Neutrinos in the Universe

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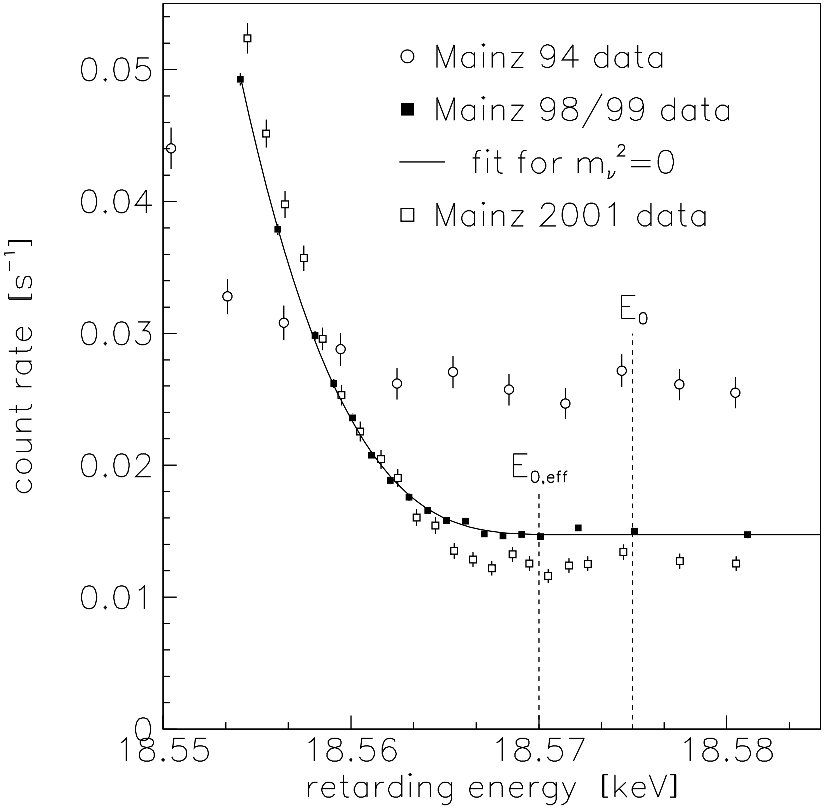
ECFA/BENE Workshop on
The future of accelerator neutrino experiments in Europe
DESY, Hamburg, D, November 2-3, 2004

1. Introduction

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

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

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



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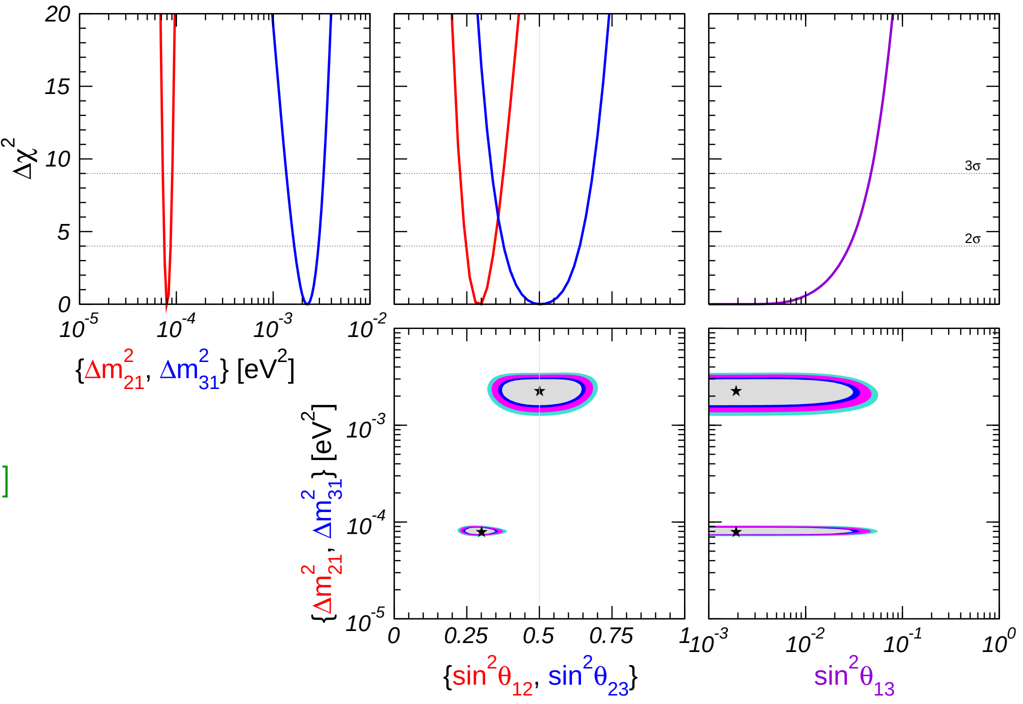
  ◇ Solar, atmospheric, and reactor ν’s:

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

parameter	best fit	3σ range
Δm^2_{21} $[10^{-5}\ \text{eV}^2]$	8.1	7.2–9.1
Δm^2_{31} $[10^{-3}\ \text{eV}^2]$	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	$\leq$ 0.047

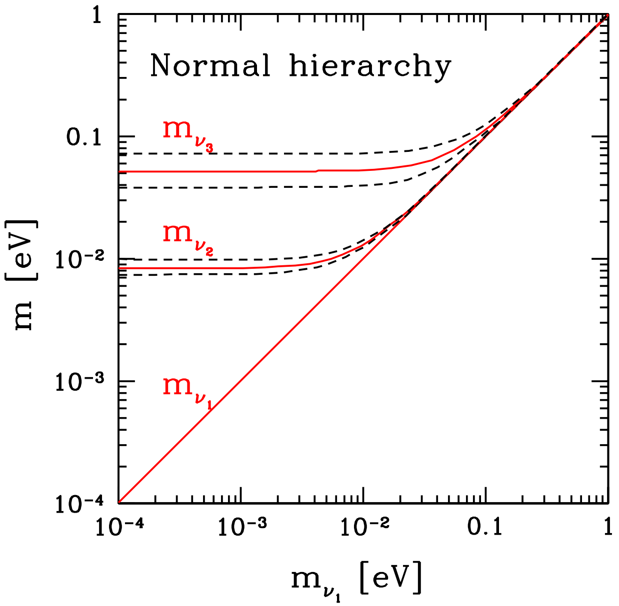
[Maltoni *et al.* ‘04]

