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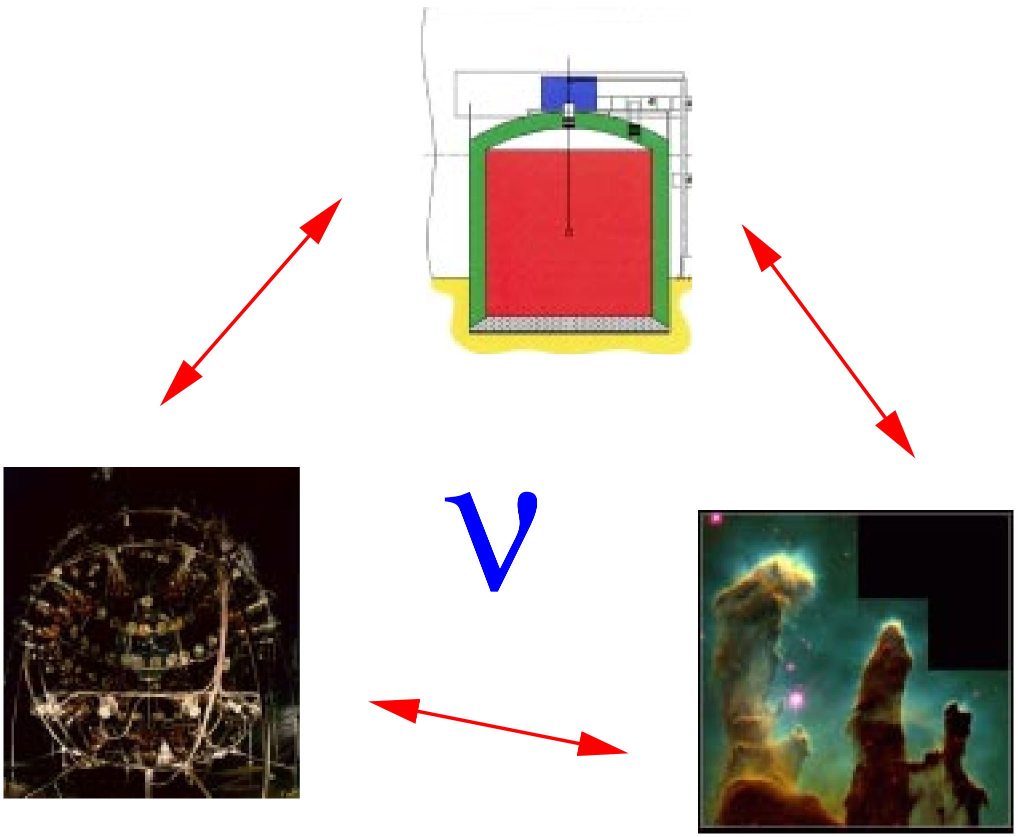
Absolute neutrino mass determination

double beta decay



neutrino oscillations

cosmology

In Collaboration with:
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T.J. Weiler (Vanderbilt University)

Outline

- What are neutrino oscillations?
- Experimental evidence:
  solar and atmospheric neutrinos
- What is double beta decay?
- Double beta decay and neutrino oscillations:
  correlations
- Neutrino mass schemes:
  the reconstruction of the spectrum

Why lepton number violation?

Specific rôle of the neutrino:

- only neutral fermion
- $m_\nu \ll m_{q^+,q^-,l}$

SM: massless “by hand”

Grand Unification:

ν together in a multiplett with q^+, q^-, l

→ Dirac mass $m^D \overline{\nu}_L \nu_R$

with $m_D \simeq m_q^+, m_{q^-}, m_l$

⇒ contradiction to experiment

- Cancellation with 2nd mass term

Majorana mass

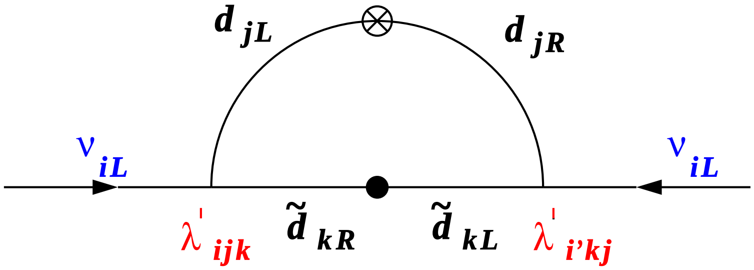
$m_M(\overline{\nu_L}\nu_R^C + \overline{\nu_R^C}\nu_L)$

→ L violated: $\nu = \nu^C$

→ only possible for neutral particles

Neutrino mass and $\not{R}_p$SUSY

$\not{R}_p$SUSY couplings may induce neutrino mass via one loop self-energy graphs



