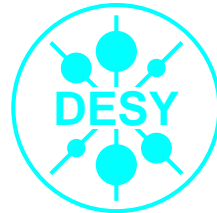


Neutrinos in the Universe

Andreas Ringwald

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



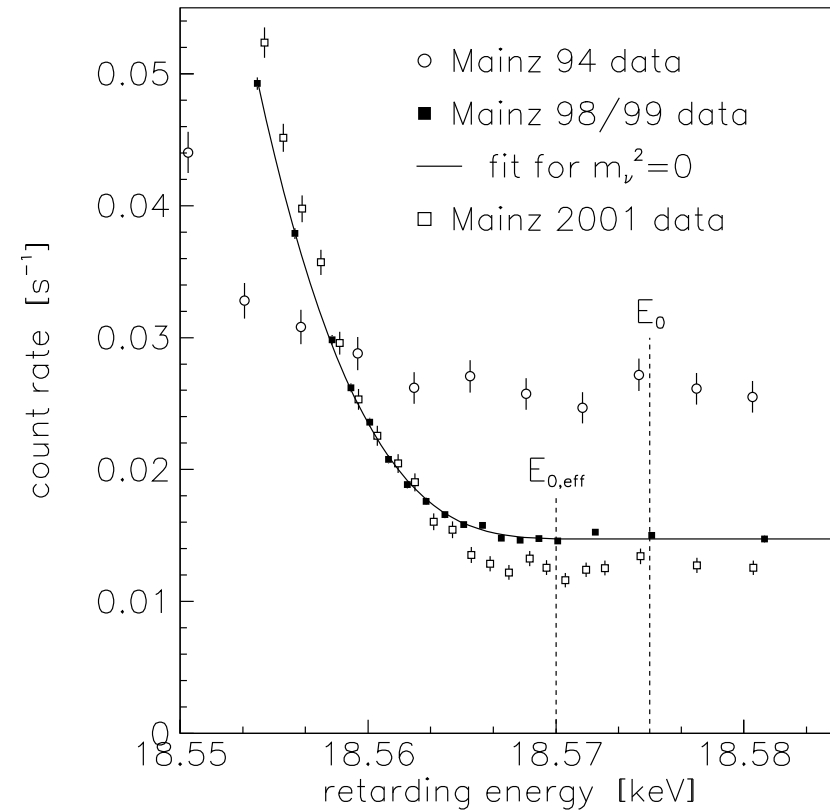
ECFA/BENE Workshop on
The future of accelerator neutrino experiments in Europe
DESY, Hamburg, D, November 2-3, 2004

1. Introduction

- Neutrino experiments and observatories have told us a great deal about neutrino masses and mixings:

◇ Tritium β decay: [Lobashev '02, Weinheimer '03]

$$m_\beta \equiv \sqrt{\sum_j |U_{ej}|^2 m_{\nu_j}^2} < 2.2 \text{ eV}$$



[Weinheimer '03]

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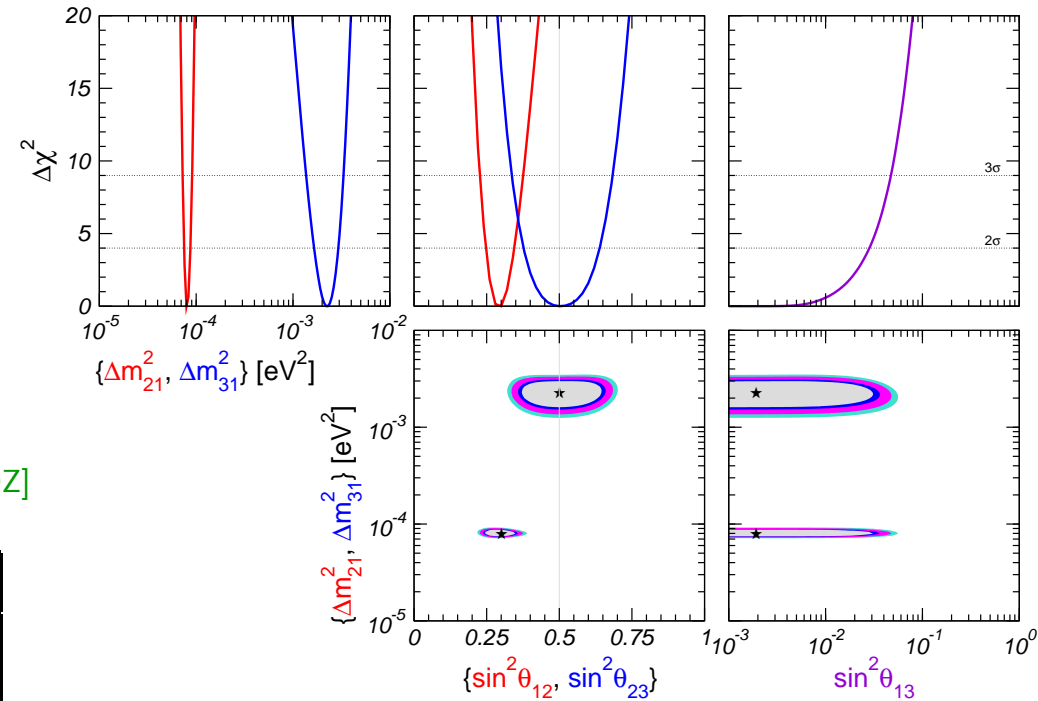
- ◇ Solar, atmospheric, and reactor ν 's:

[Homestake,...,SNO,KamLAND...;SuperKamiokande,K2K,...;CHOOZ]

parameter	best fit	3σ range
Δm_{21}^2 [10^{-5} eV^2]	8.1	7.2–9.1
Δm_{31}^2 [10^{-3} eV^2]	2.2	1.4–3.3
$\sin^2 \theta_{12}$	0.30	0.23–0.38
$\sin^2 \theta_{23}$	0.50	0.34–0.68
$\sin^2 \theta_{13}$	0.000	≤ 0.047

A. Ringwald (DESY)

[Maltoni *et al.* '04]



[Maltoni *et al.* '04]

