Probing the absolute neutrino mass scale

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EIPS Lyon

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Measurement of neutrino mass

- Remember oscillations only measure difference in mass square
- Several probes:
  - Astrophysics measurements
  - Cosmological measurement
  - Beta decay spectrum
  - Double beta decay

Different neutrino mass terms

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

Cosmology. Kinetic term

$$M_\beta = \left(\sum |U_{ei}|^2 m_i^2\right)^{1/2}$$

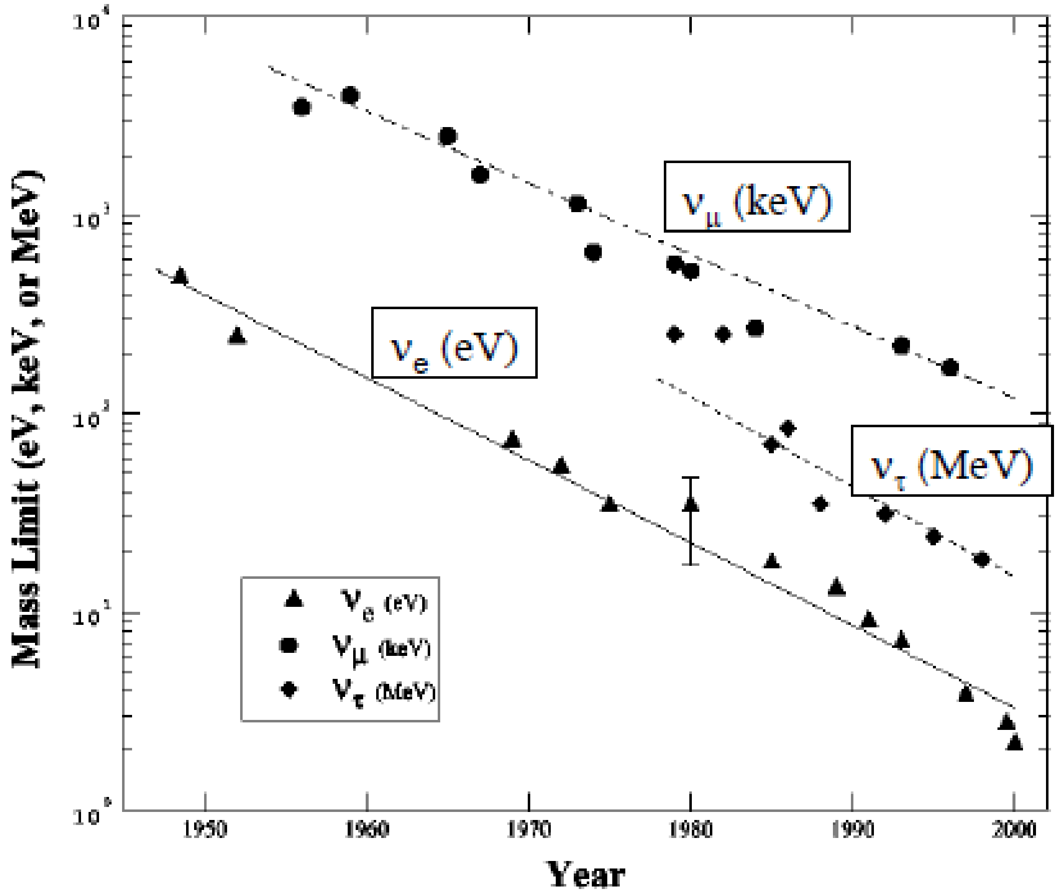
Beta decay. Real neutrinos. Incoherent sum.

$$M_{\beta\beta} = \left|\sum |U_{ei}| e^{i\alpha_i} m_i\right|$$

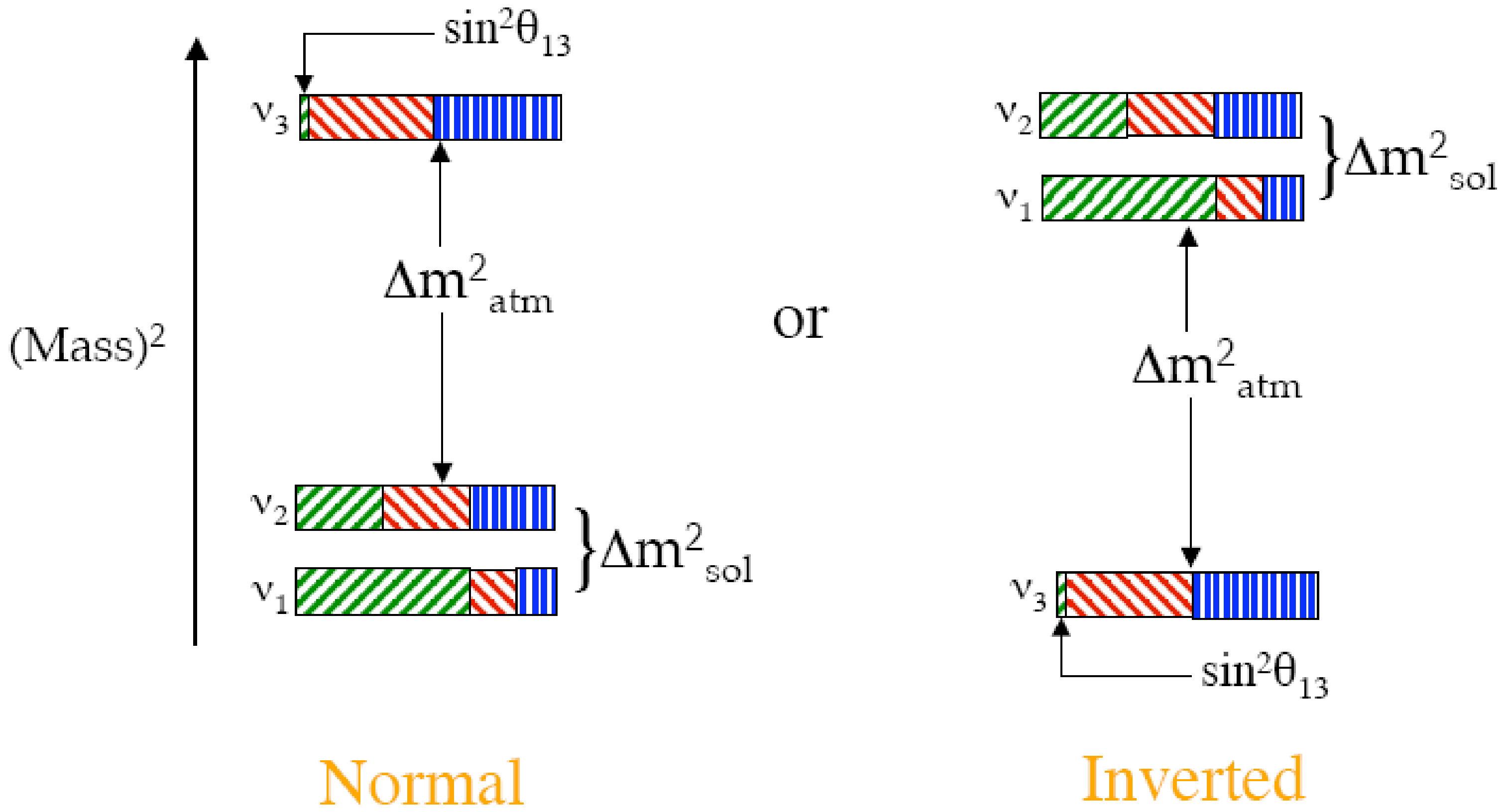
Double beta decay. Can also probe Majorana phases (in principle)

Direct decays

- Electron neutrino: < *2 eV*
  - $^3H \rightarrow {}^3He + \nu_e + e^-$
- Muon neutrino: < *170 keV*
  - $\pi \rightarrow \mu\nu_\mu$ decays
- Tau neutrino: < *18 MeV*
  - $\tau \rightarrow (n\pi)\ \nu_\tau$ decays



