Double Beta Decay
What if we see it?

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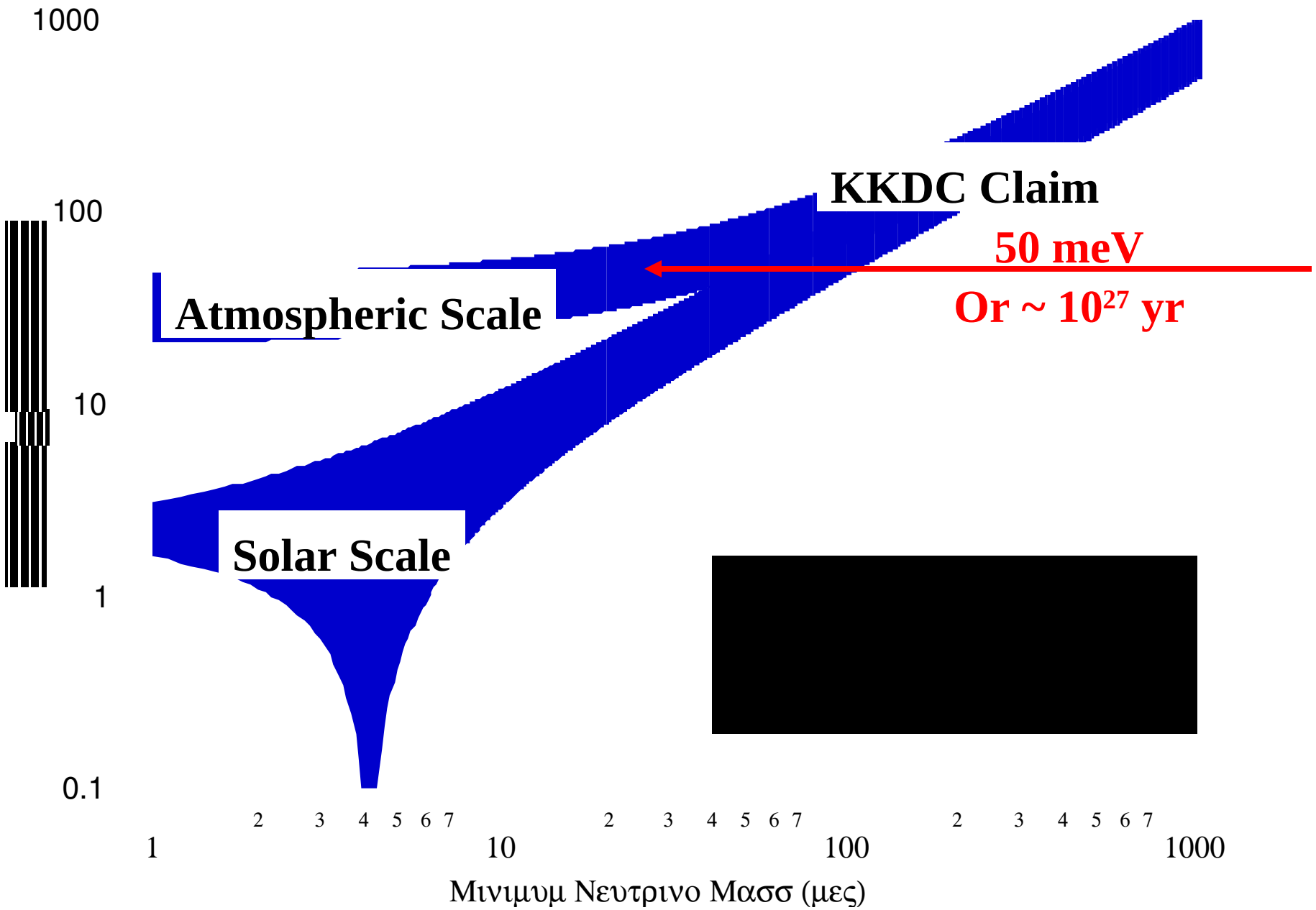
Outline

- Physics/Technical Goals
- Experimental Uncertainties
- NEMO/SuperNEMO
  - Sean Sutton had to cancel.
  - Sasha Barabash is here for discussion


1000
100
10
1
0.1
KKDC Claim
50 meV
Or ~ 10^27 yr
Atmospheric Scale
Solar Scale
1
2 3 4 5 6 7
10
2 3 4 5 6 7
100
2 3 4 5 6 7
1000
Μινιμυμ Νευτρινο Μασσ (μες)

APS Study and M-180

The APS neutrino study on the future US Neutrino Program made a few things clear. **(http://www.aps.org/neutrino/)**

- **Double-beta decay as one of the highest priorities.**
- **It recommends a staged approach beginning with 100-200 kg scaling later to 1 ton.**
  - **Precision measurement at degenerate scale**
  - **Followed by discovery potential at atmospheric scale**

Begs the questions:

Why precision measurements?

What is required to approach the atmospheric scale?

What about the solar scale?

Why a precision measurement?

If $<m_{\beta\beta}>$ is near the degenerate scale:

- We will want to compare results from several isotopes to fully understand the underlying physics.
- A 10-20% decay rate measurement will allow effective comparisons between isotopes, when the matrix element uncertainty nears ~50%.

