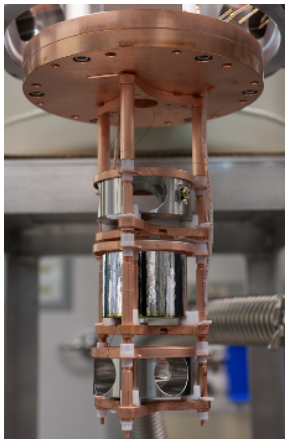
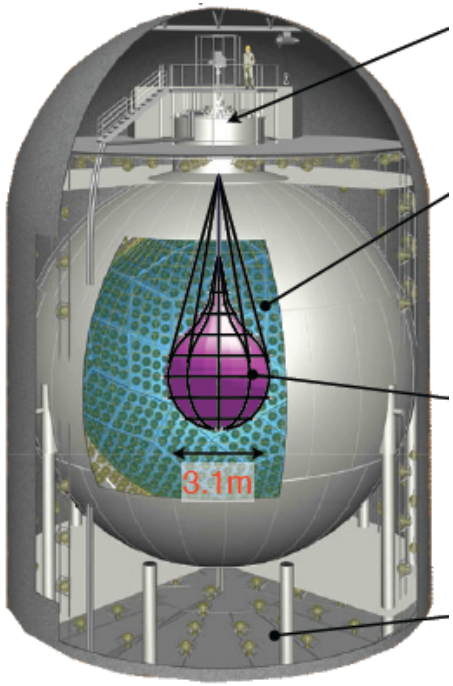
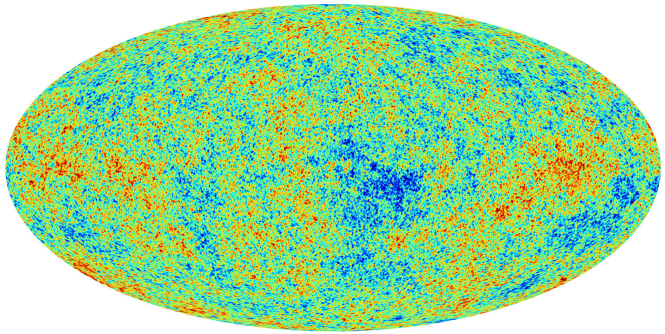
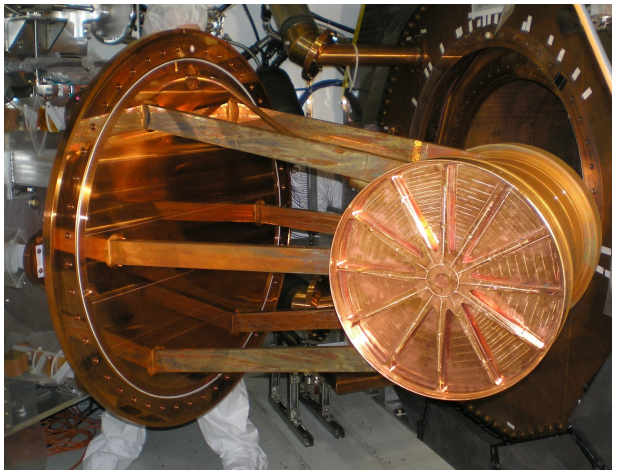


Prospects for Absolute Neutrino Mass Measurements

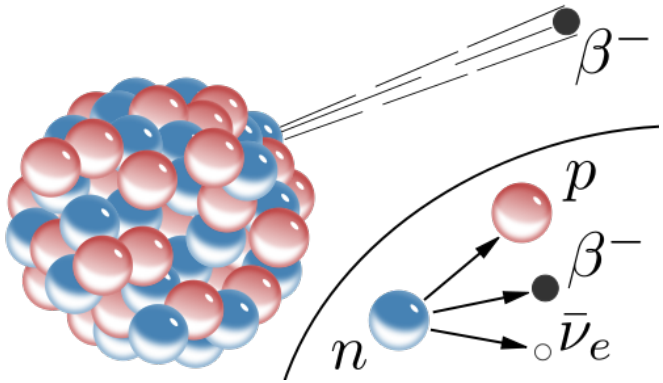
Carter Hall, Univ. of Maryland

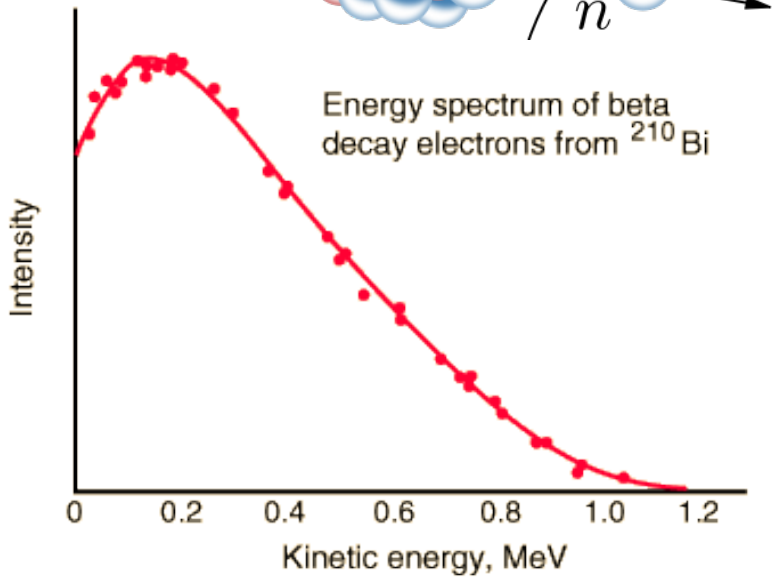






Neutrino mass from beta decay (1932)





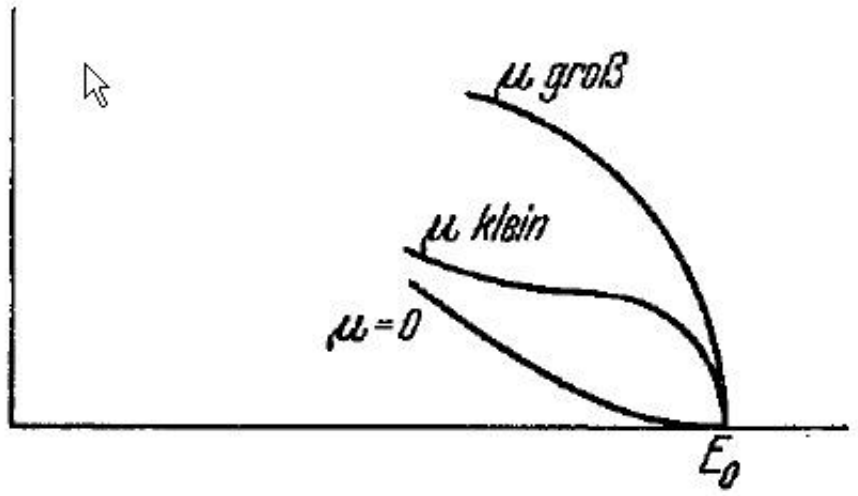
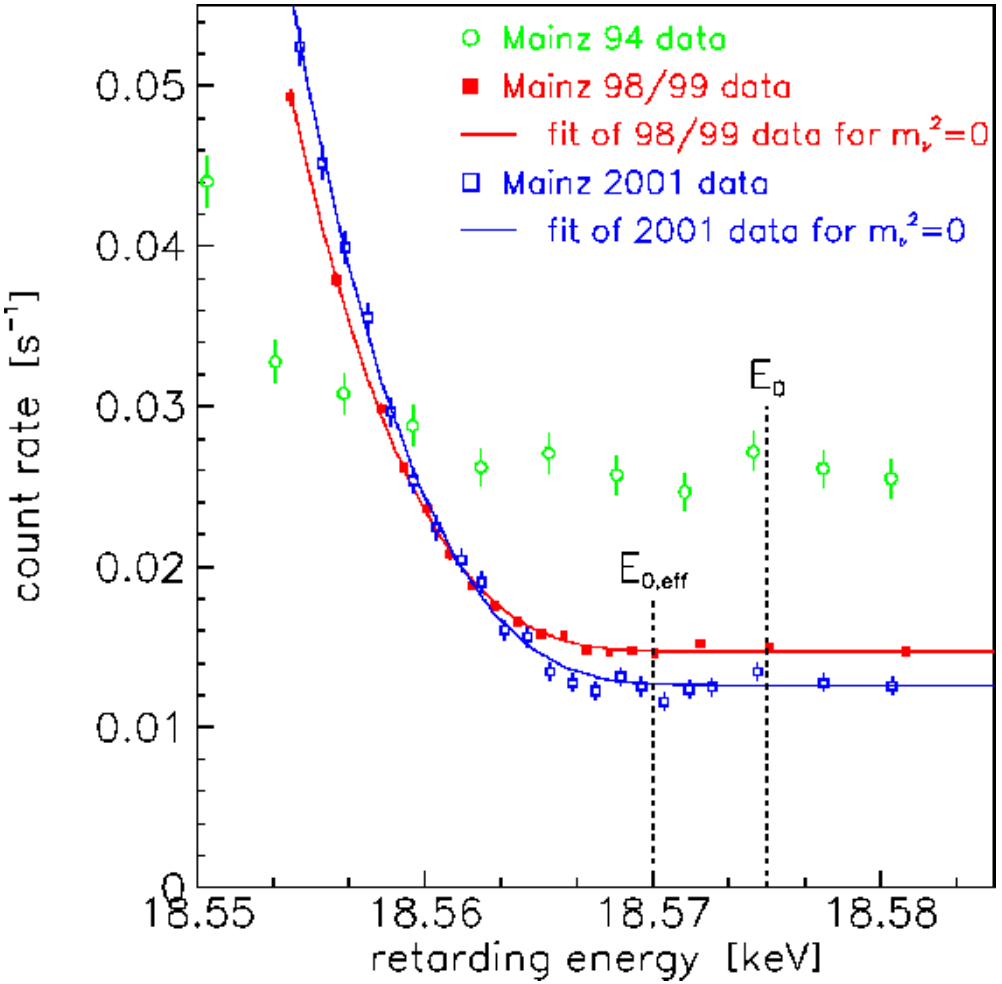


Fig. 1.

"The greatest similarity to the empirical curve is given by the theoretical curve for m = 0. Hence we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron."

Mainz tritium beta decay experiment (2005)



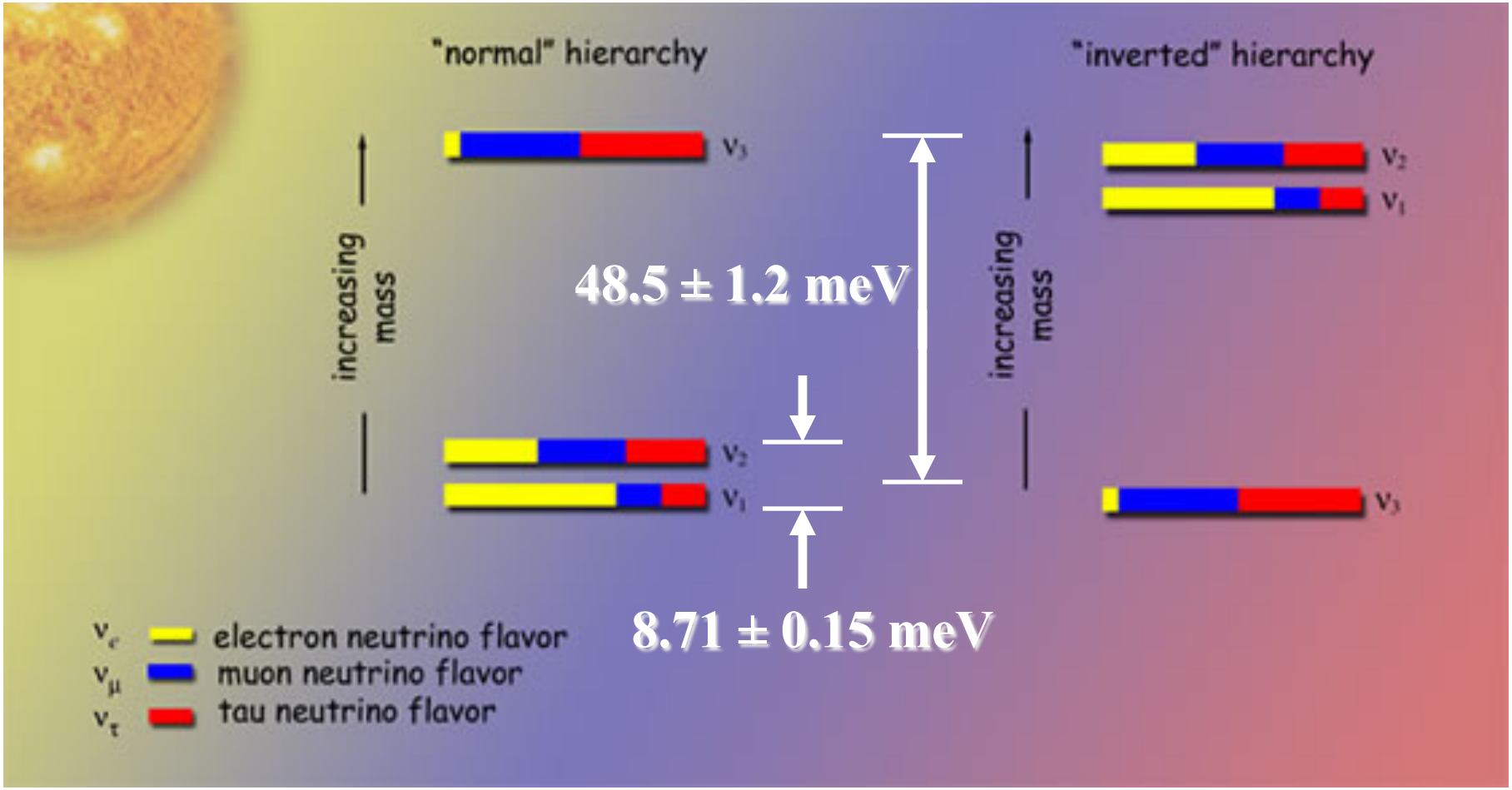
$$m^2(\nu) = \sum_i |U_{ei}|^2 m^2(\nu_i)$$

(incoherent sum)

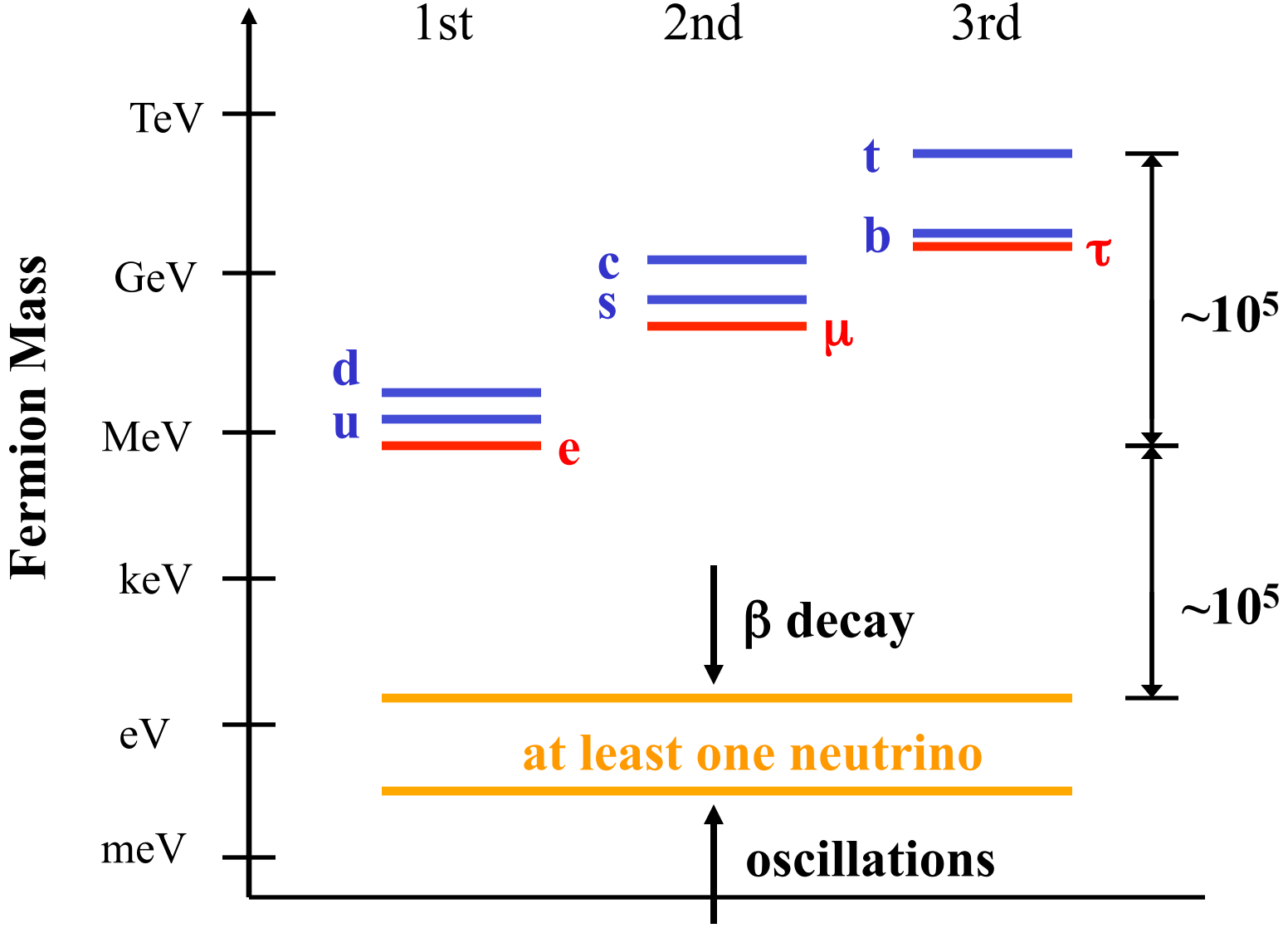
Mainz: $m^2(\nu) = -0.6 \pm 2.2 \pm 2.1$ eV2 ➔ $m(\nu) < 2.3$ eV (95% C.L.)

Troisk experiment (2011): $m(\nu) < 2.05$ eV (95% C.L.)

