Transition from Galactic to Extragalactic Cosmic Rays

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Outline of the talk

1. Introduction
2. Observations and their interpretation:
   - CR composition $> 10^{17}$ eV
   - Galactic CRs above the knee
   - EGRB and cascade limit
   - Neutrino data
3. Models:
   - Dip model
   - Mixed models
   - Minimal mixed model
4. Conclusions

Introduction

- We can model UHECRs, using photons and neutrinos merely as constraints, e.g.
  - thin UHECR sources, e.g. lobes of radio galaxies
  - IceCube Neutrinos: hidden sources
  - EGRB: starburst galaxies and blazars
- Aproach: model as much as possible with single source class

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a single source class that

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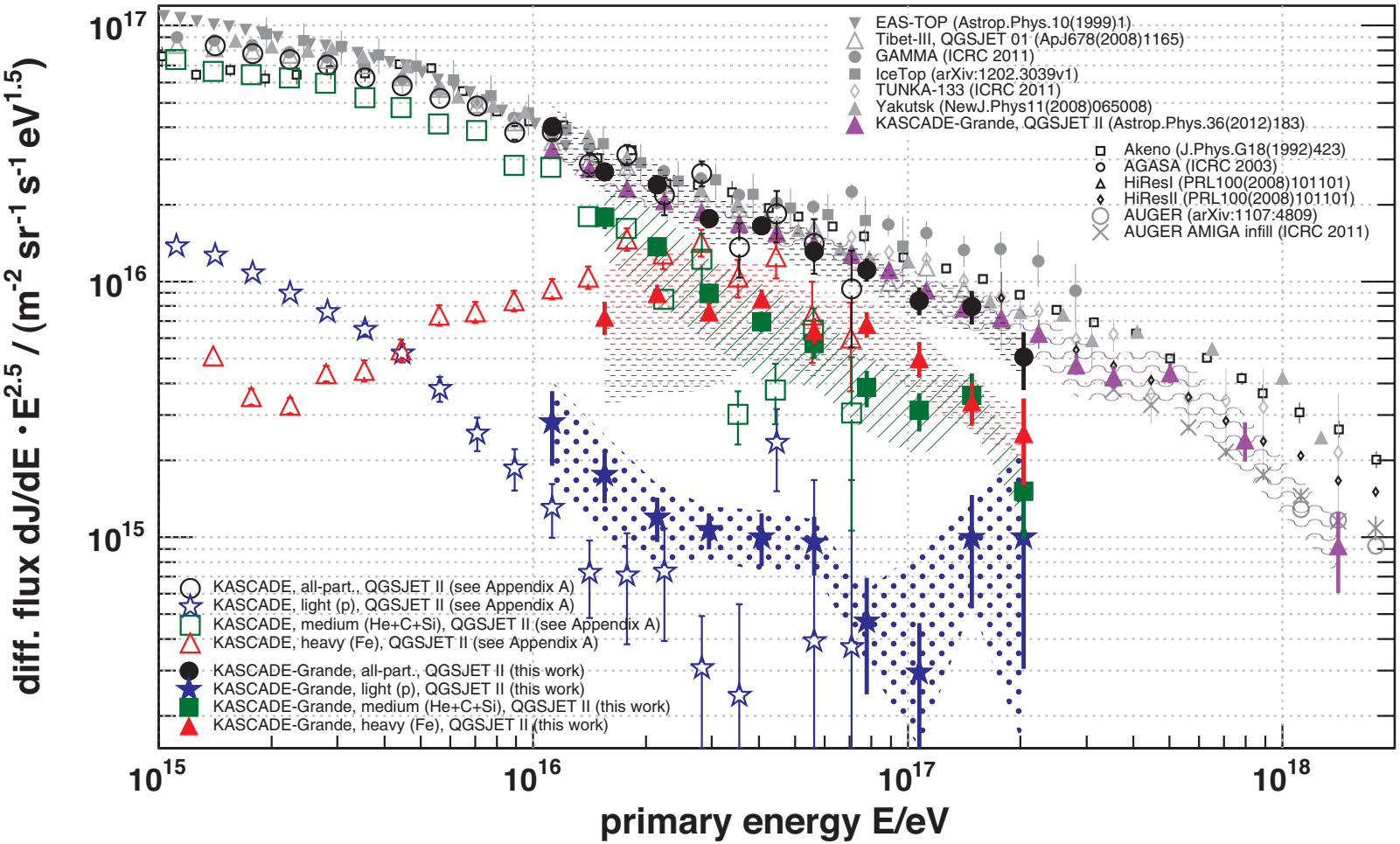
- fits the (extragalactic) neutrino flux
- gives subdominant contribution to EGRB

Composition of CRs:

[KASCADE-Grande '13]



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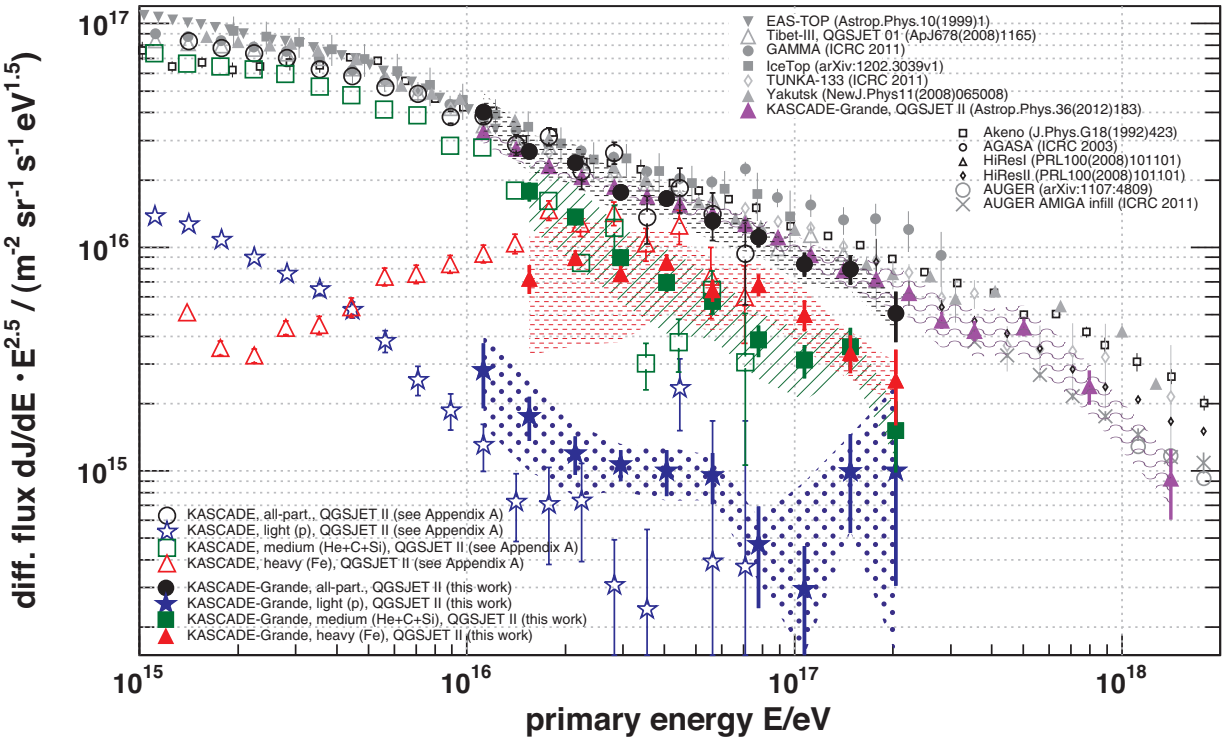

Rigidity dependent knee:

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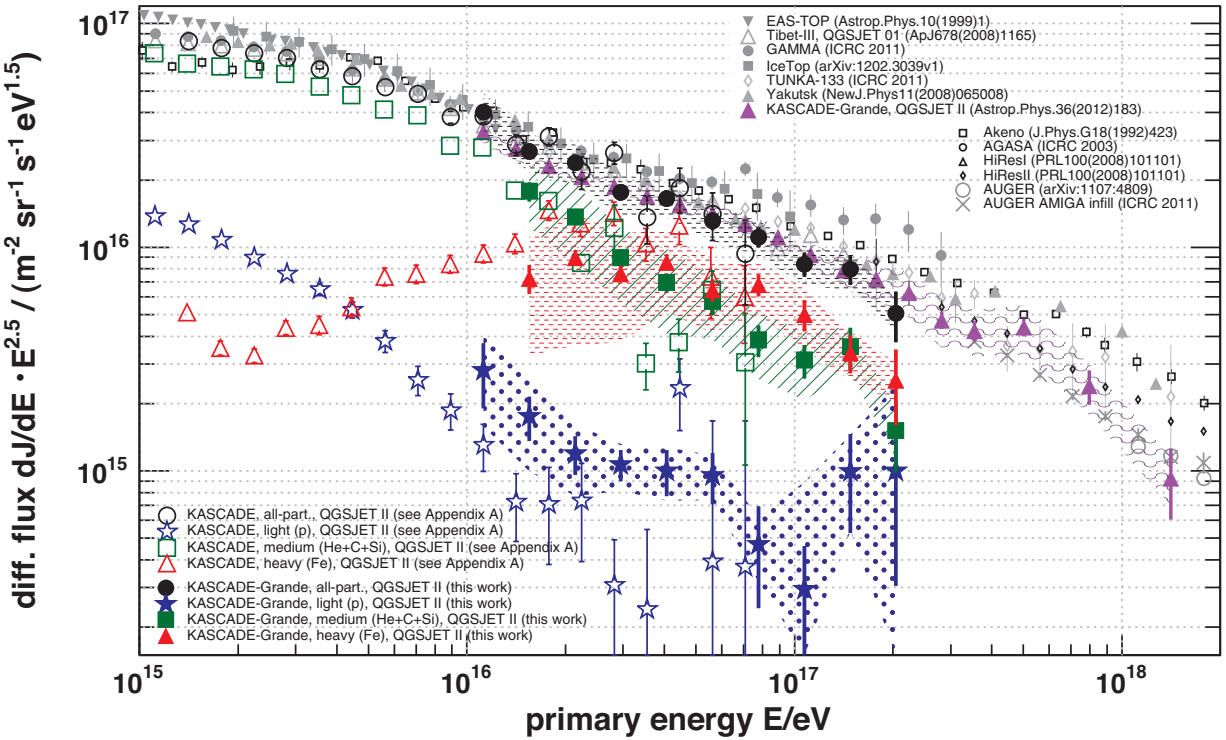
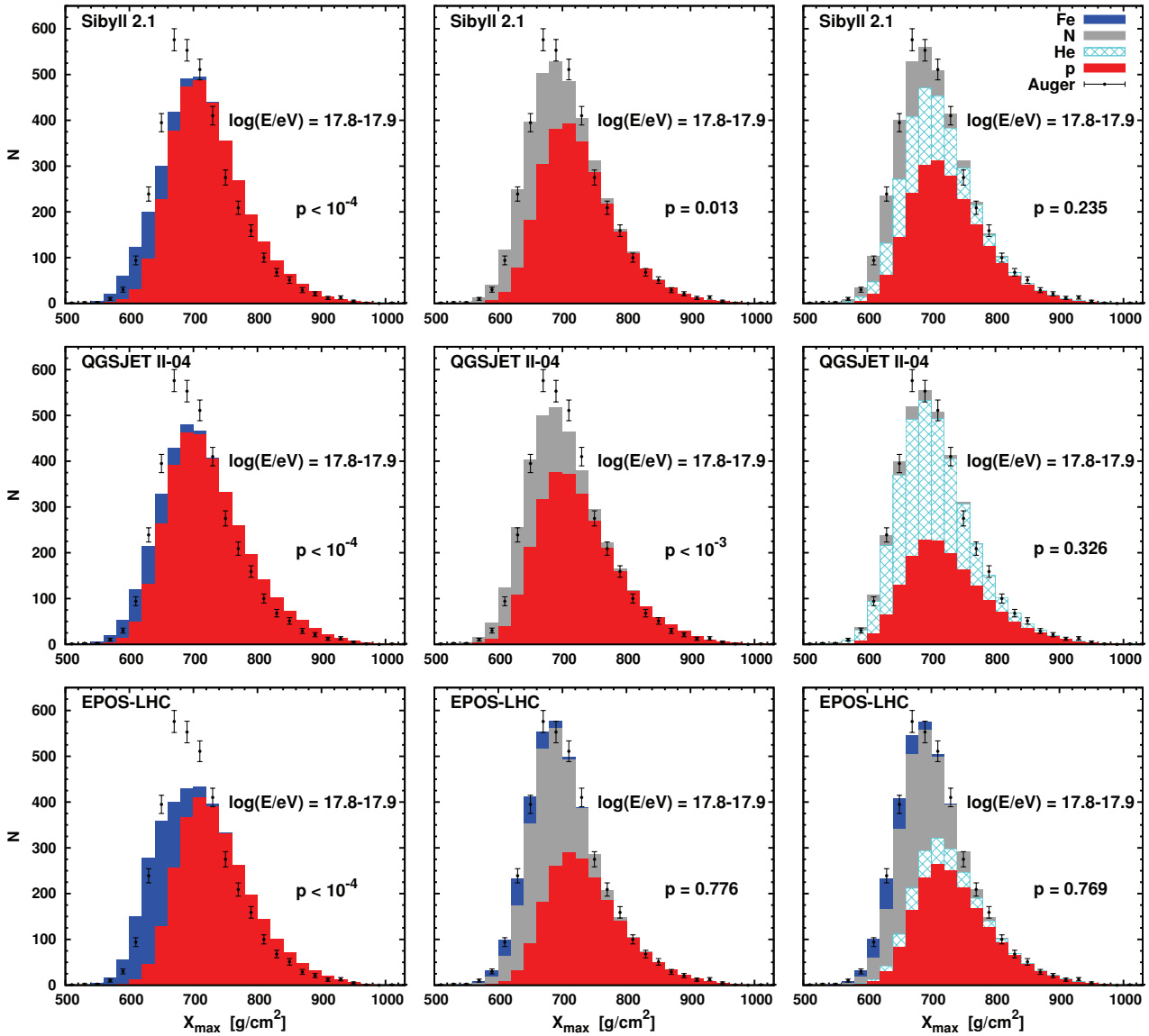


Rigidity dependent knee:

- light knee agrees with knee in all-particle spectrum at 4×10^{15} eV
- light component recovers

Composition of CRs:

[*PAO '14*]



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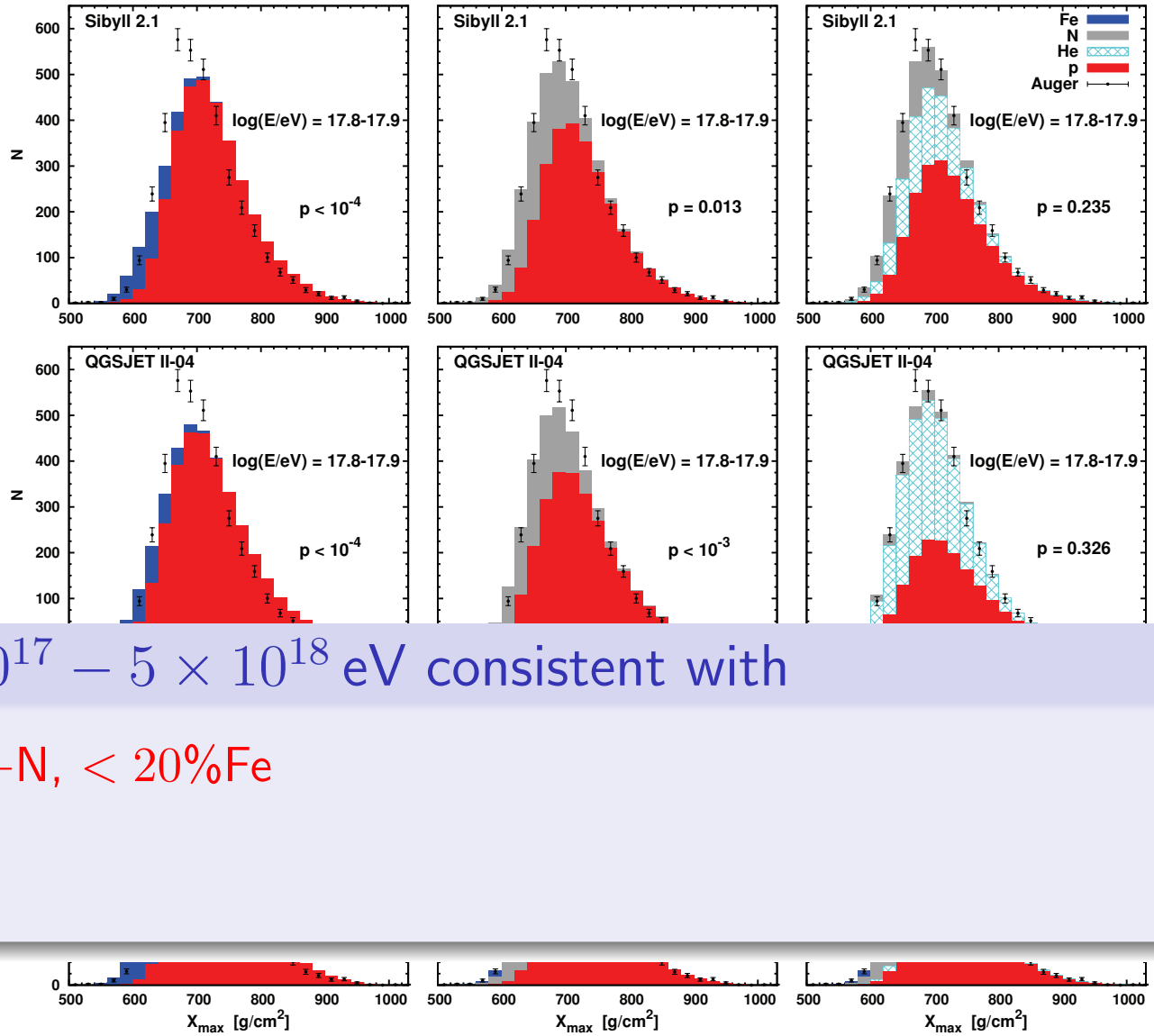

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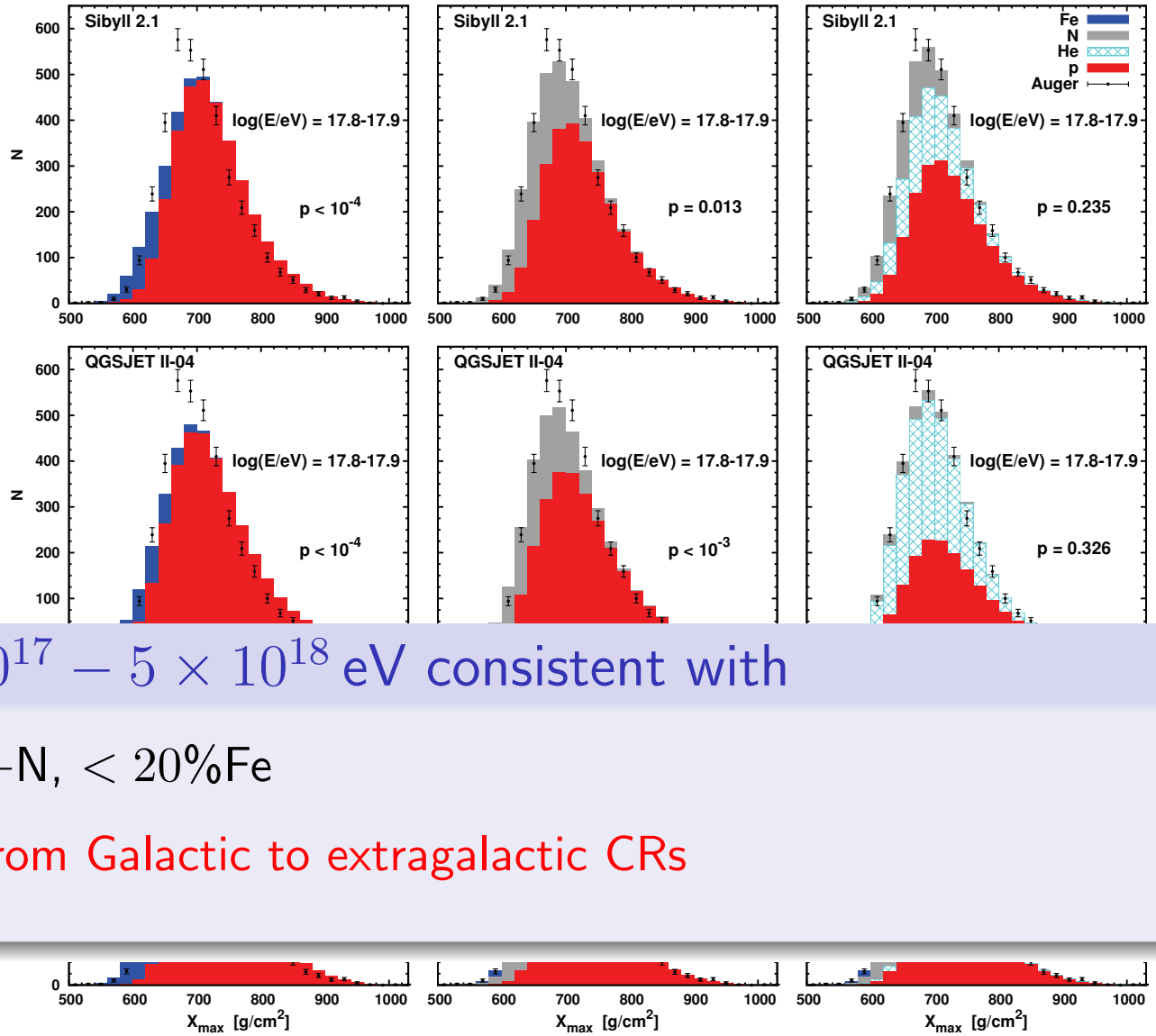

