# A unified interpretation to cosmic-ray spectra and dipole anisotropy problem

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# Outline

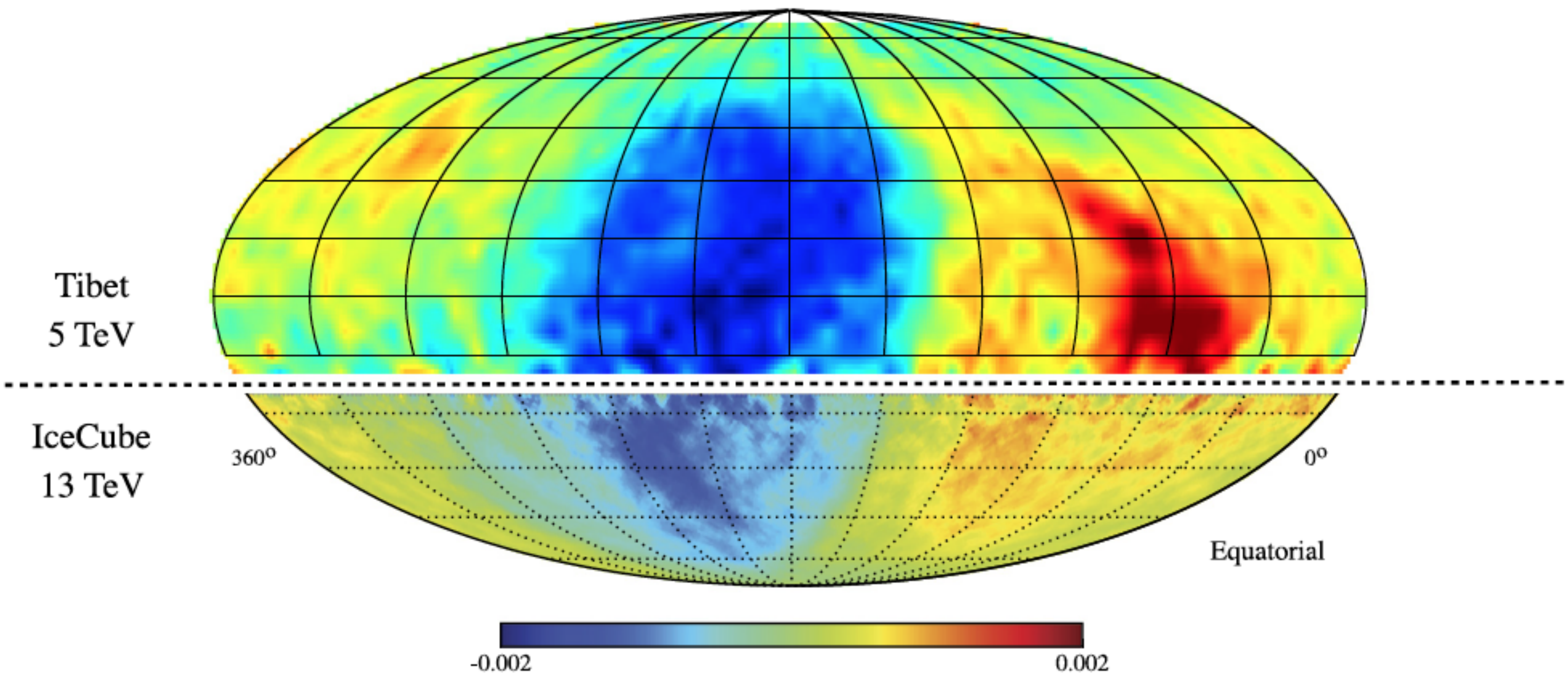
- Observations of cosmic-ray large-scale anisotropy
- Possible origin of dipole anisotropy
- Spatial-dependent propagation plus Local source model
- Results
- Summary

# Observations of cosmic-ray large-scale anisotropy

anisotropy of arrival distributions of cosmic rays

relative intensities are roughly $10^{-4} \sim 10^{-3}$

$$\mathbf{I}(\mathbf{n}) \equiv \frac{\phi(\mathbf{n})}{\phi^{\text{iso}}} = 1 + \delta\mathbf{I}(\mathbf{n})$$




M. Ahlers, P. Mertsch, 2017PrPNP..94..184A

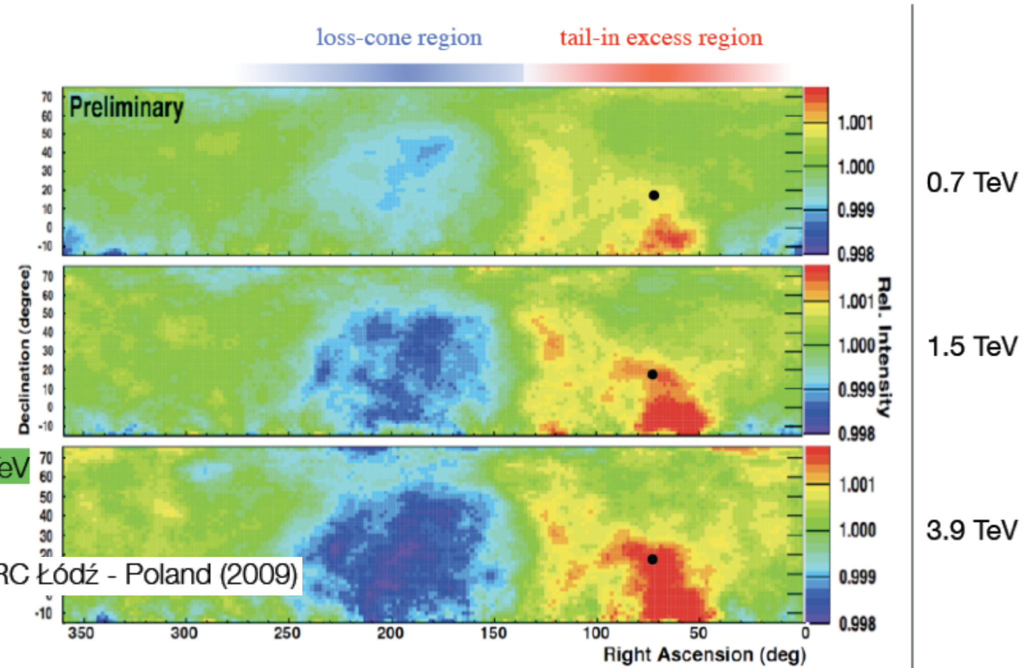
Combined cosmic ray anisotropy of Tibet-ASgamma and IceCube

# Energy evolution of 2D anisotropy

## ARGO-YBJ

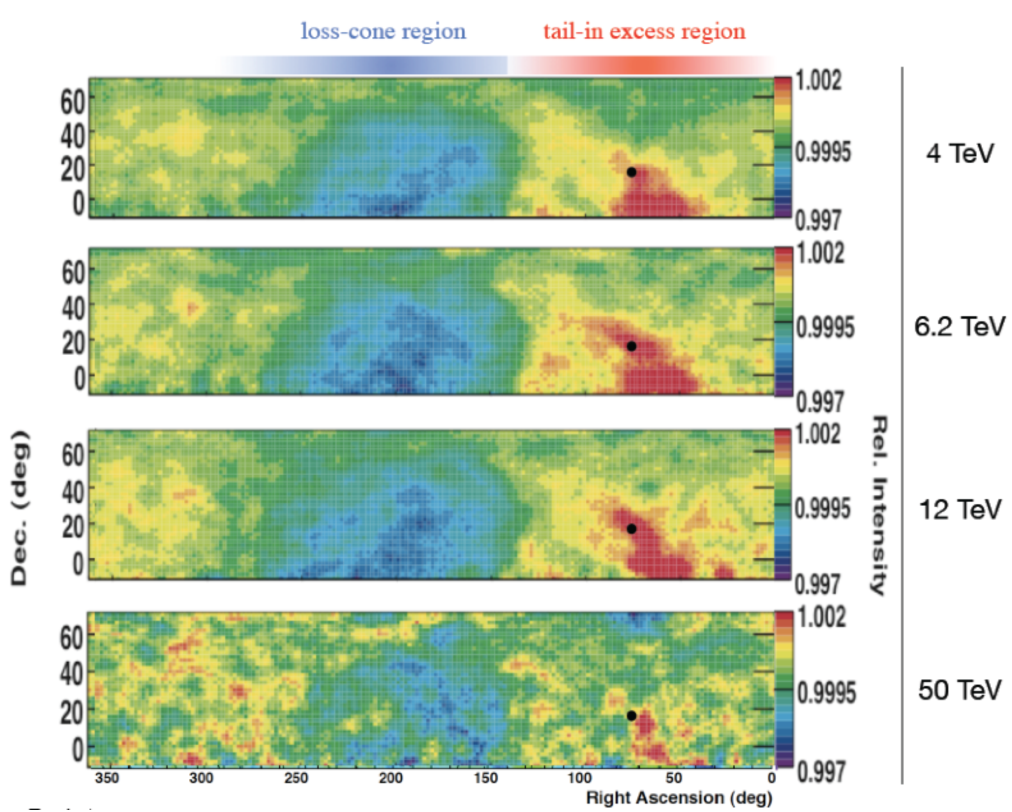
- data from 2008
- 365 days livetime
- $6.5 \cdot 10^{10}$ events
- median CR energy ~ 1.1 TeV

J.L. Zhang et al., 31st ICRC Łódź - Poland (2009)

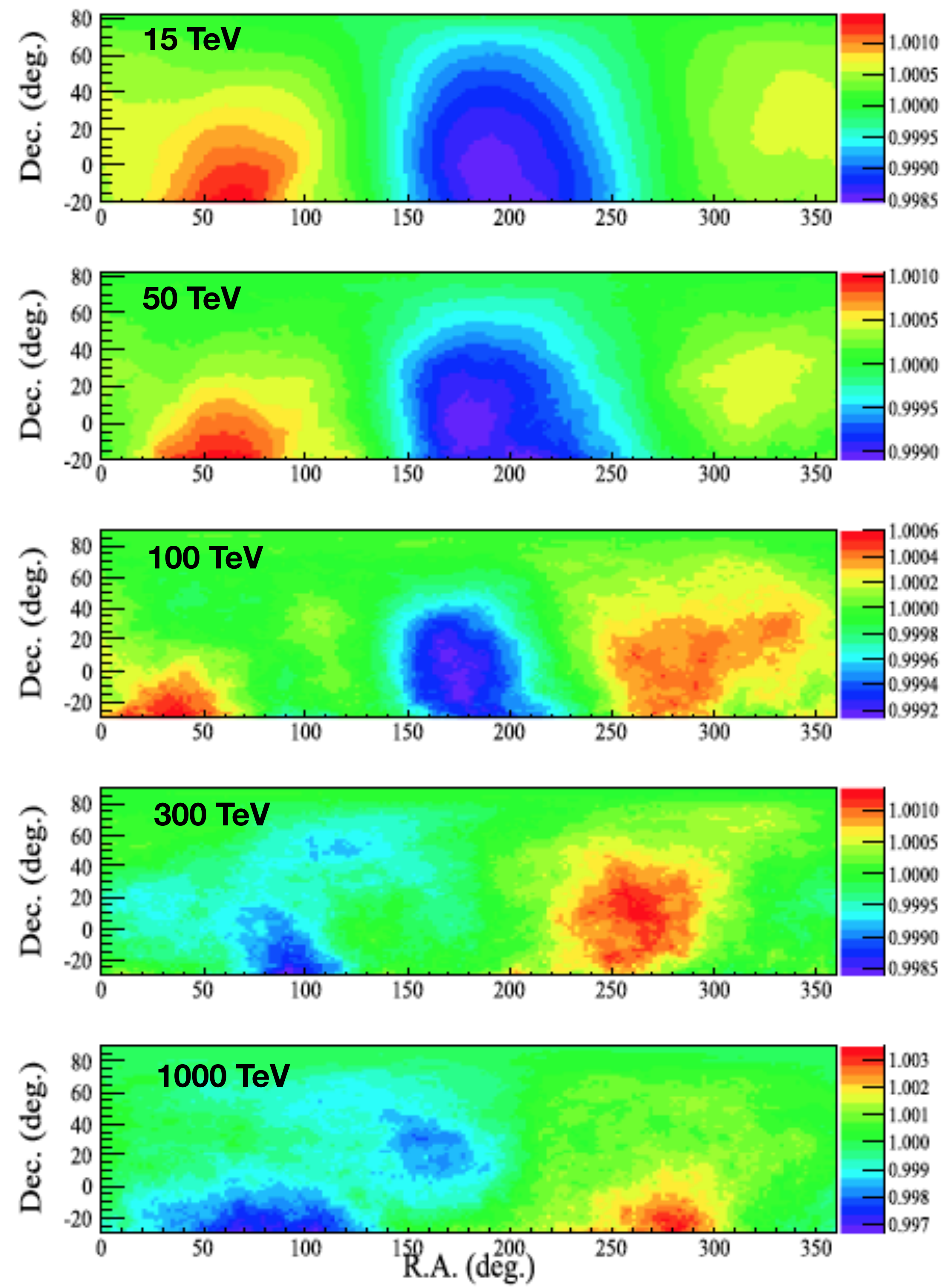



## Tibet-III

- data from 1997 to 2005
- 1874 days livetime
- $3.7 \cdot 10^{10}$ events
- angular resolution ~ 0.9°
- modal CR energy ~ 3 TeV




Amenomori et al., Science Vol. 314, pp. 439 (2006)



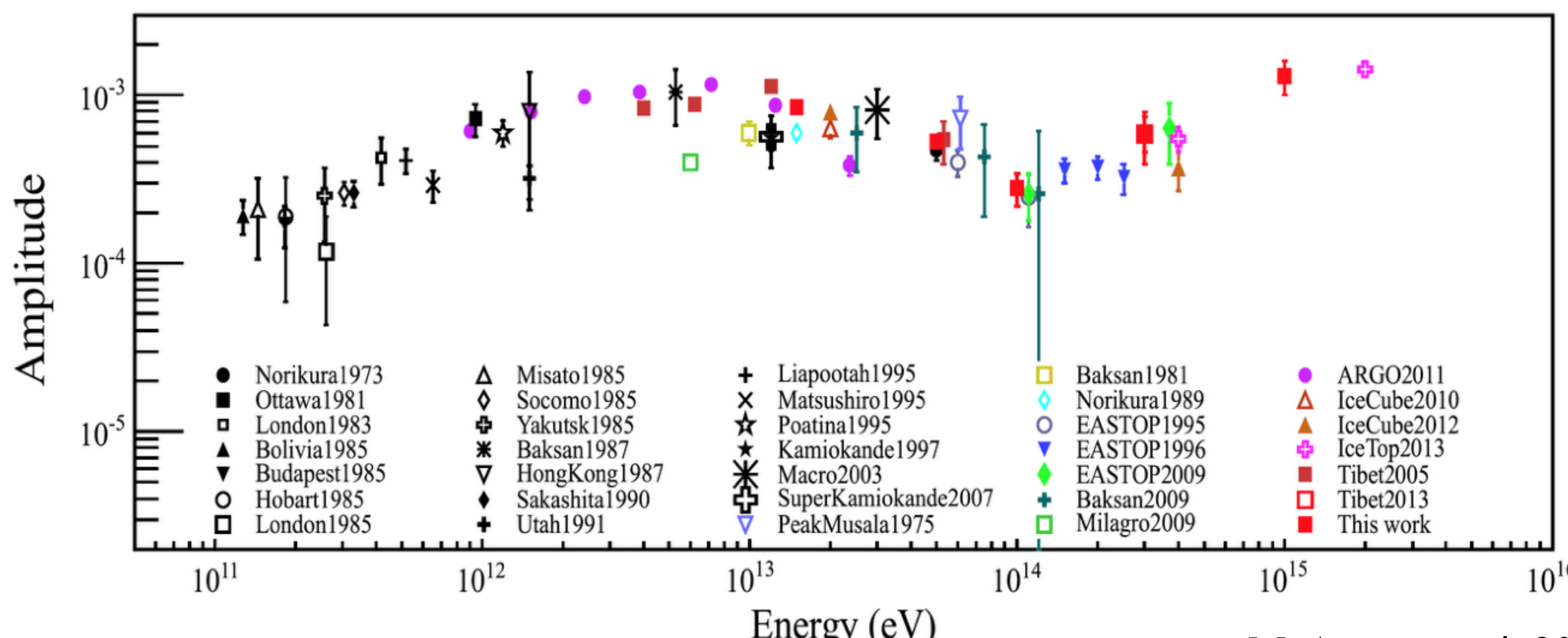

M. Amenomori, 2017ApJ…836..153A

# Energy dependence of dipole anisotropy's amplitude and phase

$$R(\alpha) = 1 + A_1 \cos(\alpha - \phi_1)$$

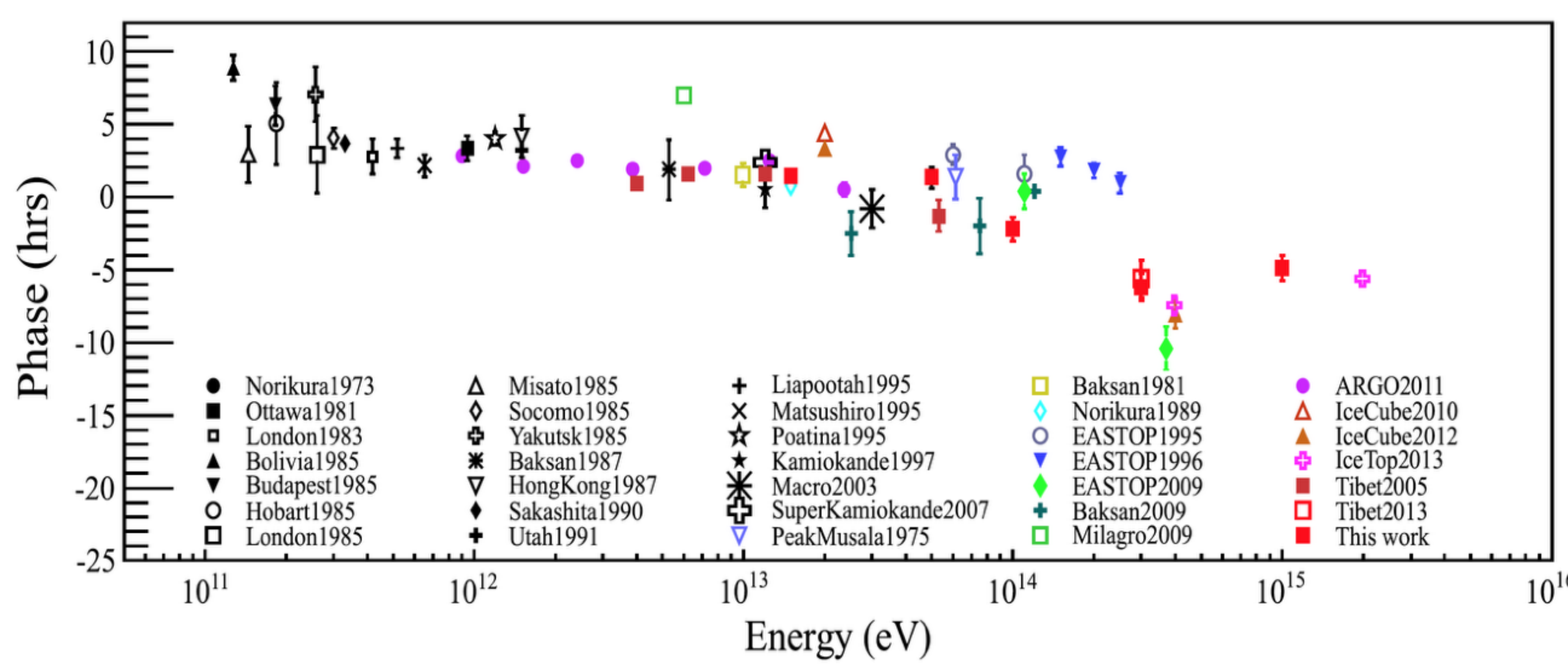
$R(\alpha)$: the relative intensity of CRs at R.A.

