Prospects of Relic Neutrino Detection

Andreas Ringwald

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

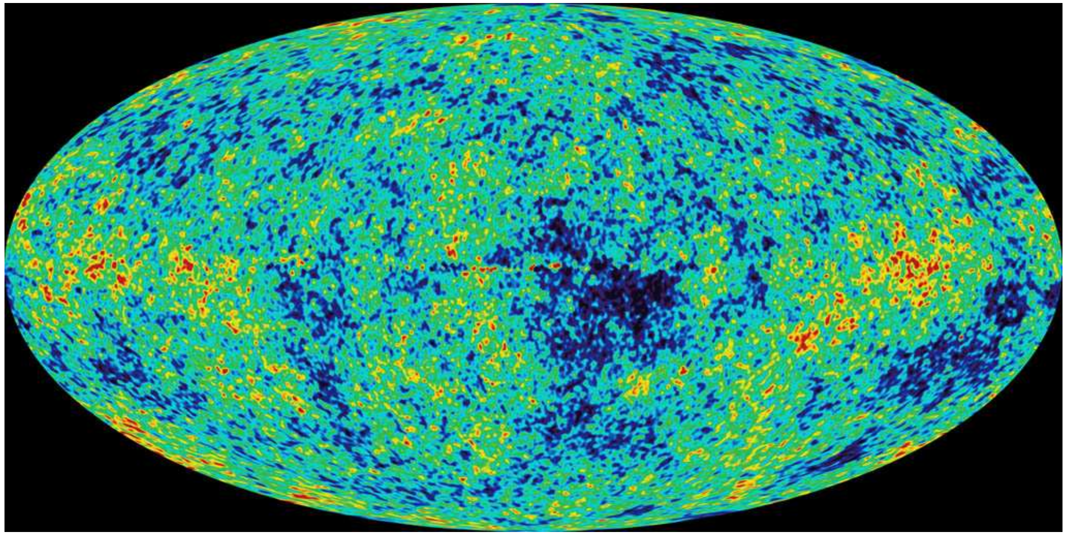
with: **B. Eberle, Z. Fodor, S. Katz, L. Song, T. Weiler, Y. Wong**

Theorie Seminar
April 21, 2005, Aachen, Germany

0. Introduction

- Progress in observational cosmology

Cosmic Microwave Background:



[WMAP '03]

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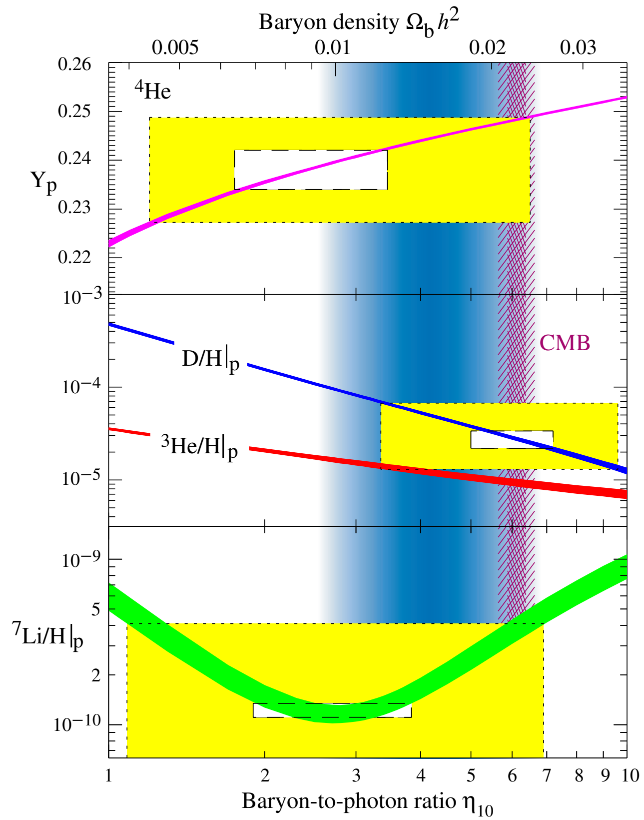
Big **B**ang **N**ucleosynthesis:



[Particle Data Group '04]

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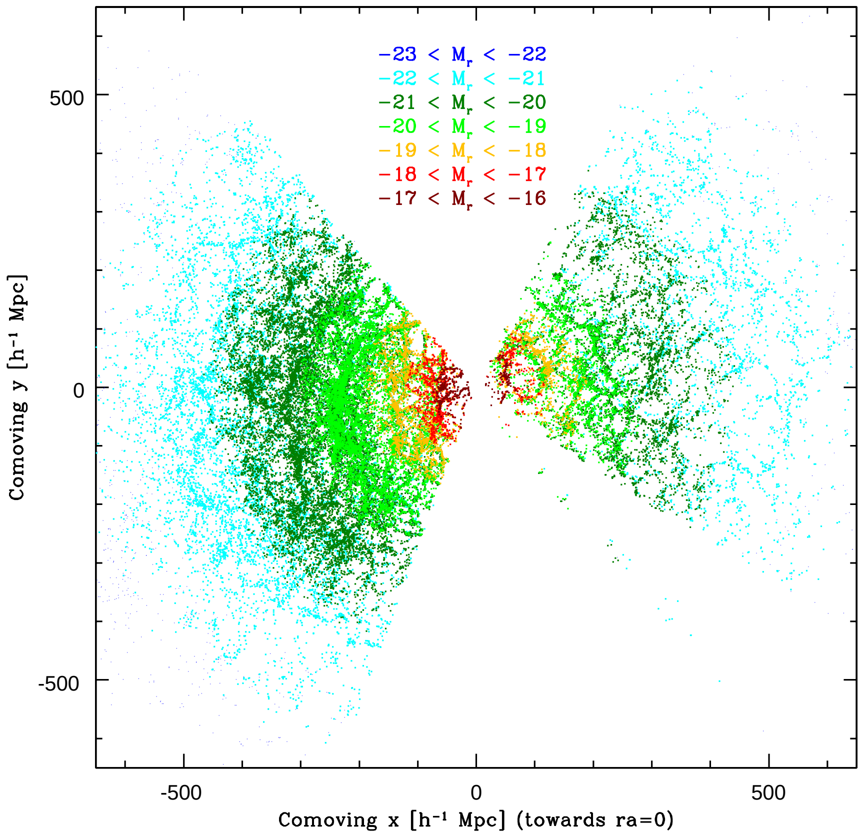
Large **S**cale **S**tructure:



[Sloan Digital Sky Survey '04]

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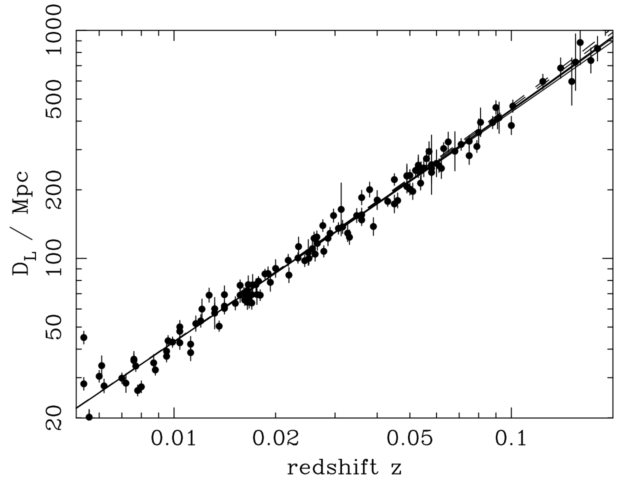
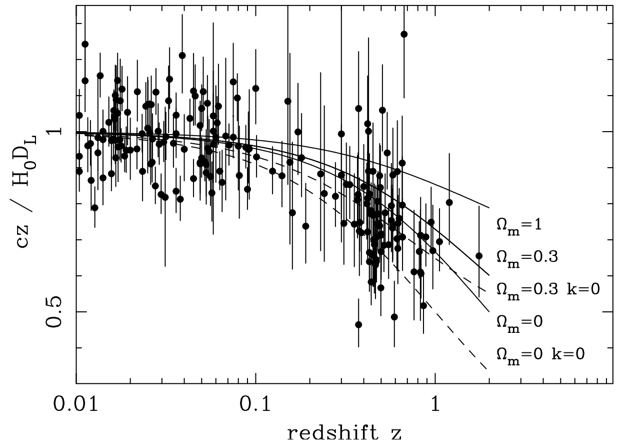
SuperNovae 1a:





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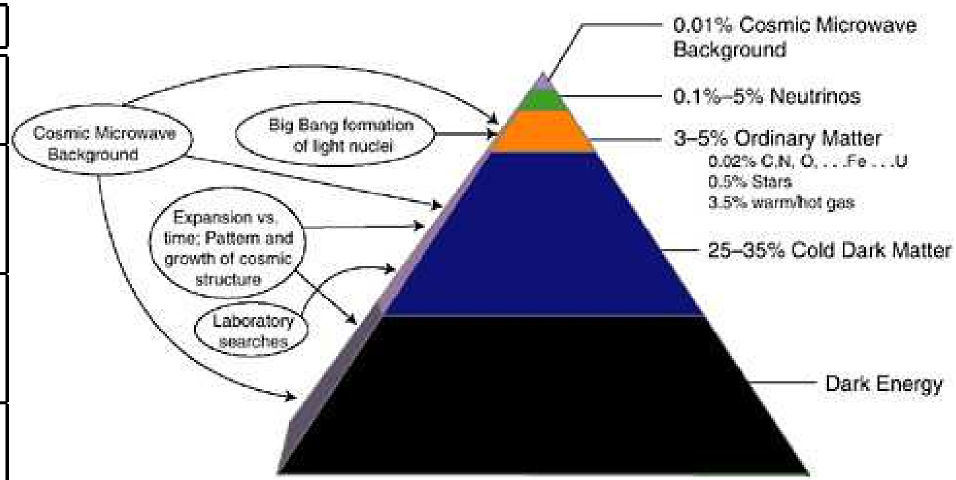
$\Rightarrow$ Cosmic recipe emerged:

Material	Particles	$\langle E \rangle$ or m	N	$\langle \rho \rangle / \rho_c$	Obs.
Radiation	γ	0.1 meV	10^{87}	0.01 %	CMB
Hot Dark Matter	Neutrinos	> 0.04 eV < 0.6 eV	10^{87}	> 0.1 % < 2 %	BBN CMB LSS
Ordinary Matter	p, n, e	MeV-GeV	10^{78}	5 %	BBN CMB
Cold Dark Matter	WIMPs? Axions?	$\gtrsim 100$ GeV $\lesssim$ meV	$\lesssim 10^{77}$ $\gtrsim 10^{91}$	25 %	LSS CMB
Dark Energy	?	10^{-33} eV	?	70 %	SN CMB



[Connecting quarks ... cosmos]

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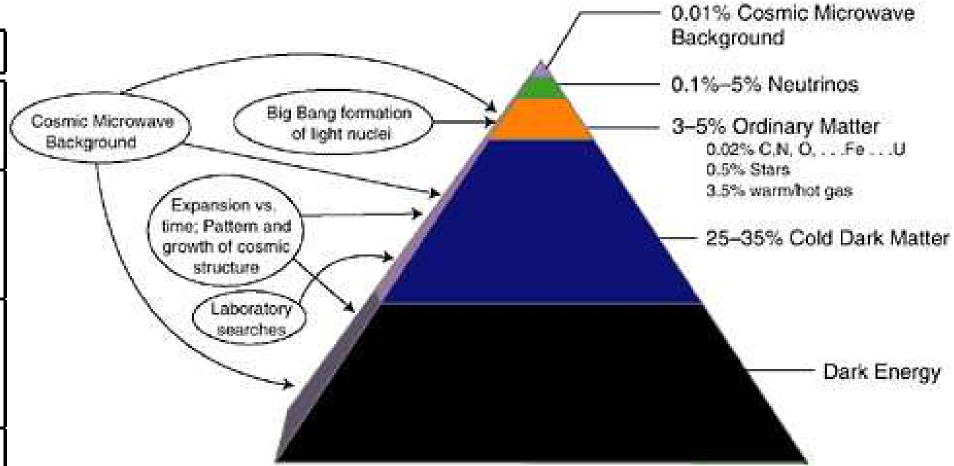


[Connecting quarks ... cosmos]

$\Rightarrow$ Direct, weak interaction based detection of the **Cosmic Neutrino Background** (**CνB**)?