Neutrino masses and hierarchy

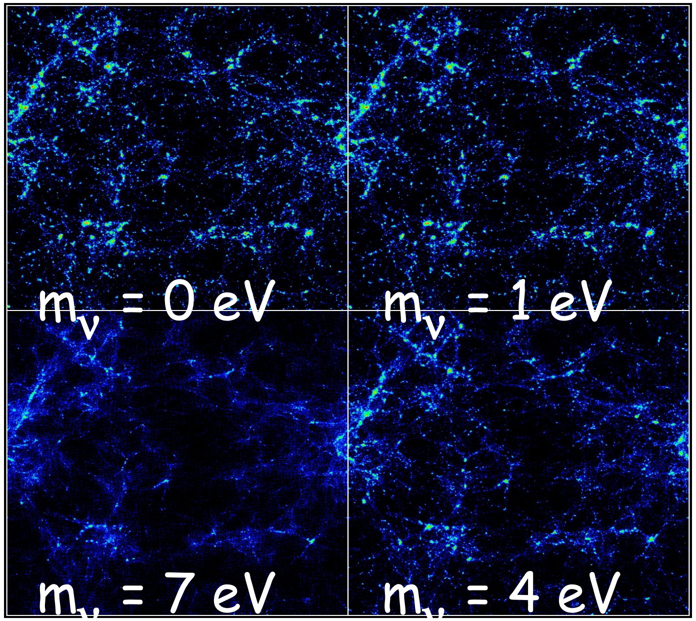


Sum(masses) > 0.06 eV

Sum(masses) > 0.1 eV

Cosmology

Probing neutrino masses with cosmology



(E..g., Ma 1996)

The neutrinos suppress low scale structures because they are free-streaming (not gravitationally bound).
The neutrino masses determine the fraction of energy carried by them => impact of "smoothing"

Probing neutrino masses with cosmology

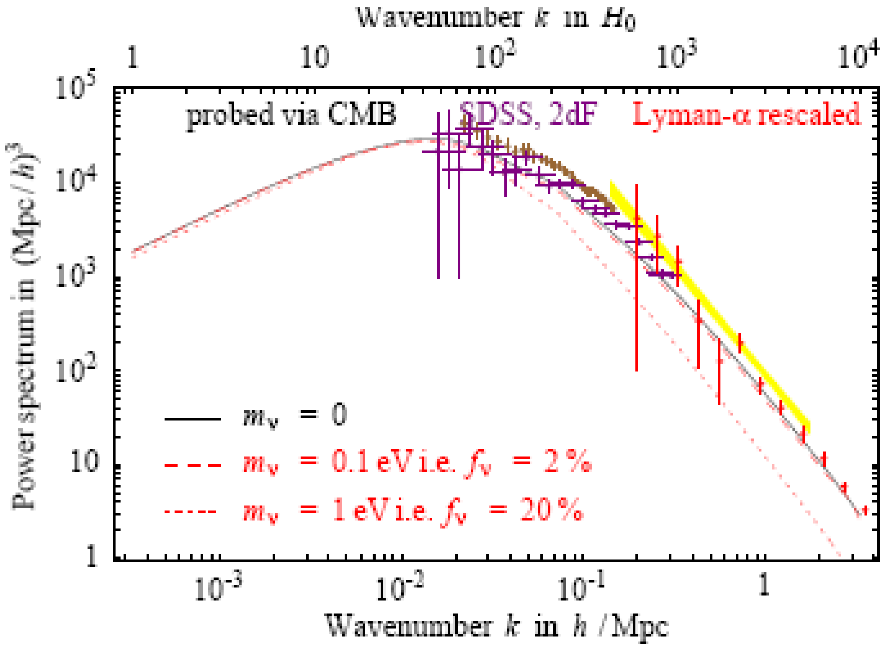
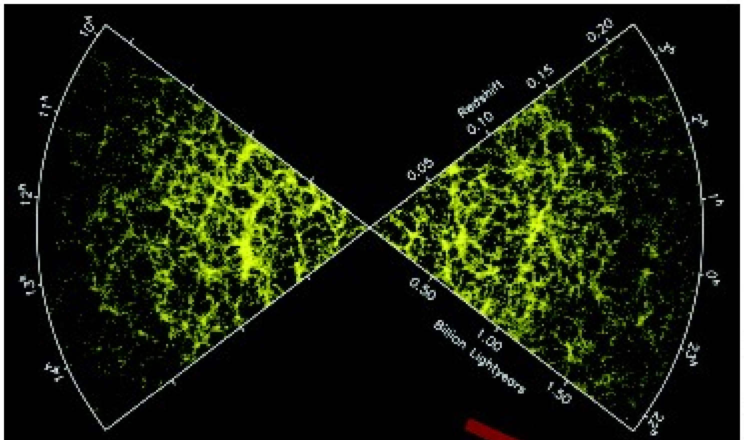
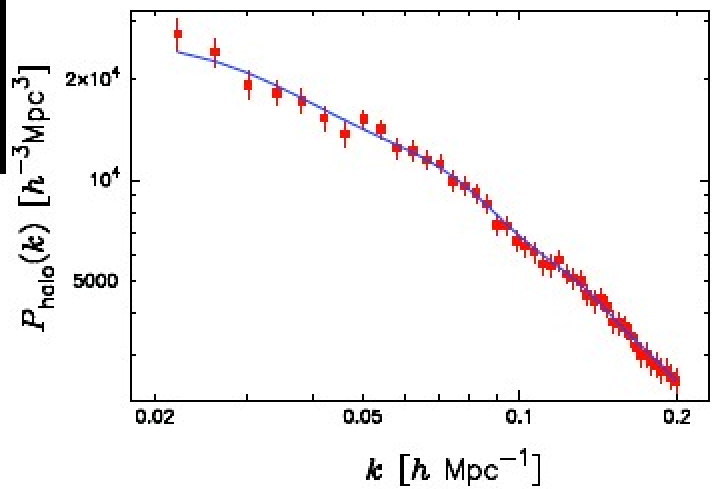


Figure 10.5: *The matter power spectrum $P(k)$ predicted by the best-fit ΛCDM cosmological model (continuous curve) and how neutrino masses affect it (dashed curves). Measurements at different scales have been performed with different techniques, that slightly overlap. The data points do not show the overall uncertainty that plagues galaxy surveys (SDSS, 2dF) at intermediate scales and especially Lyman-α data at smaller scales i.e. at larger k.*

LSS from galaxy maps



2-pt correlation function in Fourier space
= matter spectrum



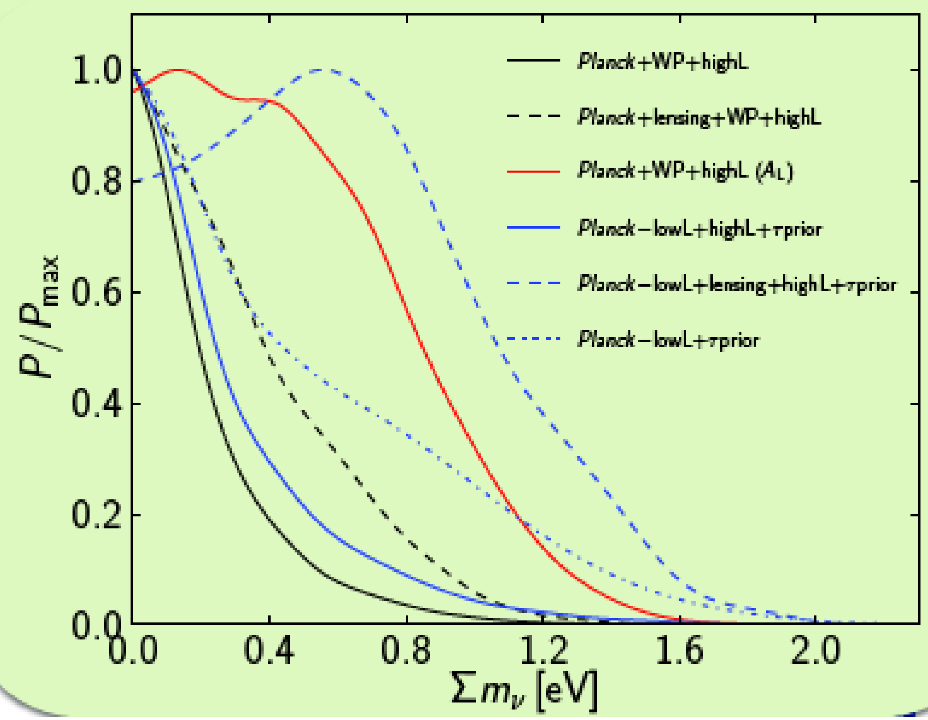
Excellent agreement with predictions of minimal ΛCDM model

Other probes: LSS from lensing maps, Lyman alpha forests ...

