Neutrino Masses

4th IDPASC School
Braga, January 2014

Sofia Andringa – LIP (sofia@lip.pt)

The Neutrino Mass Matrix is (almost) complete !

$\theta 12 \sim 34^{o}$ $\Delta m^2 \sim 7\text{x}10^{-5}$ eV^2
$\theta 23 \sim 45^{o}$ $\Delta m^2 \sim 3\text{x}10^{-3}$ eV^2
$\theta 13 \sim 5^{o}$ $\Delta m^2 \sim 3\text{x}10^{-3}$ eV^2

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 0.82 & 0.55 & -0.15 \\ -0.35 & 0.70 & 0.61 \\ 0.44 & -0.45 & 0.77 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Δm^2 with precision of ~3%

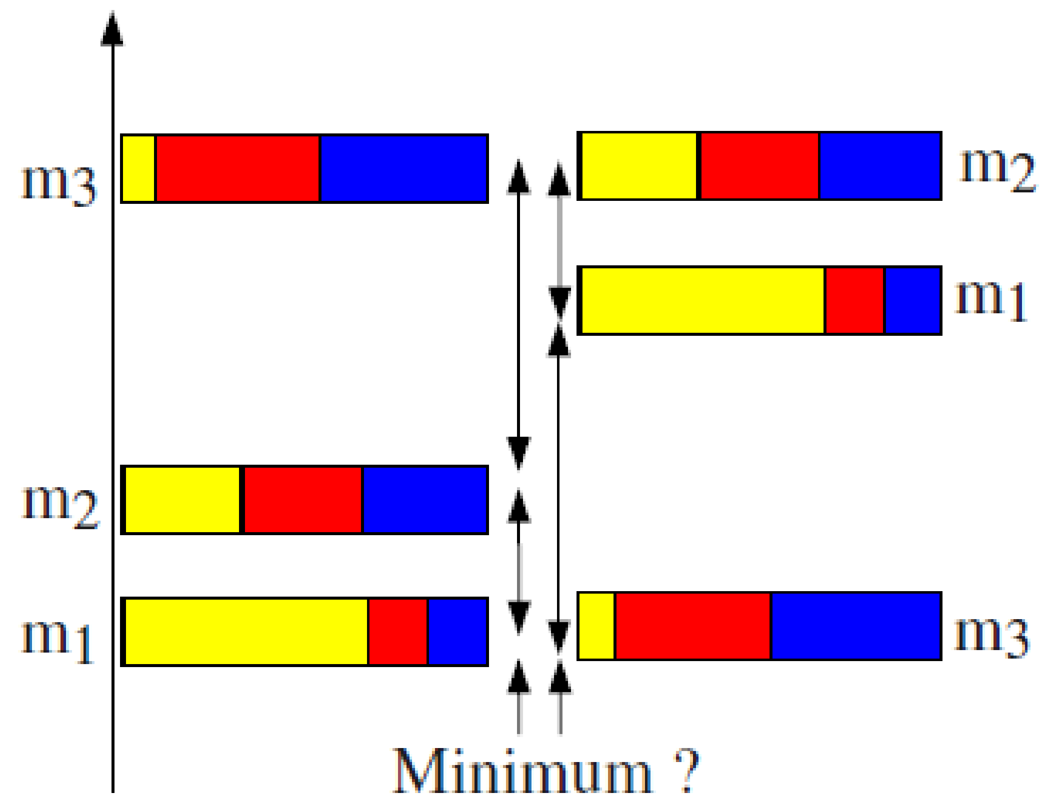
$\sin^2\theta$ with precision of 5%-20%

Exact PMNS still has large errors
But very different from CKM

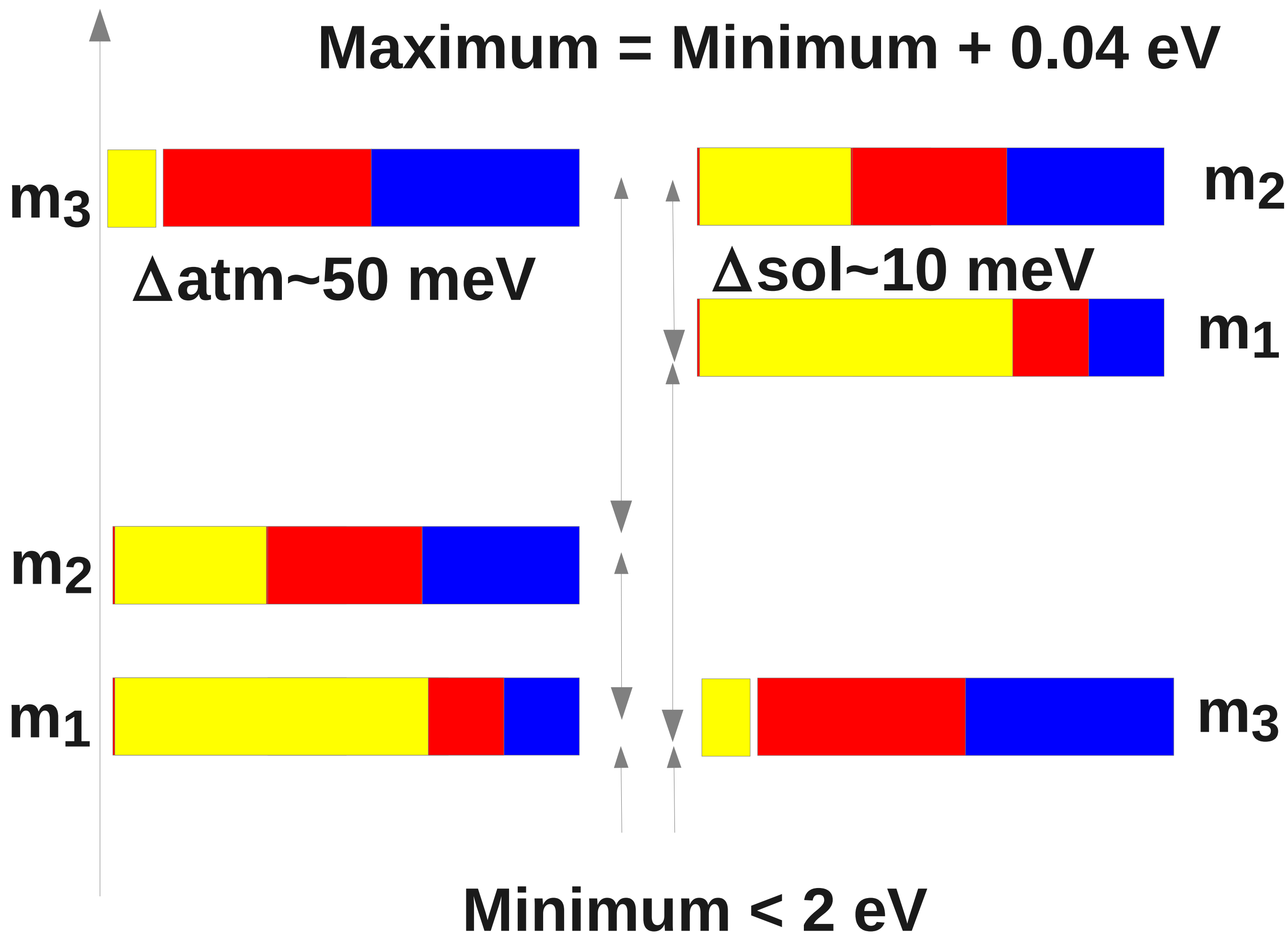
*** delta CP will also enter PMNS**

*** hierarchy not measured yet**

*** Majorana phases can also exist**



Neutrino Mass spectrum



Mτ = 1.8 GeV

Mμ= 0.1 GeV

Me = 0.5 MeV

Mν ~ meV – eV?

extra δm² => sterile neutrino

Neutrino masses are much smaller than for other elementary particle.
Hierarchy, lowest or average mass values, are still to be measured.

3 neutrinos : νe, $\nu\mu$, $\nu\tau$: $\nu 1$, $\nu 2$, $\nu 3$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} & & \\ & U & \\ & & \end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

PMNS (Pontecorvo, Maki, Nakagawa, Sakata)

PMNS Matrix, same as CKM for quarks (but very different values)
Can be factorized in three rotations (needed for CP violation),
which are experimentally selected by resonant (Δm^2) ~ L / E,

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

Historically:

Solar (small) Atmospheric (extra)

Neutrino mass origin: Dirac and/or Majorana

Neutrinos produced in weak interactions with left-handed helicity

With M>0

neutrino helicity can be flipped, into:

right-handed neutrino (if Dirac spinor): without weak interactions

right-handed anti-neutrino (if Majorana spinor): with interaction

Pure neutrino source

$\nu L + \varepsilon\, \nu R$

$\varepsilon \sim m/E$

anti-neutrino detector:

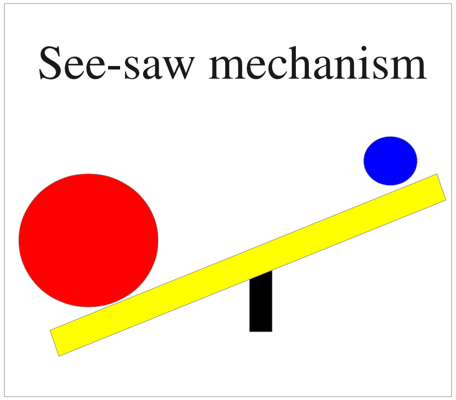
No signal if Dirac

Small signal if Majorana

$\sim 10^{-6}$ in reactors

$\sim 10^{-9}$ in accelerators

Neutrino mass origin: Dirac and/or Majorana



$$\begin{bmatrix} 0 & m_D \\ m_D & m_M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix} \text{--->} \begin{bmatrix} m_D^2/m_M & 0 \\ 0 & m_M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

with m_D ~ EWT ~ 100 GeV and m_M ~ GUT ~ 10^{15} GeV
gives a very light ~ Dirac left-handed neutrino of 10 meV
and a very heavy ~ Majorana right-handed sterile neutrino

Majorana mass terms (in addition to Higgs mechanism) are only possible for fermions without electric charge (just neutrinos)

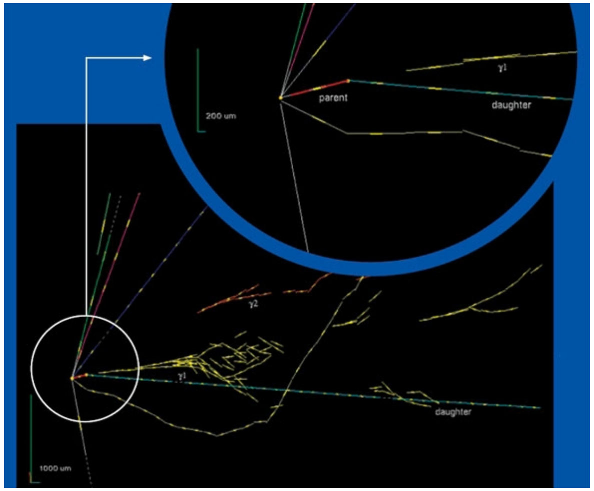
Can explain difference in masses but will break (the non-fundamental) lepton-number conservation

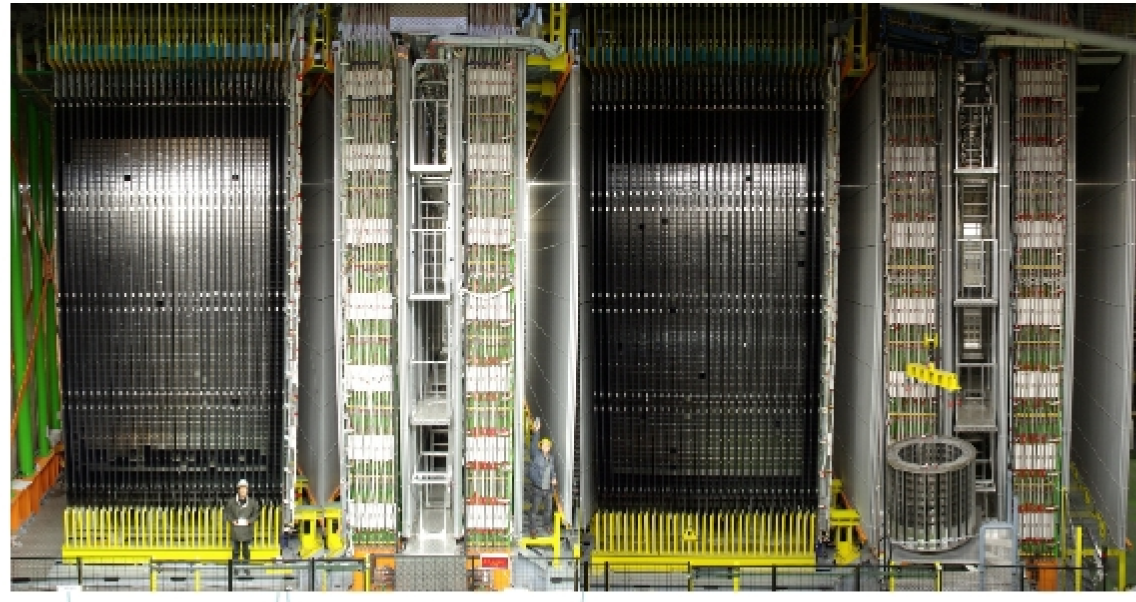
Neutrino mass measurements

Invisible neutrinos	Visible neutrinos	
Electron spectrum in beta decays: $M = \lim (dM - Ee)$	Neutrino velocity in long baselines: $M^2 = E^2 (1 - (v/c)^2)$	Kinematics
Neutrinoless* double beta decays: $M = s(Q)/U$	Neutrino oscillations: $dM^2 = m_i^2 - m_j^2$	Resonant Processes

+ Cosmology: indirect indications from other observations

Neutrino mass from kinematics: the CERN to LNGS case





OPERA Oscillation Experiment:

Tau neutrino appearance from a pure muon neutrino beam, needs E~17 GeV for tau production, L= 732 km +- 20 cm

Time stamp at CERN and at LNGS indicated

$$(v-c)/c = (2.48 \pm 0.28\ (\text{stat.}) \pm 0.30\ (\text{sys.})) \times 10^{-5}$$

Neutrinos traveling faster than light??

