Discovery Potential of Future Neutrinoless Double-Beta Decay Experiments

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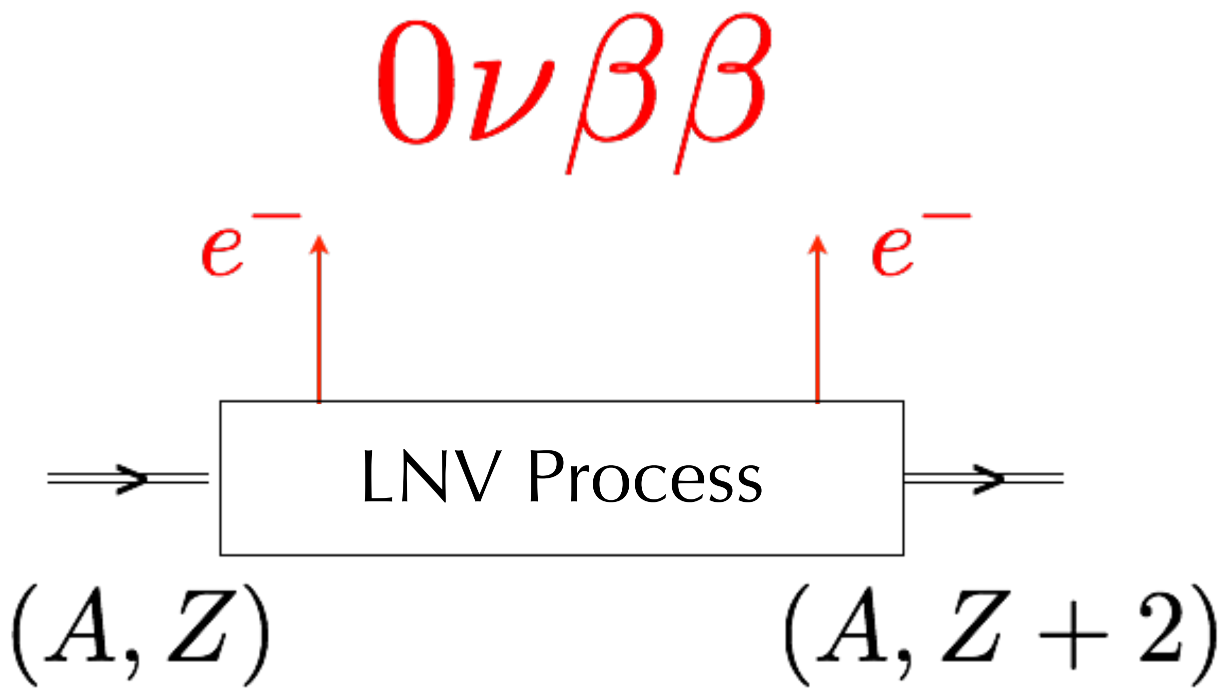
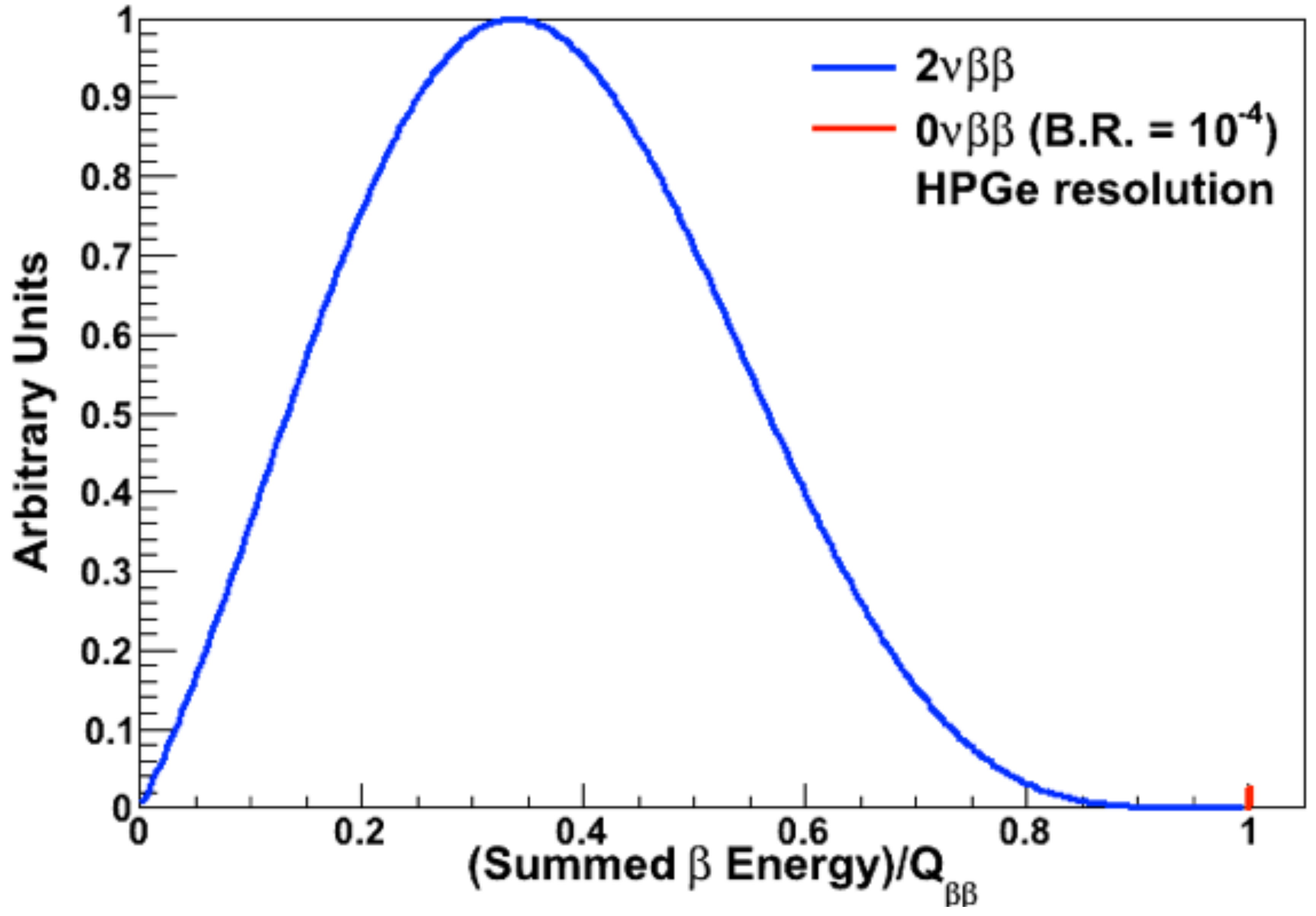
DBD18, Waikoloa, Hawaii

October 21, 2018

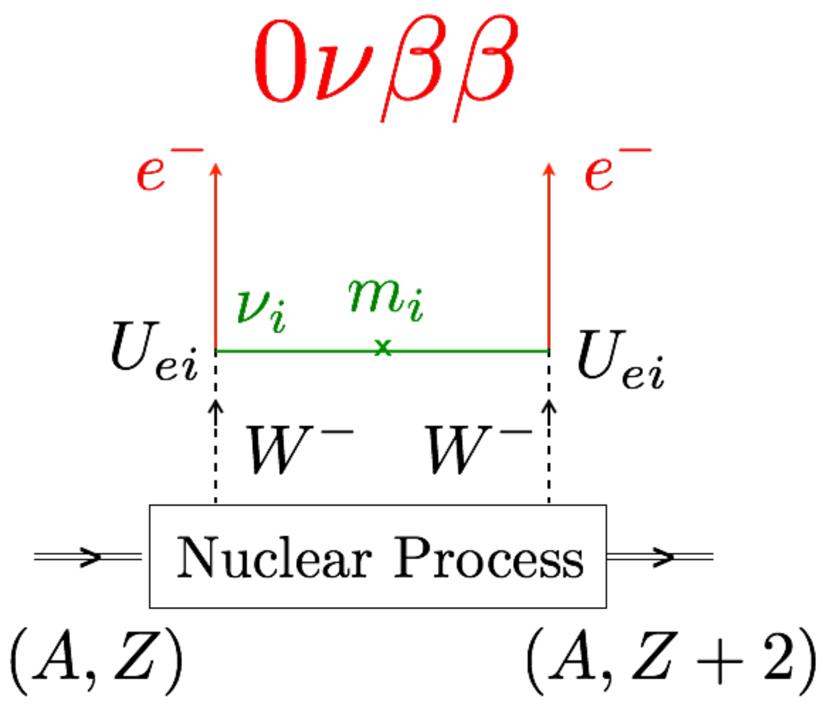
Neutrinoless Double-Beta Decay





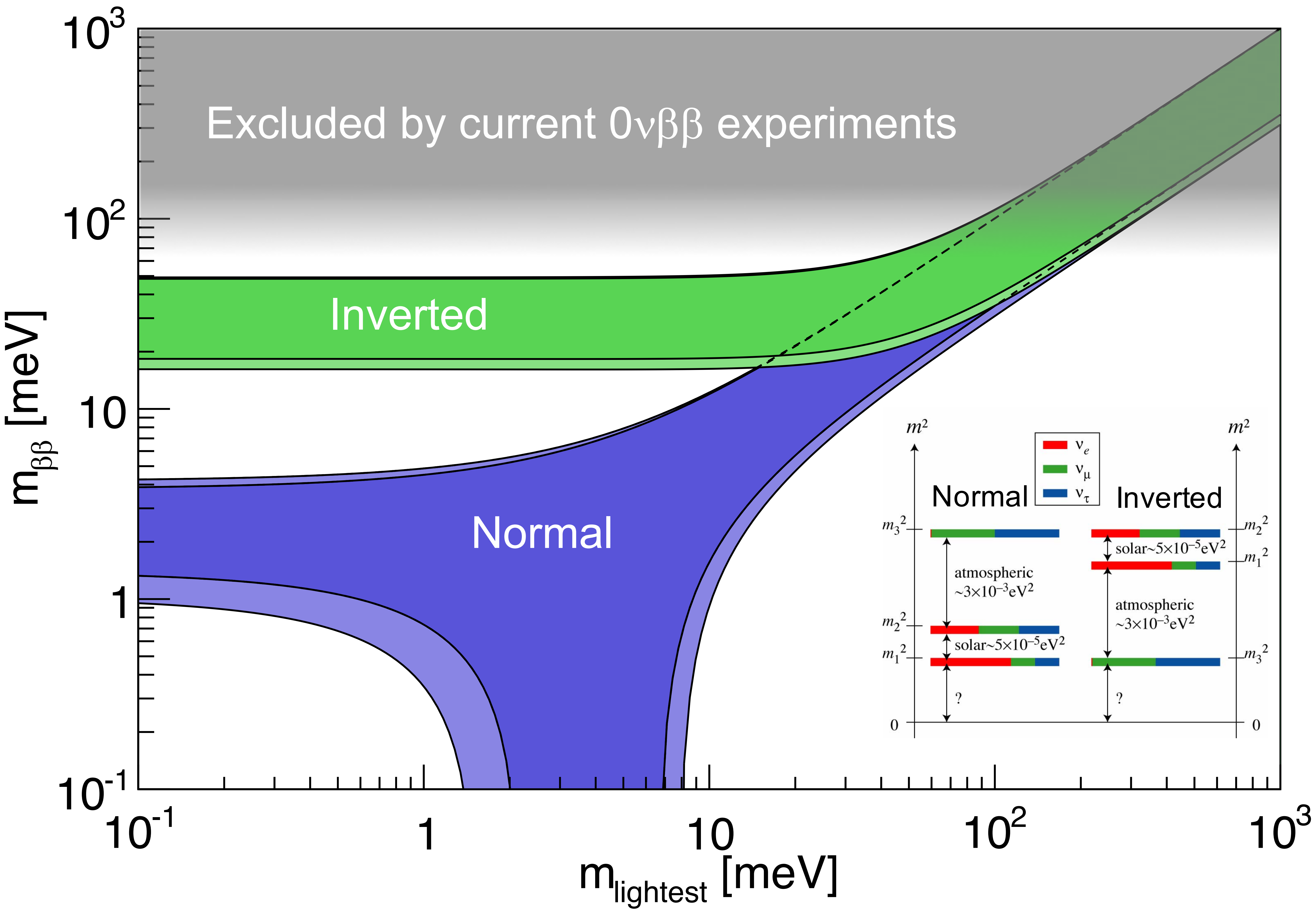
- Matter creation process
- The peak in the plot exceeds current limits
- *Must* measure summed electron kinetic energy to distinguish from Standard-Model 2ν process: scintillation, ionization, and/or heat
- Some experiments can also measure electron momenta (tracking), provides a handle on the LNV process

Pure-Majorana SM Neutrino Exchange

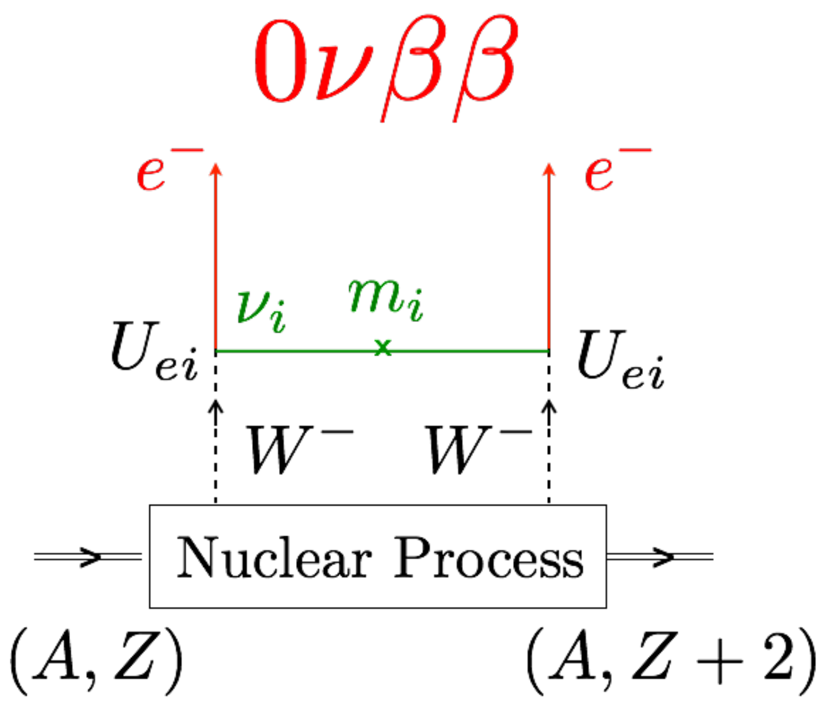


$$\Gamma^{0\nu}_{1/2} = G^{0\nu}|M^{0\nu}|^2 \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|^2$$

- "Minimal" model: add just one parameter to the SM Lagrangian
- Simple goal post for future experiments