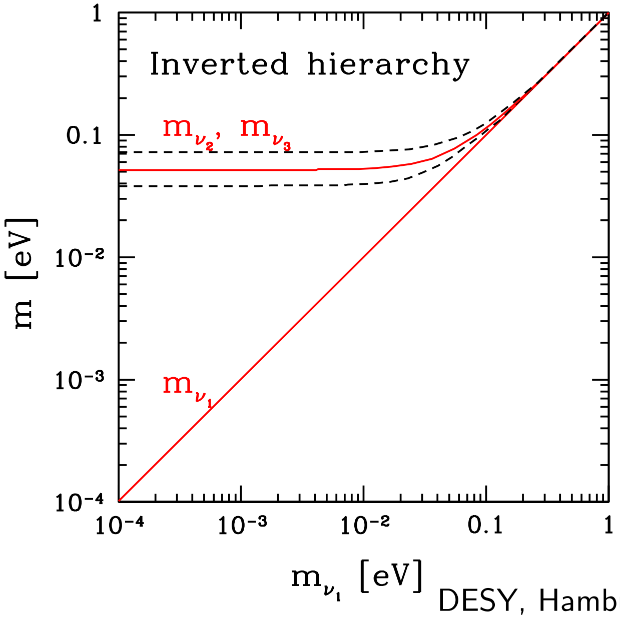


[Maltoni *et al.* ‘04]

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

$$\begin{array}{rcl} 0.04\ \mathrm{eV} \lesssim & m_{\nu_3} & \lesssim 2.2\ \mathrm{eV} \\ 0.007\ \mathrm{eV} \lesssim & m_{\nu_2} & \lesssim 2.2\ \mathrm{eV} \\ 0\ \mathrm{eV} \lesssim & m_{\nu_1} & \lesssim 2.2\ \mathrm{eV} \\ 0 \leq & \sin^2\theta_{13} & \leq 0.047 \end{array}$$





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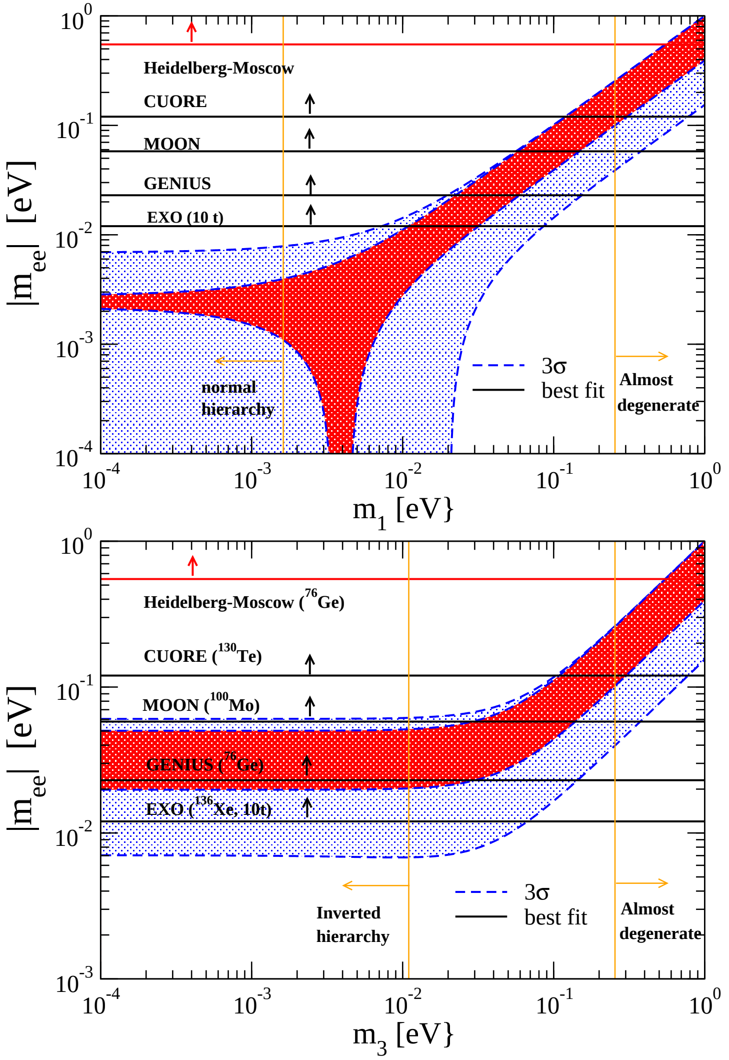

[Bilenky *et al.* '04]

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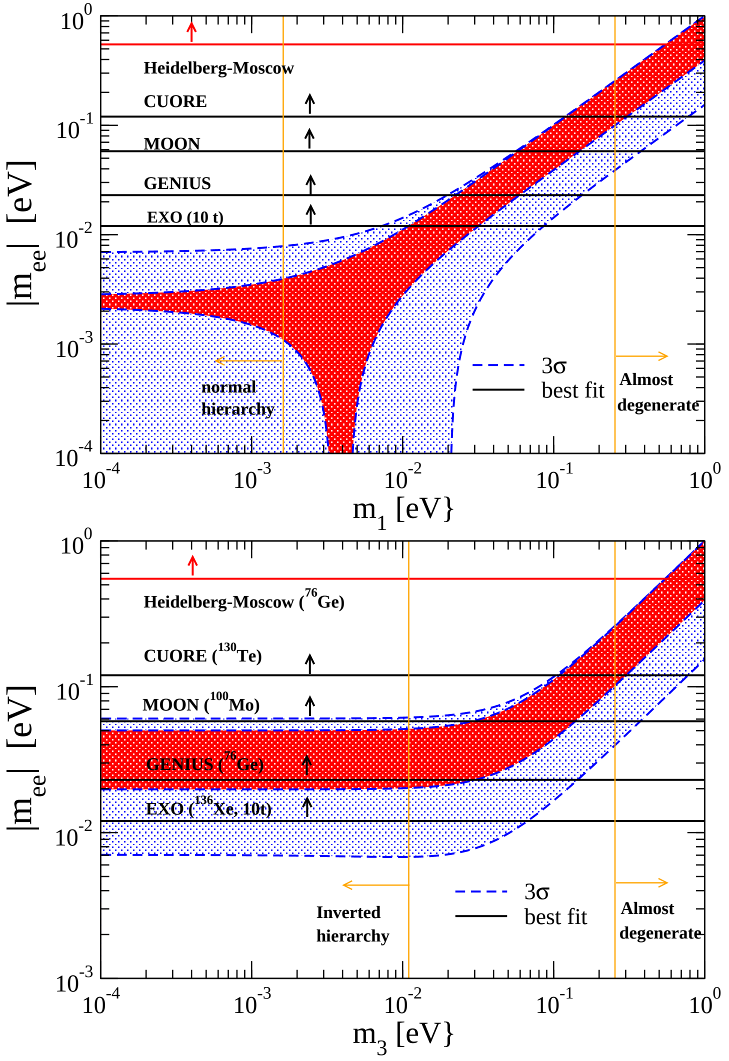
- No information on **CP violation**

