The High Energy Universe:

Opportunities for Astrophysics, Particle Physics, and Cosmology

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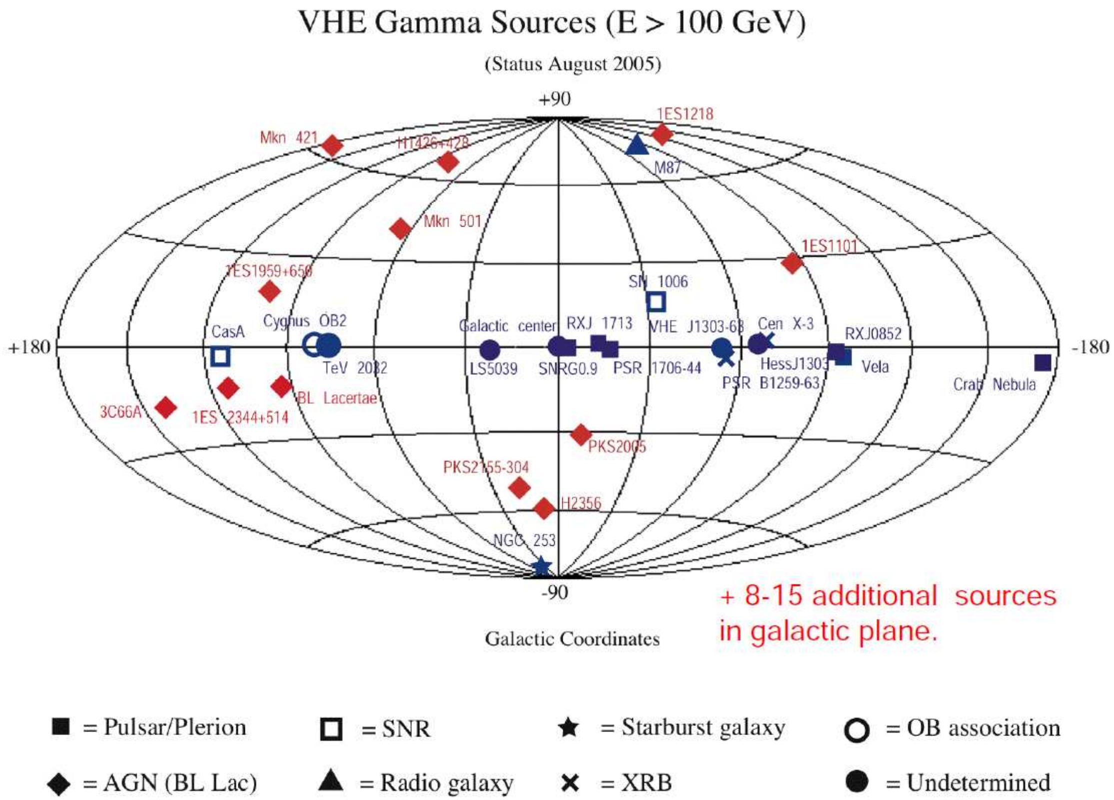
http://www.desy.de/~ringwald

Centre for Particle Theory Colloquium
February 21, 2006, University of Durham, Durham, UK

1. Introduction

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



[M. Martinez '05]

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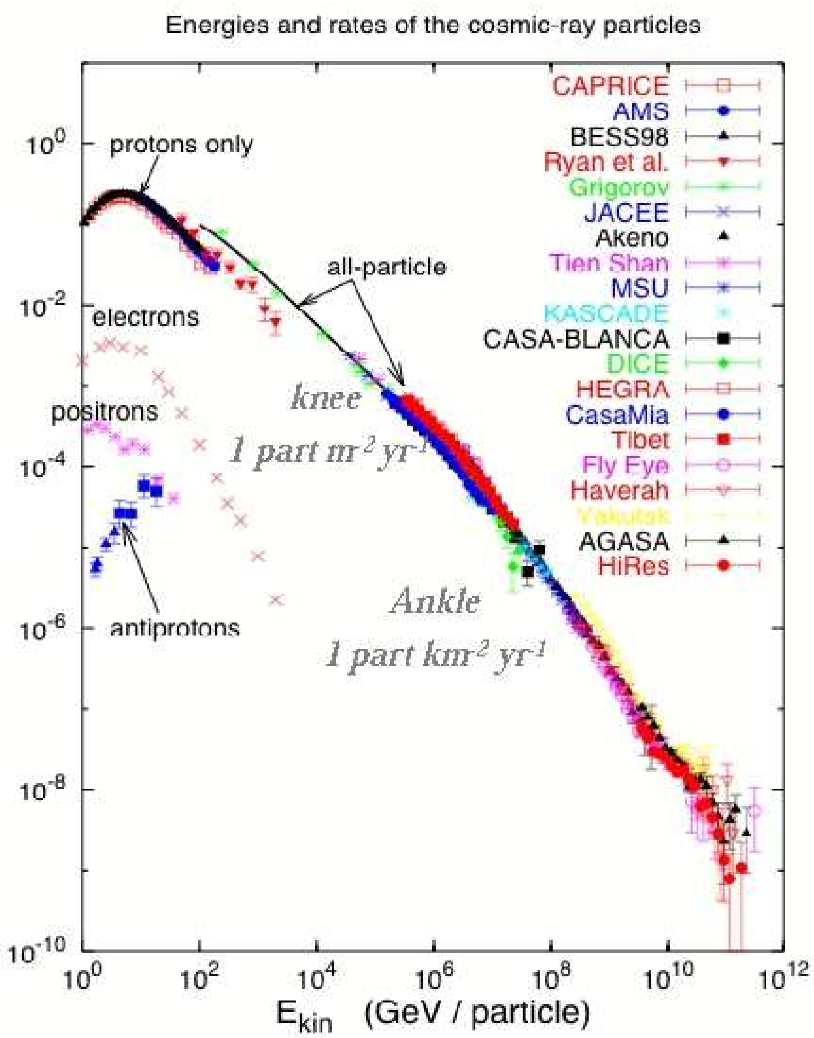

[T. K. Gaisser '05]

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- **It is under active observation:**

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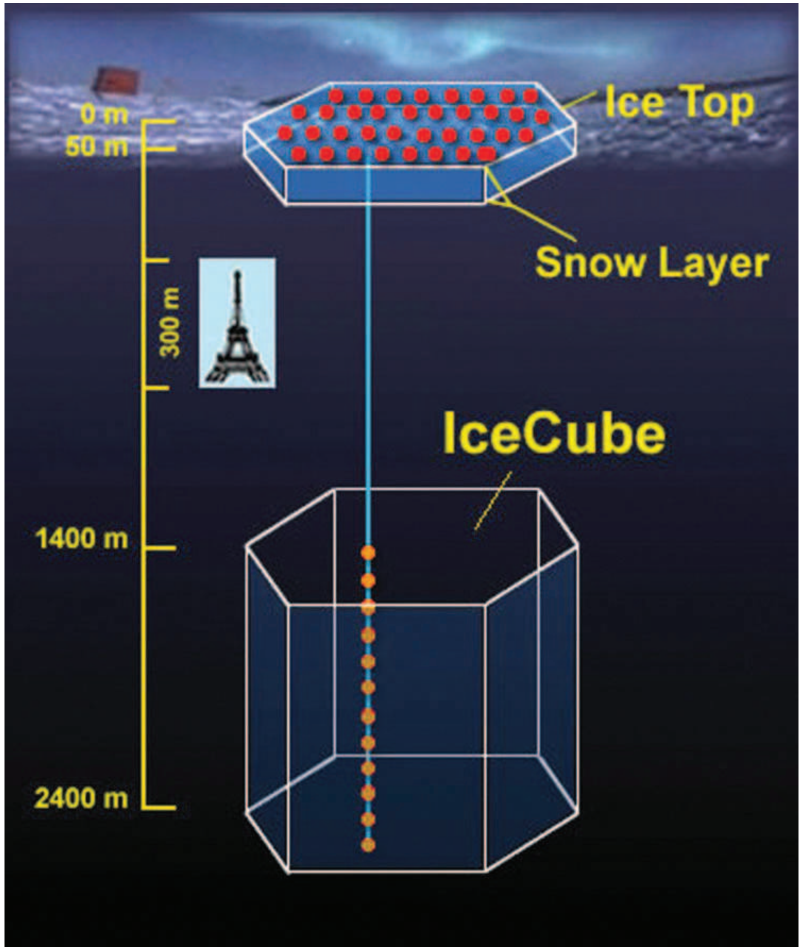
  Air shower detectors: **e.g. Pierre Auger Observatory**

  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**

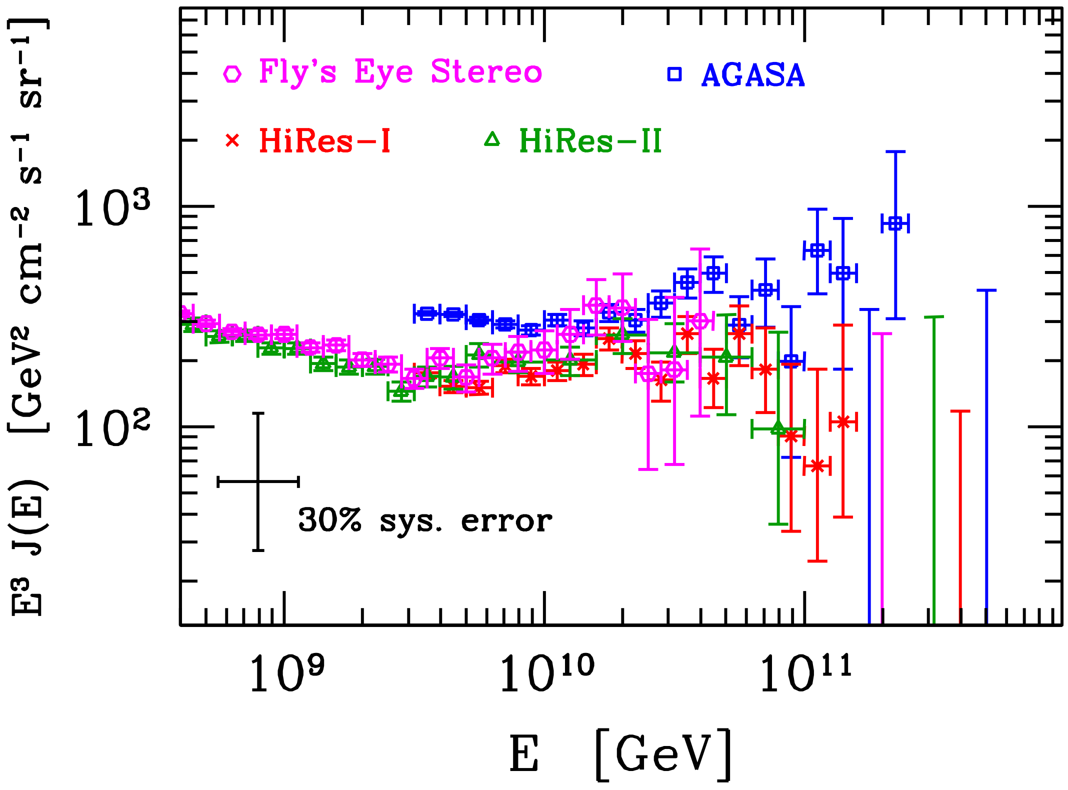
4. **The future ...**

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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- Crucial improvement by **PAO**:

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  ⇐ hybrid observations ⇒ better energy calibration through Fly's Eye technique, direction from ground array

[www.auger.org]

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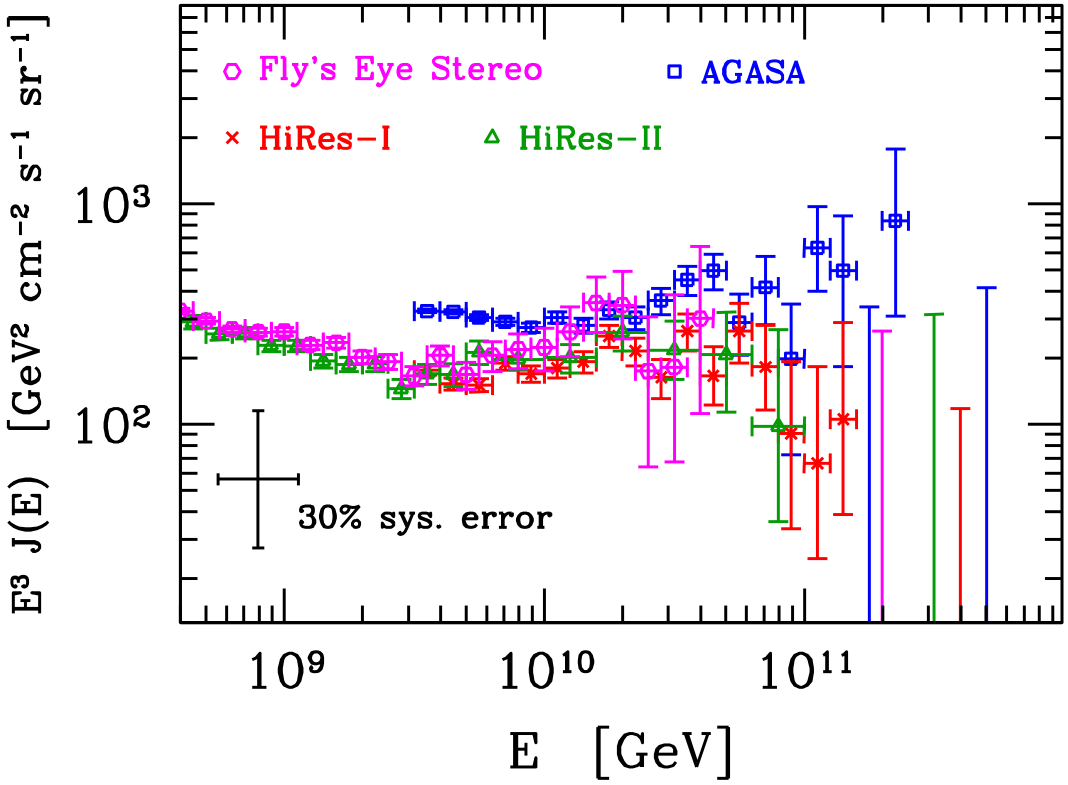

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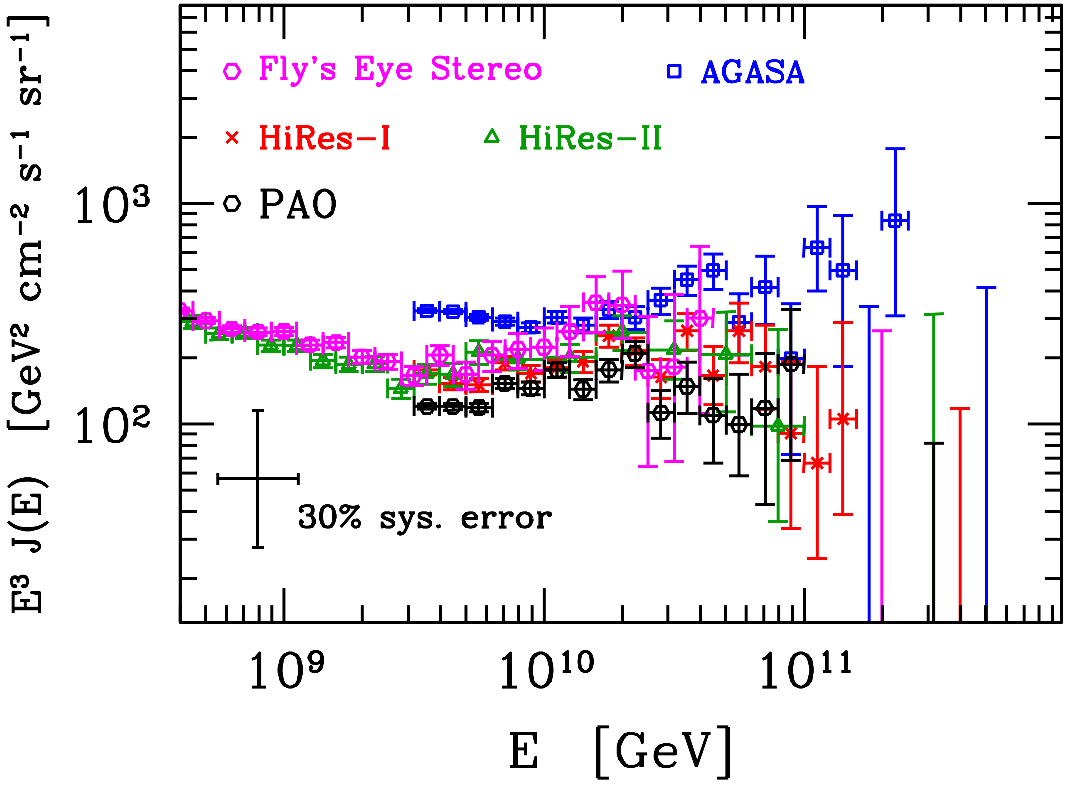
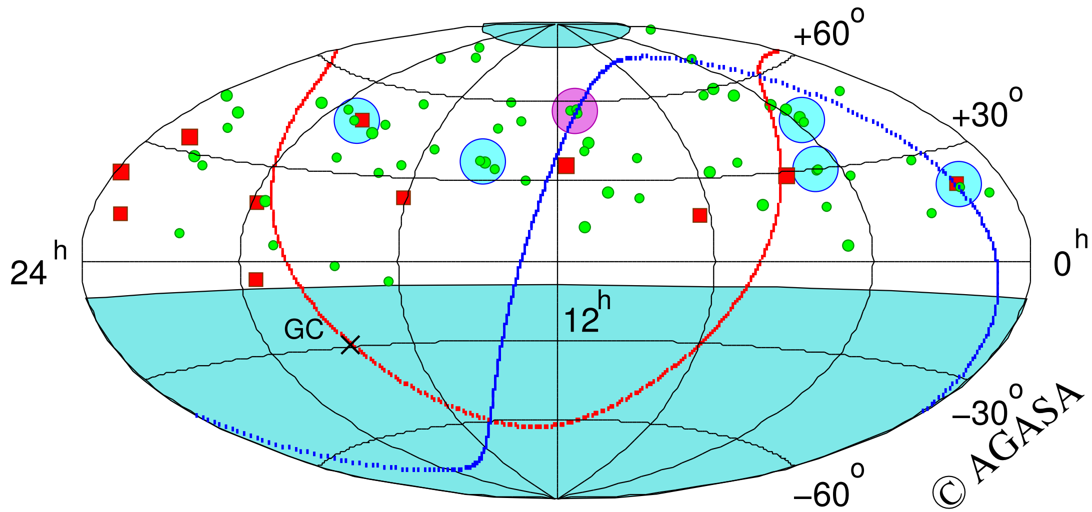


