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## Absolute neutrino masses: Current phenomenology

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#### **OSCILLATIONS** (Flavors = $\mathcal{O} \mid \mathbf{u} \mid \mathbf{\tau}$ )



Oscillations constrain neutrino mixings and mass splittings but not the absolute mass scale.

E.g., can take the lightest neutrino mass as free parameter:



However, the lightest neutrino mass is not really an "observable" We know three realistic observables to attack v masses  $\rightarrow$ 

## The "weapon":



Three prongs:



β decayOv2β decaycosmology

### The three prongs of the "trident": $(m_{\beta}, m_{\beta\beta}, \Sigma)$

1)  $\beta$  decay:  $m_i^2 \neq 0$  can affect spectrum endpoint. Sensitive to the "effective electron neutrino mass":

$$m_{\beta} = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

2)  $Ov\beta\beta$  decay: Can occur if  $m_i^2 \neq 0$  and v=v (Majorana, not Dirac) Sensitive to the "effective Majorana mass" (and phases):

$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

3) Cosmology: m<sup>2</sup><sub>i</sub> ≠ 0 can affect large scale structures in (standard) cosmology constrained by CMB + other data. Sensitive to:

$$\Sigma = m_1 + m_2 + m_3$$

# Beta decay

Classic kinematic search for neutrino mass: look at high-energy endpoint Q of spectrum.

B-decay rate: drac GF x (phase sp.)

 $\begin{array}{c} \text{MALL.} \\ \text{Omigation} \\ 1 \\ \text{TG}_F \\ \text{TG}_F \\ \end{array} \begin{array}{c} \text{TG}_F \\ \text{TG}_F \\ \end{array} \begin{array}{c} \text{C}_F \\ \\ \text{TG}_F \\ \end{array} \end{array}$ 

energy spectrum:  $\frac{d\Gamma}{dE_{e}} \propto G_{F}^{2} p_{e} E_{e} (Q - E_{e})^{2} \qquad (M_{V} \equiv O)$   $G_{F}^{2} p_{e} E_{e} (Q - E_{e}) \sqrt{(Q - E_{e})^{2} + M_{V}^{2}} \qquad (>0)$ 

µ-decay

Ju = 1 ~ G<sub>F</sub><sup>2</sup>M<sub>µ</sub><sup>2</sup> <sup>−</sup>defines" G<sub>F</sub>

#### Tritium: low-Q, fast decays

#### tritium ß-decay and the neutrino rest mass

 $^{3}H \rightarrow ^{3}He + e^{-} + \bar{\nu}_{e}$ 

half life :  $t_{1/2}$  = 12.32 a ß end point energy :  $E_0$  = 18.57 keV



Need good energy resolution

For just one (electron) neutrino family: sensitivity to  $m^2(v_e)$  (obsolete)

For three neutrino families  $v_i$ , and individual masses experimentally <u>unresolved</u> in beta decay: sensitivity to the sum of  $m^2(v_i)$ , weighted by squared mixings  $|U_{ei}|^2$  with the electron neutrino. Observable:

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$$m_{\beta} = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

(so-called "effective electron neutrino mass")

Note: mass state with largest electron flavor component is  $v_1$ :  $|U_{e1}|^2 \approx \cos^2\theta_{12} \approx 0.7$ ... and we can't exclude that  $v_1$  is ~massless in normal hierarchy.

### History plot for tritium

ITEP	$m_{v}$	
T <sub>2</sub> in complex molecule magn. spectrometer (Tret'yakov)	17-40 eV	experimental results
Los Alamos		100
gaseous T <sub>2</sub> - source magn. spectrometer (Tret'yakov)	< 9.3 eV	50 - I I
Tokio		
T - source magn. spectrometer (Tret'yakov)	< 13.1 eV	$\tilde{E}_{-50}$
Livermore		100 L Los Alamos
gaseous T <sub>2</sub> - source magn. spectrometer (Tret'yakov)	< 7.0 eV	-150 Mainz -150 Tokio
Zürich		• Troitsk
T <sub>2</sub> - source impl. on carrier magn. spectrometer (Tret'yakov)	< 11.7 eV	-200 – Troitsk (step) ▲ Zürich
Troitsk (1994-today)		-250 – electrostatic
gaseous T <sub>2</sub> - source electrostat. spectrometer	< 2.2 eV	-300 magnetic spectrometers
Mainz (1994-today)		-350
frozen T <sub>2</sub> - source electrostat. spectrometer	< 2.3 eV	1986 1988 1990 1992 1994 1996 1998 2000 <i>year</i>

Latest bounds at the level of ~2 eV

### In construction: KATRIN experiment



Magnetic Adiabatic Collimation with an Electrostatic Filter



### KATRIN sensitivity



Mainz + Troitsk:  $\mathbf{m}_{\beta} < 2 \text{ eV}$ KATRIN: O(10) improvement

Examples of prospective results at KATRIN (±10, [eV]):

