Physics of Neutrinos at Ultra High Energies

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“The UHE Universe: a vision for the next decade”
Centro Congressi Villa Mondragone, Monteporzio Catone, Italy
June 19-21, 2006

1. Introduction

- Existing observatories for **U**ltra **H**igh **E**nergy **C**osmic ν's provide sensible upper bounds on flux
- Upcoming decade: progressively larger detectors for **UHECν's**

$\Rightarrow$ $E \geq 10^{16}$ eV:

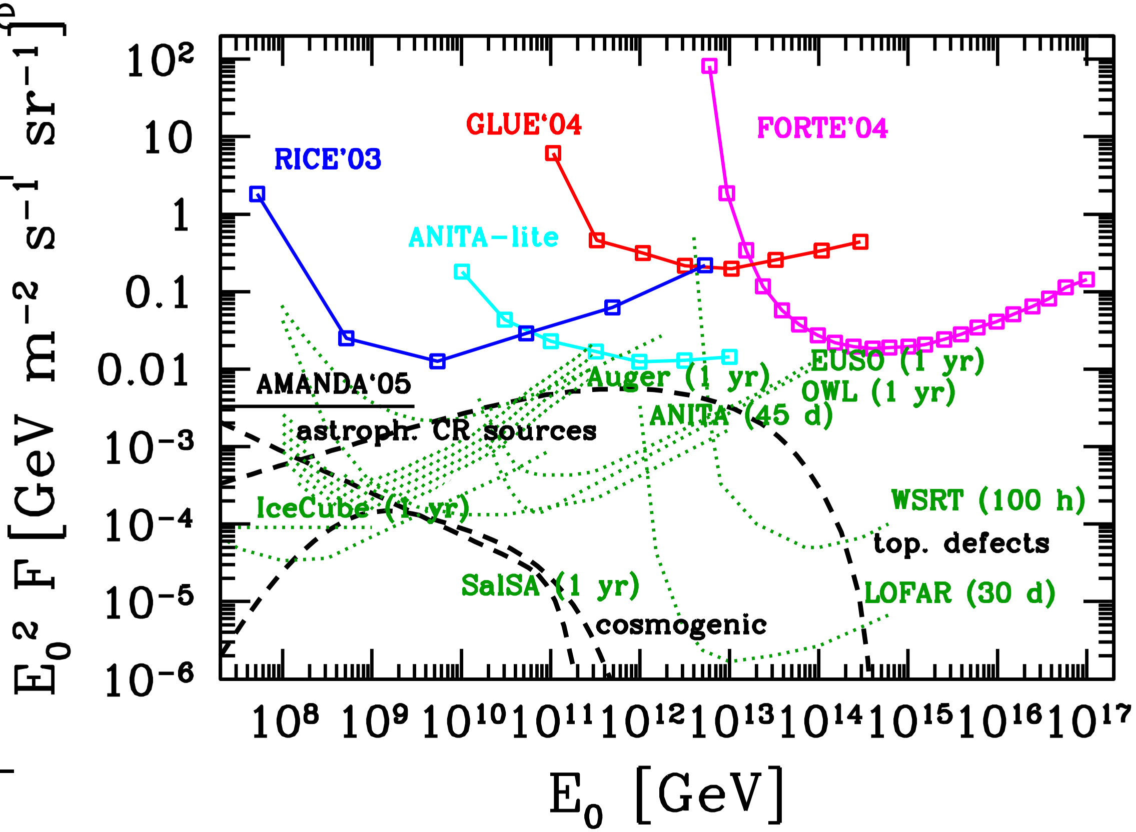
$\longrightarrow$ **Astrophysics** of cosmic rays

$\Rightarrow$ $E \geq 10^{17}$ eV:

$\longrightarrow$ **Particle physics** beyond **LHC**

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

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

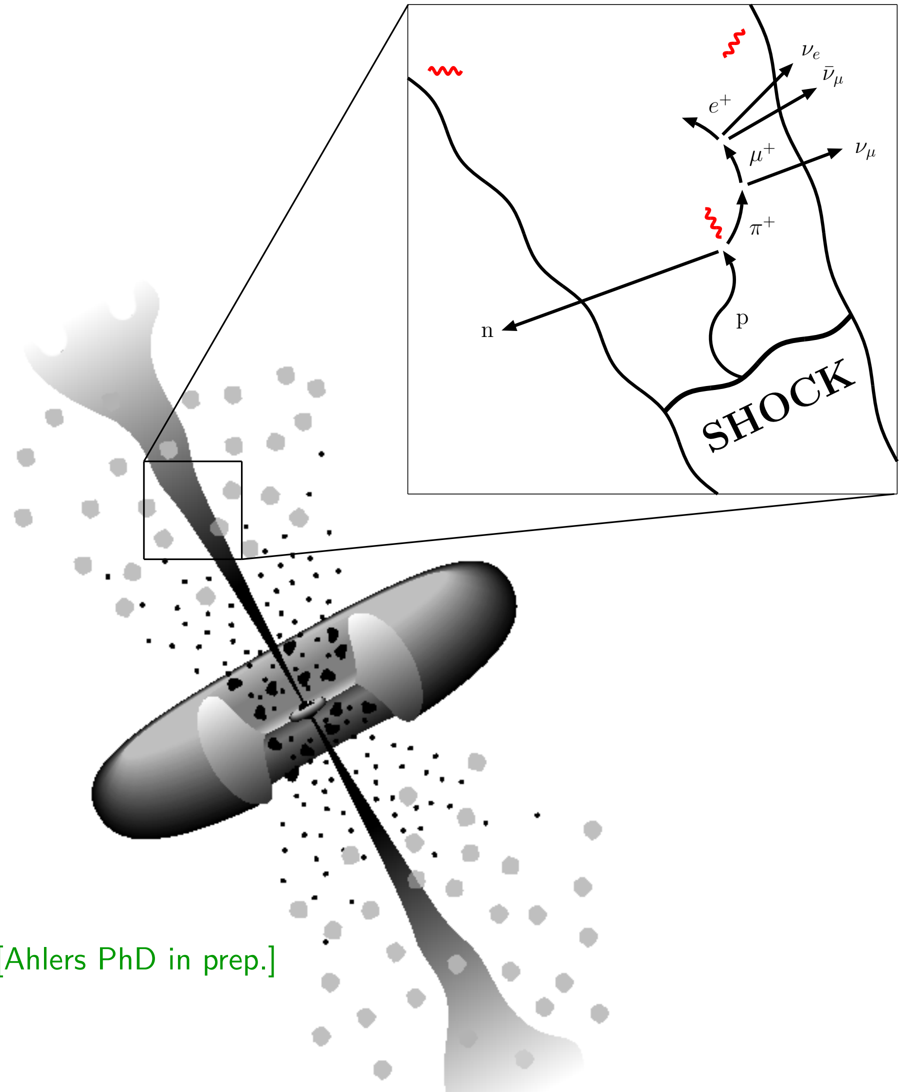


- **Further content:**

  2. **Sources and fluxes of UHEC neutrinos**
  3. **Fundamental physics opportunities of UHEC neutrinos**
  4. **Conclusions**

2. Sources and fluxes of UHEC neutrinos

- Paradigm for **astrophysical** extra-galactic source of protons and neutrinos: **shock acceleration**
  - p's, confined by magnetic fields, accelerate through repeated scattering by plasma shock fronts
  - production of π's and n's through collisions of the trapped p's with ambient plasma produces γ's, ν's and CR's (n diffusion from source)



[Ahlers PhD in prep.]

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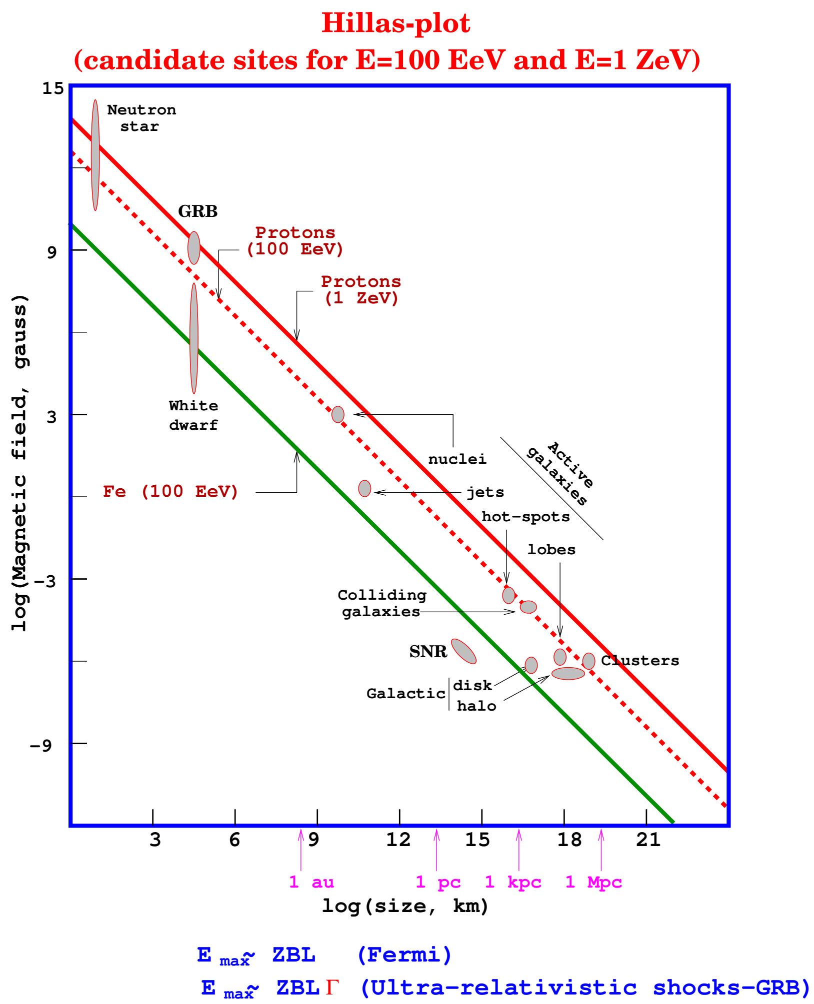

[Pierre Auger Observatory]

