Neutrinos from the Cosmos

Opportunities for Astrophysics, Particle Physics, and Cosmology

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

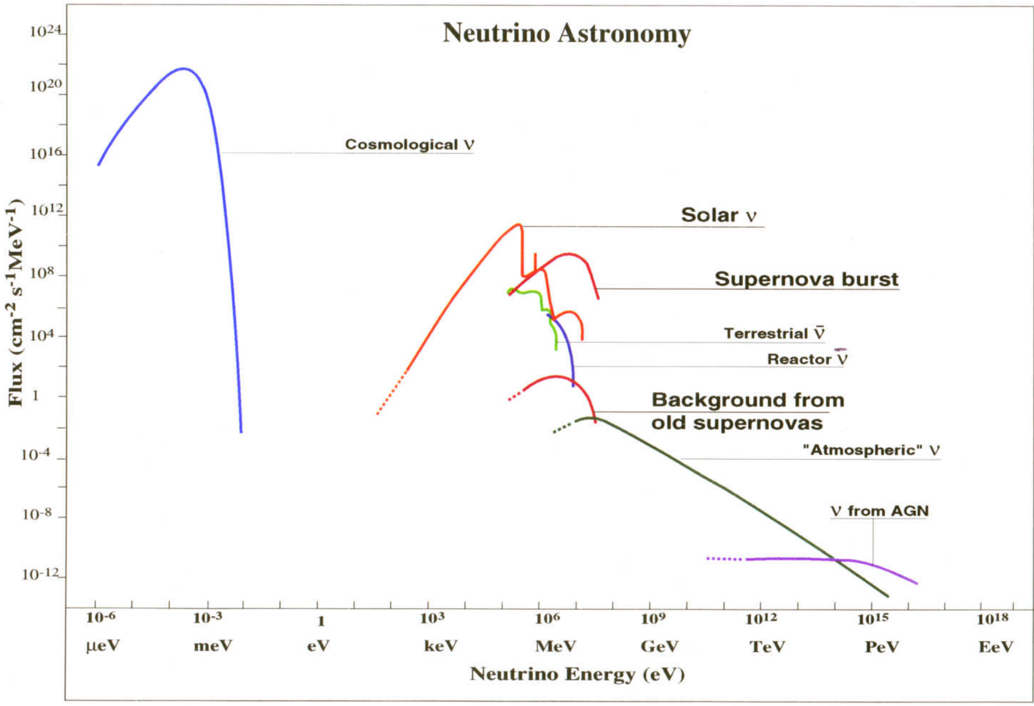
Plenary talk on "Astroparticle Physics – Theoretical Status"
Weak Interactions and Neutrinos 2005 (WIN'05)
Delphi, Greece, June 6-11, 2005

0. Introduction

- Most important progress in **WIN** physics — i.e. neutrinos massive and mix — from naturally borne neutrinos:
  - solar
  - atmospheric

- Neutrinos from the cosmos,
  - big bang relic ν's (**CνB**),
  - supernova ν's,
  - ν's from active galactic nuclei (**AGN**)
  - ν's from topological defects or unstab super-massive particles,

  offer further opportunities for **astrophysics**, **particle physics**, and **cosmology**

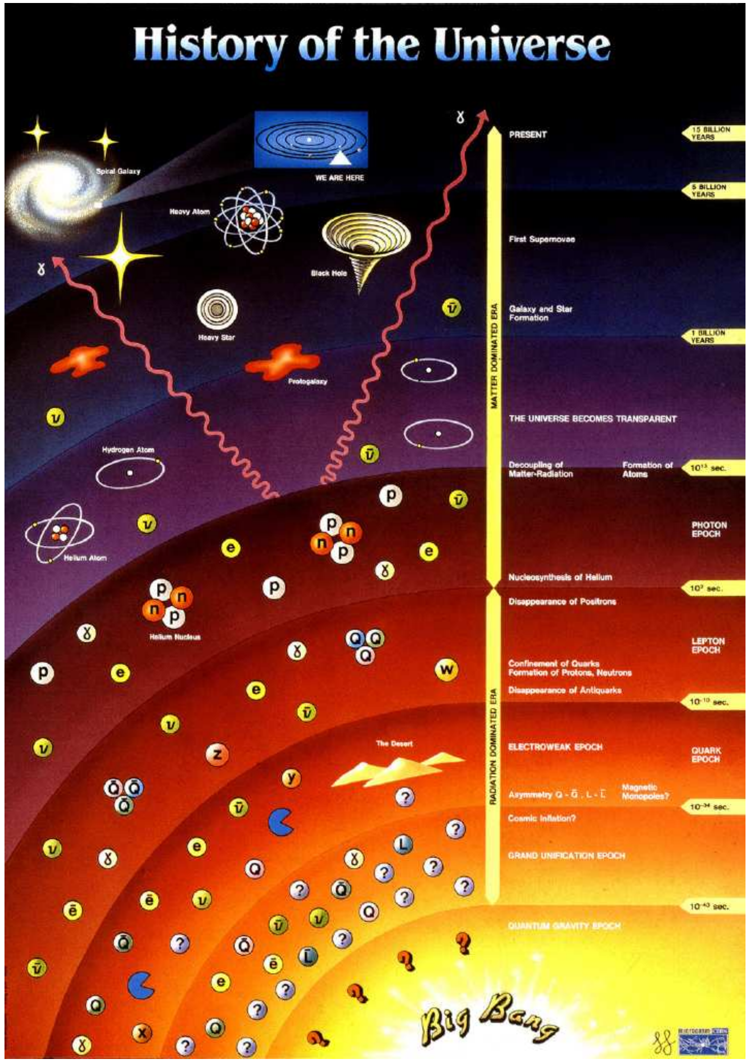


- **Further content:**

  1. **CνB and structure in universe**
  2. **Cosmic ν's as a diagnostic of astrophysical processes**
  3. **Cosmic ν's and physics beyond the Standard Model**
  4. **Cosmic ν absorption on the CνB**
  5. **Baryogenesis via leptogenesis**
  6. **Conclusions**

1. CνB and structure in universe

- **Big Bang cosmology:**
  - $\Rightarrow$ Cosmic microwave background (**CMB**)
  - $\Rightarrow$ **Cosmic neutrino background (CνB)**



[CERN]

1. CνB and structure in universe

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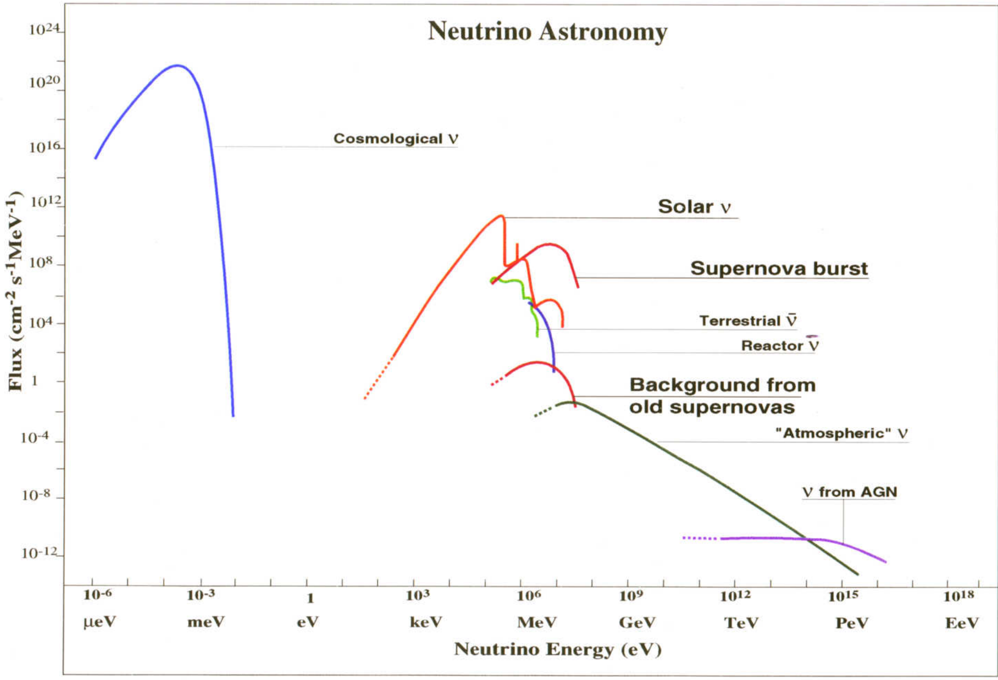
  - $\Rightarrow$ **Cosmic neutrino background (CνB)**
- Firm predictions:

$$\underbrace{\bar{n}_{\nu_i\,0} = \bar{n}_{\bar{\nu}_i\,0}}_{\mathrm{C}\nu\mathrm{B}} = \frac{3}{22}\,\underbrace{\bar{n}_{\gamma\,0}}_{\mathrm{CMB}} = 56\ \mathrm{cm}^{-3}$$

$\Rightarrow$ Big bang relic neutrinos $\approx$ as abundant as relic photons [ratio $2\times 3\times(3/22) = 9/11$]



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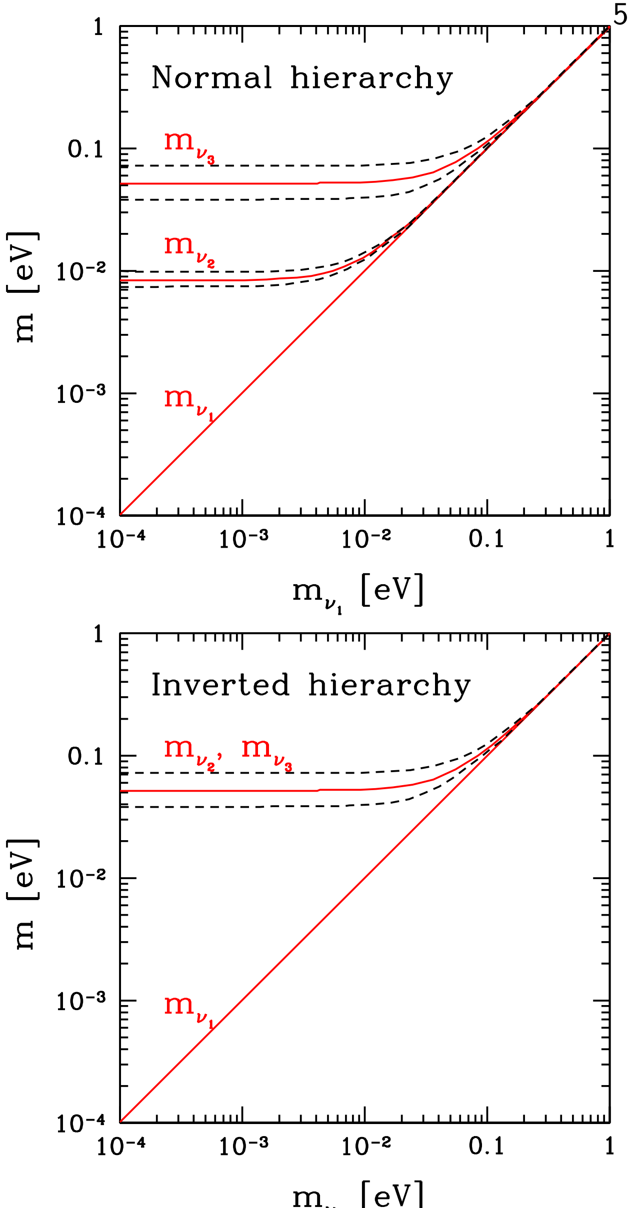
$$\underbrace{\bar{p}_{\nu_i\,0} = \bar{p}_{\bar{\nu}_i\,0}}_{\text{C}\nu\text{B}} = 3\left(\frac{4}{11}\right)^{1/3}\underbrace{T_{\gamma\,0}}_{\text{CMB}} = 5\times 10^{-4}\ \text{eV}$$

$\Rightarrow$ At least two neutrino mass eigenstates nonrelativistic ($m_{\nu_i} \gg 5\times 10^{-4}\,(1+z)$ eV)



- **CνB and large scale structure:**

  ◇ At very early time, neutrino free-streaming tends to suppress structure formation on small scales $\lambda \ll \lambda_{\rm fs}$,

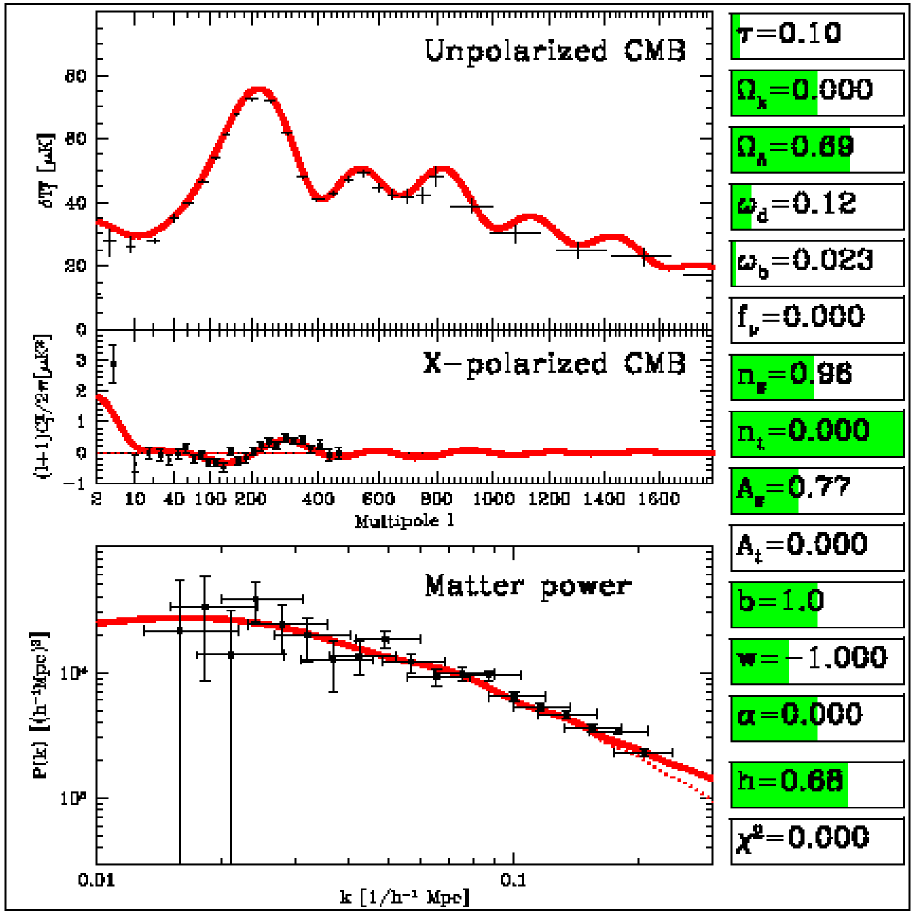
  $$\lambda_{\rm fs} \simeq 4.2\ h^{-1}\,{\rm Mpc}\ \left(\frac{(1+z)}{\Omega_m}\right)^{1/2}\left(\frac{\rm eV}{m_\nu}\right)$$

  ◇ At $\lambda \ll \lambda_{\rm fs}$, present **matter power spectrum** suppressed by $(k = 2\pi/\lambda)$

  $$\frac{\triangle P(k)}{P(k)} \simeq -8\,\frac{\Omega_\nu}{\Omega_m} \equiv -8\ f_\nu$$

  where Ω_ν fractional neutrino density

  $$\Omega_\nu\, h^2 = 1.08 \times 10^{-2}\ \sum_i (m_{\nu_i}/{\rm eV})$$



[http://space.mit.edu/home/tegmark/]