Pure-Majorana SM Neutrino Exchange



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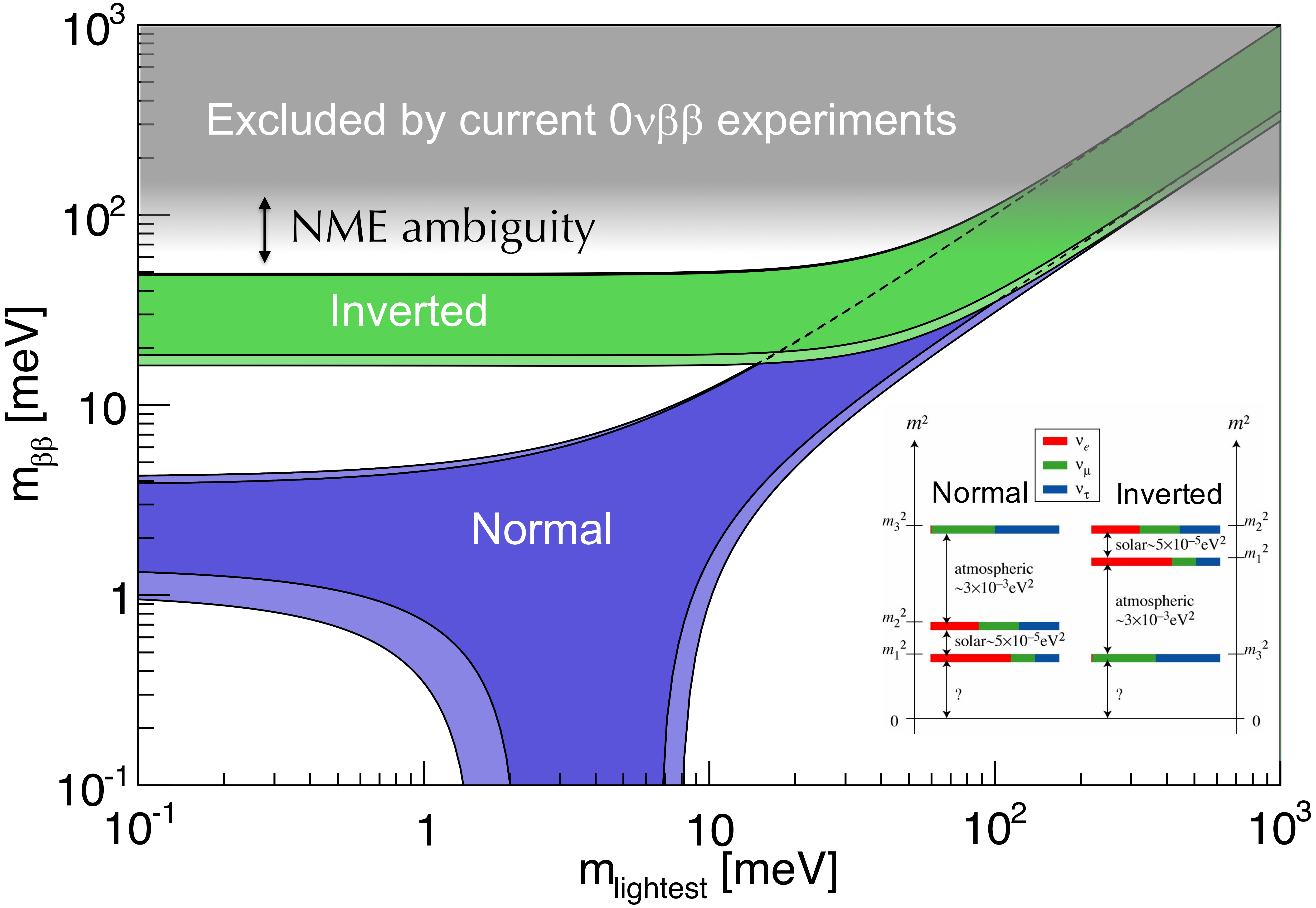
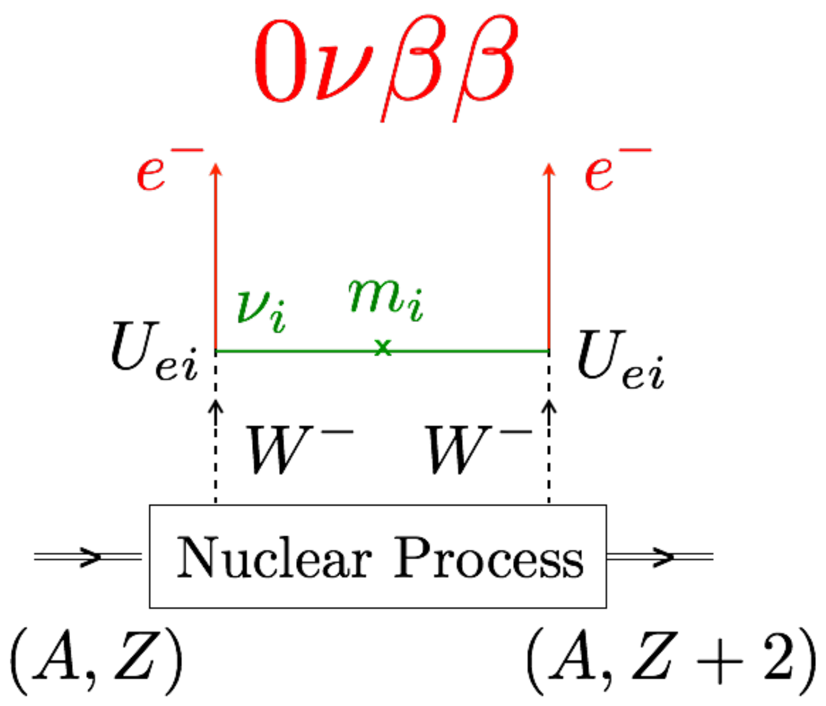


Pure-Majorana SM Neutrino Exchange



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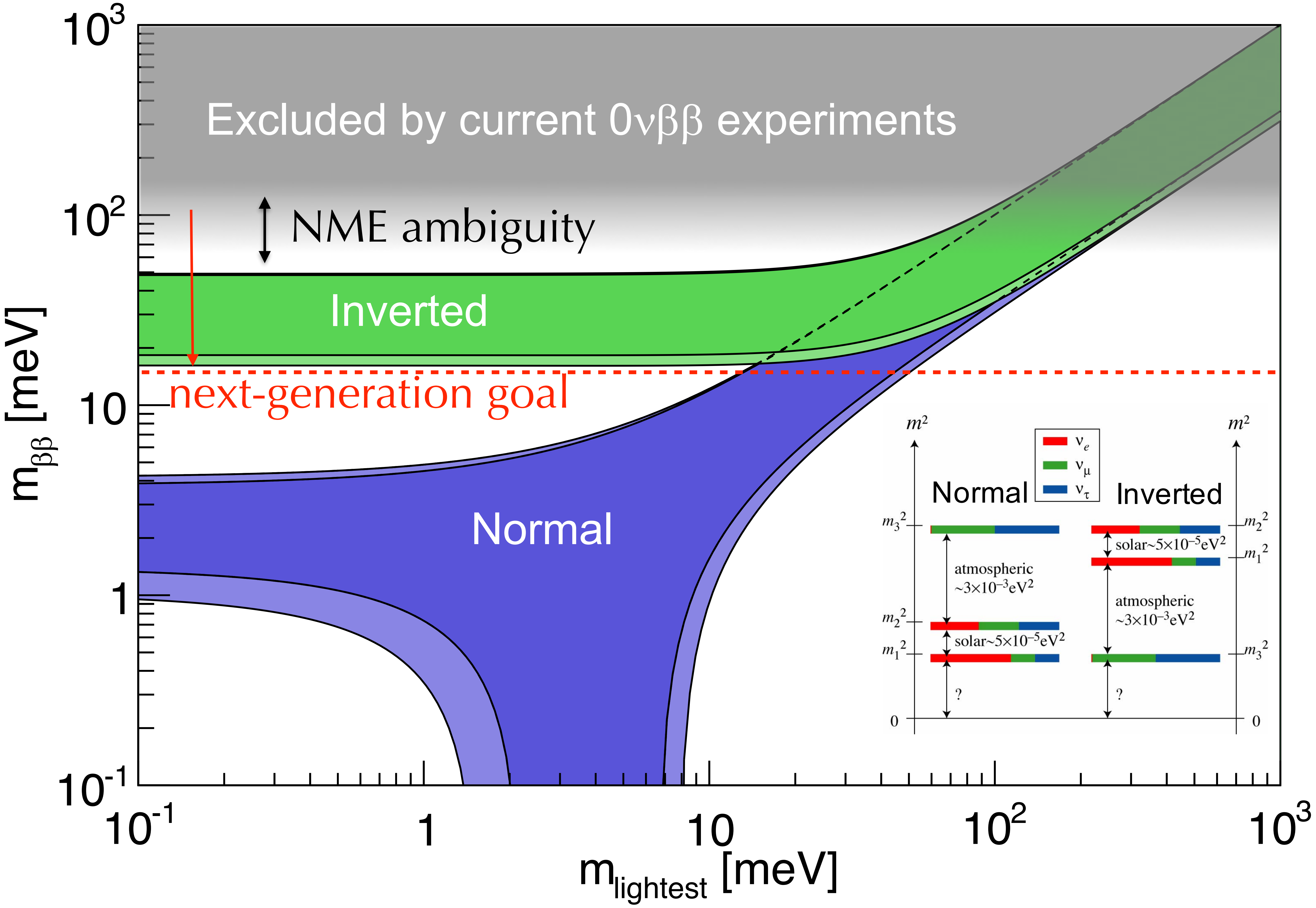
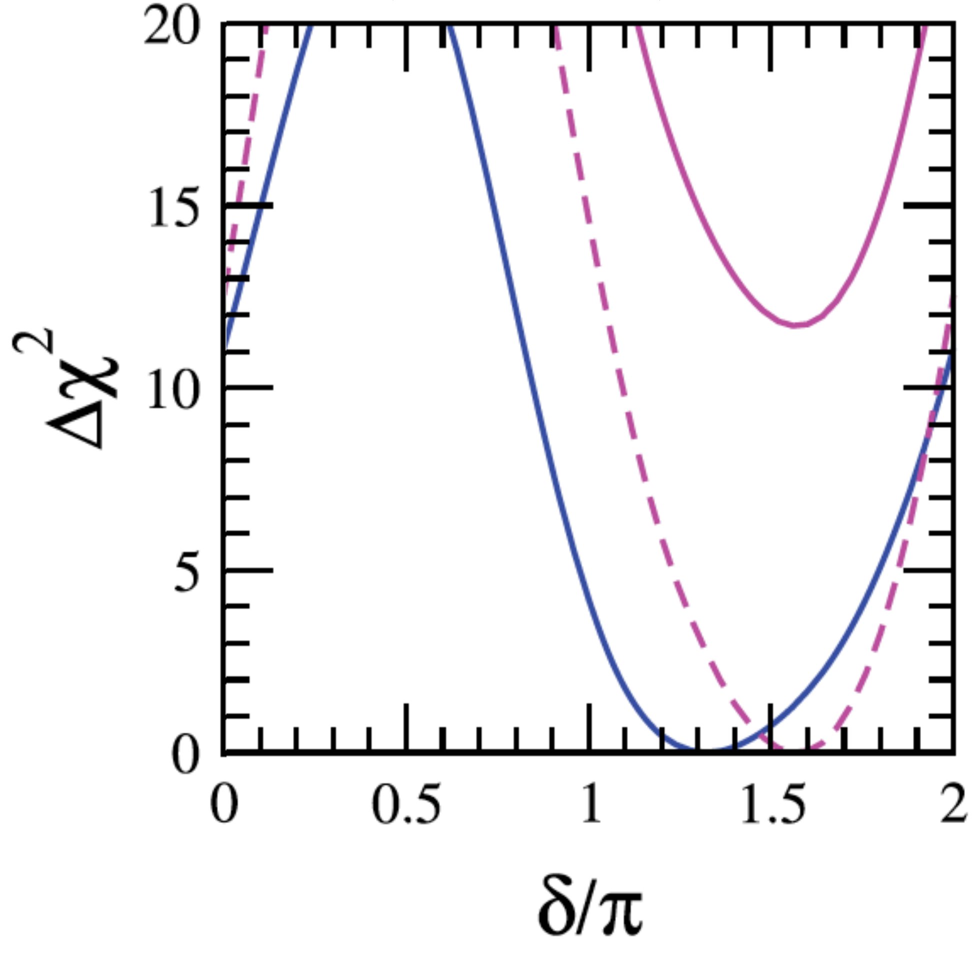


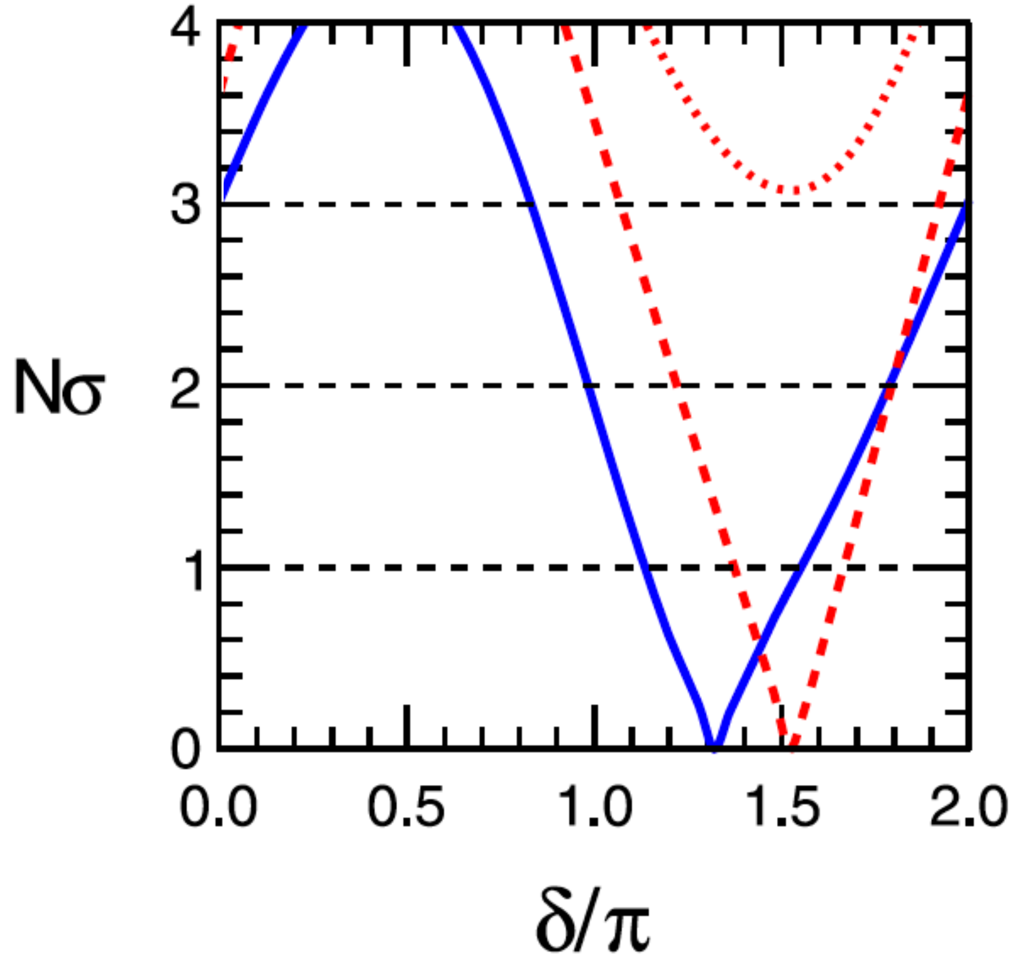
$\mathrm{IO}_{\mathrm{min}}$ is still a reasonable goal

- NO preferred at ~3σ in global oscillation analyses. Also preferred by cosmology. However:
  - Visibility of such preference in the data is still poor: large $\Delta\chi^2$ but small ΔG.O.F
  - Phenomenoligists cannot reproduce the strong contribution from SK (>3σ global analyses just use the SK χ^2 map)
  - Cosmological limits are systematic-dominated, still favor Σ → 0
- Also: $\mathrm{IO}_{\mathrm{min}}$ still represents ~2 orders-of-magnitude improvement in $T_{1/2}$ sensitivity
  - Significant potential for discovery even in the case of NO (this talk)
  - Non-minimal models open up the entire parameter space for discovery anywhere below current limits!

