Charged Cosmic Rays and Neutrinos

Michael Kachelrieß

NTNU, Trondheim

Outline of the talk

1. Introduction ⇒ talk by F. Halzen
2. SNRs as Galactic CR sources
3. Extragalactic CRs
   - transition
   - anisotropies
   - composition measurements
4. Astrophysical source models ⇒ talks of S. Ando & F. Halzen
5. Cosmogenic neutrinos
6. Summary

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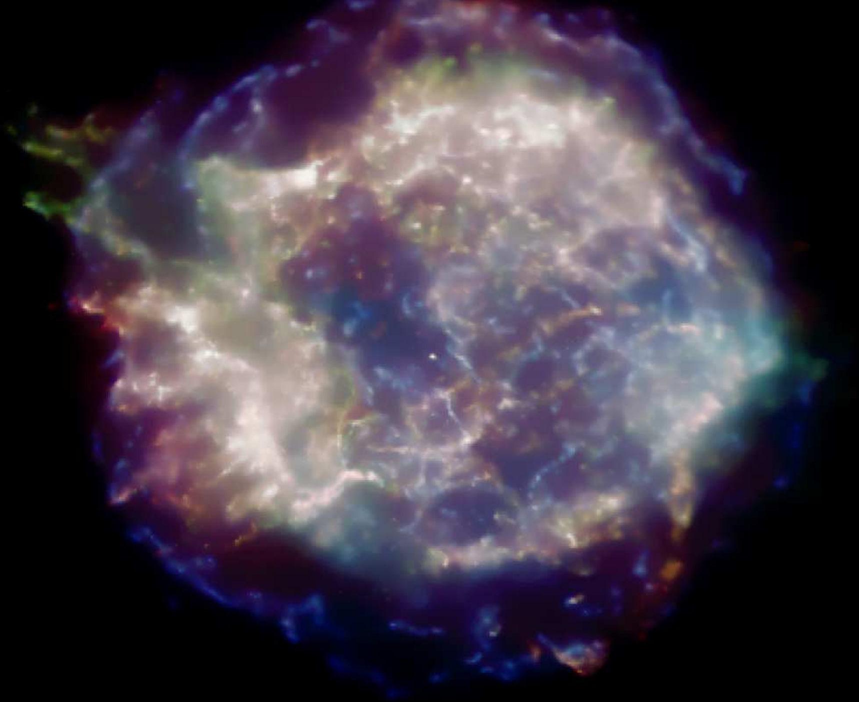
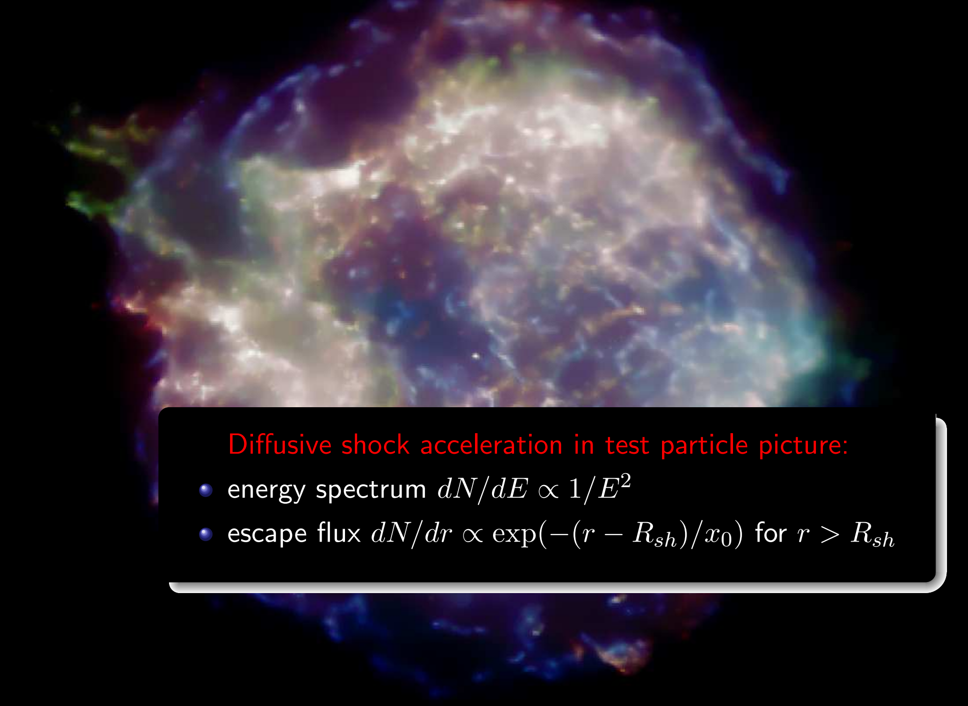
- prizes to win:
  - astronomy above 100 TeV
  - identification of CR sources
  - determine galactic–extragalactic transition of CRs
  - test/discover new particle physics



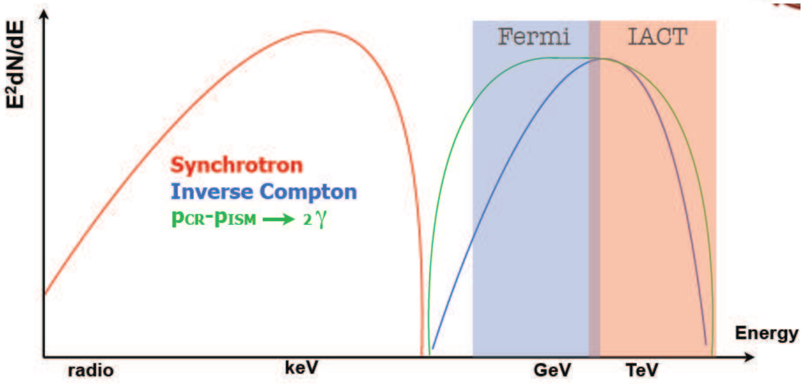


Diffusive shock acceleration in test particle picture:

- energy spectrum $dN/dE \propto 1/E^2$
- escape flux $dN/dr \propto \exp(-(r - R_{sh})/x_0)$ for $r > R_{sh}$

SNR: Leptonic versus hadronic models

[⇒ *Giordano*]



