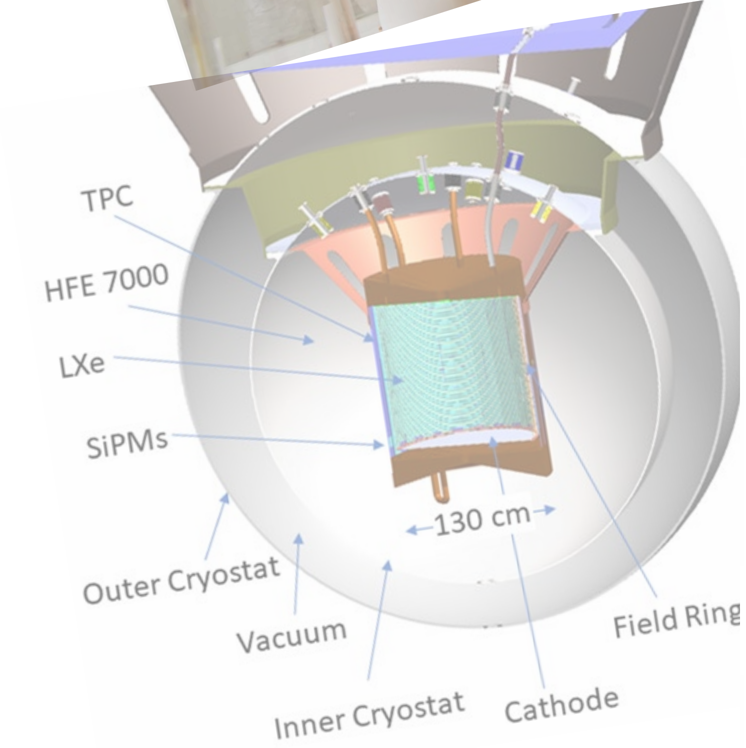
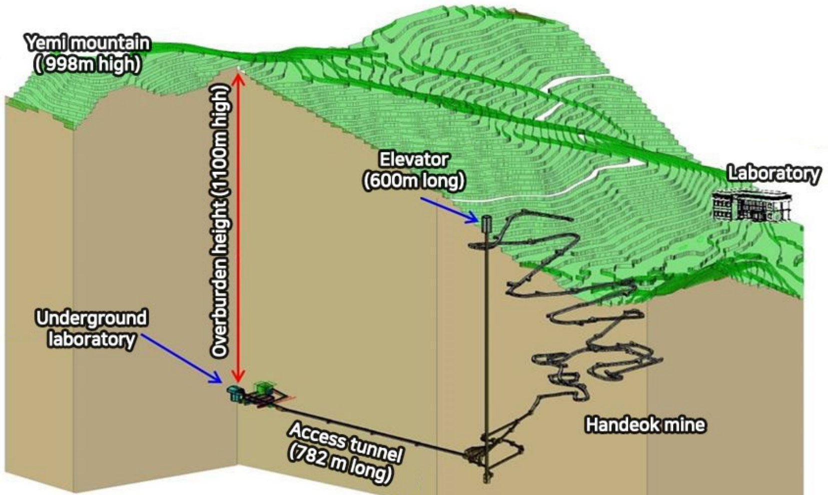
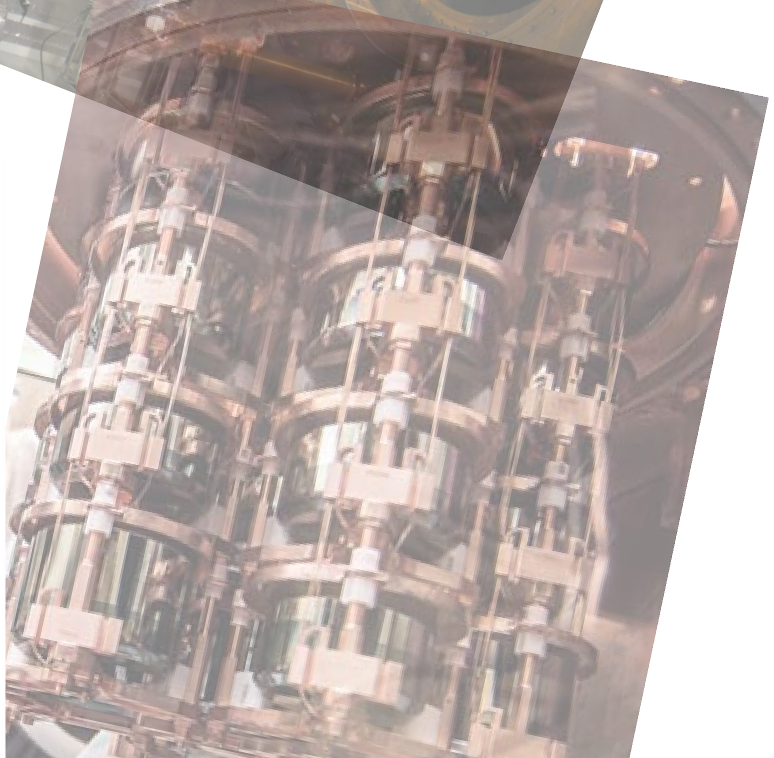
Neutrinoless double-beta decay: *The next steps*

Giorgio Gratta

Physics Department
Stanford University







Last 25 yrs: the age of ν physics

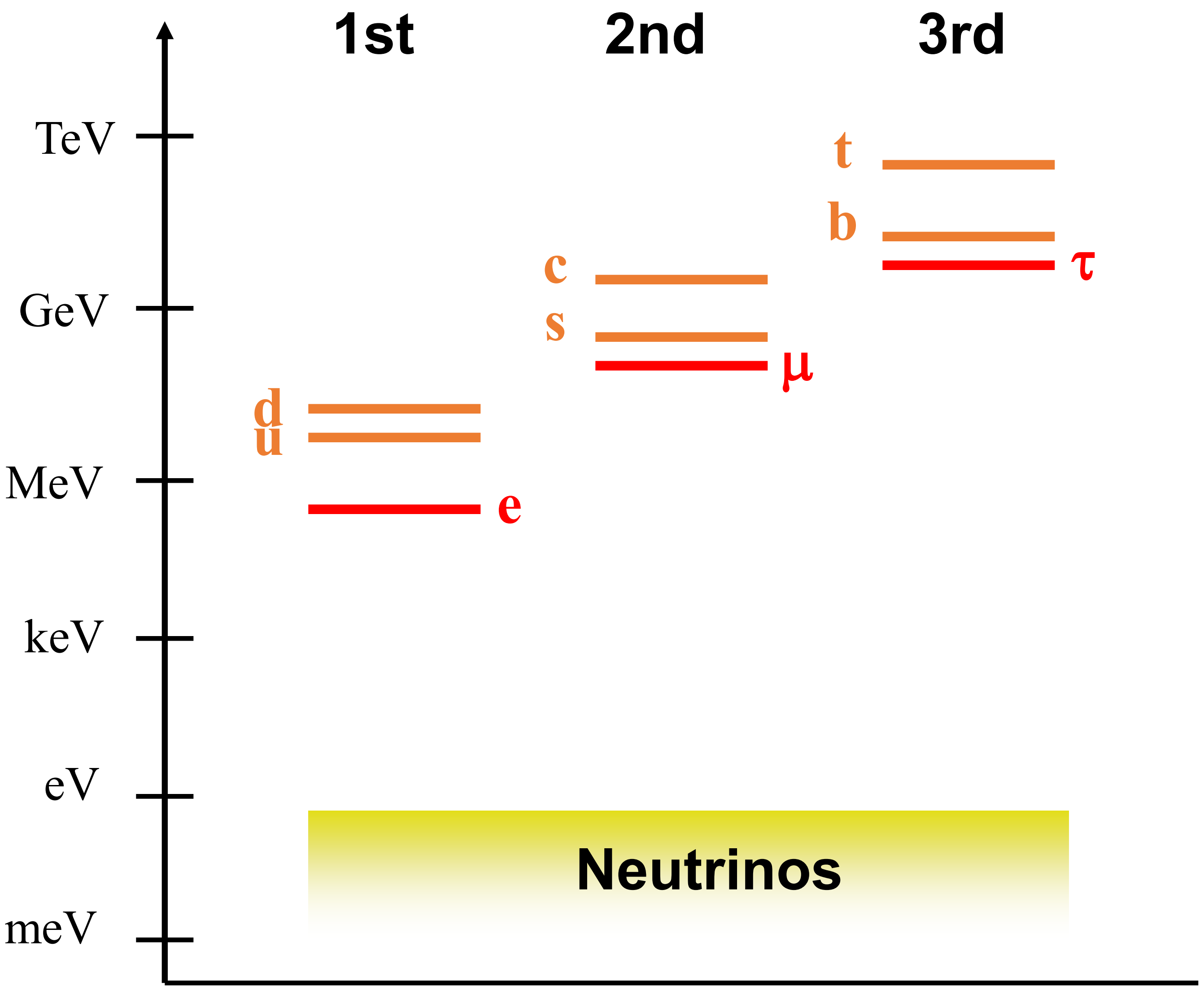
Discovery of ν flavor change 

- *Solar neutrinos (MSW effect)*
- *Reactor neutrinos (vacuum oscillation)*
- *Atmospheric neutrinos (vacuum oscillation)*
- *Accelerator neutrinos (vacuum oscillation)*

