Gravitational clustering of relic neutrinos in galactic halos and their detection

Andreas Ringwald

http://www.desy.de/˜ringwald

in collaboration with Yvonne Wong, arXiv:hep-ph/0408241

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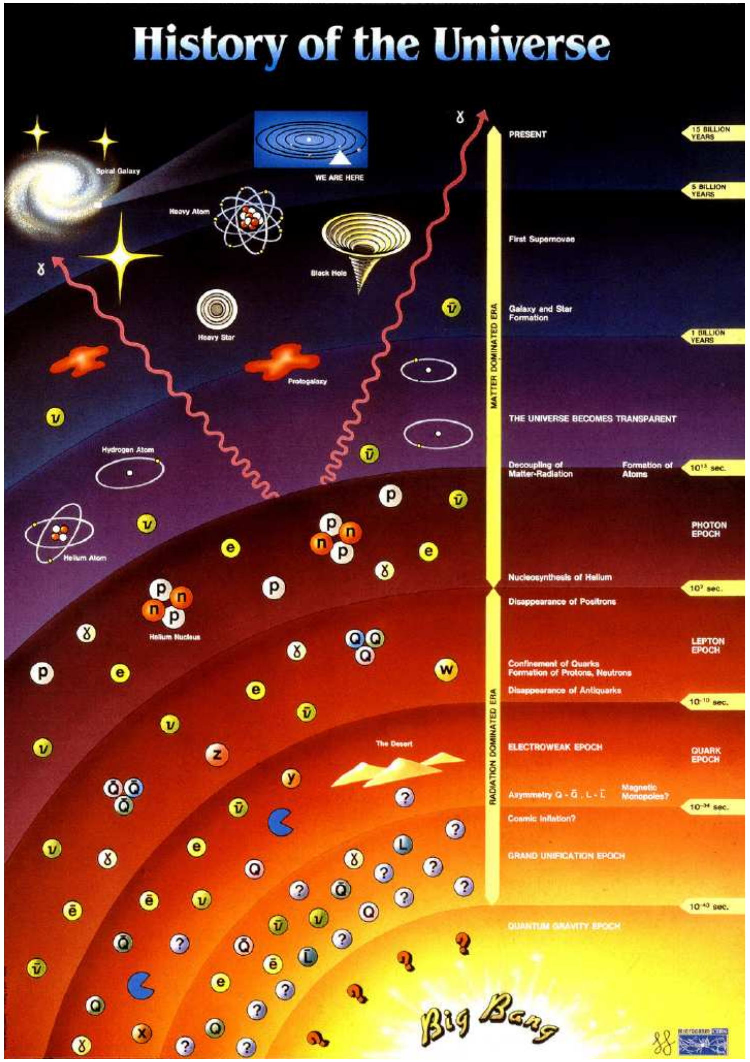
November 2004**

1. Introduction

- **Big Bang cosmology:**
  - ⇒ Cosmic microwave background (**CMB**)
  - ⇒ **Cosmic neutrino background (CνB)**



[CERN]

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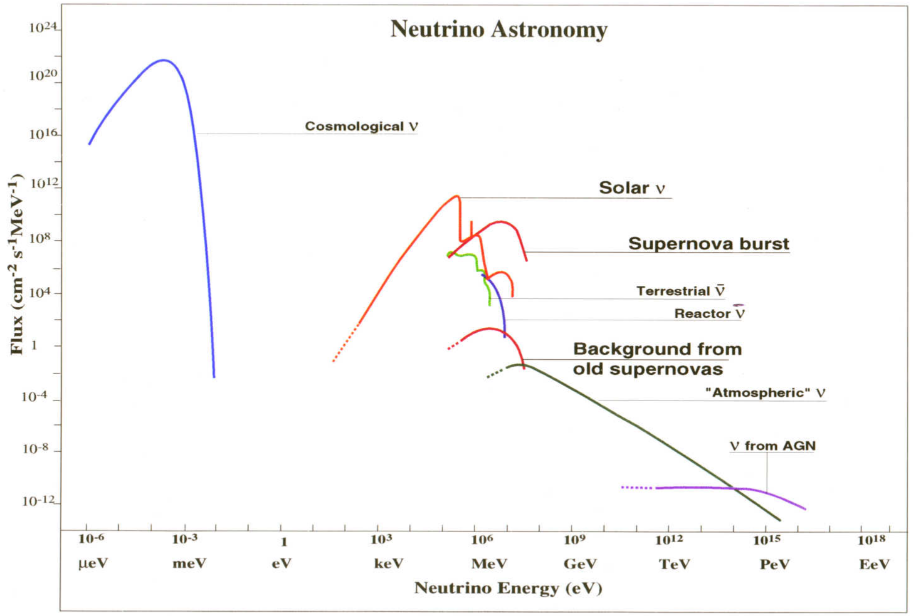
- Firm predictions:

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

⇒ Big bang relic neutrinos ≈ as abundant as relic photons [ratio $(6 \times 3)/22 = 9/11$]



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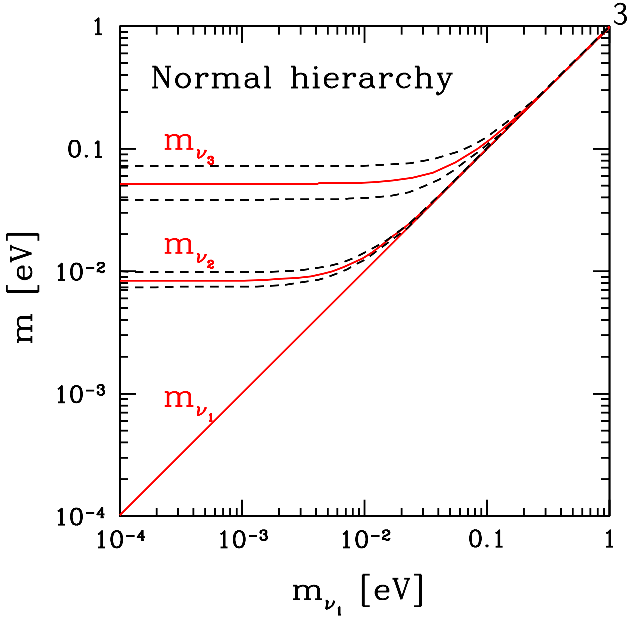
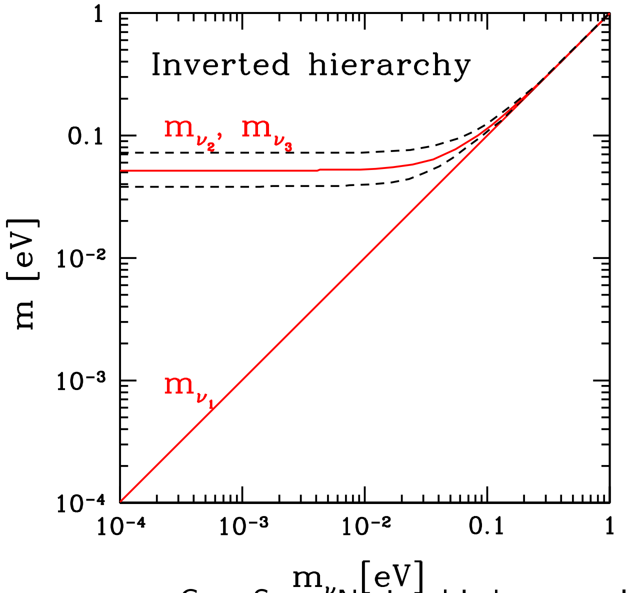
$$\underbrace{\bar{p}_{\nu_i 0} = \bar{p}_{\bar{\nu}_i 0}}_{\mathrm{C\nu B}} = 3\left(\frac{4}{11}\right)^{1/3}\underbrace{T_{\gamma 0}}_{\mathrm{CMB}} = 5 \times 10^{-4}\ \mathrm{eV}$$

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





$\Rightarrow$ Nonrelativistic relic neutrinos subject to gravitational clustering on cold dark matter (**CDM**) and baryonic structures

$\Rightarrow$ Neutrino density might be enhanced in the halo of the Milky Way or in the halos of other galaxies/clusters of galaxies

- **CνB** has not been detected **in laboratory**:
  $\Leftarrow$ Neutrinos interact only weakly
  $\Leftarrow$ Smallness of neutrino mass $\Leftrightarrow$ small momentum-transfer

- Only evidence for/inference about **CνB** from other cosmological measurements:
  - Big bang nucleonsynthesis (**BBN**) $(1.8 \le N_\nu \le 4.5)$
  - Large scale structure data together with **CMB** $(\sum m_{\nu_i} \le 1.8$ eV$)$

- Design of possible **direct, scattering-based detection experiment**: Requires precise knowledge of phase space distribution of relic neutrinos **Possible now with much more accuracy then ever!**

- **Further content:**

  2. **Gravitational clustering of relic neutrinos**
  3. **Implications for detection**
  4. **Conclusions**

2. Gravitational clustering of relic neutrinos

- In context of flat **ΛCDM** model, neutrino component $\approx$ perturbation
  - On cosmological scales, $\bar{\rho}_\nu/\bar{\rho}_m < 0.2 \stackrel{\rm free-streaming}{\Rightarrow}$ even smaller on cluster/galactic scales

  $\rightarrow$ **CDM** component ρ_m dominates in gravitational potential ϕ

$\Rightarrow$ Neutrino clustering in cold dark matter halos from **ΛCDM** simulations

[Singh,Ma '03; AR,Wong '04]

- **Neutrino** phase space distributions $f_{\nu_i}(\boldsymbol{x},\boldsymbol{p},\tau)$, depending on $\boldsymbol{x} = \boldsymbol{r}/a(t)$, $\boldsymbol{p} = a m_{\nu_i} \dot{\boldsymbol{x}}$, $d\tau = dt/a(t)$, obey the **Vlasov**, or **collisionless Boltzmann**, **equation**,

$$\frac{D f_{\nu_i}}{D\tau} \equiv \frac{\partial f_{\nu_i}}{\partial \tau} + \dot{\boldsymbol{x}} \cdot \frac{\partial f_{\nu_i}}{\partial \boldsymbol{x}} \underbrace{- a m_{\nu_i} \nabla \phi}_{\dot{\boldsymbol{p}}} \cdot \frac{\partial f_{\nu_i}}{\partial \boldsymbol{p}} = 0$$

- Poisson equation

$$\nabla^2\phi = 4\pi G a^2 \underbrace{\Big(\rho_m(\boldsymbol{x},\tau) - \overline{\rho}_m(\tau)\Big)}_{\delta_m(\boldsymbol{x},\tau)\,\overline{\rho}_m(\tau)}$$

relates ϕ to density fluctuation δ_m with respect to physical mean $\bar{\rho}_m$

