

Extremely Energetic Cosmic Neutrinos: Opportunities for Astrophysics, Particle Physics, and Cosmology

A. Ringwald

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

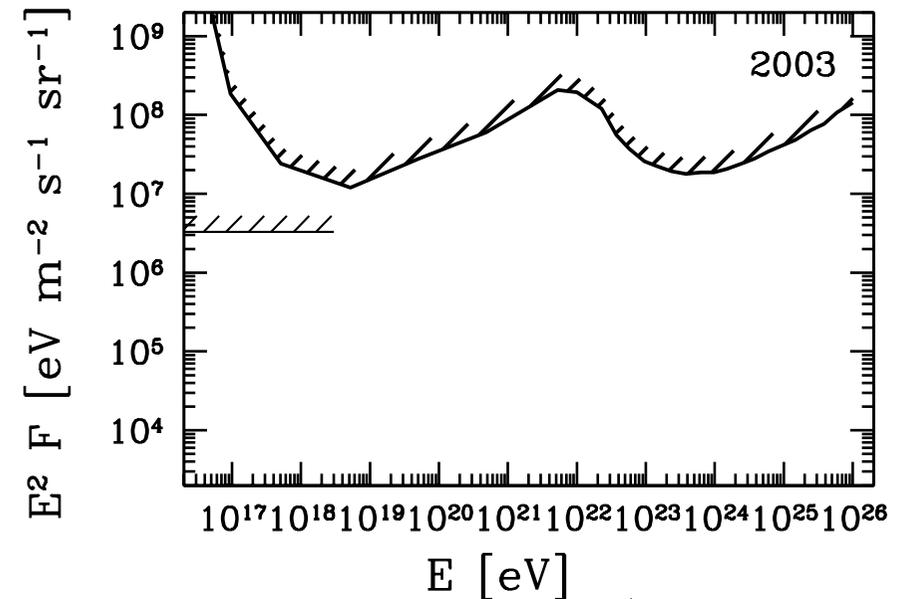
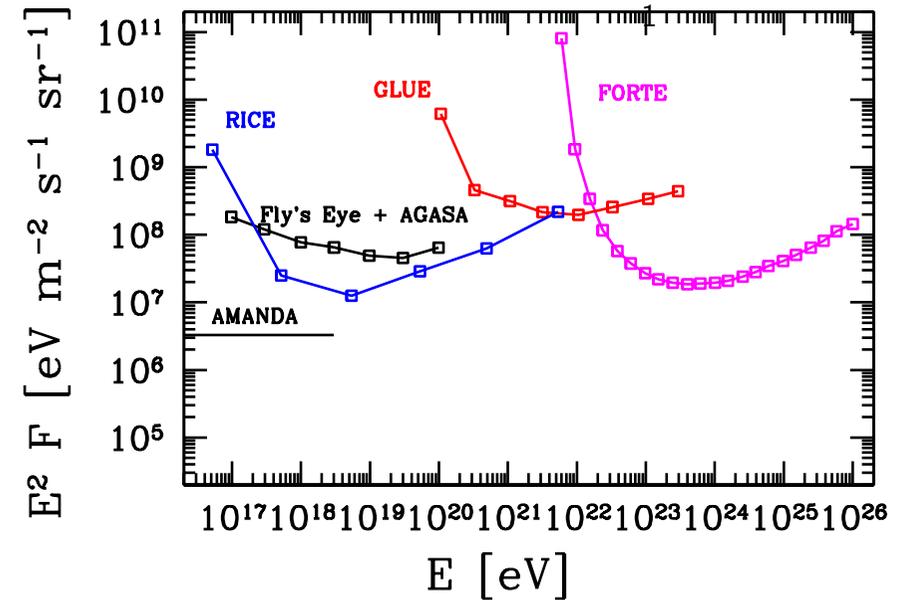


ARENA Workshop, May 17 - 19, 2005, DESY, Zeuthen, Germany

– Extremely energetic cosmic neutrinos . . . particle physics and cosmology –

1. Introduction

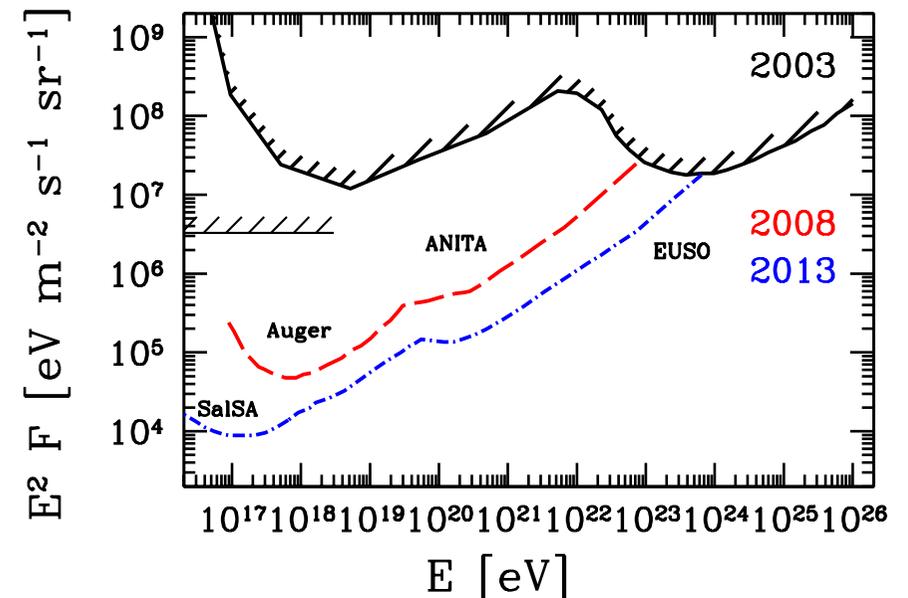
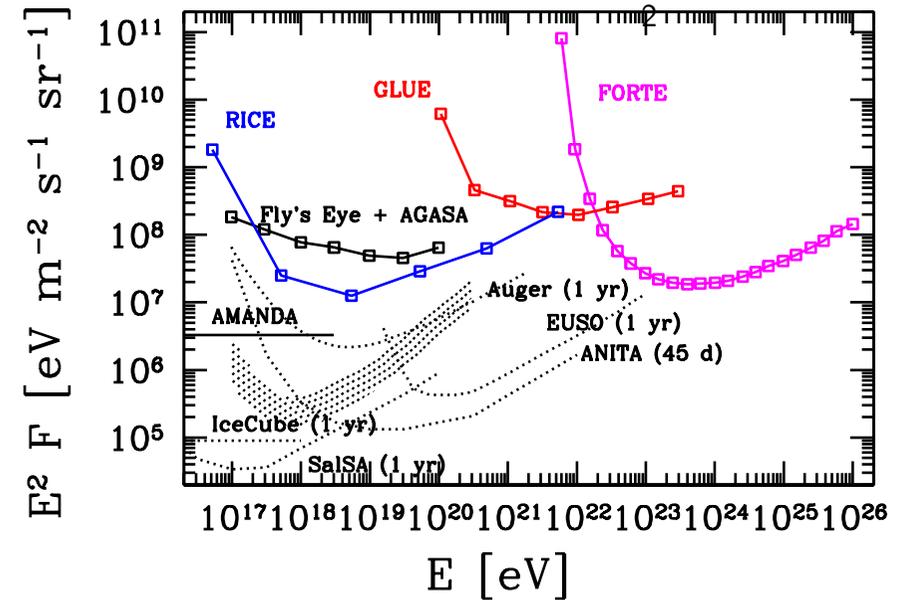
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- Upcoming decade: progressively larger detectors for **EHEC** ν 's



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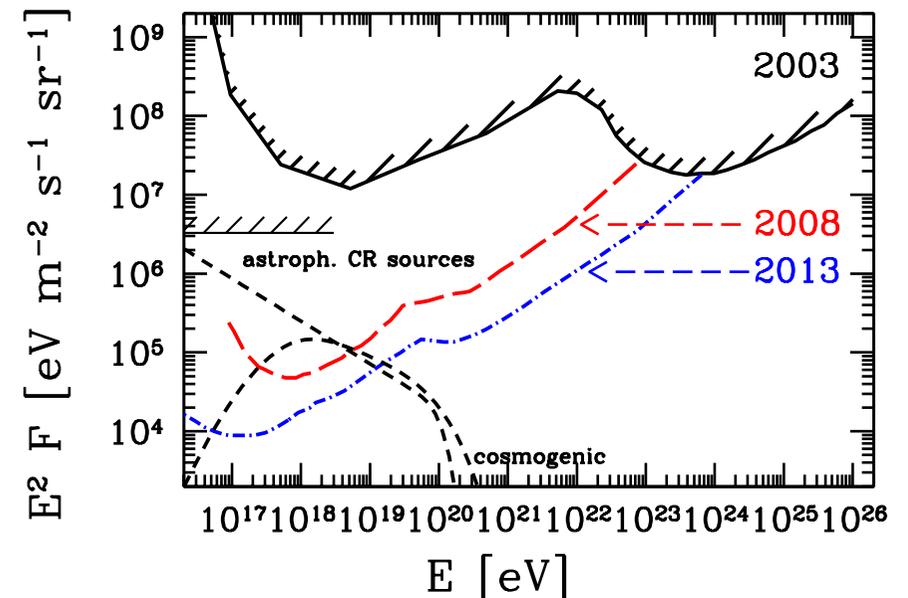
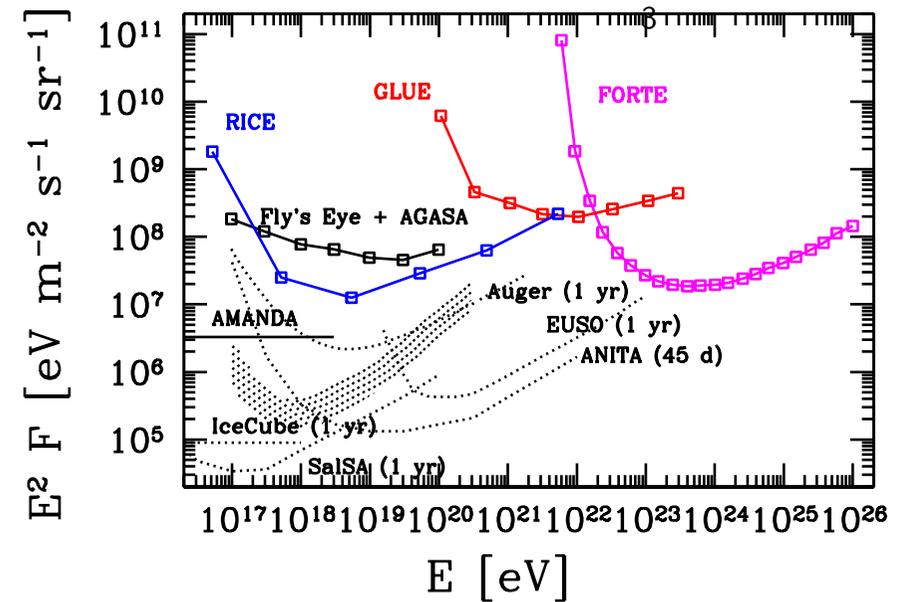
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- Upcoming decade: progressively larger detectors for **EHEC** ν 's

⇒ Huge event sample $\geq 10^{16}$ eV:

→ **Astrophysics** of cosmic rays (**CR**)

⇒ Large event sample $\geq 10^{17}$ eV:

→ **Particle physics** beyond **LHC**



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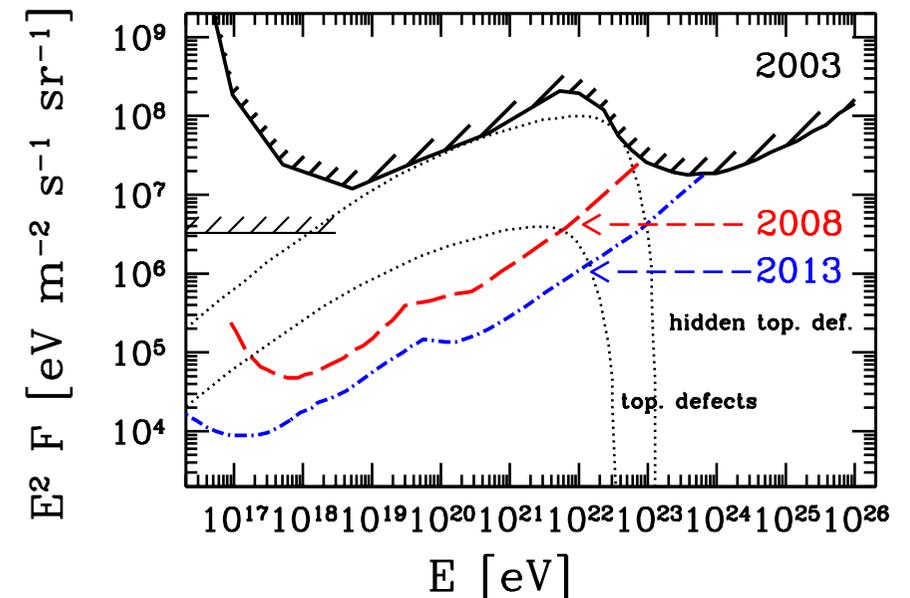
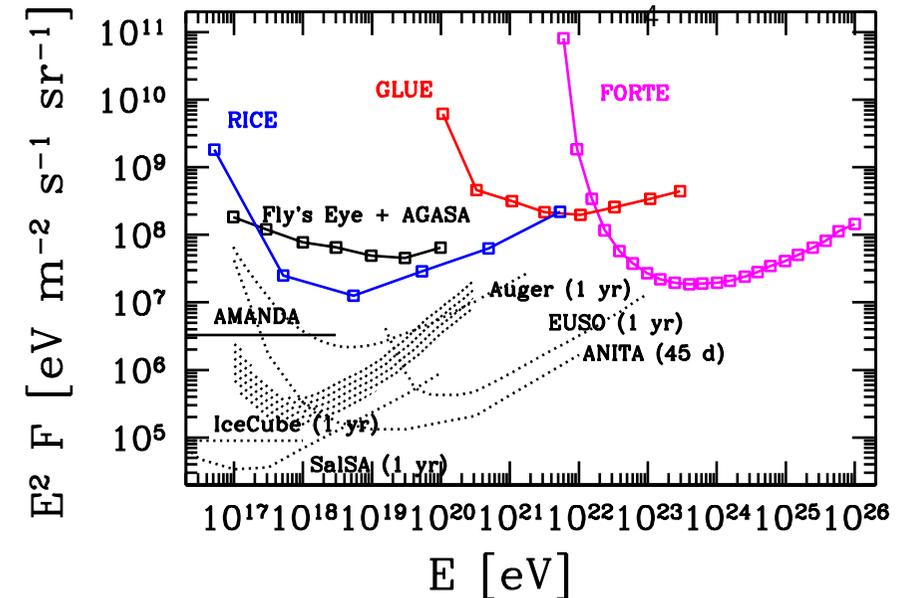
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⇒ Appreciable event sample $\geq 10^{21}$ eV:

→ **Cosmology**: detection of cosmic neutrino background (**C** ν **B**) via absorption features in ν spectra

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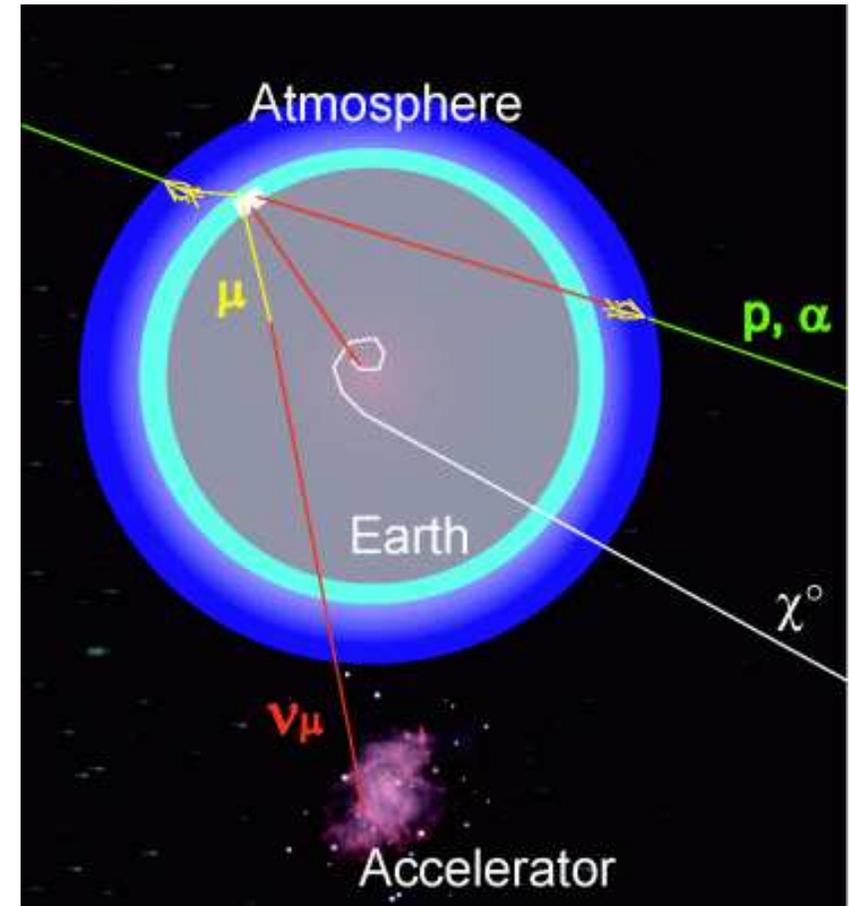
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- **Further content:**

2. **EHEC ν 's as a diagnostic of astrophysical processes**
3. **EHEC ν 's and physics beyond the Standard Model**
4. **EHEC ν absorption on the C ν B**
5. **Conclusions**

2. EHEC ν 's as a diagnostic of astrophysical processes

- Neutrinos ($E \lesssim 10^{21}$ eV) propagate essentially without interaction between source and Earth
- ⇒ Powerful probe of high energy astrophysics ⇒ Neutrino telescopes!

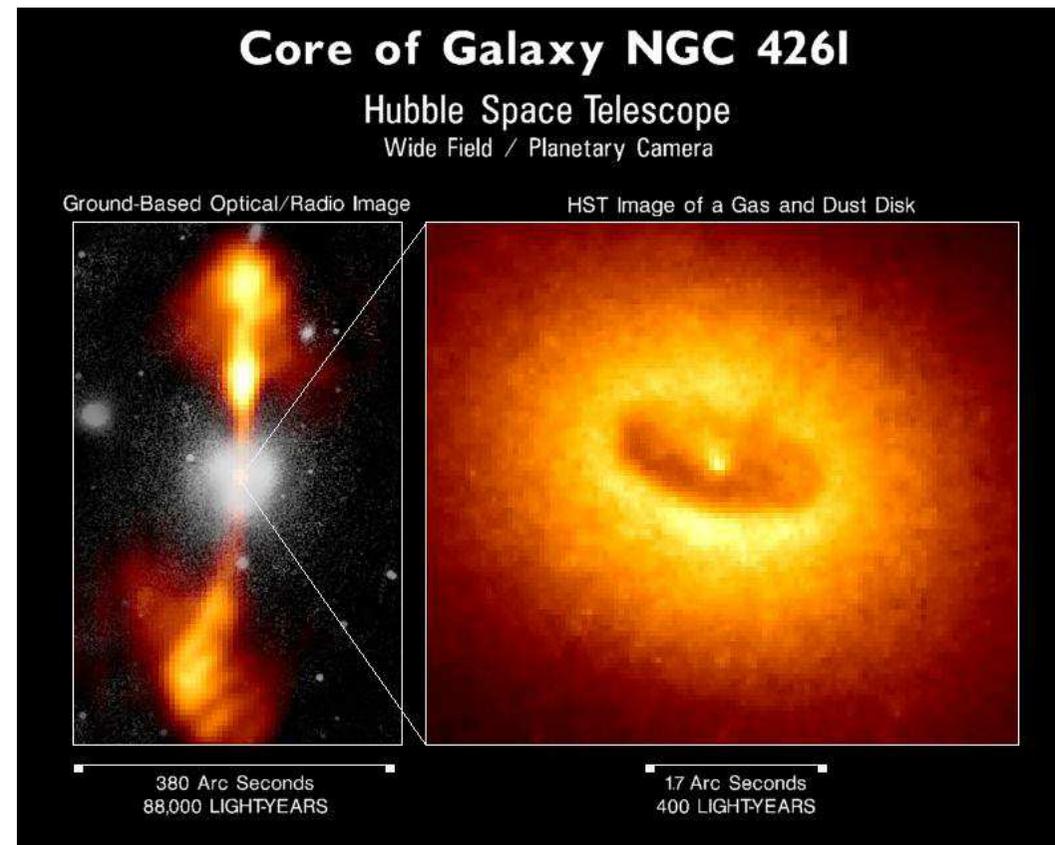


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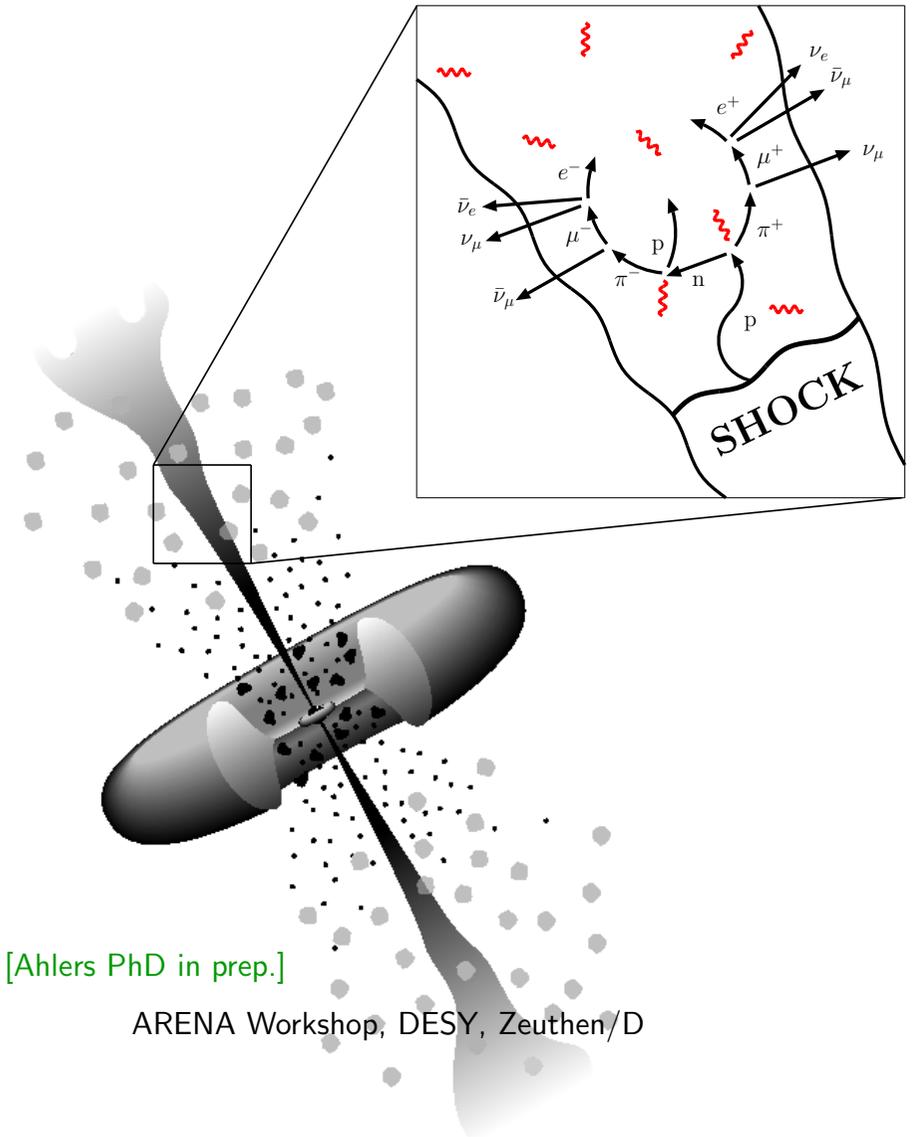
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 - p 's, confined by magnetic fields, accelerated through repeated scattering by plasma shock fronts
 - production of π 's and n 's through collisions of the trapped p 's with ambient plasma produces γ 's, ν 's and CR's (n diffusion from source)