M^2 Comparison: $\tau^{-1} = GM^2 \langle m_\nu \rangle^2$

Isotope	Shell Model	Rodin *et al.*	Civitarese & Suhonen
^{48}Ca	0.5		
^{76}Ge	2.1	5.8	11.1
^{82}Se	4.5	4.5	11.8
^{96}Zr		0.1	12.6
^{100}Mo		1.3	8.8
^{116}Cd		2.0	14.1
^{128}Te	1.6	2.6	
^{130}Te	1.2	2.2	12.2
^{136}Xe	0.5	1.0	21.5

Differences in QRPA indicate that the two are not calculating the same thing.

It goes beyond the philosophy of selecting g_{pp}.

The implementation still differs. The spread is not a measure of the uncertainty but that different groups are calculating different things.

There is reason to be optimistic that this will be resolved.

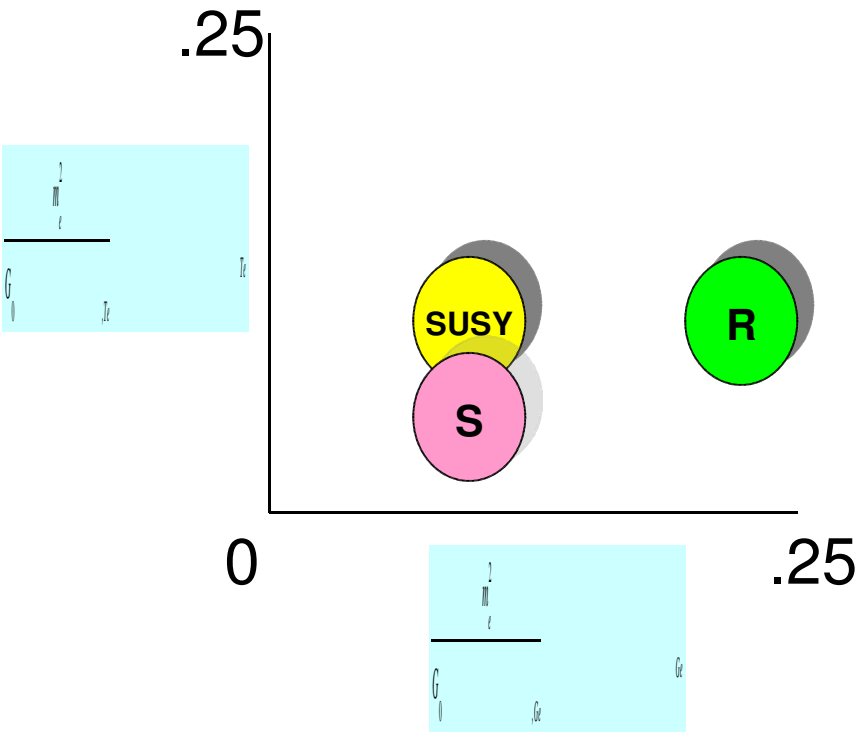
Observation of $\beta\beta(0\nu)$ implies massive Majorana neutrinos, but:

- **Relative rates between isotopes might discern light neutrino exchange and heavy particle exchange as the $\beta\beta$ mechanism.**
- **Relative rates between the ground and excited states might discern light neutrino exchange and right handed current mechanisms.**

Effective comparisons require experimental uncertainties to be small wrt theoretical uncertainties.

Discerning Models

Key ingredient: several isotopes, don't use just ratios



	Ge	Te	Xe	
C	0.4	0.5	0.9	Civitarese Suhonen NPA729, 867
R	0.2	0.1	0.04	Rodin et al. nucl-th/ 0503063
S	0.1	0.05	0.02	Caurier NPA654, 973c
SUSY	0.1	0.1	0.04	Faessler et al. PRD58, 115004