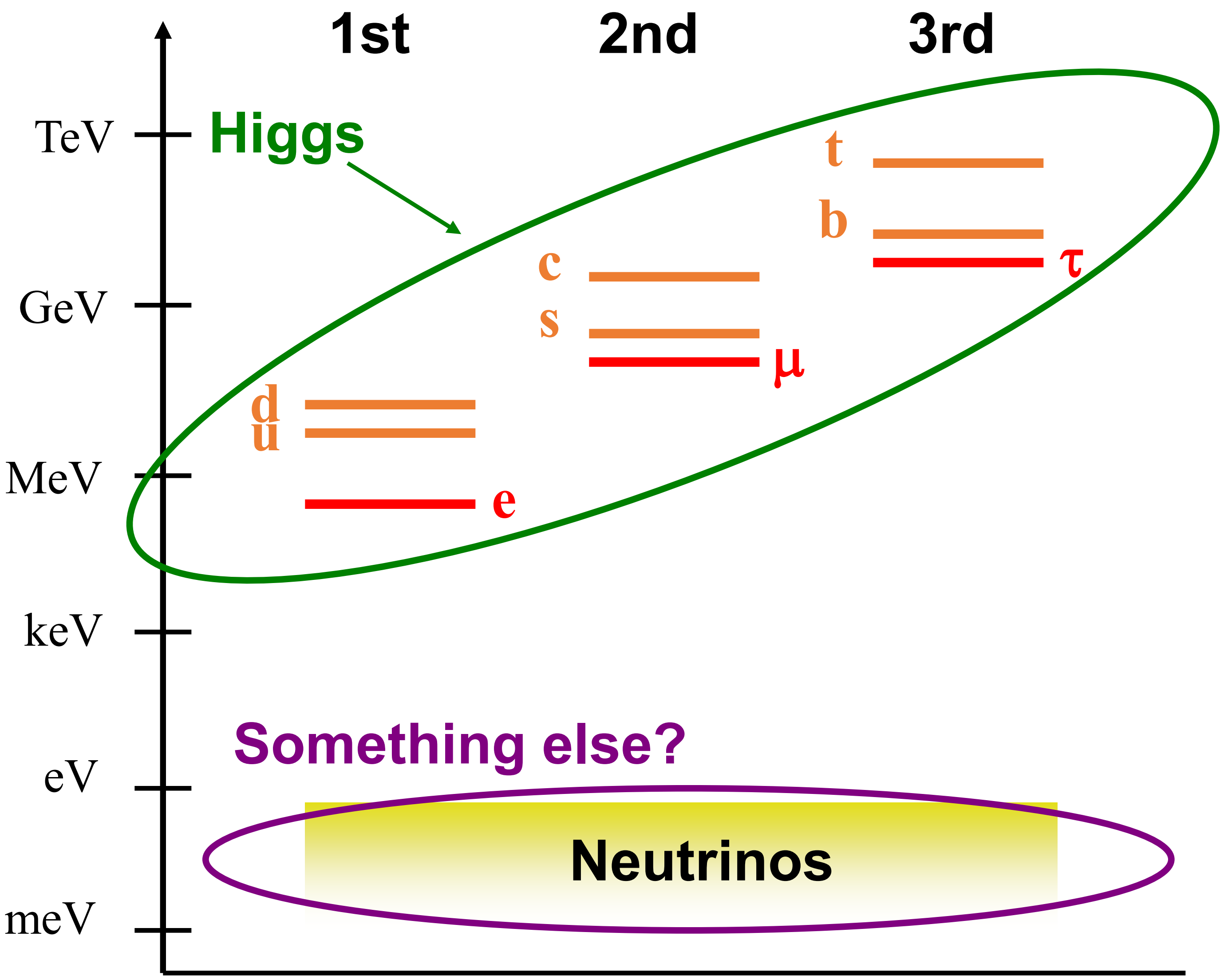
We also found that:

- ν masses are non-zero
- there are 2.981±0.008 ν (Z lineshape)
- 3 ν flavors were active in Big Bang Nucleosynthesis
- The Sun emits neutrinos as expected 
- Supernovae emit neutrinos 

Fermion mass spectrum



Fermion mass spectrum



Neutrinos have other peculiarities:
They are the only electrically neutral fermions

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?

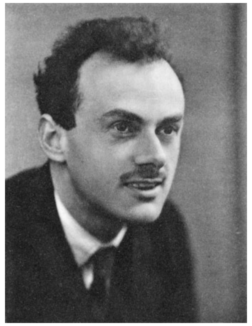
Maybe the anomalously small mass and the absence of charge point to something quite extraordinary!

There are two possible ways to describe neutrinos:

"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…)

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

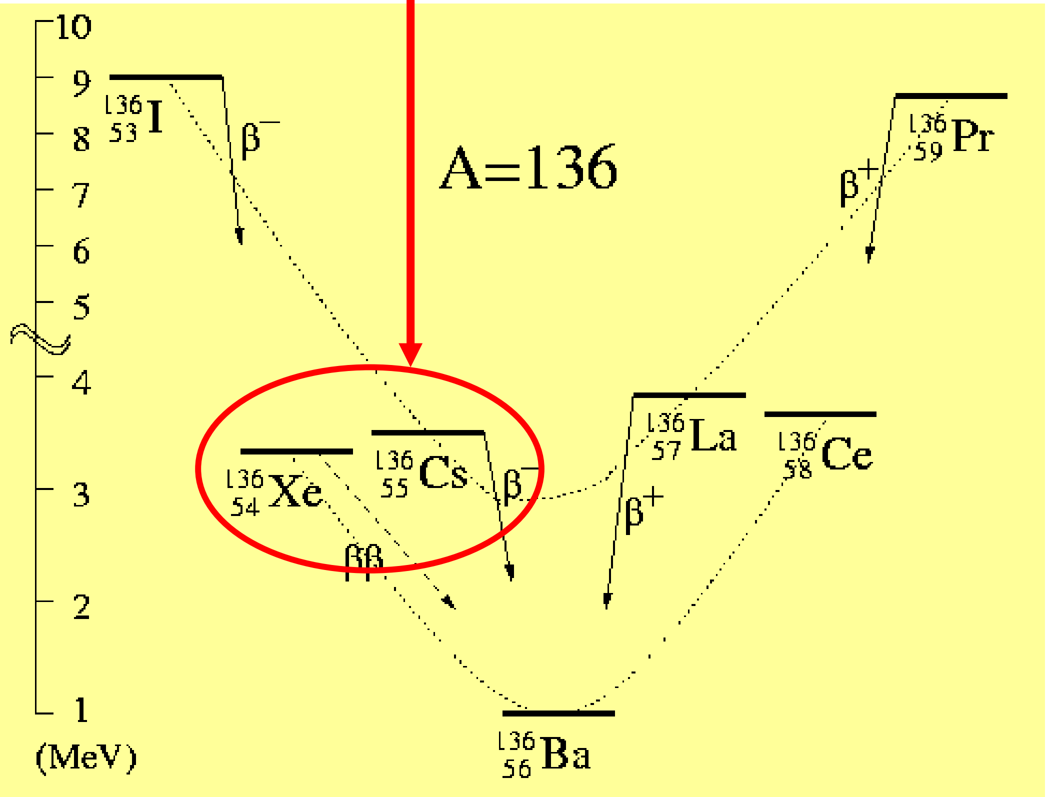
Which way Nature has chosen to proceed is an experimental question

But the two descriptions are distinguishable only if $m_\nu \neq 0$

(and the observable difference → 0 for $m_\nu \rightarrow 0$)

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
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

There are two varieties of ββ decay

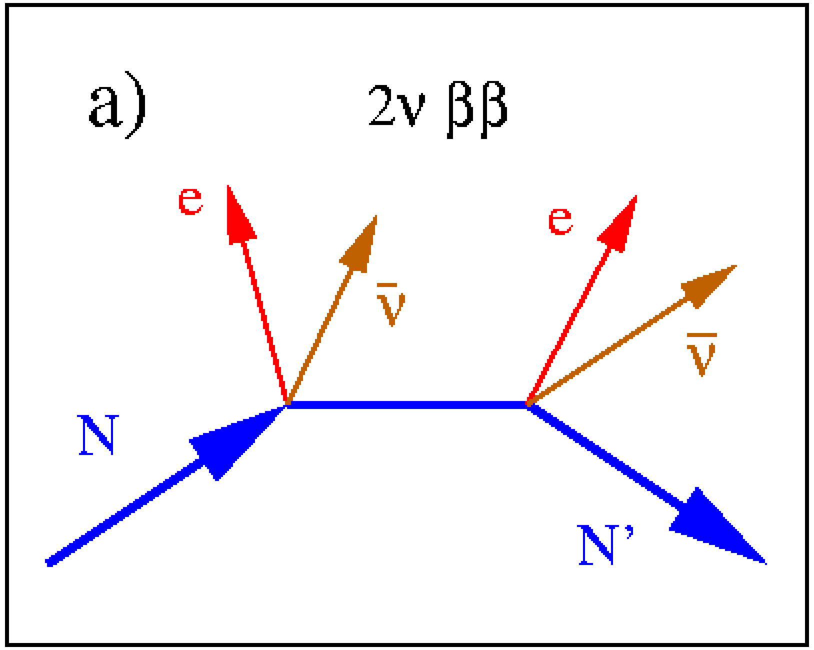
2ν mode: a conventional
2nd order process
in nuclear physics

