Status and Prospects of Neutrinoless Double Beta Experiments

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UC Berkeley/LBNL
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Disclaimer

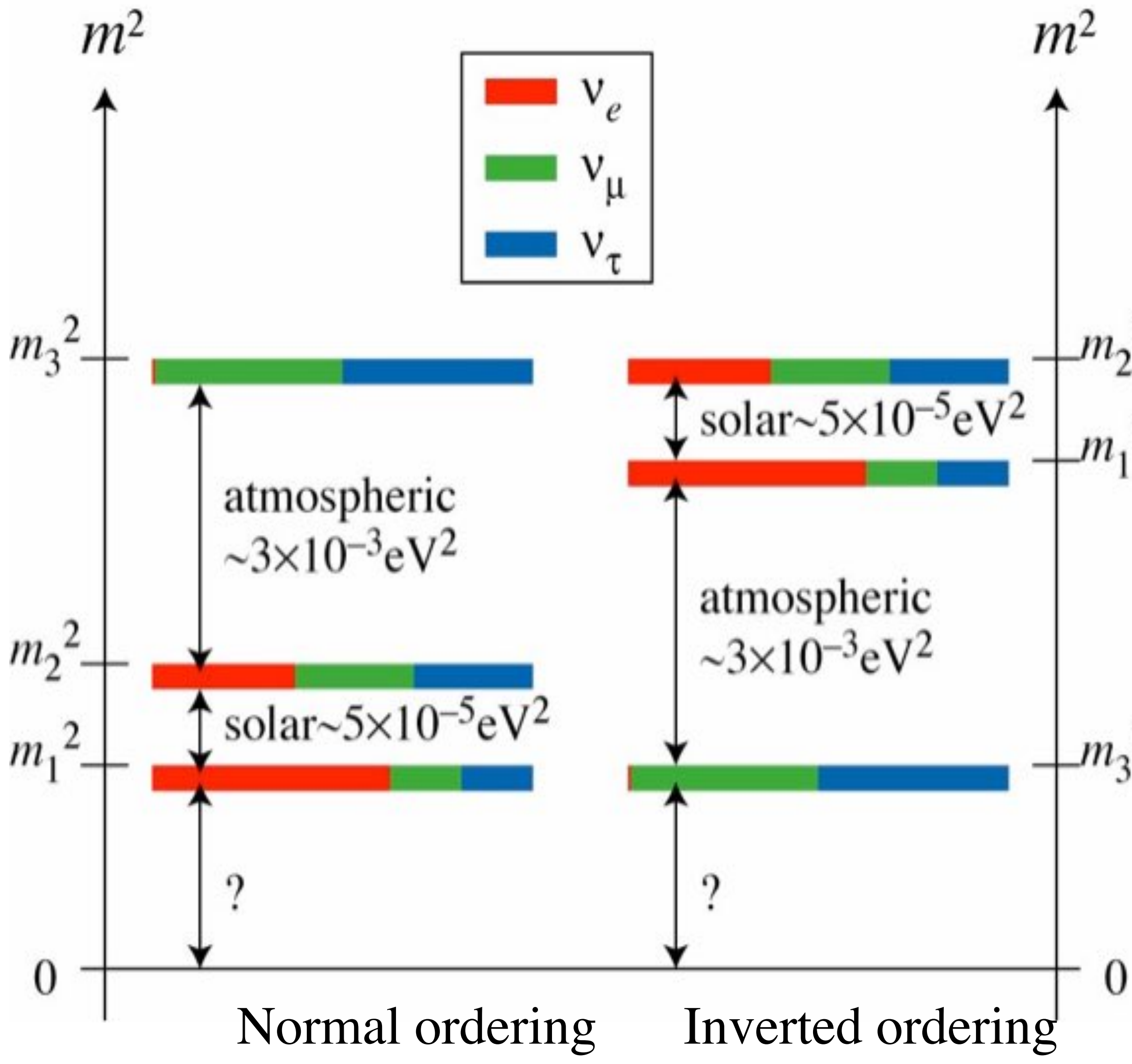
- Many exciting developments: impossible to cover all
- Will focus on the future
  - My apologies for any omissions !

Many thanks: S. Biller, G. Benato, M. Dolinski, C. Grant. G. Gratta, J. Gruszko, K. Han, A. McDonald, Y. Mei, H. Ma, G.D. Orebi Gann, M. Sorel, N. Xu and others

Neutrino Physics Landscape

- Compelling evidence for
  - Neutrino flavor-changing oscillations
  - (therefore) finite neutrino masses
  - Mixing angles are well measured
- Open questions in ν Physics:
  - How many neutrinos?
    - ☞ Sterile neutrinos ?
  - What is absolute scale of ν mass ?
  - How are masses arranged ?
  - Are neutrinos responsible for matter-antimatter asymmetry ?
  - Majorana or Dirac neutrinos ?
  - Is Lepton Number conserved ?

Neutrino mass hierarchy



At least one ν has m > 55 meV

Dirac vs Majorana Neutrinos

- Dirac
  - Requires new fundamental global symmetry $U(1)_{\text{lepton number}}$
    - ☞New physics ?
    - ☞Matter and antimatter are fundamentally different

- Majorana
  - Cannot be explained by "standard" Higgs Yukawa coupling
    - ☞ Lepton number violated: New Physics !
    - ☞ Potentially sensitive to very high mass scales (see-saw mechanism)
    - ☞ Can generate matter⇔antimatter transitions

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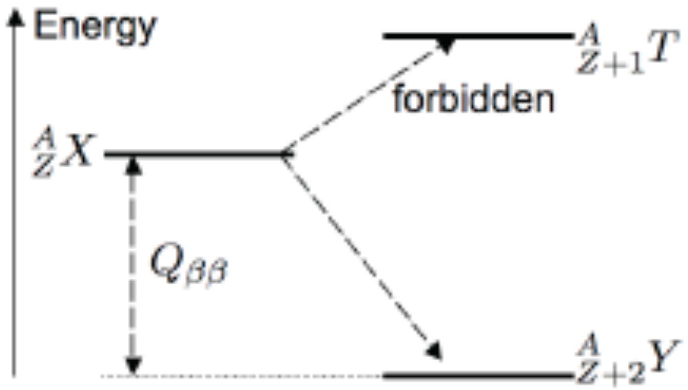
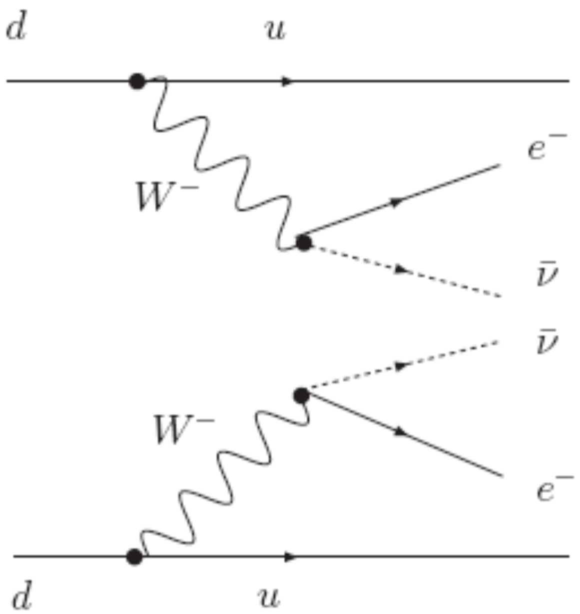
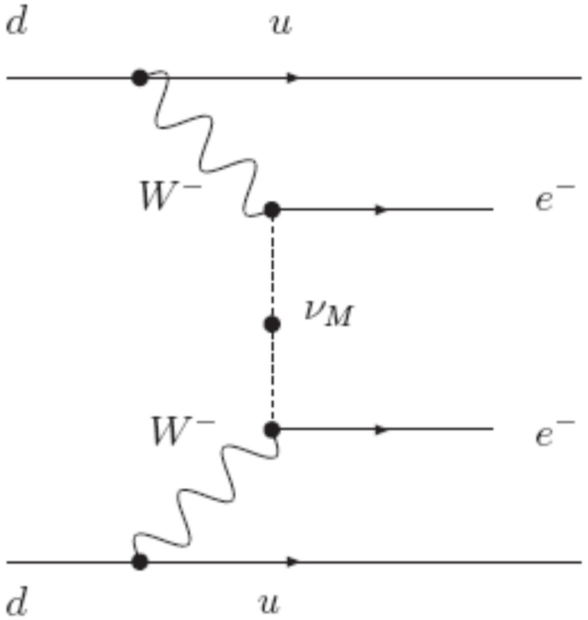
Neutrinoless Double-Beta Decay

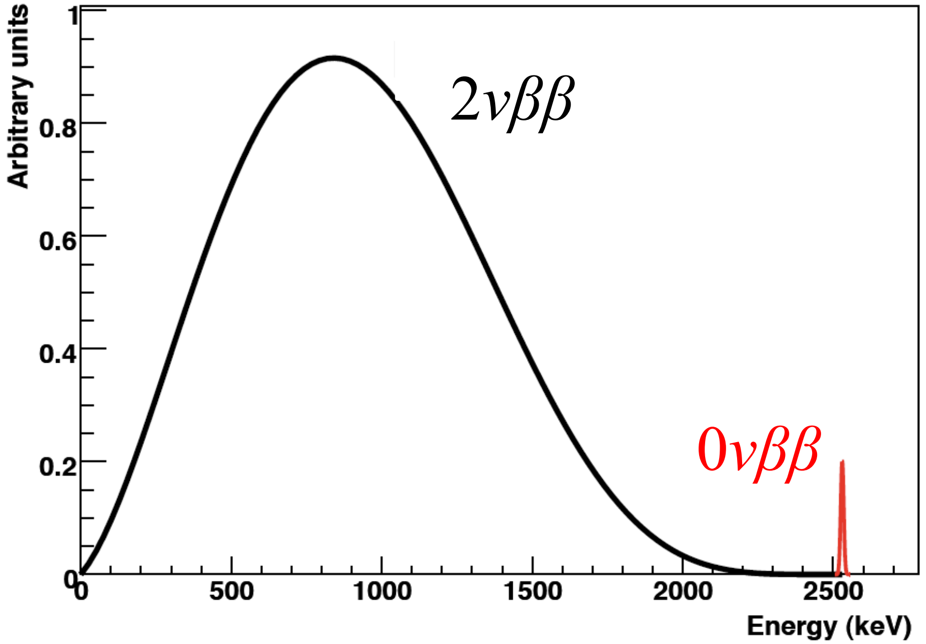




SM 2νββ decay τ ≥ 10^{19} y



0νββ τ ≥ 10^{25} y



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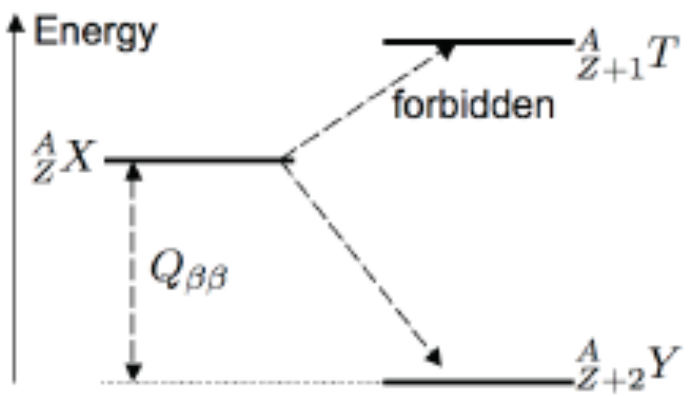

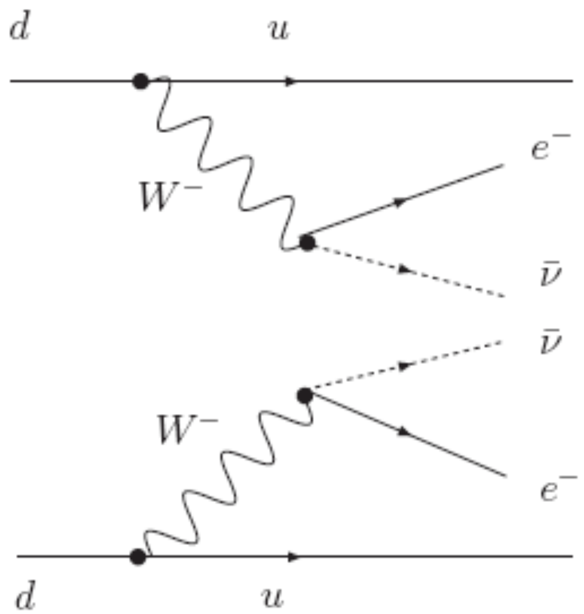

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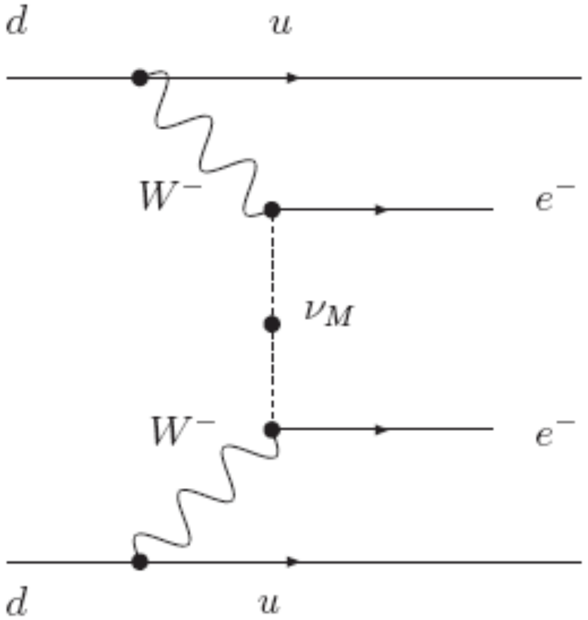
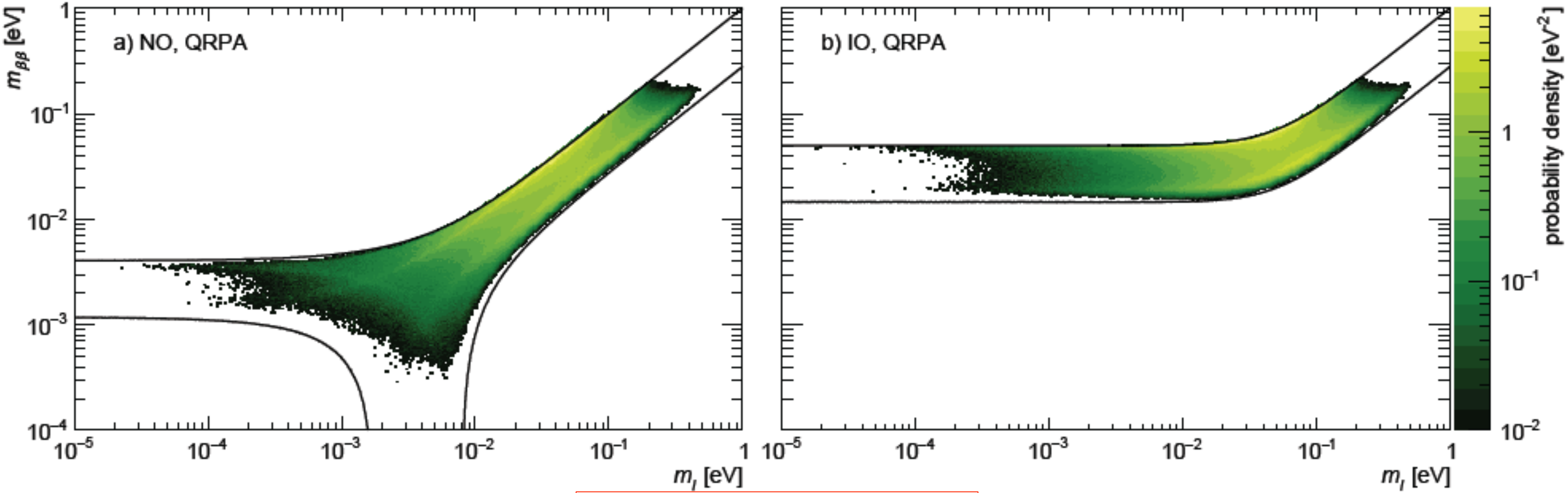


