Cosmic Rays: An Overture

Günter Sigl

1. Galactic Cosmic Rays
2. Extragalactic Cosmic Rays

DFG Deutsche Forschungsgemeinschaft

PROJEKTTRÄGER FÜR DAS Bundesministerium für Bildung und Forschung

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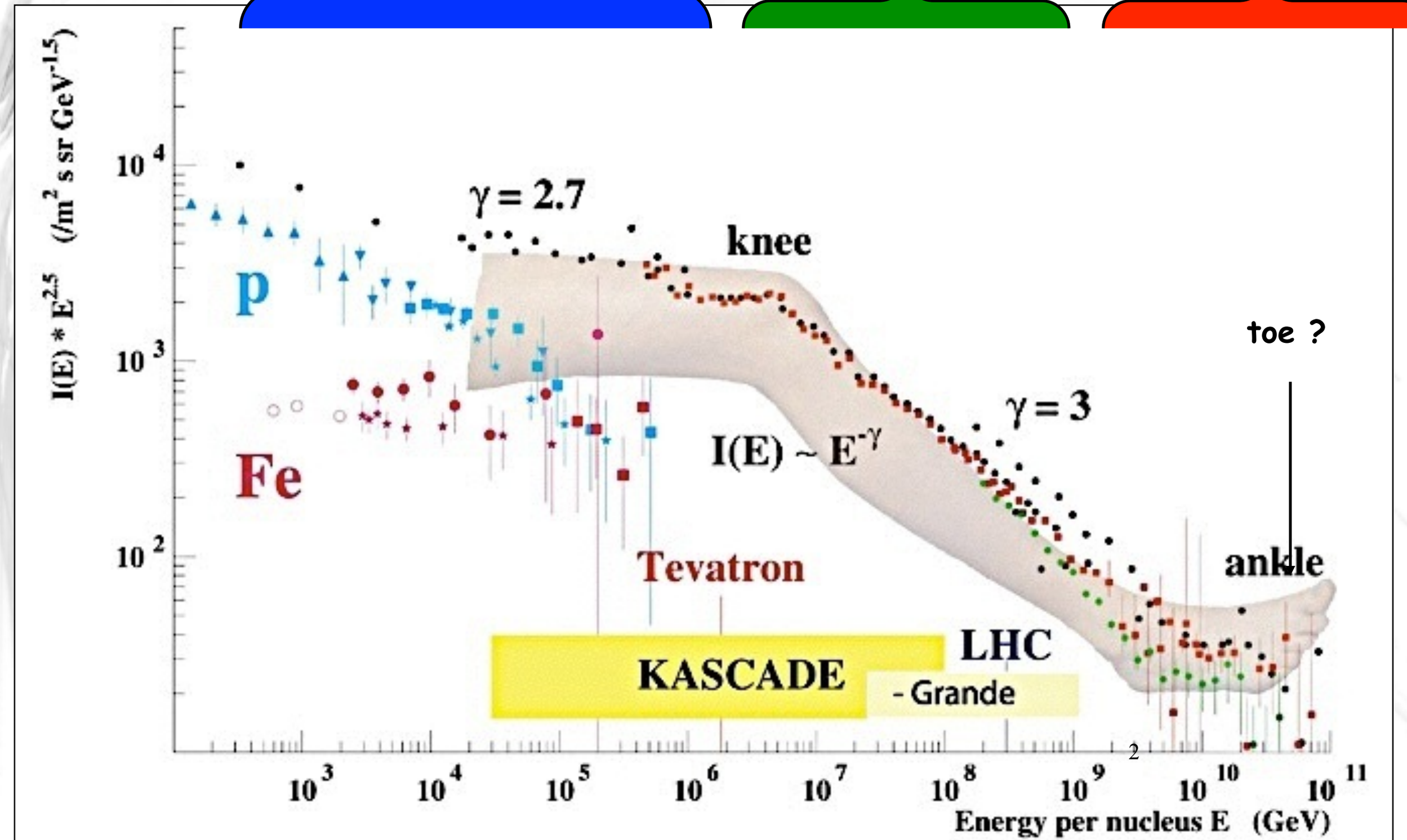
Günter Sigl
II. Institut theoretische Physik, Universität Hamburg

The structure of the spectrum and scenarios of its origin

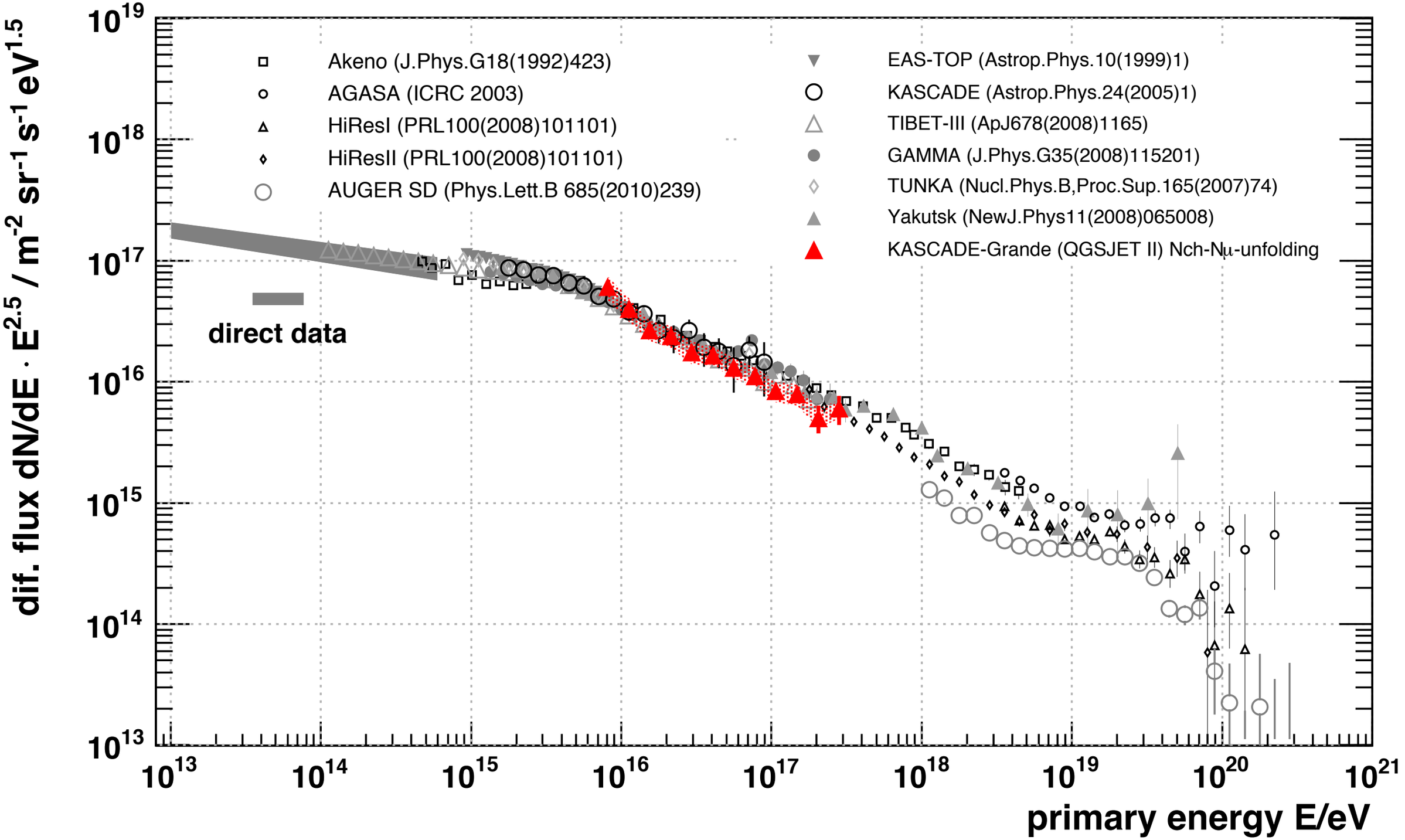
supernova remnants

wind supernovae

AGN, GRBs ?

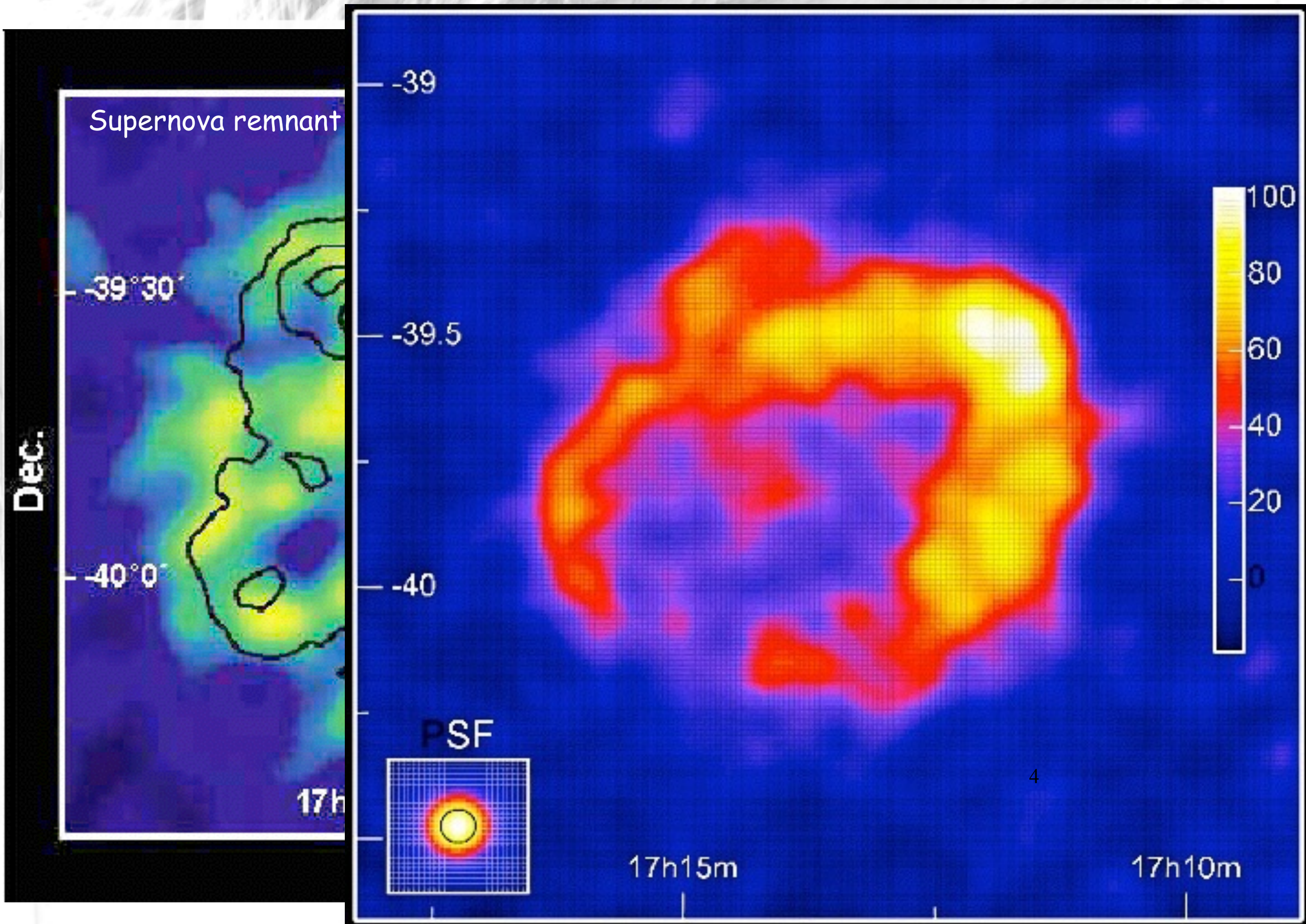


Another View of the All Particle Spectrum

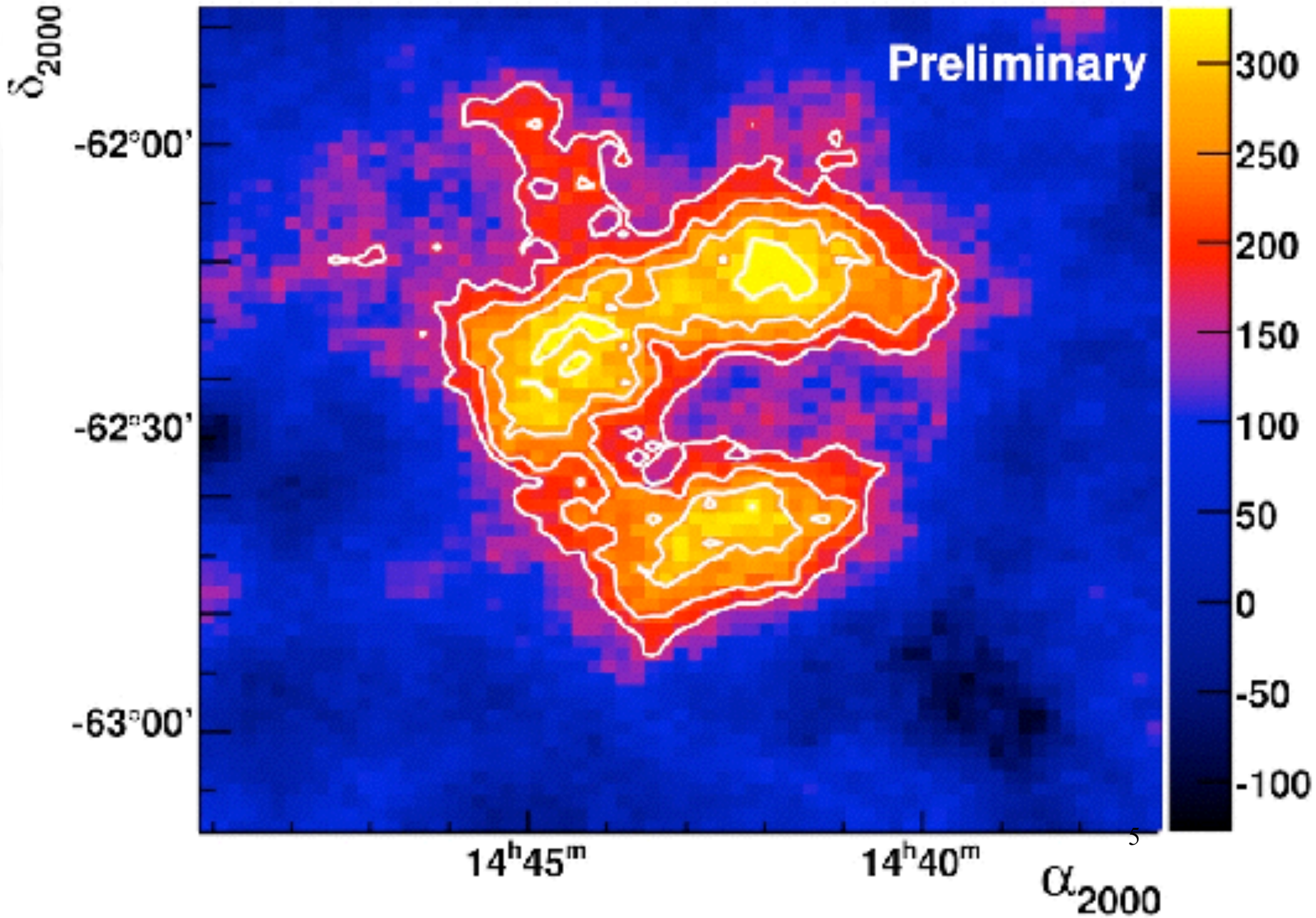


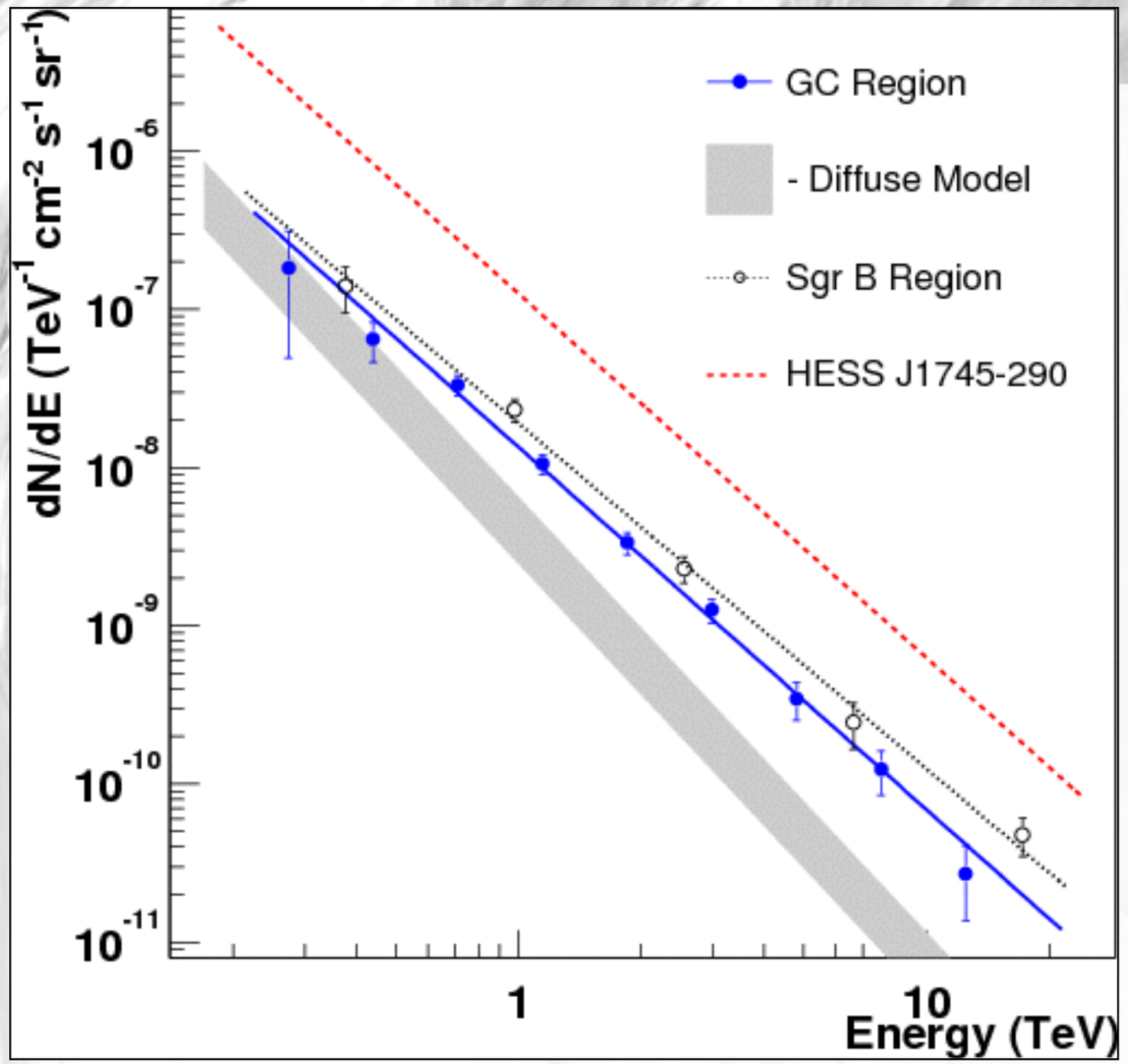
KASCADE-Grande collaboration, arXiv:1111.5436 (ICRC 2011)

Identifying galactic sources from their secondary gamma-ray signatures



Shell-type supernova remnant RCW 86 seen by HESS

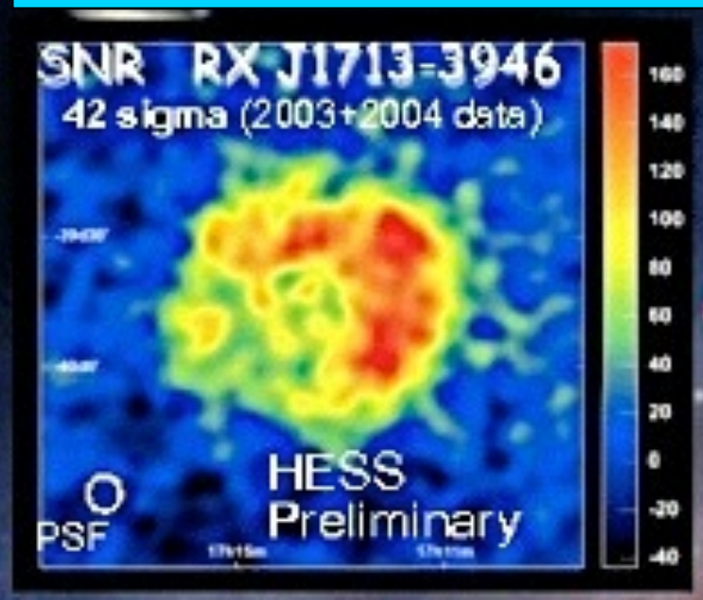


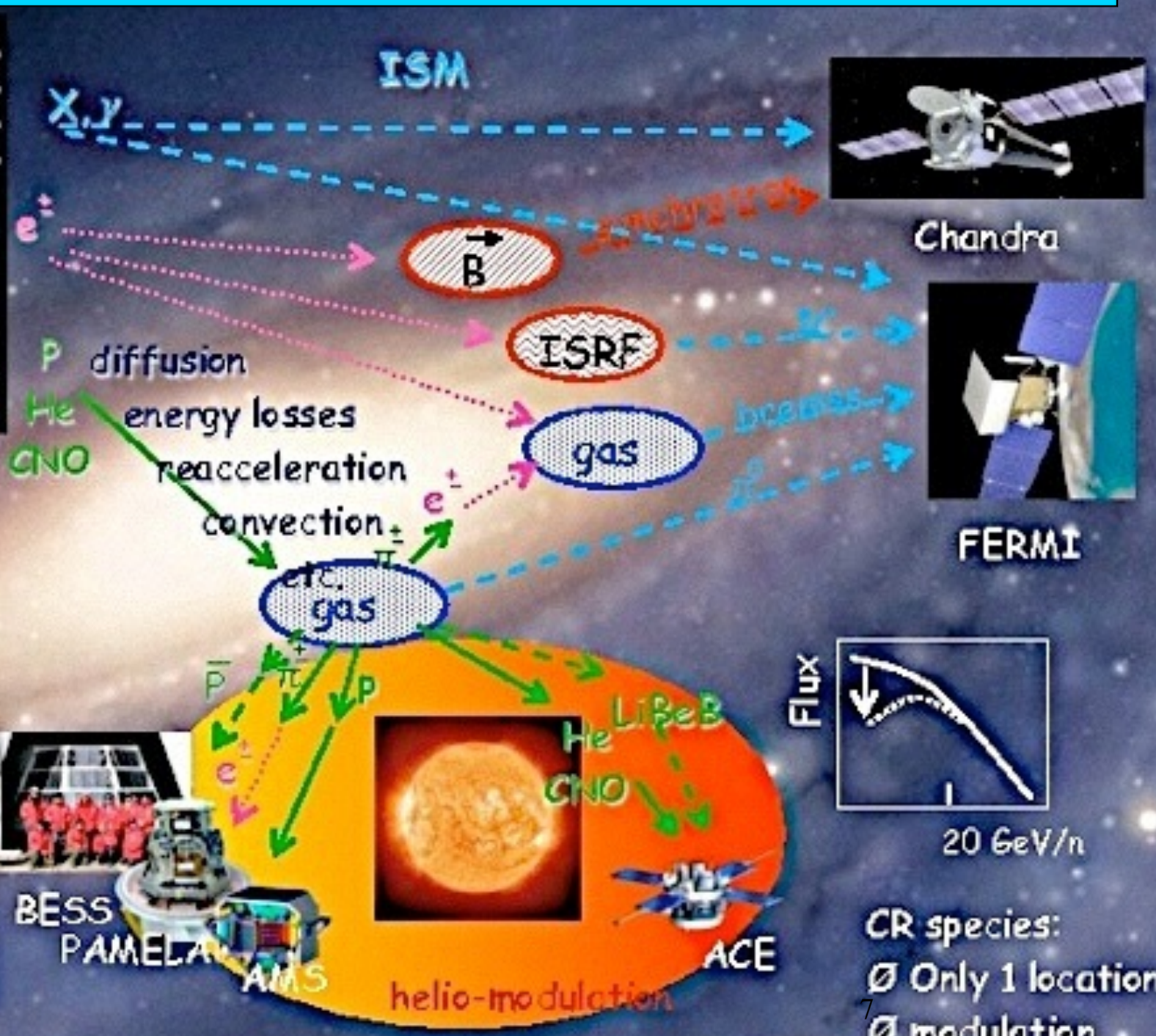


Given the observed spectrum $E^{-2.3}$, this can be interpreted as photons from π^0 decay produced in pp interactions where the TeV protons have the same spectrum and could have been produced in a SN event.

