The High Energy Universe: Observations and Implications

Andreas Ringwald

http://www.desy.de/~ringwald

DESY

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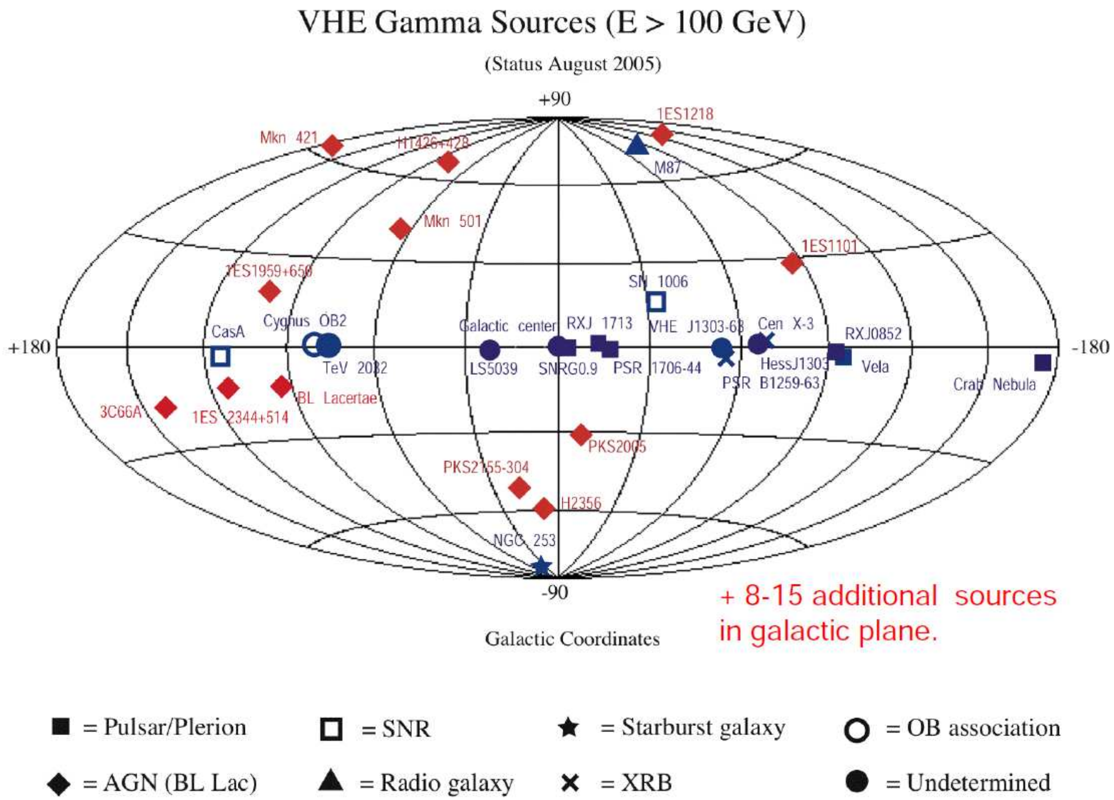
1. Introduction

- **There is a high energy universe:** **Gamma rays** have been identified up to energies $E \lesssim \text{few} \times 10^3$ GeV



[M. Martinez '05]

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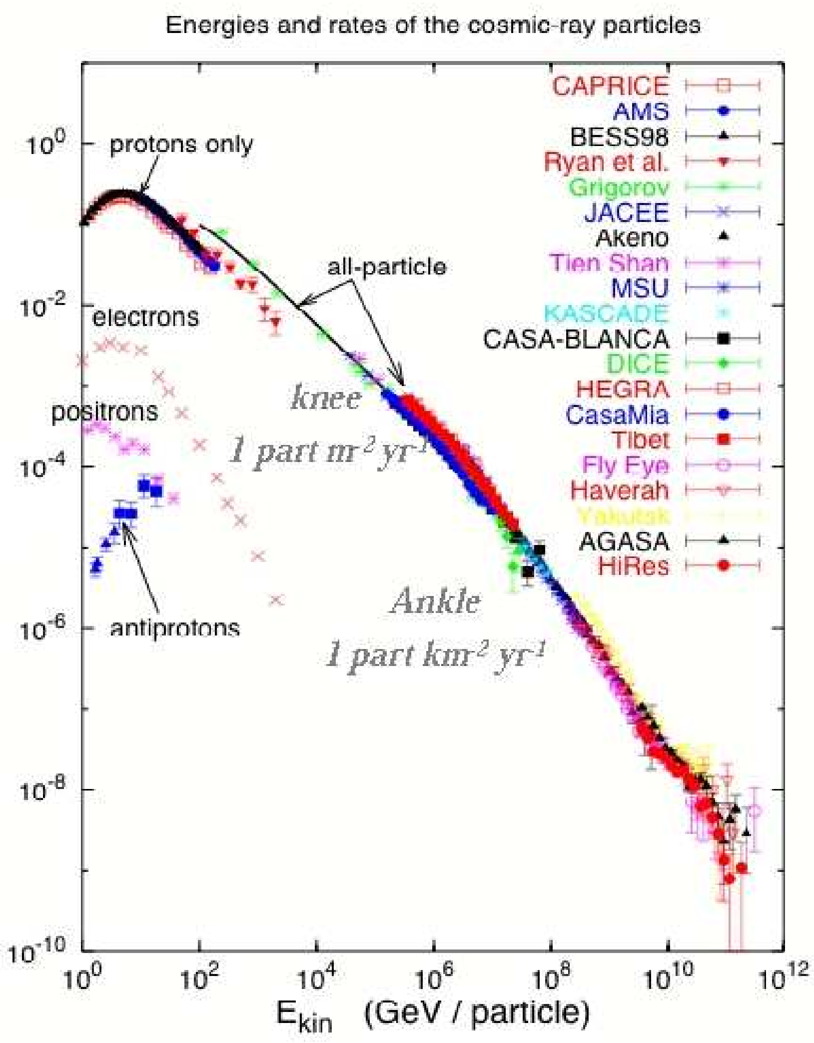

[T. K. Gaisser '05]

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  Gamma ray observatories: **e.g. H.E.S.S., MAGIC**

  Air shower detectors: **e.g. Pierre Auger Observatory**

[www.auger.org]

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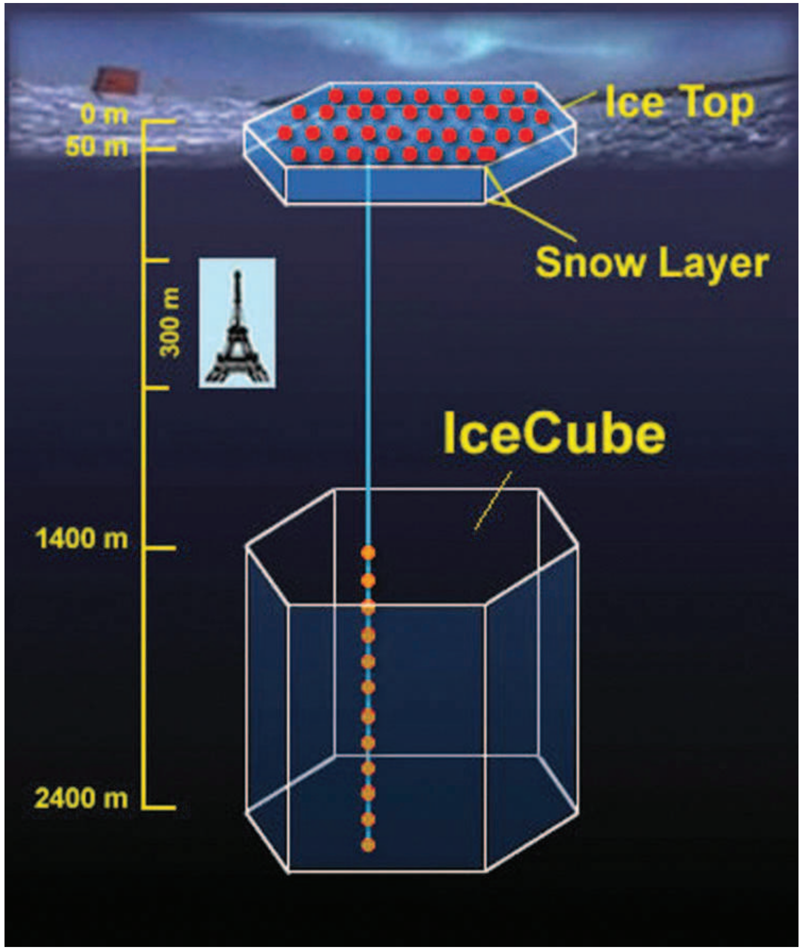
  Air shower detectors: **e.g. Pierre Auger Observatory**

  Neutrino telescopes: **e.g. IceCube**

- **Attack fundamental questions:**

  What is it made of? What are the cosmic accelerators? Can we exploit them also for particle physics?



[icecube.wisc.edu]

Outline:

2. **Observations at ultrahigh energies**

3. **Non-observations at ultrahigh energies**

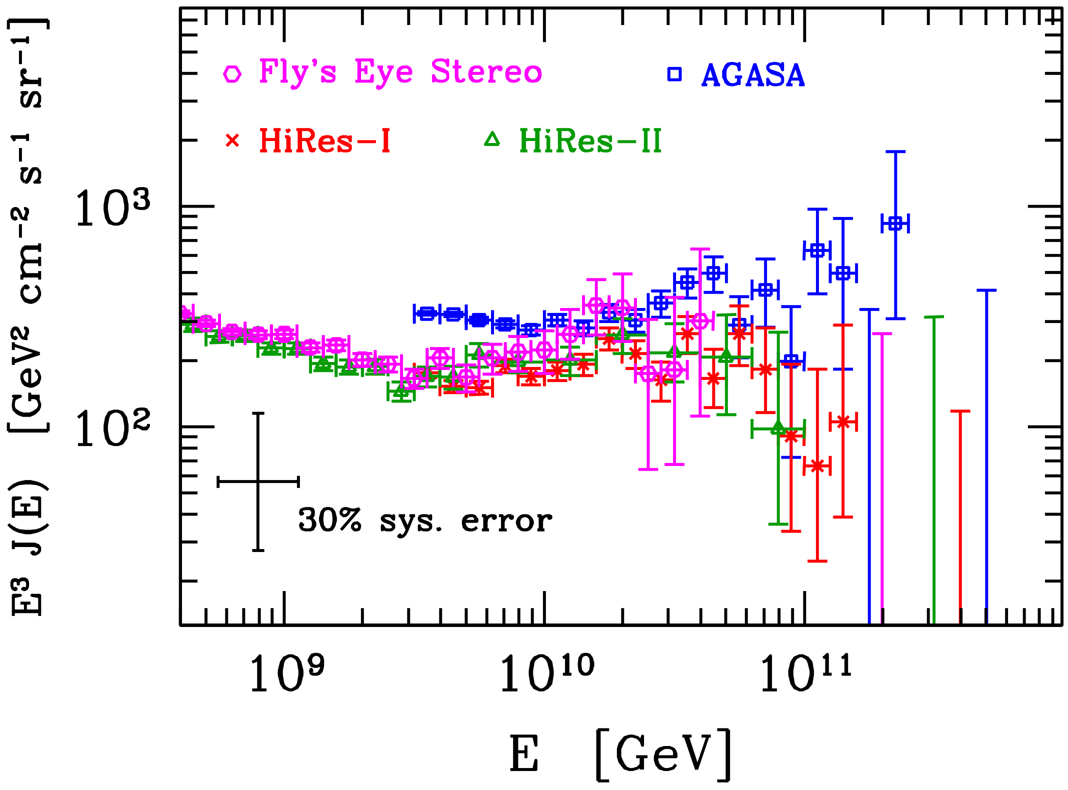
4. **Future observations at ultrahigh energies**

5. **Conclusions**

2. Observations at ultrahigh energies

- **Spectrum:** Large statistical and systematic uncertainties

⇐ low flux
⇐ energy from shower simulations



[Ahlers *et al.* '05]

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  $\Leftarrow$ energy from shower simulations

- Crucial improvement by **PAO**:

  $\Leftarrow$ huge size $\Rightarrow$ better statistics
  $\Leftarrow$ hybrid observations $\Rightarrow$ better energy calibration through Fly's Eye technique, direction from ground array

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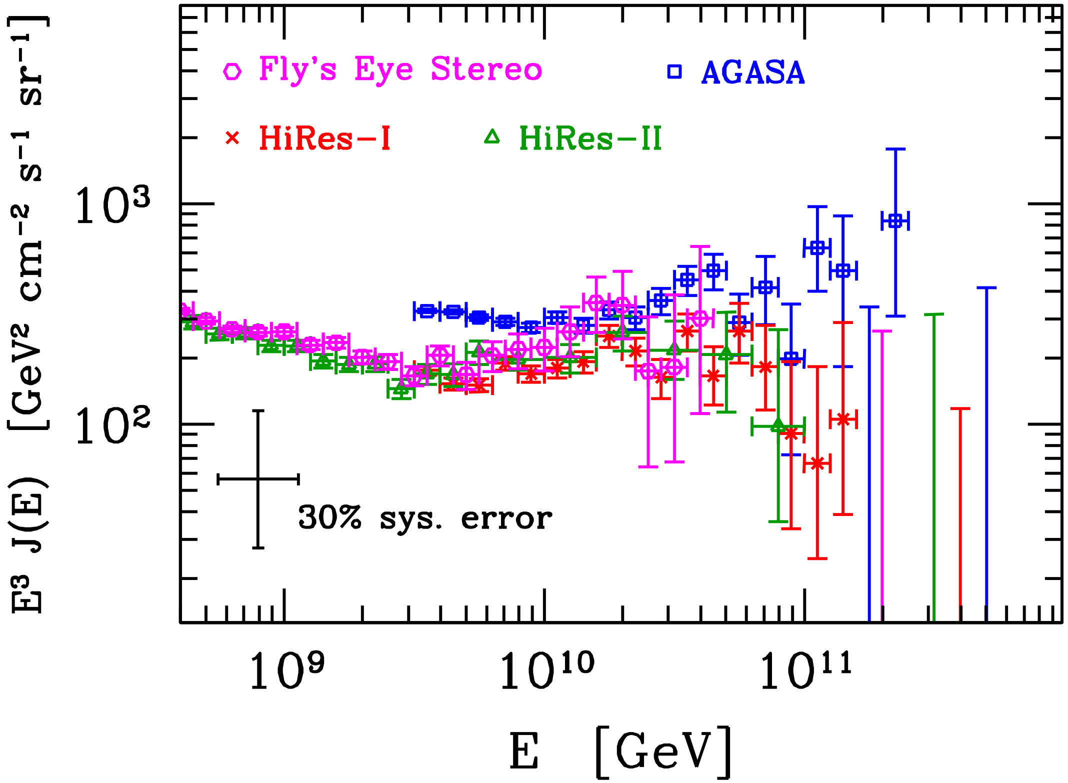

