The Escape Model

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with G.Giacinti, O.Kalashev, A.Nernov, V.Savchenko, D.Semikoz

Outline of the talk

1. Introduction
   - Results on Composition
2. Escape model
   - Fluxes of groups of CR nuclei & knee
   - Transition to extragalactic CRs
   - Exgal. protons, γ's and ν's as CR secondaries
3. A recent nearby SN?
   - Anisotropy
   - Antimatter fluxes
4. Conclusions

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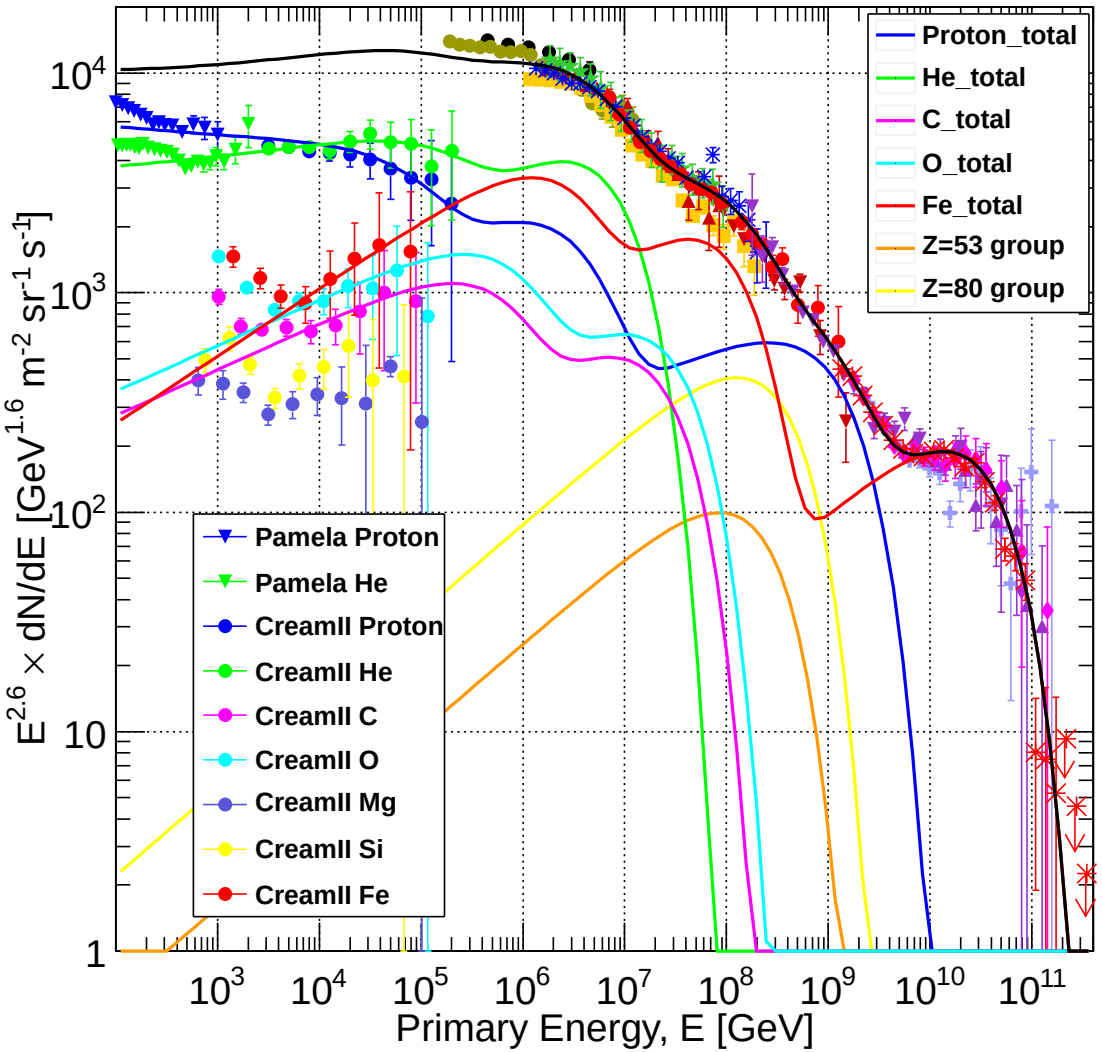
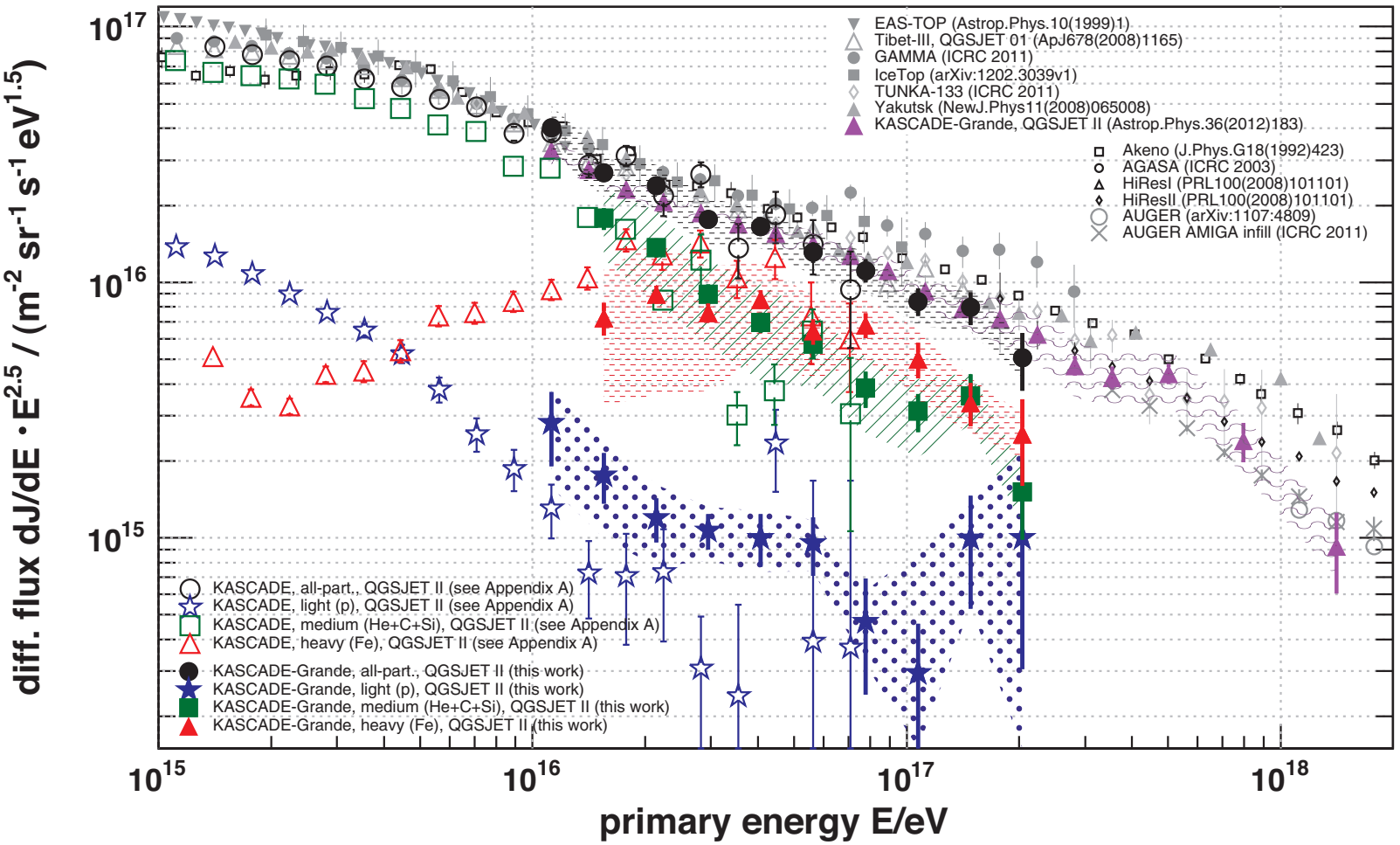
Composition of Galactic CRs: traditional view [*Gaisser, Stanev, Tilav '13*]

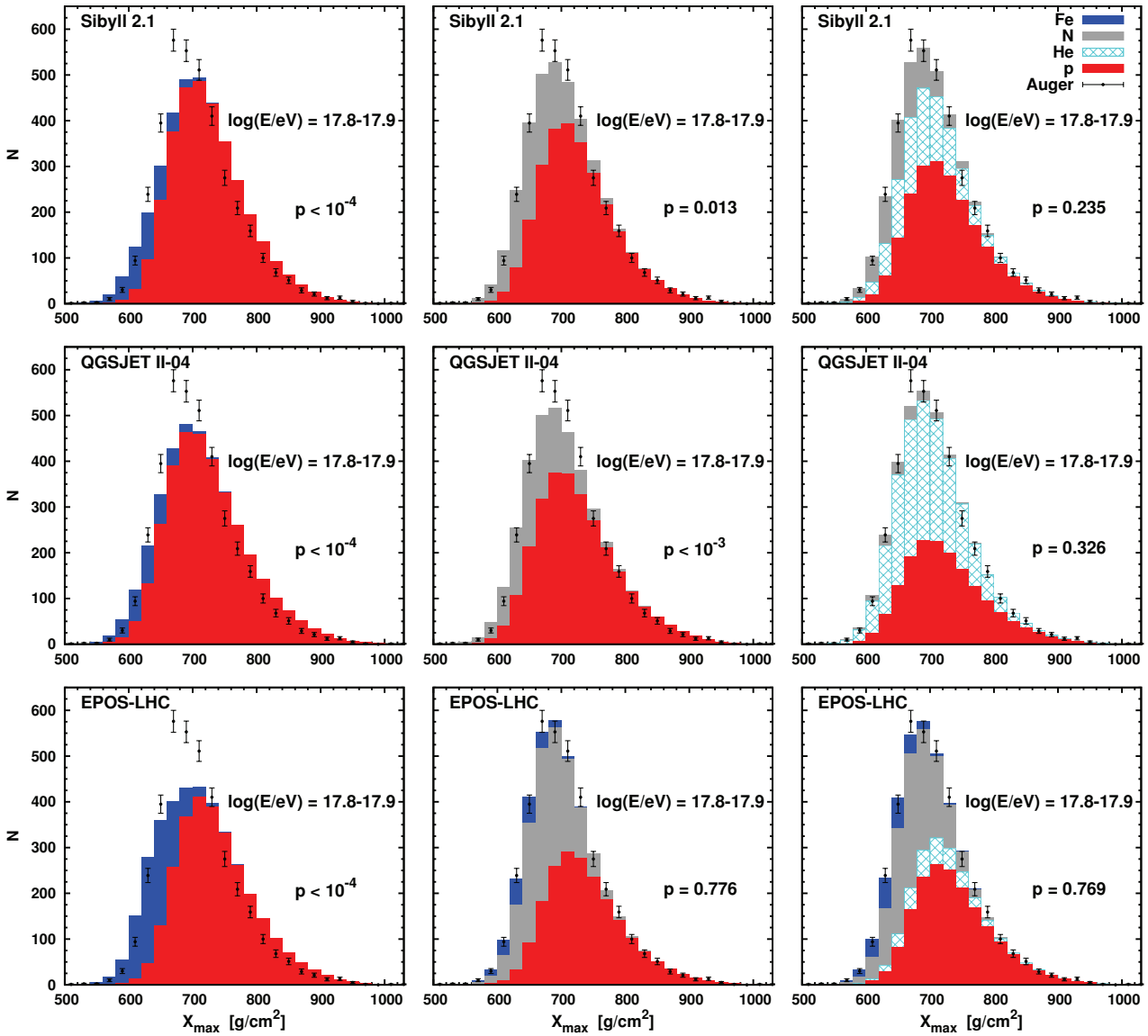


Composition of Galactic CRs: KASCADE-Grande 2013



Composition of Galactic CRs: Auger

[arXiv:1409.5083]



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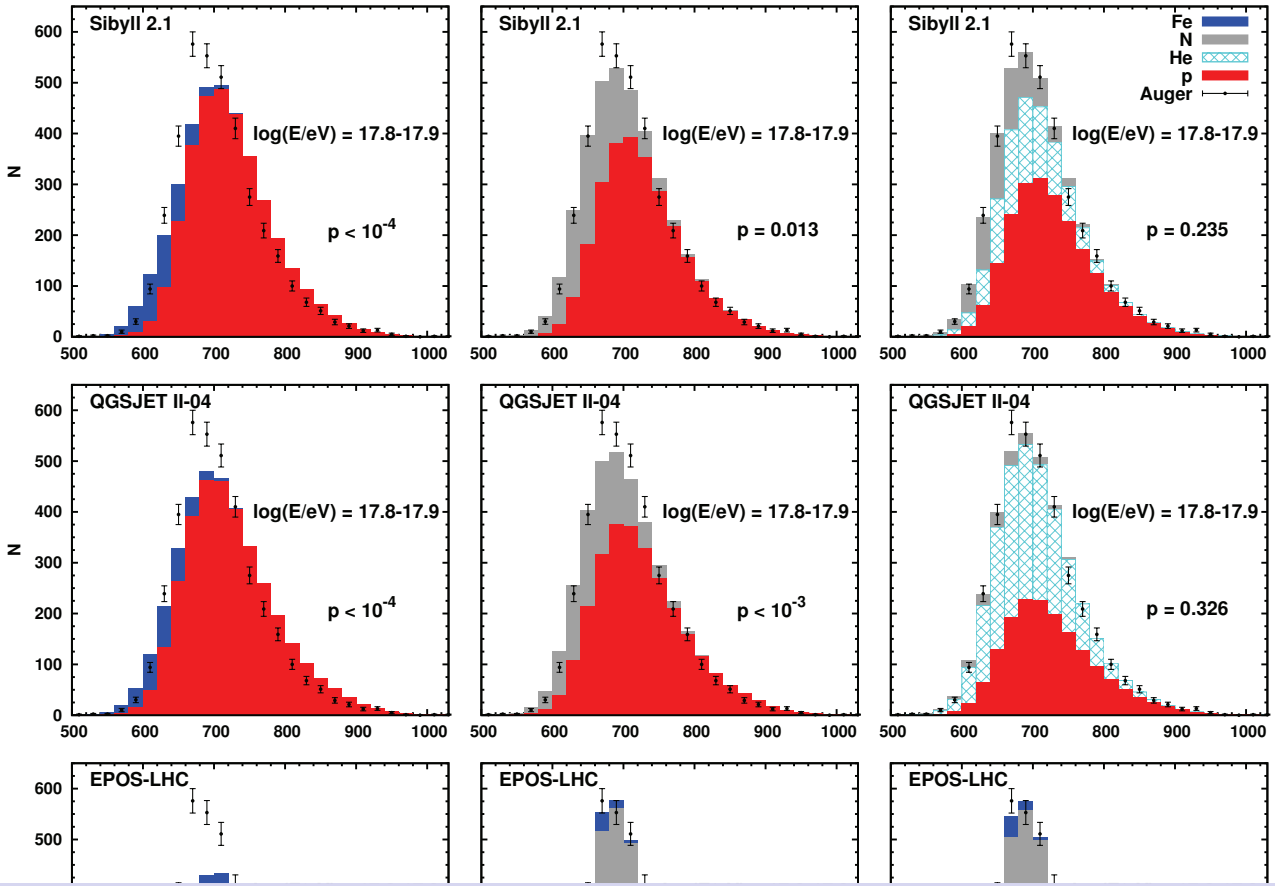

composition $6 \times 10^{17} - 5 \times 10^{18}$ eV consistent with

- 50% p, 50% He+N, $< 20\%$Fe

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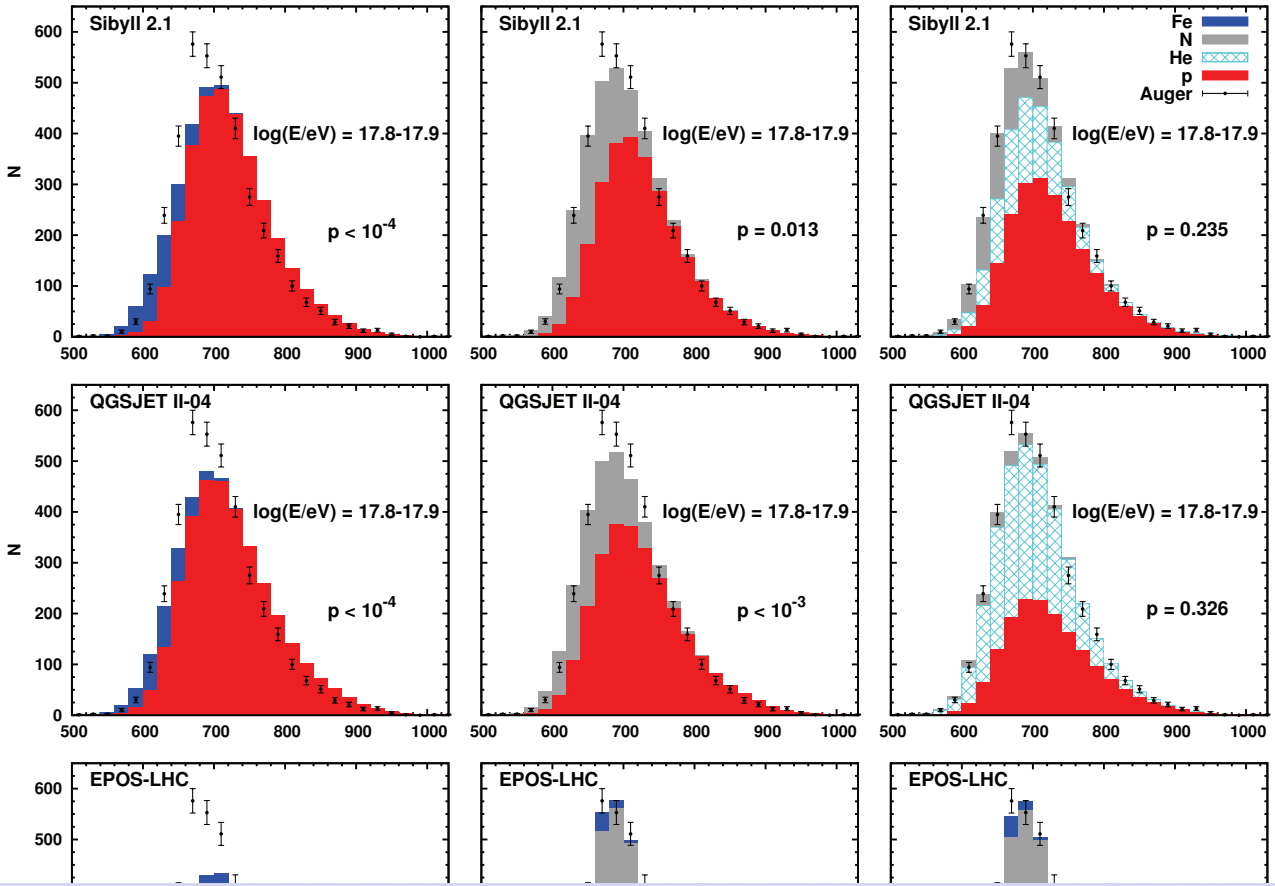
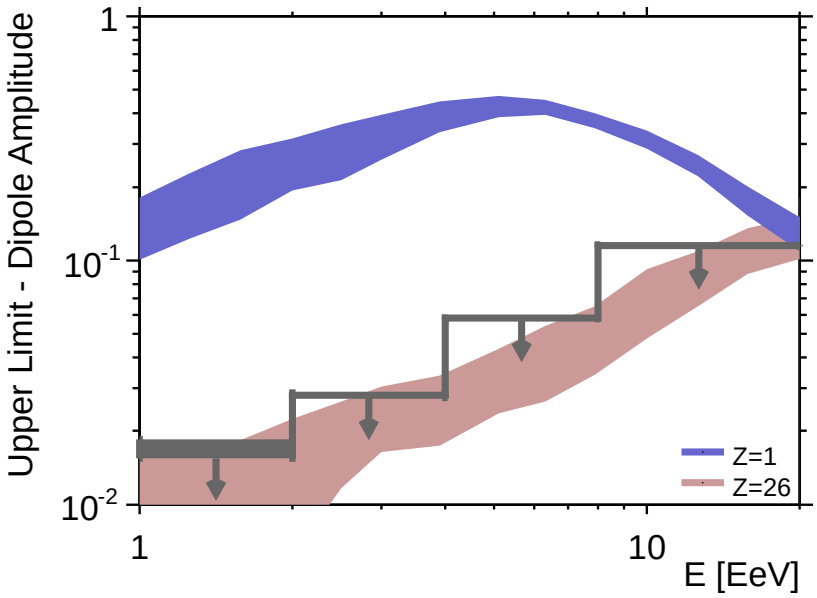


composition $6 \times 10^{17} - 5 \times 10^{18}$ eV consistent with

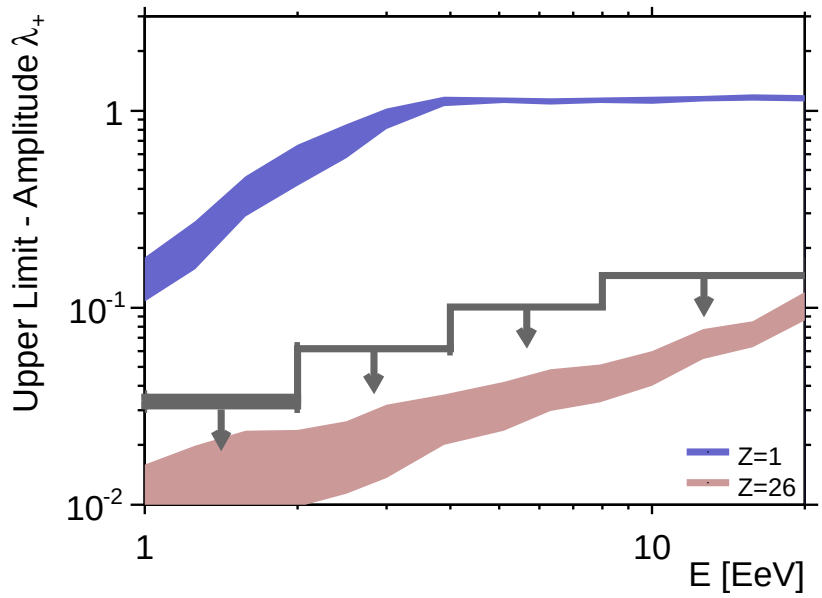
- 50% p, 50% He+N, < 20%Fe
- early transition from Galactic to extragalactic CRs