Neutrino mass from kinematics: how fast?

Finally, the mistake was found.
CNGS   L = 730 km   E ~ 17 GeV

New numbers give (at 90% CL)
$-1.8\times10^{-6} < (v-c)/c < 2.3\times10^{-6}$

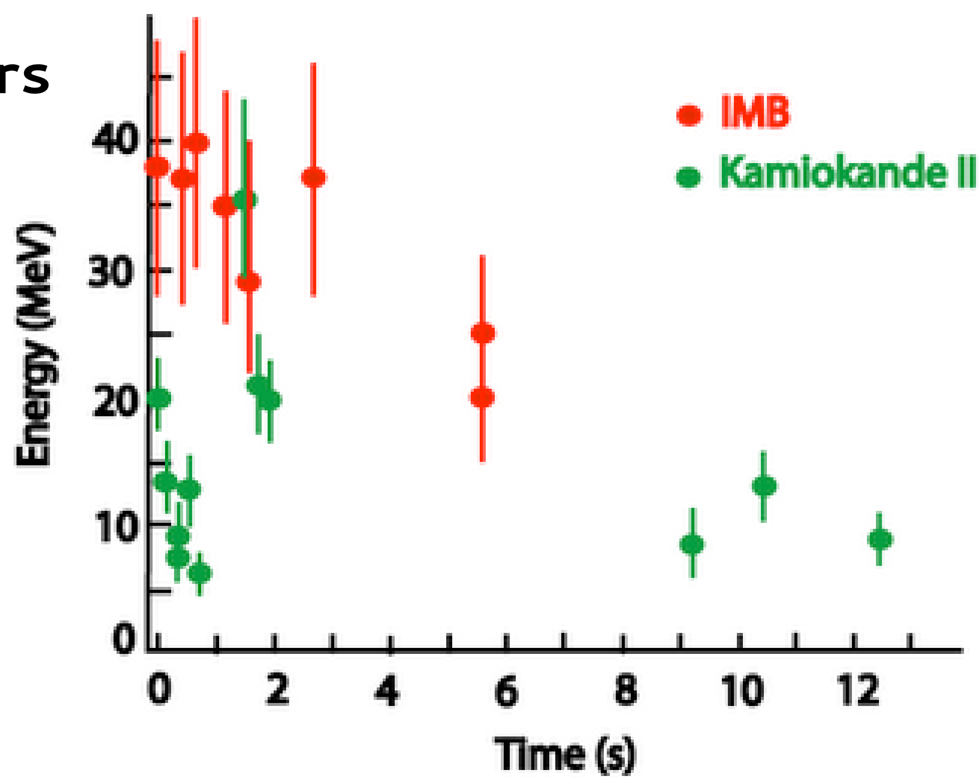
Different beams can be tested:
MINOS L = 730 km   E ~ 3 GeV

$(v-c)/c = (5.1 \pm 2.9)\times10^{-5}$

SN   L = parsecs   E~10 MeV;

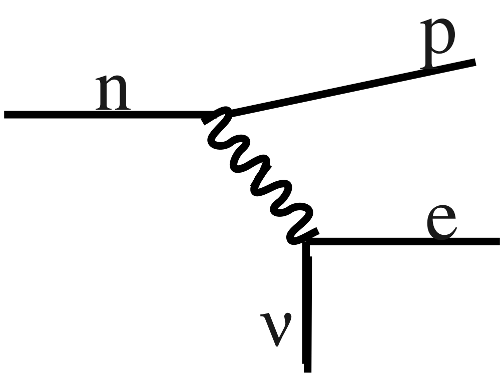
$(v-c)\,/\,c < 10^{-9}$ from SN1987A

SN1987A neutrinos were seen 3 hours before the photons arrived at Earth (photons are delayed by interactions)



Expected delays much smaller:
$(v-c)\,/\,c = -\,10^{-19}$ for m = 2 eV...
(not enough precision!)

Neutrino mass from kinematics: back to beta decays

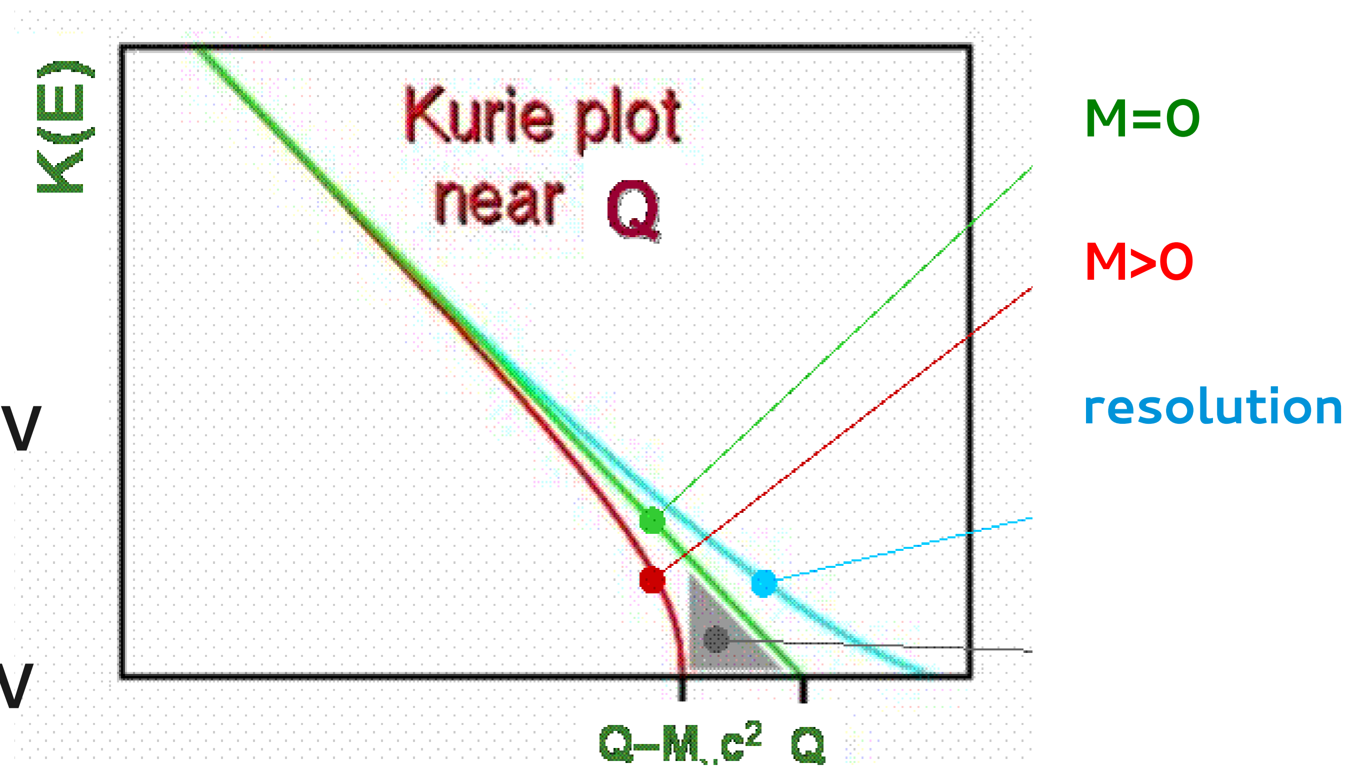


$$K(E) \equiv \left[\frac{dN/dE}{pEF(Z,E)}\right]^{\frac{1}{2}} \propto \left\{(E_0 - E)\left[(E_0 - E)^2 - m_\nu{}^2\right]^{\frac{1}{2}}\right\}^{\frac{1}{2}} \approx E_0 - E$$

Beta decay (electrons)
upper limit ~ 1 eV

Pion decay (muons)
upper limit ~ 100 keV

Tau decay (taus)
upper limit ~ 10 MeV



Neutrino mass from kinematics: which beta decay?

$^{3}H \rightarrow {}^{3}He + e^{-} + \overline{\nu}$

Eo = 18.37 keV; T1/2 = 13 y

Simple final state, well understood shape

** spectrometer for 0-20 keV (ex: KATRIN)

$^{187}Re \rightarrow {}^{187}Os + e^{-} + \overline{\nu}$

Eo = 2.47 keV; T1/2 = 43 Gy; 63% abundance

More difficult initial and final states corrections

** bolometer for 0-3 keV (ex: MARE)

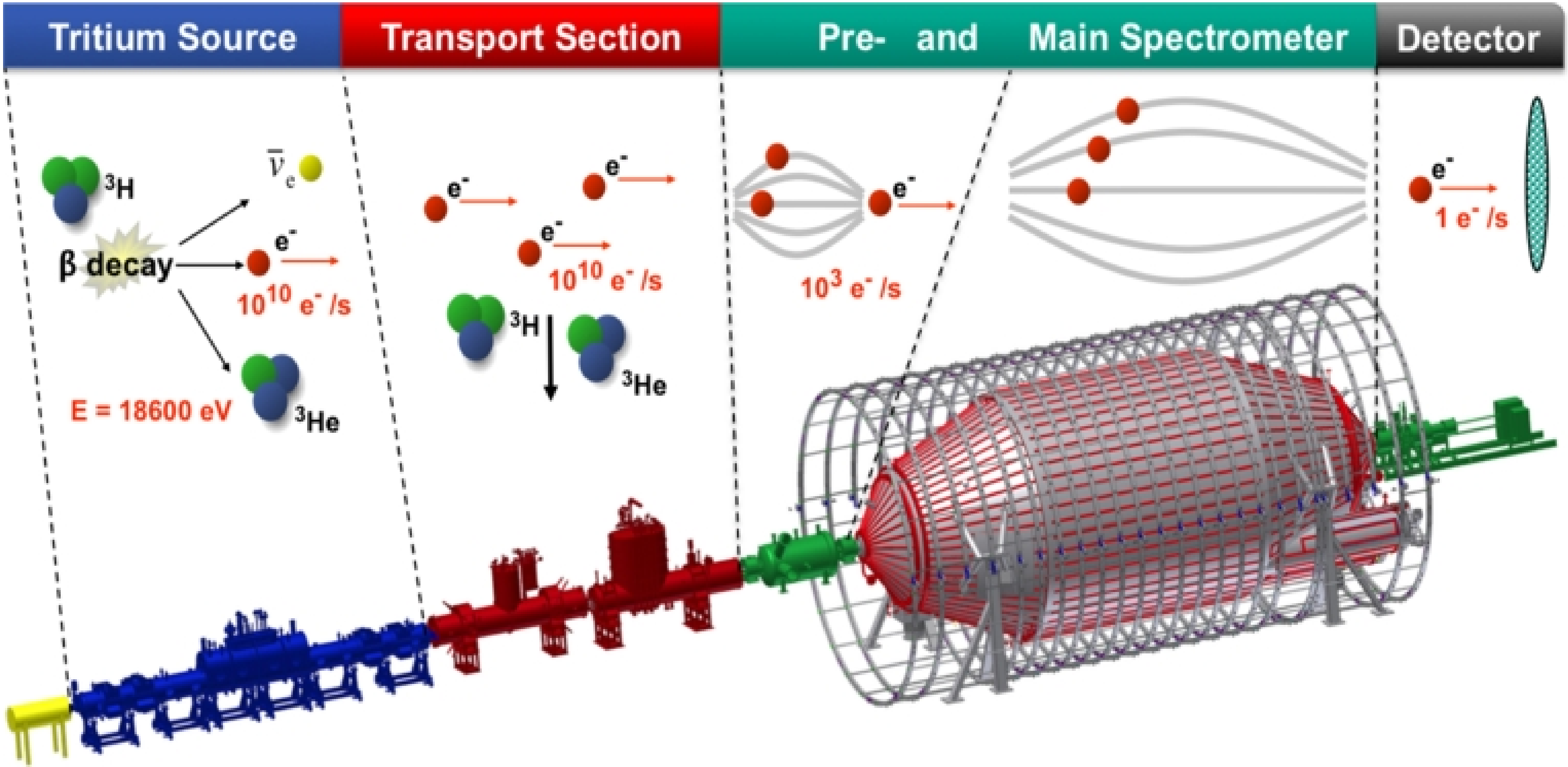
$^{163}Ho + e^{-} \rightarrow {}^{163}Dy^{*} + \nu$