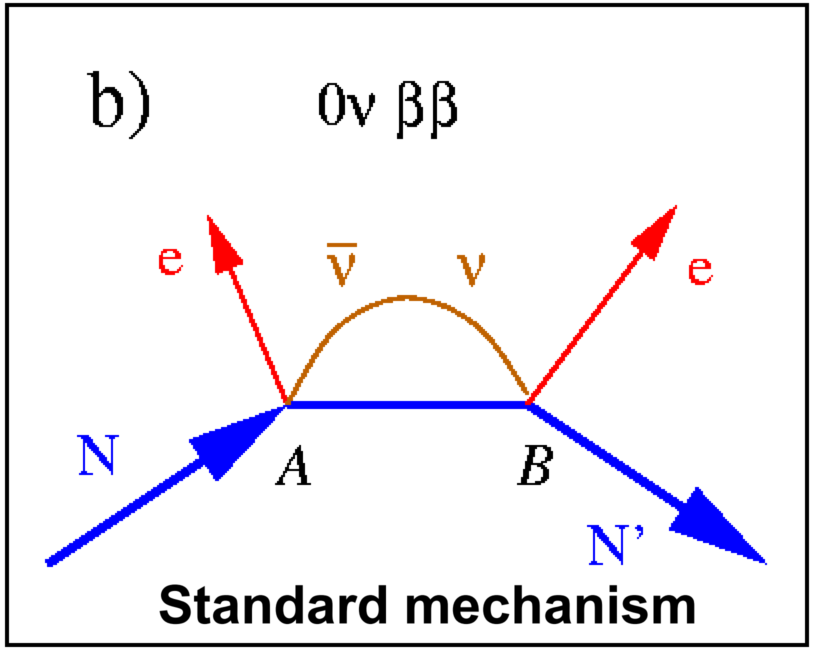
0ν mode: a hypothetical process
can happen only if: $M_\nu \neq 0$

$\nu = \bar{\nu}$

$|\Delta L|=2$

$|\Delta(B\text{-}L)|=2$





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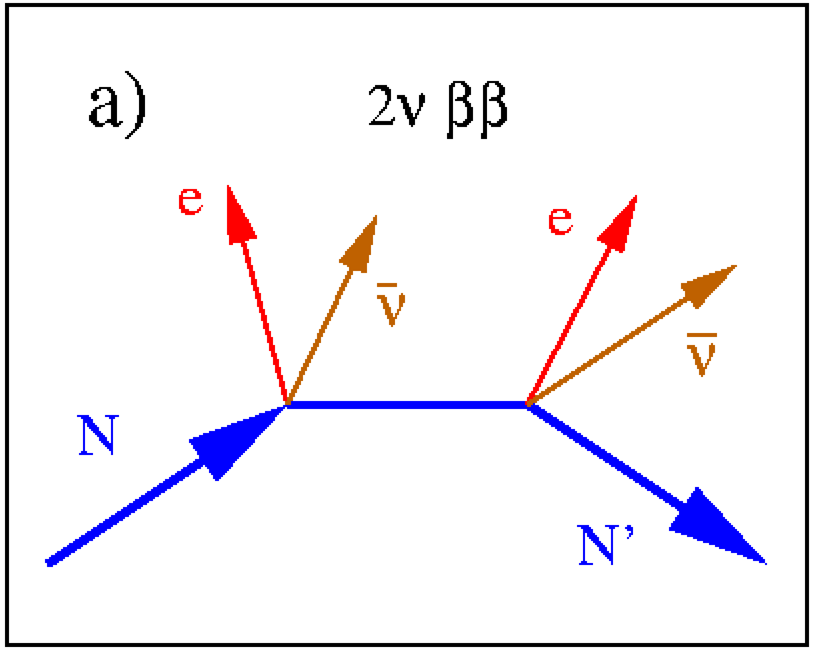
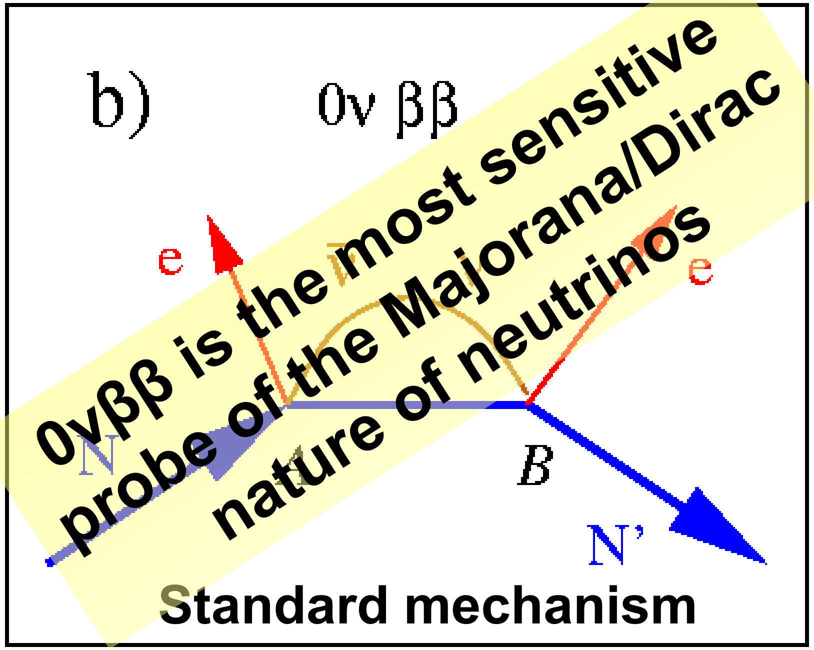
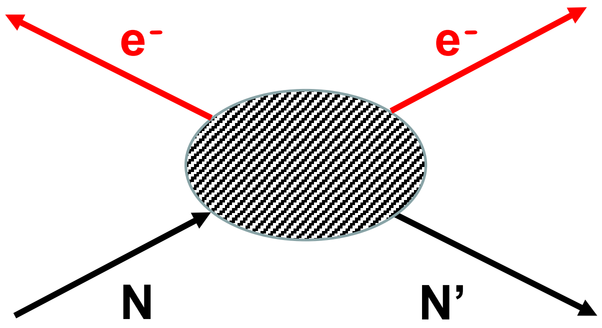




0νββ is the most sensitive probe of the Majorana/Dirac nature of neutrinos

“Black box” theorem*: “$0\nu\beta\beta$ decay always implies new physics”

* J. Schechter, and J. W. F. Valle, Phys. Rev. D25, 2951 (1982).



Discovery potential complementary with colliders

- ➔ **Majorana neutrinos: a new window into quantum physics**
- ➔ **Lepton number violation**
- ➔ **Probe new mass mechanism up to the GUT scale**
- ➔ **Probe key ingredient in generating cosmic baryon asymmetry**

The connection to neutrino masses is trickier and involves a number of uncertainties on the mechanism and nuclear physics

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$ can be calculated within particular nuclear models

$G^{0\nu\beta\beta}$ a known phasespace factor

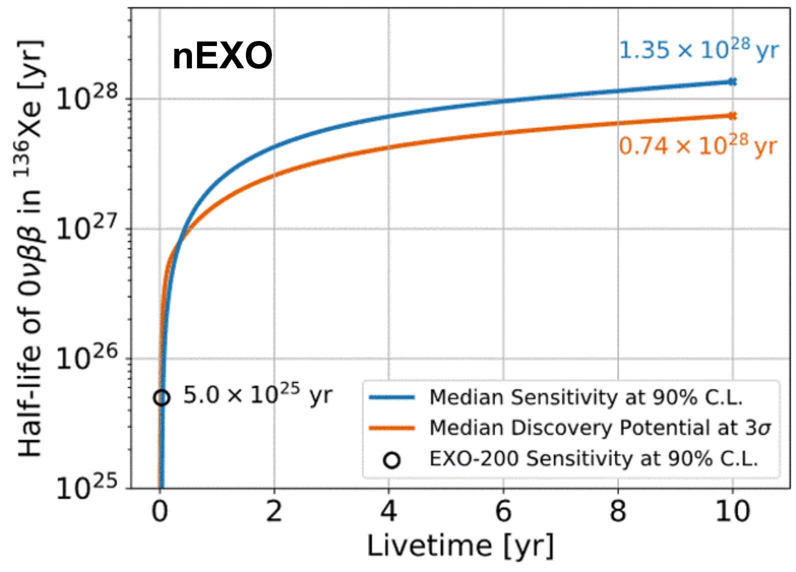
$T_{1/2}^{0\nu\beta\beta}$ is the quantity to be measured

$$\langle m_\nu \rangle = \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \; \varepsilon_i$$

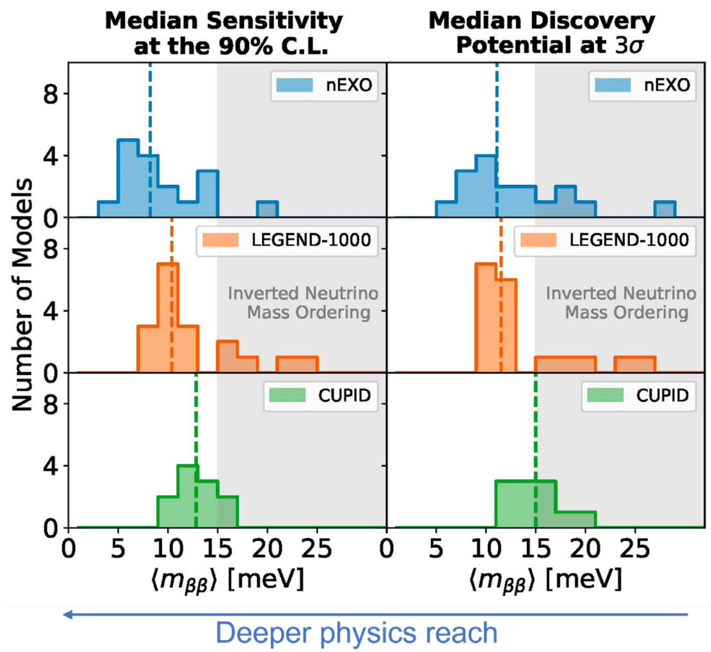
is the effective Majorana ν mass ($\varepsilon_i = \pm 1$ if CP is conserved)

