The ββ Experimental Program

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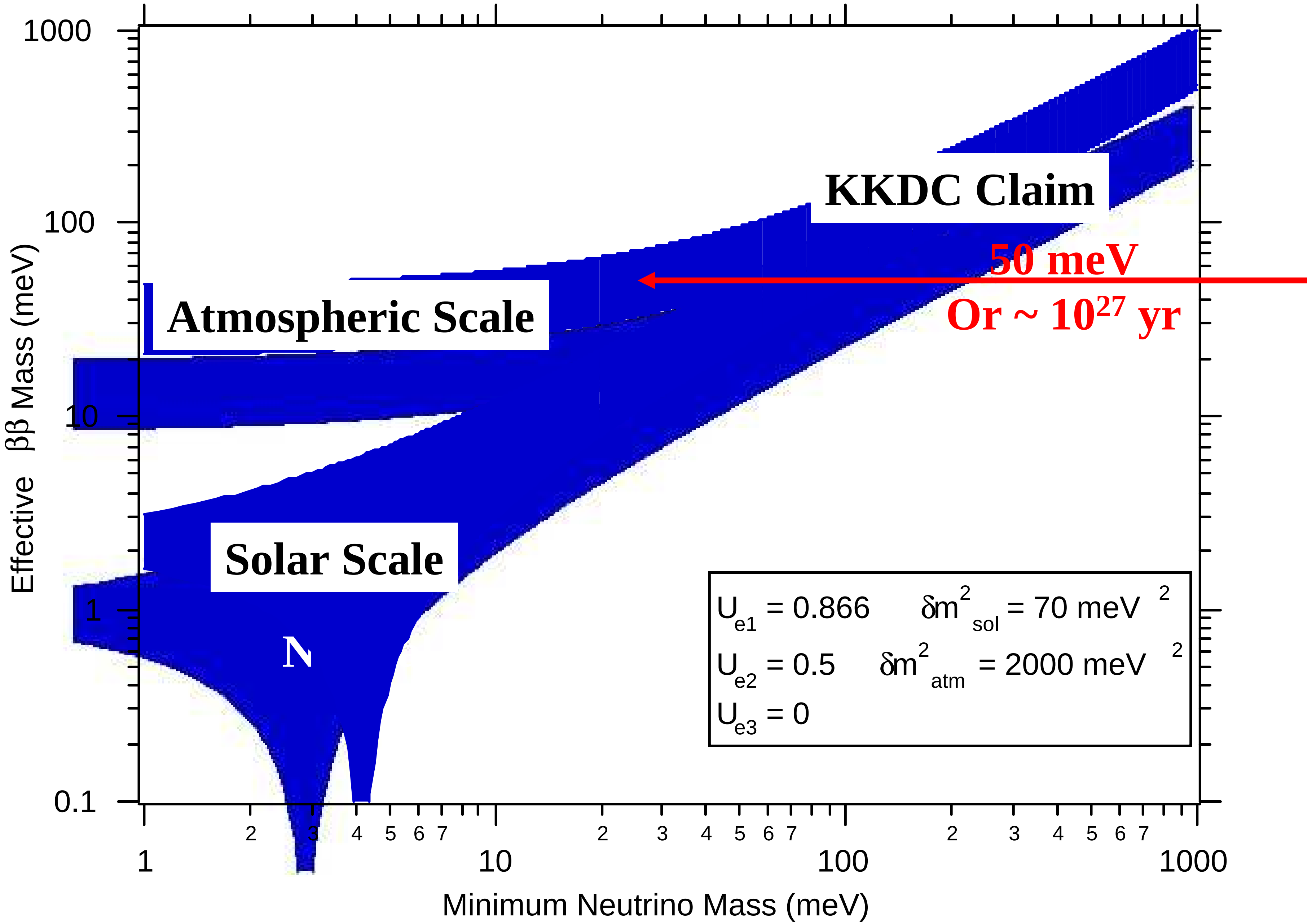
An exciting experimental program

- **Experimental techniques**
- **General requirements**
- **Discovery vs. measurement**
- **Backgrounds**
- **Required number of measurements and their precision**
- **Various other measurements pertinent to ββ**
- **Some words about matrix elements**

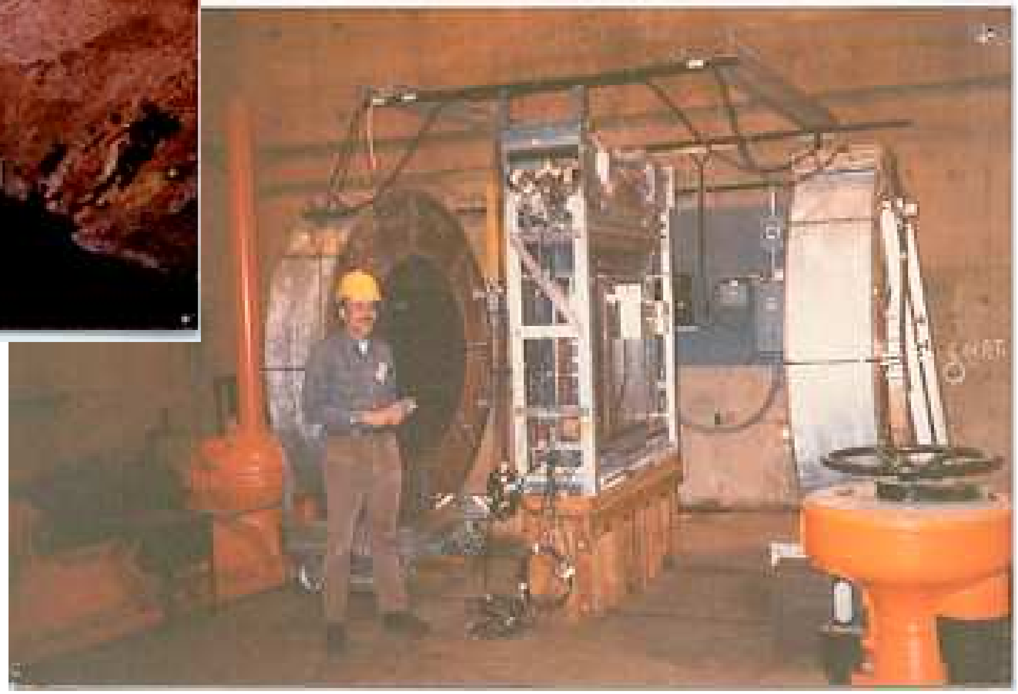
If we see ββ, the qualitative physics results are profound, but next we'll want to quantify the underlying physics.