$A_1$




M. Amenomori, 2017ApJ…836..153A

$\phi_1$



# Possible origin of dipole anisotropy

dipole anisotropy is defined as $$\delta \equiv \frac{f_{\rm max} - f_{\rm min}}{f_{\rm max} + f_{\rm min}} = \frac{3\mathbf{K}}{v}\frac{\nabla n_{\rm CR}}{n_{\rm CR}}$$

## Compton-Getting effect

- phase-space distribution is Lorentz-invariant, $f^\star(\mathbf{p}^\star) = f(\mathbf{p})$ [Forman'70]
- Lorentz boost (starred quantities in plasma rest-frame):

$$\mathbf{p}^\star = \mathbf{p} + \left(p + \frac{1}{2}\boldsymbol{\beta}\cdot\mathbf{p}\right)\boldsymbol{\beta} + \mathcal{O}(\beta^3)$$

- Taylor expansion

$$f(\mathbf{p}) \simeq f^\star(\mathbf{p}) + (\mathbf{p}^\star - \mathbf{p})\nabla_{\mathbf{p}^\star} f^\star(\mathbf{p}) + \mathcal{O}(\beta^2) \simeq f^\star(\mathbf{p}) + p\boldsymbol{\beta}\nabla_{\mathbf{p}^\star} f^\star(\mathbf{p}) + \mathcal{O}(\beta^2)$$

→ splitting in $\phi$ and $\boldsymbol{\Phi}$ is not invariant: [Compton & Getting'35;Jones'90]

$$\phi = \phi^\star \qquad \boldsymbol{\Phi} = \boldsymbol{\Phi}^\star + \frac{1}{3}\boldsymbol{\beta}\frac{\partial\phi^\star}{\partial \ln p}$$

- remember: $\phi \sim p^{-2} n_{\rm CR} \propto p^{-(2+\Gamma_{\rm CR})}$

$$\boldsymbol{\delta} = \boldsymbol{\delta}^\star + \underbrace{(2+\Gamma_{\rm CR})\boldsymbol{\beta}}_{\text{Compton-Getting effect}}$$

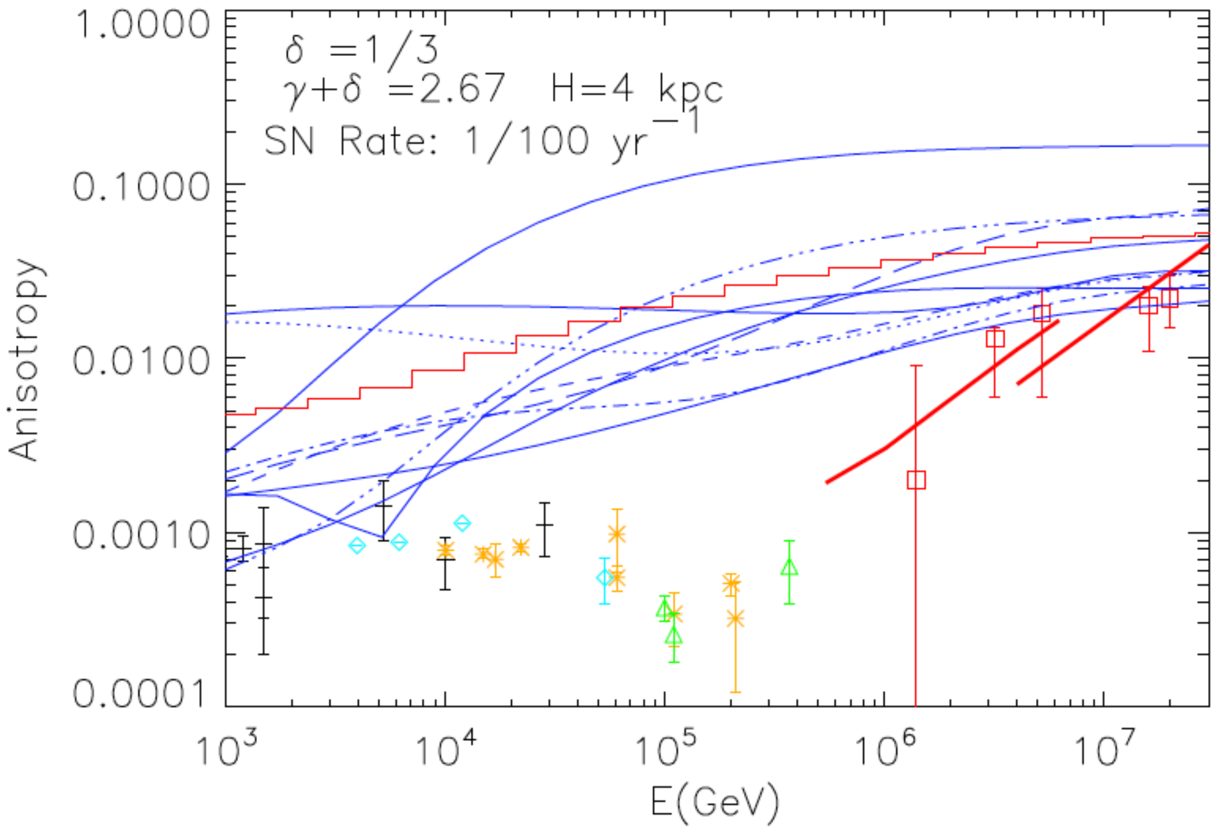
Compton & Getting, Phys. Rev. 47 (1935) 817; Gleeson & Axford, Astrophys. Space Sci. 2 (1968) 431

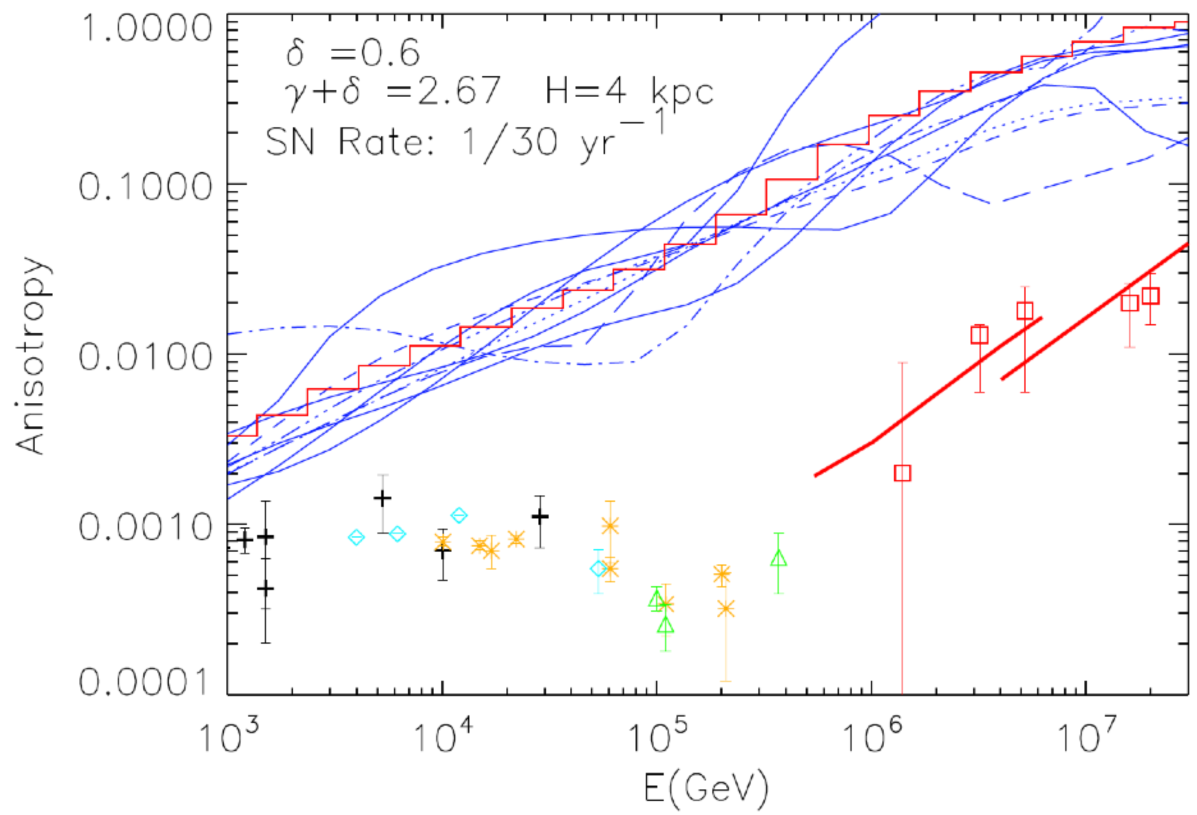
Cosmic rays co-rotate with local magnetic environment.