DESY, Hamburg, D

– Neutrinos in the Universe –

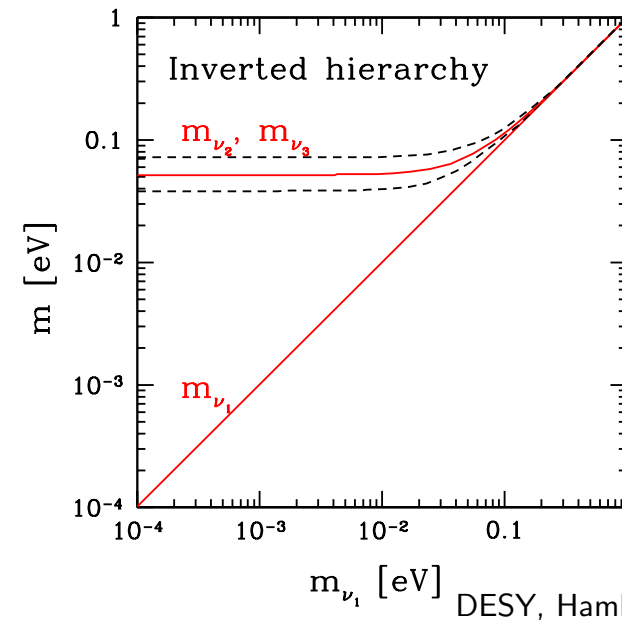
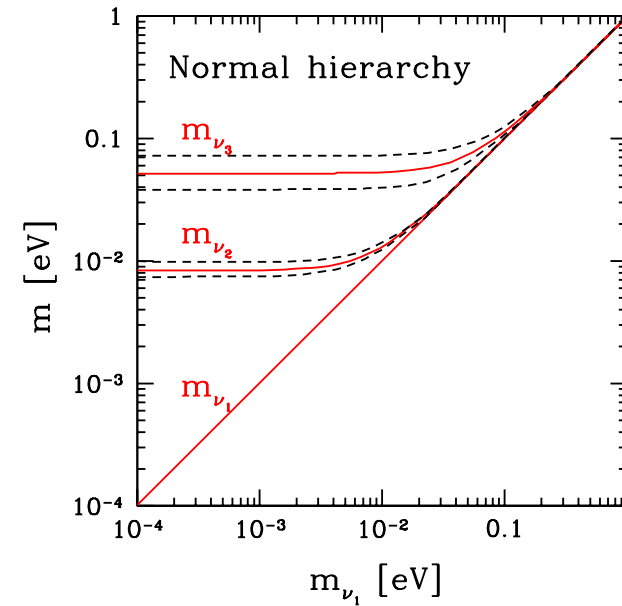
- Only limited information on **absolute neutrino mass** scale and $\sin^2 \theta_{13}$:

$$0.04 \text{ eV} \lesssim m_{\nu_3} \lesssim 2.2 \text{ eV}$$

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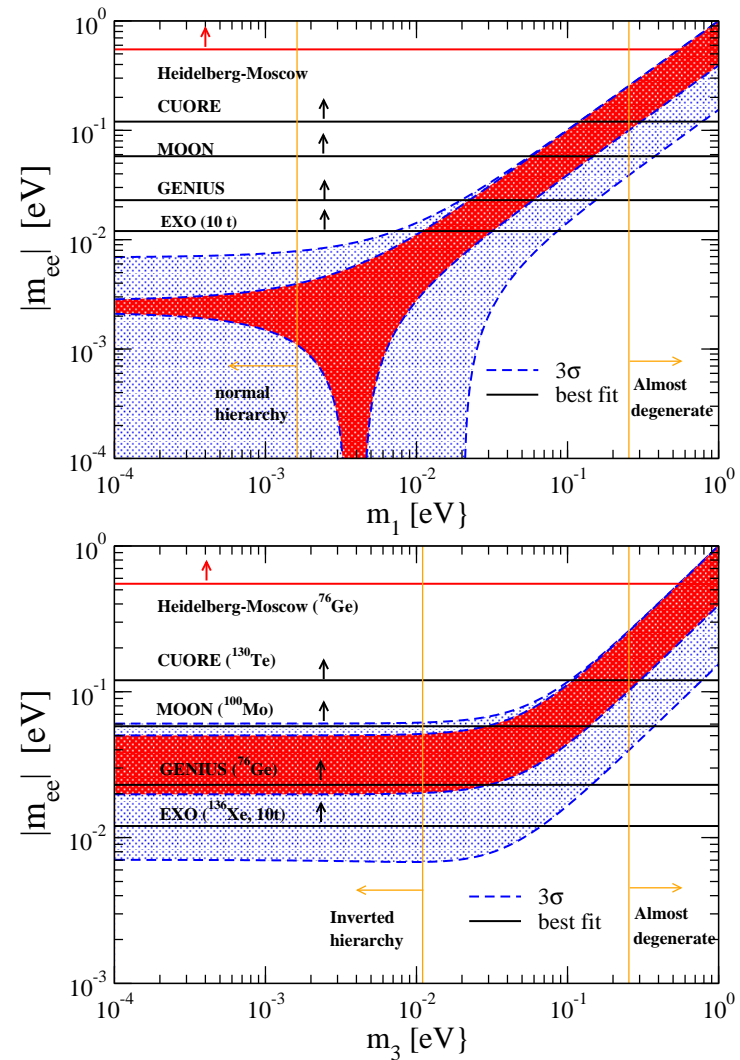
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[Bilenky *et al.* '04]

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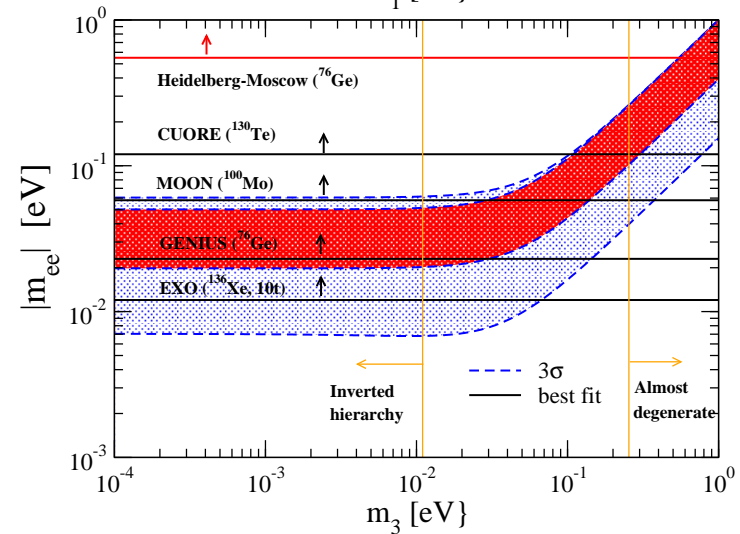
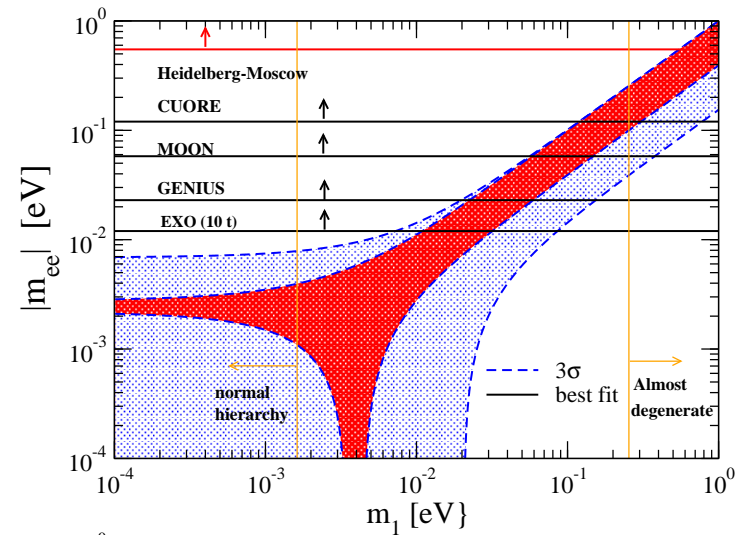
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- Improved by upcoming experiments

