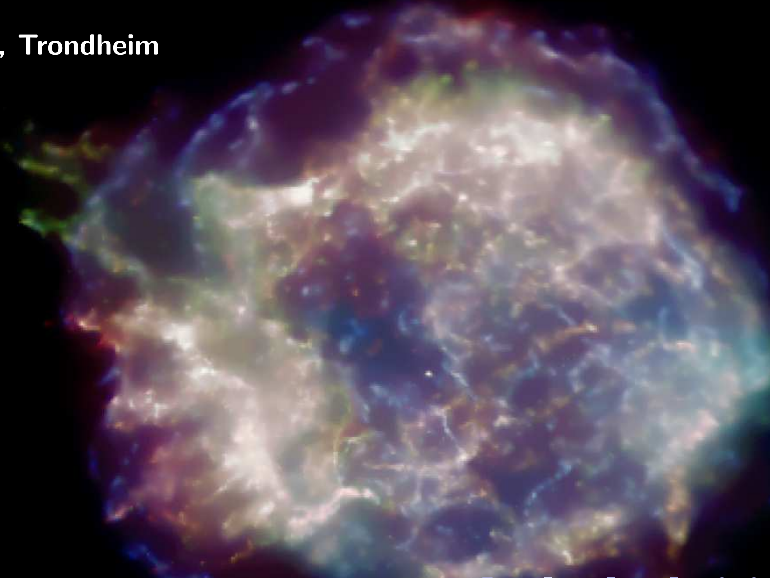
News from High-Energy Cosmic Rays and Neutrinos

Michael Kachelrieß

NTNU, Trondheim



Outline of the talk

1. Introduction
   - Is progress slow?
   - Results on Composition
   - γ's and ν's as CR secondaries
2. Origin of the CR knee: Escape model
   - Fluxes of groups of CR nuclei
   - Transition to extragalactic CRs
   - Anisotropy
3. IceCube excess
   - Disentangling signal/prompt/background
   - Characteristica of proposed sources
4. Conclusions

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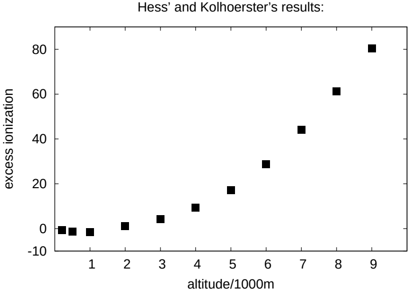
1912: Victor Hess discovers cosmic rays

Two key questions

- what are their sources?
- how do they accelerate?



102 years later: no definite answers yet

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- How to overcome these problems?
  1. Multi-messenger astronomy,
     - ⋆ γ: distinguish "hadronic" from "leptonic", only below ~ 10 TeV
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- How to overcome these problems?
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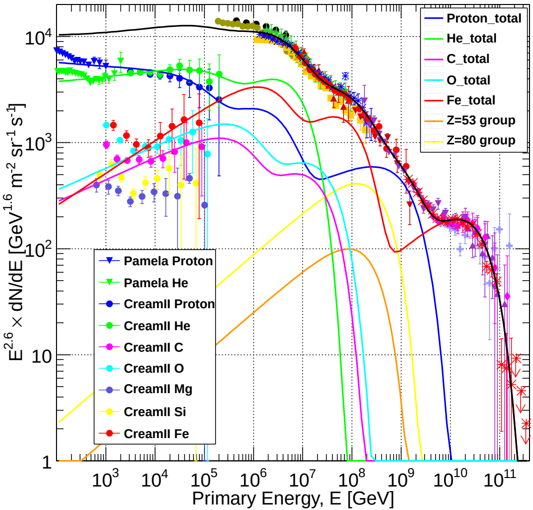
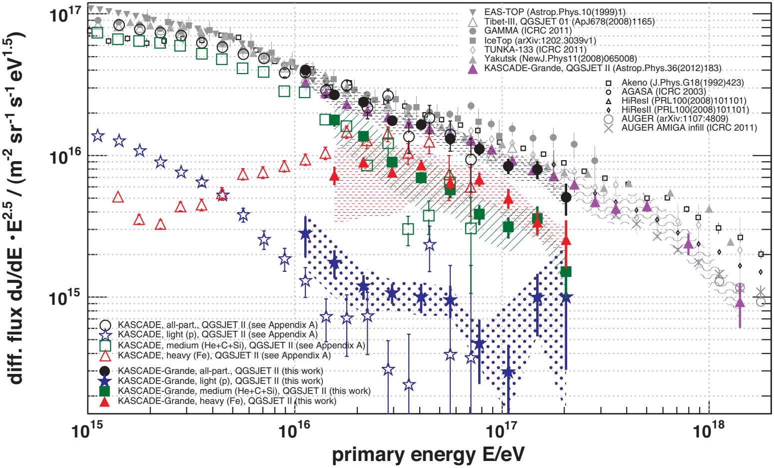
     - γ: distinguish "hadronic" from "leptonic", only below ~ 10 TeV
     - ν: low event rates requires km^3 detectors
  2. improve
     - experiments: combining different techniques (KASCADE-Grande, PAO, TA)
     - models: new data from LHC (EPOS-LHC, QGSJET-II-04)

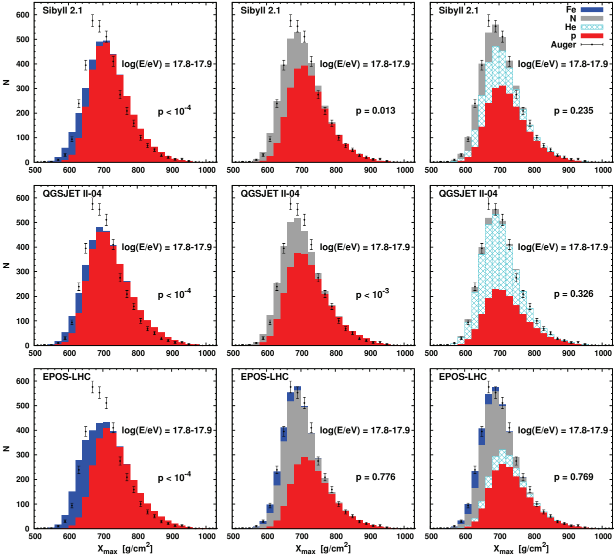
Composition of Galactic CRs: traditional view [*Gaisser, Stanev, Tilav '13*]



Composition of Galactic CRs: KASCADE-Grande 2013



Composition of Galactic CRs: Auger [arXiv:1409.5083]



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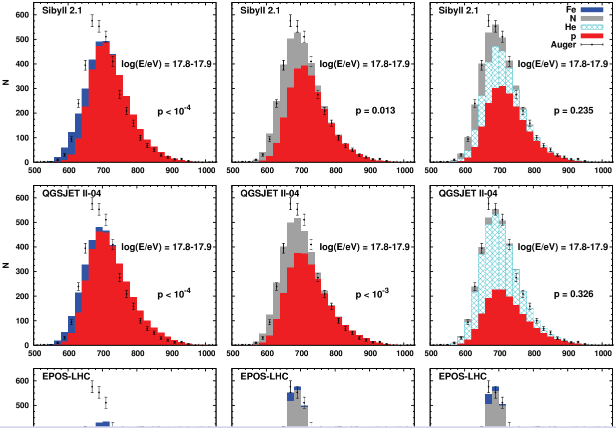

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- $\mathcal{O}$(50% p, 50% He+N, $< 20\%$Fe)

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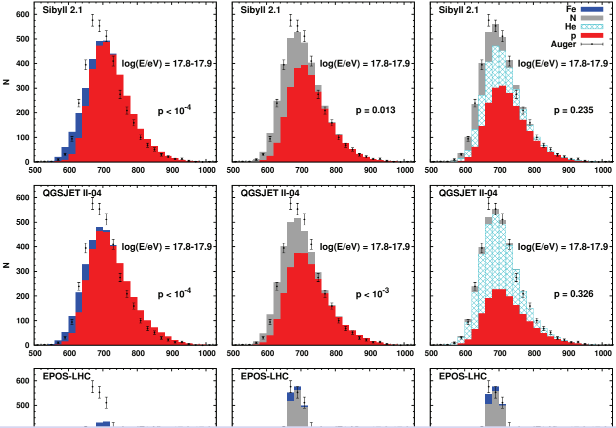
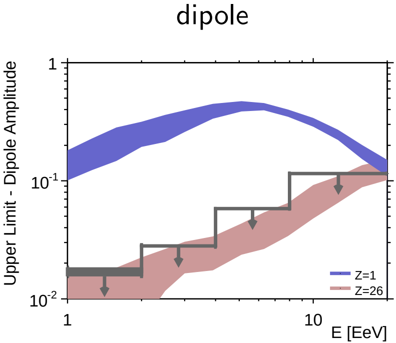
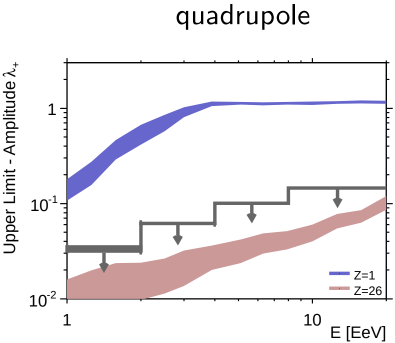


composition $6 \times 10^{17} - 5 \times 10^{18}$ eV consistent with

- $\mathcal{O}$(50% p, 50% He+N, $< 20\%$Fe)
- early transition from Galactic to extragalactic CRs