J. Lesgourgues, 2014

Current constraints from cosmology

- Planck+WP alone: $M_\nu < 0.66$ eV (twice better than WMAP) from non-observation of eISW depletion + strong smoothing of the peaks (actually more lensing than in ΛCDM preferred…)
- adding H0: $M_\nu < 0.18$ eV
- adding BAO: $M_\nu < 0.23$ eV
- but lensing extraction compatible with larger value…
- CFHTLens also prefers non-zero valu



But other measurements prefer higher values

- Planck+WP alone: $M_\nu < 0.66$ eV (twice better than WMAP) from non-observation of eISW depletion + strong smoothing of the peaks (actually more lensing than in LCDM preferred…)
- adding H0: $M_\nu < 0.18$ eV
- adding BAO: $M_\nu < 0.23$ eV
- but lensing extraction compatible with larger value
- SZ cluster count prefers non-zero value ~ 0.3 eV
- CFHTLens also prefers non-zero value

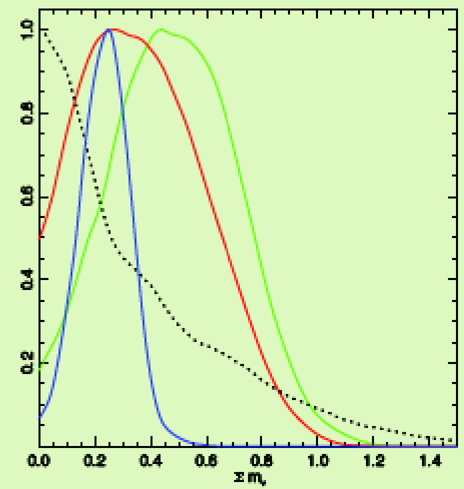


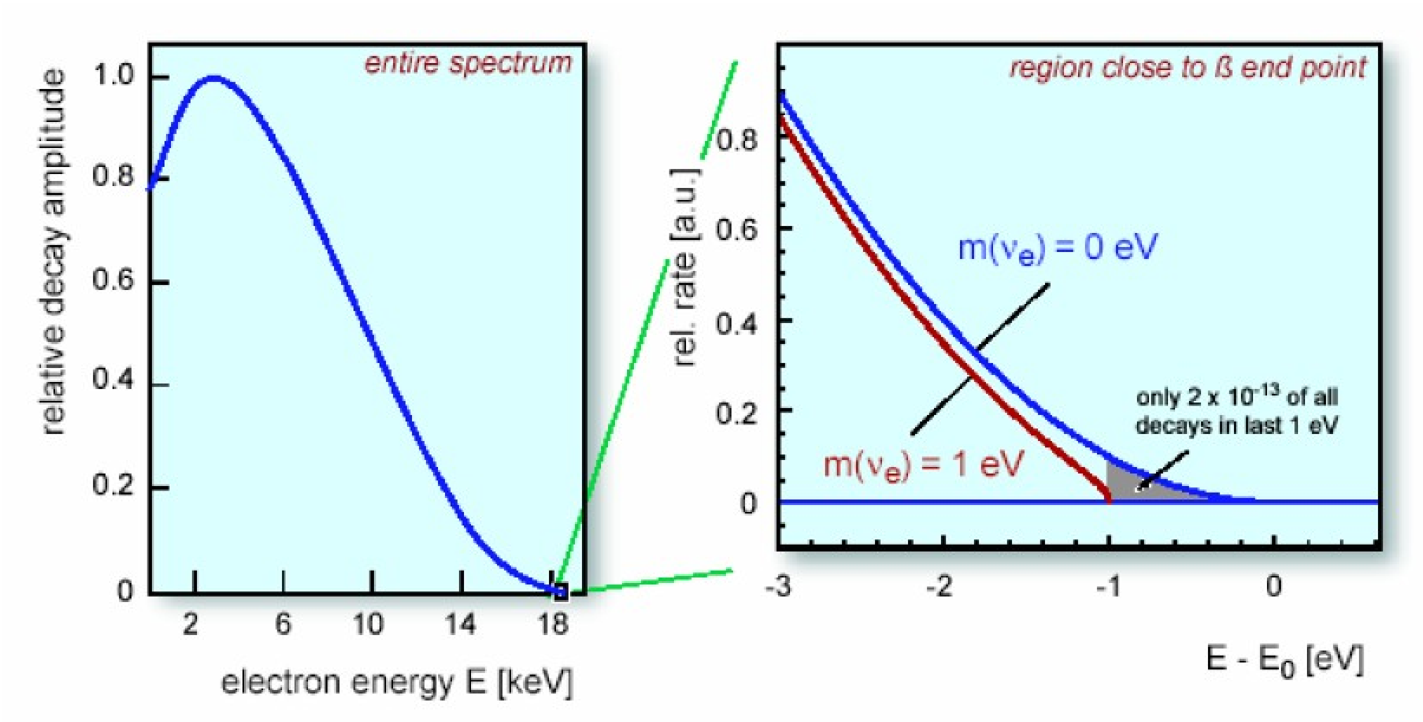
Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1-b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1-b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1-b = 0.8$ (green).

(Some) measurements affected by systematic uncertainties not yet under control

Beta decay

Measurement of the beta spectrum

- Method described already in Fermi 1934 paper!



$$dN(E) = K|M|^2 F(Z,R,E)\, p_e E\, (E_0-E)\, \{(E_0-E)^2 - m^2_{\nu_e} c^4\}^{1/2}\, dE$$

Katrin experiment: aim at 0.2 eV sensitivity

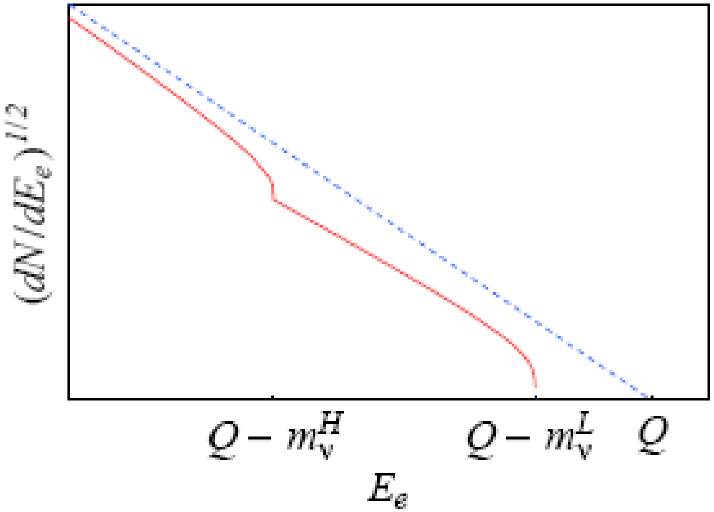
Measurement of the beta spectrum

Single β-decay probes

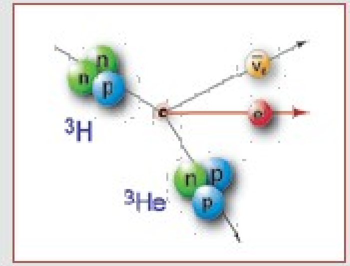
$$m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2} = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$

Effective nu_e mass

Notice that if our detector were very precise then we would see



Neutrino mass from Beta Spectra



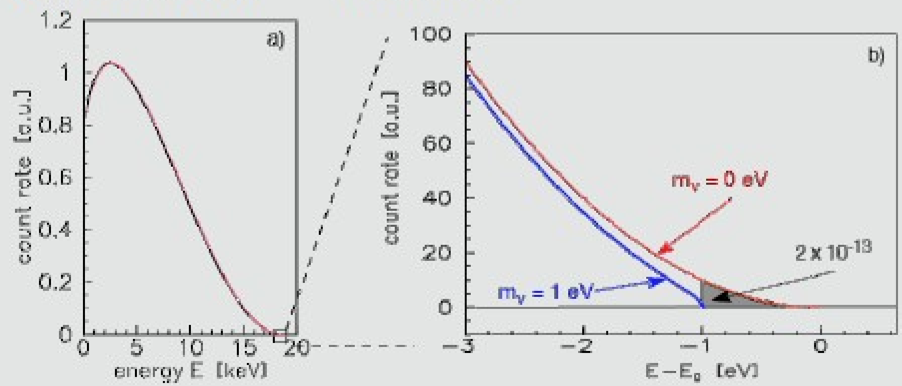
With flavor mixing:

$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

mixing — neutrino masses

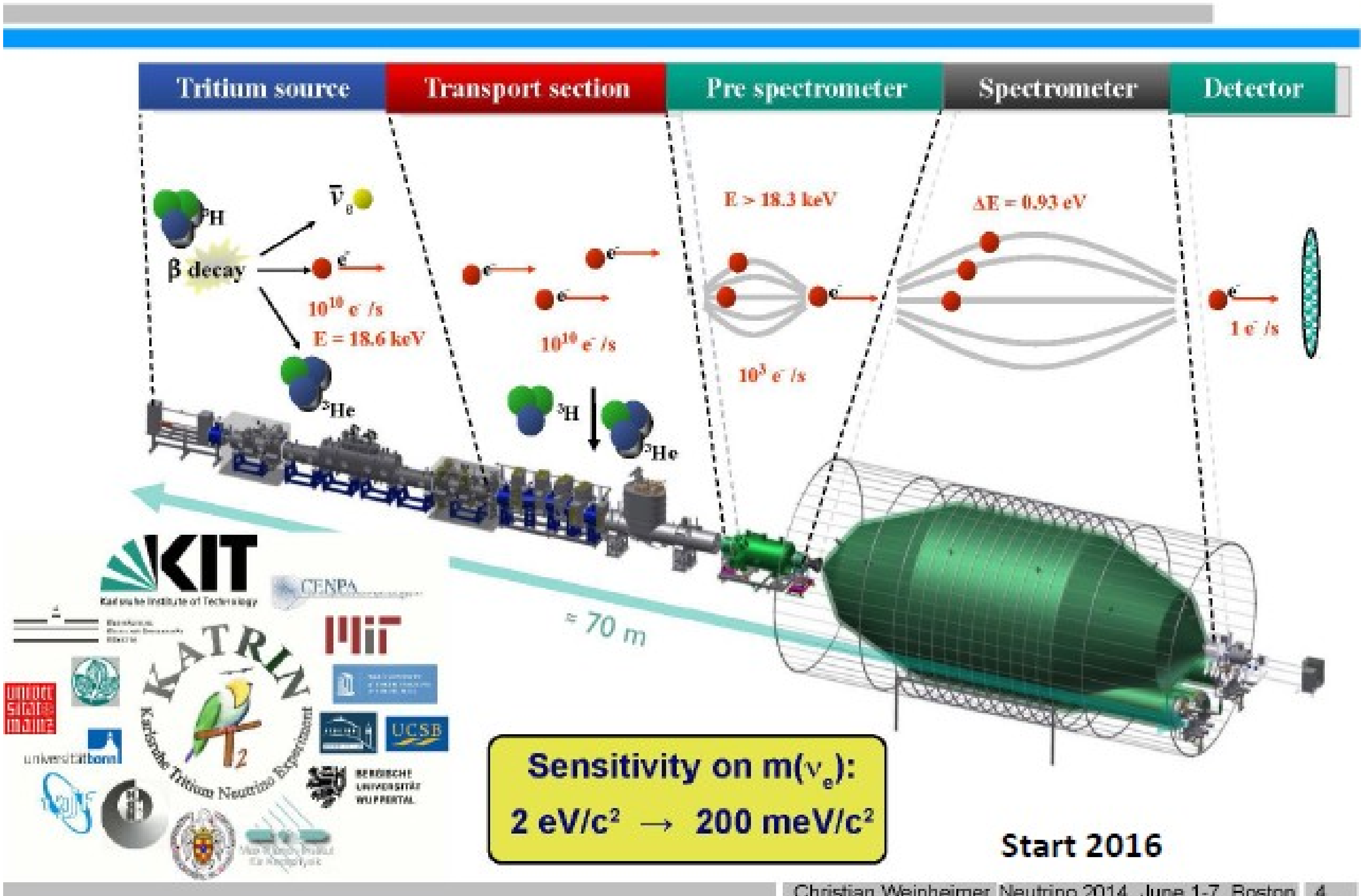
$$m_i^2 = \Delta m_{i0}^2 + m_0^2$$

from oscillations — mass scale



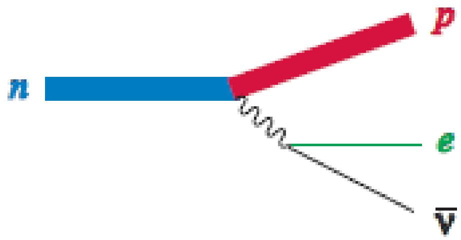
From H. Robertson

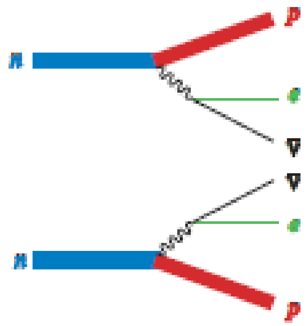
KATRIN experiment

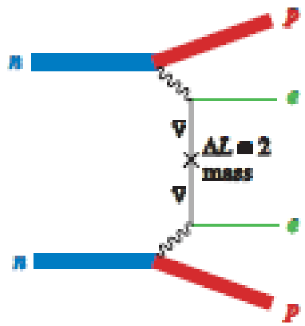


Not anymore a tabletop experiment

Double beta decay





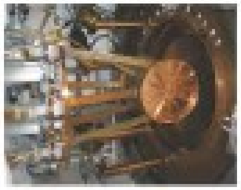


β decay ββ decay 2 ν ββ decay 0 ν

Requires Majorana neutrino!

0νββ decay Experiments - Efforts Underway

EXO200



CUORE

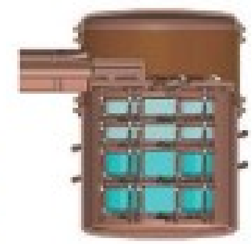
SNO+

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
GERDA II	Ge-76	Point contact Ge in LAr or LN	30-35 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	26 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
CAMEO	Cd-116	$CdWO_4$ crystals	21 kg	R&D
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUORICINO	Te-130	TeO_2 Bolometer	11 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
SNO+	Te-130	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	370 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	R&D
EXO-200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	5 tonnes	R&D
DCBA	Nd-150	Nd foils & tracking chambers	32 kg	R&D

