Minimal Model for Cosmic Rays and Neutrinos

Michael Kachelrieß

NTNU, Trondheim

Outline of the talk

1. Introduction
   - CR–γ–ν connection
   - CR composition
   - elmag. cascades
   - constraints & wishes
2. Escape model for Galactic CRs
   - main properties
   - neutrinos from starburst galaxies
3. Minimal model for UHECRs and neutrinos
   - with only Ap interactions
   - with $A\gamma$ and Ap interactions
4. Conclusions

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The CR–γ–ν connection:

HE neutrinos and photons are unavoidable byproducts of HECRs

- astrophysical models, cosmogenic flux:
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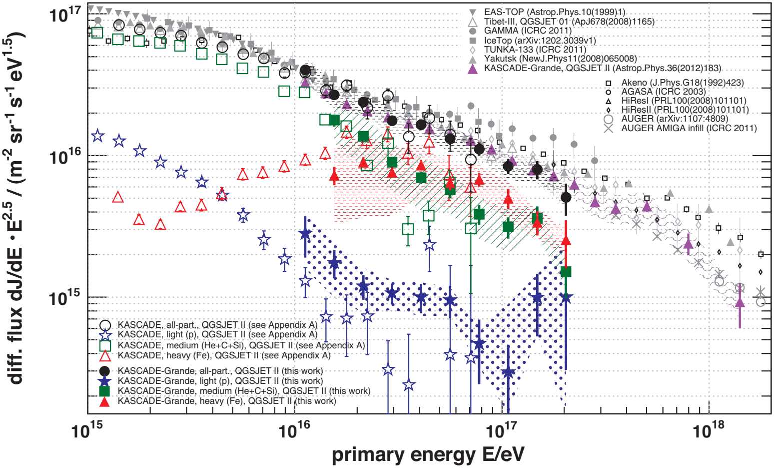
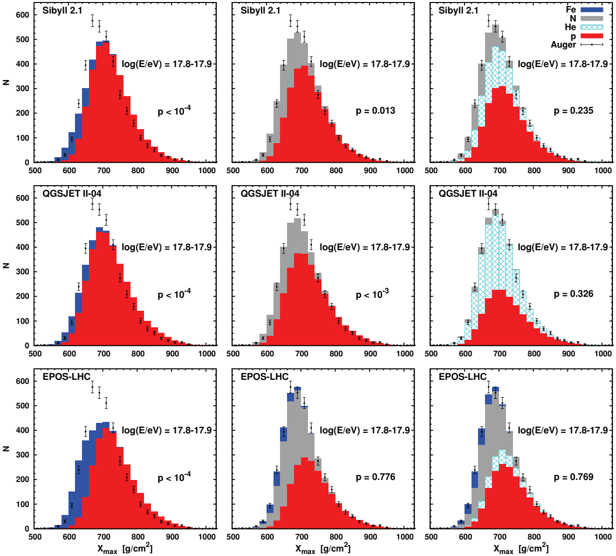
- Our aim:
  - is a single source class responsible for extragalactic CRs, photons and neutrinos?

Composition of CRs: KASCADE-Grande 2013



Composition of CRs: Auger

[arXiv:1409.5083]



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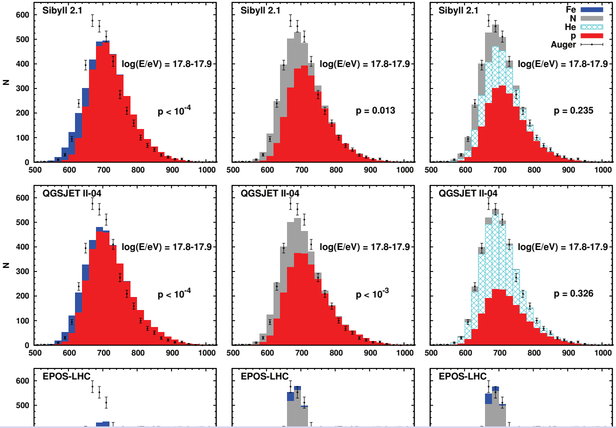