0νββ τ ≥ 10^{26} y

- Observation of 0νββ would mean
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate related to (effective) electron neutrino mass

$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

Constraints on $m_{\beta\beta}$



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M. Agostini, G. Benato, J. Detwiler, Phys. Rev. **D96**, 053001 (2017)

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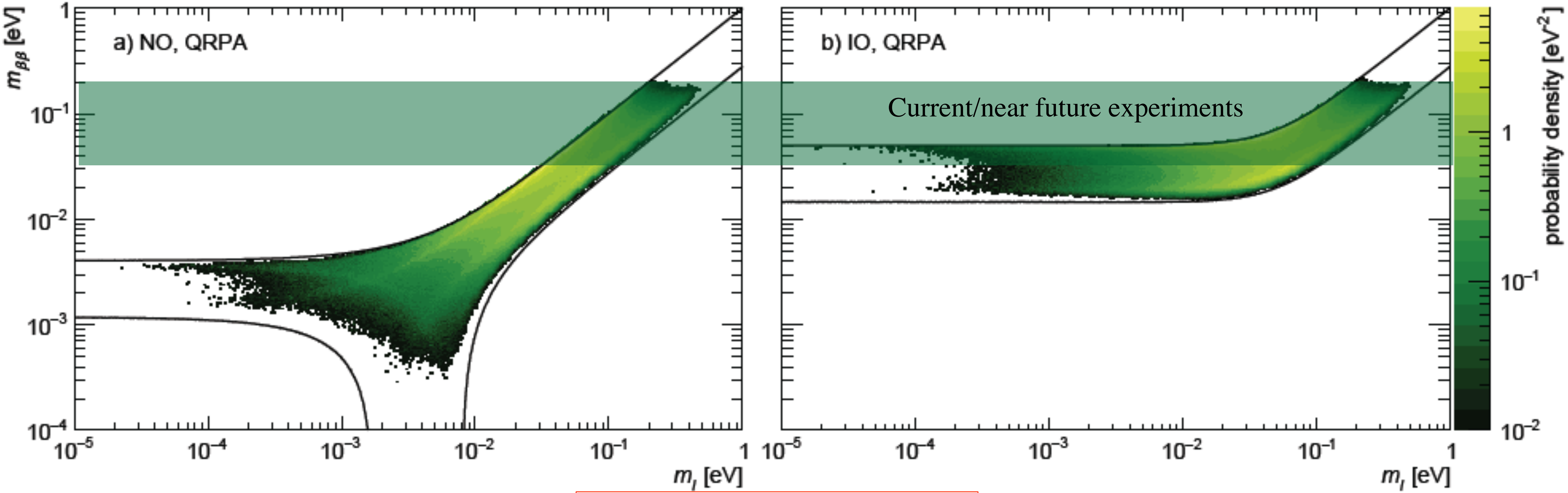

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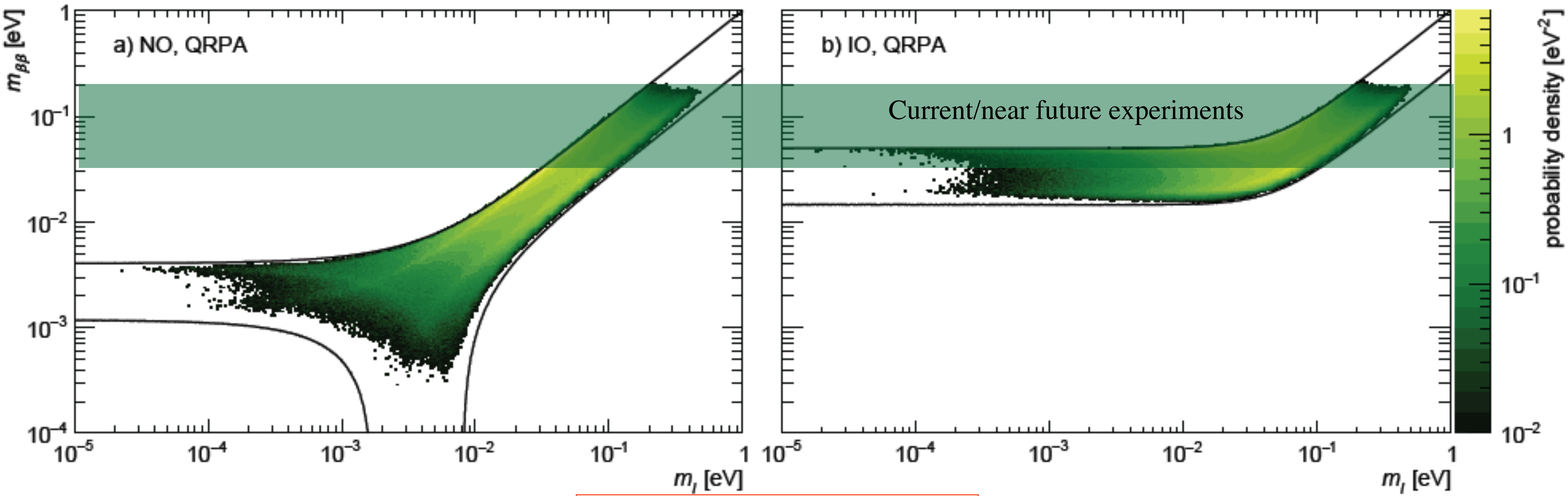

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NB: simplest interpretation (3 light neutrinos). Sterile neutrinos or heavy new physics could change the interpretation dramatically !

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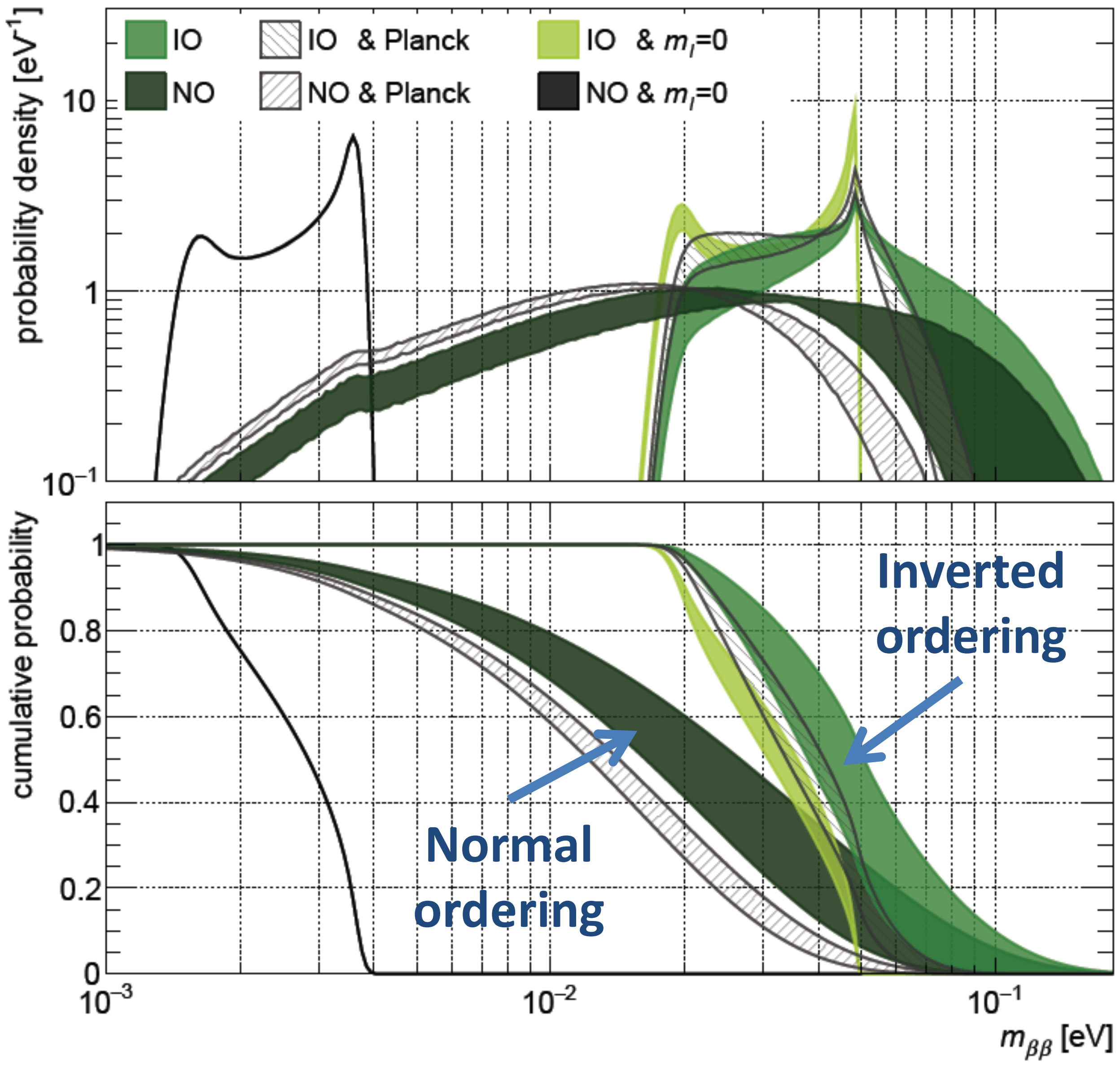

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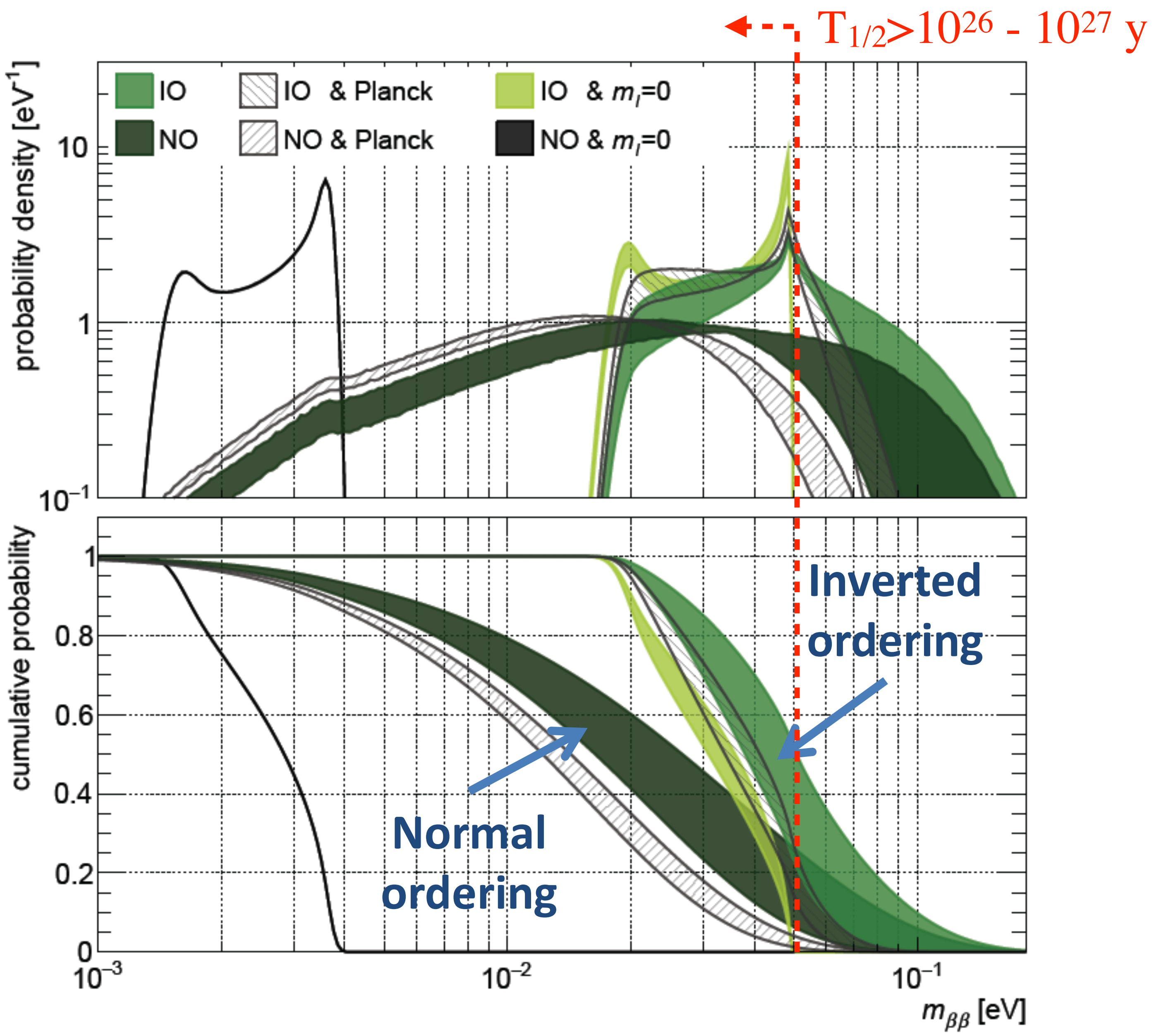

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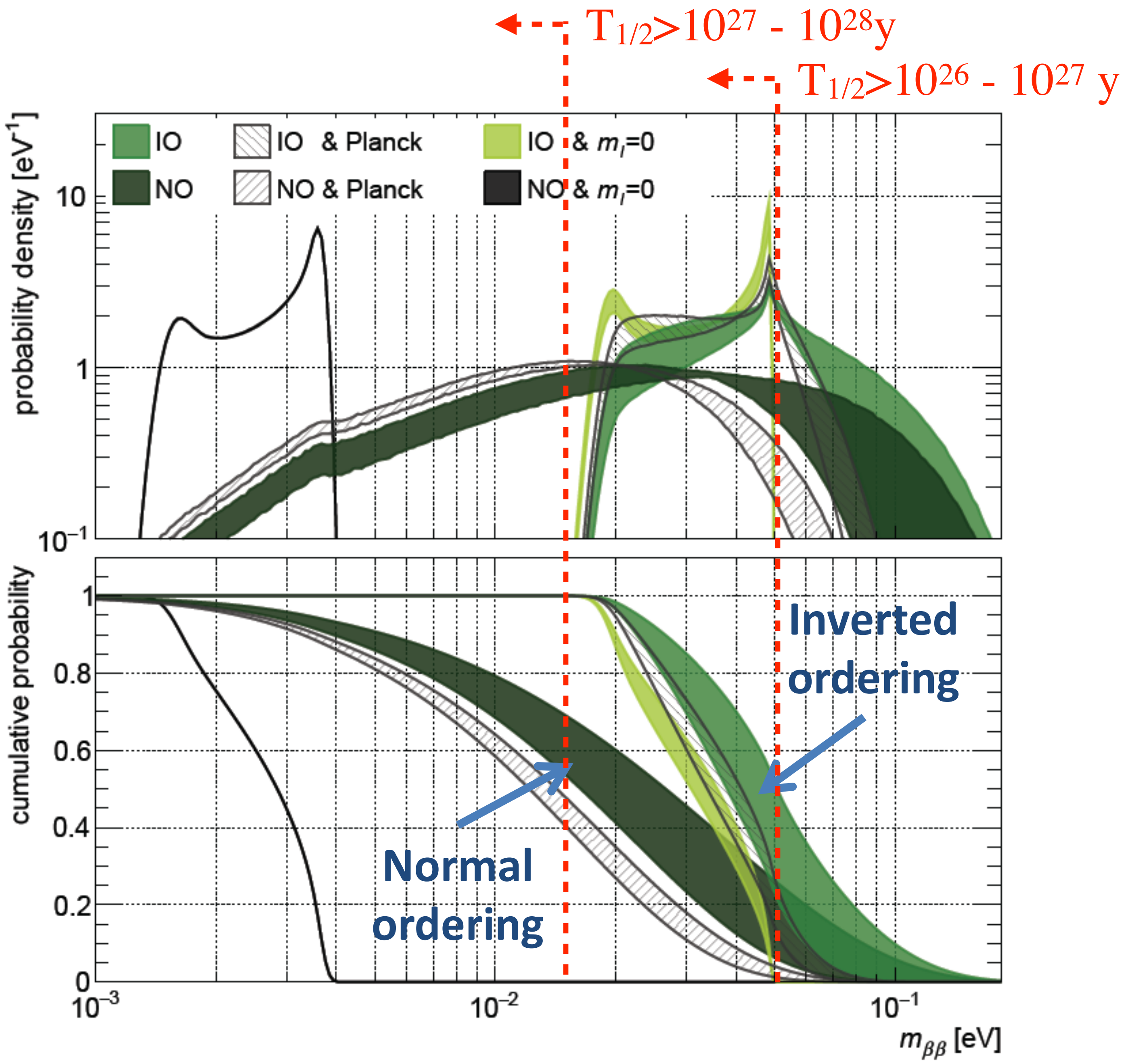

