A new sensitivity goal for neutrino-less double beta decay experiments

Srubabati Goswami
Physical Research Laboratory, Ahmedabad
Leverhulme Trust Visiting Professor, Imperial College, London

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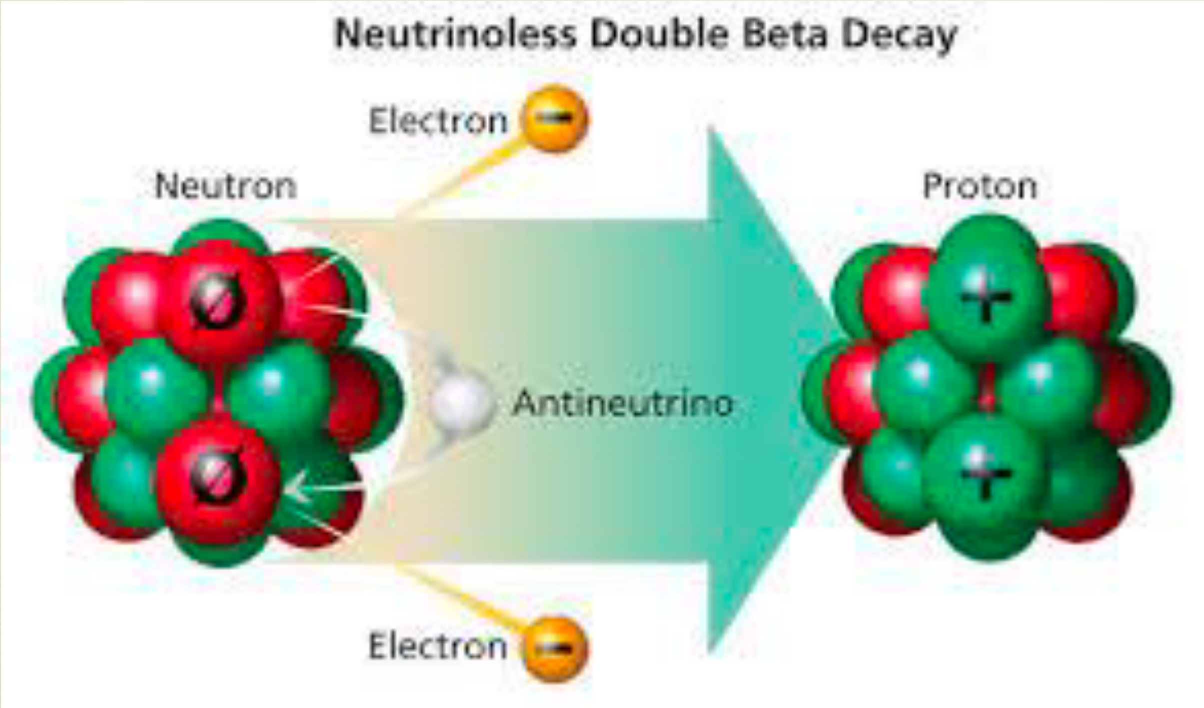
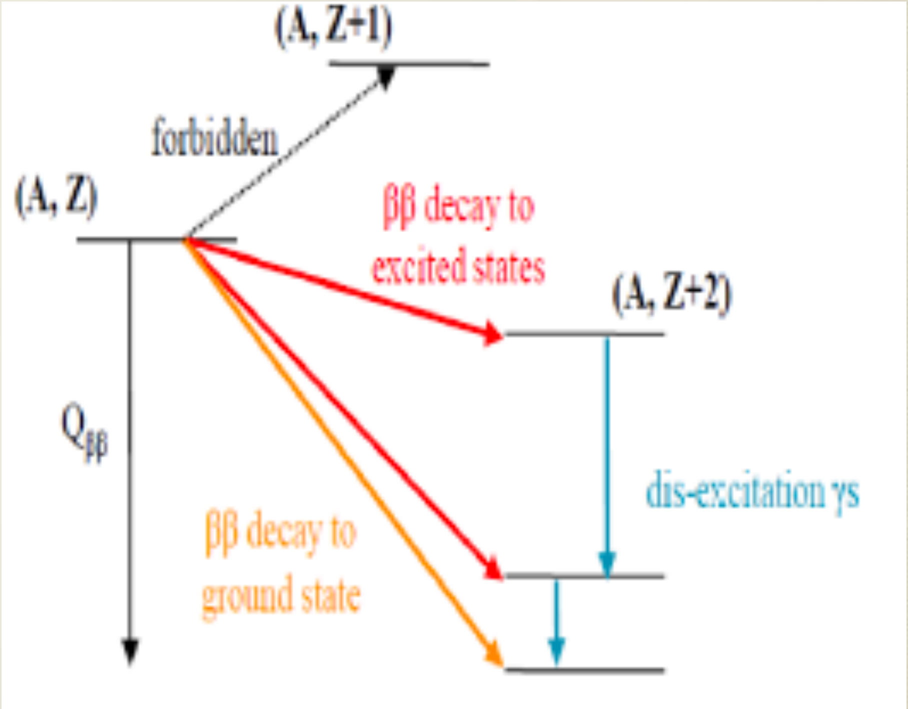
Neutrino-less double beta decay