Transition to extragalactic CRs – anisotropy limits



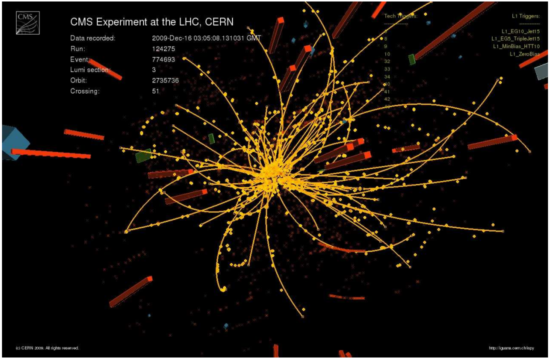


dominant light Galactic composition around $E = 10^{18}$ eV excluded

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

The pion peak

- CR scattering on gas or photons: $pp \to$ mesons, baryons $\to e, \gamma, \nu, p$



- the lightest mesons, π^0 and $\pi^\pm$, are produced most often
- decays: $\pi^0 \to 2\gamma$ and $\pi^\pm \to 3\nu + e^\pm$

The pion peak

- $\pi^0 \to \gamma(\boldsymbol{k}_1) + \gamma(\boldsymbol{k}_2)$ at rest:
  - energy conservation: $m_\pi c^2/2 = E_1 = E_2$
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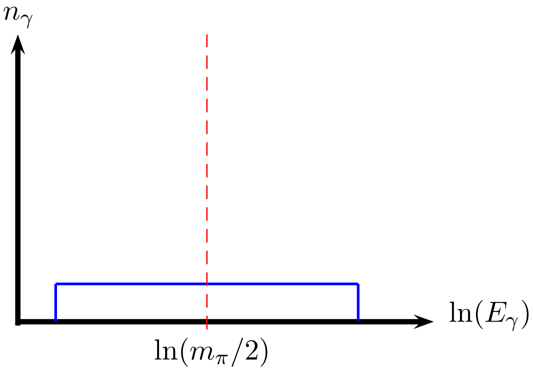
  - geometric mean $\sqrt{E_{\rm min} E^{\rm max}} = \frac{m_{\pi^0}}{2}$

The pion peak



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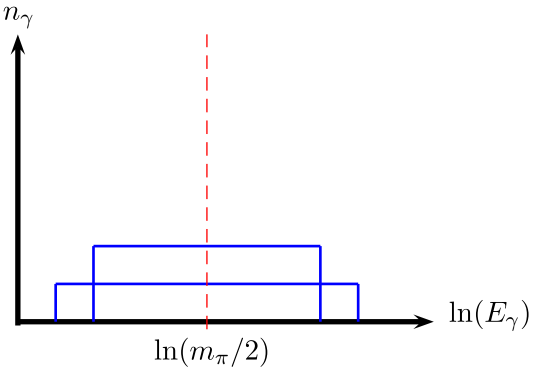

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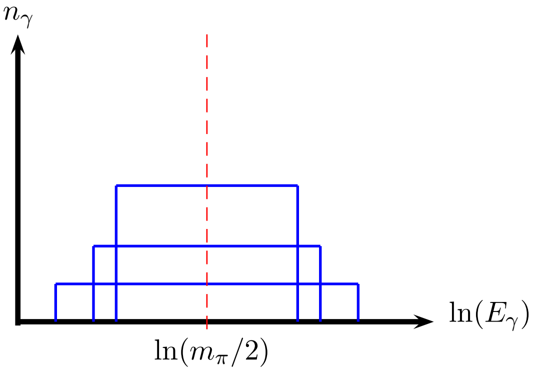

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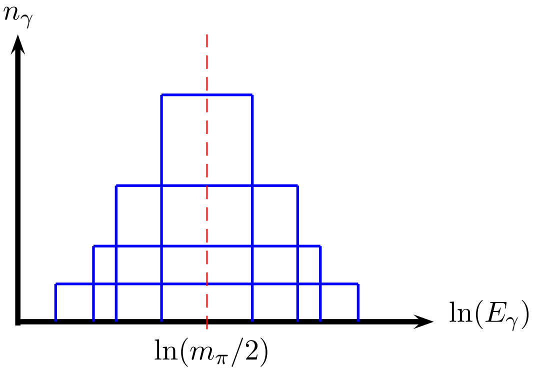

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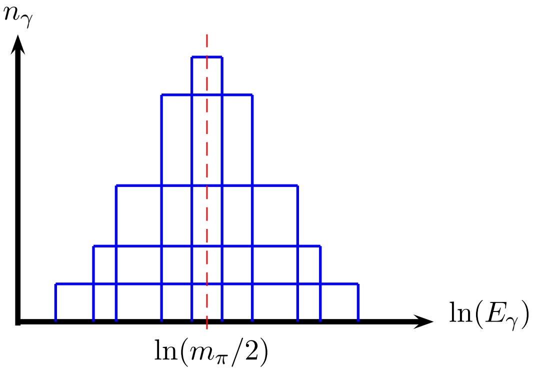

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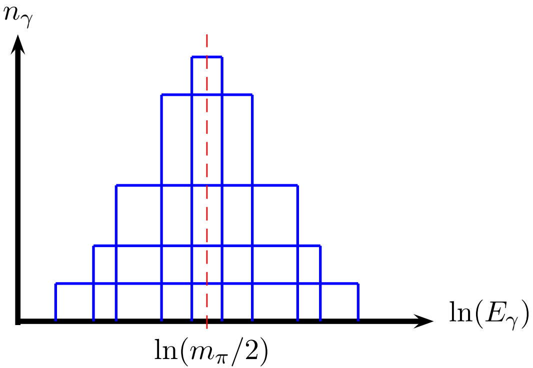
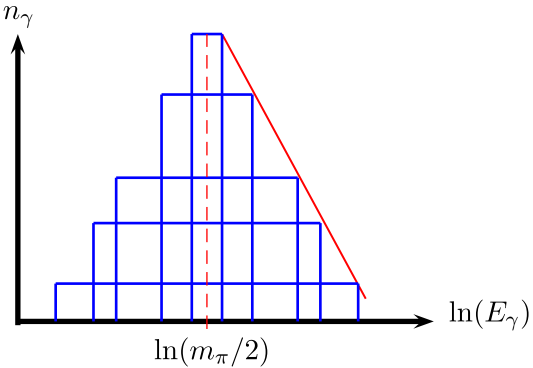


- independent of velocity distribution of pions:

$\Rightarrow$ symmetric photon distribution w.r.t. $m_{\pi^0}/2$

The pion peak: pp interactions



- low threshold & approx. Feynman scaling

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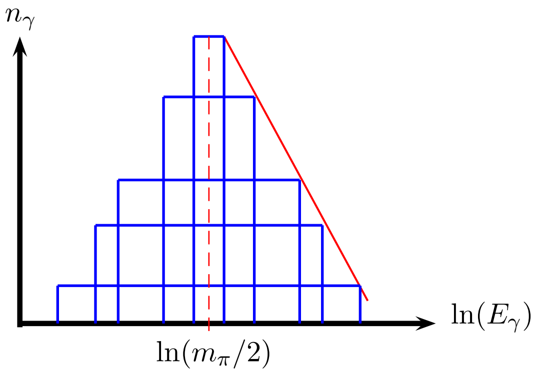

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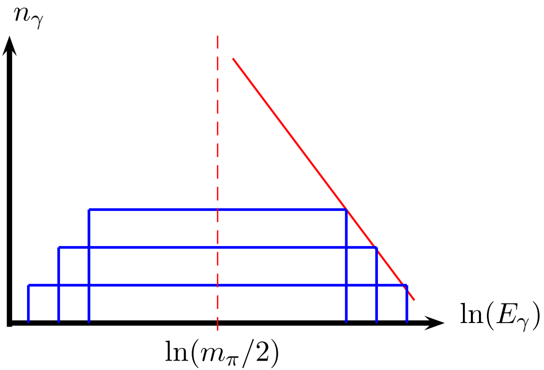
$\Rightarrow$ $dN_\gamma/dE \sim dN_{CR}/dE$

The pion peak: pγ interactions



- threshold $E_{\rm th} \gtrsim m_\pi m_p/\varepsilon_\gamma \sim 10^{16}$ eV with $\varepsilon_\gamma \lesssim 10\,\mathrm{eV}$