# Non-uniform distribution of CR sources

$\nabla n_{CR} \neq 0$

anisotropy scales with diffusion coefficient K



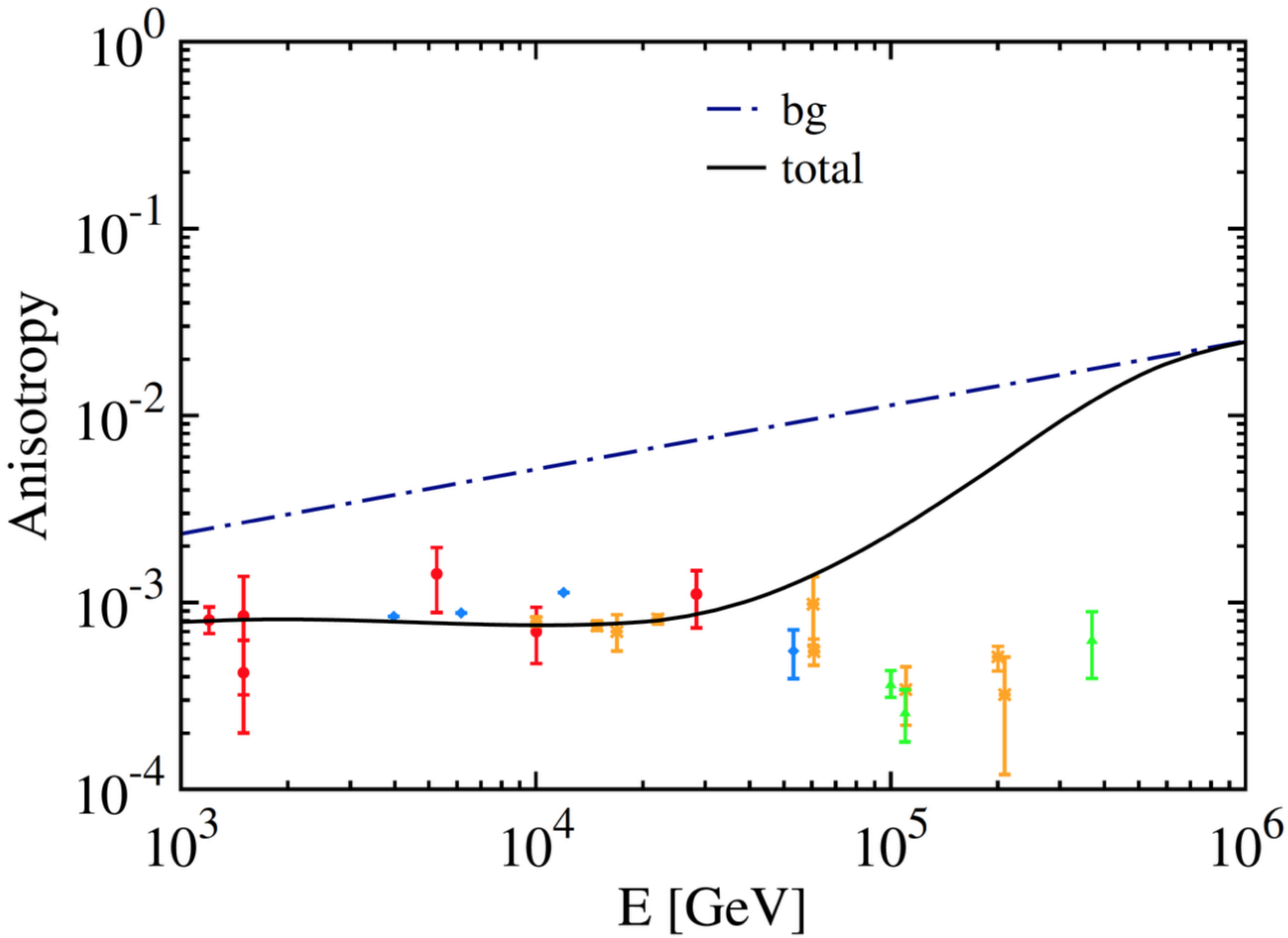




P. Blasi, E. Amato, 2012JCAP…01..011B

# Local source

local source at Galactic anti-center could effectively suppress the magnitude

the magnitude problem could be partially settled



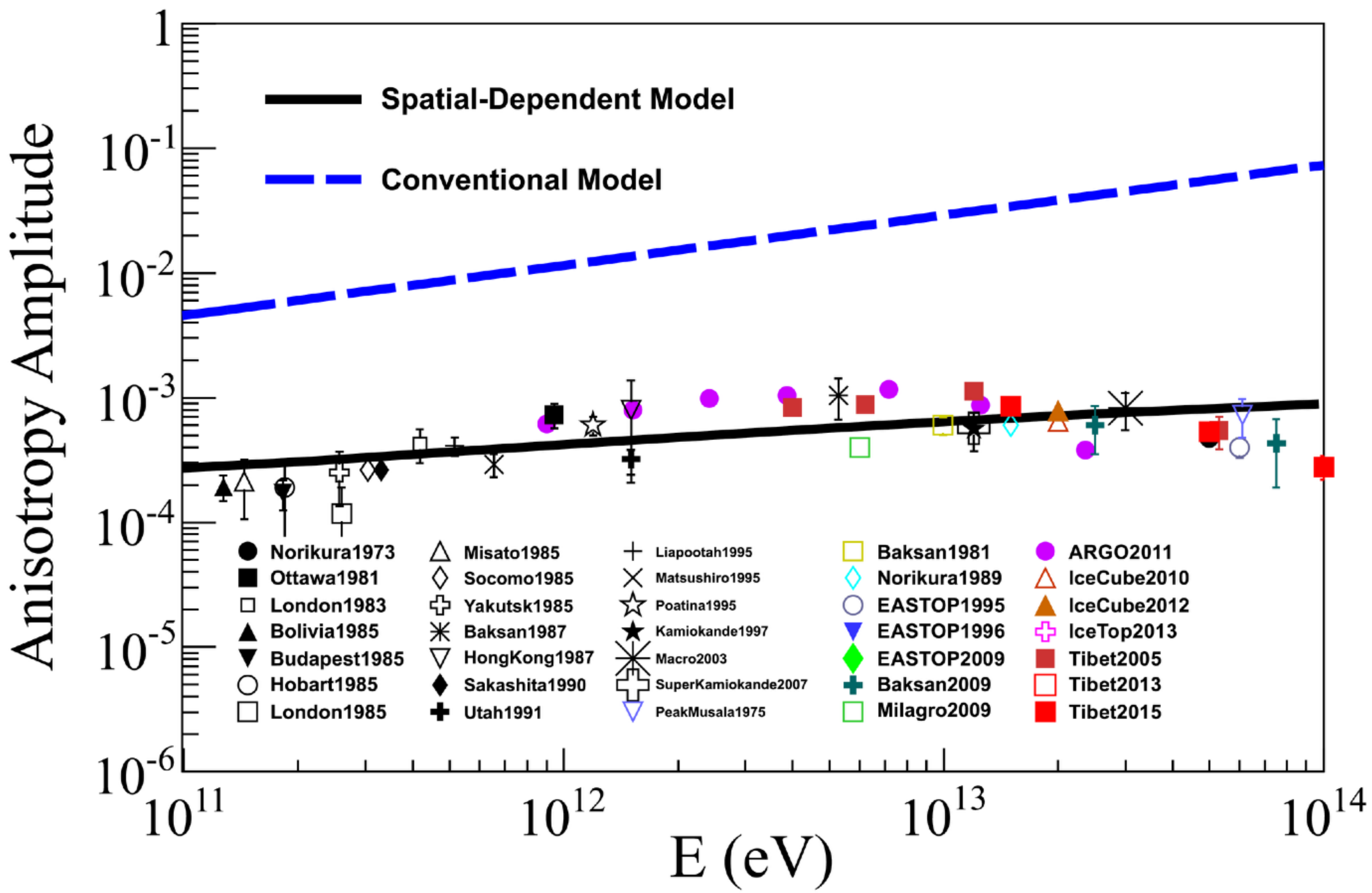

W. Liu, X. J. Bi, S. J. Lin, B. B. Wang, and P. F. Yin, 2017PhRvD..96b3006L

# Spatial-dependent diffusion

background anisotropy is significantly suppressed

power-law dependence

Galactic center




Y. Q. Guo, Z. Tian, and C. Jin, 2016ApJ…819...54G

# Local magnetic field plus Vela SNR

- strong ordered magnetic fields in the local environment

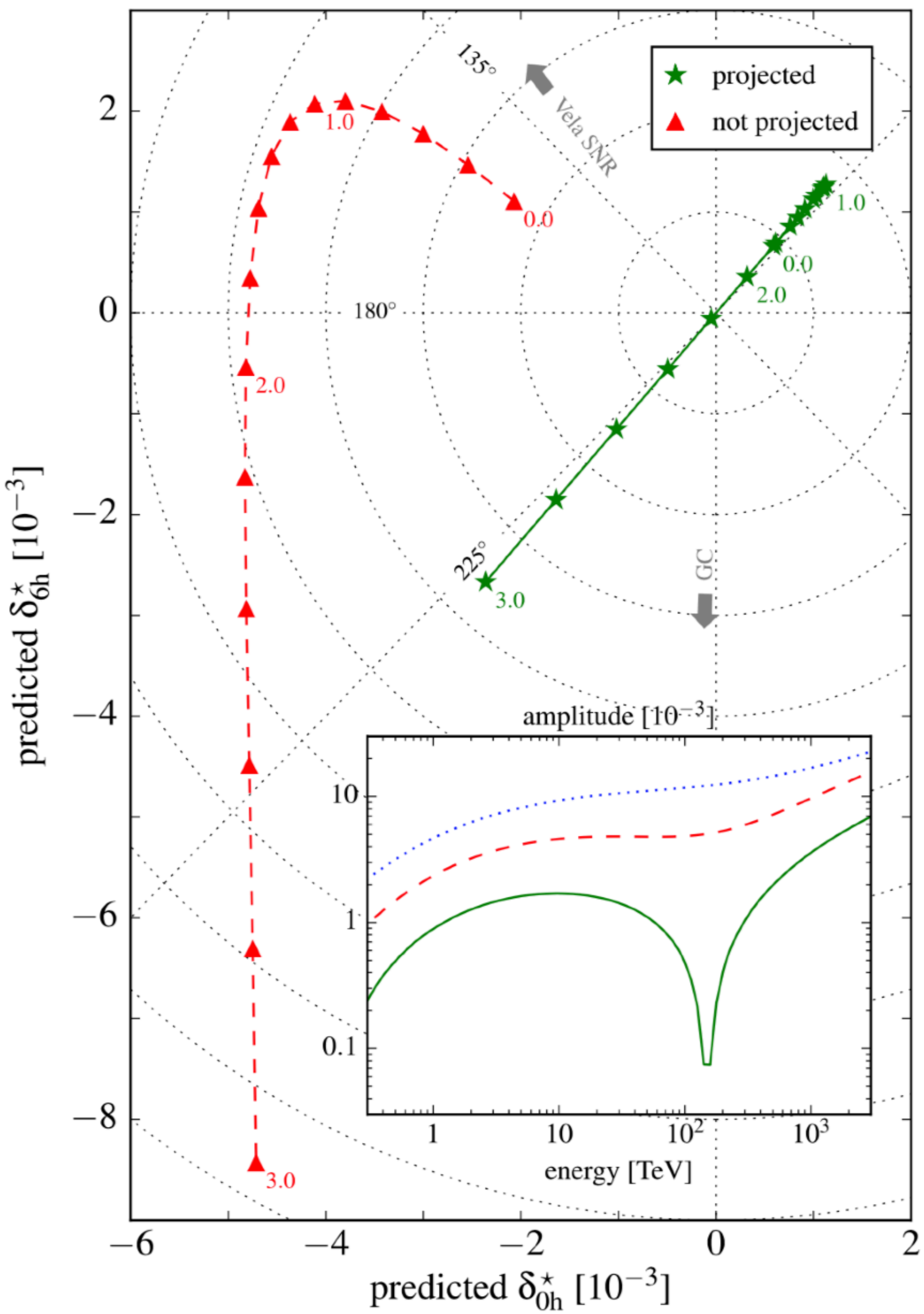
➜ diffusion tensor reduces to projector:

$$K_{ij} \to \frac{\hat{B}_i \hat{B}_j}{3\nu_{\|}}$$

- TeV–PeV dipole data consistent with magnetic field direction inferred by IBEX data [McComas *et al.*'09]
- 1–100 TeV phase indicates a local gradient within longitudes:

$$120^\circ \lesssim l \lesssim 300^\circ$$

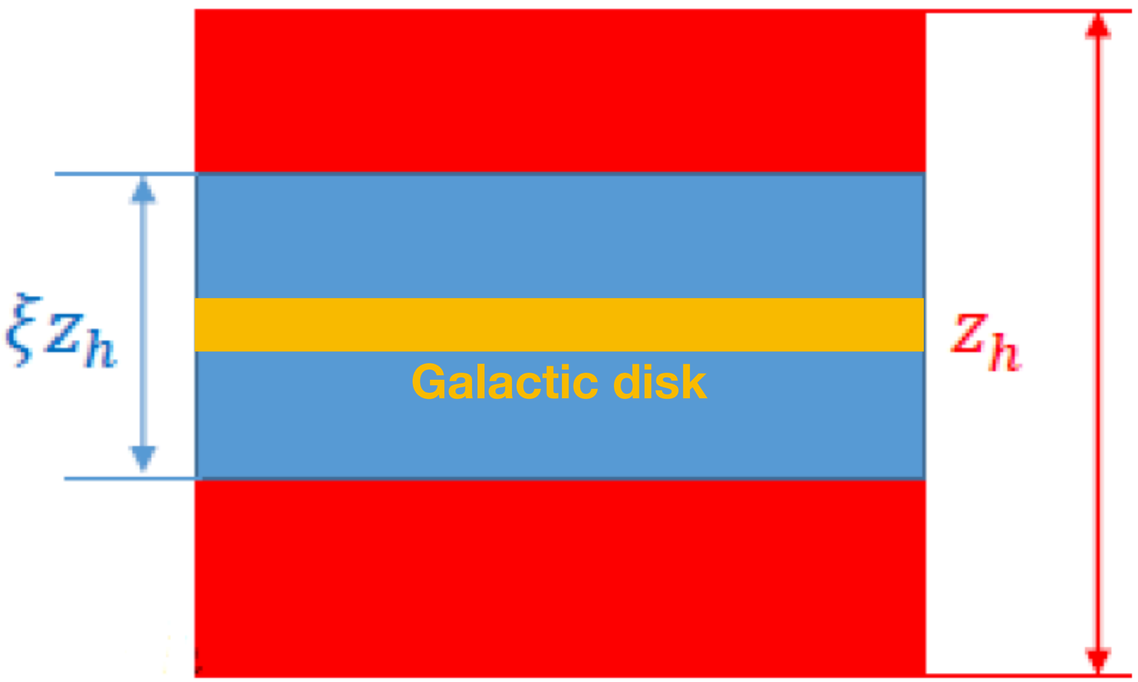
- phase flip induced by Vela SNR? [MA'16]
- or a luminous 2Myr old SNR? [Savchenko, Kachelrieß & Semikoz'15]




M. Ahlers, PRL, 2016

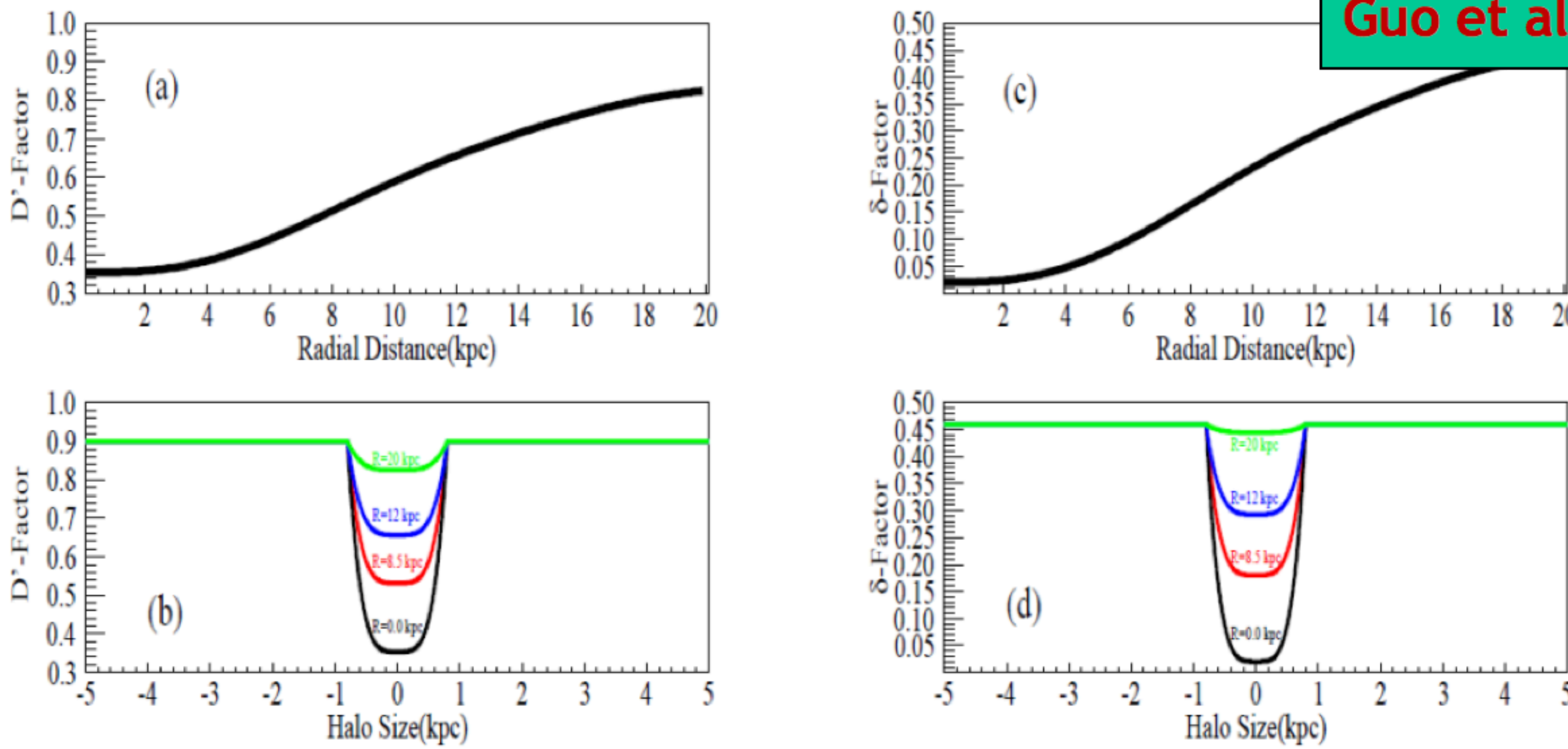
# Spatial-dependent Propagation plus Local source model

Spatial-dependent diffusion model



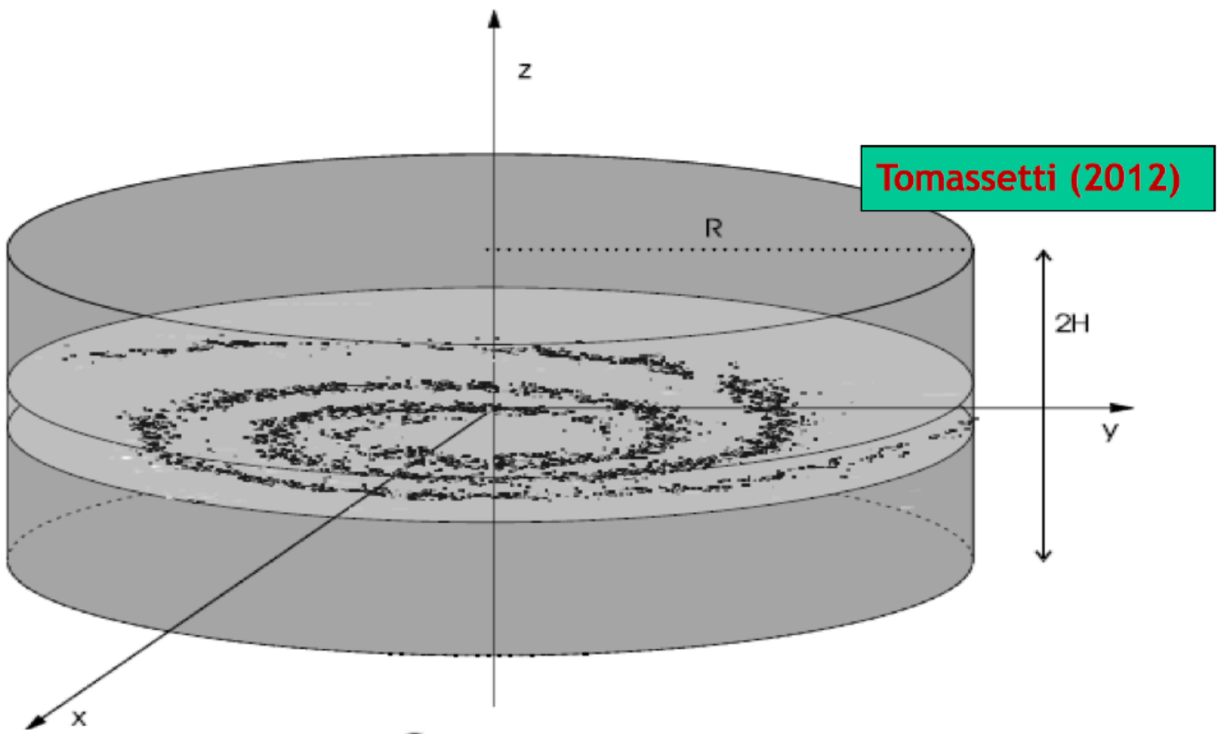

$$D_{xx}(r,z,p) = \begin{cases} \eta(r,z) D_0 \beta \left(\frac{p}{p_0}\right)^{\varepsilon(r,z)\delta_0} & |z| < \xi z_h \quad (IH) \\ D_0 \beta \left(\frac{p}{p_0}\right)^{\delta_0} & |z| > \xi z_h \quad (OH) \end{cases}$$

$$F(r,z) = \frac{N_m}{1+f(r,z)} + \left(1 - \frac{N_m}{1+f(r,z)}\right) \cdot \left(\frac{z}{\xi z_h}\right)^n$$



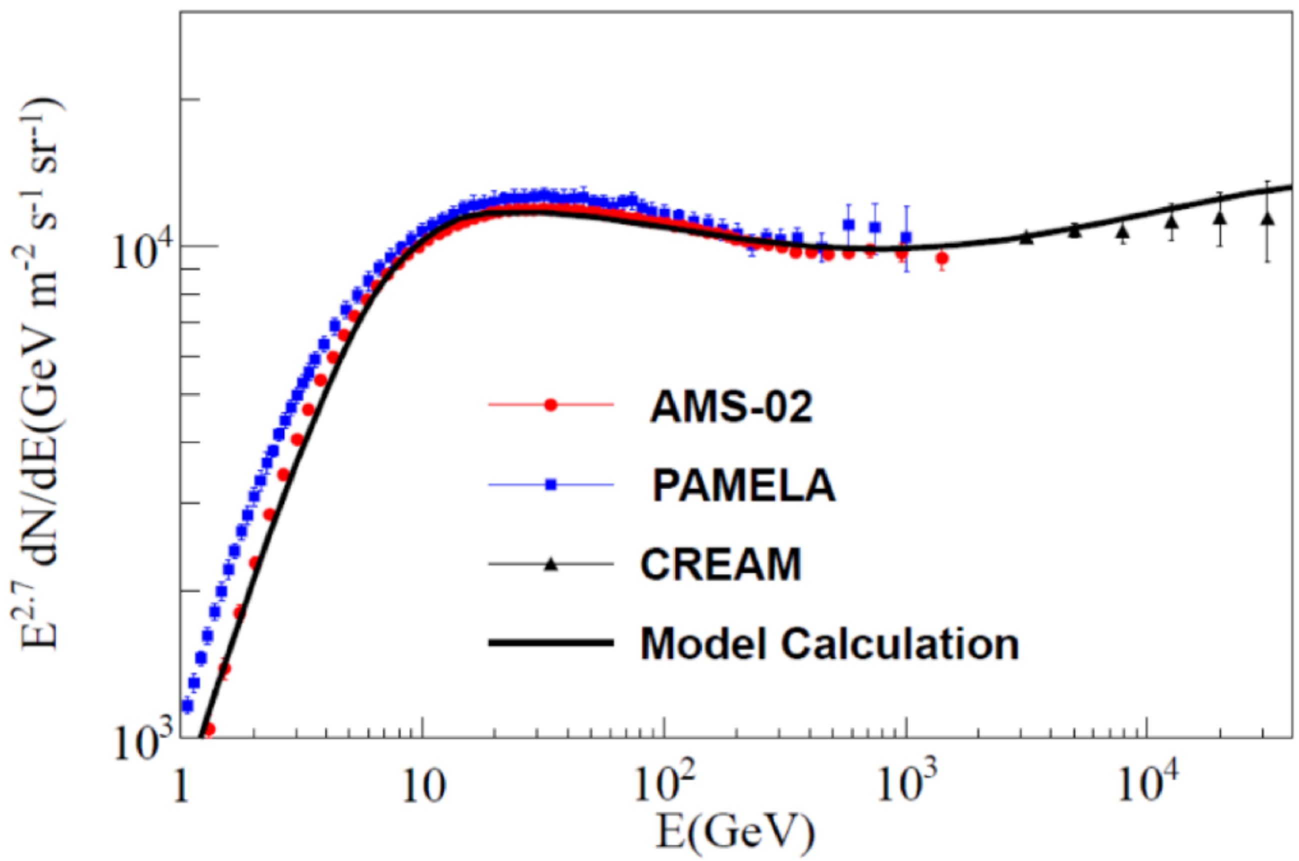

Guo et al. (2016)

