

How to Detect Big Bang Relic Neutrinos?

Andreas Ringwald

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



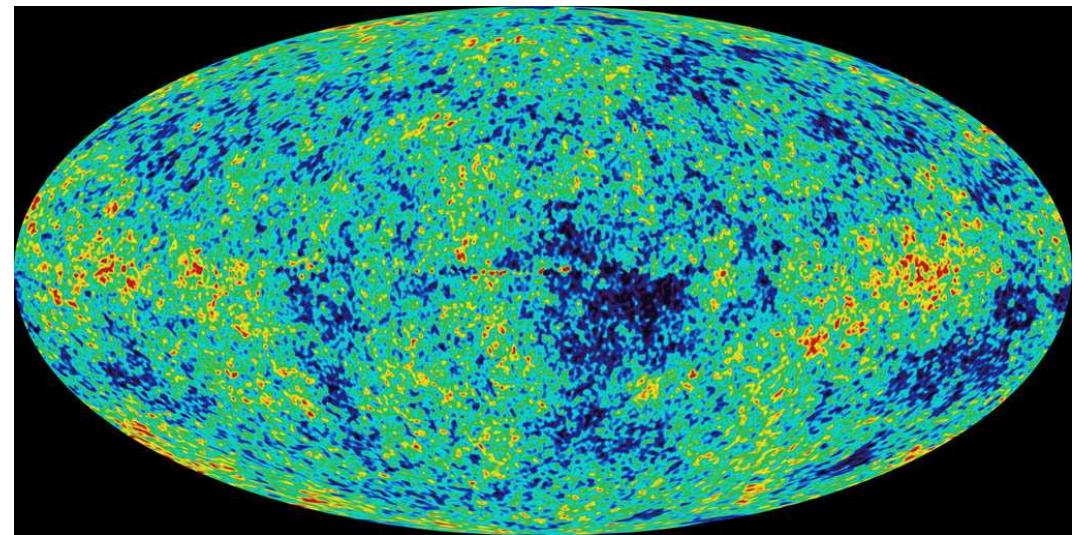
with: **B. Eberle, Z. Fodor, S. Katz, L. Song, T. Weiler, Y.Y.Y. Wong**

XI International Workshop on “Neutrino Telescopes”
February 22-25, 2005, Venice, Italy

0. Introduction

- Progress in observational cosmology

Cosmic **Microwave Background:**



[WMAP '03]

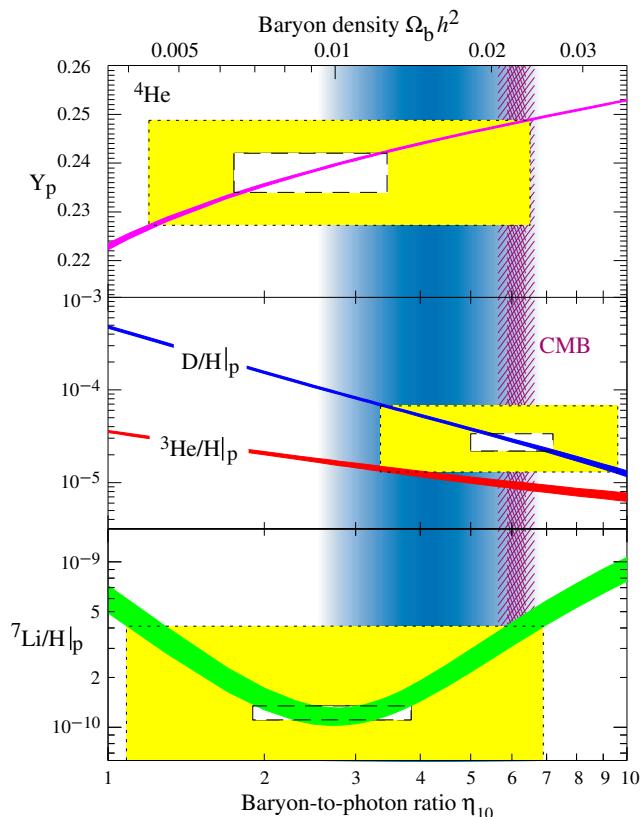
- How to detect big bang relic neutrinos? –

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Big Bang Nucleosynthesis:

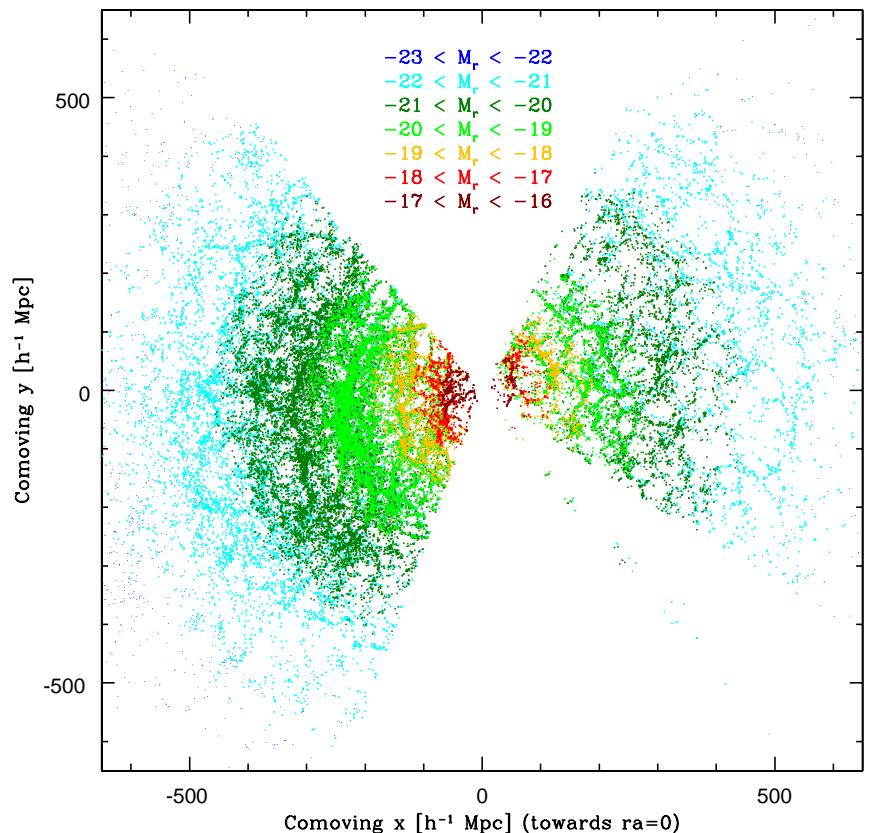


[Particle Data Group '04]

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Large Scale Structure:



[Sloan Digital Sky Survey '04]

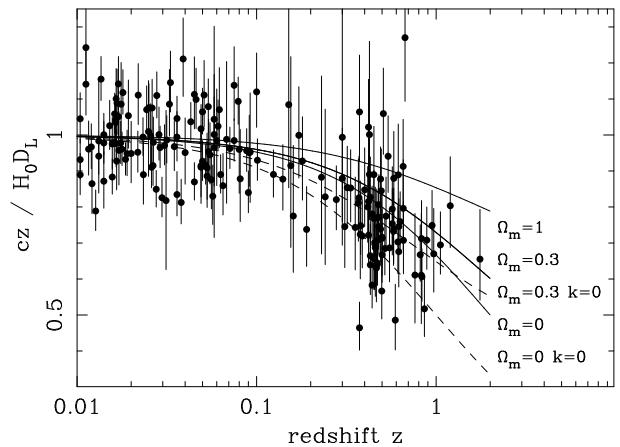
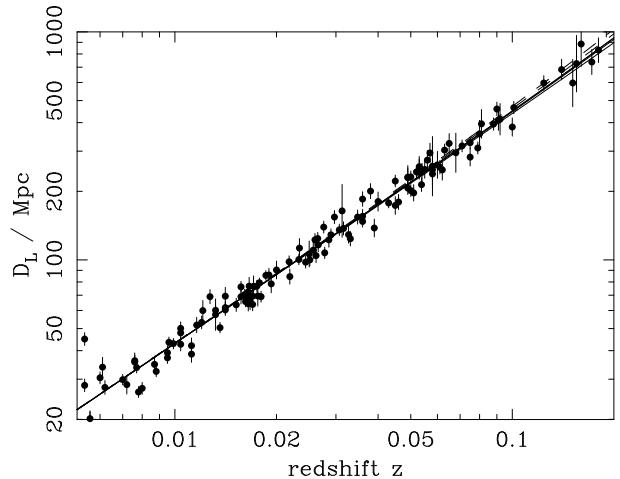
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SuperNovae 1a:

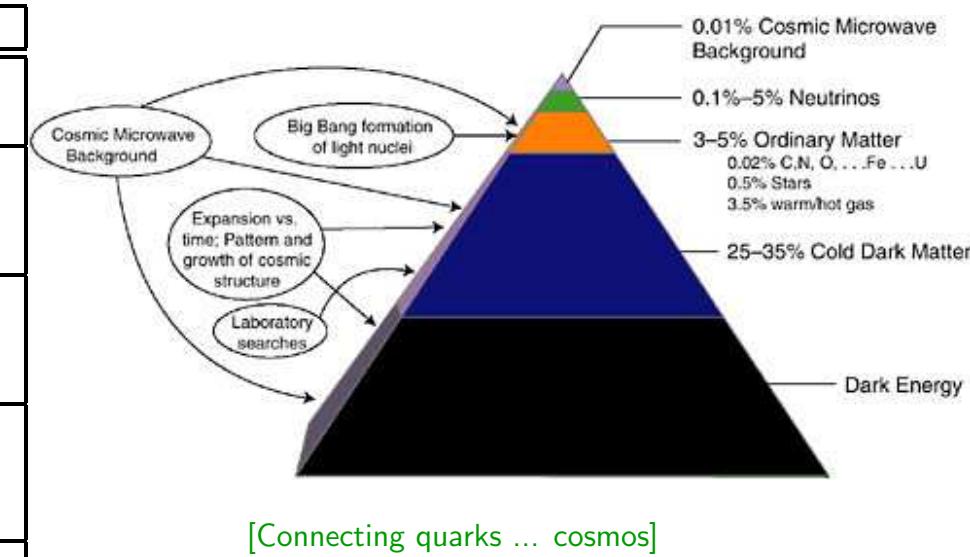


0. Introduction

- Progress in observational cosmology

⇒ 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

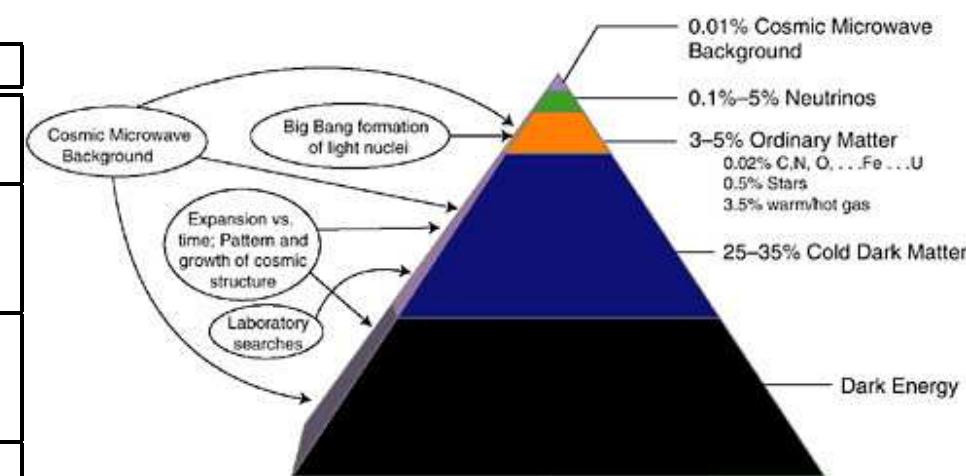


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[Connecting quarks ... cosmos]