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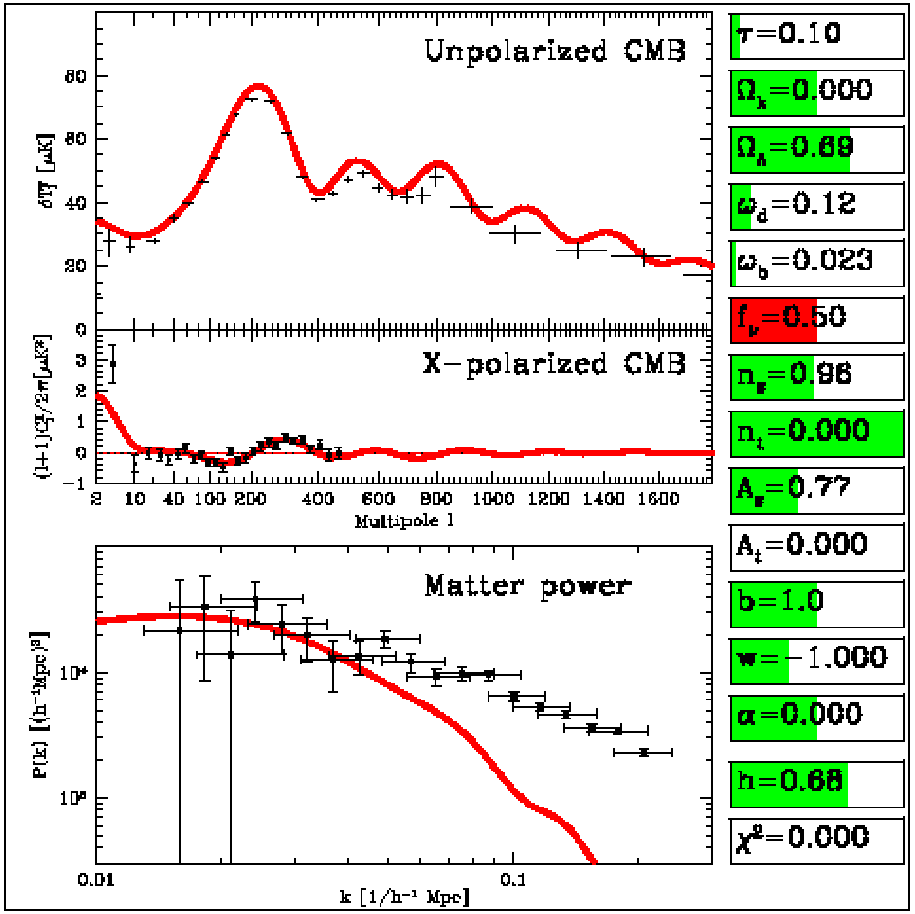

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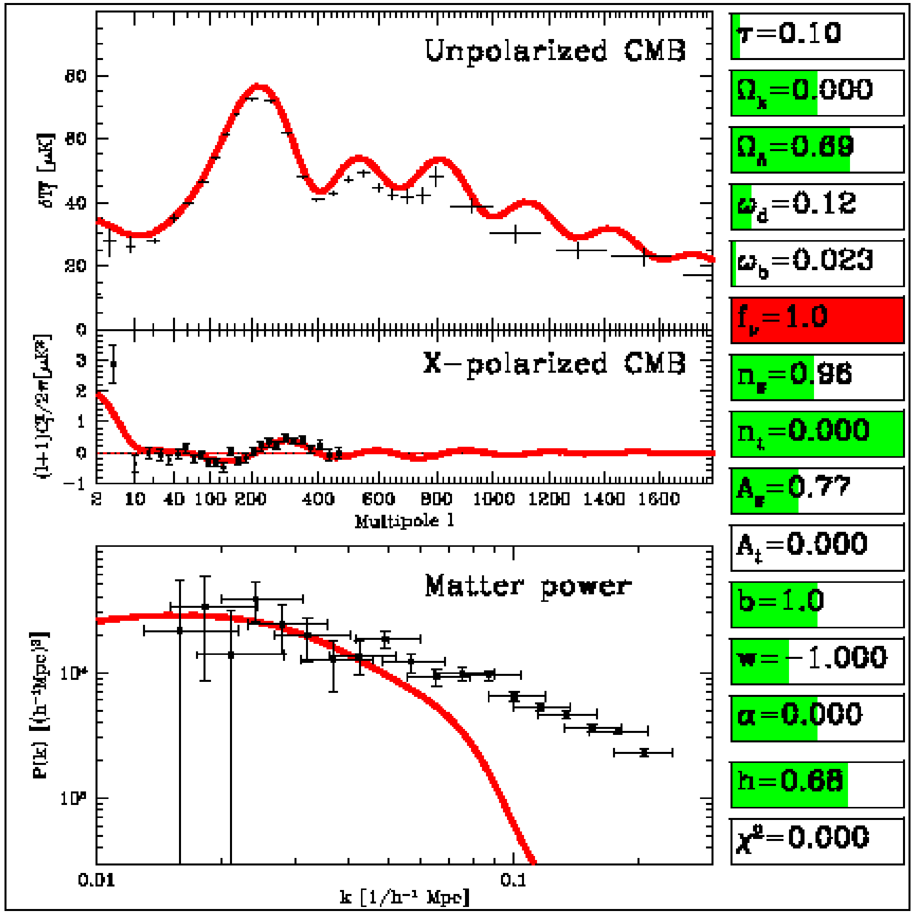

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$\Rightarrow$ Constraints from **LSS** and **CMB**

Ref.	$\sum m_\nu$ bound	Data used
[Spergel *et al.*]	0.69 eV	2dF,WMAP,CMB, σ_8,H_0
[Hannestad]	1.01 eV	2dF,WMAP,CMB, H_0
[Allen *et al.*]	$0.56^{+0.30}_{-0.26}$ eV	2dF,WMAP,CMB, σ_8,H_0
[Tegmark *et al.*]	1.8 eV	SDSS,WMAP
[Barger *et al.*]	0.75 eV	2dF,SDSS,WMAP, CMB,H_0
[Crotty *et al.*]	1.0 eV	2dF,SDSS,WMAP, CMB,H_0
[Seljak *et al.*]	0.42 eV	SDSS,WMAP, σ_8,CMB,H_0,Ly-α
[Fogli *et al.*]	0.50 eV	2dF,SDSS,WMAP, σ_8,CMB,H_0,Ly-α
[Hannestad]	1.48 eV	SDSS,WMAP, H_0,SN-Ia

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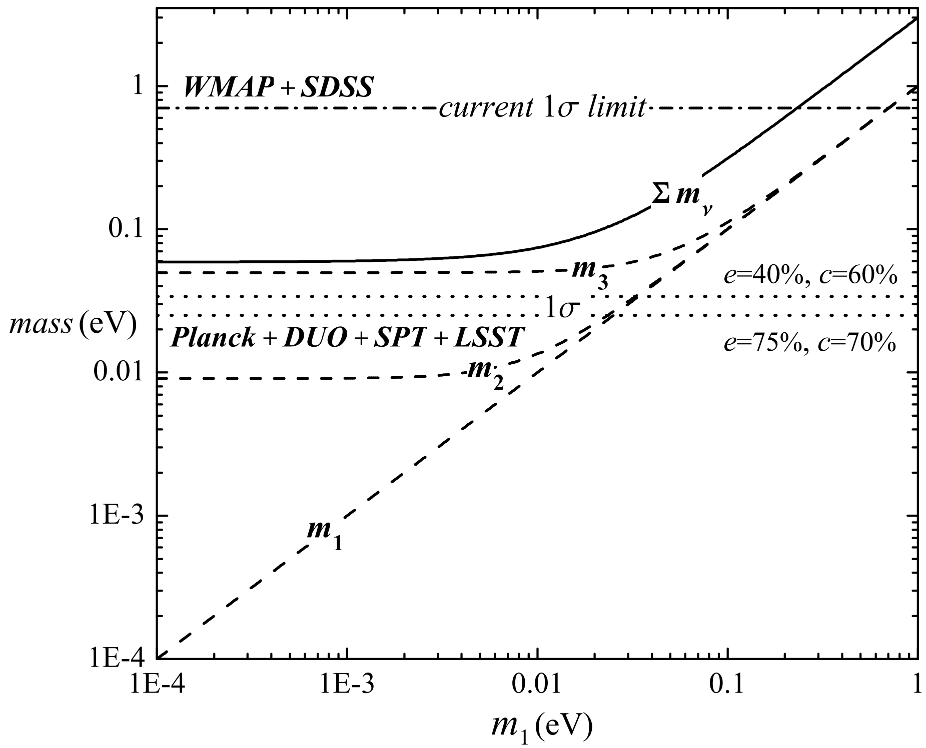
$\Rightarrow$ Future: $\sum m_\nu \gtrsim (0.03-0.2)$ eV



[Wang *et al.* '05]

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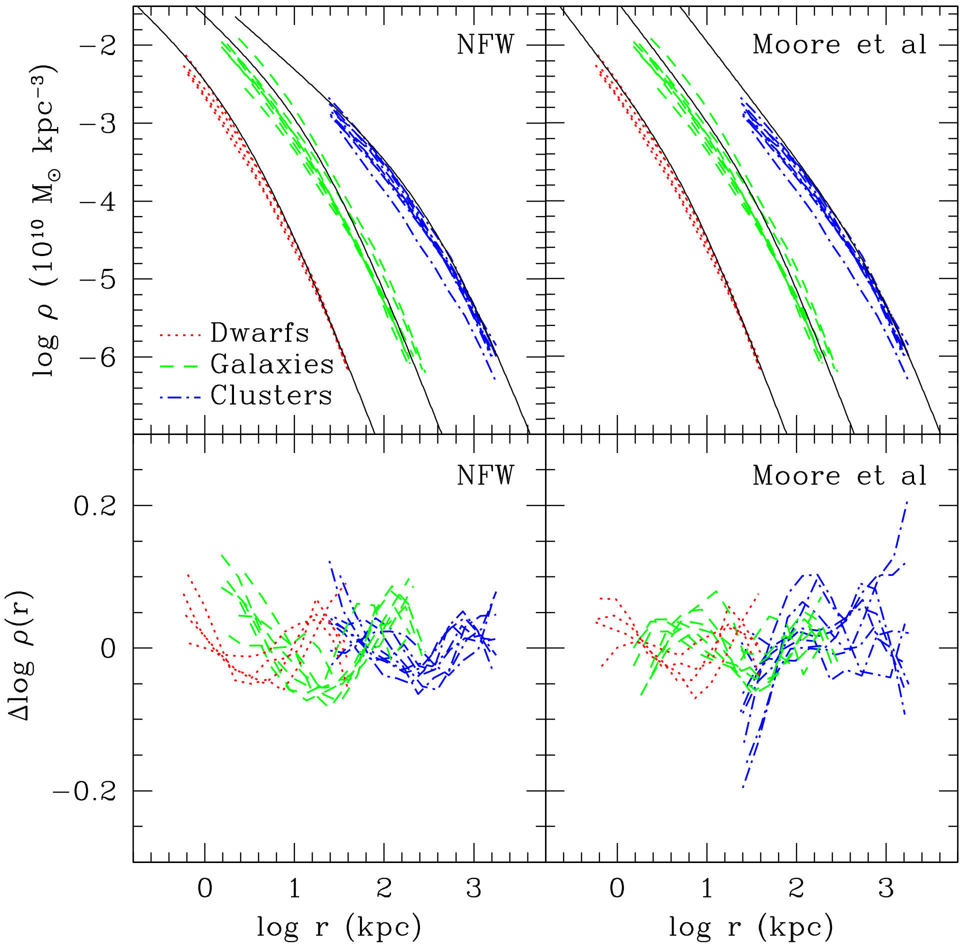

[Navarro *et al.* '04]

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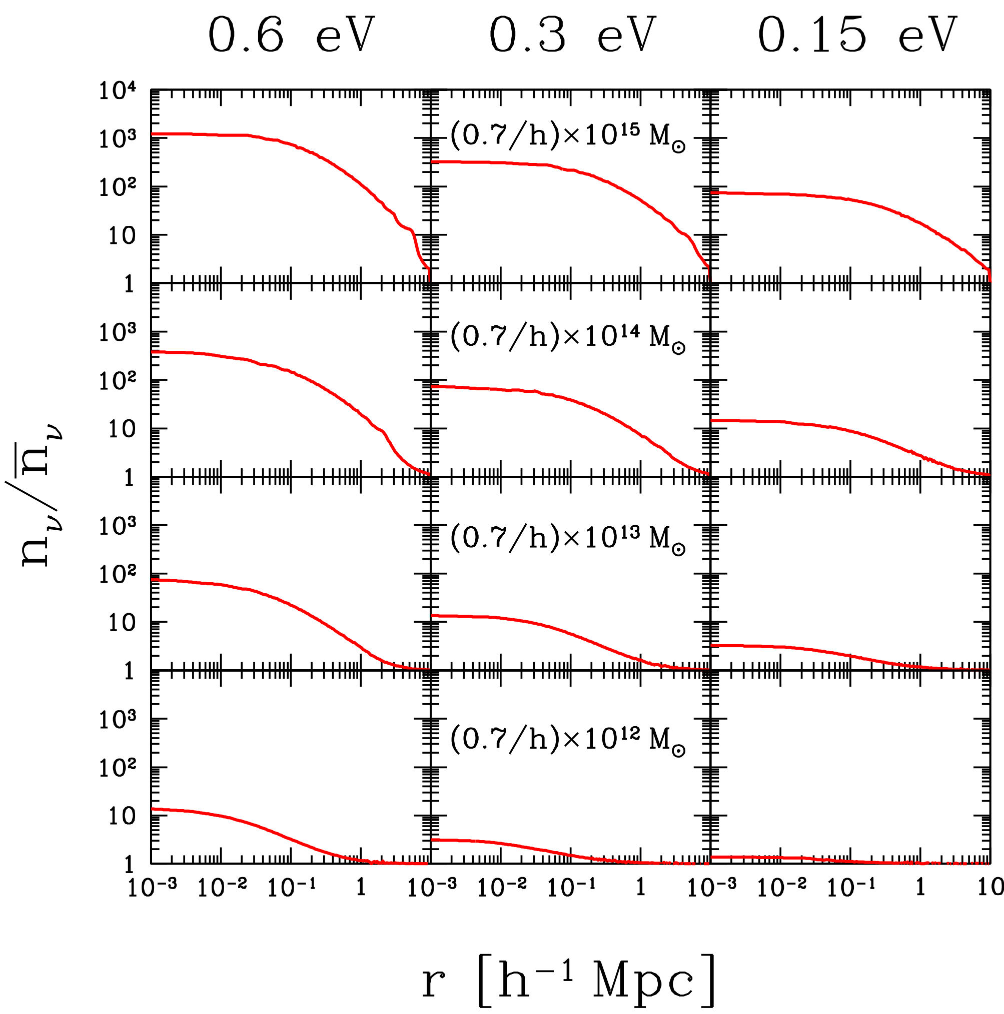

[AR,Wong '04]

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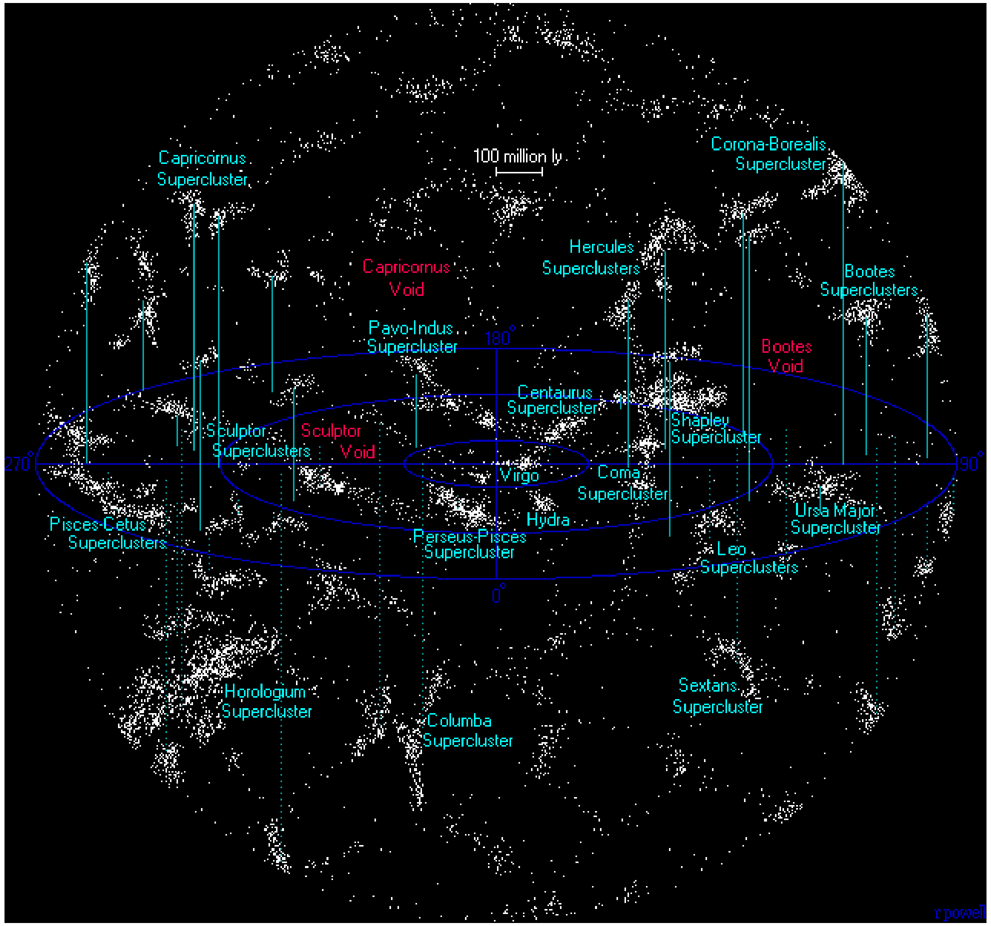