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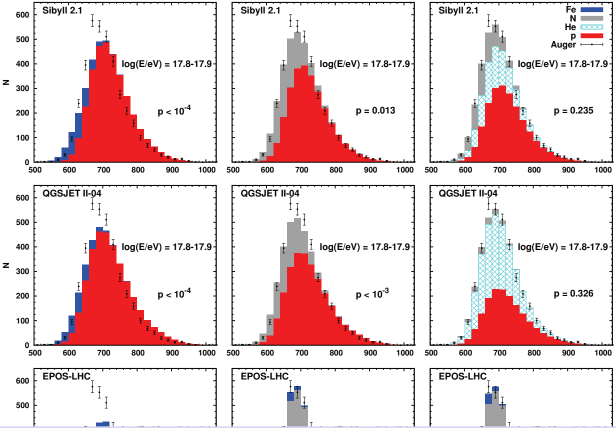

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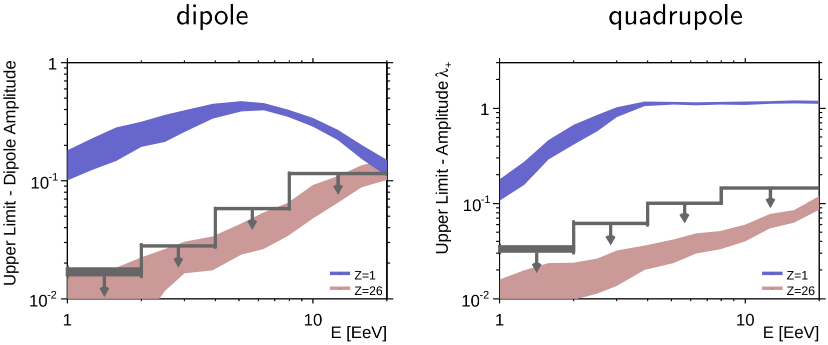
- 50% p, 50% He+N, $< 20\%$Fe
- early transition from Galactic to extragalactic CRs

Transition to extragalactic CRs – anisotropy limits



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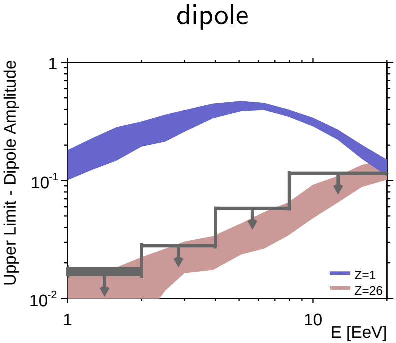

dominant light Galactic composition around $E = 10^{18}$ eV excluded

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

Effect of heavier nuclei

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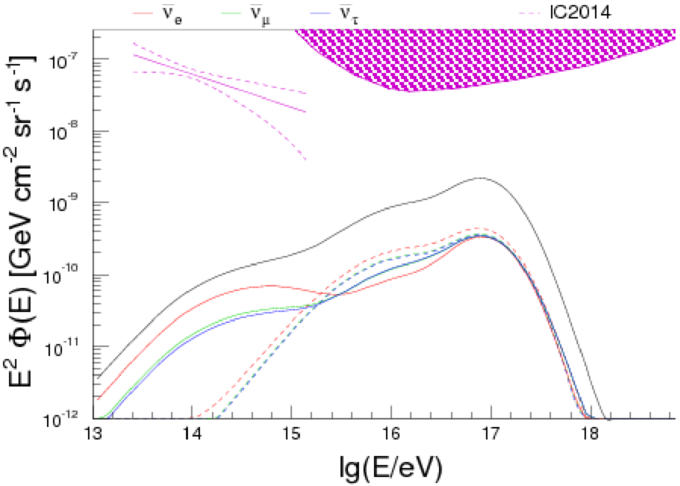
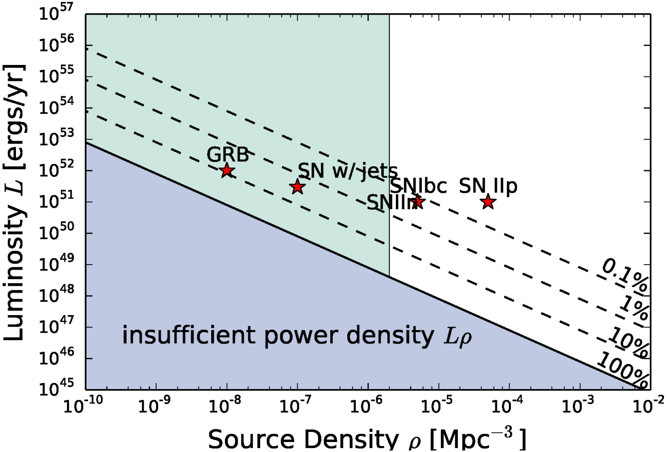
- ν flux is too small, at too high E