Neutrino mass spectrum



Spin 1/2 mass spectrum

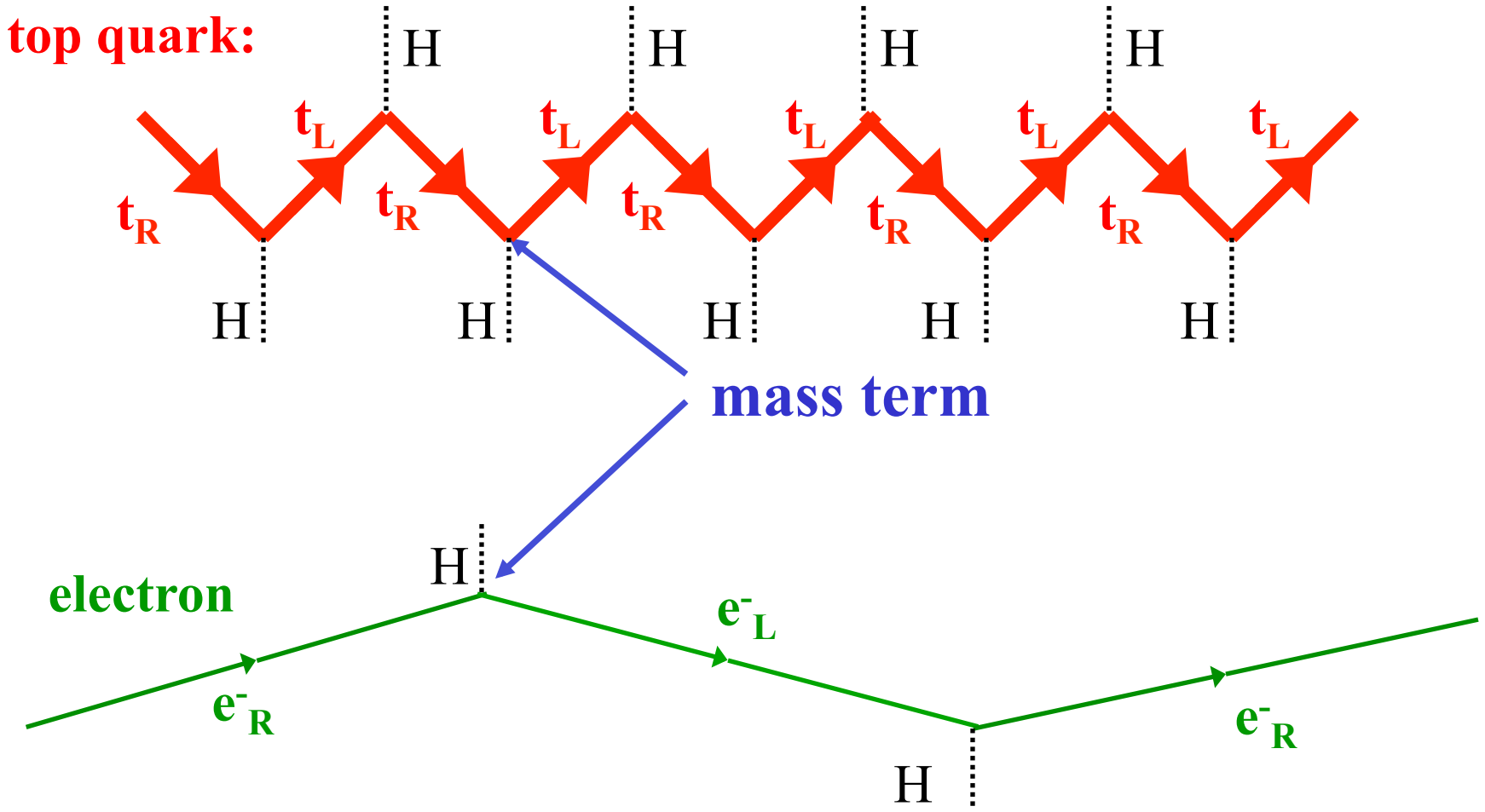


Is neutrino mass new physics?

"It's likely that neutrino mass is new physics, but we cannot yet be certain."

A standard model neutrino mass should be generated by a Yukawa coupling to the Higgs.

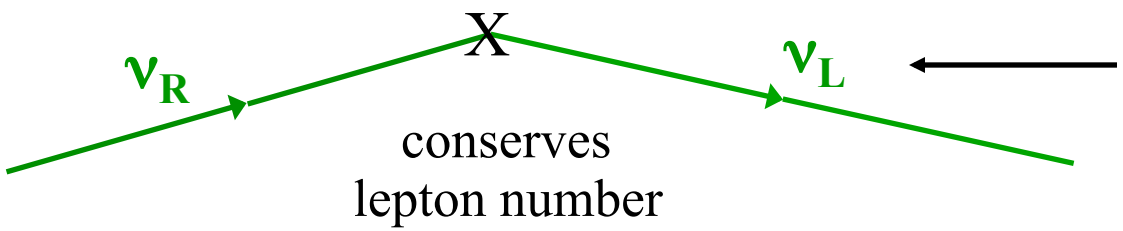
Fermions masses are due to the Higgs



Dirac mass term: conserves charge ($e^- \rightarrow e^-$)

Types of Neutrino mass terms

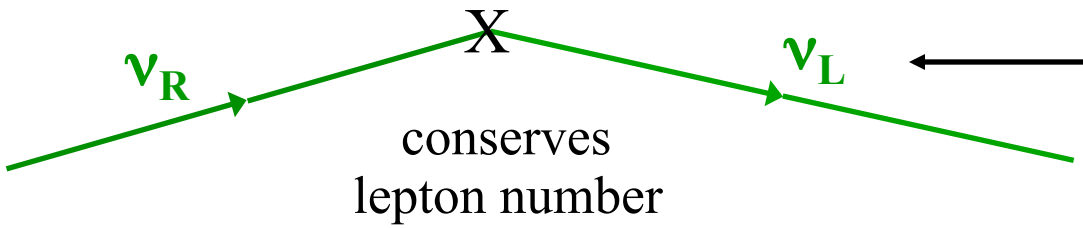
Dirac Neutrino Mass



Standard model
Higgs creates only
Dirac masses

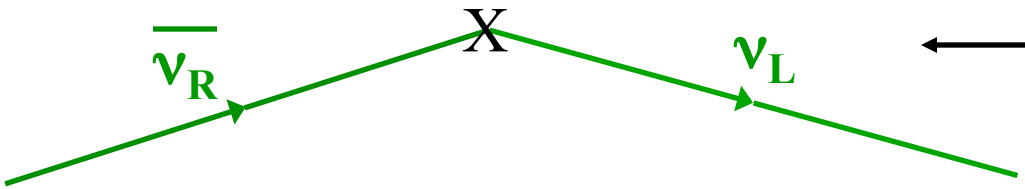
Types of Neutrino mass terms

Dirac Neutrino Mass



Standard model Higgs creates only Dirac masses

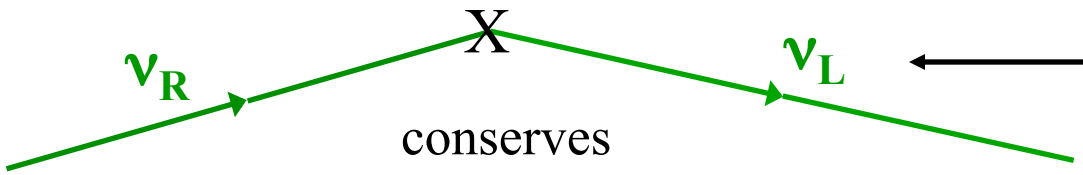
Majorana Mass 1



Requires new physics

Types of Neutrino mass terms

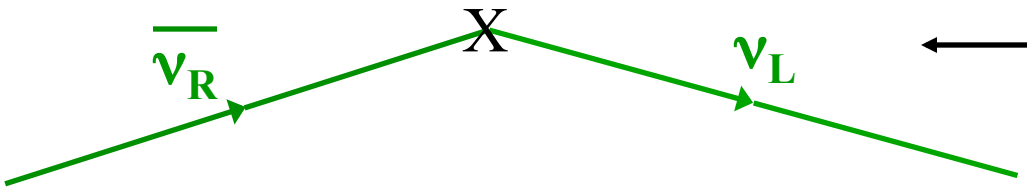
Dirac Neutrino Mass



conserves
lepton number

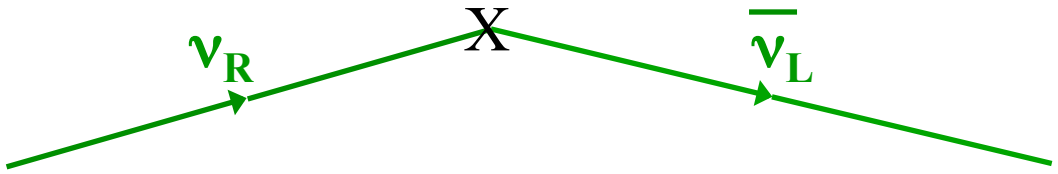
Standard model
Higgs creates only
Dirac masses

Majorana Mass 1



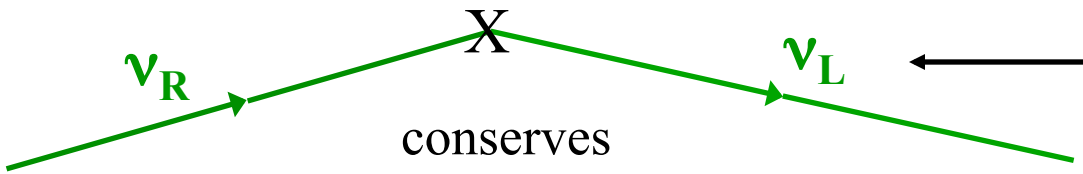
Requires new
physics

Majorana Mass 2



Types of Neutrino mass terms

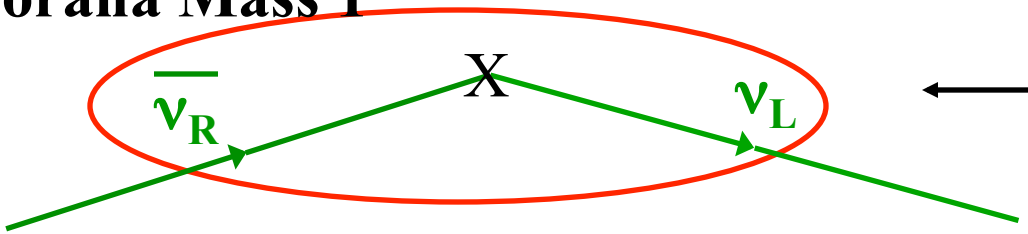
Dirac Neutrino Mass



conserves
lepton number

Standard model
Higgs creates only
Dirac masses

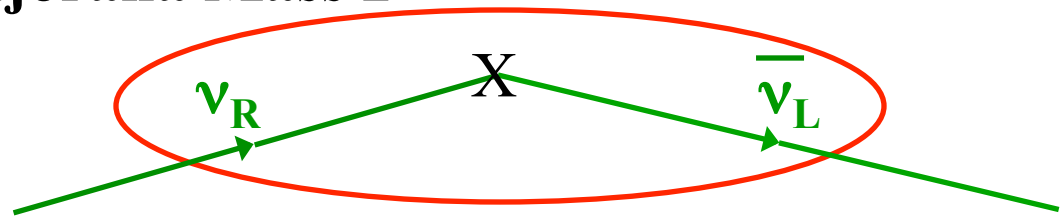
Majorana Mass 1



Requires new
physics

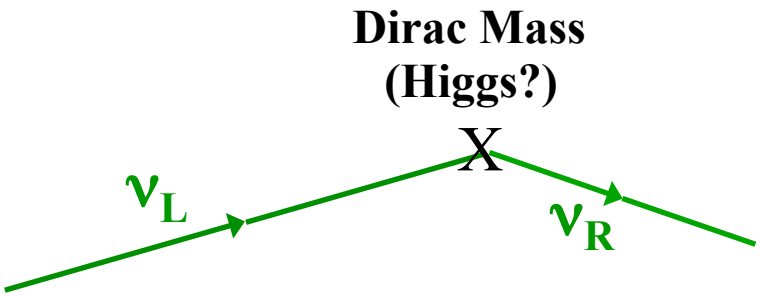
violates conservation of
lepton number

Majorana Mass 2

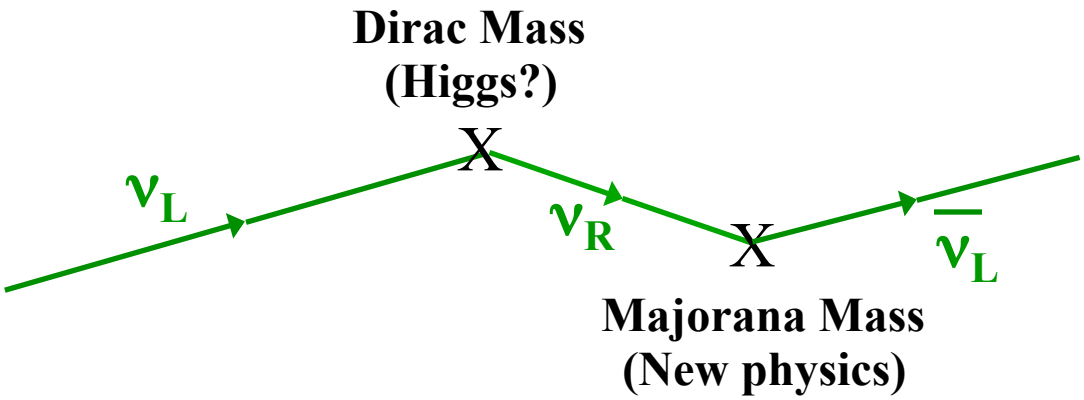


Neutrinos could, in principle, have more than one mass term.

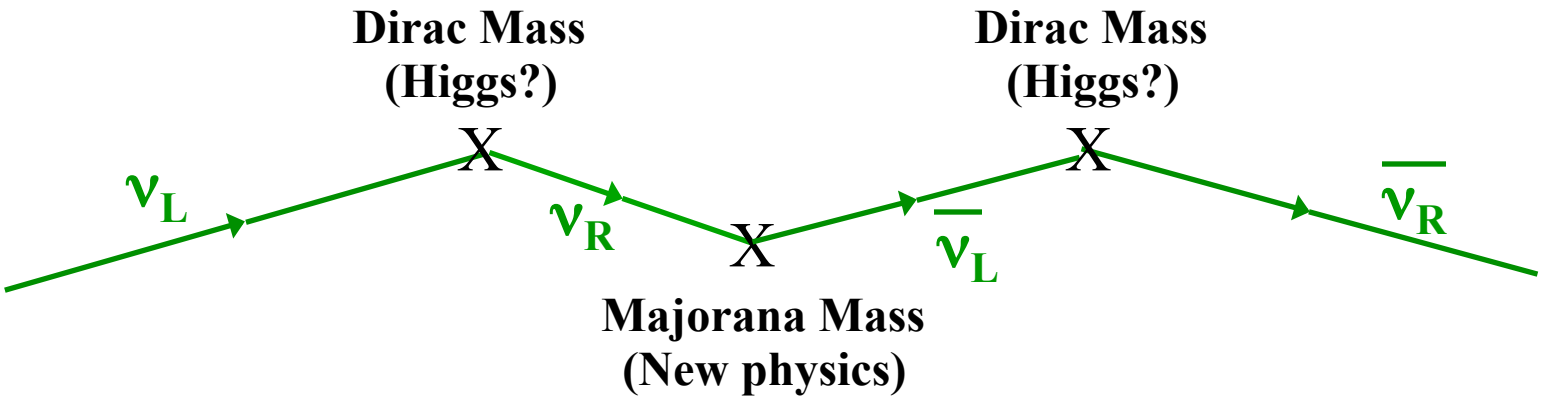
What if neutrinos have two mass terms?



What if neutrinos have two mass terms?



What if neutrinos have two mass terms?



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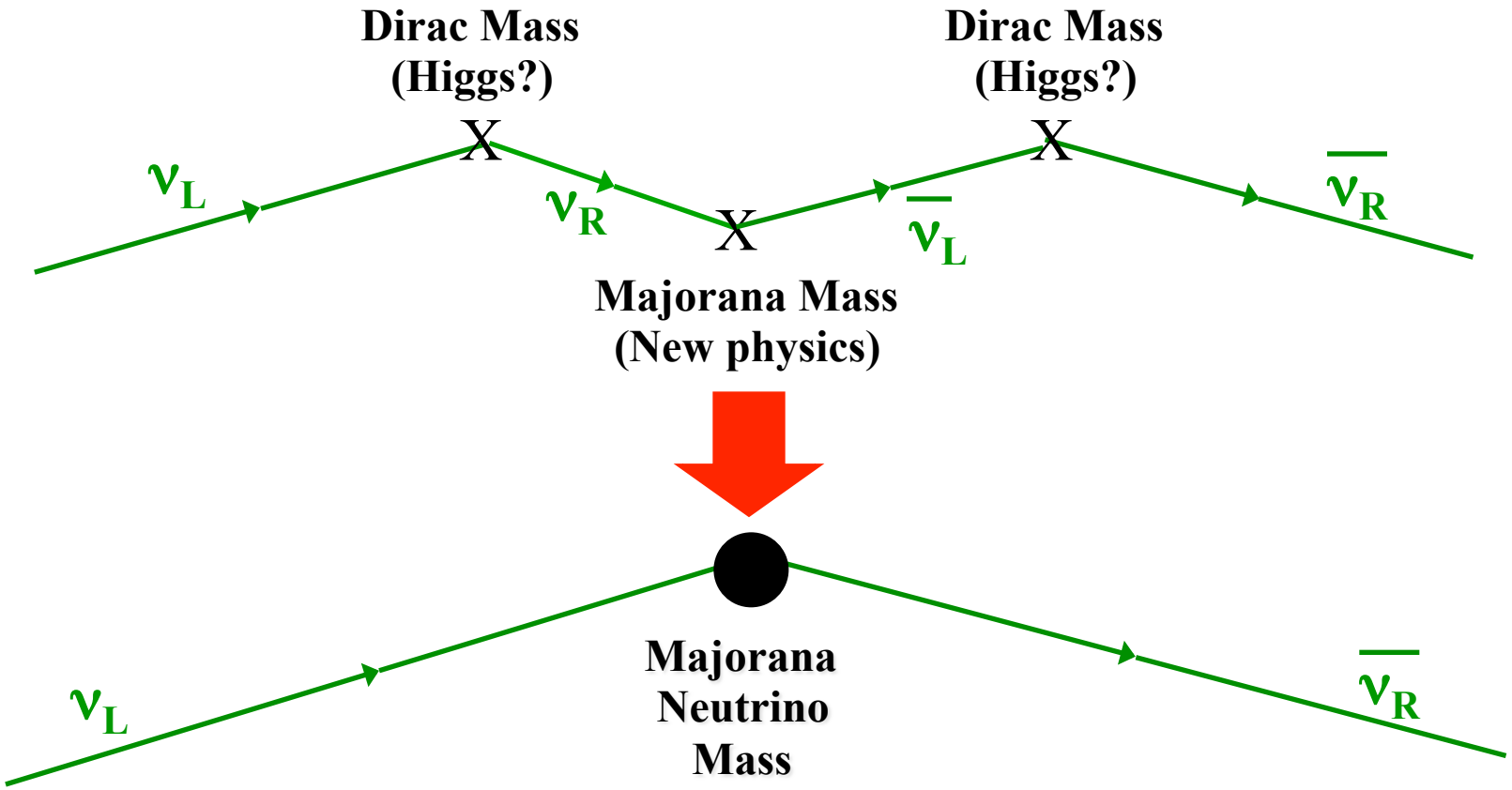
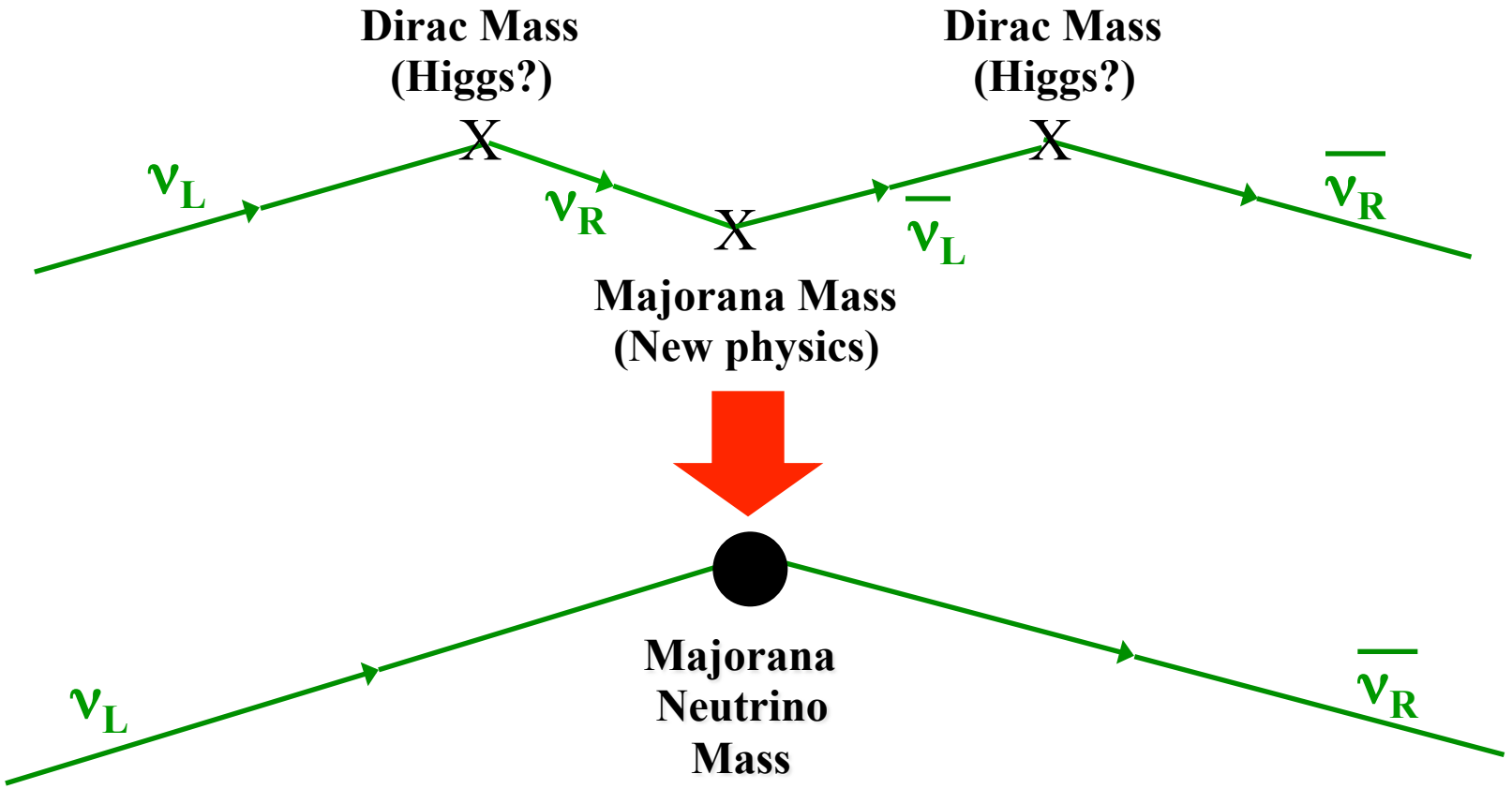


What if neutrinos have two mass terms?