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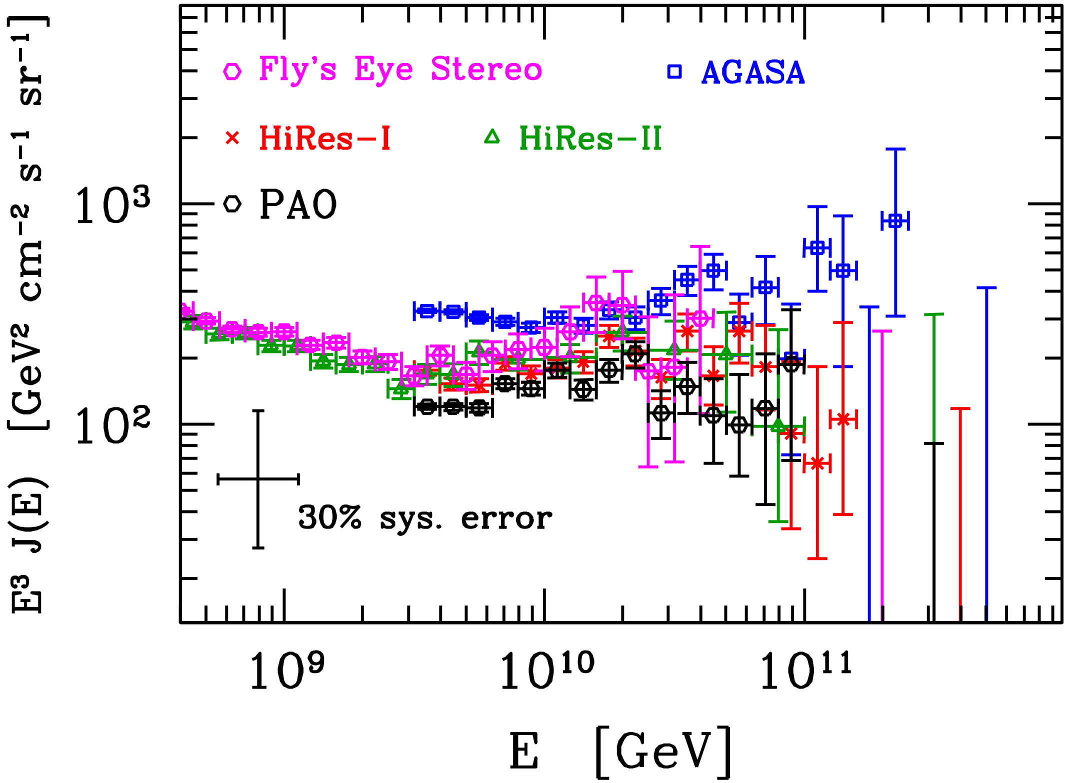

[Ahlers *et al.* '05]

2. Observations at ultrahigh energies

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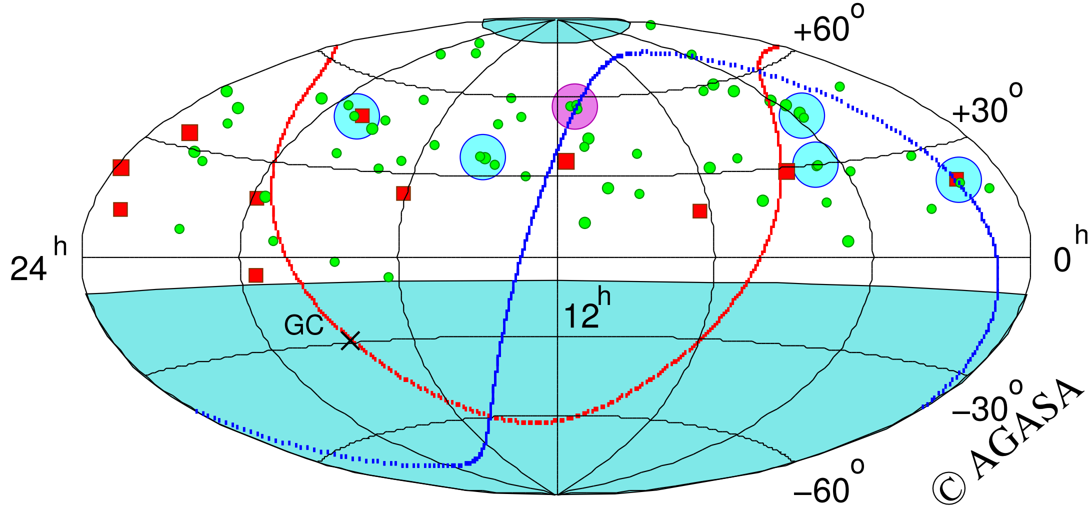

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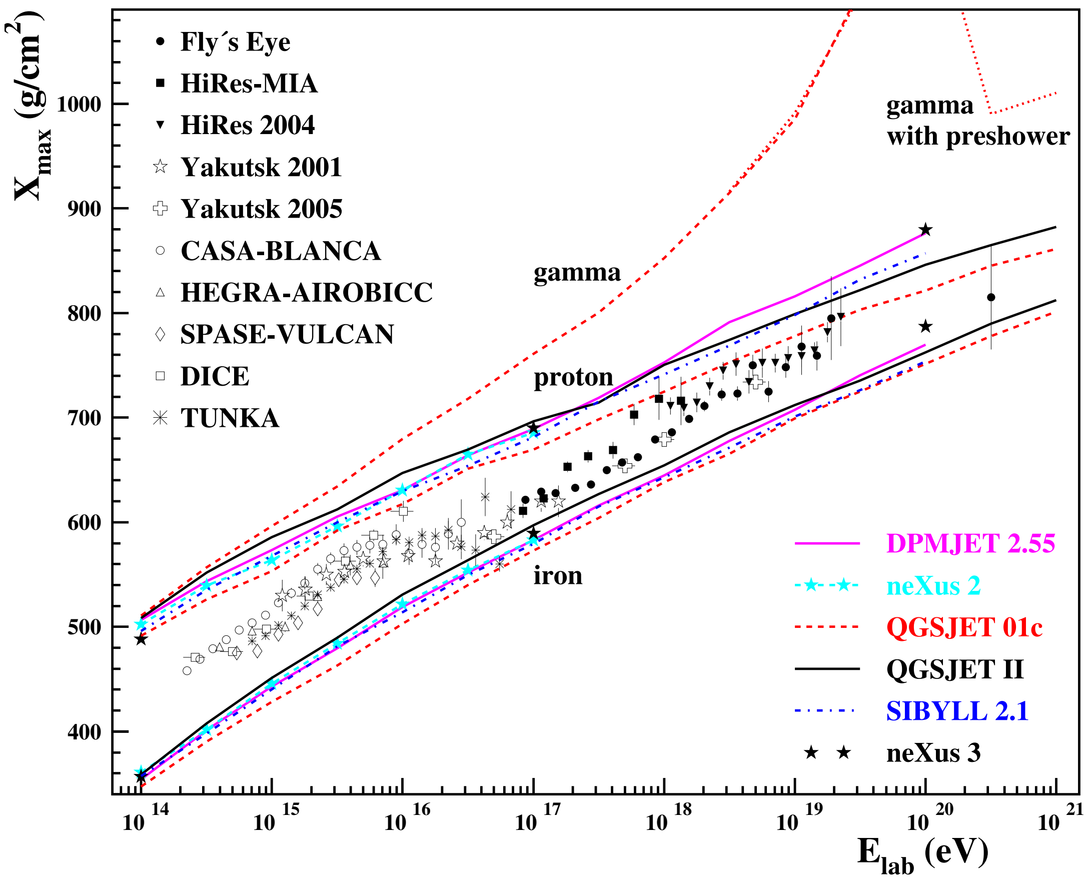
- Cosmic rays above $\gtrsim 10^{17.6}$ eV dominantly protons



[Heck '05]

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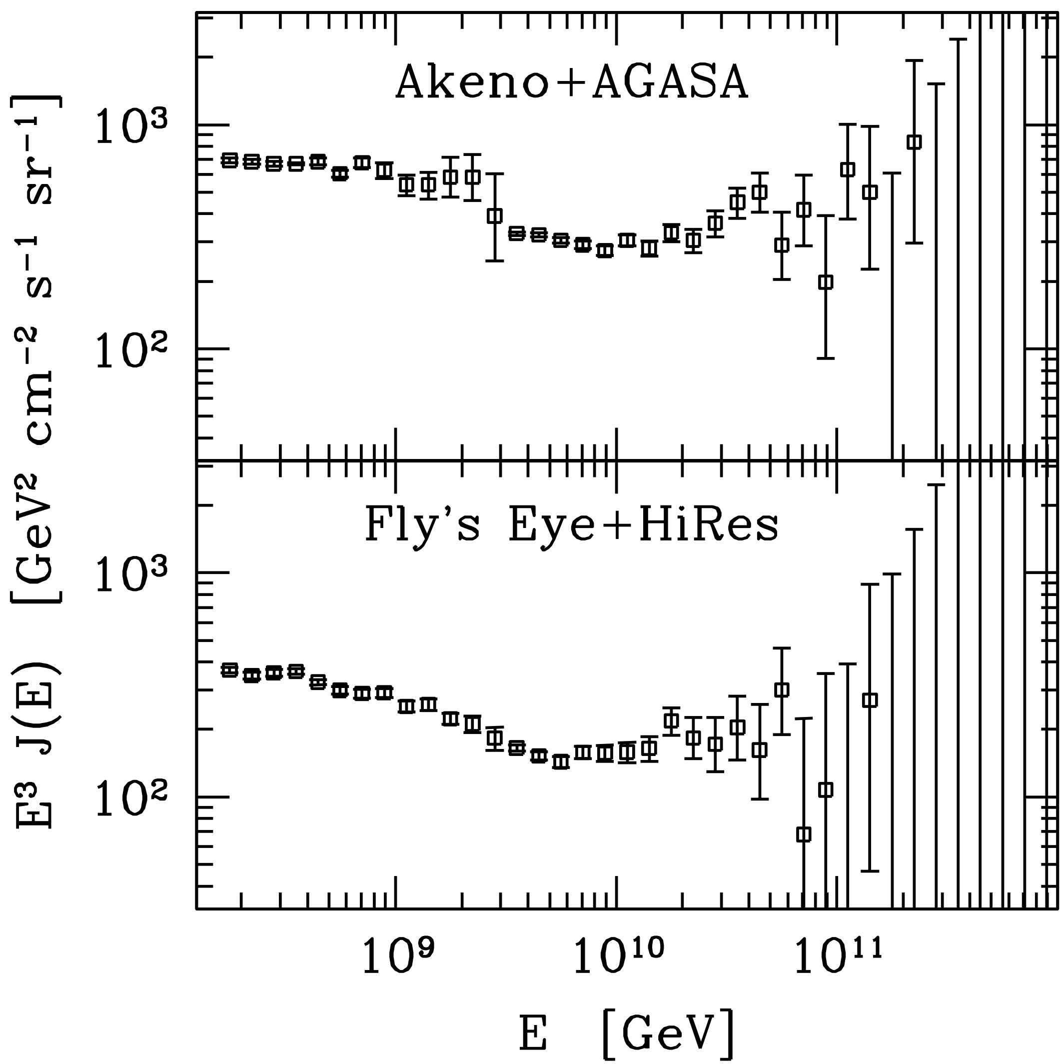
- Assume that CR's in $10^{[8.6,11]}$ GeV range originate from isotropically distributed extragalactic proton sources, with simple power-law injection spectra $\propto E_i^{-\gamma}(1+z)^n$

[Berezinsky,..'02-'05;...;Ahlers *et al.* '05]



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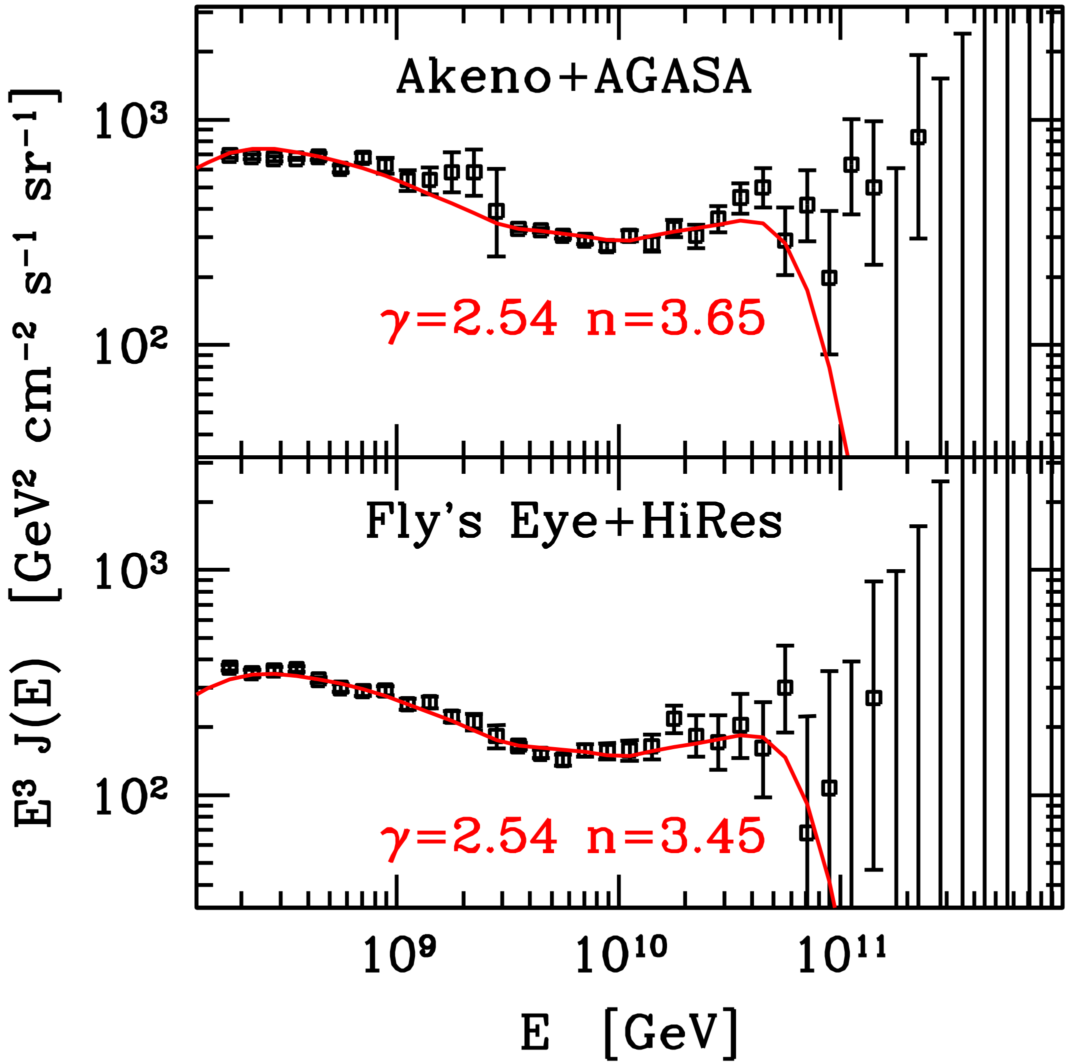
[Berezinsky,..'02-'05;...;Ahlers *et al.* '05]

$\Rightarrow$ Good fit; inelastic interactions with **CMB** (e^+e^- "dip"; π "bump") visible; some **post-GZK events**?

