Prospects for the Direct Detection of the Cosmic Neutrino Background

Andreas Ringwald

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

PANIC 2008

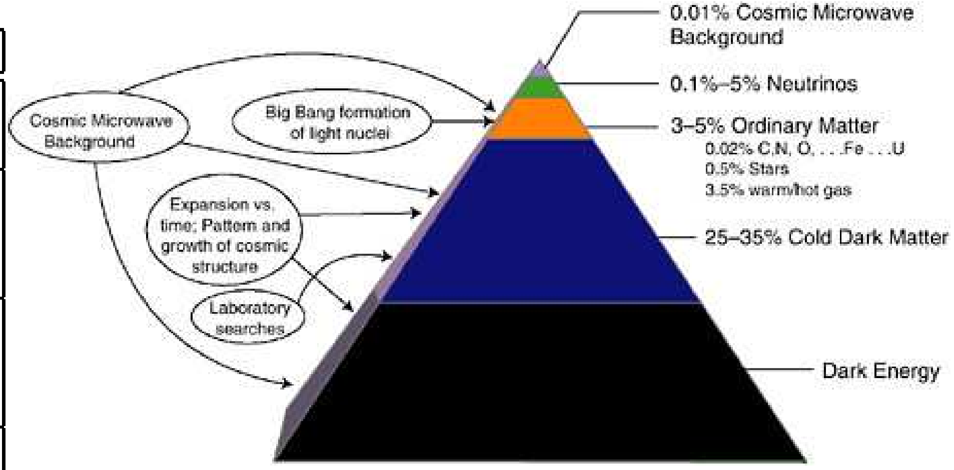
November 9–14, 2008, Eilat, Israel

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



[Connecting quarks ... cosmos]

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

- Indirect evidence for **CNB** from cosmological probes:
  - **BBN** prefers $N_\nu > 0$ (expansion rate during BBN $\Rightarrow$ He-4 abundance)
  - **CMB** and **LSS** prefer $N_\nu > 0$ (matter/radiation eq. $\Rightarrow$ fluctuation power spectra)
- **CNB** has not been detected **directly 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

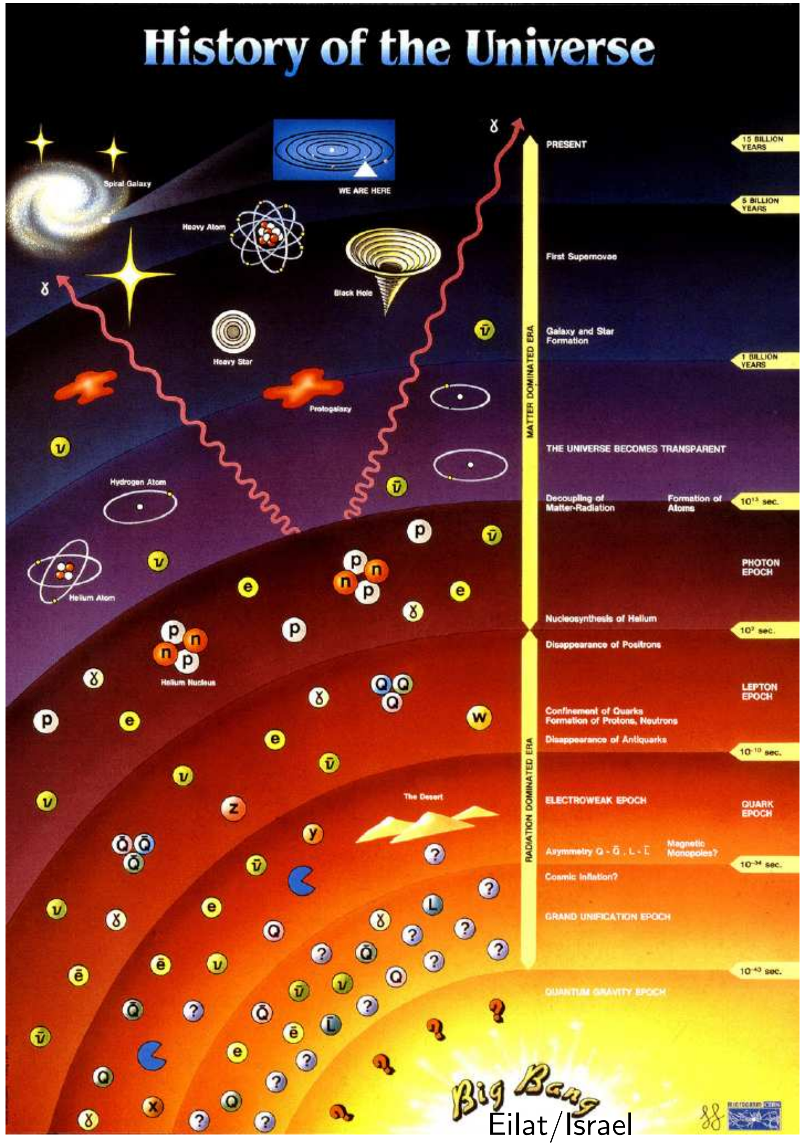
$\Leftarrow$ **theoretically known better than ever!**