1000
100
10
1
0.1
Effective ββ Mass (meV)
Atmospheric Scale
KKDC Claim
50 meV
Or ~ 10^27 yr
Solar Scale
N
U_e1 = 0.866 δm^2_sol = 70 meV^2
U_e2 = 0.5 δm^2_atm = 2000 meV^2
U_e3 = 0
1
10
100
1000
Minimum Neutrino Mass (meV)

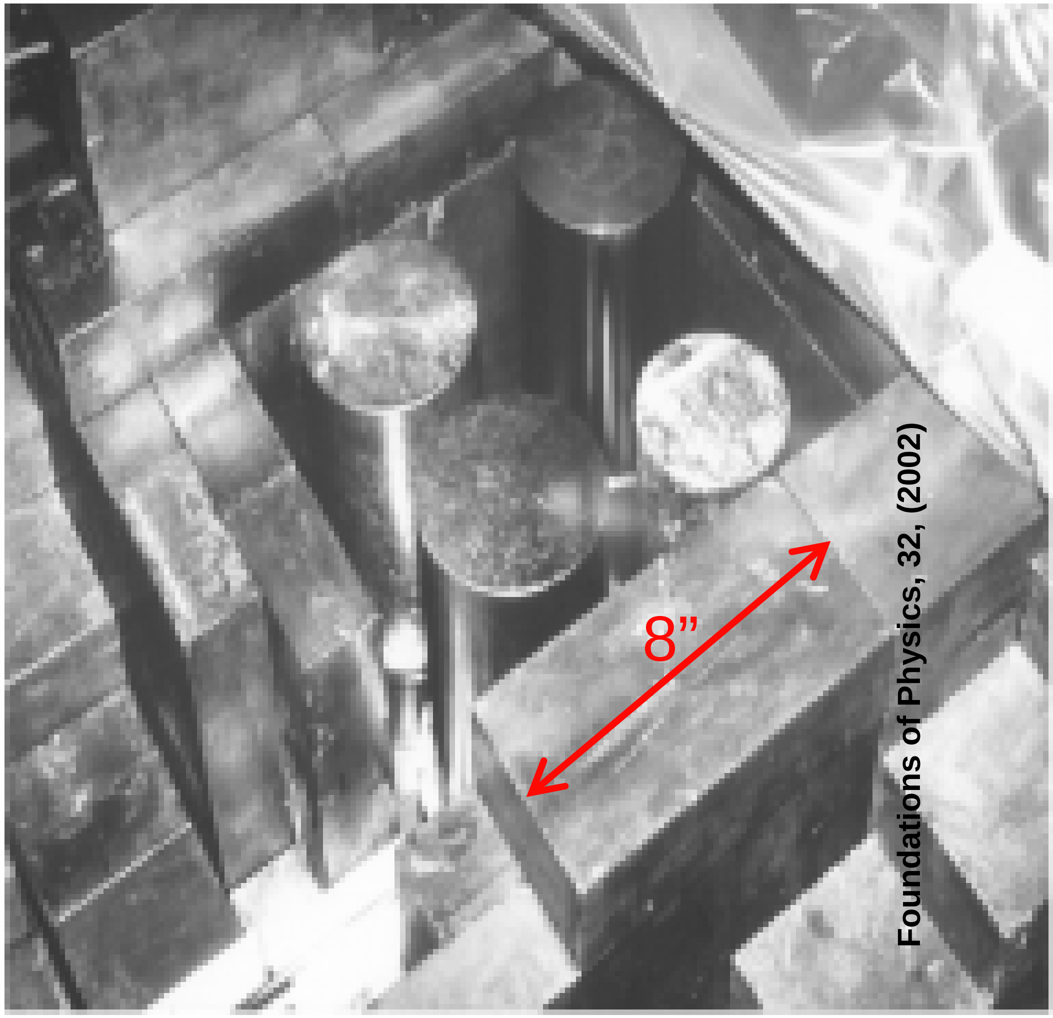
The 1st Direct Observation of ββ(2ν)

~13 g of ^{82}Se



The Heidelberg-Moscow Experiment

~10 kg of ^{76}Ge
13 years of data



An Ideal Experiment

Maximize Rate/Minimize Background

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\Delta E}{Mt_{live}} \right)^{\frac{1}{4}}$$

Large Mass (~ 1 ton)
Large Q value, fast $\beta\beta(0\nu)$
Good source radiopurity
Demonstrated technology
Ease of operation
Natural isotope
Small volume, source = detector
Good energy resolution
Slow $\beta\beta(2\nu)$ rate
Identify daughter in real time
Event reconstruction
Nuclear theory

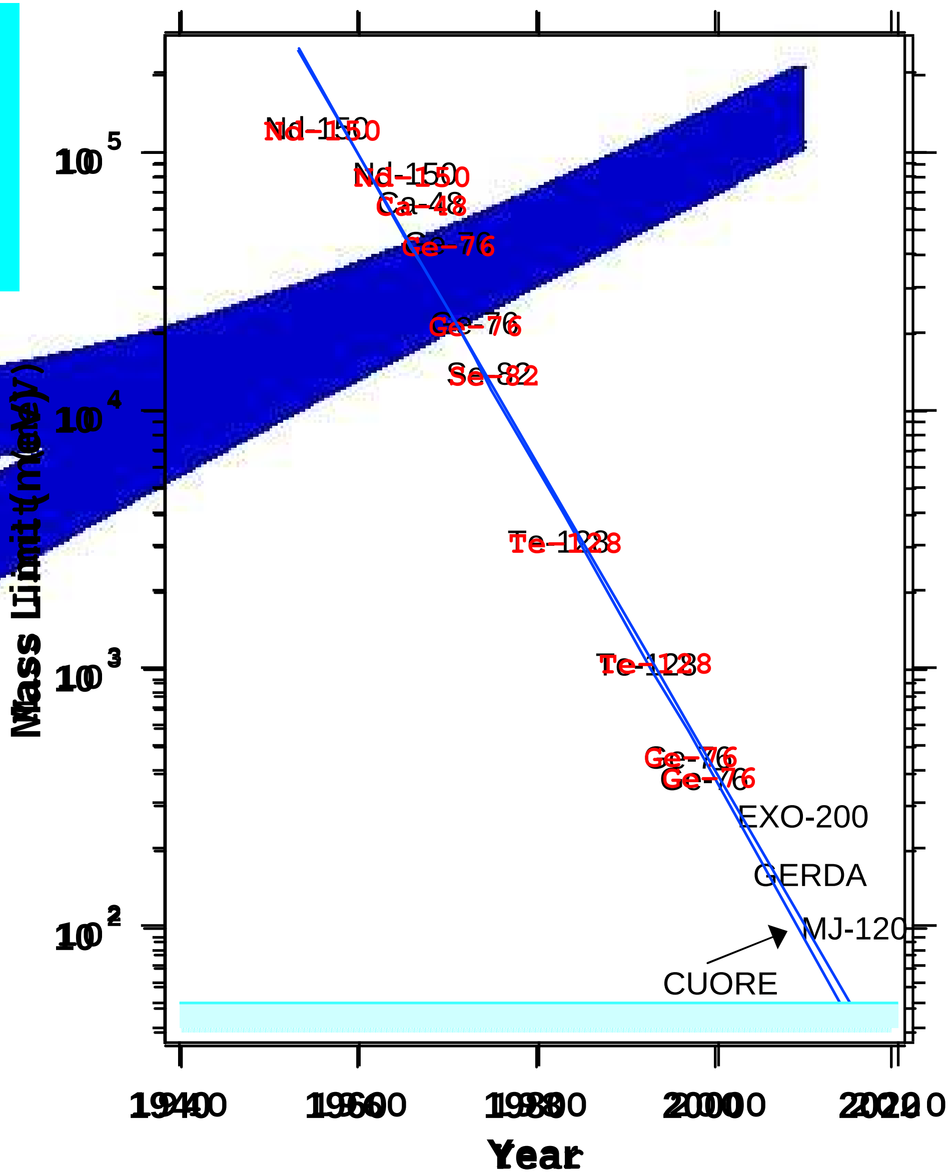
Great Number of Proposed Experiments

- Calorimeter
  - Semi-conductors
  - Bolometers
  - Crystals/nanoparticles immersed in scintillator
- Tracking
  - Liquid or gas TPCs
  - Thin source with wire chamber or scintillator

