Strongly interacting neutrinos as the highest energy cosmic rays

– A quantitative analysis –

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Budapest, Hungary, August 1-3, 2005

1. Introduction

1965: Cosmic microwave background

- A. A. Penzias and R. W. Wilson, "A Measurement Of Excess Antenna Temperature At 4080-Mc/S," Astrophys. J. **142** (1965) 419

1966: Cutoff in cosmic ray spectrum

- K. Greisen, "End To The Cosmic Ray Spectrum?," Phys. Rev. Lett. **16** (1966) 748
- G. T. Zatsepin and V. A. Kuzmin, "Upper Limit Of The Spectrum Of Cosmic Rays," JETP Lett. **4** (1966) 78

1969: Strongly interacting cosmogenic neutrinos as post-GZK events

- V. S. Beresinsky and G. T. Zatsepin, "Cosmic Rays At Ultrahigh-Energies (Neutrino?)," Phys. Lett. B **28**, 423 (1969)

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COSMIC RAYS AT ULTRA HIGH ENERGIES (NEUTRINO?)

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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_0**,

(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.

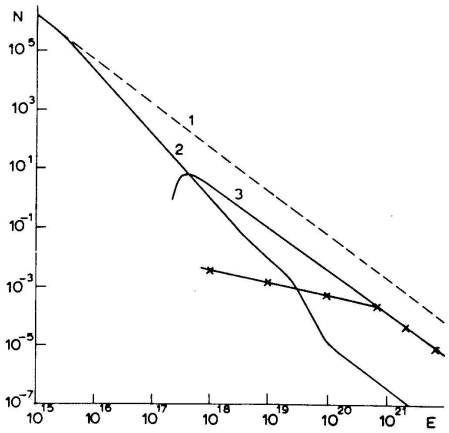


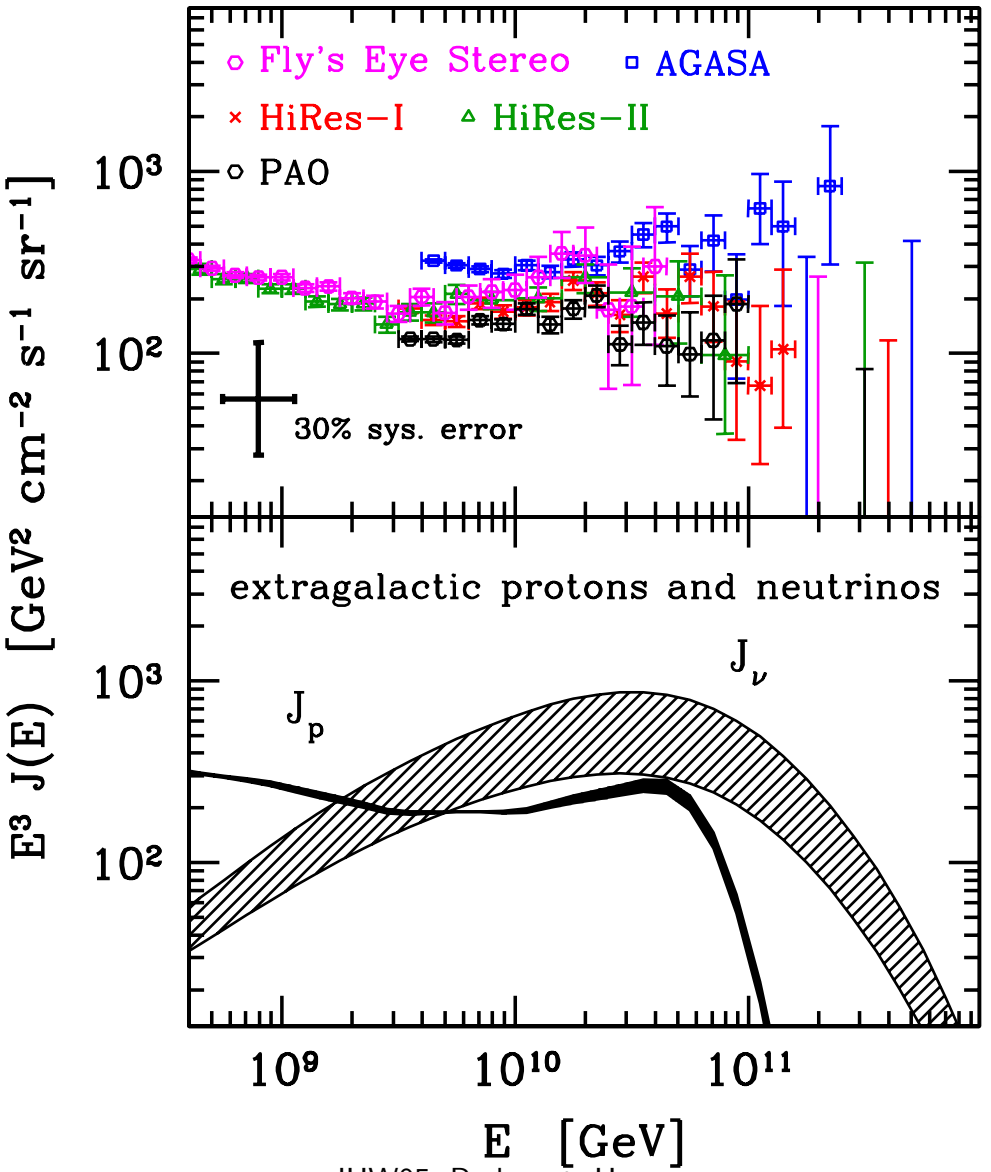
Fig. 1.

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

2005: Current status?

