Reach of future non-accelerator neutrino efforts

Reyco Henning
U. of North Carolina
and
Triangle Universities National Laboratory
North Carolina, USA

Overview

- Current knowledge of neutrino properties
- Non-accelerator based experimental reaches:
  - Neutrinoless double beta-decay
  - Direct mass measurements
  - Limits from cosmology
  - Reactor neutrinos
  - Solar neutrinos
  - Cosmic-rays neutrinos
  - Others
- Conclusion & Open Issues

Neutrino Flavor Mixing

Compelling evidence propagating neutrinos undergo flavor oscillations.

In 3-neutrino mixing model:

Mass to flavor relationship described by PMNS neutrino mixing matrix with 5 parameters:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

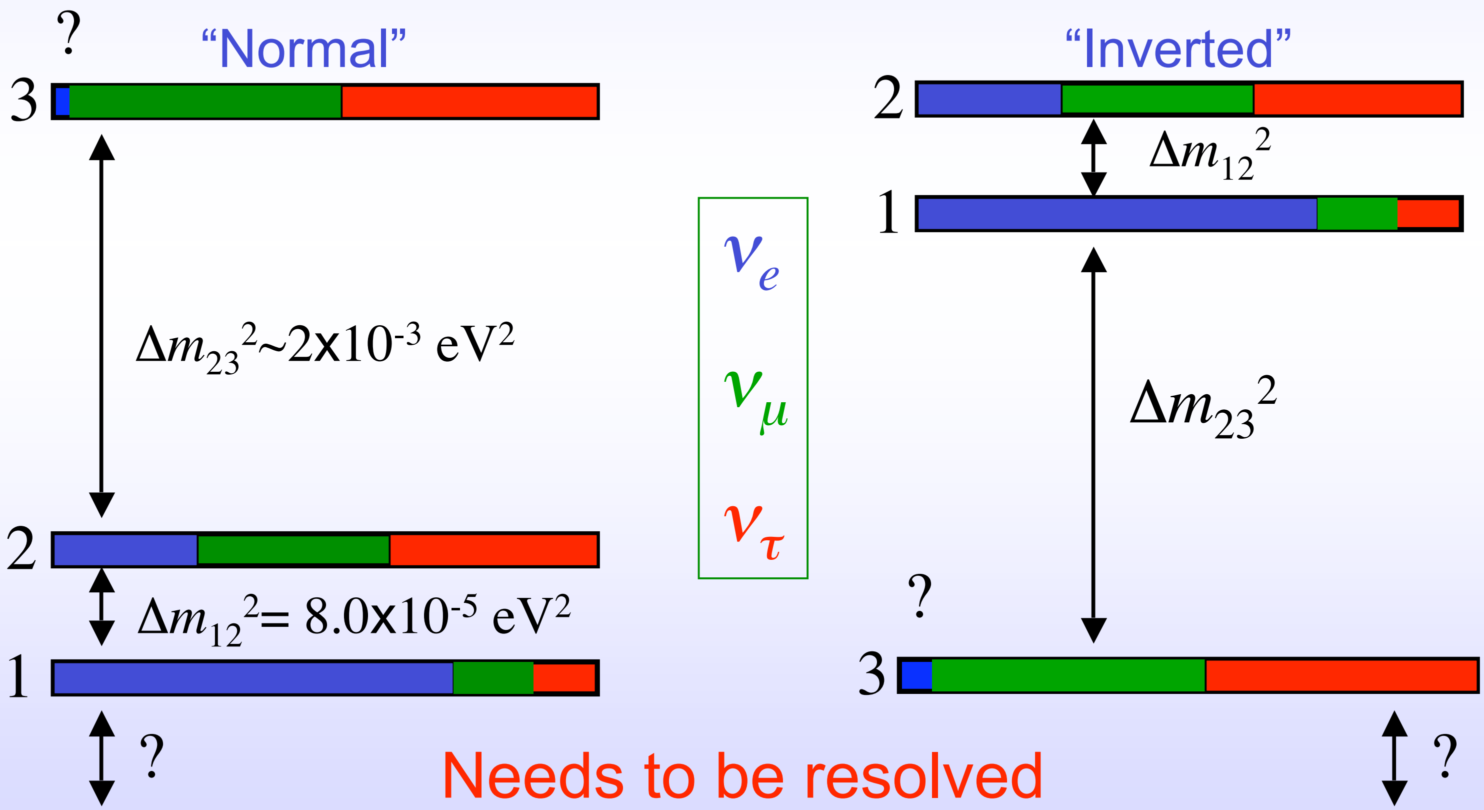
Majorana Phases

Neutrino Masses

Absolute masses weakly constrained.