E = 2.3-2.8 keV; T1/2 ~ 4.6 ky; produced in reactors

Difficult initial and final states

** control of electron energy

Neutrino mass from kinematics: $^3H(pnn) \to {}^3He(ppn)\, e^- \bar{\nu}$



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

Neutrino mass from kinematics: ^{3}H(pnn) –> ^{3}He(ppn) $e^- \bar{\nu}$

Tritium Source | Transport Section | Pre- and Main Spectrometer | Detector

Start data taking in 2014

Goal is to reach 0.35 eV

in electron neutrino mass

(~0.1 of the current limit)

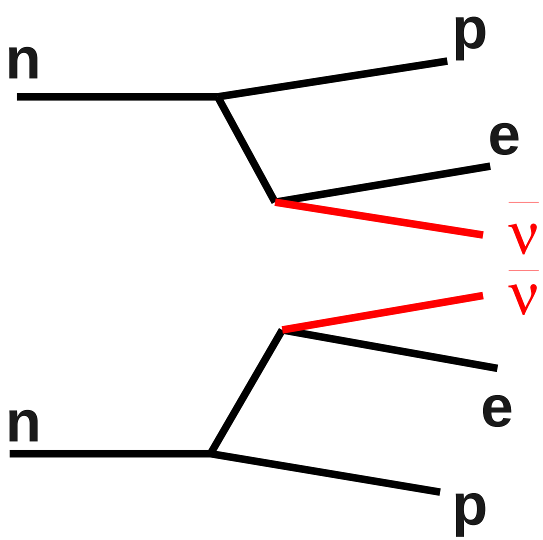
Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

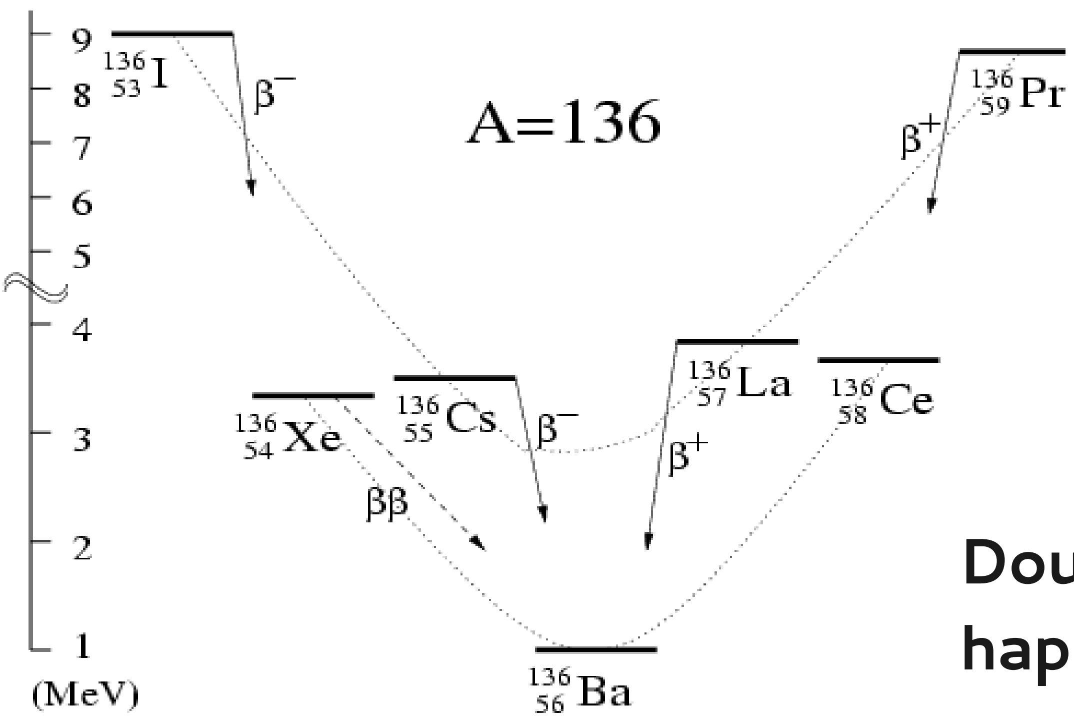
Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

Beta and double beta decays





	Q(MeV)	I(%)
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	12.
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.6
$^{130}Te \rightarrow {}^{130}Xe$	2.533	35.
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

Double beta decays are rare, happening only for some 15 nuclei

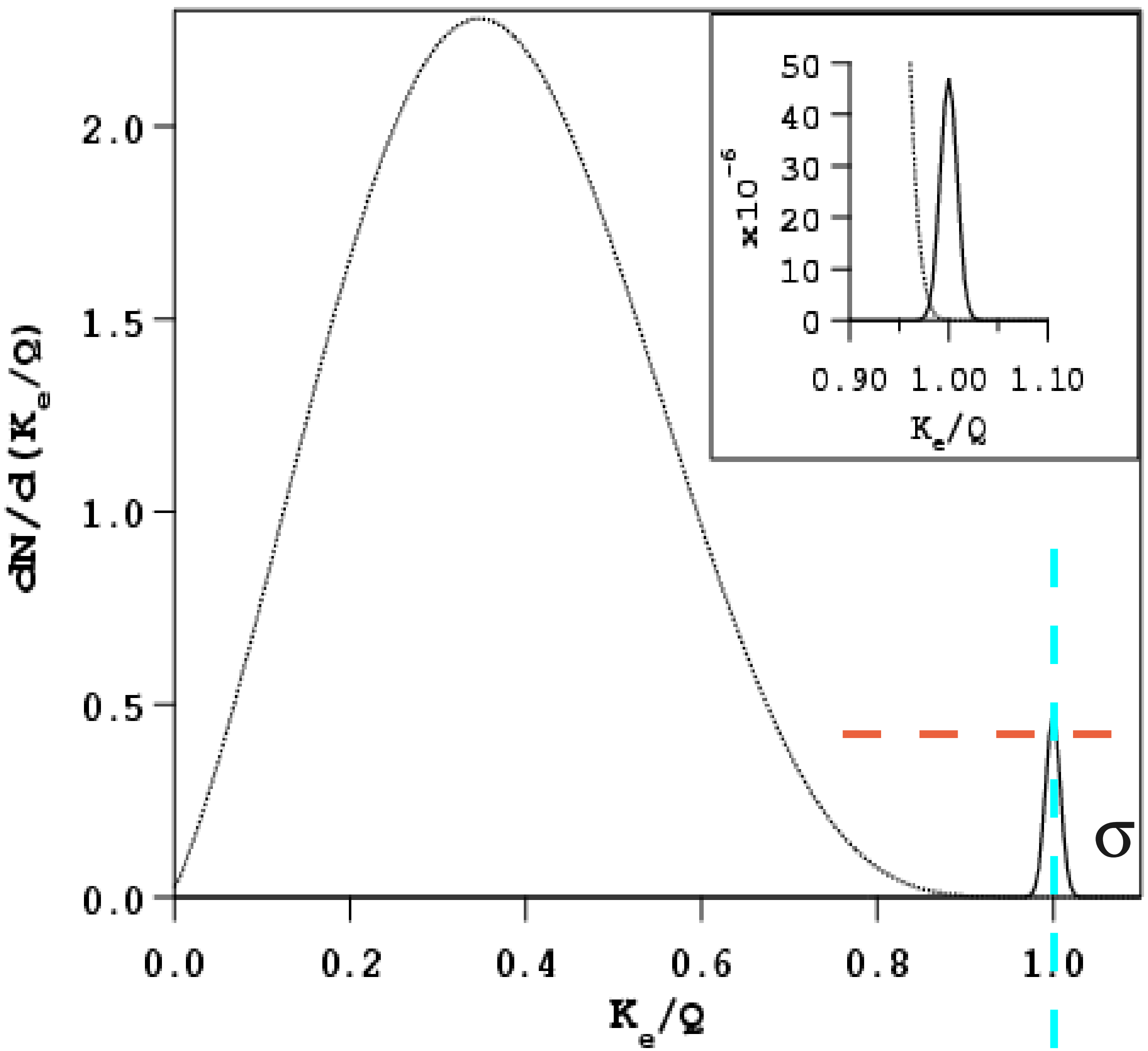
2 or 0 neutrinos in double beta decays

if neutrinos are Majorana particles, lepton number is not conserved

promising channel for measurement of lepton number violation

resonant process, increasing cross-section with neutrino mass,
increased phase-space for protons and electrons,
similar matrix elements as for the 2 neutrino double beta decay

Beta and double beta decays and effective νe masses



$Q^2 \sim (\Delta M - E_e)^2 = 2x$

$$\langle m_\beta \rangle^2 = \sum_i^{n_\nu} |\, U_{ei} \,|^2 \, m_{\nu,i}^2$$

σ α

$$\langle m_{\beta\beta}^2 \rangle = \Big| \sum_i^{n_\nu} U_{ei}^2 m_{\nu,i} \Big|^2$$

Different mass mixing combinations from beta measurements, both should give an idea of an absolute mass scale for neutrinos

Neutrinoless double beta decay sensitivity

$$N_{\beta\beta}^{0\nu} = \frac{a \cdot M \cdot N_A}{A} \frac{\ln 2}{T_{1/2}^{0\nu}} \cdot \epsilon \cdot t$$

$$N_{bg} = M \cdot t \cdot B \cdot \Delta E$$

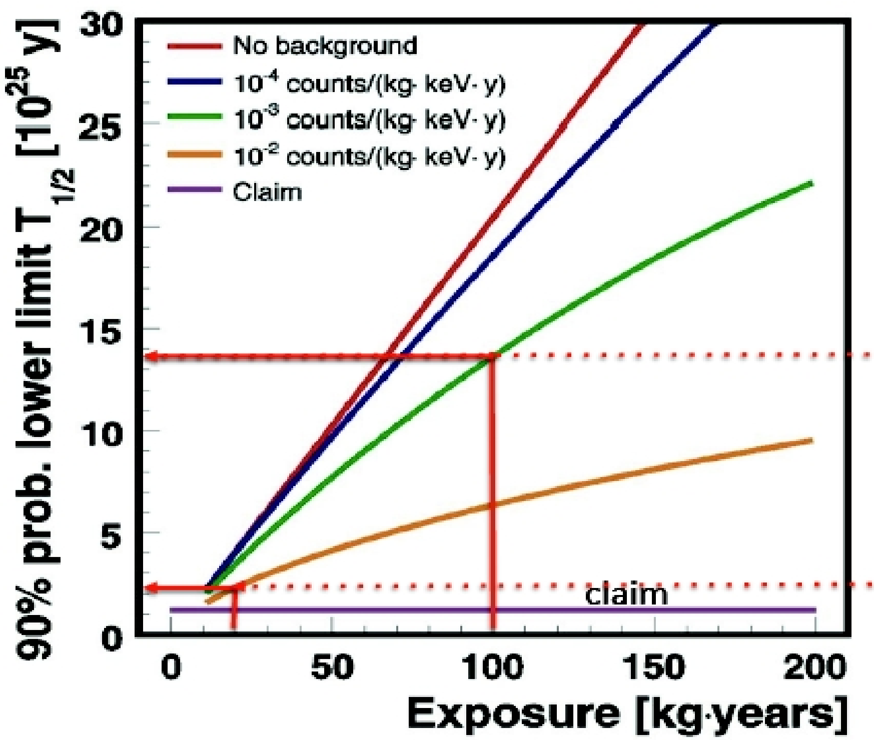
$$T_{1/2}^{0\nu}(n_\sigma) = \frac{N_A \ln 2}{\sqrt{2} n_\sigma} \frac{a \cdot \epsilon}{A} \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Exposure = Mass . Time . efficiency

Isotope abundance and half-life

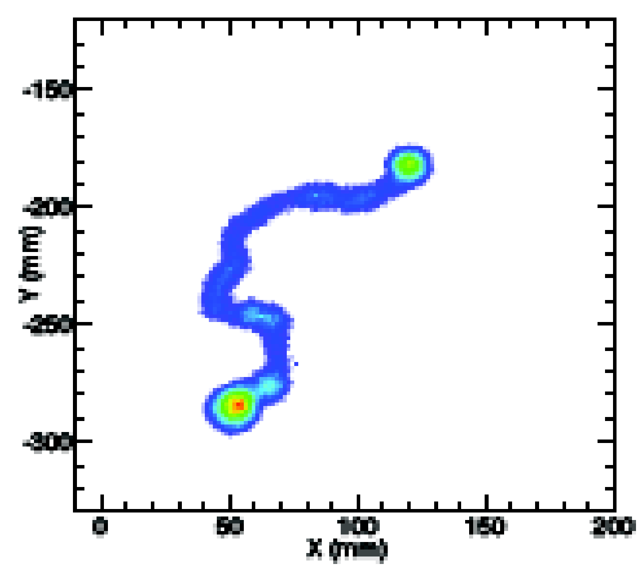
Purity and energy resolution

(Again "simple detectors")