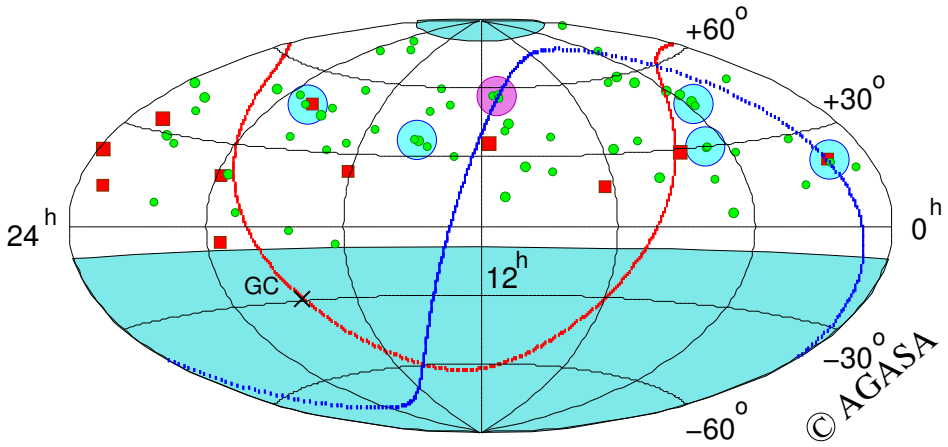
- GZK-feature in data?
- Are there post-GZK events?
- Can they be quantitatively described by strongly interacting cosmogenic neutrinos?

* Z. Fodor, S. D. Katz, A. R. and H. Tu, "Electroweak instantons as a solution to the ultrahigh energy cosmic ray puzzle," Phys. Lett. B **561** (2003) 191 [arXiv:hep-ph/0303080]
* M. Ahlers, A. R. and H. Tu, "Cosmic rays at ultra high energies (Neutrinos!)," arXiv:astro-ph/0506698



2. Extragalactic cosmic protons and neutrinos

- Origin and composition of ultrahigh energy cosmic rays ($E \gtrsim 10^9$ GeV)?
  - Isotropy $\Rightarrow$ extragalactic
  - Shower characteristics $\Rightarrow$ protons



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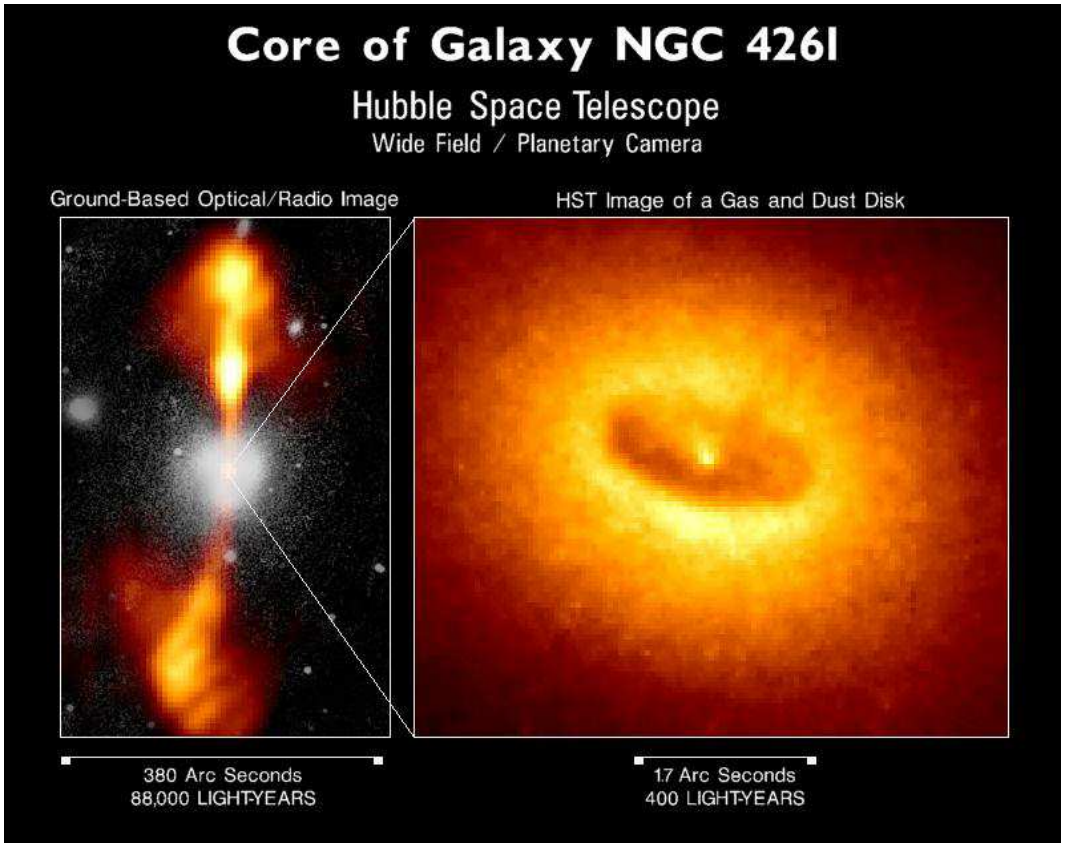