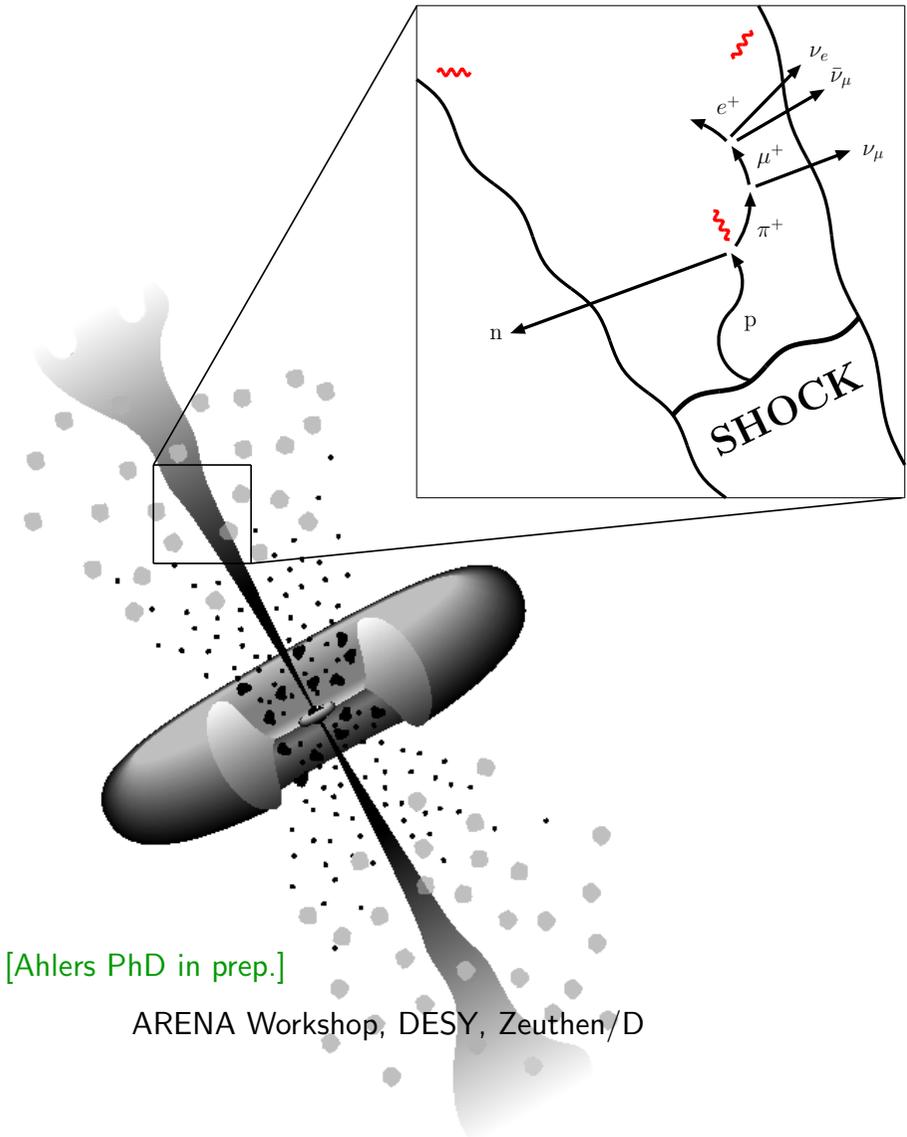
[Ahlers PhD in prep.]

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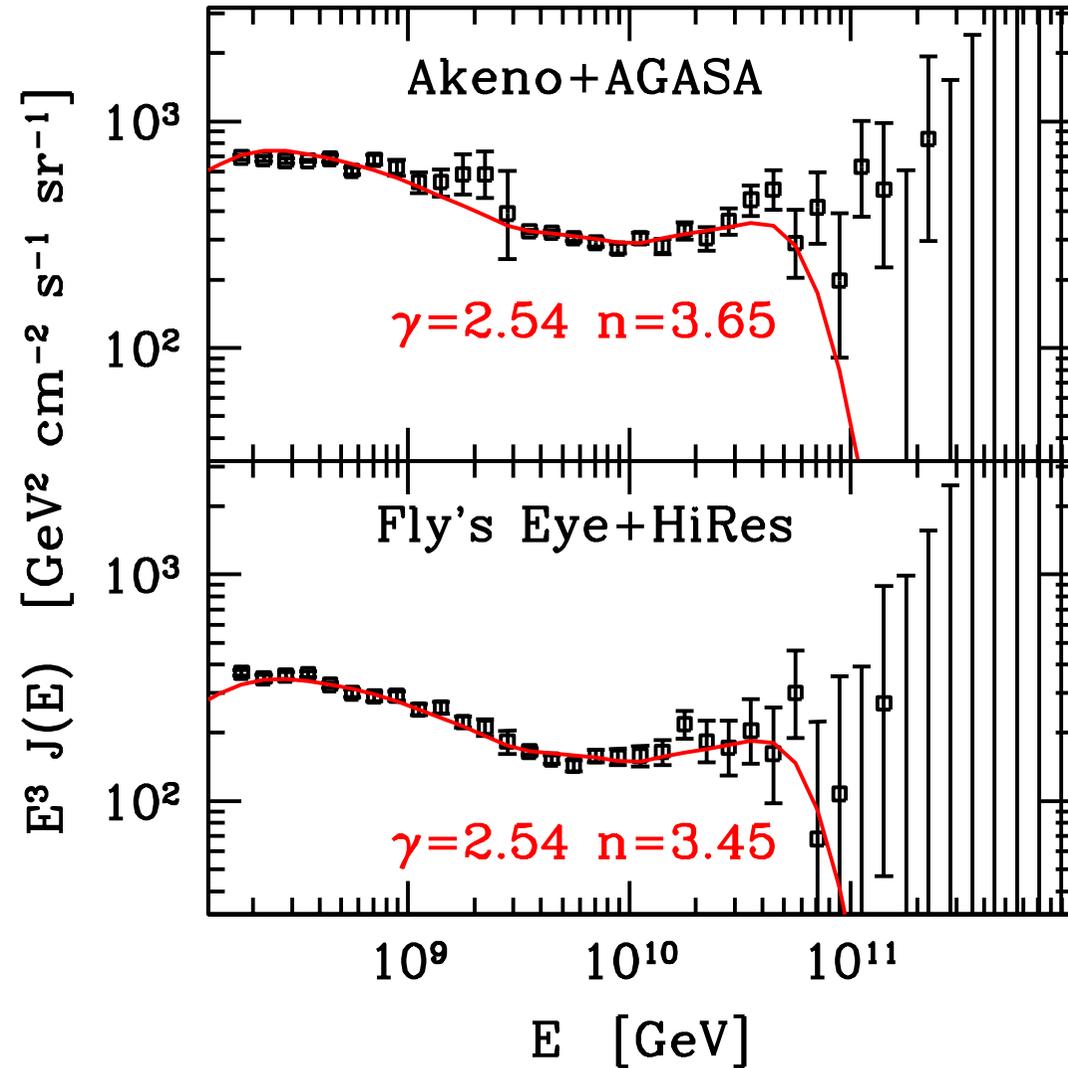
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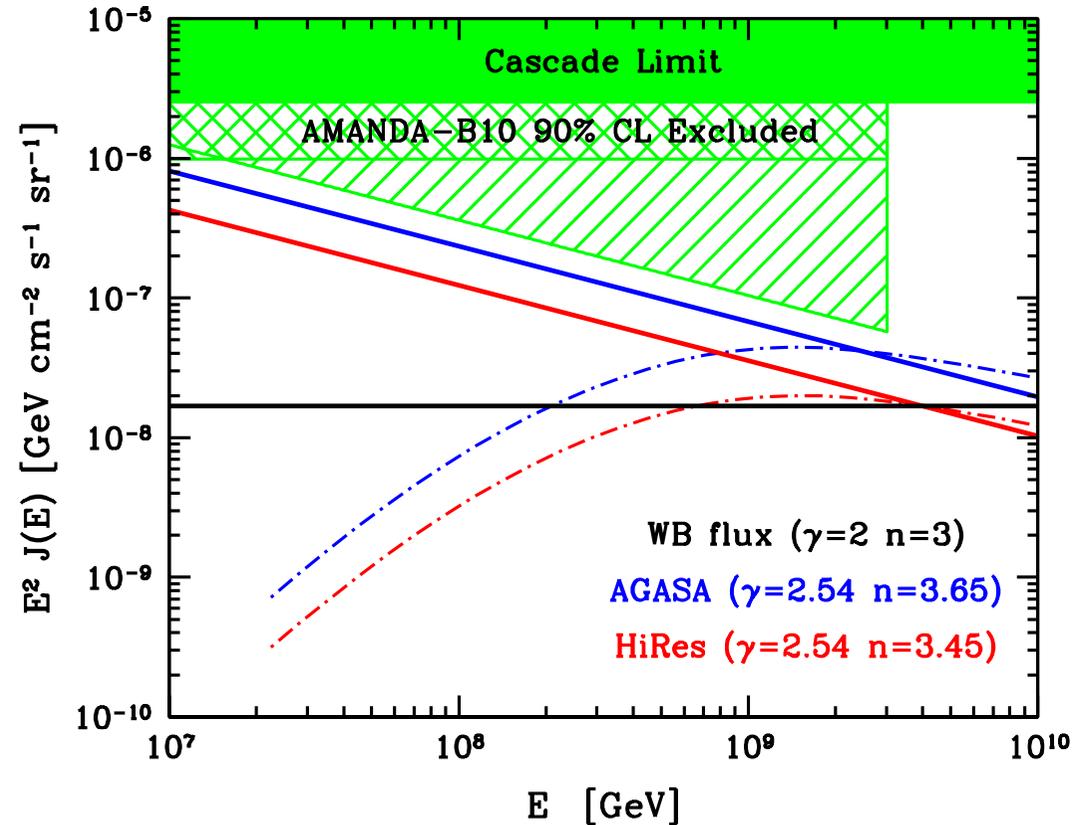
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- Quantitative analysis: [Ahlers *et al.* '05]
 - Assume that CR's in $10^{[8.6,11]}$ GeV range originate from isotropically distributed optically thin sources, with simple power-law n injection spectra [Berezinsky,..'02-'05; Abbasi,..[HiRes] '04;...]
 - $\Rightarrow n$ emissivity at the sources
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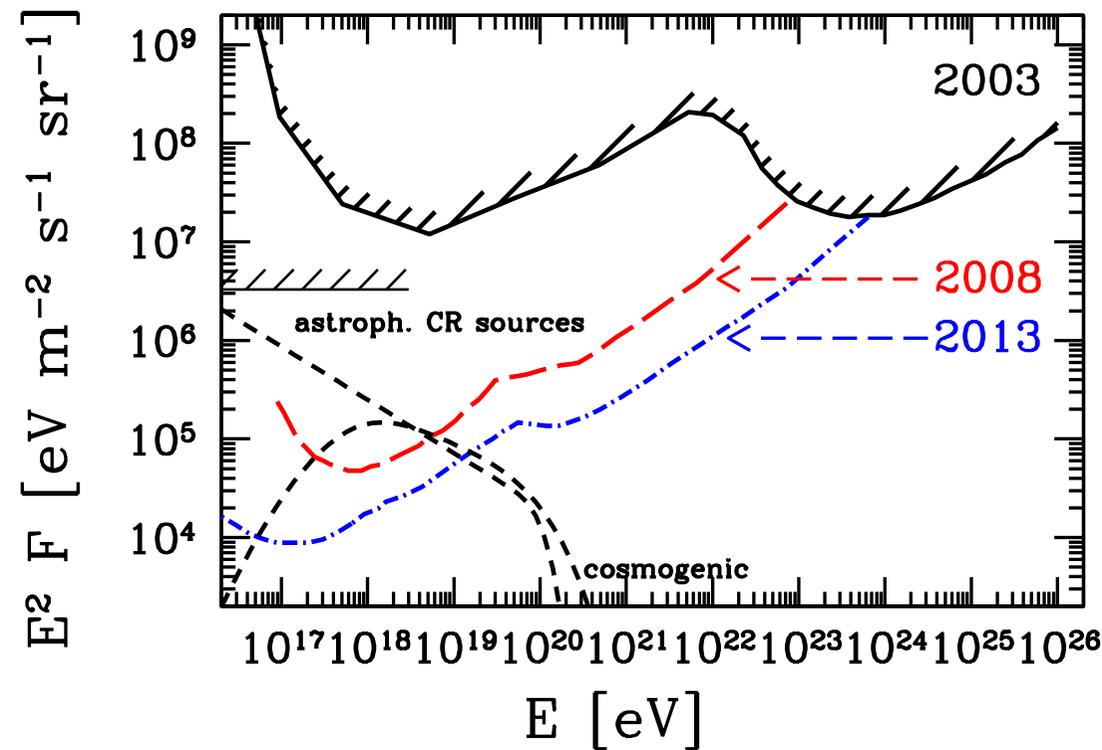
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 - $\Rightarrow \nu$ flux at Earth:
 - * ν 's from $pp \rightarrow np + \pi$'s excluded by AMANDA-B10
 - * ν 's from $p\gamma \rightarrow n + \pi$'s still consistent, but close to be measured