Past Results

^{48}Ca	>1.4x10^{22} y	<(7.2-44.7) eV
^{76}Ge	>1.9x10^{25} y	<0.35 eV
^{76}Ge	>1.6x10^{25} y	<(0.33-1.35) eV
^{76}Ge	=1.2x10^{25} y	=0.44 eV
^{82}Se	>2.1x10^{23} y	<(1.2-3.2) eV
^{100}Mo	>5.8x10^{23} y	<(0.6-2.7) eV
^{116}Cd	>1.7x10^{23} y	<1.7 eV
^{128}Te	>7.7x10^{24} y	<(1.1-1.5) eV
^{130}Te	>3.0x10^{24} y	<(0.41-0.98) eV
^{136}Xe	>4.5x10^{23} y	<(1.8-5.2) eV
^{150}Nd	>1.2x10^{21} y	<3.0 eV

Elliott & Vogel
Annu. Rev. Part. Sci. 2002 52:115



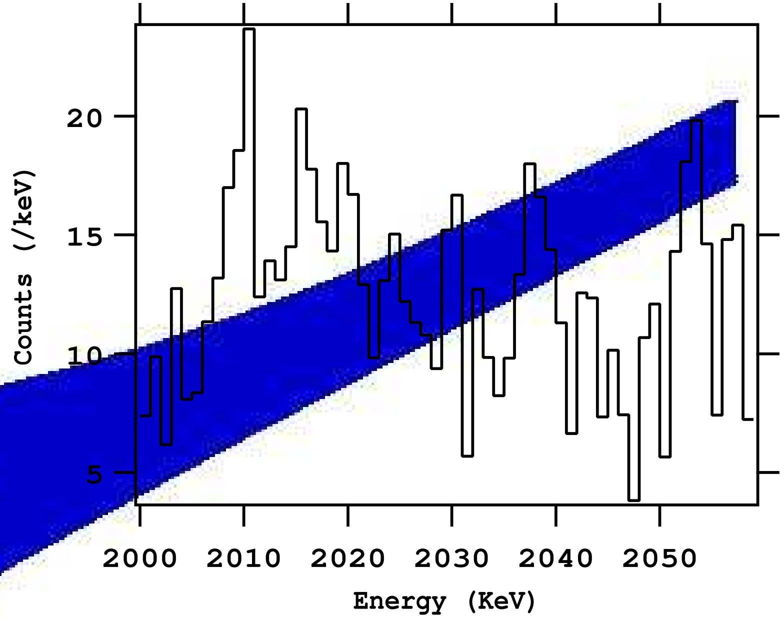
A Recent Claim

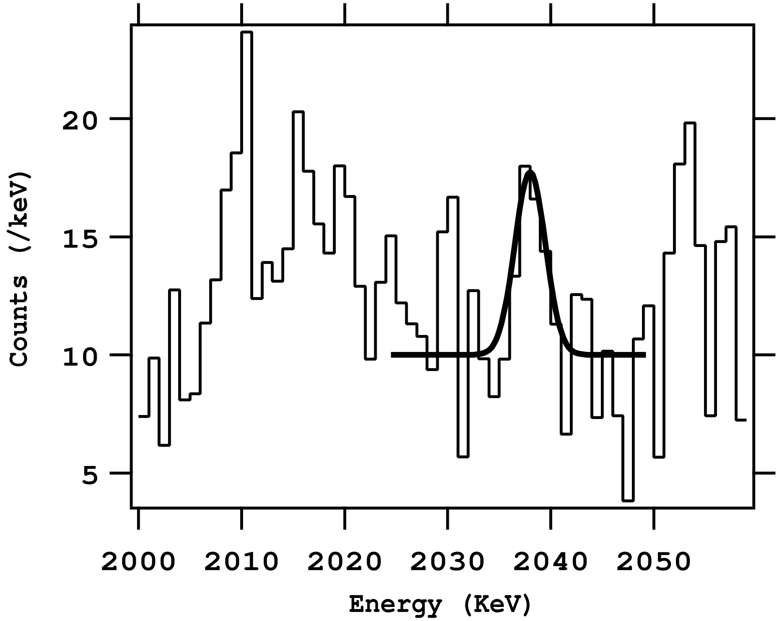
has become a litmus test for future efforts

ββ is the search for a *very* rare peak on a continuum of background.

~70 kg-years of data
13 years

The "feature" at 2039 keV is arguably present.





NIM A522, 371 (2004)

Future Data Requirements

Why wasn't this claim sufficient to avoid controversy?

- **Low statistics of claimed signal - hard to repeat measurement**
- **Background model uncertainty**
- **Unidentified lines**
- **Insufficient auxiliary handles**

Result needs confirmation or repudiation

Various Levels of Confidence

- **A preponderance of the evidence**: a combination of
  - Correct peak 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
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay
- **Beyond a reasonable doubt**: the smoking gun
  - See the process in several isotopes

Discovery vs. Measurement

a future decision point

Did 100 to 200-kg expts. find double beta decay

- **Yes** — Is it a precision result
  - **No** — Scale up as needed to do precision measurement
  - **Yes** — Design new expts to measure statistical dist.
- **No** — Scale up to 1 ton

These two goals may require different technical approaches.

As yet, there is no viable proposal for an experiment sensitive to the solar scale.

Signal:Background ~ 1:1

Its all about the background

Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
5×10^{26}	10	100	
5×10^{27}		40	Atmospheric
$>10^{29}$	<0.05	<10	Solar

To reach atmospheric scale need BG on order 1/t-y.