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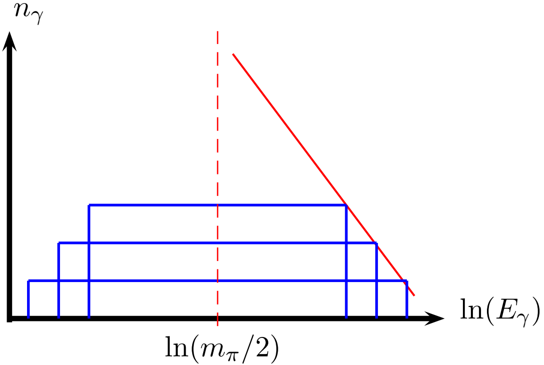

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$\Rightarrow$

$$dN_\gamma/dE \sim \begin{cases} \sim E^{-1} & \text{for } E < E_{\rm th} \\ \sim dN_{CR}/dE & \text{for } E > E_{\rm th} \end{cases}$$

The pion peak: Neutrinos from pp and pγ interactions

Only change from $pX \to Y\gamma$ to $pX \to Y\nu$:

- two mass scales $m_\pi, m_\mu \Rightarrow$ two boxes

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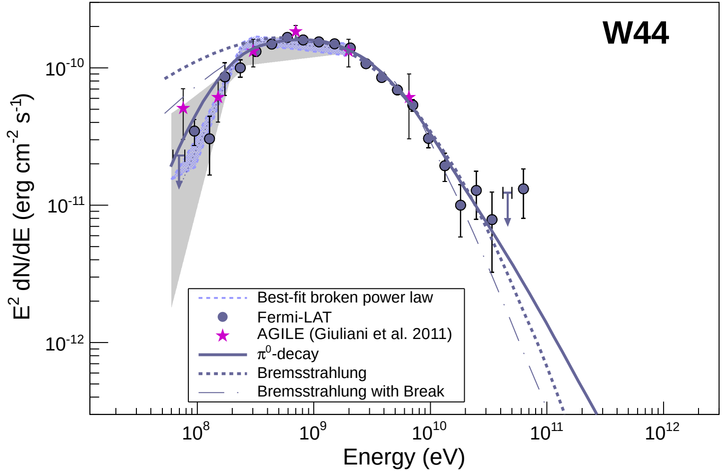
for a single source:

- pp: $dN_\nu/dE \sim dN_{CR}/dE$
- pγ:

$$dN_\nu/dE \sim \begin{cases} \sim E^{-1} & \text{for } E < E_{\rm th} \\ \sim dN_{CR}/dE & \text{for } E > E_{\rm th} \end{cases}$$

- steeper spectra for pγ as result of $E_{\max}$ distribution and evolution

Observing the π^0 bump in SNR W44:



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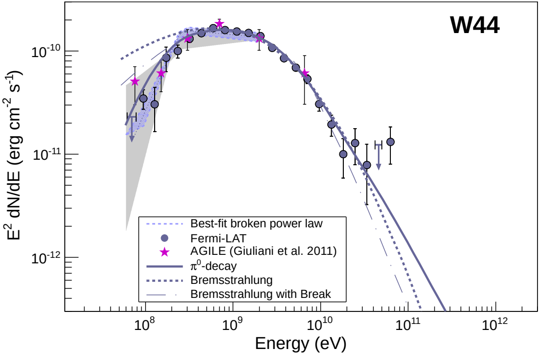

- strong evidence for proton acceleration

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

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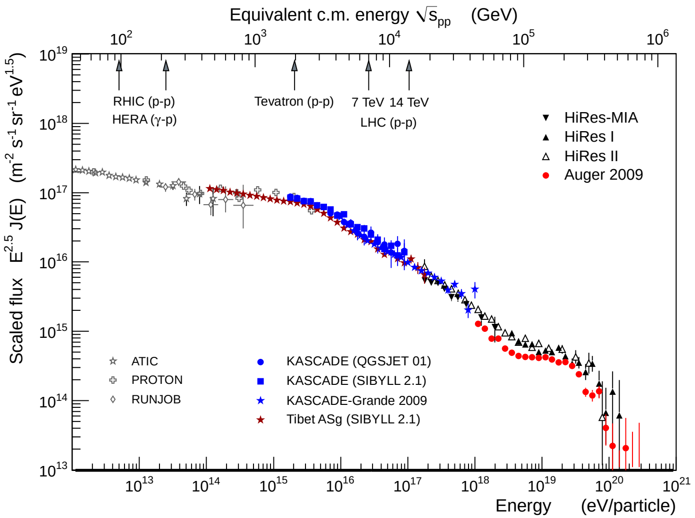

Cosmic Ray Knee: 3 explanations

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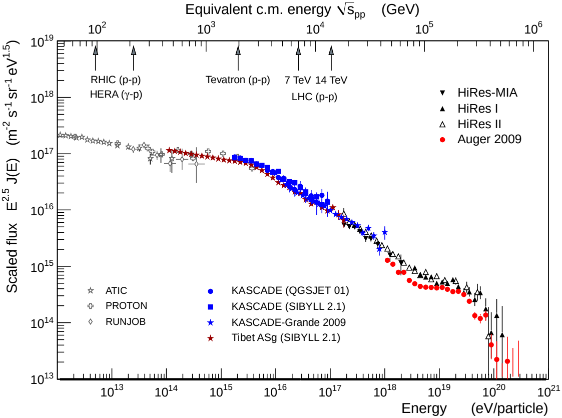

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- change of interactions at multi-TeV energies: excluded by LHC
- change of propagation at $R_L \simeq l_{\rm coh}$ or $E_c \propto ZeB\, l_{\rm coh}$:

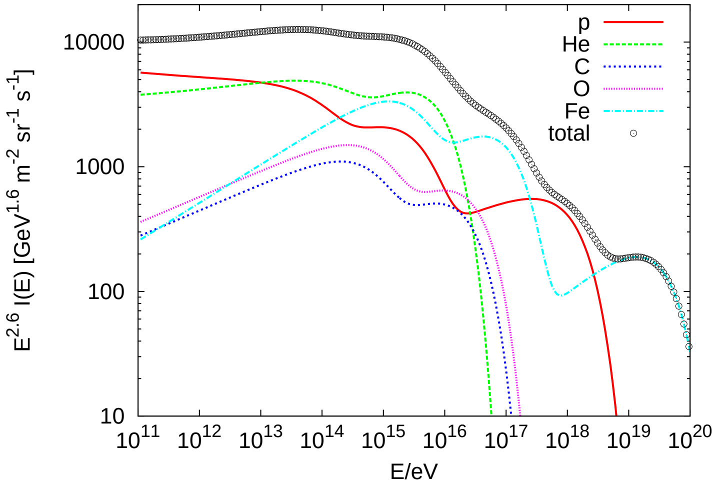
  $\Rightarrow$ change in diffusion from $D(E) \sim E^{1/3}$ to
  - Hall diffusion $D(E) \sim E$
  - small-angle scattering $D(E) \sim E^2$
  - something intermediate?

  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



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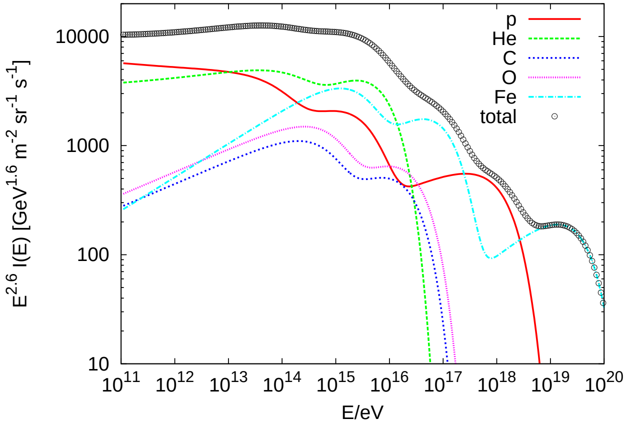

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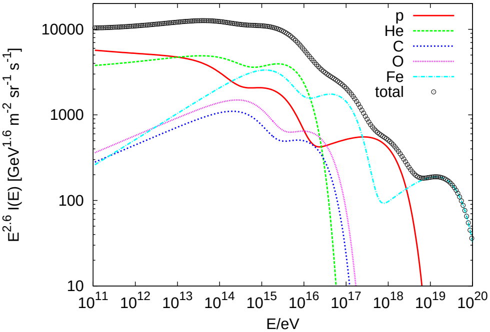
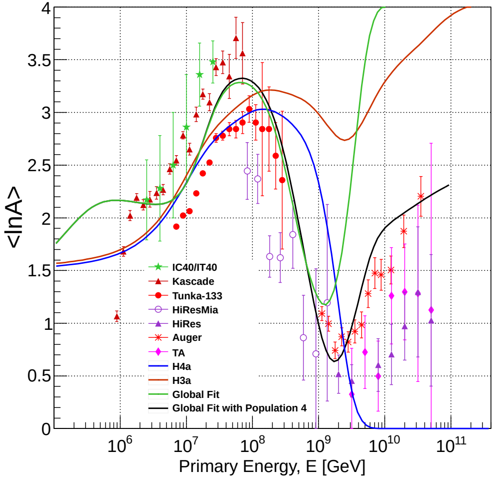


- $i = 1, \ldots, 3$ types of CR sources, with slopes $\alpha_{A,i}$, rel. fractions $f_{A,i}$
- no reliable estimate of $E_{\max,i}$, $\alpha_{A,i}$, and $f_{A,i}$

