Neutrino Physics with everything else
(i.e. without accelerators)

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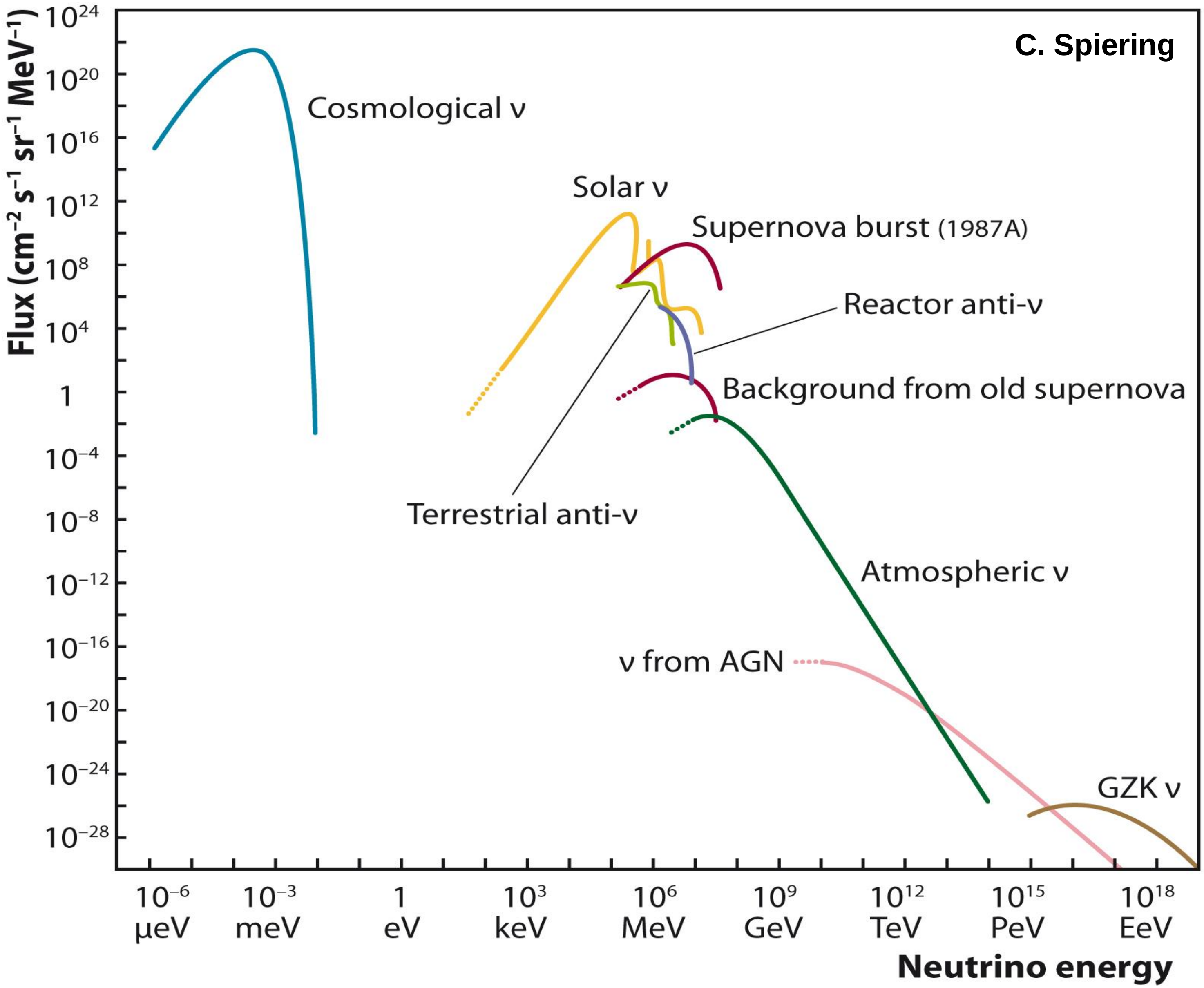
With thanks to many colleagues for slides and, especially, for their hard work!

The overall spectrum of non-accelerator neutrinos on planet Earth



There is no way to cover the entire field in 25min, particularly because the field contains a spectacular array of bright, creative and very different ideas!!

So I have limited the scope, following some logic and my own taste:

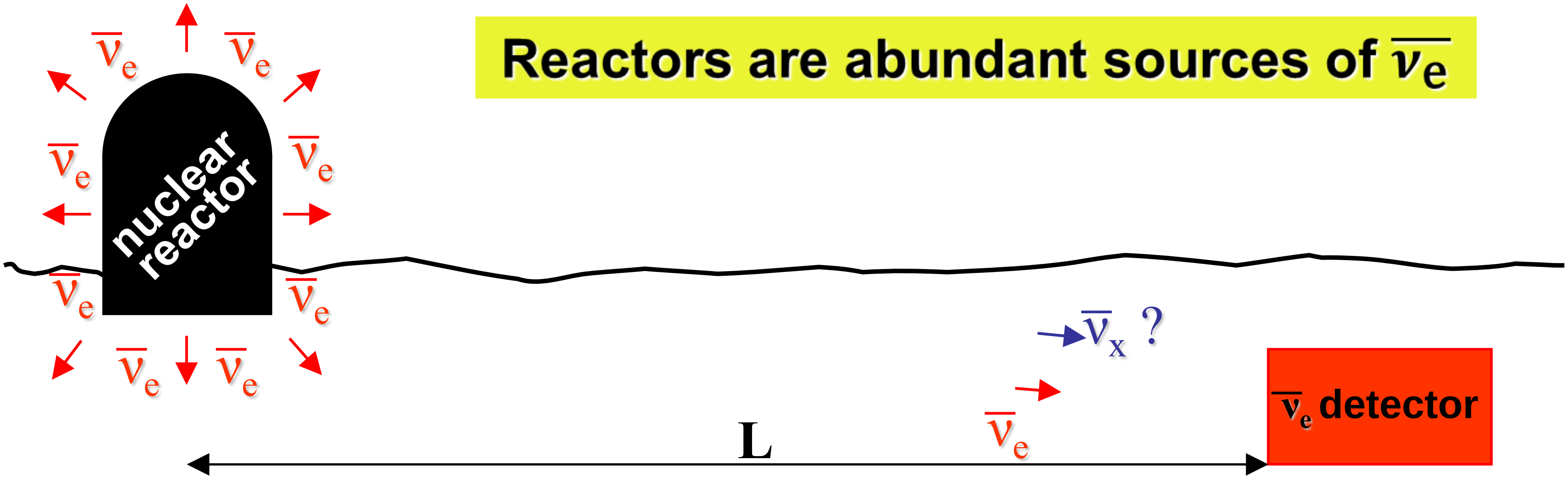
- ***Reactor oscillation experiments***
- ***Geo-neutrinos***
- ***β end-point mass measurements***
- ***Double-β decay experiments***

Solar neutrinos, atmospheric neutrinos, astrophysical (including from supernovae) and cosmological neutrinos, magnetic moments and many techniques have been unfairly left out.

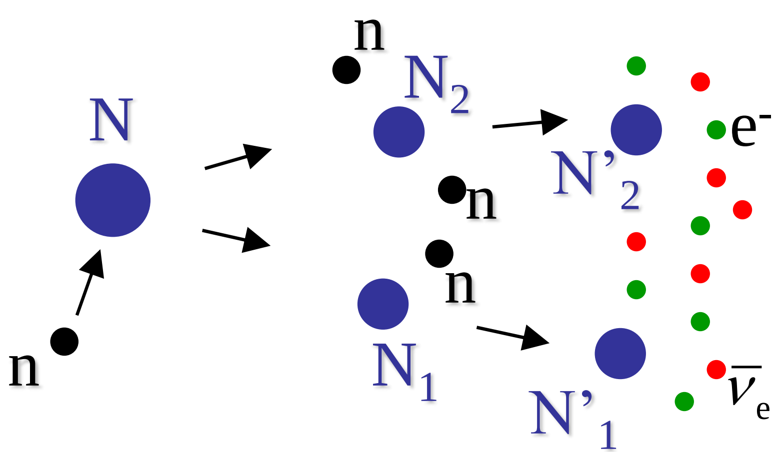
Apologies to many people!

All these topics are covered by a number of great posters and parallel talks!!

Reactors are abundant sources of $\overline{\nu}_e$



Fission produces two unstable nuclides that then β decay to stable matter



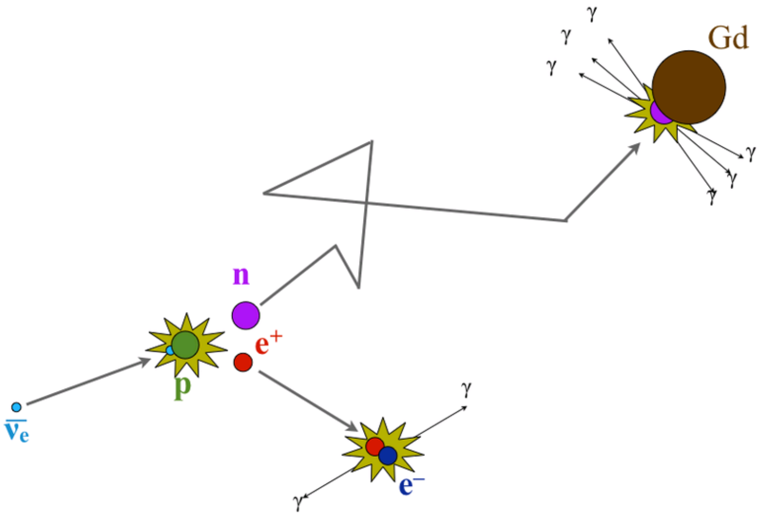
Yields:

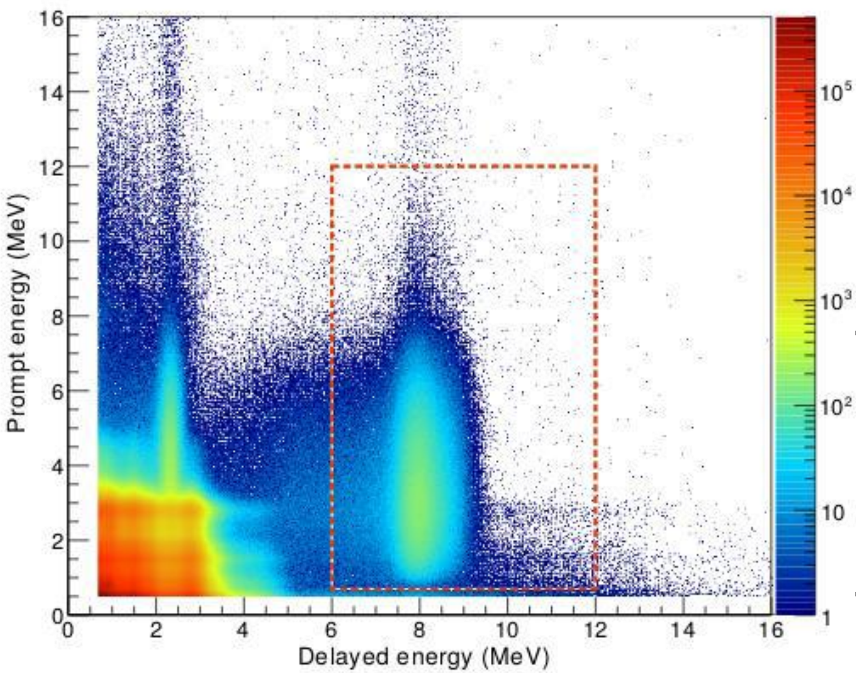
$$200\,\mathrm{MeV}/\mathrm{fission}$$

$$6\overline{\nu}_e/\mathrm{fission}$$

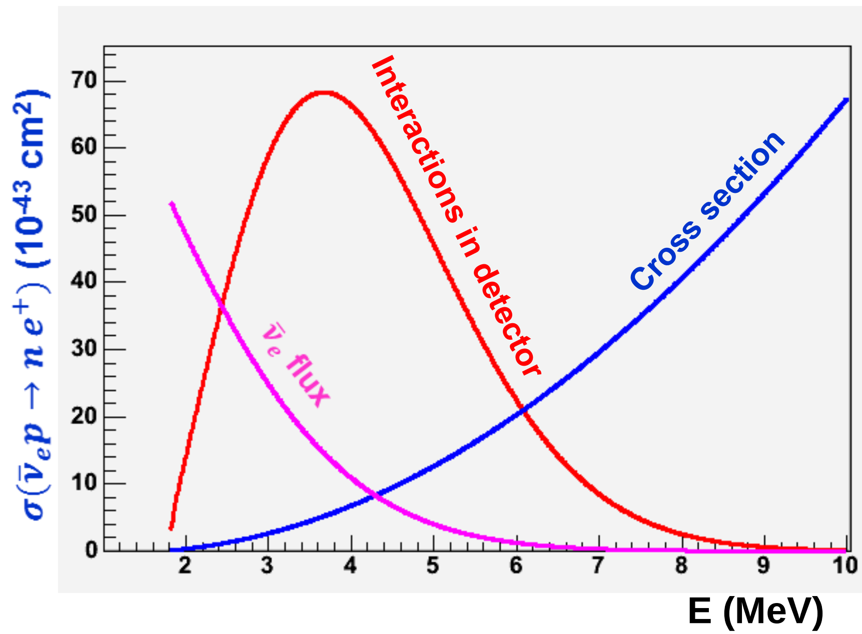
$$\Rightarrow 6\cdot 10^{20}\,\overline{\nu}_e/\mathrm{GW}_{\mathrm{thermal}}$$