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

- Evidence for/inference about **C ν B** 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**): $\sum m_{\nu_i} \leq 1.8 \text{ eV}$
- **C ν B** has not been detected **in laboratory**:
 - ⇐ Neutrinos interact only weakly
 - ⇐ Smallness of neutrino mass \Leftrightarrow small momentum-transfer
- Design of **direct, weak interaction based detection experiment**
 - ⇐ Need phase space distribution of relic neutrinos
 - ⇐ **Theoretically known better than ever!**

Further content:

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

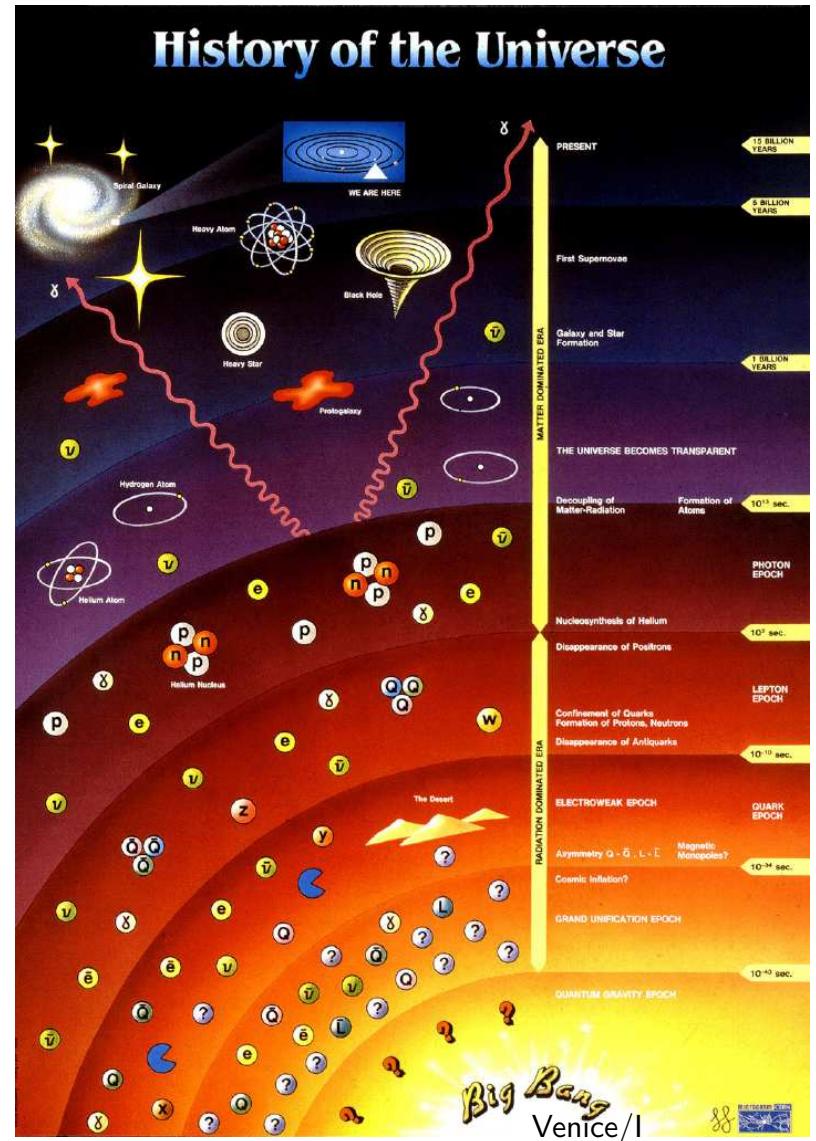
- How to detect big bang relic neutrinos? –

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1. How many, how fast?

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

A. Ringwald (DESY)

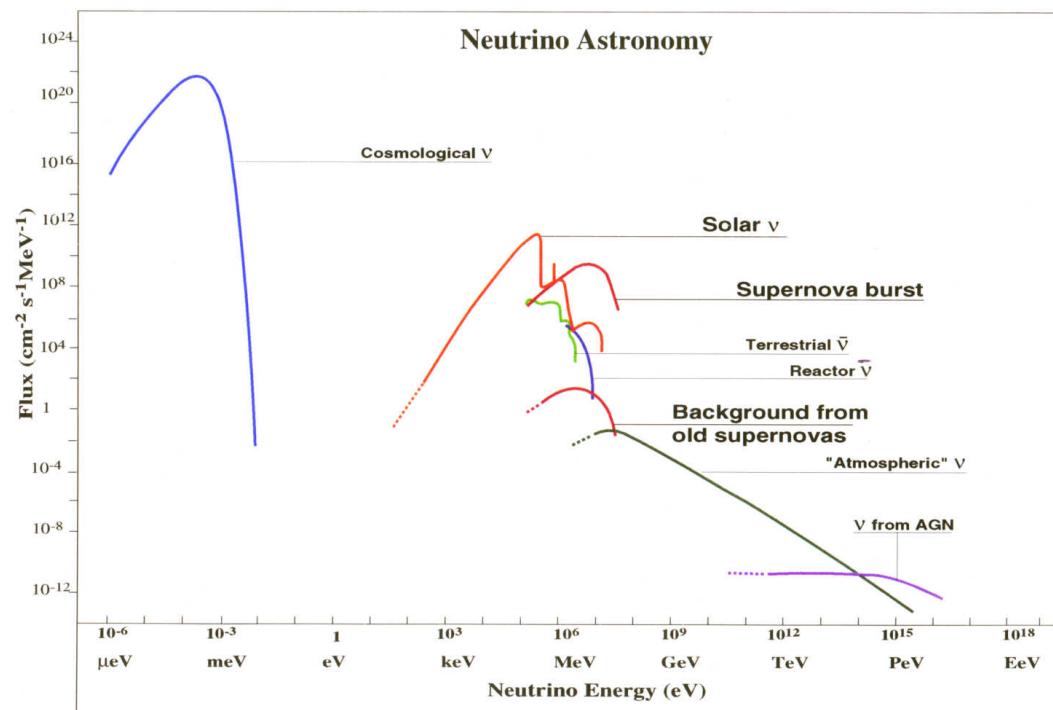


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- Firm predictions:

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

relic neutrinos \approx # relic photons



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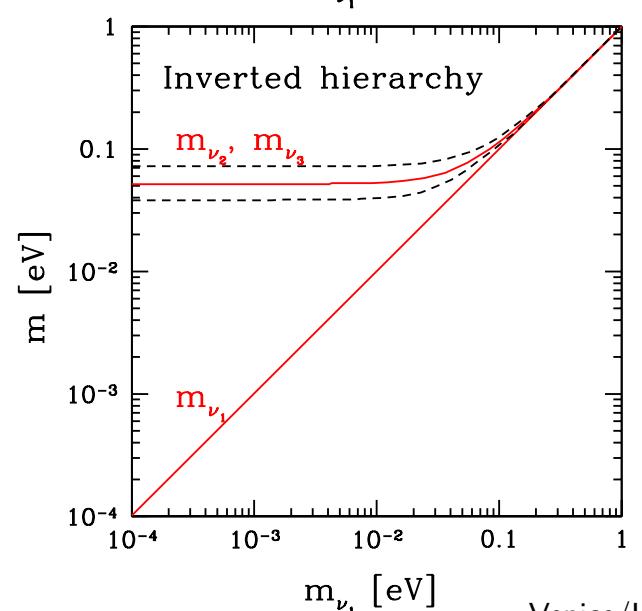
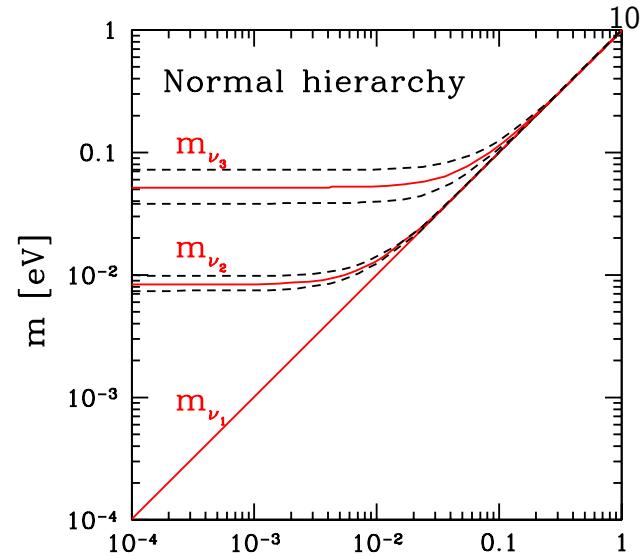
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At least two neutrino mass eigenstates nonrelativistic ($m_{\nu_i} \gg 5 \times 10^{-4}$ eV)



