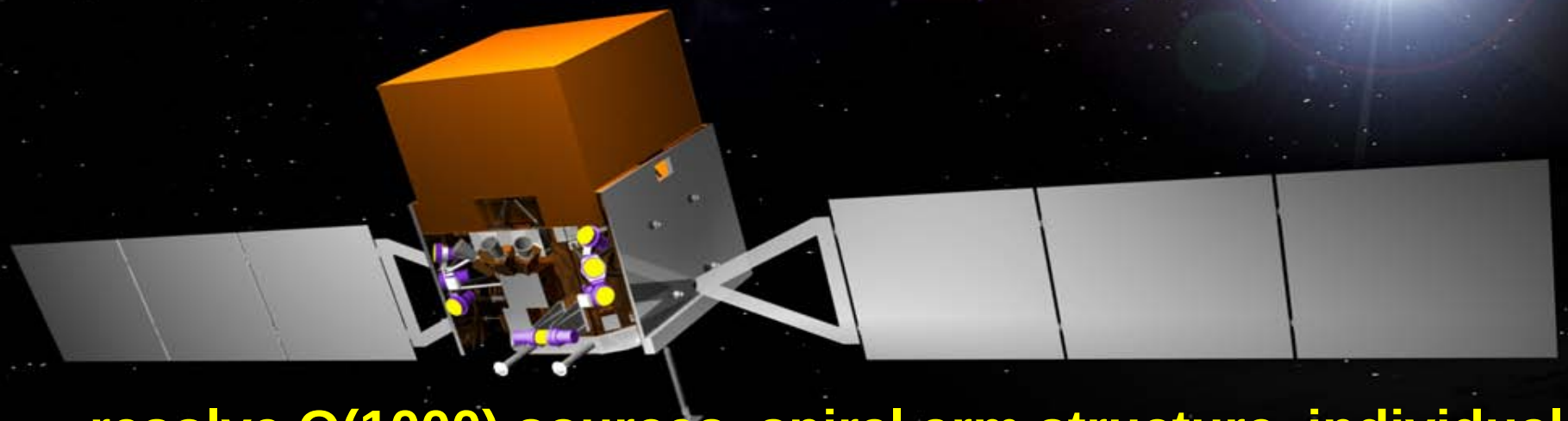
No easy pick for gamma-ray astronomy,

…still upper limits:



Outlook for the photon messenger

→ Fermi continues measuring the GeV sky with unprecedented quality



→ resolve O(1000) sources, spiral arm structure, individual molecular clouds, local group galaxies, continues indirect DM searches …

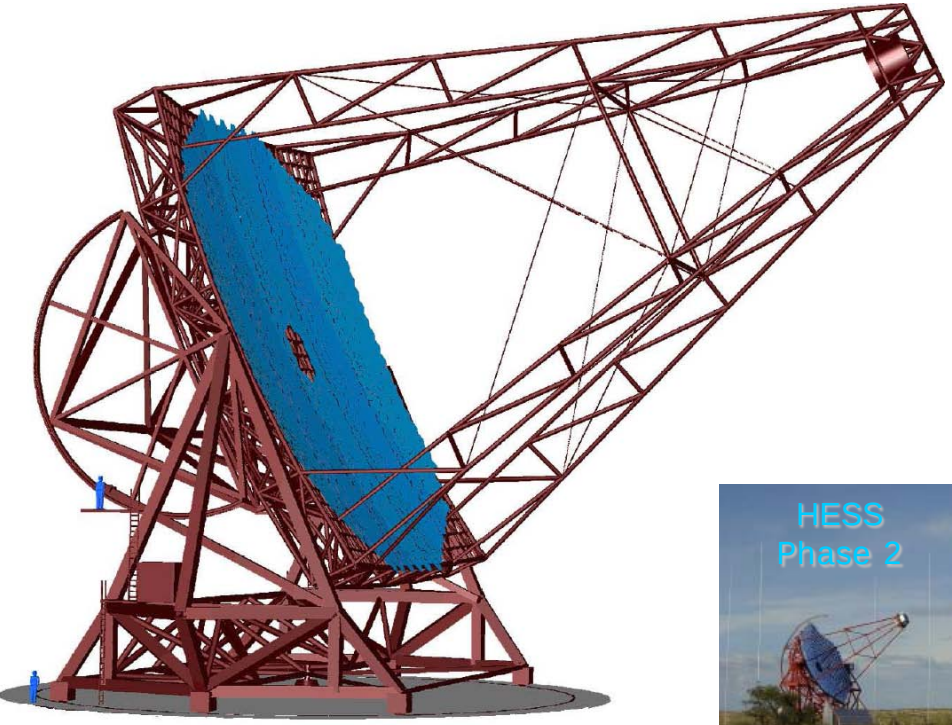
Quo vadis, European γ-ray astroparticle physics?