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:

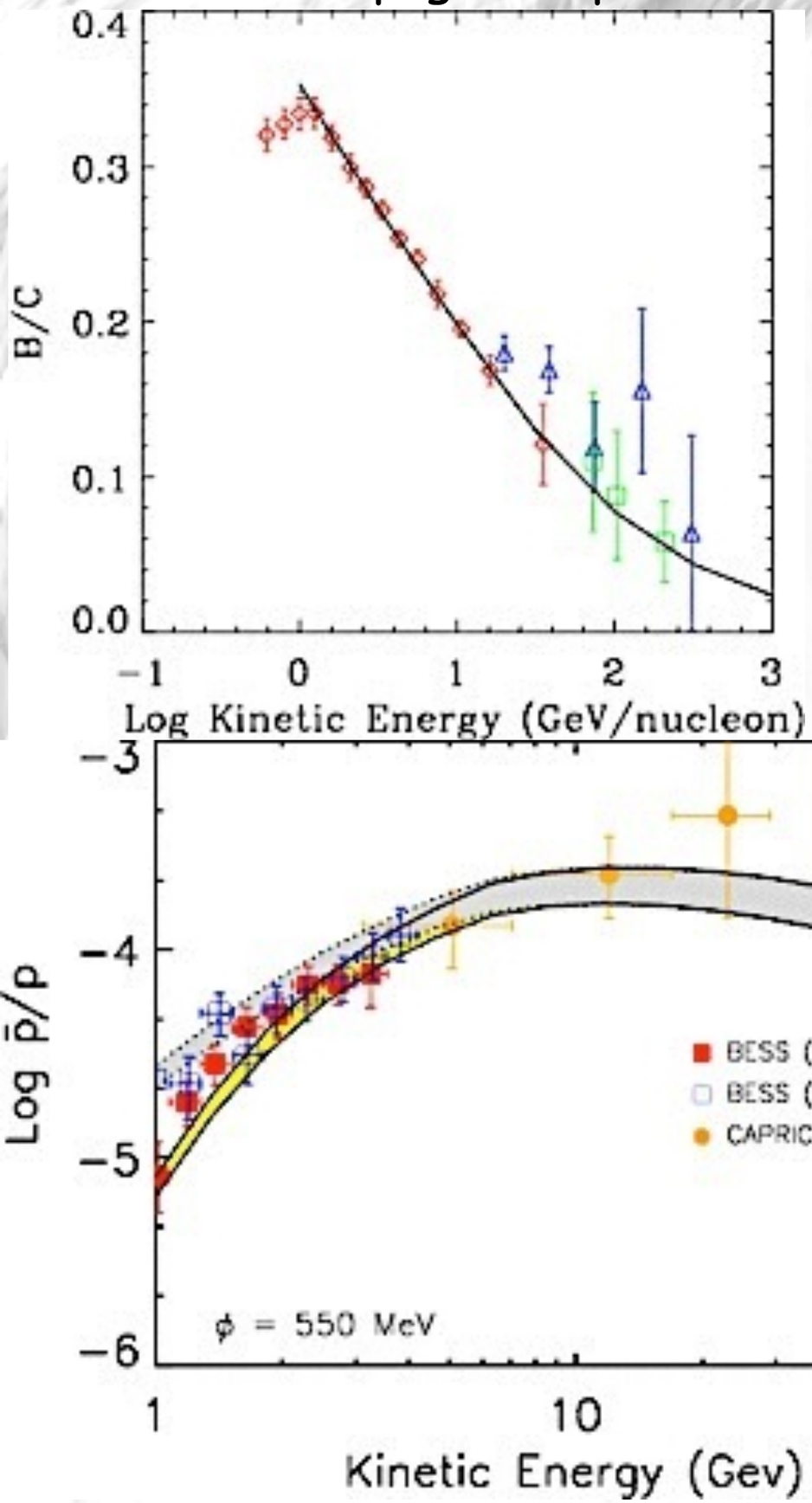
$$\partial_t n = \nabla \cdot (D_{xx} \nabla n - \mathbf{v_c}) + \partial_p \left(p^2 D_{pp} \partial_p \frac{n}{p^2} \right) - \partial_p \left[\dot{p}\, n - \frac{p}{3} (\nabla \cdot \mathbf{v_c} n) \right] + Q(\mathbf{r}, p)$$

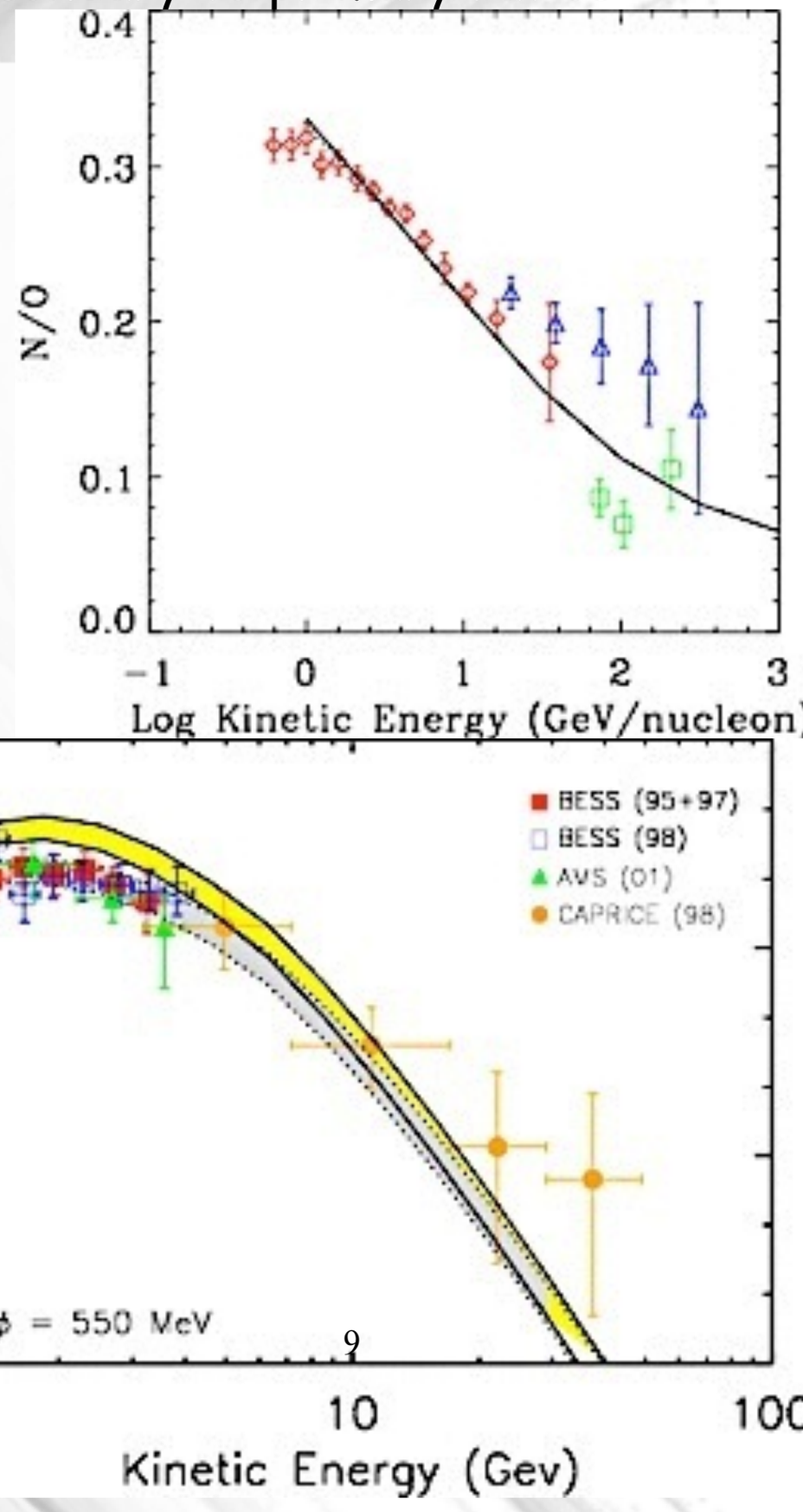
spatial diffusion — convection — reacceleration — energy loss — adiabatic compression/ expansion — source term

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:

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

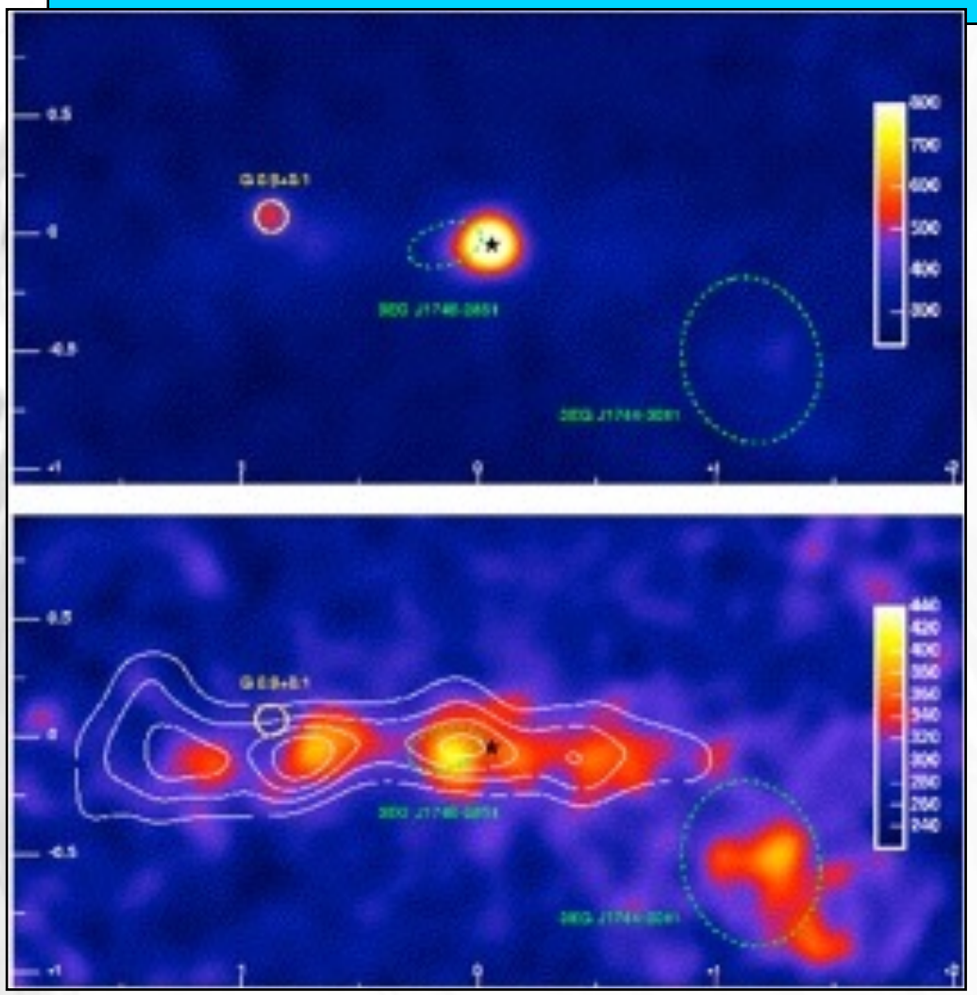
$$D_{pp} = \frac{4p^2 v_{\mathrm{A}}^2}{3\delta(4-\delta^2)(4-\delta) D_{xx}}$$

where v_A is the Alfven speed

Models often considered:

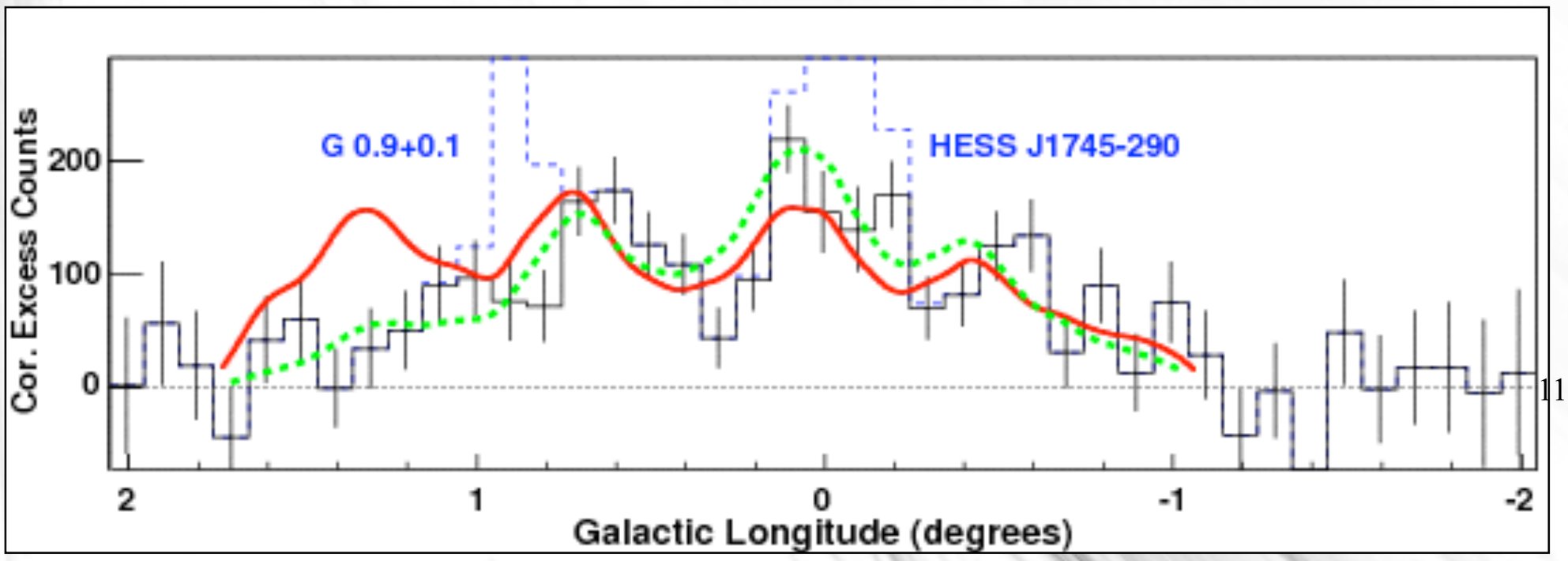
Model	δ§	D_0 [kpc^2/Myr]	R [kpc]	L [kpc]	V_c [km/s]	dV_c/dz km/s/kpc	V_a [km/s]
MIN	0.85/0.85	0.0016	20	1	13.5	0	22.4
MED	0.70/0.70	0.0112	20	4	12	0	52.9
MAX	0.46/0.46	0.0765	20	15	5	0	117.6
DC	0/0.55	0.0829	30	4	0	6	0
DR	0.34/0.34	0.1823	30	4	0	0	32

Diffusion in Action seen from secondary γ-Rays

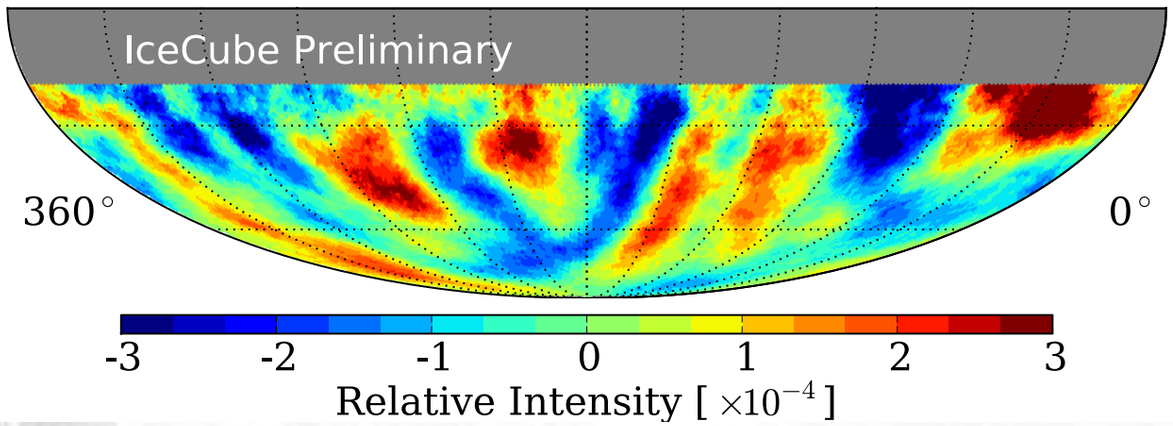


HESS has observed γ-rays from objects around the galactic centre which correlate well with the gas density in molecular clouds for a cosmic ray diffusion time of $T \sim R^2/D \sim 3 \times 10^3 (\theta/1^o)^2/\eta$ years where $D = \eta\, 10^{30}$ cm^2/s is the diffusion coefficient for protons of a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

Aharonian et al., Nature 439 (2006) 695

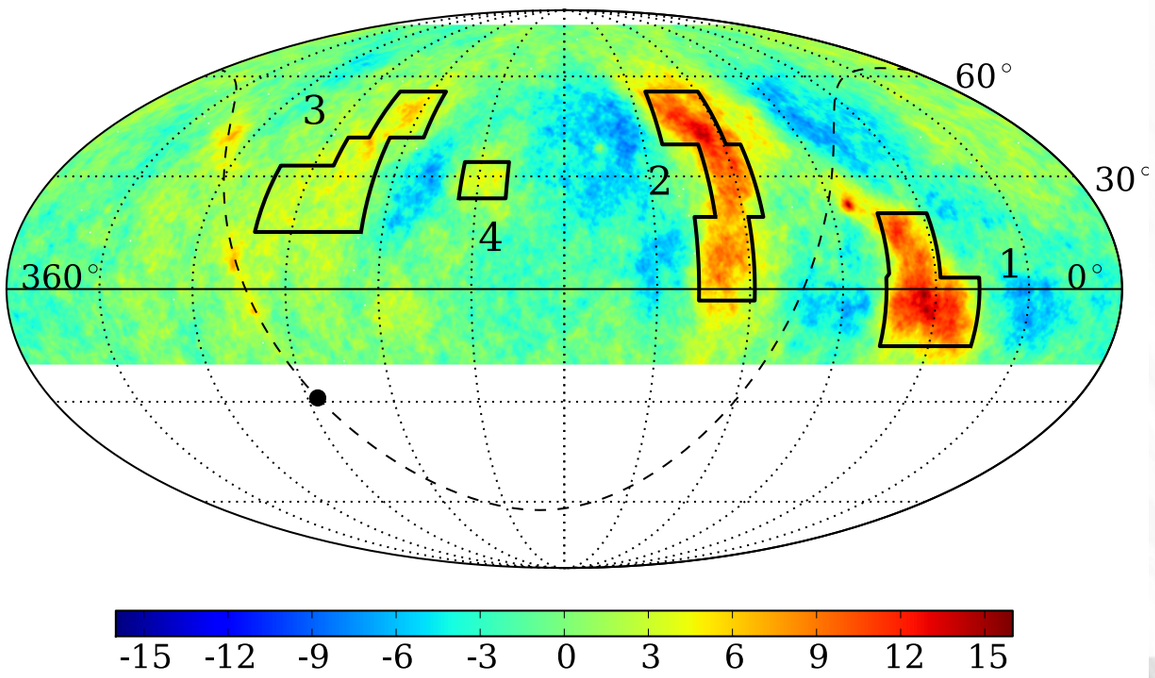


Do Cosmic Ray Anisotropies at 1-100 TeV reveal the Sources ?



@20 TeV after dipole subtraction

P. Desiati et al, ICECUBE collaboration, arXiv:1308.0246



B. Bartoli et al, ARGO-YBJ collaboration, arXiv:1309.6182

Observed by Milagro, ARGO-YBJ, IceCube

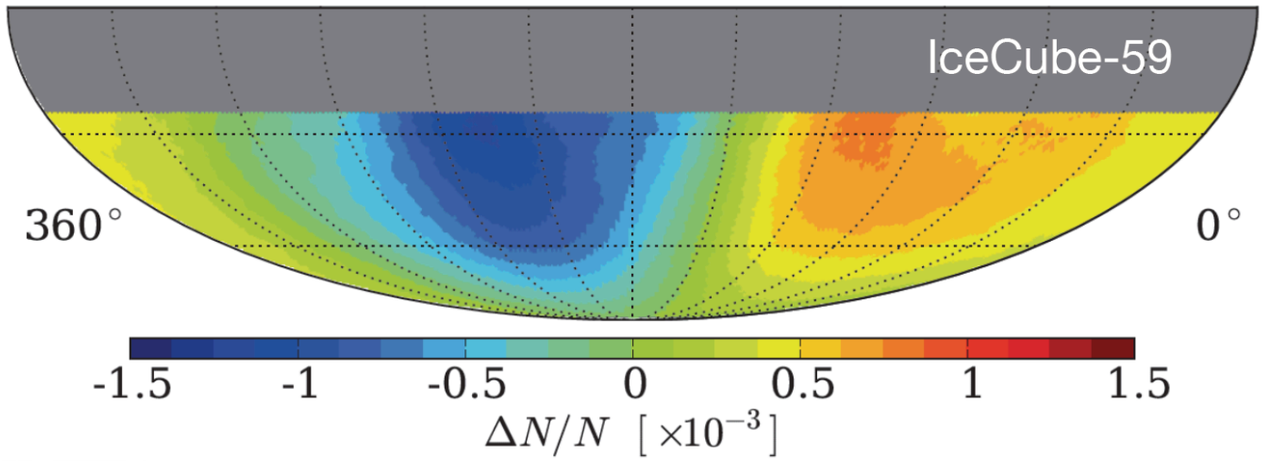
Observed level ~ 10^{-3} is surprisingly high and difficult to explain:

wrong structure for Compton-Getting effect

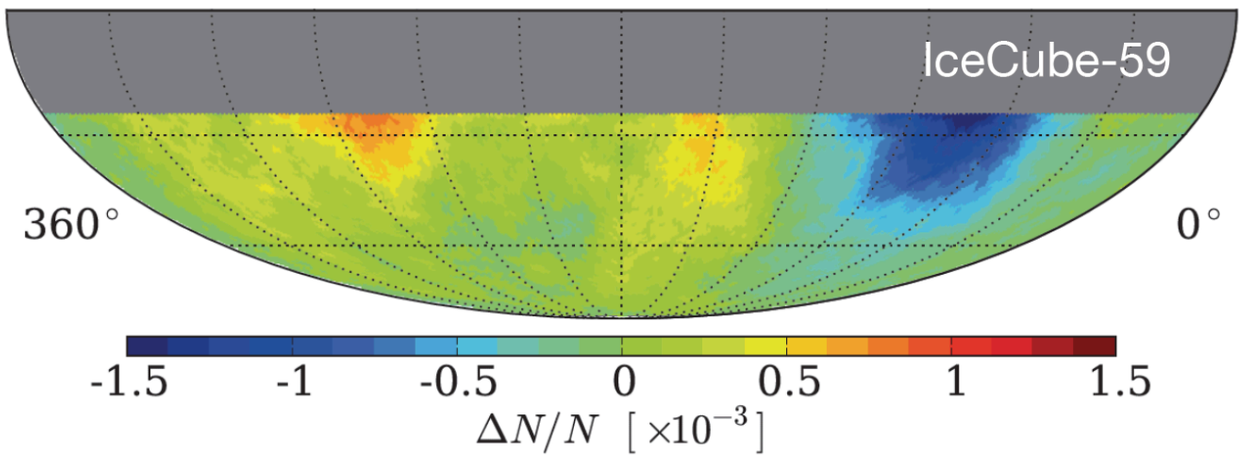
too large for sources like Vela and beyond (> 100 pc) because gyro-radius < 0.1 pc

propagation mode, magnetic field structure ?

