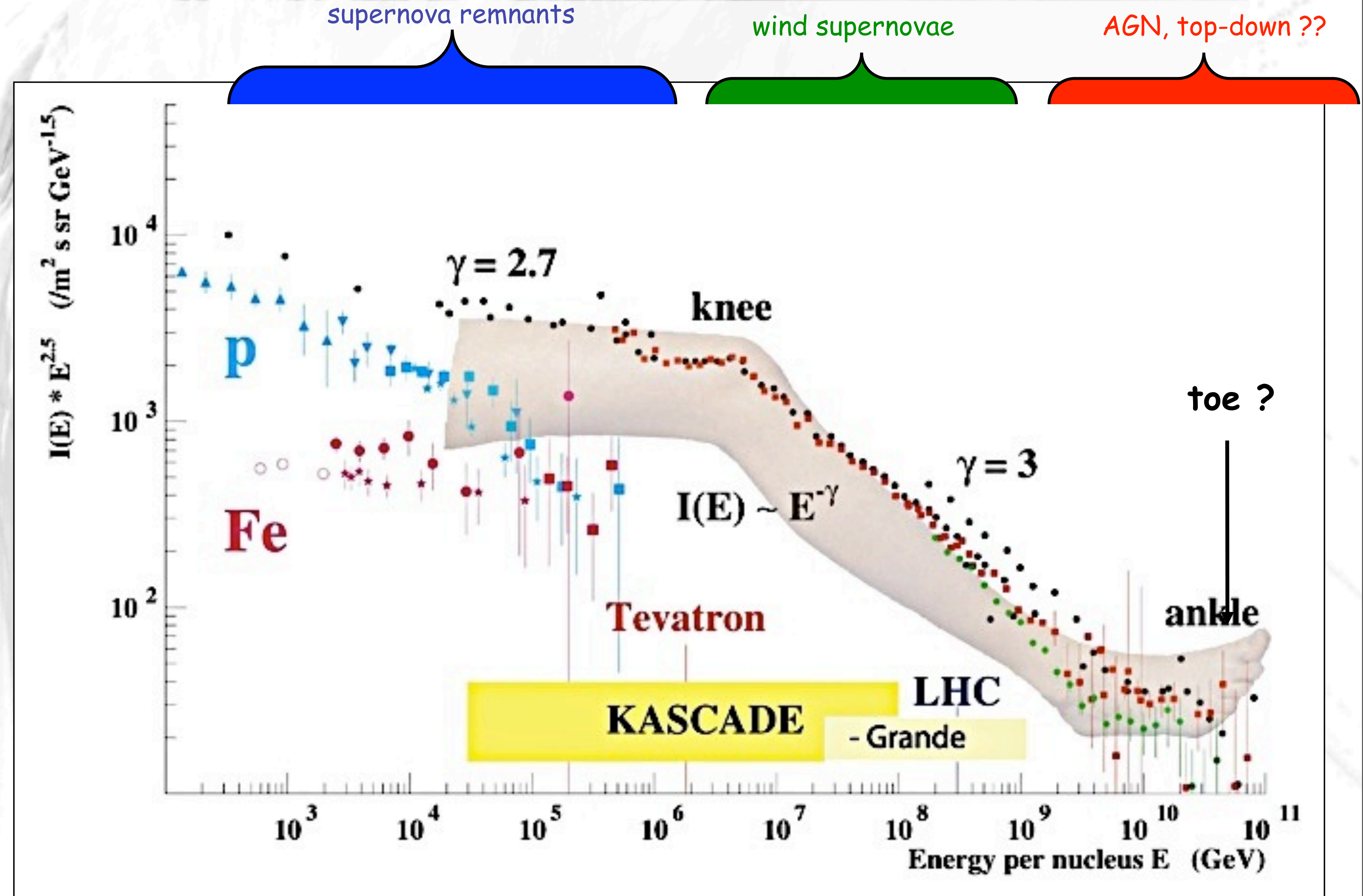
Astroparticle Physics with Multiple Messengers

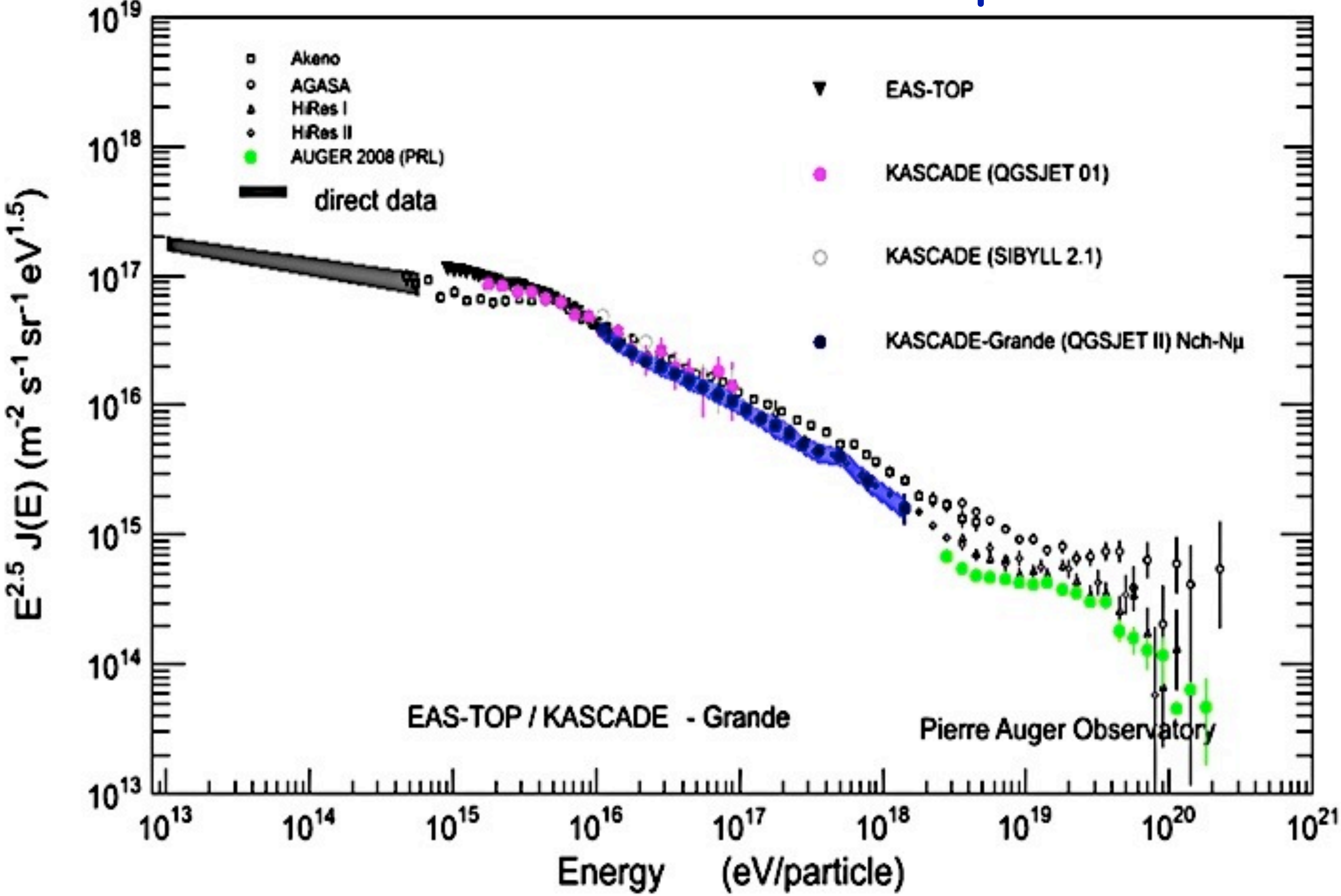
- Cosmic radiation from our Galaxy
- Extragalactic Cosmic Radiation
- Open Questions: Nature of the sources, chemical composition
- Role of cosmic magnetic fields
- Ultra-High Energy Cosmic Rays and secondary γ-rays and neutrinos: Constraints and detection prospects with different experiments.
- Testing physics beyond the Standard Model: Cross sections at PeV scales, Lorentz symmetry violation

Günter Sigl
II. Institut theoretische Physik, Universität Hamburg
http://www2.iap.fr/users/sigl/homepage.html

The structure of the spectrum and scenarios of its origin

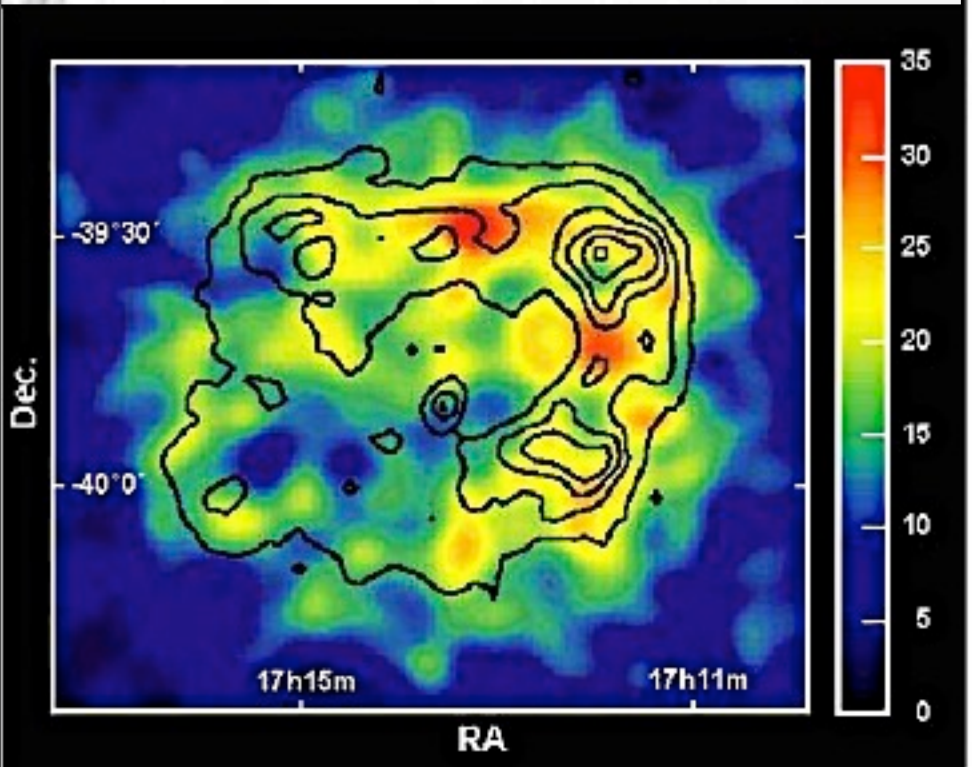


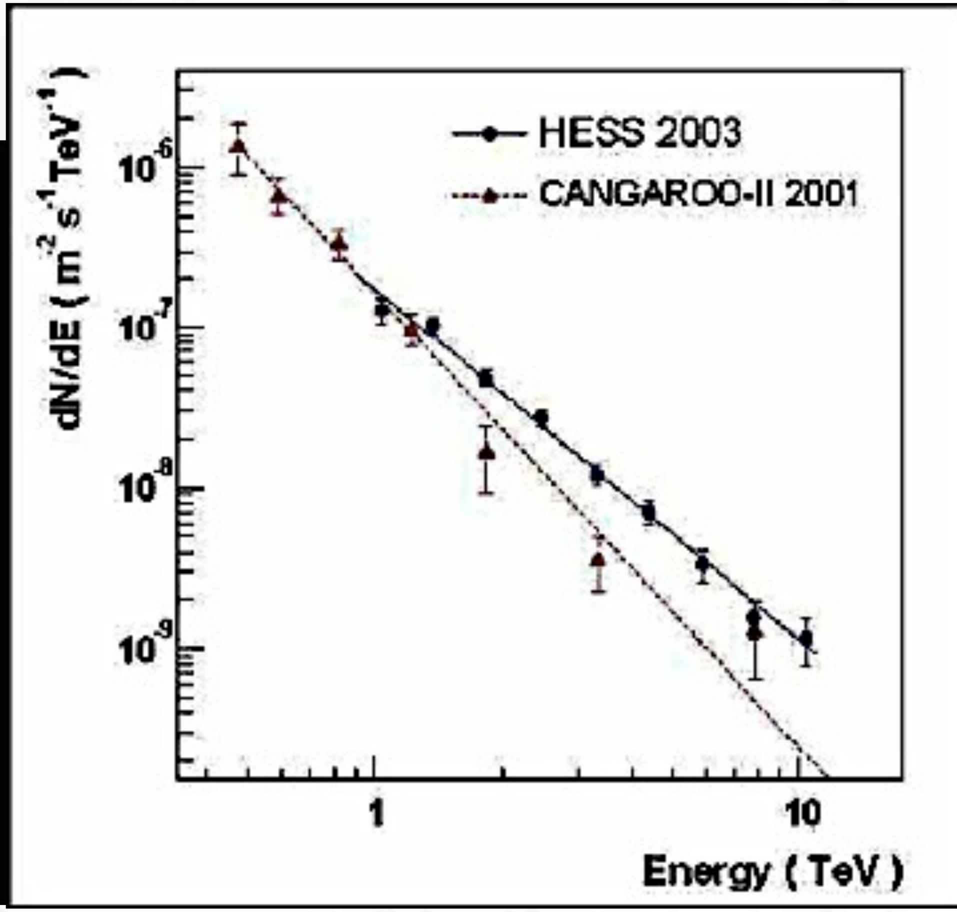
Another View of the All Particle Spectrum