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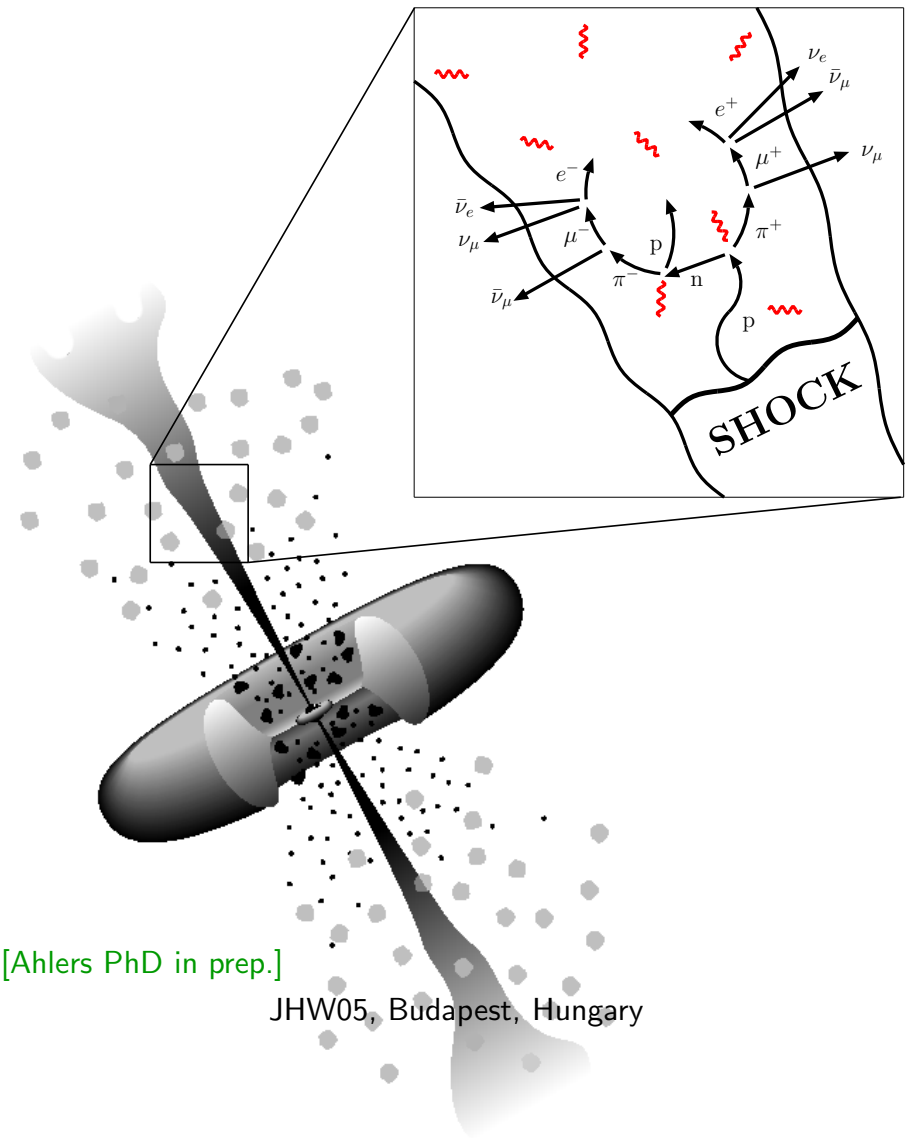
  - p's, confined by magnetic fields, accelerated through repeated scattering by plasma shock fronts
  - production of π's and n's through collisions of the trapped p's with ambient plasma produces γ's, ν's



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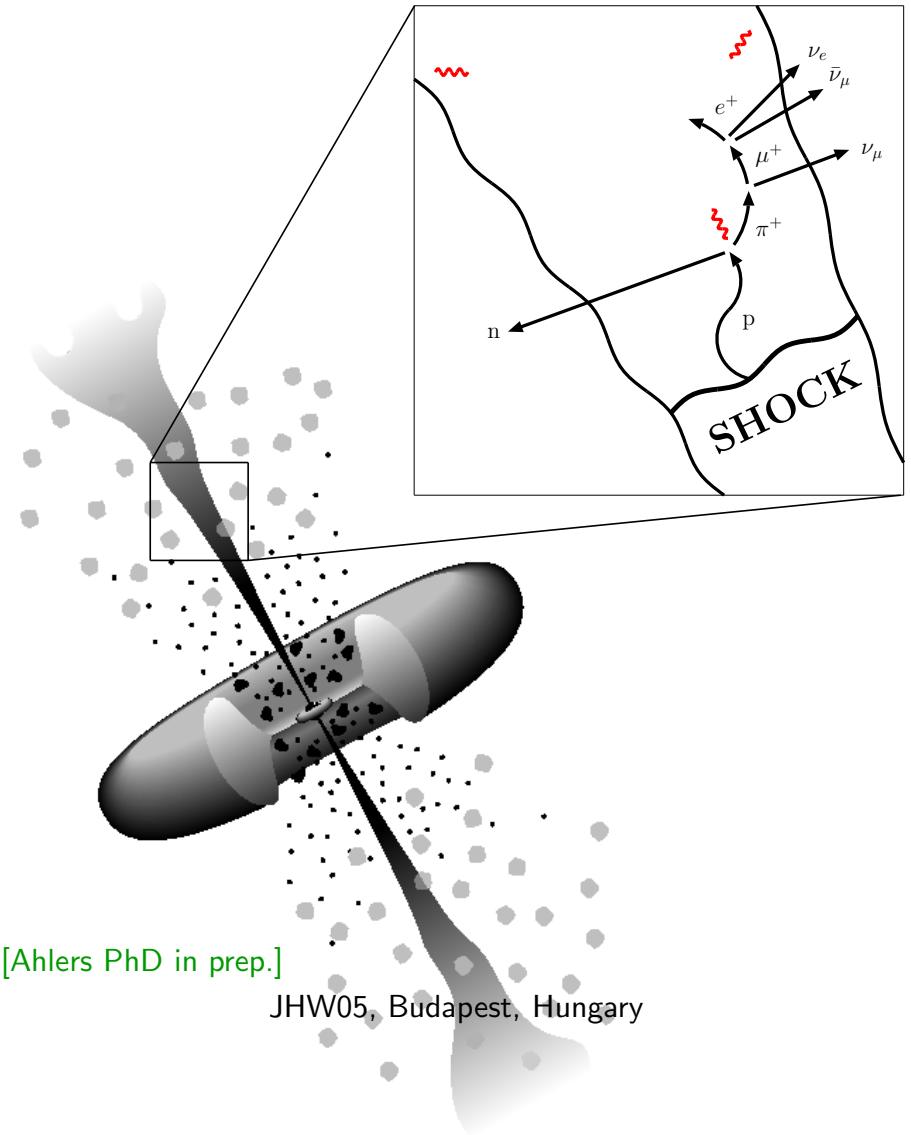

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- Quantitative analysis: [Fodor..'03;Ahlers..'05]
  - Assume that CR's in $10^{[8.6,11]}$ GeV range originate from isotropically distributed optically thin sources, with simple power-law injection spectra $\propto E_i^{-\gamma}(1+z)^n$

    [Berezinsky,..'02-'05; Abbasi,..[HiRes] '04;...]