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

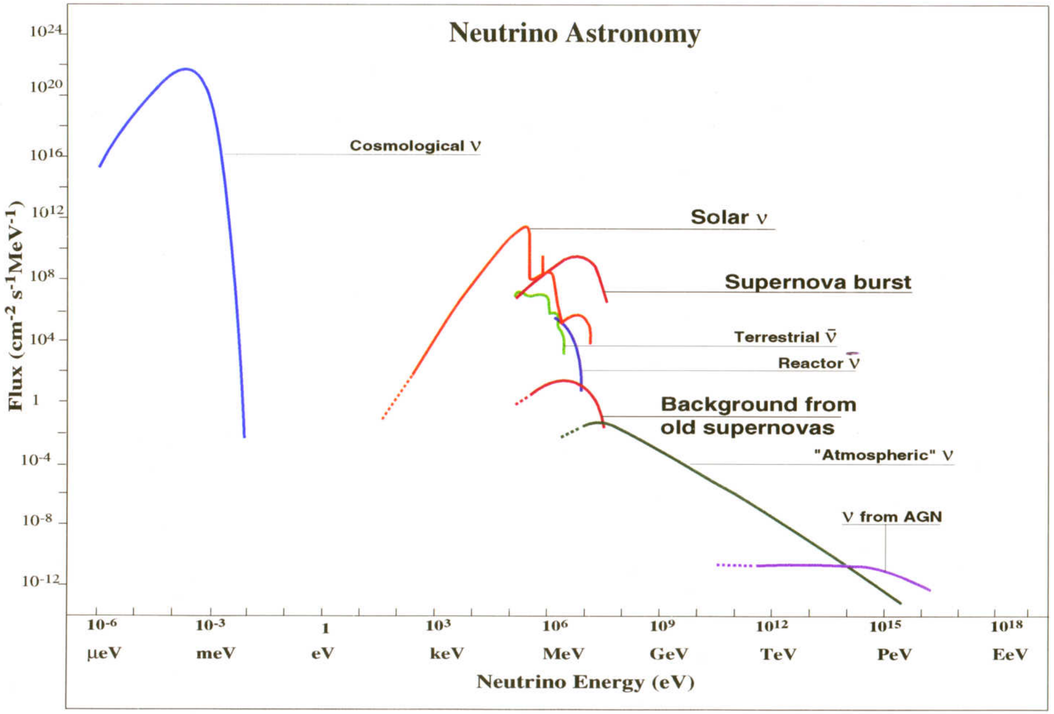


1. How many, how fast?

- Relic neutrinos decoupled at $t \sim 1$ s
- Predictions (for small degeneracy):