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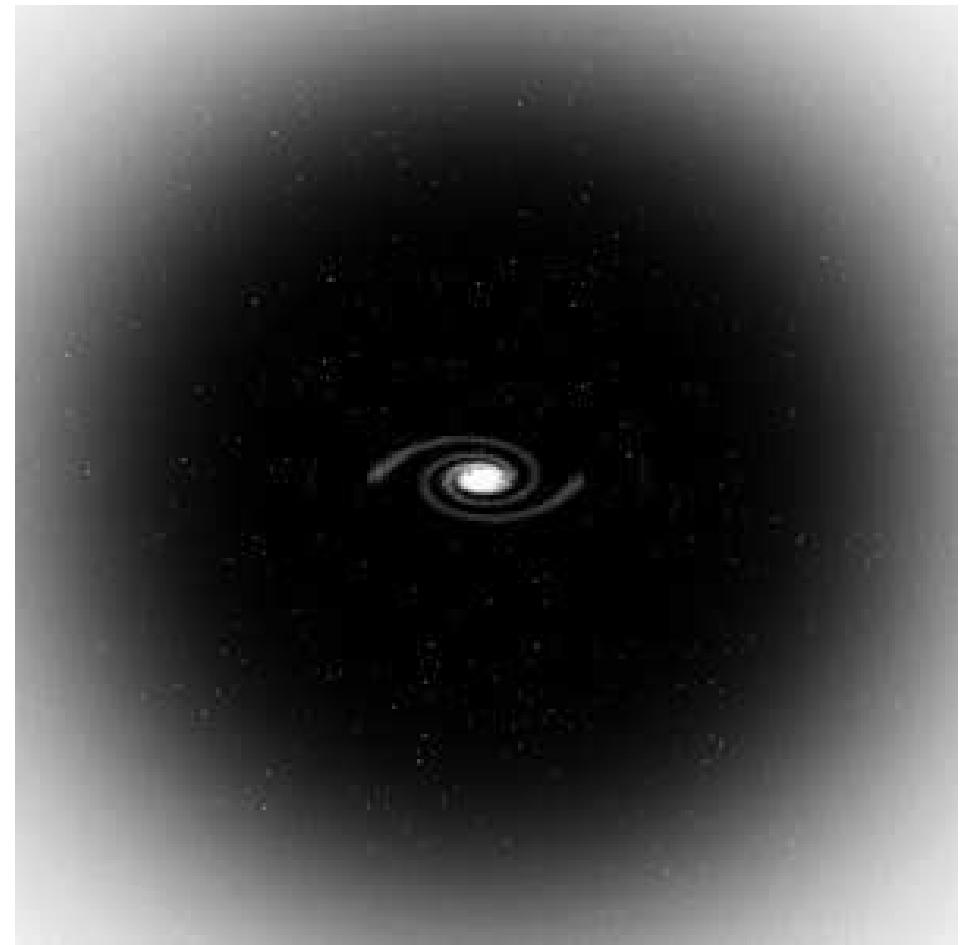
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At least two neutrino mass eigenstates nonrelativistic ($m_{\nu_i} \gg 5 \times 10^{-4}$ eV)

\Rightarrow Gravitational clustering on **CDM**

\Rightarrow Density enhanced in galactic halos



[archive.ncsa.uiuc.edu]

Neutrino clustering in cold dark matter halos from Λ CDM simulations

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

- In context of flat Λ CDM model, neutrino component \approx perturbation
 - ⇒ CDM component ρ_m dominates in gravitational potential ϕ
 - ⇒ Study clustering in ρ_m profiles from Λ CDM N -body simulations

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

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

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- Poisson equation

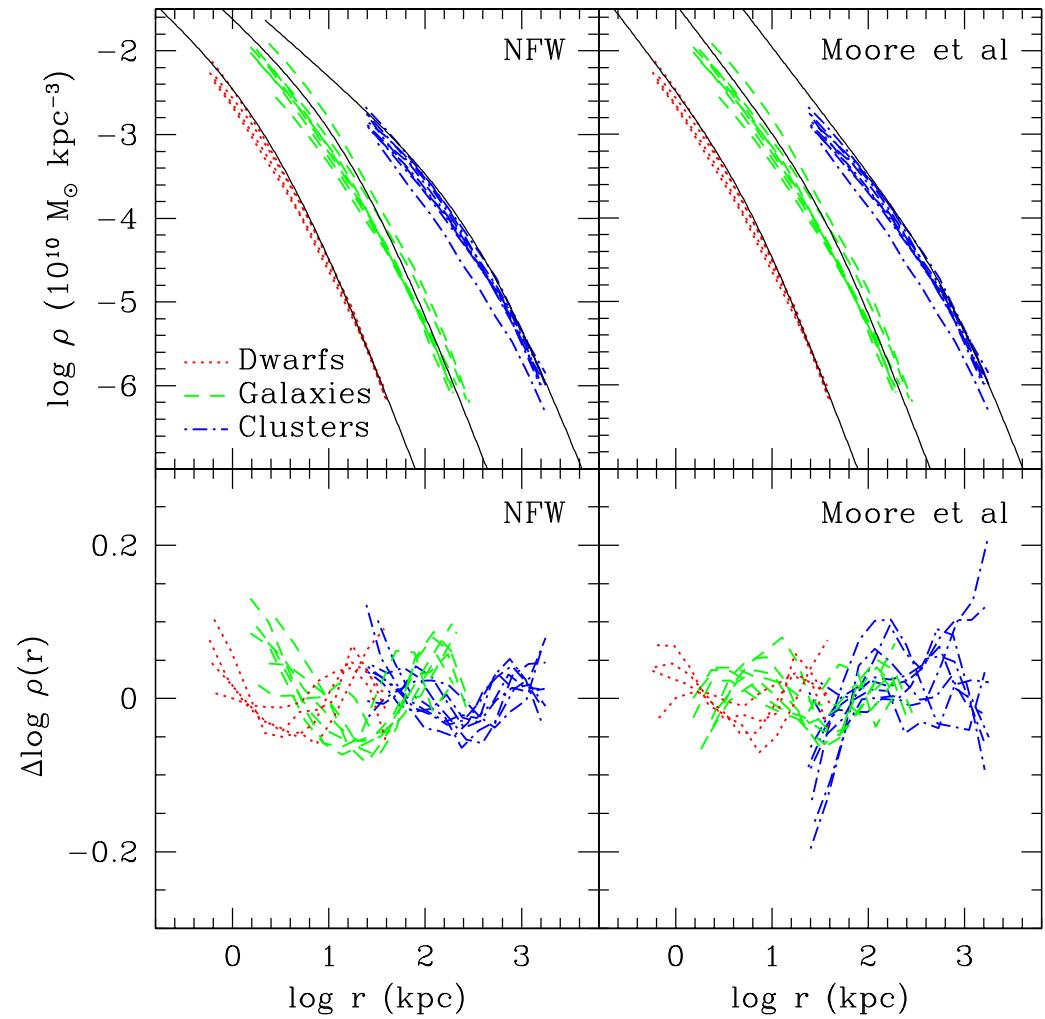
$$\nabla^2 \phi = 4\pi G a^2 \underbrace{\left(\rho_m(\mathbf{x}, \tau) - \bar{\rho}_m(\tau) \right)}_{\delta_m(\mathbf{x}, \tau) \bar{\rho}_m(\tau)}$$

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

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

- Use **Navarro Frenk White CDM** halo profiles,

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



[**Navarro et al. '04**]

