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Neutrino Masses and Double Beta Decay

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Content

- Dirac/Majorana mass beyond SM.
- Neutrino oscillations: updated data, neutrino mass patterns.
- Limits on absolute mass scales: (double) beta decay. cosmology
- Conclusion

Neutrino beyond Standard Model

- Dirac neutrino

  $\mathfrak{L} = \mathfrak{L}_{SM} + y_\nu LH\nu^c$ $y_\nu \sim 10^{-12}$

- Majorana neutrino

  $\mathfrak{L}=\mathfrak{L}_{SM} + y_\nu^2 LHLH/2M$ $y_\nu \sim 1, M \sim 10^{14}$ GeV

  (Seesaw)

  $\mathfrak{L}=\mathfrak{L}_{SM} + y_\nu LH\nu^c + \nu^c\nu^c/2M$

Neutrino mass

Weak eigenstates: ν_α

Mass eigenstates: ν_i

- Majorana

$$\frac{1}{2}\sum_{\alpha\beta} m^{\nu}_{\alpha\beta}\,\nu_\alpha\nu_\beta = \frac{1}{2}\sum_i m_i\nu_i\nu_i$$

- Dirac

$$\frac{1}{2}\sum_{\alpha\beta} m^{\nu}_{\alpha\beta}\,\nu_\alpha\nu^c_\beta = \frac{1}{2}\sum_i m_i\nu_i\nu^c_i$$

Three mass eigen values : $m_{1,2,3}$

Two mass differences measured in oscillation experiments:

$$\Delta m^2_{31} = m^3_3 - m^2_1 \ : \ \text{atmospheric}$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 \ : \ \text{solar}$$

Neutrino Mixing

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$
$$|\nu_\mu\rangle = U_{\mu1}|\nu_1\rangle + U_{\mu2}|\nu_2\rangle + U_{\mu3}|\nu_3\rangle$$
$$|\nu_\tau\rangle = U_{\tau1}|\nu_1\rangle + U_{\tau2}|\nu_2\rangle + U_{\tau3}|\nu_3\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\theta_{23}} & s_{\theta_{23}} \\ 0 & -s_{\theta_{23}} & c_{\theta_{23}} \end{pmatrix} \begin{pmatrix} c_{\theta_{13}} & 0 & s_{\theta_{13}} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{\theta_{13}} e^{-i\delta} & 0 & c_{\theta_{13}} \end{pmatrix} \begin{pmatrix} c_{\theta_{12}} & s_{\theta_{12}} & 0 \\ -s_{\theta_{12}} & c_{\theta_{12}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}$$

