Neutrino physics II

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The Known Unknowns

★ **Next generation Long-Baseline experiments (such as DUNE) can address three of these questions:**

- **Are neutrinos Dirac or Majorana ?**
  - Is there a connection to the GUT scale?
- **Are there light sterile neutrino states ?** → Breaks 3-flavor paradigm
  - No clear theoretical guidance on mass scale, M, …
- **What is the neutrino mass hierarchy ?**
  - An important question in flavor physics, e.g. CKM vs. PNMS

- **Is CP violated in the leptonic sector ?**
  - Are νs key to understanding the matter-antimatter asymmetry?

We determined that $m(K_L) > m(K_S)$ by

- Passing kaons through matter (regenerator)
- Beating the unknown sign$[m(K_L) - m(K_S)]$ against the known sign[reg. ampl.]

We will determine the sign(Δm^2_{31}) by

- Passing neutrinos through matter (Earth)
- Beating the unknown sign(Δm^2_{31}) against the known sign[forward $\nu_e e \longrightarrow \nu_e e$ ampl]

$$L \approx \frac{2\pi}{G_F n_e} \approx 1.16\ 10^4\ \mathrm{km}\left(\frac{1.69\ 10^{24}\ cm^3}{n_e}\right)$$

In principle, it is straightforward

★ CPV ⇨ different oscillation rates for νs and $\bar{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4 s_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \times \left[\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \times \sin\left(\frac{\Delta m_{23}^2 L}{4E}\right) \times \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right)\right]$$

vacuum osc.

★ Requires $\{\theta_{12}, \theta_{13}, \theta_{23}\} \neq \{0, \pi\}$

- now know that this is true, $\theta_{13} \approx 9^\circ$
- but, despite hints, don't yet know "much" about δ

★ So "just" measure $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$?

★ Not quite, there is a complication…

Neutrino Oscillations in Matter

★ Accounting for this potential term, gives a Hamiltonian that is not diagonal in the basis of the mass eigenstates

$$\mathcal{H}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = \begin{pmatrix}E_1 & 0 & 0\\0 & E_2 & 0\\0 & 0 & E_3\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} + V|\nu_e\rangle \leftarrow \text{ME}$$

★ Complicates the simple picture !!!!

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) =$$

ME $$\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

ME $$-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

CPV $$-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta\; s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$

with $A = 2\sqrt{2}G_F n_e E = 7.6\times10^{-5}\mathrm{eV}^2\cdot\frac{\rho}{\mathrm{g\,cm^{-3}}}\cdot\frac{E}{\mathrm{GeV}}$

Experimental Strategy

EITHER:

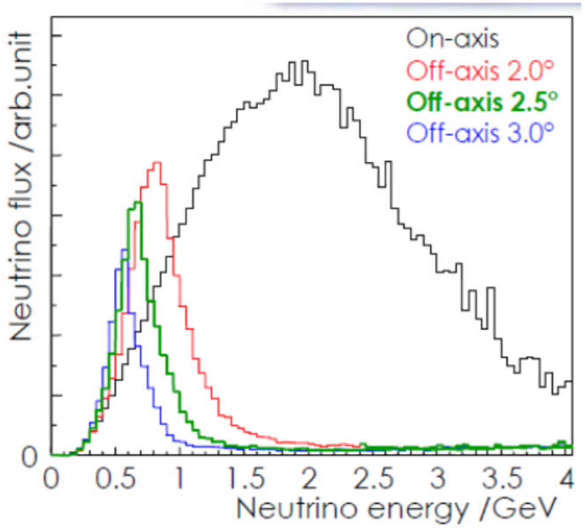
★ Keep L small (~200 km): so that matter effe

- First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \quad \Rightarrow \quad E_\nu < 1\,\mathrm{GeV}$$

- Want high flux at oscillation maximum

⇨ **Off-axis beam:** narrow range of neutrino energies



OR:

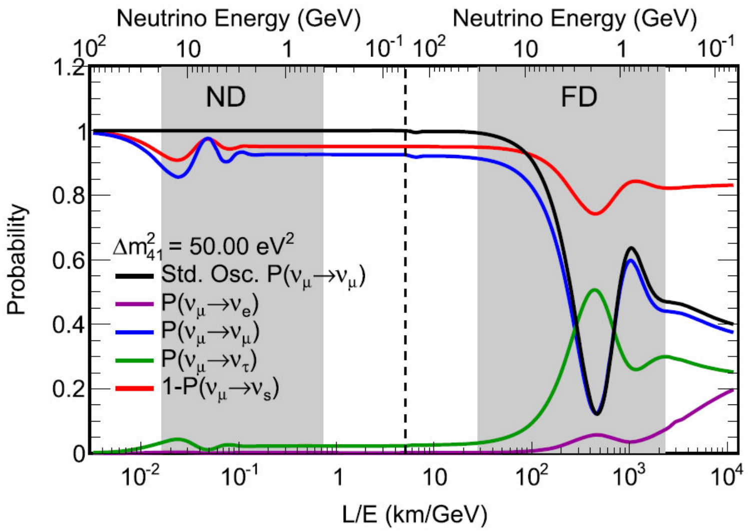
★ Make L large (>1000 km): measure the matter effects (i.e. MH)

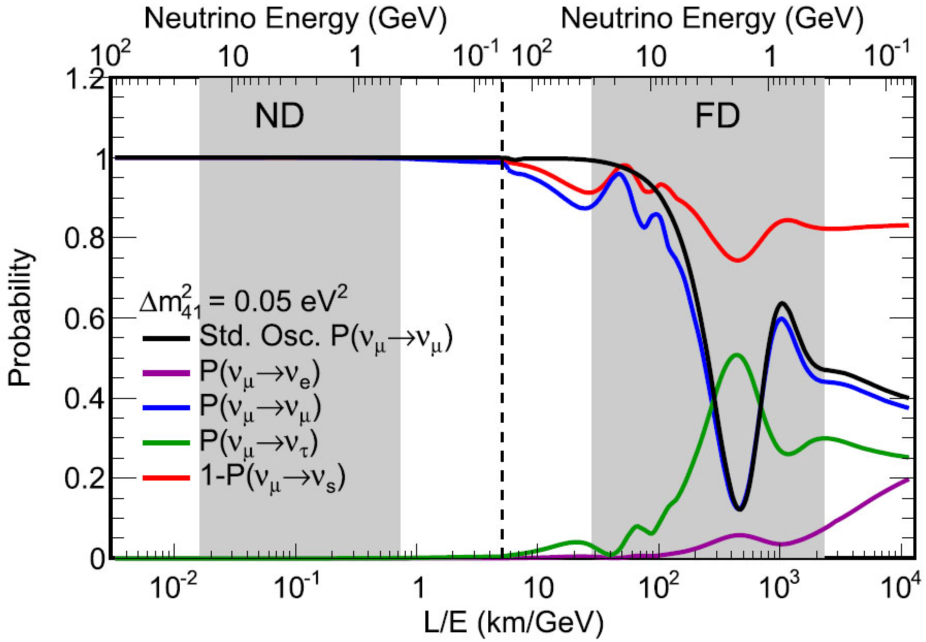
- First oscillation maximum:

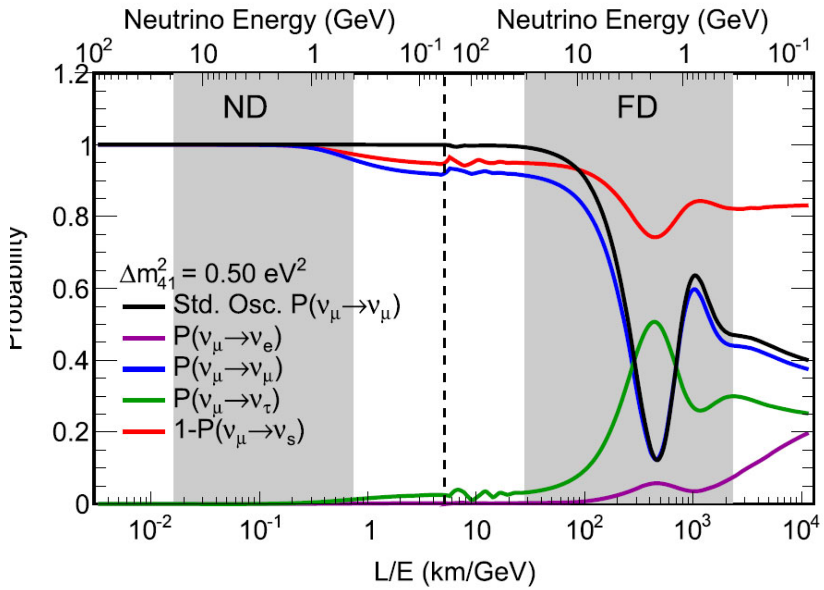
$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \quad \Rightarrow \quad E_\nu > 2\,\mathrm{GeV}$$

- **Unfold CPV from Matter Effects through E dependence**

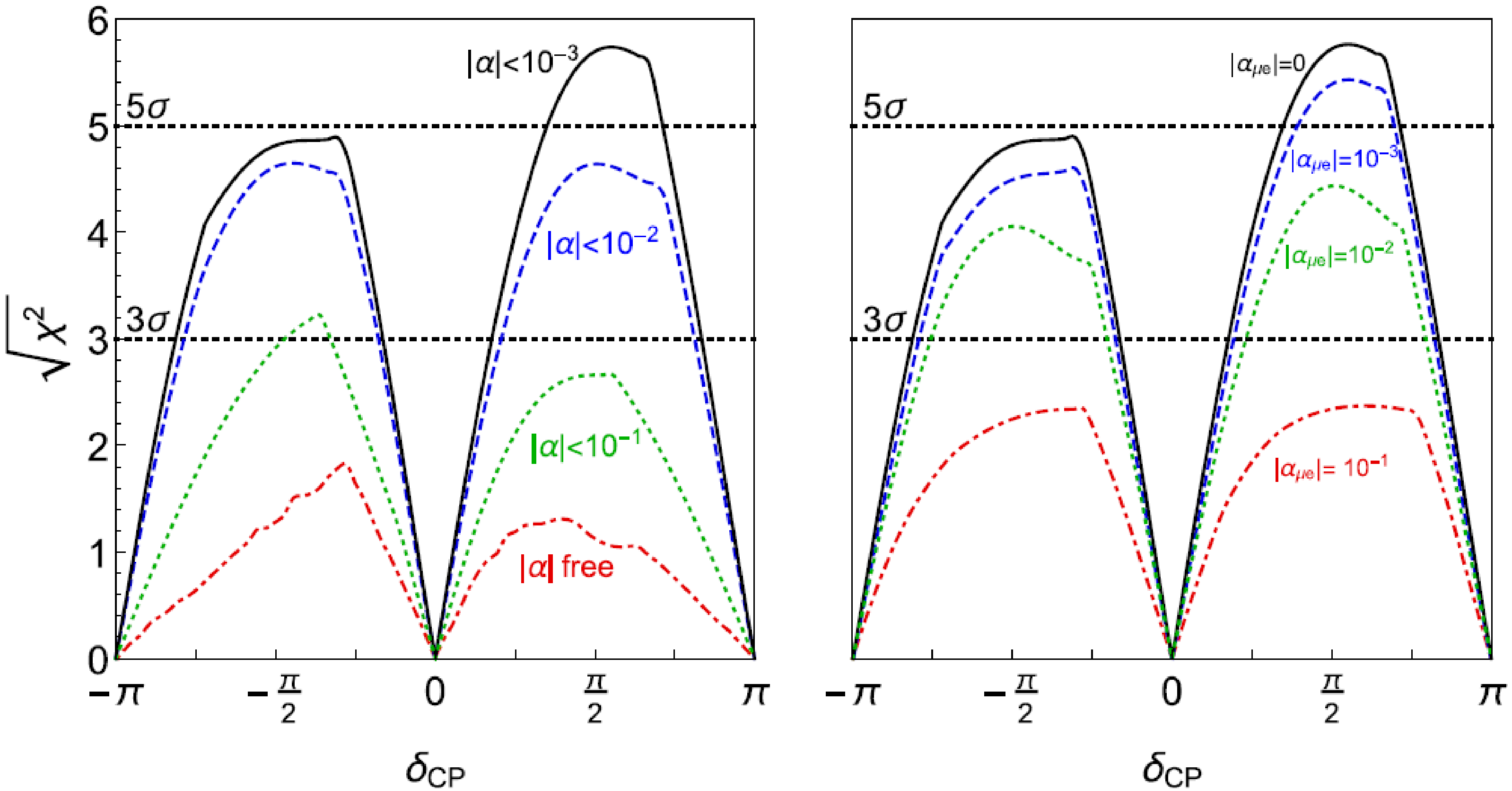
⇨ **On-axis beam:** wide range of neutrino energies