KASCADE-Grande collaboration, arXiv:1009.4716

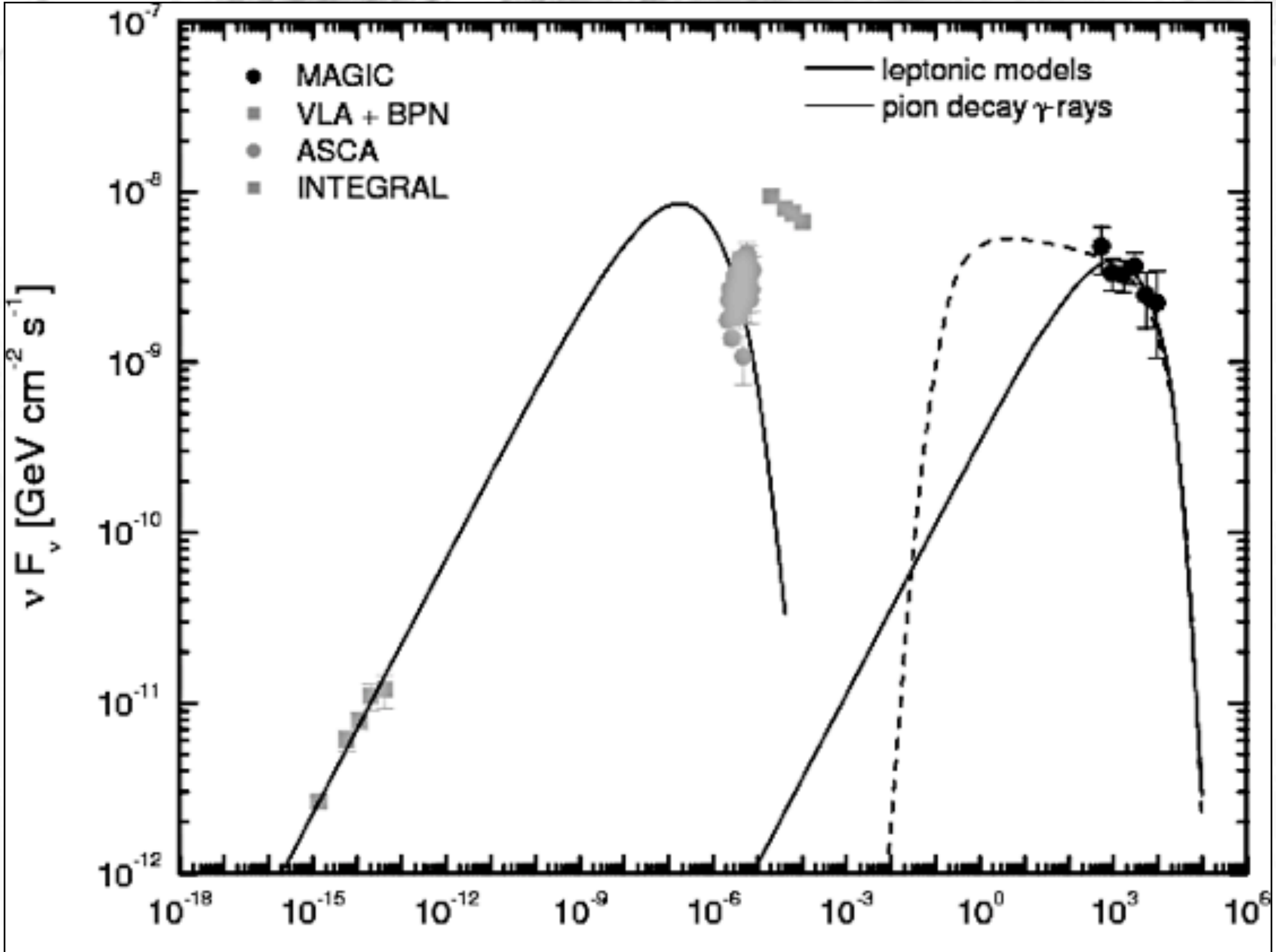
Supernova Remnants and Galactic Cosmic and γ-Rays





Aharonian et al., Nature 432 (2004) 75

Supernova remnants have been seen by HESS in γ-rays: The remnant RXJ1713-3946 has a spectrum ~$E^{-2.2}$: => Charged particles have been accelerated to > 100 TeV. Also seen in 1-3 keV X-rays (contour lines from ASCA)

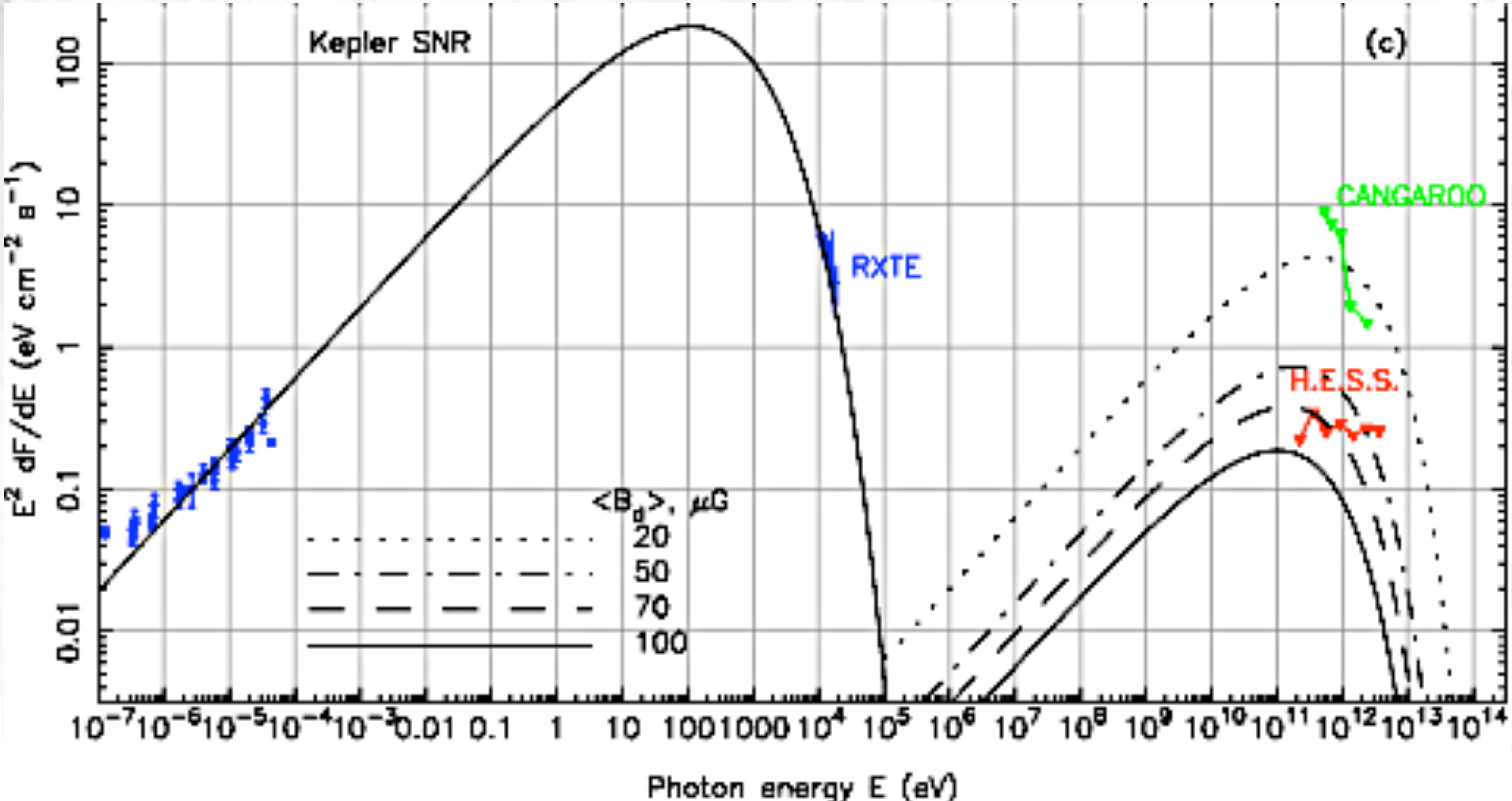


Albert et al., ApJ 637 (2006) L41

Hadronic versus leptonic model of SN remnant HESS J1813-178: both are still possible

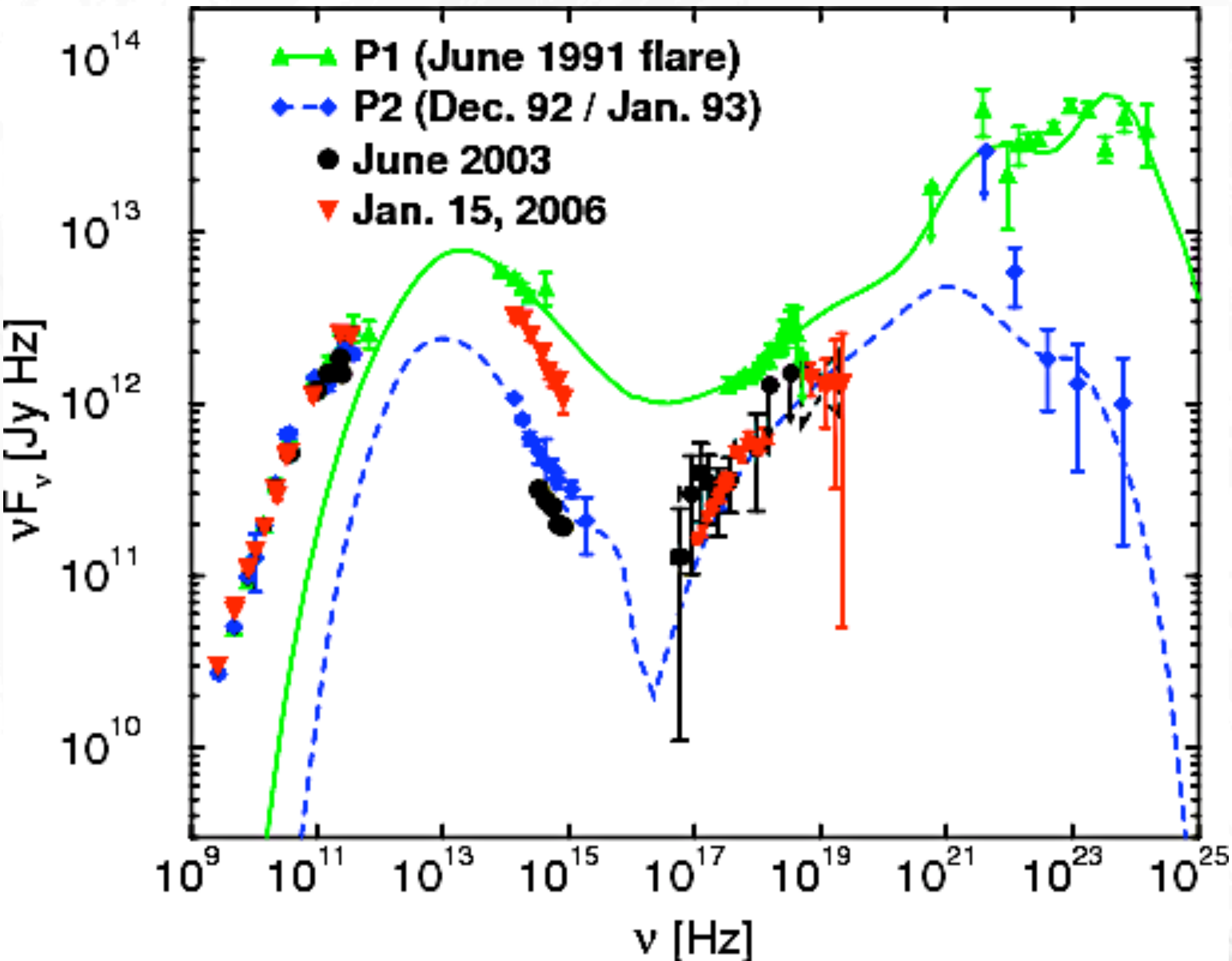
But in some supernova remnants the magnetic field needed to explain relative height of synchrotron and inverse Compton peak in the leptonic model would be too high:

$$\frac{P_{\text{synch}}}{P_{\text{IC}}} = \frac{u_B}{u_{\text{CMB+IR}}}$$

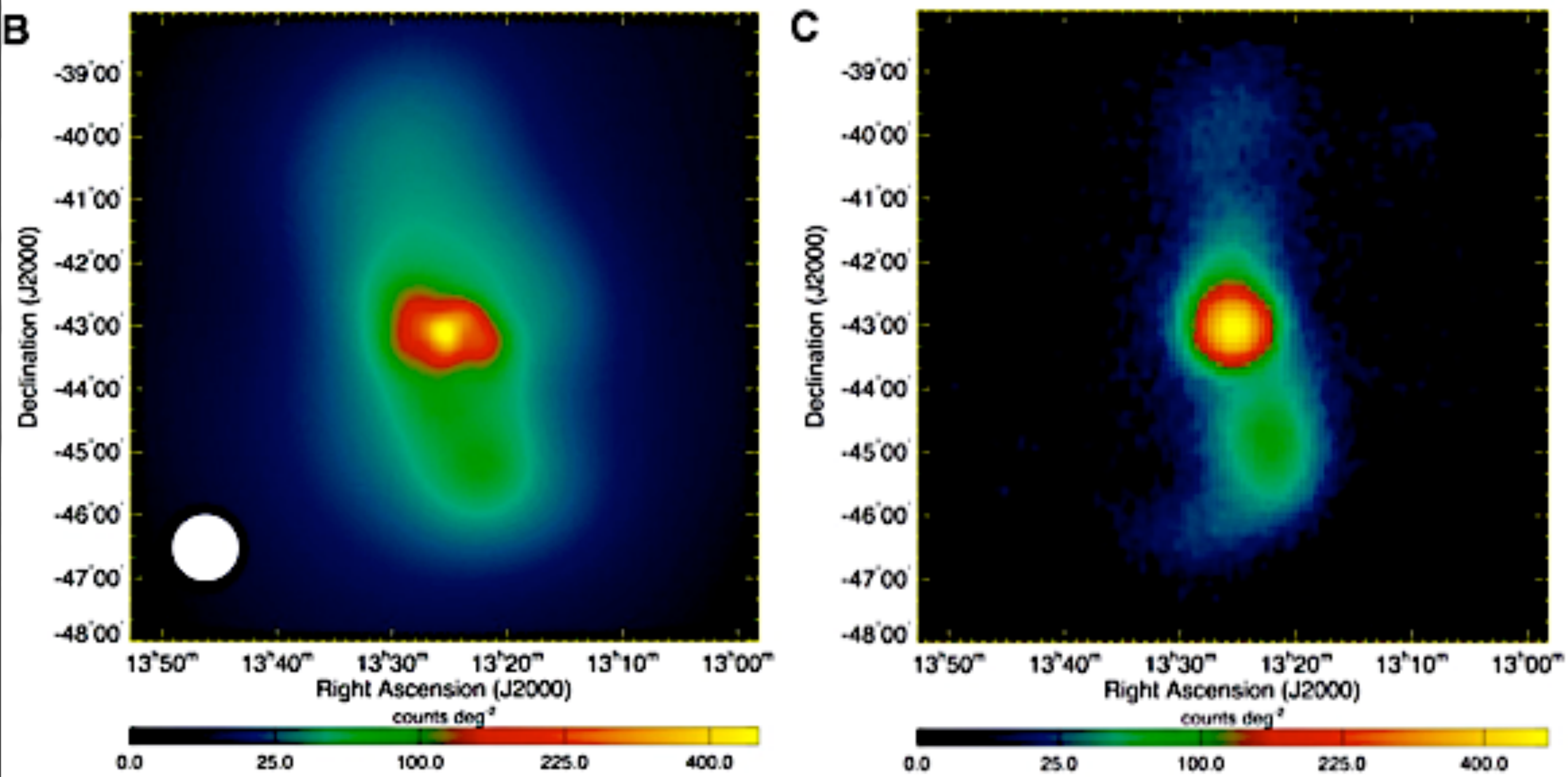


Voelk, Ksenofontov, Berezhko, arXiv:0809.2432

„double-humped" spectra are also typical for AGNs



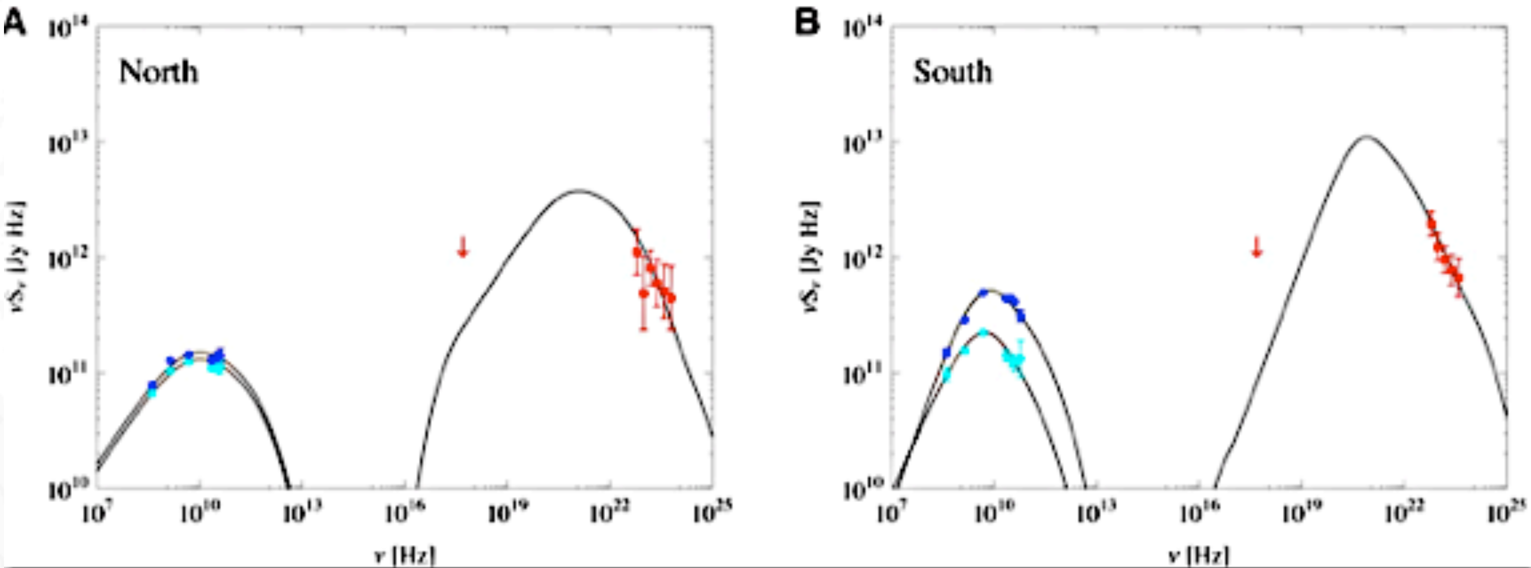
Latest example: Lobes of Centaurus A seen by Fermi-LAT

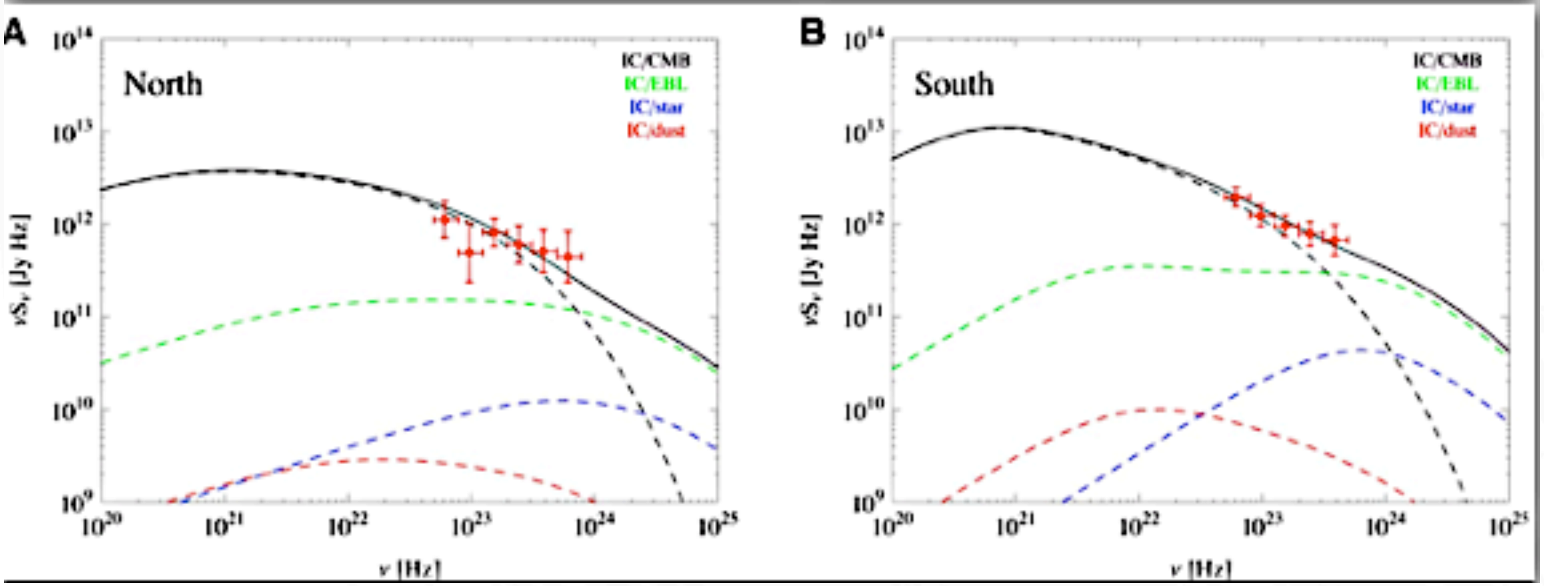


> 200 MeV γ-rays

Radio observations

Abdo et al., Science Express 1184656, April 1, 2010



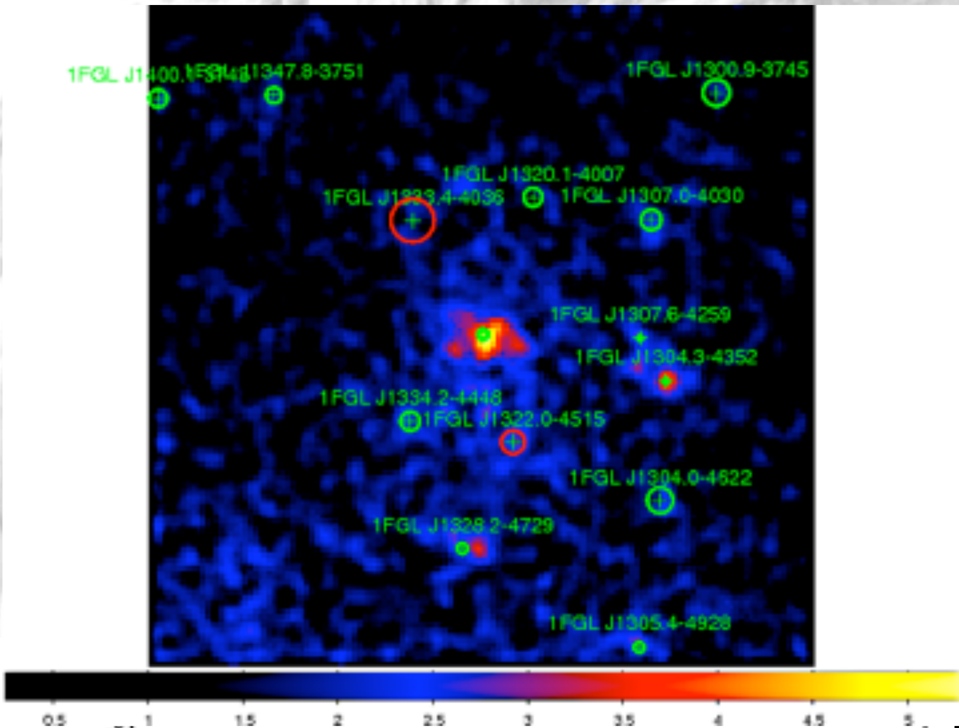


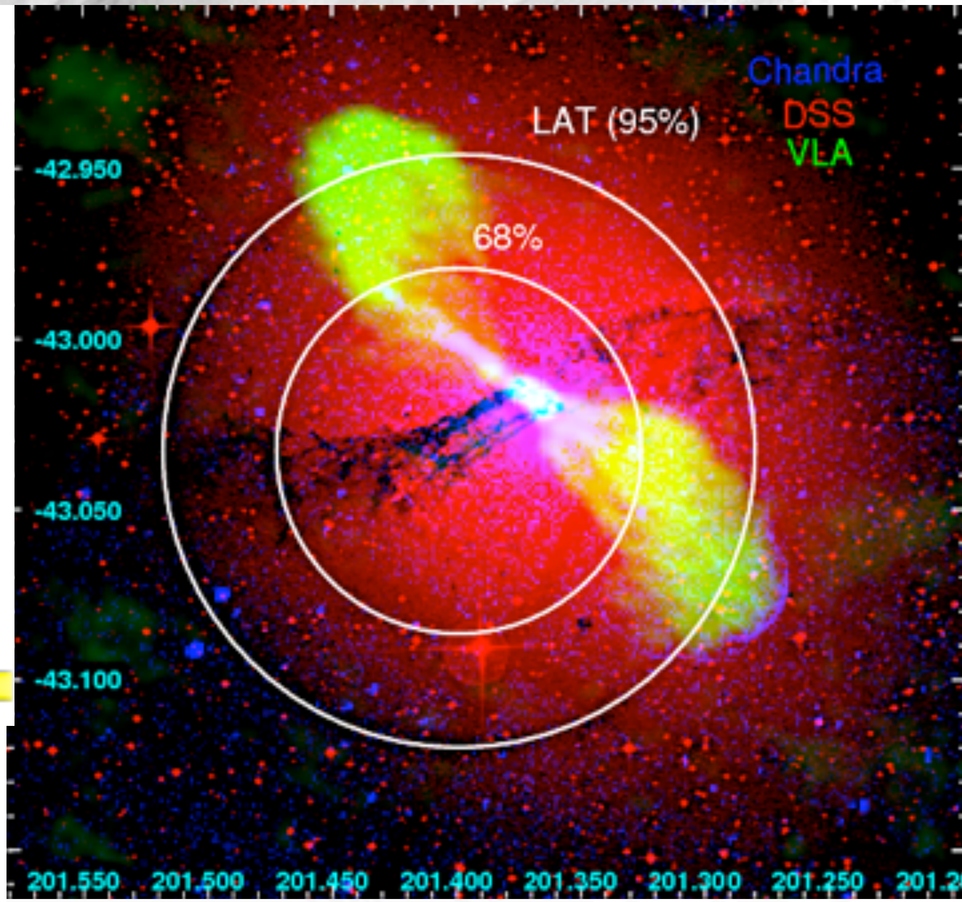
Low energy bump = synchrotron

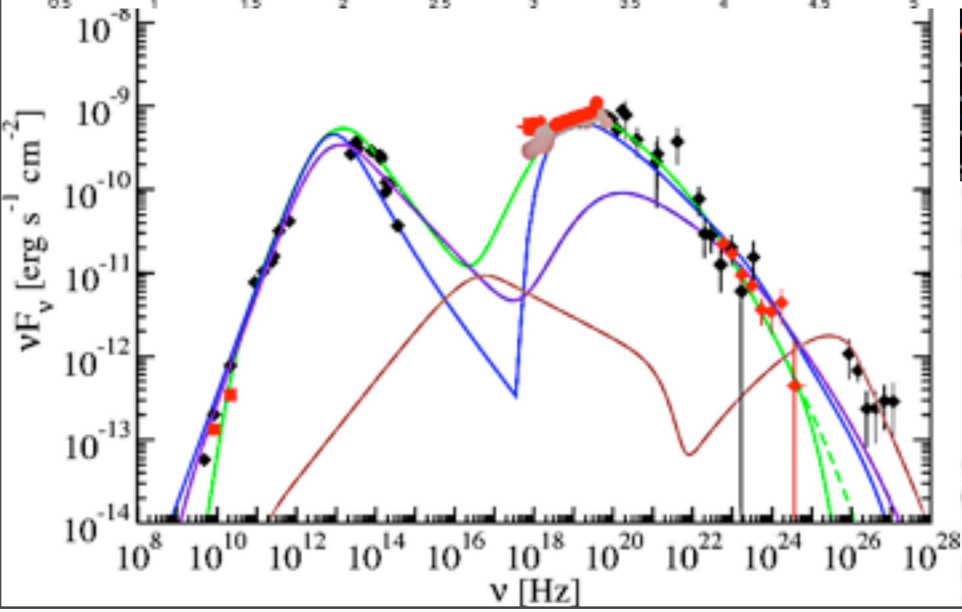
high energy bump = inverse Compton on CMB in ~0.85μG field