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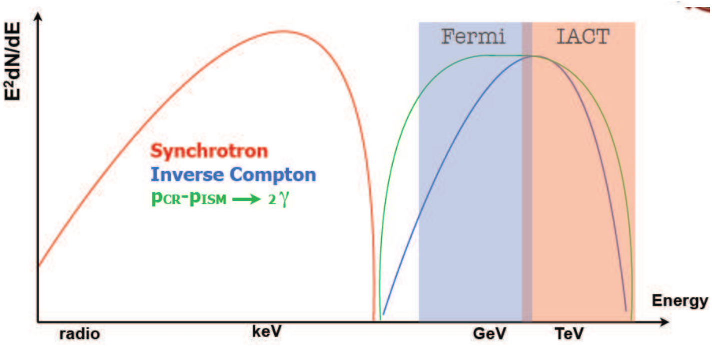

- combining Fermi and IACT contrains models tightly

Maximal energy of SNR: Lagage-Cesarsky limit

- acceleration rate

$$\beta_{\rm acc} = \left.\frac{dE}{dt}\right|_{\rm acc} = \frac{3Ev_{sh}^2}{\zeta D(E)} \quad , \qquad \zeta \sim 8-20$$

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$\Rightarrow$ $E_{\rm max} \sim 10^{13}$—10^{14} eV

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[Bell, Luzcek '02, Bell '04]

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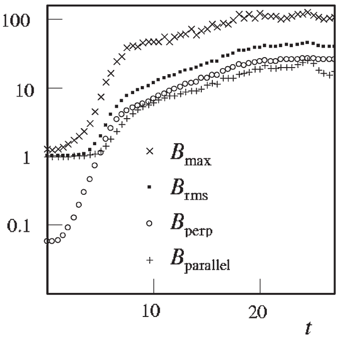

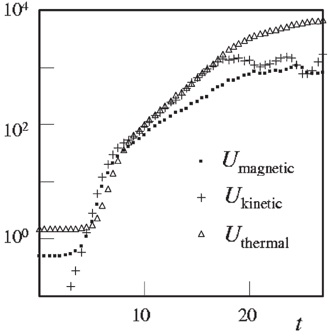

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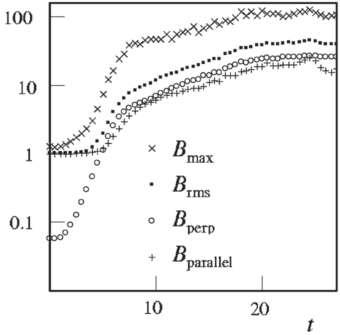
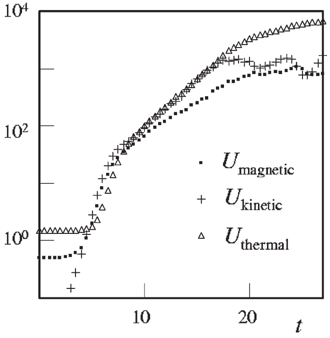
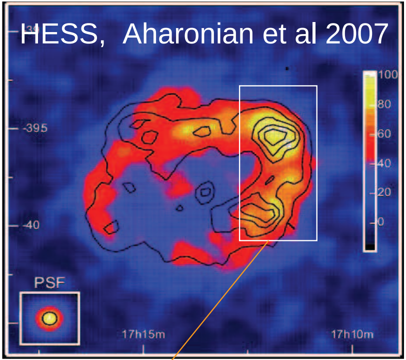
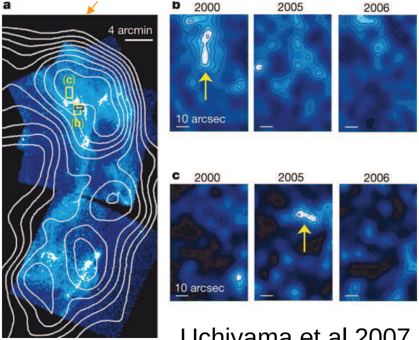




- observational evidence for $B \sim 0.1 - 1\,$mG in young SNR rims

SNR RX J1713.7-3946

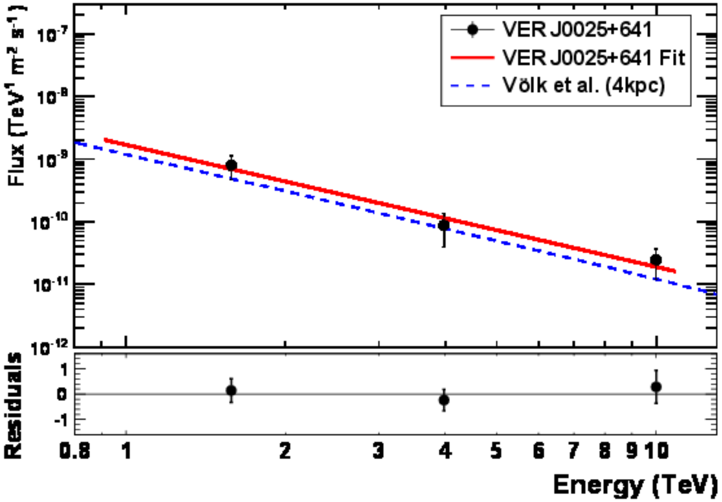




Uchiyama et al 2007

- changes on $\delta t \sim 1\,$yr imply $B \sim 1m$G
  $\Rightarrow E_{\max} \sim 10^{16}\,$eV for protons

Tycho observations by VERITAS



$$\Gamma = 1.95 \pm 0.51_{\rm stat} \pm 0.30_{\rm sys}$$

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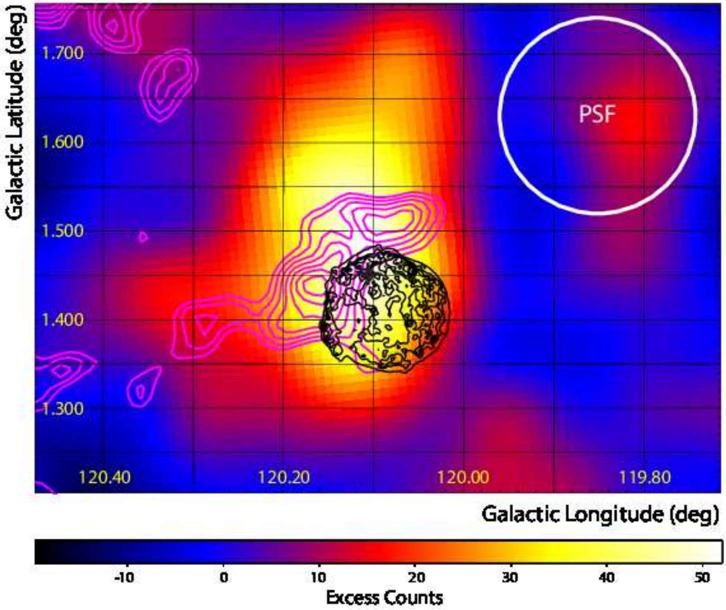