M_ν=200 meV, η =10^{-9}

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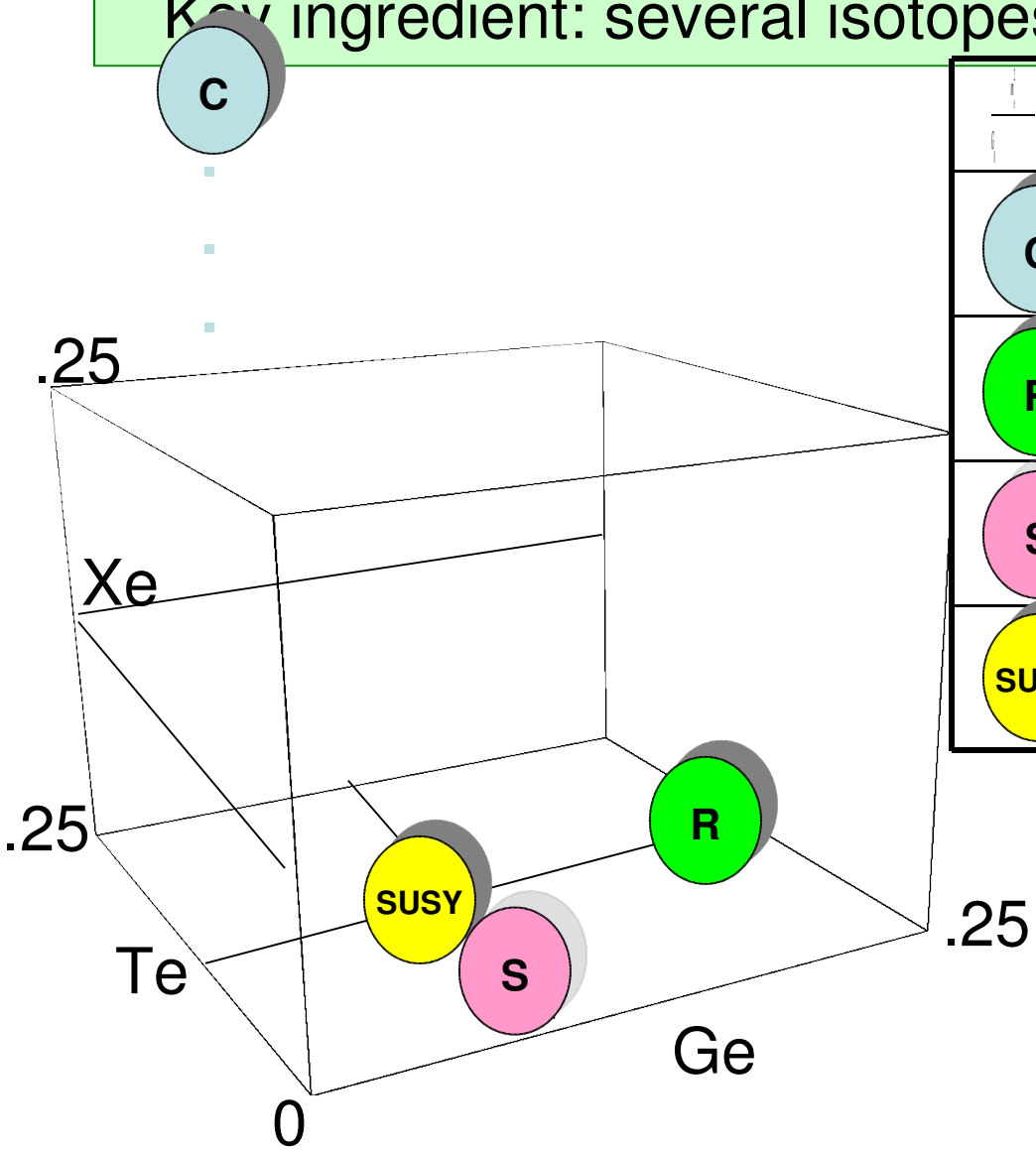

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A 50% uncertainty in these calculations is a good goal.

NuSAG Recommendations

"Recommendation: The Neutrino Scientific Assessment Group recommends that the highest priority for the first phase of a neutrino-less double beta decay program is to support research in two or more neutrino-less double beta decay experiments to explore the region of degenerate neutrino masses ($m_{\beta\beta}$ > 100 meV). The knowledge gained and the technology developed in the first phase should then be used in a second phase to extend the exploration into the inverted hierarchy region of neutrino masses ($m_{\beta\beta}$ > 10–20 meV) with a single experiment."

Three Experiments with significant US involvement were endorsed:

CUORE
EXO
Majorana

Energy Spectrum for the 2 e^-

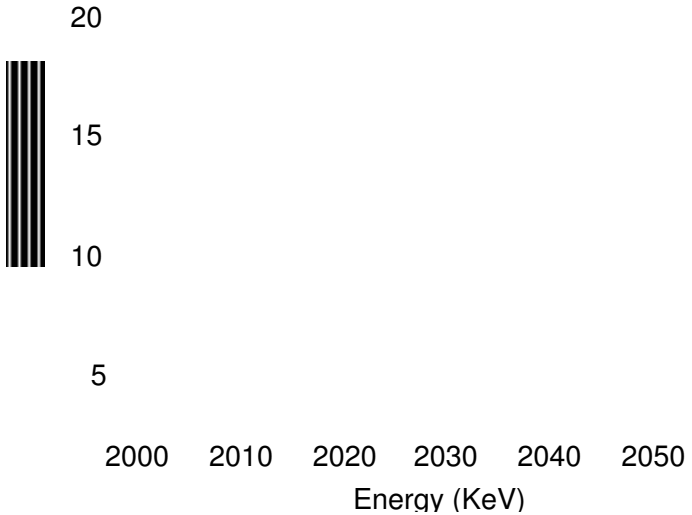
Looking for a rare peak on a continuum. What background levels do we require?

0.0 0.5 1.0 1.5 2.0

Sum Energy for the Two Electrons (MeV)

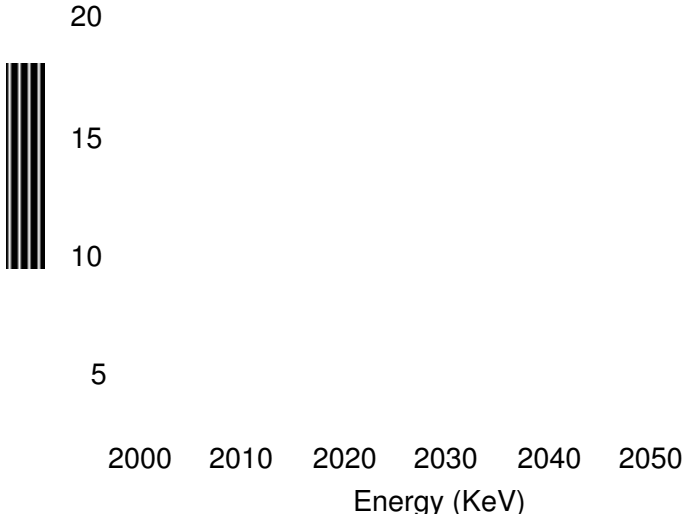
Endpoint Energy

A Recent Example



The "feature" at 2038 keV is arguably present. This will probably require experimental testing.

