Concluding Remarks

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INFN, Sezione di Torino

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2015 Physics Nobel Prize

FOR THE DISCOVERY OF NEUTRINO OSCILLATIONS,
WHICH SHOWS THAT NEUTRINOS HAVE MASS

1998: Oscillations of atmospheric neutrinos observed by the Super-Kamiokande experiment

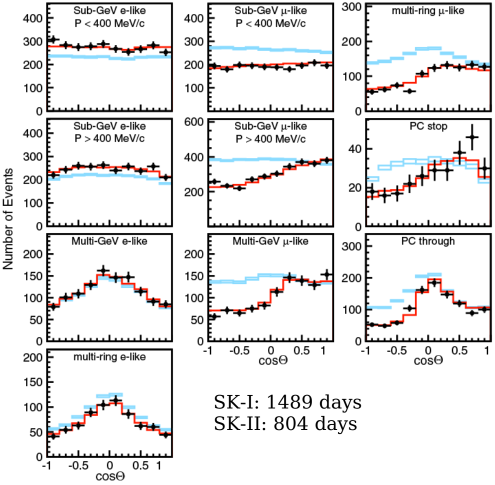
Takaaki Kajita

2002: Oscillations of solar neutrinos observed by the SNO experiment

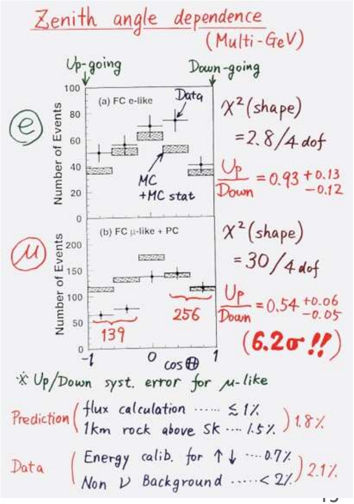
Arthur B. McDonald

i-3 sector: θ_{i3} and Δm^2_{3i} *(i=1,2)*

atmospheric neutrinos:



SK-I: 1489 days
SK-II: 804 days



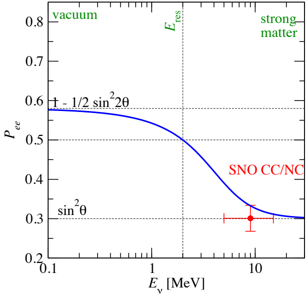
1-2 sector: θ_{12} and Δm^2_{21}

MSW conversion in the Sun

2002: SNO: CC to NC ratio of solar neutrino flux

CC: $\nu_e + d \to p + p + e^-$
NC: $\nu_x + d \to p + n + \nu_x$

- evidence for $\nu_e \to \nu_\mu, \nu_\tau$ conversion
- MSW effect inside the sun adiabatic conversion through resonance
- fixes ordering of the 1-2 mass states



$$P_{ee} = \frac{\phi_e}{\phi_e + \phi_\mu + \phi_\tau} = \frac{\phi_{CC}}{\phi_{NC}}$$

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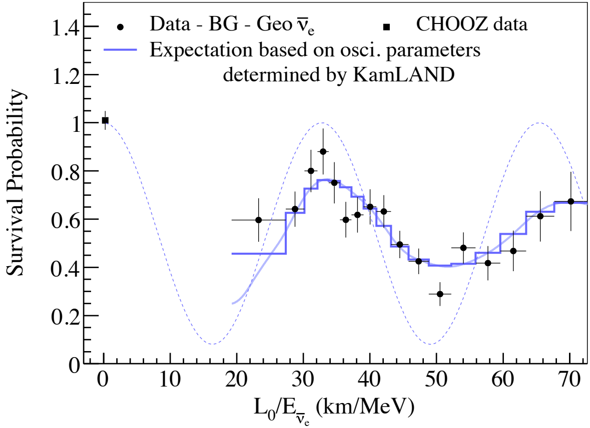
1-2 sector: θ_{12} and Δm^2_{21}

Evidence for spectral distortion: KamLAND 2004



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see also Marco Drewes talk

Textboox Example: type I seesaw

introduce $N_R \sim (1,0)$, automatically has two possible couplings:

- couples to $g_\nu \overline{L}\,\tilde{\Phi} \sim (1,0)$, becomes $g_\nu v\,\overline{\nu_L}\,N_R \equiv m_D\,\overline{\nu_L}\,N_R$
- in addition: Majorana mass term for N_R: $\frac{1}{2} M_R \overline{N_R^c} N_R$

$$\mathcal{L} = \frac{1}{2}\,(\overline{\nu_L}, \overline{N_R^c}) \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix} + h.c.$$
$$\equiv \frac{1}{2}\,\overline{\Psi}\,\mathcal{M}_\nu\,\Psi^c + h.c.$$

diagonalization gives $\mathrm{diag}(m_\nu, M)$ with (in limit $M_R \gg m_D$)

$m_\nu = m_D^2/M_R$ and $M = M_R$

MASSIVE MAJORANA NEUTRINOS!

Paths to Neutrino Mass

approach	ingredient	quantum number of messenger	$\mathcal{L}$	m_ν	scale
"SM" (Dirac mass)	RH ν	$N_R \sim (1,0)$	$h\overline{N_R}\Phi L$	hv	$h = \mathcal{O}(10^{-12})$
"effective" (dim 5 operator)	new scale + LNV	–	$h\,\overline{L^c}\,\Phi\,\Phi\,L$	$\frac{h\,v^2}{\Lambda}$	$\Lambda = 10^{14}$ GeV
"direct" (type II seesaw)	Higgs triplet + LNV	$\Delta \sim (3,-2)$	$h\overline{L^c}\Delta L + \mu\Phi\Phi\Delta$	hv_T	$\Lambda = \frac{1}{h\mu}M_\Delta^2$
"indirect 1" (type I seesaw)	RH ν + LNV	$N_R \sim (1,0)$	$h\overline{N_R}\Phi L + \overline{N_R}M_R N_R^c$	$\frac{(hv)^2}{M_R}$	$\Lambda = \frac{1}{h}M_R$
"indirect 2" (type III seesaw)	fermion triplets + LNV	$\Sigma \sim (3,0)$	$h\overline{\Sigma}\,L\Phi + \mathrm{Tr}\overline{\Sigma}M_\Sigma\Sigma$	$\frac{(hv)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h}M_\Sigma$

plus seesaw variants (linear, double, inverse,...)

plus radiative mechanisms

plus extra dimensions

plusplusplus

Common to essentially all mechanisms

"3 Majorana neutrino paradigm"

at low energies:

$$\mathcal{L} = \frac{1}{2}\,\nu^T\,m_\nu\,\nu \quad \text{with} \quad m_\nu = U\,\mathrm{diag}(m_1, m_2, m_3)\,U^T$$

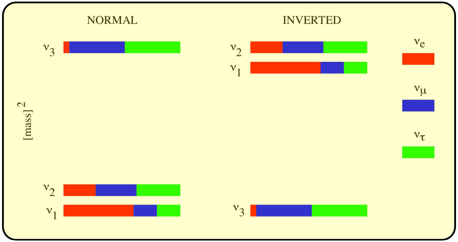
with PMNS matrix

$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta} & c_{23}\,c_{13} \end{pmatrix} P$$

with $P = \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$ ($\leftrightarrow$ Majorana, lepton number violation)

$\Rightarrow$ 3 angles, 3 phases, 3 masses

3-flavour oscillations



6 oscillation parameters:
3 mixing angles,
1 complex phase,
2 mass-squared differences

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21}, θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12}, θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}	$\lvert\Delta m^2_{3\ell}\rvert$
Atmospheric Experiments	θ_{23}	$\lvert\Delta m^2_{3\ell}\rvert$, θ_{13},δ
Accelerator LBL ν_μ Disapp (Minos, T2K)	$\lvert\Delta m^2_{3\ell}\rvert$, θ_{23}	
Accelerator LBL ν_e App (Minos, T2K)	δ	θ_{13}, θ_{23}, sign($\Delta m^2_{3\ell}$)

global analysis

Table 1. Experiments contributing to the present determination of the oscillation parameters.

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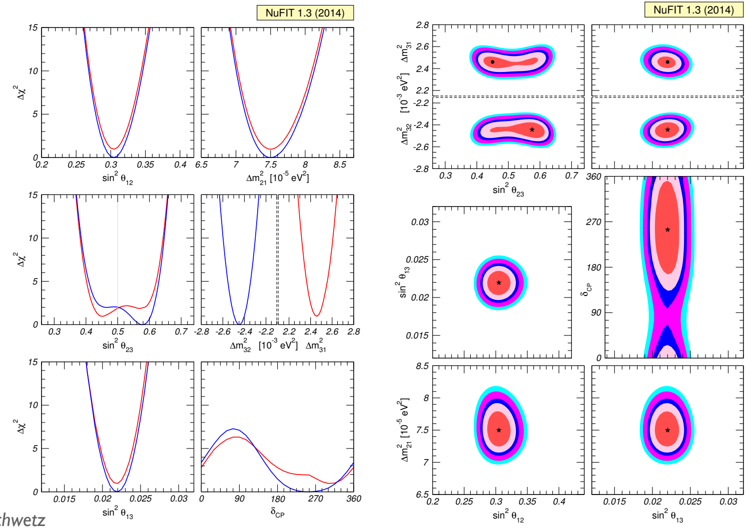
3-flavour global fit to oscillation data



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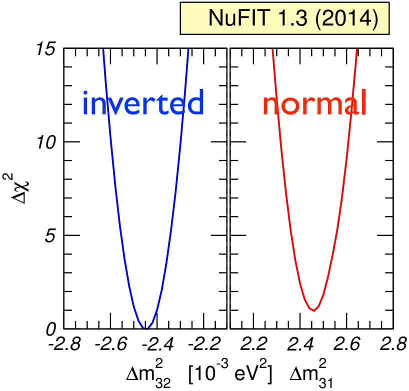
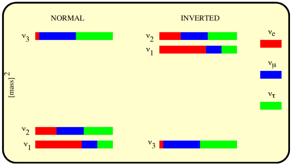
see also: Capozzi, Lisi, Marrone, Montanino, Palazzo, arXiv:1601.07777
Forero, Tortola, Valle, PRD 90 (2014) 093006, arXiv:1405.7540

Neutrino mass ordering





almost complete degeneracy in present data

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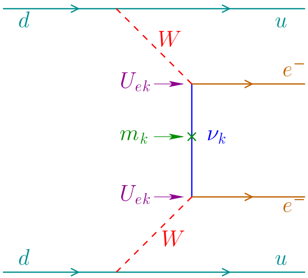
Neutrinoless Double-Beta Decay

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu} \, |\mathcal{M}_{0\nu}|^2 \, |m_{\beta\beta}|^2$$

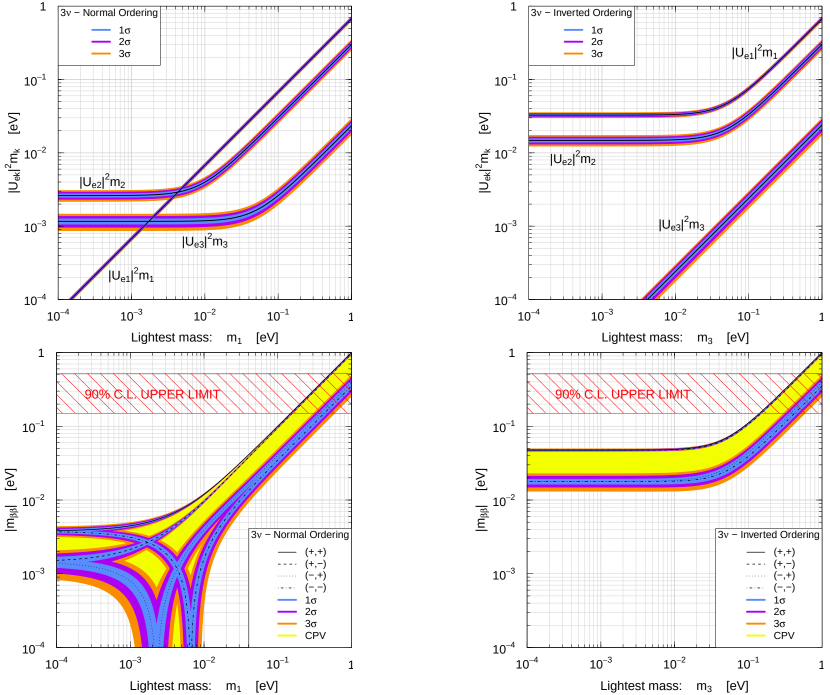
$$|m_{\beta\beta}| = \left| \sum_k U_{ek}^2 \, m_k \right|$$