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

$\#$ relic neutrinos $\approx$ $\#$ relic photons



1. How many, how fast?

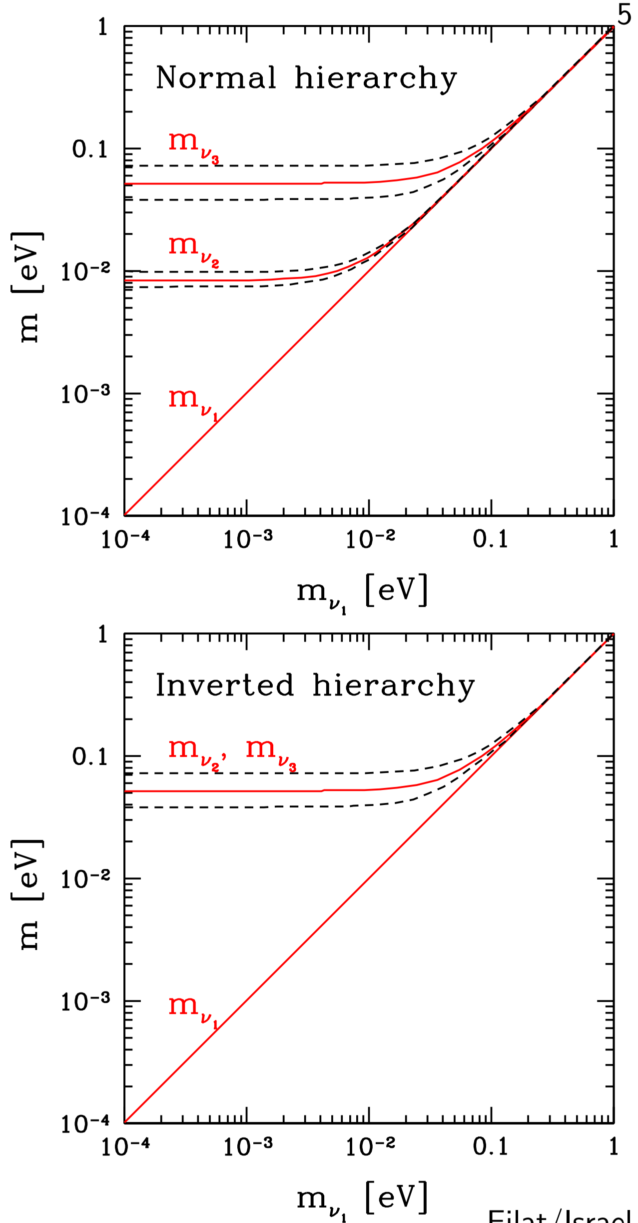
- Relic neutrinos decoupled at $t \sim 1$ s
- Predictions (for small degeneracy):

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

relic neutrinos ≈ # relic photons

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

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



1. How many, how fast?

- Relic neutrinos decoupled at $t \sim 1$ s
- Predictions (for small degeneracy):

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

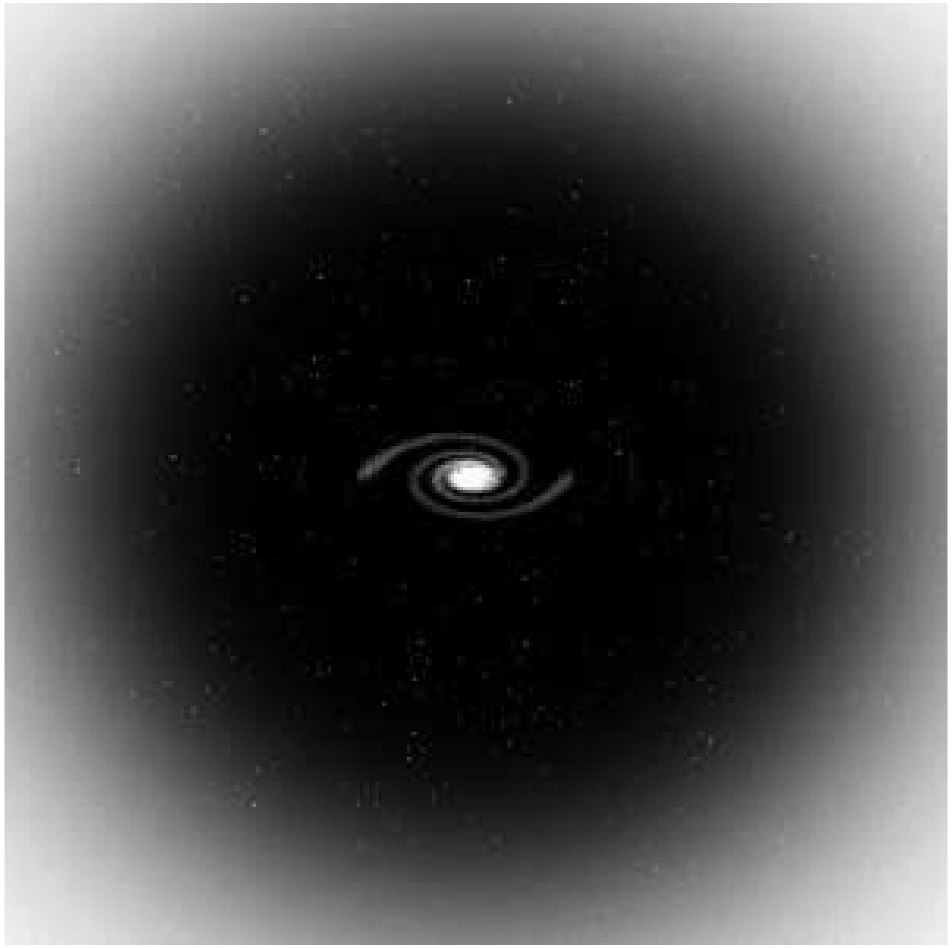
$\#$ relic neutrinos $\approx$ $\#$ relic photons