How can a future experiment produce a convincing case?



Signal:Background ~ 1:1

Calc. done for Ge: Ratio of M.W. required for comparison

Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)
10^{25}	530	400
$5x10^{26}$	10	100
$5x10^{27}$	To reach atmospheric scale need BG on order 1/t-y.	40
10^{29}	0.05	2

- Tl and Bi in materials are the most difficult problems.
- If we reach 1/t-y: Tl and Bi will be eliminated. But a "soup" of low-% contributions will remain. One must consider the large variety of neutron-induced background channels.

Different techniques for different objectives

- Beyond a reasonable doubt: a combination of
  - Correct energy
  - Single-site energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
- Open and shut case: include the following
  - Observe the two-electron nature of the event.
  - Observe the daughter
  - Observe the excited state decay
- Smoking Gun
  - See the process in several isotopes

Discovery vs. Measurement

a future decision point

Did 200-kg expts. find double beta decay

Yes
Is it a precision result

No
Scale up to 1 ton

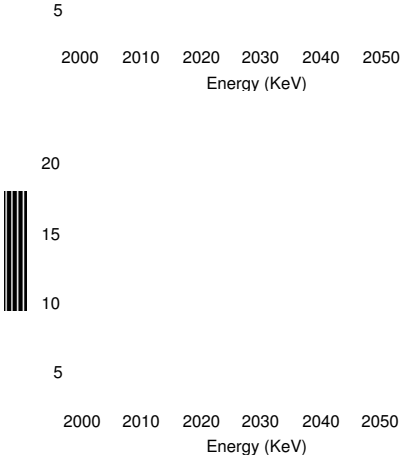
No
Scale up as needed to do precision measurement

Yes
Design new expts to measure statistical dist.

These two goals may conflict. The plan forward is murky at present.

Systematic Uncertainties

Only recently has this become a critical issue for ββ.



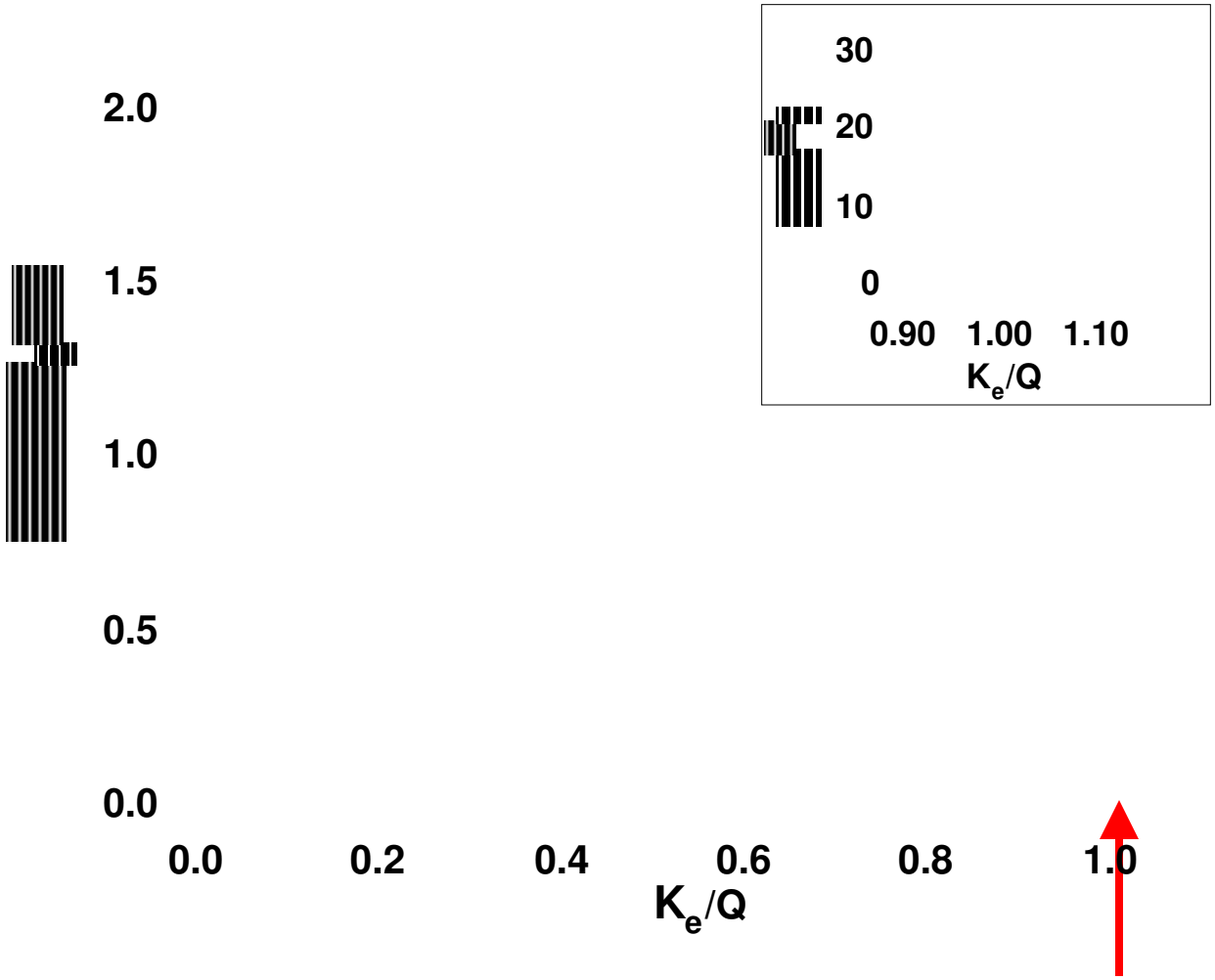
Statistics set the scale.