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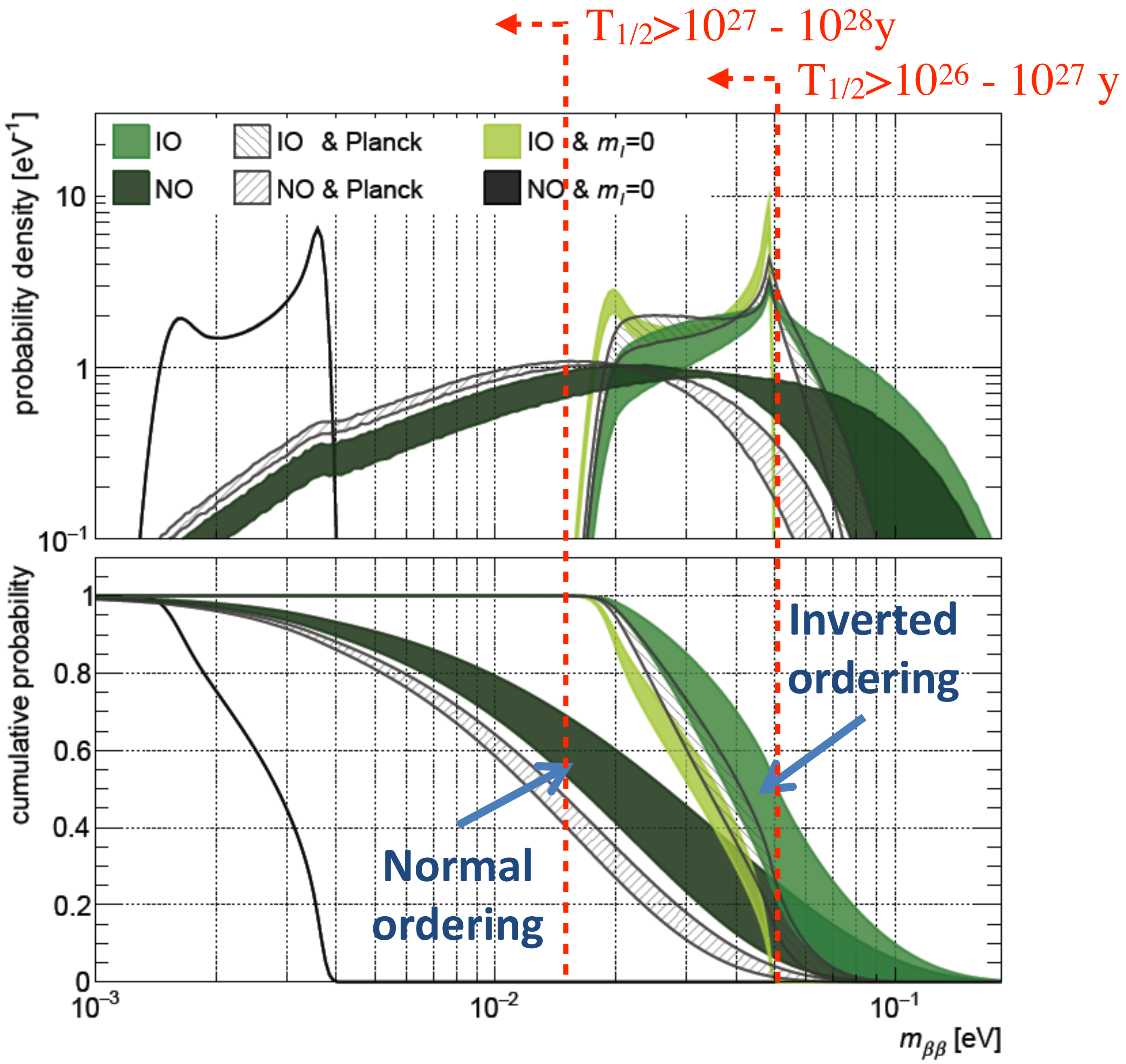

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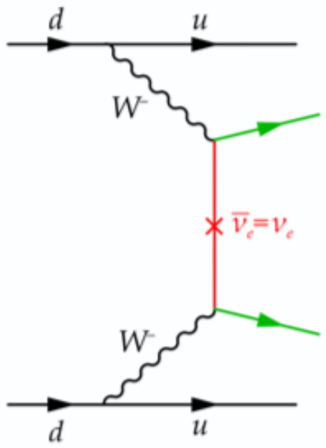

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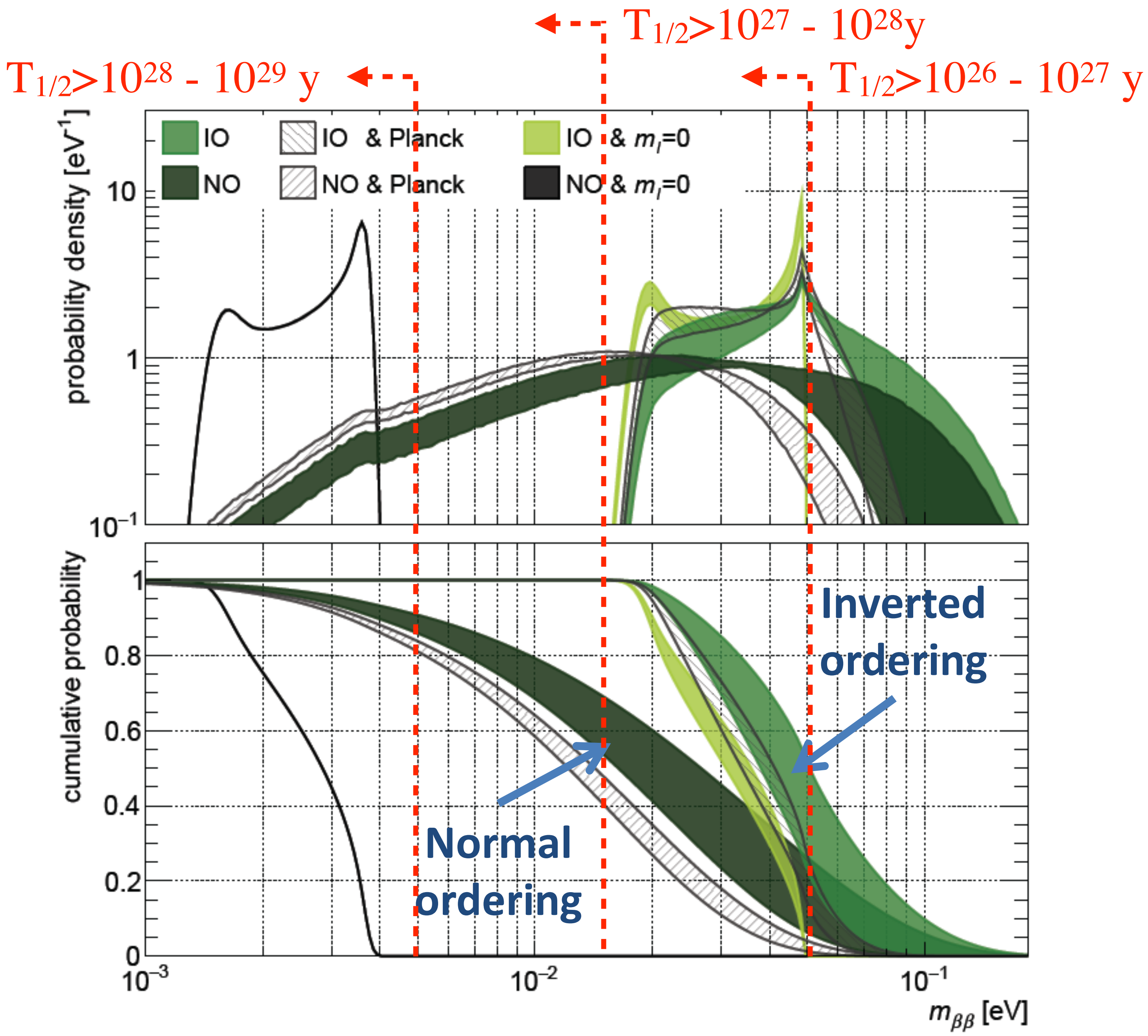

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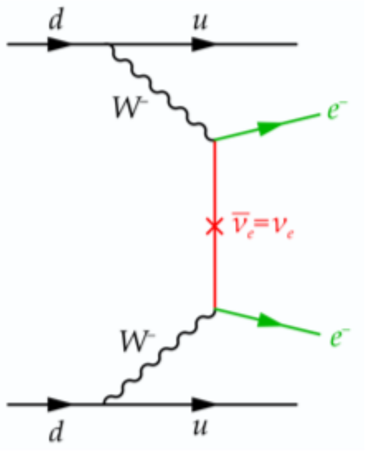

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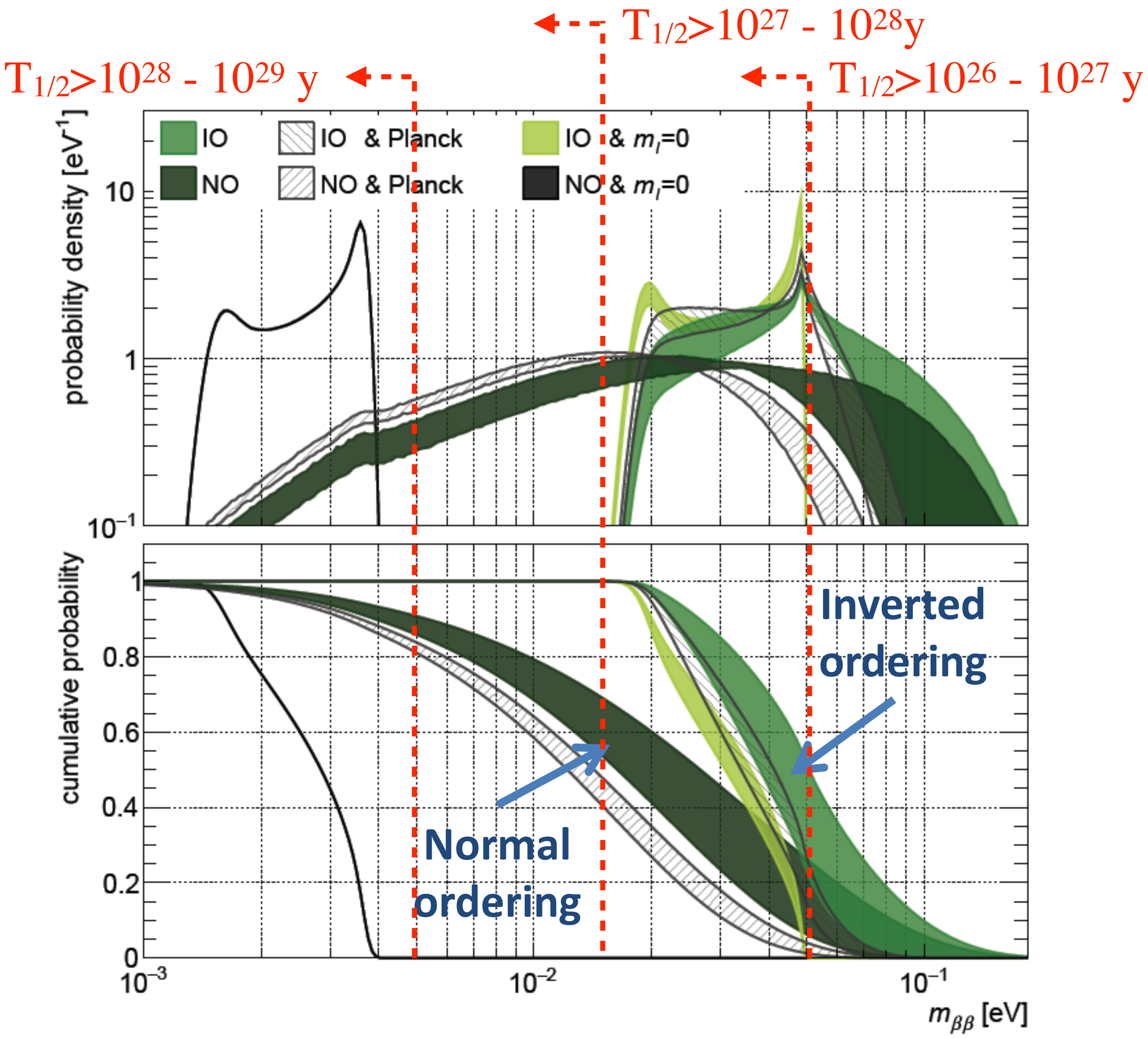

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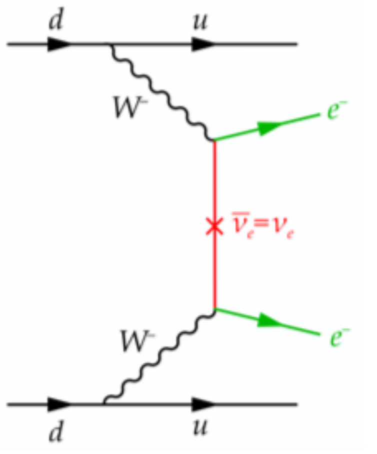

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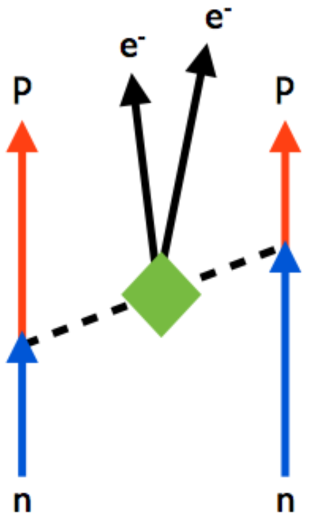
Factor of 10-100 improvement in sensitivity next decade.