Neutrino Energy (GeV)
Neutrino Energy (GeV)
ND
FD
Probability
Δm^2_{41} = 50.00 eV^2
Std. Osc. P($\nu_\mu \to \nu_\mu$)
P($\nu_\mu \to \nu_e$)
P($\nu_\mu \to \nu_\mu$)
P($\nu_\mu \to \nu_\tau$)
1-P($\nu_\mu \to \nu_s$)
L/E (km/GeV)


Neutrino Energy (GeV)
Neutrino Energy (GeV)
ND
FD
Probability
Δm^2_{41} = 0.05 eV^2
Std. Osc. P($\nu_\mu \to \nu_\mu$)
P($\nu_\mu \to \nu_e$)
P($\nu_\mu \to \nu_\mu$)
P($\nu_\mu \to \nu_\tau$)
1-P($\nu_\mu \to \nu_s$)
L/E (km/GeV)


Neutrino Energy (GeV)
Neutrino Energy (GeV)
ND
FD
Δm^2_{41} = 0.50 eV^2
Std. Osc. P($\nu_\mu \to \nu_\mu$)
P($\nu_\mu \to \nu_e$)
P($\nu_\mu \to \nu_\mu$)
P($\nu_\mu \to \nu_\tau$)
1-P($\nu_\mu \to \nu_s$)
L/E (km/GeV)

Non unitarity



Non standard neutrino interactions

They can be described by effective four-fermion operators of the form

$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\bar{\nu}_\beta\gamma^\mu P_L l_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f'\right)$$

normalizing the operator with the Fermi constant

$$\varepsilon_{\alpha\beta} = \frac{M_W^2}{M^2_{NSNI}}$$

NSNI can appear at every step. It is therefore necessary to break down the analysis in three stages

- the production process
- the time evolution
- the detection process

We are left "only" with neutral current NSNI

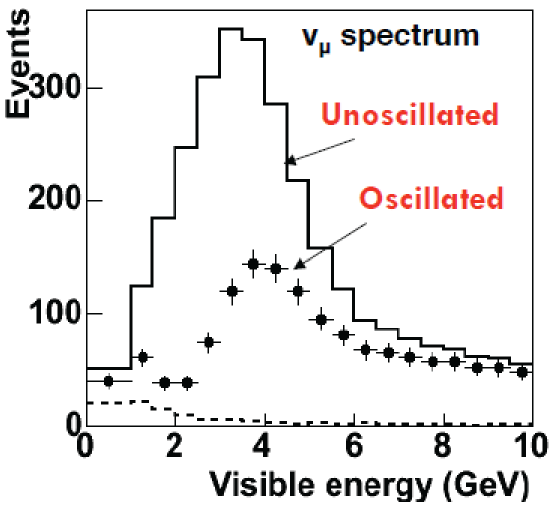
$$2\sqrt{2}G_F\varepsilon_{\alpha\beta}\left(\overline{\nu}_\beta\gamma^\mu P_L\nu_\alpha\right)\left(\bar{f}\gamma_\mu P_{L,R}f\right)$$

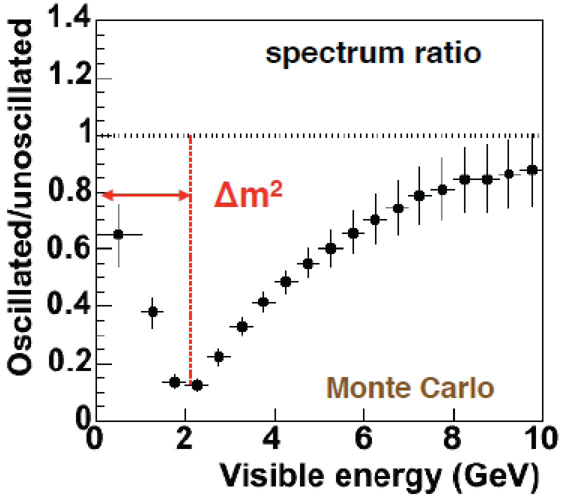
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

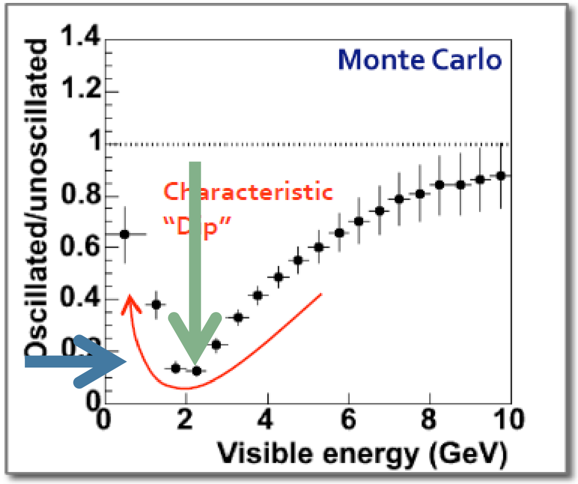
$$a \equiv 2\sqrt{2}G_F n_e E$$

$$H = \frac{1}{2E}\left[U\begin{pmatrix}0 & \\ & \Delta m^2_{32}\end{pmatrix}U^\dagger + a\begin{pmatrix}\epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L / E)$$







$\varepsilon_{\mu\tau}$ changes the disspearence probability at large energies shifts the position of the minimum in energy

$$\Delta m^2$$

$\varepsilon_{\tau\tau}$ modifies the dissapearence probability near the first oscillation minimum, especially the depth of the minimum

$$sin^2(2\,\theta_{23})$$

CPT violation

$$\frac{|\ m(K_0)\ -m(\overline{K_0\ })\ |}{m_{K-av}} < 10^{-18}$$

$$m_{K-av} \approx \frac{1}{2}\ 10^{9}\ \text{eV}$$

$$(m(K_0) - m\left(\overline{K_0}\ \right)\ )(m(K_0) + m\left(\overline{K_0\ }\right)) < 2\ \ 10^{-18}\, {m_{K-av}}^{2}$$

$$\left|m^2(K_0)\ -m^2\left(\overline{K_0\ }\right)\right| \approx \frac{1}{2}\ \text{eV}^{\,2}$$

CPT tests

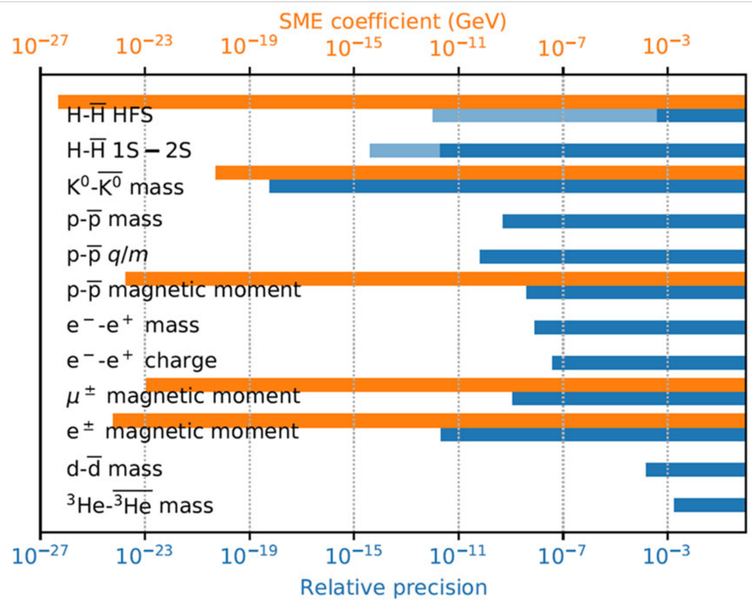
CPT invariance tested in several matter-antimatter systems:

neutral kaons

electron/positron

proton/antiproton

H/anti-H



E. Widmann, arXiv:2111.04056 [hep-ex]

Several experiments at the Antiproton Decelerator and ELENA(Extra Low Energy Antiproton) @CERN

Current bounds

- We can use data of various experiments to calculate the neutrino and antineutrino oscillation parameters:
  - Solar neutrino data: $\theta_{12}, \Delta m^2_{21}, \theta_{13}$
  - Neutrino mode in LBL: $\theta_{23}, \Delta m^2_{31}, \theta_{13}$
  - KamLAND data: $\overline{\theta}_{12}, \Delta \overline{m}^2_{21}, \overline{\theta}_{13}$
  - SBL reactors: $\overline{\theta}_{13}, \Delta \overline{m}^2_{31}$
  - Antineutrino mode in LBL: $\overline{\theta}_{23}, \Delta \overline{m}^2_{31}, \overline{\theta}_{13}$
- No bounds on CP-phases since all values are allowed

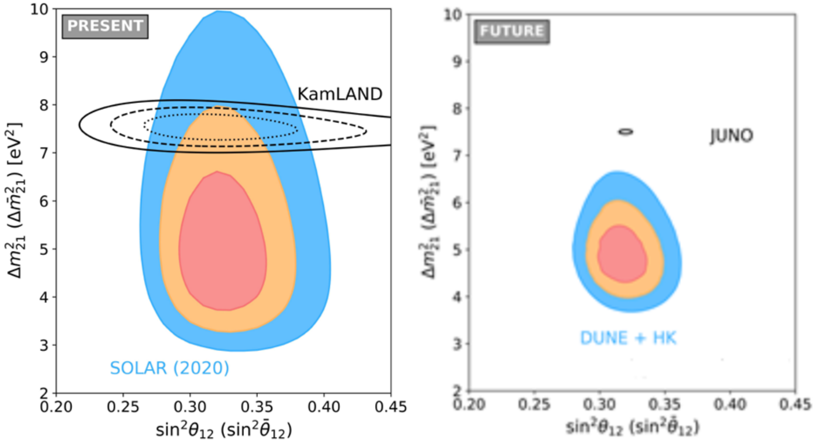
Parameter	Main contribution	Other contributions
θ_{12}	SOL	KamLAND
θ_{13}	REAC	ATM+LBL and SOL+KamLAND
θ_{23}	ATM+LBL	-
$\delta_{\rm CP}$	LBL	ATM
Δm^2_{21}	KamLAND	SOL
$\lvert\Delta m^2_{31}\rvert$	LBL+ATM+REAC	-
MO	LBL+REAC and ATM	-

SOL: Solar
ATM: Amtopsheric neutrinos
LBL: Long baseline accelerator experiments
REAC: Short-baseline reactor experiments

Current bounds

- We use the same data (except atmospheric neutrinos) as for the global fit to obtain

$$
\begin{aligned}
|\Delta m^2_{21} - \Delta \overline{m}^2_{21}| &< 4.7 \times 10^{-5}\ \mathrm{eV}^2, \\
|\Delta m^2_{31} - \Delta \overline{m}^2_{31}| &< 2.5 \times 10^{-4}\ \mathrm{eV}^2, \\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14, \\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.029, \\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.19.
\end{aligned}
$$



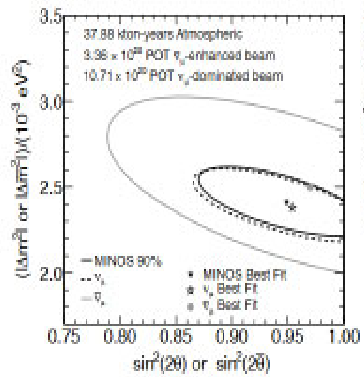
T2K results, a hint ?