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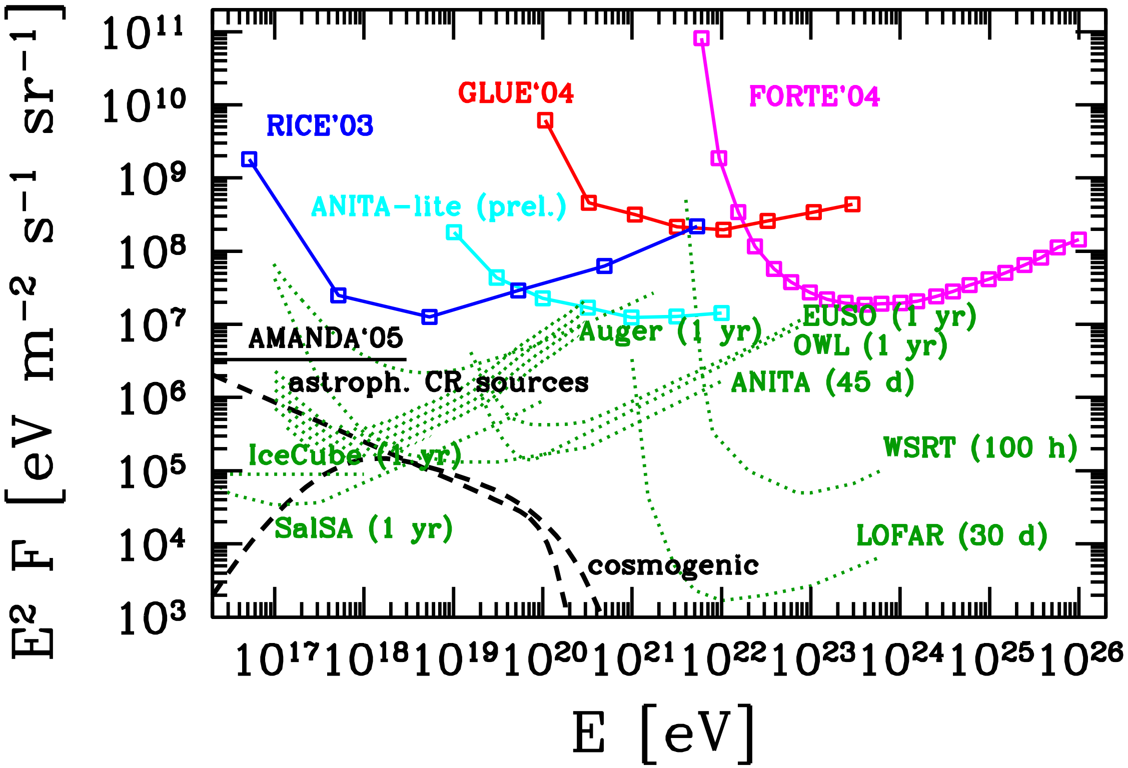

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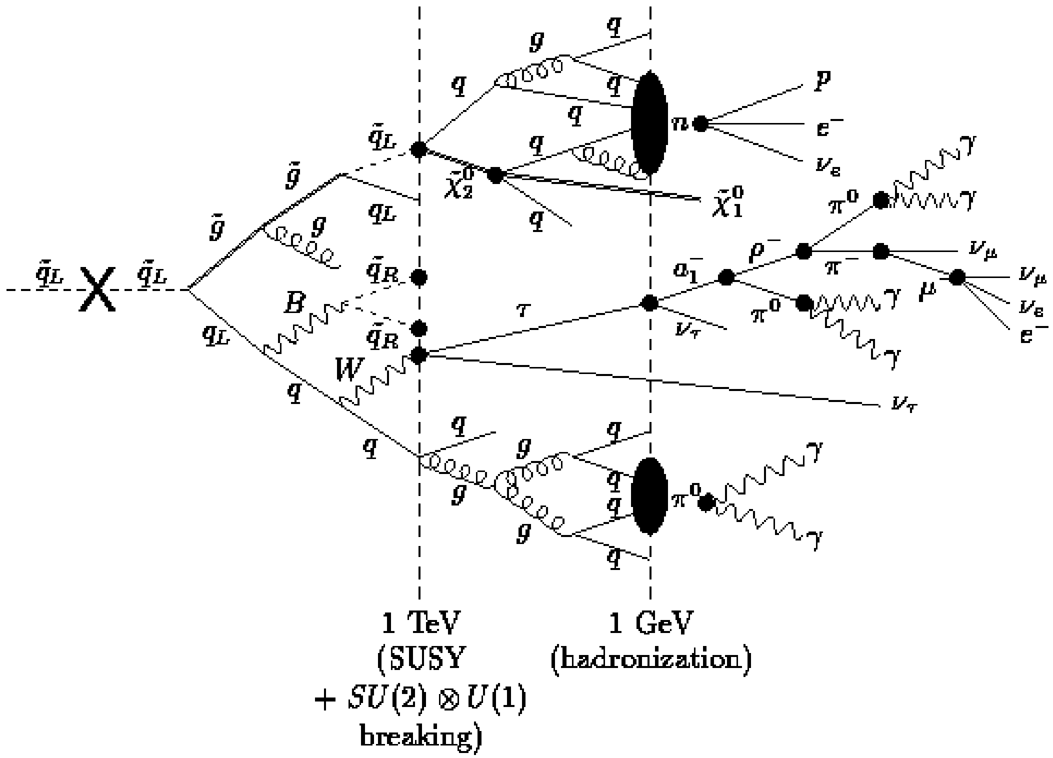
$\Rightarrow$ $E_\nu \gtrsim 10^{20}$ eV (super-GZK) ν's:

$\leftarrow$ yet unknown acceleration sites
$\leftarrow$ other acceleration mechanism
$\leftarrow$ **decay of superheavy particles**



[Barbot,Drees '02]

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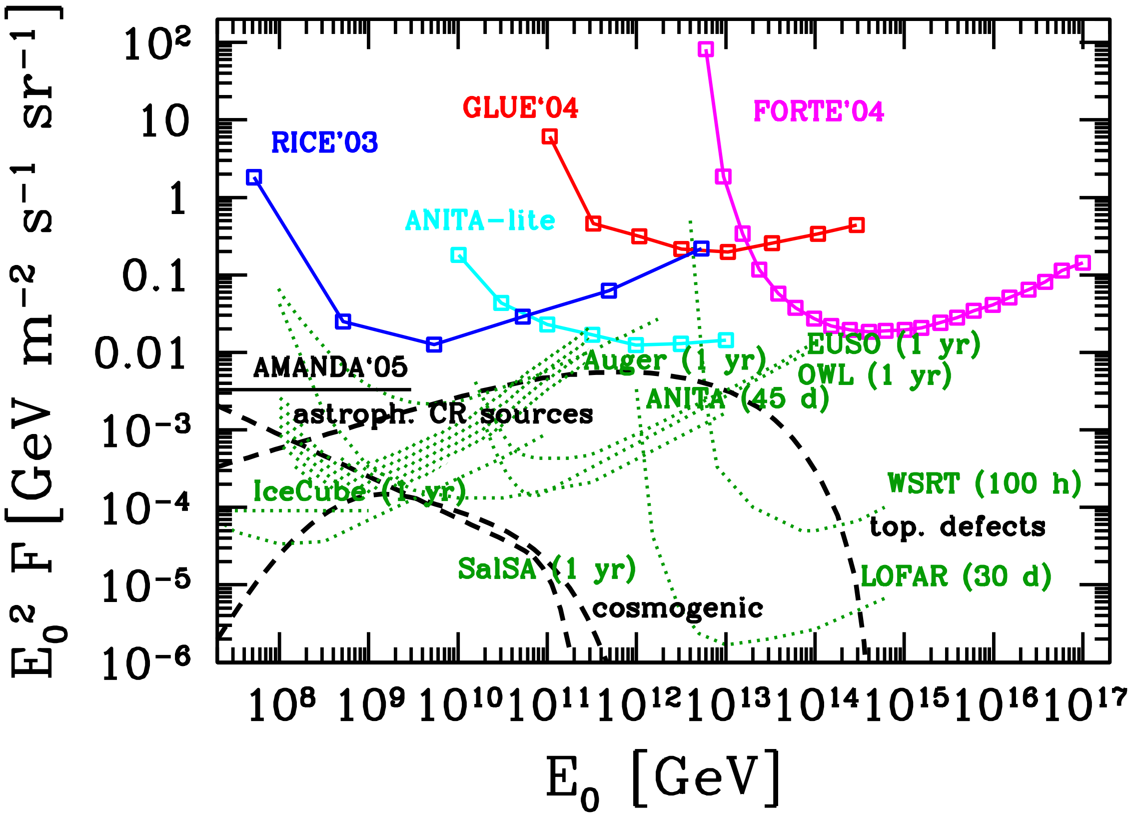
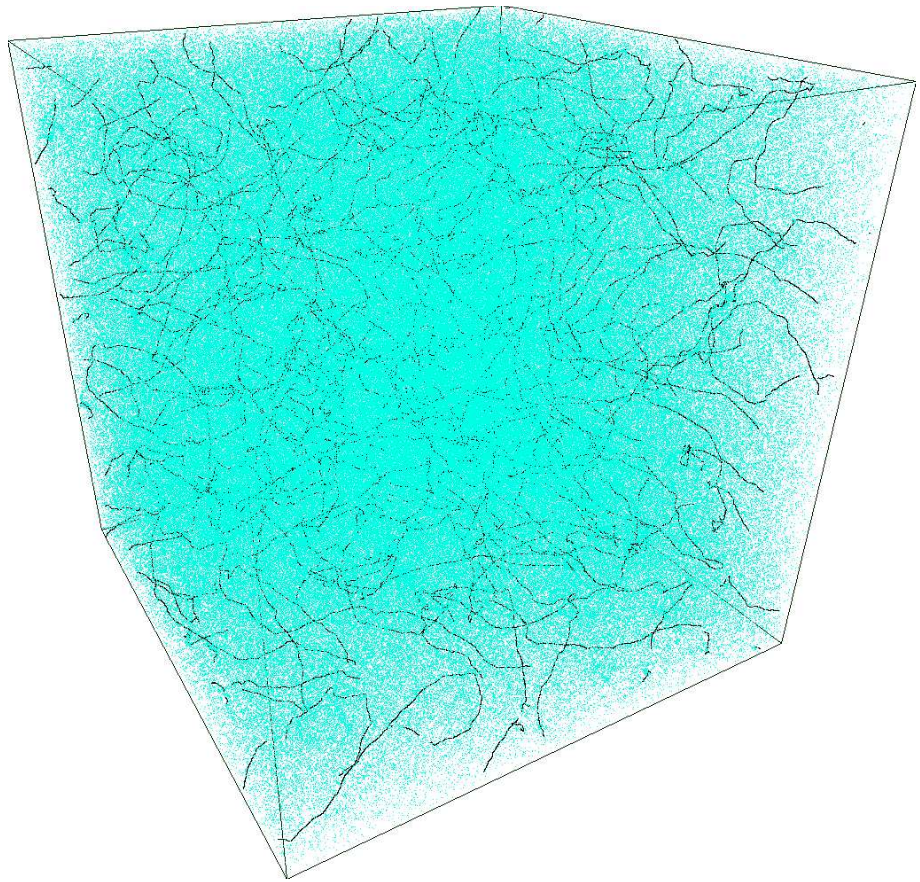