Solar Scale: showstoppers

- **Need 100 tons of isotope**
  - **Enrichment costs and production rates are not sufficient yet**
  - **Will need R&D to improve capability**
- **Need excellent energy resolution**
  - **Better than 1% FWHM**
  - **Perhaps an experiment with 10^6 solid state is possible**
    - **Cost/detector will need to be greatly reduced**
    - **Large multi-element detector electronics are improving**
  - **Metal loaded liquid scintillator or Xe techniques scale more easily and cost effectively, but resolution requires R&D**

Background Considerations

- $\beta\beta(2\nu)$
- **natural occurring radioactive materials**
- **neutrons**
- **long-lived cosmogenics**

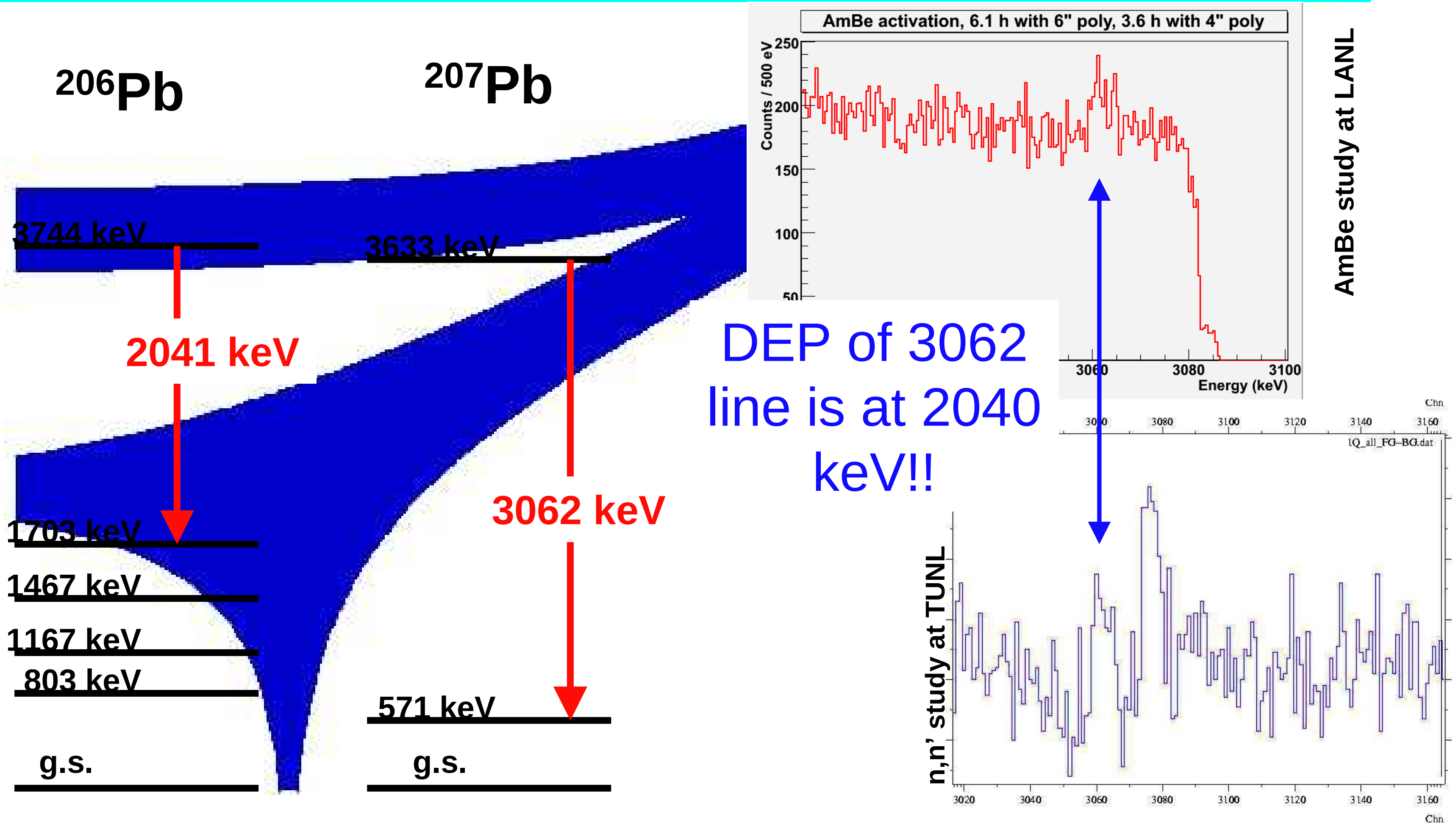
The usual suspects

- ββ(2ν)
  - For the current generation of experiments, resolutions are sufficient to prevent tail from intruding on peak. Becomes a concern as we approach the ton scale
  - Resolution, however, is a very important issue for signal-to-noise
- Natural Occurring Radioactive Materials
  - Solution mostly understood, but hard to implement
    - Great progress has been made understanding materials and the U/Th contamination, purification
    - Elaborate QA/QC requirements
  - Future purity levels greatly challenge assay capabilities
    - Some materials require levels of 1μBq/kg or less for ton scale expts.
    - Sensitivity improvements required for ICPMS, direct counting, NAA

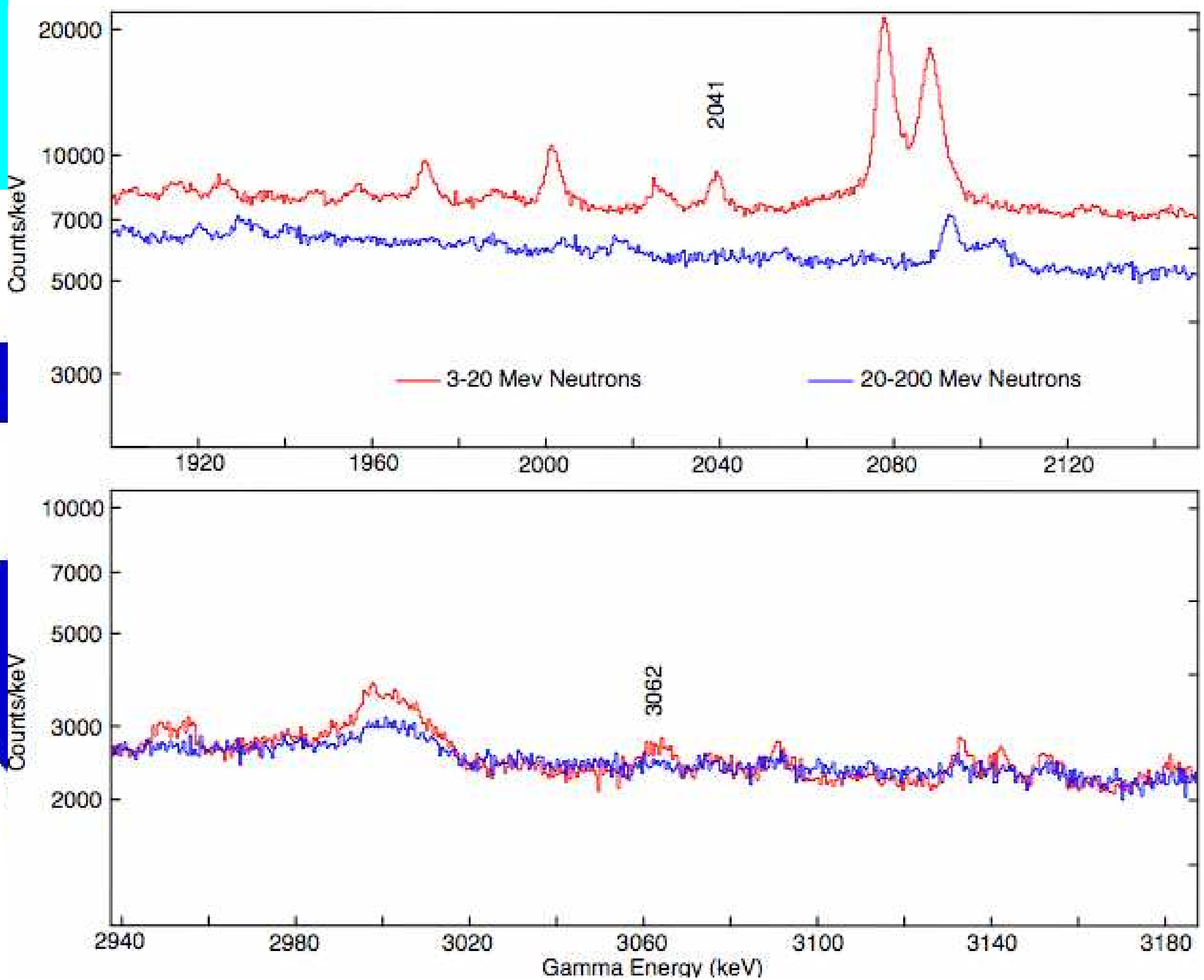
As we approach 1 cnt/ton-year, a complicated mix emerges.