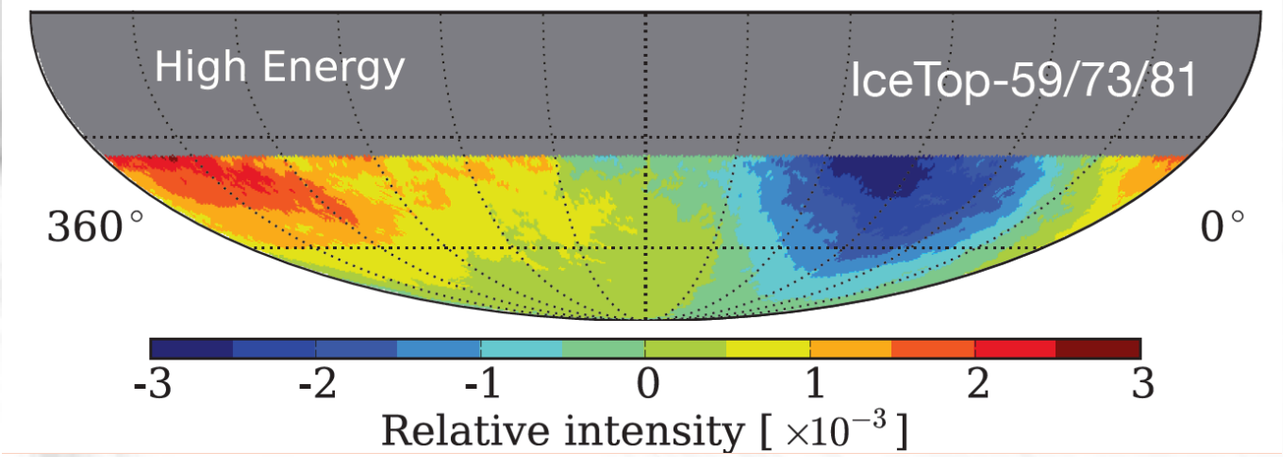
Anisotropy Patterns are strongly Energy dependent



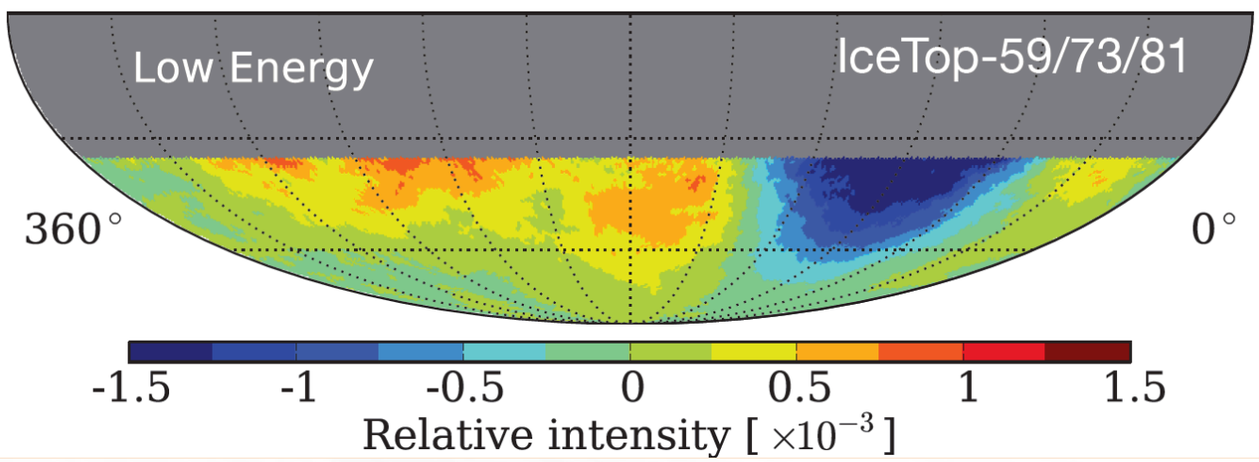
@20 TeV



@400 TeV



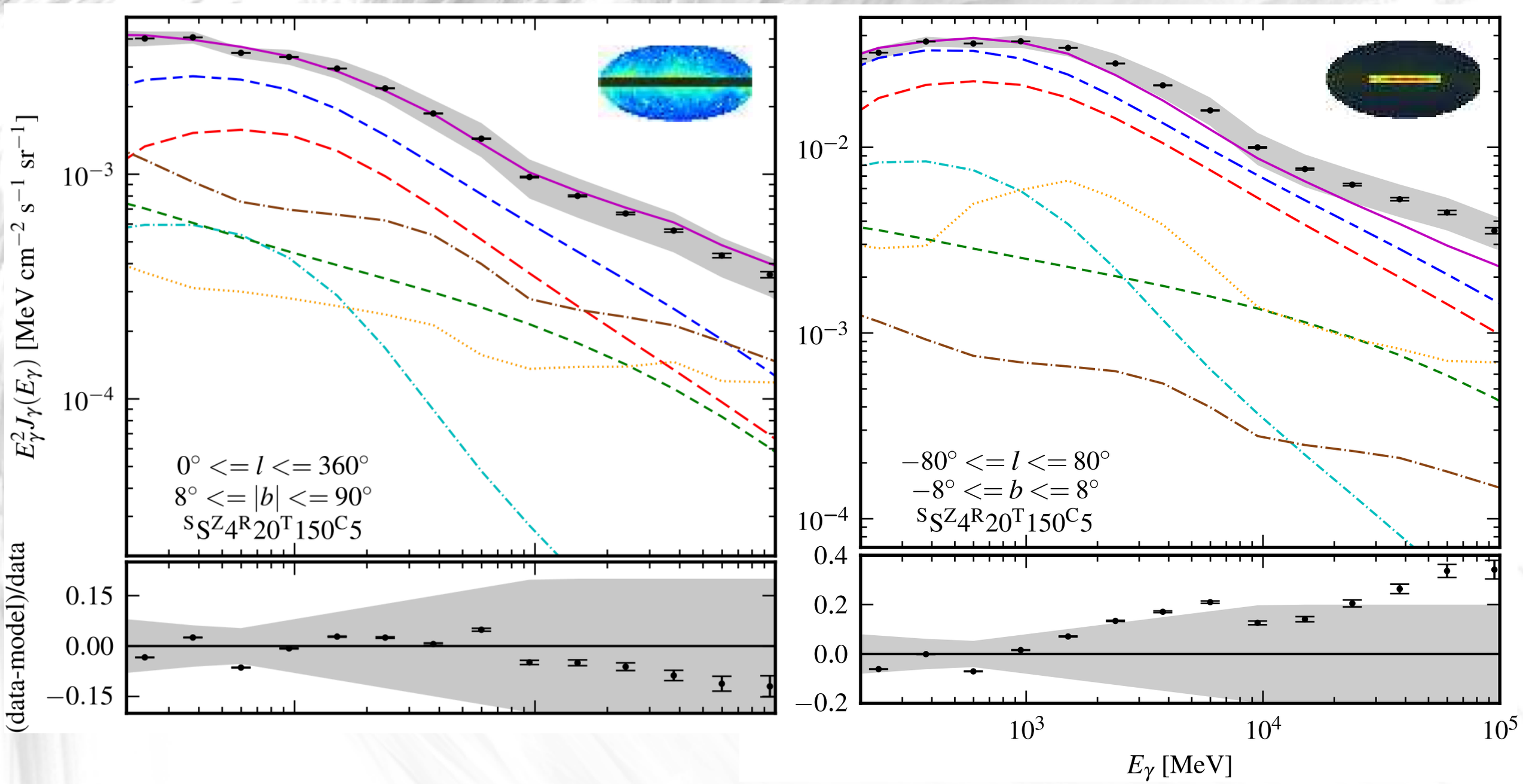
@400 TeV



@2 PeV

The anisotropies may reflect the structure of the magnetic field within one scattering length (on magnetic inhomogeneities) around the observer. This structure is "missed" in the diffusion approximation which averages over magnetic field ensembles.

G.Giacinti and G.Sigl, PRL 109 (2012) 071101, M.Ahlers, arXiv:1310.5712

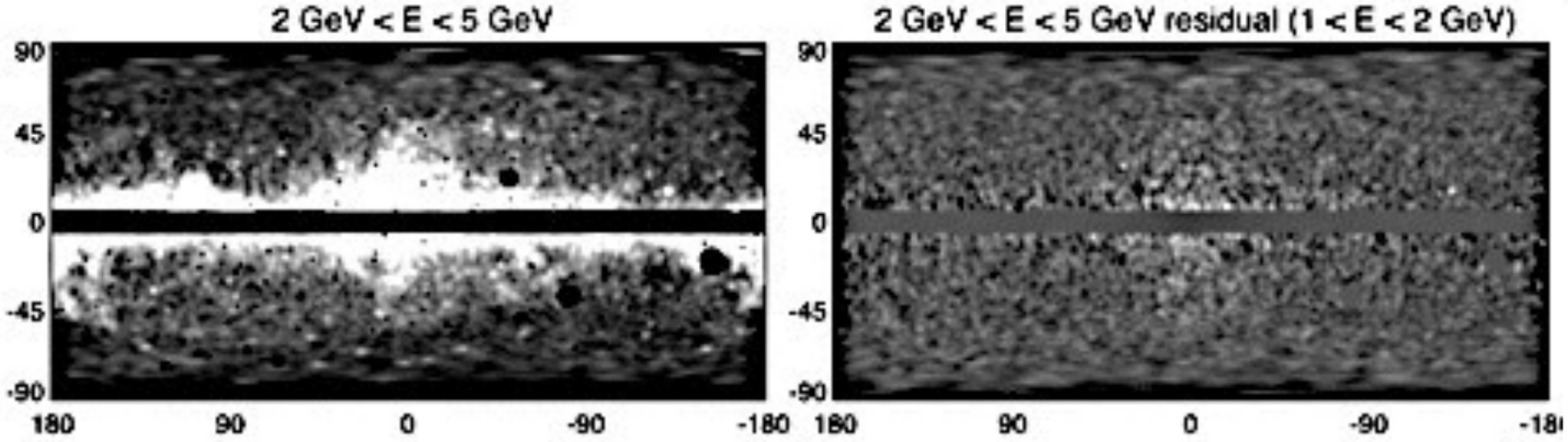


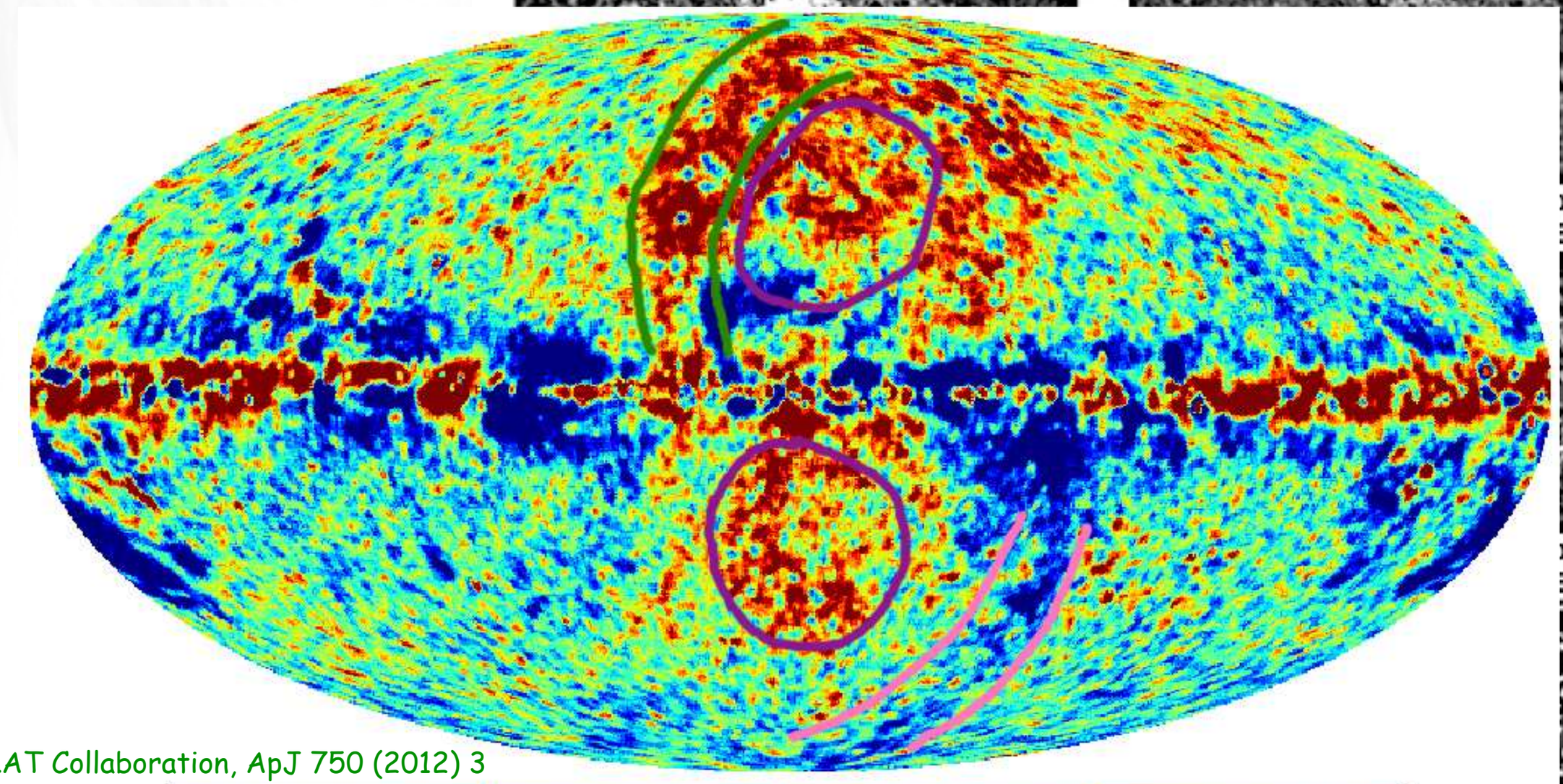
galactic diffuse γ-ray flux in outer Galaxy consistent with models, close to the galactic center there may be a small excess

M. Ackermann et al., FERMI collaboration, ApJ 750 (2012) 3

Fermi haze residual after subtracting template from Fermi sky at 1-2 GeV itself, which should be dominated by π^0 channel

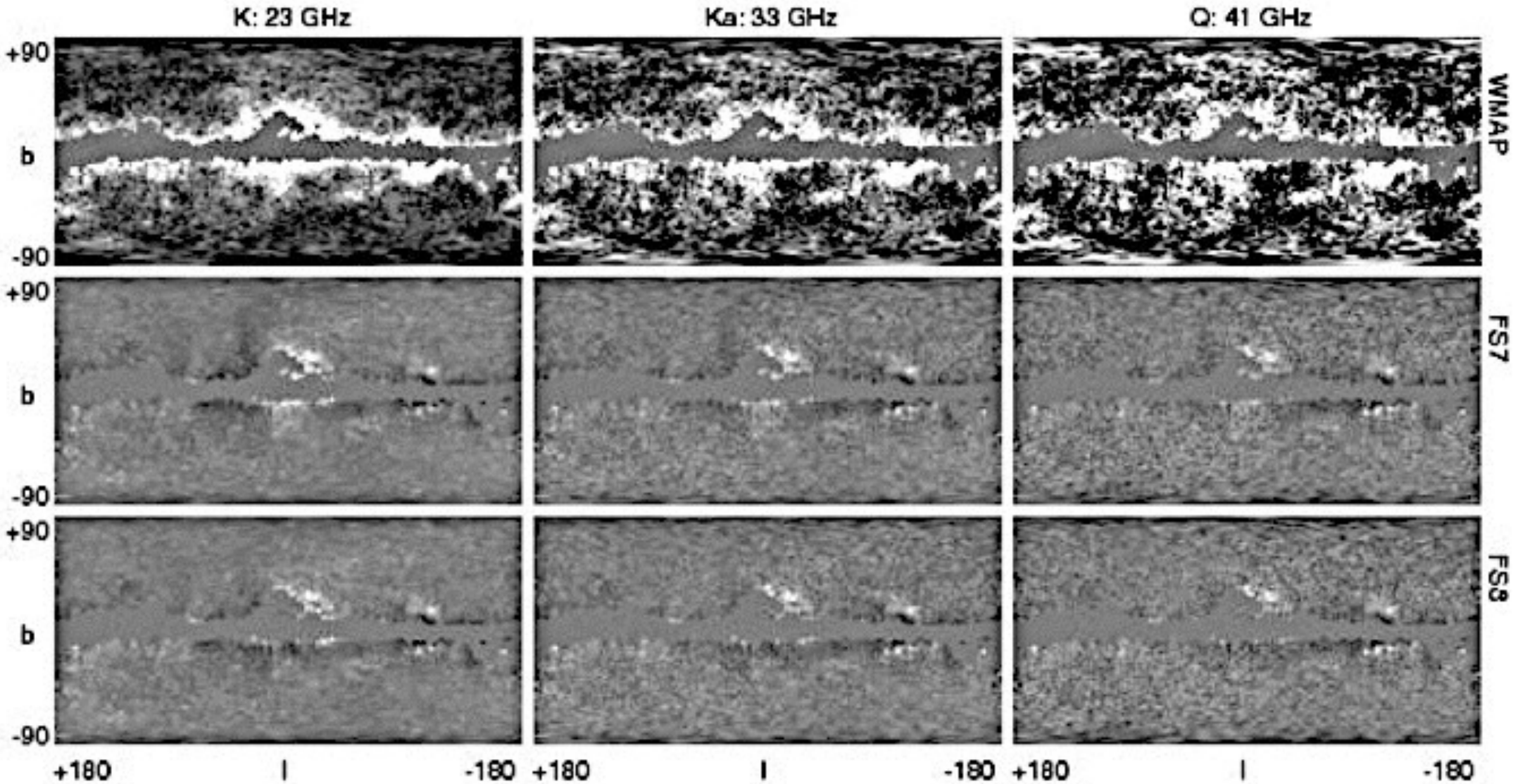
Dobler et al, ApJ 717 (2010) 825





Fermi LAT Collaboration, ApJ 750 (2012) 3

WMAP haze

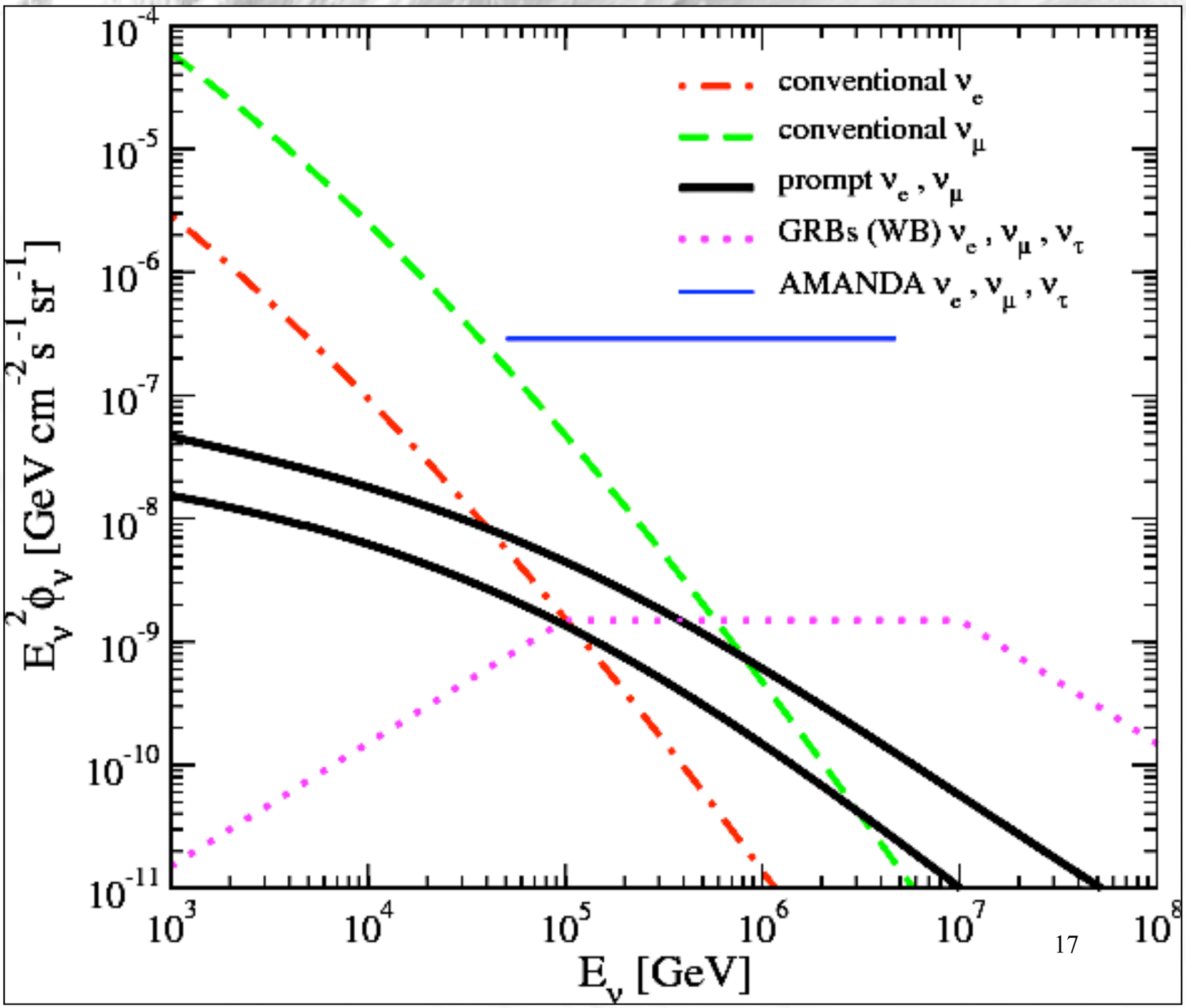


Dobler and Finkbeiner, ApJ 680 (2008) 1222

WMAP haze is the residual after subtracting a template obtained from extrapolating the Haslam 408 MHz map.