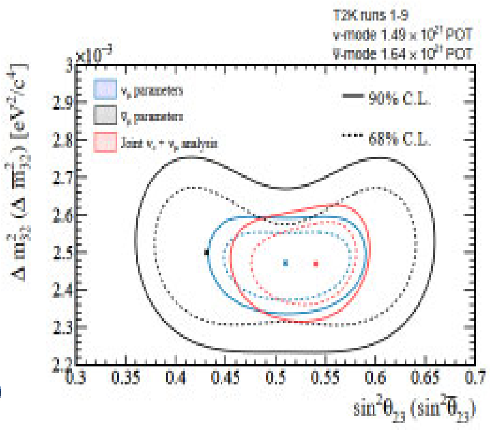
- T2K studied neutrino and anti-neutrino oscillations separated

$$\sin^2\theta_{23} = 0.51, \quad \Delta m^2_{32} = 2.53 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\overline{\theta}_{23} = 0.42, \quad \Delta \overline{m}^2_{32} = 2.55 \times 10^{-3}\mathrm{eV}^2$$

- Results are consistent with
- CPT-conservation





- In experiments and in fits normally you assume CPT-conservation
- If CPT is not conserved this leads to impostor (fake) solutions in the fits

- To perform the standard fit you would calculate

$$\chi^2_{\mathrm{total}} = \chi^2(\nu) + \chi^2(\overline{\nu})$$

and then minimize this function

$$h(x, y) = f(x) + g(y)$$

$$\partial_x f(x) = 0 \qquad \partial_y g(y) = 0$$

$$x = y$$

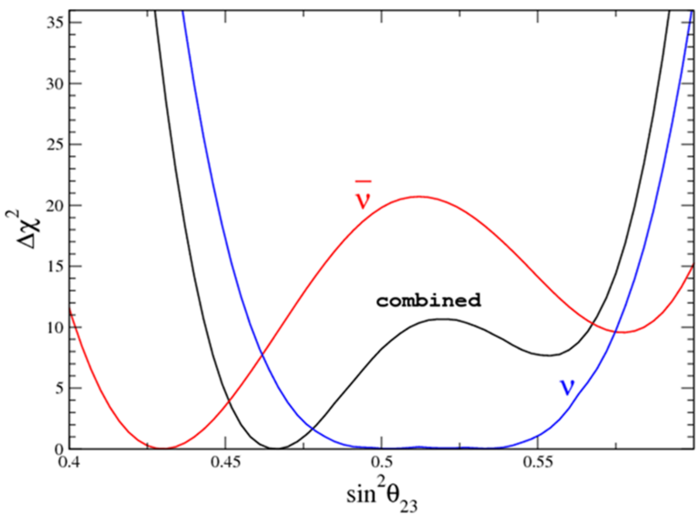
$$h(x) = f(x) + g(x)$$

$$\partial_x f(x) = \partial_x g(x) = 0$$

$$\partial_x f(x) = -\partial_x g(x)$$

Obtaining impostor solutions

- This was done for $\sin^2(\theta_{23}) = 0.5,\ \sin^2(\overline{\theta}_{23}) = 0.43$



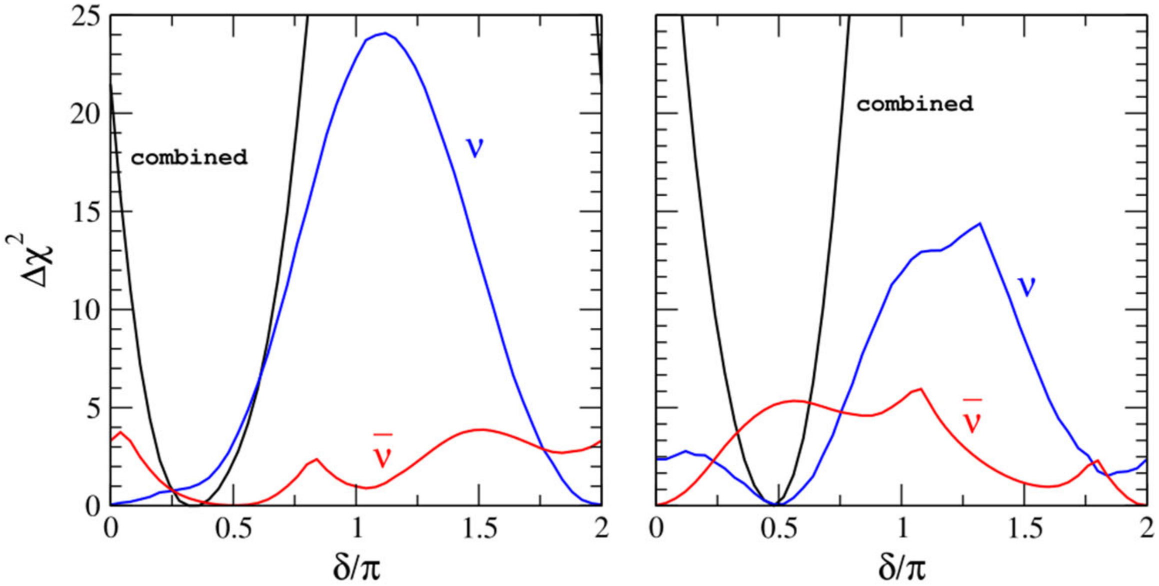
Combined best fit value is now

$$\sin^2(\theta_{23}^{\text{comb}}) = 0.467$$

Real true values are disfavored at close to 3σ and more 5σ confidence levels

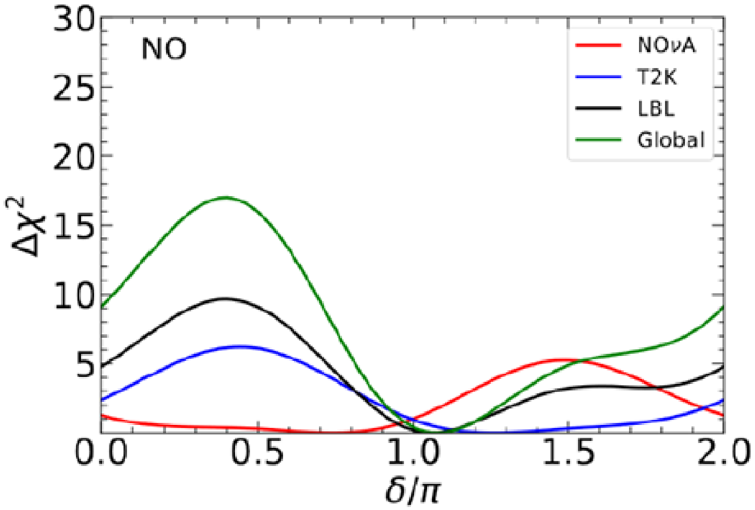
This can also happen

$$\delta = \begin{cases} \pi/2 \\ 0 \end{cases} \quad \text{and} \quad \bar{\delta} = \begin{cases} 0 \\ \pi/2 \end{cases}$$



G.B., C. Ternes and M. Tortola, JHEP 07 (2020) 155

$\theta_{13} \neq \theta_{13}$ can account for different behavior in neutrino and antineutrino channels



Tension between NOvA, T2K and SK atm. and $\delta_{bf} = 1.08\pi$

- Disfavours:
  - $\delta = \pi/2$ at 4.0σ
  - $\delta = 0$ at 3.0σ
  - $\delta = 3\pi/2$ with $\Delta\chi 2 = 4.9$

all values of δ and $\bar{\delta}$ remain allowed at $\sim 1\sigma$

Distinguishing CPT violation from NSNI

The muon neutrino survival probability in matter can be written as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_\nu \sin^2\left(\frac{\Delta m_\nu^2 L}{4E}\right).$$

in matter

$$\begin{aligned}
\Delta m_\nu^2 \cos 2\theta_\nu &= \Delta m^2 \cos 2\theta + \epsilon_{\tau\tau} A\,, \\
\Delta m_\nu^2 \sin 2\theta_\nu &= \Delta m^2 \sin 2\theta + 2\epsilon_{\mu\tau} A\,.
\end{aligned}
\qquad
\begin{aligned}
\Delta m_{\bar\nu}^2 \cos 2\theta_{\bar\nu} &= \Delta m^2 \cos 2\theta - \epsilon_{\tau\tau} A\,, \\
\Delta m_{\bar\nu}^2 \sin 2\theta_{\bar\nu} &= \Delta m^2 \sin 2\theta - 2\epsilon_{\mu\tau} A\,.
\end{aligned}$$

$$4\Delta m^4 = \Delta m_\nu^4 + \Delta m_{\bar\nu}^4 + 2\Delta m_\nu^2 \Delta m_{\bar\nu}^2 \cos(2\theta_\nu - 2\theta_{\bar\nu})$$

$$\sin^2(2\theta) = \frac{\left(\Delta m_\nu^2 \sin(2\theta_\nu) + \Delta m_{\bar\nu}^2 \sin(2\theta_{\bar\nu})\right)^2}{\Delta m_\nu^4 + \Delta m_{\bar\nu}^4 + 2\Delta m_\nu^2 \Delta m_{\bar\nu}^2 \cos(2\theta_\nu - 2\theta_{\bar\nu})}$$

$$\begin{aligned}
2\epsilon_{\tau\tau}^m A &= \Delta m_\nu^2 \cos(2\theta_\nu) - \Delta m_{\bar\nu}^2 \cos(2\theta_{\bar\nu}) \\
4\epsilon_{\mu\tau}^m A &= \Delta m_\nu^2 \sin(2\theta_\nu) - \Delta m_{\bar\nu}^2 \sin(2\theta_{\bar\nu})
\end{aligned}$$

G.B., C. Ternes and M. Tortola, Eur.Phys.J.C 79 (2019) 5, 390

Violations of Lorentz invariance

Lorentz violation

$$(h_{\text{eff}})_{ab} = \frac{m^2_{ab}}{2E} + \frac{1}{E}\left[(a_L)^{\alpha} p_{\alpha} - (c_L)^{\alpha\beta} p_{\alpha} p_{\beta}\right]_{ab}.$$

standard
Lorentz
covariant term

violates both CPT and
Lorentz invariance

Violations of Lorentz invariance

Lorentz violation

$$(h_{\text{eff}})_{ab} = \frac{m_{ab}^2}{2E} + \frac{1}{E}\left[(a_L)^{\alpha} p_{\alpha} - (c_L)^{\alpha\beta} p_{\alpha} p_{\beta}\right]_{ab}$$

standard Lorentz covariant term

violates both CPT and Lorentz invariance

As usual, the oscillation probability is governed by the difference of the eigenvalues of the effective hamiltonian.

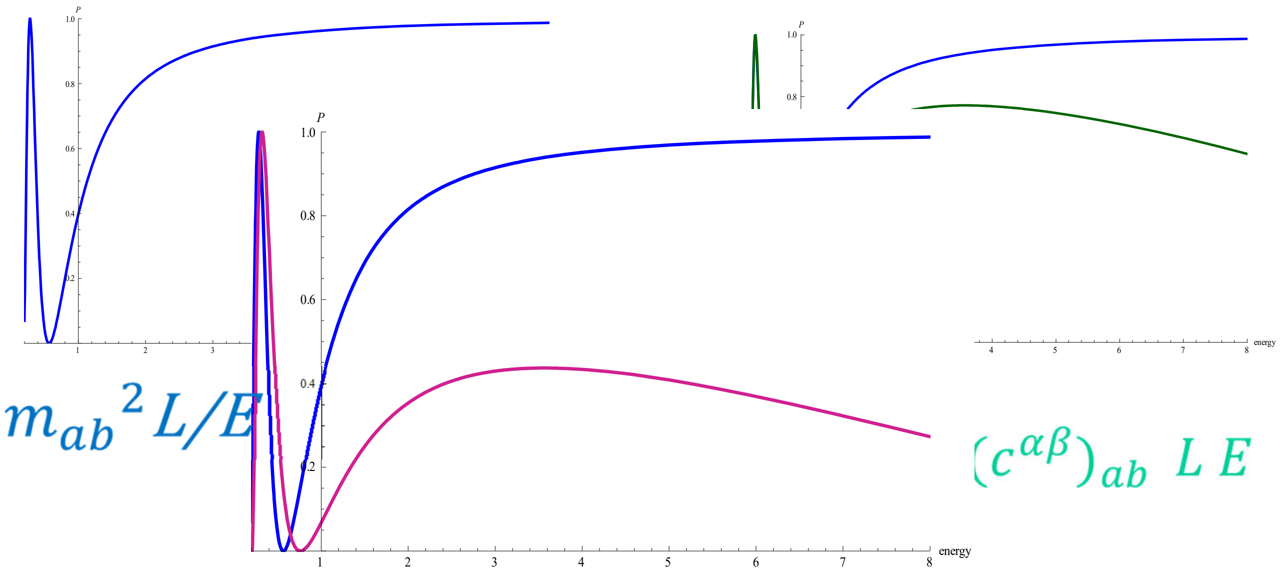
$$\sin^2(\Delta_{ab}\ L/2)$$

${m_{ab}}^2 L/E$

$(a^{\alpha})_{ab}\ L$

$(c^{\alpha\beta})_{ab}\ L\ E$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L / E)$$



$m_{ab}{}^2 L/E$

$(c^{\alpha\beta})_{ab}\ L\ E$

$(a^\alpha)_{ab}\ L$

Neutrinos,

In and Beyond the Standard Model:

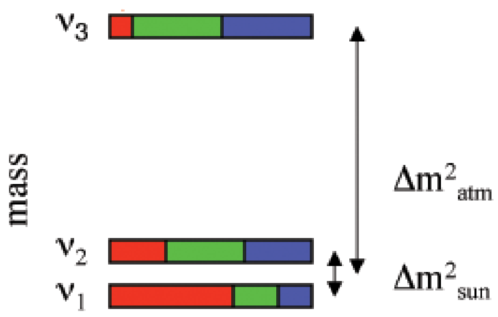
NEUTRINO MASS:

$$\delta m^2_{atm} = 2.7^{+0.4}_{-0.3} \times 10^{-3} eV^2 \qquad L/E = 500\ km/GeV$$

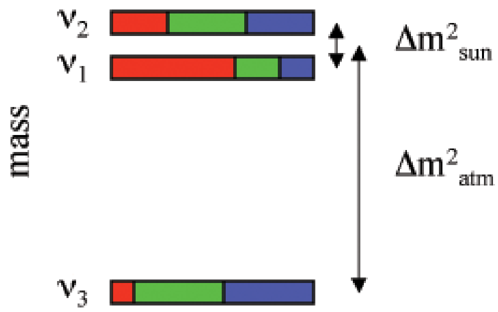
$$\delta m^2_{solar} = 8.0 \pm 0.4 \times 10^{-5} eV^2 \qquad L/E = 15\ km/MeV$$

$$\Downarrow$$

$$m_\nu^{Heavy} > \sqrt{\delta m^2_{atm}} = 50 meV$$

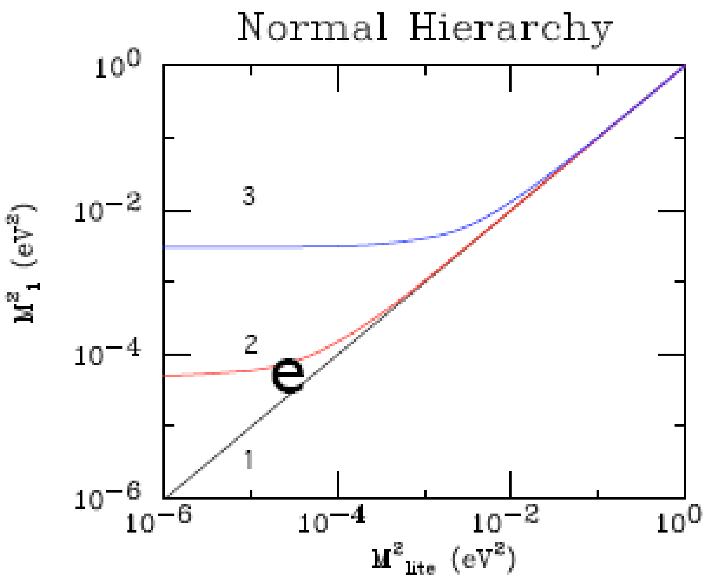


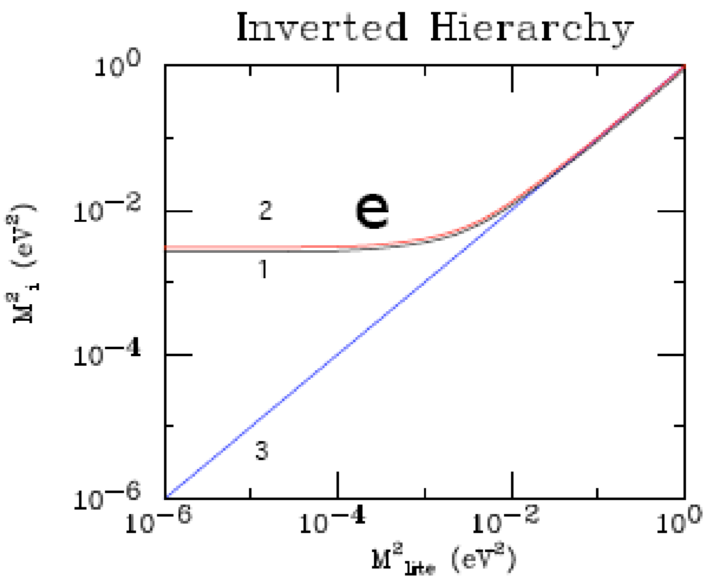
Normal mass hierarchy



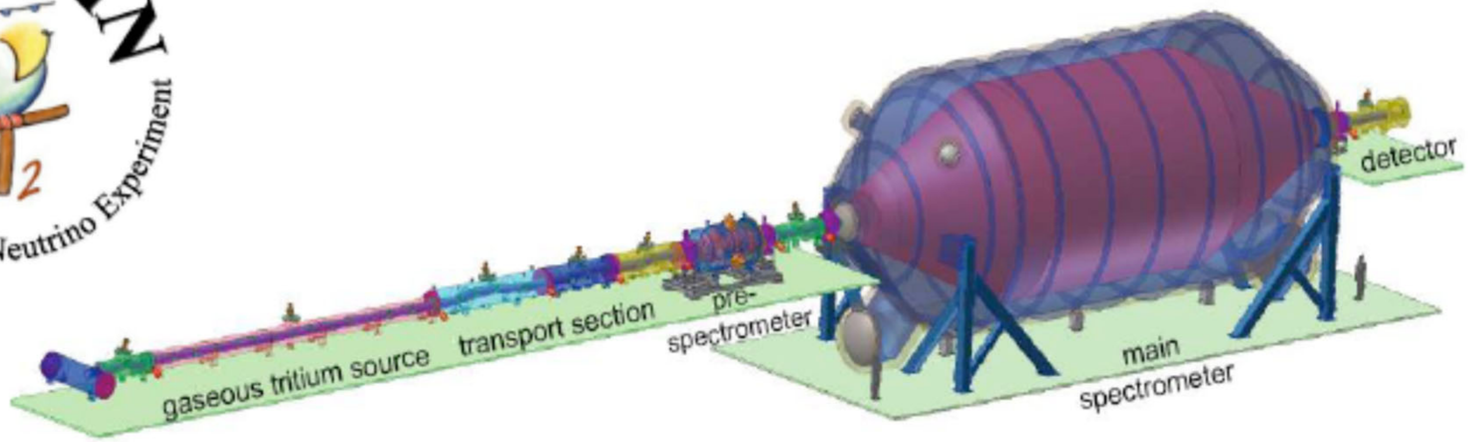
Inverted mass hierarchy

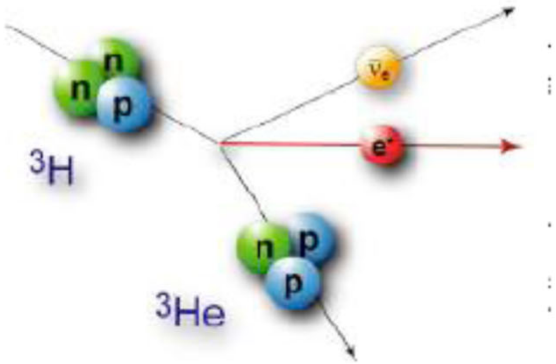
Masses:





States 1 and 2 are ν_e rich.



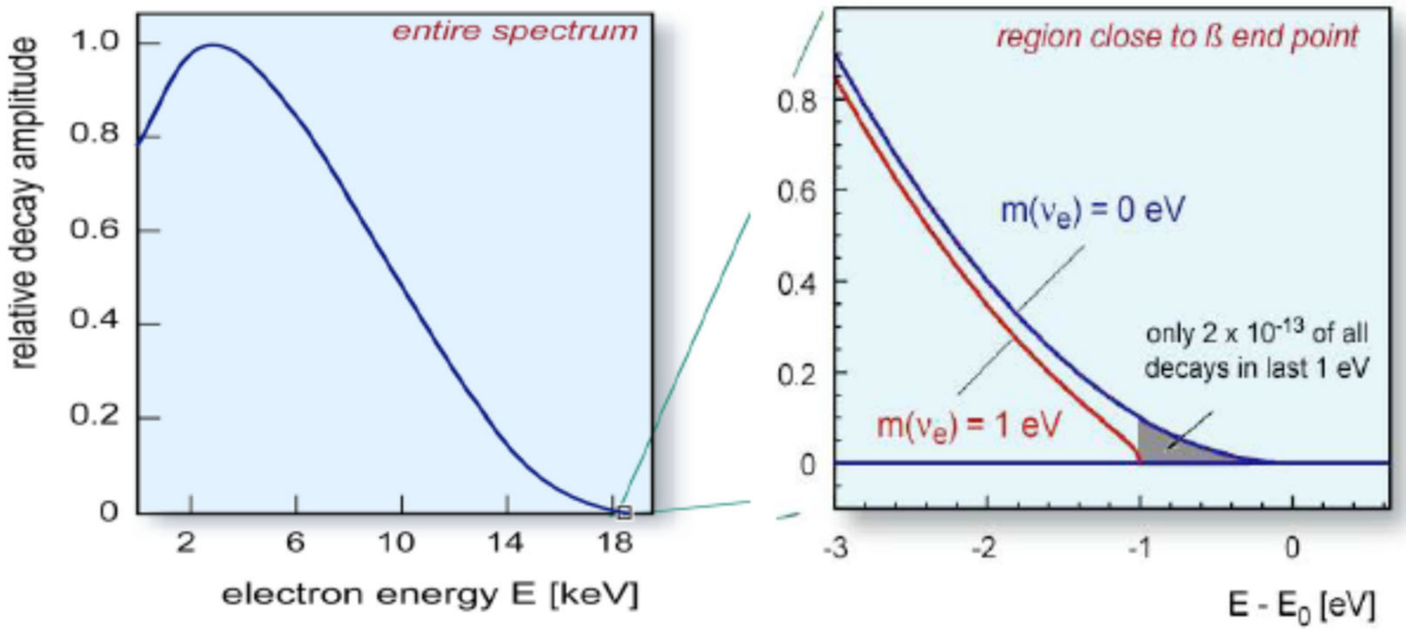


Requirements:

- Strong source
- Excellent energy resolution
- Small endpoint energy E_0
- Long term stability
- Low background rate

KATRIN Task:
Investigate Tritium endpoint with sub-eV precision

KATRIN Aim:
Improve m_ν sensitivity 10 x (2eV → 0.2eV)