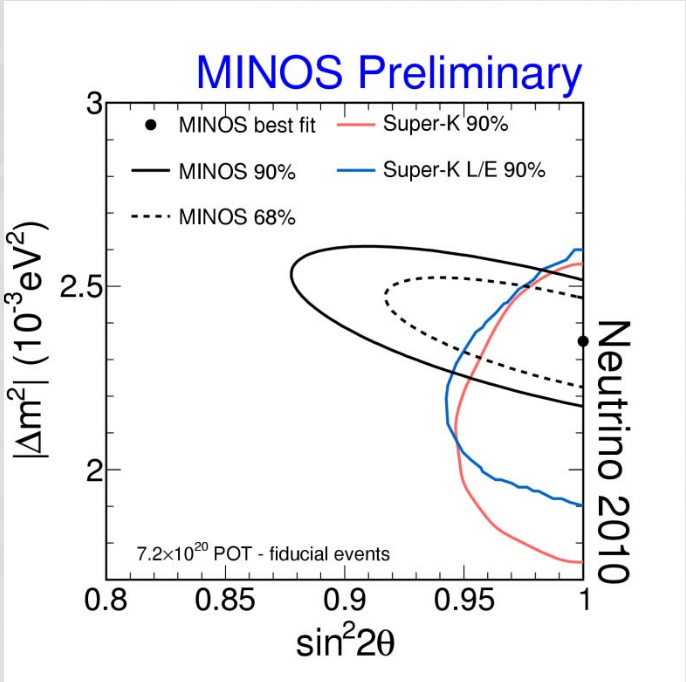
atmoshperic reactor solar Majorana

Three mixing anlges : $\theta_{23}, \theta_{13}, \theta_{12}$

One Dirac & two Majorana phases : δ & $\phi_{2,3}$

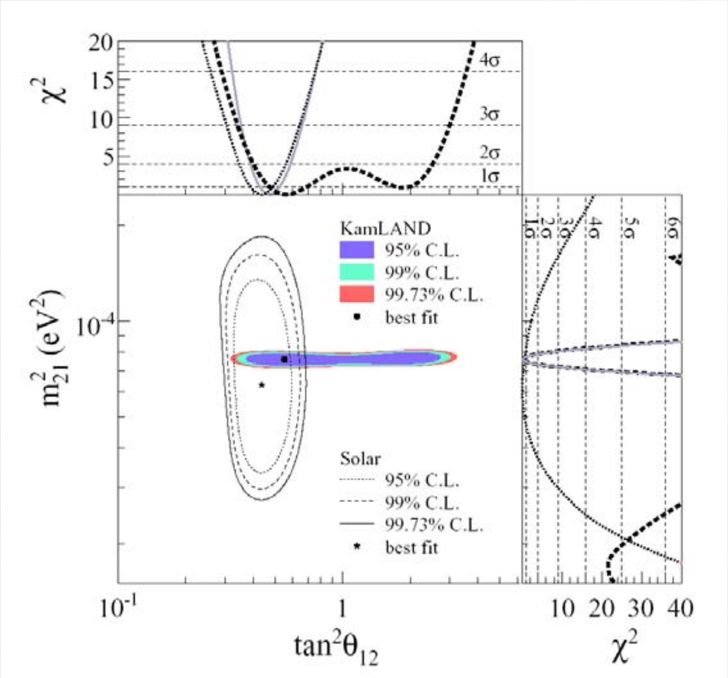
Recent oscillation data

MINOS (10)



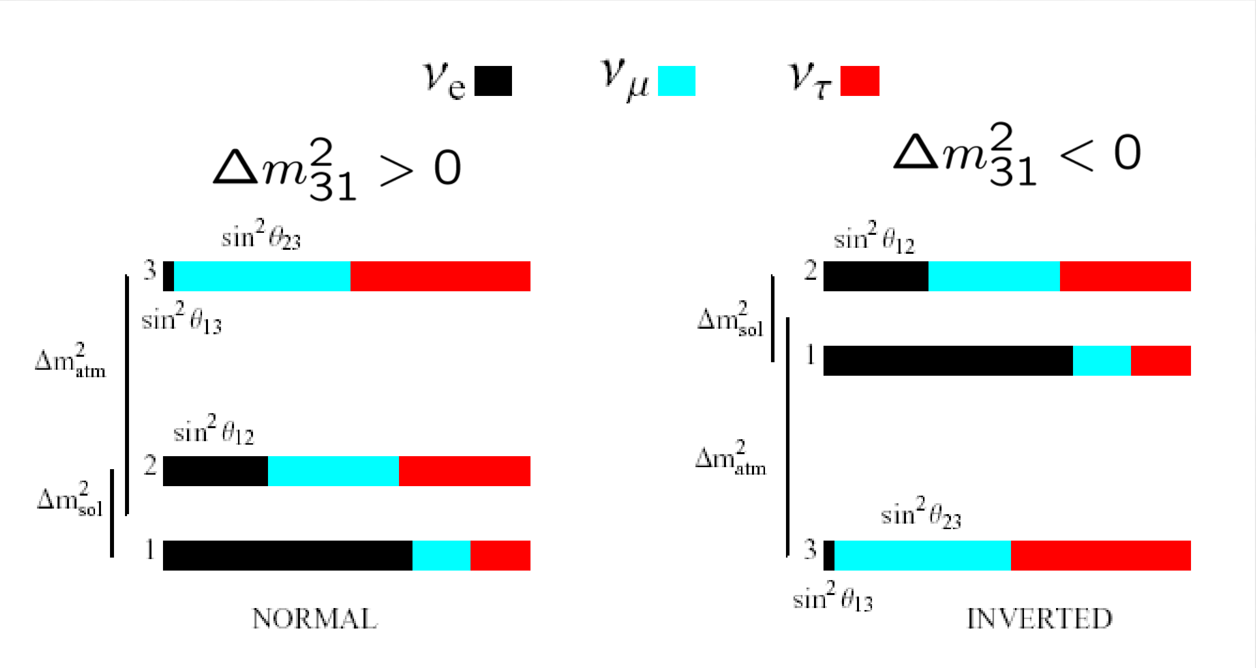
$$|\Delta m^2_{31}| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2 2\theta_{23} > 0.91$$

KAMLAND (Jan. 08)



$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

Neutrino mass hierarchy



Quasi Degenerate

$m_1 \approx m_2 \approx m_3$

$\approx 0.05 - 0.3eV$

Bounds on absolute masses

- $\Delta m_{31}^2 > 2.27 \times 10^{-3}$ eV^2
  $\Delta m_{21}^2 > 7.38 \times 10^{-5}$ eV^2
- Normal Hierarchy:
  $m_3 > 0.0476$, $m_2 > 0.0086$, $\sum m_\nu > 0.056$
- Inverted Hierarchy:
  $m_2 > 0.0484$, $m_1 > 0.0476$, $\sum m_\nu > 0.096$
- Qausi-Degeneracy:
  $m_{3,2,1} > 0.0476$, $\sum m_\nu > 0.14$