Completing major upgrades in current Cherenkov experiments!

MAGIC: 2nd telescope up → stereoscopy to overcome background at E_{thres}

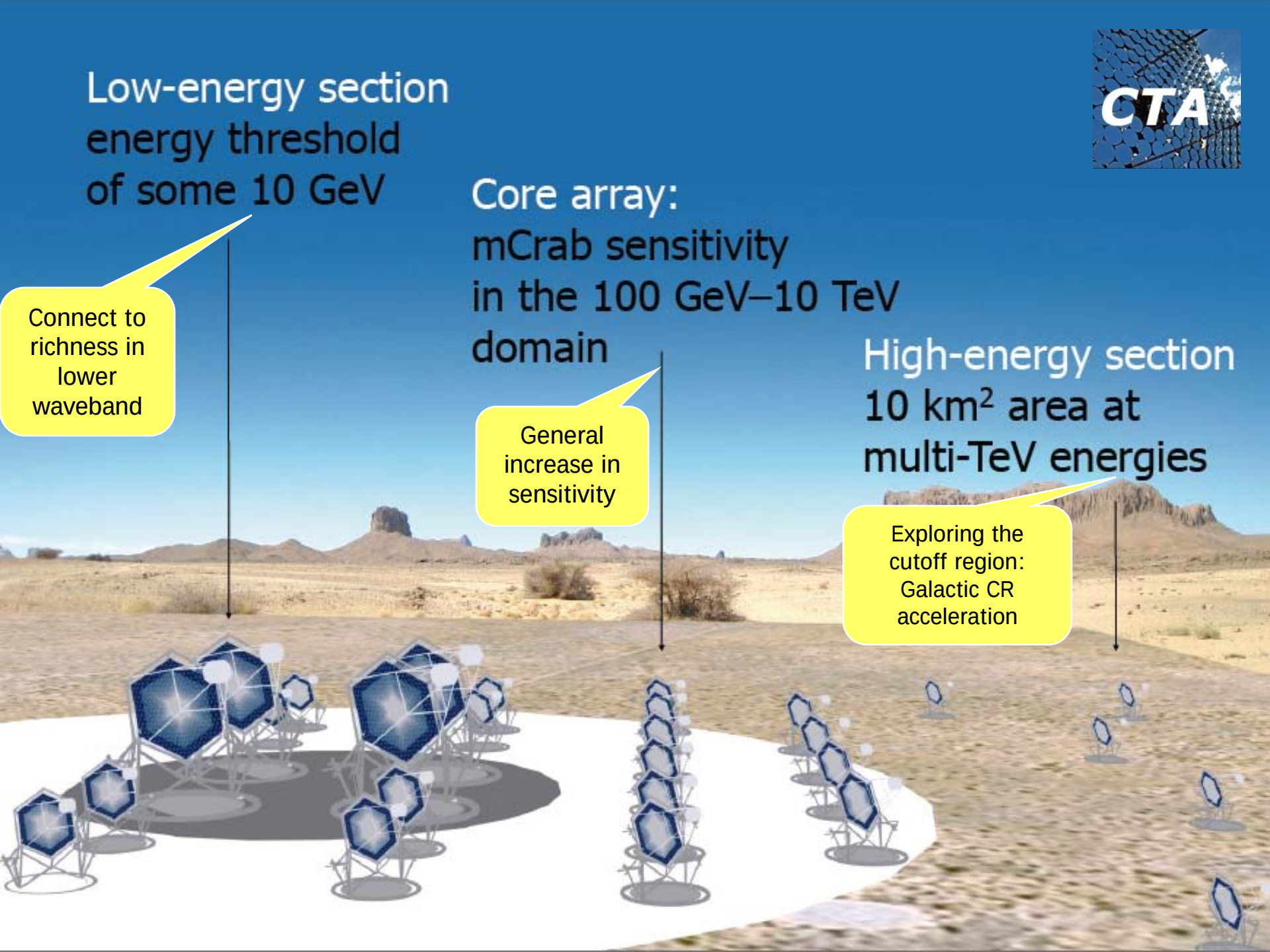
H.E.S.S.: Large center telescope → increase A_{eff} + lower E_{thres}