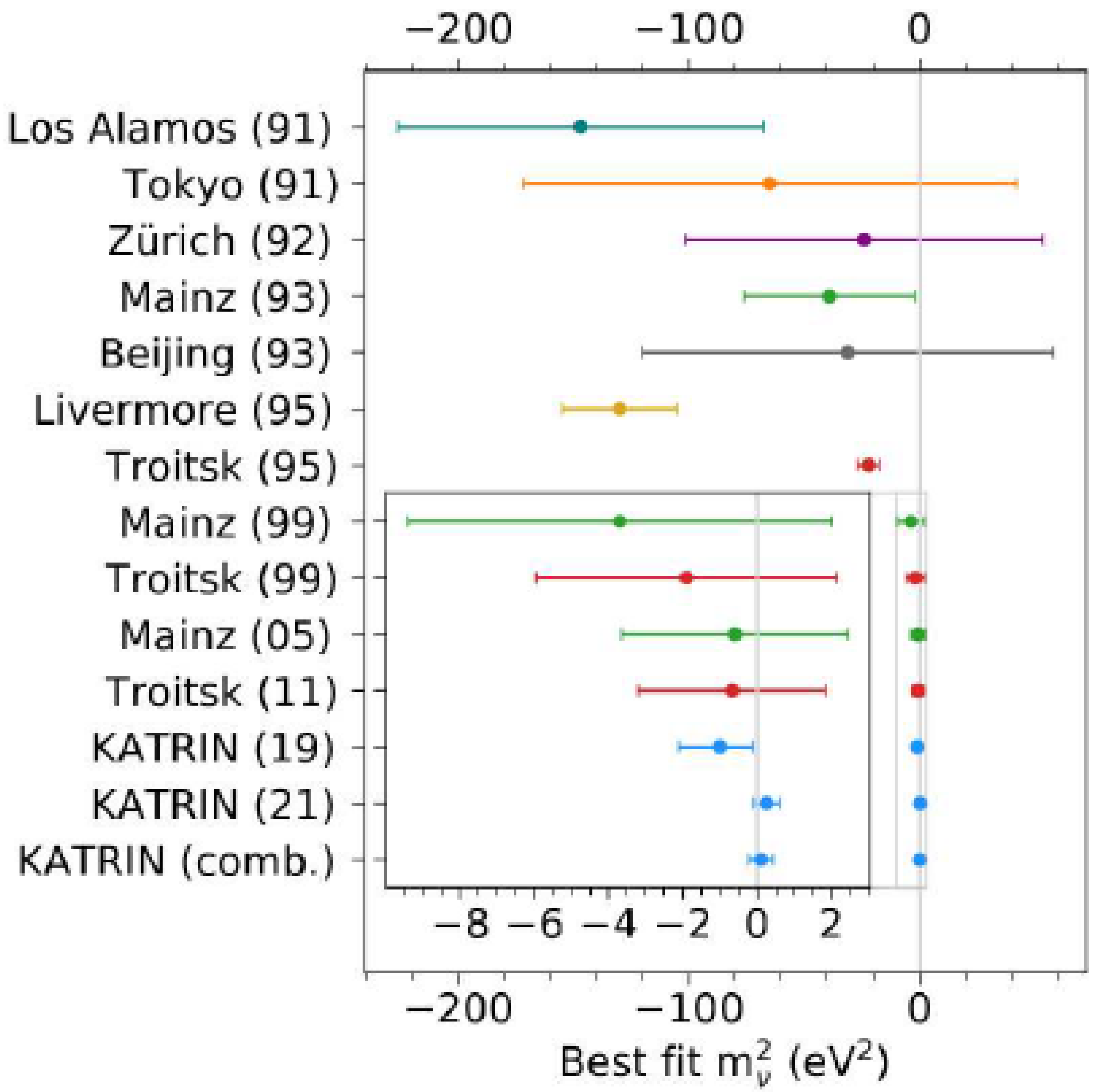


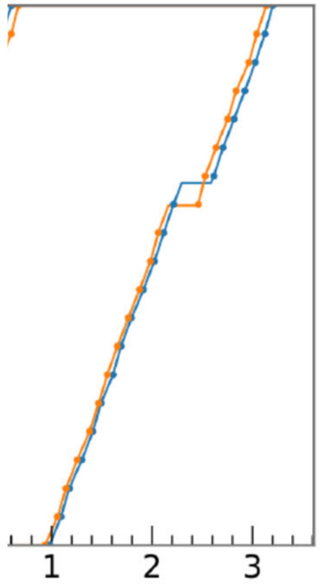
Decay Rate:

$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sum_k |U_{ek}|^2\sqrt{(E_0 - E)^2 - m_k^2}$$

if ν's quasi-degenerate: $m_1 \approx m_2 \approx m_3$

$$|\langle {}^3He + e^- + \bar{\nu}|T|{}^3H\rangle|^2 \sim pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$





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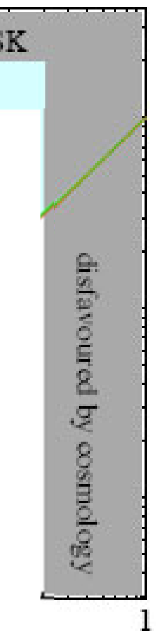
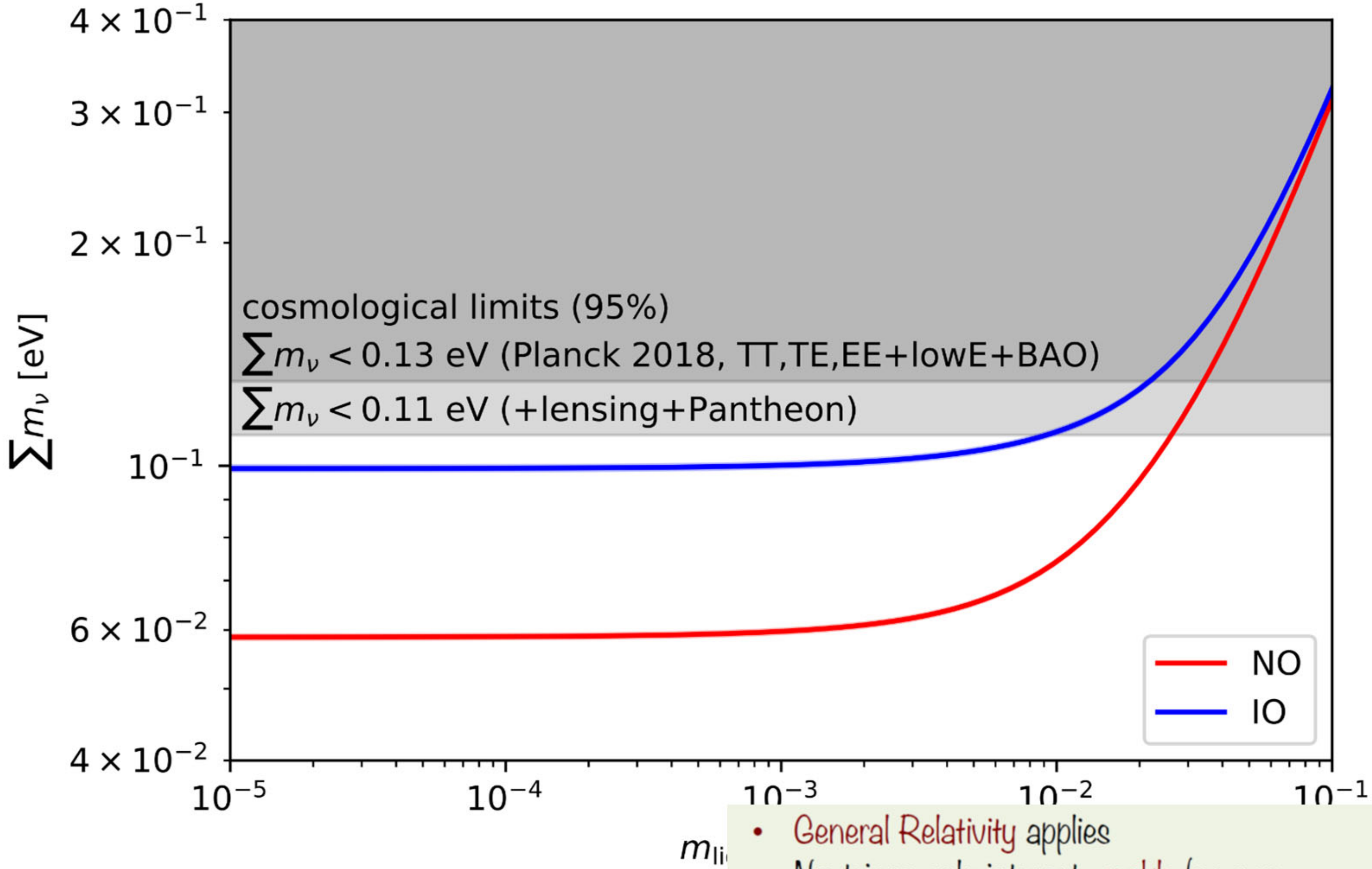


$\sum m_i$ m_{cosmo} in eV



$\sum$ ... er.

Si

could exclude $m_{\nu_e} > \frac{1}{30}\ eV$, t

- General Relativity applies
- Neutrinos only interact weakly (no non-standard interactions)
- Universe reached thermal equilibrium before T ~ few MeV

CMB: neutrino mass

Spherical harmonics decomposition:

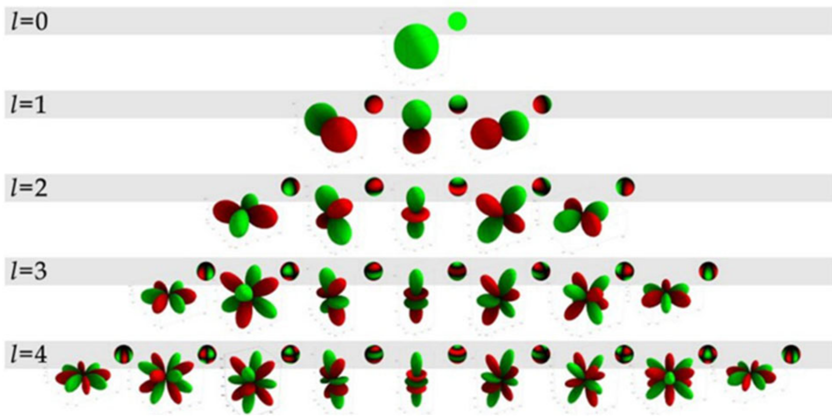
$$T(\hat{n}) = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

With expansion coefficients:

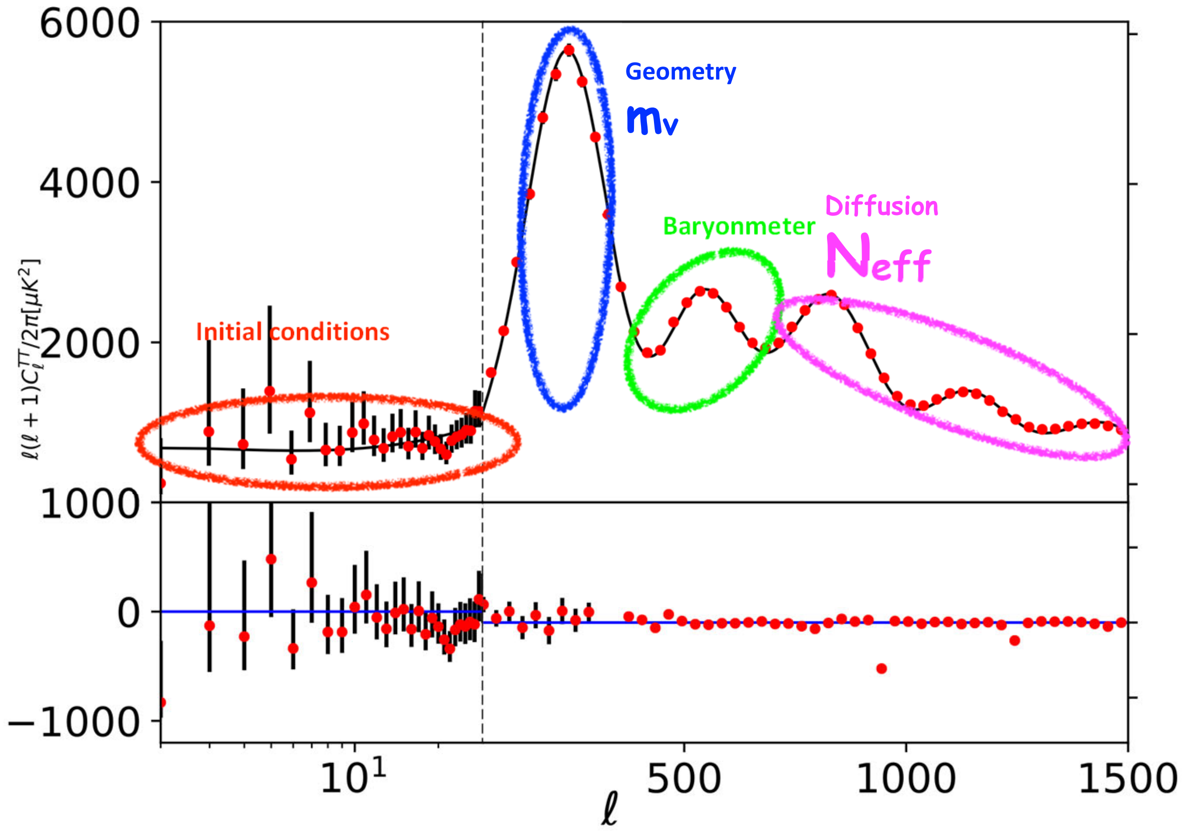
$$a_{\ell m} = \int_{4\pi} T(\hat{n}) Y^{*}_{\ell m}(\hat{n}) d\Omega$$

The angular power spectrum measures the amplitude of the expansion coefficients as a function of the wavelength:

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

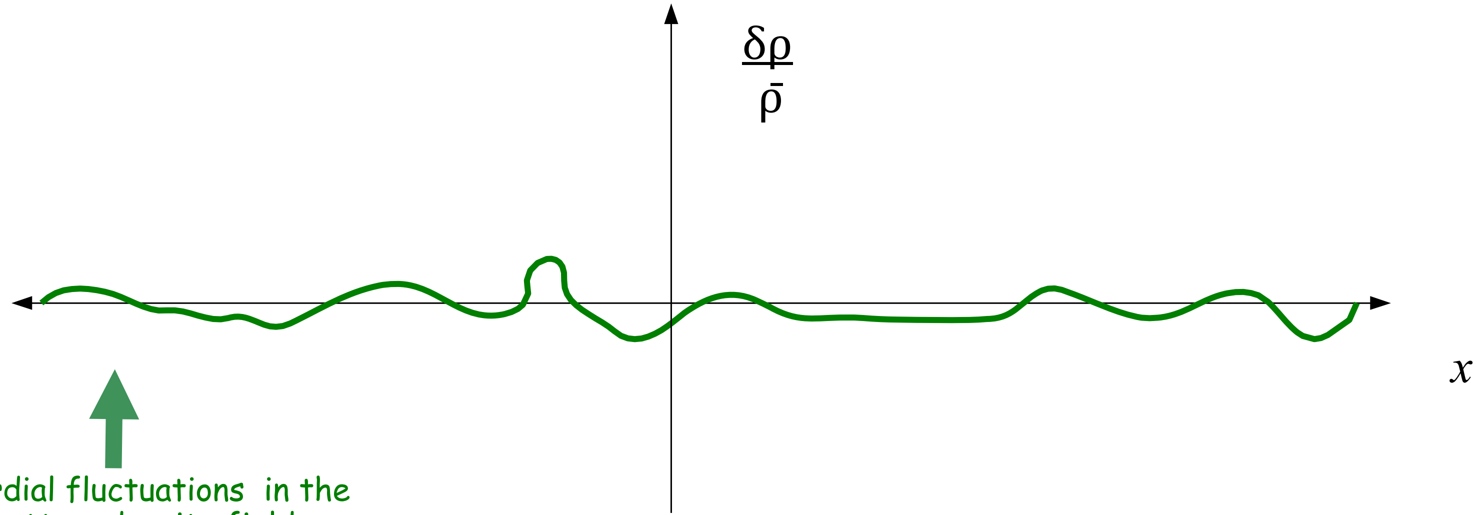


CMB: a lot to learn about….



