Escape Model, Transition and Neutrinos

Michael Kachelrieß

NTNU, Trondheim

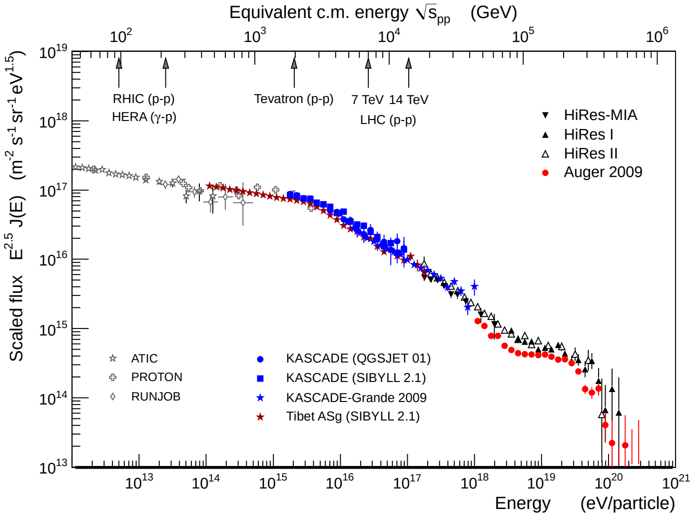
with G.Giacinti, O.Kalashev, A.Neronov, S.Ostapchenko, D.Semikoz

Outline of the talk

1. Introduction
   - Knee
   - Results on Composition ⇒ M. Unger
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? ⇒ A. Nernov
   - Anisotropy
   - Antimatter fluxes
4. Conclusions

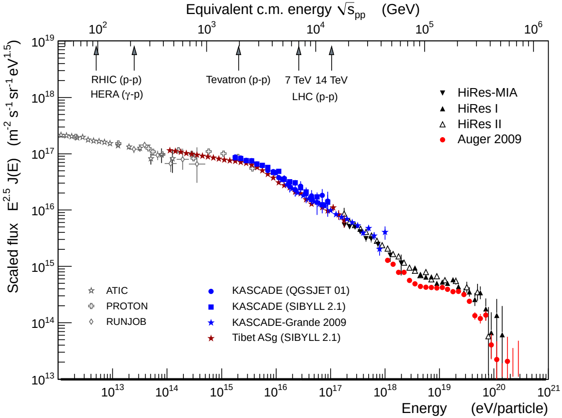
Cosmic Ray Knee: steepening $\Delta\gamma \simeq 0.4$ at few $\times 10^{15}$ eV

.



Cosmic Ray Knee: 3 explanations

.



- change of interactions at multi-TeV energies: excluded by LHC

Cosmic Ray Knee: 3 explanations

.

- change of interactions at multi-TeV energies: excluded by LHC
- 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

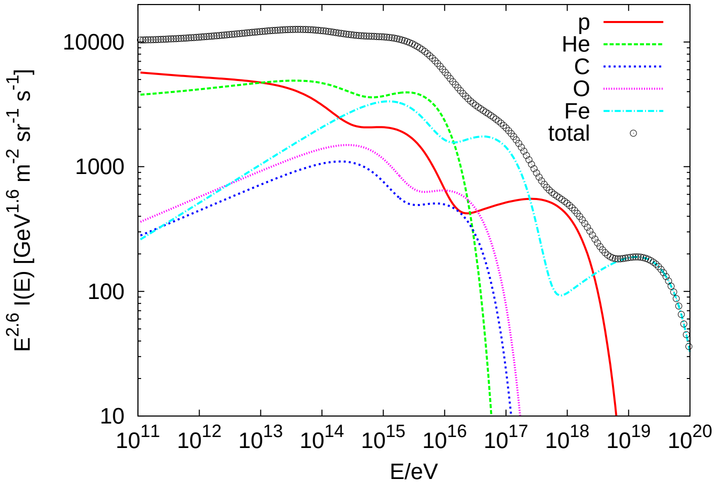
  - Hall diffusion $D(E) \sim E$
  - small-angle scattering $D(E) \sim E^2$
  - something intermediate?

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

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

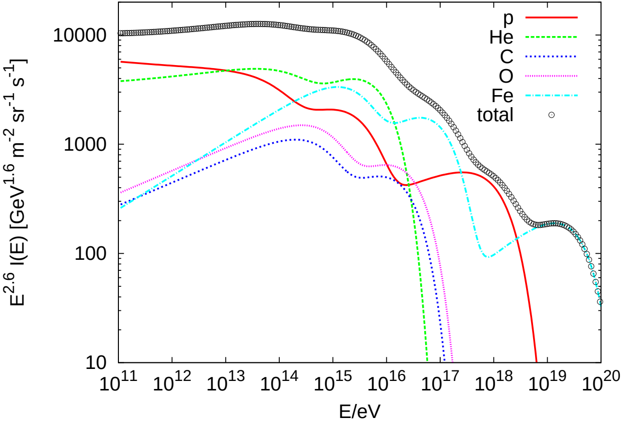
Cosmic Ray Knee: 3 explanations

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



Cosmic Ray Knee: 3 explanations

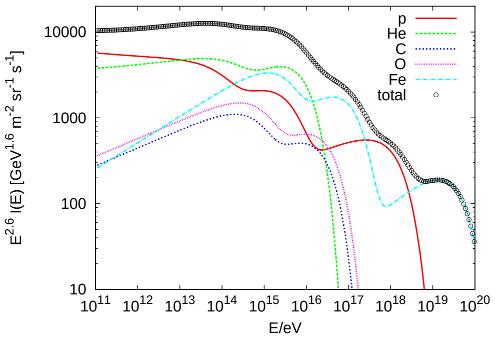
- maximal rigidity of dominant CR sources – e.g. Hillas model