But distribution of primary electrons may be different for these energies, e.g. Mertsch and Sarkar arXiv:1004.3056

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 INTEGRAL

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)

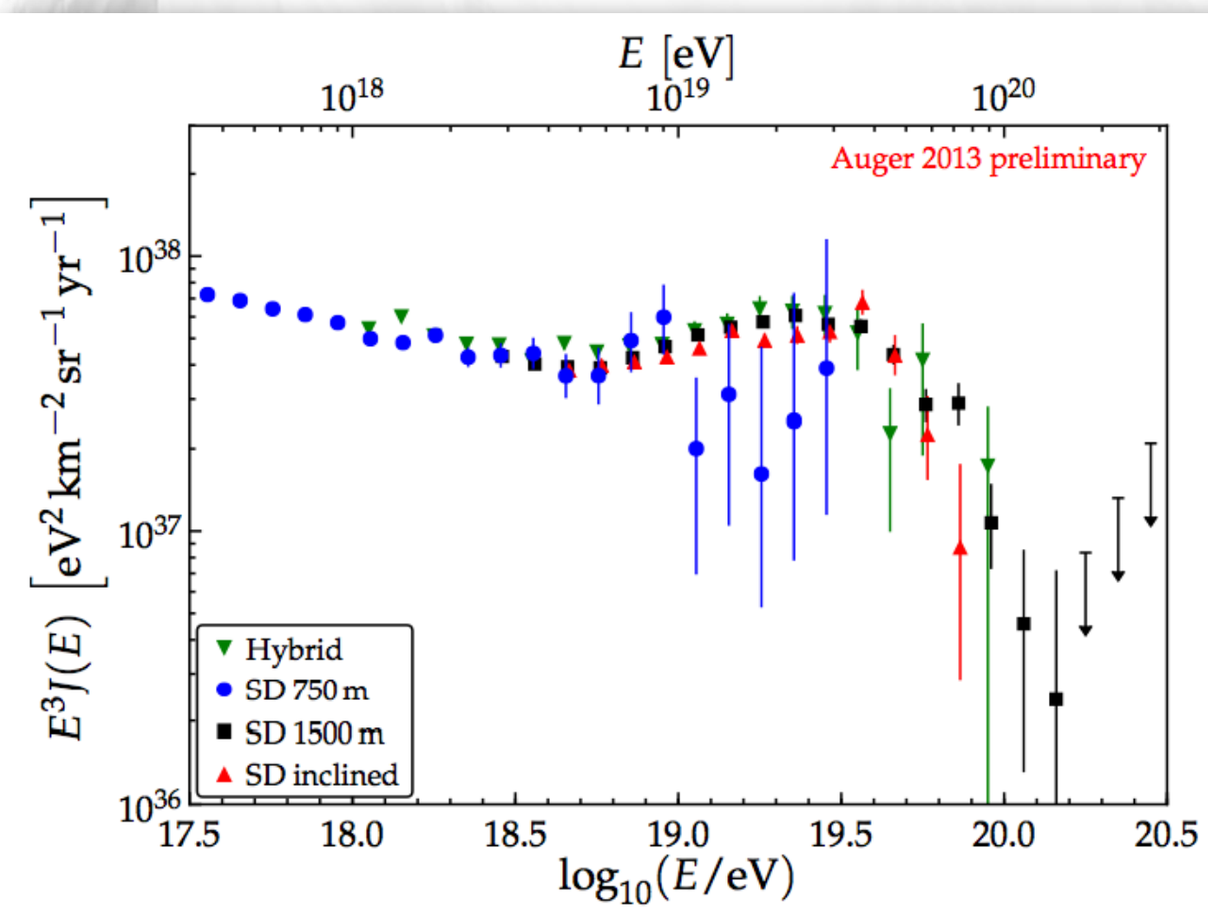
An excess observed in the combined electron/positron flux observed by ATIC and FERMI/GLAST

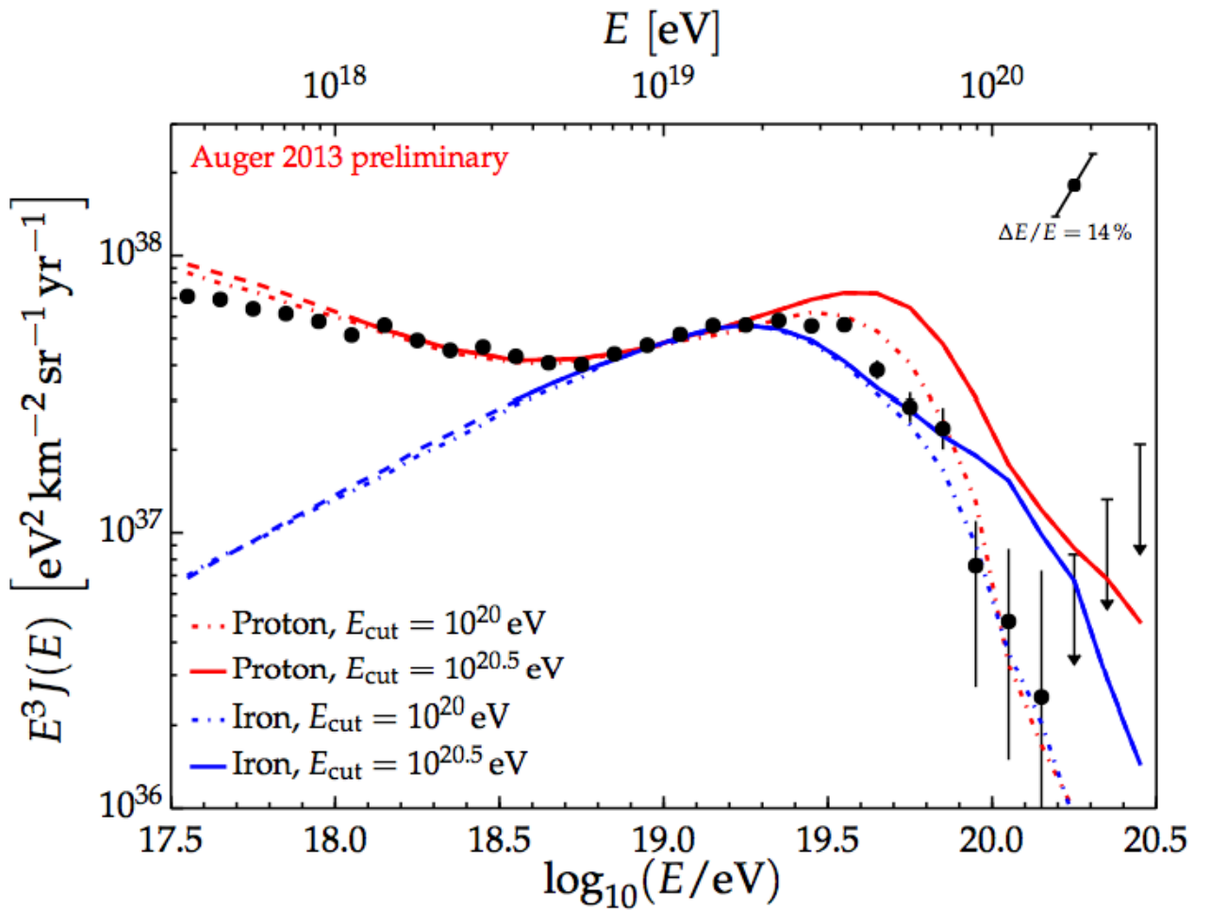
Ultra-High Energy Cosmic Rays

Auger and HiRes Spectra

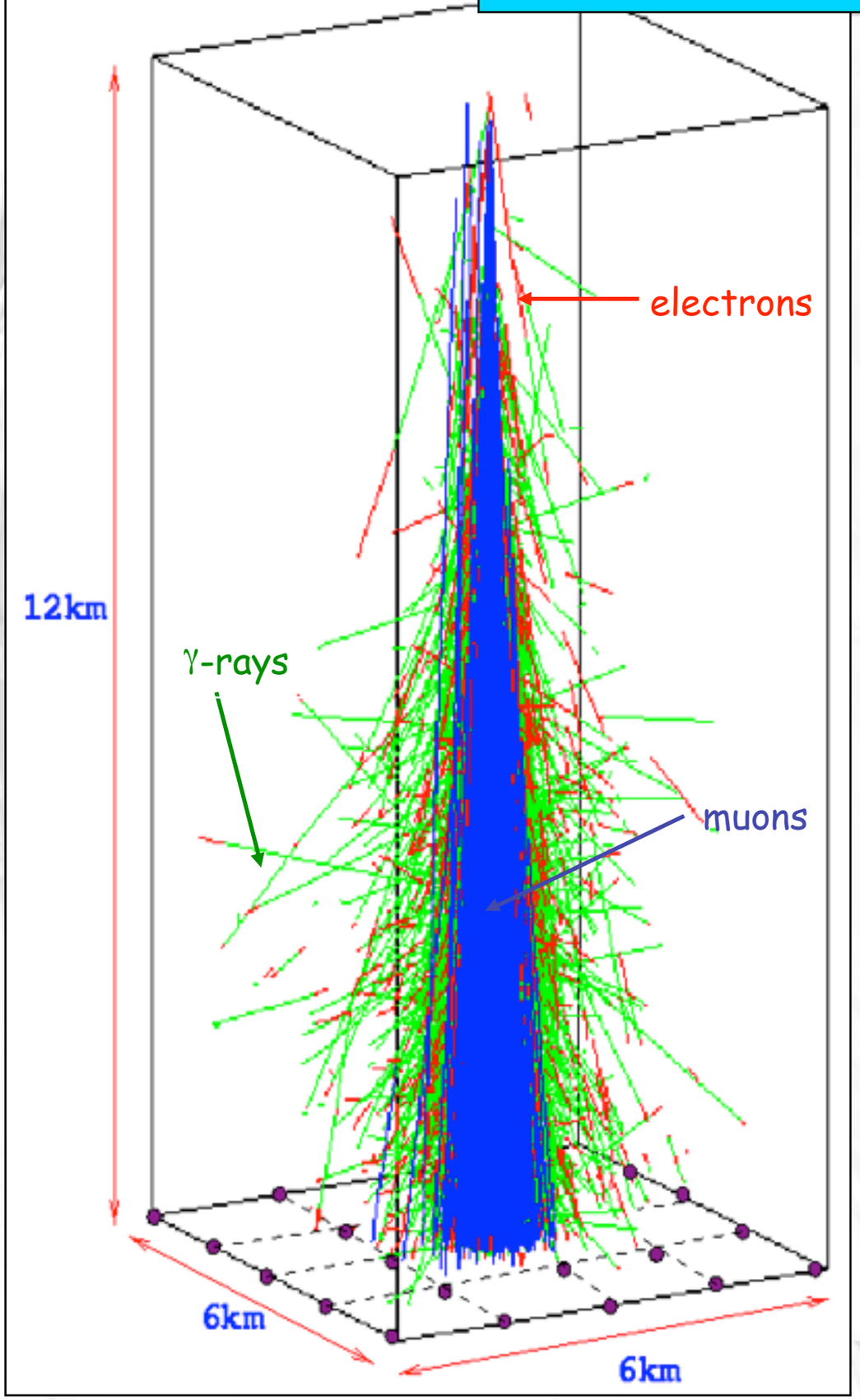
Auger exposure = 31645 km^2 sr yr up to December 2012

Pierre Auger Collaboration, PRL 101, 061101 (2008)
and Phys.Lett.B 685 (2010) 239
and ICRC 2013, arXiv:1307.5059, higlight talk Letessier-Selvon





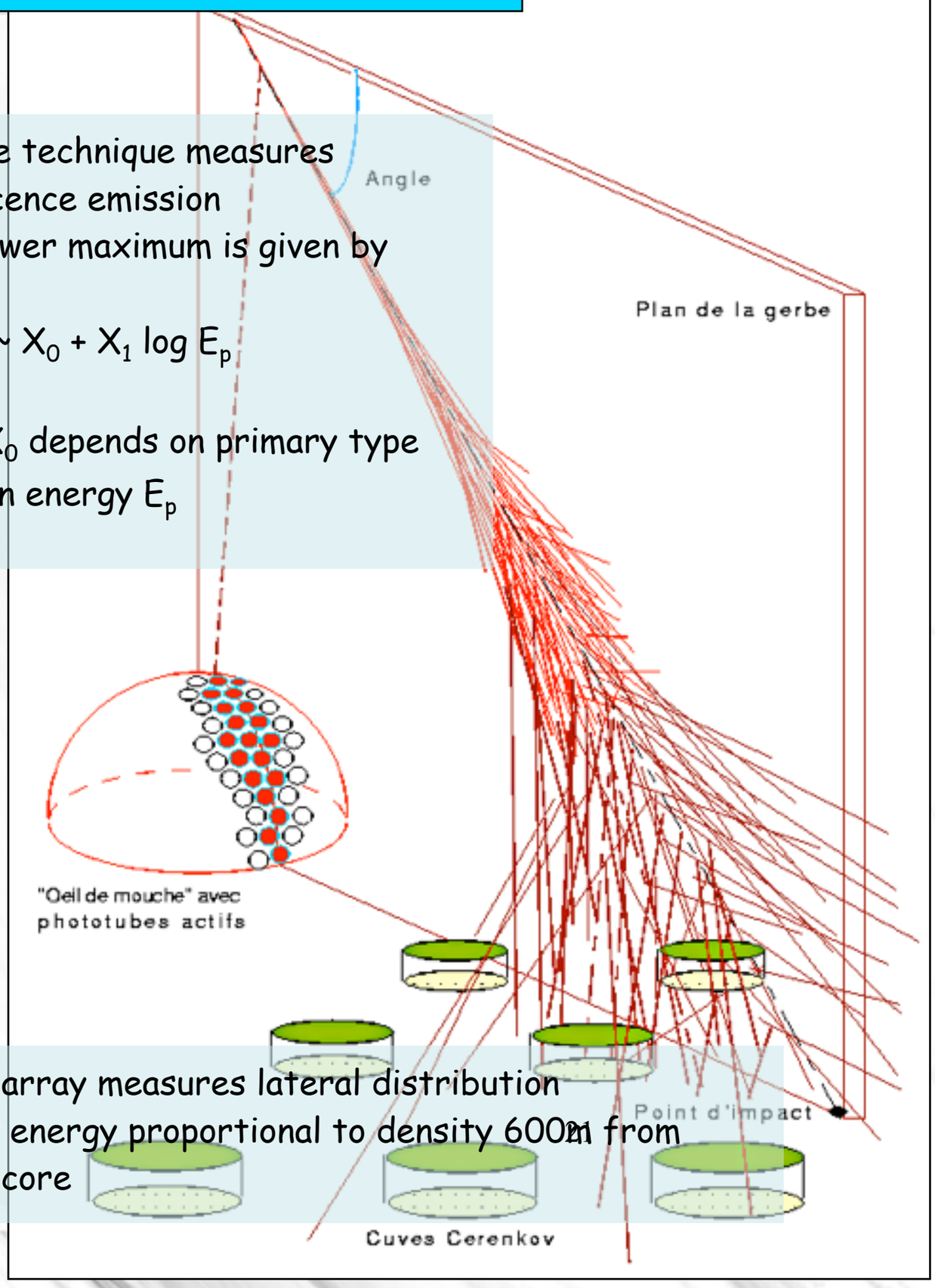
Atmospheric Showers and their Detection



Fly's Eye technique measures fluorescence emission
The shower maximum is given by

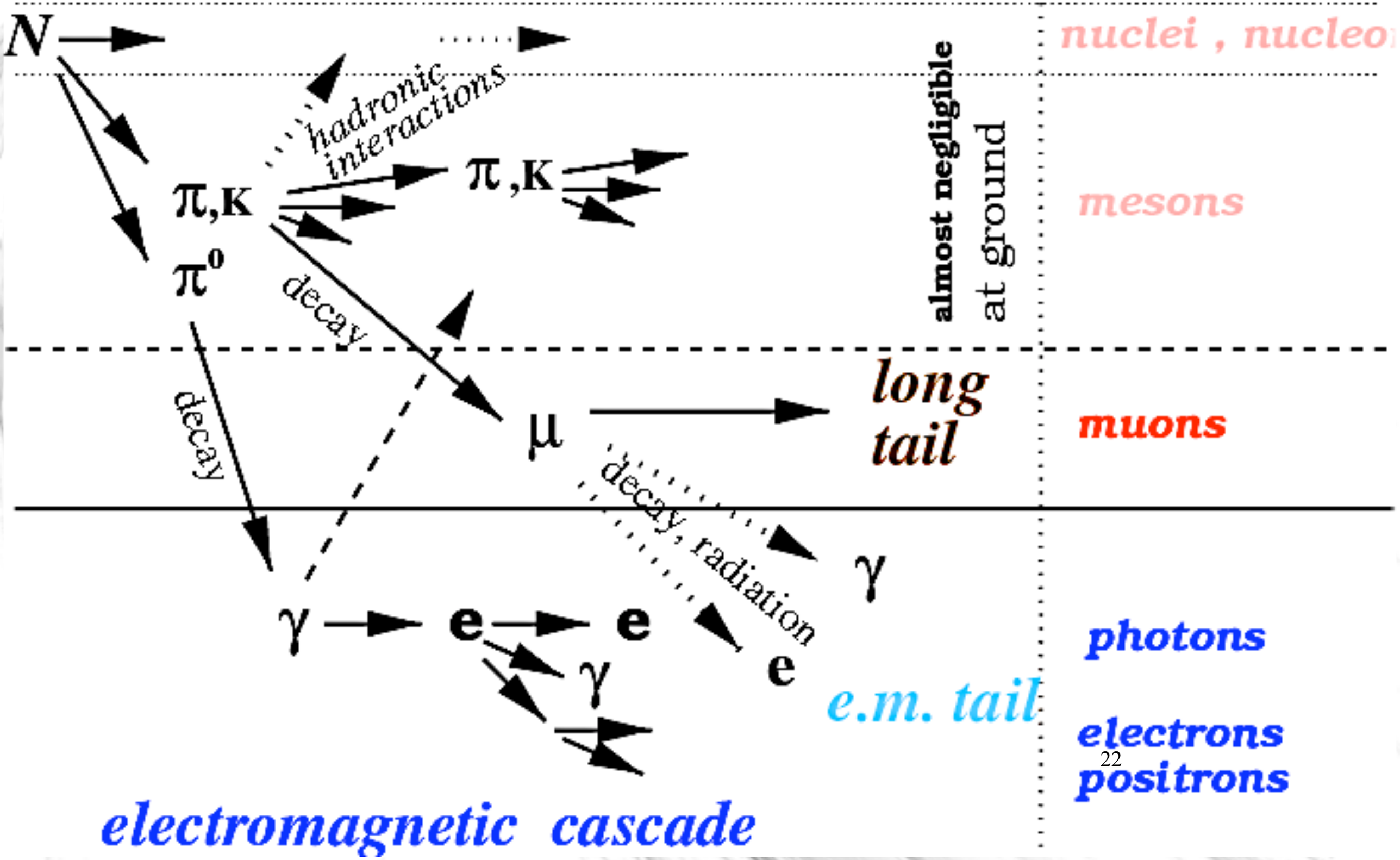
$$X_{max} \sim X_0 + X_1 \log E_p$$

where X_0 depends on primary type for given energy E_p

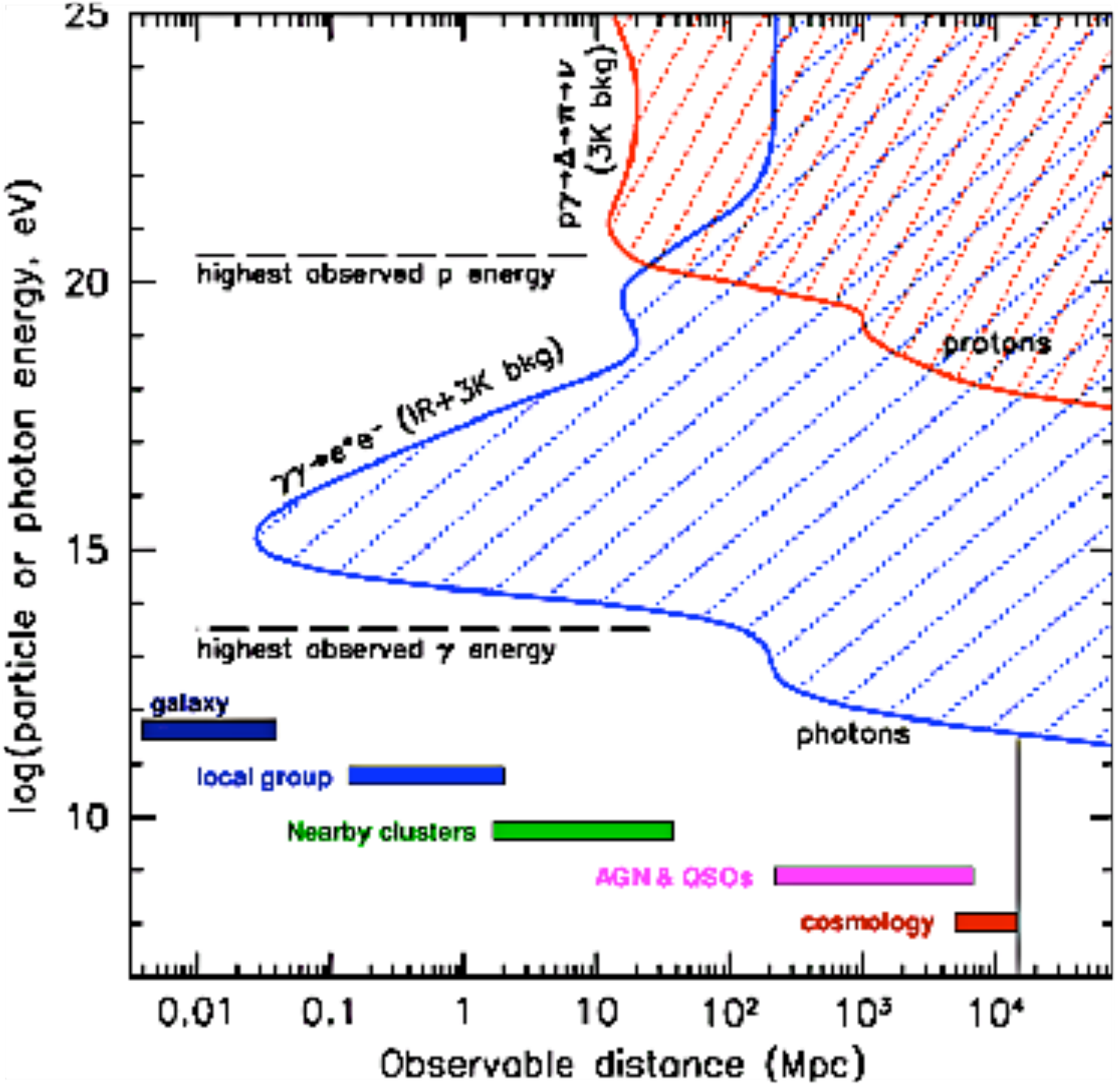


Ground array measures lateral distribution
Primary energy proportional to density 600m from shower core