Relative mass-squared differences known.

Three possible scenarios: Quasi-degenerate, also:



Current Best Values

(PDG 2007)

Parameter	**Value**	**Method**
$\sin^2(2\theta_{12})$	$0.86^{+0.03}_{-0.04}$	Solar+ KamLAND
$\sin^2(2\theta_{23})$	>0.92	Atmospheric ν
$\sin^2(2\theta_{13})$	<0.19	Reactor (CHOOZ)
$\lvert\Delta m^2_{32}\rvert$	$1.9\text{-}3.0\times10^{-3}$ eV^2	Super-K+MINOS
$\lvert\Delta m^2_{21}\rvert$	$8.0\pm0.3\times10^{-5}$ eV^2	Solar+ KamLAND
α_1, α_2	?	DBD?
δ	?	Future LBL?

Neutrinoless double-beta decay ($0\nu\beta\beta$)

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-}$$

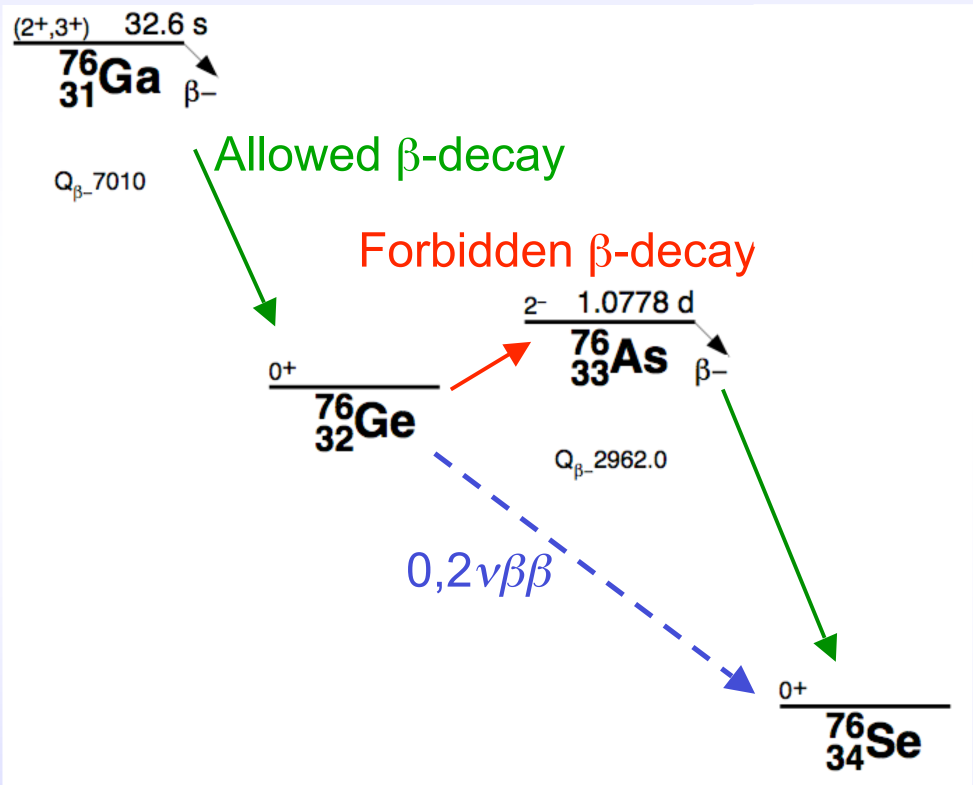
Violates Total Lepton Number Conservation

Existence implies Neutrino is Majorana fermion*

Also ECEC, $e^{+}e^{+}$, ECe^{+}

$2\upsilon\beta\beta$: Observed 2nd order weak process.

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-} + 2\overline{\nu}_{e}$$



*Schechter et al, Phys. Rev. D**25**, 2951 (1982)

Majorana vs. Dirac

$\stackrel{?}{=}$

- DBD implies Majorana mass term in Lagrangian that mixes ν and $\bar{\nu}$.
- No good QM # to distinguish between ν and $\bar{\nu}$.
- **Experimental evidence consistent with both Majorana or Dirac neutrinos.**
- Verification difficult due to small neutrino masses.

Ettore Majorana

Paul Dirac

The observation of neutrinoless double-beta decay is the only practical way to show that the neutrino is Majorana.

