# 0νββ-decay - Current Results, Future Implications

- Motivation, ν mass, and 0νββ
- Current Results and Considerations
- Next generation experiments
- Future Considerations
- Summary

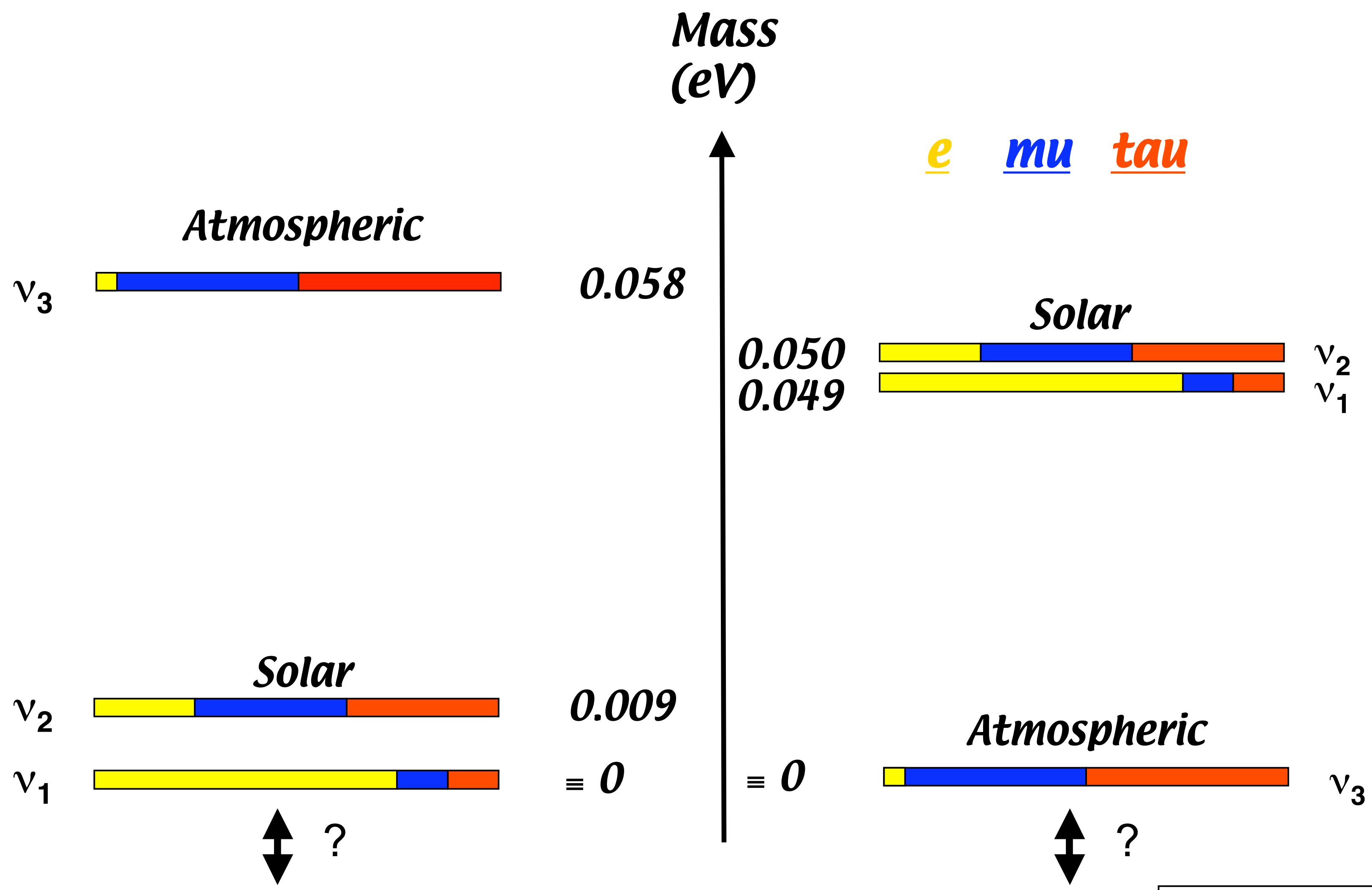
# Motivation for 0νββ-decay experiments

The recent discoveries of solar, reactor, and atmospheric neutrino oscillations provide a compelling argument for new 0νββ-decay experiments with increased sensitivity.

## 0νββ-decay probes fundamental physics.

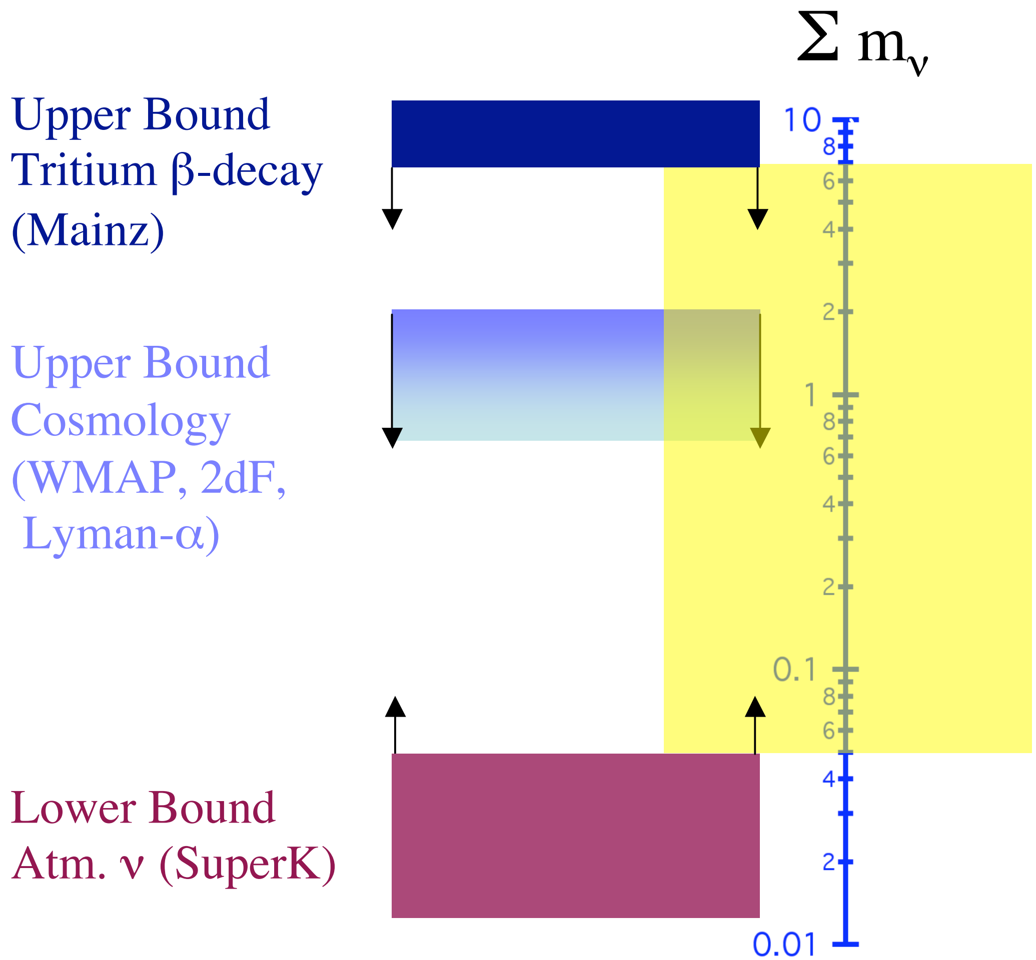
- It is the only technique able to determine if neutrinos might be their own anti-particles, or Majorana particles.
- If Majorana particles, 0νββ offers the most promising method for determining the overall absolute neutrino mass scale.
- Tests one of nature's most fundamental symmetries, lepton number conservation.