$$(A, Z) \to (A, Z+2) + 2\,e^- \quad (0\nu\beta\beta)$$



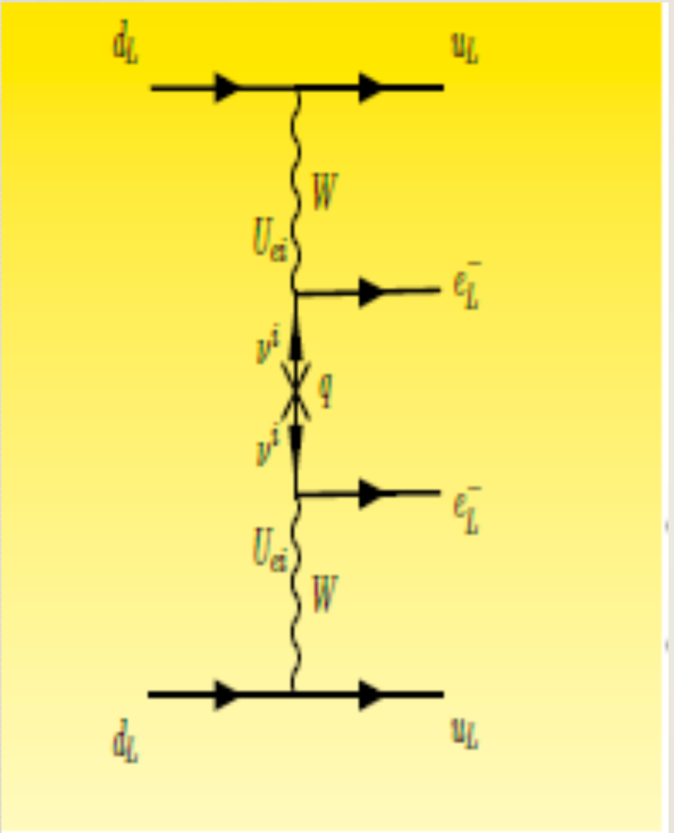


Rare Process

Violates Lepton Number by 2 Units

Standard Picture for $0\nu\beta\beta$

- $0\nu\beta\beta$ mediated by light neutrinos



- The half-life for $0\nu\beta\beta$,

$$\frac{1}{T_{1/2}^{0\nu}} = G|\mathcal{M}_\nu|^2 \left|\frac{m_{ee}^\nu}{m_e}\right|^2 ,$$

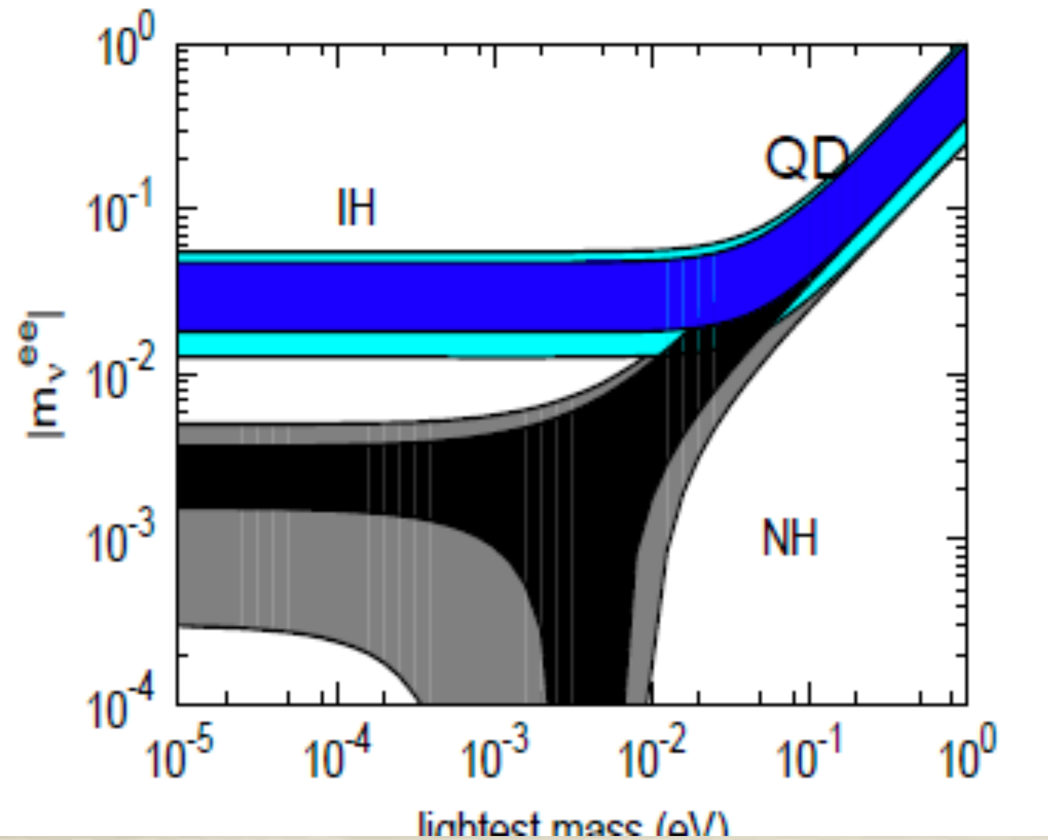
- $G \rightarrow$ contains the phase space factors (calculable)
- $\mathcal{M}_\nu$ is the nuclear matrix element (important and complicated.)

- $|m_\nu^{ee}| = |U_{ei}^2 m_i| \rightarrow$ the effective mass, (interesting)

The effective mass

$$|m_\nu^{ee}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2i\alpha_1} + m_3 U_{e3}^2 e^{2i\alpha_2}|$$

- ν Mass Spectrum
- Absolute ν Mass Scale
- CP phases



NH: $m_1 << m_2 << m_3$

IH: $m_3 << m_1 \approx m_2$

QD: $m_1 \approx m_2 \approx m_3$

Experimental Results

- Results from experiments using ^{136}Xe

➤ $T_{1/2}^{0\nu} > 1.07 \times 10^{26}$ **years at 90% C.L. (KamLAND-ZEN)**

A. Gando et al. Phys. Rev. Lett.117, no. 8, 082503 (2016)

➤ $T_{1/2} > 1.6 \times 10^{25}$ years at 90% C.L. (EXO)

J.B. Albert et al. , Nature 510 ,229 (2014)

- **Results from GERDA using** ^{76}Ge

$T_{1/2}^{0\nu} > 5.2 \times 10^{25}$ **years at 90% C.L**

M. Agostini et al., Nature 54, 47 (2017)

- Disfavours the positive claim by Klapdor-Kleingotherus et al.

$\dot{T}_{1/2}^{0\nu} = 2.23_{-0.31}^{+0.44} \times 10^{25}$ **years at 68% C.L.**

Klapdor-Kleingrothaus, Krivosheina , Mod. Phys. Lett. A21, 1547 (2006)

