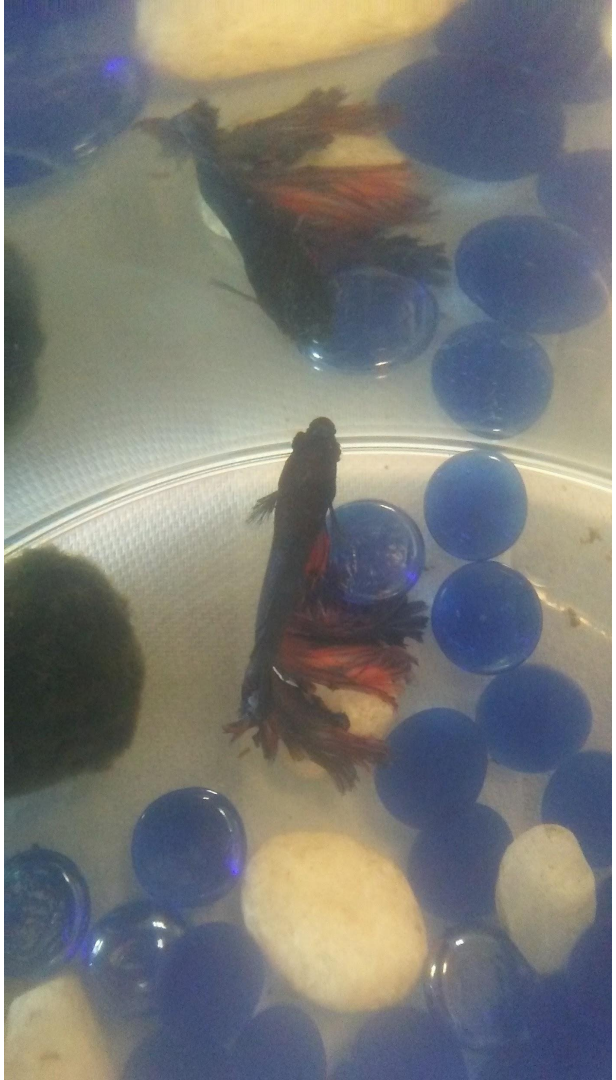


A New Approach to Neutrinoless Double-Beta Decay Searches

Group 17
Baran Bodur, Mahesh Jakkapu, William Parker, Vivek Sharma, Bei Zhou

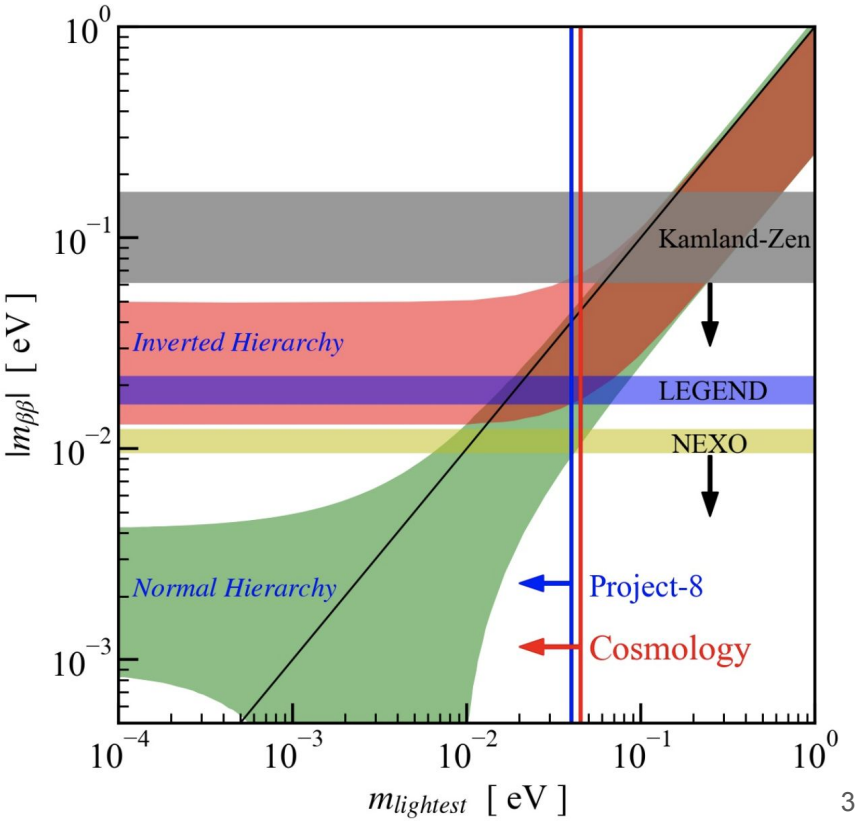
Scenario

- The year is 2030
- England have just won the men's World Cup
- Neutrinoless double beta decay has been discovered!
- LEGEND have measured a half life of $5*10^{27}$ years for ^{76}Ge
- NEXO have measured a half life of $7.5*10^{27}$ years for ^{136}Xe