Top-down scenarios for super-GZK neutrinos

- 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.
  - decomposition of topological defects from late phase transitions into their constituents



[Ringeval,Sakellariadou,Bouchet '06]

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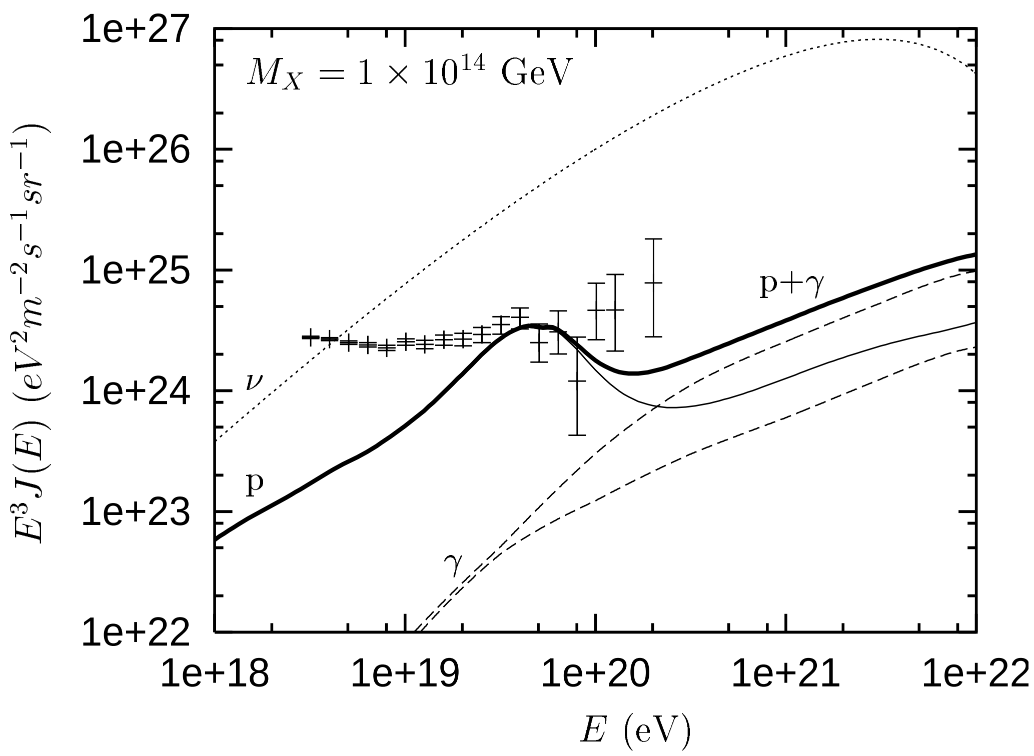

[Aloisio,Berezinsky,Kachelriess '04]

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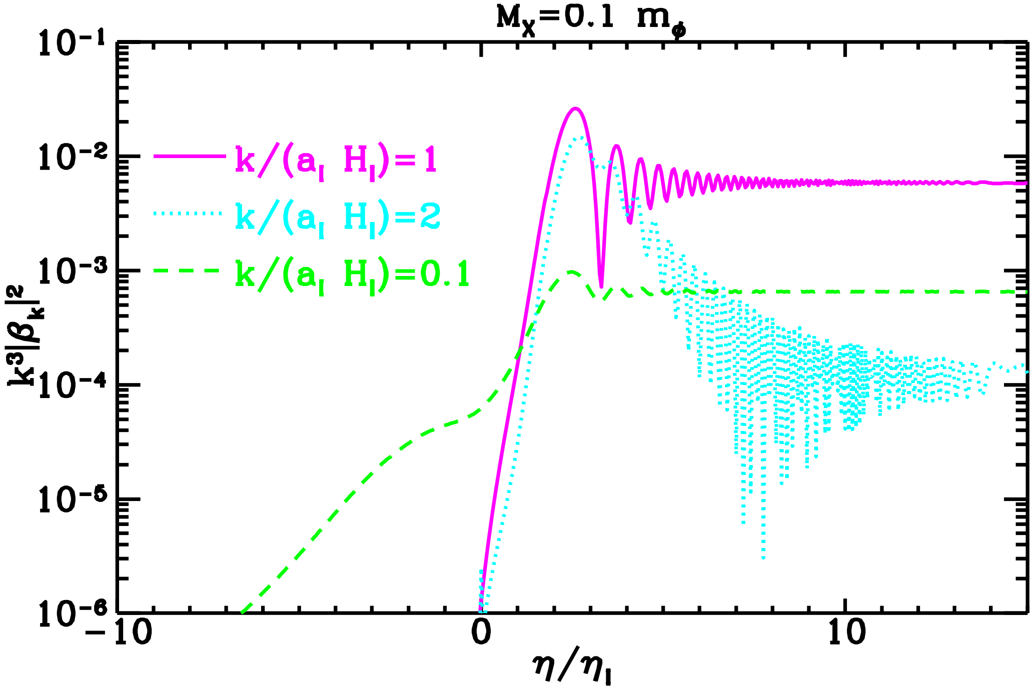

[Kolb,Chung,Riotto '98]

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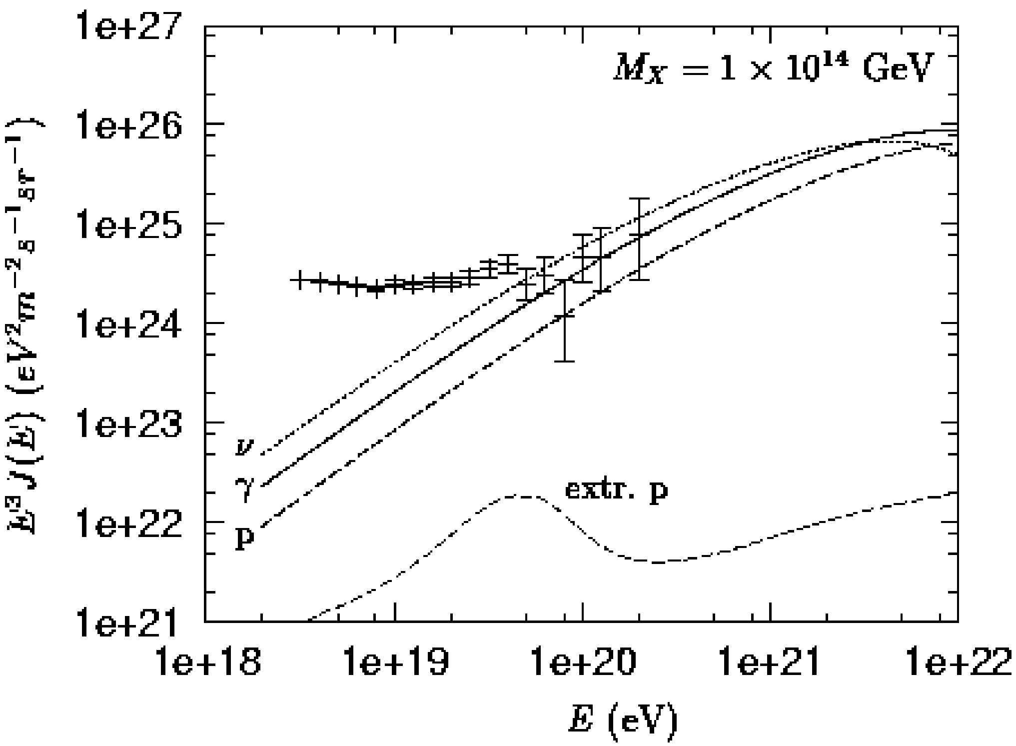
  $\Rightarrow$ super-GZK ν's from decay or annihilation of superheavy dark matter (for $\tau_X \gtrsim \tau_U$)



[Aloisio,Berezinsky,Kachelriess '04]

Top-down scenarios for super-GZK neutrinos

- **How generic?**
  - **Topological defects:** generic prediction of symmetry breaking (SB) in GUT's, and even fundamental string theory, e.g.
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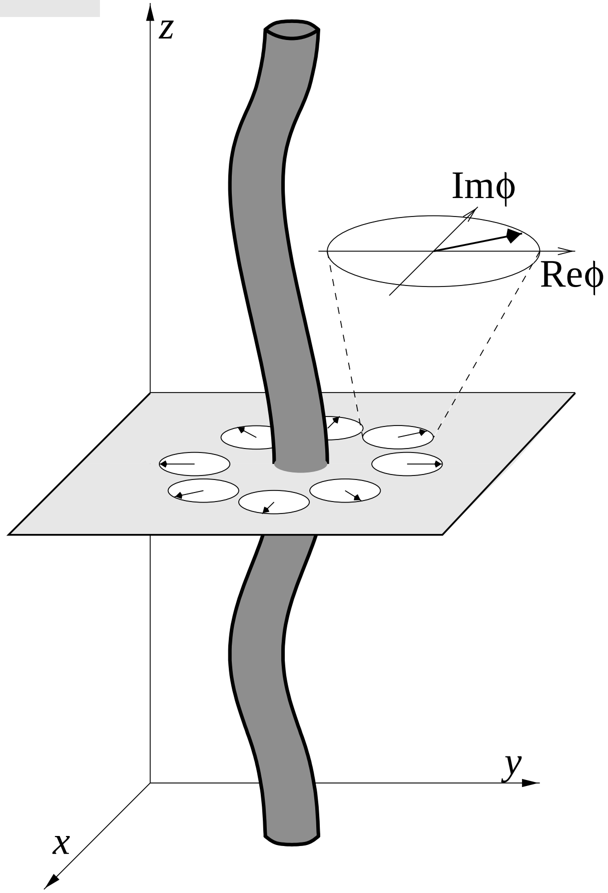