Transition to extragalactic CRs – anisotropy limits

dipole



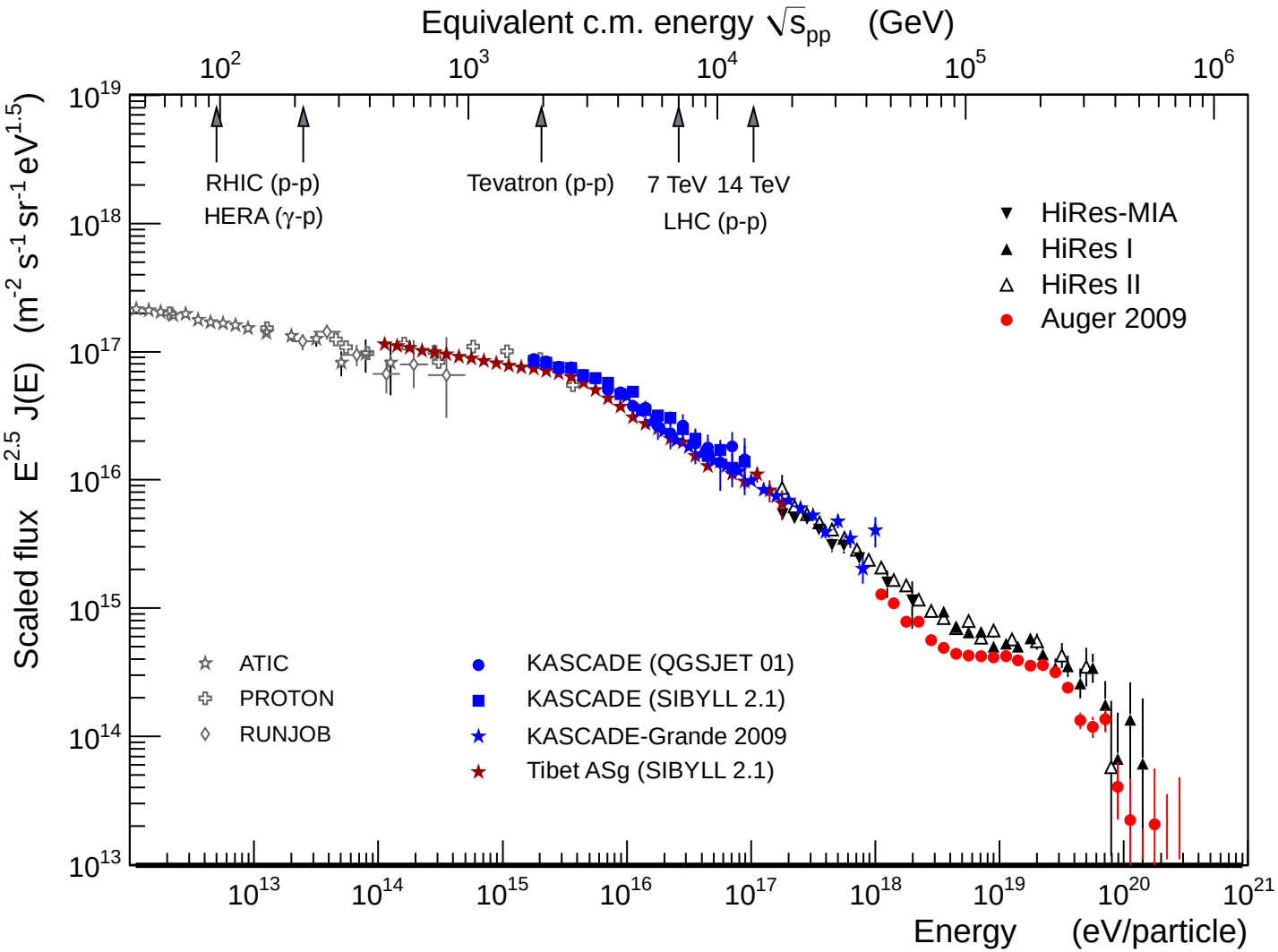
quadrupole



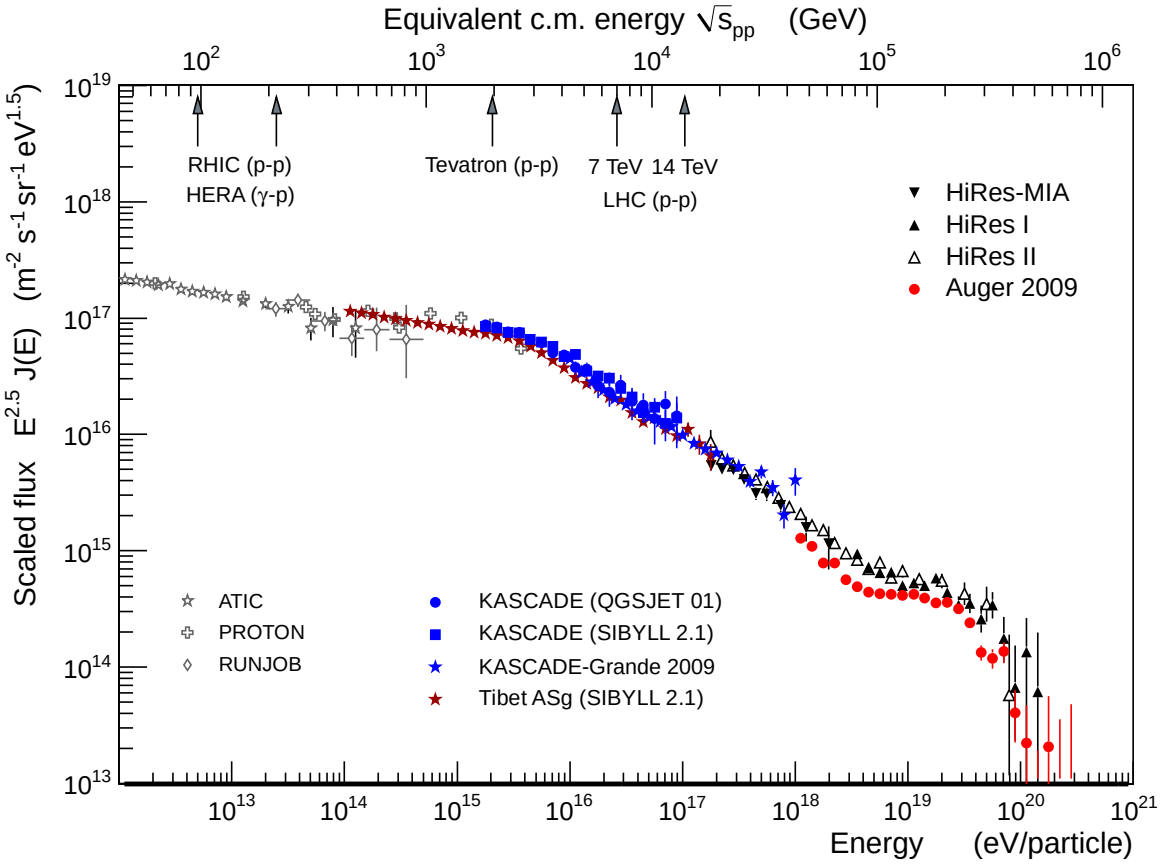
dominant light Galactic composition around $E = 10^{18}$ eV excluded

[Giacinti, MK, Semikoz, Sigl '12, PAO '13]

Cosmic Ray Knee: steepening $\Delta\gamma \simeq 0.4$ at few $\times 10^{15}$ eV



Cosmic Ray Knee: 3 explanations



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- change of propagation at $R_L \simeq l_{\rm coh}$ or $E_c \propto ZeB\, l_{\rm coh}$:

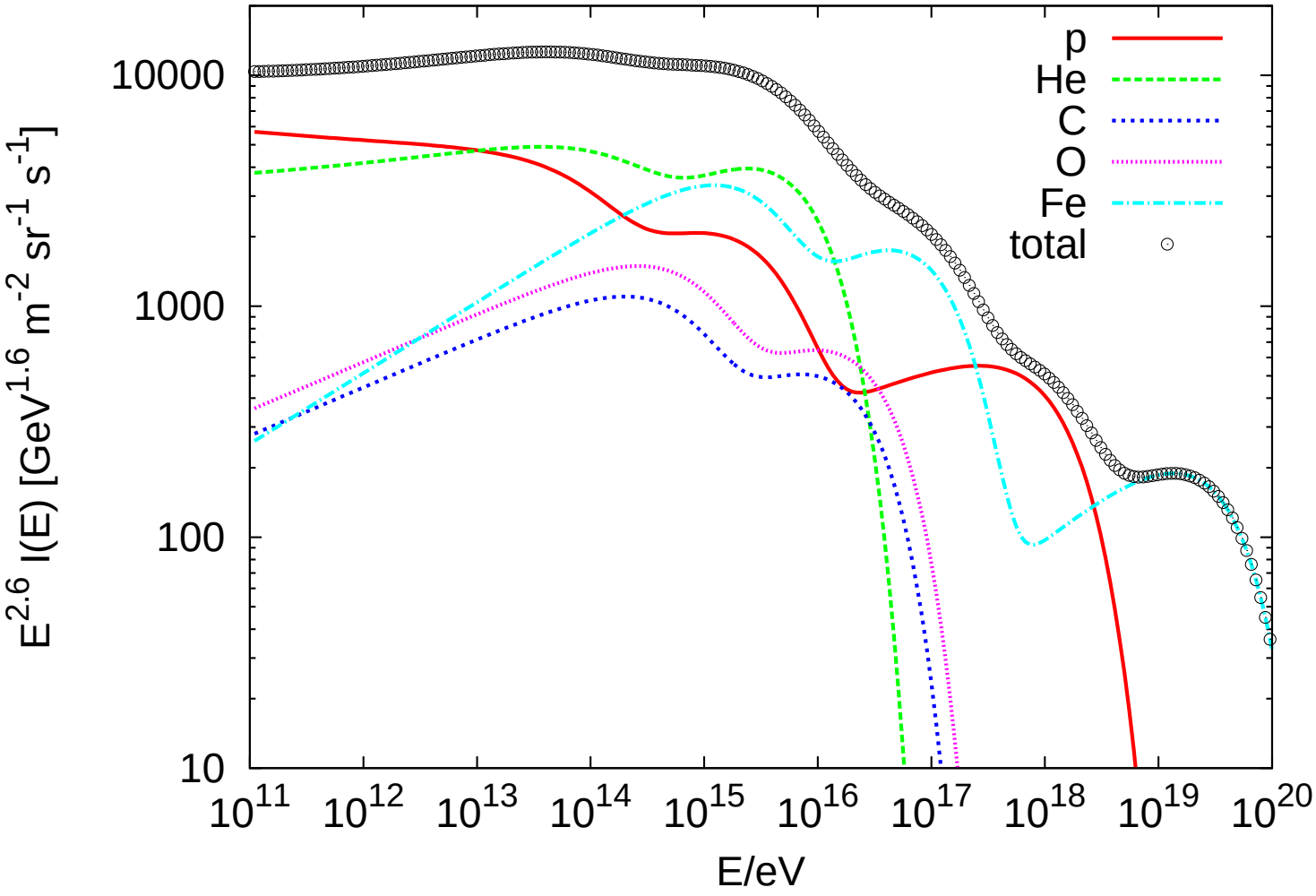
  $\Rightarrow$ change in diffusion from $D(E) \sim E^{1/3}$ to
  - Hall diffusion $D(E) \sim E$
  - small-angle scattering $D(E) \sim E^2$
  - something intermediate?

  unavoidable effect, but for B ~few μG and $l_{\rm coh} \sim 30\,$pc at too high energy:

$$E_c/Z \sim 10^{15}\, \frac{B}{\mu\rm G}\, \frac{l_c}{\rm pc}$$

Cosmic Ray Knee: 3 explanations

- maximal rigidity of dominant CR sources – e.g. Hillas model



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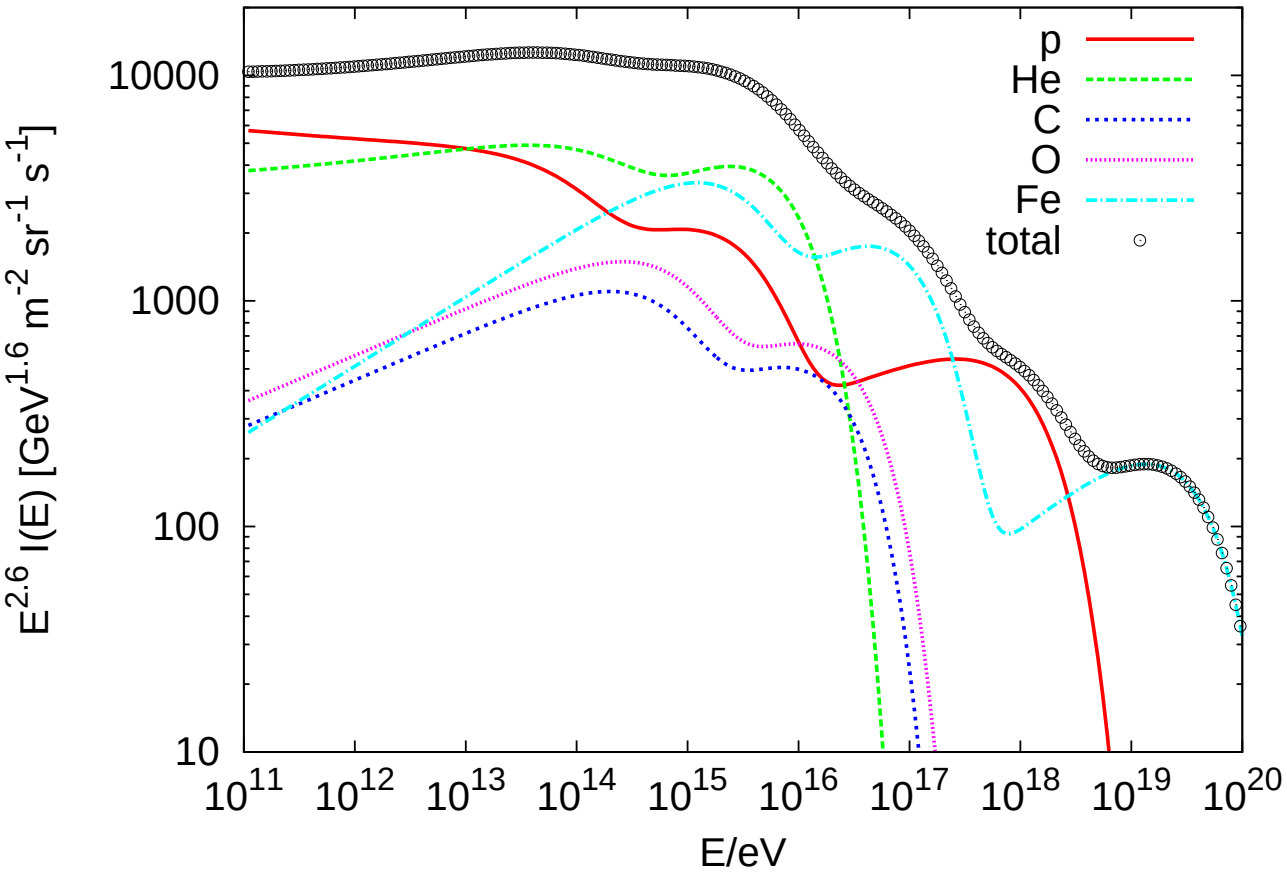