Bounds on $|m^{\nu}_{ee}| = m_{\beta\beta}$

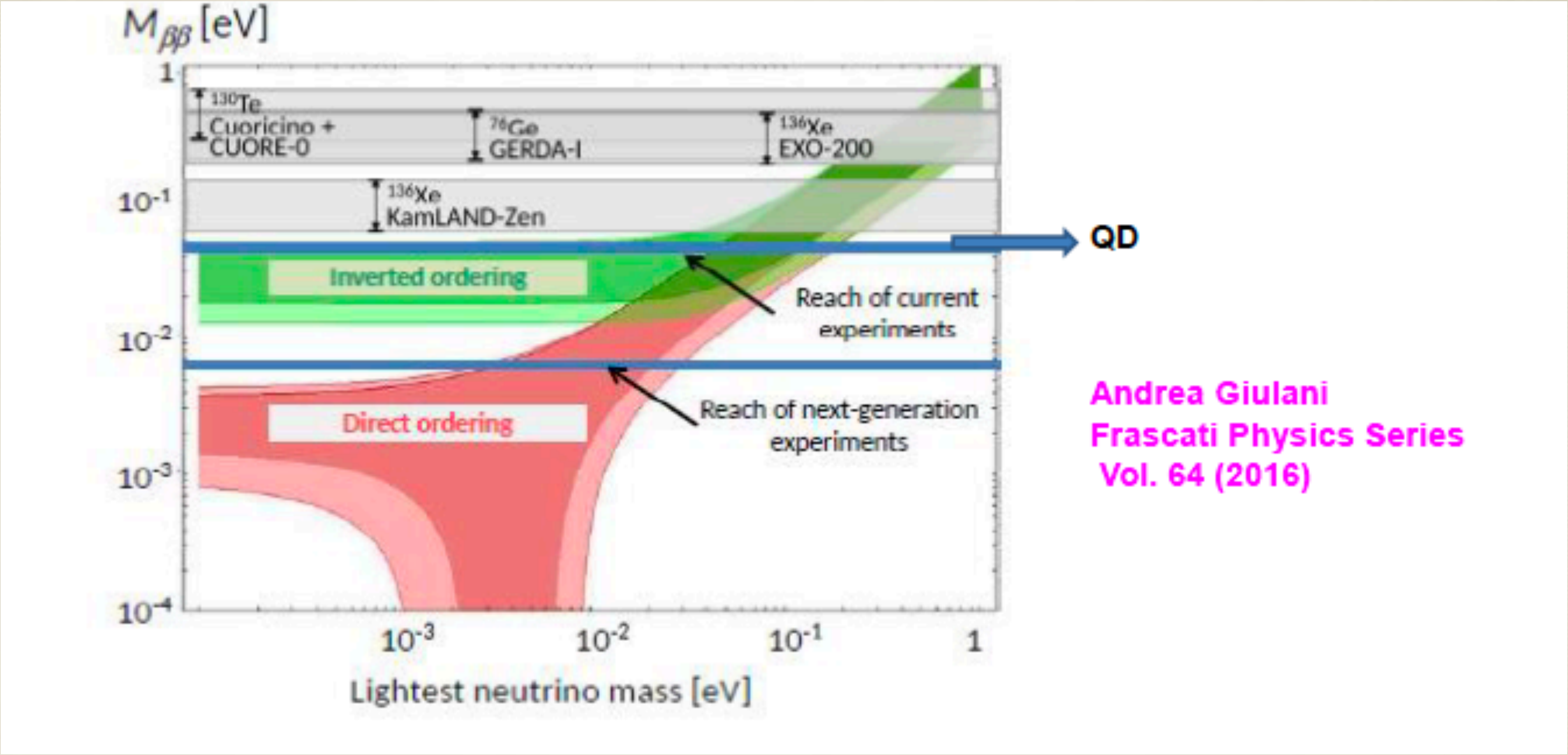
* The lower bound on half-life can be translated to an upper bound on $m_{\beta\beta}$

NME			$\lvert m^{\nu}_{ee}\rvert$	$\lvert m^{\nu}_{ee}\rvert$
Method	$\mathcal{M}^{0\nu}$ (^{76}Ge)	$\mathcal{M}^{0\nu}$ (^{136}Xe)	(^{76}Ge)	(^{136}Xe)
EDF(U)[52]	4.6	4.2	0.20	0.06
ISM(U) [53]	2.81	2.19	0.33	0.12
IBM-2 [54]	5.42	3.33	0.17	0.08
pm-QRPA(U)[55]	5.18	3.16	0.18	0.08
SRQRPA-B[56]	5.82	3.36	0.16	0.08
SRQRPA-B[56]	4.75	2.29	0.20	0.11
QRPA-B [57]	5.57	2.46	0.17	0.11
QRPA-A[57]	5.16	2.18	0.18	0.12
SkM-HFB-QRPA [58]	5.09	1.89	0.18	0.14

Awasthi, Dasgupta, Mitra, Phys. Rev. D. 2016

The variation in the upper bound is due to different NME

Current limit and future reach



* Width in $m_{\beta\beta}$ due to oscillation parameters and Majorana phases
* Next generation experiments can probe IH
* New physics predictions in the desert region ?

Non-Standard Interactions

- Standard NC interaction:

$$\nu_\alpha + f \to \nu_\alpha + f$$

- Non-standard NC interaction

$$\nu_\alpha + f \to \nu_\beta + f$$

$$\mathcal{L} = -G^{\alpha\beta}\epsilon^f_{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\nu_\beta\bar{f}\gamma_\mu f$$

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d}\frac{N_f}{N_e}\epsilon^f_{\alpha\beta}$$

$$H = \frac{1}{2E}\left[U\mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})U^\dagger + V\right],$$