- We now know neutrinos are Majorana particles and lepton number is violated, and football (soccer) has finally come home

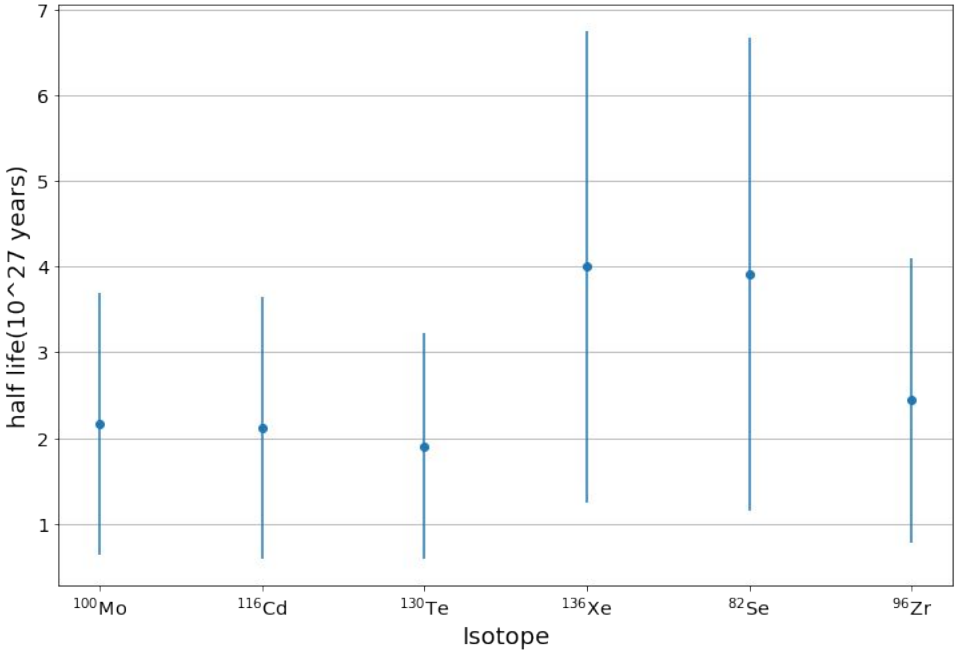
2030 Lobster Plot

- LEGEND has a constraint on $m_{\beta\beta}$ of 0.0192 ± 0.003 eV
- NEXO has a constraint on $m_{\beta\beta}$ of 0.0110 ± 0.001 eV
- From Project 8 and cosmology we get a constraint on the lightest neutrino mass of 40 meV and 50 meV