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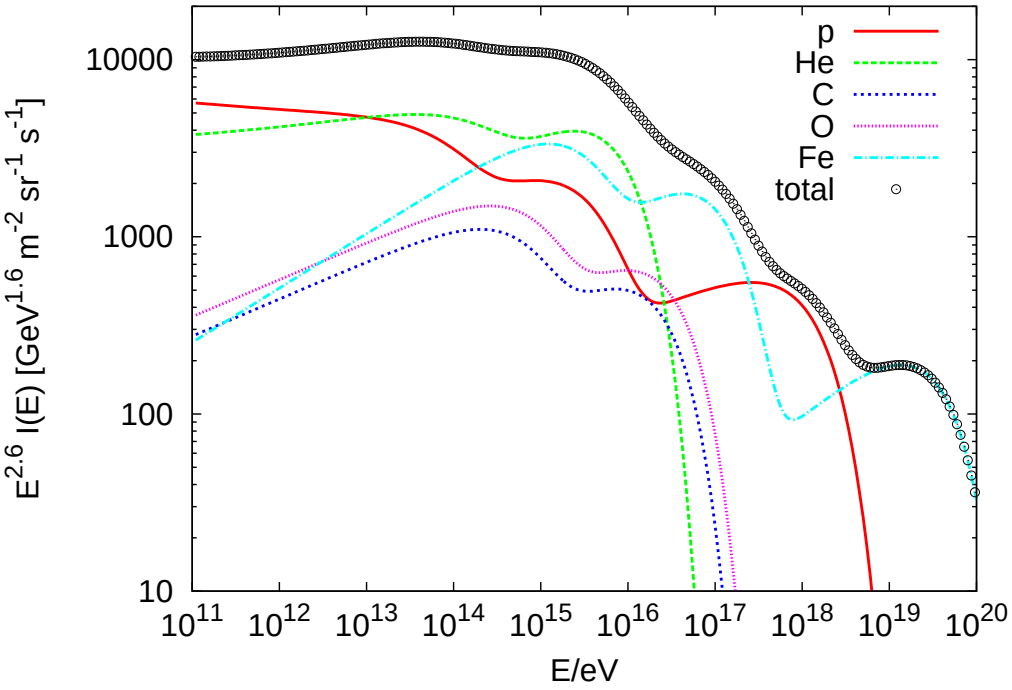
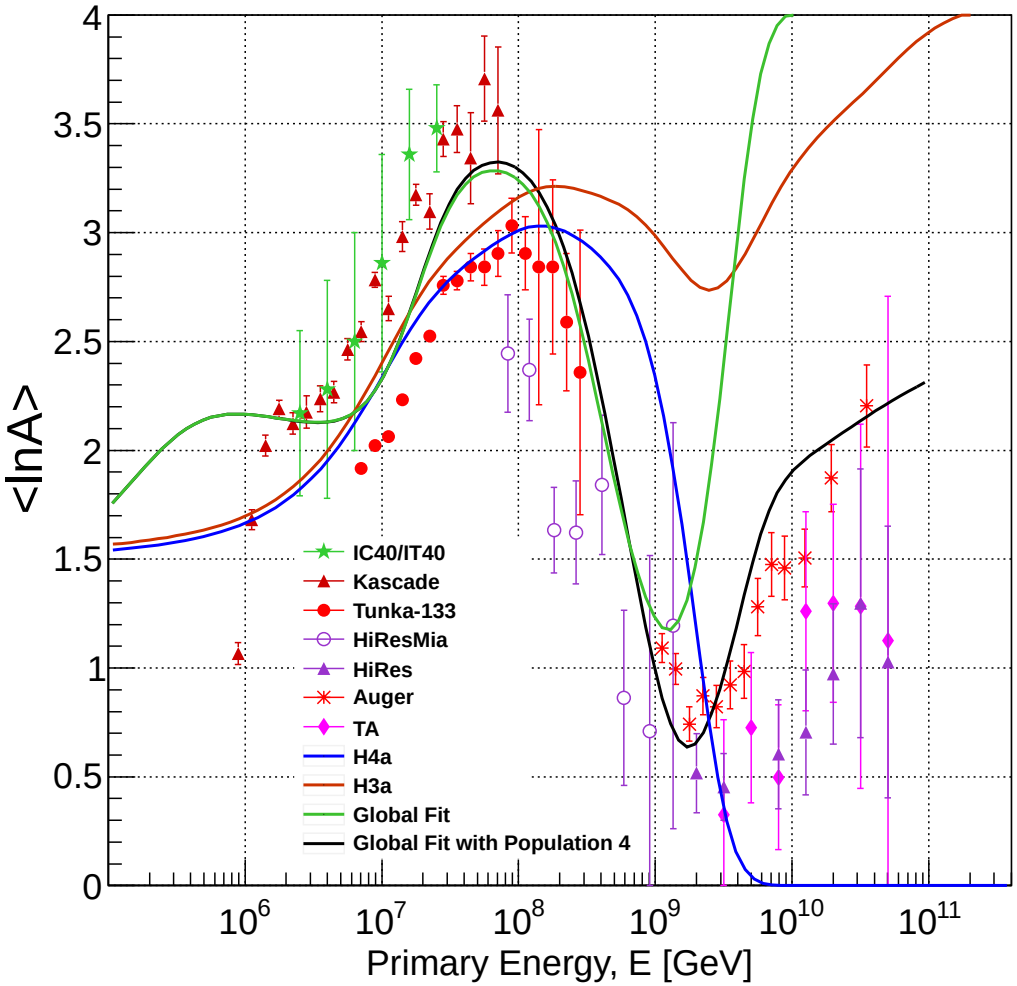


- $i = 1, \ldots, 3$ types of CR sources, with slopes $\alpha_{A,i}$, rel. fractions $f_{A,i}$
- no reliable estimate of $E_{\mathrm{max},i}$, $\alpha_{A,i}$, and $f_{A,i}$

$\Rightarrow$ fit of many-parameter model to two observables: I_{tot} and $\ln(A)$

Cosmic Ray Knee: 3 explanations

- maximal energy: Gaisser, Stanev & Tilav version [*1303.3665*]



Propagation in turbulent magnetic fields:

- Galactic magnetic field: regular + turbulent component

  turbulent: fluctuations on scales $l_{\rm min} \sim$ AU to $l_{\rm max} \sim (10 - 150)$ pc

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- slope of power spectrum $\mathcal{P}(k) \propto k^{-\alpha}$ determines energy dependence of diffusion coefficient $D(E) \propto E^{\beta}$ as $\beta = 2 - \alpha$:

Kolmogorov	$\alpha = 5/3$	$\Leftrightarrow$	$\beta = 1/3$
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- anisotropy $\delta = -3D_{ij}\nabla_i \ln(n)$

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- use model for Galactic magnetic field
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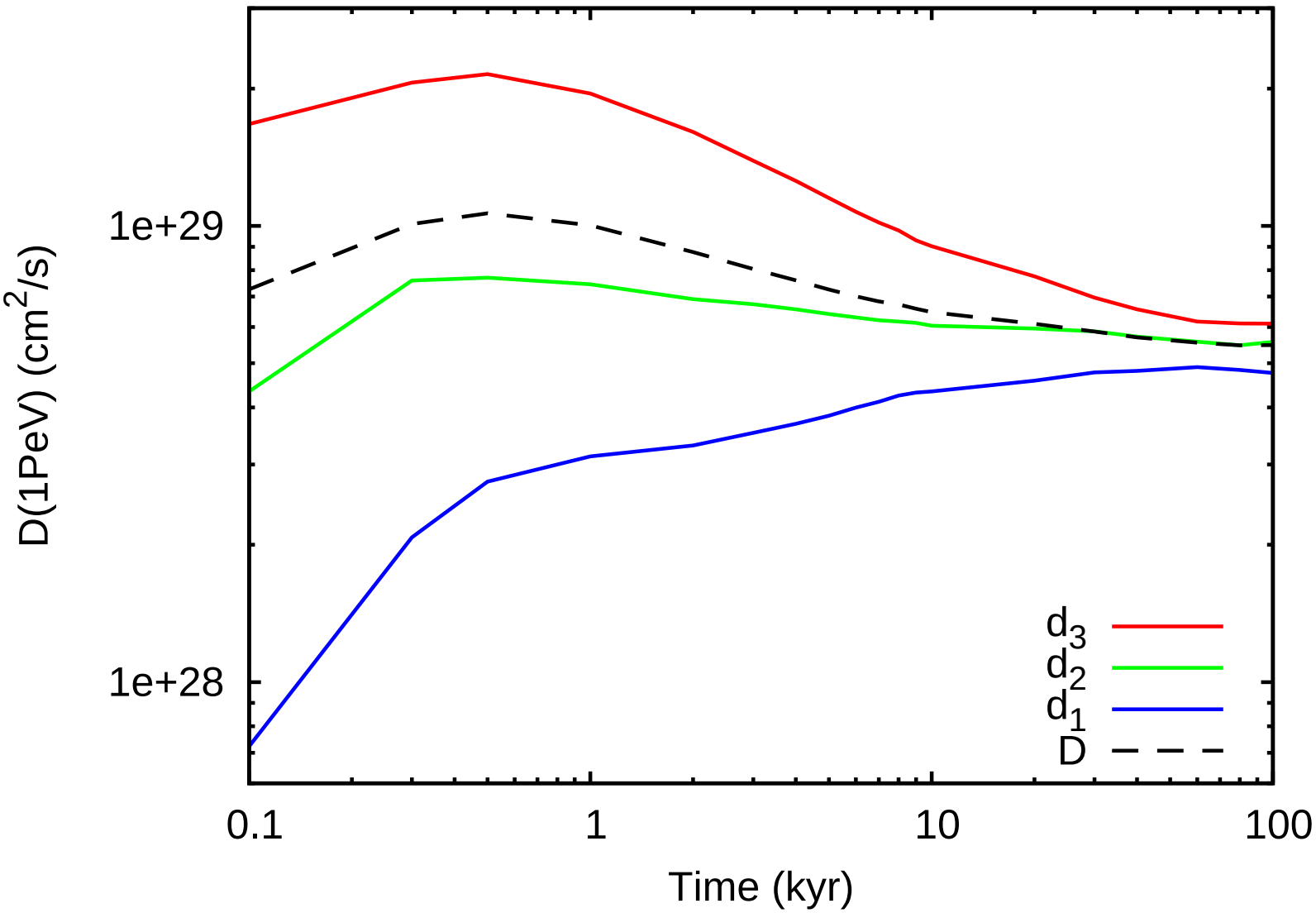
- as preparation, let's calculate diffusion tensor in pure, isotropic turbulent magnetic field

Eigenvalues of $D_{ij} = \langle x_i x_j \rangle / (2t)$ for $E = 10^{15}$ eV



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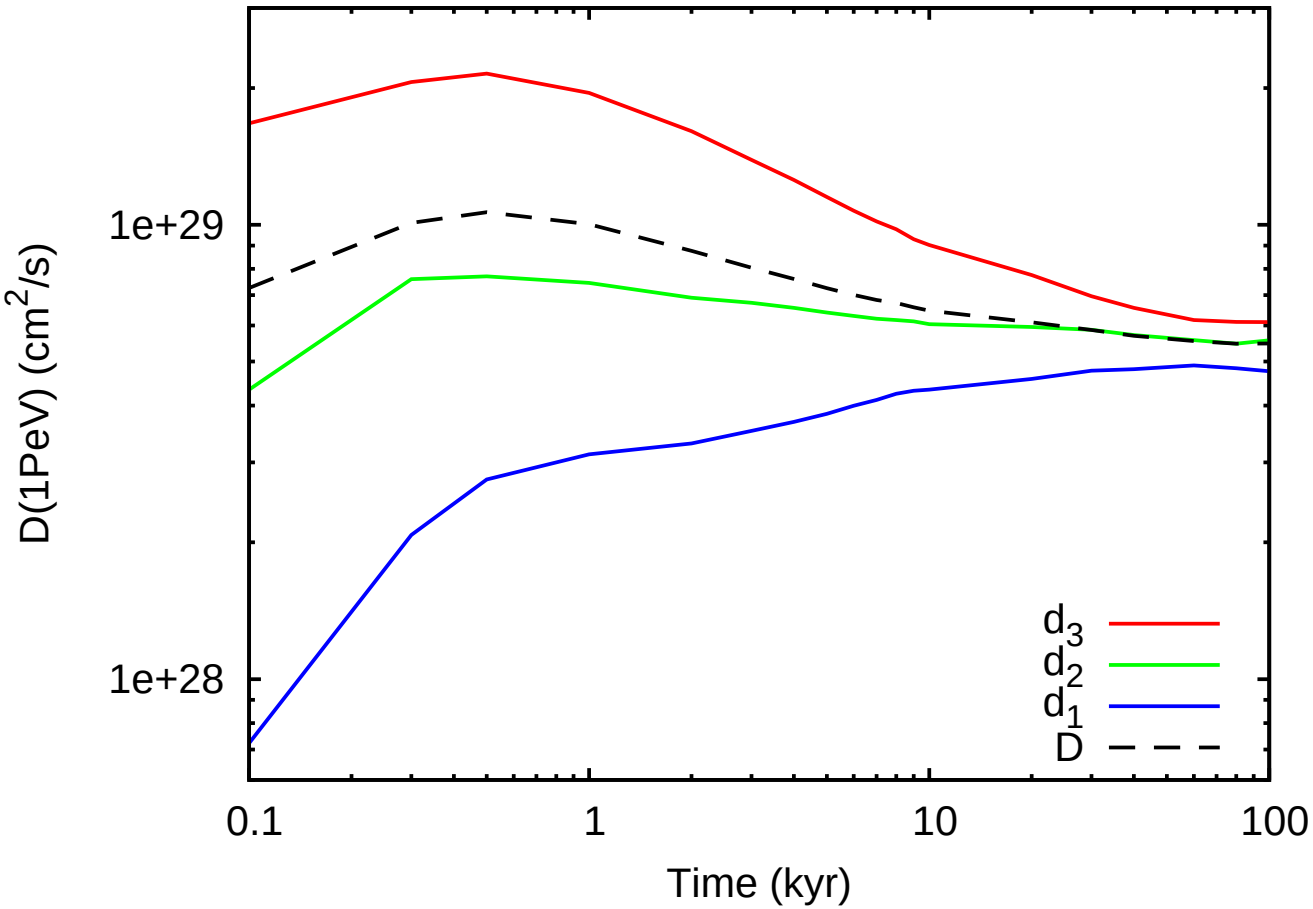

- asymptotic value is ~ 10 smaller than extrapolated "Galprop value"

[*Giacinti, MK, Semikoz ('12)*]

Knee from Cosmic Ray Escape

- $l_{\rm coh}$ and regular field $\boldsymbol{B}(\boldsymbol{x})$ fixed from observations
  - LOFAR: $l_{\rm coh} \lesssim 10\,{\rm pc}$ in disc
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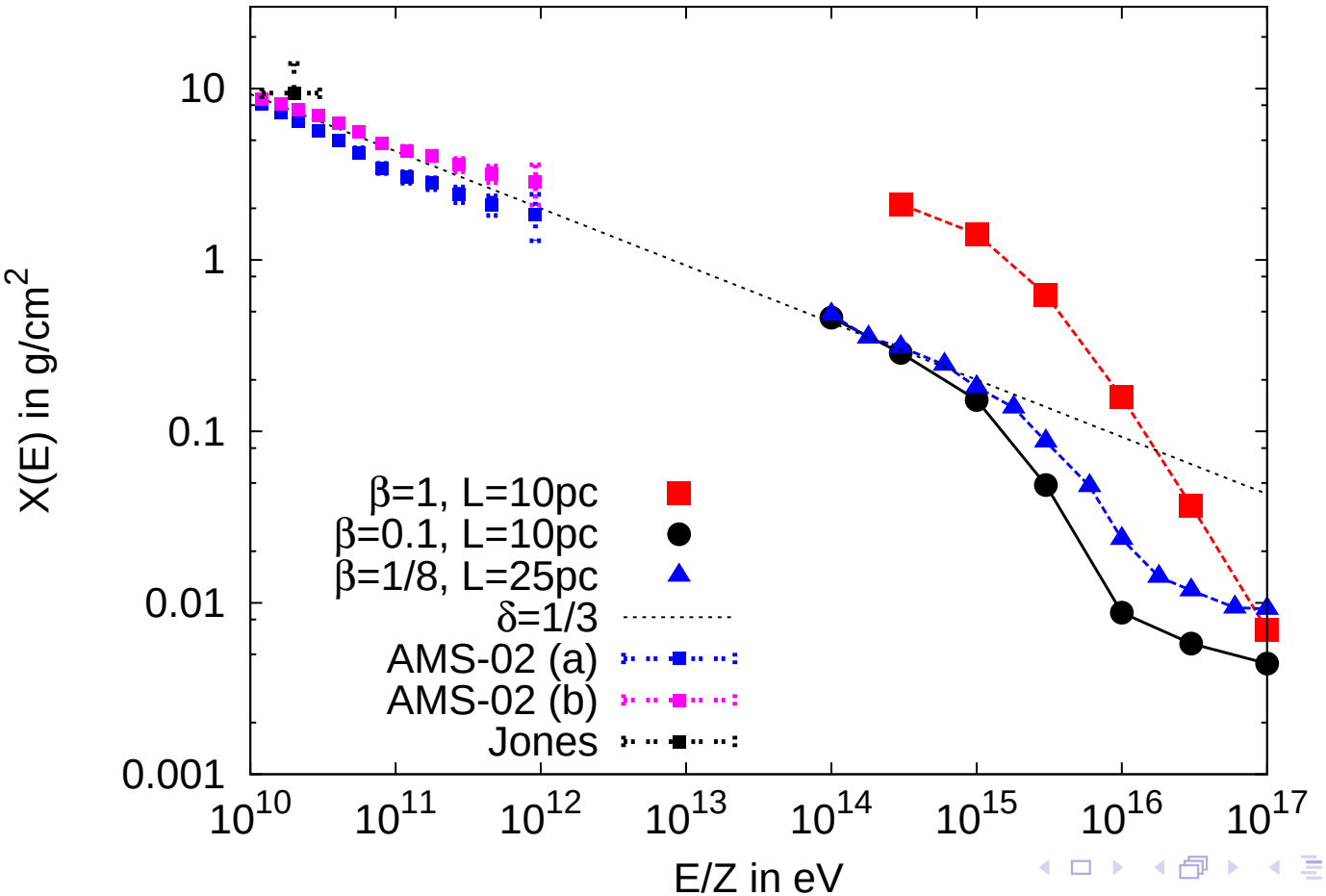

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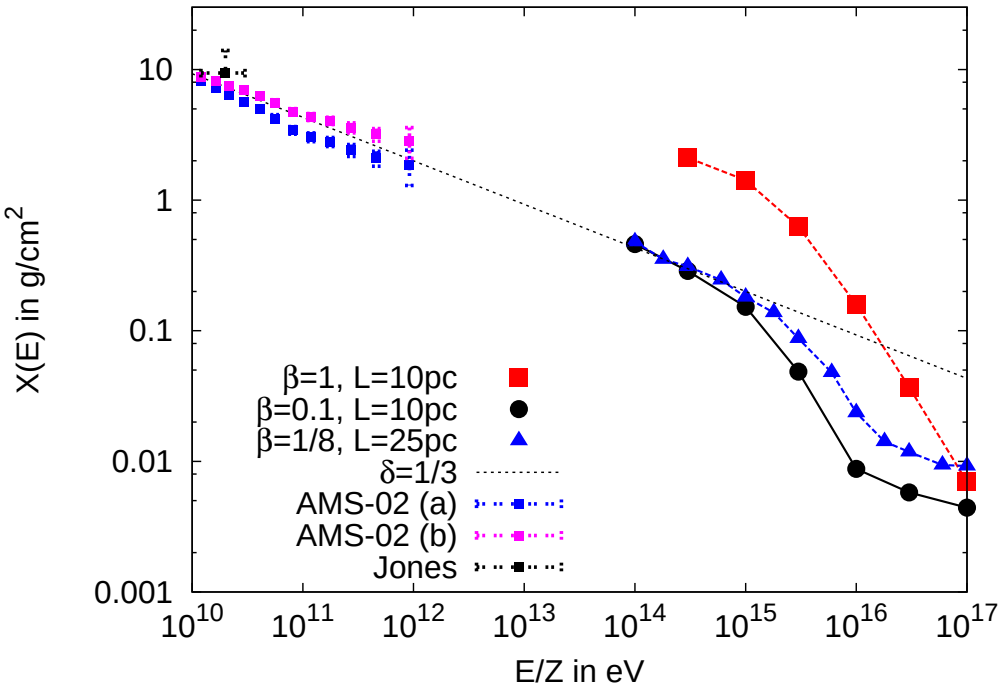
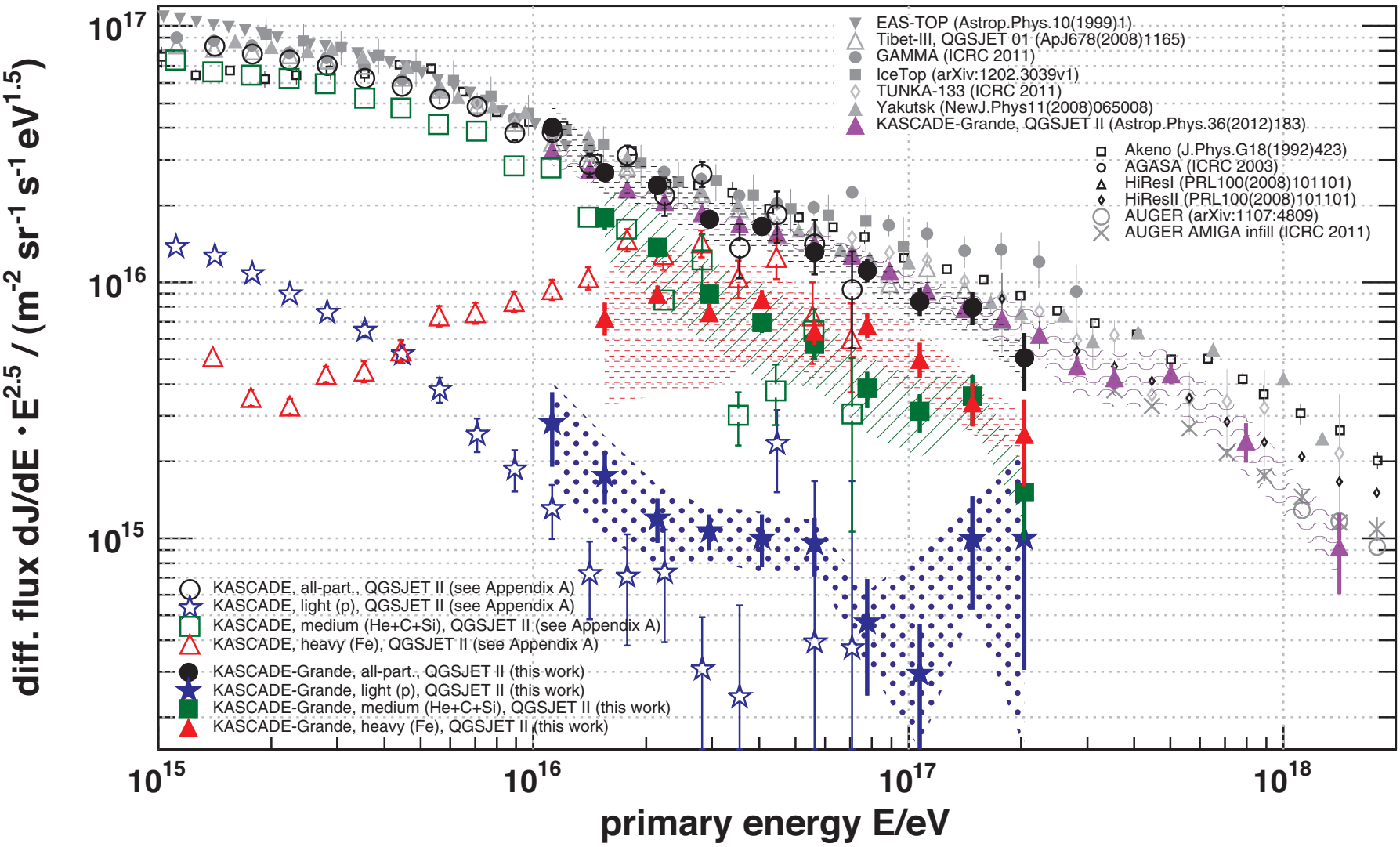