# Neutrino Masses and Flavor Content



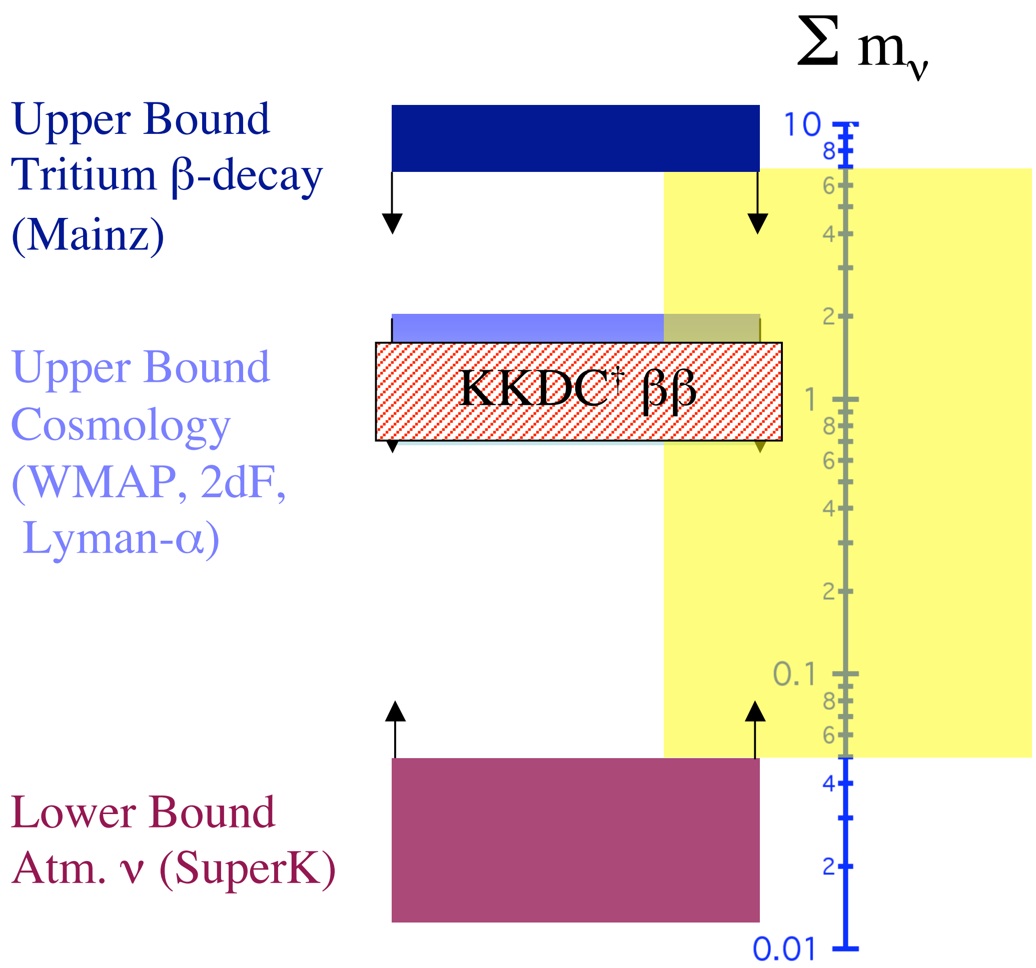

R.G.H. Robertson

# Constraints on ν masses



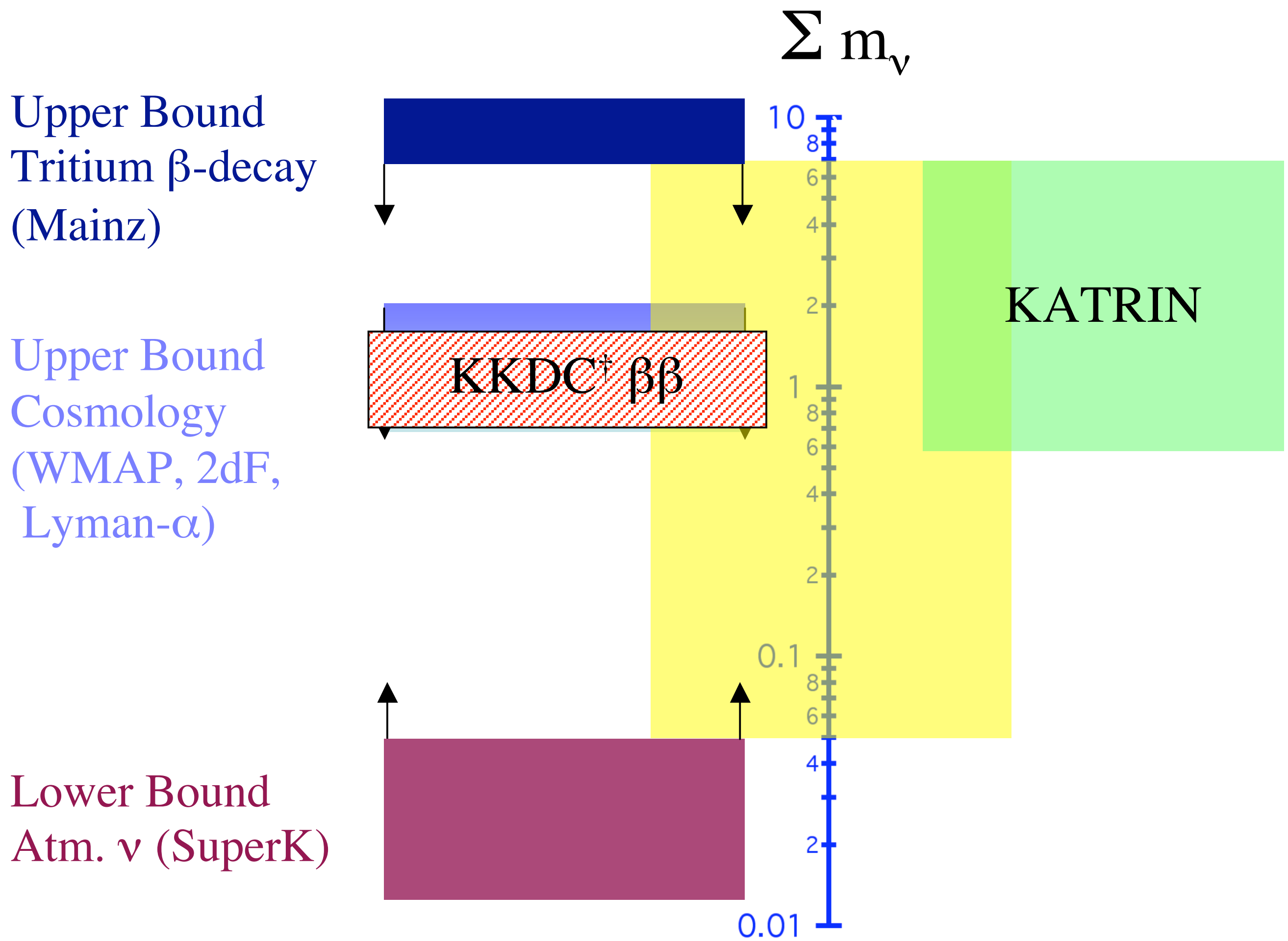

† Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

# Constraints on ν masses




† Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

# Constraints on $\nu$ masses

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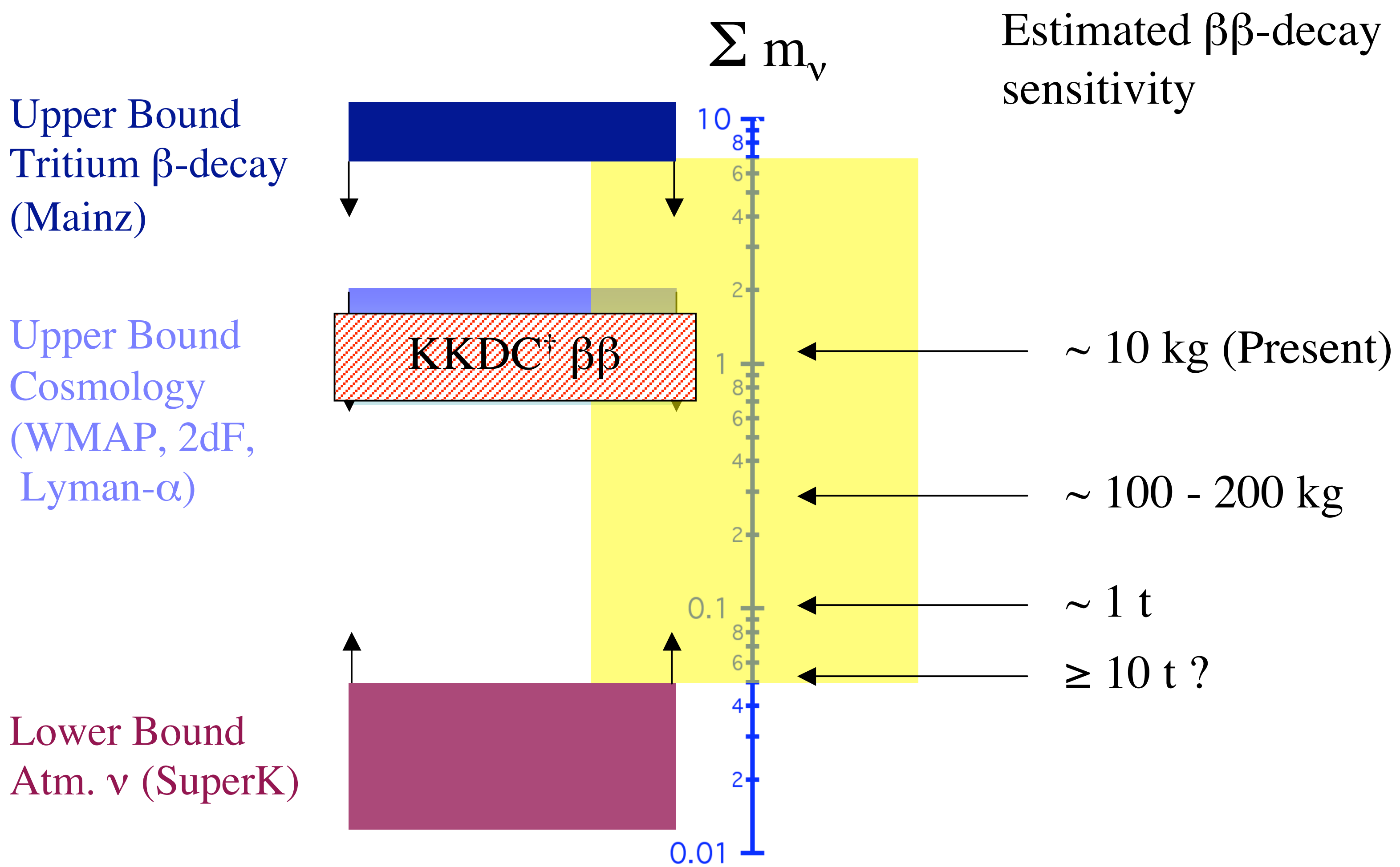
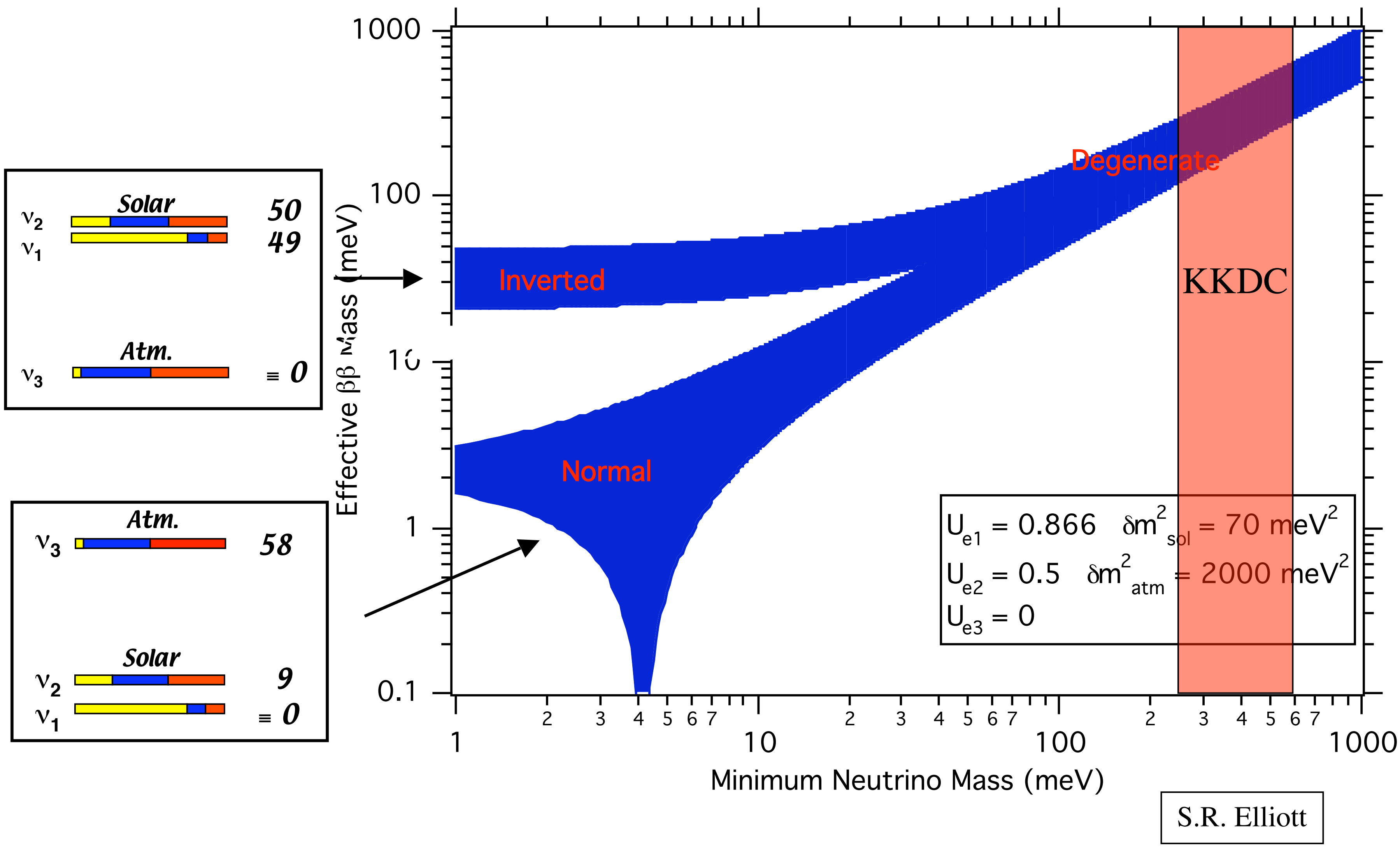
# Constraints on ν masses