[Greisen;Zatsepin,Kuzmin '67]



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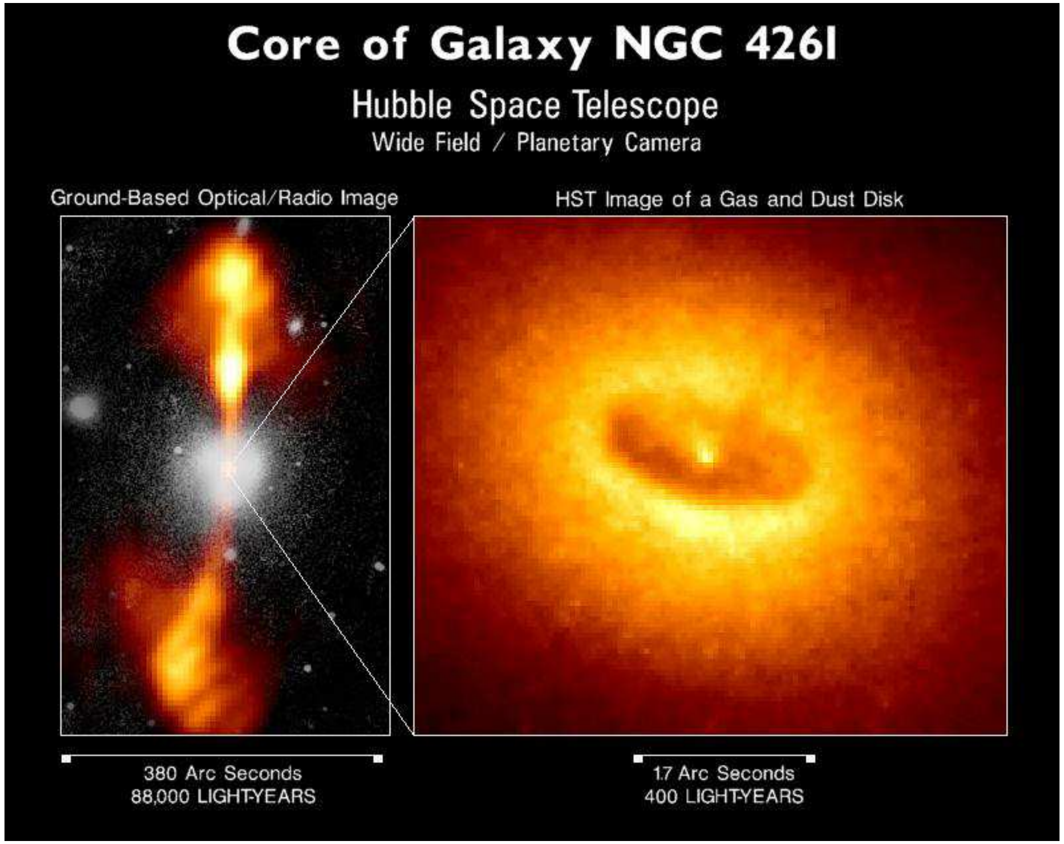

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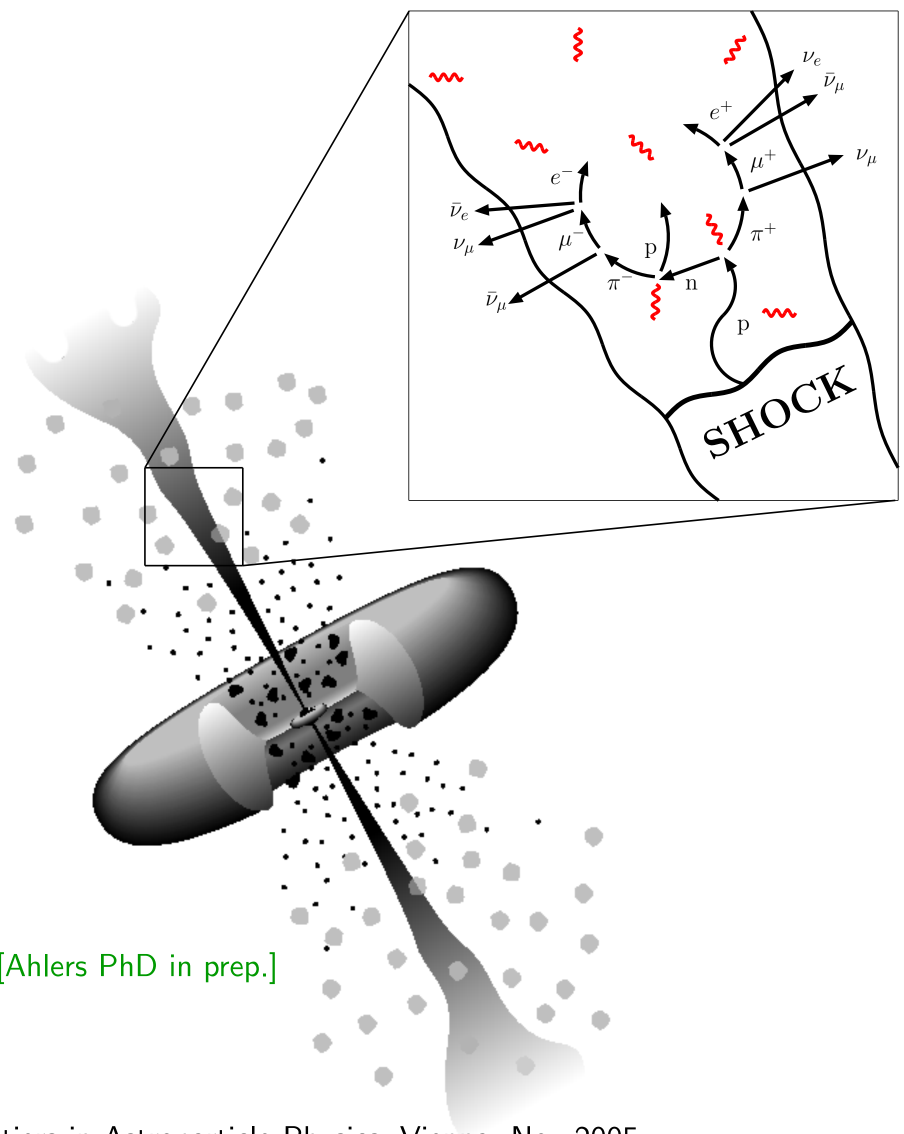
  - p's, confined by magnetic fields, accelerate through repeated scattering by plasma shock fronts



[Ahlers PhD in prep.]

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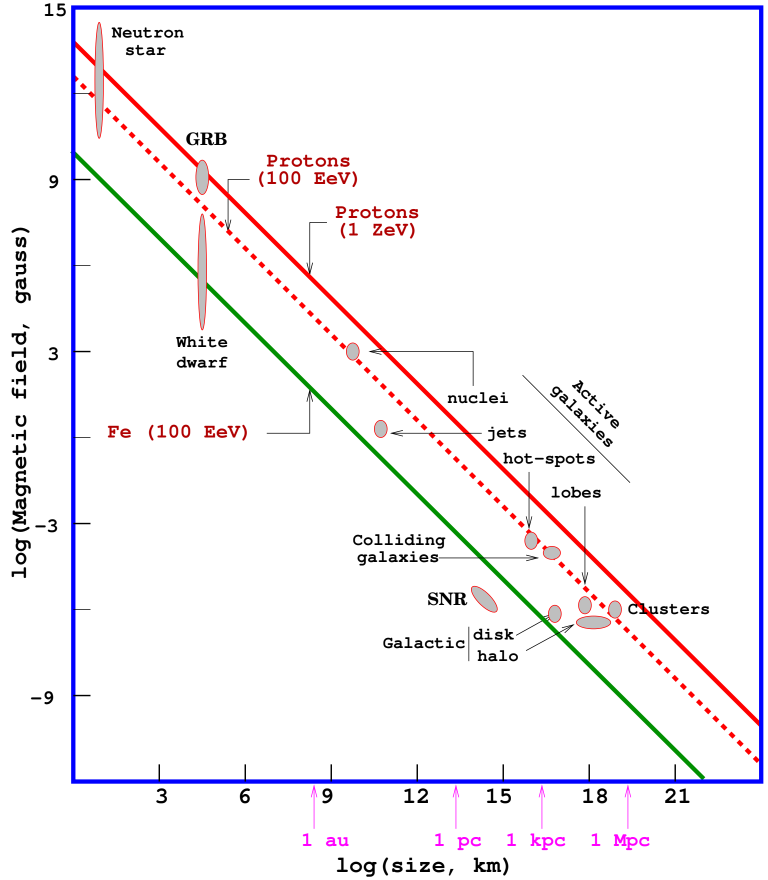
Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)



$E_{max} \sim$ ZBL (Fermi)
$E_{max} \sim$ ZBLΓ (Ultra-relativistic shocks-GRB)

[Pierre Auger Observatory]

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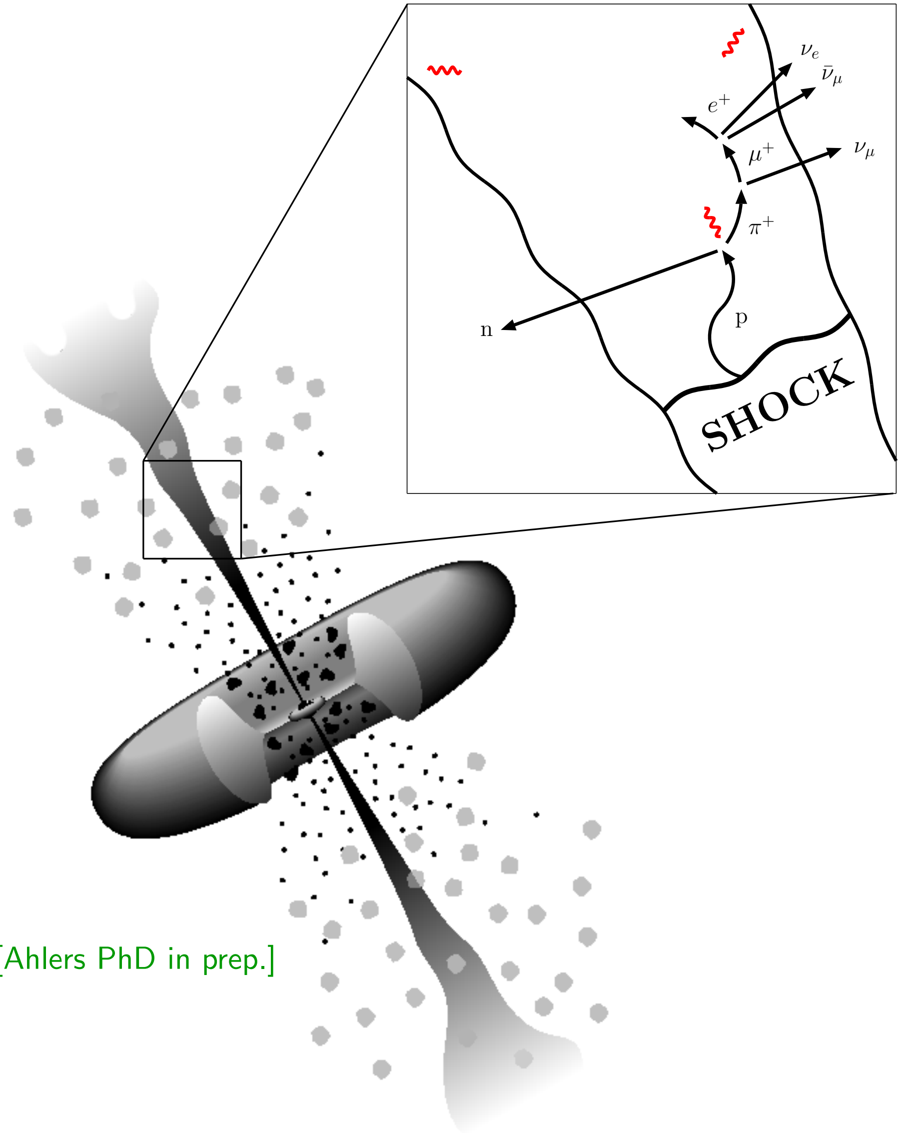

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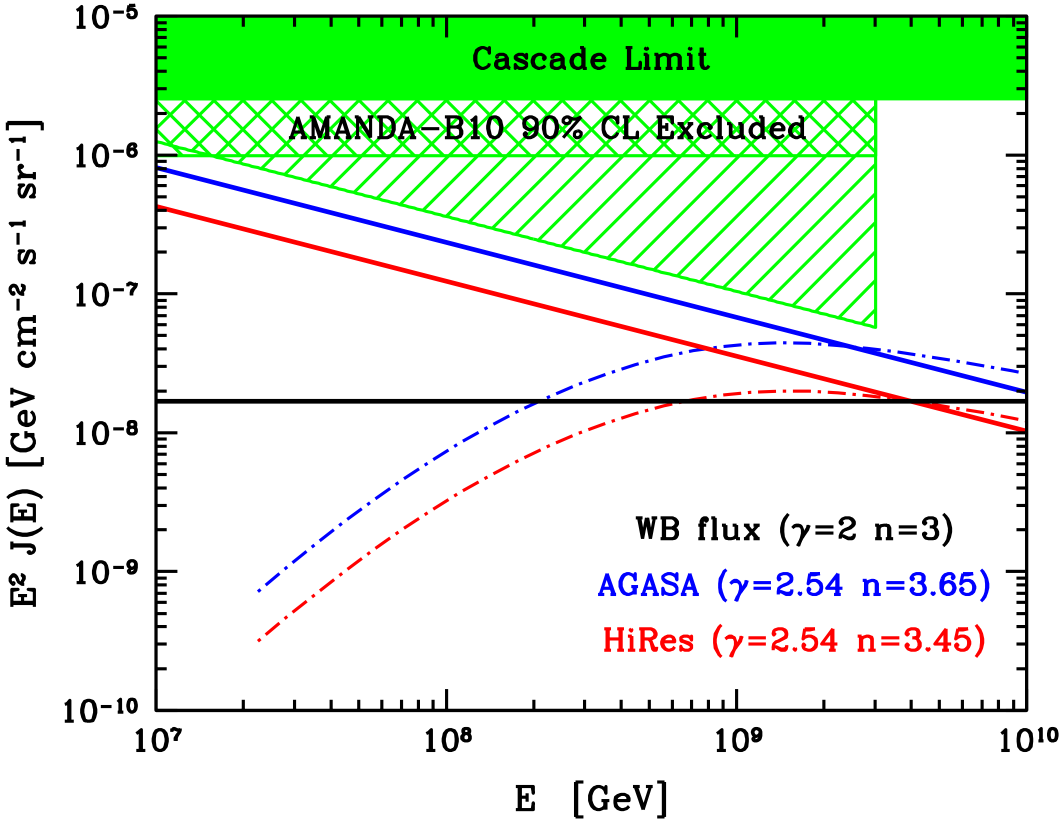
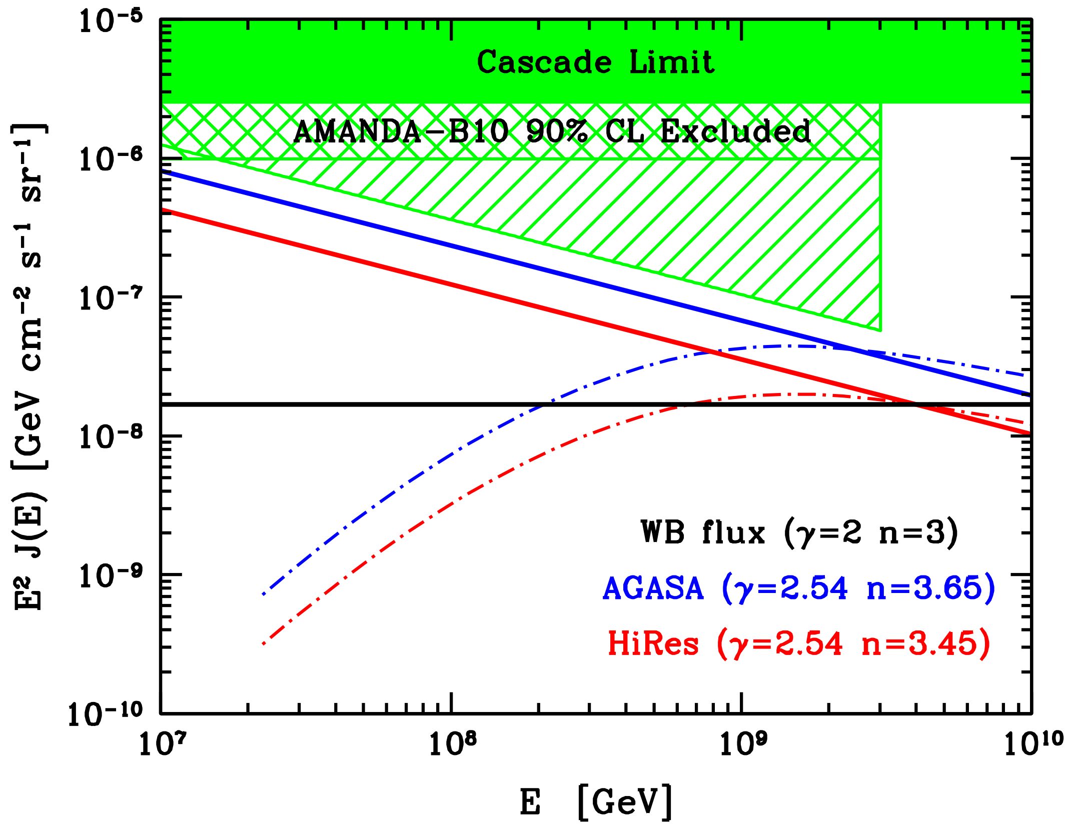
- **Neutrinos as diagnostic tool:**
  - ν's from sources ($p\gamma \to n + \pi$'s) close to be measured
  - Cosmogenic neutrino flux (from $p\gamma_{\rm CMB} \to N\pi$'s) dominates above 10^9 GeV