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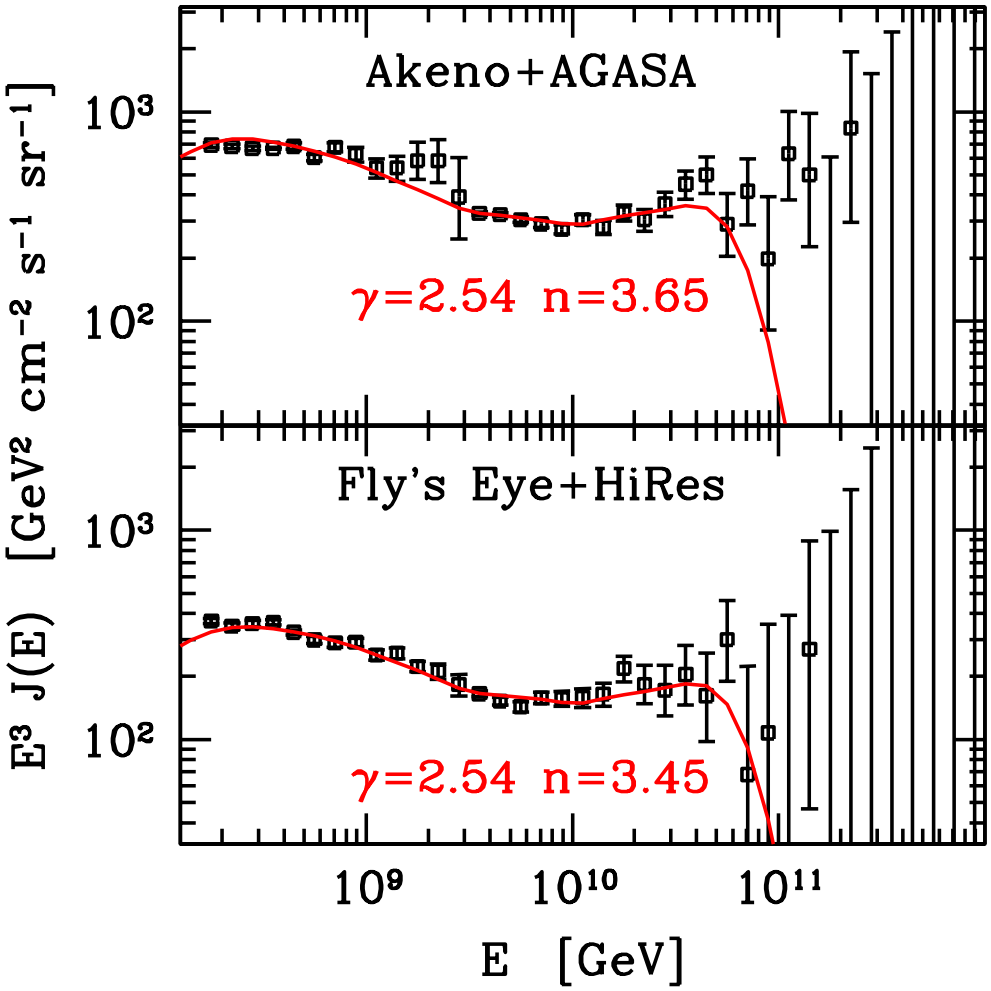

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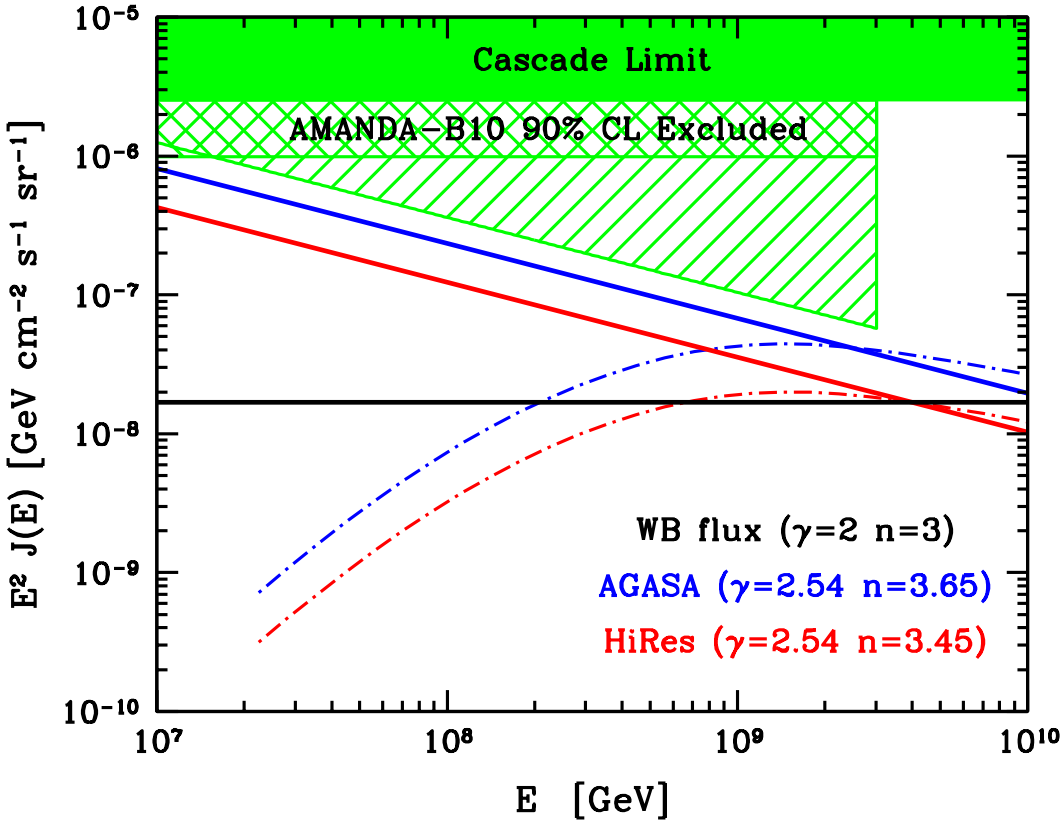
  $\Rightarrow$ ν's from sources ($p\gamma \rightarrow n + \pi$'s) close to be measured

  $\Rightarrow$ Cosmogenic neutrino flux (from $p\gamma_{\rm CMB} \rightarrow N\pi$'s) dominates above 10^9 GeV



[Ahlers *et al.* '05]

