# The Effect of Cancellation in Neutrinoless Double Beta Decay

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arXiv:1310.6218, Manimala Mitra, Silvia Pascoli, Steven Wong

# Outline:

- Neutrinoless double beta decay-the canonical interpretation
- The cancellation framework
- Phenomenological implications
  - Sterile neutrinos
  - R-parity violating supersymmetry
- Model realization
- Summary

# Experimental Observation

Small non-zero eV neutrino masses $m_i$ and mixing $U$ from oscillation and non-oscillation experiments

Neutrino oscillation $(\nu_\alpha \to \nu_\beta)$

(From solar, atmospheric, reactor, long-baseline experiments)

Non-Oscillation $\Rightarrow$ Cosmology, $\beta$-decay, $(\beta\beta)_{0\nu}$-decay...

## Oscillation Experiments

Information about mass square differences and mixing angles.

- $\Delta m^2_{12} \sim 10^{-5}\,\mathrm{eV}^2$, $\Delta m^2_{13} \sim 10^{-3}\,\mathrm{eV}^2$
- Large mixing angles $\theta_{12} \sim 34^\circ$, $\theta_{23} \sim 42^\circ$
- Non-zero $\theta_{13} \sim 8^\circ$ (DAYA BAY, RENO)

## Cosmology

- Bound from cosmology $\Sigma m_i < \mathcal{O}(0.1)$ eV.

BOSS result $\to \Sigma_i m_i \sim 0.35$ eV

( arXiv: 1403.4599)

Super Kamiokande, Long Baseline $\sim$ T2K, MINOS, K2K ; Reactor $\sim$ DAYA BAY, RENO,...;

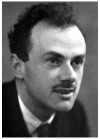
Solar $\sim$ SNO, Borexino,...

# Contd

Light Neutrinos $\Rightarrow$ Dirac or Majorana?

Neutrino Mass

$\Downarrow$



Dirac or Majorana?

- Dirac mass, $m_D \bar{\nu}_L N_R \rightarrow$ lepton number is conserved
- Majorana mass, $m \nu^T C^{-1} \nu \rightarrow$ lepton number is violated by two unit

Lepton number is a Global $U(1)$ symmetry of standard model

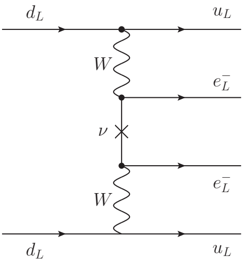
# Neutrinoless double beta decay

The process is $(A, Z) \to (A, Z+2) + 2e^-$

Probing lepton number violation

- L and B numbers are accidental symmetries of the standard model
- Light neutrinos can mediate the process, if Majorana (Racah, 1937; Furry 1939)

Majorana Nature of Light Neutrinos

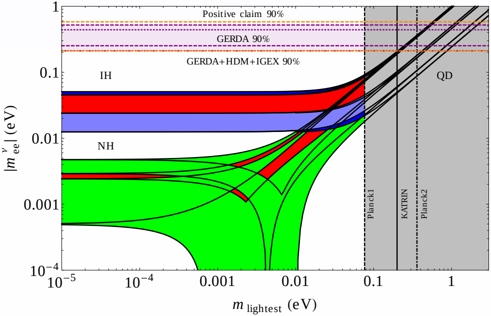



Schechter-Valle, PRD, 82

- Experiments at GRAN SASSO, Italy, Japan, Sudan...
- Existing bound on half-life from GERDA, KamLAND-Zen...
- Claim of observation of $(\beta\beta)_{0\nu}$-decay...
- Promising forthcoming experiments $\to$ GERDA Phase-II, Majorana, SuperNEMO

# The light neutrino contribution

The half-life $\rightarrow$ $\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}|\mathcal{M}_\nu|^2 \left|\frac{m^\nu_{ee}}{m_e}\right|^2$




- $G_{0\nu} \rightarrow$ phase-space
- $\mathcal{M}_\nu \rightarrow$ nuclear matrix element
- $m^\nu_{ee} = \Sigma m_i U^2_{ei}$ effective mass of $(\beta\beta)_{0\nu}$-decay