hardening of cosmic-ray nuclei



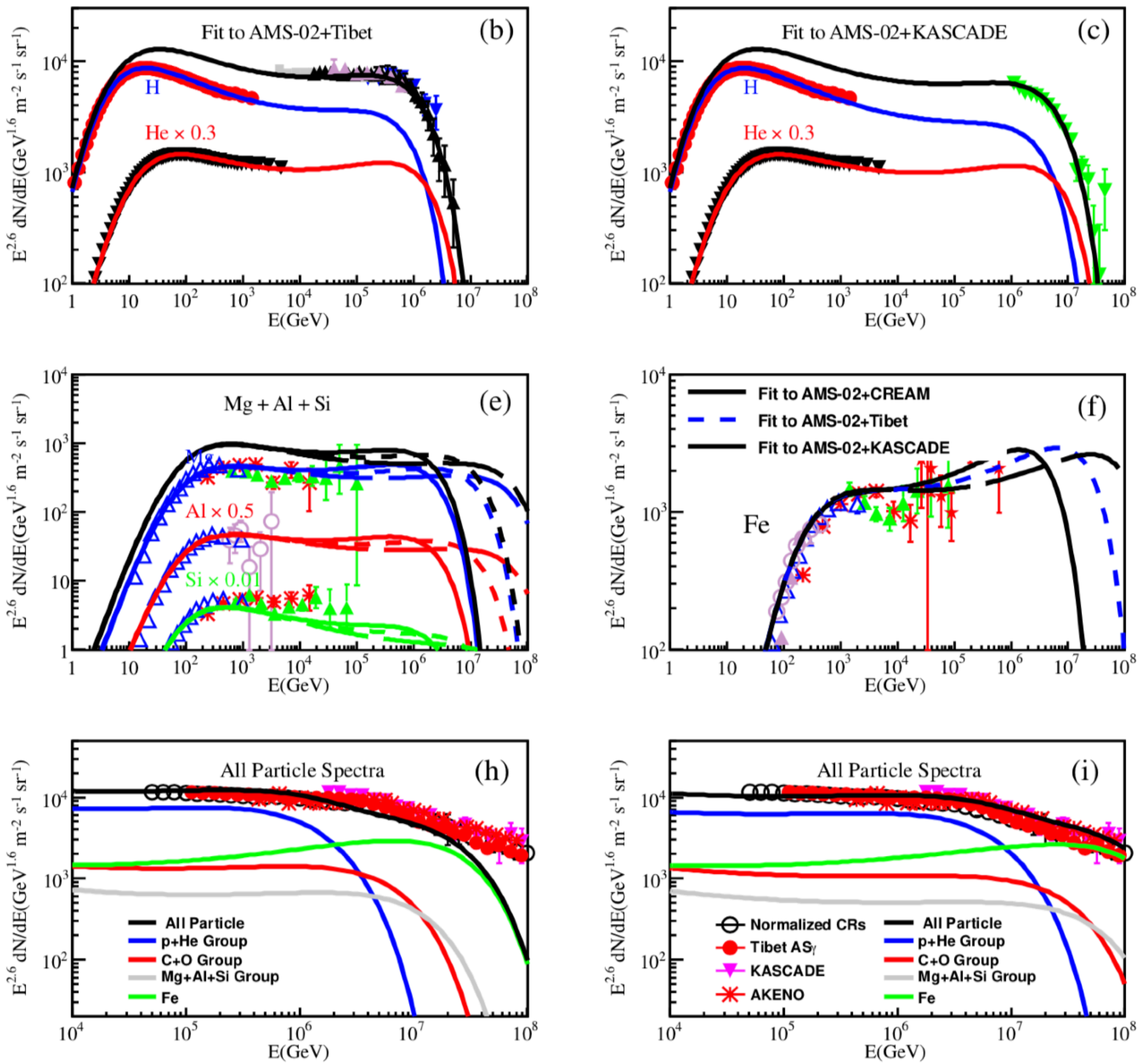

$$N_0 \equiv N(z=0) \sim \frac{L}{k_0}\left\{\xi\rho^{-\nu-\delta} + (1-\xi)\rho^{-\nu-\delta-\Delta}\right\}$$

硬成分　　软成分




Y. Q. Guo, Z. Tian, and C. Jin, 2016ApJ…819...54G

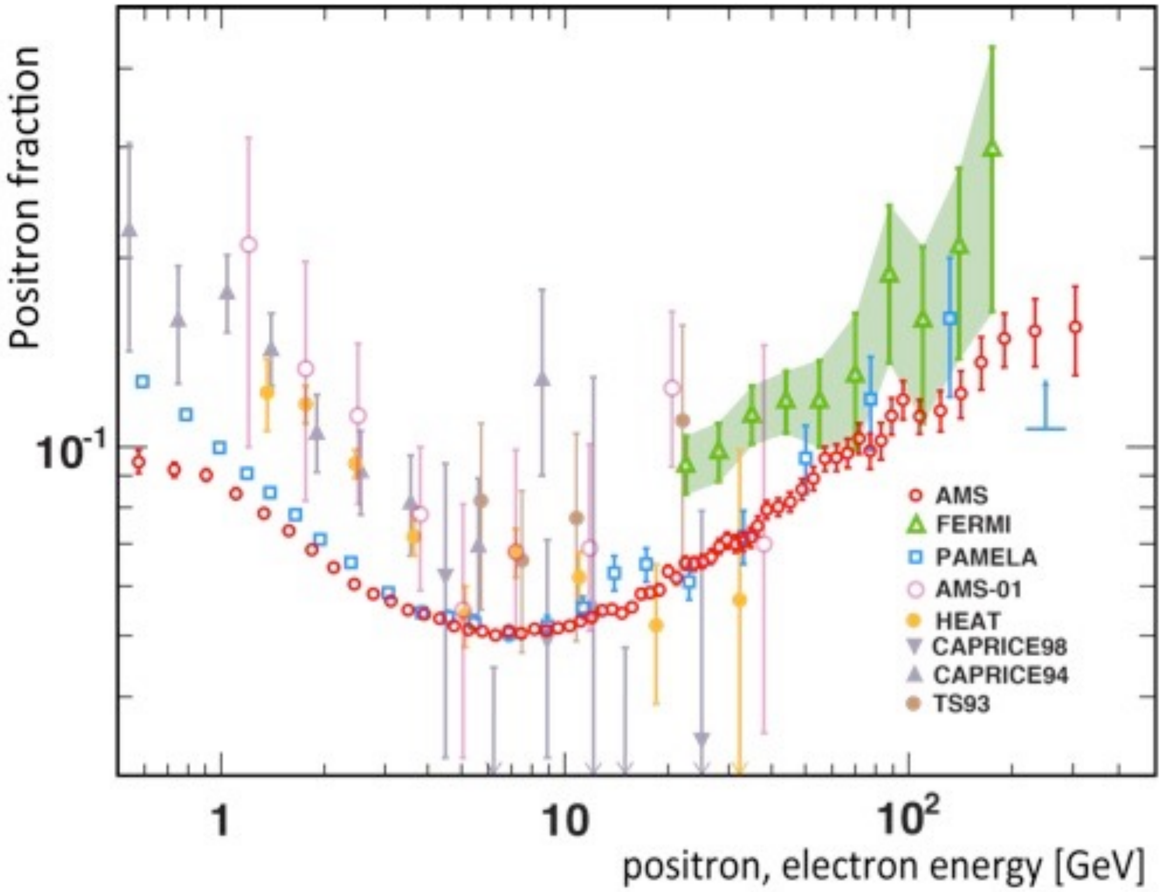
# cosmic-ray knee

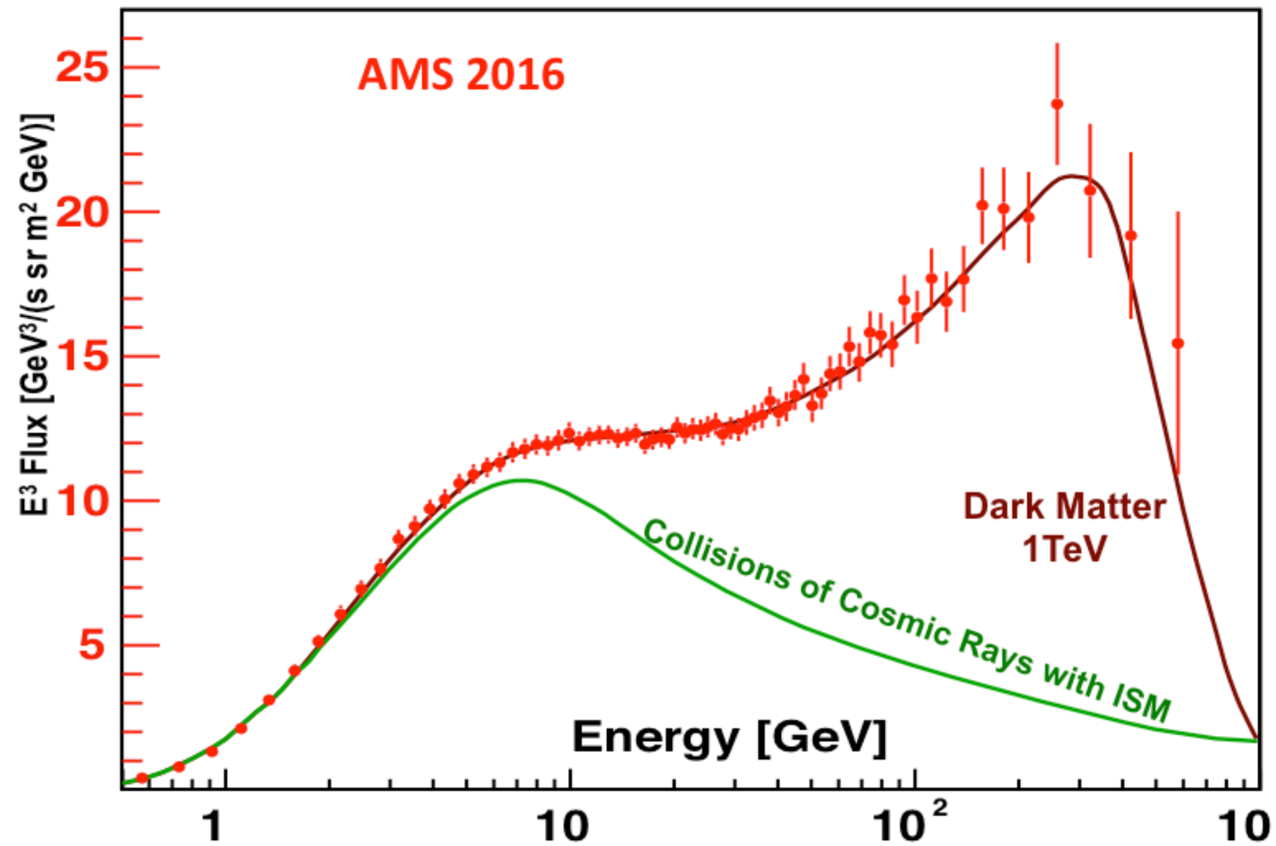


Local source, Geminga

positron excess above 10 GeV

from nearby pulsars?

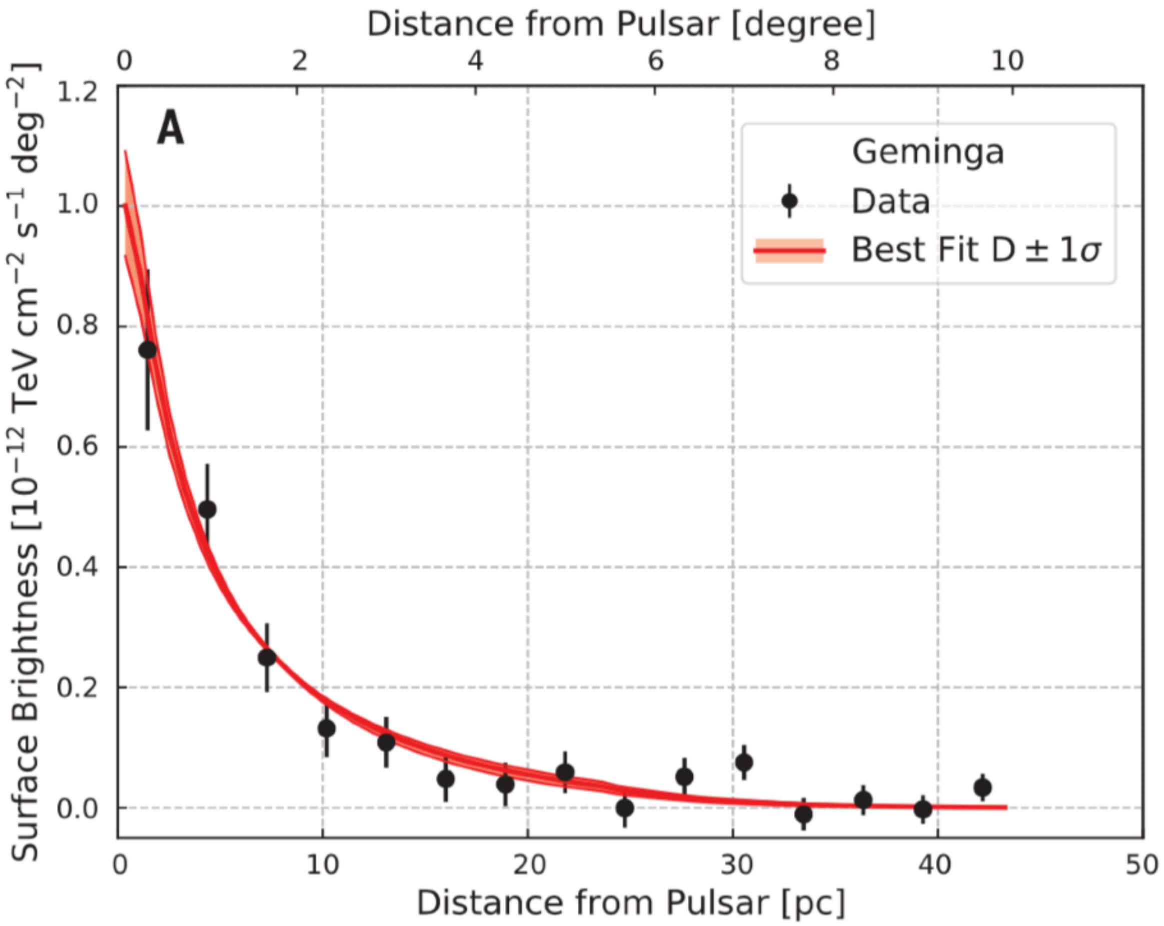


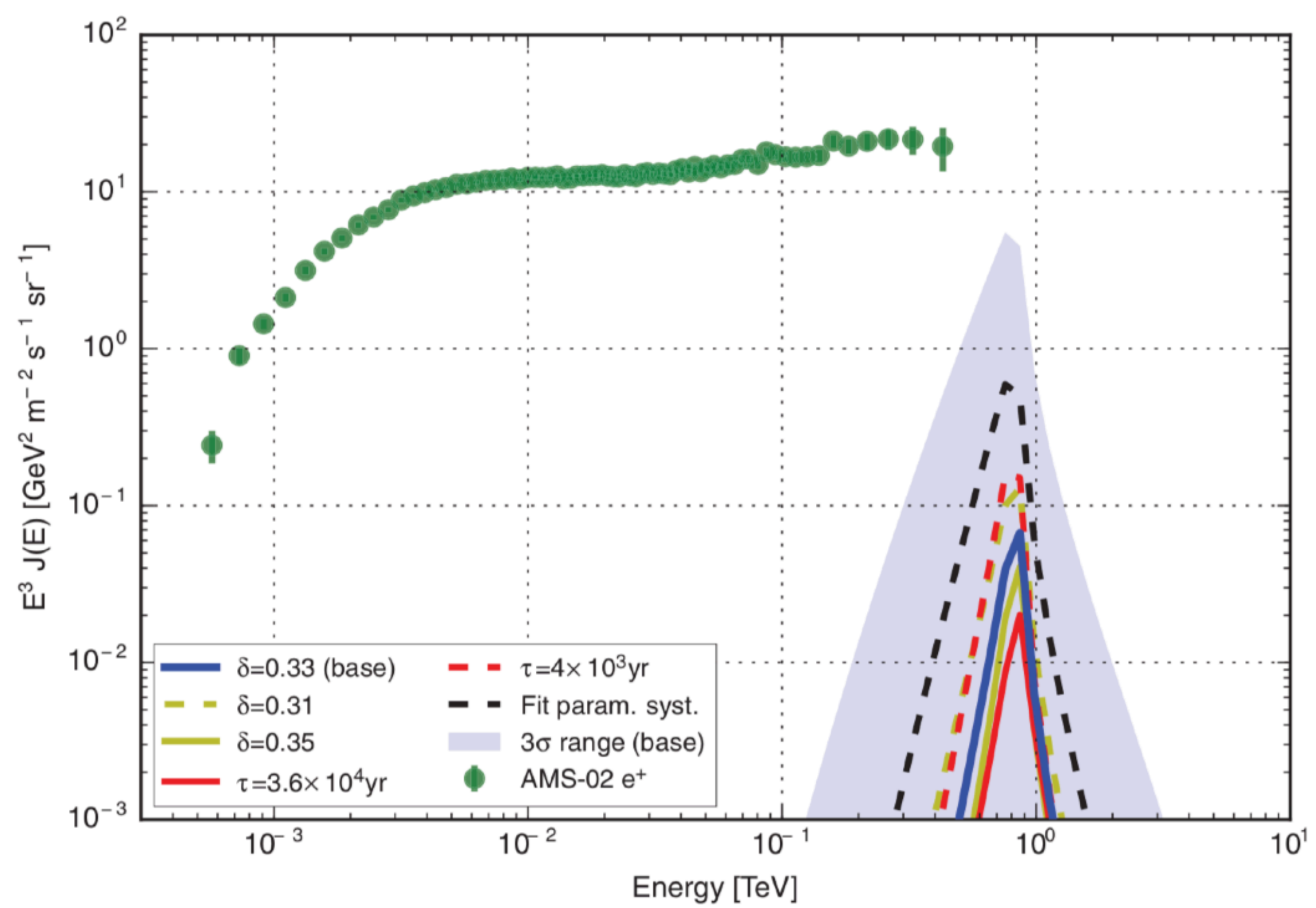




M. Aguilar, et al. PRL 110, 141102 (2013)

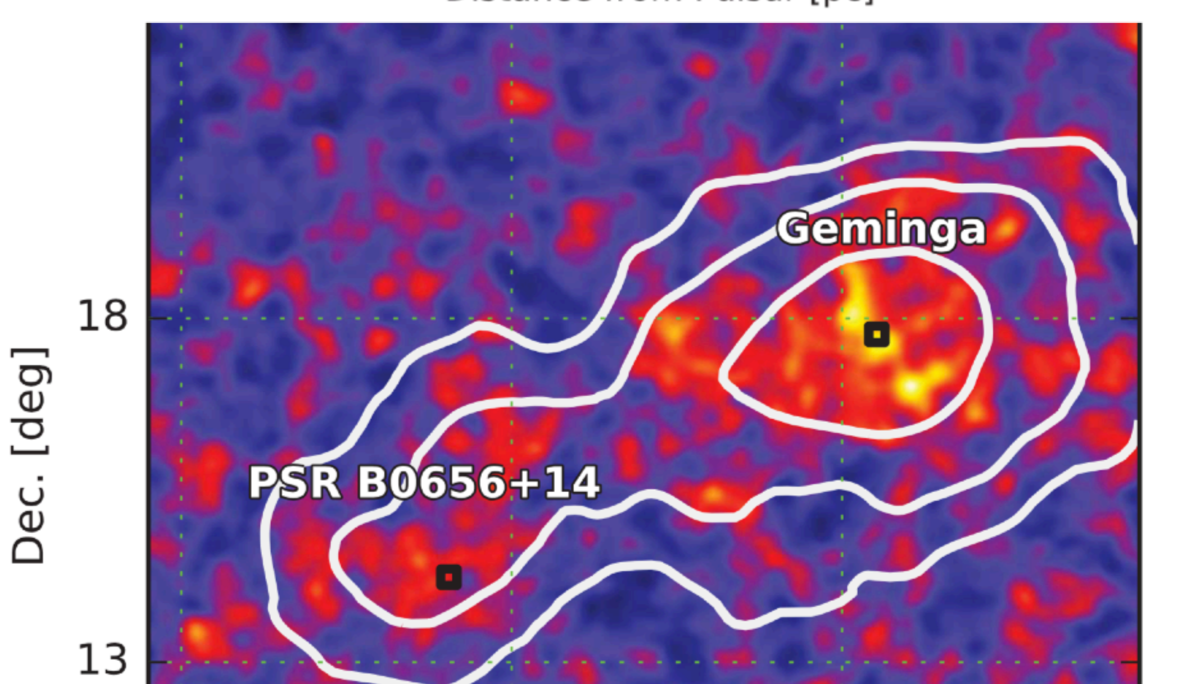
# HAWC observation

slower diffusion coefficient than predicted from B/C ratio




Abeysekara et al., Science 358, 911–914 (2017)