3. Strongly interacting cosmic ν's vs. CR data

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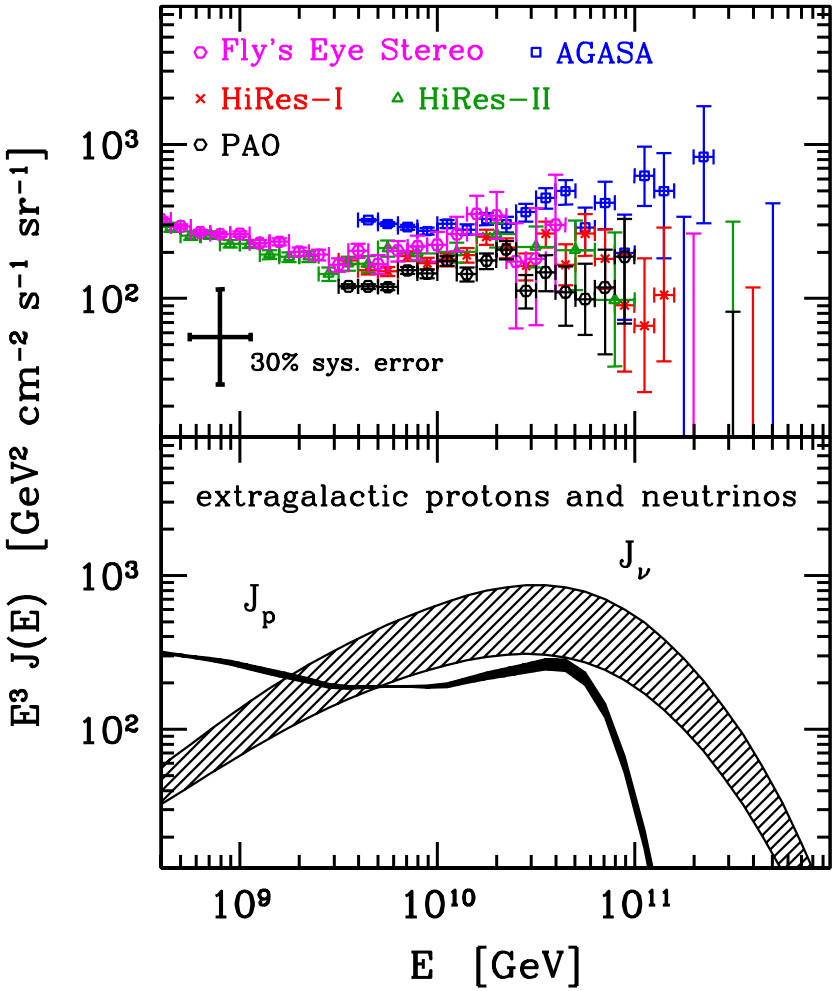

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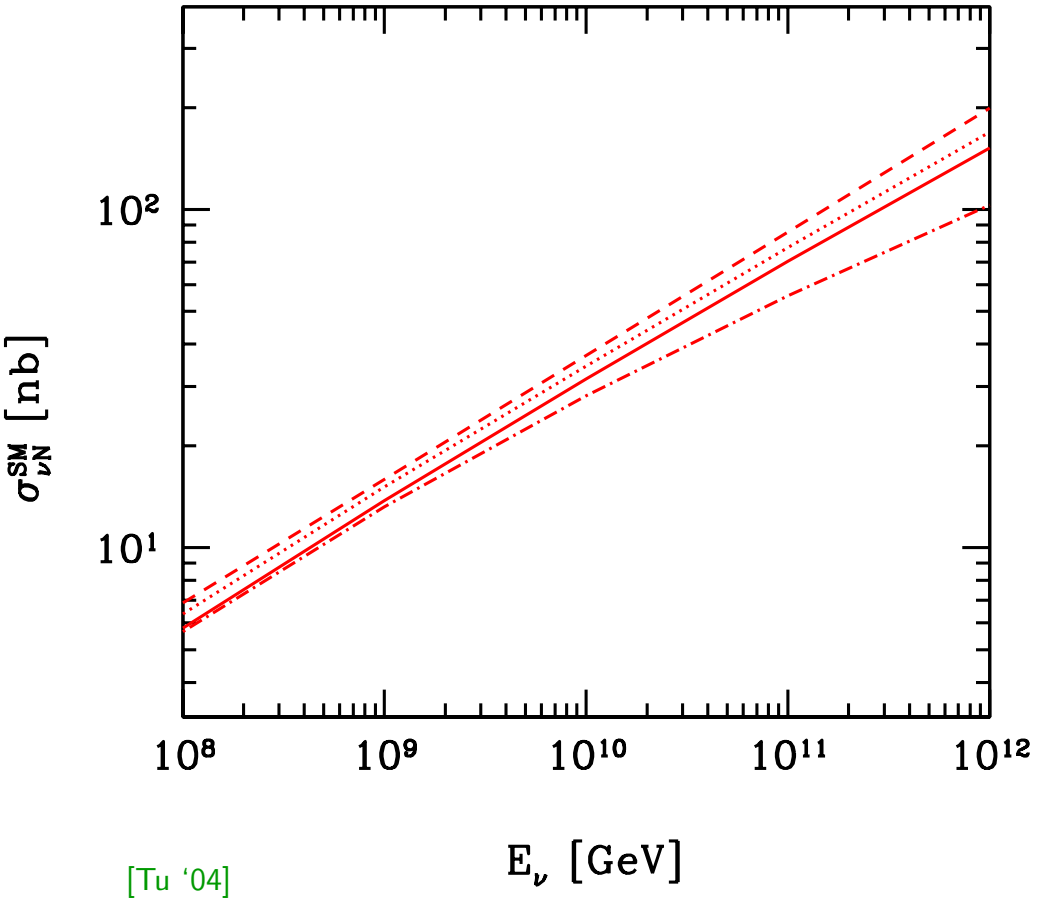
[Gandhi *et al.* '98; Kwiecinski *et al.* '98; ...]