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

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

$\Rightarrow$ Gravitational clustering on **CDM**

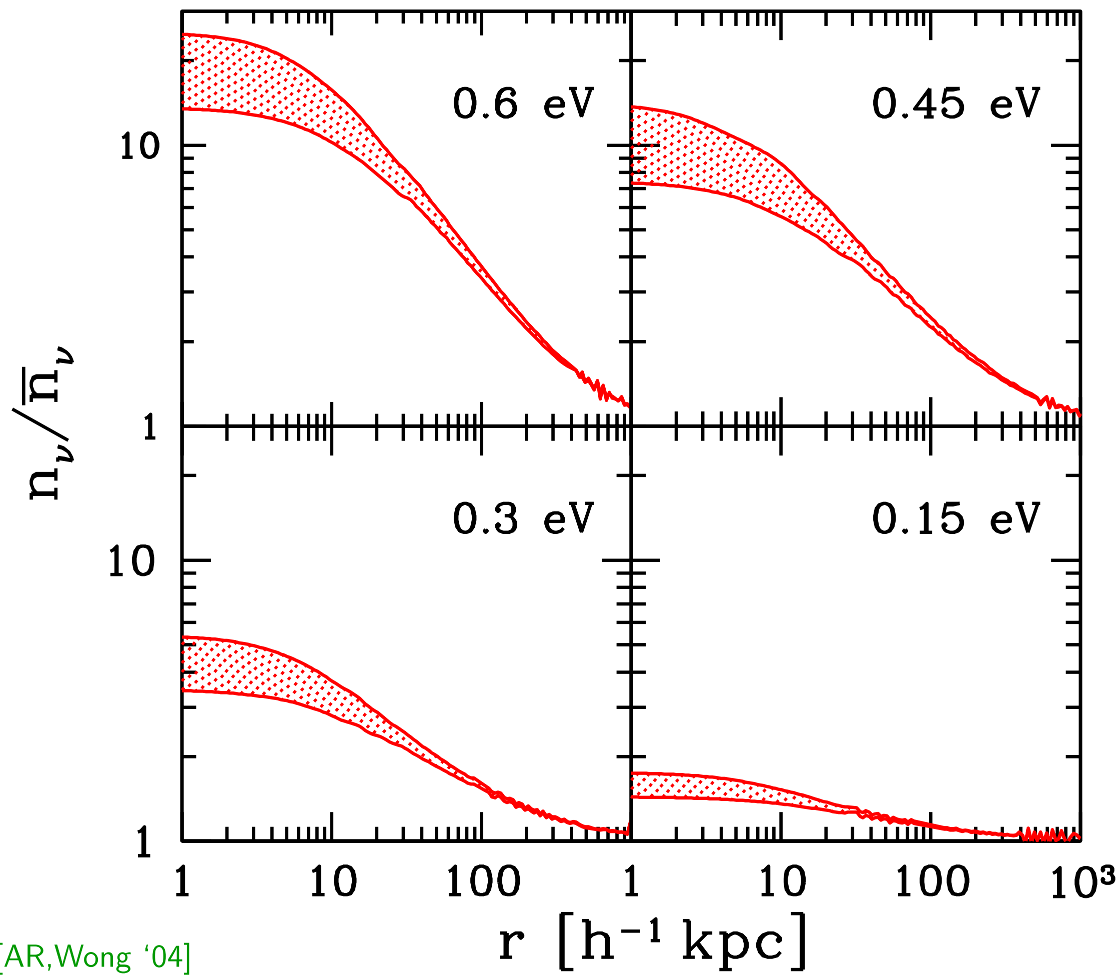
$\Rightarrow$ Density enhanced in galactic halos



[archive.ncsa.uiuc.edu]