Detection in liquid scintillator occurs by the inverse β decay on protons





Zheyuan Yu, Neutrino 2016



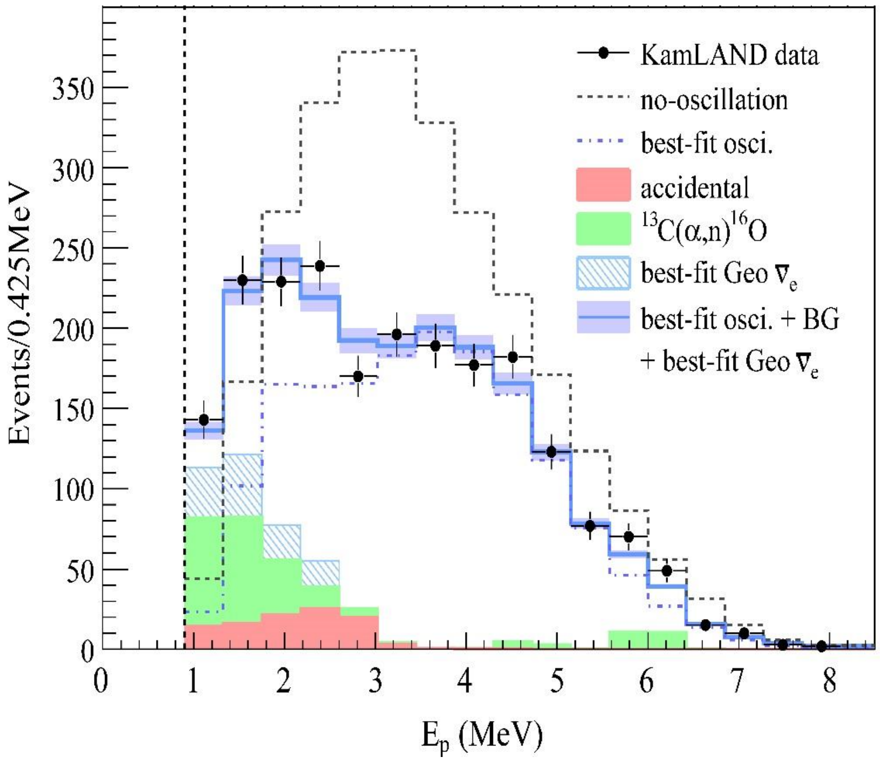
Bemporad, Gratta, Vogel, RMP 74 (2002) 297

In spite of the low deposited energy, the double-correlated signature is very powerful in suppressing backgrounds.

The neutrino energy can be extracted from the “prompt” energy (with a threshold of 1.8MeV)

Signal in KamLAND

- Baseline ~100km
- Mainly sensitive to θ_{12}



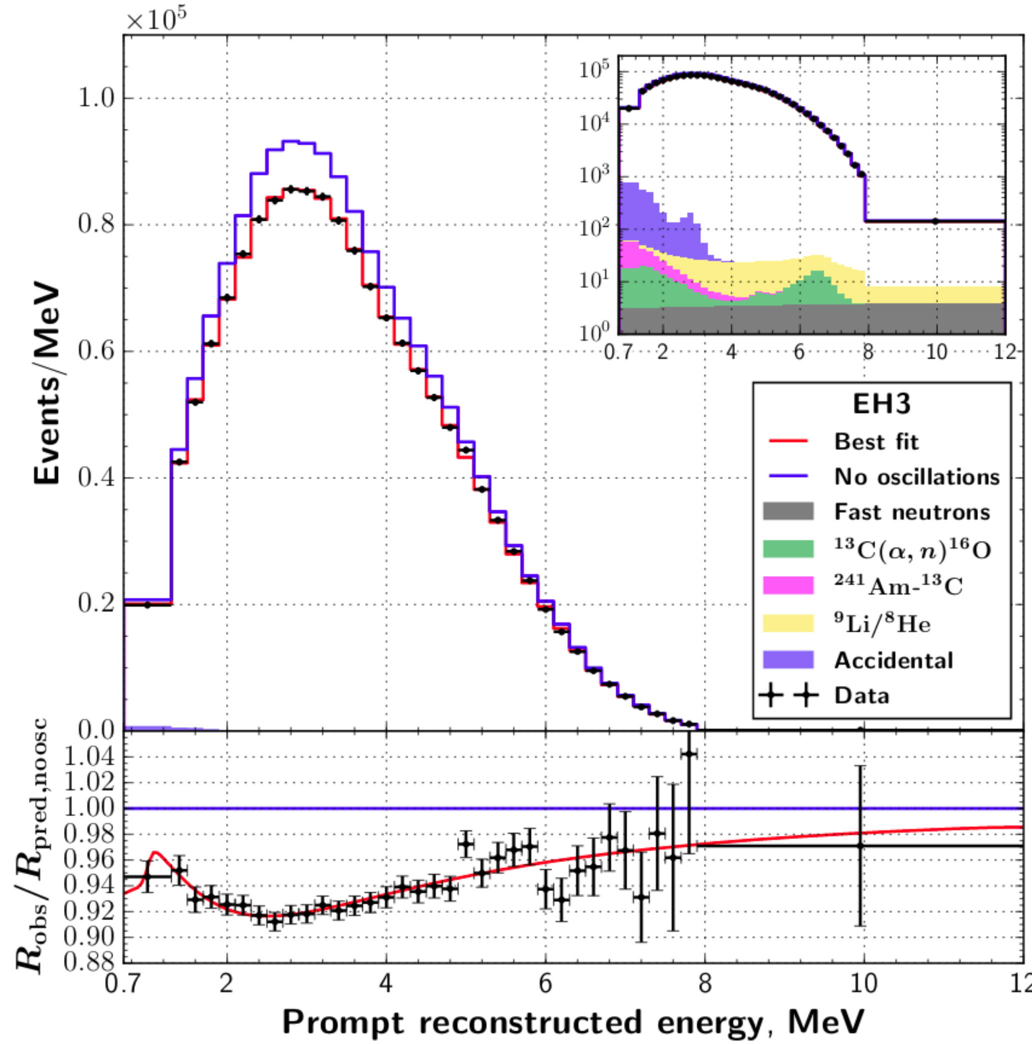
$$\Delta m^2_{12} = (7.49 \pm 0.20) \times 10^{-5} \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.436^{+0.102}_{-0.081}$$

KamLAND only: Phys.Rev. D 83 (2011) 052002
A better measurement of $\tan^2\theta_{12}$ is provided by other experiments