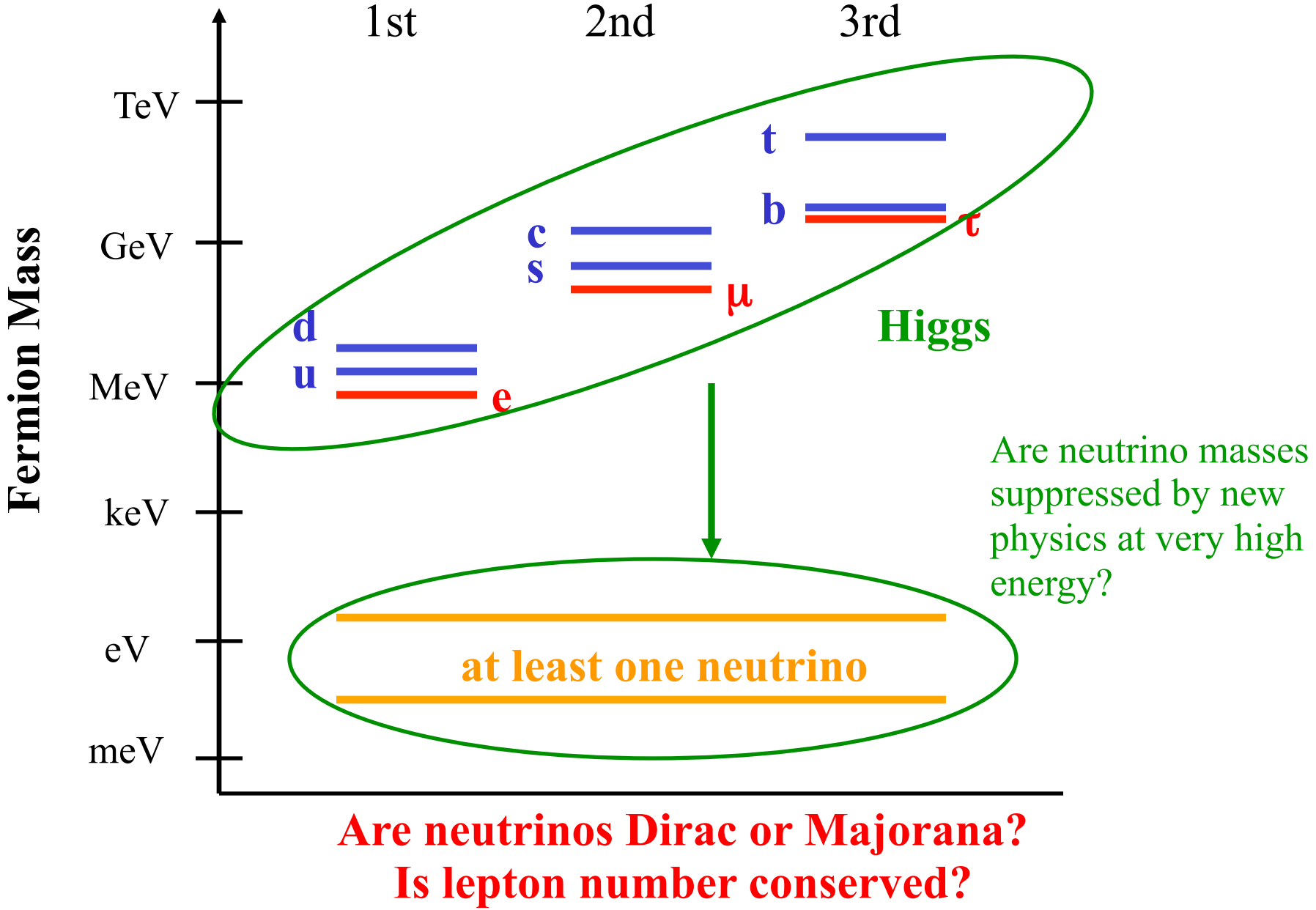


If neutrinos have more than one mass term, then they behave as Majorana particles.

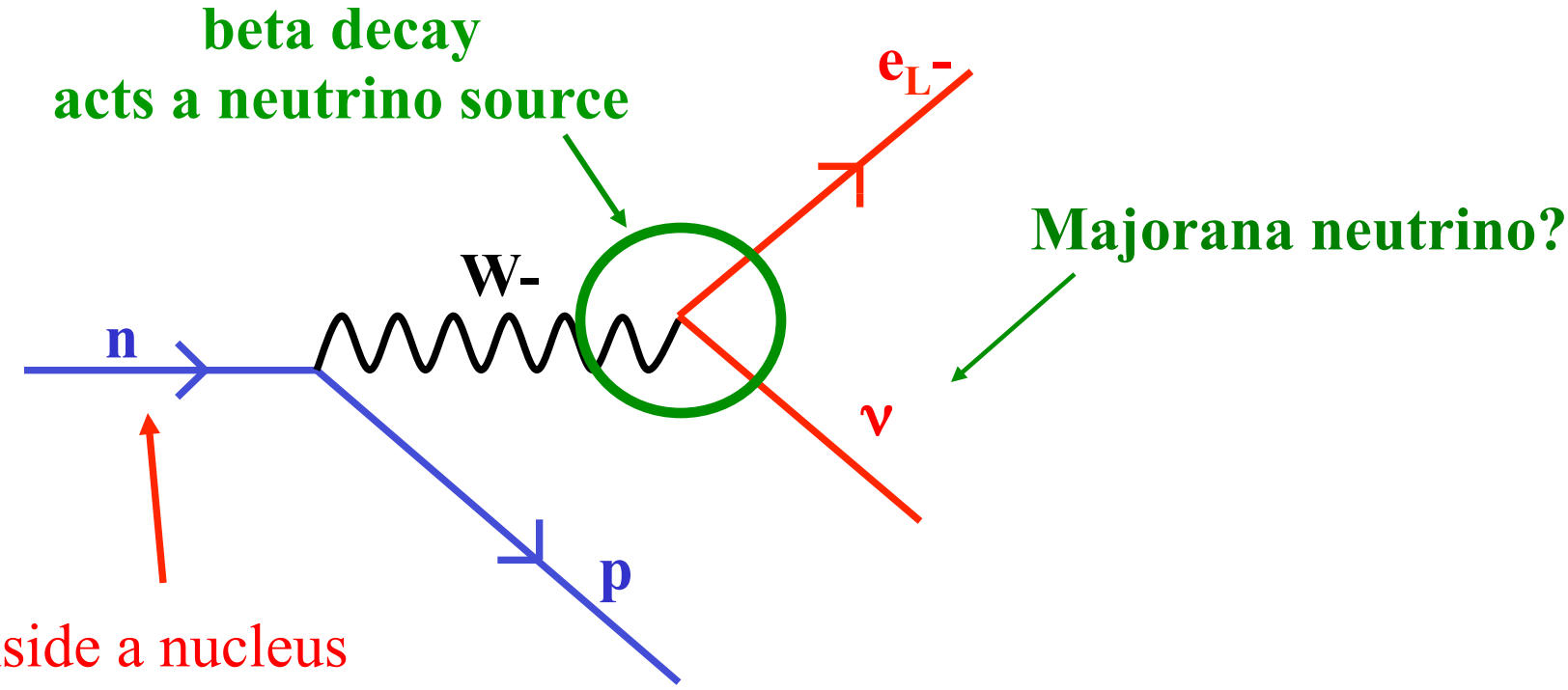
OR

A Dirac neutrino is a special case where both Majorana mass terms are exactly zero.

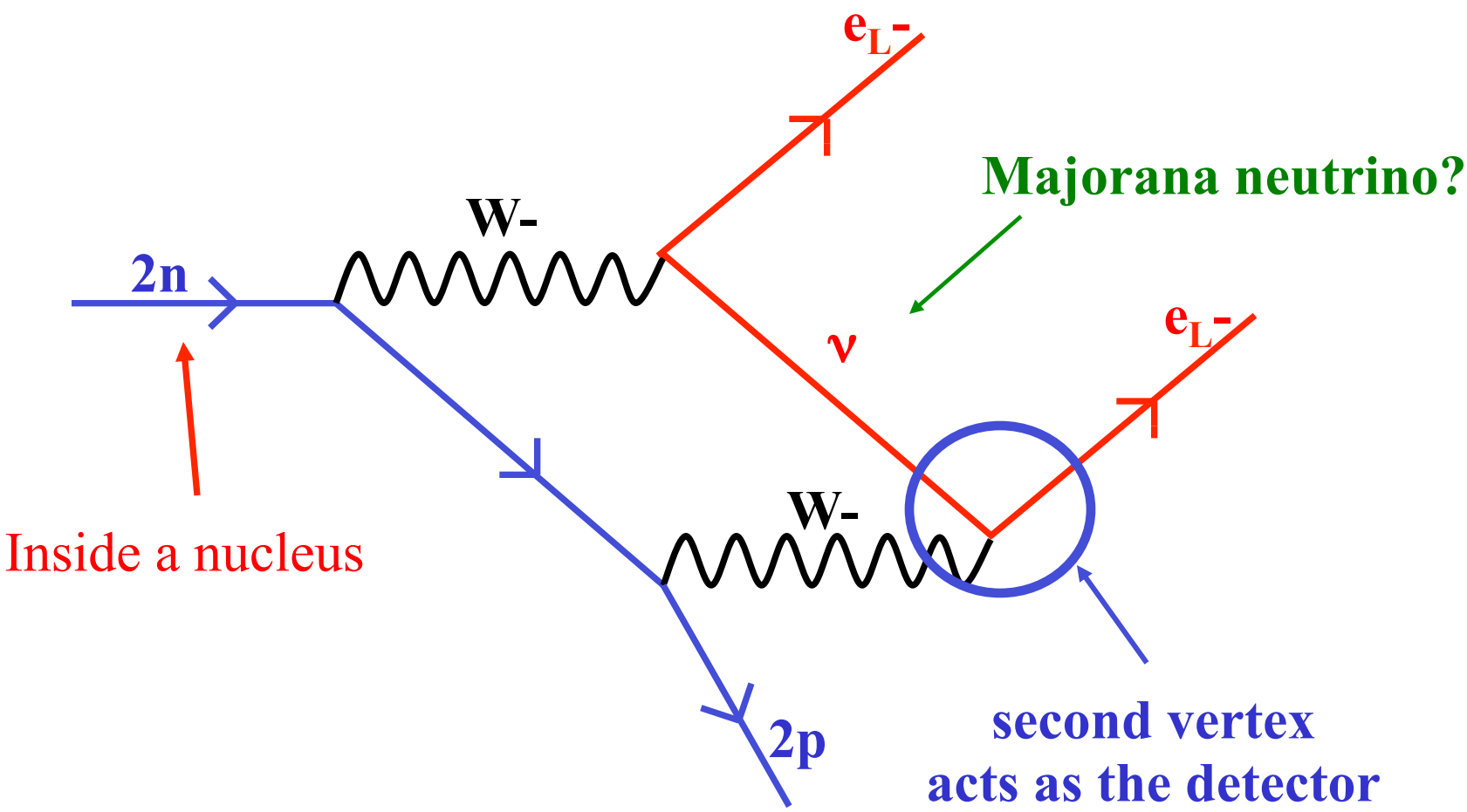
Spin 1/2 mass spectrum



Use nuclear physics to test neutrino charge properties:

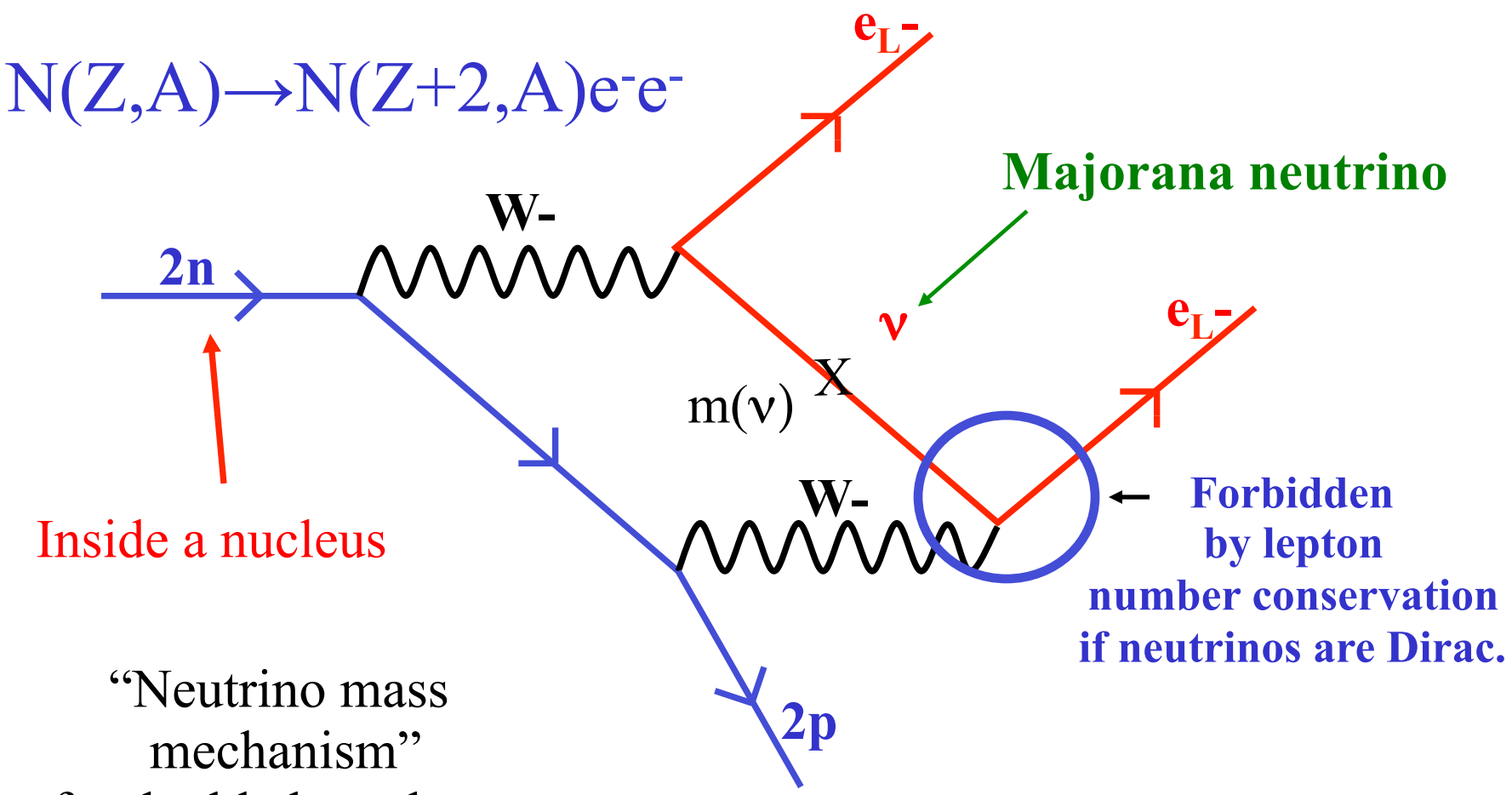


Use nuclear physics to test neutrino charge properties:



Neutrinoless Double Beta Decay ($\beta\beta0\nu$)

Forbidden if neutrino mass is Dirac only



ββ0ν half-life depends directly on m(ν)