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

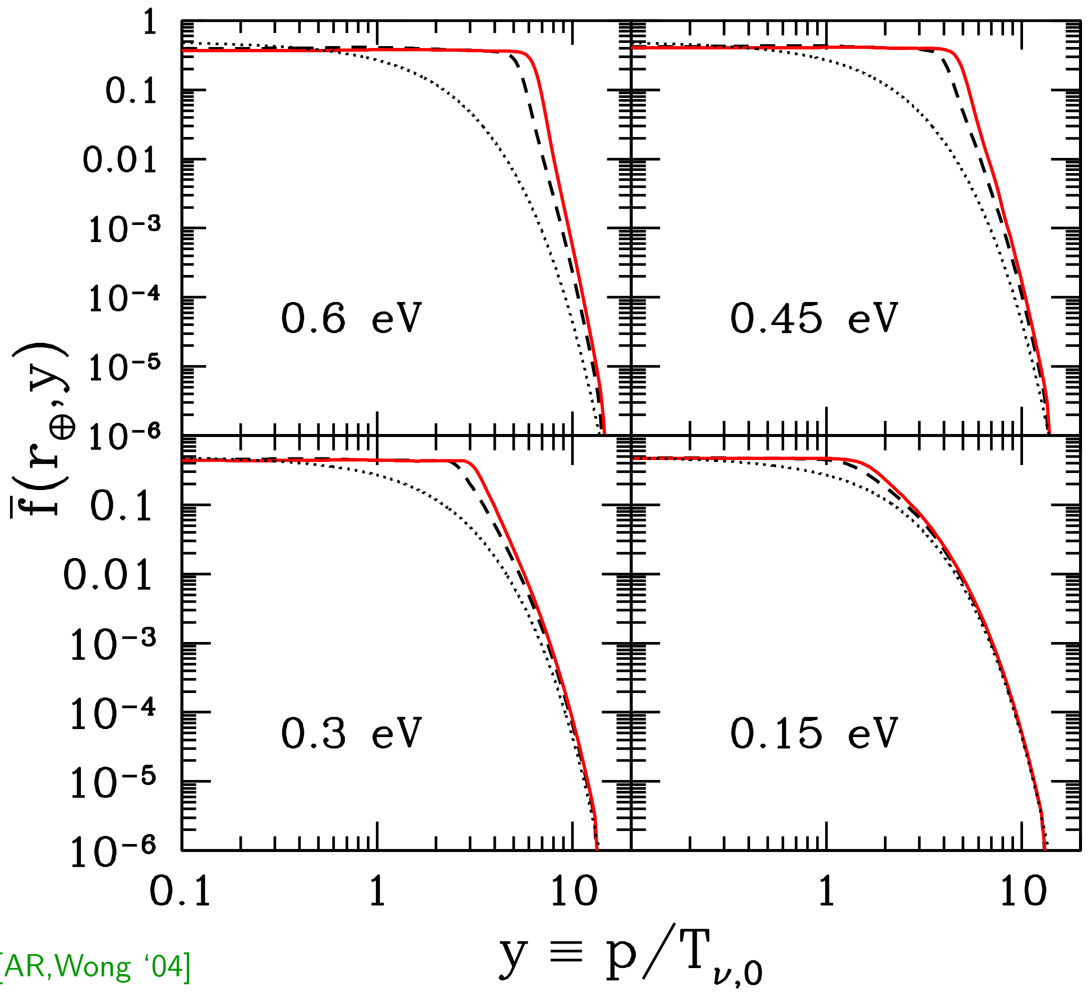
- Overdensity $\approx 1 - 20$



[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?

- Some possibilities of direct detection:
  - mechanical force through coherent scattering of relic neutrinos
  - neutrino capture on β decaying nuclei
  - Pauli blocking effects near thresholds for atomic neutrino pair emission enhanced by laser irradiation
  - scattering of accelerator beams off the relic neutrinos

Mechanical force based detection

- Low average momentum of relic neutrinos corresponds to a (reduced) **de Broglie wavelength** of **macroscopi**c 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