- **Long-lived cosmogenics**
  - **material and experimental design dependent**
  - **Minimize exposure on surface of problematic materials**
- **Neutrons (elastic/inelastic reactions, short-lived cosmogenics)**
  - **(α,n) up to 10 MeV can be shielded**
  - **High-energy-μ generated n are a more complicated problem**
    - **Depth and/or well understood anti-coincidence techniques**
    - **Rich spectrum and hence difficult at these low rates to discern actual process, e.g. (n,n'γ) reactions - which isotope/level**
    - **Simulation codes not entirely accurate wrt low-energy nuclear physics**
    - **Low energy nuclear physics is tedious to implement and verify**

Pb(n,n’γ) and ^{76}Ge: an example



LANSCE Data



20000
10000
7000
5000
3000
Counts/keV
2041
3-20 Mev Neutrons
20-200 Mev Neutrons
1920
1960
2000
2040
2080
2120
10000
7000
5000
3000
2000
Counts/keV
3062
2940
2980
3020
3060
3100
3140
3180
Gamma Energy (keV)

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.

So: how many experiments?

- **Compare theories**
  - **Even though theory is uncertain, consider the predicted difference between two models as representative of the true difference**
  - **Leads to an estimate for the number of experiments**
- **Is there a preferred set of isotopes?**
  - **Perhaps, but this a dangerous stretch for the theory.**

Underlying $\beta\beta(0\nu)$ Mechanisms

$$\Gamma^{0\nu} = G^{0\nu}\left|M_{0\nu}\eta\right|^2 = G^{0\nu}\left|M_{0\nu}\right|^2\left\langle m_{\beta\beta}\right\rangle$$

- **There are many physics models that lead to Lepton Number Violation (η), |M| can change with the model**
  - **Light neutrino exchange**
  - **Heavy neutrino exchange**
  - **R-parity violating supersymmetry**
  - **RHC**
  - **etc.**

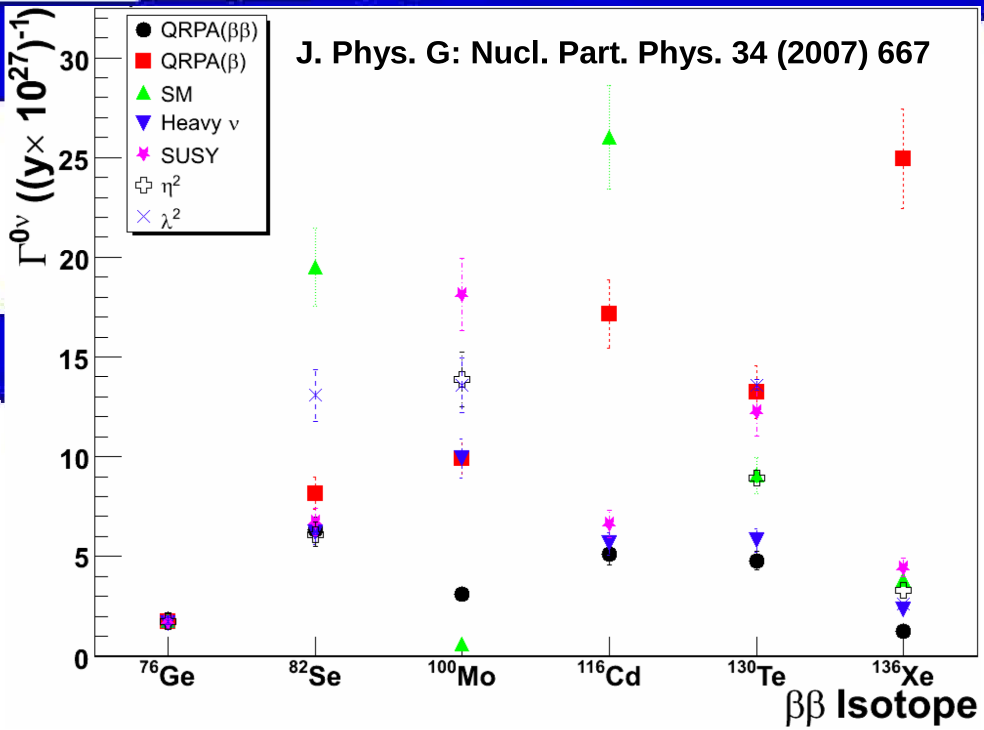
And: why a precision measurement?

If $\langle m_{\beta\beta} \rangle$ is near the degenerate scale:

- **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 ~20%.**

ββ(0ν) as a probe of new physics

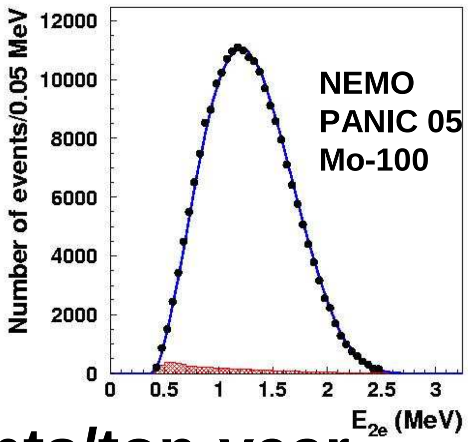
If ββ(0ν) observed in 3-4 isotopes, might be able to discern underlying physics mechanism.



Comparison assumes a single dominate mechanism

Requires results from 3-4 isotopes and calculation of NME to ~20%

Also: PR D70 033012; hep-ph/0405237; hep-ph/061265



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**
  - **Small for the above 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 as theory improves.

Total uncertainty vs. difference in $|M_{0\nu}|$ estimates

- **Statistical uncertainty: maybe 10%**
- **Systematic uncertainty: maybe 10%**
- **Theoretical uncertainty: maybe 50%**
- **Total: about 50% (better for the phase)**

- **Currently a factor of 2 or more between $|M_{0\nu}|$**

Hoping for an improvement in the theory.

ββ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu} \left| M_{2\nu} \right|^2$$

$$\Gamma_{0\nu} = G_{0\nu} \left| M_{0\nu} \right|^2 m_{\nu}^2$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.

What about mixing, m_ν & ββ(0ν)?

No mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \, \varepsilon_i$$

virtual ν exchange

ε = ±1, CP cons.