Abdo et al., Science Express 1184656, April 1, 2010

Core of Centaurus A seen by Fermi-LAT







Can be explained by synchrotron self Compton except for HESS observation

Abdo et al., (Fermi LAT collaboration), arXiv:1006.5463

Interactions of Hadronic primary cosmic rays

γ-rays can be produced by **pp -> ppπ^0 -> pp$\gamma\gamma$**

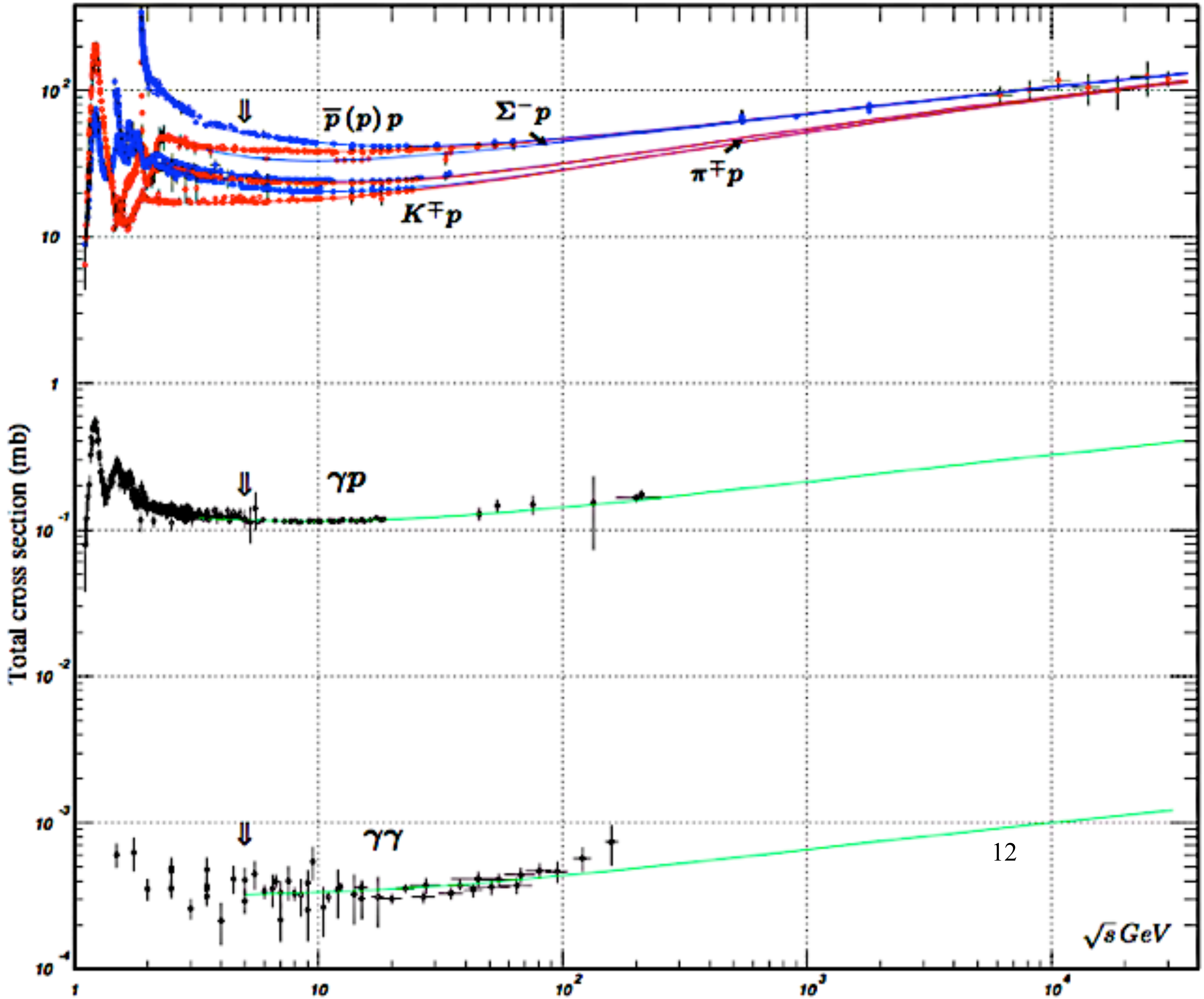
$$\sigma_{pp}(s) \simeq \left[35.49 + 0.307 \ln^2 \left(s/28.94\,\mathrm{GeV}^2\right)\right] \ \mathrm{mb}$$

This cross section is almost constant -> secondary spectra roughly the same shape as primary fluxes as long as meson cooling time is much larger than decay time.

γ-rays can also be produced by **pγ interactions:**

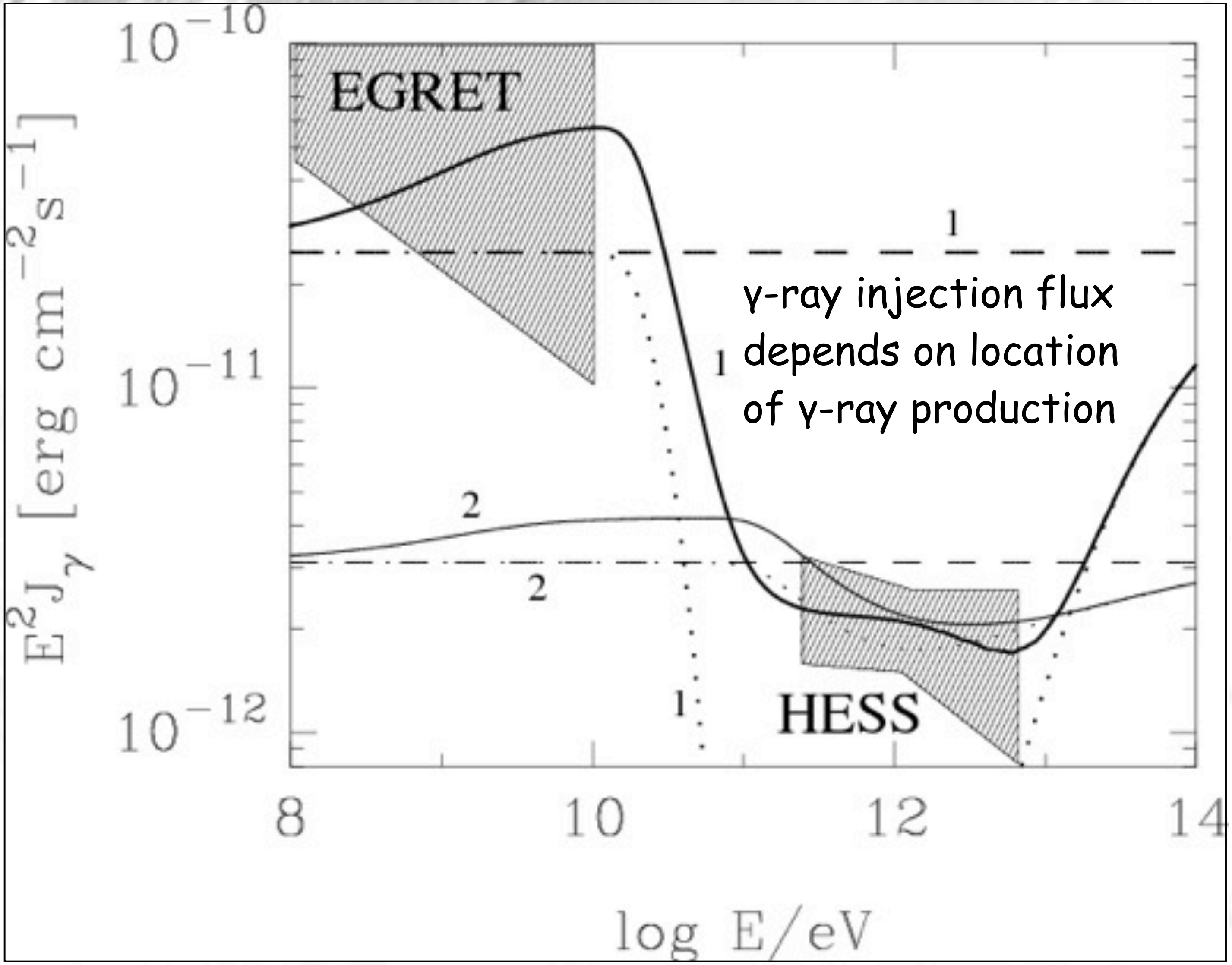
For sub-MeV photons the cross section has a threshold and is typically ~ 100 mb and weakly energy dependent at energies much above the threshold

=> Secondary neutrino flux also has a (very high energy) threshold above which it roughly follows the primary spectrum.


$\overline{p}\,(p)\,p$
$\Sigma^- p$
$\pi^{\mp} p$
$K^{\mp} p$
γp
$\gamma\gamma$
Total cross section (mb)
$\sqrt{s}$ GeV
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3
10^4

HESS sources: X-ray binary LS 5039

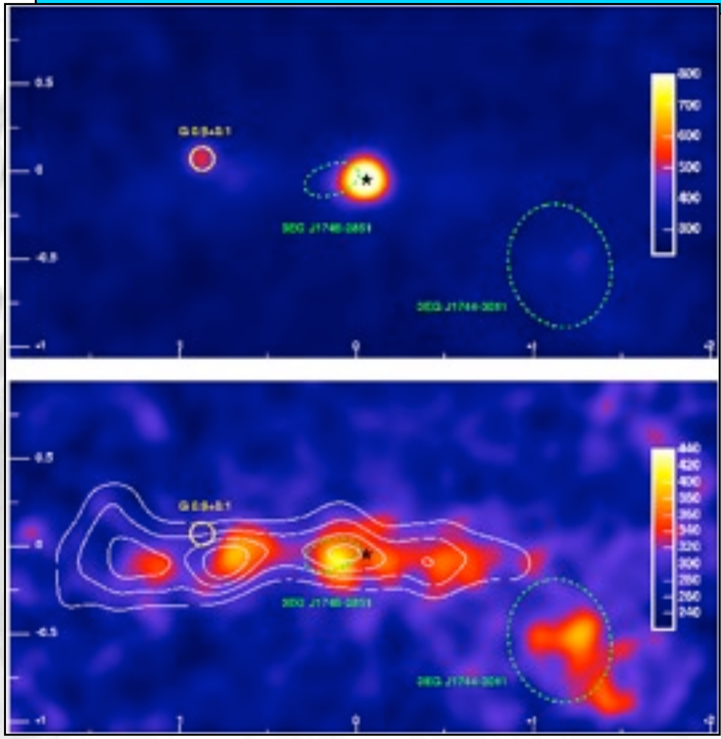
Secondary γ-rays and neutrinos mostly produced by pp interactions in this model



F.Aharonian et al., astro-ph/0508658

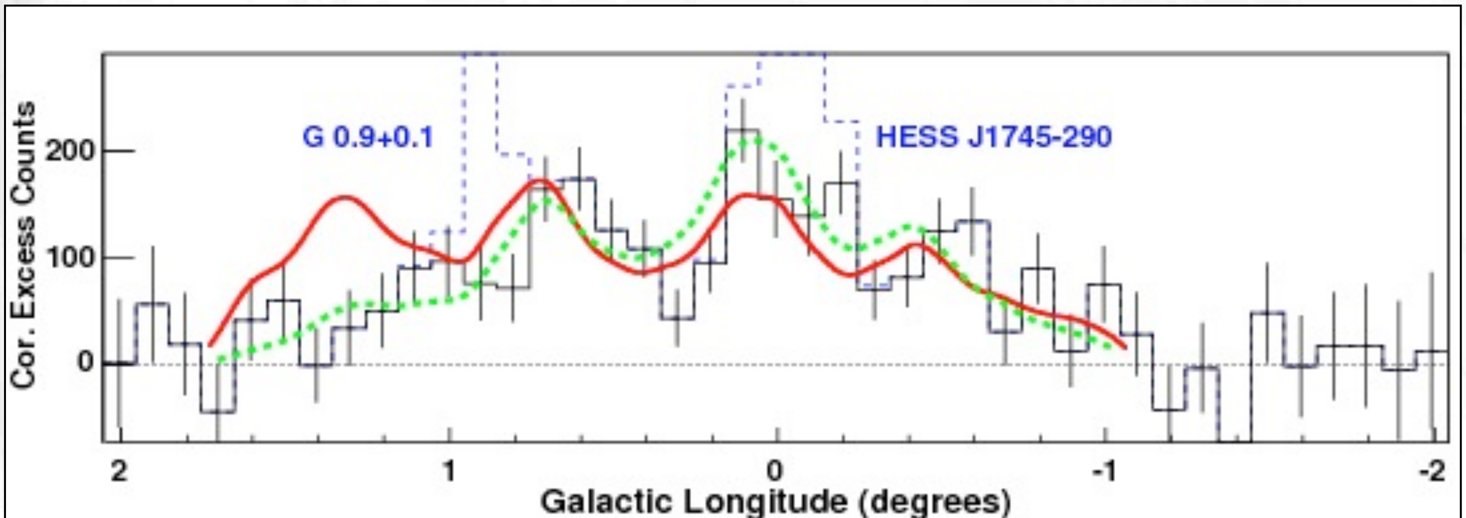
Expected neutrino fluxes above TeV ~10^{-9}-10^{-7} GeV cm^{-2}s^{-1}

