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Cosmic Neutrinos Parallel Session

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The ν generation: present and future constraints on neutrino masses from cosmology and laboratory experiments

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Based on M.Gerbino, M. Lattanzi and A. Melchiorri, arXiv:1507.08614

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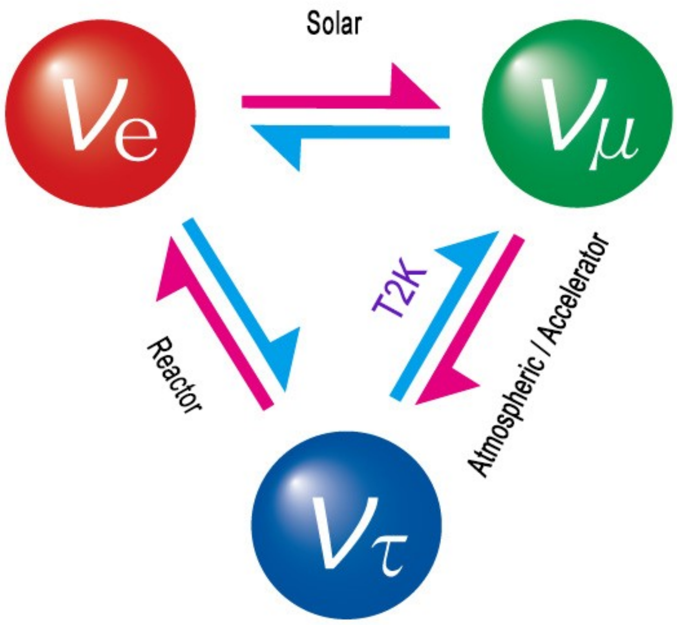
A jigsaw puzzle

- **The pieces: probes and observables (what we measure, how we measure)**
- **Composing the puzzle: the likelihood code (how to combine what we measure)**
- **Identifying the picture: results**

Oscillations



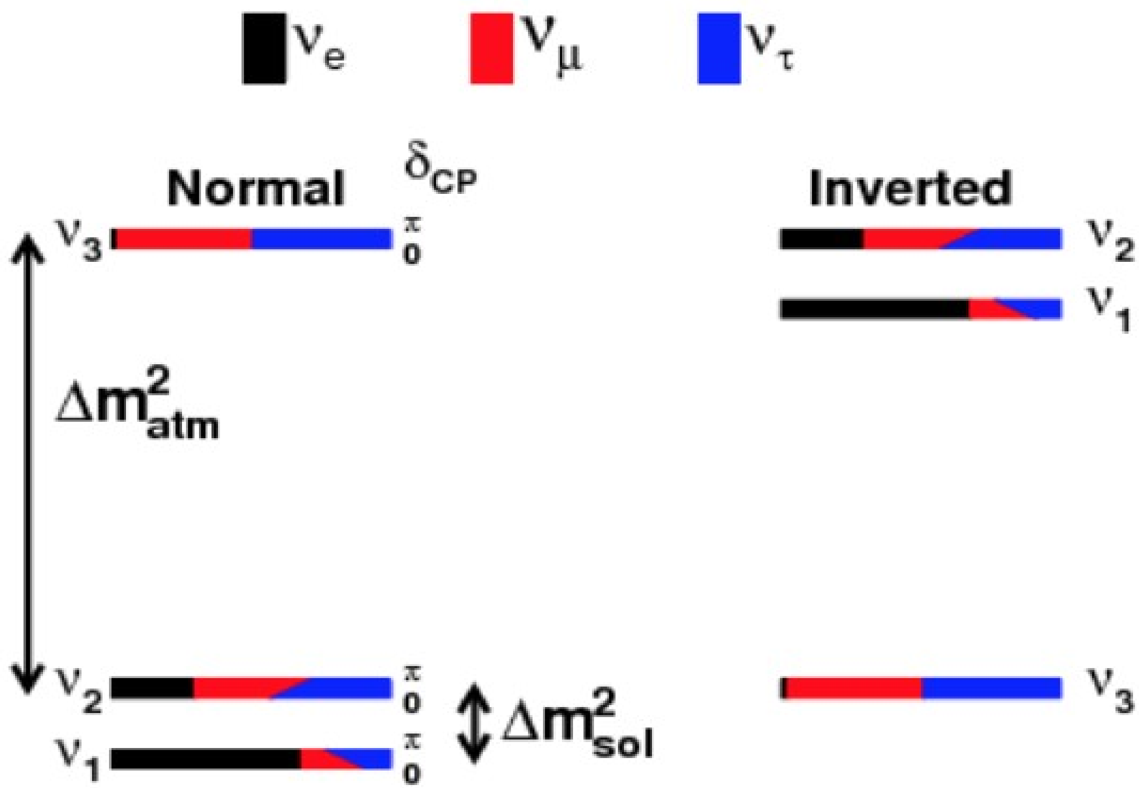
Neutrino oscillation between three generations