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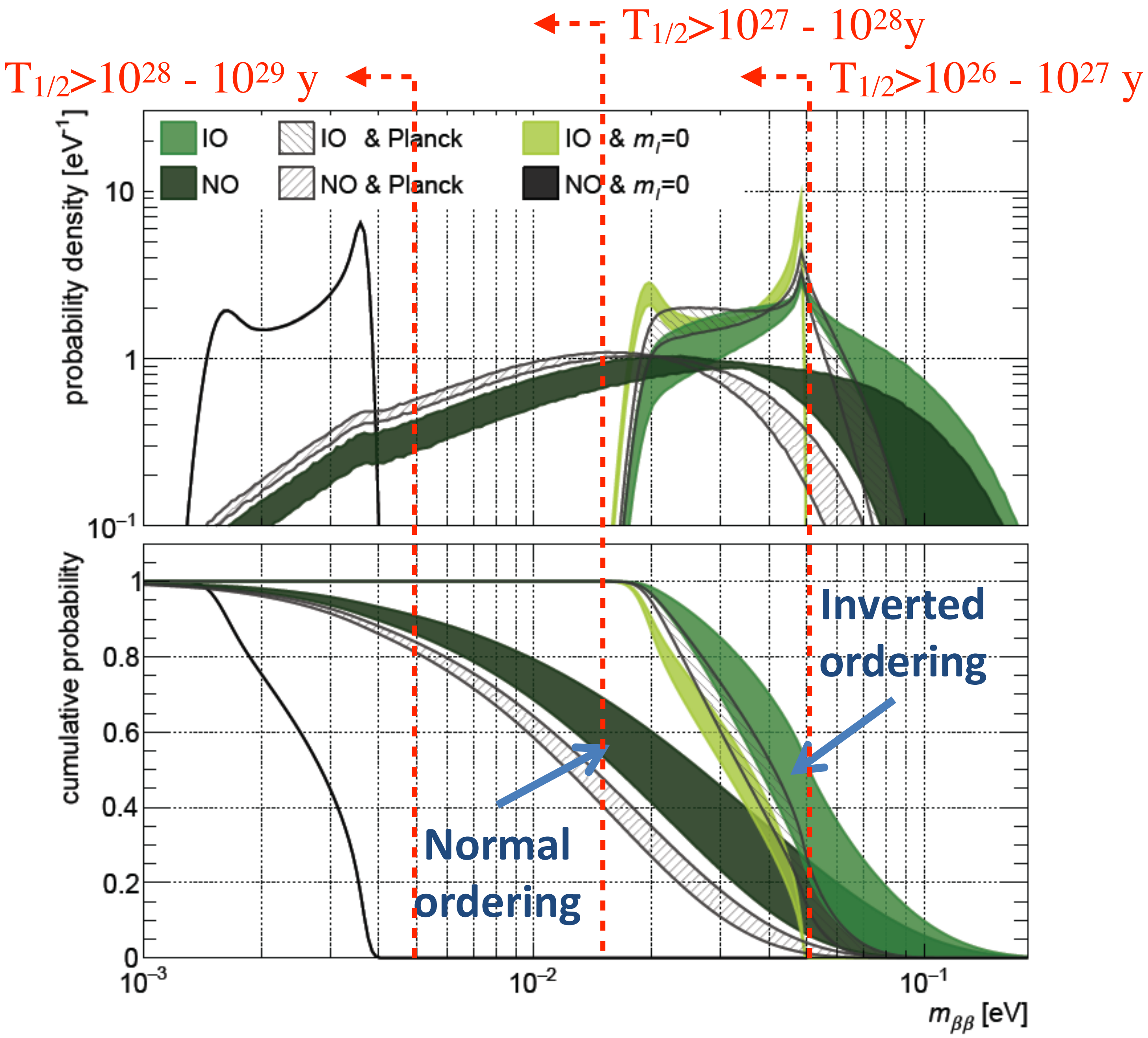

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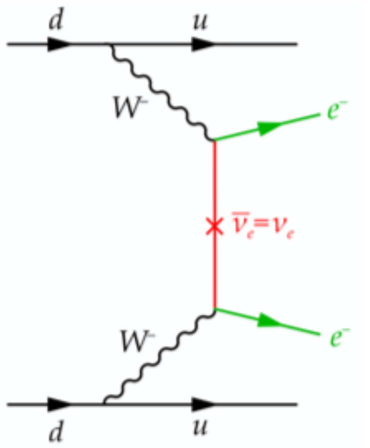

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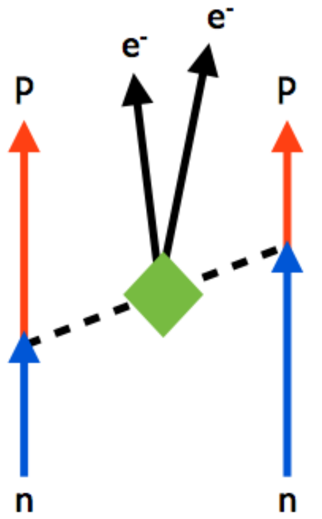

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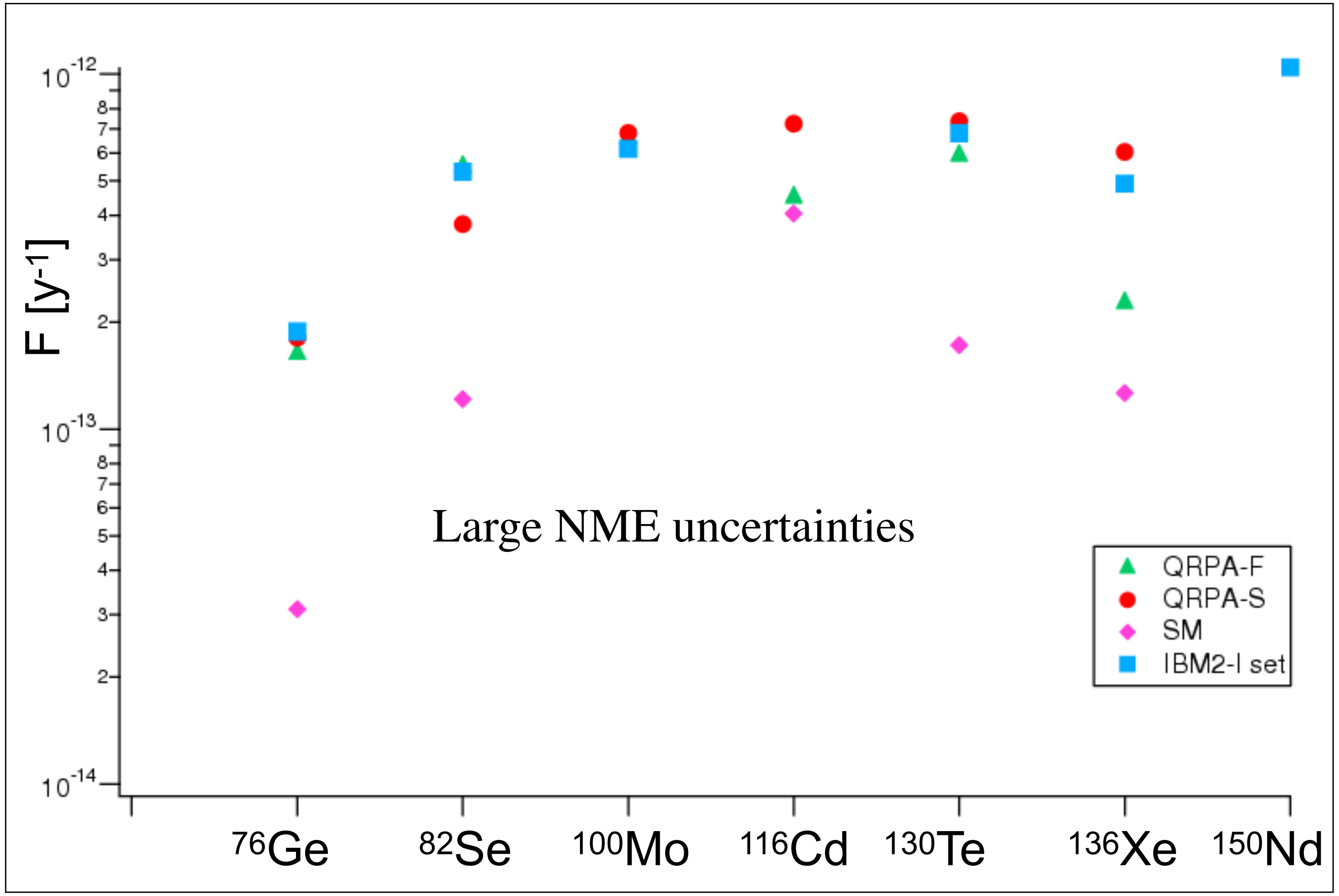
High discovery potential independently of neutrino mass ordering

Connecting Half-life to $m_{\beta\beta}$: Isotope Choice

$$T_{1/2}^{-1} = G_F^2 \Phi(Q,Z) \,|\, M_{0\nu} \,|^2 m_{\beta\beta}^2 \equiv F \frac{m_{\beta\beta}^2}{m_e^2}$$



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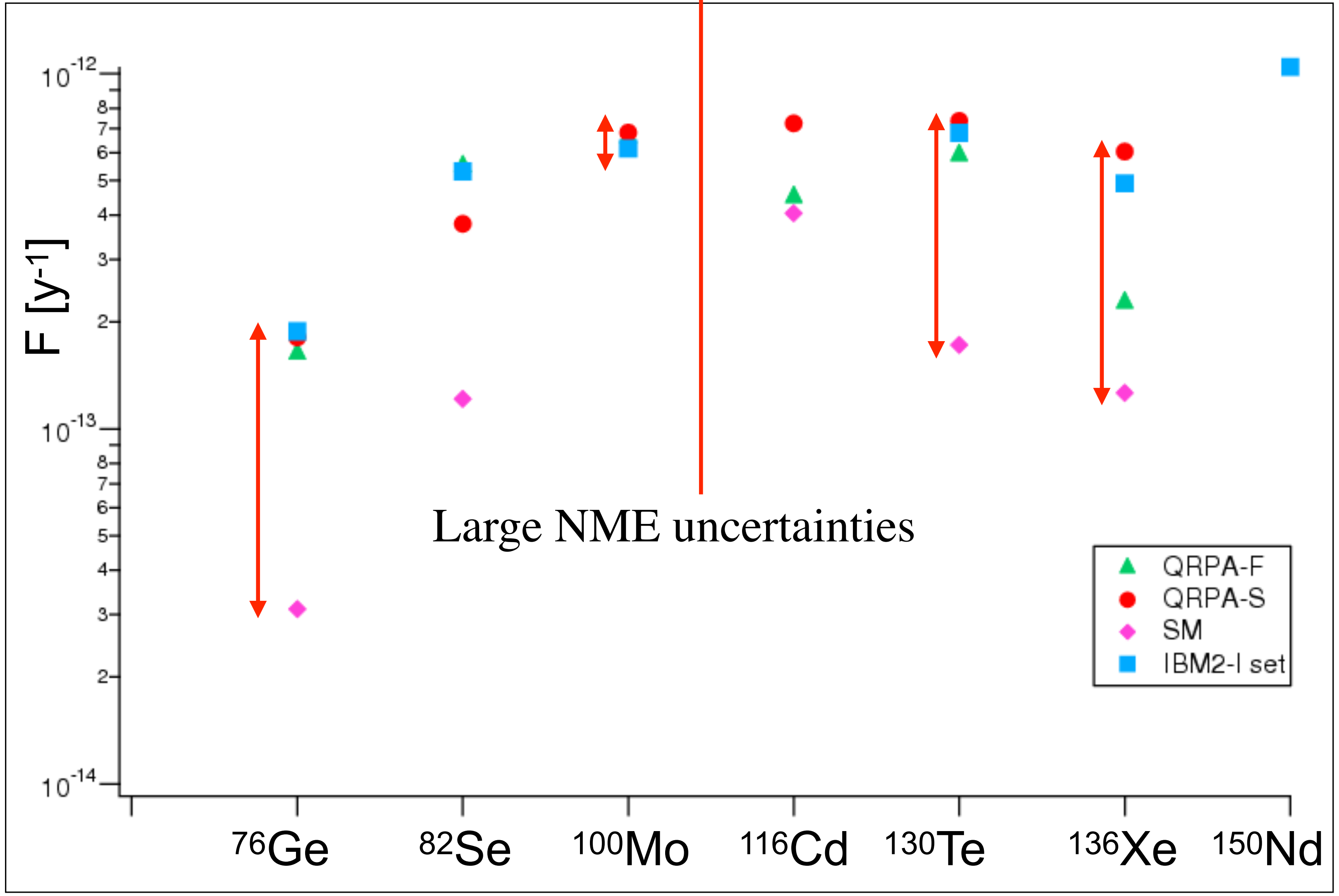

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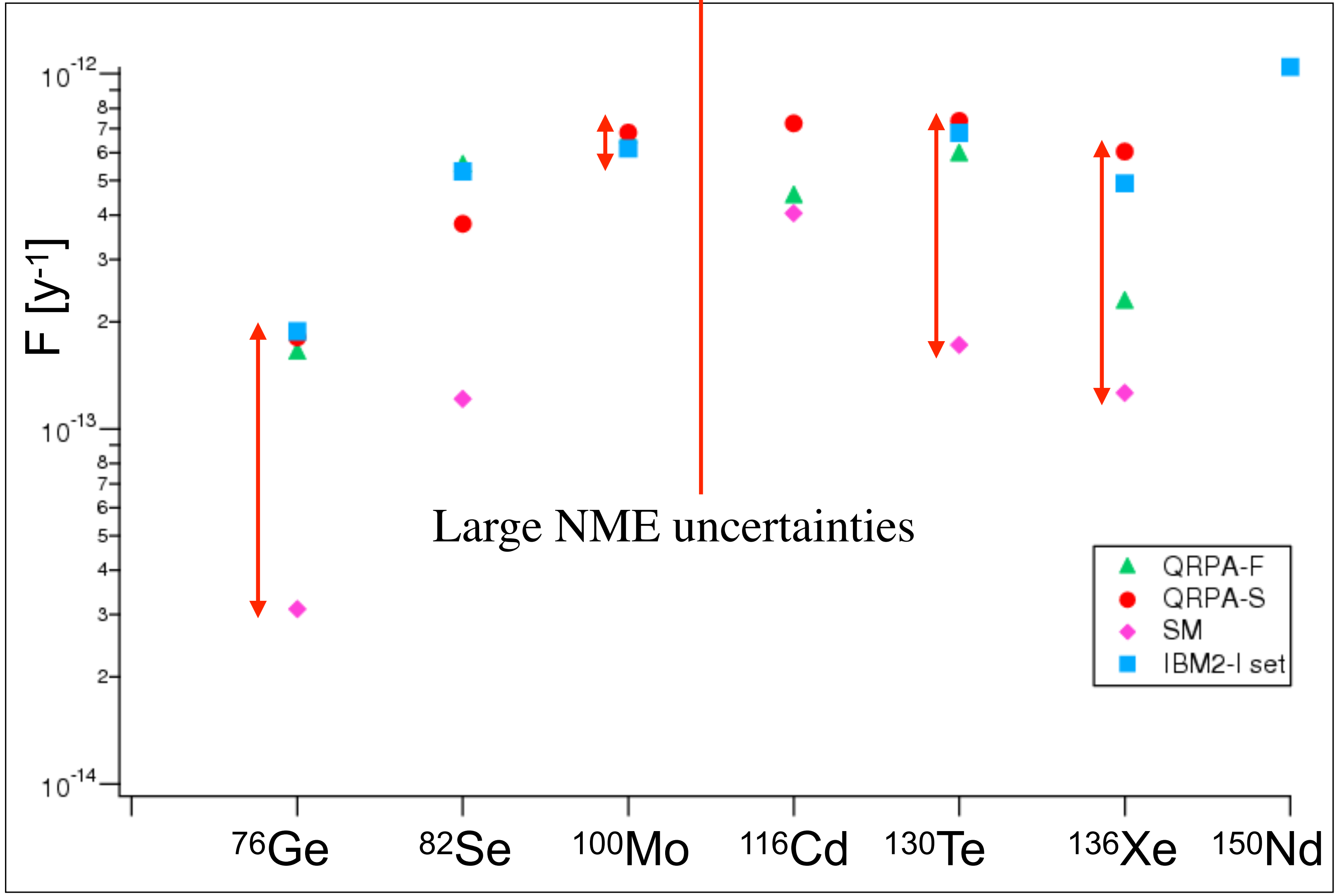