- Vlasov equation $\Leftrightarrow$ conservation of f_{ν_i} along characteristics $\{\boldsymbol{x}(\tau), \boldsymbol{p}(\tau)\}$,

$$\frac{d\boldsymbol{x}}{d\tau} = \frac{\boldsymbol{p}}{a m_{\nu_i}}, \qquad \frac{d\boldsymbol{p}}{d\tau} = -a m_{\nu_i}\nabla\phi$$

  – Complete set of characteristics coming through every point in phase space exactly equivalent to Vlasov equation
  – Particle-based solution methods (***N*-body simulations**):
  Follow a sufficiently large, but still manageable set of characteristics selected from the initial phase space distribution

- Velocity of unperturbed ν distribution,

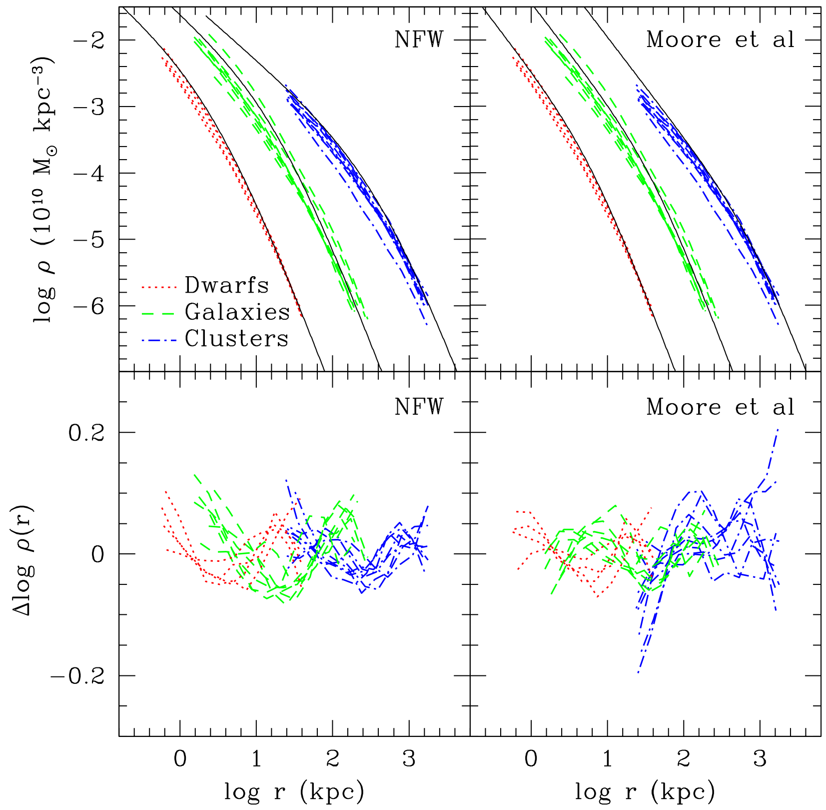
$$\bar{v}_\nu \simeq 1.6\times 10^2\ (1+z)\left(\frac{\mathrm{eV}}{m_\nu}\right)\ \mathrm{km/s}$$

$\simeq$ ($\lesssim$) velocity dispersion of galaxy (cluster) 2×10^2 km/s (10^3 km/s) today

$\Rightarrow$ For sub-eV neutrinos, clustering on small scales can only have been a $z\lesssim 2$ event

- In this epoch, exploit ρ_m of **CDM** halos, $\approx$ conform to a universal shape, e.g. the **N**avarro **F**renk **W**hite profile,

$$\rho_{\rm halo}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2},$$

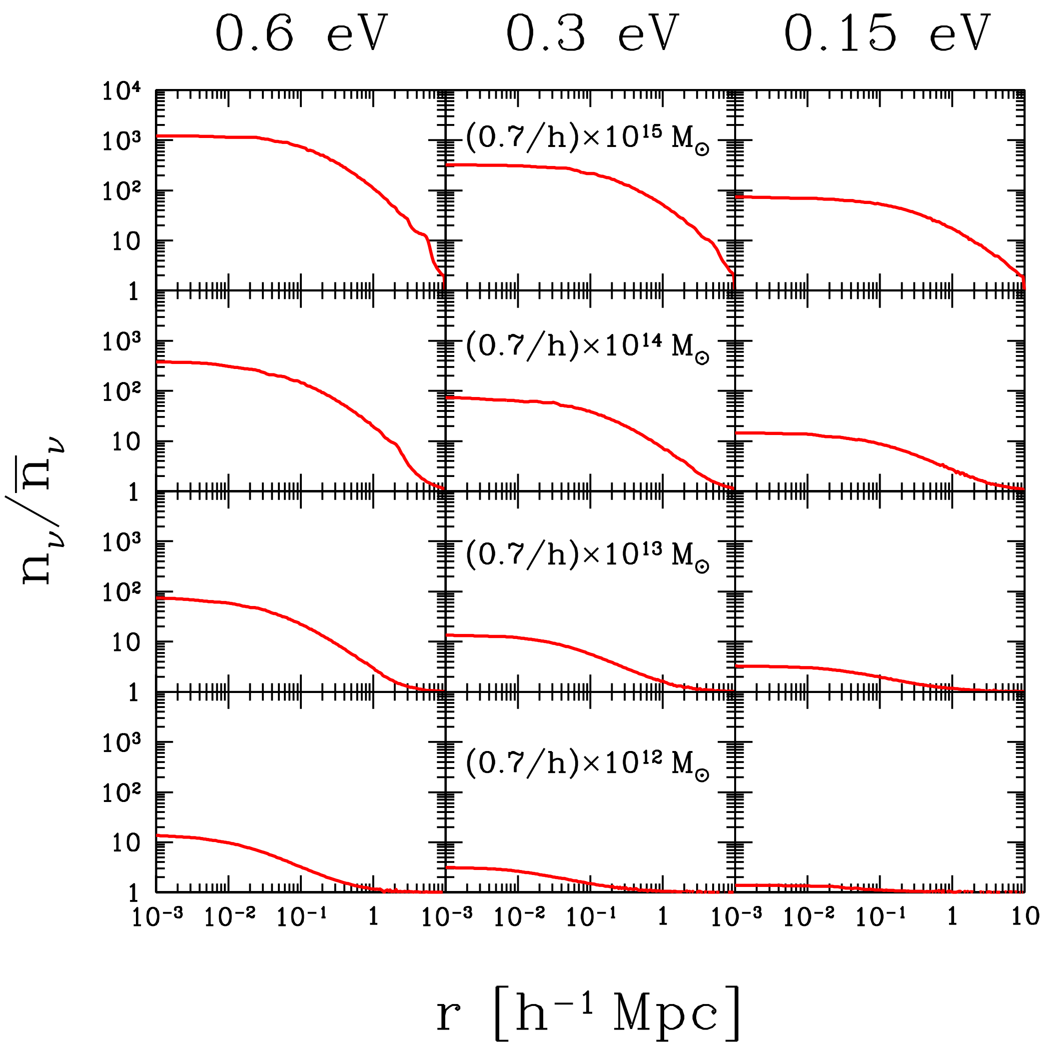


[Navarro *et al.* '04]

Comparative analysis for various $\{m_\nu, M_{\rm vir}\}$:

- Neutrino free-streaming:

  $\Rightarrow$ $n_\nu/\bar{n}_\nu$ flattens out at small radii



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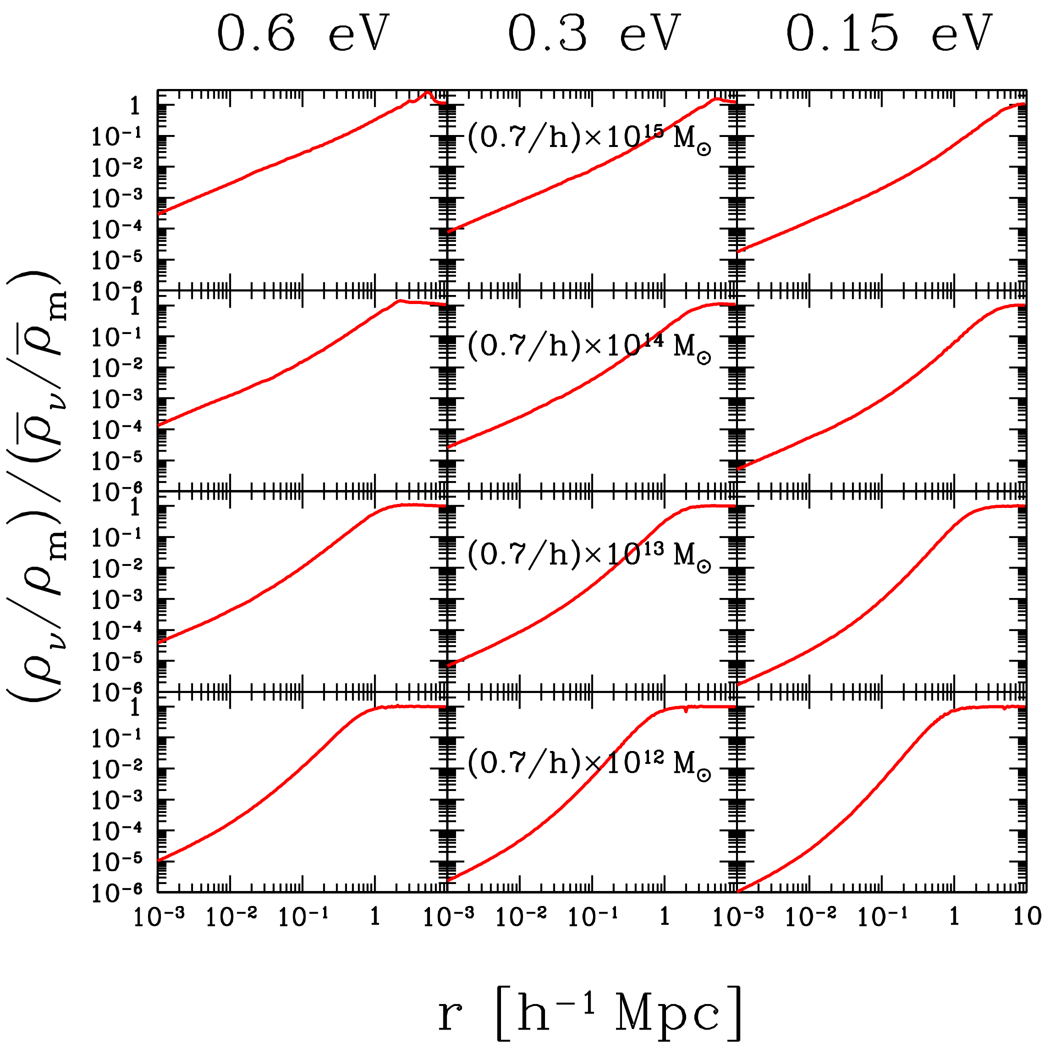