$$\langle m_{ee} \rangle = |\sum U_{ei}^2 m_i|$$



Extrapolated Half-Lives



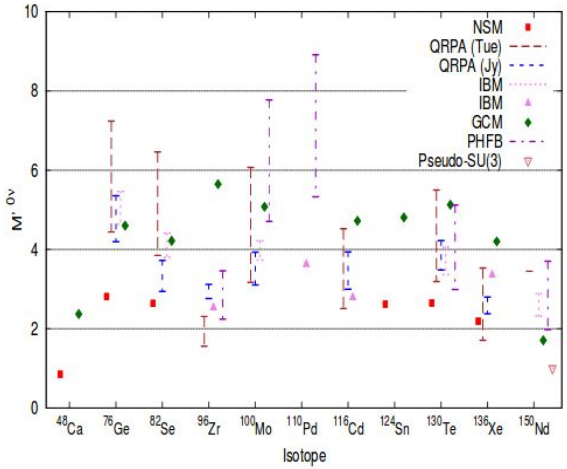


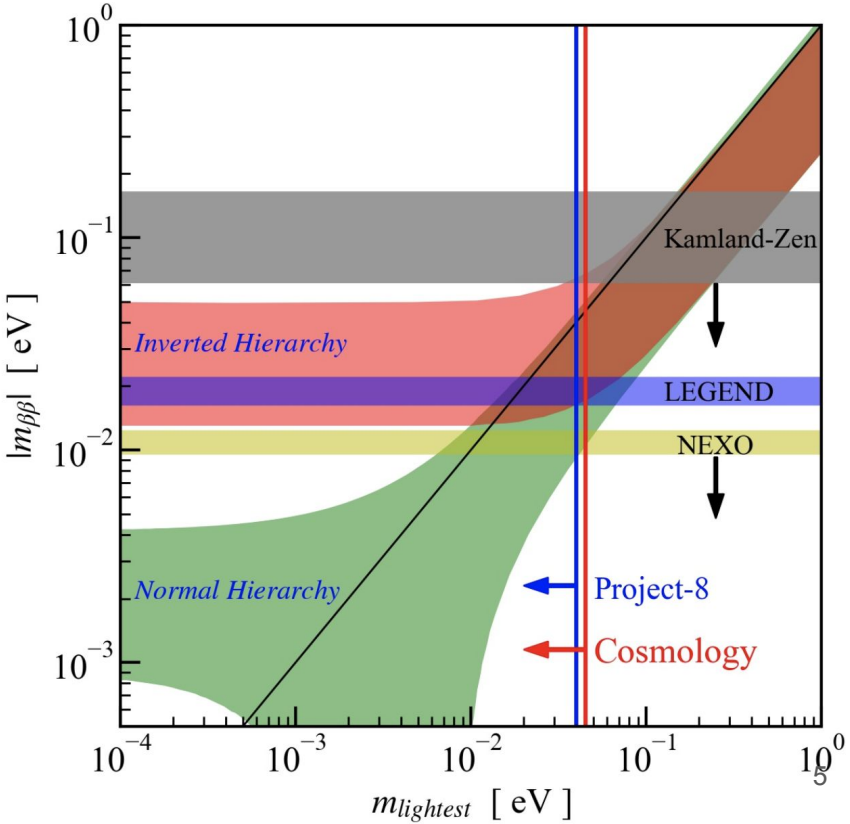
Figure 5. Nuclear matrix element compilation for $0\nu\beta\beta$, different isotopes and calculational approaches.

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle}{m_e^2}$$

Model used for Nuclear Matrix Elements: QRPA

Motivation

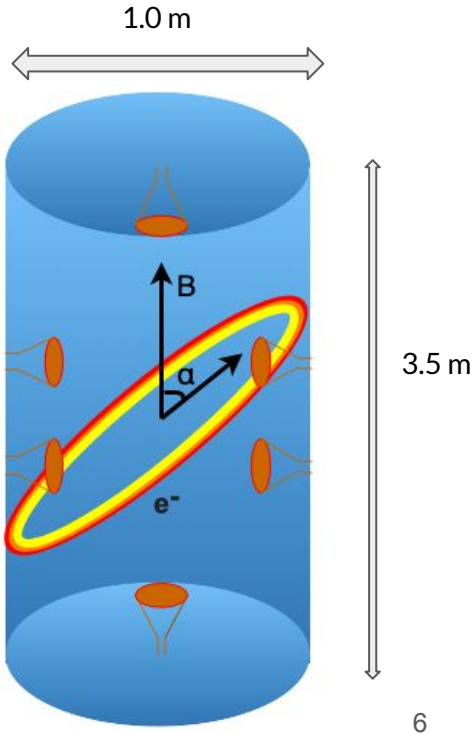
- Reduce the existing 20% uncertainty on $T_{1/2}$
- Resolve tension among the LEGEND and NEXO values for $m_{\beta\beta}$
- Polarisation of decay electrons and individual electron energy distribution to explore decay mechanisms
- We need a new and improved detection technique!