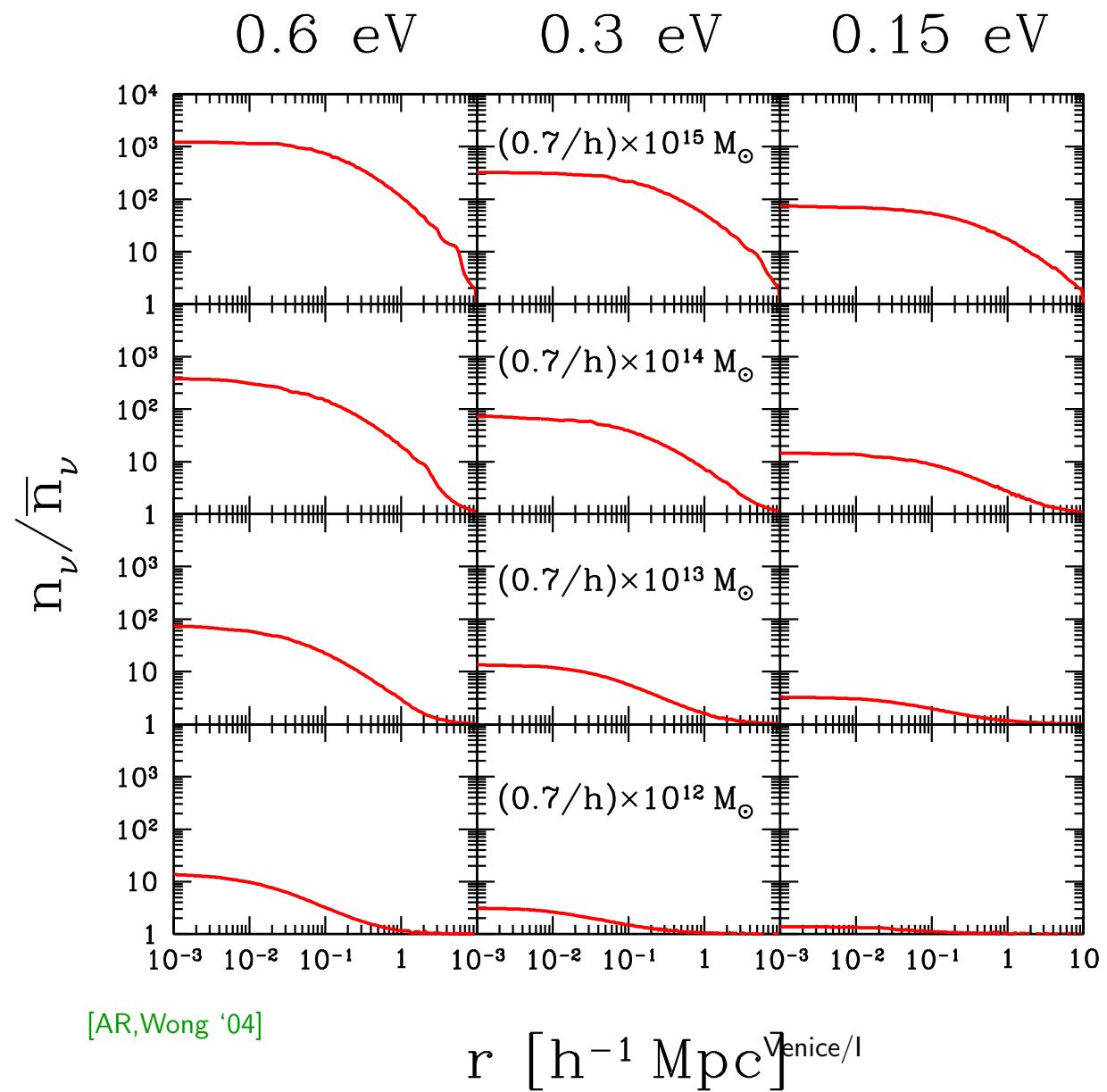
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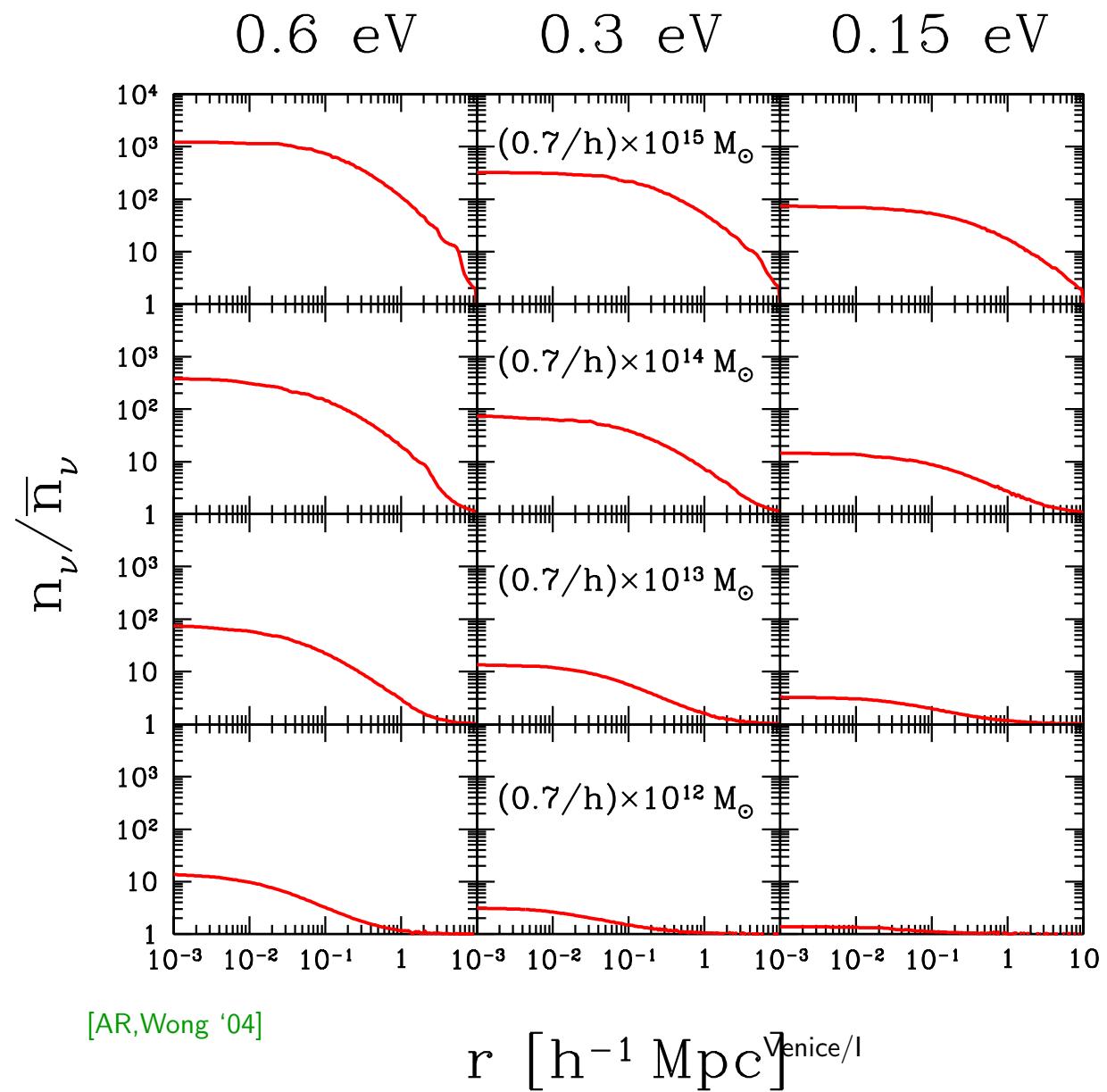
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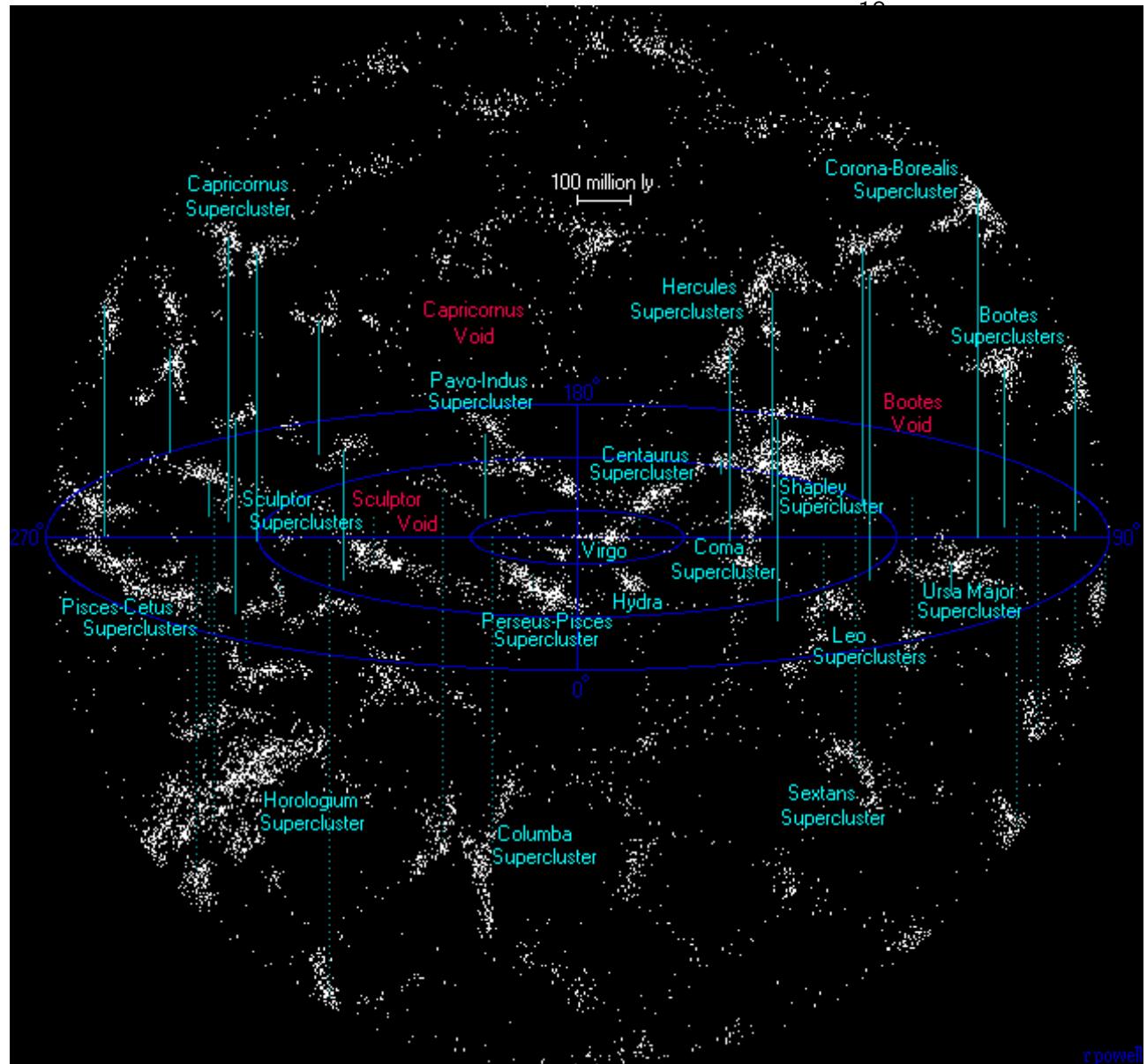
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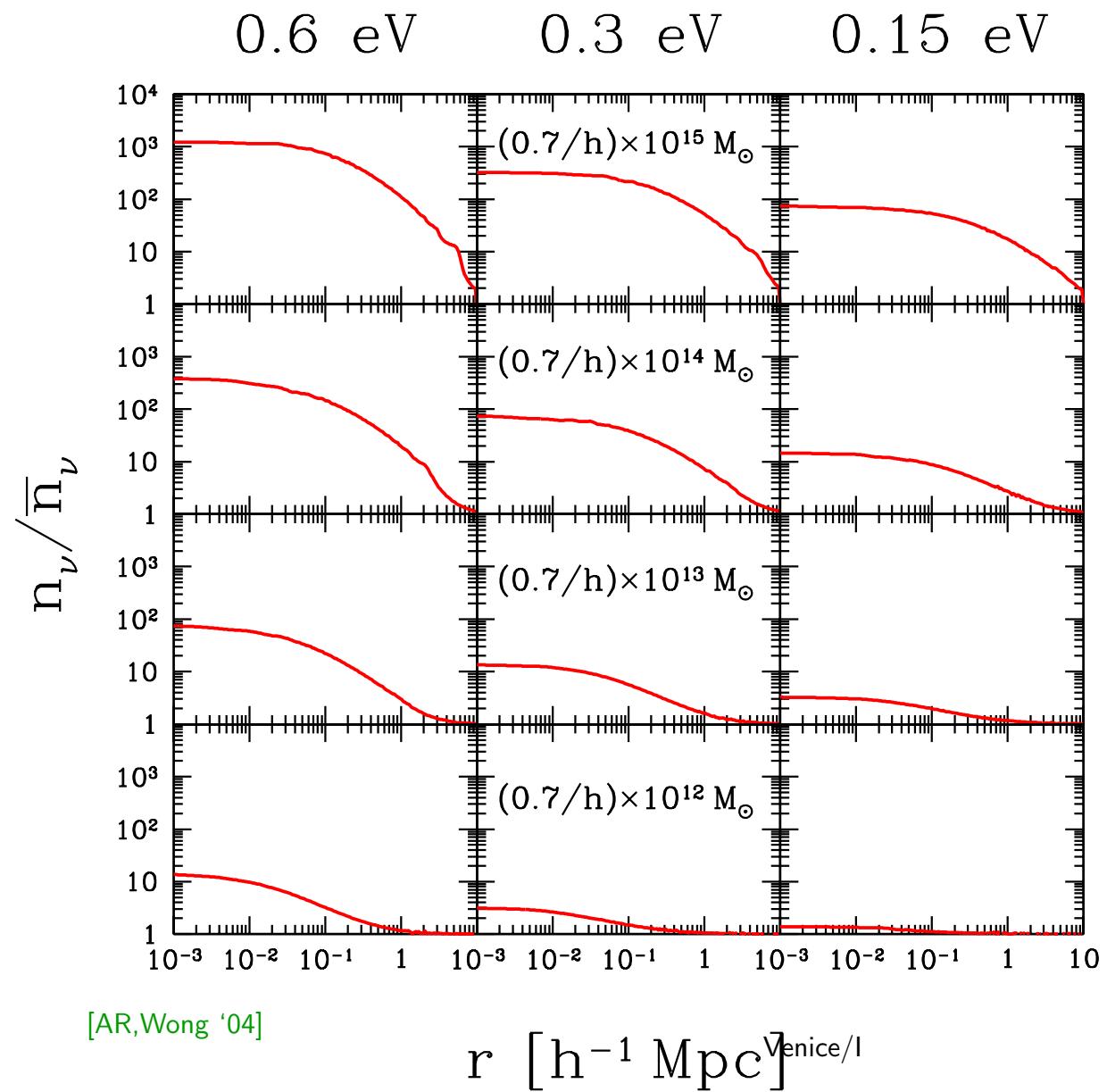
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– **Galaxies** ($10^{12} M_\odot$):