$V \Rightarrow$ matter potential in presence of NSI,

$$V = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}.$$

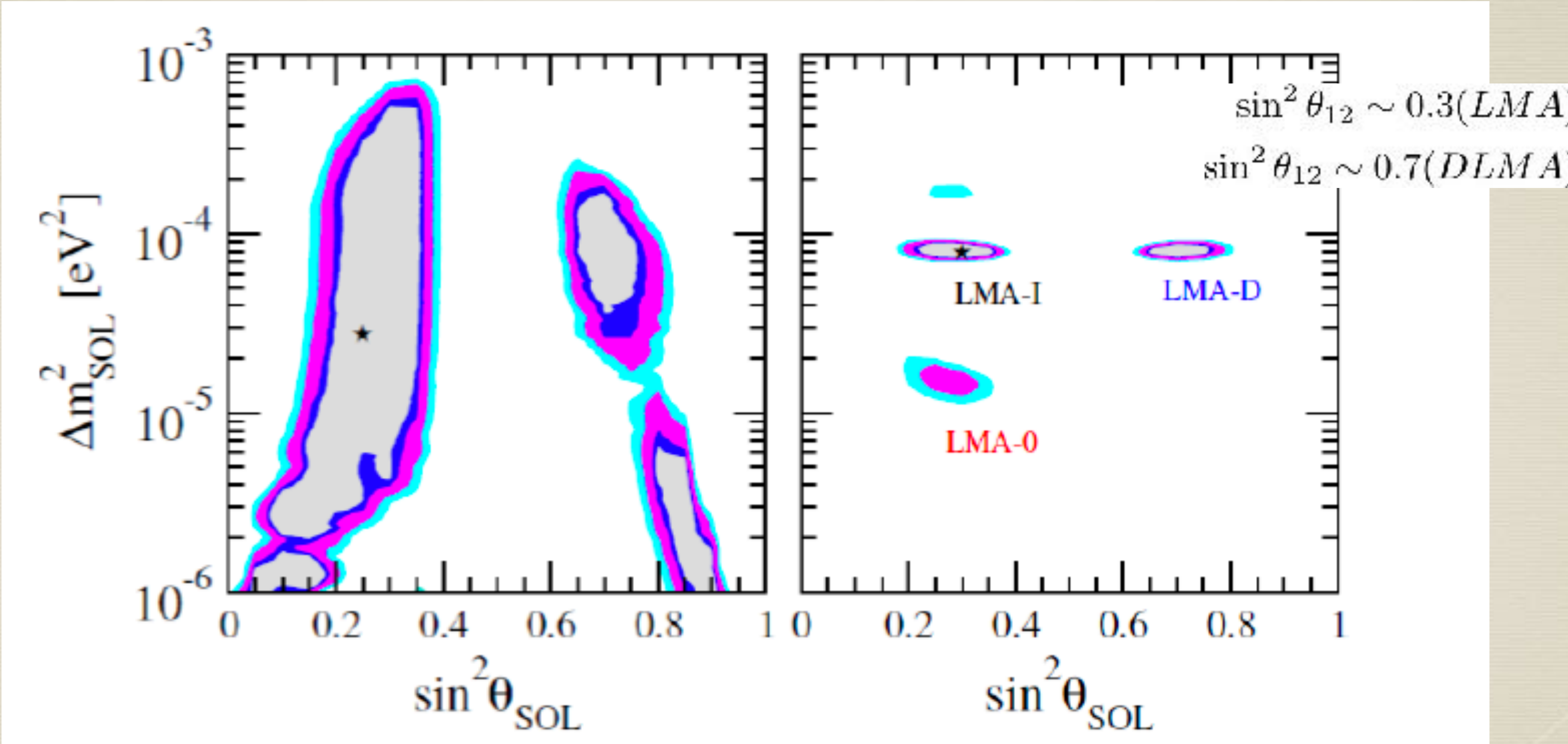
Here, $A \equiv 2\sqrt{2}G_F N_e E$ and $\epsilon_{\alpha\beta}e^{i\phi_{\alpha\beta}} \equiv \sum_{f,C}\epsilon^{fC}_{\alpha\beta}\frac{N_f}{N_e}$

$H \to -H^*$ under

$$\theta_{12} \to \pi/2 - \theta_{12},\ \delta \to \pi - \delta,$$
$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21}$$
$$V \to -S.V.S$$
$$S = Diag(1, -1, -1)$$

Coloma, Schwetz, 1604.05772
P. Bakhti, Y Farzan 1403.0744

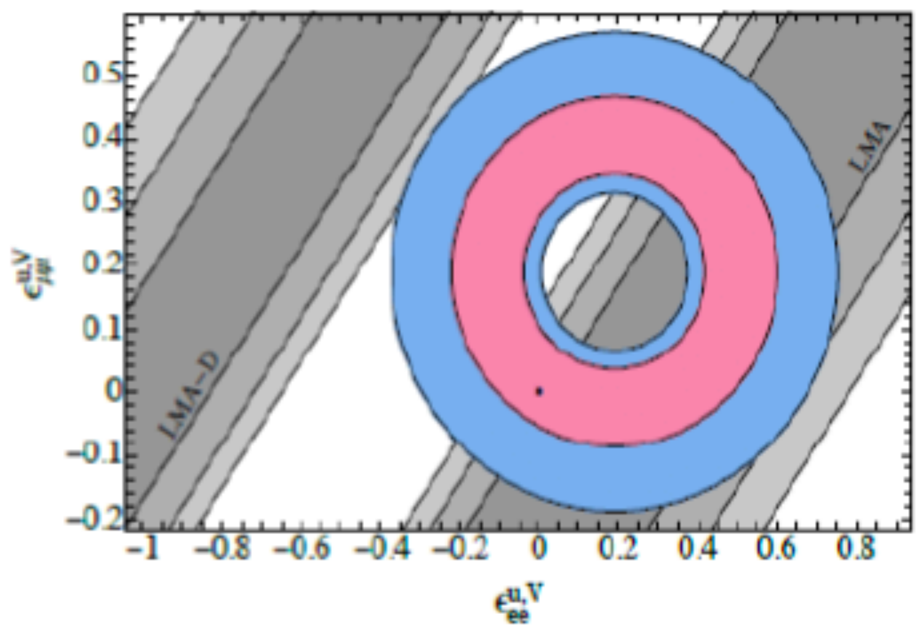
The Dark-LMA Solution(NSI)



Miranda, M. A. Tortola, and J. W. F. Valle,J. HighEnergy Phys. 10 (2006) 008.

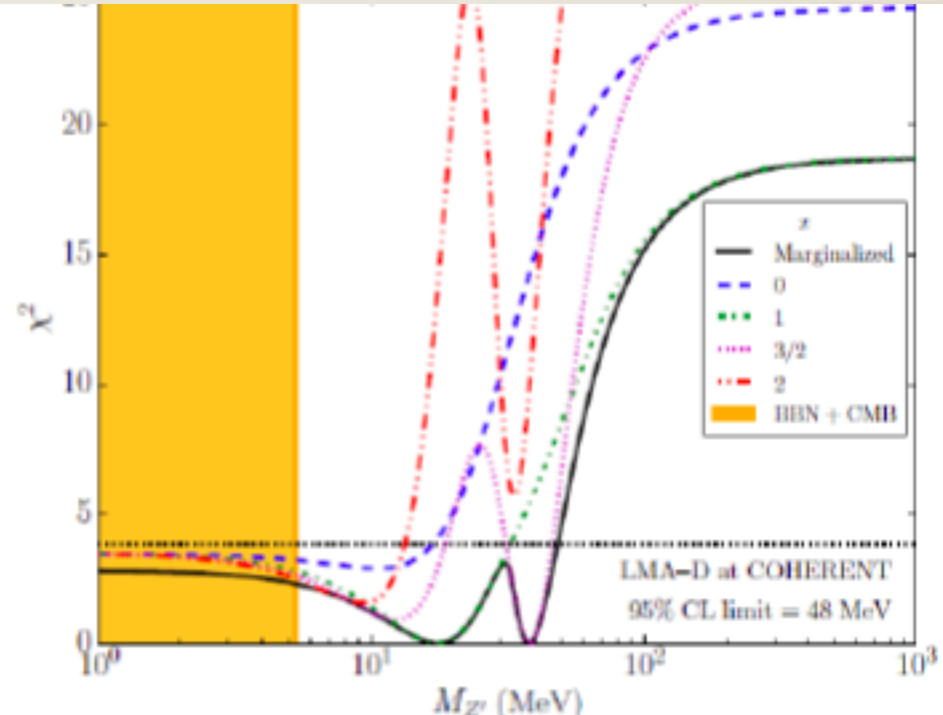
Do Scattering Experiments disfavour DLMA ?