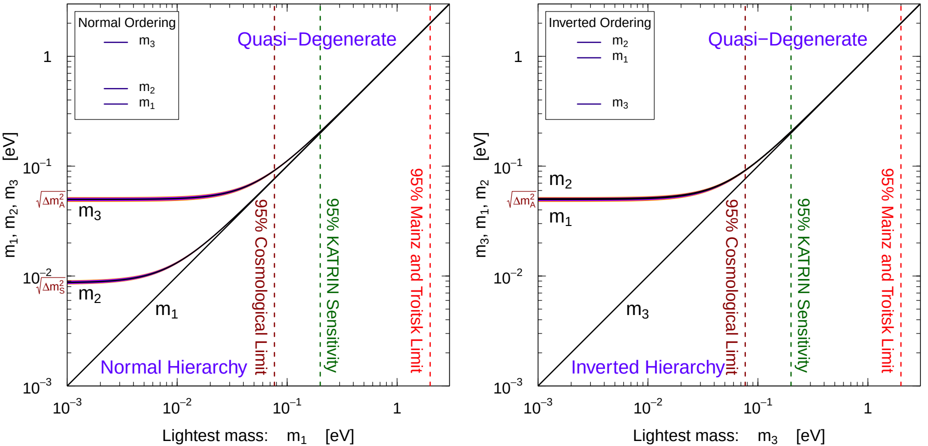
$$\Delta L = 2$$

Effective Majorana Neutrino Mass

$$m_{\beta\beta} = |U_{e1}|^2 \, m_1 + |U_{e2}|^2 \, e^{i\alpha_2} \, m_2 + |U_{e3}|^2 \, e^{i\alpha_3} \, m_3$$


3ν − Normal Ordering
1σ
2σ
3σ
$|U_{e2}|^2 m_2$
$|U_{e3}|^2 m_3$
$|U_{e1}|^2 m_1$
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: m_1 [eV]
3ν − Inverted Ordering
1σ
2σ
3σ
$|U_{e1}|^2 m_1$
$|U_{e2}|^2 m_2$
$|U_{e3}|^2 m_3$
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: m_3 [eV]
90% C.L. UPPER LIMIT
$|m_{\beta\beta}|$ [eV]
3ν − Normal Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
Lightest mass: m_1 [eV]
90% C.L. UPPER LIMIT
$|m_{\beta\beta}|$ [eV]
3ν − Inverted Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
Lightest mass: m_3 [eV]

Neutrino Masses

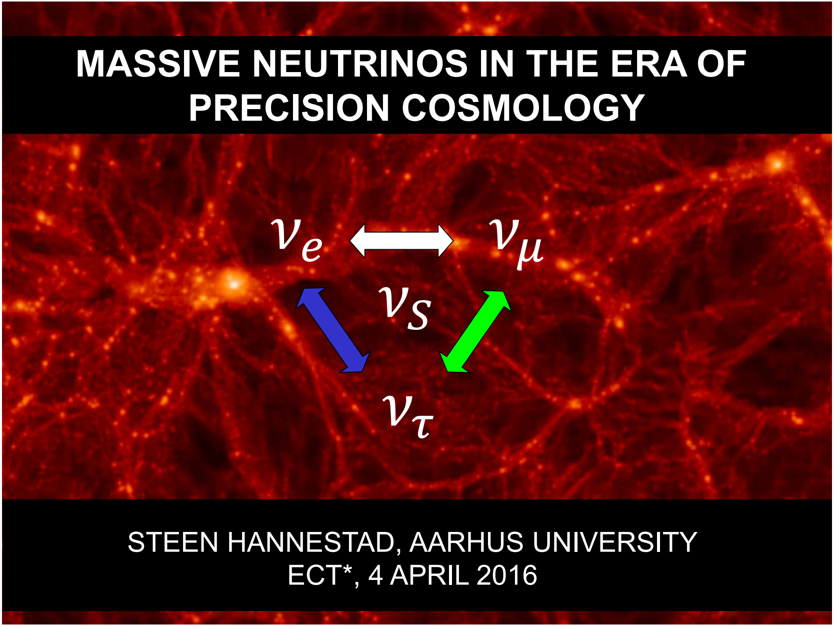


$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\,\text{eV}$

95% Cosmological Limit: Planck TT + lowP + BAO [arXiv:1502.01589]


MASSIVE NEUTRINOS IN THE ERA OF PRECISION COSMOLOGY
ν_e
ν_μ
ν_S
ν_τ
STEEN HANNESTAD, AARHUS UNIVERSITY
ECT*, 4 APRIL 2016

- neutrinos in equilibrium in early Universe through weak interactions:

$$\nu\bar{\nu} \leftrightarrows e^+e^- \qquad \overset{(-)}{\nu} e \leftrightarrows \overset{(-)}{\nu} e \qquad \overset{(-)}{\nu} N \leftrightarrows \overset{(-)}{\nu} N$$

$$\nu_e n \leftrightarrows p e^- \qquad \bar{\nu}_e p \leftrightarrows n e^+ \qquad n \leftrightarrows p e^- \bar{\nu}_e$$

- weak interactions freeze out $\Longrightarrow$ active $(\nu_e, \nu_\mu, \nu_\tau)$ neutrino decoupling

$$\Gamma_{\text{weak}} = N\sigma v \sim G_F^2 T^5 \sim T^2/M_P \sim \sqrt{G_N T^4} \sim \sqrt{G_N \rho} \sim H$$

$$T_{\nu\text{-dec}} \sim 1\,\text{MeV} \qquad t_{\nu\text{-dec}} \sim 1\,\text{s}$$

- relic neutrinos: $T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma \simeq 1.945\,\text{K} \Longrightarrow k\,T_\nu \underset{(T_\gamma = 2.725 \pm 0.001\,\text{K})}{\simeq} 1.676 \times 10^{-4}\,\text{eV}$

- number density: $n_f = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_f T_f^3 \Longrightarrow n_{\nu_k,\bar{\nu}_k} \simeq 0.1827\,T_\nu^3 \simeq 112\,\text{cm}^{-3}$

- density contribution: $\Omega_k = \frac{n_{\nu_k,\bar{\nu}_k} m_k}{\rho_c} \simeq \frac{1}{h^2}\frac{m_k}{94.1\,\text{eV}} \Rightarrow \boxed{\Omega_\nu h^2 = \frac{\sum_k m_k}{94.1\,\text{eV}}}$

$\left(\rho_c = \frac{3H^2}{8\pi G_N}\right)$

[Gershtein, Zeldovich, JETP Lett. 4 (1966) 120; Cowsik, McClelland, PRL 29 (1972) 669]

NEUTRINO MASS AND ENERGY DENSITY FROM COSMOLOGY

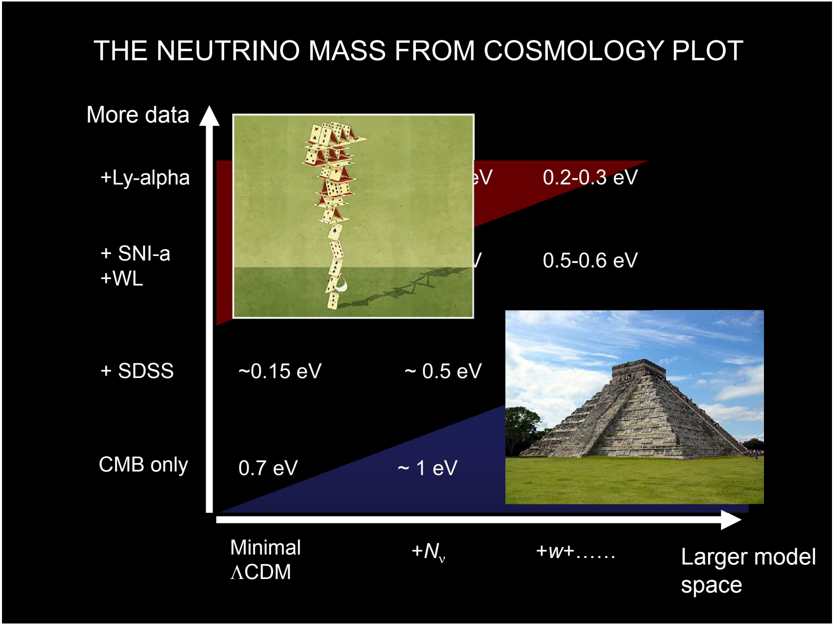
NEUTRINOS AFFECT STRUCTURE FORMATION BECAUSE THEY ARE A SOURCE OF DARK MATTER ($n \sim 100\ \mathrm{cm}^{-3}$)

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

HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

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

SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO SUPPRESSION OF POWER ON SMALL SCALES


THE NEUTRINO MASS FROM COSMOLOGY PLOT
More data
+Ly-alpha
0.2-0.3 eV
+ SNI-a
+WL
0.5-0.6 eV
+ SDSS
~0.15 eV
~ 0.5 eV
CMB only
0.7 eV
~ 1 eV
Minimal
ΛCDM
+N_ν
+w+……
Larger model
space

MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS

Determination of neutrino mass with a sub-eV uncertainty

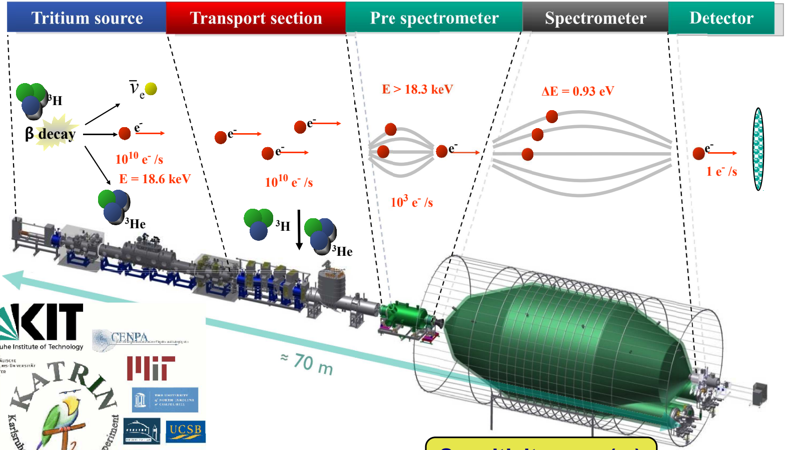
KATRIN - Project Project 8	β^--decay of Tritium
ECHo - Project HOLMES - Project NuMECS - Project	EC in ^{163}Ho
MARE- Project ☹	β^--decay of ^{187}Re

Q_{Re}= 2466.7(1.5) eV ☺

Measurements of Q-Values are required with a relative uncertainty ($\delta Q/m$) < 10^{-11}

Westfälische Wilhelms-Universität Münster

The Karlsruhe Tritium Neutrino Experiment
KATRIN - overview



KIT Karlsruhe Institute of Technology · CENPA · Westfälische Wilhelms-Universität Münster · MIT · Universität Mainz · The University of North Carolina at Chapel Hill · UCSB · universität bonn · Bergische Universität Wuppertal · Max-Planck-Institut für Kernphysik · KATRIN Karlsruhe Tritium Neutrino Experiment

new: cea Saclay · TUM Technische Universität München

Sensitivity on m(ν_e):

2 eV → 200 meV

Westfälische Wilhelms-Universität Münster

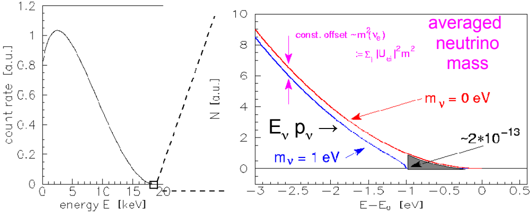
Direct determination of $m(\nu_e)$ from β decay

β: $dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$

phase space: p_e E_e E_ν p_ν

with "electron neutrino mass": $m(\nu_e)^2 := \Sigma |U_{ei}|^2\ m(\nu_i)^2$

(modified by electronic final states, recoil corrections, radiative corrections)



$m(\nu) < 2$ eV (Mainz, Troitsk)

Recent review:
G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, Adv. High Energy Phys., 2013 (2013) 293986

Need: low endpoint energy $\Rightarrow$ **Tritium ^3H (^{187}Re, ^{163}Ho)**

very high energy resolution &
very high luminosity &
very low background $\Rightarrow$ **MAC-E-Filter**
(or bolometer for ^{187}Re, ^{163}Ho)

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

Summary: β-spectrum incl. electronic final states + ν mixing

Including electronic excited final states of excitation energy V_j with probability W_j

$$W_j = |\langle \Psi_0 | \Psi_{f,j} \rangle|^2$$

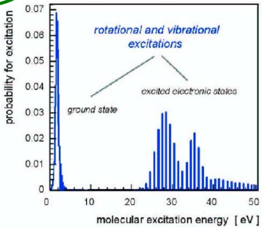
⇒ look at endpoint region

Using $\varepsilon_j = E_0 - V_j - E$

$$\frac{d^2N}{dt\,dE} = A \cdot F(E, Z+1) \cdot p \cdot (E+m) \cdot \sum_j W_j \cdot \varepsilon_j \sqrt{\varepsilon_j^2 - m^2(\nu_c)} \cdot \Theta(\varepsilon_j - m(\nu_c))$$

Final states of T_2 β-decay:

(A. Saenz et al. Phys. Rev. Lett. 84 (2000) 242, N. Doss et al., Phys. Rev. C73 (2006) 025502)



⇒ electronic final states are very important

Including neutrino mixing

$$\frac{d^2N}{dt\,dE} = A \cdot F(E, Z+1) \cdot p \cdot (E+m) \cdot \sum_j W_j \cdot \varepsilon_j \cdot \left(\sum_i |U_{ci}|^2 \sqrt{\varepsilon_j^2 - m^2(\nu_i)} \cdot \Theta(\varepsilon_j - m(\nu_i)) \right)$$

⇒ "Electron neutrino mass"

$$m^2(\nu_c) := \sum_i |U_{ci}|^2 \cdot m^2(\nu_i)$$

⇒ the different $m(\nu_i)$ are not important at present precision

NEW TESTS FOR AND BOUNDS ON NEUTRINO MASSES AND LEPTON MIXING

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Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, NY 11794, USA

Received 5 May 1980

We propose a new class of correlated tests for neutrino masses and lepton mixing. Two particular tests based on $(\pi, K)_{\ell 2}$ decay and nuclear β decay are discussed and applied to present data to derive bounds on these quantities.