[Ahlers *et al.* '05]

3. EHEC ν 's and physics beyond the Standard Model

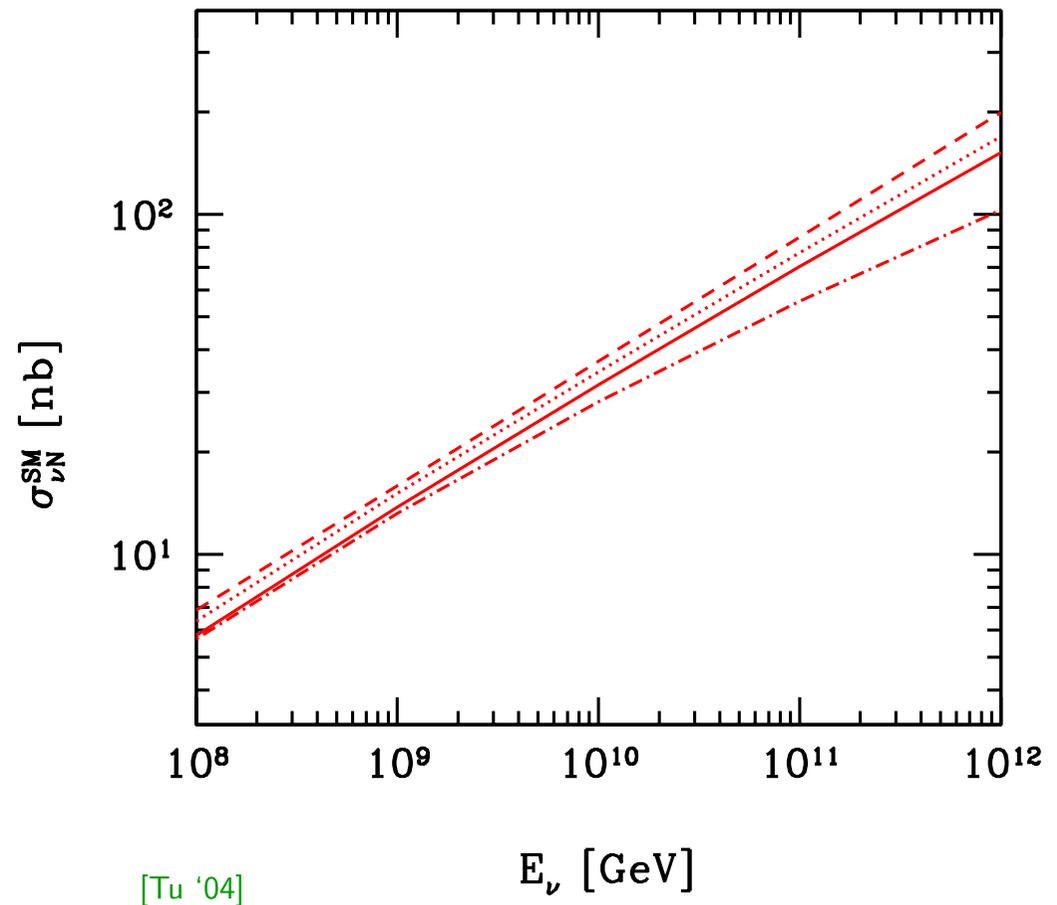
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- Perturbative Standard Model (**SM**) \approx under control (\leftarrow **HERA**)

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



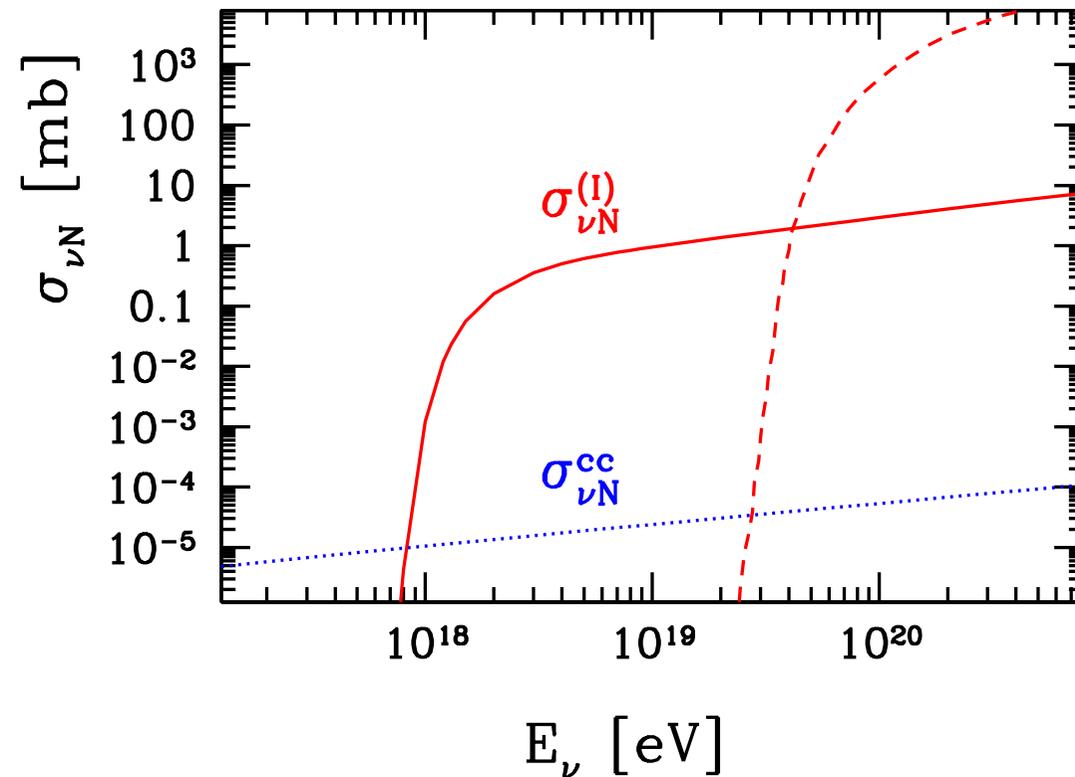
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\Rightarrow Search for enhancements in $\sigma_{\nu N}$ beyond (perturbative) SM:

- ◇ **Electroweak sphaleron production** (non-perturbative $B + L$ violating processes)



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

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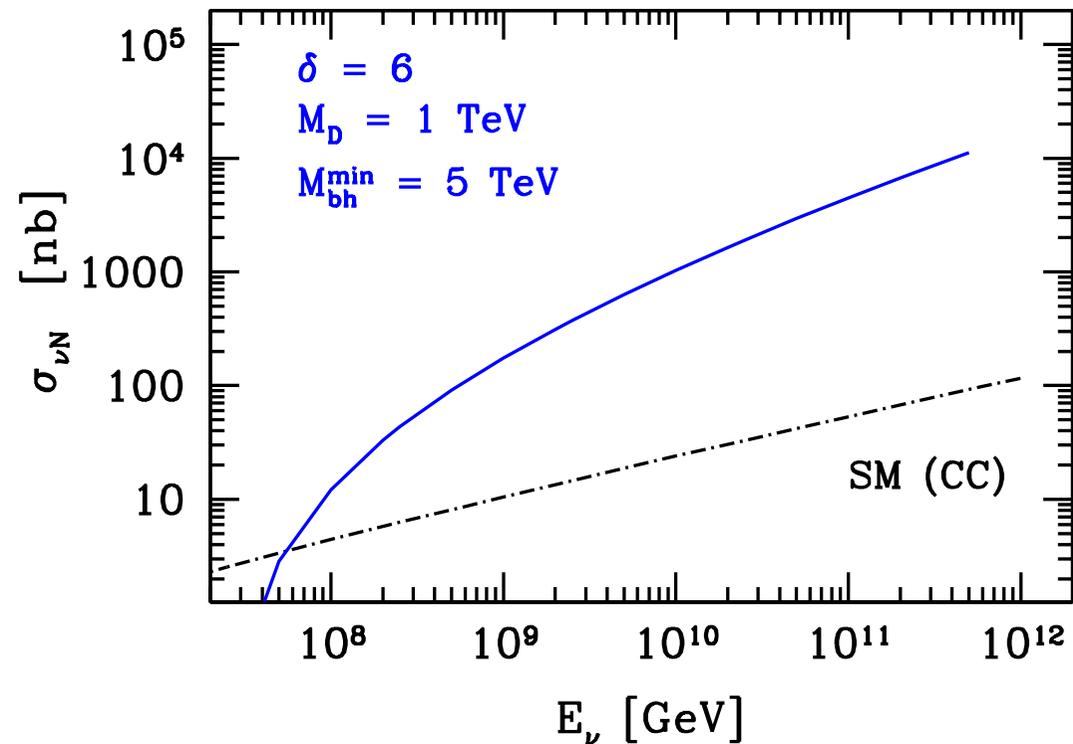
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\Rightarrow Search for enhancements in $\sigma_{\nu N}$ beyond (perturbative) SM:

- ◇ Electroweak sphaleron production (non-perturbative $B + L$ violating processes)
- ◇ Kaluza-Klein, **black hole**, p -brane or string ball production in TeV scale gravity models

◇ . . .