[www.extrasolar.org]

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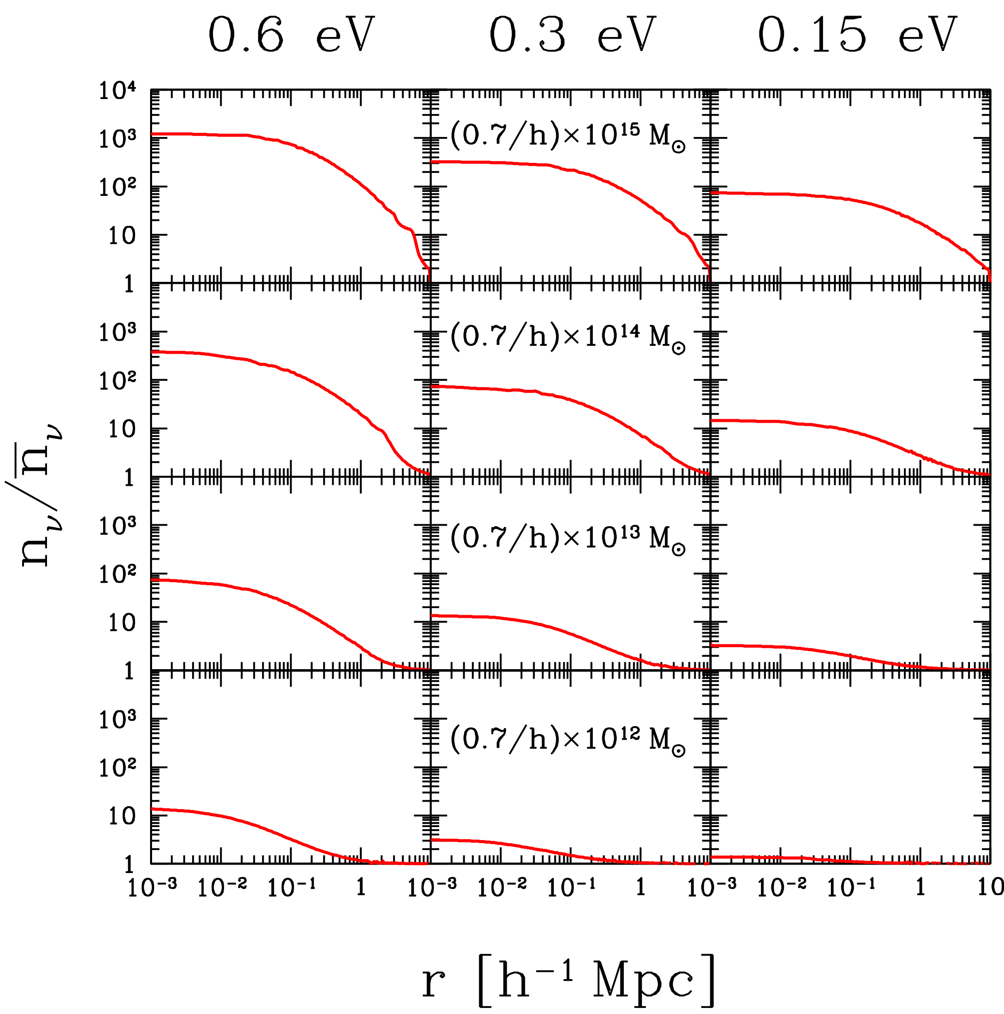

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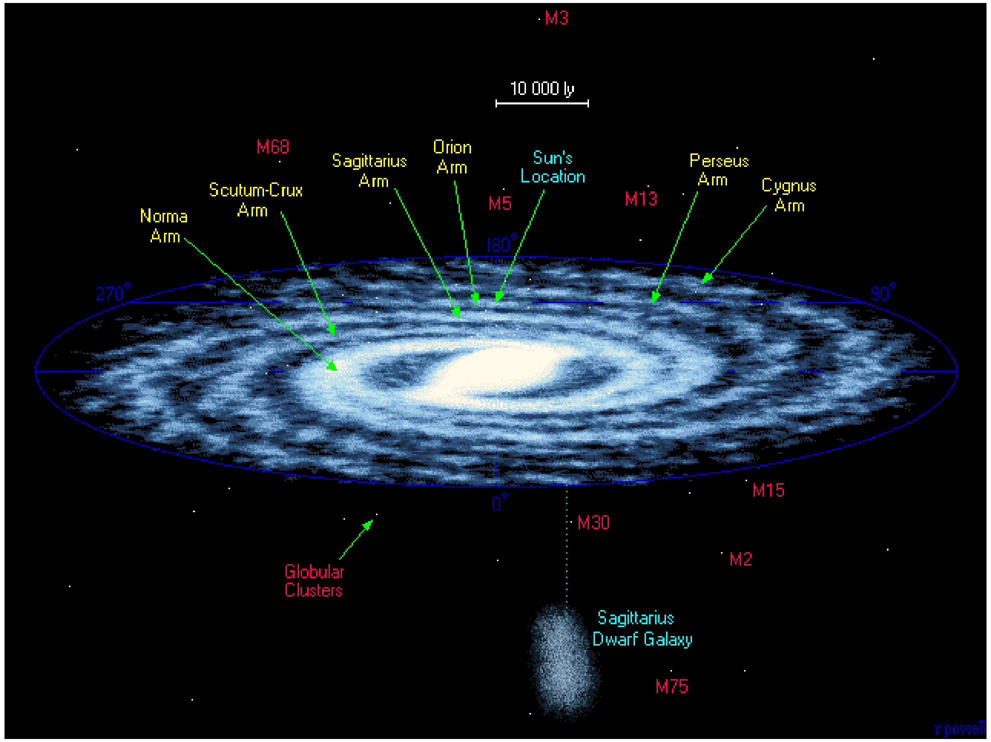

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⇒ Search for clustered relic ν's:

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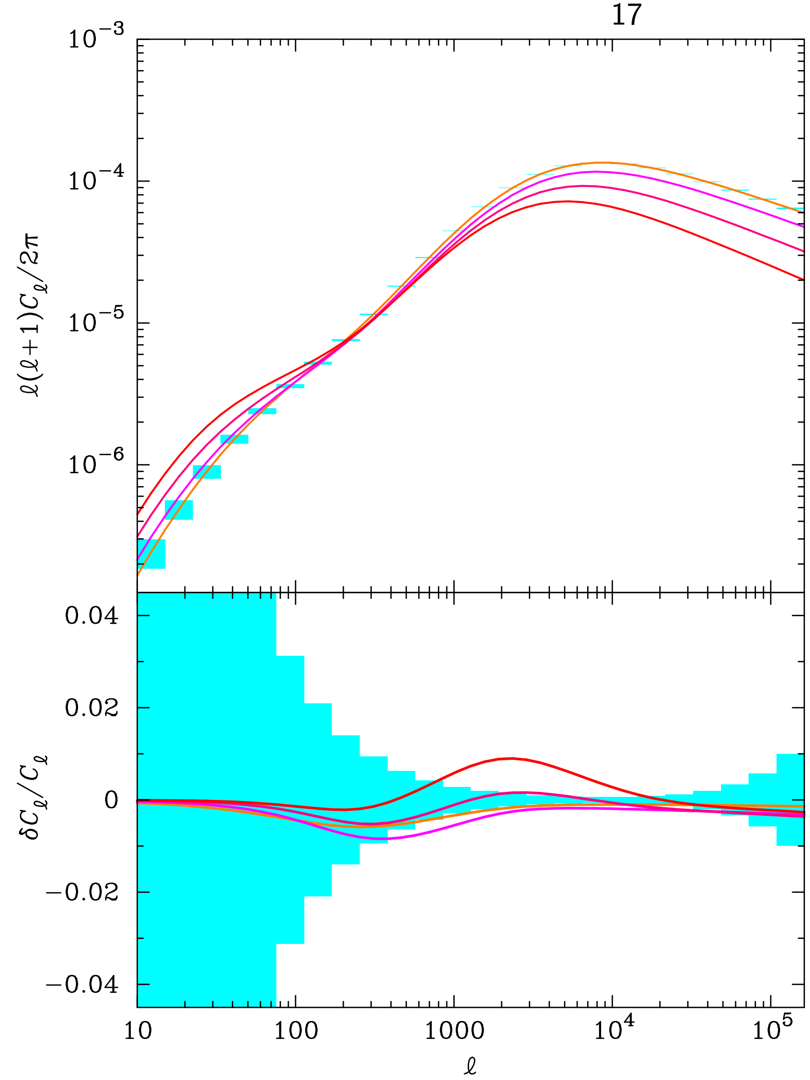

[Abazajian *et al.* '04]

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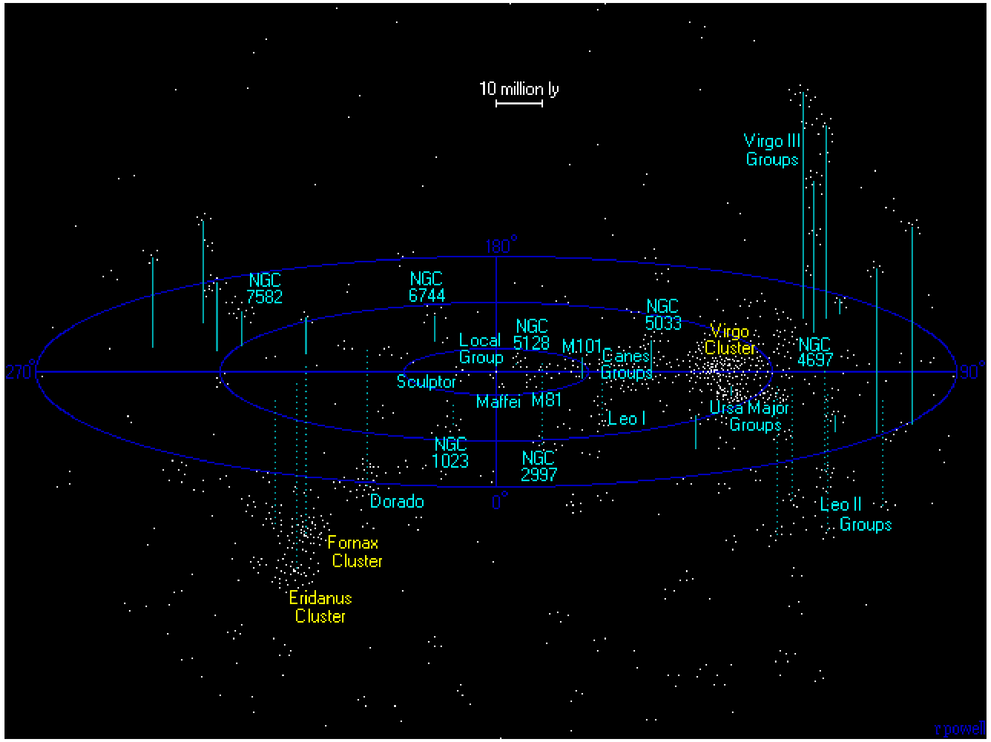
  ∗ Z-bursts from Virgo cluster ($\rightarrow$ later)



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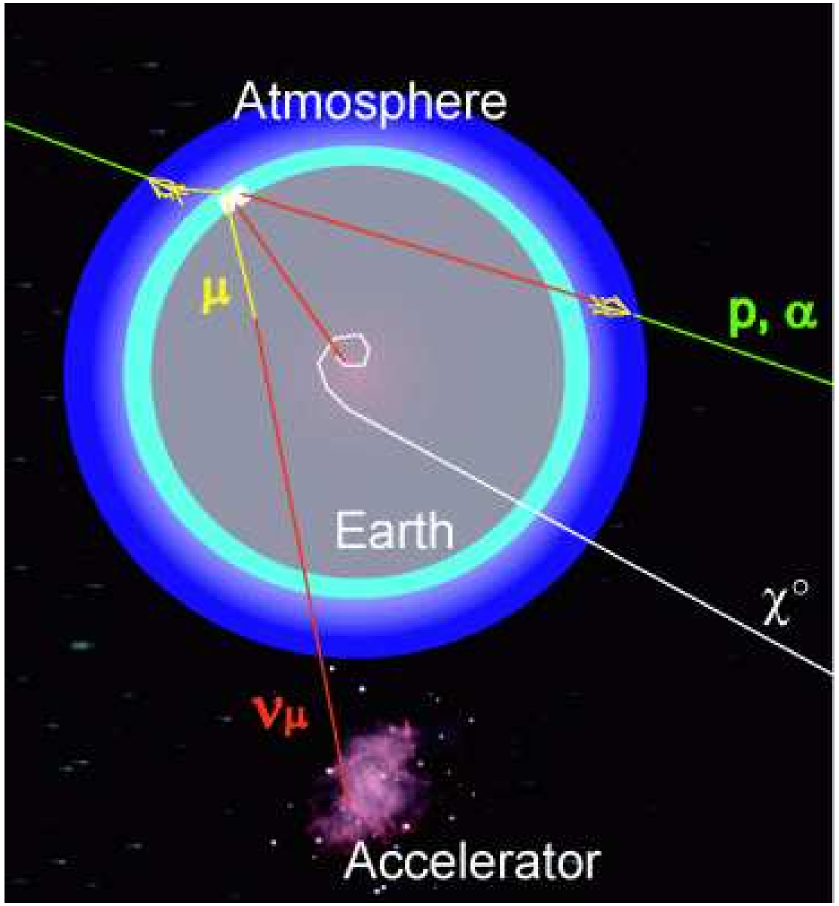
2. Cosmic ν's as a diagnostic of astrophysical processes

- Neutrinos ($E \lesssim 10^{21}$ eV) propagate essentially without interaction between source and Earth

$\Rightarrow$ Powerful probe of high energy astrophysics $\Rightarrow$ **Neutrino telescopes**!



