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U.S. DEPARTMENT OF ENERGY
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NEUTRINOLESS DOUBLE-BETA DECAYS

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Nuclear Science Division

Lawrence Berkeley National Laboratory

Snowmass at LBNL

September 17, 2021

NSD goals

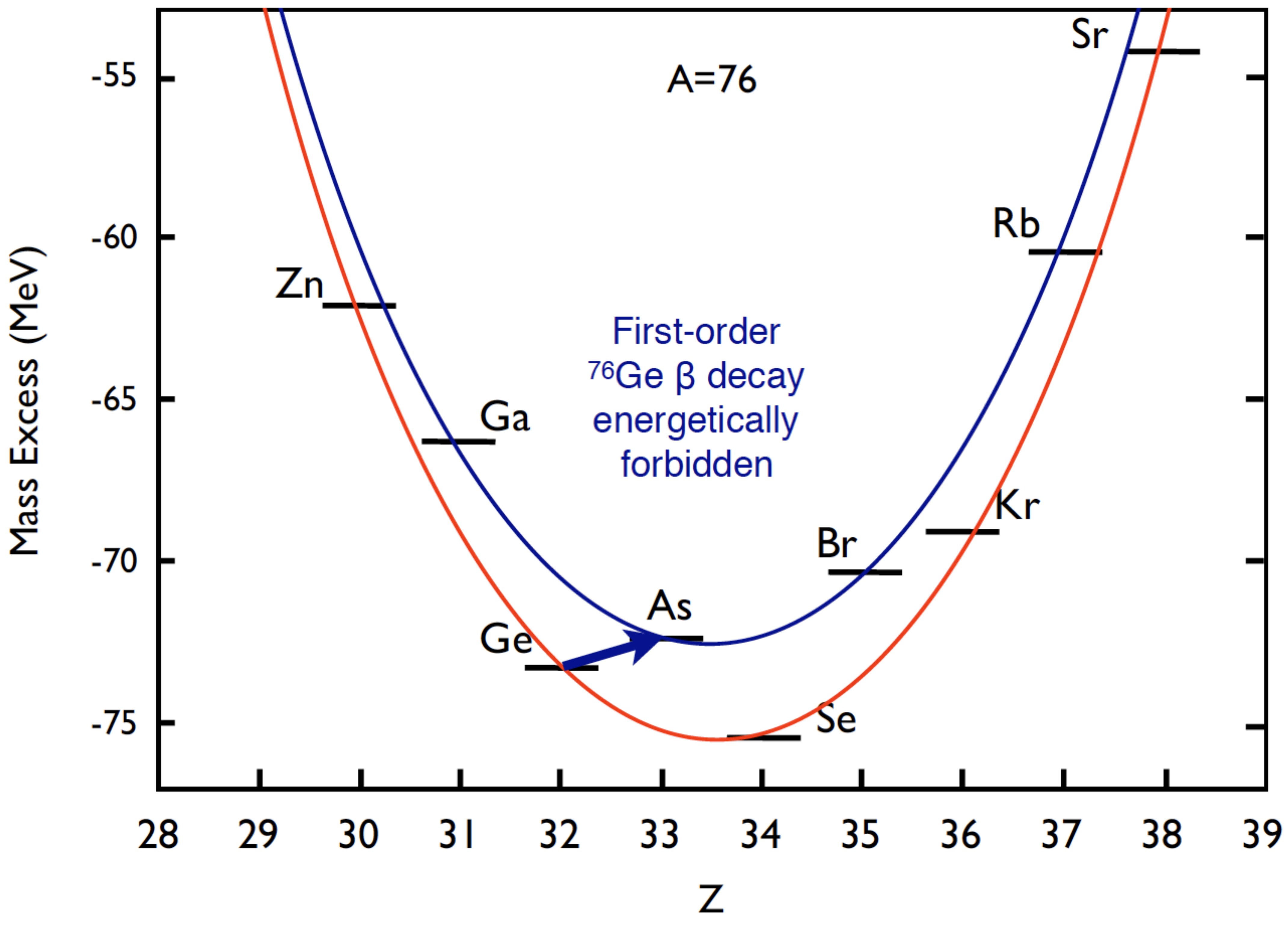
- LBNL-NSD played a major role in the discovery of neutrino mass and mixing - SNO and KamLAND
- Our next goal: **Leadership in the search for neutrinoless double-beta (0νββ) decay**
  - Determine whether lepton number is violated, and thus whether neutrinos might be their own antiparticles

- Double-Beta Decay:
  - 2νββ (lepton-number conserving):

$$(N, Z) \rightarrow (N-2, Z+2) + 2e^- + 2\bar{\nu}_e$$

  - 0νββ (lepton-number violating):

$$(N, Z) \rightarrow (N-2, Z+2) + 2e^-$$



Our goals

Neutrinos unique among SM fermions in lacking charges: allows them to have two types of mass, Dirac & Majorana

This leads to a new mass mechanism which accounts for the unusual lightness of the neutrino:

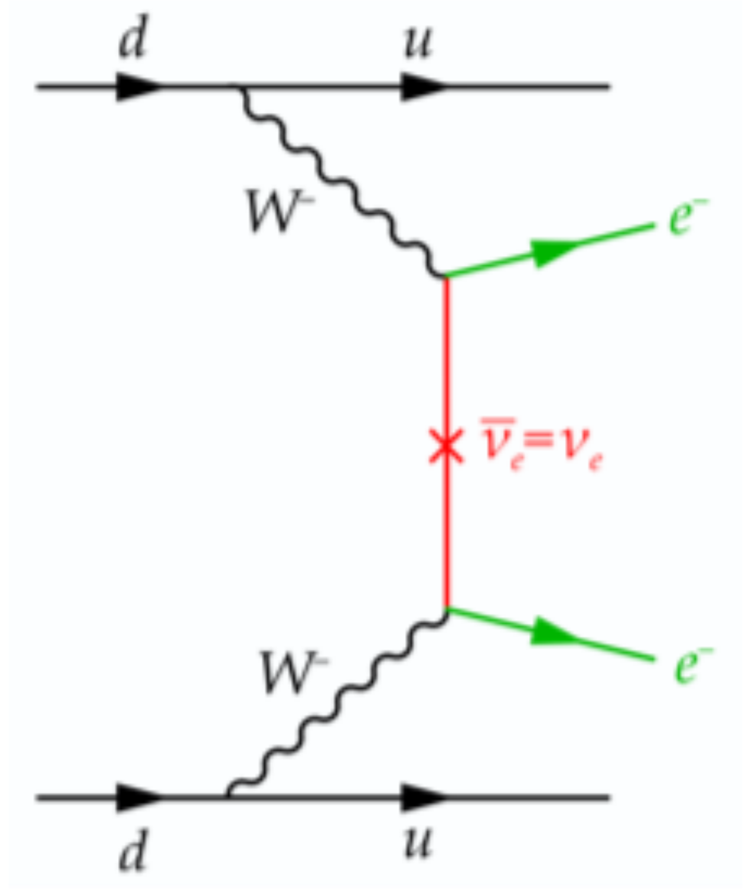
$$m_\nu \sim m_D \frac{m_D}{m_R}$$

The nucleus is the unique laboratory for studying this extremely rare 2nd-order-weak process: is lepton number violated, are there Majorana neutrino masses?

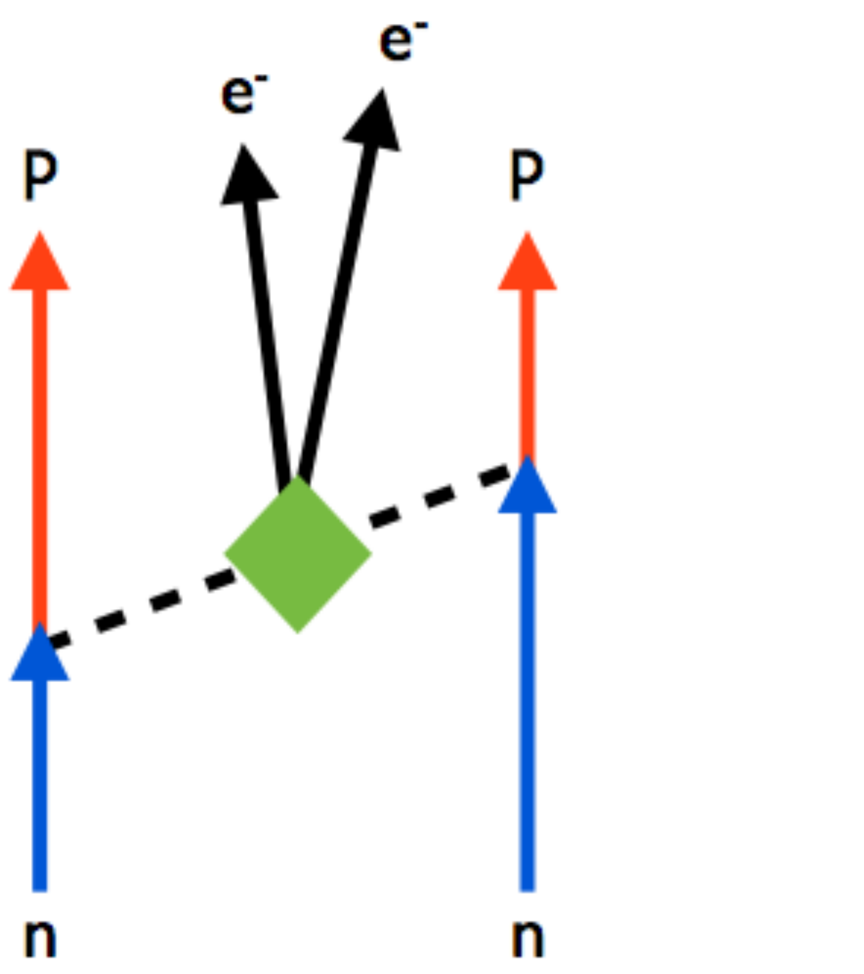
Discovery possible at the 1-ton scale

- ***standard mechanism*** in the inverted hierarchy
- ***short-range mechanisms*** in the normal hierarchy

Also connects to neutrino mass measurement (KATRIN) and Physics Division program (cosmology).