- Evidence for/inference about **CνB** from cosmological measurements:
  - **BBN**: $1.3 \leq N_\nu \leq 7.1$
  - **CMB**: $0.9 \leq N_\nu \leq 8.3$
  - **LSS** (together with **CMB**): $\sum m_{\nu_i} \leq 1.8$ eV
- **CνB** has not been detected **in laboratory**:

$\Leftarrow$ Neutrinos interact only weakly

$\Leftarrow$ Smallness of neutrino mass $\Leftrightarrow$ small momentum-transfer

- Design of **direct, weak interaction based detection experiment**

$\Leftarrow$ Need phase space distribution of relic neutrinos

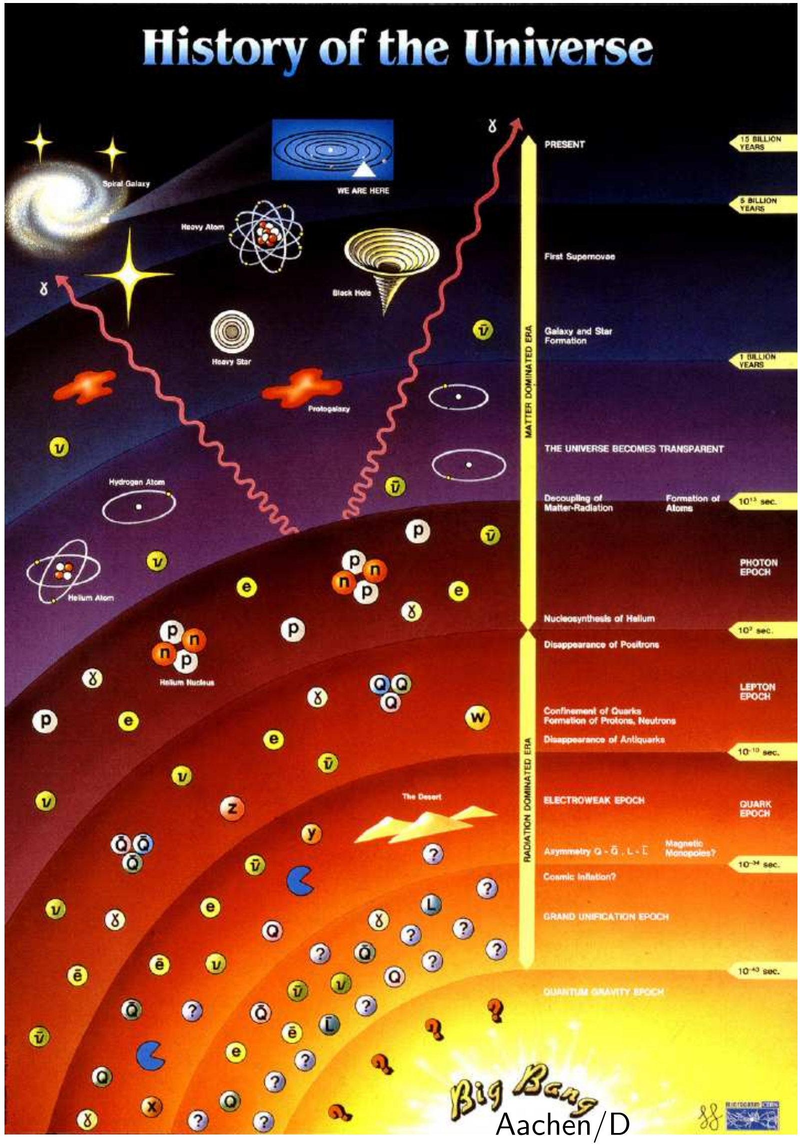
$\Leftarrow$ **Theoretically known better than ever!**

Further content:

1. **How many, how fast?**
2. **How to detect?**
3. **Conclusions**

1. How many, how fast?

- Relic neutrinos decoupled at $t \sim 1$ s



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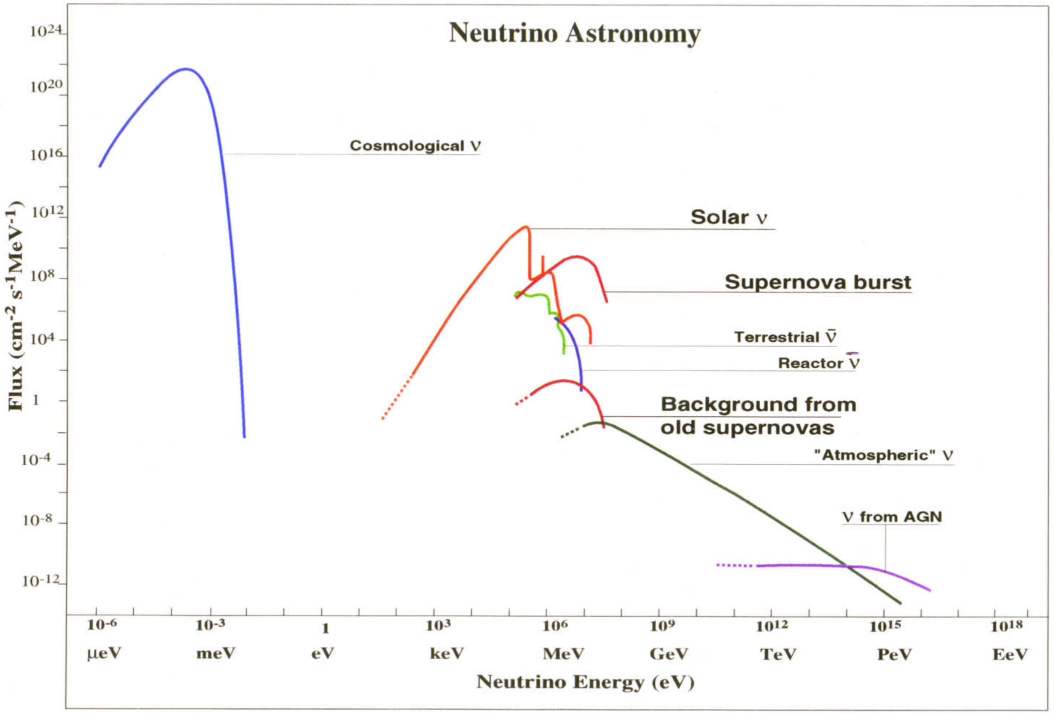
$$\underbrace{\bar{n}_{\nu_i\,0} = \bar{n}_{\bar{\nu}_i\,0}}_{\mathrm{C}\nu\mathrm{B}} = \frac{3}{22}\underbrace{\bar{n}_{\gamma\,0}}_{\mathrm{CMB}} = 56\ \mathrm{cm}^{-3}$$

relic neutrinos ≈ # relic photons



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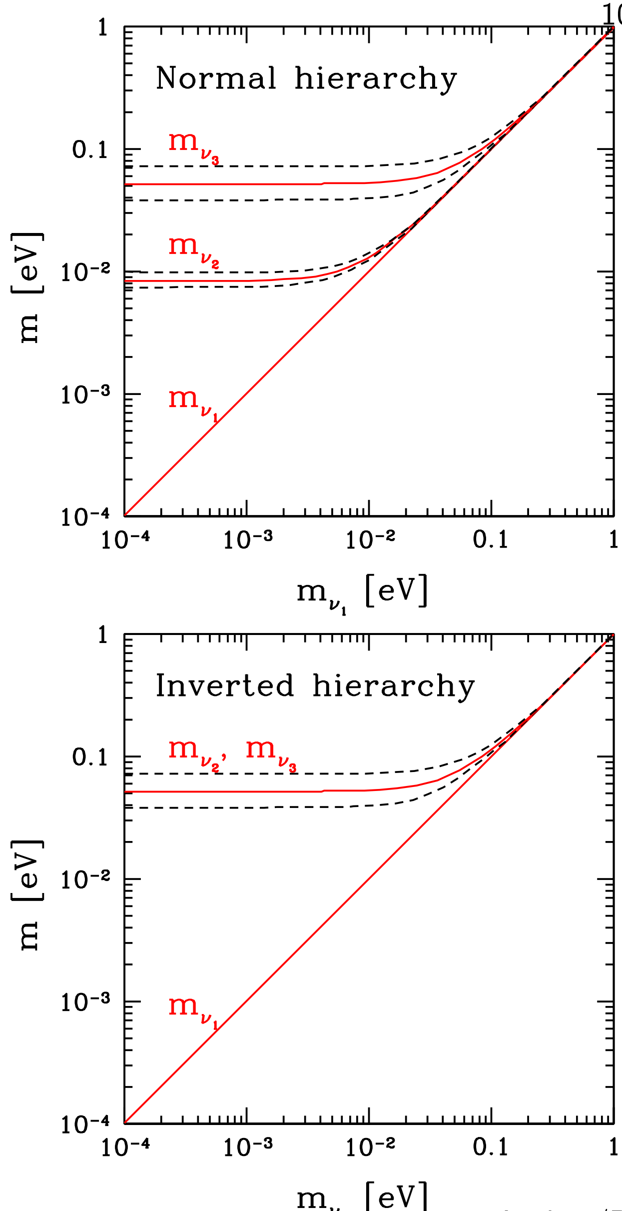
At least two neutrino mass eigenstates nonrelativistic ($m_{\nu_i} \gg 5\times 10^{-4}$ eV)