5



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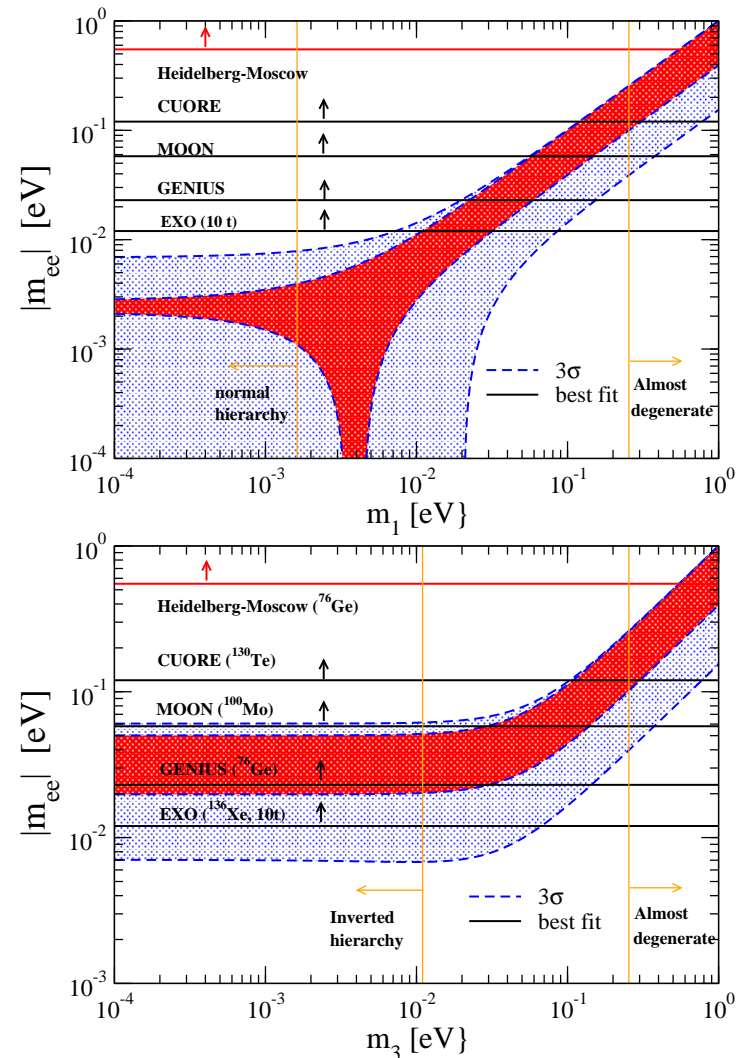
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⇒ **Impact of neutrino masses and leptonic CP violation on our understanding of the universe?**

2. Cosmic Neutrino Background and Structure in the Universe

3. Baryogenesis via Leptogenesis

A. Ringwald (DESY)

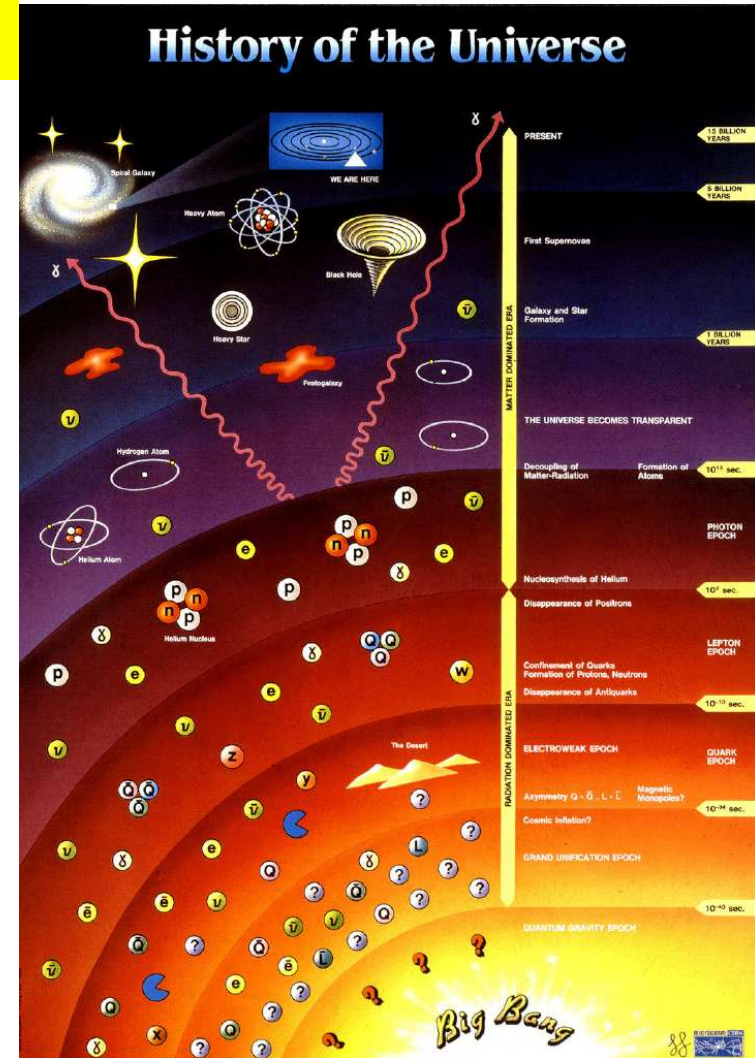


[Bilenky *et al.* '04]

DESY, Hamburg, D

2. $C\nu B$ and Structure in Universe

- Big Bang cosmology:
 - ⇒ Cosmic microwave background (CMB)
 - ⇒ Cosmic neutrino background ($C\nu B$)