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

Cosmic Ray Knee: 3 explanations

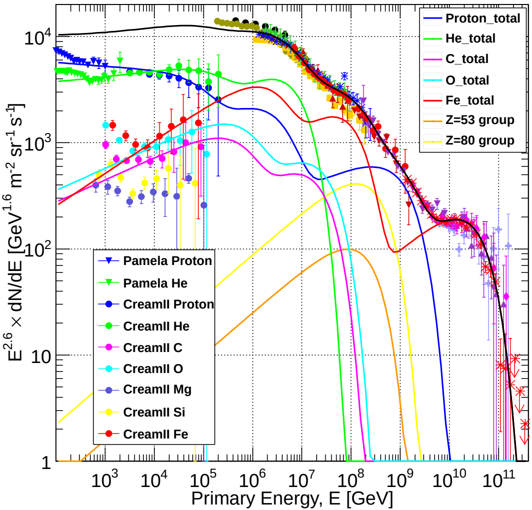
- maximal rigidity of dominant CR sources – e.g. Hillas model



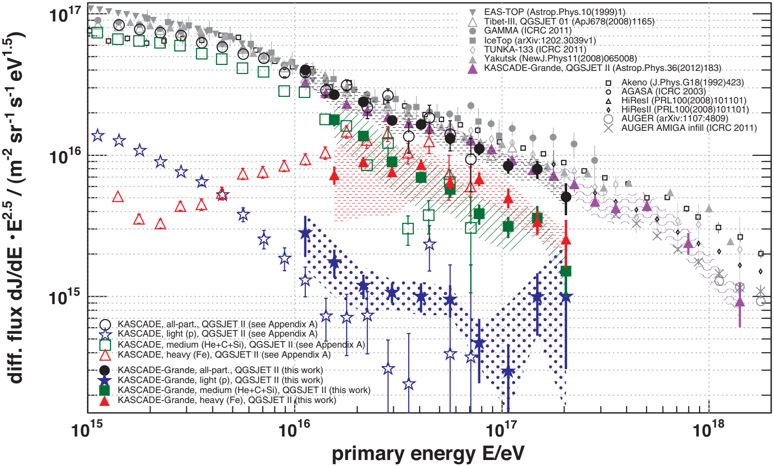
- $i = 1, \ldots, 3$ types of CR sources, with slopes $\alpha_{A,i}$, rel. fractions $f_{A,i}$
- no reliable estimate of $E_{\max,i}$, $\alpha_{A,i}$, and $f_{A,i}$

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

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

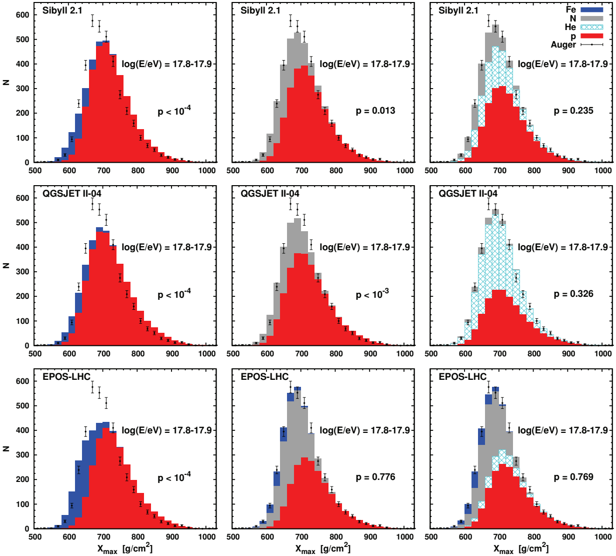


Composition of Galactic CRs: KASCADE-Grande 2013



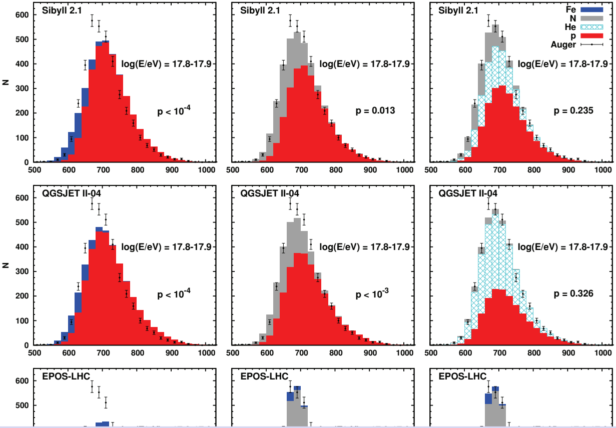
Composition of Galactic CRs: Auger

[arXiv:1409.5083]



Composition of Galactic CRs: Auger

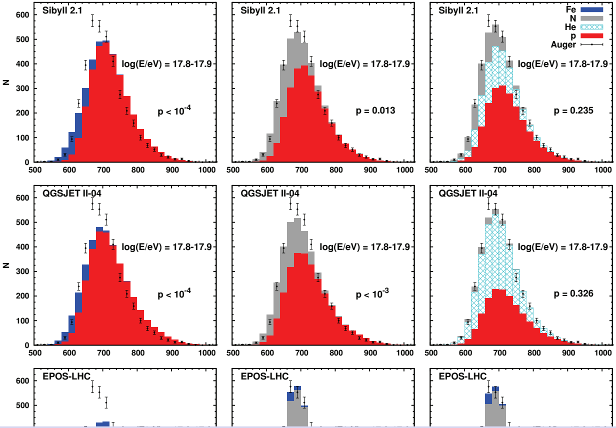
[arXiv:1409.5083]



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

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

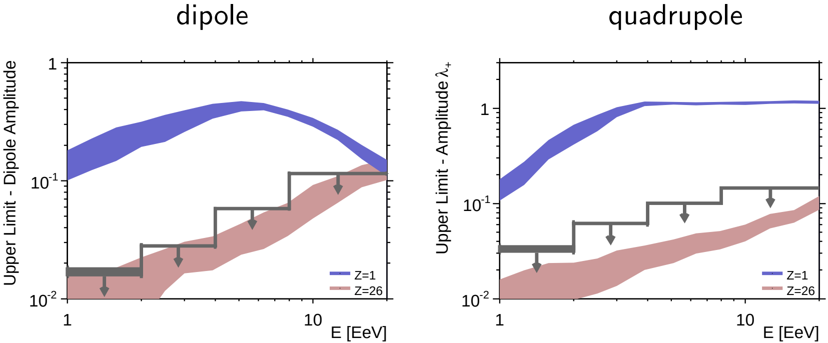
Composition of Galactic CRs:



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



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

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

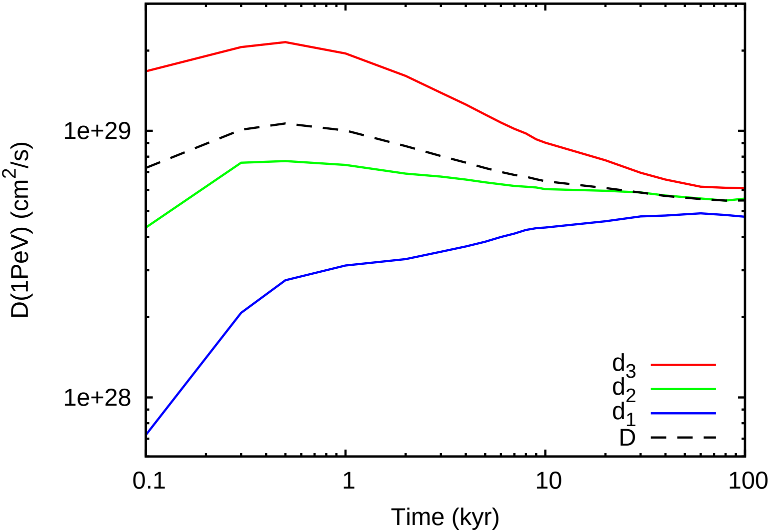
Our approach:

- use model for Galactic magnetic field
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.

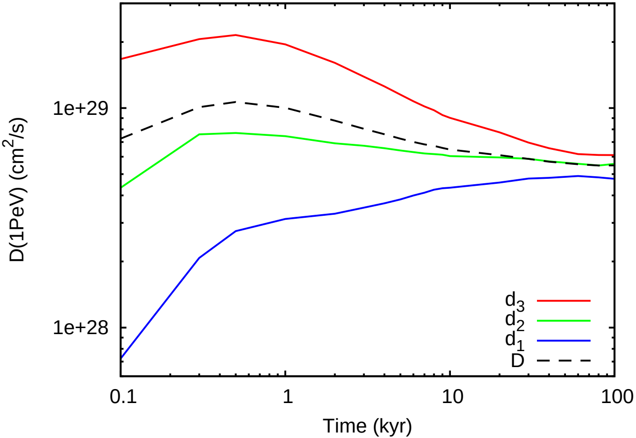
Our approach:

- use model for Galactic magnetic field
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.
- 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



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



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

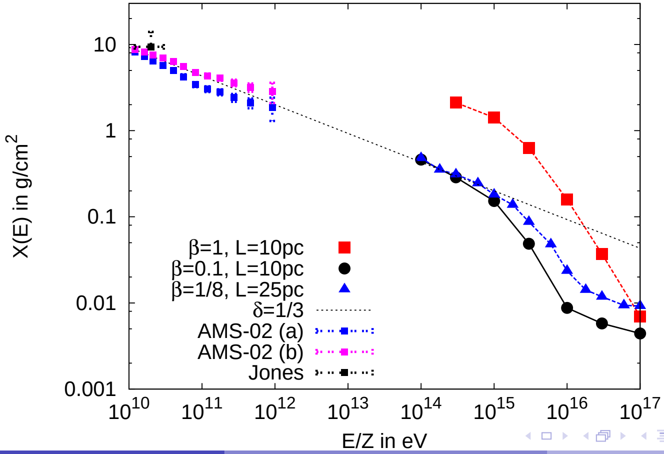
[*Giacinti, MK, Semikoz ('12)*]

Knee from Cosmic Ray Escape

- $l_{\rm coh}$ and regular field $\boldsymbol{B}(\boldsymbol{x})$ fixed from observations
  - LOFAR: $l_{\rm coh} \lesssim 10\,$pc in disc
- determine magnitude of random $\boldsymbol{B}_{\rm rms}(\boldsymbol{x})$ from grammage $X(E)$

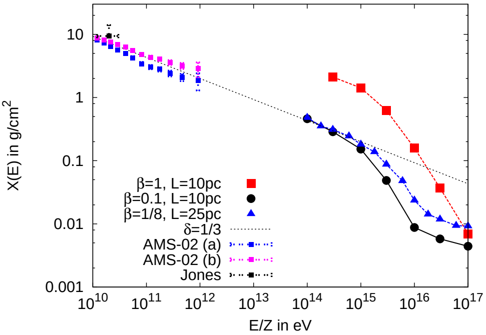
Knee from Cosmic Ray Escape

- $l_{\rm coh}$ and regular field $\boldsymbol{B}(\boldsymbol{x})$ fixed from observations
  - LOFAR: $l_{\rm coh} \lesssim 10\,$pc in disc
- determine magnitude of random $\boldsymbol{B}_{\rm rms}(\boldsymbol{x})$ from grammage $X(E)$