Flavor eigenstate

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

Mass eigenstate

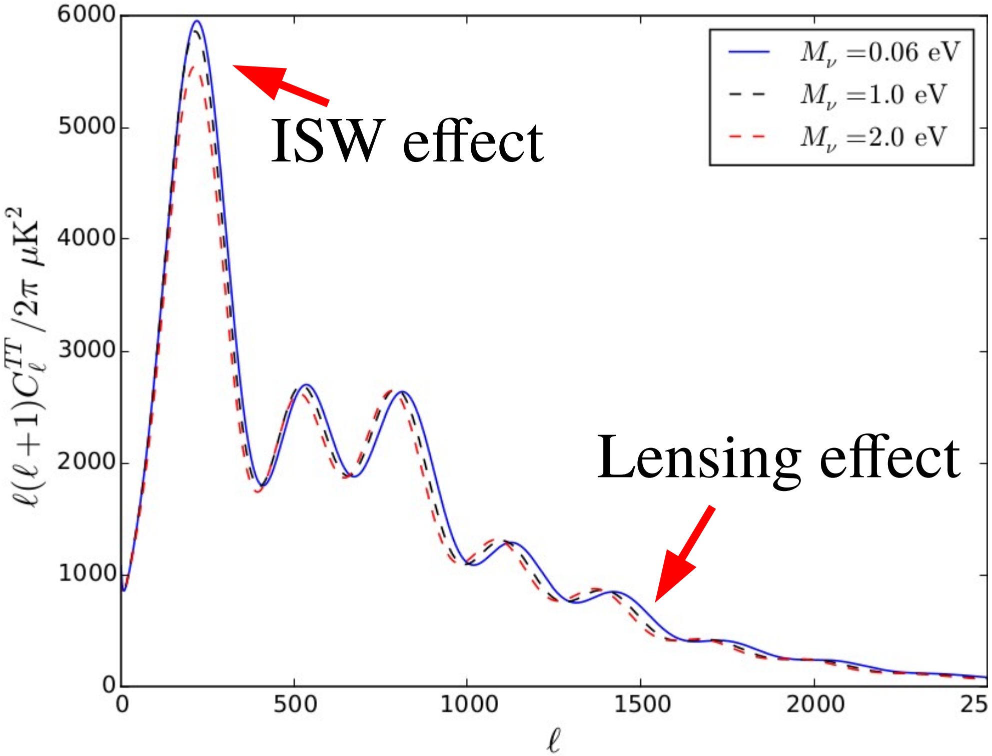
Mixing angles and phases

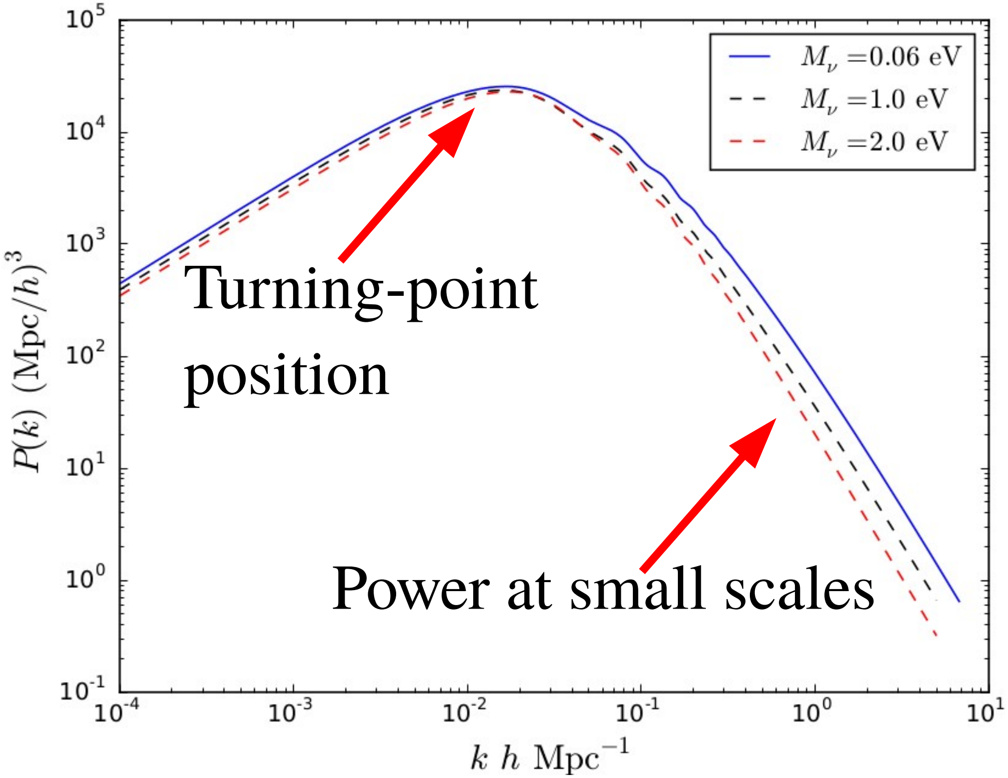


Open issues:
Neutrino nature?
Hierarchy?
Mass scale?