Decay rate

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu\beta\beta} \cdot \left|NME\right|^2 \cdot \left|\left\langle m(\beta\beta)\right\rangle\right|^2, \quad \left\langle m(\beta\beta)\right\rangle = \sum_i U_{ei}^2 m(\nu_i) e^{i\alpha_i}$$

phase space

Nuclear Matrix Element

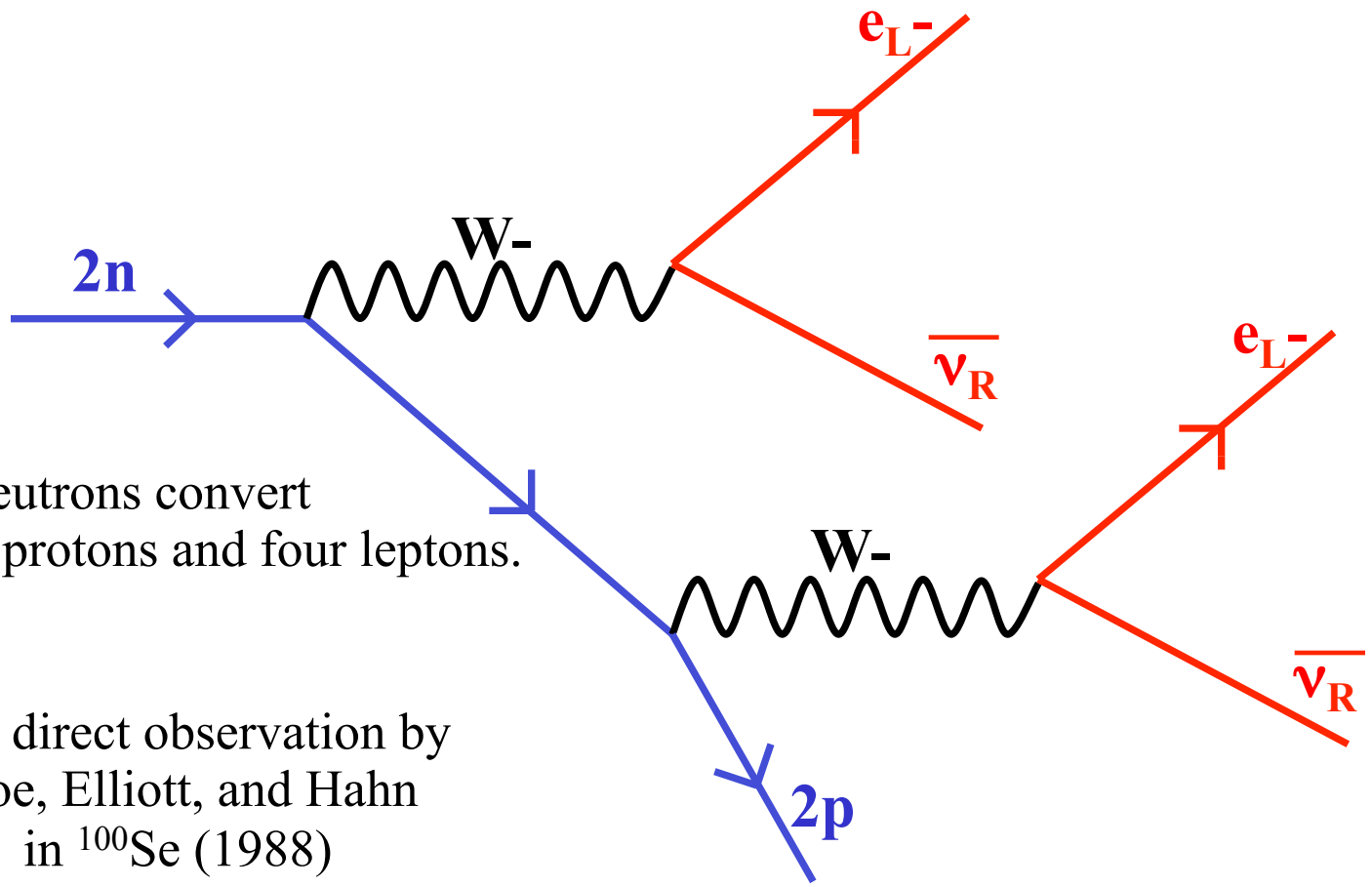
effective mass

Majorana phases

Model dependence: we can use the ββ0ν decay rate to measure the absolute neutrino mass if:

1) neutrinos are Majorana
2) we have a reliable calculation of the nuclear matrix element
3) the neutrino mass mechanism dominates the decay

Two-Neutrino Double Beta Decay:

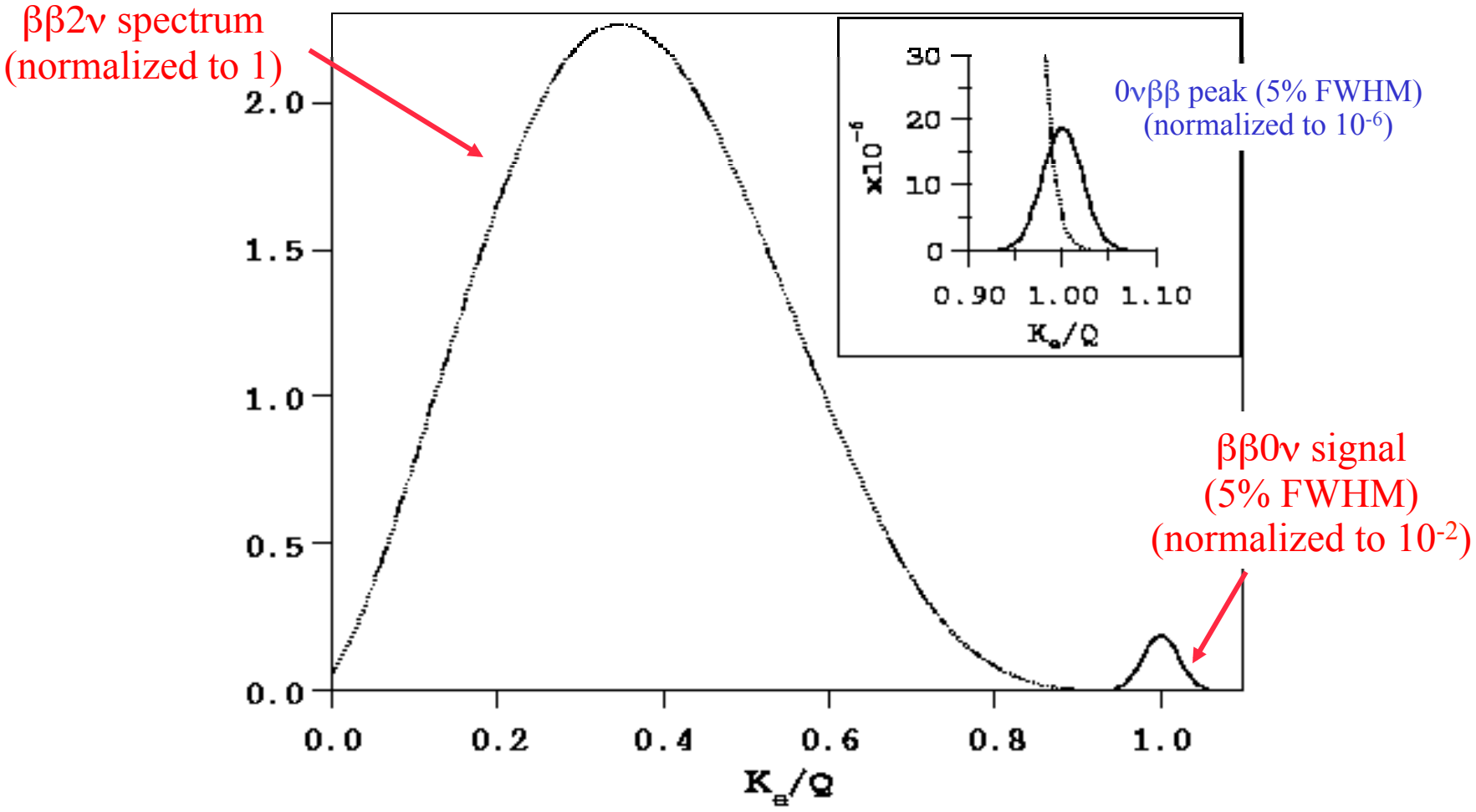


Two neutrons convert
to two protons and four leptons.

First direct observation by
Moe, Elliott, and Hahn
in ^{100}Se (1988)

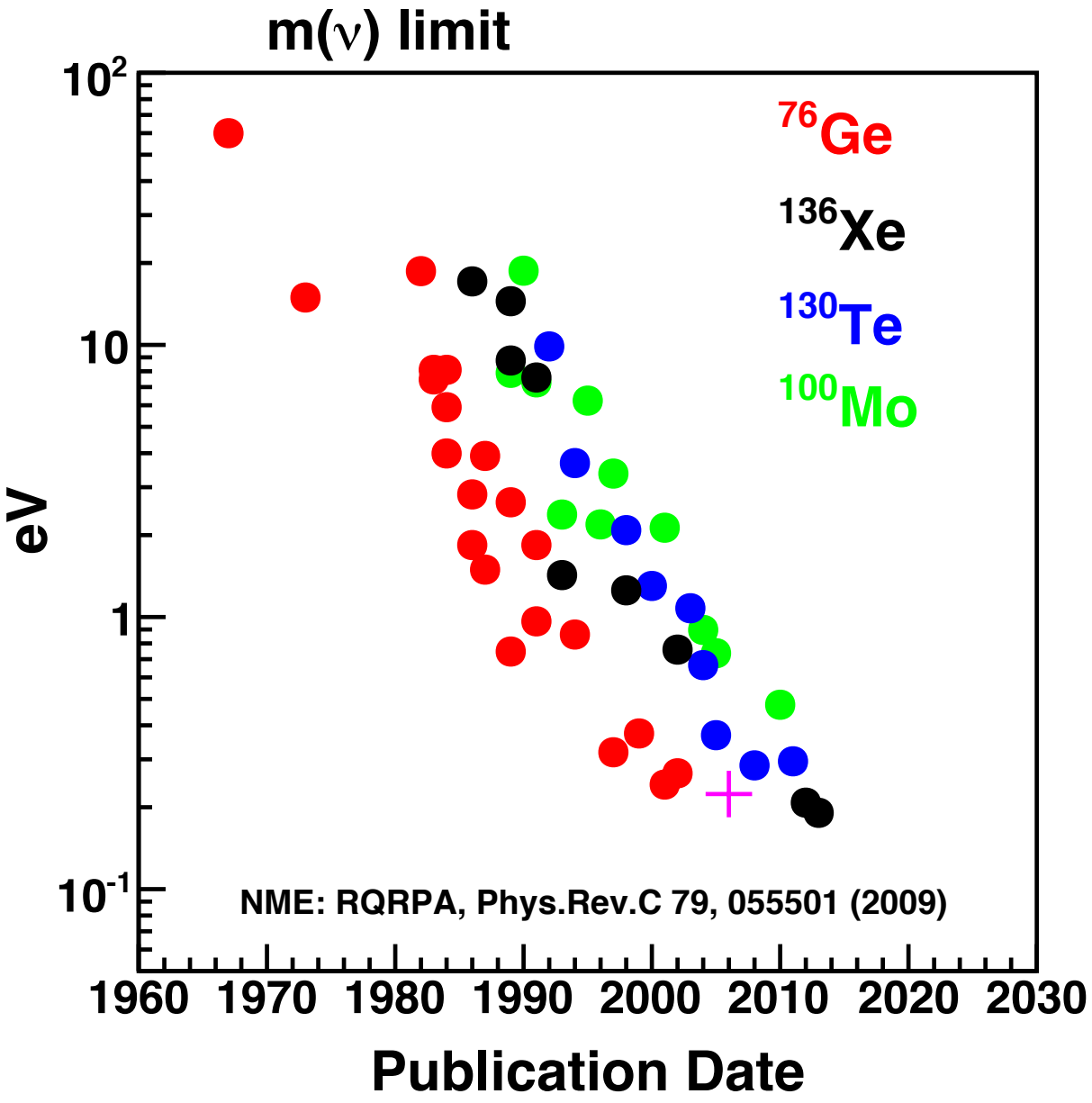
No direct implications for neutrino mass, but useful for constraining and testing the nuclear matrix element calculations.

ββ0ν signature: a peak in the ββ energy spectrum

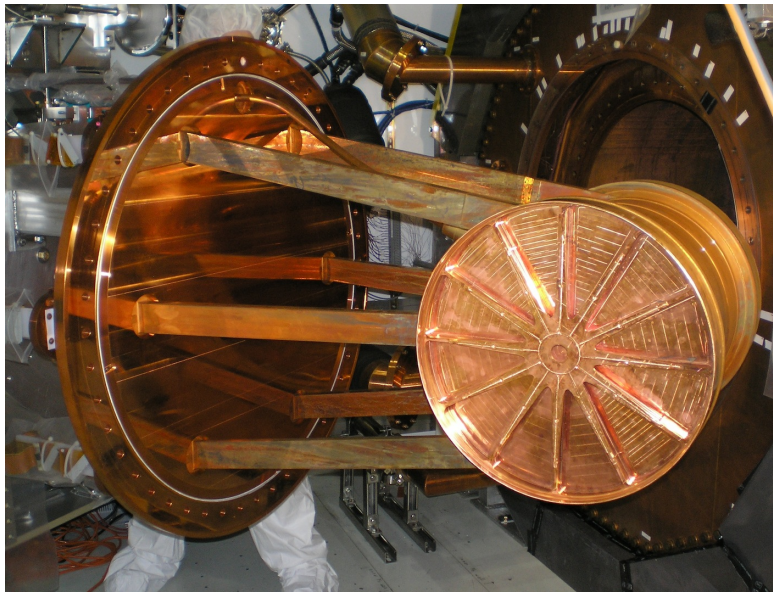


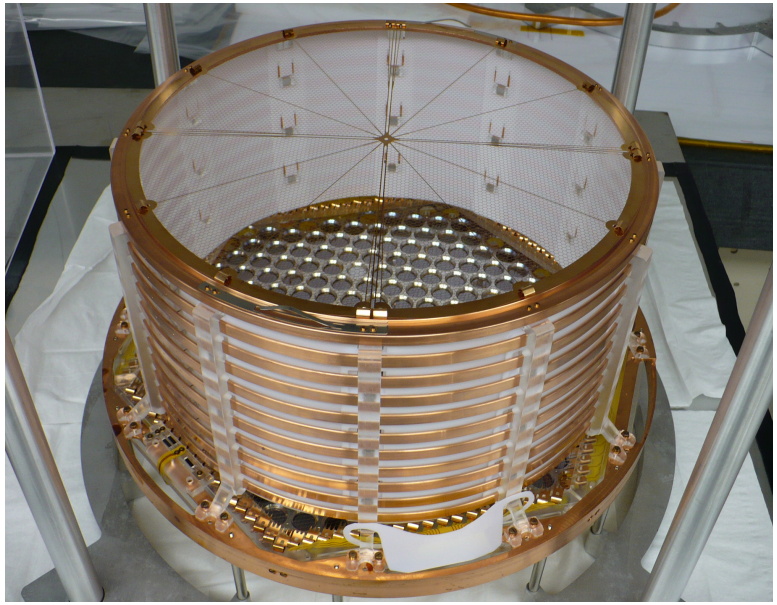
Summed electron energy in units of the kinematic endpoint (Q)

Historical progress



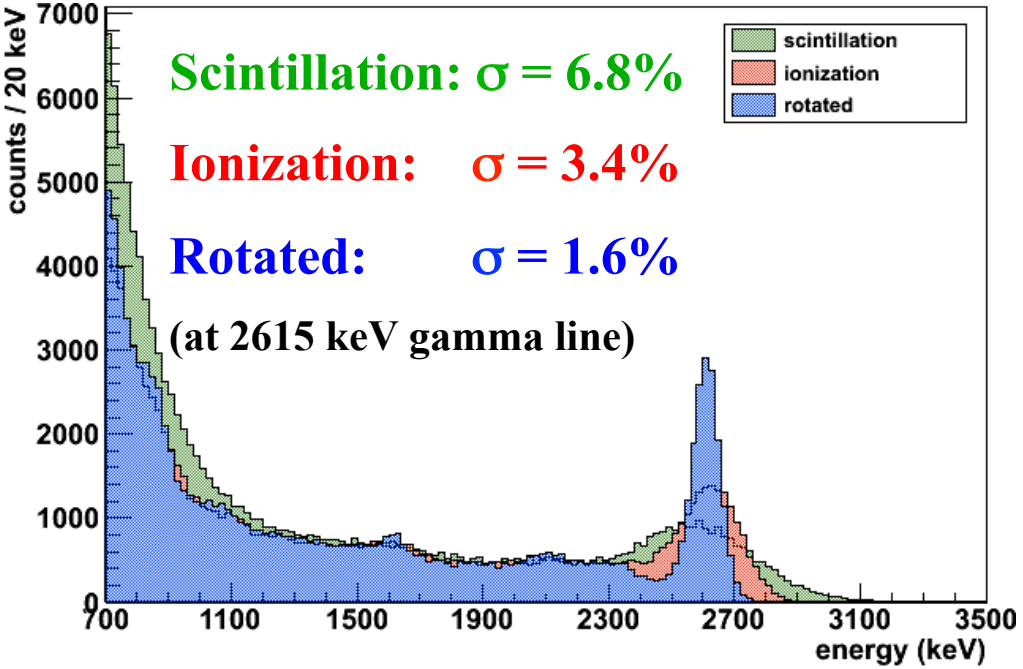
^{136}Xe: EXO-200, a liquid xenon TPC (2011-present)



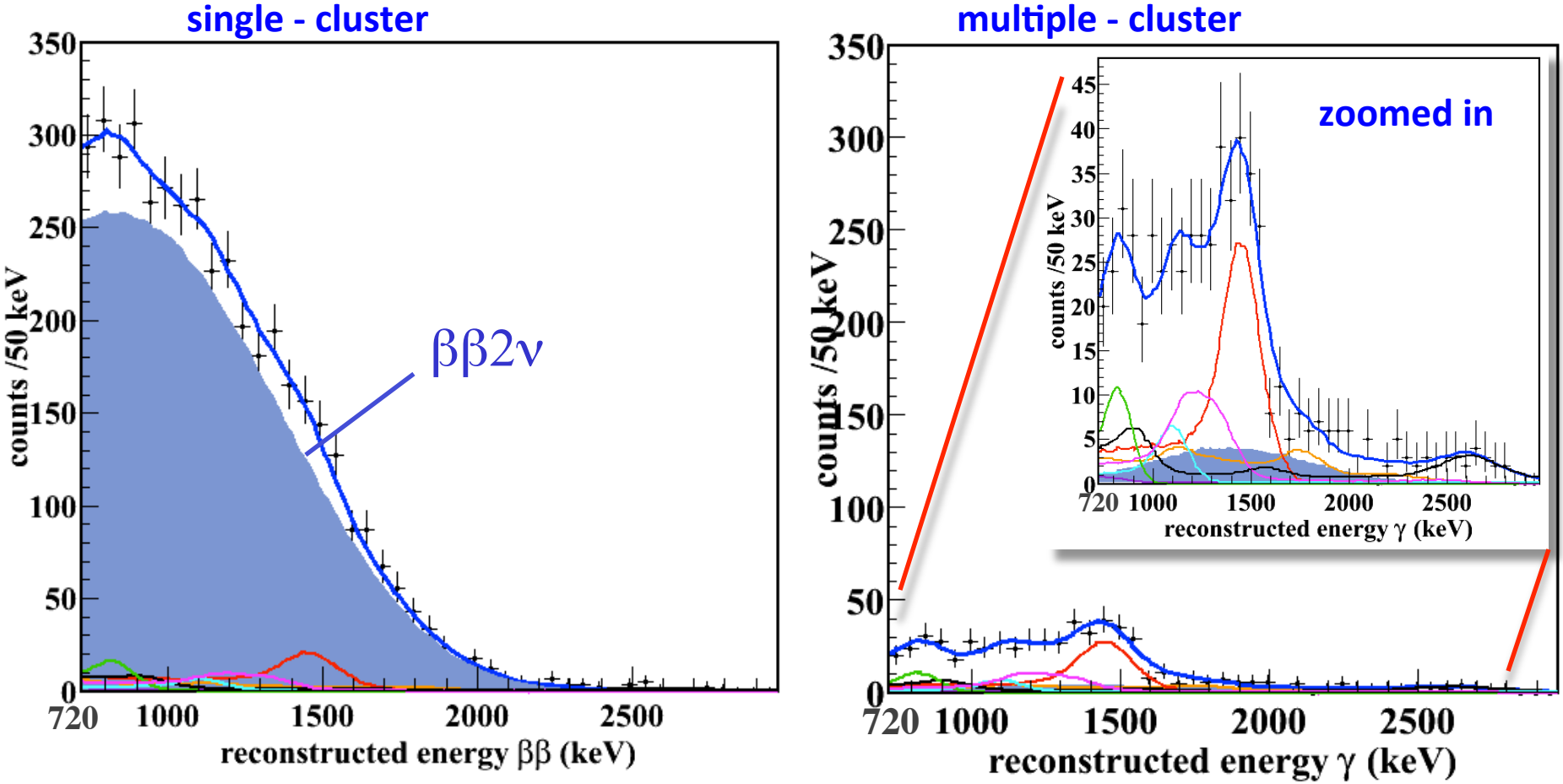


Active mass: 98.5 kg LXe
(79.4 kg ^{136}LXe)