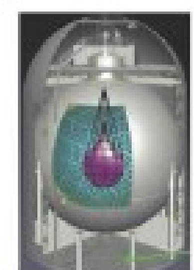
Complete | Construction | Operating

GERDA

MAJORANA



KamLAND ZEN



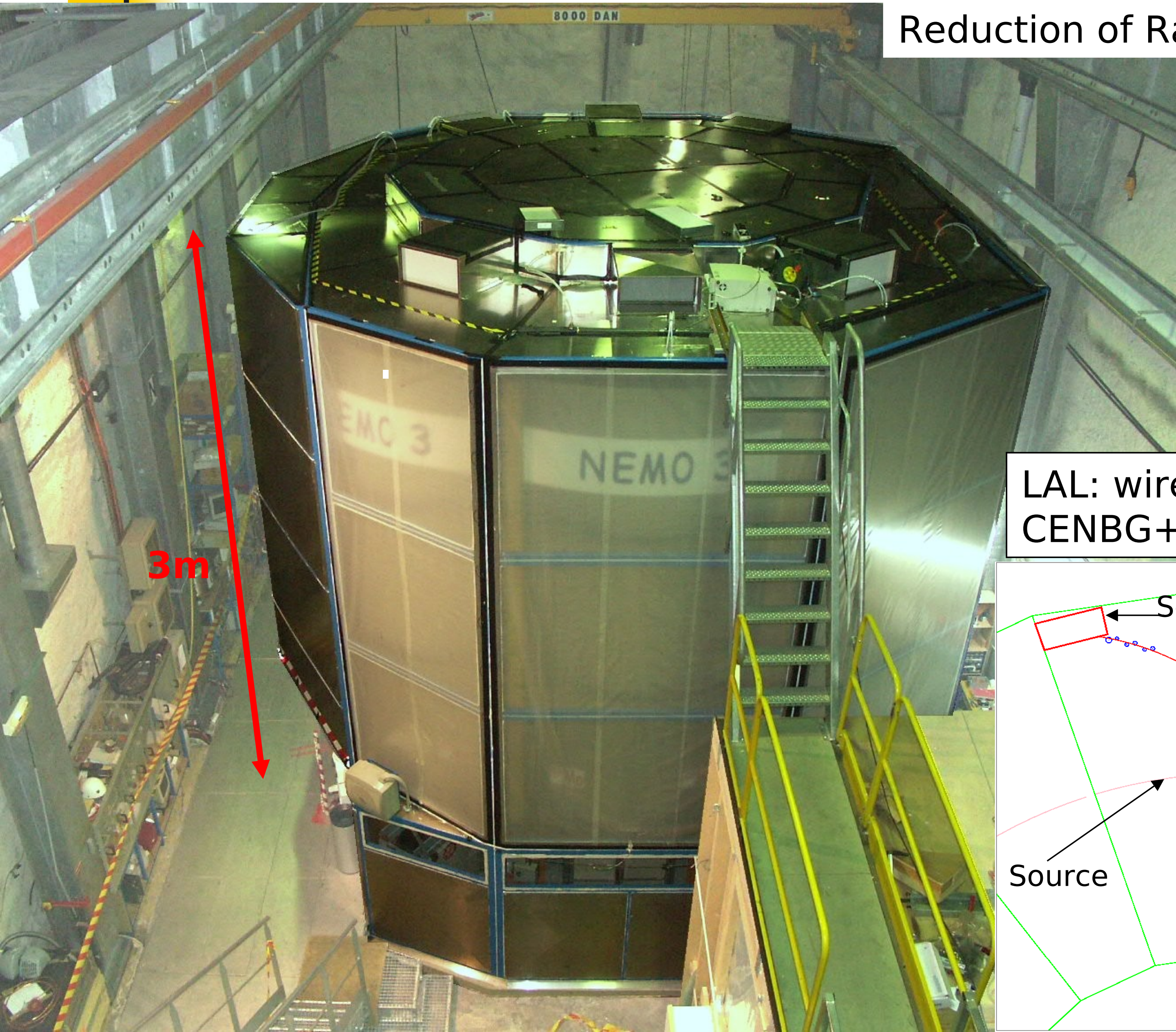
Next Generation: >~$100 M

From J. Wilkerson

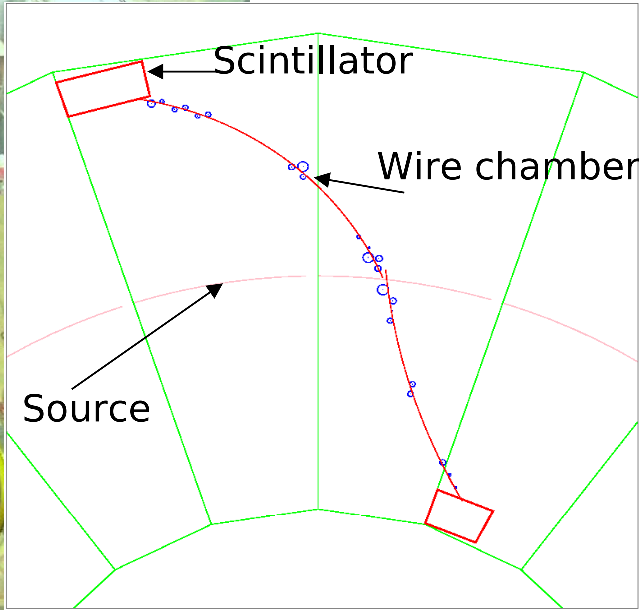
E

NEMO3 detector with the radon-free air tent (dec 2004)

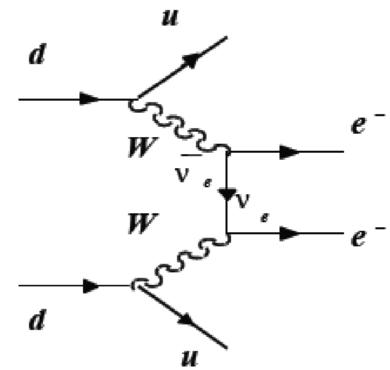
Reduction of Radon BKG ~ 10



LAL: wire chambers, DAQ
CENBG+IreS:calorimeter



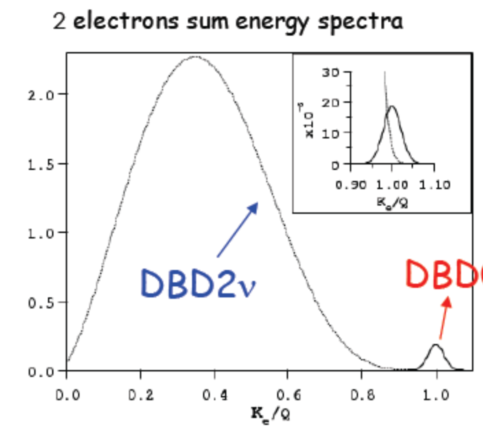
Neutrinoless double beta decay



Double beta decay (0 ν): only if ν is a Majorana particle!

Mixing matrix ±1 if CP conserved

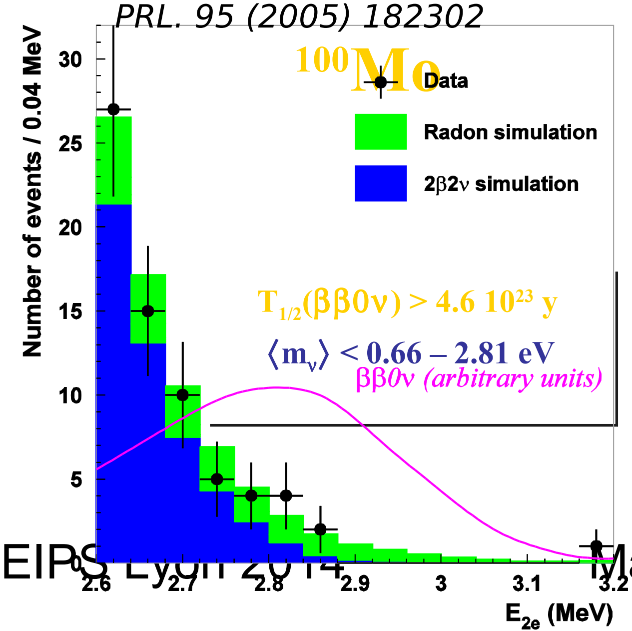
$$\left|\langle m_\nu \rangle\right| \equiv m_{ee} = \left|\sum_k U_{ek}^2 m_k\right| = \left|\sum_k |U_{ek}|^2 e^{i\alpha_{ek}} m_k\right|$$



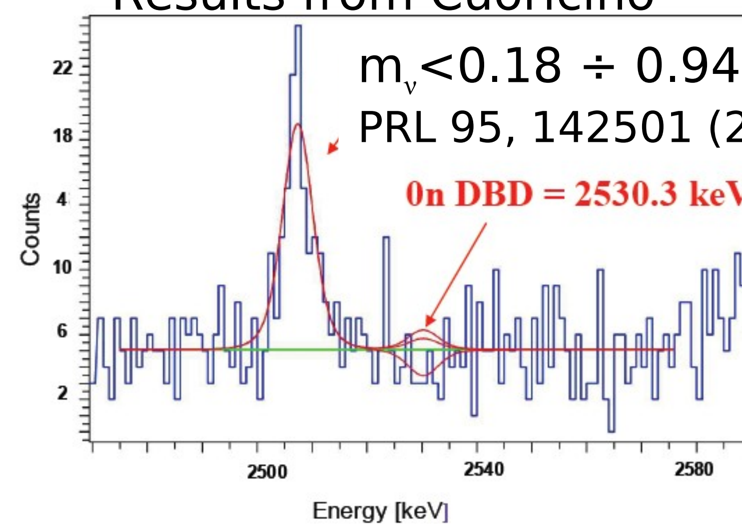
Best sensitivity: Heidelberg-Moscow ^{76}Ge experiment