$0\nu\beta\beta$ Rate and Neutrino Mass

Majorana

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0,Z)\left|\langle m_{\beta\beta}\rangle\right|^2\left|M^{0\nu}\right|^2$$

$T_{1/2}^{0\nu}$: Half-life

$G^{0\nu}$: Phase Space (Known)

$M^{0\nu}$: Nuclear Matrix Element (large uncertainty)

$$\left|< m_{\beta\beta} >\right| = \left|\sum_i \left|U_{ei}\right|^2 m_{\nu_i} e^{i\alpha_i}\right|$$

Effective Majorana electron neutrino mass*

- ☞ $0\upsilon\beta\beta$ decay can probe **absolute** neutrino mass scale and mixing.
- ☞ Current neutrino experiments measure mass squared differences: Δm^2.

* Assumes ν_m exchange

Upcoming Experimental Program and Reach

Majorana?

- Experiments require extreme reduction in radioactive backgrounds (underground sites, materials, analysis, etc…)
- Current generation:
  - 10s of kg of enriched isotope
  - $T_{1/2} \sim 10^{26}$-10^{27} years
  - $m_{\beta\beta} \sim 100$ meV
  - ~$10-20M
- Next Generation (~10 years from now):
  - ~ 1 tonne of enriched isotope
  - $T_{1/2} \sim 10^{28}$ years
  - $m_{\beta\beta} \sim 20$meV (atmospheric mass-scale)
  - ~$100-200 M

Selected Current and Future Experiments

Many different technologies…

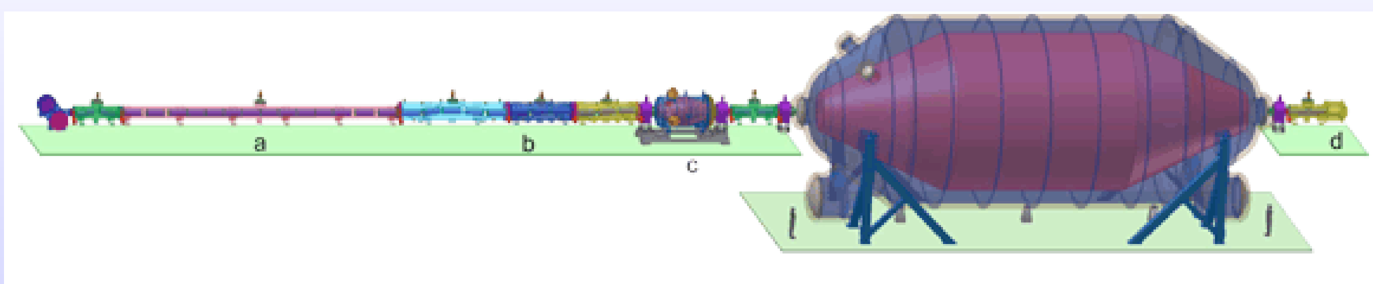
Cryogenic Bolometry	CUORE/Cuoricino-^{130}Te
Scintillation	CAMEO-^{116}Cd, CANDLES-^{48}Ca, EXO-^{136}Xe, SNO+ ^{150}Nd XMASS- ^{136}Xe
Ionization	COBRA-CdTe , GERDA-^{76}Ge (LA MAJORANA-^{76}Ge
Time Projection and Tracking	MOON-^{100}Mo, Nemo/Super-Nemo (many), HPXeTPC-^{136}Xe, DCBA-^{150}Nd

Possible Discovery Requires Confirmation with Different Isotope(s)

Direct Mass Measurements

- Tritium beta decay endpoint measurements
- Current: m_β < 2eV
- New Generation: KATRIN (Karlsruhe Tritium Neutrino Experiment)
  – Massive spectrometer
  – Sensitivity to m_β = 0.2eV
  – Anticipated Start in 2009, 5 year run.
- Cryogenic bolometers promising future alternative.

$$< m_\beta > = \sum_i \left|U_{ei}\right|^2 m_i^2$$



KATRIN Main Spectrometer

(world’s largest beer keg)