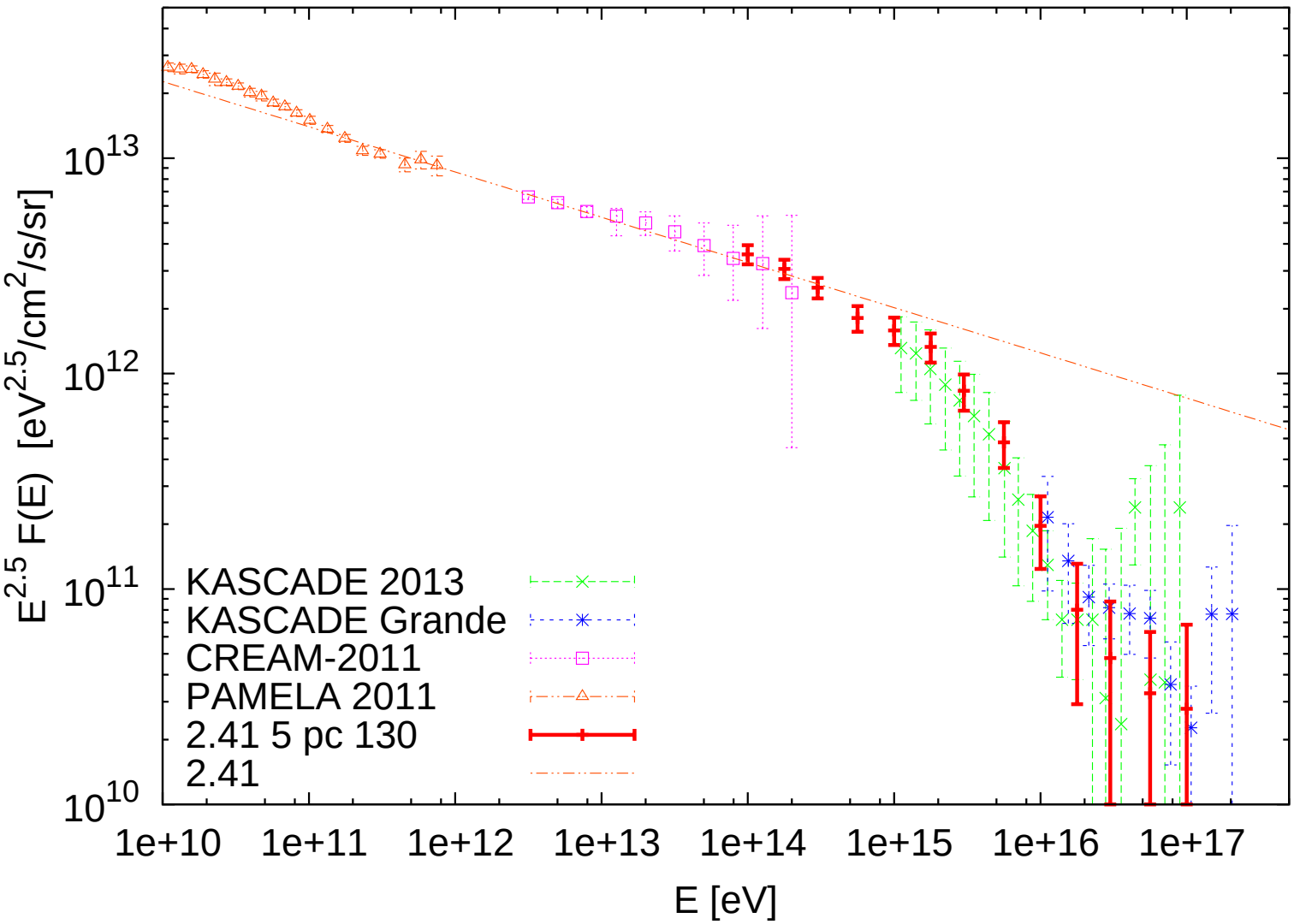
$\Rightarrow$ prefers weak random fields

$\Rightarrow$ fluxes $I_A(E)$ of all isotopes fixed by low-energy data

Galactic CRs: KASCADE-Grande 2013



Knee from Cosmic Ray Escape: proton energy spectra



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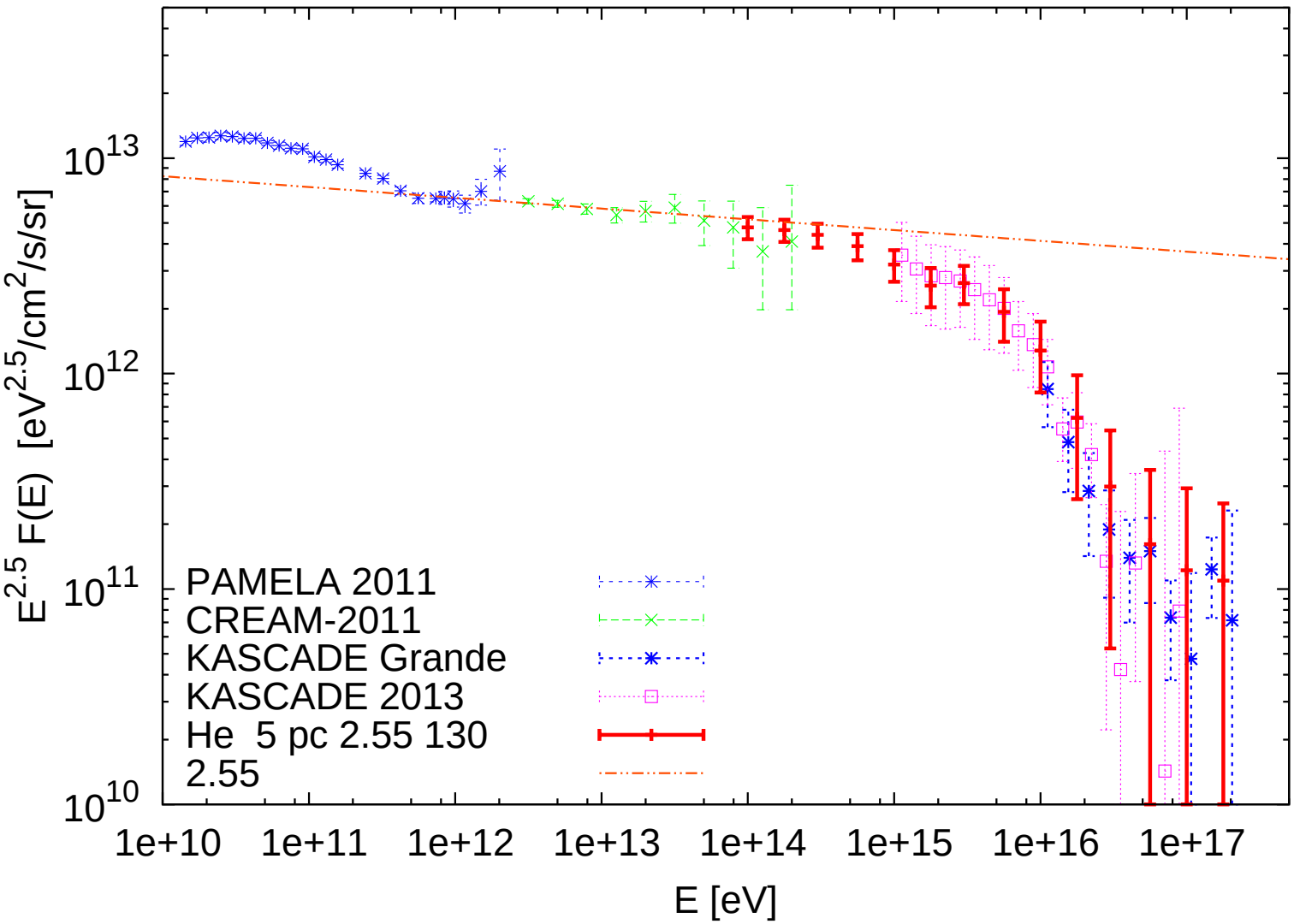
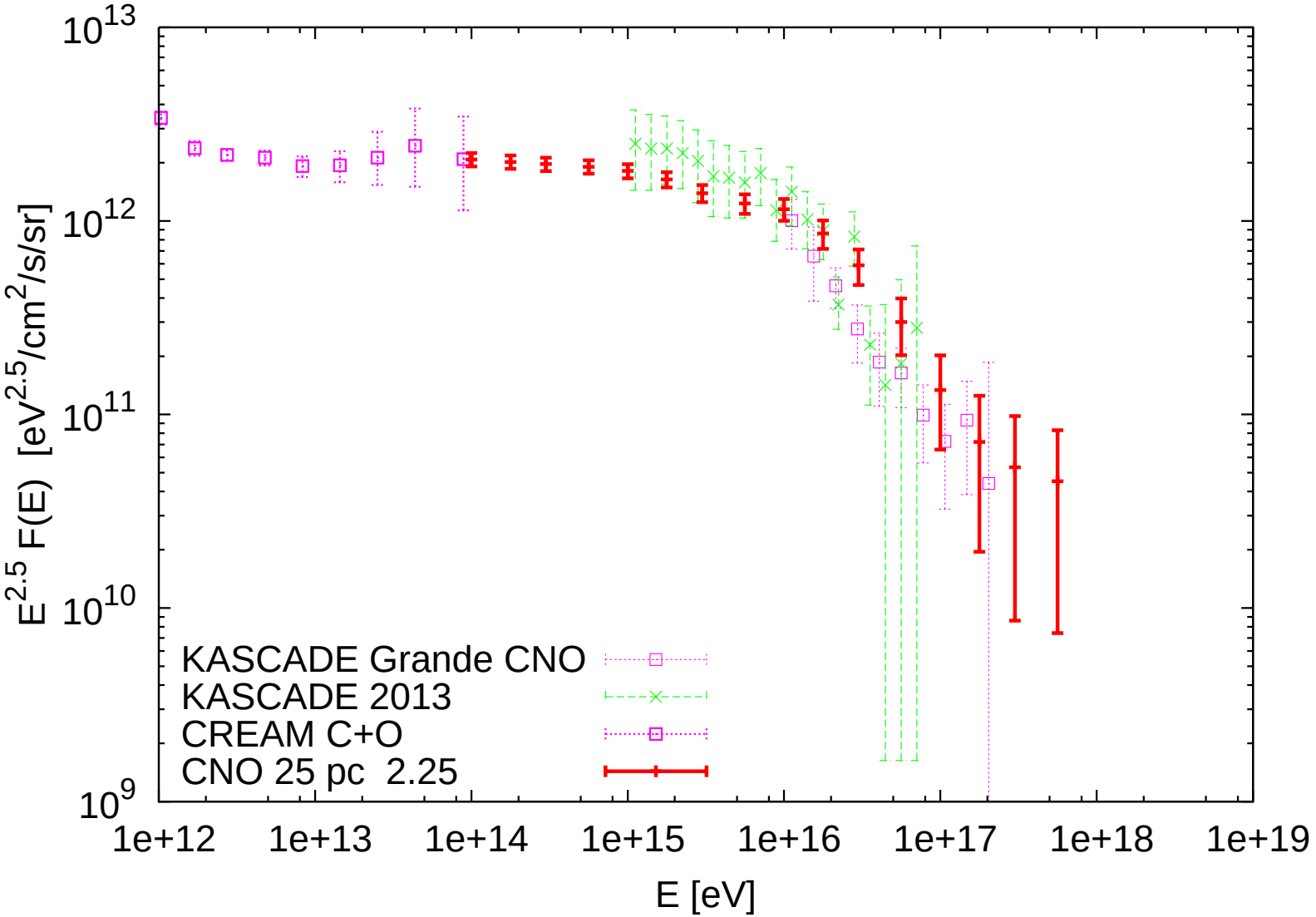
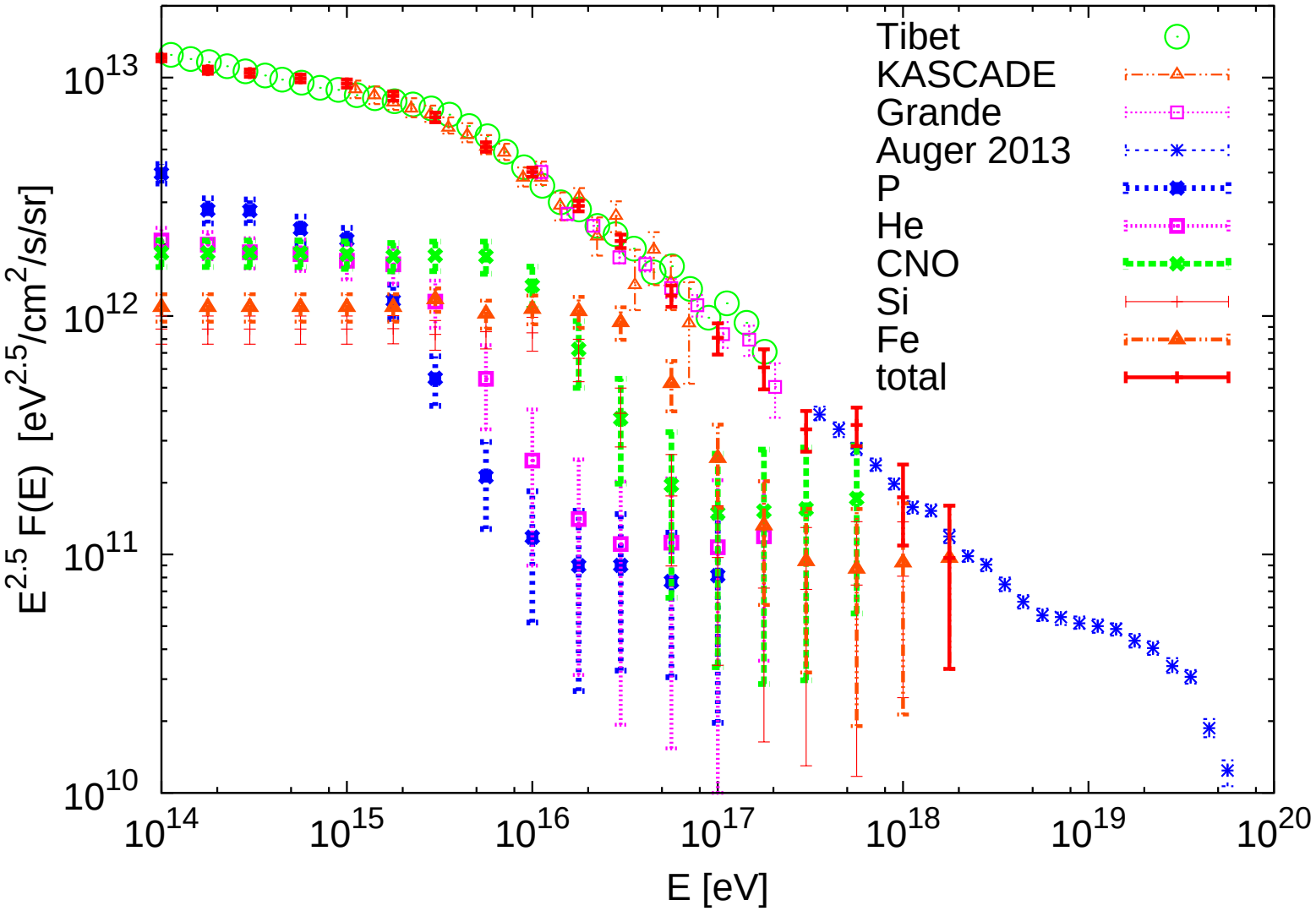


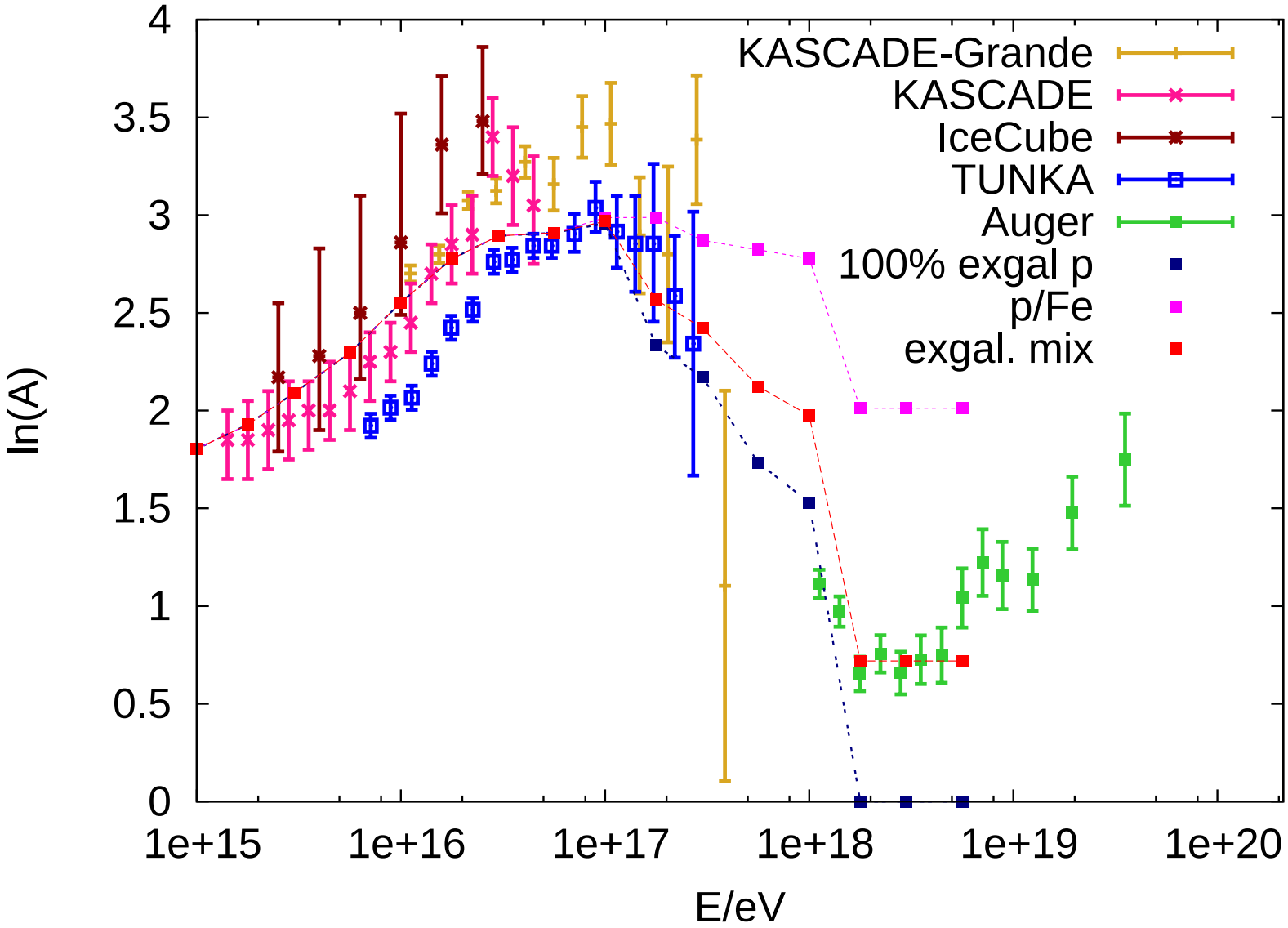
Knee from Cosmic Ray Escape: CNO energy spectra