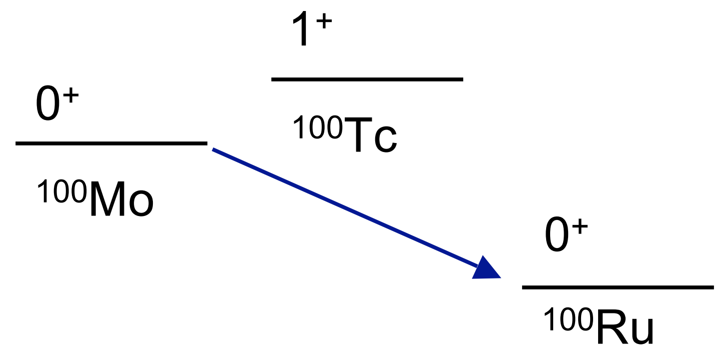

† Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

# 0νββ-decay ν mass sensitivity



# 0νββ-decay

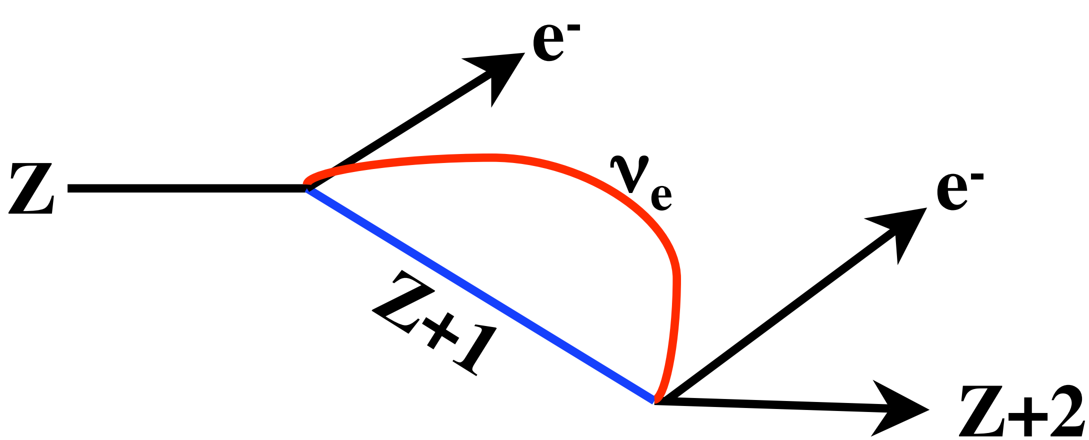
There are a series of even-even nuclei, where single β-decay is energetically forbidden, but ββ-decay is allowed




2νββ-decay: $2n \Rightarrow 2p + 2e^- + 2\bar{\nu}_e$

0νββ-decay: If neutrinos are Majorana particles and have mass then

$$n \Rightarrow p + e^- + \bar{\nu}_e \quad (\text{RH } \bar{\nu}_e) \longrightarrow \nu_e + n \Rightarrow p + e^- \quad (\text{LH } \nu_e)$$



# $0\nu\beta\beta$-decay Searches - Current Results

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left\langle m_{\beta\beta}\right\rangle^2$$

$\propto M \bullet t_{exp}$

Best case,
0 background !

| Isotope | Half-life (y) | $\lvert\langle m_\nu\rangle\rvert$ (eV) | Exposure kg-yr | Background (cts/keV/kg-yr ) | Reference |
|---|---|---|---|---|---|
| Ca-48 | $> 1.4 \times 10^{22}$ | $< 7.2 - 44.7$ | 0.037 | 0.03 | You91 |
| Ge-76 | $> 1.9 \times 10^{25}$ | $< 0.32 - 1$ | 35.5 | 0.19 | Kla01 |
| Ge-76 | $> 1.6 \times 10^{25}$ | $< 0.33 - 1.35$ | 8.9 | 0.06 | Aal02 |
| Ge-76 | $= 1.2 \times 10^{25}$ | $= 0.24 - 0.58$ | 71.7 | 0.11 | Kla04 |
| Se-82 | $> 1.9 \times 10^{23}$ | $< 1.3 - 3.2$ | 0.68 | | Sar04 |
| Zr-96 | $> 1 \times 10^{21}$ | $< 16.3 - 40$ | 0.0084 | | Arn98 |
| Mo-100 | $> 3.5 \times 10^{23}$ | $< 0.7 - 1.2$ | 5.02 | $3.5 \times 10^{-3}$ | Sar04 |
| Cd-116 | $> 1.7 \times 10^{23}$ | $< 2.2 - 4.6$ | 0.15 | 0.03 | Dan00 |
| Te-128 | $> 7.7 \times 10^{24}$ | $< 1.1 - 1.5$ | Geoch. | Geoch. | Ber93 |
| Te-130 | $> 1.8 \times 10^{24}$ | $< 0.2 - 1.1$ | 10.85 | 0.18 | Cap05 |
| Xe-136 | $> 4.4 \times 10^{23}$ | $< 2.2 - 5.2$ | 4.84 | | Lue98 |
| Nd-150 | $> 3.6 \times 10^{21}$ | $< 4.9 - 17.1$ | 0.015 | | Bar05 |

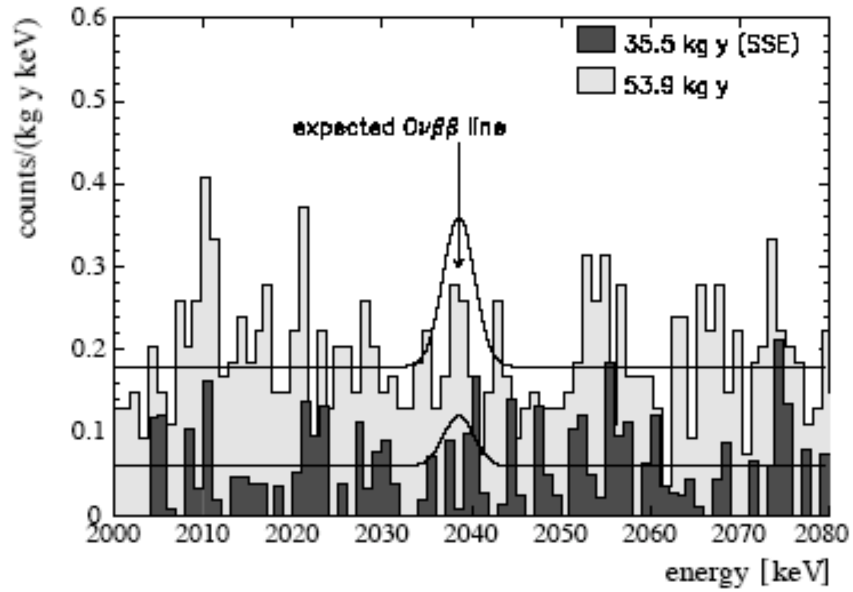
Typical “source” masses .5 - 10 kg

# An Example - $^{76}$Ge Measurement

Heidelberg-Moscow used five 86% enriched $^{76}$Ge crystals with a total of 10.96 kg of mass and found:

$T_{1/2} > 1.9 \times 10^{25}$ y (90%CL)

Klapdor-Kleingrothaus et al.,
Eur. Phys. J 12, 147 (2001)



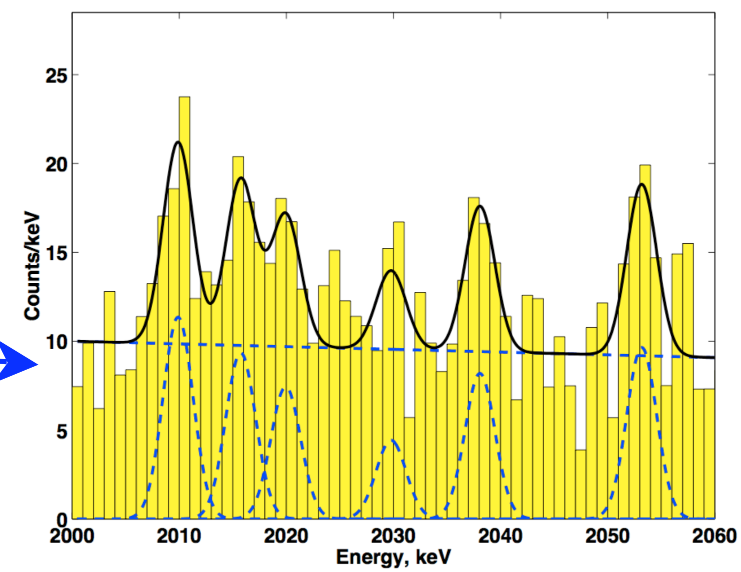

KKDC with additional data, 71 kg-years, and a refined analysis found:

$T_{1/2} = 1.2 \times 10^{25}$ y

$0.24 < m_\nu < 0.58$ eV (3 sigma)

Background level depends on intensity fit to other peaks.

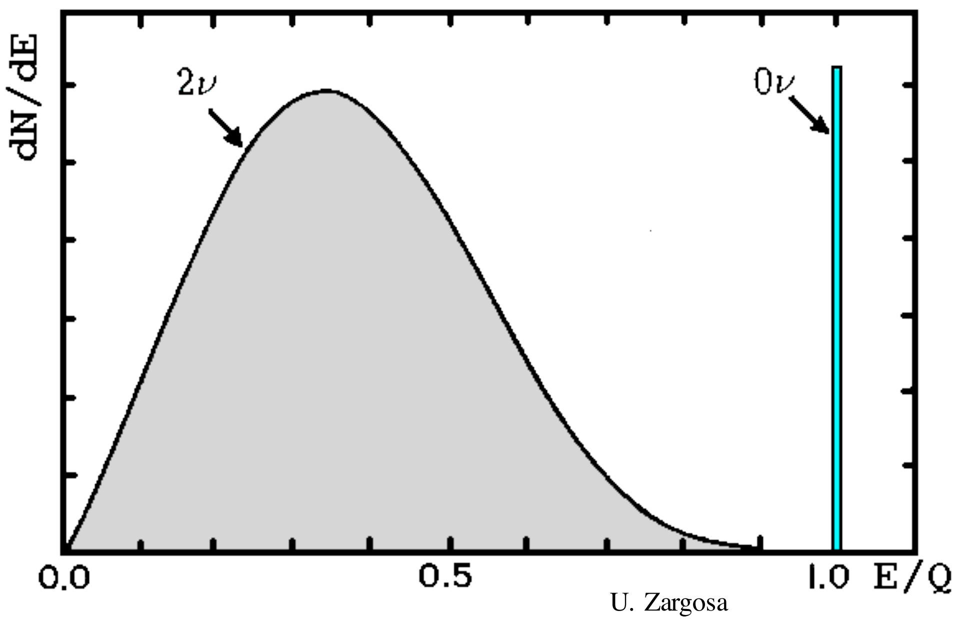
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).



# Experimental Considerations

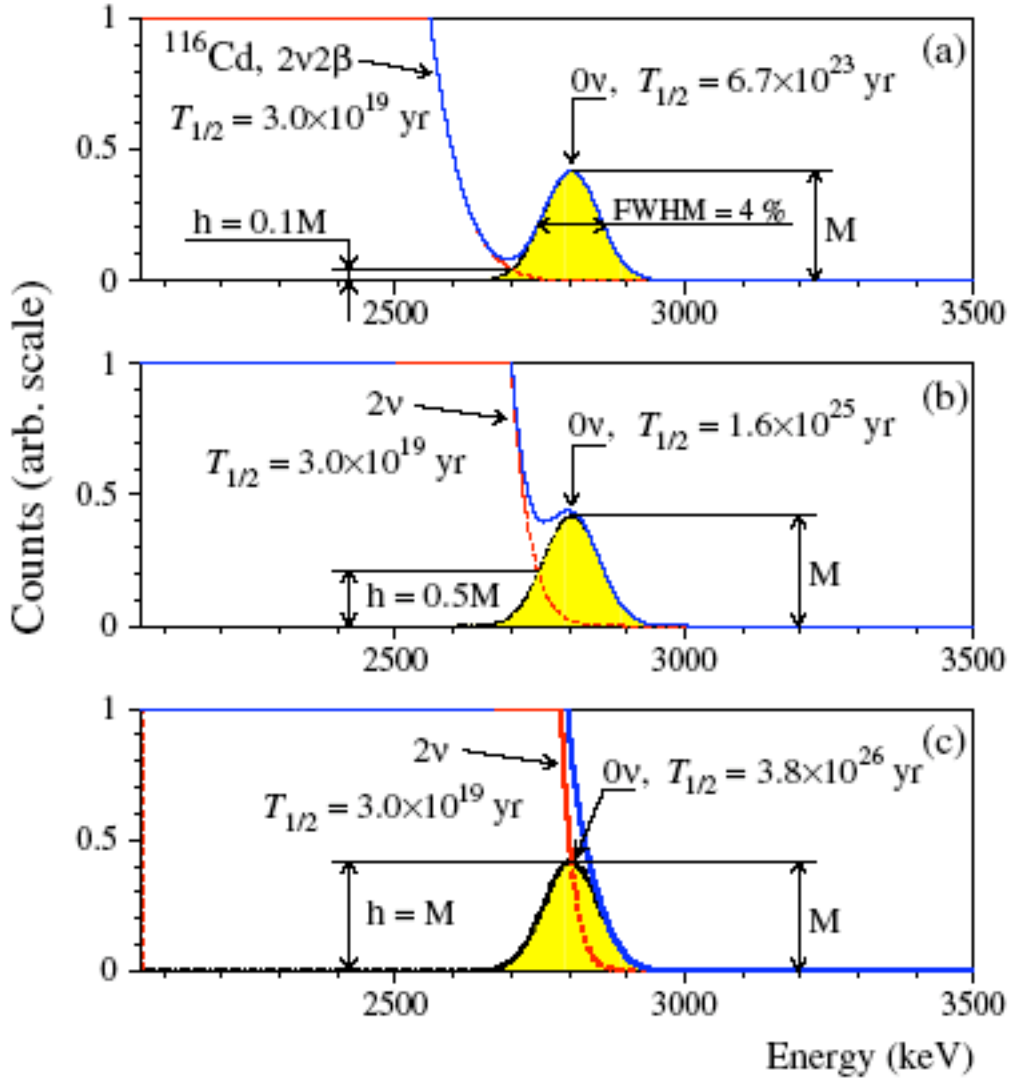
To measure *extremely* rare decay rates
($T_{1/2}$ ~ $10^{24}$ - $10^{27}$ years)

- Large, highly efficient source mass
- Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region
  - Requires ultra-clean radiopure materials
  - the ability to discriminate signal from background
- Best possible energy resolution
  - Minimize $0\nu\beta\beta$ peak ROI to maximize S/B
  - Separate $2\nu\beta\beta/0\nu\beta\beta$