- Improved by upcoming experiments



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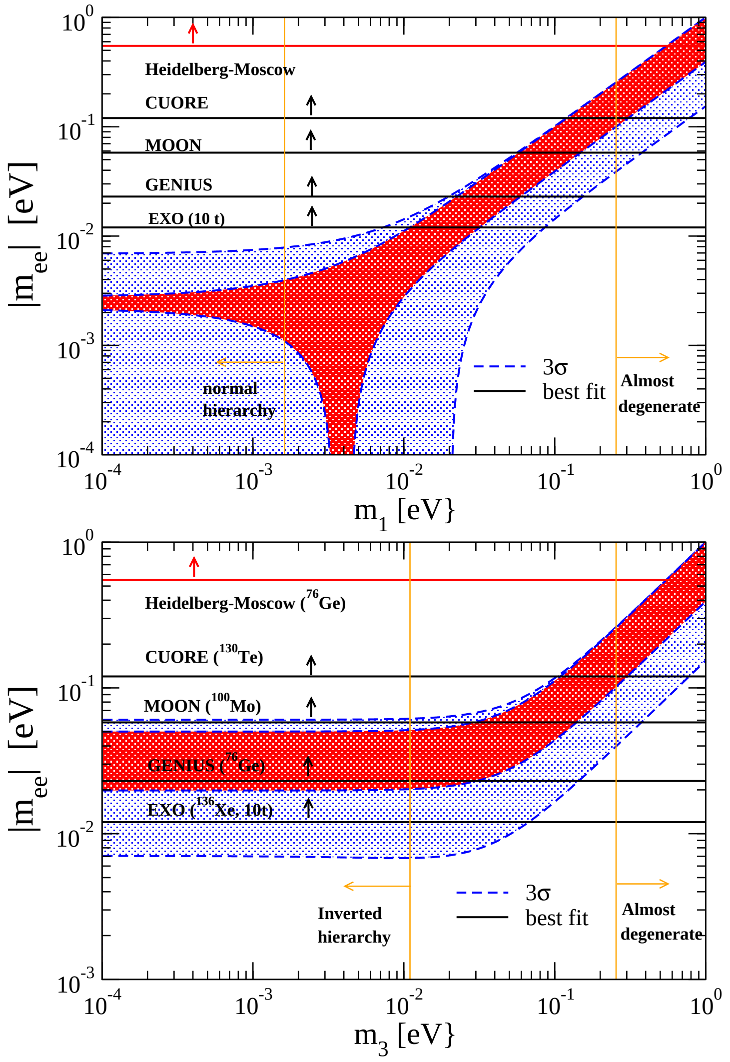
⇒ **Impact of neutrino masses and leptonic CP violation on our understanding of the universe?**



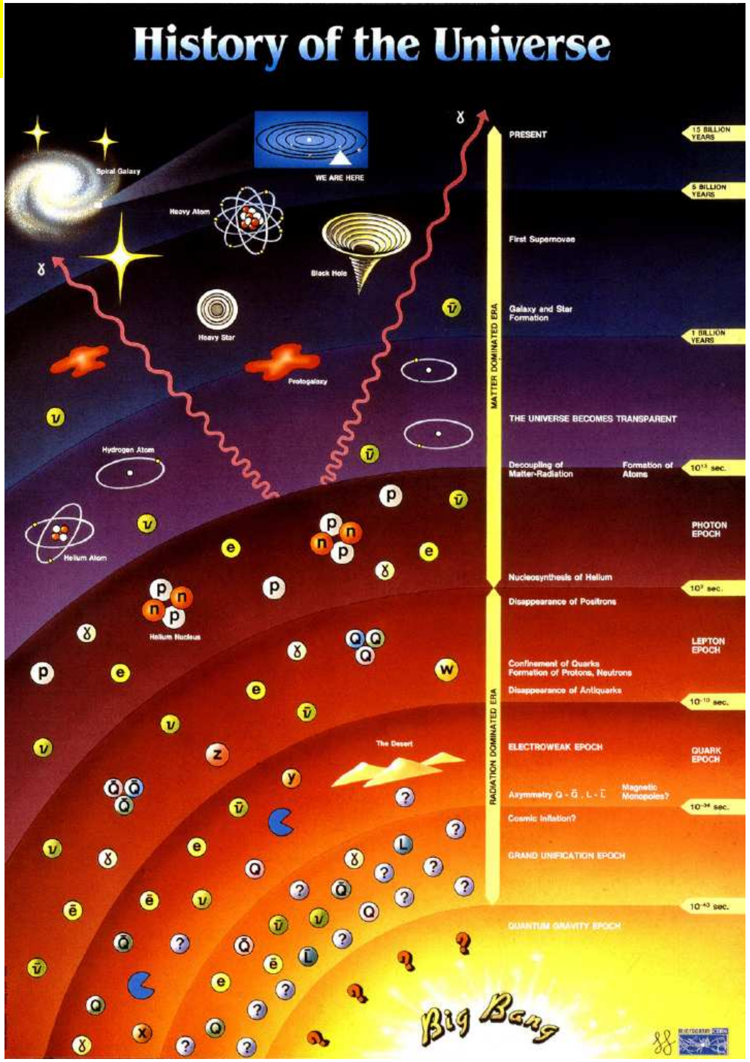
[Bilenky *et al.* '04]

2. Cosmic Neutrino Background and Structure in the Universe

3. Baryogenesis via Leptogenesis

2. CνB and Structure in Universe

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



[CERN]