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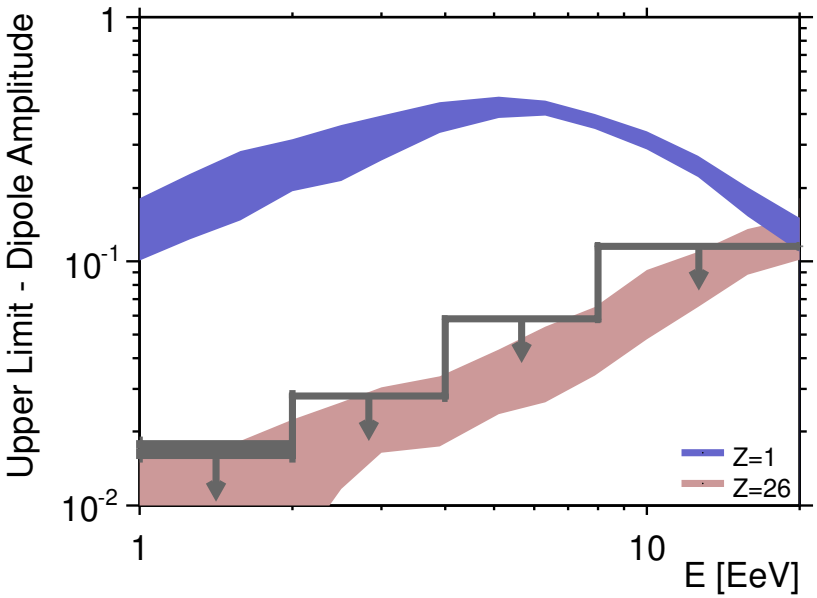
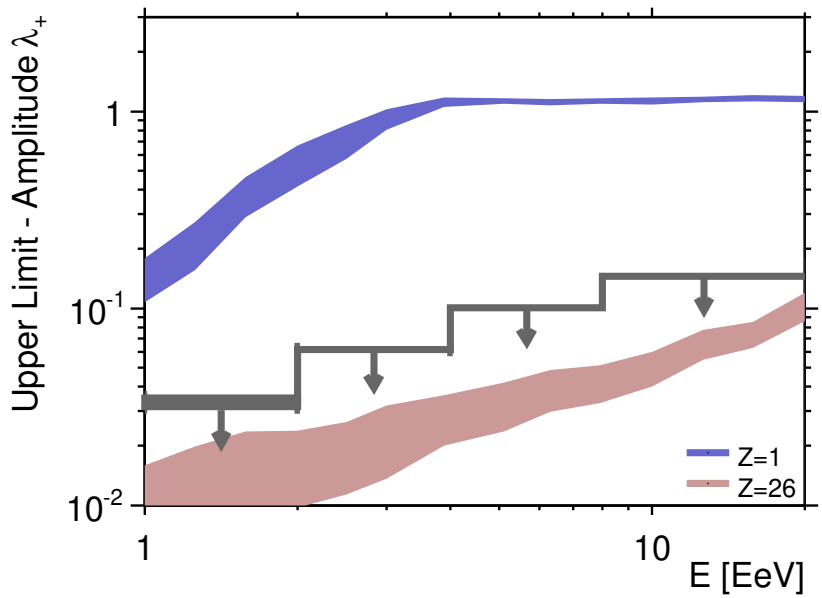
- 50% p, 50% He+N, < 20%Fe
- early transition from Galactic to extragalactic CRs

Transition to extragalactic CRs – anisotropy limits

dipole



quadrupole



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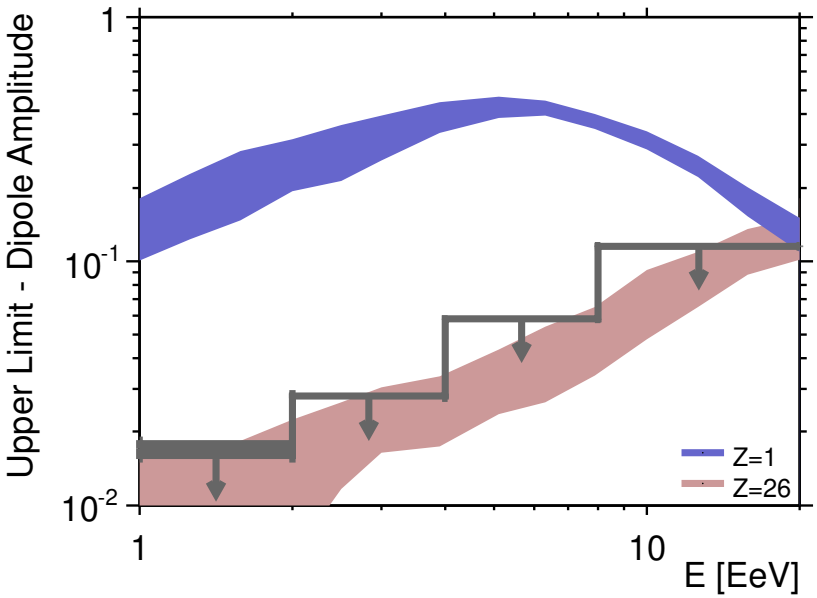

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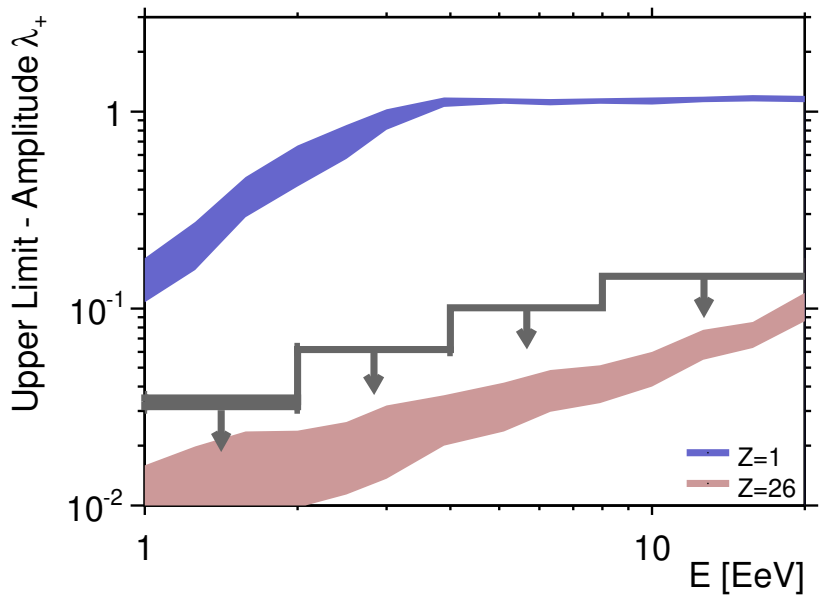
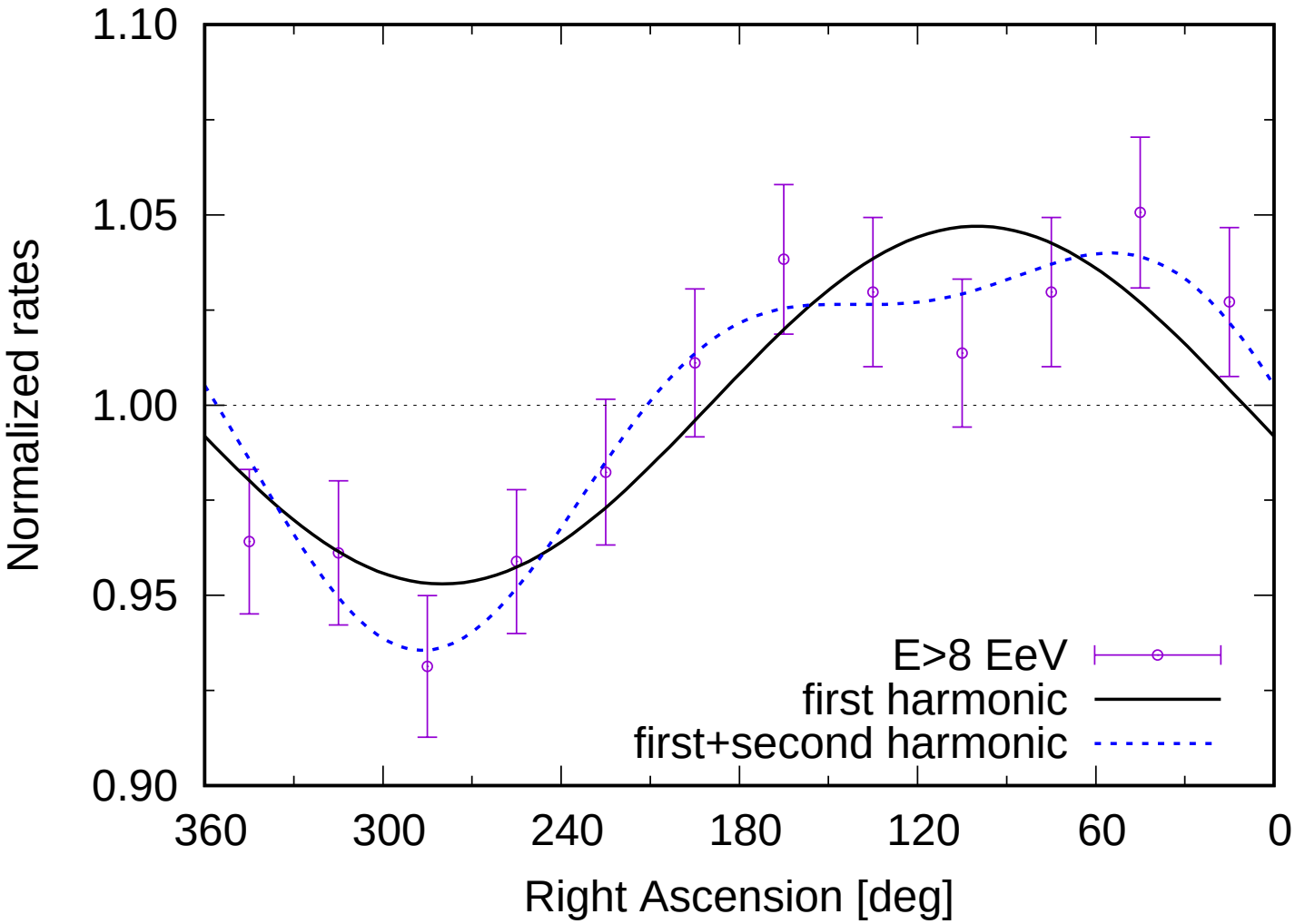


dominant light Galactic composition around $E = 10^{18}$ eV excluded

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

Transition to extragalactic CRs – observed dipole [PAO '17, '18]

- $E > 8\,\text{EeV}$: dipole observed with $A \simeq 6.5\%$ and $\text{R.A.} \simeq 120^\circ$



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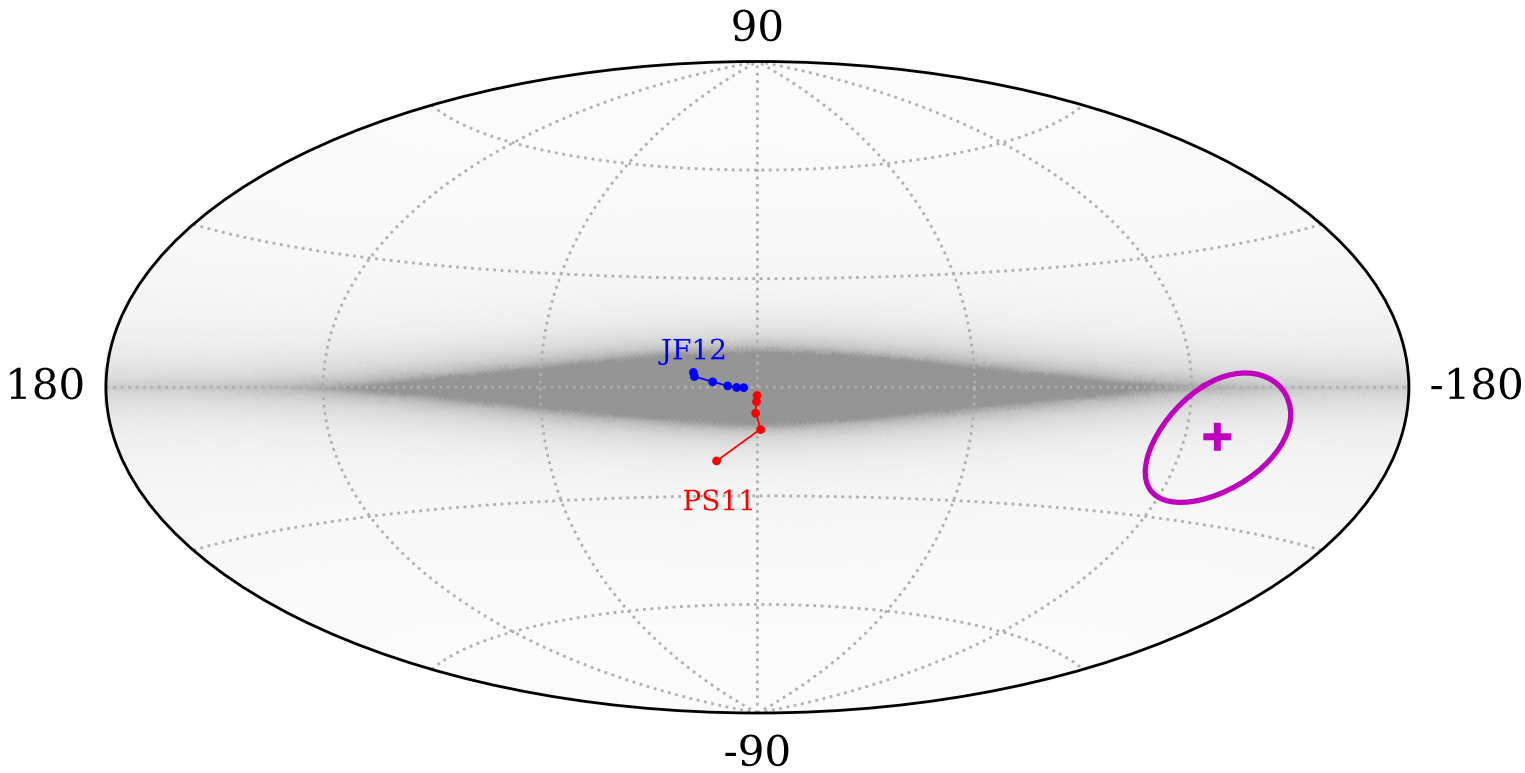

- direction consistent with extragalactic mass distribution

Galactic CRs above the knee

- to test quantitatively extragalactic models, we need to model also Galactic fluxes

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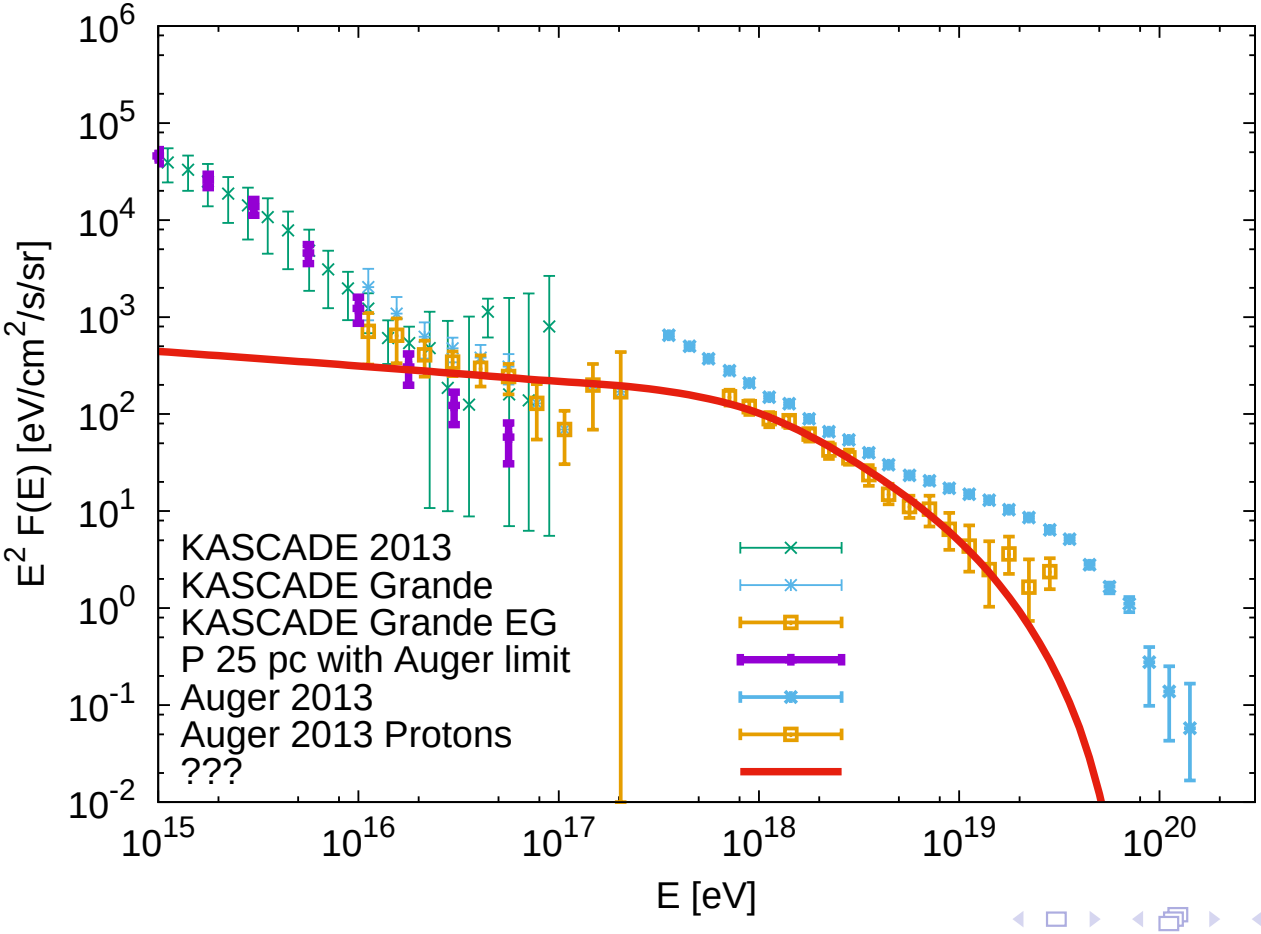