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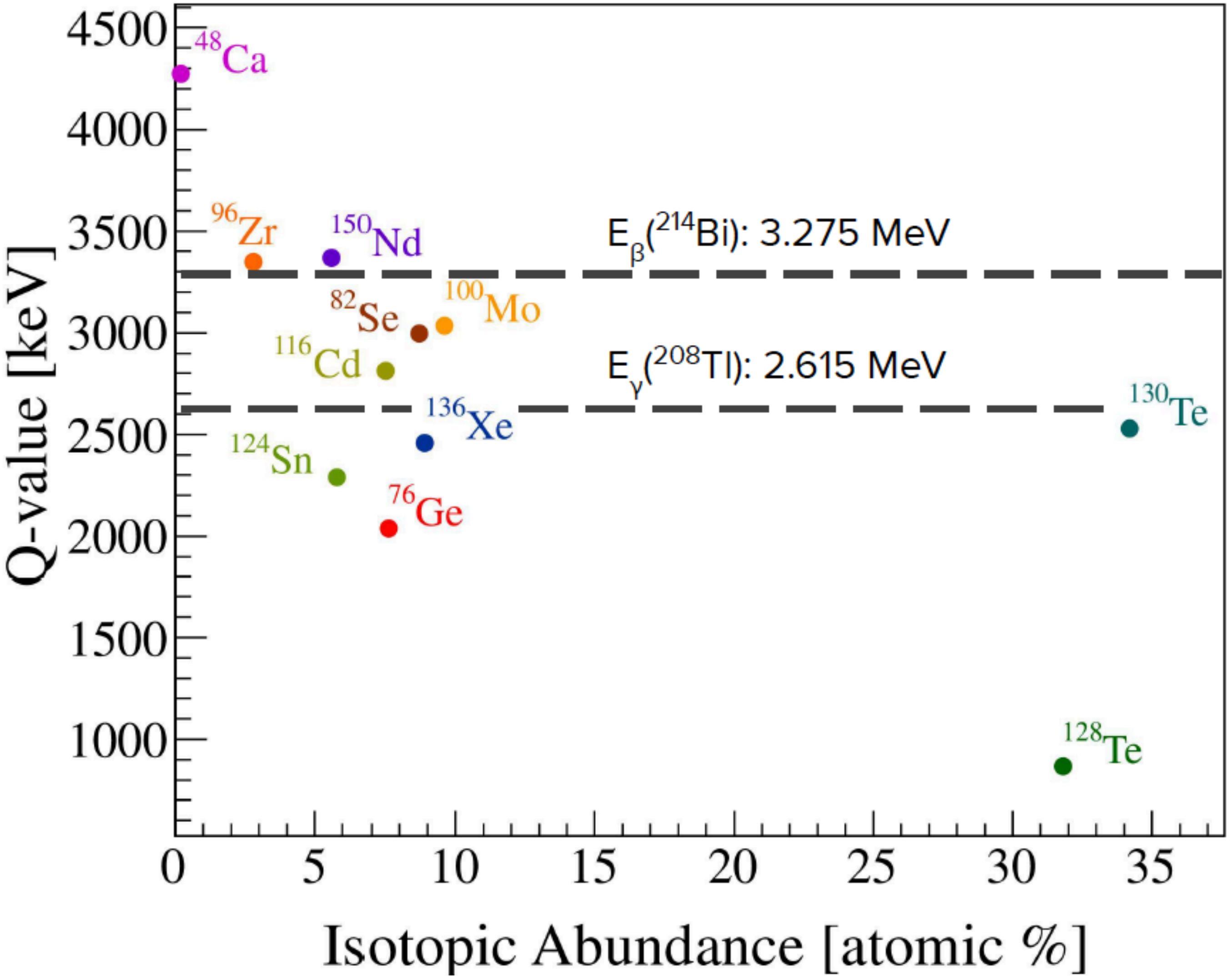
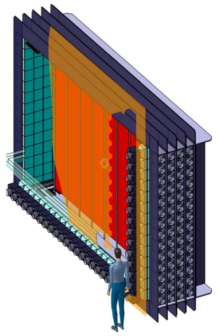
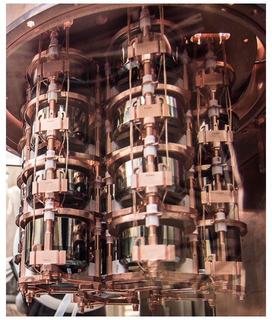
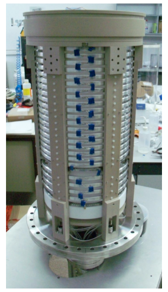
Experimental constraints:
- Detector technology
- Backgrounds
- Isotopic abundance

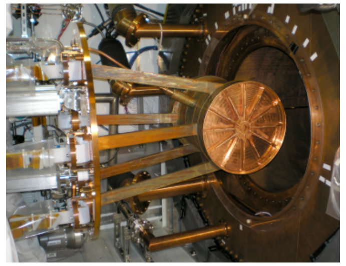


Diverse Worldwide Experimental Program









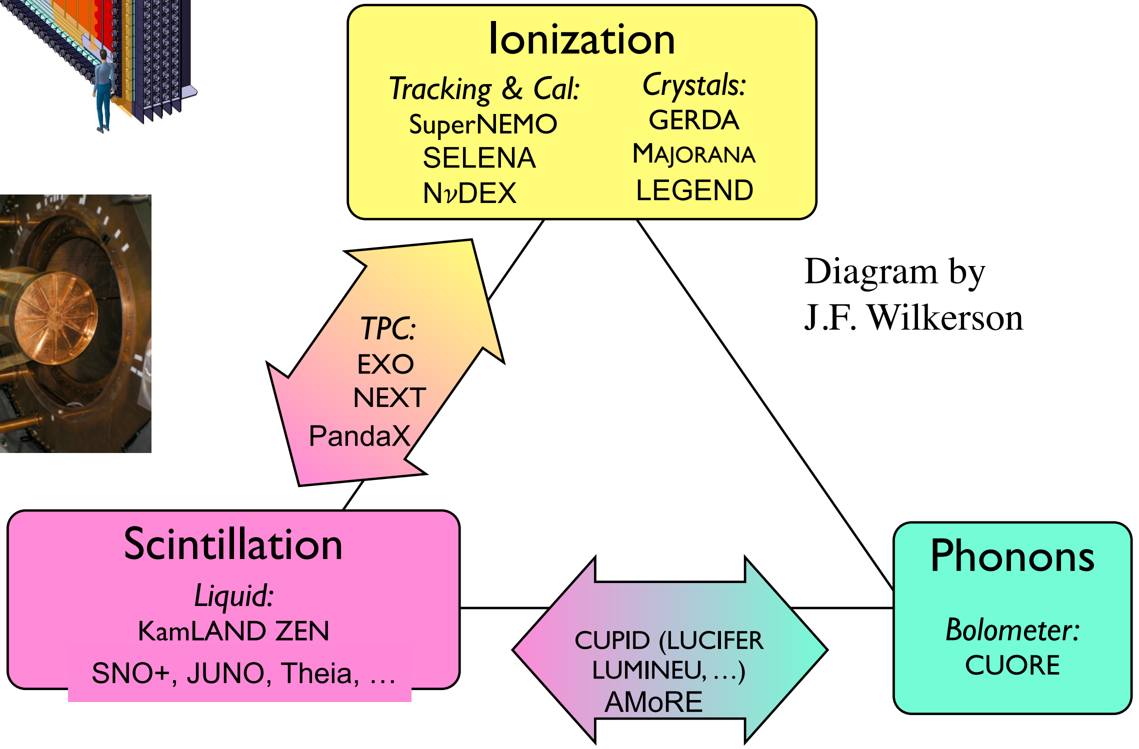
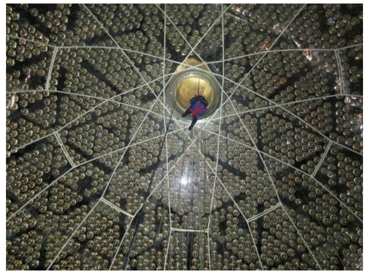
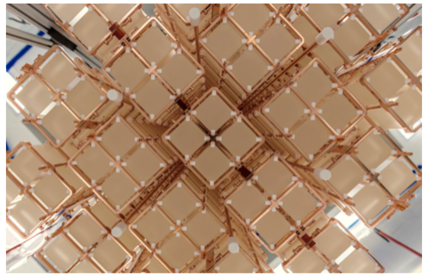


Diagram by
J.F. Wilkerson





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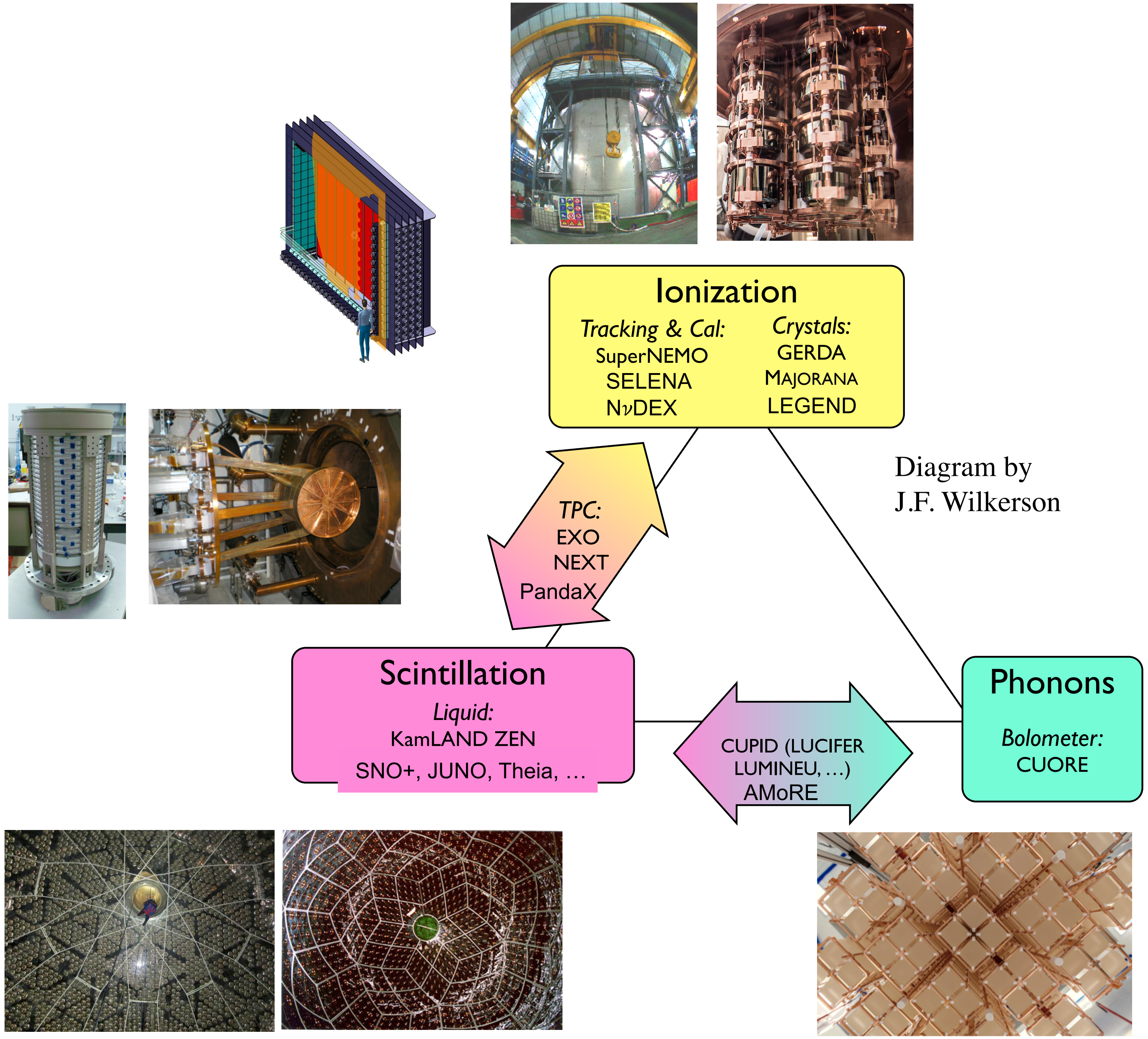

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Convincing discovery requires

Multiple isotopes
Technological tradeoffs
Different systematics

Next generation (ton-scale):
3-4 experiments worldwide

Challenges

Practical challenge: very rare process !

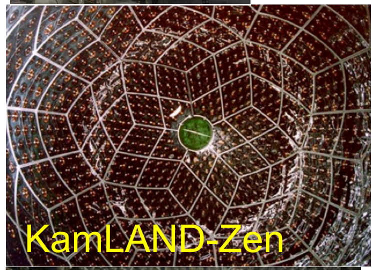
Half-life	Expected Signal (counts/tonne-year)
10^{26} years	~50
10^{27} years	~5
10^{28} years	~0.5

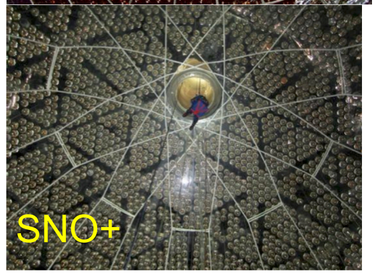
current gen
next gen
next-next gen

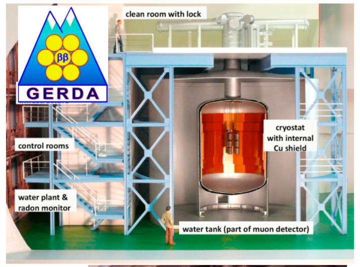
Experimental challenge -- sensitivity scaling:

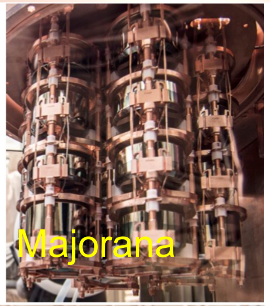
Non-zero backgrounds (most current experiments):

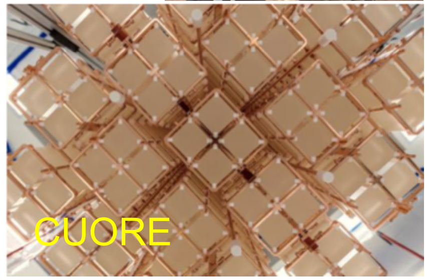
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon \cdot I_{\text{abundance}} \cdot \sqrt{\frac{\text{Mass} \cdot \text{Time}}{\text{Bkg} \cdot \Delta E}}$$











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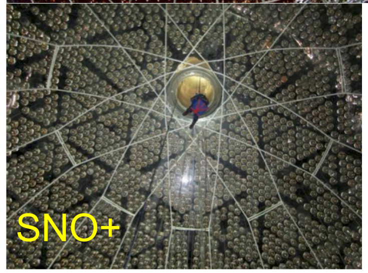

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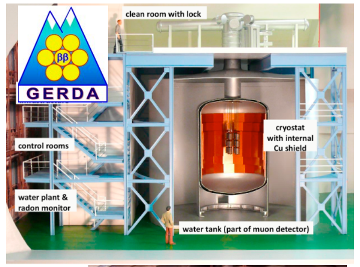