[antares.in2p3.fr]

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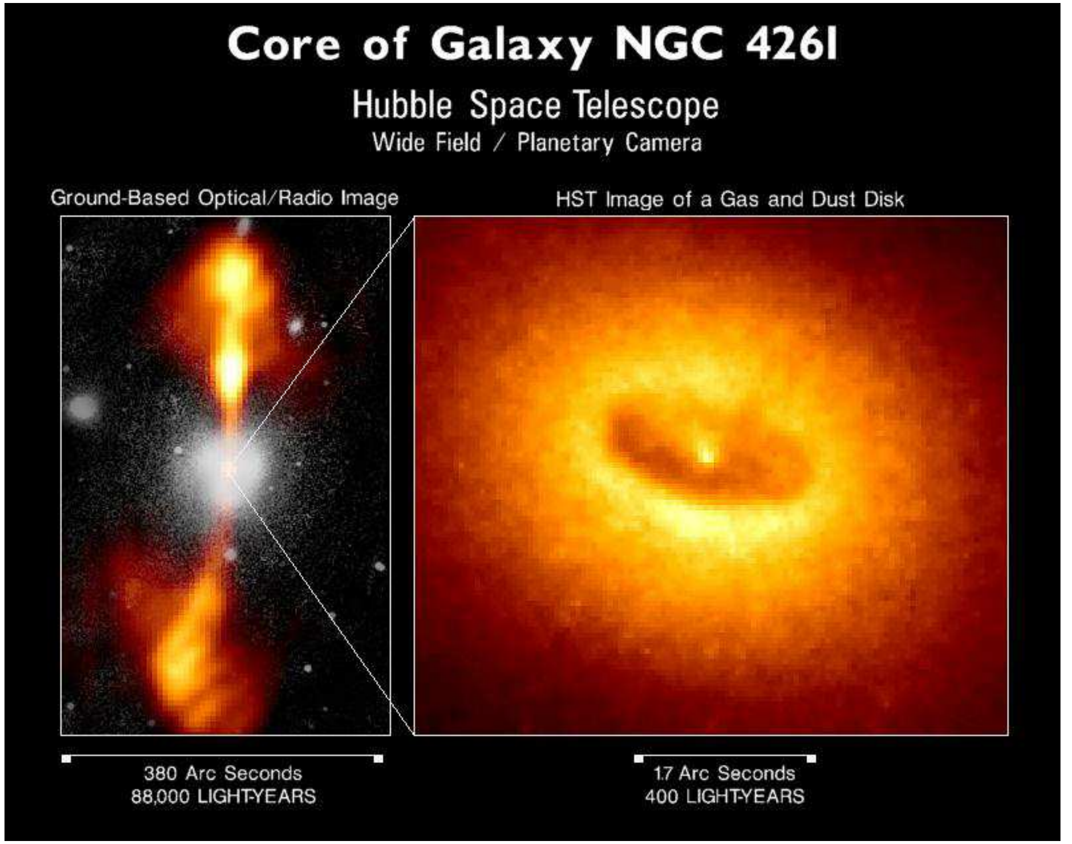

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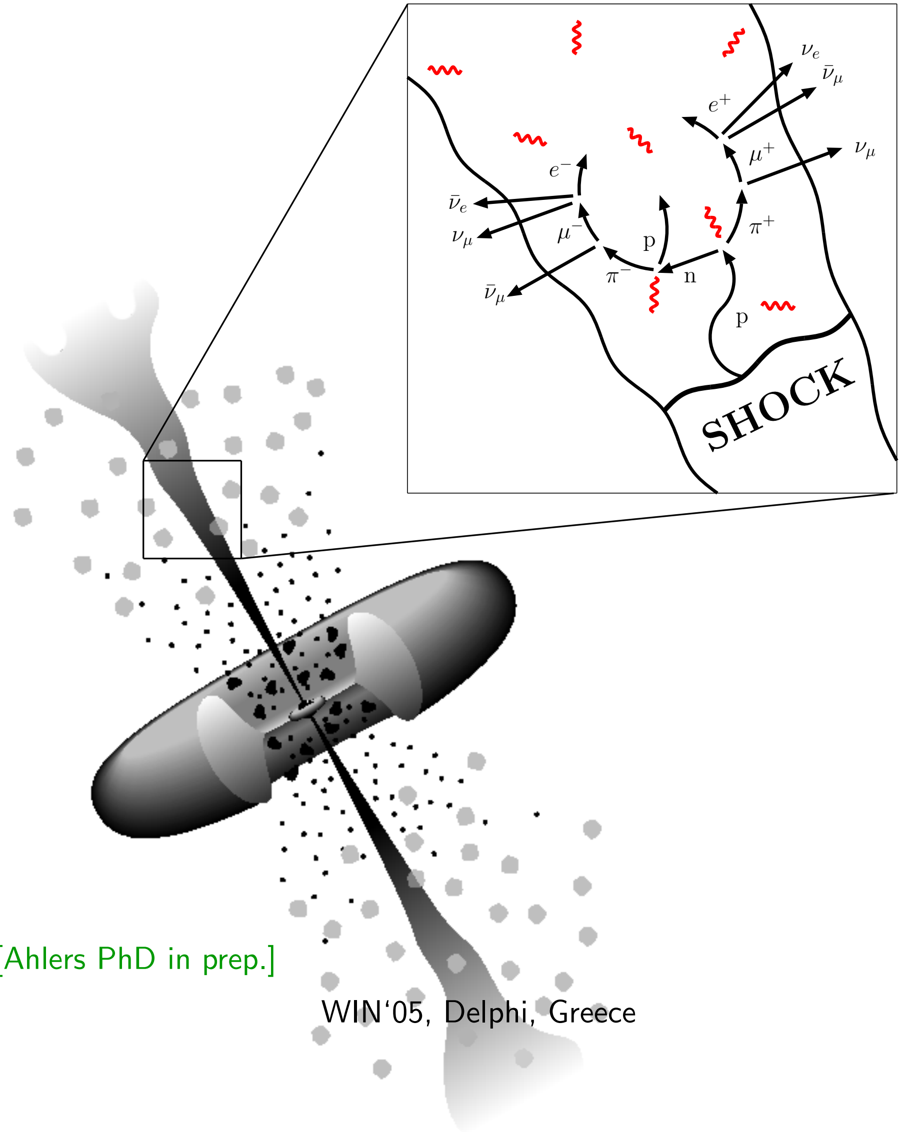
  - p's, confined by magnetic fields, accelerated through repeated scattering by plasma shock fronts
  - production of π's and n's through collisions of the trapped p's with ambient plasma produces γ's, ν's



[Ahlers PhD in prep.]

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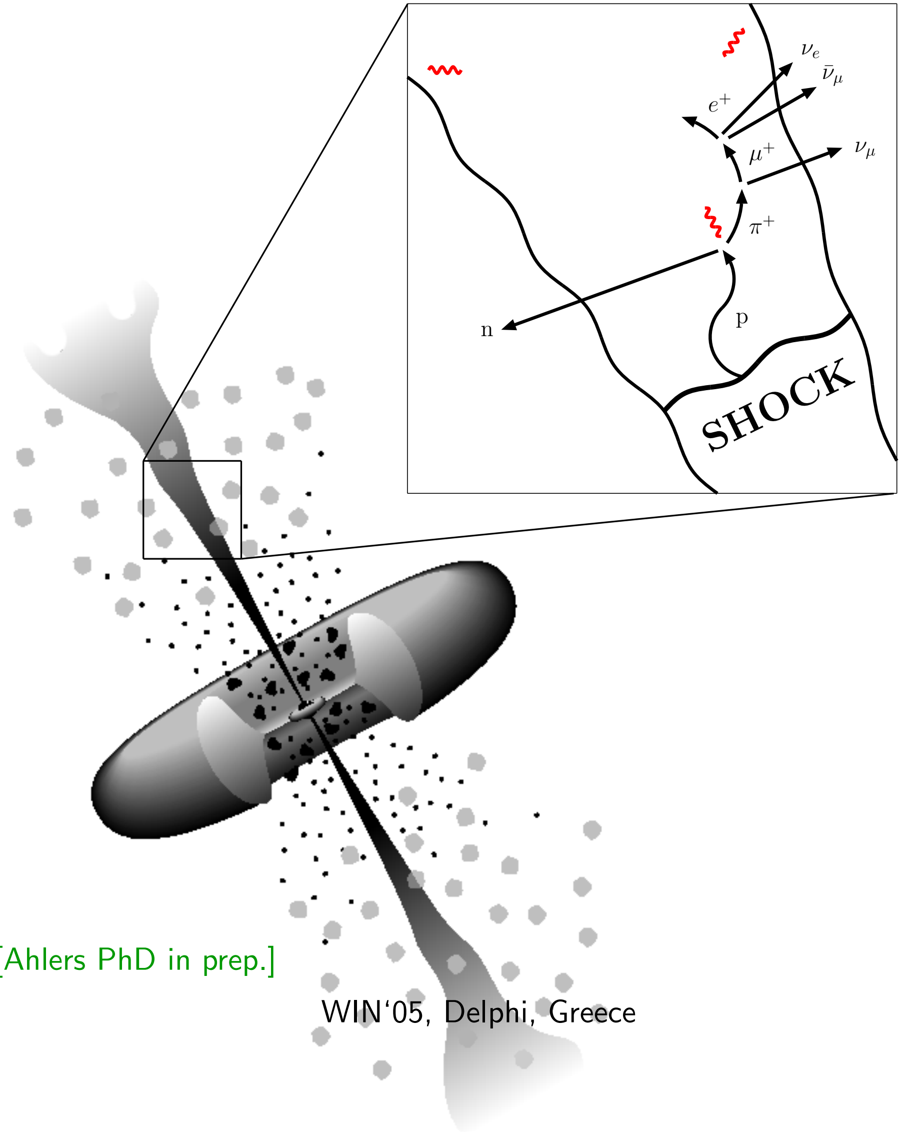

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- **Optically thin sources** (n leakage model): $\mathrm{CR}'\mathrm{s} \Leftrightarrow \nu'\mathrm{s}$ [Waxman,Bahcall '99]
- Quantitative analysis: [Ahlers *et al.* '05]
  - Assume that CR's in $10^{[8.6,11]}$ GeV range originate from isotropically 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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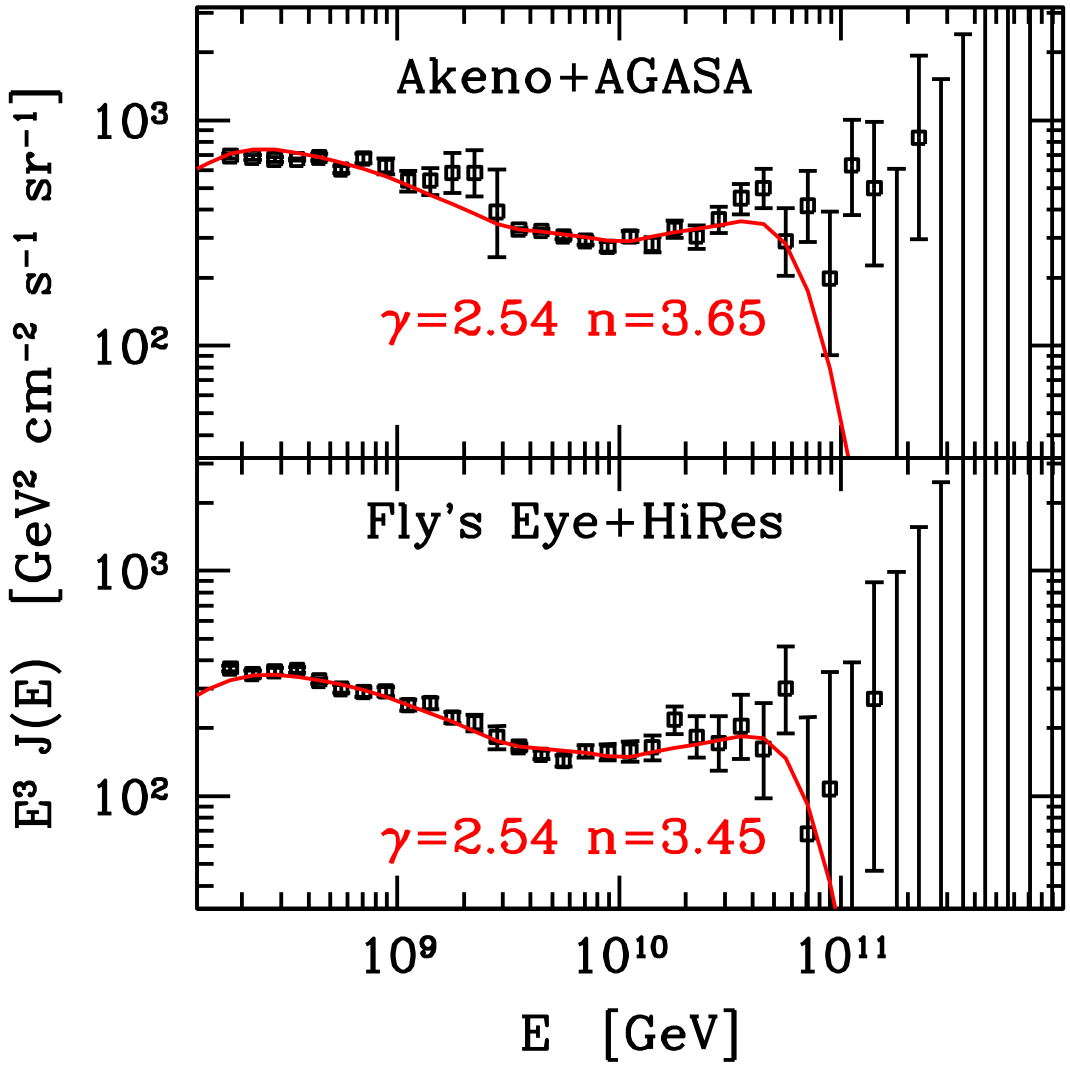

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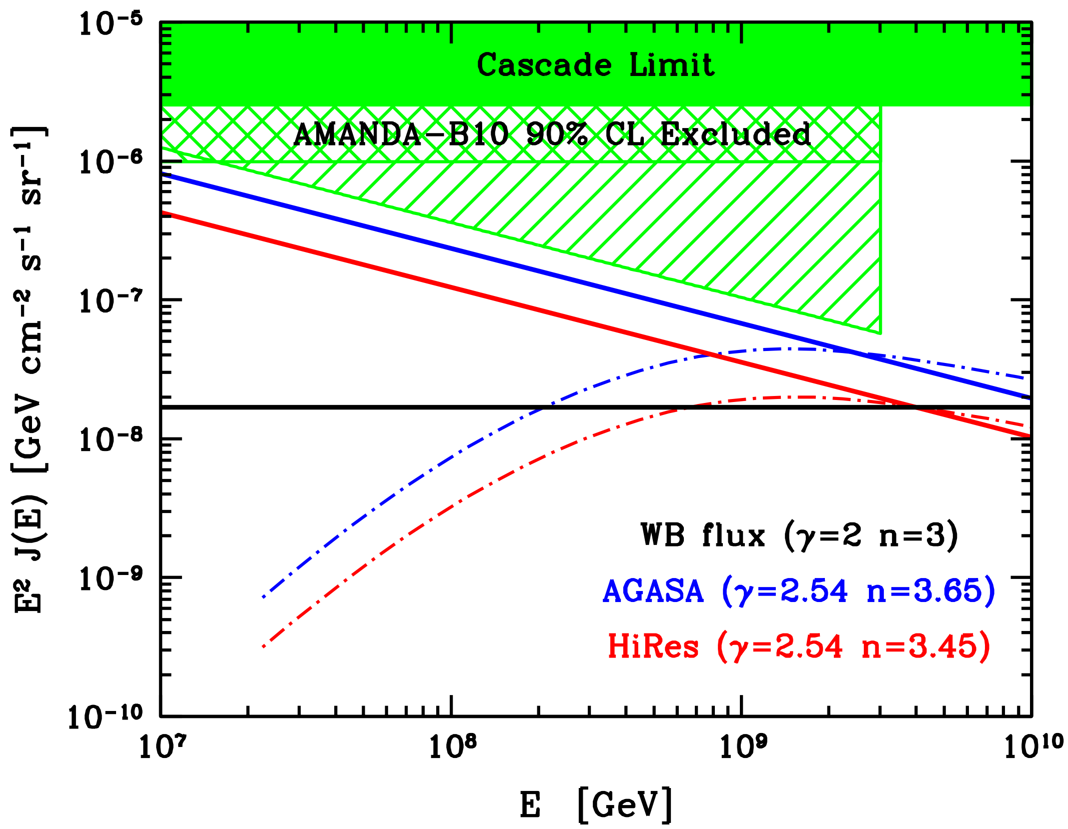
$\Rightarrow$ **ν flux at Earth:**

- ν's from $p\gamma \to n + \pi$'s close to be measured
- dominates cosmogenic ν flux (from $p\gamma_{\mathrm{CMB}} \to N\pi$'s) below 10^9 GeV



[Ahlers *et al.* '05]