Galactic CRs above the knee

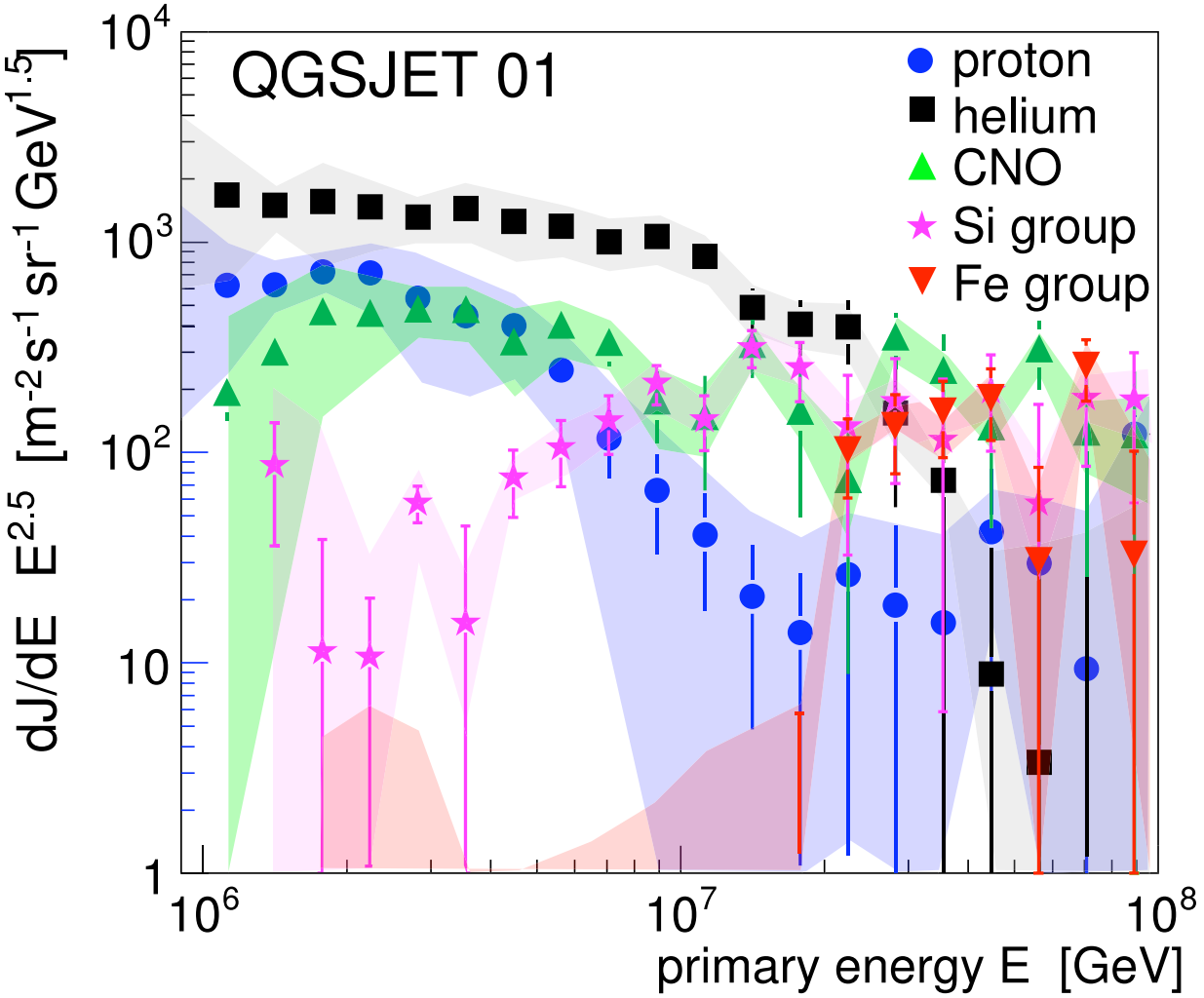
- to test quantitatively extragalactic models, we need to model also Galactic fluxes

$$I_A(E) = I_A^{\rm Gal}(E) + I_A^{\rm ex}(E)$$

- how certain are observations/models for Galactic fluxes?
- e.g. position of light knee?

Uncertainties: CR composition

Kascade-Grande: dependence on interaction model



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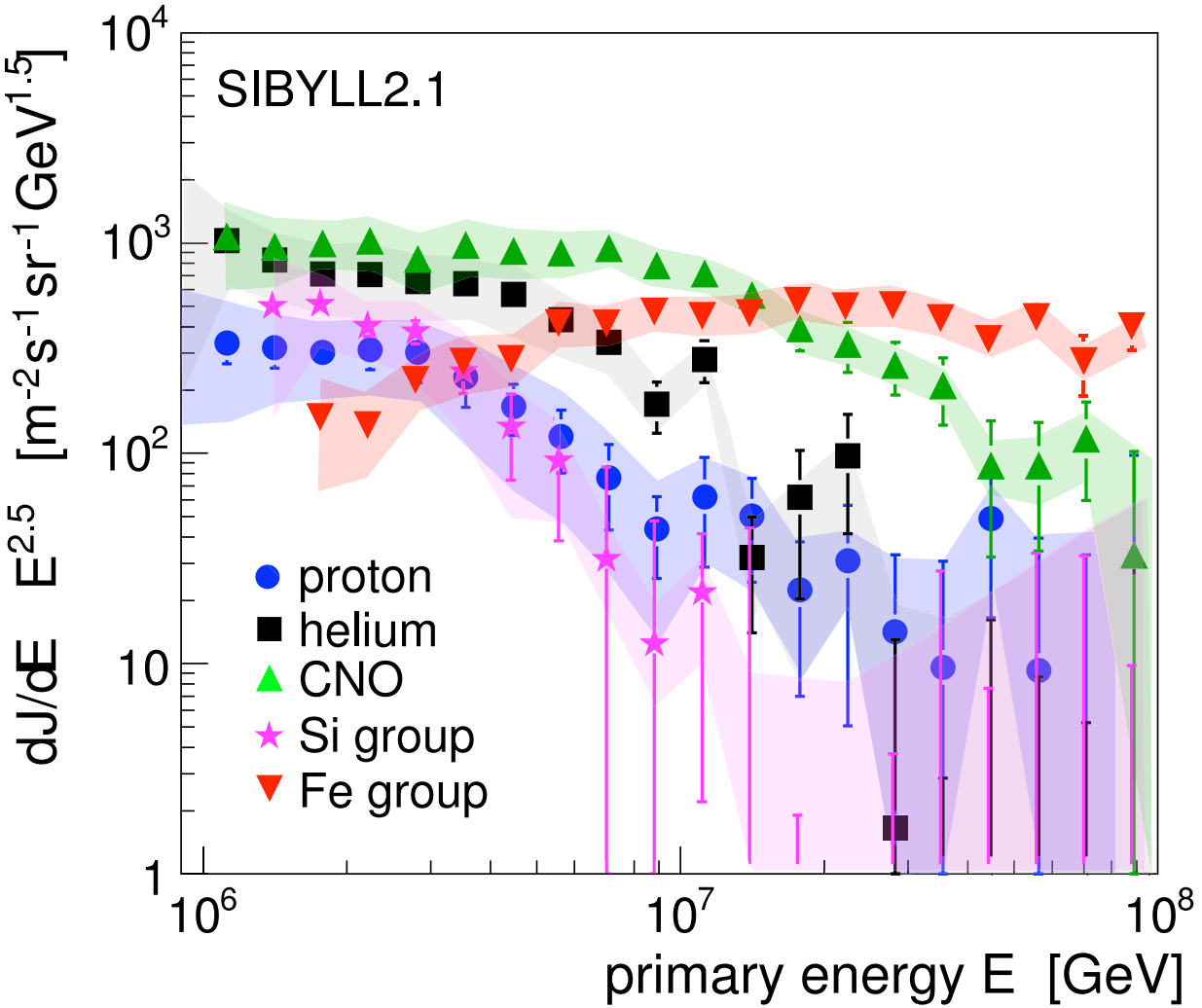

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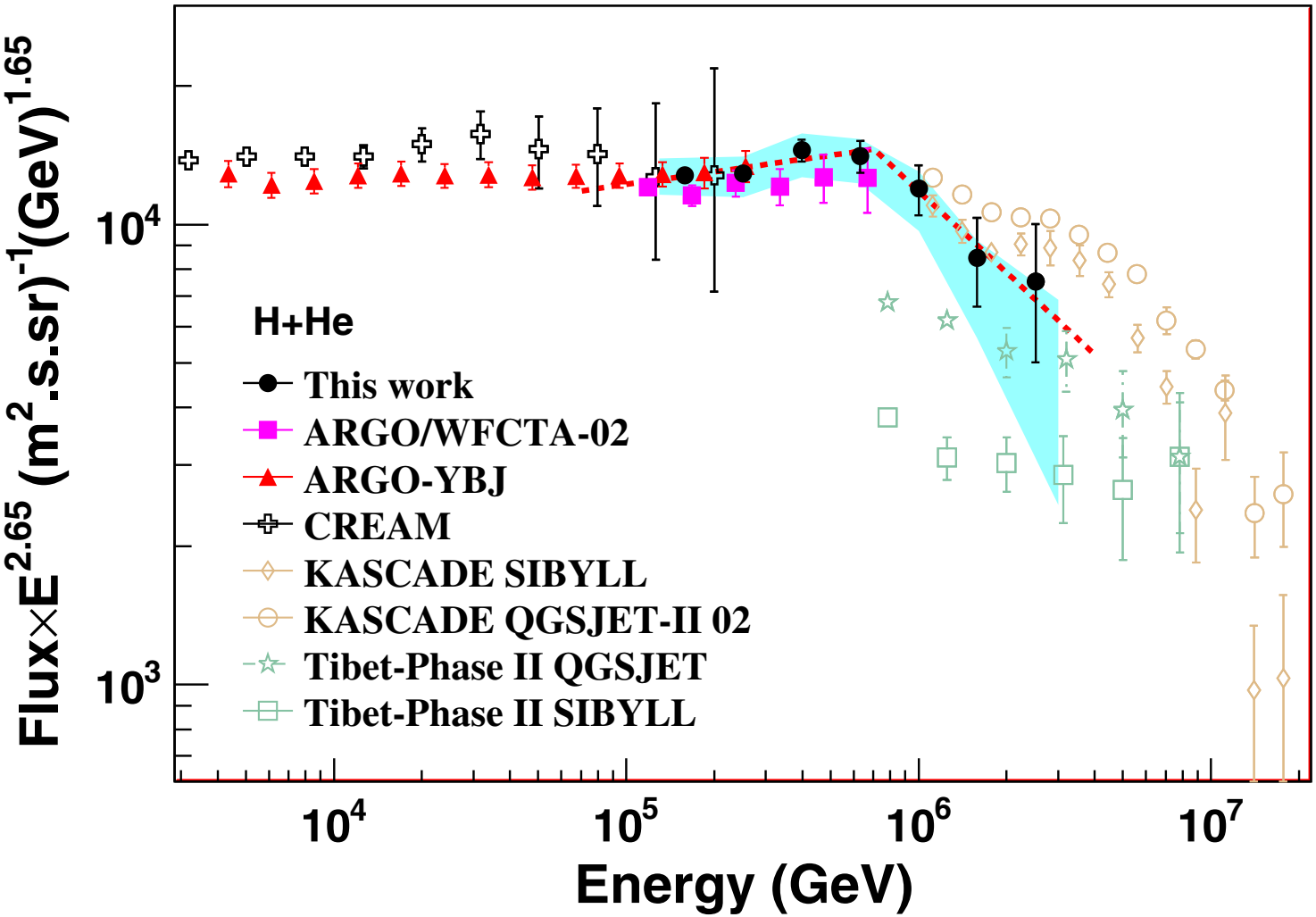
ARGO-YBJ: position of "p+He knee" $\simeq 700\,\mathrm{TeV}$



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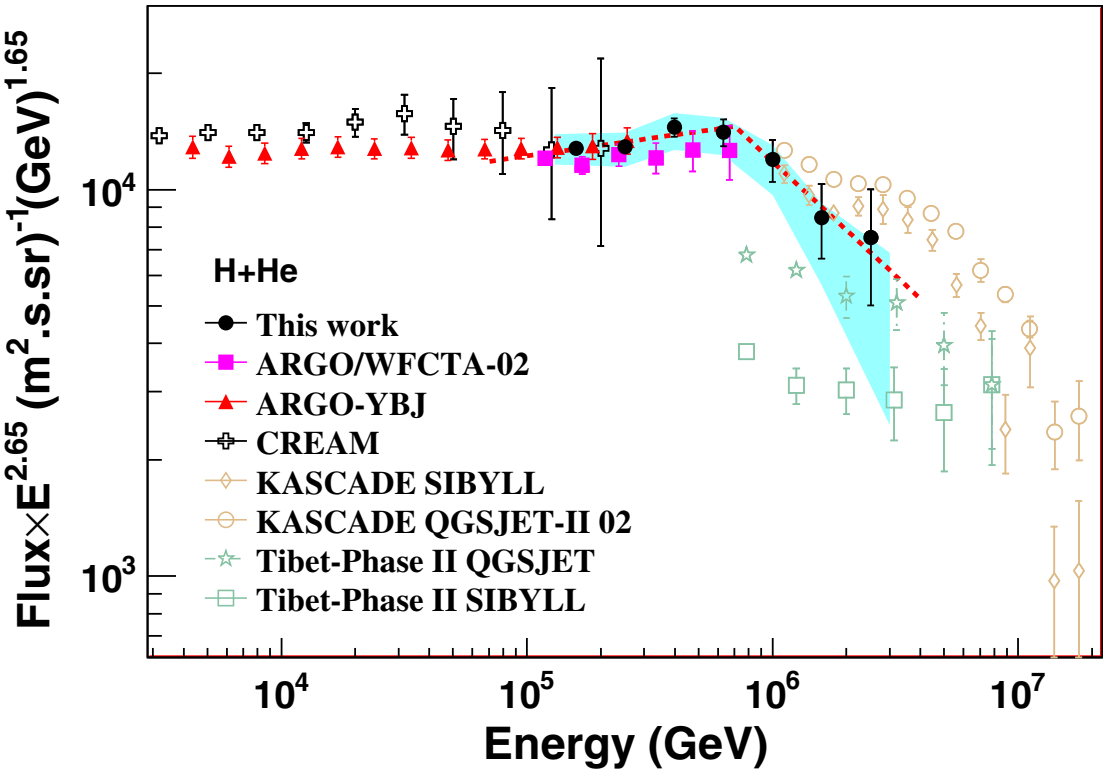
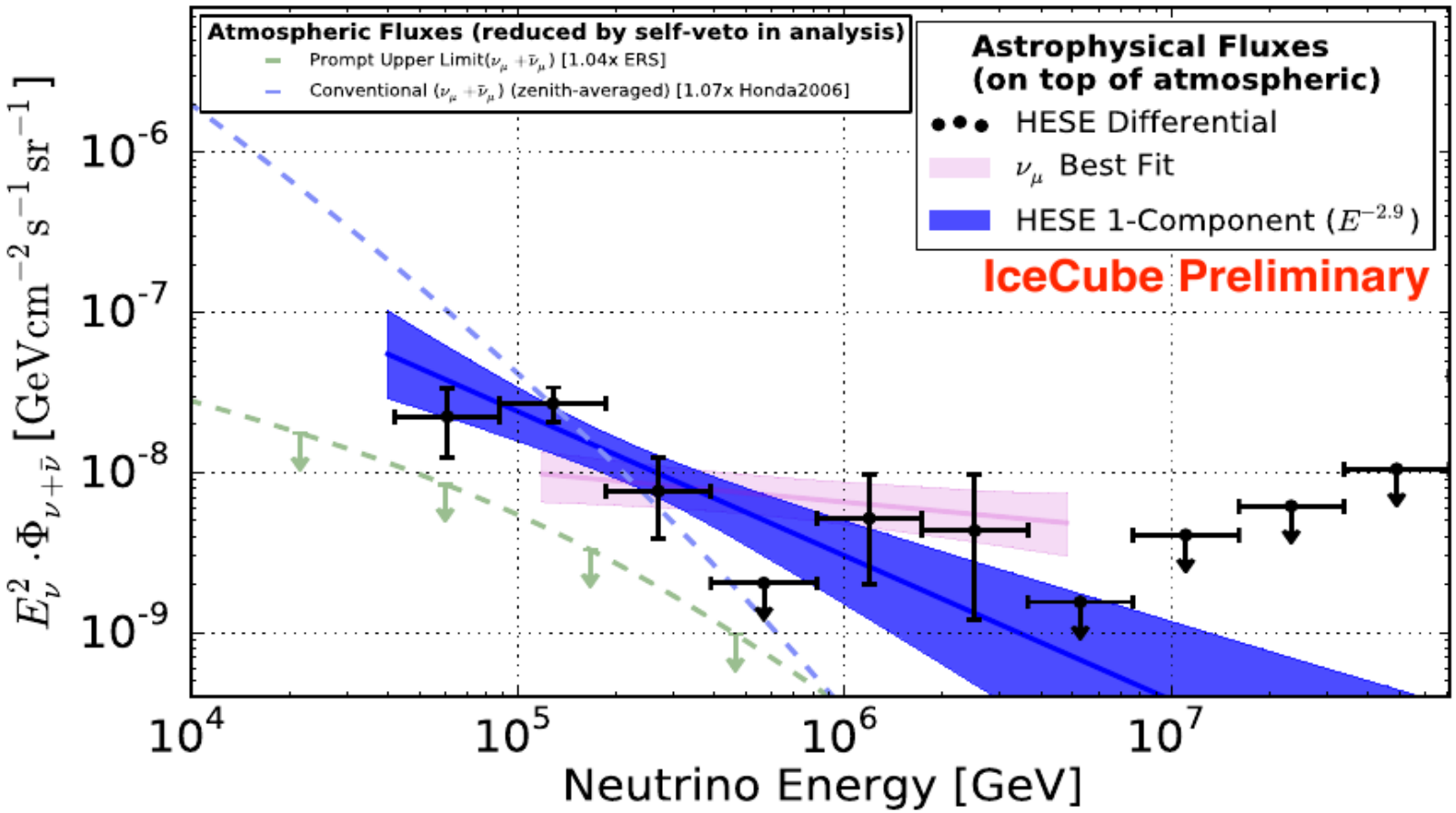
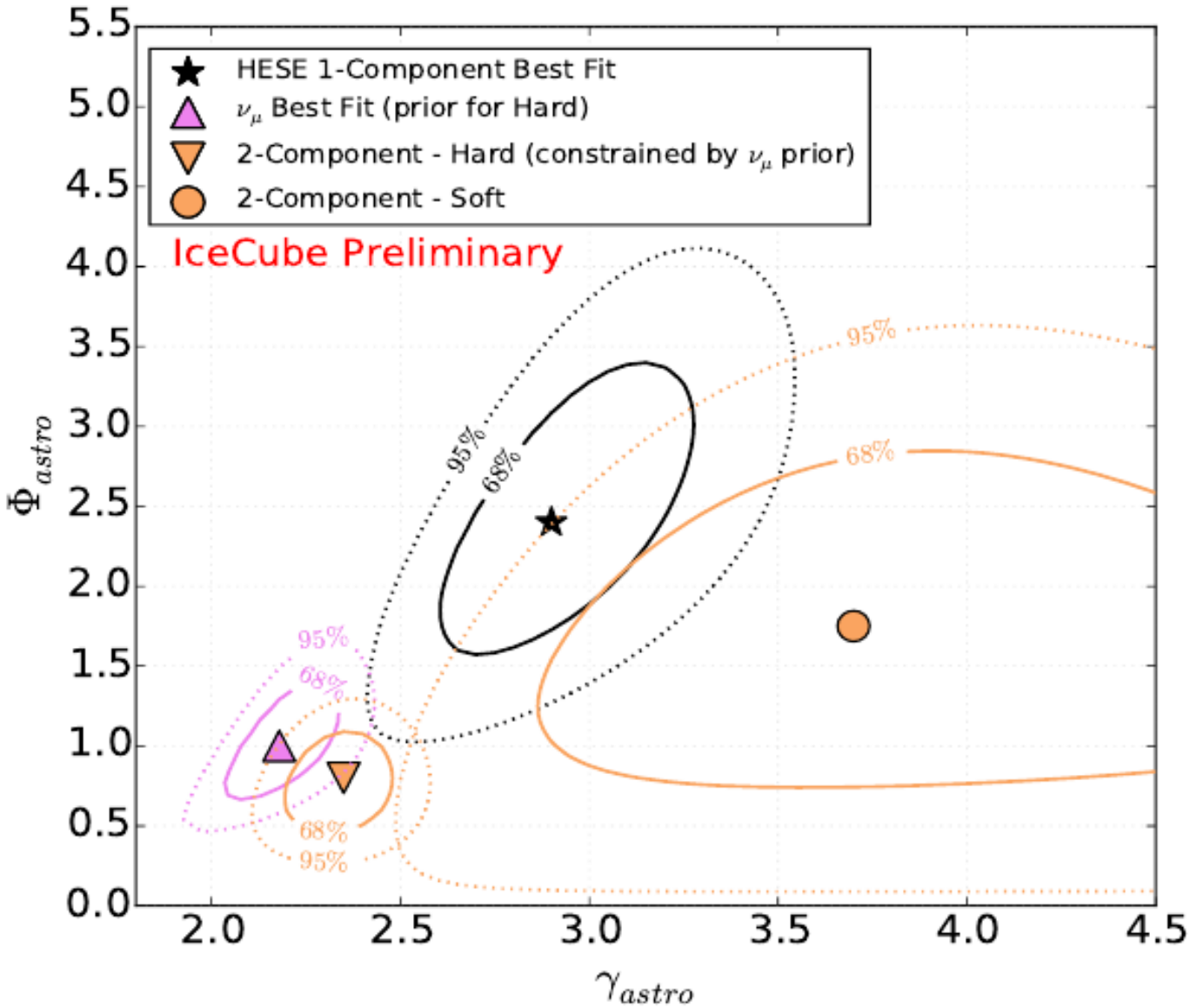


- iron knee at $\simeq 20\,\mathrm{PeV}$?