Knee from Cosmic Ray Escape

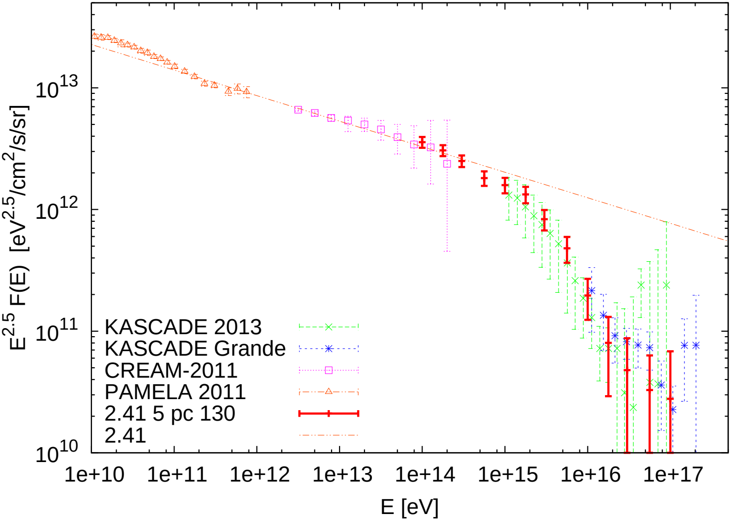
- $l_{\rm coh}$ and regular field $\boldsymbol{B}(\boldsymbol{x})$ fixed from observations
  - LOFAR: $l_{\rm coh} \lesssim 10\,$pc in disc
- determine magnitude of random $\boldsymbol{B}_{\rm rms}(\boldsymbol{x})$ from grammage $X(E)$



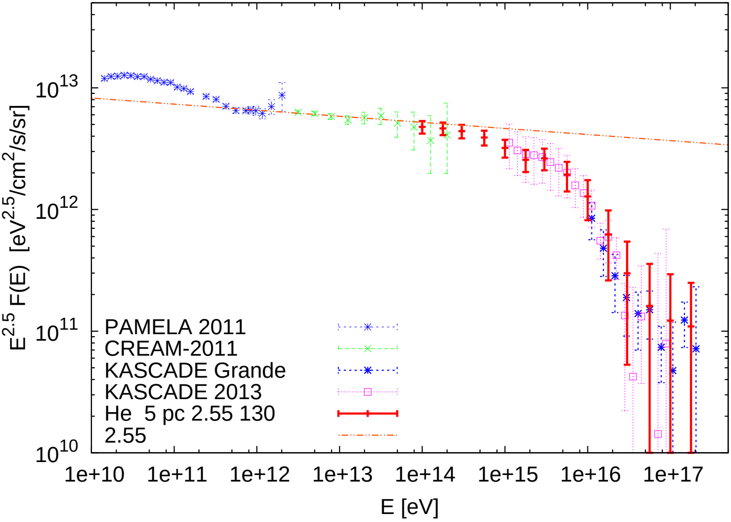
$\Rightarrow$ prefers weak random fields

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

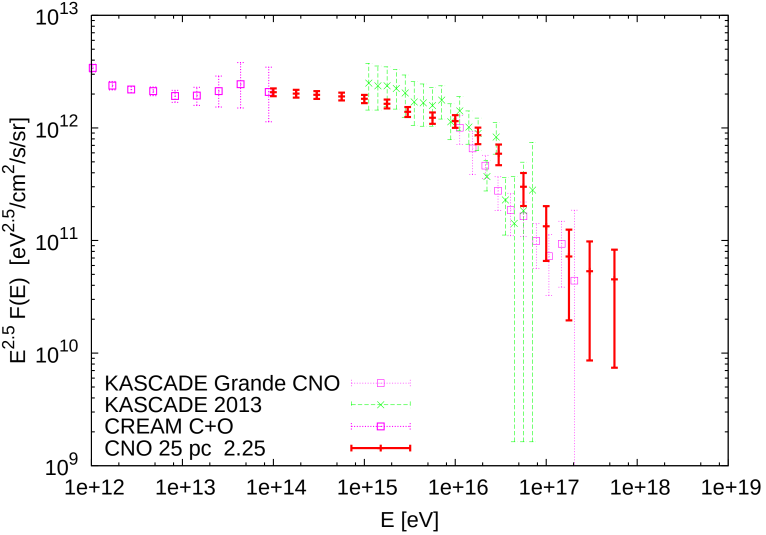
Knee from Cosmic Ray Escape: proton energy spectra



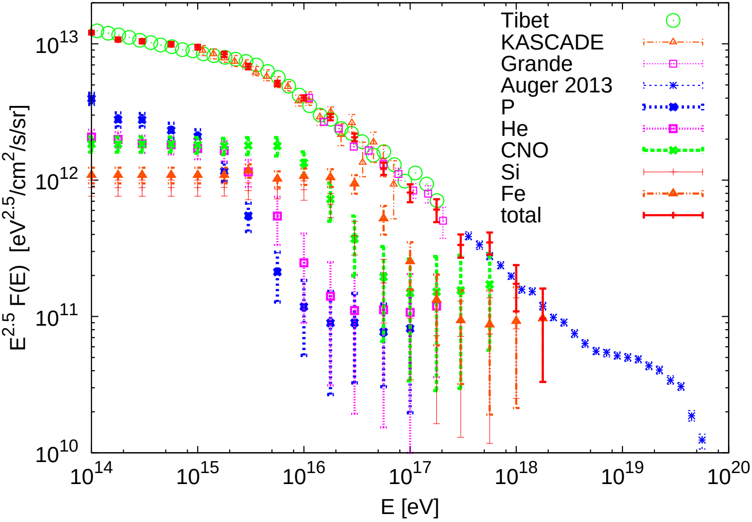
Knee from Cosmic Ray Escape: He energy spectra



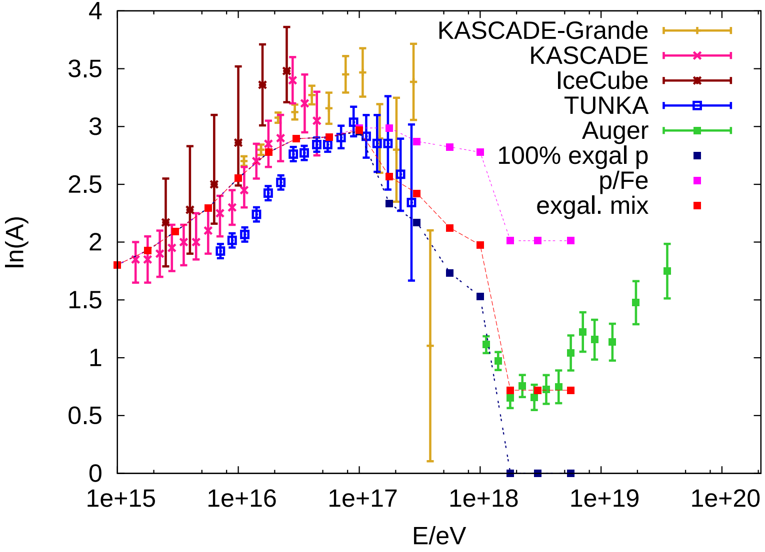
Knee from Cosmic Ray Escape: CNO energy spectra