[Rajantie '03]

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SO(10) \xrightarrow{1} 4_{\rm C}\,2_{\rm L}\,2_{\rm R}
\left\{
\begin{array}{lll}
\xrightarrow{1} & 3_{\rm C}\,2_{\rm L}\,2_{\rm R}\,1_{\rm B-L} &
\left\{
\begin{array}{llll}
\xrightarrow{1} & 3_{\rm C}\,2_{\rm L}\,1_{\rm R}\,1_{\rm B-L} & \xrightarrow{2\ (2)} & G_{\rm SM}\ (Z_2) \\
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[Jeannerot,Rocher,Sakellariadou ‘03]

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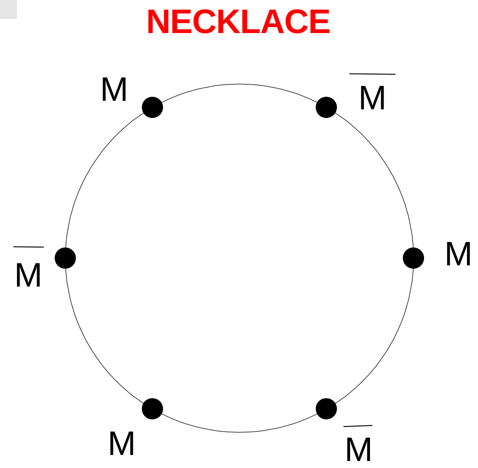

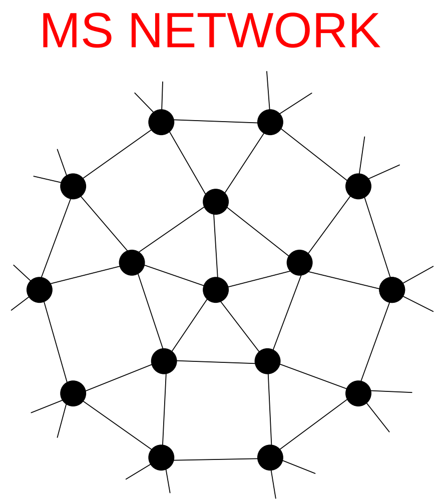

[Berezinsky '05]

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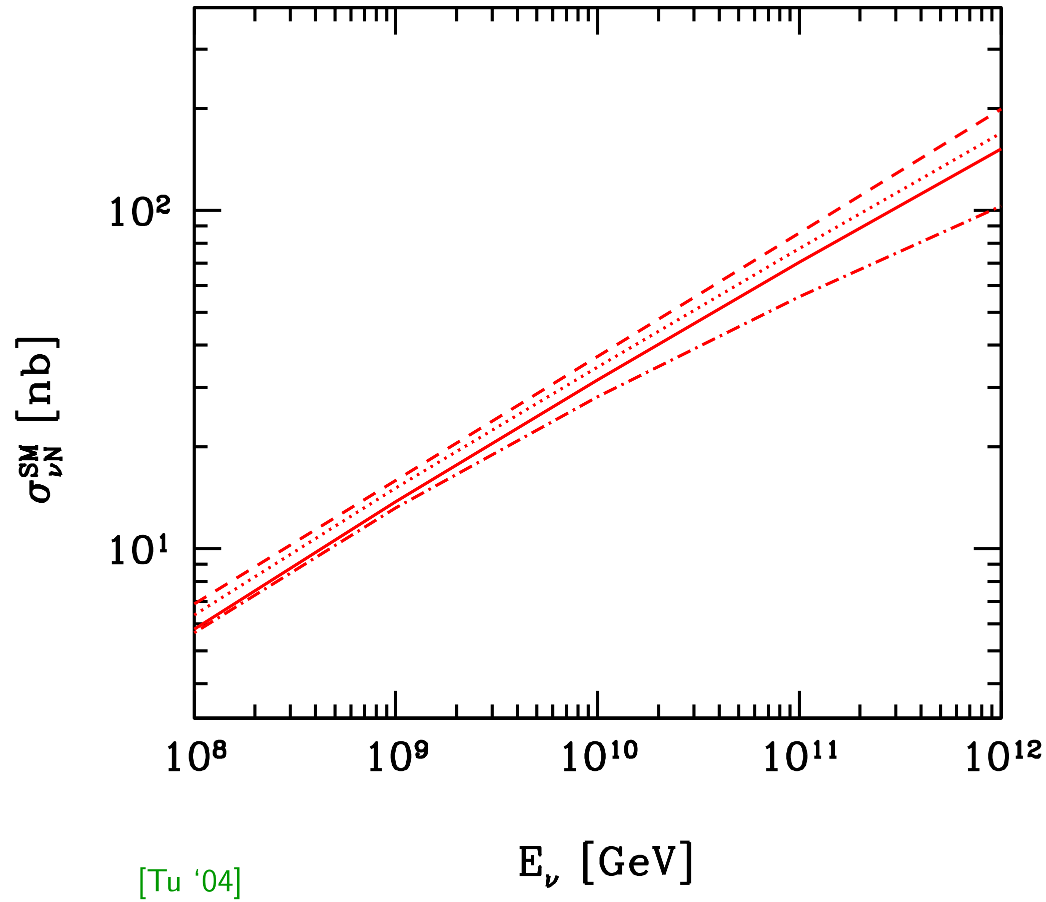
    - $\mathrm{G} \to \mathrm{H} \times \mathrm{U}(1) \to \mathrm{H} \times \mathrm{Z}_N$ SB: monopoles connected by strings
  - **Superheavy dark matter:** need symmetry to prevent fast X decay
    - gauge $\Rightarrow$ X stable
    - discrete $\Rightarrow$ stable or quasi-stable

3. Fundamental physics opportunities with UHEC neutrinos

- **Cν's** with $E_\nu \gtrsim 10^8$ GeV probe $\boldsymbol{\nu N}$ scattering at $\sqrt{s_{\nu N}} \gtrsim 14$ TeV (**LHC**)
- Perturbative Standard Model (**SM**) $\approx$ under control ($\leftarrow$ **HERA**)

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



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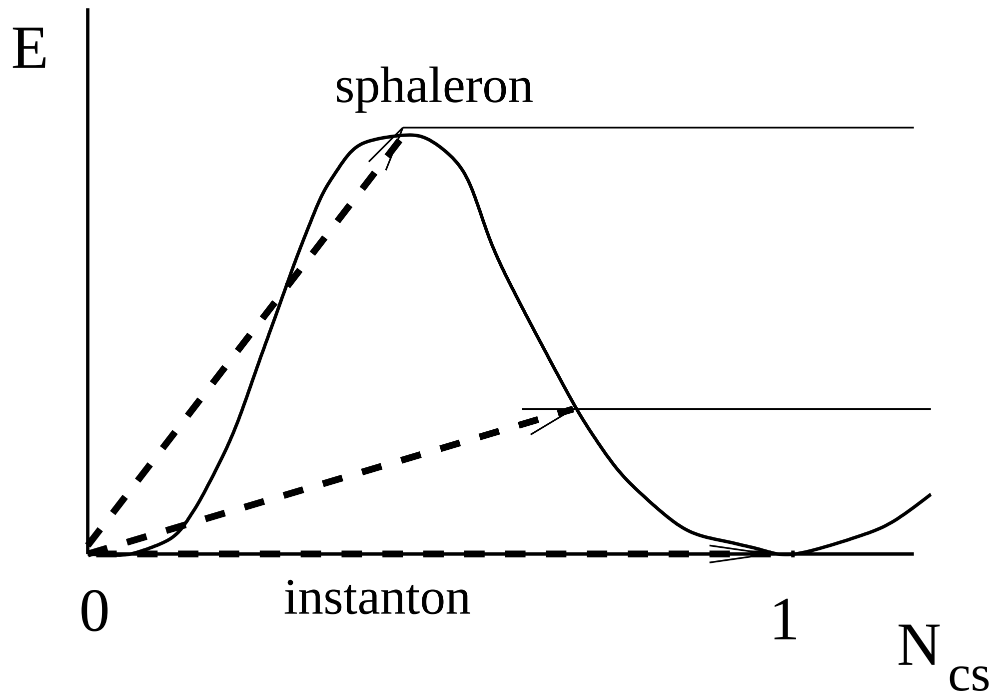
⇒ Search for enhancements in $\boldsymbol{\sigma_{\nu N}}$ beyond (perturbative) SM:

◇ Electroweak sphaleron production



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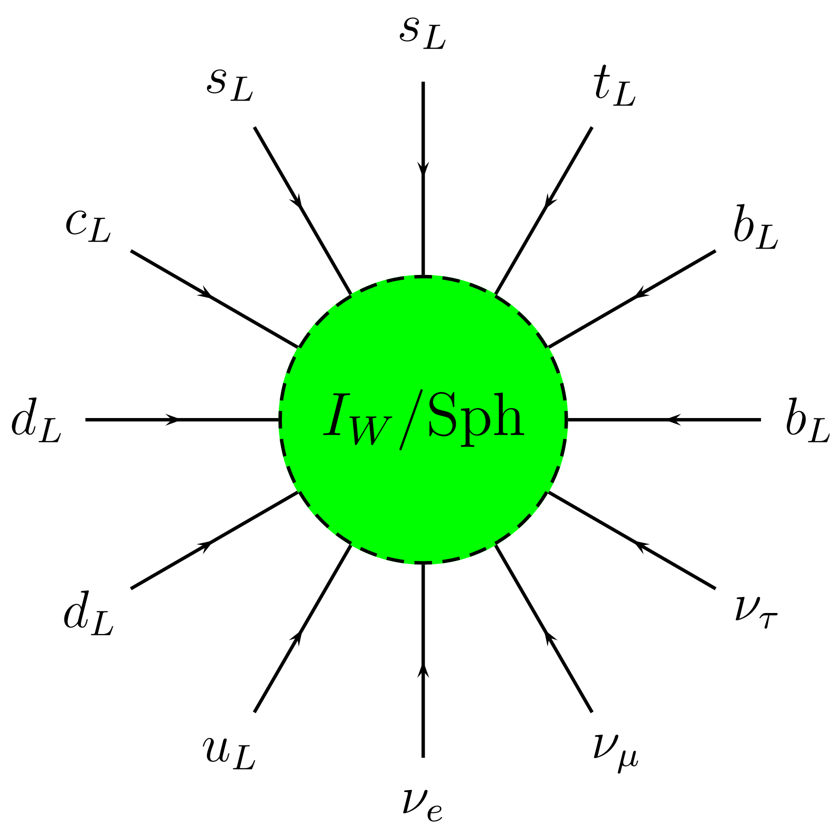