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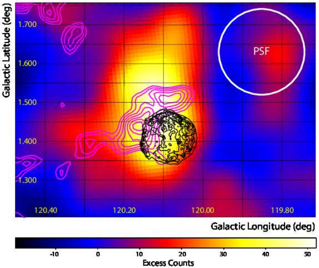

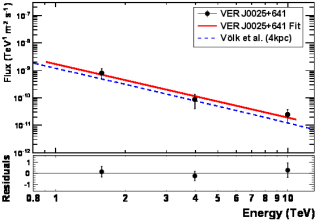

- CRs escape before Sedov phase

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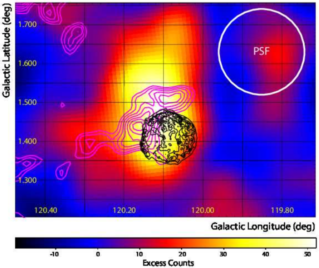

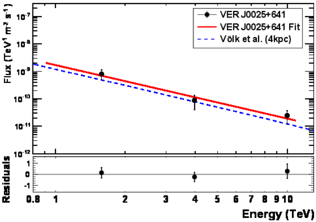

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  - protons with $E > 100$ TeV

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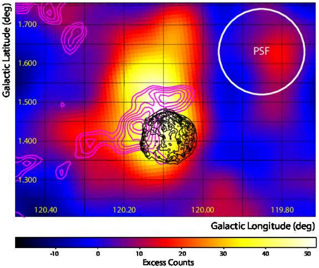

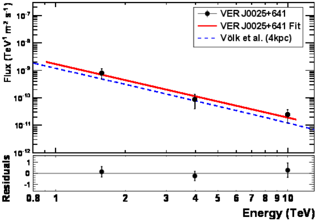

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$$E_\gamma = \frac{4}{3}\frac{\varepsilon_\gamma E_e^2}{m_e^2} \approx 3\,\text{GeV}\left(\frac{E_e}{1\text{TeV}}\right)^2$$

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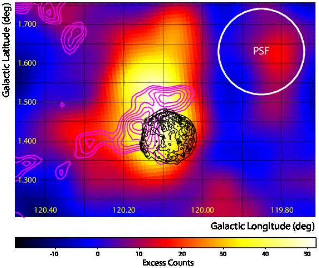

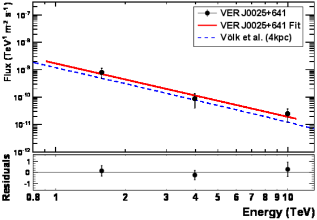

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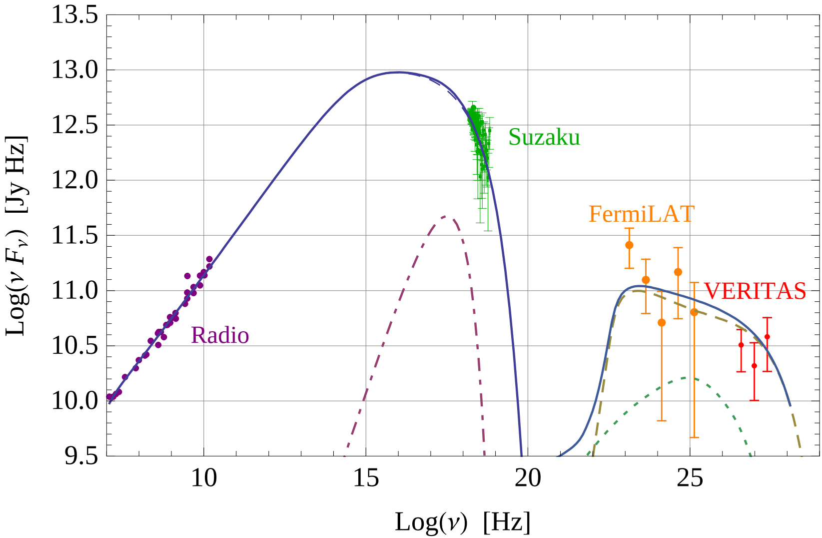
electrons with $E > 50$ TeV

Tycho: Leptonic versus hadronic models

[Morlino, Capriolo '11]



Why is there a universal CR spectrum?

- age-limited
  - CRs are advected down-stream, released at end of Sedov phase
  - adiabatic losses, reduced $E_{\max}$, no B amplification

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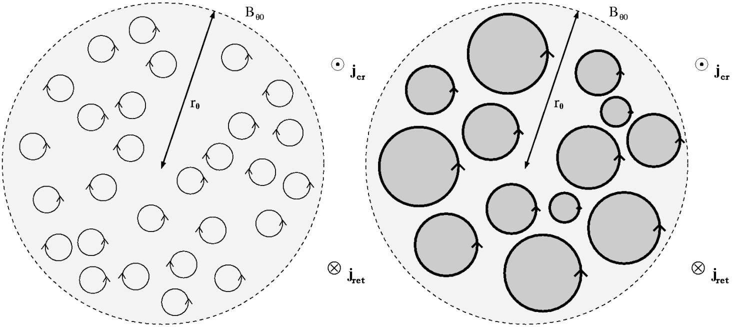