2. CνB and Structure in Universe

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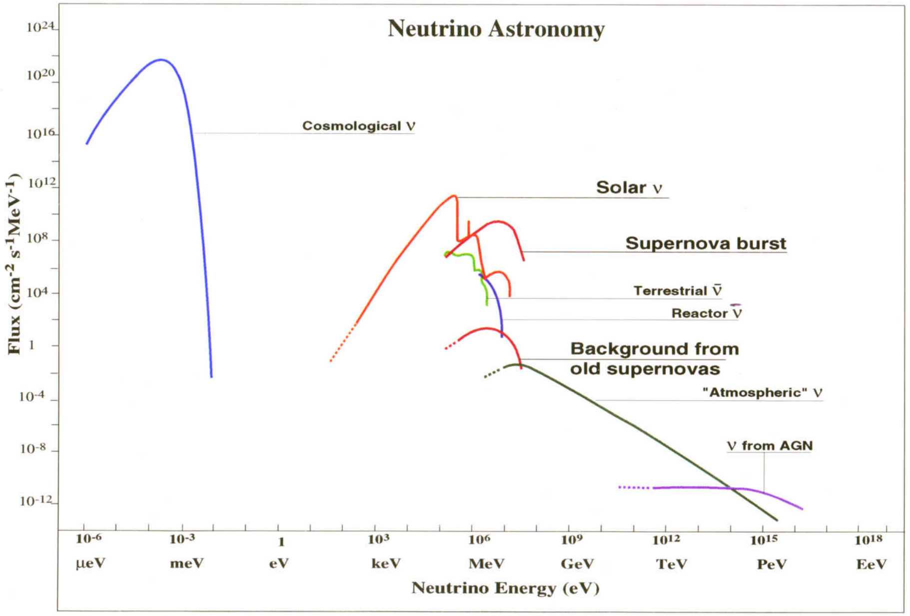
  $\Rightarrow$ Cosmic microwave background (**CMB**)
  $\Rightarrow$ **Cosmic neutrino background (CνB)**

- Firm prediction:

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

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

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



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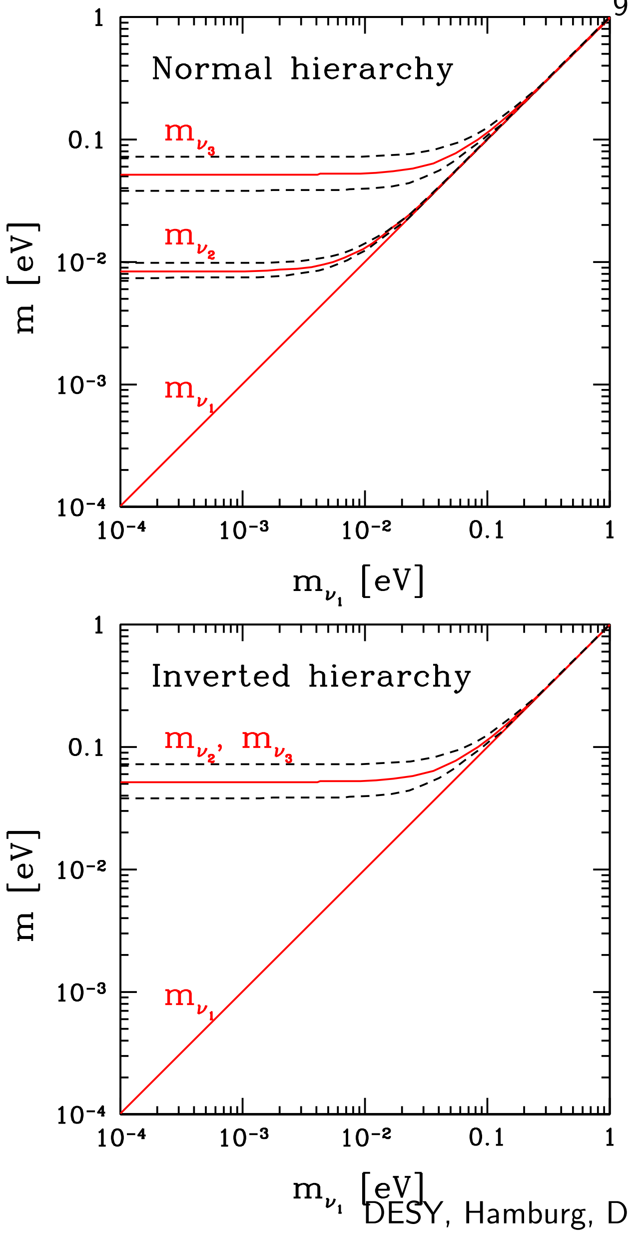
⇒ Big bang relic neutrinos ≈ as abundant as relic photons [ratio $(6\times 3)/22 = 9/11$]

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



- **CνB and large scale structure:**
  - ◇ At very early time, neutrino free-streaming tends to suppress structure formation on small scales $\lambda \ll \lambda_{\rm fs}$,

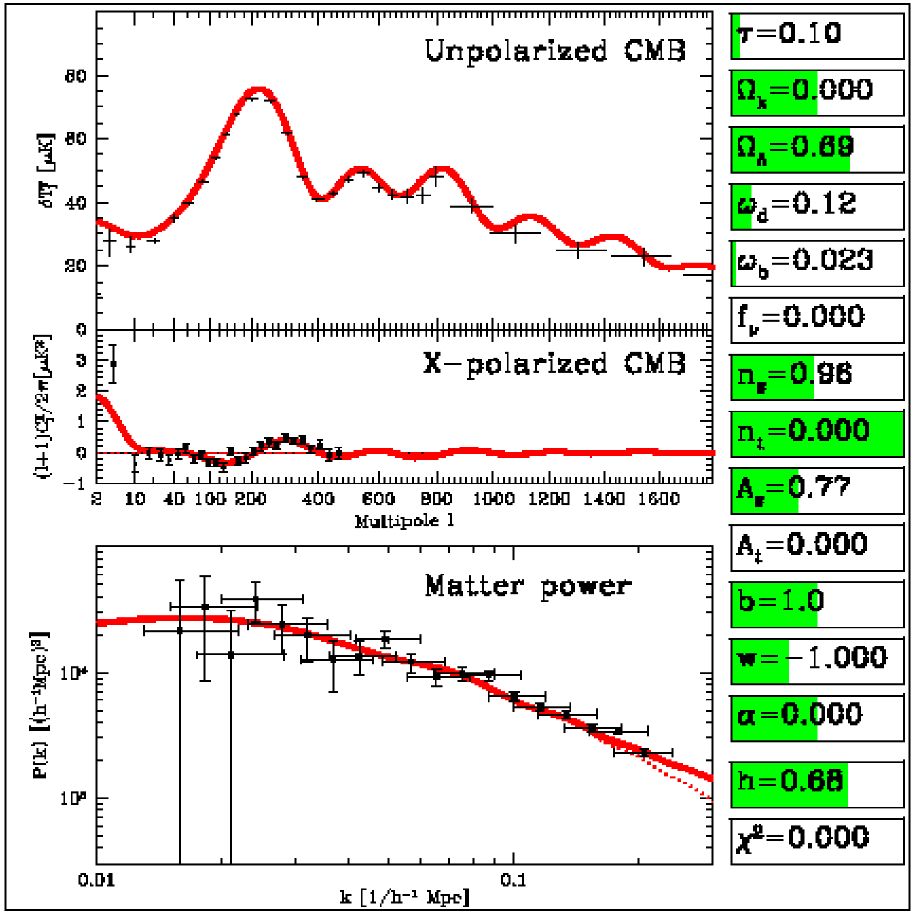
$$\lambda_{\rm fs} \simeq 4.2 \left(\frac{(1+z)}{\Omega_m}\right)^{1/2} \left(\frac{\rm eV}{m_\nu}\right) h^{-1}\,{\rm Mpc}$$