Cosmology

$$M_\nu \equiv \sum_i m_i = m_1 + m_2 + m_3$$

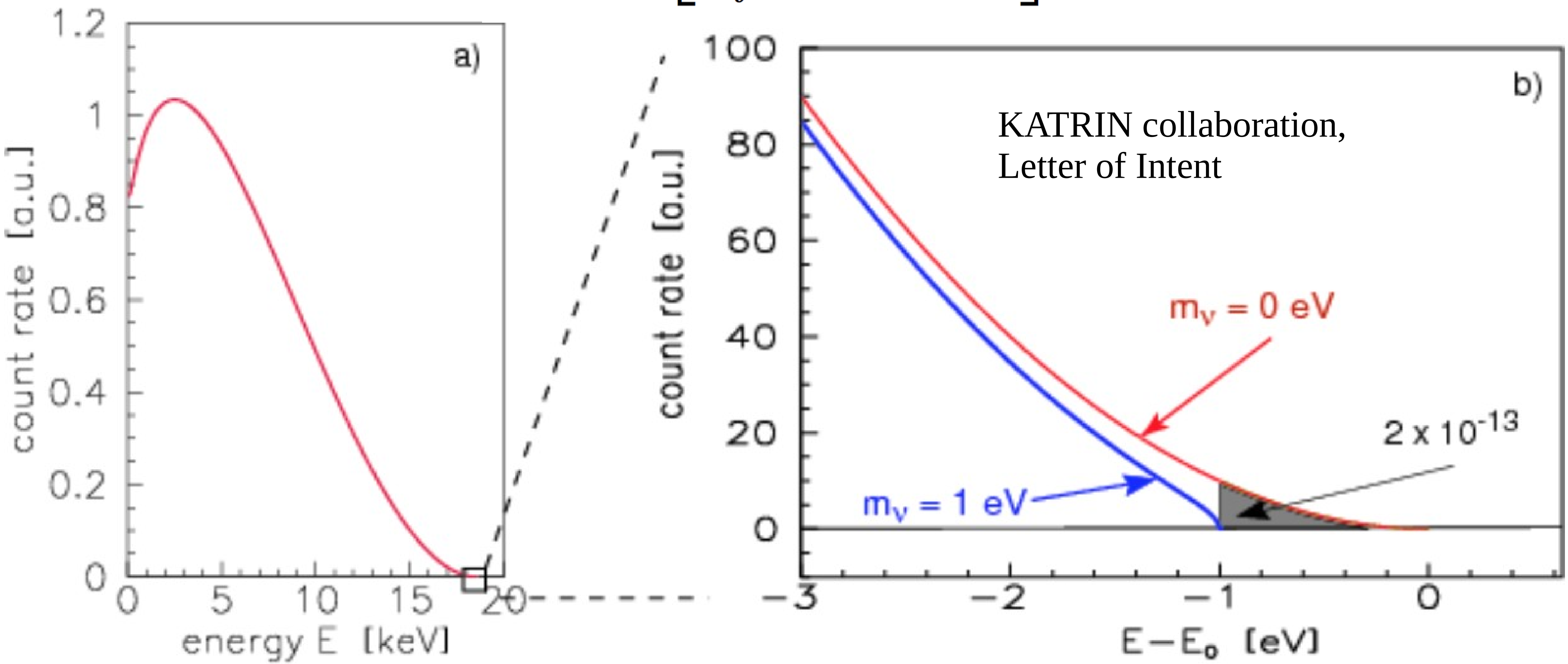




Tightest constraints on the total mass BUT model dependent

Direct measurements

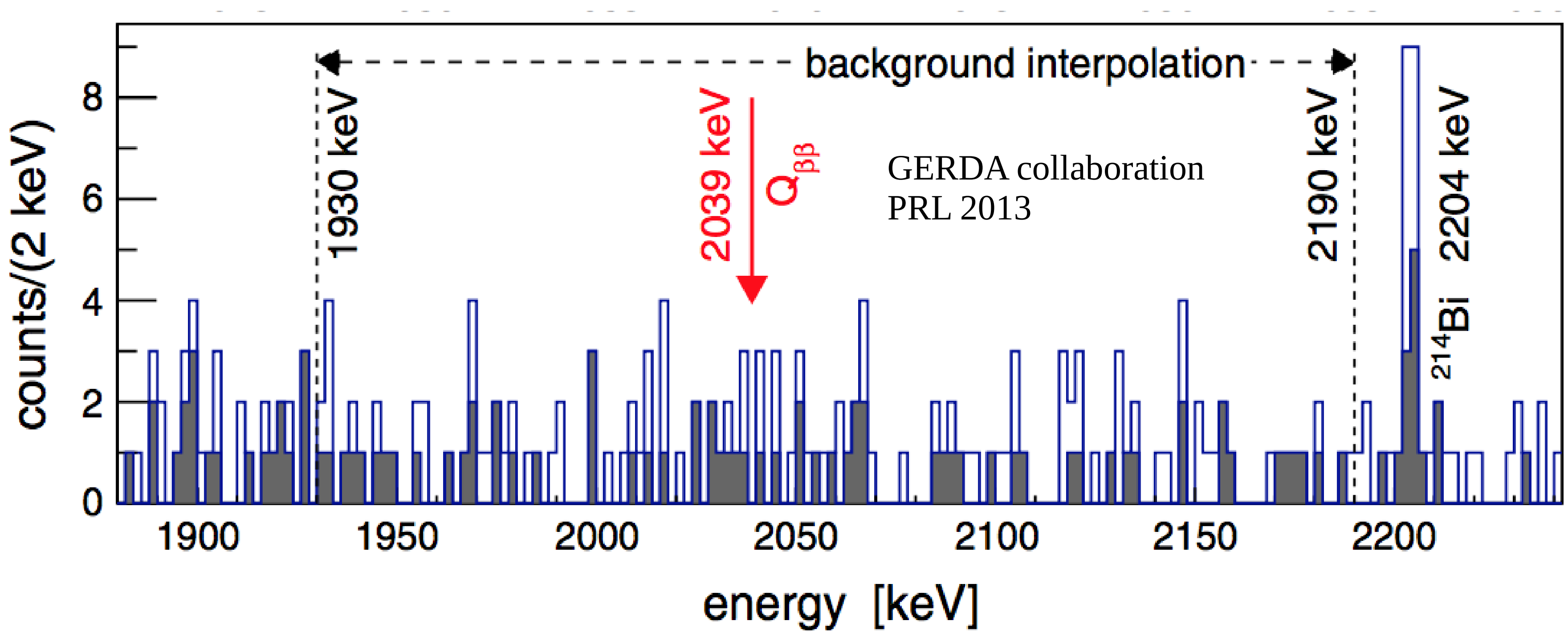
$$m_\beta \equiv \left[\sum_i |U_{ei}|^2 m_i^2\right]^{1/2}$$



Robust and model independent BUT the less tight

Neutrinoless double-beta decay

$$m_{\beta\beta} \equiv \left| \sum_i U_{ei}^2 m_i \right| \qquad T_{1/2}^{0\nu} = \frac{1}{G^{0\nu} \left| \mathcal{M}^{0\nu} \right|^2} \frac{m_e^2}{m_{\beta\beta}^2}$$



Solution to the Dirac/Majorana dilemma

BUT

highly tackling and limited by NME uncertainties

Datasets

Current, forthcoming, next-generation

- Oscillations: Global fit (Homestake, Gallex, Sage, Borexino, SNO, Super-Kamiokande, KamLAND, Daya Bay, Reno, Minos, T2K) after Neutrino 2014
- Cosmology: Planck 2015, BAO (SDSS, WiggleZ), Euclid
- Beta decay: Katrin, Holmes
- Double-beta decay: Gerda I, Gerda II, nEXO

Data analysis

parameter data Likelihood function

$$\mathcal{P}(\boldsymbol{\theta}|\mathbf{d}) = \frac{\mathcal{L}(\mathbf{d}|\boldsymbol{\theta})\mathcal{P}(\boldsymbol{\theta})}{\mathcal{P}(\mathbf{d})}$$

Prior

Posterior distribution function

$$\boldsymbol{\theta} = (M_\nu,\ \Delta m^2_{21},\ \Delta m^2_{31},\ \theta_{12},\ \theta_{13},\ \phi_1,\ \phi_2,\ \xi)$$

Nuisance parameter for NME

Receipt:

1. Fix the hierarchy
2. Extract the model
3. Compute the likelihood
4. Marginalize for posteriors

Until converged

Likelihood - Oscillations

$$\mathcal{L} = \mathcal{L}_{\rm osc} \cdot \mathcal{L}_{\rm dir} \cdot \mathcal{L}_{0\nu2\beta} \cdot \mathcal{L}_{\rm cosm}$$