10^{25} y; 100 kg isotope, about 400 counts/ton-year for 75% eff. 3 t-y, negligible background: ~10% result

- Live Time (Veto, various timing cuts)
  - 1%
- Number of atoms (mass, enrichment, fiducial volume)
  - few %
- Analysis (gain, resolution, event selection)
  - few to maybe 10%, depending on sophistication of cuts.
- Background Model (The KDHK claim is a good test case)
  - small for this fast decay example, can dominate if background peaks have comparable strength to the ββ peak. Especially problematic if the peaks are unidentified.

At the degenerate scale, 20% measurements should be feasible. Hence, comparisons will be powerful when theory is reliable to ~50%.

Energy Spectrum

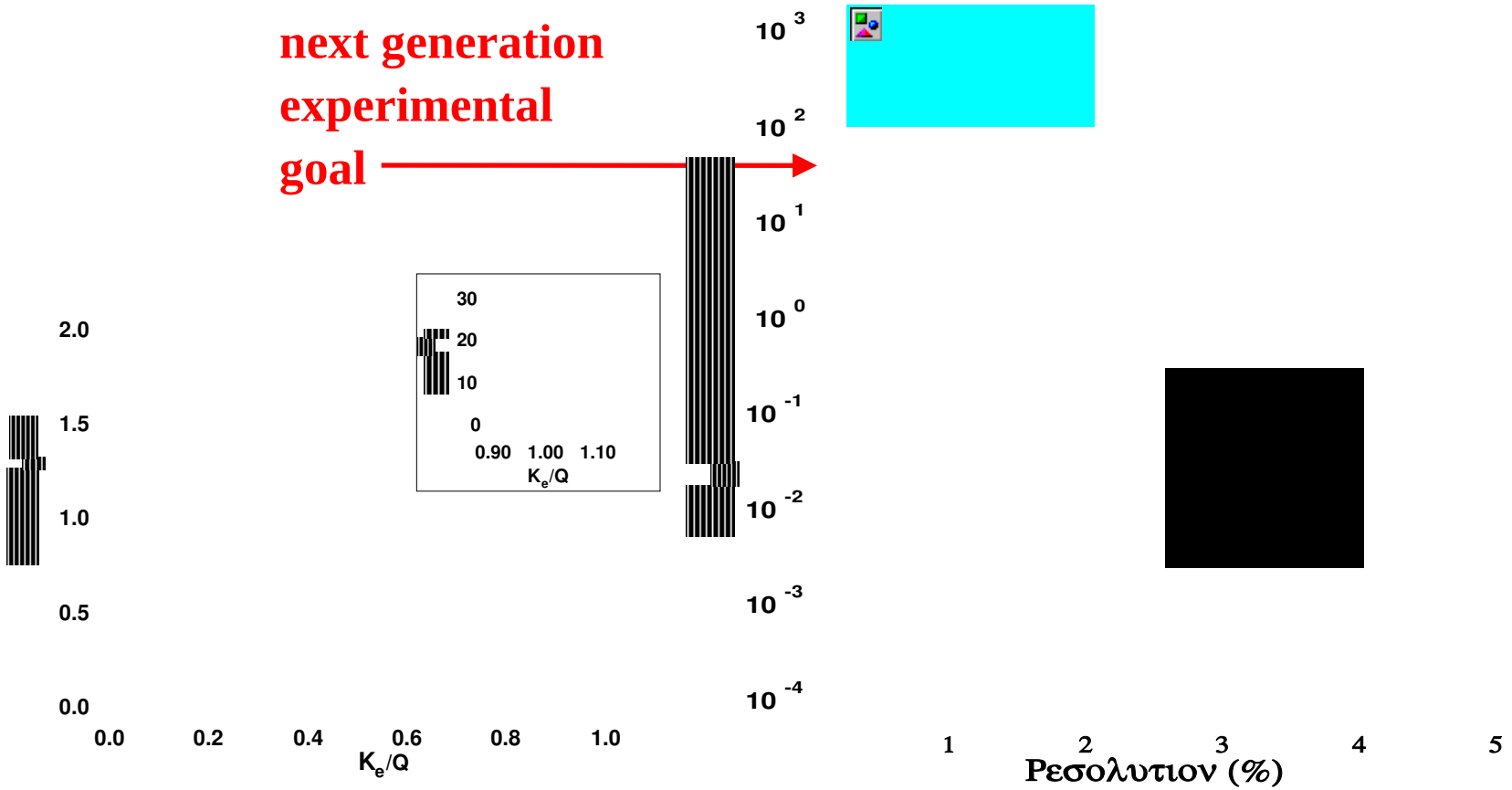


Two-neutrino tail. Won't be a problem.