[Ahlers *et al.* '05]

3. Non-observations at ultrahigh energies

- **Cν's** with $E_\nu \gtrsim 10^8$ GeV probe $\boldsymbol{\nu N}$ scattering at $\sqrt{s_{\nu N}} \gtrsim 14$ TeV (**LHC**)



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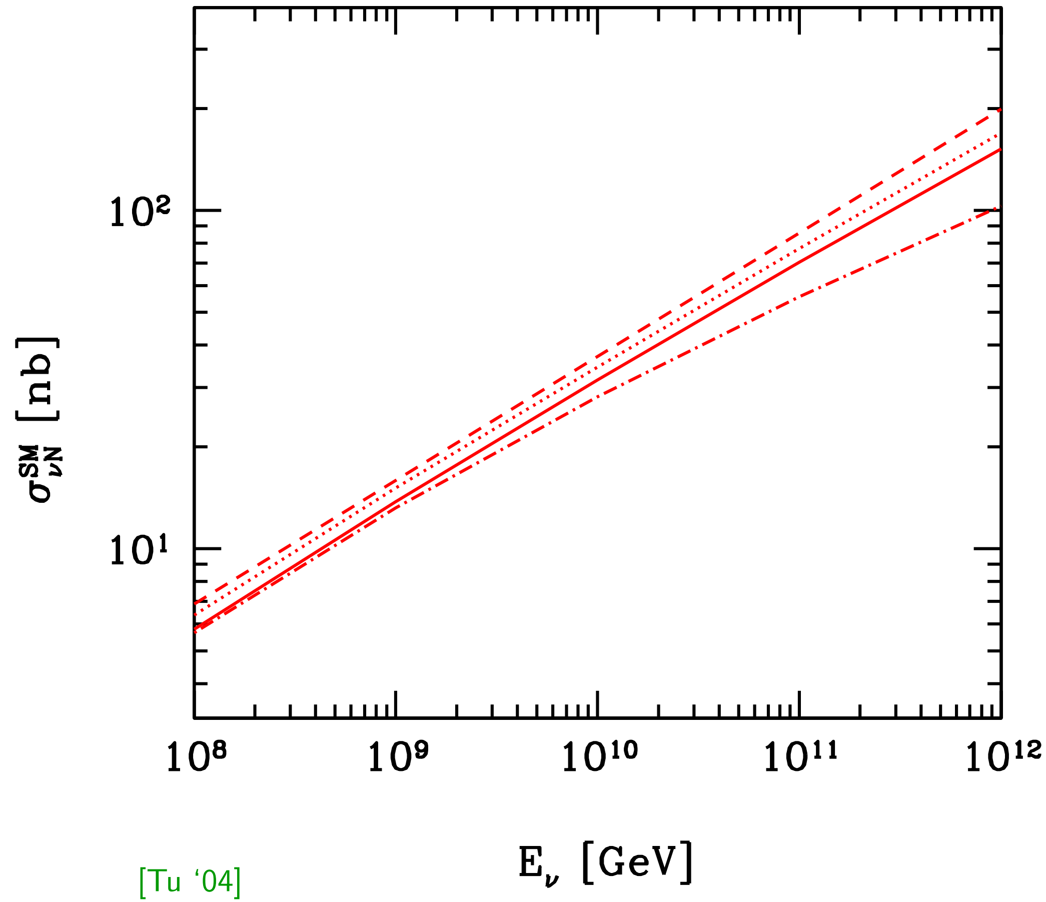
[Gandhi *et al.* '98; Kwiecinski *et al.* '98; ...]



[Tu '04]

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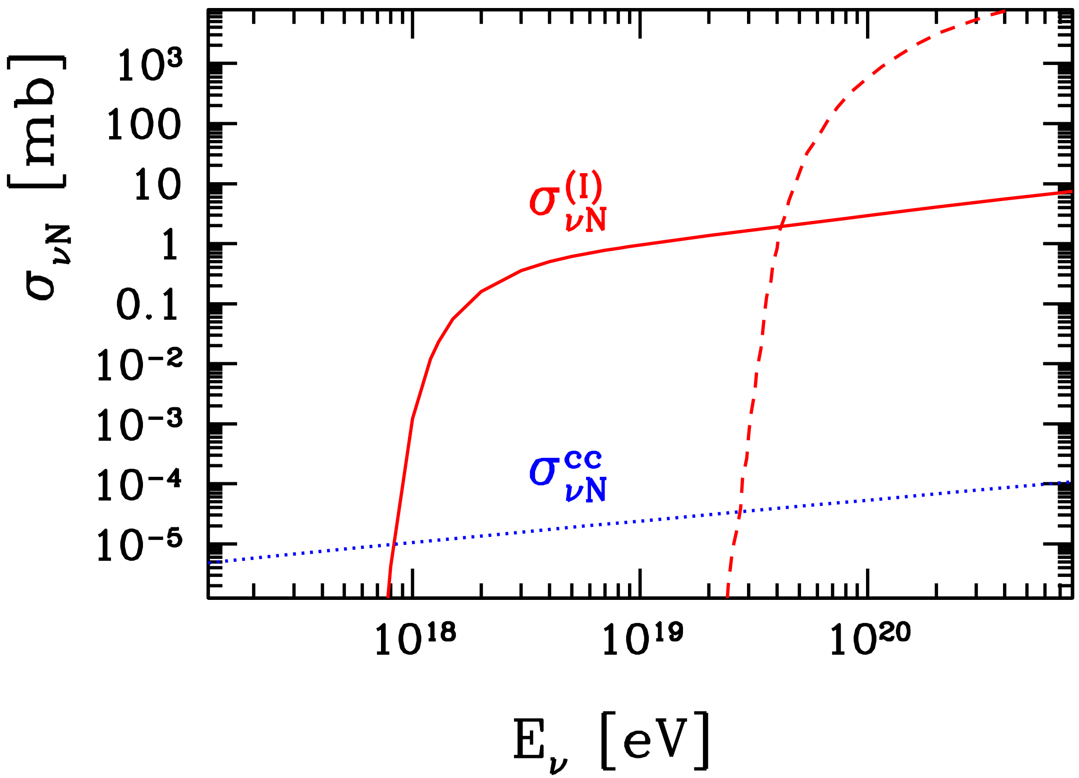
[Gandhi *et al.* '98; Kwiecinski *et al.* '98; ...]

$\Rightarrow$ Search for enhancements in $\boldsymbol{\sigma_{\nu N}}$ beyond (perturbative) SM:

◇ Electroweak sphaleron production ($B + L$ violating processes in SM)



[Fodor,Katz,AR,Tu '03; Han,Hooper '03]

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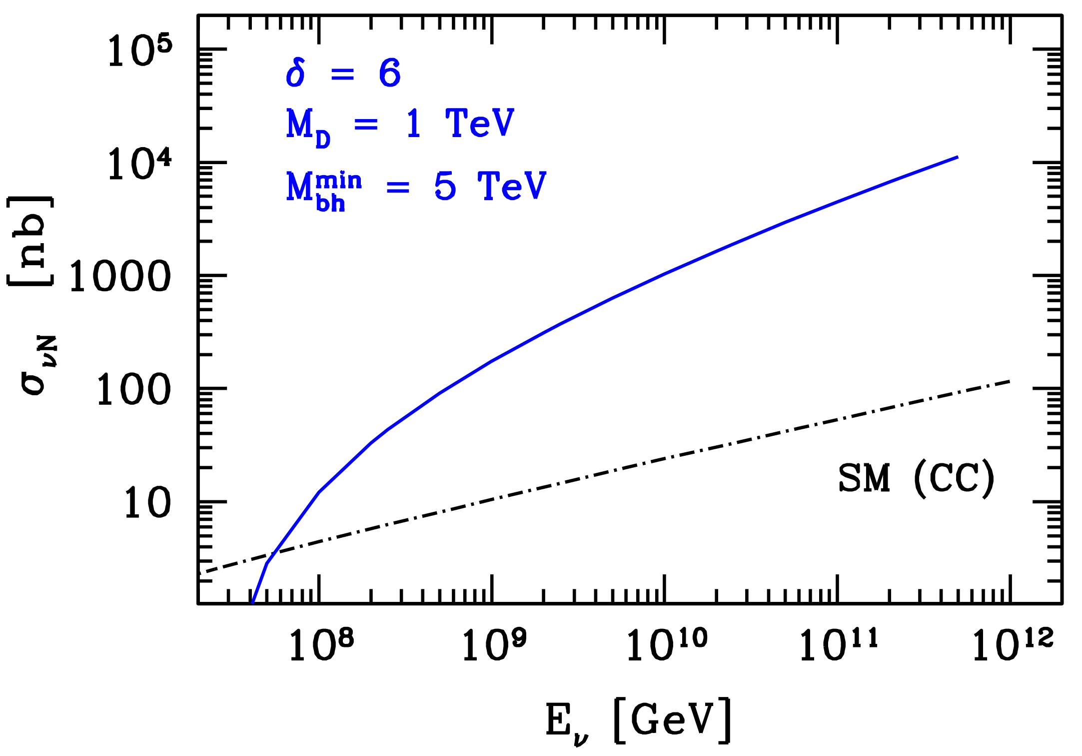
- ◇ Kaluza-Klein, black hole, p-brane or string ball production in TeV scale gravity models
- ◇ . . .



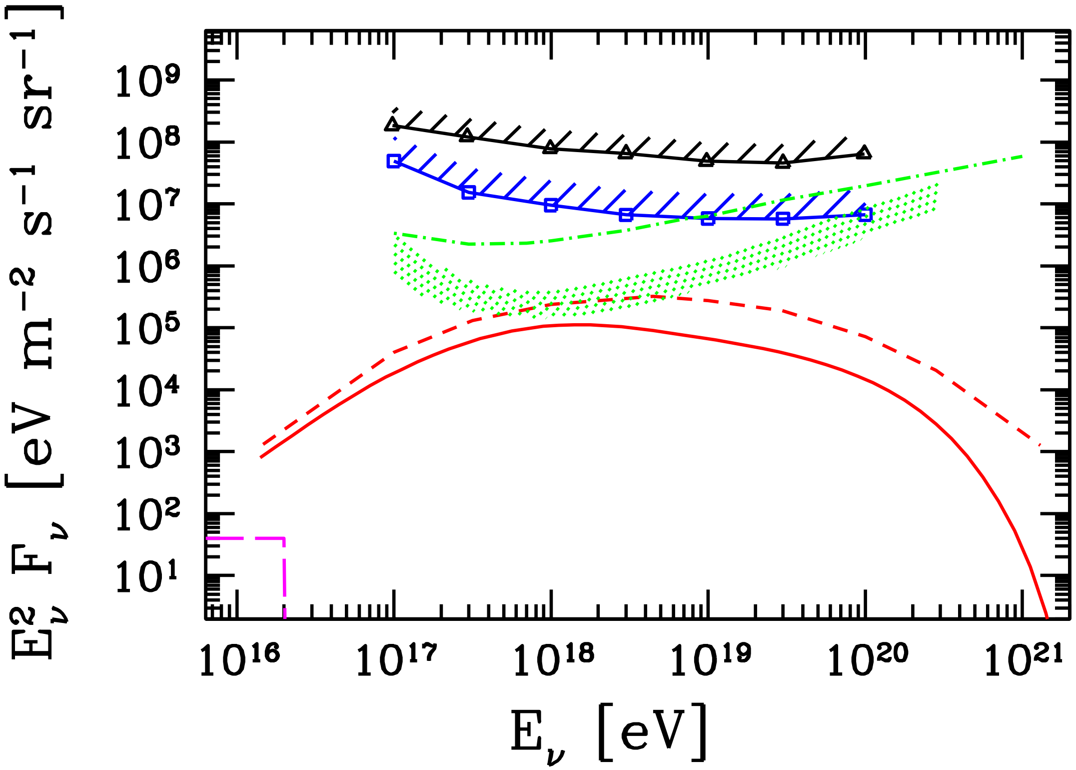
[AR,Tu '01; Tu '04]

"Model-independent" upper bounds on $\sigma_{\nu N}$

$$\frac{\mathrm{d}N}{\mathrm{d}t} \propto \int \mathrm{d}E_\nu \, F_\nu(E_\nu)\, \sigma_{\nu N}(E_\nu)$$

⇒ Non-observation of deeply-penetrating particles, together with lower bound on F_ν (e.g. cosmogenic ν's) ⇒ upper bound on $\sigma_{\nu N}$

[Berezinsky,Smirnov '74; Morris,AR '94; Tyler,Olinto,Sigl '01;..]