ν and mixed composition

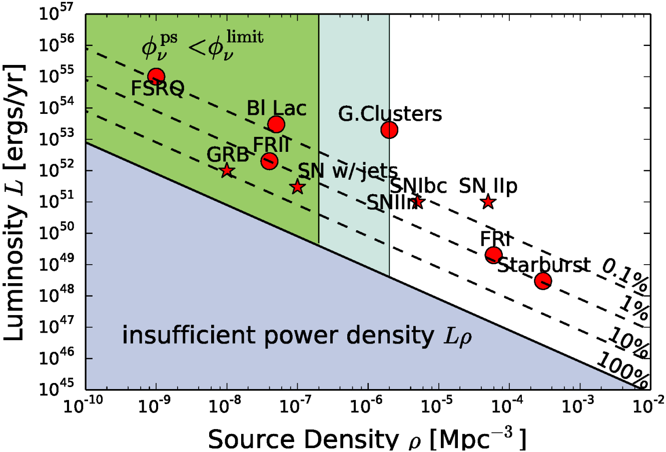
[e.g. Unger, Farrar, Anchordoqui '15]



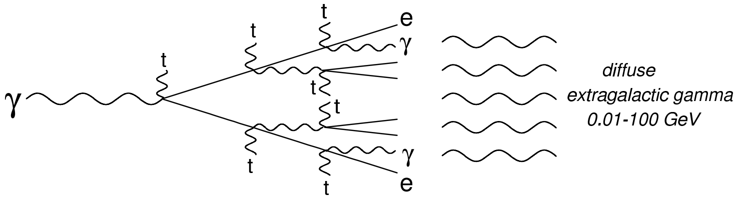
IceCube searches for sources: transient sources



IceCube searches for sources: stationary sources



Development of the elmag. cascade:



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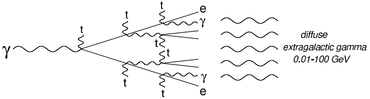


- analytical estimate: [Strong '74, Berezinsky, Smirnov '75]

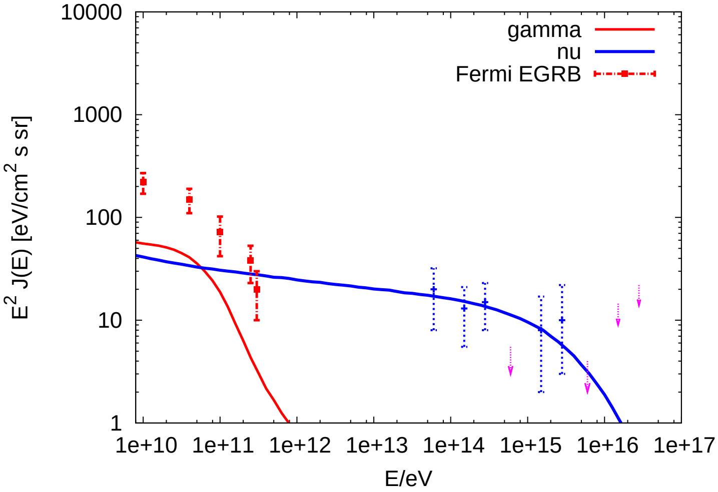
$$J_\gamma(E) = \begin{cases} K(E/\varepsilon_X)^{-3/2} & \text{at} \quad E \leq \varepsilon_X \\ K(E/\varepsilon_X)^{-2} & \text{at} \quad \varepsilon_X \leq E \leq \varepsilon_a \\ 0 & \text{at} \quad E > \varepsilon_a \end{cases}$$

- three regimes:
  - Thomson cooling:

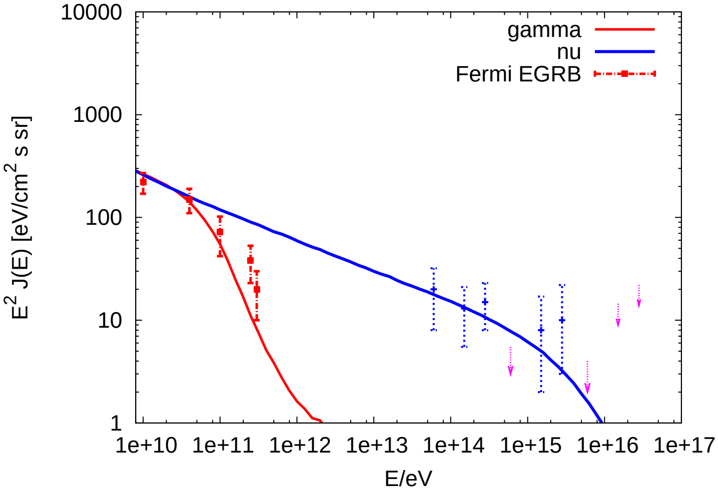
$$E_\gamma = \frac{4}{3}\frac{\varepsilon_{bb}E_e^2}{m_e^2} \approx 100\,\mathrm{MeV}\left(\frac{E_e}{1\mathrm{TeV}}\right)^2$$

  - plateau region: ICS $E_\gamma \sim E_e$
  - above pair-creation threshold $s_{\min} = 4E_\gamma\varepsilon_{bb} = 4m_e^2$: flux exponentially suppressed

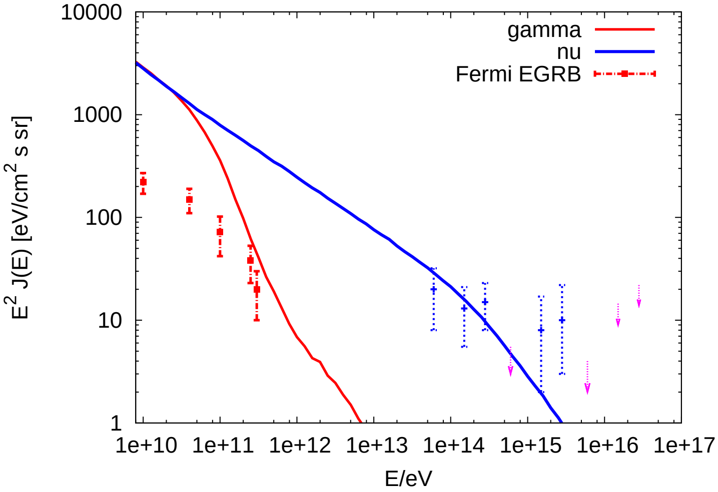
Cascade limit: $\alpha = 2.1$



Cascade limit: $\alpha = 2.3$



Cascade limit: $\alpha = 2.5$



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- leptonic blazar models favored to explain EGRB
- neutrino sources should give sub-dominant contribution to EGRB

Constraints on a minimal model:

a single source class that

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a single source class that

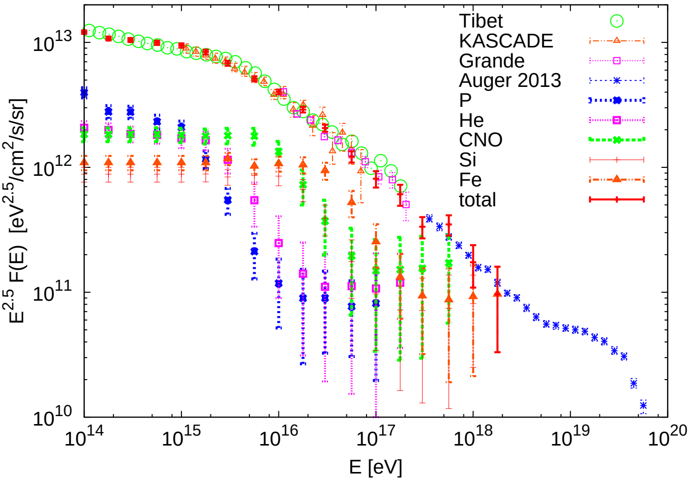
- fits the extragalactic UHECR flux and composition
- fits the (extragalactic) neutrino flux
- gives subdominant contribution to EGRB
- consistent with early Galactic to extragalactic transition

$\Rightarrow$ ankle has to be a feature of source spectrum

Escape model for Galactic cosmic rays

[Giacinti, MK, Semikoz '14+]