2. $C\nu$ B and Structure in Universe

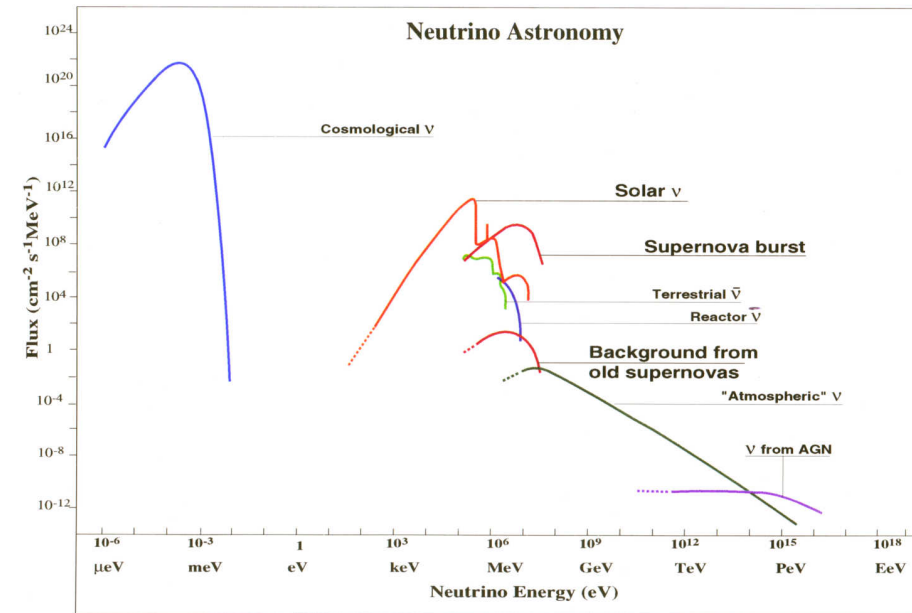
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 - ⇒ **Cosmic neutrino background ($C\nu$ B)**

● Firm prediction:

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

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

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



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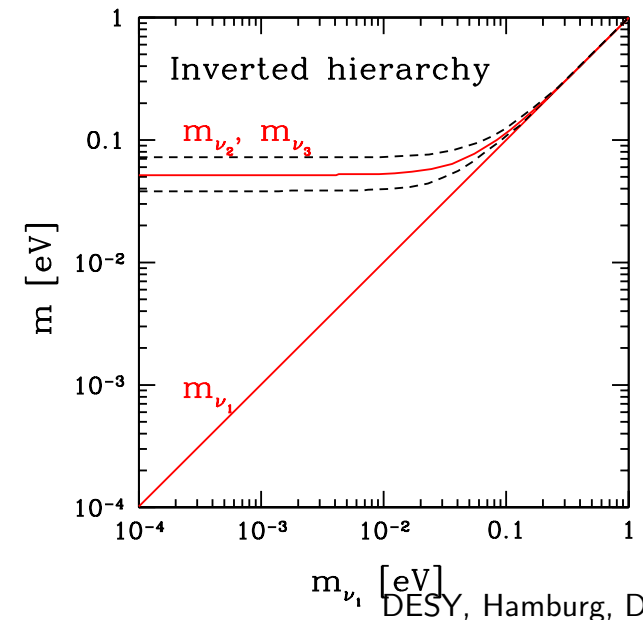
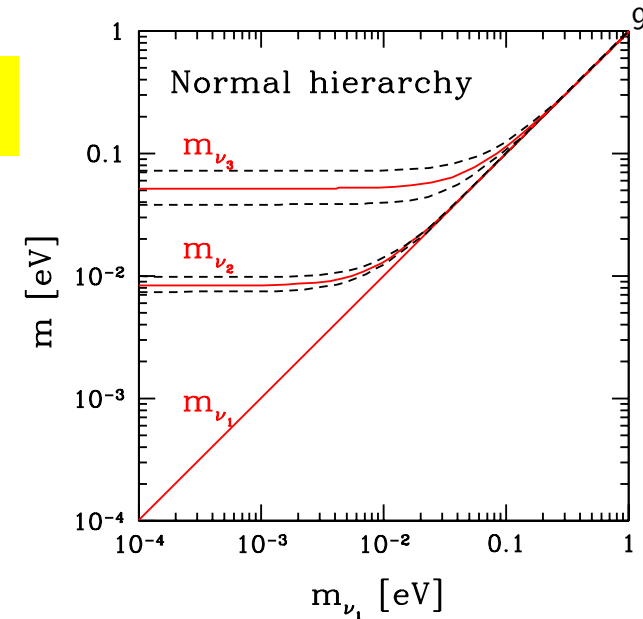
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⇒ Big bang relic neutrinos \approx as abundant as relic photons [ratio $(6 \times 3)/22 = 9/11$]

⇒ Relic neutrinos non-relativistic as long as $m_{\nu_i} \gg 5 \times 10^{-4} (1+z) \text{ eV}$



• **CνB and large scale structure:**

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

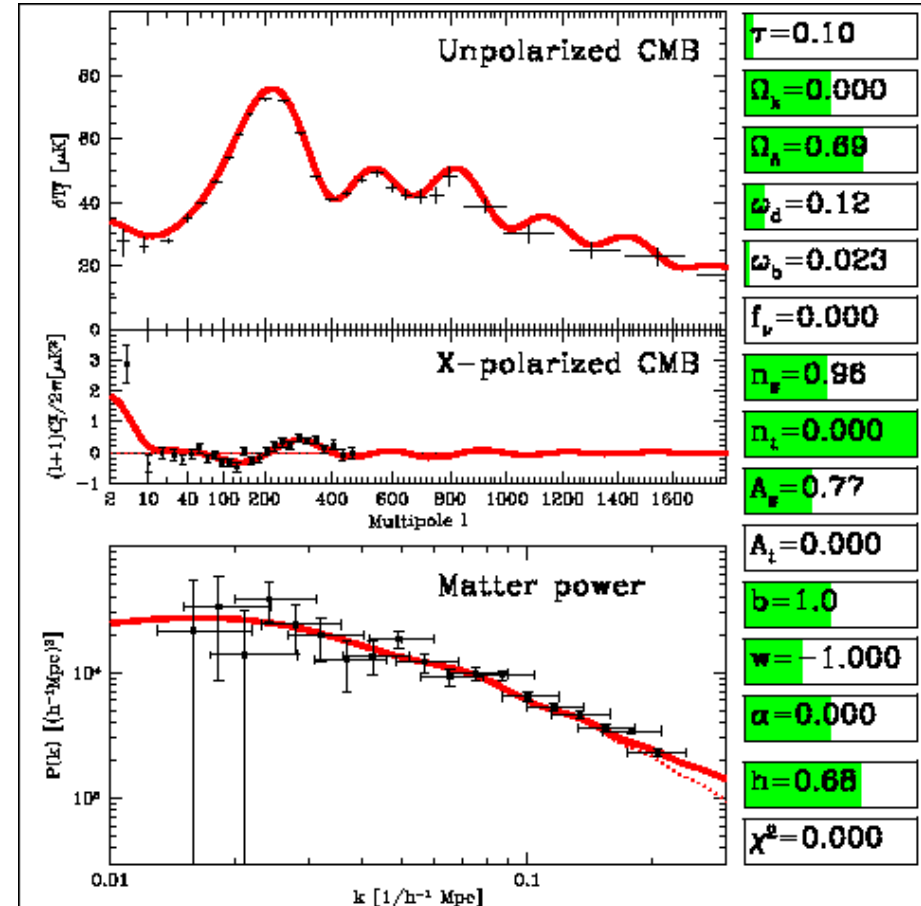
$$\lambda_{fs} \simeq 4.2 \left(\frac{(1+z)}{\Omega_m} \right)^{1/2} \left(\frac{\text{eV}}{m_\nu} \right) h^{-1} \text{Mpc}$$