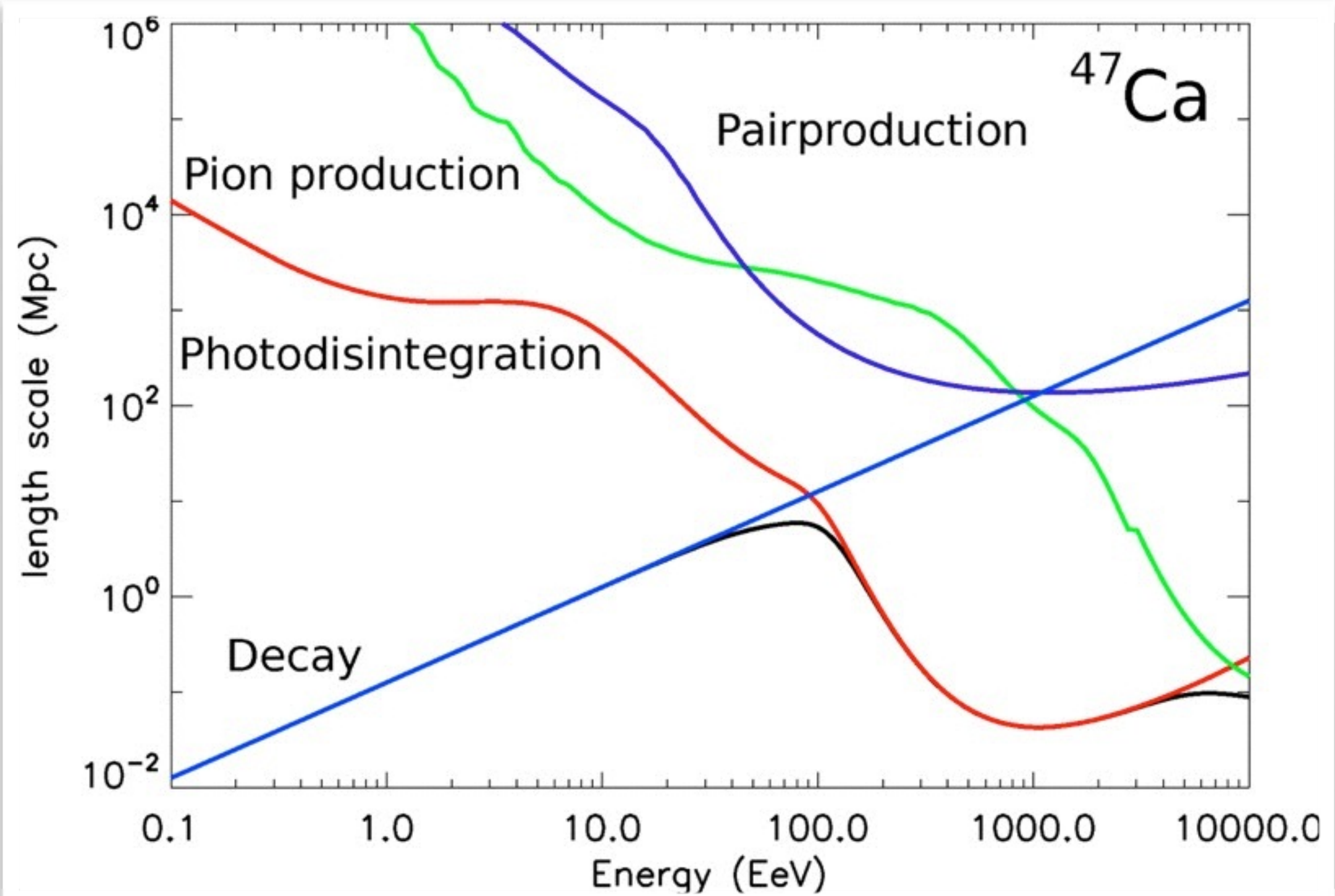
hadronic cascade



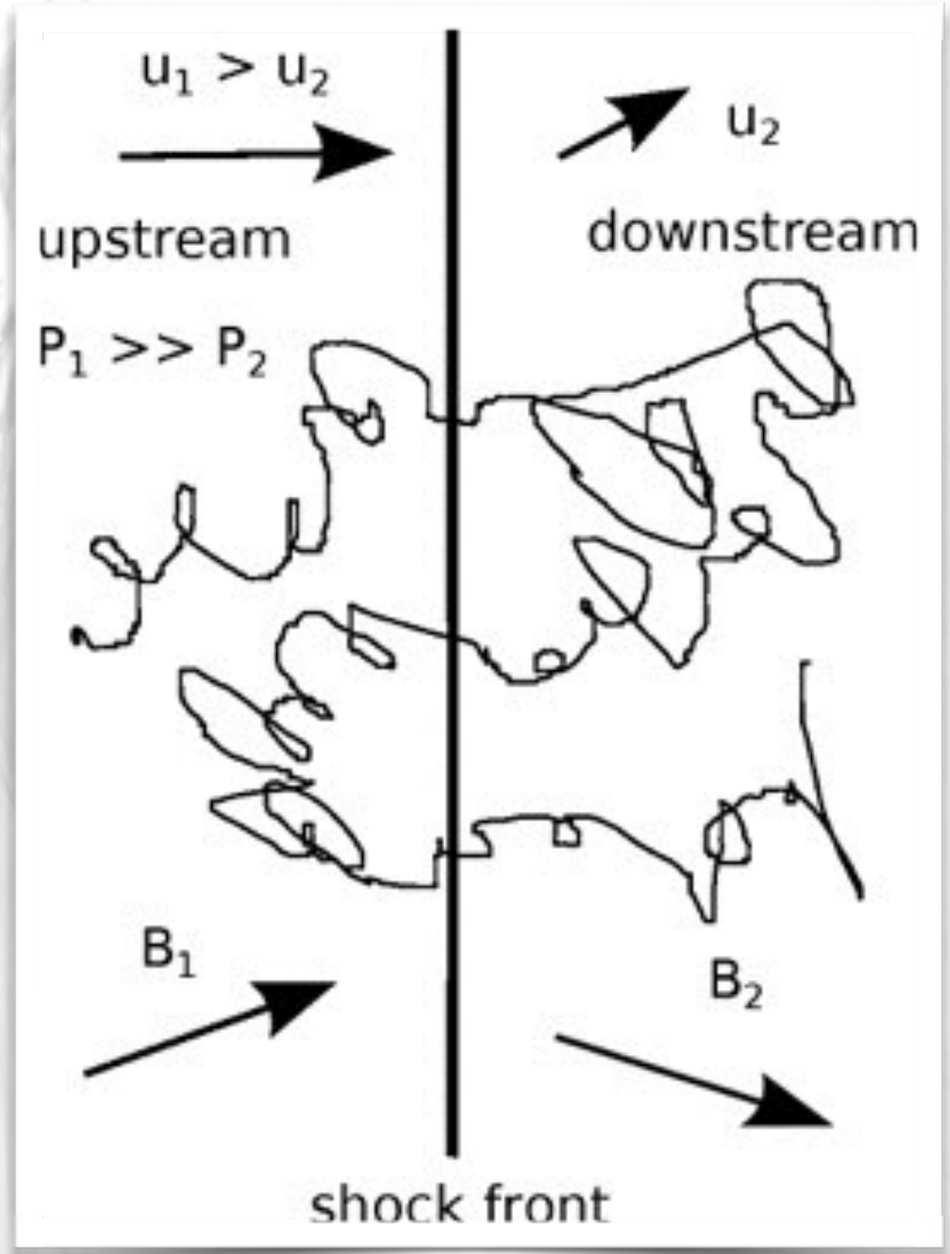
Interaction Horizons

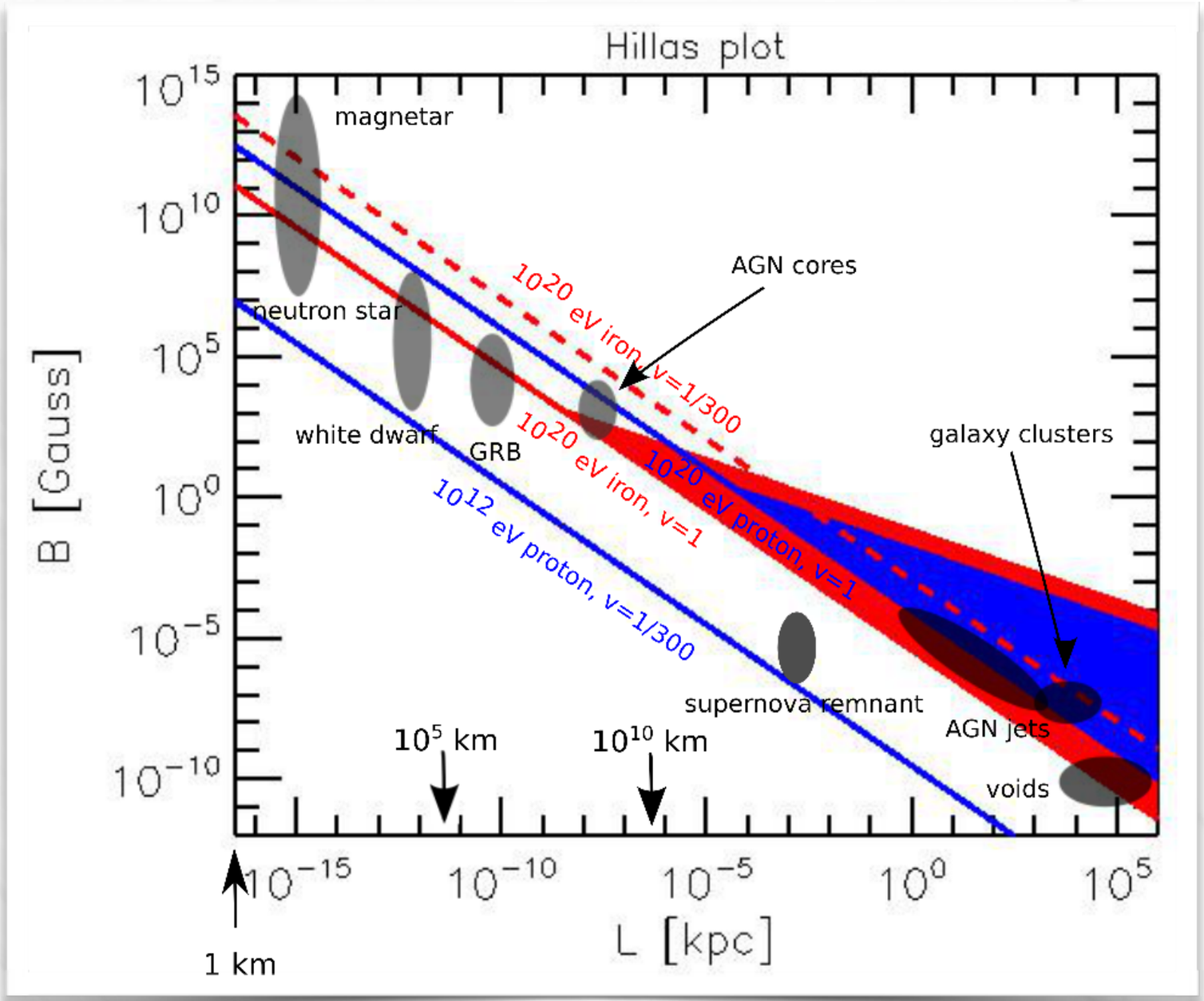


Length scales for relevant processes of a typical heavy nucleus



1st Order Fermi Shock Acceleration





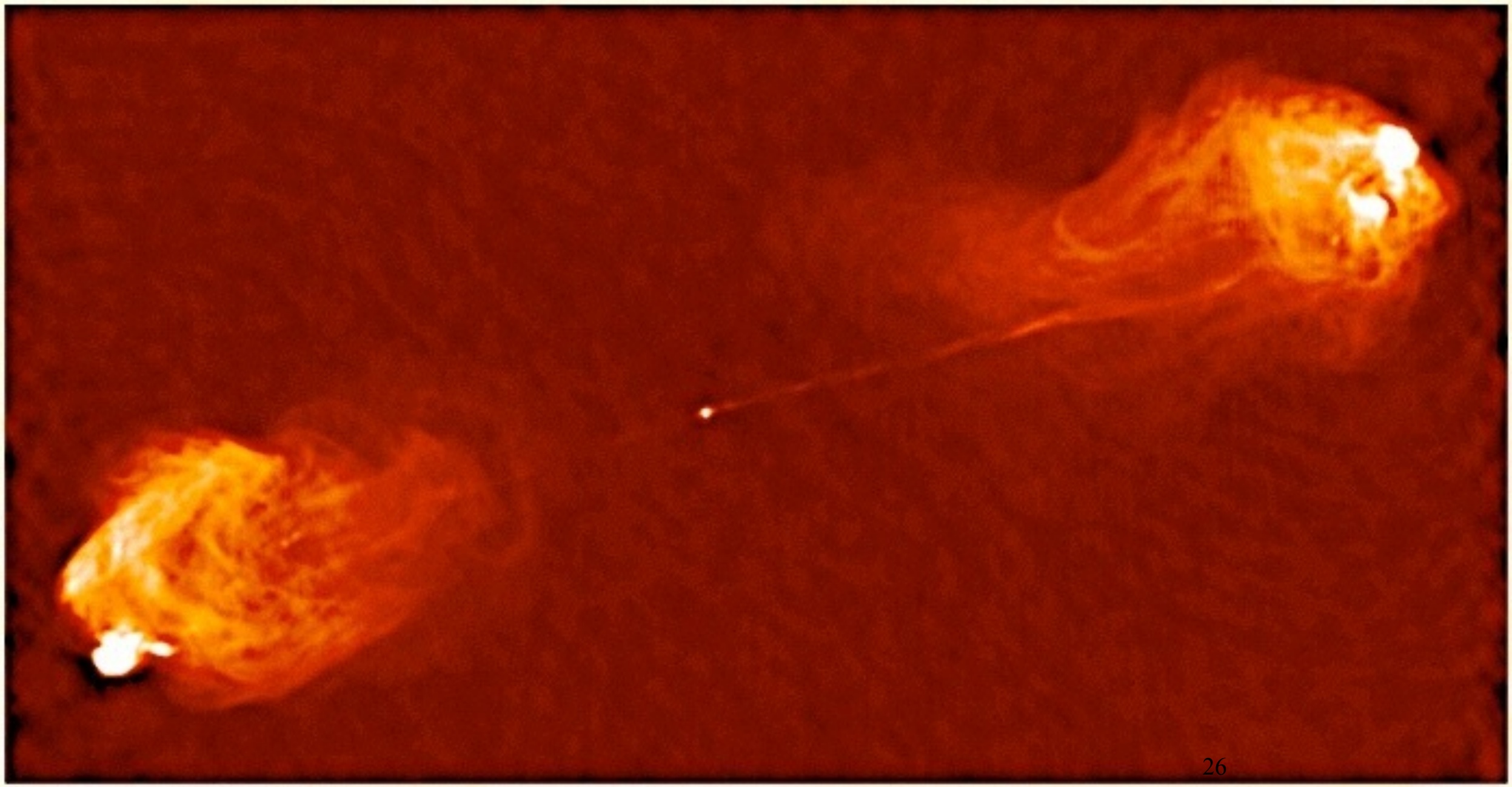
Fractional energy gain per shock crossing $\sim u_1 - u_2$ on a time scale r_L/u_2.

Together with downstream losses this leads to a spectrum E^{-q} with $q > 2$ typically.

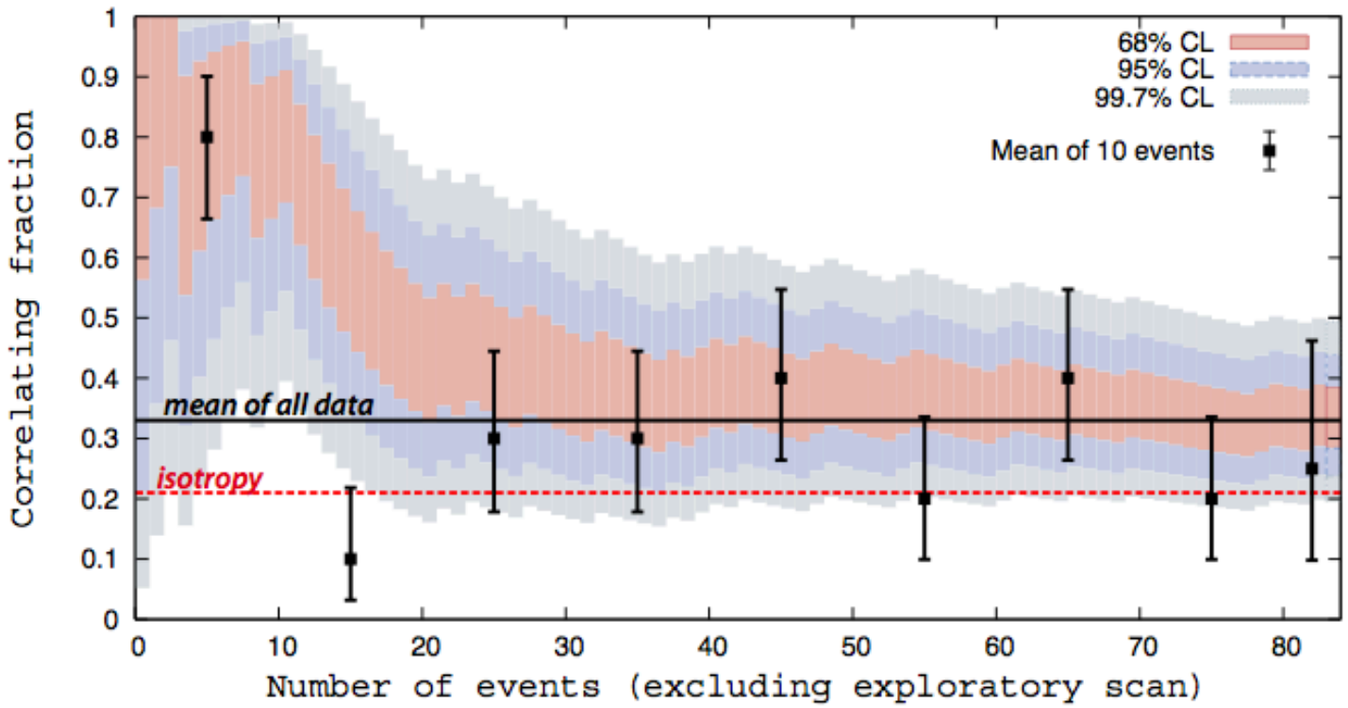
Confinement, gyroradius < shock size, and energy loss times define maximal energy