# Geminga pulsar

$250^{+120}_{-62}$ pc   R. A. : 6h 33m 54s, Dec: $+17^{\circ}46'12''$

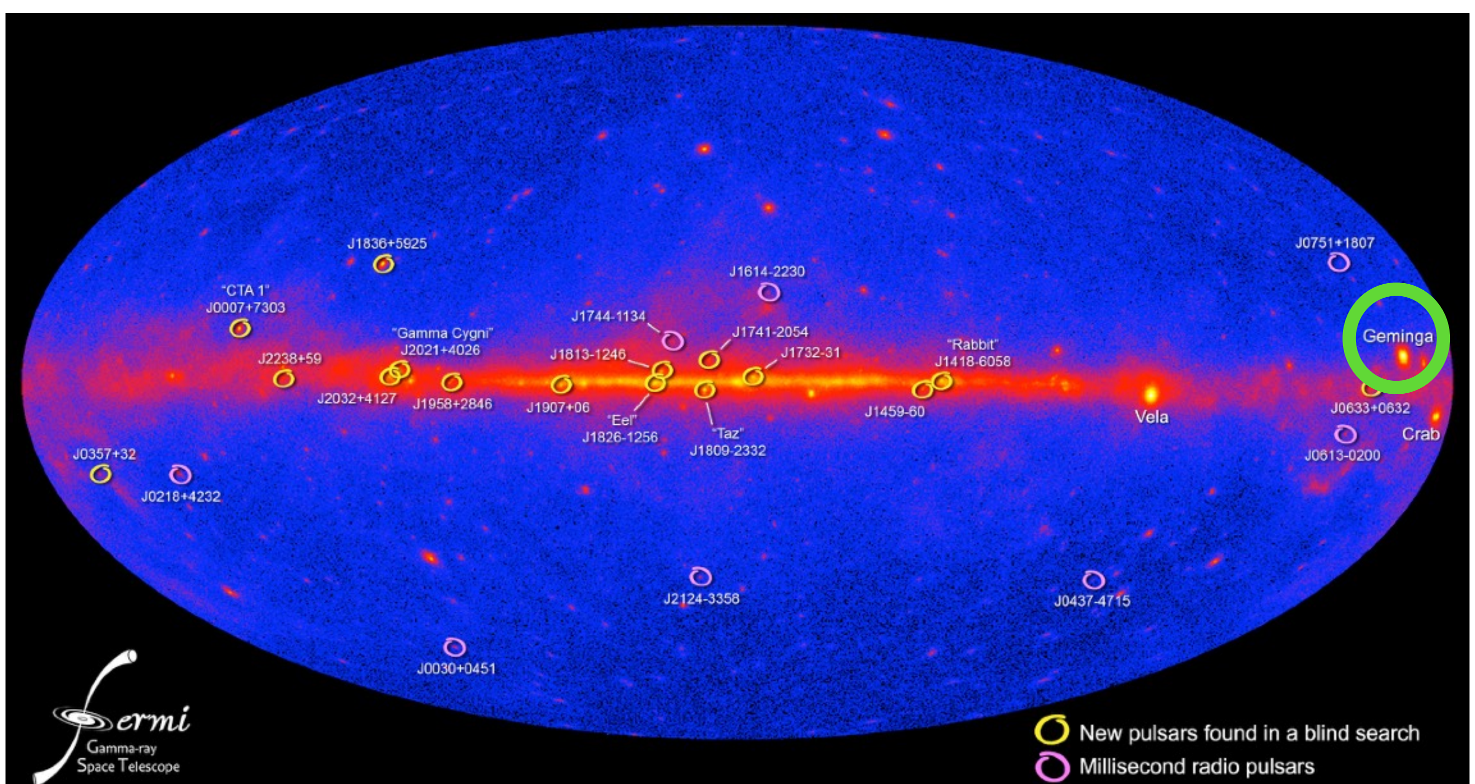
spin-down age $\tau_{\mathrm{SD}} = 340$ kyr

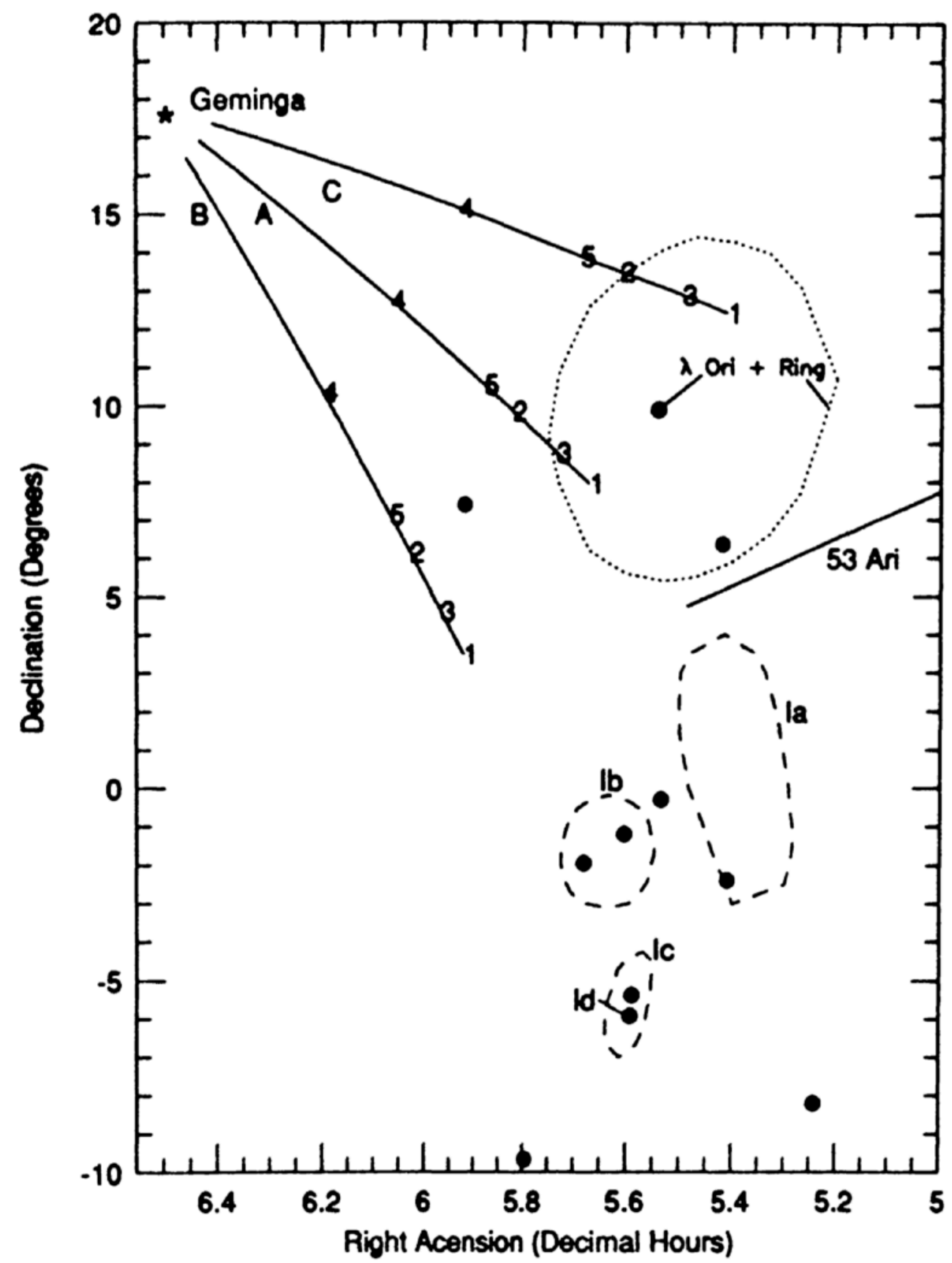
proper motion is $178.2 \pm 1.8$ mas/year ($\mu_{\alpha} = 142.2 \pm 1.2$ mas/year $\mu_{\delta} = 107.4 \pm 1.2$ mas/year)

from Geminga's space motion and its age, it is thought to be a runaway from the **Orion OB association**.