Compare to β decay result:

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

real ν emission

Compare to cosmology:

$$\Sigma = \sum m_i$$

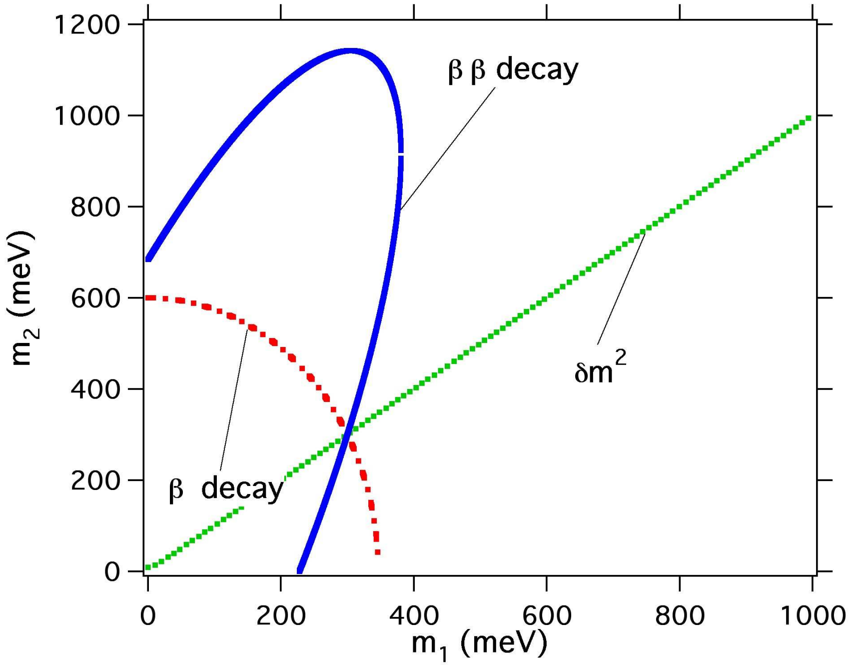
What about the Majorana Phases?

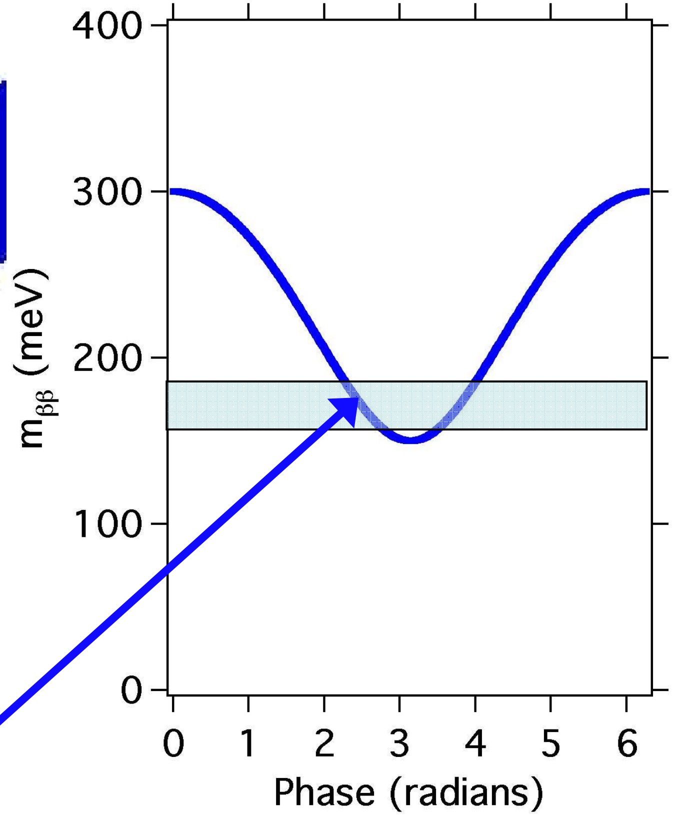
- **If θ_{13} = 0, and the neutrino masses are quasi-degenerate, we might be able to study one of the Majorana phases, if the total uncertainty is ~20% or less.**
- **Very hard**

The phase (if $U_{e3} = 0$)

For 3-d generalization including Σ, see
J. Phys. G: Nucl. Part. Phys. 30 (2004) R183

Similar work hep-ph/0205290





±10% band

<u>Toy model example</u>

M_1 = 300 meV, $\delta m^2 = (9\ \text{meV})^2$
U_{e1} = 0.866, U_{e2} = 0.5, α_{21}=2.5
m_β = 300 meV, $m_{\beta\beta}$ = 171 meV

Matrix Elements - Where are we?

- **Most "good" calculations give the same result to within a factor of 2-3**
- **Assuming no systematically missing many-body effects are absent from all calculations - this range reflects uncertainty**
- **Short term - be careful to quantify uncertainties in weak nucleon current, short-range correlations, form factors, quenching etc.**
- **Medium term - Best hope is better Shell Model calculations**
- **Long term - coupled cluster approximation applied to higher A nuclei.**

Input Needed from Auxiliary Measurements

See nucl-ex/0511009

- **Atomic masses (Cd, Te & radiative EC-EC candidates - better Q values**
- **Precise $\beta\beta(2\nu)$ data; β^-, β^+ data on intermediate-state isotopes - g_{pp}**
- **Charge exchange reactions on parent & daughter (p,n), (n,p), (^{3}He,t), (d,^{2}He), etc. - charge-changing weak currents**
- **Muon capture - all multipoles populated**
- **Pair correlation studies, e.g. pair removal reaction (p,t)**
- **Pion double-charge exchange**
- **Electromagnetic transitions to isobaric analogue states**

Conclusions

- **We can do it!**
  - **The technology is ready for atmospheric scale sensitivity**
- **We need to do it!!!**
  - **Even null results will be interesting**
  - **Qualitative and quantitative data will be critical to ν physics**
- **We need to do it more than once.**
  - **need 3 or more measurements**
- **We need to do it well.**
  - **Need measurements with a total uncertainty (experiment & theory) of ~50% or less, and eventually even better.**
- **We need to do it in different ways.**
  - **There may be "branch point" in the technological focus of experiments on the horizon: Will process be observed at degenerate scale?**