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

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

where Ω_ν fractional neutrino density

$$\Omega_\nu\, h^2 = 1.08 \times 10^{-2} \underset{i}{\qquad} (m_{\nu_i}/{\rm eV})$$



[Tegmark '04]

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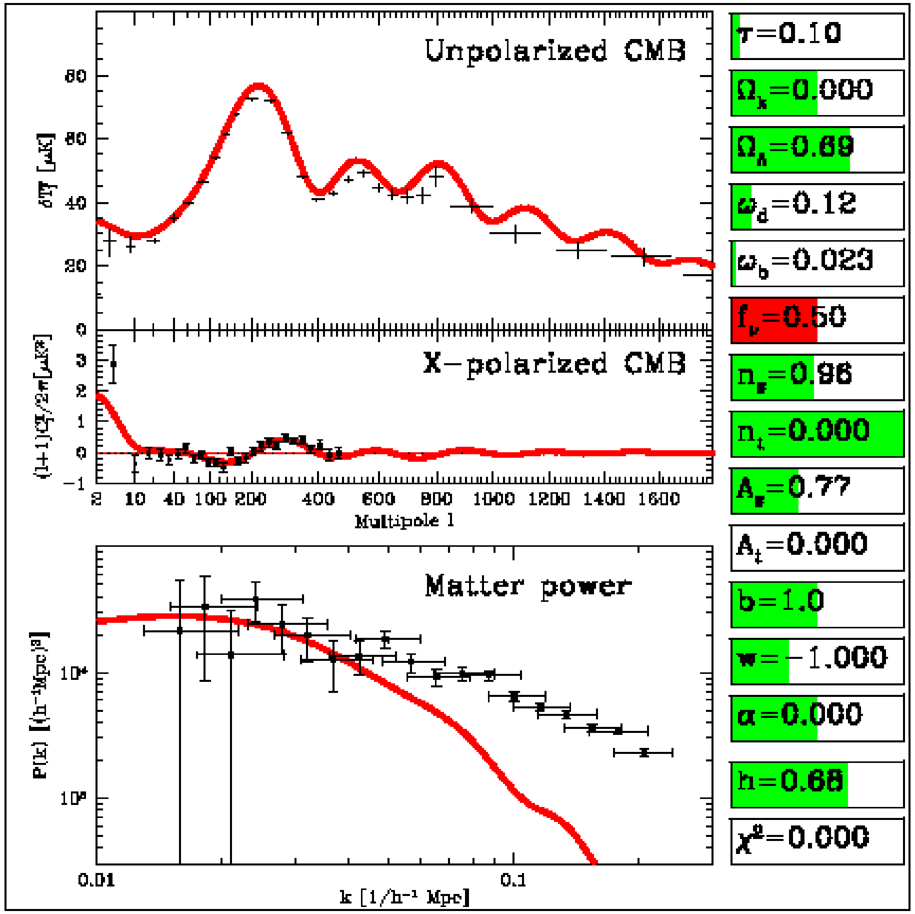

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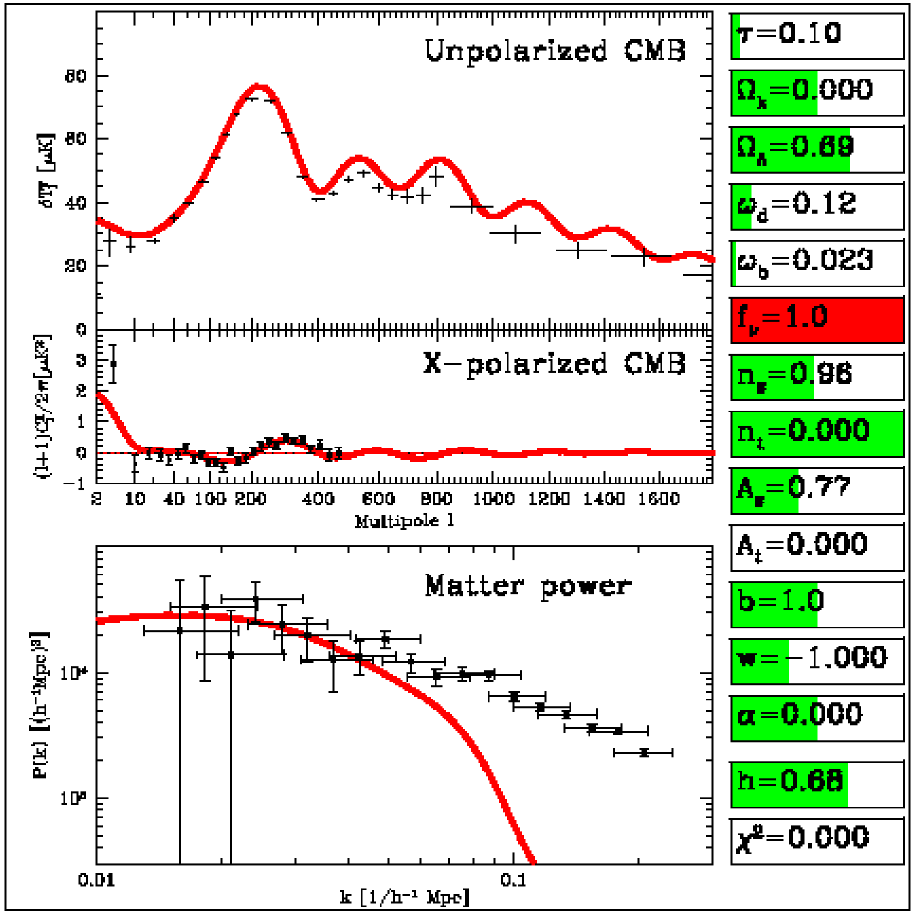