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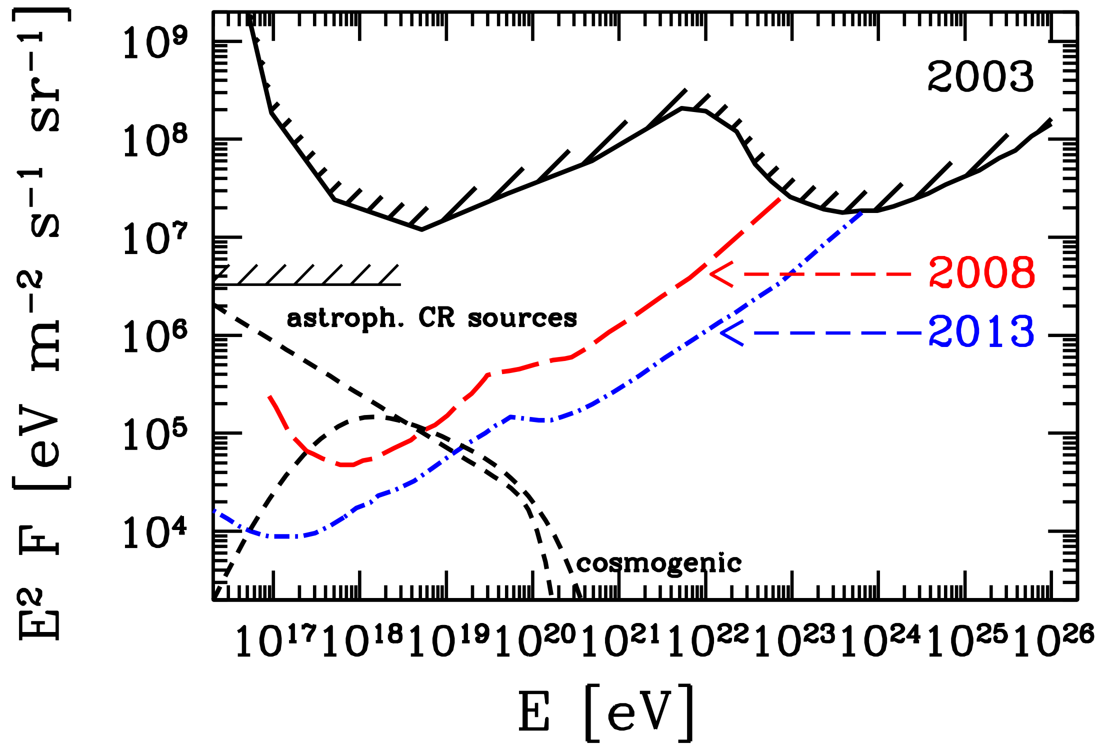
- **Cν's** with $E_\nu \gtrsim 10^{17}$ eV probe $\boldsymbol{\nu N}$ scattering at $\sqrt{s_{\nu N}} \gtrsim 14$ TeV (**LHC**)



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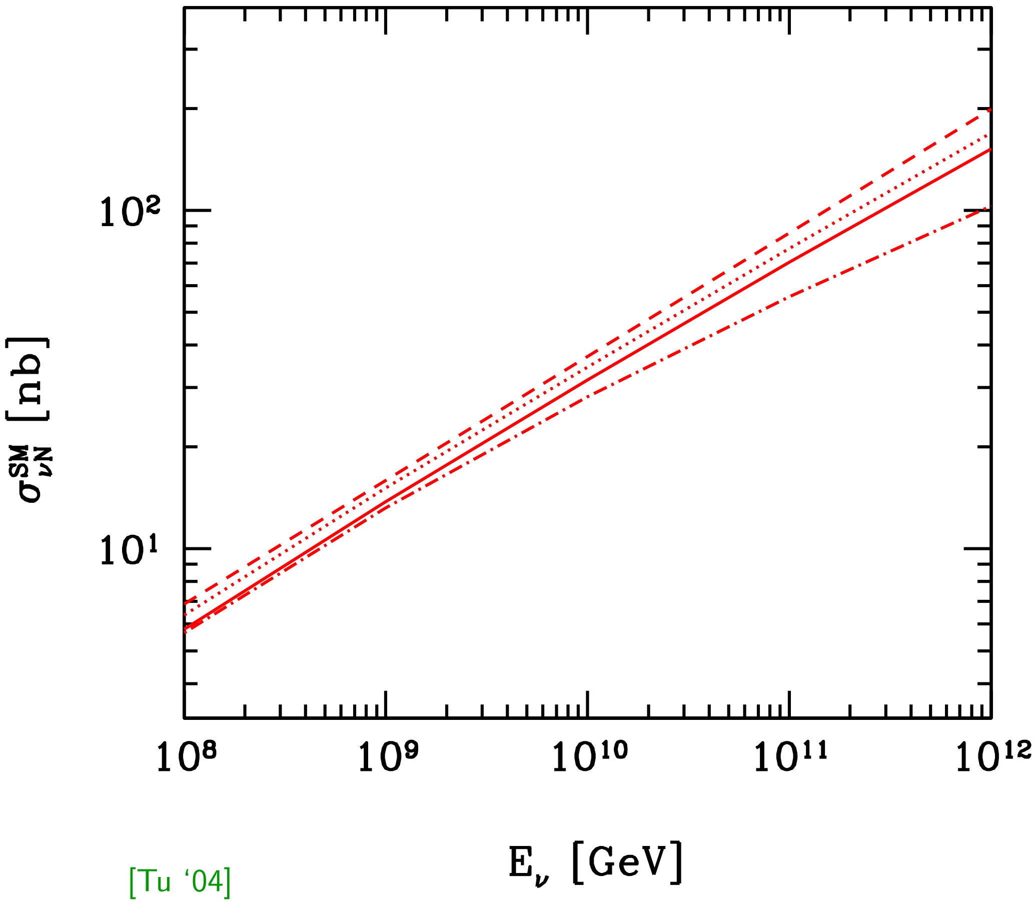
[Gandhi *et al.* '98; Kwiecinski *et al.* '98; ...]



[Tu '04]

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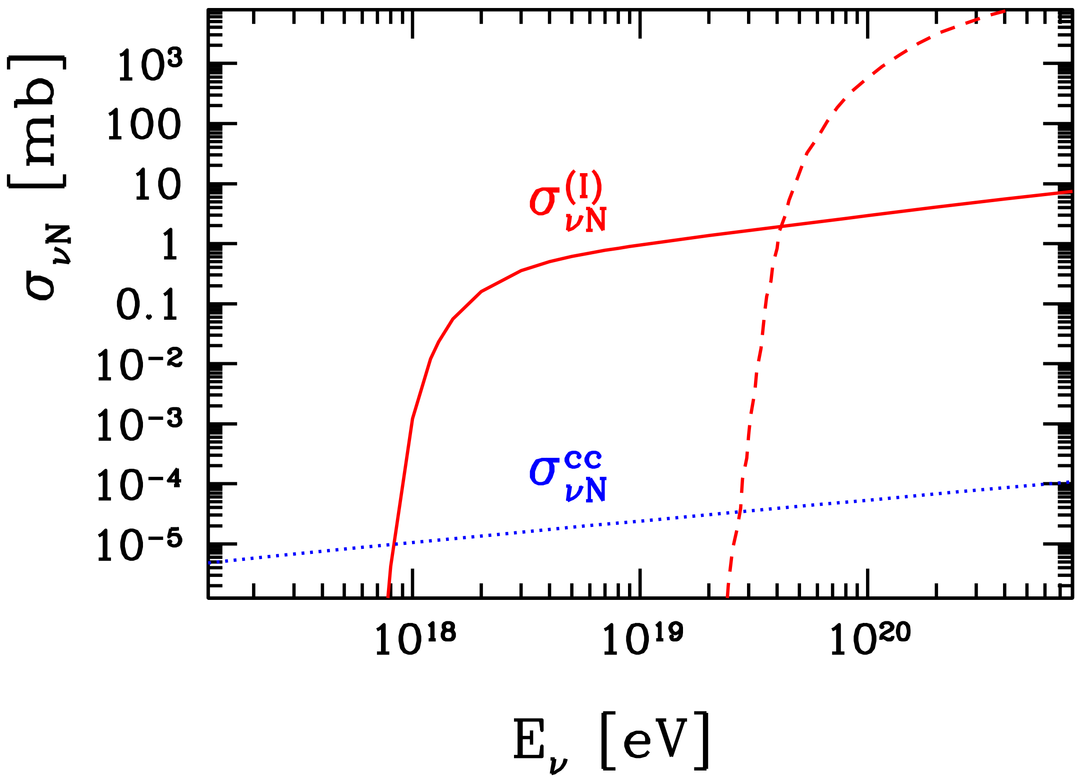
[Gandhi *et al.* '98; Kwiecinski *et al.* '98; ...]

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

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



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

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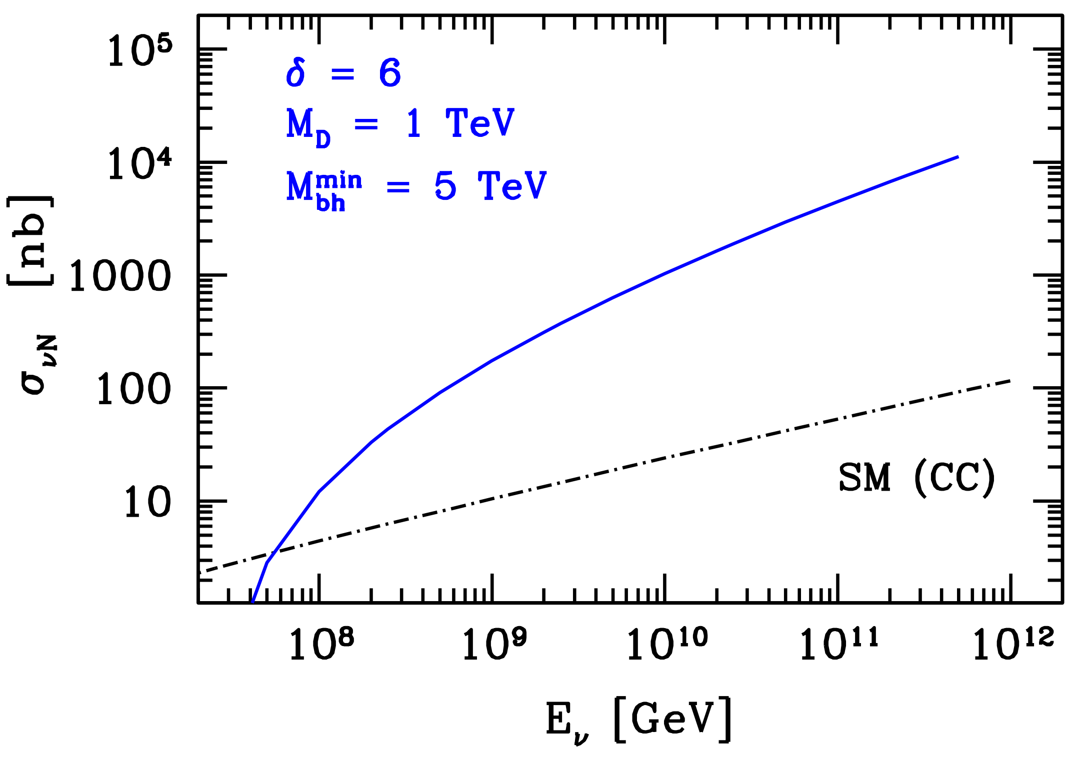
- ◇ Kaluza-Klein, black hole, p-brane or string ball production in TeV scale gravity models
- ◇ . . .



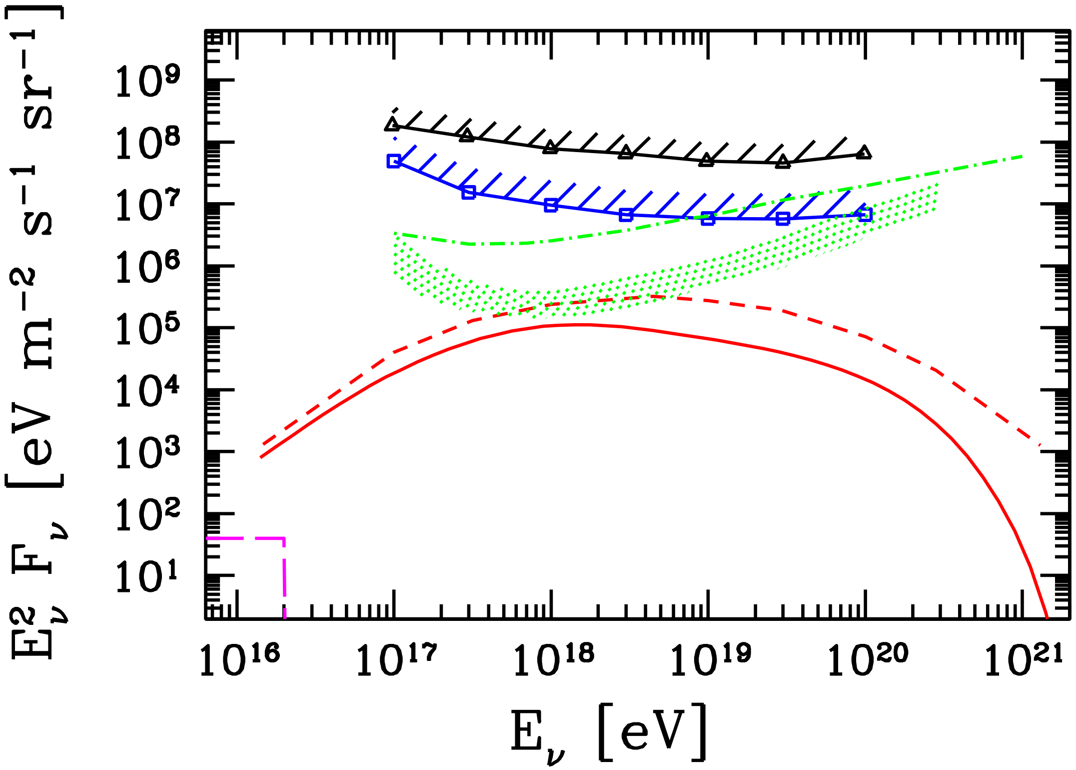
[AR,Tu '01; Tu '04]

“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;..]



[Anchordoqui,Fodor,Katz,AR,Tu ‘04]

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

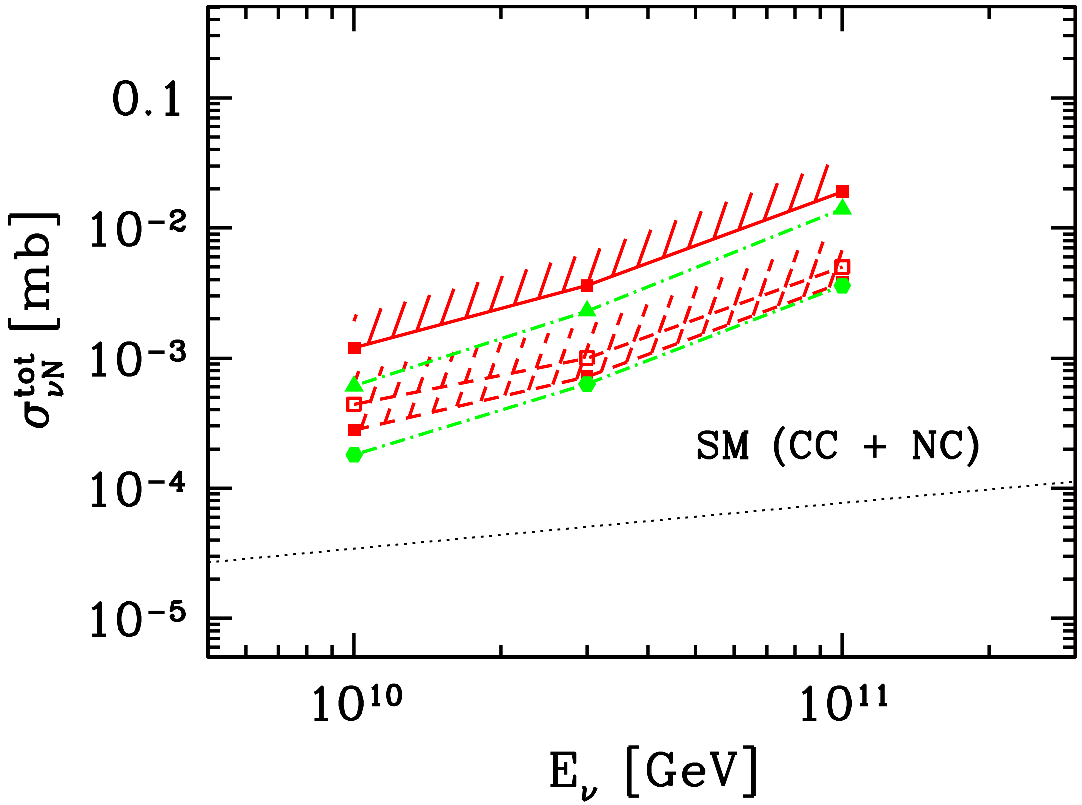
- Recent quantitative analysis:

  [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]

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_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.

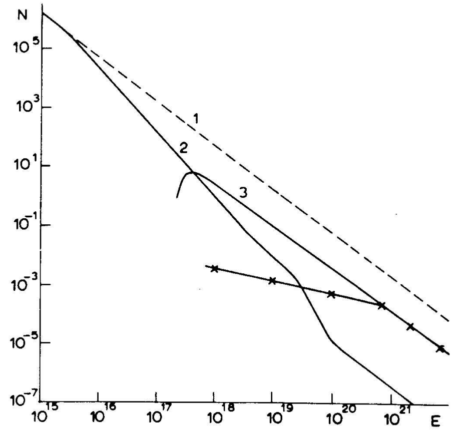


Fig. 1.