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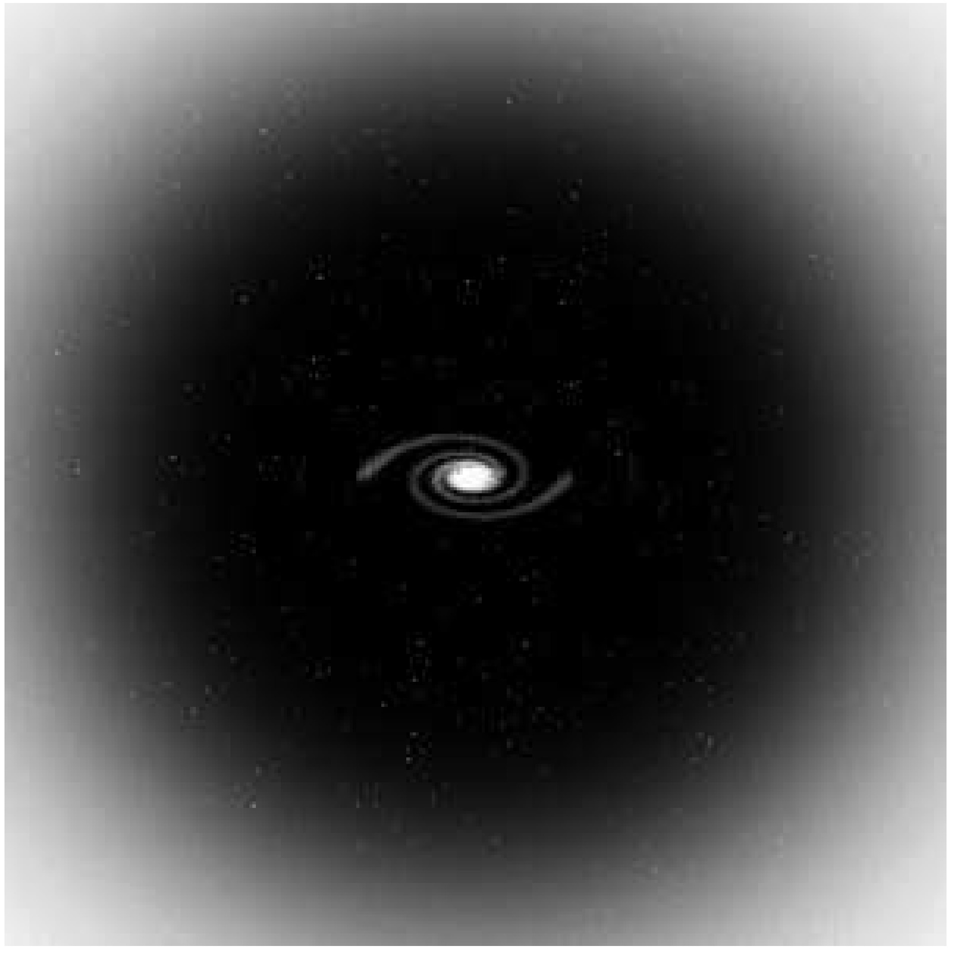
⇒ Gravitational clustering on **CDM**

⇒ Density enhanced in galactic halos



[archive.ncsa.uiuc.edu]

Neutrino clustering in cold dark matter halos from ΛCDM simulations

[Singh,Ma '03; **AR, Yvonne Y. Wong, JCAP 0412 (2004) 005 [hep-ph/0408241]**]

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  $\Rightarrow$ **CDM** component ρ_m dominates in gravitational potential ϕ
  $\Rightarrow$ Study clustering in ρ_m profiles from Λ**CDM** N-body simulations

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- Poisson equation

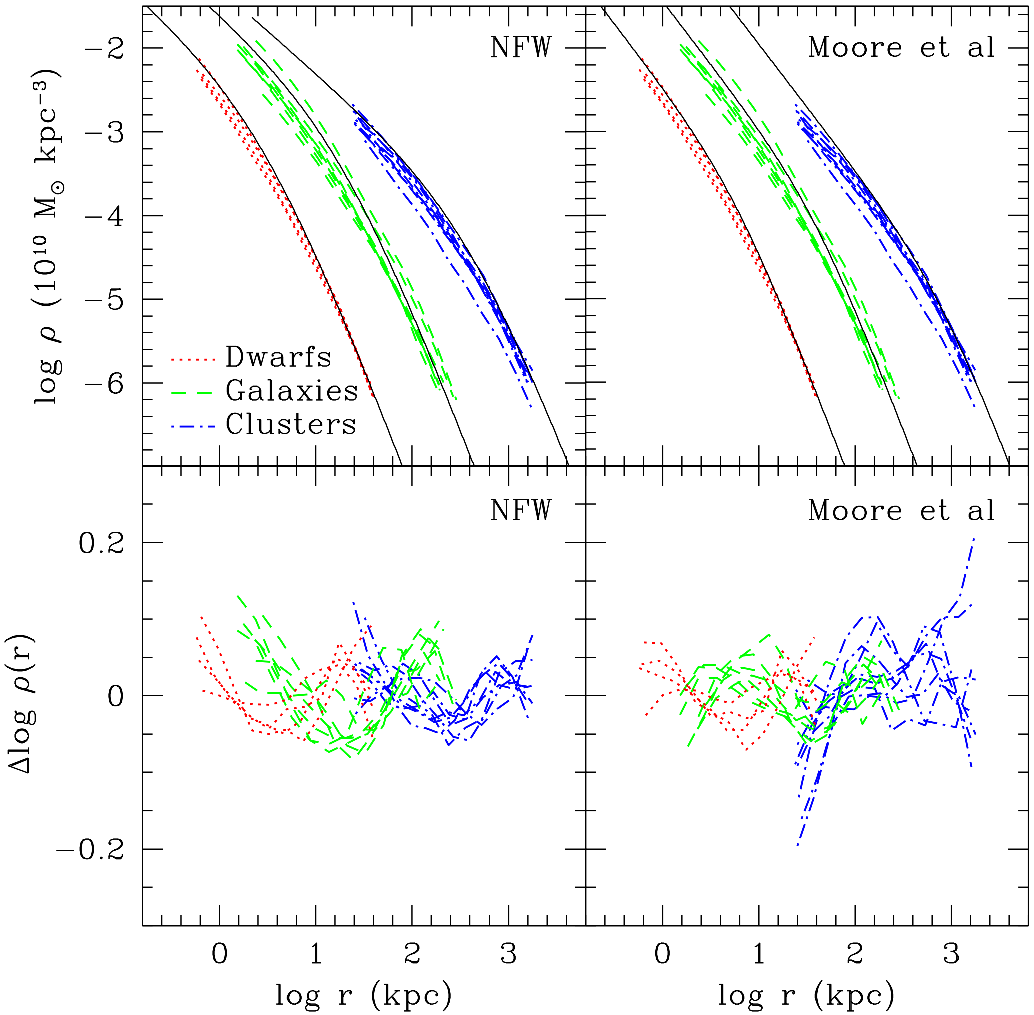
$$\nabla^2 \phi = 4\pi G a^2 \underbrace{\left(\rho_m(\boldsymbol{x},\tau) - \overline{\rho}_m(\tau)\right)}_{\delta_m(\boldsymbol{x},\tau)\,\overline{\rho}_m(\tau)}$$

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

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

- Use **N**avarro **F**renk **W**hite **CDM** halo profiles,

$$\rho_m(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$



[Navarro *et al.* '04]

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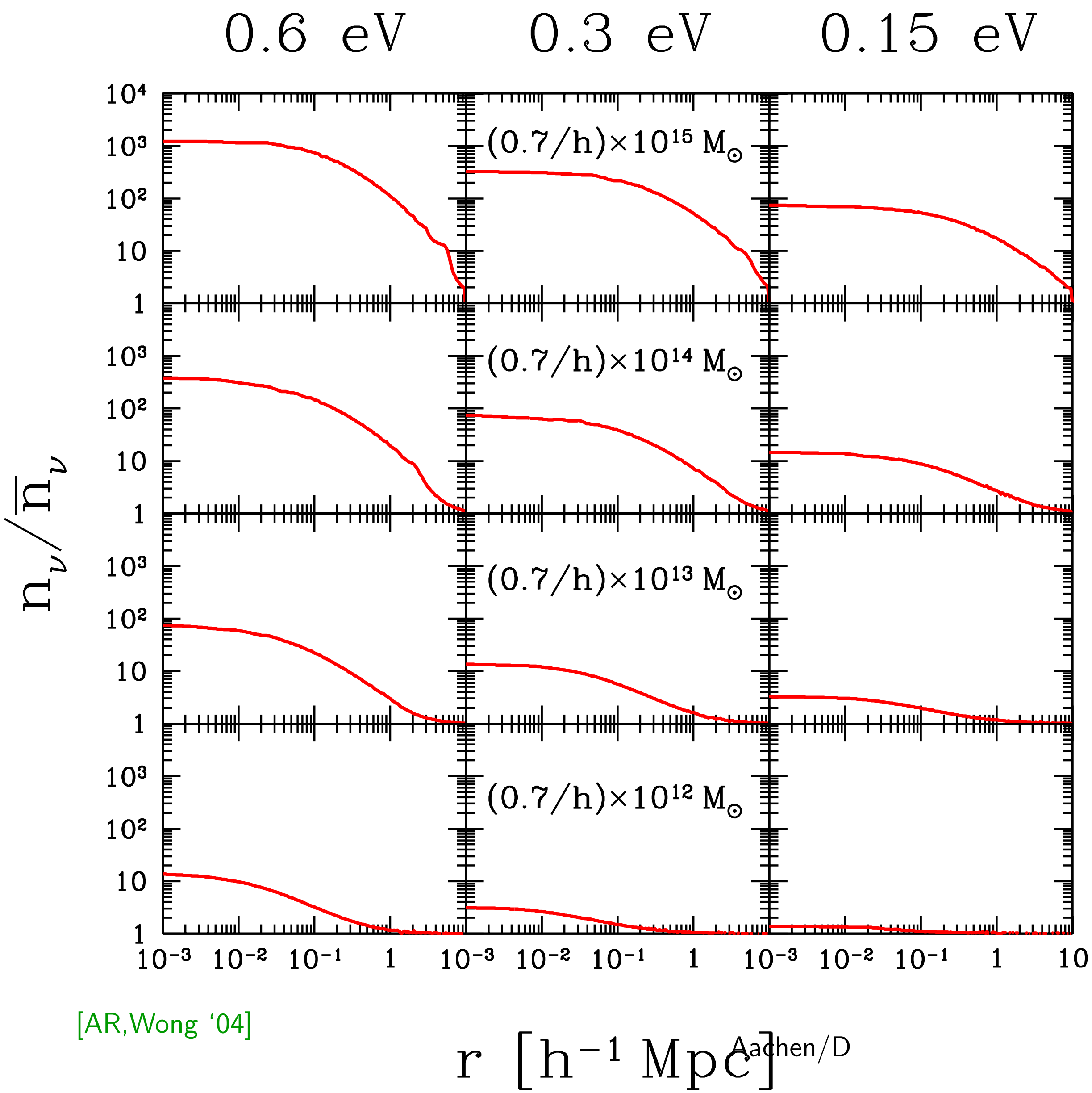