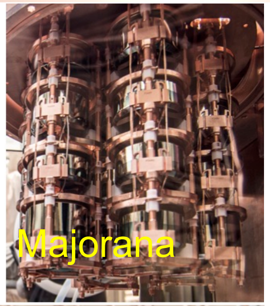

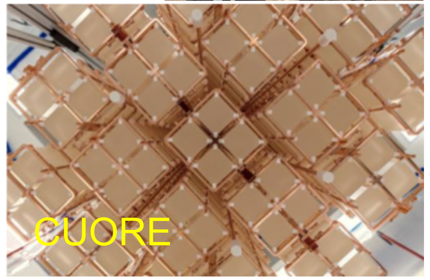

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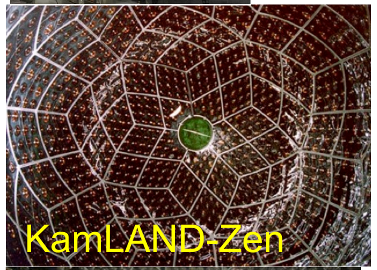

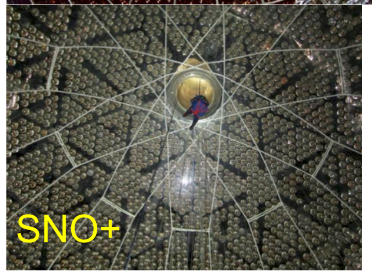

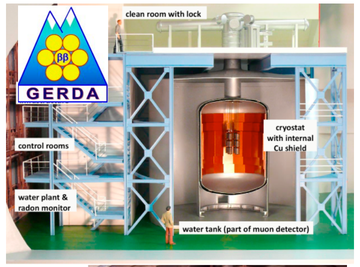

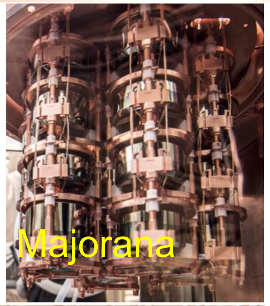

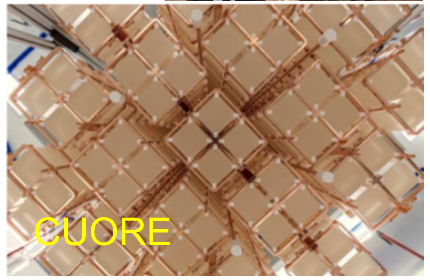

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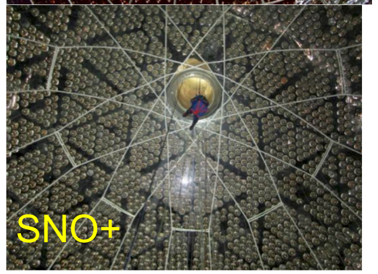

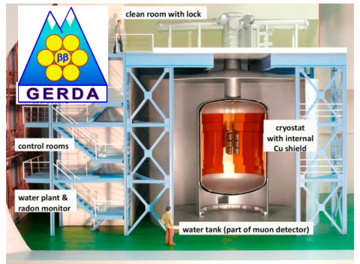

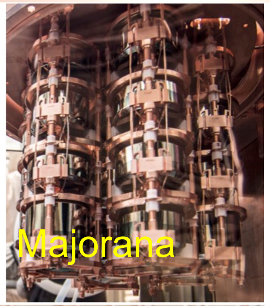

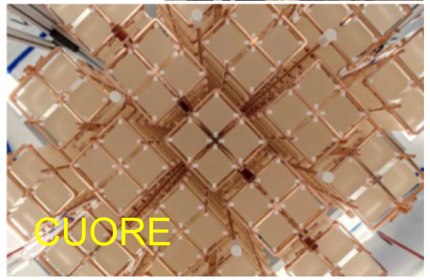

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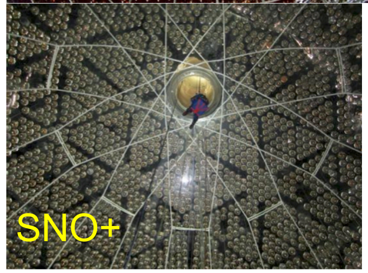
Half-life	Expected Signal (counts/tonne-year)
10^{26} years	~50
10^{27} years	~5
10^{28} years	~0.5

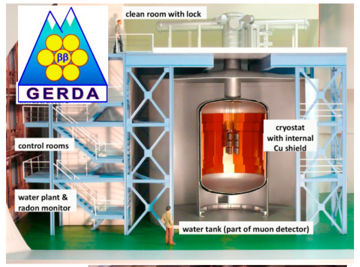
current gen
next gen
next-next gen

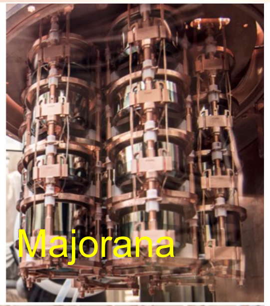
Experimental challenge -- sensitivity scaling:

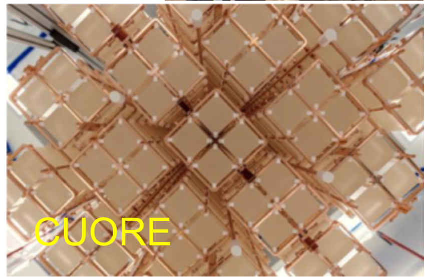
Non-zero backgrounds (most current experiments):

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon \cdot I_{\mathrm{abundance}} \cdot \sqrt{\frac{\mathrm{Mass} \cdot \mathrm{Time}}{\mathrm{Bkg} \cdot \Delta E}}$$









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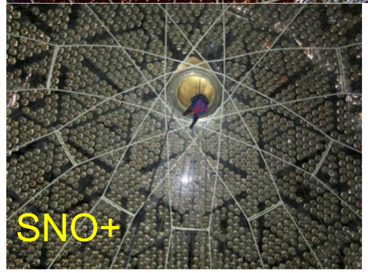

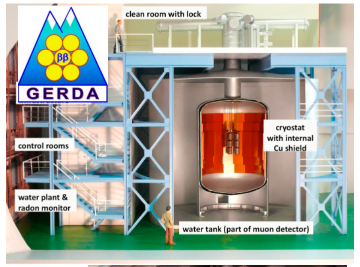

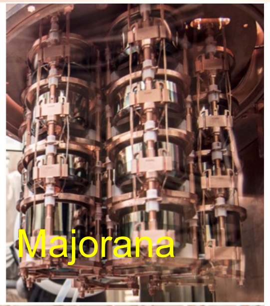

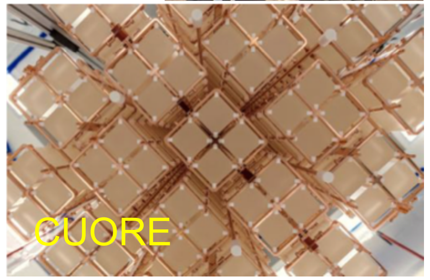

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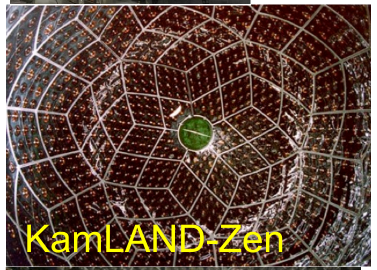

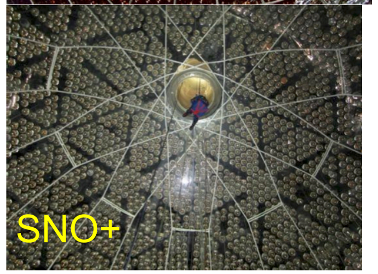

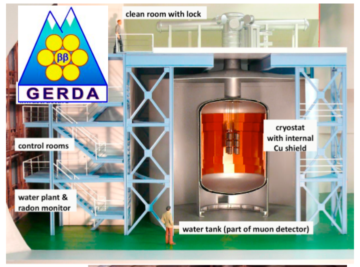

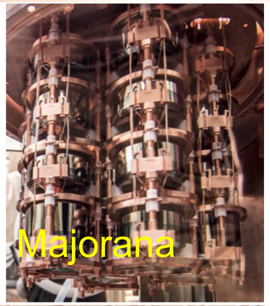

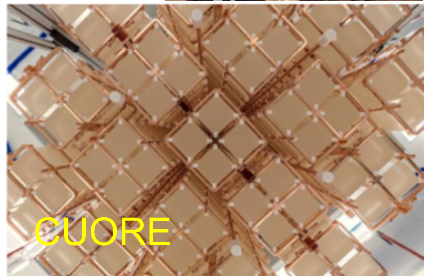

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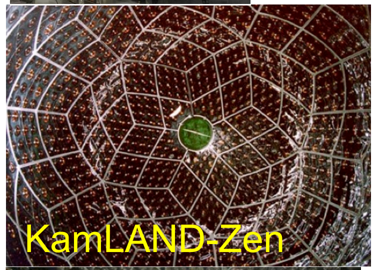

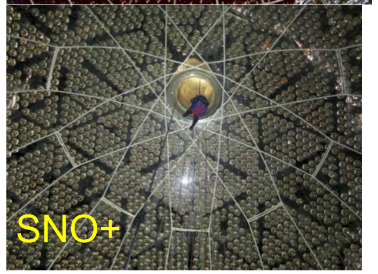

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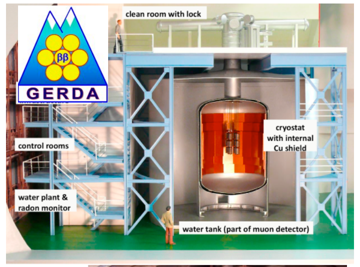
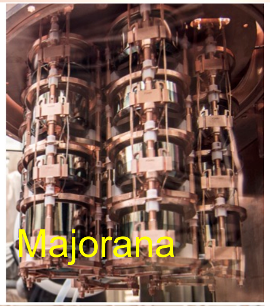
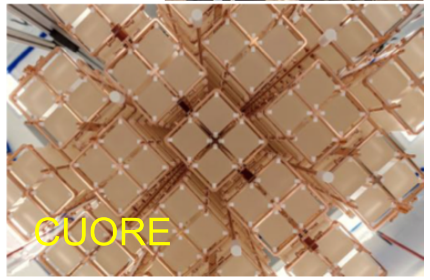
$$\left[T^{0\nu}_{1/2}\right] \propto \varepsilon \cdot I_{\text{abundance}} \cdot \text{Mass} \cdot \text{Time}$$

(background-free, next generation)