Hadronic Interactions and Galactic Cosmic and γ-Rays

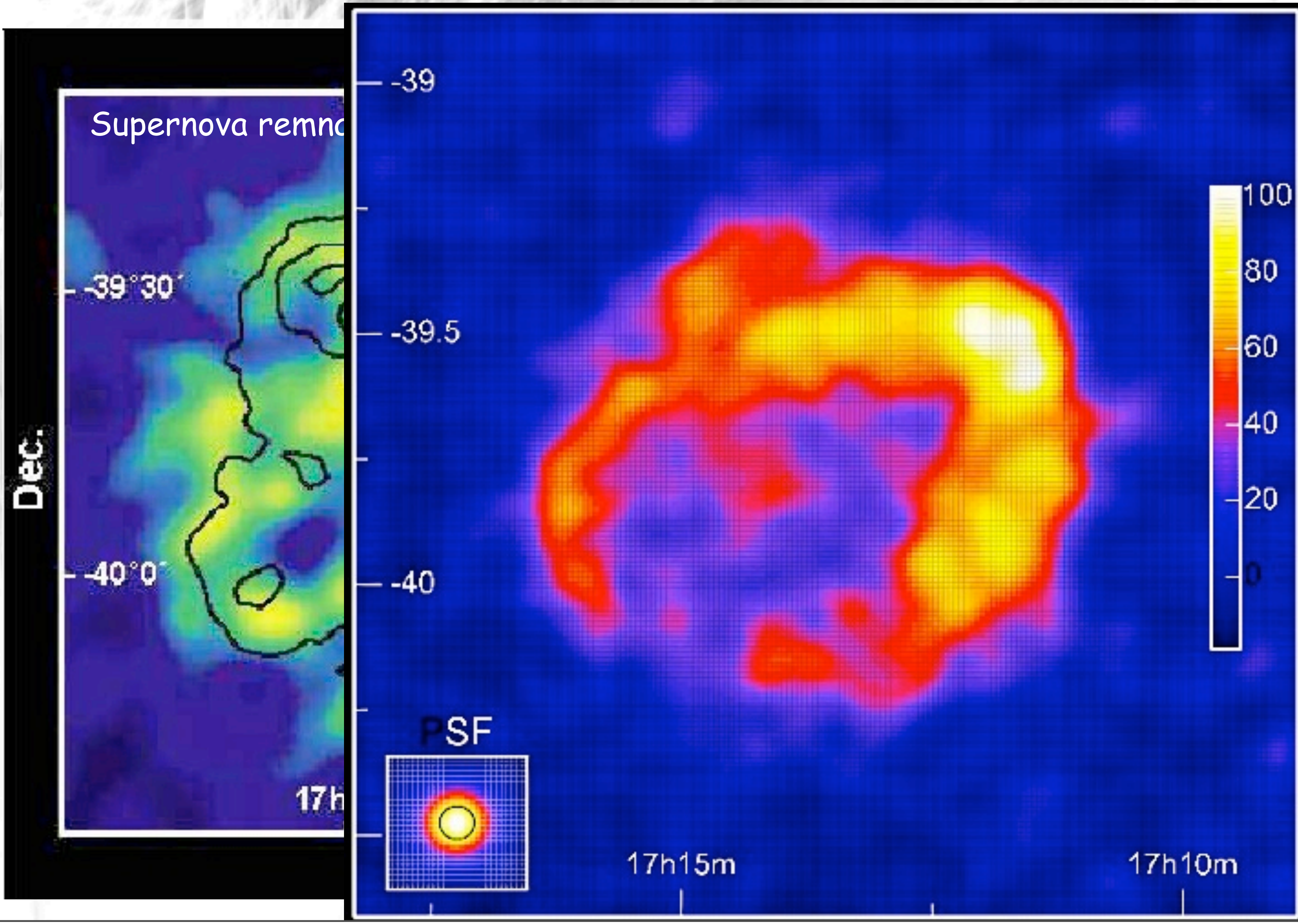


HESS has observed γ-rays from objects around the galactic centre which correlate well with the gas density in molecular clouds for a cosmic ray diffusion time of $T \sim R^2/D \sim 3\times10^3\ (\theta/1^o)^2/\eta$ years where $D = \eta\ 10^{30}\ cm^2/s$ is the diffusion coefficient for protons of a few TeV.