[Tu '04]

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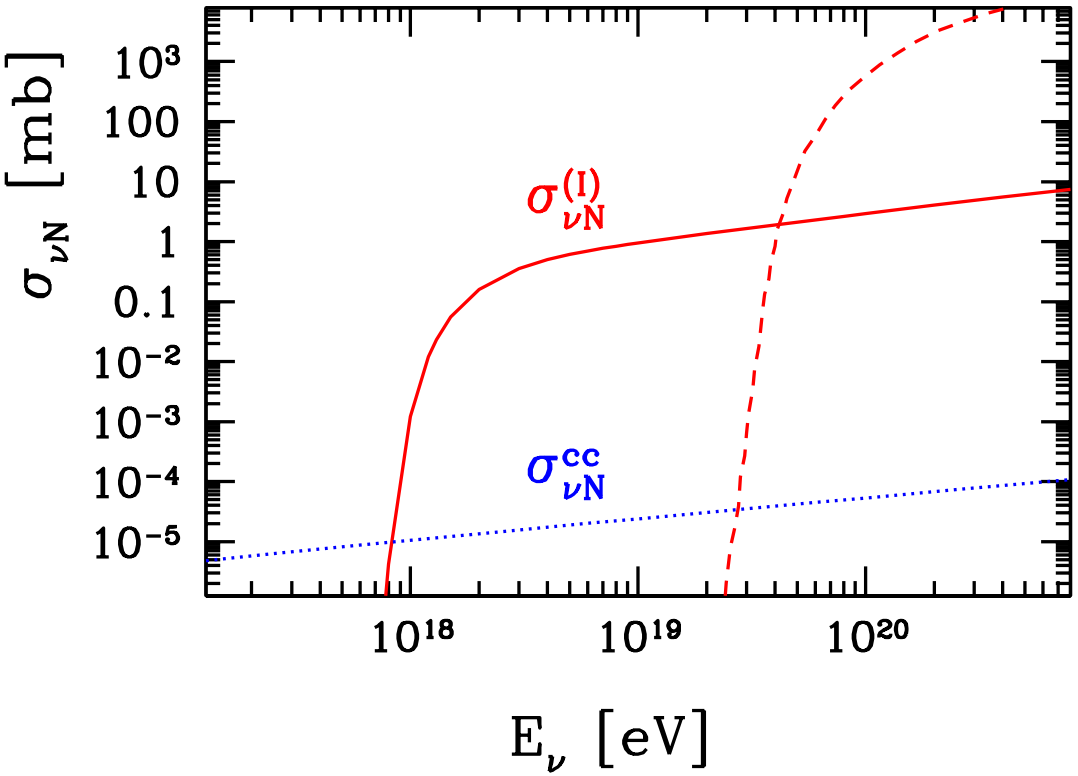
[Gandhi *et al.* '98; Kwiecinski *et al.* '98; ...]

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

- ◇ Compositeness [Domokos,Nussinov '87]
- ◇ Electroweak sphaleron production ($B + L$ violating processes in SM)



[Fodor,Katz,A.R.,Tu '03; Han,Hooper '03]

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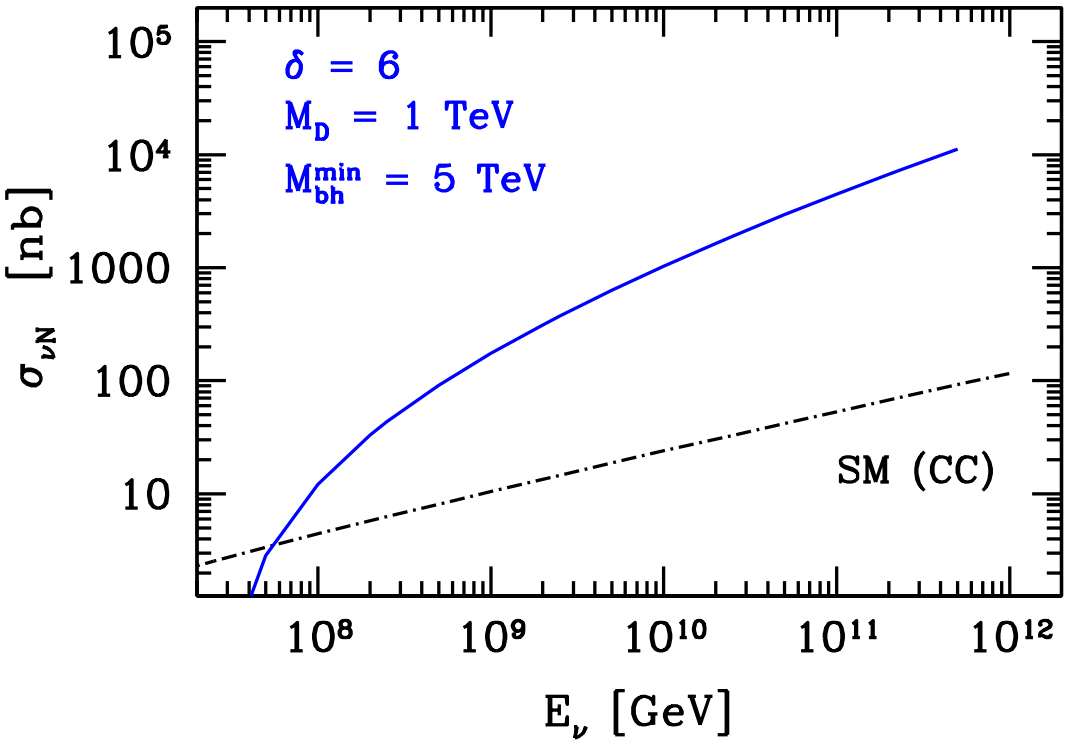
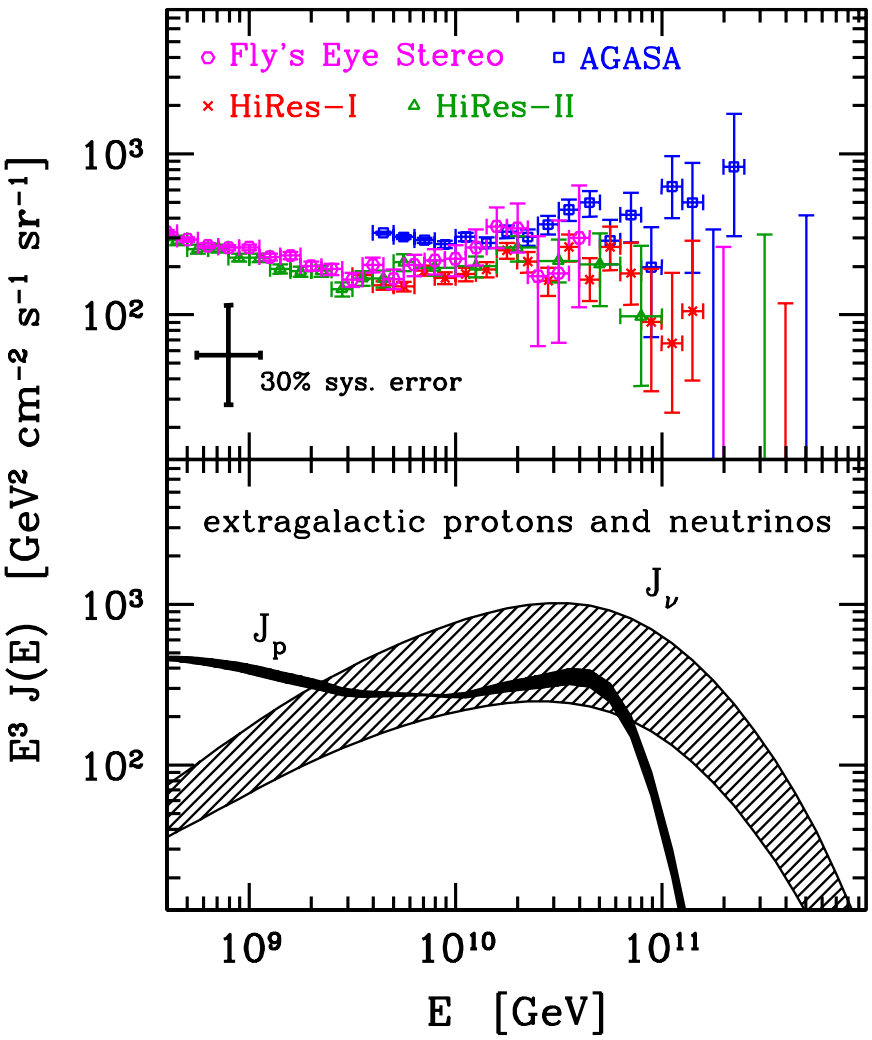
- ◇ Kaluza-Klein, black hole, p-brane or string ball production in TeV scale gravity models