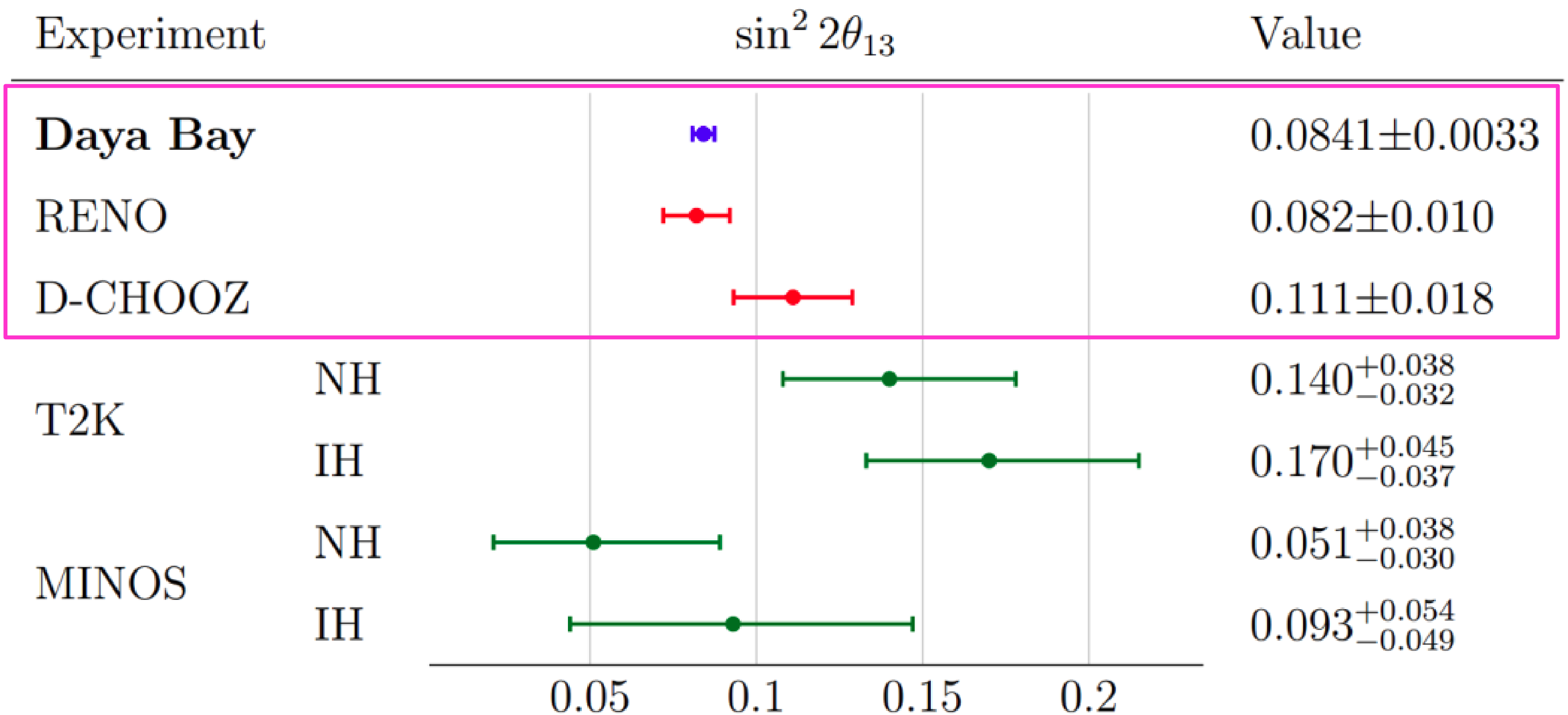
Signal in Daya Bay

- Baseline ~1km
- Mainly sensitive to θ_{13}

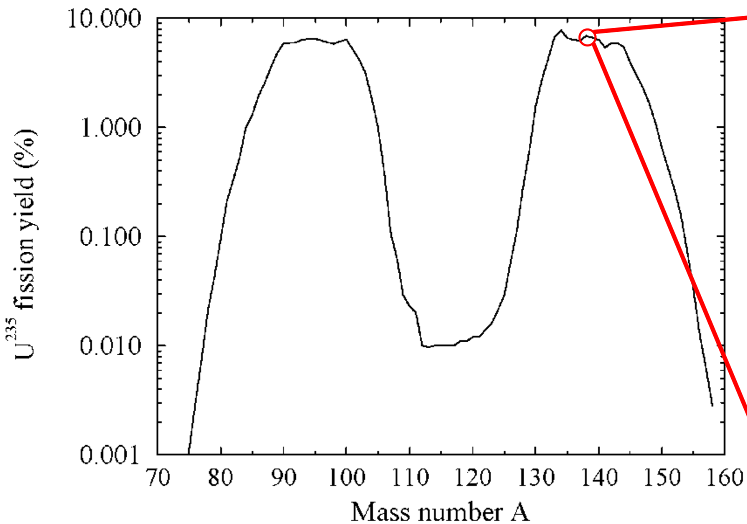


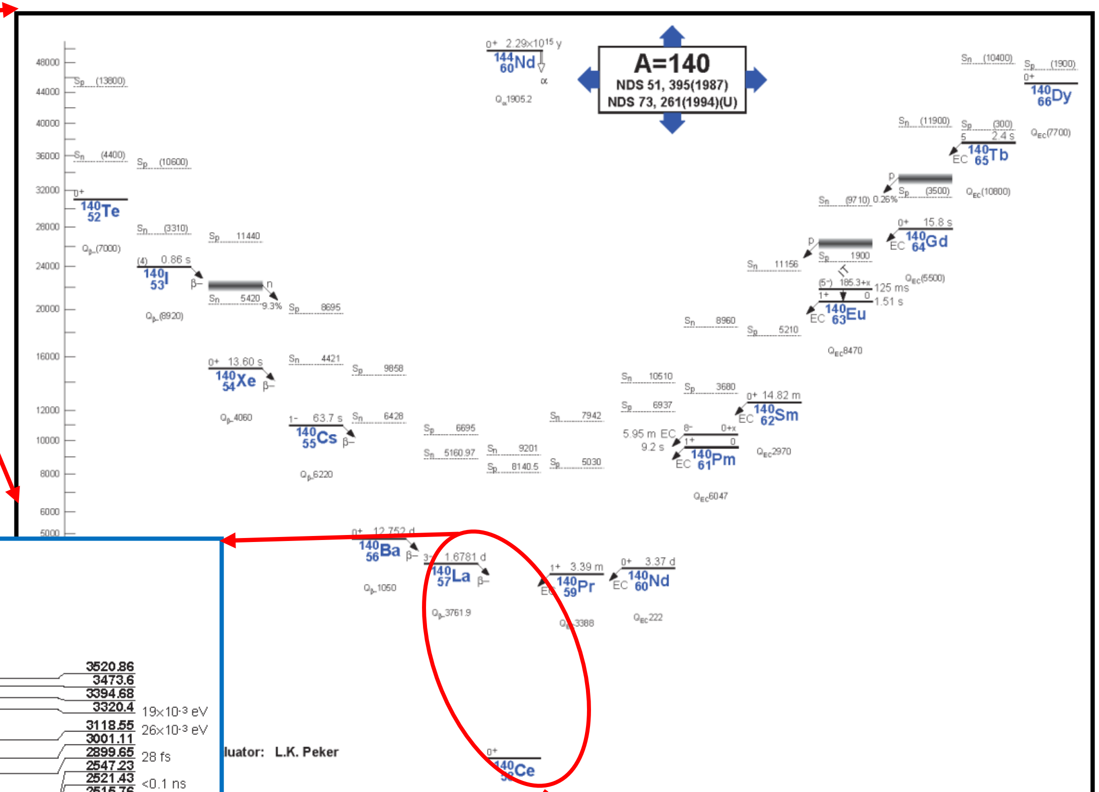
Zheyuan Yu, Neutrino 2016

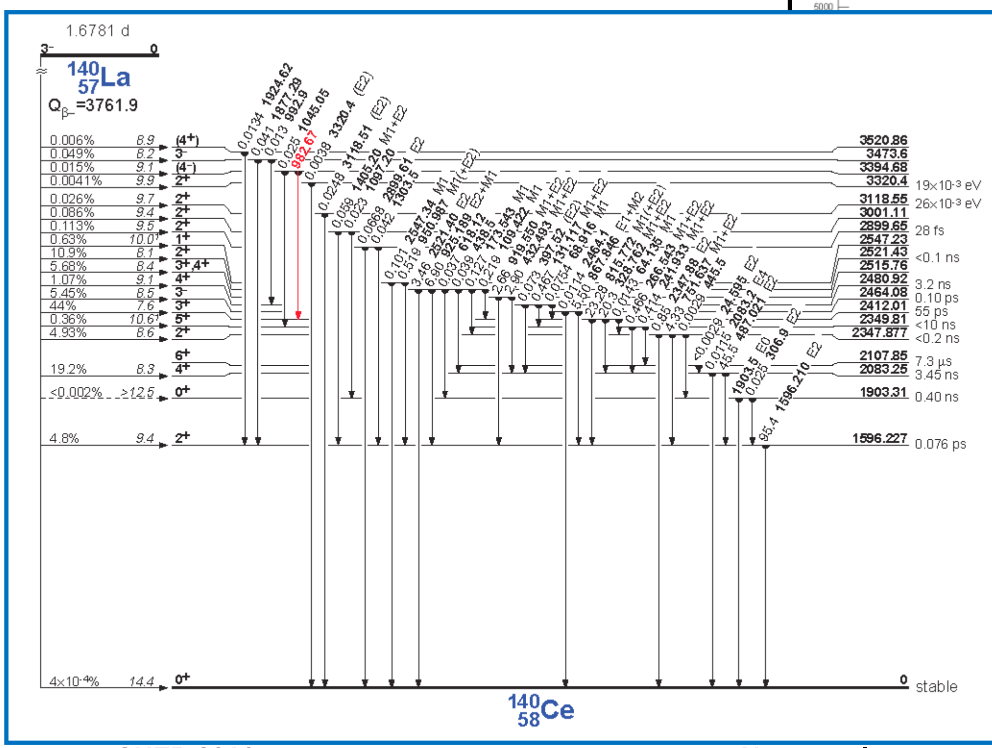
Summary of θ_{13} results from reactors compared to accelerator experiments



Life is hard…, for each of ^{238}U, ^{235}U, ^{239}Pu and ^{241}Pu there is a fission spectrum…

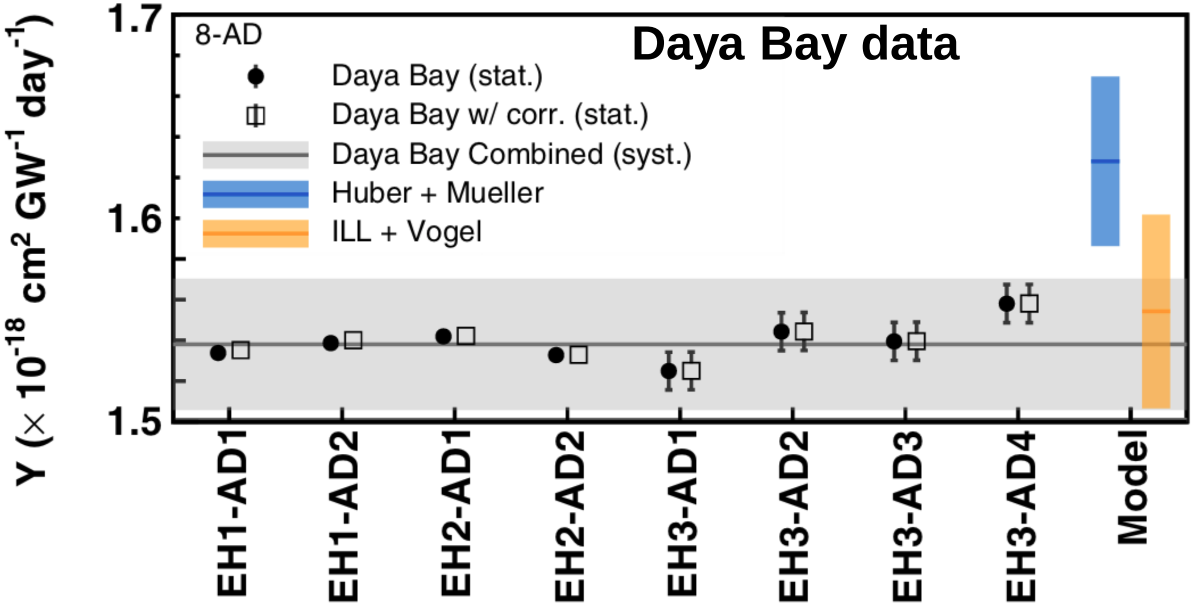


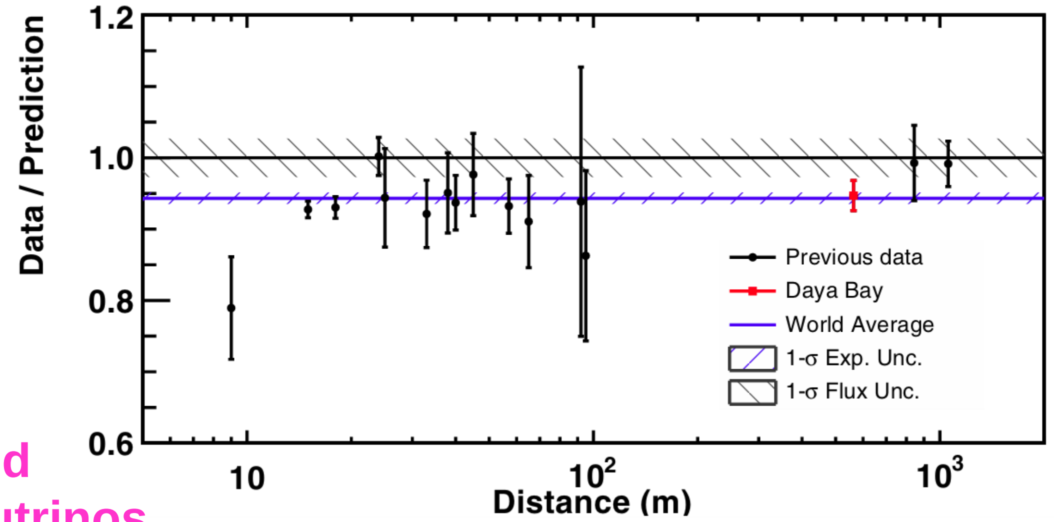




In the end,
an *ab initio* calculation
has to deal with
~5000 different branches

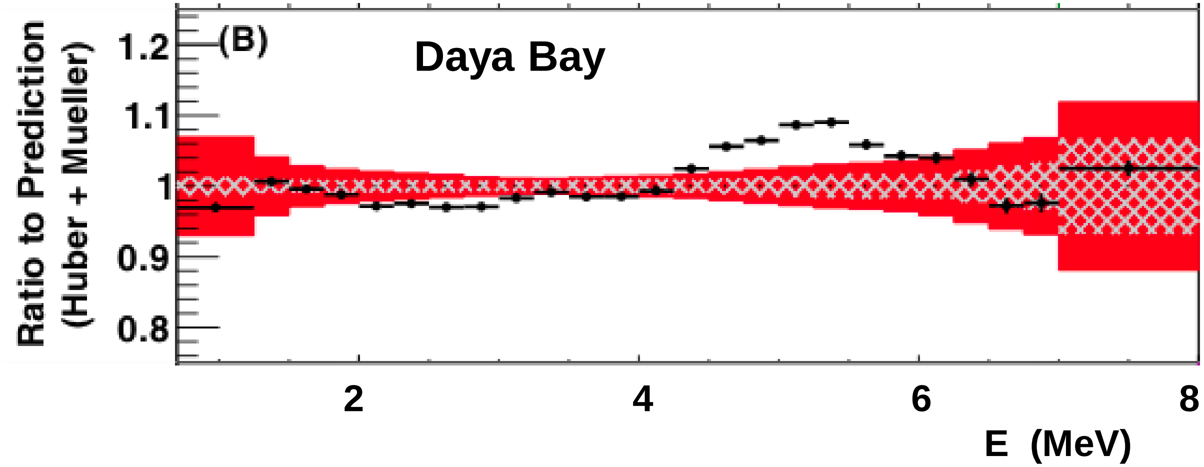
Total measured flux is low compared to the models



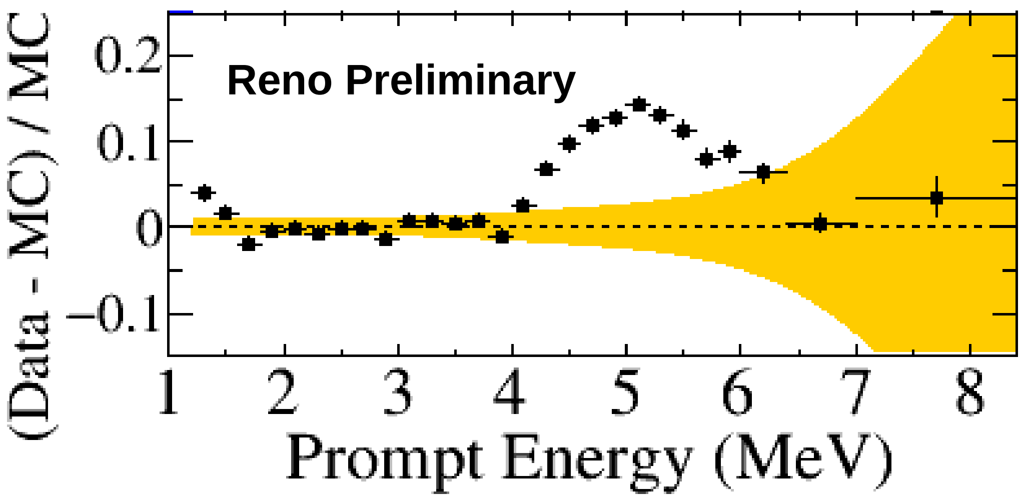


Actually this is not new, it was already the case for the body of previous data.