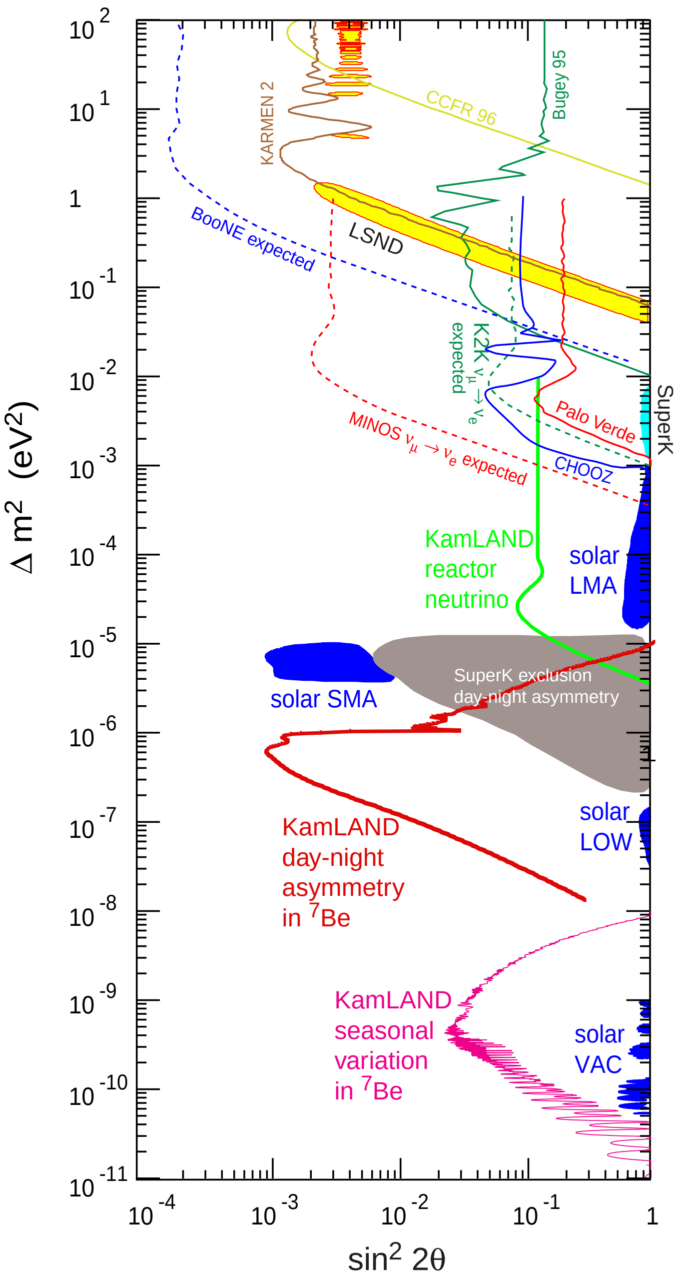
$\Rightarrow \lambda^{(\prime)}_{ijk}\lambda^{(\prime)}_{ikj}$
products directly constrained from $m_{\nu_{ii'}}$:

$$m_{\nu_{ii'}} \simeq \frac{N_c \lambda'_{ijk}\lambda'_{i'kj}}{16\pi^2} m_{d_j} m_{d_k} \left[\frac{f(m^2_{d_j}/m^2_{\tilde{d}_k})}{m_{\tilde{d}_k}} + \frac{f(m^2_{d_k}/m^2_{\tilde{d}_j})}{m_{\tilde{d}_j}} \right]$$

	Our Bounds	Previous Bounds
$\lambda'_{133}\lambda'_{133}$	$3.0 \cdot 10^{-8}$	$4.9 \cdot 10^{-7}$
$\lambda'_{132}\lambda'_{123}$	$7.5 \cdot 10^{-7}$	$1.6 \cdot 10^{-2}$
$\lambda'_{122}\lambda'_{122}$	$1.8 \cdot 10^{-5}$	$4.0 \cdot 10^{-4}$
$\lambda_{133}\lambda_{133}$	$5.3 \cdot 10^{-7}$	$9.0 \cdot 10^{-6}$
$\lambda_{132}\lambda_{123}$	$8.7 \cdot 10^{-6}$	$2.0 \cdot 10^{-3}$
$\lambda_{122}\lambda_{122}$	$1.4 \cdot 10^{-4}$	$1.6 \cdot 10^{-3}$

463 (1999) 77)

Neutrino Oscillations Summary



(C. Albright, hep-ex/0008064)

3 or 4 light neutrinos?