$$n_\nu/\bar{n}_\nu \approx 1 - 20$$



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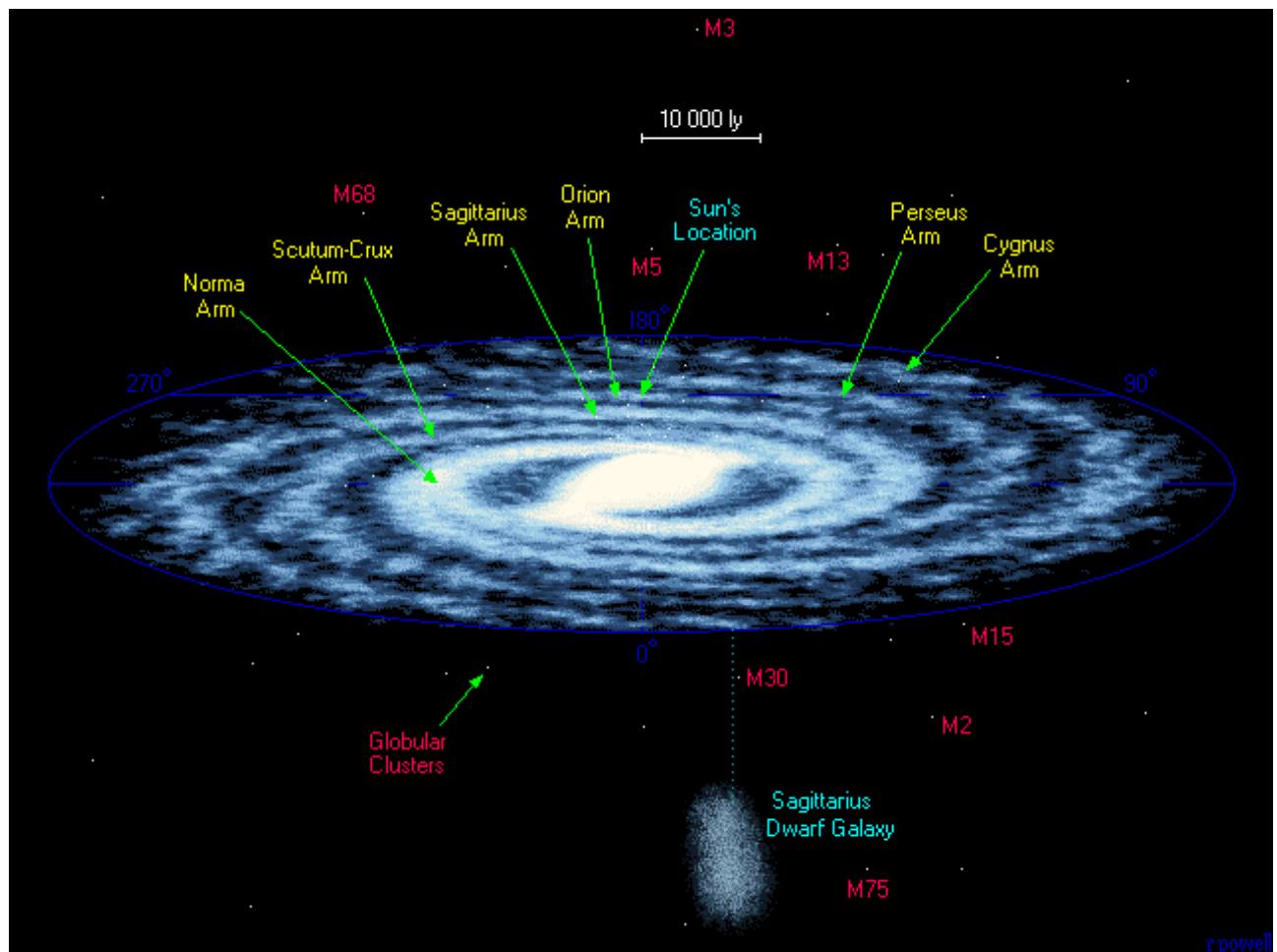
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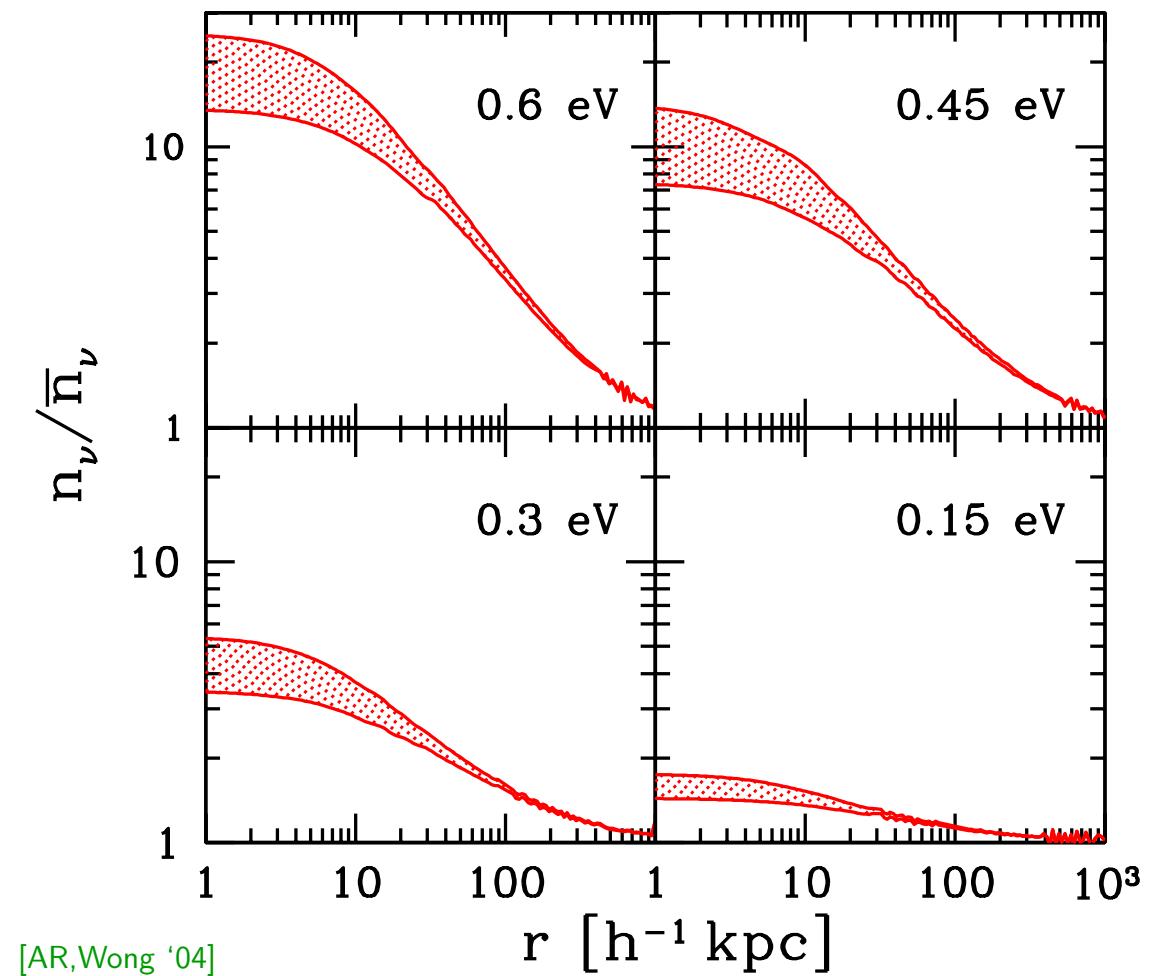
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[www.extrasolar.org]