 $\mathbf{m}_{\beta} = 0.35 \pm 0.07$  (5 $\sigma$  discovery)

 $\mathbf{m}_{\beta} = 0.30 \pm 0.10$  (3 $\sigma$  evidence)

 $m_{\beta} = 0 \pm 0.12$  (<0.2 at 90% CL)

[Need new ideas to go below ~0.2 eV]

## Neutrinoless double beta decay

(only for Majorana neutrinos)

### For each mass state $v_i$ , $Ov\beta\beta$ amplitude proportional to:



... mixing of  $v_e$  with  $v_i$ ... mass of  $v_i$  [O(m/E)] ... mixing of  $v_i$  with  $v_e$ (times an unknown  $v_i$  phase)

### Summing up for three massive neutrinos:

Amplitude ~ "effective Majorana mass"

$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

[complex linear combination of masses;  $c_{ij} = \cos \theta_{ij}$  etc.]

#### Warning: previous expression invalid for nonstandard $\text{Ov}\beta\beta$ decays



Experimentally: Look at sum energy of both electrons Need to see the  $Ov\beta\beta$  line emerge above bkgd, at endpoint of spectrum from "conventional"  $2v\beta\beta$  decay.





### What sets the uncertainty of $m_{\beta\beta}$ ?

In case of positive signal, a major concern is the accuracy of the **nuclear matrix element** [M], rather than the expt. uncertainty on the decay half life:





Barea and Iachello 2009

Luckily, independent nuclear physics models converge better than it could be hoped only a few years ago ...



... especially when using the same theo. inputs for comparison (e.g, same description of short range nucleon repulsion) and exploiting additional data BUT: errors remain large for each candidate nucleus.

Simkovic et al 2009

 $0\nu\beta\beta$  search: No signal observed so far, except in the most sensitive experiment to date (Heidelberg-Moscow):  $6\sigma$  signal claimed by (part of) the experimental collaboration. Still hotly debated.



H.V. Klapdor-Kleingrothaus et al. Phys. Lett. B 586 (2004) 198-212 Nucl. Instr. Meth. A 522 (2004) 371 - 406

#### Claim versus current limits (in terms of Majorana mass)



arXiv:0810.5733

#### Claim versus current limits (in terms of half-life)



#### Let me just mention: Experimental techniques



Semiconductors, Cryogenic bolometers, Scintillators Time projection chambers (TPC)

[Geochemical: look for isotopic anomalies]

Important to exploit different techniques and to use different candidate nuclei in order to get "consensus" on possible signals.

### History plot





(a "modern" probe)

Standard big bang cosmology predicts a relic neutrino background with total number density 336/cm<sup>3</sup> and temper. T<sub>v</sub> ~ 2 K ~ 1.7 × 10<sup>-4</sup> eV <<  $\int \delta m^2$ ,  $\int \Delta m^2$ .

 $\rightarrow$  At least two relic neutrino species are nonrelativistic today (we can't exclude the lightest to be ~ massless)

 $\rightarrow$  Their total mass contributes to the normalized energy density as  $\Omega_v \approx \Sigma / 50 \text{ eV}$ , where

$$\Sigma = m_1 + m_2 + m_3$$

⇒So, if we just impose that neutrinos do not saturate the total matter density,  $\Omega_v < \Omega_m \approx 0.25$ , we get  $\mathbf{m}_i < 4 \text{ eV} - \text{not bad!}$  Much better bounds can be derived from neutrino effects on structure formation.

Massive neutrinos are difficult to cluster because of their relatively high velocities: they suppress matter fluctuations on scales smaller than their mass-dependent free-streaming scale.

→ Get mass-dependent suppression of small-scale structures



(E..g., Ma 1996)

### Constraints from CMB also help removing degeneracies.

### Observations:

Spectra:













#### Spectral effect of massive neutrinos (e.g., from Lesgourgues & Pastor)



Fig. 14. CMB temperature anisotropy spectrum  $C_l^T$  and matter power spectrum P(k) for three models: the neutrinoless  $\Lambda$ CDM model of section 4.4.6, a more realistic  $\Lambda$ CDM model with three massless neutrinos ( $f_{\nu} \simeq 0$ ), and finally a  $\Lambda$ MDM model with three massive degenerate neutrinos and a total density fraction  $f_{\nu} = 0.1$ . In all models, the values of ( $\omega_{\rm b}$ ,  $\omega_{\rm m}$ ,  $\Omega_{\Lambda}$ ,  $A_s$ , n,  $\tau$ ) have been kept fixed.

Significant progress after WMAP

Smaller scales probed by Ly-alpha

#### Just an example of recent limits on the sum of v masses from various data sets (assuming the "flat $\Lambda CDM$ model"): [arXiv:0805.2517]

TABLE II: Representative cosmological data sets and corresponding  $2\sigma$  (95% C.L.) constraints on the sum of  $\nu$  masses  $\Sigma$ .