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

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

where Ω_ν fractional neutrino density

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



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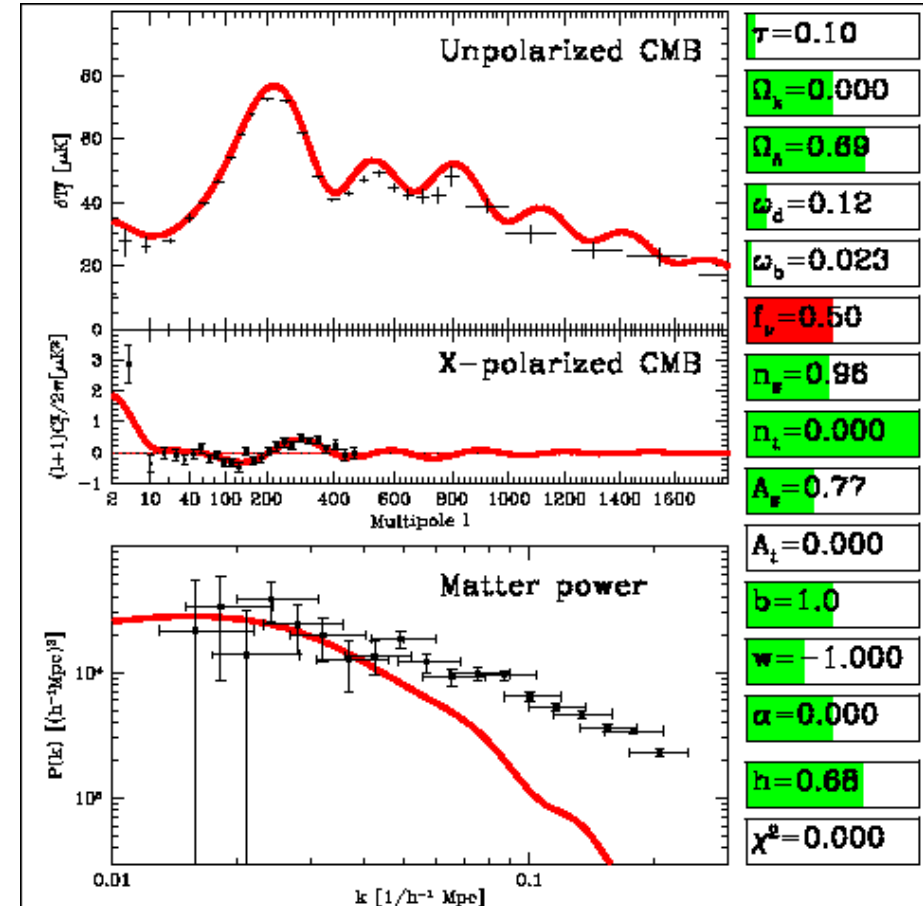
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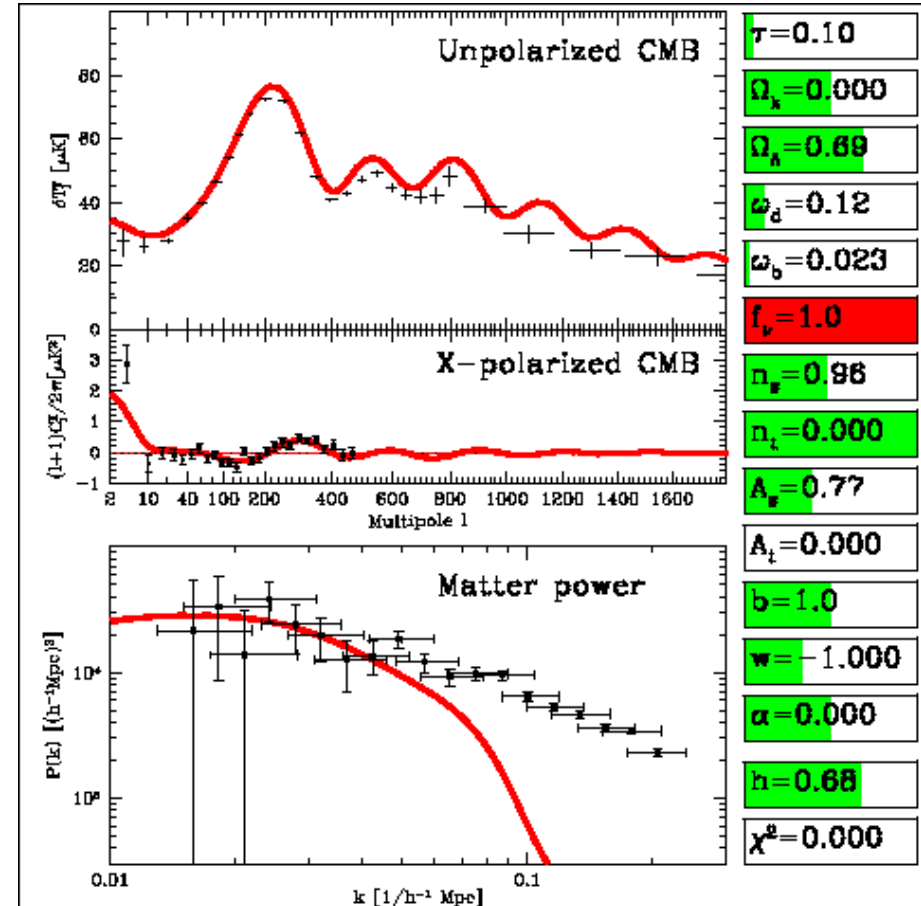
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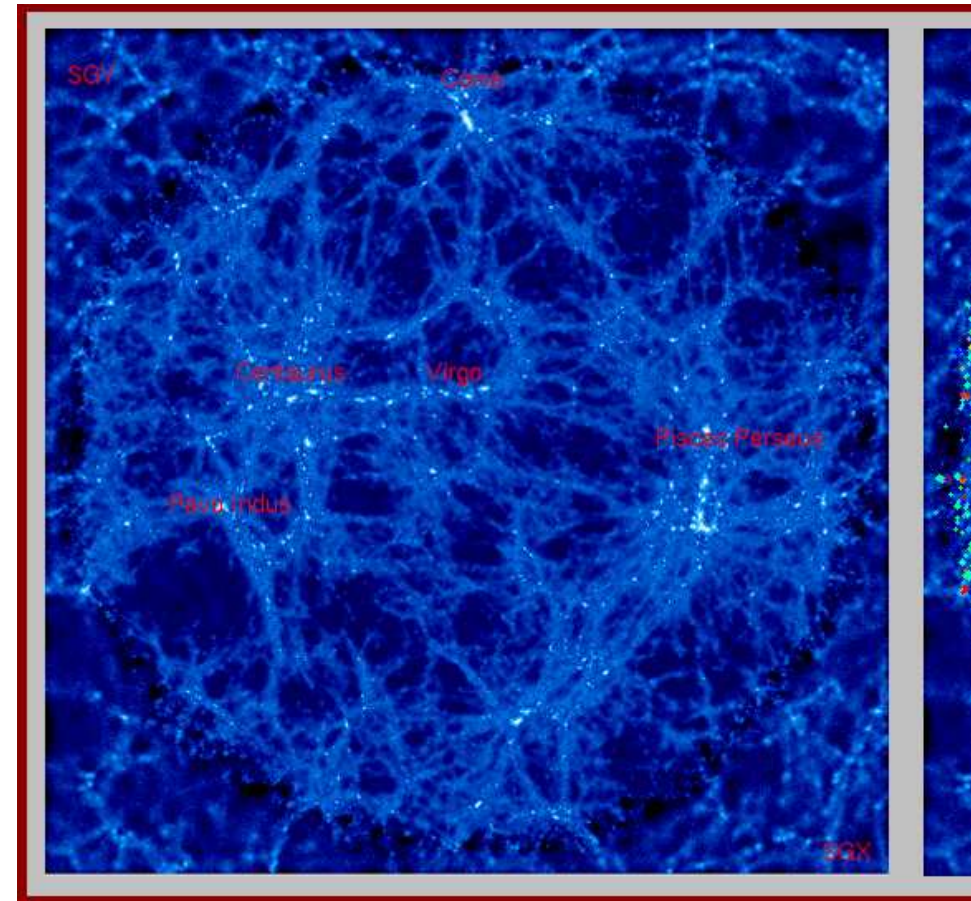
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- ⇒ Constraints from **LSS** and **CMB**
- ⇒ **Less cosmological parameters if $\sum m_\nu$ known from lab experiments**