Knee from Cosmic Ray Escape: total energy spectra



Knee from Cosmic Ray Escape: $\ln(A)$



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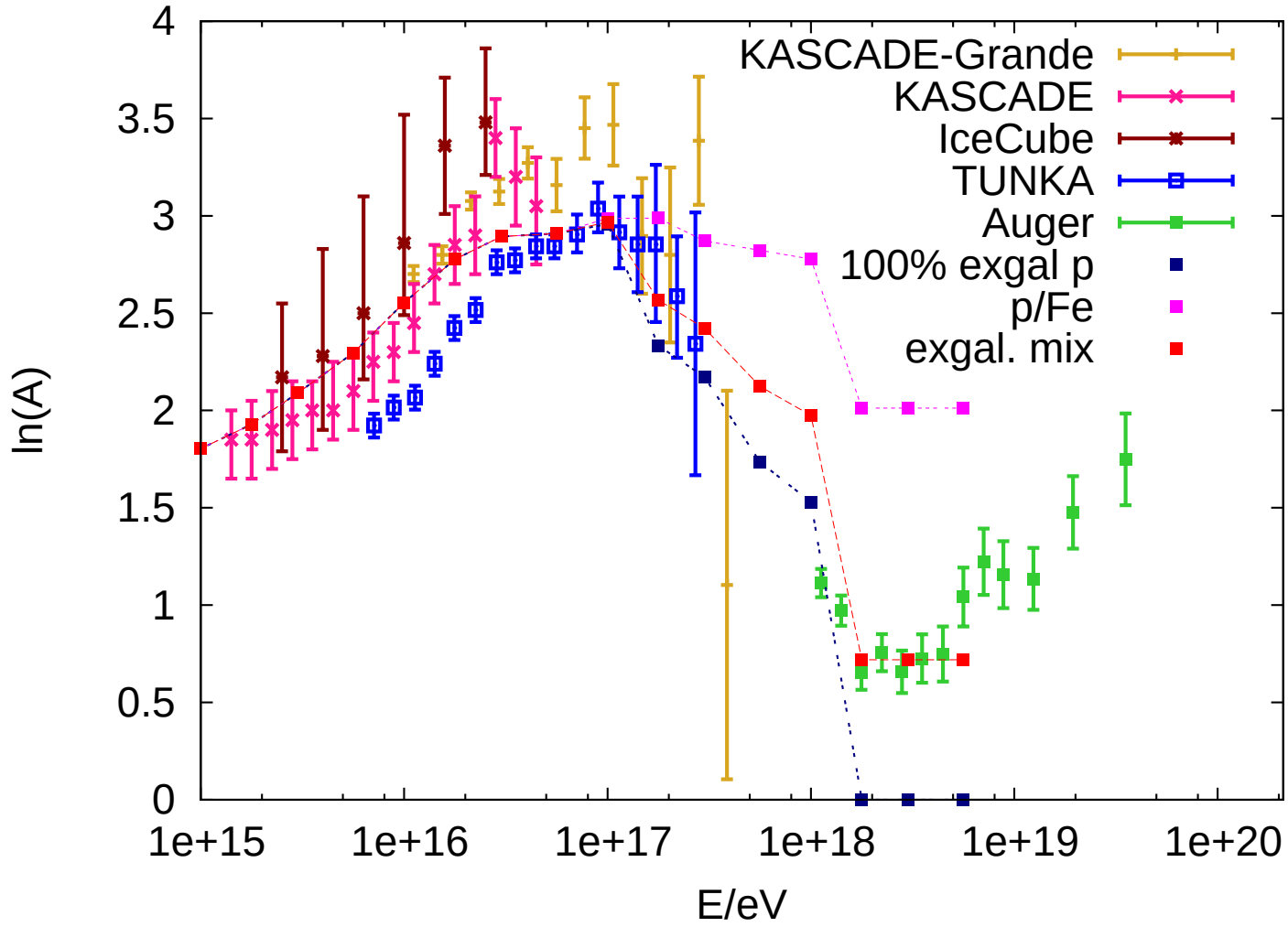
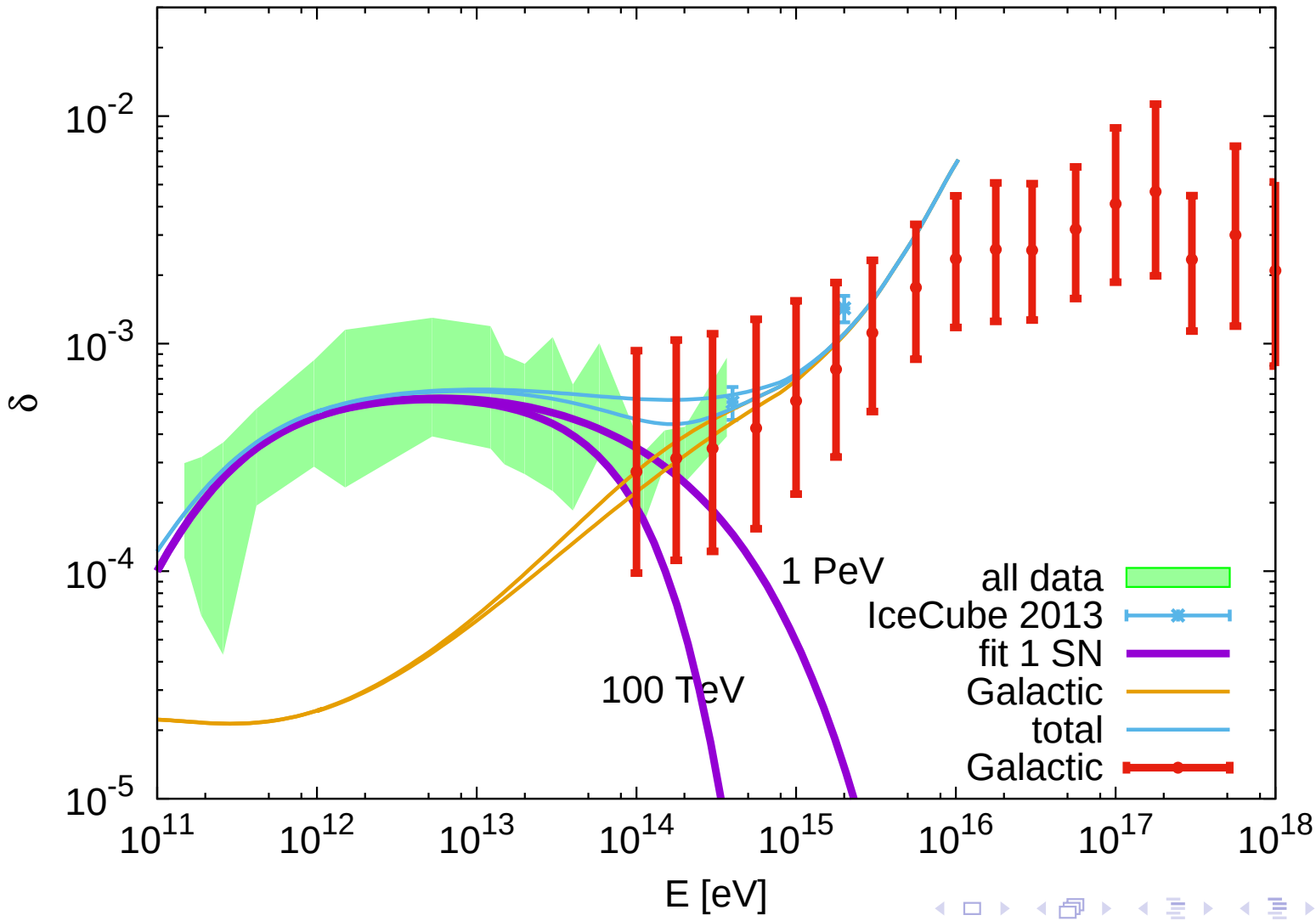


exgal. mix: 60% p, 25% He, 15% N

Knee from Cosmic Ray Escape: dipole anisotropy



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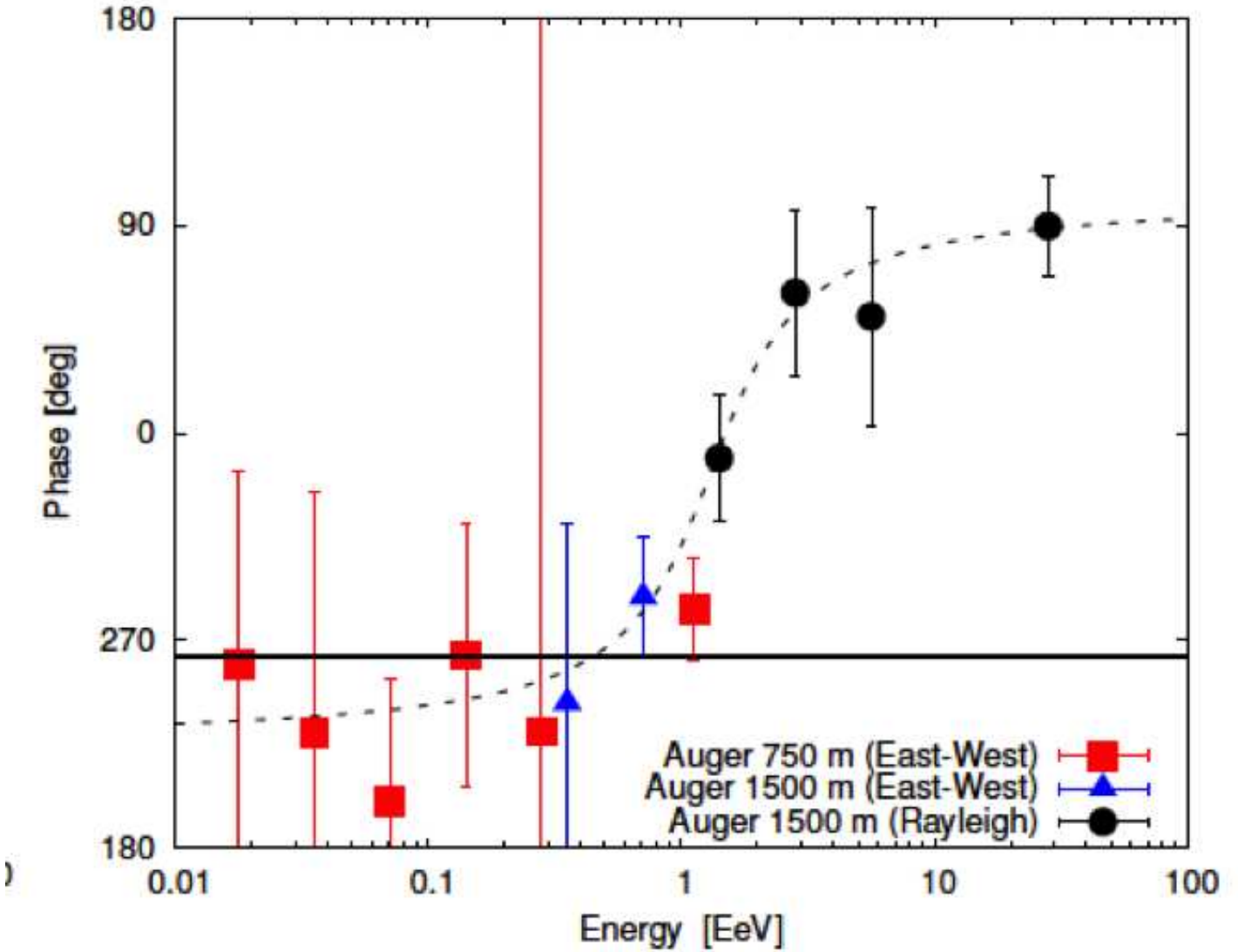
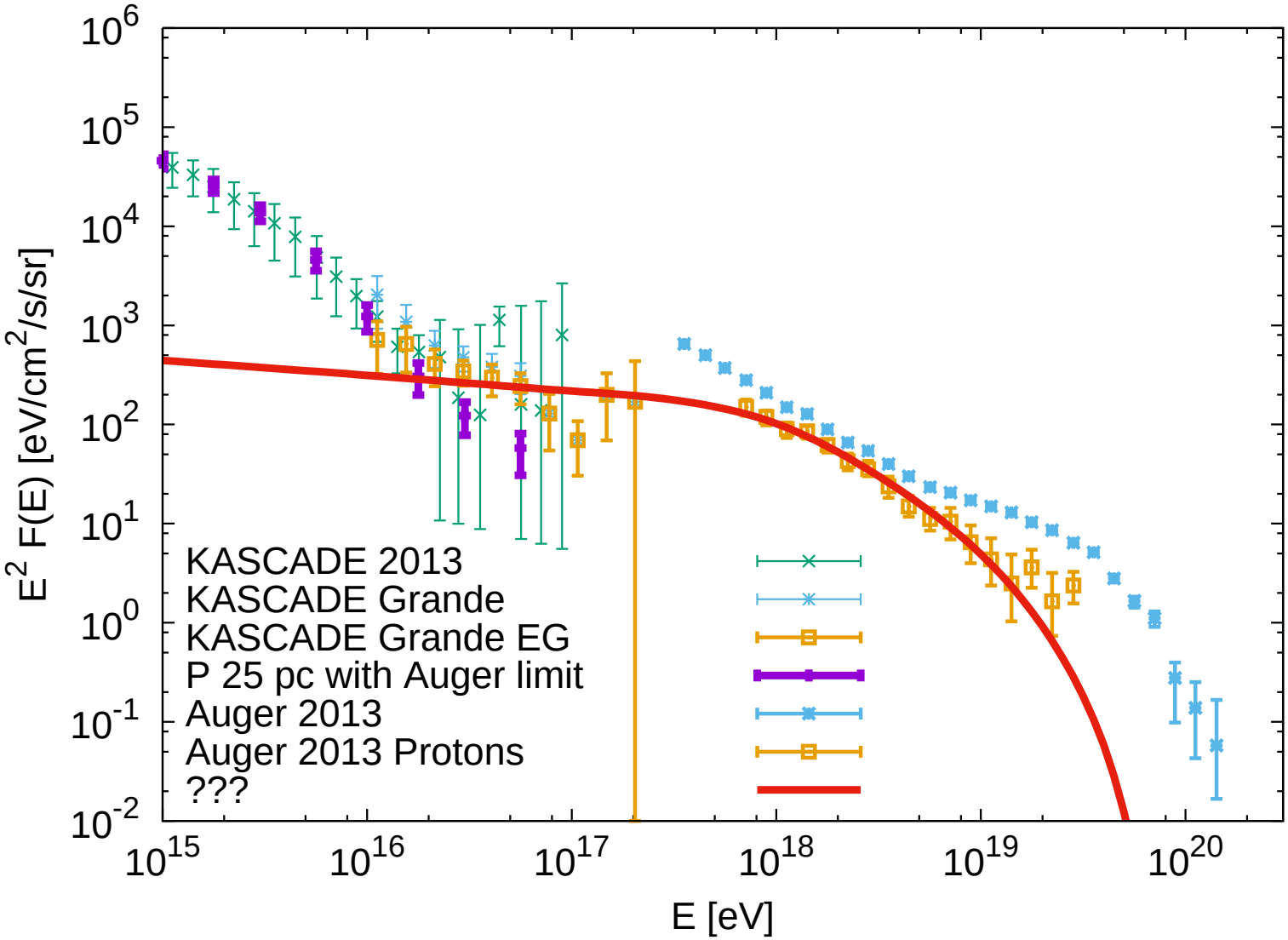


Extragalactic proton flux in escape model:



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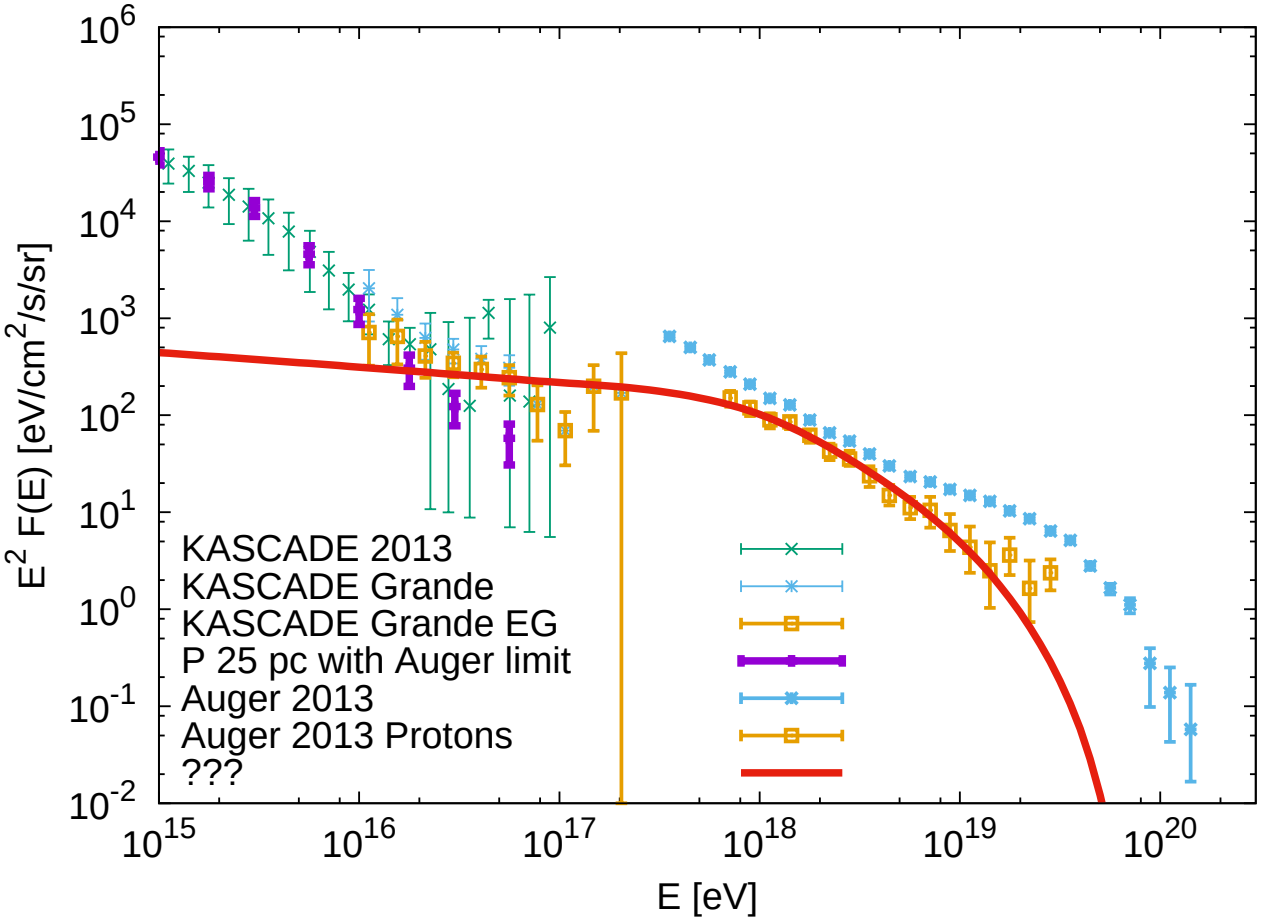

- what are the sources?
- testable via γ-ray and neutrinos?