Light neutrino mechanism: inverted hierarchy



Leading-order short-range contribution: normal hierarchy

Neutrinoless Double-Beta (0νββ) Decay

$$(A, Z) \rightarrow (A, Z+2) + 2\,e^{-} + Q_{\beta\beta}$$

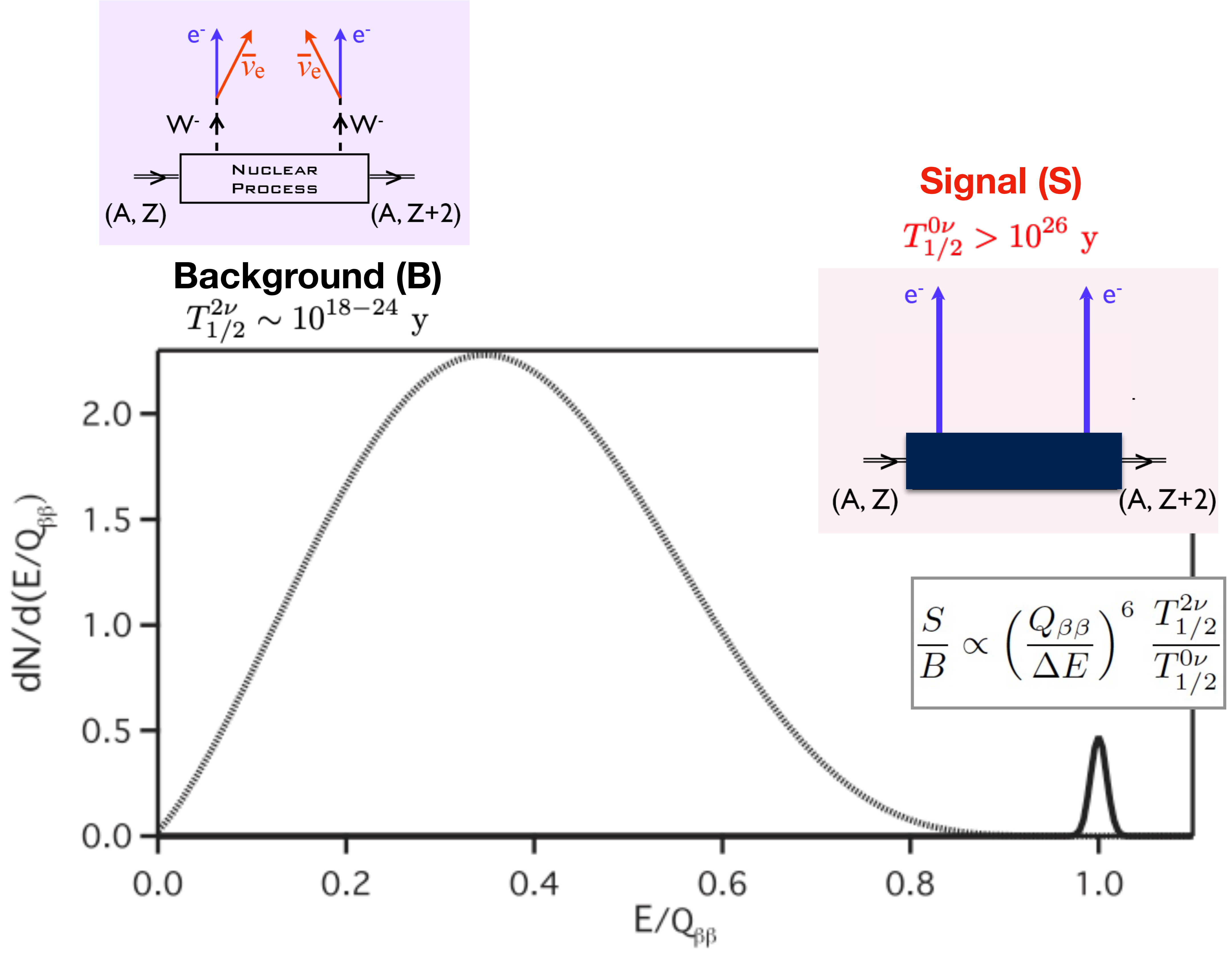
Measure half-life : $T^{0\nu}_{1/2}$

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_x(Q_{\beta\beta}, Z)\,|\mathcal{M}_x(A, Z)\eta_x|^2$$

$G_x(Q_{\beta\beta}, Z)$ ➡ Calculable phase-space factor.

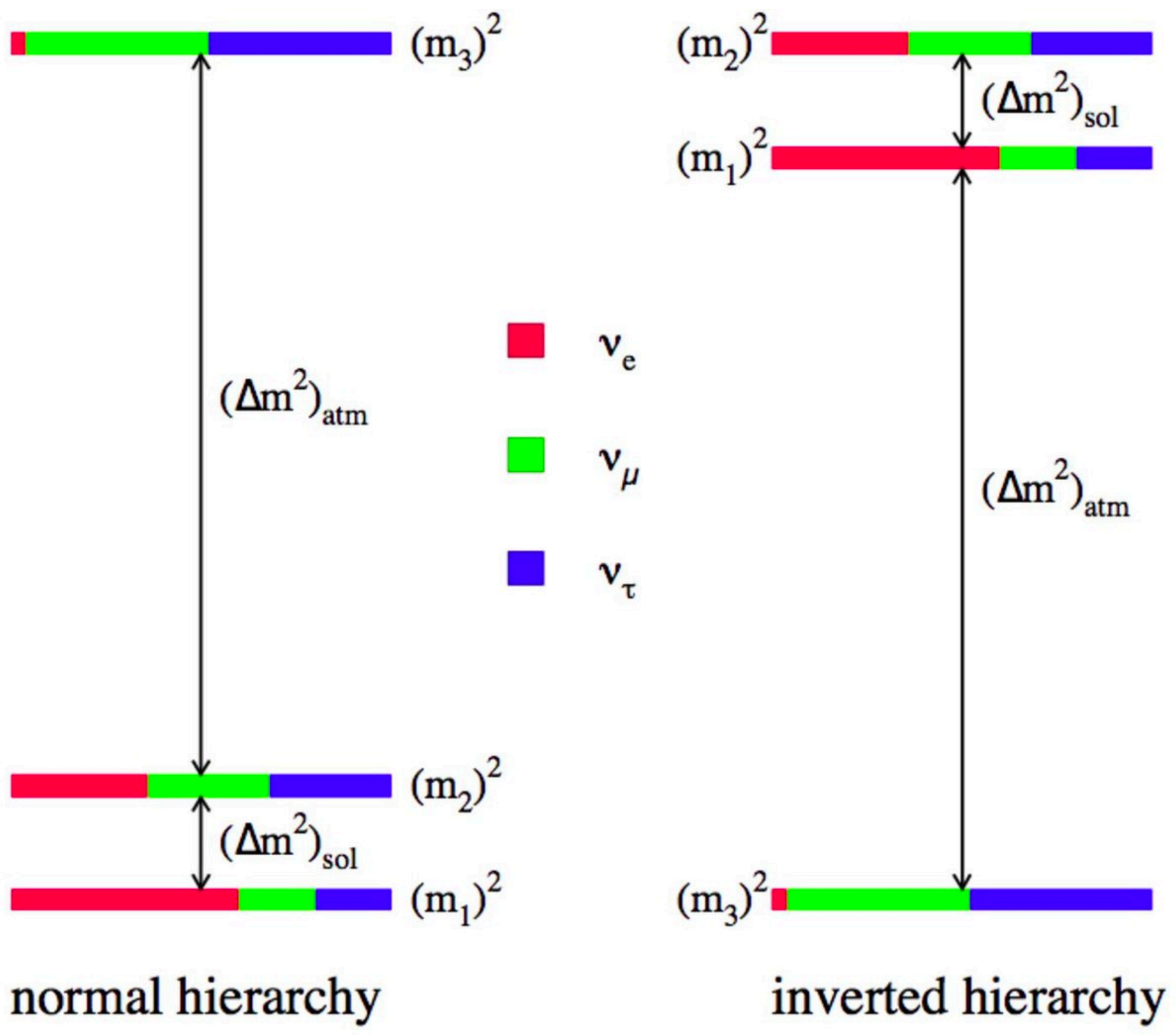
$\mathcal{M}_x(A, Z)$ ➡ Hard-to-calculate nuclear matrix elements (NME).

η_x ➡ Particle physics parameter.

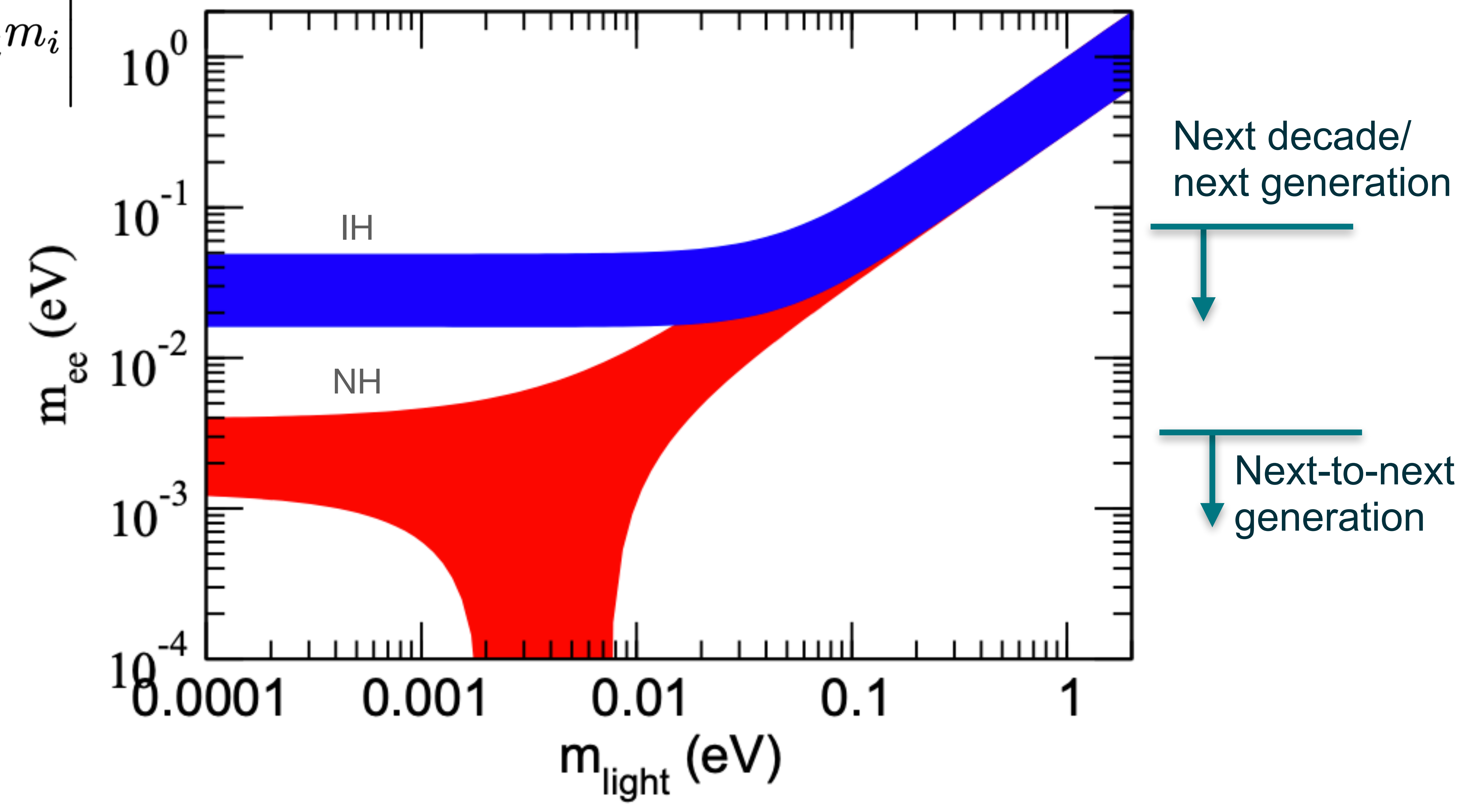


NSD goals (next decade)

To probe the effective Majorana mass in the inverted hierarchy region and beyond



$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

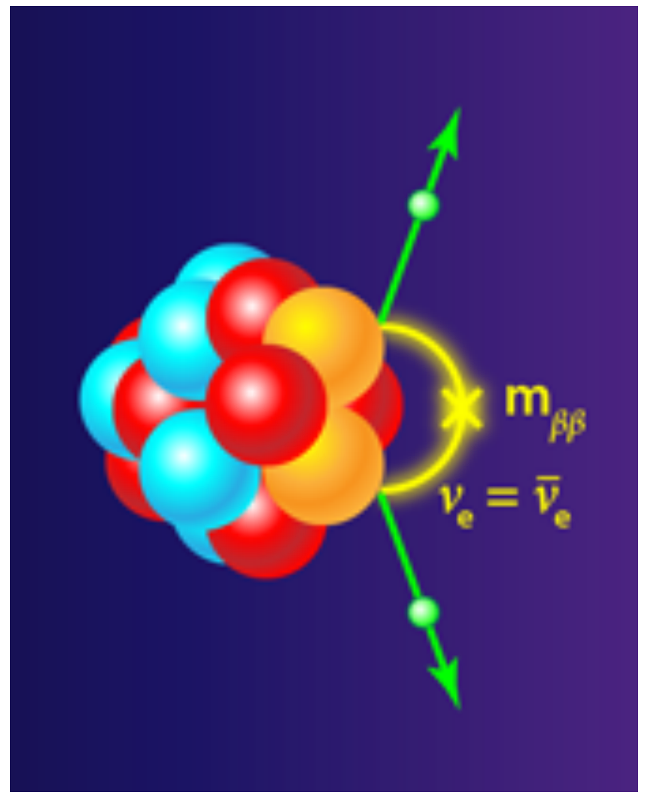


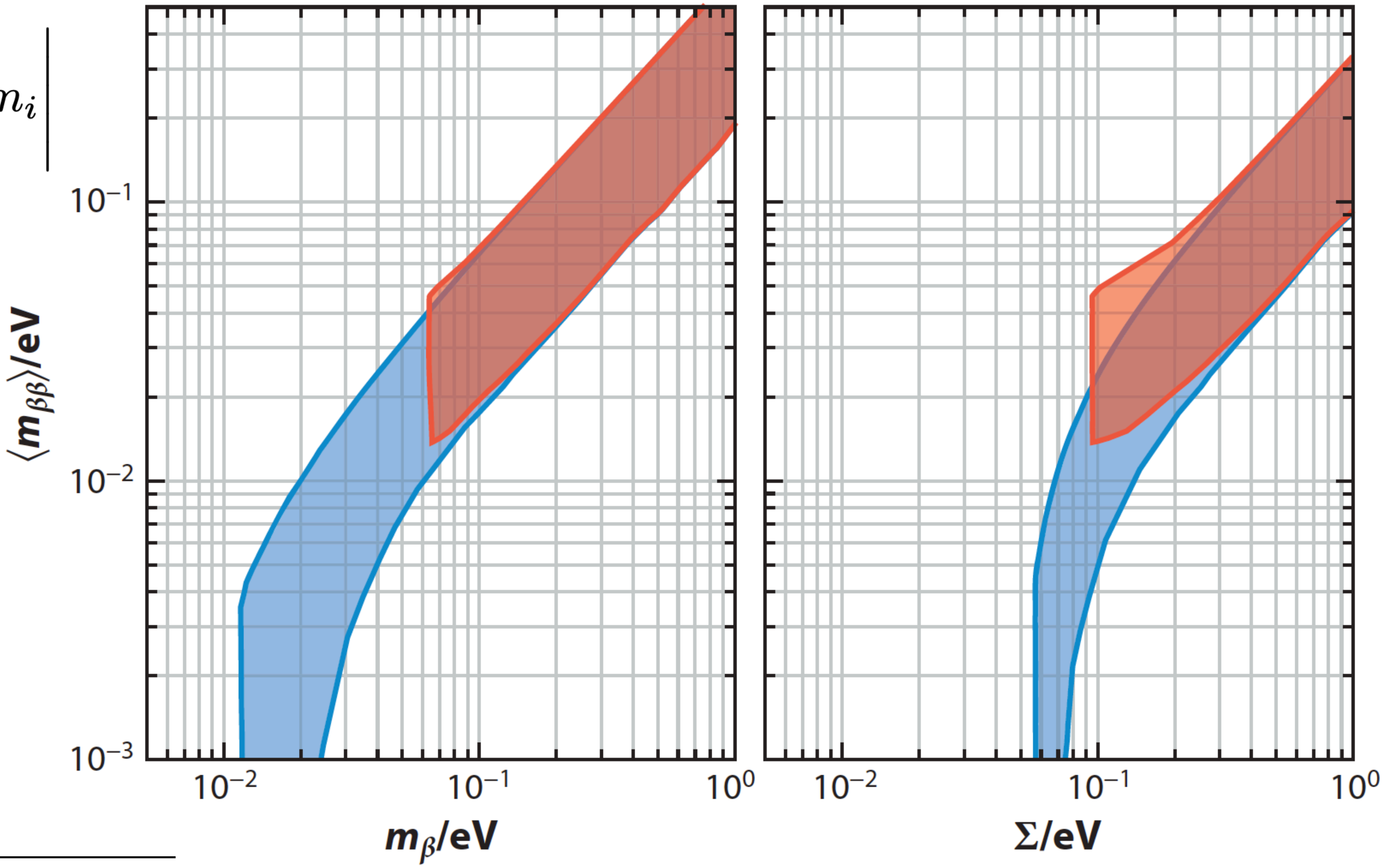
Particle Data Book 2020

Targeting the neutrino mass scale

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

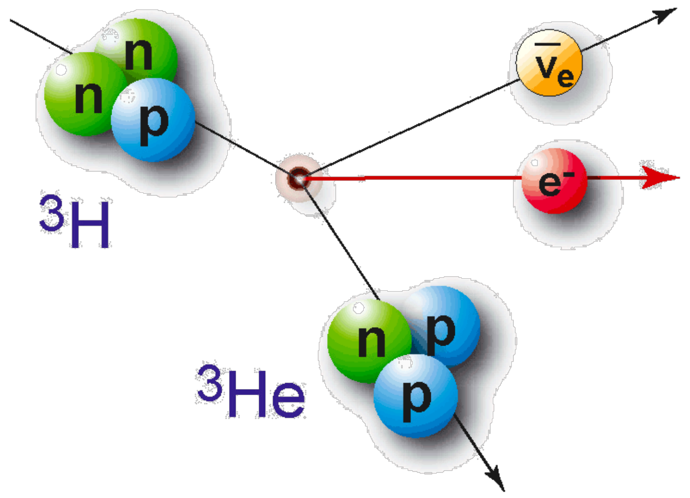
CUORE - ^{130}Te
CUPID - ^{100}Mo
MAJORANA - ^{76}Ge
LEGEND - ^{76}Ge
SNO+ - ^{130}Te
THEIA

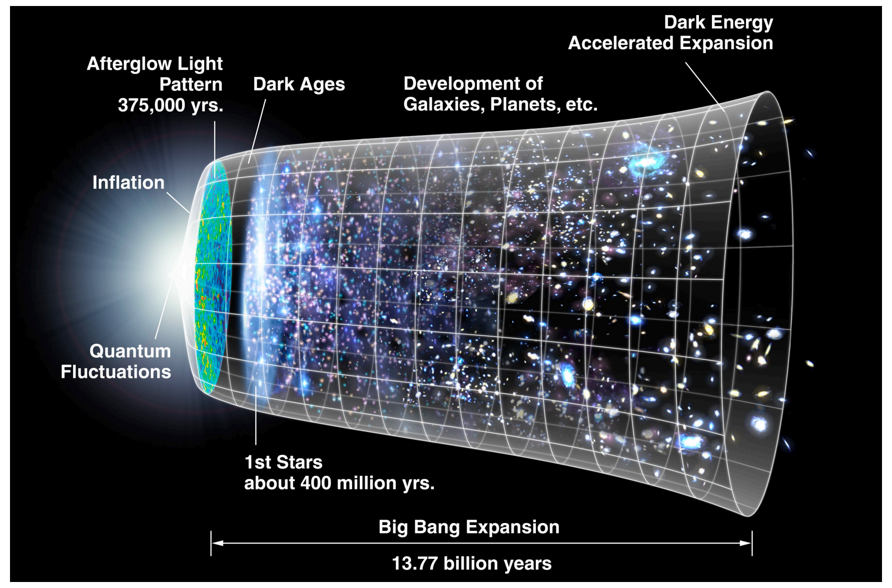




$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

KATRIN - ^{3}H





Physics Division

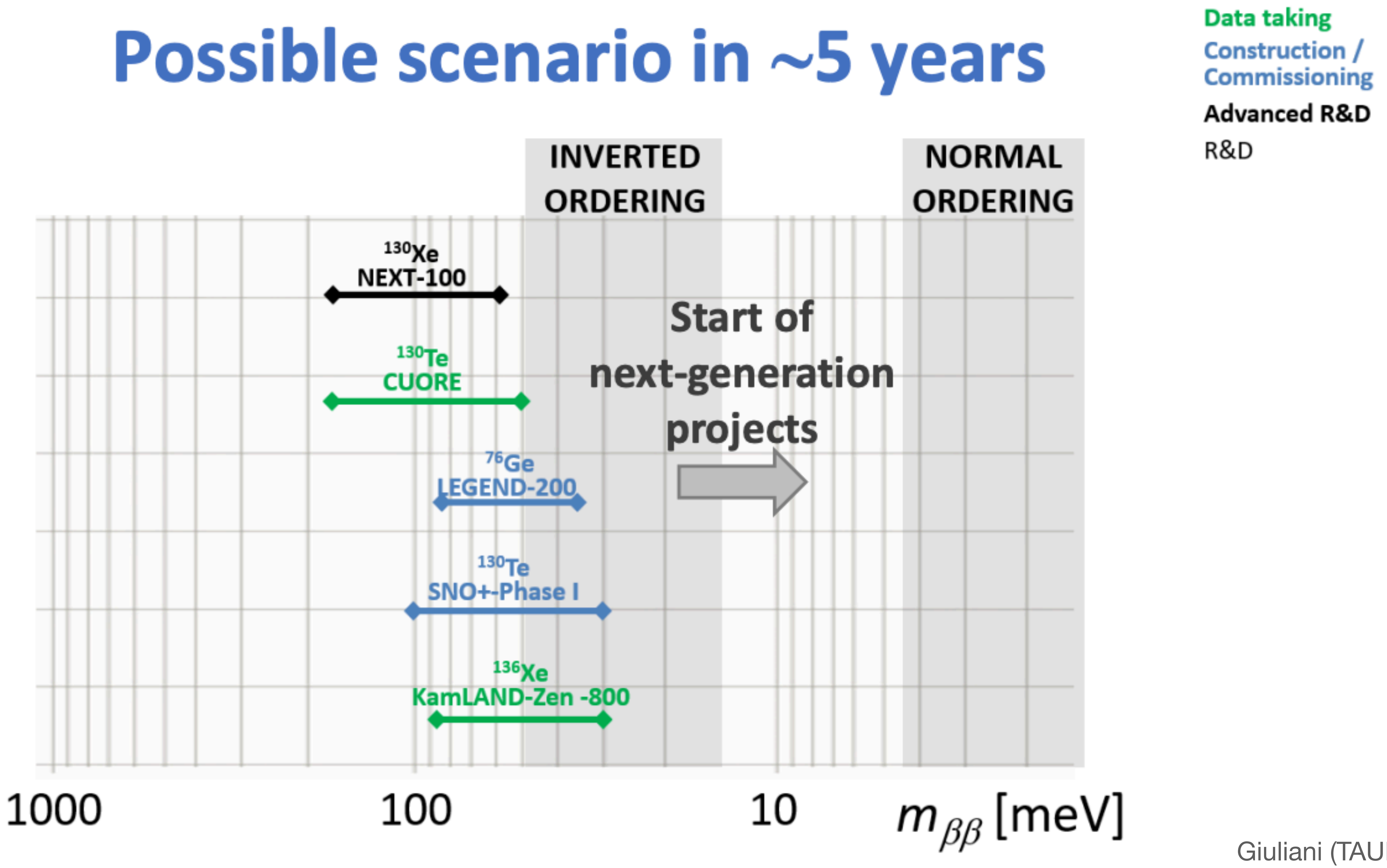
$$\Sigma = \sum_{i=1}^{3} m_i$$

DOE NP “portfolio review” of $0\nu\beta\beta$: 07/13-16/21

& North American - EU APPEC “workshop”: 9/29 - 10/1/21

	Isotope	Portfolio Review	APPEC workshop	Competitors of same isotope
CUPID	^{100}Mo	✓	✓	AMoRE-II
LEGEND-1000	^{76}Ge	✓	✓	CDEX-1Tnu
nEXO	^{136}Xe	✓	✓	KamLAND2-ZEN, NEXT-BOLD, DARWIN
NEXT	^{136}Xe		✓	KamLAND2-ZEN, nEXO, DARWIN
THEIA	^{130}Te (?)			

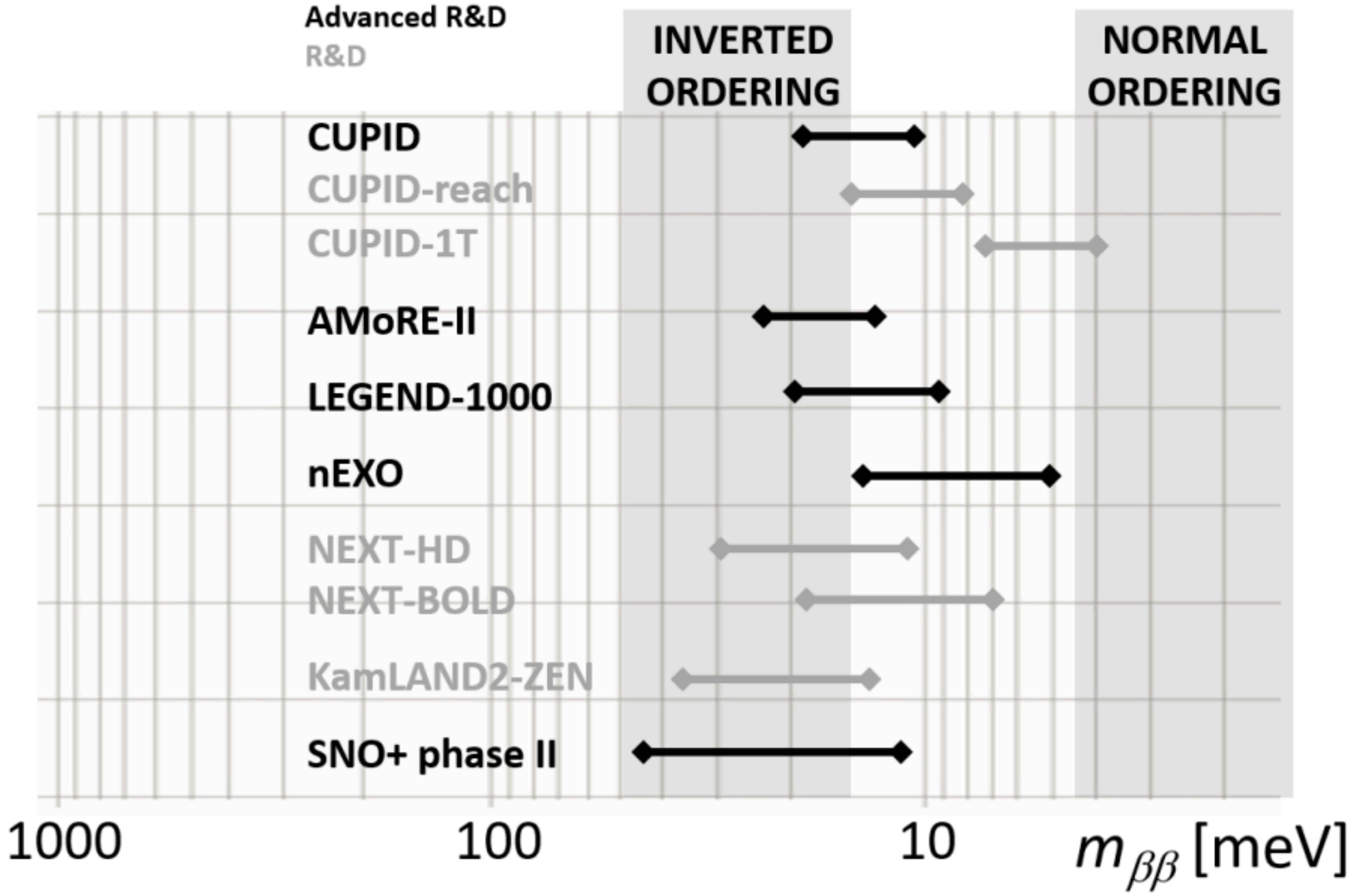
Sensitivity



Giuliani (TAUP 2021)

Sensitivity

Promising next-generation projects



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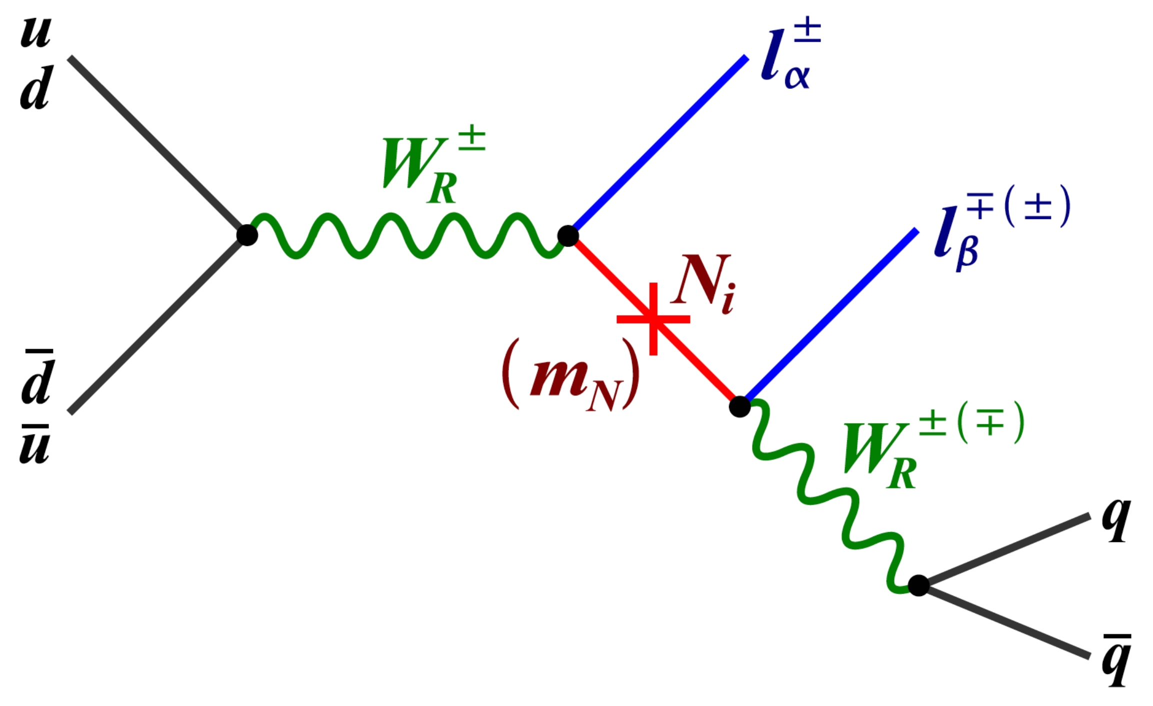
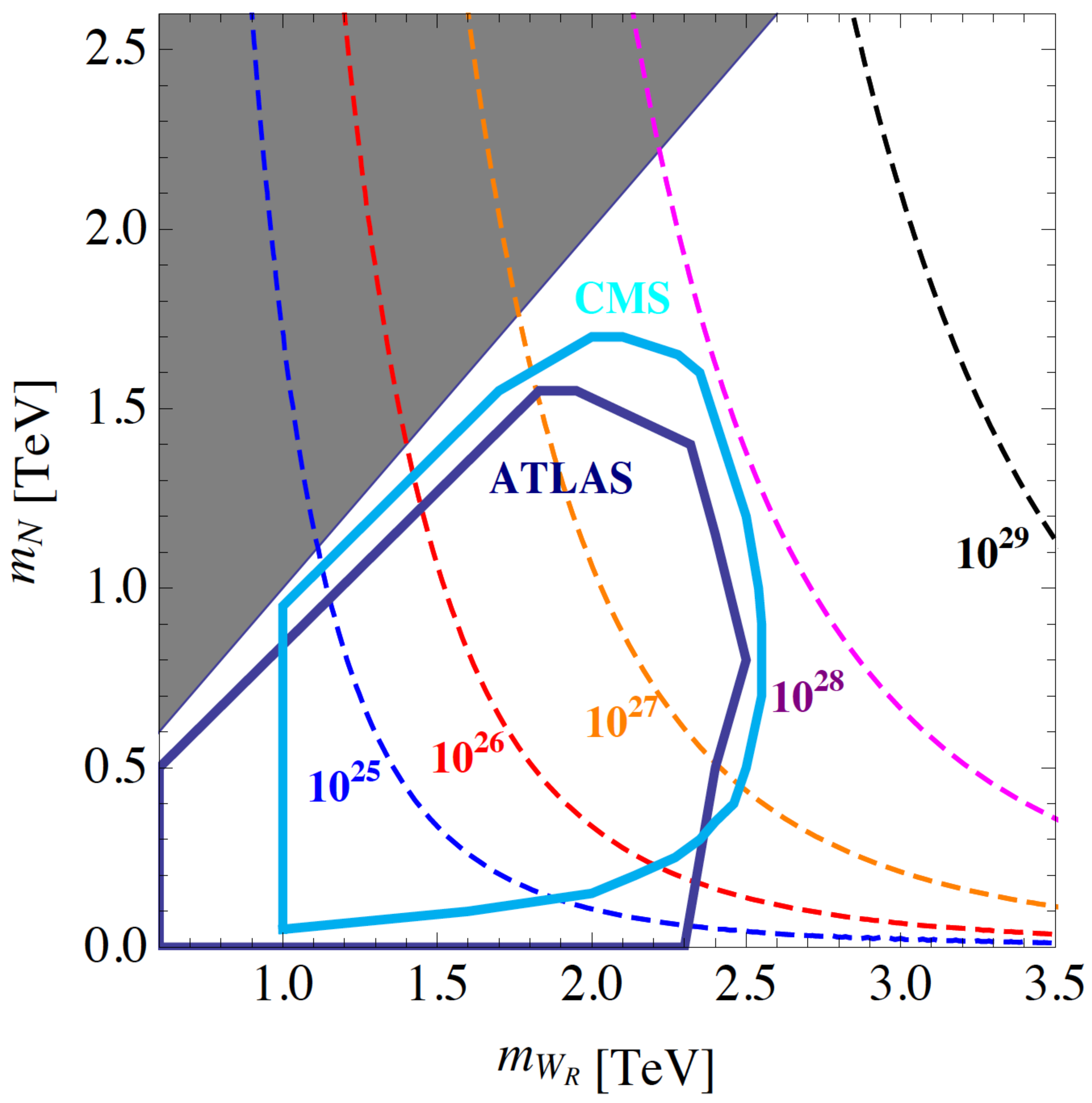
Complementarity to LHC / heavy flavor physics

LNV via heavy right-handed neutrino exchange can be probed via $l^{\pm}l^{\pm} + 2j$



Hirsch 2016



Same sign: $l^{\pm}l^{\pm} + 2j$

Non-observation gives stringent limits on short-range W_R mechanisms

CUORE → CUPID

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

Small scale demonstrators

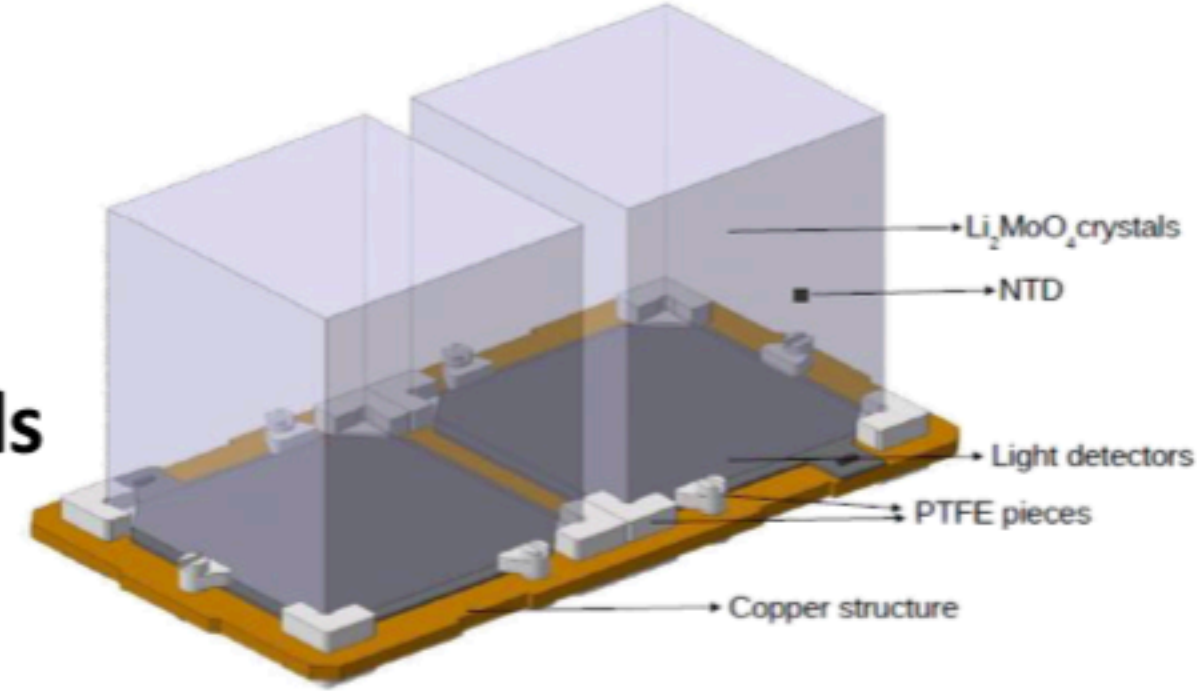
CUPID-Mo
CUPID-0
CUORE

→ **CUPID** → CUPID Reach / CUPID-1T

CUPID (under DoE Portfolio Review) – **LNGS, Italy**

Concept

- Single module: $Li_2{}^{100}MoO_4$ **45×45x45 mm – ~280 g**
- 57 towers of 14 floors with 2 crystals each - **1596 crystals**
- **~240 kg of ^{100}Mo** with >95% enrichment
- **~1.6×10^{27}** ^{100}Mo atoms
- **Bolometric Ge light detectors** as in CUPID-Mo, CUPID-0

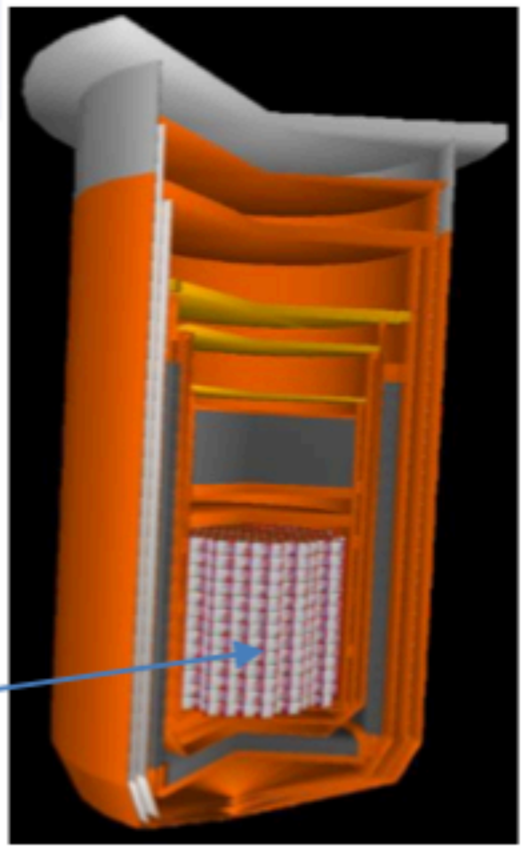


J. Ouellet, this conference
arXiv:1907.09376

CUPID is built on successful CUPID-Mo + CUORE

Li_2MoO_4 scintillating bolometer technology, with demonstration of energy resolution, crystal radiopurity and α rejection

Ton-scale bolometric experiment is possible
Electronics and data analysis tools
Reuse CUORE infrastructure



CUPID sensitivity

Data driven background model

- Information from CUPID-Mo, CUPID-0
- CUORE background model (same infrastructure!)

Projected background index: **1×10^{-4} c/(keV kg y)**

Critical background component: random coincidence of $2\nu\beta\beta$ events (^{100}Mo fastest $2\nu\beta\beta$ emitter: $T_{1/2} = 7.1\times10^{18}$ y)

10 y discovery sensitivity 1.1×10^{27} $m_{\beta\beta} < 12 – 20$ meV

Possible follow-up of CUPID

CUPID-reach - Same sensitive mass and cryostat as CUPID
Background improvement by factor 5
2.3×10^{27} y → $m_{ee} < 7.9 – 14$ meV

CUPID-1T - 1 ton isotope → new cryostat
Background improvement by factor 20
9.2×10^{27} y → $m_{ee} < 4.0 – 6.9$ meV

Criticalities:
- $2\nu\beta\beta$
- Surface events

Intense R&D to improve background in Li_2MoO_4 and TeO_2 based bolometric experiments

CROSS → reject **surface events** by **PSD assisted by metal film coating**
A. Zolotarova, this conference

BINGO →
- Internal active shield ($ZnWO_4$ scintillators)
- Enhanced-sensitivity light detectors
- Revolutionary detector assembly

C. Nones, this conference

Giuliani (TAUP 2021)

P. Krause, this conference
J. Gruszko, this conference
R. Massarczyk, this conference

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

GERDA → LEGEND

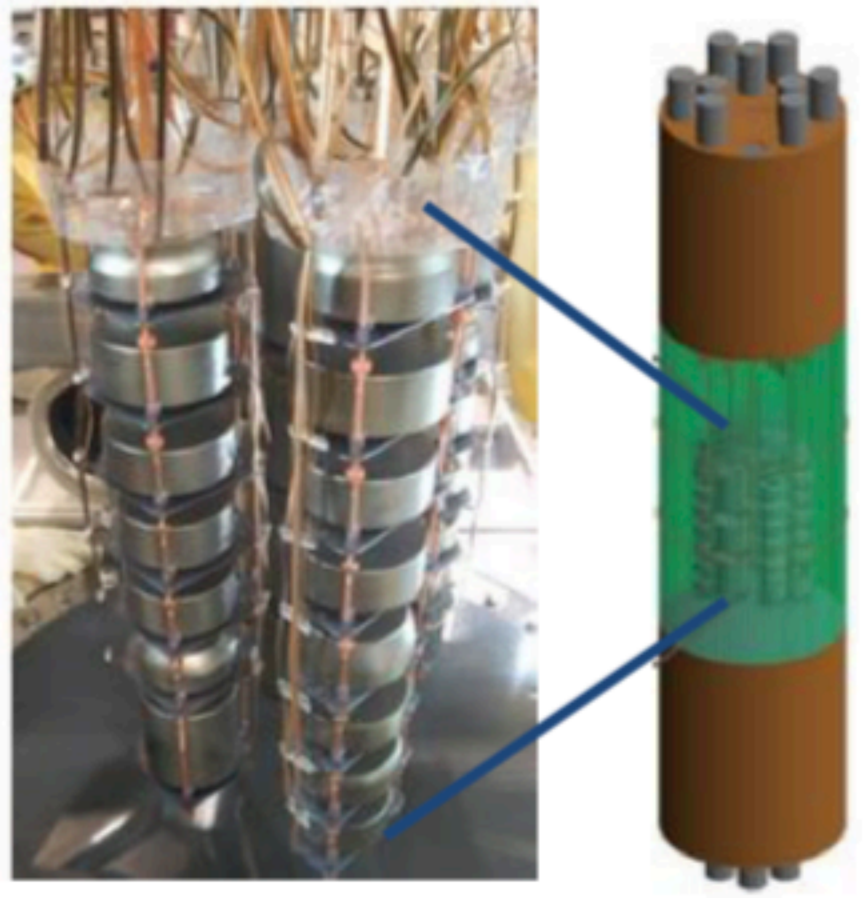
GERDA
MAJORANA dem.
→ **LEGEND-200** → **LEGEND-1000**

GERDA - LNGS, Italy $T_{1/2} > 1.8\times10^{26}$ y – $m_{\beta\beta} < 79 - 180$ meV
35 kg of ^{76}Ge – Leading experiment in terms of half-life

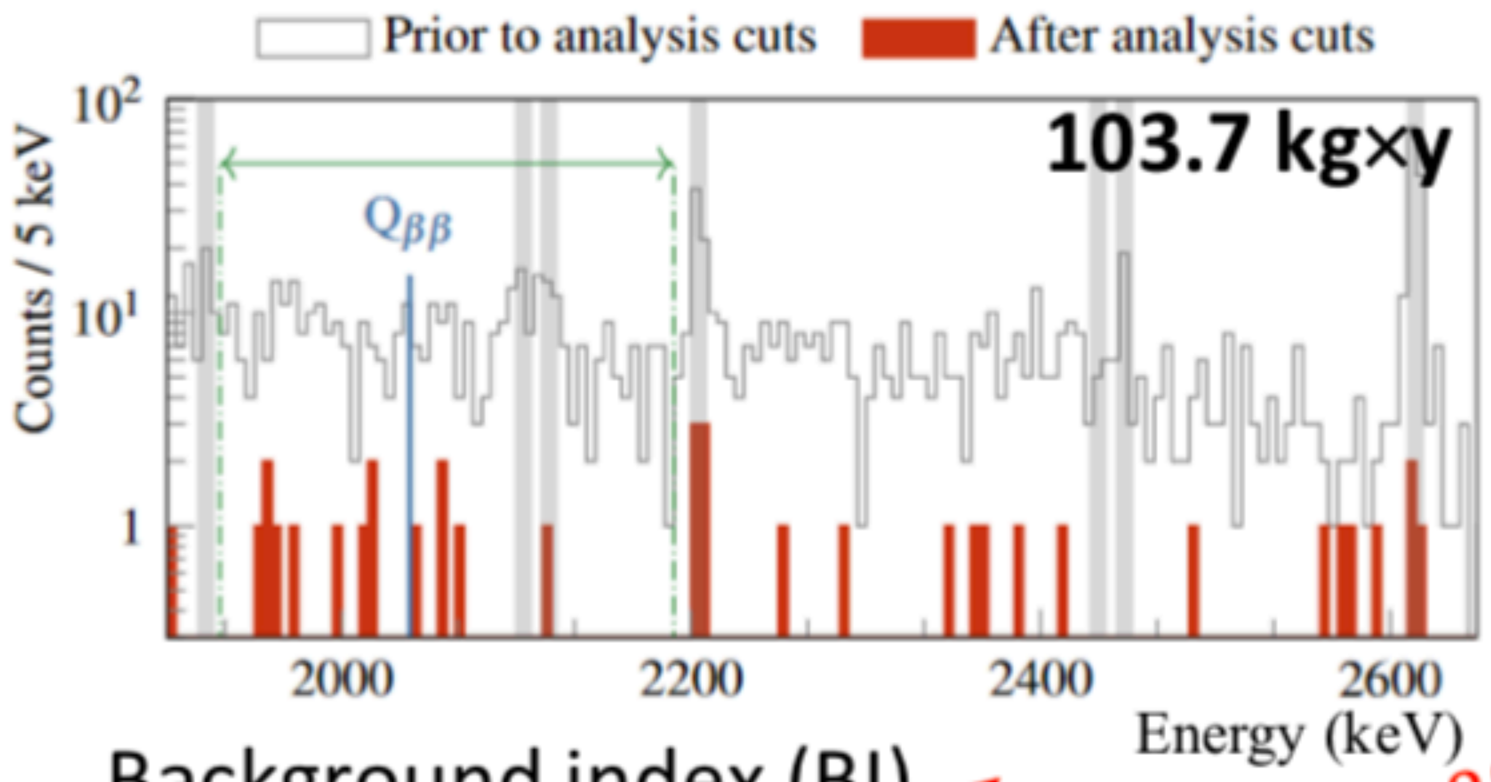
Concept

High purity naked Ge detectors immersed in instrumented LAr

- Energy resolution ΔE ~ 3 keV FWHM @$Q_{\beta\beta}$
- Pulse shape discrimination: **multi site vs. single site events**
- Anticoincidence with **LAr active shield**, instrumented with
  - Wavelength shifting fiber shroud coupled to SiPMs
  - PMTs on top and bottom of the setup



37 HP Ge detectors



Background index (BI)
$5.2^{+1.6}_{-1.3} \times 10^{-4}$ c/(keV kg y) ← Lowest in all ββ experiments

Phys. Rev. Lett. 125, 252502 (2020)

LEGEND-200 combines the best of GERDA and MJD

- Adopt GERDA detector configuration
- **Reuse GERDA infrastructure at LNGS** (after upgrade)
- Follow MJD selection of radiopure parts
- MJD electronics and low threshold
- ^{76}Ge: **35 kg** from GERDA, **30 kg** from MJD
  140 kg are new material
- **New detector type**, already tested in GERDA
  ICPC detector, **> 2 kg** vs. previous 0.7-0.9 kg
  → same energy resolution and PSD capability

Commissioning:
Detector deployment starts in Sep 2021
Data taking: end 2021 / beginning 2022

AIP Conference Proceedings 1894, 020027 (2017)

LEGEND-1000 (under DoE Portfolio Review)

- Same technology, **new larger infrastructure**
- Phased approach, up to **1000 kg of ^{76}Ge**
- Site to be decided – baseline: **SNOLAB**

Discovery sensitivity
Background free approach

LEGEND-200	LEGEND-1000
BI: 2× 10^{-4} c/(keV kg y)	BI: 10^{-5} c/(keV kg y)
$T_{1/2} > 10^{27}$ y - 5 y live time	$T_{1/2} > 1.3\times10^{28}$ - 10 y live time
$m_{\beta\beta} < 34 - 78$ meV	$m_{\beta\beta} < 9 - 21$ meV

arXiv:2107.11462v1

Giuliani (TAUP 2021)

A. Jamil, this conference

nEXO

Completed
Data taking
Construction / Commissioning
Advanced R&D
R&D

EXO-200 → nEXO

nEXO is built on the successful **EXO-200** – **WIPP, US**

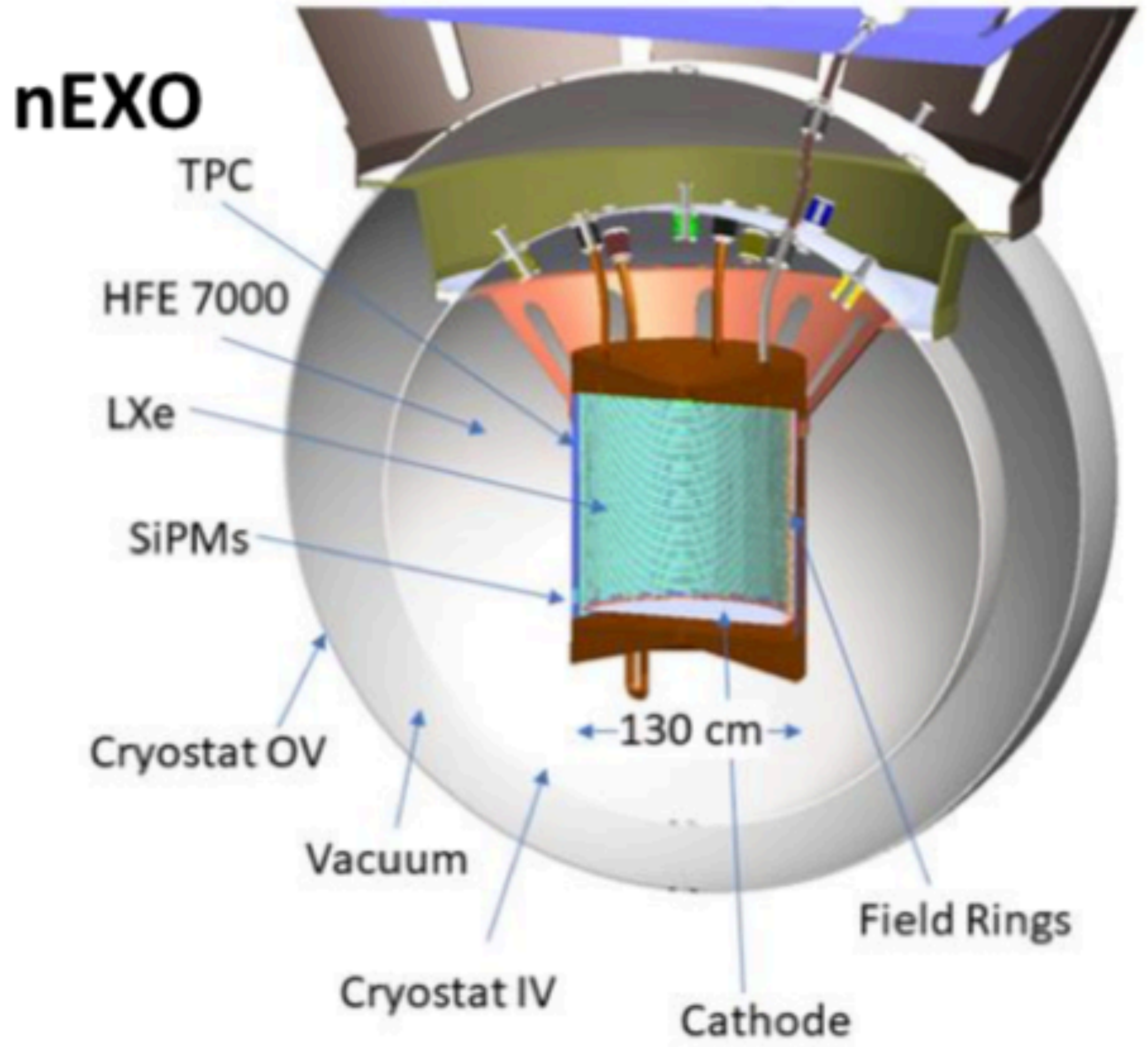
150 kg of ^{136}Xe – $T_{1/2} > 3.5\times10^{25}$ y – $m_{\beta\beta} < 93 – 286$ meV

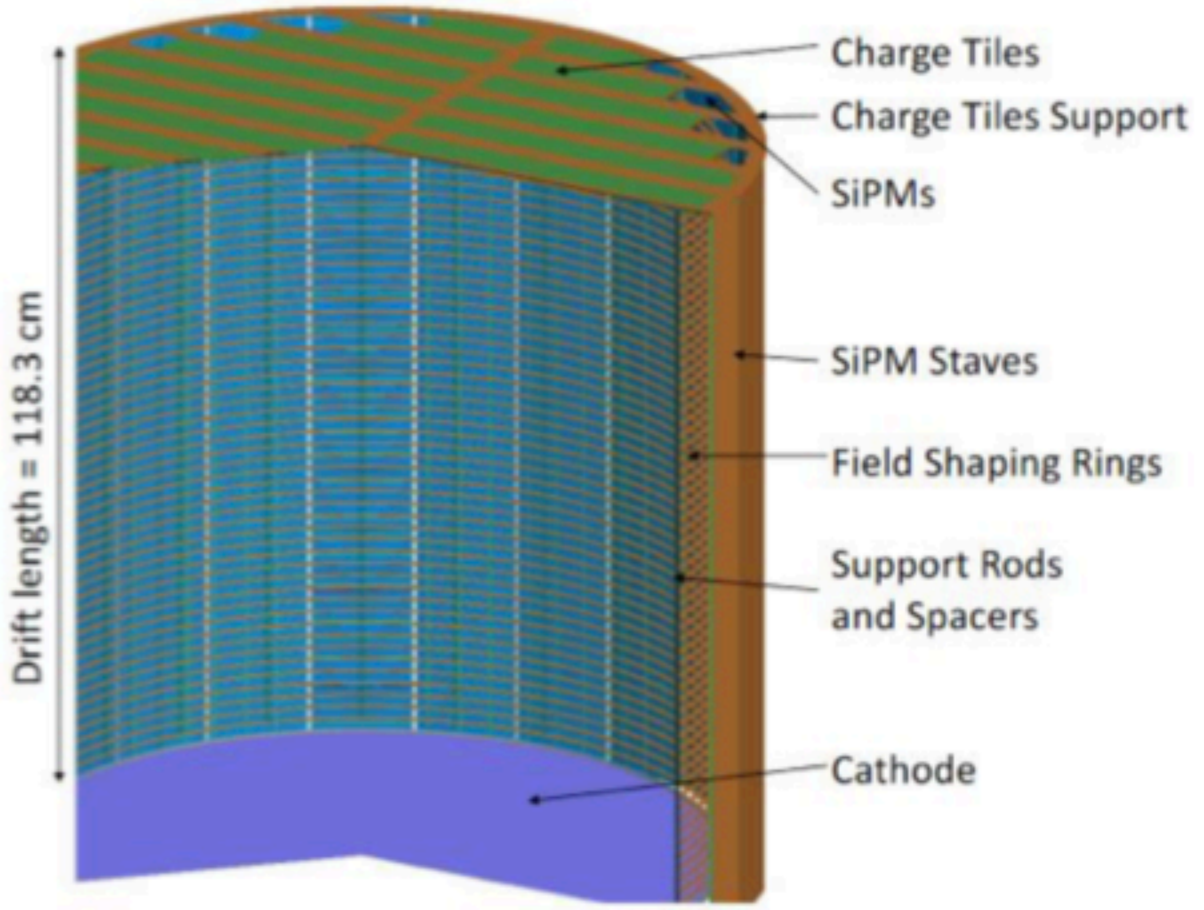
First observation of $2\nu\beta\beta$ of ^{136}Xe (2011) – **$T_{1/2} = 2.165\times10^{21}$ y**

Concept

Single phase enriched LXe TPC

- Energy resolution **ΔE(σ) ~ 0.8%@$Q_{\beta\beta}$**
- Measurement of both charge and scintillation
- **Single site** (including signal) **vs. multi site events** (background)
- Multi-dimensional analysis using energy, 3D position and topology





Main components inside the TPC vessel

nEXO (under DoE Portfolio Review) – SNOLab

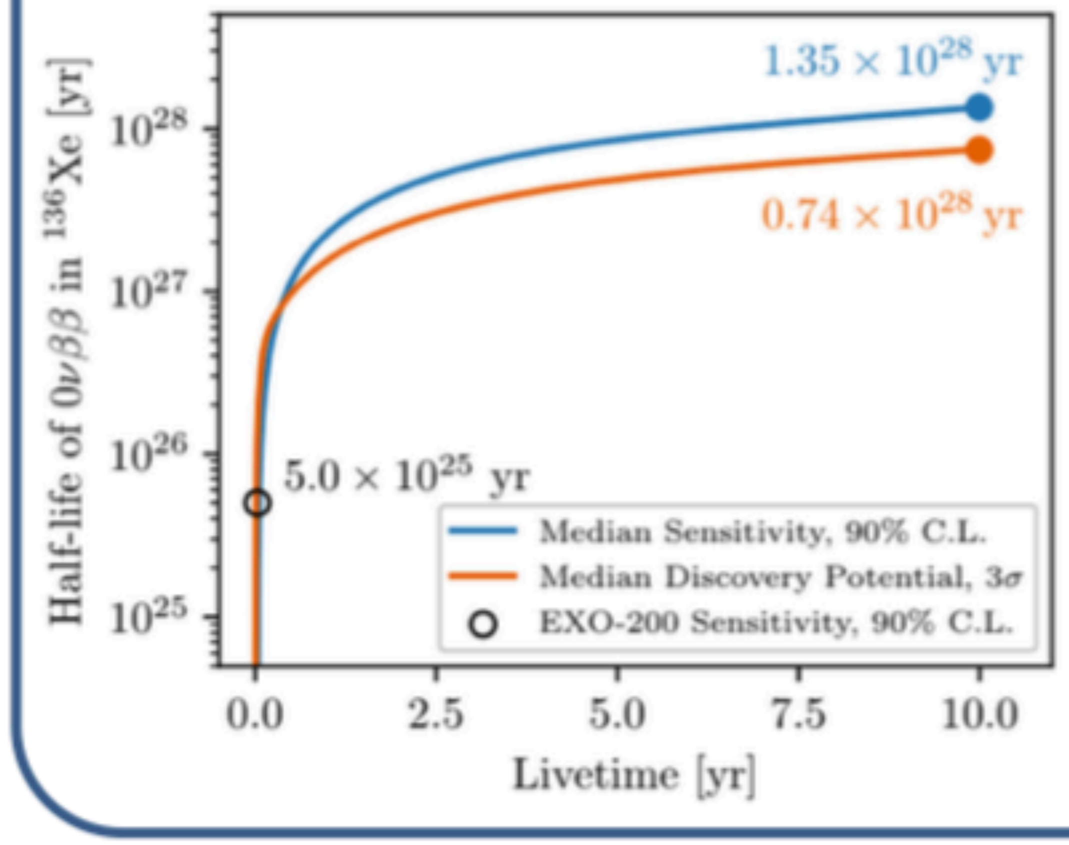
Major upgrades with respect to EXO-200

- More isotope – **~5000 kg of ^{136}Xe**
- Improvement in light sensors (LAAPDs→SiPM)
- Increased light collection *Liang Xie, this conference*
- Improvement in radiopurity (electroformed Cu)
- Cold electronics

	EXO-200	nEXO
Fiducial Mass [kg]	74.7	3281
Energy resolution σ/$Q_{\beta\beta}$ [%]	1.2%	0.8%

LXe self shielding

preCDR - arXiv:1805.11142v2
arXiv:2106.16243



Background dominated by Rn outgassing and intrinsic radioactivity

Equivalent background index: 7×10^{-5} c/keV kg y)

10 y sensitivity
1.35×10^{28} y
$m_{\beta\beta} < 5 - 15$ meV

Tagging of individual ^{136}Ba daughter

$^{136}Xe \rightarrow {}^{136}Ba + 2e^-$

Demonstrated by fluorescence in solid Xenon *Nature 569, 203–207 (2019)*

Giuliani (TAUP 2021)

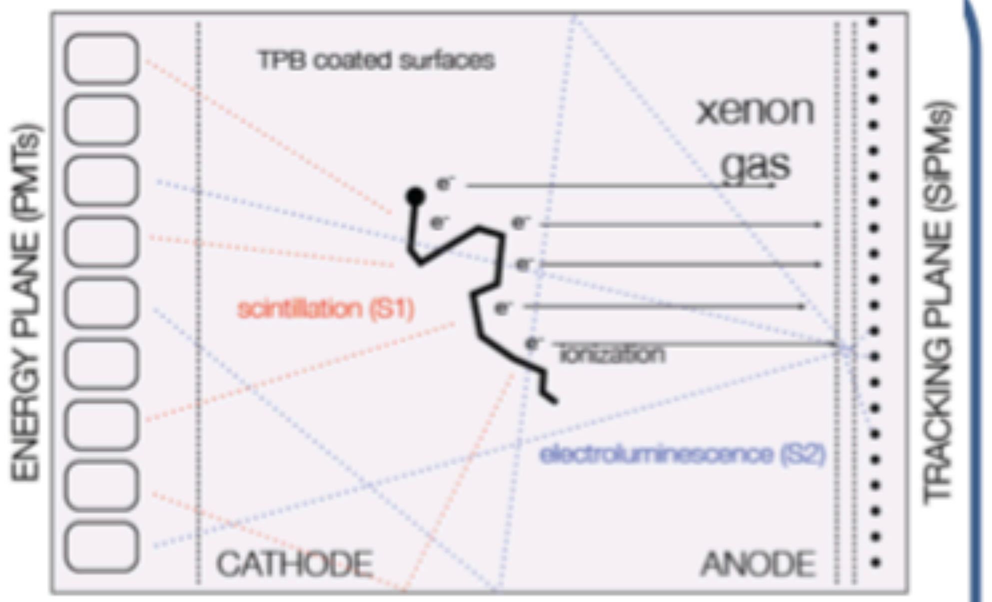
A. Usón, this conference

NEXT

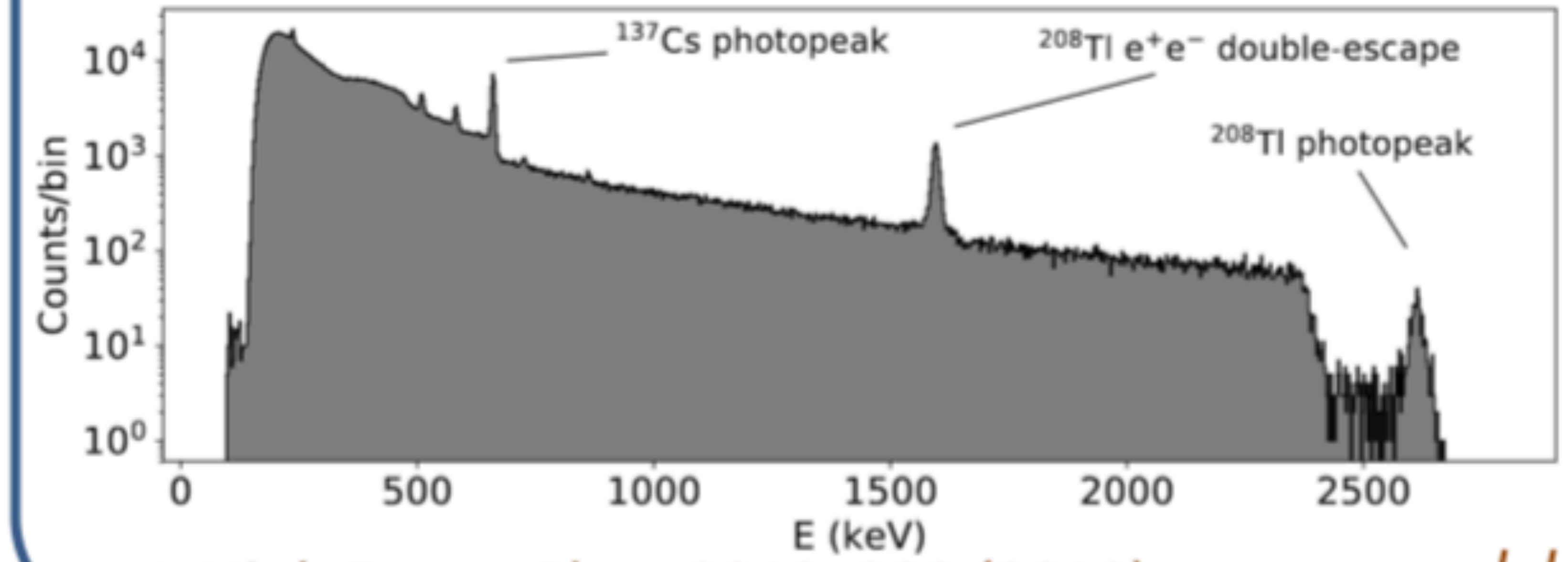
NEXT-White → **NEXT-100** → NEXT-HD / NEXT-BOLD

Concept

High pressure (10-15 bar) enriched Xe TPC
- Primary scintillation ($t_0 \rightarrow$ z coordinate)
- Electroluminescence for energy resolution (PMT plane) and for tracking (SiPMs plane) → only light detection, also for the charge readout

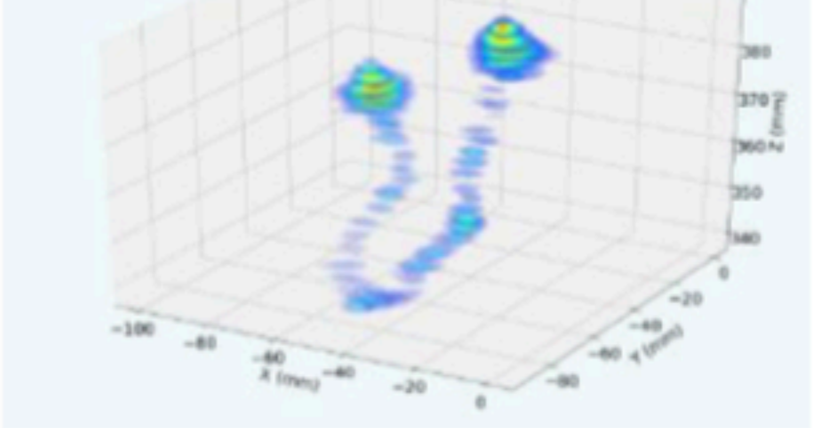


Proof of concept: NEXT-White (started in 2016) – **LSC, Spain**
- 5 kg prototype – enriched Xe from 2019
- Stability
- Long electron lifetime (> 20 ms)
- **ΔE < 1% FWHM in the ROI (< 25 keV)**
- **Event topological reconstruction**
- $2\nu\beta\beta$ detected at more than 5σ
- Infrastructure usable for NEXT-100



J. High Energ. Phys. 2019, 230 (2019)

Real $\beta\beta$ event



J. High Energ. Phys. 2019, 52 (2019)

NEXT-100 (funded) – **LSC, Spain** (2022-2025)

Upscaling of NEXT-White
- More isotope – **~97 kg of enr Xe gas (^{136}Xe: 90%)**
- 15 bar operation
- Same structure/technology of NEXT-White
- Larger vessel, 60x PMTs and 5600x SiPMs
- Projected background index: 4×10^{-4} c/keV kg y)

400 kg×y sensitivity 1×10^{26} y $m_{\beta\beta}$ < 60 - 160 meV

Main goal: **prepare future stages** of NEXT technology

NEXT-HD (High Definition) – start in 2026
- Up to 1 ton enriched Xe gas at 20 bar
- Replacement of PMTs by SiPMs
- Xe-He mixture: lower diffusion, better definition
- Projected background index: 5×10^{-5} c/keV kg y)

Target sensitivity: 2×10^{27} y   **6 ton×y**

arXiv:1906.01743

NEXT-BOLD (Barium On Light Detection)
- NEXT-HD-like module with **Ba tagging**
- Ba tagging by **SMFI** (Single Molecule Fluorescence Imaging) was proved *Phys. Rev. Lett. 120, 132504 (2018)*
- R&D to adapt SMFI to the NEXT dry environment
- Background free

B. Jones, this conference

Target sensitivity: 8×10^{27} y   **10 ton×y**

Giuliani (TAUP 2021)