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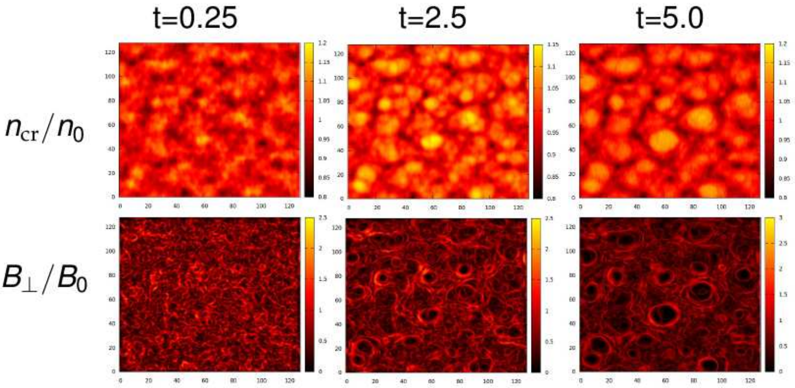
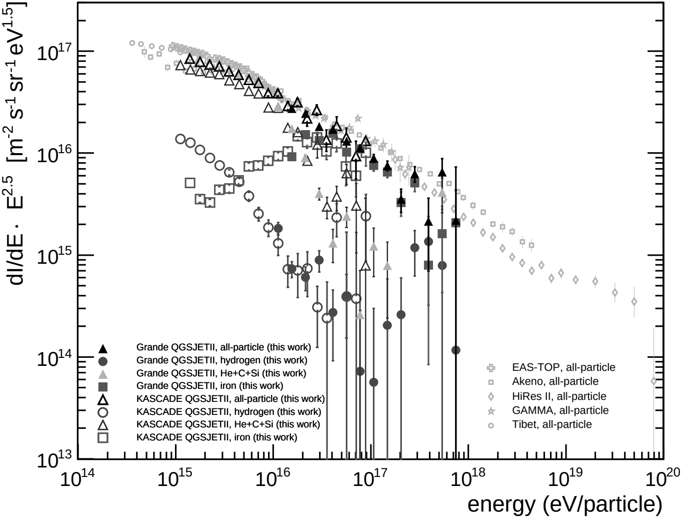


Transition – KASCADE Grande data



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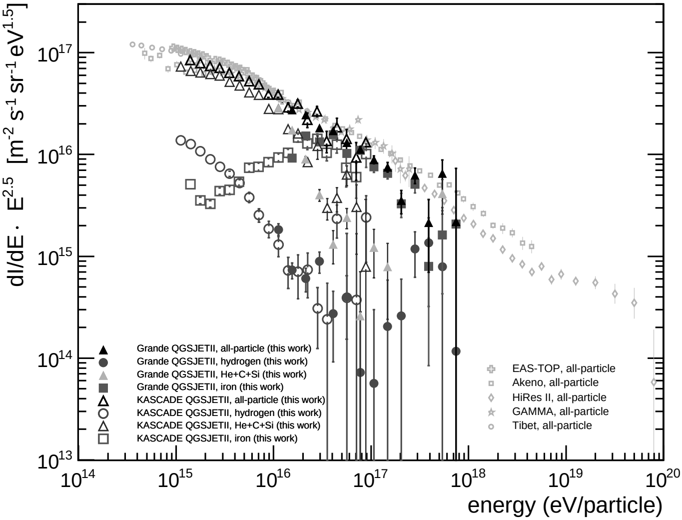
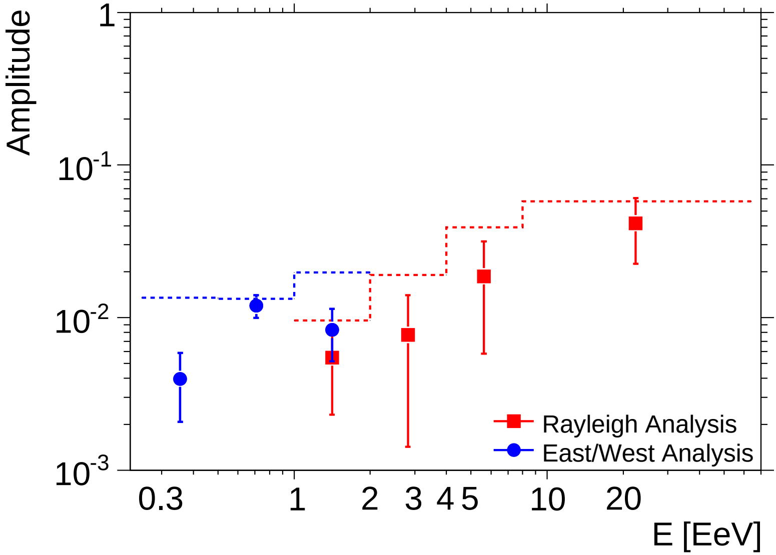


- rising proton fraction $E \gtrsim 10^{17}$ eV?

PAO result on dipole anisotropy:



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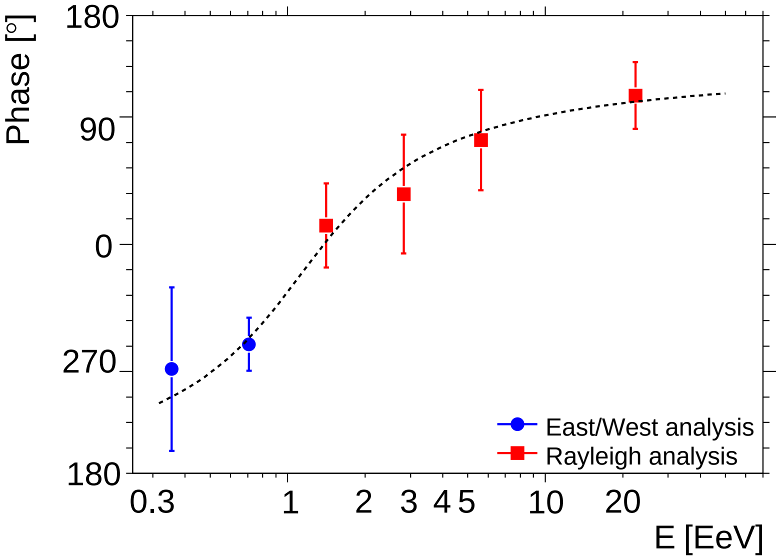
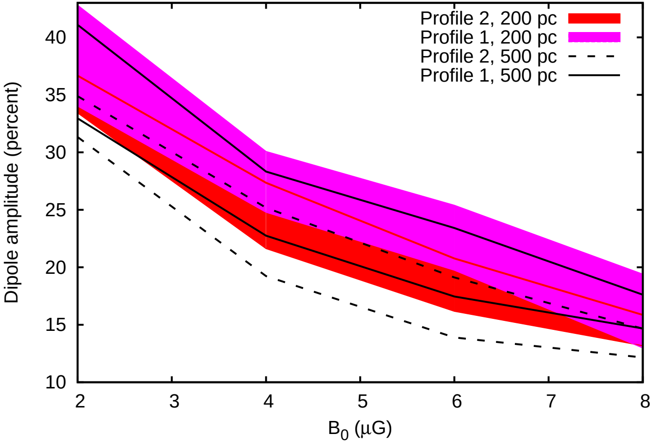