# Resolution and Sensitivity to 0νββ

From Zdesenko, Danevich, Tretyak, J. Phys. G 30 (2004) 971

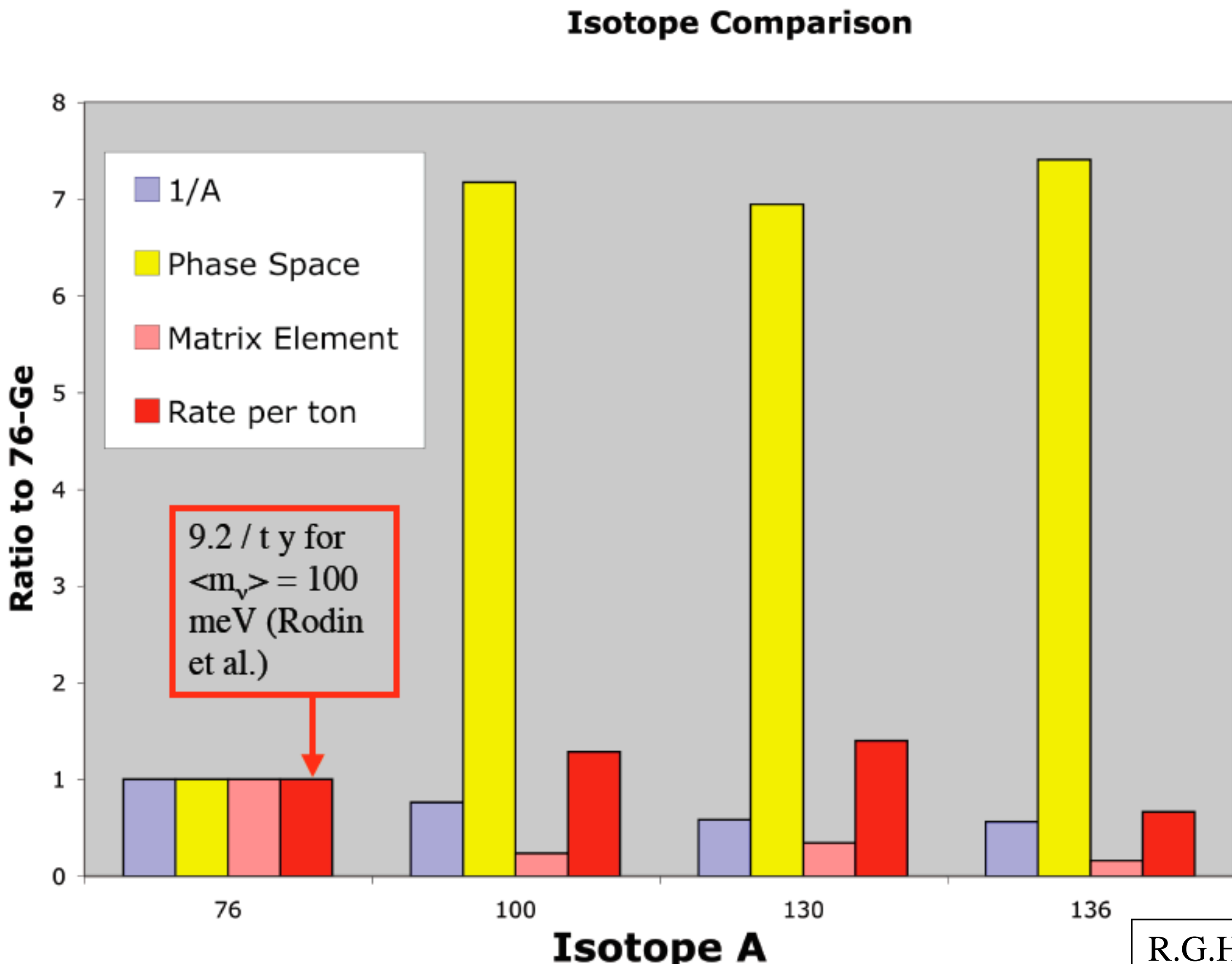


# Additional Considerations

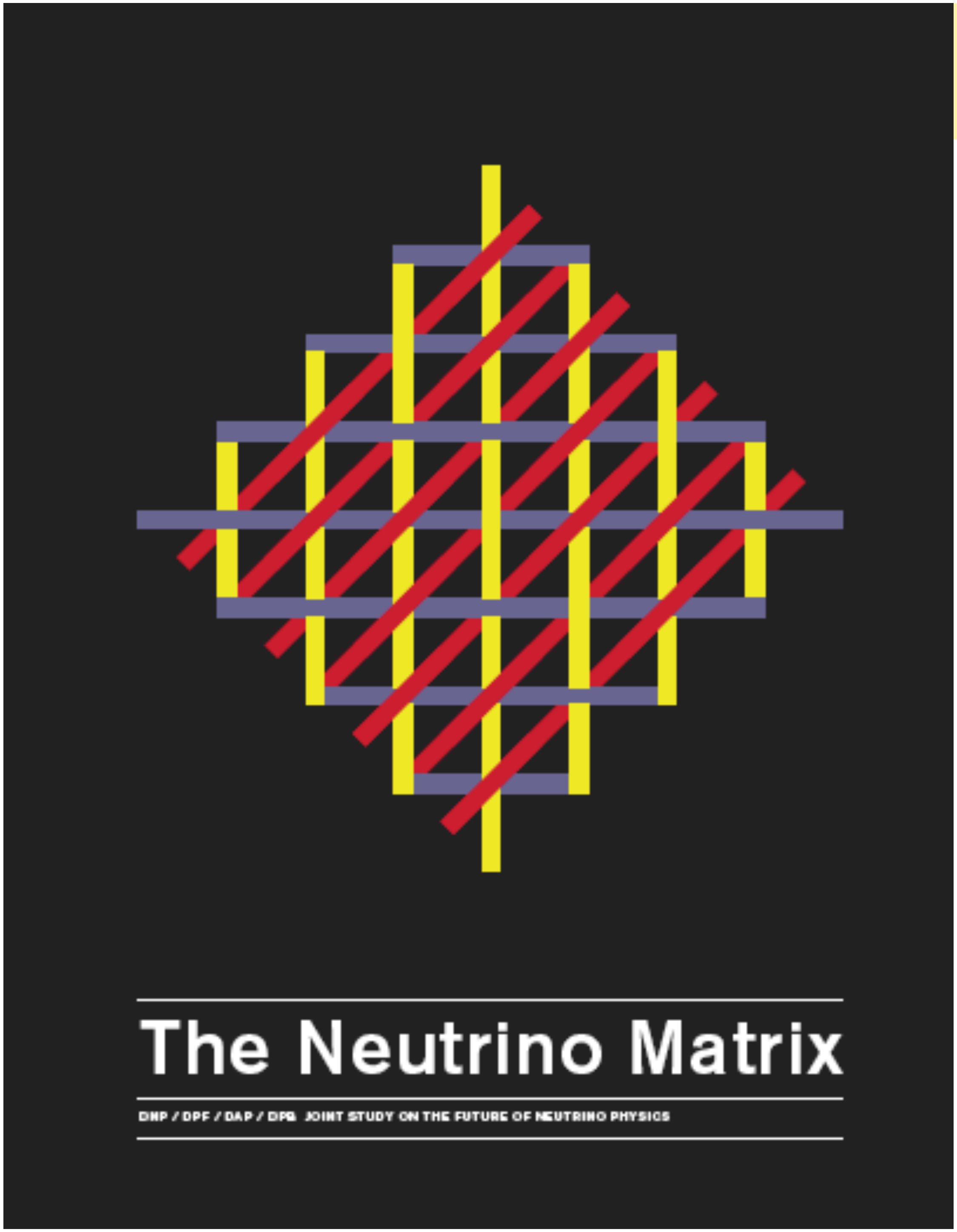
- Source serves as the detector
- Elemental (enriched) source to minimize active material.
- A large Q value - faster $0\nu\beta\beta$ rate and also places the region of interest above many potential backgrounds.
- A relatively slow $2\nu\beta\beta$ rate helps control this irreducible background.
- Identifying the decay progeny in coincidence with the $0\nu\beta\beta$ decay energy eliminates potential backgrounds except $2\nu\beta\beta$.
- Event reconstruction, providing kinematic data such as opening angle and individual electron energy aids in the elimination of backgrounds and demonstration of signal (can possibly use $2\nu\beta\beta$)
- Good spatial resolution and timing information helps reject background processes.
- Demonstrated technology at the appropriate scale.
- The nuclear theory is better understood in some isotopes than others. The interpretation of limits or signals might be easier to interpret for some isotopes.

# “Relative” Sensitivities

Using Rodin et al. Nucl. Matrix elements




R.G.H Robertson




- 4 APS Divisions
  DNP, DPF, DAP, DPB
- 200+ members
- 7 Working Groups
- B. Kayser and S. Freedman co-chairs
- R.G.H. Robertson - writing committee chair
- www.aps.org/neutrino

# APS Multidivisional ν Study and 0νββ-decay

- One of the three principal conclusions:

  *WE RECOMMEND, AS A HIGH PRIORITY, A PHASED PROGRAM OF SENSITIVE SEARCHES FOR NEUTRINOLESS NUCLEAR DOUBLE BETA DECAY.*

- Additional guidance
  - Initial "Phase 1" Goal: sensitivity to $m_\nu$ in the "quasi-degenerate" region (≥ 100 meV).
  - Experiments will need ~200 kg of target mass, the actual quantity being dependent on specific experimental parameters.
  - Experiments should be scalable to a 1-ton-scale, with discovery potential near the atmospheric neutrino oscillation mass scale, that is about 45 meV.
  - The study identified the need to undertake multiple 0νββ experiments that use different isotopes and are based on different experimental techniques.