Controversial claim of observation

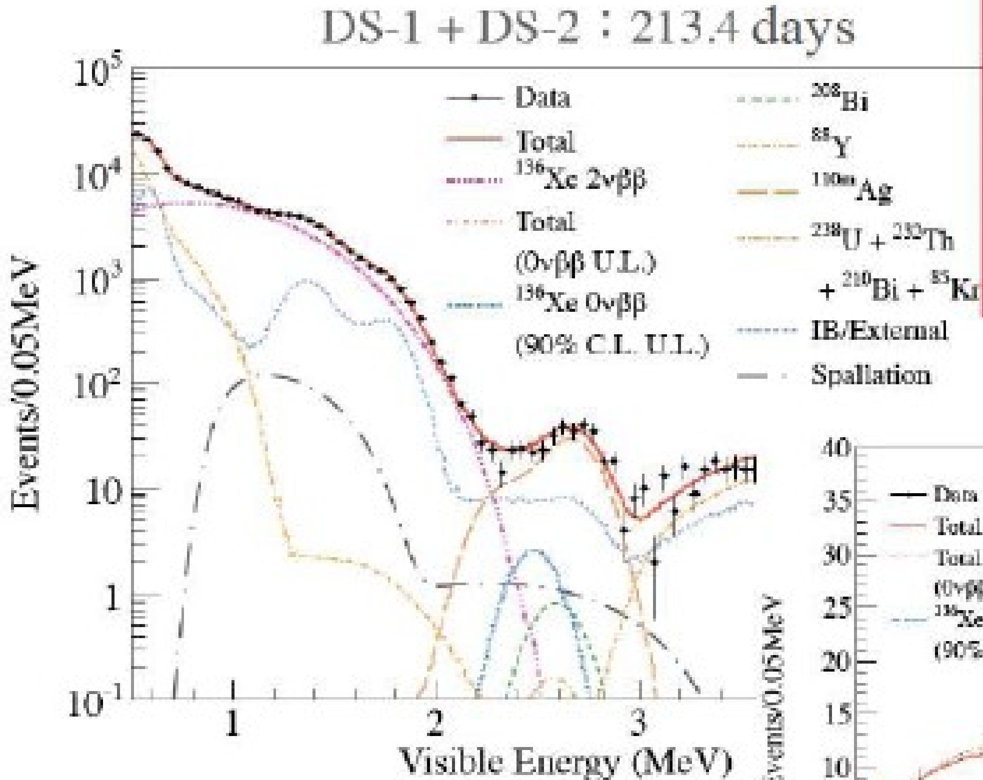
PRL. 95 (2005) 182302



Results from Cuoricino

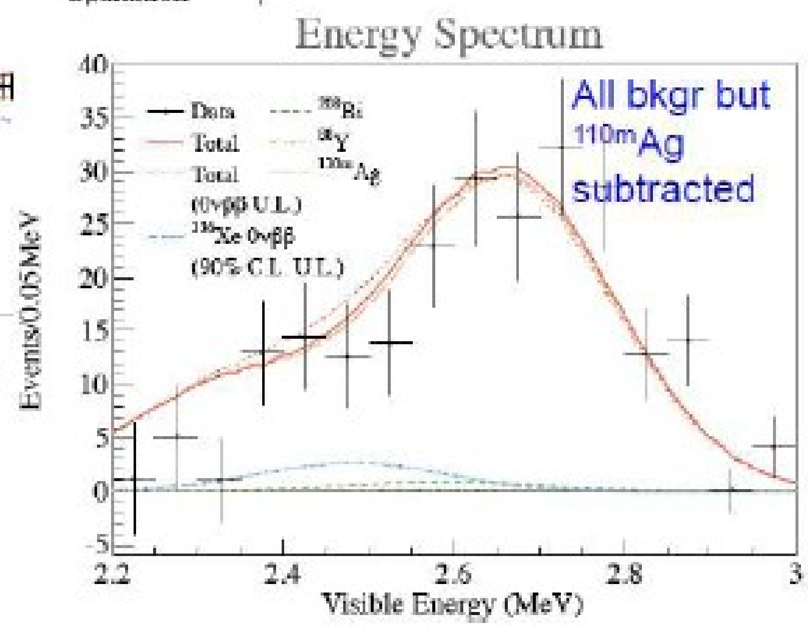


KamLAND-Zen phase I



Half life limit (90% CL) derived using this background subtraction:

$T_{1/2} > 1.9 \cdot 10^{25}$ yr
$<m_{\beta\beta}> < 129\text{-}341$ meV



Exposure: 89.5 kg·yr

E

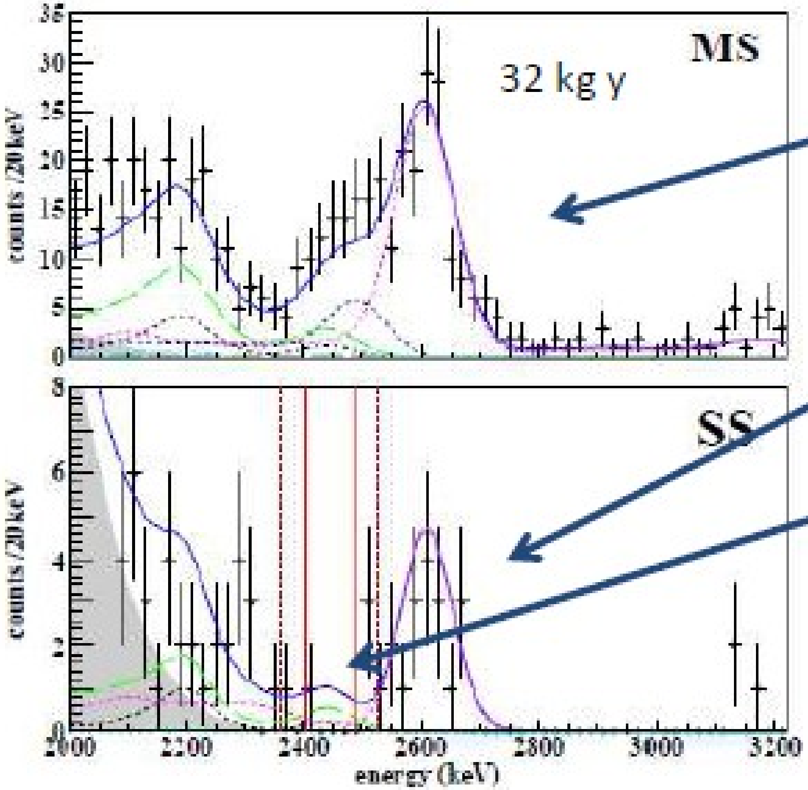
A. Piepke – TAUP2013

EXO-200

EXO-200 is a **TPC** containing **200 kg of enriched liquid xenon** .

- The detector measures both the scintillation light and the ionization.
- Multi-site and single site events are separated.

Zoom in the region of DBD



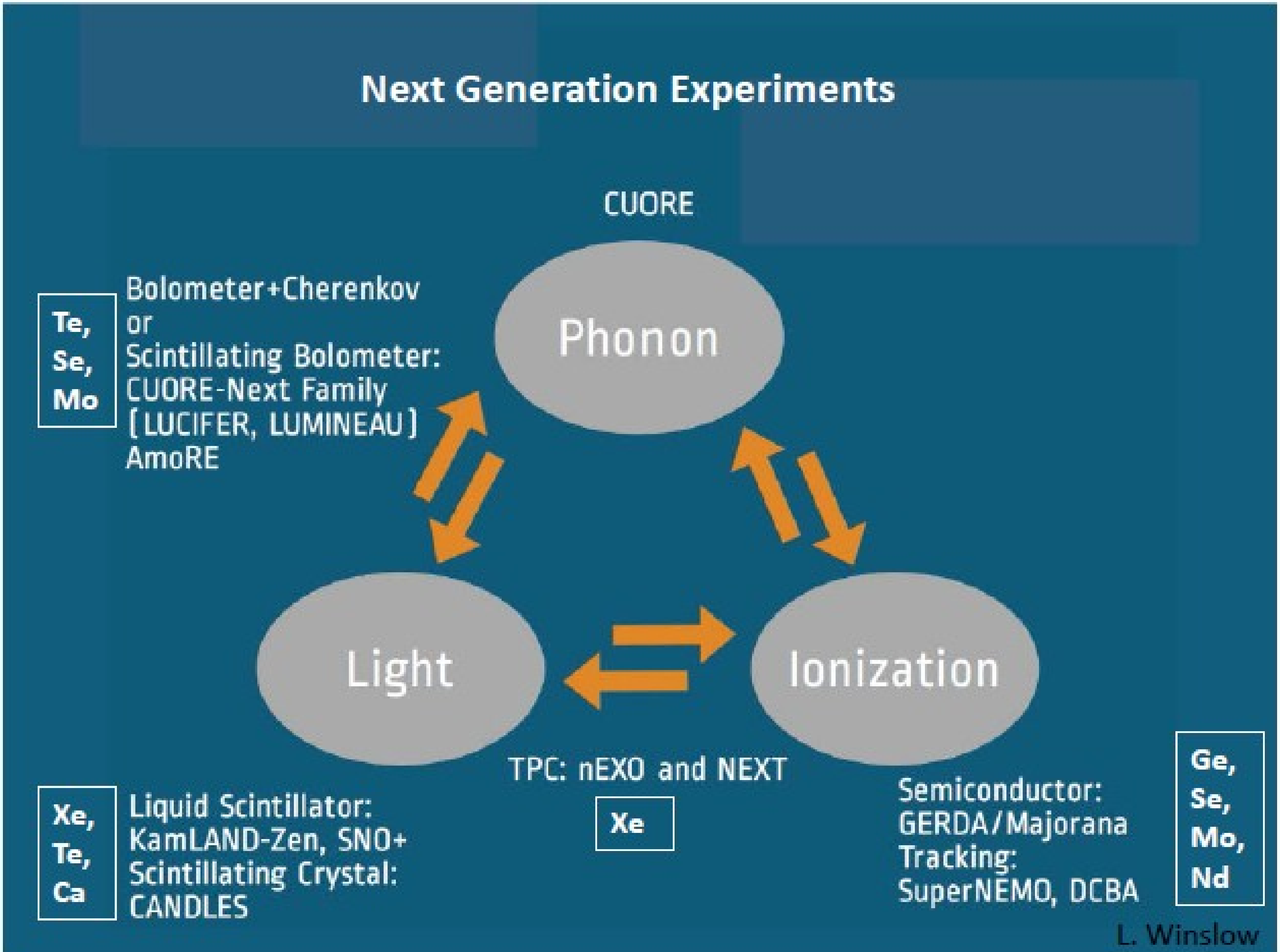
Multisite events

Single site events
(potential signal)