LSND: Requires 3rd $\Delta m^2 \Rightarrow$ 4th (sterile) neutrino

atmosheric ν's:
Results of matter effects, NC rate and
τ appearance strongly disfavor $\nu_\mu \rightarrow \nu_s$

solar ν's:
$\nu_\mu \rightarrow \nu_s$ disfavored by matter effects in the sun;
Comparison of Super-K ES and SNO CC
$\rightarrow$ Total active flux fits SSM prediction

$\Rightarrow$ superposition of ν_s and ν_τ?

solar ν's: $\nu_e \rightarrow \cos\alpha \;\; \nu_s + \sin\alpha \;\; \nu_\tau$

atmospheric ν's: $\nu_\mu \rightarrow \cos\alpha \;\; \nu_\tau - \sin\alpha \;\; \nu_s$

This implies:

$$\left[\frac{P(\nu_e \rightarrow \nu_s)}{P(\nu_e \rightarrow \nu_{\cancel{e}})}\right]_{sun} + \left[\frac{P(\nu_\mu \rightarrow \nu_s)}{P(\nu_\mu \rightarrow \nu_{\cancel{\mu}})}\right]_{atm} = \cos^2\alpha + \sin^2\alpha = 1$$

for $\theta_{LSND} = \theta_{SBL1} = \theta_{SBL2} = 0$

(O.L.G. Peres, A. Yu. Smirnov, Nucl.Phys. B 599 (2001) 3)

3 or 4 light neutrinos?

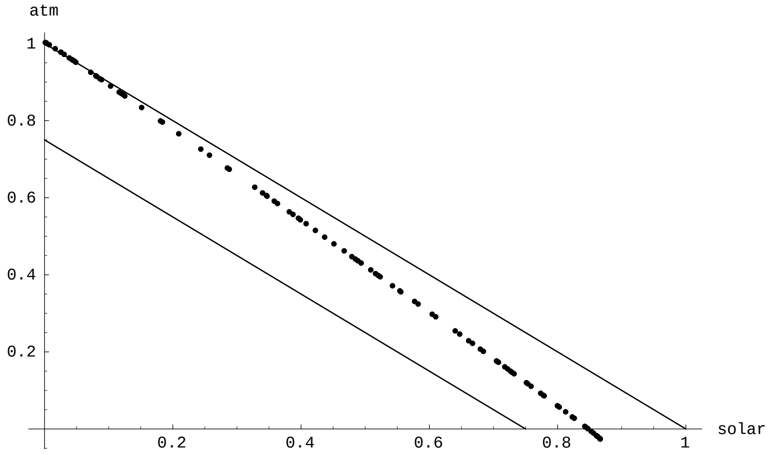
Experimental data:

$\cos^2\alpha + \sin^2\alpha < 0.63(SMA)$ (90 % C.L.)
$\cos^2\alpha + \sin^2\alpha < 0.75(LMA)$ (90 % C.L.)
$\cos^2\alpha + \sin^2\alpha < 0.64(QVO)$ (90 % C.L.)

Contradiction!

(C. Gonzalez-Garcia, C. Peña-Garay, PRD 63 (2000) 073013)

What about non-vanishing $\theta_{LSND}, \theta_{SBL1}, \theta_{SBL2}$?



Preliminary: Experimental data don't fit sumrule!

(adiabatic approximation, no matter effects)

(H. Päs, T.J. Weiler, L. Song, work in progress)

How large are ν-masses?

Direct measurements:

→ supernova ν's → sensitivity $\lesssim$ 1 eV

→ tritium decay → sensitivity $\lesssim$ 0.3 eV

→ π, τ decay → much worse

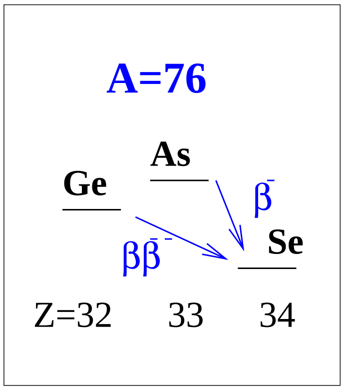
3 assumptions for indirect ν-mass determination:

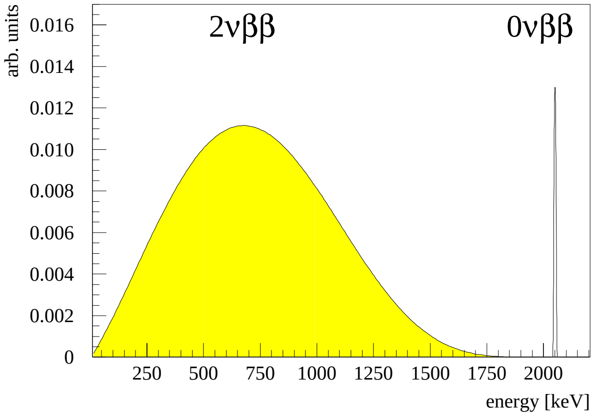
ν's are Majoranas (see-saw, $R\!\!\!/_p$-generated, etc.)

only 3 ν's (LSND neglected)

solar ν's: LMA or LOW solution

What is double beta decay?