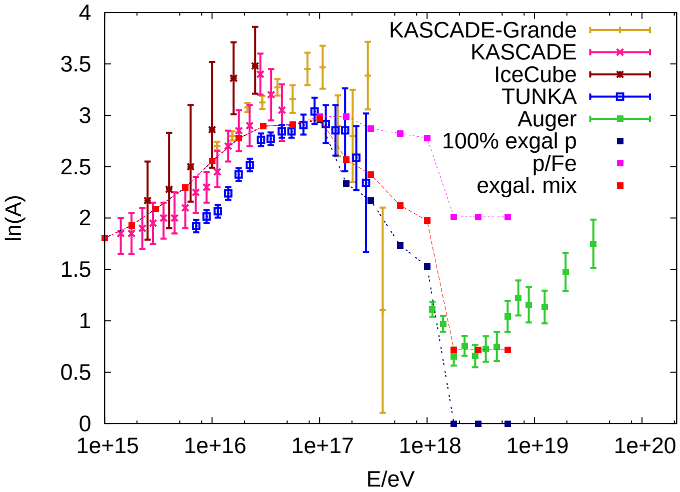
Knee from Cosmic Ray Escape: total energy spectra



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

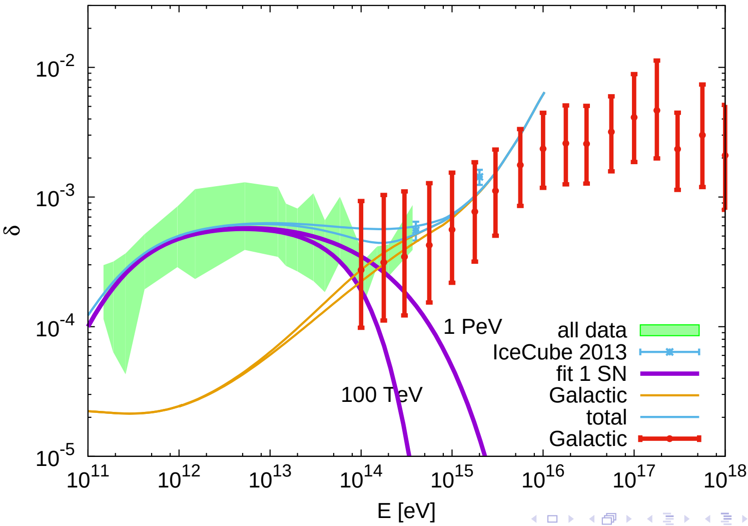


Knee from Cosmic Ray Escape: $\ln(A)$

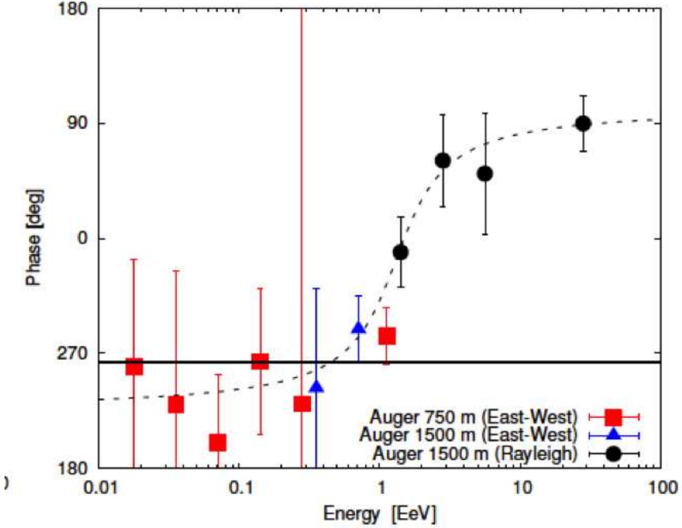


exgal. mix: 60% p, 25% He, 15% N

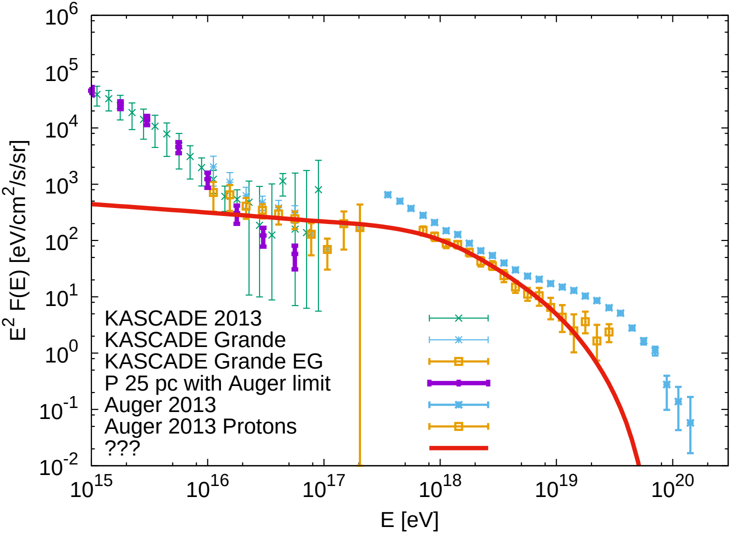
Knee from Cosmic Ray Escape: dipole anisotropy