[A.R.,Tu '01; Tu '04]

Quantitative analysis:

- Assume power-law neutron injection spectrum $\propto E_i^{-\gamma}(1+z)^n$
- Derive associated neutrino flux



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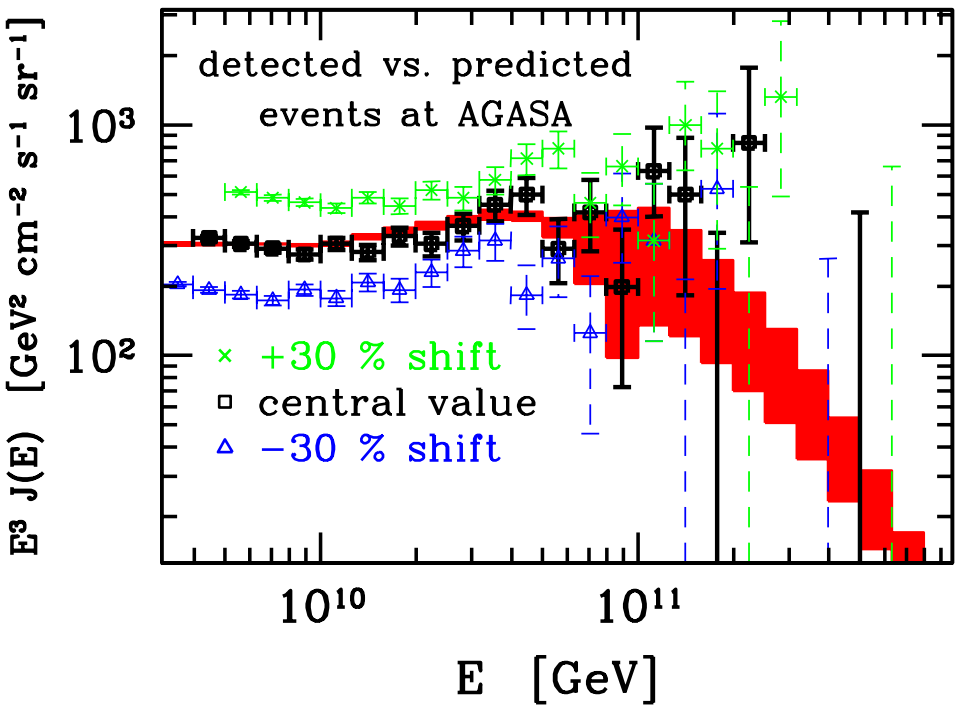

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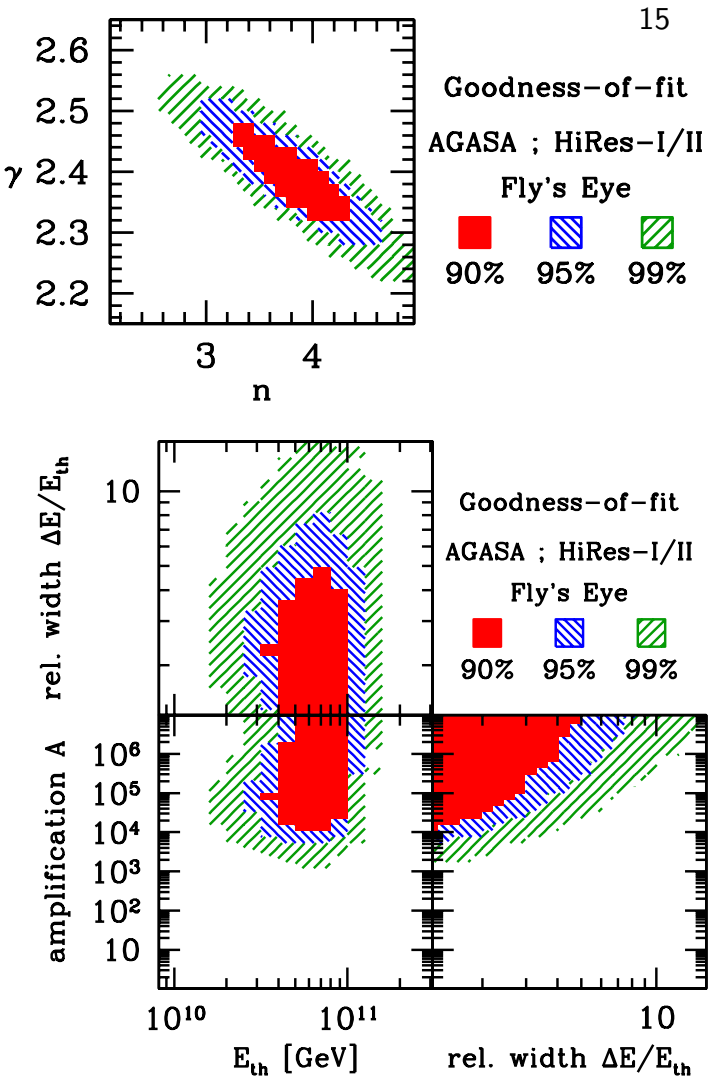