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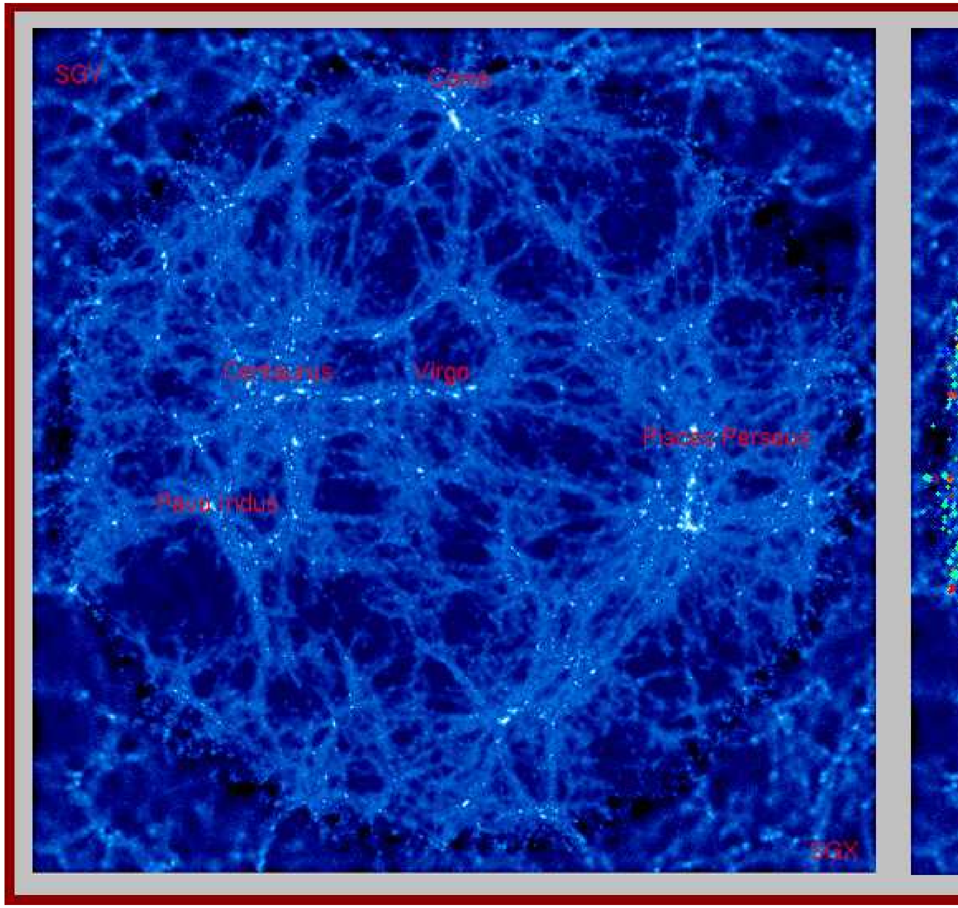
  $$\Omega_\nu\,h^2 = 1.08 \times 10^{-2} \underset{i}{\quad} (m_{\nu_i}/{\rm eV})$$

$\Rightarrow$ Constraints from **LSS** and **CMB**

$\Rightarrow$ **Less cosmological parameters if $\sum m_\nu$ known from lab experiments**

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

- **CνB gravitational clustering:**
  - ◇ At late time, non-relativistic neutrinos cluster gravitationally on cold dark matter (**CDM**) and baryonic structures



[Mathis *et al.* ‘02]

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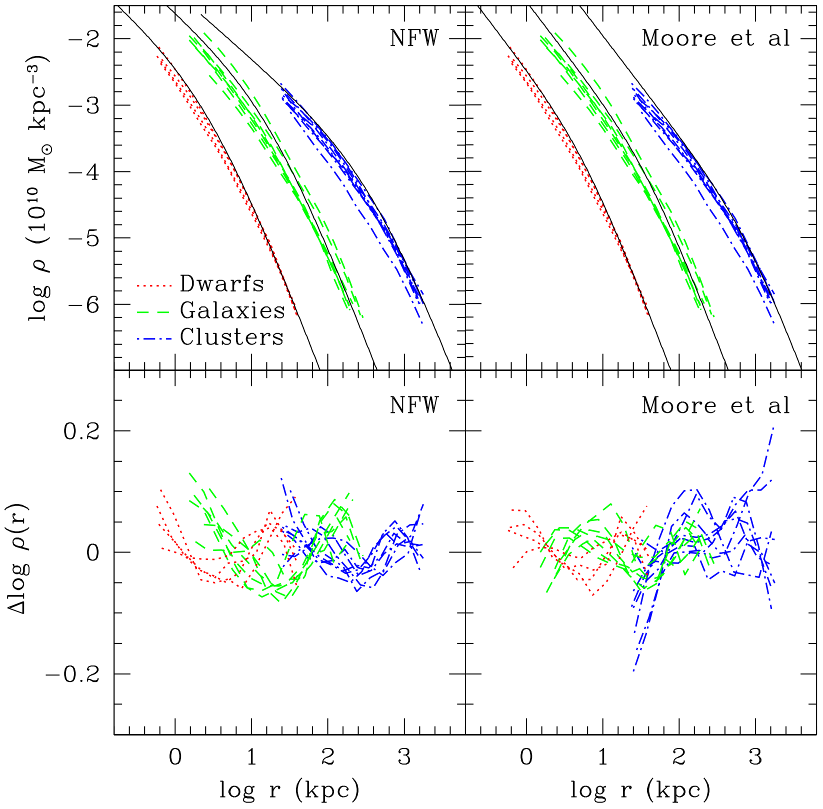
  - Study neutrino clustering in **CDM** halos



[Navarro *et al.* ‘04]