Absolute mass & β decays

- Oscillation experiments cannot tell.
- Tritium beta decay:

$$m_{\nu_e}^2 \equiv \sum_i m_i^2 |U_{ei}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$

Mainz & Troitsz
$m_{\nu_e} < 2.2$ eV

- Neutrinoless double beta decay:

$$m_{\beta\beta} = |\sum_i m_i U_{ei}^2| \approx |m_1 c_{12} + m_2 s_{12} e^{i\phi_2} + m_3 s_{13} e^{i\delta + i\phi_3}|$$

CUORICINO (Feb. 08)

$$T_{1/2}^{0\nu}\left({}^{130}Te\right) \geq 3.0 \times 10^{24} \text{ yr.}$$

$m_{\beta\beta} < 0.19–0.68$ eV

NEMO3 (2008)

Nucleus	$T_{1/2}^{0\nu}$ (90%CL)	$\|m_{\beta\beta}\|$(eV)
^{100}Mo	$\geqslant 5.8 \cdot 10^{23}$ y	$\leqslant (0.6 - 1.3)$
^{82}Se	$\geqslant 2.1 \cdot 10^{23}$ y	$\leqslant (1.2 - 2.2)$
^{96}Zr	$\geqslant 8.6 \cdot 10^{21}$ y	$\leqslant (7.4 - 20.1)$
^{48}Ca	$\geqslant 1.3 \cdot 10^{22}$ y	$\leqslant$ (29.7
^{150}Nd	$\geqslant 1.8 \cdot 10^{22}$ y	$\leqslant (4.0 - 6.3)$

Nuclear matrix elements

Bilenky, 1001.1946

Nuclear Shell Model

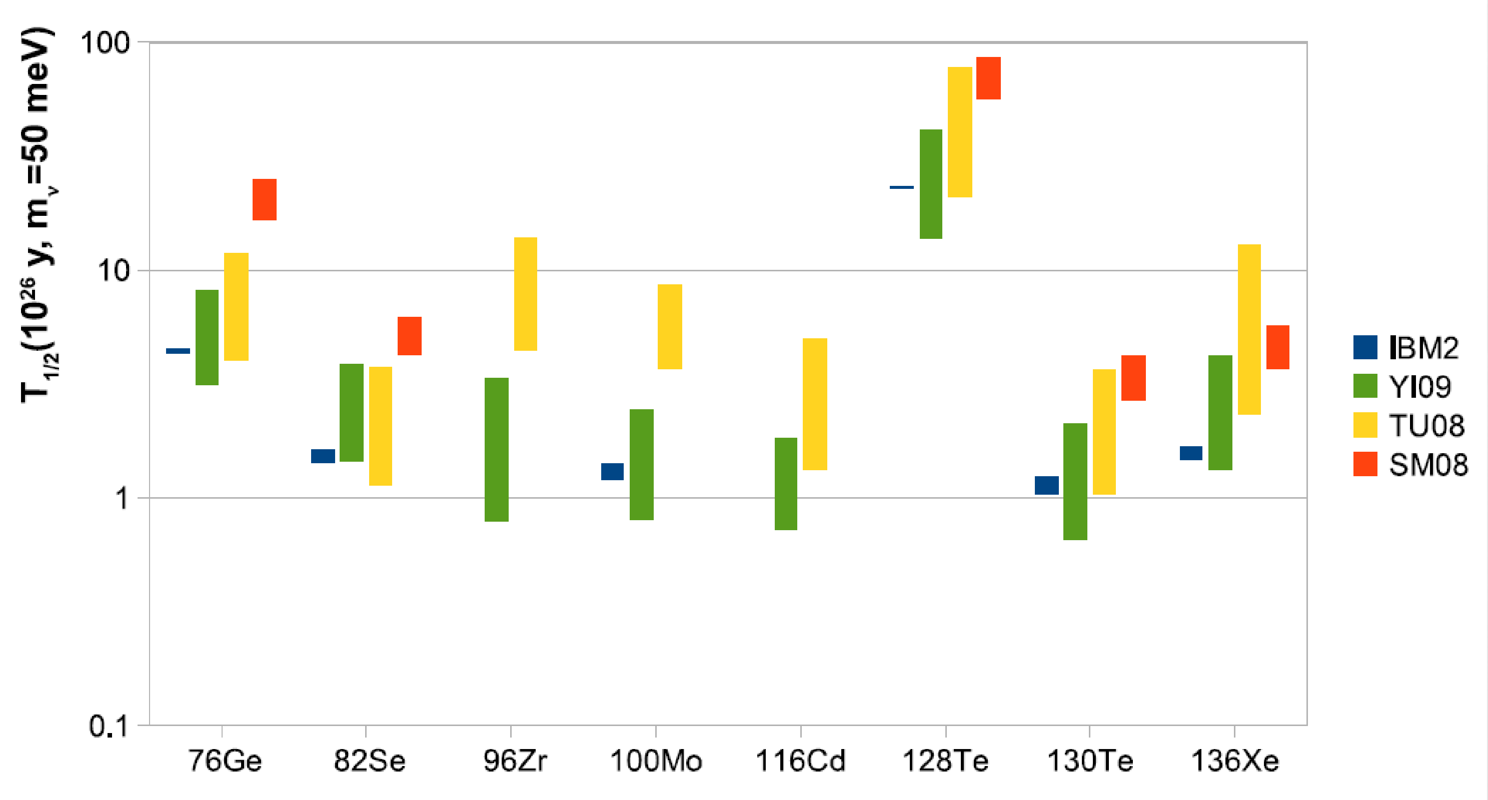
Nuclei transition	$M^{0\nu}$(UCOM)	$M^{0\nu}$(Jastrow)
$^{48}Ca \rightarrow {}^{48}Ti$	0.85	0.64
$^{76}Ge \rightarrow {}^{76}Se$	2.81	2.30
$^{82}Se \rightarrow {}^{82}Kr$	2.64	2.18
$^{124}Sn \rightarrow {}^{124}Te$	2.62	2.10
$^{128}Te \rightarrow {}^{128}Te$	2.88	2.34
$^{130}Te \rightarrow {}^{130}Xe$	2.65	2.12
$^{136}Xe \rightarrow {}^{136}Ba$	2.19	1.76