On half lives and
Majorana neutrino masses

Examples

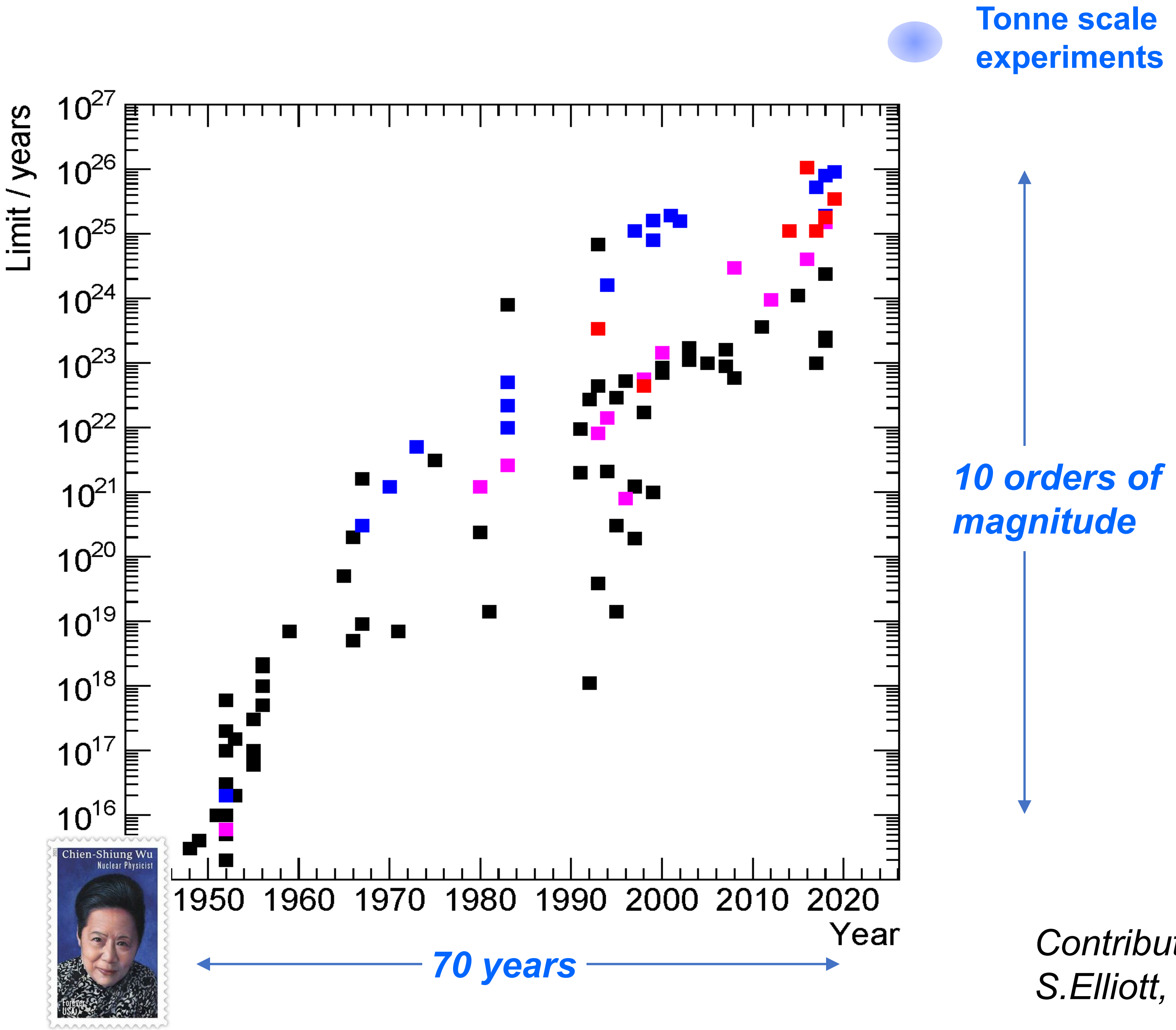


- The discovery potential comes from the half life sensitivity, without uncertainties of theoretical nature.
  ➔ ***Like the sensitivity to ever smaller cross section for a new physics channel at a collider***



- The comparison among different isotopes has to go through Majorana masses and hence involves some theory uncertainties (both because of nuclear physics and because we do not know what physics produces the decay).

A vague but startling measure of progress of the field



Contributions from
S.Elliott, A.Piepke and the PDG

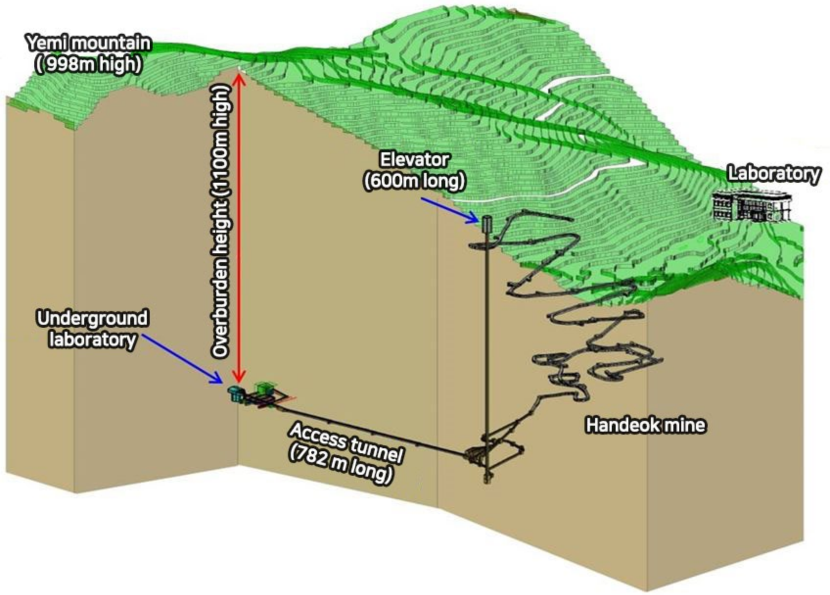
Four fundamental requirements for modern experiments:

1) Isotopic enrichment of the source material (that is generally also the detector)

100kg – class experiment running or completed. Ton – class experiments under planning.

2) Underground location to shield cosmic-ray induced background

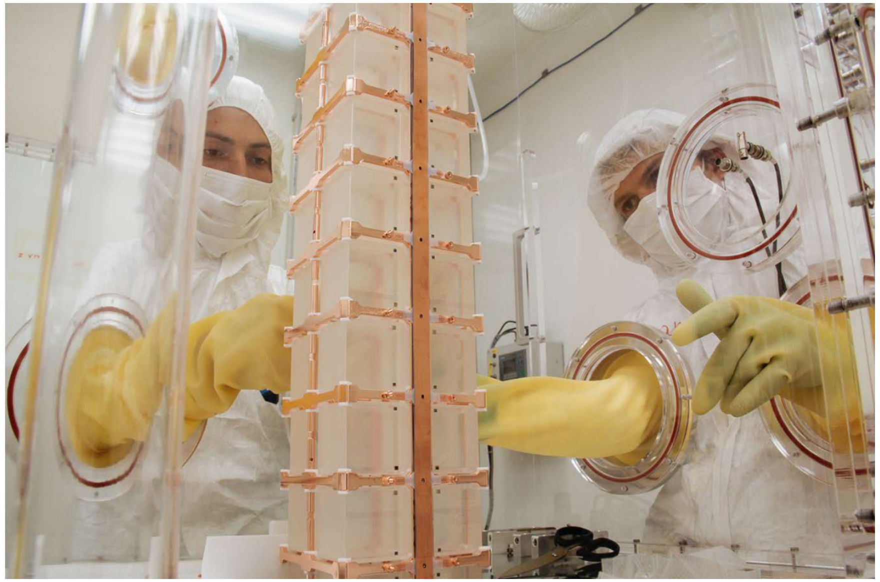
Several underground labs around the world, next round of experiments 1-2 km deep.



Four fundamental requirements for modern experiments:

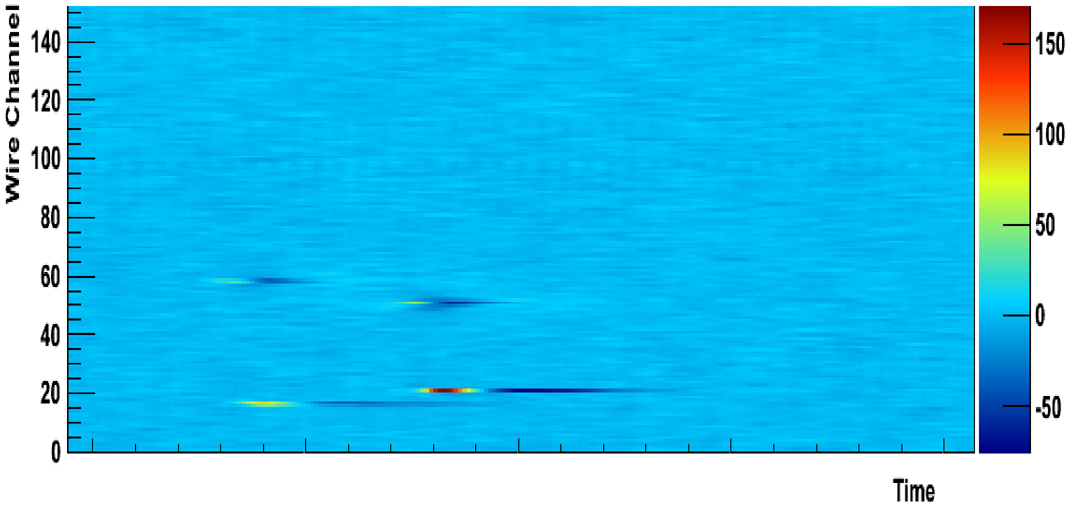
3) Ultra-low radioactive contamination for detector construction components