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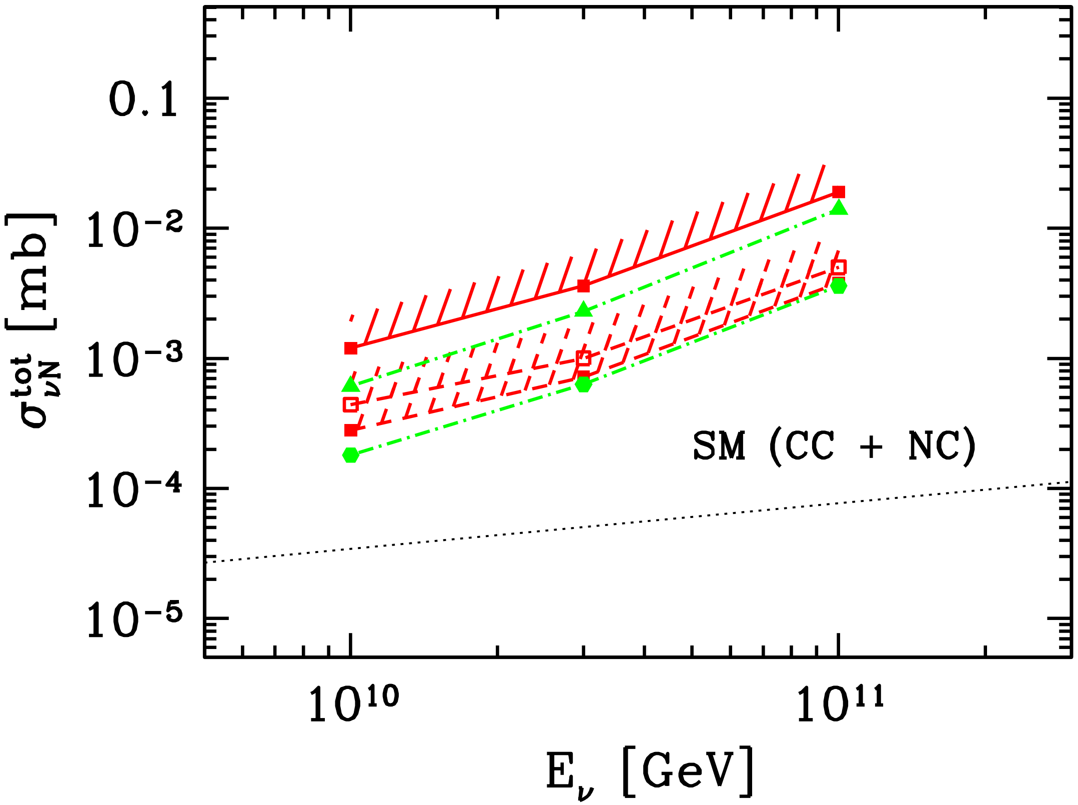
- Recent quantitative analysis:

  [Anchordoqui,Fodor,Katz,AR,Tu '04]

  ◇ Best current limits from exploitation of **RICE** search results

  [Kravchenko *et al.* [RICE] '02,03]

  ◇ **Auger** will improve these limits by one order of magnitude



[Anchordoqui,Fodor,Katz,AR,Tu '04]

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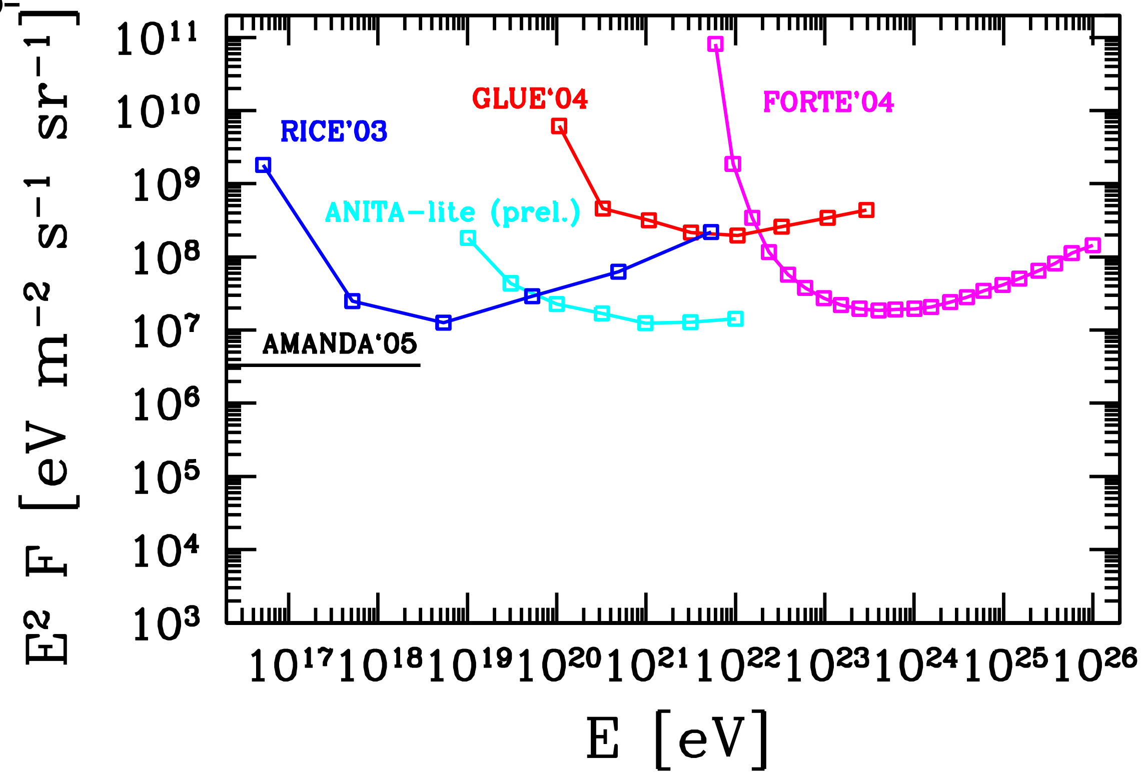

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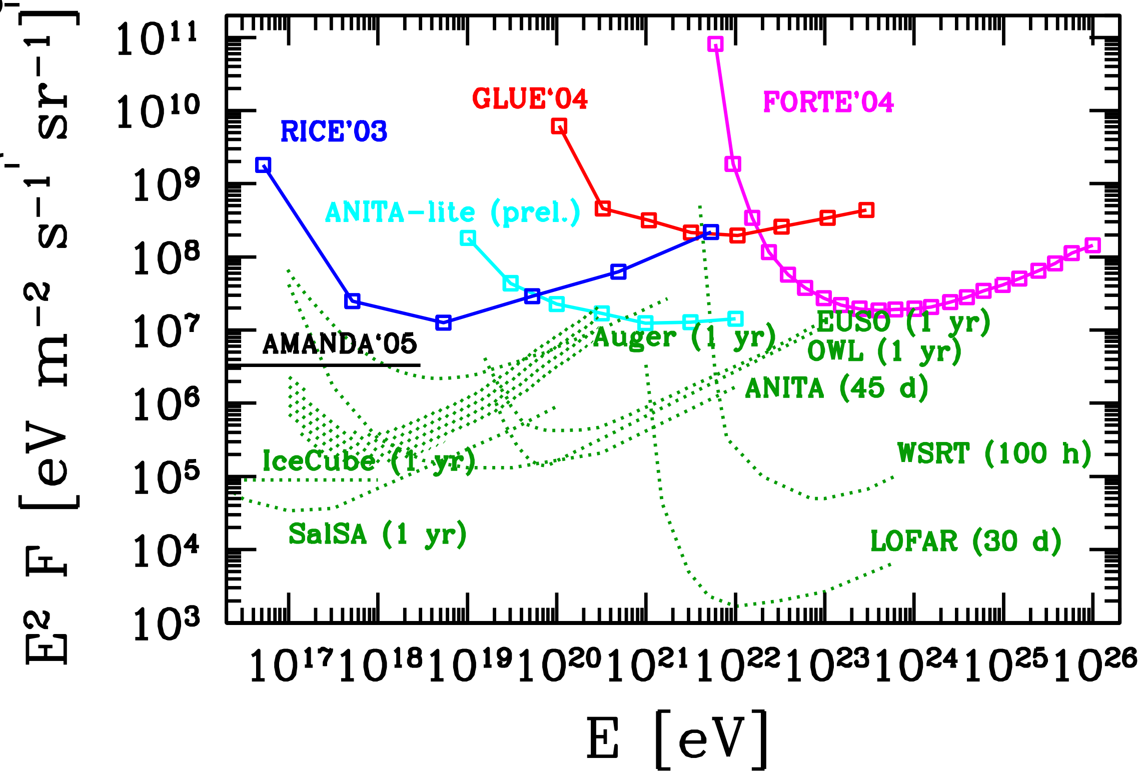

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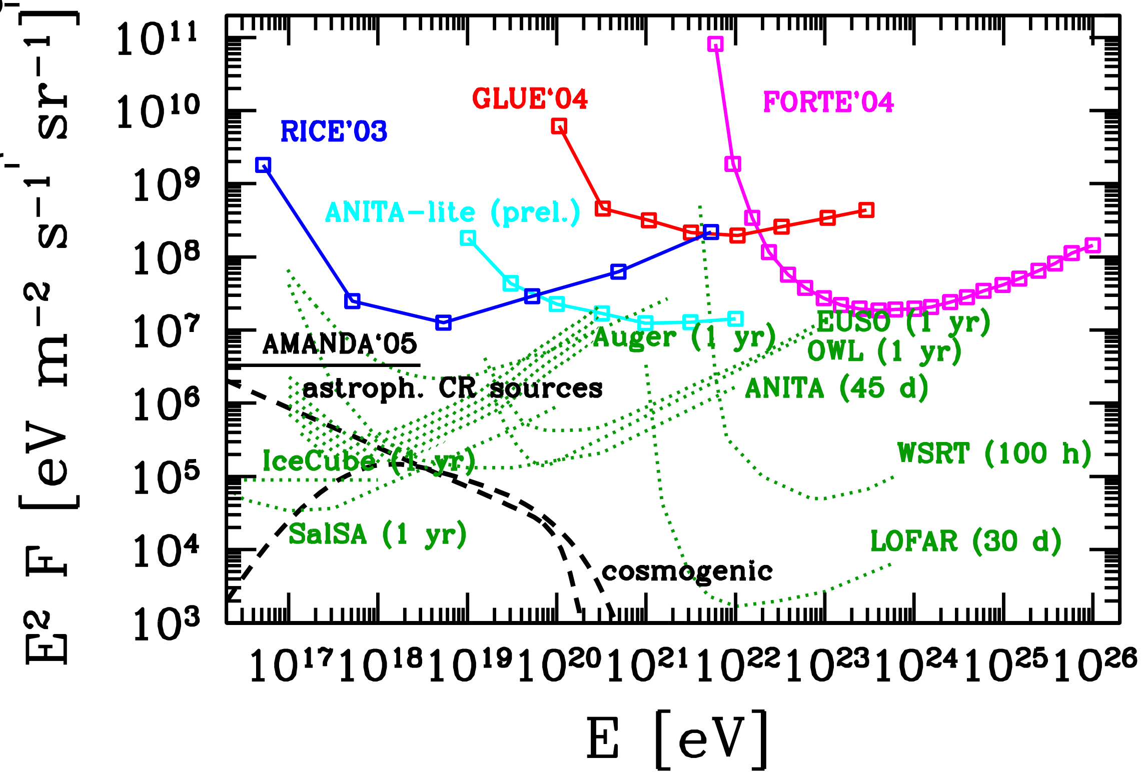

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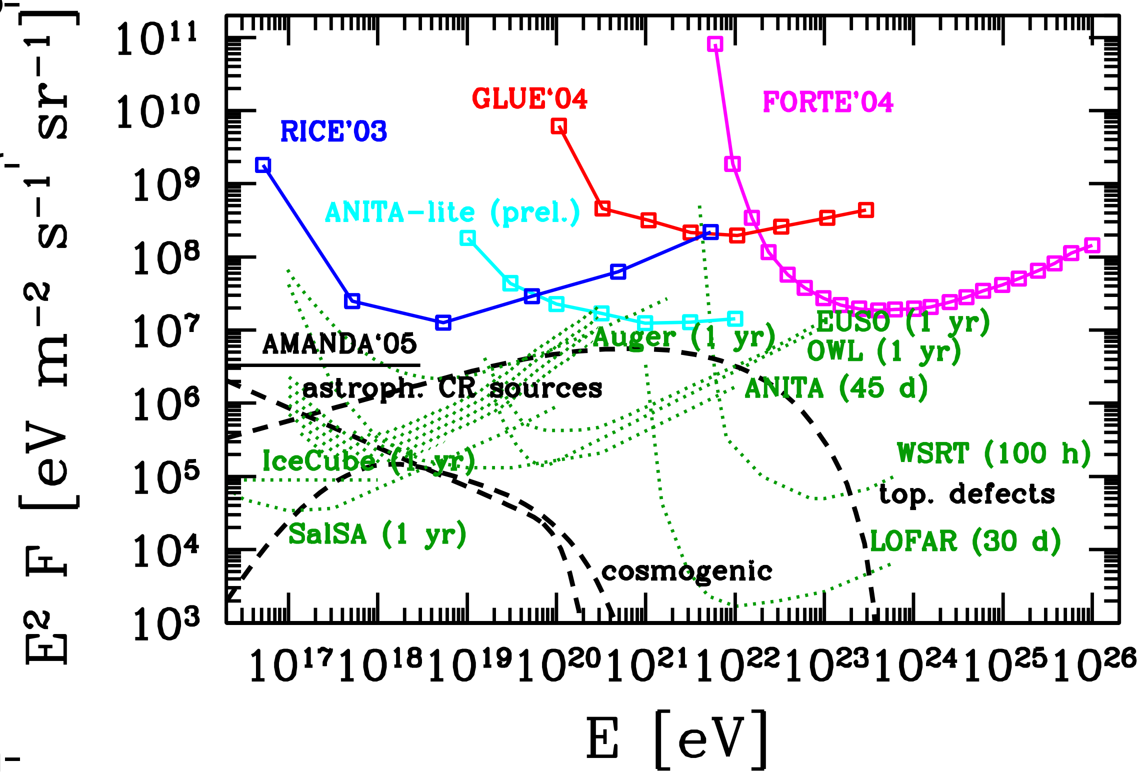
$\Rightarrow$ $E \geq 10^{21}$ eV:

$\longrightarrow$ **Cosmology:** relics of phase transitions; absorption on big bang relic neutrinos



Top-down scenarios for super-GZK neutrinos

- Existence of superheavy particles with $10^{12}\ \mathrm{GeV} \lesssim m_X \lesssim 10^{16}\ \mathrm{GeV}$, produced during and after inflation through e.g.
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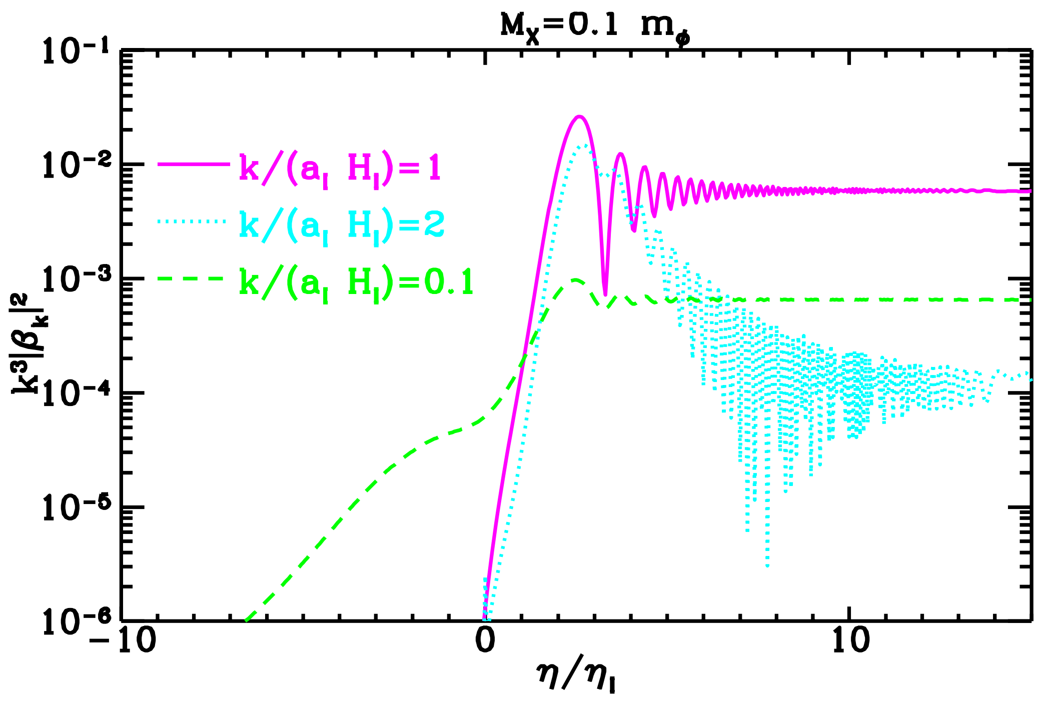