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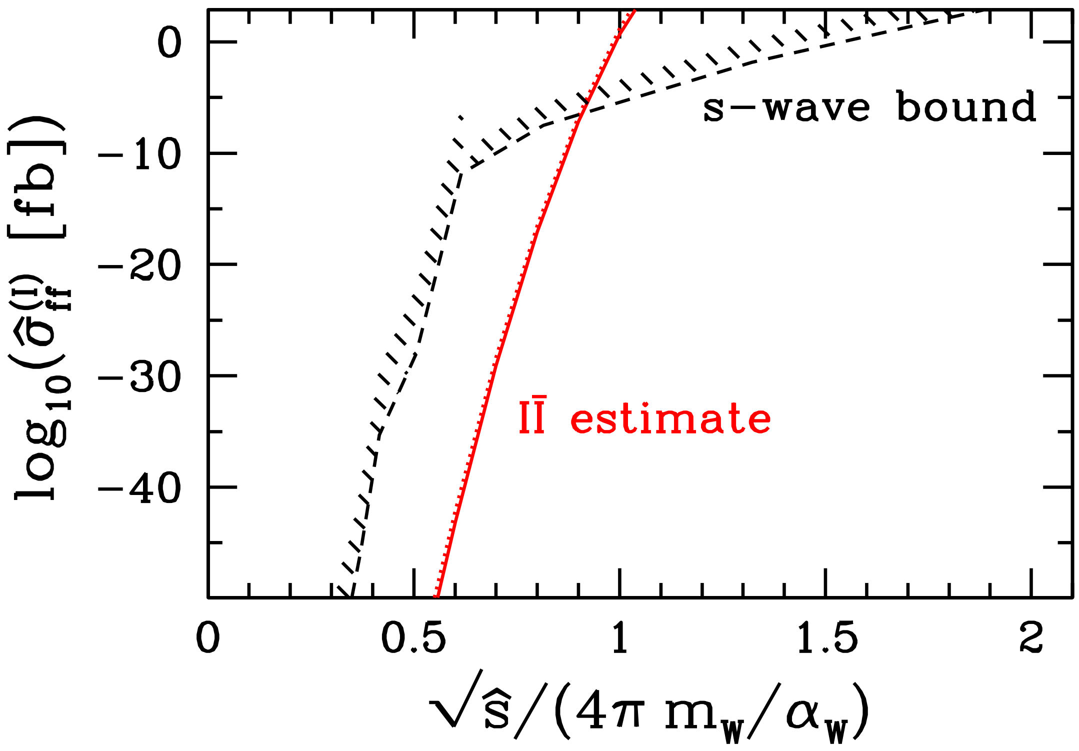

[AR '03]

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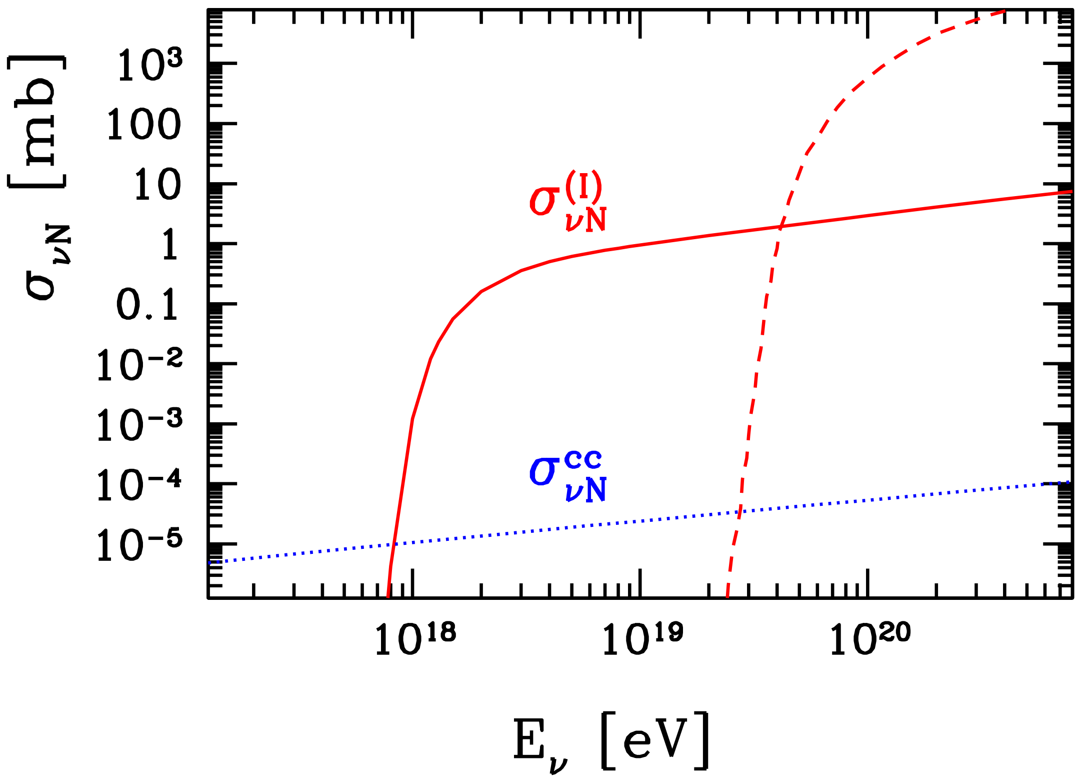

[Fodor,Katz,AR,Tu '03; Han,Hooper '03]

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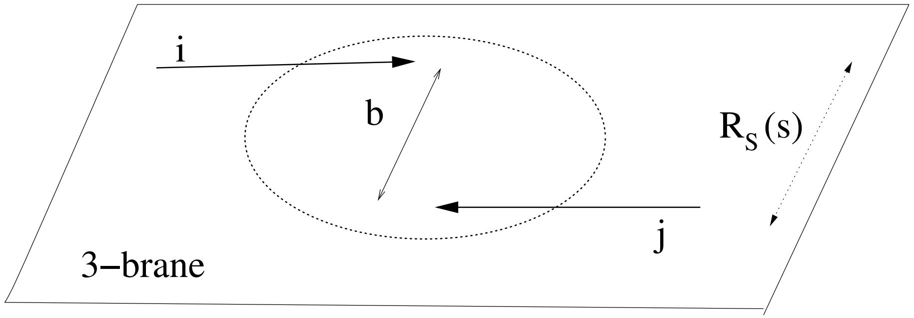

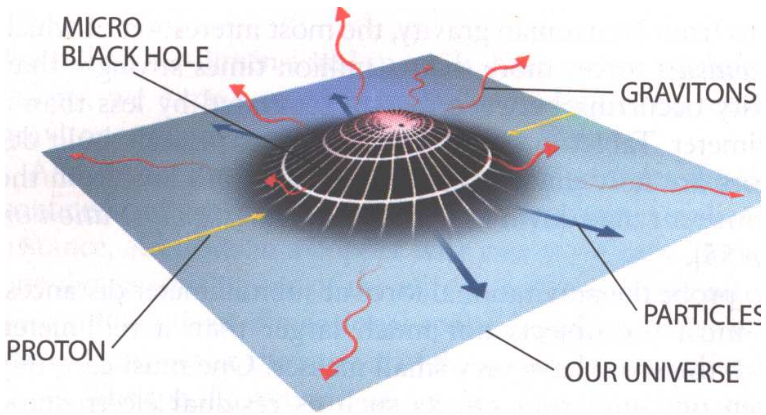

[Scientific American '00]

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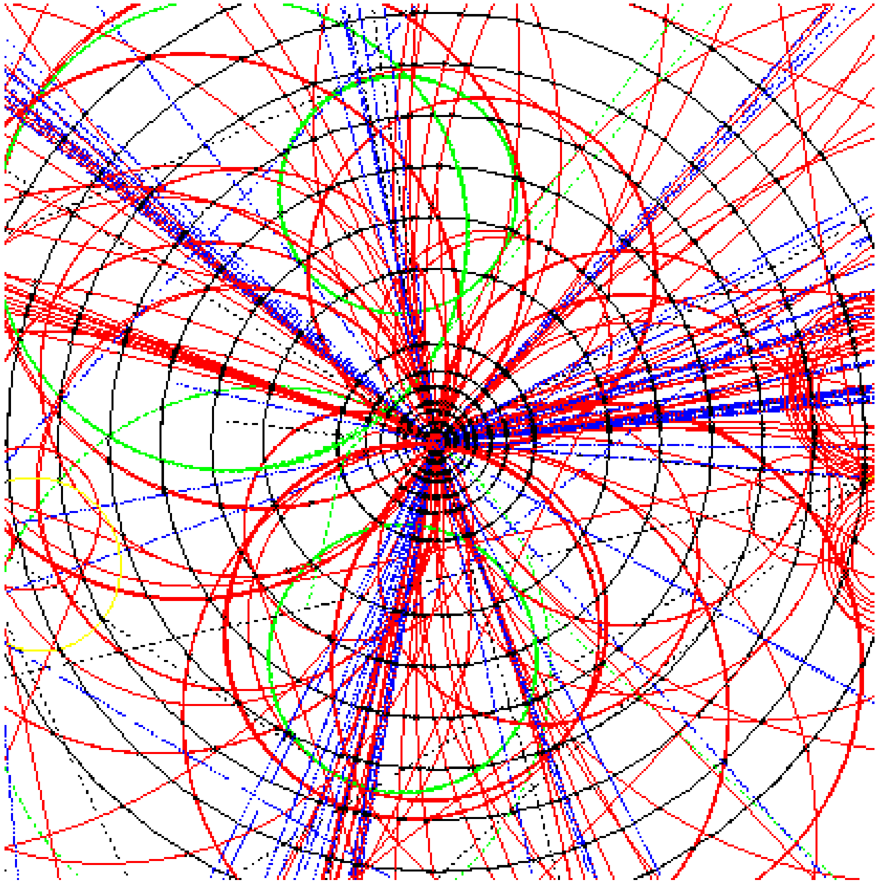