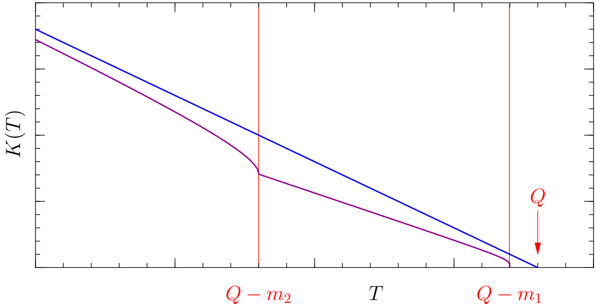
$\to (E_e)_{max}$. An analysis of the decay $^3H \to {}^3He + e^- + \bar{\nu}_e$ yielded the best upper limit quoted as "$m(\nu_e)$" < 35 eV (90% CL) [10]. The precise meaning is that $m(\nu_i) < 35$ eV for all LDC modes i occurring in this β decay. In fact, however, previous discussions do not seem to have recognized that, as a corollary of our beginning observation, the early falloff near $(E_e)_{max}$ in a Kurie plot is not the only signature of massive neutrinos. Rather, a Kurie plot would in general consist of k' components due to the separate decays $(Z_1, A_1) \to (Z_1 \pm 1, A_1) + e^\pm + {}^{(}\bar{\nu}^{)}_e$. Of these, a subset $i \in \{i_L\}$

every β decay can be used. The characteristic signature of the ith HSC mode is a kink in the Kurie plot at its endpoint energy

$$(E_e^{(i)})_{max} = \{M_1^2 + m_e^2 - [M_2 + m(\nu_i)]^2\}/(2M_1) ,$$

where $M_{1,2}$ are the initial and final nuclear masses, together with the small incremental addition which it contributes for $E_e < (E_e^{(i)})_{max}$. From the position of the ith kink one can determine $m(\nu_i)$. Next, one can deter-

Neutrino Mixing $\Longrightarrow K(T) = \left[(Q-T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$



Eventually it may be possible to

- determine the individual masses m_1, m_2, m_3;
- determine the mixings $|U_{e1}|^2$, $|U_{e2}|^2$, $|U_{e3}|^2$;
- check the unitarity relation $\sum_{k=1}^{3} |U_{ek}|^2 = 1$.

Energy resolution $\Delta E \gtrsim 1\,\text{eV} \gg m_1, m_2, m_3 \Longrightarrow Q - T \gg m_1, m_2, m_3$

$$
\begin{aligned}
K^2 &= (Q-T) \sum_{k=1}^{3} |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \\
&= (Q-T)^2 \sum_{k=1}^{3} |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q-T)^2}} \\
&\simeq (Q-T)^2 \sum_{k=1}^{3} |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q-T)^2}\right] \\
&= (Q-T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q-T)^2}\right] \\
&\simeq (Q-T) \sqrt{(Q-T)^2 - m_\beta^2}
\end{aligned}
$$

EFFECTIVE MASS: $m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2$

What happens if $\Delta E \approx m_1 \simeq m_2 \simeq m_3$ (quasi-degenerate)?

$$m_k^2 = m_1^2 + m_k^2 - m_1^2 = m_1^2 + \Delta m_{k1}^2$$

$$K^2 = (Q-T) \sum_{k=1}^{3} |U_{ek}|^2 \sqrt{(Q-T)^2 - m_1^2 + \Delta m_{k1}^2}$$

$(Q-T)^2 - m_1^2 \gg \Delta m_{k1}^2 \quad \Longrightarrow \quad$ first order mass effect:

$$K^2 \simeq (Q-T) \underbrace{\sum_{k=1}^{3} |U_{ek}|^2}_{1} \sqrt{(Q-T)^2 - m_1^2}$$

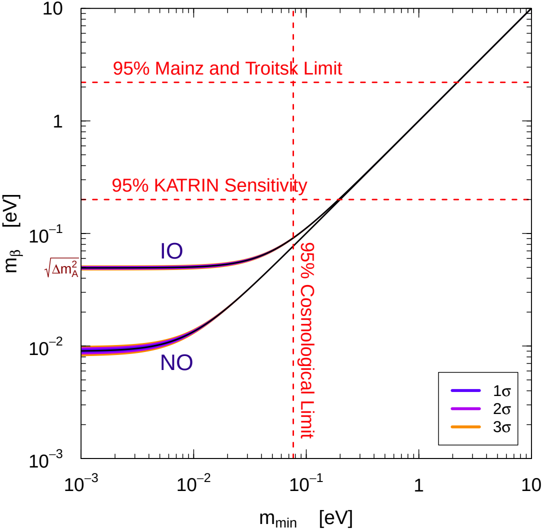
$$\simeq (Q-T) \sqrt{(Q-T)^2 - m_\beta^2}$$

$$m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2 \simeq \underbrace{\sum_{k=1}^{3} |U_{ek}|^2}_{1} m_1^2 = m_1^2$$

the effective mass is valid down to an energy resolution $\Delta E \approx 0.1\,\text{eV}$ where the masses are quasi-degenerate

Effective Neutrino Mass

$$m_\beta^2 = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2$$



- Quasi-Degenerate:

  $m_\beta^2 \simeq m_\nu^2 \sum_{k=1}^3 |U_{ek}|^2 = m_\nu^2$

- Inverted Hierarchy:

  $m_\beta^2 \simeq (1 - s_{13}^2)\Delta m_A^2 \simeq \Delta m_A^2$

- Normal Hierarchy:

  $m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2$

  $\simeq 2 \times 10^{-5} + 6 \times 10^{-5}\,\text{eV}^2$

- $m_\beta \lesssim 4 \times 10^{-2}\,\text{eV}$

  $\Downarrow$

  Normal Spectrum

Project 8

Coherent radiation emitted can be collected and used to measure the energy of the electron in non-destructively.

PROJECT 8

Frequency Approach

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

I. I. Rabi

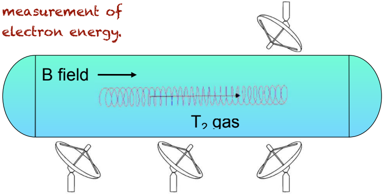
"Never measure anything but frequency."

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

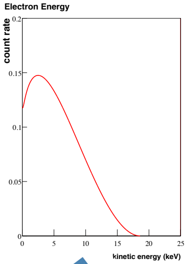
- Non-destructive measurement of electron energy.



B. Monreal and JAF, Phys. Rev D80:051301

Unique Advantages

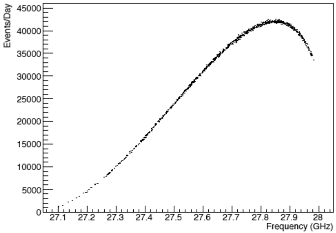
- **Source = Detector** (no need to separate the electrons from the tritium)
- **Frequency Measurement** (can pin electron energies to well-known frequency standards)
- **Full Spectrum Sampling** (full differential spectrum measured at once, large leverage for stability and statistics)



Beta spectrum

Cyclotron Frequency

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



Beta (frequency) spectrum

Joseph Formaggio

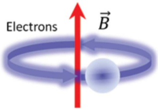
Project 8

...and Challenges

- **Power Emitted**
  Less than 1 fW of power radiated (depends on antenna geometry) is challenging.

- **Confinement Period**
  One needs time to make sufficiently accurate measurement (> 10 μs). Employ magnetic bottle for trapping.

- **Full Spectrum**
  The full spectrum is available. Fortunately, linearity of frequency space helps separate regions of interest.



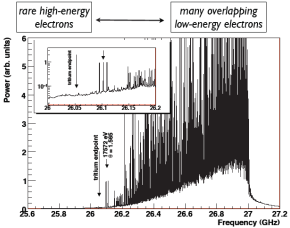
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

Relativistic cyclotron frequency

$$P_{\rm tot}(\beta_\parallel, \beta) = \frac{1}{4\pi\epsilon_0}\frac{2e^2\omega_0^2}{3c}\frac{\beta_\parallel^2}{1-\beta^2}$$

(Free) Radiative Power Emitted

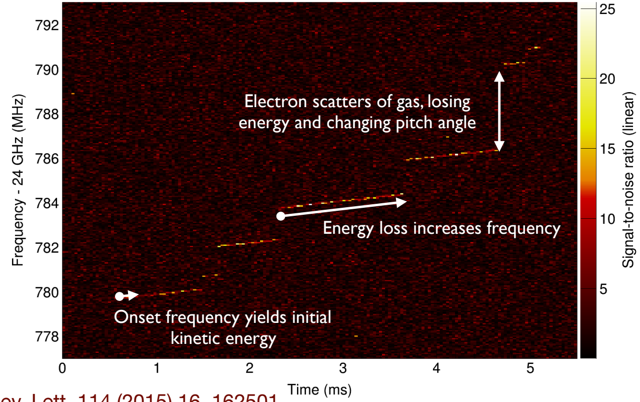
Simulation of electron motion in magnetic bottle



100,000 tritium decays in 30μs

Simulation of beta (frequency) spectrum

Project 8's "Event Zero"



Phys. Rev. Lett. 114 (2015) 16, 162501

Exhibits all predicted characteristics:

- Onset frequency
- Energy loss due to cyclotron radiation
- Quantum jumps due to inelastic scattering

A Phased Approach

Given the novelty of the project, we are pursuing a phased approach toward neutrino mass measurements:

	Timeline	Scientific Goal	Source	R&D Milestone
Phase I	2010-2014	Proof of principle; Kr spectrum	^{83m}Kr	COMPLETED! Single electron detection
Phase II	2015-2017	T-He mass difference	T_2	Tritium spectrum; calibration and error studies
Phase III	2016-2020	2 eV scale	T_2	
Phase IV	2018+	0.04 eV scale	T	High rate sensitivity

We have completed Phase I, we are preparing for Phase II

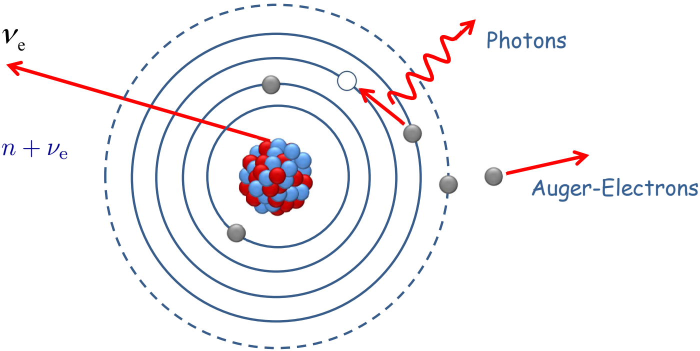
Electron Capture: ^{163}Ho

A. De Rujula, M. Lusignoli, Phys. Lett. B **118** (1982) 429

$$^{163}_{67}\mathrm{Ho} \rightarrow\ ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

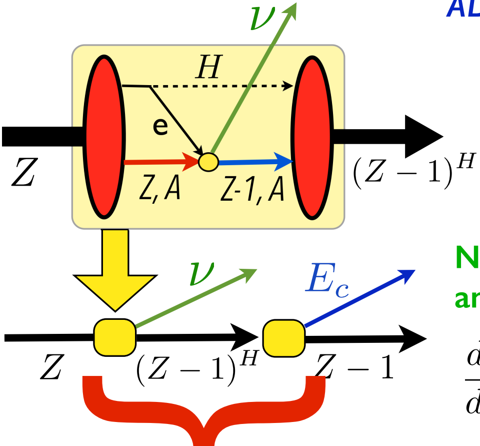
$$\hookrightarrow\ ^{163}_{66}\mathrm{Dy} + E_C$$

$$p + e^- \rightarrow n + \nu_e$$



“Effective” calorimetric theory,

ADR & Lusignoli (1982)



Q = M[det.,before]
- M[det.,after]
(Chem. pure detector)

$$Q = E_\nu + E_c$$

No matter what H was and how it de-excited !

$$\frac{dW}{dE_c} = -\frac{dW}{dE_\nu}\Big|_{E_\nu = Q - E_c}$$

$$\frac{dW}{dE_c} \propto \underbrace{(Q - E_c)}_{E_\nu}\underbrace{\sqrt{(Q - E_c)^2 - m_\nu^2}}_{p_\nu}\sum_H \frac{\varphi_H^2(0)\ \Gamma_H}{(E_c - E_H)^2 + \Gamma_H^2/4}$$

For Electron Capture (in Holmium 163):

1) Electron at nucleus → s1/2 and p1/2

2) Electron binding energy < Q-value ≈ 2.8 [keV]

$E(1s_{1/2}, K, Ho) = 55.6$ keV
$E(2s_{1/2}, L1, Ho) = 9.4$ keV
$E(2p_{1/2}, L2, Ho) = 8.9$ keV
$E(2p_{3/2}, L3, Ho) = 8.1$ keV