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

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:

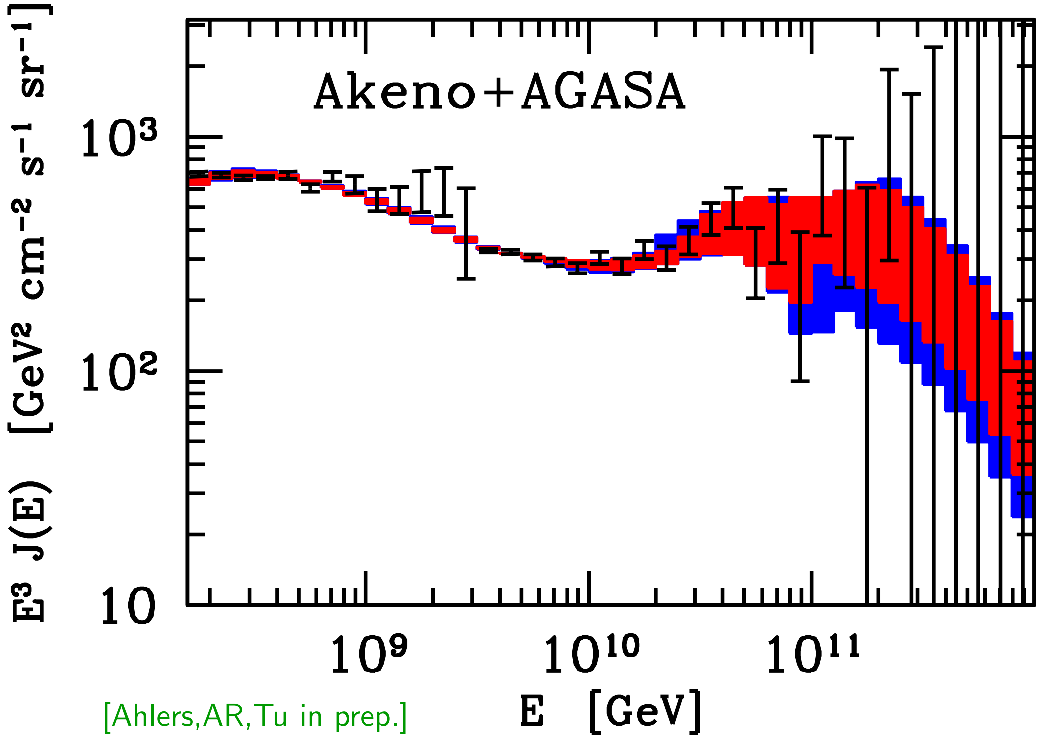
⇒ Strongly interacting neutrino scenario for the post-GZK events

[Berezinsky,Zatsepin '69]

- Quantitative analysis:

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

  – Very good fit to CR data



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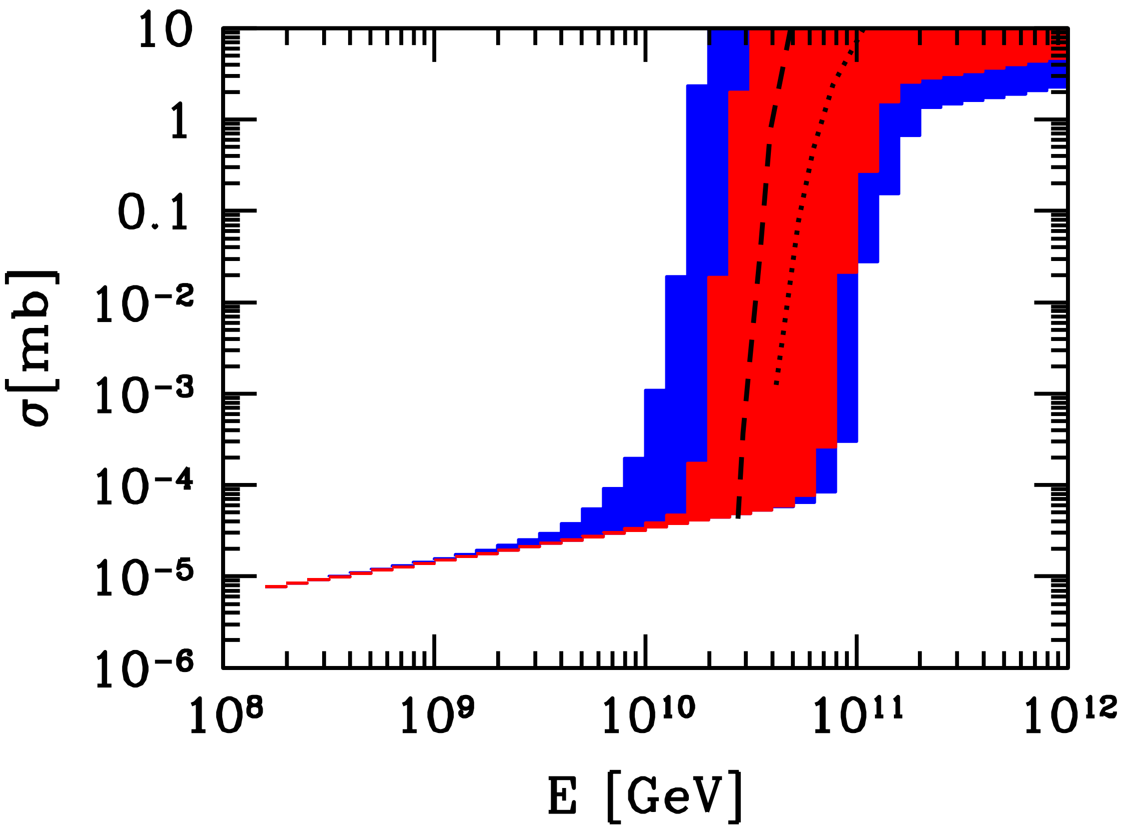
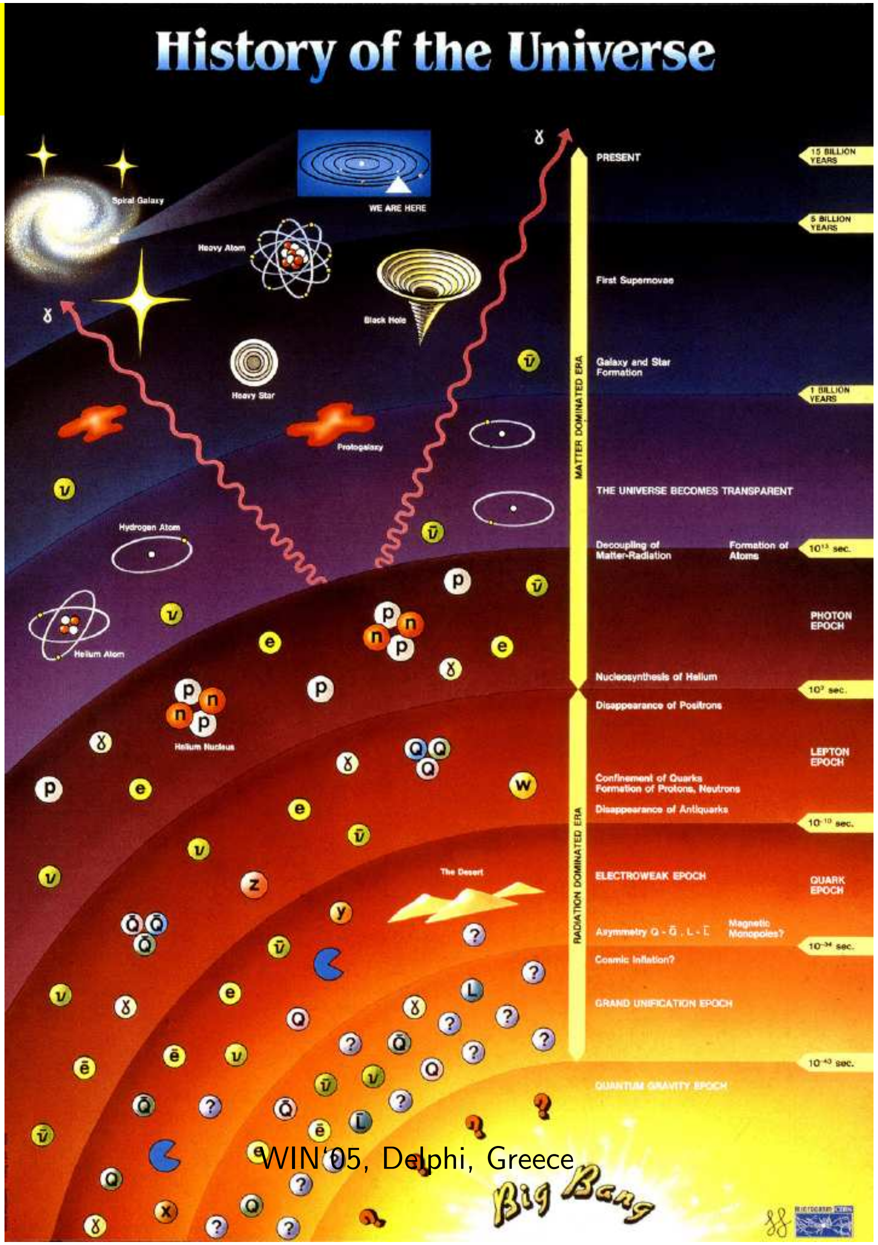


[Ahlers,AR,Tu in prep.]

4. Cosmic ν absorption on the CνB

- How to detect the **CνB**?



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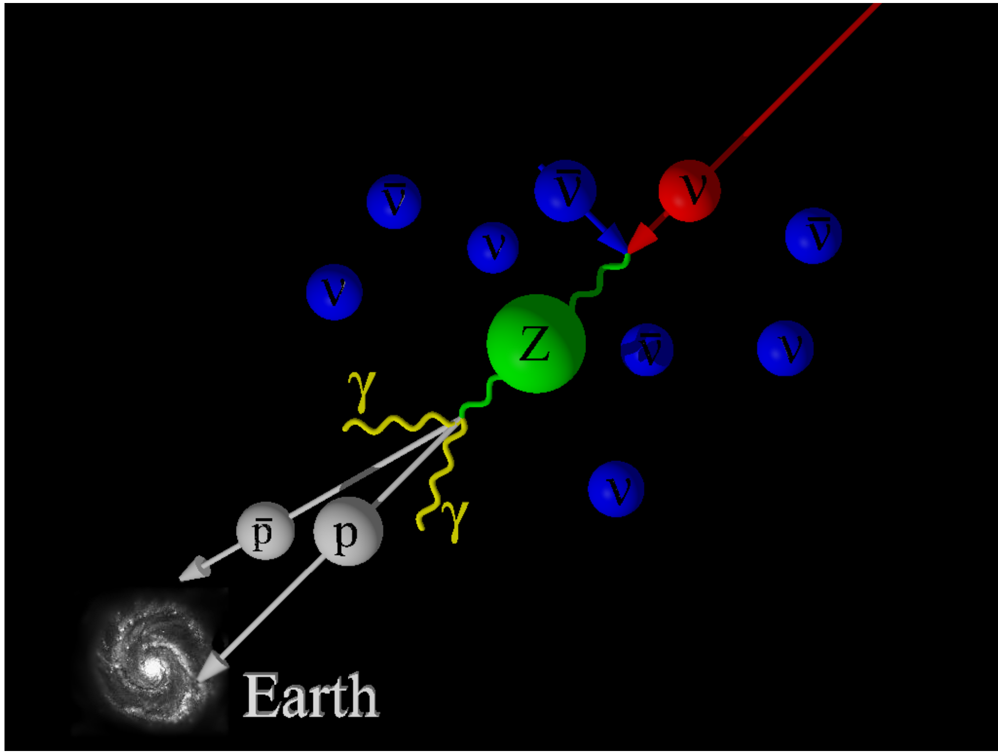
- How to detect the **CνB**?
- Unique: resonant annihilation of **EHECν**

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

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



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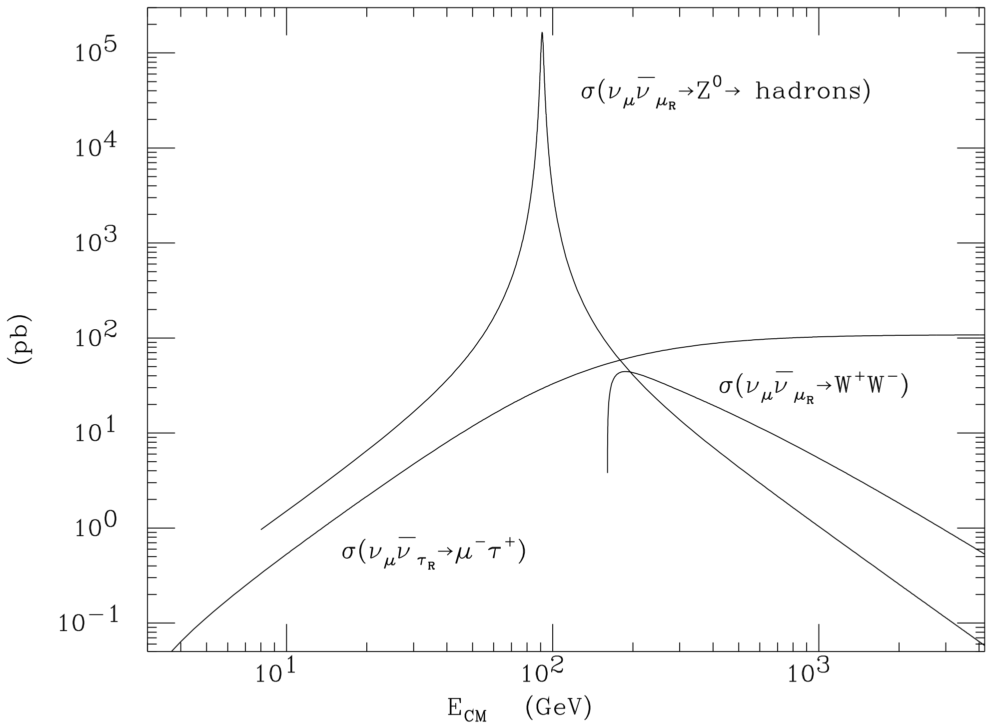

[Fargion,Mele,Salis '99]

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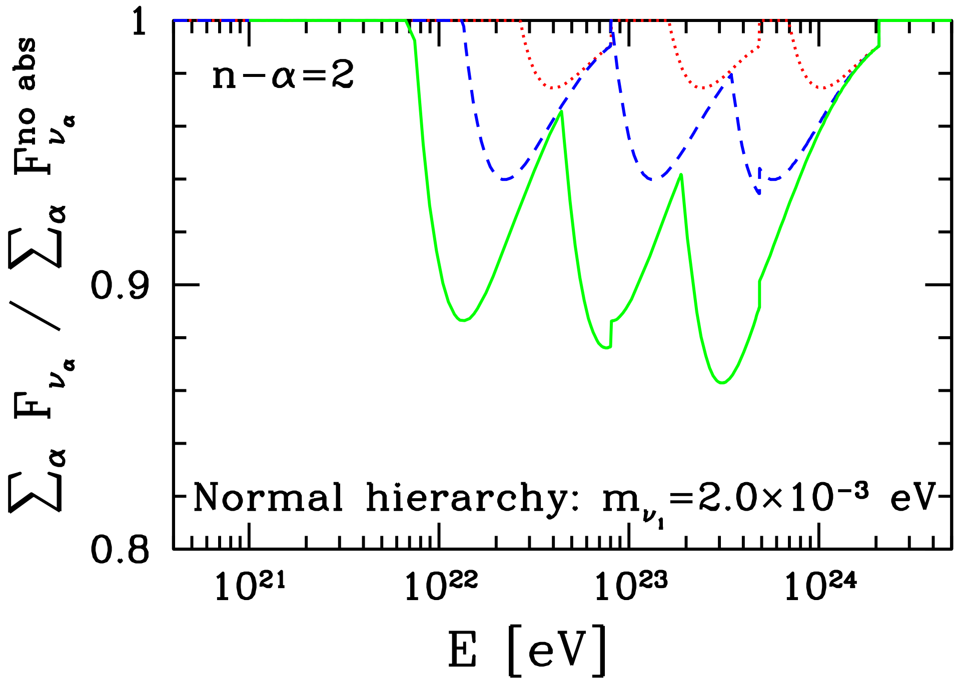
◇ **Absorption dips** in **EHECν** spectrum