birthplace is R. A. : 5.5h, Dec: $+10^{\circ}$

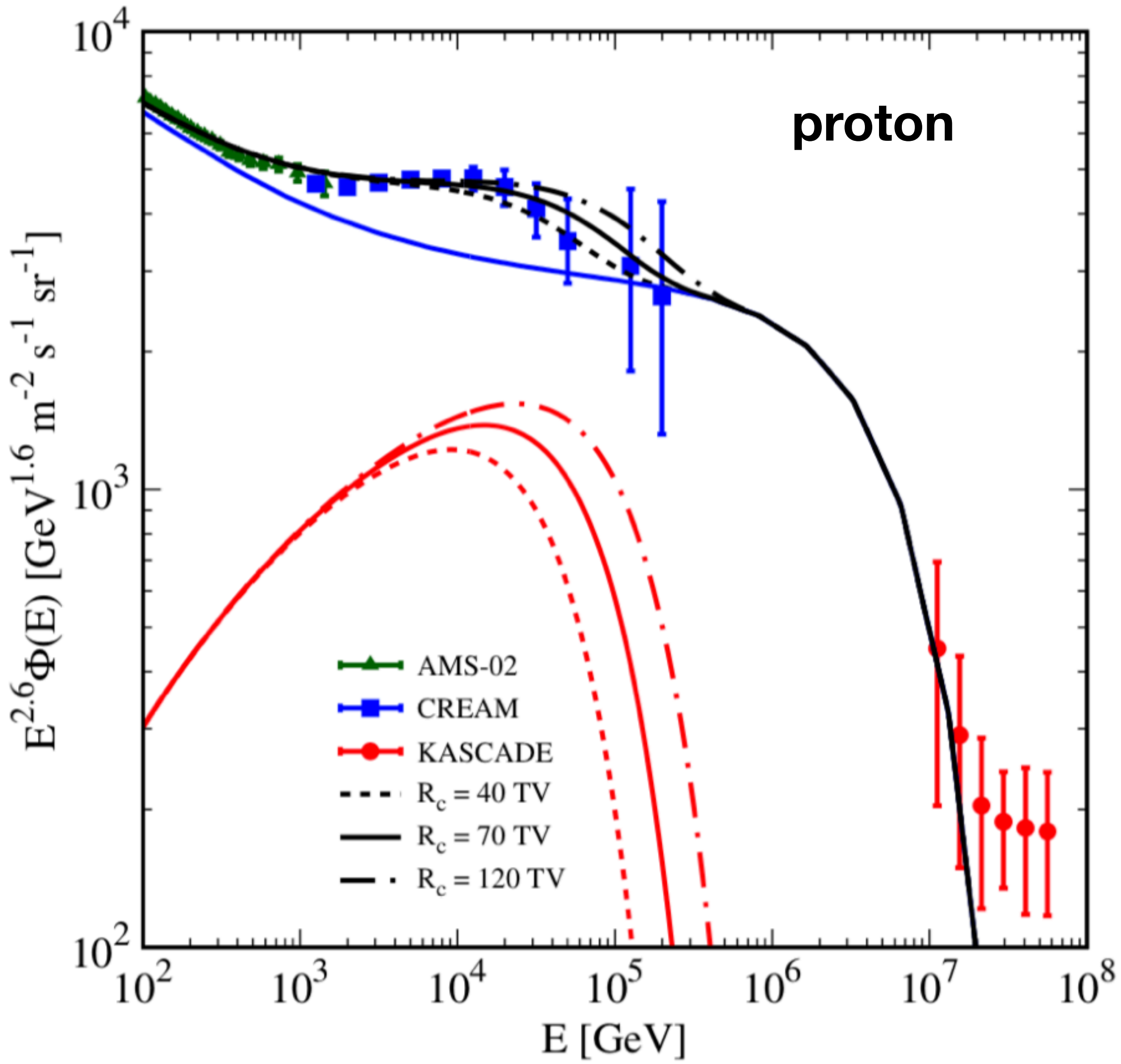
distance to solar system is 330 pc

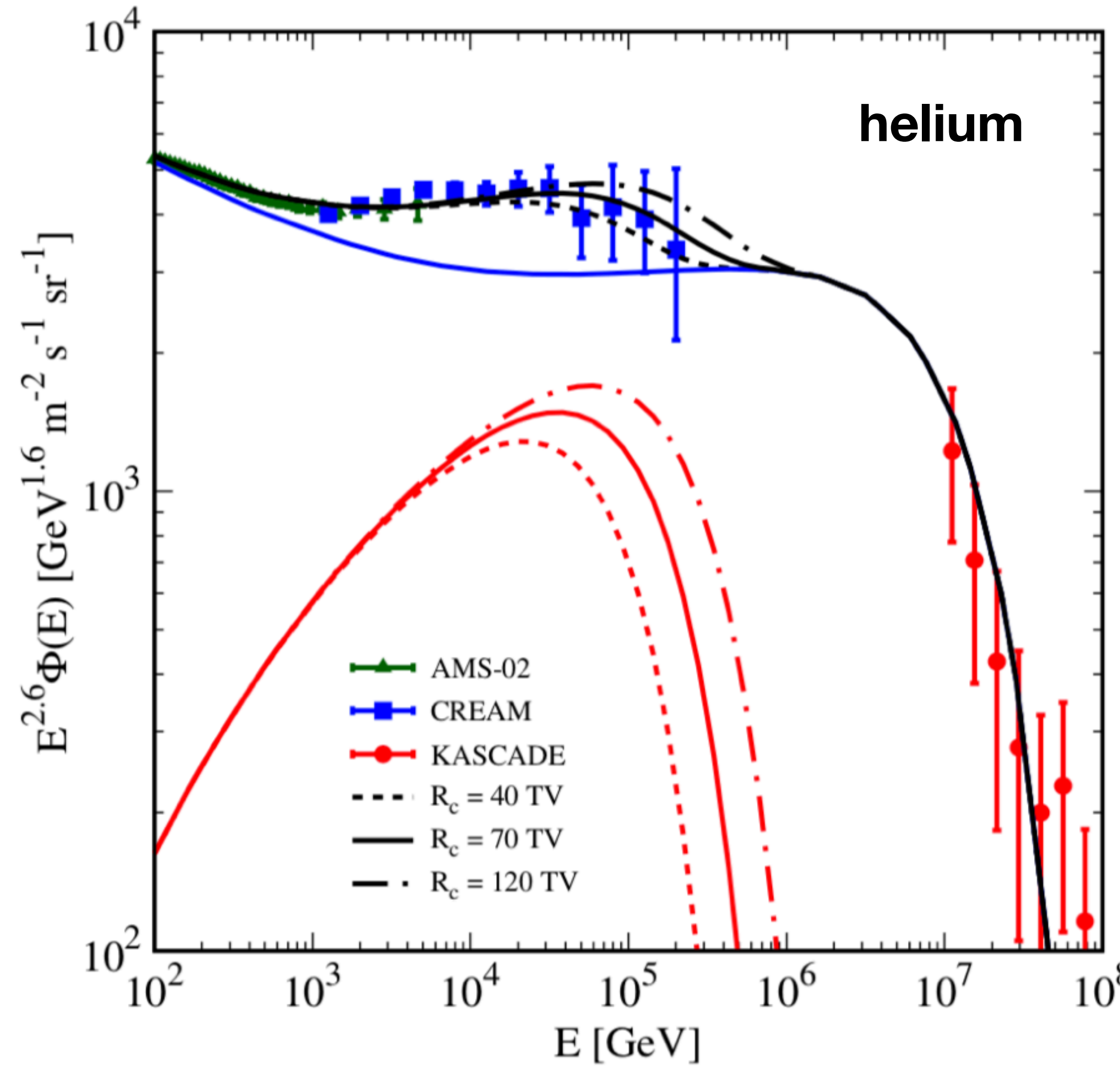


# Results

CR nuclei spectrum




a break at 10 TeV for proton

$K_0 = 4.46\times10^{28}\,\mathrm{cm}^2/s$

$\delta_0 = 0.62$

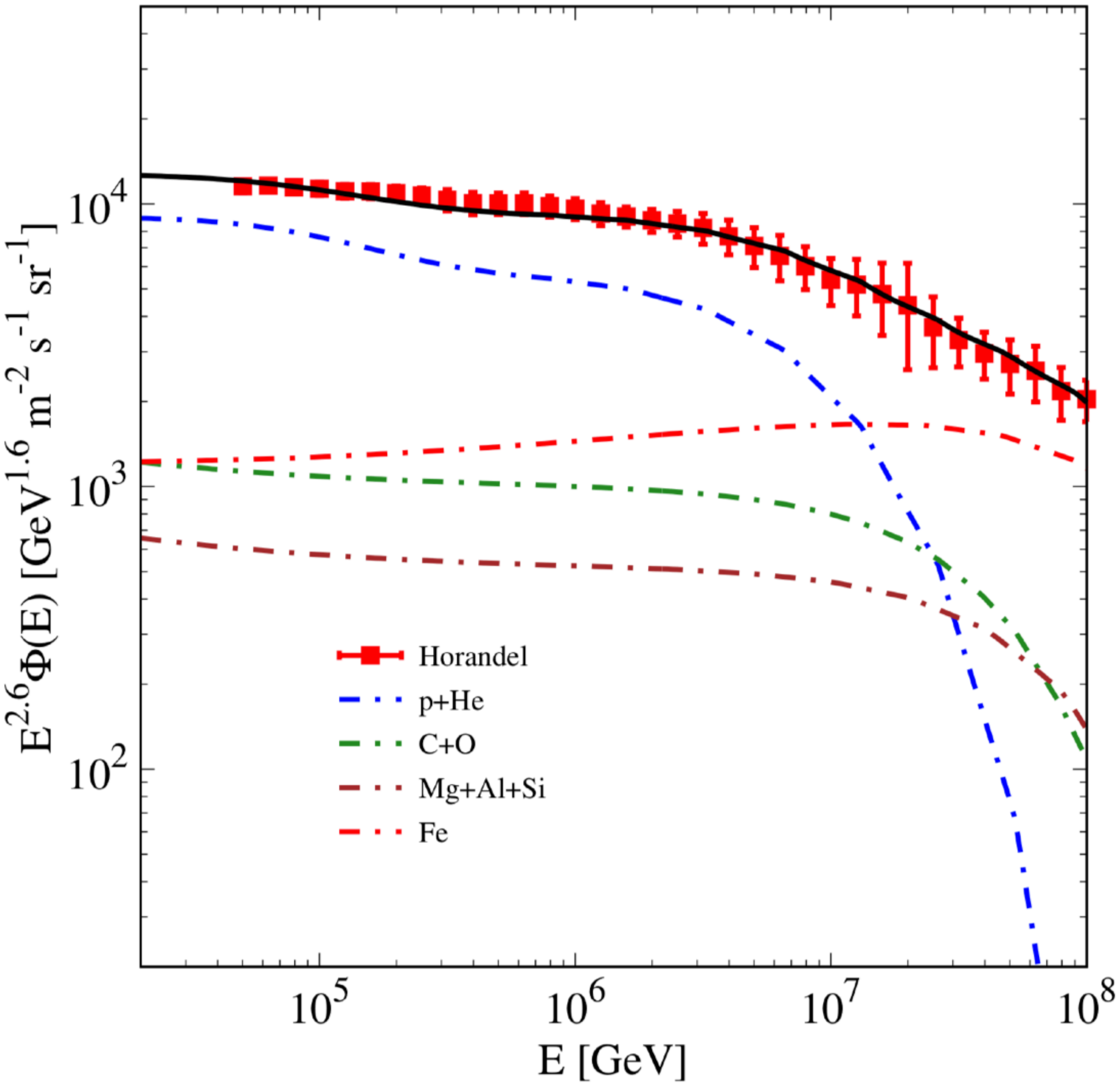
$\alpha_{bg} = 2.4$

$\alpha_G = 2.2$

All particle spectrum

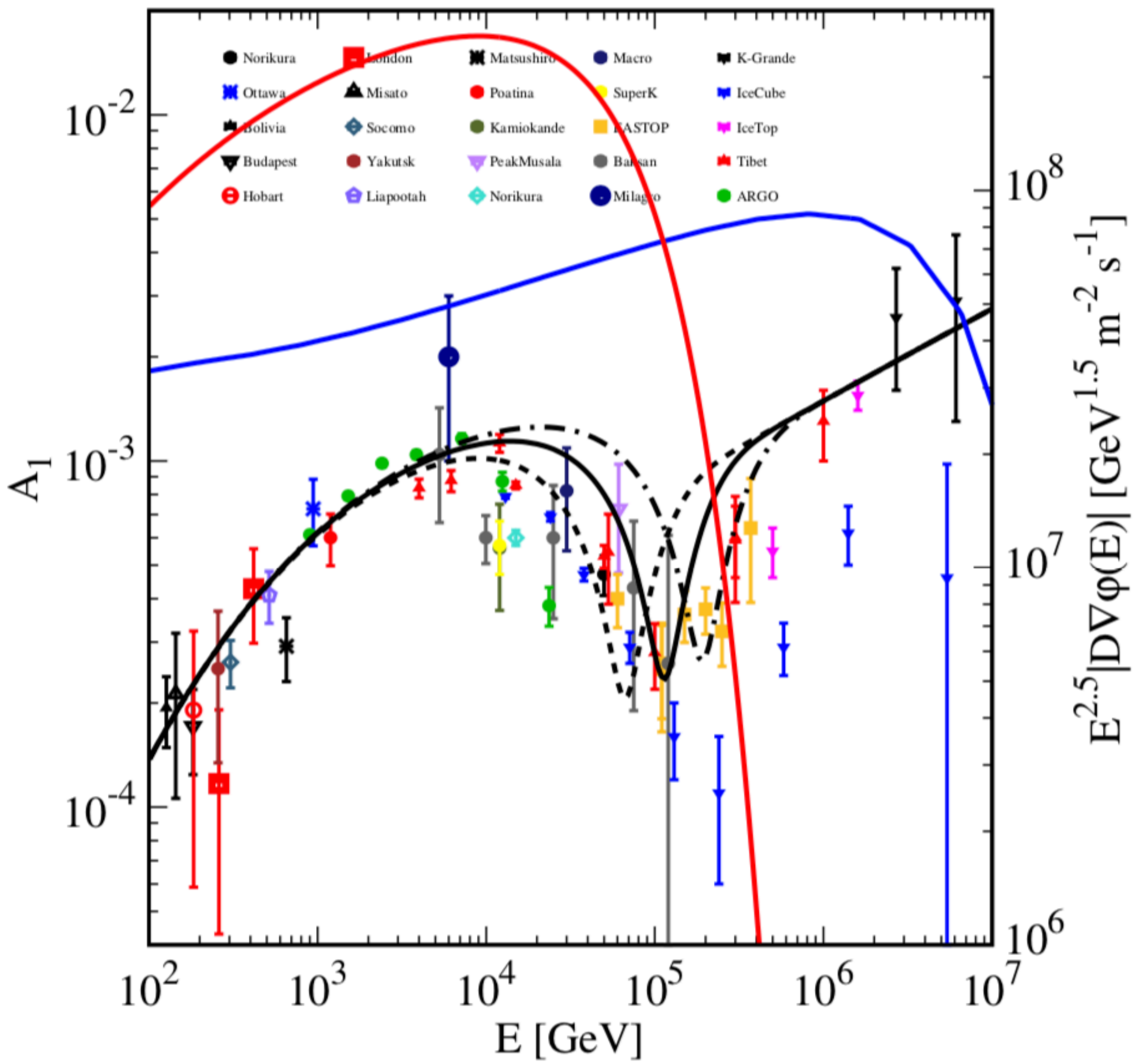
high energy cutoff of background is rigidity dependent

rigidity cutoff of proton is 6.5 PV

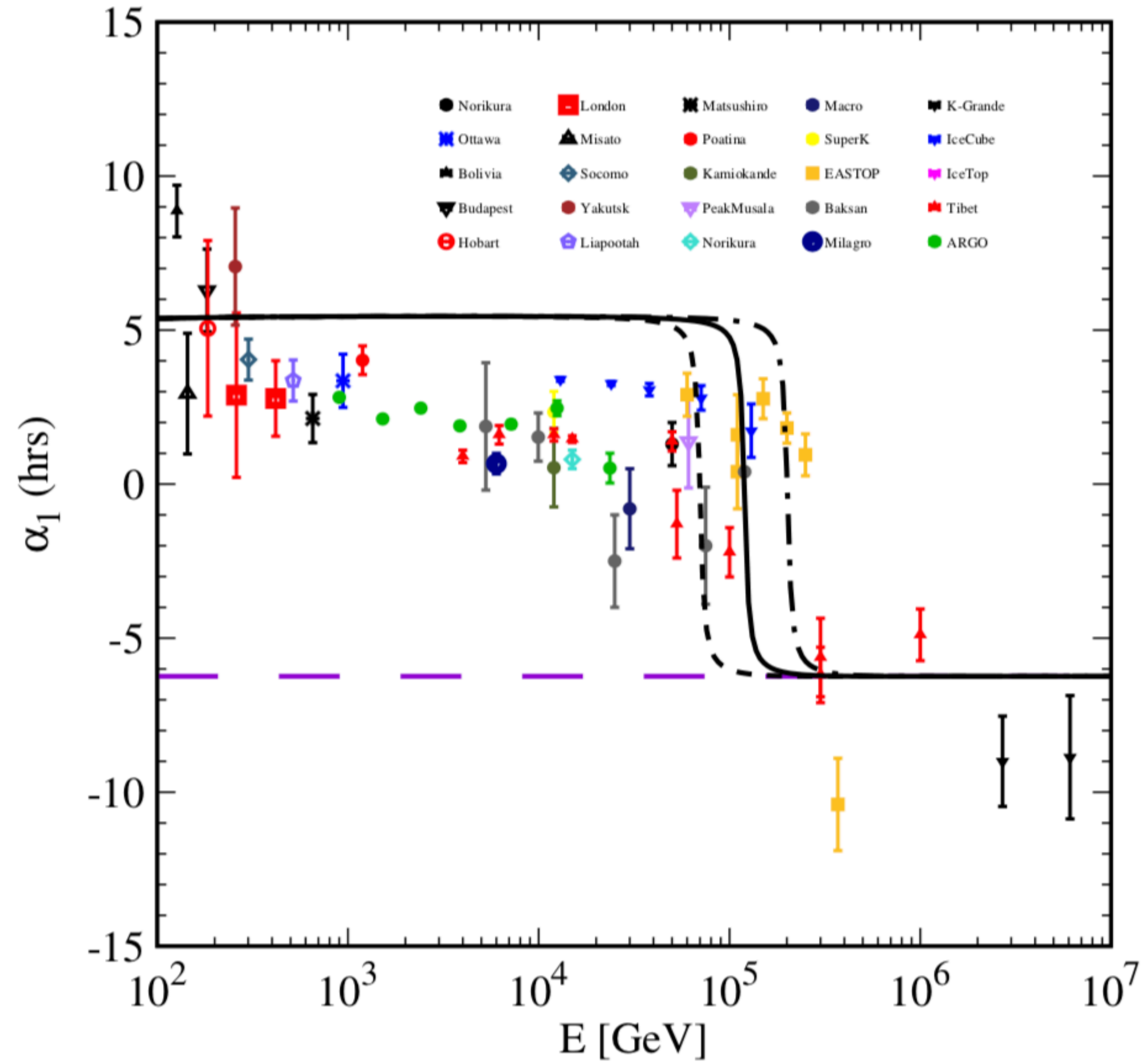


dipole anisotropy

Amplitude




Phase

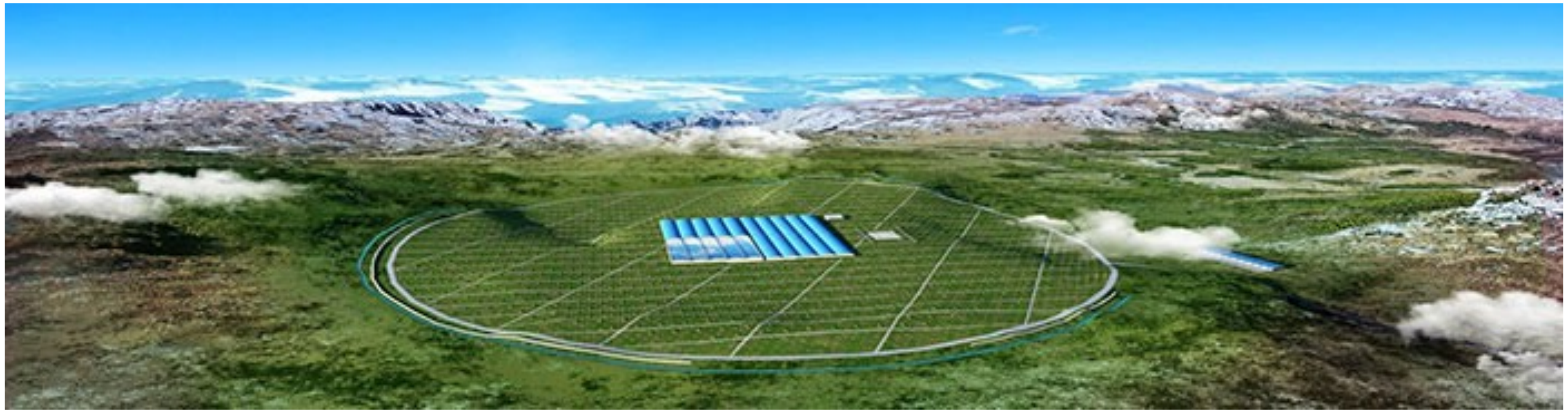



dip at 100 TeV is sensitive to the cutoff energy of local source

bottom point could be used for the calibration of ground-base detection experiment

# Summary

- We build up an integrated picture based on spatial-dependent propagation model
- The non-trivial energy evolution of dipole anisotropy below 100 TeV indicates a local CR source, Geminga could be a possible candidate, which also responsible for the positron excess
- Both CR spectra and amplitude of dipole anisotropy are well reproduced
- The phase less than 100 TeV does not well account for. Possible solutions: another nearby source, local regular magnetic field
- LHAASO experiment could perform more precise measurements of the 100 TeV break of anisotropy



Thank you for your attention!