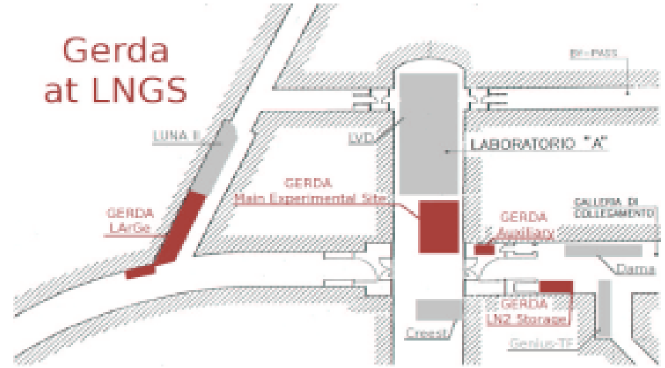
# 0νββ-decay Searches - Efforts Underway

| Collaboration | Isotope | Technique | Mass | Status | Talk at Workshop |
|---|---|---|---|---|---|
| CAMEO | Cd-116 | $CdWO_4$ crystals | 1 t | | |
| CANDLES | Ca-48 | 60 $CaF_2$ crystals in liq. scint | 191 kg | Construction | Kishimoto |
| CARVEL | Ca-48 | $^{48}CaWO_4$ crystal scint. | 100 kg | | |
| COBRA | Cd-116, Te-130 | CdZnTe detectors | 10 kg | R&D | |
| CUROICINO | Te-130 | $TeO_2$ Bolometer | | Operating | Gutierrez |
| CUORE | Te-130 | $TeO_2$ Bolometer | 206 kg | Initial Const. | Gutierrez |
| DCBA | Nd-150 | Nd foils & tracking chambers | 20 kg | R&D | |
| EXO200 | Xe-136 | Xe TPC | 200 kg | Construction | Pocar |
| EXO | Xe-136 | Xe TPC | 1-10t | R&D | Pocar |
| GEM | Ge-76 | Ge diodes in LN | 1 t | | |
| GERDA | Ge-76 | Ge diodes in LN<br>Seg. Ge in LN | 15 kg<br>35-40 kg<br>1 t | Construction<br>Construction<br>Future | |
| GSO | Gd-160 | $Gd_2SiO_5$:Ce crystal scint. in liquid scint | 2t | | |
| Majorana | Ge-76 | Segmented Ge | 180 kg<br>1 t | Proposed<br>Future | Lesko |
| NEMO3 | Mo-100<br>Se-82 | Foils with tracking | 6.9 kg<br>0.9 kg | Operating | Ohsumi |
| SuperNEMO | Se-82 | Foils with tracking | 100 kg | Proposed | Lang |
| MOON | Mo-100 | Mo sheets | 200 kg<br>1 t | R&D | Nomachi |
| SNO ββ | | suspended material | | Feasibility | Hallin |
| Xe | Xe-136 | Xe in liq. Scint. | 1.56 t | | |
| XMASS ββ | Xe-136 | Liquid Xe | 10 t | | Moriyama |

# GERDA $^{76}$Ge 0νββ-decay

- European effort at Gran Sasso
- Concept - bare Ge diodes in a high-purity $LN_2$ shield
- Phase I
  - 15 kg 86% enriched $^{76}$Ge
  - non-segmented (IGEX and H-M detectors)
  - Estimated Start Nov. 2006
- Phase II
  - ~25 kg of segmented detectors
  - Estimated start - Late 2007
- Phase III
  - Scale towards 1 ton

- Majorana and GERDA believe that for a future large 500 - 1000 kg scale experiment, the experiments will likely combine using the best technology.



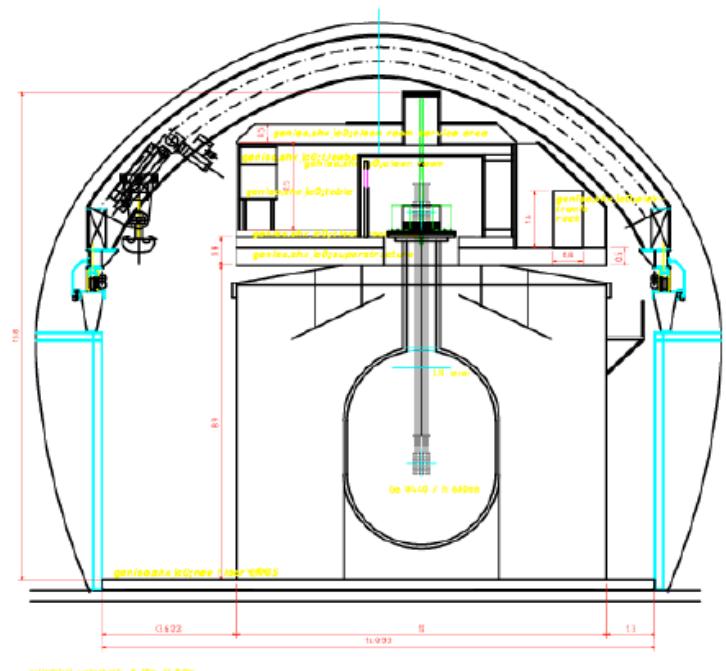



Figure 4: View of GERDA cross section from TIR tunnel. The shielding structure below the roof of the water tank might be not needed.

# Future Challenges

- Backgrounds and Scalability - Next generation experiments must strive for backgrounds in the $0\nu\beta\beta$ region of **cnts/t-y**.
  - Requires materials with μBq/kg level radioimpurities.
    - Difficult to achieve sensitivity with direct radioassays
  - Requires large scale cleanliness.
  - "New background regimes", new background sources that could previously be ignored (see Hime's talk, this workshop)
- Signal and Background Characterizations
  - Reliably simulate the entire observed spectrum.
  - Demonstrate capability to measure the $2\nu\beta\beta$ spectrum
- Extracting the effective mass of the neutrino requires an understanding of the nuclear matrix elements.
  - Theoretical uncertainties are a major limitation -- a factor of 2-3 between techniques
  - much theoretical work is needed
  - Additional complementary experimental work may help

# Reducing Backgrounds - Two Basic Strategies

- Directly reduce intrinsic, extrinsic, & cosmogenic activities
  - Select and use ultra-pure materials
  - Minimize all non "source" materials
  - Clean passive shield
  - Go deep – reduced μ's & related induced activities
- Utilize background rejection techniques
  - Energy resolution
    - $0\nu\beta\beta$ is a single site phenomenon
    - Many backgrounds have multiple site interactions
  - Granularity [multiple detectors]
  - Single Site Time Correlated events (SSTC)
  - Tracking
  - Angular correlations
  - Ion Identification
  - Active veto detector
  - Pulse shape discrimination (PSD)
  - Segmentation

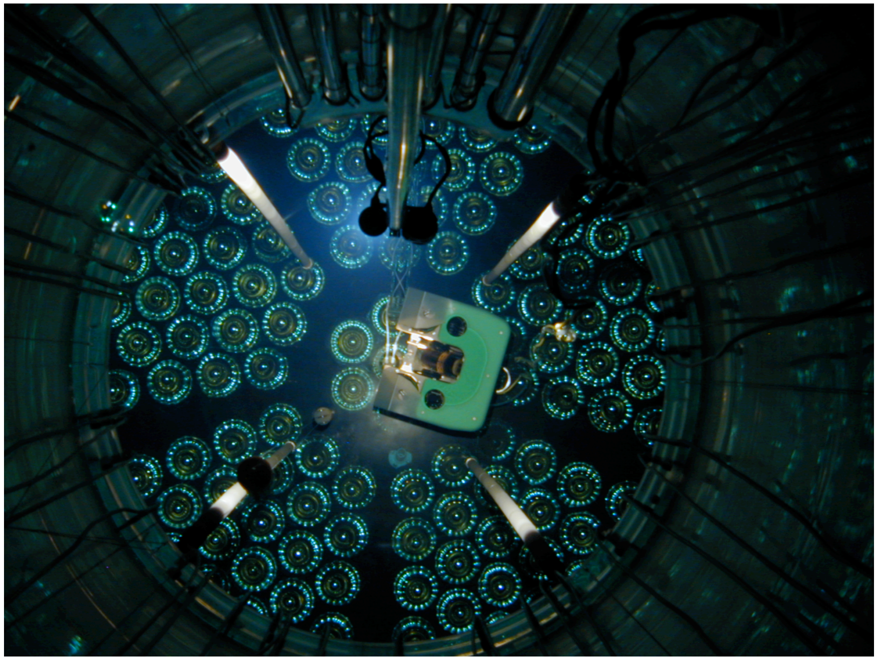
# Background reduction at the larger scale

- Many groups have built $0\nu\beta\beta$-decay experiments at the few to 10 kg level. - Need to scale this up to the 100s of kg level.
- Can utilize knowledge from groups that have demonstrated the construction of low-background, large-scale detectors underground:

  e.g. KamLAND, SNO, SAGE, GNO, Borexino CTF

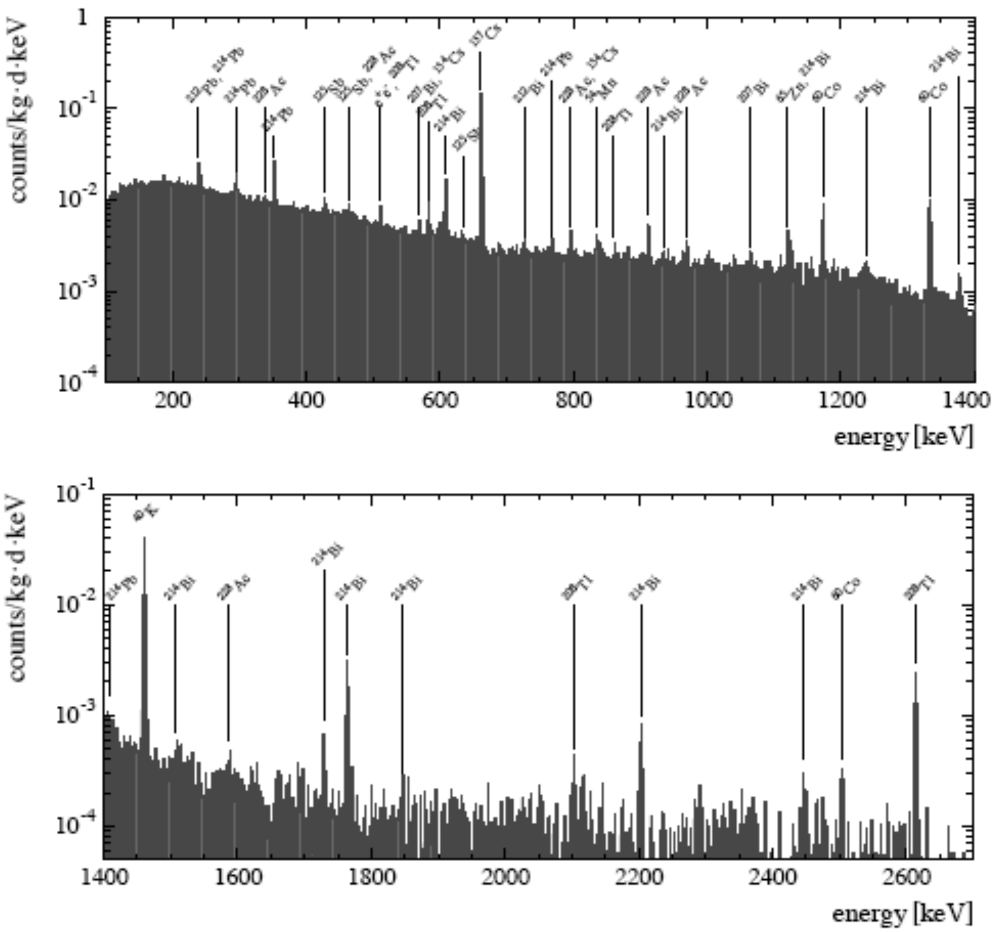
  - SNO Acrylic Sphere, 30 t, 120 segments, < 2 μBq/kg $^{232}$Th