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



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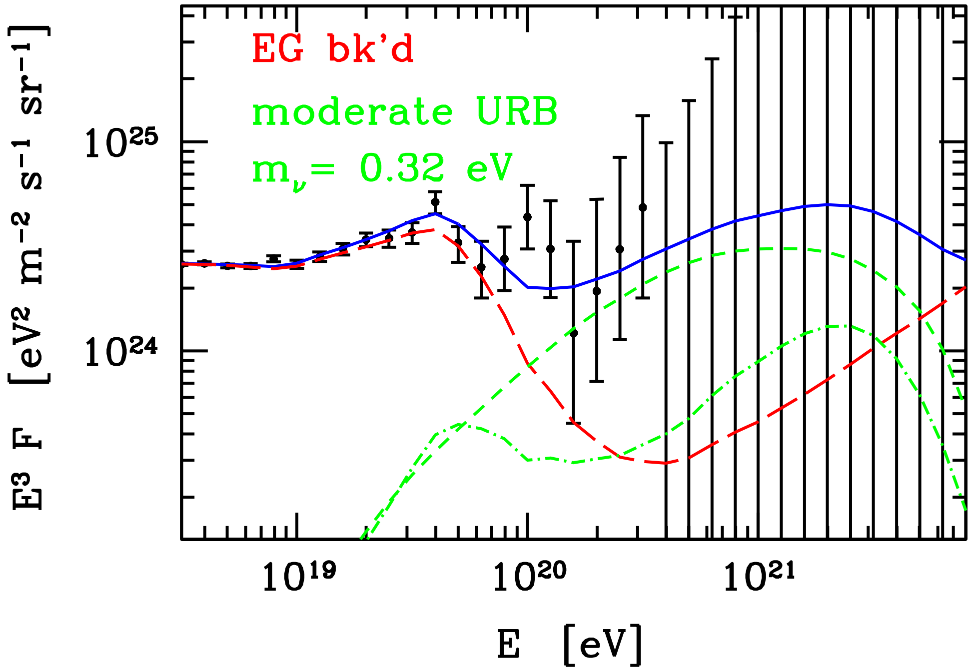
◇ Emission features (***Z*-bursts**):
[Fargion *et al.* '99; Weiler '99;...; Fodor,Katz,AR '01,'02]

protons and photons with energies above the predicted **G**reisen–**Z**atsepin–**K**uzmin (**GZK**) cutoff at $E_{\rm GZK} \simeq 4 \times 10^{19}$ eV
[Greisen '66; Zatsepin,Kuzmin '66]



[Fodor,Katz,AR '02]

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

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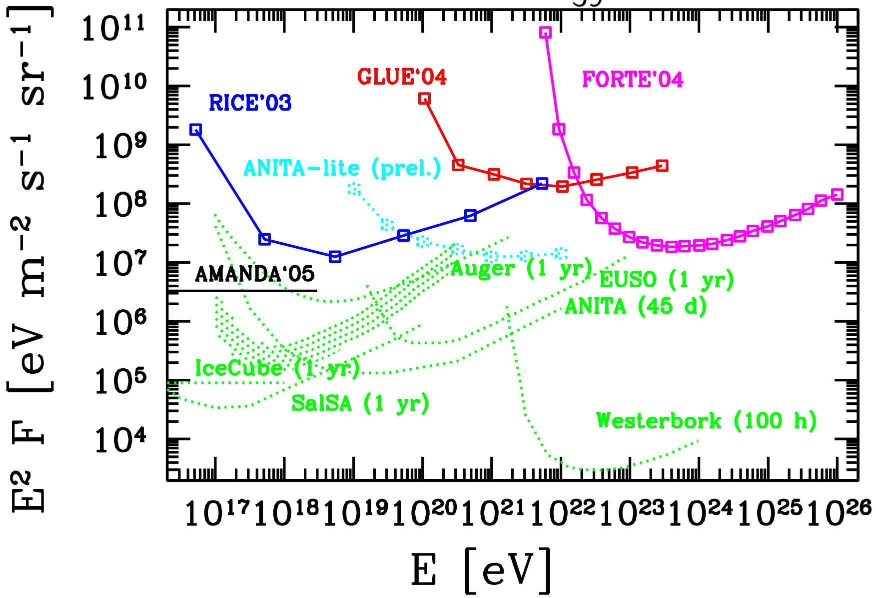

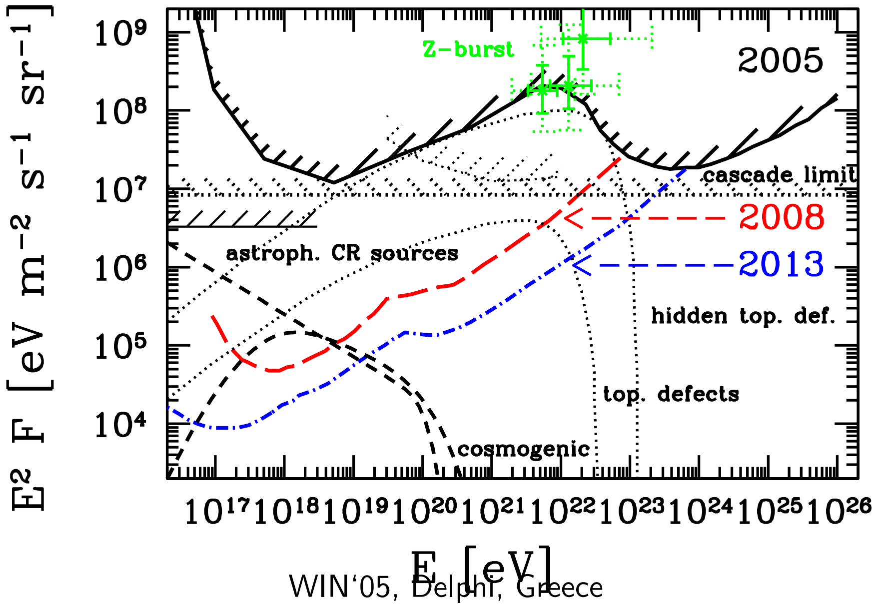

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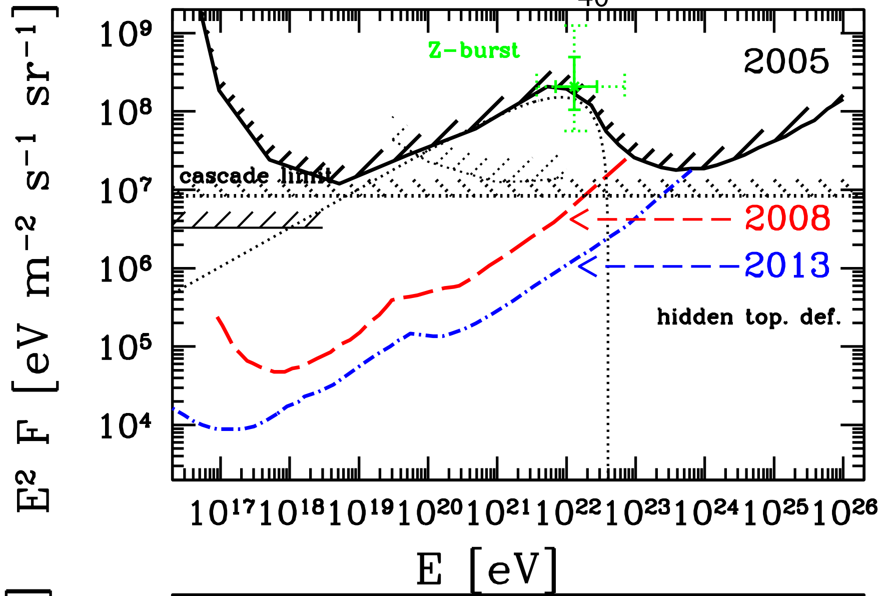

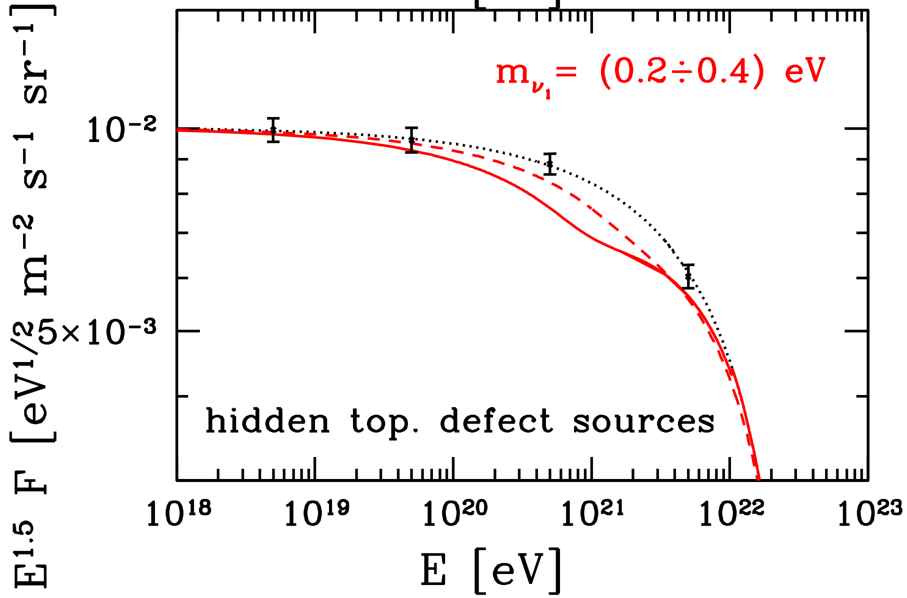

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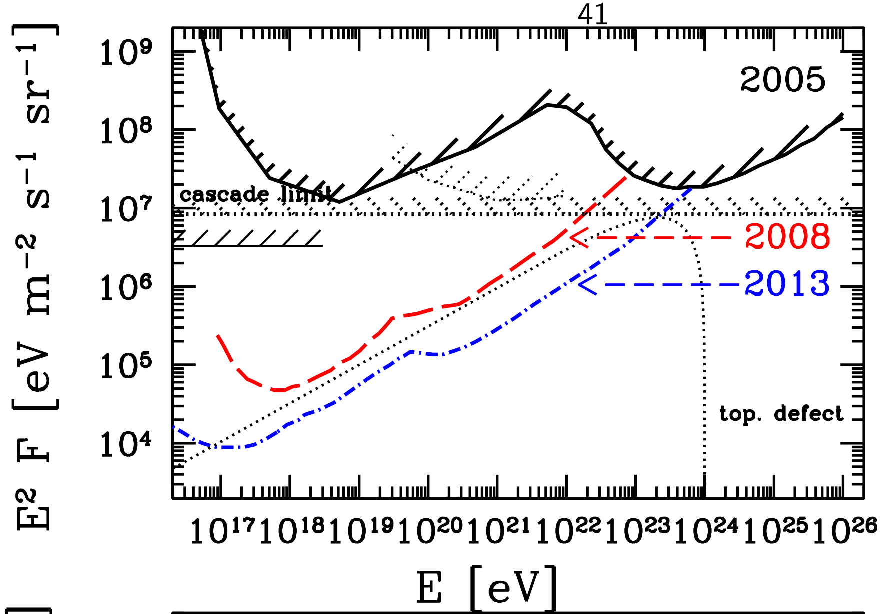

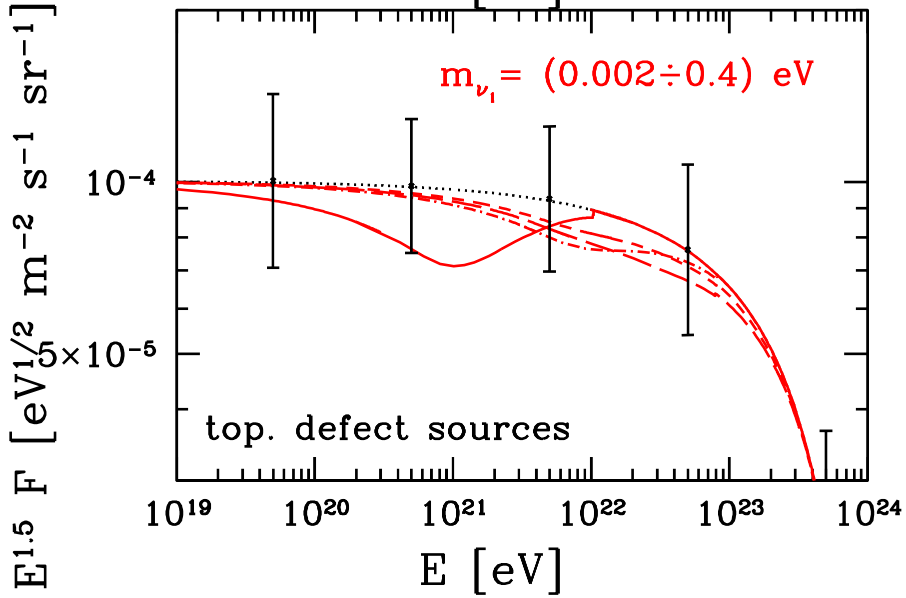

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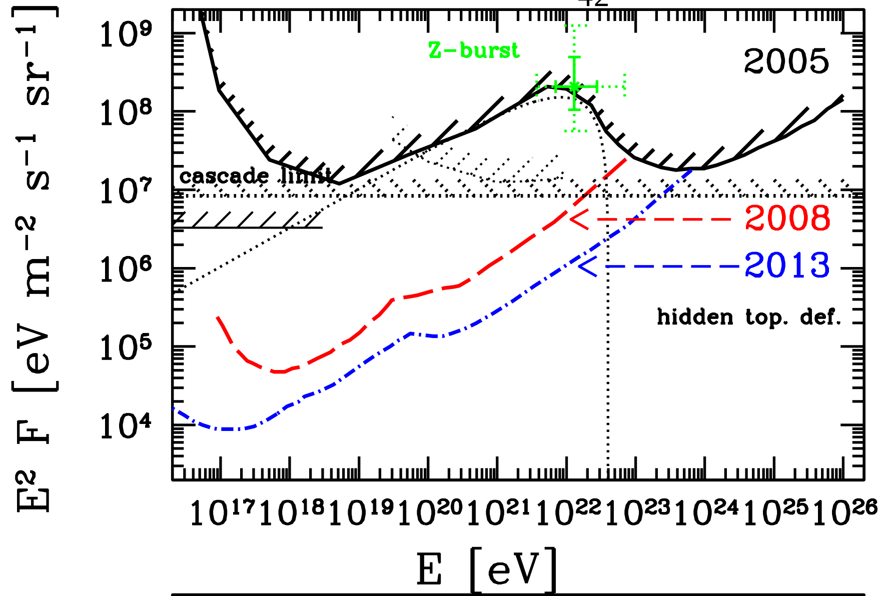