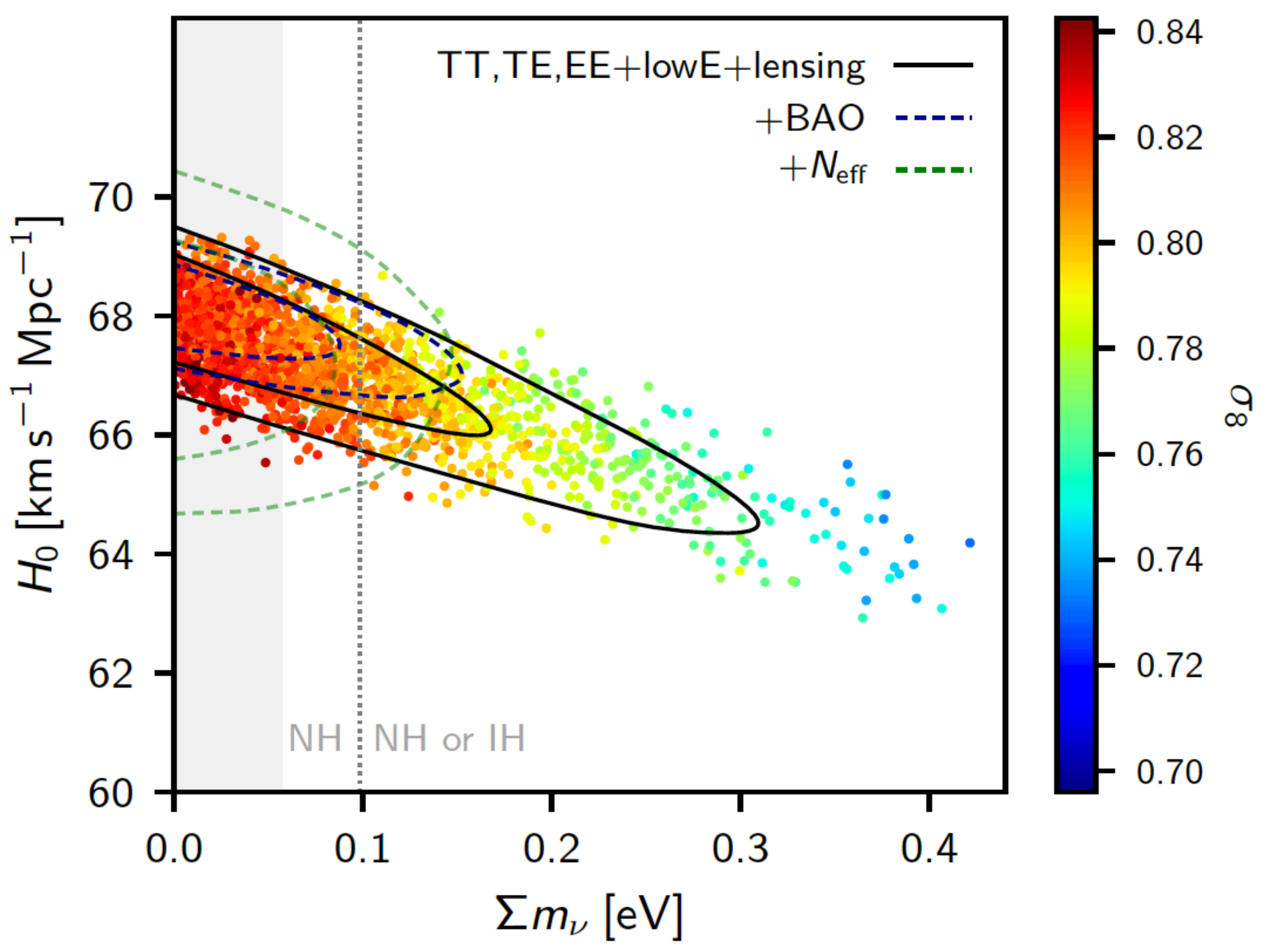
Valencia, PLB **782**, 633 (2018)



Bari, PPNP **102**, 48 (2018)



Planck, arXiv:1807.06209



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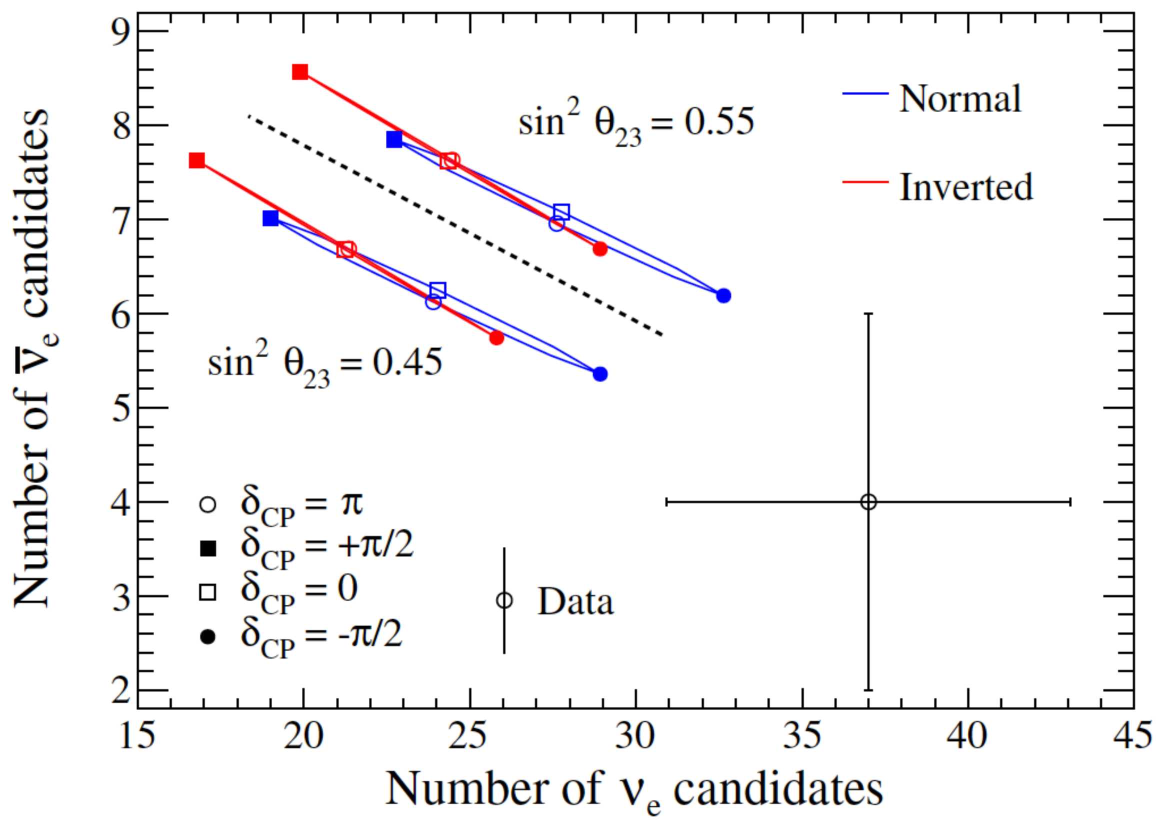
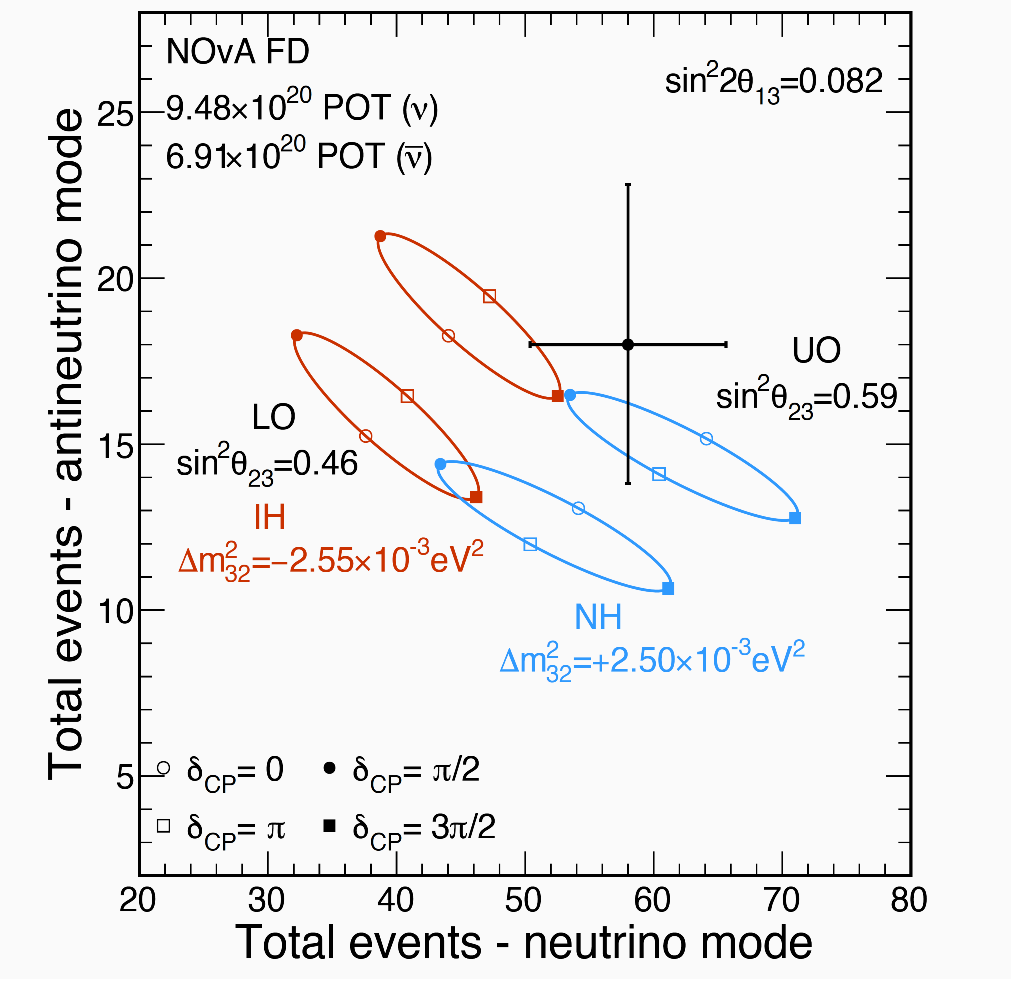
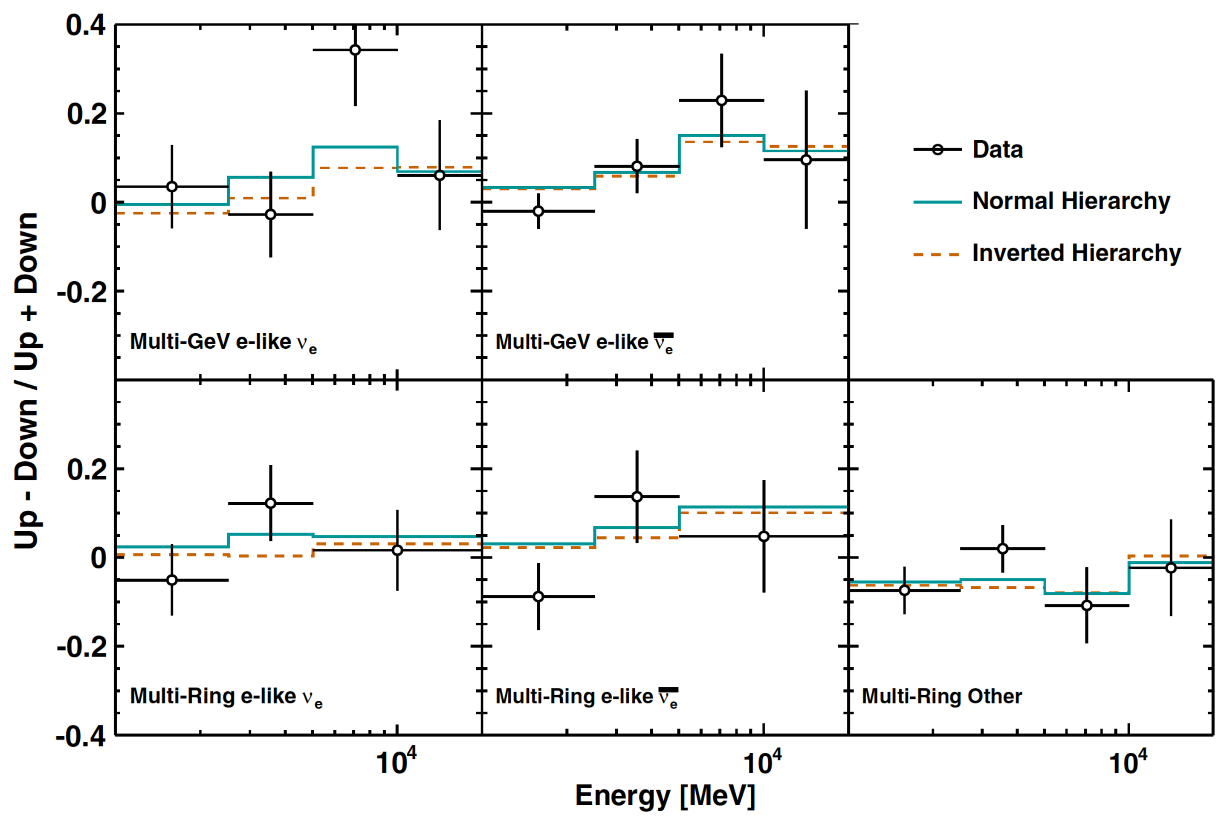
T2K, PRD **96**, 092006 (2017)