Anisotropy of protons at $E = 10^{18}$ eV

[*Giacinti et al. '11*]

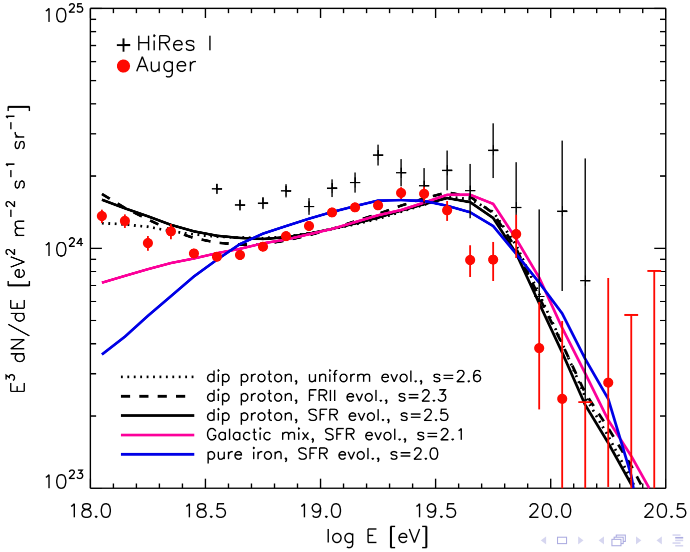


- protons excluded for all reasonable parameters

$\Rightarrow$ measuring protons at $E = 10^{18}$ eV means fixing transition energy

Energy spectrum

- PAO confirmed the "GZK-suppression" seen first by HiRes



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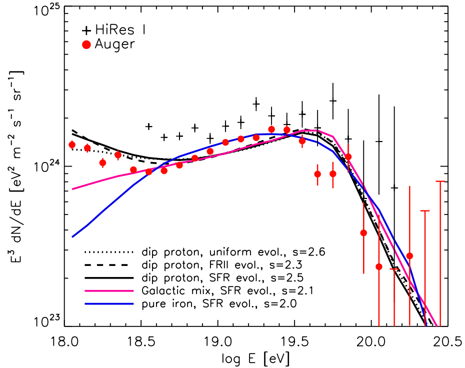

- interpretation:
  - $E_{\rm max}$ of sources?
  - does not fix composition: proton GZK, Fe photo disintegration

Determining nuclear composition: $X_{\rm max}$ and RMS$(X_{\rm max})$

- Bethe-Heitler model: $N_{\rm max} \propto E_0$ and $X_{\rm max} \propto \ln(E_0)$

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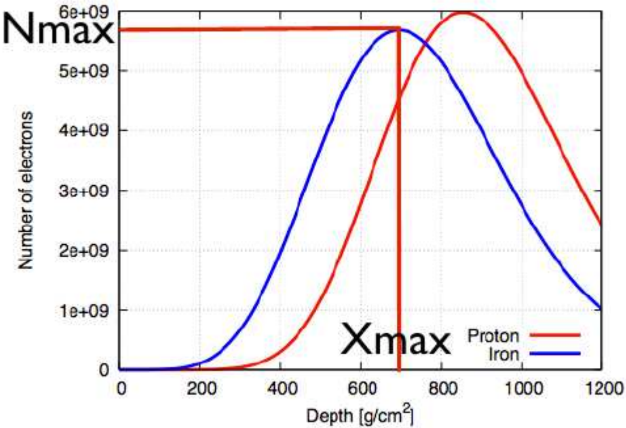

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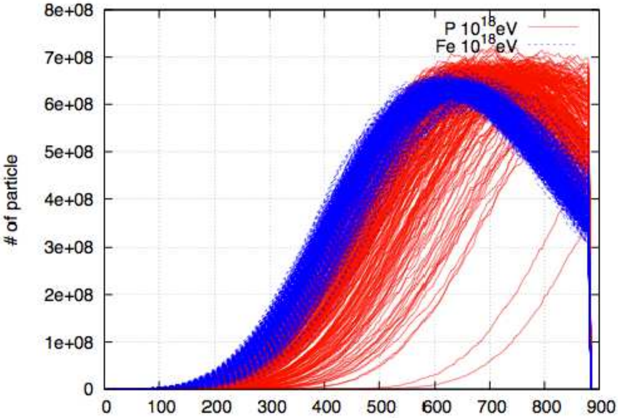

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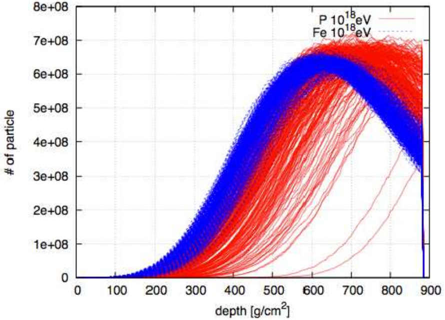
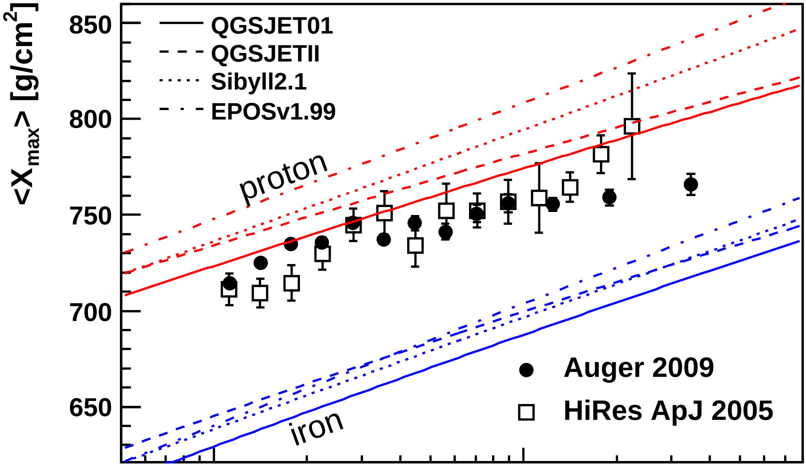
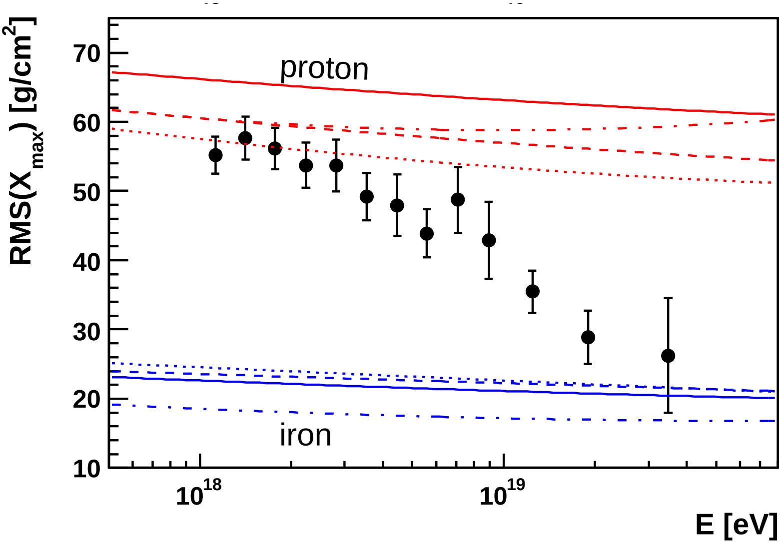