advanced photodetectors for a next generation camera

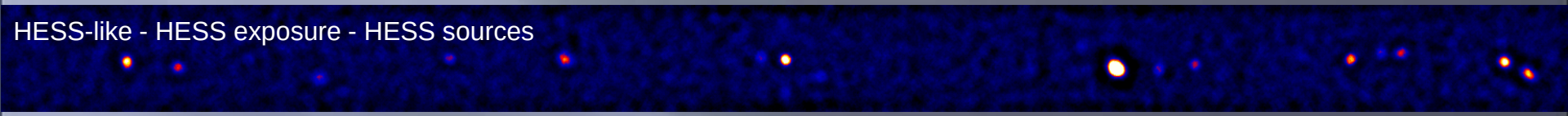


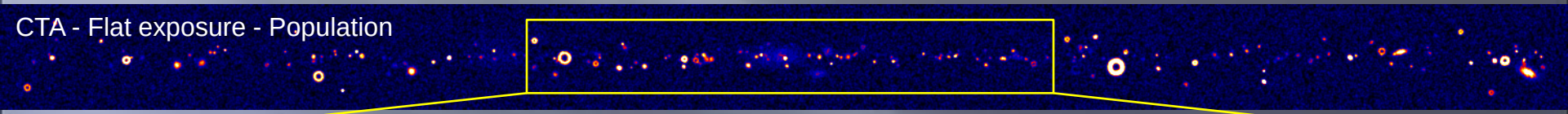
Quo vadis, European γ-ray astroparticle physics?

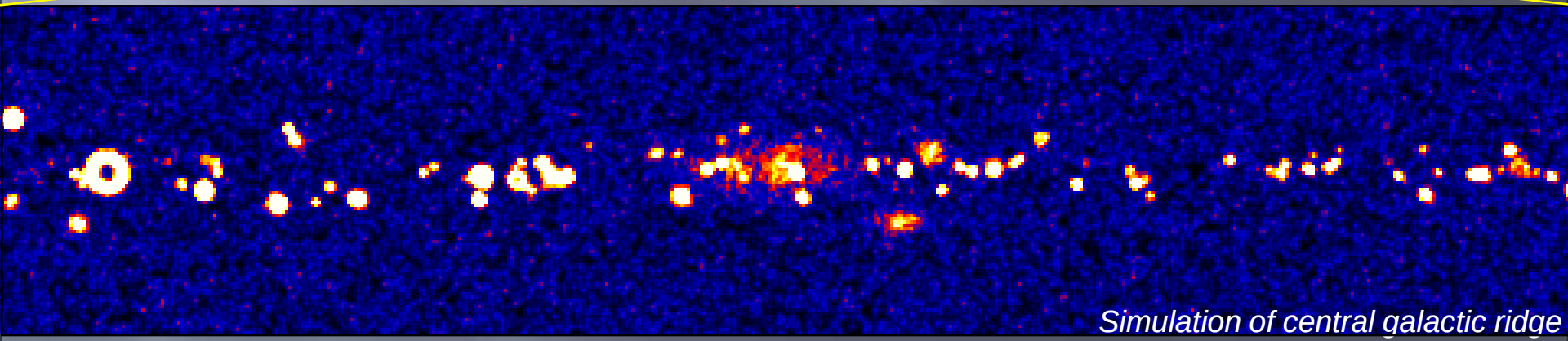
- **The field has matured, thus thrust towards a Cherenkov <u>observatory</u>**
- **Merger of MAGIC + HESS + large number of additional collaborators**
- **Currently in the process of optimising design parameters for array based on MC simulations**
- **Formed collaboration, elected spokesperson**
- **Part of the ASPERA and ESFRI roadmaps**
- **Aim to build a prototype by 2012**


Low-energy section
energy threshold
of some 10 GeV
Connect to richness in lower waveband
Core array:
mCrab sensitivity
in the 100 GeV–10 TeV domain
General increase in sensitivity
High-energy section
10 km² area at
multi-TeV energies
Exploring the cutoff region: Galactic CR acceleration
CTA

A CTA view of the Galaxy?







Simulation of central galactic ridge
by Digel, Funk & Hinton