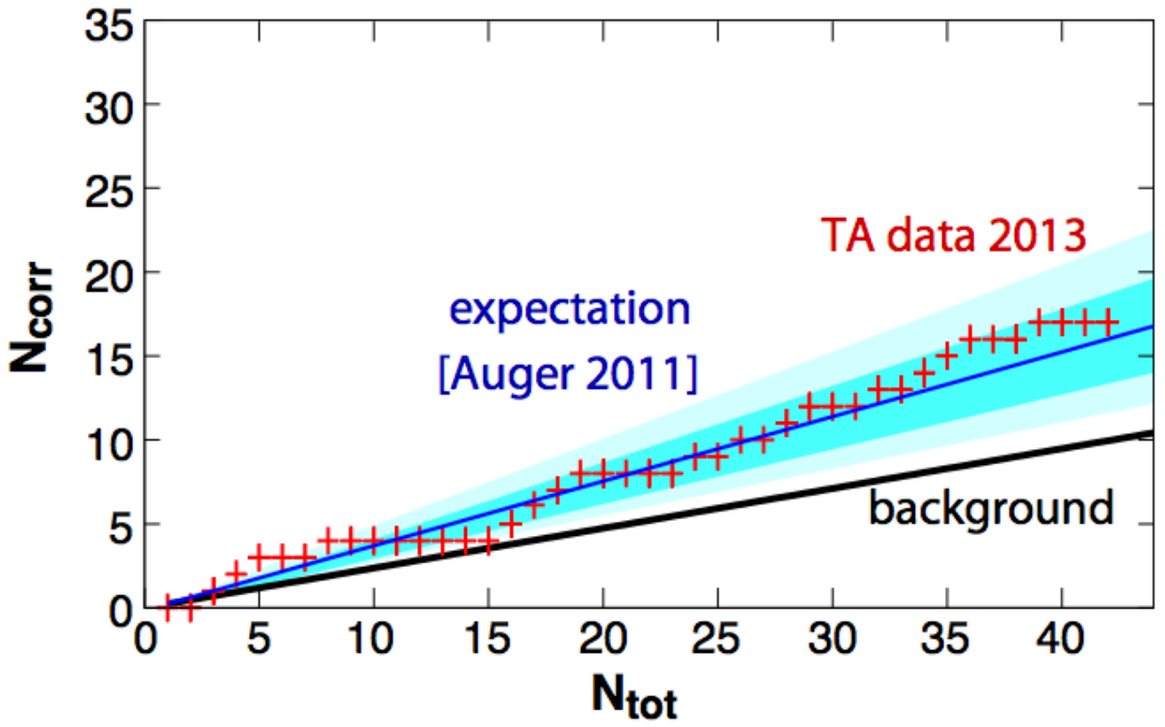
$r_{L_{25}}$

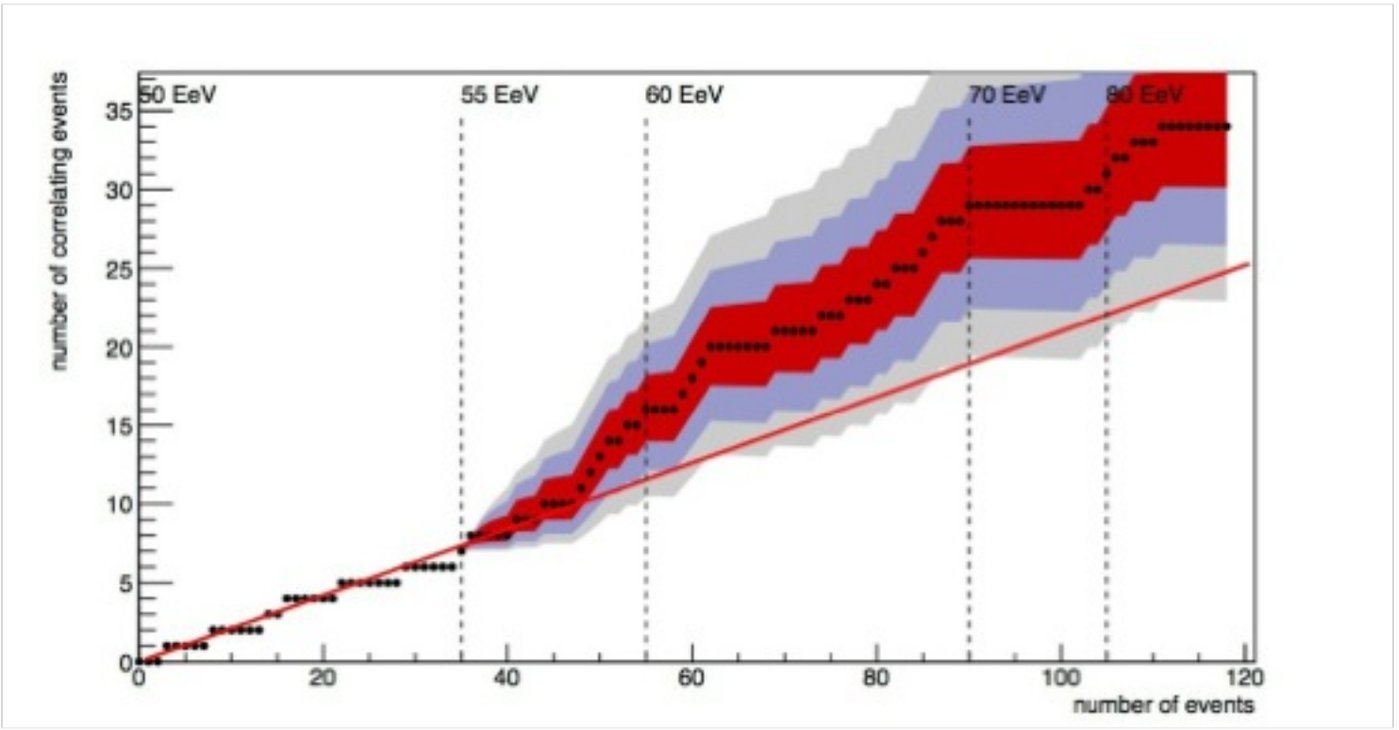
Possible Sources



Status of Large Scale UHECR Anisotropy

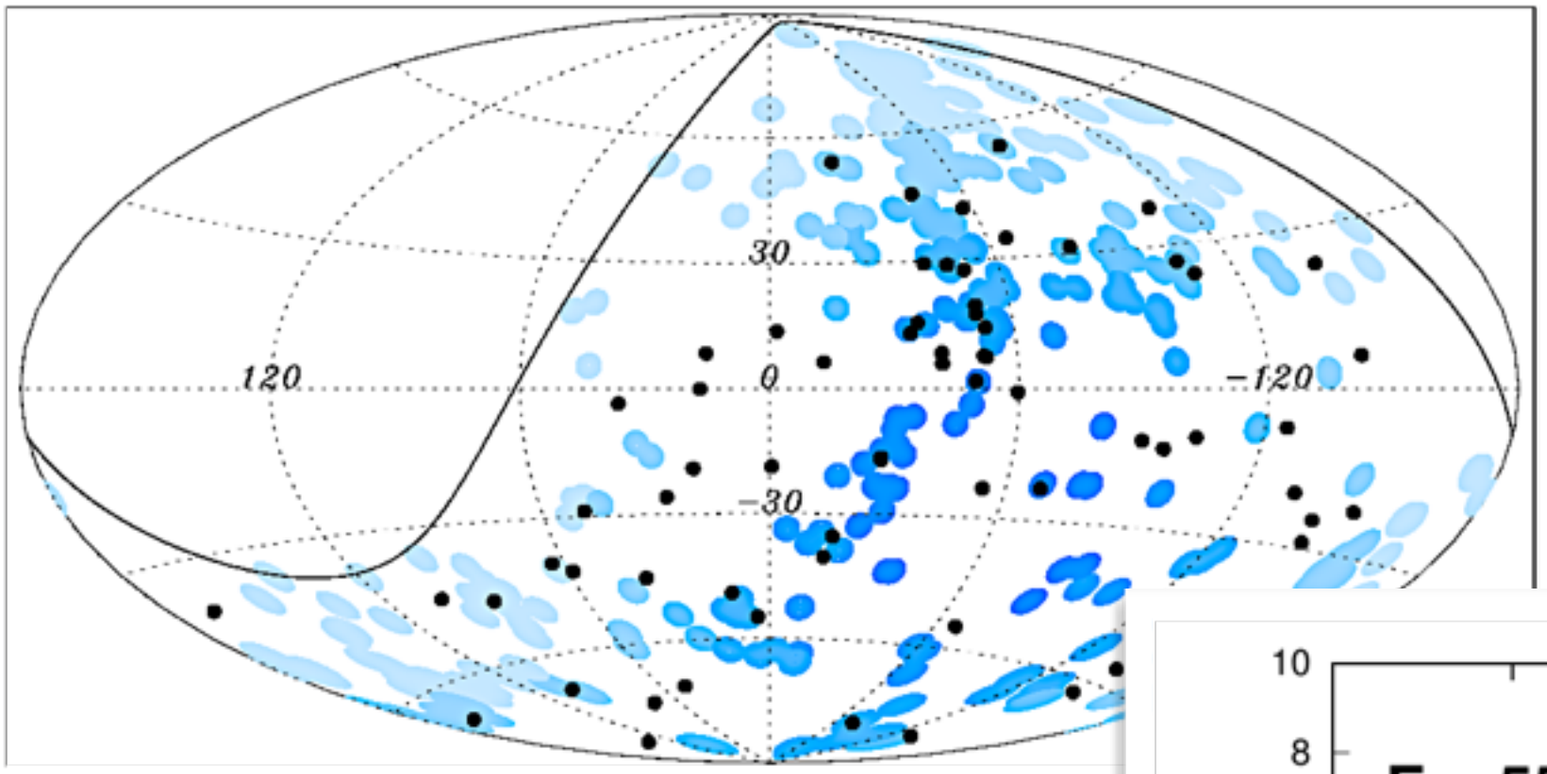






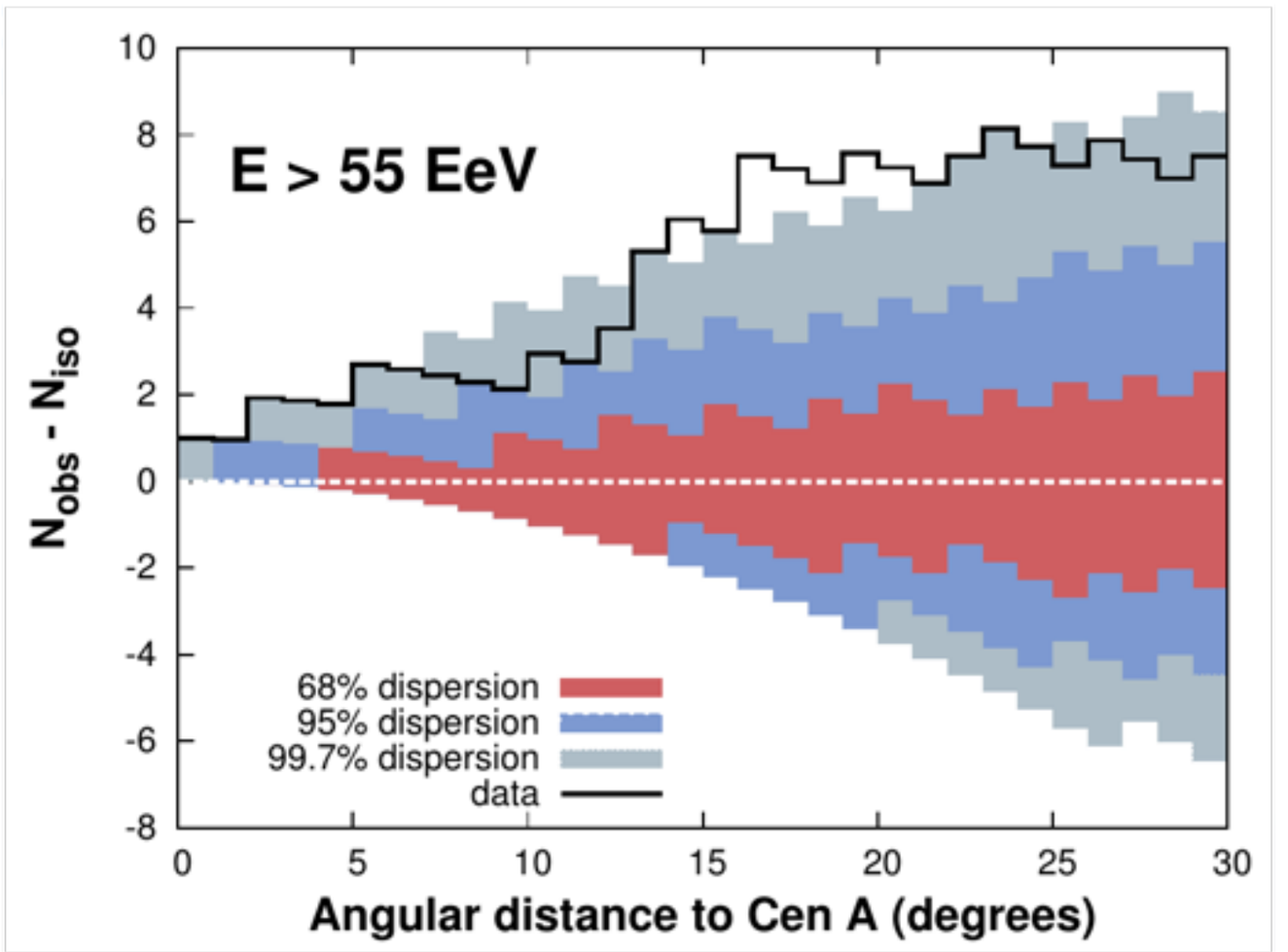
Kampert and Tinyakov,arXiv:1405.0575

Centaurus A is a UHECR source candidate



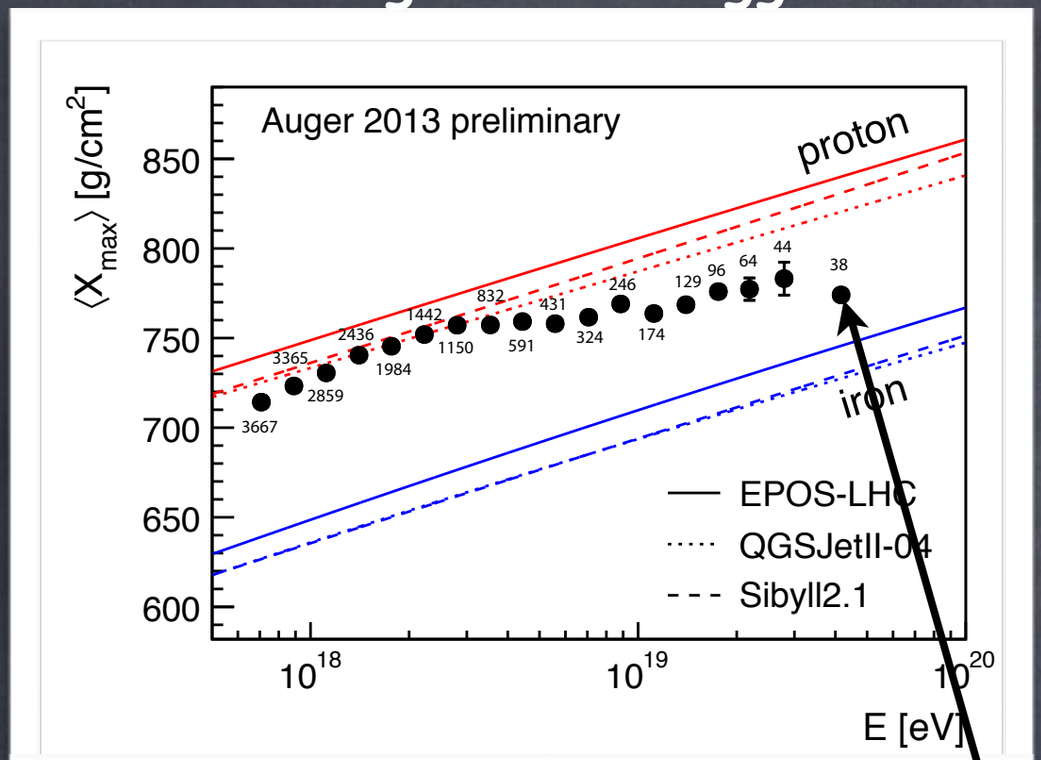
Pierre Auger Collaboration,
Astropart.Phys. 34 (2010) 314

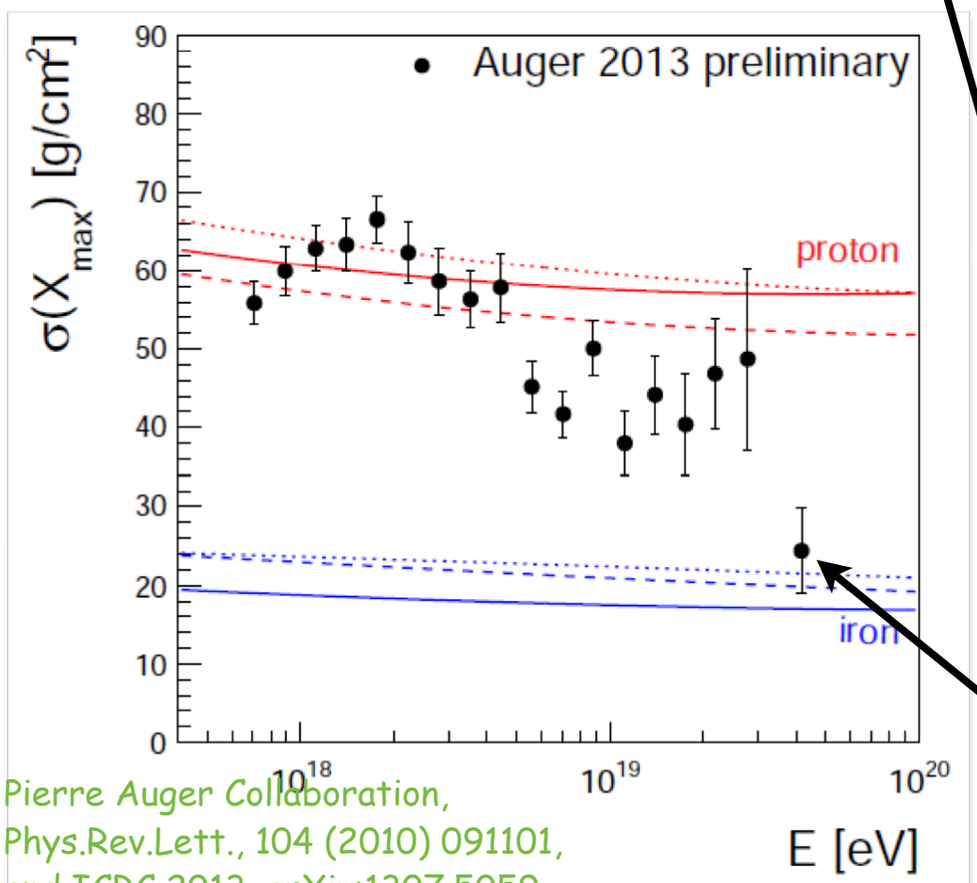
Pierre Auger sees an excess
in the direction of Centaurus A
above 55 EeV



Kampert and Tinyakov,arXiv:1405.0575

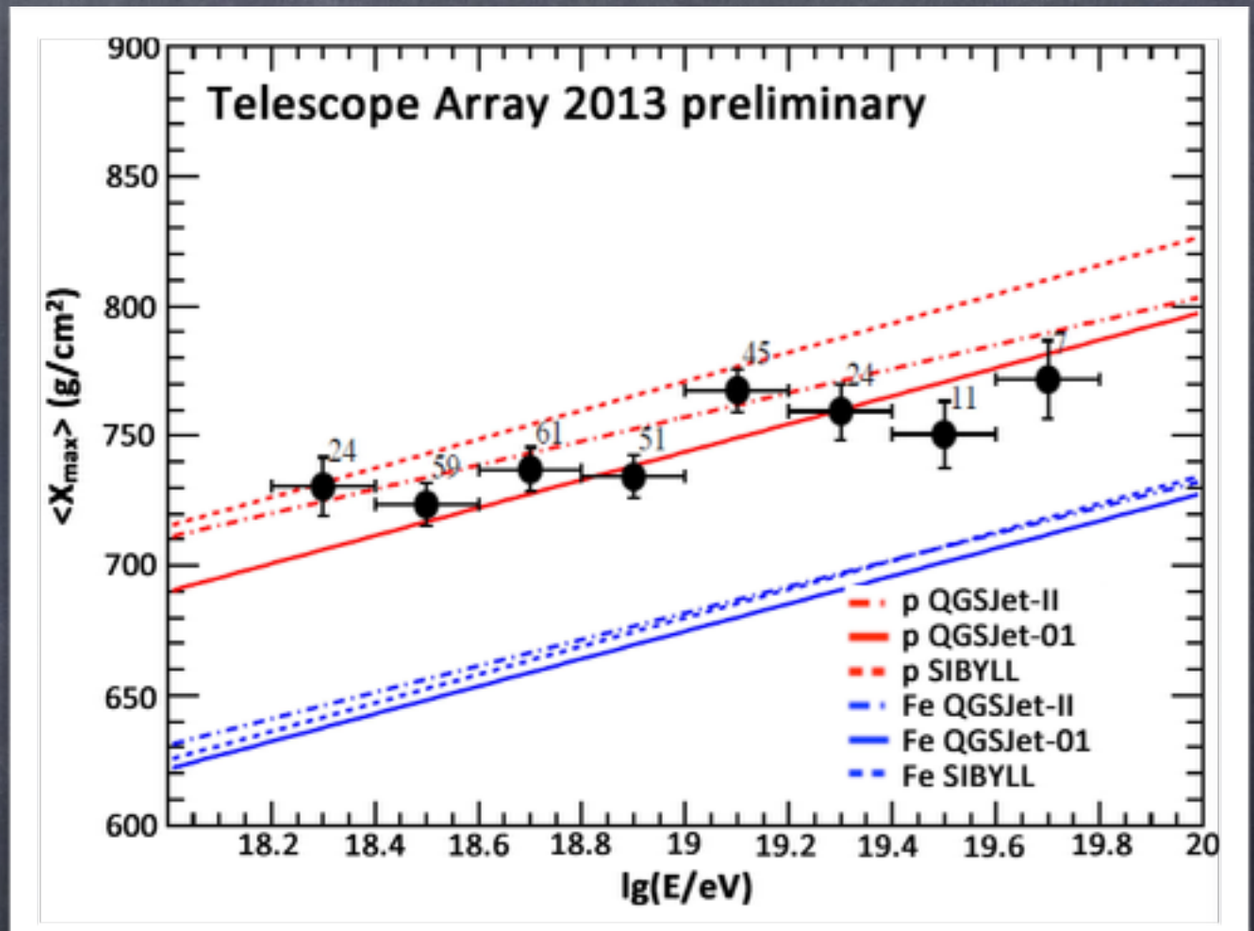
Pierre Auger data suggest a heavier composition toward highest energies:





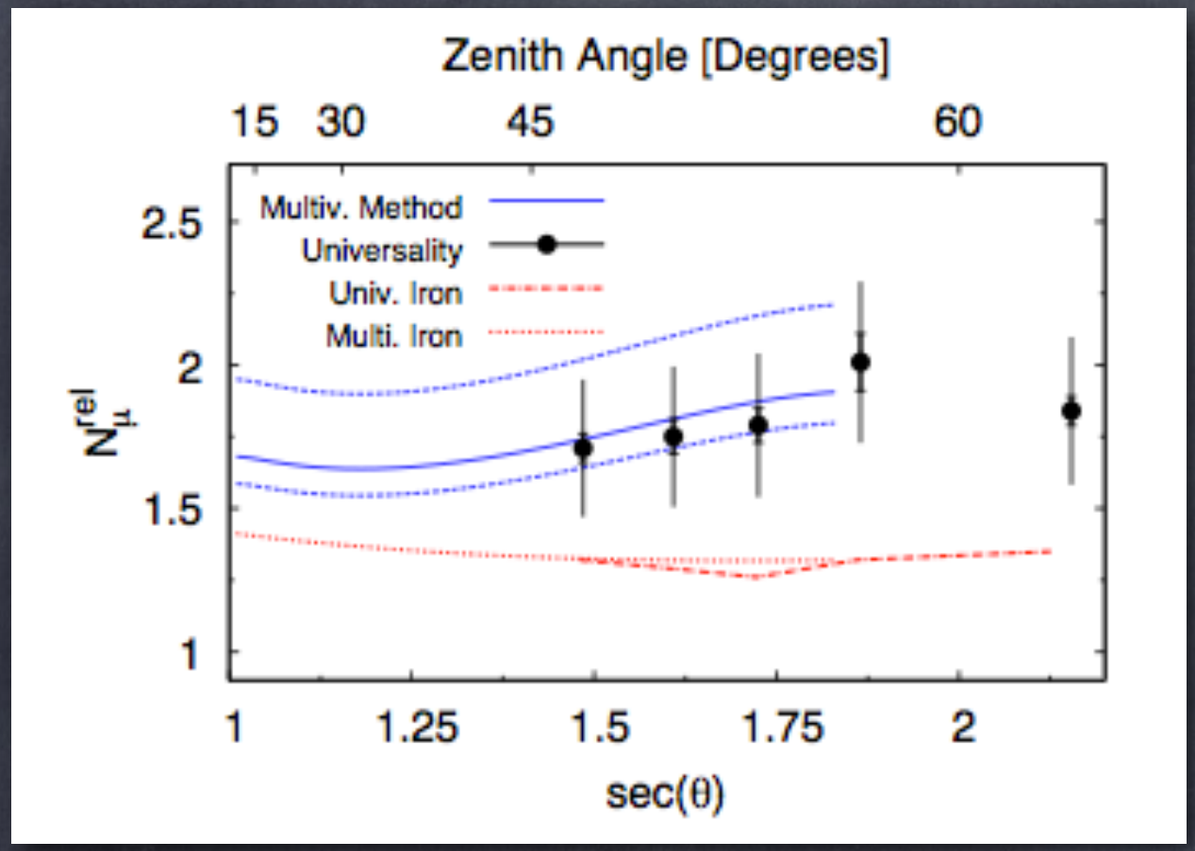
Pierre Auger Collaboration,
Phys.Rev.Lett., 104 (2010) 091101,
and ICRC 2013, arXiv:1307.5059

but not confirmed on the northern hemisphere by HiRes and Telescope Array which are consistent with protons

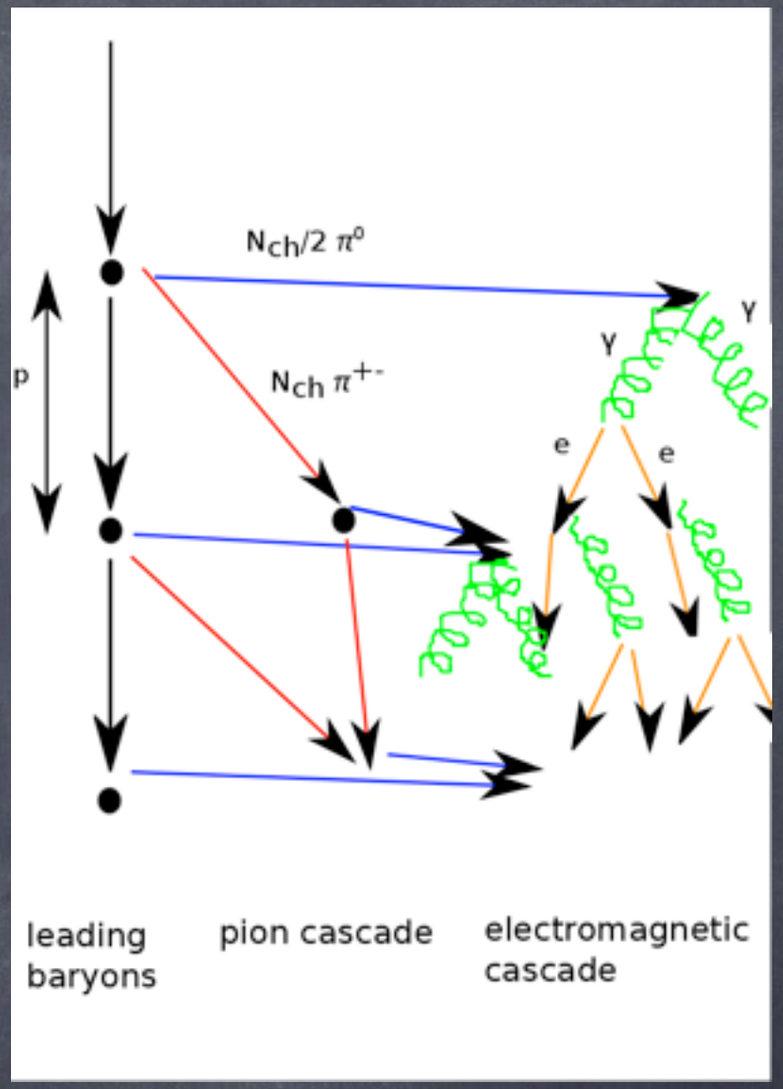


potential tension with air shower simulations and some hadronic interaction models because a mixed composition would predict larger RMS(X_{max})

Muon number measured at 1000 m from shower core a factor ~2 higher than predicted



Pierre Auger Collaboration, ICRC 2011, Allen et al., arXiv:1107.4804

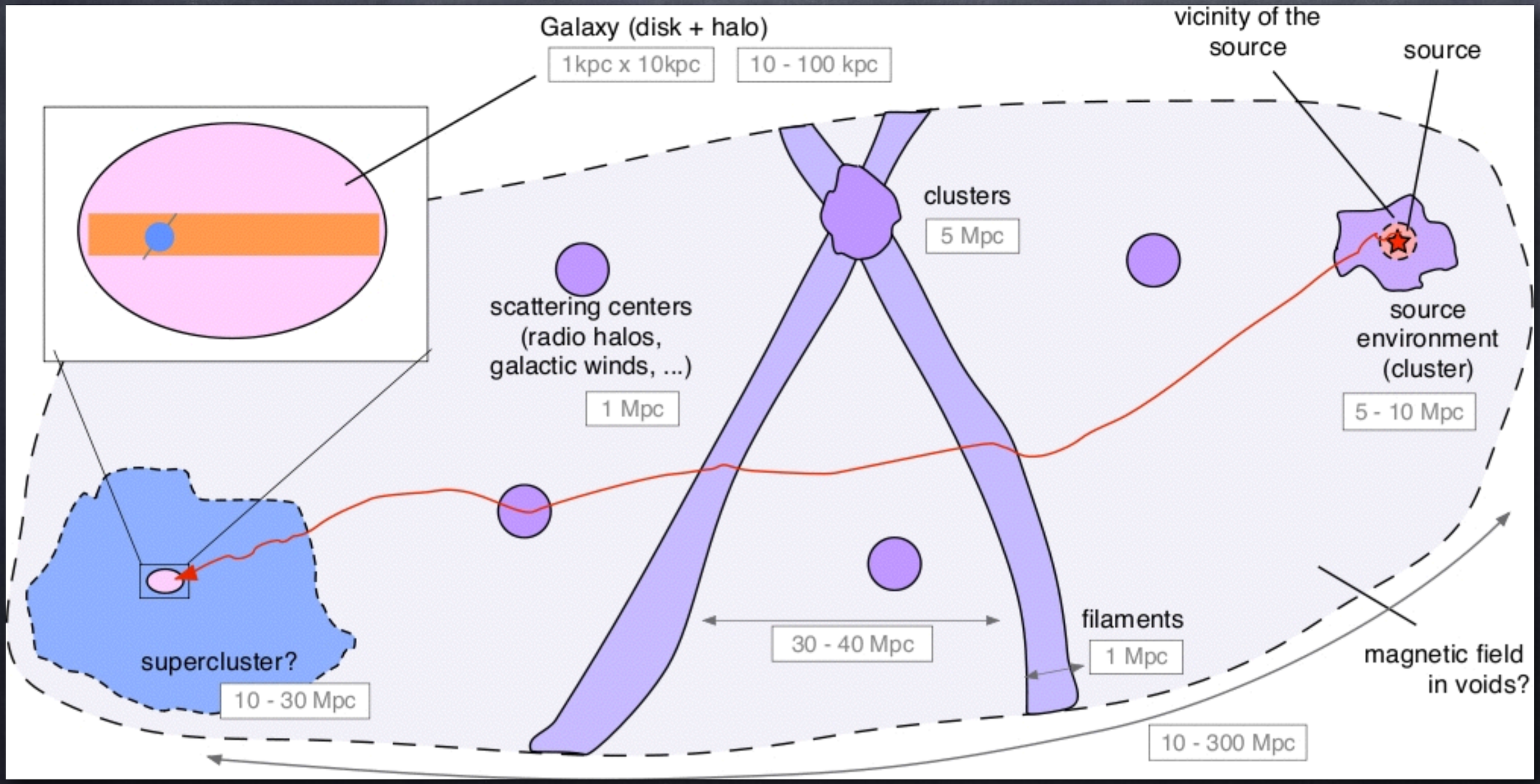


The muon number scales as

$$N_\mu \propto E_{\rm had} \propto (1 - f_{\pi^0})^N \ ,$$

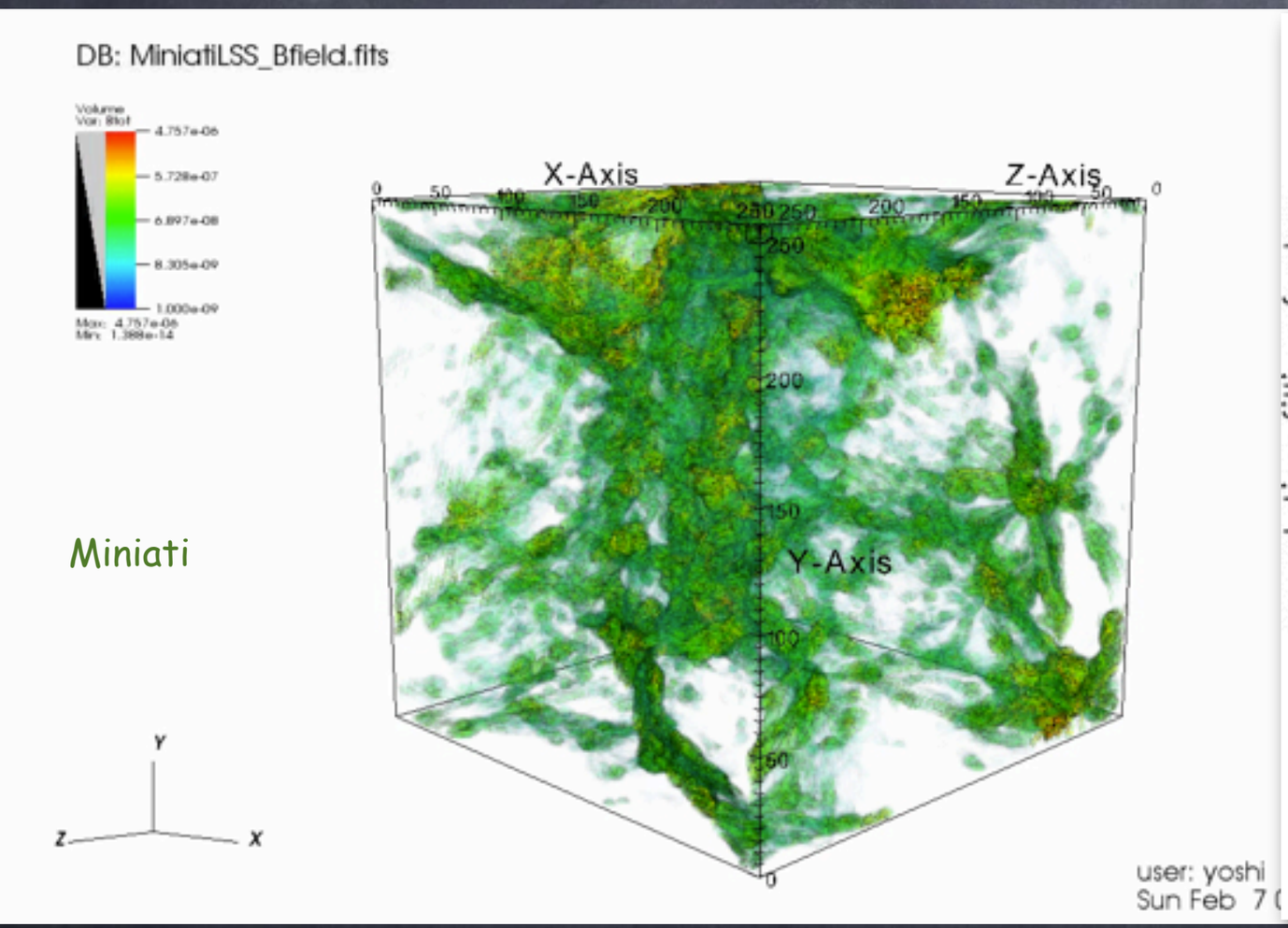
with the fraction going into the electromagnetic channel $f_{\pi^0} \simeq \frac{1}{3}$ and the number of generations N strongly constrained by $X_{\rm max}$. Larger N_μ thus requires smaller f_{π^0} !