[Ahlers *et al.* '05]

2. Observations at ultrahigh energies

- **Angular distribution:** ≈ isotrop



2. Observations at ultrahigh energies

- **Angular distribution:** $\approx$ isotrop
- **Composition:** Large uncertainty

  $\Leftarrow$ studies rely on simulations

- Cosmic rays above $\gtrsim 10^{8.6}$ GeV
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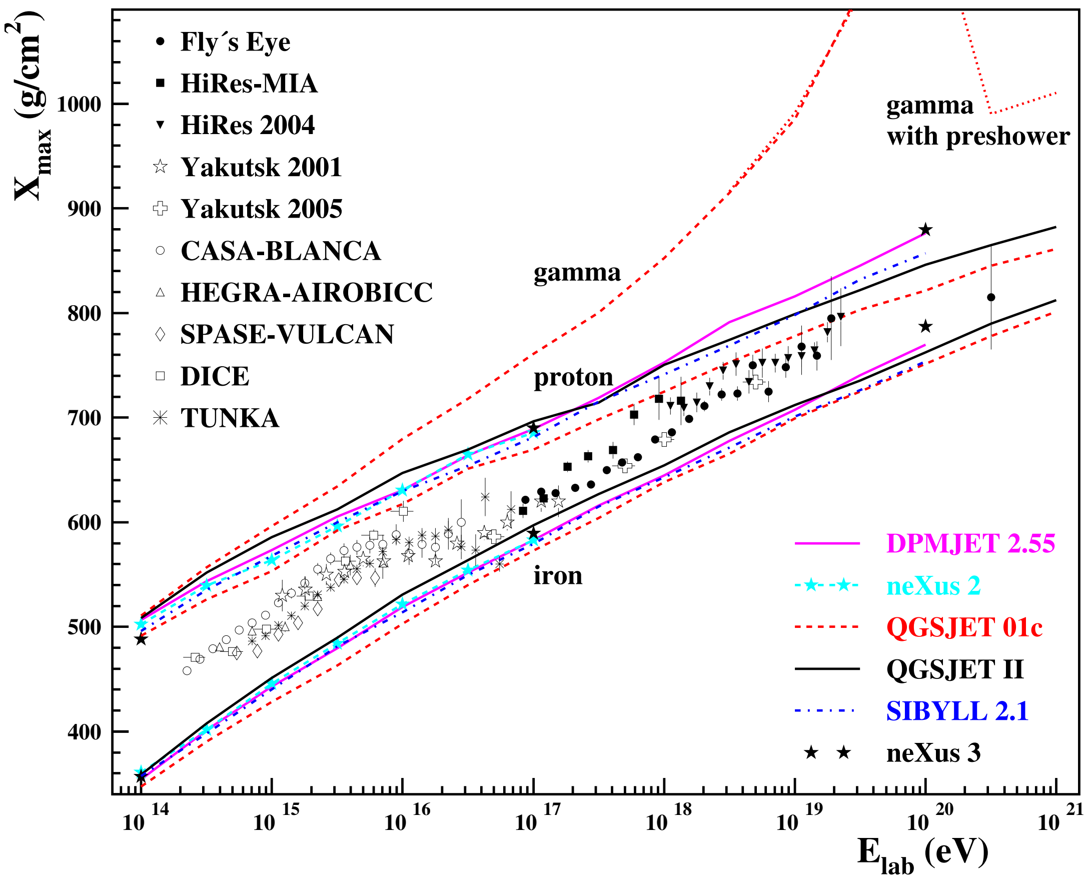

[Heck '05]

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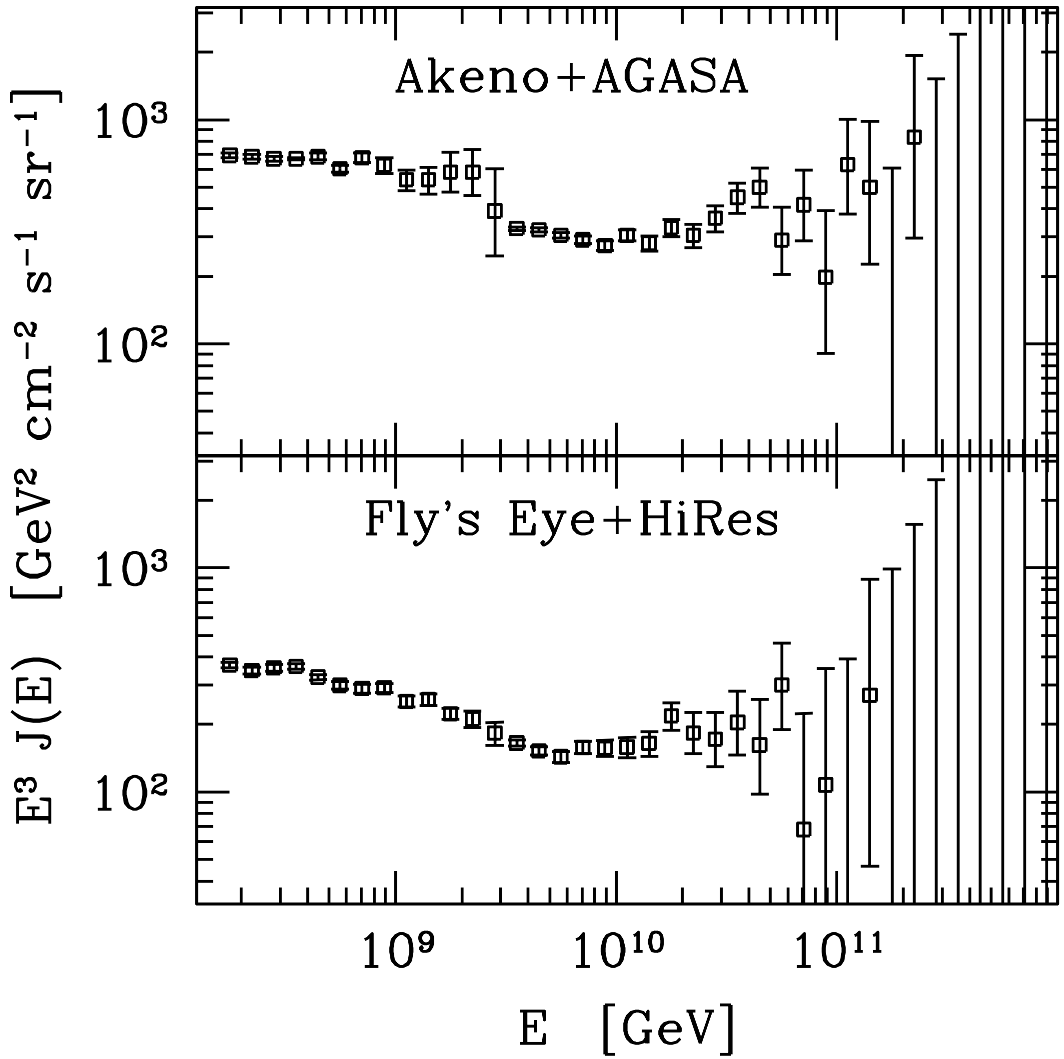
- Cosmic rays above $\gtrsim 10^{8.6}$ eV, the "second knee", dominantly protons
- Assume that CR's in $10^{[8.6,11]}$ GeV range originate from isotropically distributed extragalactic proton sources, with simple power-law injection spectra $\propto E_i^{-\gamma}(1+z)^n$

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



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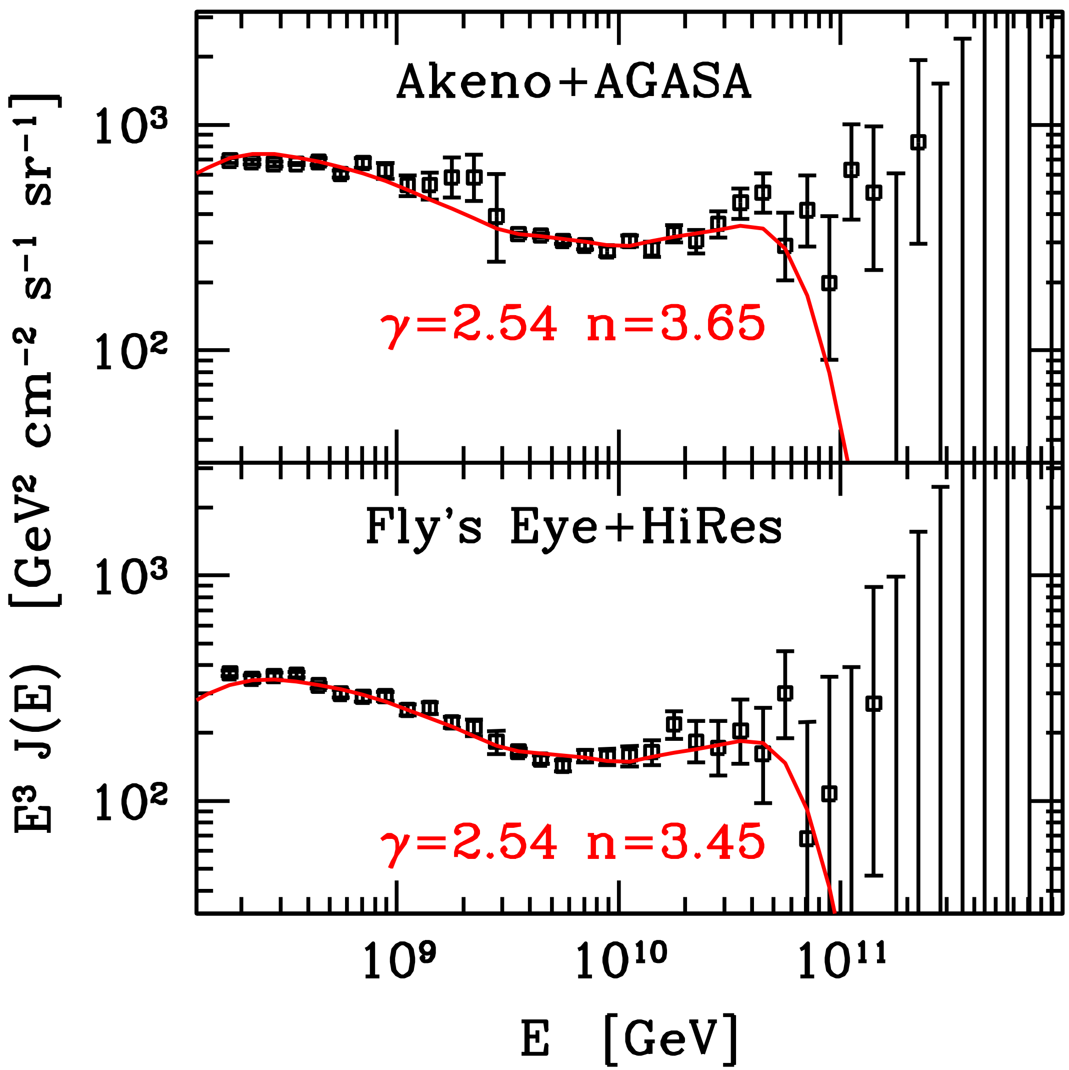
  [Berezinsky,..'02-'05;...;Ahlers *et al.* '05]

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

[Greisen;Zatsepin,Kuzmin '67]



[Ahlers *et al.* '05]

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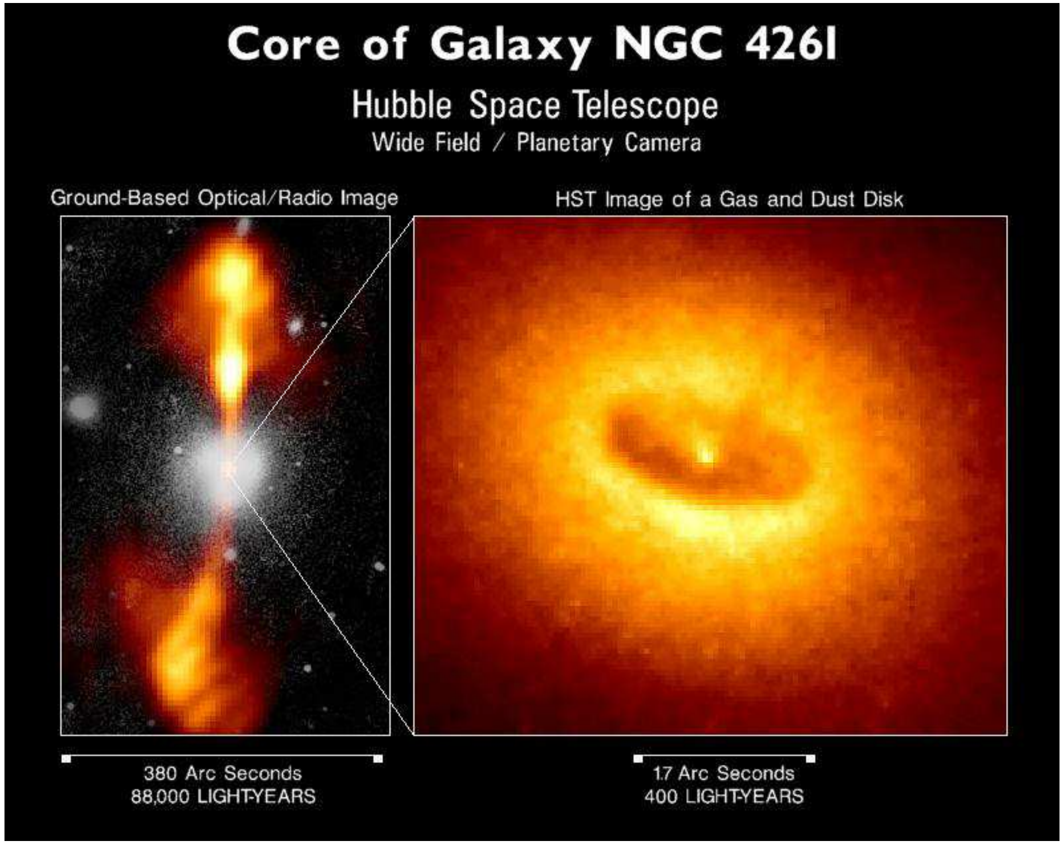

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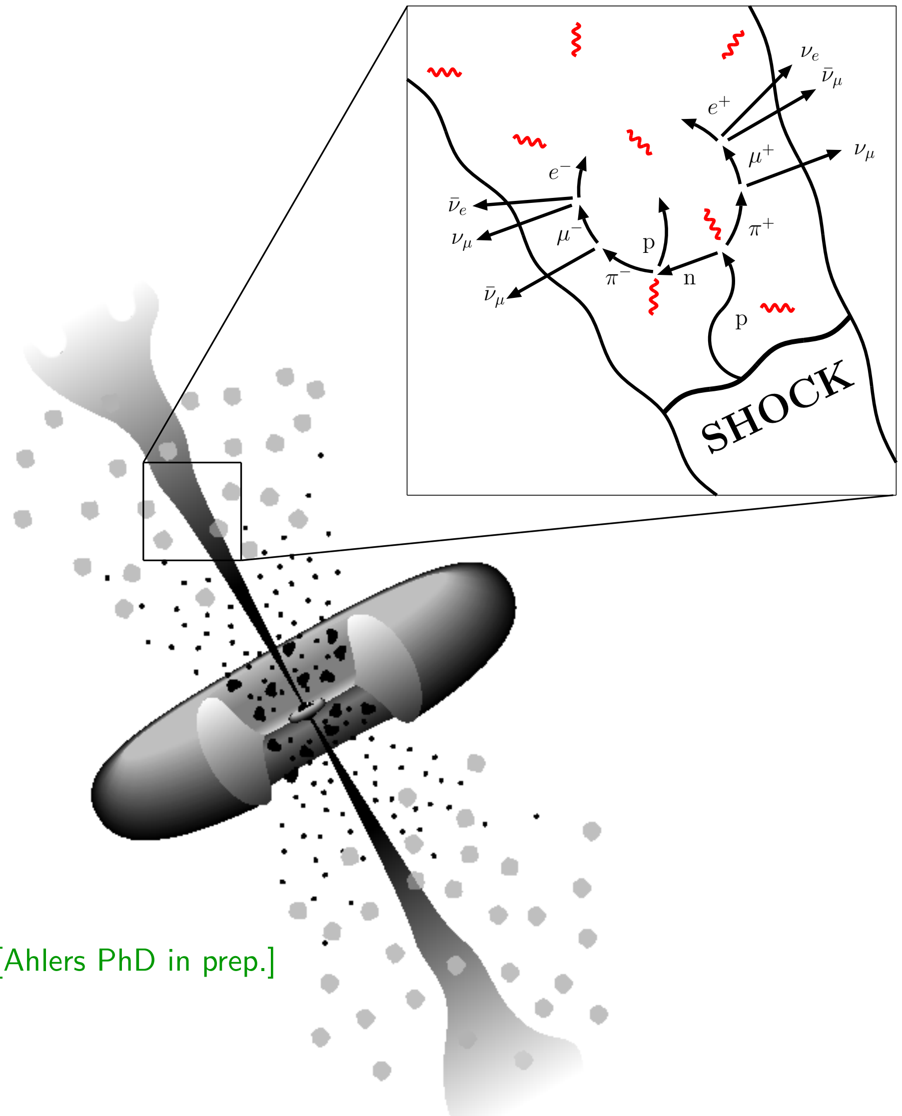
  - p's, confined by magnetic fields, accelerate through repeated scattering by plasma shock fronts



[Ahlers PhD in prep.]