Detector Design: PROJECT 17

- High pressure (15 atm) gaseous ^{136}Xe surrounded by 1 T magnet **(Q-value - 2457 keV)**
- Double beta decay electrons will emit synchrotron radiation which will be picked up by antennae covering the inner wall
- Antennae based detectors will have been successfully demonstrated by Project-8
- Neighbouring antennae will have perpendicular orientation
- For **10 events**, **2500 kg** of ^{136}Xe and 10 years of live time
- Located at the site of Majorana Demonstrator, with a background of $(6.7\pm1.4)*10^{-8}$ counts/(keV kg yr)
- With 50% efficiency and resolution of **10 eV**, sensitivity of $(1.3)*10^{29}$ yr

$$T^{0\nu}_{\frac{1}{2}} = ln(2)\frac{\epsilon a_I N_A \eta}{W}\sqrt{\frac{Mt}{b\Delta E}}$$



Polarization Dependence

$||\boldsymbol{k} \times \boldsymbol{B}$

$$\Gamma_{(\mp,p'_z=0)} = \frac{\alpha}{2}\int_0^{\frac{\pi}{2}} \frac{\omega \sin\theta d\theta}{E'_0(E'_0 - \omega\sin^2\theta)} e^{-(\frac{\omega^2\sin^2\theta}{2m^2B'})}$$
$$[\varepsilon_+\varepsilon_+^*(E'_0 \mp m)(E'_0 - \omega \pm m) - \omega^2\sin\theta\cos\theta(\varepsilon_+\varepsilon^{*3(\lambda)}e^{-i\varphi}$$
$$+\varepsilon^{3(\lambda)}\varepsilon_+^* e^{i\varphi}) + \varepsilon^{3(\lambda)}\varepsilon^{*3(\lambda)}(E'_0 \pm m)(E'_0 - \omega \mp m)(\frac{\omega^2\sin^2\theta}{2m^2B'})].$$

$\perp \boldsymbol{k} \times \boldsymbol{B}$

$$\Gamma^{1\to 0}_{(\mp,p'_z=0)} = \frac{\alpha}{2}\int_0^{\frac{\pi}{2}} \frac{\omega \sin\theta d\theta}{E'_0(E'_0 - \omega\sin^2\theta)} e^{-(\frac{\omega^2\sin^2\theta}{2m^2B'})}[(E'_0 \pm m)(E'_0 - \omega \mp m)\frac{\omega^2\sin^4\theta}{2m^2B'}$$
$$+(E'_0 \mp m)(E'_0 - \omega \pm m)\cos^2\theta + 2\omega^2\sin^2\theta\cos^2\theta];$$

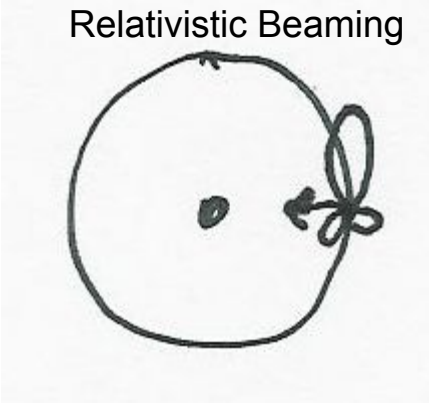
Research in Astron. Astrophys. 2010 Vol. 10 No. 10, 1023–1040