How do we do it? This workshop is packed with exciting suggestions

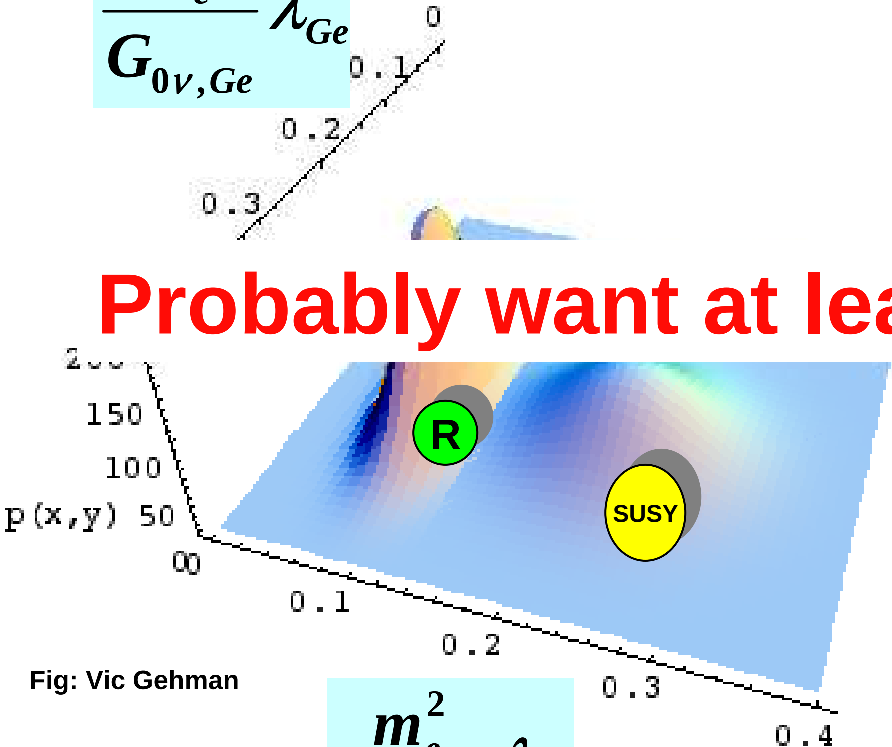
END

Discerning Models

Key ingredient: several isotopes

See hep-ph/0405237
For similar work

$$\frac{m_e^2}{G_{0\nu,Ge}}\lambda_{Ge}$$



$$\frac{m_e^2}{G_{0\nu,Te}}\lambda_{Te}$$

Fig: Vic Gehman

$\frac{m_e^2}{G_{0\nu}}\lambda$	Ge	Te	Xe	
	0.4	0.5	0.9	Civitarese Suhonen NPA729, 867
R	0.2	0.1	0.04	Rodin et al. nucl-th/
	[illegible]	[illegible]	[illegible]	NPA654, 973c
SUSY	0.2	0.2	0.08	Faessler et al. PRD58, 115004

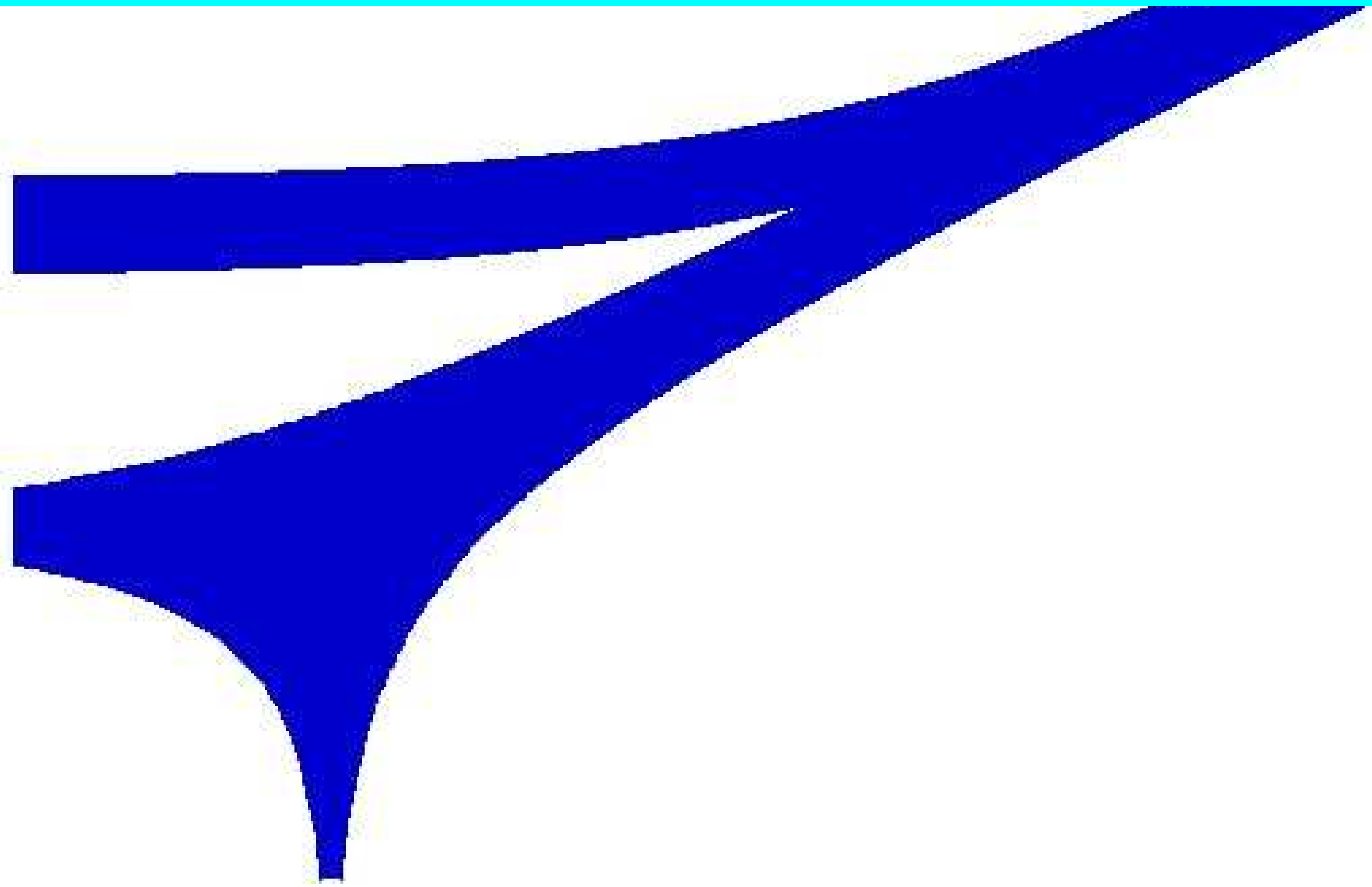
Probably want at least 3 measurements!