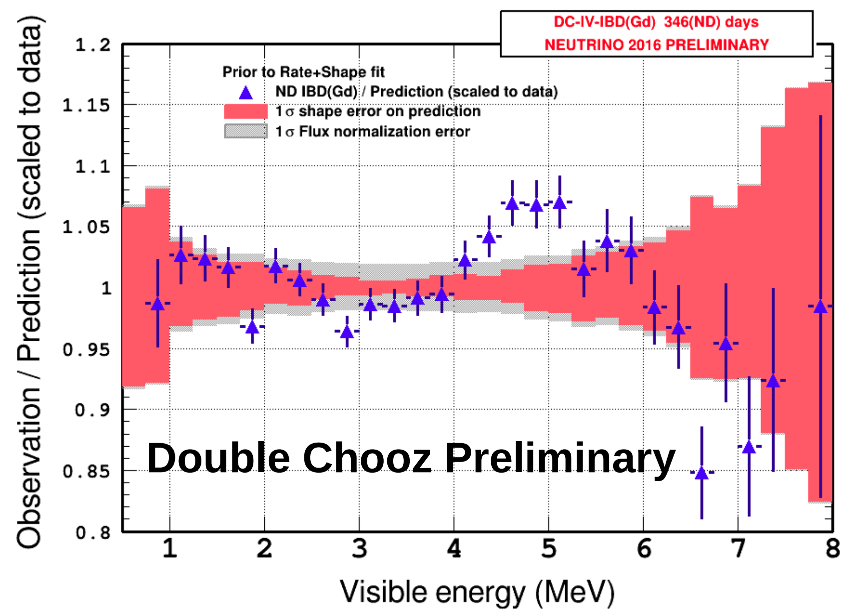
None of this is very significative but, if the uncertainty on the calculations is disregarded, would support oscillations to sterile neutrinos.



In addition there is definitely a bump around 5MeV that is not in the model.

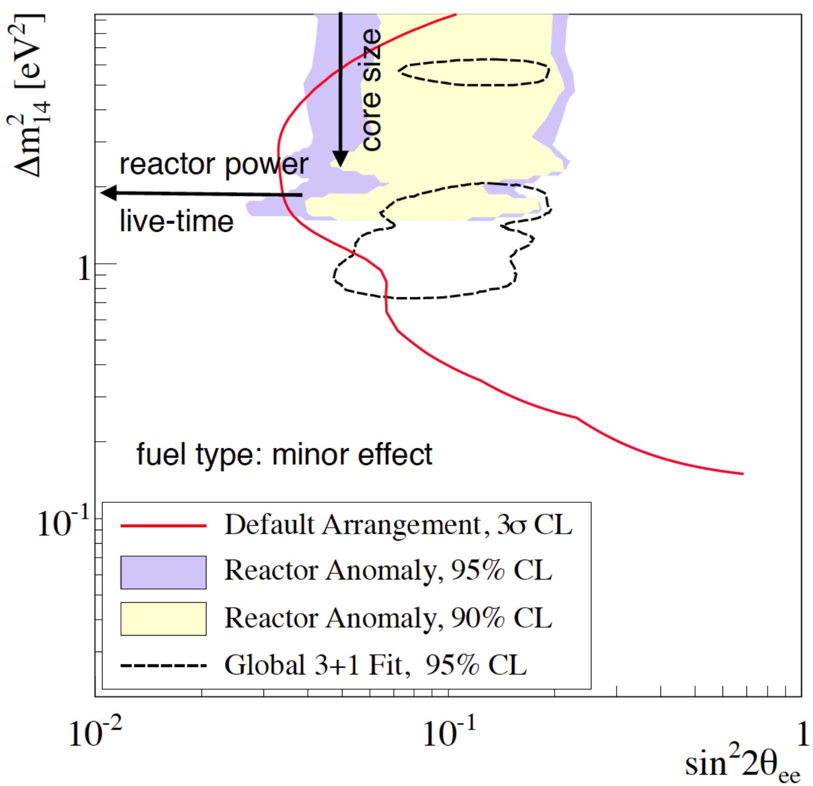


In this case the explanation ought to be in the modeling of the reactor spectrum.

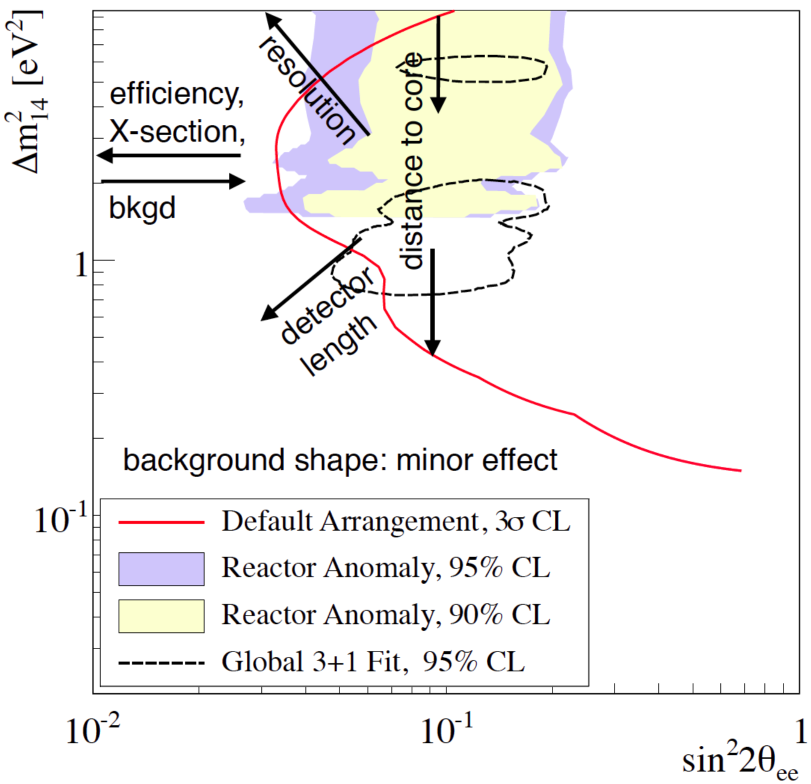


Very short baseline reactor experiments and LARGE radioactive sources (in addition to other experiments) will shed light on the issue of sterile neutrinos

Sensitivity to *reactor* parameters



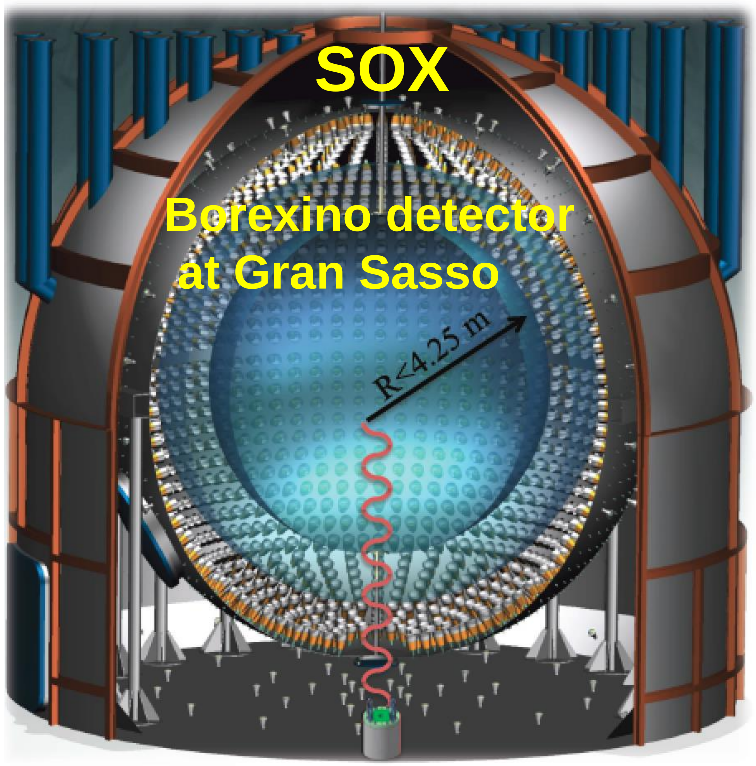
Sensitivity to *detector* parameters



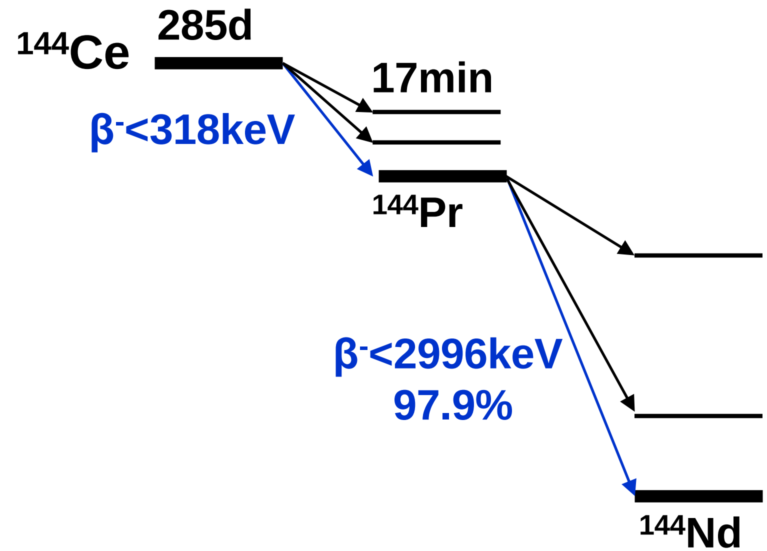
K.M. Heeger et al, PRD 87 (2013) 073008

Example of reactor experiment sensitivity

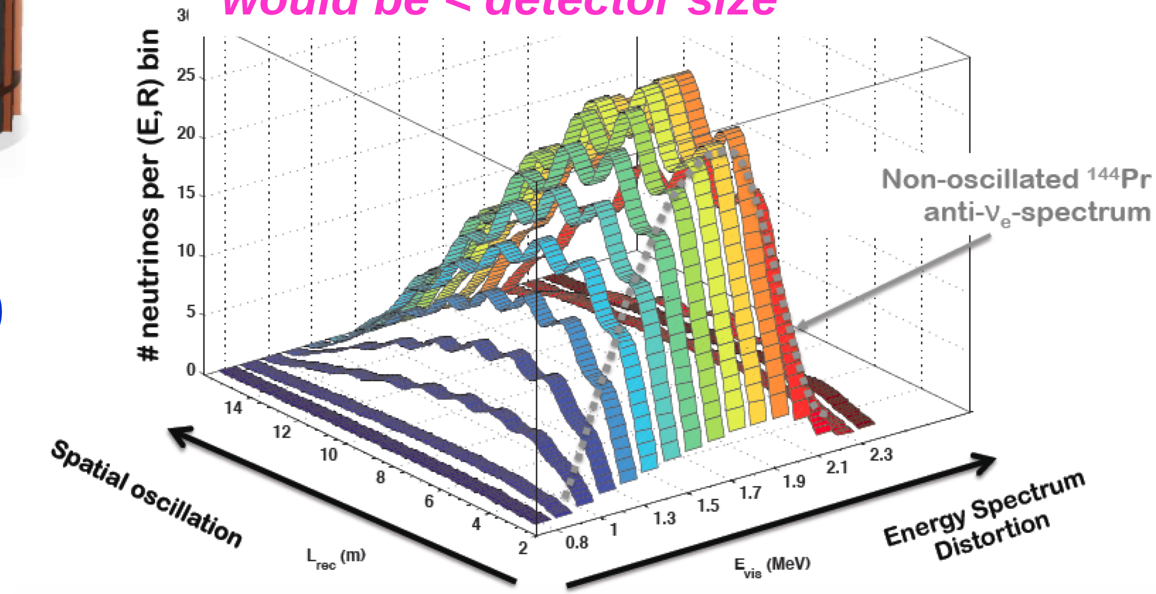
The source case is interesting because exotic/creative



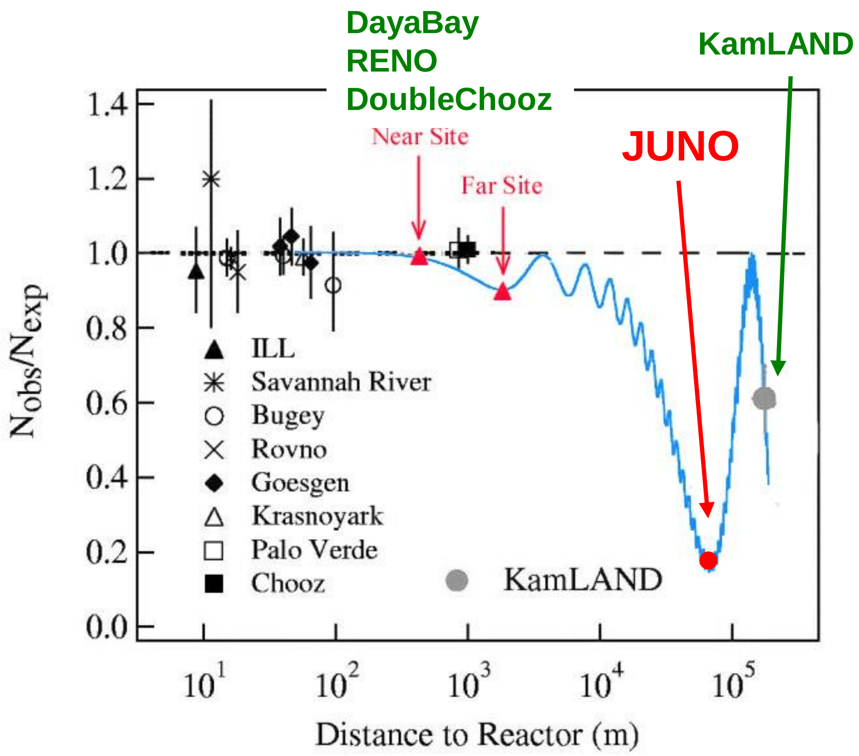
^{144}Ce 100-150 kCi source (!)