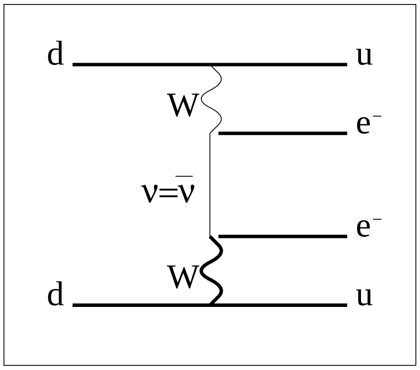


$2\nu\beta\beta:\ {}^A_Z X \rightarrow {}^A_{Z+2} X + 2e^- + 2\overline{\nu}_e$

- SM allowed: $T^{2\nu}_{1/2} \simeq 10^{19} - 10^{24}$y
- observed for 10 isotopes

$0\nu\beta\beta:\ {}^A_Z X \rightarrow {}^A_{Z+2} X + 2e^-$

- Physics beyond SM (L violation)



Sensitive on:

- effective Neutrino–Majorana mass:

$\langle m_\nu \rangle = \sum_j' U^2_{ej} m_j$

$\langle m_\nu \rangle < 0.27$ eV (68 % C.L.)

(Heidelberg-Moscow-Experiment)

Future Projects:

CUORE: 0.1 eV

MOON: 0.03 eV

EXO, GENIUS 1t: 0.02 eV

GENIUS 10 t: 0.002 eV

$0\nu\beta\beta$ and ν oscillations

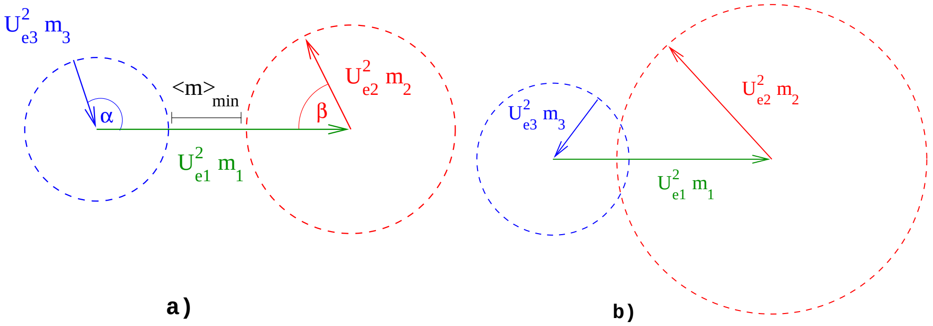
$0\nu\beta\beta$ observable:

$$\langle m \rangle \equiv |m_{ee}| = \left| \sum_j |U_{ej}|^2 e^{i\phi_j} m_j \right|$$

$$m_{ee} = |m_{ee}^{(1)}| + e^{i\phi_2}|m_{ee}^{(2)}| + e^{i\phi_3}|m_{ee}^{(3)}|$$

$$\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{\Delta m_{21}^2 + m_1^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{\Delta m_{31}^2 + m_1^2}. \end{aligned}$$

sum of 3 vectors in complex space:



Neutrino oscillations observable:

$$\Delta m_{ij}^2 \equiv |m_i|^2 - |m_j|^2 \ , \qquad |U_{ej}|^2, \qquad \delta$$

solar neutrinos: Δm_{12}^2, $|U_{e1}|^2 = \cos^2\theta_\odot$, $|U_{e2}|^2 = \sin^2\theta_\odot$
atmospheric neutrinos: Δm_{23}^2
CHOOZ, Palo Verde: Δm_{13}^2, $|U_{e3}|^2 = \frac{1}{4}\sin^2(2\theta_{e\not{e}}) < 0.025$

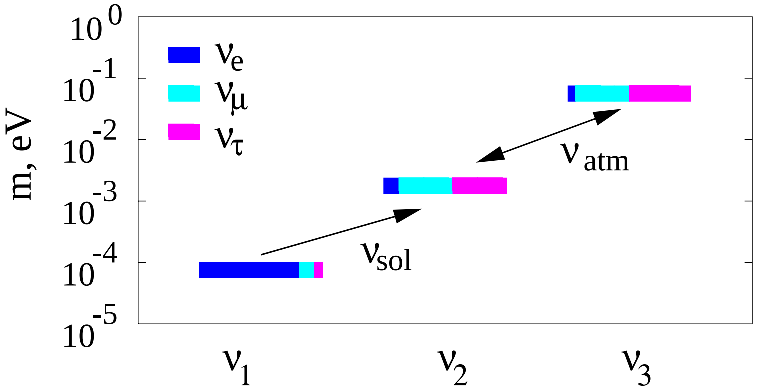
Correlations of m_{ee} and Δm^2

- character of hierarchy
  - direct: $|U_{e1}|^2 > |U_{e2}|^2, |U_{e3}|^2$
  - inverse: $|U_{e1}|^2 < |U_{e2}|^2,\ |U_{e3}|^2$