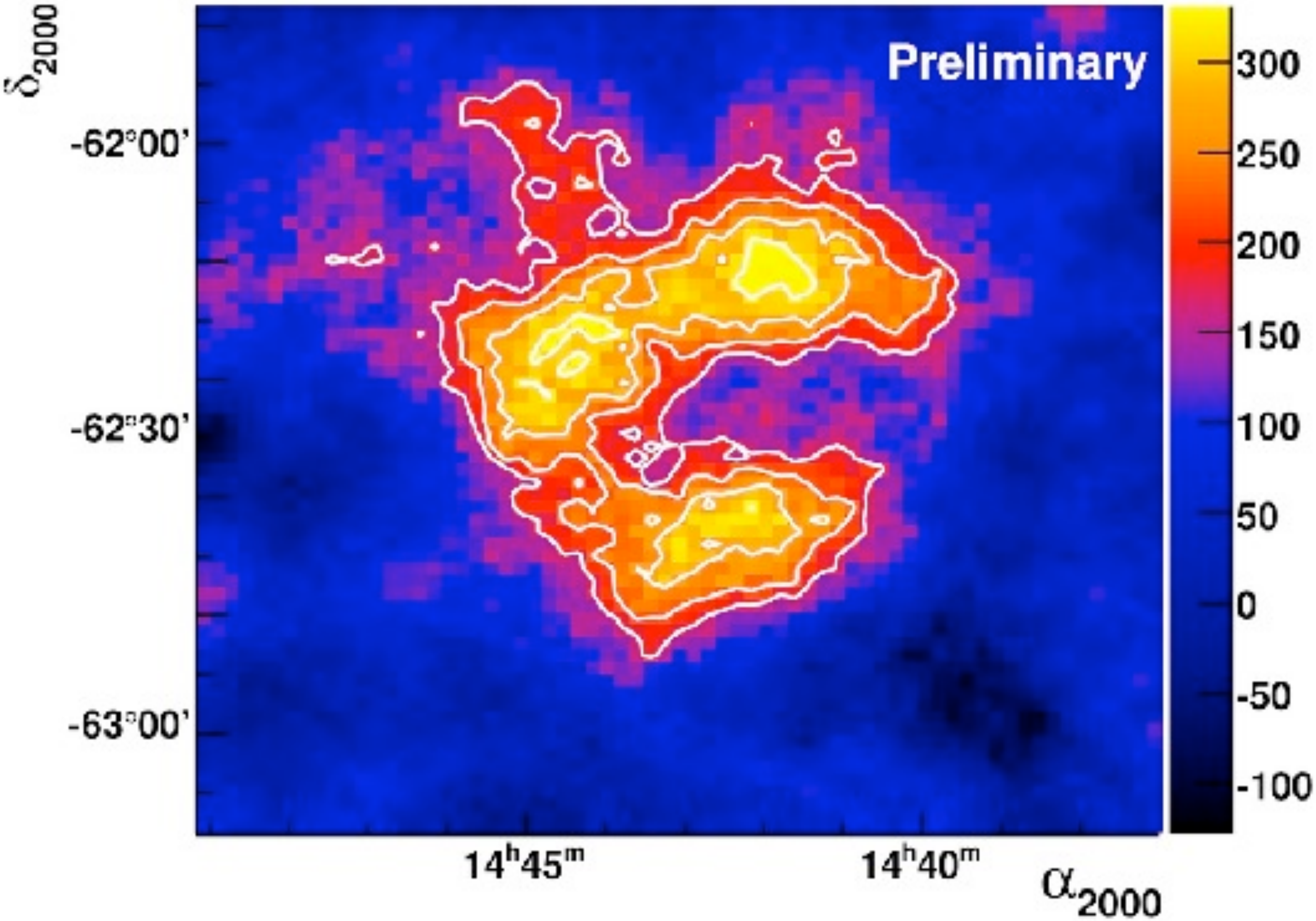
Aharonian et al., Nature 439 (2006) 695

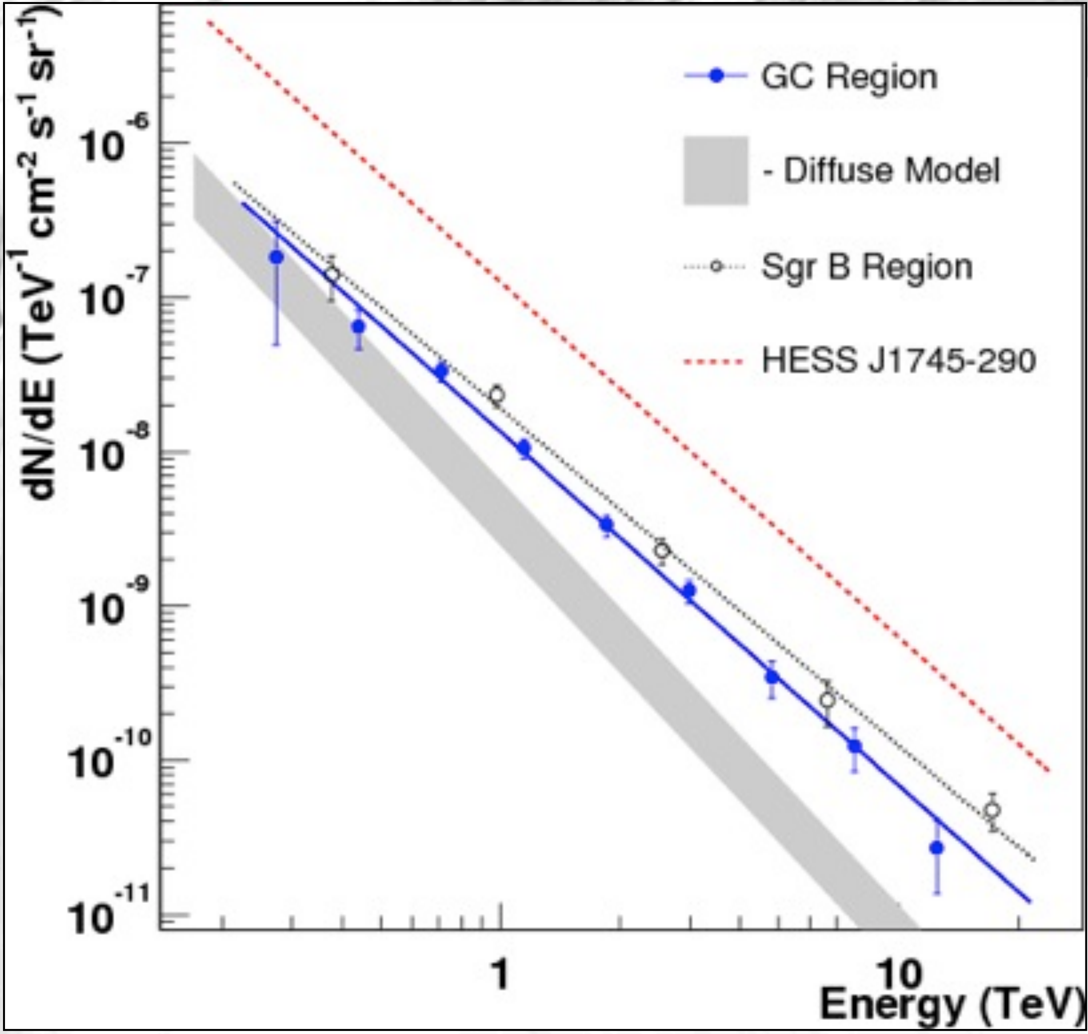


Identifying galactic sources from their secondary gamma-ray signatures



Shell-type supernova remnant RCW 86 seen by HESS

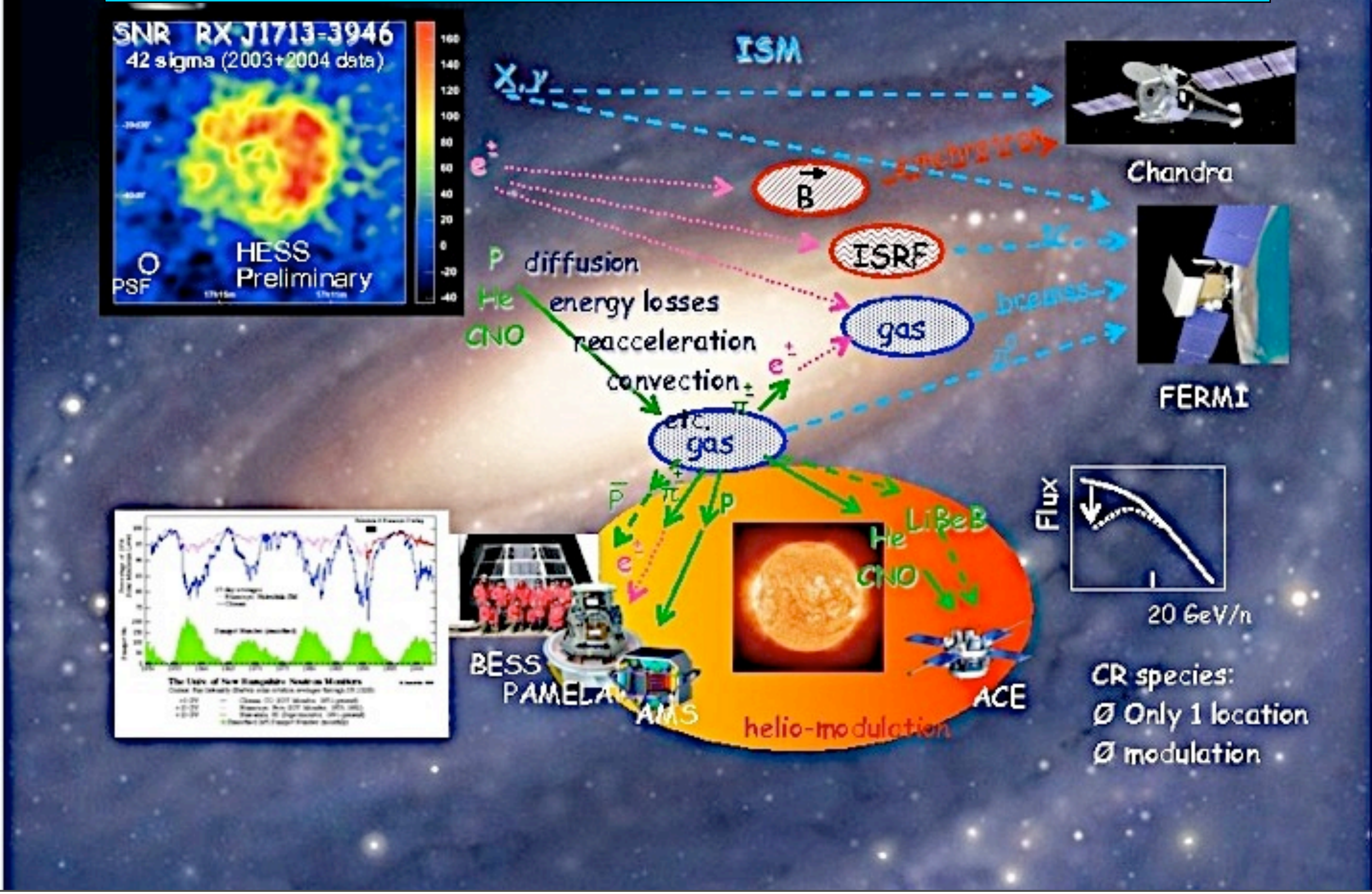




Given the observed spectrum $E^{-2.3}$, this can be interpreted as photons from π^0 decay produced in pp interactions where the TeV protons have the same spectrum and could have been produced in a SN event.

Note that this is consistent with the source spectrum both expected from shock acceleration theory and from the cosmic ray spectrum observed in the solar neighborhood, $E^{-2.7}$, corrected for diffusion in the galactic magnetic field, $j(E) \sim Q(E)/D(E)$.

Galactic Cosmic Ray Propagation and Signatures of Dark Matter Annihilation



Galactic Cosmic Ray Propagation

Galactic propagation is described by solving the diffusion-convection-energy loss equation:

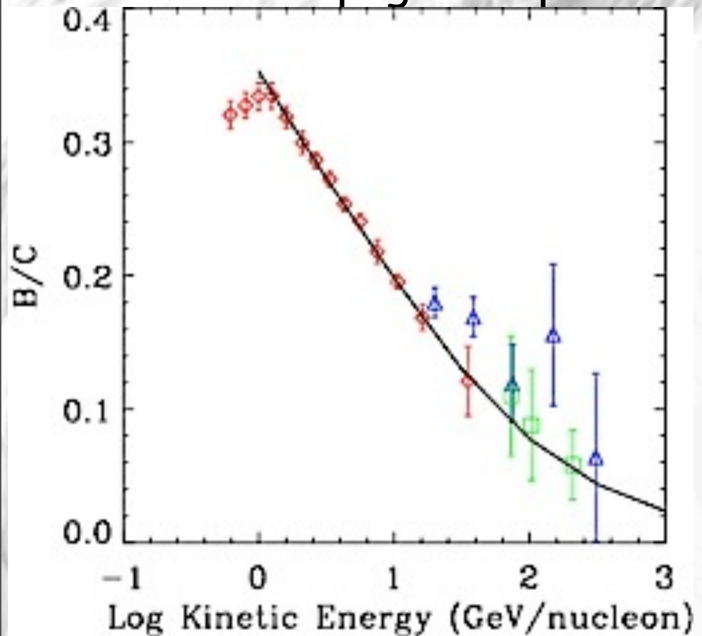
$$\partial_t n = \nabla \cdot (D_{xx} \nabla n - \mathbf{v_c}) + \partial_p \left(p^2 D_{pp} \partial_p \frac{n}{p^2} \right) - \partial_p \left[\dot{p}\, n - \frac{p}{3} (\nabla \cdot \mathbf{v_c} n) \right] + Q(\mathbf{r}, p)$$

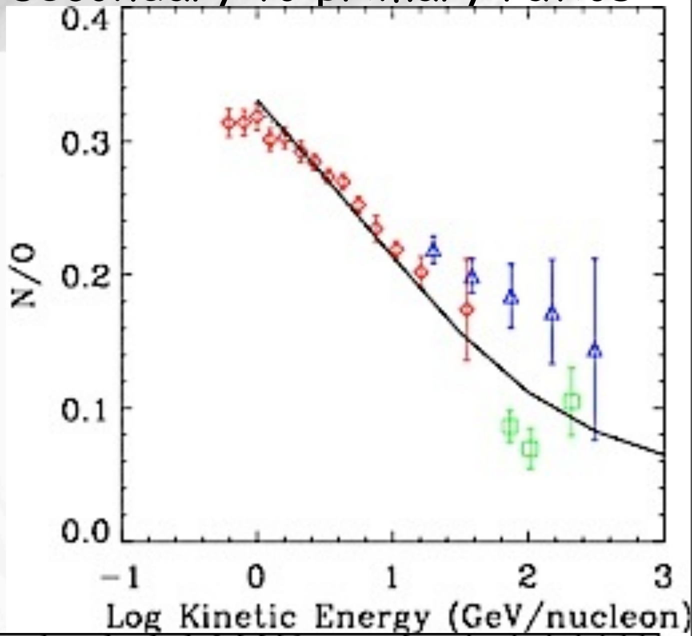
spatial diffusion | convection | reacceleration | energy loss | adiabatic compression/ expansion | source term

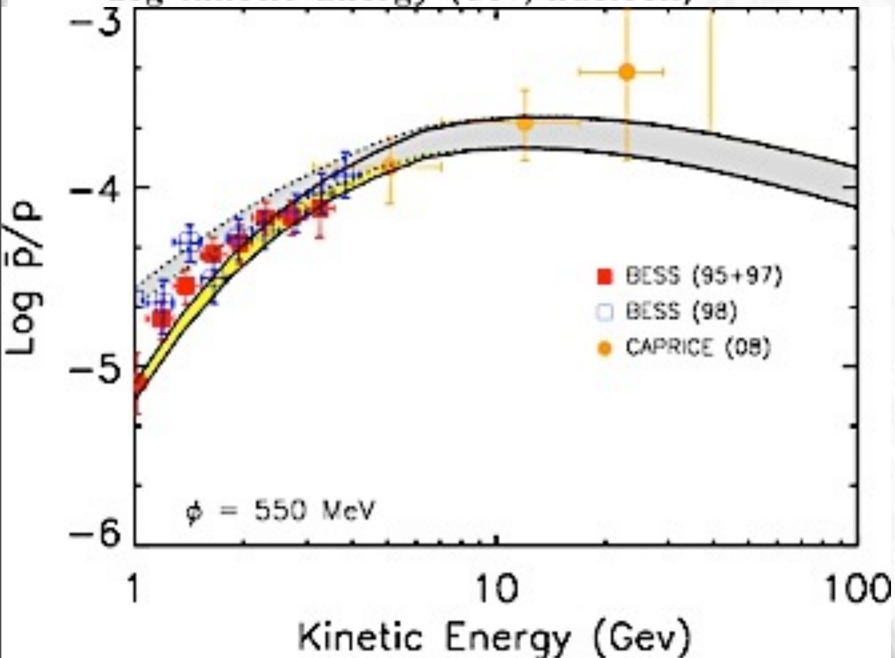
This equation is solved in a cylindrical slab geometry with suitable boundary Conditions.

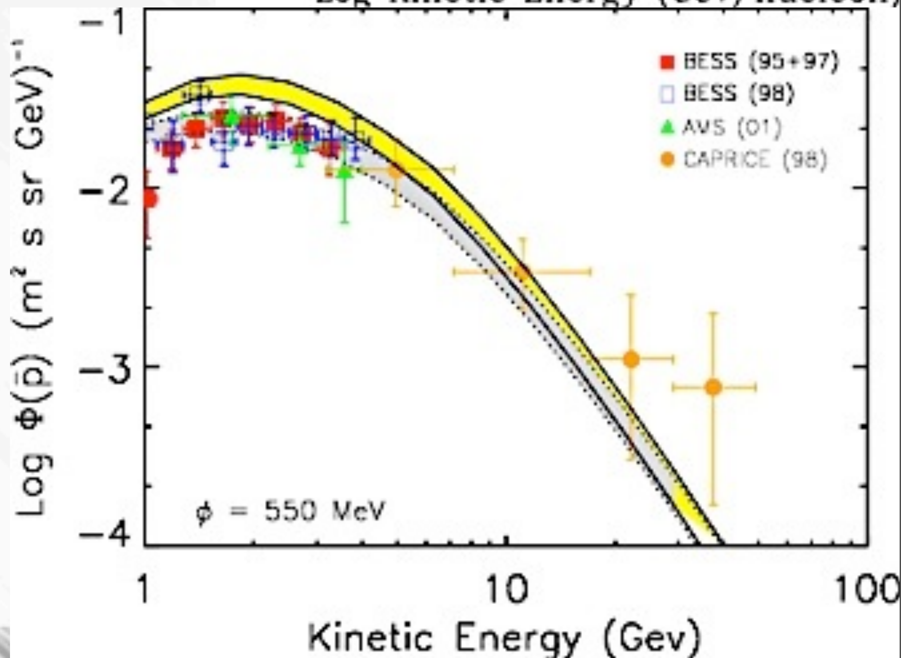
Out of the resulting electron/positron distribution one can compute synchrotron emission (and also inverse Compton scattering) along any line of sight.

Note: Propagation parameters are constrained by secondary to primary ratios:









Evoli, Gaggero, Grasso, Maccione, JCAP 0810, 018 (2008)

Propagation Models

Definition of diffusion coefficients:

$$D_{xx} = \frac{v}{c_0} D_0 \left(\frac{E/Z}{\mathrm{GV}}\right)^{\delta}$$

$$D_{pp} = \frac{4p^2 v_{\mathrm{A}}^2}{3\delta(4-\delta^2)(4-\delta)D_{xx}}$$

where v_A is the Alfven speed

Models often considered:

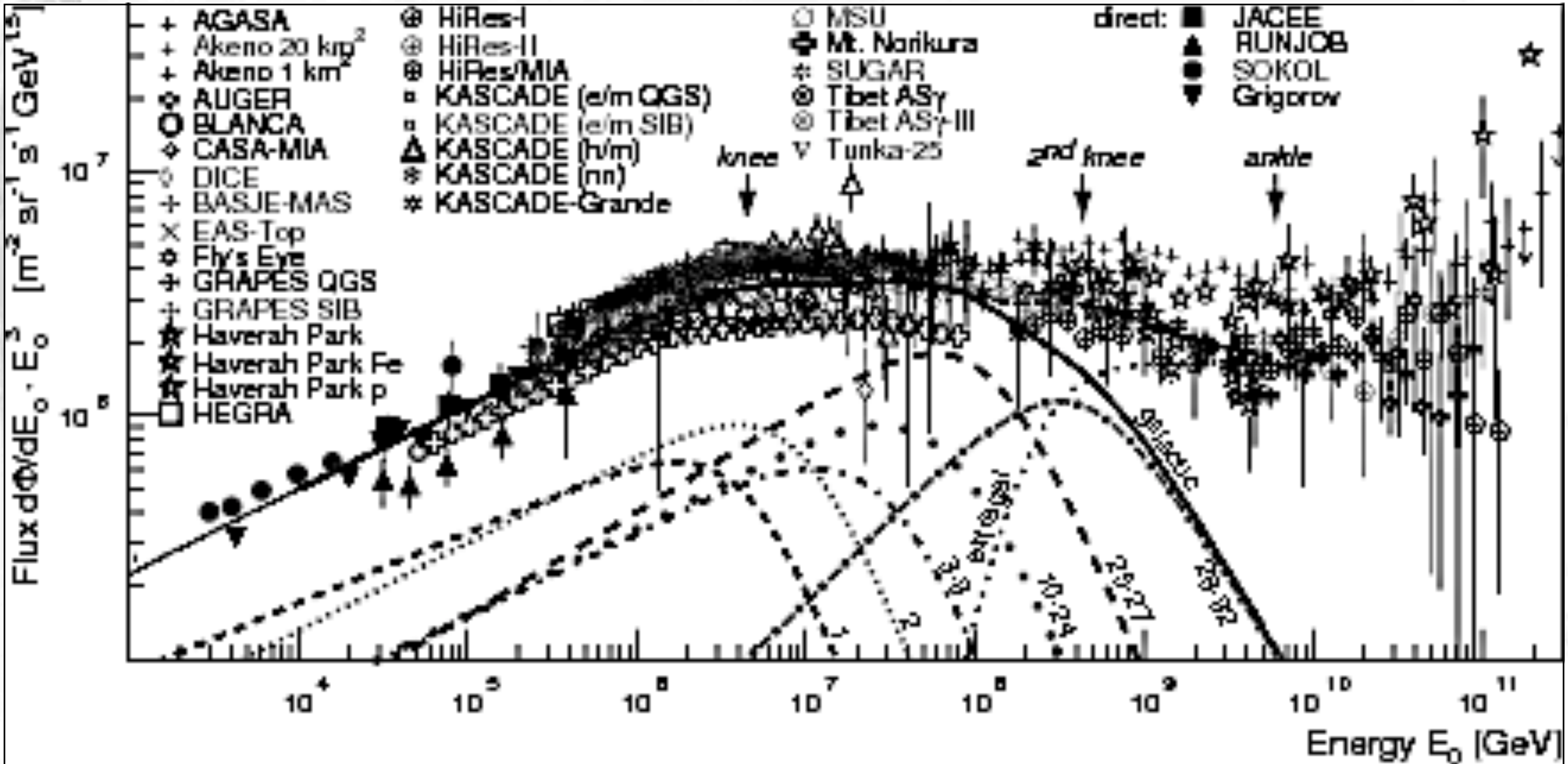
Model	δ§	D_0 [kpc^2/Myr]	R [kpc]	L [kpc]	V_c [km/s]	dV_c/dz km/s/kpc	V_a [km/s]
MIN	0.85/0.85	0.0016	20	1	13.5	0	22.4
MED	0.70/0.70	0.0112	20	4	12	0	52.9
MAX	0.46/0.46	0.0765	20	15	5	0	117.6
DC	0/0.55	0.0829	30	4	0	6	0
DR	0.34/0.34	0.1823	30	4	0	0	32