The signal would be spectacular because the oscillation length would be < detector size



Large enough detectors (20kton JUNO, 18kton RENO-50) can sit at a large distance and, with enough stability and energy resolution, detect a spectrum containing information on the mass hierarchy.



Large "low frequency" suppression:

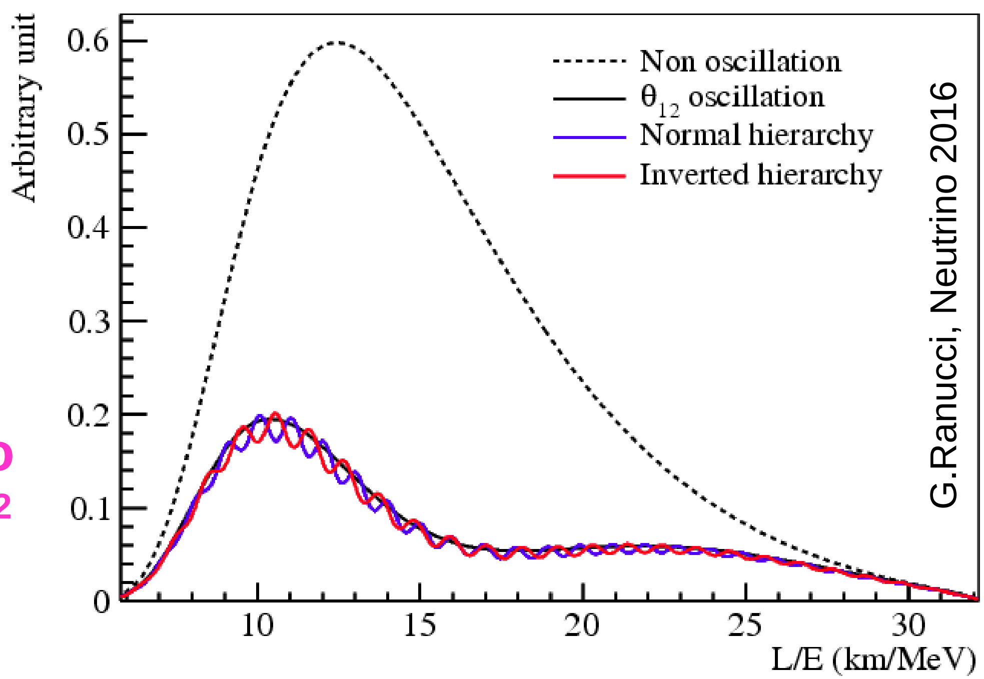
➔ Δm_{12}^2 , $\sin^2 \theta_{12}$

High frequency ripples:

Frequency ➔ $|\Delta m_{31}^2|$

Phase ➔ NH/IH

This only works because θ_{13} is large!



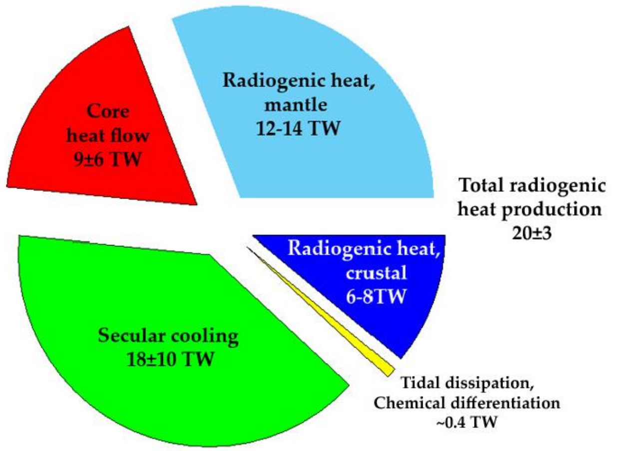
Expect 3σ NH/IH discrimination in 6 yr dataset w/o external info and 4σ discrimination with Δm^2 measurements from LBL exps.

While we study physics for the sake of knowledge it helps to show that the field has some impact on other areas of science and technology.

Perhaps surprisingly, neutrinos have already found applications!

An example is the measurement of geo-neutrinos.

According to the Standard Model of the Earth the planet produces 46±3 TW of power, ~half of which is radiogenic.



after Jaupart et a 2008 Treatise of Geophysics

This heat is responsible for plate tectonics volcanos, earthquakes and pretty much all the geological phenomena that we know.

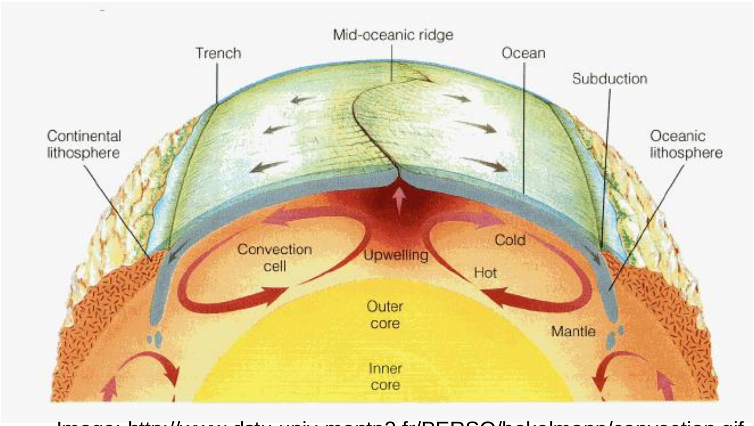
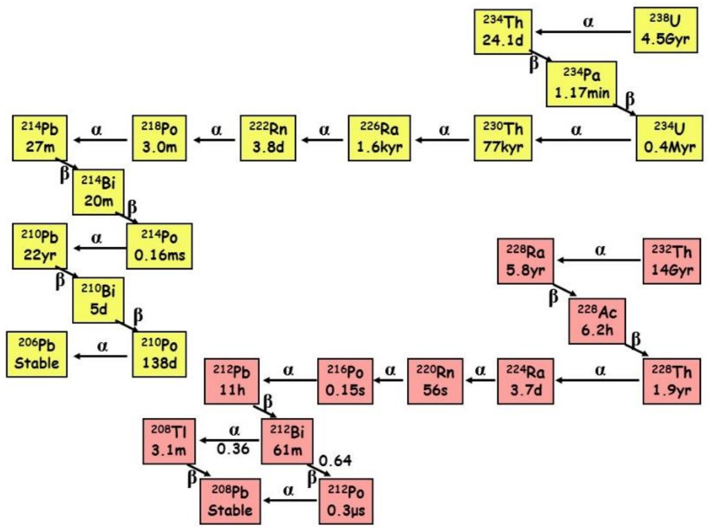
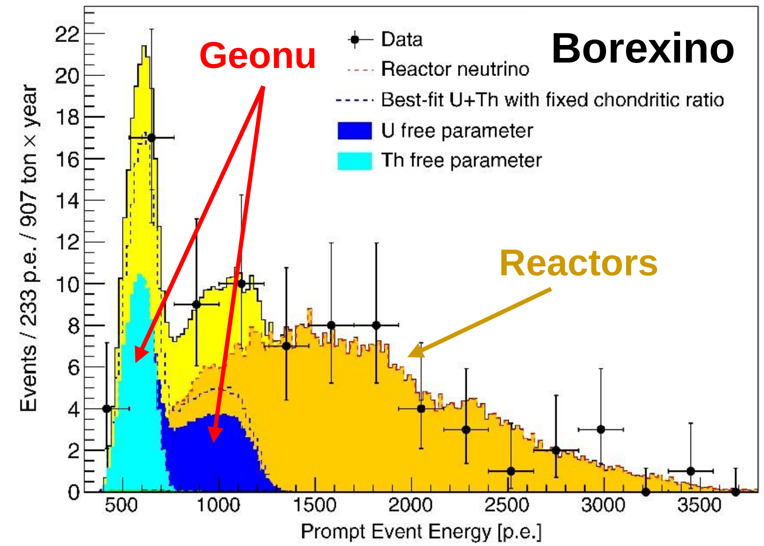


Image: http://www.dstu.univ-montp2.fr/PERSO/bokelmann/convection.gif

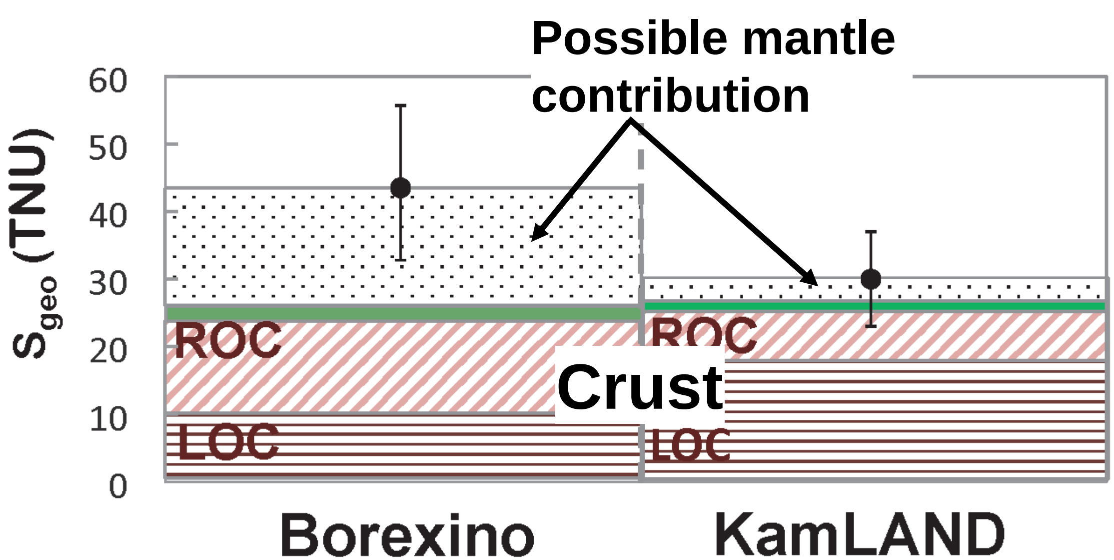
Yet, our knowledge of the interior of the Earth is very tentative and almost entirely based on seismic data, i.e. elastic properties of rocks.