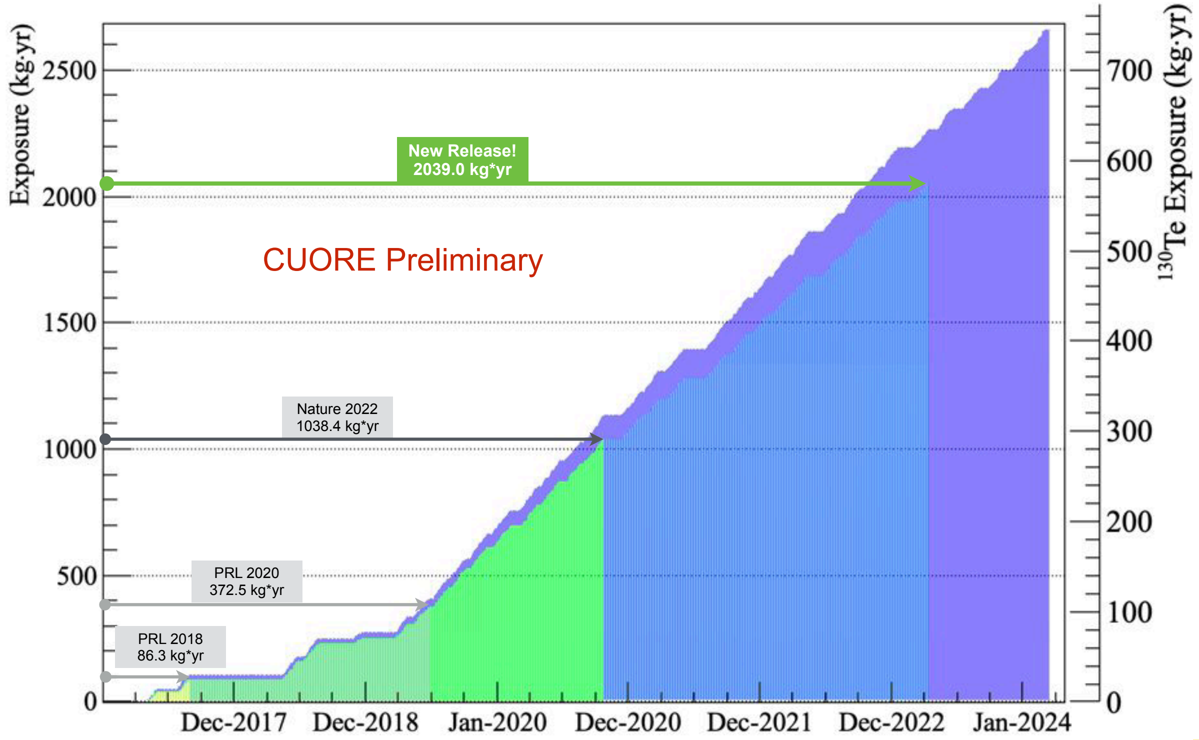
Recent Results: CUORE

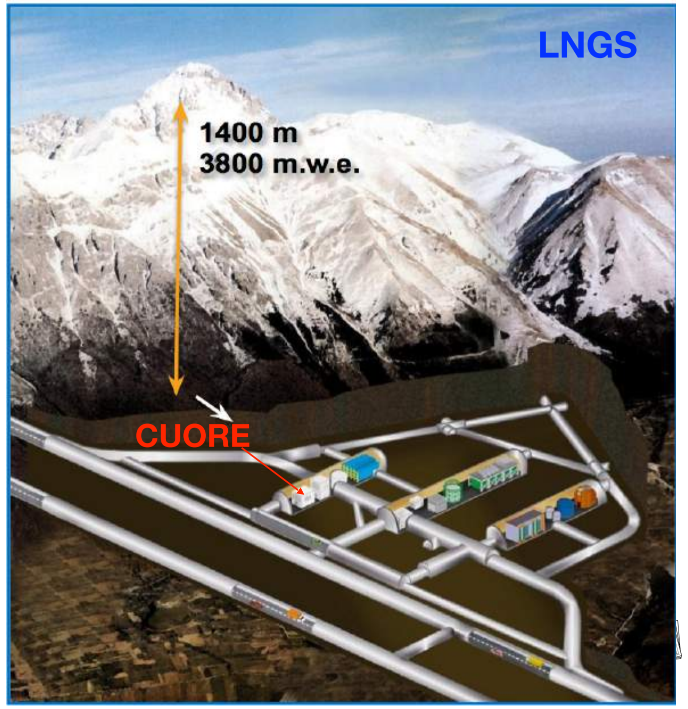
Array of 988 TeO_2 crystals

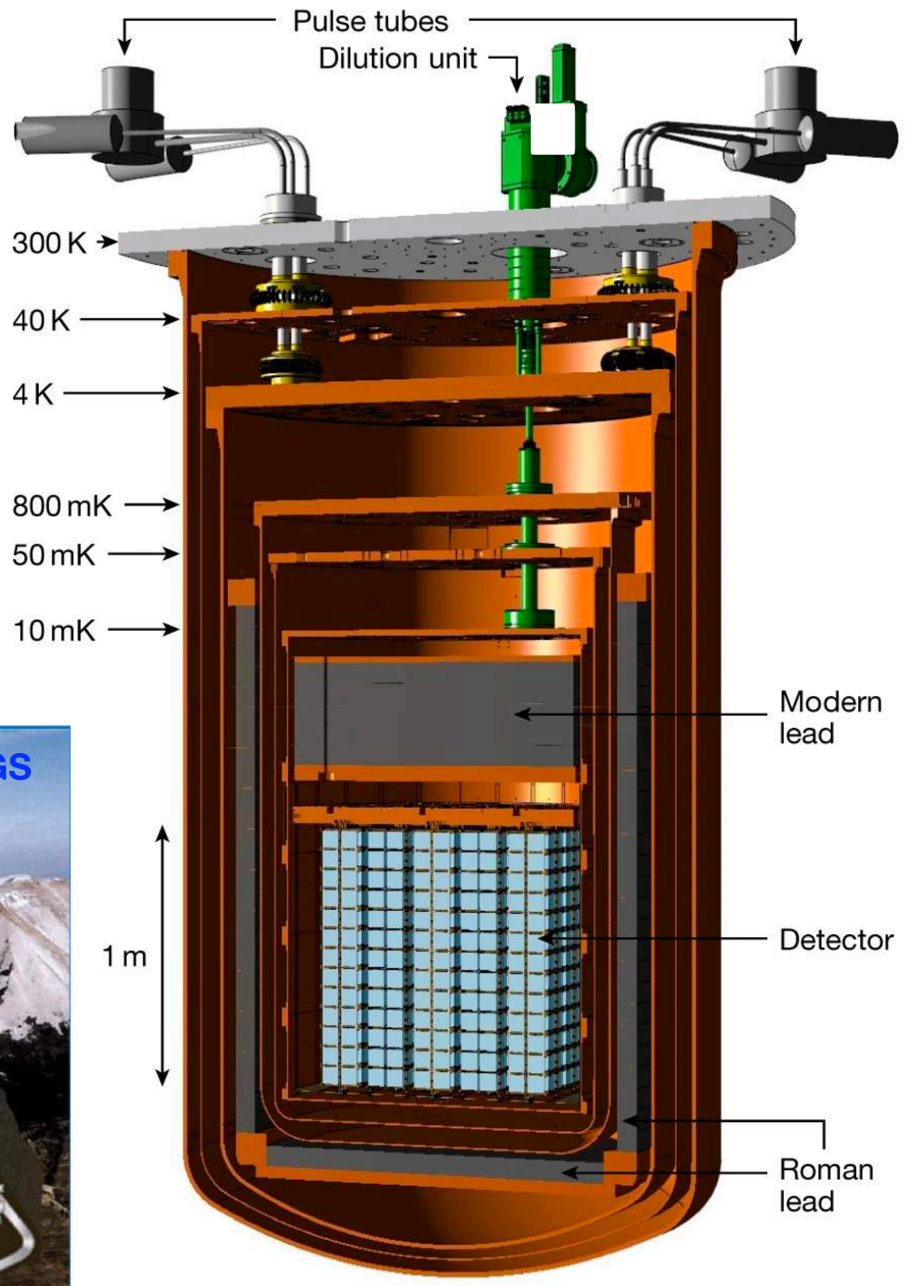
- **19** towers suspended in a cylindrical structure (**13** levels, **4** crystals each)
- 5x5x5 cm^3 (750g each); ^{130}Te: 34.1% natural isotope abundance

750 kg TeO_2 => 206 kg ^{130}Te

- Pulse tube refrigerator and cryostat
- Radio-purity techniques and high resolution: low backgrounds
- Joint venture between Italy (INFN) and US (DOE, NSF) at LNGS in Italy
- Data taking since 2017, now >2.5 ton-years of TeO_2 exposure collected

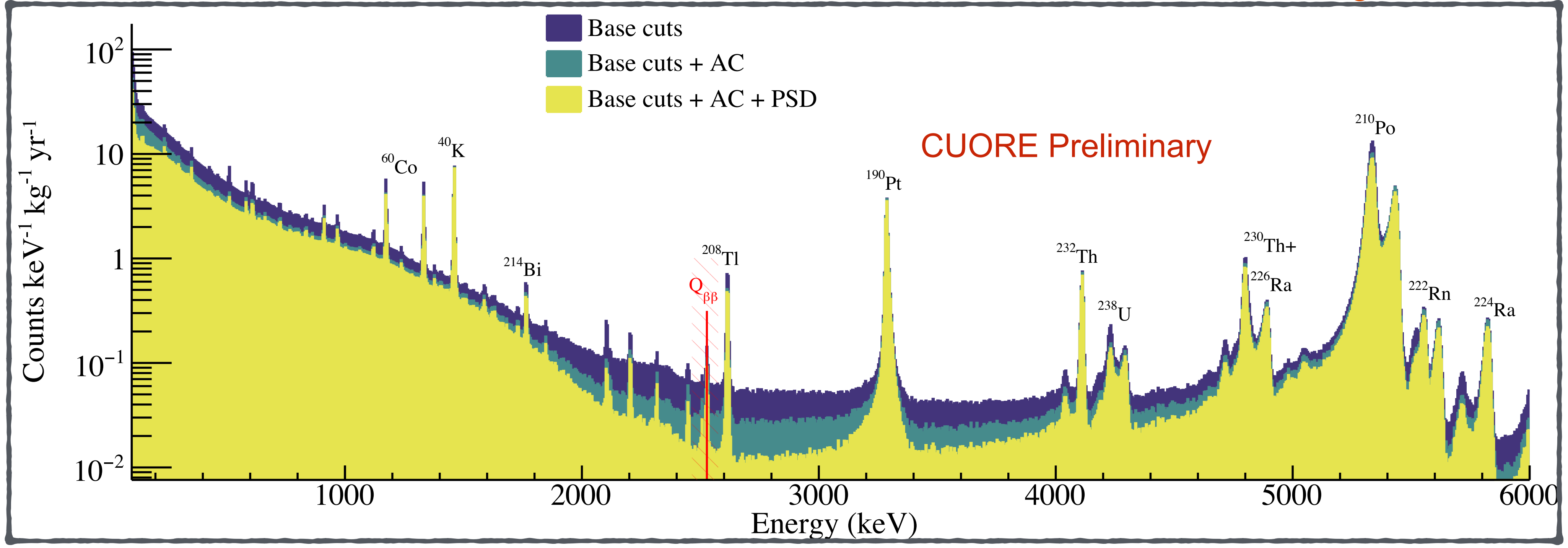






Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011
Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902,
https://doi.org/10.1016/j.ppnp.2021.103902

CUORE results with 2 ton-year of exposure



- No evidence for 0νββ decay

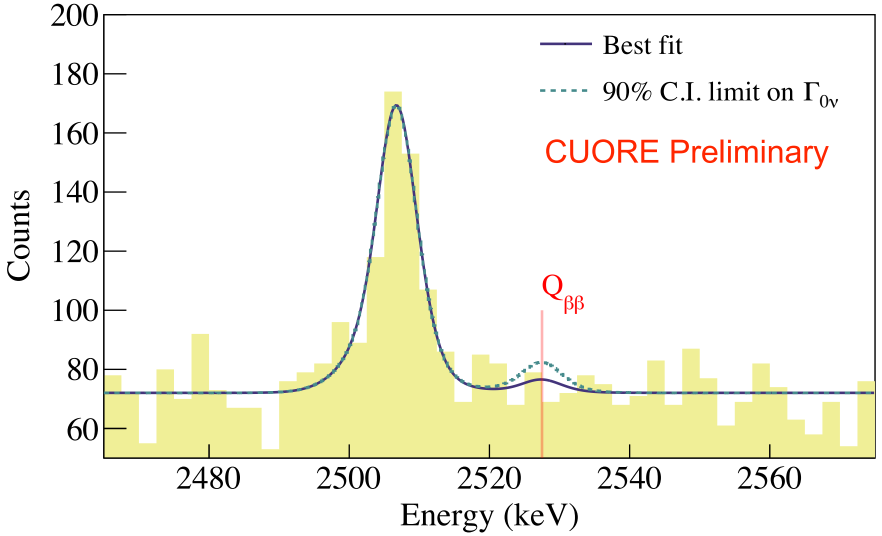
$$T^{0\nu}_{1/2} > 3.8 \times 10^{25} \text{ years (90 \% CI)}$$

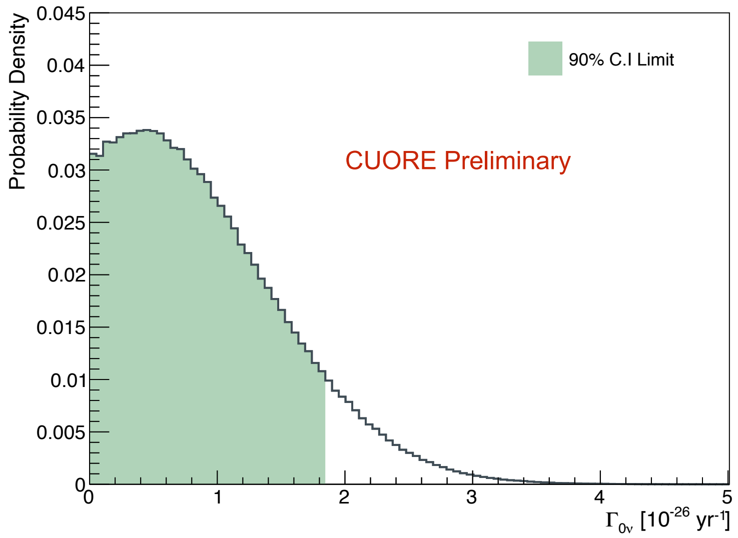
- Interpretation in context of light Majorana neutrino exchange

$$m_{\beta\beta} < 70 - 240 \text{ meV}$$

arXiv:2404.04453

β/γ and $2\nu\beta\beta$ backgrounds ⟵⟶ α backgrounds





Detector Performance Parameters

Background Index

$$[1.42 \pm 0.02] \times 10^{-2} \text{ cts/kg/keV/yr}$$

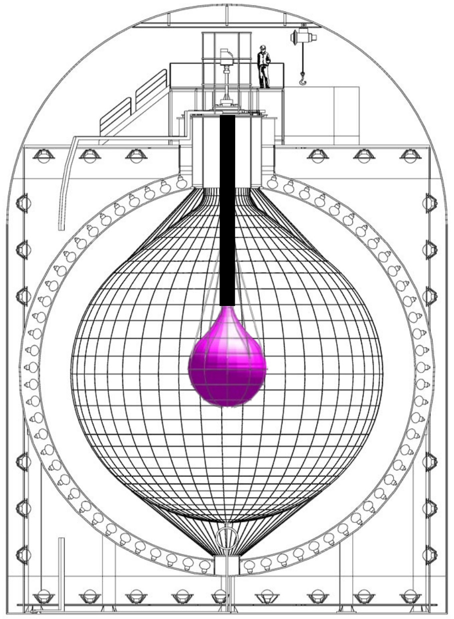
Characteristic FWHM ΔE at $Q_{\beta\beta}$

$$7.53^{+1.45}_{-1.15} \text{ keV}$$

Recent Results: KamLAND-Zen

C. Grant

KamLAND-Zen 400

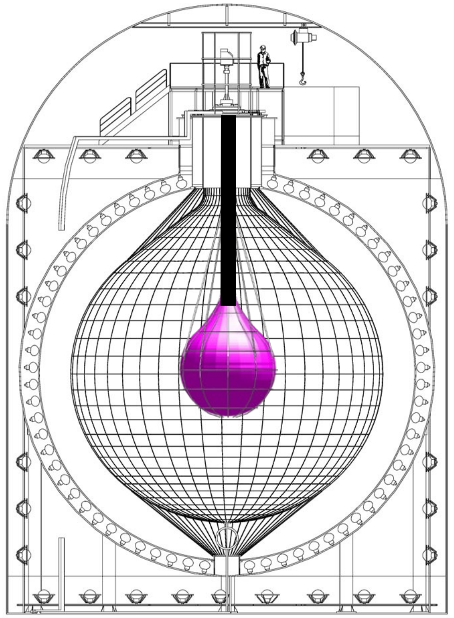


380kg deployed

$$T_{1/2}^{0\nu} > 1.07 \times 10^{26}\ \mathrm{yr}$$

PRL117, 082503 (2016)

KamLAND-Zen 800



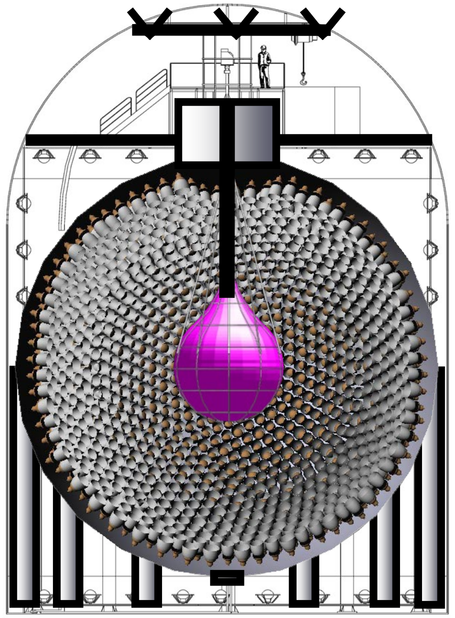
Now, 745kg deployed

$$> 2.3 \times 10^{26}\ \mathrm{yr}$$

PRL130, 051801 (2023)

Further improvements going on;
better neutron tagging
machine learning (ML) for long-lived tagging
ML for beta/gamma discrimination
muon-bundle tracking, and so on

KamLAND2-Zen



Mirror
HQE-PMT
new LS
} x5 p.e.
full volume effective
w/ scintillation film

1 ton planned (scalable)

$> 2 \times 10^{27}\ \mathrm{yr}$ (target sensitivity)

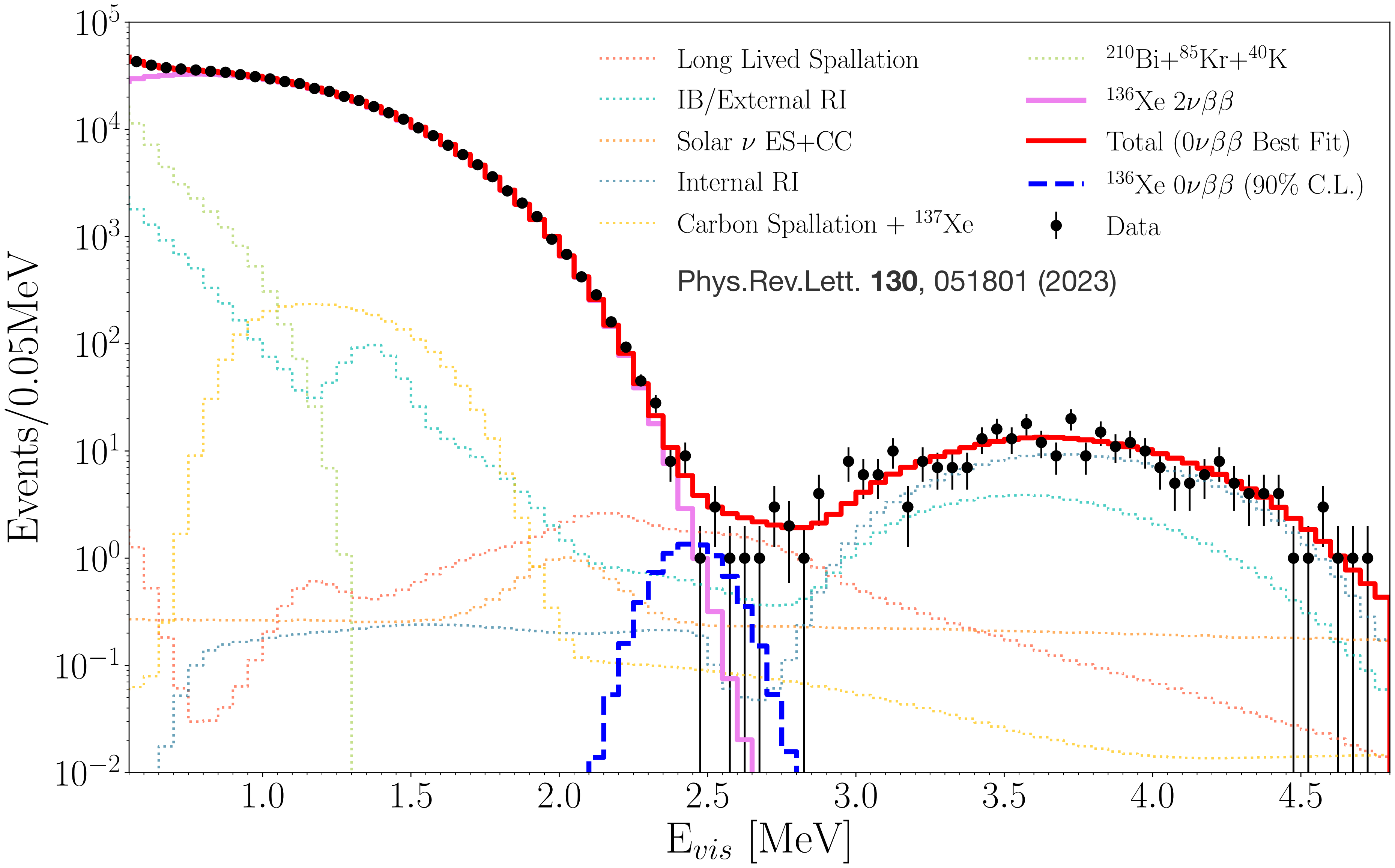
$< 12 \sim 53\,\mathrm{meV}$ (corresponding mass limit)