Quasi-particle Random Phase Approximation

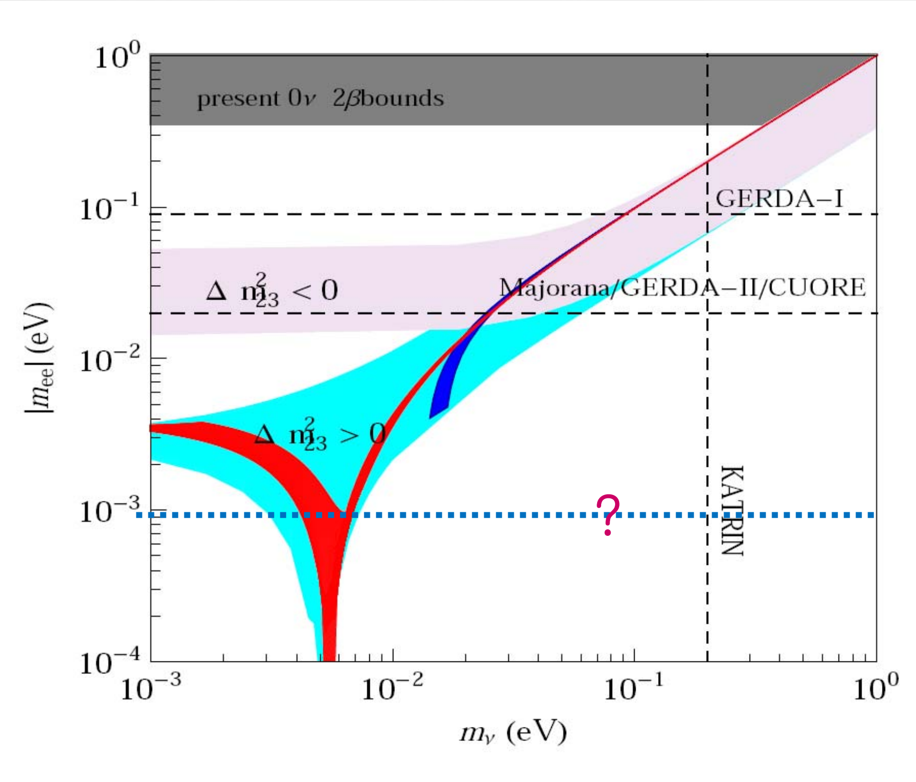
Nucleus	$M^{0\nu}$ (Jastrow)	$M^{0\nu}(CCM)$
^{76}Ge	3.33 - 4.68	4.07 - 6.64
^{82}Se	2.82 - 4.17	3.53 - 5.92
^{96}Zr	1.01 - 1.34	1.43 - 2.12
^{100}Mo	2.22 - 3.53	2.94 - 5.56
^{100}Mo	2.22 - 3.53	2.94 - 5.56
^{116}Cd	1.83 - 2.93	2.30 - 4.14
^{128}Te	2.46 - 3.77	3.21 - 5.65
^{130}Te	2.27 - 3.38	2.92 - 5.04
^{136}Xe	1.17 - 2.22	1.57 - 3.24