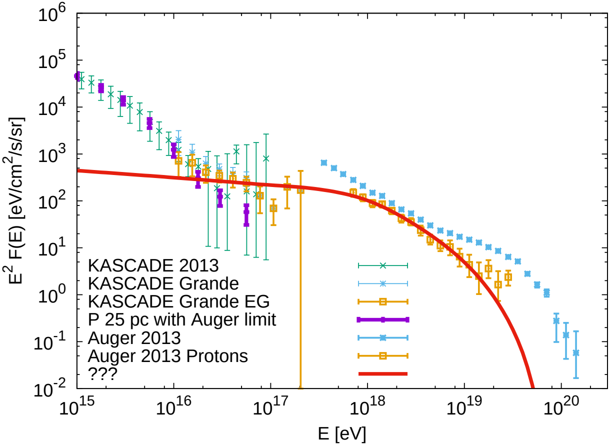
Knee from Cosmic Ray Escape: dipole anisotropy



Extragalactic proton flux in escape model:



Extragalactic proton flux in escape model:

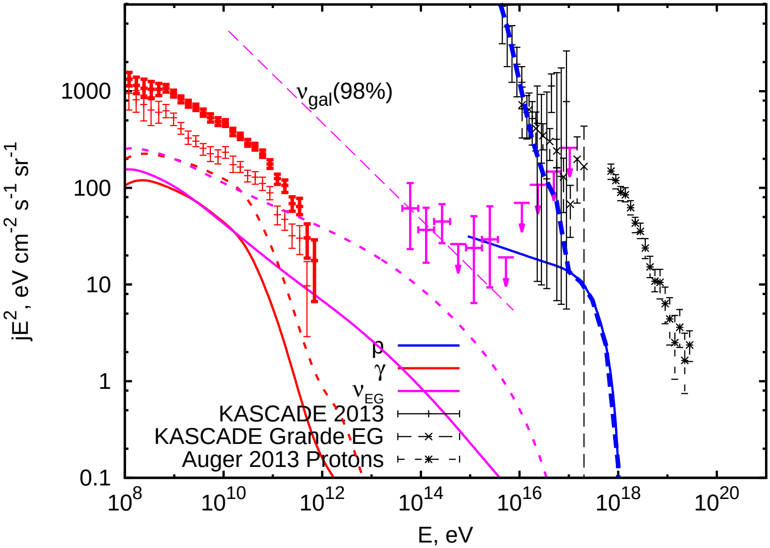


- what are the sources?
- testable via γ-ray and neutrinos?

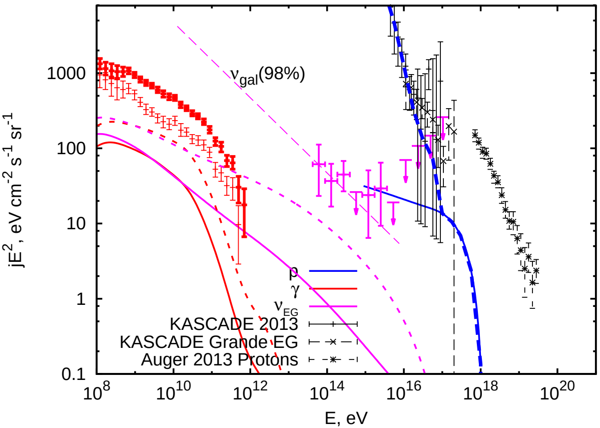
Normal and starburst galaxies:

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

Normal and starburst galaxies:



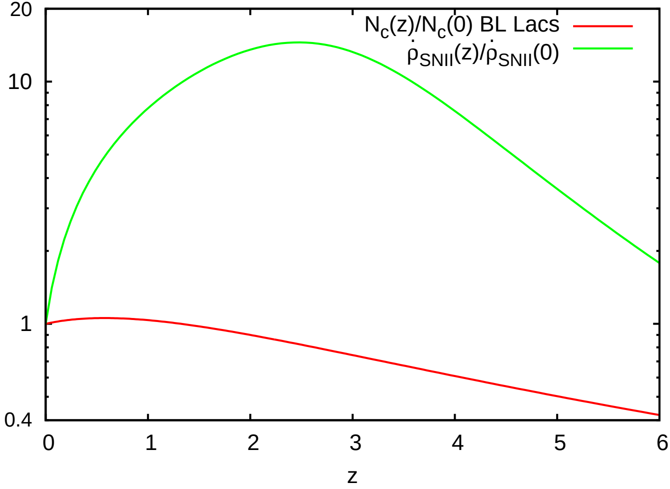
Normal and starburst galaxies:



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

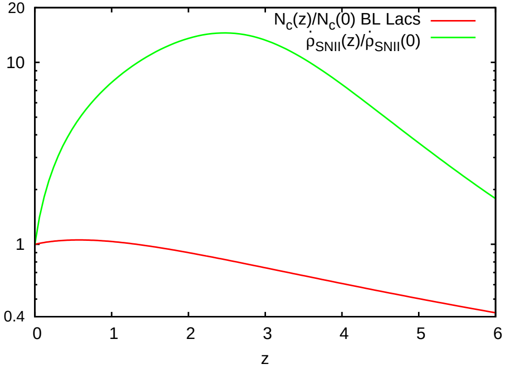
Extragalactic proton flux in escape model:

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



Extragalactic proton flux in escape model:

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

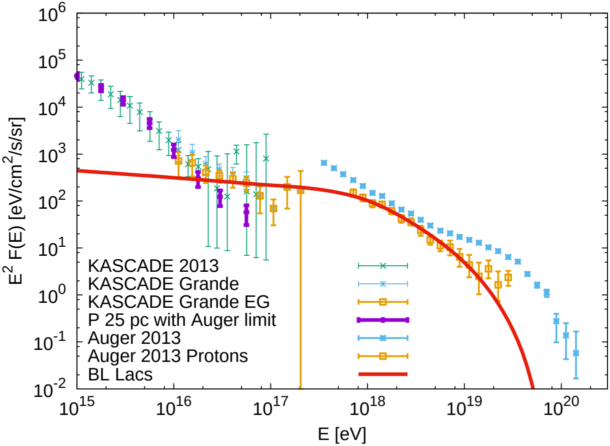


$\Rightarrow$ BL Lacs/FR-I are promising sources

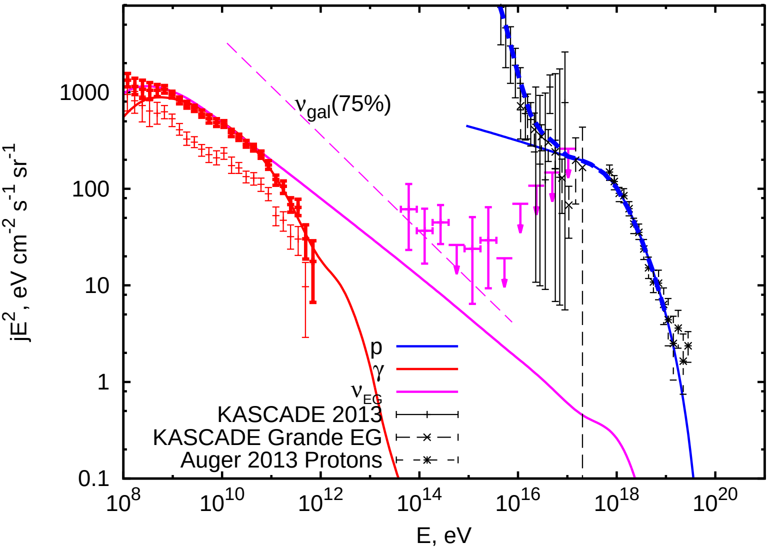
Extragalactic proton flux in escape model:

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

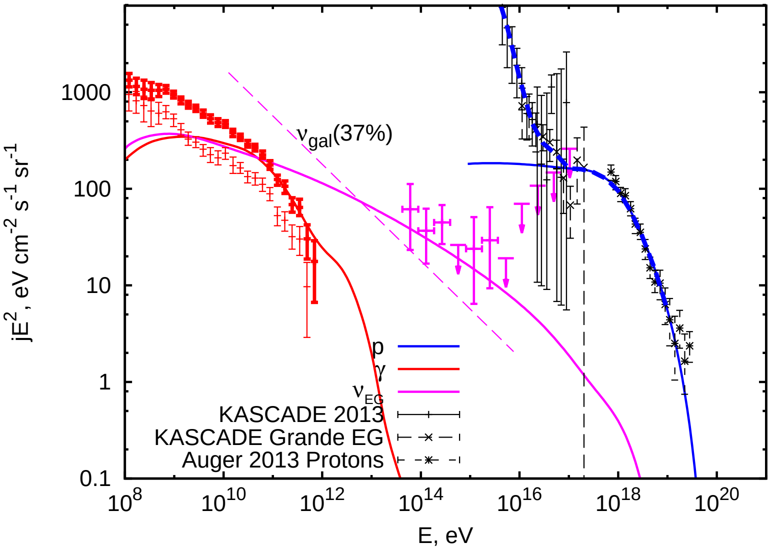
$\Rightarrow$ BL Lacs/FR-I are promising sources



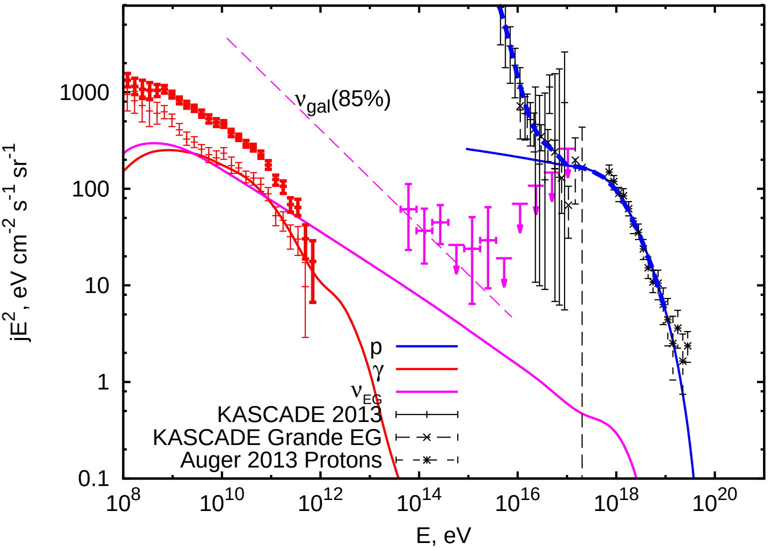
Diffuse fluxes from BL Lacs $\alpha = 2.17$ and $E_\tau = 3 \times 10^{11}$ eV



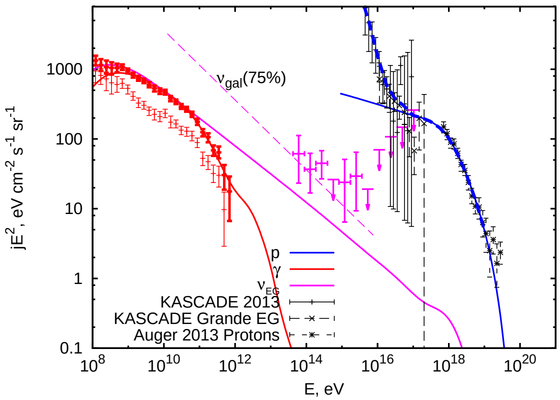
Diffuse fluxes from BL Lacs $\alpha = 2.1$ and $E_\tau = 3 \times 10^{11}$ eV



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



Diffuse fluxes from BL Lacs



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

What about heavier nuclei?