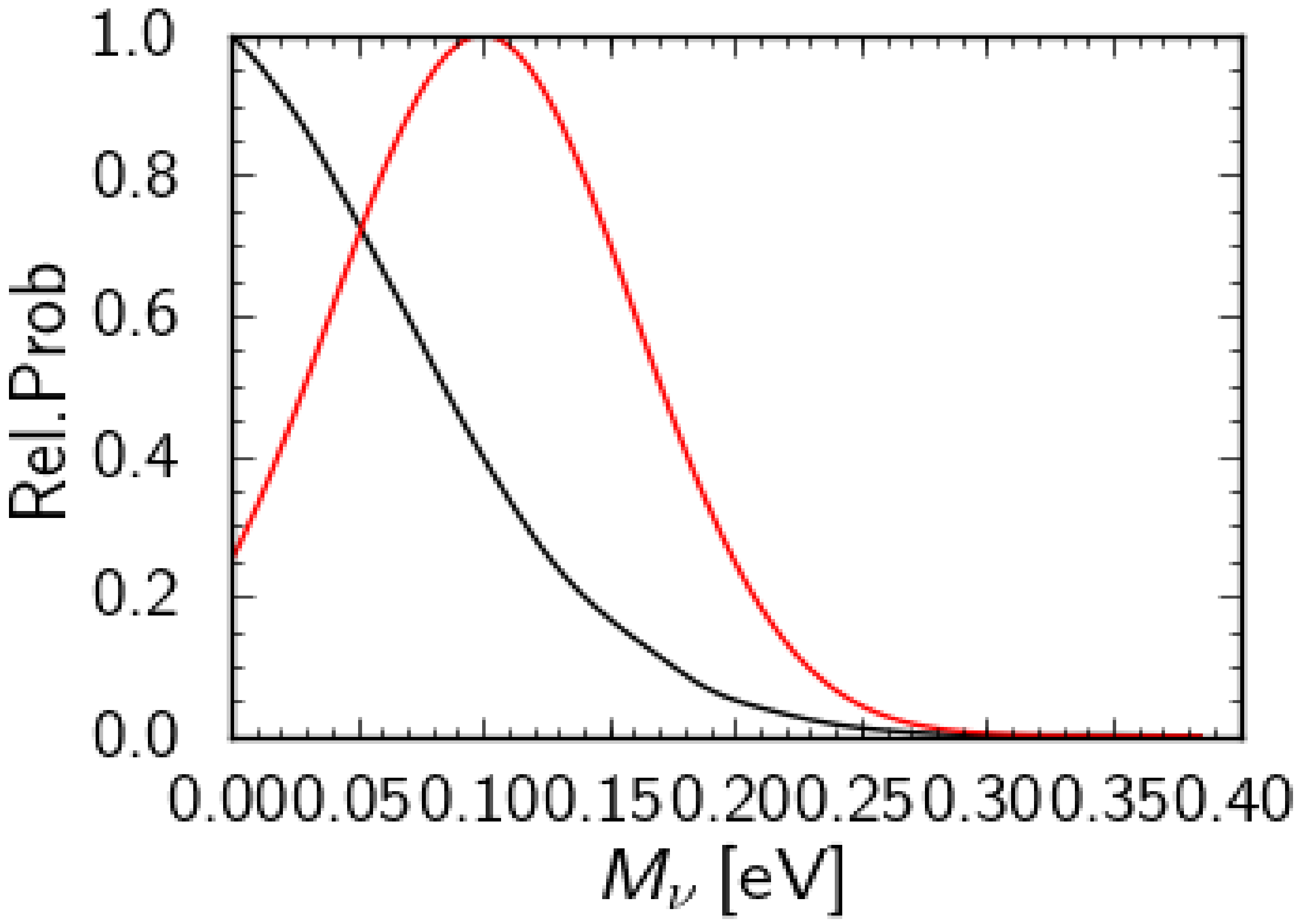
$$\mathcal{L} \propto \prod_i \exp\left[-\frac{(\theta_{{\rm osc},i} - \bar{\theta}_{{\rm osc},i})^2}{2\sigma^2_{\theta_{{\rm osc},i}}})\right]$$

Parameter	68% $c.l.$
$\Delta m^2_{12}\,[10^{-5}]\,\mathrm{eV}^2$	7.60 ± 0.19
$\lvert\Delta m^2_{13}\rvert\,[10^{-3}]\,\mathrm{eV}^2$	$2.48 \pm 0.07\,(2.38 \pm 0.06)$
s^2_{12}	0.323 ± 0.016
$100\,s^2_{13}$	$2.26 \pm 0.12\,(2.29 \pm 0.12)$

Forero, Tortola, Valle, PRD 2014

Likelihood - Cosmology

$$\mathcal{L} = \mathcal{L}_{\rm osc} \cdot \mathcal{L}_{\rm dir} \cdot \mathcal{L}_{0\nu2\beta} \cdot \mathcal{L}_{\rm cosm}$$

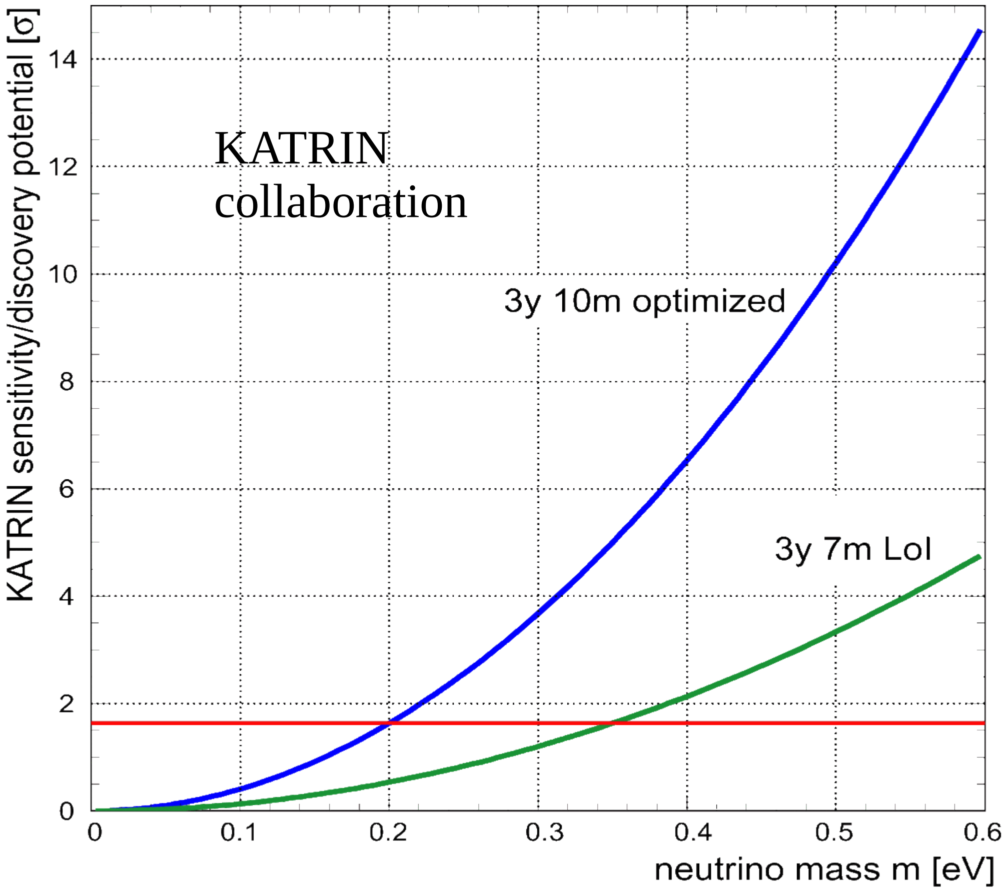


Planck TT,TE,EE+lowP
+BAO (Planck collaboration XIII 2015)
Mν < 0.168 eV (95% c.l.)