Background:Signal scales as the resolution. This is an issue.

ββ(2ν) as a Background.

Sum Energy Cut Only, Gaussian peak shape



Resolution: Peak Shapes

Parameters	Shape	Fraction of $\beta\beta(2\nu)$ in ROI
2% resol.	Pure Gaussian	3×10^{-9}
2% resol.	B-W	2×10^{-5}
2% resol. 0.1 tail norm. 0.1 exp scale	Gauss+ Exp Tail	4×10^{-8}

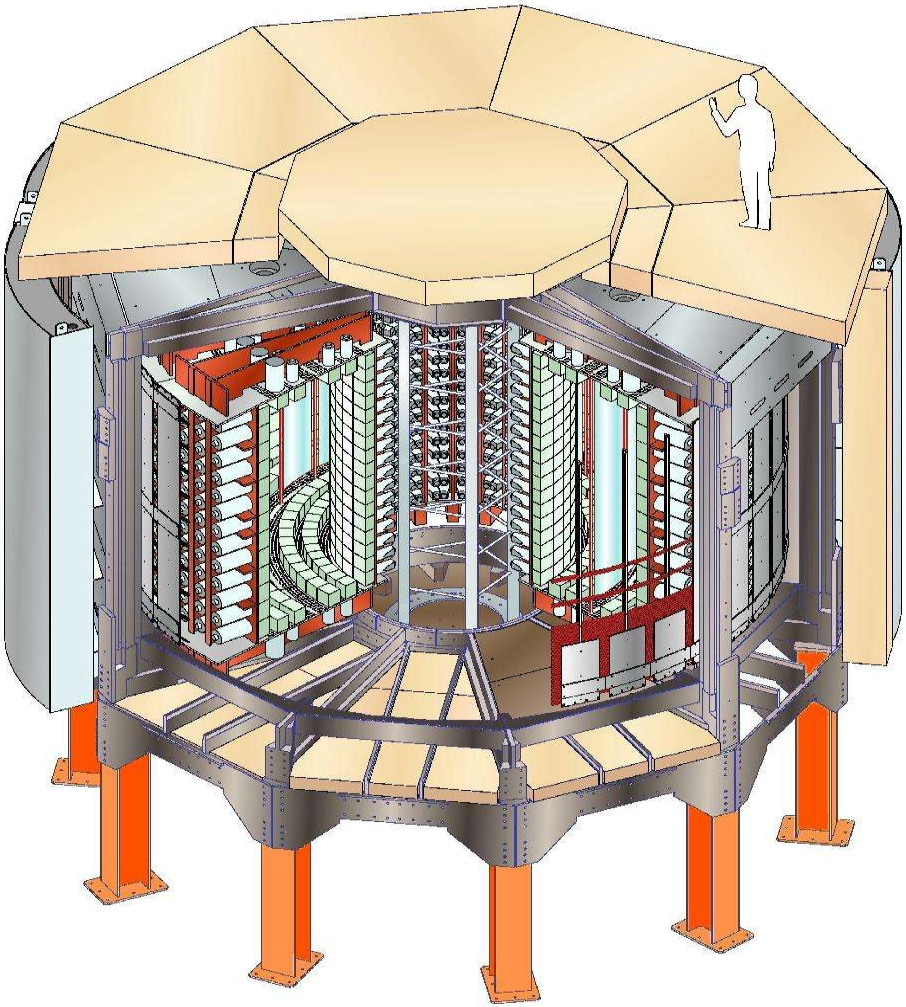
2025 2030 2035 2040 2045 2050 2055

Energy (keV)

Shouldn't be a problem for ~200-kg experiments, but peak shape should be understood.

The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.



Source: 10 kg of ββ isotopes

cylindrical, S = 20 m², 60 mg/cm²

Tracking detector:

drift wire chamber operating in Geiger mode (6180 cells)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

Calorimeter:

1940 plastic scintillators coupled to low radioactivity PMTs

Magnetic field: 25 Gauss

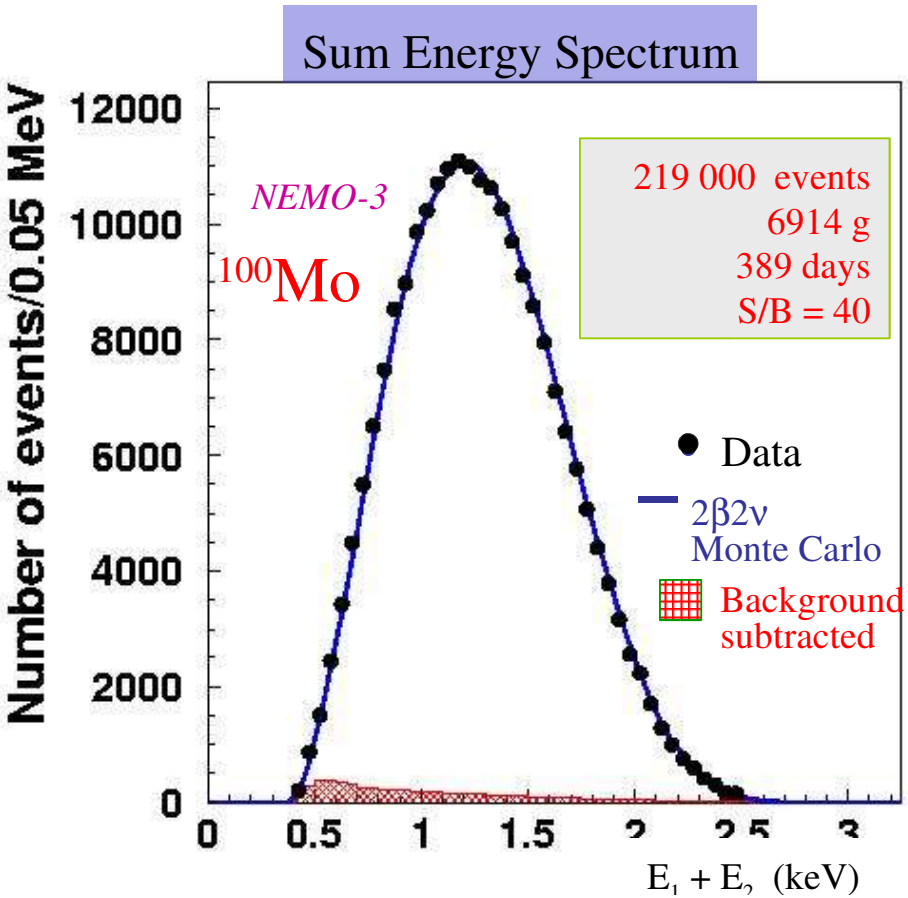
Gamma shield: Pure Iron (18 cm)

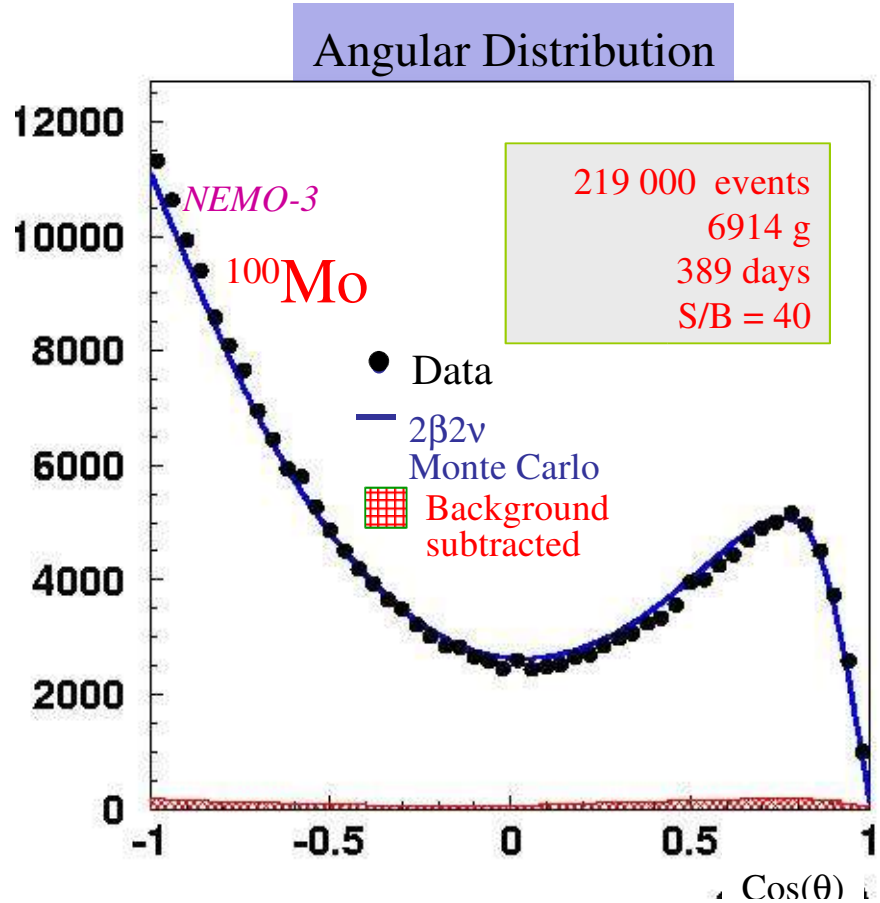
Neutron shield: borated water + Wood

Background: natural radioactivity, mainly ^{214}Bi et ^{208}Tl (γ 2.6 MeV)
Radon, neutrons (n,γ), muons, $\beta\beta(2\nu)$

^{100}Mo 2β2ν results

Data Phase I Feb. 2003 – Dec. 2004)





$T_{1/2}(\beta\beta2\nu) = 7.11 \pm 0.02\ (\text{stat}) \pm 0.54\ (\text{syst}) \times 10^{18}$ y

ββ factory with very high signal/bkg ratio → New tools for precision test

For example: Bosonic nature of the neutrino

(Dolgov and Smirnov, Phys. Lett. B621, 2005, 1-10)