All Particle Spectrum and chemical Composition

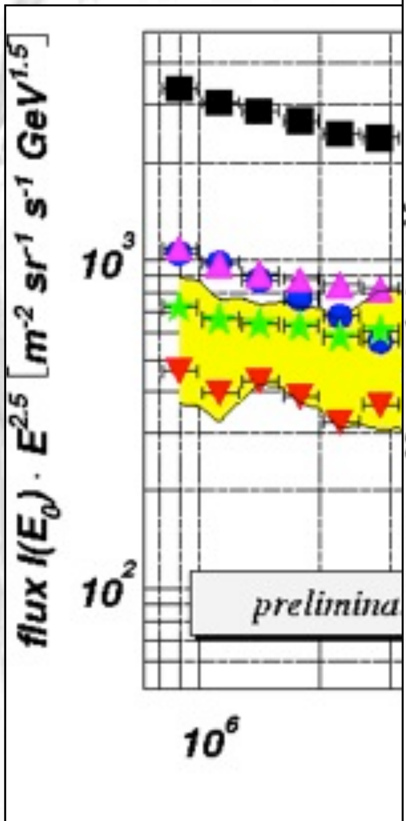
Heavy elements start to dominate above knee

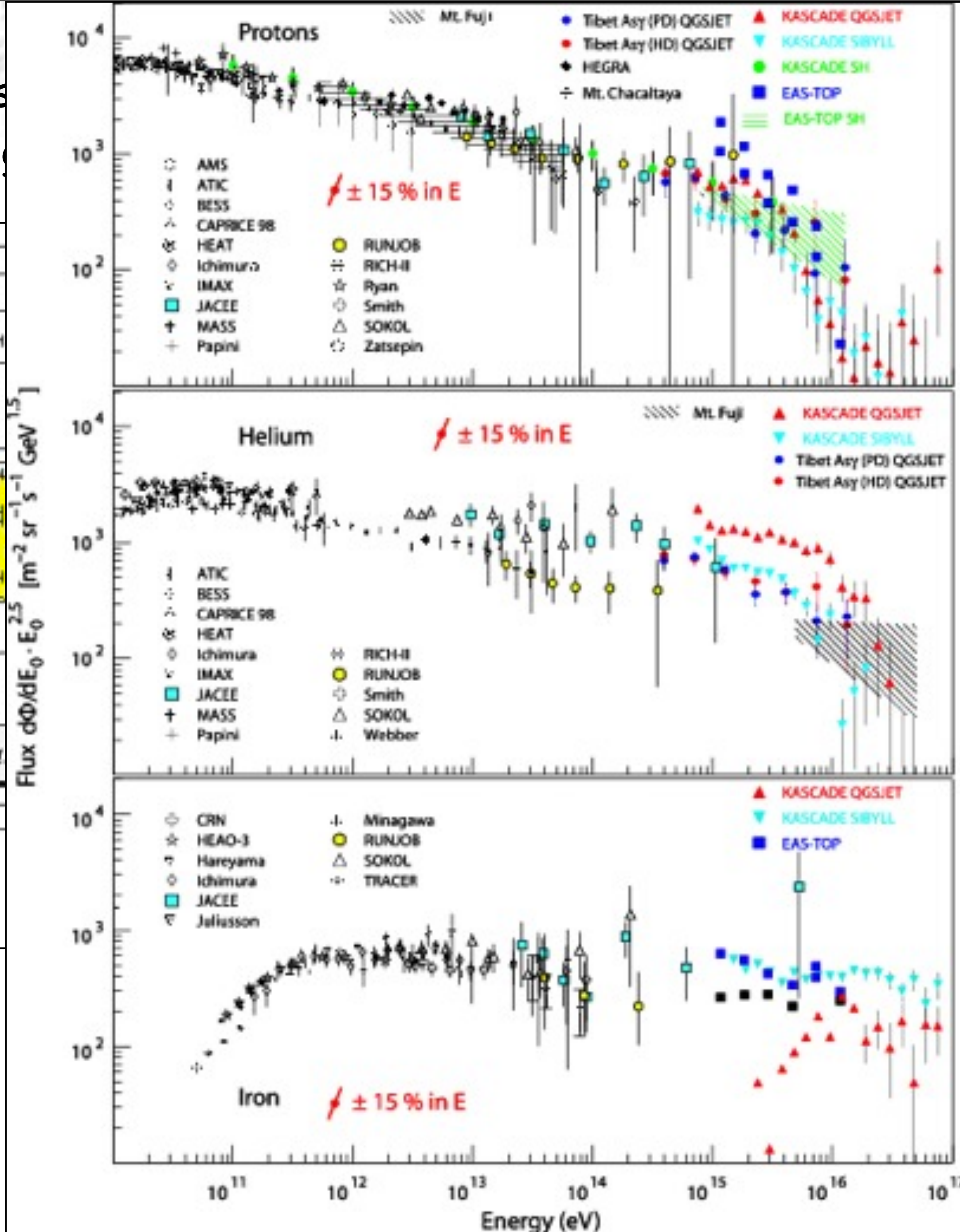
Rigidity (E/Z) effect: combination of deconfinement and maximum energy

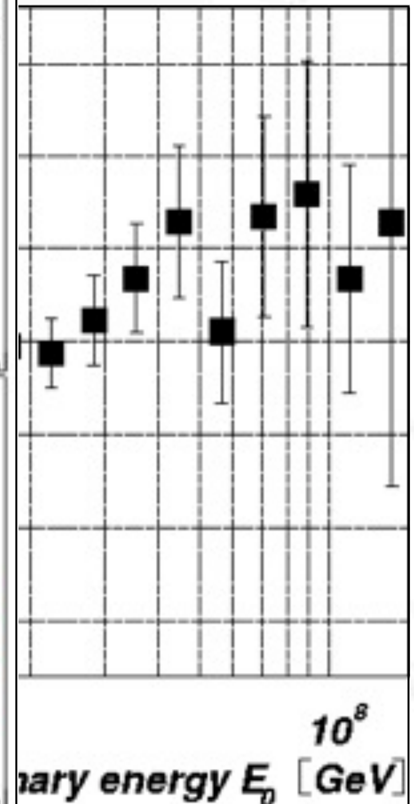
Hoerandel, astro-ph/0702370



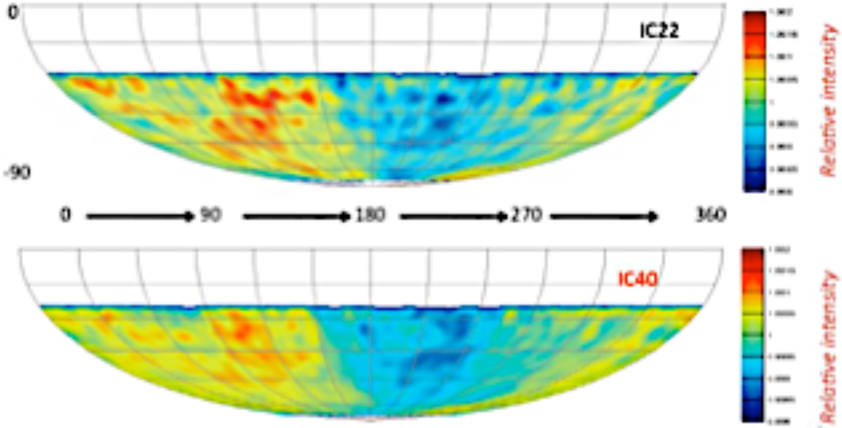
3.) The knee is ... magnetic field as su... SCADE:

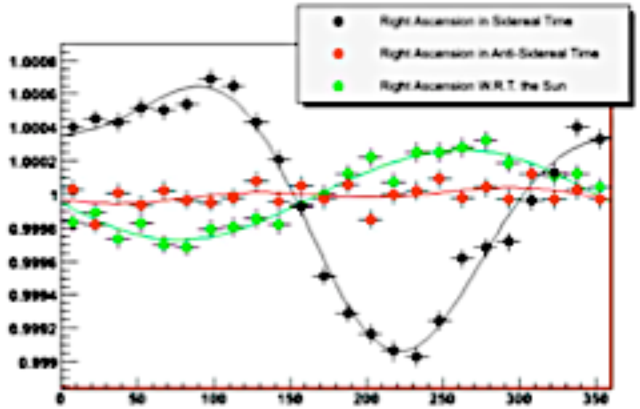


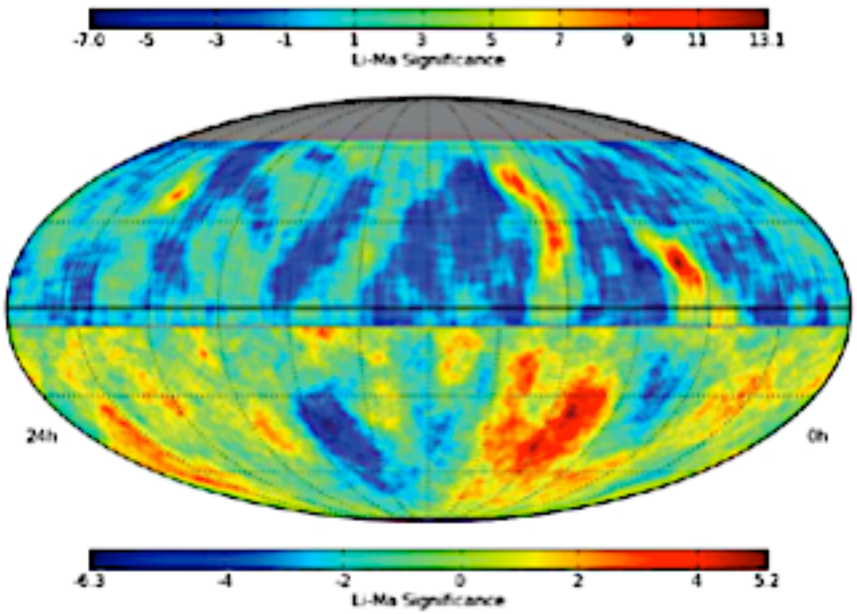




Do Cosmic Ray Anisotropies at 1-100 TeV reveal the Sources ?







P. Desiati, ICECUBE collaboration, arXiv:1007.2621

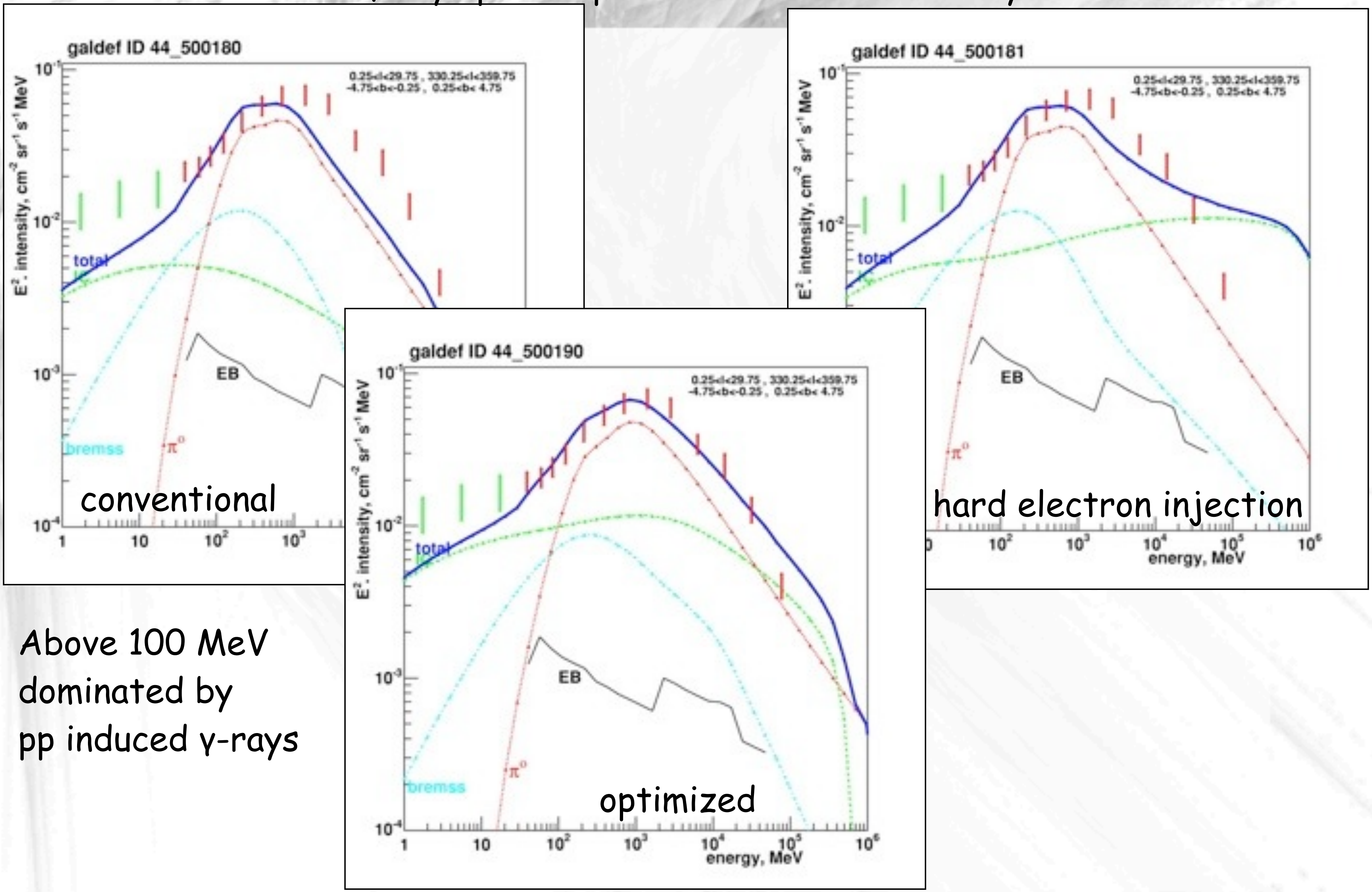
Observed level ~ 10-3 is surprisingly high and difficult to explain:

wrong structure for Compton-Getting effect

too large for sources like Vela and beyond (> 100 pc) because gyro-radius < 0.1 pc

propagation mode, magnetic fied structure ?