Euclid+Planck TT,TE,EE
(forecast, arXiv:1110.3193)
Mν = (0.10±0.06) eV

Likelihood – Beta decay

$$\mathcal{L} = \mathcal{L}_{\rm osc} \cdot \mathcal{L}_{\rm dir} \cdot \mathcal{L}_{0\nu 2\beta} \cdot \mathcal{L}_{\rm cosm}$$



Sensitivity

Katrin (Design report 2004)

$\sigma_{m_\beta\text{^}2} = 0.025$ eV^2

Holmes (EPJC 2015)

$\sigma_{m_\beta\text{^}2} = 0.006$ eV^2

Likelihood – Double-beta decay

$$\mathcal{L} = \mathcal{L}_{\rm osc} \cdot \mathcal{L}_{\rm dir} \cdot \mathcal{L}_{0\nu2\beta} \cdot \mathcal{L}_{\rm cosm}$$

$$\langle N_{\rm s} \rangle = \frac{\ln 2 N_A \mathcal{E} \epsilon}{m_{enr} T^{0\nu}_{1/2}} \qquad \mathcal{L}(N_{\rm obs}|T^{0\nu}_{1/2}) = \sum_{N_{\rm s}=0}^{N_{\rm obs}} \frac{\lambda^{N_{\rm s}} e^{-\lambda}}{N_{\rm s}!} \cdot \frac{\lambda_b^{N_{\rm obs}-N_{\rm s}} e^{-\lambda_b}}{(N_{\rm obs}-N_{\rm s})!}$$

Important assumptions: neutrinos are Majorana and 0n2b is driven mainly by mass mechanism

Data set	$\mathcal{E}$ (kg yr)	$\langle \epsilon \rangle$	Background	BI[a]	Counts
With PSD					
Golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
Silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

[a]In units of 10^{-3} counts/(keV kg yr).

Coax	54	0.619	0.432	0.001	0(B+S)
BEGe	63	0.663	0.504	0.001	0(B+S)

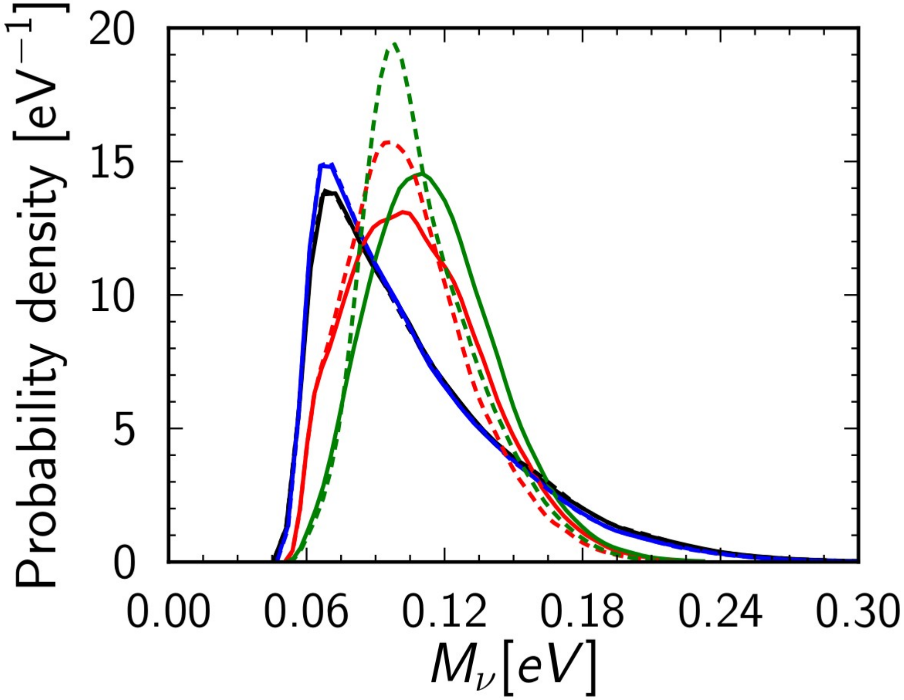
Gerda I

GERDA collaboration, PRL 2013

Gerda II – Expected performance (talk by Cattadori at NOW14) and fiducial counts given Osc+Planck+BAO

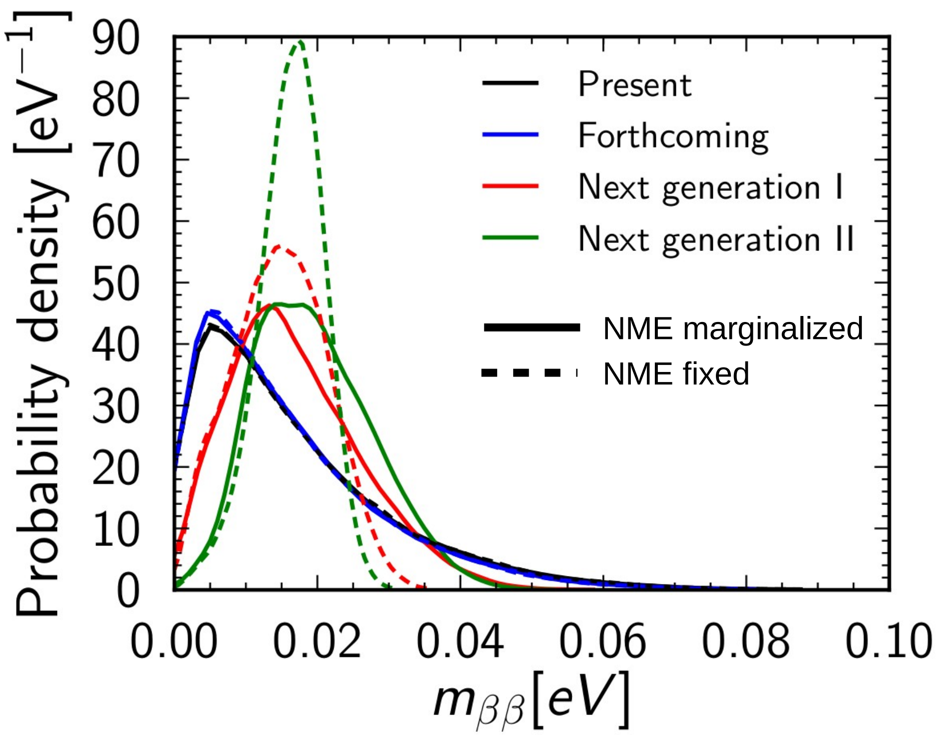
Xe	23900	0.864	88.43	3.7/ROI	88(B)+13(S-nh) 88(B)+57(S-ih)
Ba tag	30000	0.864	35.42	1.2/ROI	35(B)+13(S-nh)[+68(S-ih)]