Scattering experiments like CHARM, NuTeV, COHERENT can measure the NSI parameters



DLMA disfavoured at approx 3σ

For light mediators $M'_Z \gtrsim 10$ MeV,



DLMA disfavoured for

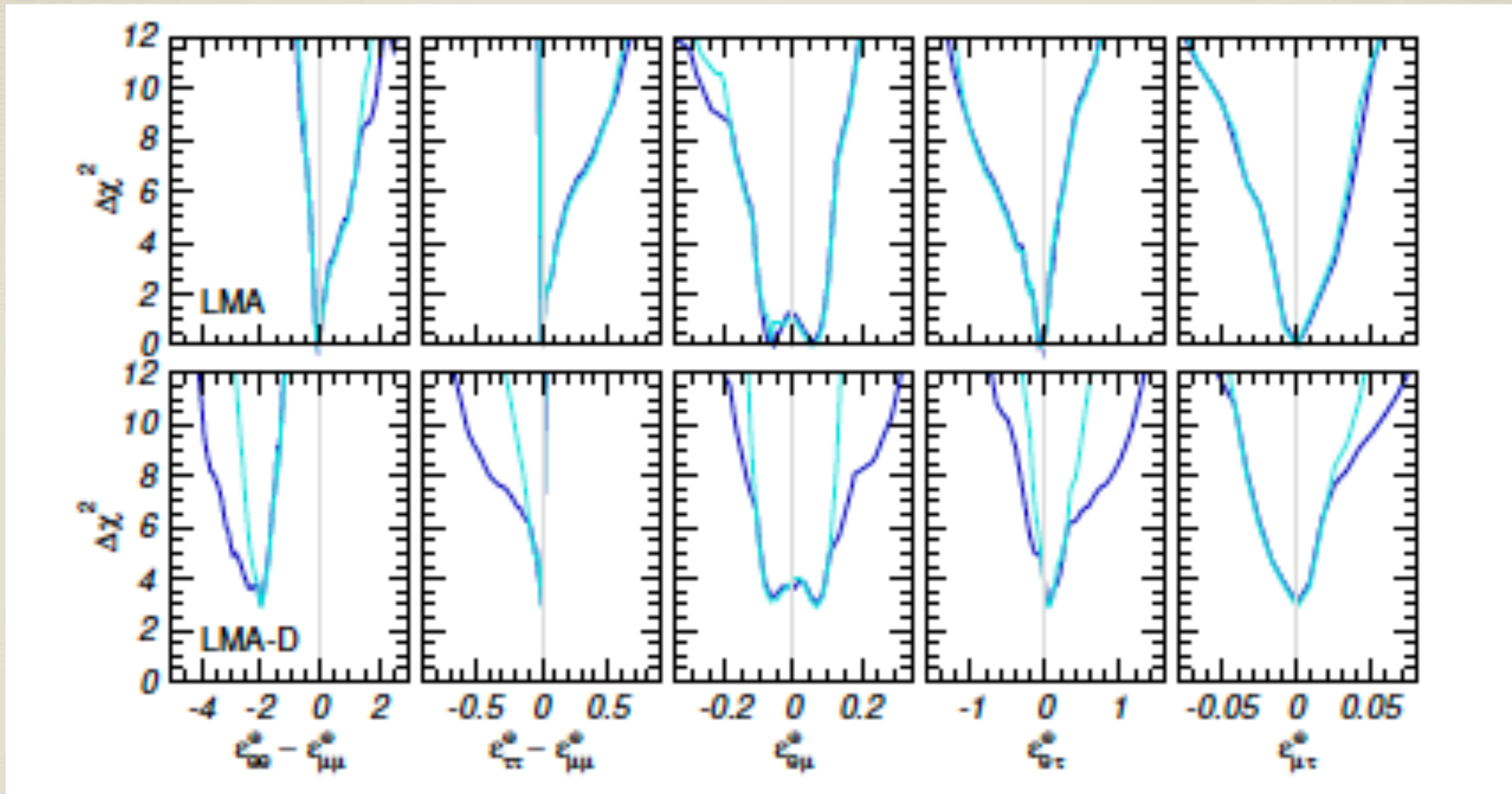
$M_{Z'} > 48$ MeV at 95% C.L. (1 d.o.f.)

$\epsilon^{u,V}_{ee} = \epsilon^{d,V}_{ee} = \frac{x}{4} - \frac{1}{2}$

Coloma, Gonzalez-Garcia, Maltoni, Schwetz
Phys. Rev. D(2017).

Denton, Farzan, Shoemaker,
J. HighEnergy Phys (2018).