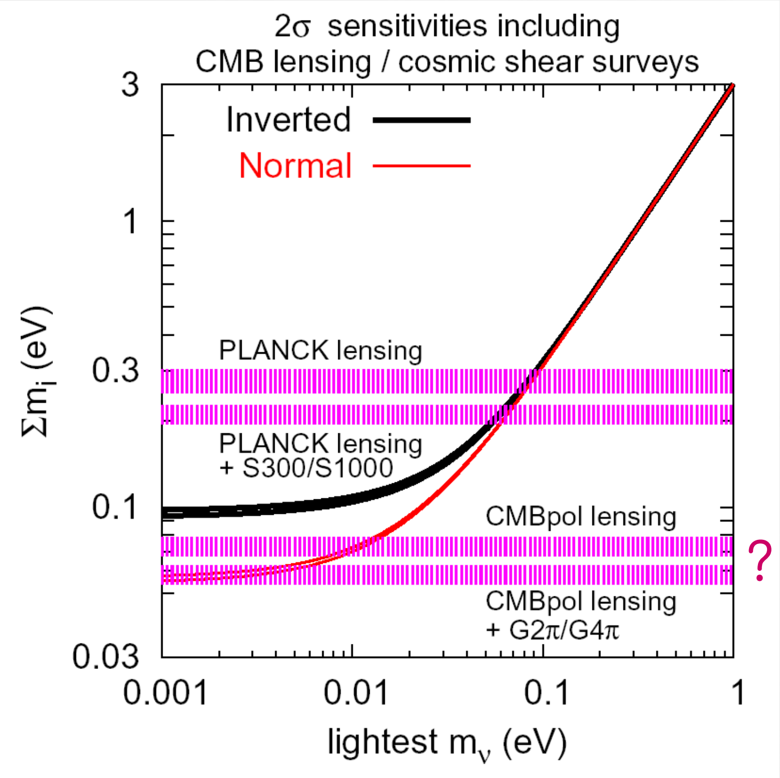
Nuclear matrix elements

Cremonesi, 1002.1437



Future limits





Hirsch et al, PLB679:454-459,2009

Lesgourgues-Pastor, 0603494

Absolute mass & cosmology

- For a light neutrino,

$$\Omega_\nu h^2 = 3\times\frac{3}{4}\times\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma m_\nu / \rho_c \approx \frac{m_\nu}{30\ \mathrm{eV}}$$

- A generous limit on the relic density, $\Omega h^2 < 0.1$, gives

$$m_\nu \leq 3\,\mathrm{eV}$$

Impact on structure formation

- Neutrinos are hot dark matter.

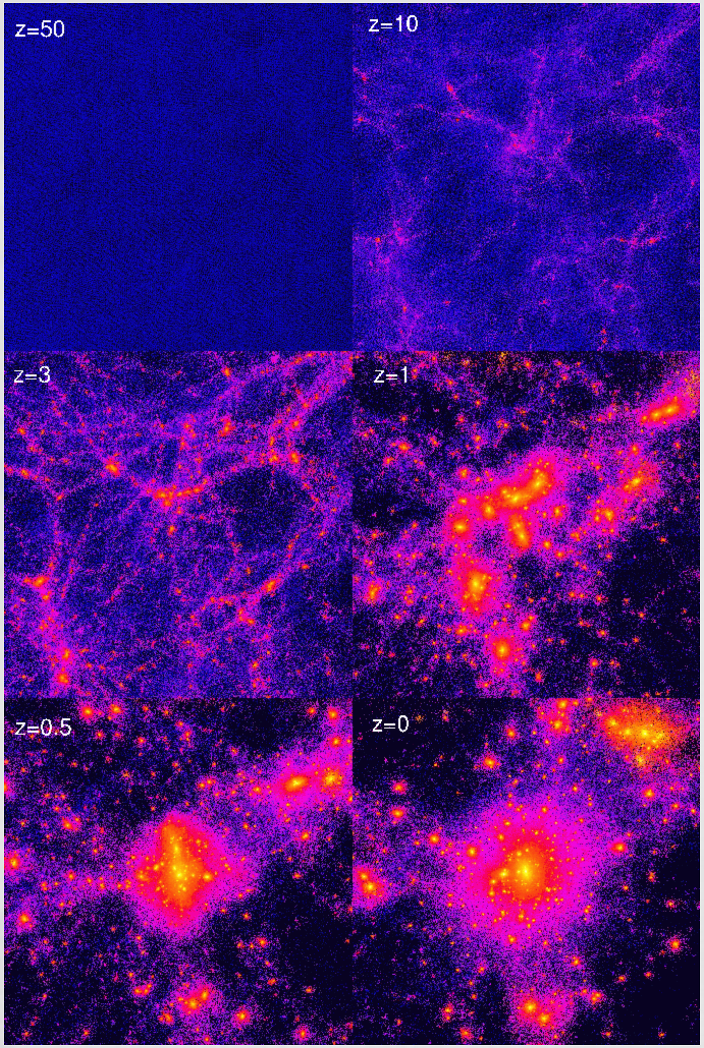
$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93\,\mathrm{eV}} \qquad T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \approx 2\,\mathrm{K}$$

- They freely stream away to disturb the formation of small scale structures.