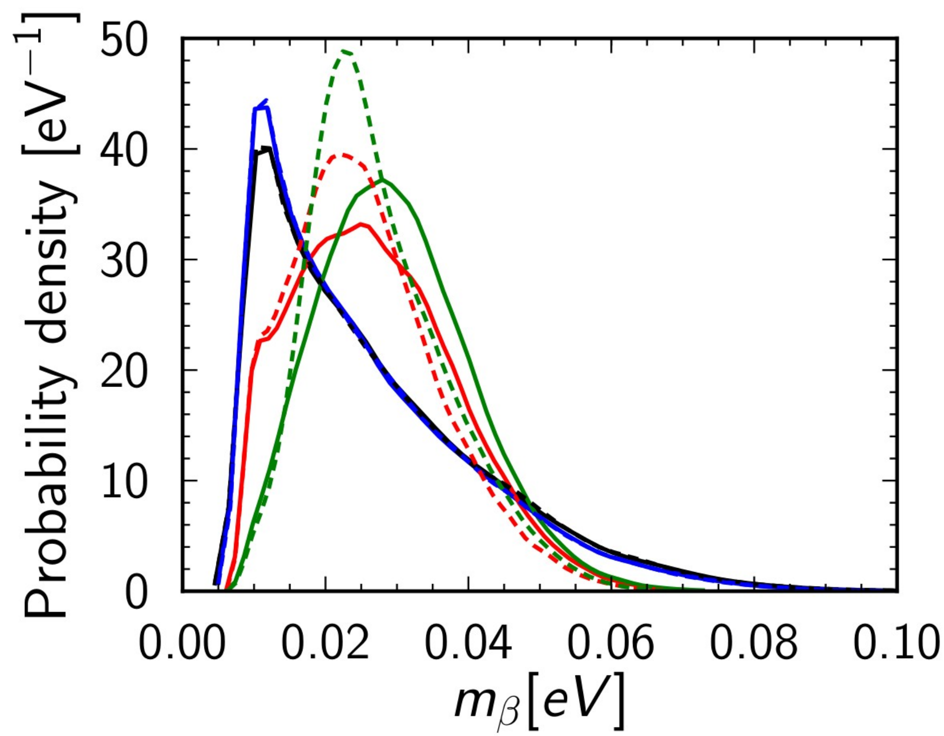
nEXO – Expected performance (talk by Pocar at NOW14) and fiducial counts given Osc+Euclid

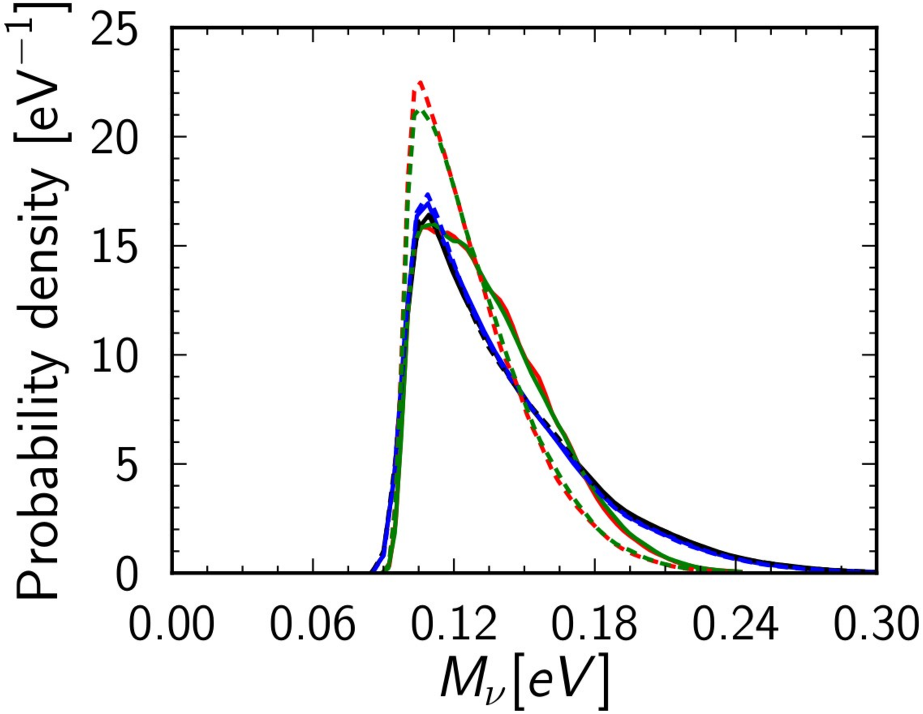


NORMAL HIERARCHY – 95% C.L.

	Present	Forthcom.	N.G. I	N.G. II
M_ν, ξ free	$[53-170]$	$[54-165]$	109^{+43}_{-49}	116^{+43}_{-45}
$M_\nu, \xi \equiv 1$	$[53-170]$	$[54-165]$	105^{+40}_{-45}	110^{+42}_{-38}
$m_{\beta\beta}, \xi$ free	< 36	< 34	17^{+14}_{-15}	20^{+14}_{-13}
$m_{\beta\beta}, \xi \equiv 1$	< 36	< 34	15^{+10}_{-12}	16 ± 8
m_β, ξ free	$[6-50]$	$[7-48]$	27^{+16}_{-19}	30^{+16}_{-18}
$m_\beta, \xi \equiv 1$	$[6-50]$	$[7-48]$	26^{+15}_{-17}	28^{+16}_{-15}