Normal and starburst galaxies:

- assume $E^{-2.2}$ source spectrum
- starburst: $B \sim 100 B_{MW} \Rightarrow$ rescale grammage and $E_{\rm max}$
- fix Q_{CR} via SN/star formation rate
- vary gas density

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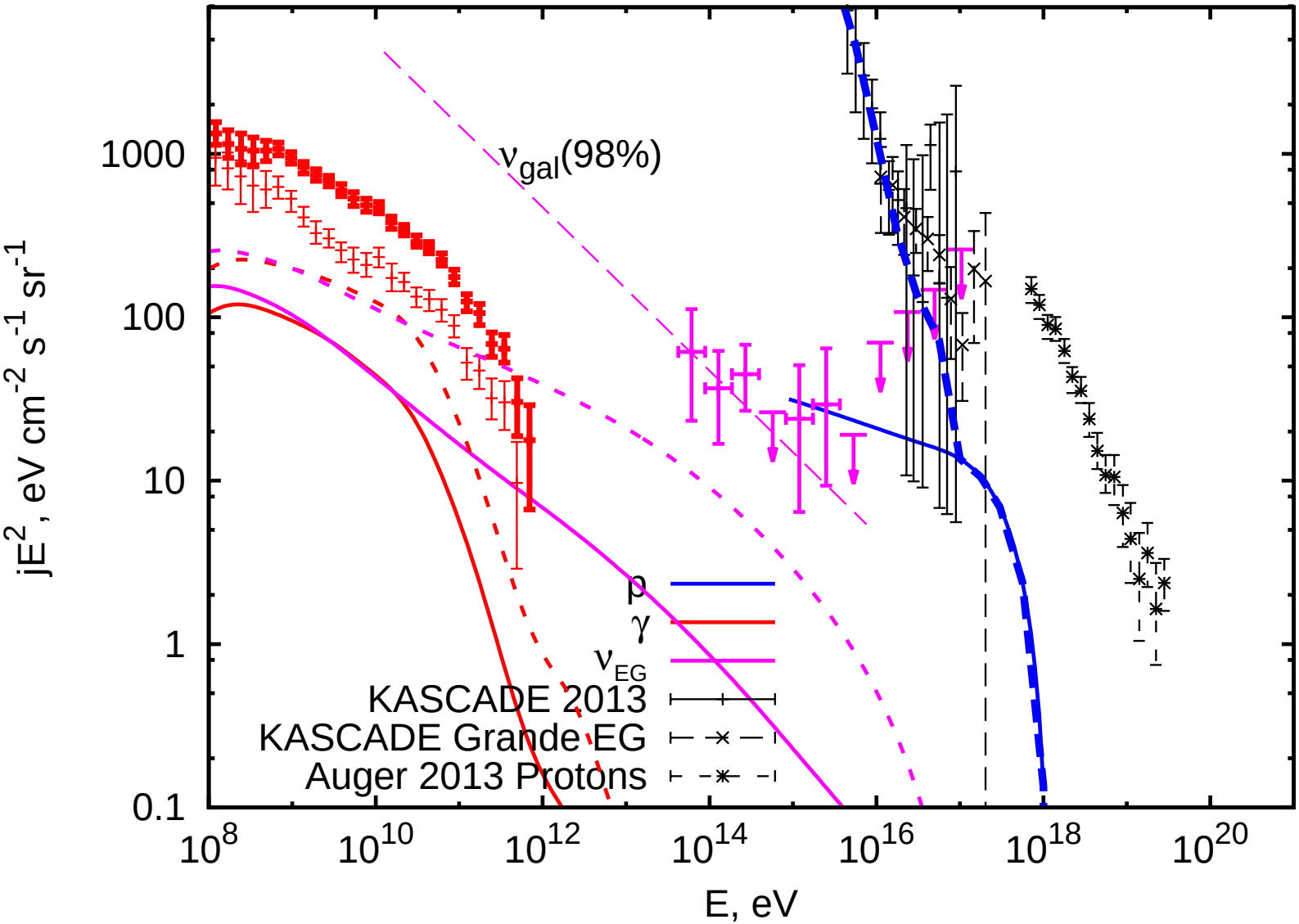

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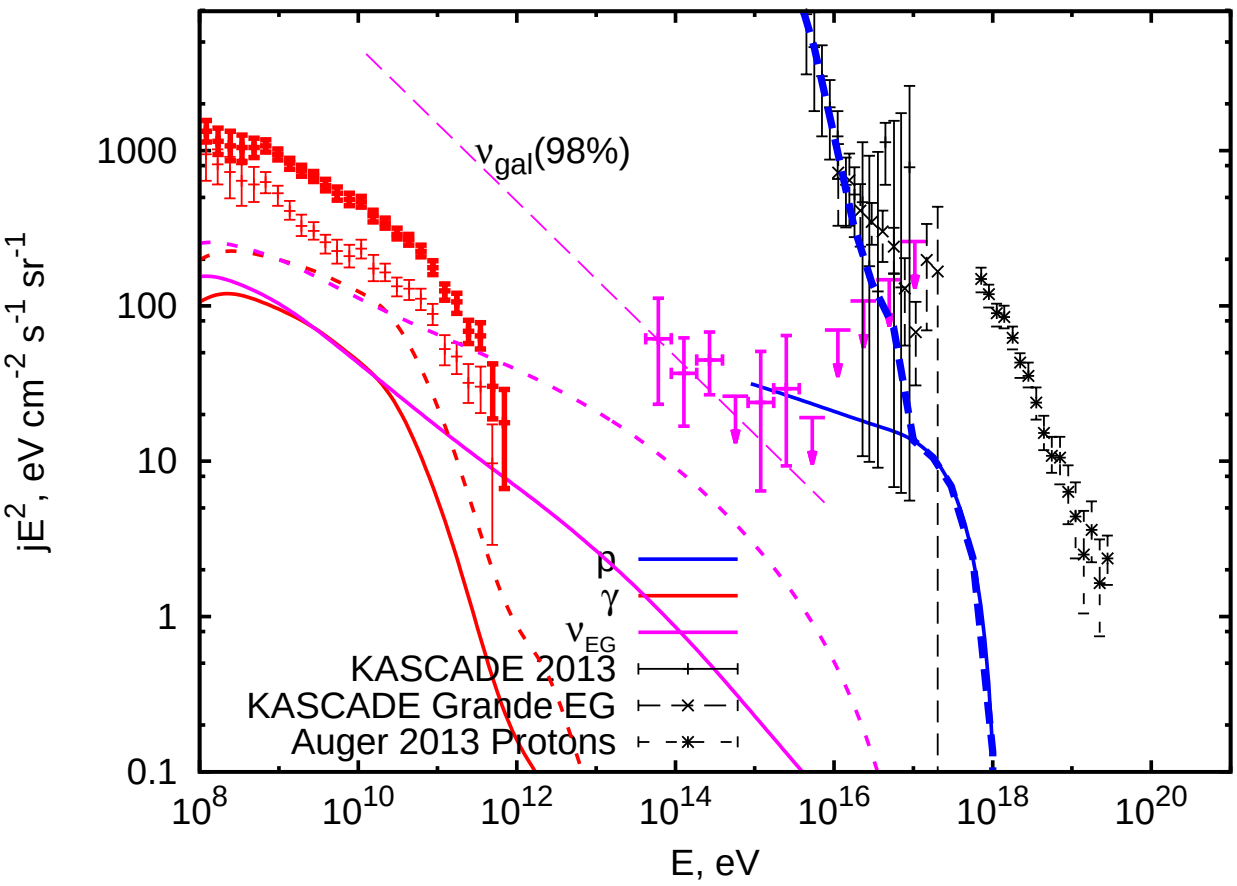
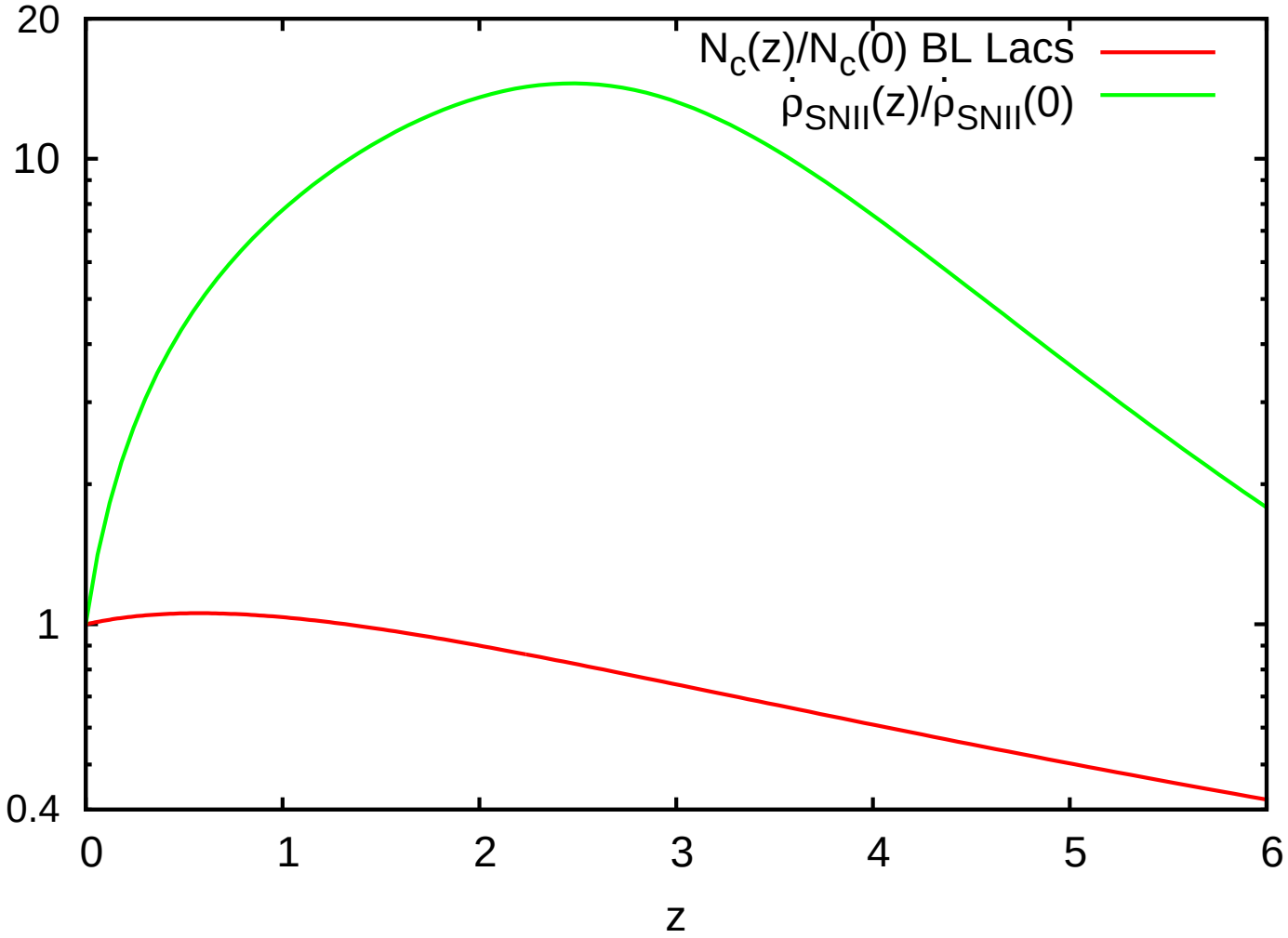


- can not explain exgal. protons
- sources are thick $\Rightarrow$ can not be dominant sources of both EGRB and neutrinos

Extragalactic proton flux in escape model:

- $\alpha_p = 2.2$ requires "late" redshift evolution:



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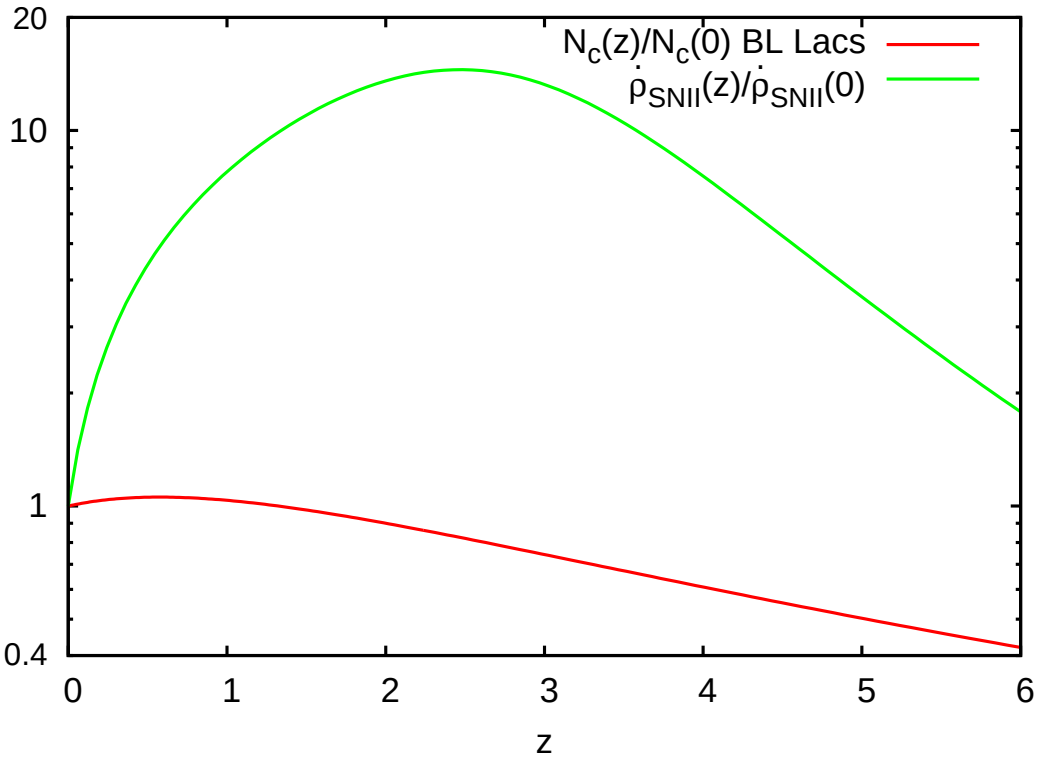

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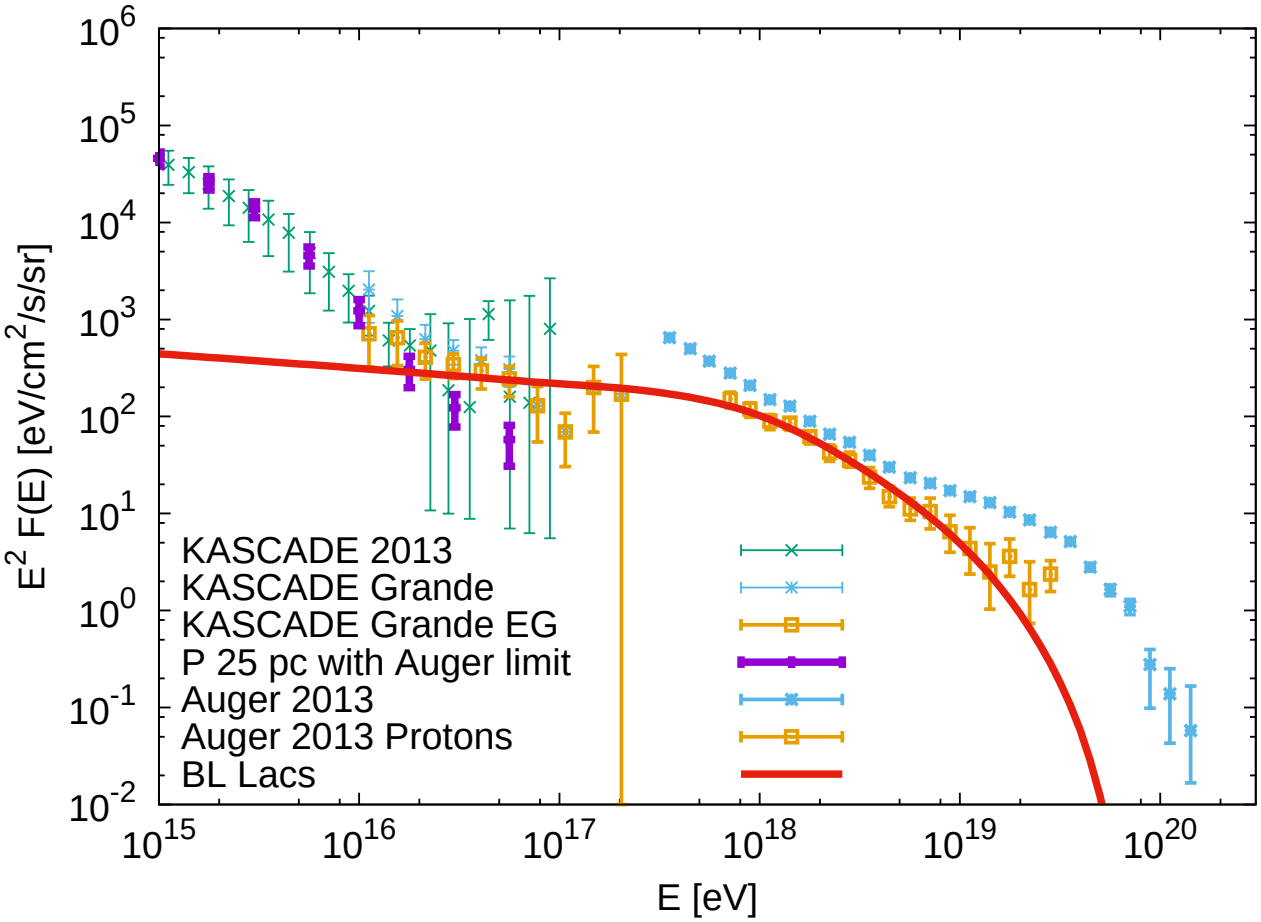
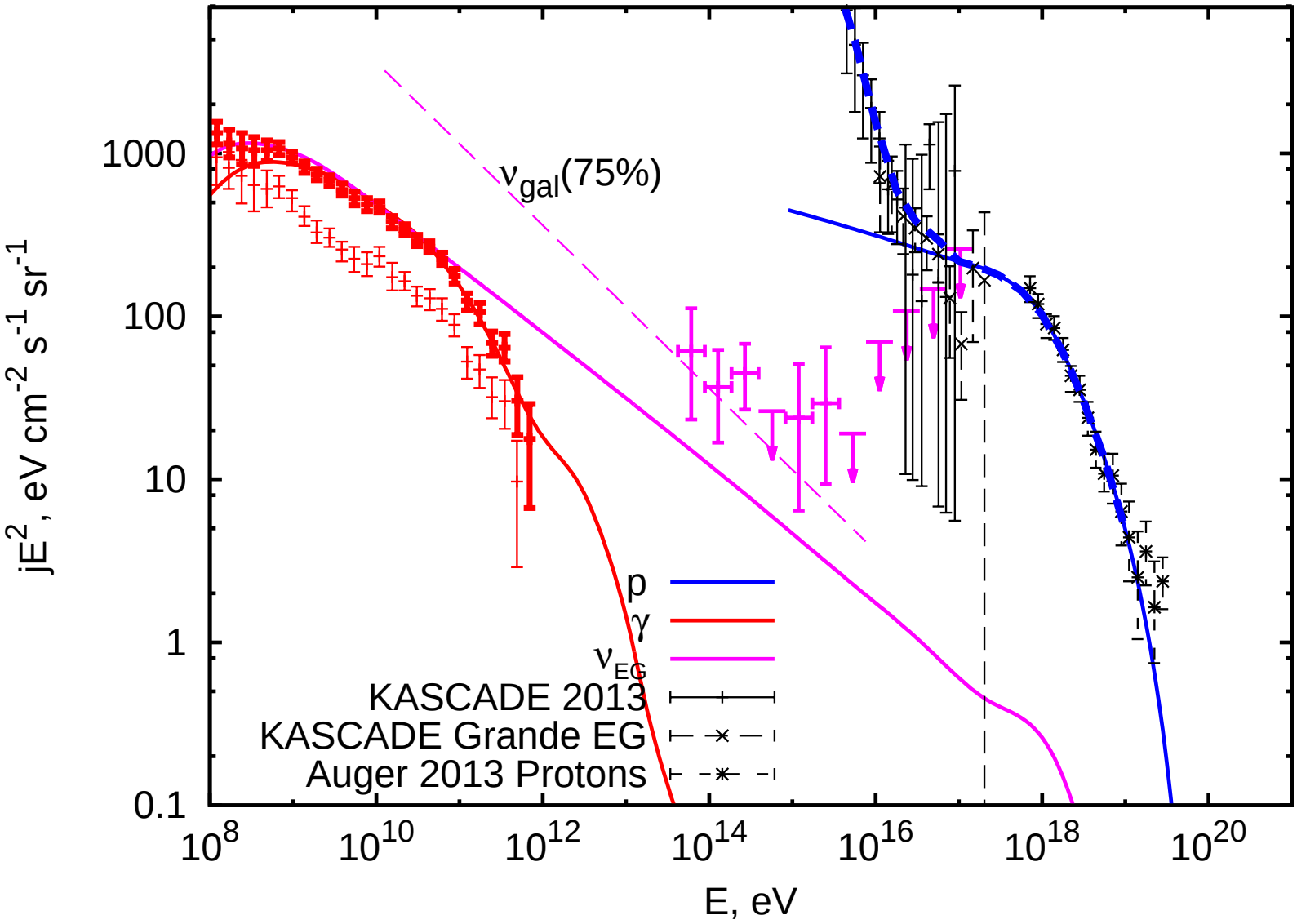
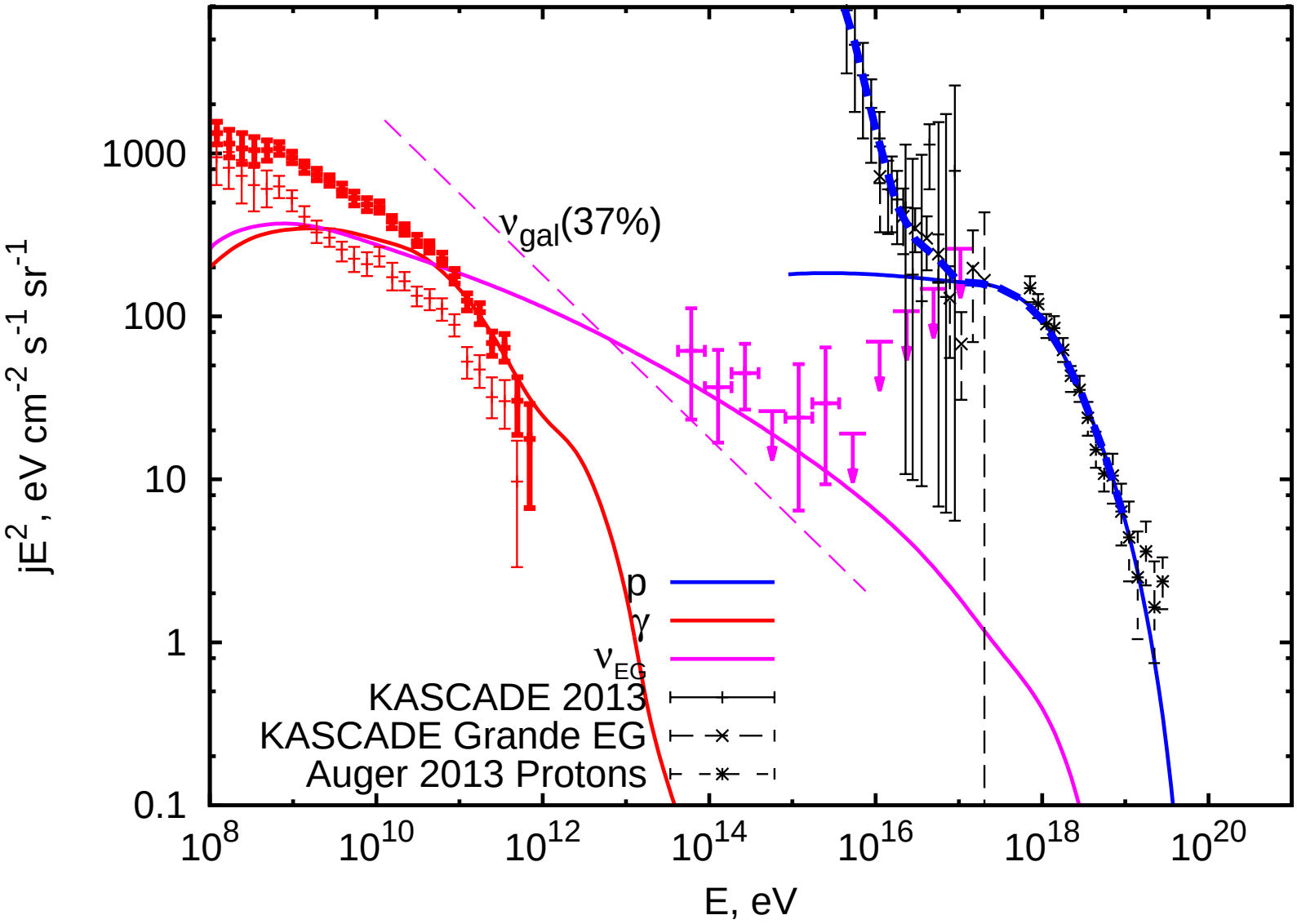