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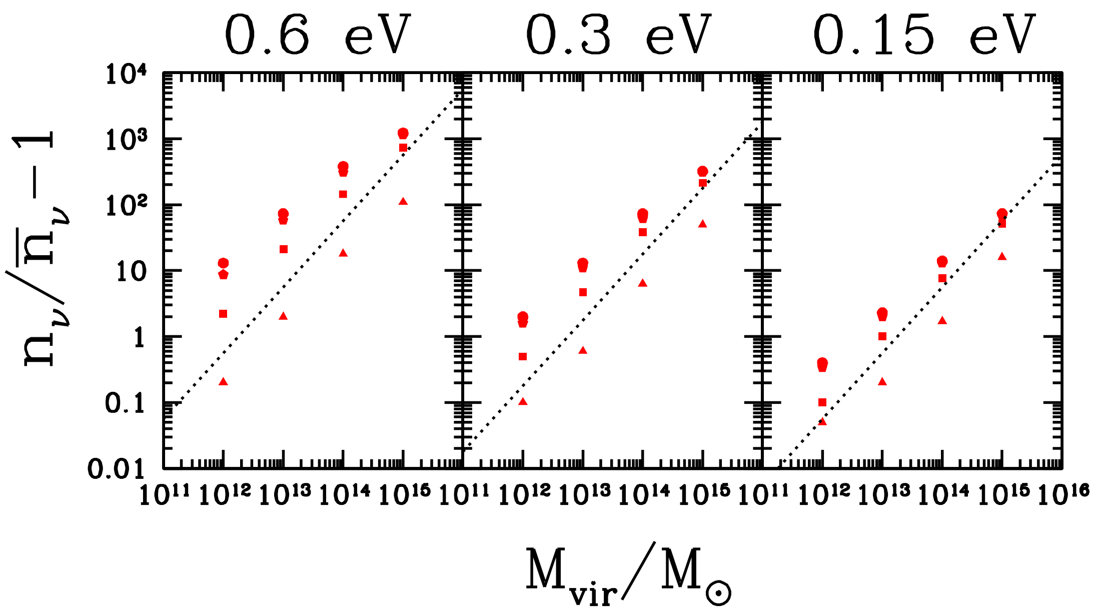
  - ◇ Overdensity $\propto M_{\rm vir}$ for fixed r, m_ν



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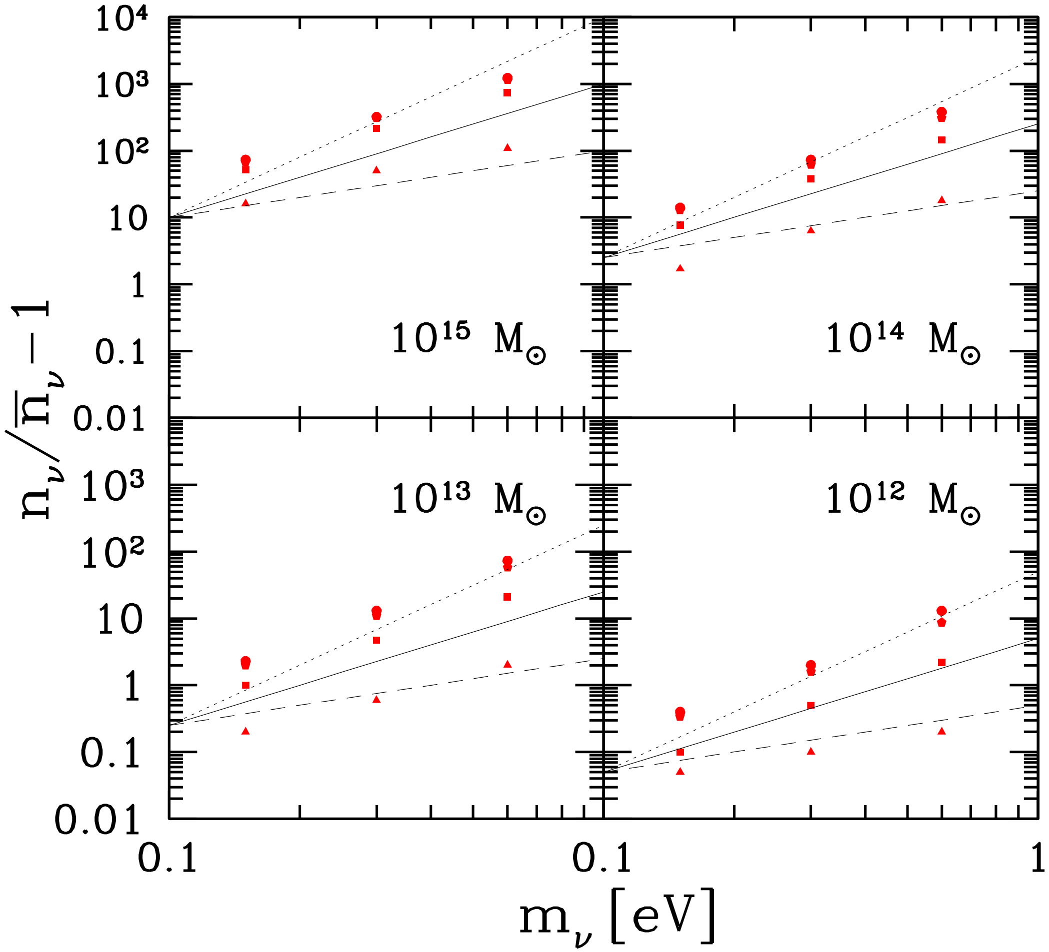

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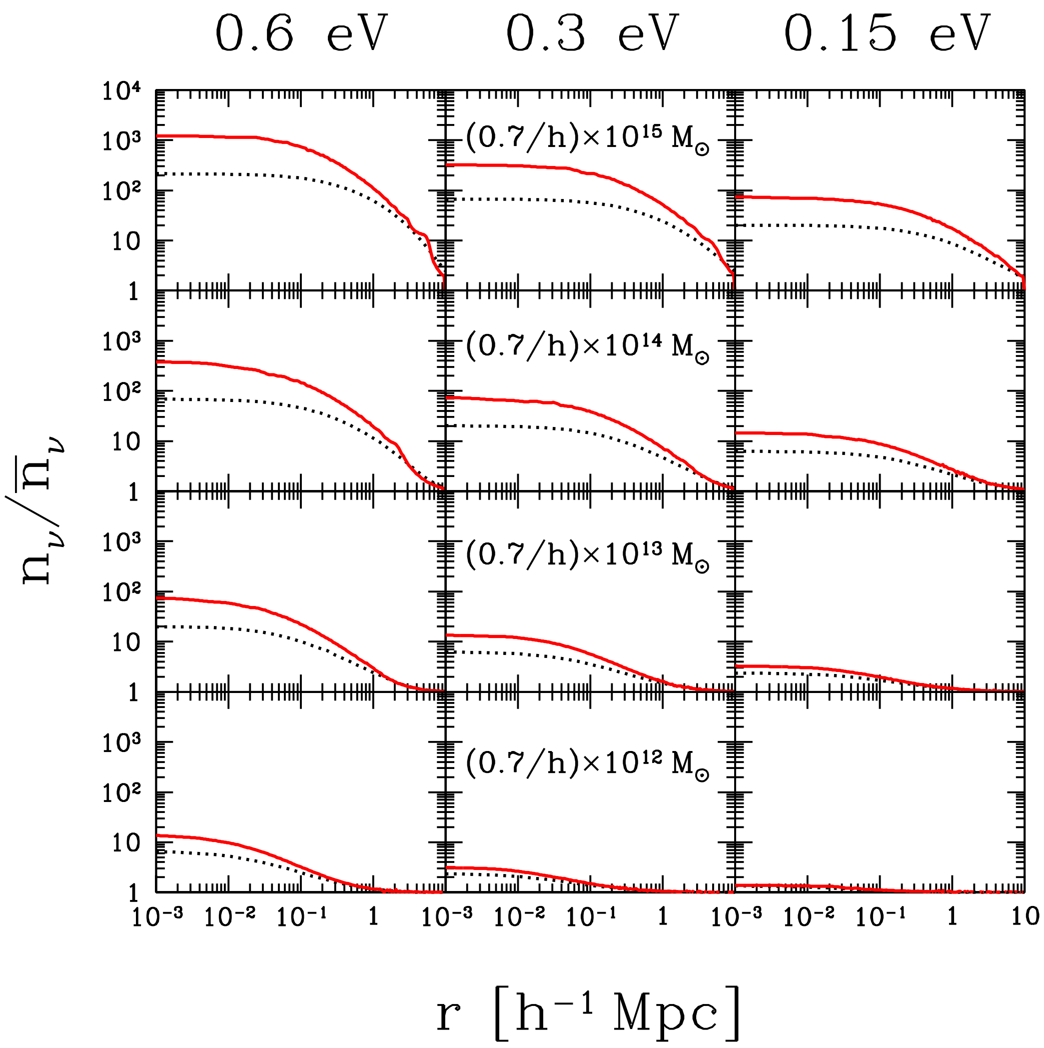
- Linear approximation fails, unless $n_\nu/\bar{n}_\nu \lesssim 2$