$E(3s_{1/2}, M1, Ho) = 2.0$ keV
$E(3p_{1/2}, M2, Ho) = 1.8$ keV
$E(4s_{1/2}, N1, Ho) = 0.4$ keV
$E(4p_{1/2}, N2, Ho) = 0.3$ keV
$E(5s_{1/2}, O1, Ho) = 0.05$ keV

Deexcitation Spectrum (X-rays, Auger- electrons by a Calorimeter) of excited Dy* (Atom)

$$\frac{d\Gamma}{dE_c} \propto (Q-E_c)\sqrt{(Q-Ec)^2 - m_\nu{}^2}\ \sum_{ff'} \lambda_0\, B_{ff'}\, \frac{\Gamma_{f'}}{2\pi}\, \frac{1}{(E_c - E_{f'})^2 + \Gamma_{f'}/4}$$

$$B_{f,f'} \approx \left|\langle Dy^*{}_{f'} | a_f | G \rangle\right|^2 |\psi_f(R)|^2 / |\psi_{3s1/2}(R)|^2$$

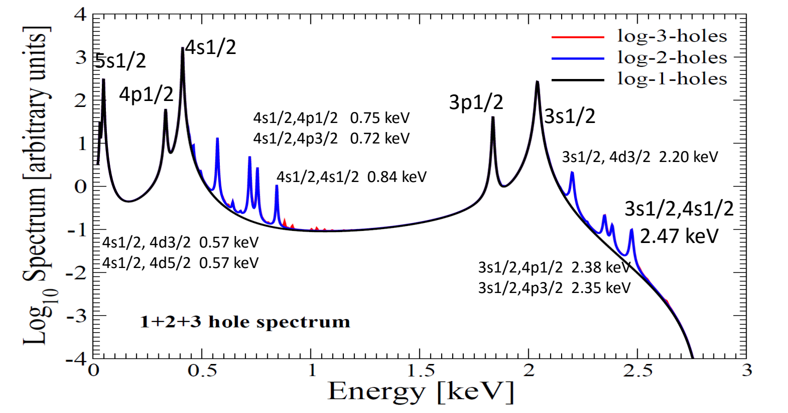
$$\lambda_0 \propto G^2_{weak}\, \xi$$

$$\psi_A(r) = \frac{1}{r}\begin{pmatrix} P_A \\ Q_A \end{pmatrix}$$

$$\langle A|B'\rangle = \int_{0,\infty} \left(P_A(r)\cdot P_{B'}(r) + Q_A(r)\cdot Q_{B'}(r)\right)\cdot dr = overlap(A, B')$$

Amand Faessler, University of Tuebingen

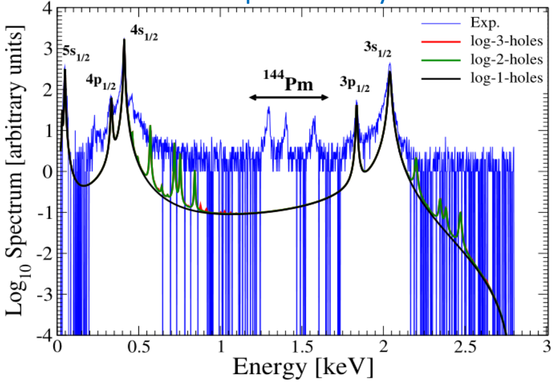
One-, two- and three-hole state deexcitation in Dy*



Comparison with the ECHo data.

Background must be included into theoretical treatment.

ECHo Exp binned by 2 eV

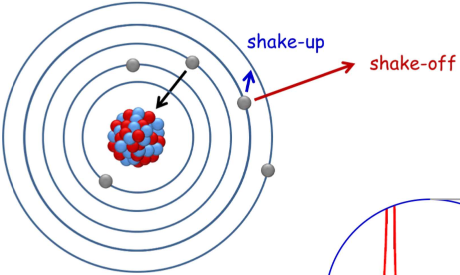


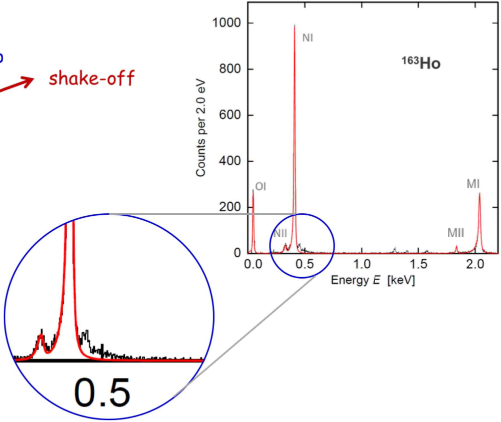
Amand Faessler, University of Tuebingen

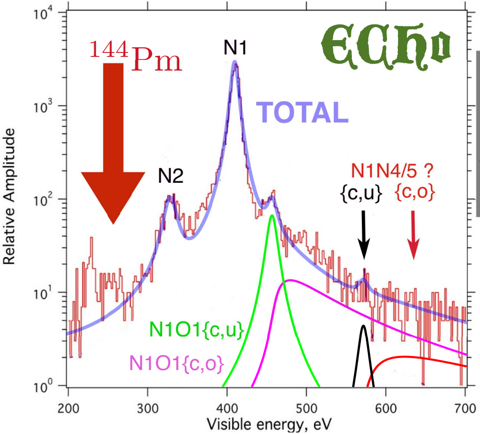
Spectral Shape: Higher Order Processes

R.G.H. Robertson, Phys. Rev. C **91**, 035504 (2015)
A. Faessler, *et al.*, *J. Phys. G* **42**, 015108 (2015)
A. Faessler, *et al.*, Phys. Rev. C **91**, 045505 (2015)
A. Faessler, *et al.*, Phys. Rev. C **91**, 064302 (2015)
A. De Rujula, *et al.*, arXiv:1601.04990v1 [hep-ph]

two-hole processes







$\sim$ %

Maurizio Lusignoli + ADR

(à la 1967 Intemann & Pollock)

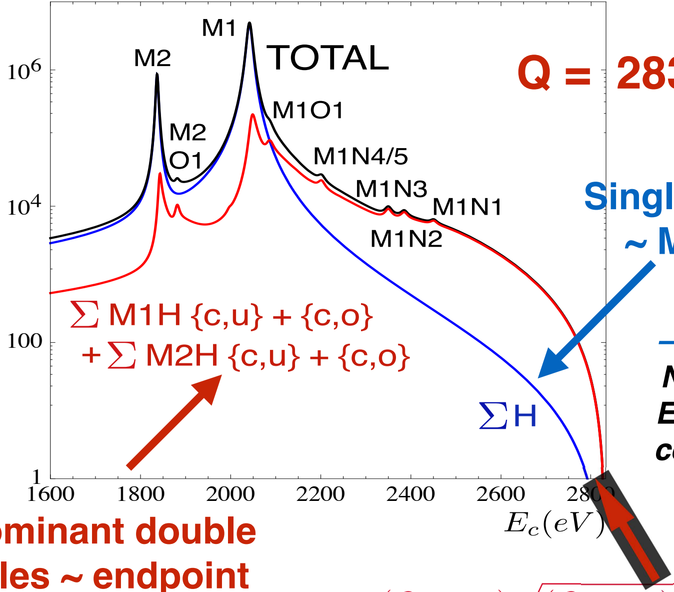
{ , }

$\mathcal{O}(2)$ Massage

{c,u} 1 e captured; 1 e up to unoccupied level

{c,o} 1 e captured; 1 e off to the continuum

Electron ShakeOff previously FORGOTTEN!!



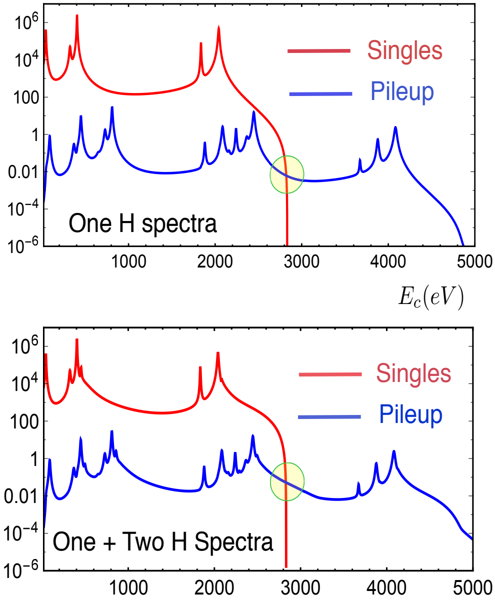
Q = 2833 eV

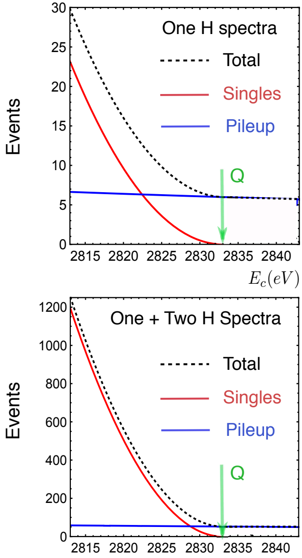
Single hole ~ M1

— to —
Notice Enhancement

Dominant double holes ~ endpoint

$$E_\nu \, p_\nu = (Q - E_c)\sqrt{(Q - E_c)^2 - m_\nu^2}$$





x ~ 6 IMPROVEMENT

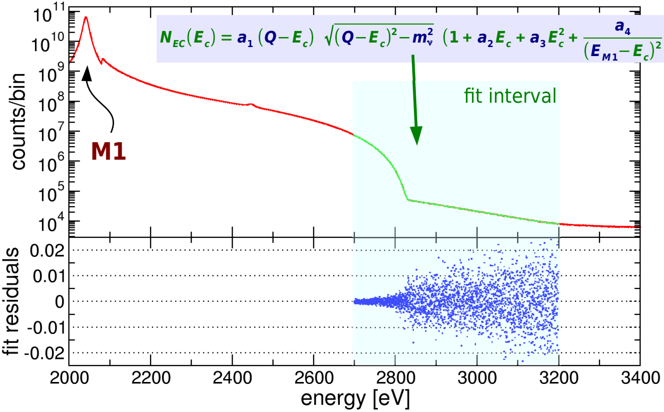
- Different theoretical opinions about the size of the shake-off effect.
- We all hope that it is as large as calculated by Alvaro and Maurizio.
- Plausible statement by Alvaro (as I remember): theoretical calculations are important for the development of the experiments, but will not be crucial for the mass measurements.
- This is because the spectrum near the end point can be fitted by the sum of a smooth function and a Breit-Wigner tail.

Statistical sensitivity: shake-off processes

MC simulation with the *optimistic* spectrum in arXiv:1601.04990

Q = 2833 eV, N_{ev} = 3x10^{13}, f_{pp} = 3.0×10^{-4}, ΔE = 1.0 eV

$$N_{EC}(E_c) = a_1\,(Q-E_c)\,\sqrt{(Q-E_c)^2 - m_\nu^2}\,\left(1 + a_2 E_c + a_3 E_c^2 + \frac{a_4}{(E_{M1}-E_c)^2}\right) + f_{pp} N_{pp}(E_c)$$

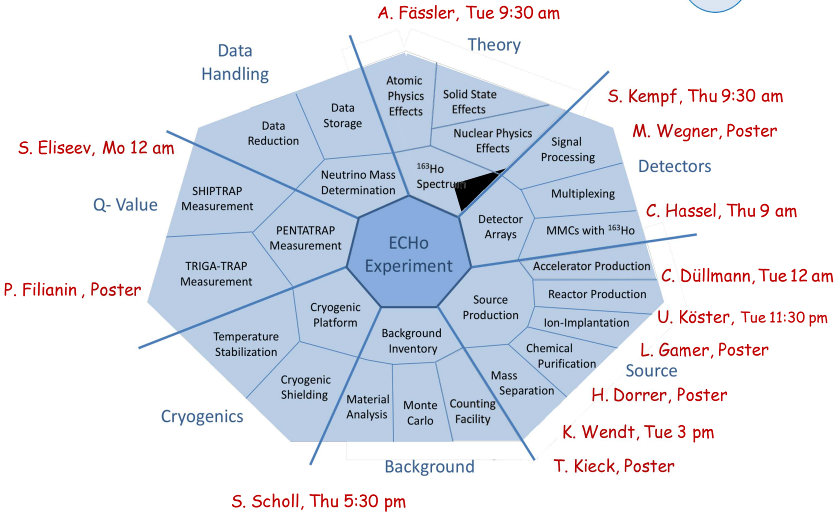


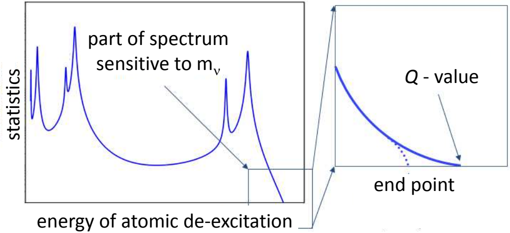
statistical sensitivity **Σ(m_ν) ≈ 0.64 ± 0.03 eV**