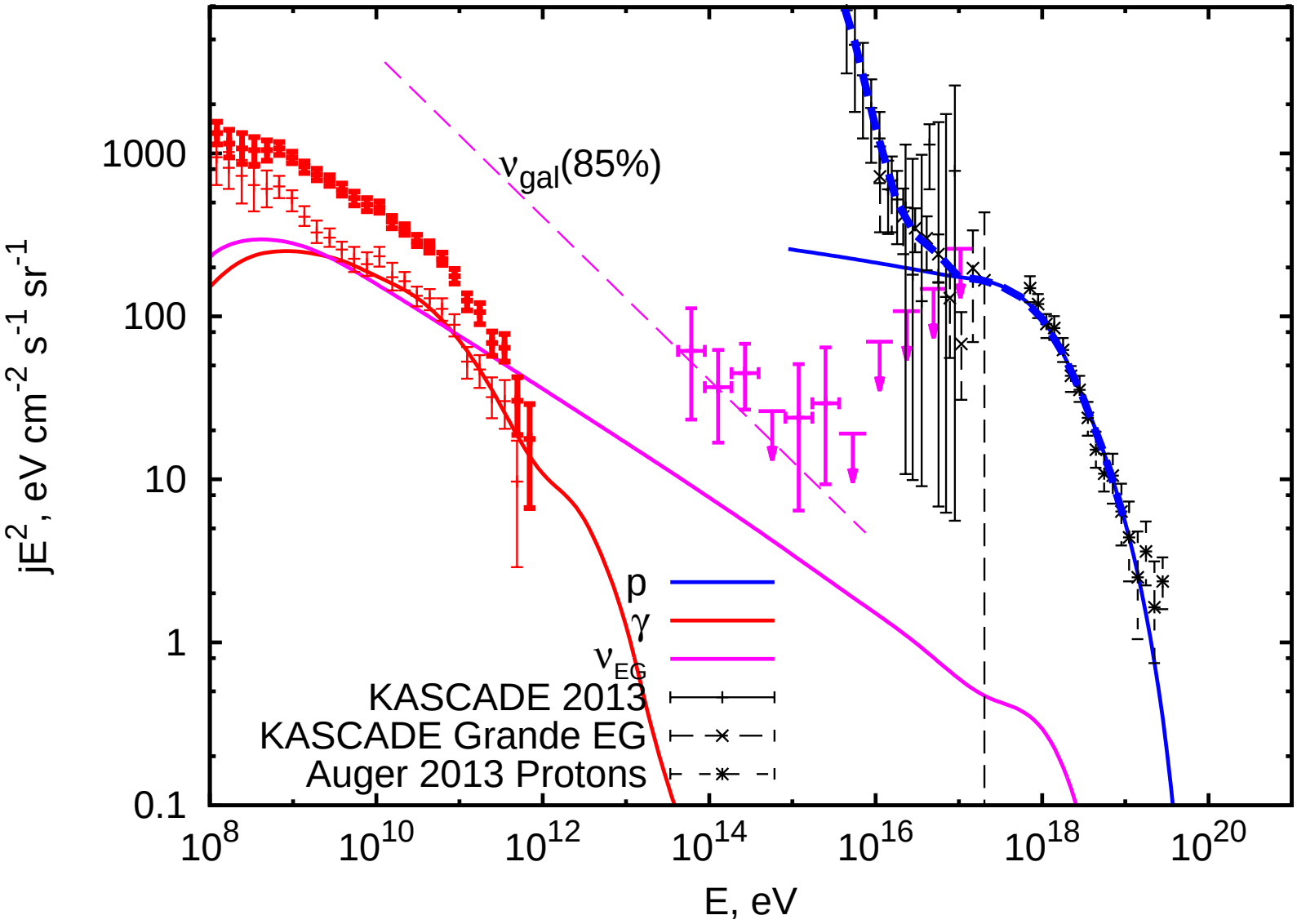
Diffuse fluxes from BL Lacs $\alpha = 2.17$ and $E_\tau = 3 \times 10^{11}$ eV



Diffuse fluxes from BL Lacs $\alpha = 2.1$ and $E_\tau = 3 \times 10^{11}$ eV



Diffuse fluxes from BL Lacs $\alpha = 2.1$ and $E_\tau = 3 \times 10^{14}$ eV



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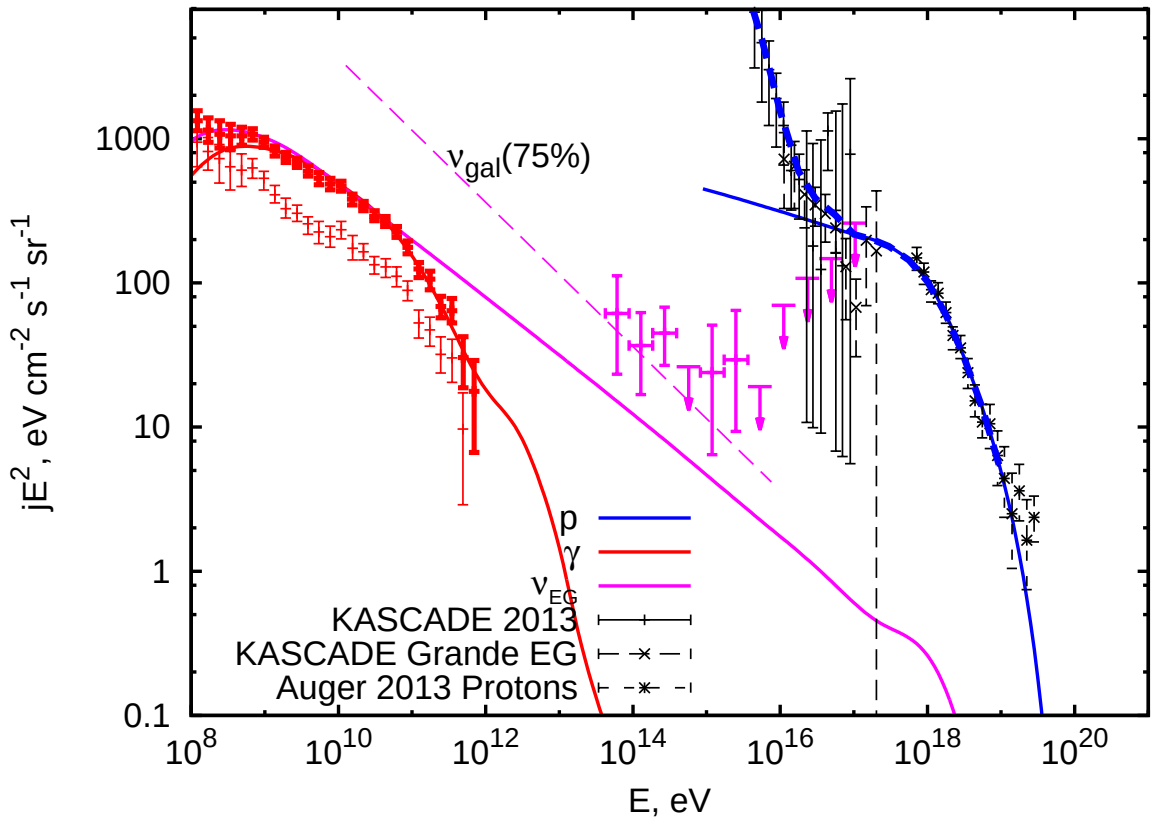

- BL Lac's can explain CR proton flux
- EGRB and large fraction of IceCube ν from pp interactions

Anisotropy of a single source

- if only turbulent field:
  diffusion = random walk = free quantum particle
- number density is Gaussian with $\sigma^2 = 4DT$

$$\delta = \frac{3D}{c}\frac{\nabla n}{n} = \frac{3R}{2T}$$

- what happens for general fields?

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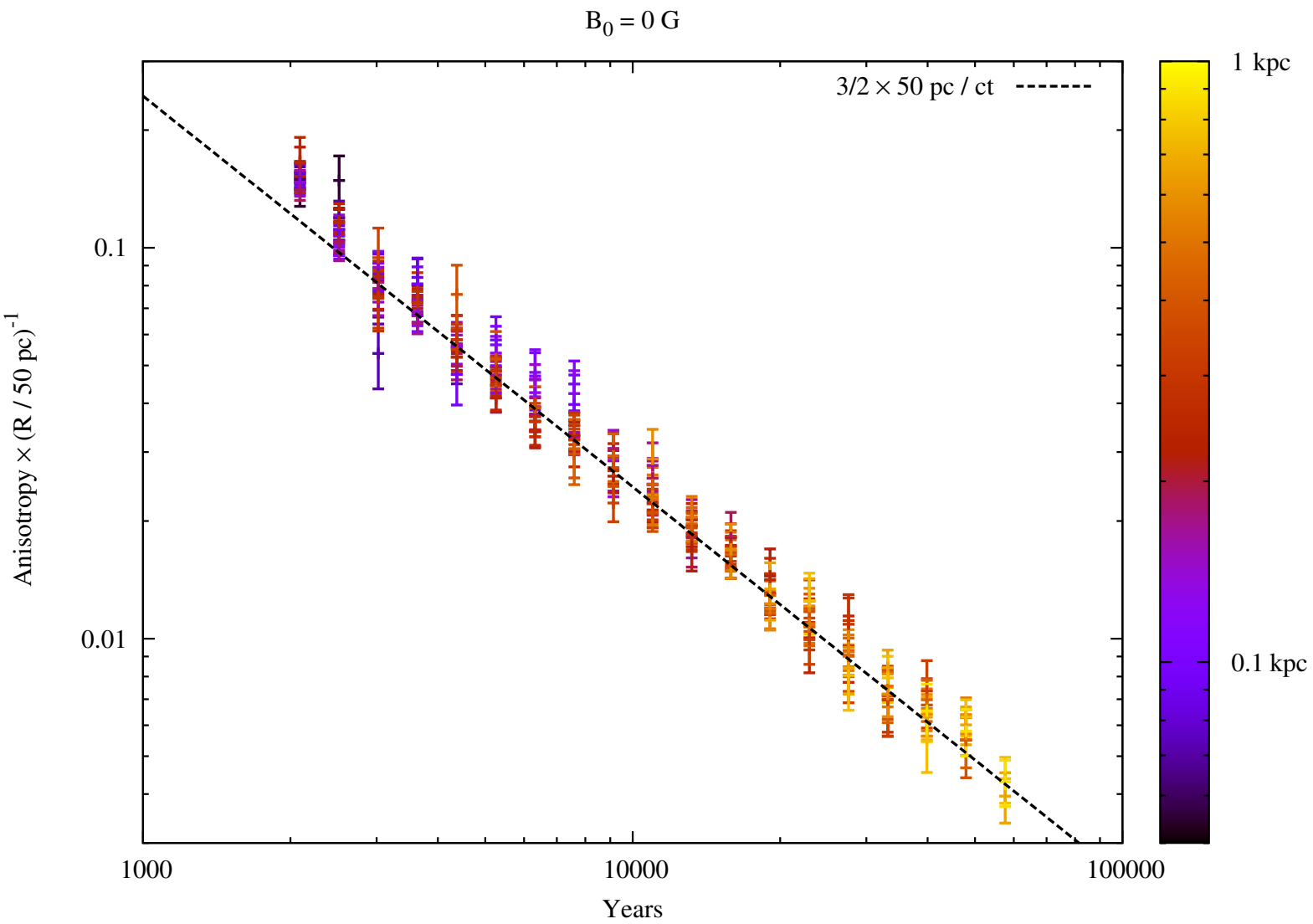
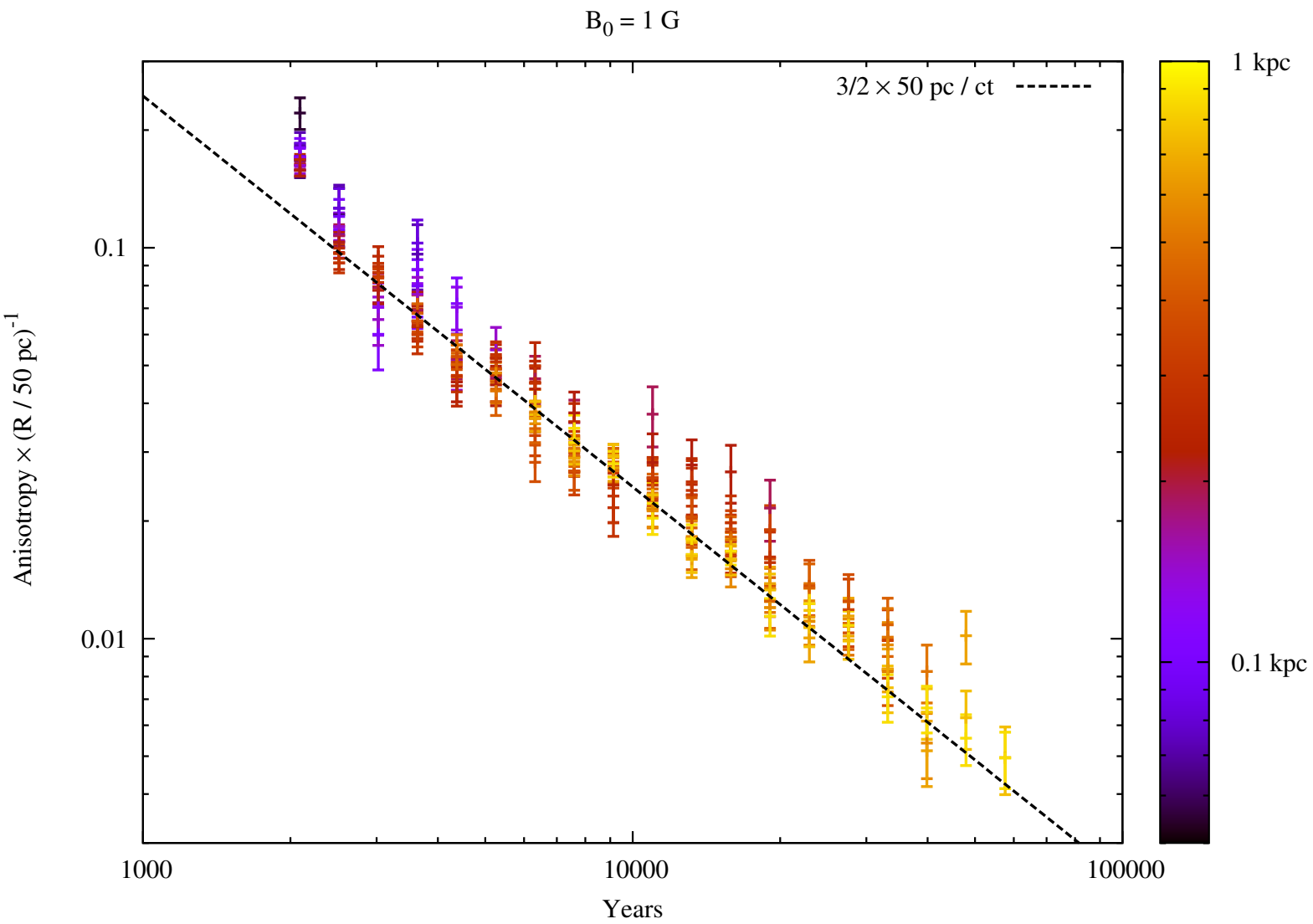