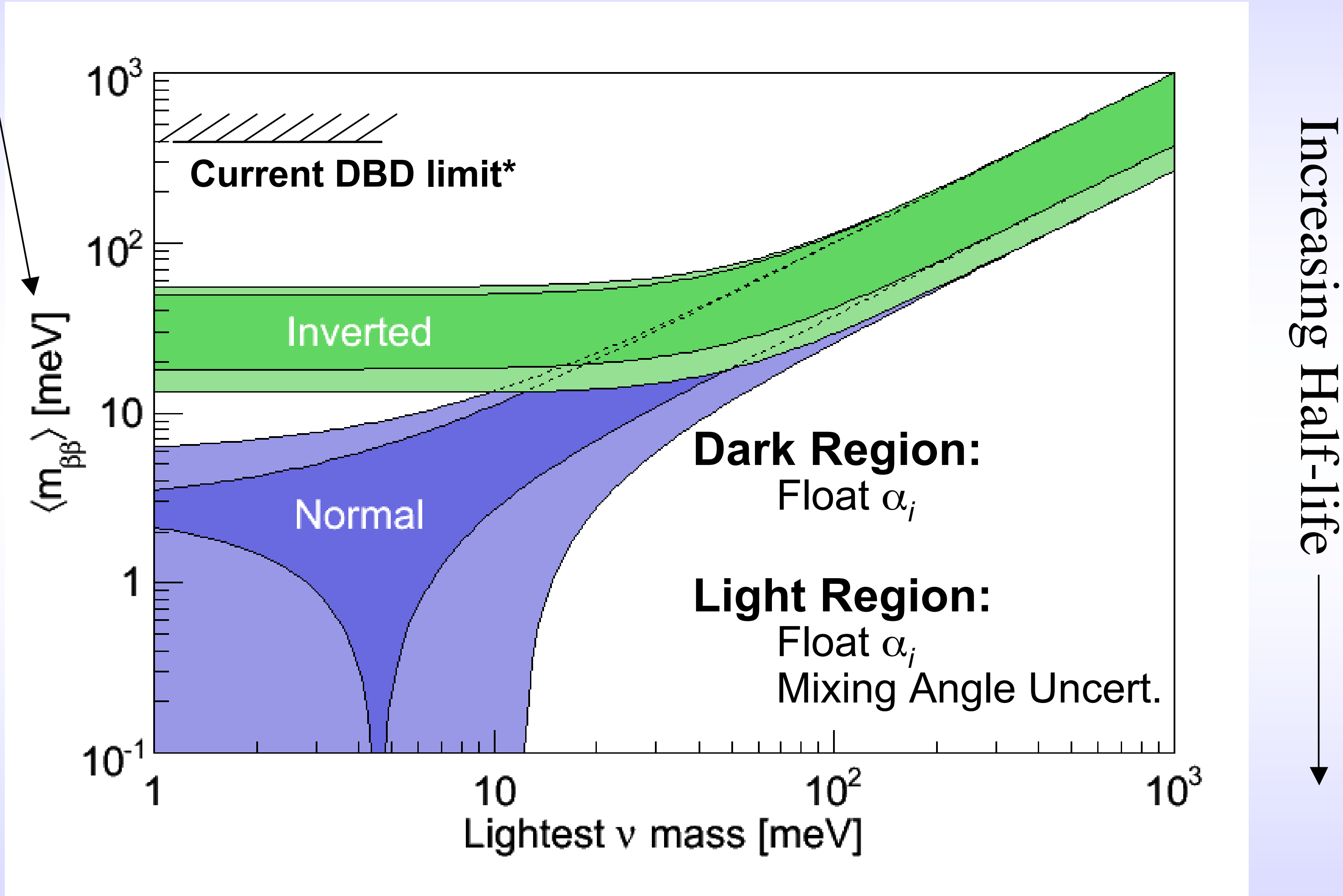
Indirect Limits from Cosmology

- Relic Big Bang Neutrinos
  - $T = 1.7\text{K}$
  - $\rho \sim 300\ \text{cm}^{-3}$
- $\boldsymbol{m_1+m_2+m_3 < 0.17\text{eV}}$
  - JCAP 0610:014,2006. Recent CMB, large scale structure, Lyman-α forest, and SN1a data.
- Model-dependent
- Possible improvement with better understanding of systematics.
- Factor of 2 improvement probes inverted hierarchy.

$0\nu\beta\beta$ Mass Limits

$$|\langle m_{\beta\beta}\rangle| = \left|\sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i}\right|$$