A. Nucciotti, ECT*, Trento (Italy), April 4th-8th, 2016 10

improvement by a factor $\approx 40^{1/4} \simeq 2.5$

Overview ECHo





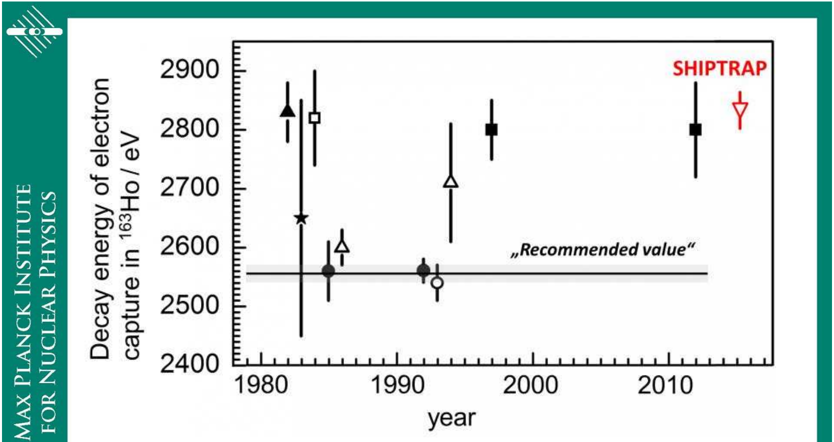
[redacted] [redacted] 2

2
4

$Q_{\text{microcalorimetry}}$ → $\Delta Q\ (\delta Q \sim 1\text{eV})$ ← $Q_{\text{Penning trap}}$

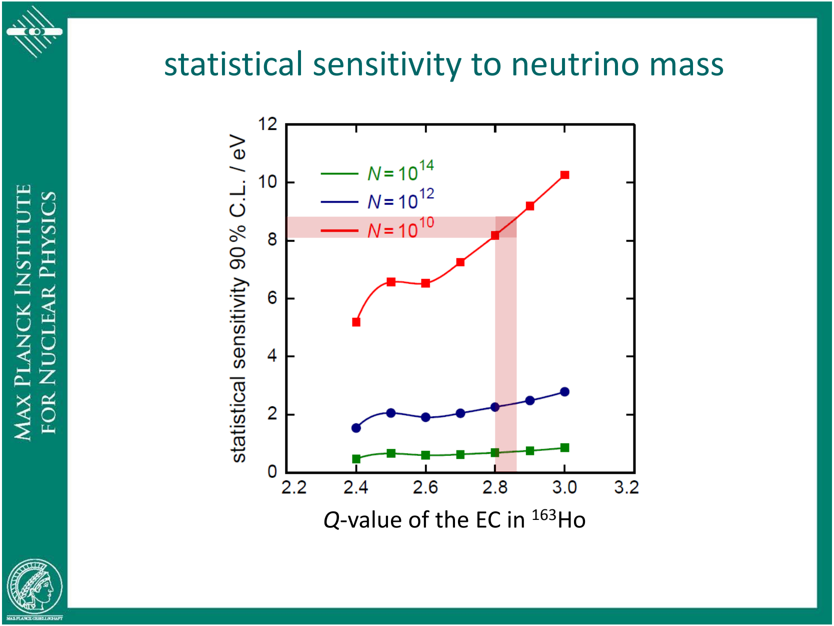
↓

$\delta m_{\nu}^{\text{sys}}$

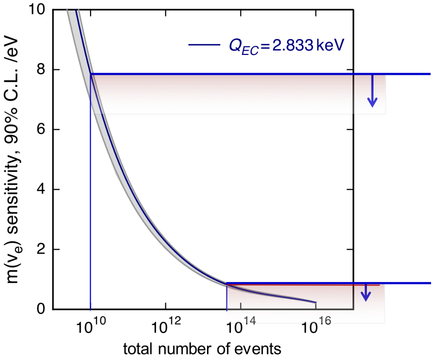


$$Q_{Ho} = 2833(30_{stat})(15_{sys})\ \mathrm{eV}$$

S. Eliseev et al. Phys. Rev. Lett. 115 (2015) 062501


MAX PLANCK INSTITUTE
FOR NUCLEAR PHYSICS
statistical sensitivity to neutrino mass
statistical sensitivity 90 % C.L. / eV
$N = 10^{14}$
$N = 10^{12}$
$N = 10^{10}$
Q-value of the EC in ^{163}Ho

Expected Sensitivity for $\Delta E_{\mathrm{FWHM}} = 3$ eV and $f_{\mathrm{pu}} = 10^{-5}$



ECHo-1k

2 x 50 pixel x 10 Bq

4 months → 10^{10} events

↓

sub 10 eV resolution

ECHo-1M

50 x 2000 pixel x 10 Bq

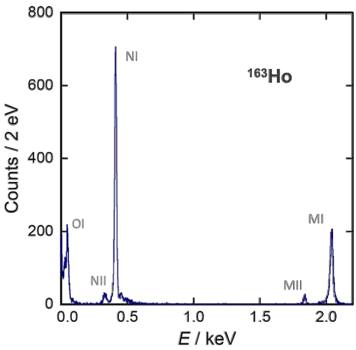
24 months → 6×10^{13} events

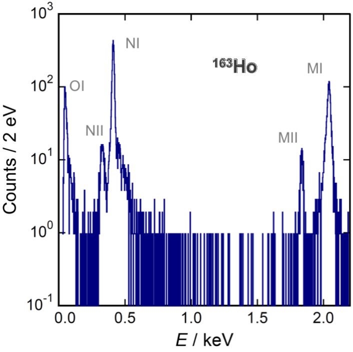
↓

sub 1 eV resolution

Latest Results: First Spectrum

1 pixel about 2 days





activity per pixel $A \sim 0.2$ Bq

energy resolution $\Delta E_{FWHM} \sim 5$ eV

→ no evidence of radioactive contamination in the source

Electron capture end-point experiment / 1

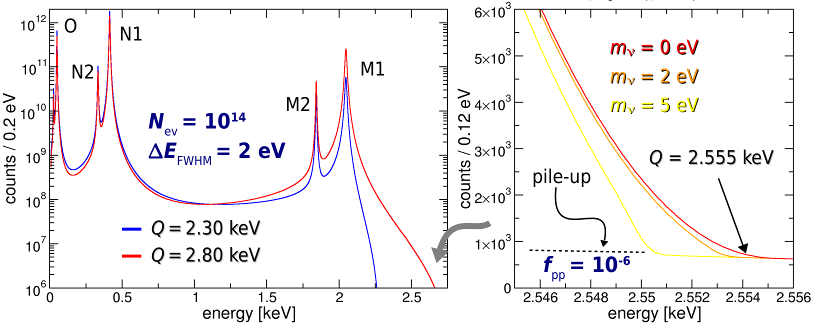
$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$

electron capture from shell ⩾ M1

A. De Rújula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

- calorimetric measurement of Dy atomic de-excitations (mostly non-radiative)
- Q = 2.8 keV (recent measurement with Penning trap)
  - rate at end-point and ν mass sensitivity depend on $Q - E_{M1}$
- $\tau_{1/2} \approx$ 4570 years → few active nuclei are needed (2×10^{11} ^{163}Ho nuclei ↔ 1Bq)

$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q-E_c)\sqrt{(Q-E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4}$$



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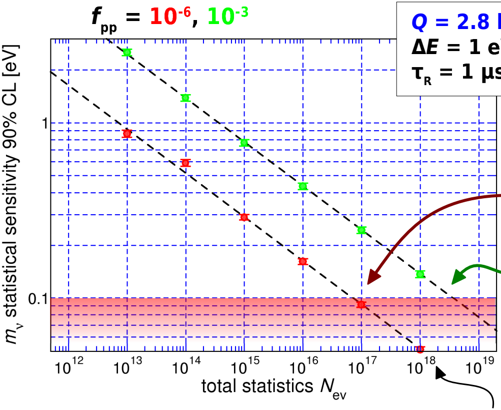
Statistical sensitivity: Montecarlo simulations



Q = 2.8 keV
ΔE = 1 eV
τ_R = 1 µs

for $\Sigma(m_\nu) \leq 0.1$ eV

A = 1Bq
$N_{det} t_M \approx 2\times10^9$ det×y

A = 1000Bq
$N_{det} t_M \approx 10^8$ det×y

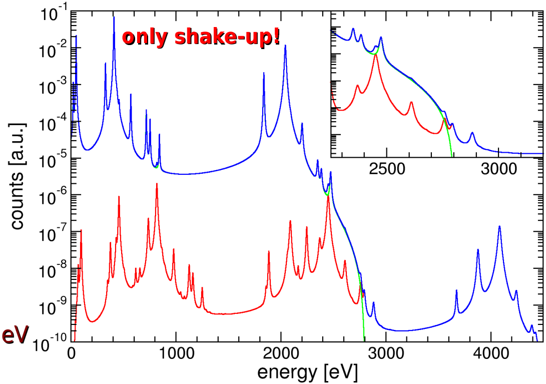
$\propto \sqrt[4]{1/N_{ev}}$

M. Galeazzi et al., arXiv:1202.4763v2
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

Electron capture end-point experiment / 3

- shake-up/shake-off → **double hole excitations**
  - *n*-hole excitations possible but less probable
  - authors do not fully agree on energies and probabilities
- even more complex **pile-up spectrum**
  - it may be worth keeping f_{pp} **smaller than 10^{-4}**

A.De Rújula, arXiv:1305.4857
R.G.H.Robertson, arXiv:1411.2906
A.Faessler et al., PRC 91 (2015) 45505



$Q = 2800$ eV
$f_{pp} = 10^{-4}$

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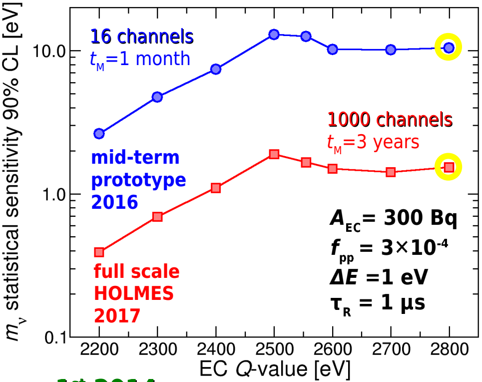
HOLMES (ERC-Advanced Grant n. 340321)

goal

- neutrino mass measurement: m_ν statistical sensitivity as low as 0.4 eV
- prove technique potential and scalability:
  - assess EC spectral shape
  - assess systematic errors

baseline

- TES with **implanted** ^{163}**Ho**
  - 6.5×10^{13} nuclei per pixel
    → **300 dec/sec**
  - $\Delta E \approx 1$ eV and $\tau_R \approx 1\,\mu s$
- **1000 channel** array
  - 6.5×10^{16} ^{163}Ho nuclei
    → ≈18μg
  - 3×10^{13} events in **3 years**



→ Project Started on February 1st 2014

B. Alpert et al., Eur. Phys. J. C, (2015) 75:112
http://artico.mib.infn.it/holmes

A. Nucciotti, ECT*, Trento (Italy), April 4th-8th, 2016 12

Project goals

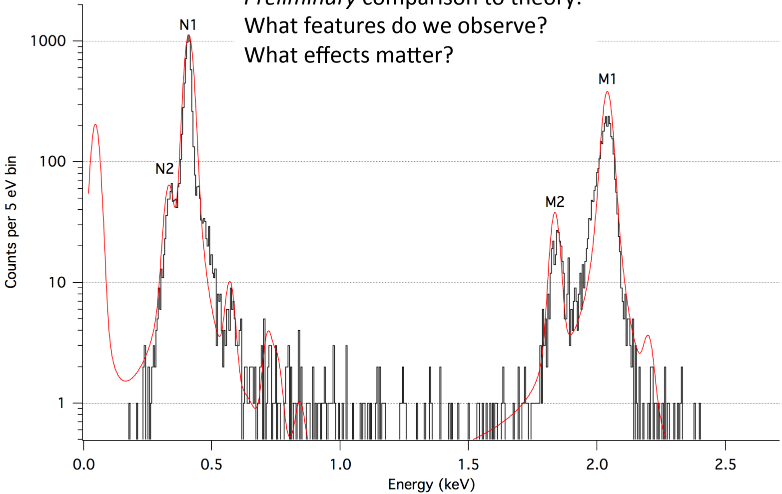
Develop experimental methods to enable calorimetric ECS for neutrino mass measurement

- Make ^{163}Ho with high isotopic and chemical purity
- Develop optimized sensors
- Develop methods to incorporate EC-decaying isotopes into sensors
- Demonstrate high-resolution ECS at single-pixel scale

Different methods by independent groups → good science!

- **Contribute data to aid theoretical understanding of EC spectra**

Preliminary comparison to theory:
What features do we observe?
What effects matter?



Red line: 35 eV FWHM Gaussian convolved with calculation from *Faessler et al., Phys. Rev. C. 2015*

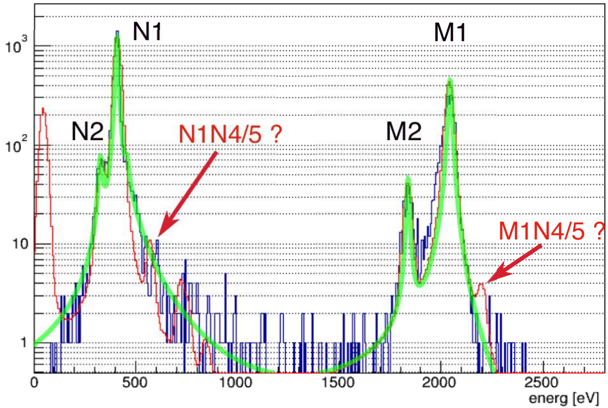
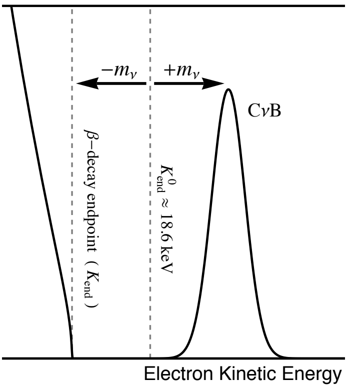


FIG. 2. Blue: the calorimetric spectrum measured by NuMECS [8]. Red: the theoretical prediction of Faessler et al. [13]. Green: the same description as in Fig. (1b).