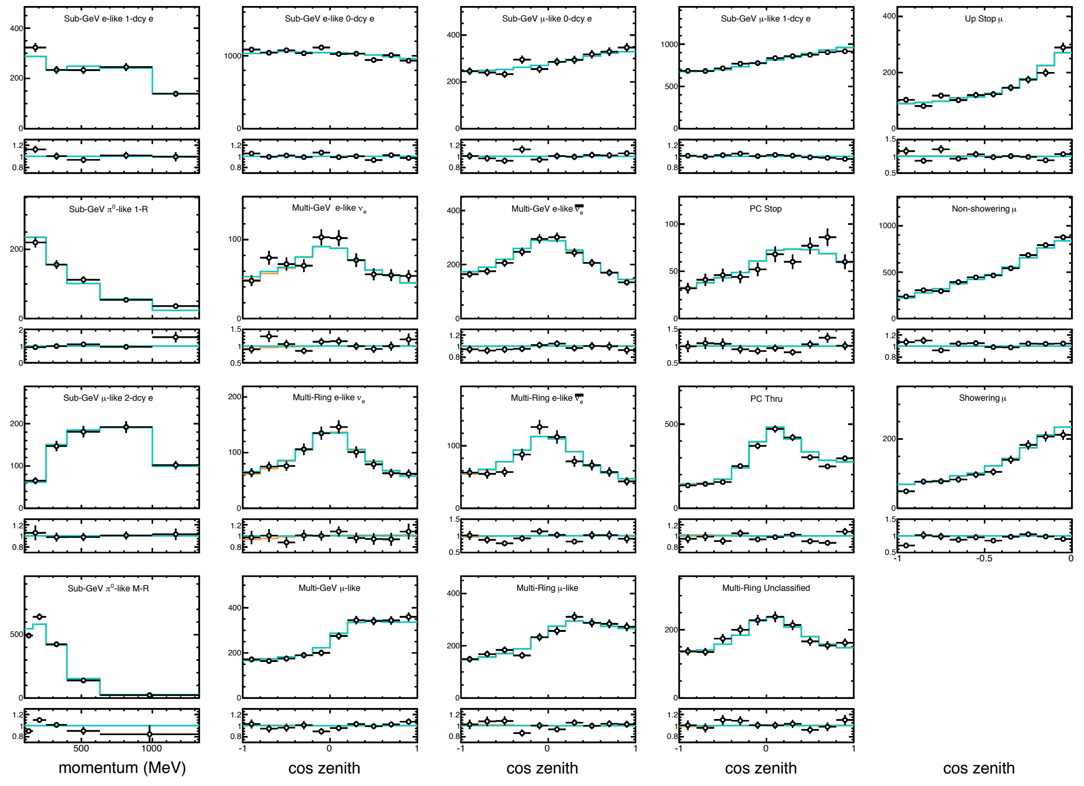
NOvA, Nu2018



SuperK, PRD **97**, 072001 (2018)

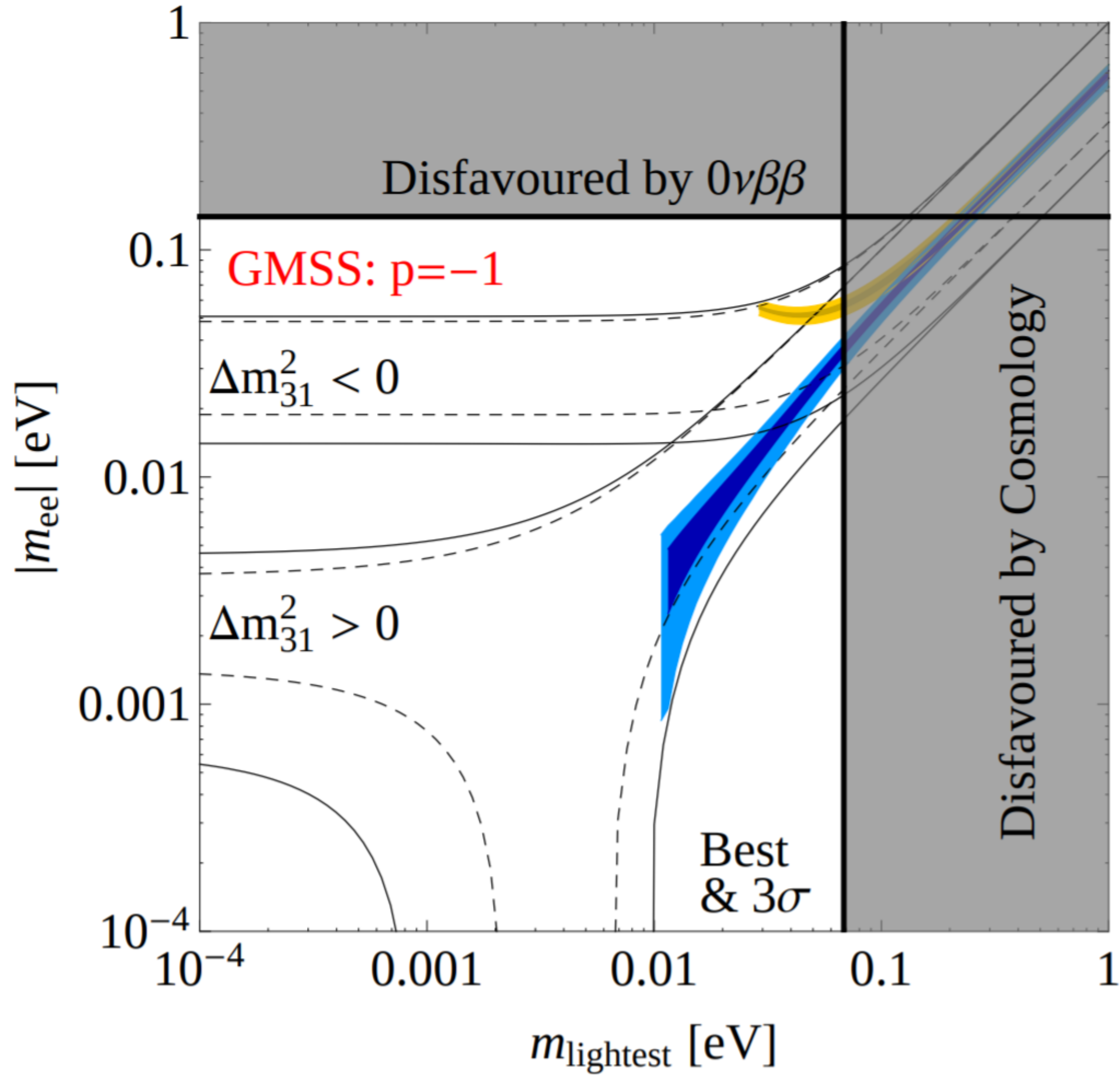


SuperK (R. Wendell, p.c.)

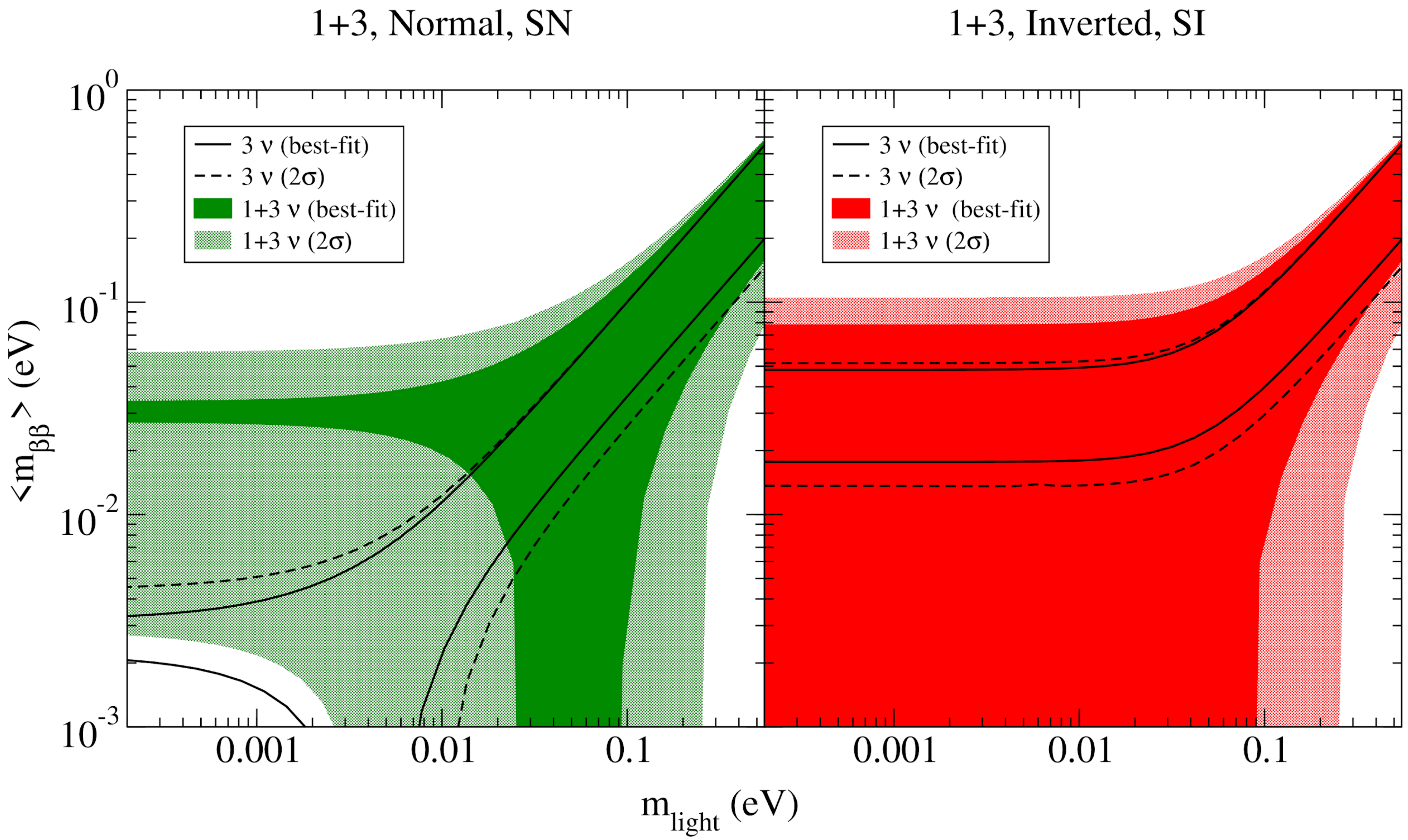


Alternative Mechanisms

Flavor Models



King, Merle, Stuart, JHEP **1312**, 005 (2013)



Rodejohann, Int. J. Mod. Phys. E **20**, 1833 (2011)

0νββ: Qualitative Experimental Description

- Energy is the only observable quantity that is both a necessary and sufficient condition for discovery of 0νββ decay
- Sensitivity is dominated by Poisson counting in the region-of interest (ROI): observing some number of counts during an exposure in the presence of background.
- Relevant parameters:

Sensitive Exposure

$$\mathcal{E} = \epsilon\, m_{iso}^{FV}\, t$$

detection efficiency

fiducial mass of isotope

counting time

Sensitive Background

$$\mathcal{B} = N_{bg}/\mathcal{E}$$

background counts

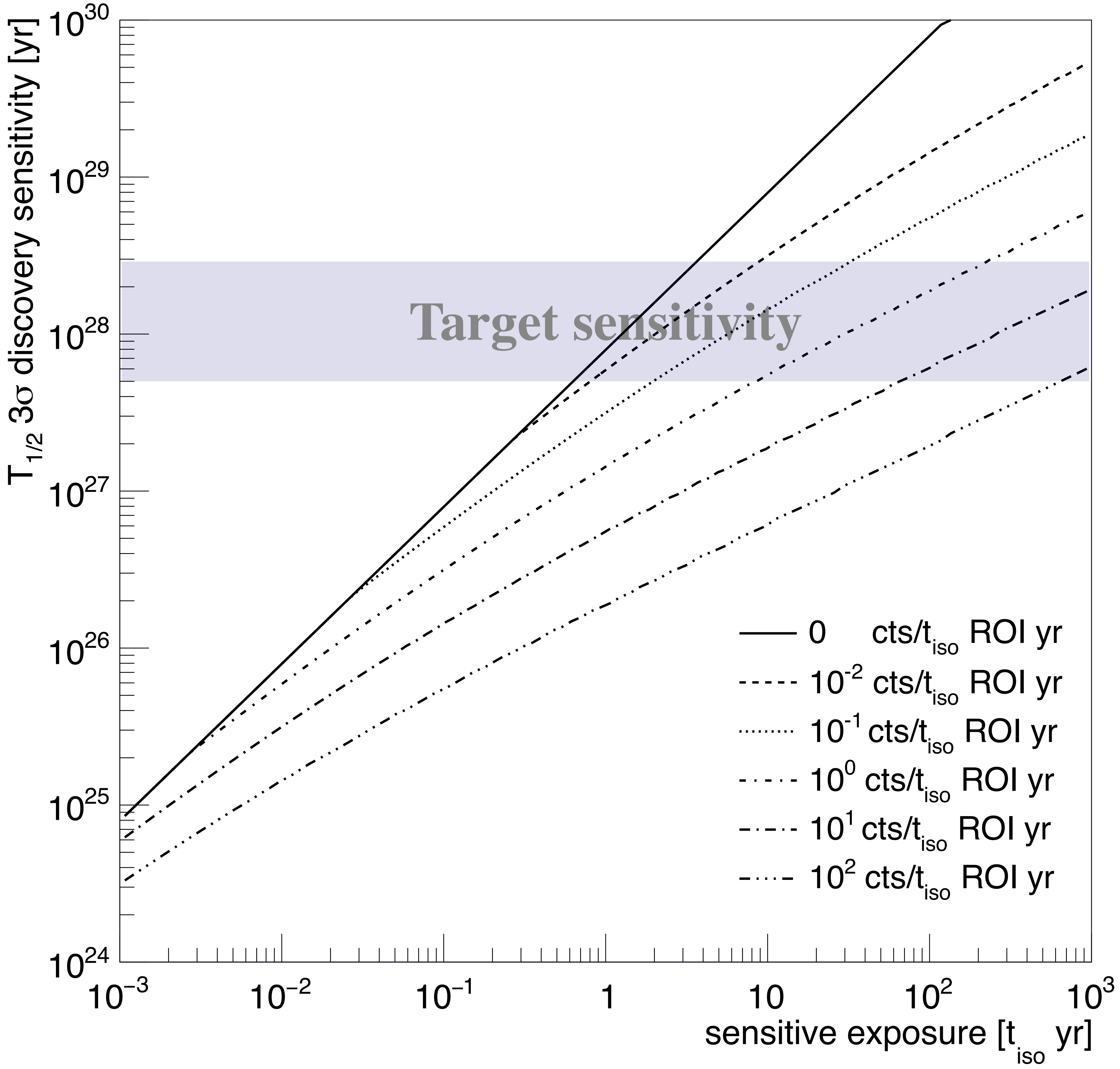
- In most (all) experiments, background is well-constrained, either from energy or volumetric side-bands

Experimental Focus: Discovery

- Discovery sensitivity: the value of $T_{1/2}$ for which an experiment has a 50% chance to observe a signal above background with 3σ significance:

$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

- $S_{3\sigma}(B)$ = Poisson signal expectation at which 50% of experiments report 3σ fluctuation above $B = \mathcal{B}\mathcal{E}$



PRD **96**, 053001 (2017)