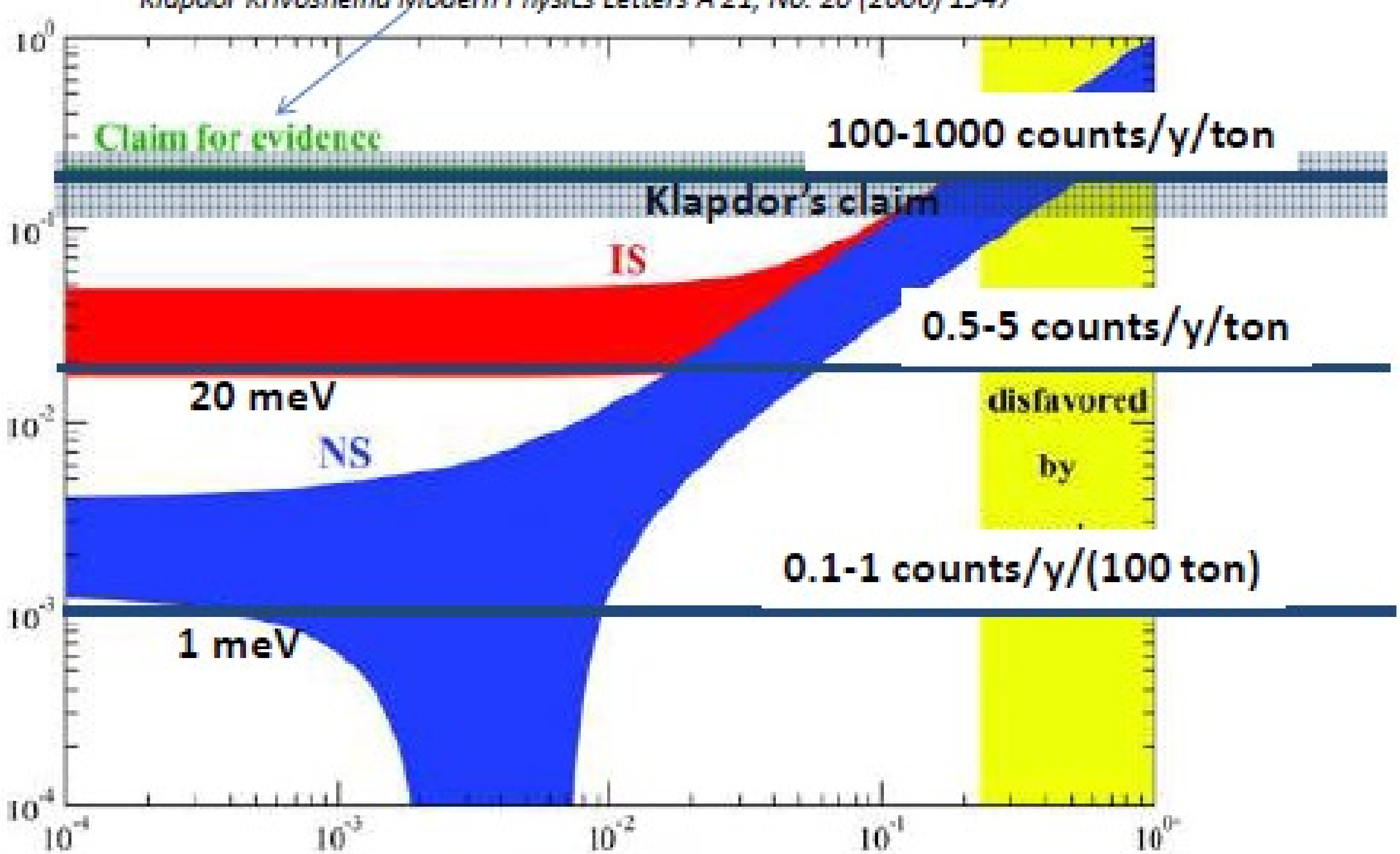
Background:
b = 1.5x10^{-3} counts/(keV kg y)

$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}\ yr$ (90% CL)

$\langle m \rangle_{\beta\beta} < 140 - 380$ meV


Next Generation Experiments
CUORE
Phonon
Light
Ionization
Te,
Se,
Mo
Bolometer+Cherenkov
or
Scintillating Bolometer:
CUORE-Next Family
(LUCIFER, LUMINEAU)
AmoRE
Xe,
Te,
Ca
Liquid Scintillator:
KamLAND-Zen, SNO+
Scintillating Crystal:
CANDLES
TPC: nEXO and NEXT
Xe
Semiconductor:
GERDA/Majorana
Tracking:
SuperNEMO, DCBA
Ge,
Se,
Mo,
Nd
L. Winslow

Klapdor Krivosheina Modern Physics Letters A 21, No. 20 (2006) 1547

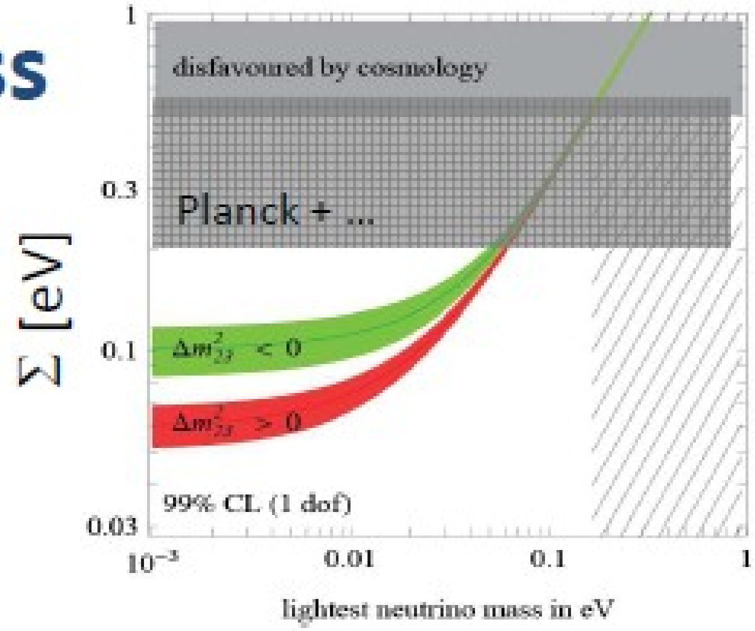


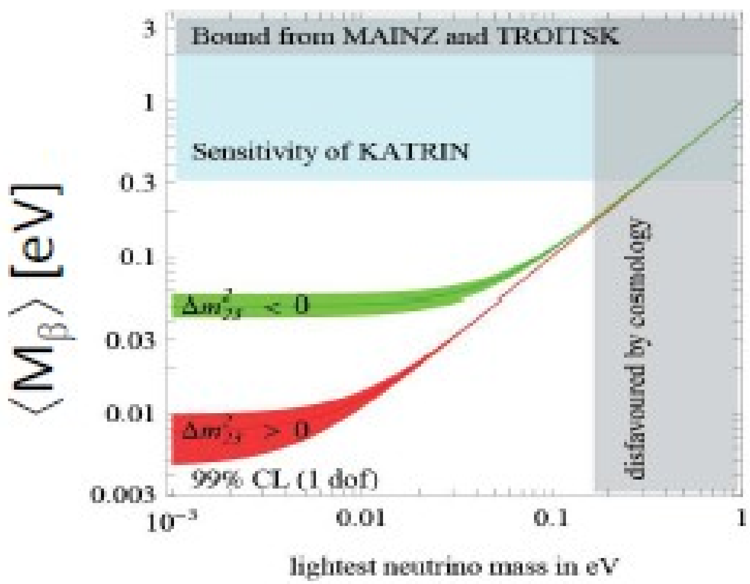
Status on neutrino mass

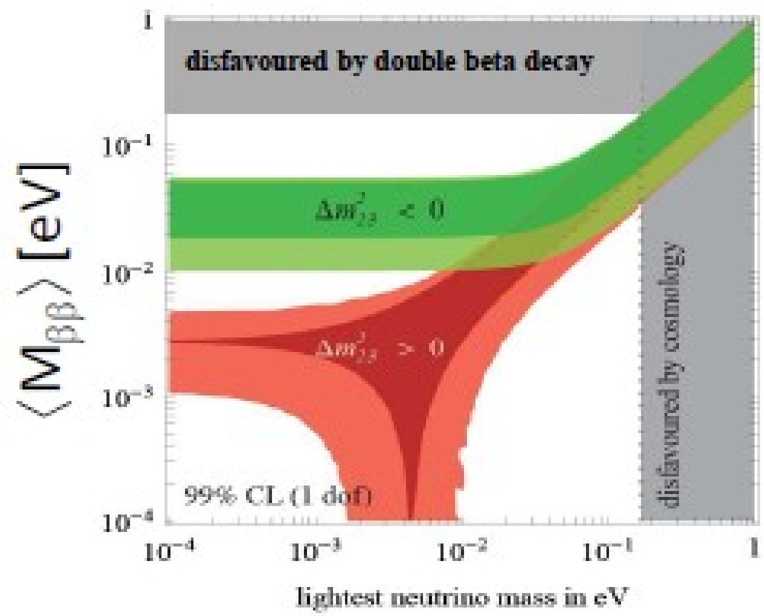
The three constrained parameters can be plotted as a function of the lightest neutrino mass