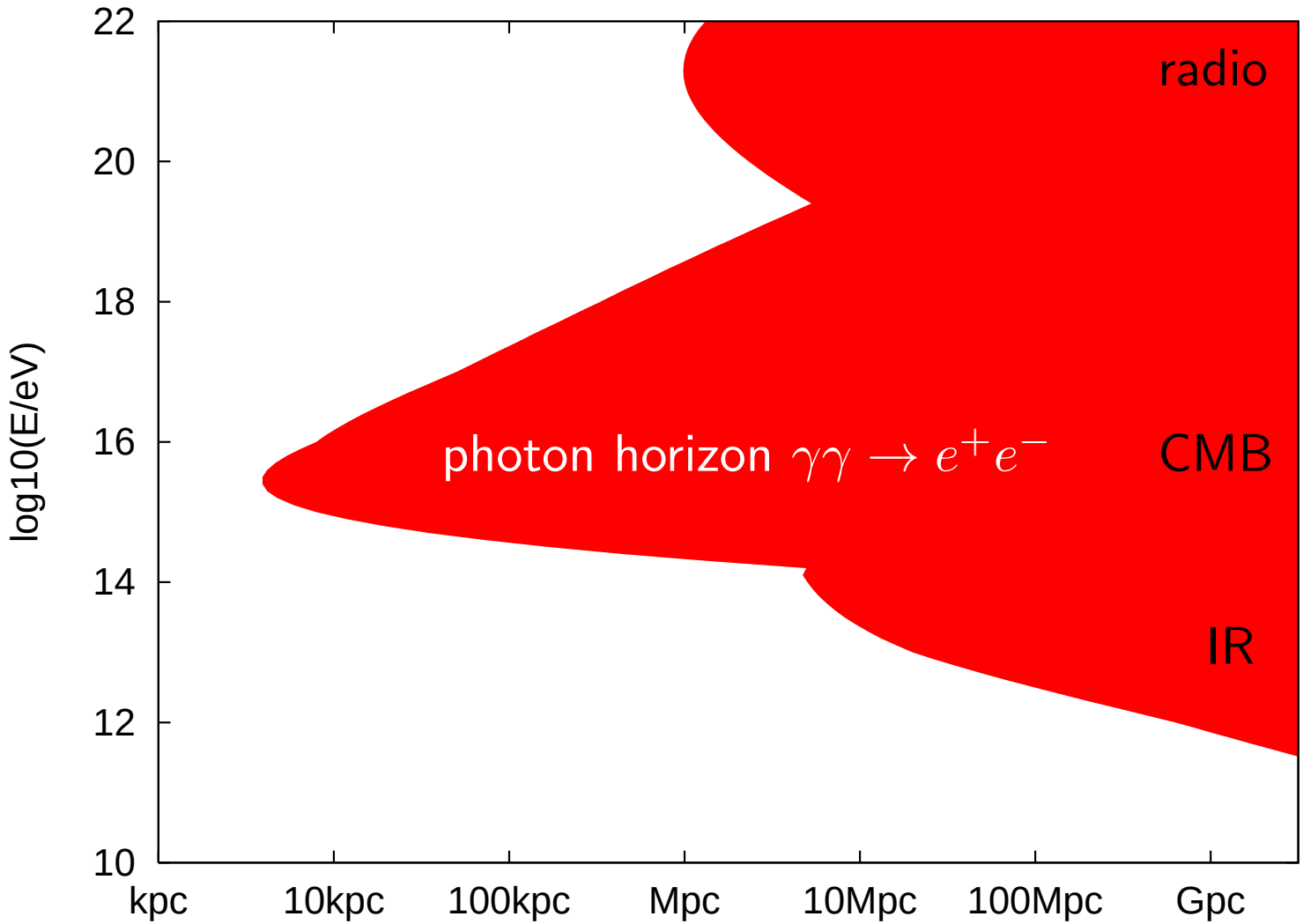
IceCube events: Large soft component?



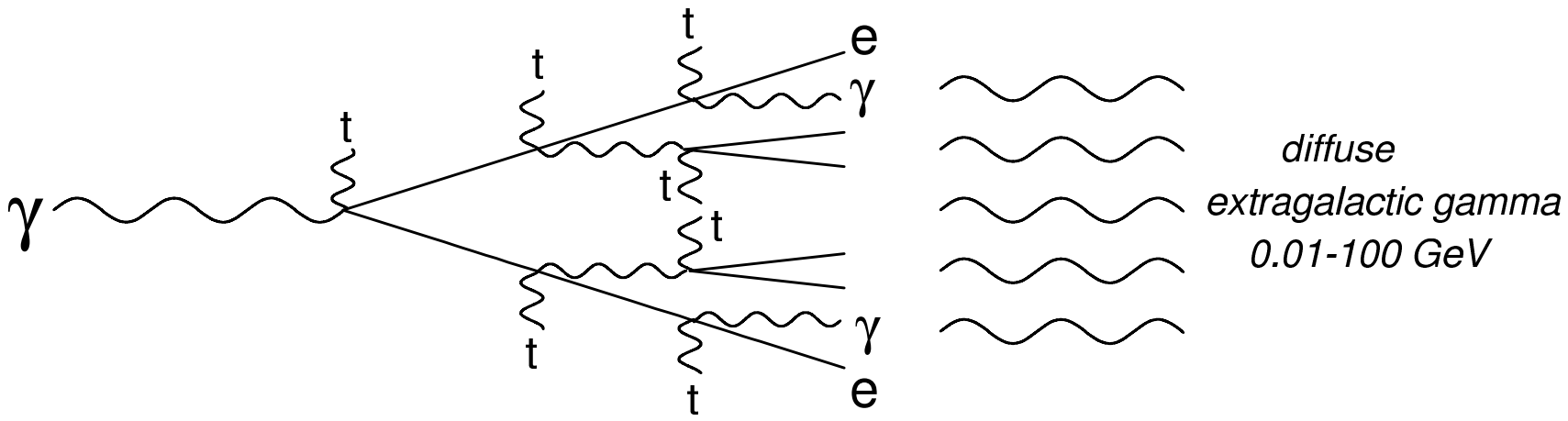
IceCube events: power-law fit of energy spectrum



The photon horizon



Development of the elmag. cascade:



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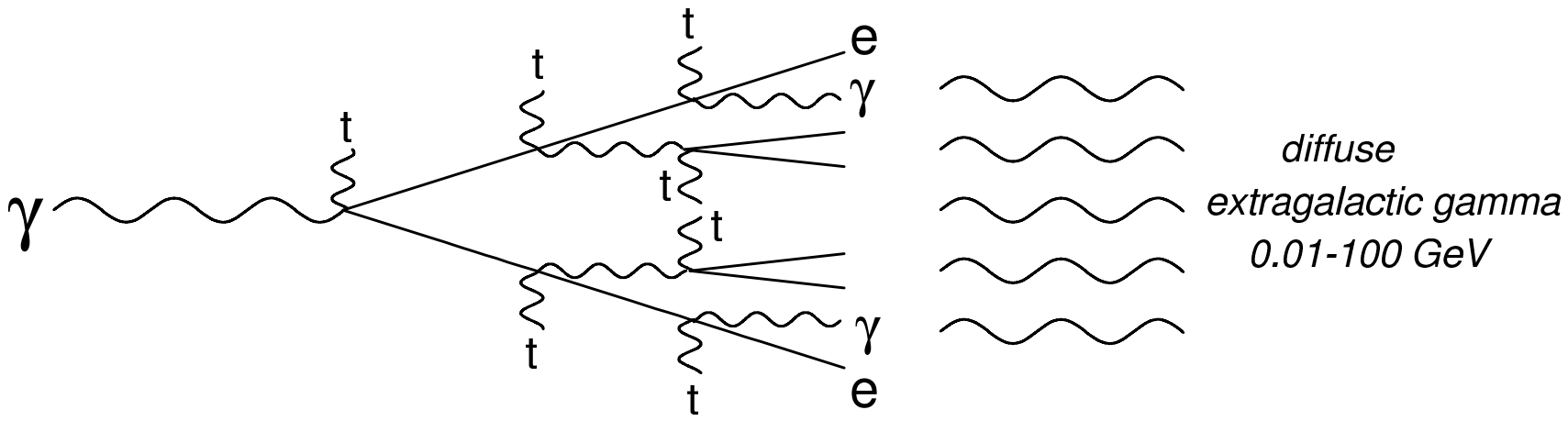
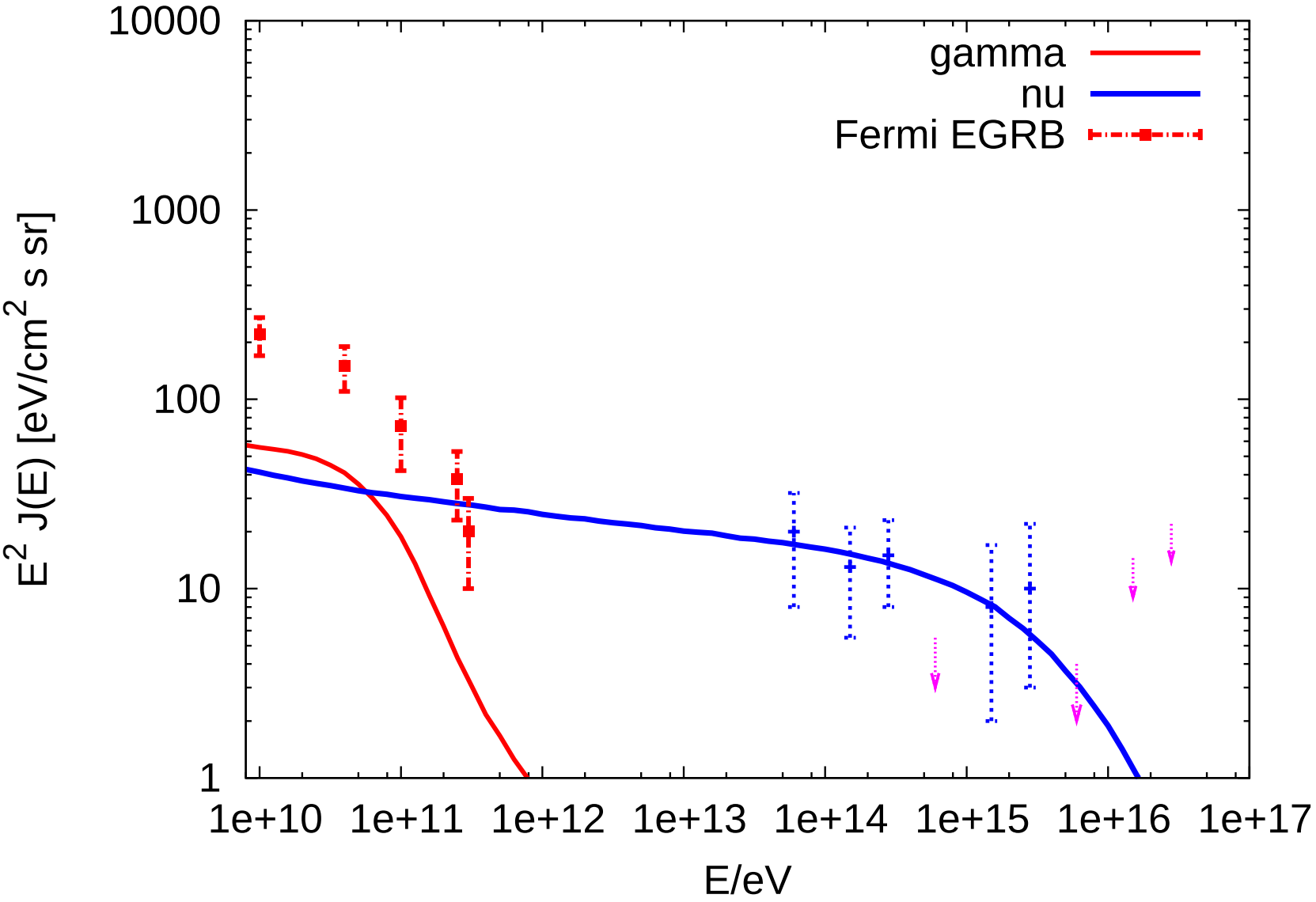
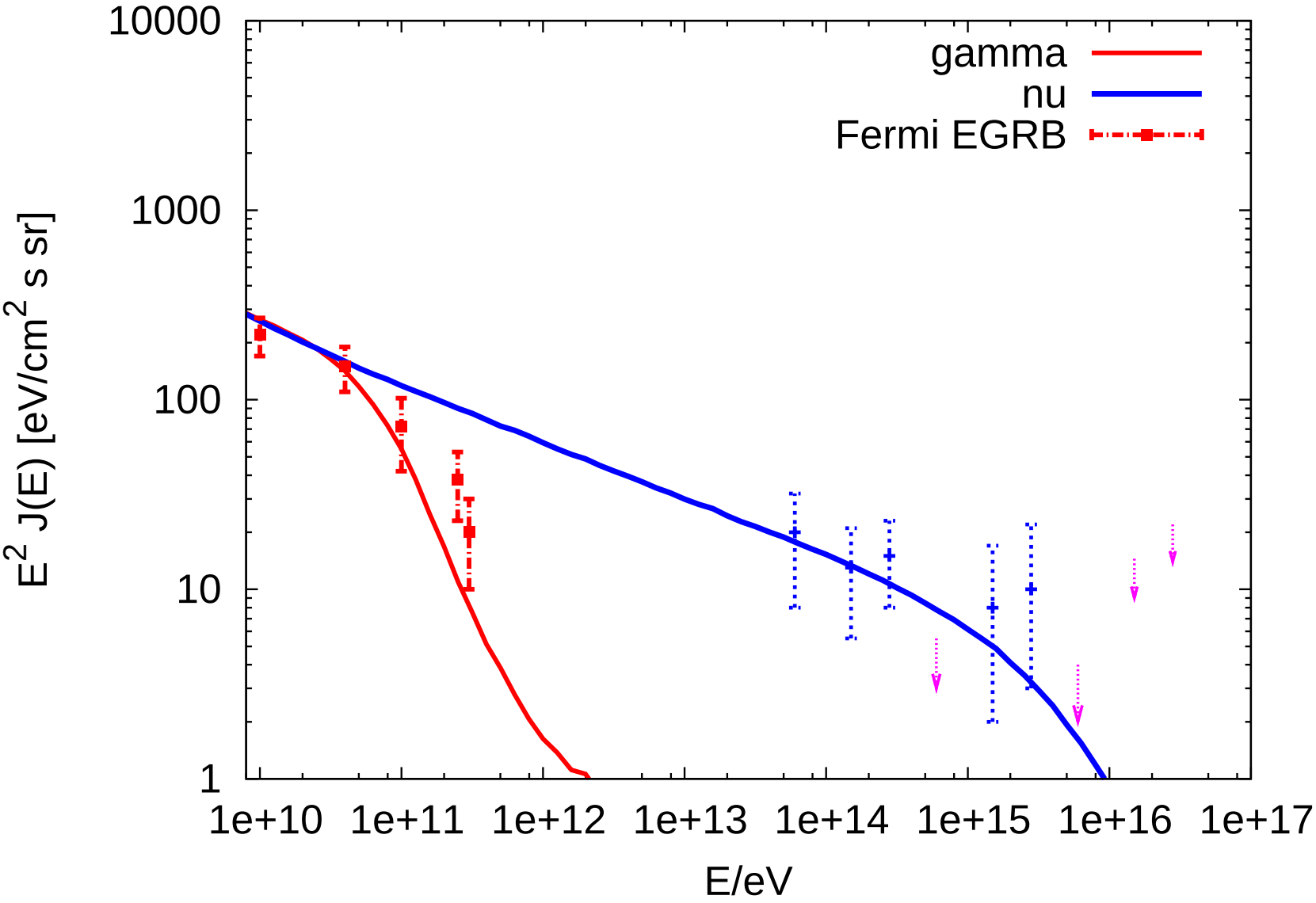


$\Rightarrow$ photons shifted below $m_e^2/\varepsilon_{\rm bb} \simeq 250\,\text{GeV}$