The radioactive decays (mostly from the U and Th decay chains) producing the heat also emit $\bar{\nu}_e$



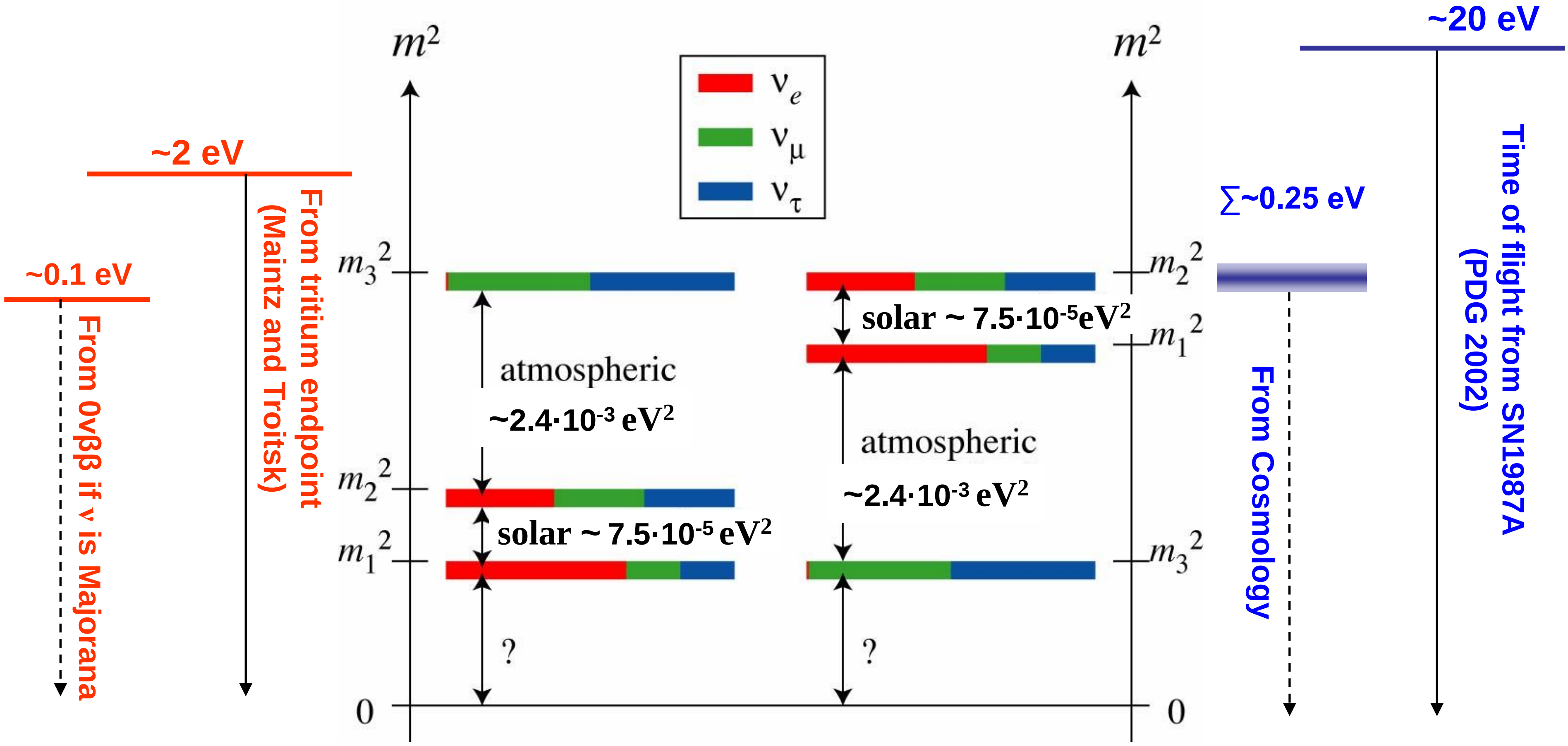


The rate is tiny (~1 event/month in 1 kton), but the inverse-beta decay signature helps.

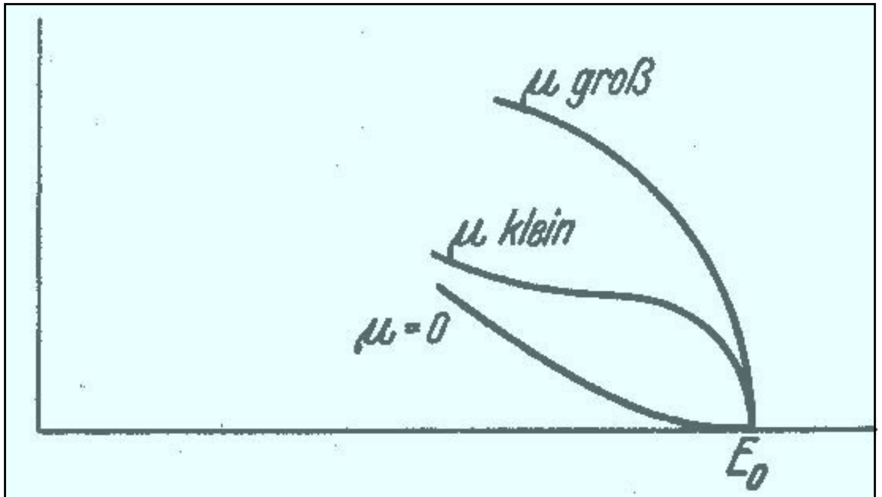


L.Ludhova and S.Zavatarelli, arXiv:1310.3961
M.Agostini et al., PRD 92 (2015) 031101(R)

Non-accelerator techniques are required to address the issue of the neutrino mass scale



The shape of the β decay end-point contains information about the neutrino mass (the energy of the end-point is generally not known well enough to make an absolute measurement)



Principle almost as old as neutrino itself:
E. Fermi, Z. Phys. 88 (1934) 161

For finite energy resolution what is measured is the combination:

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 m_i^2$$

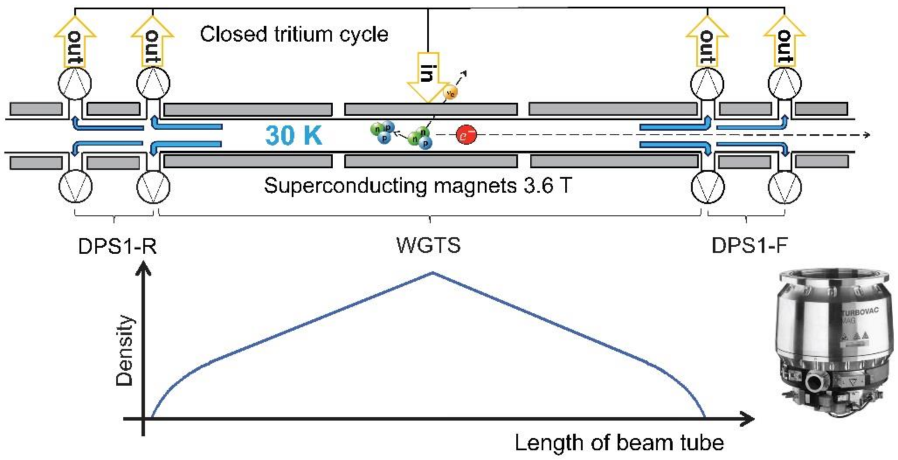
Modern experiments mostly use $^3_1\mathrm{H} \rightarrow {}^3_2\mathrm{He} + e^- + \bar{\nu}_e$

a super-allowed transition with a rather good combination of low end point (E_0=18.6 keV) and short half life ($T_{1/2}$=12.3 yr).
Still, *most* of the electrons are far from the end-point, i.e. not useful.

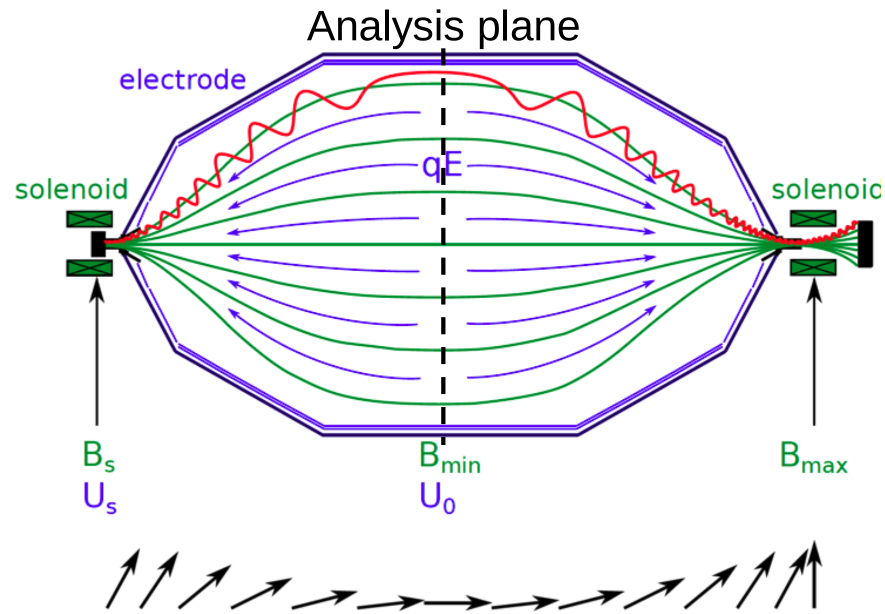
About 1 electron in 10^{11} emitted is close enough to the endpoint!

KATRIN

Differentially pumped, window-less gaseous tritium source

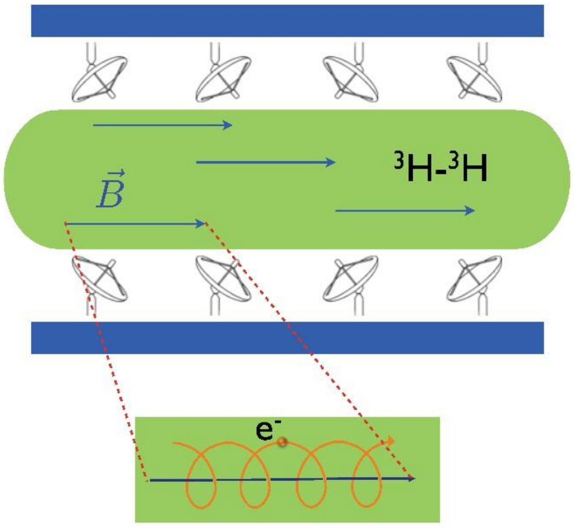


MAC-E integrating spectrometer



- **Very high (2π) acceptance**
- **Electrons away from the end-point are reflected back**
- **Low background**
- **Good energy resolution**
- **Gaseous tritium source with high activity (~5Ci)**
- **Expect ~250 meV sensitivity with in 3 yr dataset (5 cal yr)**
- **First tritium data in 2017**

K.Valerius, Neutrino 2016



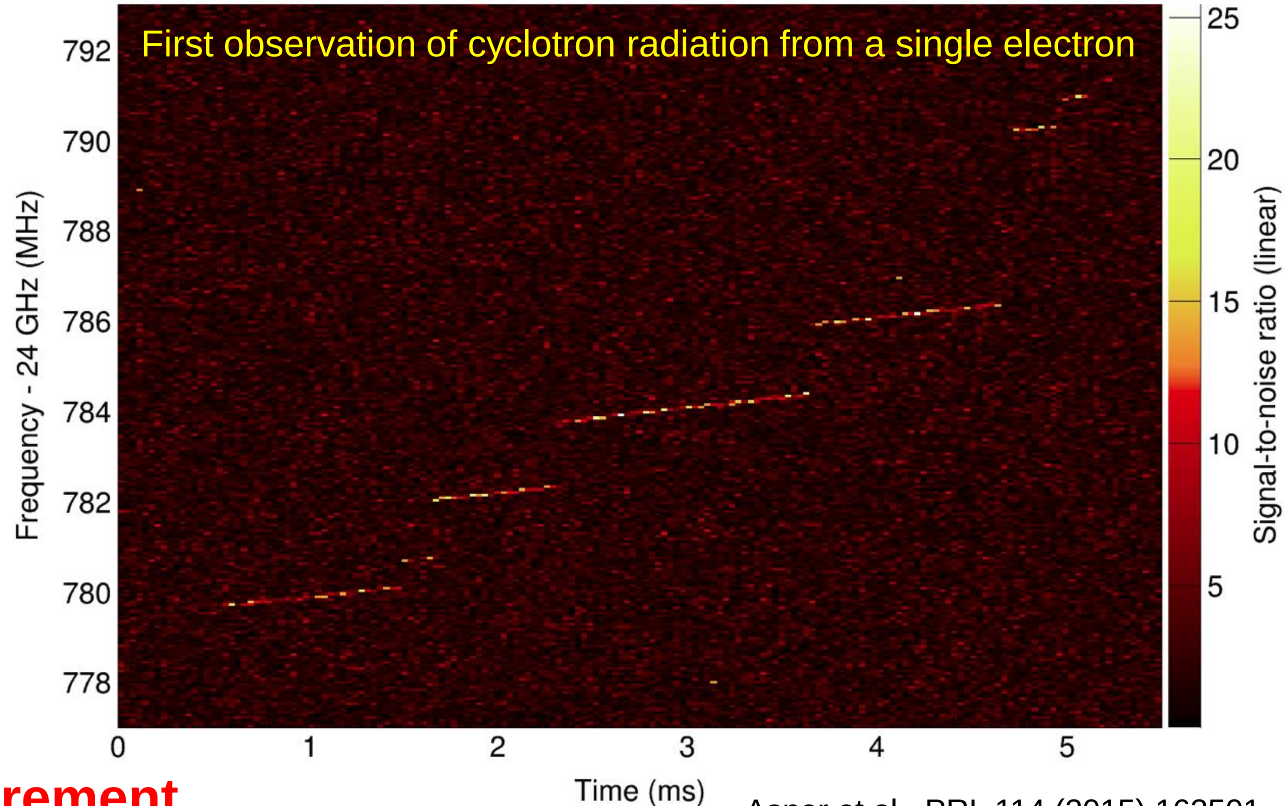
Best would be to measure the electron energy within the bulk of the source either calorimetrically (ECHo, HOLMES, NuMECS) or in a magnetic field.