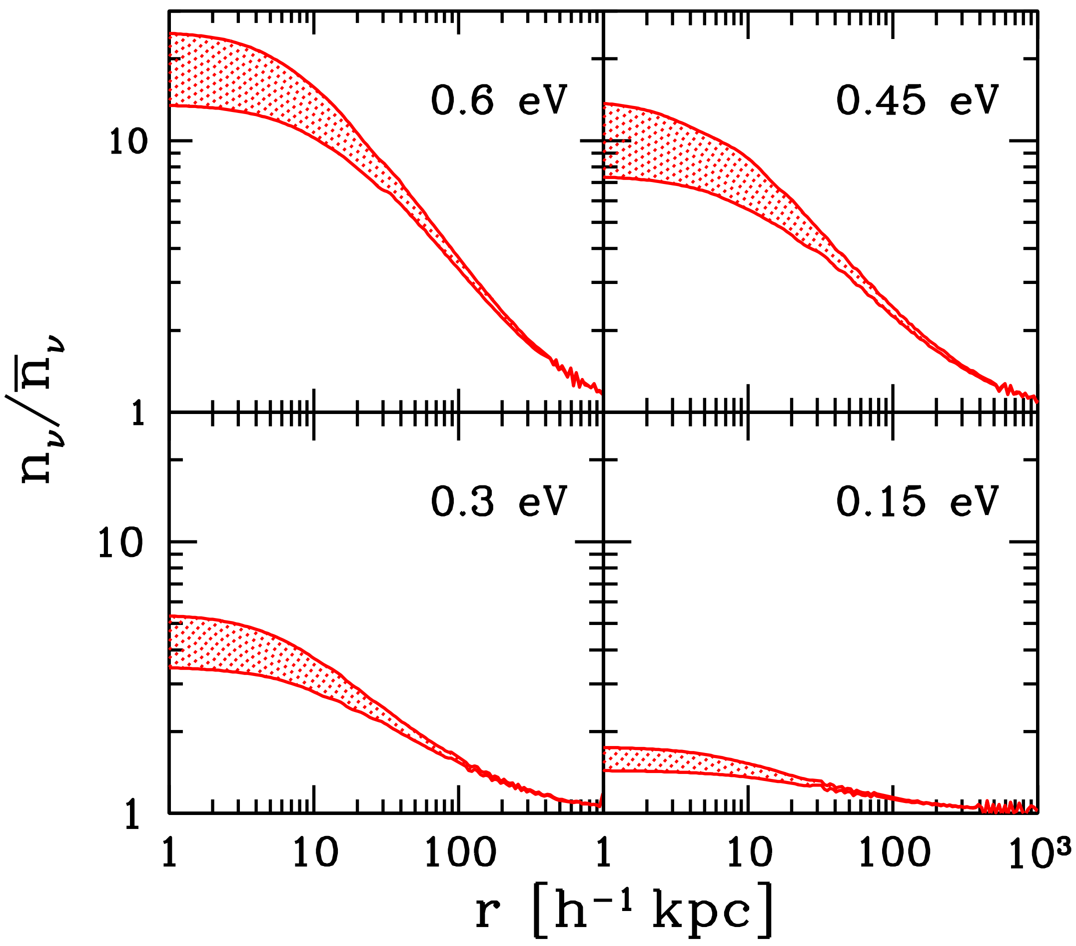
[AR,Wong '04]

Phase space distribution of neutrinos in neighbourhood of Earth ($r_\oplus \approx 8$ kpc)?

- Central region of Milky Way ($\lesssim 10\,\mathrm{kpc}$) dominated by baryonic matter in form of disk + bulge (+ bar?)

$\Rightarrow$ Use N-one-body method with following $\phi \Leftrightarrow$ mass distribution

- **MWnow:** present day one from observations; static
- **NFWhalo: NFW** profile for Milky Way parameters; dynamic



[AR,Wong '04]

Momentum distribution of neutrinos in neighbourhood of Earth ($r_\oplus \approx 8$ kpc):

- almost isotropic:
  - $\langle p_r \rangle \simeq 0$
  - $2\langle p_r^2 \rangle \simeq \langle p_T^2 \rangle$

	$\frac{n_\nu}{\bar{n}_\nu}$	$\langle y_r \rangle$	$\langle y_T \rangle$	$\langle y \rangle$	$\langle y_r^2 \rangle$	$\langle y_T^2 \rangle$	$\langle y^2 \rangle$
Fermi–Dirac	1	0	2.5	3.2	4.3	8.6	12.9
MWnow $m_\nu =$							
0.6 eV	20	0.0	4.0	5.1	9.3	18	28
0.45 eV	10	0.0	3.1	4.0	6.1	12	18
0.3 eV	4.4	0.0	2.5	3.2	3.9	8.0	12
0.15 eV	1.6	0.0	2.3	2.9	3.7	7.3	11
NFWhalo $m_\nu =$							
0.6 eV	12	0.0	3.4	4.3	6.9	13	20
0.45 eV	6.4	0.0	2.8	3.5	4.6	9.5	14
0.3 eV	3.1	0.0	2.3	3.0	3.6	7.3	11
0.15 eV	1.4	0.0	2.3	2.0	3.8	7.6	11

$$y = p/T_{\nu,0} = m_\nu v/T_{\nu,0}$$

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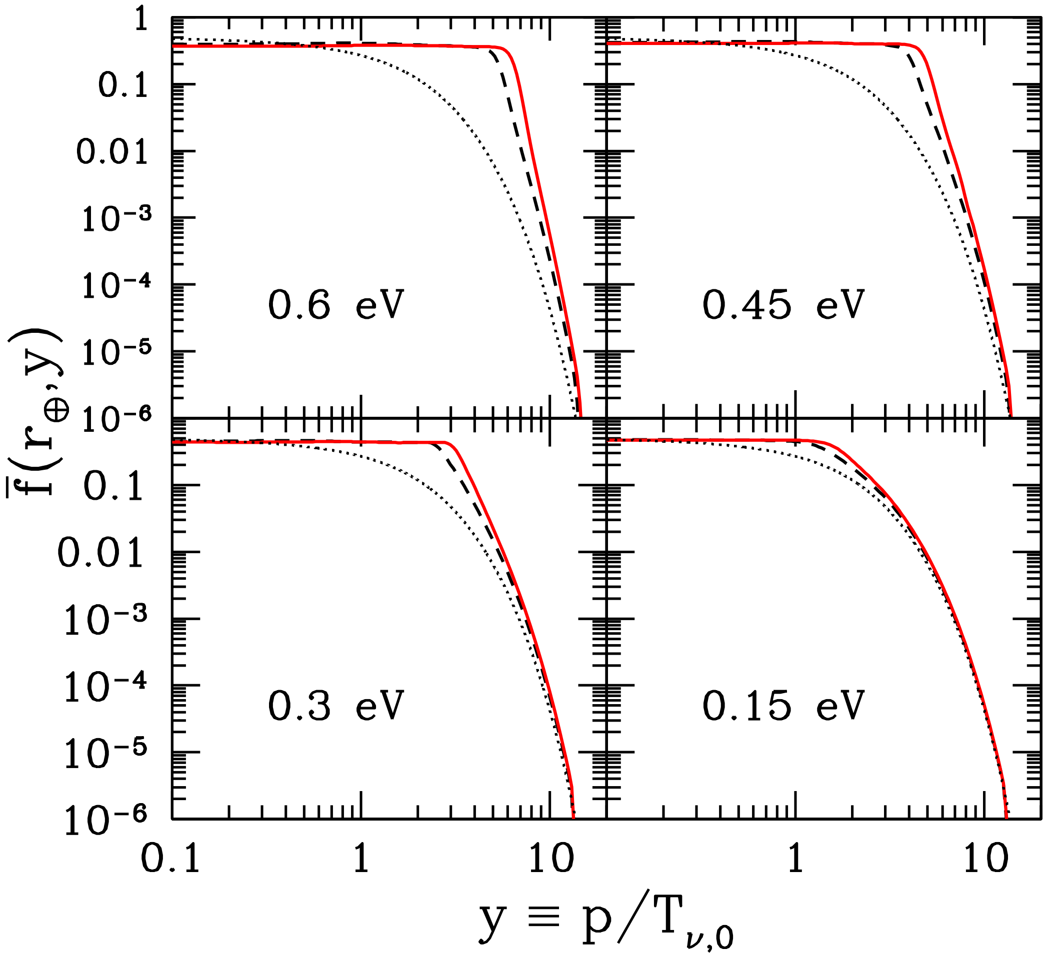
- almost isotropic:
  - ◇ $\langle p_r \rangle \simeq 0$
  - ◇ $2\langle p_r^2 \rangle \simeq \langle p_T^2 \rangle$
- flat at low momenta, with common value $\sim 1/2$
- turning point at $\simeq p_{\rm esc} \equiv m_\nu v_{\rm esc} \equiv m_\nu \sqrt{2|\phi(r_\oplus)|}$
- matches Fermi-Dirac at high momenta

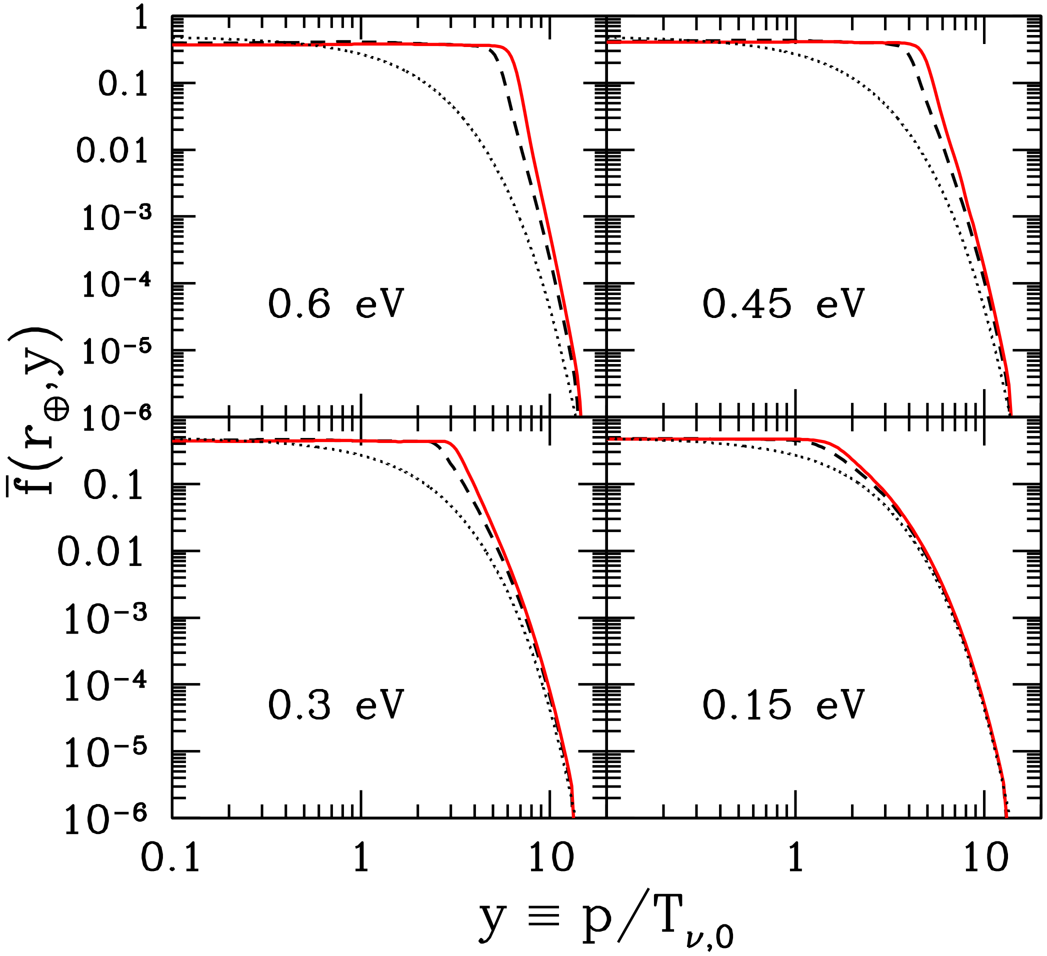


[AR,Wong '04]

Phase space bounds?