$\Rightarrow$ fit of many-parameter model to two observables: $I_{\rm tot}$ 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

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- anisotropy $\delta = -3D_{ij}\nabla_i \ln(n)$

Our approach:

- use model for Galactic magnetic field
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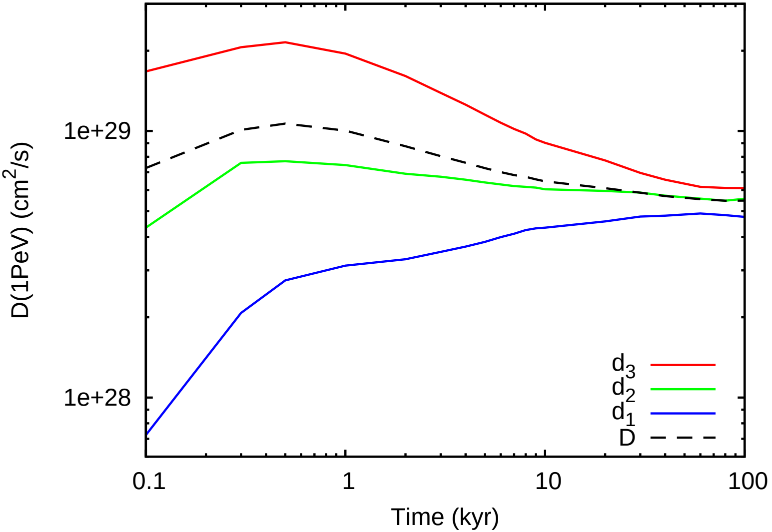
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.
- as preparation, let's calculate diffusion tensor in pure, isotropic turbulent magnetic field

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



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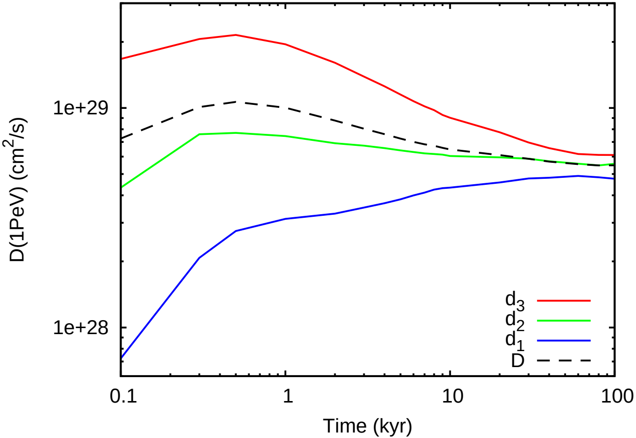

- asymptotic value is ~ 10 smaller than extrapolated "Galprop value"

[Giacinti, MK, Semikoz ('12)]

Knee from Cosmic Ray Escape

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

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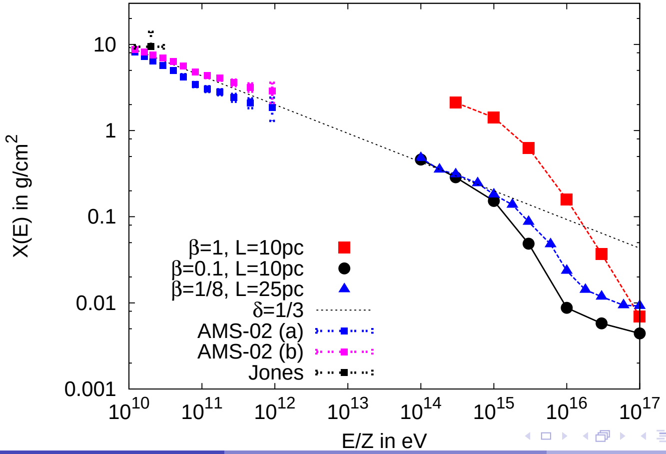

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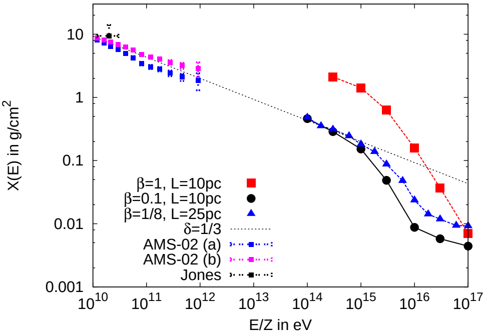
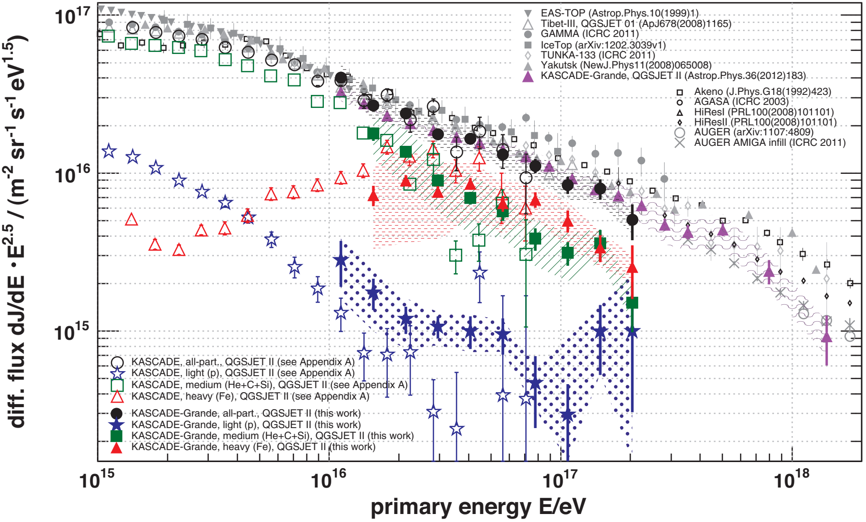


$\Rightarrow$ prefers weak random fields

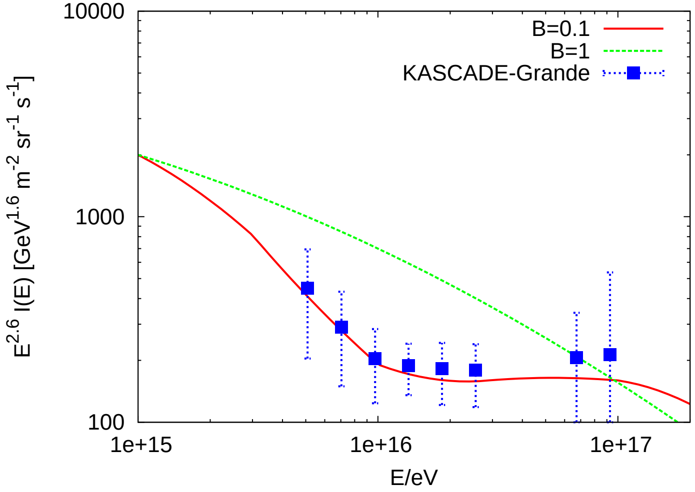
$\Rightarrow$ fluxes $I_A(E)$ of all isotopes fixed by low-energy data

Galactic CRs: KASCADE-Grande 2013

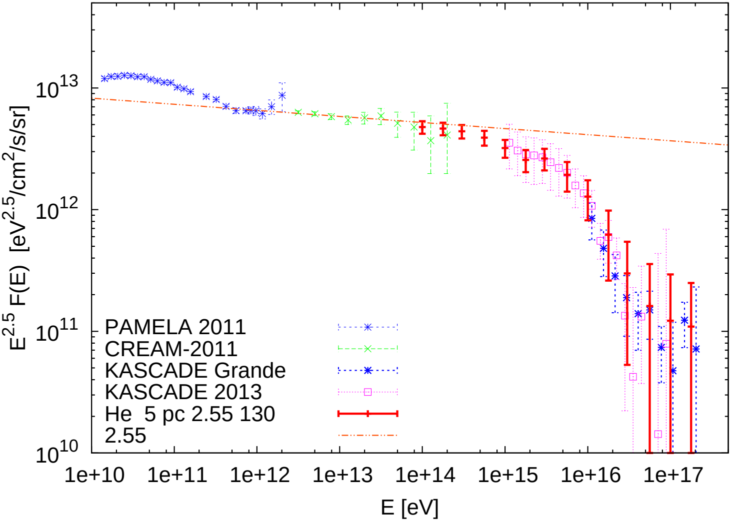


Knee from Cosmic Ray Escape: energy spectra

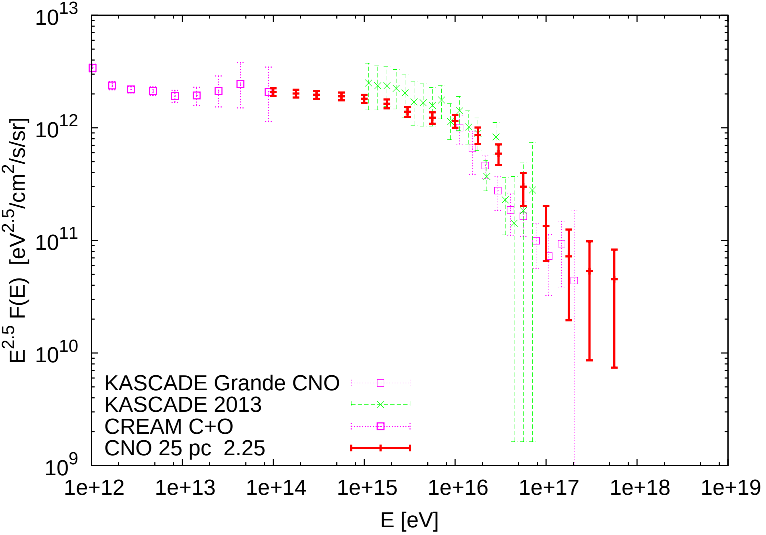
- protons from $X(E)$:



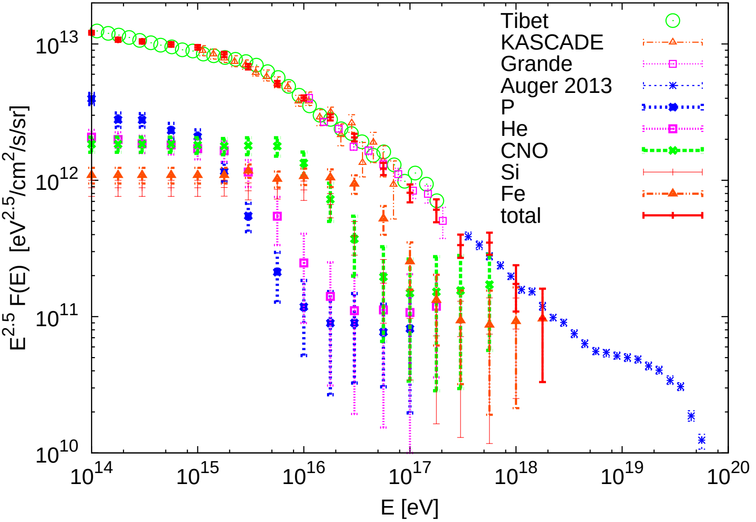
Knee from Cosmic Ray Escape: He energy spectra



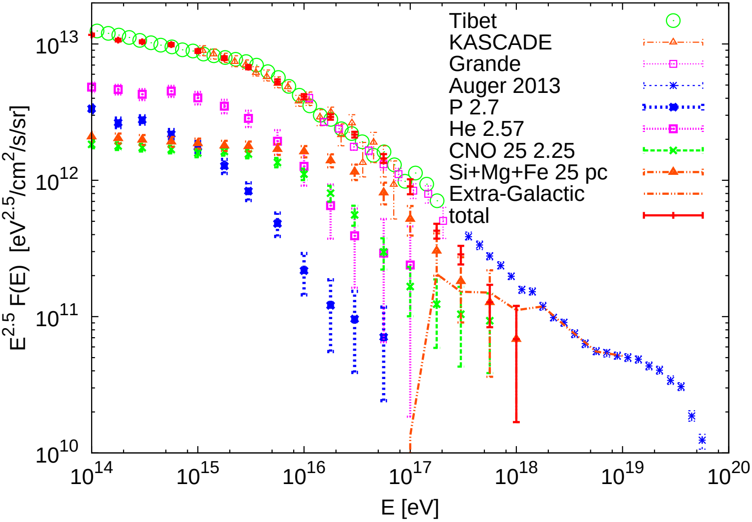
Knee from Cosmic Ray Escape: CNO energy spectra



Knee from Cosmic Ray Escape: total energy spectra



Transition to extragalactic CRs



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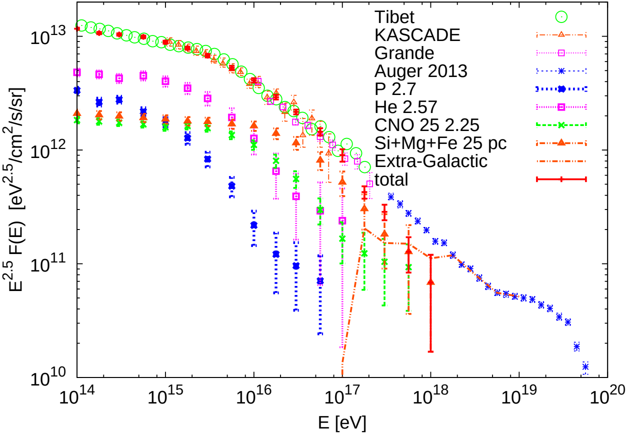
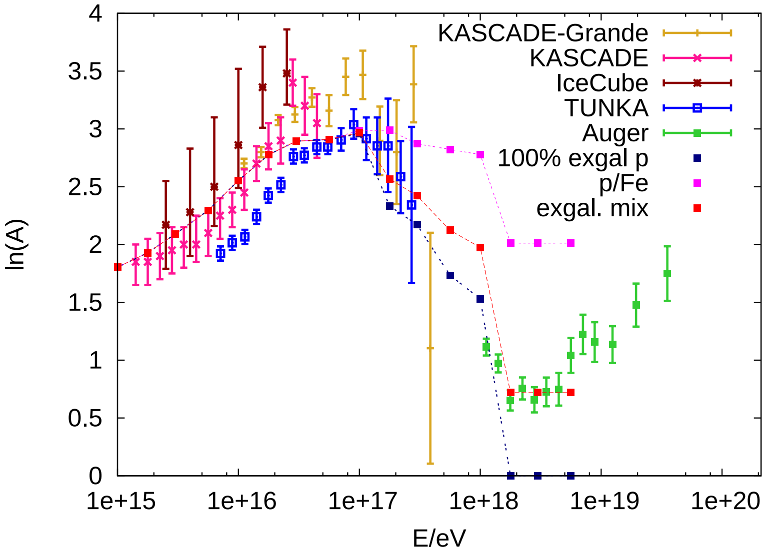


- at $E \approx 2 \times 10^{17}$ eV: $F_{\rm gal}(E) : F_{\rm exgal}(E) = 1 : 1$
- at $E \approx 2 \times 10^{18}$ eV: $F_{\rm gal}(E) : F_{\rm exgal}(E) = 0 : 1$

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



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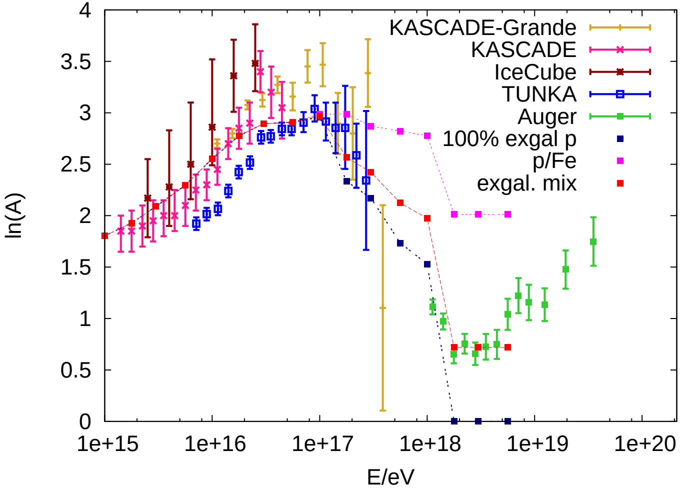
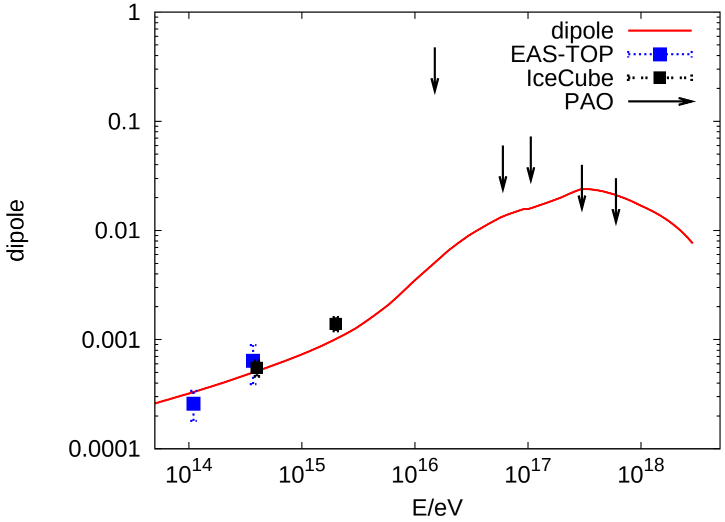