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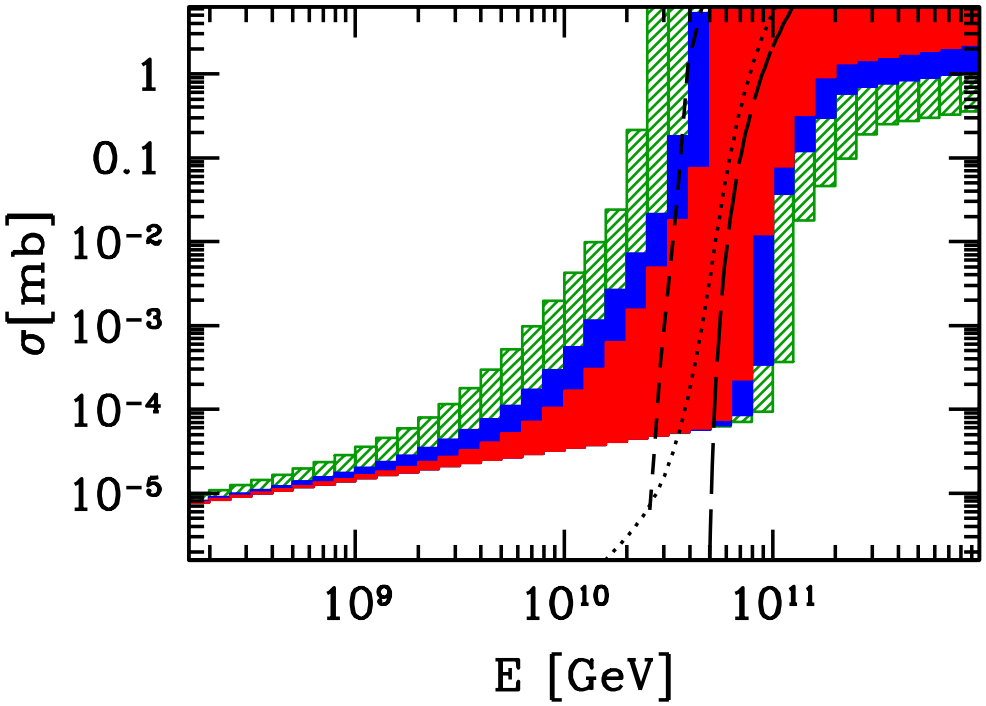
  - Need steep increase in $\sigma_{\nu N}^{\rm inel}$ within one energy decade around $E_{\rm GZK}$ by four orders of magnitude
  - Consistent with, e.g., sphaleron production, p-brane production or production of string excitations



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[Han,Hooper '04] - - - sphalerons

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

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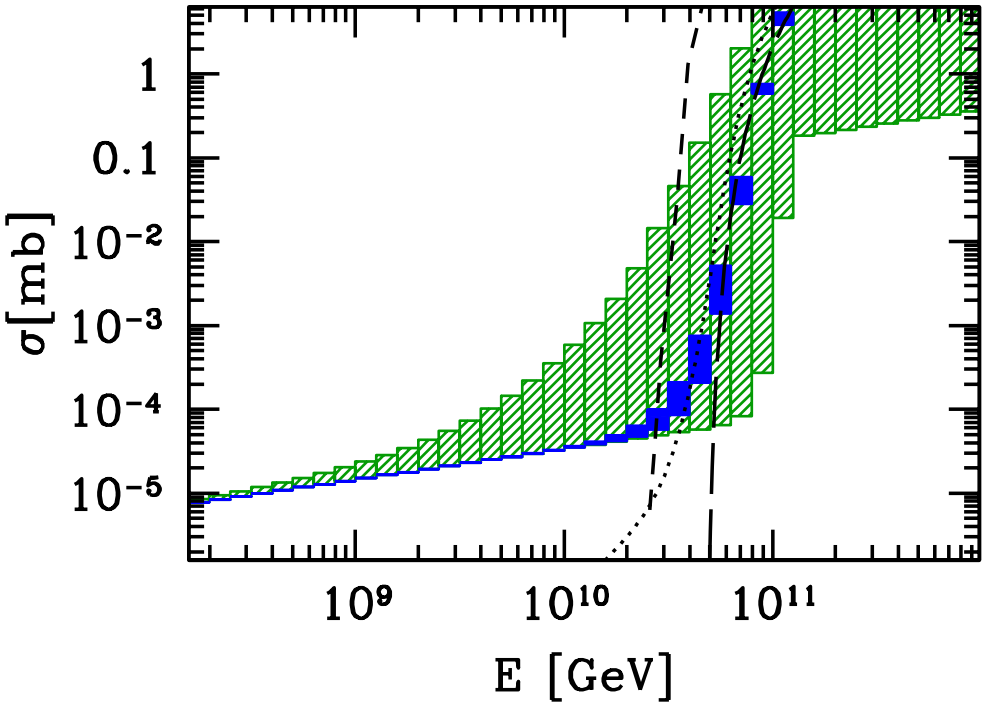
  - Survives inclusion of PAO data



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

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4. Conclusions

- Current data on highest energy cosmic ray events can be interpreted favorably as manifestation of extragalactic protons plus strongly interacting extragalactic neutrinos.
- For flux of neutrinos associated with neutrons from optically thin sources:
  - Inelastic neutrino-nucleon cross section should steeply increase within one energy decade around $E_{\rm GZK}$ by four orders of magnitude.
  - Such steep increase required by search results on quasi-horizontal showers at AGASA and contained events in RICE.
  - Allowed region for cross section compatible with theoretical predictions from production of, e.g., electroweak sphalerons, p-branes, or string excitations.
- More PAO data anxiously expected!