^{228}Th Calibration source



First Observation of ββ2ν in ^{136}Xe (2011)

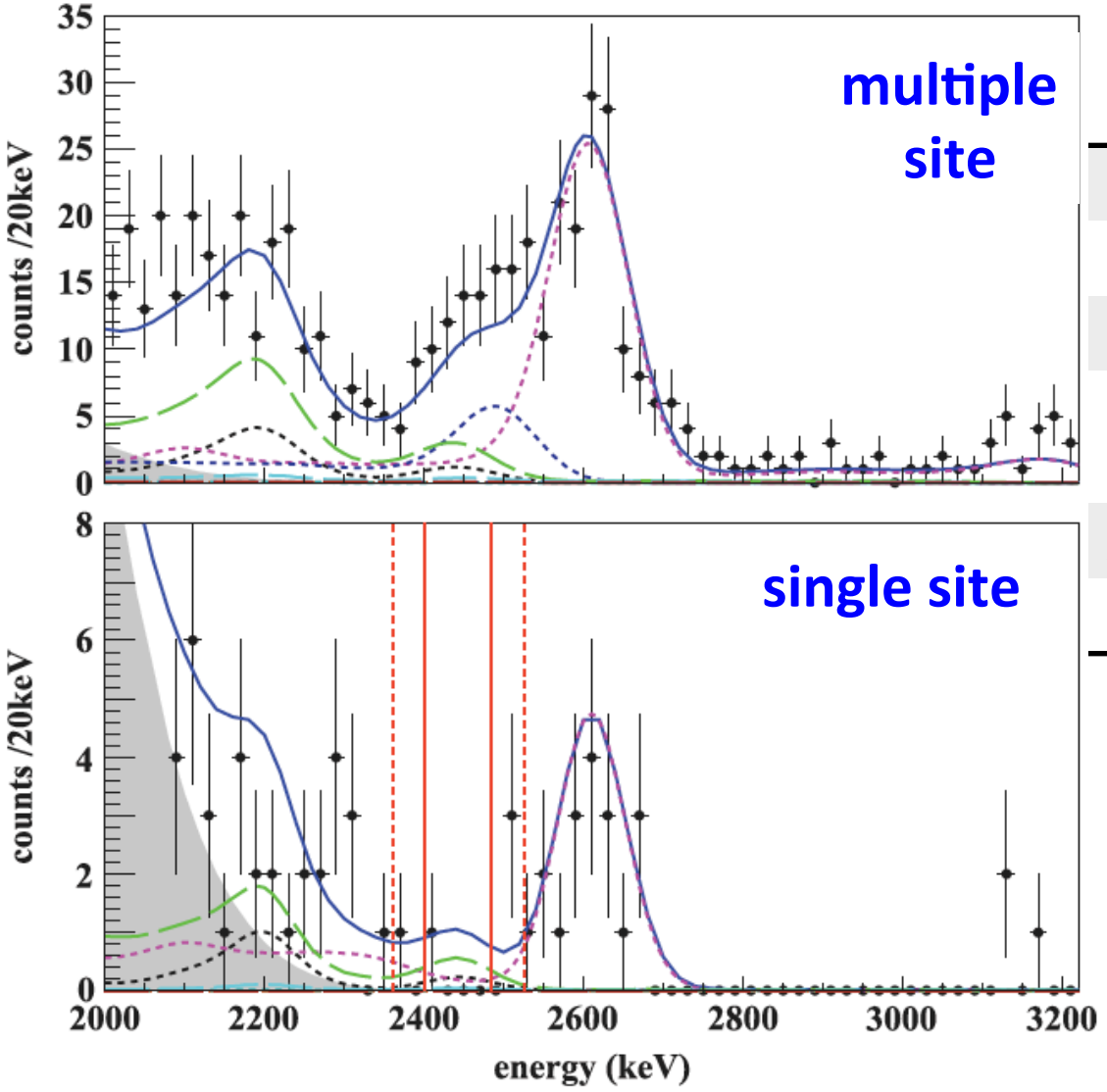


$T_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) yr (± 0.21 sys), PRL 107 212501 (2011)

Longest half-life ever directly observed. 31 days of data.
Signal-to-background ratio 10:1

EXO-200 ββ0ν search results (2012)

ROI closeup



Observe 1 count.

expect from fit:

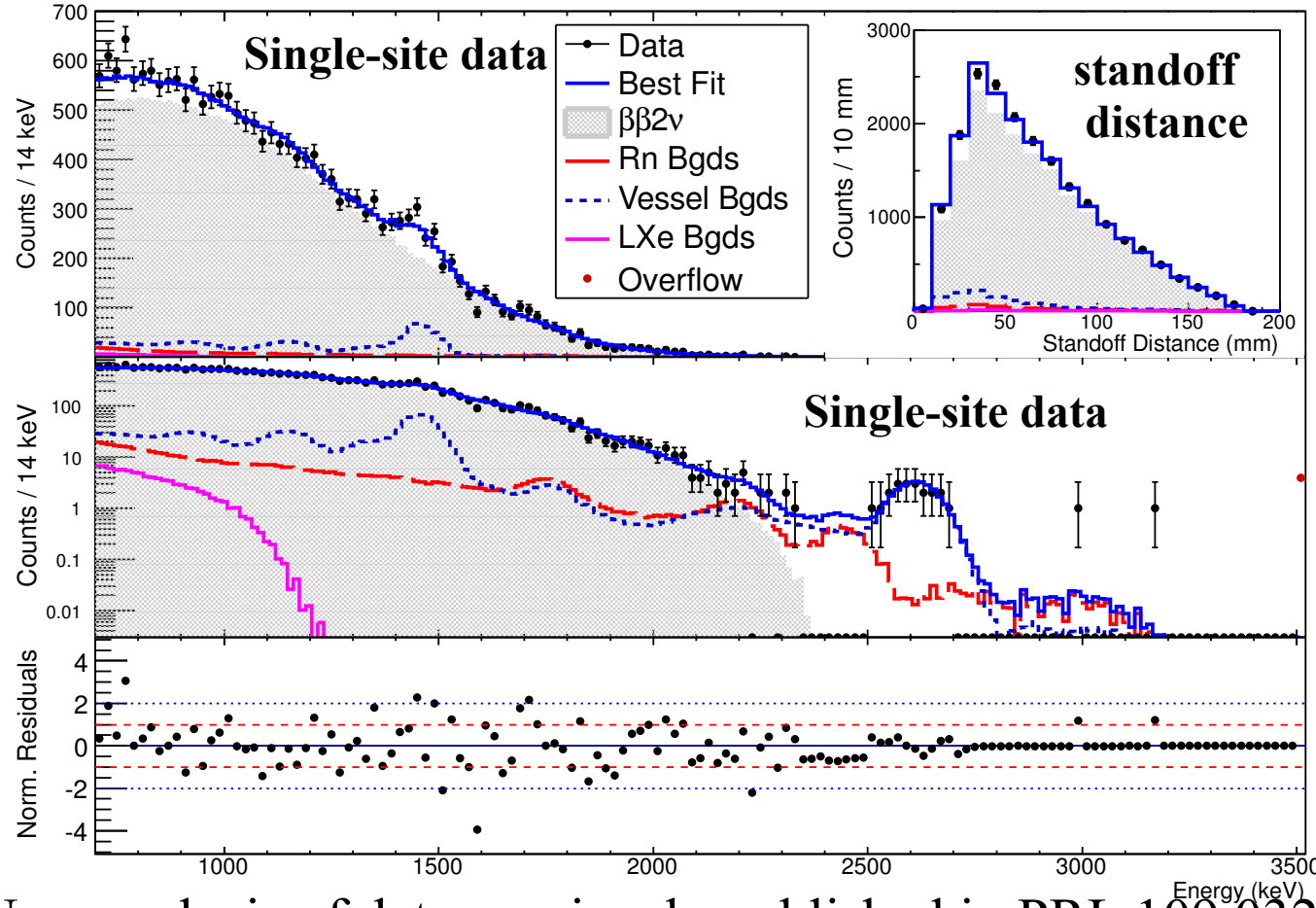
^{222}Rn in cryostat air-gap	1.9	±0.2
^{238}U in LXe Vessel	0.9	±0.2
^{232}Th in LXe Vessel	0.9	±0.1
^{214}Bi on Cathode	0.2	±0.01
All Others	~0.2	
Total	4.1	±0.3

$T_{1/2}(\beta\beta0\nu) > 1.6 \times 10^{25}$ years (90% C.L.)

$m_{\beta\beta} < 140 - 380$ meV

PRL 109 032505 (2012)

New result: Improved measurement of the ββ2ν half-life of ^{136}Xe



arXiv:1306.6106, submitted to PRC.

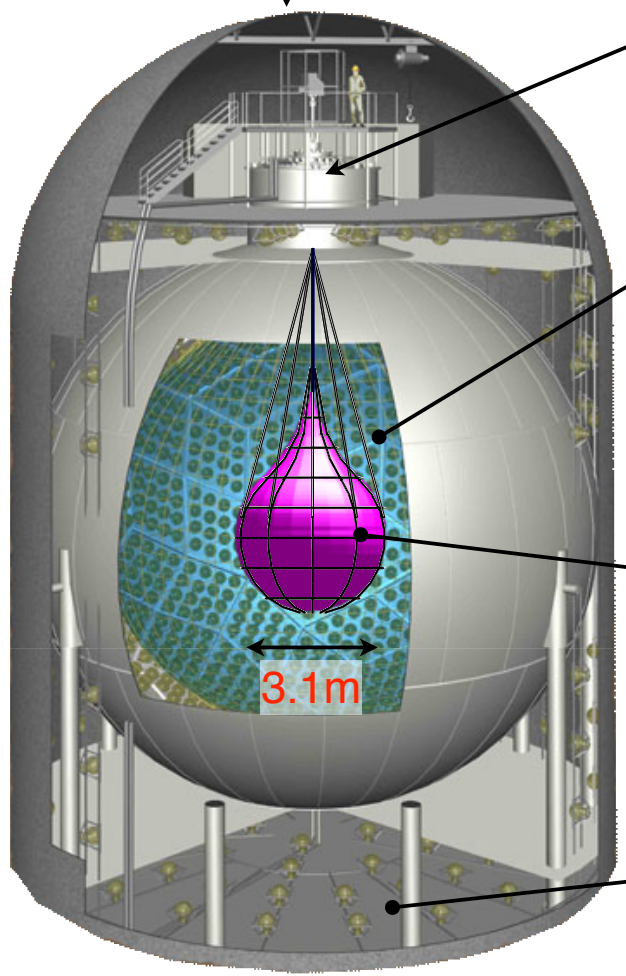
New analysis of data previously published in PRL 109 032505 (2012).

$T_{1/2} = 2.172 \pm 0.017$ (stat) ± 0.060 (sys) x 10^{21} years (2.85 % uncert.)

Twice as precise as any other ββ2ν decay of any isotope.

1.77 % fiducial volume uncertainty, improvements to reconstruction.

KamLAND-Zen



Calibration access

1200 m^3 LS+1800m^3 BO

1325 17”PMTs + 554 20”PMTs

$\sigma_{Energy} = 6.6\ \% / \sqrt{E}$

$\sigma_{Position} = 15\ cm / \sqrt{E}$

^{238}U: 3.5×10^{-18} g/g ^{232}Th: 5.2×10^{-17} g/g

^{136}Xe loaded LS in mini-balloon

320 kg (2.4 % by weight)