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[AR, Tu '01; Tu '04]

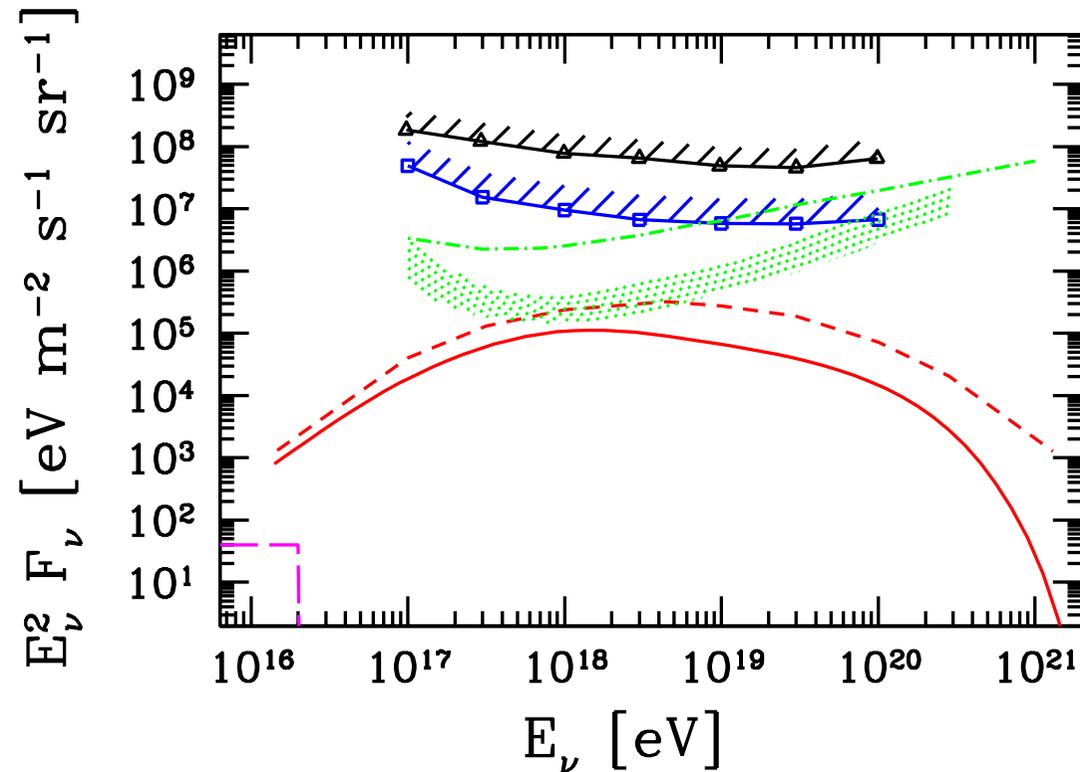
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“Model-independent” upper bounds on $\sigma_{\nu N}$

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

⇒ Non-observation of deeply-penetrating particles, together with lower bound on $F_{\nu} \Rightarrow$ 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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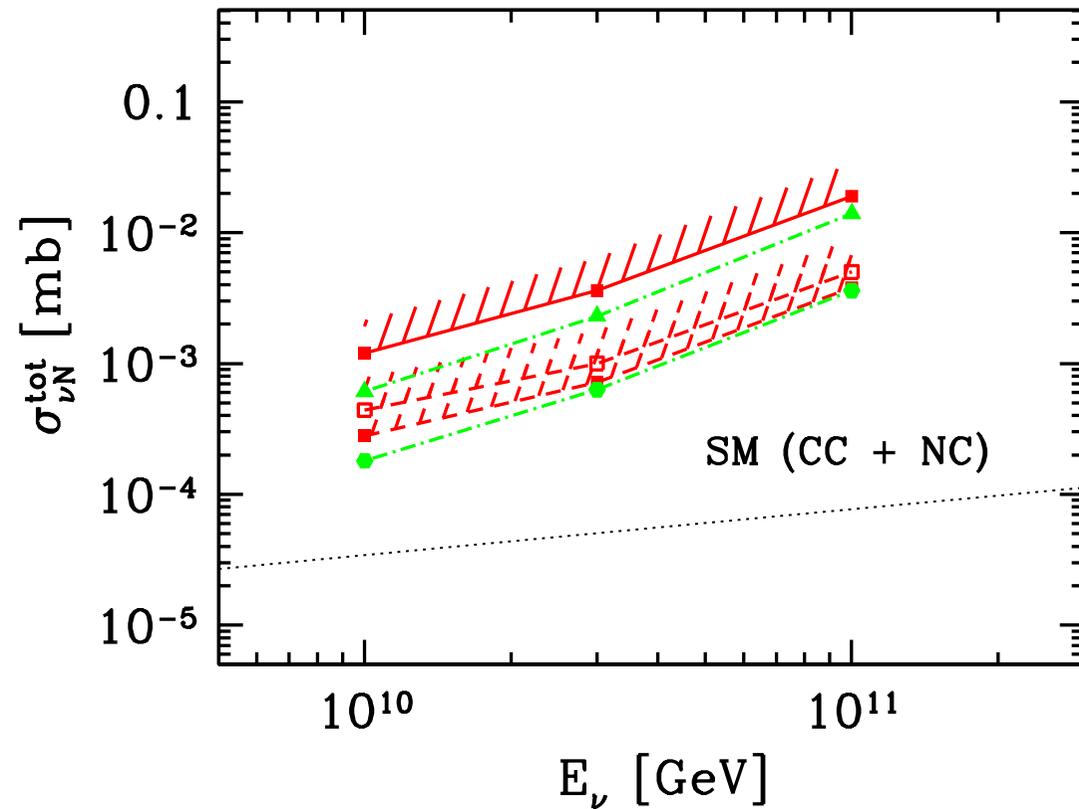
- Recent quantitative analysis:

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

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

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

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



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

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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:

⇒ Strongly interacting neutrino scenario for the post-GZK events

[Berezinsky,Zatsepin '69]

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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 to 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 hypothetical 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 Longair's [6] assumptions for evolution of radiogalactics, the latter chosen to fit experimental data.

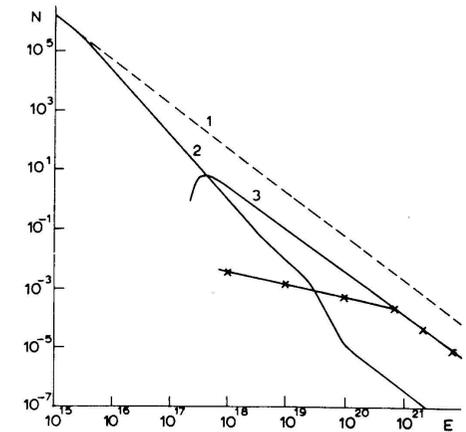


Fig. 1.

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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Strongly interacting neutrino scenarios

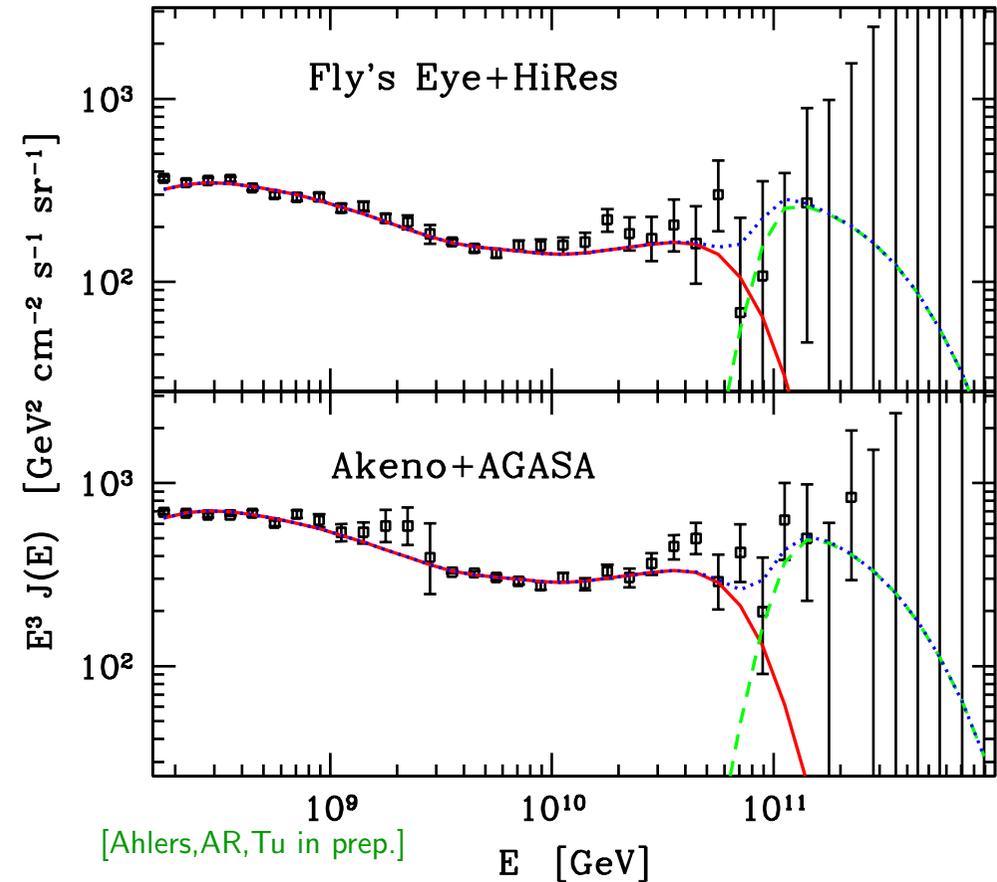
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[Berezinsky,Zatsepin '69]

- Quantitative analysis:

[Fodor,Katz,AR,Tu '03; Ahlers,AR,Tu in prep.]

- Very good fit to CR data



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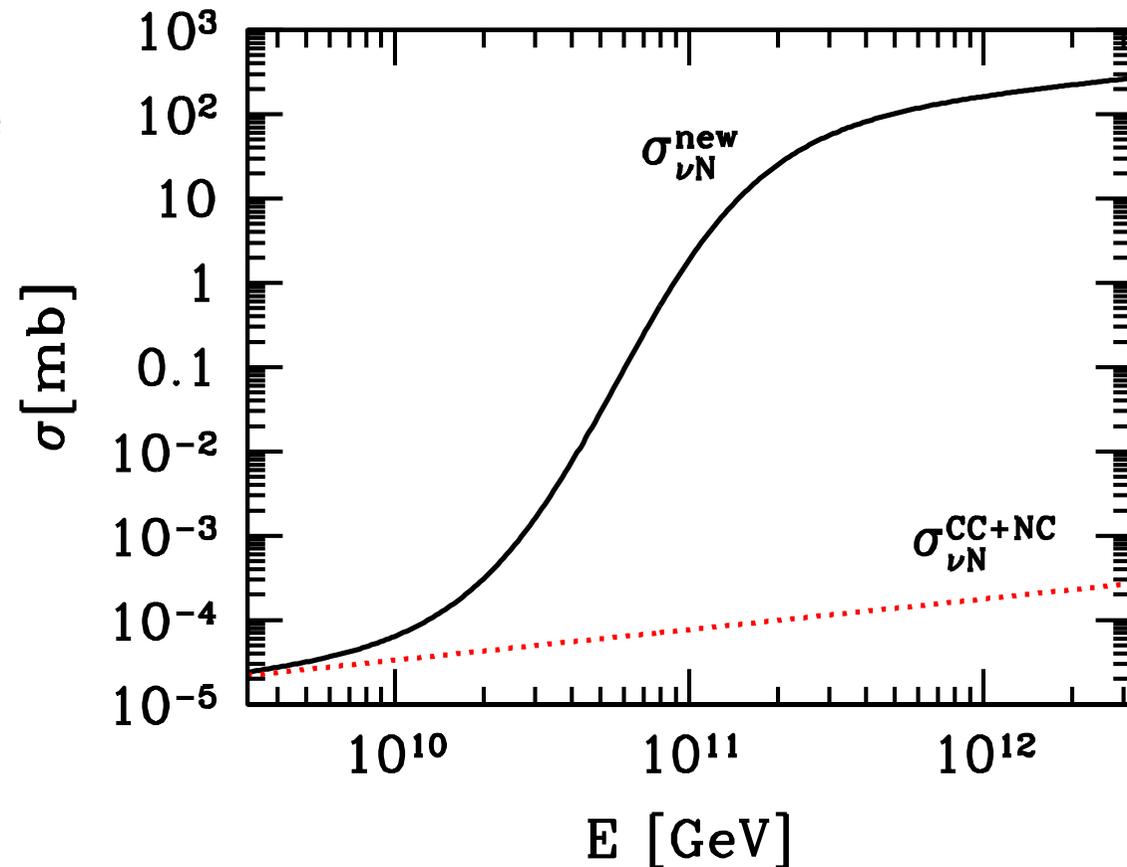
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- Very good fit to CR data
- Need steeply rising cross section, otherwise clash with nonobservation of deeply-penetrating particles