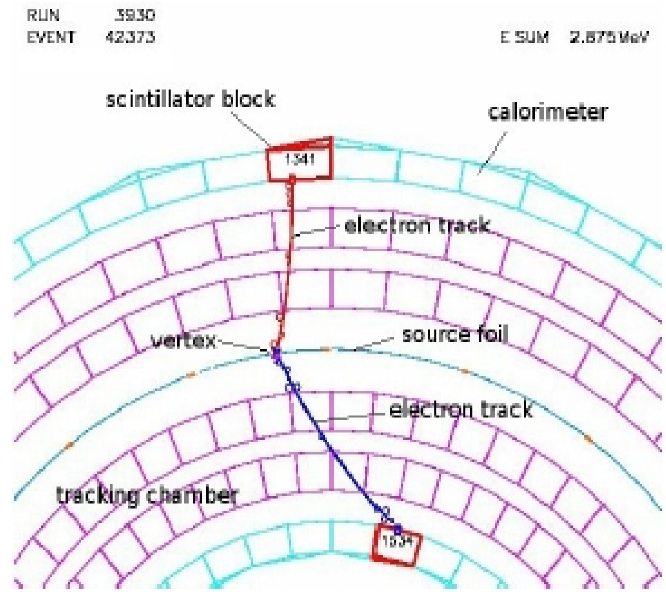
But event reconstruction / tagging can improve resolution and purity

Ex: NEXT

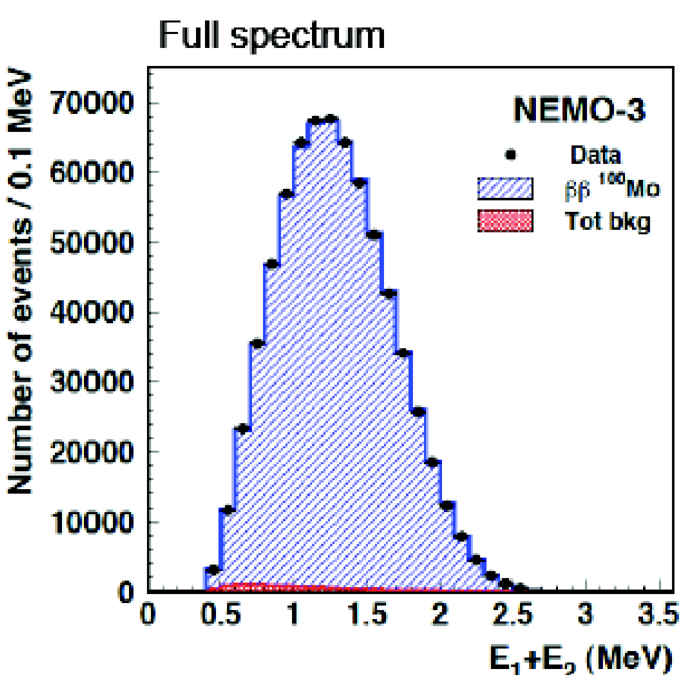


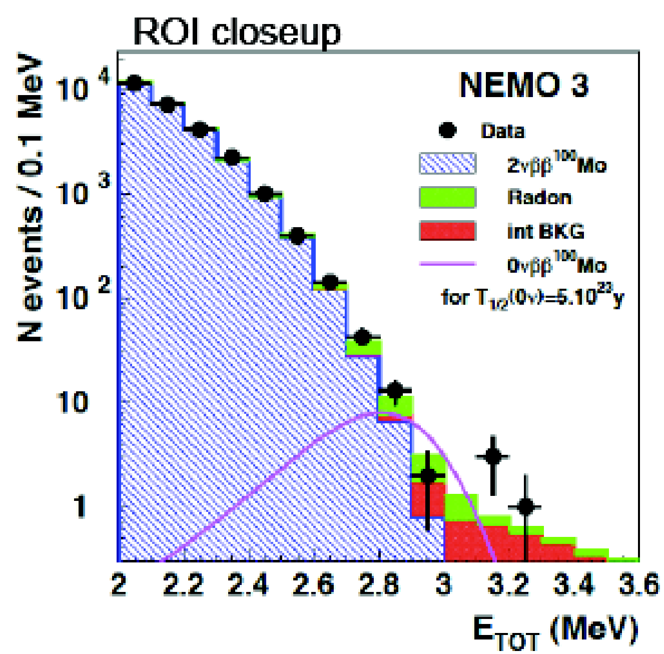
Neutrinoless double beta decay sensitivity

NEMO-3 detector



An ^{100}Mo $2\nu\beta\beta$ event





Uncertainty from $2\nu\beta\beta$ is dominant

Big campaign to cross-check predictions for half-lives

(ex: ^{100}Mo)

0 and 2 neutrinos double beta decays

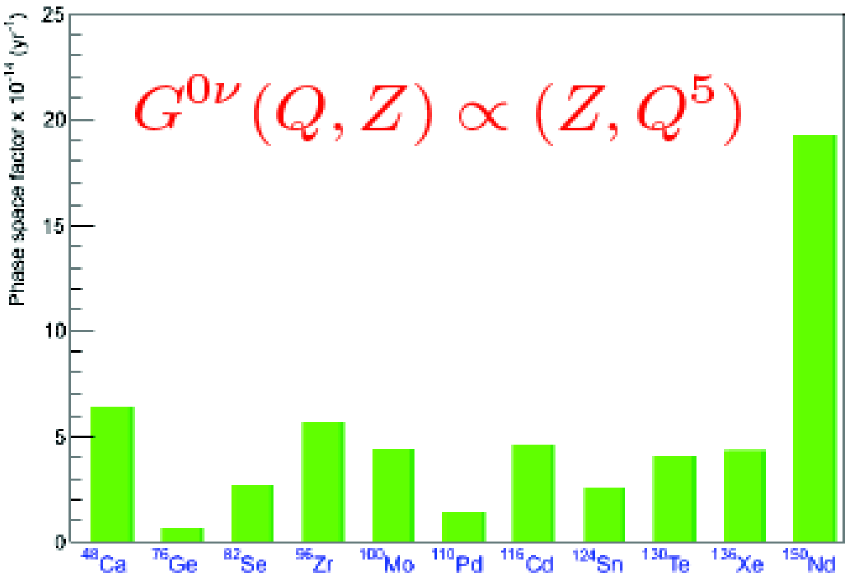
Measured by NEMO-3 for most Isotopes

$$\Gamma^{2\nu} = \frac{1}{T^{2\nu}_{1/2}} = G^{2\nu}(Q,Z)|M^{2\nu}|^2$$

$$G^{2\nu} \propto (G_F \cos\theta_C)^4 Q^7 \left(1 + \frac{Q}{2} + \frac{Q^2}{9} + \frac{Q^3}{90} + \frac{Q^4}{1980}\right)$$

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

$$G^{0\nu} \propto (G_F \cos\theta_C)^4 \cdot \left[\frac{Q^5}{30} - \frac{2Q^2}{3} + Q - \frac{2}{5}\right] \propto (G_F \cos\theta_C)^4 \cdot Q^5$$



F. Piquemal, Neutrino2012, Kyoto

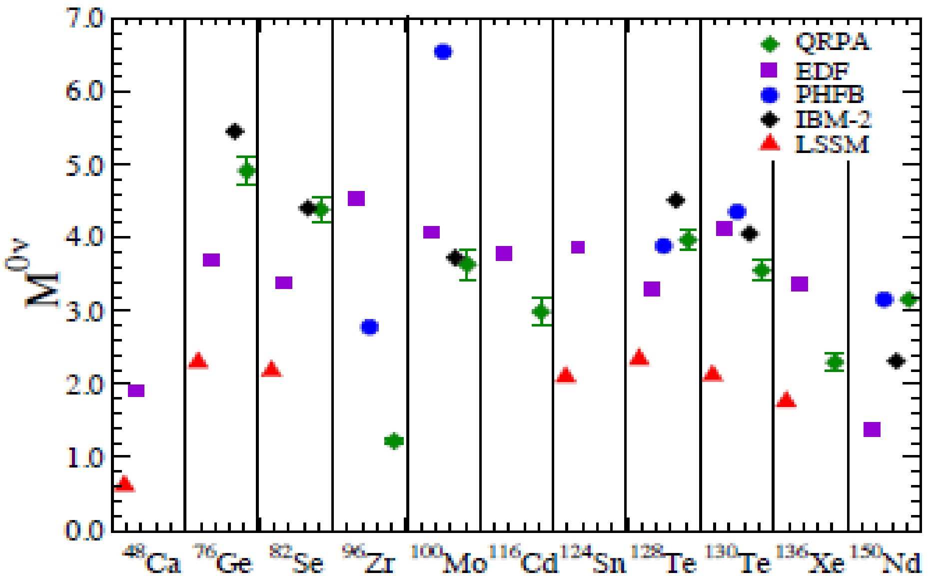


Fig. 3. Values of the NME calculated with the methods in Tab. 2 [74].

Bilenky, Giunti: arXiv:1203.5250v2

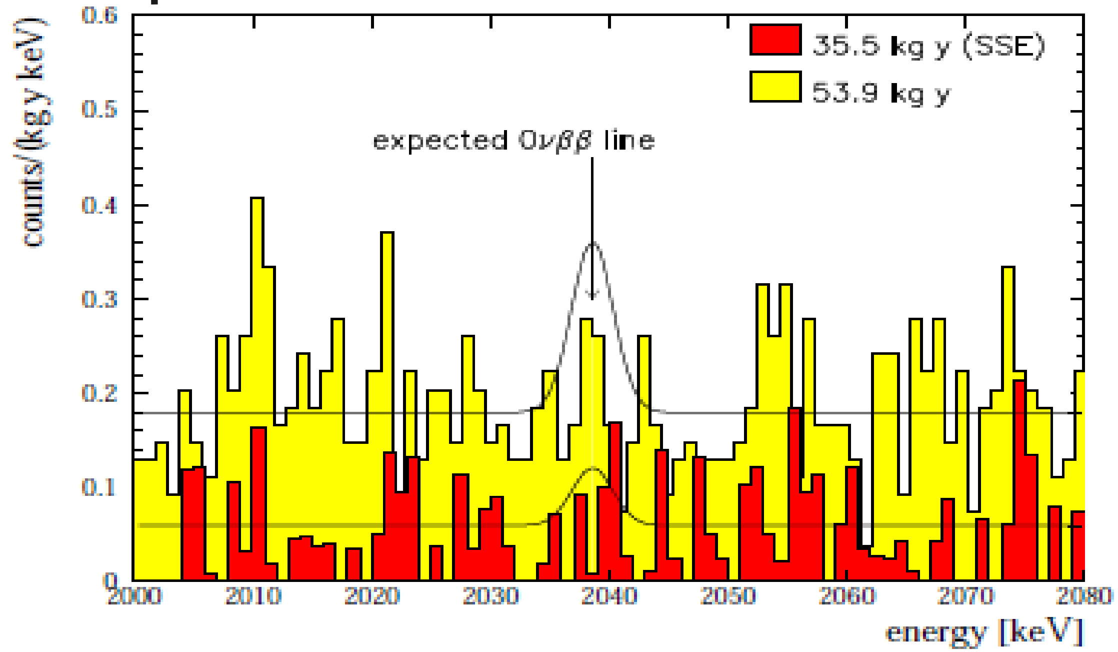
$$|m_{\beta\beta}| = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i(\alpha_1-\alpha_2)} + m_3|U_{e3}|^2 e^{i(-\alpha_1-2\delta)}|$$ (with Majorana phases)

Neutrinoless double beta decays: choosing the isotope

	Q(MeV)	I(%)	
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8	*
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2	*
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8	
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6	*
$^{110}Pd \rightarrow ^{110}Cd$	2.013	12.	
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5	
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.6	
$^{130}Te \rightarrow ^{130}Xe$	2.533	35.	*
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9	*
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6	*

Results on neutrino mass should be confirmed in several isotopes

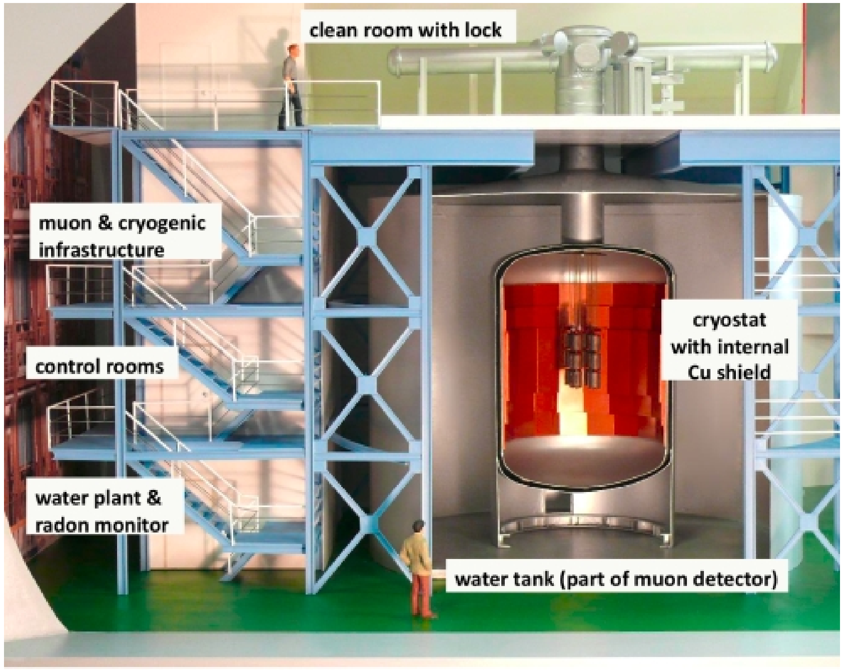
One claim of signal with ^{76}Ge from part of Heidelberg-Moskow collab.