How structures form...

Initial fluctuations seeded by, e.g., inflation.



Primordial fluctuations in the dark matter density field

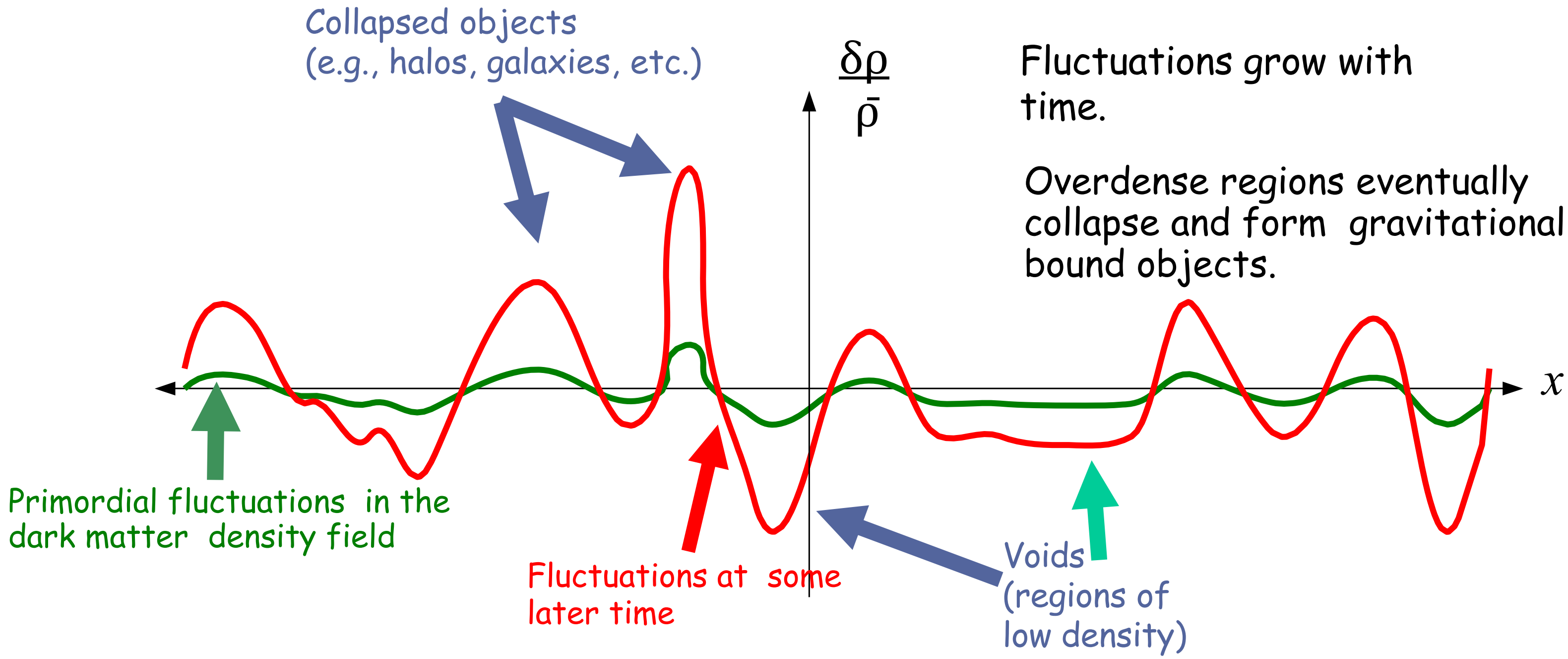
How structures form...

Photons freestream: Inhomogeneities turn into anisotropies

Initial fluctuations seeded by, e.g., inflation.

Fluctuations grow with time.

Overdense regions eventually collapse and form gravitationally bound objects.

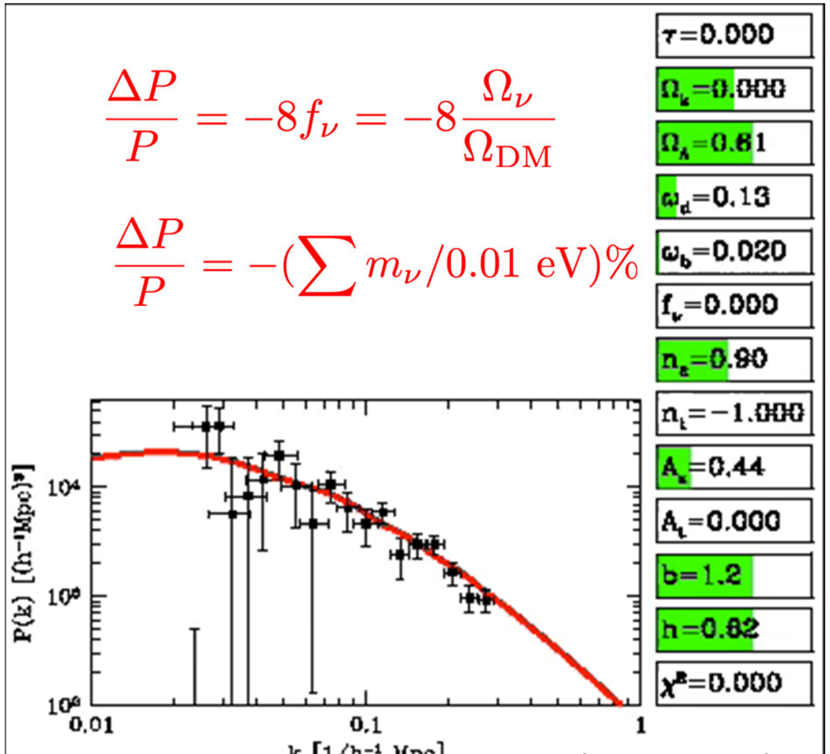


Large scale structure

Matter power spectrum suppression

$$\frac{\Delta P}{P} = -8 f_\nu = -8 \frac{\Omega_\nu}{\Omega_{\rm DM}}$$

$$\frac{\Delta P}{P} = -\left(\sum m_\nu / 0.01 \text{ eV}\right)\%$$



(From M. Tegmark)

Σm_ν

Planck
TTTEEE+lowT+lowE+lensing

$$\sum m_\nu < 0.24 \text{ eV } 95\%\text{CL}$$

+ BAO

$$\sum m_\nu < 0.12 \text{ eV } 95\%\text{CL}$$

+ BAO + SNIa

$$\sum m_\nu < 0.11 \text{ eV } 95\%\text{CL}$$

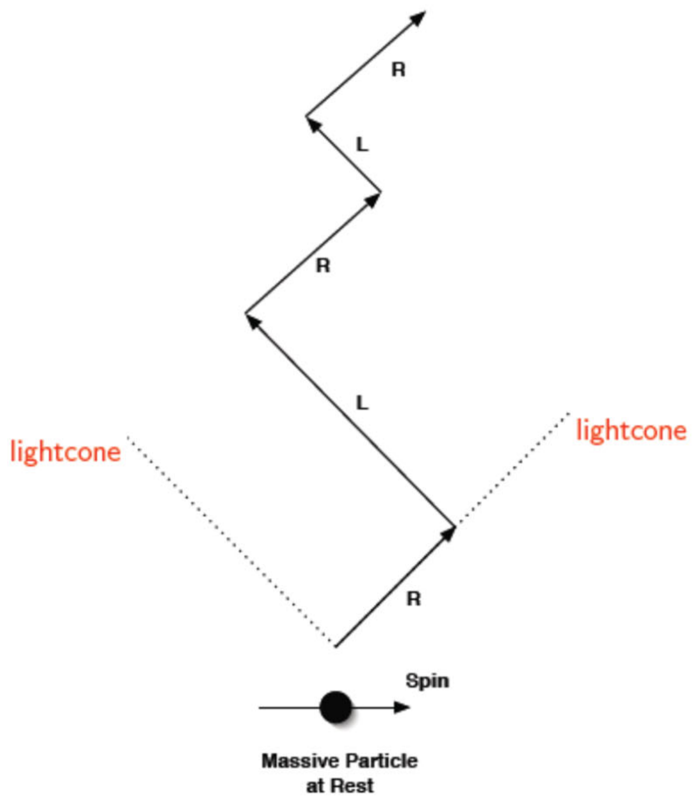
+ SDSS-IV (BAO + RSD) + SNIa

$$\sum m_\nu < 0.099 \text{ eV } 95\%\text{CL}$$

+ BAO + SNIa + H_0=73.45 ±1.66 km/s/Mpc

$$\sum m_\nu < 0.0970 \text{ eV } 95\%\text{CL}$$

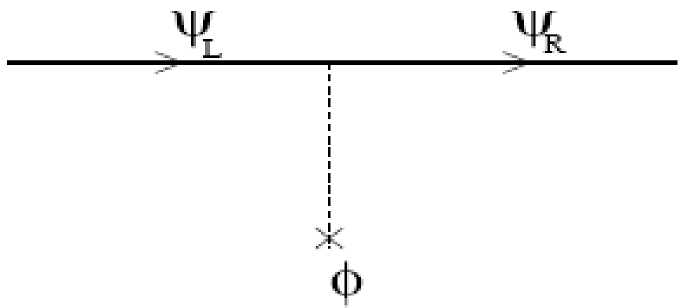
What is Fermion Mass ???



A mass can be thought of as a $L \leftrightarrow R$ transition:

$$m\ \overline{\psi_L}\psi_R + h.c.$$

In the SM fermion masses originate in the interaction with the Higgs field:



$$\lambda_f\ \overline{\psi_L}\ \Phi\ \psi_R + h.c. \rightarrow m_f = \lambda_f\ v$$

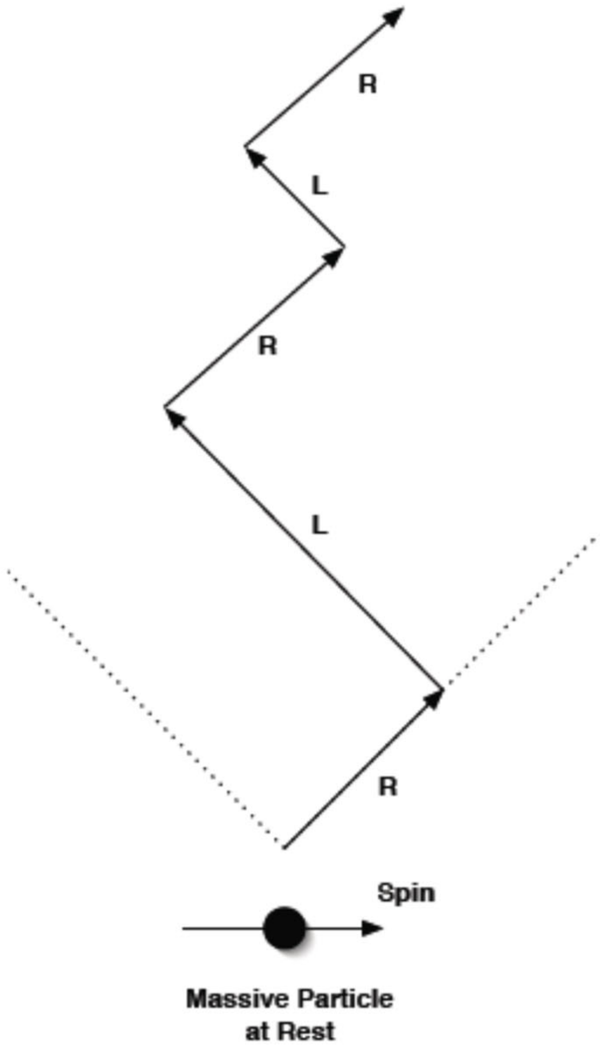
Fermion Masses:

	electron	positron	
Left Chiral	e_L	$\bar{e}_R$	SU(2)×U(1)
Right Chiral	e_R	$\bar{e}_L$	U(1)

CPT: $e_L \leftrightarrow \bar{e}_R$ and $e_R \leftrightarrow \bar{e}_L$

Mass couples L to R:

e_L to e_R AND also $\bar{e}_R$ to $\bar{e}_L$ Dirac Mass terms.