exgal. mix: 60% p, 25% He, 15% N

Knee from Cosmic Ray Escape: dipole anisotropy

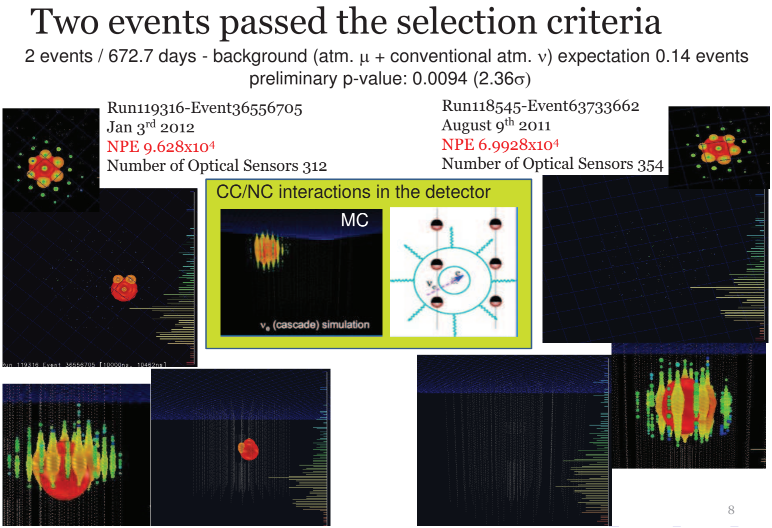


Knee from Cosmic Ray Escape: dipole anisotropy

IceCube

Icecube: 2 events presented at Neutrino 2012

- 2 cascade events close to $E_{\rm min} = 10^{15}$ eV, bg $= 0.14$

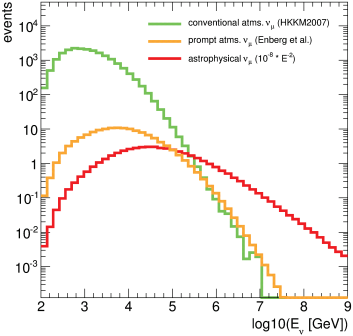


Icecube: prompt neutrino analysis

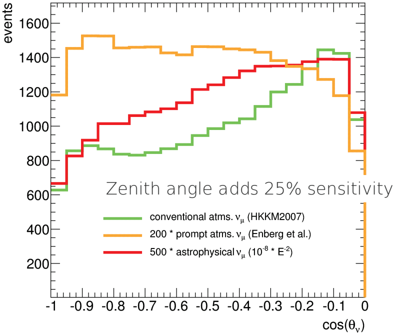
[A. Schukraft, NOW2012]

Signatures of high energy ν_μ in IceCube

Energy distribution
The three neutrino components have different spectral slopes



Zenith angle distribution
Additional sensitivity through characteristic angular distributions



Conventional, prompt and astrophysical neutrinos can't be decoupled and need to be looked at together in a HE neutrino analysis.

IceCube events: specifications for candidate sources

36 events with ~ 14 bg: flukes are possible...

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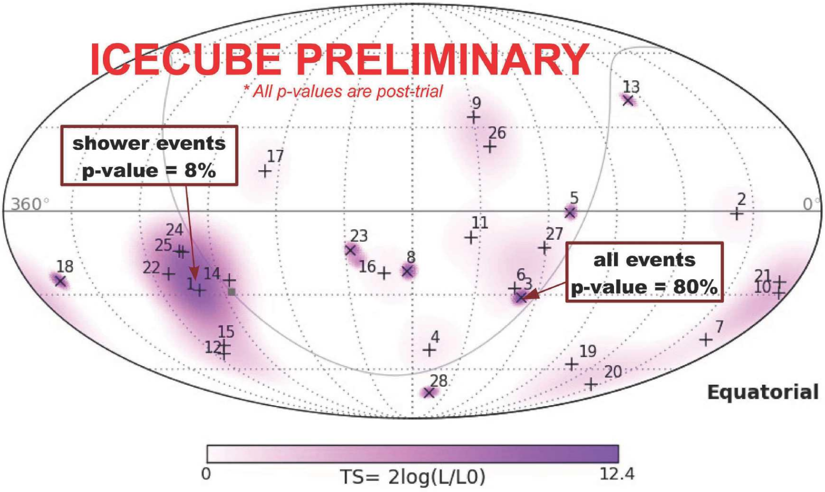
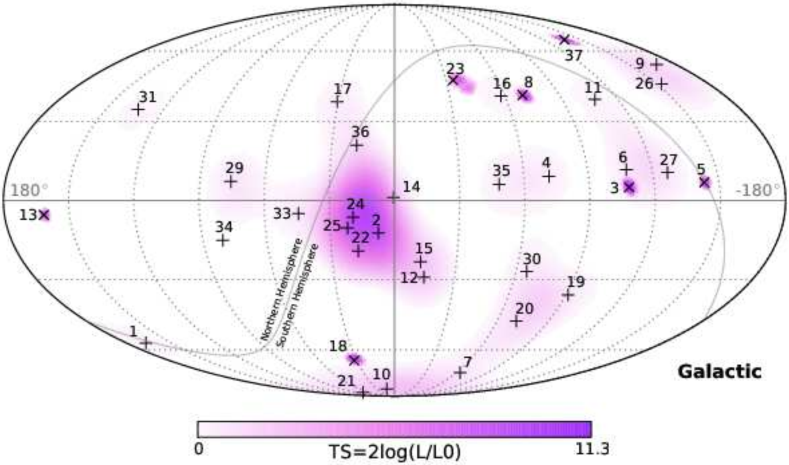
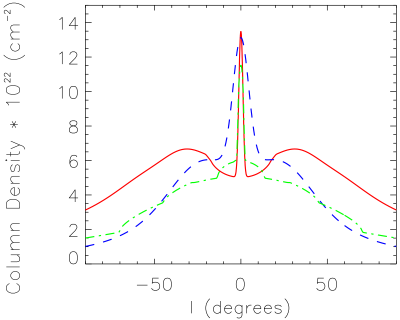
IceCube events: 2 years 28 events

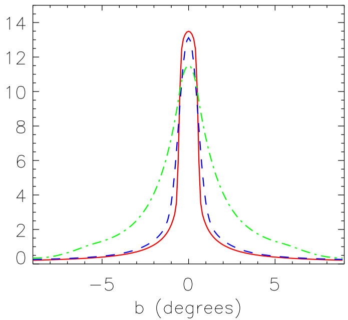


IceCube events: 3 years 36 events



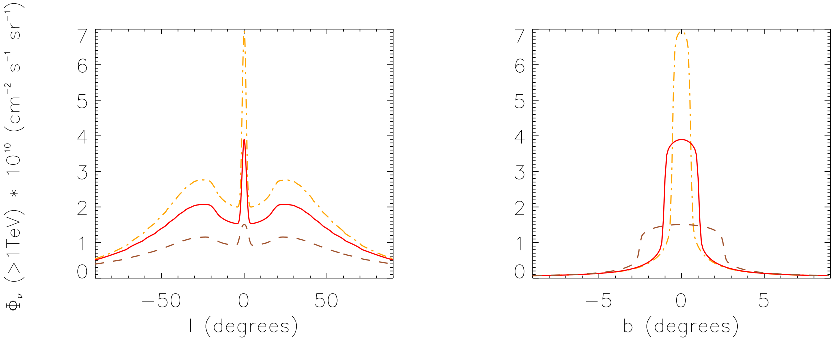
Column density of gas





[*Evoli, Grasso, Maccione '07*]

Diffuse ν flux from Galactic plane



[*Evoli, Grasso, Maccione '07*]

averaged over 1,2,5 degrees

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Flavour ratio

- ratio $R = N_{\rm sh}/N_{\rm tr} \sim (N_e + N_\tau)/N_\mu \sim 21/7$ consistent with 1:1:1
- including atm. bg. favors (weakly) 1:0:0 at source *[Mena, Palomares, Vincent '14]*

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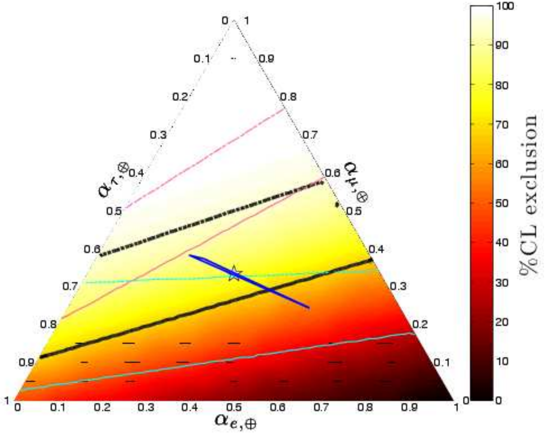


Sources of high-energy neutrinos

Galactic sources:

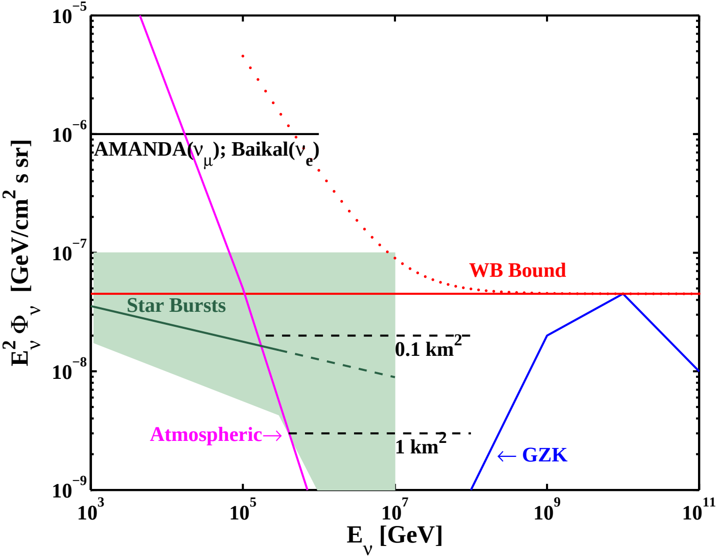
- Galactic plane and bulge
- SNR
- hypernova, GRB
- micro-quasar, . . .