$$\frac{m_e^2}{G_{0\nu}}\lambda$$

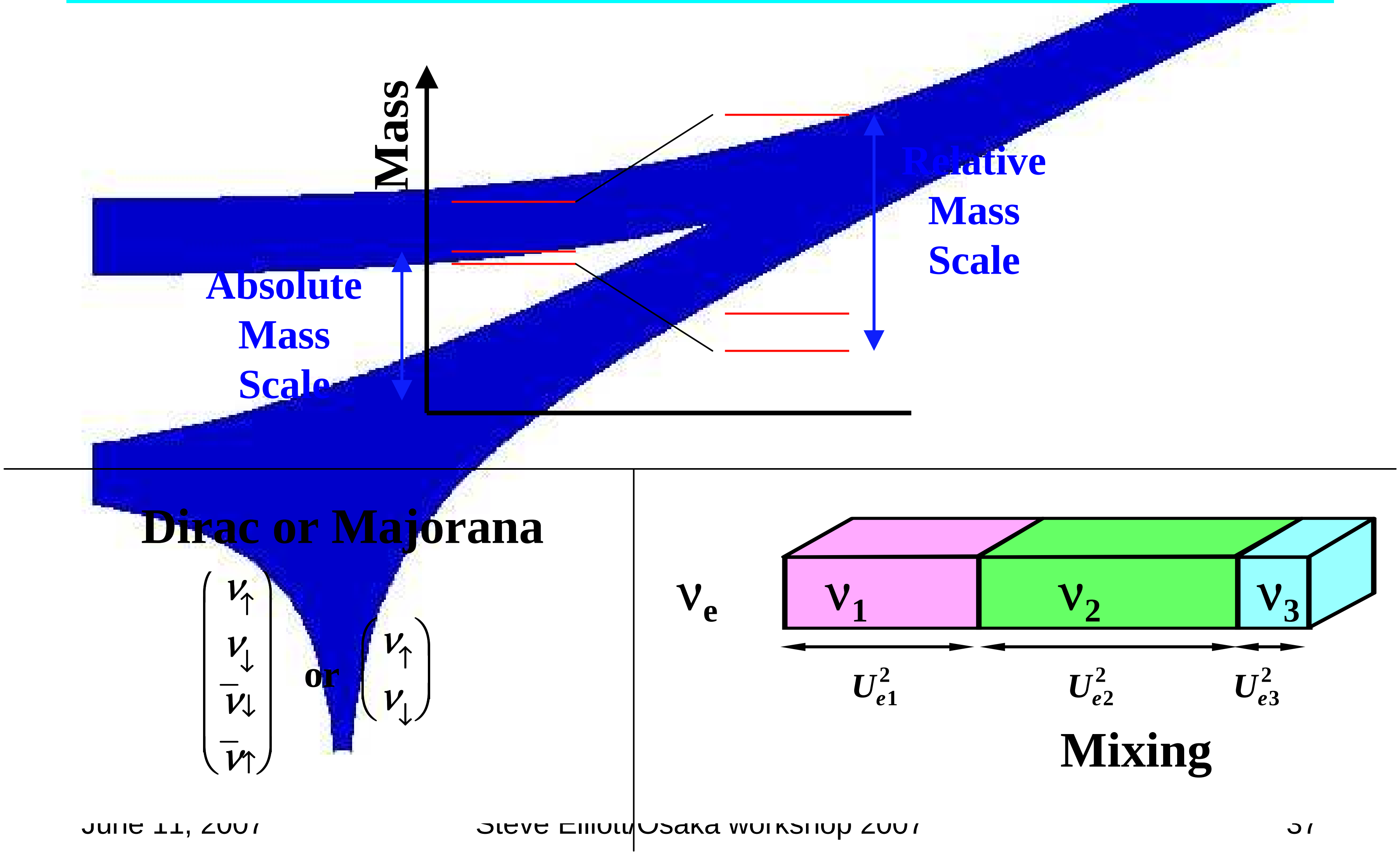
$$= M_{0\nu}^2 m_\nu^2 \quad \text{- or -} \quad = m_e^2 \eta_{SUSY}^2 M_{SUSY}^2$$

M_ν=200 meV, η =1.5x10^{-9}

Teach the Controversy

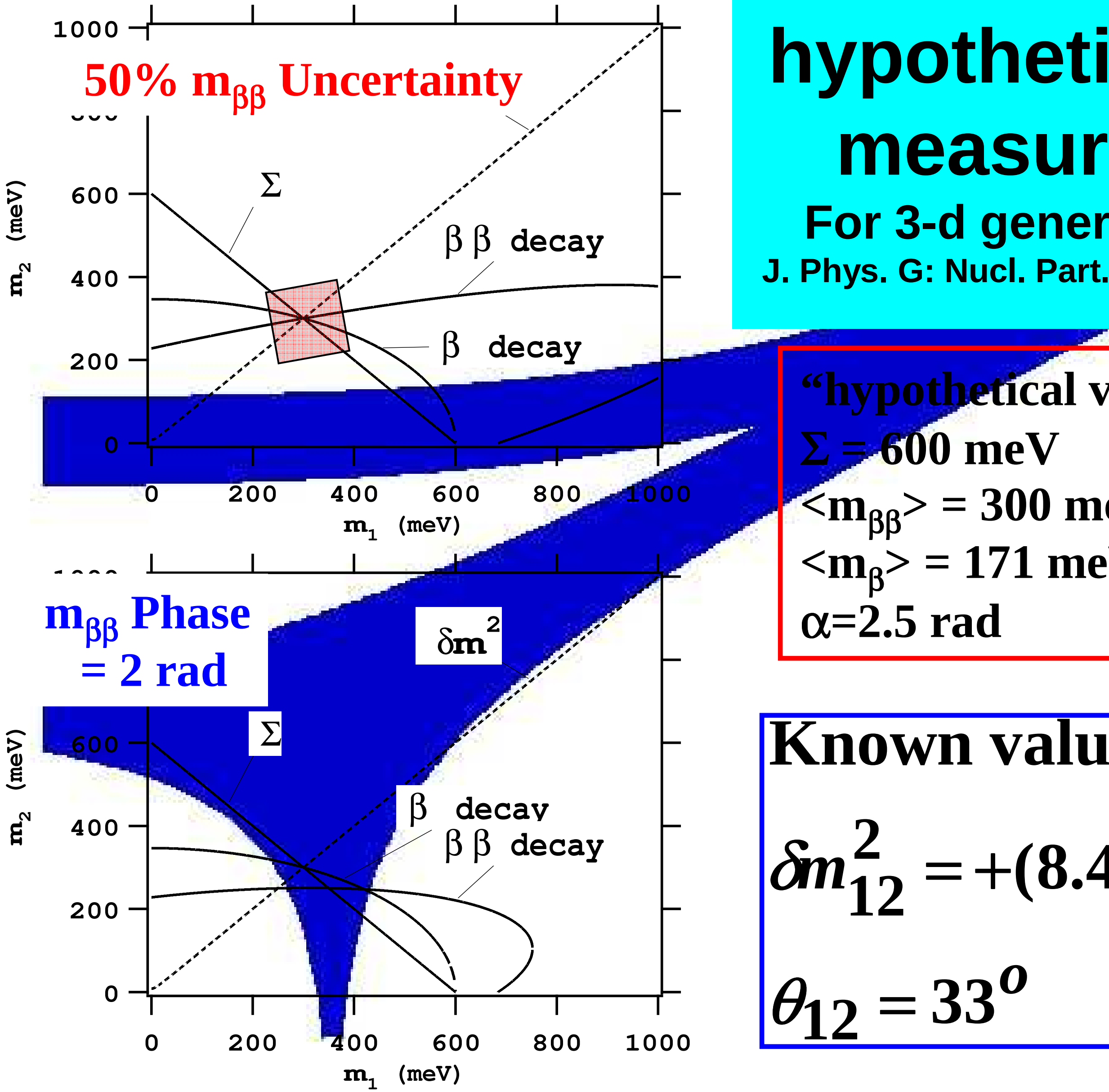


ββ in the context of ν physics



hypothetical set of measurements

For 3-d generalization, see
J. Phys. G: Nucl. Part. Phys. 30 (2004) R183



"hypothetical values"
Σ = 600 meV
$<m_{\beta\beta}>$ = 300 meV
$<m_{\beta}>$ = 171 meV
α=2.5 rad

Known values

$$\delta m_{12}^2 = +(8.4\ \text{meV})^2$$

$$\theta_{12} = 33^o$$