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

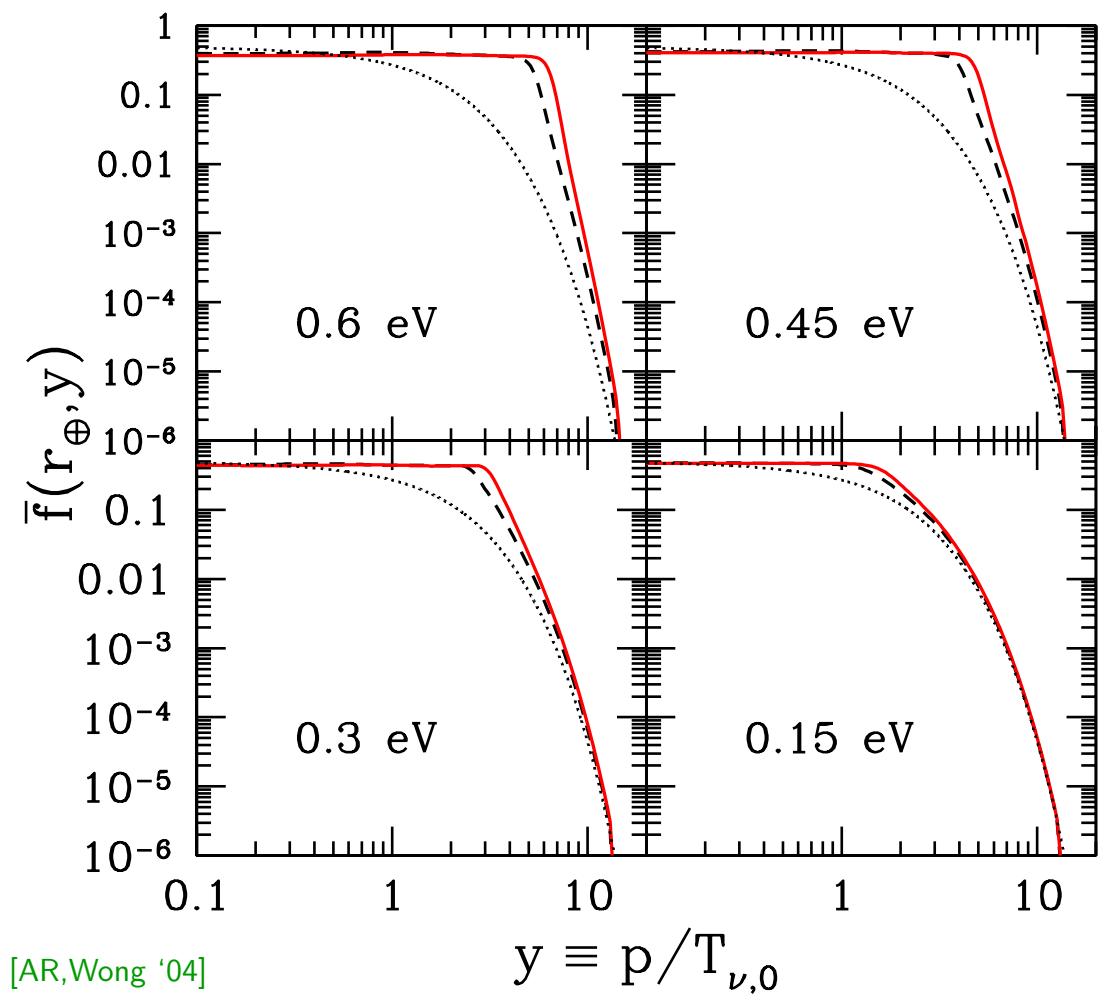
- Overdensity $\approx 1 - 20$



[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 $\approx p_{\text{esc}} \equiv m_{\nu} v_{\text{esc}} \equiv m_{\nu} \sqrt{2|\phi(r_{\oplus})|}$
 - matches Fermi-Dirac at high momenta



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,

$$\lambda = 1/\langle p \rangle = 0.12 \text{ cm}/\langle y \rangle$$

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

$$\frac{N_A}{A} \rho_t \lambda^3 \simeq 6 \times 10^{18} \left(\frac{100}{A} \right) \left(\frac{\rho_t}{\text{g/cm}^3} \right) \left(\frac{\lambda}{0.1 \text{ cm}} \right)^3$$

compared to case where neutrinos are elastically scattered coherently only on the individual nuclei of the target

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

– How to detect big bang relic neutrinos? –

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

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

$$\begin{aligned} a_t &\simeq \sum_{\nu, \bar{\nu}} \underbrace{n_\nu v_{\text{rel}}}_{\text{flux}} \frac{4\pi}{3} N_A^2 \rho_t r_t^3 \sigma_{\nu N} \underbrace{2 m_\nu v_{\text{rel}}}_{\text{mom. transfer}} \\ &\simeq 2 \times 10^{-28} \left(\frac{n_\nu}{\bar{n}_\nu} \right) \left(\frac{10^{-3} c}{v_{\text{rel}}} \right) \left(\frac{\rho_t}{\text{g/cm}^3} \right) \left(\frac{r_t}{\text{km}} \right)^3 \frac{\text{cm}}{\text{s}^2} \end{aligned}$$

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

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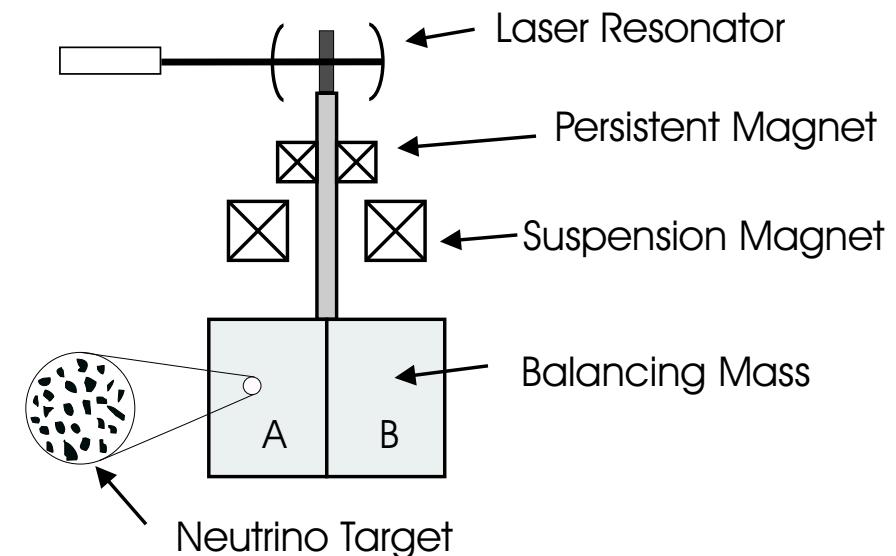
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- At present, smallest measurable acceleration $\gtrsim 10^{-13} \text{ cm/s}^2$, using conventional **Cavendish-type torsion balance**. Improvements to $\gtrsim 10^{-23} \text{ cm/s}^2$ proposed

[Hagmann '99]



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[Hagmann '99]

- ⇒ Detection possible in 30–40 years, if neutrinos are Dirac particles

[Smith '03]

	$\frac{n_\nu}{\bar{n}_\nu}$	$\lambda = \frac{1}{\langle p \rangle}$	$\langle v \rangle$
MWnow $m_\nu =$			
0.6 eV	20	$2.3 \times 10^{-2} \text{ cm}$	1.4×10^{-3}
0.45 eV	10	$2.9 \times 10^{-2} \text{ cm}$	1.5×10^{-3}
0.3 eV	4.4	$3.7 \times 10^{-2} \text{ cm}$	1.8×10^{-3}
0.15 eV	1.6	$4.1 \times 10^{-2} \text{ cm}$	3.2×10^{-3}
NFWhalo $m_\nu =$			
0.6 eV	12	$2.7 \times 10^{-2} \text{ cm}$	1.2×10^{-3}
0.45 eV	6.4	$3.4 \times 10^{-2} \text{ cm}$	1.3×10^{-3}
0.3 eV	3.1	$3.9 \times 10^{-2} \text{ cm}$	1.7×10^{-3}
0.15 eV	1.4	$5.9 \times 10^{-2} \text{ cm}$	2.2×10^{-3}

Target detection

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

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

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

⇒ Exploit a flux of extremely energetic particles

- **accelerator beams**
- **from cosmic rays**

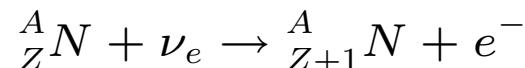
for scattering on relic neutrinos as **target**

Exploit accelerator beams:

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

$$\begin{aligned}
 R_{\nu}{}^A_N &\simeq \sum_{\nu, \bar{\nu}} n_\nu \sigma_{\nu}{}^A_Z L I / (Z e) \\
 &\simeq 2 \times 10^{-8} \left(\frac{n_\nu}{\bar{n}_\nu} \right) \left(\frac{m_\nu}{\text{eV}} \right) \frac{A^2}{Z} \left(\frac{E_N}{10 \text{ TeV}} \right) \left(\frac{L}{100 \text{ km}} \right) \left(\frac{I}{0.1 \text{ A}} \right) \text{ yr}^{-1}
 \end{aligned}$$

- ⇒ Too small to give rise to an observable effect in the foreseeable future (**LHC**, **VLHC**)
- ⇒ Need **Ultimate Large Hadron Collider**
- Few **elastic** scattering events per year; hard to detect, due to small momentum transfers ($\sim 1 \text{ GeV}$ at $E_N \sim 10^7 \text{ TeV}$)
 - Alternative: exploit inverse beta decay



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

[Melissinos '99; Zavattini unpubl.]

accel.	N	E_N [TeV]	L [km]	I [A]	$R_{\nu}{}^A$ $\left[\frac{n_\nu}{\bar{n}_\nu} \frac{m_\nu}{\text{eV}} \right] \text{ yr}^{-1}$
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

Exploit cosmic rays:

- Before **ULHC**: target detection only via extremely energetic cosmic rays

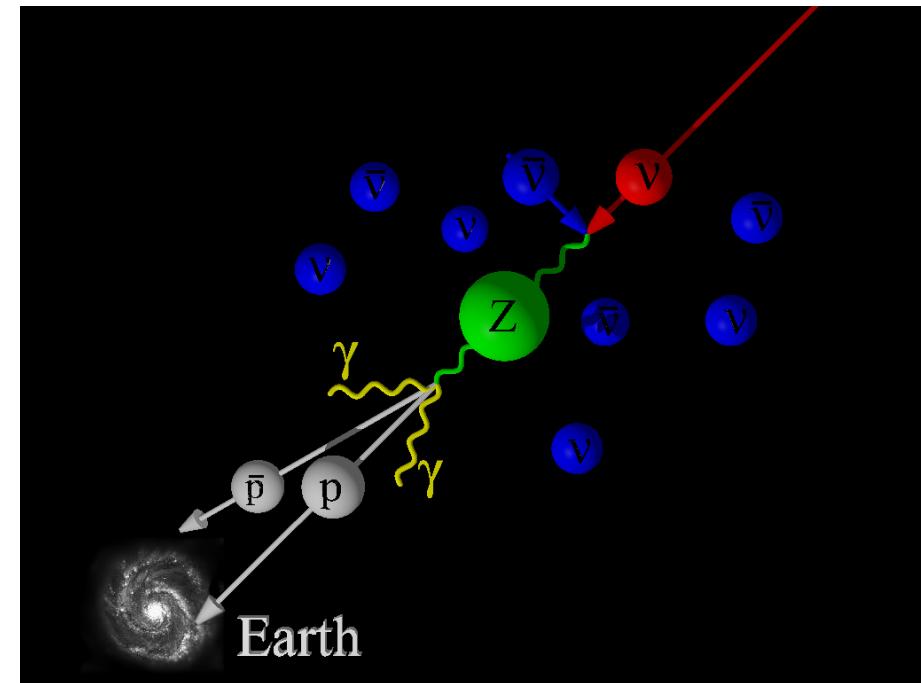
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- Unique: resonant annihilation of extremely energetic cosmic neutrinos (**EHEC ν**)

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

with relic $\bar{\nu}$ into **Z-bosons**

[Weiler '82]



[Fodor,Katz,AR '02]