- **CνB gravitational clustering:**
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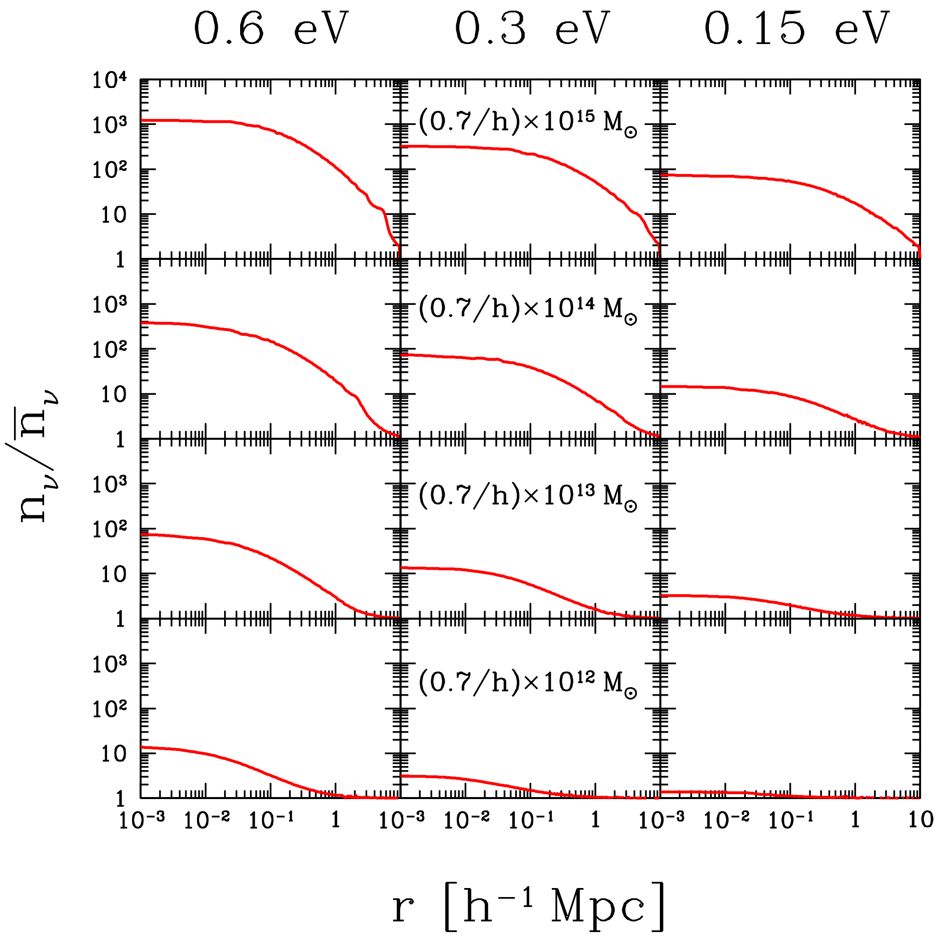
  - ◇ Improved clustering for big m_ν a/o$M_{\rm vir}$:
    - $*$ Local universe:
      - · Overdensity ≈ 1000 (≈ 100) for $m_\nu = 0.6$ eV $(= 0.15$ eV) for inner part ($\lesssim 100$ kpc) of Virgo and Centaurus clusters ($\approx 10^{15}\,M_\odot$)
    - $*$ Local neighbourhood of Earth:
      - · Overdensity ≈ 20 (≈ 2) for $m_\nu = 0.6$ eV $(= 0.15$ eV)

$\Rightarrow$ **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,

$$m_\nu = -m_\mathrm{D}\,\frac{1}{M_\mathrm{M}}\,m_\mathrm{D}^T$$

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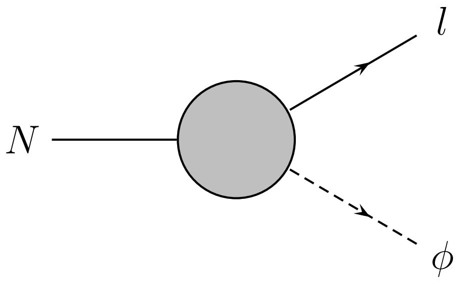
- ***CP* and *L* violating out-of-equilibrium decays of heavy Majorana neutrino *N*** into light leptons l and Higgs bosons ϕ



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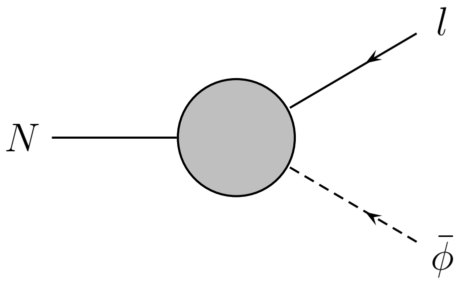

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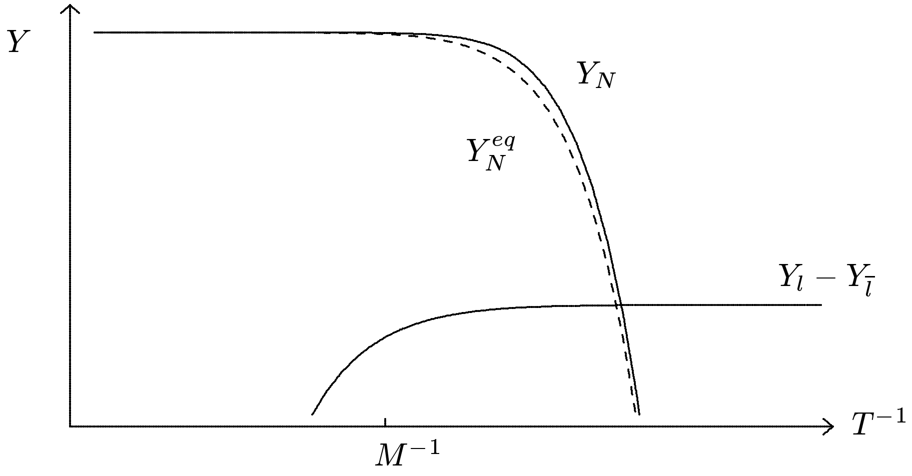
$\Rightarrow$ $\boldsymbol{Y_L \neq 0}$



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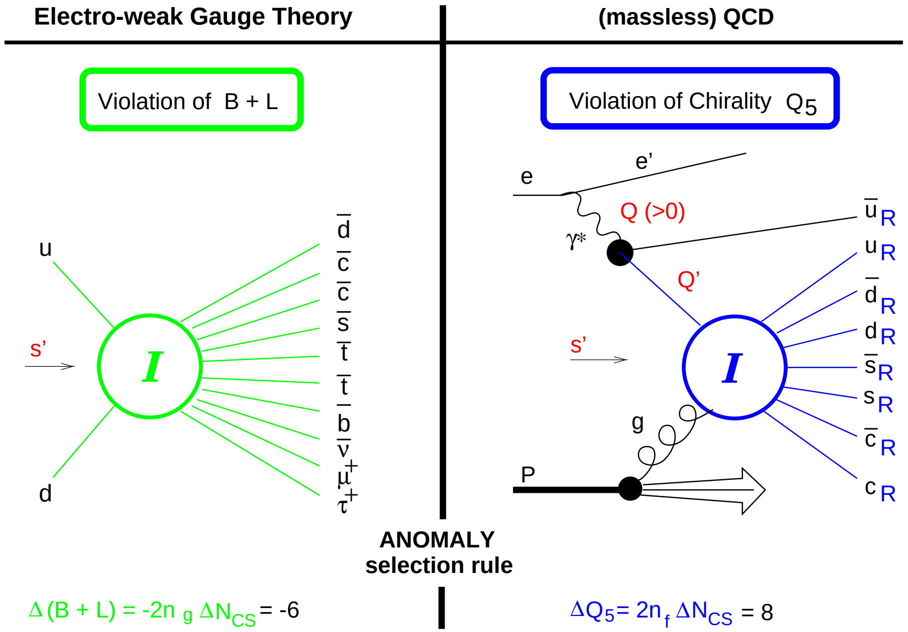
$\Rightarrow$ $Y_L \neq 0$ which, by means of electro-weak instanton/sphaleron processes,