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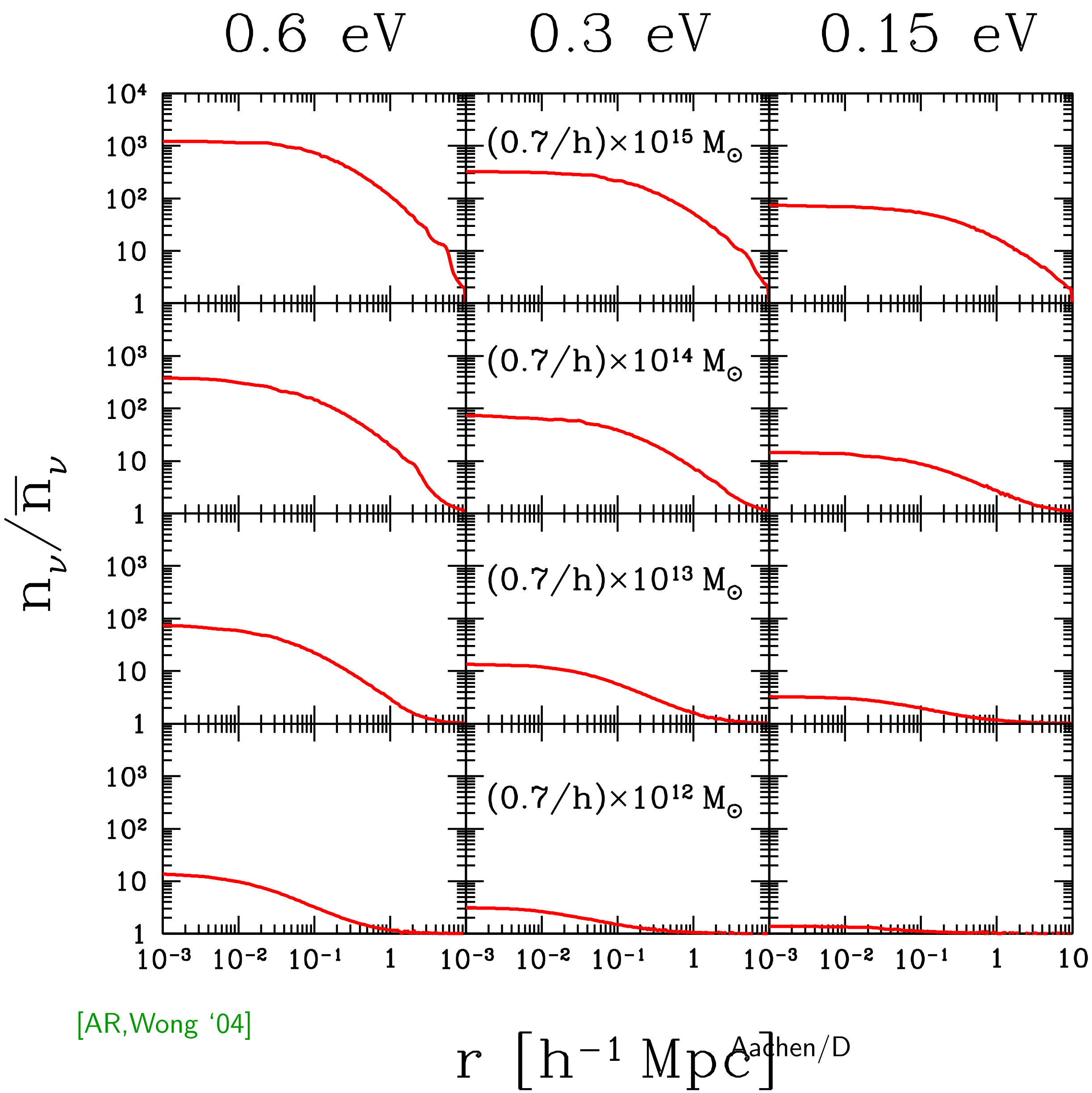

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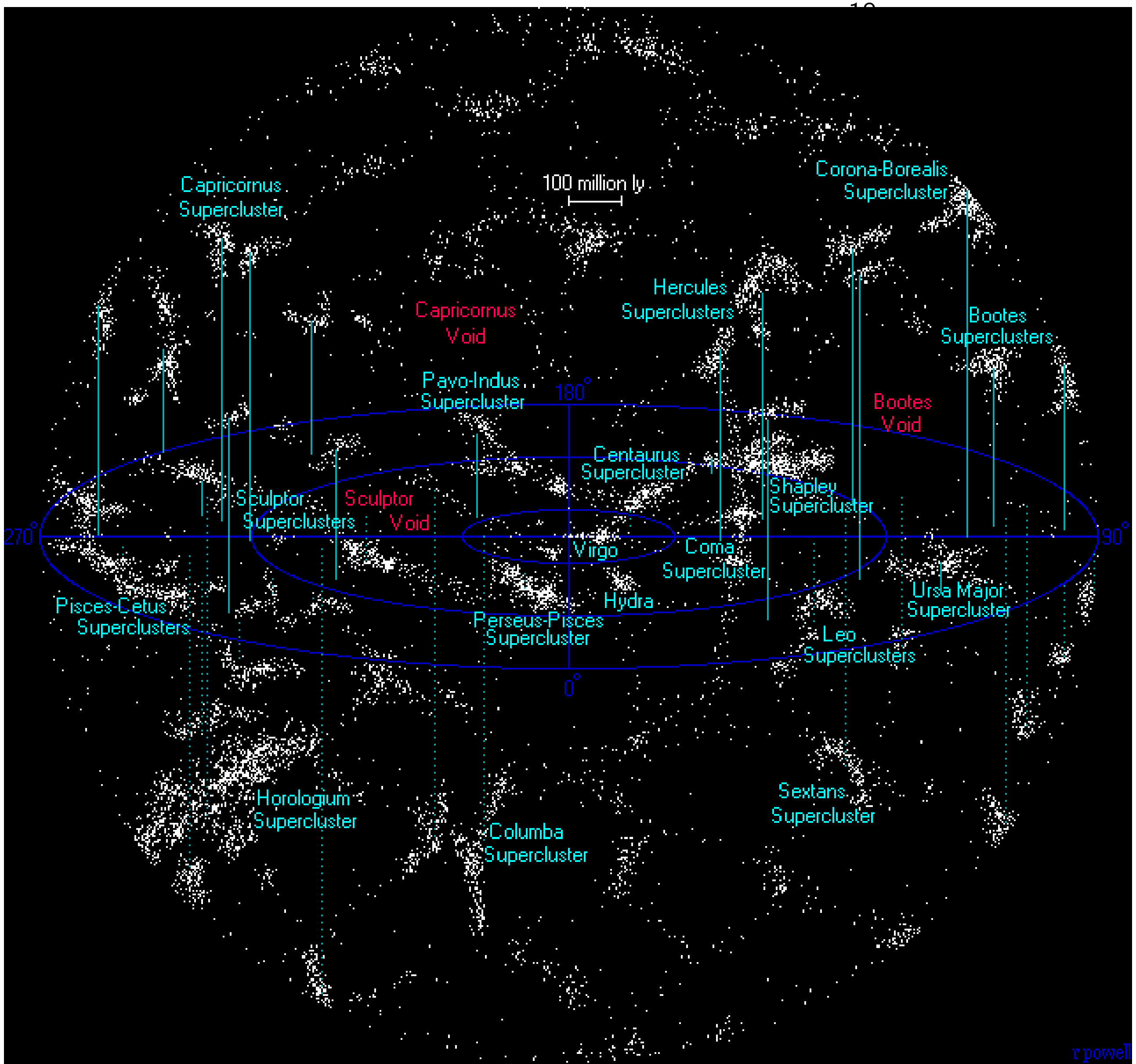

[www.extrasolar.org]

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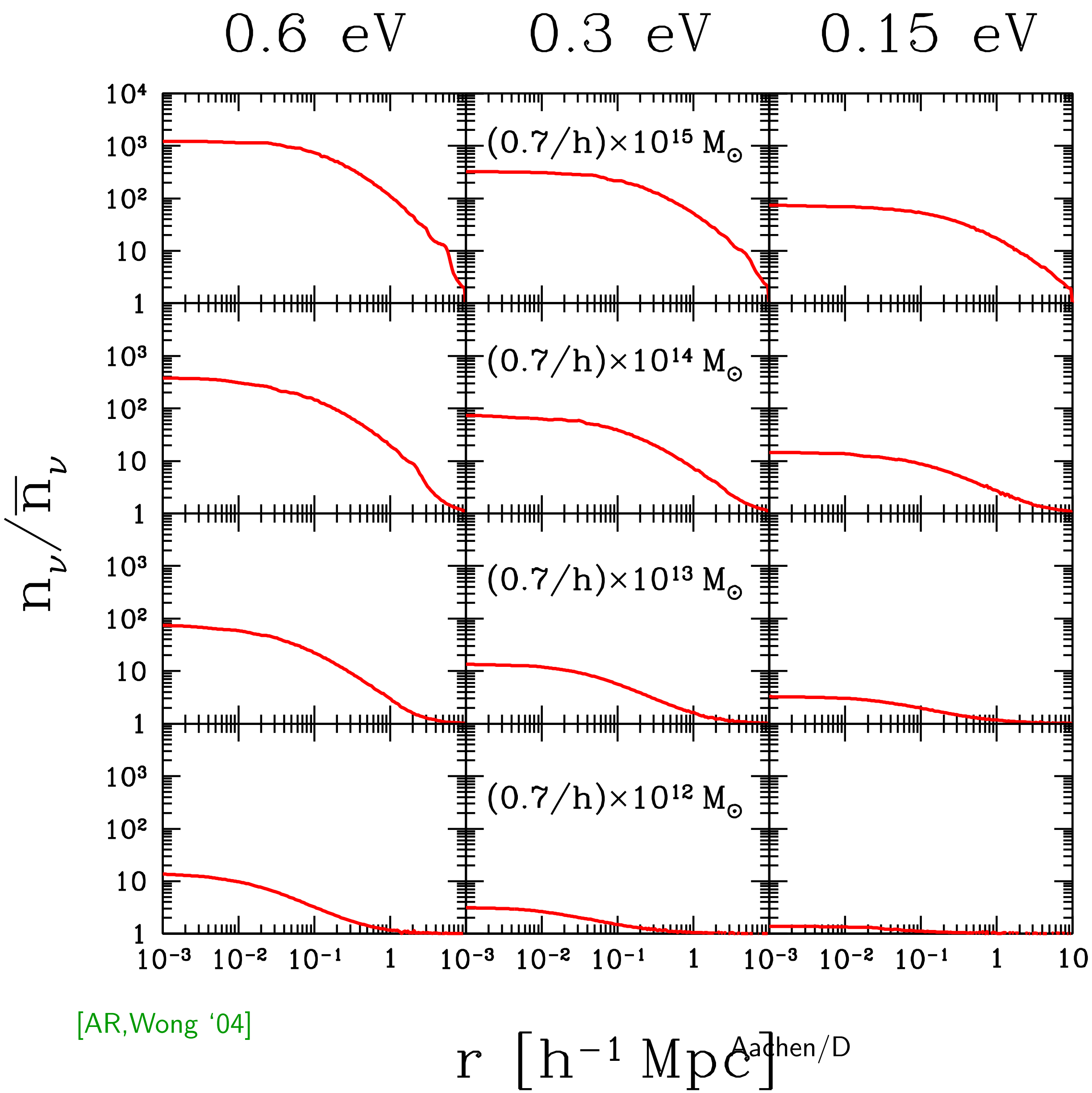