Ref.	$\sum m_\nu$ bound	Data used
[Spergel <i>et al.</i>]	0.69 eV	2dF, WMAP, CMB, σ_8, H_0
[Hannestad]	1.01 eV	2dF, WMAP, CMB, H_0
[Allen <i>et al.</i>]	$0.56^{+0.30}_{-0.26}$ eV	2dF, WMAP, CMB, σ_8, H_0
[Tegmark <i>et al.</i>]	1.8 eV	SDSS, WMAP
[Barger <i>et al.</i>]	0.75 eV	2dF, SDSS, WMAP, CMB, H_0
[Crotty <i>et al.</i>]	1.0 eV	2dF, SDSS, WMAP, CMB, H_0

- **$C\nu B$ gravitational clustering:**

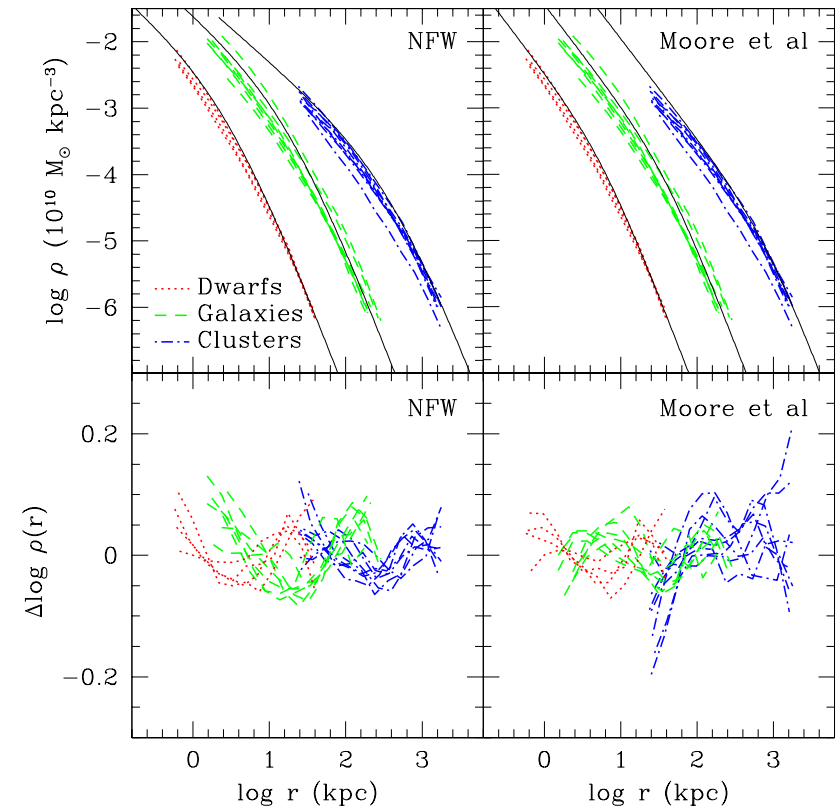
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[Mathis *et al.* '02]