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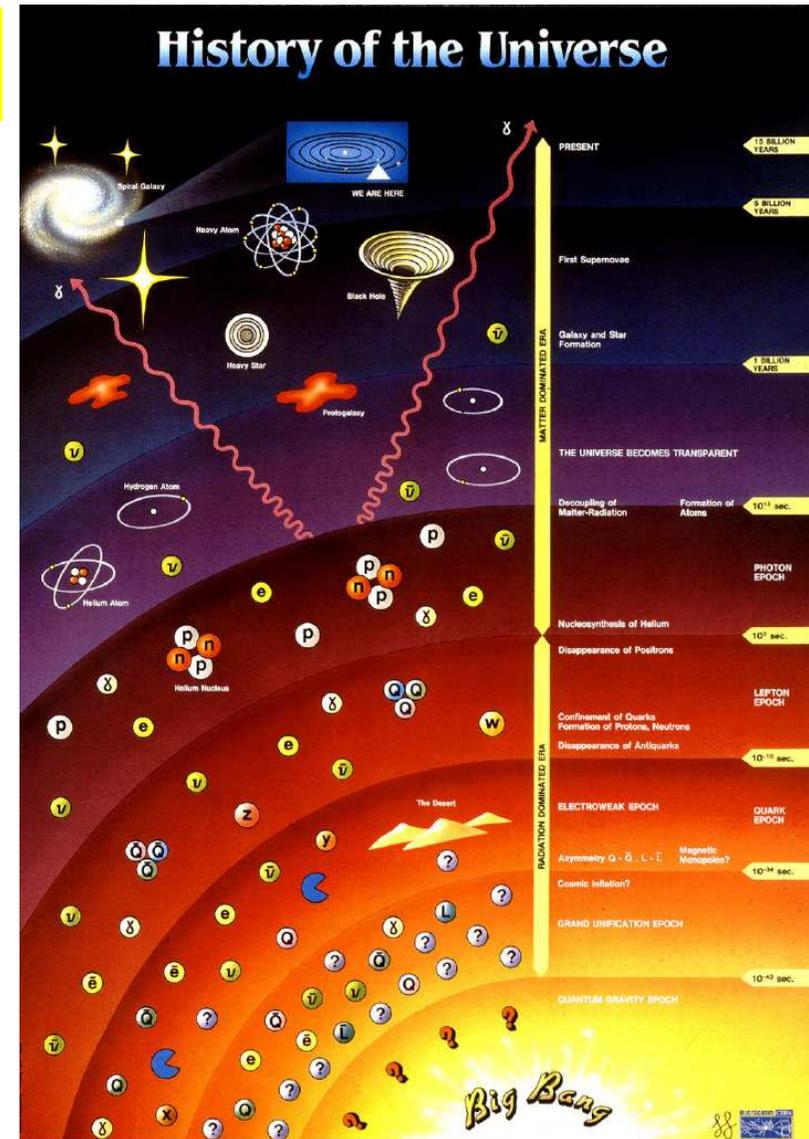


[Ahlers,AR,Tu in prep.]

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4. EHEC ν absorption on the C ν B

- How to detect the C ν B?



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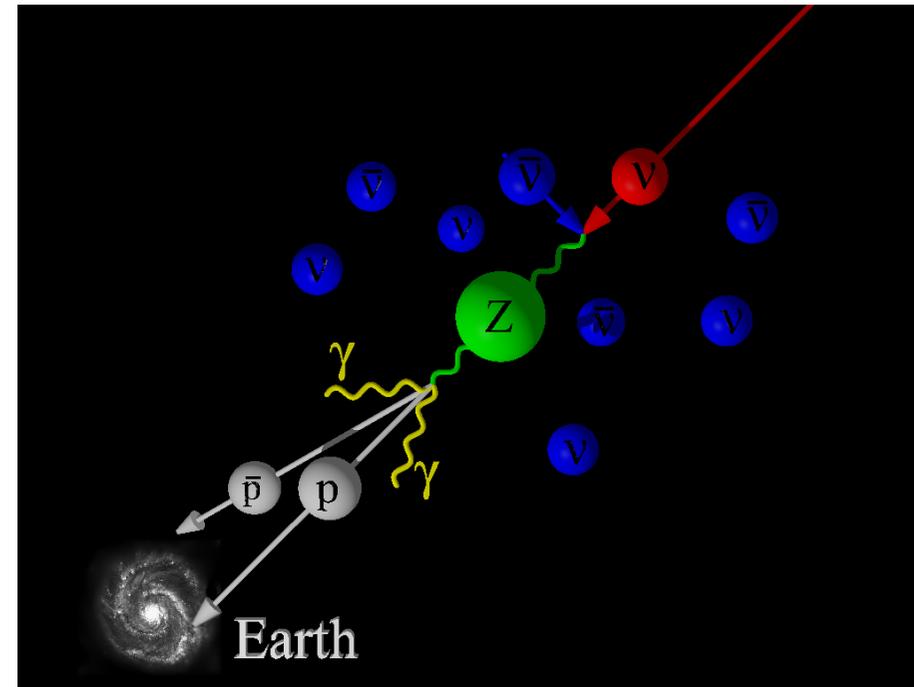
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$$E_{\nu}^{\text{res}} = \frac{m_Z^2}{2m_{\nu}} \simeq 4 \times 10^{21} \text{ eV} \left(\frac{\text{eV}}{m_{\nu}} \right)$$

with relic $\bar{\nu}$ into **Z-bosons** [Weiler '82]



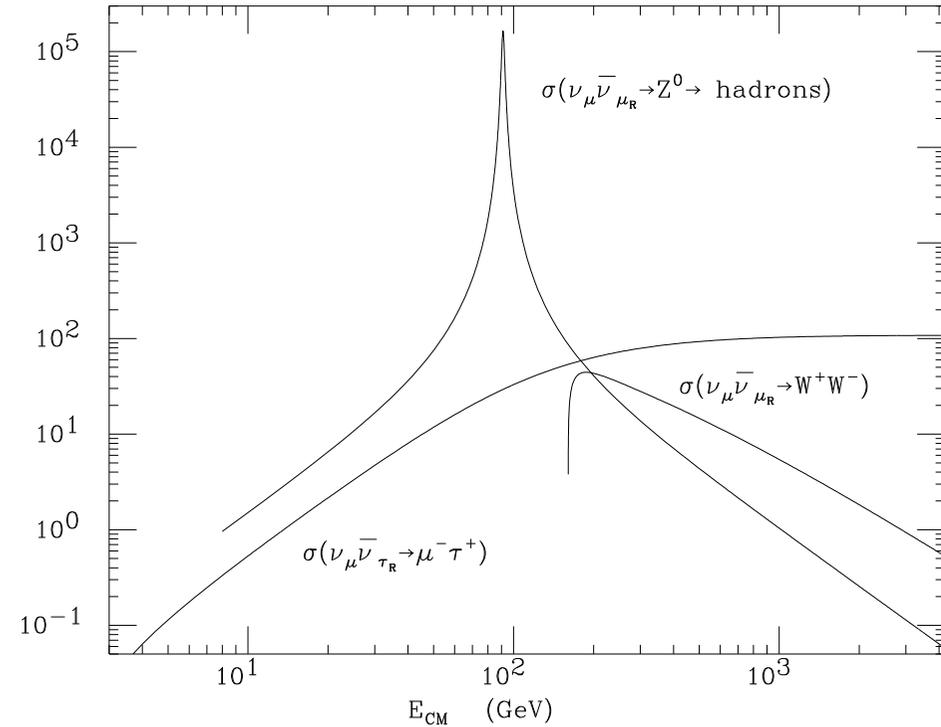
[Fodor, Katz, AR '02]

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[Fargion, Mele, Salis '99]

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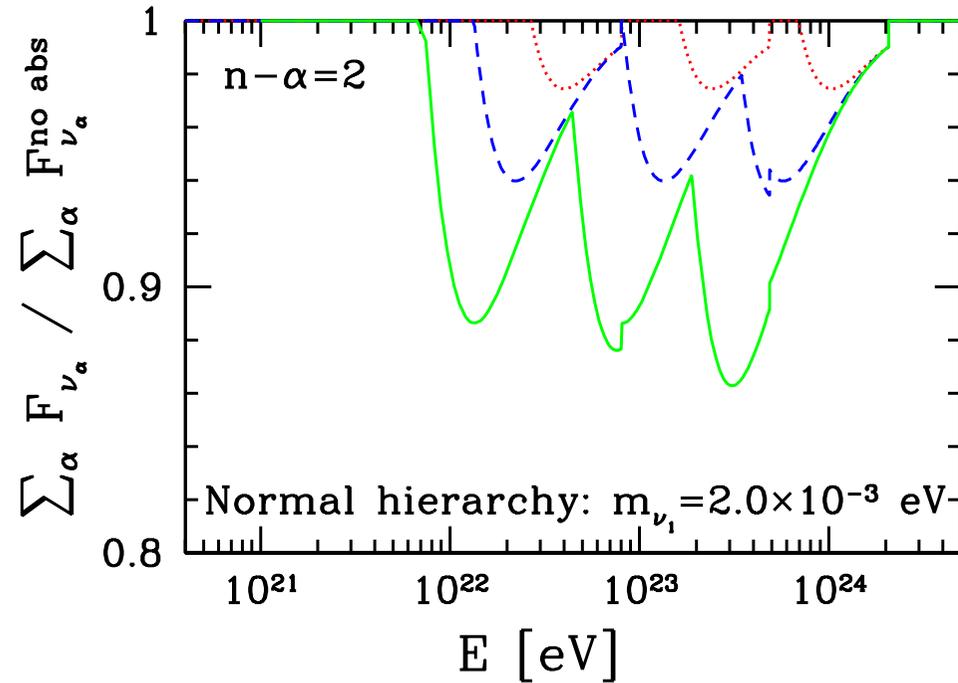
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- ◇ Absorption dips in **EHEC ν** spectrum

[Weiler'82;...;Eberle,AR,Song,Weiler'04;Barenboim,Requejo,Quigg'04]



[Eberle,AR,Song,Weiler '04]