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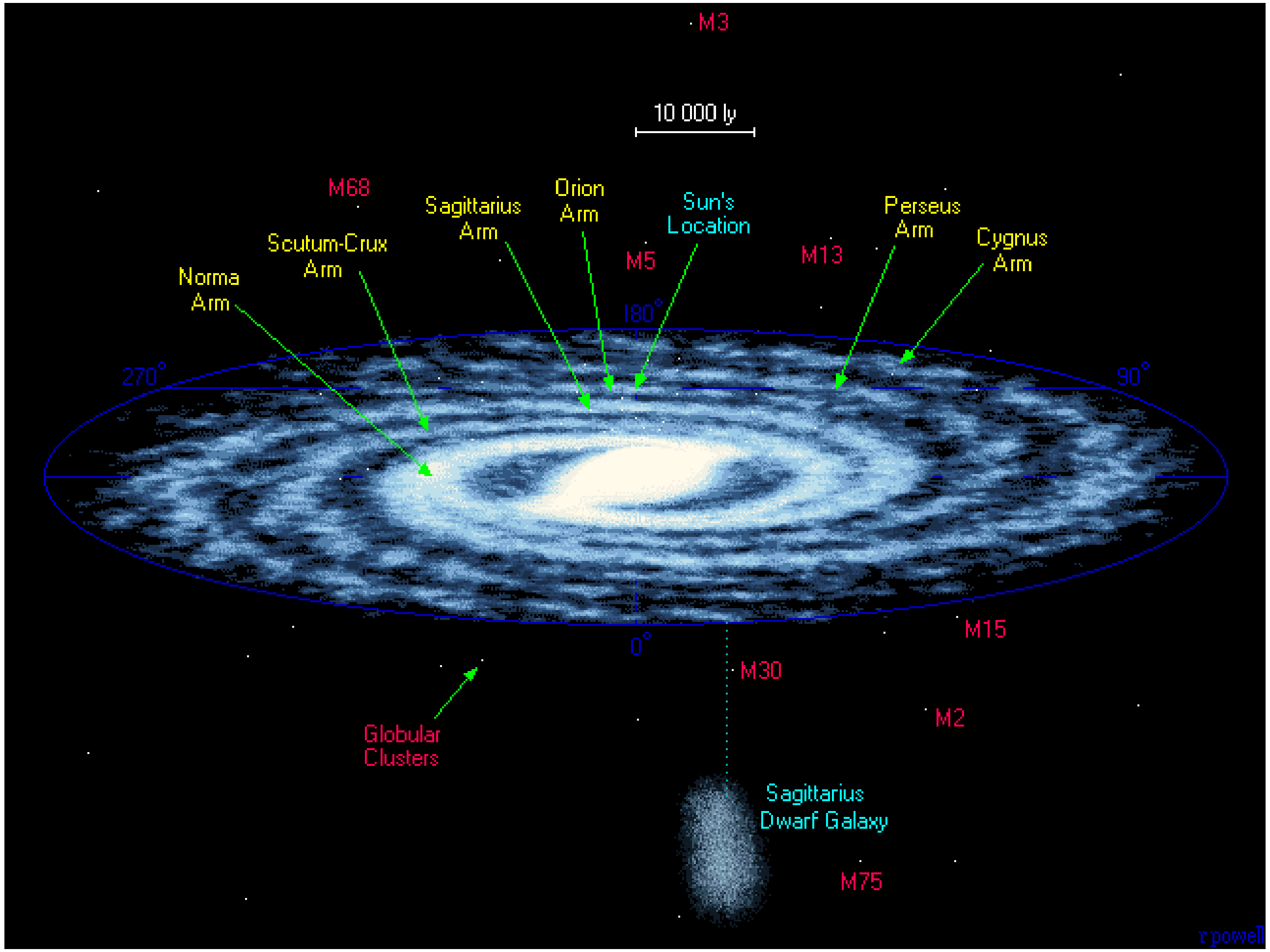

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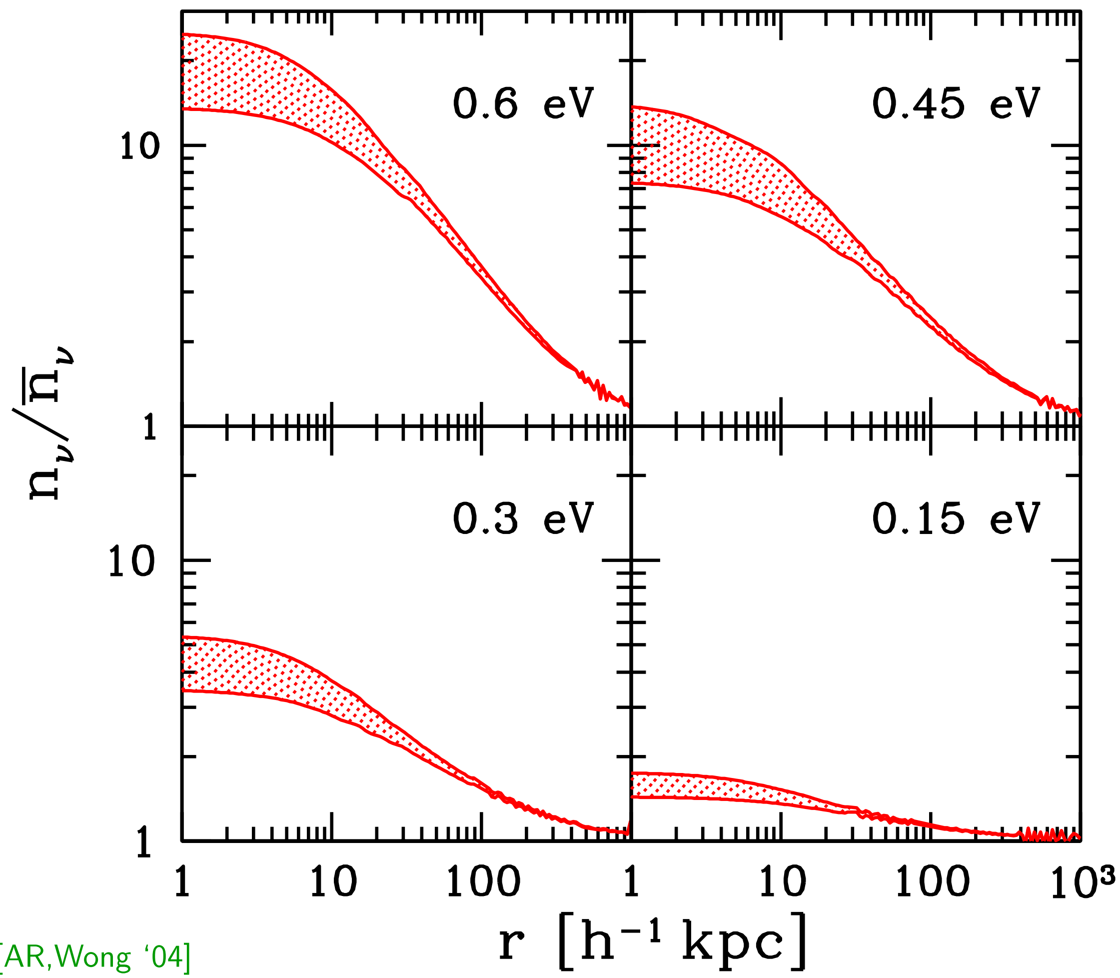
Relic neutrinos in neighbourhood of Earth ($r_\oplus \approx$ 8 kpc):

- Overdensity $\approx 1 - 20$

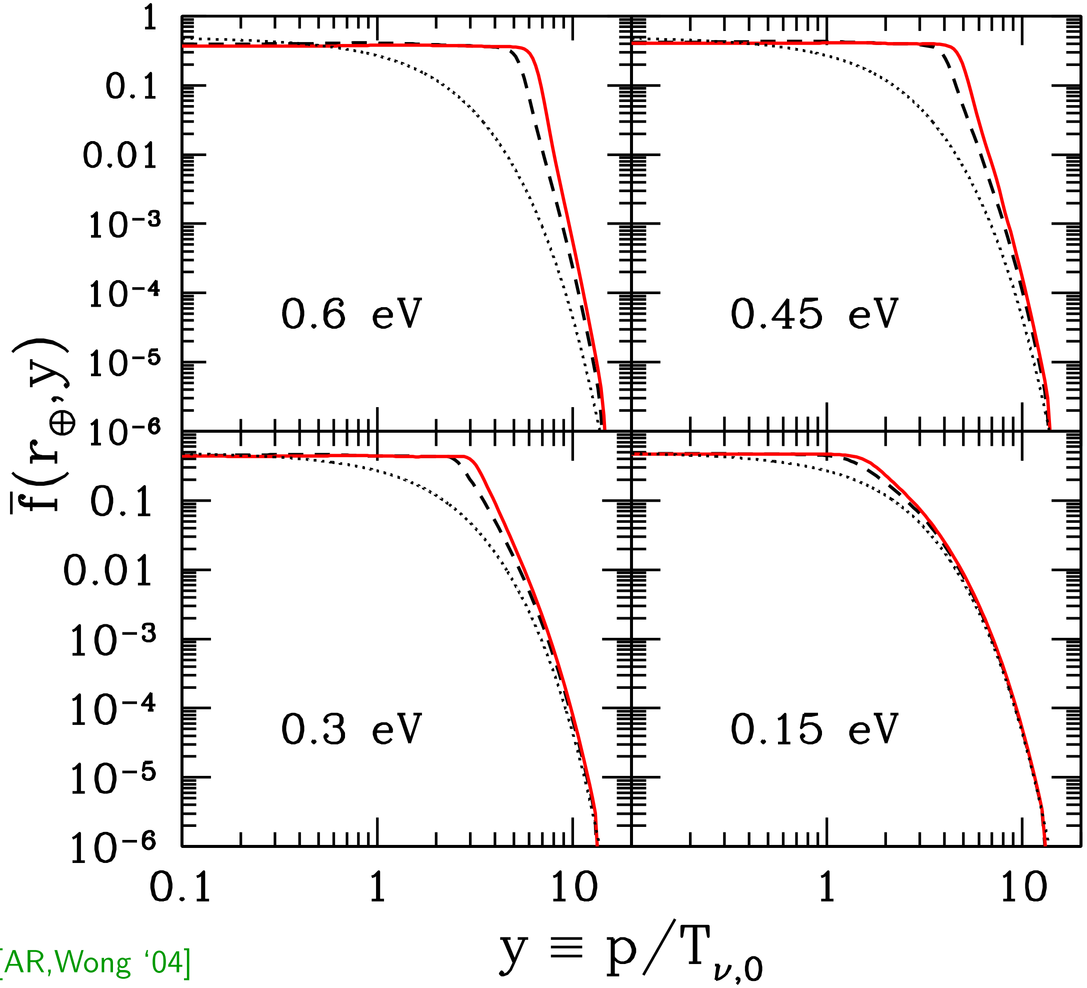


[AR,Wong '04]