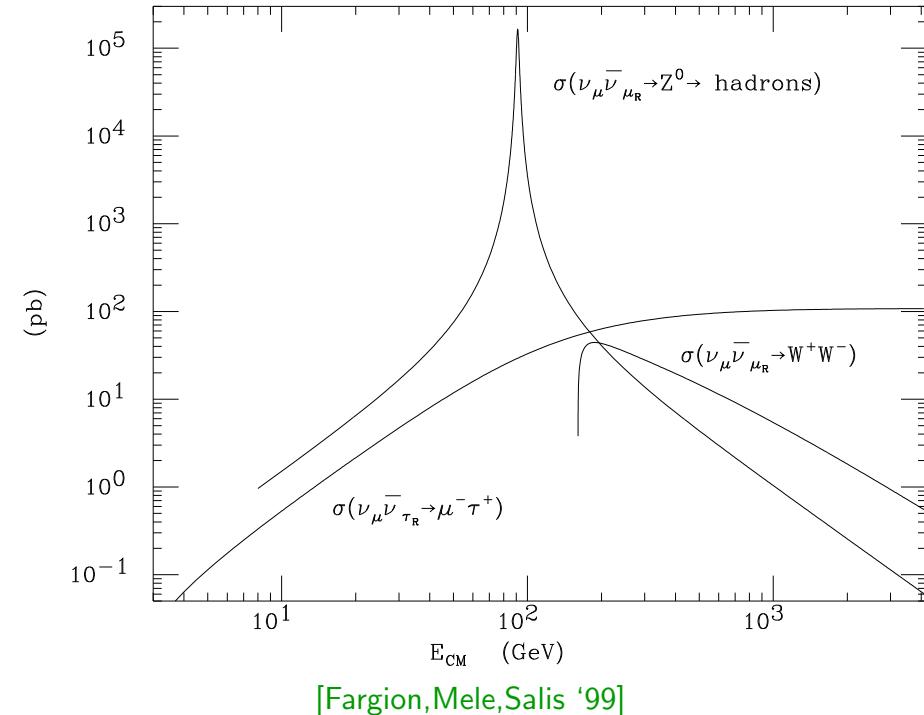
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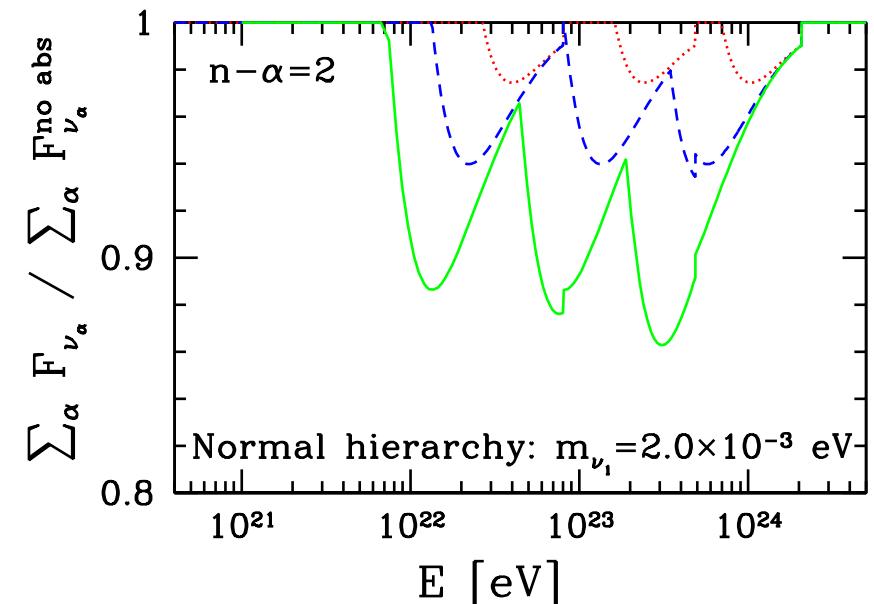
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with relic $\bar{\nu}$ into **Z-bosons** [Weiler '82]

◇ Absorption dips in **EHEC ν** spectrum

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



[Eberle,AR,Song,Weiler '04]

Exploit cosmic rays:

- Before **ULHC**: target detection only via extremely energetic cosmic rays
- Unique: resonant annihilation of extremely energetic cosmic neutrinos (**EHEC ν**)

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

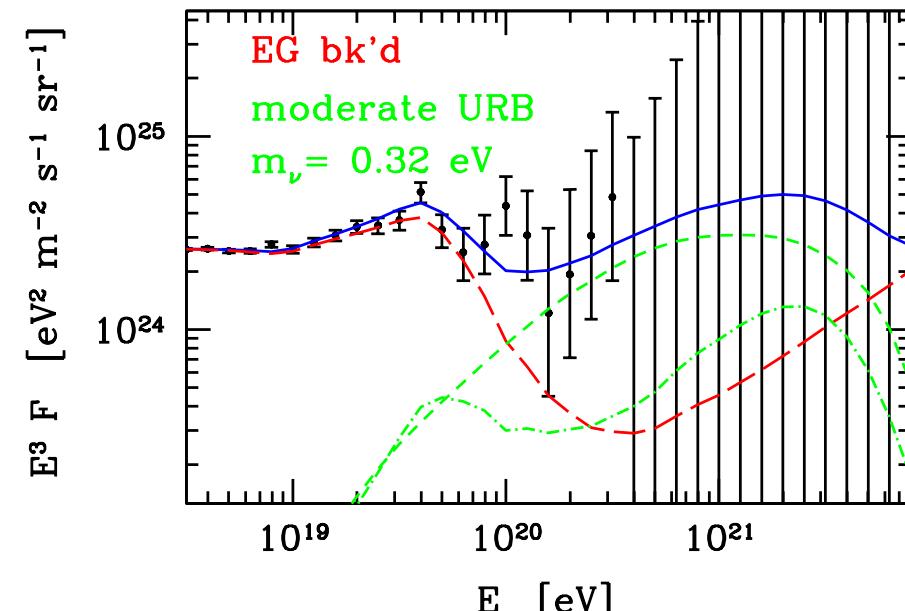
with relic $\bar{\nu}$ into **Z-bosons** [Weiler '82]

◊ Absorption dips in **EHEC ν** 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 **Greisen–Zatsepin–Kuzmin (GZK)** cutoff at $E_{\text{GZK}} \simeq 4 \times 10^{19}$ eV

[Greisen '66; Zatsepin,Kuzmin '66]

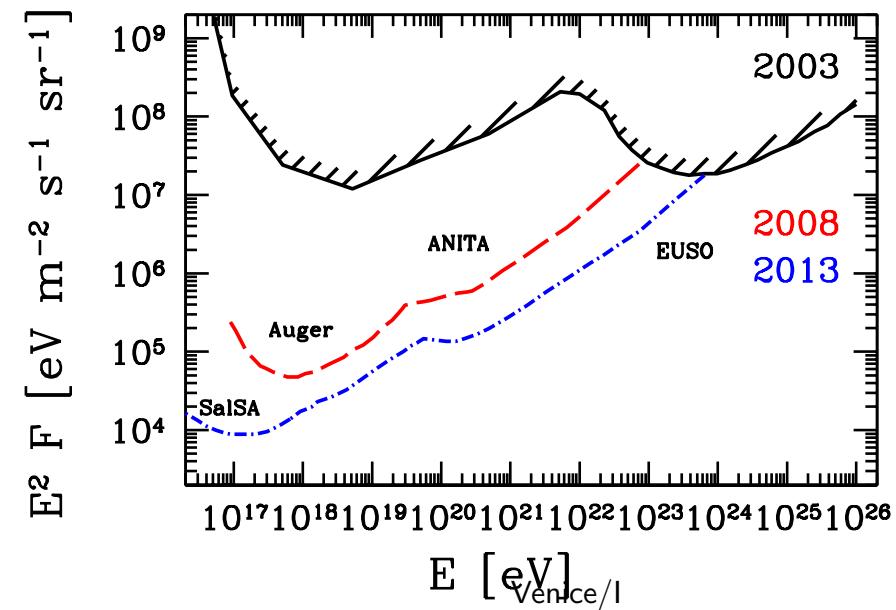
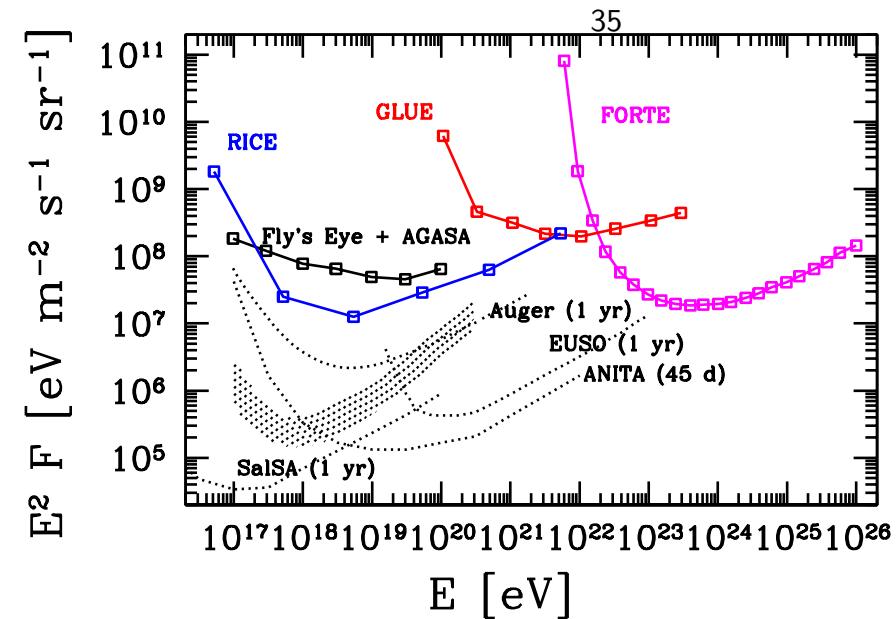


[Fodor,Katz,AR '02]