Neutrino beta capture

- Capture on beta-decaying nuclei
  $\overset{(-)}{\nu}_{e} + N \to N' + e^{\pm}$
  - *zero threshold*

- excess electrons
  - ~ 2 m_ν beyond beta decay endpoint



S. Weinberg, Phys.Rev. 128 (1962) 1457–1473

Lusignoli: need to cite Irvine and Humphreys (1983)

Neutrino history: Dirac

Decoupling: T>>m — **Today: T<<m**

$\nu_L = \nu_{hL}$ $\quad n_\nu(z) \longrightarrow \nu_{hL} \quad n_0 \quad L = 1$ ***Detected!***

$\nu_R = \nu_{hR}$ $\quad 0$

$\bar{\nu}_L = \bar{\nu}_{hL}$ $\quad 0$

$\bar{\nu}_R = \bar{\nu}_{hR}$ $\quad n_\nu(z) \longrightarrow \bar{\nu}_{hR} \quad n_0 \quad L = -1$

Propagation:
Helicity conserved

$n_\nu(z) = n_0(1+z)^3$ $\qquad n_0 \approx 56\,\mathrm{cm}^{-3}$

Duda, Gelmini, Nussinov, Phys.Rev. D64 (2001) 122001

Neutrino history: Majorana

Decoupling: T>>m **Today: T<<m**

$\nu_L = \nu_{hL} \quad n_\nu(z) \longrightarrow \nu_{hL} \quad n_0 \quad \cancel{L}$ ***Detected!***

$\nu_R = \nu_{hR} \quad n_\nu(z) \longrightarrow \nu_{hR} \quad n_0 \quad \cancel{L}$ ***Detected!***

$N_L = N_{hL} \quad 0$

$N_R = N_{hR} \quad 0$

Propagation:
Helicity conserved

Duda, Gelmini, Nussinov, Phys.Rev. D64 (2001) 122001

Macroscopic difference Dirac/Majorana!

$$\Gamma_{\mathrm{C}\nu\mathrm{B}} = \bar{\sigma}_0 \left[n(\nu_{h_R}) + n(\nu_{h_L}) \right] N_{\mathrm{Tri}}$$

$$\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}} = \bar{\sigma}_0 n_0 N_{\mathrm{Tri}} \approx 4.1\ \mathrm{yr}^{-1}$$

$n(\nu_{hL}) = n_0$
$n(\nu_{hR}) = 0$

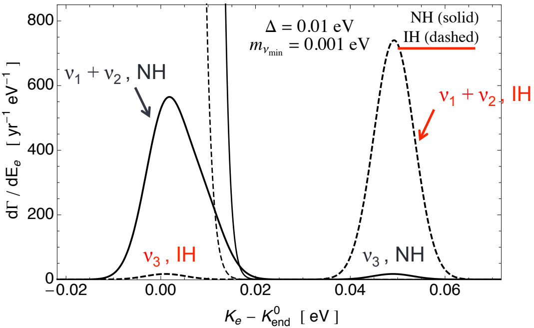
$$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} = 2\bar{\sigma}_0 n_0 N_{\mathrm{Tri}} \approx 8.1\ \mathrm{yr}^{-1}$$

$n(\nu_{hL}) = n_0$
$n(\nu_{hR}) = n_0$

(rates for 100 g of ^{3}H)

see also Lisanti, Safdi and Tully, PRD90 (2014) no.7, 073006

- Even for optimistic Δ, ν_1 and ν_2 can not be resolved
- Inverted hierarchy more promising



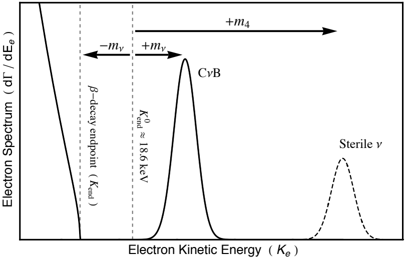
Detectable at beta capture experiment!

- Clustering compensates small mixing:

$$\frac{\Gamma_{\nu_4}}{\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}}} \approx 0.45 \left(\frac{|U_{e4}|^2}{3\times 10^{-2}}\right)\left(\frac{f_{\mathrm{clus}}}{50}\right)\left(\frac{\Delta N_{\mathrm{eff}}}{0.3}\right) \qquad f_{clus} = n_s/n_0 \leq 50$$

- *Background-free!*

$$\Delta \ll m_4 - m_1$$

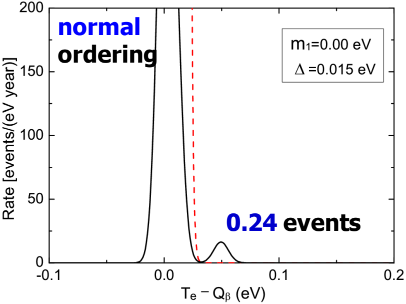


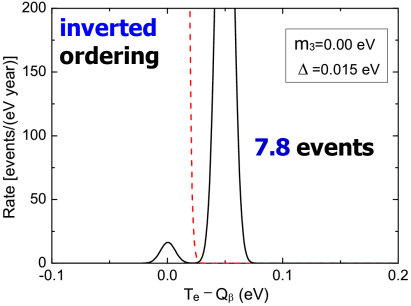
Illustration

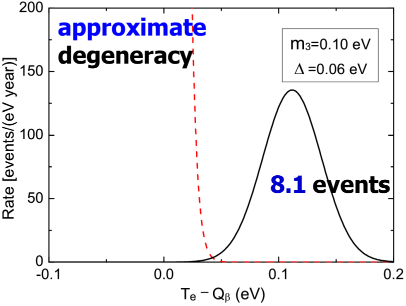
- **Target mass: 100 g tritium atoms**
- **Input θ(13) : 8.8 degrees**
- **Number of events per year: ~ 8**

(Li, Xing, Luo 2011).

The gravitational clustering effect may help enhance the signal rates (Ringwald, Wong 2004).







Discovery potential of experiments

The number of signal events is given by

$$S = \frac{\lambda_{\nu(\bar{\nu})}}{\lambda_{\beta(EC)}} \frac{\log 2}{T_{1/2}} \, N_A \, n_{\rm mol} \, t$$

Assume we want to record a total number of S = 10 signal events. We need:

- for an experiment with NCB, 135 g y of ^{3}H
- for an experiment with ANEC, depending on the Q-value, 23.2 (307, 1274) kg y of ^{163}Ho
- with present estimate of shake-off, 30.6 kg y

M. L., M. Vignati (2011)

New

A. De Rùjula, M.L. (2016)

If the relic neutrino density is $\langle n_\nu \rangle$

PTOLEMY Approach

- R&D program to reduce molecular smearing at the tritium source
- New geometries for TES calorimeters for 0.05-0.15 eV energy resolution at the tritium endpoint
- Design of a high mass tritium source EM geometry using a Crossed-Field MAC-E filter and time-dependent triggering with Project 8 technologies

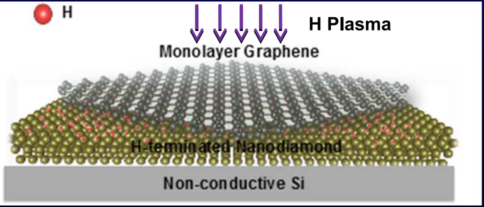
9

Hydrogenation of Graphene

- Investigate the influence of different diamond platforms to support graphene
- Tune the electronic properties of CVD graphene in terms of

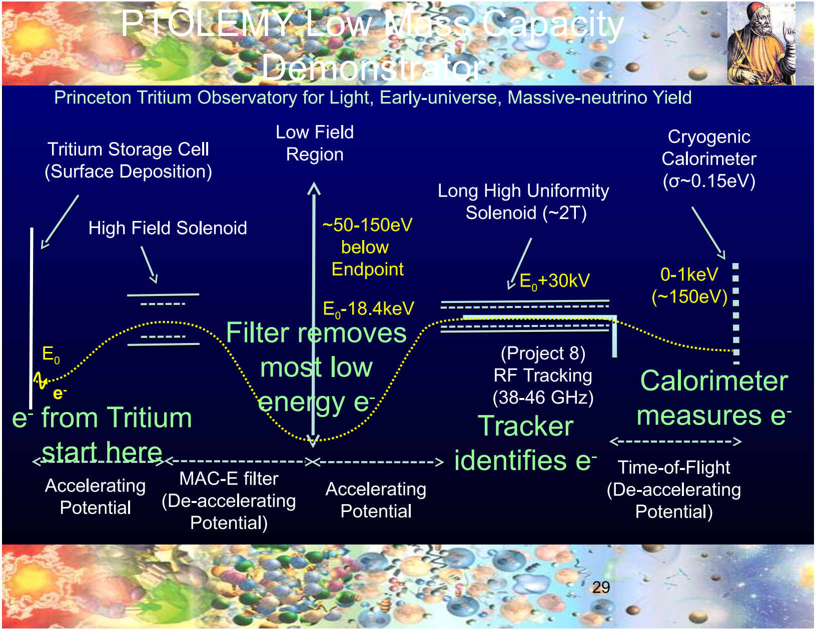
Fang Zhao

  - Different functional terminating groups on diamond samples
  - Graphene hydrogenation process (Change the hybridization of carbon atom from sp^2 to sp^3, thus removing the conducting π band and opening a band gap)



Why interesting?
C-H sp^3 bond expected to be less than 3eV
He^3 recoils into the continuum (minimal molecular broadening)

CRADA with SRNL for first tritiated-graphene sample signed by DOE and will be delivered to PPPL in March for analysis


PTOLEMY Low Mass Capacity Demonstrator
Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield
Tritium Storage Cell (Surface Deposition)
High Field Solenoid
Low Field Region
~50-150eV below Endpoint
E0-18.4keV
Long High Uniformity Solenoid (~2T)
E0+30kV
Cryogenic Calorimeter (σ~0.15eV)
0-1keV (~150eV)
E0
e-
e- from Tritium start here
Filter removes most low energy e-
(Project 8) RF Tracking (38-46 GHz)
Tracker identifies e-
Calorimeter measures e-
Accelerating Potential
MAC-E filter (De-accelerating Potential)
Accelerating Potential
Time-of-Flight (De-accelerating Potential)
29

Chris Tully

PTOLEMY

PTOLEMY Physics

- R&D program may lead to advancement in the precision on the neutrino mass
  - First results expected in 2016
- Spectrum analysis can contribute to search for sterile neutrino “thresholds” down to low mixing angles
  - Initial systematics analysis included in white paper (Mertens et al.)
- Graphene-only source has unique sensitivity to MeV-scale dark matter
  - New paper in preparation
- Relic neutrino direct detection
  - Goal by 2017 : design for a 100g tritium capacity with as compact a source and filter geometry as possible from simulation

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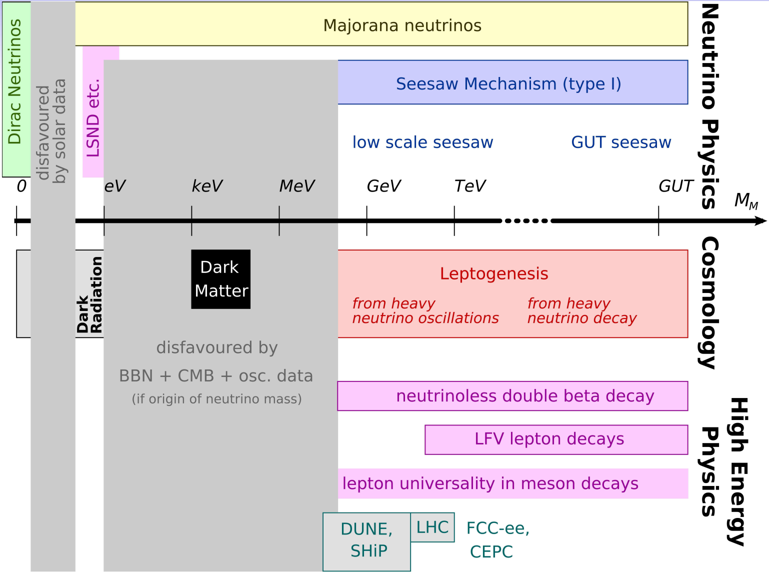
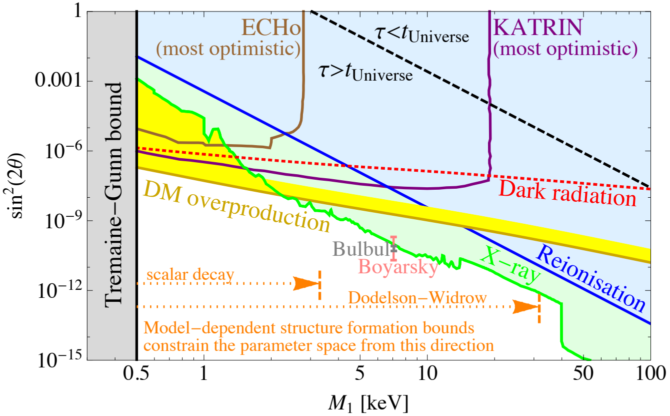
Heavy Sterile Neutrinos