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

- Overdensity $\approx 1 - 20$

- Momentum distribution:
  - almost isotropic
  - flat at low momenta
  - 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]

2. How to detect?

- 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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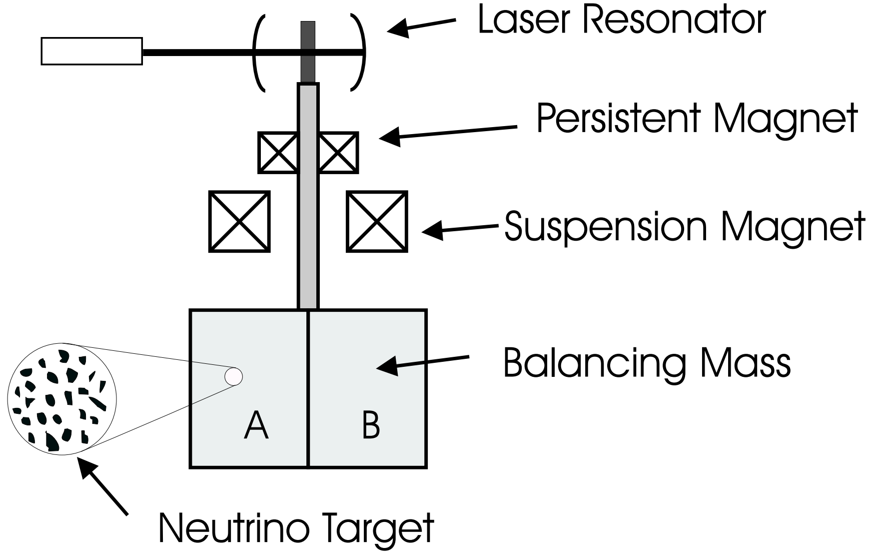
[Hagmann '99]



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

	$\frac{n_\nu}{\bar n_\nu}$	$\lambdabar = \frac{1}{\langle p\rangle}$	$\langle v\rangle$
MWnow $m_\nu =$			
0.6 eV	20	2.3×10^{-2} cm	1.4×10^{-3}
0.45 eV	10	2.9×10^{-2} cm	1.5×10^{-3}
0.3 eV	4.4	3.7×10^{-2} cm	1.8×10^{-3}
0.15 eV	1.6	4.1×10^{-2} cm	3.2×10^{-3}
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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]

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

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

⇒ 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]	$\frac{R_{\nu A}}{\left[\frac{n_\nu}{\bar n_\nu}\frac{m_\nu}{\rm eV}\right]}$ [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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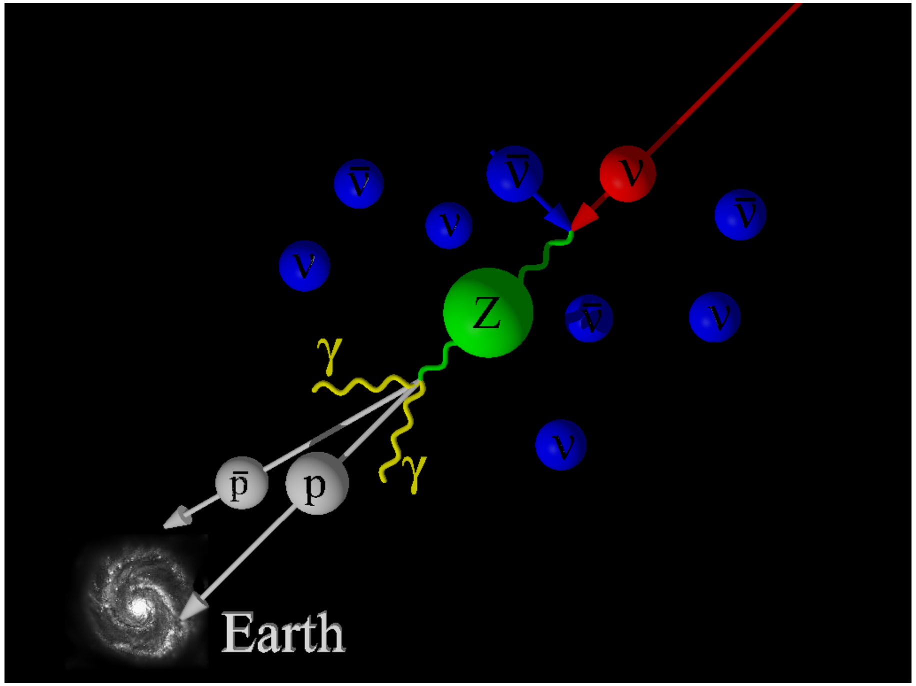
- Unique: resonant annihilation of extremely energetic cosmic neutrinos (**EHECν**)

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

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



[Fodor,Katz,AR '02]

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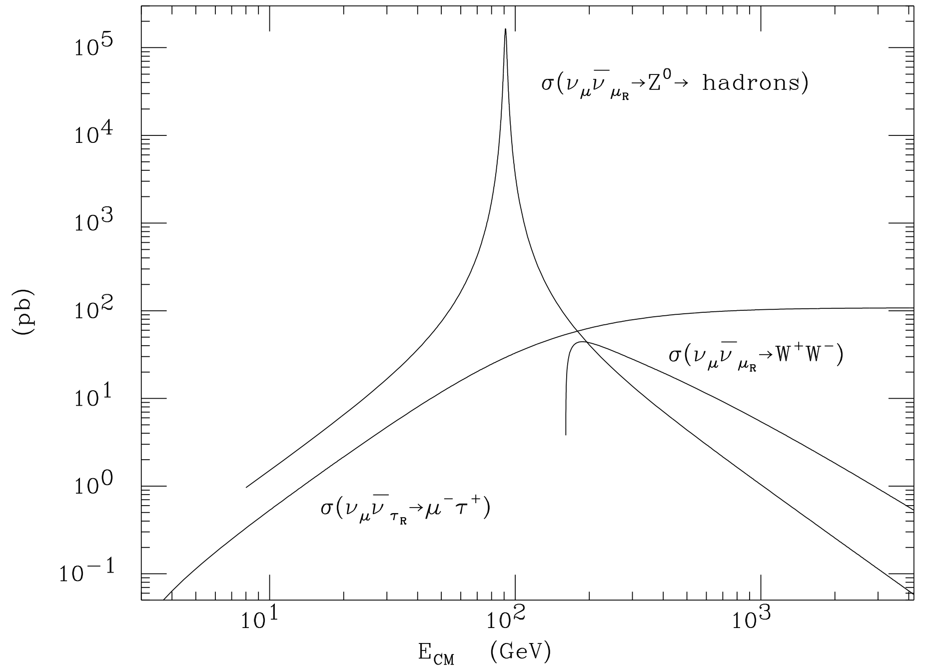

[Fargion,Mele,Salis '99]

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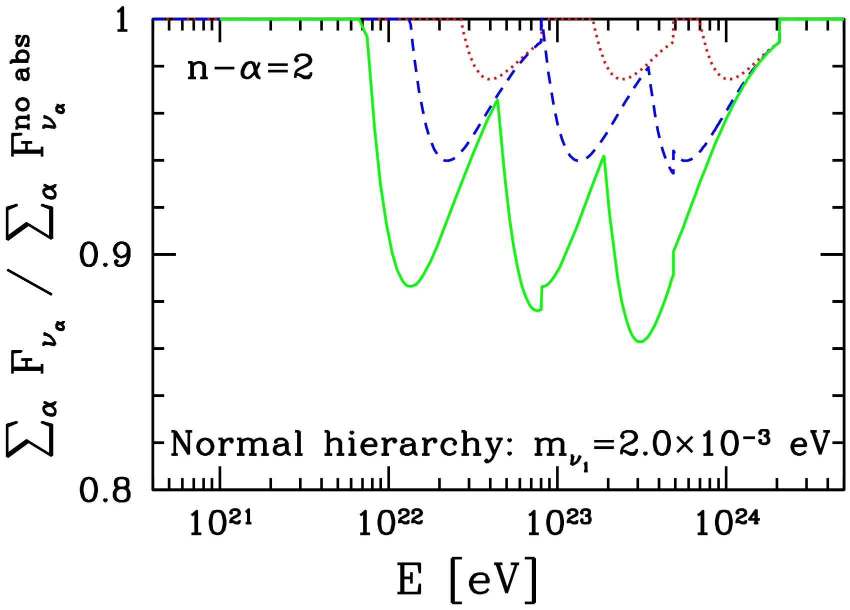
$$E_\nu^{\rm res} = \frac{m_Z^2}{2m_\nu} \simeq 4 \times 10^{21} \left(\frac{\rm eV}{m_\nu}\right) \ {\rm eV}$$

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

◇ Absorption dips in **EHECν** spectrum
[Weiler'82;...;Eberle,AR,Song,Weiler'04;Barenboim,Requejo,Quigg'04]



[Eberle,AR,Song,Weiler '04]

Exploit cosmic rays:

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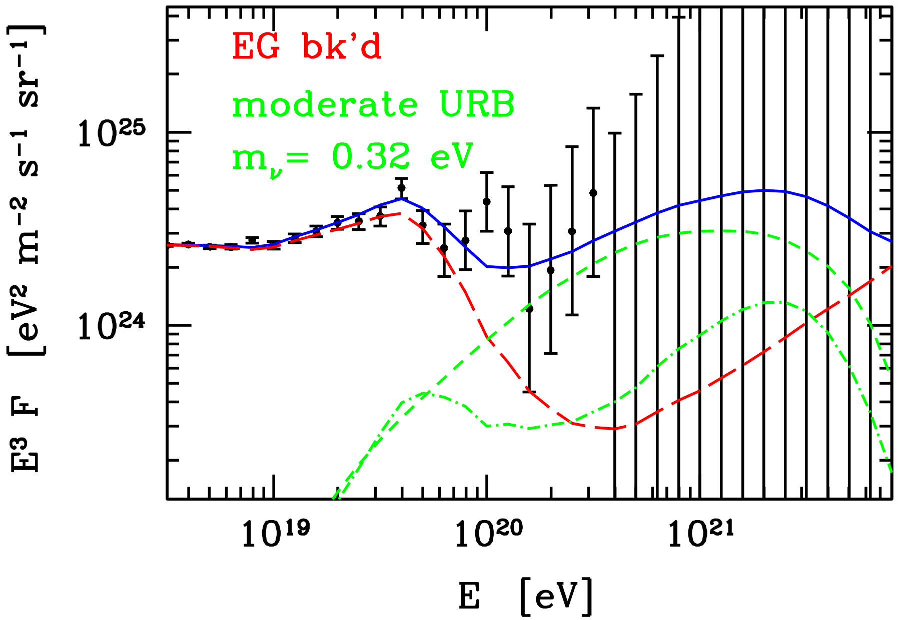
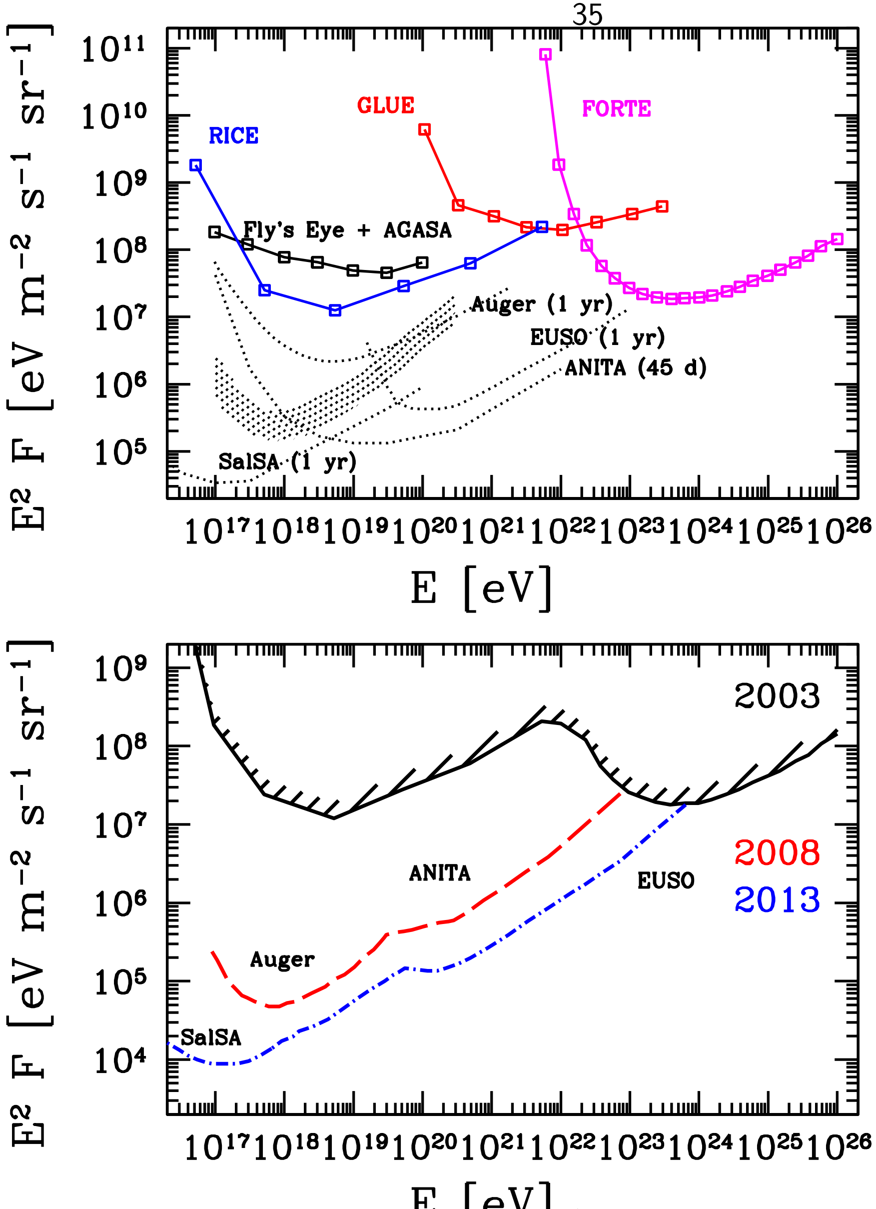
  - ◇ Absorption dips in **EHECν** spectrum [Weiler '82;...; Eberle,AR,Song,Weiler '04]
  - ◇ Emission features (**Z-bursts**): [Fargion *et al.* '99; Weiler '99;...; Fodor,Katz,AR '01,'02]
    protons and photons with energies above the predicted **G**reisen–**Z**atsepin–**K**uzmin (**GZK**) cutoff at $E_{\rm GZK} \simeq 4 \times 10^{19}$ eV [Greisen '66; Zatsepin,Kuzmin '66]



[Fodor,Katz,AR '02]

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

- Presently planned **EHECν** detectors appear to be sensitive enough to lead us, within the **next decade**, into an **era of relic neutrino absorption spectroscopy**, provided



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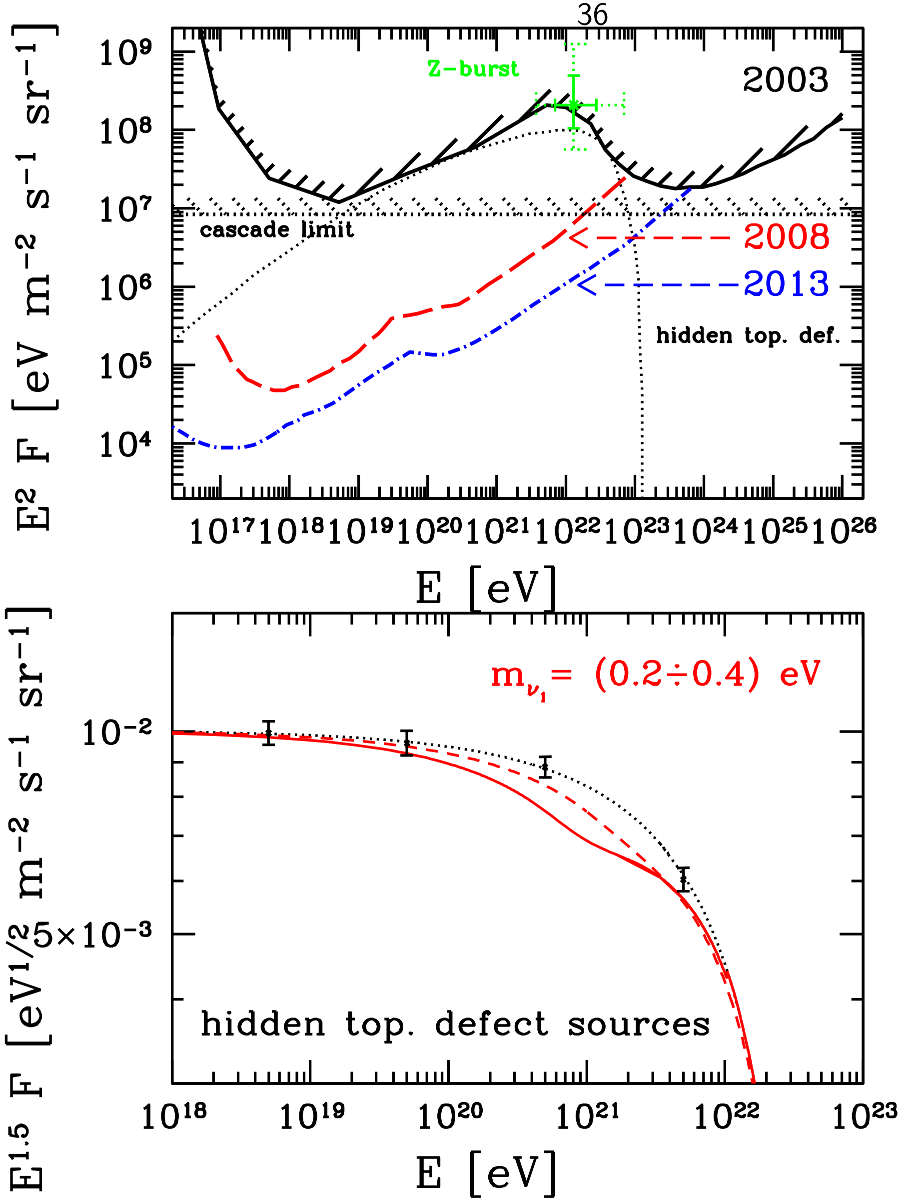

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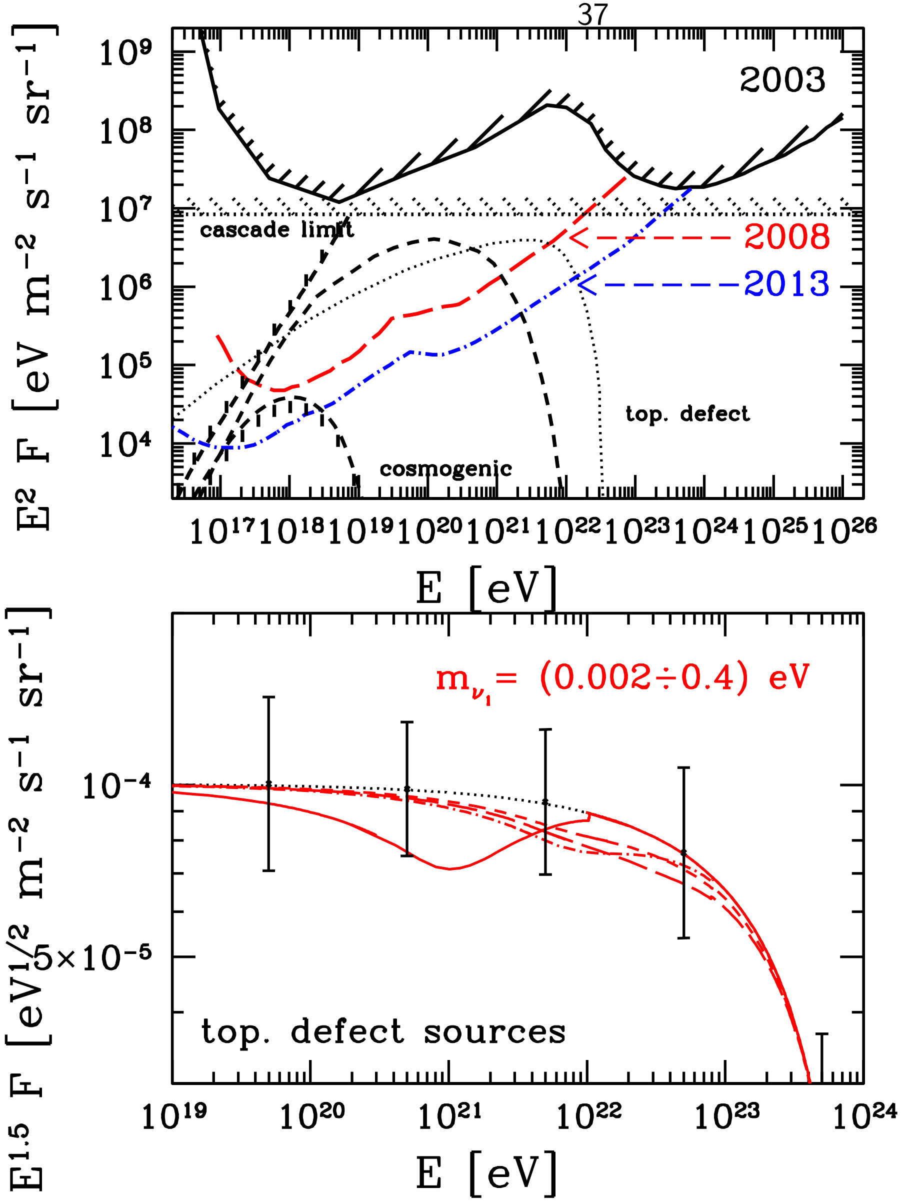