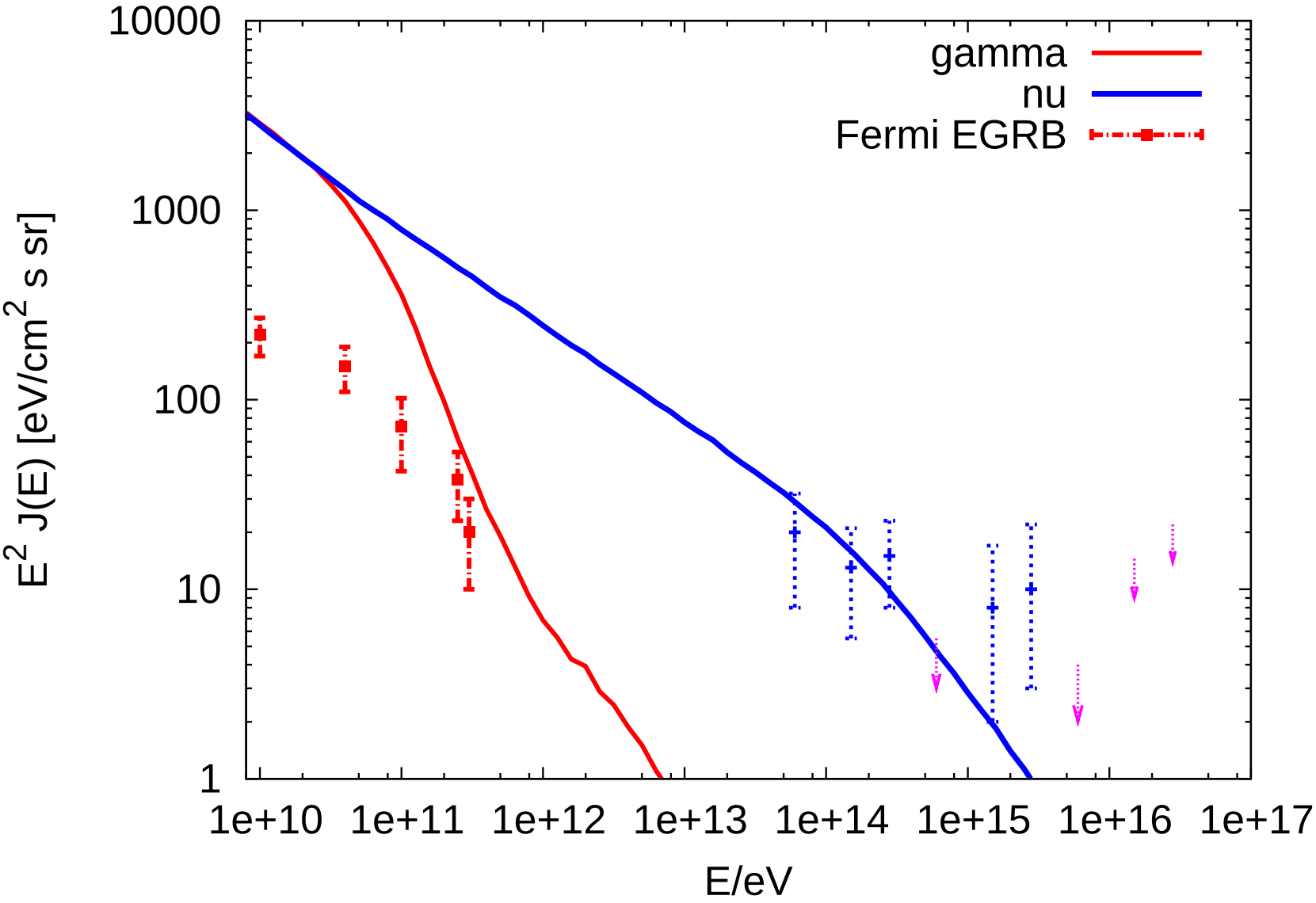
Cascade limit: $\alpha = 2.1$



Cascade limit: $\alpha = 2.3$



Cascade limit: $\alpha = 2.5$



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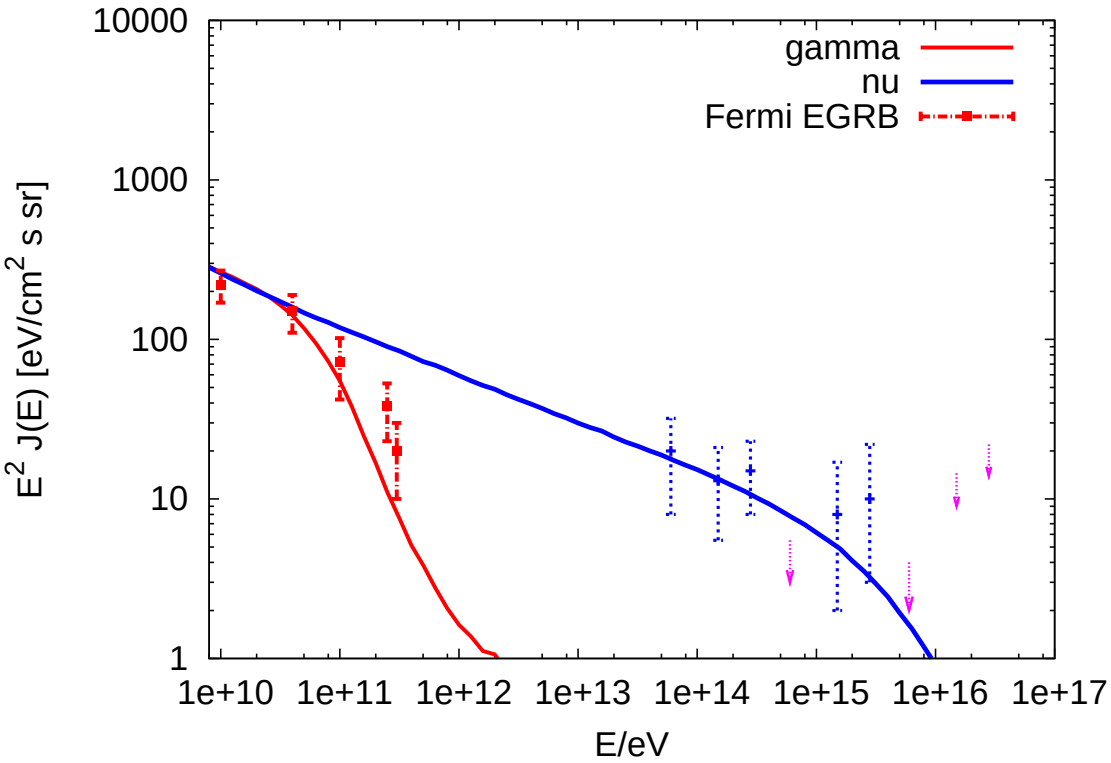
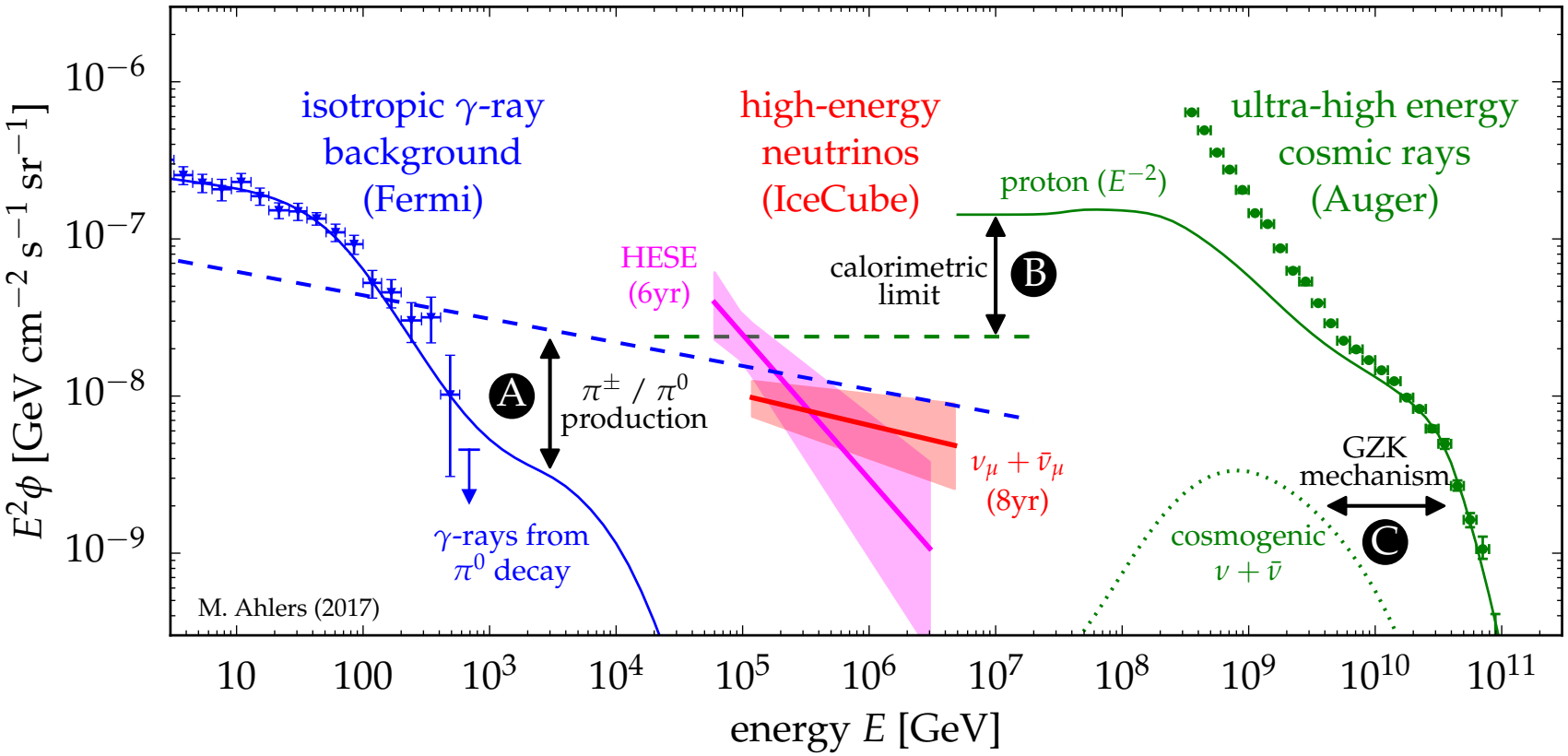


Slope $\alpha \gtrsim 2.2$

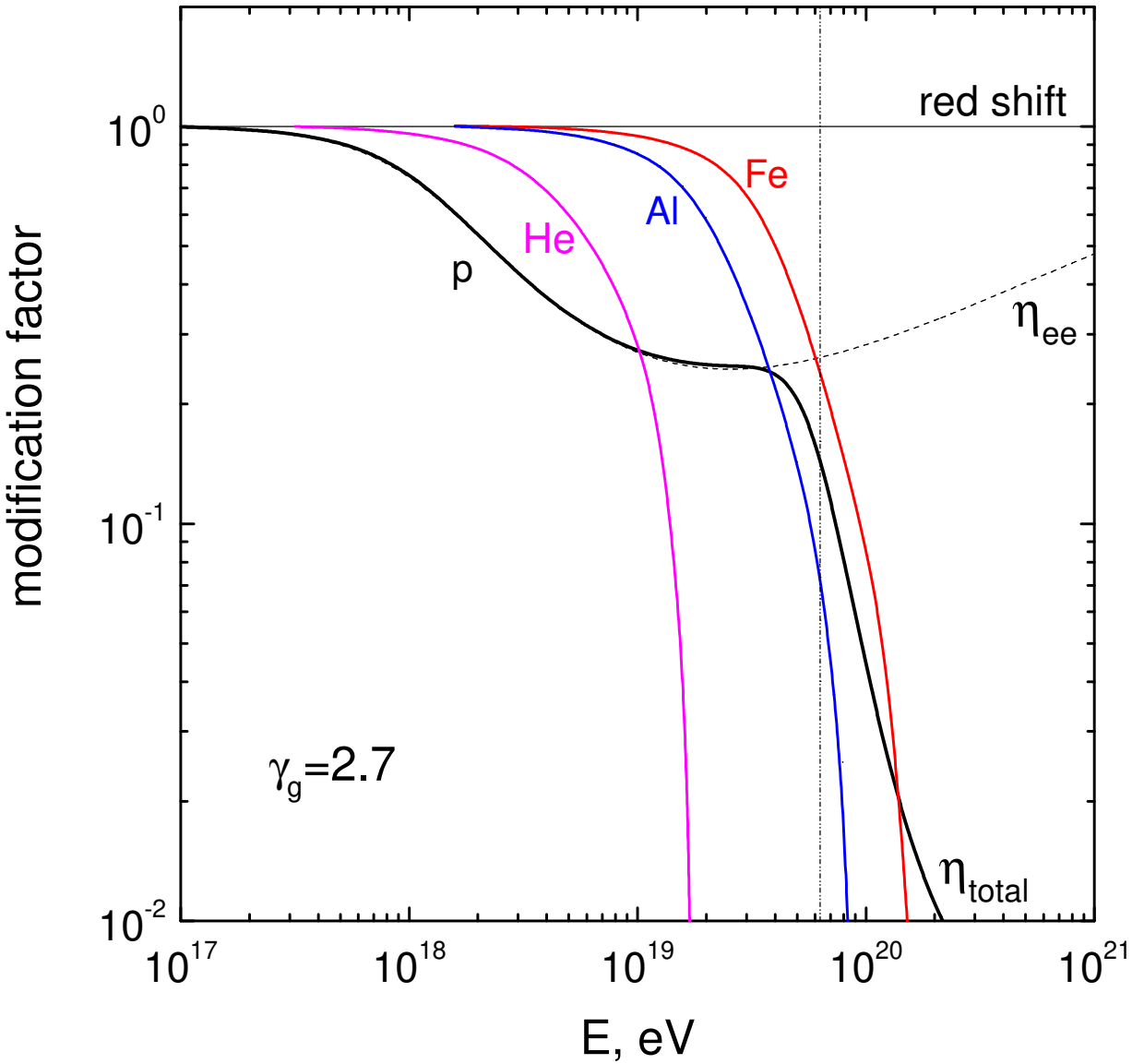
- requires "hidden sources" or
- Galactic origin

Multi-messenger picture



The dip model

[Berezinsky, Gazizov, Grigorieva '03]



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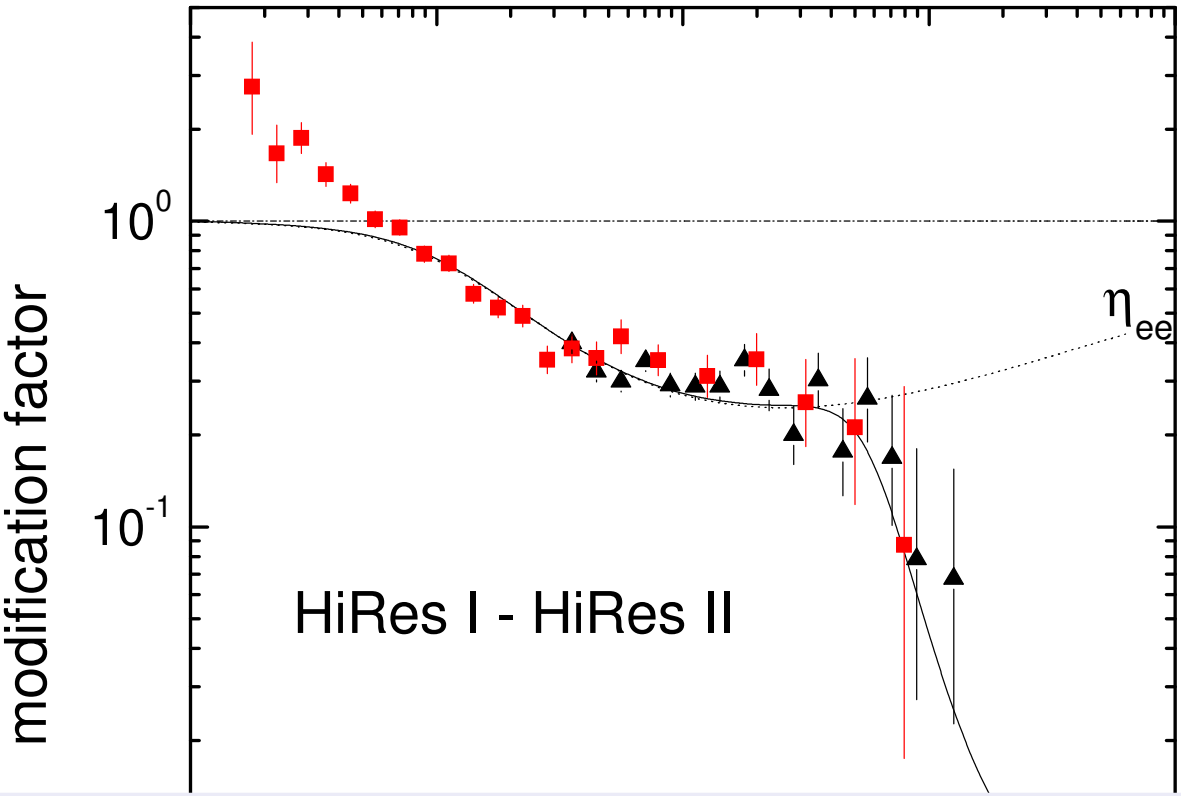

- good fit w. 1 parameter
- transition below $E \sim 10^{18}$ eV
- requires $\lesssim 15\%$ of He

E, eV

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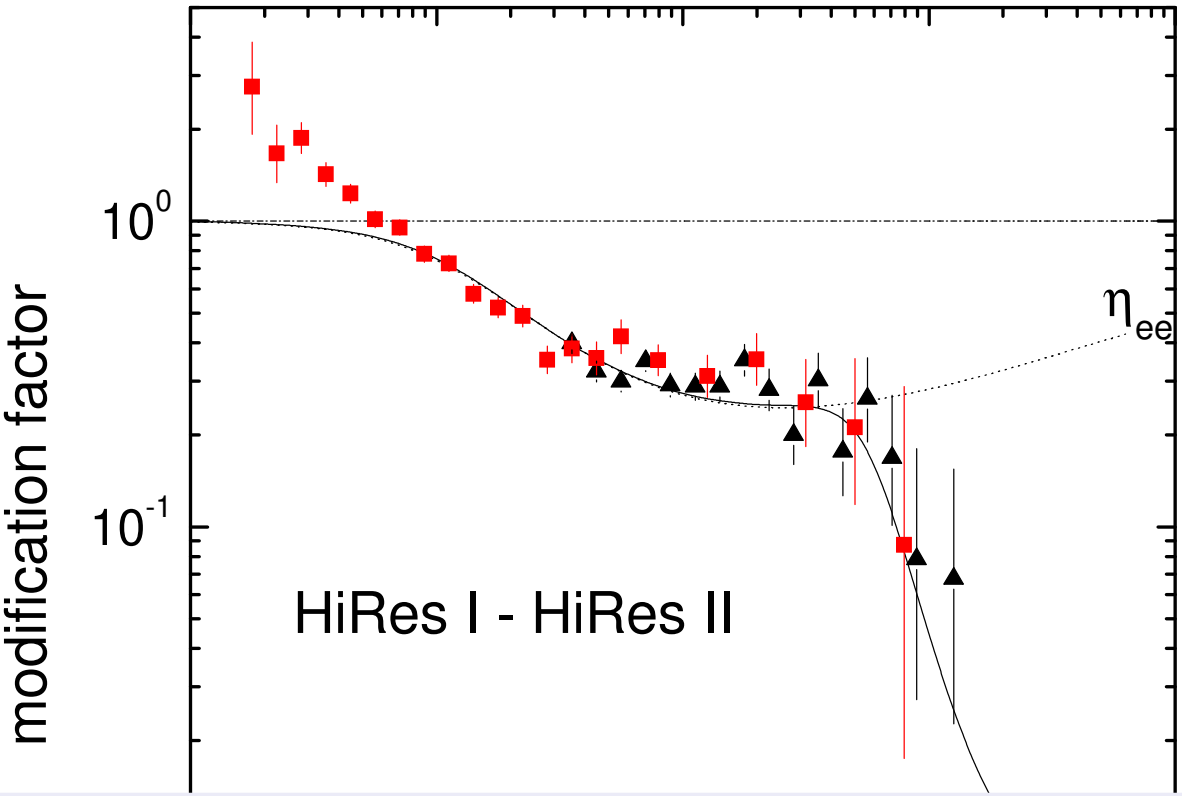