Two bands appear in each plot, corresponding to **inverted** and **direct hierarchy**

The two bands merge in the **degenerate case** (the only one presently probed)

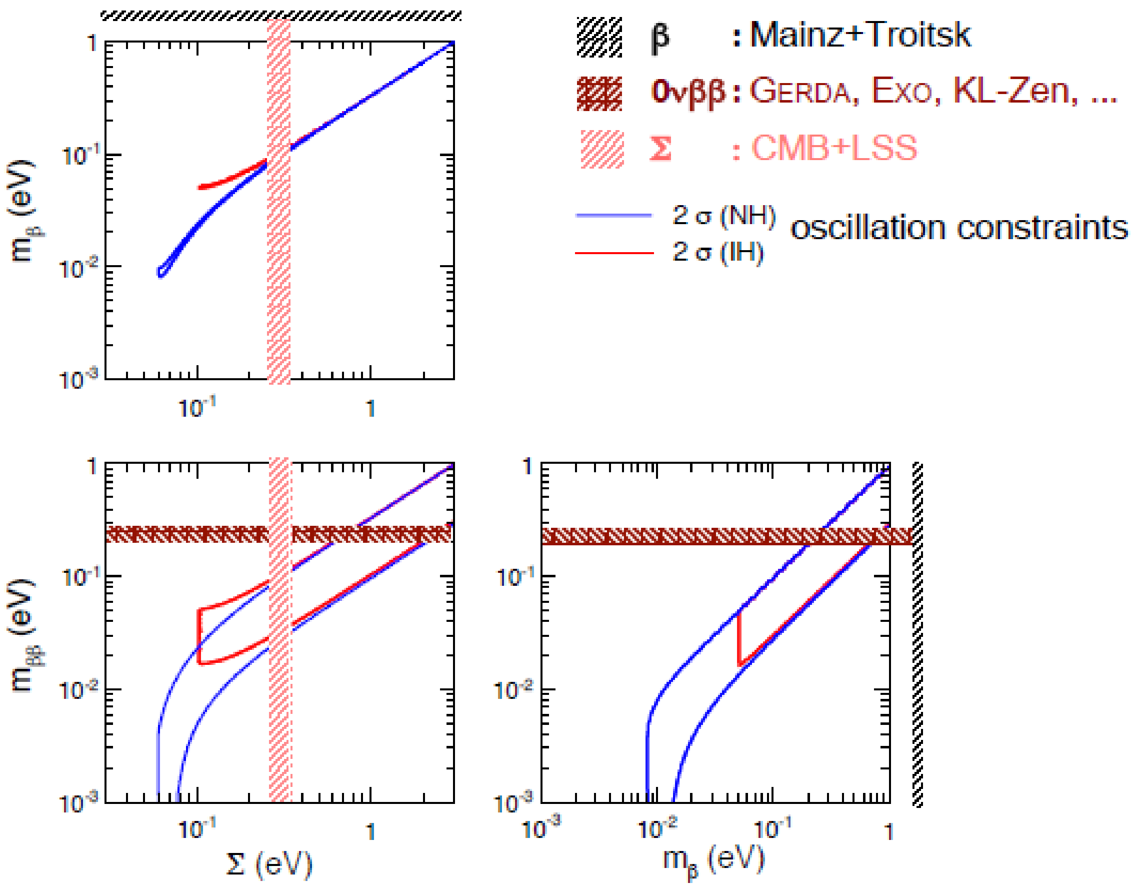






Current limits

Upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.) + osc. constraints*



*arXiv:1205.5254 by Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno

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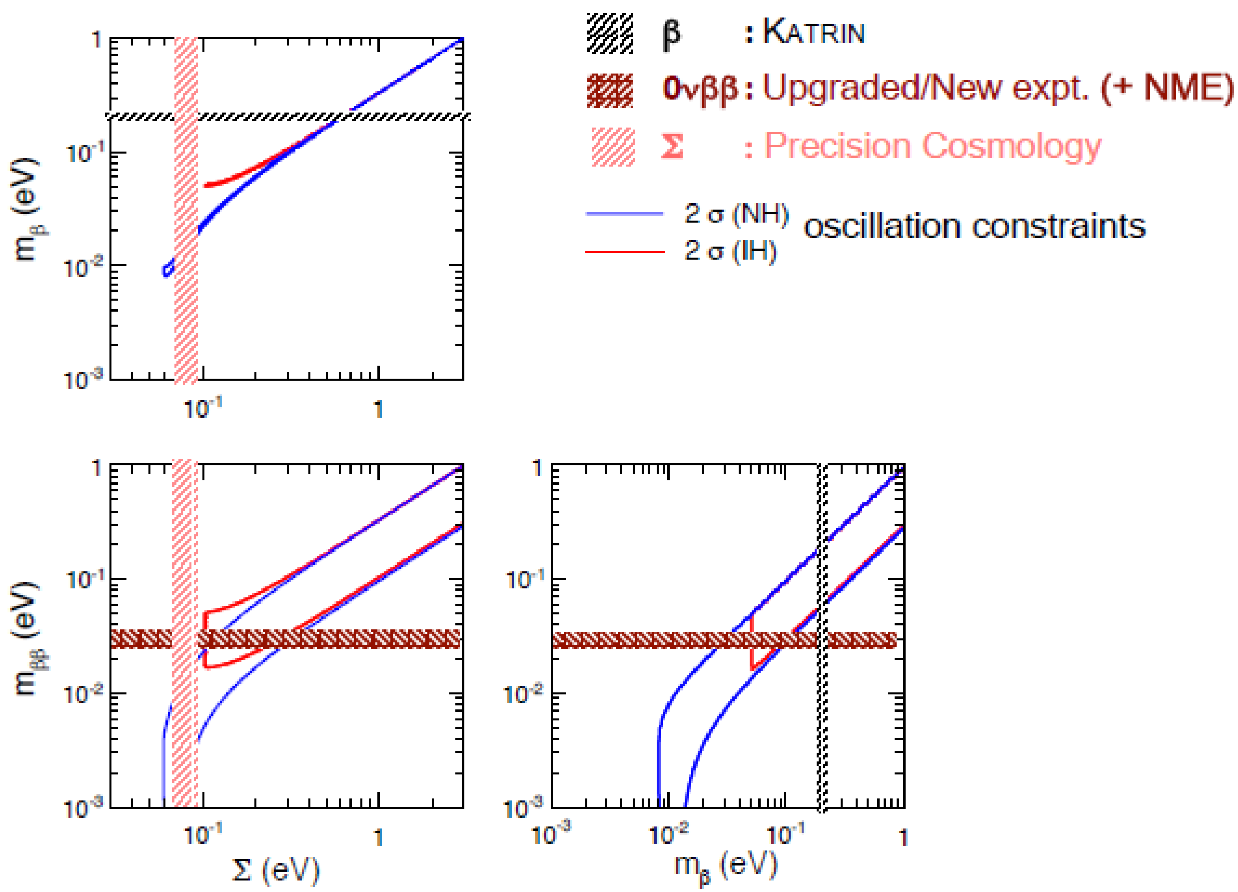
Prospects

Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?



Conclusion

- Current limits point to the sub eV range, an extremely difficult region to probe
- Beta and double beta experiments will be increasingly difficult to improve
- Impressive progress by cosmological measurements, however the control of the systematic uncertainties remains a difficult point