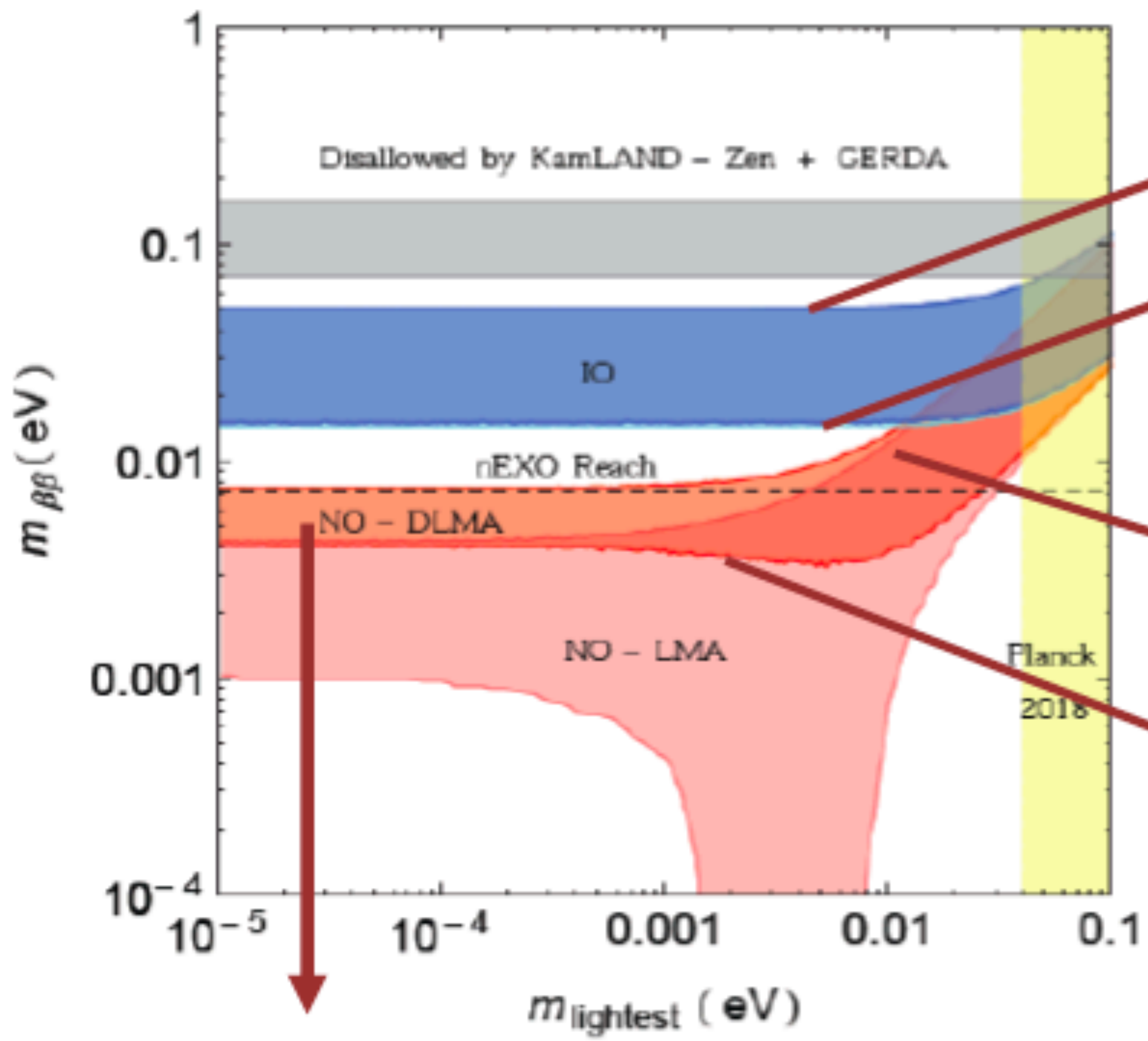
Current Status of the DLMA solution



* Constraints including COHERENT (cyan lines)

Esteban,. Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado,J. High Energy Phys. 08 (2018)

DLMA Solution and $0\nu\beta\beta$



$m_{\beta\beta IOmax} = |c_{13}^2 \sqrt{\Delta m^2_{atm}}|$ $\quad (\alpha_2 = 0, \pi)$.

$m_{\beta\beta IOmin} = |c_{13}^2 \cos 2\theta_{12} \sqrt{\Delta m^2_{atm}}|$ $\quad (\alpha_2 = \pi/2)$

$m_1 \approx m_2 \approx \sqrt{\Delta m^2_{sol}} << m_3 \approx \sqrt{\Delta m^2_{atm}}$

$m_{\beta\beta NOmax} \approx \sqrt{\Delta m^2_{atm} r c_{13}^2}$ $\quad (\alpha_2 = \alpha_3 = 0)$,

$m_{\beta\beta min} \approx m_1 |(1 - 3 s_{12}^2 c_{13}^2 - 11 s_{13}^2)|$.

$(\alpha_2 = \alpha_3 = \pi/2)$

No cancellation for DLMA

$m_{\beta\beta NO} = \sqrt{\Delta m^2_{atm}} |\sqrt{r}\, s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3\, s_{13}^2 e^{2i\alpha_3}|$; $\quad \alpha_2 = \alpha_3 = 0, \pi$; $\quad \alpha_2 = 0$ and $\alpha_3 = \pi/2$.