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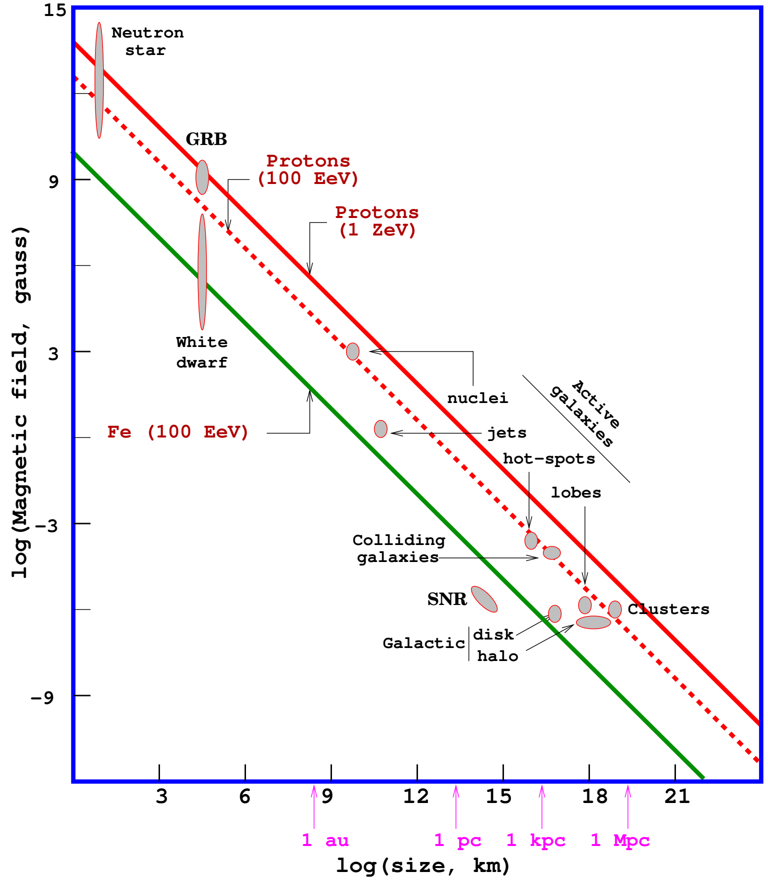
Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)



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

[Pierre Auger Observatory]

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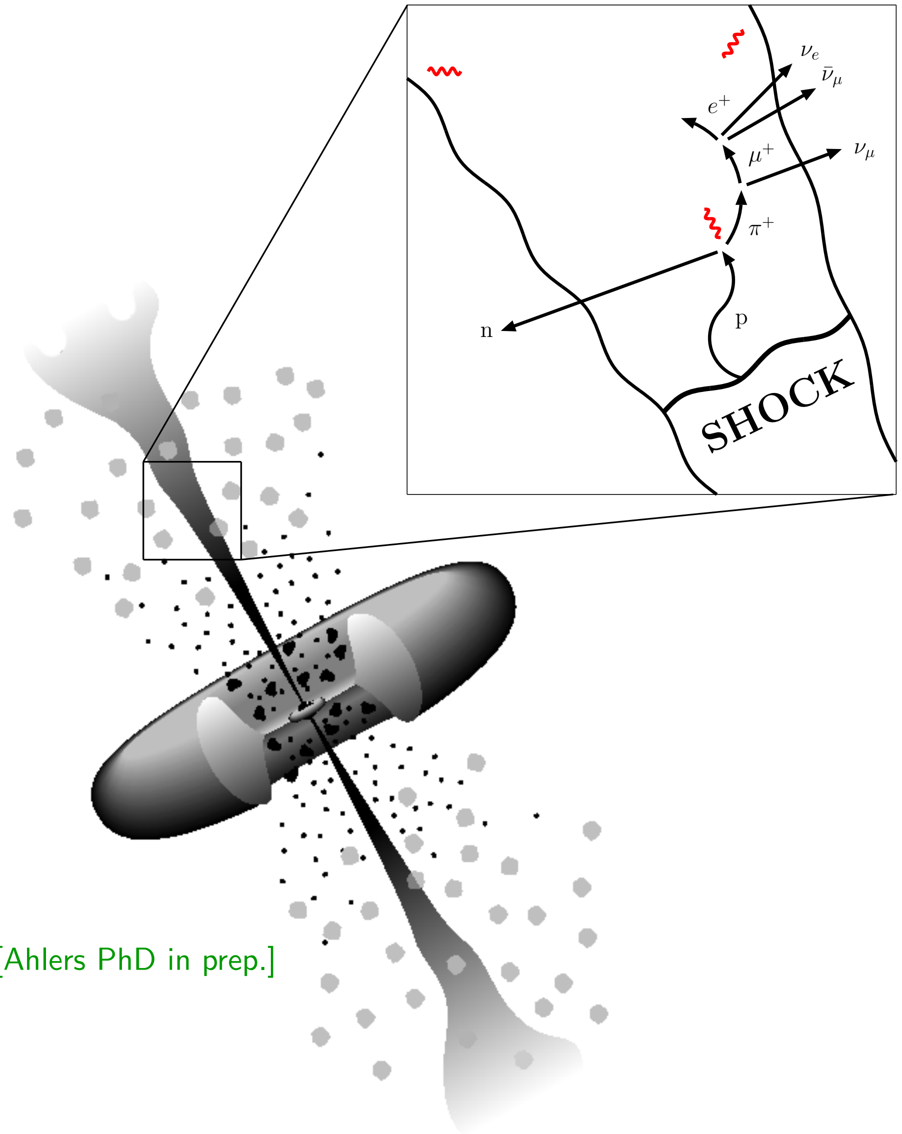

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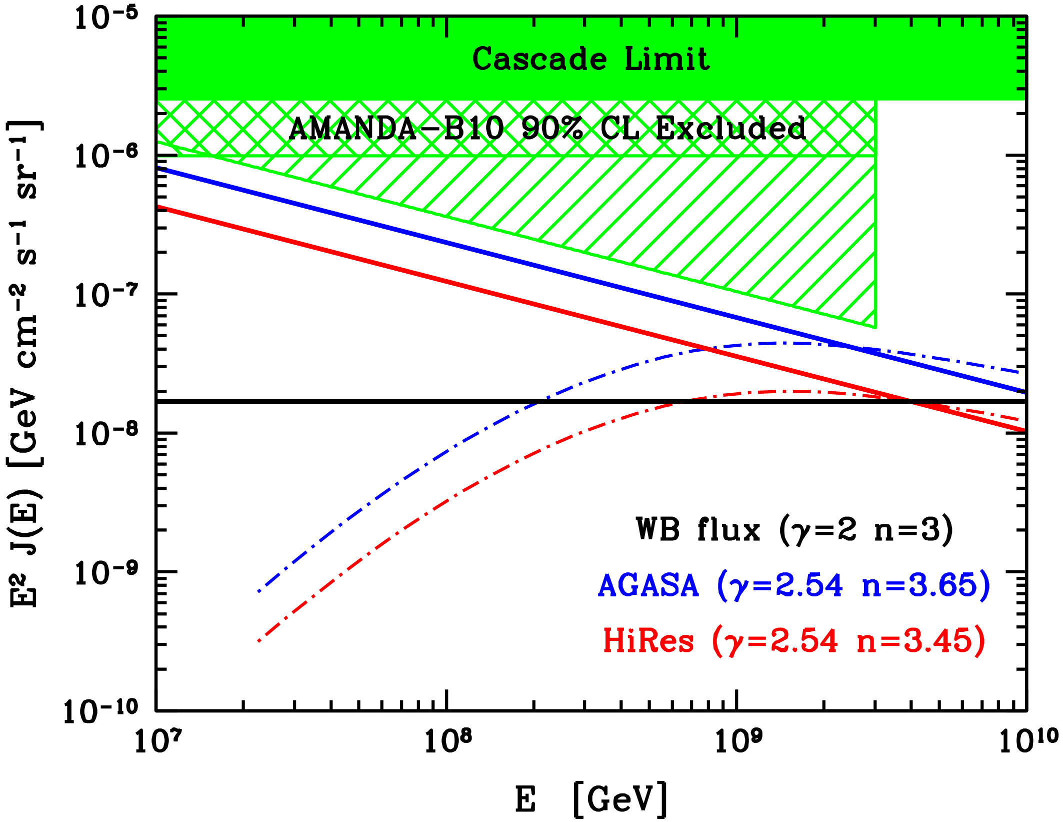
- **Neutrinos as diagnostic tool:**
  - ν's from sources ($p\gamma \to n + \pi$'s) close to be measured
  - Cosmogenic neutrino flux (from $p\gamma_{\rm CMB} \to N\pi$'s) dominates above 10^9 GeV



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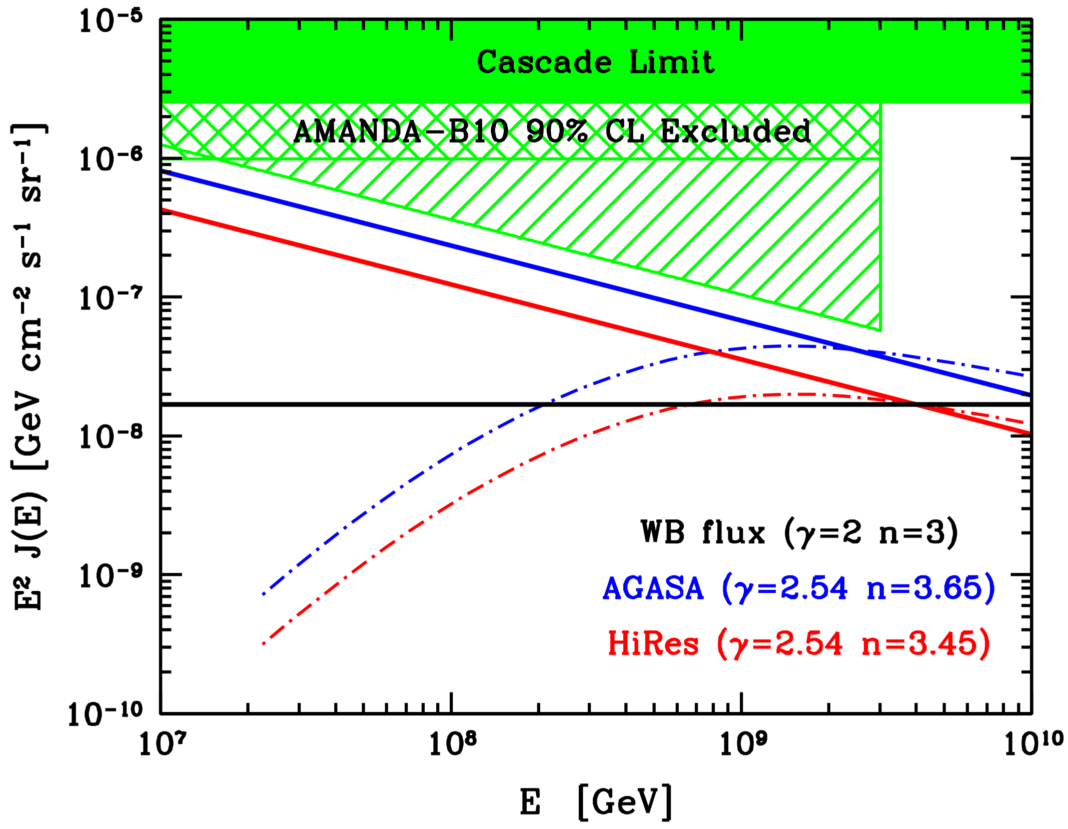
3. Non-observations at ultrahigh energies

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



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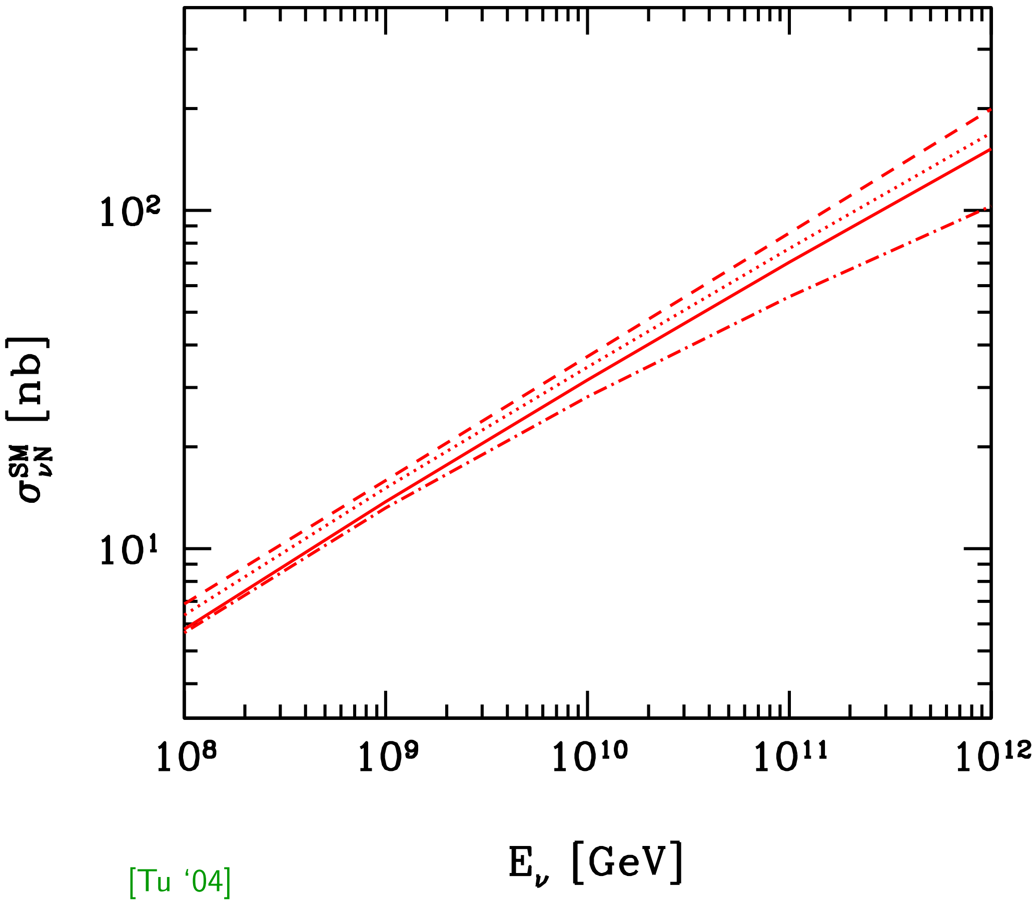
[Gandhi *et al.* '98; Kwiecinski *et al.* '98; ...]



[Tu '04]

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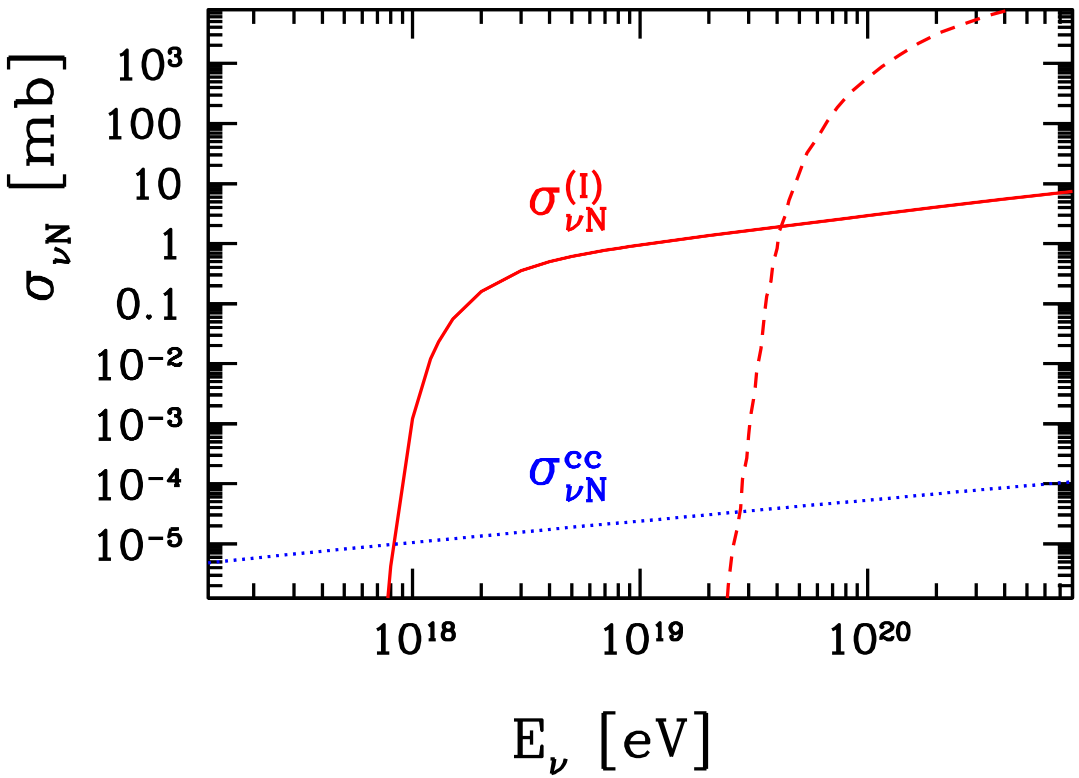
[Gandhi *et al.* '98; Kwiecinski *et al.* '98; ...]