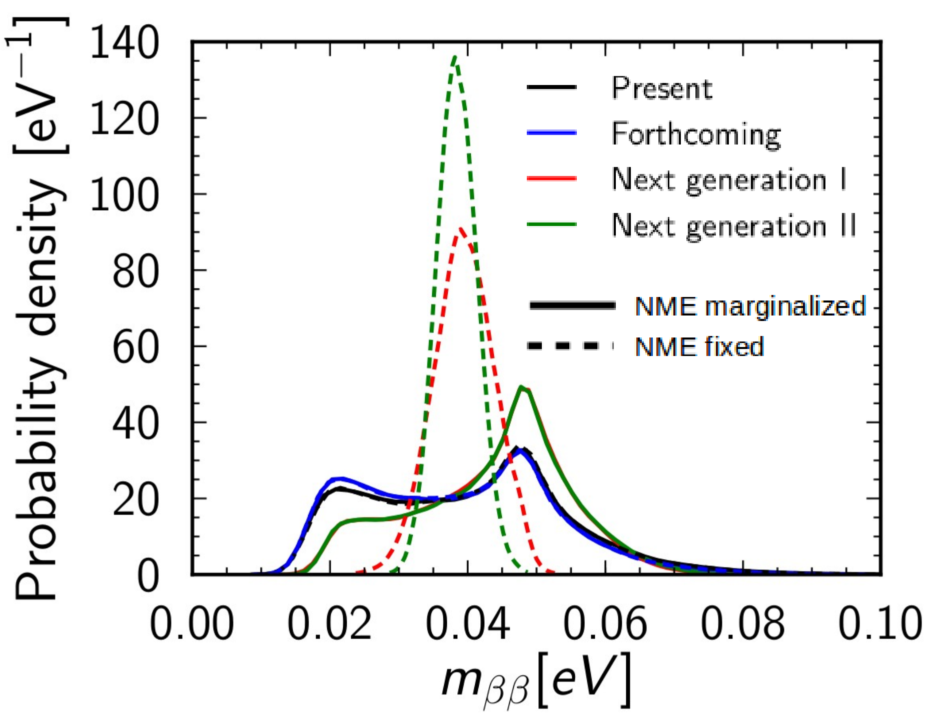


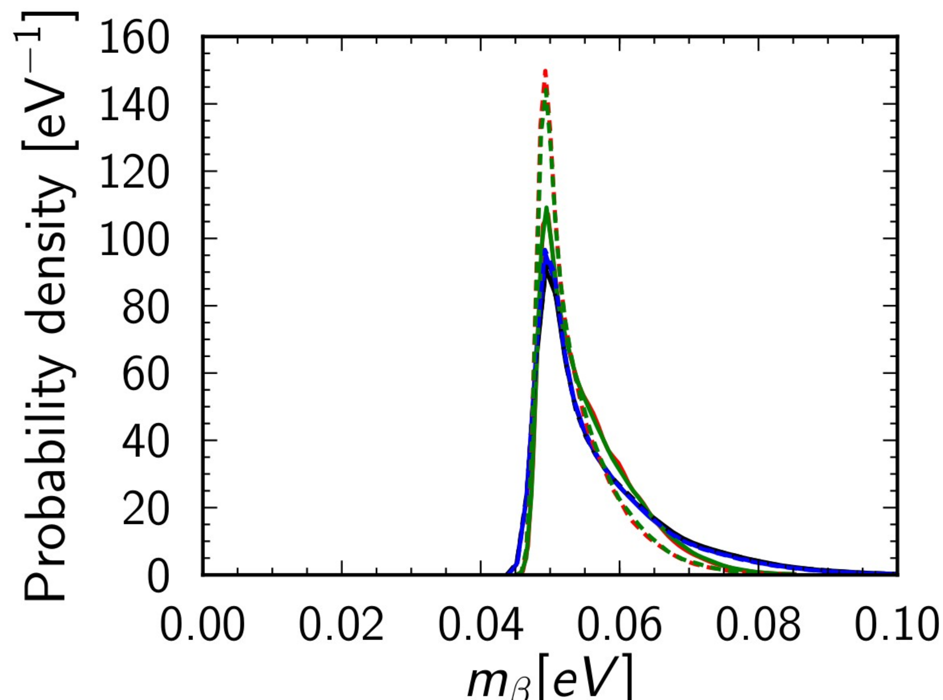




INVERTED HIERARCHY – 95% C.L.

	Present	Forthcom.	N.G. I	N.G. II
M_ν, ξ free	[93 − 195]	[93 − 191]	[97 − 174]	[97 − 175]
$M_\nu, \xi \equiv 1$	[93 − 194]	[93 − 190]	[96 − 163]	[96 − 164]
$m_{\beta\beta}, \xi$ free	[16 − 59]	[16 − 58]	43^{+16}_{-22}	43^{+16}_{-22}
$m_{\beta\beta}, \xi \equiv 1$	[16 − 59]	[16 − 57]	39 ± 7	38 ± 5
m_β, ξ free	[46 − 71]	[46 − 70]	[47 − 65]	[47 − 65]
$m_\beta, \xi \equiv 1$	[46 − 71]	[46 − 69]	[47 − 62]	[47 − 62]