Tension between $(\beta\beta)_{0\nu}$-decay and cosmology (Fogli et al., 2008; Mitra et al., 2012, 2013)

$$|m^\nu_{ee}| = |m_1 U^2_{e1} + m_2 U^2_{e2} e^{2i\alpha} + m_3 U^2_{e3} e^{2i\beta}|$$

- $\alpha$, $\beta$ $\rightarrow$ Majorana phase, $m_i$ $\rightarrow$ light neutrino masses
- Unknown $\rightarrow$ neutrino mass spectra, absolute mass scale, CP phases

# Experimental Results

## Experimental Results for $^{76}\mathrm{Ge}$

- GERDA, $T^{0\nu}_{1/2} > 2.1 \times 10^{25}\mathrm{yr}$, $90\%$ C.L
- GERDA combined (IGEX+Heidelberg-Moscow) $T^{0\nu}_{1/2} > 3.0 \times 10^{25}\mathrm{yr}$, $90\%$ C.L
  GERDA collaboration, 2013

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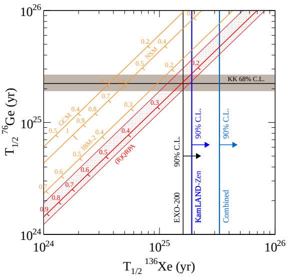
## Experimental Results for $^{136}\mathrm{Xe}$

- EXO-200, $T^{0\nu}_{1/2} > 1.6 \times 10^{25}\mathrm{yr}$ at $90\%$ C.L EXO collaboration, 2012
- KamLAND-Zen, $T^{0\nu}_{1/2} > 2.6 \times 10^{25}\mathrm{yr}$ at $90\%$ C.L (Neutrino 2014)
- KamLAND-Zen combined, $T^{0\nu}_{1/2} > 3.4 \times 10^{25}\mathrm{yr}$ at $90\%$ C.L
  KamLAND-Zen collaboration, 2012

- The half-life for $^{76}\mathrm{Ge}$, $T^{0\nu}_{1/2} = 1.19^{+037}_{-0.23} \times 10^{25}$ yr, 68% CL.
  H. V. Klapdor-Kleingrothaus *et al.*, 2004
- The half-life for $^{76}\mathrm{Ge}$, $T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr, 68% CL.
  H. V. Klapdor-Kleingrothaus *et al.*, 2006

GERDA combined rules out the positive claim for almost all of the NME calculations. The individual bound is still consistent

Dev, Goswami, Mitra and Rodejohann, PRD, 2013




From A. Gando et al., 2012

- KamLAND-Zen rules out the positive claim for most of the NME calculation
- How to overcome the mutual conflict between two different sets of experiments?

# Contd

Escaping the mutual conflict between two different experiments?

- Different experiments that use different isotopes
- Experiment A $\rightarrow$ Measurement of half-life
- Experiment B $\rightarrow$ Bound on half-life. Result of experiment A is constrained

Possible solution $\rightarrow$ Effect of Interference

In a realistic model of neutrino mass generation more than one contribution can be present in $(\beta\beta)_{0\nu}$-decay $\rightarrow$ can interfere

# Contd:

Previous and recent studies → additional contributions in $(\beta\beta)_{0\nu}$-decay

- R parity violating supersymmetry (Mohapatra 1986; Hirsch et al, 1995; Choi et al, 2002; Allanach et al, 2009. )
- Left Right symmetry (Hirsch et al., PLB, 96, Tello et al., PRL, 2011, Goswami et al., JHEP, 2012, Barry et al., JHEP, 2013, Vogel et al., PRD, 2003; Patra et al., 2012)
- Quasi-dirac neutrinos (Petcov, Ibarra, 2010)
- Sterile neutrinos ( S. Pascoli et al., 2012; M. Blennow et al., 2010; M. Mitra, F. Vissani, G. Senjanović, 2012; Meroni et al, 2012 )