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

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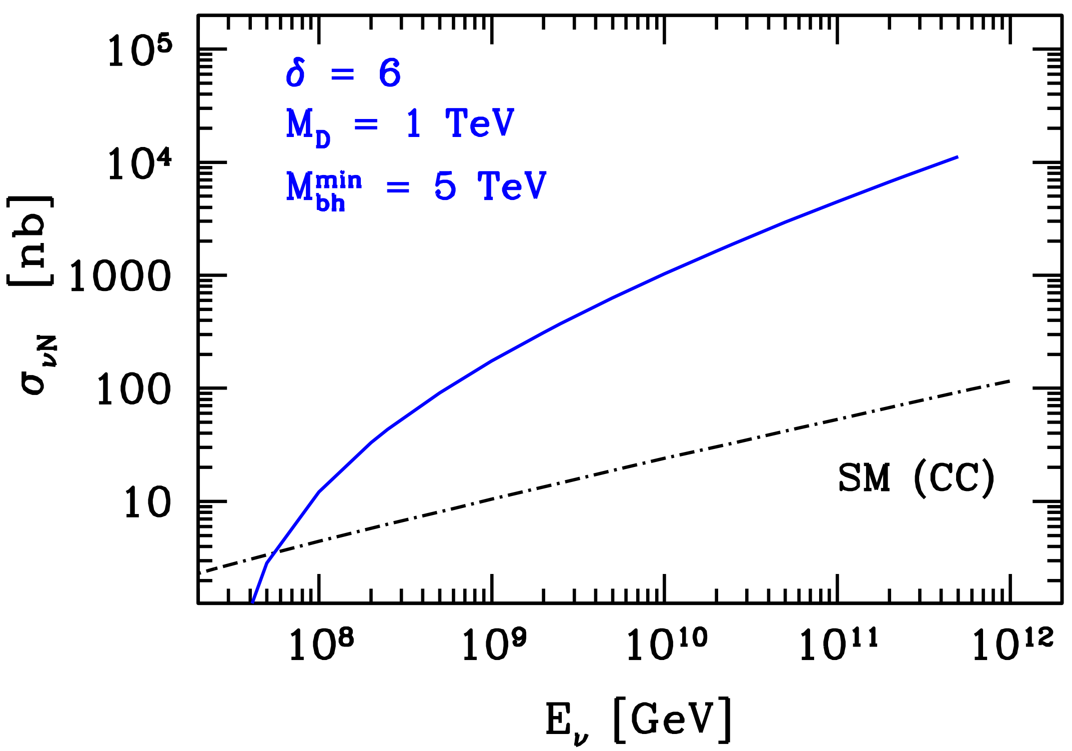
- ◇ Kaluza-Klein, black hole, p-brane or string ball production in TeV scale gravity models
- ◇ . . .



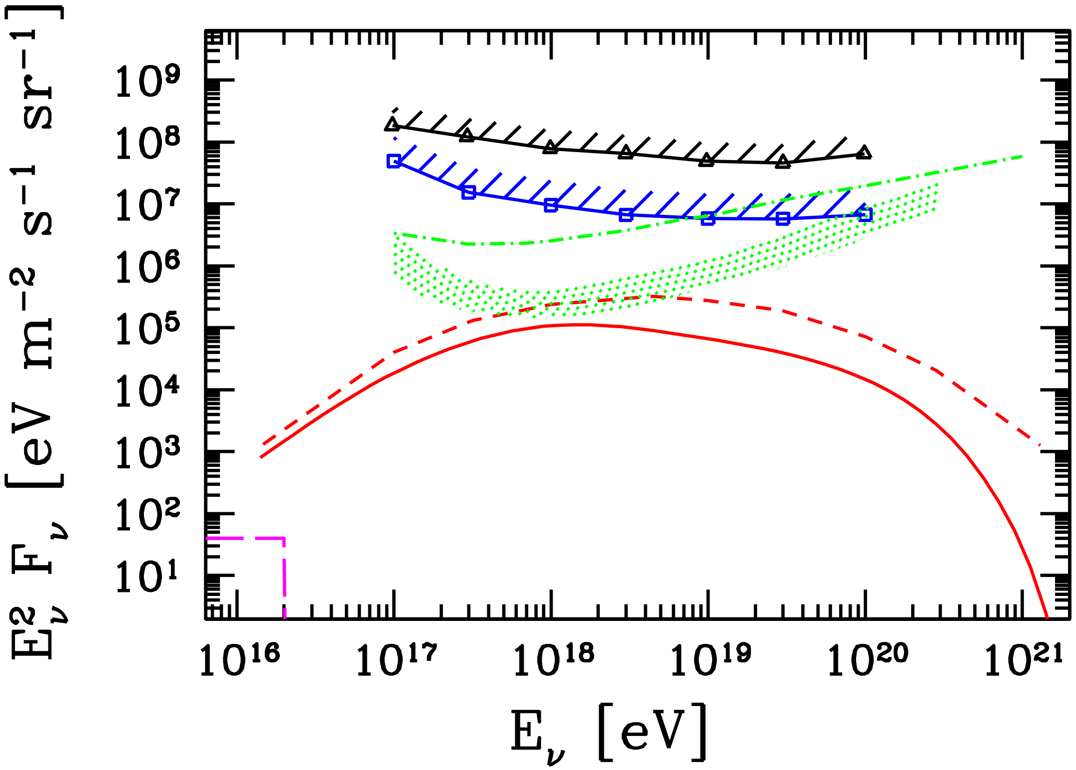
[AR,Tu '01; Tu '04]

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

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

$\Rightarrow$ Non-observation of deeply-penetrating particles, together with lower bound on F_ν (e.g. cosmogenic ν's) $\Rightarrow$ 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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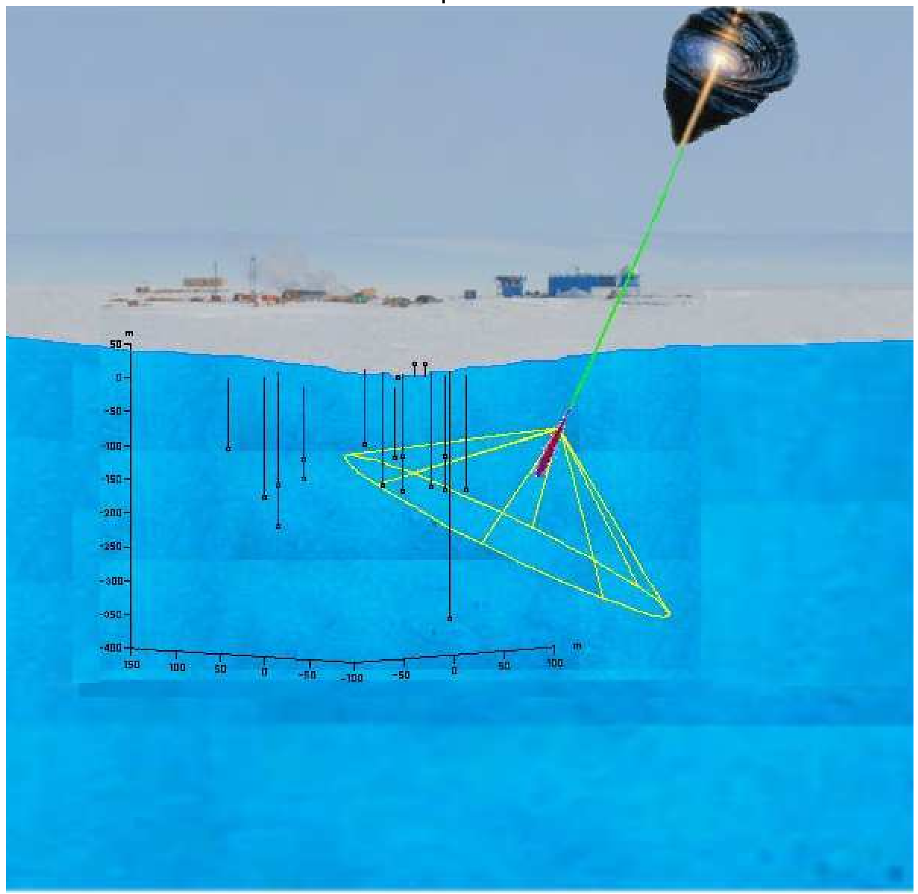
- Recent quantitative analysis:

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

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

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

RICE: **R**adio **I**ce **C**erenkov **E**xperiment



[www2.phys.canterbury.ac.nz/rice]

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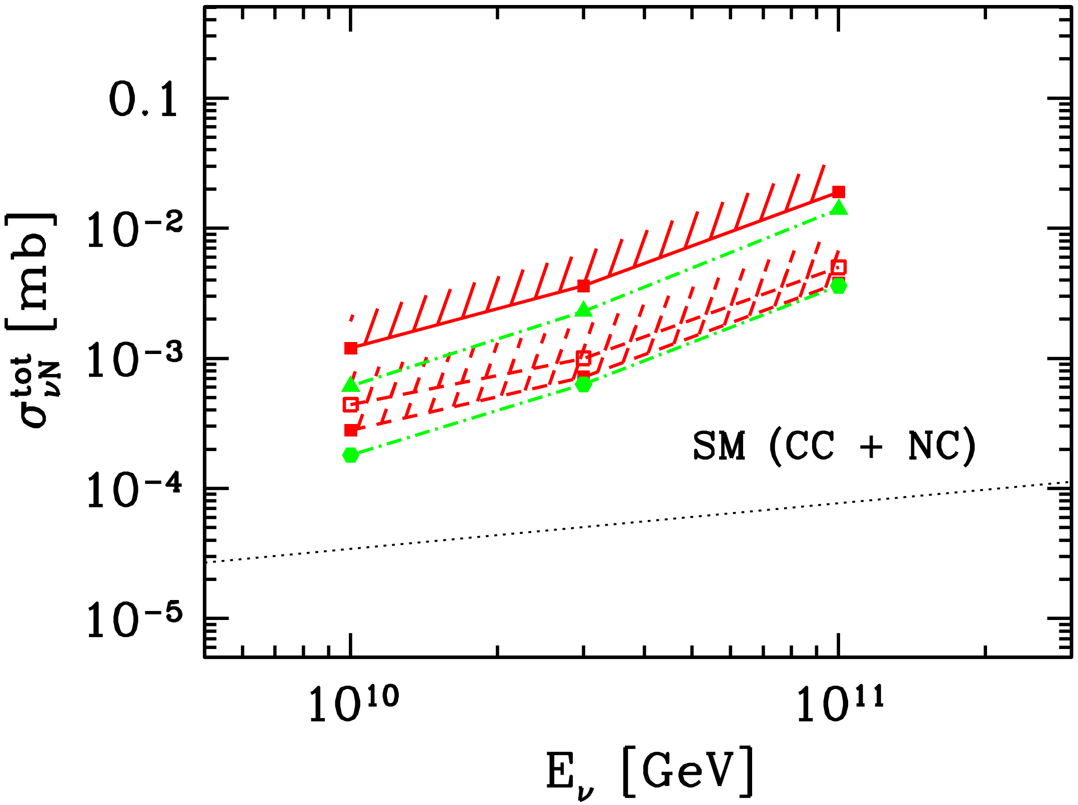
  [Kravchenko *et al.* [RICE] ‘02,03]

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



[Anchordoqui,Fodor,Katz,AR,Tu ‘04]

Strongly interacting neutrino scenarios

- 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]

Volume 28B, number 6 PHYSICS LETTERS 6 January 1969

COSMIC RAYS AT ULTRA HIGH ENERGIES (NEUTRINO?)

V. S. BERESINSKY and G. T. ZATSEPIN
Academy of Sciences of the USSR, Physical Institute, Moscow

Received 8 November 1968

The neutrino spectrum produced by protons on microwave photons is calculated. A spectrum of extensive air shower primaries can have no cut-off at an energy $E > 3 \times 10^{19}$ eV, if the neutrino-nucleon total cross-section rises up to the geometrical one of a nucleon.

Greisen [1] and then Zatsepin and Kusmin [2] have predicted a rapid cut-off in the energy spectrum of cosmic ray protons near $E \sim 3 \times 10^{19}$ eV because of pion production on 2.7° black body radiation. Detailed calculations of the spectrum were made by Hillas [3]. Recently there were observed [4] three extremely energetic extensive air showers with an energy of primary particles exceeding 5×10^{19} eV. The flux of these particles turned out ot be 10 times greater than according to Hillas' calculations.

In the light of this it seems to be of some interest to consider the possibilities of absence of rapid (or any) fall in the energy spectrum of showerproducing particles. A hypothetic possibility we shall discuss* consists of neutrinos being the showerproducing particles at $E > 3 \times 10^{19}$ eV due to which the energy spectrum of shower producing particles cannot only have any fall but even some flattening.

The neutrinos under consideration are originated in decays of pions, which are generated in collisions of cosmic ray protons with microwave photons. When calculating the neutrino spectrum the same assumptions were made as by Hillas [3]:

(1) The protons of high and extremely high energies are of extragalactic origin with an output of generation varying with time as t^{-s} after a certain starting time t_o**,

(2) The integral energy spectrum of generated protons is of the form $E^{-\gamma}$ up to an energy not less than 10^{22} eV.

* Cocconi was the first, who supposed that ultra high energy extensive air showers can be caused by neutrinos [5].
** The Hillas' assumptions about evolution of proton sources are based on Longairs [6] assumptions for evolution of radiogalactics, the latter chosen to fit experimental data.

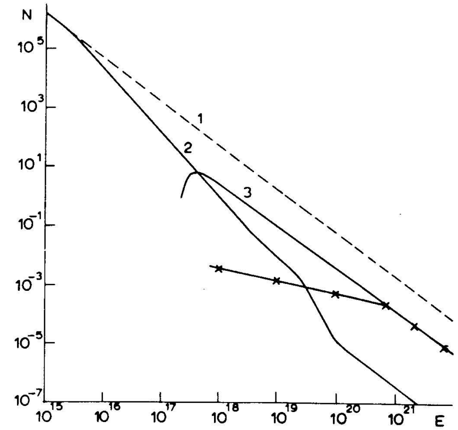


Fig. 1.

The calculated neutrino spectrum is represented by curve 3. It has the same spectrum exponent as the spectrum of generated protons. The calculations were made assuming that the pion originating in nucleon-microwave photon collision takes in average near 20% proton energy and the value $\gamma = 1.5$ was used. The calculated ratio of the neutrino intensity to that of the unmodified spectrum of protons (curve 1) at the same energy is $\sim 6 \times 10^{-2}$. We call "unmodified" a proton spectrum at present in the case when a red shift is the only kind of energy losses. The mentioned ratio does not depend on evolution of proton sources and the cosmological model. The proton spectrum at present is shown by curve 2. The curves 1 and 2 were obtained by Hillas using

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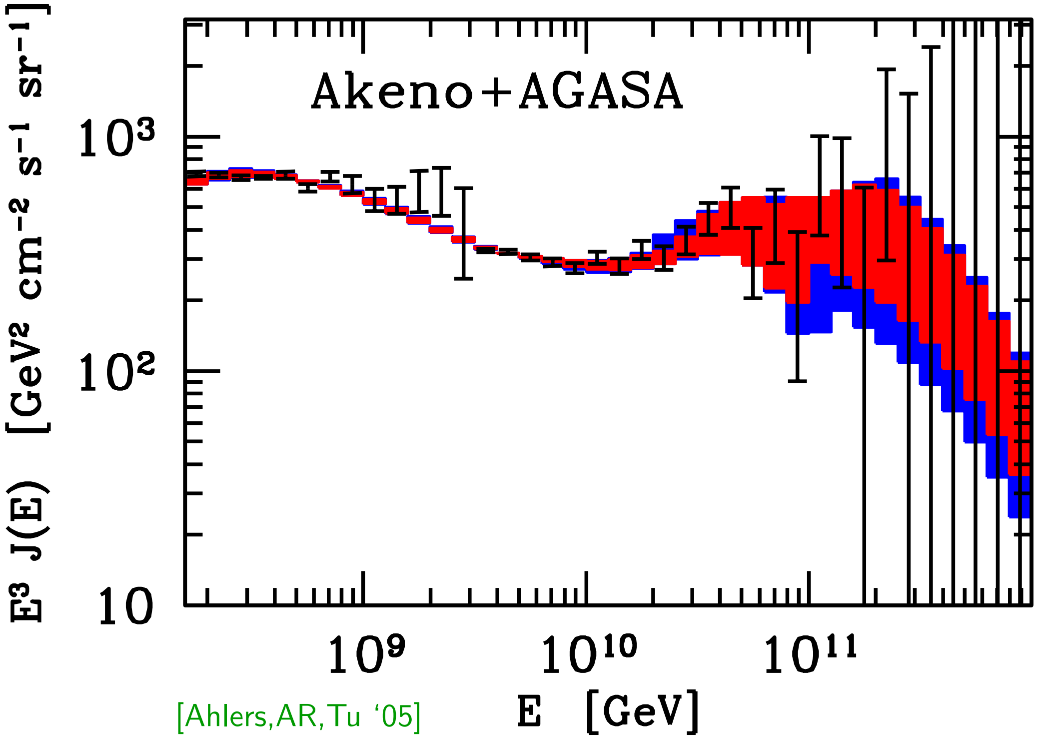
[Berezinsky,Zatsepin '69]

- Quantitative analysis:

[Fodor,Katz,AR,Tu '03; Ahlers,AR,Tu '05]

  – Very good fit to CR data



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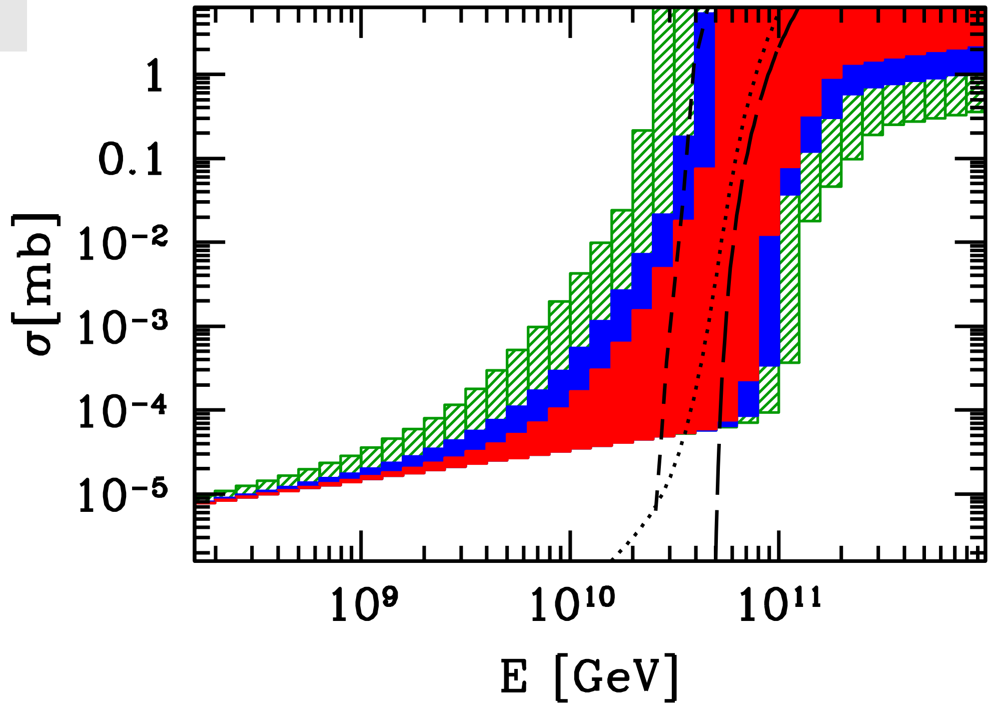
  – Very good fit to CR data
  – Need steeply rising cross section, otherwise clash with nonobservation of deeply-penetrating particles



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

[Han,Hooper '04] - - - sphalerons

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

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

4. The future ...

- Existing observatories for **E**xtremely **H**igh **E**nergy **C**osmic ν's

GLUE: **G**oldstone **L**unar **U**ltra-high energy neutrino **E**xperiment

[http://www.physics.ucla.edu/ moonemp/public/]

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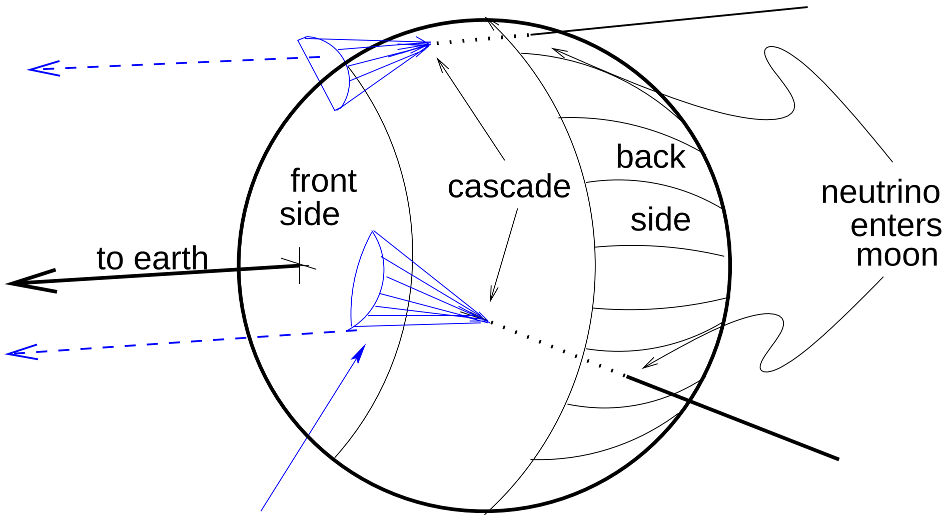

[Gorham *et al.* '04]

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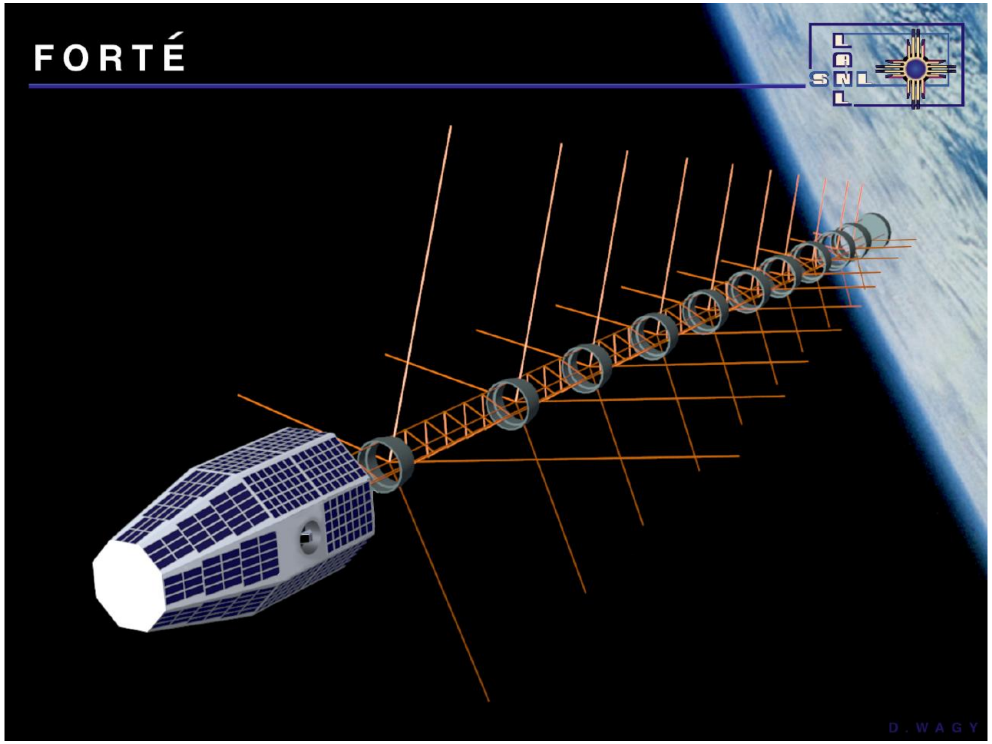
FORTE: **F**ast **O**n-orbit **R**ecording of **T**ransient **E**vents



[nis-www.lanl.gov/nis-projects/forte/]

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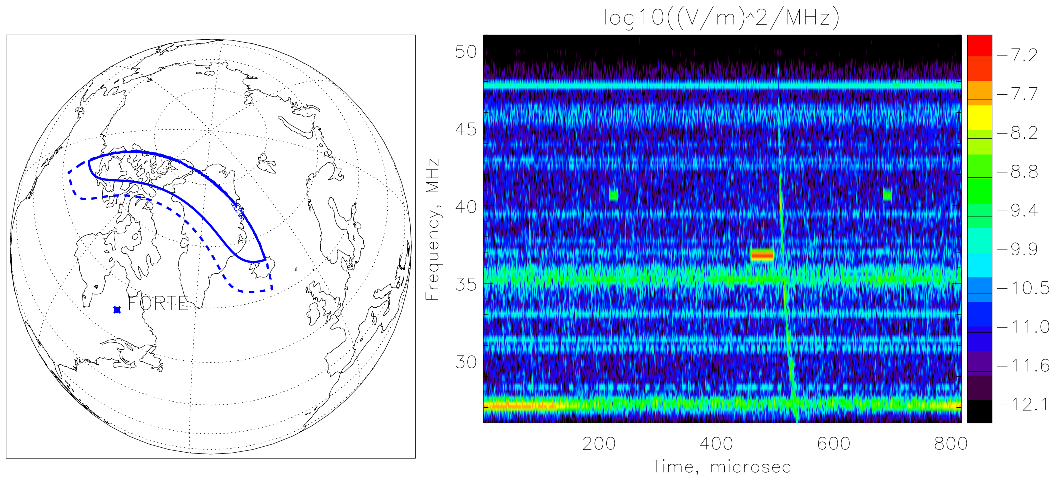

[Lehtinen *et al.* '04]

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ANITA-LITE: Prototype of **AN**tarctic **I**mpulsive **T**ransient **A**ntenna

[www.phys.hawaii.edu/ anita/web/index.htm]

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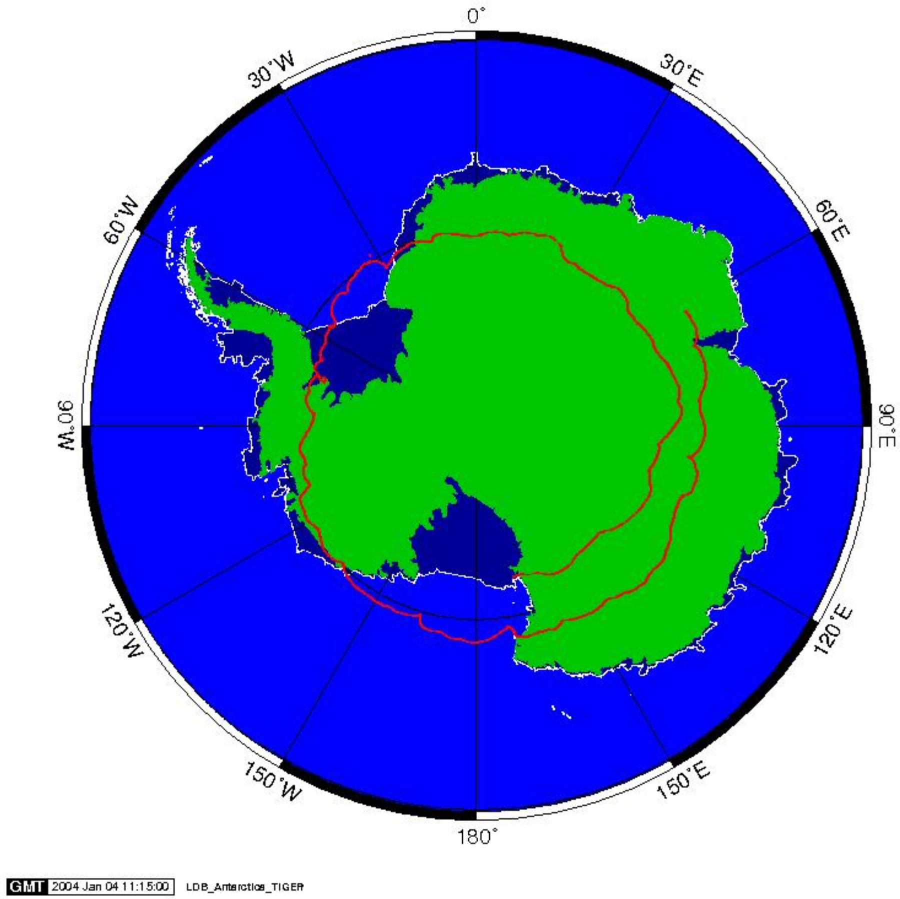

[cosray2.wustl.edu/tiger/index.html]

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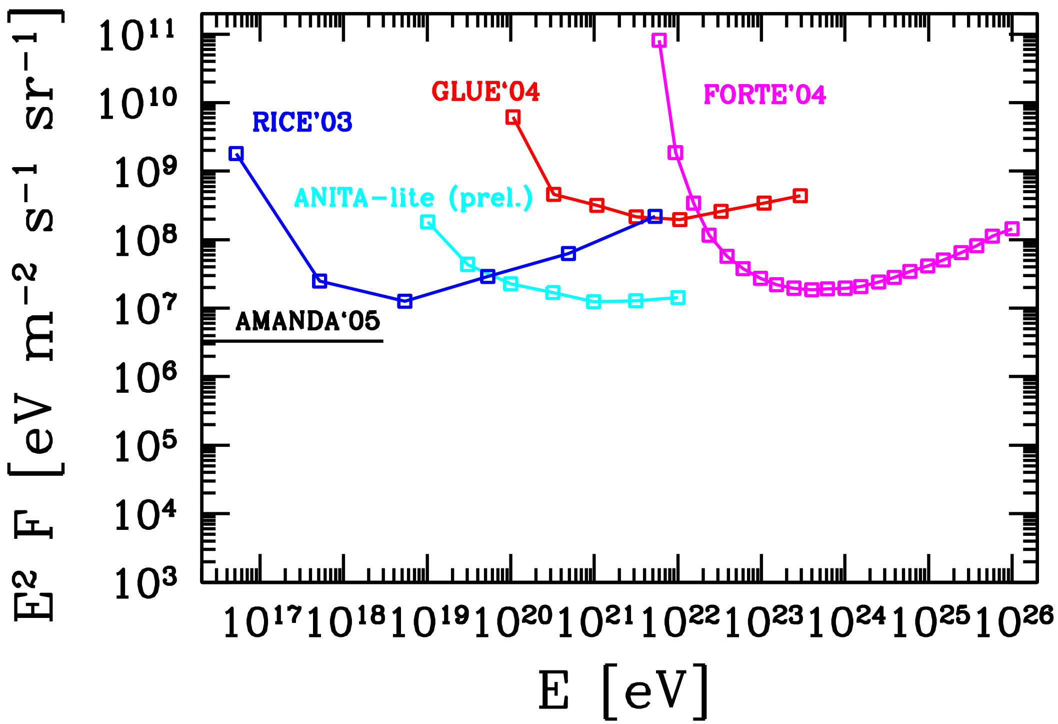

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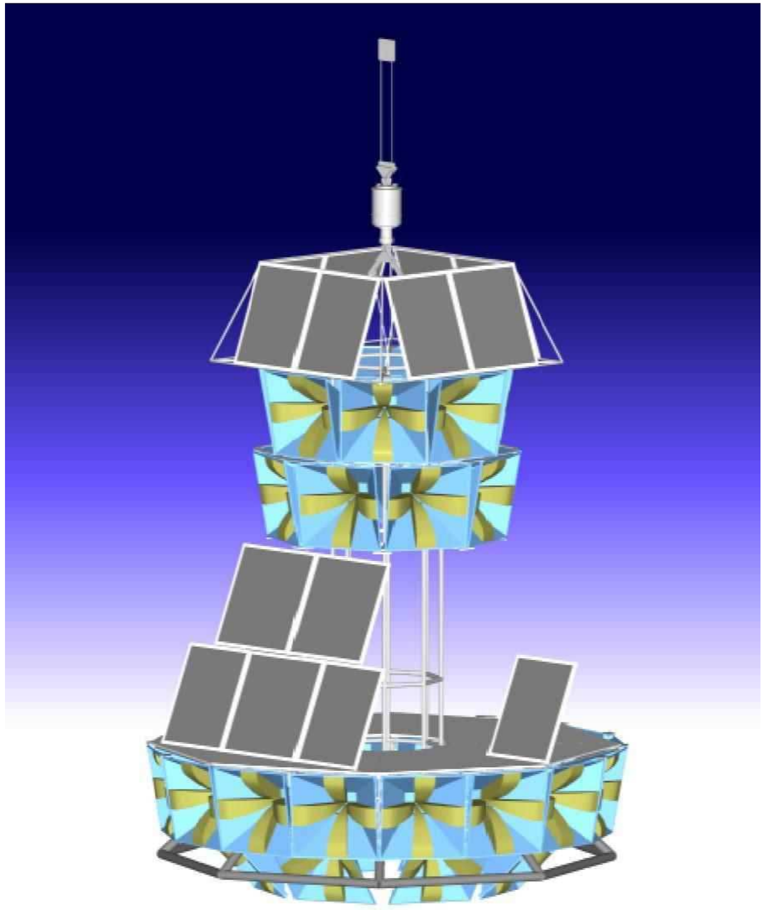
- Upcoming decade: progressively larger detectors for **EHECν's**

ANITA:



[www.ps.uci.edu/ anita/]

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WSRT: **W**e**S**terbork **R**adio **T**elescope

[Bacelar, ARENA Workshop '05]

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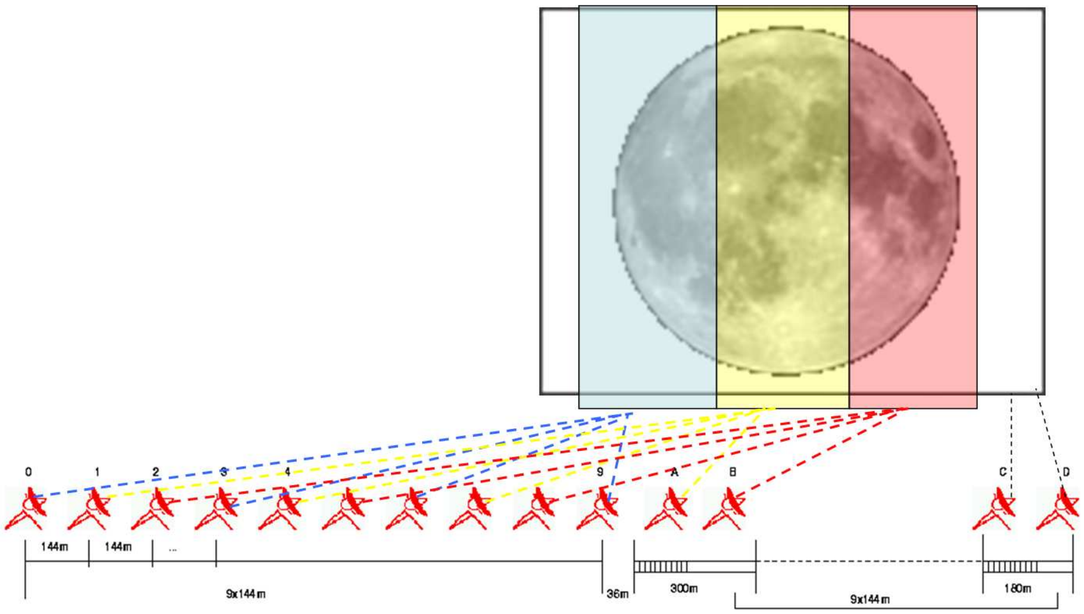

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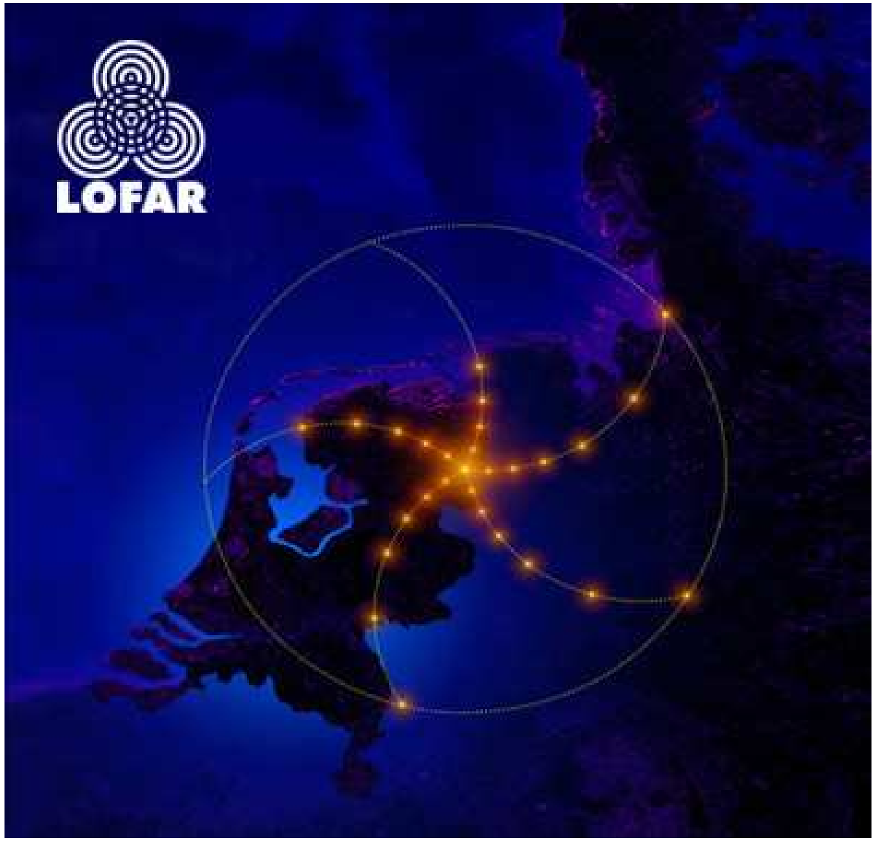
LOFAR:



[www.lofar.org]

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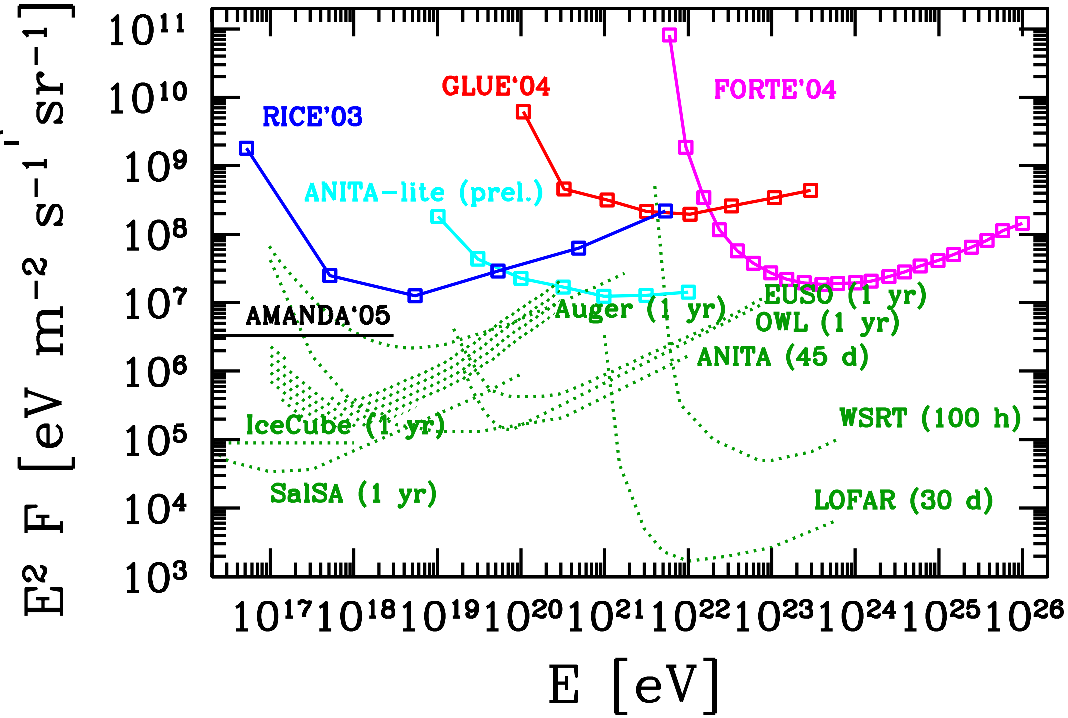

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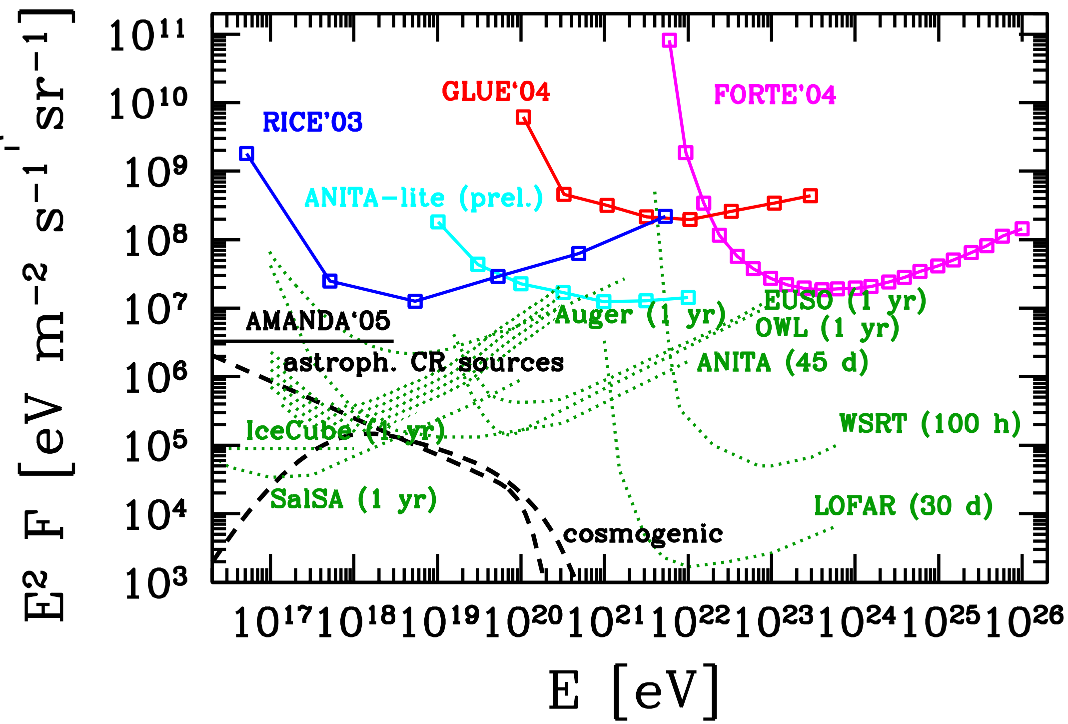

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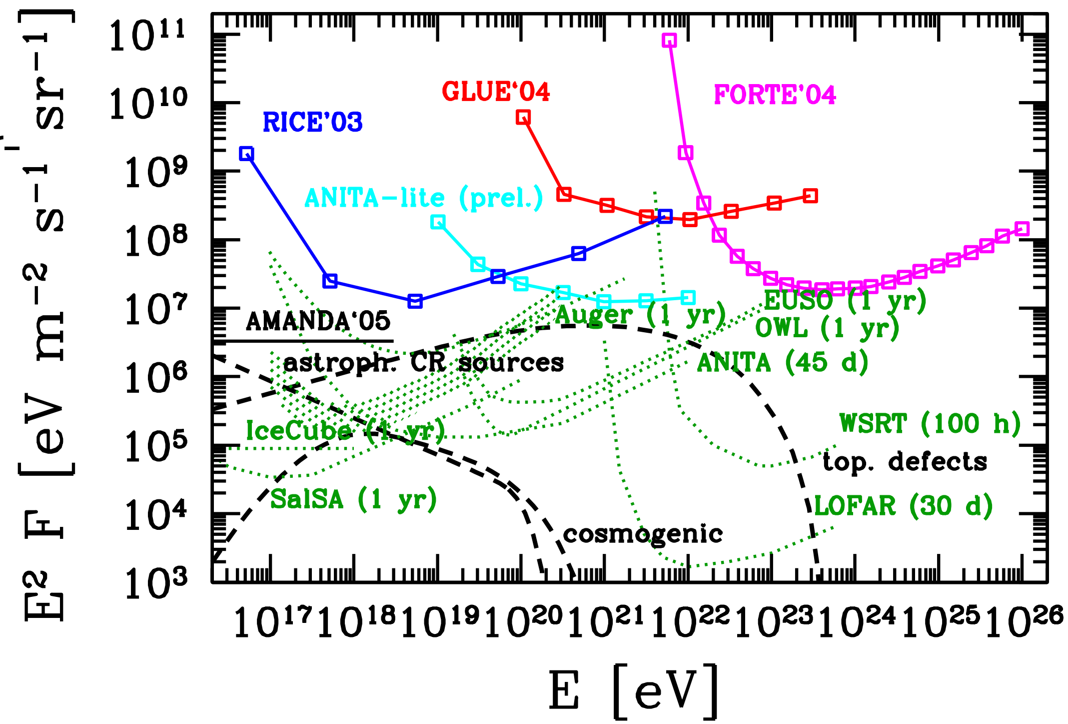
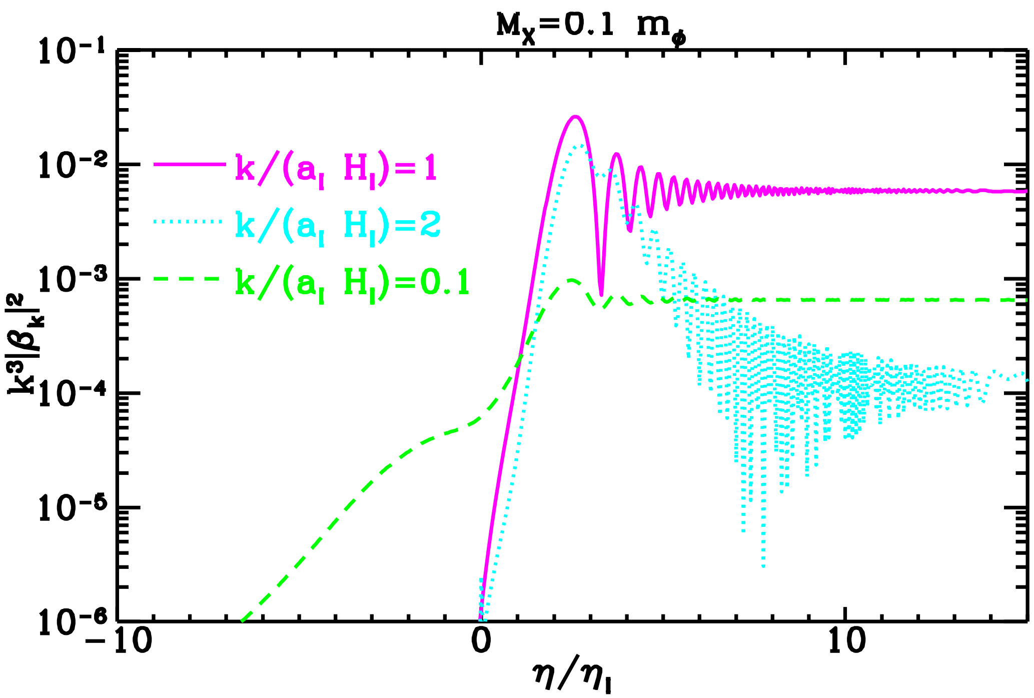
$\Rightarrow$ $E \geq 10^{21}$ eV:

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



Top-down scenarios for EHEC 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.
  - particle creation in time-varying gravitational field



[Kolb,Chung,Riotto '98]

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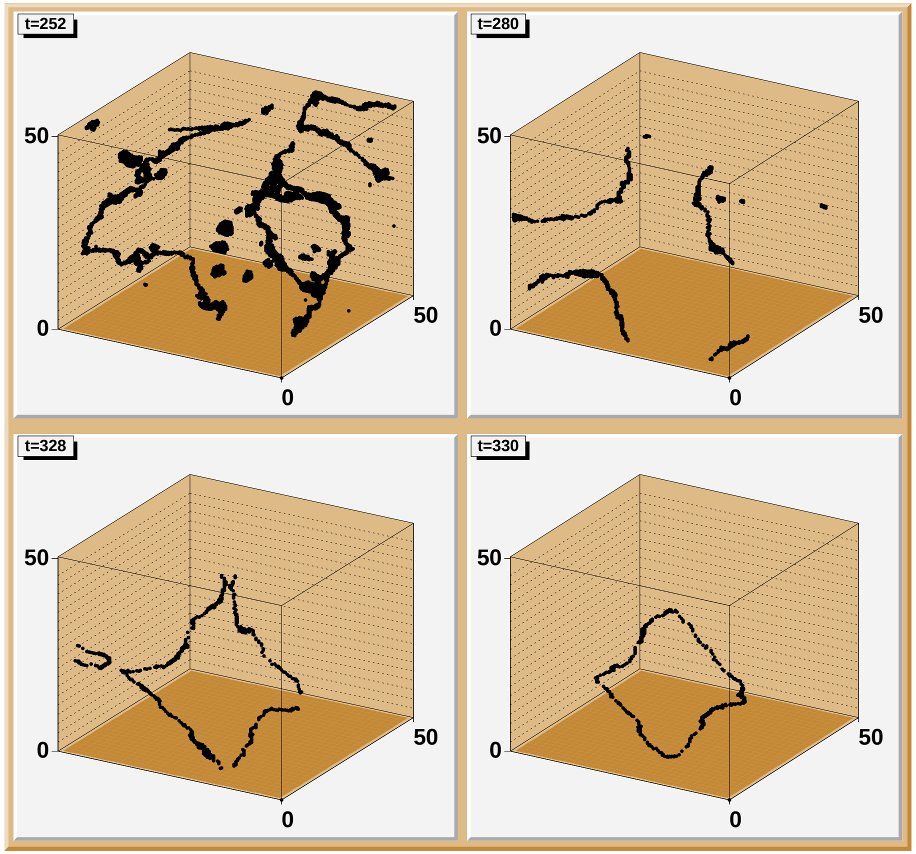

[Tkachev,Khlebnikov,Kofman,Linde '98]

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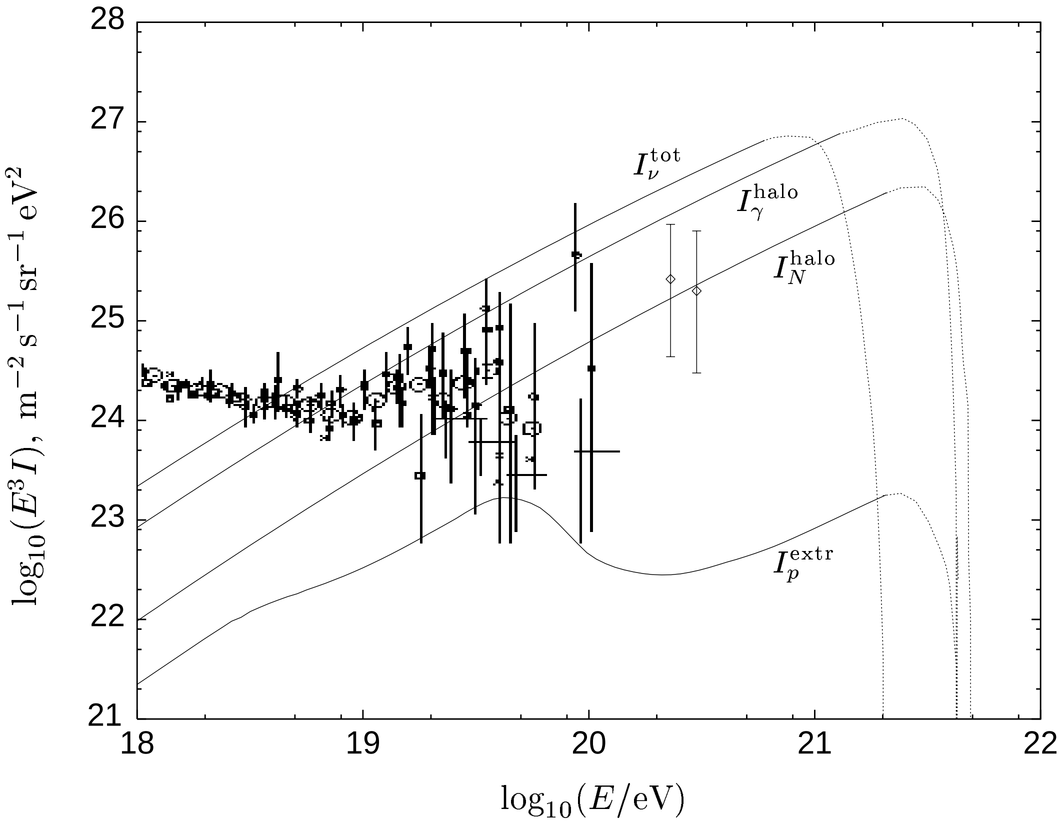

[Berezinsky,Kachelriess,Vilenkin '97]

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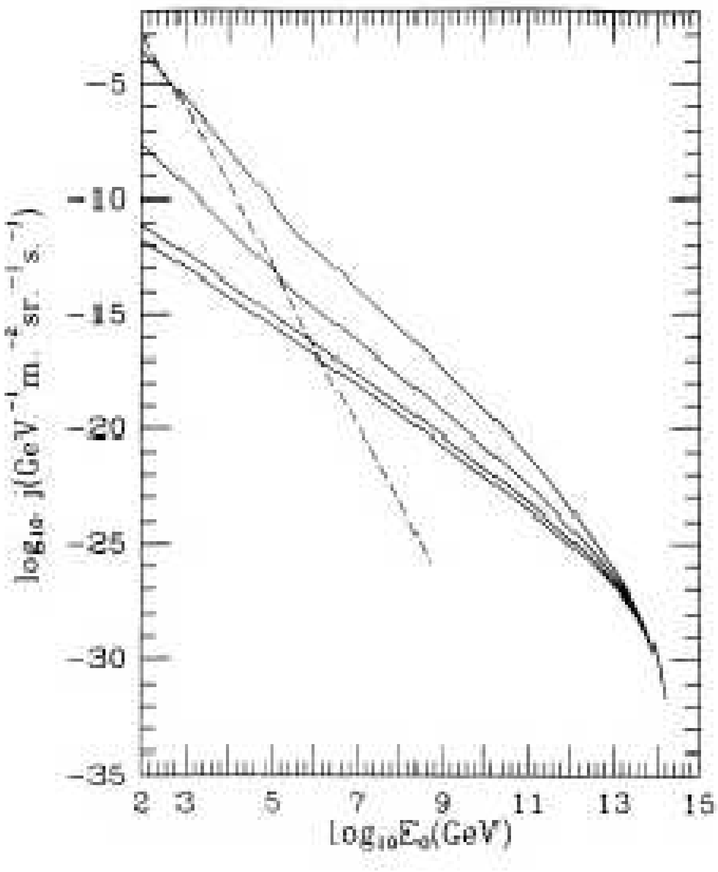

[Bhattacharjee,Hill,Schramm '92]