Materials used ≈< 10^{-15} in U, Th
(U, Th in the earth crust ~ppm)



4) New techniques to discriminate signal from background

Non trivial for E~1MeV.
- *Signal ($2e^-$) more localized than most background.*
- *Good E resolution helps.*
- *Low density shows the two e^- tracks but hard for large fiducial masses.*
- *In some cases final state ID may be possible.*



One (my own) possible classification of technologies

Low density trackers
- NEXT (^{136}Xe gas TPC)
- SuperNEMO (foils and gas tracking, ^{82}Se)
  - Pros: Superb topological information
  - Cons: Very large size

Liquid (organic) scintillators
- KamLAND-ZEN (^{136}Xe)
- SNO+ (^{130}Te)
  - Pros: "simple", large detectors exist
  - Cons: Not very specific, poor energy resolution (2νββ background)

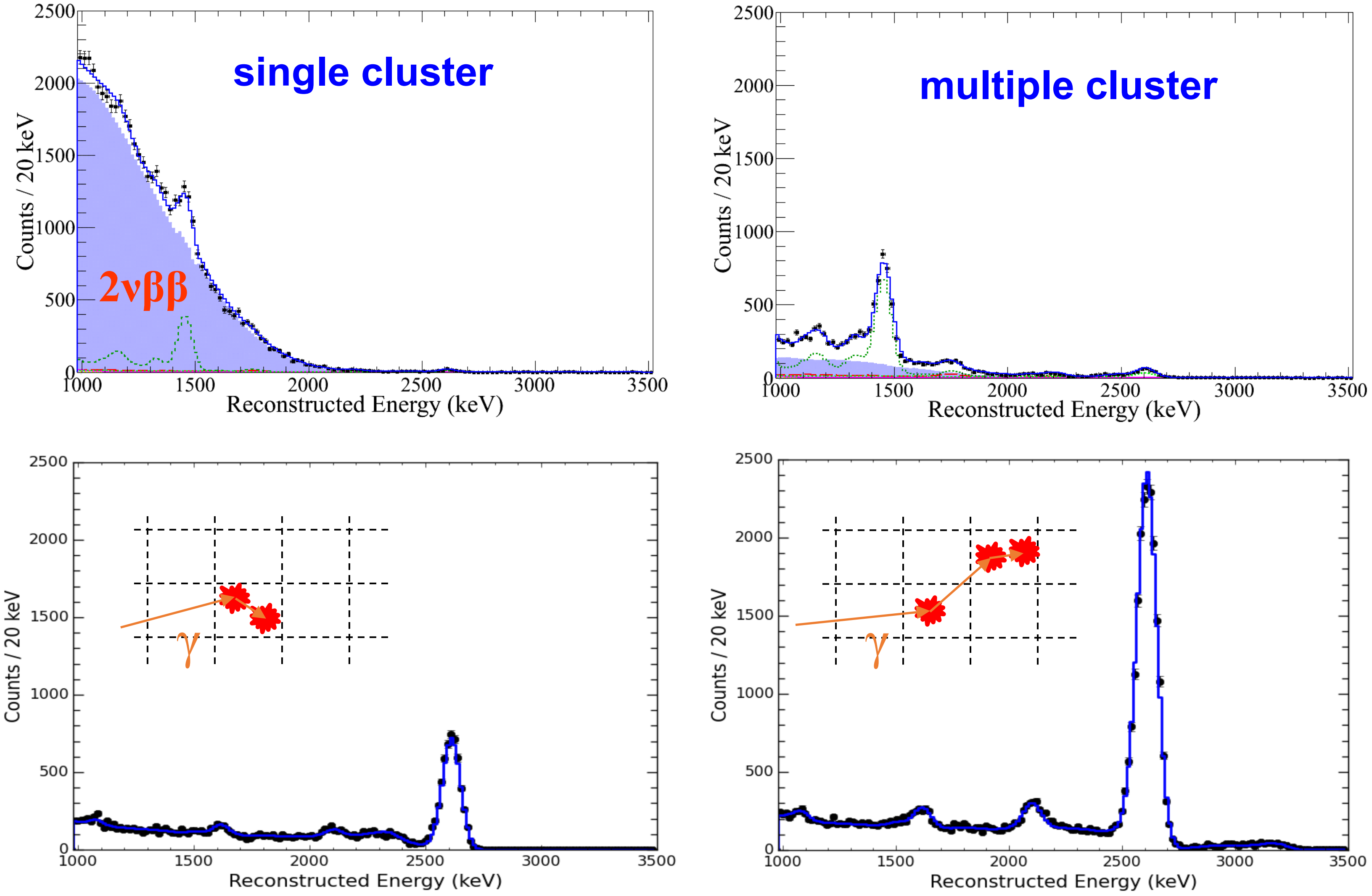
Crystals
- LEGEND, GERDA, Majorana (^{76}Ge)
- CUORE (^{130}Te), CUPID, AMORE (^{100}Mo)
  - Pros: Superb energy resolution, possibly 2-parameter measurement
  - Cons: Intrinsically segmented

Liquid TPC
- nEXO (^{136}Xe)
  - Pros: Homogeneous with good E resolution and topology
  - Cons: Does not excel in any single parameter