Experimental Focus: Discovery

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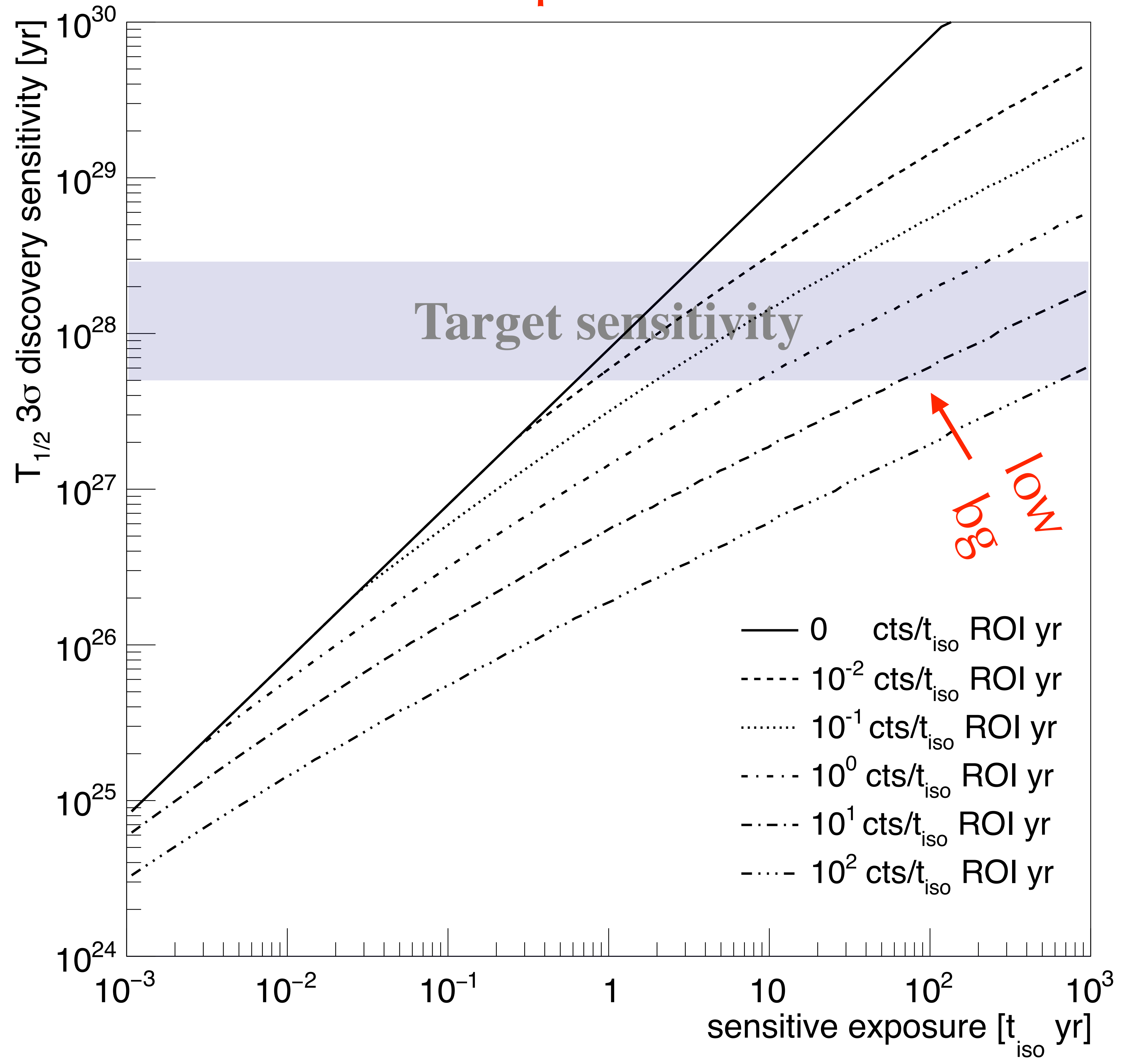
Requirements:



low bg

high exposure →

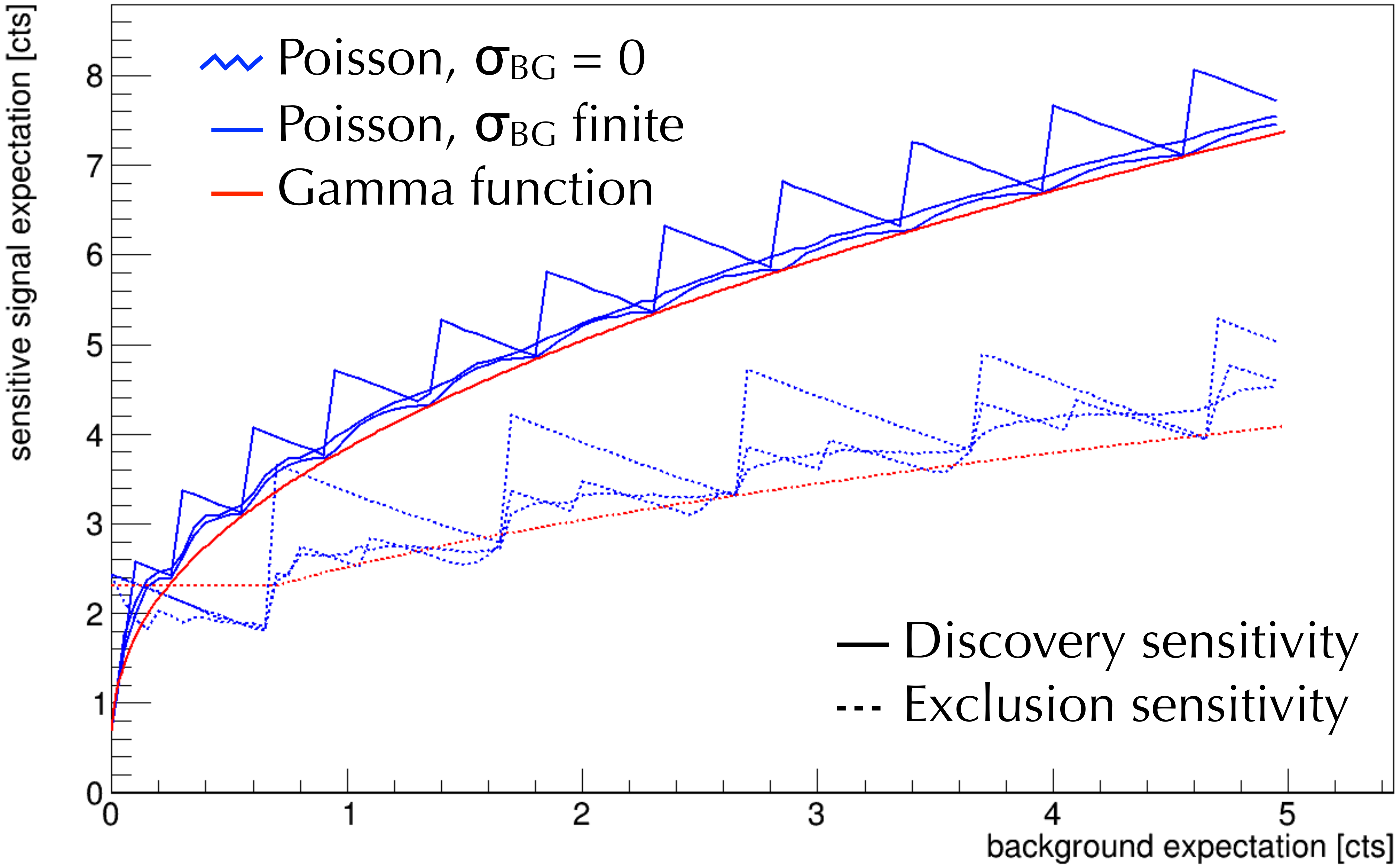
PRD **96**, 053001 (2017)

Poisson + BG Uncertainty

- Shortcut: approximate the Poisson CDF using the Γ function

$$CDF(C|\mu) \approx \frac{\Gamma(C+1|\mu)}{\Gamma(C+1)}$$

- Extremely fast calculation (avoid lengthy MC)
- Better approximation when BG uncertainty is considered

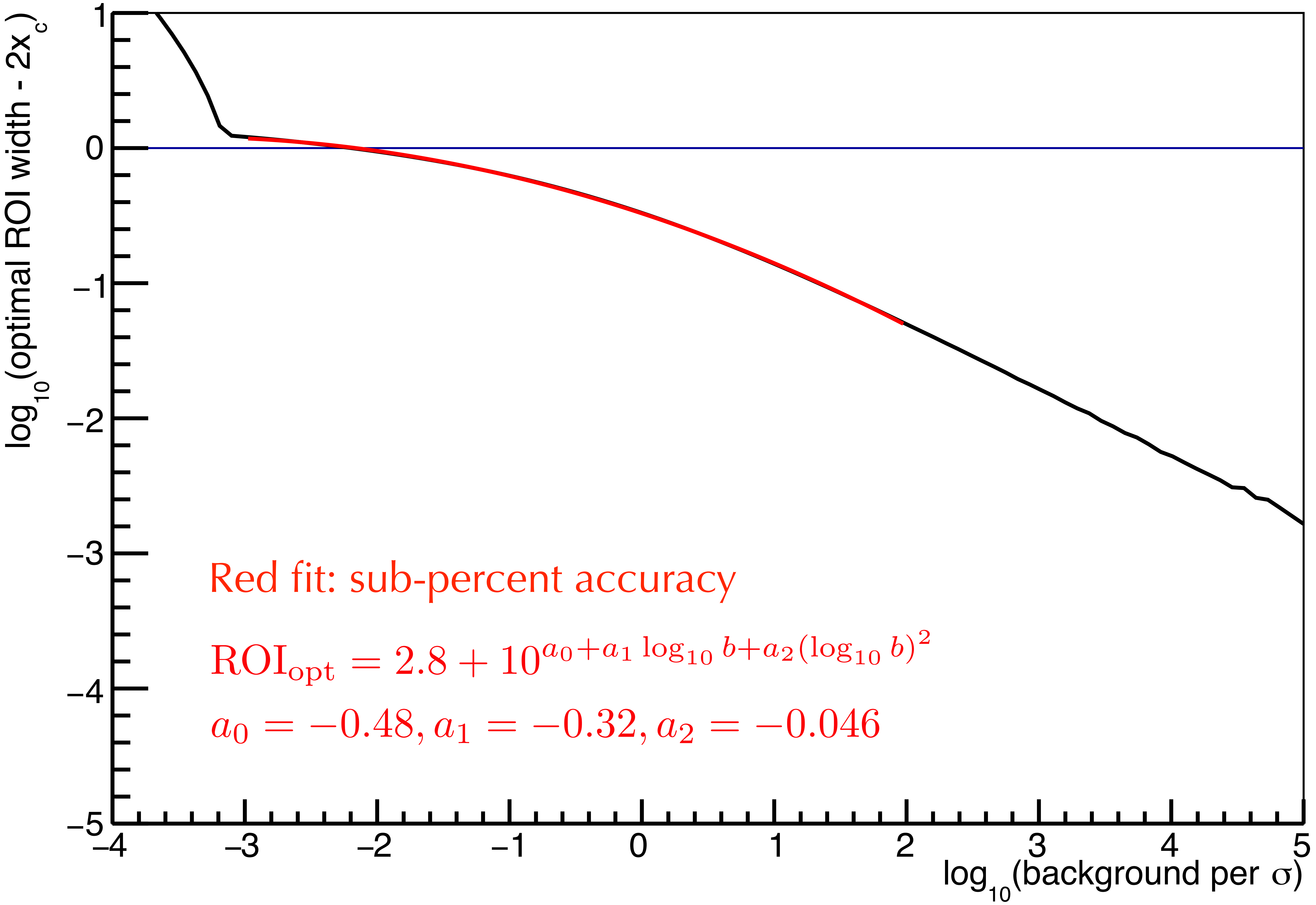


ROI Optimization

- Optimize ROI to maximize discovery sensitivity
- $x_c \approx 1.4$ solves

$$x_c\, e^{-\frac{x^2}{2}} = \frac{\sqrt{2\pi}}{4}\mathrm{erf}\left(\frac{x_c}{\sqrt{2}}\right)$$

- Kink: “Truly” BG-free at -ln[erf(3/√2)] = 0.0027 cts / ROI
- Typical approximations
  - “Nearly” BG-free: $Q_{\beta\beta} \pm 2\sigma$
  - Large, flat BG: $Q_{\beta\beta} \pm 1.4\sigma$
  - Poor resolution: $[Q_{\beta\beta}, Q_{\beta\beta} + 1.4\sigma]$



Red fit: sub-percent accuracy

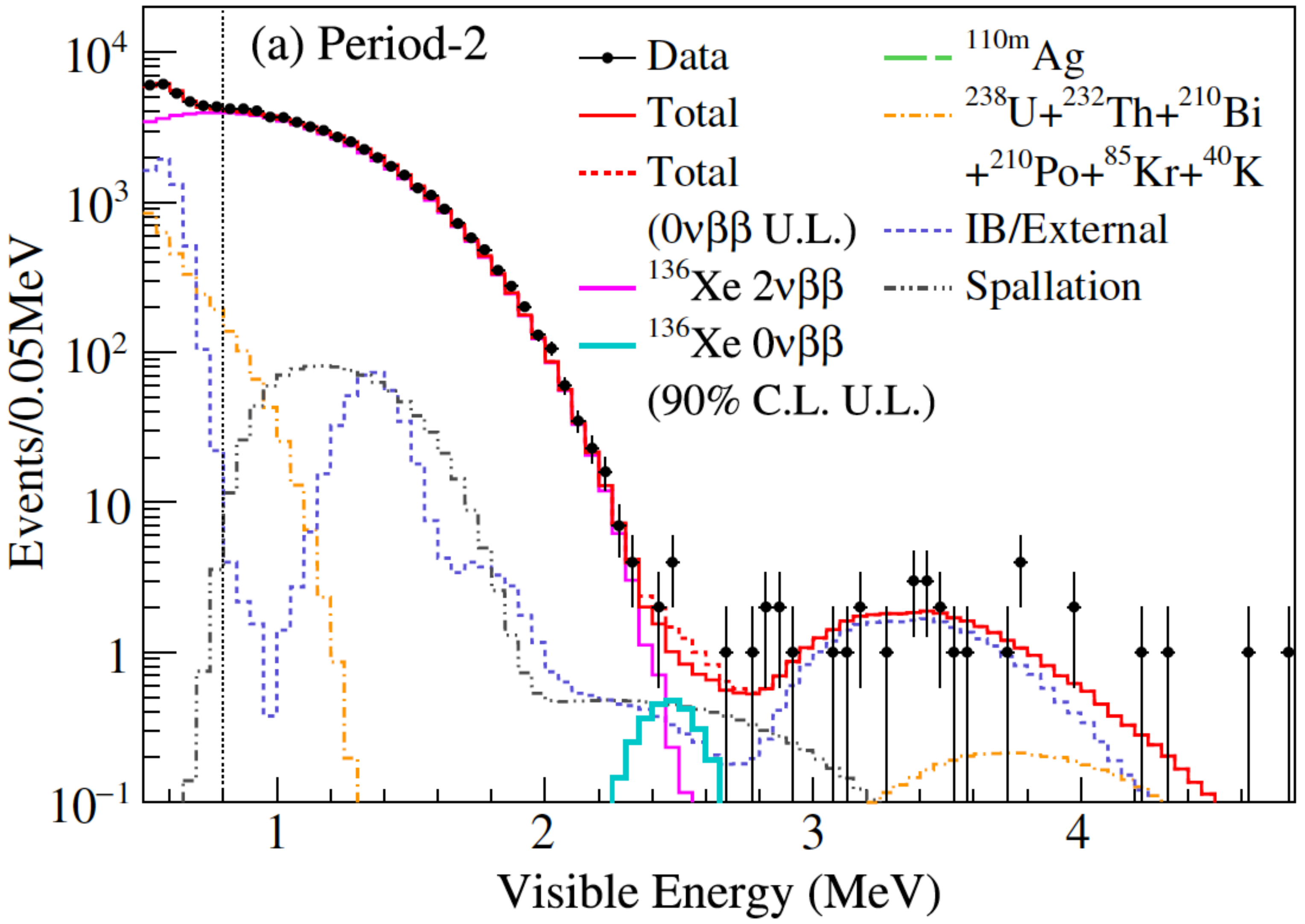
$$\mathrm{ROI_{opt}} = 2.8 + 10^{a_0 + a_1 \log_{10} b + a_2 (\log_{10} b)^2}$$