Majorana neutrinos
Dirac Neutrinos
disfavoured by solar data
LSND etc.
Seesaw Mechanism (type I)
low scale seesaw
GUT seesaw
Neutrino Physics
0
eV
keV
MeV
GeV
TeV
GUT
M_M
Dark Radiation
Dark Matter
Leptogenesis
from heavy neutrino oscillations
from heavy neutrino decay
Cosmology
disfavoured by
BBN + CMB + osc. data
(if origin of neutrino mass)
neutrinoless double beta decay
LFV lepton decays
lepton universality in meson decays
High Energy Physics
DUNE, SHiP
LHC
FCC-ee, CEPC

Synopsis of current and future bounds

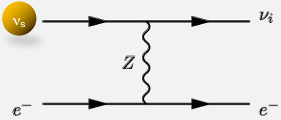


courtesy of A. Merle

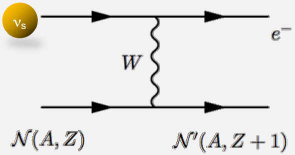
Experimental searches for ν_s-DM

Direct detection

- neutrino conversion



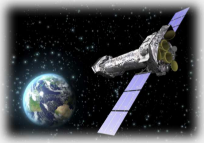
- neutrino capture



ν_s

Indirect detection

XMM-Newton
Chandra
Suzaku
Astro-H
Micro-X
eRosita

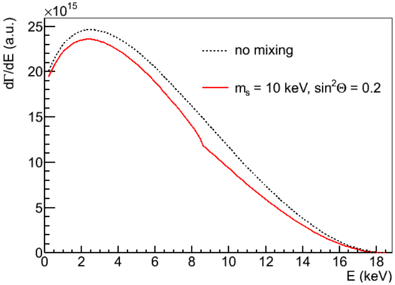


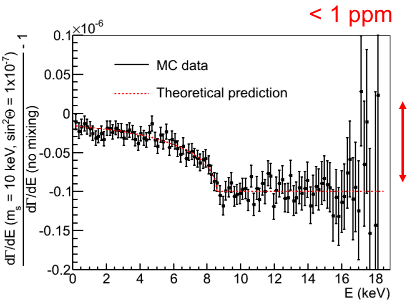
Production

KATRIN
Troitsk
ECHo
NuMecs
Holmes
Ptolemy

23

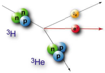
KATRIN Signature





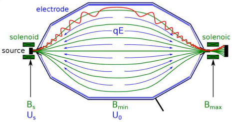
- We need large statistics
- And extremely low systematic uncertainties

Pre-Measurement



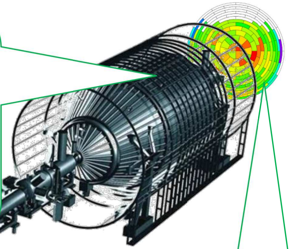
Reduce count rate

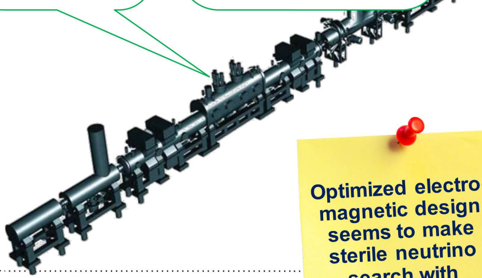
- Less T_2
- Small B_{source}

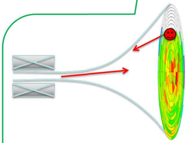


Adiabatic transport

- Large $B_{aircoil}$







Backscattering

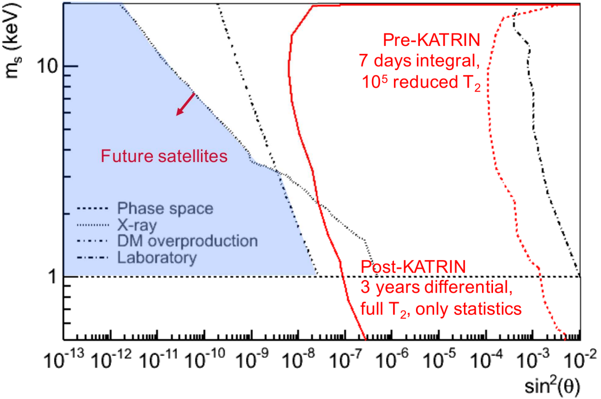
- Small $B_{detector}$

Optimized electro-magnetic design seems to make sterile neutrino search with KATRIN possible

Susanne Mertens

BERKELEY LAB

Targeted sensitivity

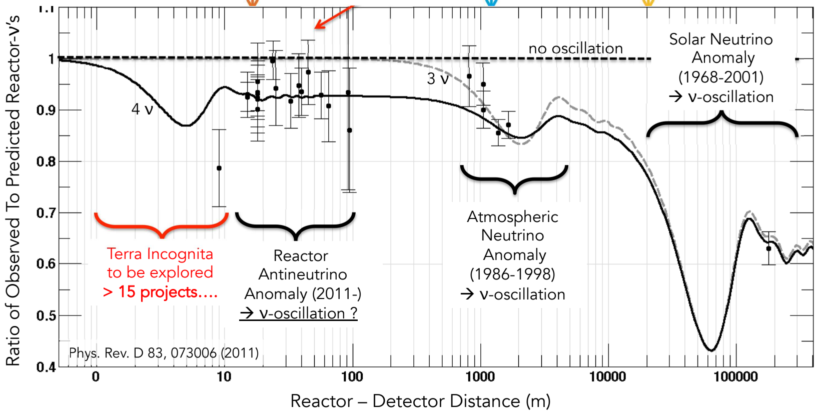


Susanne Mertens 45

Light Sterile Neutrinos

The Reactor Anomaly (RAA)

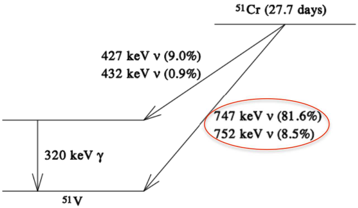
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\Theta_{14} \sin^2(1.27\Delta m^2_{41} \frac{L}{E}) - c^4_{14} \sin^2 2\Theta_{13} \sin^2(1.27\Delta m^2_{31} \frac{L}{E}) - c^4_{14} c^4_{13} \sin^2 2\Theta_{12} \sin^2(1.27\Delta m^2_{21} \frac{L}{E})$$



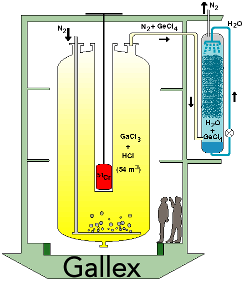
Th. Lasserre – Trento – 07/04/2016

The Gallium Anomaly (GA)

- Test of solar neutrino radiochemical detectors GALLEX and SAGE
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$



- 4 calibration runs with 20-60 PBq Electron Capture ν_e emitters
  - Gallex, <L>=1.9 m
    - ^{51}Cr, 750 keV
  - Sage, <L>=0.6 m
    - ^{51}Cr & ^{37}Ar (810 keV)



- Deficit observed
  - 3σ anomaly

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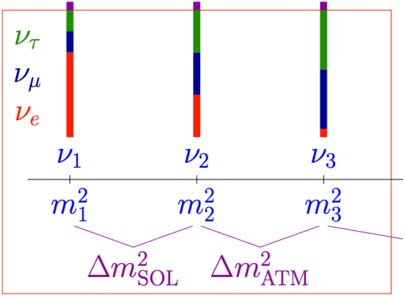
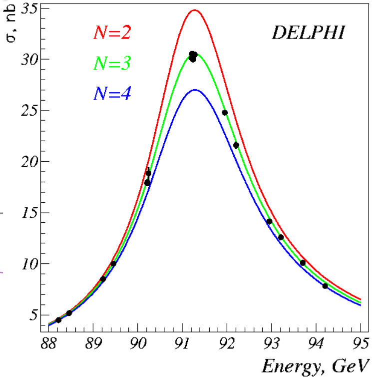
Three Active Neutrinos

Only 3 light n's coupling to Z boson



3ν-mixing



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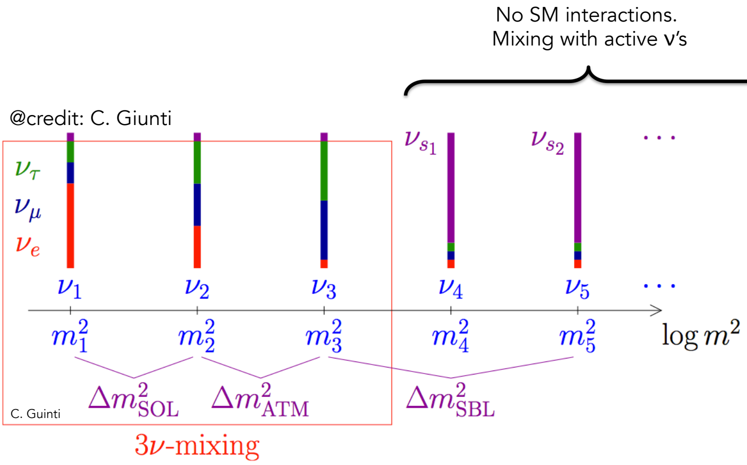
Adding Sterile Neutrinos



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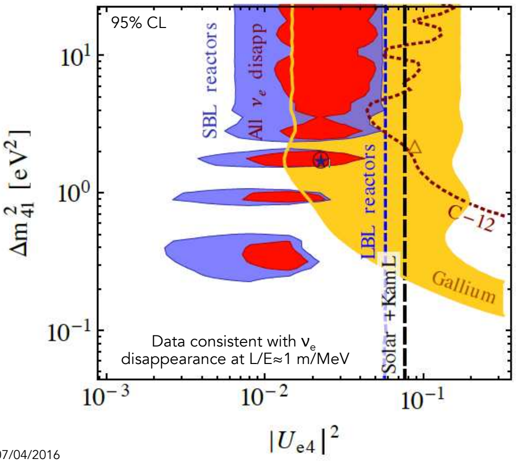
$\overset{(-)}{\nu}_e$ disappearance (3+1)

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$



J. Kopp et al., arXiv:1303.3011

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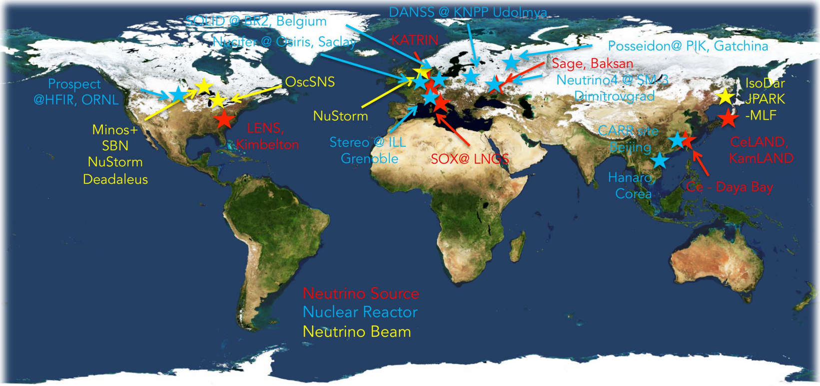
Searches for eV Sterile-ν



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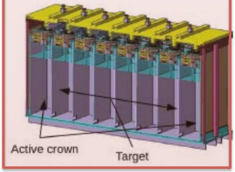
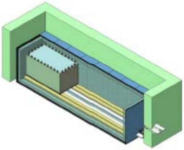
A selection of Ongoing Efforts

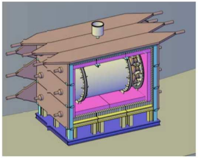
STEREO: **Gd-LS detector** at 10m from ILL , France



Neutrino-4: **Gd-LS detector** at 6-12m from SM-3, Russia

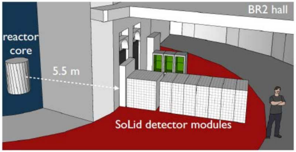


NEOS: **Gd-LS detector** at ~30m from Hanbit, Korea

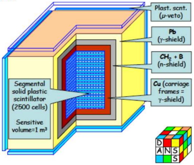


NuLAT: Li-loaded plastic scintillator cubes

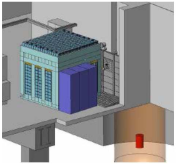
SoLid/CHANDLER: segmented composite scintillator cubes at 5.5m from BR2, Belgium