Using event multiplicity to recognize backgrounds

Low background data

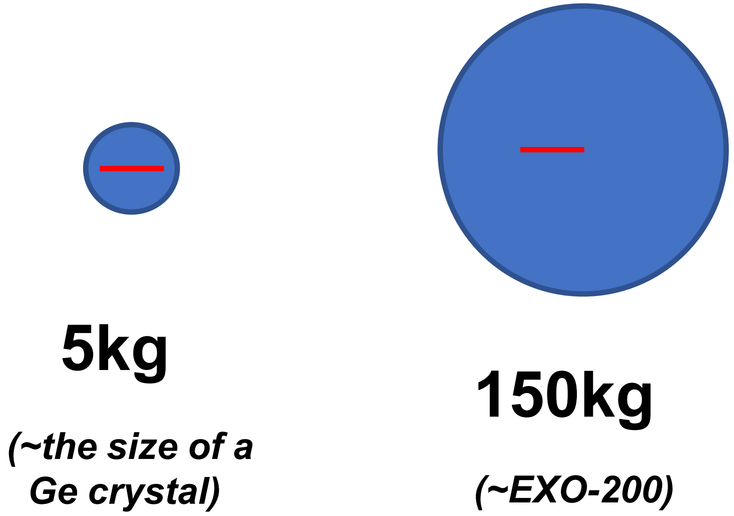
^{228}Th calibration source

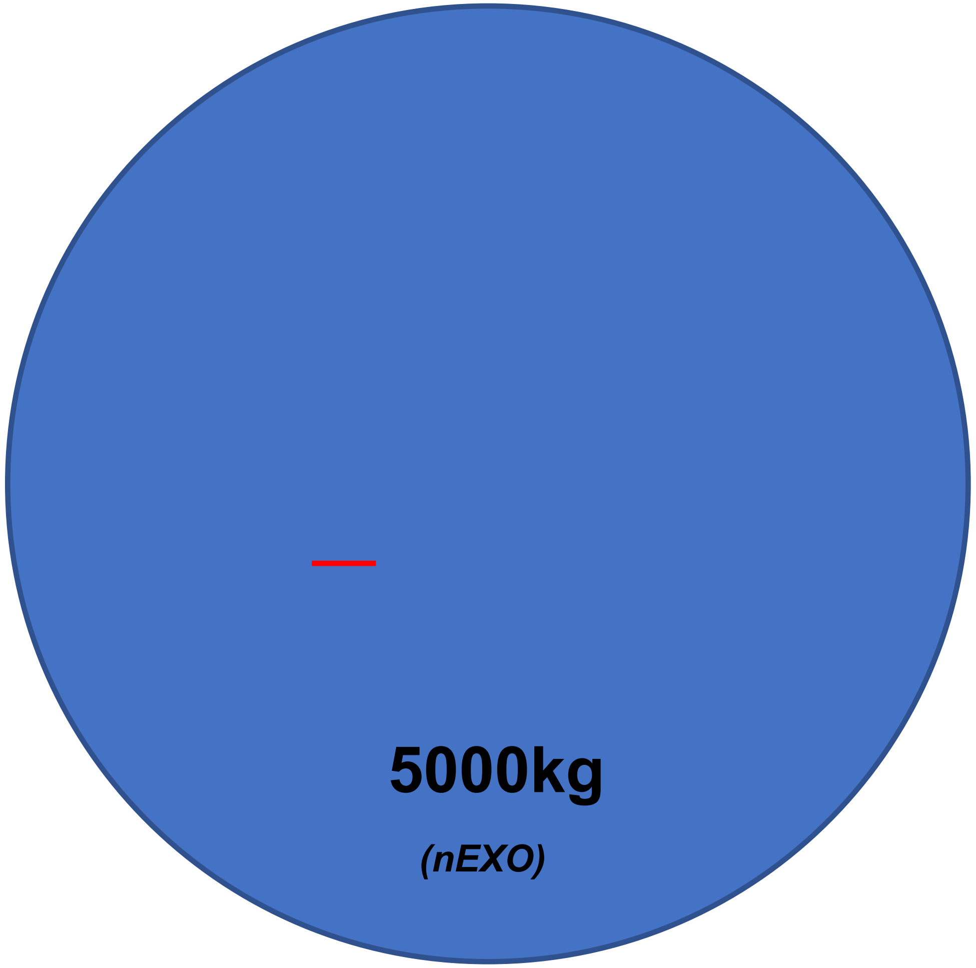


Monolithic/Homogeneous

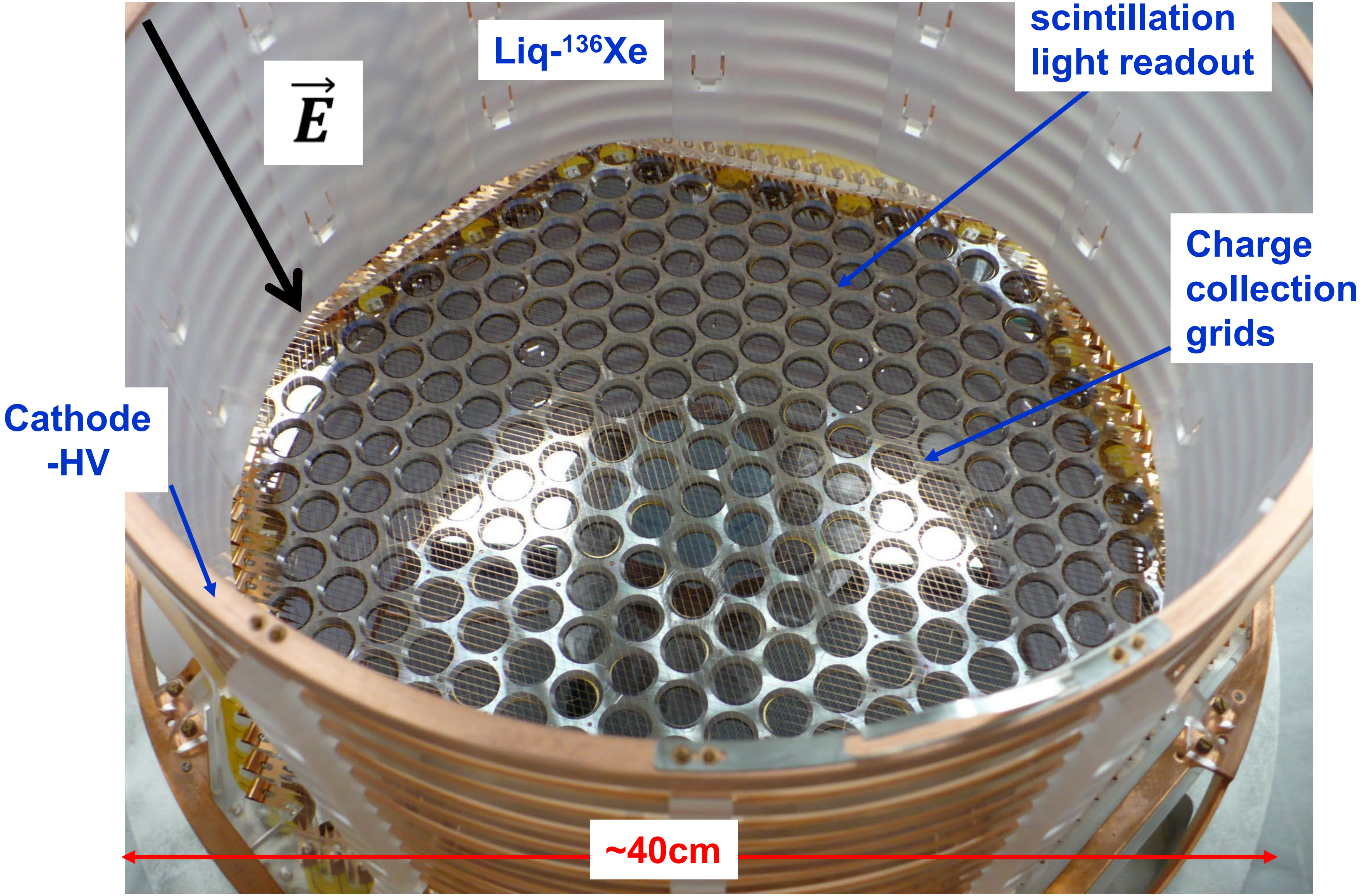
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5 MeV γ attenuation length 8.7cm = —

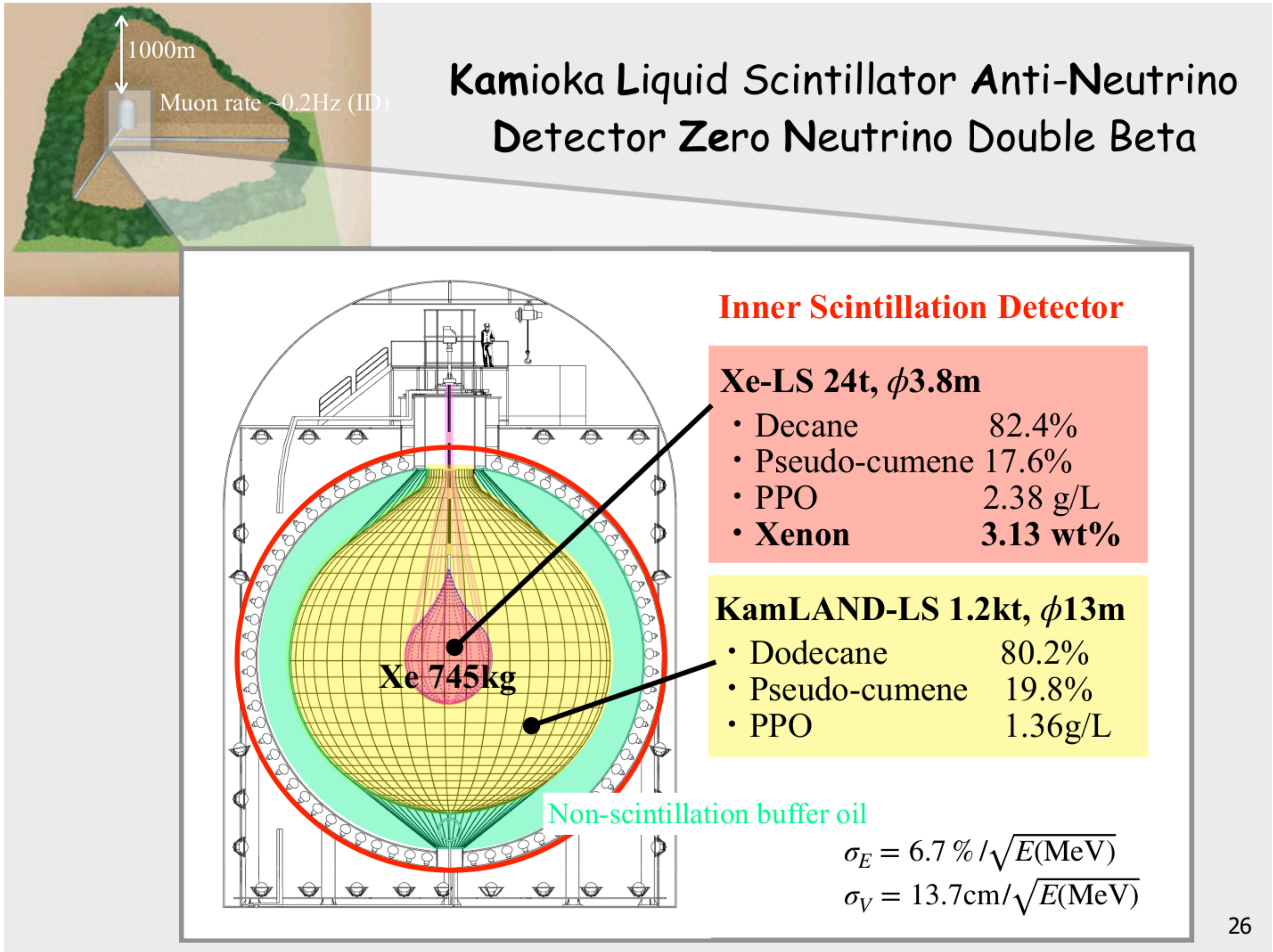




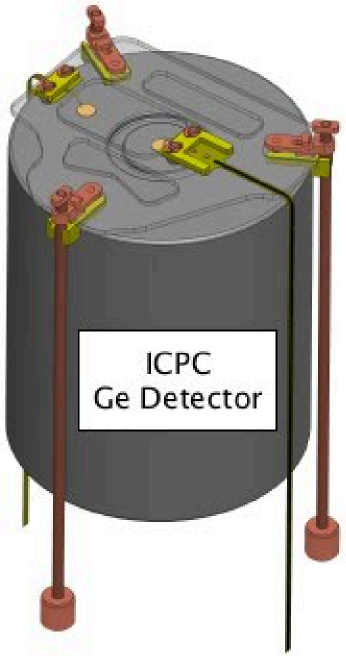
TPCs can do full 3D reconstruction + energy measurement in a bulk material



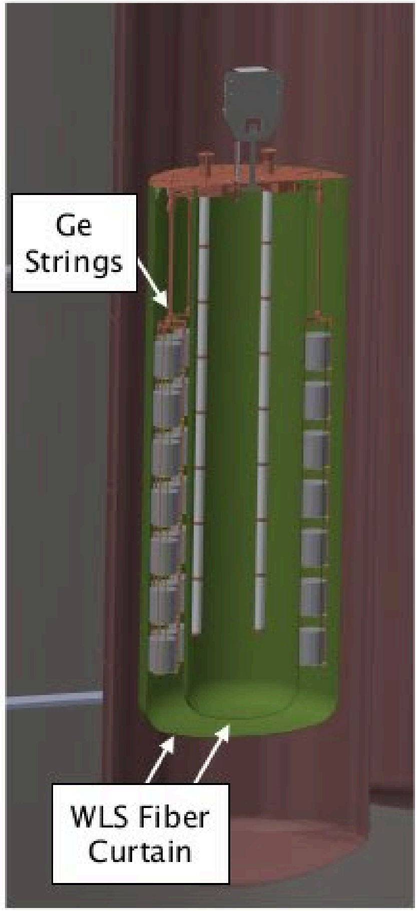
Very large scintillation detectors also offer homogeneous volume, but
- not as good energy and topological reconstruction, dilute source
- really extreme volume and self shielding