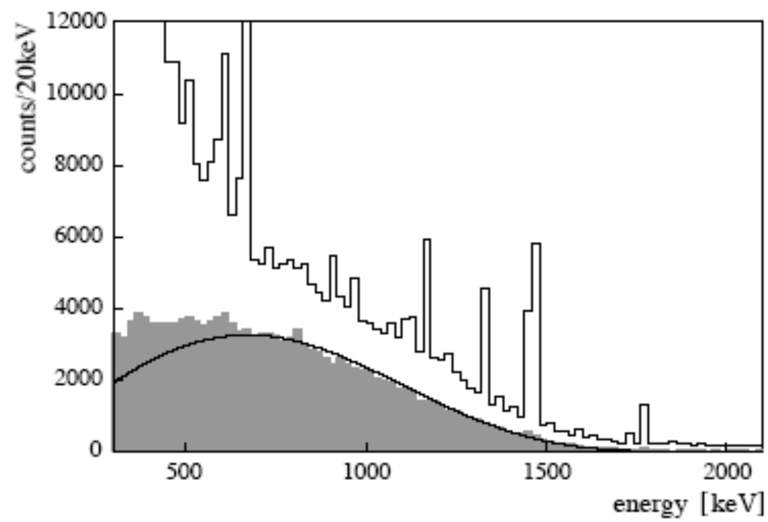
- SNO Neutral Current Detector Array of $^{3}$He proportional counters
  - 450 kg of material
  - 300 detector segments
  - Activity 100 - 1000 x cleaner than best previous counters
  - Activity <= 6 μBq/kg $^{232}$Th



# Characterization of Signal and Background

Heidelberg-Moscow

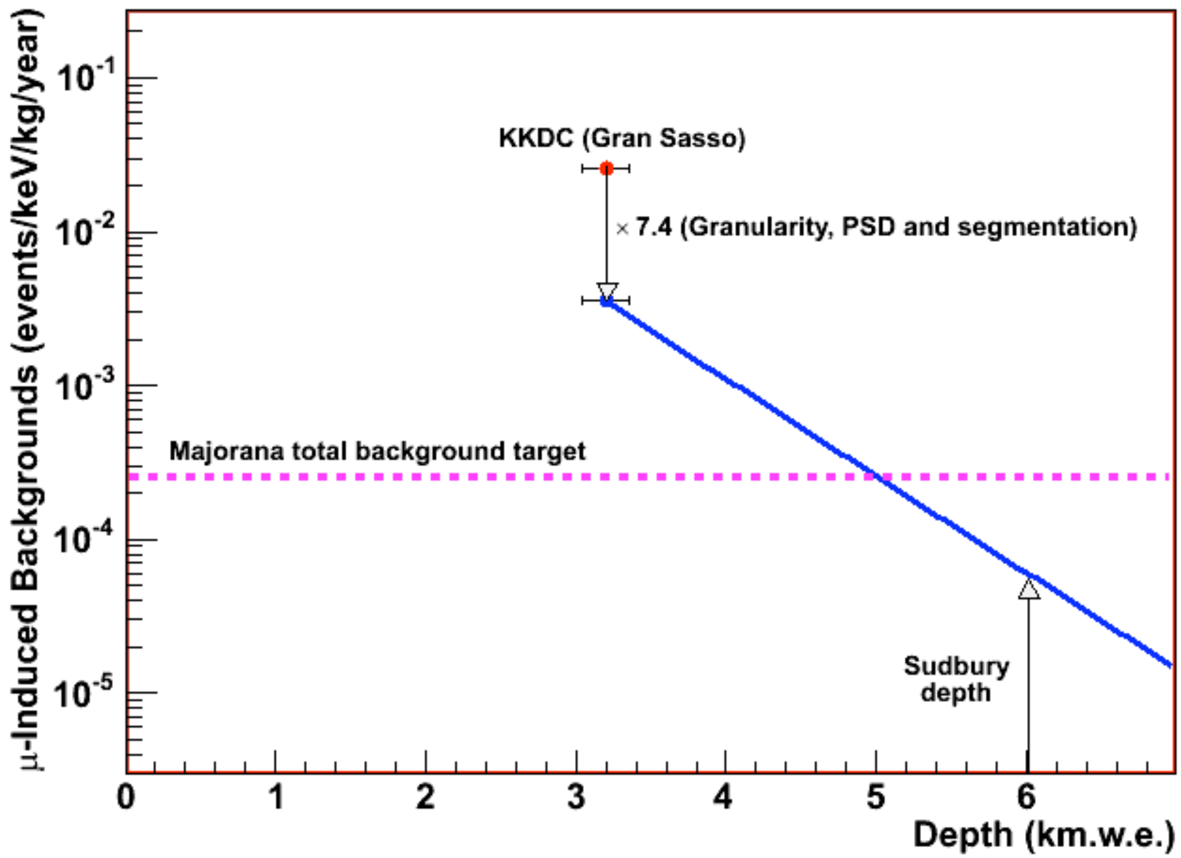



Klapdor-Kleingrothaus et al.,
Eur. Phys. J 12, 147 (2001)

# Backgrounds for Majorana vs. Depth

At Sudbury depth, 6000 mwe, calculate that about 15-20% of the expected background in the ROI will be from μ induced activities in Ge and the nearby cryostat materials (dominated by fast neutrons).




**Hime and Mei 2005**

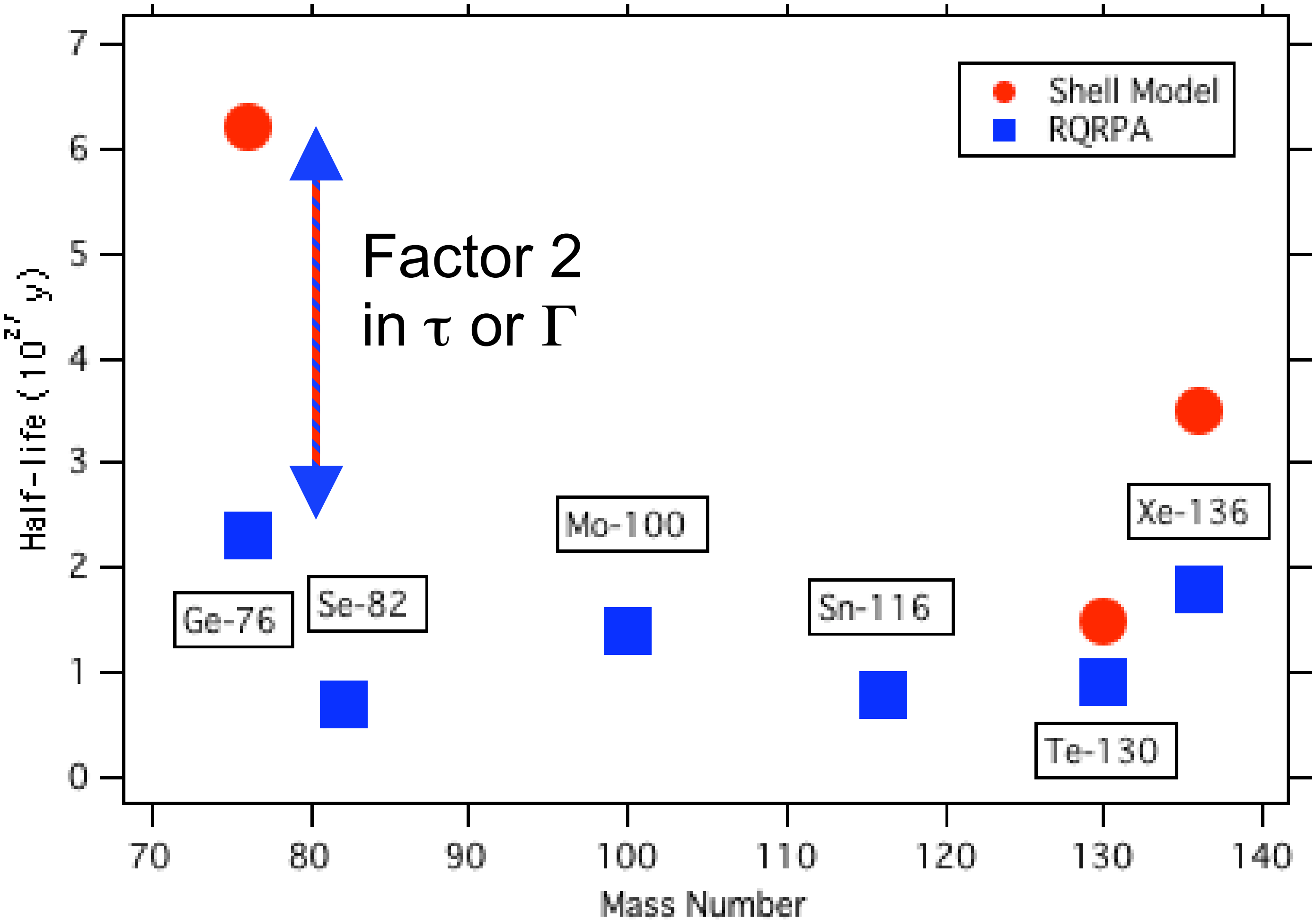
# $0\nu\beta\beta$-decay Nuclear Matrix elements

- Extracting the effective mass of the neutrino requires an understanding of the nuclear matrix elements.