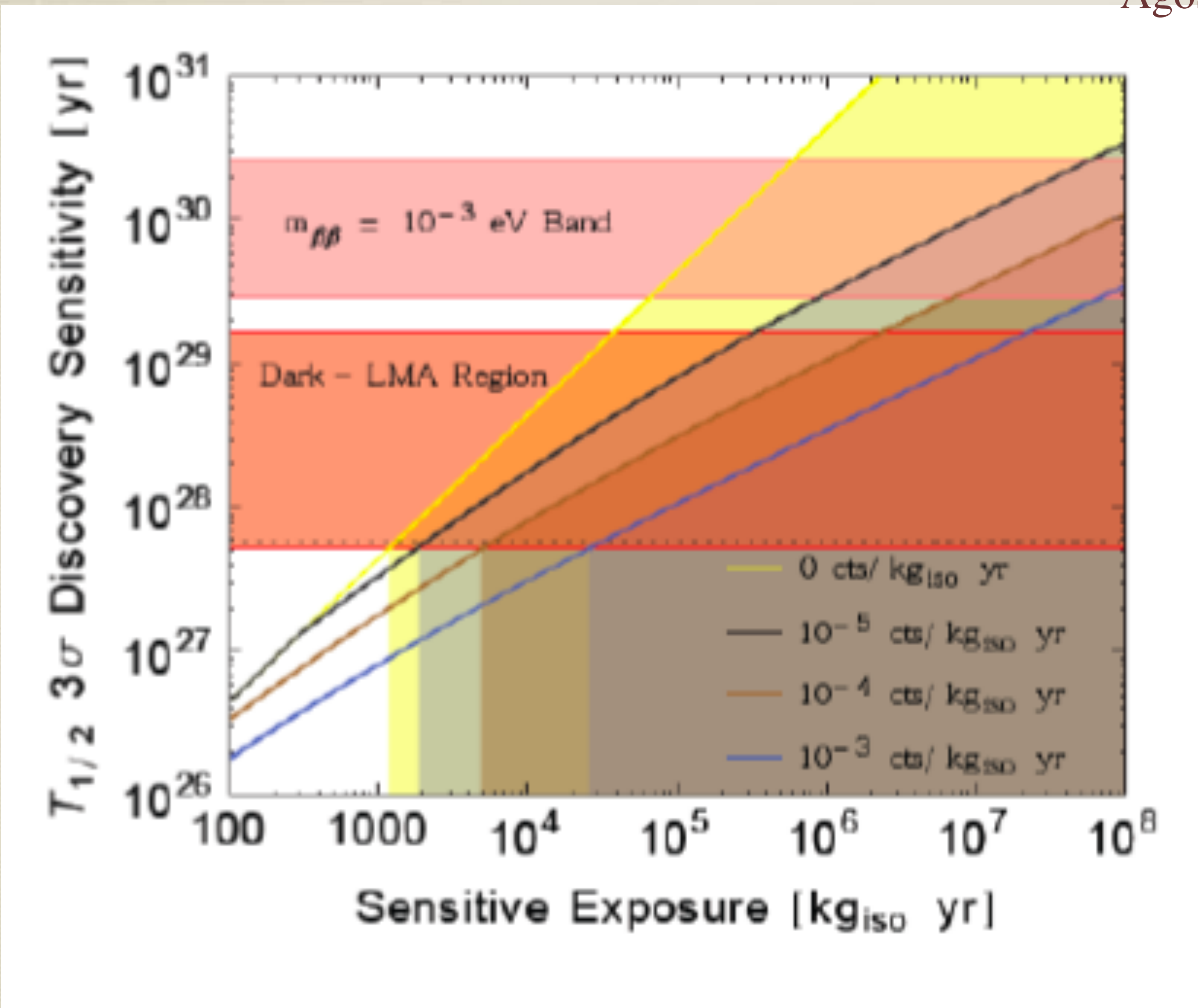
Higher value for DLMA

$r = |\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}|$.

Vishnudath, Choubey, Goswami, Phys, Rev. D. (2019)

Probing the DLMA region in $0\nu\beta\beta$

Agostini, Benato, Detwiler,Phys. Rev. D (2017)



$$T_{1/2} = \ln 2 \frac{N_A \epsilon}{m_a S_{3\sigma}(B)}.$$

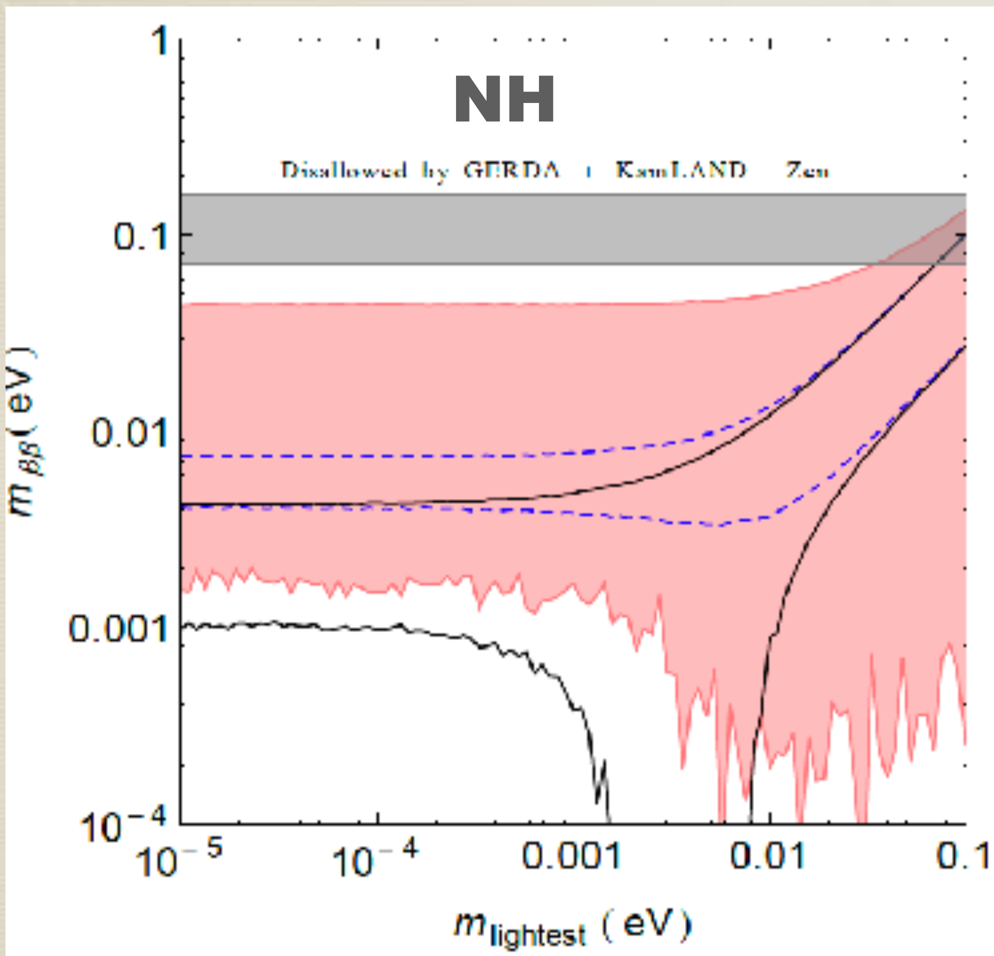
Isotope	NME (M_ν)	$G(10^{-15}\text{year}^{-1})$	$T_{1/2}$ range (years)
^{136}Xe	1.6 – 4.8	14.58	$5.3 \times 10^{27} - 1.7 \times 10^{29}$
^{76}Ge	2.8 – 6.1	2.363	$2.0 \times 10^{28} - 3.4 \times 10^{29}$
^{130}Te	1.4 – 6.4	14.22	$4.9 \times 10^{28} - 2.2 \times 10^{29}$