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Models with right handed neutrinos at colliders ( Keung, Senjanovic, 83; A. Datta et al., 1994; Kersten, Smirnov, 2007; P. S. Bhupal Dev, Franceschini, Mohapatra, 2012; Chang-Hun Lee et al., 2013; P.S.Bhupal Dev, Apostolos Pilaftsis, Un-ki Yang, 2013; S. P. Das et al., 2012; Atre et al., 2009; F. Del. Aguila et al., 2008... )

- Light neutrino and sterile neutrino contribution
- Light neutrino and squark-gluino contributions in RPV

# Cancellation in $(\beta\beta)_{0\nu}$-decay

Two large contributions in $(\beta\beta)_{0\nu}$-decay → Interference

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(|\eta_1^2|\mathcal{M}_1^2 + |\eta_2^2|\mathcal{M}_2^2 + 2\cos\alpha\,|\eta_1||\eta_2|\mathcal{M}_1\mathcal{M}_2)$$

- $\eta_1$ and $\eta_2$ are two different contributions. $\alpha \rightarrow$ relative phase

Cancellation between two contributions in isotope A.

$$|\eta_1|\mathcal{M}_{1,A} = |\eta_2|\mathcal{M}_{2,A}$$

↓

Infinite half-life $T^{0\nu}_{1/2}(A)$

Any bound on the half-life of the isotope A can be escaped.

The half-life of any other isotope B is larger than no interference

$$\frac{1}{T^{0\nu}_{1/2}(B)} = G^B_{0\nu}|\eta_1^2|(\mathcal{M}_{1,B} - \frac{\mathcal{M}_{1,A}}{\mathcal{M}_{2,A}}\mathcal{M}_{2,B})^2$$

# Contd

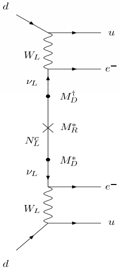
Cancellation between active and sterile neutrino contributions

$n_h$ heavy Majorana neutrinos $N_i \to$ mixing $V_{li} \to$ mass $M_i$.

$M_i^2 > p^2 \sim (200)^2 \mathrm{MeV}^2$; $p \to$ intermediate momentum

$$\text{Half-life } \frac{1}{T_{1/2}} = G_{0\nu} \left|\mathcal{M}_\nu \eta_\nu + \mathcal{M}_N \eta_N\right|^2$$

$$\eta_\nu = U_{ei}^2 m_i / m_e,\ \eta_N = V_{ei}^2 m_p / M_i$$




Cancellation in isotope A

$$|\eta_N| = |\eta_\nu| \frac{\mathcal{M}_\nu}{\mathcal{M}_N}$$

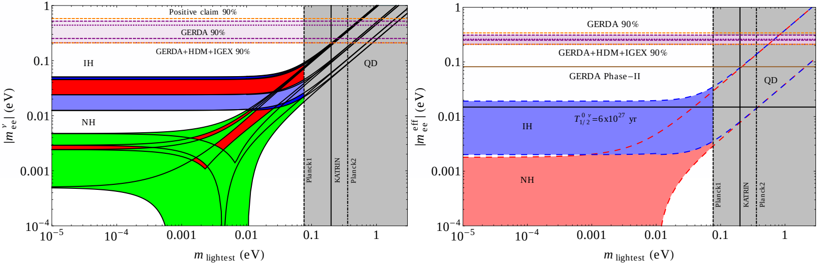
# Contd

The half-life in isotope B is larger

$$\frac{1}{T^{0\nu}_{1/2}(B)} = G^{B}_{0\nu} \left| \frac{m^{\nu}_{\rm ee}}{m_{\rm e}} \right|^2 \mathcal{M}^2_{\nu,B} \left( 1 - \frac{\mathcal{M}_{\nu,A}}{\mathcal{M}_{N,A}} \frac{\mathcal{M}_{N,B}}{\mathcal{M}_{\nu,B}} \right)^2$$