(Relatively) new idea: *Project 8*

Measure the frequency of the cyclotron radiation in a constant magnetic field.

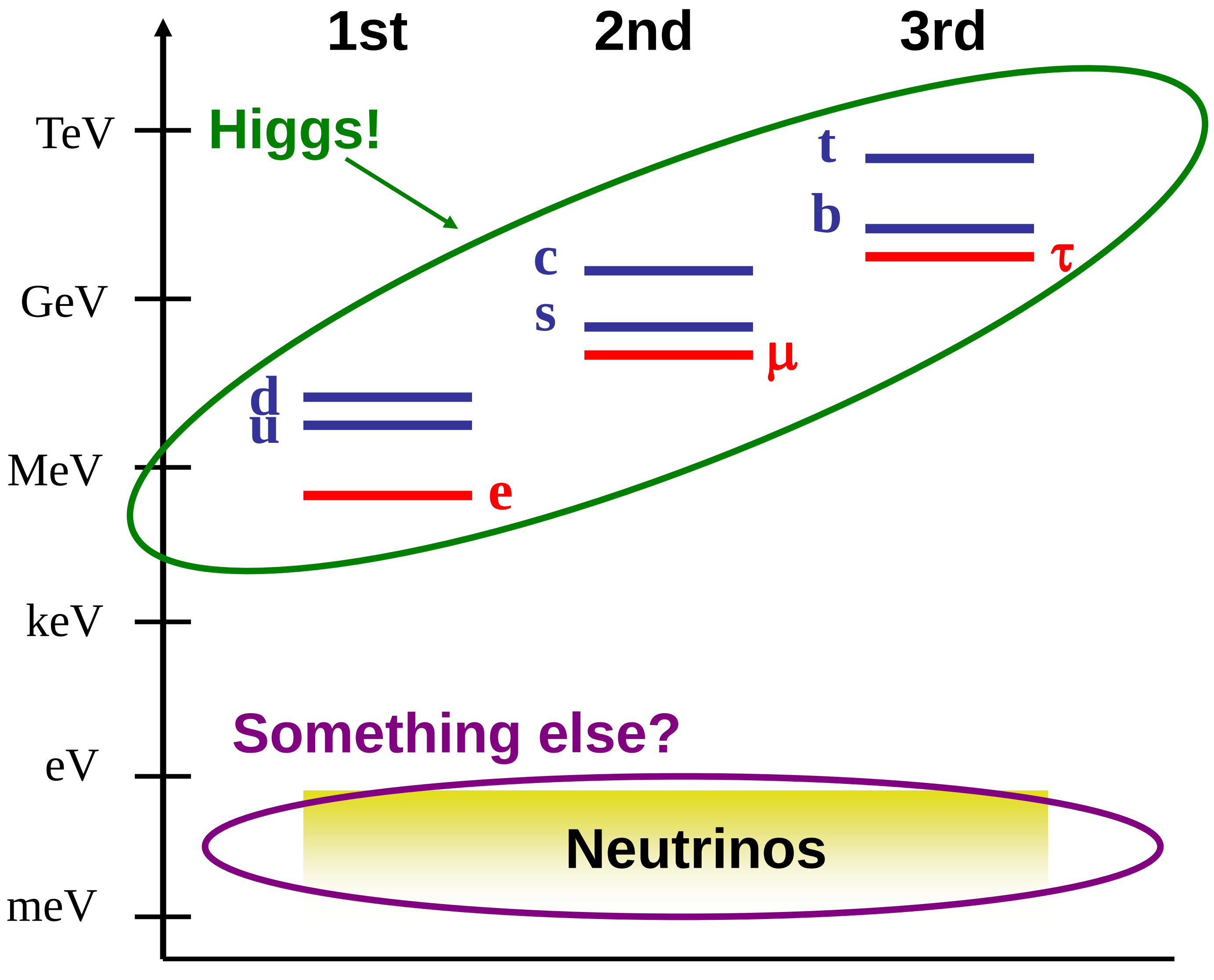
$$\omega(E_{kin}) = \frac{eB}{E_{kin} + m_e}$$

This is also a non-destructive measurement



Asner et al., PRL 114 (2015) 162501

And, BTW, why are neutrino masses so small?



Maybe this is related to the fact that neutrinos are also the only neutral fermion

Generation

Charge	1st	2nd	3rd
1	e^+	μ^+	τ^+
2/3	u	c	t
1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$
0	ν_e	ν_μ	ν_τ
-1/3	d	s	b
-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
-1	e^-	μ^-	τ^-

Neutrinos do not carry charge
What about lepton number?

Possibly charge=0 corresponds also to lepton number violation and only 2 neutrino states are required

"Dirac" neutrinos

(some "redundant" information but the "good feeling" of things we know…)

$$\nu^D = \begin{pmatrix} \nu_L \\ \overline{\nu}_L \\ \nu_R \\ \overline{\nu}_R \end{pmatrix}$$

"Majorana" neutrinos

(more efficient description, no total lepton number conservation, new paradigm…)

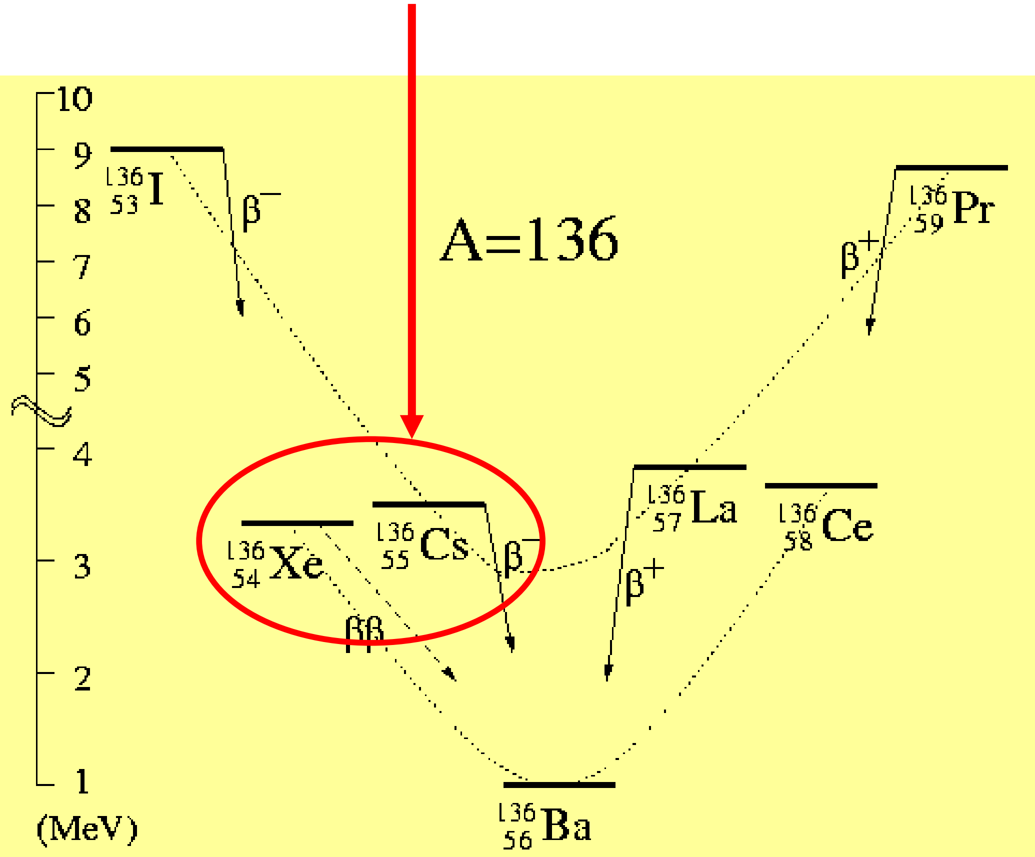
$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Which way Nature has chosen to proceed is an experimental question

But the two descriptions are distinguishable only if $m_\nu \neq 0$
(and the observable difference → 0 for m_ν → 0)

This is best investigated in double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	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	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

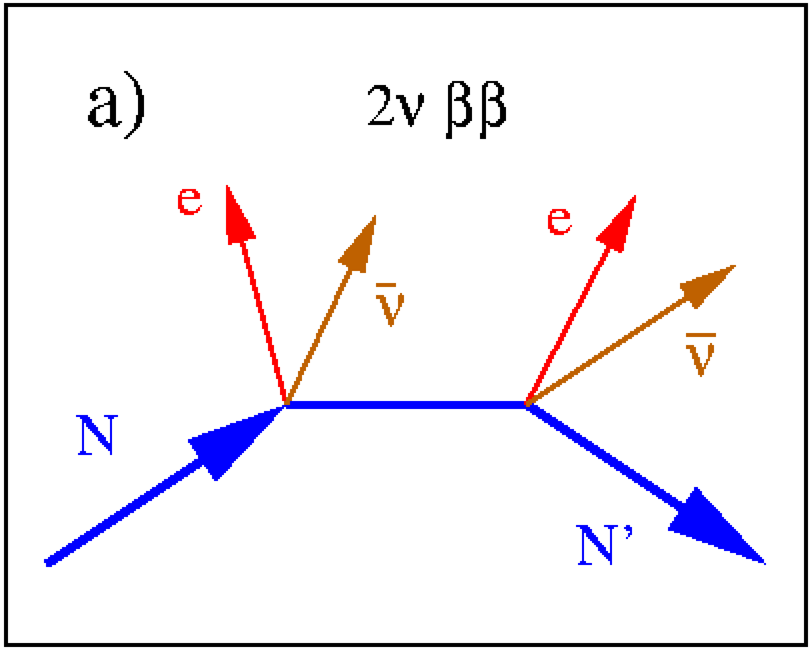
2ν mode:
a conventional 2nd order process in nuclear physics

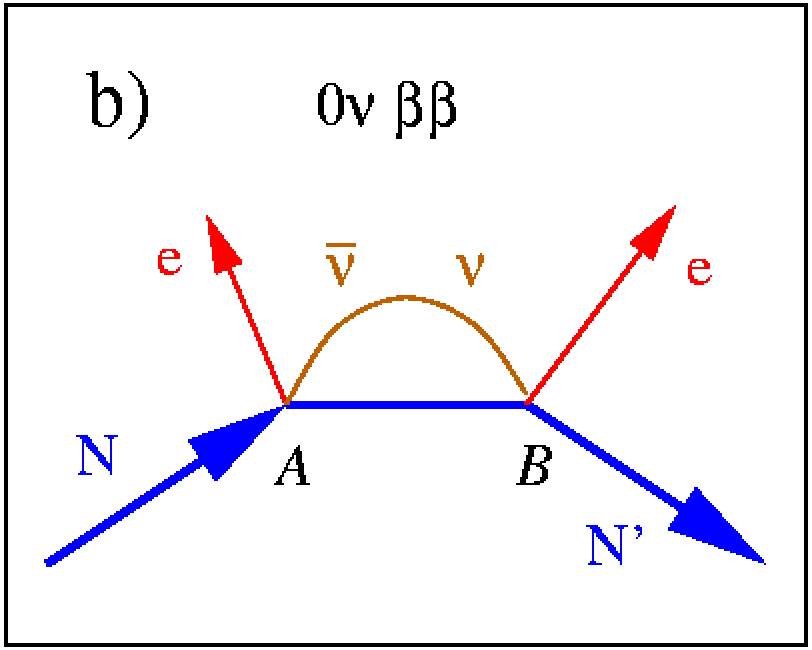
0ν mode: a hypothetical process can happen only if: $M_\nu \neq 0$

$\bar{\nu} = \nu$

$|\Delta L|=2$

$|\Delta(B-L)|=2$





Recent results (>10^{25} yr half life)

Isotope	Experiment	Exposure (kg yr)	$T^{0\nu\beta\beta}_{1/2}$ average sensitivity (10^{25}yr)	$T^{0\nu\beta\beta}_{1/2}$ (10^{25}yr) 90%CL	$T^{0\nu\beta\beta}_{1/2}$ (13.8Gyr) 90%CL	$< m_{\nu} >$ (meV) Range from NME*	Reference
^{76}Ge	Gerda	34.36	4.0	>5.2	>3.7x10^{15}	160-260	M.Agostini, Neutrino 2016
^{136}Xe	EXO-200	100	1.9	>1.1	>8.0x10^{14}	190-450	Albert et al. Nature 510 (2014) 229
	KamLAND-ZEN	504**	4.9	>11 (run 2)	>8.0x10^{15}	60-161	Gando et al., arXiv:1605.02889 (2016)