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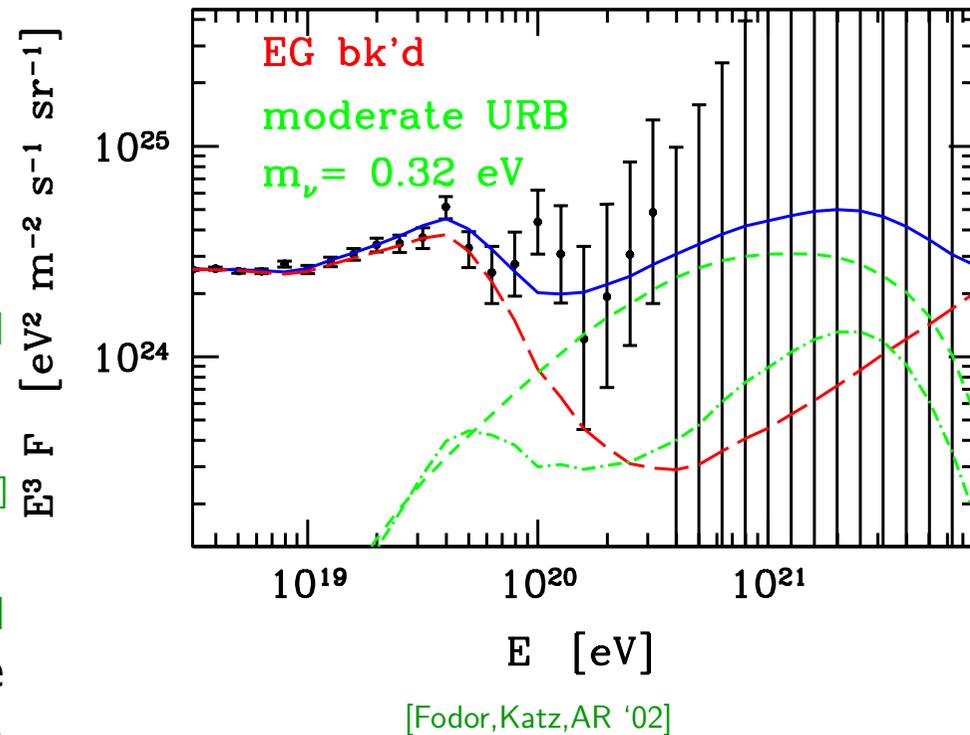
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[Weiler'82;...;Eberle,AR,Song,Weiler'04;Barenboim,Requejo,Quigg'04]
- ◇ Emission features (**Z-bursts**):

[Fargion *et al.* '99; Weiler '99;...; Fodor,Katz,AR '01,'02]

protons and photons with energies above the predicted **Greisen–Zatsepin–Kuzmin (GZK)** cutoff at $E_{\text{GZK}} \simeq 4 \times 10^{19} \text{ eV}$

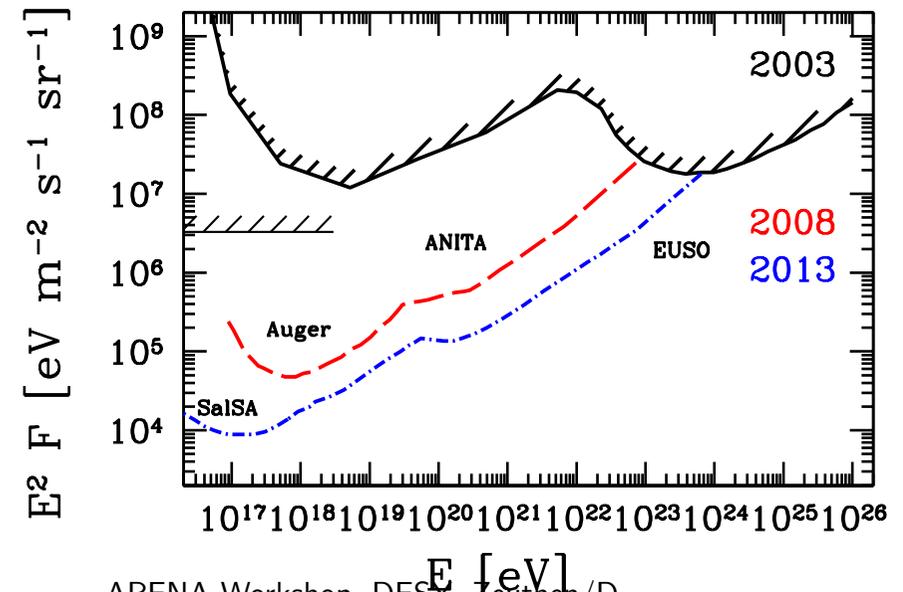
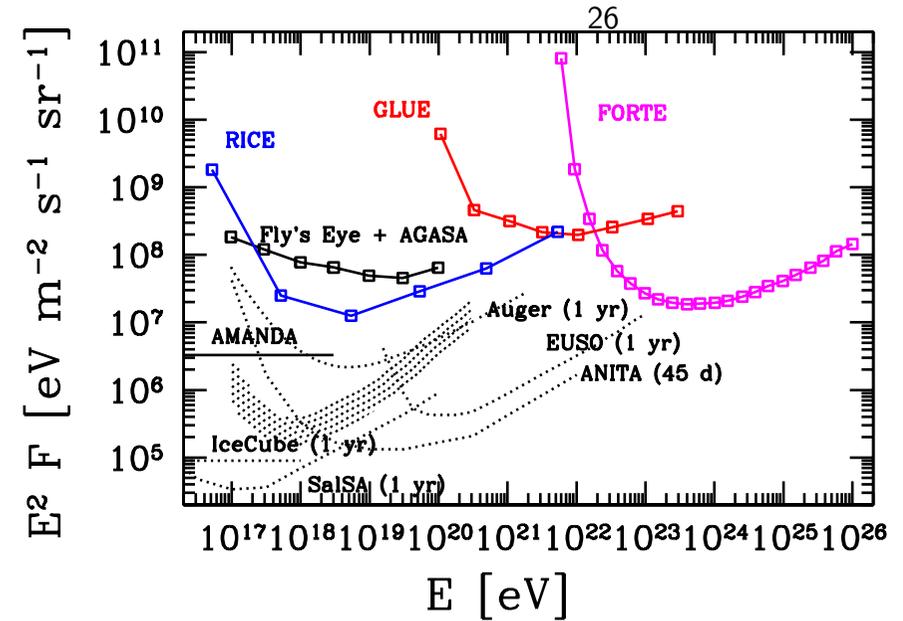
[Greisen '66; Zatsepin,Kuzmin '66]



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Absorption spectroscopy: [Eberle,AR,Song,Weiler '04]