$$a_0 = -0.48, a_1 = -0.32, a_2 = -0.046$$

Signal Extraction and Shape Uncertainties

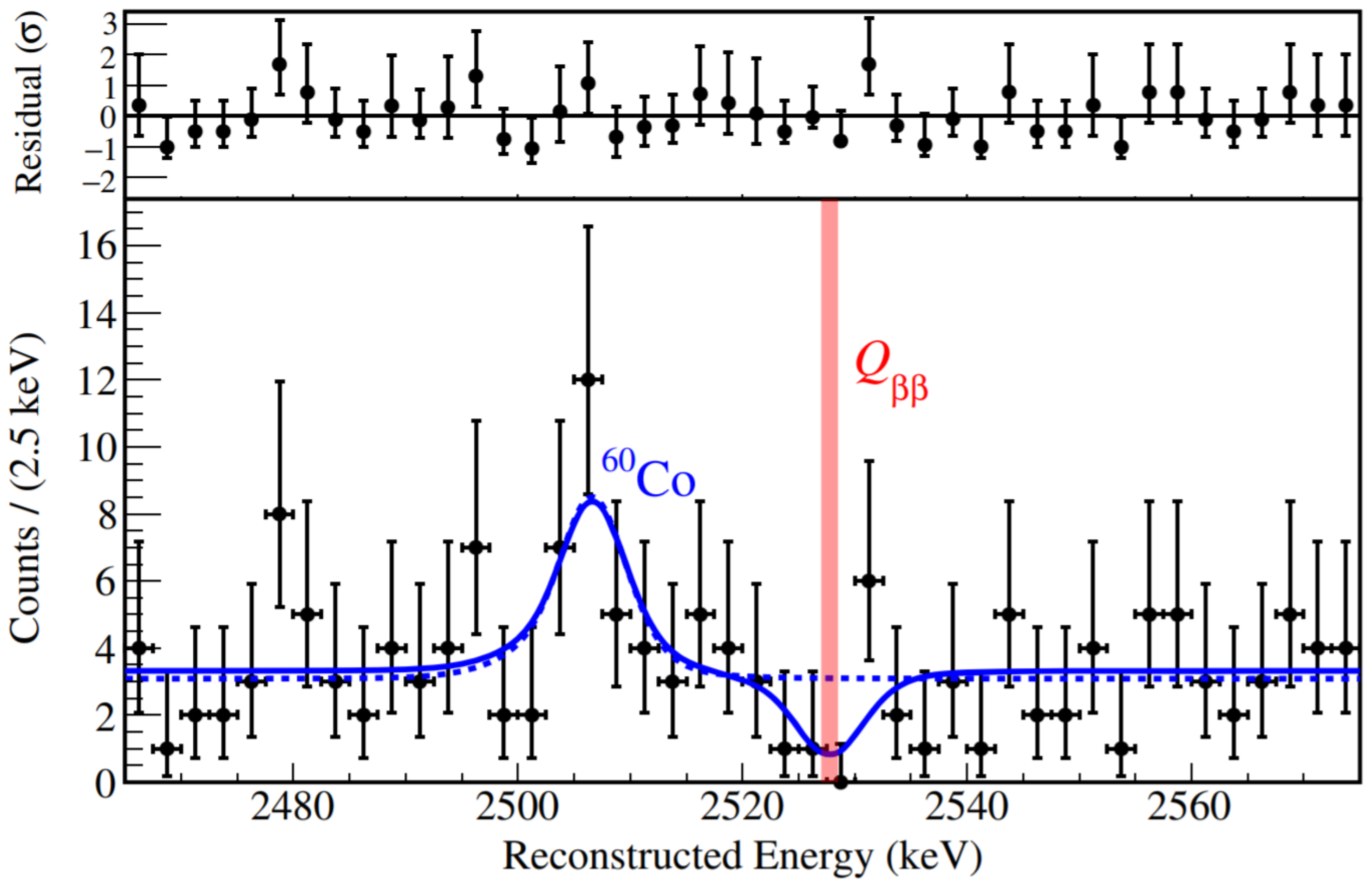
- Sensitivity doesn’t capture well systematic background shape uncertainties
- Several illustrative examples:

KamLAND-Zen: O(10) c/ROI, complex shape



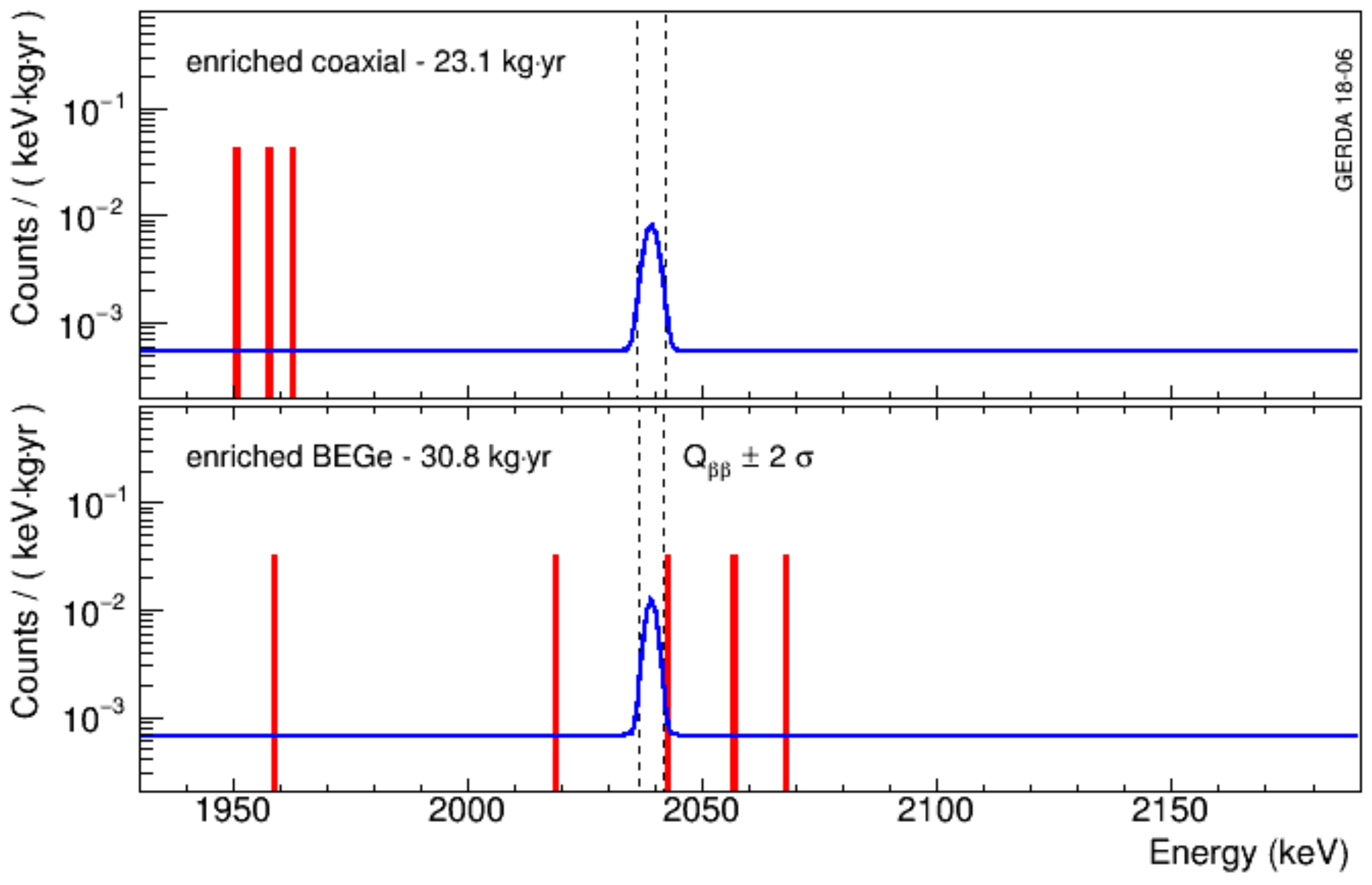
PRL **117**, 109903 (2016)

CUORE: O(10) c/ROI, simple shape



Nu18

GERDA: O(0.1) c/ROI, simple shape



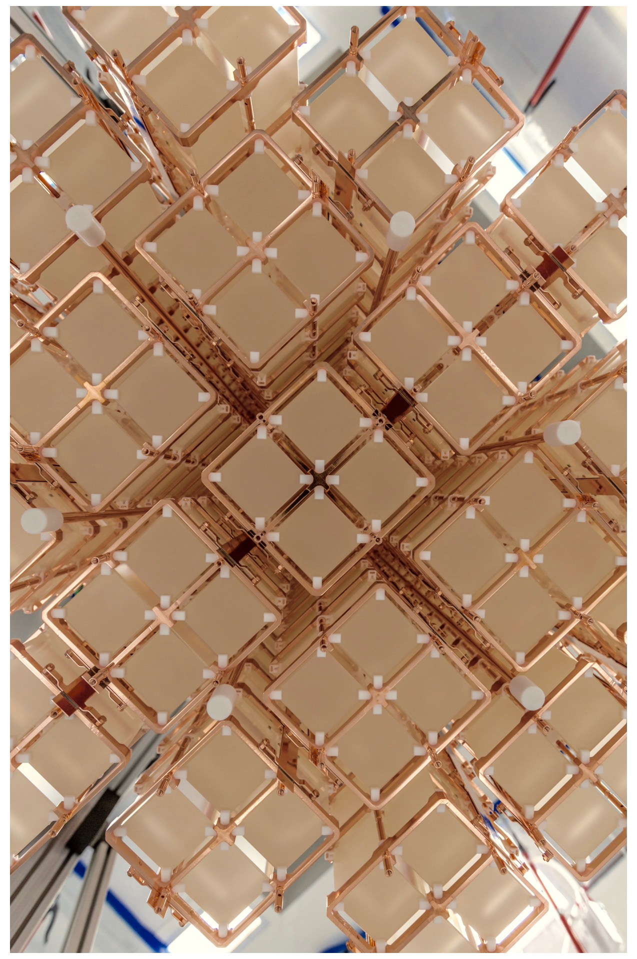
Nu18

Experimental Techniques

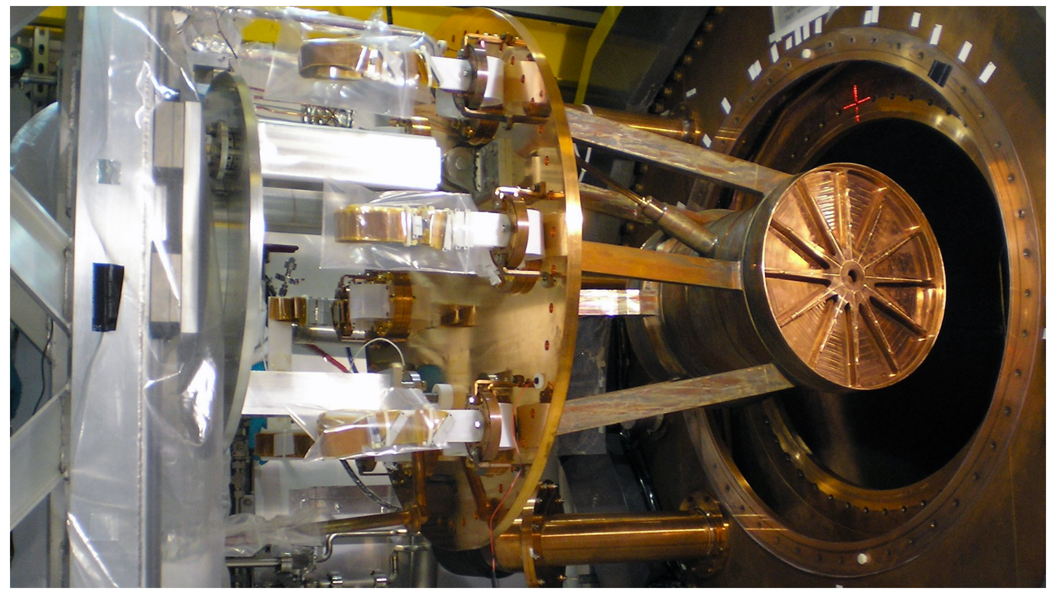
- Scintillators (KamLAND-Zen, SNO+, CANDLES)
  - Measure energy (σ ~ 3-10%) + position from scintillation light; some PID
- TPCs (EXO, NEXT, PandaX)
  - Collect scintillation + ionization: measure energy (σ ~1-3%) + tracks / position + PID
- Bolometers (CUORE, CUPID, AMORE)
  - Measure energy (σ ~ 0.2%) from phonons; some PID
  - R&D underway for instrumenting with photon detectors for background rejection
- Semiconductors (GERDA, Majorana, COBRA, SELENA)
  - Measure energy (~0.1-0.3%) from ionization; some PID and tracking / position sensitivity
- External detectors (NEMO, SuperNEMO, DCBA)
  - Trackers + calorimeters, measure energy (σ ~ 3-10%) + tracks / positions + PID