Top-down scenarios for EHEC neutrinos

- **Injection spectra:** fragmentation functions $D_i(x,\mu)$, $i=p,e,\gamma,\nu$, determined via
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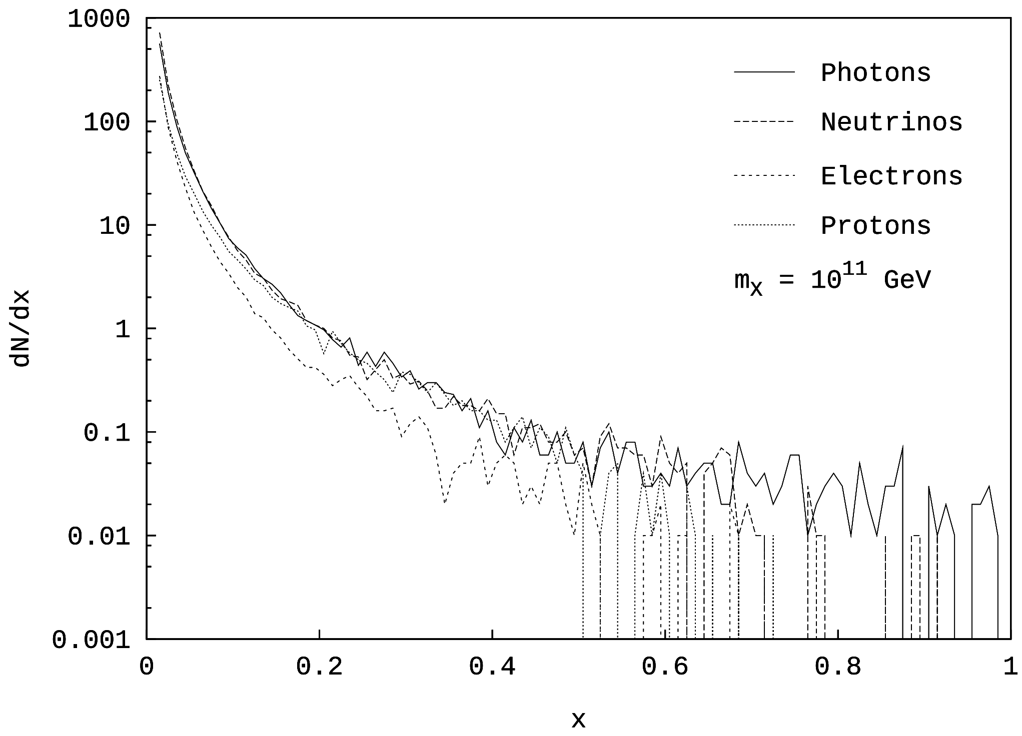

[Birkel,Sarkar '98]

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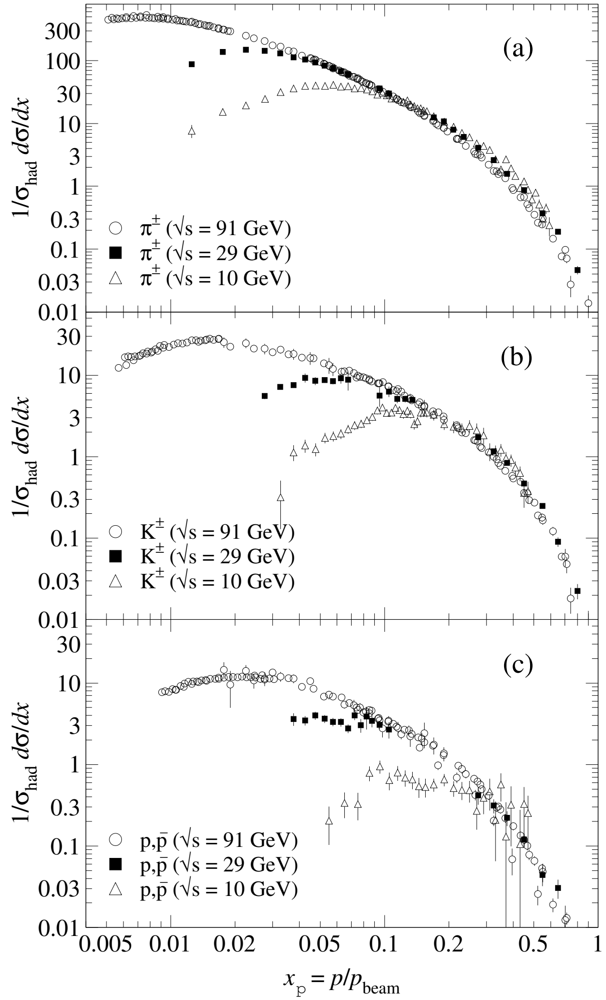

[Particle Data Group '04]

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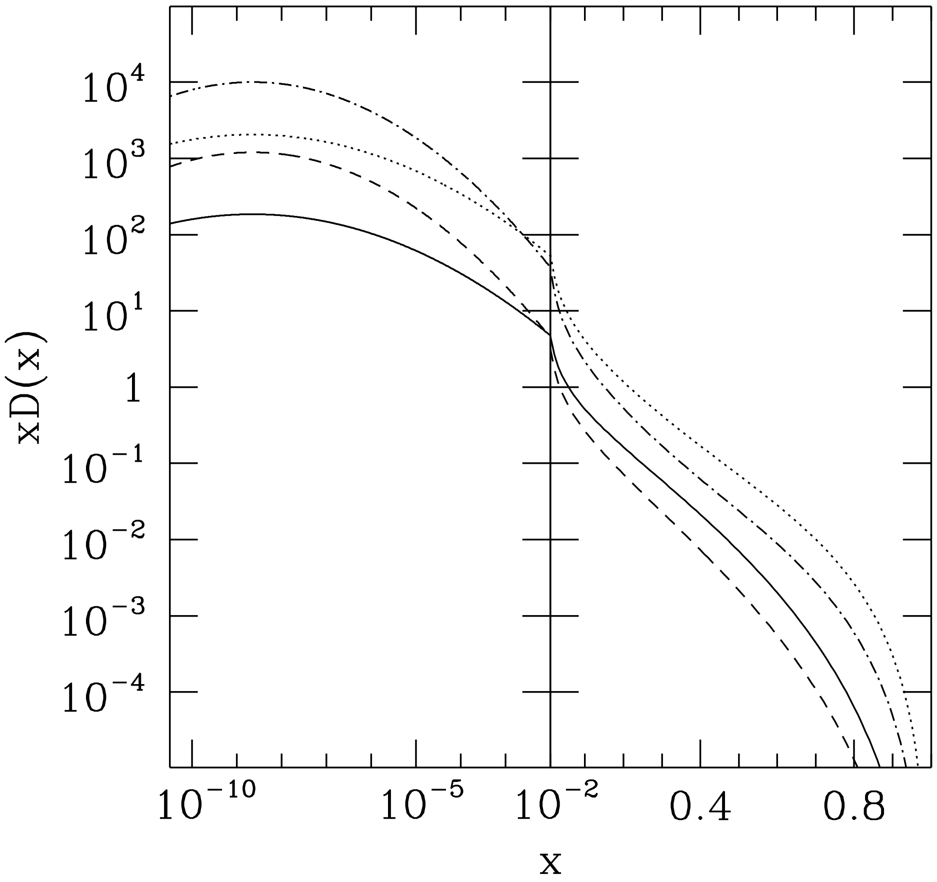

[Fodor,Katz '01]

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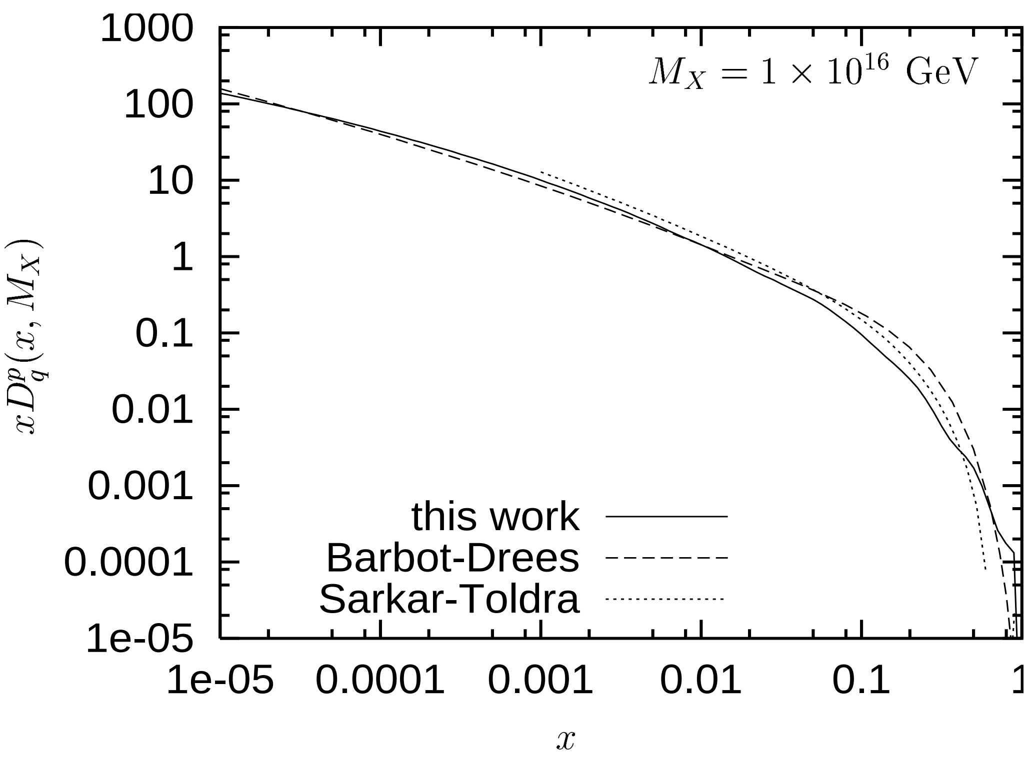

[Aloisio,Berezinsky,Kachelriess '04]

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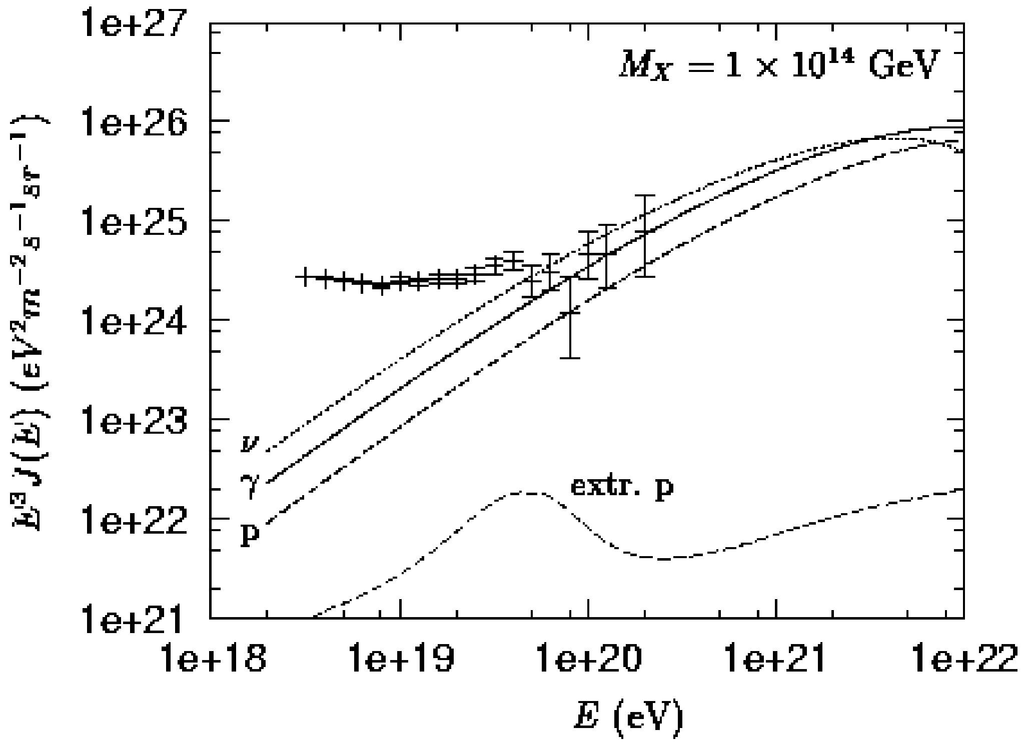

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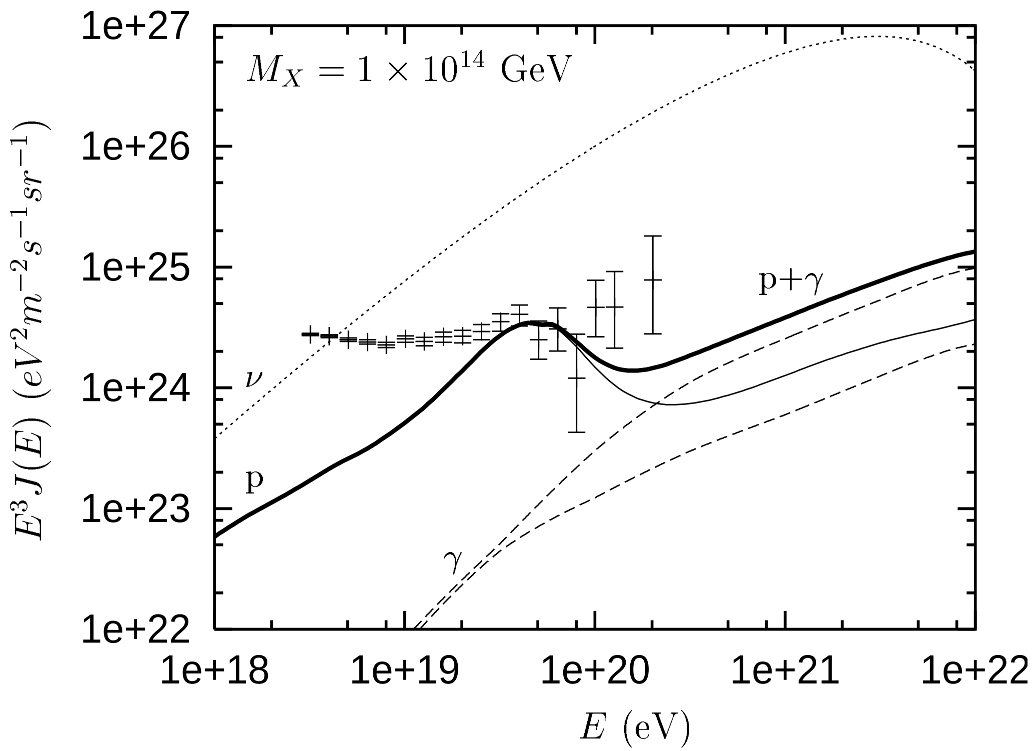
  - for topological defects, injection far away: $j_\nu \gg j_\gamma \sim j_p$



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Top-down scenarios for EHEC neutrinos

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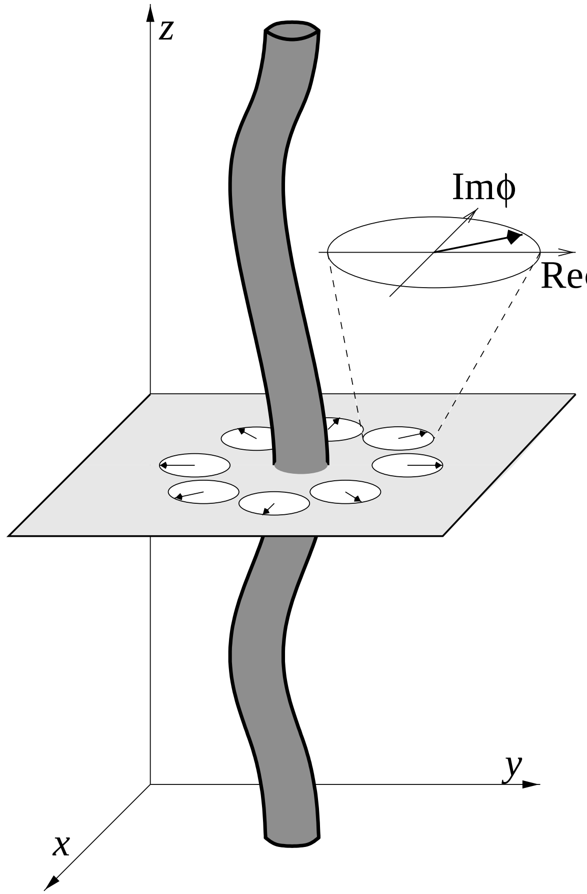

[Rajantie '03]

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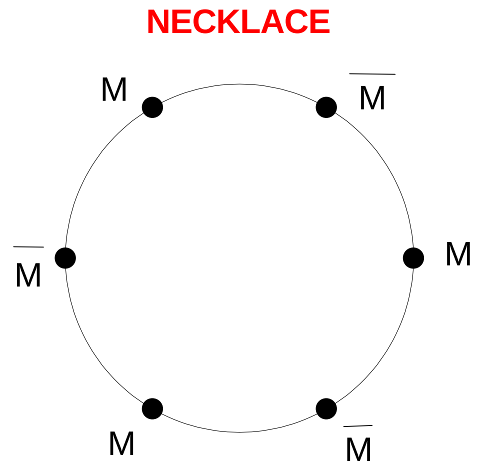

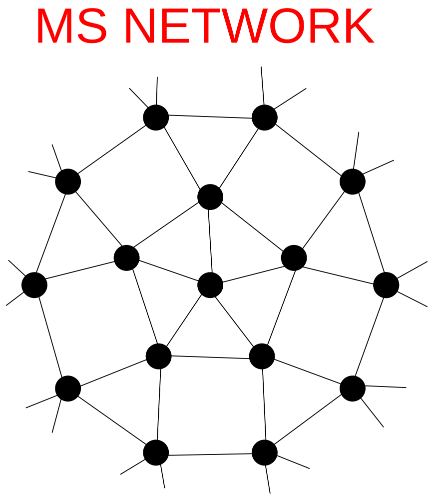

[Berezinsky '05]

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- Strong impact of measurement for
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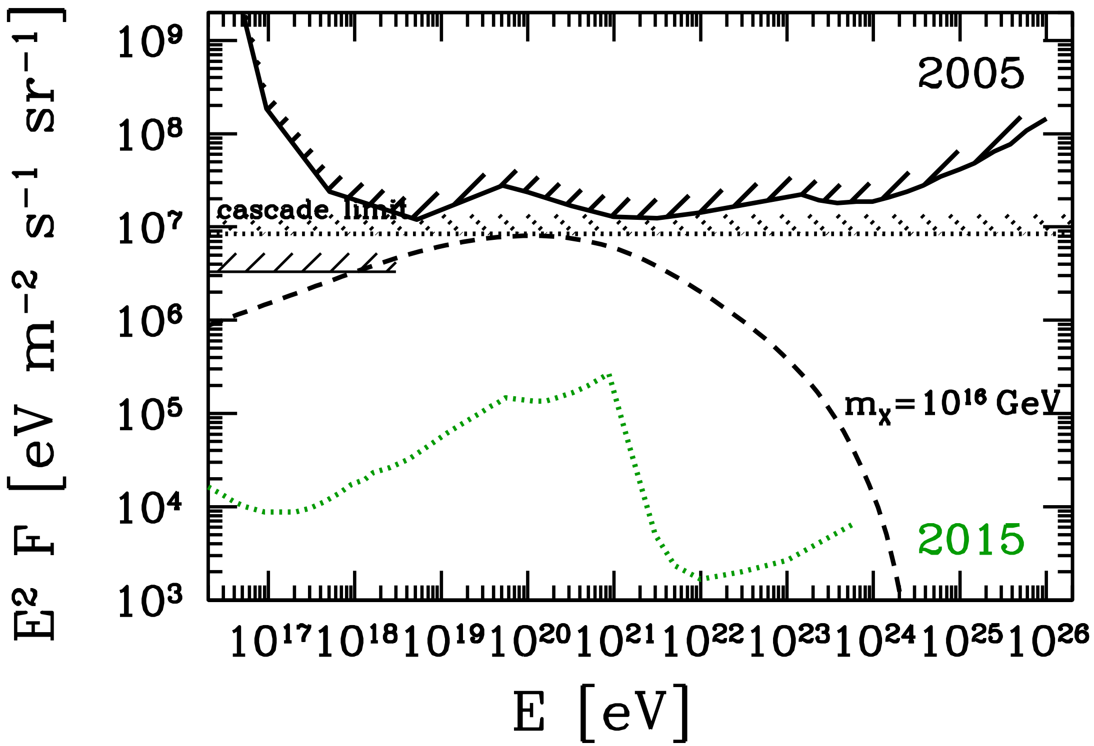

[Fodor,Katz,AR,Weiler,Wong,in prep.]