- reproduces fluxes of individual CR groups



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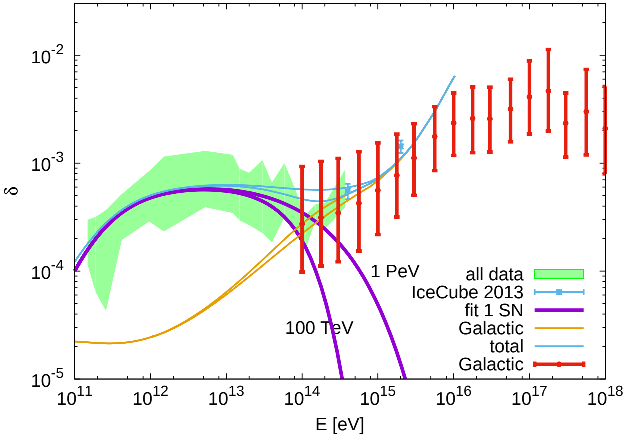

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- reproduces fluxes of individual CR groups
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- fixes extragalactic flux: $F^i_{\rm exgal}(E) = F^i_{\rm obs}(E) - F^i_{\rm gal}(E)$
- escape model applies also to other normal galaxies as starburst galaxies:
  - magnetic fields factor 100 higher:
  - if knee is caused by
    - ★ diffusion: $E_{\rm cr} \sim B$, neutrino knee at few $\times 10^{16}$ eV
    - ★ source: $E_{\rm max} \sim B_{\rm CR}$, neutrino knee at few $\times 10^{14}$ eV

Normal and starburst galaxies:

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

Normal and starburst galaxies:

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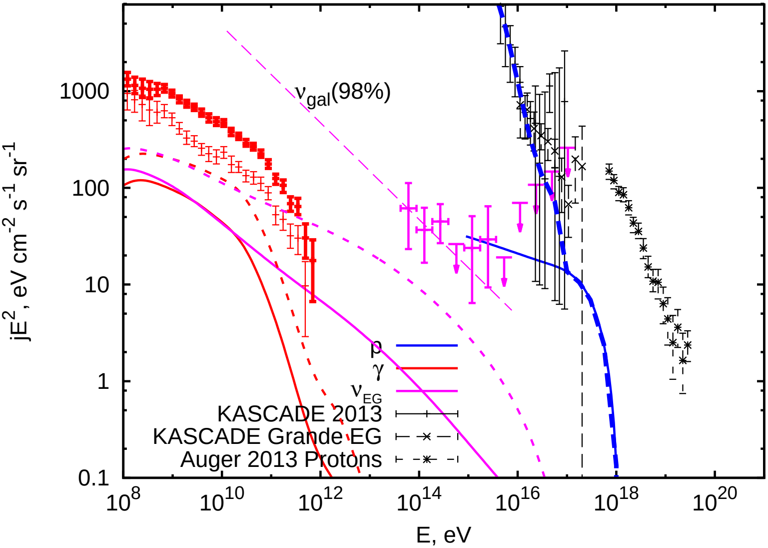

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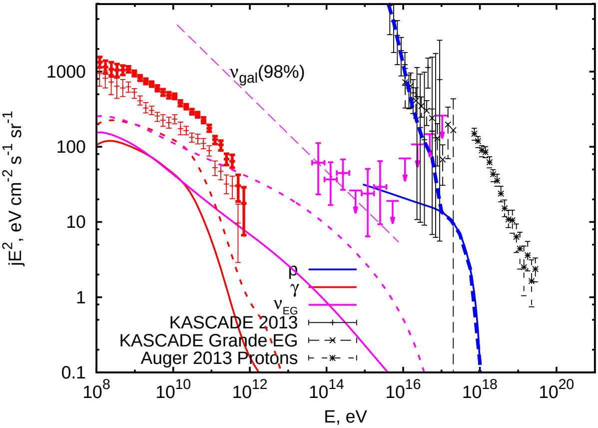

- can not explain exgal. protons
- sources can not be dominant sources of both EGRB and neutrinos

Source model:

- 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
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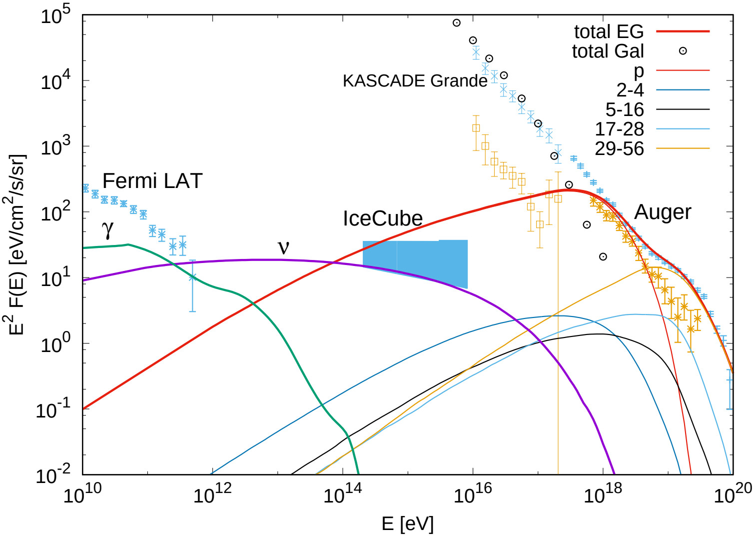
Late evol., only interactions on gas: $\alpha = 1.8$, $\tau_0^{pp} = 0.035$ at $E_0 = 10^{19}$ eV



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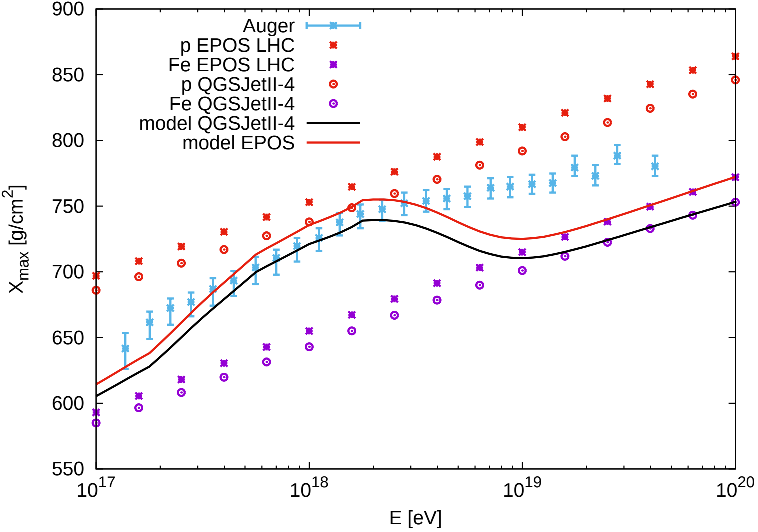

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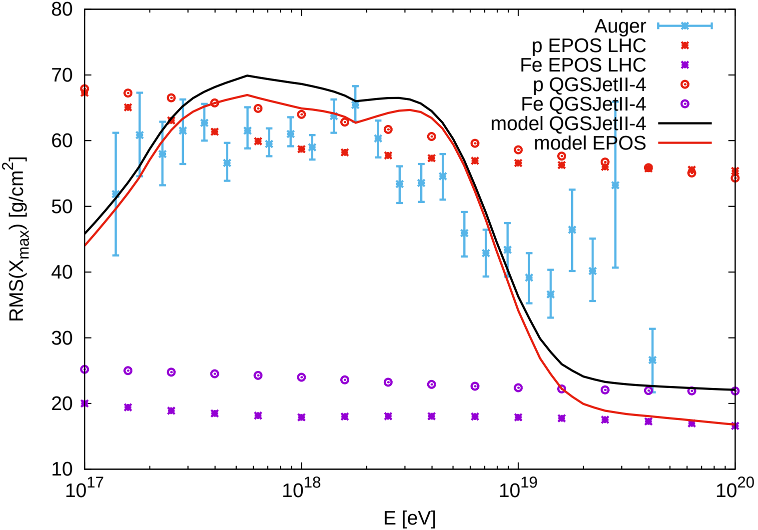