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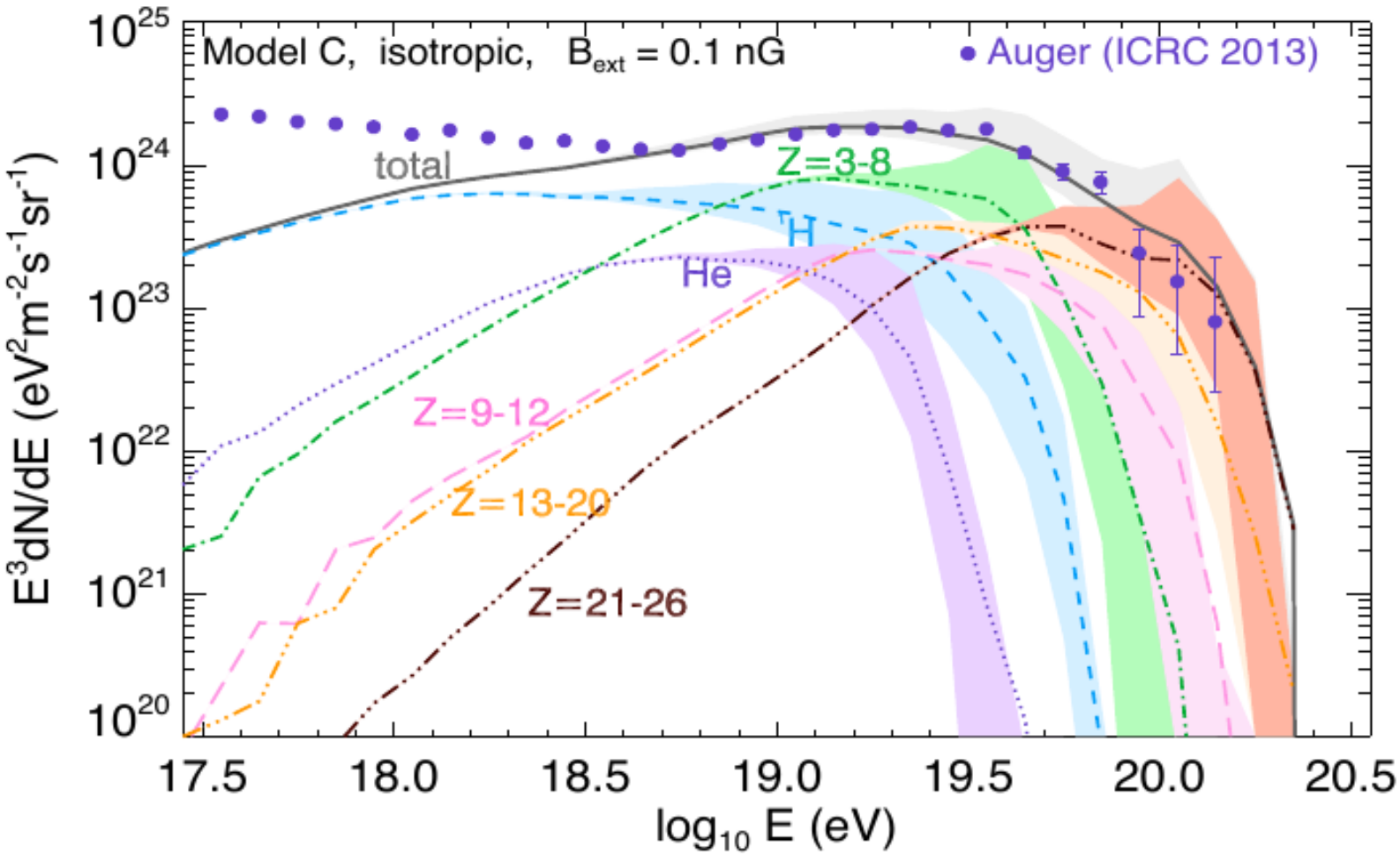
  $=$ feature of extragalactic spectrum
- neutrino flux from $p\gamma$ suppressed, at too high E

GRB inspired ankle model

[*Globus et al. '15, '17*]

- spectrum:



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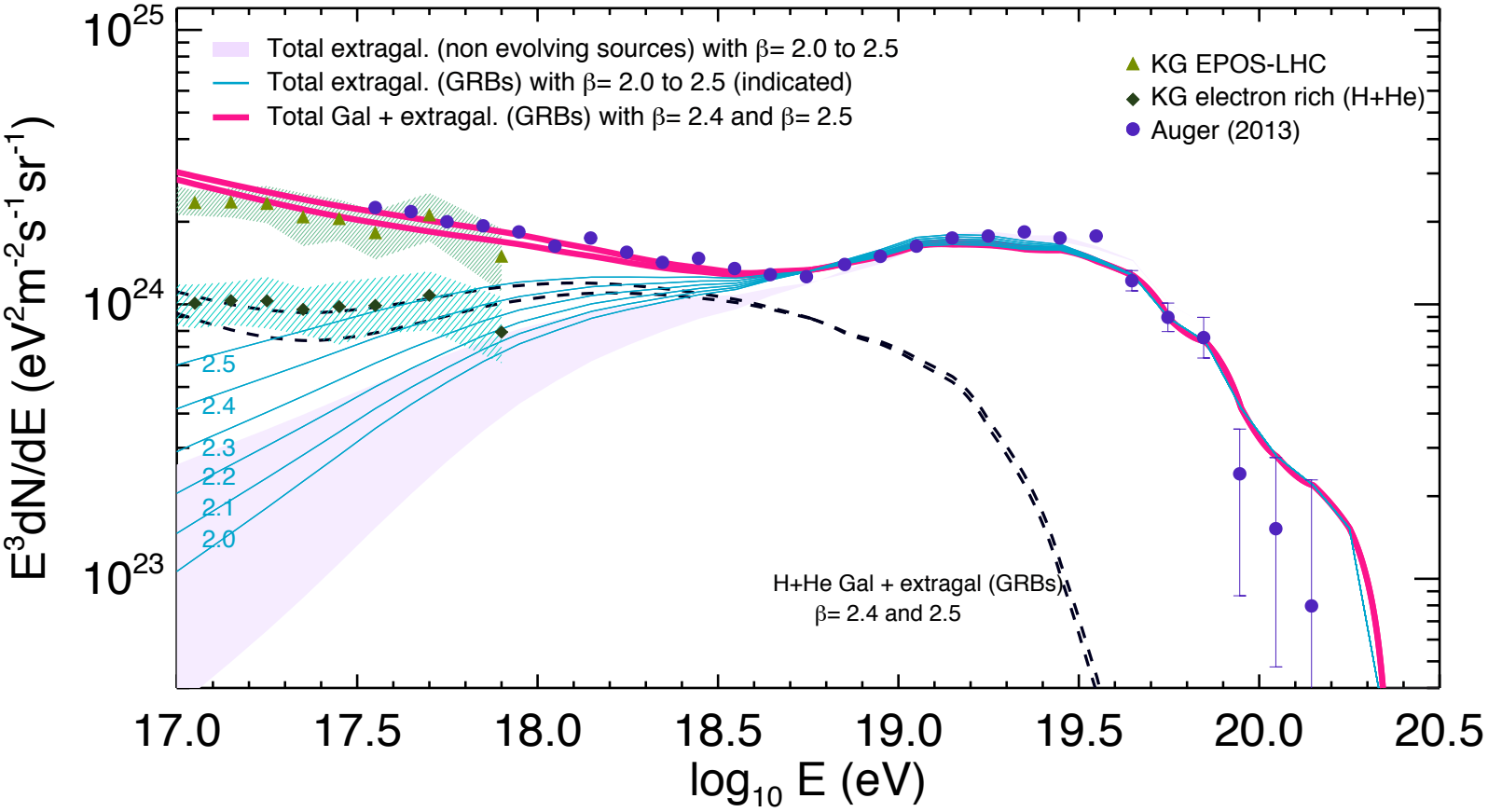
- light component:



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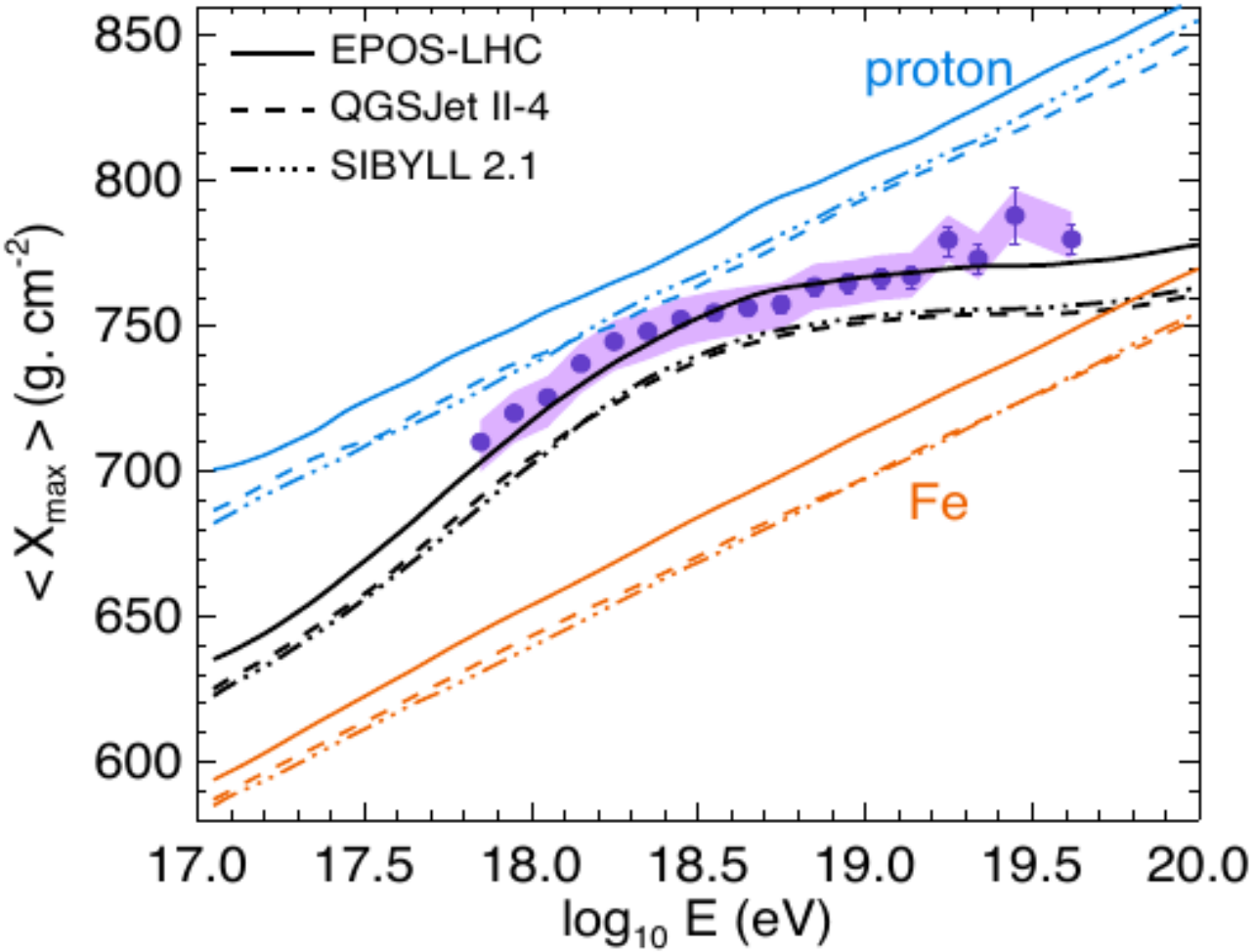

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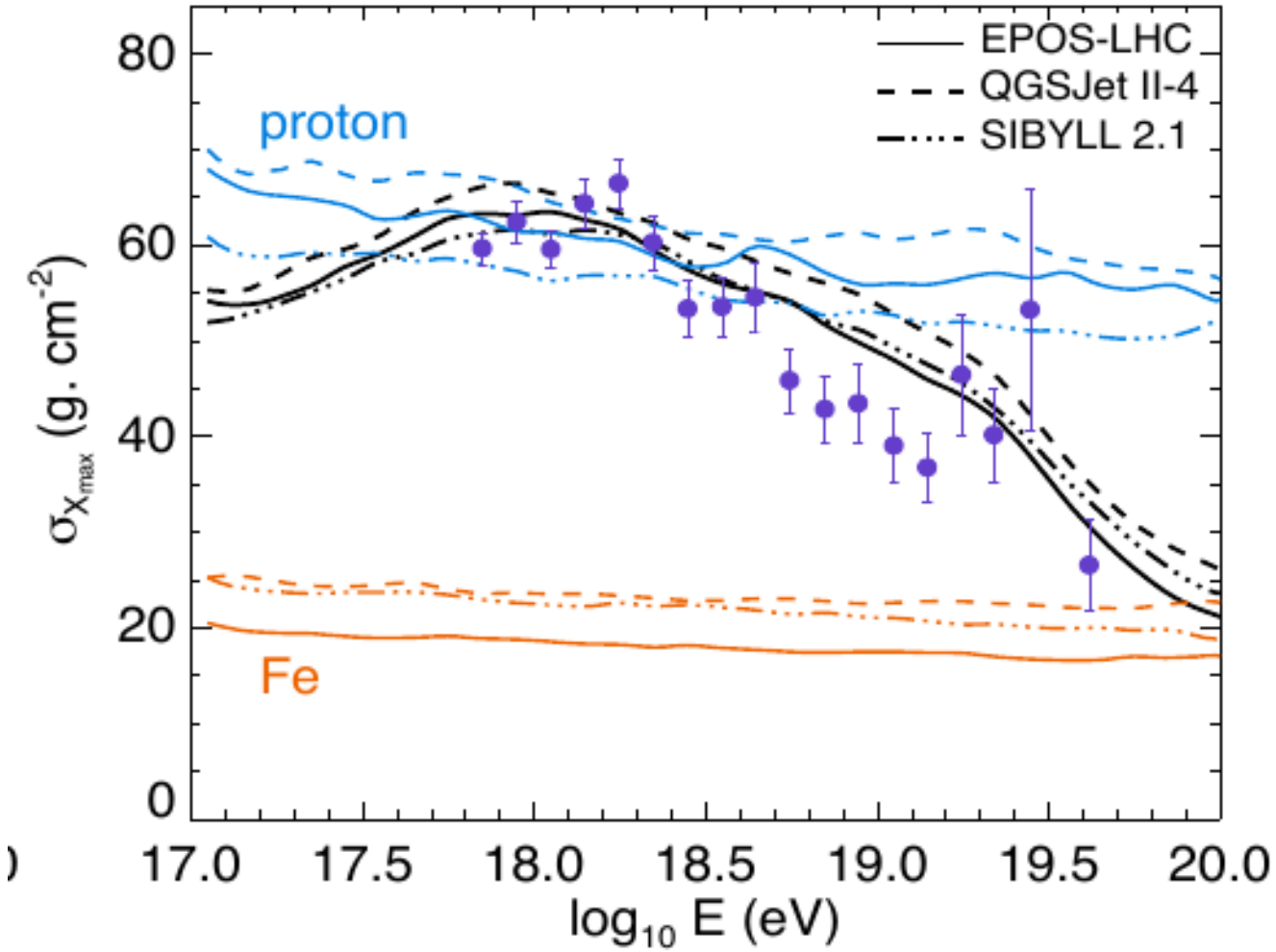

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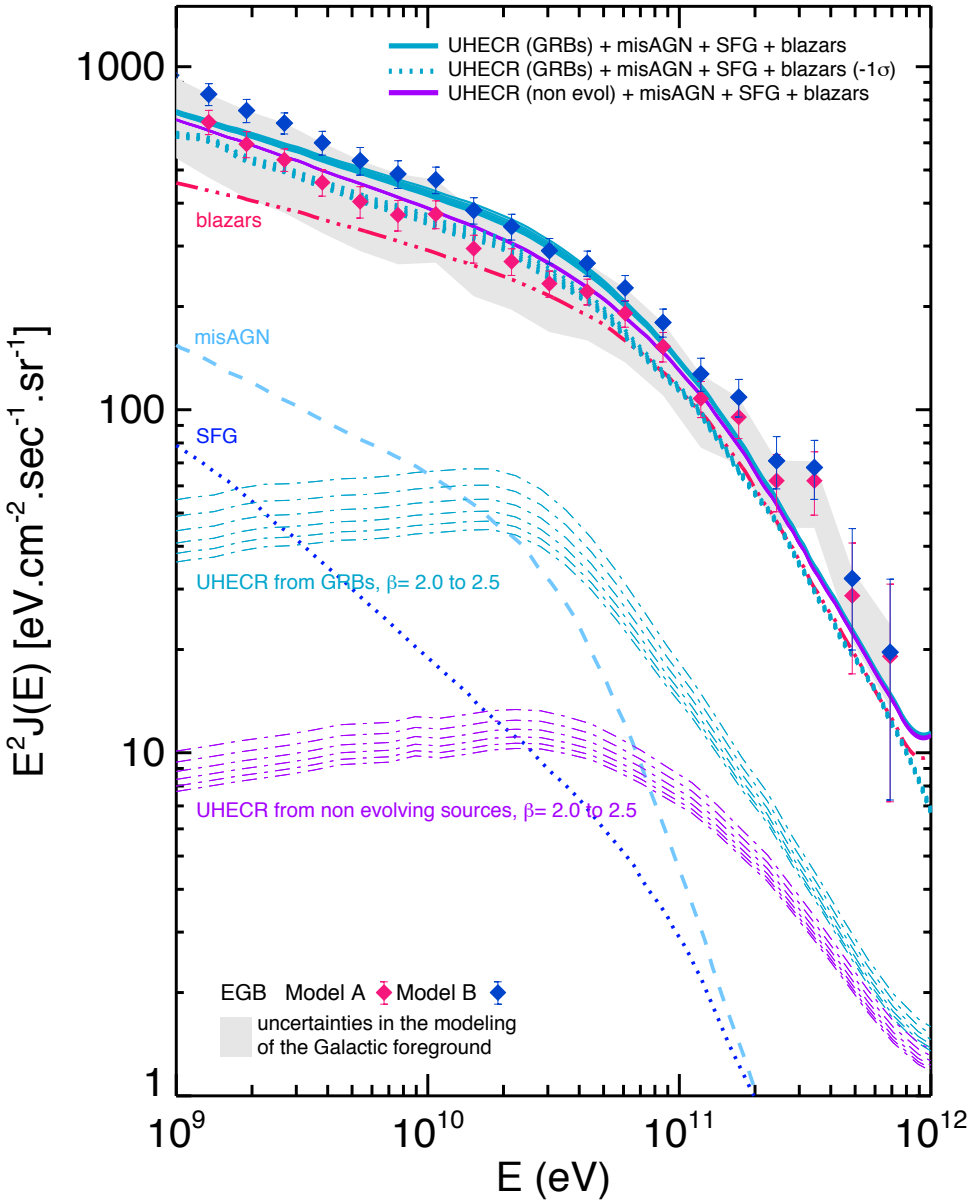

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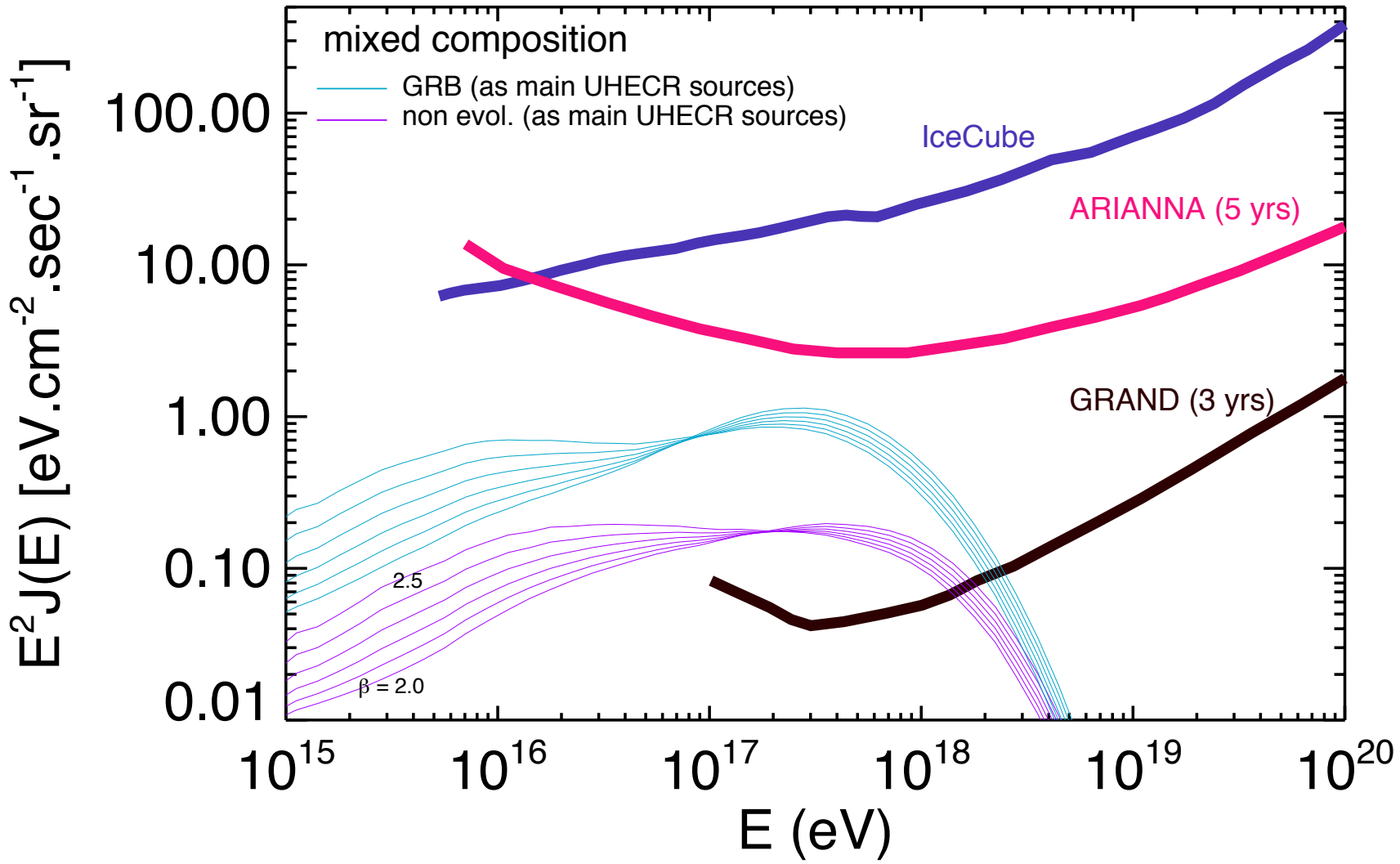