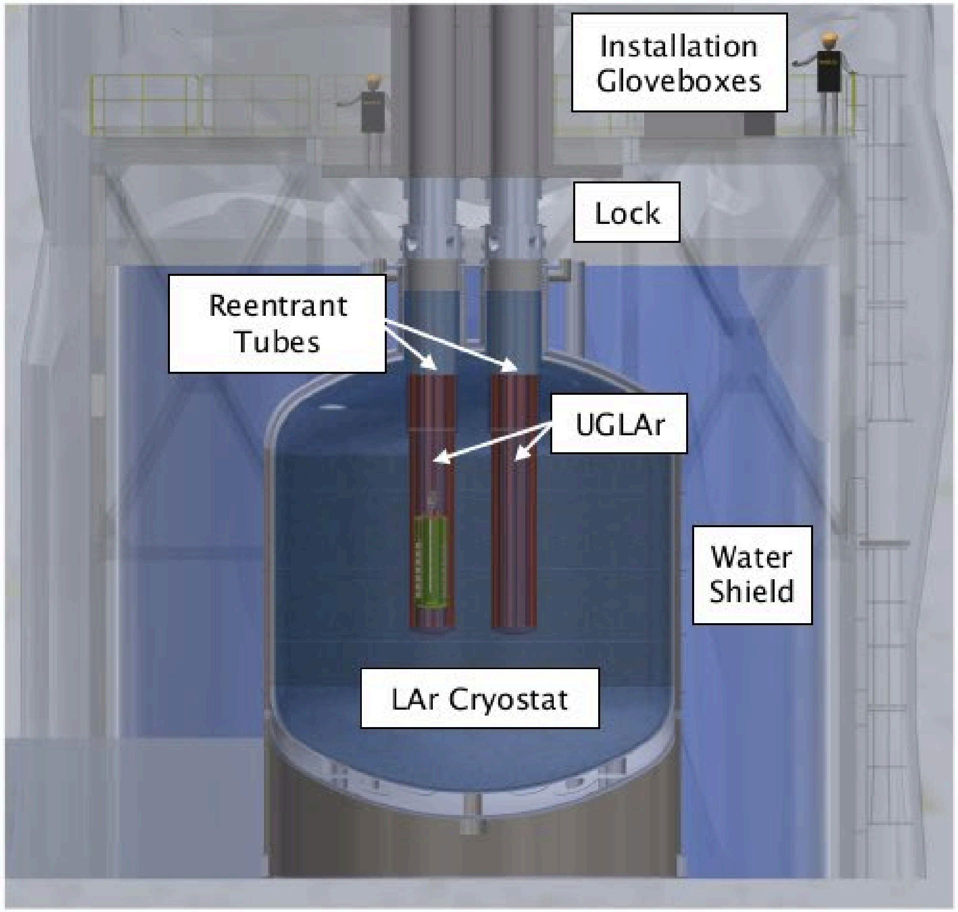


Ge detectors unavoidably distribute some inactive material in between crystals however, they have superb energy resolution (σ<0.1% @ Q-value)



ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar





Example: LEGEND

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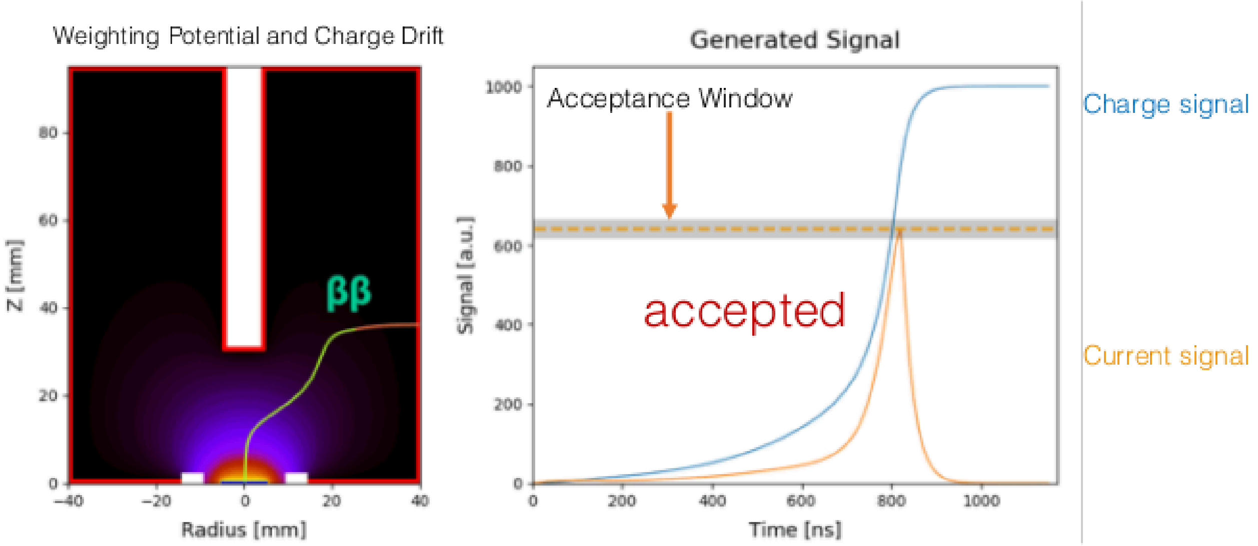
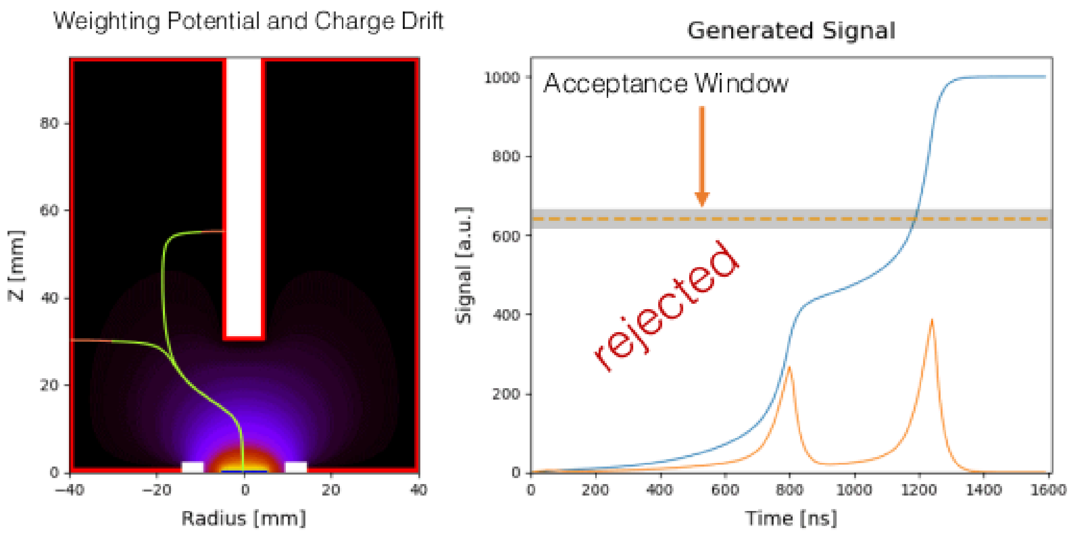
Even in Ge detectors some single-sete-multi-site discrimination is possible

0νββ signal candidate (single-site)



γ-background (multi-site)



Also highly efficient suppression of surface events

Example: LEGEND

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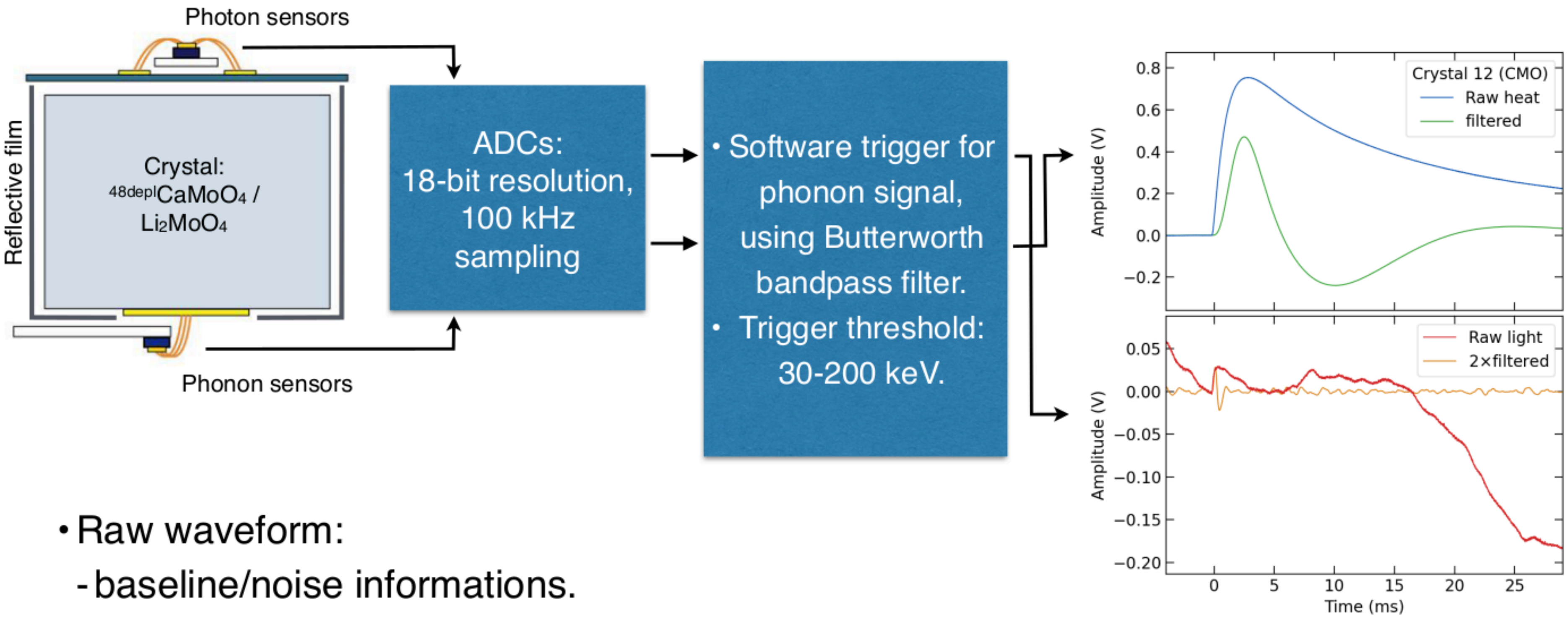
Different strategy for bolometric detectors: Phonons and Scintillation readout



- Raw waveform:
  - baseline/noise informations.
  - timings (rise/fall): pulse shape discrimination (PSD).
- Reconstruction for improving energy resolution and β/α discrimination power (DP):
  - Butterworth bandpass filter— mainly for noise suppression:
    - pulse amplitude: pulse height or a least square fit to the template signal.
  - Stabilization heater signal every 10 seconds for gain drift corrections.