90 % enriched

^{238}U: 1.3×10^{-16} g/g ^{232}Th: 1.8×10^{-15} g/g

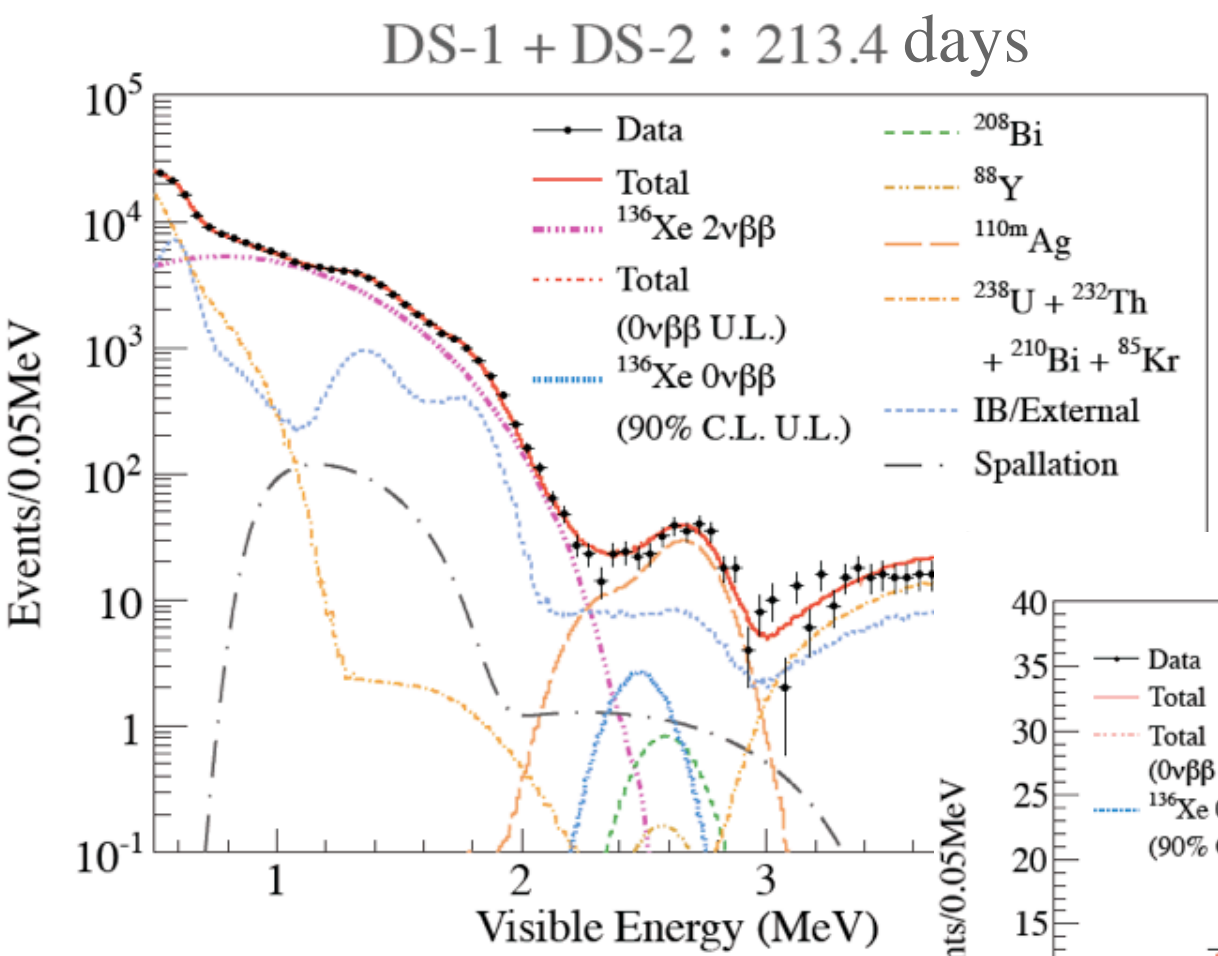
Water Cherenkov Outer Detector

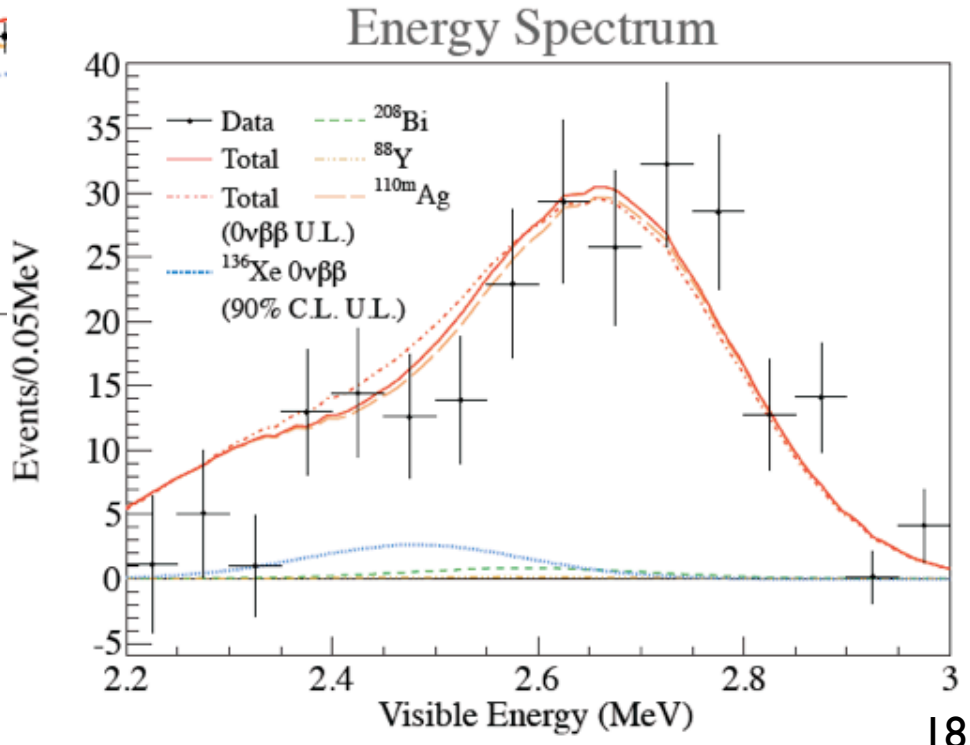
225 20” PMTs

From K. Nakamura (Tohoku University), presented at Neutel 2013

Results from KamLAND-Zen phase I

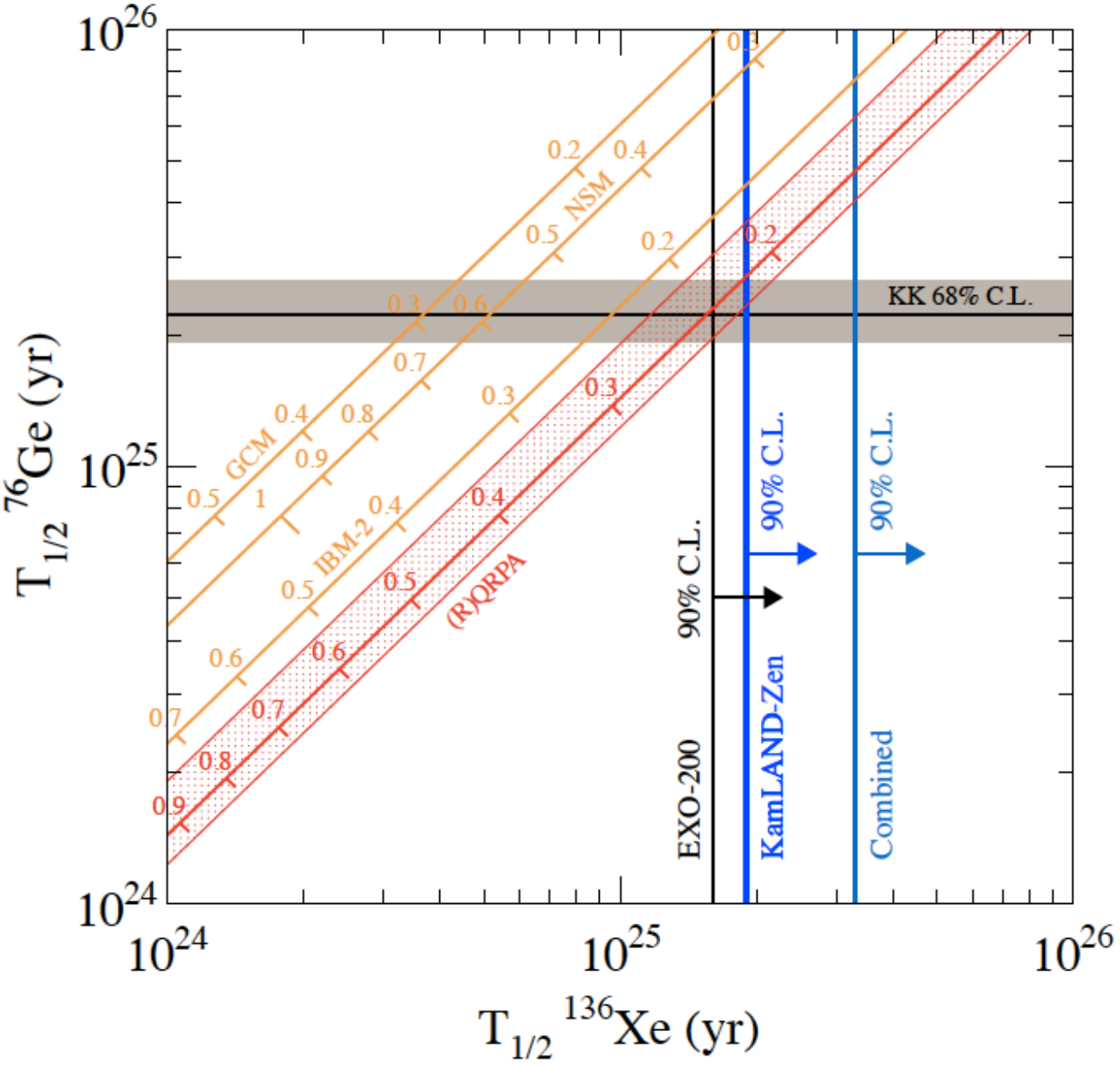
Phys.Rev.Lett. 110 (2013) 062502





$\langle m_{\beta\beta} \rangle$ <160~330 meV

^{76}Ge discovery claim is in tension with ^{136}Xe results

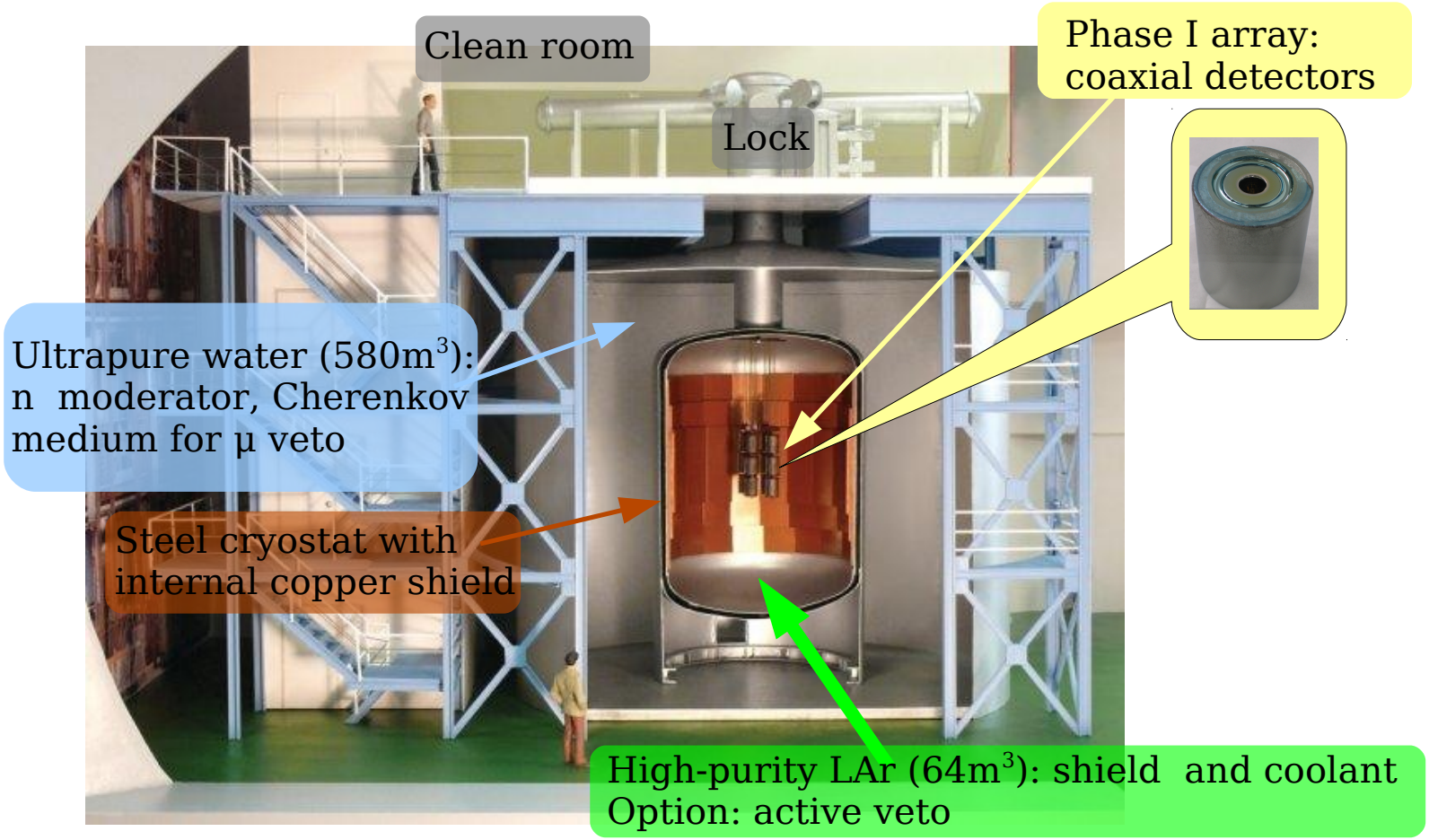


KamLAND-Zen & EXO-200

Phys. Rev. Lett. 110 062502 (2013)

^{76}Ge: Gerda experiment at Gran Sasso (2011-present)

- Graded shielding against ambient radiation
- Rigorous material selection, avoid exposure above ground for detectors

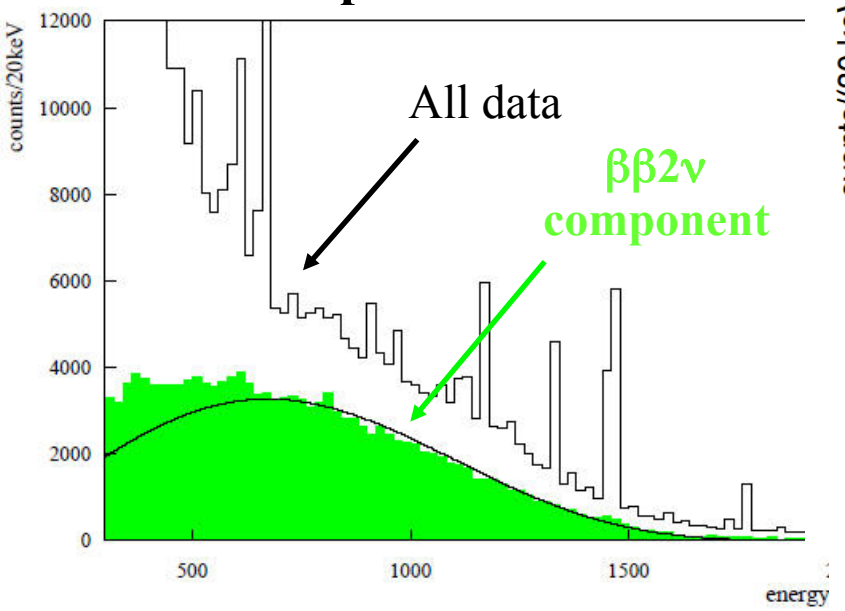


The Gerda experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge

Eur. Phys. J. C (2013) 73:2330

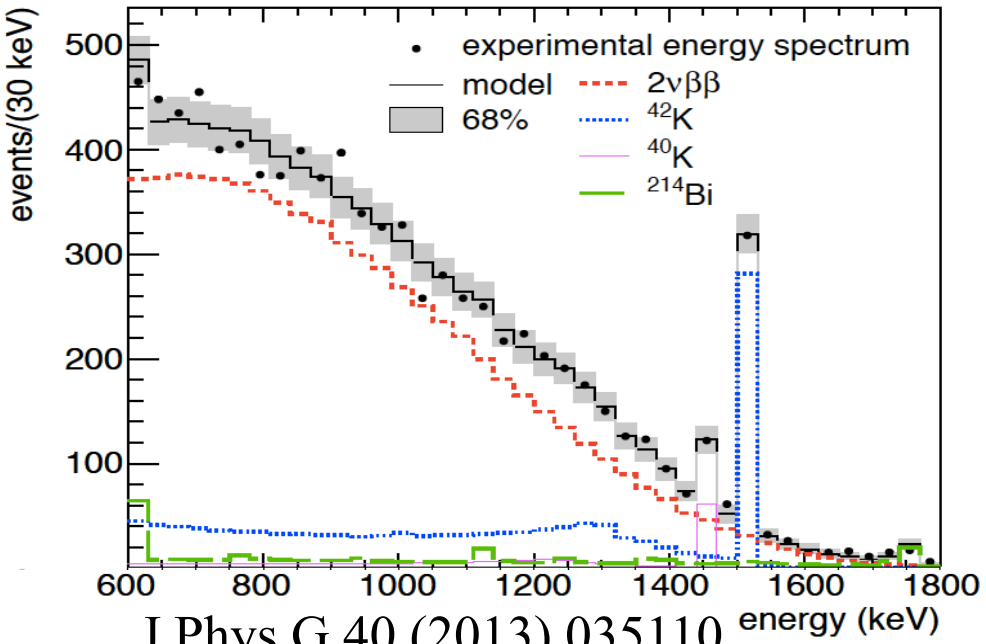
Progress in ^{76}Ge: ββ2ν measured by GERDA

HdM experiment - 2001



Eur. Phys. J. A 12, 147–154 (2001)

Gerda - 2013



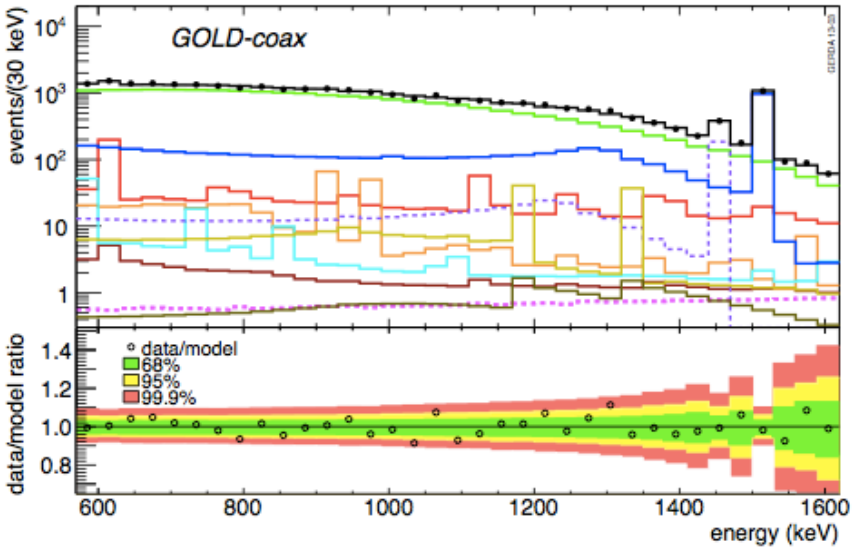
J.Phys.G 40 (2013) 035110

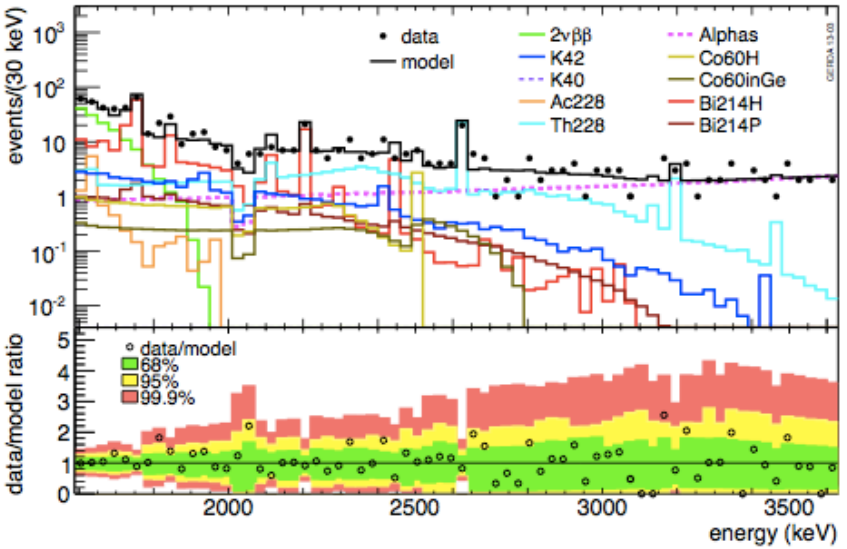
$T_{1/2}(\beta\beta2\nu)=(1.84 + 0.14 - 0.1)\times10^{21}$ years

- Gerda Phase I (present): Re-use HdM & IGEX crystals, demonstrated 10x lower backgrounds
- Gerda Phase II (start 2013): 20 kg enriched low-background BeGE crystals
  - Use LAr as active veto, pulse shape analysis, lower background materials.
  - Reduce backgrounds a factor of 10 below Phase I levels.

Gerda – Background Model (2013)

arXiv:1306.5084



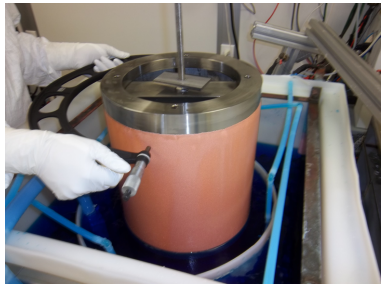


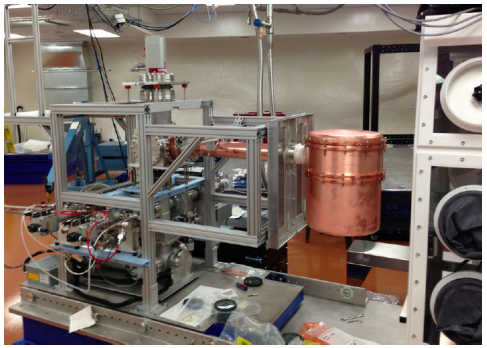
Background rate in region of interest = 18.5 x 10^{-3} counts/(keV*kg)

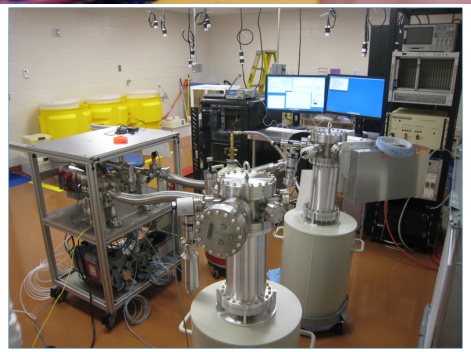
Expected sensitivity = 1.9 x 10^{25} years (equiv. to Heidelberg-Moscow). Some sensitivity to the ββ0ν observation claim (2.23 x 10^{25} years).

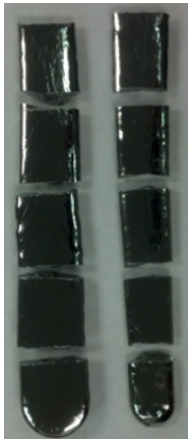
Region of interest partially unblinded in May 2013, full unblinding expected soon.

MJD Progress in FY13







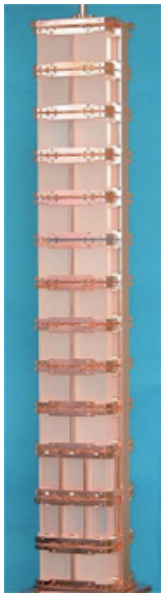
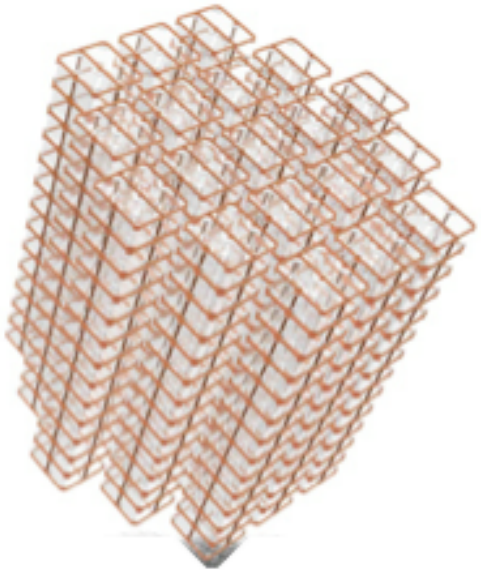


From Reyco Henning (UNC), Pre-Snowmass Neutrino Workshop

March 7, 2013

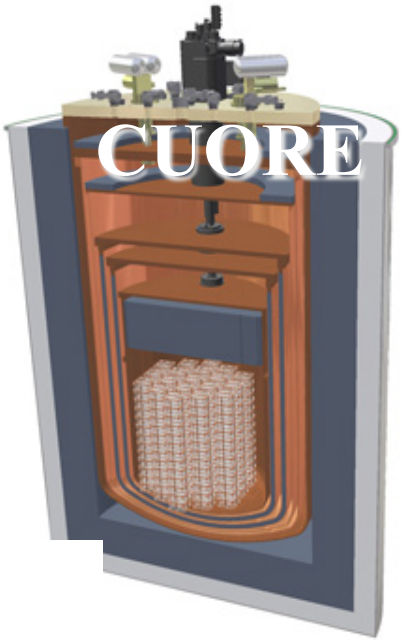
0νββ research with TeO_2

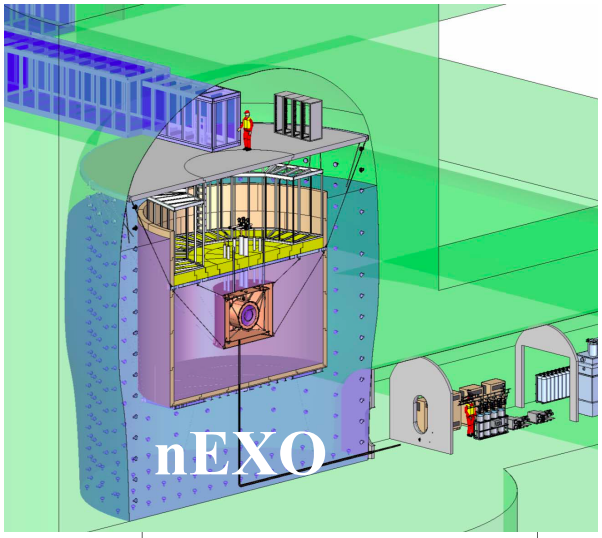
- ^{130}Te is a good DBD candidate ($^{130}Te \rightarrow {}^{130}Xe + 2\,e^-$) with high natural i.a. (34.2 %) and reasonably high Q-value (Q~2528 keV) leading to high G(Q,Z) and low background
- TeO_2 is a compound with good mechanical and thermal properties containing ^{130}Te
- 5x5x5 cm^3 TeO_2 crystals have a high detection efficiency for 0νββ events: ~87.4%

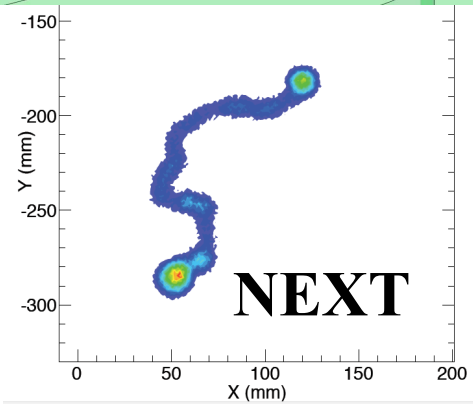
MiDBD	Cuoricino	CUORE-0	CUORE
1.8 kg ^{130}Te	11 kg ^{130}Te	11 kg ^{130}Te	206 kg ^{130}Te
			
1997-2001	2003-2008	2012...2014	2014...