Image: A. G. Schubert and J. Detwiler



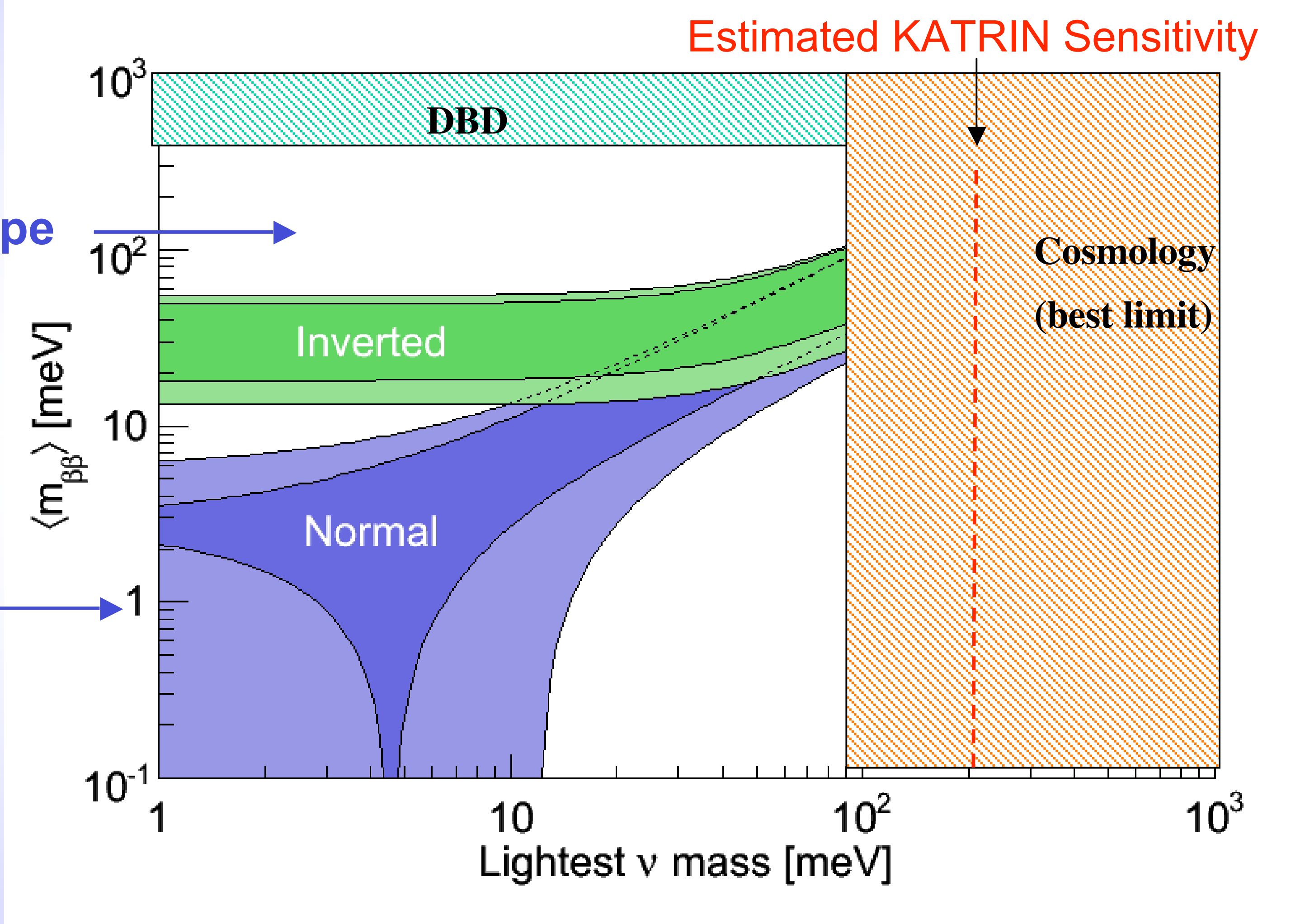
*IGEX & KKDC Limits, excluding controversial discovery claim