  → ν oscillations in matter & supernova ν

- level of hierarchy
  - hierarchy: $m_1^2 \ll \Delta m_{21}^2 \ll \Delta m_{31}^2$
  - partial degeneracy: $\Delta m_{21}^2 \ll m_1^2 \ll \Delta m_{31}^2$
  - degeneracy: $\Delta m_{21}^2 \ll \Delta m_{31}^2 \ll m_1^2$
- solution of the solar neutrino problem
  - MSW SMA: energy spectrum distortion
  - MSW LOW: day-night effect
  - MSW LMA: spectrum + day-night effect
  - VAC: seasonal variations

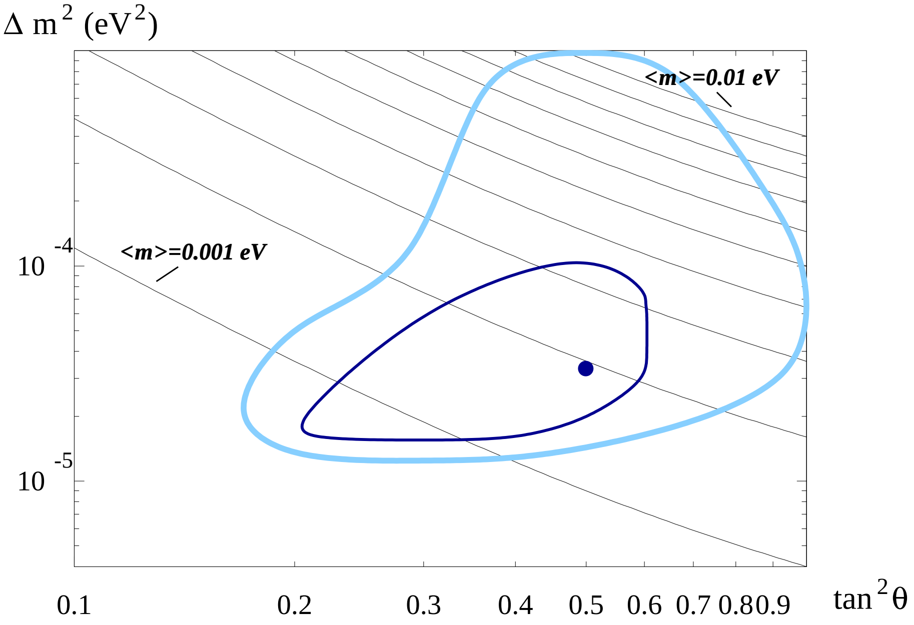
Hierarchical schemes



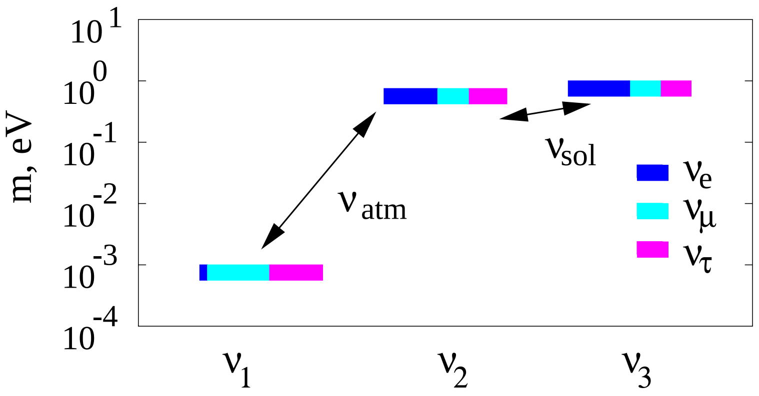
$$m_{ee}^{(1)} \simeq 0$$

$$m_{ee}^{(2)} = \sin^2\theta_\odot\sqrt{\Delta m_\odot^2} \simeq (1-3)\cdot 10^{-3}\ \mathrm{eV}$$

$$m_{ee}^{(3)} = \frac{1}{4}\sqrt{\Delta m_{atm}^2}\sin^2 2\theta_{e\not{e}} \lesssim 10^{-3}\ \mathrm{eV}$$