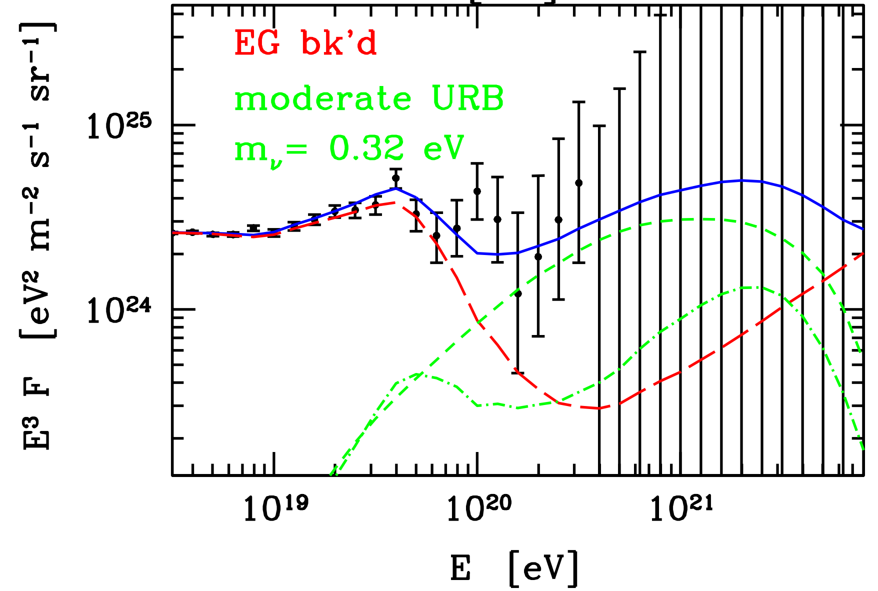

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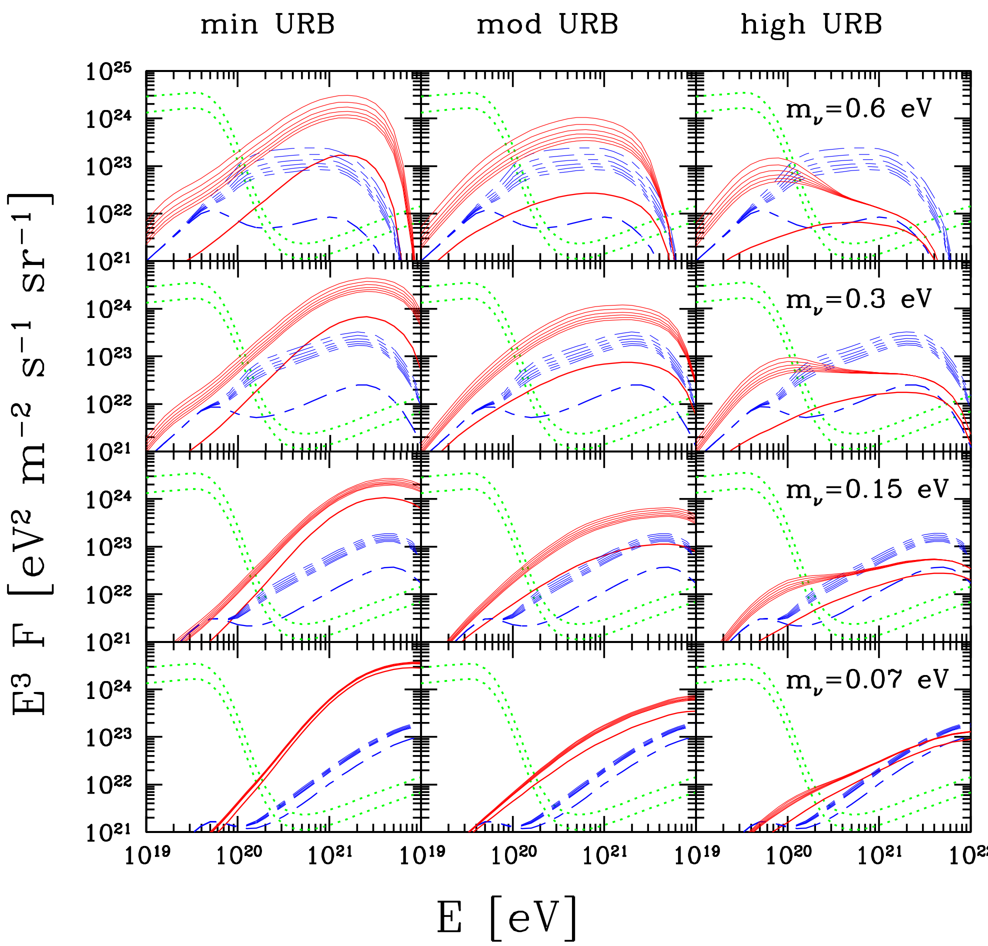

[AR,Weiler,Wong '05]

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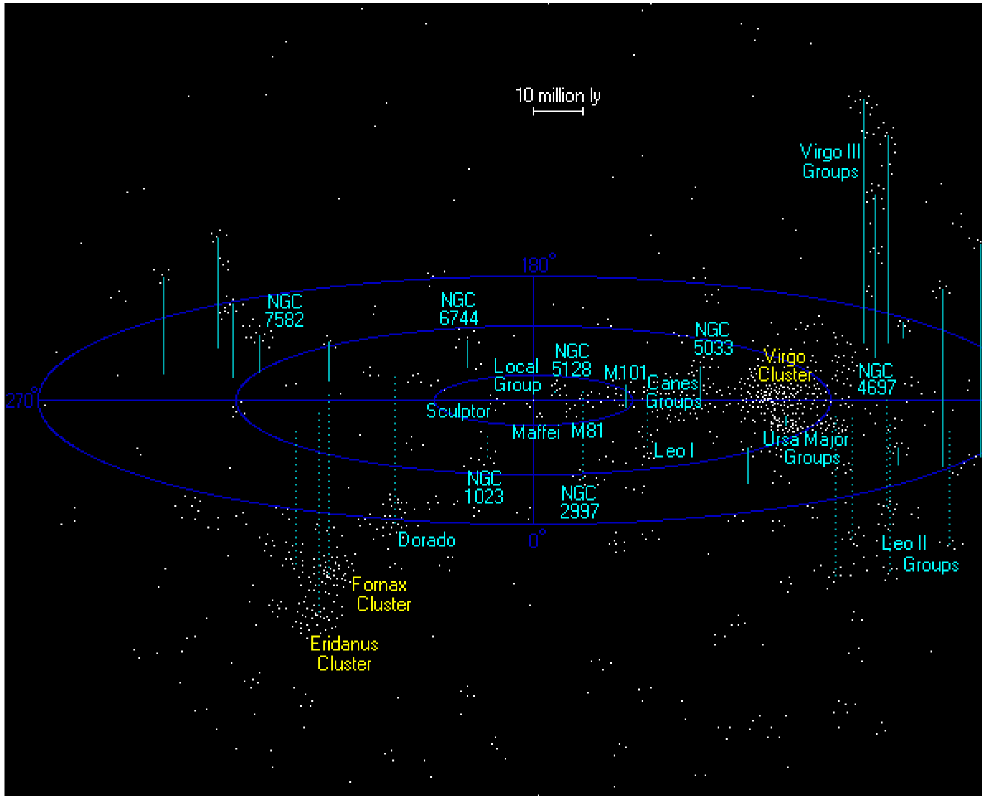


[www.extrasolar.org]

5. Baryogenesis via leptogenesis

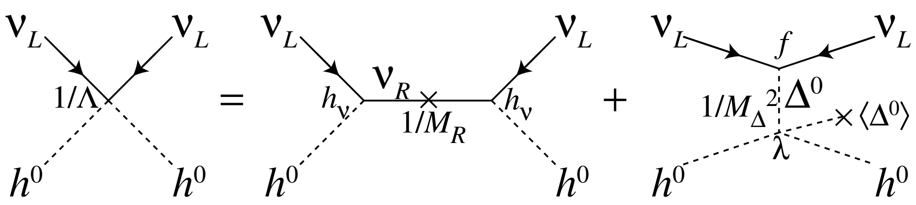
[Fukugita,Yanagida '86]

- (Minimal, Type I) **See-saw mechanism:**

  [Minkowski '77; Yanagida '79; Gell-Mann,Ramond,Slansky '79]

  Introduce three right-handed Majorana neutrinos N_i with mass $M_{\rm M}$ $\Rightarrow$ small Majorana m_ν through large $M_{\rm M}$,

$$m_\nu = -m_{\rm D}\,\frac{1}{M_{\rm M}}\,m_{\rm D}^T$$



[Mohapatra *et al.* '04]

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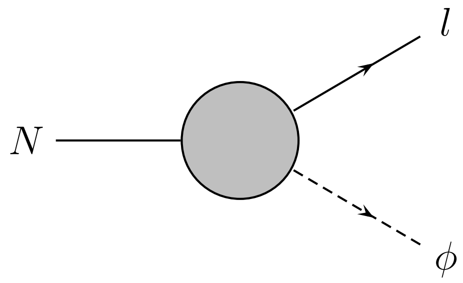
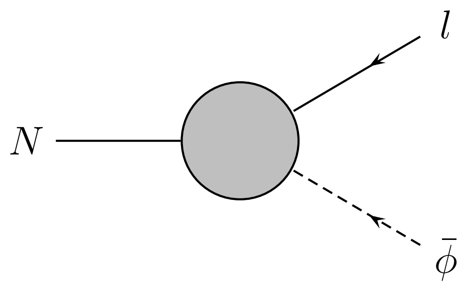


$$\Gamma(N\to l\phi) \quad = \quad (1+\varepsilon)\,\Gamma/2$$



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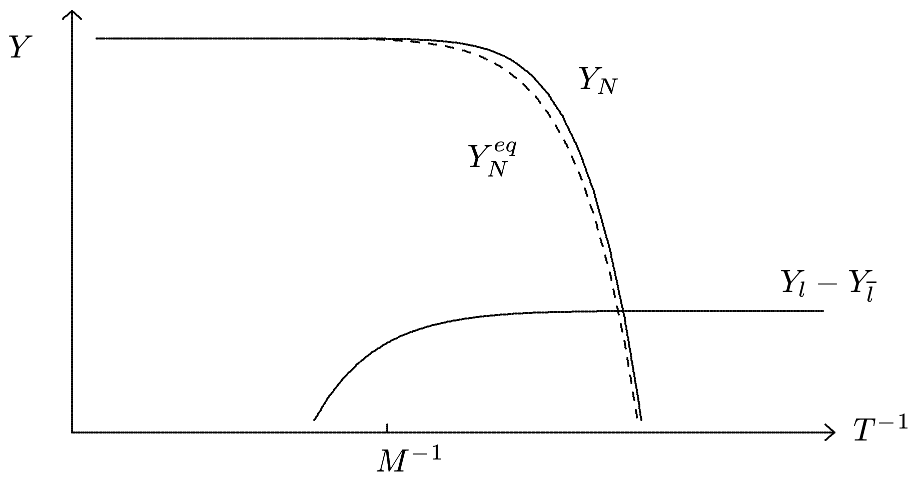
$\Rightarrow$ $\boldsymbol{Y_L \neq 0}$



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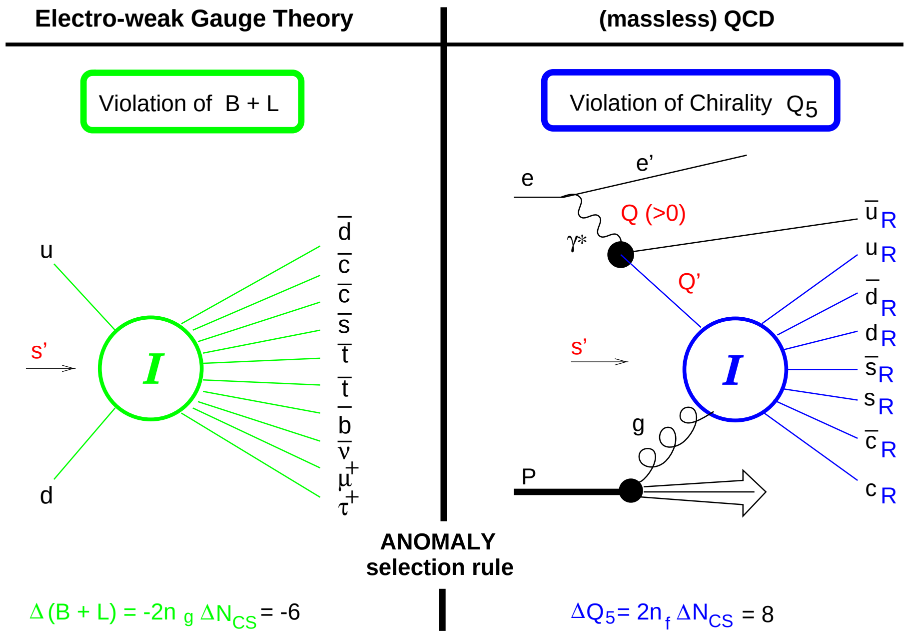
$\Rightarrow$ $Y_L \neq 0$ which, by means of electro-weak **instanton/sphaleron processes**,

$\Rightarrow$ **Baryon asymmetry**

$$Y_B = c\,Y_L = c\,\kappa\,\varepsilon/g_*$$



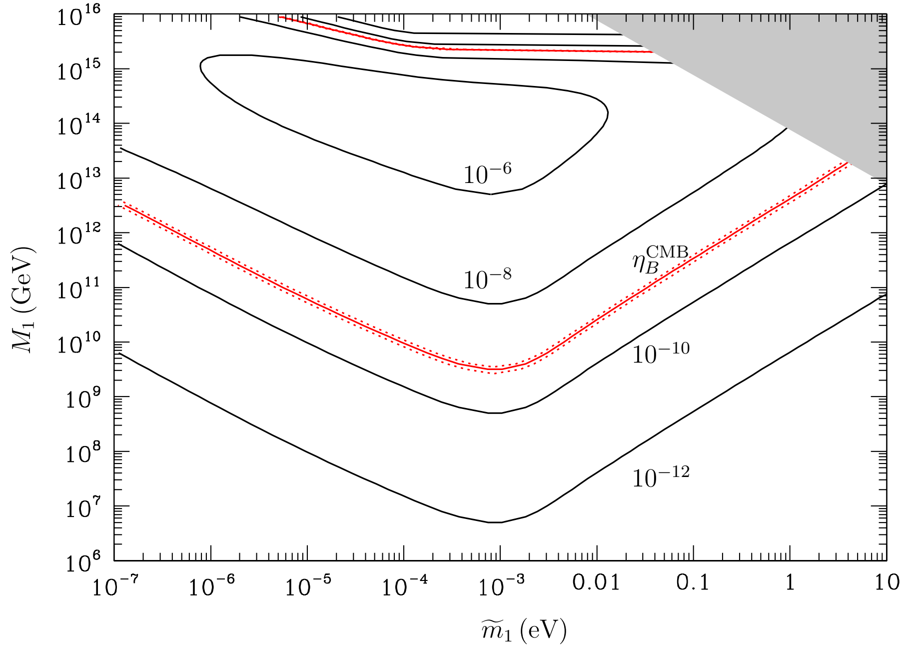
- Constraints on neutrino parameters from requirement of successful leptogenesis?
  - ◇ **Robust mass bounds** in models exploiting **thermal leptogenesis** based on
    - ⊕ minimal, i.e. type I, see-saw
    - ⊕ hierarchical N's, $M_1 < \mathcal{O}(2)\, M_{2,3}$:

[Buchmüller *et al.*; Giudice *et al.*]

$$M_1 \gtrsim 4 \times 10^8 \text{ GeV}$$

$$m_{\nu_i} \lesssim 0.1 \text{ eV}$$

  - – May be circumvented by relaxing above assumptions



$$\left[\widetilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} \geq m_{\nu_1}\right]$$

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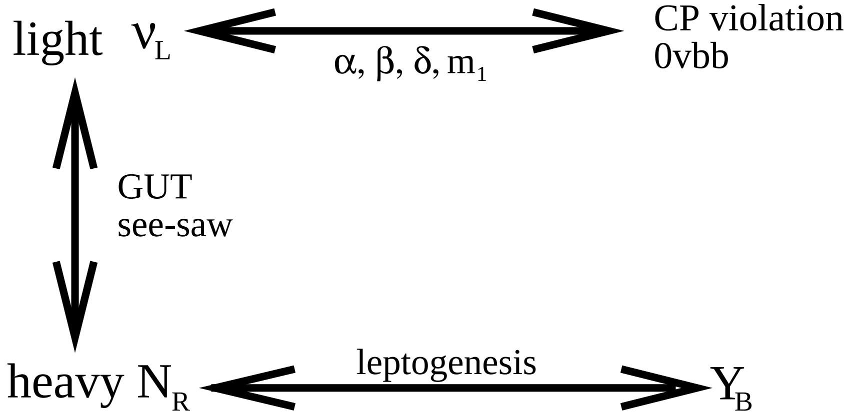
  - ◇ **CP violation in neutrino oscillations and in leptogenesis are unrelated** unless symmetry light $\leftrightarrow$ heavy sector



[Pascoli,Petcov,Rodejohann ‘03]

6. Conclusions

- Cosmic ν's offer exciting opportunities in astrophysics, particle physics and cosmology:
  - **Structure in universe:**
    - Currently probing quasi-degenerate ν spectra
    - Sensitivity to truely hierarchical spectra foreseen
  - **Astrophysics:**
    - ν's 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
  - **CνB absorption dips:**
    - Next decade detection needs flux $\gtrsim$ cascade limit and $m_{\nu_1} \gtrsim 0.1$ eV
  - **Leptogenesis:**
    - Economic way to produce the baryon asymmetry of the universe
    - Works best in the window $0.001\ \mathrm{eV} \lesssim m_{\nu_i} \lesssim 0.1$ eV