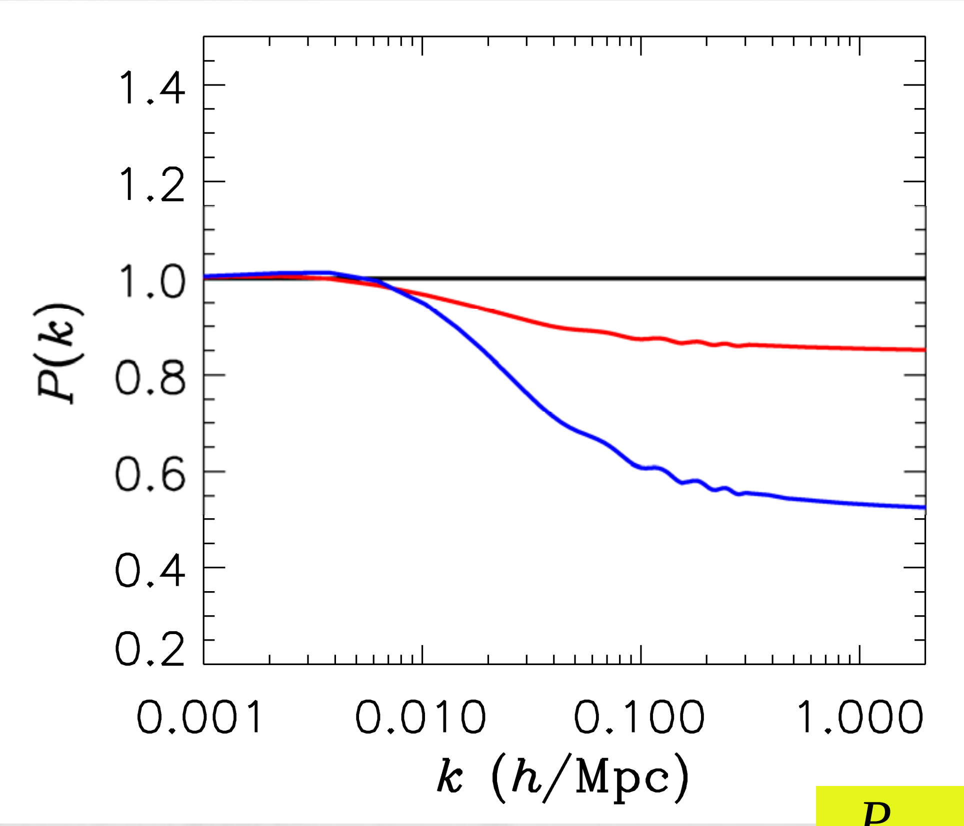
$$d_{\mathrm{FS}} \sim 1\,\mathrm{Gpc}\; m_{\mathrm{eV}}^{-1}$$

- Scales smaller than d_{FS} damped out→ suppressed power spectrum.