Inverse Hierarchy

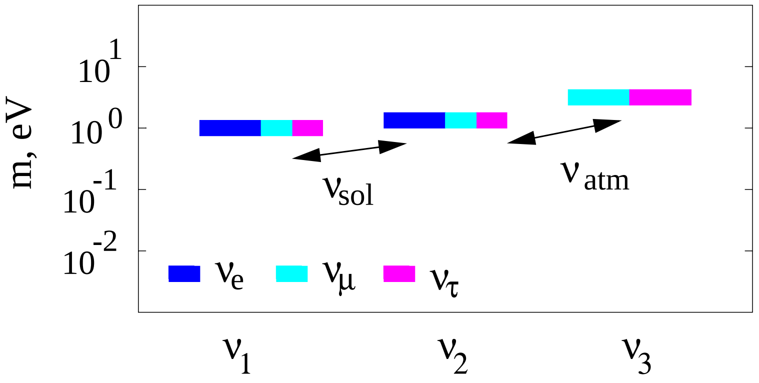


Disfavored from SN87A
(C. Lunardini, A. Yu. Smirnov, hep-ph/0009356)

$$\begin{aligned} m_{ee}^{(1)} &= \cos^2\theta_\odot \cdot \sqrt{\Delta m^2_{atm}} \\ m_{ee}^{(2)} &= \sin^2\theta_\odot \cdot \sqrt{\Delta m^2_{atm}} \\ m_{ee}^{(3)} &\simeq 0 \end{aligned}$$

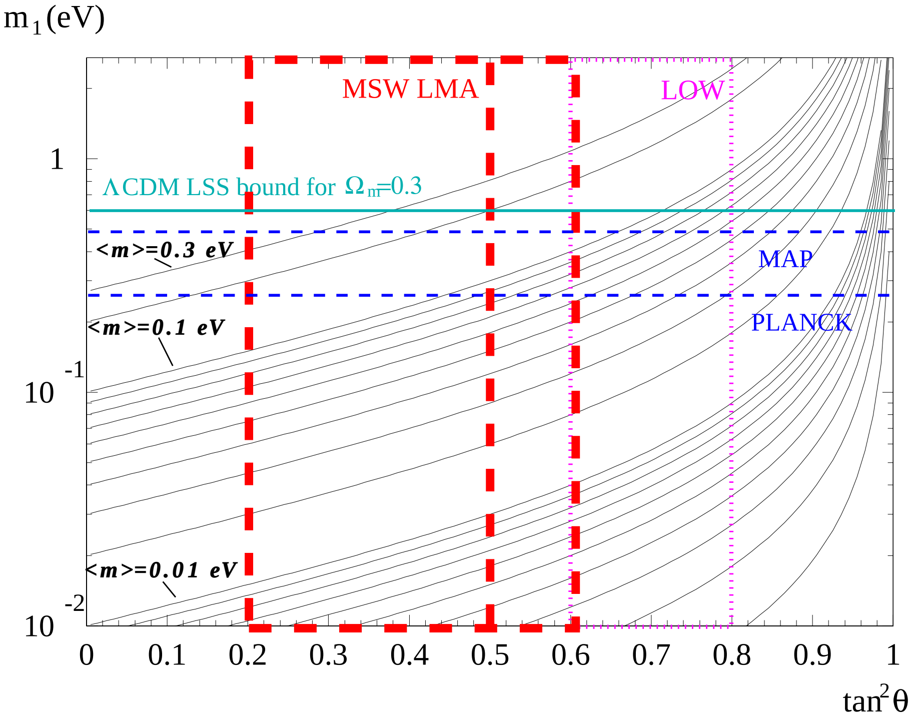
$$\begin{aligned} \langle m \rangle &= (\cos(2\theta_\odot) - 1) \cdot \sqrt{\Delta m^2_{atm}} \\ &= (1-7)\cdot 10^{-2}\ \mathrm{eV\ (LMA)} \\ &= (0.4-7)\cdot 10^{-2}\ \mathrm{eV\ (LOW)} \end{aligned}$$

Degenerate schemes

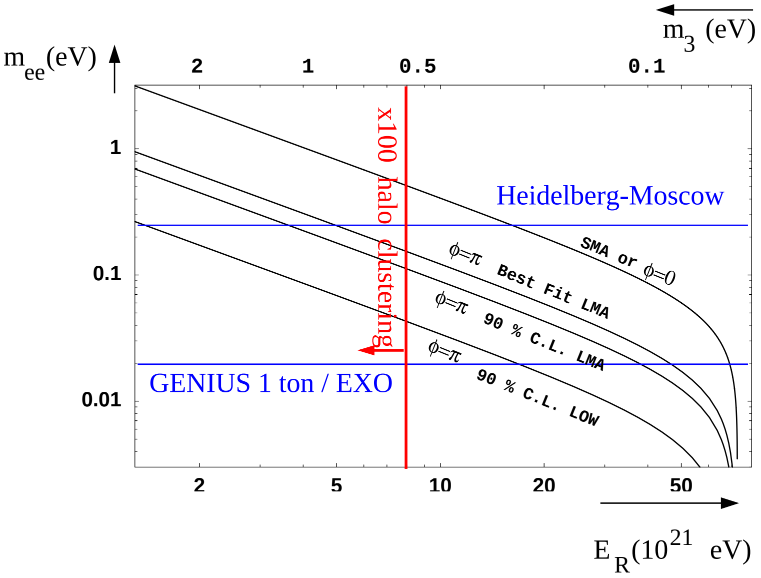


$$\begin{aligned} m_{ee}^{(1)} &= \cos^2\theta_\odot \cdot m_1 \\ m_{ee}^{(2)} &= \sin^2\theta_\odot \cdot m_1 \\ m_{ee}^{(3)} &\lesssim 0.025 \text{ eV} \end{aligned}$$