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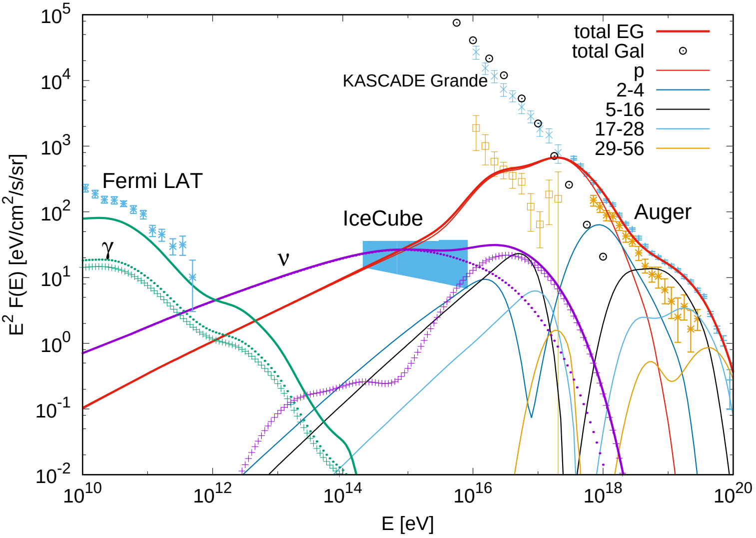

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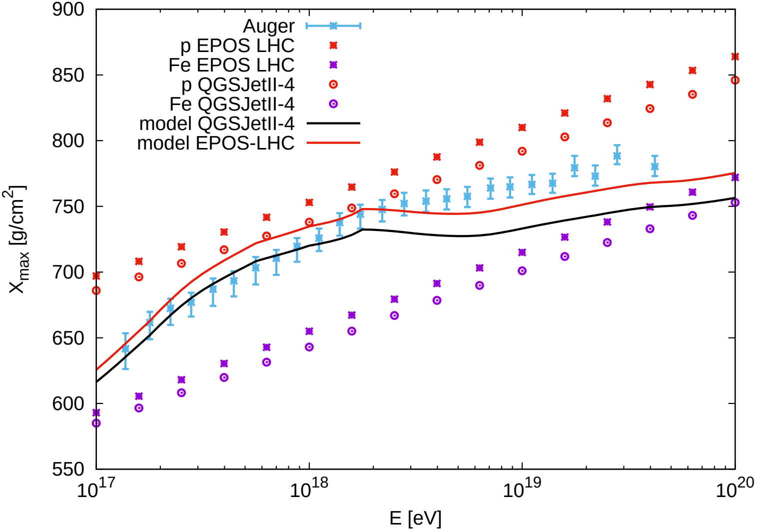

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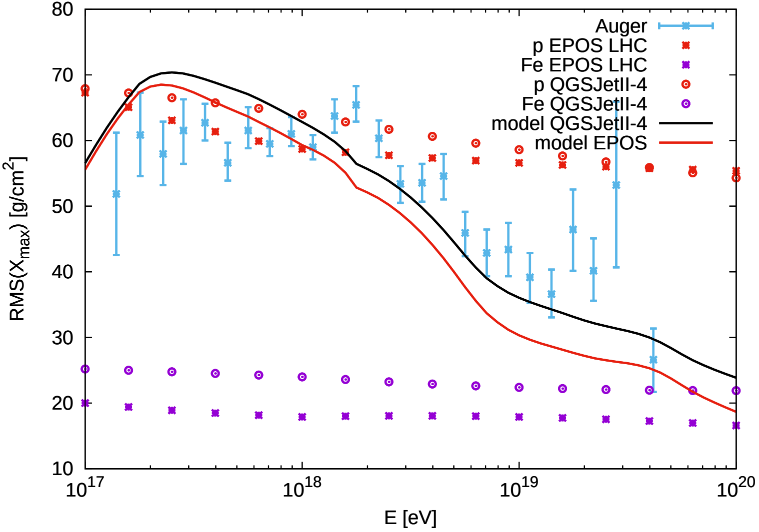

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Summary

1. EGRB constrains stronly neutrino sources:
   - slope of extragal. neutrino $\alpha \lesssim 2.3$
   - neutrino sources are not main source class of EGRB
2. neutrino signal in IceCube:
   - isotropy favours dominant extragalactic origin above 10–100 TeV
   - steeper additional contribution dominating at low energies (?)
3. 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 favours nuclei with $A\gamma$
   - sources with both Ap and $A\gamma$ interactions favoured