SuperNEMO preliminary design

Plane and modular geometry: ~5 kg of enriched isotope per module

1 module: Source (40 mg/cm2) 4 x 3 m^2

Tracking volume: drift wire chamber in Geiger mode, ~ 3000 cells

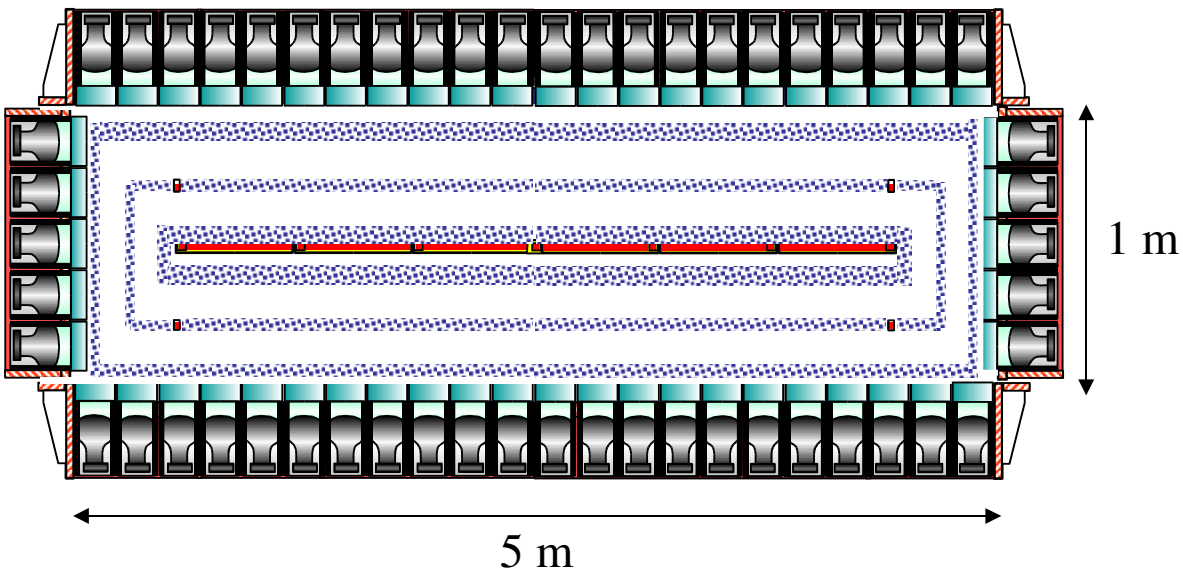
Calorimeter: scintillators + PMTs

20 modules: 100 kg of enriched isotope

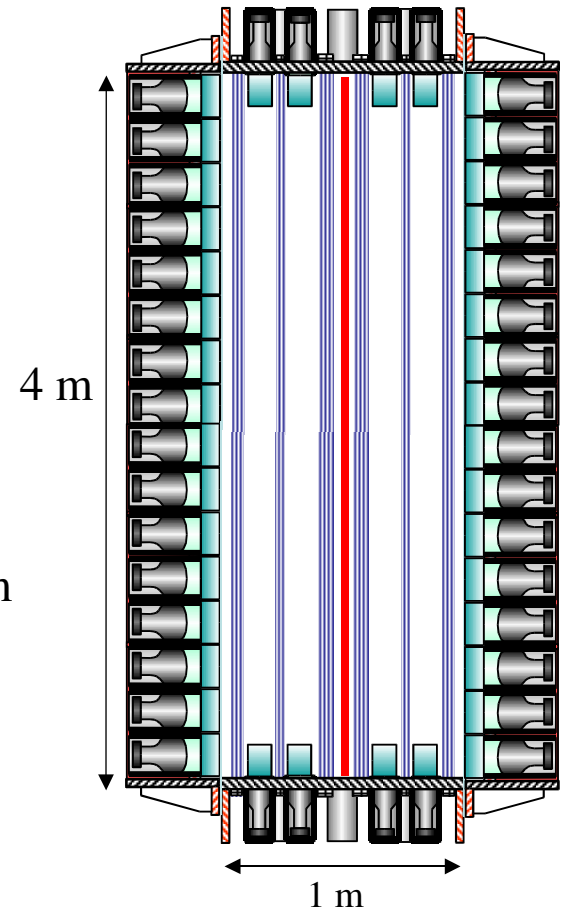
~ 60 000 channels for drift chamber

~ 20 000 PMT if scint. block

~ 2 000 PMT if scint. bars



Top view



Side view

My Opinions: Not necessarily universally held

- **Ratios of matrix element calc. are ambiguous.**
  - **need 3 or more measurements**
  - **compare absolute values along with ratios.**
- **Need measurements with a total uncertainty of ~20% or less.**
- **The theory groups need to define a program to demonstrate that QRPA gets "one" answer.**
  - **Need theory precise to about ~50%.**
- **There may be "branch point" in the technological focus of experiments on the horizon: Will process be observed at degenerate scale?**
  - **Discovery versus investigation**

Conclusions: more generally held

- We can do it!
  - The technology is ready for atmospheric scale sensitivity
- The community wants us to do it!
  - Endorsed by the APS study and NuSAG
- Double beta decay experiments will have a significant impact on our understanding of the neutrino!
  - Even null results will be interesting.