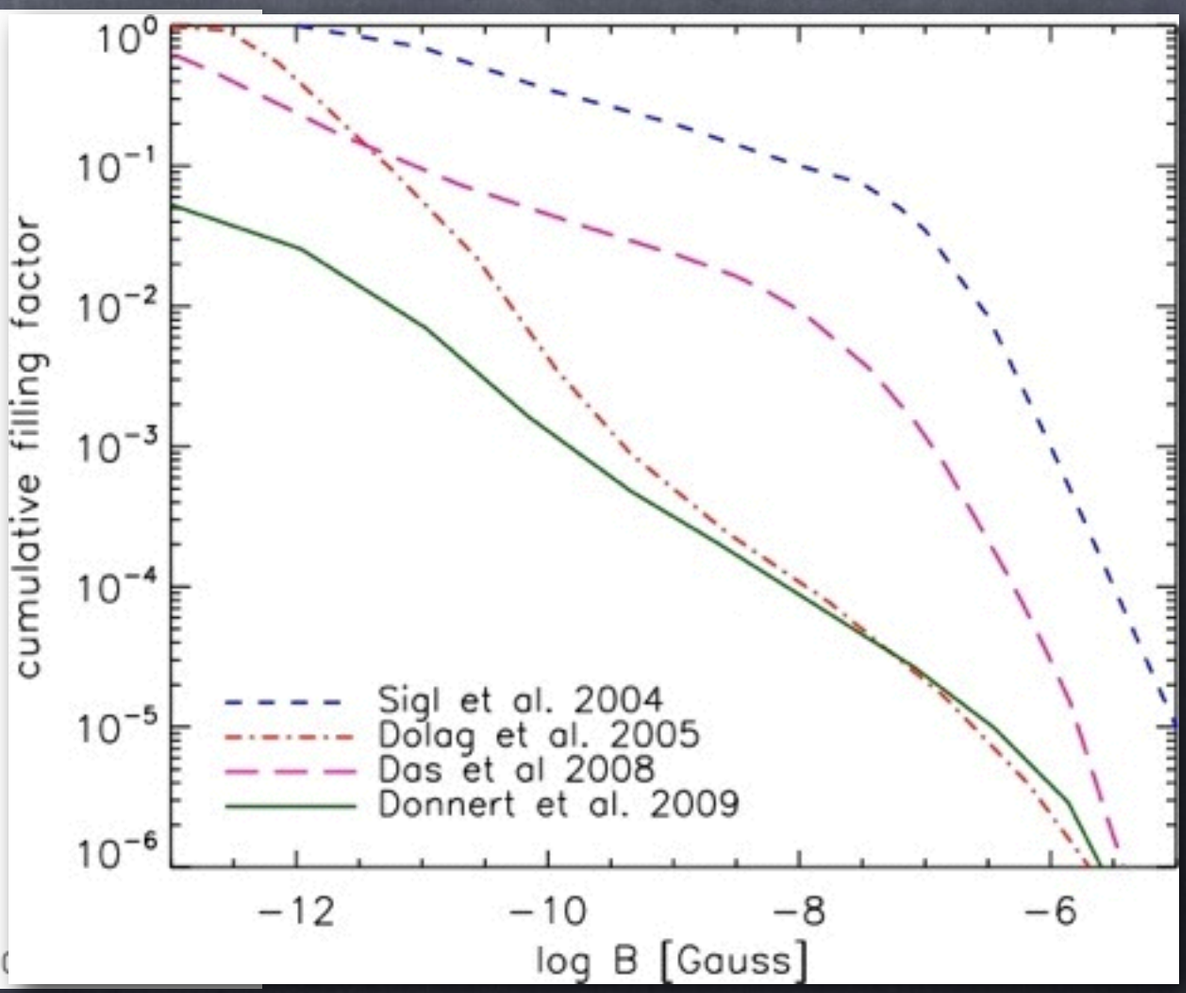
3-Dimensional Effects in Propagation



Kotera, Olinto, Ann.Rev.Astron.Astrophys. 49 (2011) 119

Structured Extragalactic Magnetic Fields

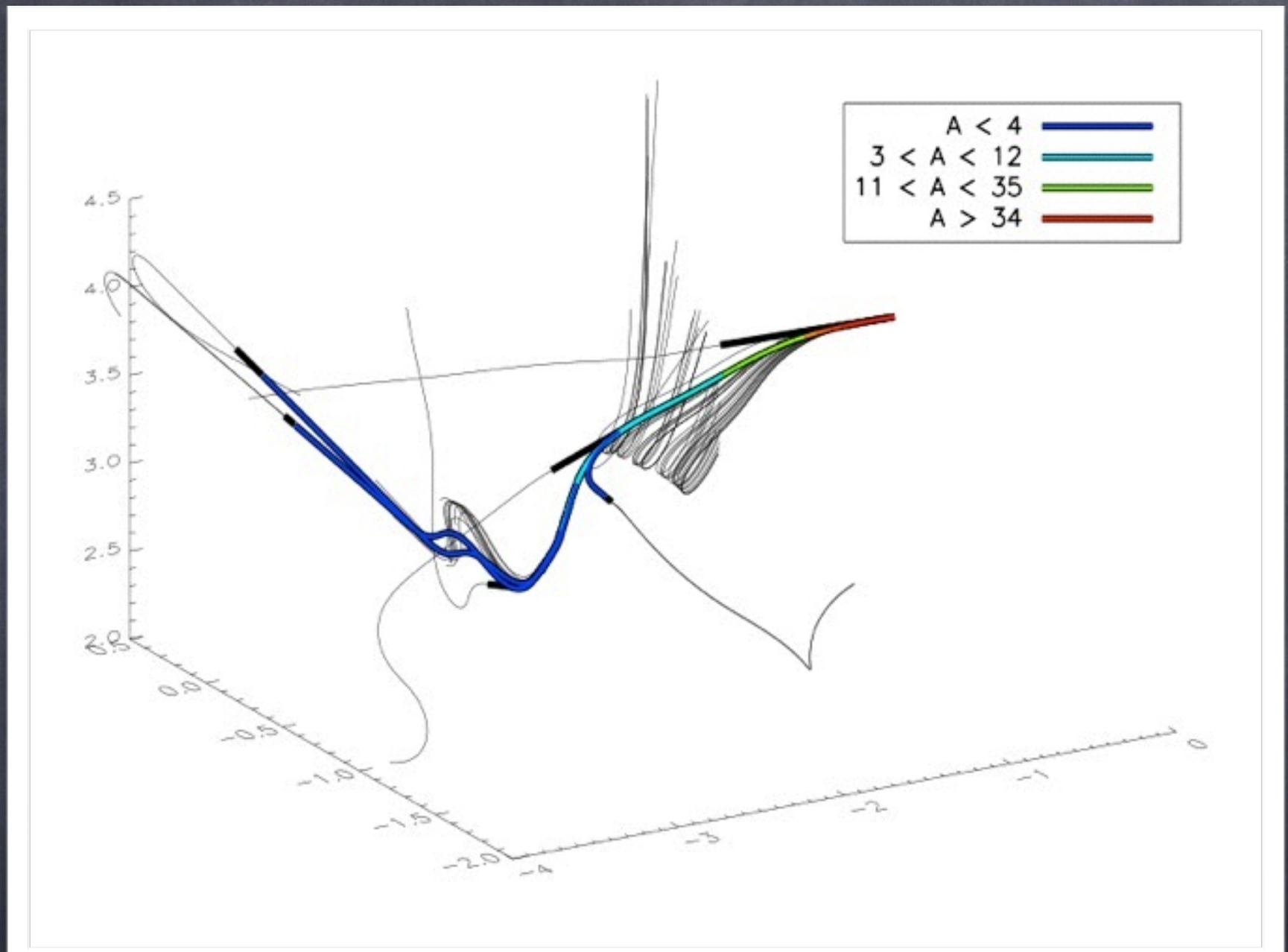




Kotera, Olinto, Ann.Rev.Astron.Astrophys. 49 (2011) 119

Filling factors of extragalactic magnetic fields are not well known and come out different in different large scale structure simulations

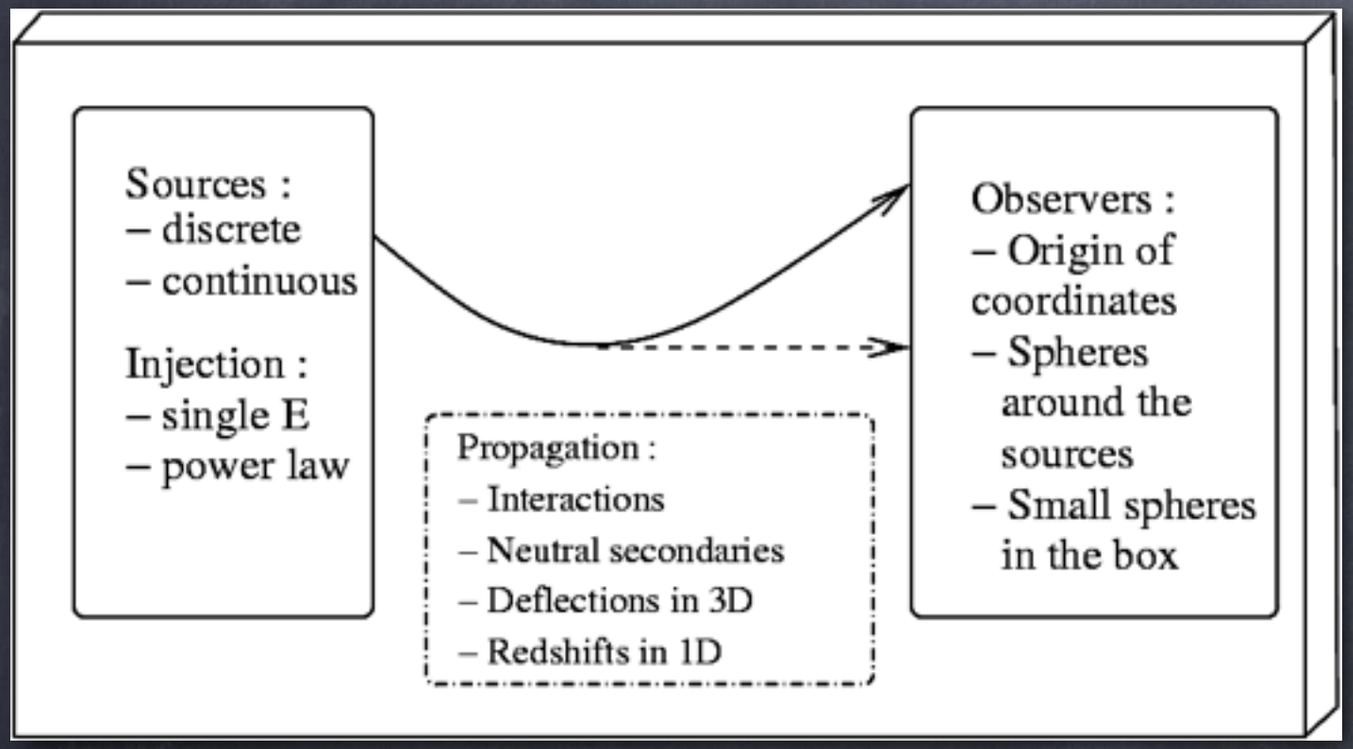
Extragalactic iron propagation produces nuclear cascades in structured magnetic fields:

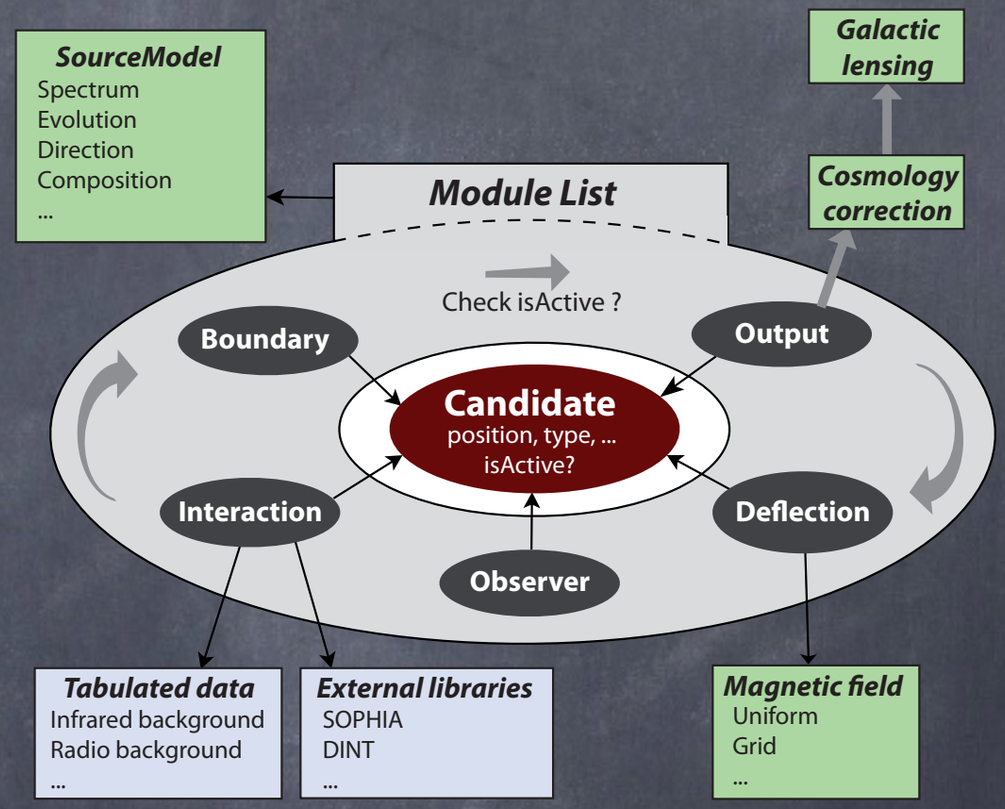


Initial energy 1.2 x 10^{21} eV, magnetic field range 10^{-15} to 10^{-6} G. Color-coded is the mass number of secondary nuclei

CRPropa 2.0/3.0

CRPropa is a public code for UHE cosmic rays, neutrinos and γ-rays being extended to heavy nuclei and hadronic interactions



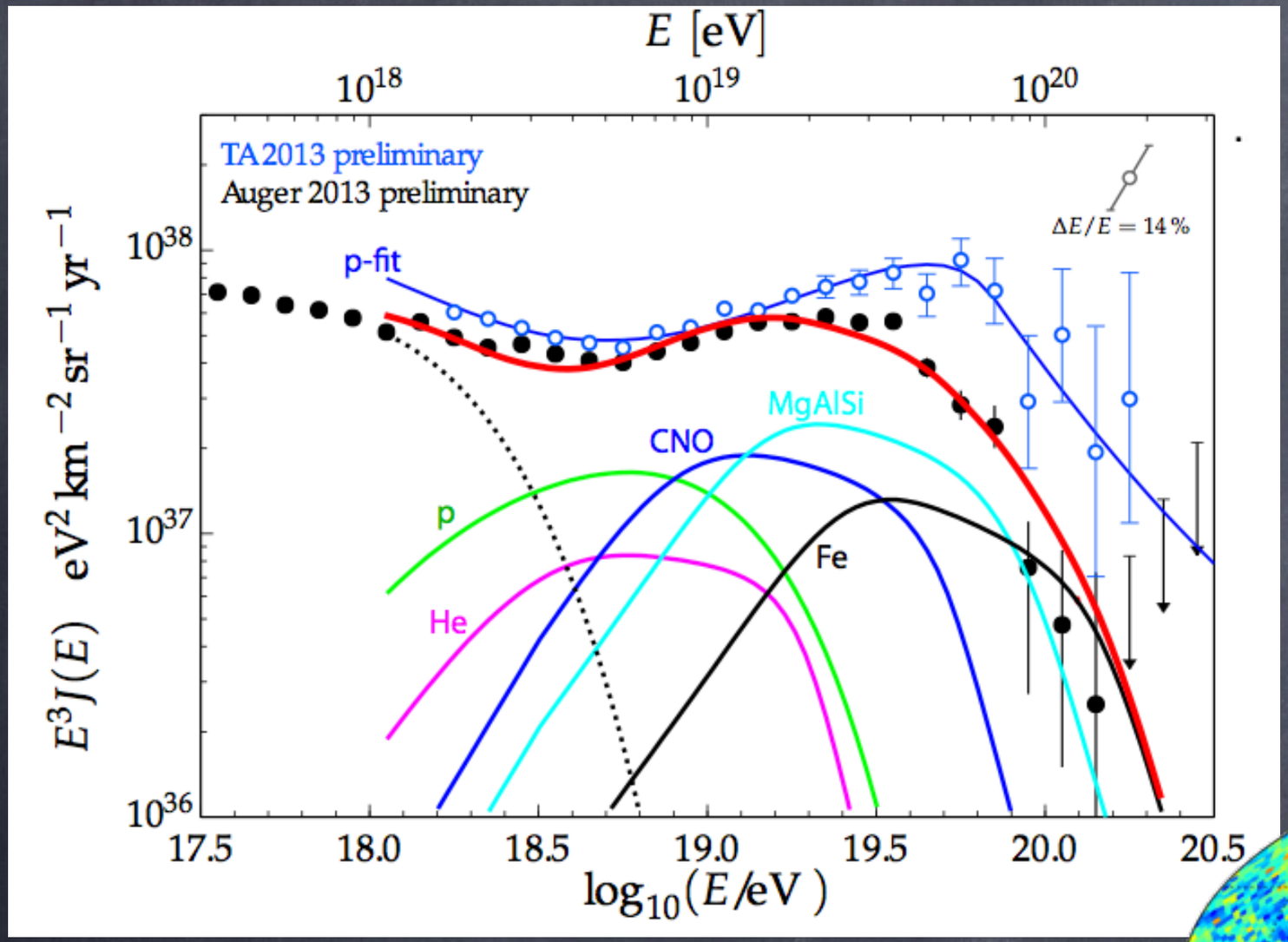


Version 1.4: Eric Armengaud, Tristan Beau, Günter Sigl, Francesco Miniati, Astropart.Phys.28 (2007) 463.

Version 2.0 at https://crpropa.desy.de/Main_Page

Version 3.0: Luca Maccione, Rafael Alves Batista, David Walz, Gero Müller, Nils Nierstenhoefer, Karl-Heinz Kampert, Peter Schiffer, Arjen van Vliet Astroparticle Physics 42 (2013) 41