$$\langle m\rangle = (\cos(2\theta_\odot) - 1)\cdot m_1$$



Z-burst model and $0\nu\beta\beta$ decay



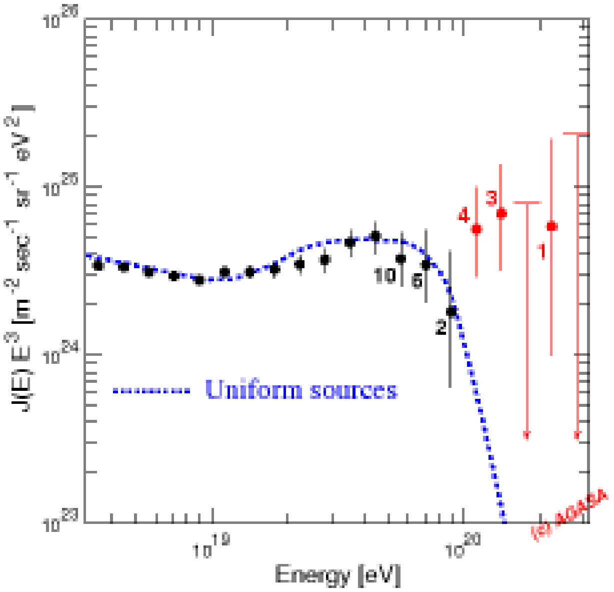
Comparison of Z-burst and EXO/GENIUS 1t sensitivity:

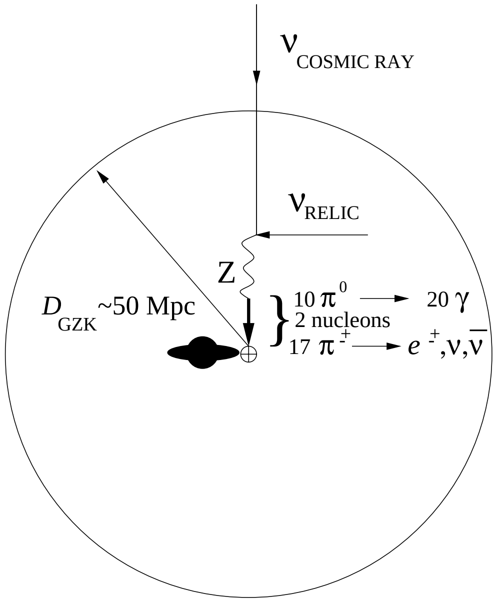
- $0\nu\beta\beta$ decay measured at $\langle m \rangle > 0.01$ eV: E_R determined up to factor 4, degeneracy yields factor of 3, halo clustering a factor of 100 and factor 2 for Majoranas is gained

- $0\nu\beta\beta$ decay not measured at $\langle m \rangle > 0.01$ eV: $E_R = \sqrt{\Delta m^2_{atm}}$, no enhancements for Z-burst