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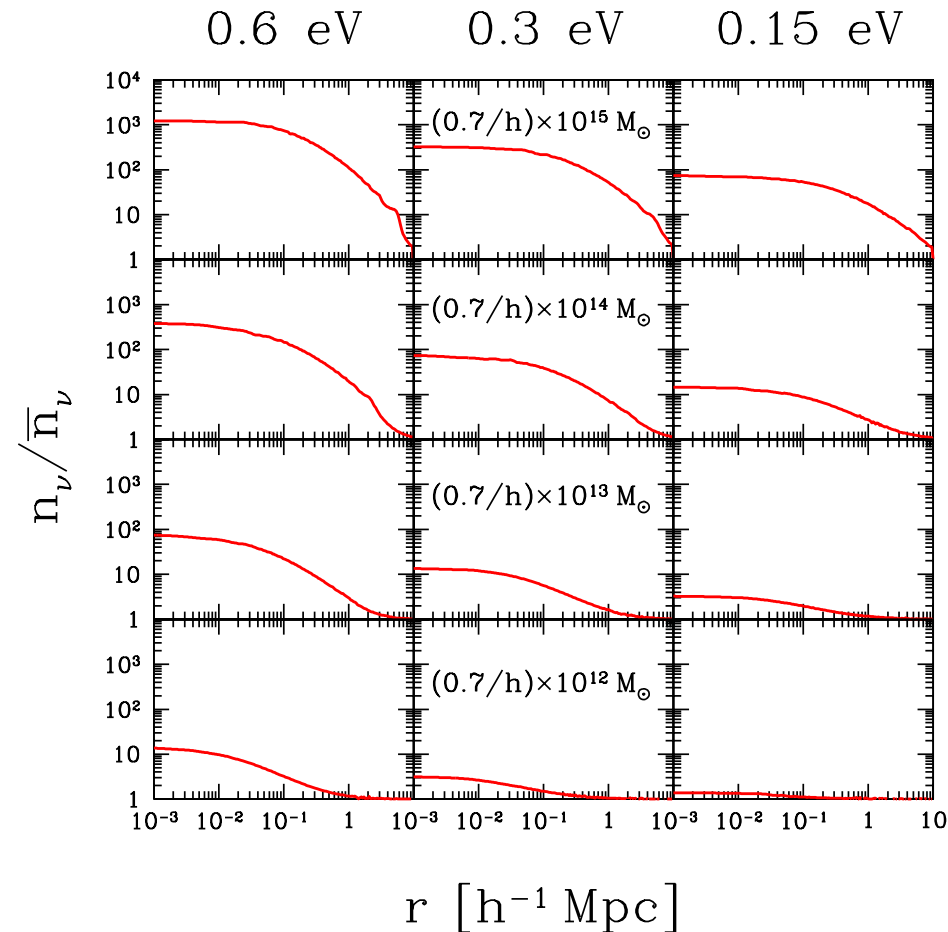


[Navarro et al. '04]

• **$C\nu B$ gravitational clustering:**

- ◇ At late time, non-relativistic neutrinos cluster gravitationally on cold dark matter (**CDM**) and baryonic structures
- ◇ Study neutrino clustering in **CDM** halos
- ◇ Improved clustering for big m_ν a/o M_{vir} :
 - * Local universe:
 - Overdensity ≈ 1000 (≈ 100) for $m_\nu = 0.6$ eV (= 0.15 eV) for inner part ($\lesssim 100$ kpc) of Virgo and Centaurus clusters ($\approx 10^{15} M_\odot$)
 - * Local neighbourhood of Earth:
 - Overdensity ≈ 20 (≈ 2) for $m_\nu = 0.6$ eV (= 0.15 eV)

⇒ **Knowledge of m_ν fixes huge uncertainty in relic neutrino clustering**



[AR,Wong '04]

3. 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 $M_M \Rightarrow$ small Majorana m_ν through large M_M ,

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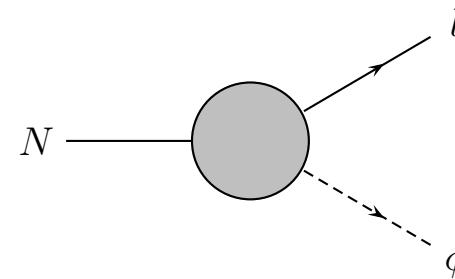
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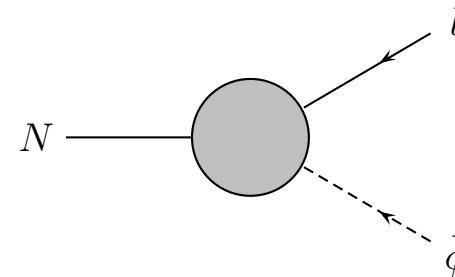
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$$\Gamma(N \rightarrow l\phi) = (1 + \epsilon) \Gamma/2$$



$$\Gamma(N \rightarrow \bar{l}\bar{\phi}) = (1 - \epsilon) \Gamma/2$$

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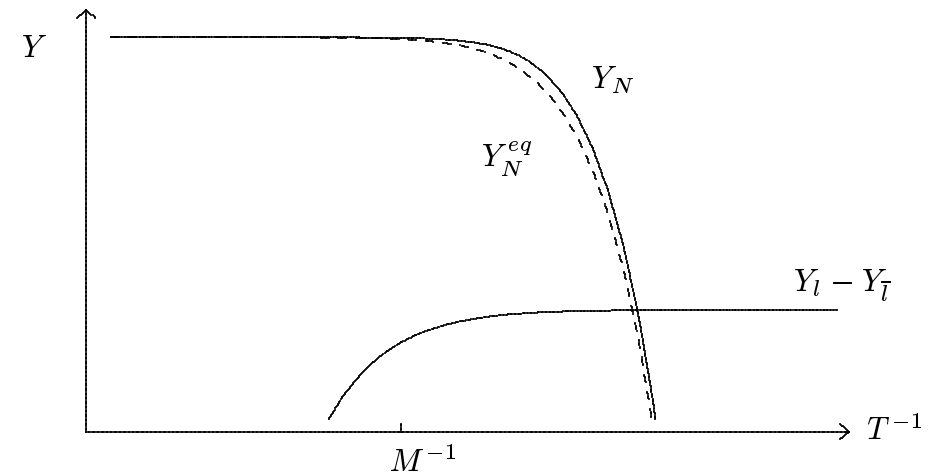
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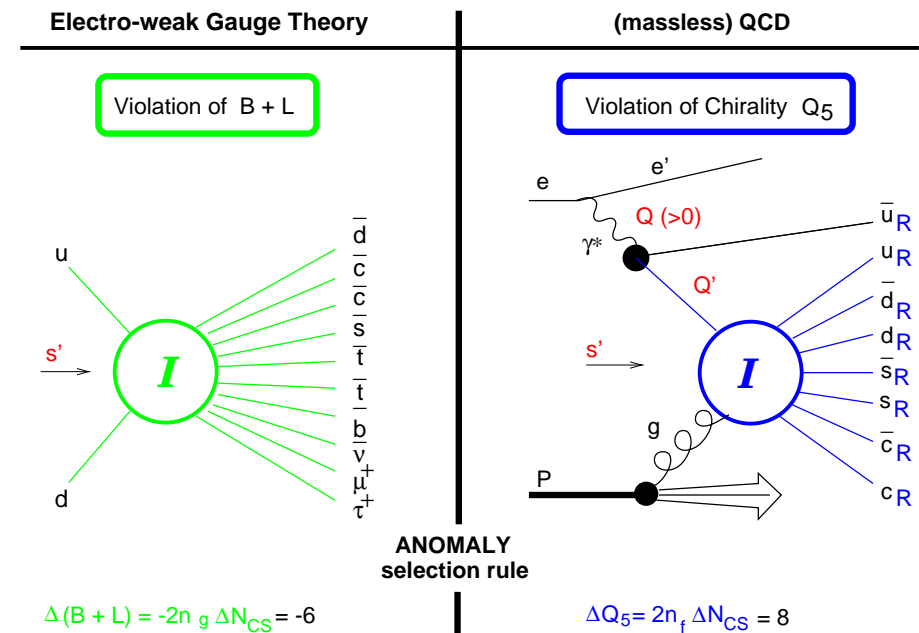
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$\Rightarrow Y_L \neq 0$ which, by means of electro-weak instanton/sphaleron processes,

\Rightarrow **Baryon asymmetry**

$$Y_B = c Y_L = c \kappa \epsilon / g_*$$

A. Ringwald (DESY)



DESY, Hamburg, D

- Constraints on neutrino parameters from requirement of successful leptogenesis?