Combined Mass Limits

~ 100kg isotope

~ 1 ton

~ 100 ton



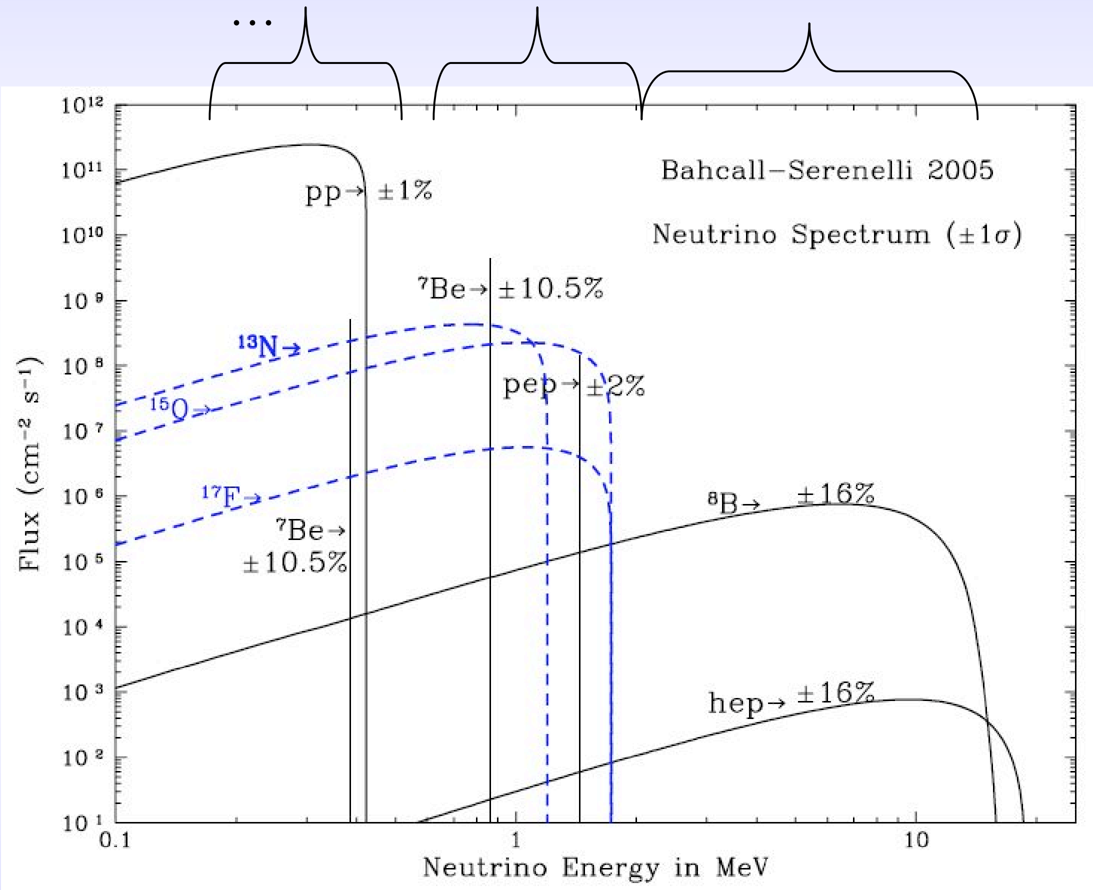
Solar Neutrinos

Gd
CLEAN
LENS
…

Borexino
KamLAND
Cl

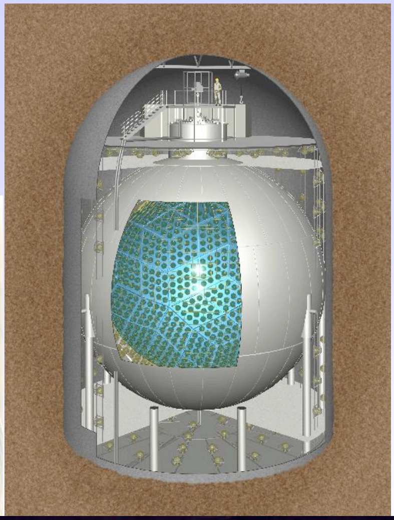
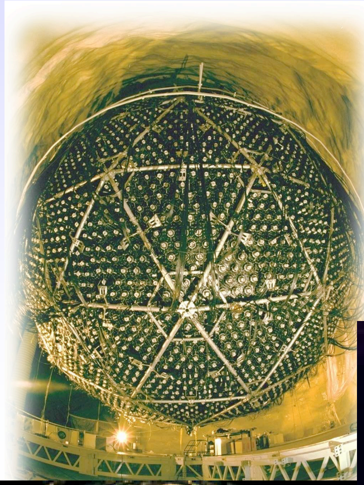
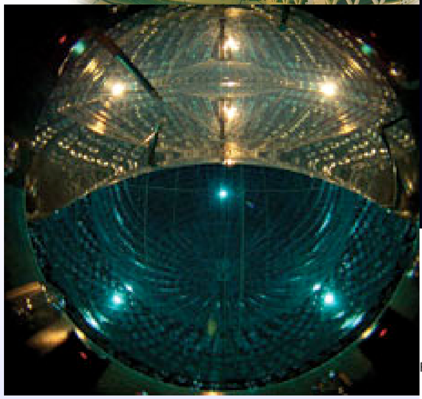
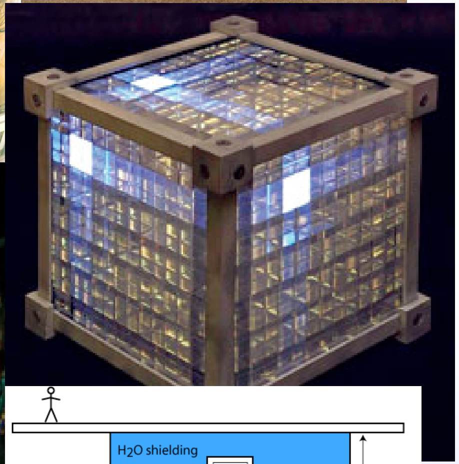
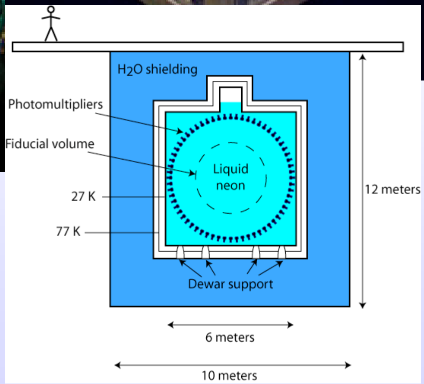
SNO
Super-K