- If Z-burst is right: Most probably $\langle m \rangle > 0.01$ eV

Cosmic rays in the Z-burst model



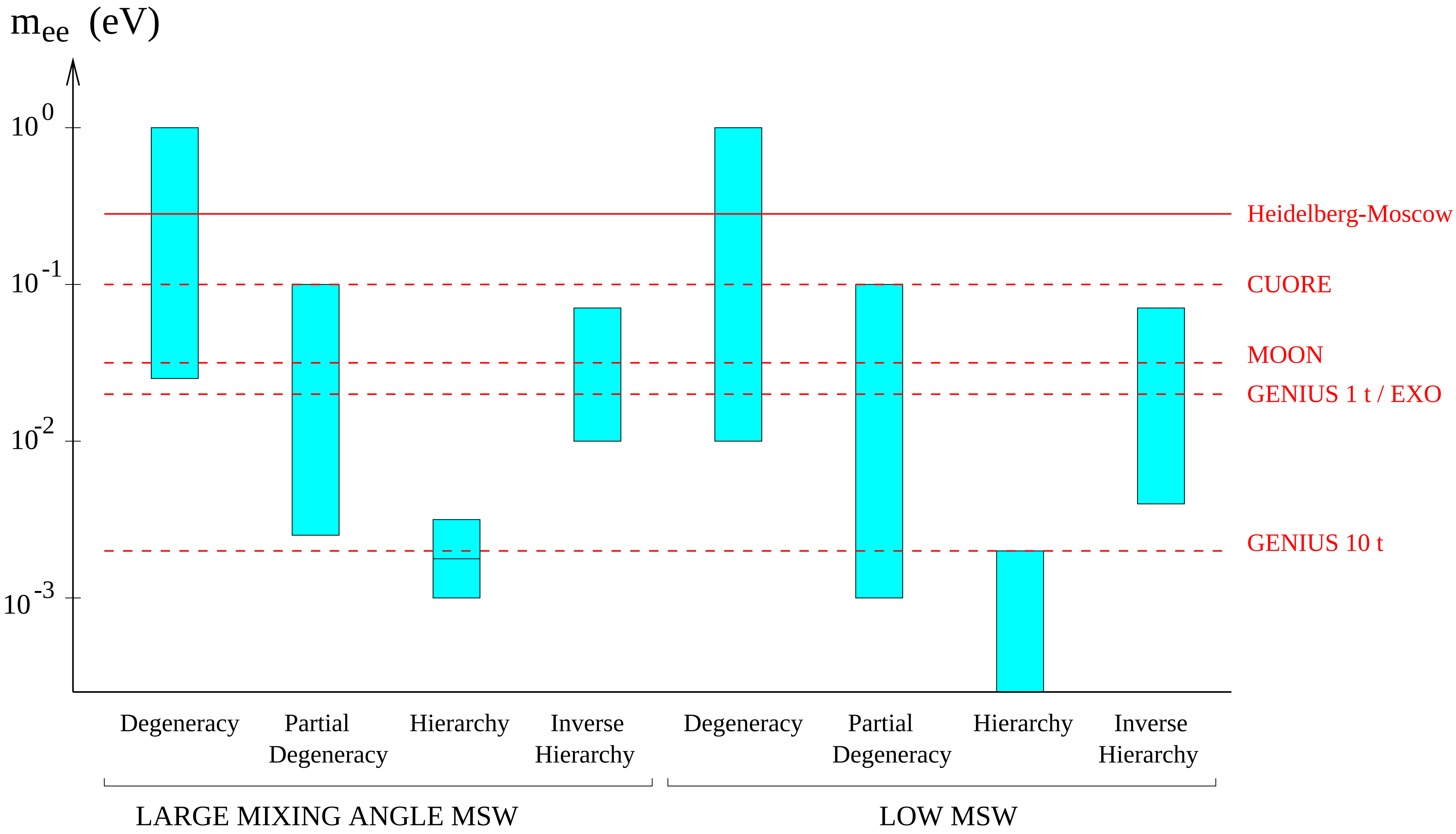


Anomalie: Extreme energy cosmic rays above GZK cutoff (due to scattering on CMB γ's)

Possible solution: Resonant scattering of extreme energy ν's on relic ν background at $E_\nu^R = 2m_Z^2/(2m_\nu)$
(T.J. Weiler, Astroparticle Physics 11 (1999) 303)

Drawback: High ν fluxes required, ν halo clustering helps!

$\Rightarrow$ $m_\nu \gtrsim$ 0.1 eV predicted!



m_{ee} (eV)
10^0
10^{-1}
10^{-2}
10^{-3}
Heidelberg-Moscow
CUORE
MOON
GENIUS 1 t / EXO
GENIUS 10 t
Degeneracy
Partial Degeneracy
Hierarchy
Inverse Hierarchy
Degeneracy
Partial Degeneracy
Hierarchy
Inverse Hierarchy
LARGE MIXING ANGLE MSW
LOW MSW

Conclusions

- Future $0\nu\beta\beta$ projects can test all scenarios but the hierarchical LOW solution (disfavored by SN87A: M. Kachelriess, R. Tomas, J.W.F. Valle, JHEP 0101 (2001) 030)

- The following conclusions for the mass spectrum can be drawn:

  - $\langle m \rangle > 0.1$ eV:
    Degenerate neutrinos,
    region for absolute mass depending on $\sin^2 2\theta_\odot$,
    (KAMLAND determines $\sin^2 2\theta_\odot$ within ±0.1 with 3 years of measurement: V. Barger, D. Marfatia, B.P. Wood, hep-ph/0011251)

  - $\langle m \rangle \simeq 0.01 - 0.1$ eV:
    Degenerate neutrinos, partial degeneracy or inverse hierarchy,
    region for absolute mass, provided that inverse/direct hierarchy can be determined in matter oscillations (inverse already disfavored)

  - $\langle m \rangle > 0.001 - 0.01$ eV:
    Partial degeneracy or inverse hierarchy,
    conclusions as above

  - $\langle m \rangle \lesssim 0.001$ eV:
    Hierarchical spectrum

H.V. Klapdor-Kleingrothaus, H. Päs, A.Yu. Smirnov, hep-ph/0003219 & PRD, in the press
H. Päs, T.J. Weiler, hep-ph/0101091, PRD, in the press