[*Savchenko, MK, Semikoz '15*]

Anisotropy of a single source: plus regular



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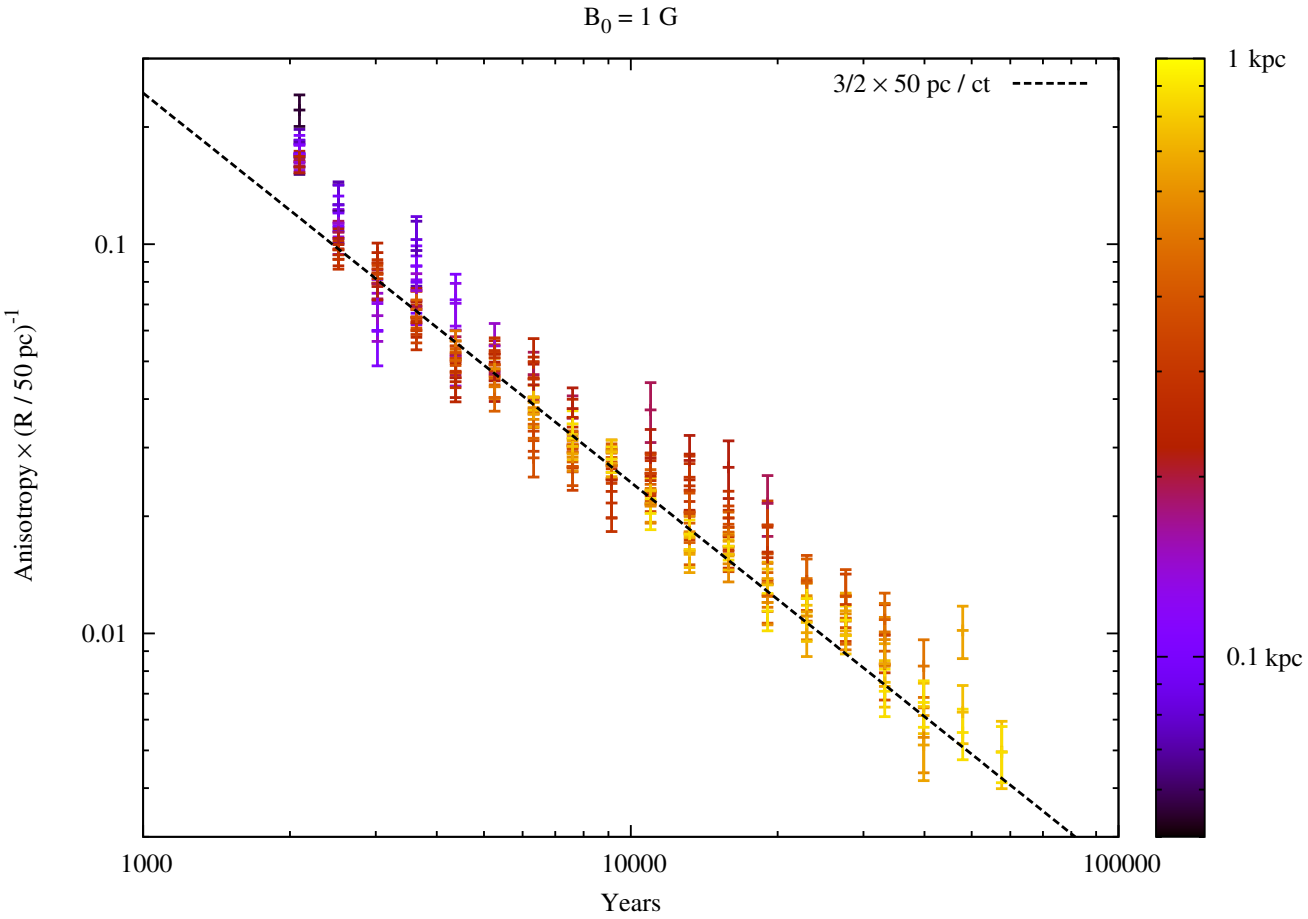
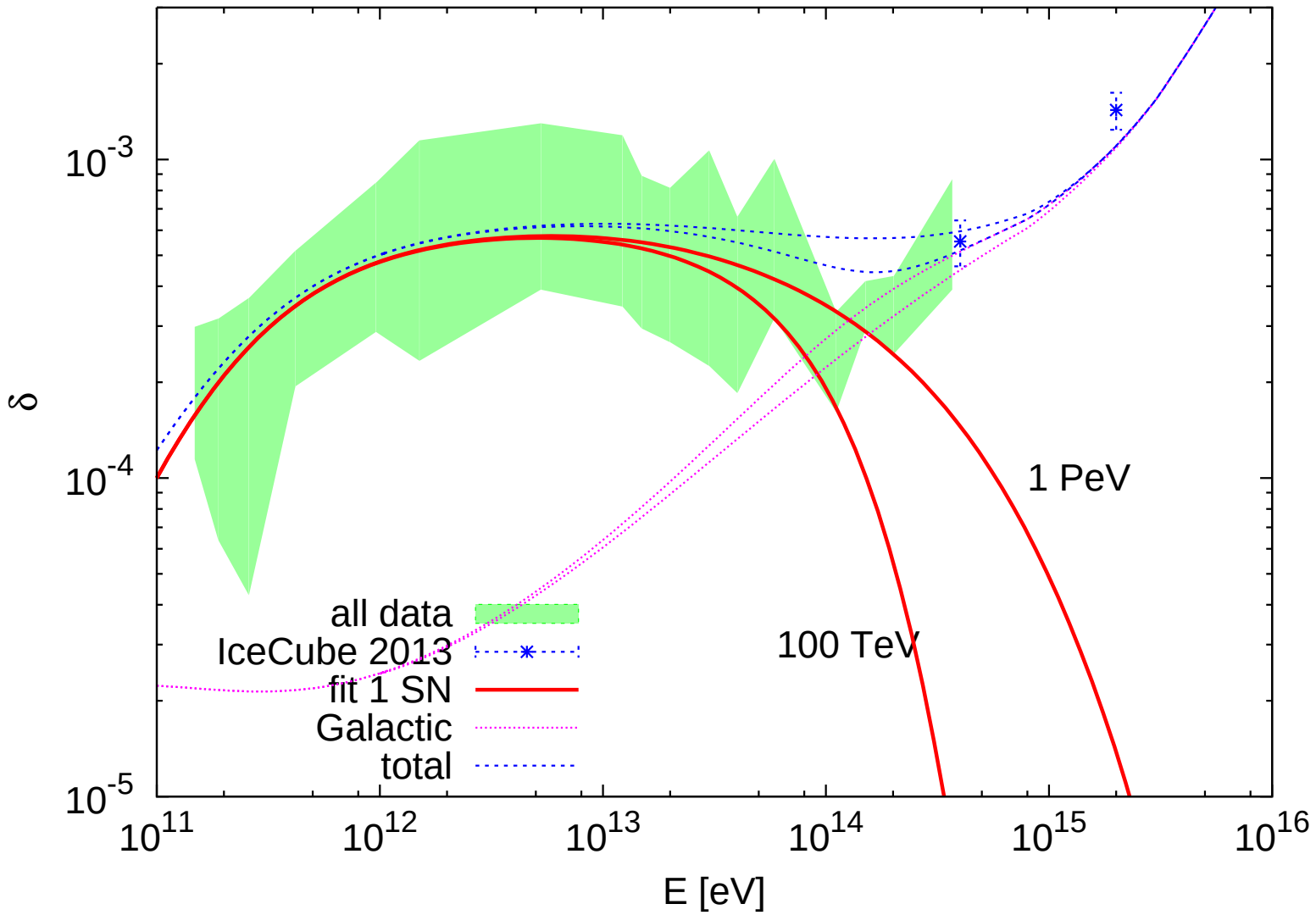


- regular field changes $n(\boldsymbol{x})$, but keeps it Gaussian

  $\Rightarrow$ no change in δ

Anisotropy of a single source:



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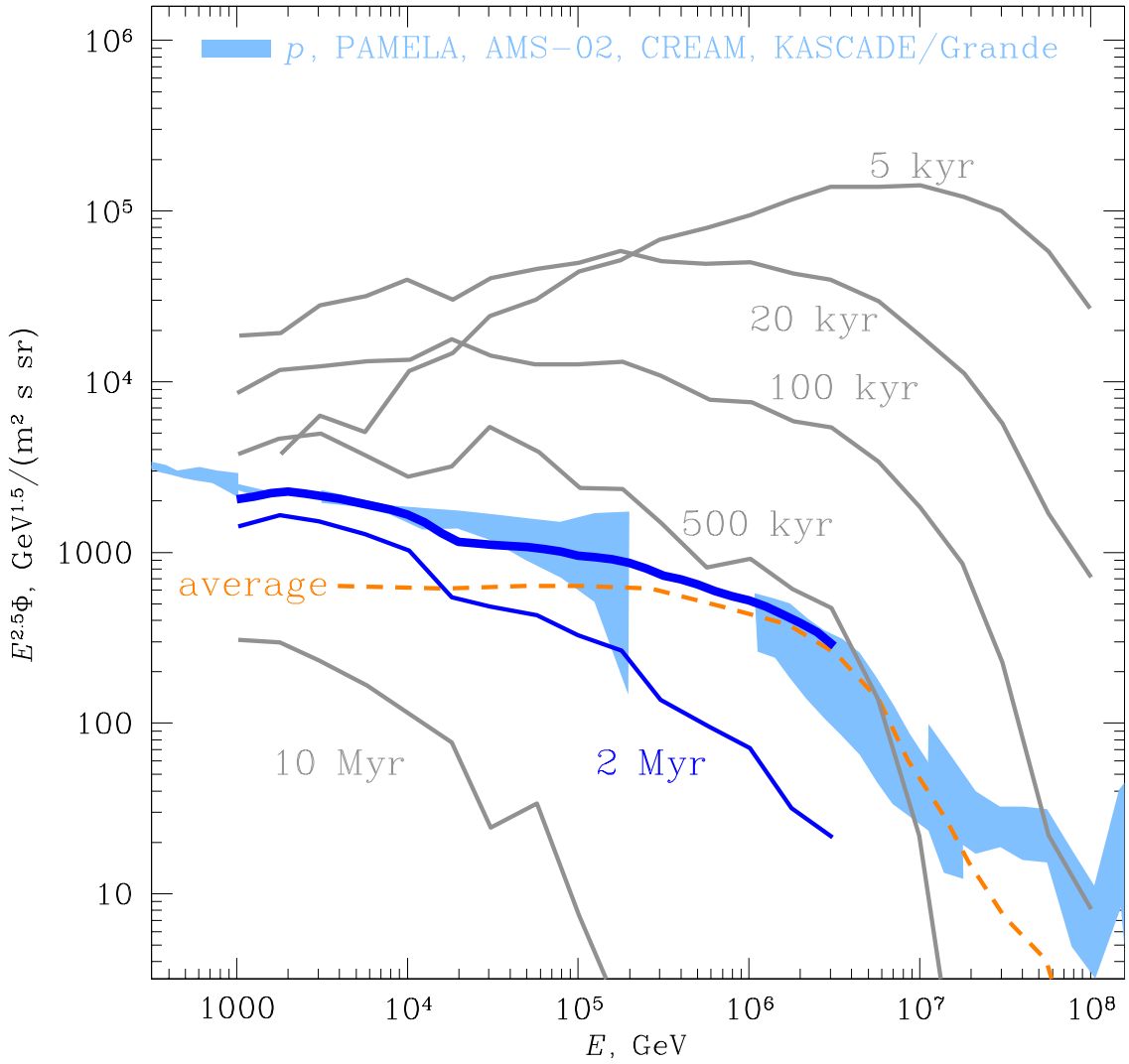
- may responsible for different slopes of local p and nuclei fluxes

Single source: proton flux



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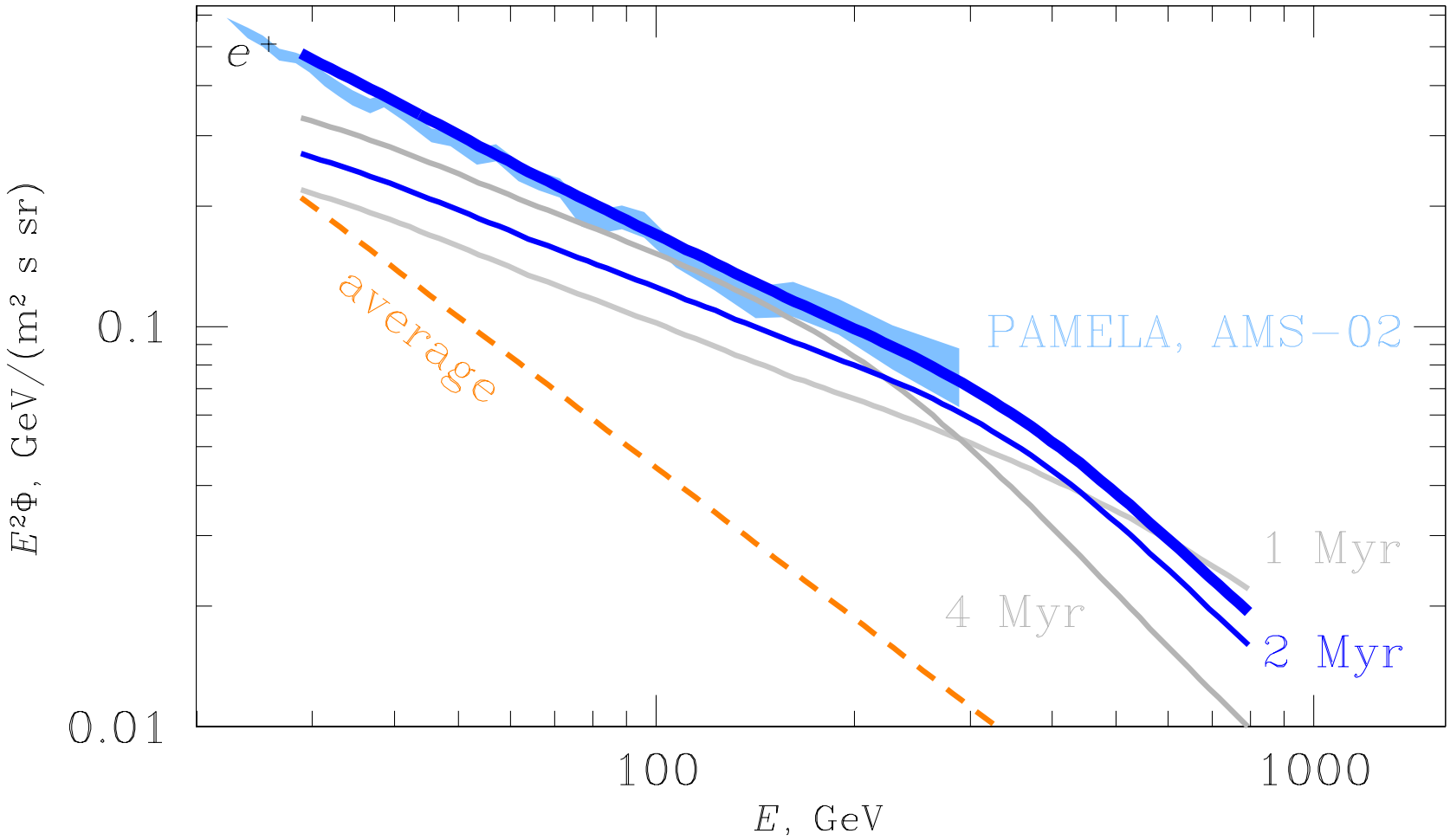
Single source: positrons



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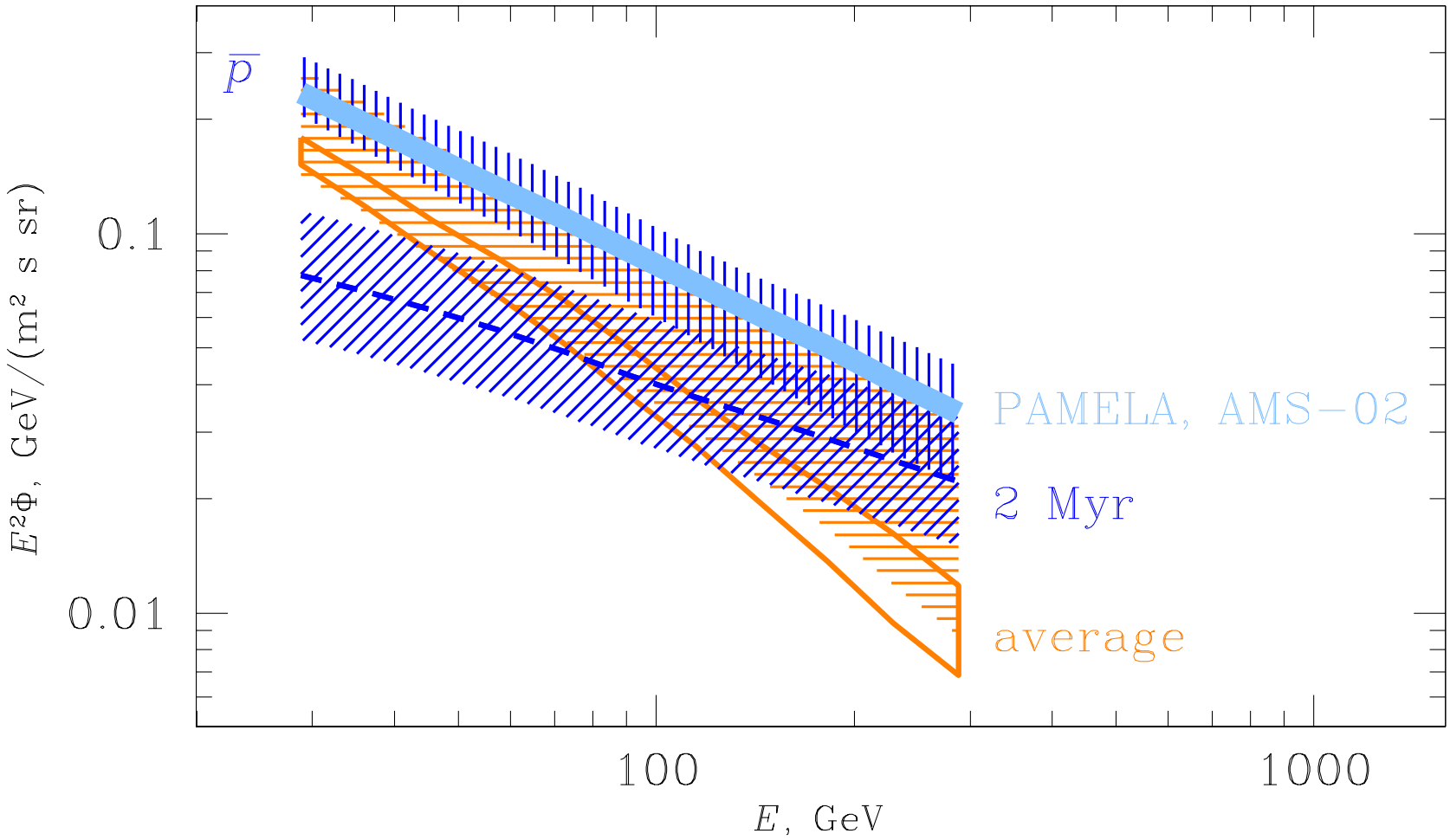
Single source: antiprotons



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Conclusions I

- Knee due to CR escape
  - recovery of fluxes as suggested by KASCADE-Grande
  - probes GMF: suggests small $B_{\rm rms}$ and small $l_{\rm coh}$
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   - dipole formula $\delta = 3R/2T$ holds universally in quasi-gaussian regime
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