- RMS$(X_{\max})$ has smaller theoretical error than $X_{\max}$

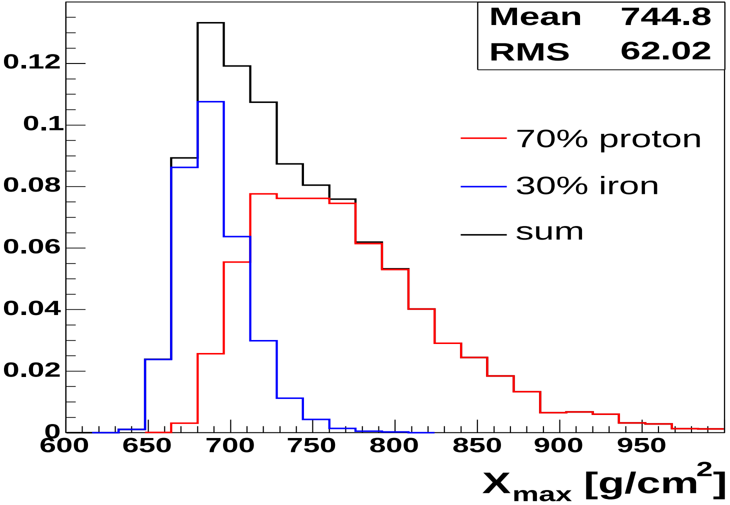
Nuclear composition via $X_{\rm max}$:



Nuclear composition via RMS($X_{\max}$) from Auger:



Mixed composition:



$$\sigma^2 = \sum_i f_i \sigma_i^2 + \sum_{i<j} f_i f_j (X_{\max,i} - X_{\max,j})^2$$

What goes wrong?

- internal discrepancy in PAO:
  - AGN correlations favor protons
  - RMS($X_{\max}$) favors heavy
  - energy spectrum, $X_{\max}$ and RMS($X_{\max}$) difficult to fit
- experimental discrepancy: HiRes/TA $\Leftrightarrow$ Auger
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- discrepancy experiment $\Leftrightarrow$ theory:
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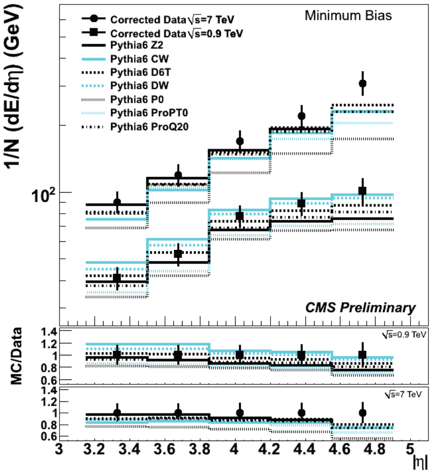
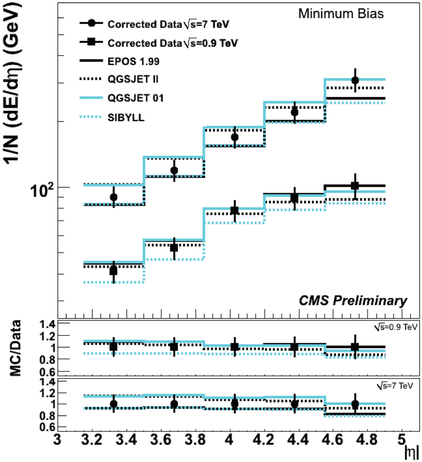
Comparison of MCs to LHC data: Energy flow

PYTHIA as typical HEP model

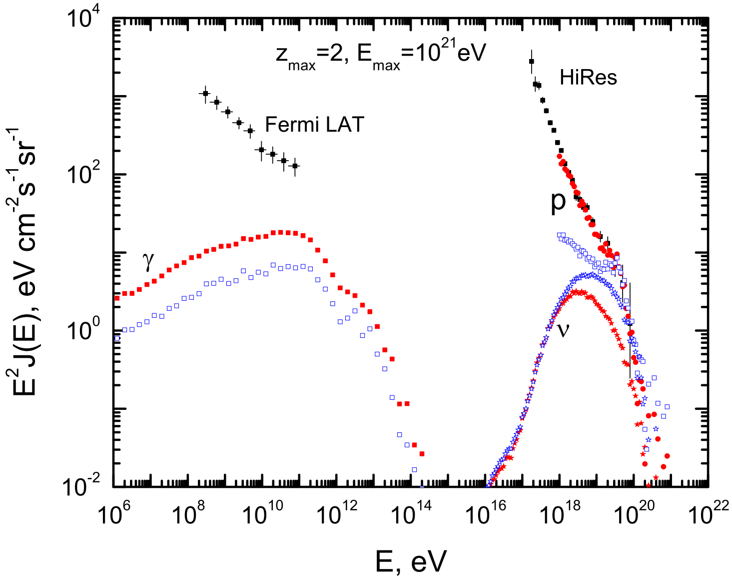


Cosmic ray interaction models



Fermi-LAT limit for cosmogenic neutrinos:

[*Berezinsky et al. '10,...*]