Extragalactic sources:

- diffuse flux from normal/starburst galaxies
- cosmogenic neutrinos
- diffuse flux from AGN
- GRB
- single AGN, . . .

Dark matter decays, topological defects

Diffuse ν flux from normal and starburst galaxies



[*Loeb, Waxman '06*]

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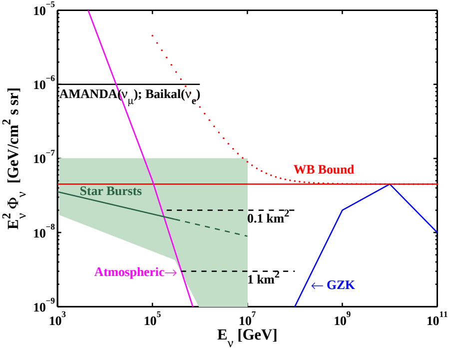
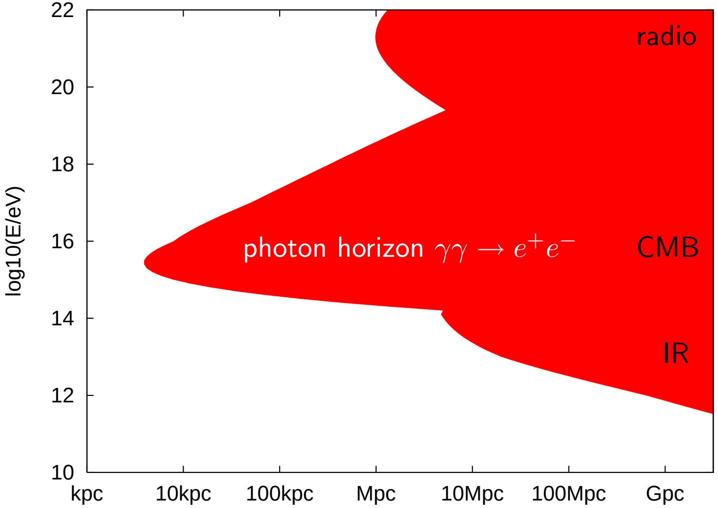


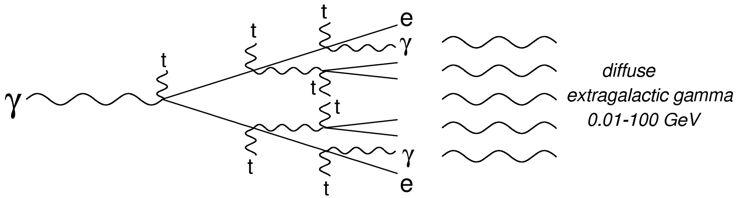
[*Loeb, Waxman '06*]

- too optimistic?
  - fraction of starburst galaxies?
  - all calorimetric?

Reminder: The photon horizon



Development of the elmag. cascade:



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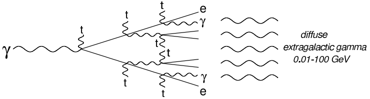


- analytical estimate: [Strong '74, Berezinsky, Smirnov '75]

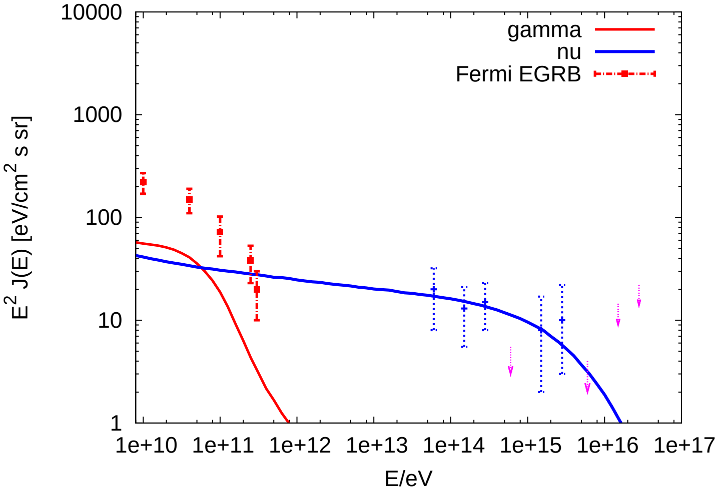
$$J_\gamma(E) = \begin{cases} K(E/\varepsilon_{\rm X})^{-3/2} & \text{at} \quad E \le \varepsilon_{\rm X} \\ K(E/\varepsilon_{\rm X})^{-2} & \text{at} \quad \varepsilon_{\rm X} \le E \le \varepsilon_{\rm a} \\ 0 & \text{at} \quad E > \varepsilon_{\rm a} \end{cases}$$

- three regimes:
  - Thomson cooling:

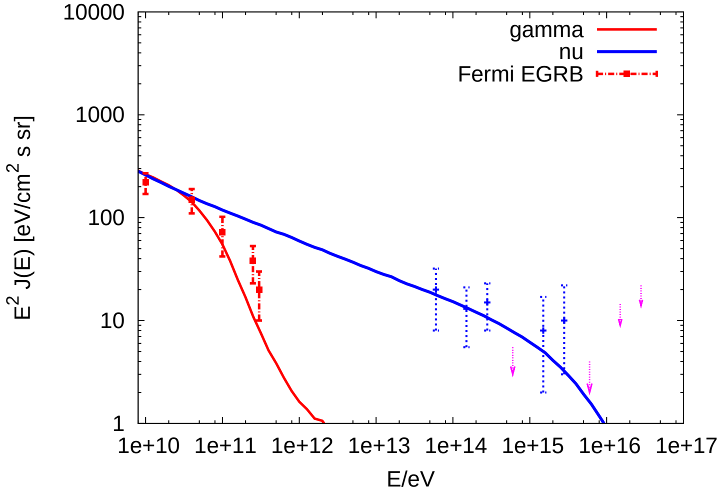
$$E_\gamma = \frac{4}{3}\frac{\varepsilon_{\rm bb}E_e^2}{m_e^2} \approx 100\,{\rm MeV}\left(\frac{E_e}{1{\rm TeV}}\right)^2$$

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

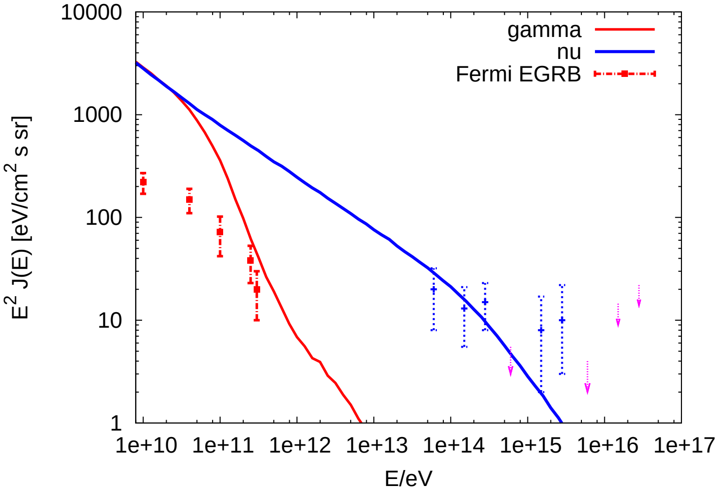
Cascade limit: for pp interactions, $\alpha = 2.1$



Cascade limit: for pp interactions, $\alpha = 2.3$



Cascade limit: for pp interactions, $\alpha = 2.5$



Cascade limit: pp vs. pγ interactions

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- pγ interactions:
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  - can be modified by max. energy & redshift evolution
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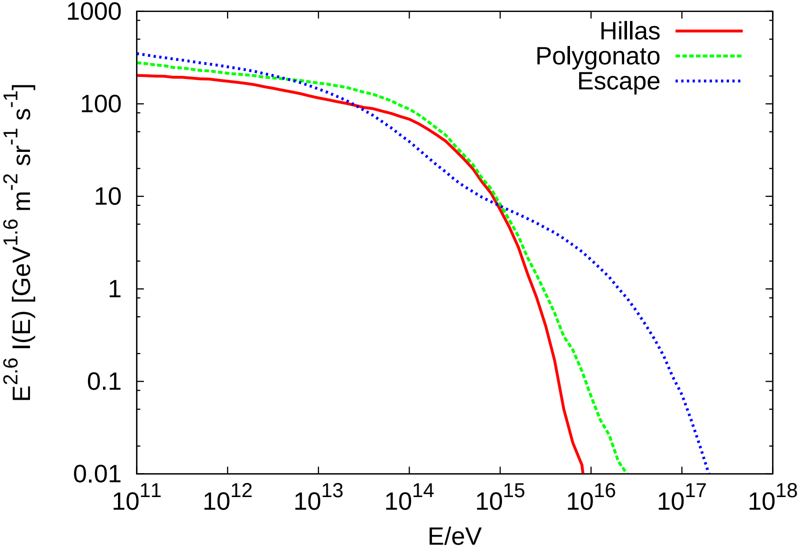
  - successful paradigm: Stecker model