obrigado
Dank U
Merci
mahalo
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спасибо
Grazie
Thank you
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Takk
Gracias
Dziękuję
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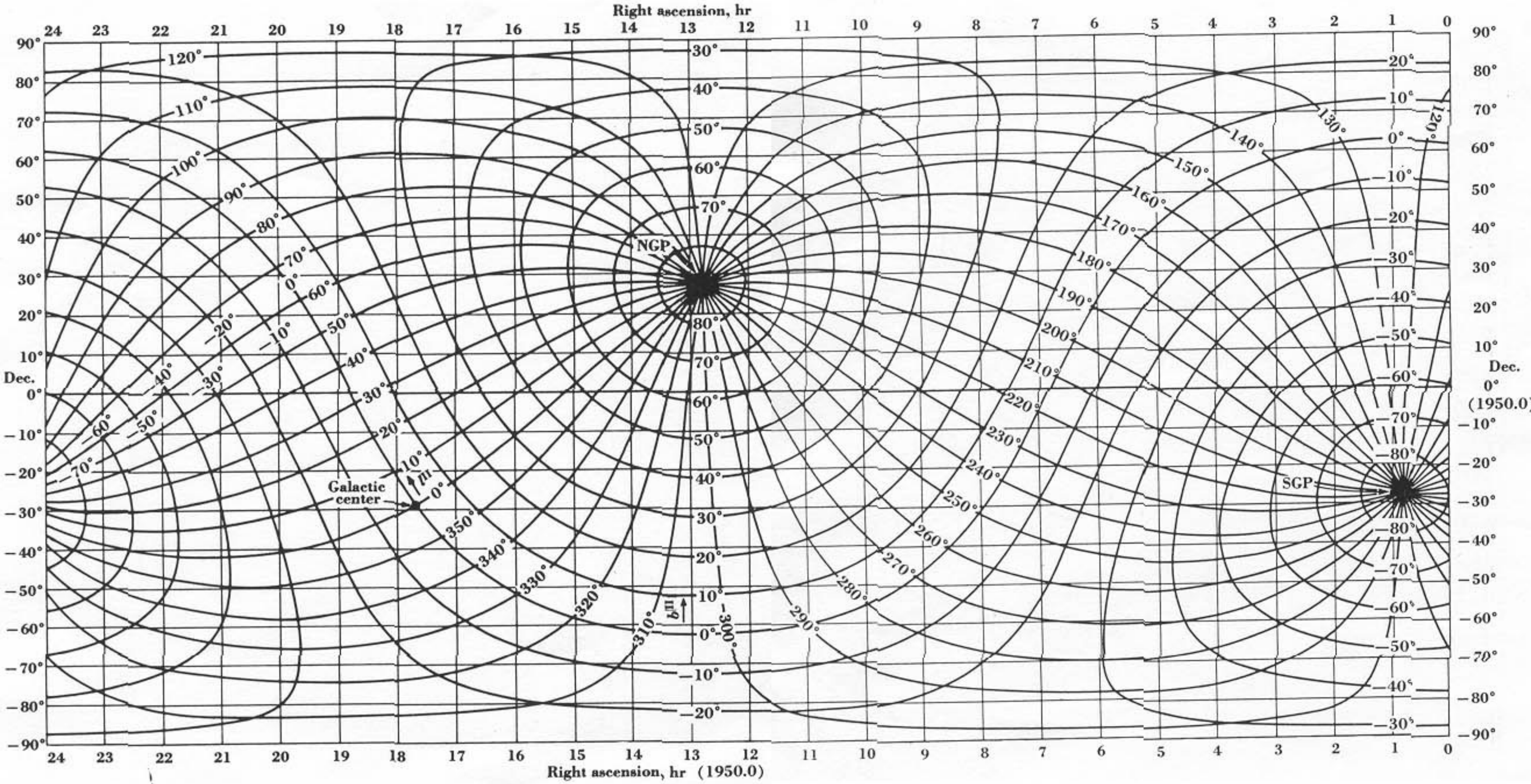
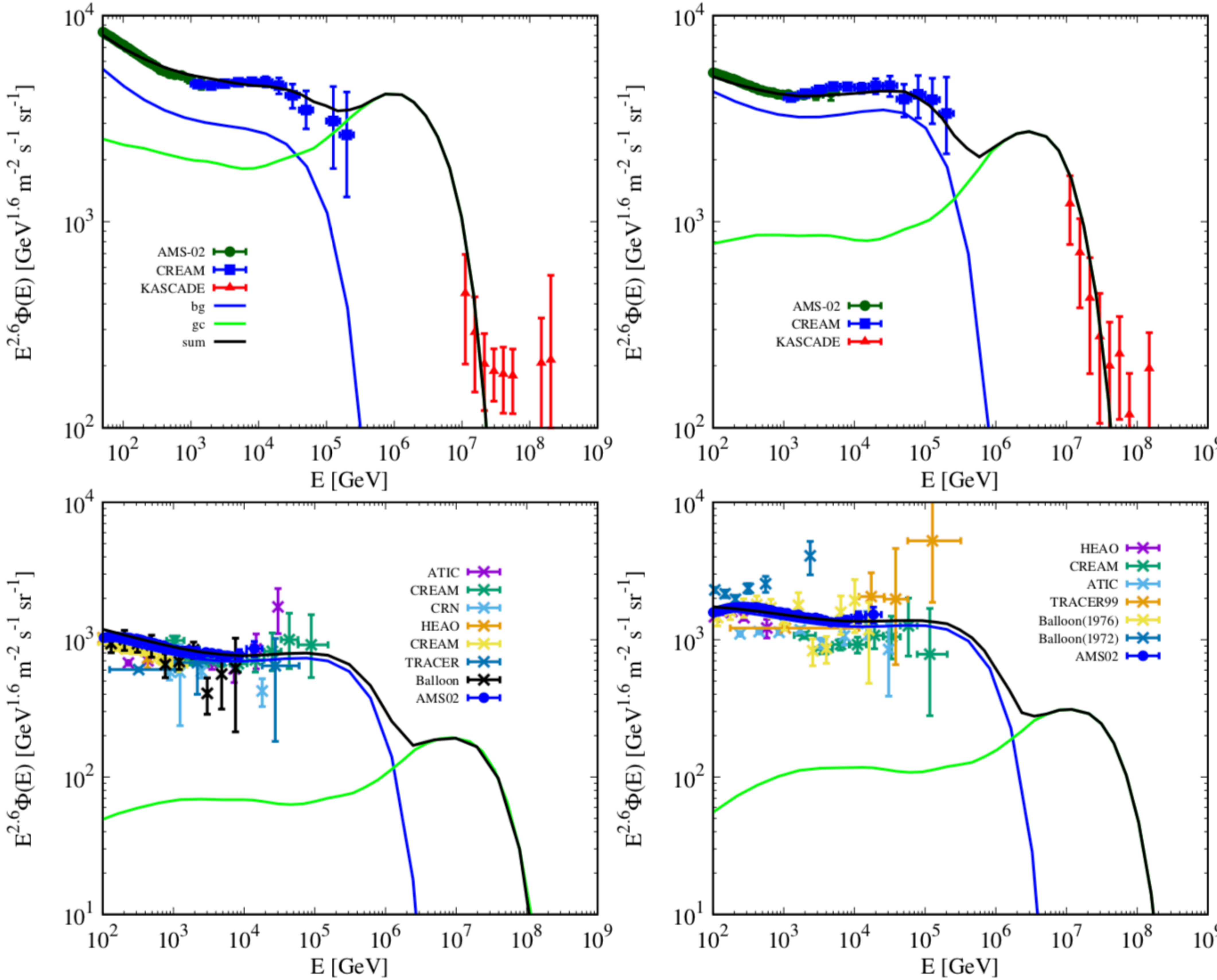
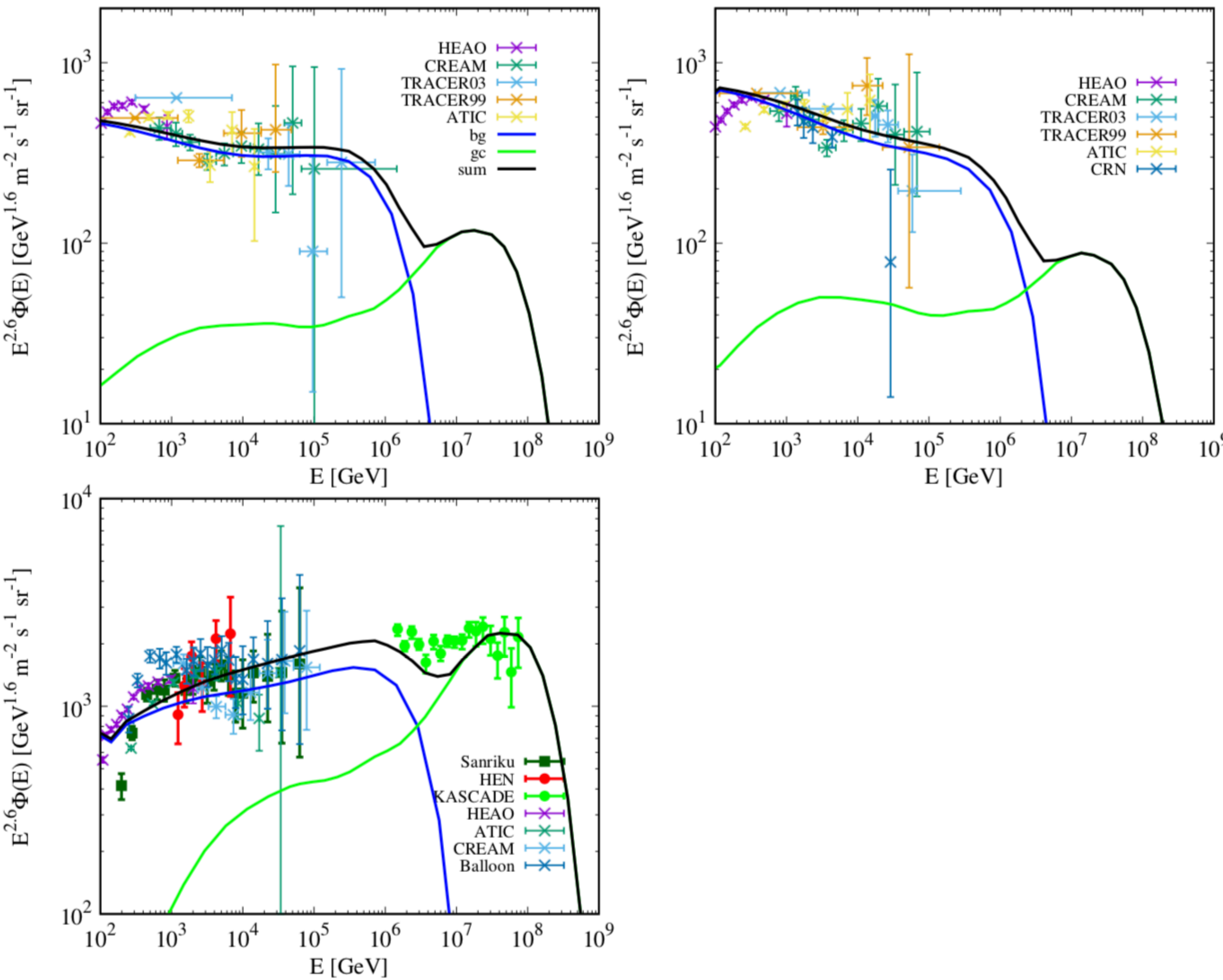

Right ascension, hr
24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
90° 80° 70° 60° 50° 40° 30° 20° 10° 0° −10° −20° −30° −40° −50° −60° −70° −80° −90°
Dec.
Dec.
0°
(1950.0)
NGP
SGP
Galactic center
$l^{II}$
$b^{II}$
Right ascension, hr (1950.0)



$E^{2.6}\Phi(E)$ [$GeV^{1.6}$ $m^{-2}$ $s^{-1}$ $sr^{-1}$]
E [GeV]
AMS-02
CREAM
KASCADE
bg
gc
sum
AMS-02
CREAM
KASCADE
ATIC
CREAM
CRN
HEAO
CREAM
TRACER
Balloon
AMS02
HEAO
CREAM
ATIC
TRACER99
Balloon(1976)
Balloon(1972)
AMS02



HEAO
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TRACER03
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$E^{2.6}\Phi(E)$ [GeV$^{1.6}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$]
E [GeV]
HEAO
CREAM
TRACER03
TRACER99
ATIC
CRN
$E^{2.6}\Phi(E)$ [GeV$^{1.6}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$]
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KASCADE
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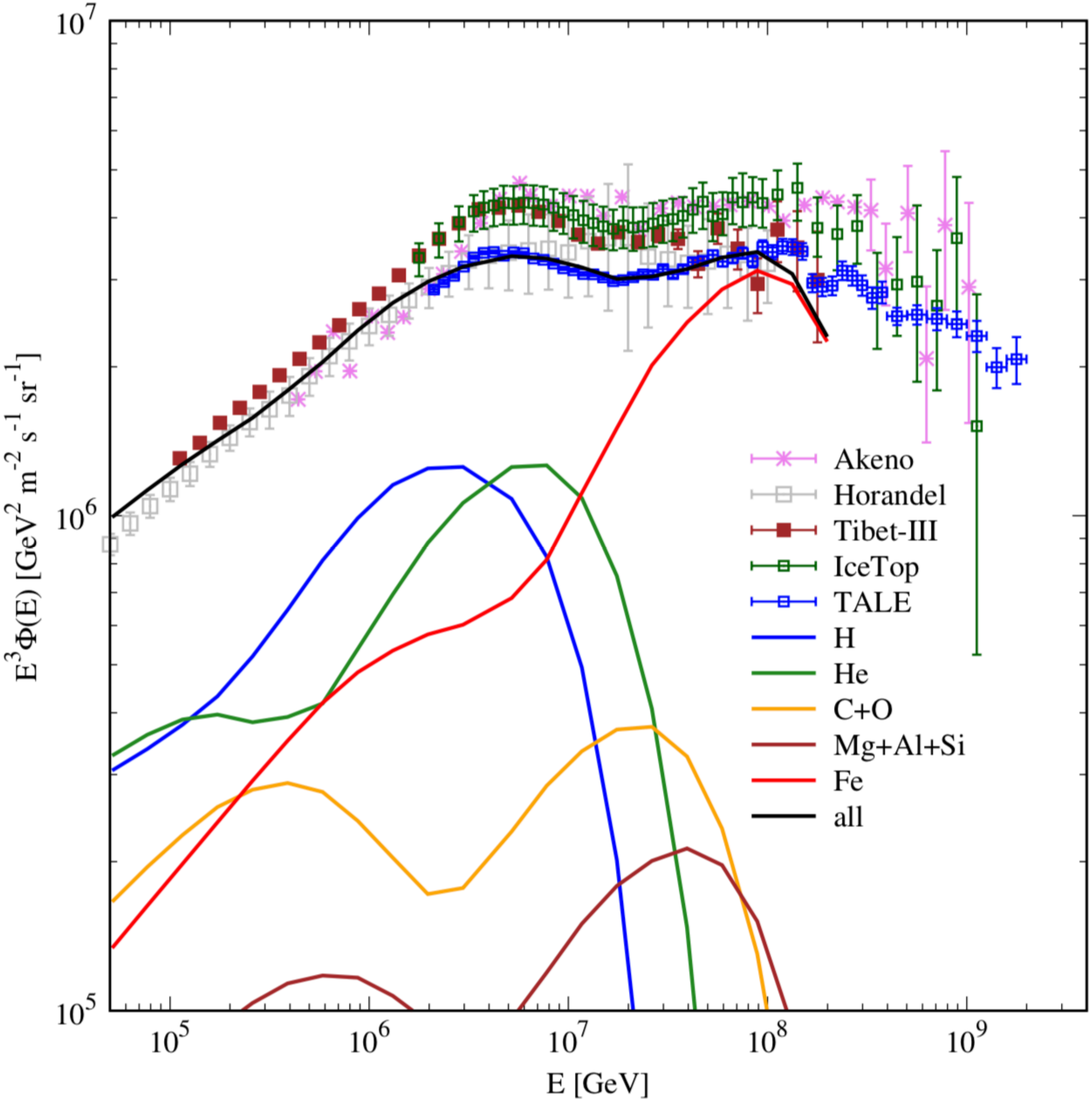
$E^{2.6}\Phi(E)$ [GeV$^{1.6}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$]
E [GeV]