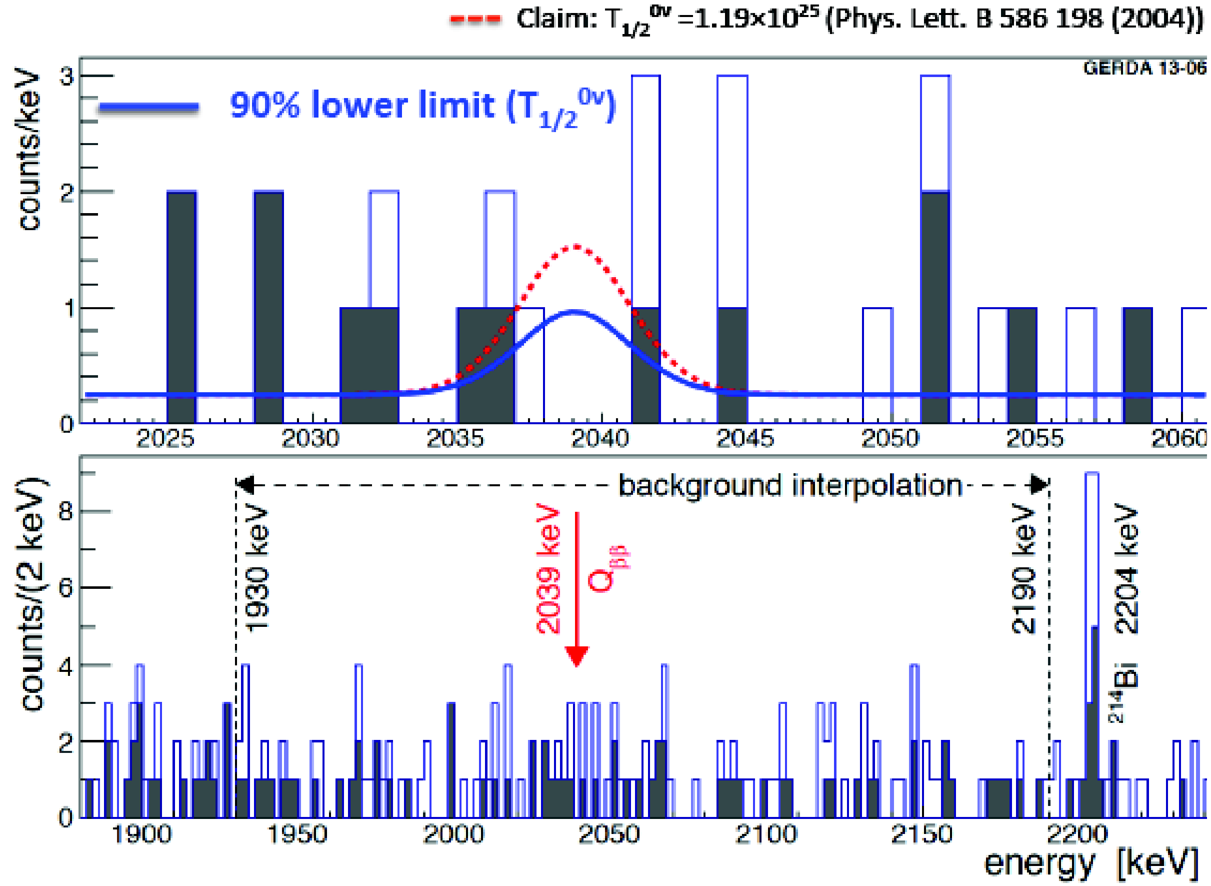


Two main strategies for high mass experiments:

- sensitive isotopes (GERDA / EXO / NEXT)
- isotopic loading (KamLand-Zen / SNO+)

$2\nu\beta\beta/0\nu\beta\beta$ in GERDA: recent results in ^{76}Ge





Phase-I : 18 kg (recycle
Phase-II: 20 kg more...

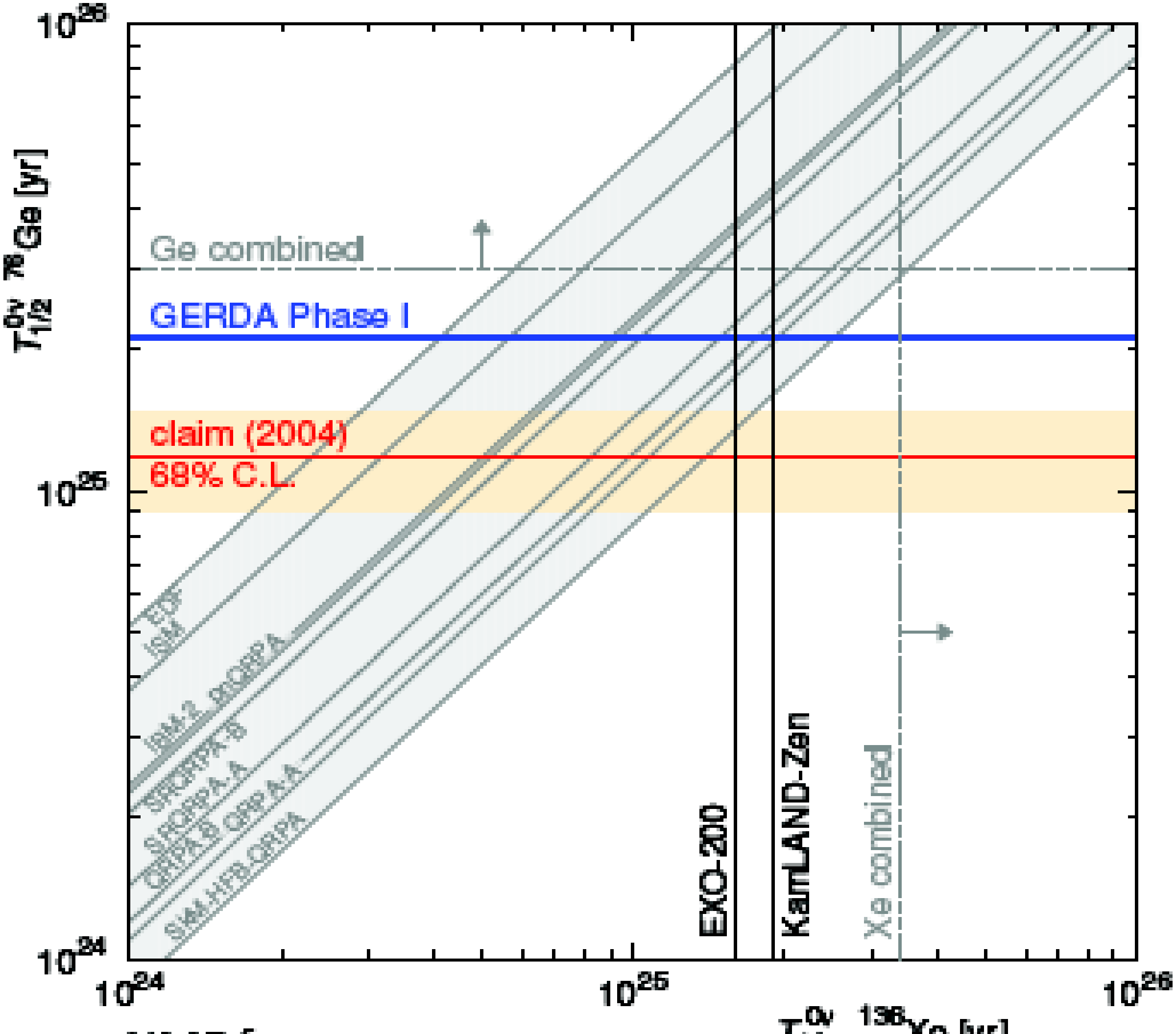
$$T_{1/2}^{2\nu} = (1.84\ ^{+0.14}_{-0.10}) \times 10^{21}\ \text{yr}$$

GERDA: $T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)

GERDA+IGEX+HdM: $T_{1/2}^{0\nu} > 3.0\times10^{25}$ yr (90% C.L.) ($\langle m_{ee}\rangle < 0.2$-$0.4$ eV)

Existing claim excluded with same experimental conditions

0νββ combining different experiments



NME from:
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

Limits on same isotope combined at T1/2 level

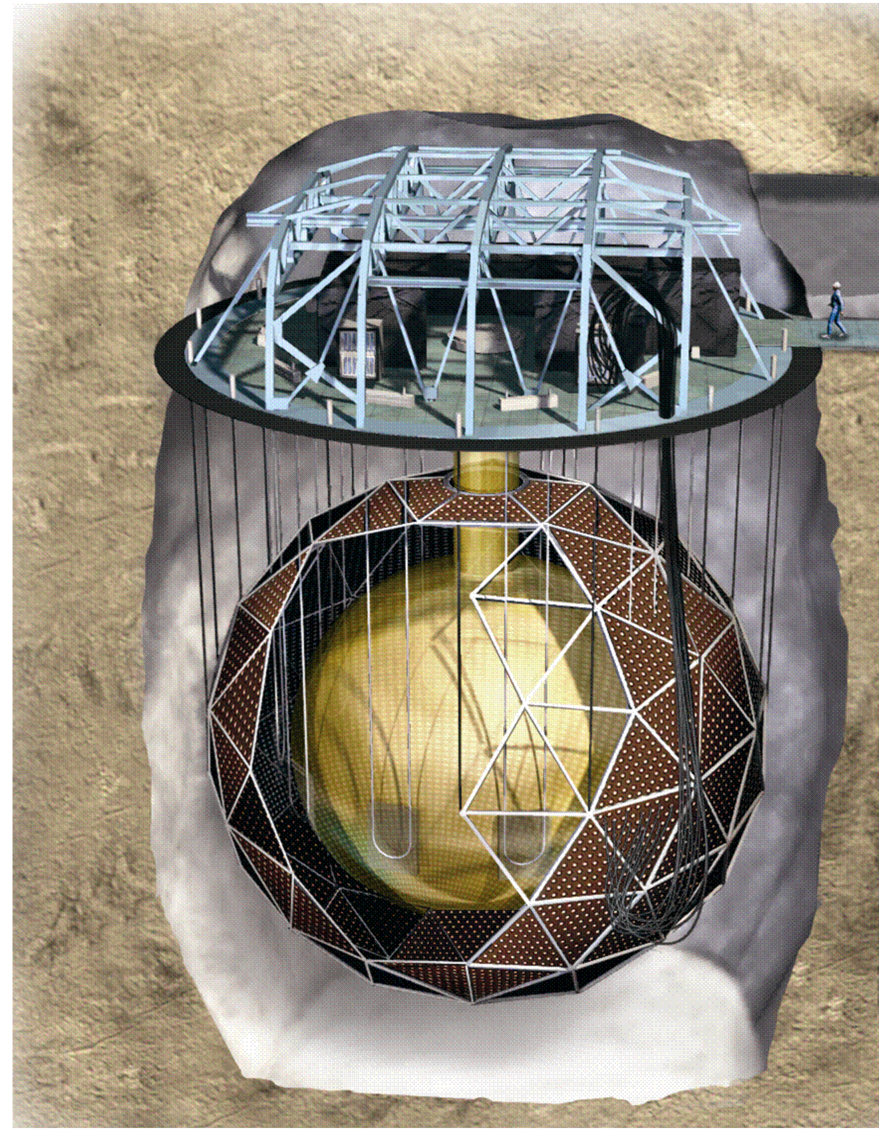
(experimental errors);

On different isotopes translated to <m²bb>

(theory uncertainties)