- $\bar{f} \leq \max(f_0)$: Final coarse-grained $\bar{f}$ must not exceed maximum of initial fine-grained f_0 [Lynden-Bell '67]

  √ $\bar{f}$ saturates bound up to $p_{\rm esc}$, $\sim$ semi-degenerate state that can only be made denser by filling in states above $p_{\rm esc}$



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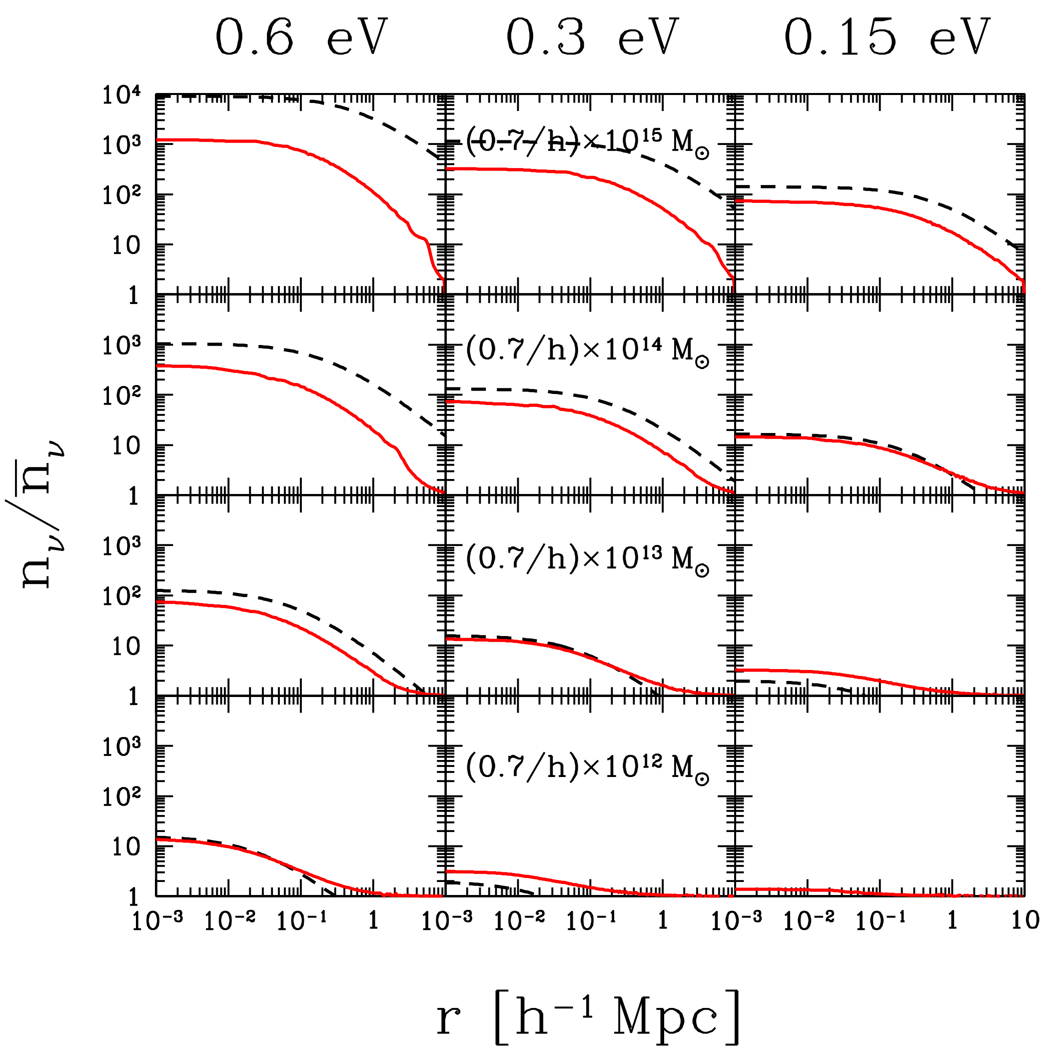
- Stronger bound: [Tremaine,Gunn '79; Kull *et al.* '96] Sum semi-degenerate distribution only up to $p_{\rm esc}$,

$$\frac{n_\nu}{\bar{n}_\nu} < \frac{m_\nu^3 v_{\rm esc}^3}{9\zeta(3)T_{\nu,0}^3}$$

  √ applicable: large $M_{\rm vir}$ (m_ν)



[AR,Wong '04]

3. Implications for detection

- Gravitational clustering of relic neutrinos significant for their detection?

- Consider detection methods based on **scattering processes**, involving the relic neutrinos either as a **beam** or as a **target**:
  - Coherent elastic scattering of the relic neutrino flux off target matter in a terrestrial detector (**flux detection**)
  - Scattering of extremely energetic particles (accelerator beams or cosmic rays) off the relic neutrinos as a target (**target detection**)

Flux detection

- Low average momentum of relic neutrinos corresponds to a (reduced) **de Broglie wavelength** of **macroscopic** dimension,

$$\lambdabar = 1/\langle p\rangle = 0.12 \ \ \mathrm{cm}/\langle y\rangle$$

⇒ Envisage scattering processes in which many target atoms act coherently over a macroscopic volume $\lambdabar^3$ ⇒ elastic scattering rate enhanced by

$$\frac{N_A}{A}\,\rho_{\rm t}\,\lambdabar^3 \simeq 6\times 10^{18}\,\left(\frac{100}{A}\right)\left(\frac{\rho_{\rm t}}{\mathrm{g/cm^3}}\right)\left(\frac{\lambdabar}{0.1\ \mathrm{cm}}\right)^3$$

compared to case where neutrinos are elastically scattered coherently only on the individual nuclei of the target [Shvartsman *et al.* ‘82; Smith,Lewin ‘83]

- Test body will experience **neutrino wind force** through random neutrino scattering:

[Shvartsman *et al.* '82; Smith,Lewin '83; ...; Duda *et al.* '01]

$$a_{\rm t} \simeq \sum_{\nu,\bar\nu} \underbrace{n_\nu\, v_{\rm rel}}_{\rm flux} \frac{4\pi}{3} N_A^2\, \rho_{\rm t}\, r_{\rm t}^3\, \sigma_{\nu N}\, \underbrace{2\, m_\nu\, v_{\rm rel}}_{\rm mom.\ transfer}$$

$$\simeq 2\times 10^{-28} \left(\frac{n_\nu}{\bar n_\nu}\right) \left(\frac{10^{-3}\, c}{v_{\rm rel}}\right) \left(\frac{\rho_{\rm t}}{\rm g/cm^3}\right) \left(\frac{r_{\rm t}}{\lambda\!\!\!^{-}}\right)^3 \frac{\rm cm}{\rm s^2}$$

Majorana neutrinos: suppressed by factor $(v_{\rm rel}/c)^2$

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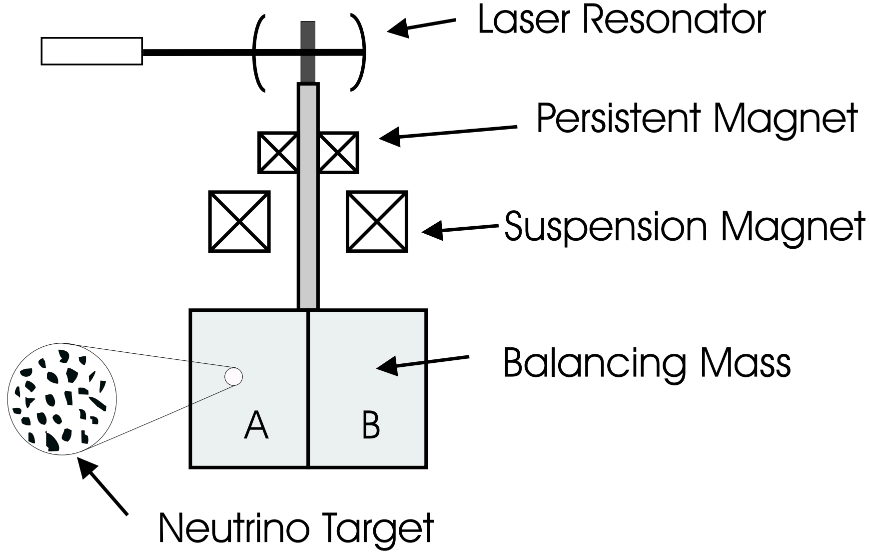
- At present, smallest measurable acceleration $\gtrsim 10^{-13}$ cm/s^2, using conventional **Cavendish-type torsion balance**. Improvements to $\gtrsim 10^{-23}$ cm/s^2 proposed

[Hagmann '99]



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	$\frac{n_\nu}{\bar n_\nu}$	$\lambda\!\!\!^{-} = \frac{1}{\langle p\rangle}$	$\langle v\rangle$
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0.45 eV	10	2.9×10^{-2} cm	1.5×10^{-3}
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[Hagmann '99]

$\Rightarrow$ Detection possible in 30 – 40 years, if neutrinos are Dirac particles [Smith '03]

Target detection

- For center-of-mass energies below W- and Z-resonances, cf.

$$\sqrt{2\,m_\nu\,E} \simeq 4.5\ \left(\frac{m_\nu}{\rm eV}\right)^{1/2} \left(\frac{E}{10\ {\rm TeV}}\right)^{1/2}\ {\rm MeV}$$

weak interaction cross sections **grow rapidly with energy**

⇒ Exploit a flux of extremely energetic particles

– **accelerator beams**
– **from cosmic rays**

for scattering on relic neutrinos as **target**

Exploit accelerator beams:

- Scattering rate [B. Müller '87; Melissinos '99, Weiler '01]

$$R_{\nu\, {}^A_Z N} \simeq \sum_{\nu,\bar\nu} n_\nu\, \sigma_{\nu\, {}^A_Z N}\, L\, I/(Z\, e)$$

$$\simeq 2\times 10^{-8} \left(\frac{n_\nu}{\bar n_\nu}\right)\left(\frac{m_\nu}{\text{eV}}\right)\frac{A^2}{Z}\left(\frac{E_N}{10\ \text{TeV}}\right)\left(\frac{L}{100\ \text{km}}\right)\left(\frac{I}{0.1\ \text{A}}\right)\ \text{yr}^{-1}$$

⇒ Too small to give rise to an observable effect in the foreseeable future (**LHC**, **VLHC**)

⇒ Need **U**ltimate **L**arge **H**adron **C**ollider

– Few **elastic** scattering events per year; hard to detect, due to small momentum transfers (~ 1 GeV at $E_N \sim 10^7$ TeV)

– Alternative: exploit inverse beta decay

$${}^A_Z N + \nu_e \to {}^A_{Z+1} N + e^-$$

⇒ detect ${}^A_{Z+1}N$ on exit of machine

[Melissinos '99; Zavattini unpubl]

accel.	N	E_N [TeV]	L [km]	I [A]	$\frac{R_{\nu A}}{\left[\frac{n_\nu}{\bar n_\nu}\frac{m_\nu}{\text{eV}}\right]}$ [yr^{-1}]
LHC	p	7	26.7	0.6	2×10^{-8}
	Pb	574	26.7	0.006	1×10^{-5}
VLHC	p	87.5	233	0.06	2×10^{-7}
	Pb	7280	233	0.0006	1×10^{-4}
ULHC	p	10^7	40 000	0.1	10

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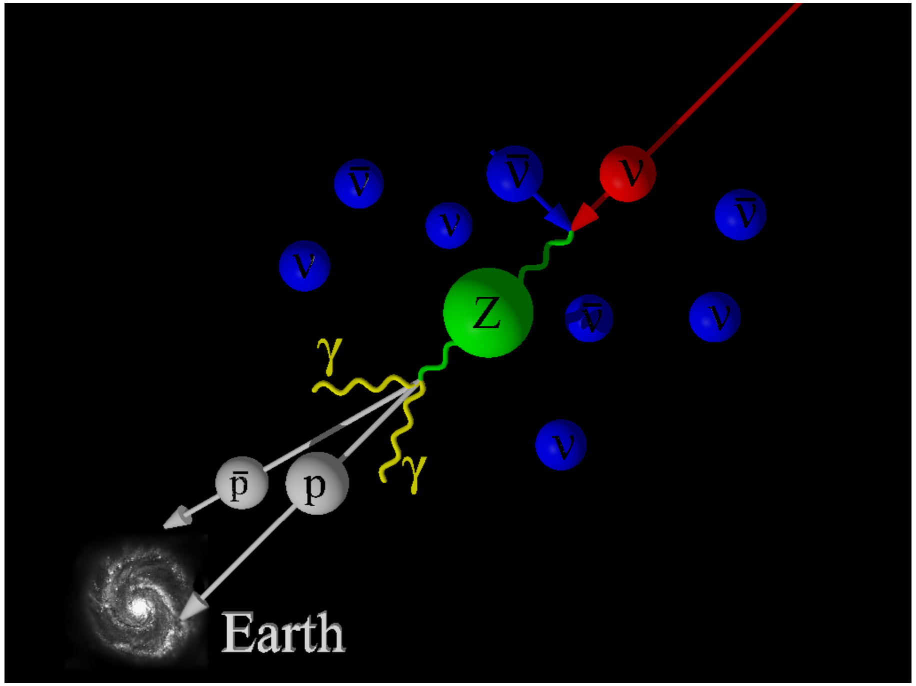
- Unique: resonant annihilation of extremely energetic cosmic neutrinos (**EHECν**)

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

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



[Fodor,Katz,AR '02]

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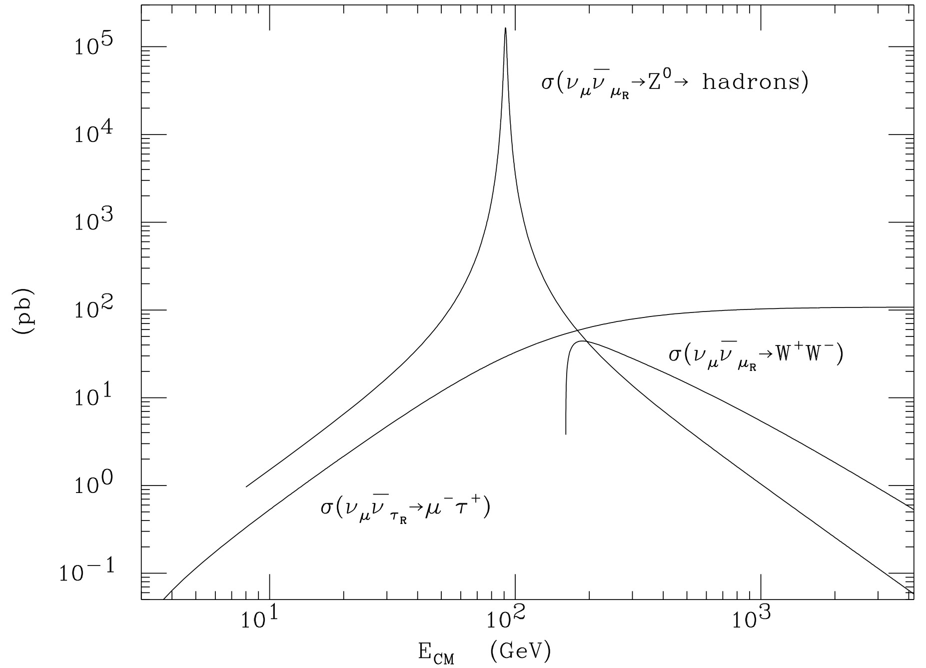

[Fargion,Mele,Salis '99]

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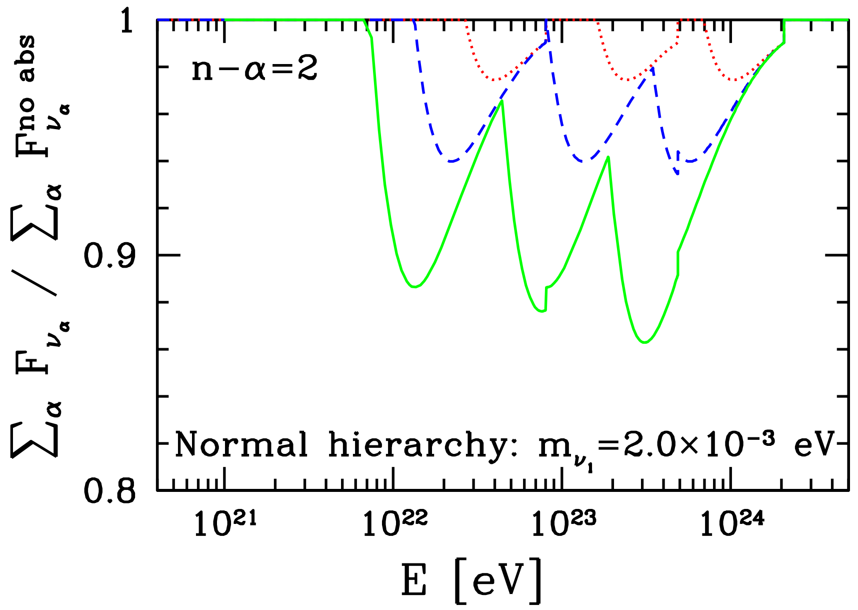
◇ Absorption dips in **EHECν** spectrum

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



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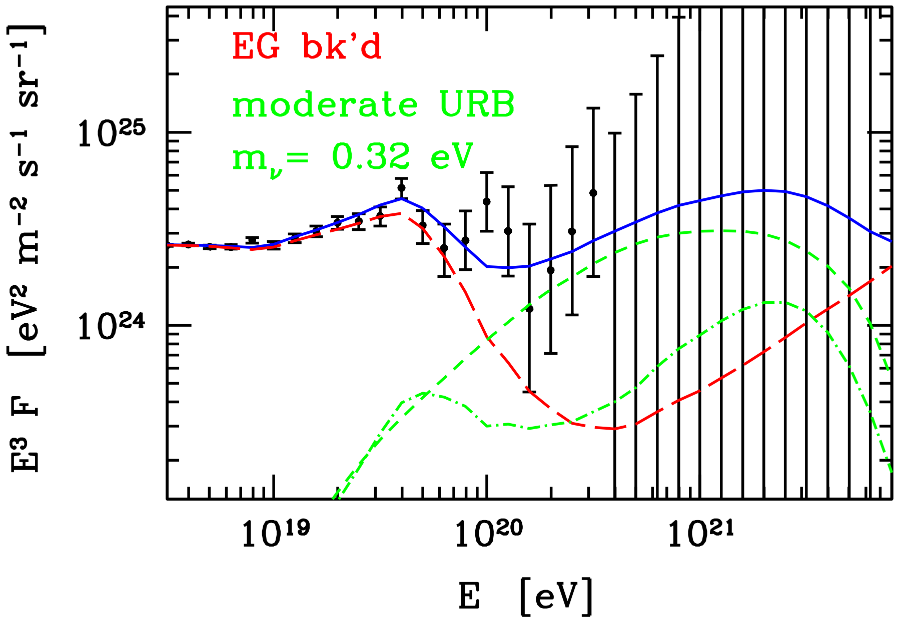
[Weiler '82;...; Eberle,AR,Song,Weiler '04]

◇ 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]



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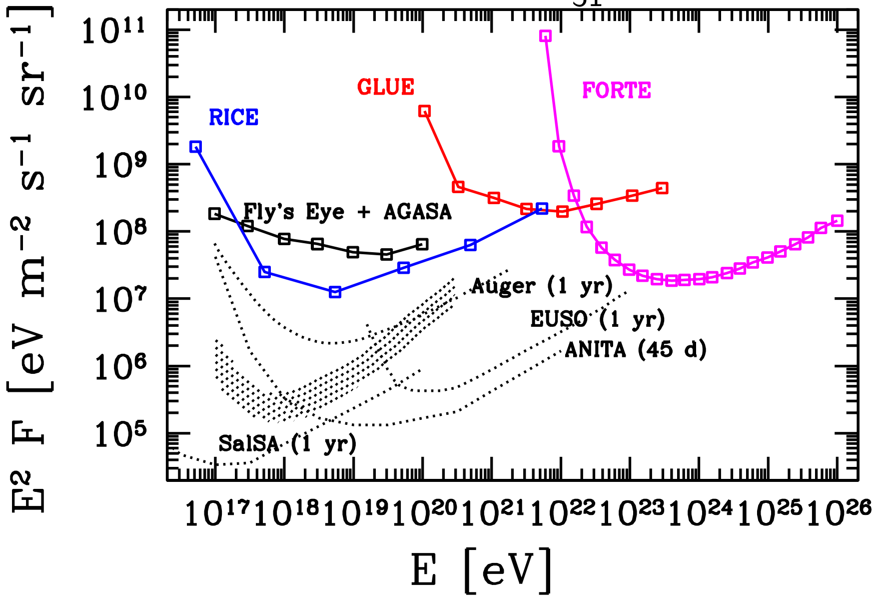

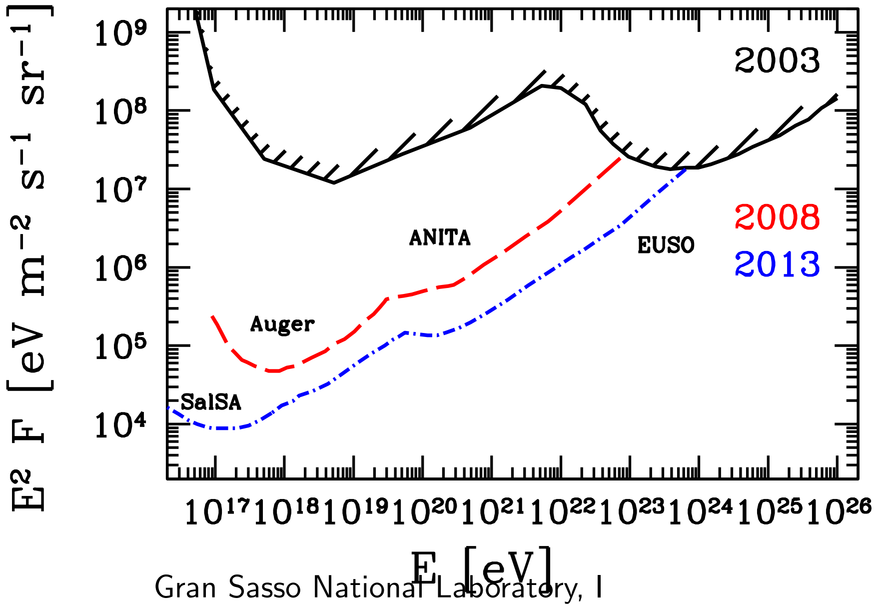

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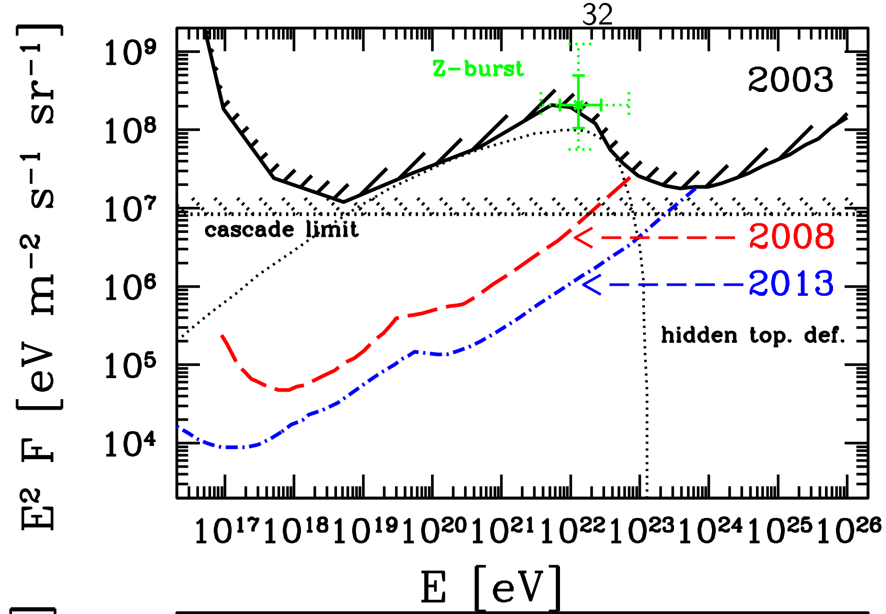

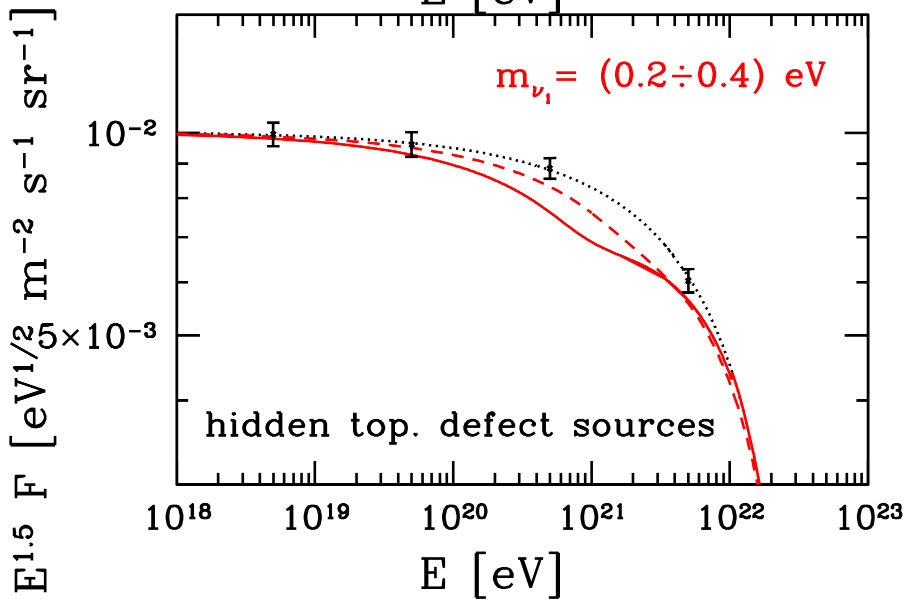

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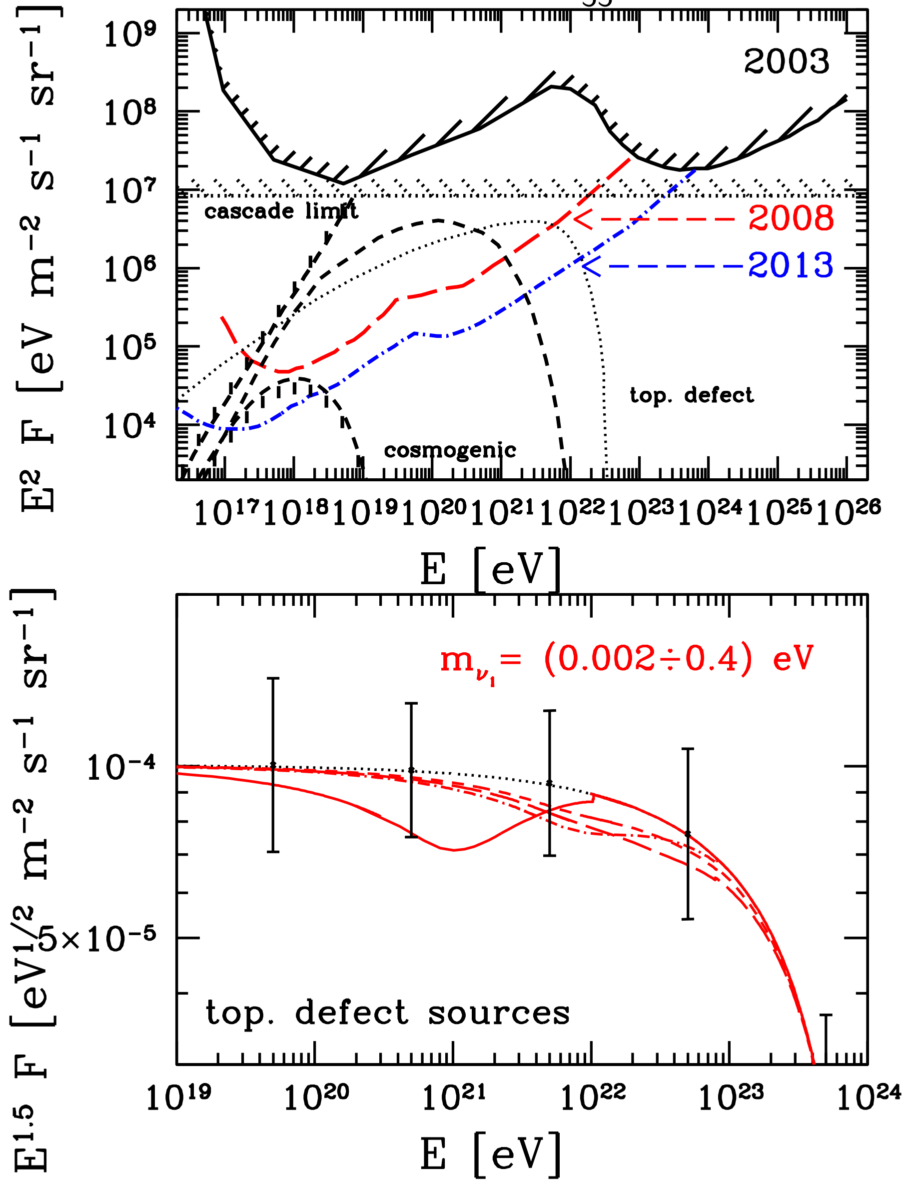