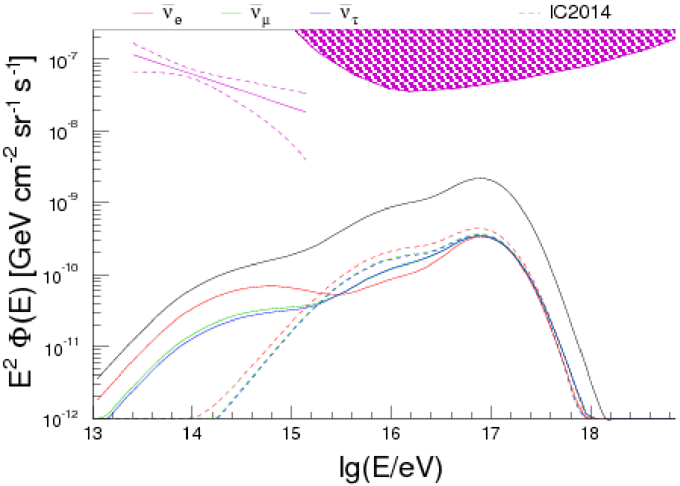
- models reproducing UHECR composition
  - based on $A\gamma$ interactions
  - Peter's cycle: $E_{\rm max} = ZE_{{\rm max},p}$

What about heavier nuclei?

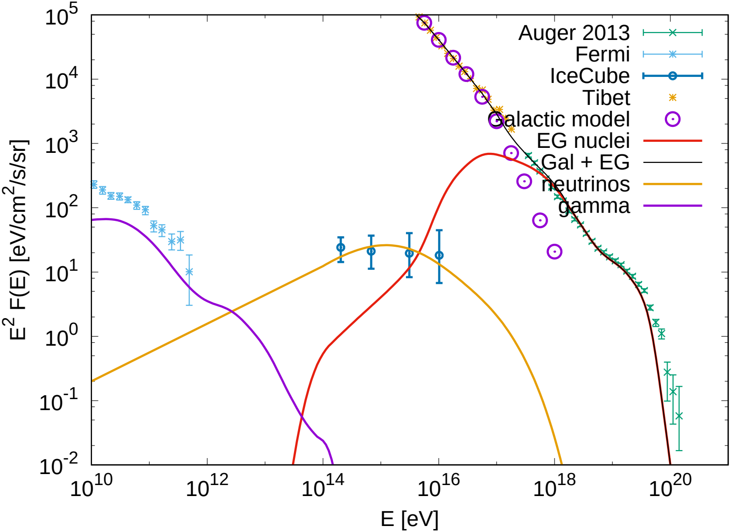
- models reproducing UHECR composition
  - based on $A\gamma$ interactions
  - Peter's cycle: $E_{\rm max} = ZE_{{\rm max},p}$
- ν flux is too small

ν and mixed composition

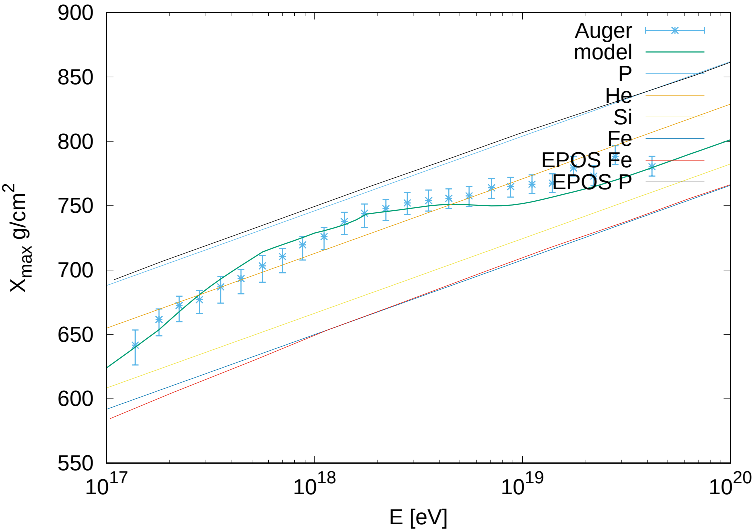
[Unger, Farrar, Anchordoqui '15]



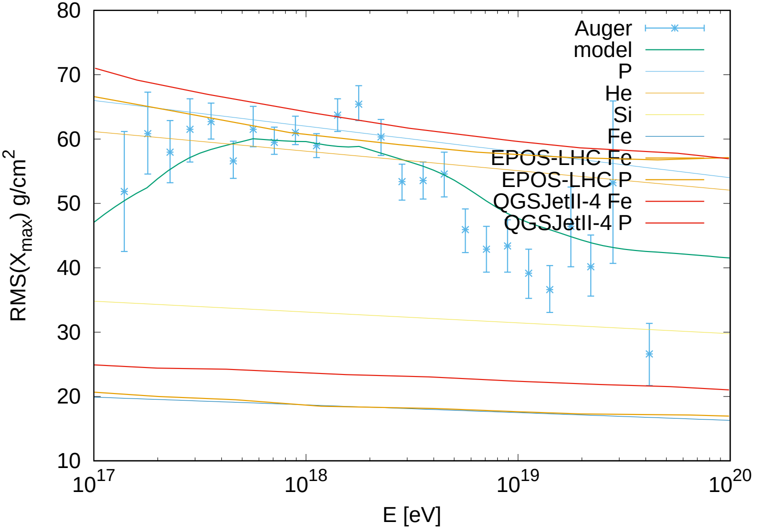
Diffuse fluxes from AGNs: $A\gamma$ and Ap interactions



Diffuse fluxes from AGNs: $A\gamma$ and Ap interactions



Diffuse fluxes from AGNs: $A\gamma$ and Ap interactions



Conclusions

- Knee due to CR escape
  - recovery of fluxes as suggested by KASCADE-Grande
  - probes GMF: suggests small $B_{\rm rms}$ and small $l_{\rm coh}$
  - transition to light-medium extragalactic CRs completed at few $\times 10^{17}$ eV
  - propagation feature is unavoidable, only possible to shift to higher energies
  - source effects may be on top, but seem not necessary
- common source class for UHECRs and neutrinos?
  - several candidates as GRBs are already excluded
  - AGNs remain attractive option