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left\langle m_{\beta\beta}\right\rangle^2$$

  Two basic approaches - Shell Model and Quasiparticle Random Phase Approximation.
- Rodin et al. show that QRPA results tighten up (typically to ~20% uncertainty in half life):
  - When implementation differences are accounted for
  - One uses $\beta\beta(2\nu)$ to set the free parameter
- Recent shell model numbers are comparable (differ < factor of 2). But these calculations are still evolving.

# RQRPA* and Shell Model Predictions




$m_{\beta\beta} = \sqrt{\Gamma}$

$\delta m_{\beta\beta} = \delta\Gamma/2$

*renormalized quasiparticle random phase approximation

NSM: Caurier, Nucl. Phys. **A654**, 973c (1999)

RQRPA: Rodin, Faessler, & Simkovic, nucl-th/0503063

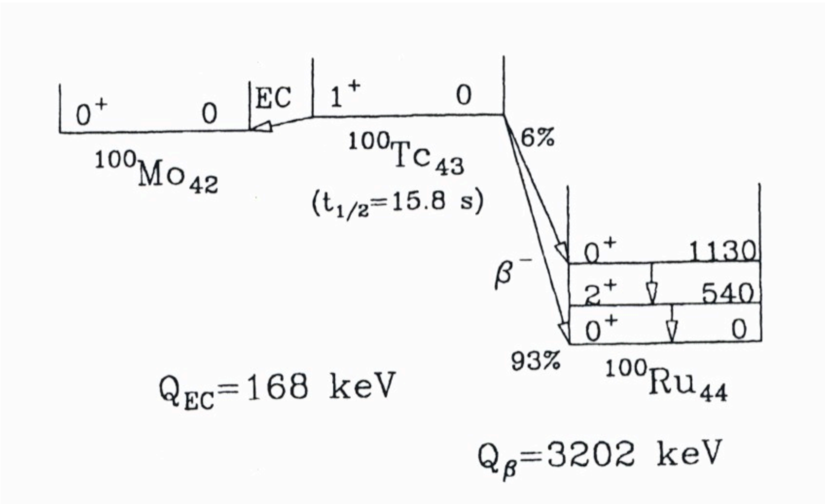
S.R. Elliott

# 0νββ-decay Nuclear Matrix Comments

- The nuclear structure is a fascinating many-body problem, motivating important developments in nuclear structure theory, including Monte Carlo & Lanczos shell model techniques and quasiparticle RPA.
- Using compilations or averages of previous sequential calculations isn't a reasonable approach.
- Complementary experiments are being pursued.
  - Garcia et al. in 100 and 116 systems.
  - Schiffer et al. in pair transfer

# Electron-Capture Branch of $^{100}$Tc (A. Garcia et al.)

A bench-mark for testing 2bb-decay nuclear matrix element calculations




**5 measurable observables in addition to energy of Giant Resonance:**

1) $^{100}$Mo → $^{100}$Ru(g.s.) (known)
2) $^{100}$Mo → $^{100}$Ru(1130 keV) (known)
3) $^{100}$Tc → $^{100}$Ru(g.s.) (known)
4) $^{100}$Tc → $^{100}$Ru(1130 keV) (known)
5) $^{100}$Tc → $^{100}$Mo (difficult to measure)

**Can calculations reproduce these?**

QRPA (Griffiths-Vogel, PRC **46**, 181 (1992)) predicts:
B(GT, 0+ →1+) = 1.75

Previous measurement: (Garcia et al, PRC **47**, 2910 (1993))
B(GT , 0+ →1+) = 0.66 ±0.33

New measurement: (Sjue et al, DNP meeting **EF 9**)
B(GT , 0+ →1+) = 1.7 ±0.3

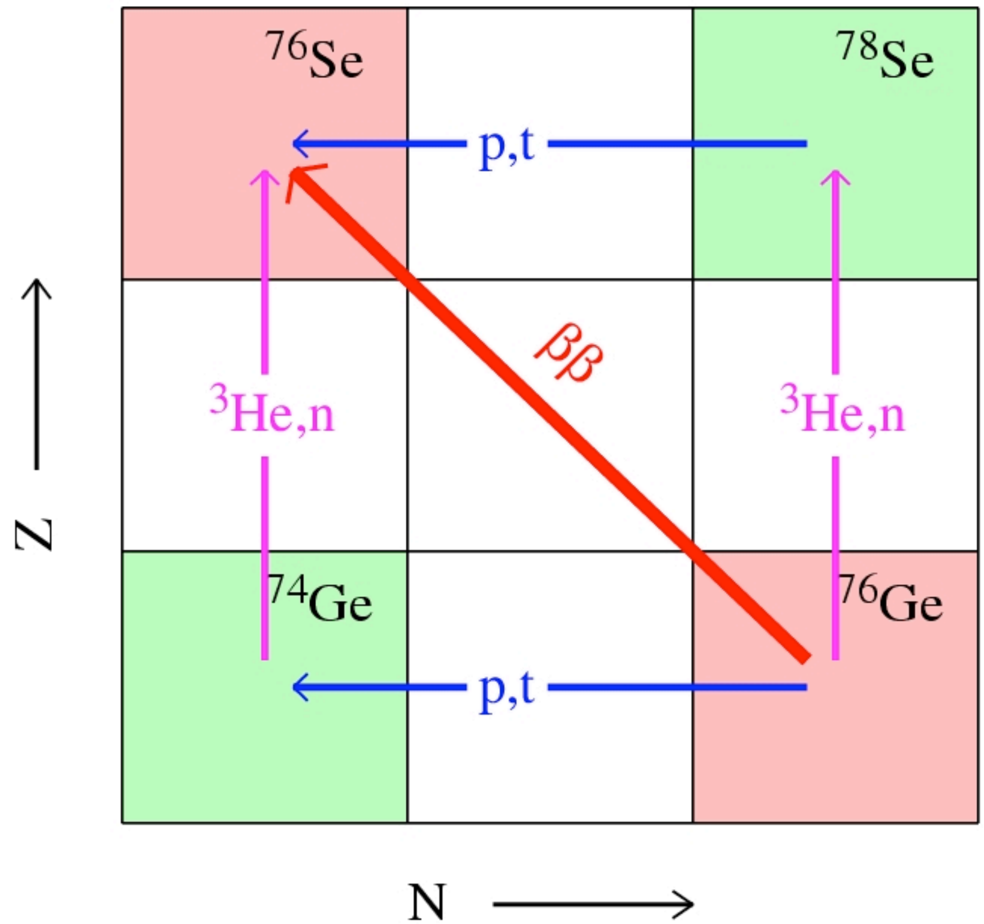
Difference between two experiments not understood. Experiment with trap at Jyvaskyla to come.

# Probing via pair transfer (J. Schiffer et al., see talk DNP EF10)

The overlap is between a pair of correlated neutrons in the $0^+$ ground state and a similar pair of protons in the final state.

For a nucleus such as $^{76}$Ge the pairing correlations produce something like a BCS state.

Such correlations are probed by (t,p) or (p,t) transfer of correlated neutrons pairs or ($^3$He,n) for protons.



# Probing via pair transfer (J. Schiffer et al.)

**But**, there are two complicating issues:

1.) To what extent is the required range of the correlations in the $0^+$ ground state similar in pair transfer to what is relevant in ($0\nu2\beta$) decay? For (p,t) the range is the distance between the pair of neutrons in the triton. How does this compare with what is relevant in ($0\nu2\beta$)? **Question for theorists!**

2.) The other is a matter of reaction mechanism -- there can be sensitivity to the microscopic orbits in (p,t) that could be different in ($0\nu2\beta$). (some limited data.)

# Summary and Outlook

- To get the maximum benefit from next generation measurements, additional theoretical and complementary experimental work on nuclear matrix elements needs to be vigorously pursued.
- A number of 100-200 kg scale experiments are under construction or preparing to submit proposals.
  - The U.S. NuSAG committee (a Joint NSAC-HEPAP sub-committee) has recently completed and issued recommendations for the U.S double beta decay program.
- Next generation $0\nu\beta\beta$ experiments should be able to:
  - Definitively test the Klapdor-Kleingrothaus claim in the 400 meV region.
  - Probe the quasi-degenerate neutrino mass region of 100 meV.
  - Demonstrate backgrounds that would justify scaling up to a 1-ton or larger detector.

# U.S. Neutrino Scientific Assessment Group

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 (*$\langle m_{\beta\beta} \rangle > 100$ 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* ($\langle m_{\beta\beta} \rangle > 10–20$ meV) *with a single experiment*.

Reviewed Five Experiments related to U.S. program.

In terms of funding (alphabetical order)

High priority: CUORE, EXO, Majorana

Lower priority: MOON, Super - NEMO

See DOE NSAC Web Page for the Report.