- First evidence of oscillations
- Constrain θ_{12} via $\nu_e \rightarrow \nu_x$
- Measurements of ^8B flux described by Large Mixing Angle with matter (MSW) effects.
- Lower energy (<2 MeV) solar neutrinos insensitive to MSW effect.
  - Probe vacuum oscillations



Solar Neutrino Status

- SNO will present results of final NCD phase soon.
- Borexino and KamLAND-solar running
  - Measure ^{7}Be flux
  - Some published early results
  - Verify Solar model
- CLEAN, LENS, others in proposal phase.
  - Measure pp flux, the dominant source of neutrinos from sun.
  - Verify solar model
  - 10 year timescale

Other Probes

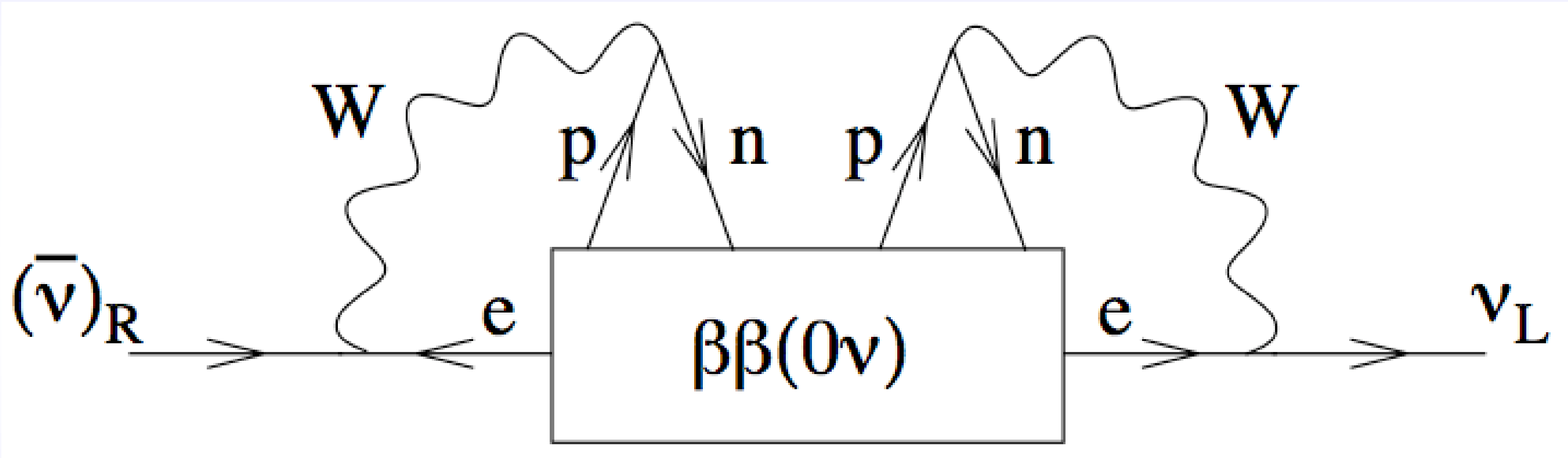
- Cosmic-rays:
  - Atmospheric: Verify LBL results
  - UHECR: Astrophysical Applications
- Coherent neutrino scattering:
  - Unobserved SM process.
  - Magnetic dipole moment - Probe for NP.
- Supernovae (prompt and relic)
- Geoneutrinos
- Neutrino-induced nuclear decays: zero-threshold
- Neutron-antineutron oscillations

Conclusion and Current Projects

- Current emphasis on
  - Neutrinoless DBD
  - θ_{13}
- Probe degenerate mass scale with current generation of DBD experiments.
- Improve direct mass measurements to 0.2eV.
- Cosmology a sensitive probe.
- Verify solar neutrino results.

Backups

$0\nu\beta\beta$–decay and Majorana Neutrinos



Schechter et al, Phys. Rev. D**25**, 2951 (1982)

Majorana nature verification ***independent*** of process that mediates $0\nu\beta\beta$ decay!