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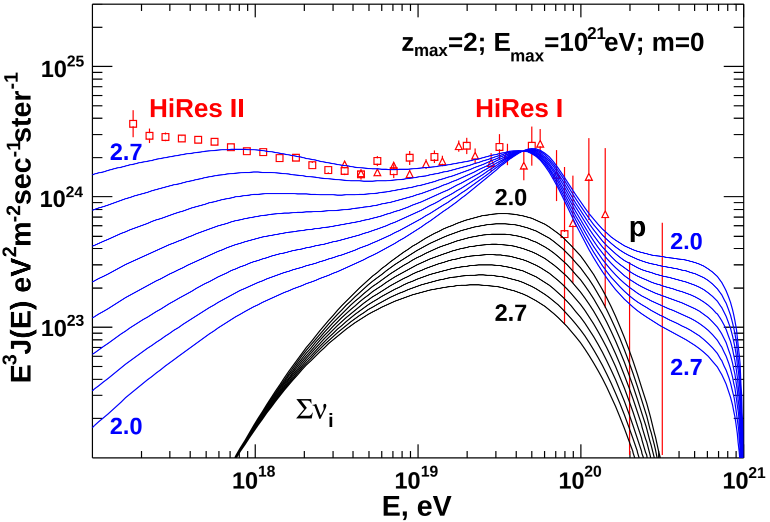

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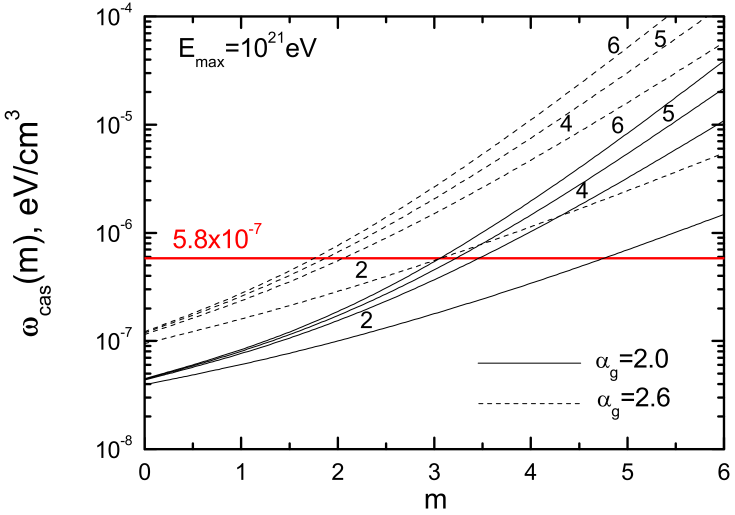

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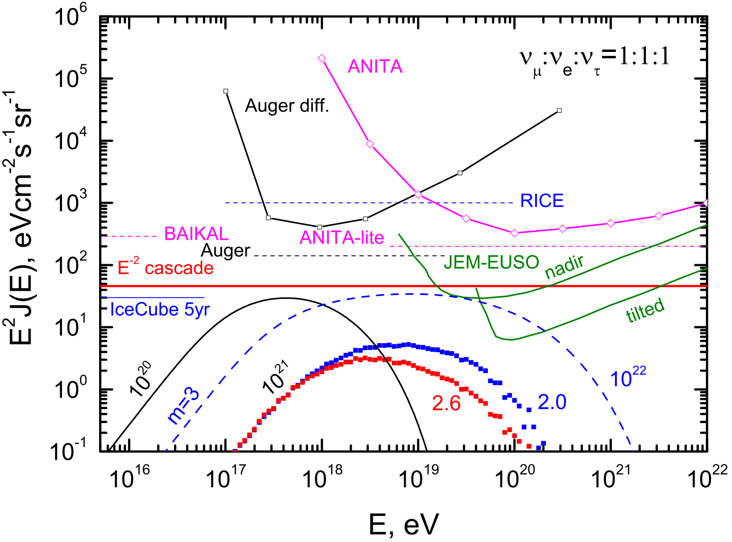

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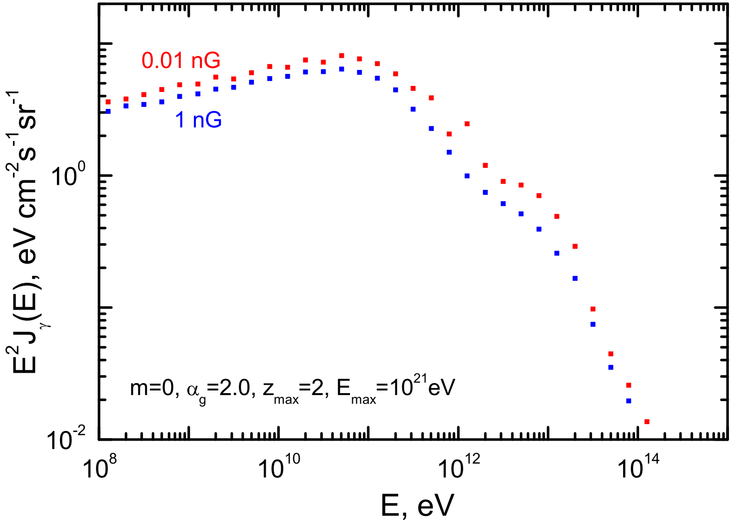
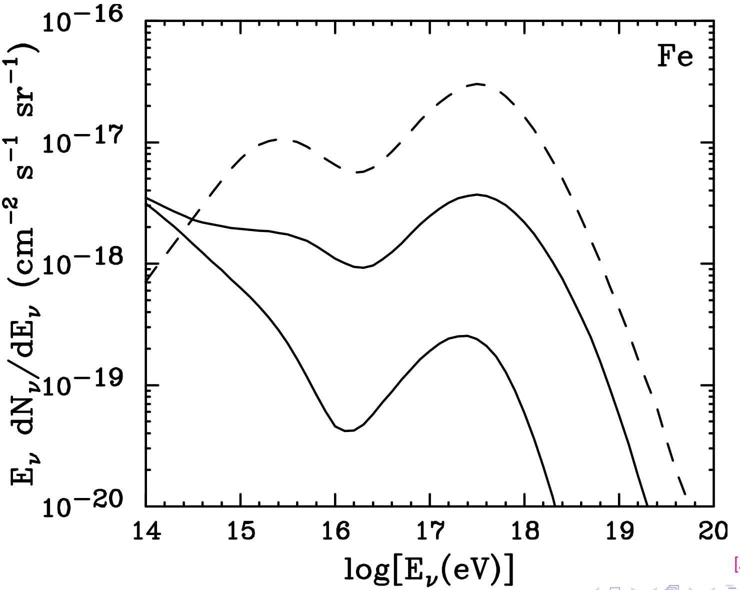