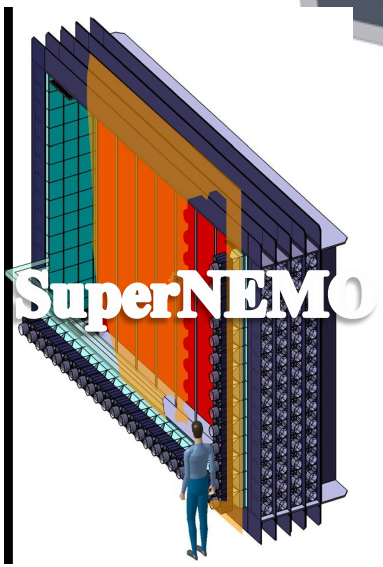
From C. Brofferio (University and INFN, Milano Bicocca), Neutel 2013

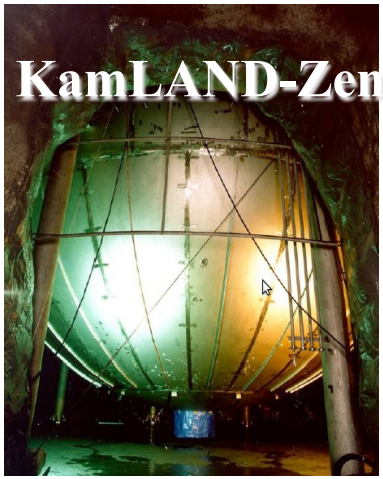
The future of ββ0ν





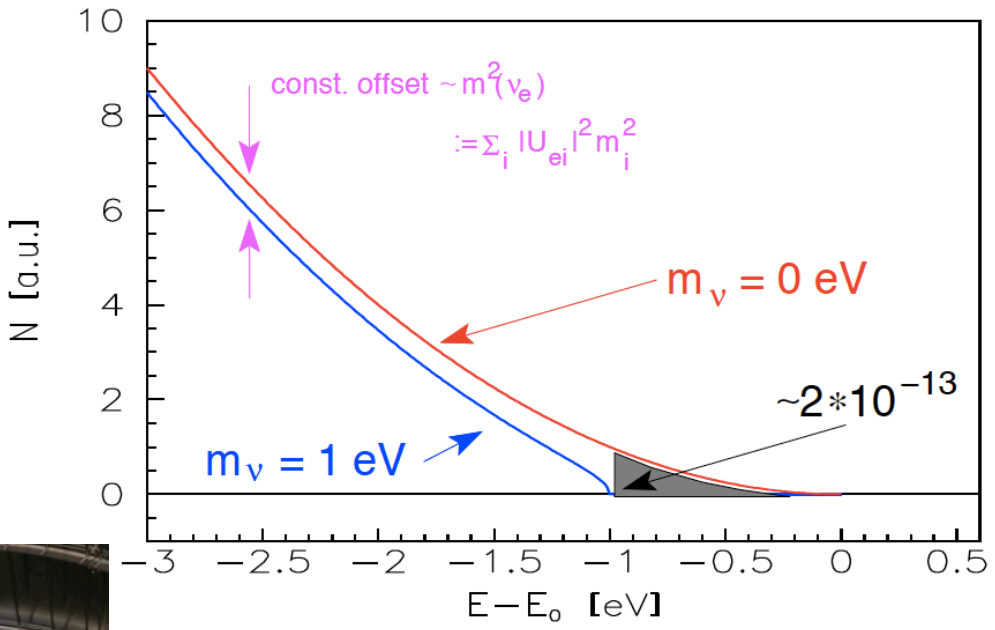






Tritium endpoint spectrum - KATRIN

$$m^2(\nu) = \sum_i |U_{ei}|^2 m^2(\nu_i)$$



Inside the KATRIN spectrometer

KATRIN´s sensitivity

Example of KATRIN simulation & fit
(last 25eV below endpoint, reference):

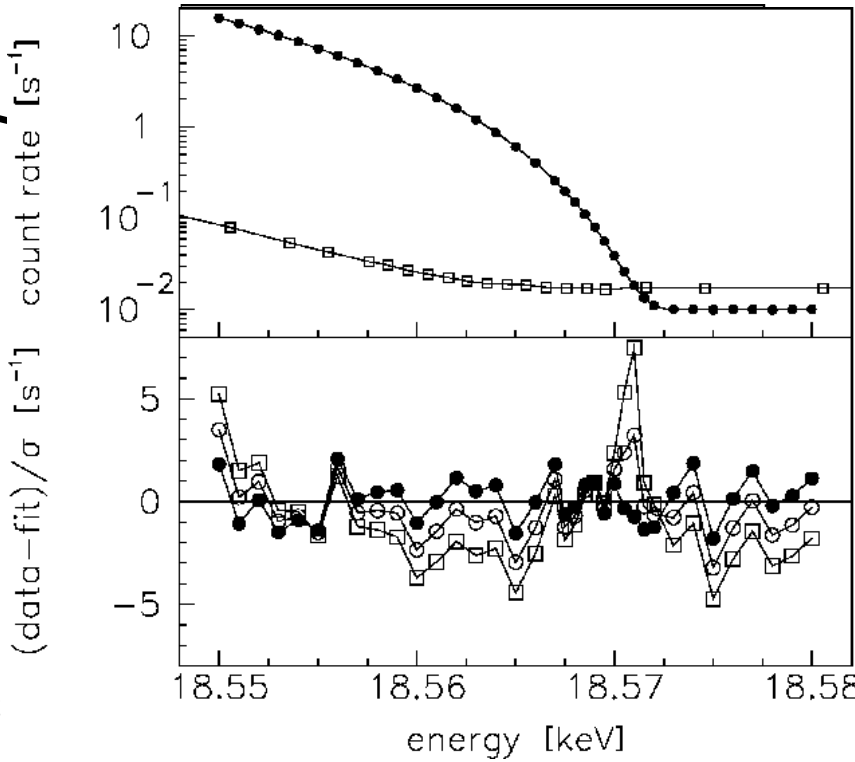
sensitivity:

$m_\nu < 0.2$eV (90%CL)

discovery potential:

$m_\nu = 0.3$eV (3σ)

$m_\nu = 0.35$eV (5σ)



Expectation for 3 full data taking years: $\sigma_{syst} \sim \sigma_{stat}$

Sensitivity is still statistically limited,

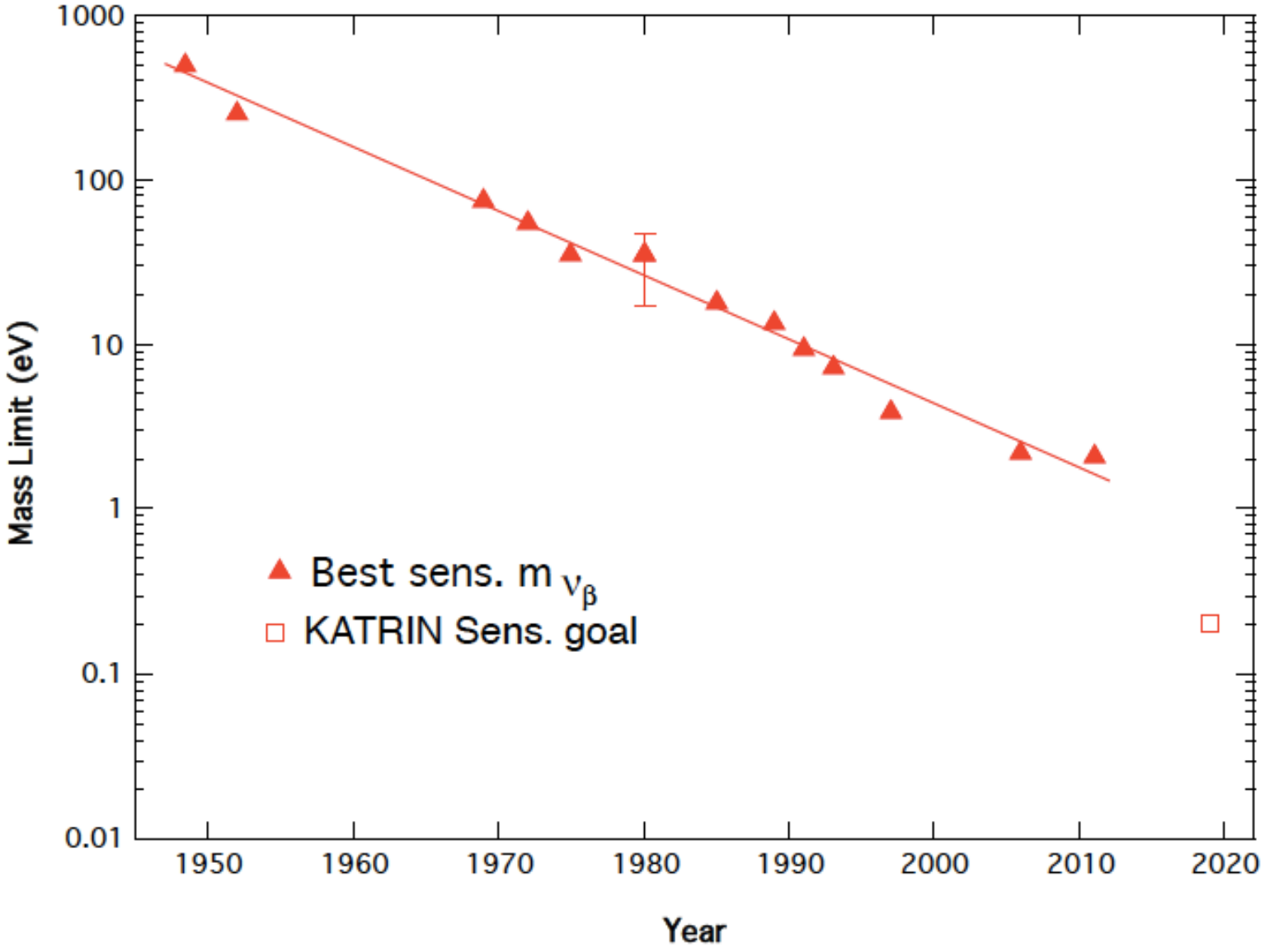
because with more statistics would go closer to the endpoint,

where most systematics nearly vanish

Sensitivity still has to proven, but there might be even some more improvements

from Christian Weinheimer, νMass, Feb. 2013

Historical progress – tritium endpoint



John Wilkerson, Neutrino 2012

Cosmological constraints – Σm(ν)

- Neutrino number density ~ 112 neutrinos per cm^3 per species.

$$f_\nu = \frac{\Omega_\nu}{\Omega_m} = \frac{\sum_i m_i(\nu)}{93\Omega_m h^2 eV} \approx 0.08 \frac{\sum_i m_i(\nu)}{1(\mathrm{eV})}$$

- Neutrinos disturb the delicate balance between gravity and the Hubble expansion.
- They suppress structure formation for scales smaller than ~0.1 Mpc/f_ν, while leaving unaffected scales larger than 100 Mpc.
- This can be detected in via small alterations to the CMB, tracers such as galaxy structure, via gravitational lensing.

Cosmological Model Dependence

The assumptions are

- General relativity holds at all length scales
- the universe is flat
- and consists of photons, three neutrinos, baryons, cold dark matter, and dark energy.
- the initial conditions are those of the simplest single-field inflation model (adiabatic perturbations described by a single spectral index).

In total there are six free parameters + neutrino masses for the simplest model.

Probes of Σm(ν)

Method	Current Σm(ν) bound (eV)	Future Σm(ν) sensitivity (eV)	Datasets
CMB primordial (ISW, lensing, polarization)	**0.66**	**0.2**	**Planck, WMAP, SPT, ACT**
CMB primoridial + distance scale	0.23		Planck, WMAP, SPT, ACT + BAO & H_0
Galaxy distributions	0.6	0.1	SDSS, BOSS (DES, BigBOSS, LSST)
Lensing of galaxies	0.6	0.07	CFHT-LS, COSMOS (WFIRST, DES, LSST, EUCLID)
Lyman α	0.2	0.1	SDSS, BOSS, KECK
21 cm mapping	-	0.1 – 0.006	SKA, FFTT
Galaxy clusters	0.3	0.1	Planck, SPT, SDSS

Adapted from Abazajian, et al., arXiv: 1103:5083.

Σm(ν) constraints from Planck/SZ

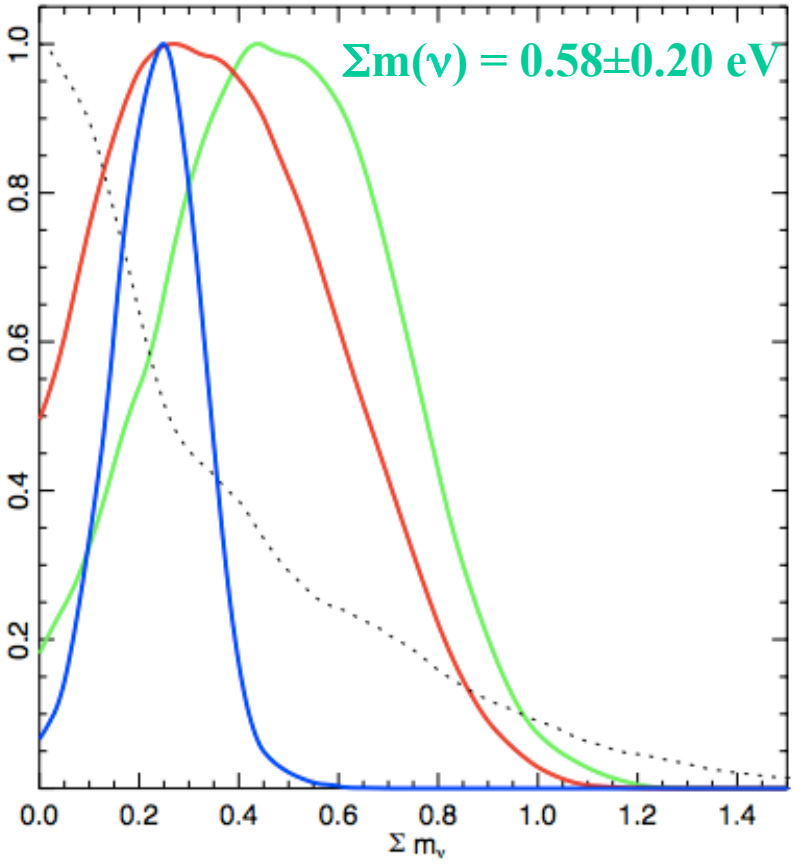


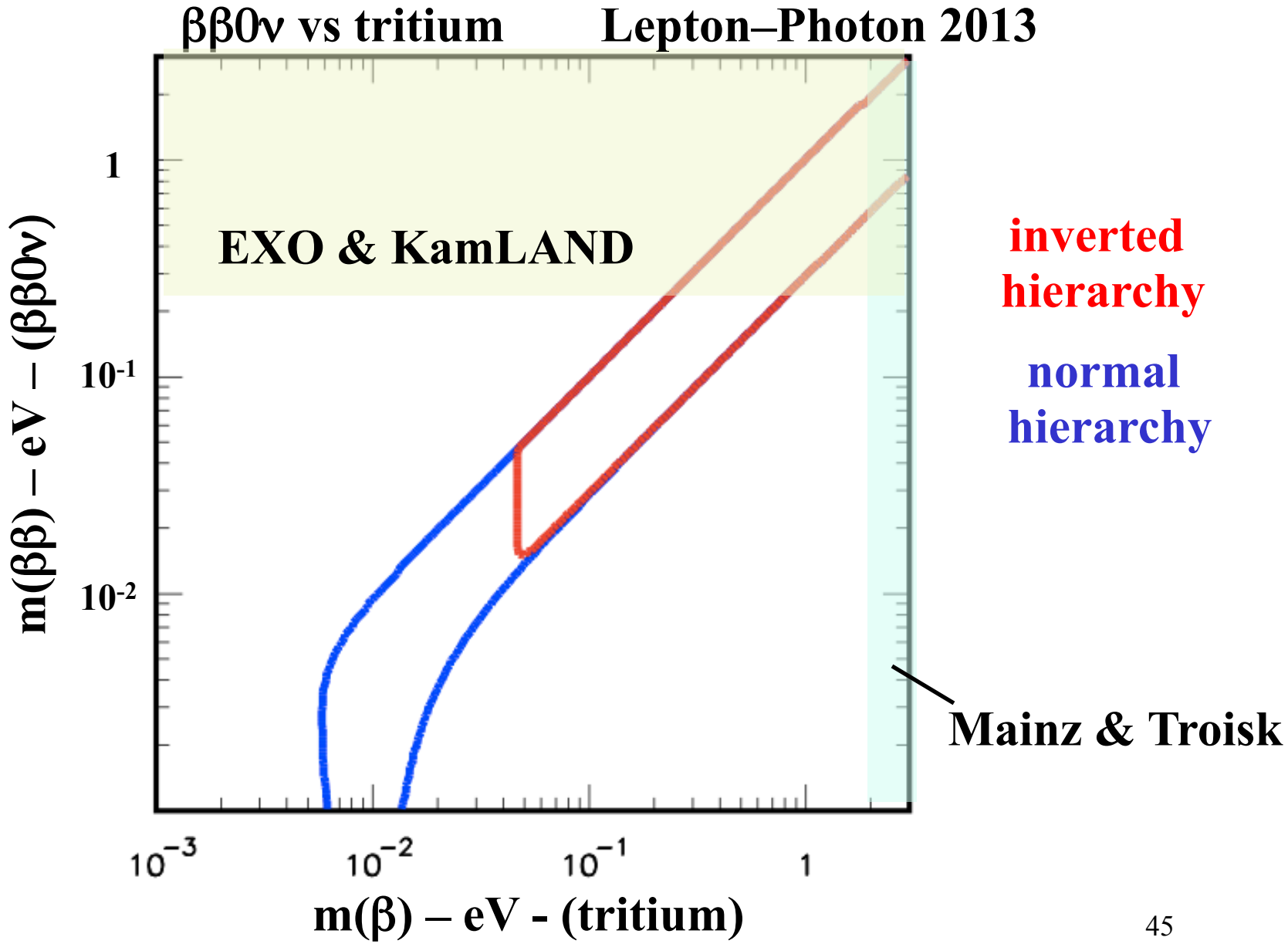
Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1-b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1-b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1-b = 0.8$ (green).