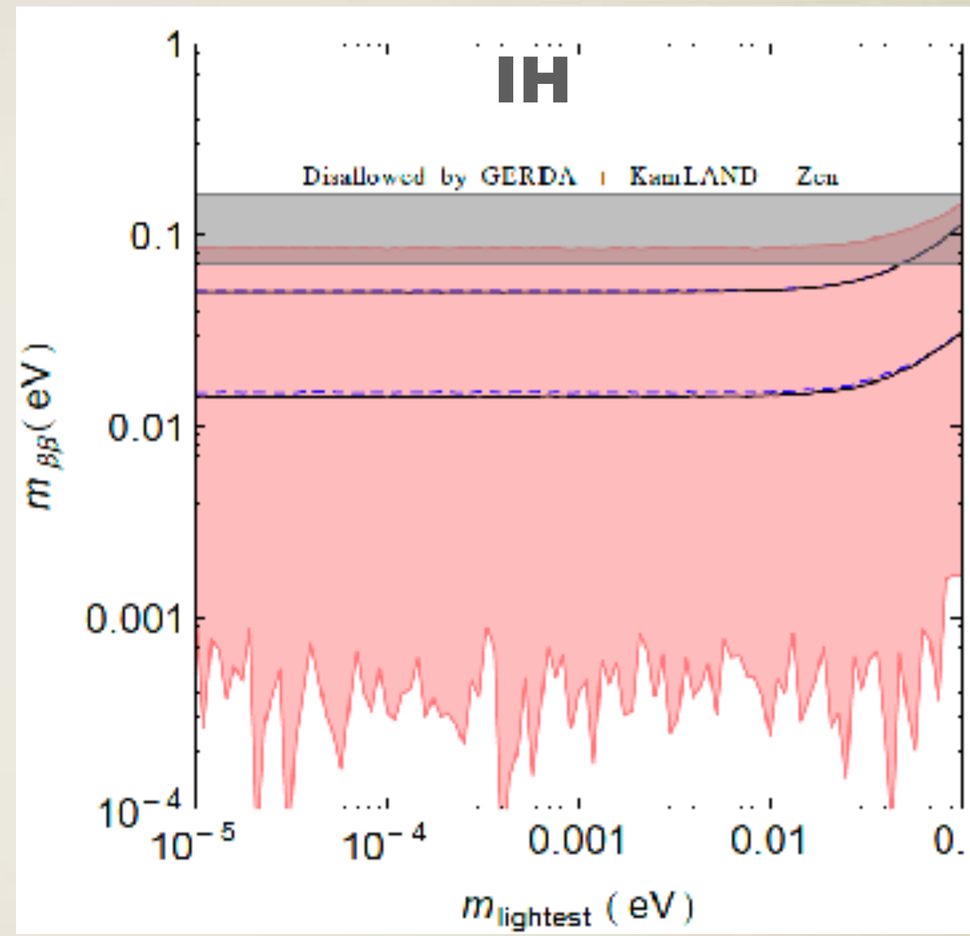
$$1 - CDF_{\text{Poisson}}(C_{3\sigma}|S_{3\sigma} + B) = 50\%.$$

Less exposure needed for DLMA

Vishnudath, Choubey, Goswmi, Phys, Rev. D. (2019)

Comparison with sterile neutrinos





* Predictions in the desert zone
* DLMA range narrower

Already in the disallowed part

Cancellation regions

Deepthi, Goswami, Poddar, Vishnudath (in progress)

Conclusions

* In presence of NSI, the solar neutrino problem admits a new solution with $\sin^2\theta_{12} \sim 0.7$ (Dark-LMA solution)
* We studied the implication of this for neutrino-less double beta decay
* ForIH, predictions remain the same
* The NH predictions are higher for smaller masses
* This is in the desert region between NH and IH (0.004 -0.007 eV)
* Future experiments can explore this region, if no signal is found for IH
* Neutrino-less double beta decay experiments can test the DLMA region in this parameter region.


Thank
you


BACKUP

Past, present and future experiments

Experiment	Isotope	Techinique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% C.L.) [10^{25} yr]
Past							
Cuoricino, [177]	^{130}Te	bolometers	40.7 (TeO_2)	19.75	5.8 ± 2.1	0.153 ± 0.006	0.24
CUORE-0, [178]	^{130}Te	bolometers	39 (TeO_2)	9.8	5.1 ± 0.3	0.058 ± 0.006	0.29
Heidelberg-Moscow, [179]	^{76}Ge	Ge diodes	11 (^{enr}Ge)	35.5	4.23 ± 0.14	0.06 ± 0.01	1.9
IGEX, [180, 181]	^{76}Ge	Ge diodes	8.1 (^{enr}Ge)	8.9	~ 4	$\lesssim 0.06$	1.57
GERDA-I, [165, 182]	^{76}Ge	Ge diodes	17.7 (^{enr}Ge)	21.64	3.2 ± 0.2	~ 0.01	2.1
NEMO-3, [183]	^{100}Mo	tracker + calorimeter	6.9 (^{100}Mo)	34.7	350	0.013	0.11
Present							
EXO-200, [184]	^{136}Xe	LXe TPC	175 (^{enr}Xe)	100	89 ± 3	$(1.7 \pm 0.2) \cdot 10^{-3}$	1.1
KamLAND-Zen, [185, 186]	^{136}Xe	loaded liquid scintillator	348 (^{enr}Xe)	89.5	244 ± 11	~ 0.01	1.9
Future							
CUORE, [187]	^{130}Te	bolometers	741 (TeO_2)	1030	5	0.01	9.5
GERDA-II, [172]	^{76}Ge	Ge diodes	37.8 (^{enr}Ge)	100	3	0.001	15
LUCIFER, [188]	^{82}Se	bolometers	17 (Zn^{82}Se)	18	10	0.001	1.8
MAJORANA D., [189]	^{76}Ge	Ge diodes	44.8 ($^{enr/nat}$Ge)	100 [a]	4	0.003	12
NEXT, [190, 191]	^{136}Xe	Xe TPC	100 (^{enr}Xe)	300	$12.3 - 17.2$	$5 \cdot 10^{-4}$	5
AMoRE, [192]	^{100}Mo	bolometers	200 (Ca^{enr}MoO$_4$)	295	9	$1 \cdot 10^{-4}$	5
nEXO, [193]	^{136}Xe	LXe TPC	4780 (^{enr}Xe)	12150 [b]	58	$1.7 \cdot 10^{-5}$ [b]	66
PandaX-III, [194]	^{136}Xe	Xe TPC	1000 (^{enr}Xe)	3000 [c]	$12 - 76$	0.001	11 [c]
SNO+, [195]	^{130}Te	loaded liquid scintillator	2340 (^{nat}Te)	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [196, 197]	^{82}Se	tracker + calorimeter	100 (^{82}Se)	500	120	0.01	10

[a] our assumption (corresponding sensitivity from Fig. 14 of Ref. [189]).
[b] we assume 3 tons fiducial volume.
[c] our assumption by rescaling NEXT.

Dell'Oro , Marcocci, Viel, Vissani, 2016