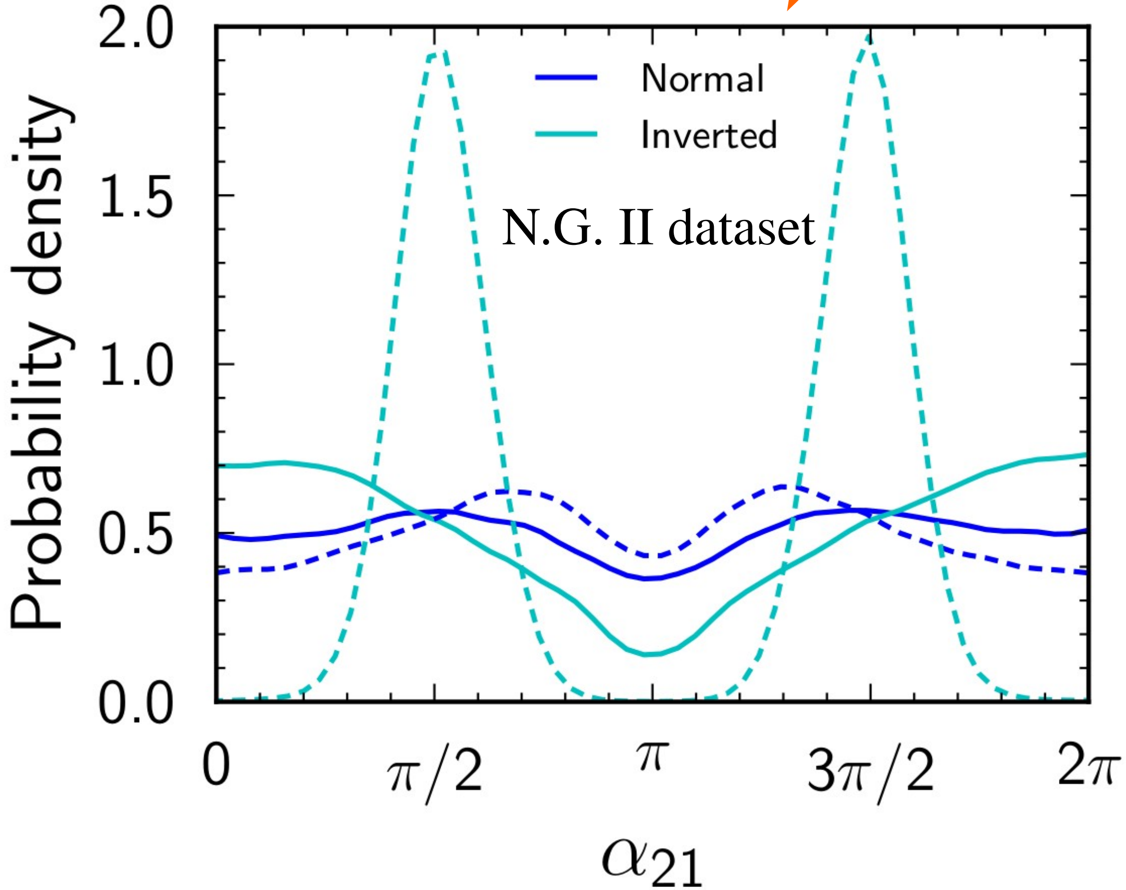




Window on the Majorana phases

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}\left(1,\, e^{i\frac{\alpha_{21}}{2}},\, e^{i\frac{\alpha_{31}}{2}}\right)$$

Qualitative take-home message:
Next generation experiment sensitivity will possibly allow to determine one of the Majorana phases



Conclusions

- Complementary approach of cosmology and laboratory experiments
- Cosmology currently (and in the near future) provides the most stringent constraints
- With proposed next-generation experiments, comparable constraining power from cosmology and laboratory avenues (need for better control of nuclear modeling)
- Possibility to break the barrier of Majorana phase estimation

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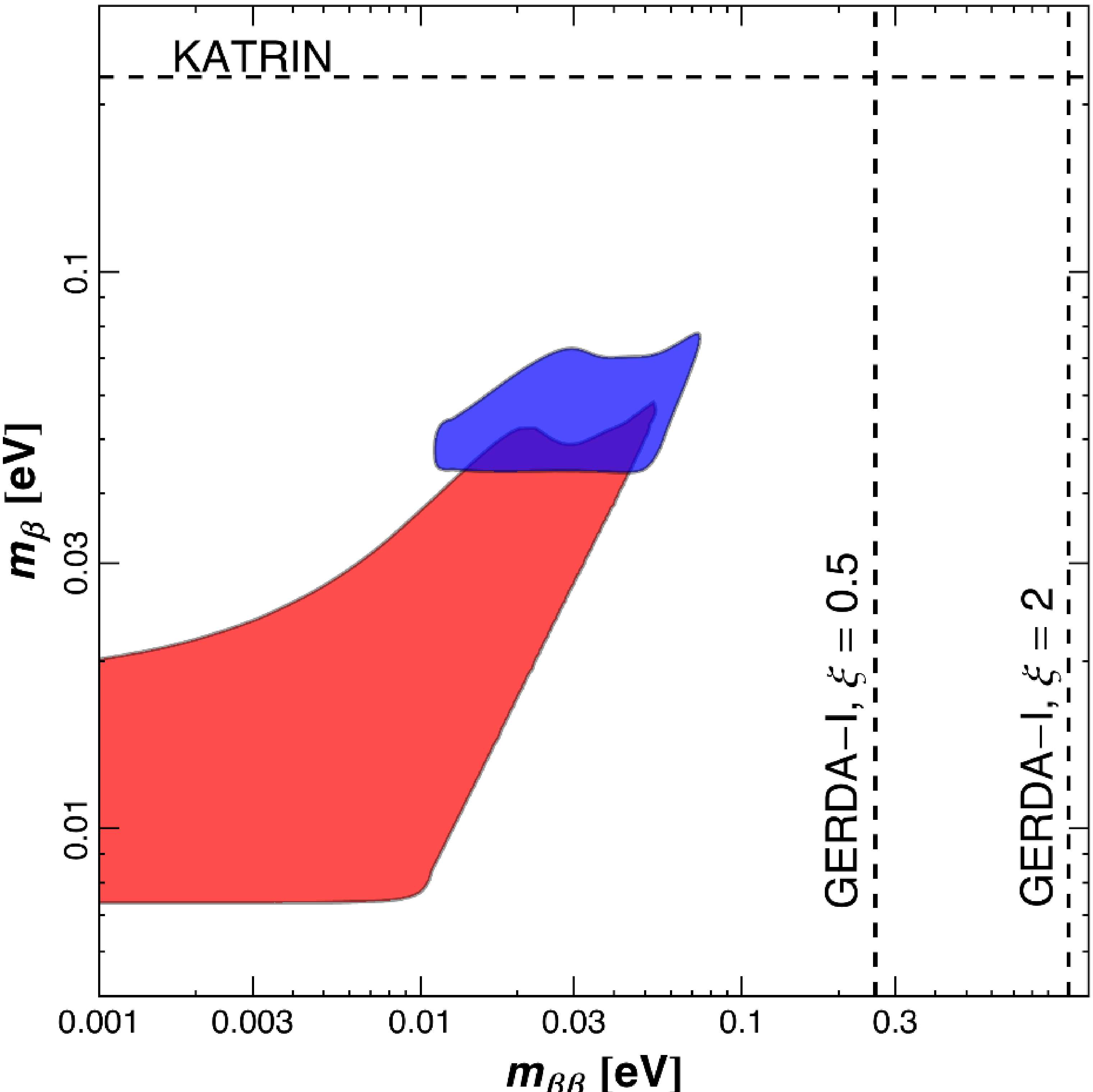

KATRIN
GERDA−I, ξ = 0.5
GERDA−I, ξ = 2
0.1
0.03
0.01
0.001
0.003
0.01
0.03
0.1
0.3
m_β [eV]
m_ββ [eV]

NuFit, **arXiv:1106.0687**