Neutrinos from Galactic Sea CRs: $X = 30\,\mathrm{g/cm}^2$



[MK, S.Ostapchenko '14]

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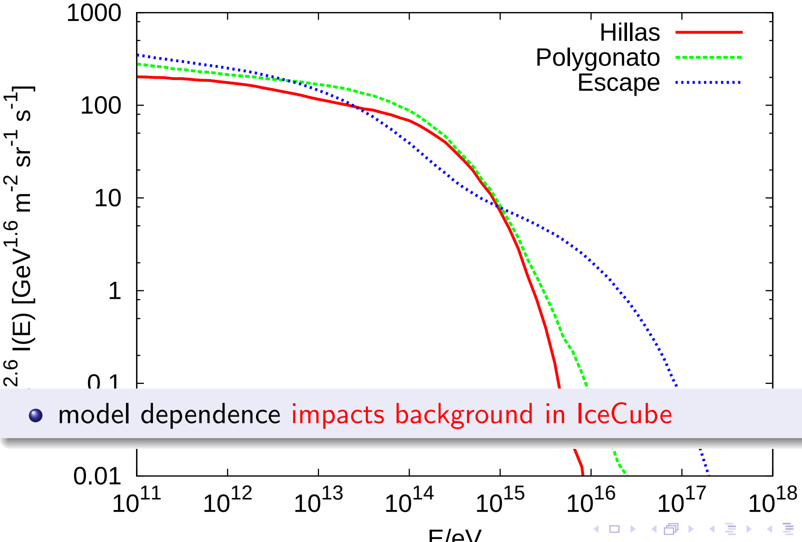

- model dependence impacts background in IceCube

Neutrinos from Galactic Sea CRs

gives negligible contribution to IceCube signal

- τ_{pp} is too small even towards GC
- gas is concentrated as $n(z) \sim n_0 \exp[-(z|/z_{12})^2]$ with $z_{12} \sim 0.2\,\mathrm{kpc}$

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results apply 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: $E_{\max} \sim B_{\rm CR}$, neutrino knee at few $\times 10^{14}\,$eV

Galactic sources

- at low energies:
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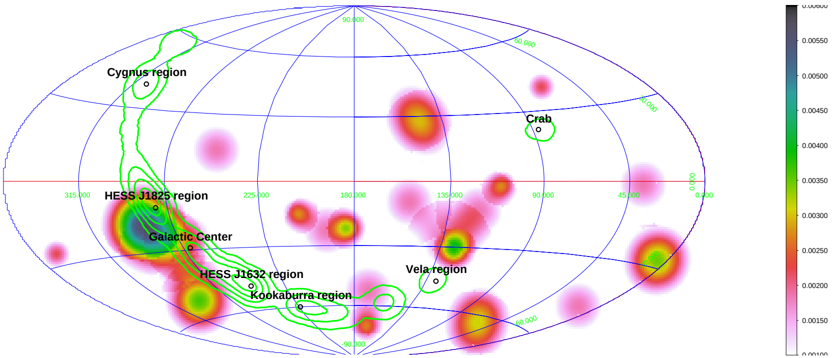
- close to the knee:
  - CRs in PeV range spread fast
  - few extreme sources
  - ⇒ inhomogenous CR sea, extended sources
  - ⇒ no clear distinction between point sources vs. Galactic bulge + plane cases

Point source in gamma-ray

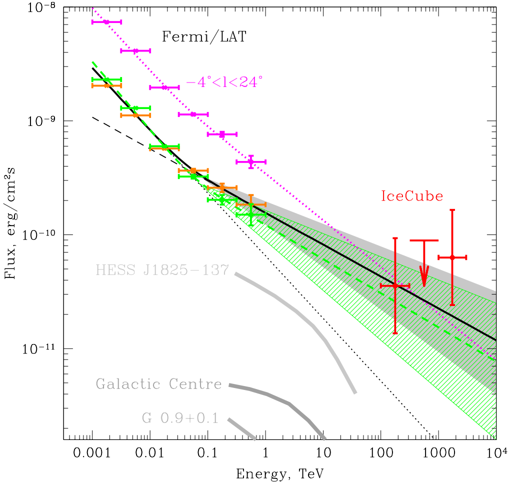
- source HESS J1825-137

[*Neronov, Semikoz, Tchernin '13*]

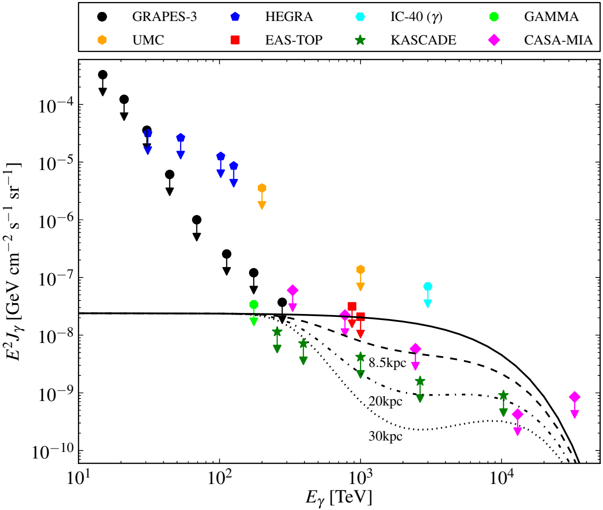


Gamma-ray point sources

- flux from HESS J1825-137, GC and GP



(Isotropic) photon limits



[Ahlers, Murase '13]

PeV dark matter

re-incarnation of SHDM idea for AGASA excess:

- non-thermal DM
- avoids cascacde limit
- Galactic anisotropy
- some option to move initial flavor ration $1:2:0$ towards $1:0:0$

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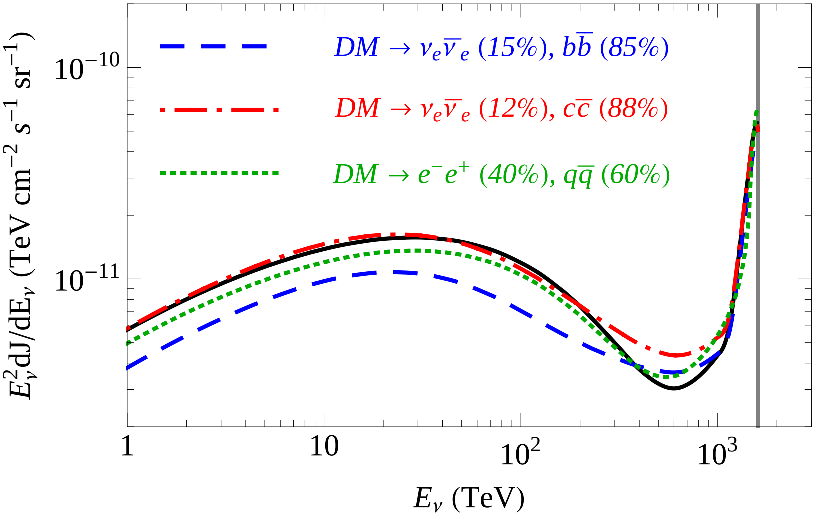

[Esmaili, Serpico '13]

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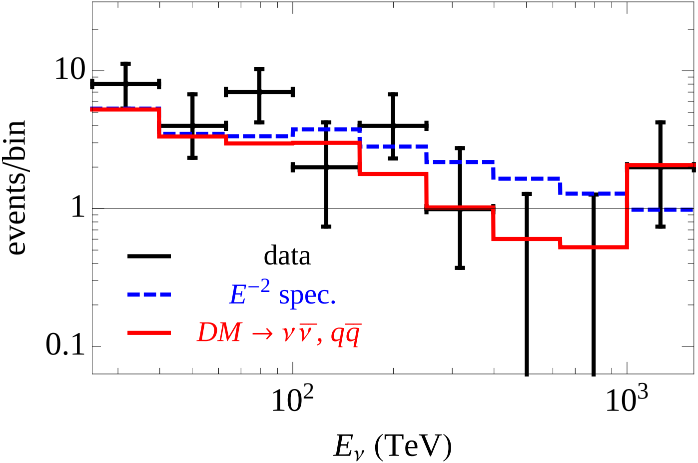

[*Esmaili, Serpico '13*]

Summary

- Knee due to CR escape
  - characteristic feature: recovery of p/He as suggested by KASCADE-Grande
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$\Rightarrow$ partly Galactic origin?

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3. some tension with (Northern) γ-ray limits

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   - ★ diffuse, difficult to identify
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