The *redefined effective mass* is suppressed

$$\left| m^{\rm eff}_{\rm ee} \right| = \left| m^{\nu}_{\rm ee} \left( 1 - \frac{\mathcal{M}_{\nu,A}}{\mathcal{M}_{N,A}} \frac{\mathcal{M}_{N,B}}{\mathcal{M}_{\nu,B}} \right) \right|$$




- Larger value of the lightest mass is required
- The tension with cosmology is even more stringent

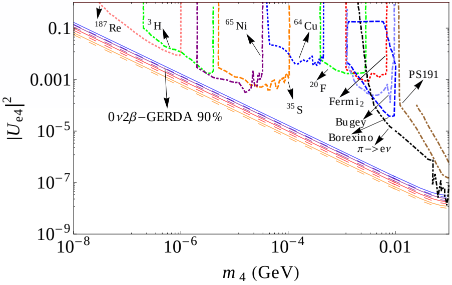
Additional light sterile neutrinos may lead to cancellation between light and heavy sterile neutrinos

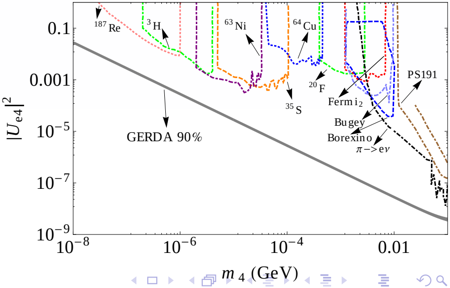
The light and heavy neutrino contributions

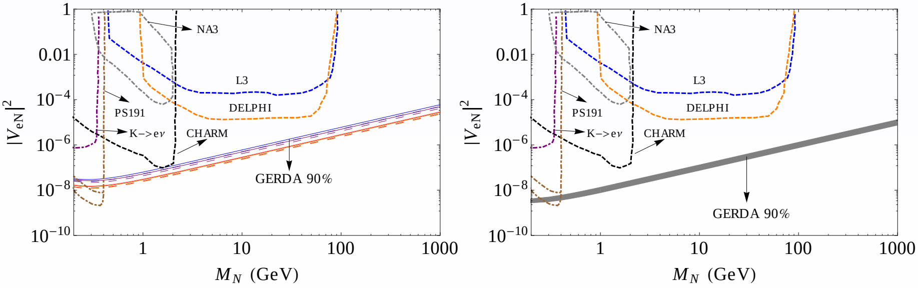
$$\eta_l = \frac{(\Sigma_i m_i U_{ei}^2 + \Sigma_k m_{4_k} U_{e4_k}^2)}{m_e}, \;\; \eta_N = \sum_j \frac{m_p V_{eN_j}^2}{M_{N_j}}$$

Cancellation condition $\rightarrow$ $|\eta_l|\mathcal{M}_l = |\eta_N|\mathcal{M}_N$

Cancellation between active and sterile neutrino for $^{136}\mathrm{Xe}$ and implications for $^{76}\mathrm{Ge}$






Atre et al., 2009; Mitra, Vissani, Senjanovic, 2012; Mitra, Pascoli, Wong, 2013

Bound on mass-mixing plane is less stringent in the presence of cancellation !!

$$|U_{e4}^2| \lesssim \frac{\kappa}{m_4} \frac{1}{\left|\left(1 - \frac{\mathcal{M}_{\nu,\mathrm{Xe}}}{\mathcal{M}_{N,\mathrm{Xe}}} \frac{\mathcal{M}_{N,\mathrm{Ge}}}{\mathcal{M}_{\nu,\mathrm{Ge}}}\right)\right|}$$

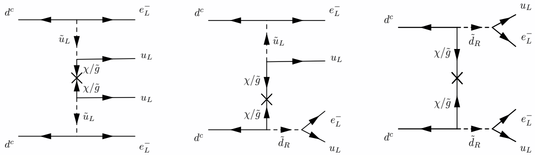
# Contd

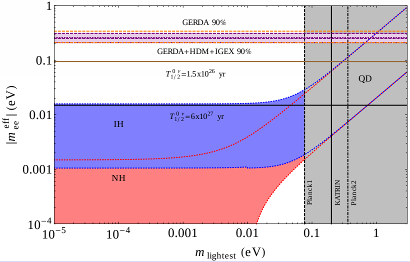
Similar suppression of the effective mass for RPV scenario