SNO+

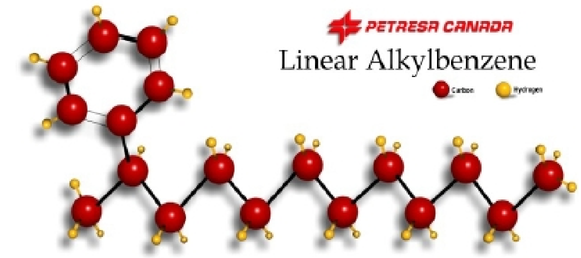
* deepest underground lab ~ 6000 m.w.e.
* Water shielding (1700 t in; 5300 t out)
* 54% coverage with ~9500 PMTs
* Acrylic Vessel of 12 m diameter, 5 cm thickness



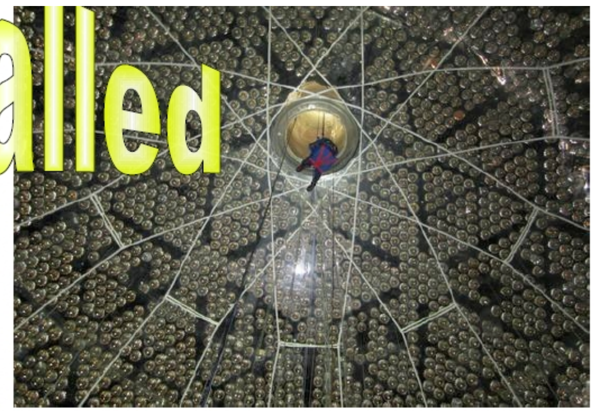
* new challenges in low energy neutrinos
* heavy water Cherenkov to liquid scintillator with high light yield
* increased need to avoid introducing radioactive materials inside

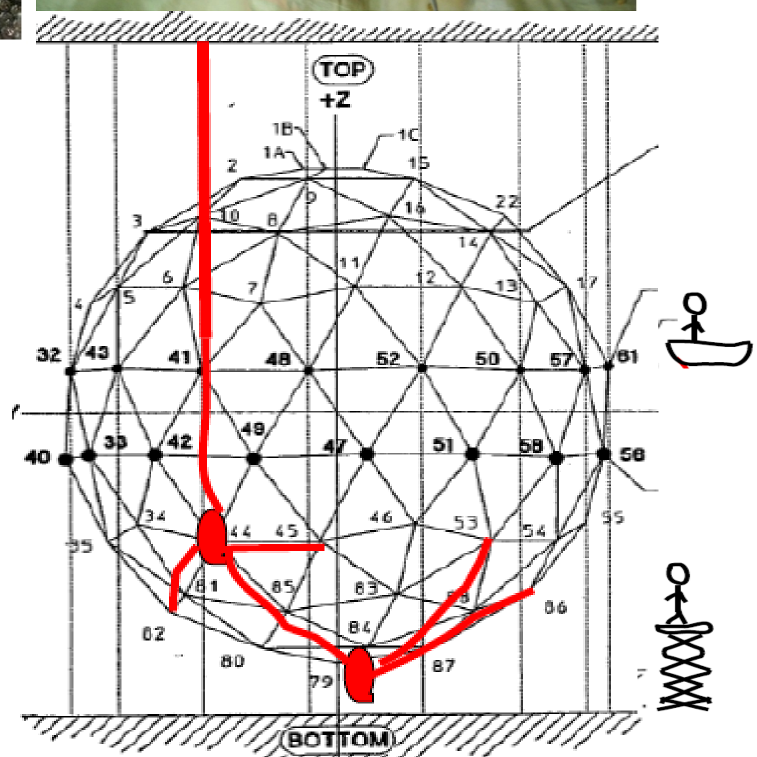
Liquid Scintillator: LAB + PPO

* chemical compatibility with AV, high purity available
* good transparency and low scattering
* inexpensive and safe (low toxicity, high flash and boiling point)
* ρ=0.86 ==> rope hold-down system installed
* new purification systems being installed



developed by SNO+, used also in DayaBay



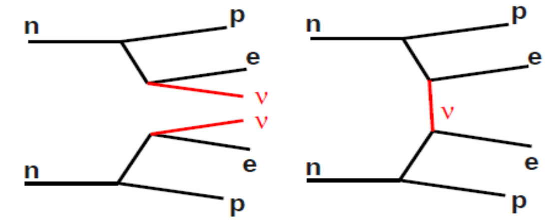


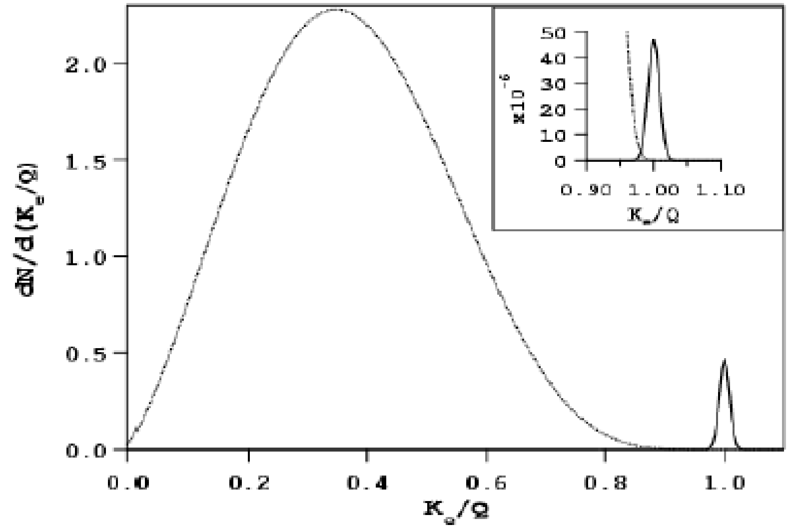
$0\nu\beta\beta$ search in SNO+

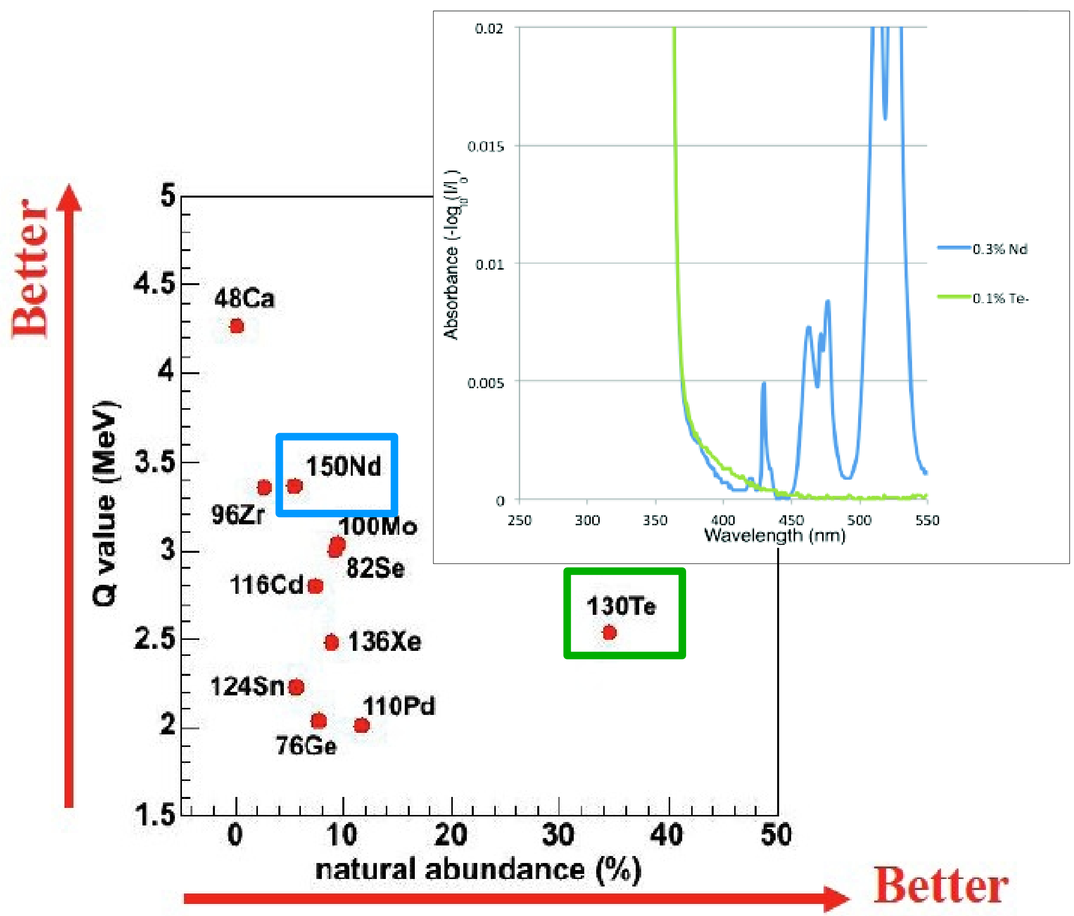
* lower energy resolution than other $\beta\beta$ detector types

* BUT very high quantity of the isotope
dissolved in active medium with low backgrounc

* NEED not to degrade too much the energy resoluti
tested ^{150}Nd-150 (higher Q) and ^{130}Te (higher NA)
(also ^{136}Xe tested and used in similar KamLAND-Ze







$$Q \sim \Delta M - E_e = 2M_\nu = \Sigma\, U_{ei}\, m_i$$

$$\Gamma\ \alpha\ |M_{\beta\beta}|^2 = |\ \Sigma\, (U_{ei})^2\, m_i\, |^2$$

	$2\nu\beta\beta$ [years] **measured** by NEMO-3:	$0\nu\beta\beta$ [years] **calculation** by IBM-2:
Nd	9×10^{18} (g.s.) 1×10^{20} (e.s.)	3×10^{23} / $(M_{\beta\beta}$ / 1 eV$)^2$
Te	7×10^{20} (g.s.)	4×10^{23} / $(M_{\beta\beta}$ / 1 eV$)^2$

Double Beta Decay Backgrounds

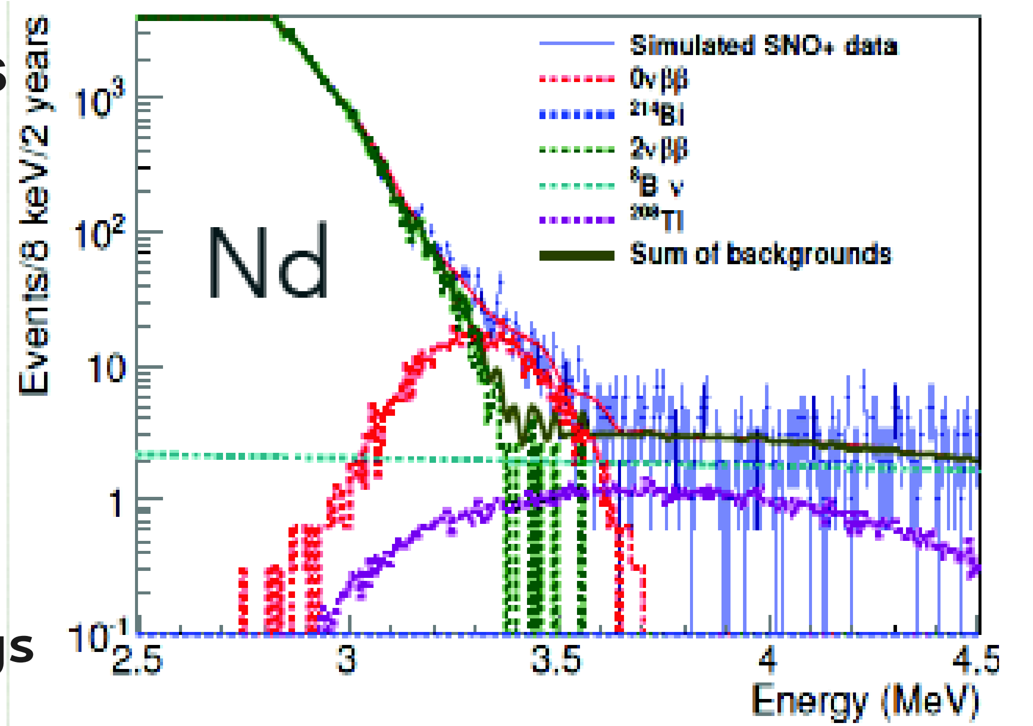
* $2\nu\beta\beta$: irreducible! (lower for Te)
  energy resolution is fundamental
  position resolution against pile-up