◇ **Robust mass bounds** in models exploiting **thermal leptogenesis** based on

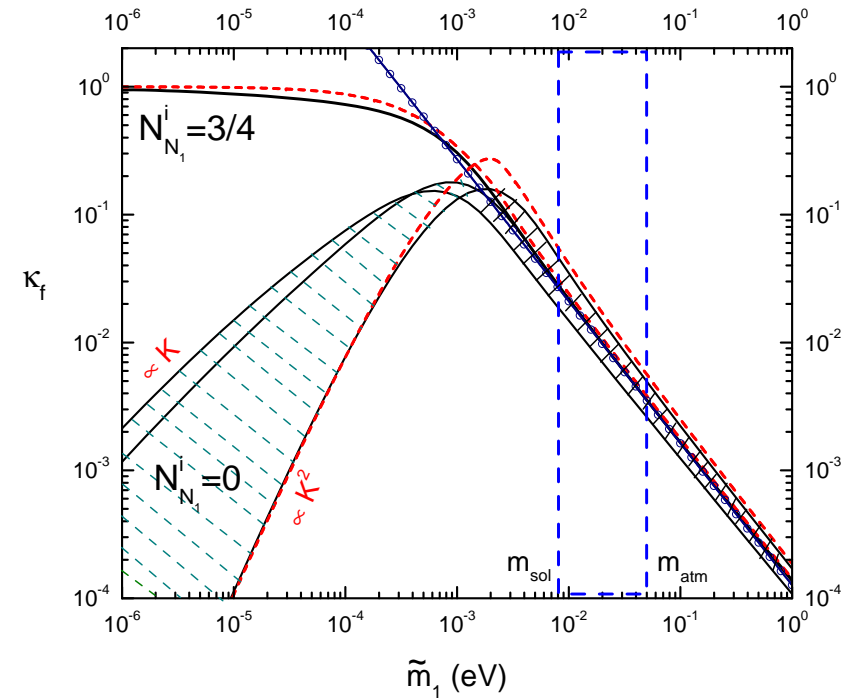
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- ⊕ hierarchical N 's, $M_1 < \mathcal{O}(2) M_{2,3}$:

[Buchmüller, di Bari, Plümacher ≥'02]

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

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

⇒ **May be confronted with lab determination of m_{ν_i}**



$$\left[\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} \geq m_{\nu 1} \right]$$

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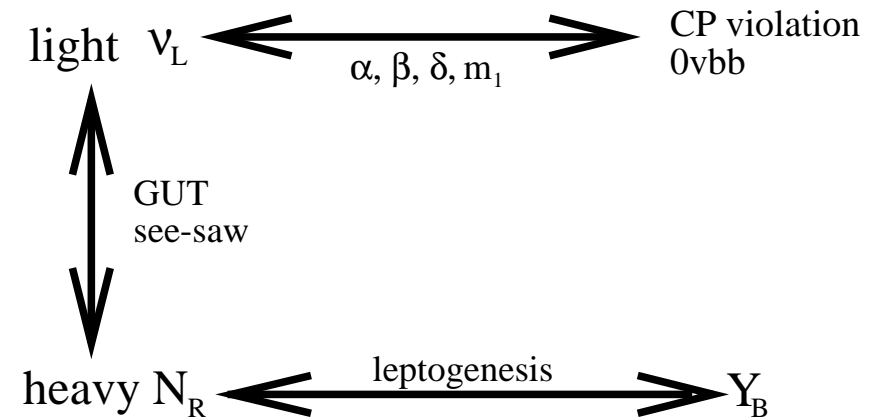
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[Pascoli, Petcov, Rodejohann '03]

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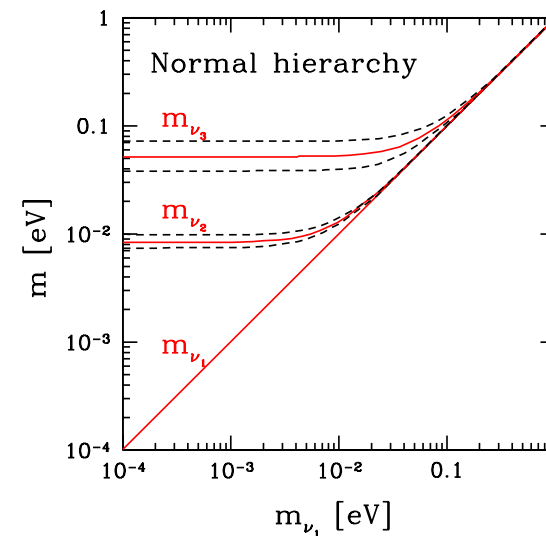
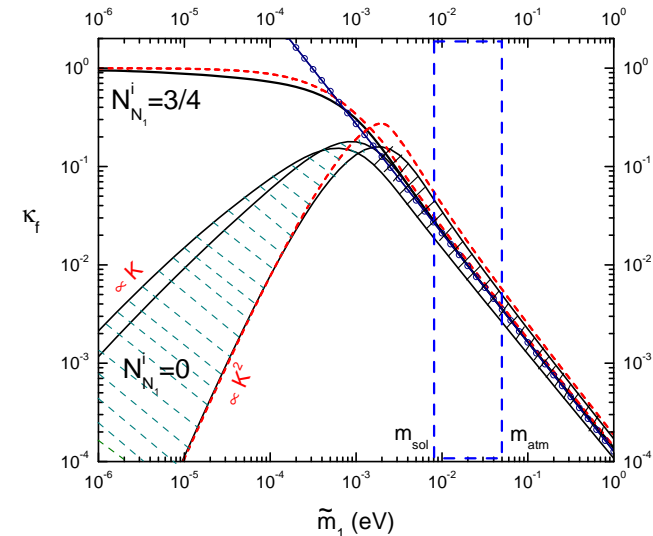
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◇ **For sizeable mixing $\sin^2 \theta_{13} \sim 0.01$ expect preferred mass spectrum $0.01 \text{ eV} \lesssim m_{\nu_i} \lesssim 0.1 \text{ eV}$**



4. Conclusions

- Precise knowledge of neutrino parameters, i.e. masses, mixing, CP violating phases, has profound impact on our understanding of the universe
 - Precise determination of cosmological parameters
 - Amount of relic neutrino clustering
 - Test/falsify specific models of baryogenesis from leptogenesis