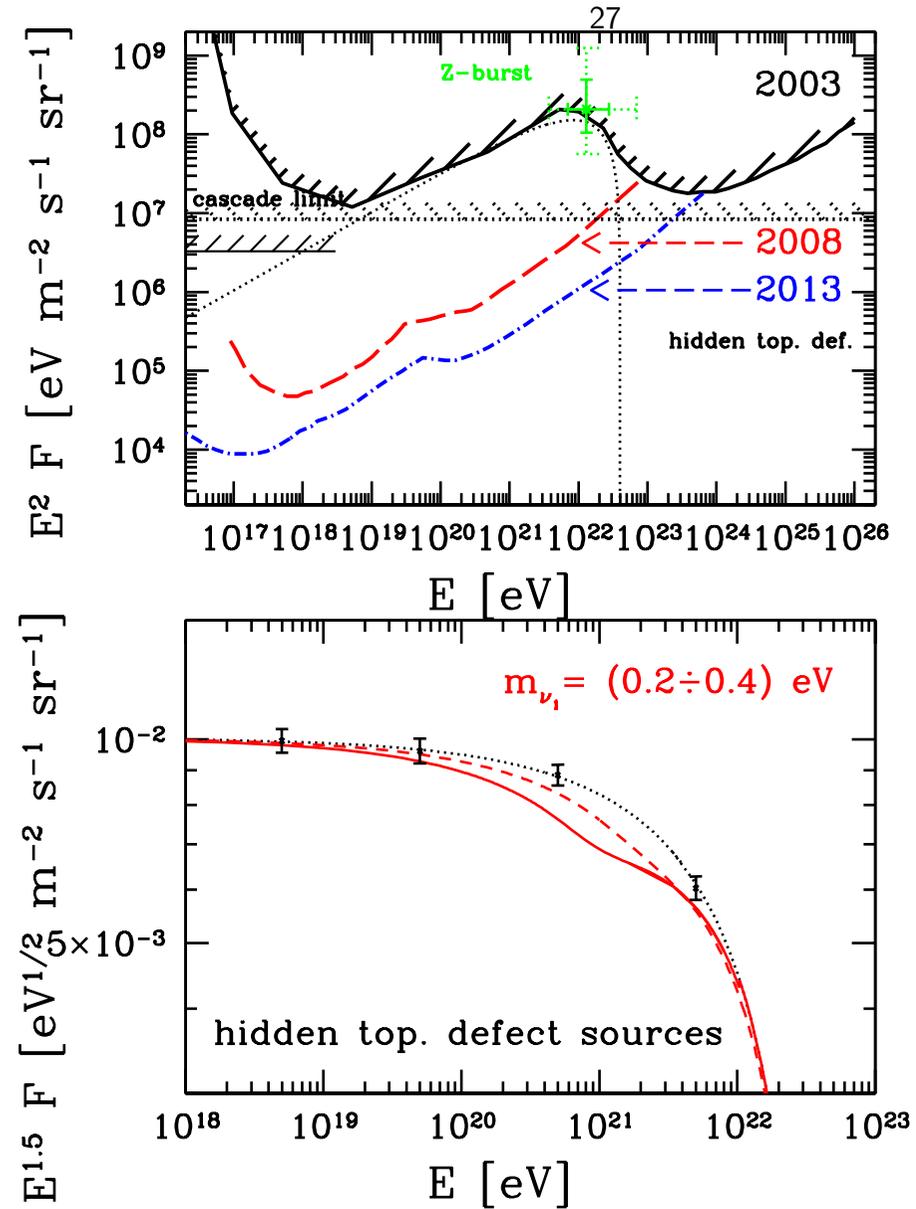
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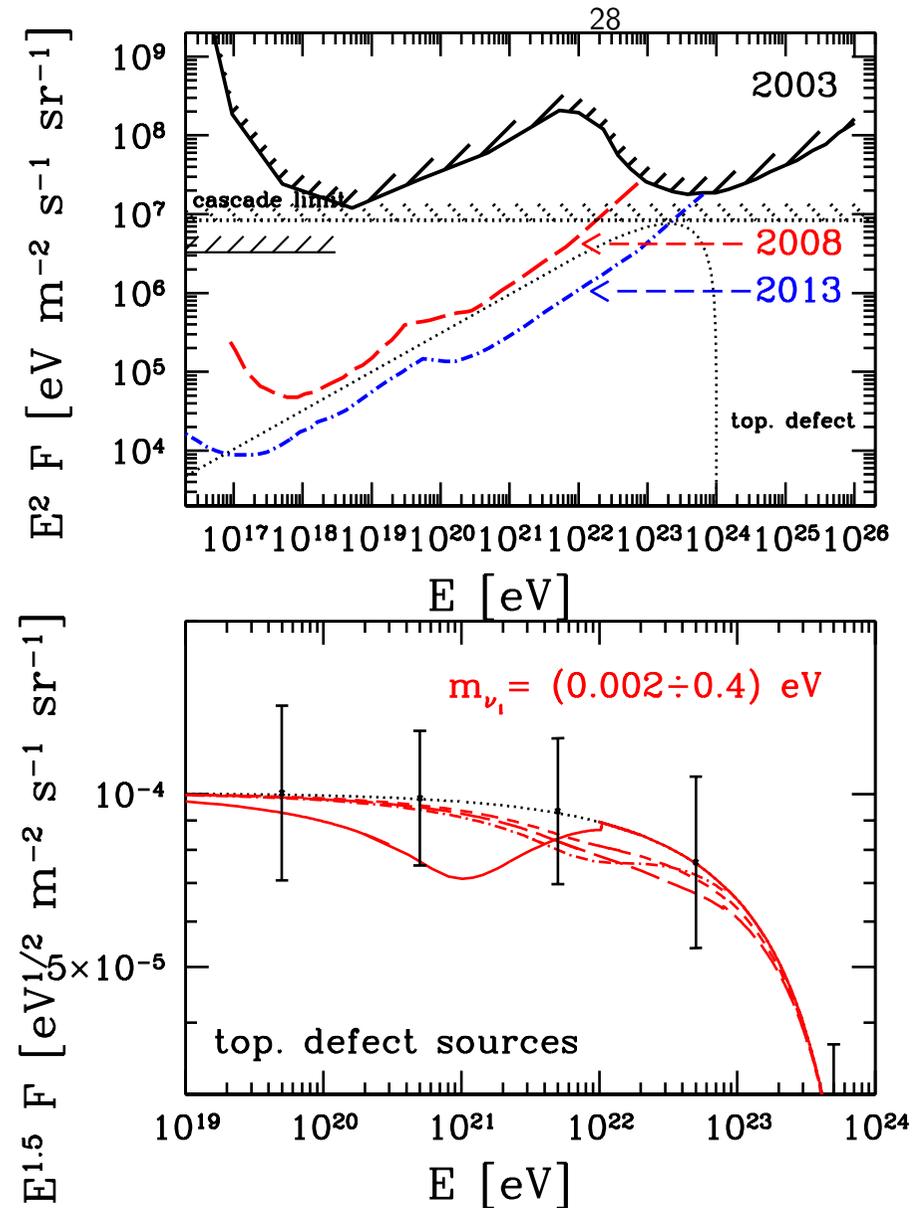
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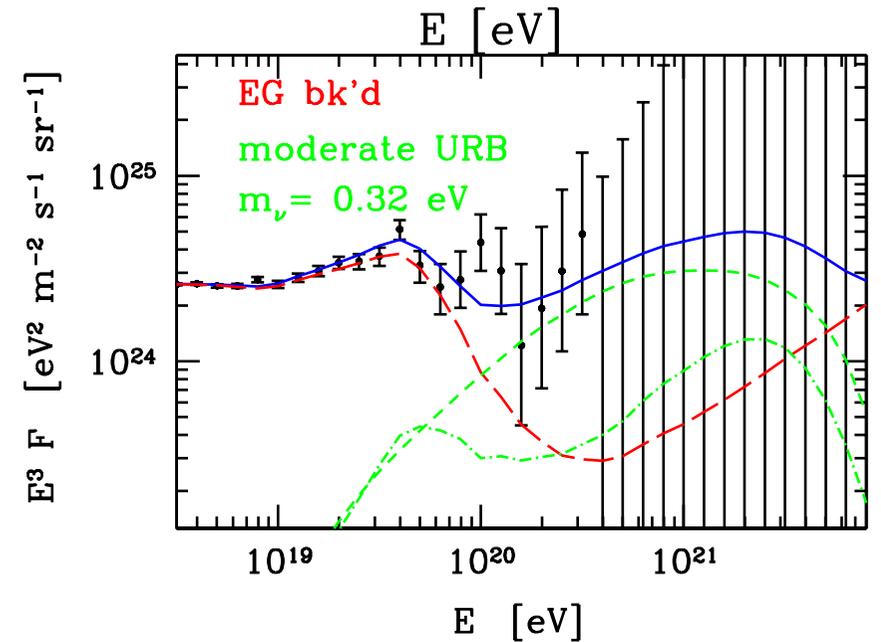
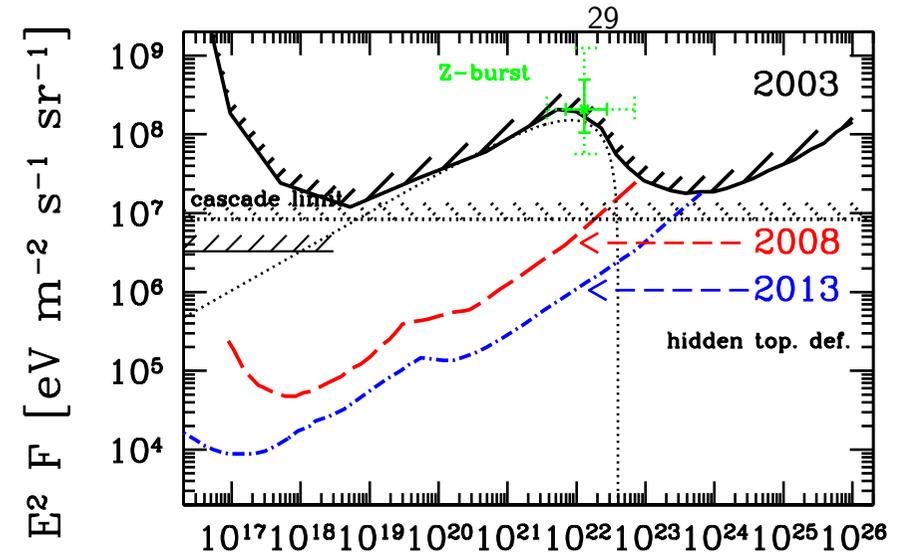
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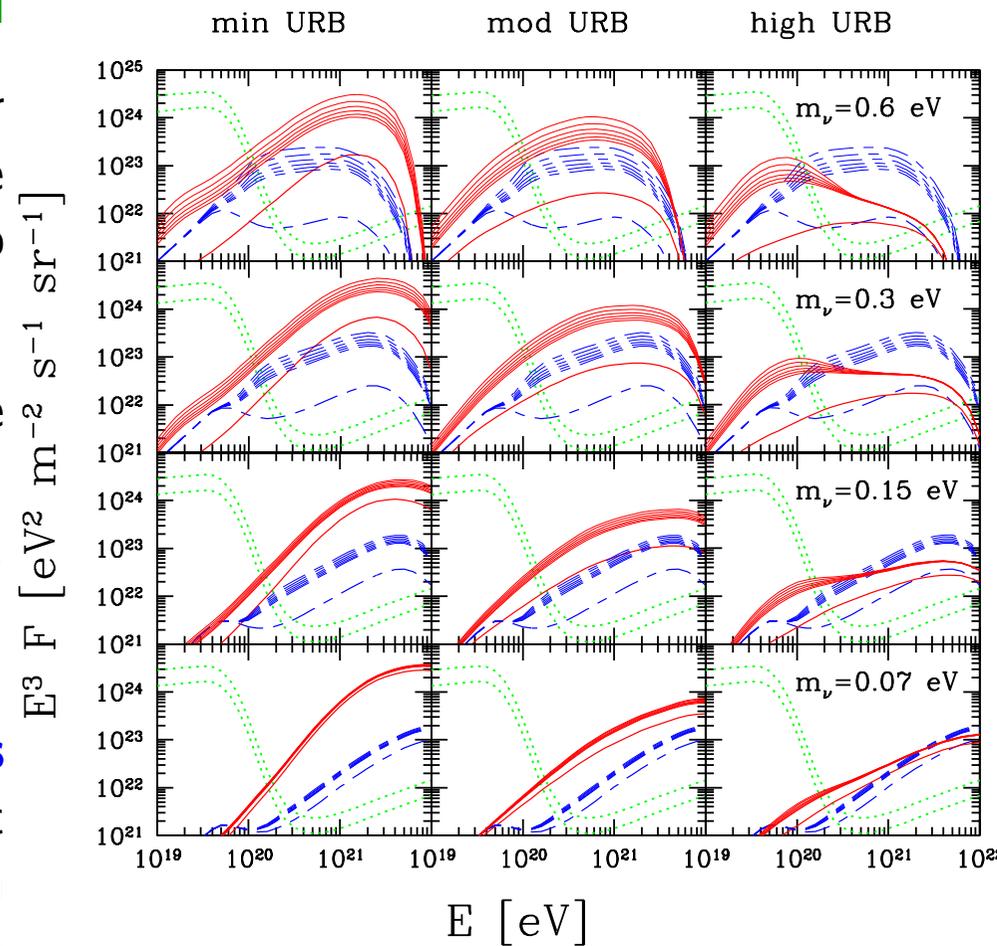
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- In this case, the associated **Z-bursts** likely to be seen as post-GZK events at the planned cosmic ray detectors



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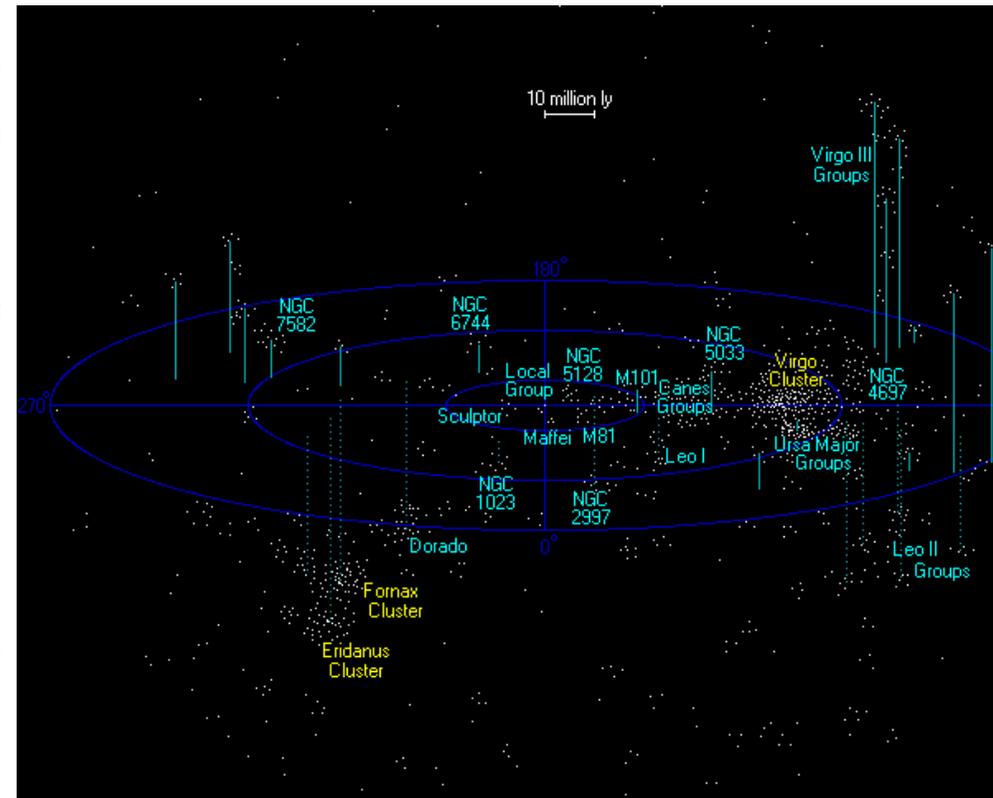
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- In this case, the associated **Z-bursts** likely to be seen as post-GZK events at the planned cosmic ray detectors, with significant rate enhancement from direction of nearby Virgo cluster



[AR,Weiler,Wong '05]

Absorption spectroscopy: [Eberle,AR,Song,Weiler '04]

- Presently planned **EHEC ν** detectors appear to be sensitive enough to lead us, within the **next decade**, into an **era of relic neutrino absorption spectroscopy**, provided
 - **EHEC ν** flux at resonant energies close to current observational bounds
 - neutrino mass sufficiently large, $m_\nu \gtrsim 0.1$ eV
- In this case, the associated **Z-bursts** likely to be seen as post-GZK events at the planned cosmic ray detectors , with significant rate enhancement from direction of nearby Virgo cluster



5. Conclusions

- Astrophysics, particle physics and cosmology prospects of EHEC ν 's:
 - **Astrophysics:**
 - * Neutrinos from extragalactic sources of UHECR should be detected soon
 - **Beyond the Standard Model:**
 - * Already now useful constraints on post-LHC enhancements in $\sigma_{\nu N}$
 - * Discovery within next decade needs large deviation from SM
 - **C ν B absorption spectroscopy:**
 - * Detection of dips within next decade needs EHEC ν flux \gtrsim cascade limit and $m_{\nu_1} \gtrsim 0.1$ eV
 - * If pre-2008 experiments do not see any EHEC ν flux in $10^{21 \div 23}$ eV region \Rightarrow absorption dips won't be observed within next 10 \div 20 y!

\Rightarrow **Next decade exciting!**