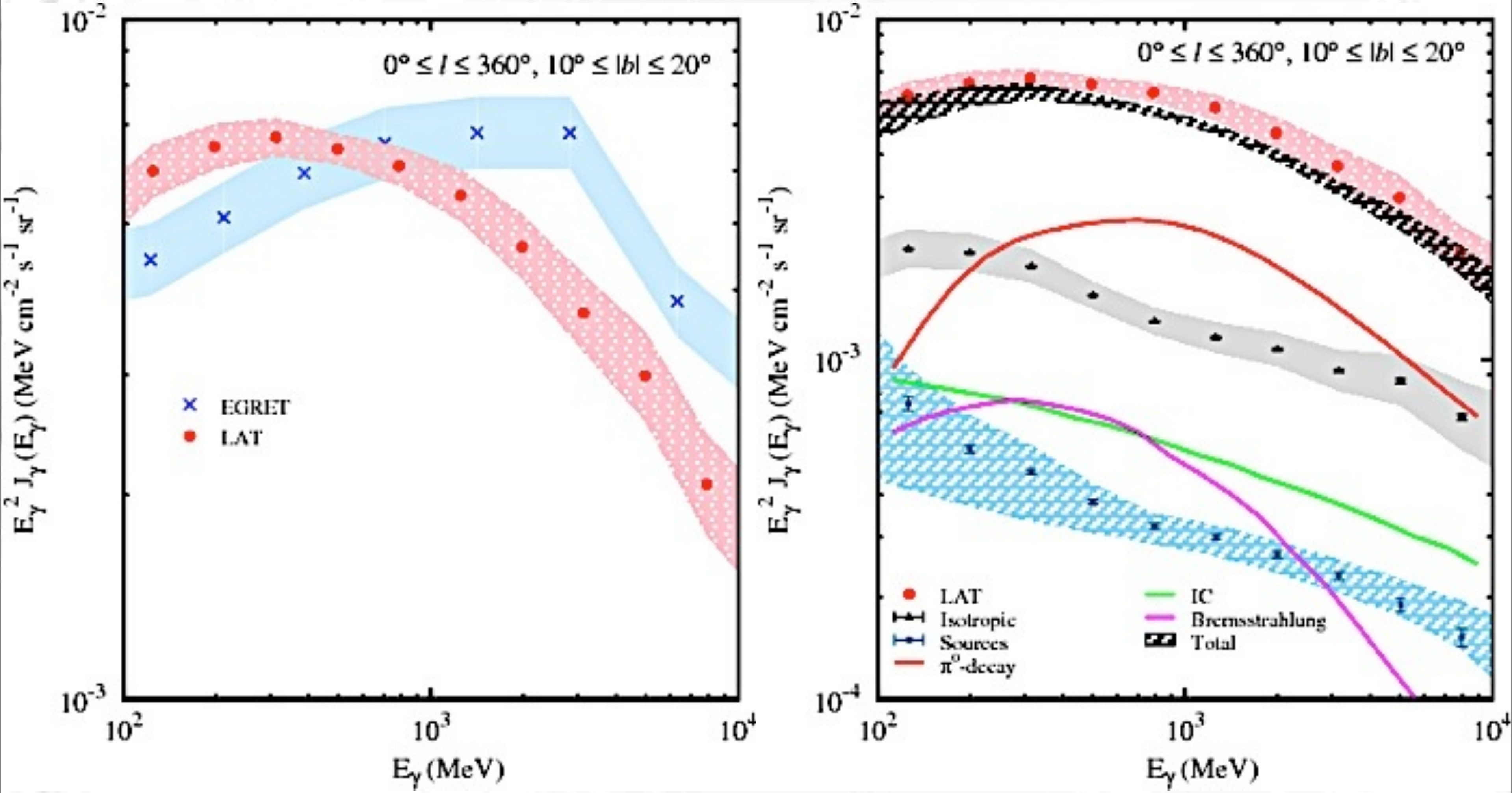
Diffuse γ-ray spectra predicted and observed by EGRET



Above 100 MeV
dominated by
pp induced γ-rays

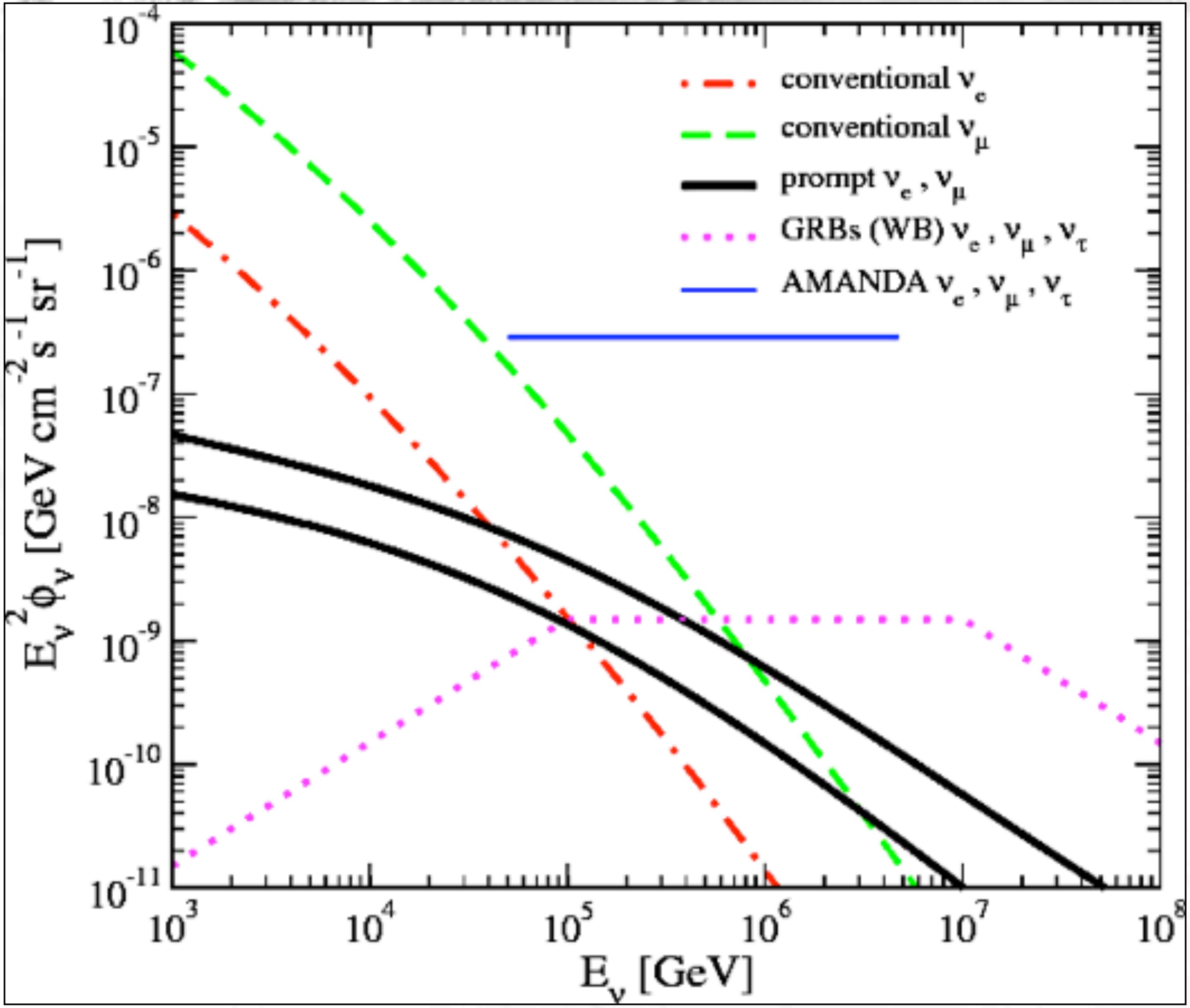
Strong, Moskalenko, and Reimer, ApJ 613 (2004) 962

But newest FERMI data do not show a GeV excess any more



Porter et al., FERMI collaboration, arXiv:0907.0294

The galactic neutrino flux is comparable to the galactic diffuse γ-ray flux



Candia and Beacom, JCAP 0411 (2004) 009

Recently Considered Indirect Signatures of Dark Matter

Gamma-ray flux from galactic centre observed by H.E.S.S.

511 keV annihilation line from near the galactic centre observed by INTGRAL

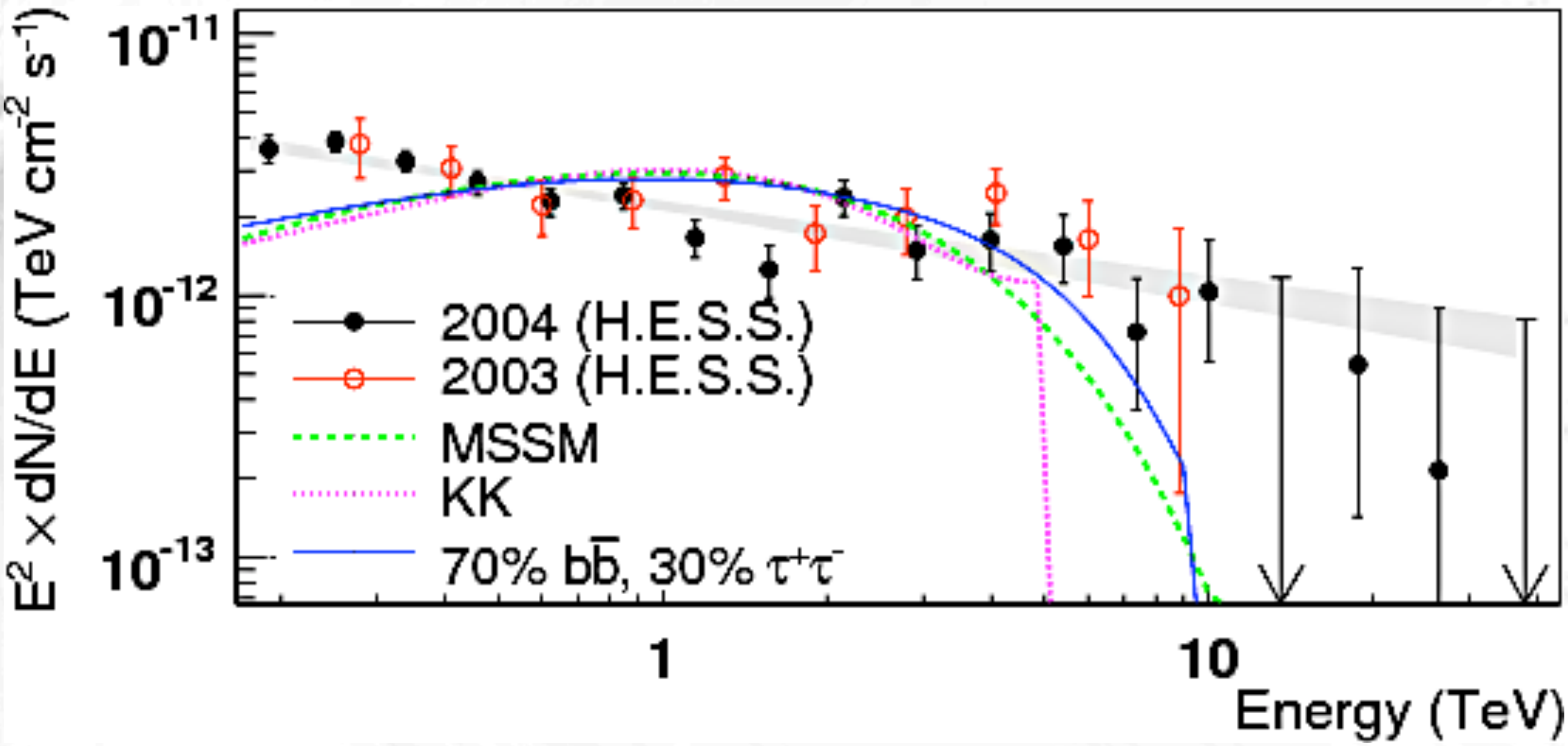
GeV galactic gamma-ray excess observed by EGRET, but not confirmed by Fermi-LAT; still, there may be a “Fermi haze”

The WMAP microwave haze of the inner Galaxy

Galactic positron excess observed by the PAMELA satellite (and earlier experiments)

An excess observed in the combined electron/positron flux observed by ATIC and FERMI/GLAST

Galactic Centre gamma-ray Flux



The H.E.S.S. data extends to beyond 30 TeV which is would require unnaturally large dark matter masses; newest data consistent with acceleration with cut-off.

Galactic Centre 511 keV Annihilation Line

But new INTEGRAL data shows line emission is not spherically symmetric as expected if from a dark matter halo. It seems instead to correlate with the Galactic bulge
[Weidenspointner et al., Nature 451, 159 (2008)]