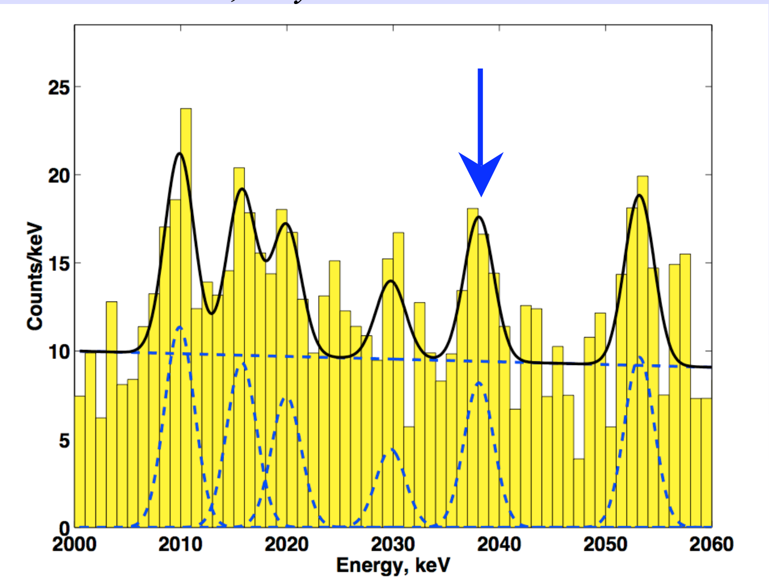
A Recent Claim

Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

KKDC used five ^{76}Ge crystals, with a total of 10.96 kg of mass, and 71 kg-years of data.

$T_{1/2} = 1.2 \times 10^{25}$ y

$0.24 < m_{\nu} < 0.58$ eV (3 sigma)

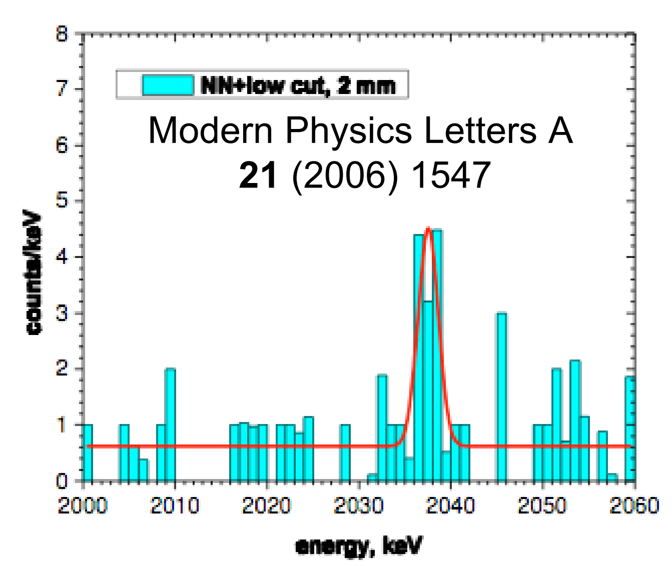


Background level depends on intensity fit to other peaks.

A More Recent Claim

6.8 sigma

Neural Net Analysis



Current Limits

~40 years of work

Isotope	Half-life Limit (y)	$|\langle m_\nu \rangle|$ limit (eV)
Ca-48	$>9.5\times10^{21}$ (76%)	<8.3
Ge-76	$>1.9\times10^{25}$	<0.35
	$>1.6\times10^{25}$	<0.33 – 1.35
Se-82	$>2.7\times10^{22}$ (68%)	<5
Mo-100	$>5.5\times10^{22}$	<2.1
Cd-116	$>7\times10^{22}$	<2.6
Te-128,130	From ratio of $T_{1/2}$s	<1.1 – 1.5
Te-128	$>7.7\times10^{24}$	<1.1 – 1.5
Te-130	$>1.4\times10^{23}$	<1.1 – 2.6
Xe-136	$>4.4\times10^{23}$	<1.8 – 5.2
Nd-150	$>1.2\times10^{21}$	<3

Background Identification

- Majorana is background limited.
- Goal: 1 event / ton-year in 4 keV ROI
- Backgrounds:
  - Compton scattered gammas, surface alphas.
  - Natural isotope chains: ^{232}Th, ^{235}U, ^{238}U, Rn
  - Cosmic Rays:
    - Activation at surface creates ^{68}Ge, ^{60}Co.
    - Hard neutrons from cosmic rays in rock and shield.
  - $2\nu\beta\beta$-decays.
- Need factor ~100 reduction over what has been demonstrated.
- Monte Carlo estimates of acceptable levels