[Barklow,De Roeck '01]

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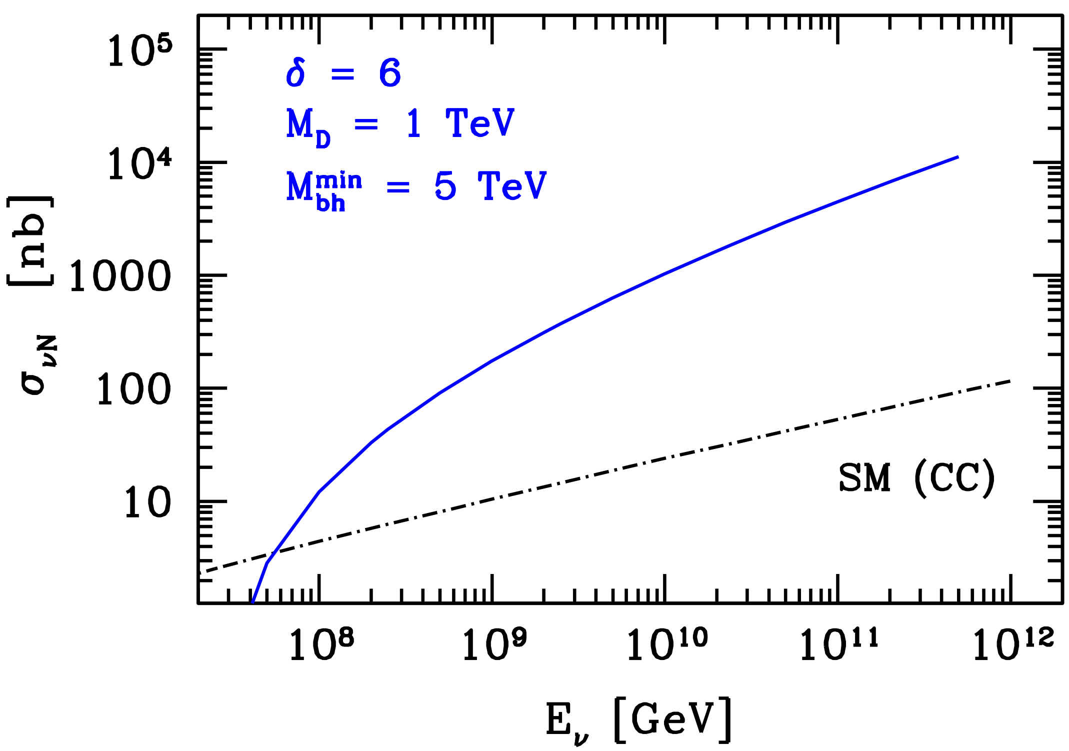


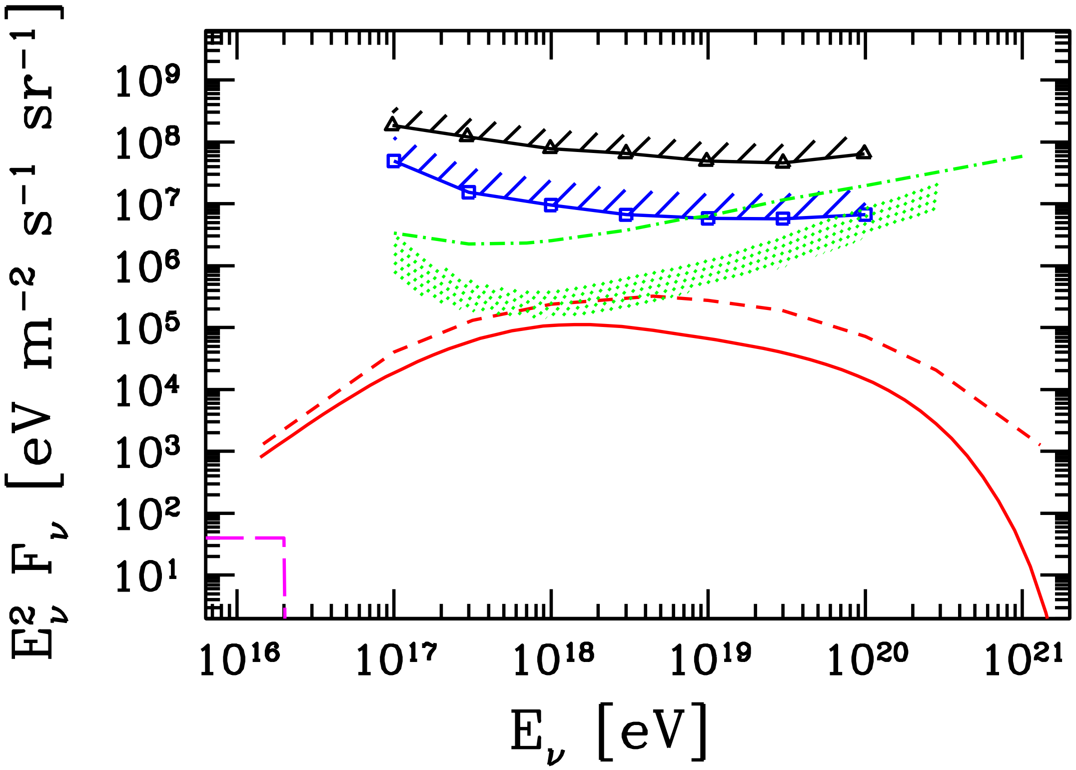
[AR,Tu '01; Tu '04]

TeV scale physics with UHEC neutrinos

$$\frac{dN}{dt} \propto \int dE_\nu \, F_\nu(E_\nu) \, \sigma_{\nu N}(E_\nu)$$

⇒ 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;..]



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

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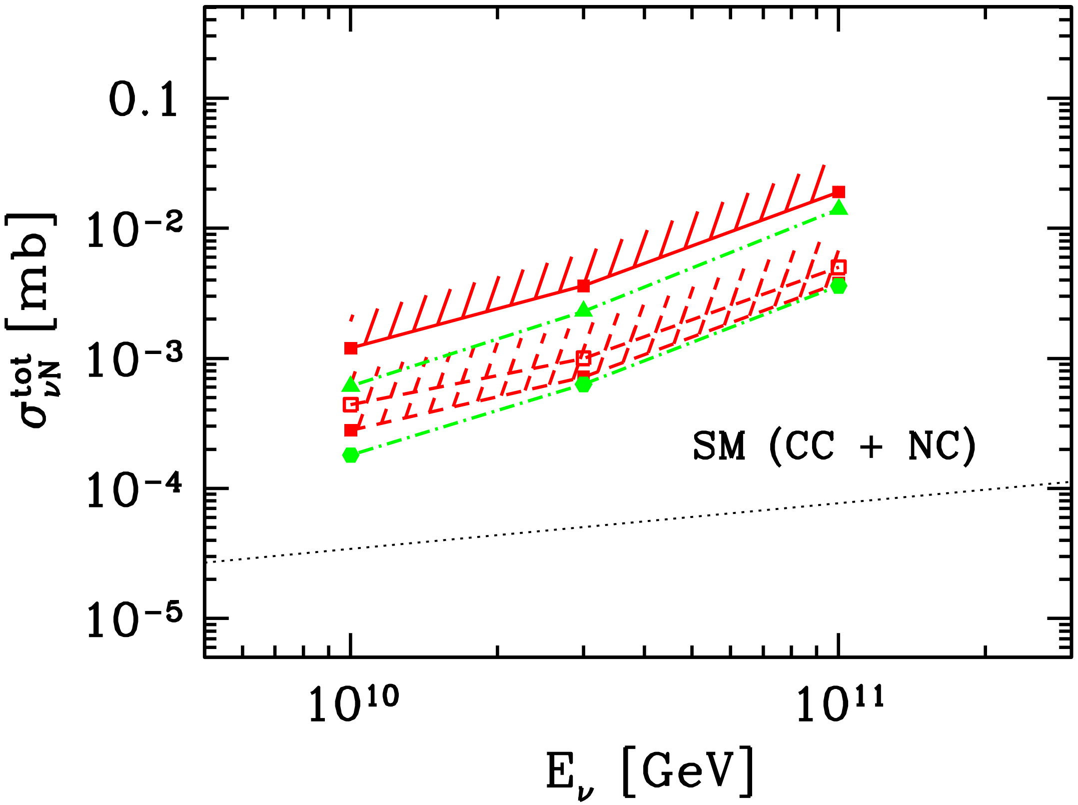
- Recent quantitative analysis:

[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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- Bounds exploiting searches for deeply-penetrating particles applicable as long as $\sigma_{\nu N} \lesssim (0.5 \div 1)$ mb
- For even higher cross sections, e.g. via sphaleron or brane production:

$\Rightarrow$ Strongly interacting neutrino scenario for the post-GZK events

[Berezinsky,Zatsepin '69]

- Quantitative analysis:

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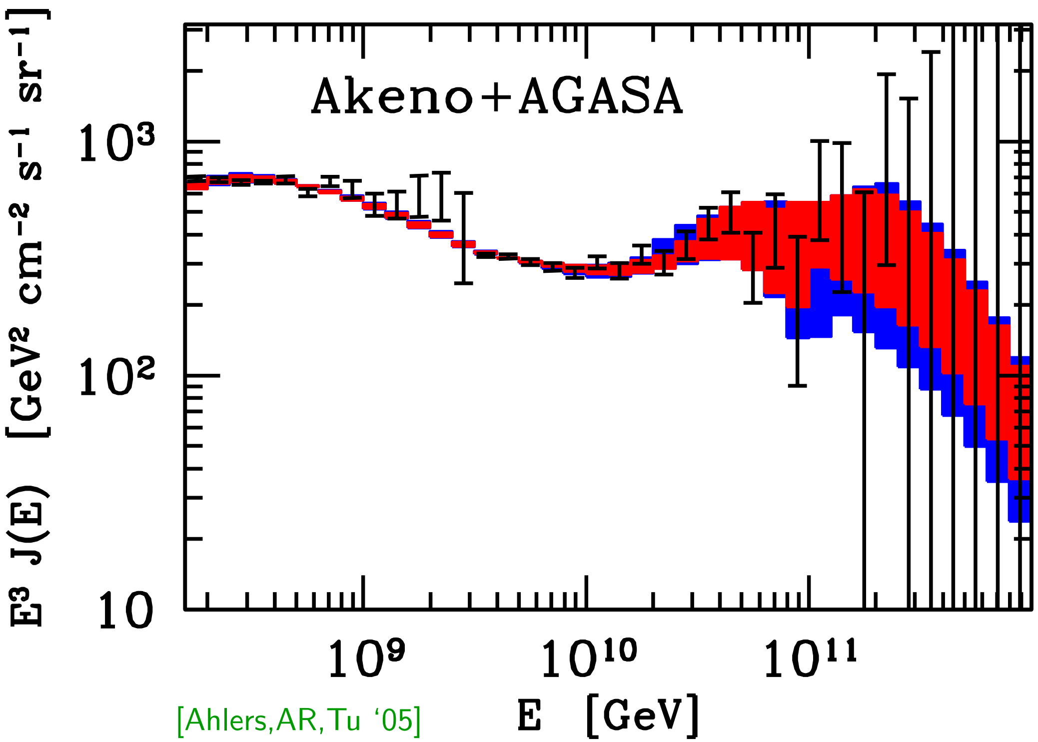
  – Very good fit to CR data



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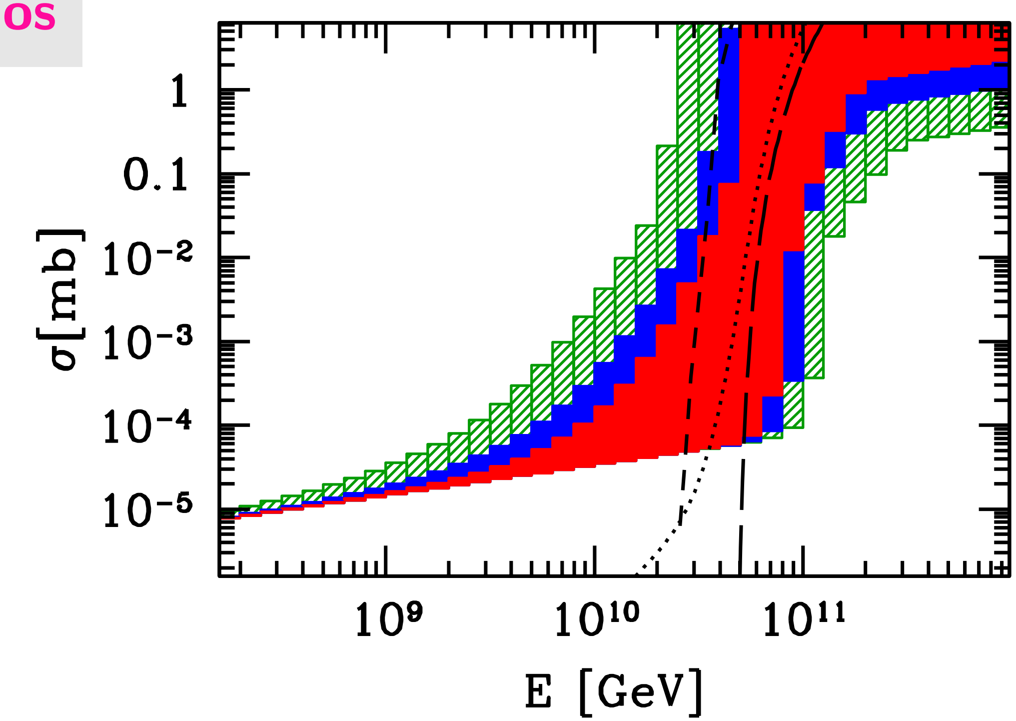
  – Very good fit to CR data
  – Need steeply rising cross section, otherwise clash with nonobservation of deeply-penetrating particles



[Ahlers,A.R.,Tu '05]

[AR '03;Han,Hooper '04] - - - sphalerons

[Anchordoqui,Feng,Goldberg '02] – – – p-branes

[Burgett,Domokos,Kovesi-Domokos '04] ...string excitations

GUT scale physics with super-GZK neutrinos

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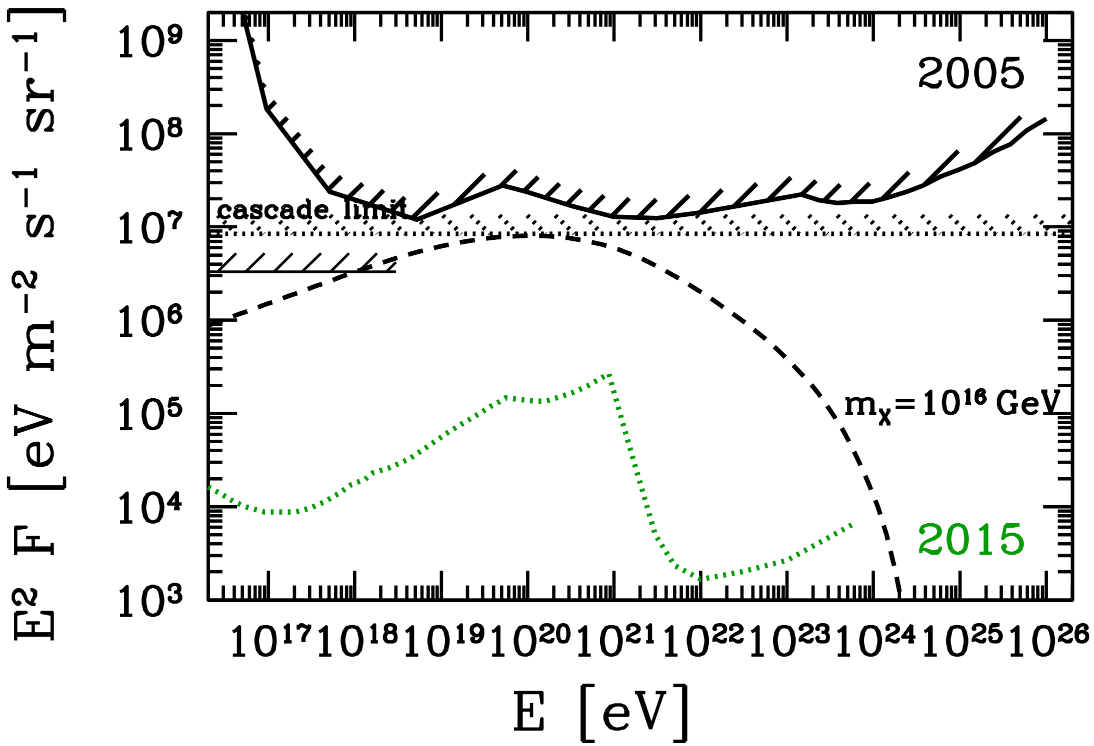
  - **cosmology**



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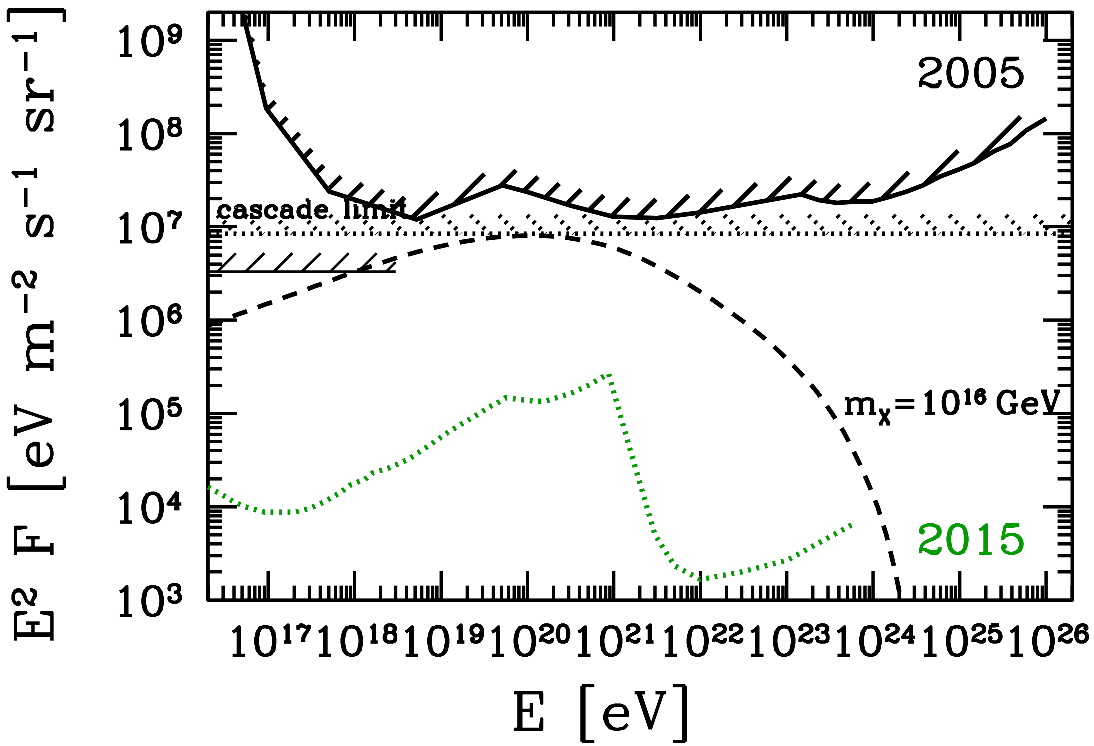