[Kolb,Chung,Riotto '98]

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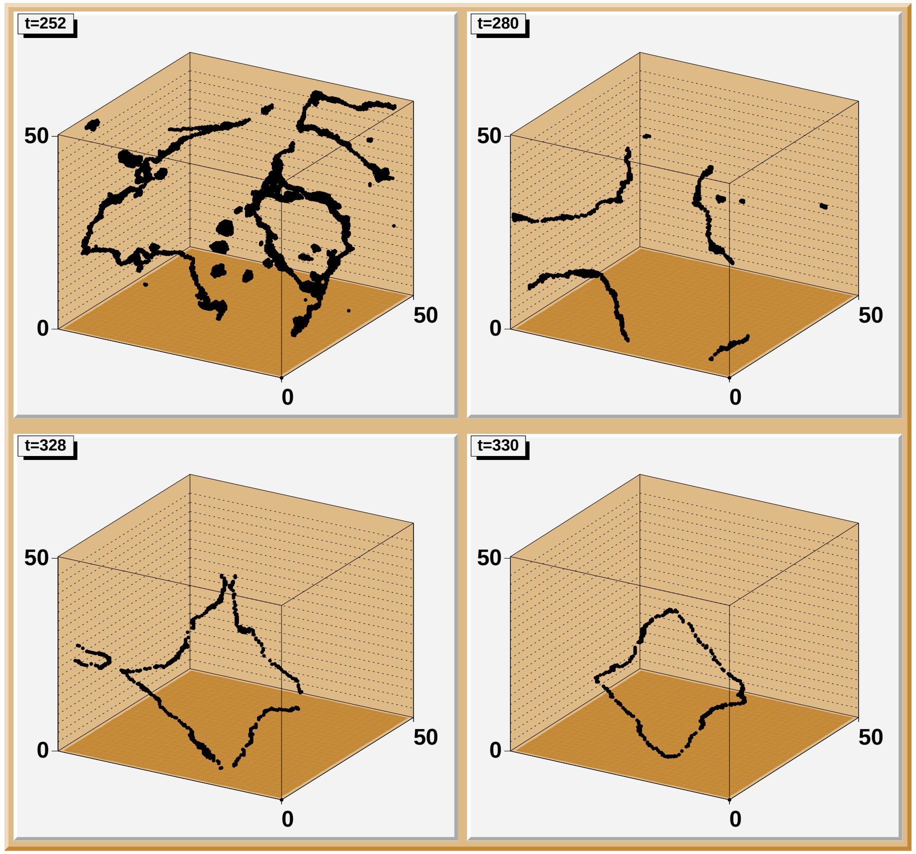

[Tkachev,Khlebnikov,Kofman,Linde '98]

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  - $\Rightarrow$ super-GZK ν's from decay or annihilation of superheavy dark matter (for $\tau_X \gtrsim \tau_U$)
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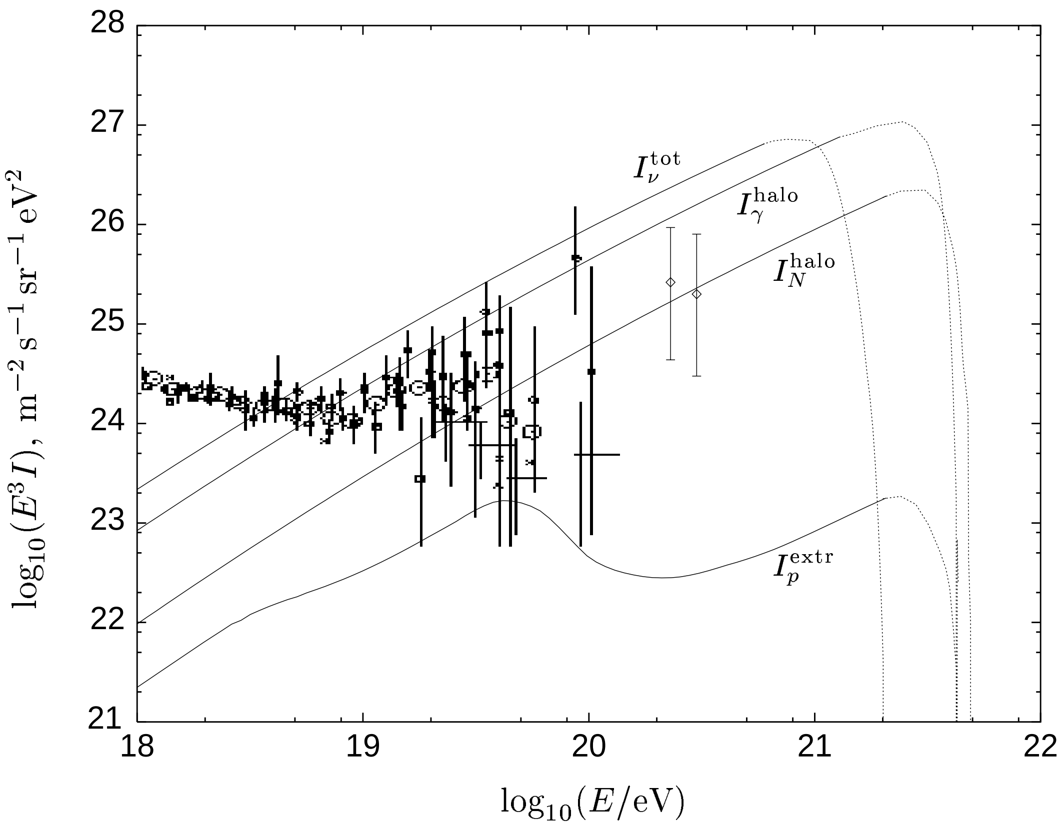

[Berezinsky,Kachelriess,Vilenkin '97]

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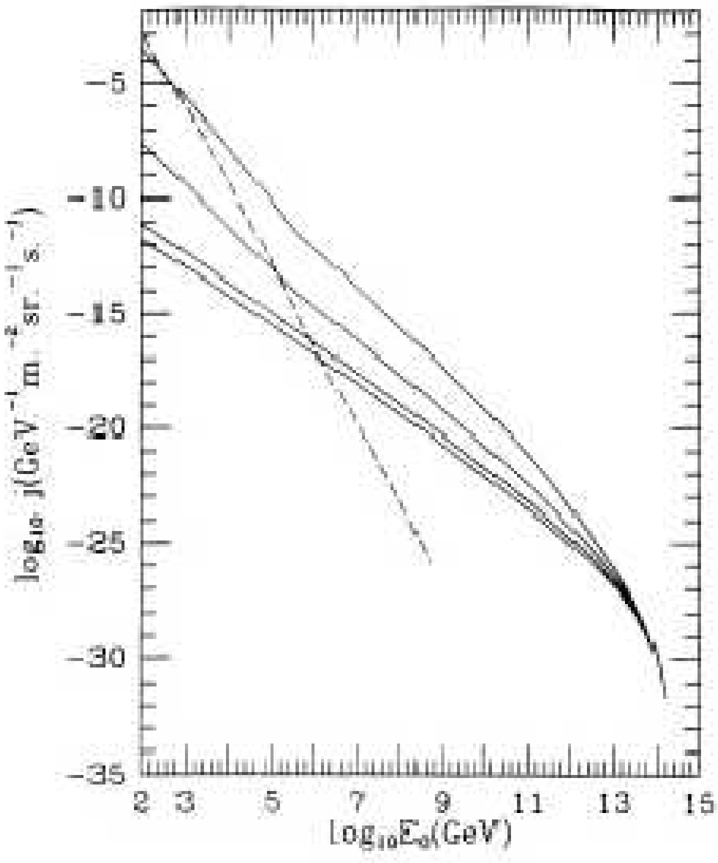

[Bhattacharjee,Hill,Schramm '92]

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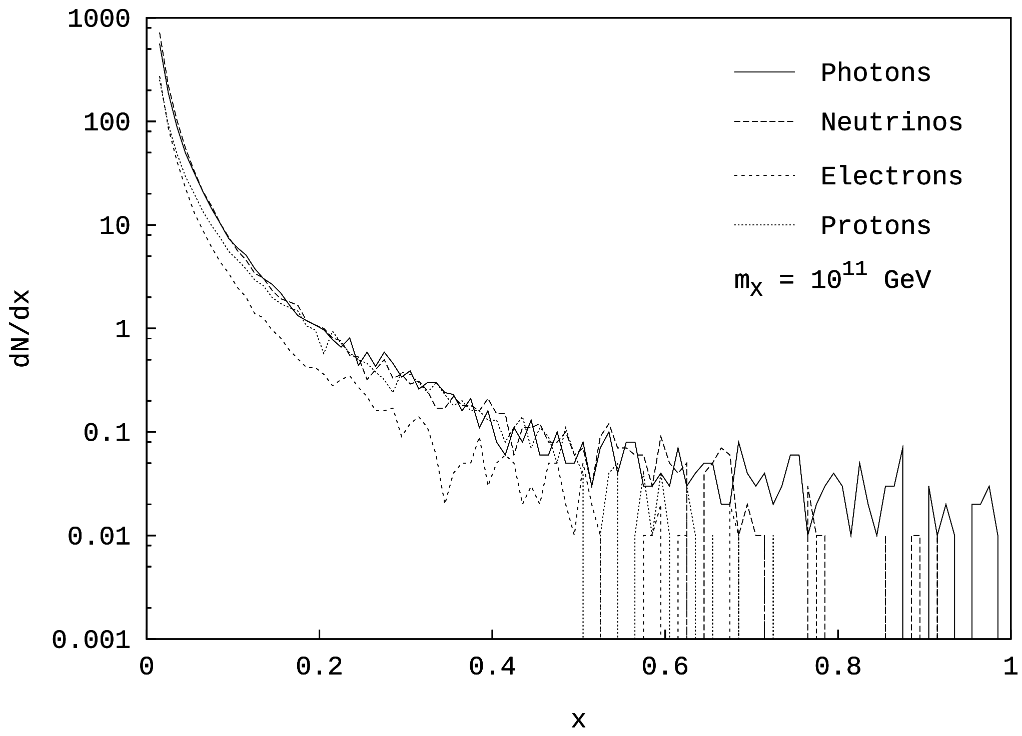

[Birkel,Sarkar '98]

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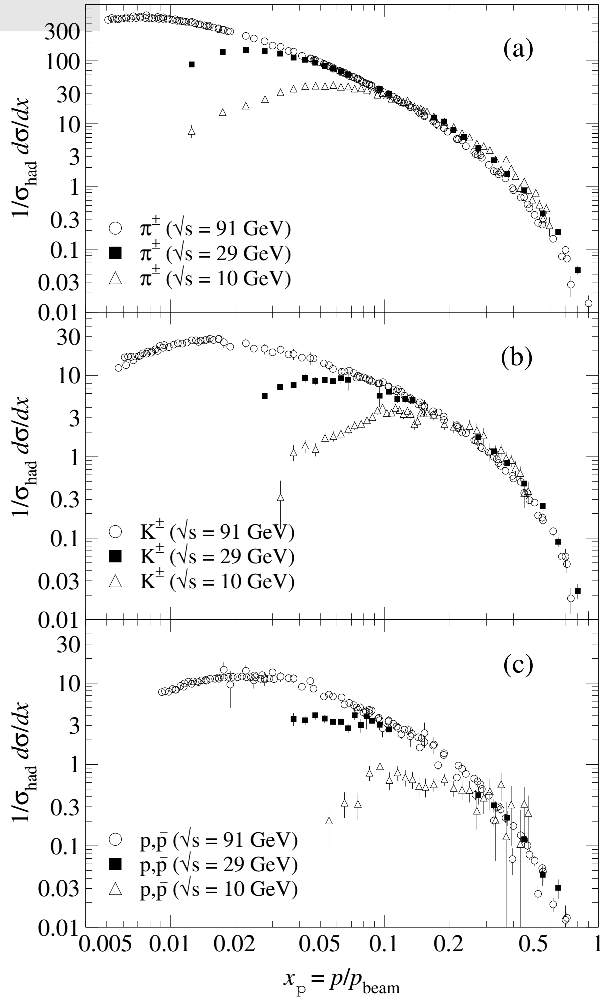

[Particle Data Group '04]

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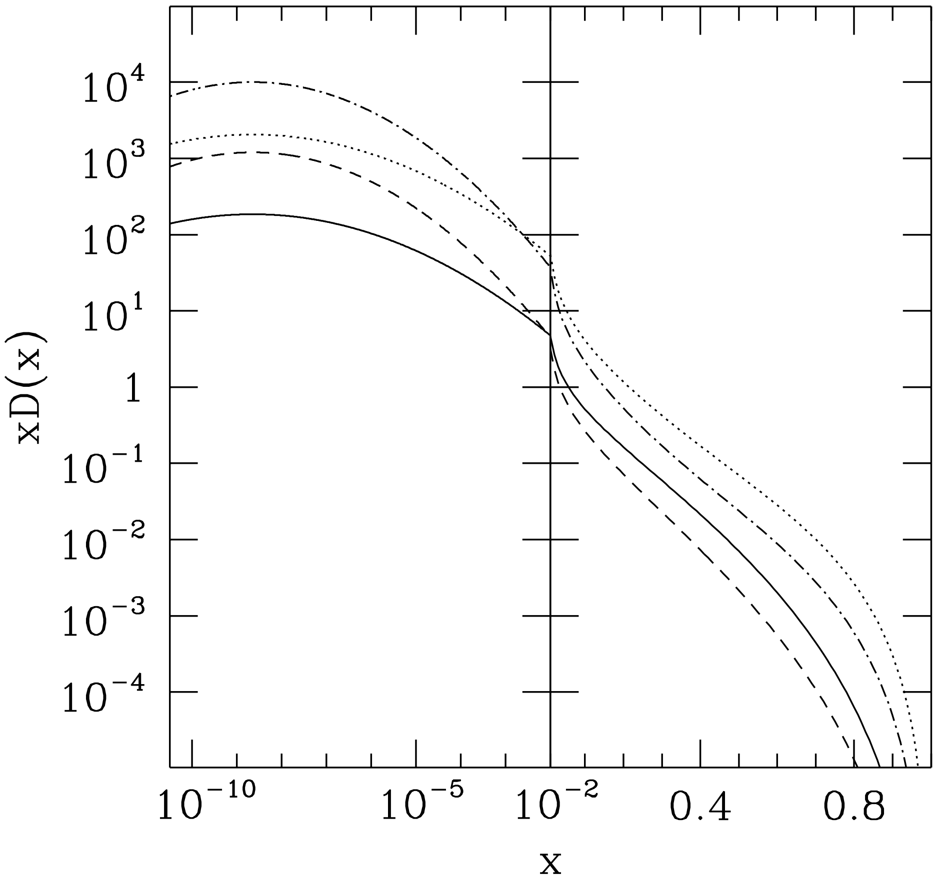