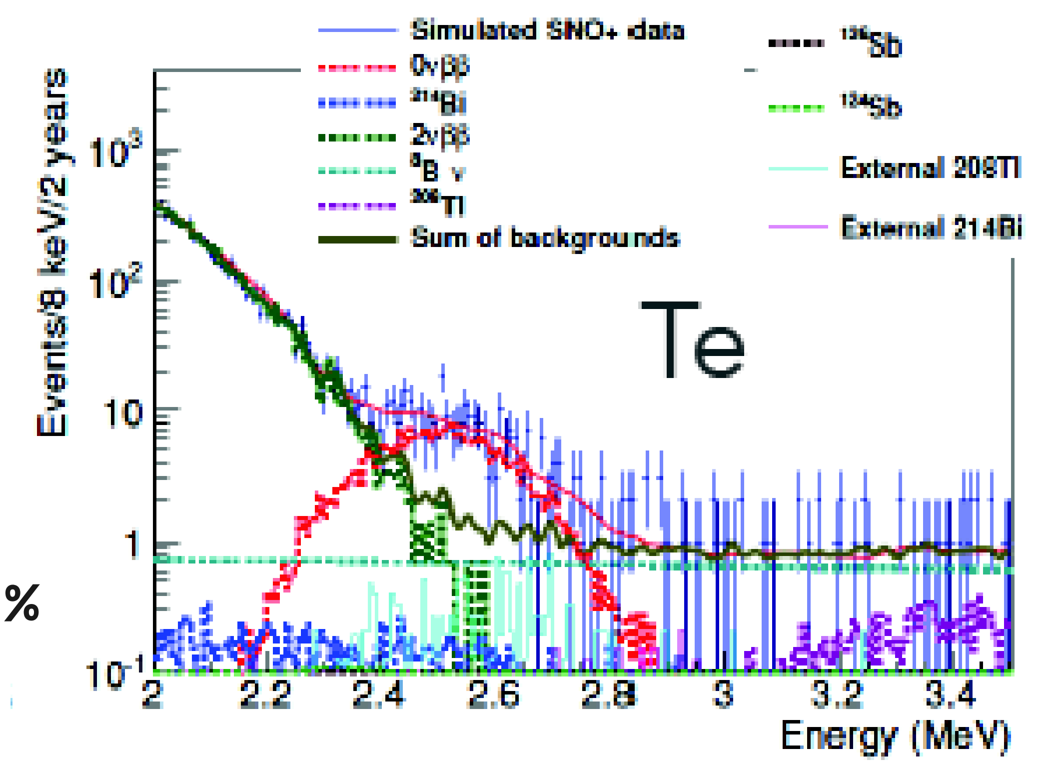
* radio-purity of scintillator
  cosmogenic activation of isotopes
  can be tested with different loadings
  (1^{st} tests with pure scintillator)

* Bi-214 and Tl-208 backgrounds
  rejected by $\alpha-\beta$ coincidences

* solar B8 neutrinos are irreducible
  but rate and distribution is known!

* Te chosen by SNO+
  0.3% loading can be increased to 3%
  And, in case of positive results
  Nd can be used for confirmation





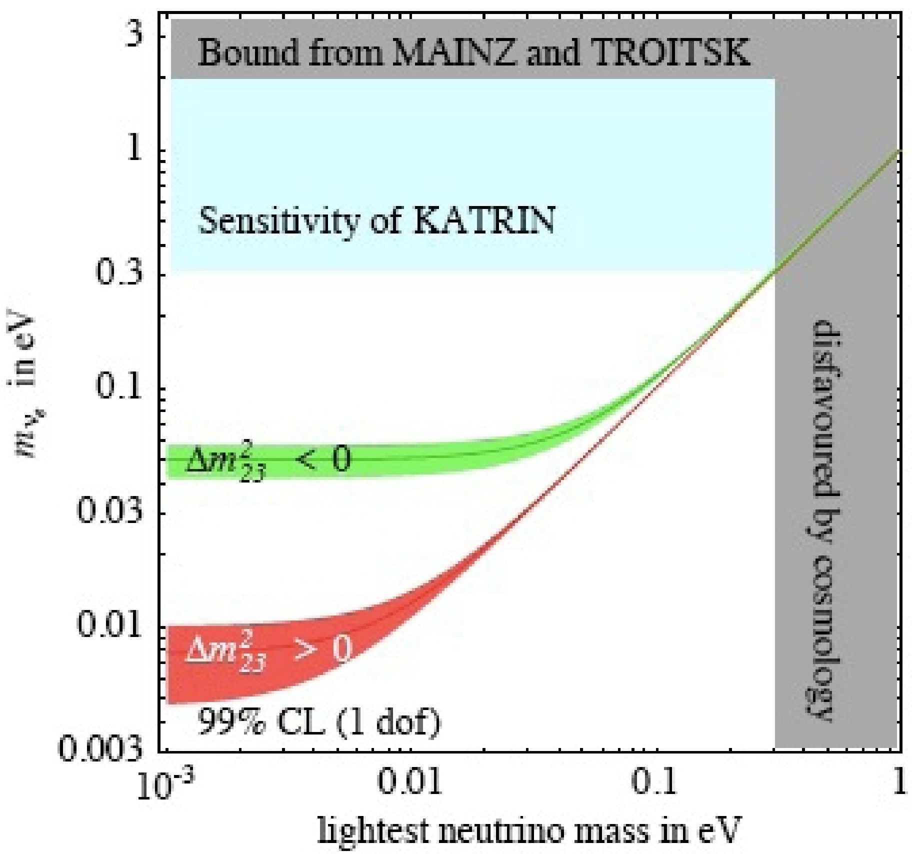
Neutrino multi-purpose experiments (SNO+ example)

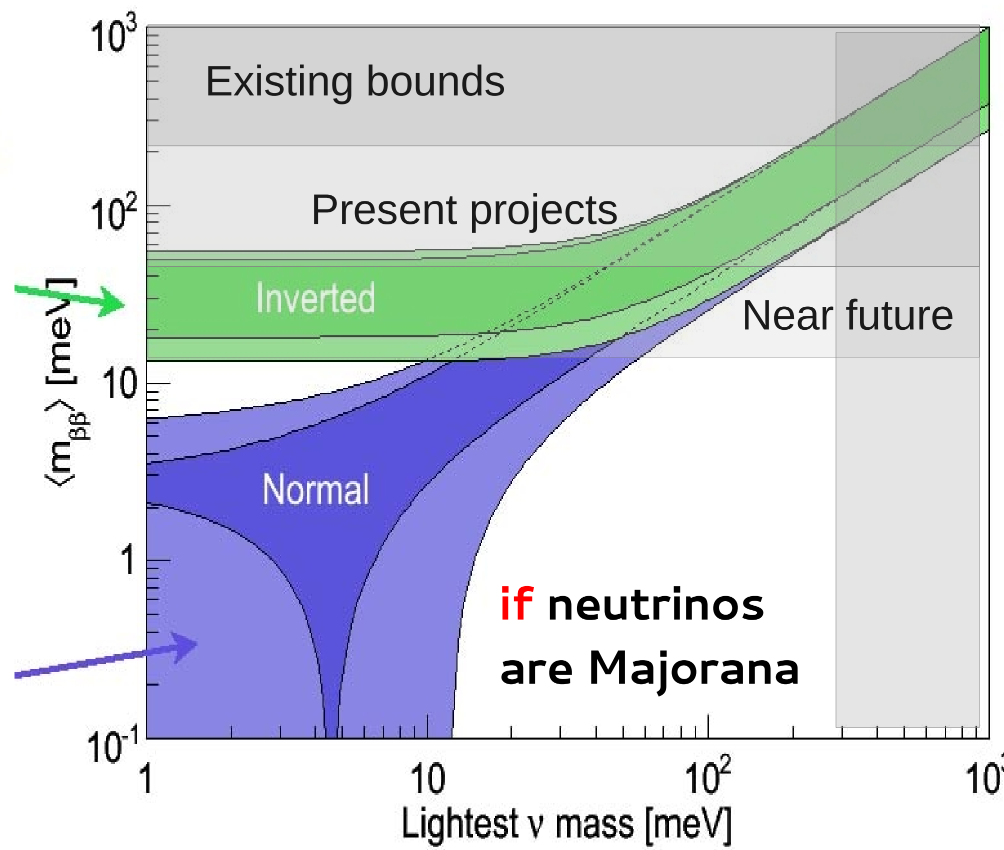
- solar neutrinos:
  - * transition from vacuum/matter dominated to improve precision on solar δm^2 / $\sin^2 2\theta$ and 2^{nd} order parameters ("atmospheric" & "13 sector")
  - * pp and CNO neutrino lines to test solar models
- reactor anti-neutrinos:
  - * to improve solar Δm^2 / $\sin^2 2\theta + 2^{nd}$ order parameters
- geo anti-neutrinos:
  - * to test Earth models (and namely its cooling history)
- Super Nova neutrinos and anti-neutrinos
  - * to test SN models and early alert observatories
- double beta decays:
  - * to search for Majorana neutrinos and measure their effective masses to be related to the minimum or average mass

Relating the mass measurements

$$\langle m_\beta \rangle^2 = \sum_i^{n_\nu} | U_{ei} |^2 \, m_{\nu,i}^2$$

$$\langle m_{\beta\beta}^2 \rangle = \left| \sum_i^{n_\nu} U_{ei}^2 m_{\nu,i} \right|^2$$