Phenomenological AGN model

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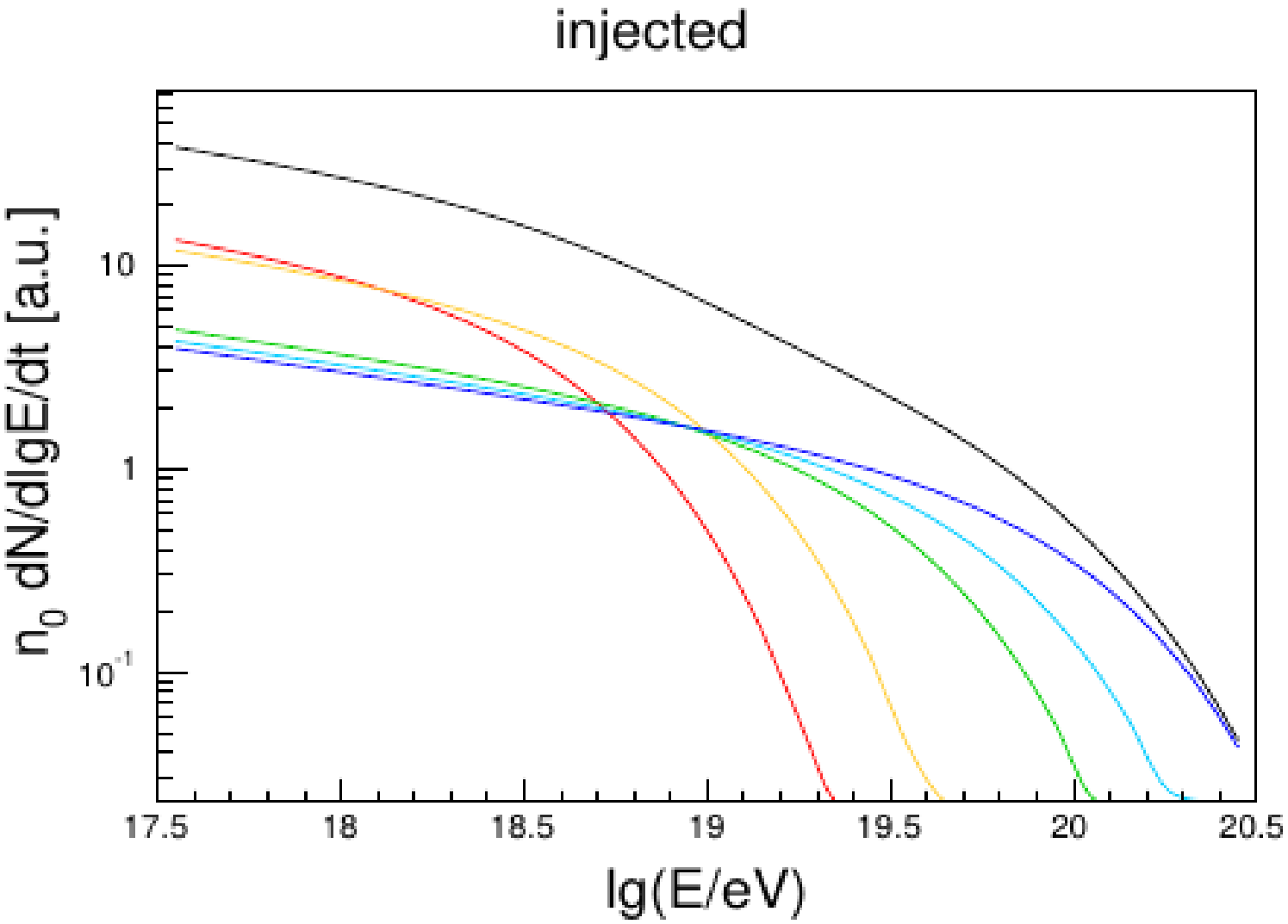

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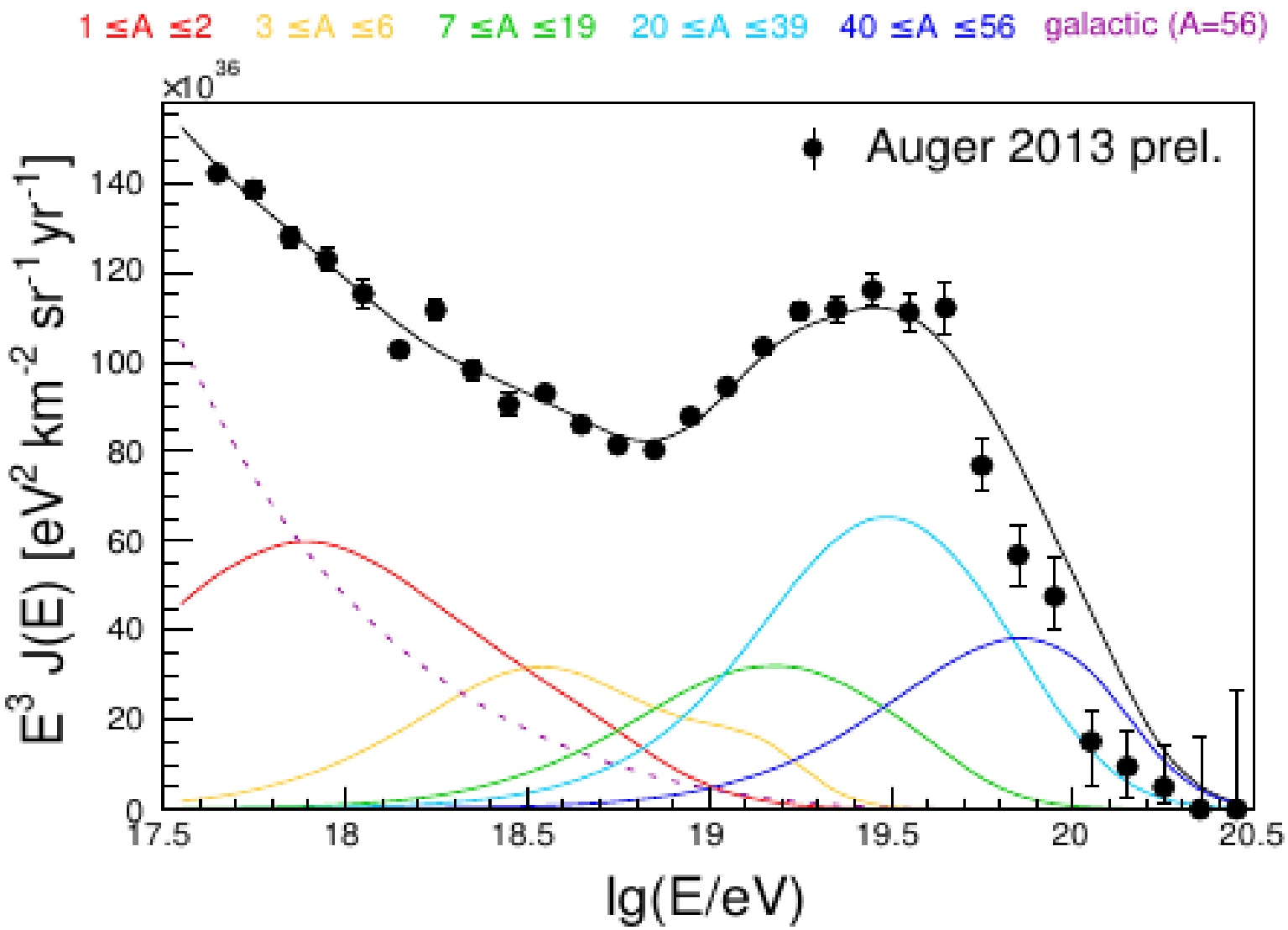

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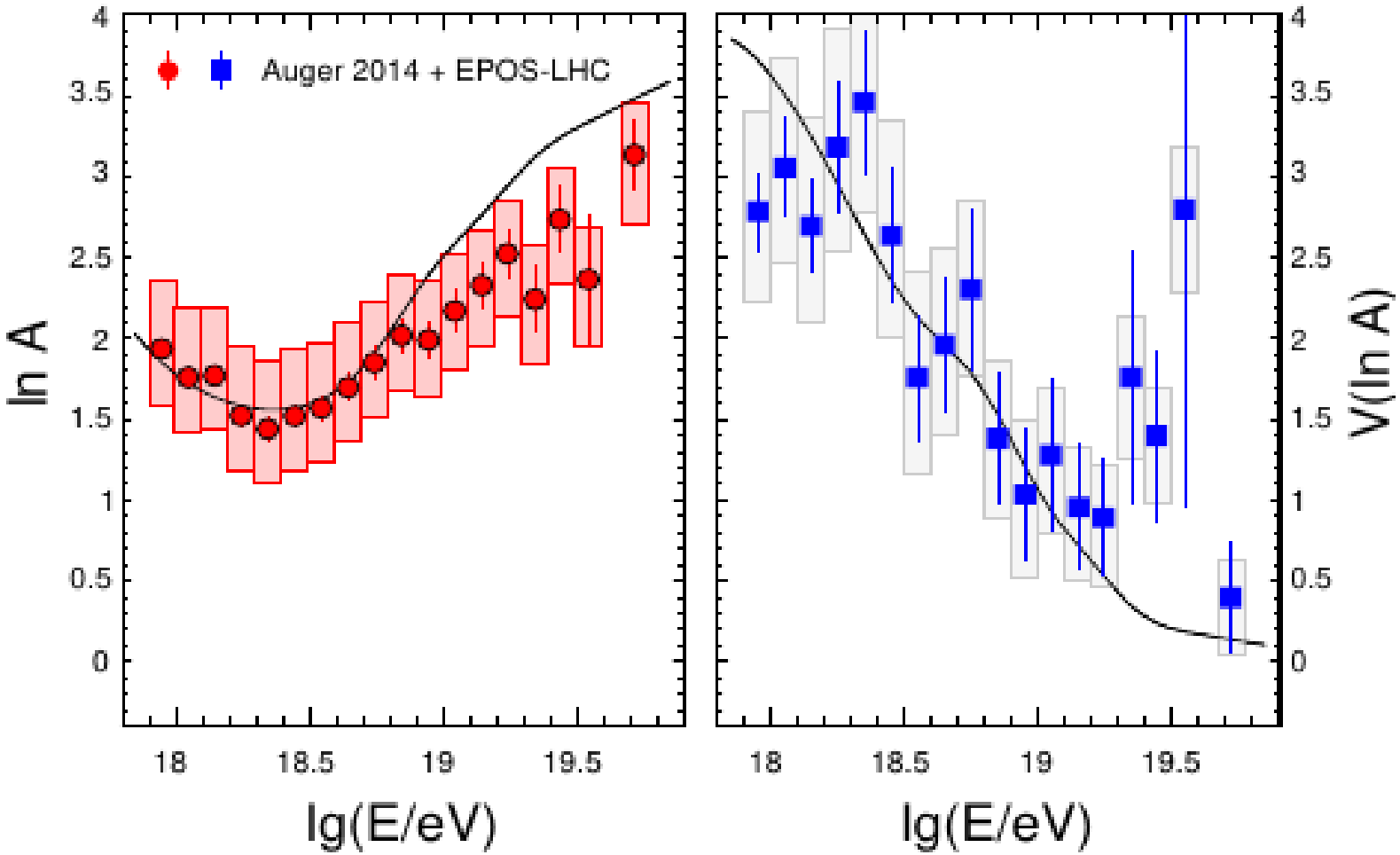

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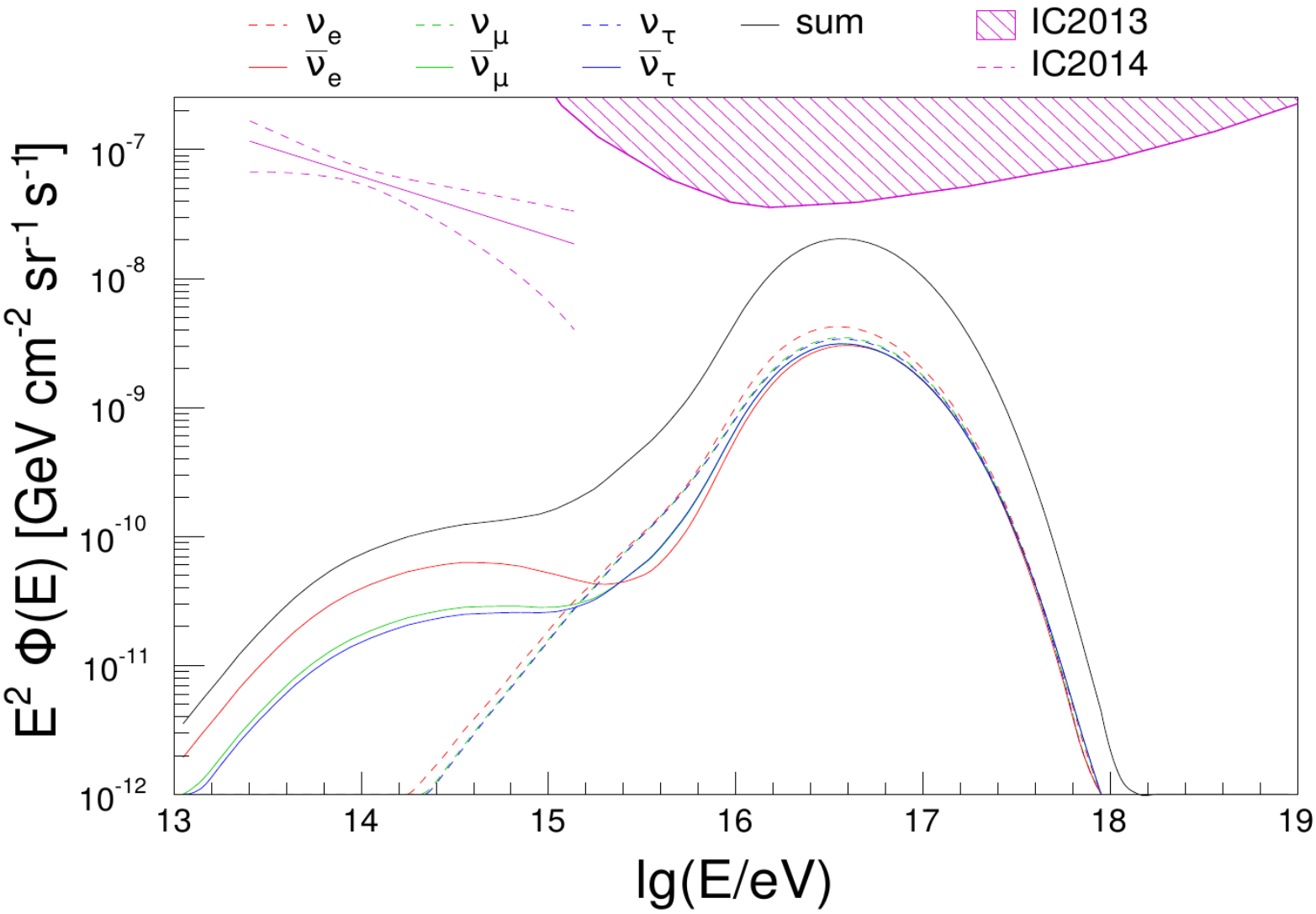

Minimal model: add neutrinos

[*MK, Kalashev, Ostapchenko, Semikoz '17*]

- 3 zones
  - core: rigidity dependent acceleration $dN/dR \propto R^{-\alpha} \exp(-R/R_{\rm max})$
  - inner zone: $A\gamma$ interactions
  - outer zone: Ap interactions
- diffusion: increase of effective $\tau_{\rm int}$
- source evolution
  - BL Lac $\simeq$ peaked at late times
  - AGN $\simeq$ peaked at early times

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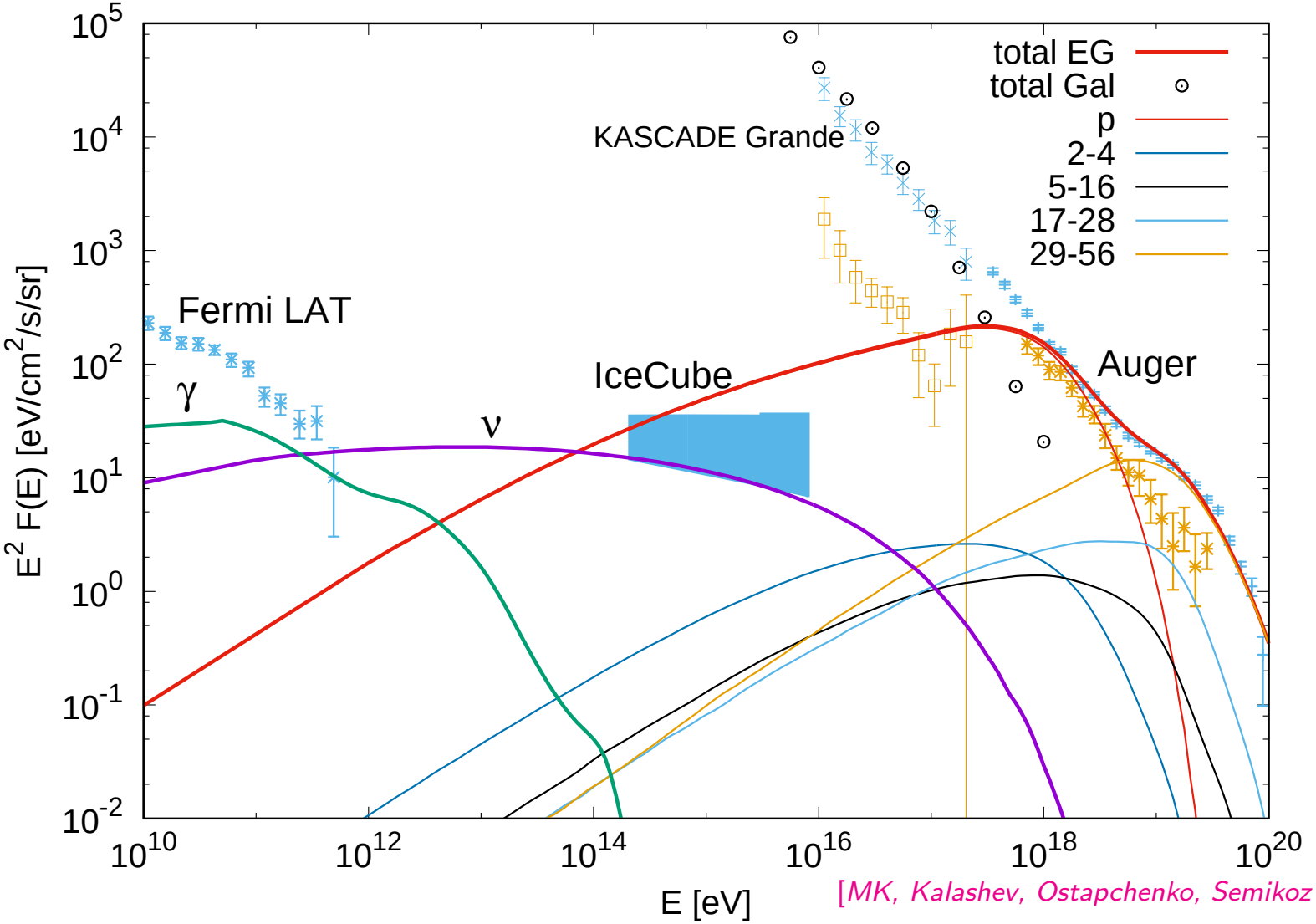