Structure formation



Power spectrum

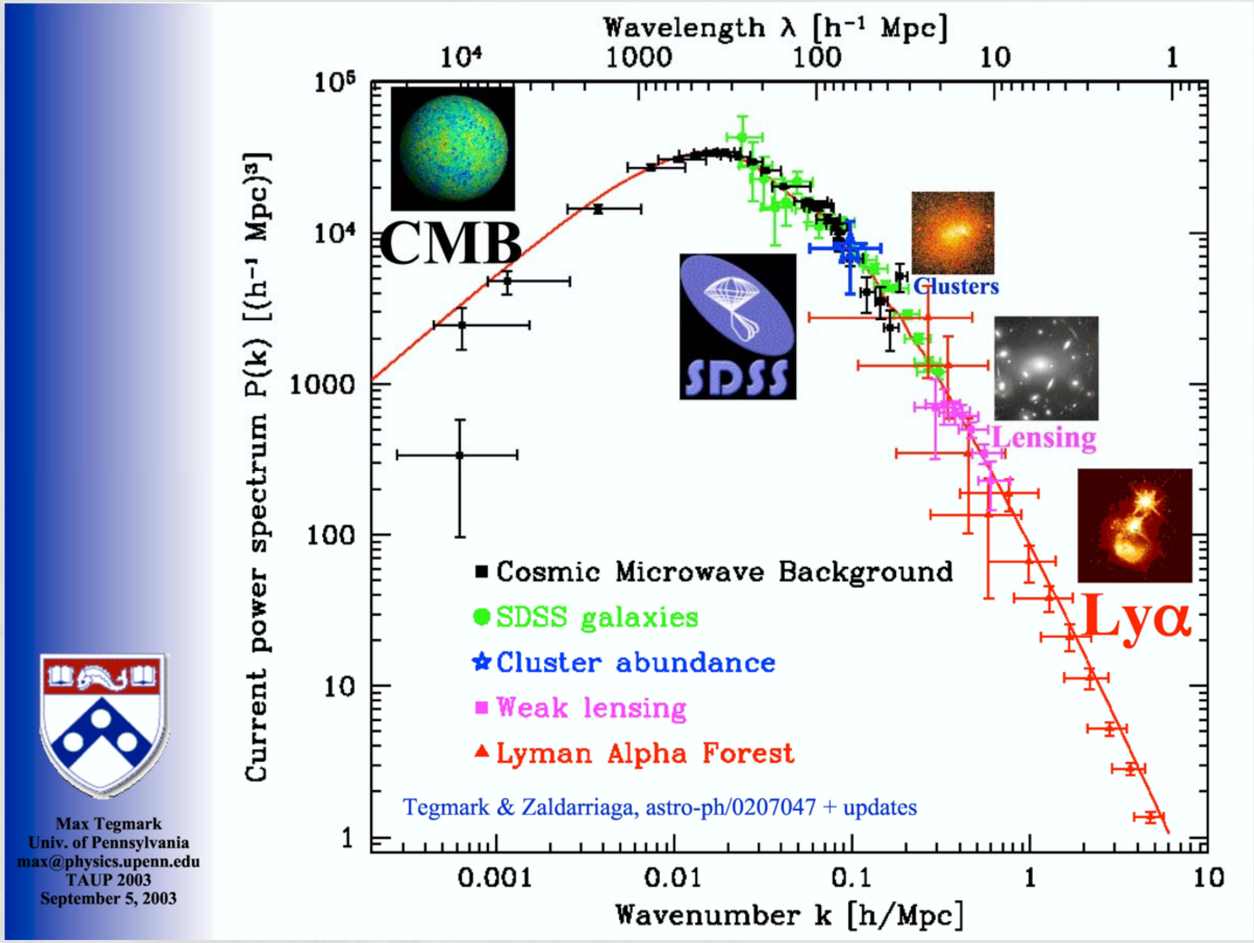


$\Sigma m = 0$

$\Sigma m = 0.3$ eV

$\Sigma m = 1$ eV

$$\frac{P}{P_{m=0}}(k >> k_{FS}) \sim -8\frac{\rho_\nu}{\rho_{TOT}}$$

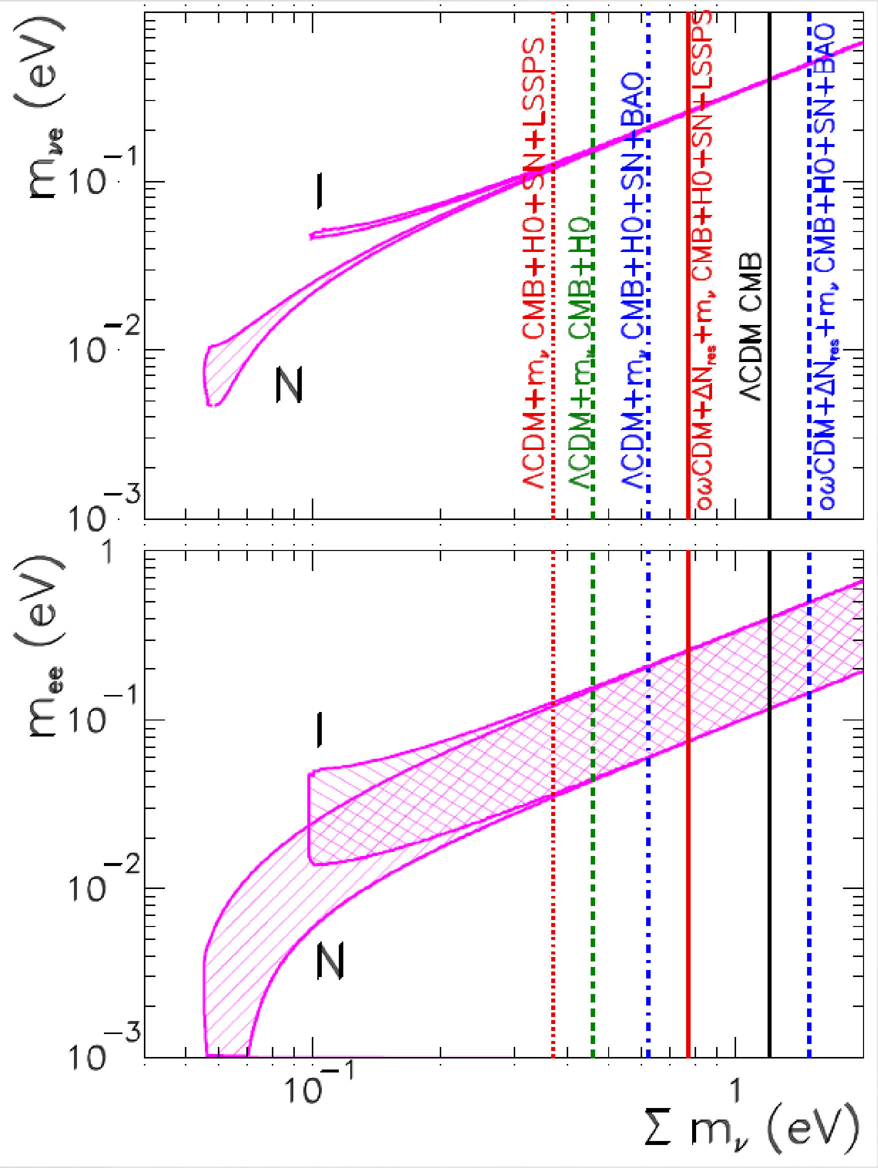


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
CMB
SDSS
Clusters
Lensing
Lyα
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
Tegmark & Zaldarriaga, astro-ph/0207047 + updates
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]
Max Tegmark
Univ. of Pennsylvania
max@physics.upenn.edu
TAUP 2003
September 5, 2003

Combined analysis

Gonzalez-Garcia, Maltoni, Salvado, 1006.3795

Model	Observables	Σm_ν (eV) 95% Bound
$o\omega$CDM + $\Delta N_{\rm rel}$ + m_ν	CMB+HO+SN+BAO	≤ 1.5
$o\omega$CDM + $\Delta N_{\rm rel}$ + m_ν	CMB+HO+SN+LSSPS	≤ 0.76
ΛCDM + m_ν	CMB+H0+SN+BAO	≤ 0.61
ΛCDM + m_ν	CMB+H0+SN+LSSPS	≤ 0.36
ΛCDM + m_ν	CMB (+SN)	≤ 1.2
ΛCDM + m_ν	CMB+BAO	≤ 0.75
ΛCDM + m_ν	CMB+LSSPS	≤ 0.55
ΛCDM + m_ν	CMB+H0	≤ 0.45



$m_{\nu e}$ (eV)
m_{ee} (eV)
I
N
ΛCDM+m_ν, CMB+H0+SN+LSSPS
ΛCDM+m_ν, CMB+H0
ΛCDM+m_ν, CMB+H0+SN+BAO
oωCDM+ΔN$_{res}$+m_ν, CMB+H0+SN+LSSPS
ΛCDM CMB
oωCDM+ΔN$_{res}$+m_ν, CMB+H0+SN+BAO