# All-particle spectrum

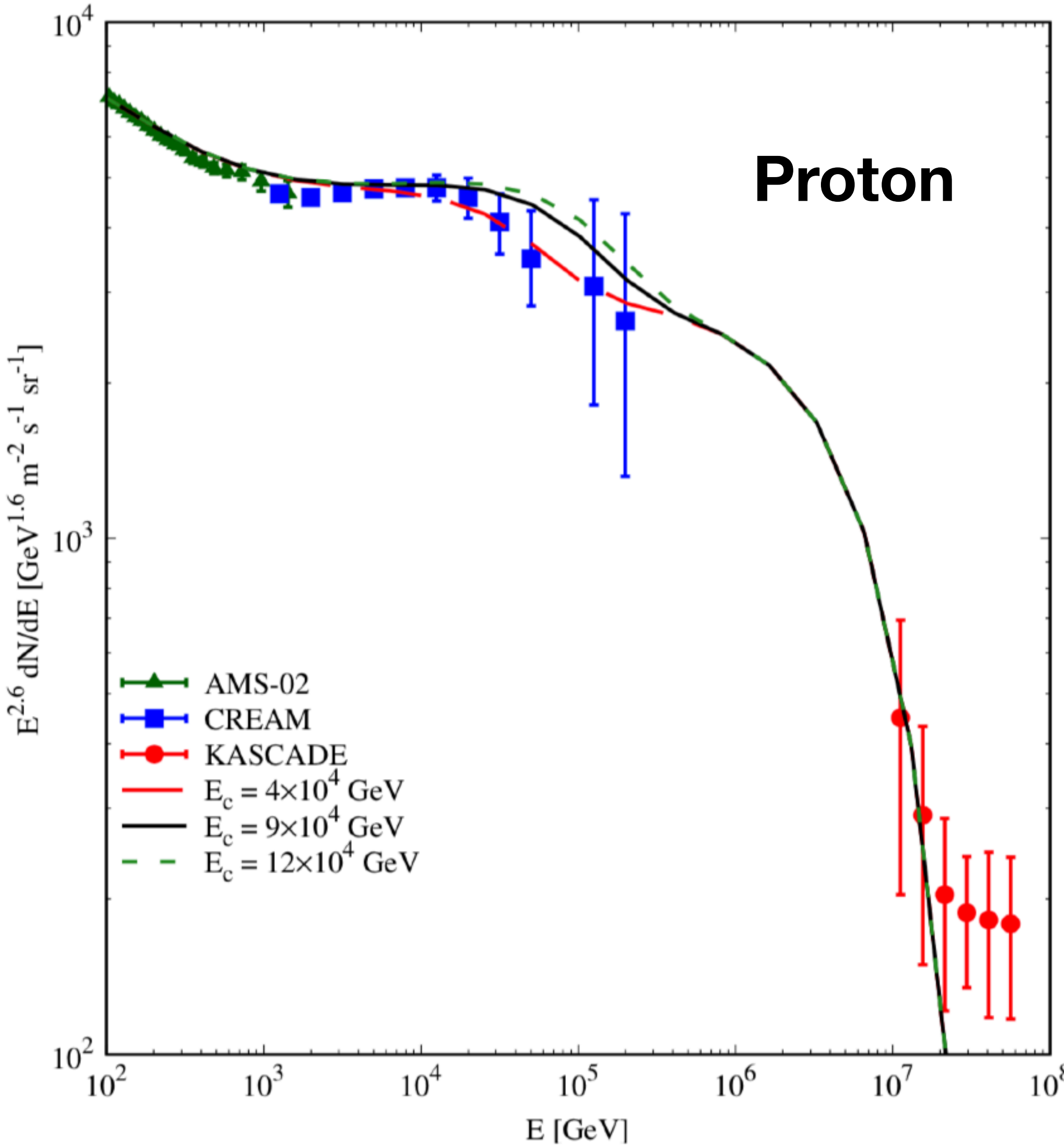


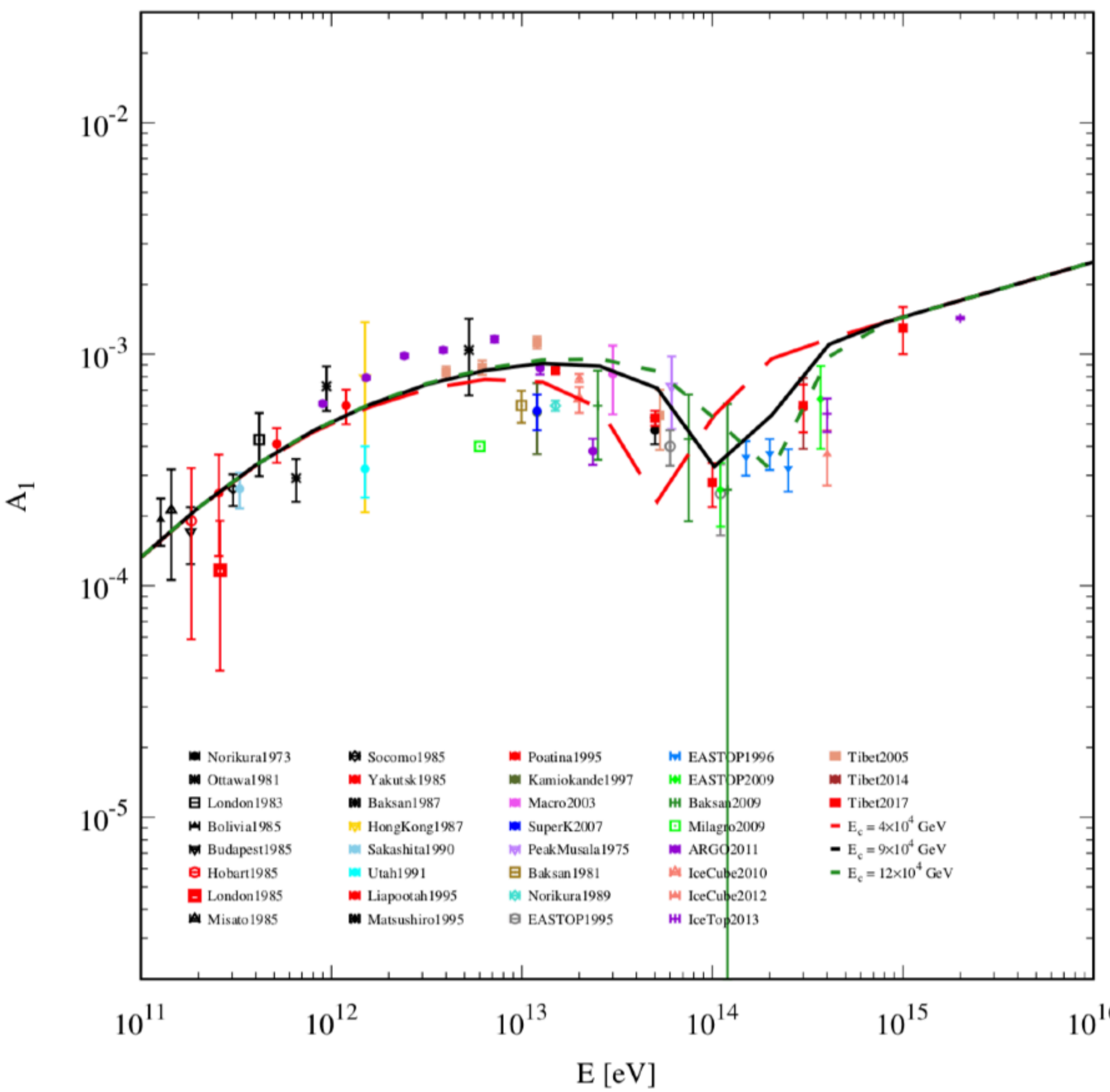
# Ec and anisotropy

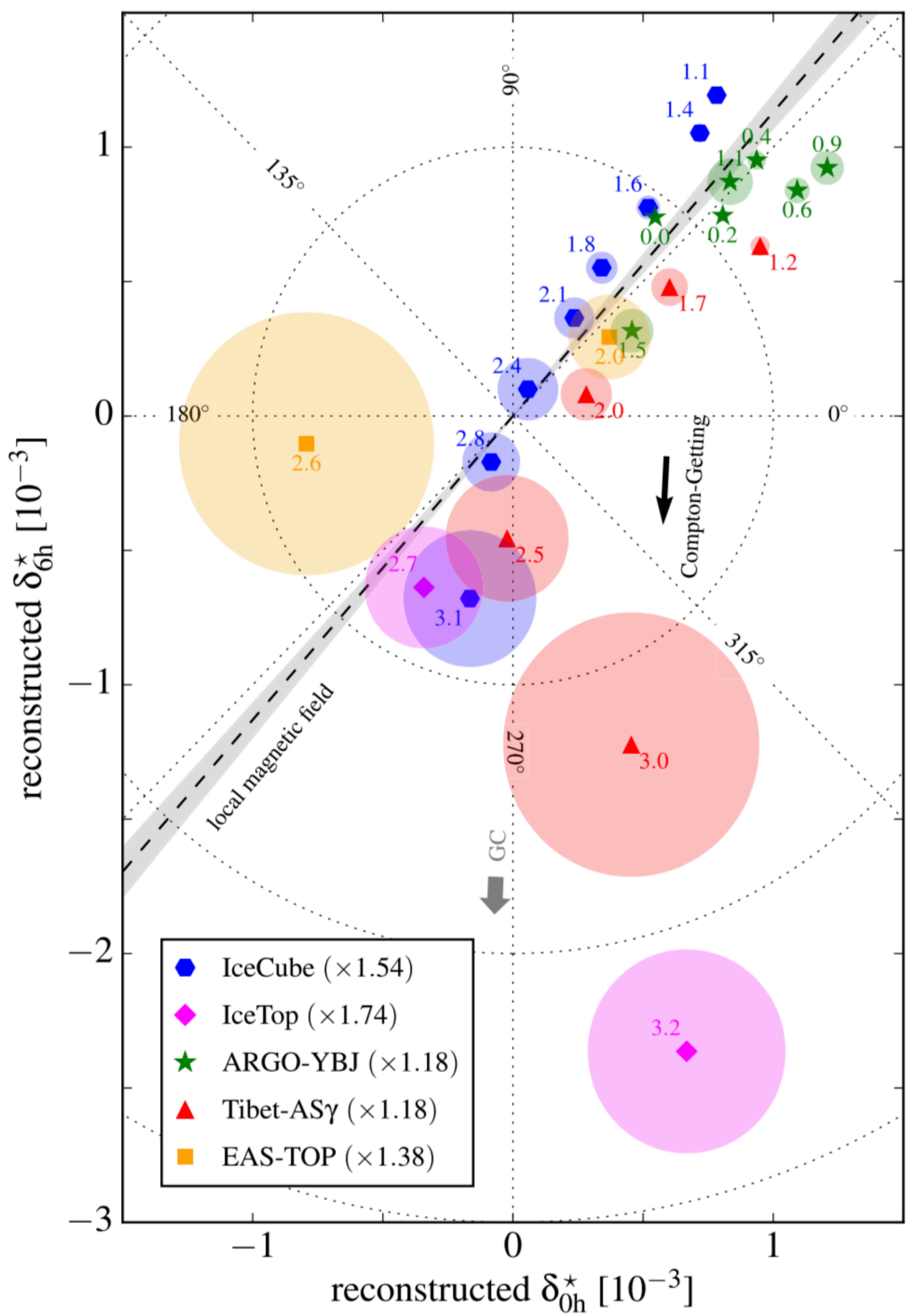
$$E_c = 4 \times 10^4 \text{ GeV}$$

$$E_c = 9 \times 10^4 \text{ GeV}$$

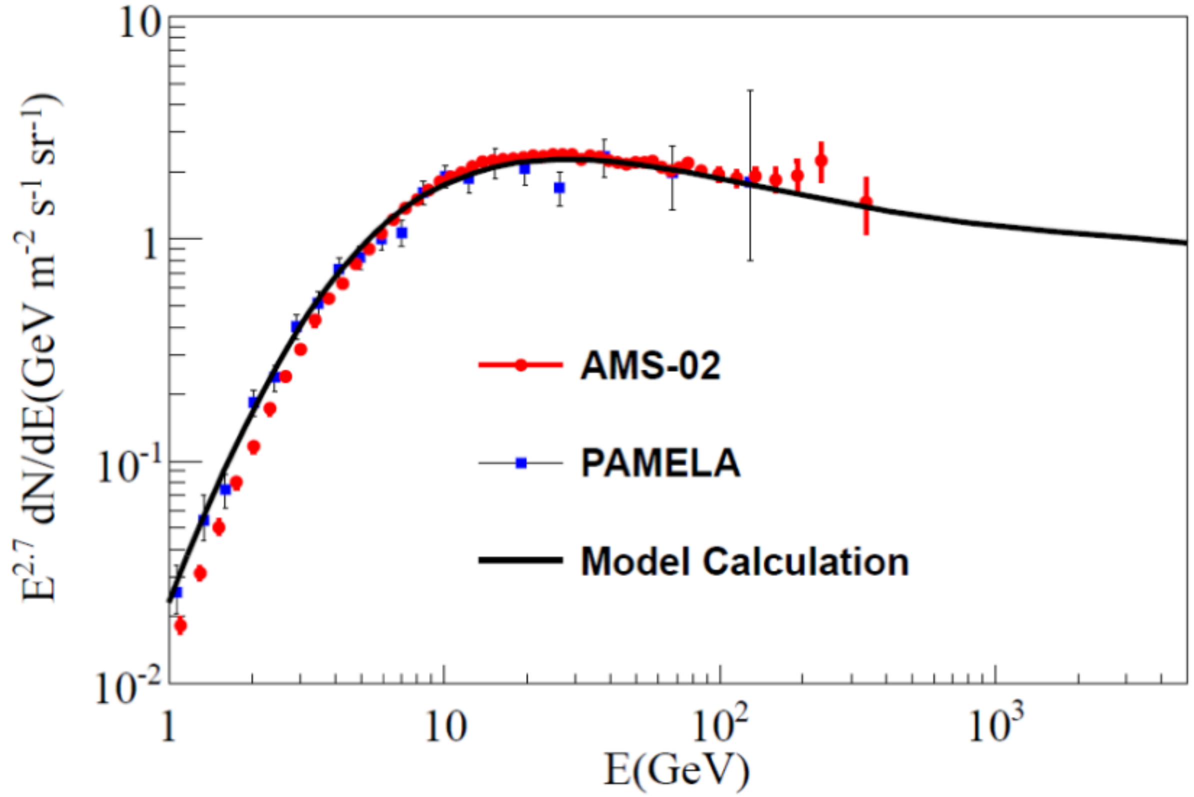
$$E_c = 12 \times 10^4 \text{ GeV}$$

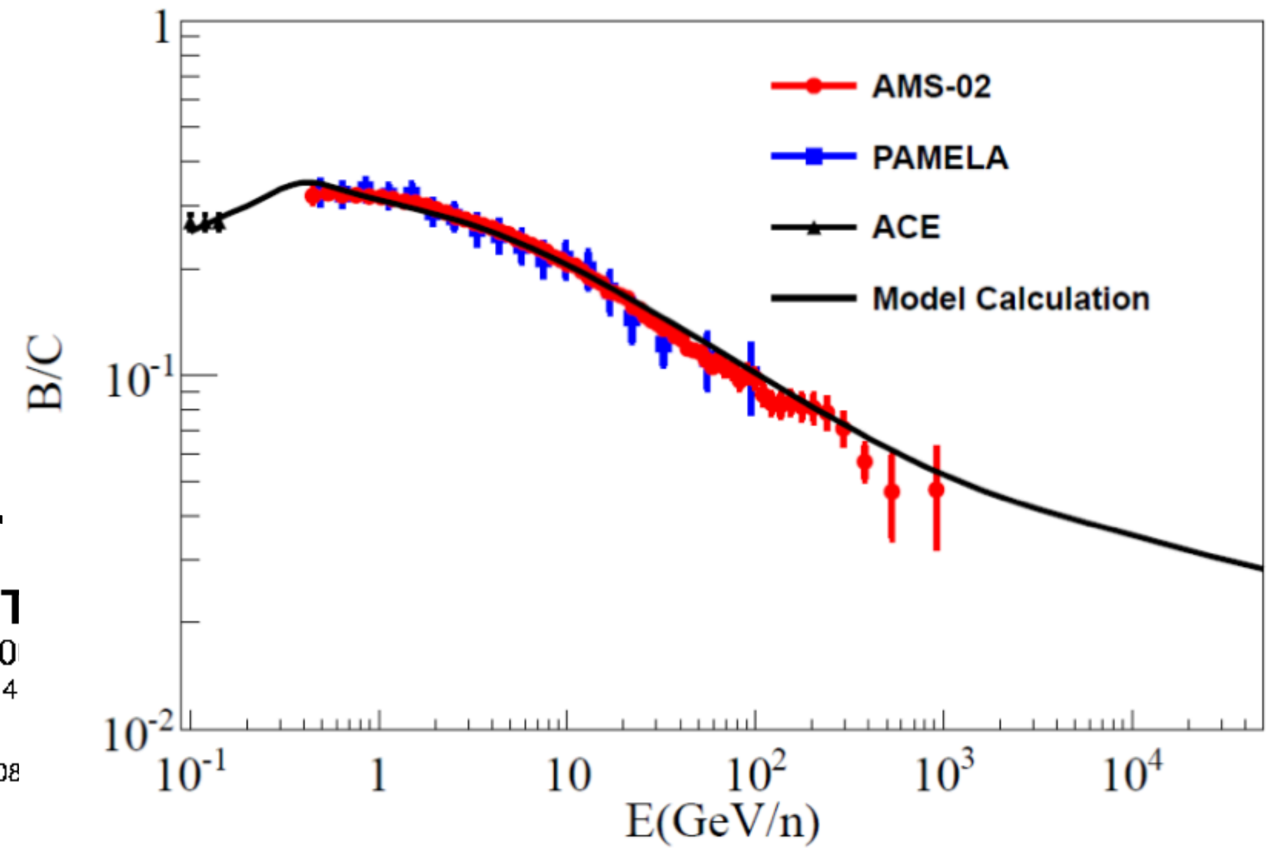


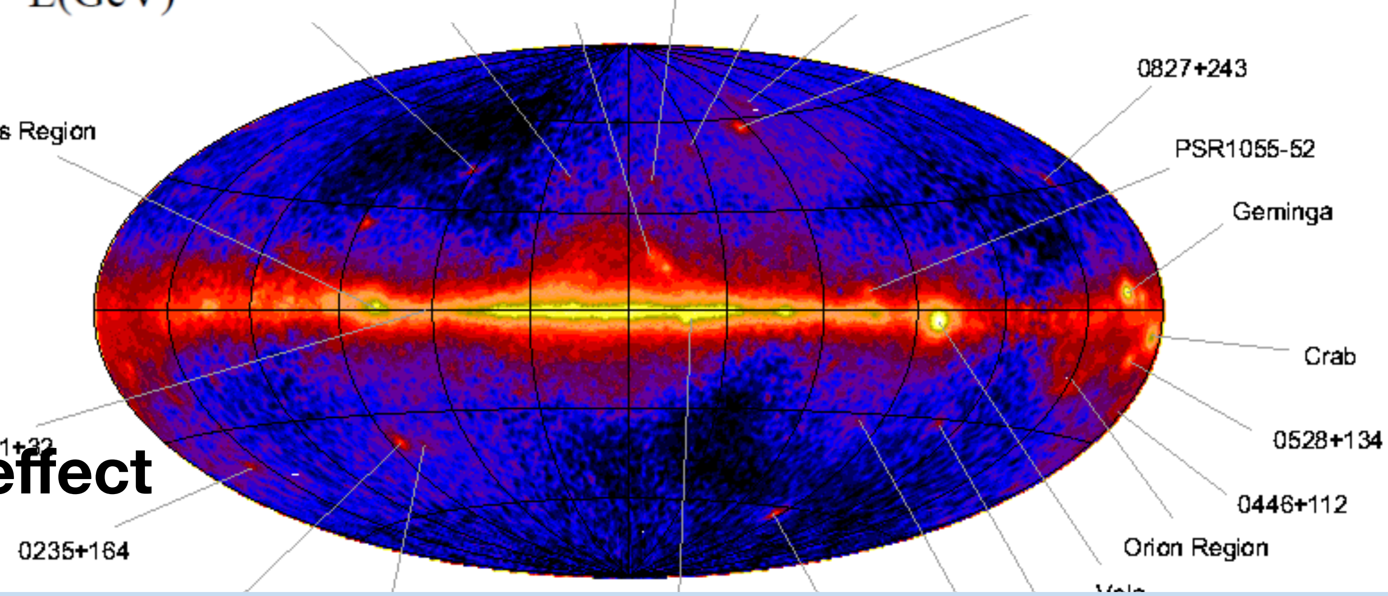






- Non-uniform distribution of sources [Blasi & Amato 12; Sveshnikova *et al.*13]
- Local sources [Liu, Bi, *et al.*17]
- Spatial-dependent diffusion [Guo, *et al.*16]
- Local magnetic field [Schwadron *et al.* 14; Mertsch & Funk 14]
- Compton-Getting effect [Compton & Getting 35]



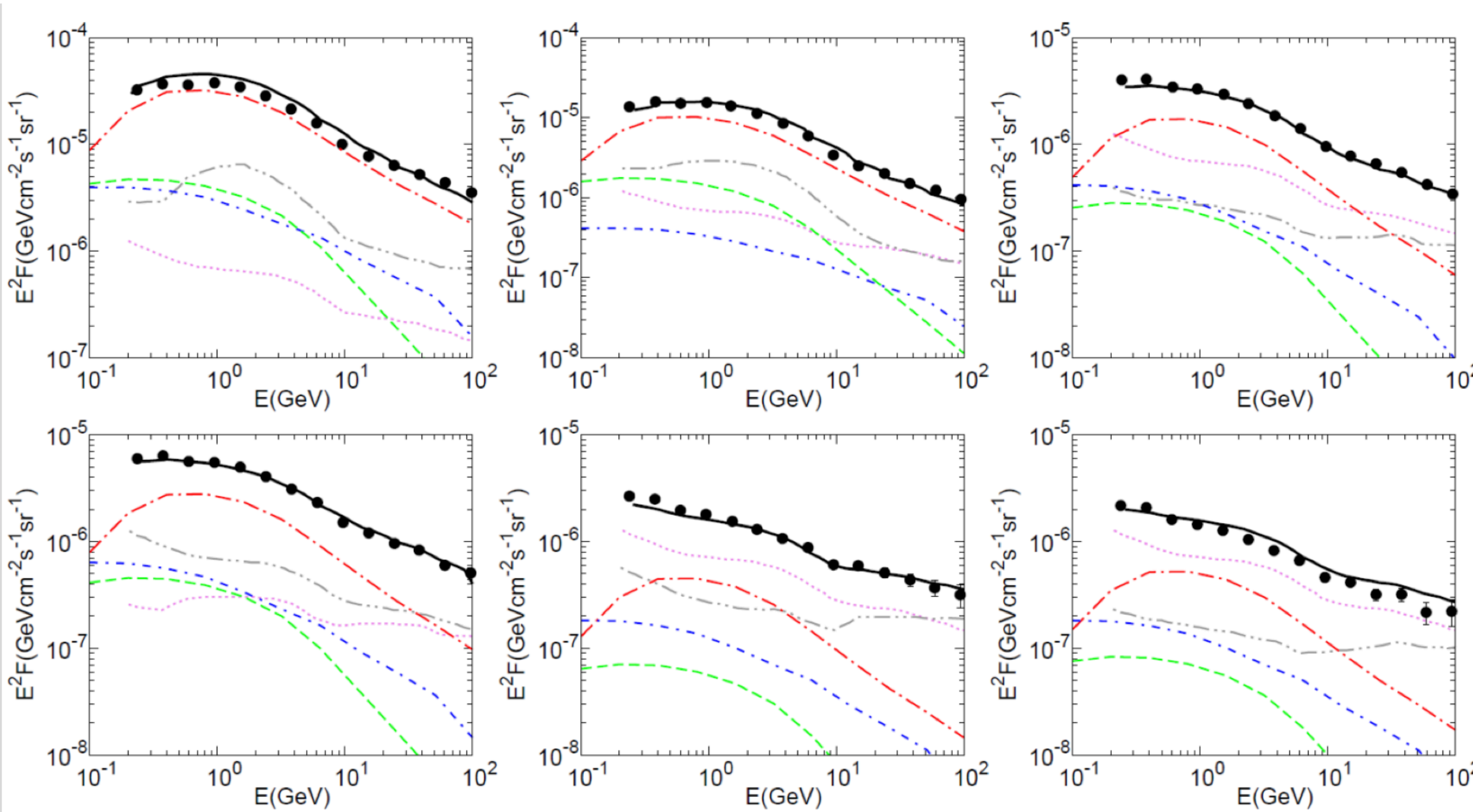

**Compton-Getting effect**

For a power-law CR spectrum $\propto p^{-2-\Gamma}$

$$\delta_{CG} \simeq (2+\Gamma)\beta$$

Compton & Getting, Phys. Rev. 47 (1935) 817; Gleeson & Axford, Astrophys. Space Sci. 2 (1968) 431

# Galactic Diffuse Gamma Rays



# Spatial distribution of Cosmic rays