Mass couples L to R:

$$P^2 = M^2, \quad P \cdot S = 0 \quad and \quad S^2 = -1$$

$$u(P,S) = \frac{(1+\gamma_5)}{2} u(\frac{P+MS}{2}) + e^{i\phi} \frac{(1-\gamma_5)}{2} u(\frac{P-MS}{2})$$

right massless left massless

A coupling of
e_L to $\bar{e}_R$ OR e_R to $\bar{e}_L$ would be (Majorana) mass term
but this violates conservation of electric charge!

Seesaw / Dirac Neutrinos / Light Sterile Neutrinos

	Nu	CPT:	Anti-Nu	
Left Chiral	$\boldsymbol{\nu_L}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_R}$	
	$\Updownarrow$		$\Updownarrow$	Dirac Masses
Right Chiral	$\boldsymbol{\nu_R}$	$\Leftrightarrow$	$\boldsymbol{\bar{\nu}_L}$	
		Majorana Masses		

Coupling of

- ν_L to ν_R AND $\bar{\nu}_R$ to $\bar{\nu}_L$ are the Dirac masses.
- ν_L to $\bar{\nu}_R$ forbidden by weak isospin.
- ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\rightarrow M)$

ν_L to $\bar{\nu}_R$ $\qquad$ ν_L to ν_R

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$$

$\bar{\nu}_R$ to $\bar{\nu}_L$ $\qquad$ ν_R to $\bar{\nu}_L$

Two Majorana neutrinos with masses m_D^2/M and M

Seesaw:
Yanagida, Gell-man-
Ramond-Slansky

- Coupling of ν_R to $\bar{\nu}_L$ allowed and coefficient is unprotected. $(\to M)$

Also applies to sterile neutrinos.

Light Sterile Neutrinos and/or Dirac Neutrinos Unexpected!!!

The consequences of this alternative are profound:

- Physics beyond the SM at a scale M!

- Majorana fermions carry no conserved charge: L is violated !

$$\nu_L \to e^{i\alpha} \nu_L$$

does not leave the Majorana mass term invariant.
$\to$ Most welcome for baryogenesis: a mechanism to understand the matter-antimatter asymmetry in the Universe emerges naturally
$\to$ Most welcome by string theory: it is difficult to get global $U(1)$ charges conserved

Leptogenesis

Baryon Asymmetry is created by a Lepton Asymmetry produced by the decays of super heavy Majorana Neutrinos.

$$\frac{\Gamma(N \to l^+ \phi^-) - \Gamma(N \to l^- \phi^+)}{\Gamma(N \to l^+ \phi^-) + \Gamma(N \to l^- \phi^+)}$$

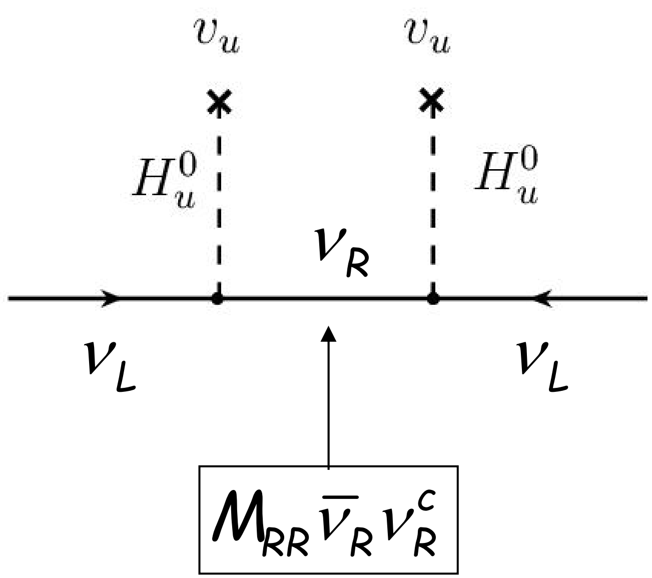
$\Gamma(N \to l^{\pm}\phi^{\mp})$ depends on the Majorana Phases in the MNS mixing matrix.

$$B_{now} = \frac{1}{2}(B-L) + \frac{1}{2}(B+L) = \frac{1}{2}(B-L)_{ini} = -\frac{1}{2}L_{ini}$$

$$\underbrace{\frac{1}{2}(B+L)}_{0}$$

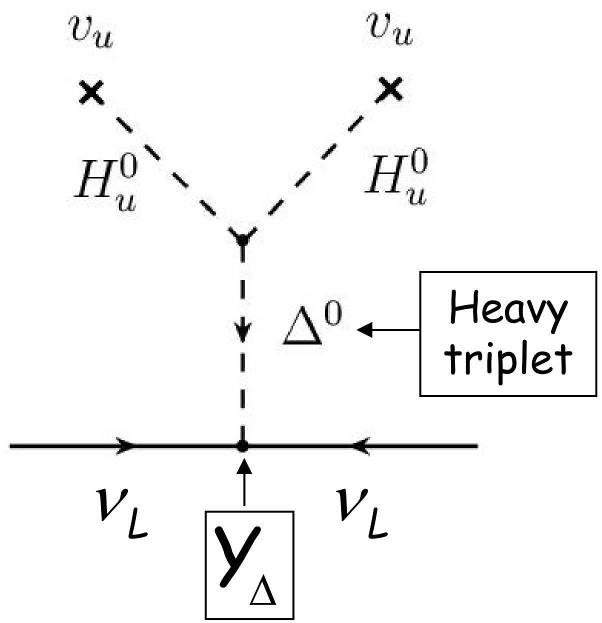
Types of see-saw mechanism

Type I see-saw mechanism



$$m_{LL}^{I} \approx -m_{LR} M_{RR}^{-1} m_{LR}^{T}$$

Type II see-saw mechanism



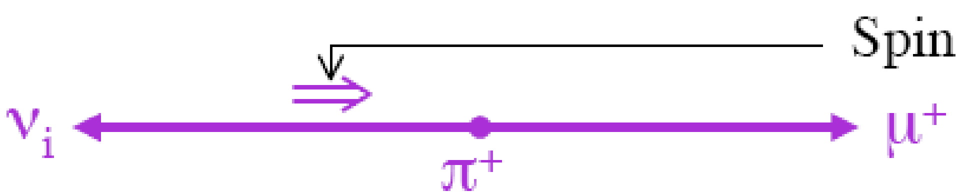
$$m_{LL}^{II} \overline{\nu}_L \nu_L^c \approx Y_\Delta \frac{v_u^2}{M_\Delta}$$

How Can We Demonstrate That $\bar{\nu}_i = \nu_i$?

We assume neutrino interactions are correctly described by the SM. Then the interactions conserve L ($\nu \rightarrow \ell^-$; $\bar{\nu} \rightarrow \ell^+$).

An Idea that Does Not Work
[and illustrates why most ideas do not work]

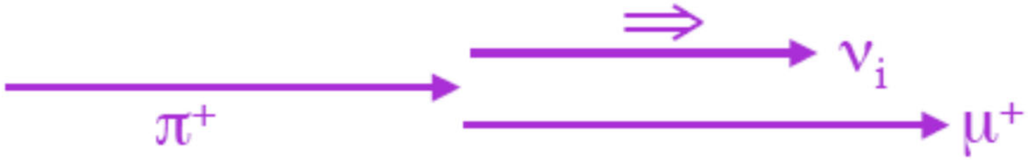
Produce a ν_i via—



Pion Rest Frame

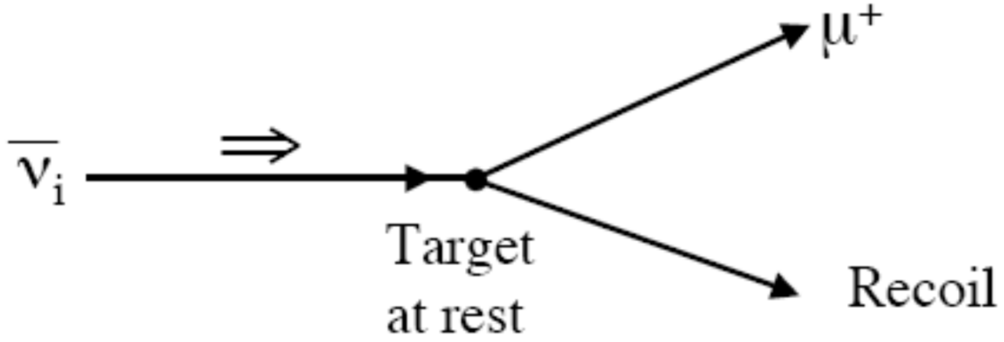
Give the neutrino a Boost:

$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$



Lab. Frame

The SM weak interaction causes —



$\nu_i = \overline{\nu_i}$ means that $\nu_i(h) = \overline{\nu_i}(h)$.

helicity

If $\nu_i \xrightarrow{\quad\Rightarrow\quad} = \overline{\nu_i} \xrightarrow{\quad\Rightarrow\quad}$,

our $\nu_i \xrightarrow{\quad\Rightarrow\quad}$ will make μ^+ too.

Minor Technical Difficulties

$$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$$

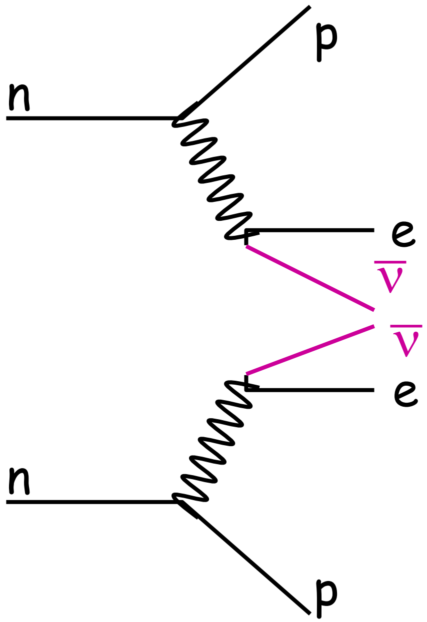
$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi \ (\text{Lab}) > 10^4 \ \text{TeV} \quad \text{if} \ m_\nu \sim 1 \text{ eV}$$

Fraction of all π–decay that get helicity flipped

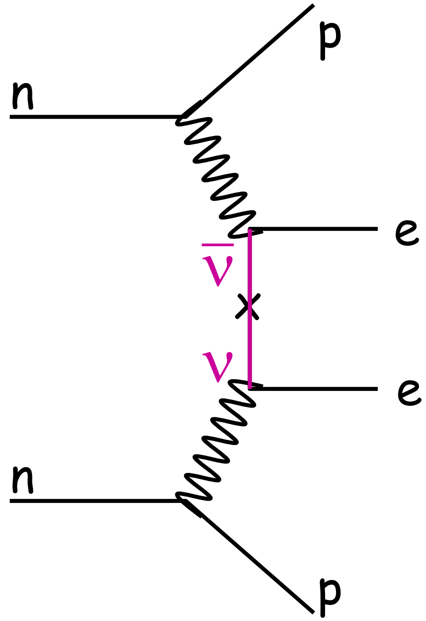
$$\approx \left(\frac{m_\nu}{E_\nu \ (\pi \text{ Rest Frame})} \right)^2 \sim 10^{-16} \quad \text{if } m_\nu \sim 1 \text{ eV}$$

➢ How we can find out ?