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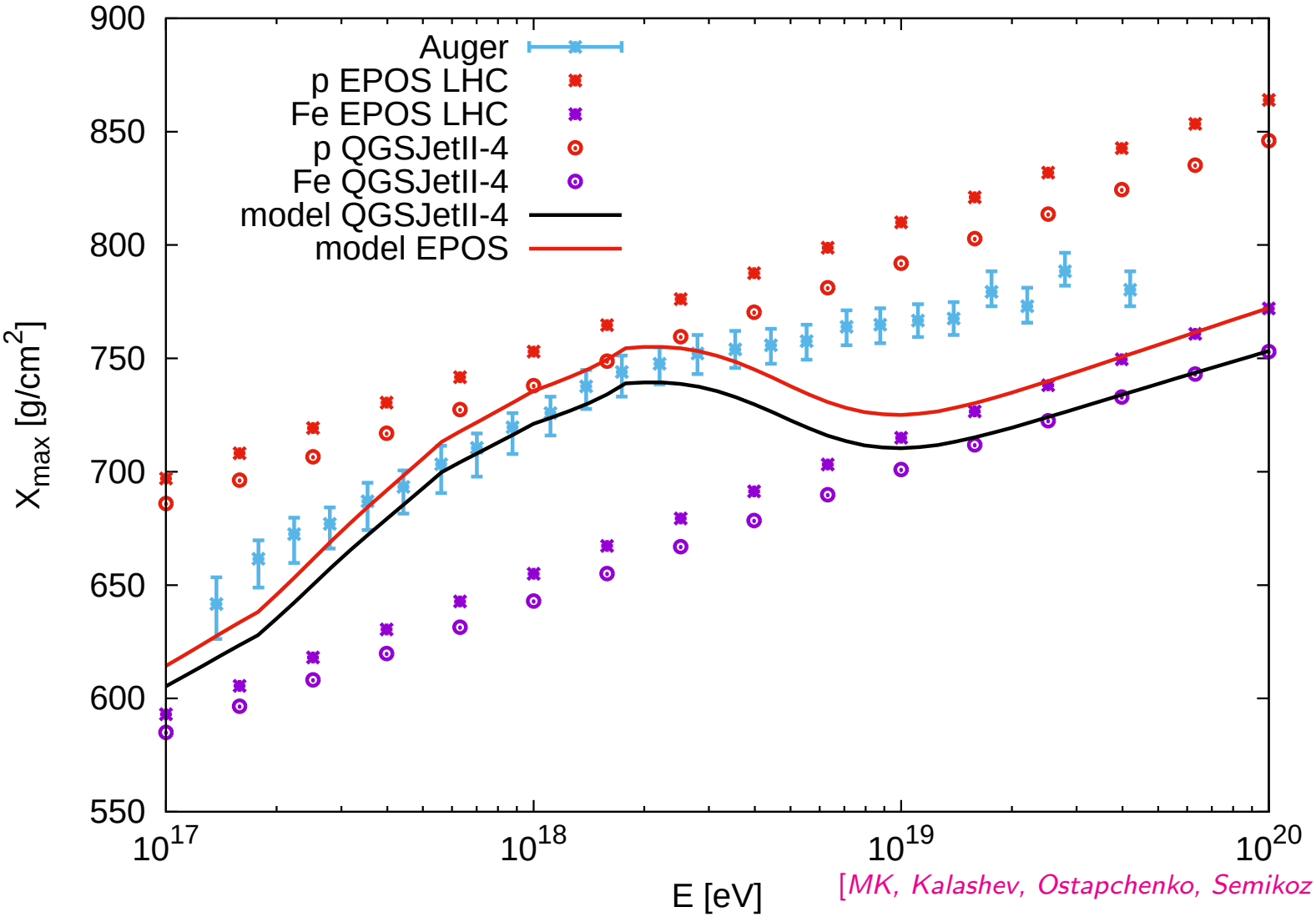

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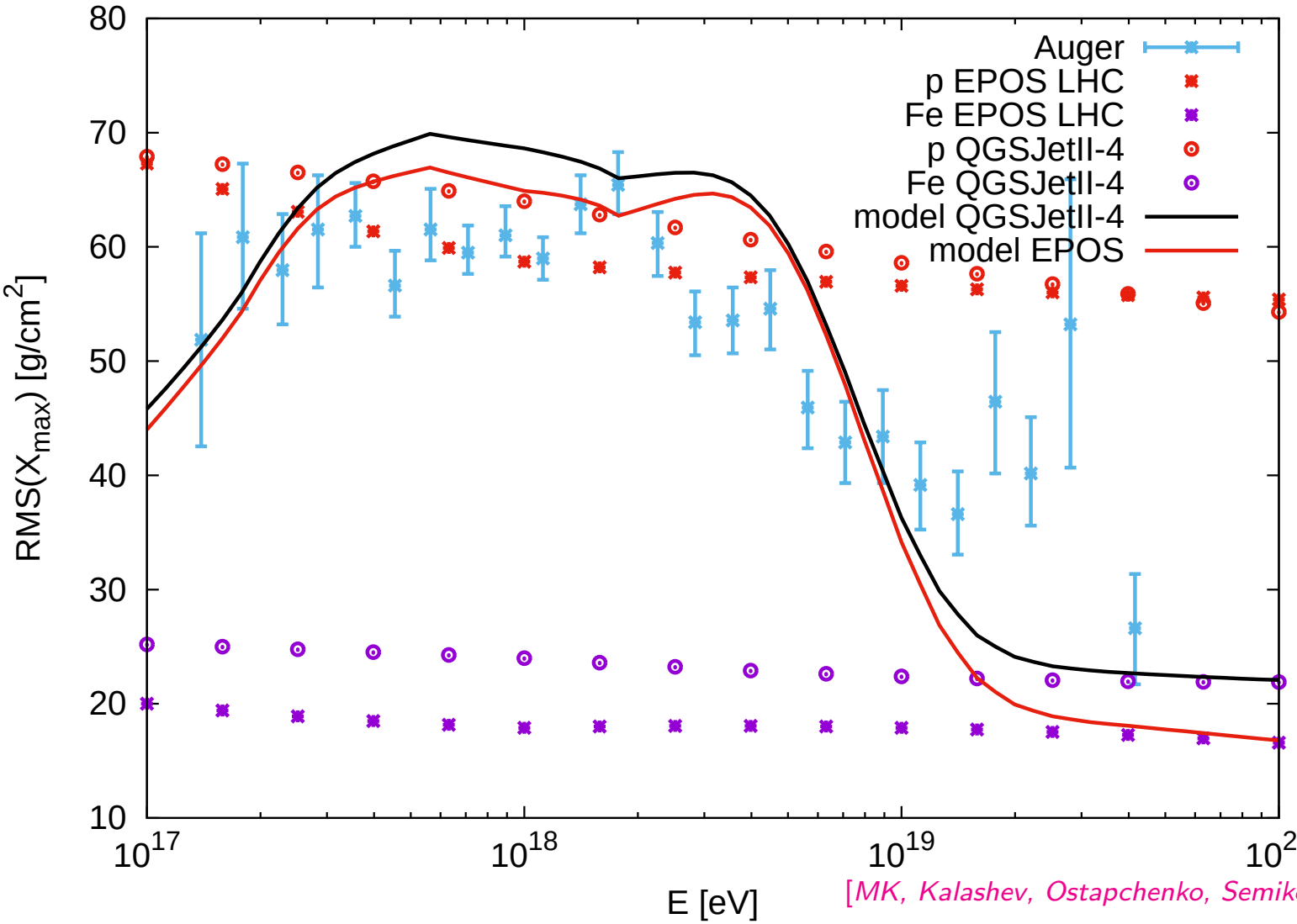
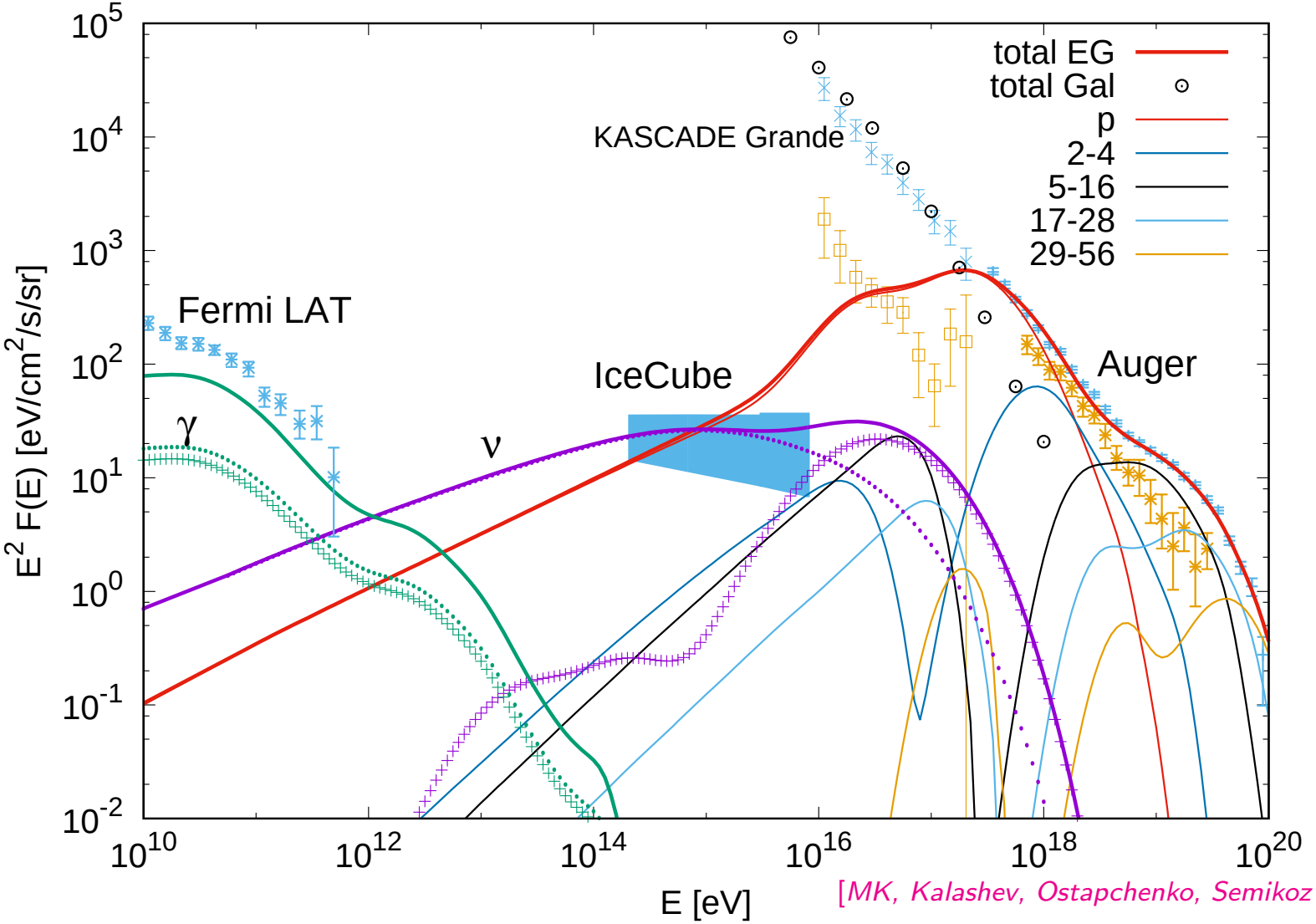


[*MK, Kalashev, Ostapchenko, Semikoz '17*]

AGN evol., gas and photons: $\alpha = 1.5$, $\tau_0^{pp} = 0.035$ and $\tau_0^{p\gamma} = 0.29$



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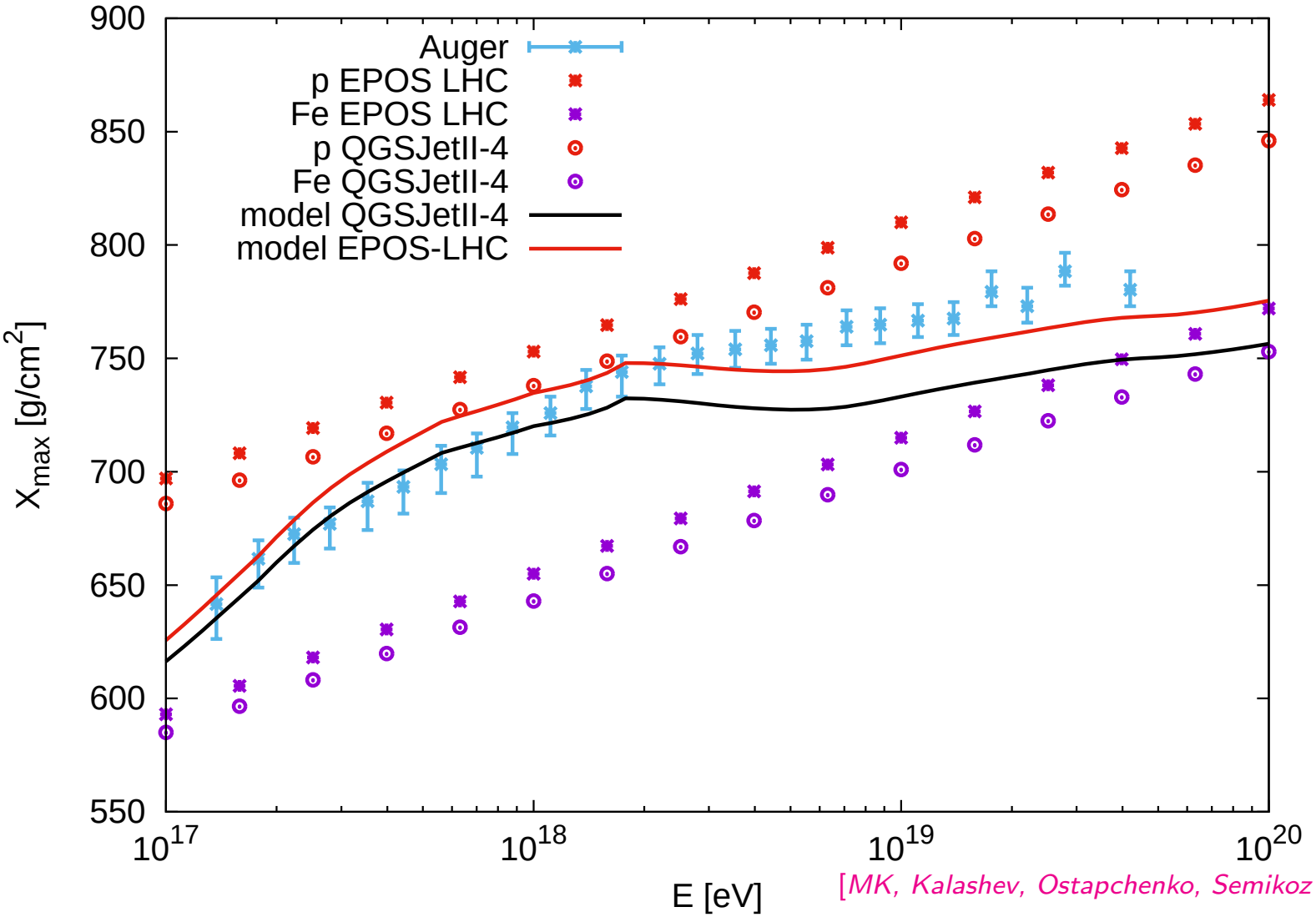

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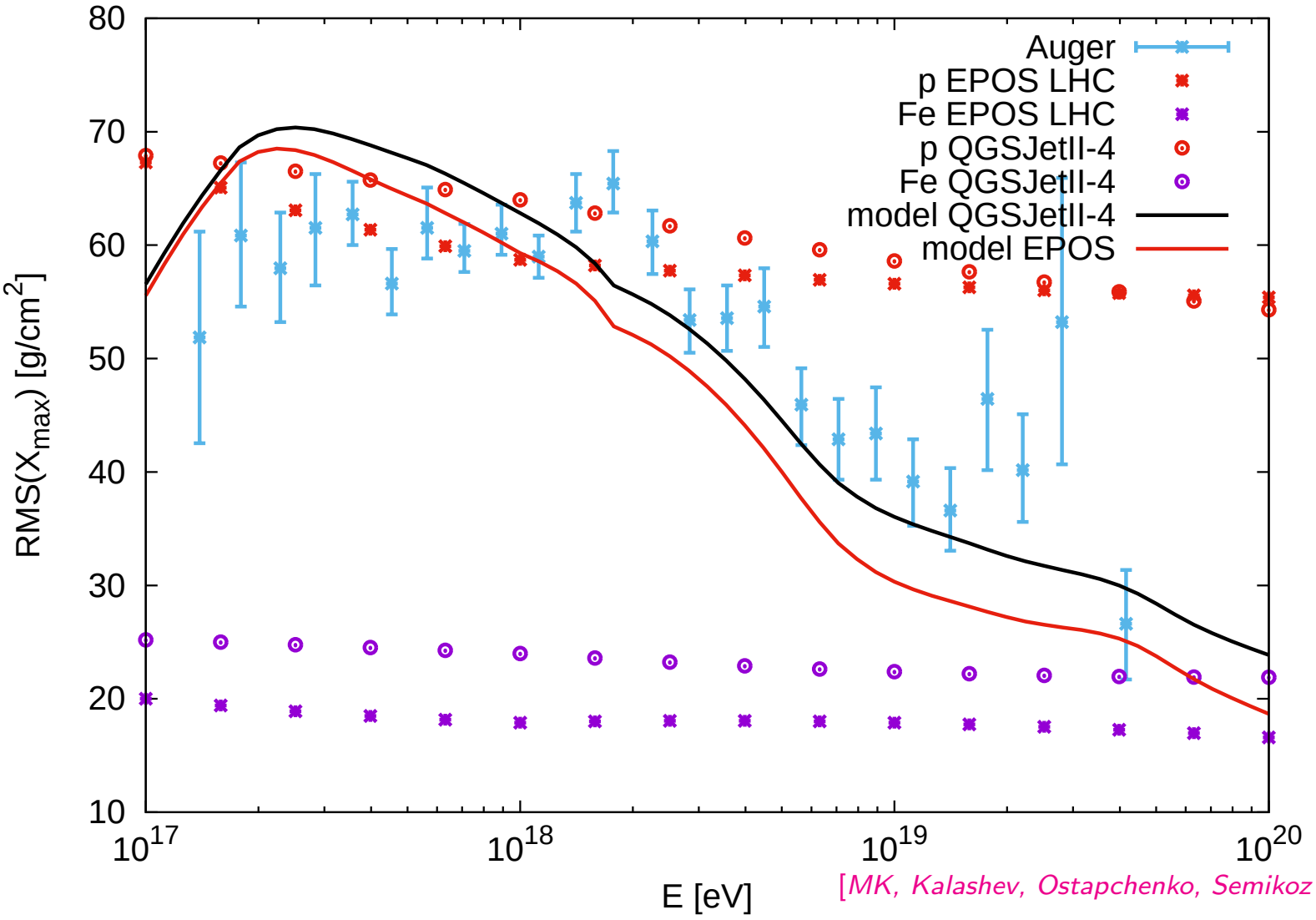

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Summary

1. common source class for UHECRs and neutrinos?
   - several candidates as GRBs are already disfavoured
   - (subclasses of) AGNs remain attractive option
   - large neutrino flux at "low" energies requires Ap interactions
   - UHECR composition requiress nuclei with $A\gamma$
   - sources with both Ap and $A\gamma$ interactions favoured
2. EGRB constrains stronly neutrino sources:
   - slope of extragal. neutrino $\alpha \lesssim 2.3$
   - neutrino sources are not main source class of EGRB
3. neutrino signal in IceCube:
   - additional Galactic contribution dominating at low energies (?)