Cosmogenic neutrinos: proton vs. Fe



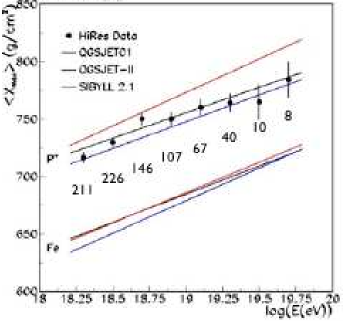
[*Anchordoqui et al. '07*]

Summary

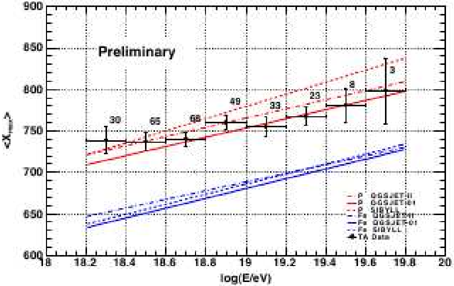
- Galactic CRs: Tycho: room left for leptonic models marginal
- UHECRs:
  - understanding differences PAO vs. TA and MC vs. experiment
  - extensions (HEAT, Amiga, infill array) allow cross checks
  - test of MC models against LHC data
  - proton dominance at 10^{18} eV fixes transition energy
- cosmogenic neutrino flux is low, because of Fermi limit
- 2 Icecube events: start of neutrino astronomy?

New TA data for $X_{\max}$:

HiRes

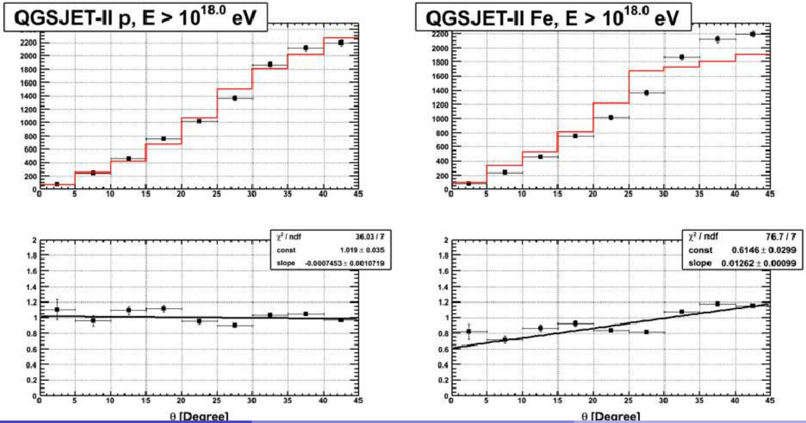


TA



Zenith angle dependence, TA scintillator:

Data/MC Comp. (TA-SD, Zenith angle)



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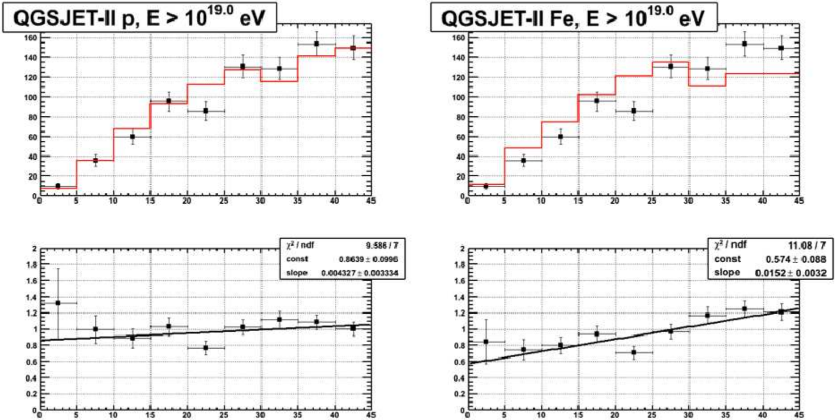
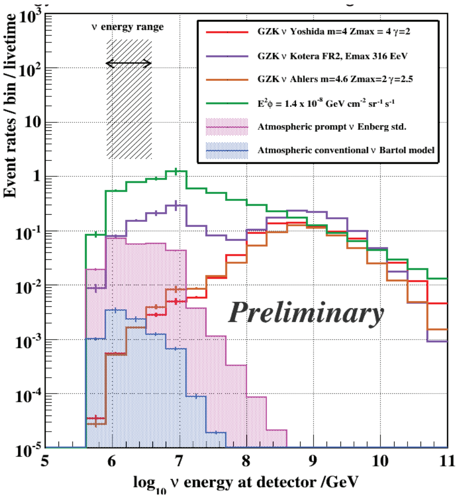


Icecube events

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



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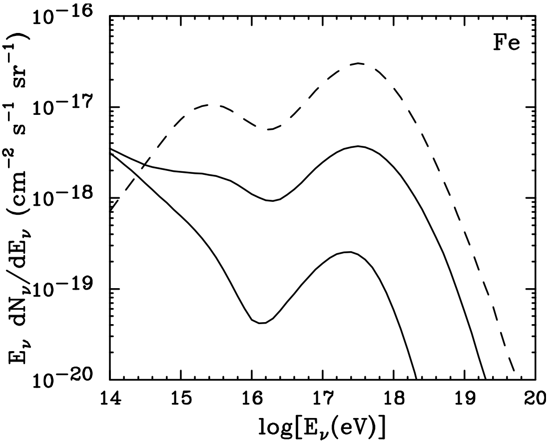
Icecube events

- 2 cascade events close to $E_{\rm min} = 10^{15}$ eV, bg = 0.14
- Glashow resonance
  - very narrow
  - if $W^- \to \bar{q}q$, detected energy too low

Icecube events

- 2 cascade events close to $E_{\min} = 10^{15}$ eV, bg $=$ 0.14
- Glashow resonance
- cosmogenic neutrinos: $\lesssim 1$ events/yr



[*Anchordoqui et al. '07*]

Icecube events

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- Glashow resonance
- cosmogenic neutrinos: $\lesssim 1$ events/yr
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  if yes, then diffuse flux

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- Glashow resonance
- cosmogenic neutrinos: $\lesssim 1$ events/yr
- extragalactic sources: extension to higher energies?
  if yes, then diffuse flux
- Galactic point sources: SNR with $d \sim 50$ pc