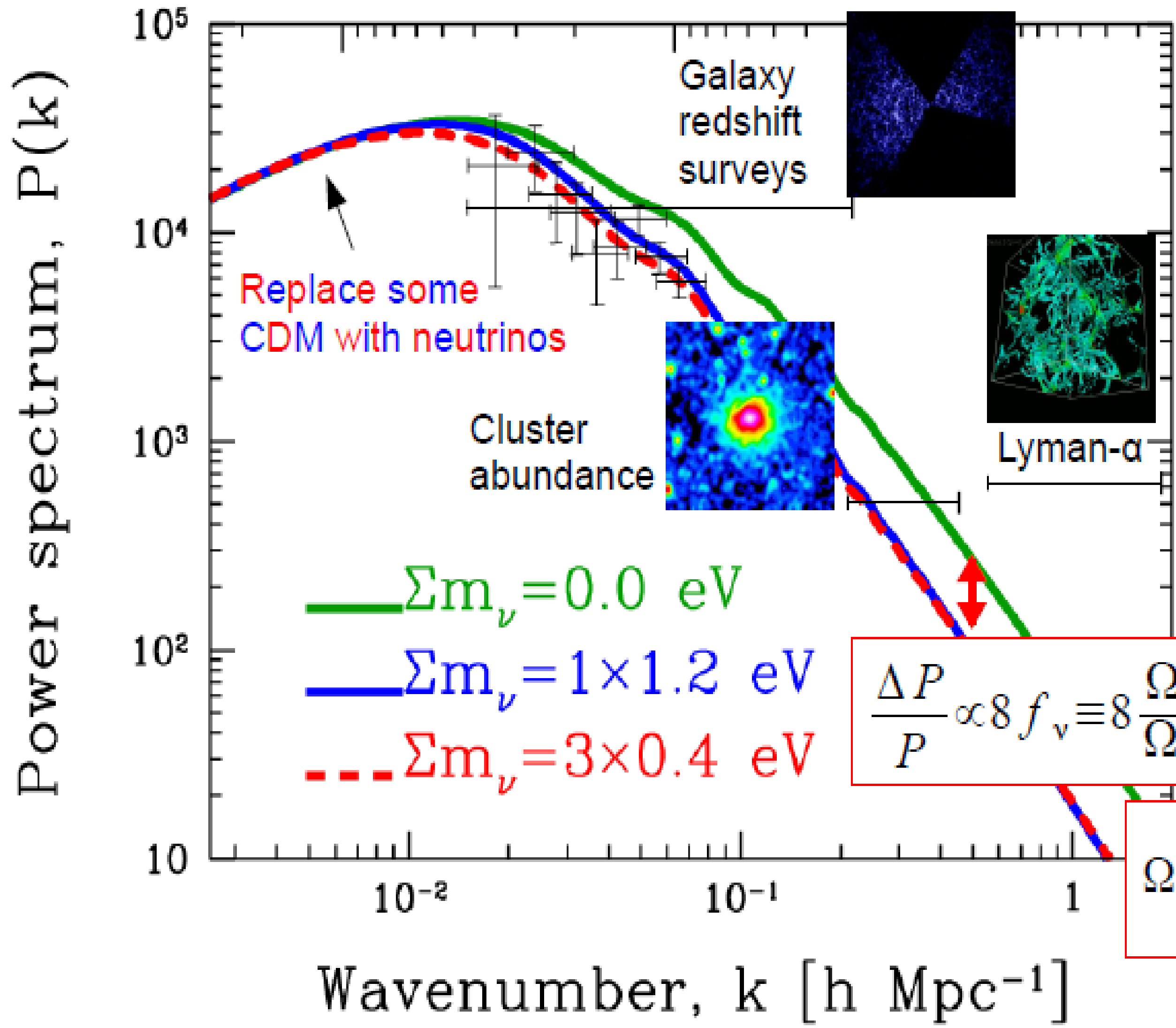


$$M = \sum_i^{n_\nu} m_{\nu,i}$$

in cosmology, no weak interaction, just gravity

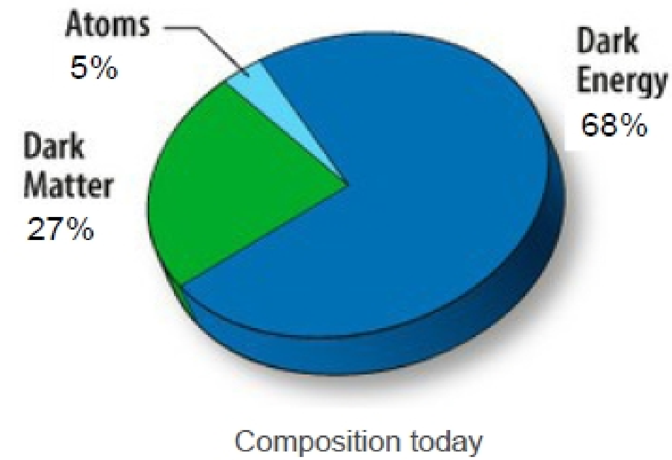
Neutrinos in cosmological measurements

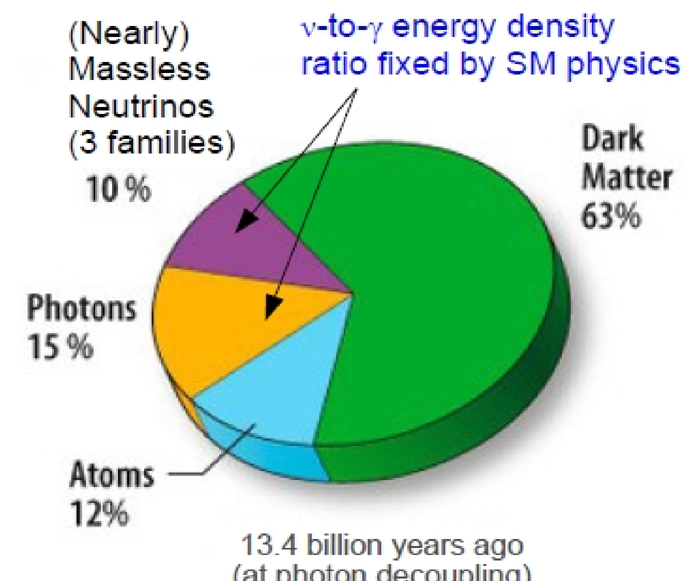
Depending on their density and masses, neutrinos change the history of the universe:



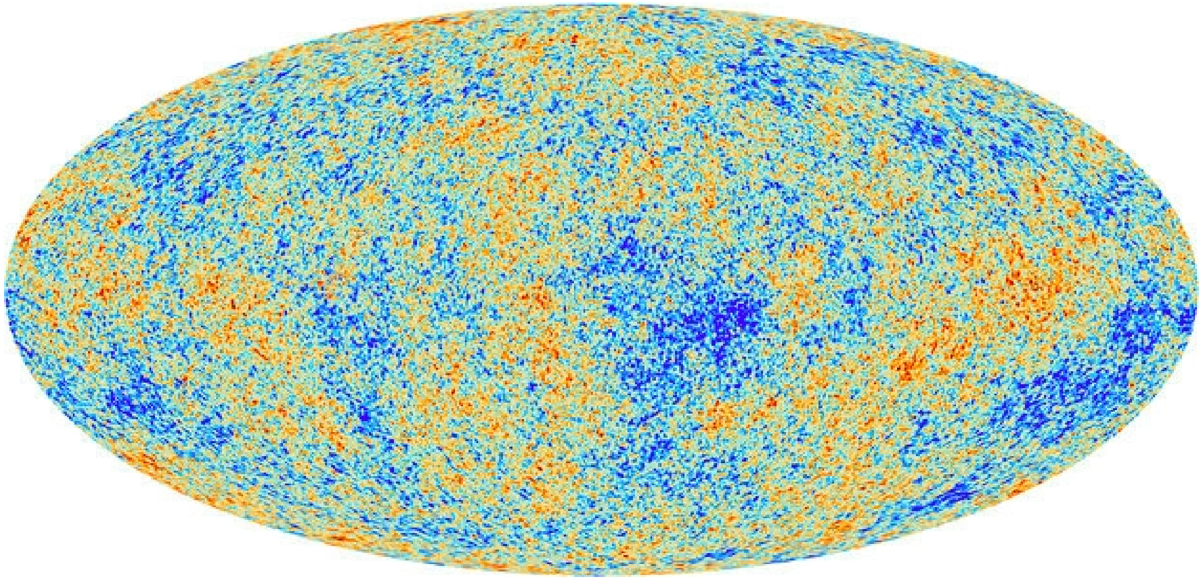
$$\frac{\Delta P}{P} \propto 8 f_\nu \equiv 8 \frac{\Omega_\nu}{\Omega_m}$$

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{94\mathrm{eV}}$$



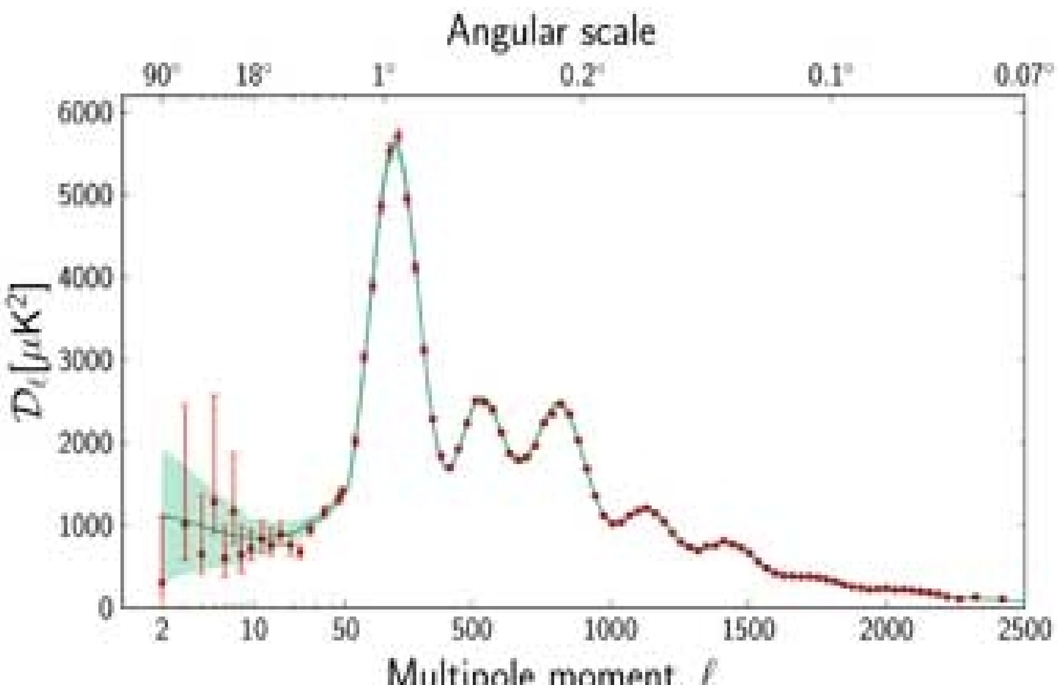


Neutrinos in cosmological measurements



$$\Omega_R h^2 = [1 + N_{\text{eff}} \frac{7}{8} (\frac{4}{11})^{\frac{4}{3}}] \Omega\gamma h^2$$

$$\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \frac{\sum_i^{n_\nu} m_{\nu,i}}{\rho_{\text{critical}}}$$

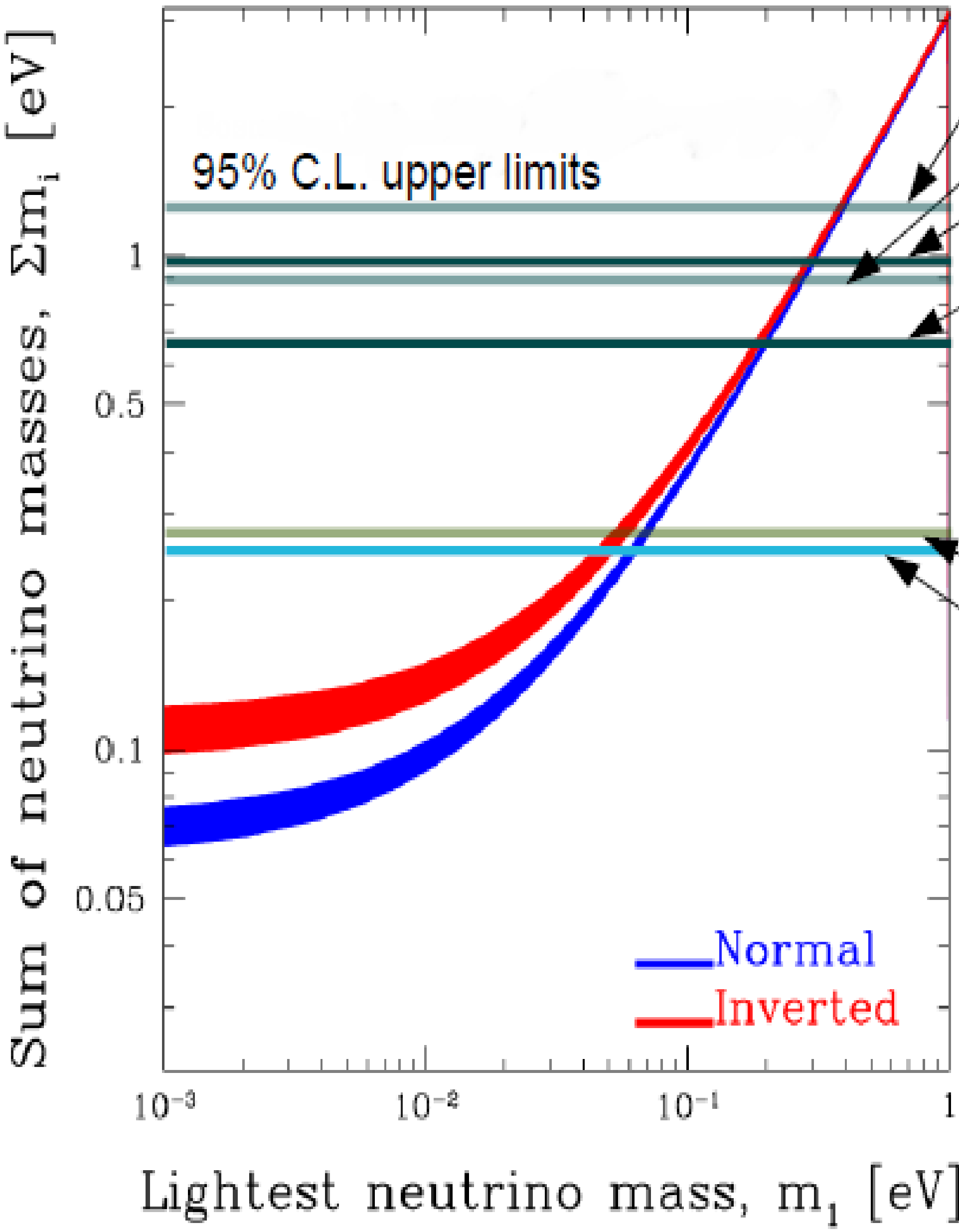


Plank results from 2013:

Sum of masses < 0.23 eV

Neff = 3.30 + 0.27
[SM=3.046 fom corrections]

Neutrino masses from Planck?



ΛCDM+neutrino mass (7 parameters)

WMAP (9 years)

W9 + ACT

Planck + WMAP Polarisation

Planck + WP + ACT ℓ > 1000 + SPT ℓ > 2000

$$\sum m_\nu < 0.66 \text{ eV} \quad (95\% \text{C.L.})$$

Best CMB-only bound

W7+ matter power spectrum + HST H_0

Planck + WP + (ACT ℓ > 1000 + SPT ℓ > 2000) + baryon acoustic oscillations

$$\sum m_\nu < 0.25 \text{ eV} \quad (95\% \text{C.L.})$$

Best minimal bound

Dropping assumption of spatial flatness:

$$\sum m_\nu < 0.32 \text{ eV} \quad (95\% \text{C.L.})$$

Other extensions??

Neutrino Masses: near future

Oscillations indicate that neutrinos have (at least 2) non-zero masses

Neutrino masses have not been measured directly

Cosmology indicates 3 families with mass sum ~ 0.23 eV

Beta Decay experiments will probe this mass region soon
if hierarchy is inverted

Double Beta Decay experiments can also probe it
if neutrinos are Majorana particles

That could explain why they are so small
And point the way for the Standard Model extension

Precision on mixing parameters is fundamental to relate all masses

Neutrinos: future open questions

In Cosmology

- measurement of the CνB
- ν CP violation in matter/anti-matter asymmetry

In Astrophysics (and Geophysics)

- measure composition and model Sun and Earth
- study SuperNova, AGN and other accelerators

In Particle Physics

- mixing properties and new symmetries
- Majorana mass terms and new interactions