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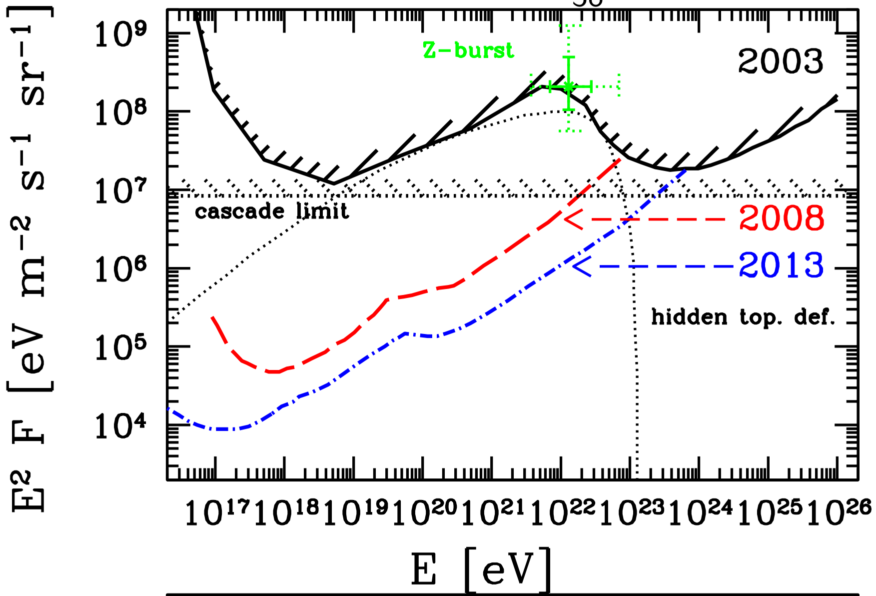

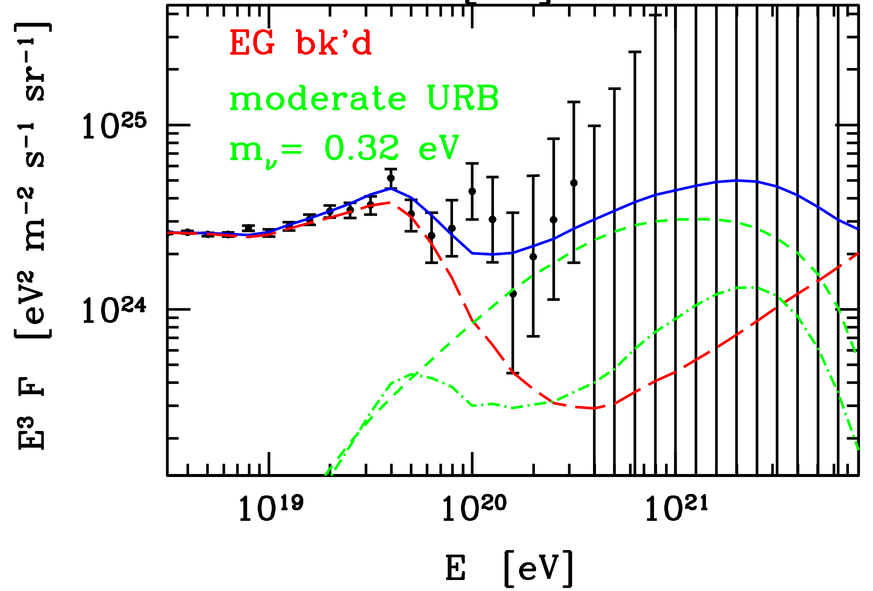

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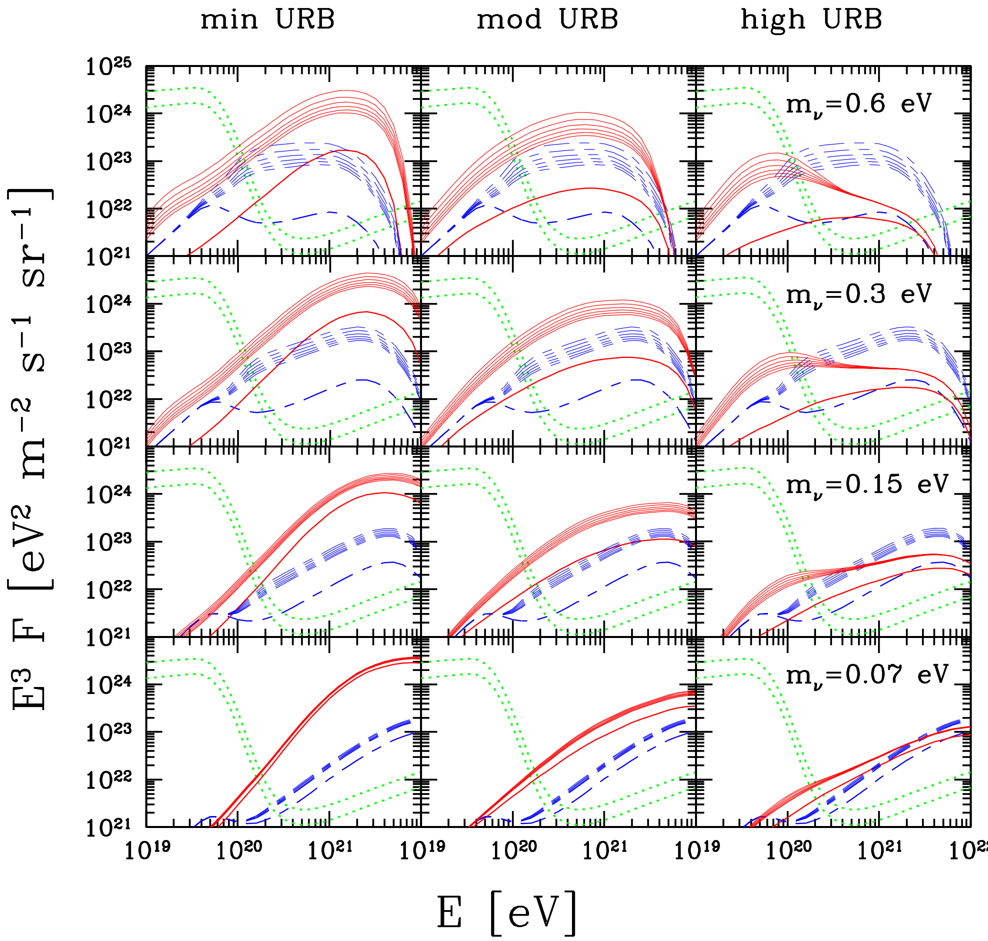

[AR,Weiler,Wong '05]

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

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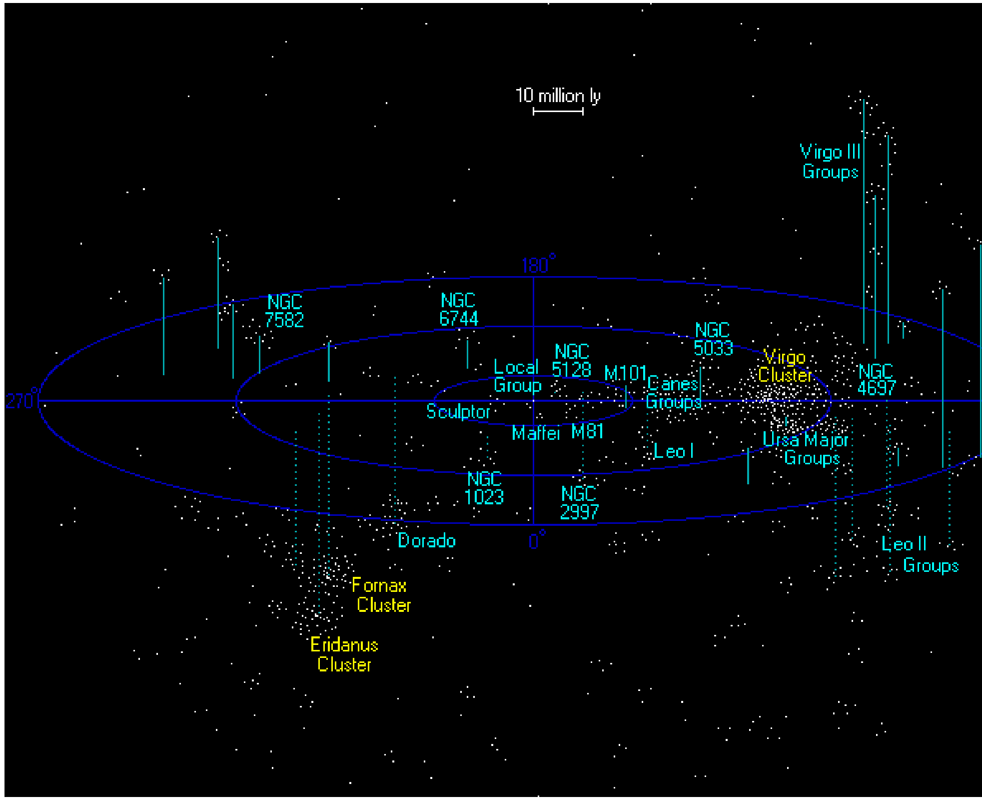

3. Conclusions

- **BBN** and **CMB** provide presently the only evidence for the **CνB**

- **Roadmap for Big Bang Relic Neutrino Detection**

  A more more direct, weak interaction based detection of the big bang relic neutrinos may proceed by measuring

  – Z-bursts in cosmic ray and absorption dips in cosmic neutrino spectra
  Remarks: not guaranteed (need ν flux at resonance energies); **now!**
  – coherent elastic scattering of relic ν's off nucleons in terrestrial detector
  Remarks: current technology 3 orders of magnitude off; **> 30 yr?**
  – interactions of very high energy particles from terrestrial accelerator beams with the relic neutrinos as target
  Remarks: need ULHC; **ever???**