Σ m_ν (eV)

Confirming Majorana vs. Dirac

- Oscillation data tell us:

	$m_{\beta\beta}(\text{eV})$	$\sum m_\nu(\text{eV})$
NH, Dirac	0	0.05
NH, Majorana	$0-10^{-3}$	0.05
IH, Dirac	0	0.1
IH, Majorana	0.01	0.1

- What we will see or not see:

	$m_{\beta\beta} > 10^{-2,-3}\text{eV}$	$\sum m_\nu > 0.07\text{eV}$
NH, Dirac	X	X
NH, Majorana	$X, (O)$	X
IH, Dirac	X	O
IH, Majorana	O	O

Majorana and Dirac seesaw

❖ Majorana and Dirac seesaw operator at low energy

$$W^M_{eff} = \frac{y}{M} LH_2LH_2$$
$$\Rightarrow m^M_\nu = y\frac{v_2^2}{M}$$

$$W^D_{eff} = \frac{y}{M} LH_2\nu^c S$$
$$\Rightarrow m^D_\nu = y\frac{v_2 v_S}{M}$$

❖ Renormalizable high energy theory can be

$$W^M = hLH_2N + \frac{1}{2}MNN$$

$$W^D = \lambda S H_1 H_2 + hLH_2\Phi^c + h'\nu^c S\Phi + M\Phi\Phi^c$$

(nb) Viable leptogenesis

Murayama–Pierce, 02
EJC–Roy, 08

Conclusion

- Neutrino oscillation experiments have been a great success.
- Future progress in non-oscillation experiments would be crucial in revealing the origin of neutrino mass.
- We discussed some theoretical aspects, and the importance of $0\nu\beta\beta$ experiments and cosmological observations in the future of neutrino physics.