Example: AMORE

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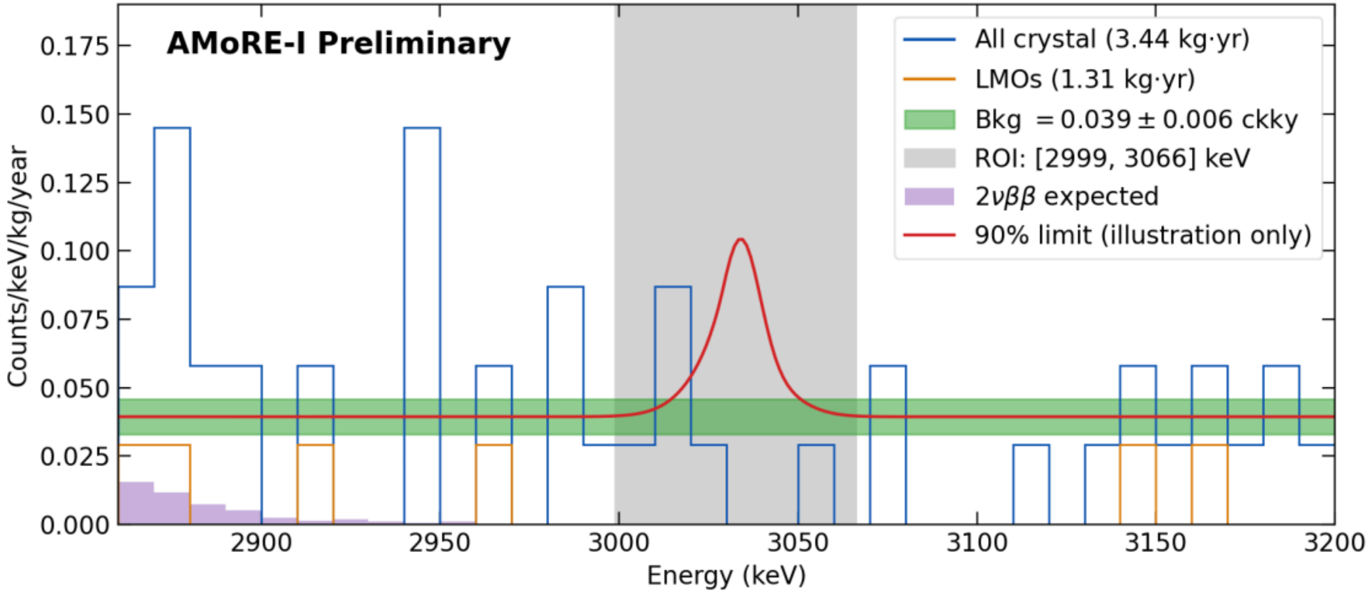
Since we are at the dedication of Yemilab…

Preliminary 0νββ limit from AMoRE-I



- ROI to contain most (> 99%) of the $0\nu\beta\beta$ signal peak, $\varepsilon_{containment} \sim 81\%$.
- Background = 0.039 ± 0.006 counts/keV/kg/year, from ROI side-band.
- Combining the result of counting analysis at ROI, with a flat background constraint from the side-band events for each crystal.
- $T^{0\nu}_{1/2} > 1.2\times10^{24}$ years at 90% CL.

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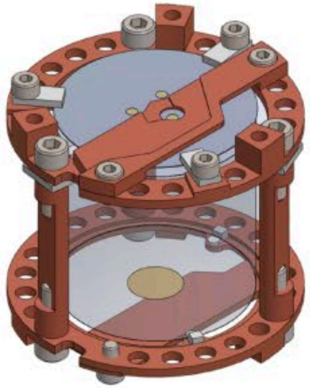
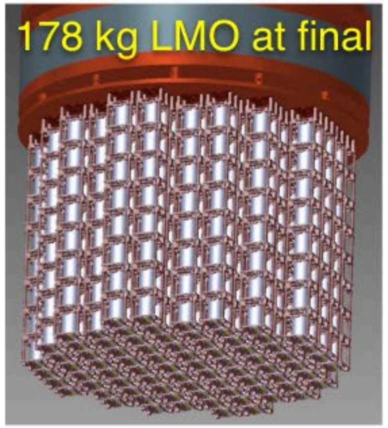
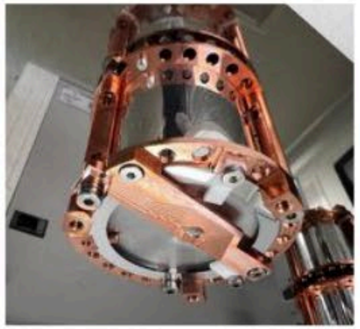
AMoRE-II in preparation

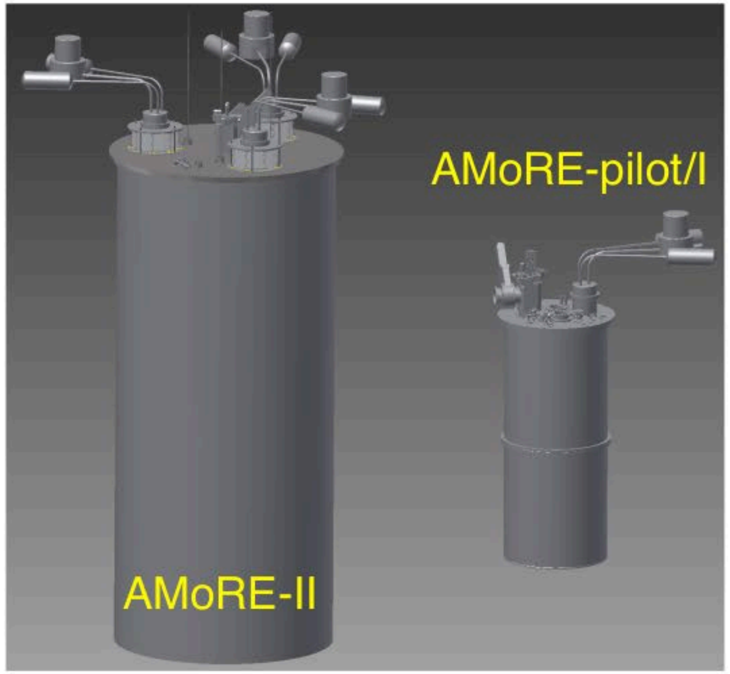
AMoRE-II
Detector module







90 modules (~27 kg LMO)
for the first stage



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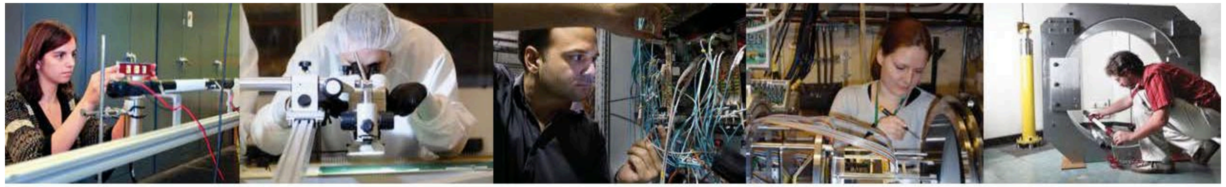
To end…
Some views from the US



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

"RECOMMENDATION II
The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.
We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

Initiative B
"We recommend vigorous detector and accelerator R&D in support of the neutrinoless double beta decay program and the EIC."

A healthy neutrinoless double-beta decay program requires several isotopes.

This is because:

- ***Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities***
- ***Different isotopes correspond to vastly different experimental techniques***
- ***2 neutrino background is different for various isotopes***
- ***Disentangling nucl. Matrix element effects from the mechanism producing the decay requires the analysis of more than one isotope***

After extensive reviews, DoE-NP is intentioned to fund at a substantial level a 5-tonne nEXO, a 1-tonne LEGEND, and the smaller CUPID.

Indeed, initial funding towards CD-1 is being provided now.

International participations in these experiment is already happening, but there is great interest in boosting this aspect, to maximize timely completion of the three experiments.

Conclusions

- **Neutrinoless double-beta decay is discovery science, indeed, I would claim is the most likely area for a big discovery in the neutrino sector.**
- **Detectors have reached impressive sophistication with more than one isotope/technology.**
- **Many ideas, but also a few well-proven technologies capable of scaling to the tonne scale.**
- **Size and cost require the international coordination that is typical of colliders and other large projects.**