Case	Cosmological data set	$\Sigma ({ m at}  2\sigma)$
1	CMB	$< 1.19 \mathrm{eV}$
2	CMB + LSS	$< 0.71  { m eV}$
3	CMB + HST + SN-Ia	$< 0.75  { m eV}$
4	CMB + HST + SN-Ia + BAO	$< 0.60  {\rm eV}$
5	$CMB + HST + SN-Ia + BAO + Ly\alpha$	$< 0.19 \mathrm{eV}$

#### Case 1: <u>"conservative"</u> (only CMB data, dominated by WMAP 5y) Case 5: <u>"aggressive"</u> (all relevant cosmological data)

Upper limits in the range  $\Sigma < 0.6-1.2$  eV have gained large consensus. More stringent limits require more "faith" in current control of syst.'s.

## The trident... in action

$$m_{\beta} = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$
$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$
$$\Sigma = m_1 + m_2 + m_3$$

Interplay: Oscillations fix the mass<sup>2</sup> splittings, and thus induce positive correlations between any pair of the three observables ( $m_{\beta}$ ,  $m_{\beta\beta}$ ,  $\Sigma$ ), e.g.:



i.e., if one observable increases, the other one (typically) must increase to match mass splitting

The "spear" (oscill. data) sets the "hunting direction" in the ( $m_{\beta}$ ,  $m_{\beta\beta}$ ,  $\Sigma$ ) parameter space:



#### <u>Footnote</u> - Previous plots project away the "unobservable" lightest neutrino mass from graphs like:



Taken from Strumia and Vissani, 2006

#### History plots $\rightarrow$ "Moore's law": factor of ~10 improvement every ~15 years



### Such "logarithmic progress" seems to be:

- maybe slowing for  $\beta$  decay (after KATRIN)
- continuing for  $0v2\beta$  decay
- "accelerating" for cosmology: the only probe where the ultimate goal ( $\Sigma_{min} = \sqrt{\Delta m^2} \approx 0.05 \text{ eV}$ ) is claimed to be reachable

You have good chances to see first successful results within your career!

Generic expectations: In the absence of new physics (beyond 3v masses and mixing), any two data among ( $m_{\beta}$ ,  $m_{\beta\beta}$ ,  $\Sigma$ ) are expected to cross the oscillation band



This requirement provides either an important consistency check or, if not realized, an indication for new physics (barring expt mistakes) ⇒ Data accuracy/reliability/redundance are crucial

#### With "dreamlike" data one could, e.g.



#### We are still far from this situation (an example with ~2006 data):



Different choices  $\Rightarrow$  Different possible combinations (and implications)

Also the most recent data do not yet lead to definite conclusions. Beta decay: no yet very constraining. Double beta vs cosmology: different possibilities. E.g.,



The tighest cosmo bounds are not compatible with Klapdor's claim. Then, either one of the two is wrong, or there is new physics beyond the standard model (of particle physics and/or of cosmology) One example [astro-ph/0608351]: "non-standard" equation of state for dark energy, ruling out a cosmological constant ...



#### Cosmo-"conservative"



The safest cosmo bounds can be made compatible with Klapdor's claim, with no new physics required. Then, the combination of data (black wedge) would prefer degenerate neutrino masses, ~few x 10<sup>-1</sup> eV Let's entertain the possibility that the "true" answer is just around the corner... For instance, that neutrinos are Majorana, with nearly degenerate and relatively large masses:

 $m_1 \sim m_2 \sim m_3 \sim 0.2 \text{ eV}$ .

Then we might reasonably hope to observe soon all three nonoscillation signals in next-generation experiments, e.g.,

$$egin{array}{rcl} m_{etaeta} &\simeq& 0.2(1\pm0.3)~{
m eV}\ \Sigma &\simeq& 0.6(1\pm0.3)~{
m eV}\ m_eta &\simeq& 0.2(1\pm0.5)~{
m eV} \end{array}$$

in which case...

...The absolute neutrino mass would be established within ~25% uncertainty, and one Majorana phase ( $\phi_2$ ) would be constrained...



Absolute masses and mixings crucial for model building

Mixing angles seem to have some "special" values:

 $sin^2\theta_{23} \approx 1/2$   $sin^2\theta_{12} \approx 1/3$  "tri-bimaximal mixing"  $sin^2\theta_{13} \approx 0$ <u>A signal of discrete symmetries in the neutrino sector?</u>

 $\theta_{12}+\theta_c \approx \pi/4$  "quark-lepton complementarity"  $[\theta_{23}+\theta_{23,q} \approx \pi/4]$ <u>A possible link between neutrino and quark mixing?</u>

Model diagnostic: also dependent on the above "≈"

### RECAP

### In the (long) process of cornering the neutrino mass ...



... neutrino oscillations currently provide very stable and reliable constraints, which will be followed by progress on non-oscillation searches in the next years. We hope in overall convergence! Future nightmares, which can't be excluded, might include situations like this (partly realized now?)...



... but we should never forget that such situations might still "converge" if something more exciting happens:

