Double-Beta Decay and Neutrino Mass

Jason Detwiler, University of Washington

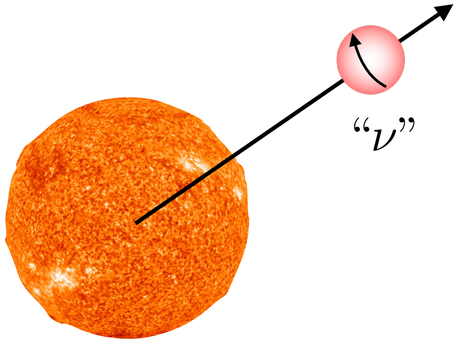
Snowmass, Seattle, WA, 22 July 2022

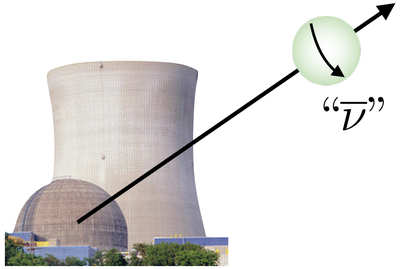
Disclaimer: I'm a member of the MAJORANA, LEGEND, and KamLAND-Zen Collaborations

Outline

- Introduction and light left-handed neutrino exchange
- Global experimental program and its reach
- Inferring neutrino mass from $0\nu\beta\beta$ decay

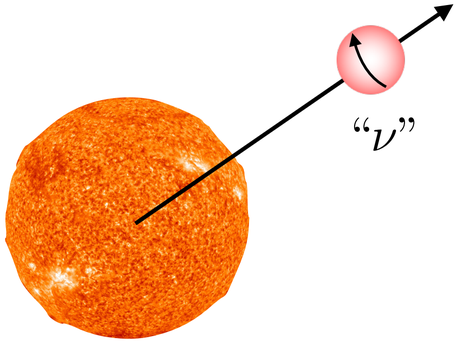
Neutrino Mass

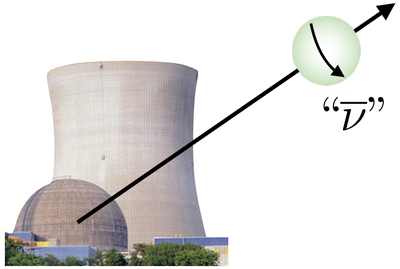


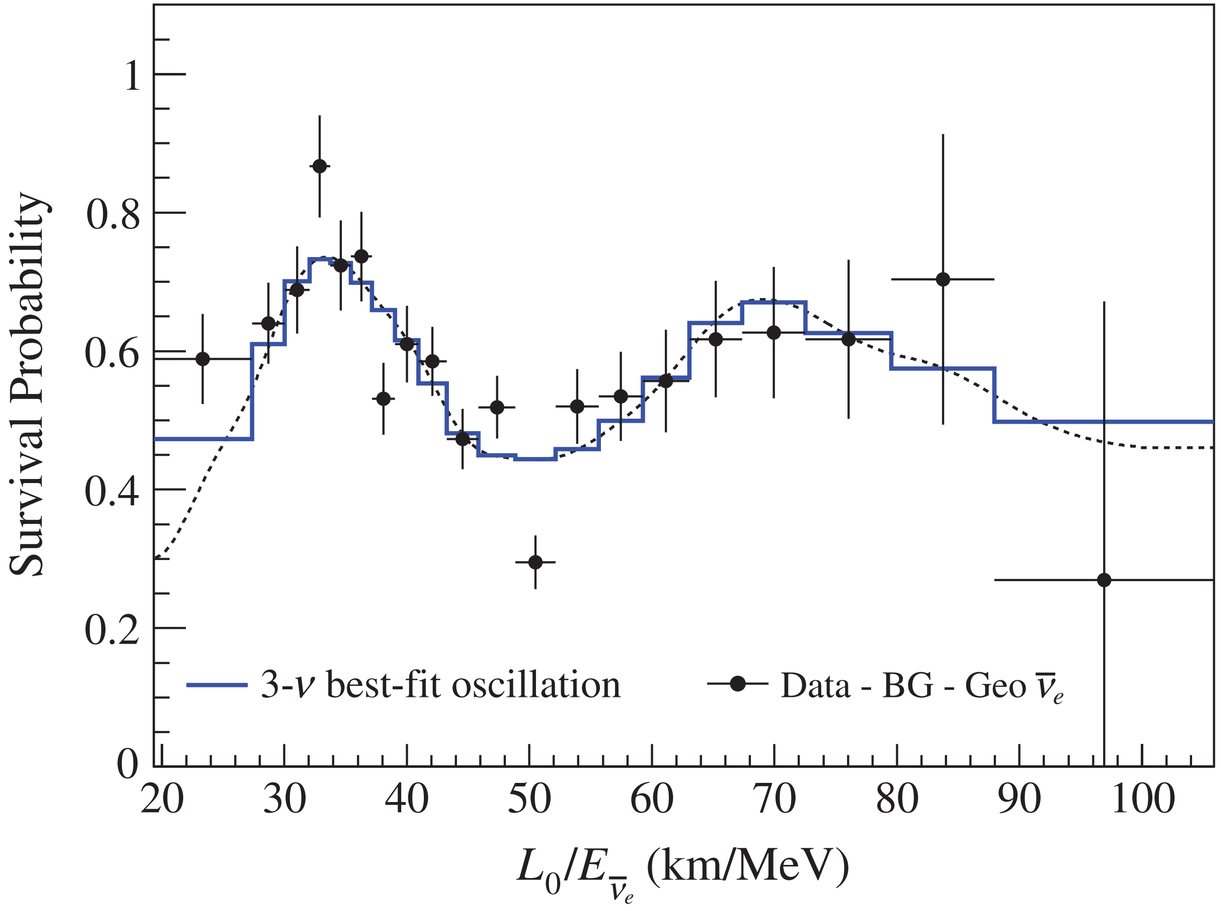


KamLAND, PRD **88**, 033001 (2013)

Neutrino Mass

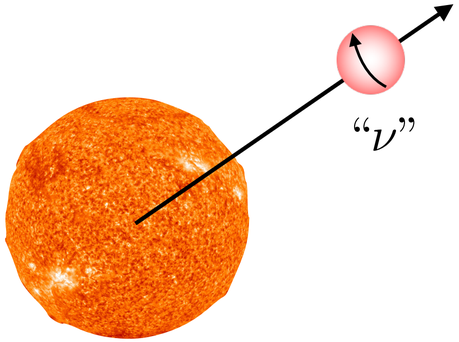


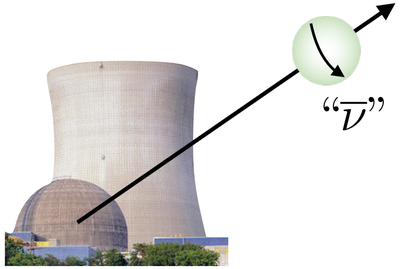




KamLAND, PRD **88**, 033001 (2013)

Neutrino Mass





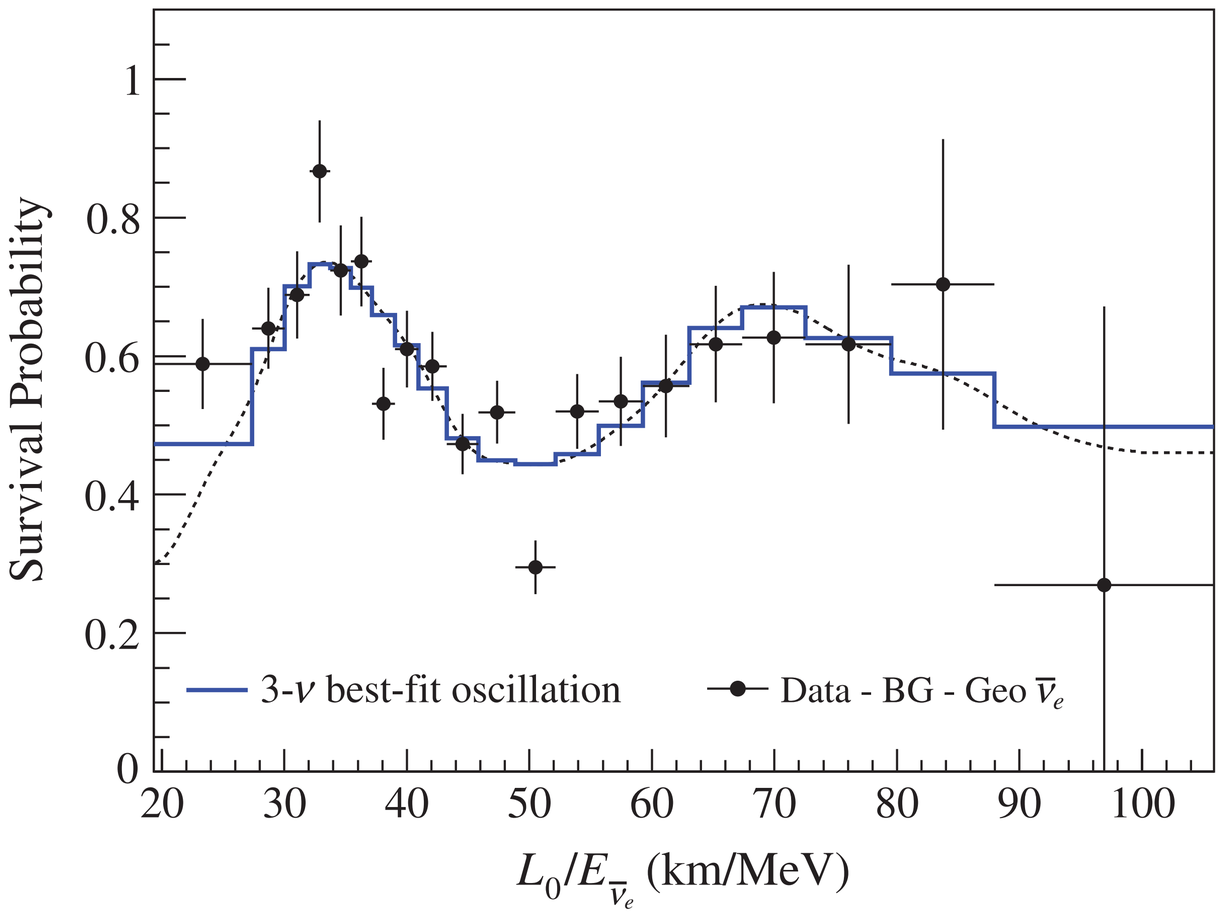
In the neutrino's rest frame:

Dirac

Majorana

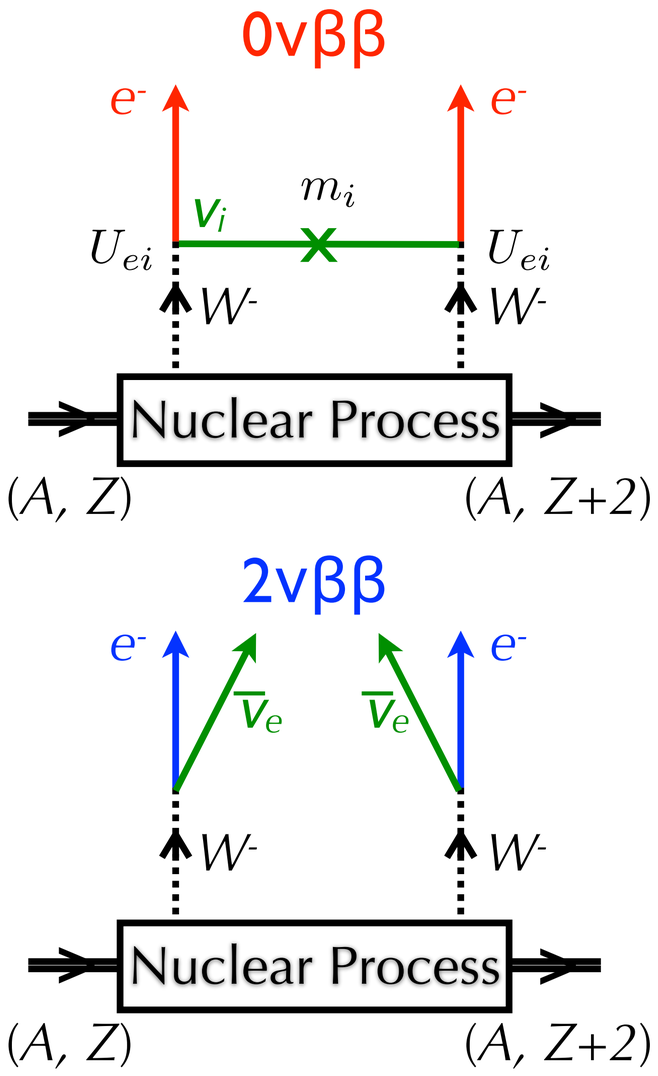
Two sterile components…

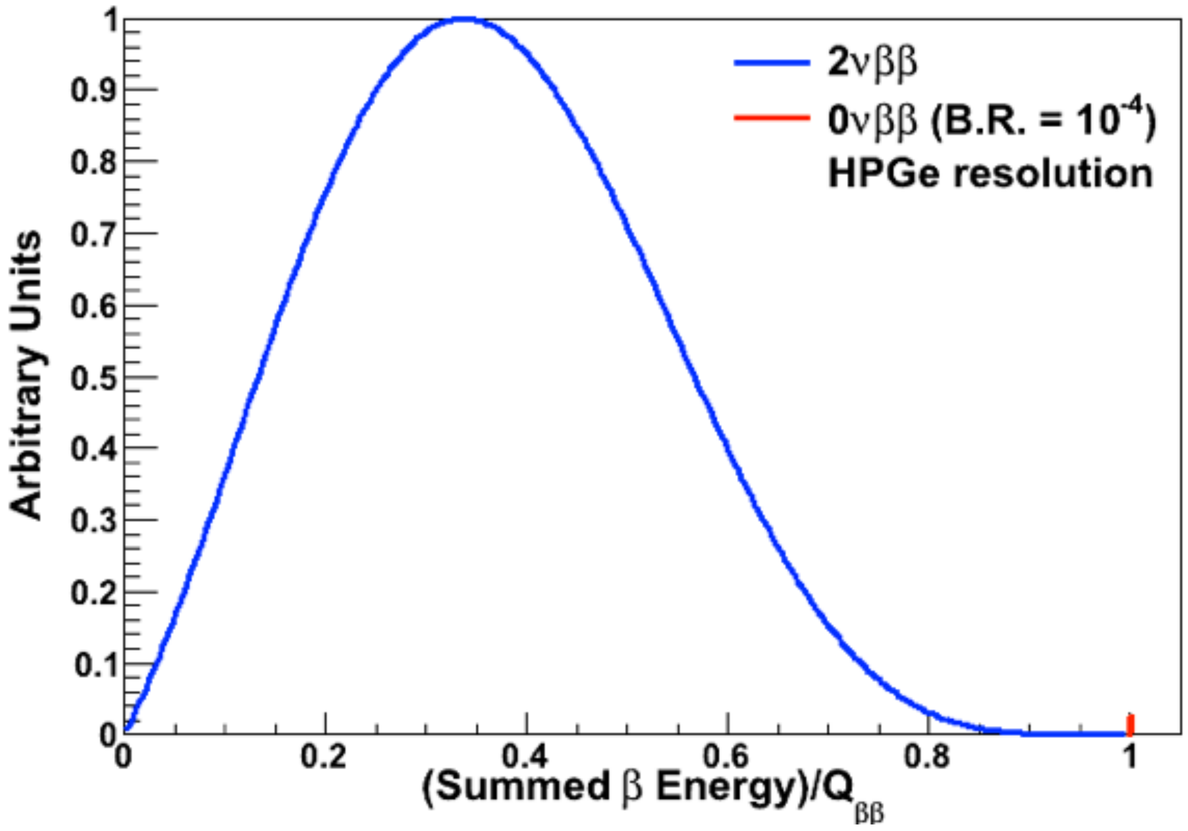
… or a new type of particle?



KamLAND, PRD **88**, 033001 (2013)

Neutrinoless Double-Beta Decay



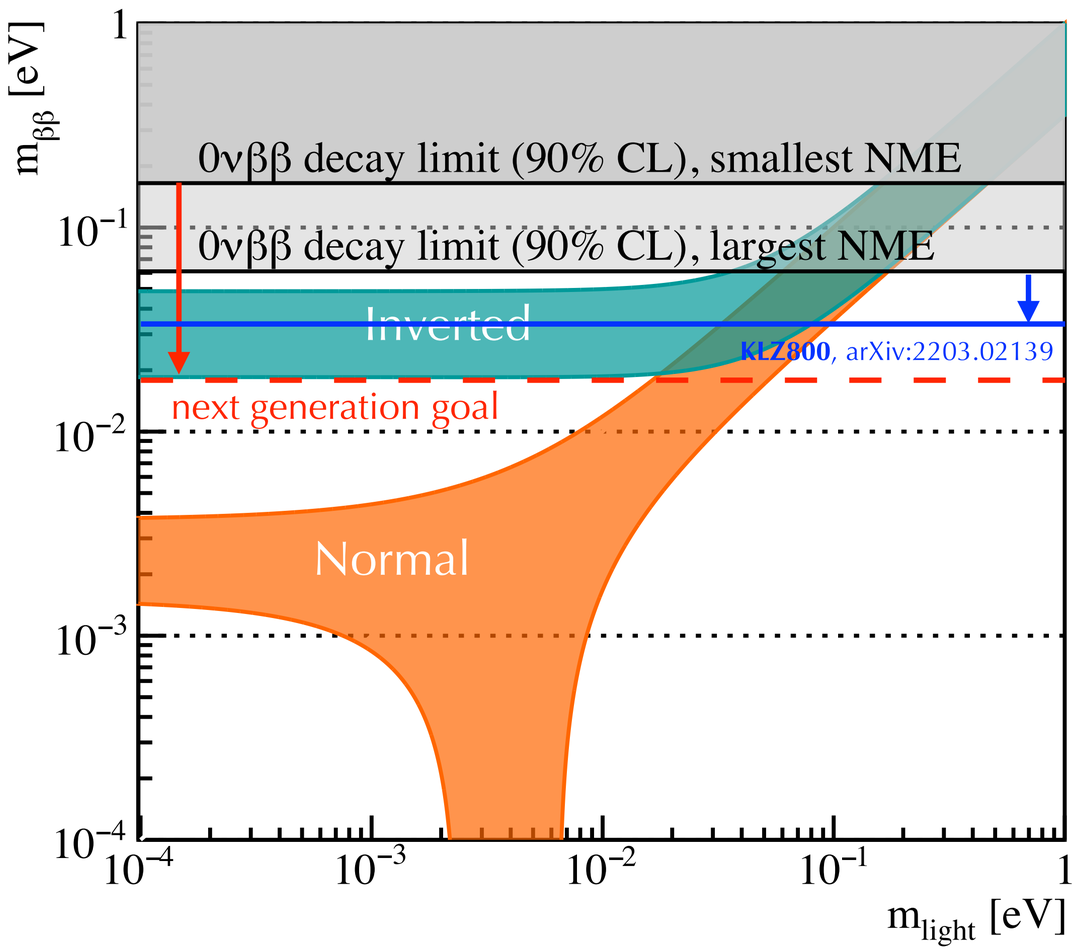


$\Gamma^{0\nu} \sim \left| \sum_i U_{ei}^2 m_i \right|^2$: peak height probes the neutrino mass scale

Light Neutrino Exchange

$$\Gamma^{0\nu} = G^{0\nu}\,|M^{0\nu}|^2\,m_{\beta\beta}^2 \qquad m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

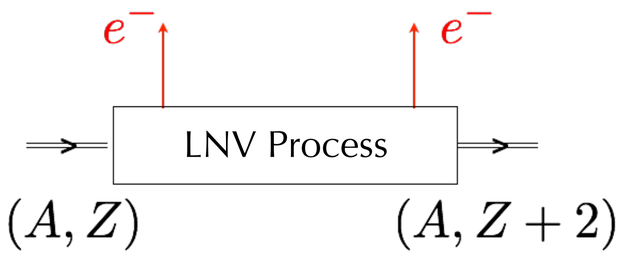
- ν mixing and splitting parameters predict different ranges for $m_{\beta\beta}$ as a function of the unknown lightest neutrino mass
- IO: "hard" lower limit on $m_{\beta\beta}$, implies $T_{1/2} \lesssim 10^{28}\mathrm{yr}$
- NO: most m_{light} values give $T_{1/2} \lesssim 10^{30}\mathrm{yr}$
- These are clear experimental goals

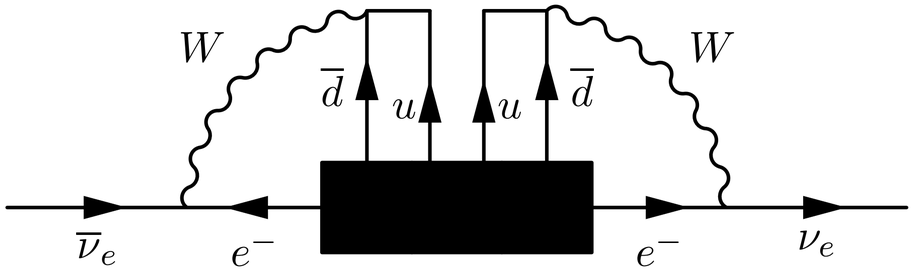


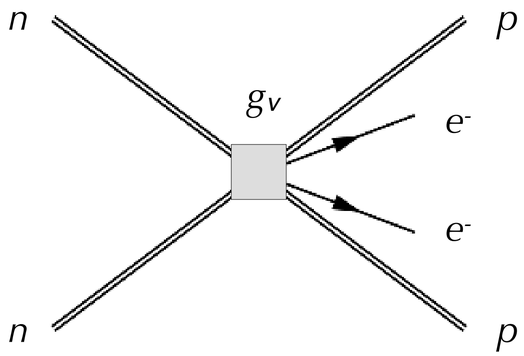
0νββ Decay, Generically

- A "Little Bang" that creates (just) two new matter particles (irrespective of mechanism)
  - Violates not just *L* but (*B*-*L*)
- Many mechanisms are available to generate 0νββ without the exchange of Majorana SM neutrinos
  - Schecter-Valle: all of these induce Majorana masses…
  - … but they are many orders of magnitude smaller than $\Delta m^2_{\rm sol}$ (Duerr, Lindner, Merle, JHEP **2011**, 91)
- Even for light neutrino exchange, the same HE physics that generates m_ν will also give a short-range contribution to 0νββ decay at leading order
  - Cirigliano *et al.*, PRL **120**, 202001 (2018)

$$T_{1/2}^{-1} = G_{01}\, g_A^4\, \left|M^{0\nu}_{\rm long} + M^{0\nu}_{\rm short}\right|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$







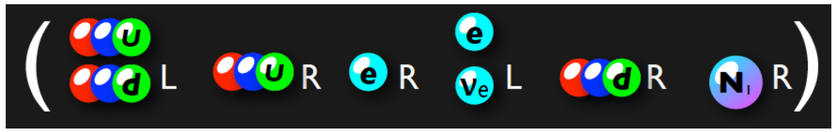
Truth In Advertising

- If $0\nu\beta\beta$ is observed:
  - $0\nu\beta\beta$ may not be mediated by SM neutrinos, in which case the decay rate is not connected to the neutrino mass scale
  - Even if it is, there are large uncertainties in the NME and the contact term
  - Even if those are eventually calculated reliably, $m_{\beta\beta}$ could be in a region where its value is not correlated with the absolute neutrino masses
  - The unknown Majorana phases generate additional degeneracy
- If $0\nu\beta\beta$ is not observed:
  - It could be due to large cancellations between SM ν exchange and other mechanisms…
  - Or due to cancellations in $m_{\beta\beta}$ itself from the Majorana phases…
  - Or it could be that neutrinos are Dirac

→ $0\nu\beta\beta$ experiments do not directly or reliably probe the neutrino mass scale

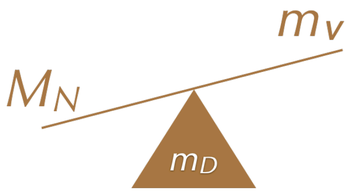
Motivation for Light Neutrino Exchange

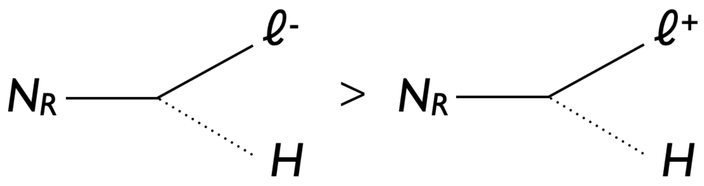
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$



- EFT: LNV appears in *L* terms of dimension 5, 7, 9…
- *d* = 5 operator (Weinberg operator) is uniquely a Majorana mass term for SM neutrinos
- Example: SO(10) GUT
  - SO(10) requires one new right-handed singlet N_R
  - N_R generates Majorana neutrino masses via the seesaw mechanism
  - CPV N_R decays immediately after the Big Bang generate the cosmic matter asymmetry (leptogenesis)

$$m_\nu = \frac{m_D^2}{M_N}$$





Cirigliano, Hamaguchi, Kayser, Murayama, Vissani, …

Modern Orthodoxy

- For a very large class of models, it is “natural” for light left-handed neutrino exchange to dominate the $0\nu\beta\beta$ decay rate.
- In some sense, light left-handed neutrino exchange is a “minimalistic” extension of the Standard Model, in that it requires no specific new field or symmetry, only a Majorana mass term for the SM neutrino.
- Light left-handed neutrino exchange sets clear experimental goal posts.
- A discovery will be most readily first interpreted in terms of light left-handed neutrino exchange until evidence is available to suggest another mechanism may play a non-negligible role.
- Within this framework, both the observation and non-observation of neutrinoless double-beta decay can provide information on the neutrino mass scale.

Outline

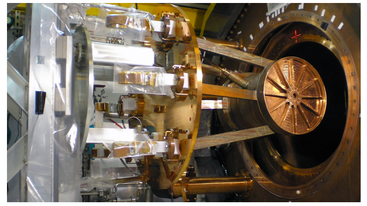
- Introduction and light left-handed neutrino exchange
- Global experimental program and its reach
- Inferring neutrino mass from $0\nu\beta\beta$ decay

Experimental Techniques

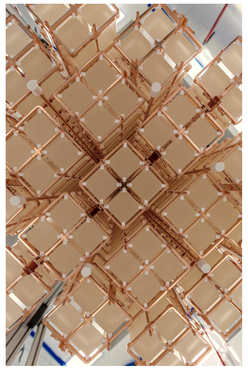
- Bolometers (CUORE/CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (NEMO3, SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND-Zen, SNO+, CANDLES-III, Theia, ZICOS)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (COBRA, MAJORANA, GERDA, LEGEND)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (EXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

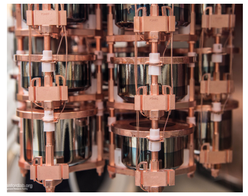

KamLAND-Zen

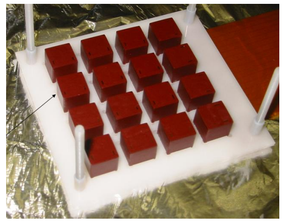

CANDLES

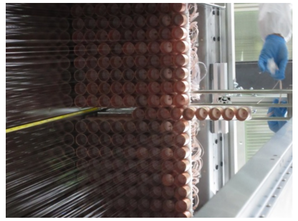

EXO-200


NEXT-100


CUORE


MAJORANA


COBRA


SuperNEMO


NEMO3

Experimental Focus: Discovery

- Energy is the only observable that is both necessary and sufficient for discovery of 0νββ decay: effectively a Poisson counting experiment

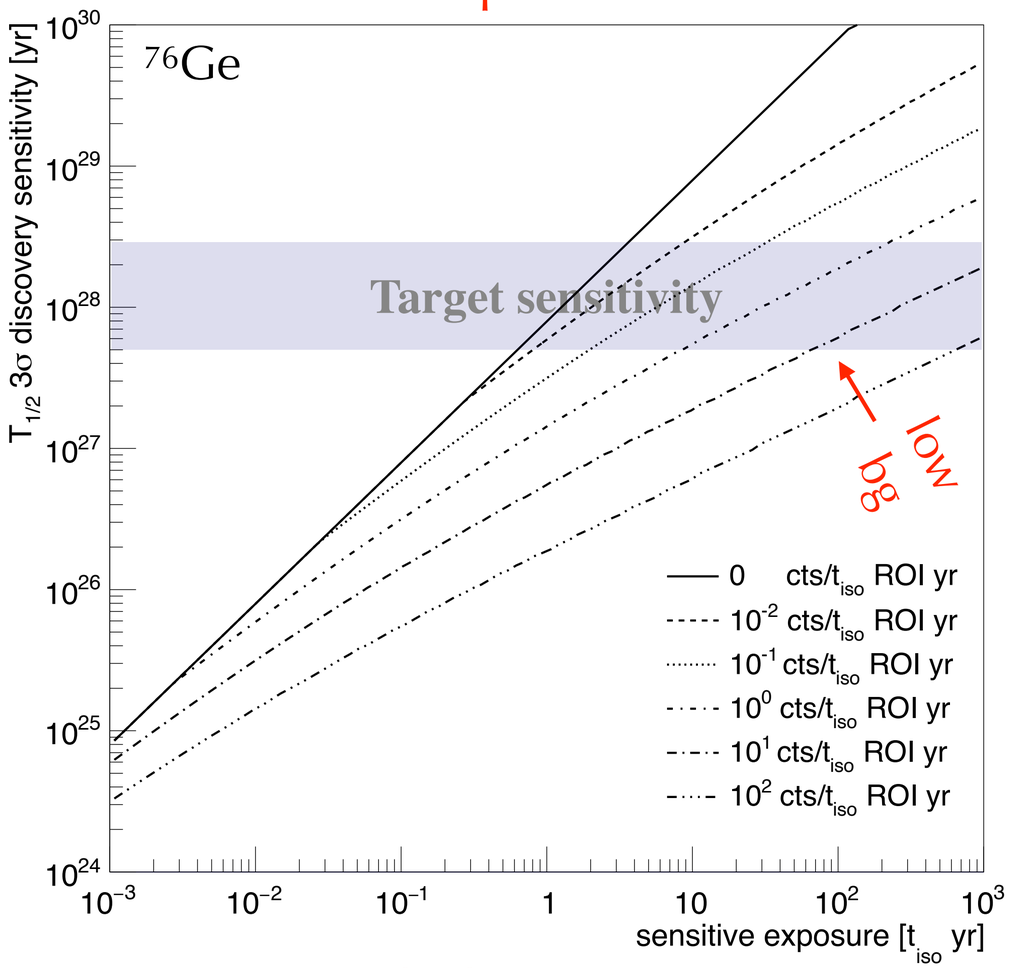
- Relevant parameters: sensitive exposure and sensitive background

$$\mathcal{E} = \epsilon\, m_{iso}^{FV}\, t \qquad \mathcal{B} = N_{bg}/\mathcal{E}$$

- 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:

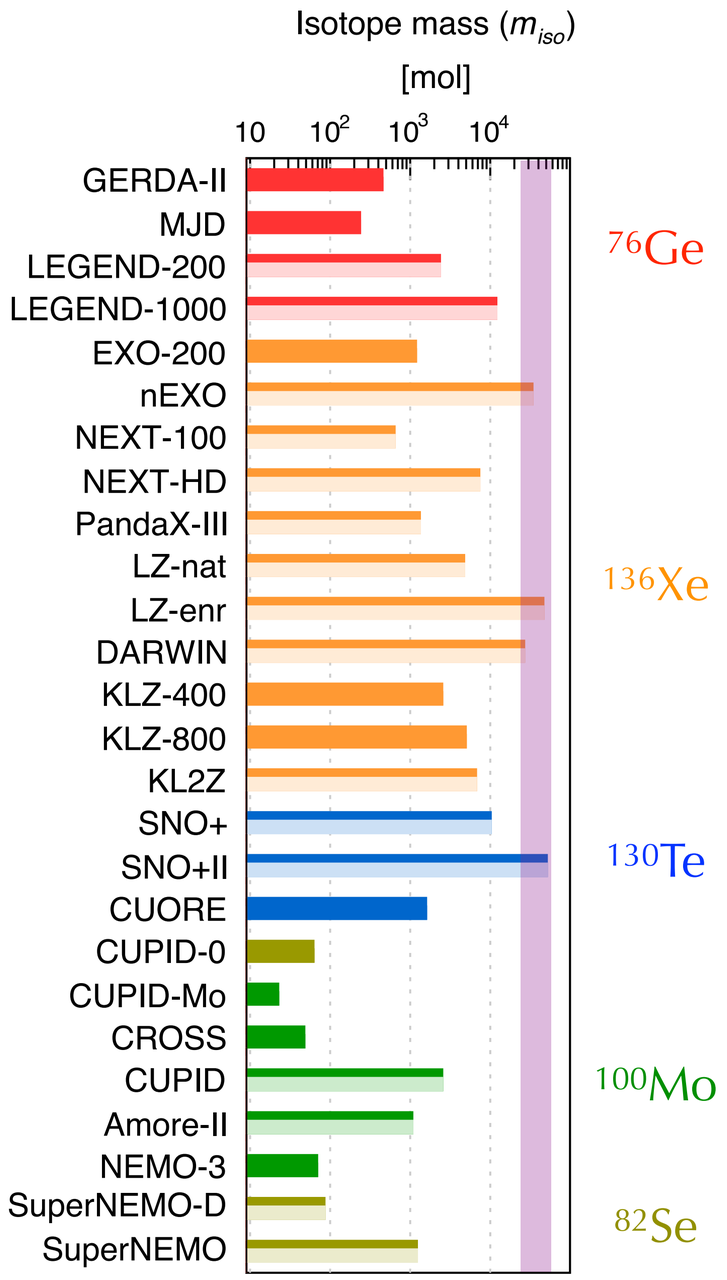
$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

Requirements:



high exposure →

PRD **96**, 053001 (2017)



^{76}Ge semiconductors

^{136}Xe liquid / gas TPCs

liquid scintillators

^{130}Te

bolometers

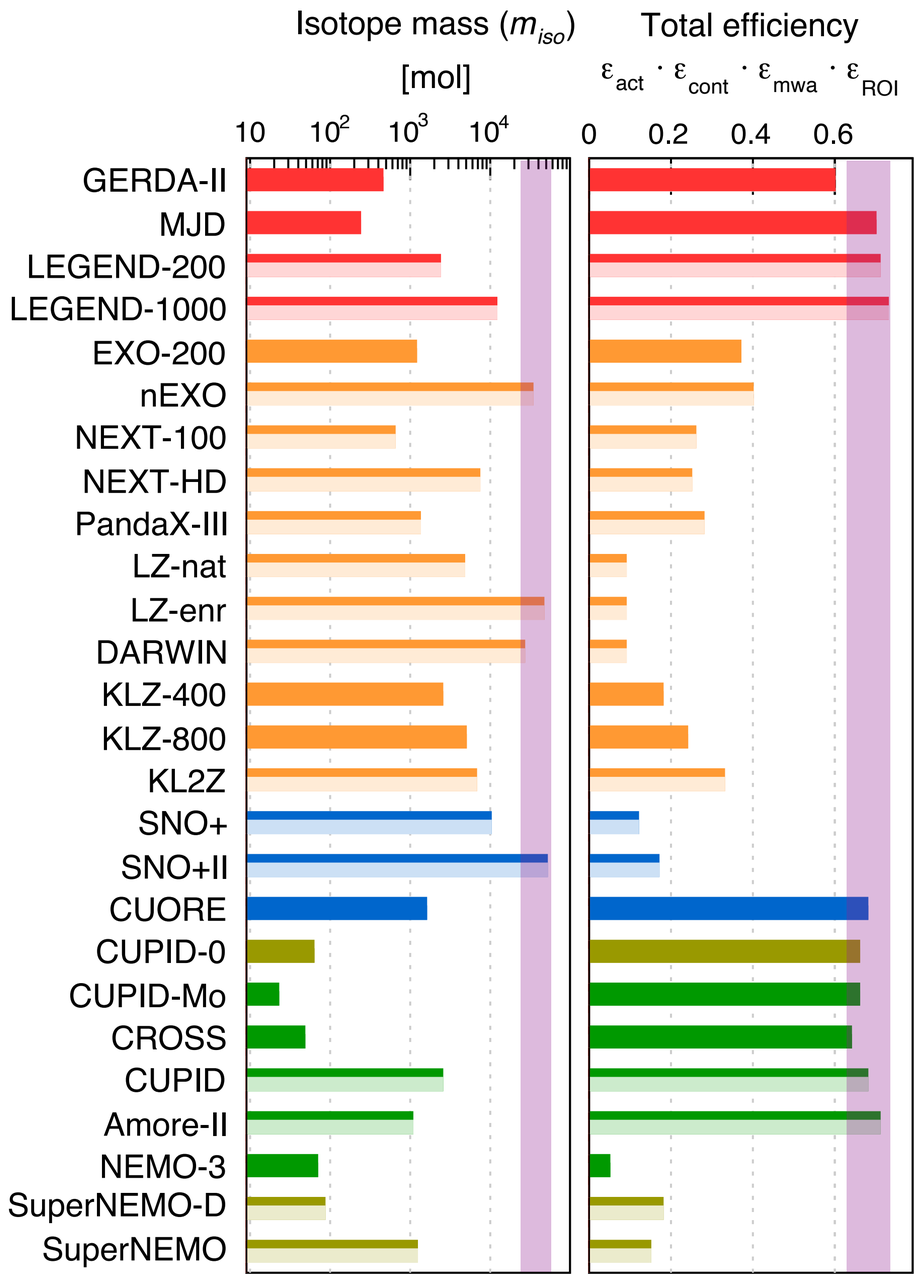
^{100}Mo

trackers

^{82}Se

current / recent

in construction / proposed



semiconductors

liquid / gas TPCs (fiducialization)

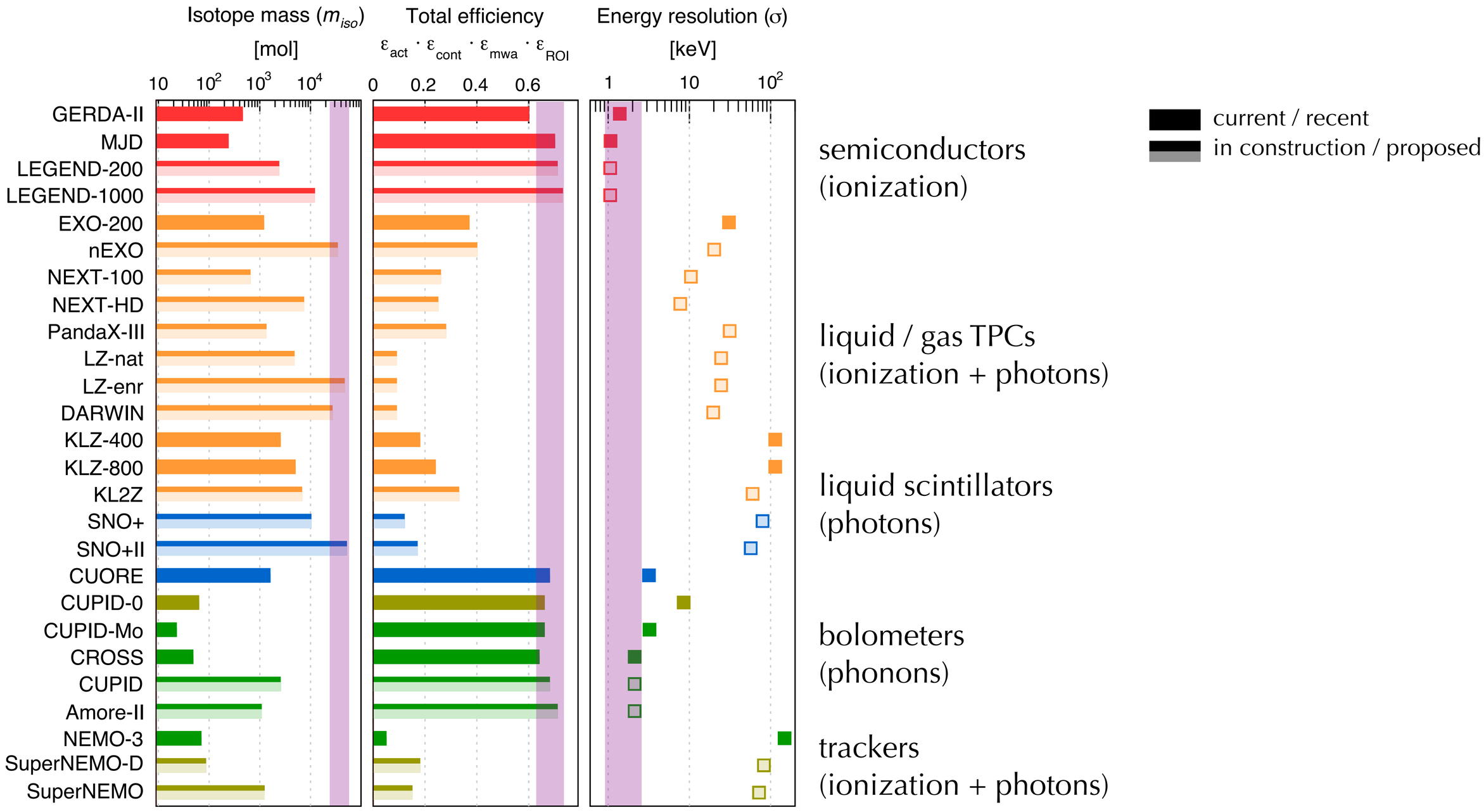
liquid scintillators (fiducialization)

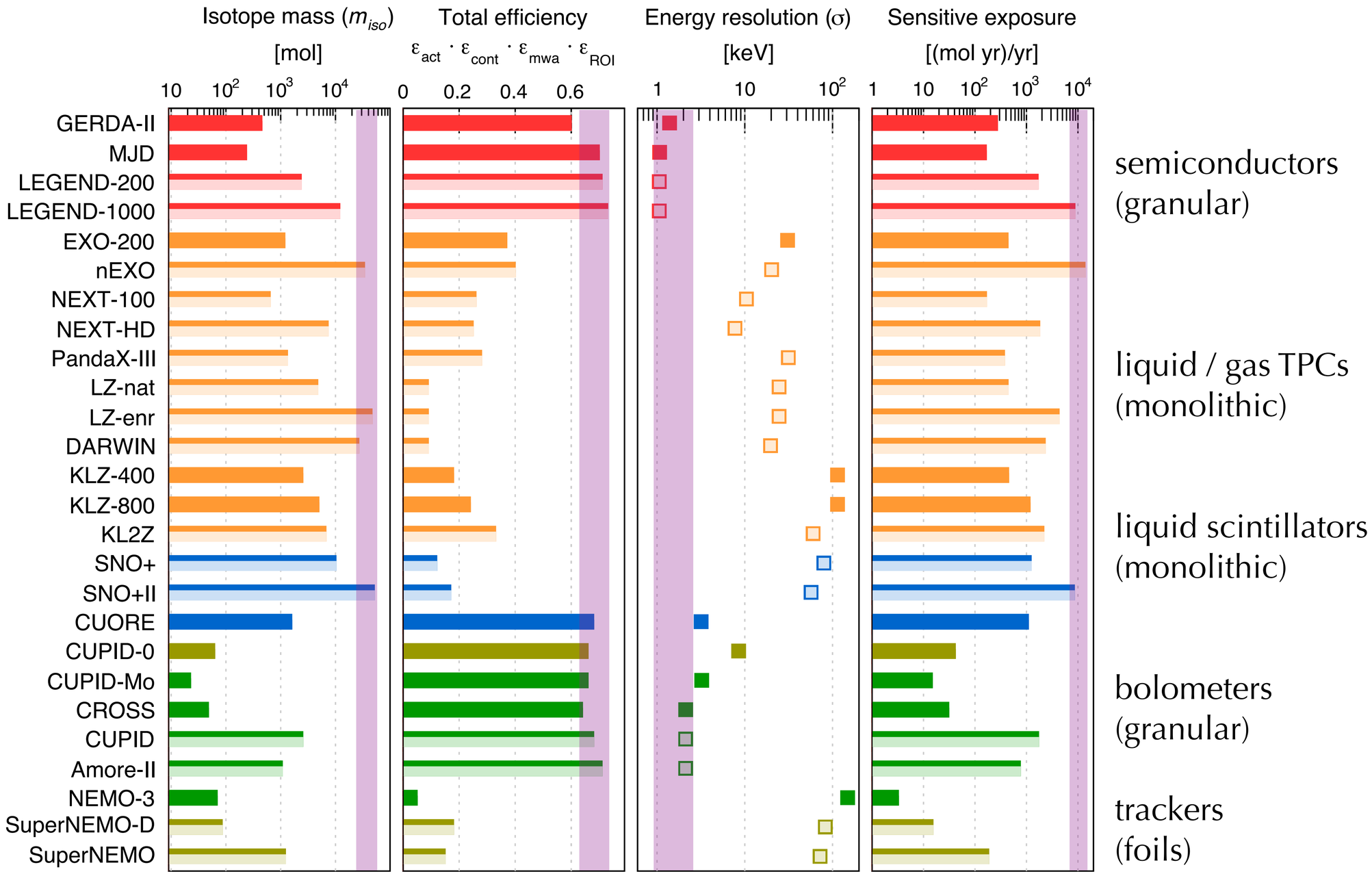
bolometers

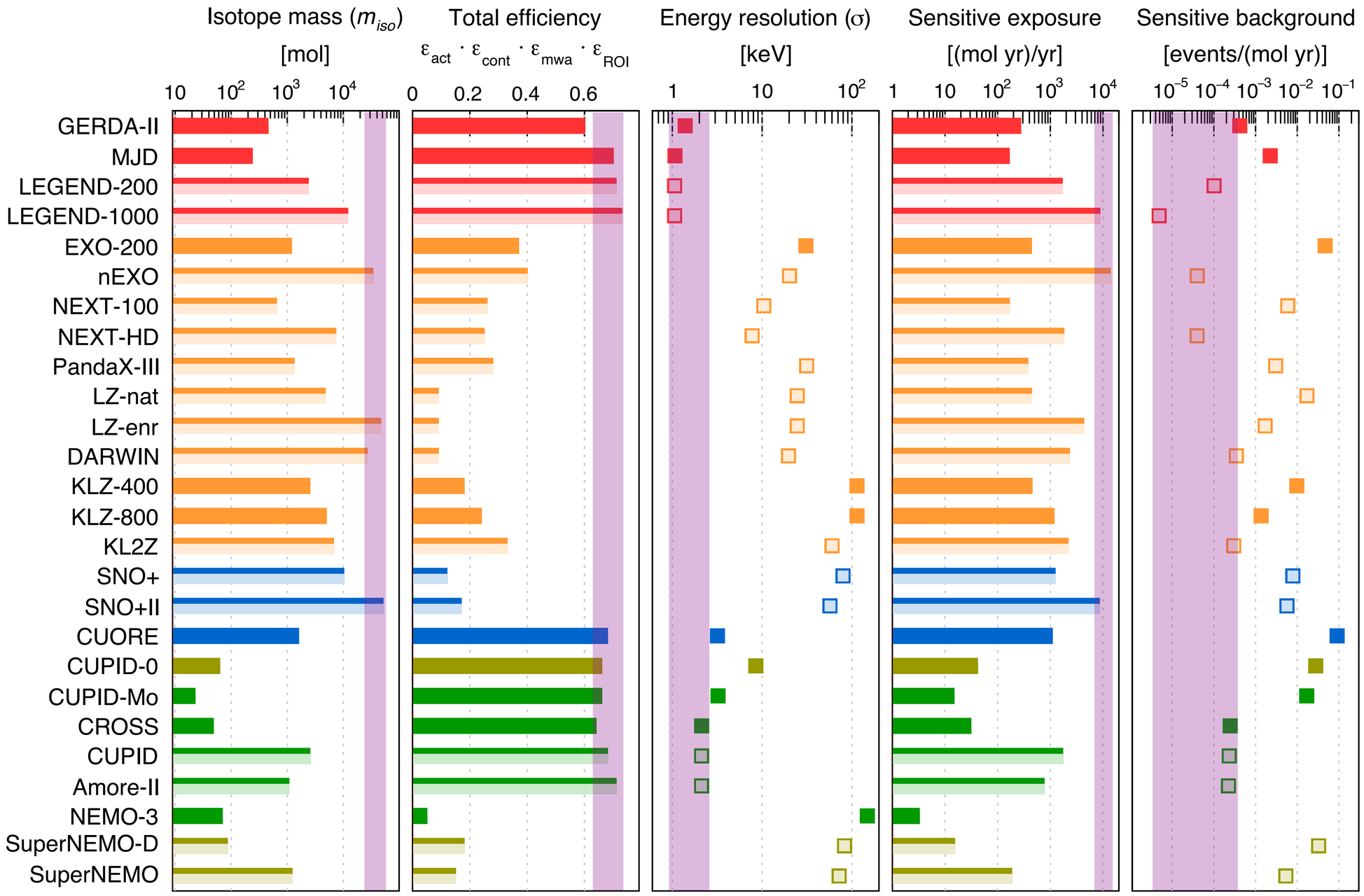
trackers (reconstruction)

current / recent

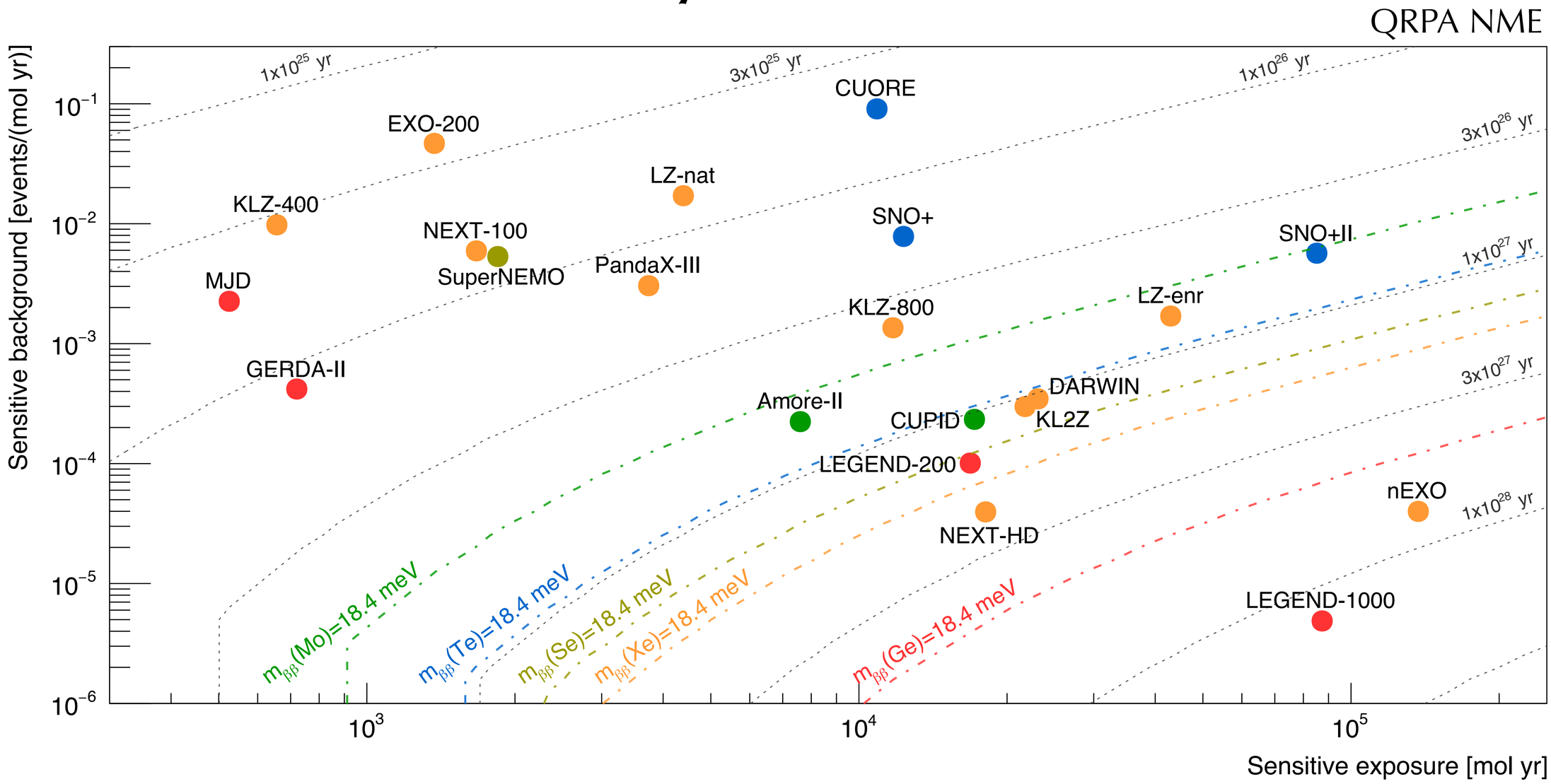
in construction / proposed


Isotope mass (m_{iso})
[mol]
10
10^2
10^3
10^4
Total efficiency
$\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
0
0.2
0.4
0.6
Energy resolution (σ)
[keV]
1
10
10^2
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO
semiconductors
(ionization)
liquid / gas TPCs
(ionization + photons)
liquid scintillators
(photons)
bolometers
(phonons)
trackers
(ionization + photons)
current / recent
in construction / proposed

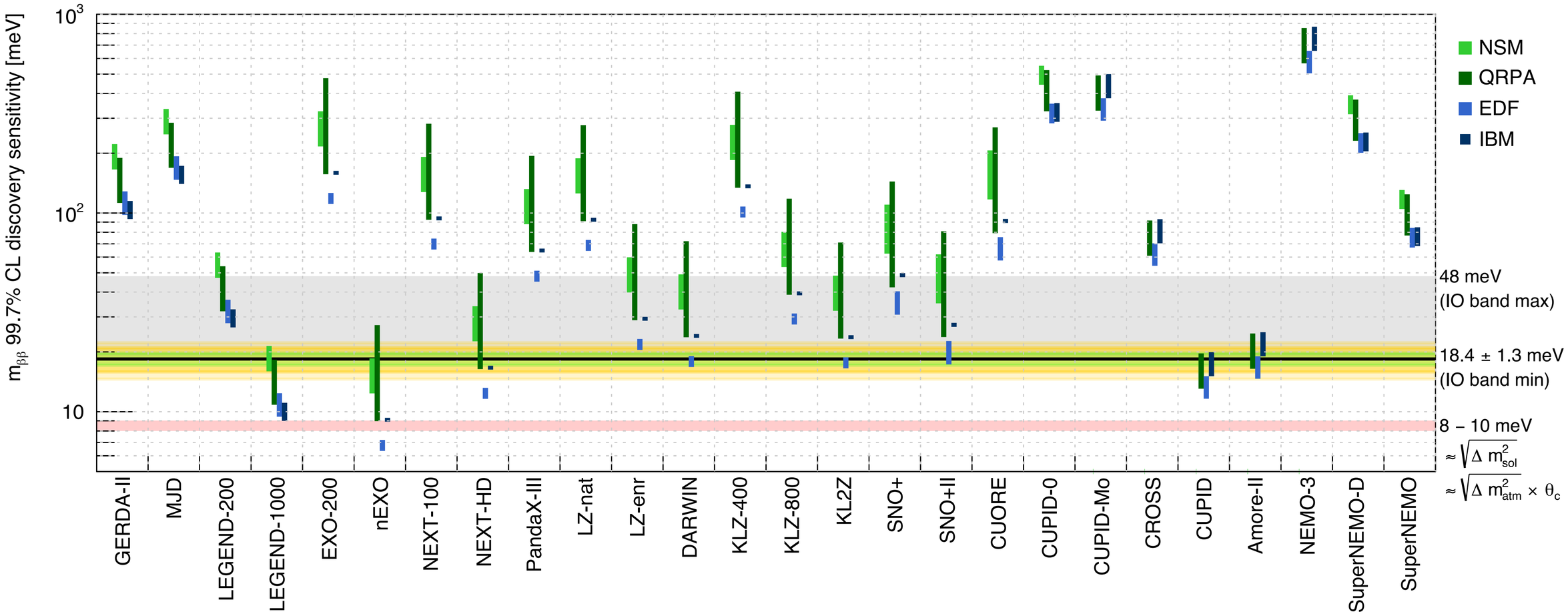

Isotope mass (m_{iso})
[mol]
Total efficiency
$\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
Energy resolution (σ)
[keV]
Sensitive exposure
[(mol yr)/yr]
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO
semiconductors
(granular)
liquid / gas TPCs
(monolithic)
liquid scintillators
(monolithic)
bolometers
(granular)
trackers
(foils)


Isotope mass (m_{iso})
[mol]
Total efficiency
$\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
Energy resolution (σ)
[keV]
Sensitive exposure
[(mol yr)/yr]
Sensitive background
[events/(mol yr)]
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO

Discovery Sensitivities

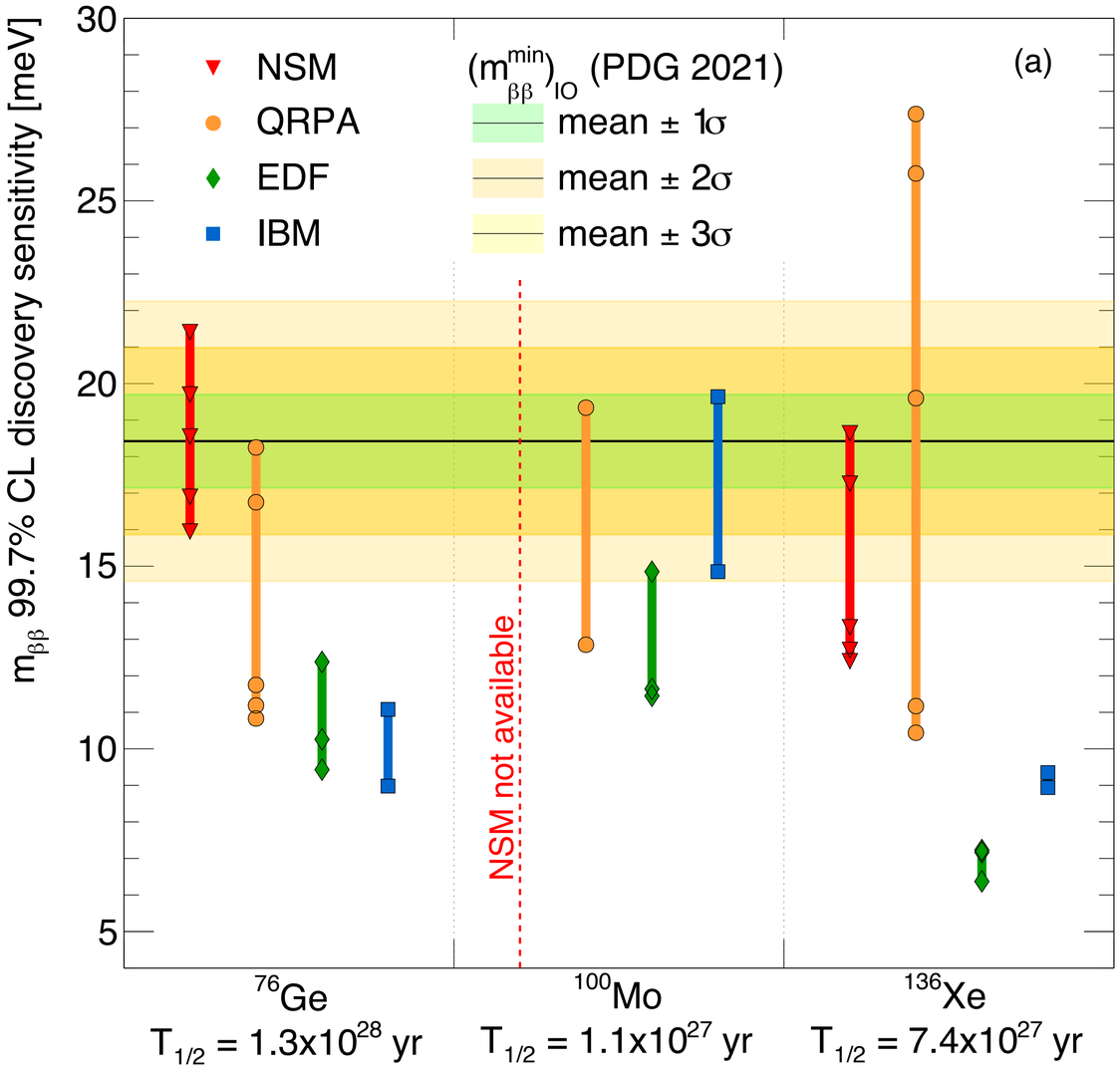


Discovery Sensitivities



Next-Generation Reach

- Next generation experiments seem poised to reach the IO minimum:
  - for most NME calculations
  - in multiple isotopes
  - With very different experimental techniques
- Some NME reach deep into the NO region
- Experiments are being designed with upgrade capability to push even further into the NO



Phys. Rev. C **104**, L042501 (2021)

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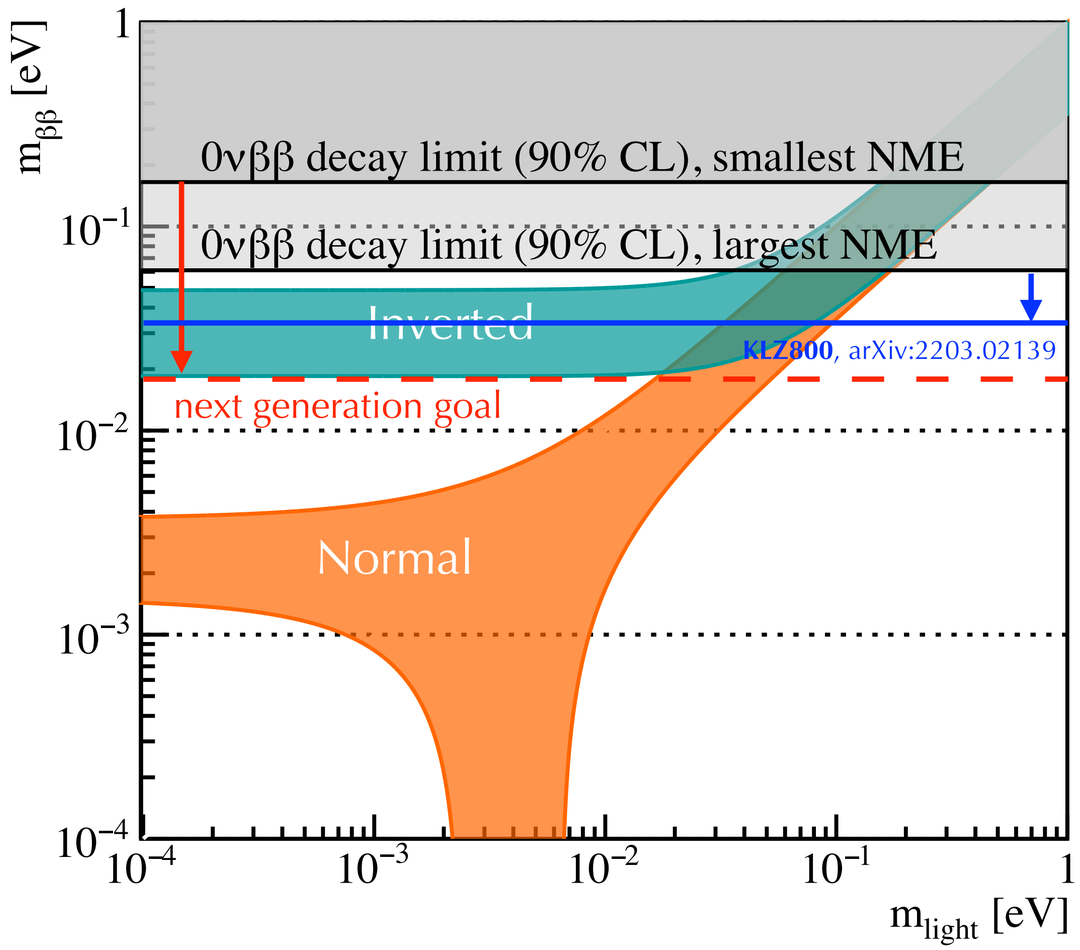
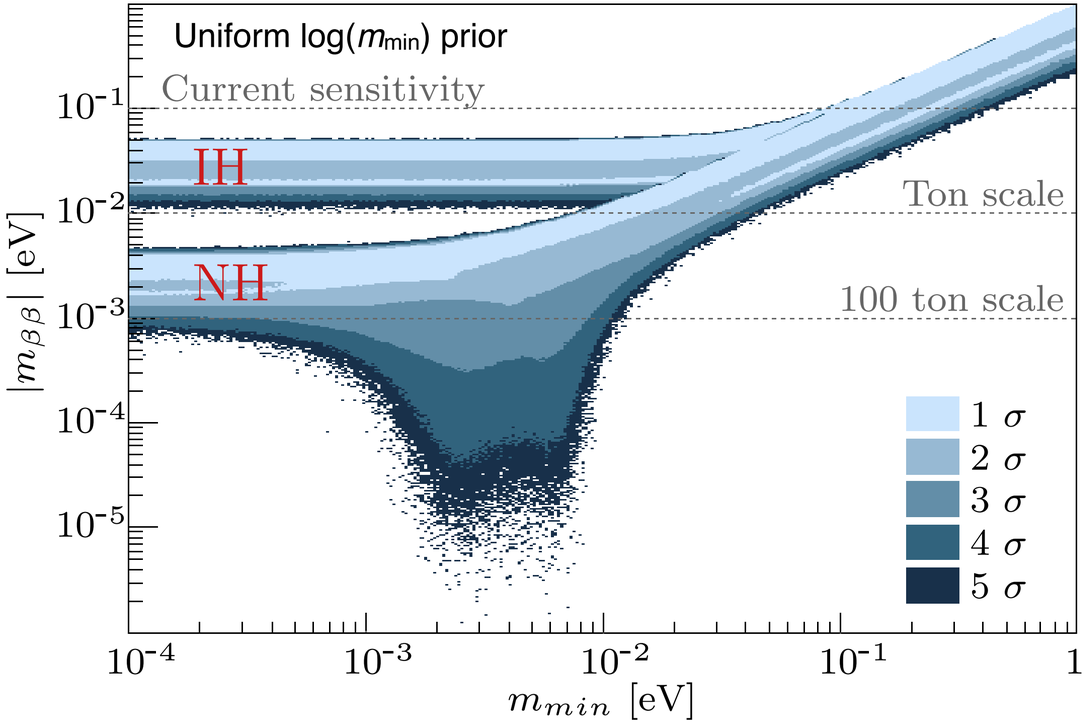
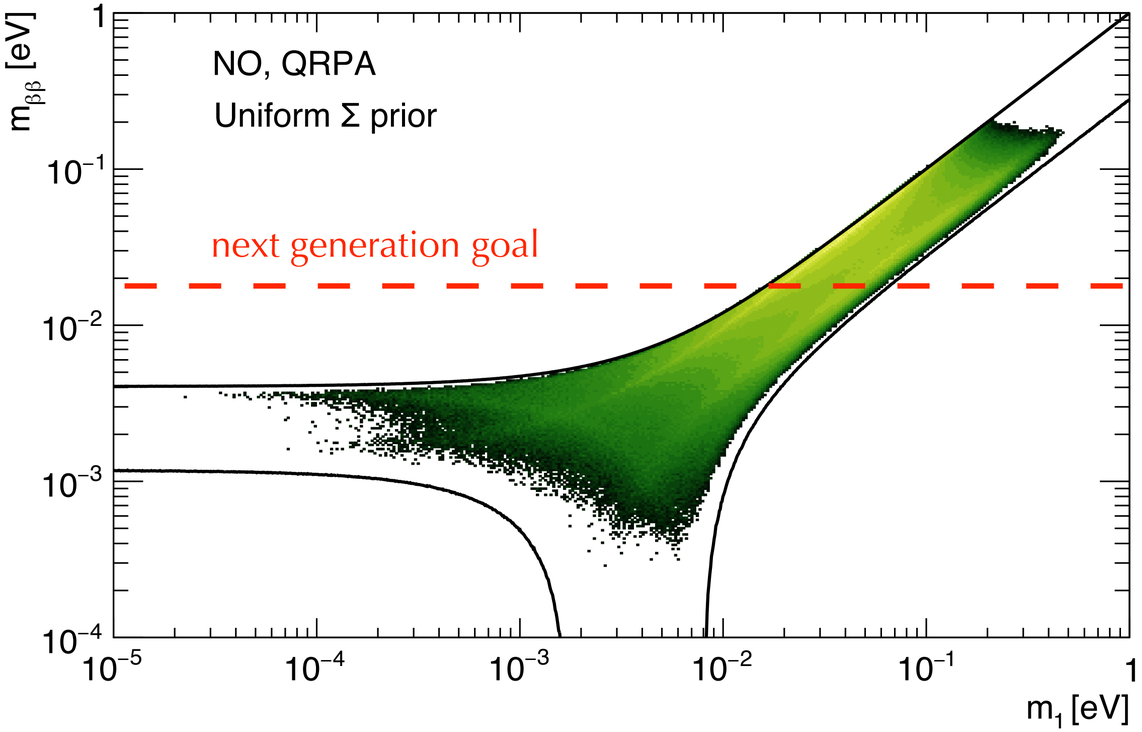
$m_{\beta\beta}$ and m_{light}

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 2.3\text{x}10^{26}$ yr
    arXiv:2203.02139 [hep-ex] (2022)
  - ^{76}Ge (GERDA): $T_{1/2} > 1.8\text{x}10^{26}$ yr
    PRL **125**, 252502 (2020)
  - ^{130}Te (CUORE): $T_{1/2} > 2.2\text{x}10^{25}$ yr
    Nature **604**, 53 (2022)
- Future goal: O(100x) further in $T_{1/2}$
  - Covers IO
  - Probes a significant portion of the NO
  - An aggressive experimental goal



Bayesian Treatments





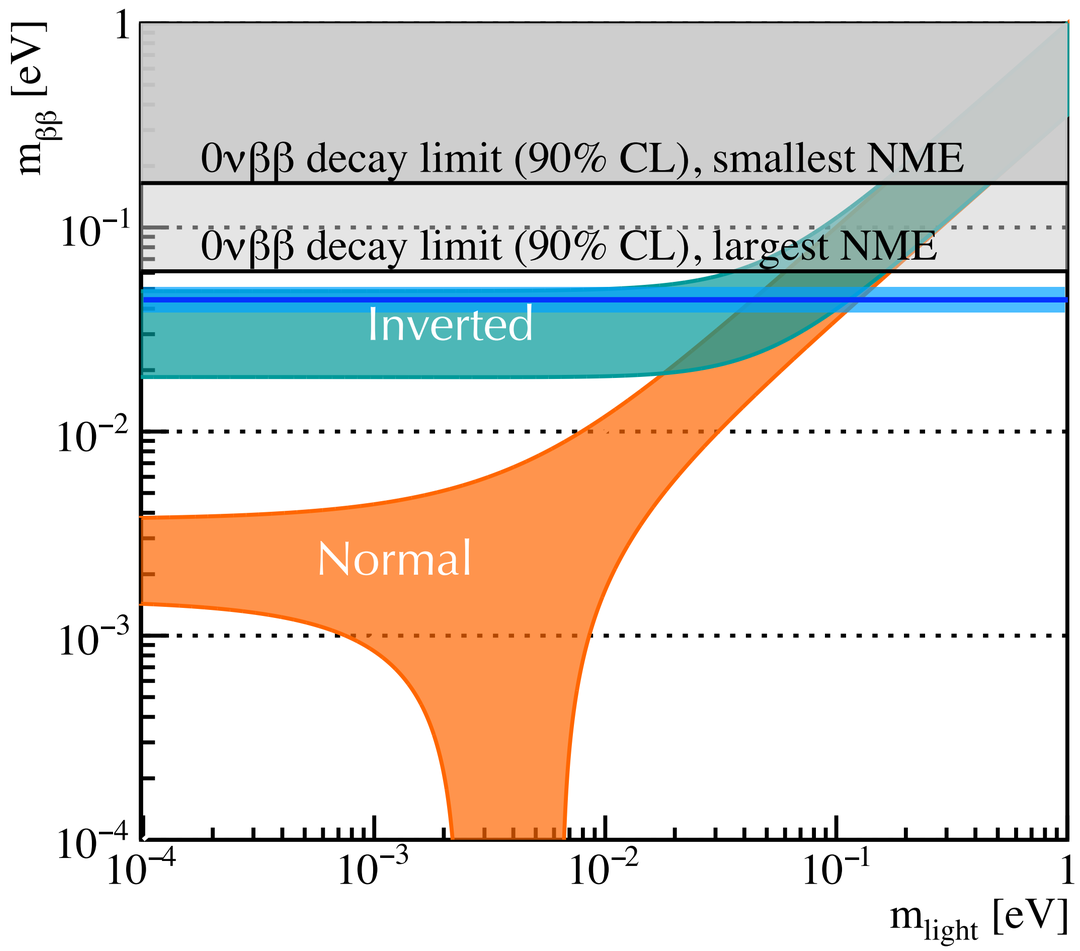
- E.g. m_i ~ NO masses like other leptons, then suppressed
- Natural cutoff for $m_{min} > 10^{-13}$ eV from loop contributions
- Ton-scale experiments will probe ~all of IH, ~very little of NO

- E.g. m_i supressed to some scale, then split about that scale
- Natural cutoff at Σ_{min} leaves little phase space for vanishing m_1
- Ton-scale experiments will probe ~all of IO, up to ~50% of NO

Benato, Eur. Phys. J. C **75**, 563 (2015)
Agostini, Benda, and Detwiler, PRD **96**, 053001 (2017)

Ton-Scale Discovery Scenarios

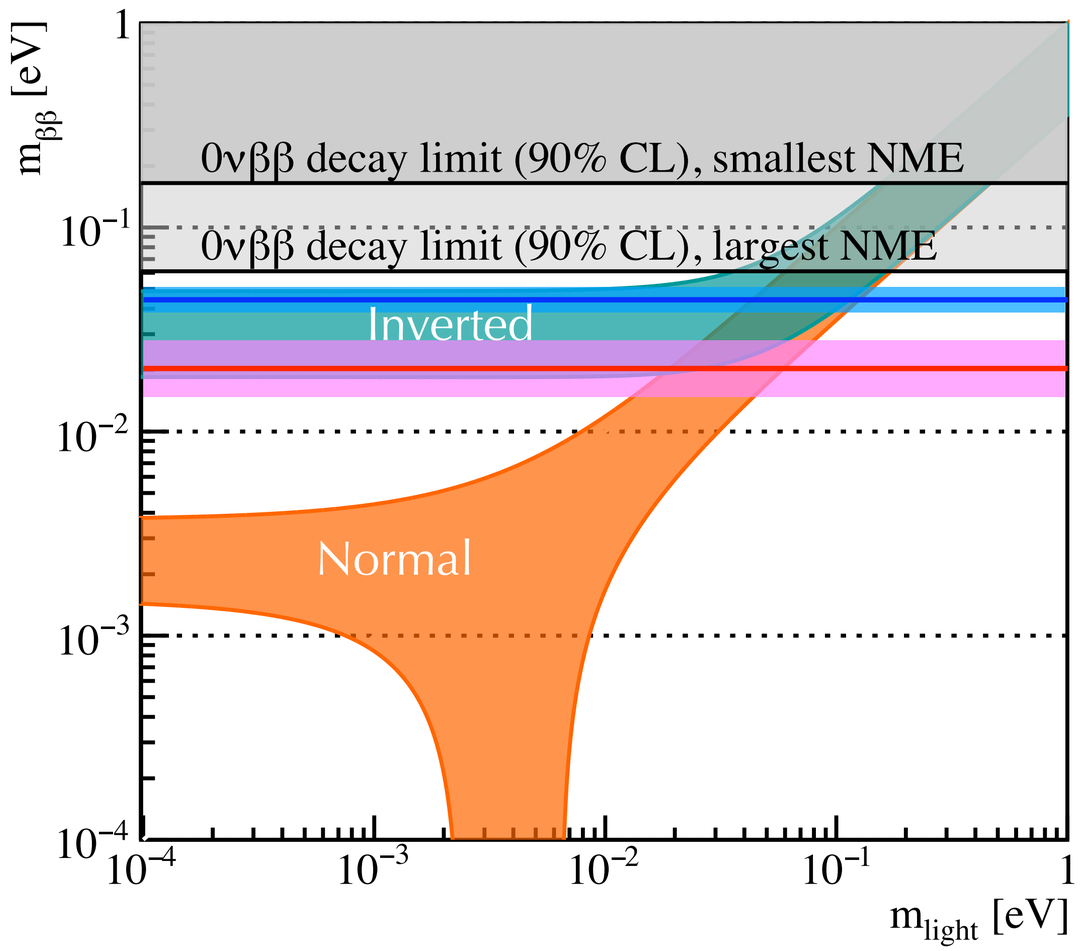
- $T_{1/2} << 10^{28}$ years: 100s of counts
  - O(10%) statistical uncertainty: NME uncertainties dominate
  - Follow up with experiments designed to probe the decay mechanism



arXiv:2202.01787

Ton-Scale Discovery Scenarios

- $T_{1/2} << 10^{28}$ years: 100s of counts
  - O(10%) statistical uncertainty: NME uncertainties dominate
  - Follow up with experiments designed to probe the decay mechanism
- $T_{1/2} \sim 10^{28}$ years: ~10 counts
  - Statistical uncertainty on same order as NME
  - Follow up with ~ton-scale experiments to confirm the discovery



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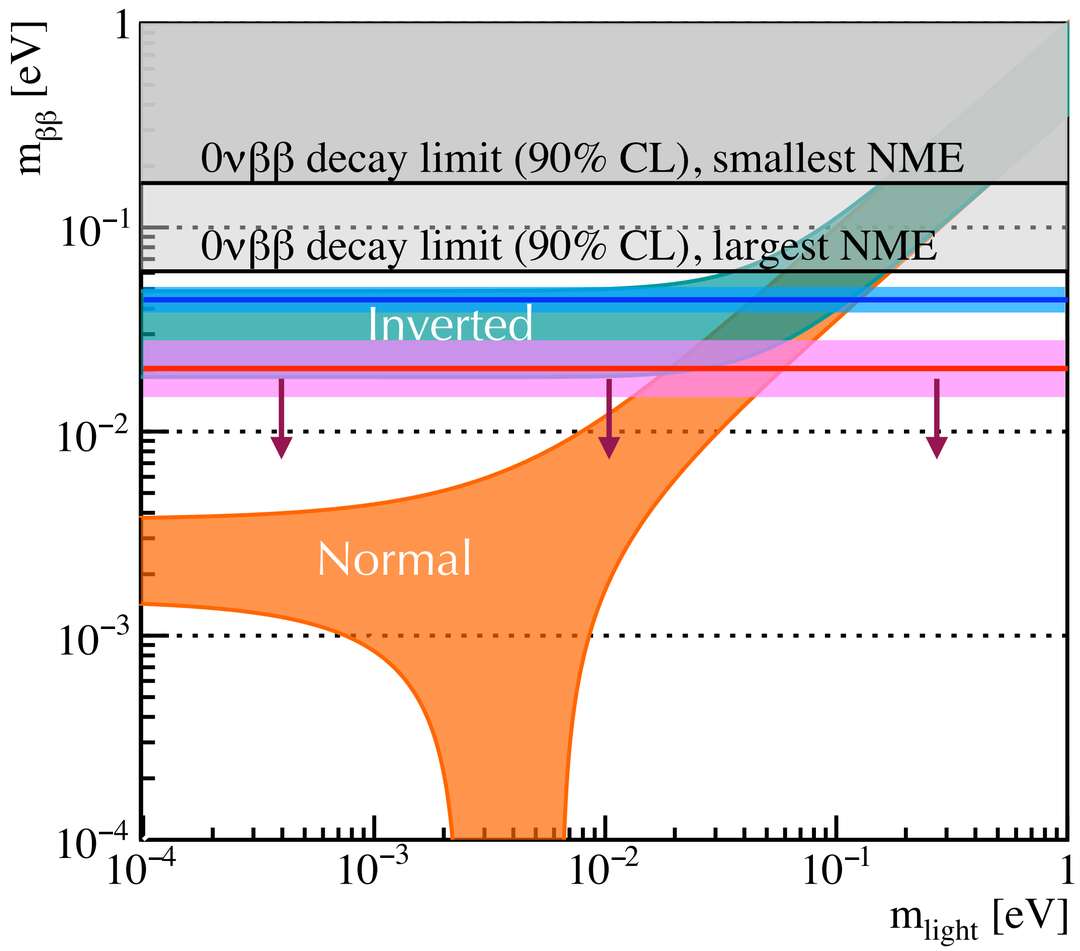
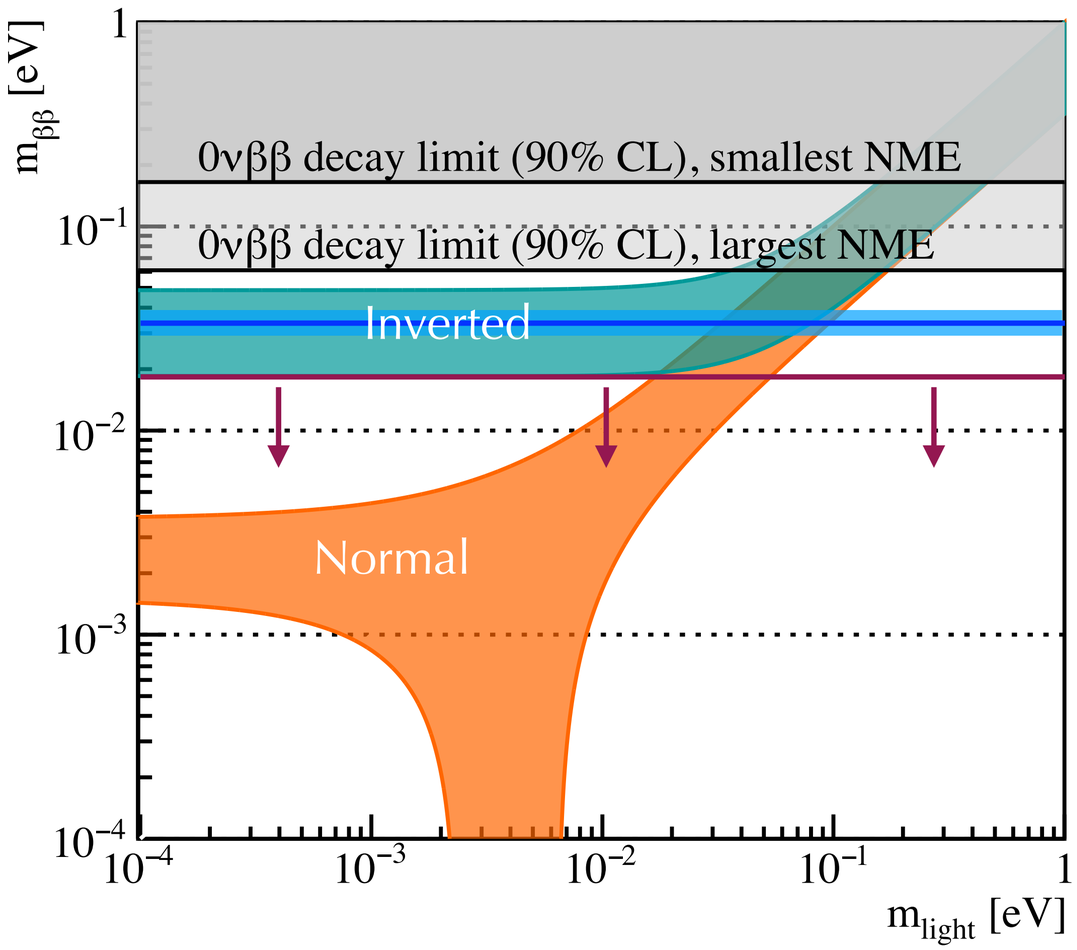
- $T_{1/2} << 10^{28}$ years: 100s of counts
  - O(10%) statistical uncertainty: NME uncertainties dominate
  - Follow up with experiments designed to probe the decay mechanism
- $T_{1/2} \sim 10^{28}$ years: ~10 counts
  - Statistical uncertainty on same order as NME
  - Follow up with ~ton-scale experiments to confirm the discovery
- $T_{1/2} >> 10^{28}$ years: < a few counts
  - R&D required to push into NO, reduce cost