Experiments

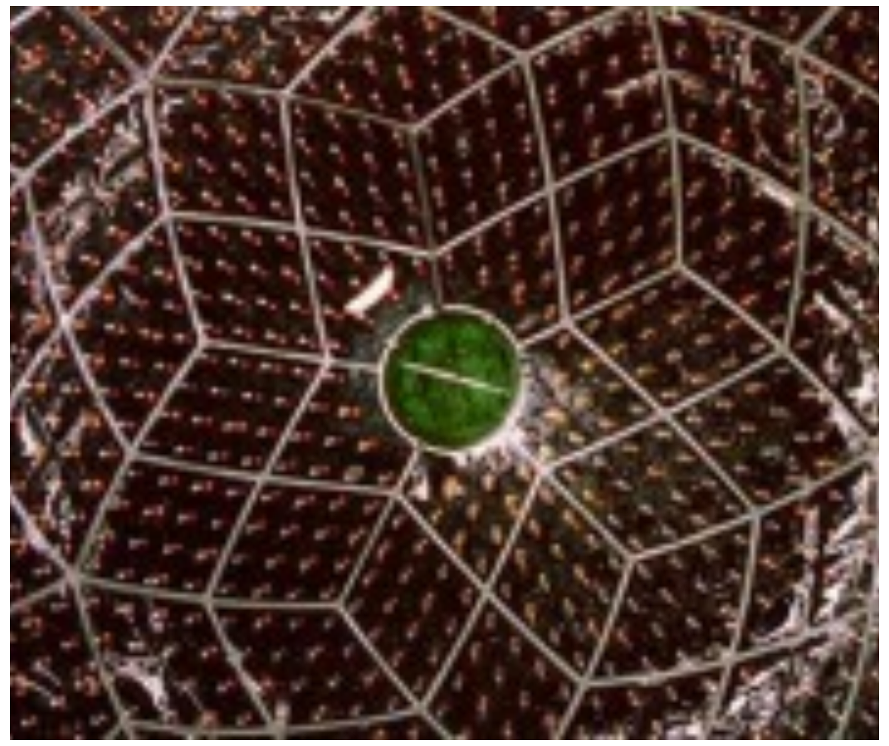
CUORE



EXO-200



KamLAND-Zen

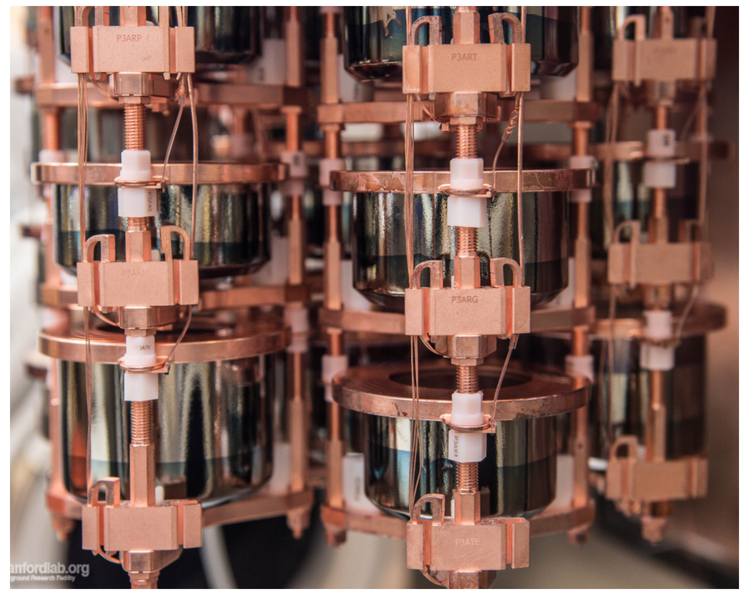


Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
AMoRE	Mo-100	CaMoO4 bolometers (+ scint.)	5 kg	Construction
CANDLES	Ca-48	305 kg CaF$_2$ crystals - liq. scint	0.3 kg	Operating
CARVEL	Ca-48	^{48}CaWO$_4$ crystal scint.	16 kg	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in active LAr	20 kg	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	Ge-76	Best of GERDA + MJD	200 kg	Construction
LEGEND 1000	Ge-76	Best of GERDA + MJD	1 tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	Operating / Construction
CUORICINO	Te-130	TeO$_2$ Bolometer	11 kg	Complete
CUORE-0	Te-130	TeO$_2$ Bolometer	11 kg	Complete
CUORE	Te-130	TeO$_2$ Bolometer	206 kg	Operating
CUPID	Several	Scintillating Bolometers	~tonne	R&D
SNO+	Te-130	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
KamLAND-Zen	Xe-136	2.7% in liquid scint.	370 kg	Complete
KamLAND-Zen 800	Xe-136	2.7% in liquid scint.	750 kg	Construction
KamLAND2-ZEN	Xe-136	2.7% in liquid scint.	~tonne	R&D
NEXT-100	Xe-136	High pressure Xe TPC	10 kg	Construction
PandaX	Xe-136	2 phase Xe liquid TPC	~tonne	R&D
EXO-200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	5 tonnes	R&D
DCBA	Nd-150	Nd foils & tracking chambers	30 kg	R&D

Complete Construction Operating

GERDA

MAJORANA



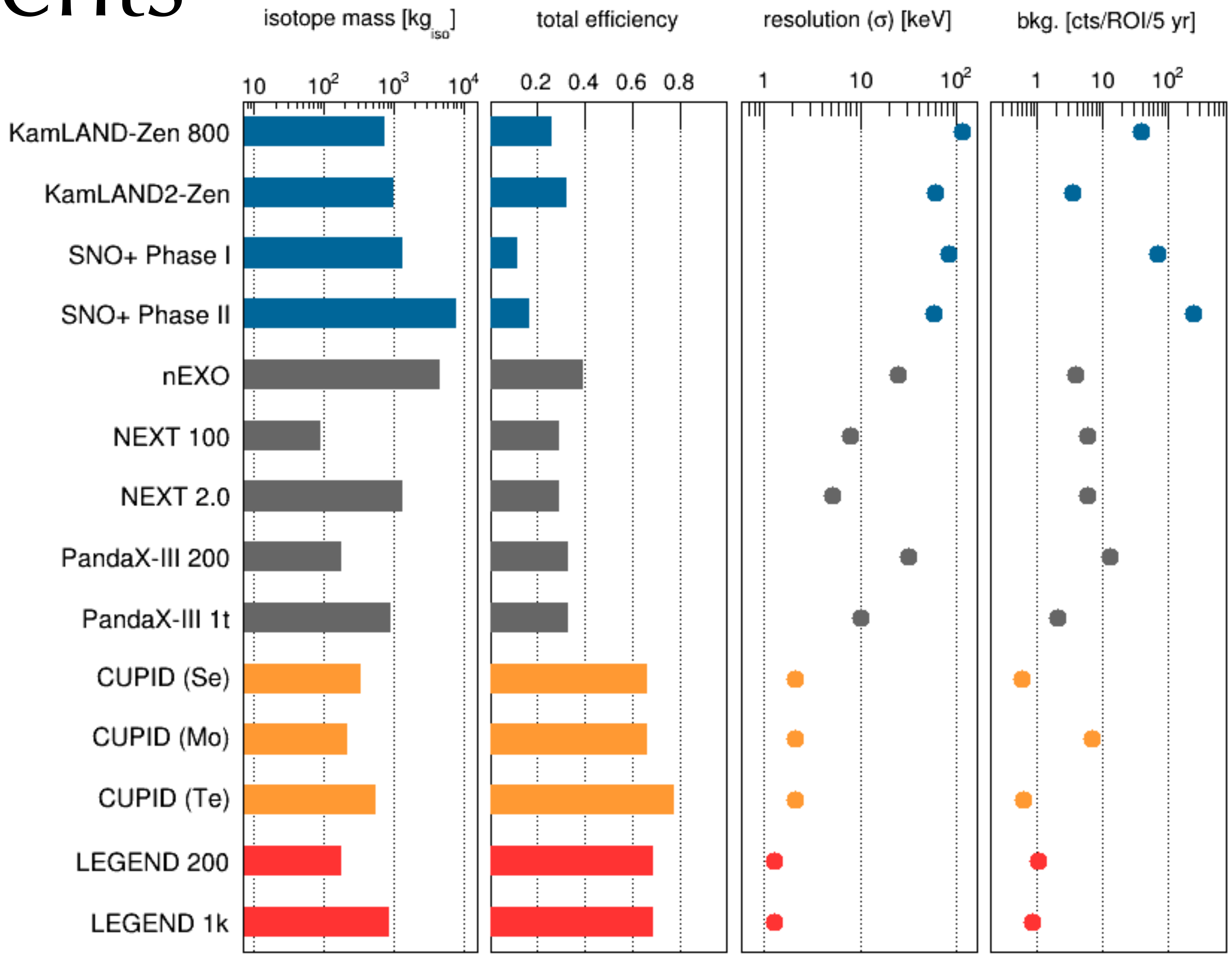
CANDLES

J. Detwiler

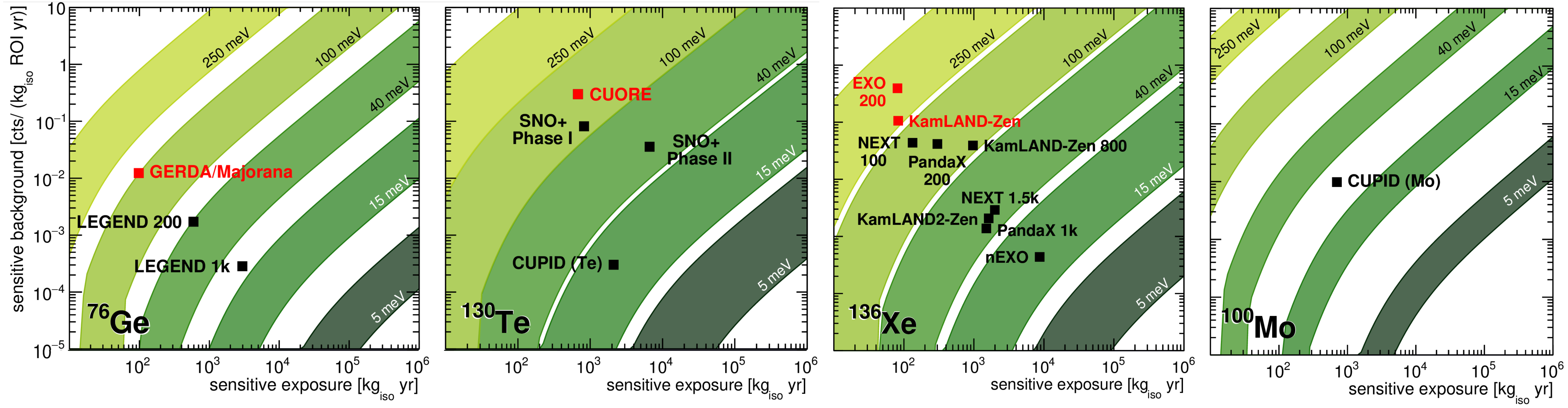
From J. Wilkerson

Future Experiments

- Compiled using quoted stats in publications, presentations
- Tune sensitive exposure and sensitive background when necessary to match published sensitivities



Discovery Sensitivity of Future Experiments



Updated from PRD **96**, 053001 (2017)

Discovery Probability

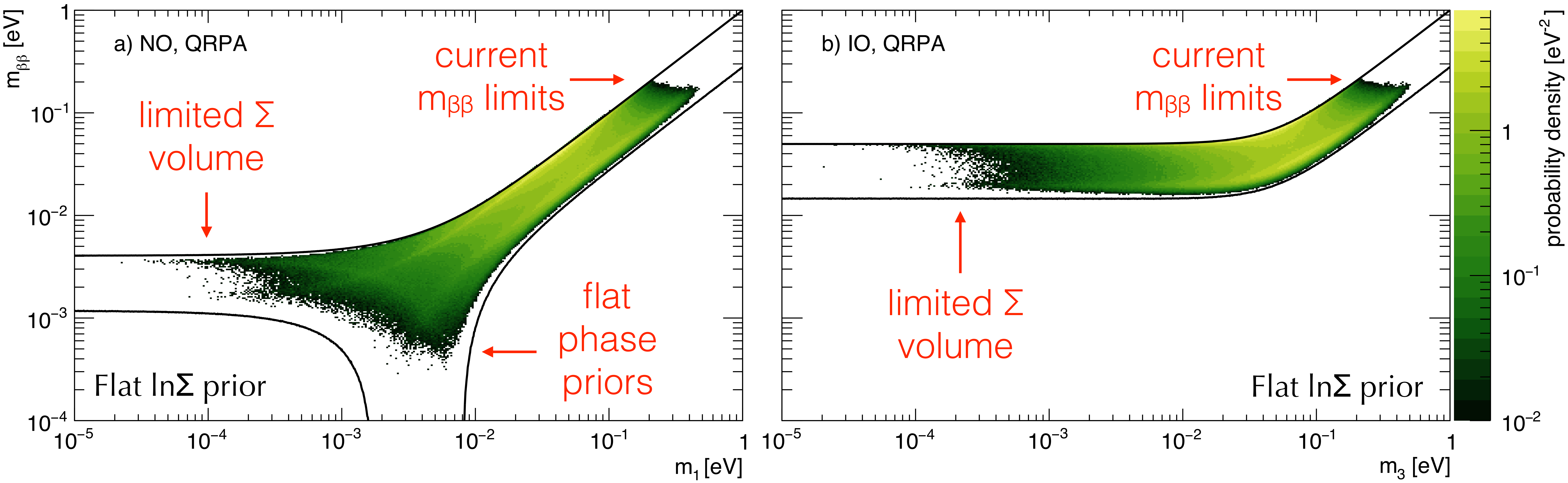
What are the chances that these next-generation experiments will make a discovery?
How much should humanity invest in 0$\nu\beta\beta$*?*

- Bayesian methods are the only tools available by which such a “value” question can be approached:
  - Quantify the “volume” in the available parameter space (assign priors). Equal volumes = equal relative probability of discovery
  - Compute the amount of volume left to be explored (apply constraints from available measurements)
  - Compute the fraction of the remaining volume that will be explored by next-generation experiments. This is the “discovery probability” (DP).
- Equivalent / technical description:
  - Compute the posterior PDF for $m_{\beta\beta}$ given all experiments to date, and use it as a prior for next-generation experiments
  - For each value of $m_{\beta\beta}$, compute the probability that a next-generation experiment will make a 3σ discovery. Then sum up those probabilities weighted by the $m_{\beta\beta}$ PDF.

Priors and Basis

- Neutrino mass scale is unknown: use log-flat prior for all mass parameters
- Angles and phases: use flat prior in $[0, 2\pi)$
- Constrain with all available data: NuFit (osc.), β-decay, ββ-decay
- Evaluate for multiple NME, with/without g_A quenching, with/without cosmological limits
- Basis choice: Σ vs. m_l
    - m_l: represents theoretical prejudice for the hierarchical scenario $m_l \ll m_2$. Results are trivial: DP ~ 100% for IO, and < ~few% for NO
    - Σ: represents theoretical prejudice that neutrino masses are generated by a different mechanism than the other SM fermions
    - We choose Σ as our "reference" basis. One can re-weight our results according to his or her own prejudice for this vs. extreme hierarchical scenarios