$\Rightarrow$ **Baryon asymmetry**

$$Y_B = c\,Y_L = c\,\kappa\,\varepsilon/g_*$$



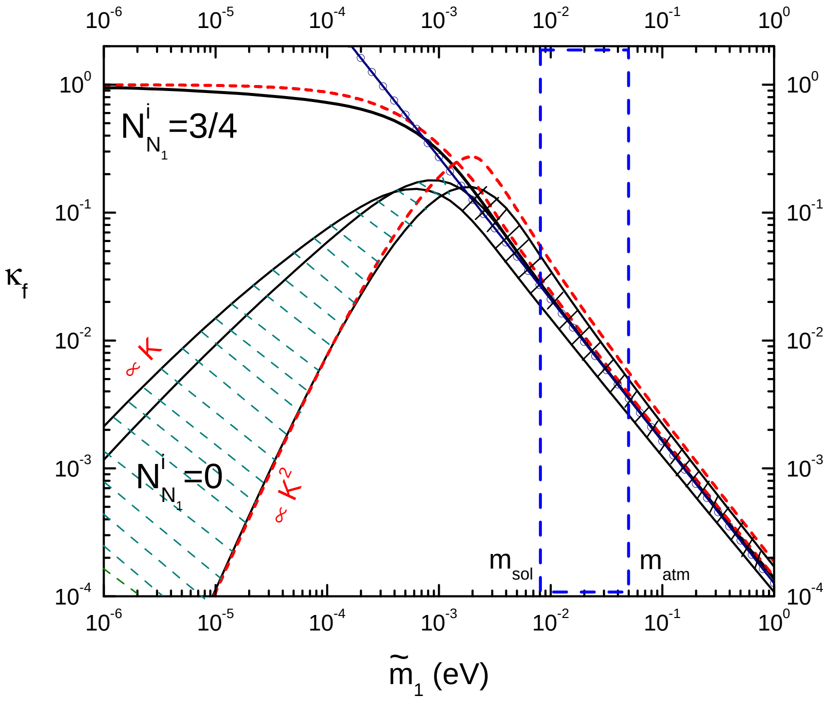
- Constraints on neutrino parameters from requirement of successful leptogenesis?
  - ◇ **Robust mass bounds** in models exploiting **thermal leptogenesis** based on
    - ⊕ minimal, i.e. type I, see-saw
    - ⊕ hierarchical N's, $M_1 < \mathcal{O}(2)\, M_{2,3}$:

[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}**



$$\left[\widetilde{m}_1 = \frac{(m_{\rm D}^\dagger m_{\rm D})_{11}}{M_1} \geq m_{\nu_1}\right]$$

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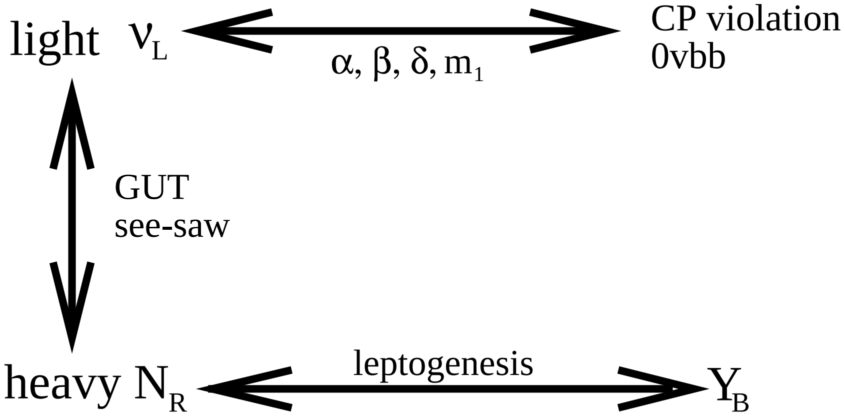

light ν_L

CP violation

0vbb

$\alpha, \beta, \delta, m_1$

GUT

see-saw

heavy N_R

leptogenesis

Y_B

[Pascoli,Petcov,Rodejohann '03]

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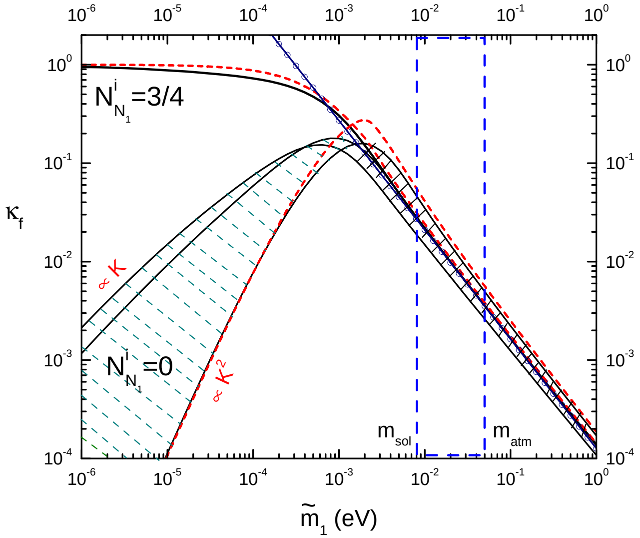
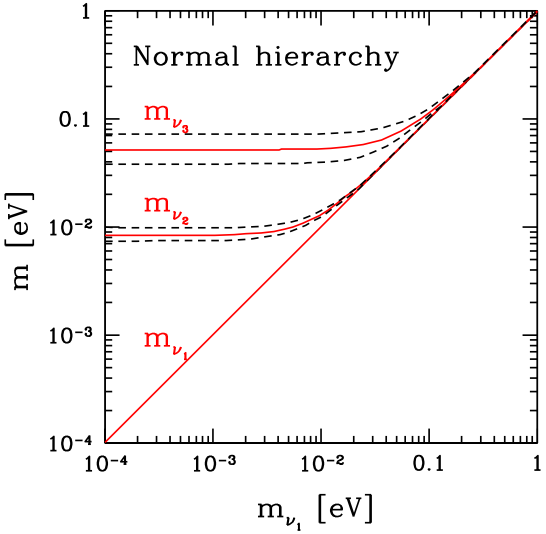
◇ **For sizeable mixing $\sin^2\theta_{13} \sim 0.01$ expect preferred mass spectrum 0.01 eV $\lesssim m_{\nu_i} \lesssim 0.1$ eV**





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