DANSS: Segmented plastic scintillator at ~10m from KNPP, Russia



PROSPECT: **Segmented ^{6}Li liquid** scintillator at 7-12m from HFIR, US

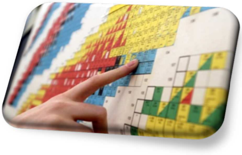


@Credit: K. Heeger

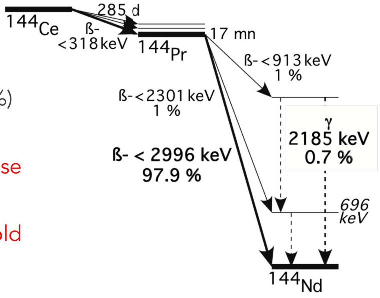
CeSOX @ BOREXINO

Antineutrino Emitter: ^{144}Ce-^{144}Pr

(ITEP N°90 1994, PRL 107, 201801, 2011)



- $\bar{\nu}_e$ detection: $\bar{\nu}_e + p \to e^+ + n$
  - large IBD cross section → 5 PBq
  - (e^+,n) coincidence → mitigate backgrounds
- ^{144}Ce-^{144}Pr
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β
    time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β
    $\bar{\nu}_e$-emitter above IBD threshold



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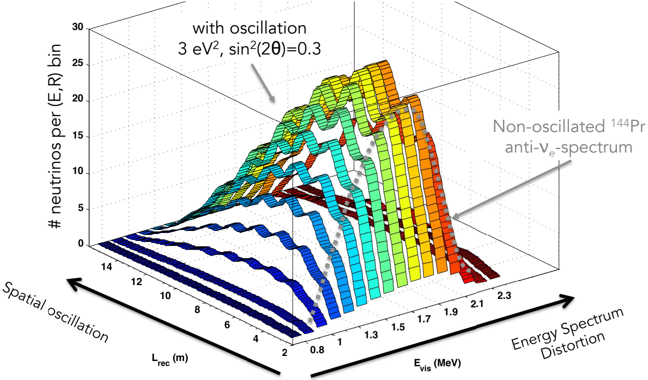
CeSOX @ BOREXINO

Expected Signal: 30/d (3.7 PBq)

$$\frac{d^5 N_{\bar{\nu}_e}}{dt\, dE\, d^3\mathscr{V}_{\rm det}} = \mathcal{A}_0\, e^{-t\,\lambda_{\rm Ce}}\, \eta_p\, \varepsilon\, \frac{1}{4\pi L^2}\, \sigma_{\rm IBD}(E)\, S_{\rm Ce}(E) \times \mathcal{P}(L,E)$$



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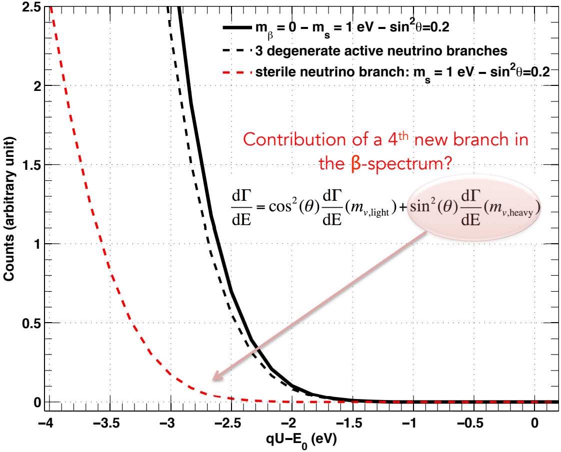
Light Sterile Neutrino in KATRIN

Integral Tritium β-decay spectrum near endpoint E_0=18.575 keV



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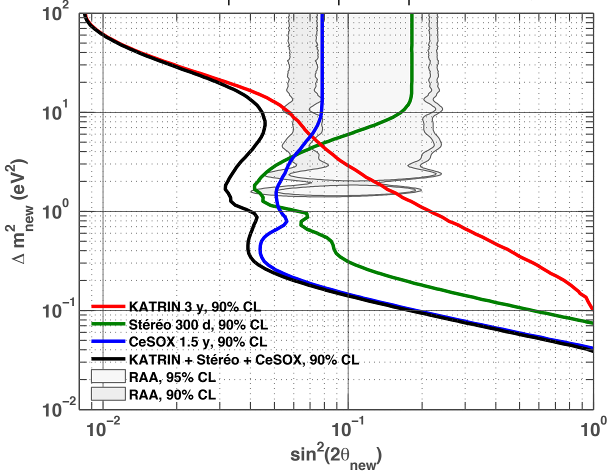
KATRIN + Stéréo + CeSOX

The RAA+GAA parameter space is probed at 98% C.L.



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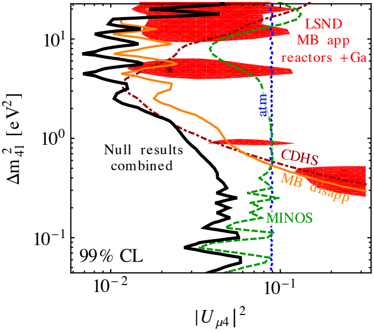
Hints from appearance experiments (LSND)

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

necessarily predict signal in ν_μ disappearance - but not seen

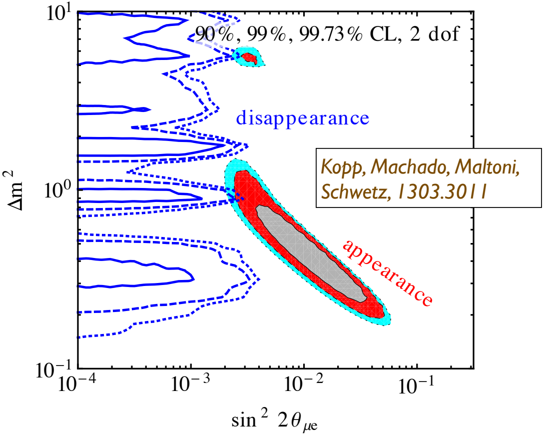


Kopp, Machado, Maltoni, Schwetz, 1303.3011

T. Schwetz 41

Strong tension in global data

- *consistency of appearance and disappearance data with p-value 10^{-4}*



expect somewhat increased tension due to recent data from MINOS, SK-atm, ICARUS, OPERA (potentially also IceCube)

C. Giunti et al find somewhat better fit: p-value 10^{-3} *1308.5288*

T. Schwetz 42

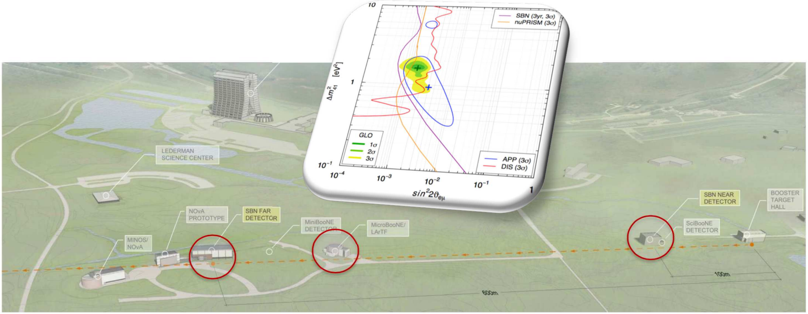
eV-scale sterile neutrinos

- *situation is ambiguous*
  see also talk by C. Giunti

- *need to clarify experimentally*
  talk by T. Lasserre

T. Schwetz 43

The Fermilab SBN program



ICARUS	MicroBooNE	SBND	Produce
Fewer ν_μ ?	Fewer ν_μ ?	ν_μ	ν_μ
More ν_e?	More ν_e?	~1% ν_e	~1% ν_e

110m

470m

600m

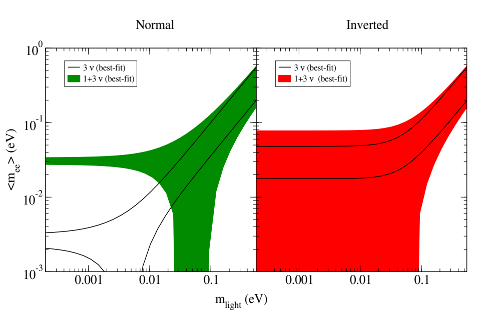
SBN Fermilab

Th. Lasserre – Trento – 07/04/2016

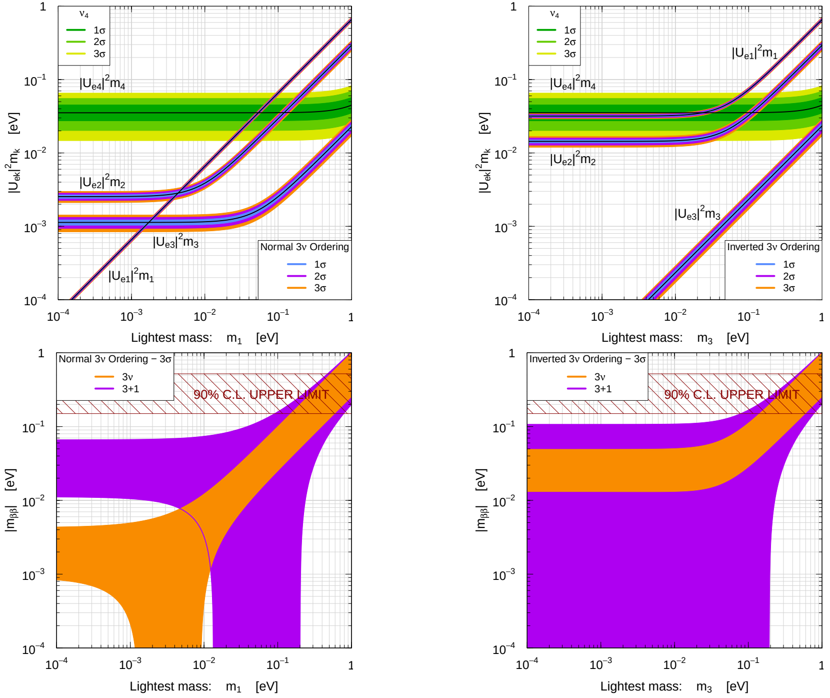
Messing up 3 Majorana neutrino paradigm?

light sterile neutrinos, with $\sqrt{\Delta m^2_{\rm st}}\,\sin^2\theta_{\rm st} \simeq |m_{ee}|^{3\nu}_{\rm IH}$

Barry, W.R., Zhang; Giunti *et al.*; Girardi, Meroni, Petcov



$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3 + |U_{e4}|^2\, e^{i\alpha_{41}}\, m_4$$


ν4
1σ
2σ
3σ
|Ue4|2m4
|Ue2|2m2
|Ue3|2m3
|Ue1|2m1
Normal 3ν Ordering
|Uek|2mk [eV]
Lightest mass: m1 [eV]
Inverted 3ν Ordering
Lightest mass: m3 [eV]
Normal 3ν Ordering − 3σ
3ν
3+1
90% C.L. UPPER LIMIT
|mββ| [eV]
Inverted 3ν Ordering − 3σ

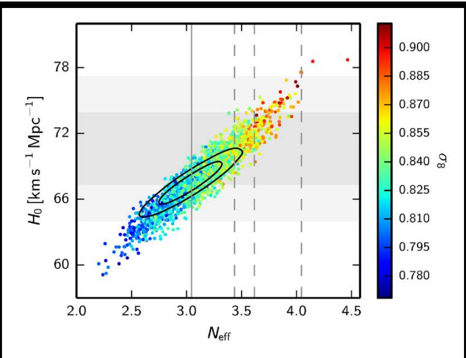
GOING BEYOND THE MASS

$$\Omega = \frac{\rho}{\rho_c} = \sum m_{\nu,i} n_{\nu,i} \qquad n_\nu = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 n_\gamma$$

Normally $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$, but could be different. Normally the relativistic energy density in neutrinos is quantified through the relation

$$N_{eff} = \frac{\rho_{\nu,rel}}{\rho_{\nu 0}} \qquad \rho_{\nu 0} = \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 \rho_\gamma$$

N_{eff} is a measure of any type of ”dark radiation”



THE CONCLUSION SEEMS TO BE THAT THERE IS NO EVIDENCE FOR ANY PHYSICS BEYOND THE STANDARD MODEL

BUT BE AWARE THAT IN EXTENDED MODELS THIS CAN BE VERY DIFFERENT!

$N_{\rm eff}^{\rm SM} = 3.046$ [Mangano, Miele, Pastor, Pinto, Pisanti, Serpico, NPB 729 (2005) 221]

Bottom line: Sterile neutrinos in the mass range preferred by SBL data can be accomodated by cosmology, but ONLY if they are not fully thermalised

How can this be achieved?

A large neutrino lepton asymmetry
(see e.g. STH, Tamborra, Tram 1204.5861, Saviano et al. arXiv:1302.1200)

New, non-standard interactions in the sterile sector
(e.g. STH, Hansen, Tram, 1310.5926, Dasgupta & Kopp 1310.6337, Bringmann, Hasenkamp & Kersten 1312.4947, Archidiacono, STH, Hansen, Tram 1404.5915 Chu, Dasgupta & Kopp 1505.02795)

Conclusions

Parameters of our universe chosen

$\ni$ ν Physics ♣♣♣

Δm^2_{ij}, θij, δ?

$E(CRs)$, $h(atms)$; $\rho(atms)$, $\tau(\mu)$, $\tau(\pi^{\pm})$

$R_{\odot}$, $\rho_{\odot}$, $R_{\otimes}$, $\rho_{\otimes}$ $\exists$ *Reactors* ♣♣♣

EC measurements of e-neutrino "mass" ??

Microcalorimeters, etc !!

$\exists$ *Hope for* $m(\nu_e)$ *experiments*

Holmium From Latin "Holmia": Stockholm.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