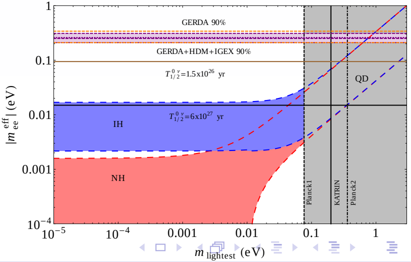
Large gluino contribution in $(\beta\beta)_{0\nu}$-decay R. N. Mohapatra, Phys. ReV. D34, 1986

- Light neutrino and gluino exchange. Light neutrino and squark exchange

Interference in $(\beta\beta)_{0\nu}$-decay $\rightarrow$ Meroni, Petcov, Simkovic, 2012; Simkovic et al., 2010; Faessler et al., 2011



# Model Realization-Extended Seesaw

Models with sterile neutrinos $N$ and $S$. The mass matrix

$$M_n = \begin{pmatrix} 0 & \alpha^T & m_D^T \\ \alpha & \mu & m_S^T \\ m_D & m_S & m_R \end{pmatrix}$$

C. S. Kim, S. K. Kang, 2006

- Two widely separated LNV scale $\mu$ and $M_R$ with $\mu \ll M_R$
- Two masses of the sterile neutrinos $m_N \sim -m_S^T m_R^{-1} m_S$ and $m_{N'} \sim m_R$
- Active-sterile neutrino mixings $m_D/m_S$ and $m_D/m_R$. Negligible contribution from sterile neutrino $N$ in $(\beta\beta)_{0\nu}$-decay

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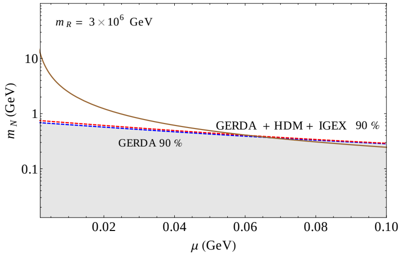
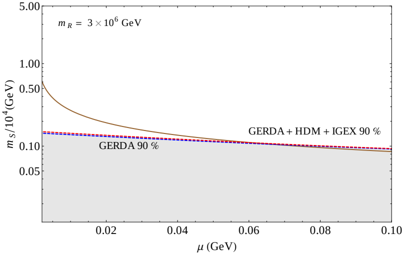
Inverse seesaw with one small lepton number violating scale $\mu$ (Mohapatra 1986; Mohapatra, Valle, 1986; Wyler et al., 1983; E. Witten, 1986). Quasi-degenerate neutrinos $\rightarrow$ small LNV signatures (Kersten, Smirnov, 2007)

# Contd

Cancellation between the active neutrino and the sterile neutrino $S$ in isotope $^{136}\mathrm{Xe}$

$$\mu = \left(\frac{m_R}{m_S^2}\right)\left(\frac{\mathcal{M}_{N,\mathrm{Xe}}}{\mathcal{M}_{\nu,\mathrm{Xe}}}\right) m_{\mathrm{e}} m_{\mathrm{p}}$$




Bound from KamLAND-Zen is satisfied. GERDA limit is saturated for sterile neutrino mass for $m_N \sim \mathcal{O}(100)$ MeV

# Summary

- Effect of interference is important. Should be taken into account
- The mutual conflict between two different experiments can be resolved
- A realistic model of neutrino mass generation may lead to additional contributions in neutrinoless double beta decay
- Interference between two large contributions
- Cancellation between two different contribution can escape any constraint of half-life
- However, non-trivial effect in the half-life prediction of other isotopes

If $(\beta\beta)_{0\nu}$-decay is not observed $\rightarrow$ Light neutrinos can be Dirac or cancellation between two contributions

Thank You