[Fodor,Katz '01]

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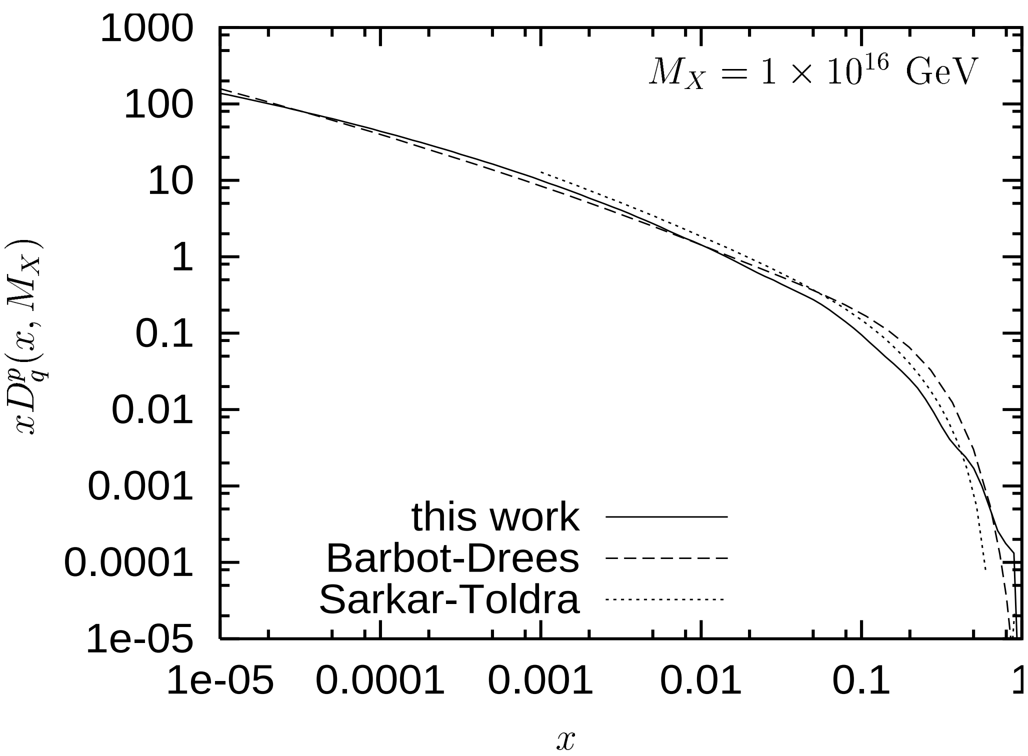

[Aloisio,Berezinsky,Kachelriess '04]

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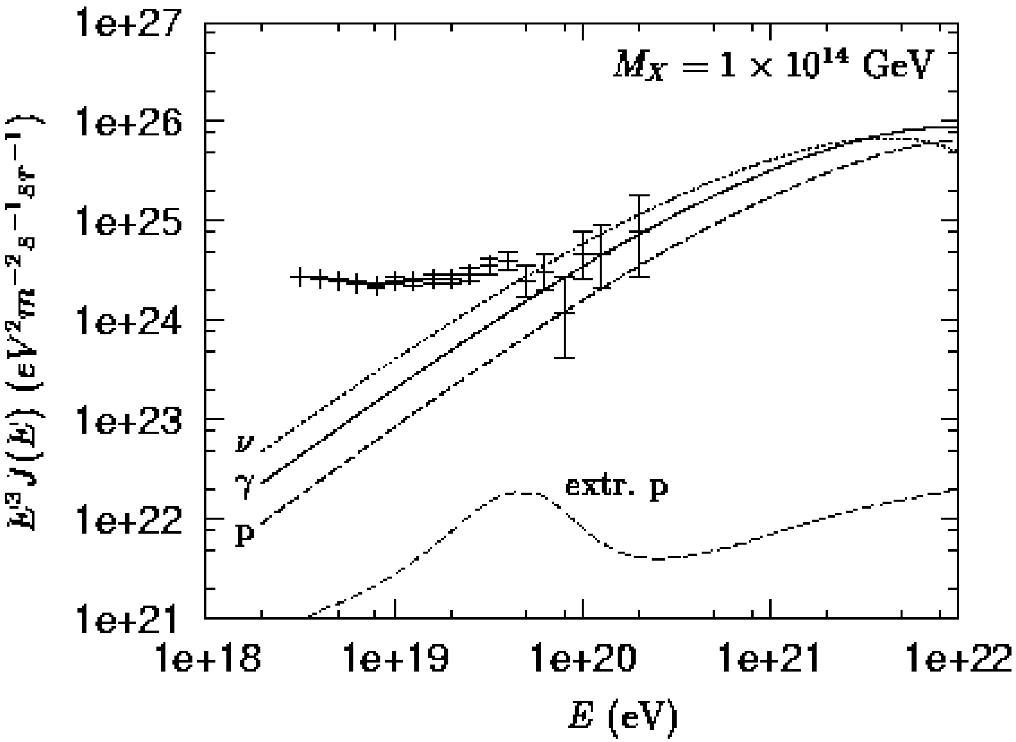

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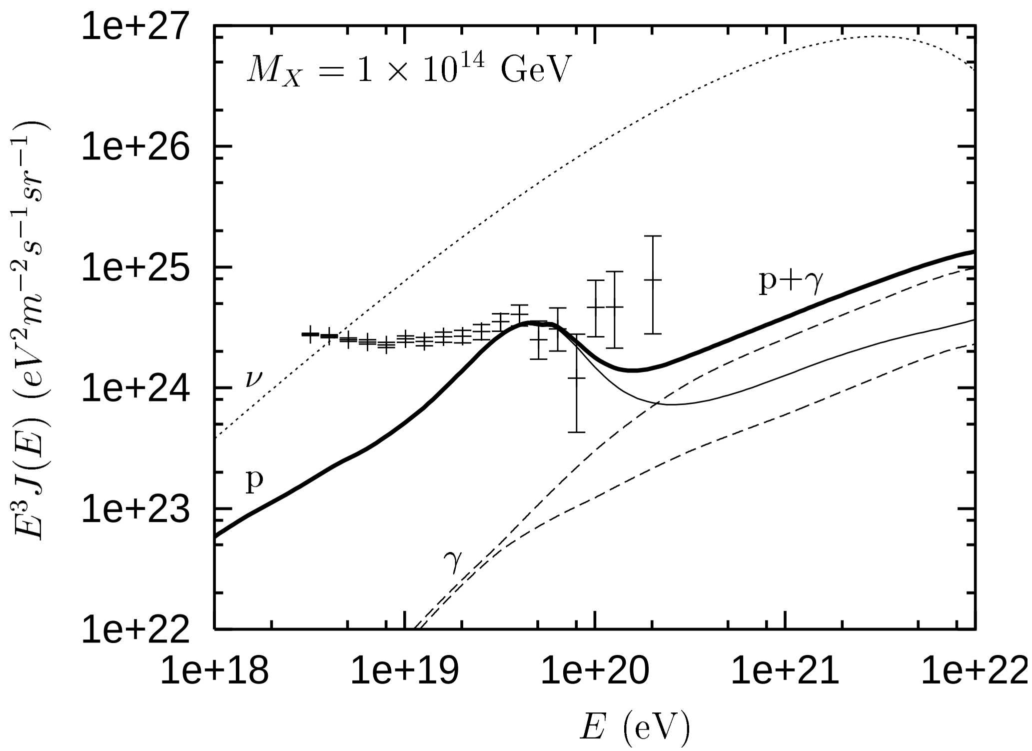
  - for topological defects, injection far away: $j_\nu \gg j_\gamma \sim j_p$



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Top-down scenarios for super-GZK neutrinos

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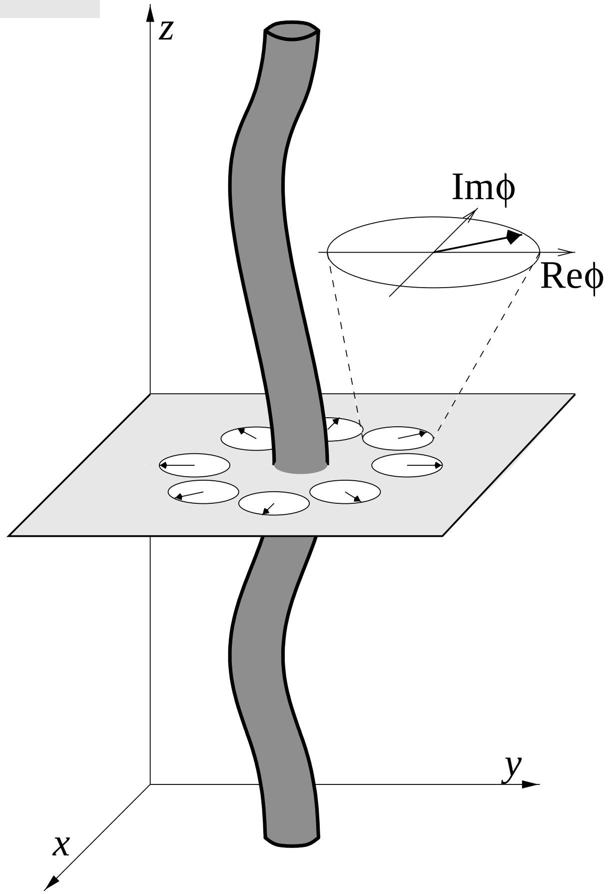
  - **Topological defects:** generic prediction of symmetry breaking (SB) in GUT's, including fundamental string theory, e.g.
    - $*$ $\mathrm{G} \rightarrow \mathrm{H} \times \mathrm{U}(1)$ SB: monopoles
    - $*$ $\mathrm{U}(1)$ SB: ordinary or superconducting strings

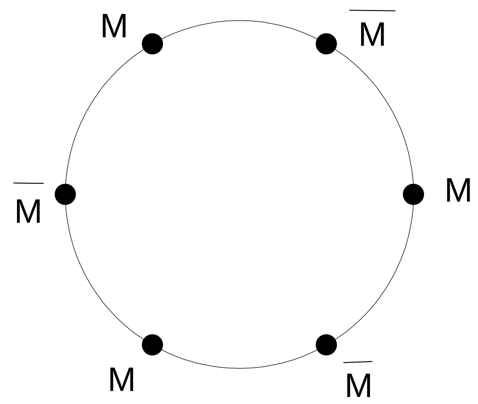


[Rajantie '03]

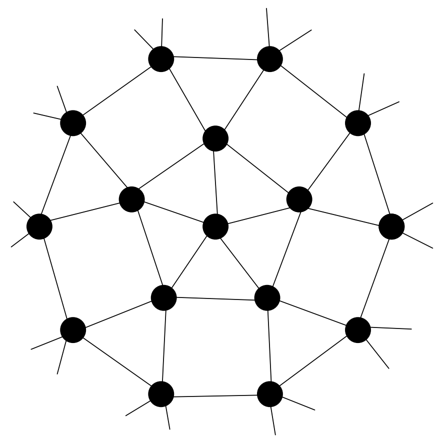
Top-down scenarios for super-GZK neutrinos

- **How natural?**
  - **Superheavy dark matter:** need symmetry to prevent fast X decay
    - $*$ gauge $\Rightarrow$ X stable
    - $*$ discrete $\Rightarrow$ stable or quasi-stable
  - **Topological defects:** generic prediction of symmetry breaking (SB) in GUT's, including fundamental string theory, e.g.
    - $*$ $\mathrm{G} \to \mathrm{H} \times \mathrm{U}(1)$ SB: monopoles
    - $*$ $\mathrm{U}(1)$ SB: ordinary or superconducting strings
    - $*$ $\mathrm{G} \to \mathrm{H} \times \mathrm{U}(1) \to \mathrm{H} \times \mathrm{Z}_N$ SB: monopoles connected by strings

NECKLACE



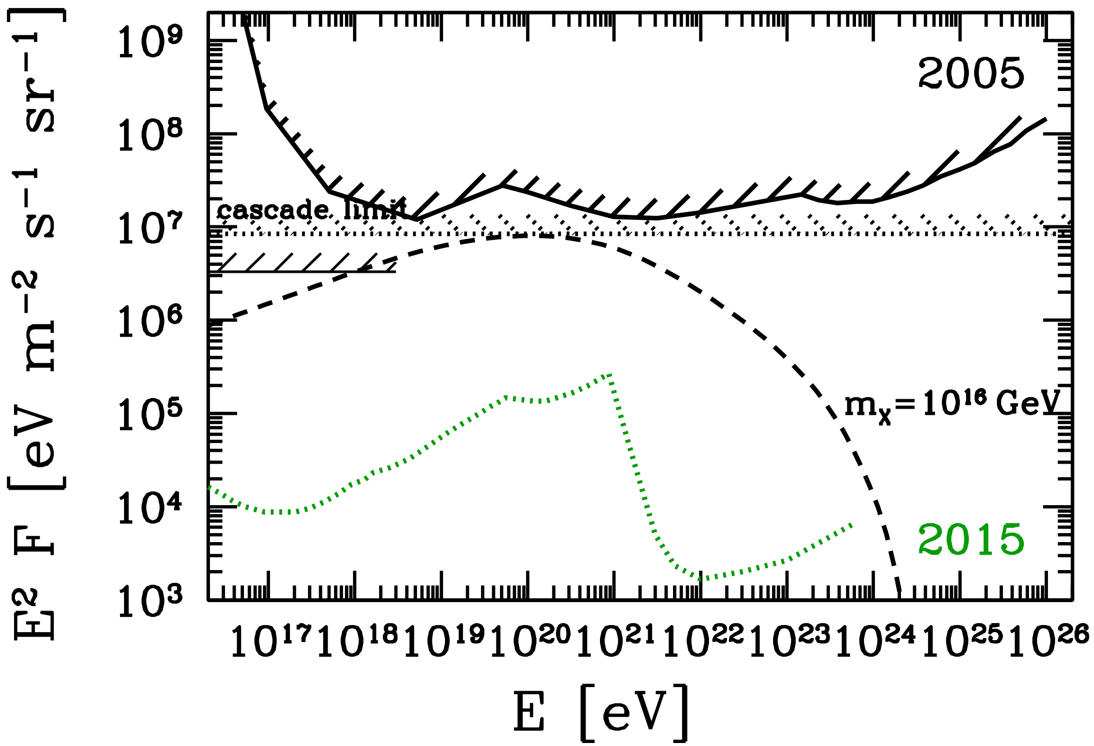
MS NETWORK



[Berezinsky '05]

Top-down scenarios for super-GZK neutrinos

- Strong impact of measurement for
  - **particle physics**
  - **cosmology**



[Fodor,Katz,AR,Weiler,Wong,in prep.]