Frequency - Energy Relation

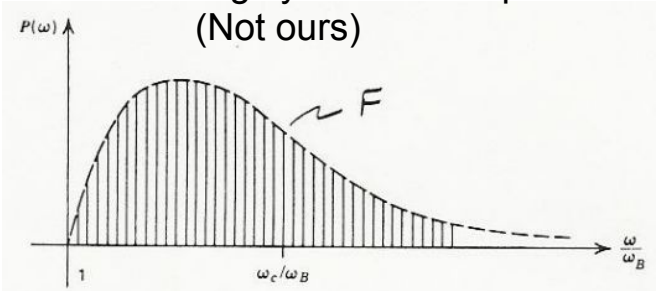
$$f = \frac{e}{2\pi\gamma m_e(1+\beta cos\theta)} = \frac{eBc^2}{2\pi}\frac{1}{E+\sqrt{E^2-m^2c^4}cos\theta}$$

- Electron Energy Range: 2.0 - 1.2 MeV
- Frequency Range With Doppler Shift: 200 GHz - 120 GHz
- Very high frequency microwaves, but antennas exist
- Between cyclotron-synchrotron radiation range

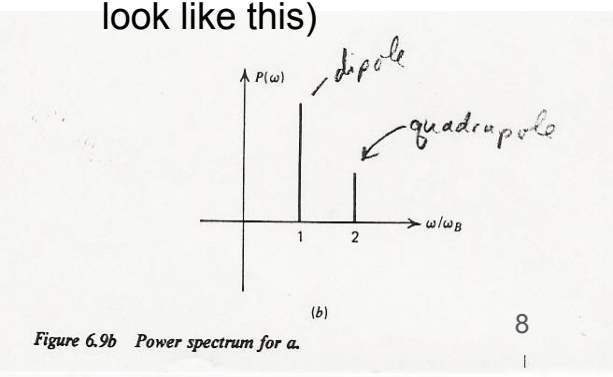
Relativistic Beaming



Highly relativistic spectrum (Not ours)



Relativistic Harmonics (will look like this)



Emitted Power

- Power ~ 50 fW -> -110 dBm, by Larmor Formula:

$$P(\gamma, \alpha) = \frac{e^4}{6\pi\epsilon_0 m_e^2 c} B^2(\gamma^2 - 1) sin^2\alpha$$

- Antennas: 15 cm x 15 cm Horn, linearly polarized:
- Horn Antenna Gain:

$$\frac{4\pi A}{\lambda^2}$$

Free Space Path Loss:

$$(\frac{4\pi d}{\lambda})^2$$

$$\frac{A}{4\pi d^2} = \frac{1}{1000} = -30dB$$

A: antenna area
d: Distance travelled
λ: Wavelength

- Receiver Sensitivity < -140 dBm : Can be achieved with commercial receivers

Energy Resolution

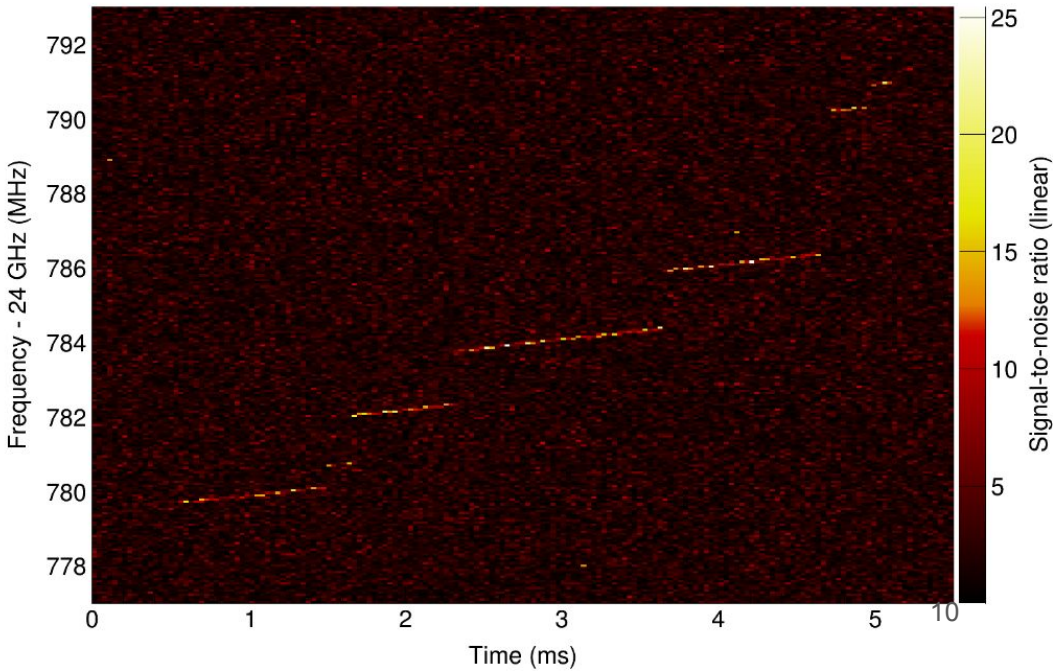
STFT: Short Time Fourier Transform

$$\delta f = -\frac{qBc^2}{2\pi} \frac{\frac{E\cos\theta}{\sqrt{E^2-m^2c^4}} + 1}{(\cos\theta\sqrt{E^2 - m^2c^4} + E)^2} \delta E$$

- 1 eV resolution -> 120 kHz
- 0.05 ms time bins -> ~20 kHz resolution in STFT
- With 50 fW power in 0.05 ms, 1.5 eV energy loss

- Overall, **a few eV** energy resolution

Phys. Rev. Lett. 114, 162501 (2015)



Summary

- In the event of a neutrinoless double beta decay discovery, investigating the decay mechanism is important

- Antenna based detector array yields excellent resolution, but there are many challenges in its implementation, including polarization measurement, low power and high synchrotron frequencies

- Innovative experimental design required to extract new physics

emielpit5

BACK UP

References

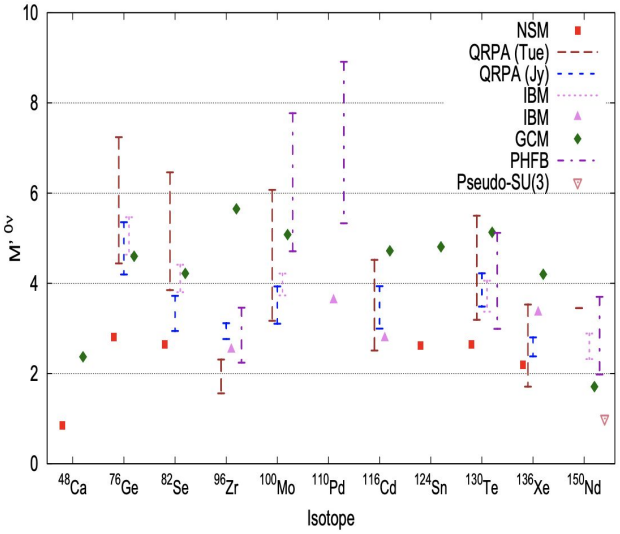


Figure 5. Nuclear matrix element compilation for $0\nu\beta\beta$, different isotopes and calculational approaches.

- Matrix elements and phase space factors. https://arxiv.org/pdf/1206.2560.pdf
- Directional microwave antenna for 200 Gigahertz http://www.jpier.org/PIERC/pierc68/10.16053008.pdf

Budget

- 90% pure ^{136}Xe costs 10 times the commercially available Xe, roughly it costs a few hundred thousand dollars plus the cost to develop the technology to purify the Xe(Project 8 has it by then hopefully).

- The 1T Electromagnet costs 2-4 million dollars.

- The site and background shielding will be reused from Majorana experiment.