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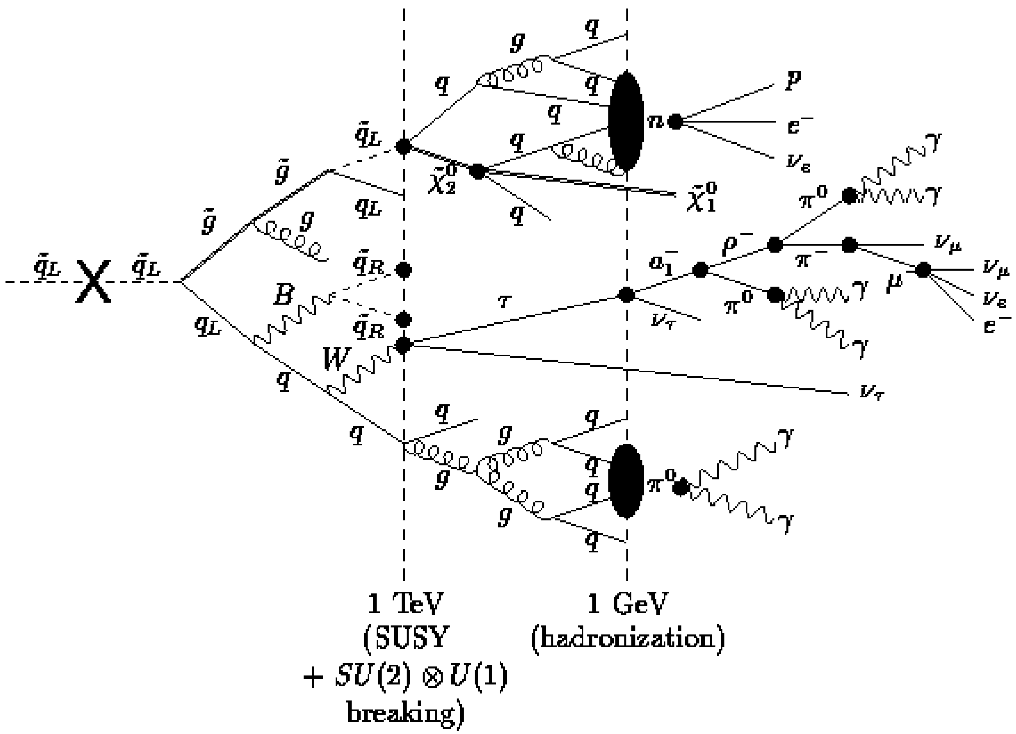

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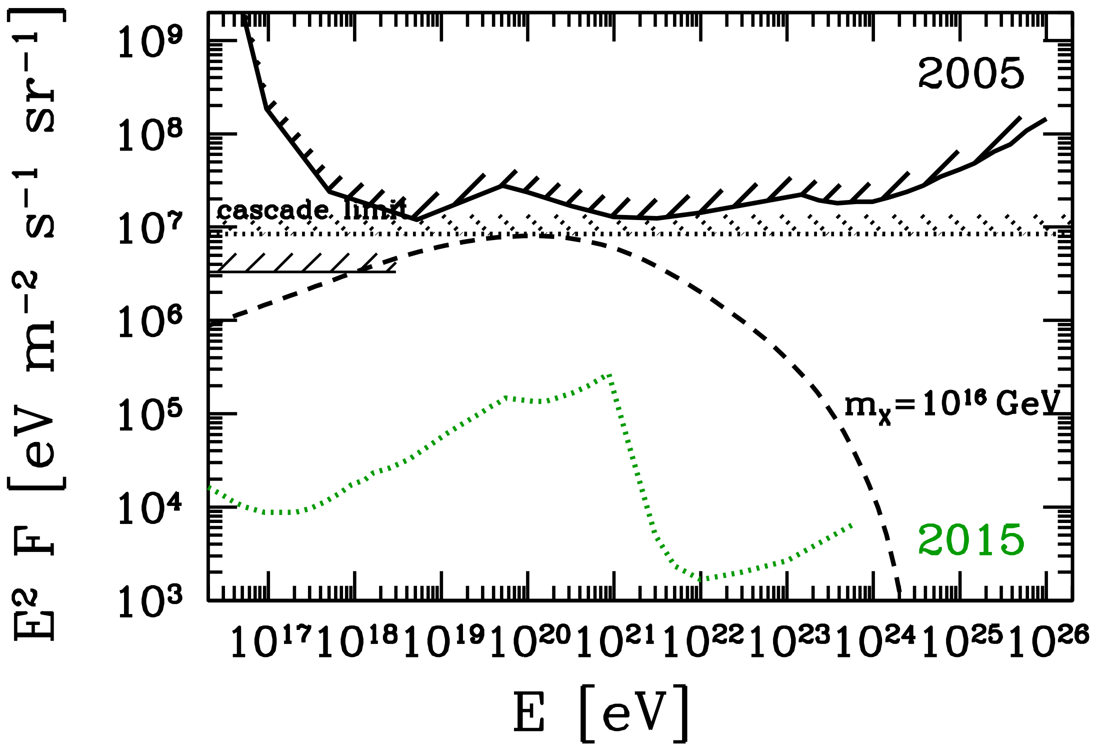
    - existence of the big bang relic neutrino background (CνB)



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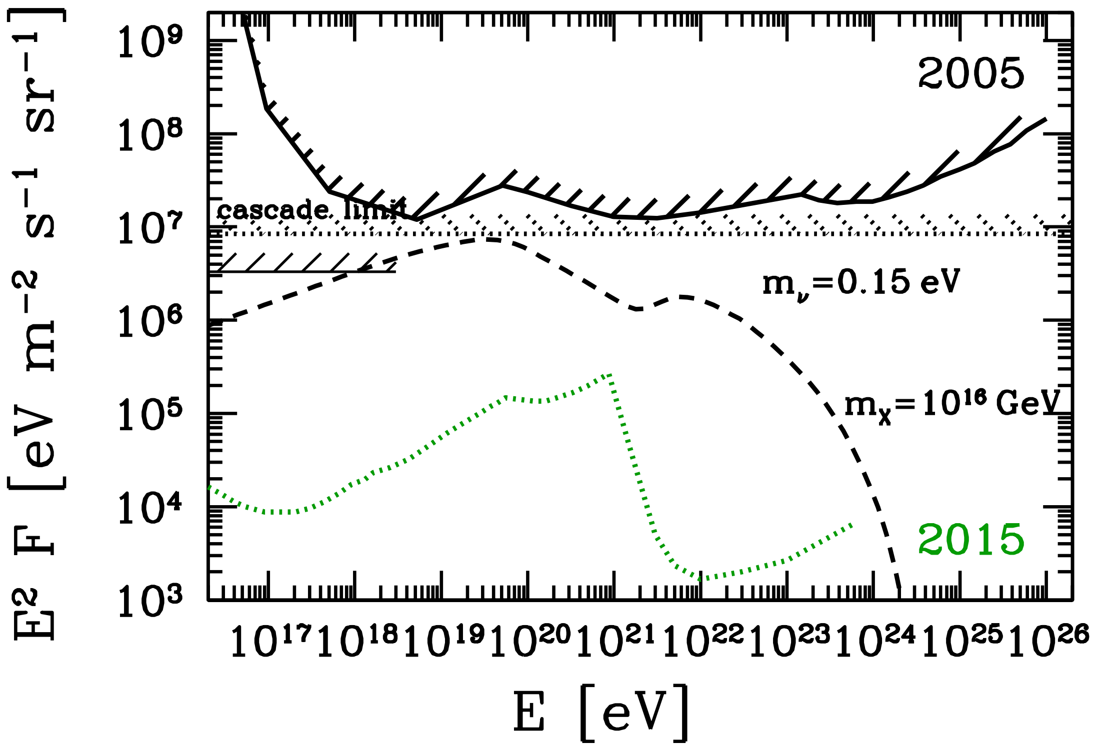
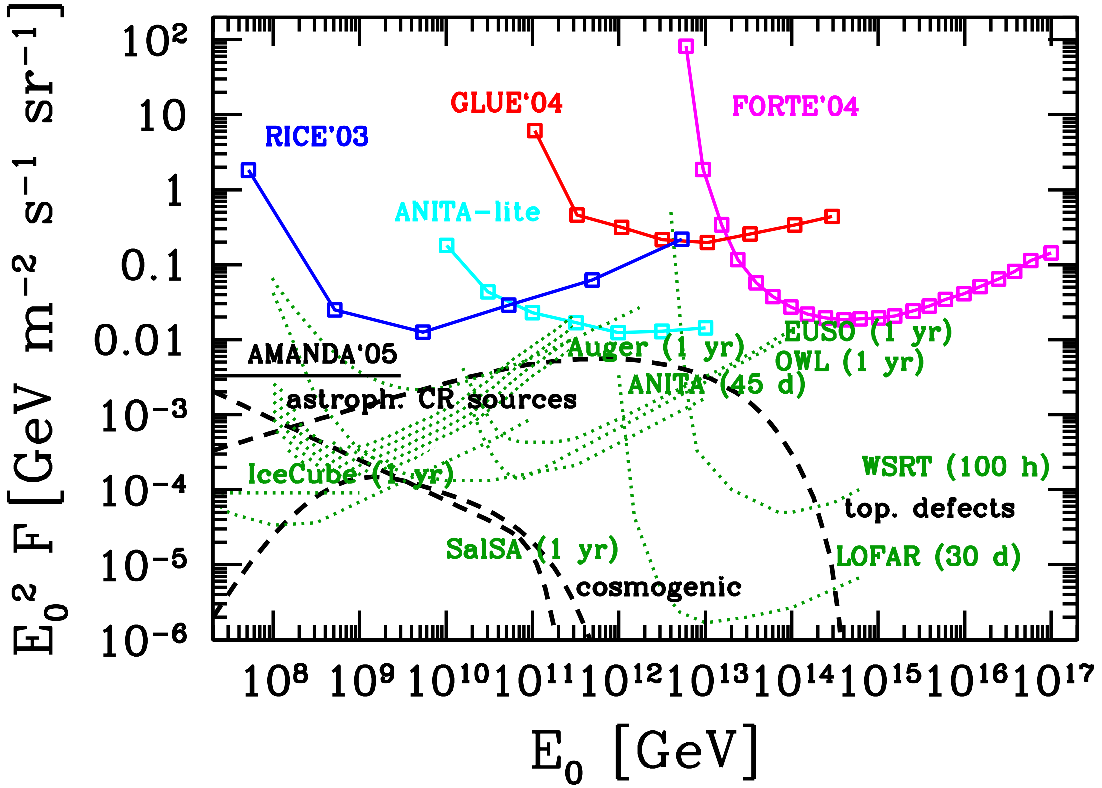


[Fodor,Katz,AR,Weiler,Wong,in prep.]

4. 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