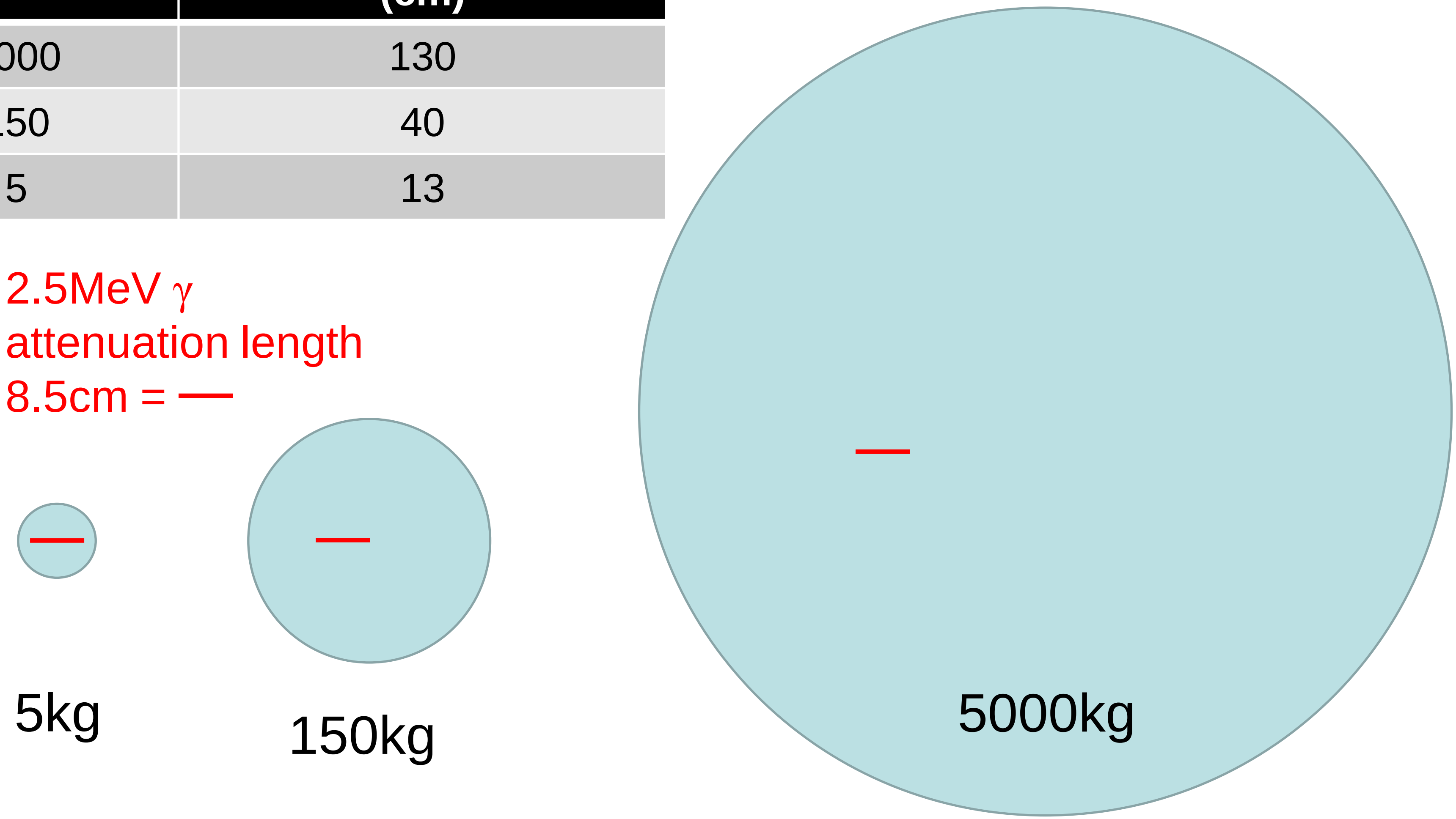
* Note that the range of "viable" NME is chosen by the experiments and uncertainties related to g_A are not included

** All Xe. Fiducial Xe is more like ~150 kg yr

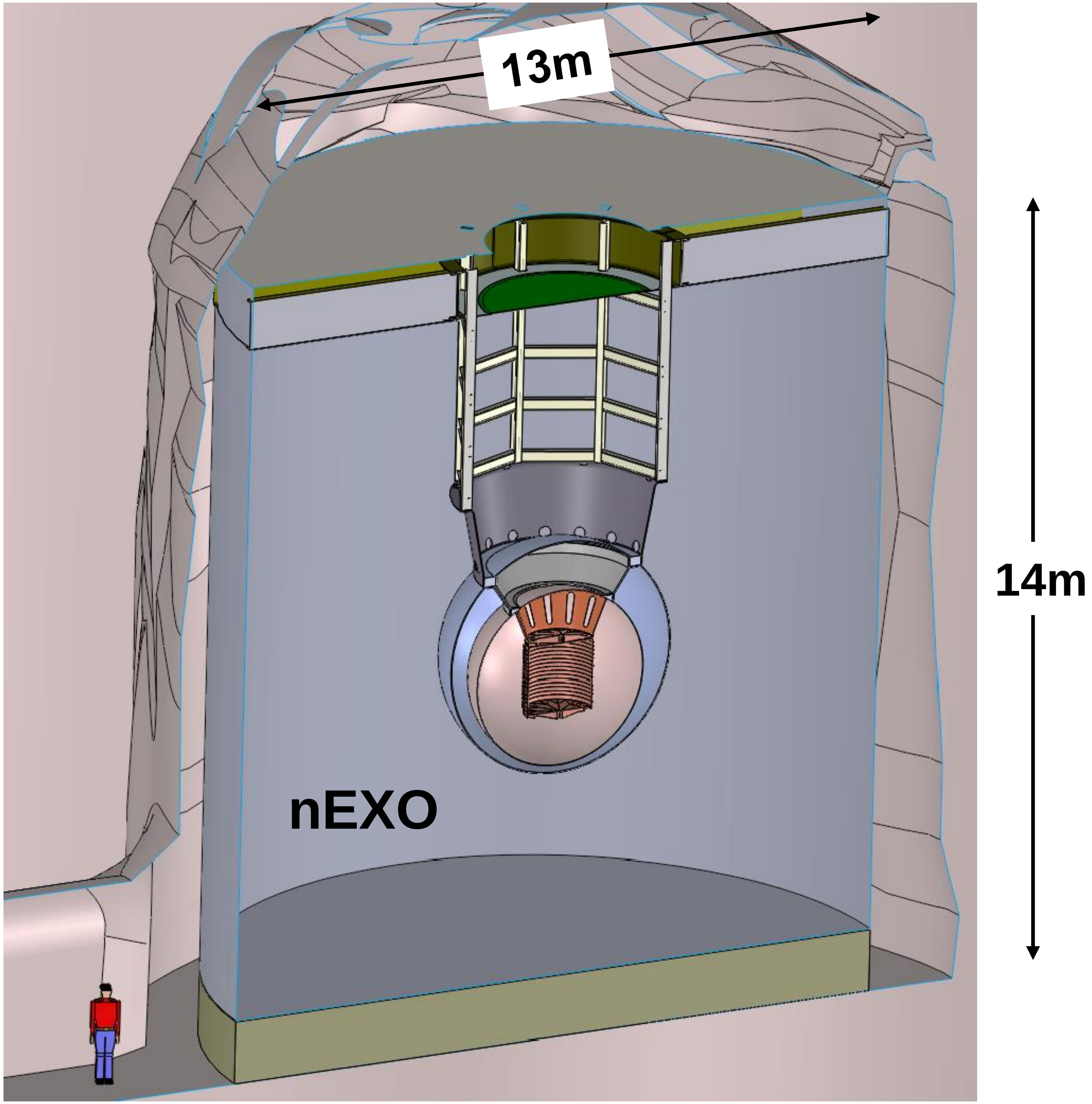
Needless to say, neutrinoless double-beta decay requires the lowest backgrounds ever achieved in particle/nuclear physics.

But, in this case, going for larger detectors actually helps!

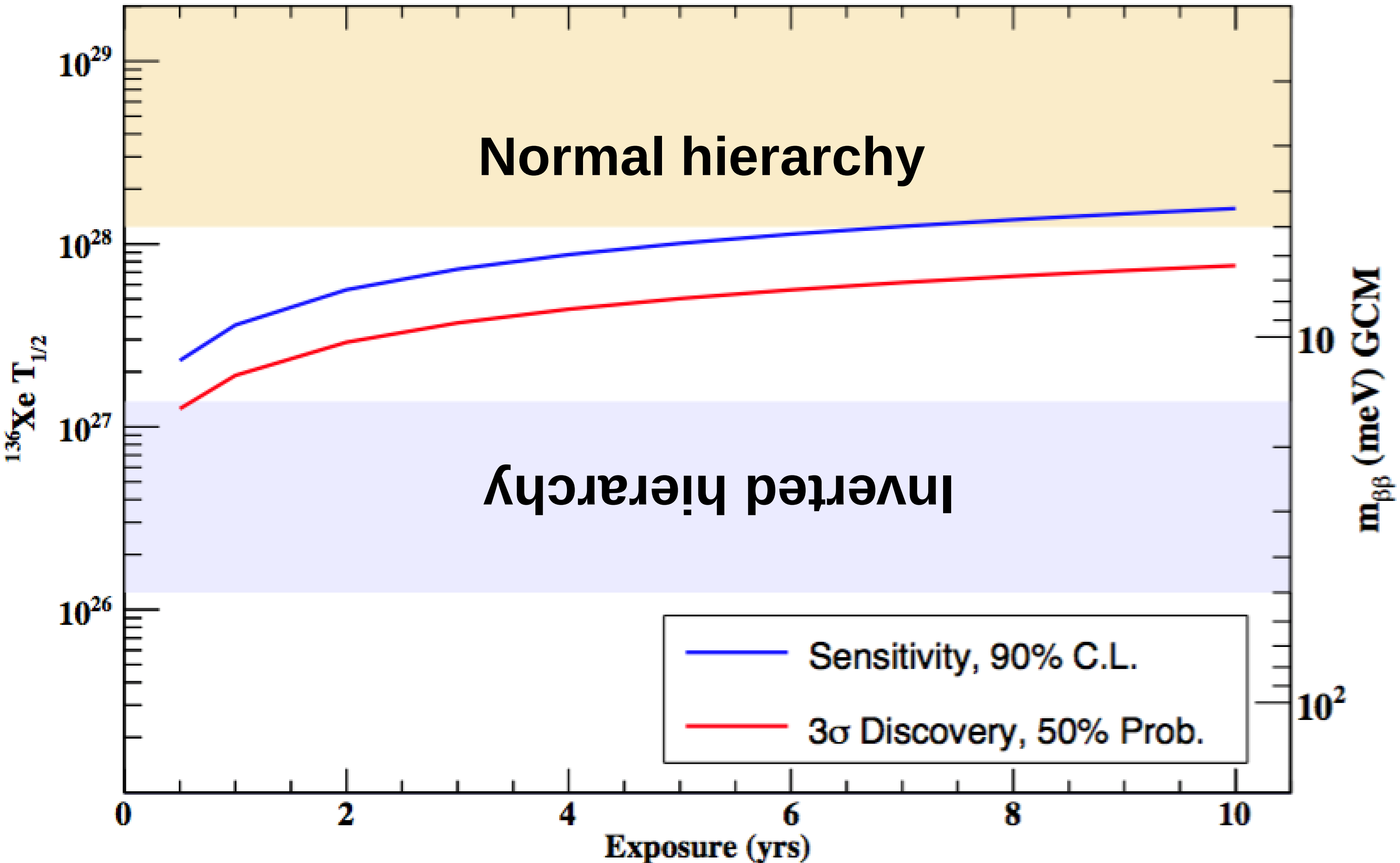
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13



And, indeed, there are advanced plans for ton-scale experiments



nEXO sensitivity as a function of time
for the best-case Nuclear Matrix Element (GCM)



GCM: Rodriguez, Martinez-Pinedo,
Phys. Rev. Lett. 105 (2010) 252503

Conclusions

- I had too little time!
- This is a very exciting (sub-)field that has produced some of the most compelling results in recent times.
- It is also a very creative field, where techniques are very diverse and not even the sky is the limit!
- We should expect more revolutions from experiments that are being built or conceived now.
- Again, apologies if your favorite measurement or idea did not make it in this talk.