arXiv:2202.01787

Inferences on the Neutrino Mass Scale

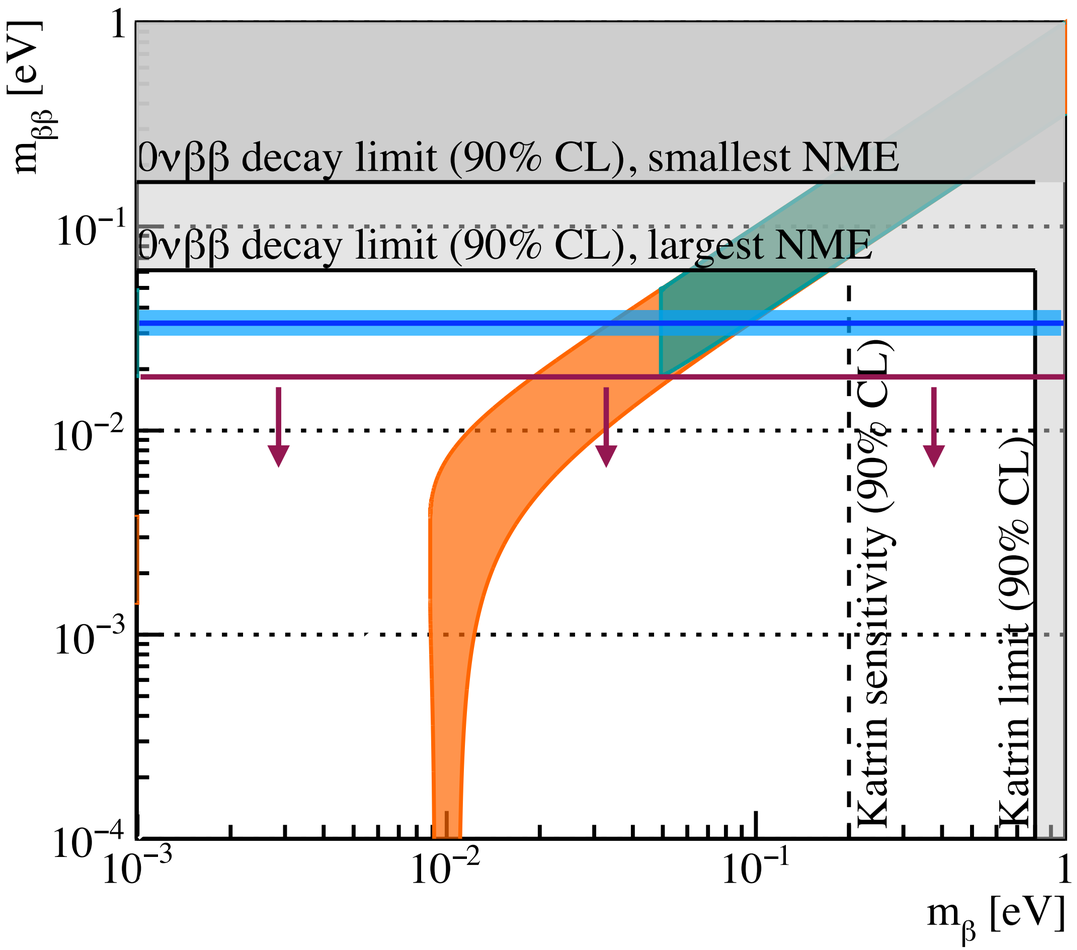
- 0νββ is observed in a ton-scale experiment
  - IO: $m_3 < \sim m_{\beta\beta}$
  - NO: $m_1 \sim m_{\beta\beta}$
- 0νββ is not observed
  - IO: neutrinos are Dirac
  - NO: $m_1 < \sim m_{\beta\beta}$



arXiv:2202.01787

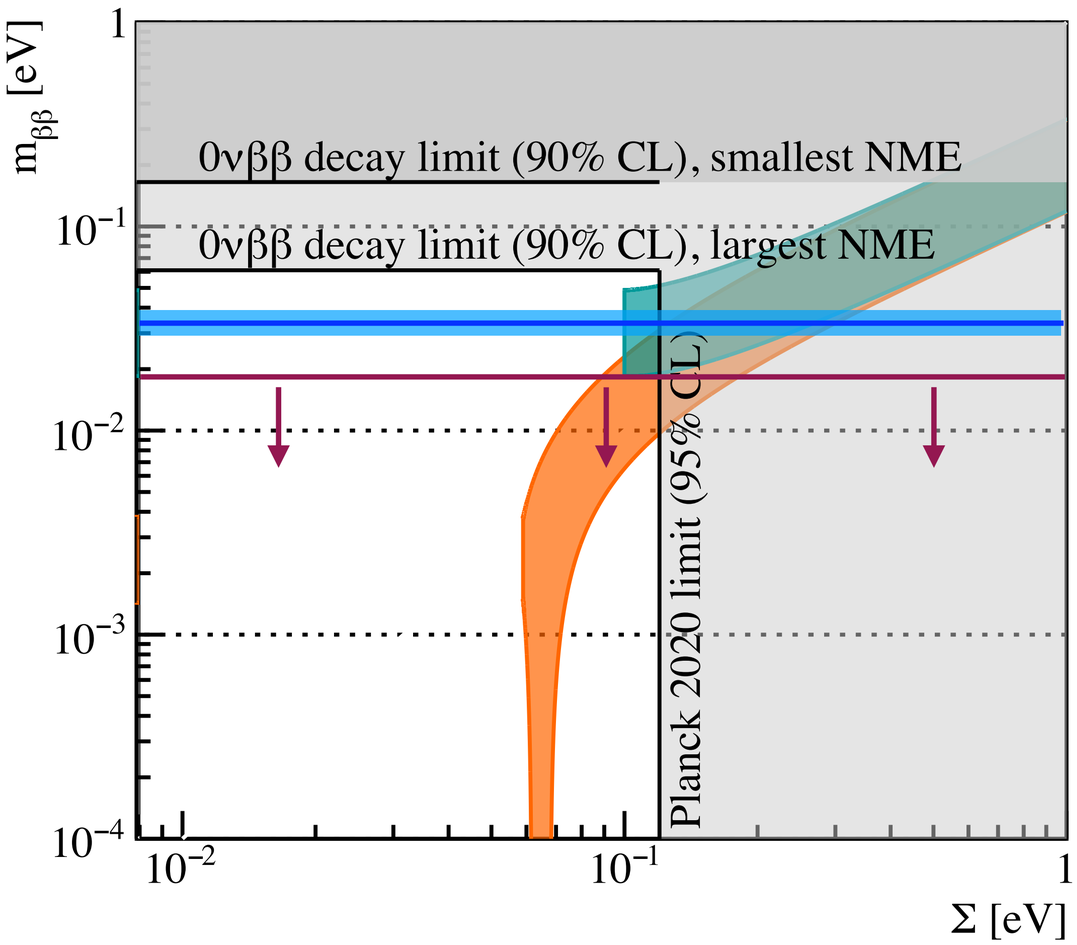
$m_{\beta\beta}$ and m_β

- 0νββ is observed in a ton-scale experiment
  - $m_\beta \sim m_{\beta\beta}$ but large uncertainty (~100%)
  - Project8 specs are somewhat loosened
  - If KATRIN measures m_β: chance to measure relative Majorana phase; NME issues
- 0νββ is not observed
  - ~10 meV < m_β < ~2$m_{\beta\beta}$
  - If KATRIN measures m_β: neutrinos are Dirac



$m_{\beta\beta}$ and Σ

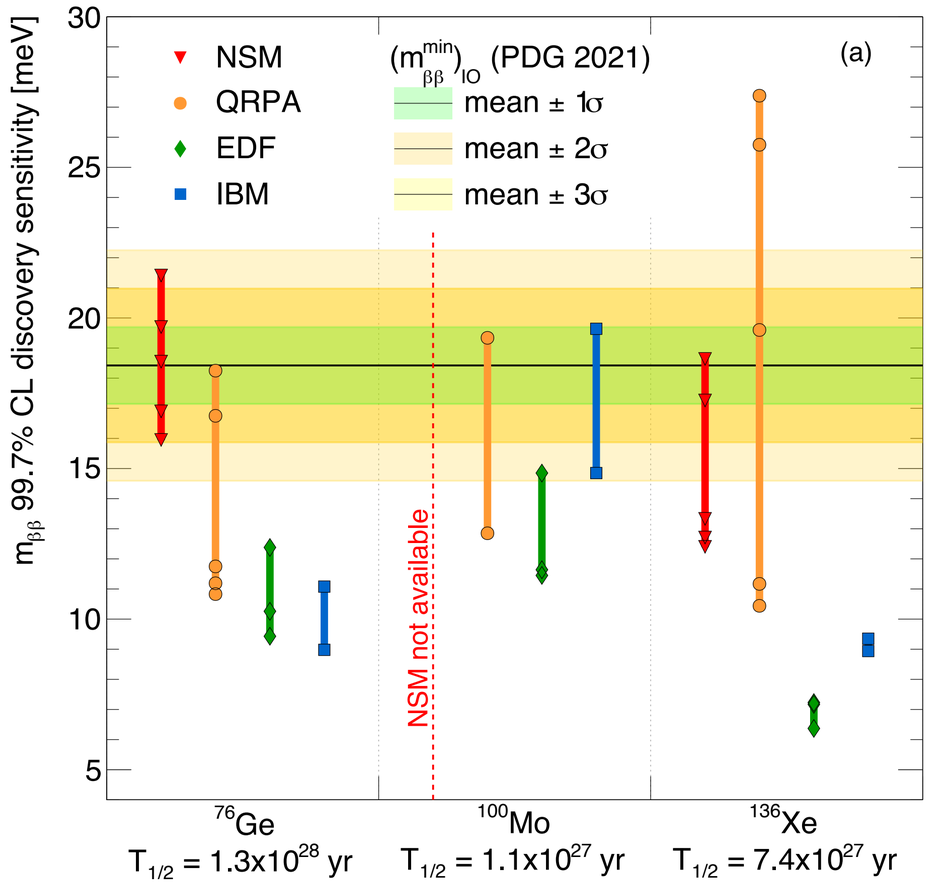
- 0νββ is observed in a ton-scale experiment
  - Would question NME, cosmology systematics
  - $\Sigma \sim 3m_{\beta\beta}$ as an input for ΛCDM fits
- 0νββ is not observed
  - $\Sigma < \sim 3m_{\beta\beta}$
  - Little impact on cosmology



arXiv:2202.01787

Summary

- The international experimental program to search for 0νββ decay is robust and aggressive
- A steady march in sensitivity improvement is expected for at least a decade in multiple isotopes
- 0νββ decay is connected to the neutrino masses in a model-dependent way.
- However the connection is strong for a very broad class of theories. So both a discovery or a limit from the ton-scale experiments will provide important information on the neutrino nature and masses



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