- How to detect big bang relic neutrinos? –

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

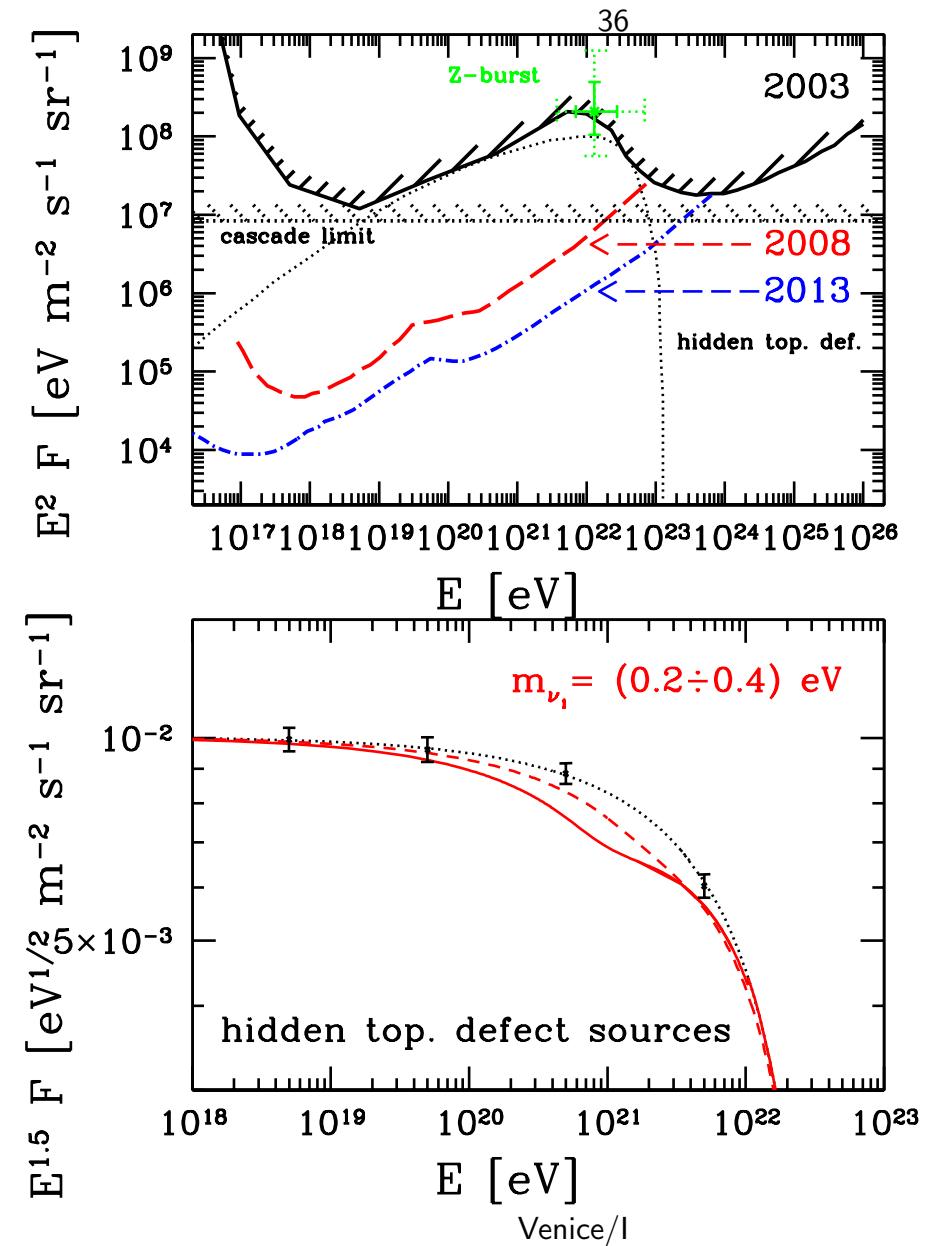
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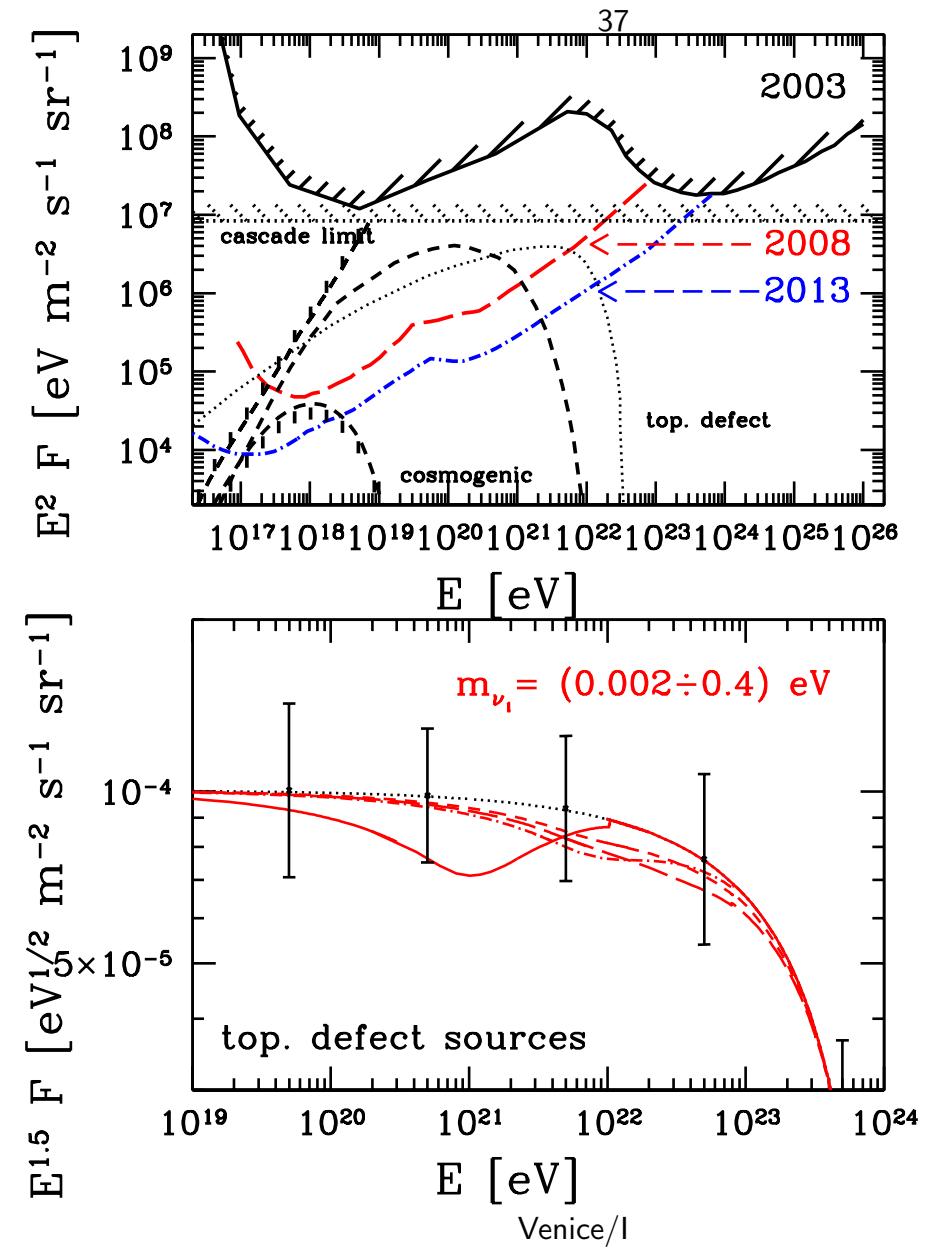
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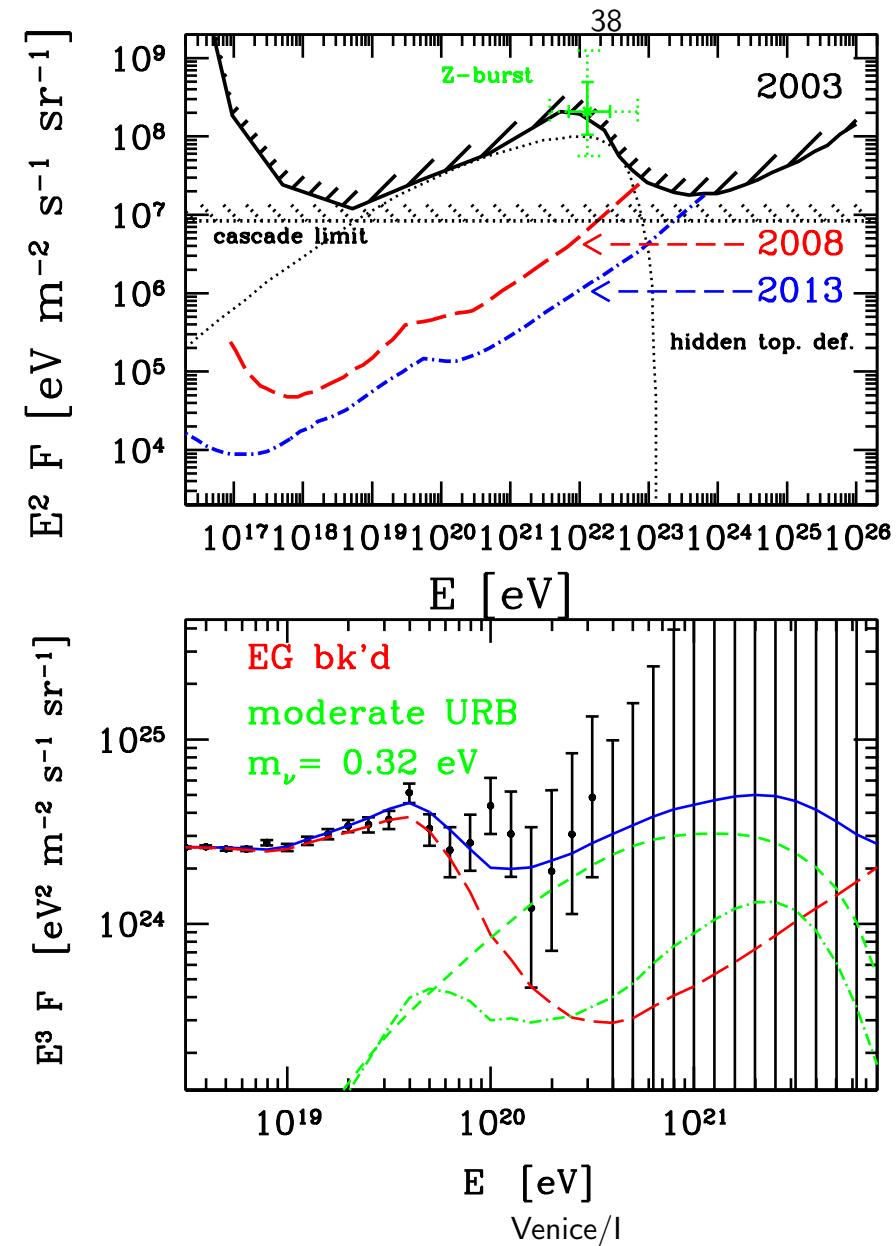
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- In this case, the associated **Z-bursts** likely to be seen as post-GZK events at the planned cosmic ray detectors



3. Conclusions

- **BBN** and **CMB** provide presently the only evidence for the **C ν B**
- **Roadmap for Big Bang Relic Neutrino Detection**

A 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???**