Building Benchmark Scenarios

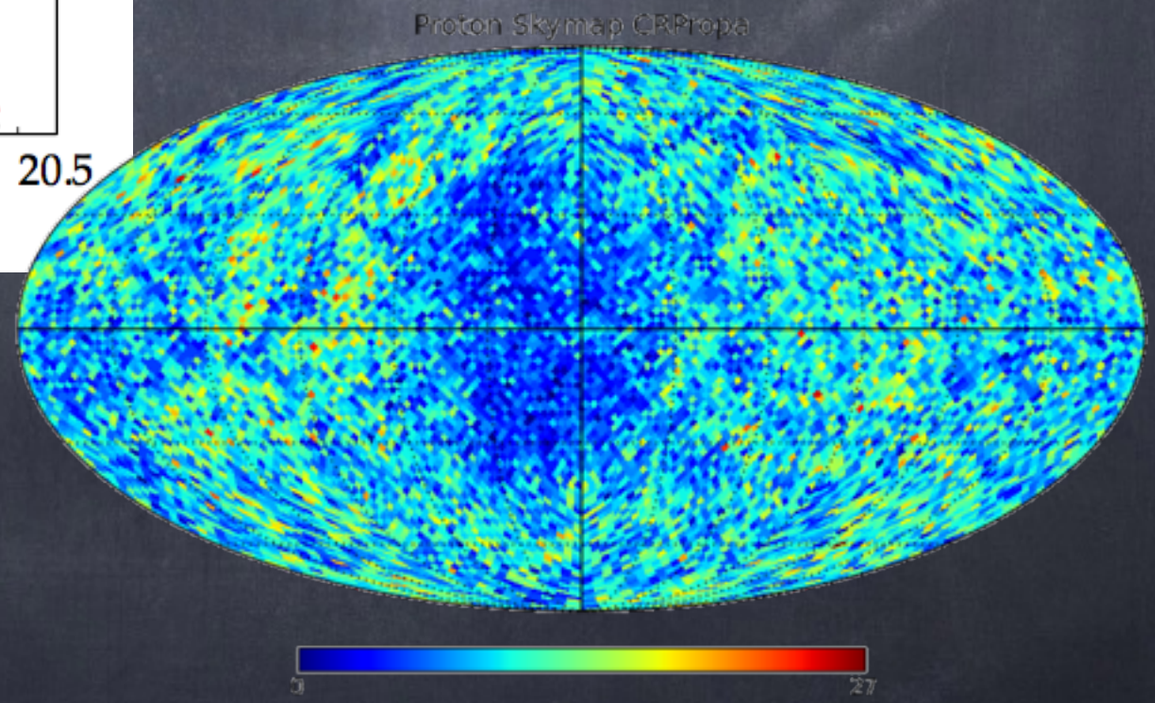


TA fit (red): pure proton injection

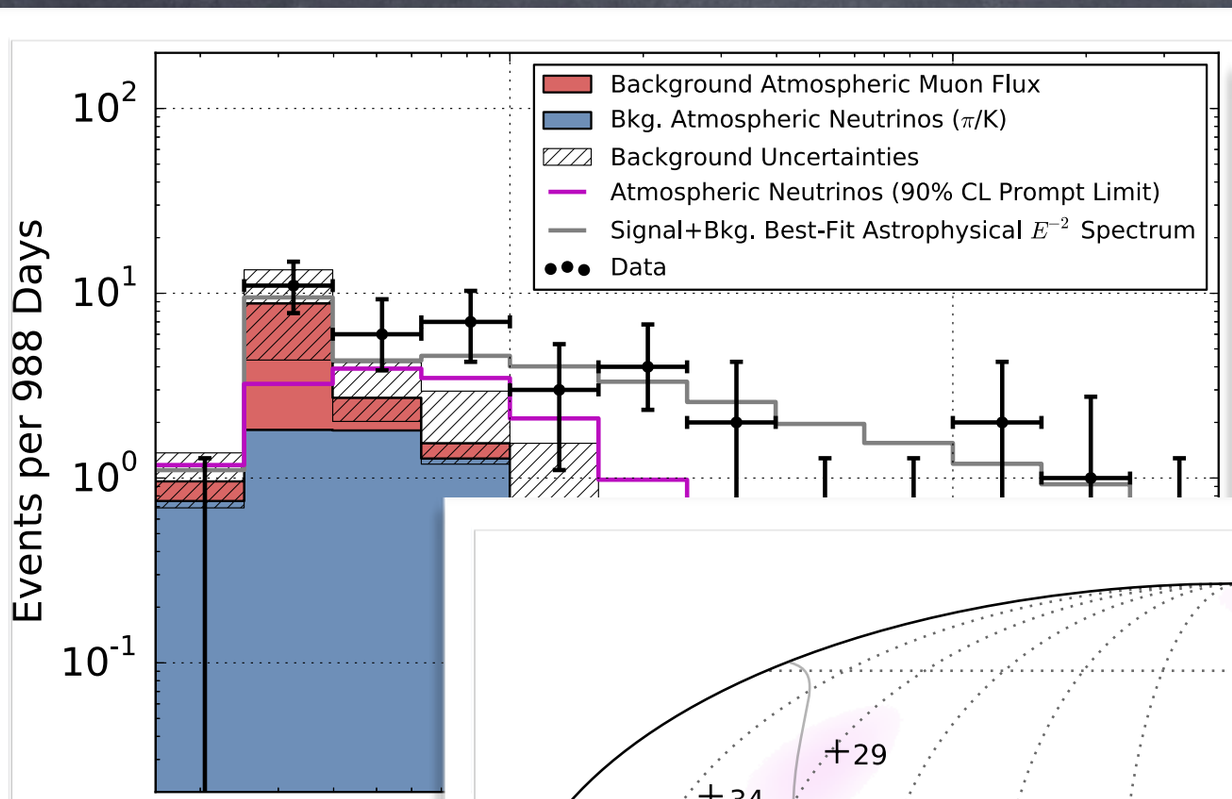
rate ∝ $(1+z)^{4.4}$ $E^{-2.36}$

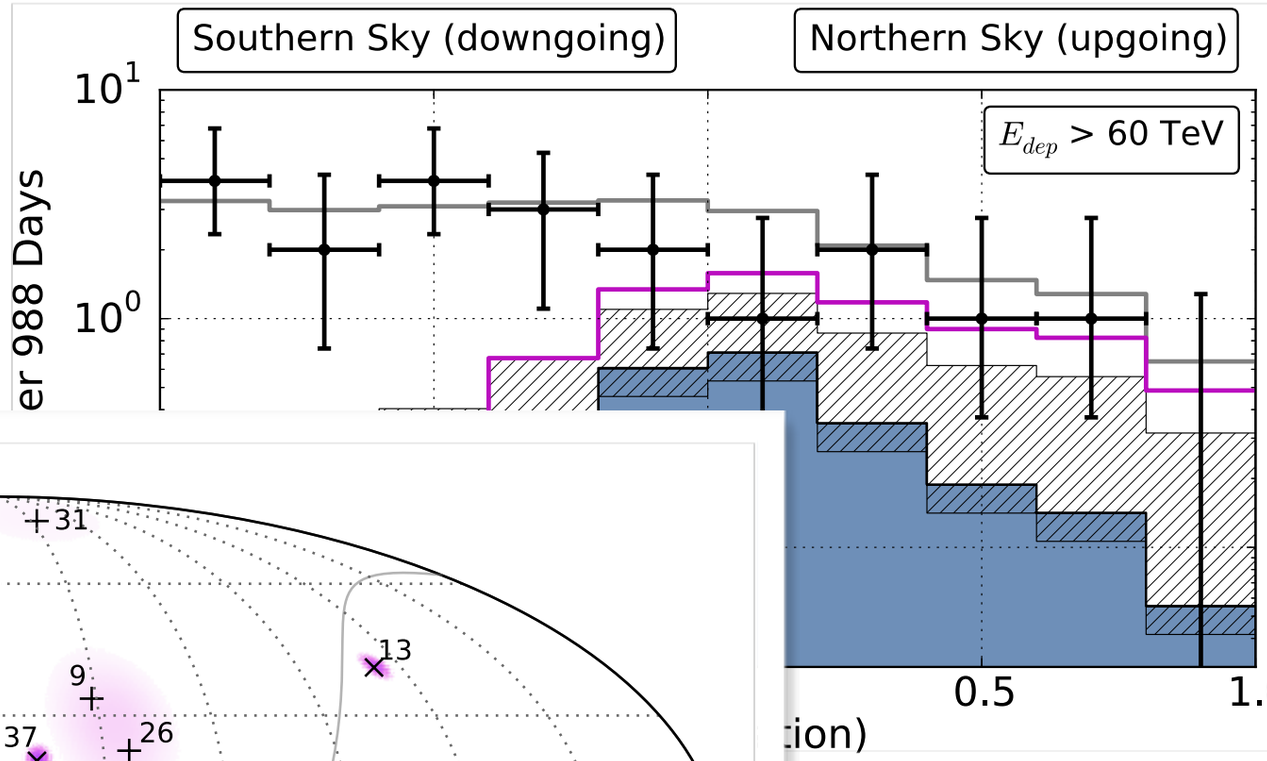
Auger fit: enhanced galactic

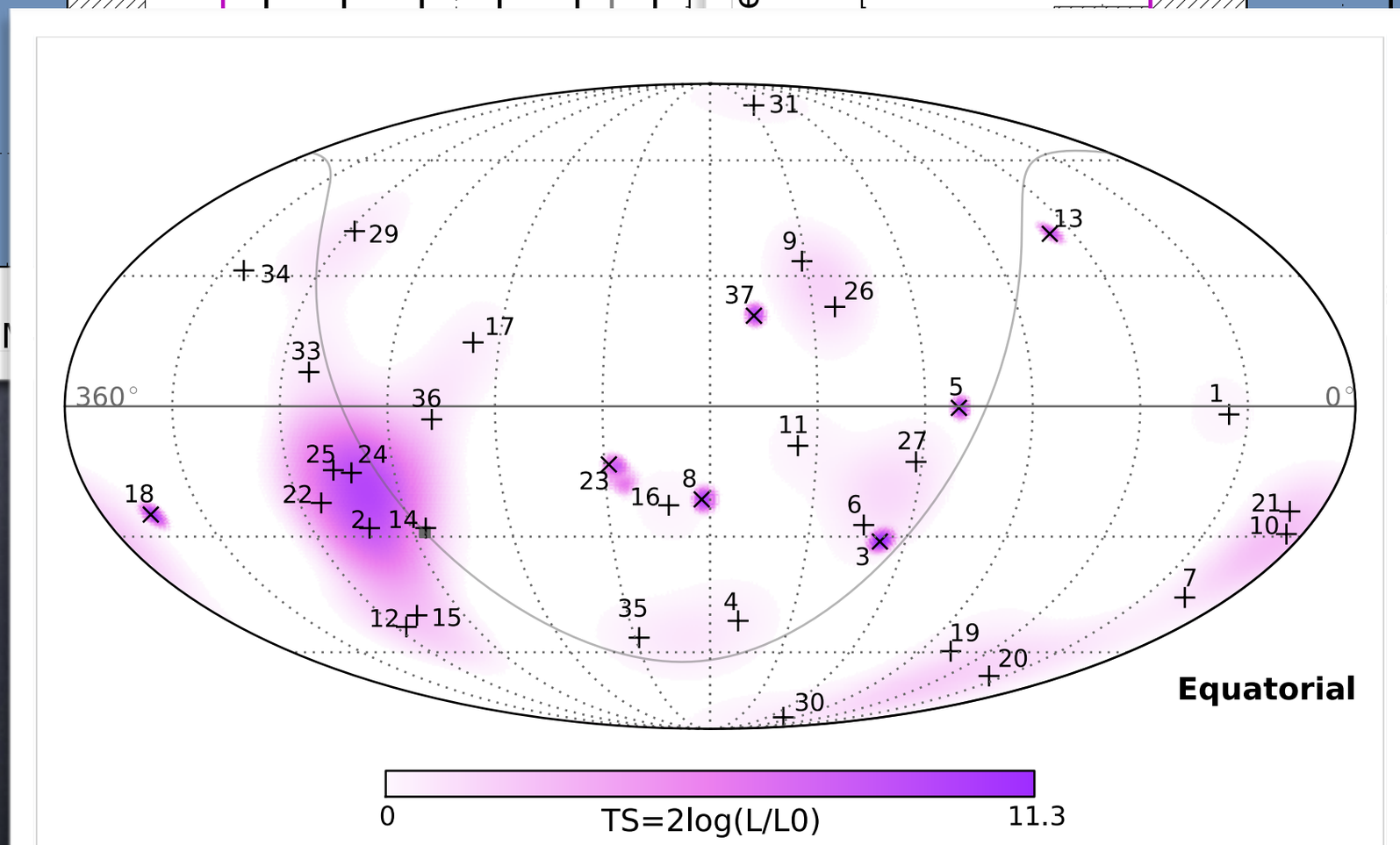
composition ∝ $E^{-1.8}$ up to $10^{18.7}$ eV*Z



IceCube started neutrino astronomy !



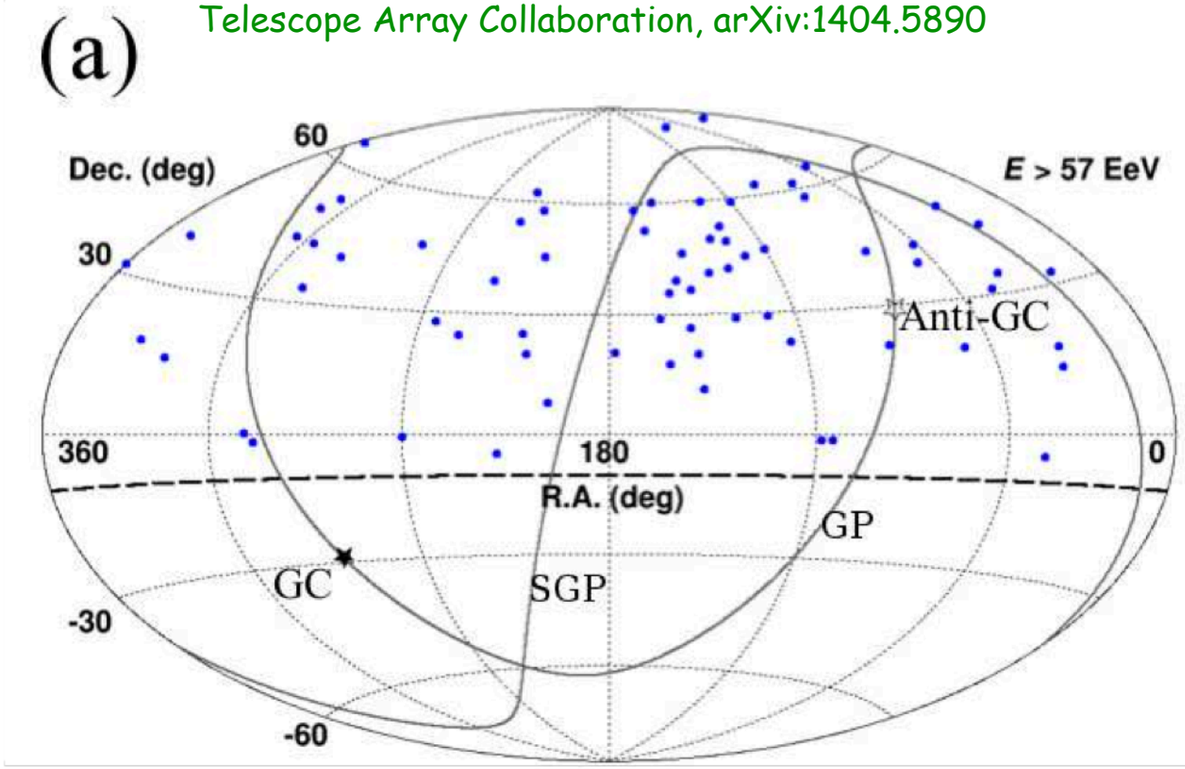


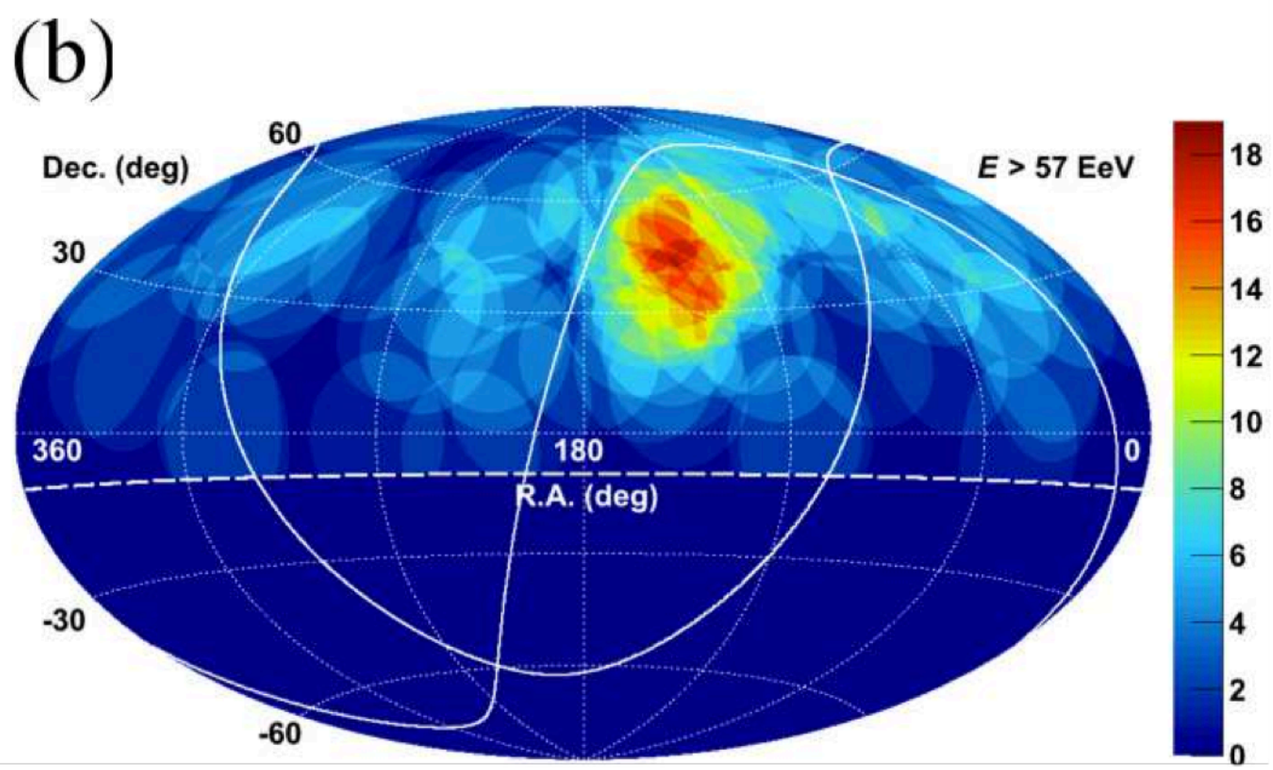


IceCube collaboration, arXiv:1405.5303

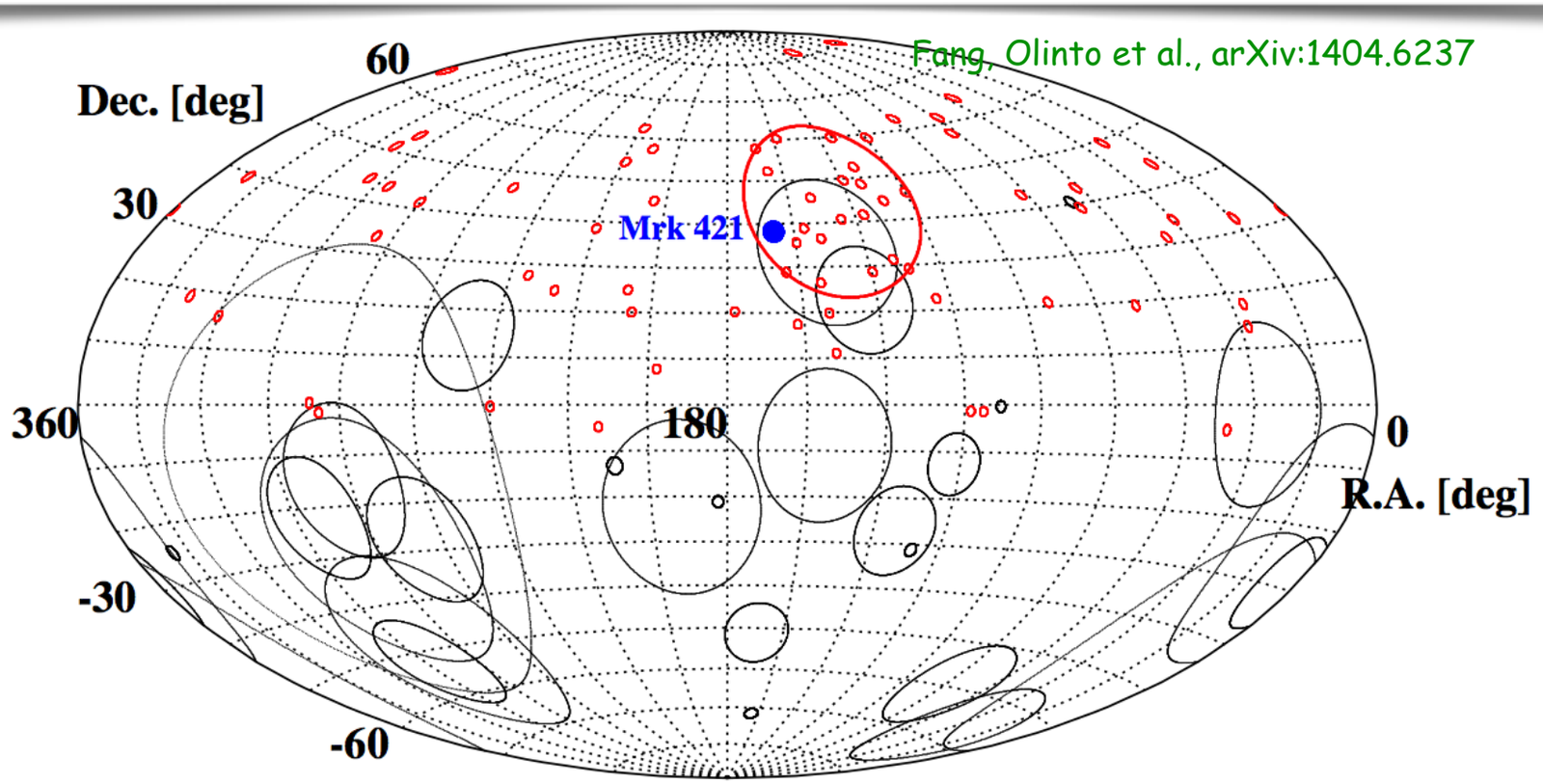
A possible Correlation of IceCube Neutrinos with the Cosmic Ray Excess seen by Telescope Array ?

Telescope Array Collaboration, arXiv:1404.5890



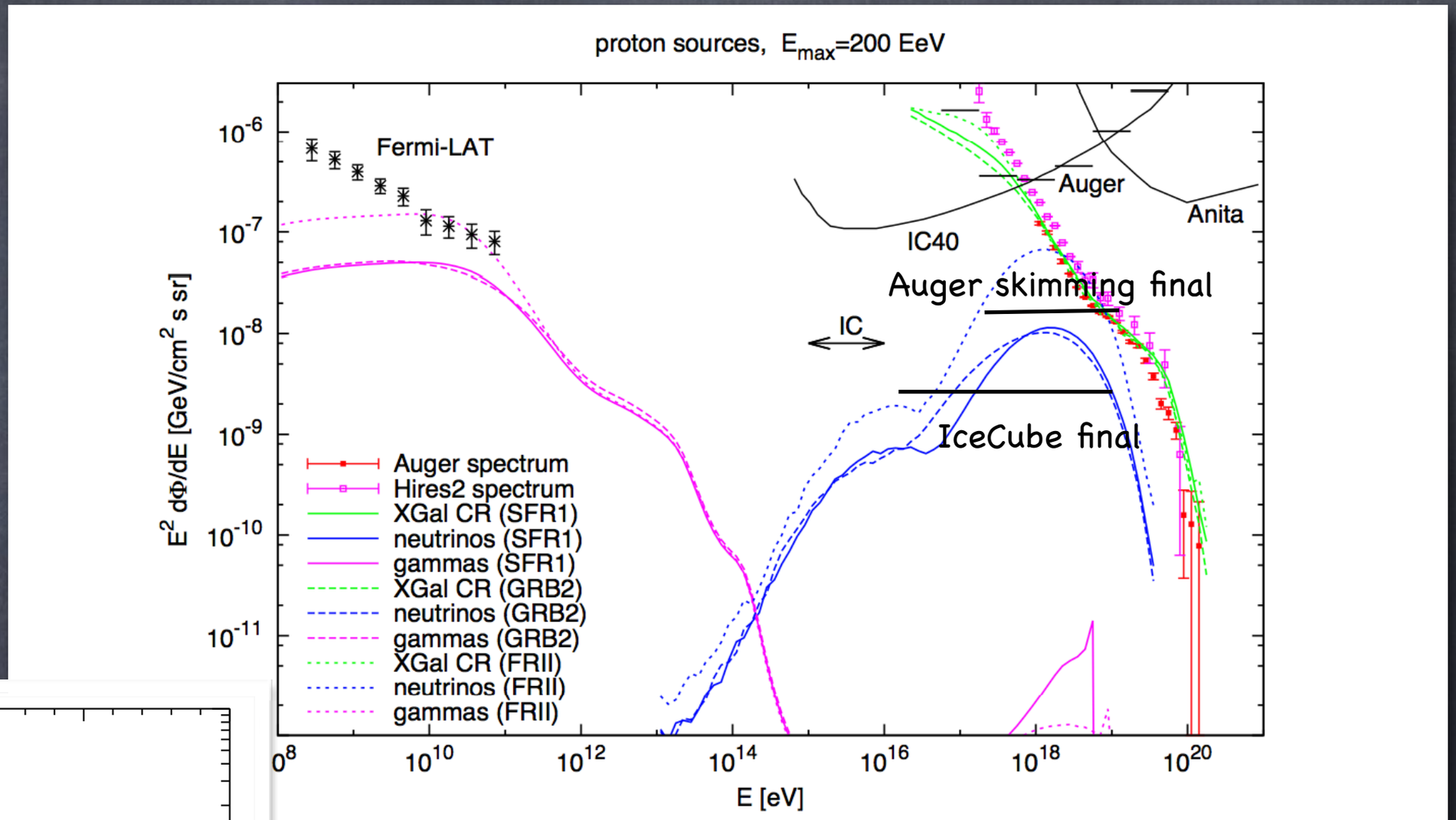


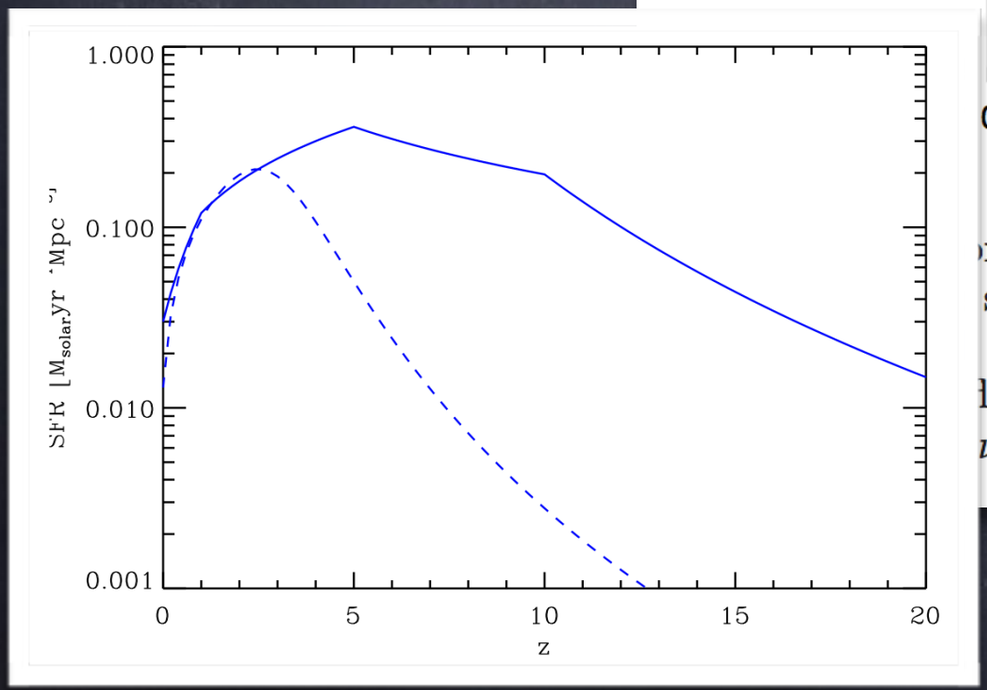
Fang, Olinto et al., arXiv:1404.6237



Cosmogenic Neutrinos: Maximal Fluxes for Pure Proton Injection

- Including secondary photons
- strong source evolution is here constrained by Fermi-LAT results





n scenario with $E_{\max} = 200\,\mathrm{EeV}$ for different source evolution models (SFR1, GRB2 source spectral index is $\alpha = 2.4$ for the SFR1 and GRB2 models, while $\alpha = 2.2$ for Indicated are the propagated proton spectrum, the resulting (all flavor) neutrino luxes. The photon background measured by Fermi-LAT [10] is indicated, besides the ν bounds included in figure 1.

Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

enjoy CASPAR 2014 !