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

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 $(v_{\rm rel}/c)^2$

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

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

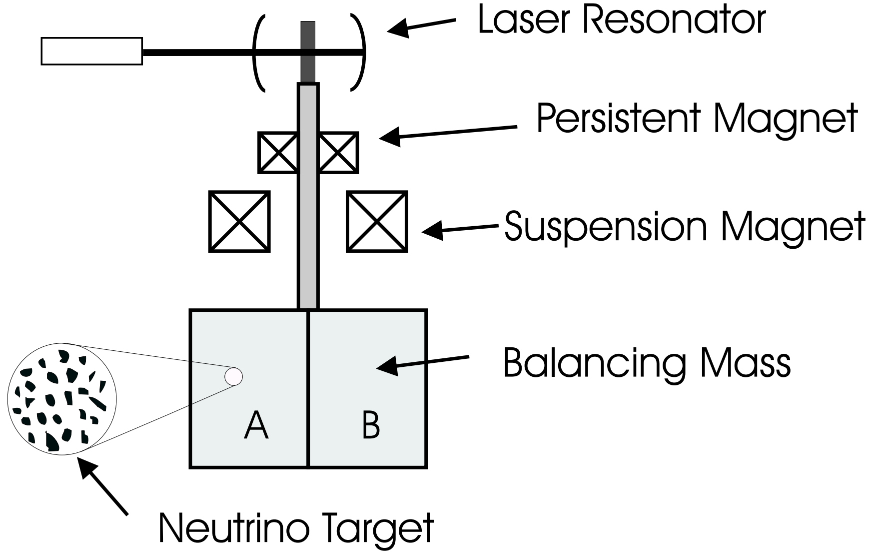
$$a_{\rm t} \simeq \sum_{\nu,\bar\nu} \underbrace{n_\nu\, v_{\rm rel}}_{\rm flux} \frac{4\pi}{3} N_A^2\, \rho_{\rm t}\, r_{\rm t}^3\, \sigma_{\nu N}\, \underbrace{2\, m_\nu\, v_{\rm rel}}_{\rm mom.\ transfer}$$

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

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

- 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]



[Hagmann '99]

- 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 $(v_{\rm rel}/c)^2$

- 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]

⇒ 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	2.3×10^{-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}
NFWhalo $m_\nu =$			
0.6 eV	12	2.7×10^{-2} cm	1.2×10^{-3}
0.45 eV	6.4	3.4×10^{-2} cm	1.3×10^{-3}
0.3 eV	3.1	3.9×10^{-2} cm	1.7×10^{-3}
0.15 eV	1.4	5.9×10^{-2} cm	2.2×10^{-3}

Neutrino capture of radioactive nuclei based detection

[Irvine,Humphrey '83; Cocco,Mangano,Messina '07; Lazauskas,Vogel,Volpe '08; Blennow '08]

- Consider neutrino capture on e.g. tritium,

$$\nu_i + {}^3\mathrm{H} \to e + {}^3\mathrm{He}$$

- **Capture rate** of CNB neutrinos,

$$N_{i,\,\mathrm{CNB}} \simeq 6.5\ \mathrm{yr}^{-1} \left(100\,\mathrm{g}\ {}^3\mathrm{H}\right)^{-1} |U_{ei}|^2\, \frac{n_{\nu_i}}{\bar{n}_{\nu_i}}$$

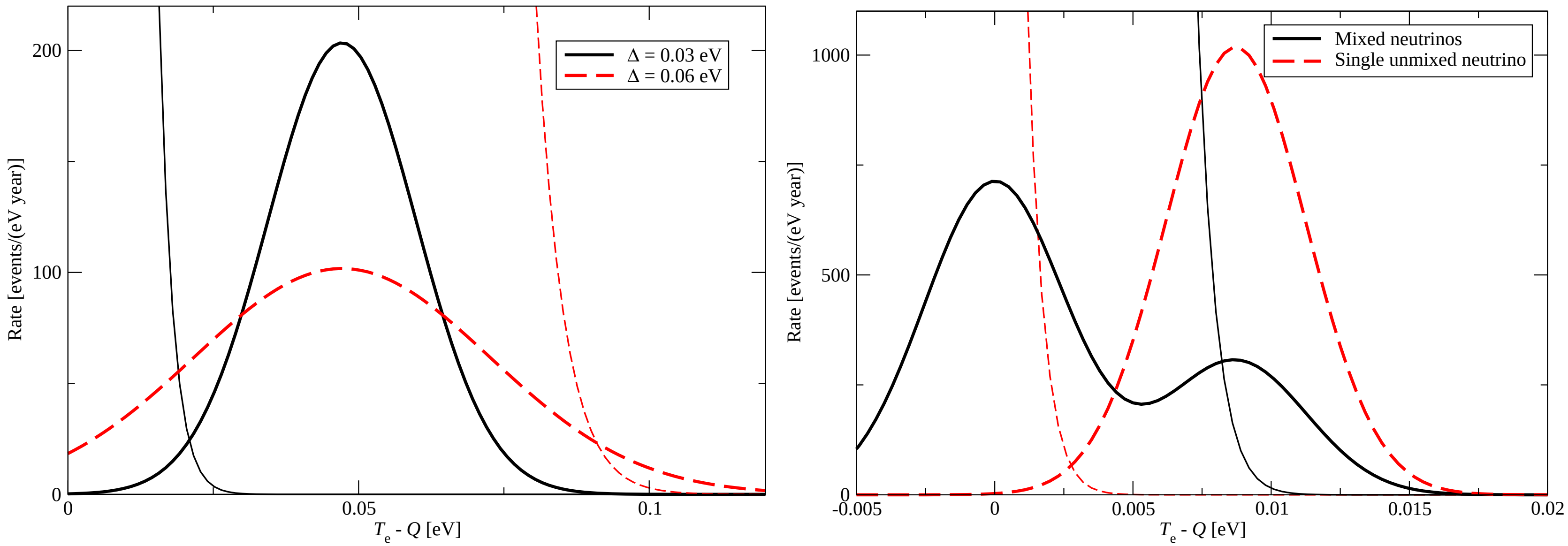
- **Signature:** monoenergetic electrons with kinetic energy