Model Dependence

$$\mathcal{A}_\theta \equiv \left(\int_{-1}^{0} \frac{d\Gamma}{d\cos\theta} d\cos\theta - \int_{0}^{1} \frac{d\Gamma}{d\cos\theta} d\cos\theta \right) / \Gamma = \frac{N_+ - N_-}{N_+ + N_-} = \frac{k_\theta}{2}.$$

$$\mathcal{A}_E \equiv \left(\int_{0}^{Q/2} \frac{d\Gamma}{d(\Delta t)} d(\Delta t) - \int_{Q/2}^{Q} \frac{d\Gamma}{d(\Delta t)} d(\Delta t) \right) / \Gamma = \frac{N_+ - N_-}{N_+ + N_-} = \frac{k_E}{2},$$

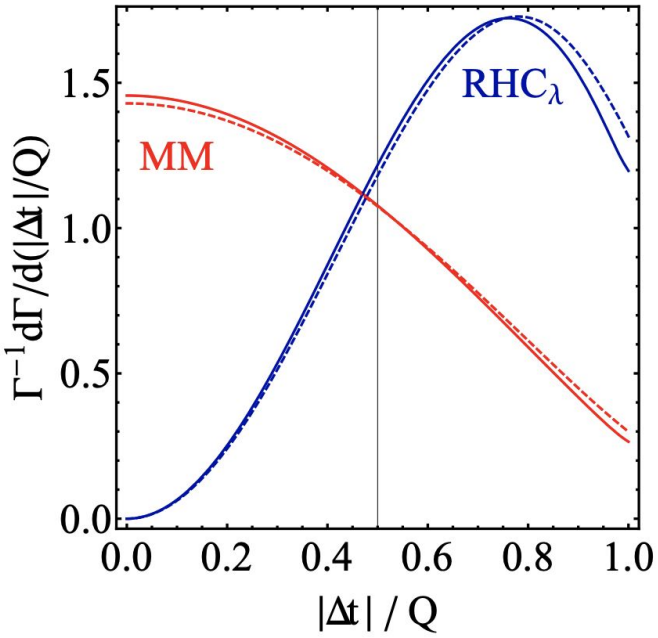


Fig. 2: Normalised $0\nu\beta\beta$ decay distribution with respect to the electron energy difference in the MM (red) and RHC$_\lambda$ mechanism (blue) for the isotopes ^{82}Se (solid curves) and ^{150}Nd (dashed curves).

https://arxiv.org/abs/1005.1241

Achieving Receiver Sensitivity

$$S_i = k(T_a + T_{rx})B \cdot \frac{S_o}{N_o}$$

K = Boltzmann constant

Total T = 10 K with good commercially

B = bandwitdh ~ 20 kHz

S/N = signal to noise ratio ~ 20 (our goal)

(see arxiv: 0904.2860 and Wikipedia)

Background Reduction

- Solar neutrinos scattering
  - Large mass increases ratio of signal to this background
- Radiation from detector materials
  - Develop techniques for radiopure materials such as electroformed Copper and alloys, and polymers
- Radiation from further away
  - Block with water or liquid cryogen shielding. This also allows a cosmic veto
- Cosmic muons induce backgrounds by: muon capture, muon-nucleon quasi-elastic scattering, EM showers, photo-neutron production
  - Numerous theoretical and experimental studies to determine production yields of isotopes common in $0\nu\beta\beta$ decay experiments
  - Minimise exposure to cosmic rays on the surface
  - Allow materials to ‘cool down’ underground after exposure

Background Reduction (cont.)

- In ^{222}Rn chain, ^{214}Bi decays in coincidence with a ^{214}Po alpha decay which has a half life of 160*ms*
  - Timing can be used to identify ^{214}Bi decays in the bulk and surface of the detector
- $0\nu\beta\beta$ and $2\nu\beta\beta$ decays will be distributed uniformly in the detector, as will events from uniformly distributed radioactive material in the detector
  - But some backgrounds from radioactive mechanical supports and localised detector components can be rejected by optimised fiducial volume cuts
- ^{136}Xe decay results in ionised Ba daughter. This can be used to distinguish from all backgrounds but $2\nu\beta\beta$ decay if the Ba ions can be identified with high efficiency
- No microwave ovens near the detector!