$m_{\beta\beta}$ PDF



limited Σ volume

current $m_{\beta\beta}$ limits

flat phase priors

Flat lnΣ prior

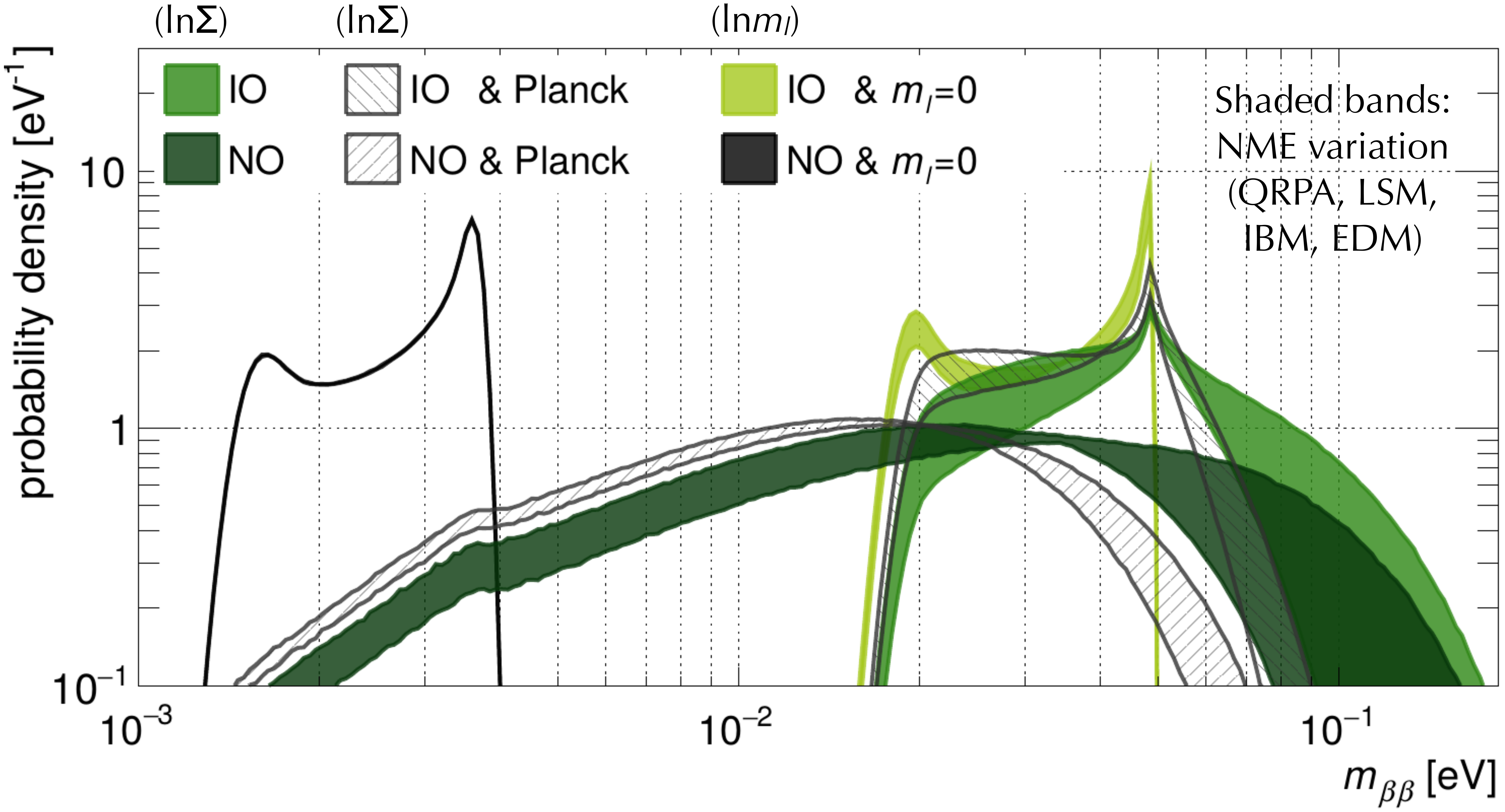
current $m_{\beta\beta}$ limits

limited Σ volume

Flat lnΣ prior

PRD **96**, 053001 (2017)

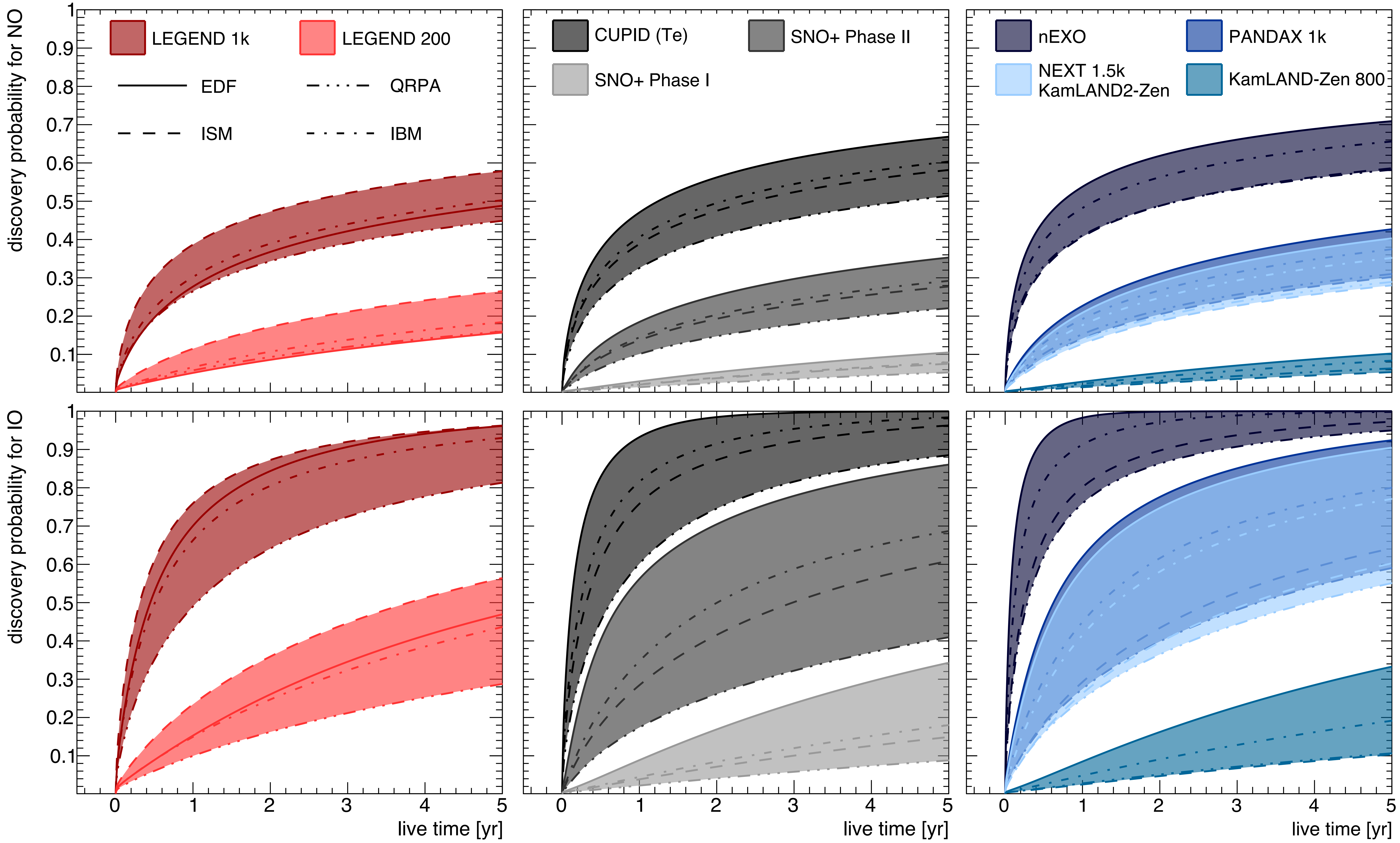
$m_{\beta\beta}$ PDF



PRD **96**, 053001 (2017)

Discovery Probabilities

- Fold $m_{\beta\beta}$ PDF with discovery sensitivity
- These plots: flat lnΣ prior
- Flat lnm_l prior:
  - IO ~unchanged
  - NO → ~few%



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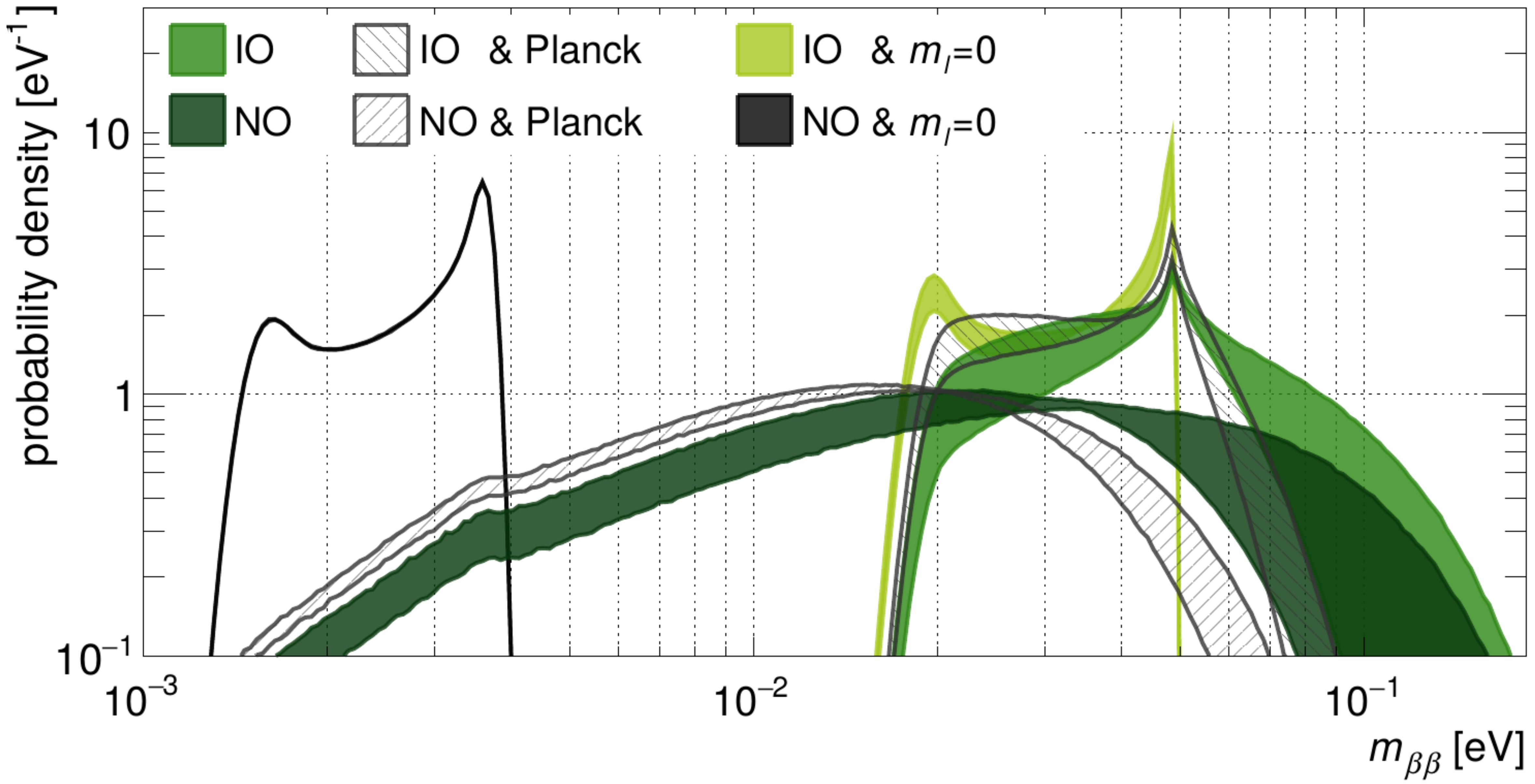
Impact of g_A Quenching

- g_A quenching could be up to tens of percent: could suppress $T_{1/2}$ by g_A^2 or g_A^4, depending on the model
- Might be partially mitigated by higher q^2 in virtual exchange loop



- Sensitivity is suppressed accordingly. But would also relax current 0νββ limits
- Phase degeneracy gives larger posterior at higher $m_{\beta\beta}$: affect on discovery probability is weak until degradation reaches the main peak

Alternative Analyses (flat lnΣ)

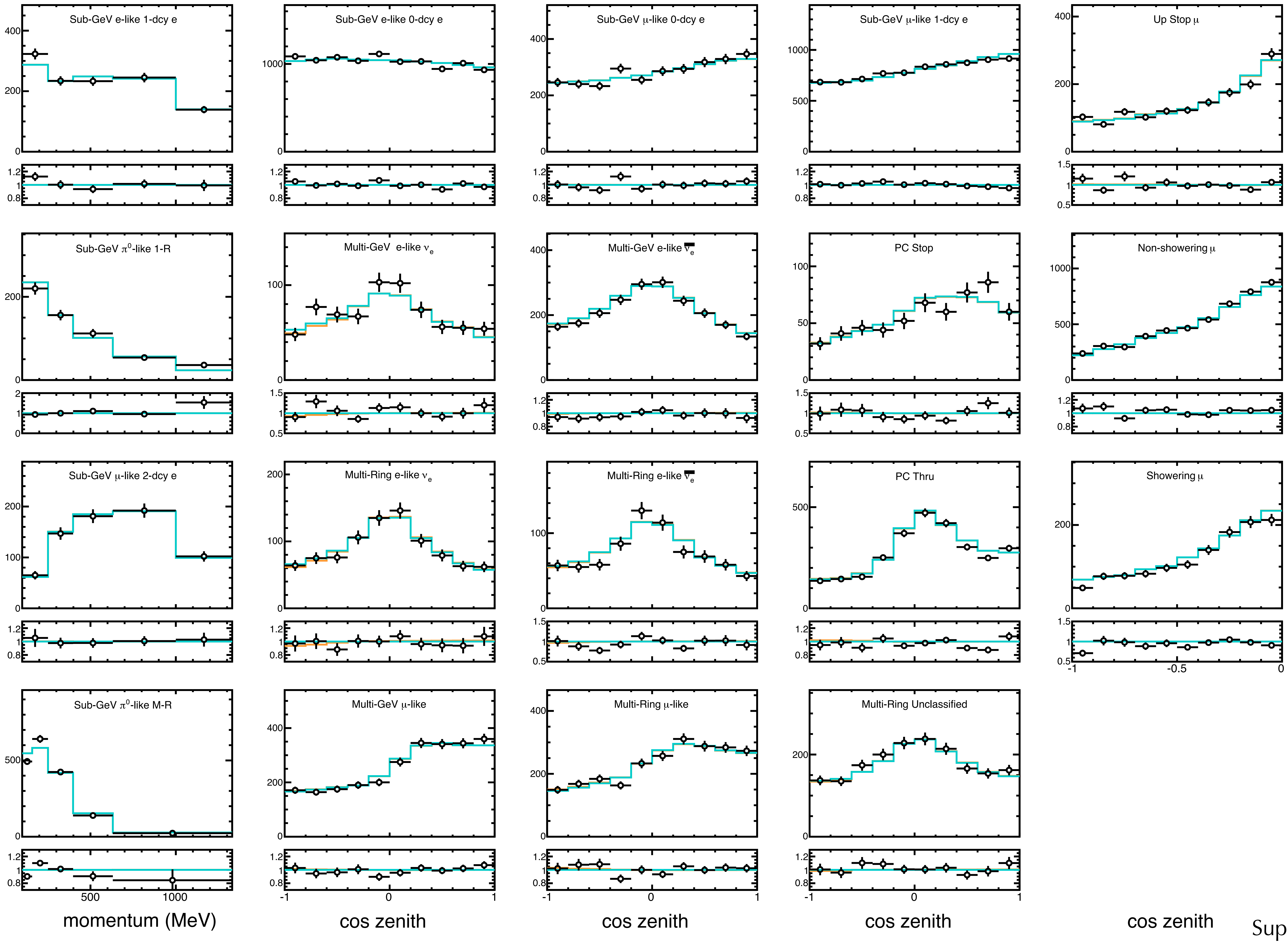
- Adding 30% g_A quenching: DP drops by only ~15% (25%) for IO (NO)
- Adding cosmological constraints: NO DP reduced by ~30%. No effect for IO.
- Both cosmological limits + g_A quenching: Planck rules out the region opened up at high $m_{\beta\beta}$ from relaxed GERDA / KLZ limits. IO DP drops to ~50%, NO DP drops to 10-20%.
- If KATRIN sees a positive signal: DP → 100% regardless of ordering, mass model, NME, quenching, cosmology.

Many scenarios have significant discovery probability for either mass ordering!

Summary

- Promising future 0νββ experiments must have high sensitive exposure with low sensitive background
- Proposed experiments balance exposure and background using different techniques in different nuclei with different systematics
- These experiments have good discovery probability: discovery may be just around the corner!

Backup



J. Detwiler

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