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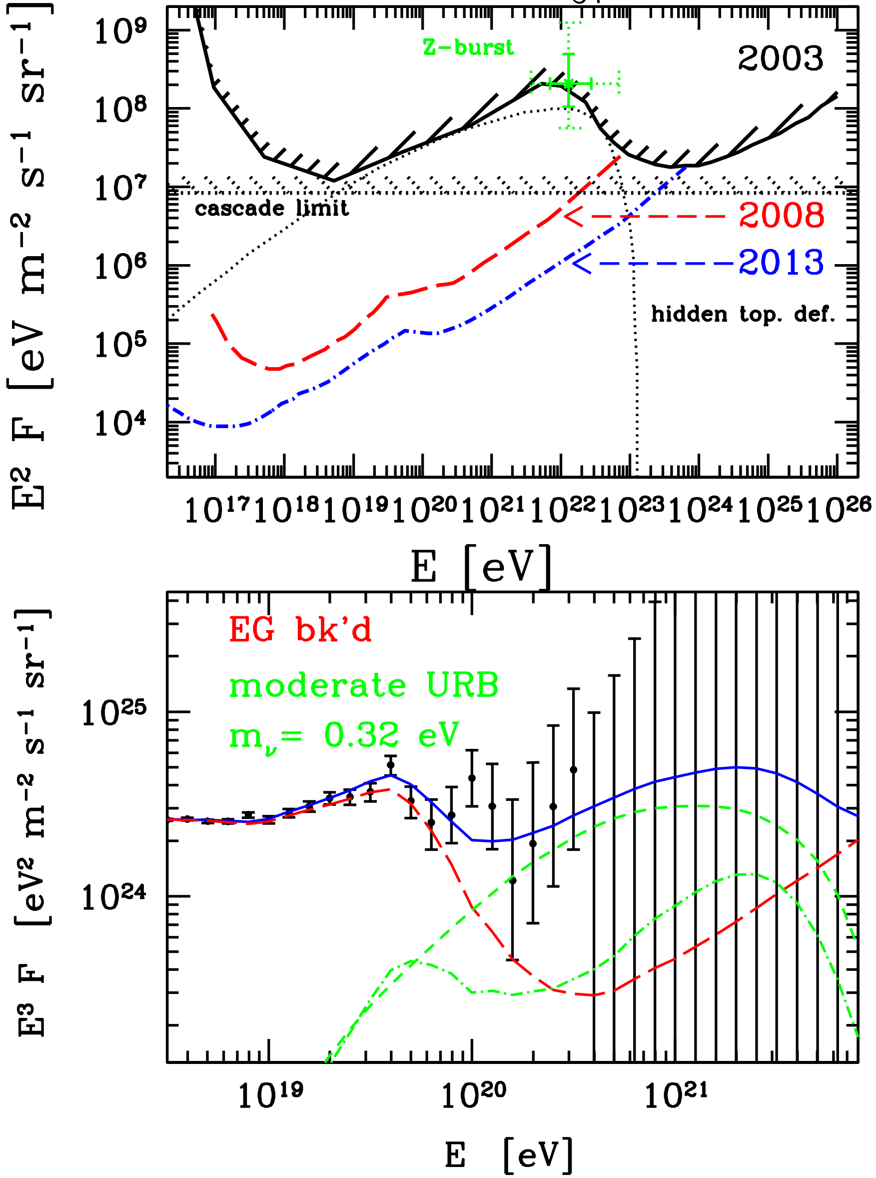
- In this case, the associated ***Z*-bursts** likely to be seen as post-GZK events at the planned cosmic ray detectors



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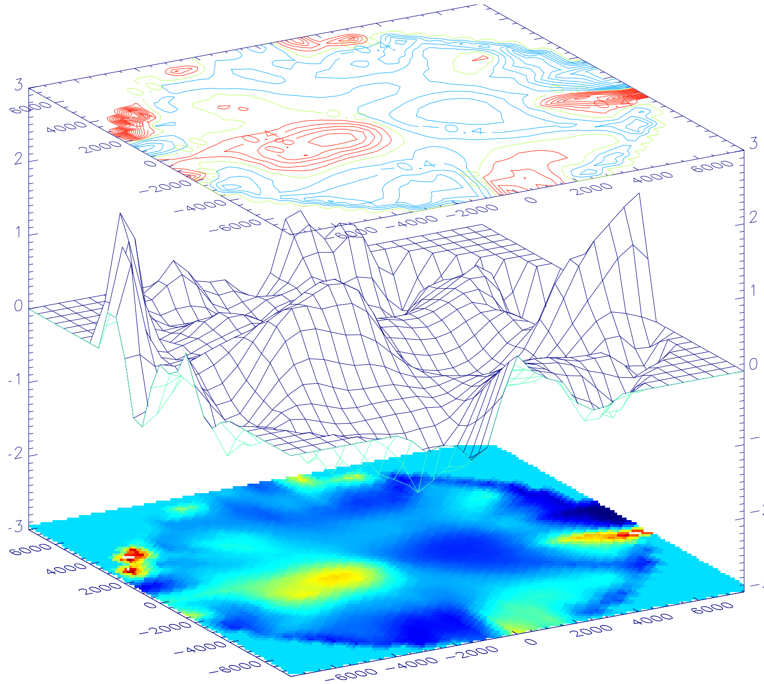

[Da Costa *et al.* '96]

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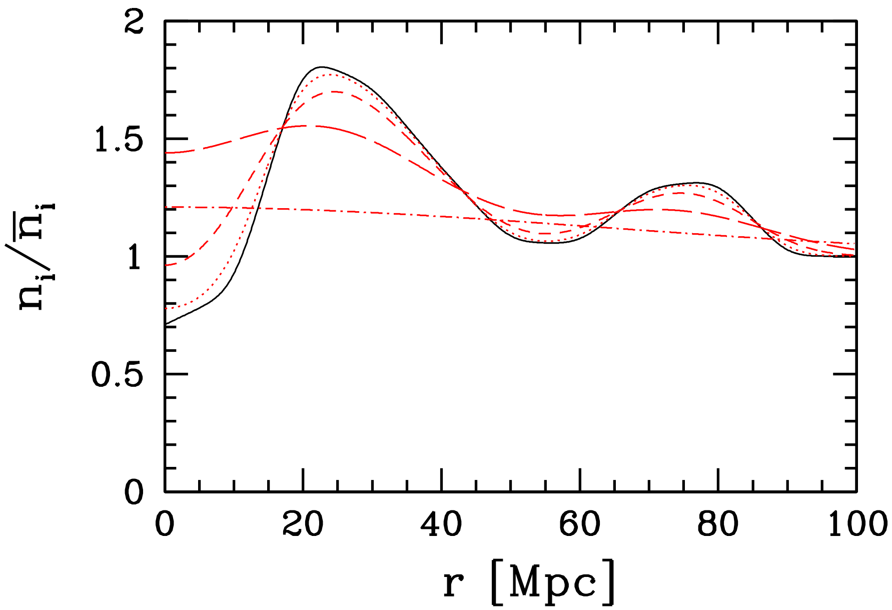

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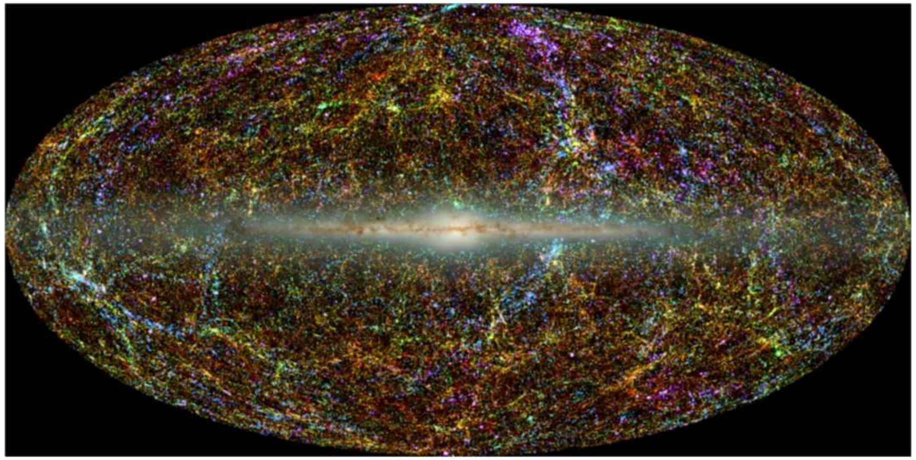
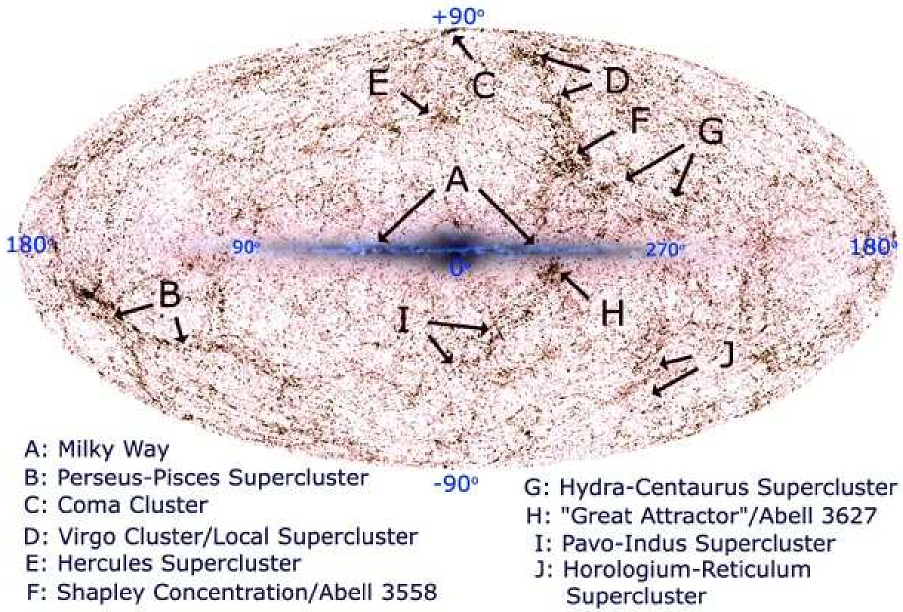
  - ⇒ **no significant enhancement of overall emission rate** by gravitational clustering
  - ◇ **relic neutrino tomography:** for $\sim 1^\circ$ angular resolution and $m_\nu \sim 0.15 - 0.6$ eV, expect $\sim 8 - 55$ increase in number of events from Virgo





[Jarrett [2MASS] '04]

4. Conclusions

- Study of gravitational clustering of big bang relic neutrinos onto existing **CDM** and baryonic structures within flat **ΛCDM** model
  - Clustering properties on galaxy cluster, galactic, and sub-galactic scales for a range of allowed neutrino masses
    - Local universe:
      - Overdensity ≈ 1000 (≈ 100) for $m_\nu = 0.6$ eV ($= 0.15$ eV) for inner part ($\lesssim 100$ kpc) of Virgo and Centaurus
    - Local neighbourhood of Earth:
      - Overdensity ≈ 20 (≈ 2) for $m_\nu = 0.6$ eV ($= 0.15$ eV)
      - Coarse-grained momentum spectrum semi-degenerate, $\bar{f} \sim 1/2$, up to escape momentum
      - Higher density needs non-standard theory
  - No tremendous increase of rate for scattering-based detection
  - Visible in non-linear matter power spectrum? [Abazajian *et al.*, talk in Trento, Oct '04]