"Planck 2013 results. XX", arXiv:1303.5080

Planck has identified 189 galaxy clusters via the Sunyaev-Zeldovich effect on the CMB. These clusters can be used to measure Σm(ν) via its effect on galaxy structure formation. CMB data + BAO indicates that *more* clusters should have been found, indicating some tension in the data. One possible solution is to introduce a neutrino mass of magnitude Σm(ν) = 0.58±0.20 eV

The same effect was seen last year by the SPT (Zou, et al., arXiv:1212:6267)

Comparison of ν mass techniques



Adapted from G.L Fogli, et al, PRD 78 033010 (2008)

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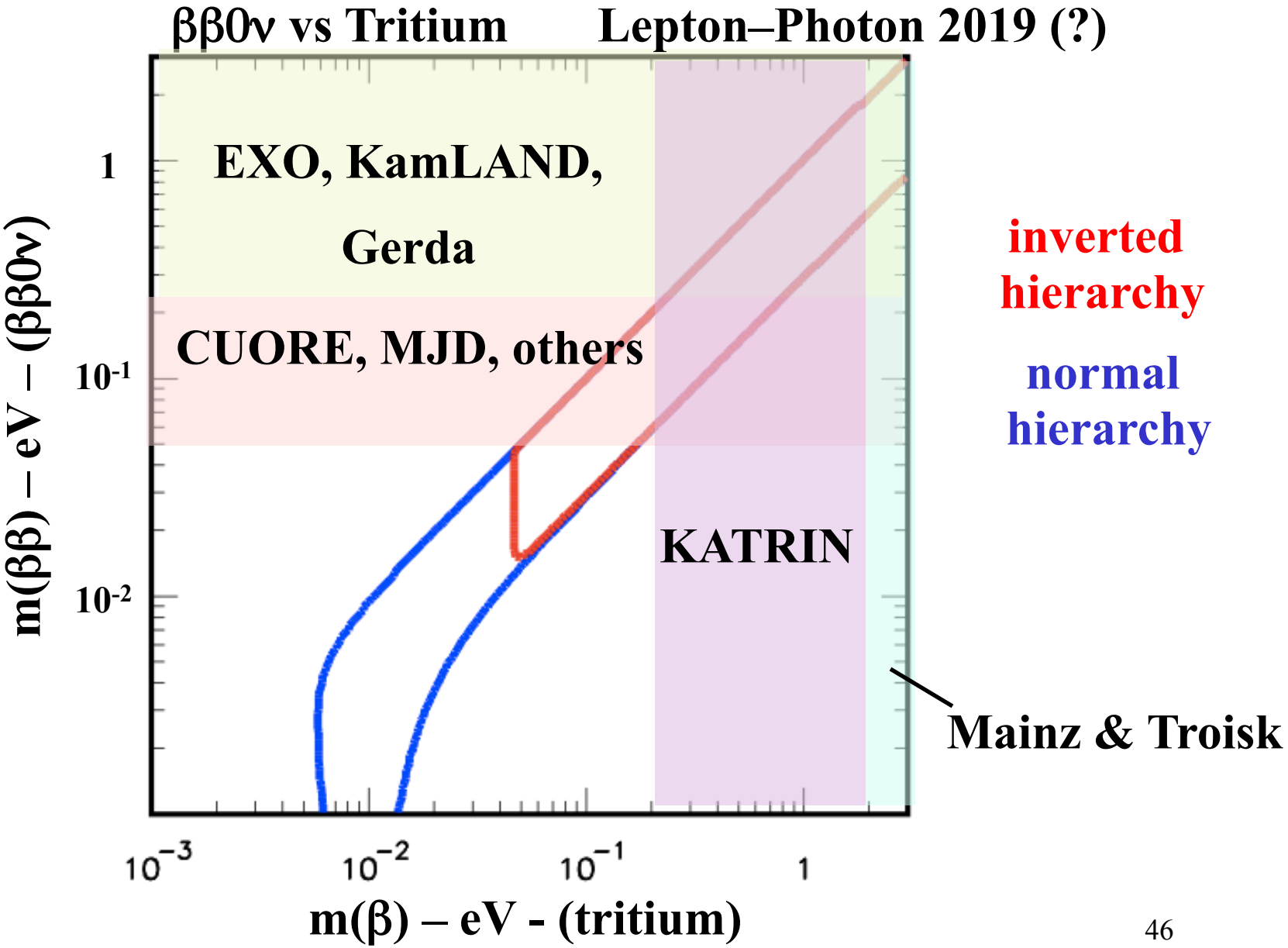

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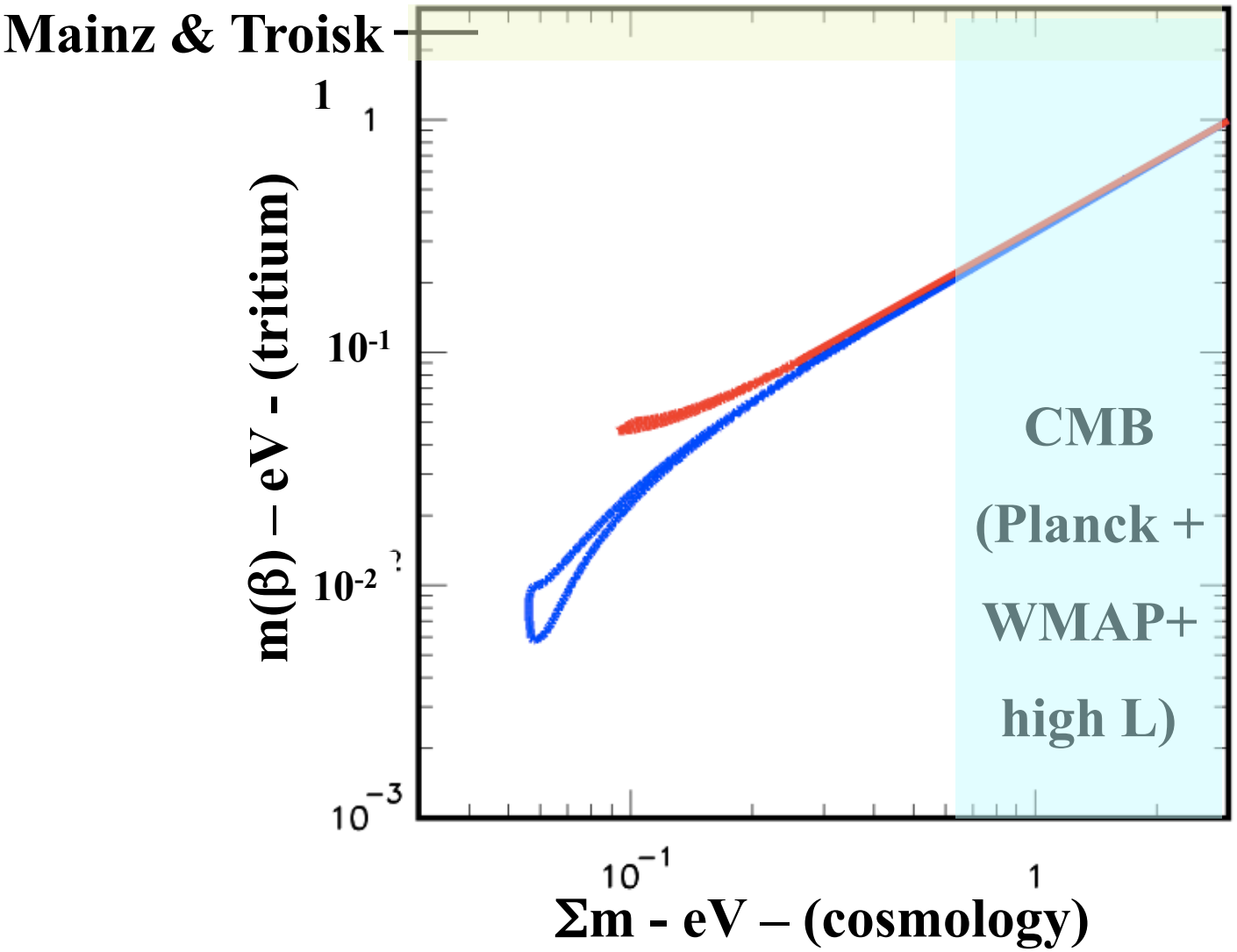
Comparison of ν mass techniques

tritium vs cosmology Lepton–Photon 2013



inverted hierarchy

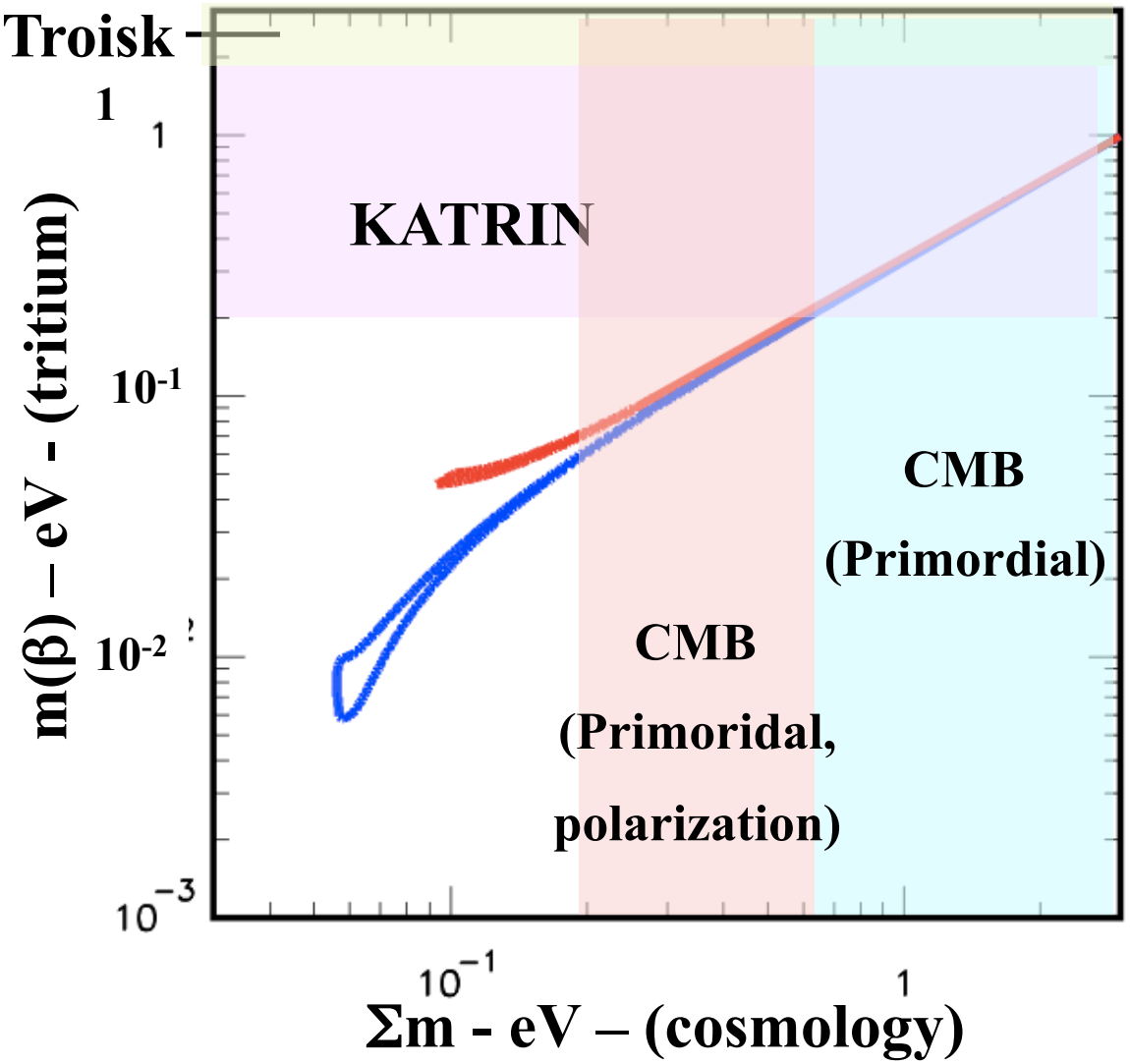
normal hierarchy

Adapted from G.L Fogli, et al, PRD 78 033010 (2008)

Comparison of ν mass techniques

tritium vs cosmology Lepton–Photon 2019 (?)

Mainz & Troisk



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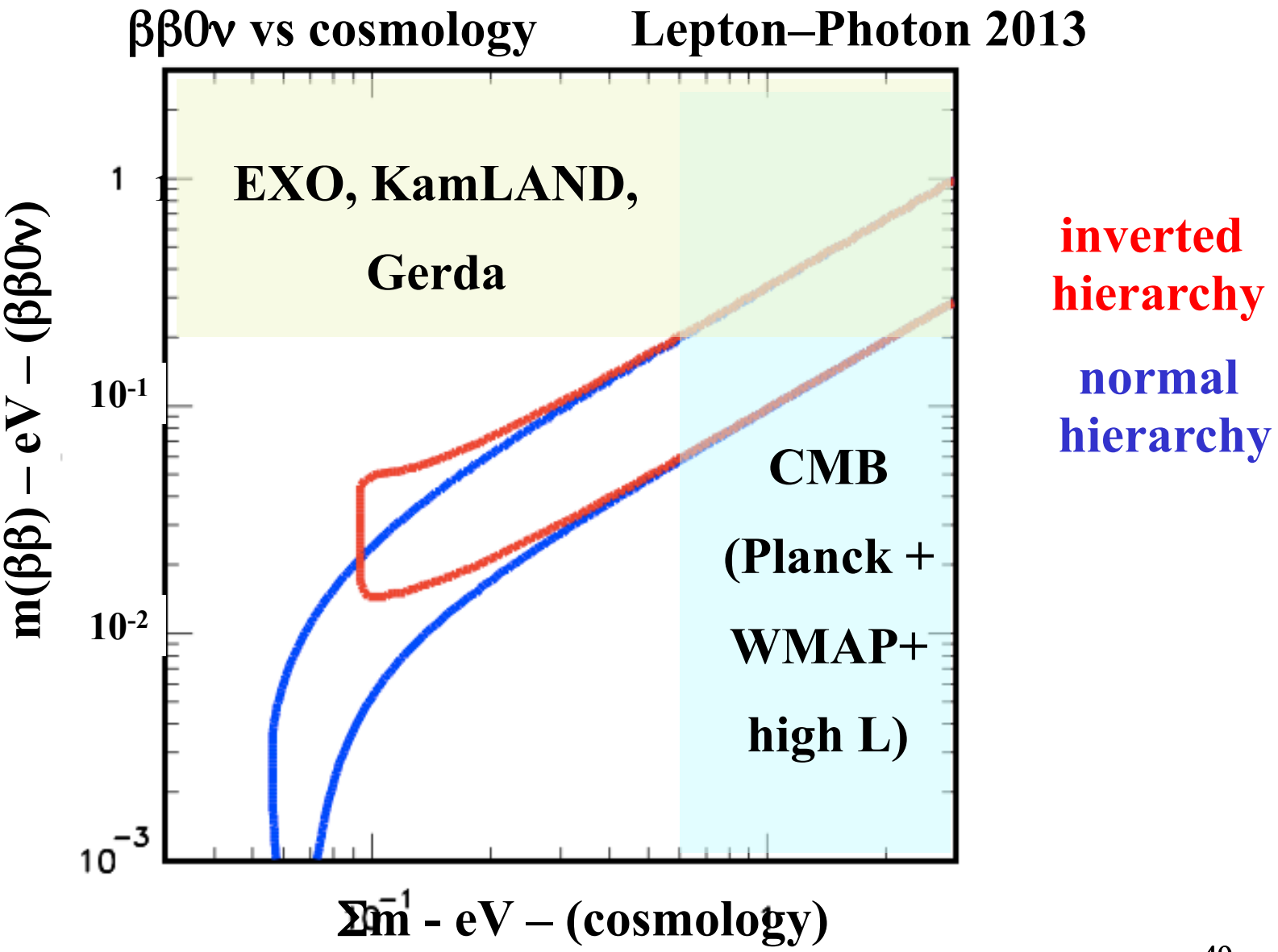

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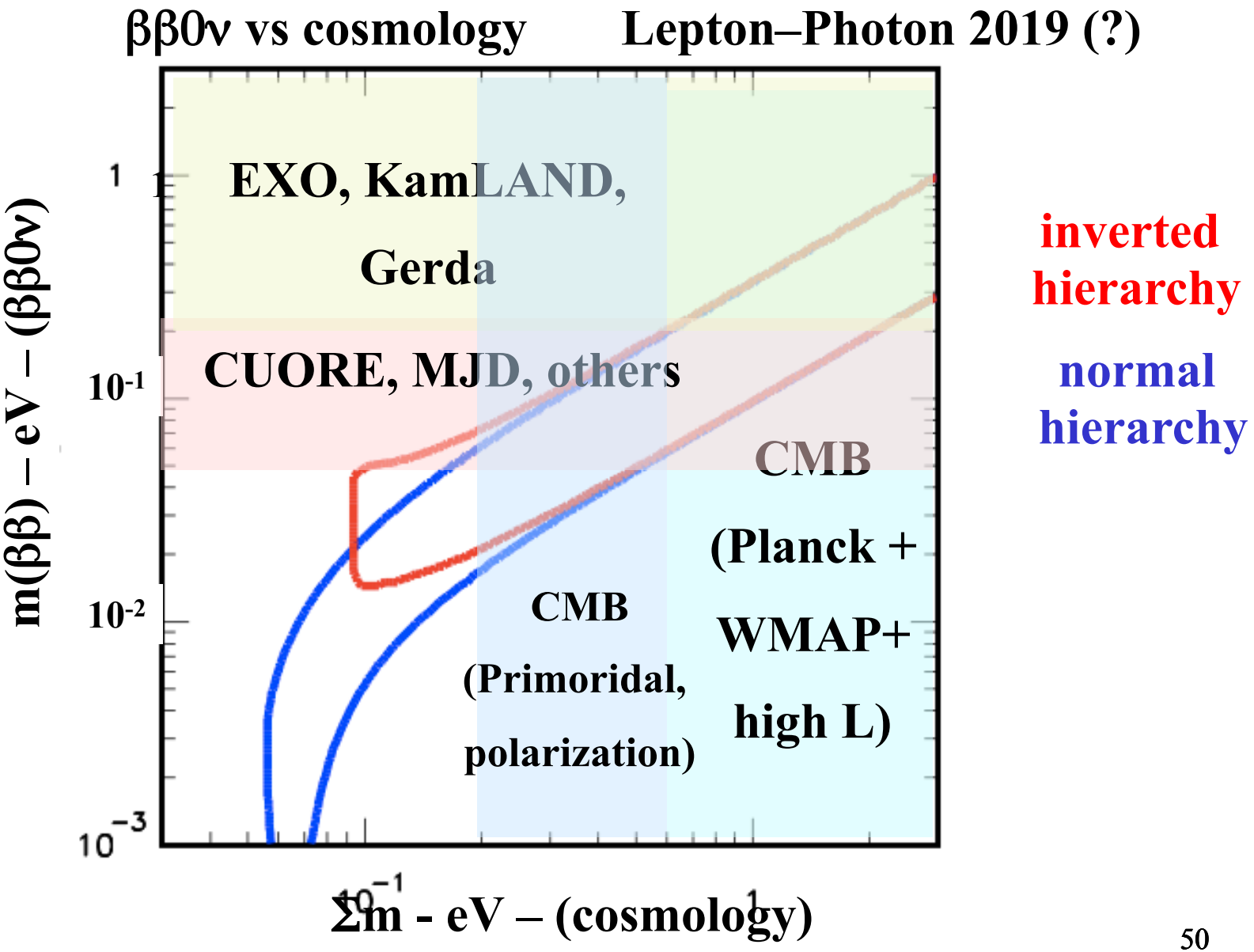

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- However, the conventional wisdom has also told us that:
  - neutrinos are massless
  - they have small mixing angles.
  - that θ_{13} will be very small.
- **A rash and agressive prediction:**
  - **By Lepton-Photon 2019 KATRIN will detect a neutrino mass of 0.35 meV.**
  - **Cosmology will converge on the same result.**
  - **Double beta decay at this mass will be ruled out, indicating a Dirac nature consistent with the Higgs mechanism.**

Thank you