SM double weak process

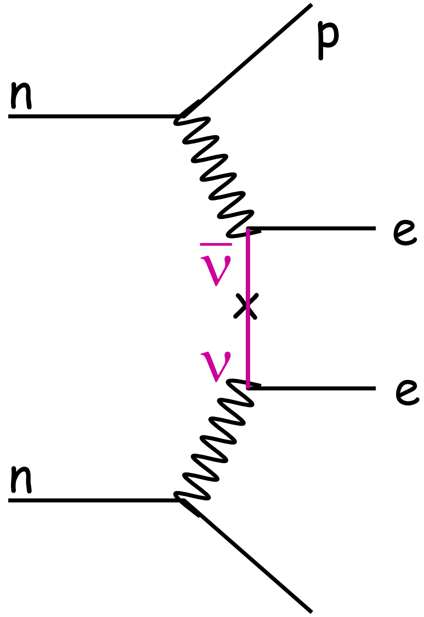
4 body decay: continuos spectrum for the e energy sum



Only allowed for Majorana ν

2 body decay: e energy sum is a delta

$\bar{\nu}_i$ is emitted (RH + O(m_i/E) LH)



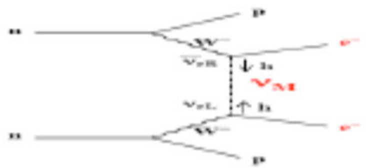
Amp[ν_i contribution] ~ m_i

$$\text{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right|$$

effective mass

Neutrinoless double beta decay

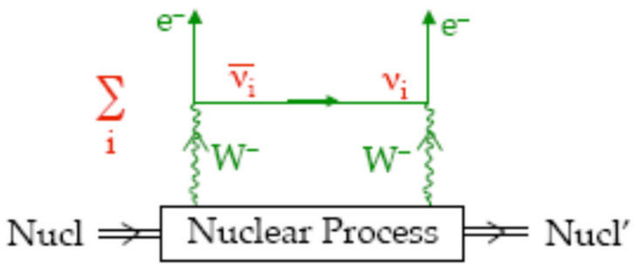
- Most sensitive (terrestrial) probe of the absolute neutrino mass
- Unique way of proving Majorana nature of ν
- If Majorana ν is the only mechanism, ===>



$$< m >_{\beta\beta} \equiv \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

$$= \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)} \right|$$

$$T_{1/2}^{0\nu} = \frac{m_e}{G_{0\nu}\, M_{\rm nucl}^2\, m_{ee}^2}$$



Best bounds from

^{136}Xe (KamLAND-ZEN):

$$T_{1/2}^{0\nu,\mathrm{Xe}} > 2.3 \times 10^{26} \ \ \mathrm{yr\ at\ 90\%CL}$$

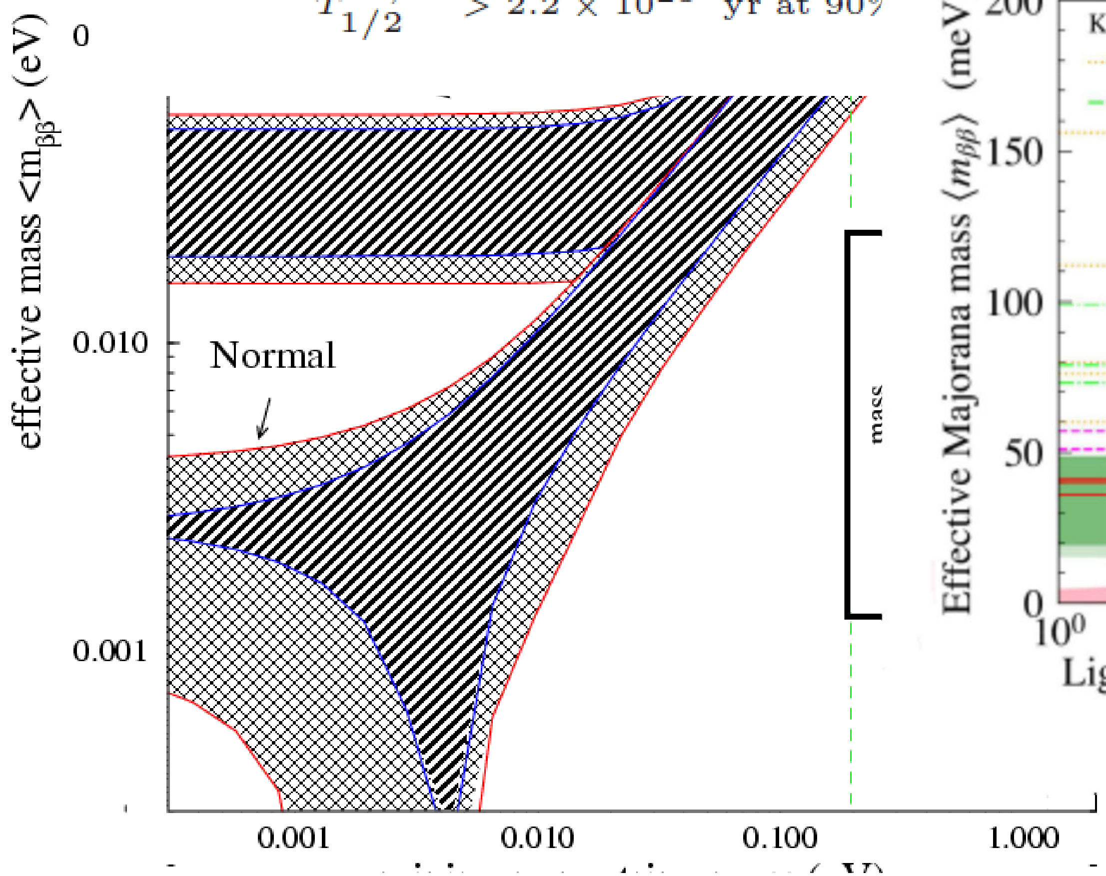
^{76}Ge (Gerda):

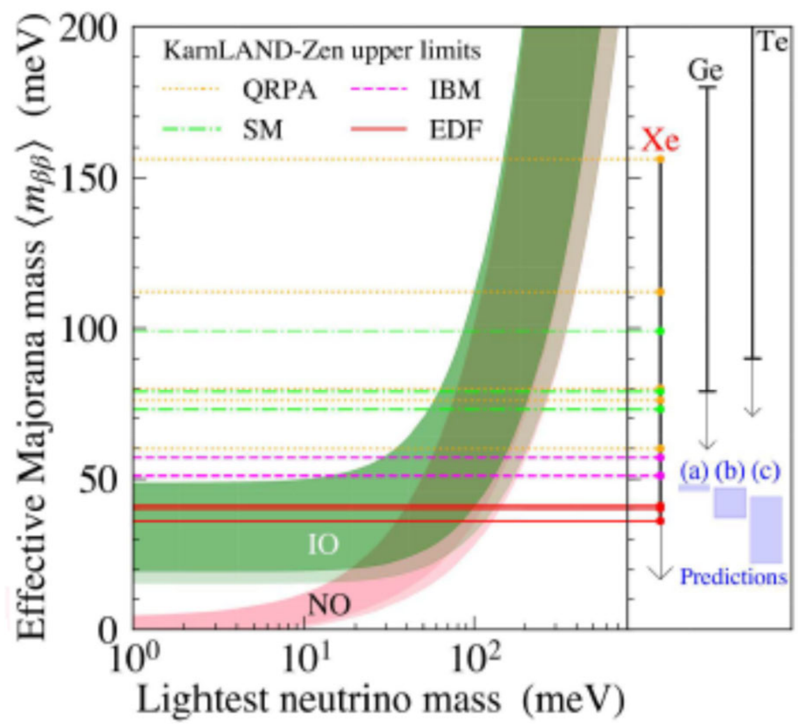
$$T_{1/2}^{0\nu,\mathrm{Ge}} > 1.8 \times 10^{26} \ \ \mathrm{yr\ at\ 90\%CL}$$

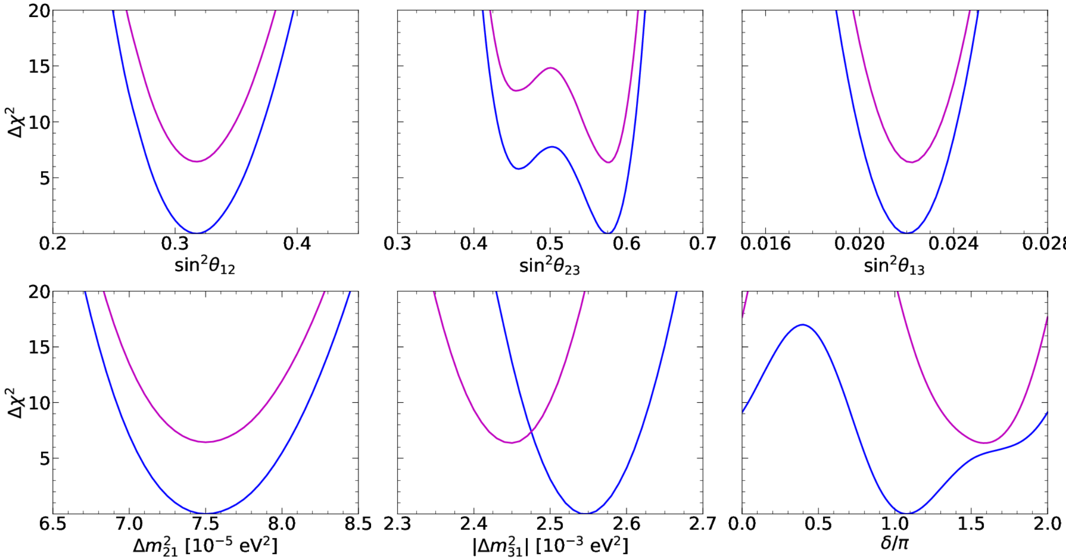
^{130}Te (Cuore):

$$T_{1/2}^{0\nu,\mathrm{Te}} > 2.2 \times 10^{25} \ \ \mathrm{yr\ at\ 90\%}$$

$$m_{\beta\beta} = | \sum m_i U_{ei}^2 |$$







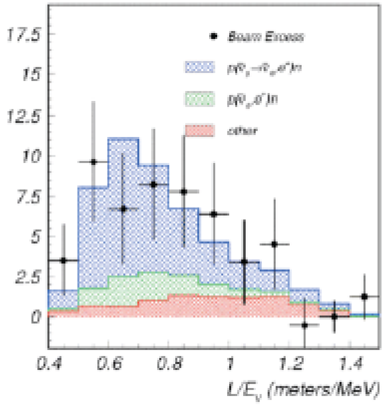
$$U_{\alpha i} = \quad s_{12} \quad c_{12} \quad 1 \quad 1 \quad e^{i\alpha} \quad e^{i\beta}$$

At

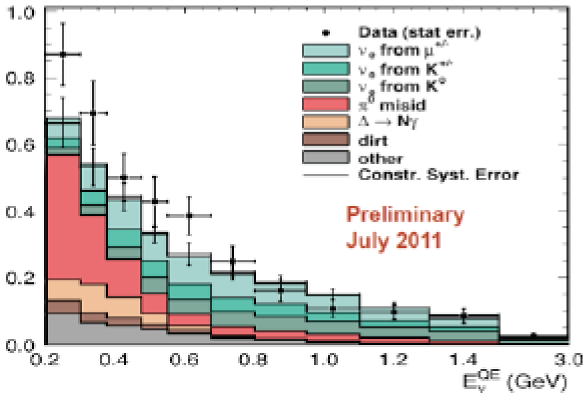
$0\nu\beta\beta$ decay

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
Δm^2_{21}: $[10^{-5}$ eV$^2]$	$7.50^{+0.22}_{-0.20}$	7.11–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert$: $[10^{-3}$ eV$^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert$: $[10^{-3}$ eV$^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18±0.16	2.86–3.52	2.71–3.69
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74±0.14	5.41–5.99	4.34–6.10
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
δ_{CP}/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
δ_{CP}/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

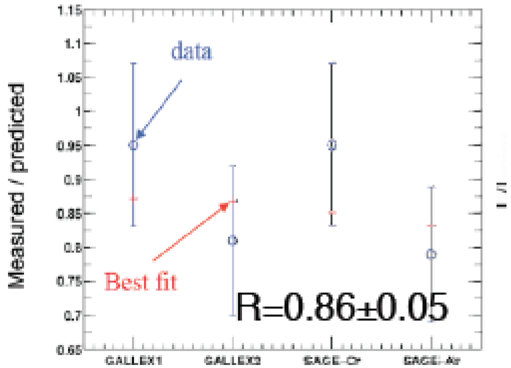
LSND



MiniBoone



Ga Anomaly



- Light Steriles ???
- Mass Hierarchy $m_3 > m_2 > m_1$ OR $m_2 > m_1 > m_3$

  using $|U_{e3}|^2 < |U_{e2}|^2 < |U_{e1}|^2$
- Is CP violated ? $\sin\delta \neq 0$
- Mass of Heaviest Neutrino
- Mass of Lightest Neutrino
- New Interactions, Surprises !!!