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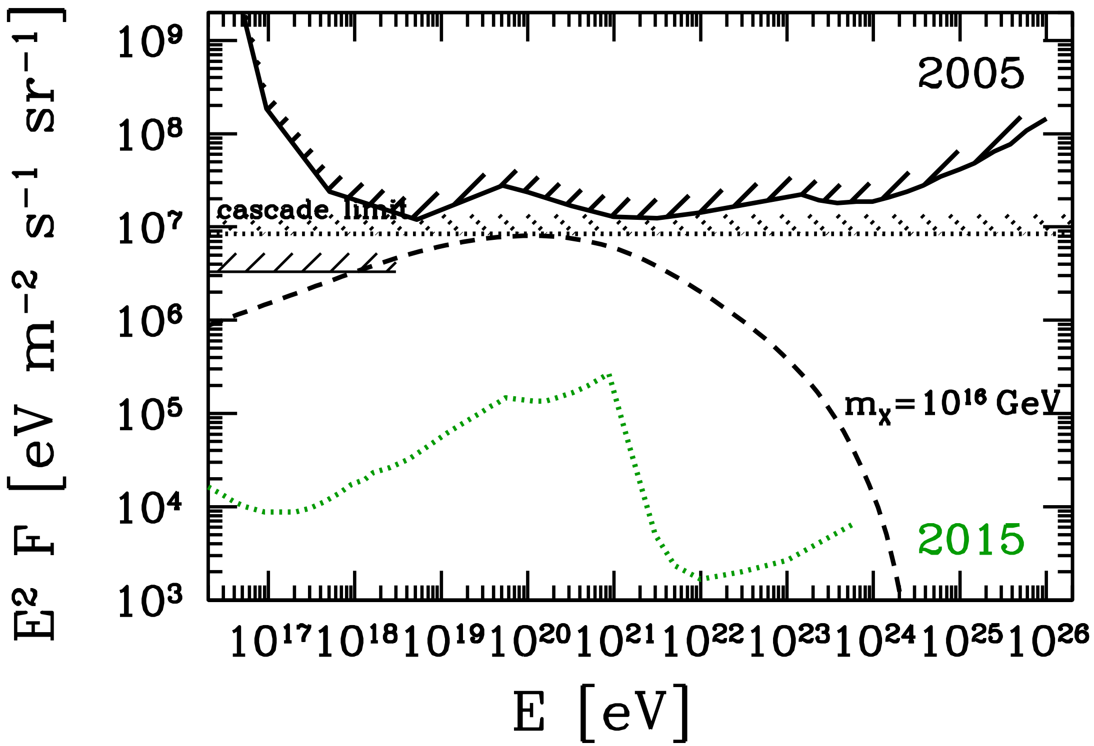

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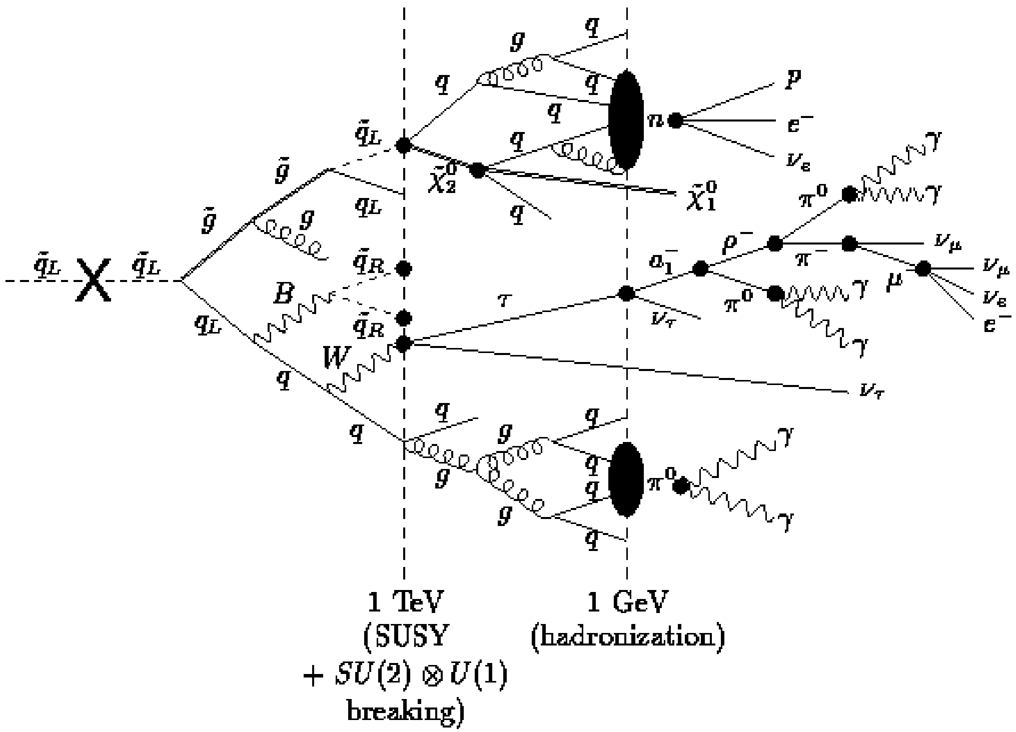

[Barbot,Drees '02]

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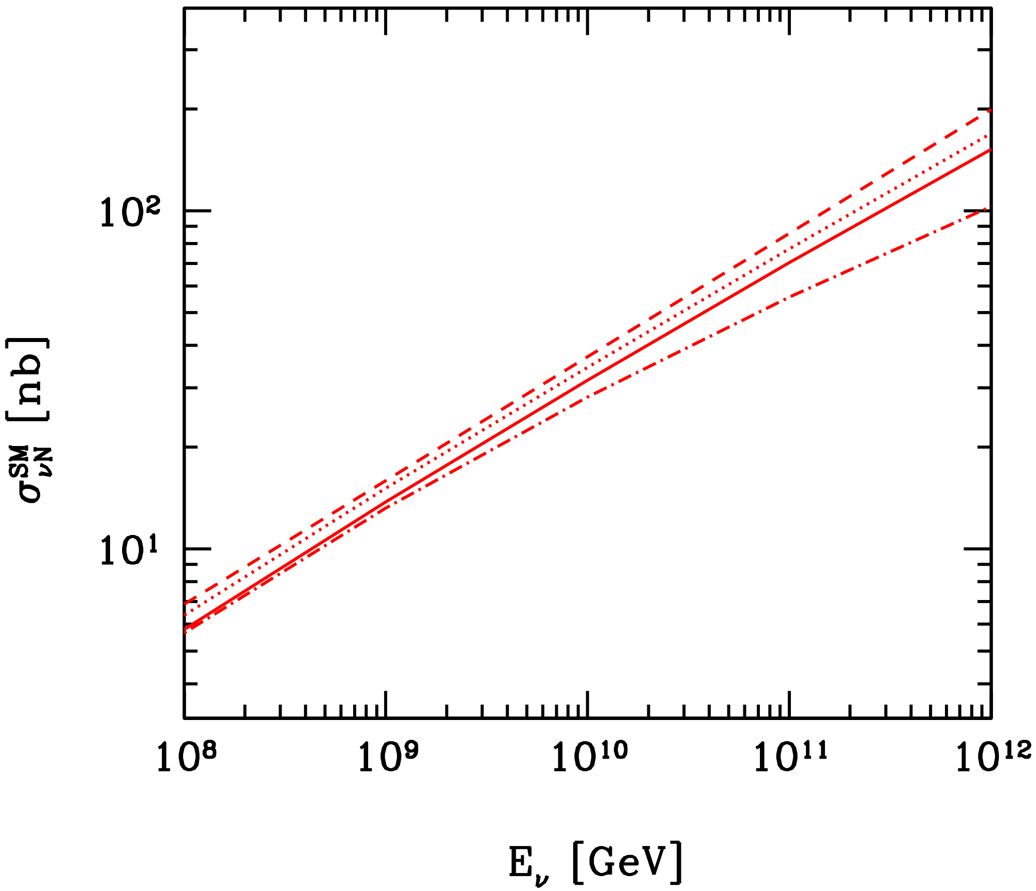

[Tu '04]

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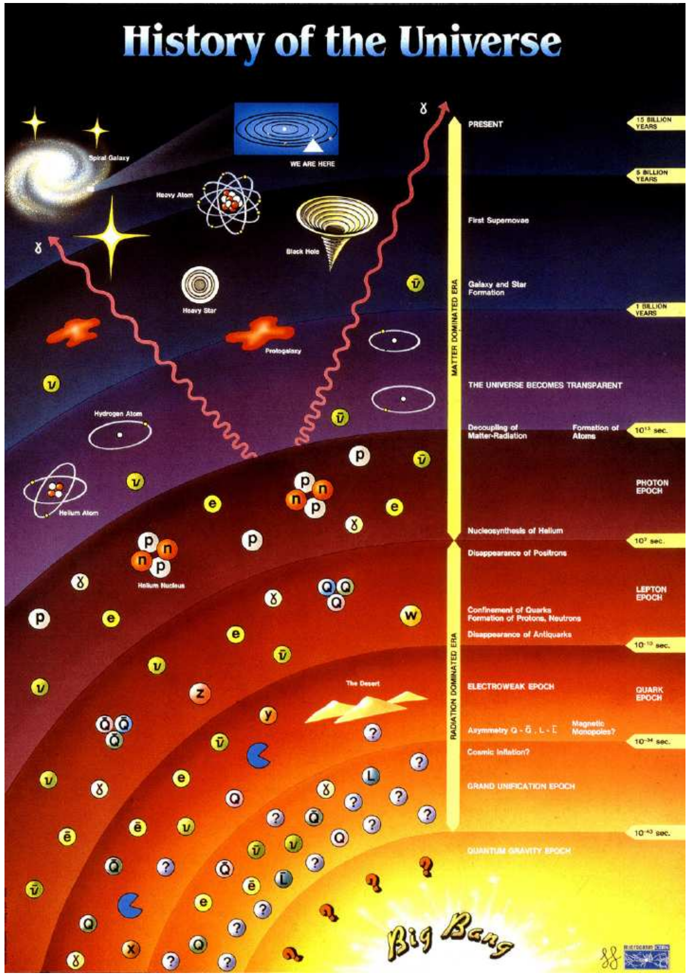

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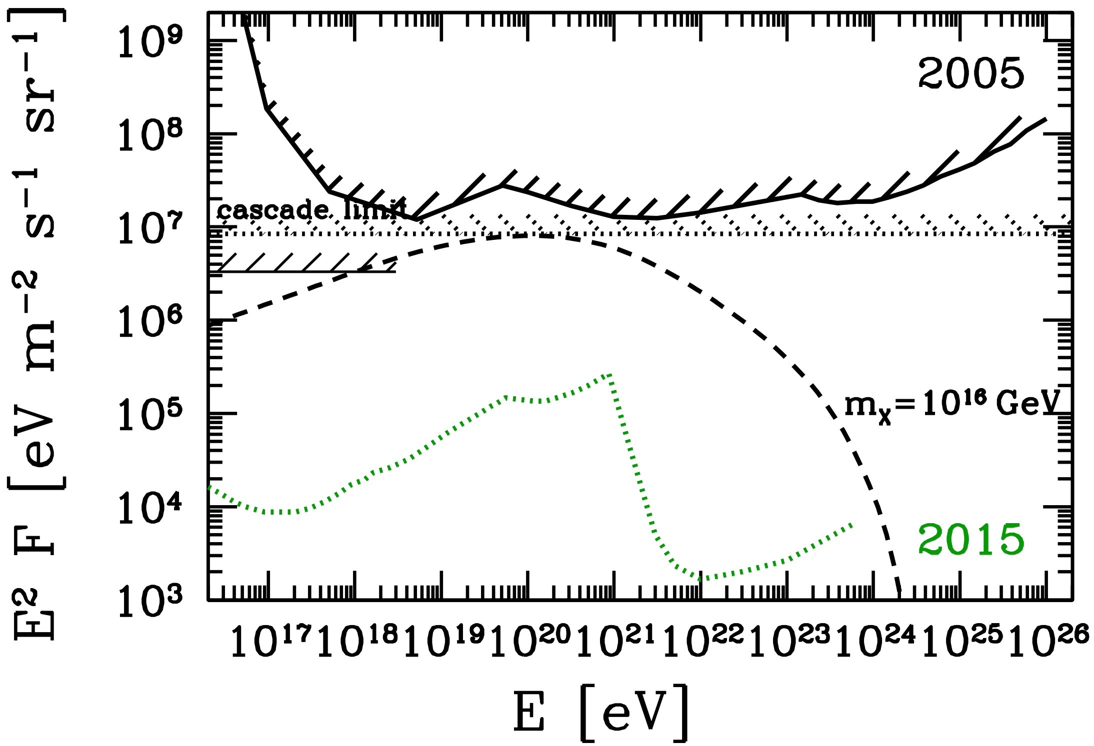

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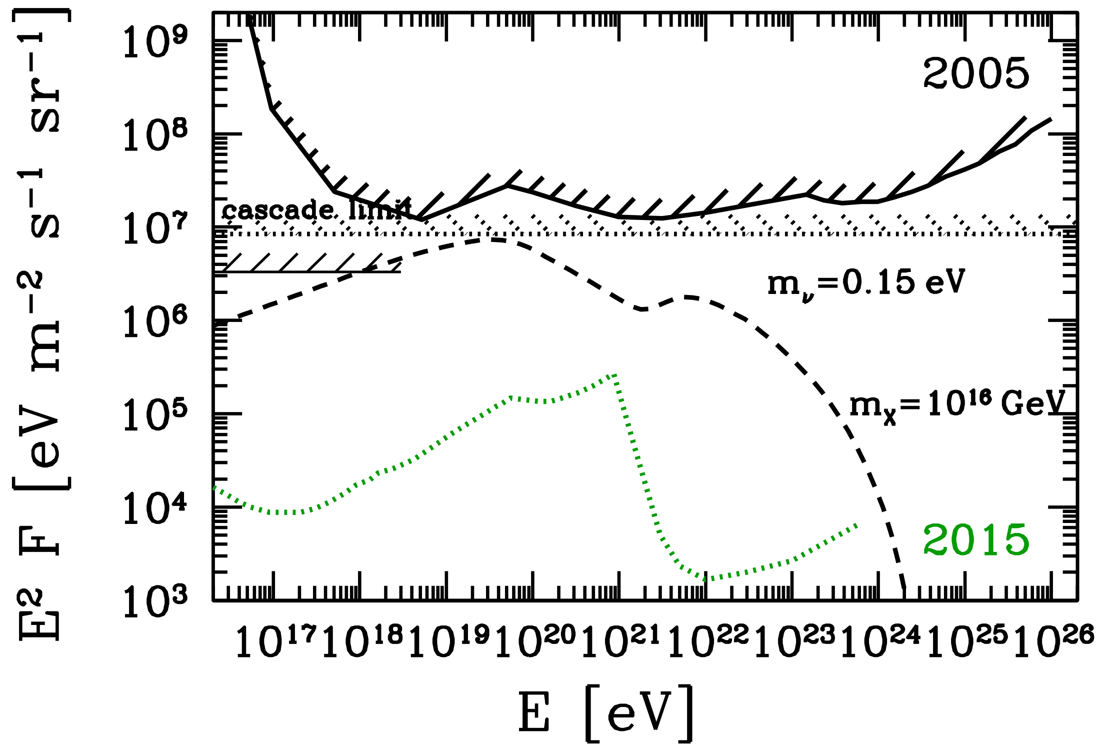

[Fodor,Katz,AR,Weiler,Wong,in prep.]

5. Conclusions

- Exciting times for extremely high energy cosmic rays and neutrinos:
  - many observatories under construction

  ⇒ appreciable event samples

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