$$T_{\mathrm{kin}} = Q_\beta + m_{\nu_i}$$

where $Q_\beta = 18.6\,\mathrm{keV}$ is the energy release in ^{3}H β-decay for $m_{\nu_i} = 0$

- **Main challenge:** Separation of signal electrons from overwhelming background of electrons from ^{3}H β-decay

⇒ Need very good energy resolution $\Delta \lesssim$ 0.5 eV (degenerate masses), 0.05 eV (inverted hierarchy), 0.005 eV (normal hierarchy)



[Blennow '08]

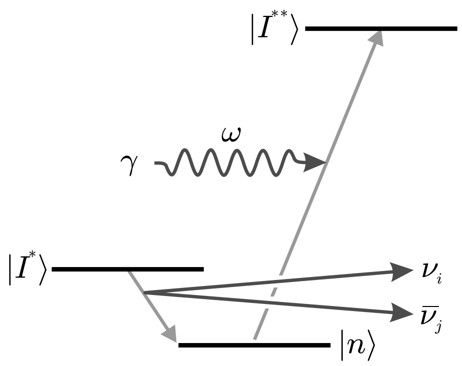
⇒ Opportunity for KATRIN ($\Delta \sim 0.5$ eV) and future ^{3}H β decay campaigns

Pauli blocking of atomic neutrino pair emission

[Yoshimura '07;Takahashi,Yoshimura '07]

- Laser irradiated neutrino pair emission from metastable ions or atoms,

$$\gamma + I^\star \to I^{\star\star} + \nu_i \bar{\nu}_i$$



- **Signature:** detection of $I^{\star\star}$; rate resonantly enhanced by tuning ω
- In presence of CNB, rate reduced near threshold due to Pauli blocking

Accelerator beam based 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** [Weiler '82;...;Fodor,Katz,AR;...;Eberle,AR,Song,Weiler;...;L.Schrempp,AR;...]

for scattering on relic neutrinos as **target**

Exploit accelerator beams:

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

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

$$\simeq \quad 2\times10^{-8}\left(\frac{n_\nu}{\bar n_\nu}\right)\left(\frac{m_\nu}{\rm eV}\right)\frac{A^2}{Z}\left(\frac{E_N}{10\ {\rm TeV}}\right)\left(\frac{L}{100\ {\rm km}}\right)\left(\frac{I}{0.1\ {\rm A}}\right)\ {\rm yr}^{-1}$$

⇒ 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

$${}^A_ZN + \nu_e \longrightarrow {}^A_{Z+1}N + e^-$$

⇒ 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

3. Conclusions

- **BBN**, **CMB**, and **LSS** provide presently the only evidence for the **CNB**
- **Roadmap for direct CNB detection**

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

  - neutrino capture in β decaying nuclei
    Remarks: current technology 1-2 orders of magnitude off
  - coherent elastic scattering of relic ν's off nucleons in terrestrial detector
    Remarks: current technology 3 orders of magnitude off
  - Pauli blocking effects in laser induced atomic neutrino pair emission
    Remarks: needs more study to estimate discovery potential
  - interactions of very high energy particles from terrestrial accelerator beams with the relic neutrinos as target
    Remarks: needs design of specialized accelerator (beyond our lifetime?)