Top-down scenarios for super-GZK neutrinos

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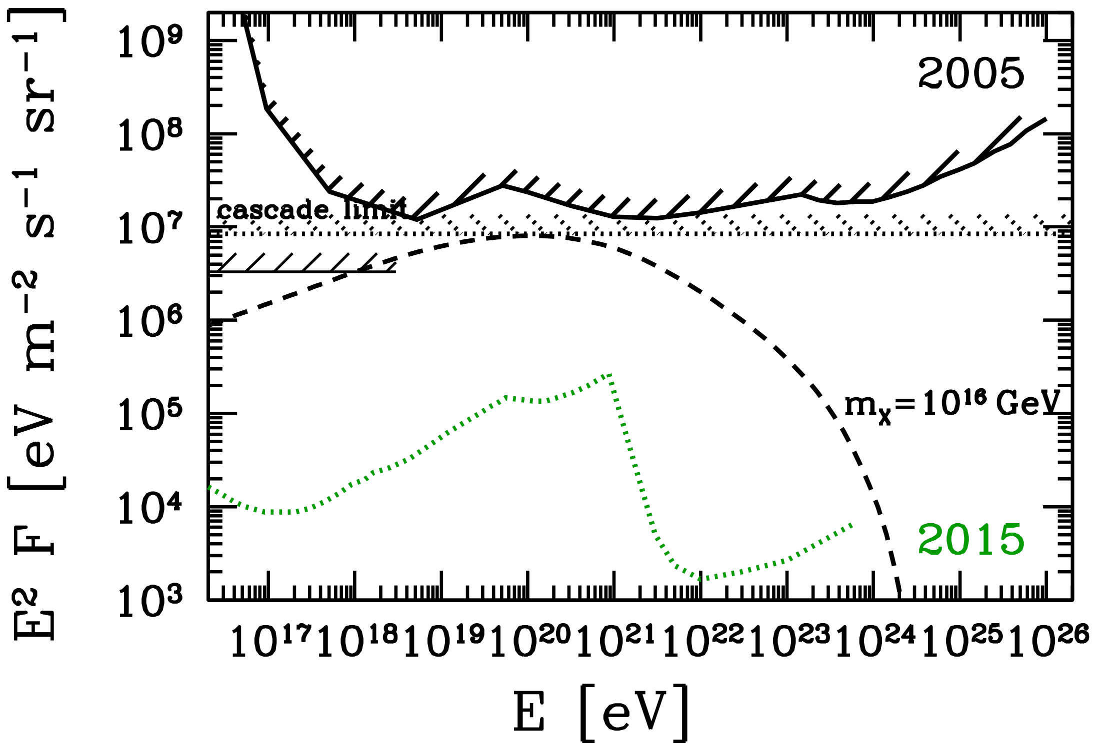

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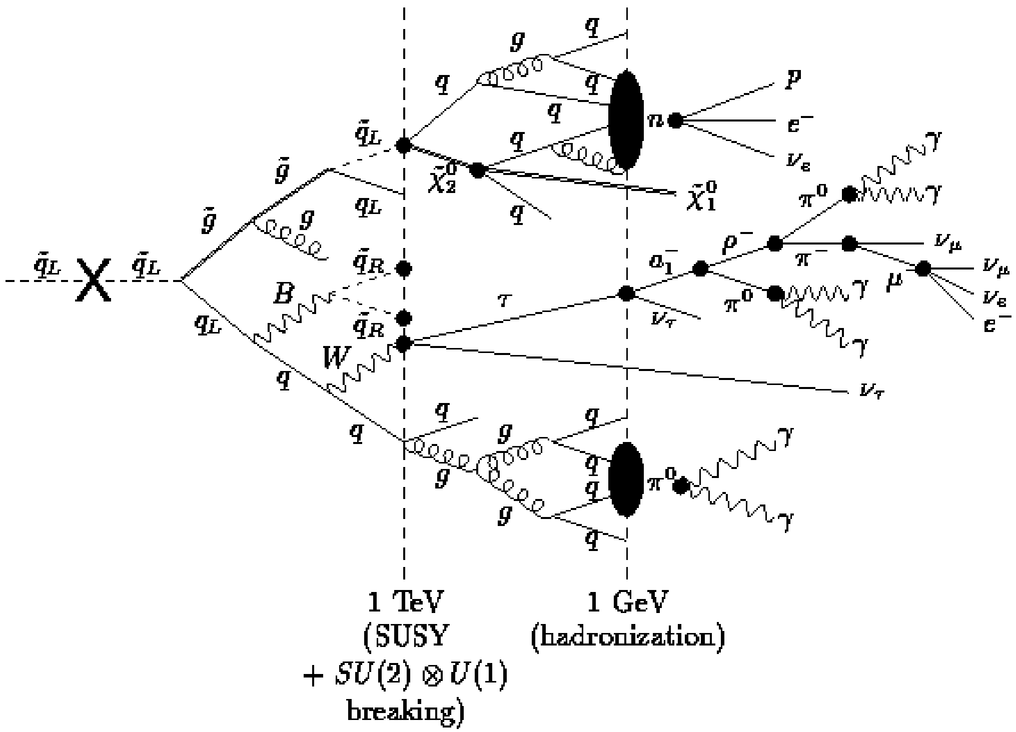

[Barbot,Drees '02]

Top-down scenarios for super-GZK neutrinos

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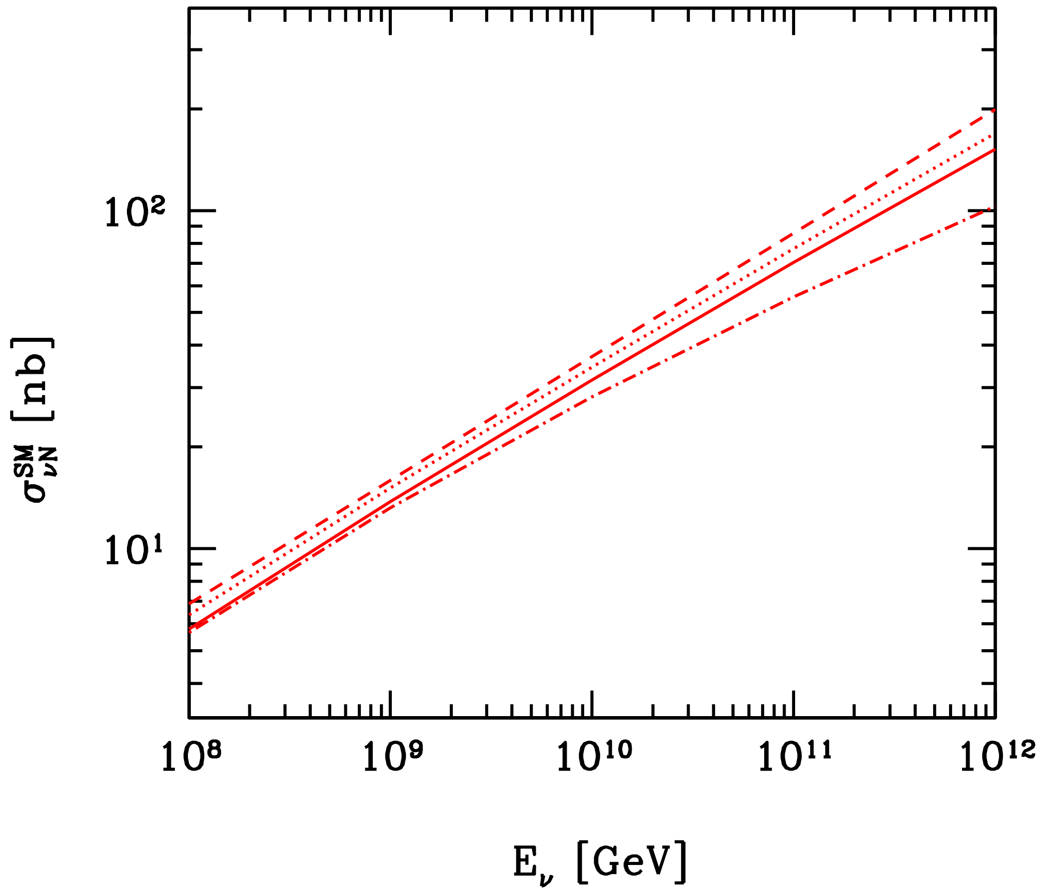

[Tu '04]

Top-down scenarios for super-GZK neutrinos

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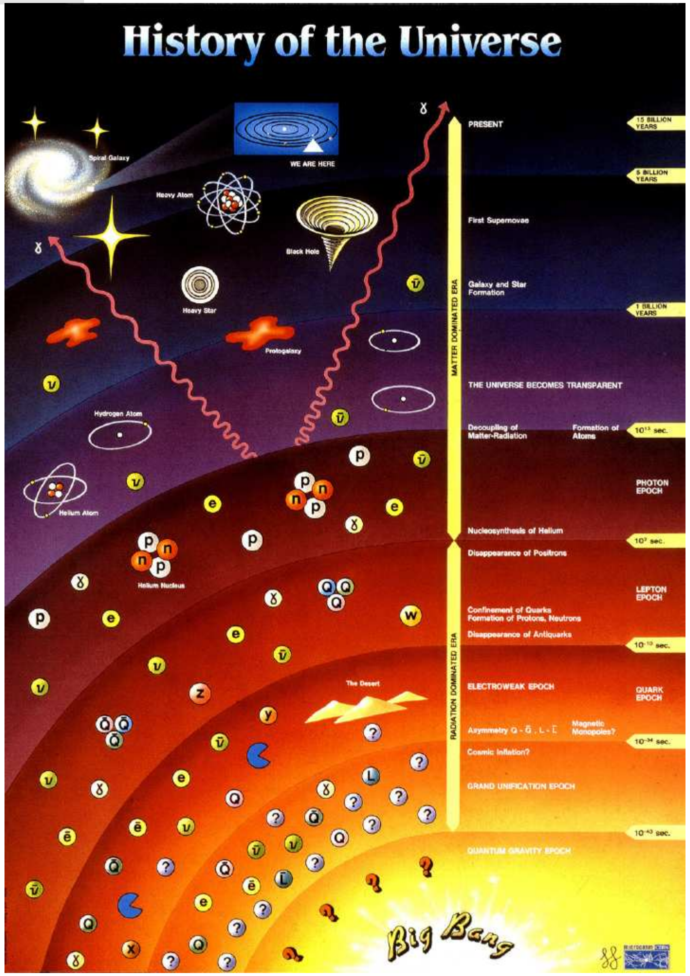
  - **cosmology**
    - ∗ window on early phase transition
    - ∗ Hubble expansion rate $H(z)$
    - ∗ existence of the big bang relic neutrino background (CνB)



Top-down scenarios for super-GZK neutrinos

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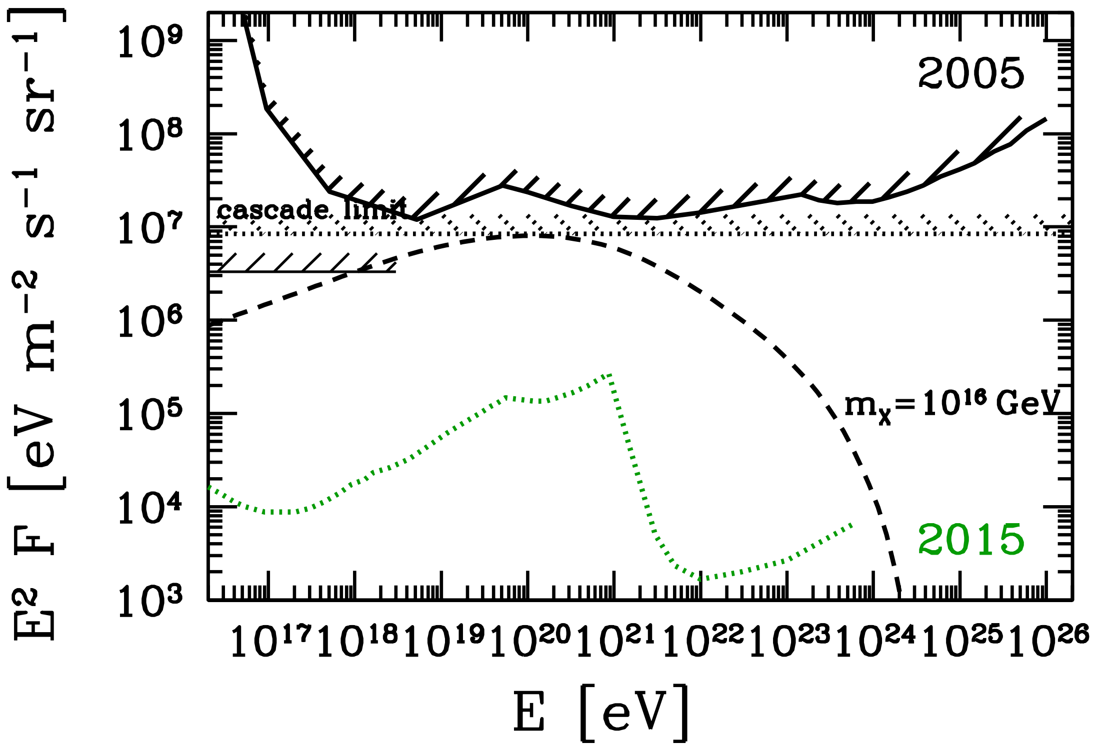

[Fodor,Katz,AR,Weiler,Wong,in prep.]

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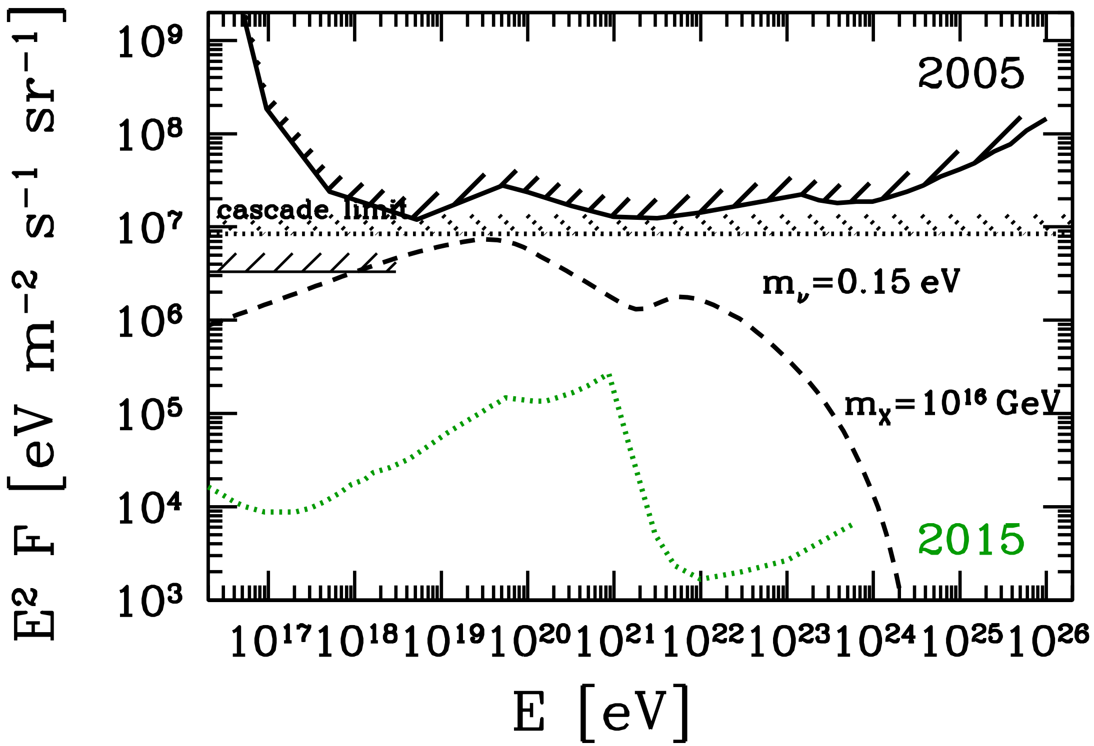

[Fodor,Katz,AR,Weiler,Wong,in prep.]

5. Conclusions

- Exciting times for ultrahigh energy cosmic rays and neutrinos:
  - many observatories under construction
  - ⇒ appreciable event samples

- Expect strong impact on
  - astrophysics
  - particle physics
  - cosmology