Further technologies being developed
imaging sensor (1/10 reduction of long-lived BG)
high-p xenon deployment (2 times more xenon)

N. Kawada: Neutrino 2022

KamLAND-Zen Results with ~1 ton-year of ^{136}Xe exposure

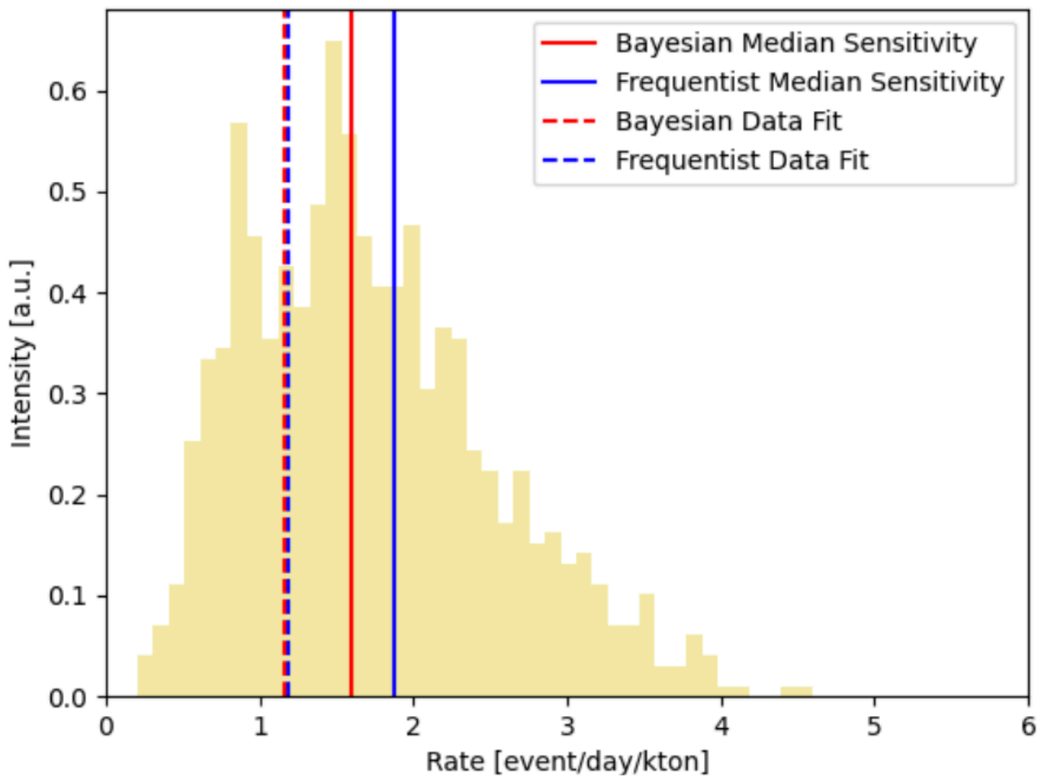
Total Livetime = 523 days   Exposure = 970 kg·yr



$$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{26} \text{yr } 90\,\%\,\text{C.L.}$$

N. Kawada: Neutrino 2022

C. Grant



Median Sensitivity:

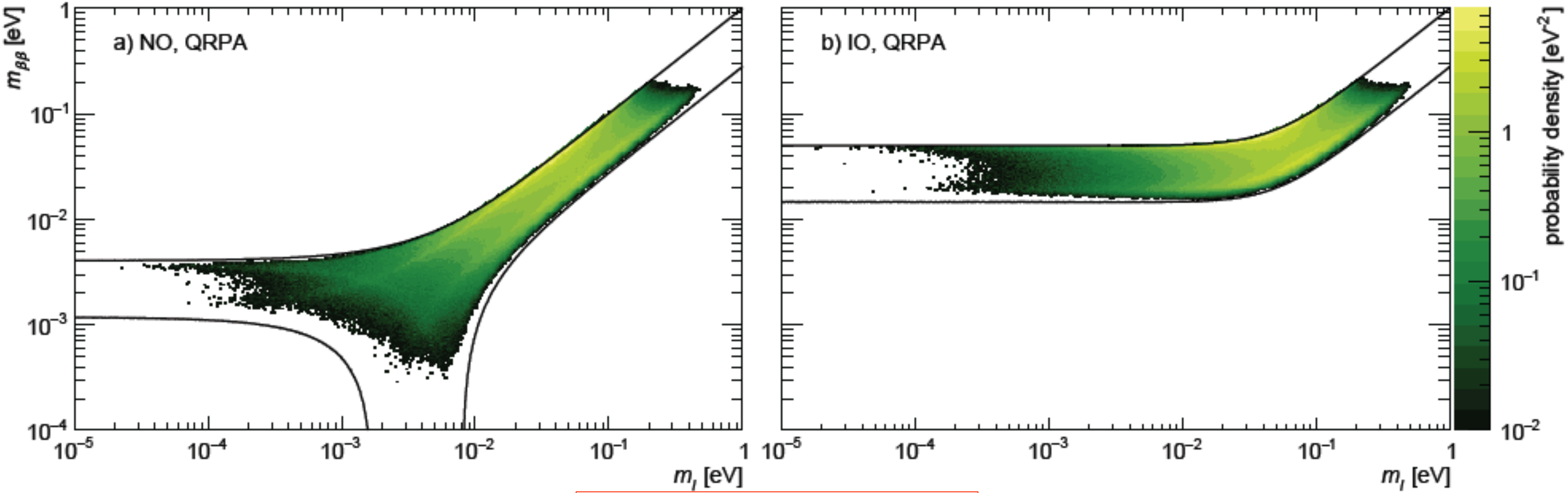
$$T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{26} \text{yr } (90\,\%\,\text{C.I.})$$

Combination of KLZ-400 and KLZ-800

$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26} \text{yr}$$

$$\langle m_{\beta\beta} \rangle < 36 - 156\,\text{meV}$$

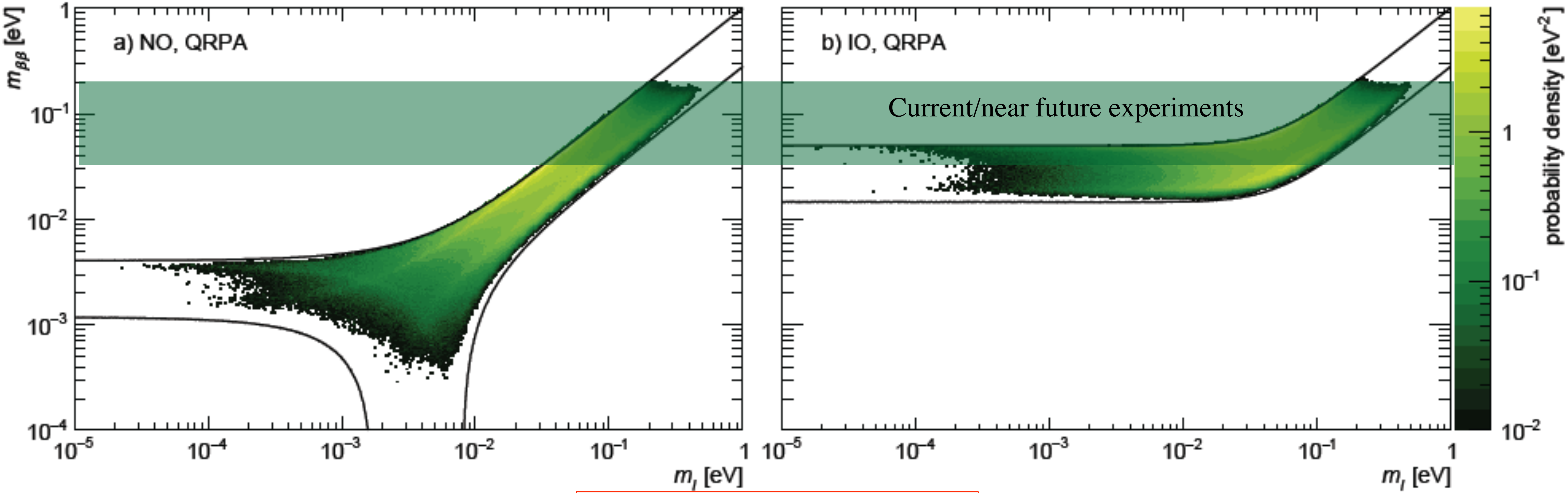
Constraints on $m_{\beta\beta}$



$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

M. Agostini, G. Benato, J. Detwiler, Phys. Rev. **D96**, 053001 (2017)

Constraints on $m_{\beta\beta}$



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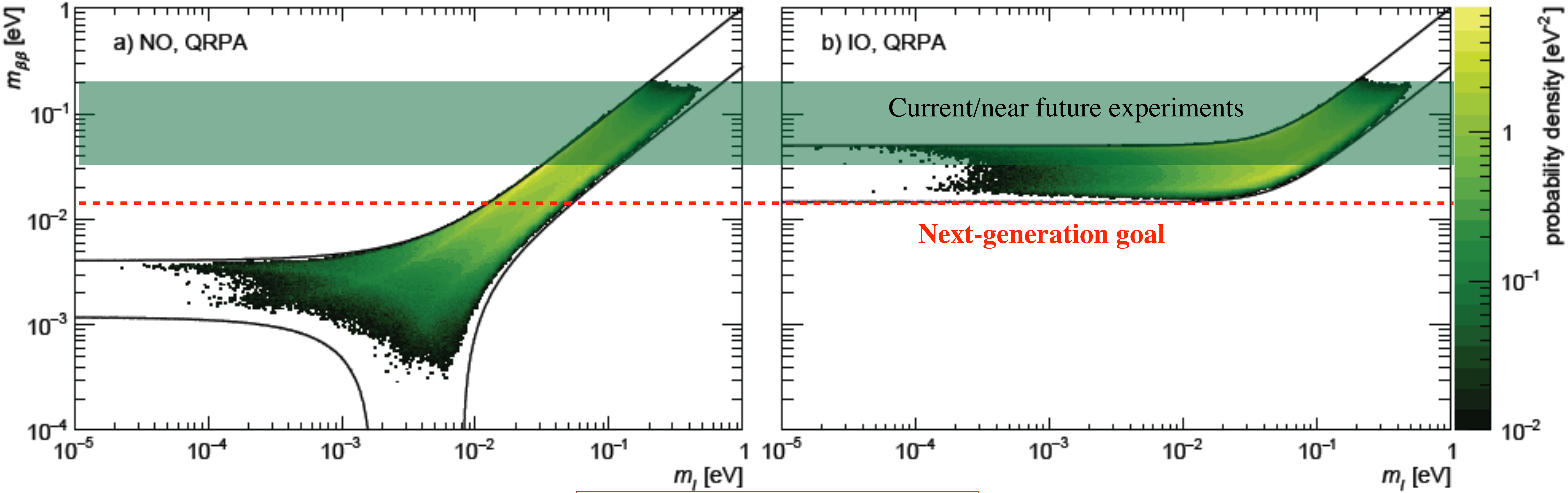

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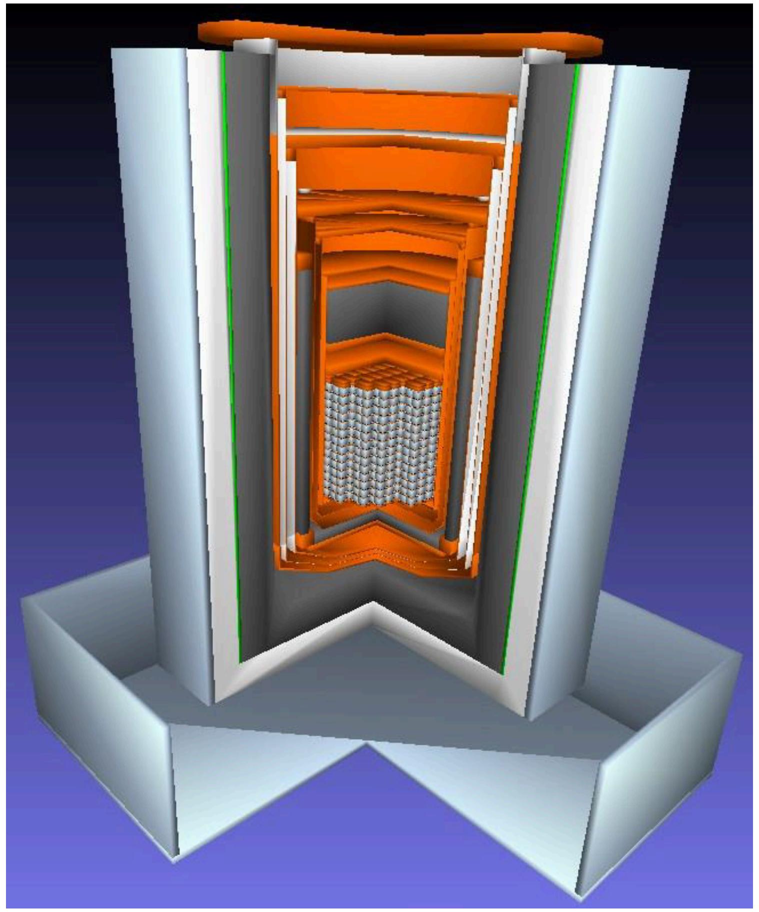
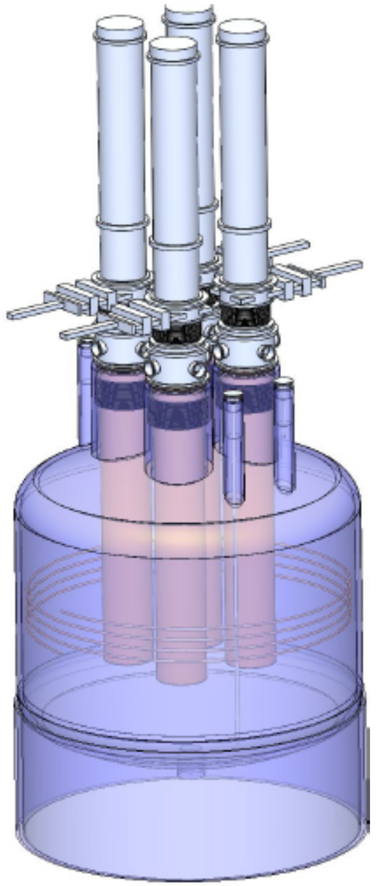
M. Agostini, G. Benato, J. Detwiler, Phys. Rev. **D96**, 053001 (2017)

Next-Generation Program, AKA ton-scale (US view)

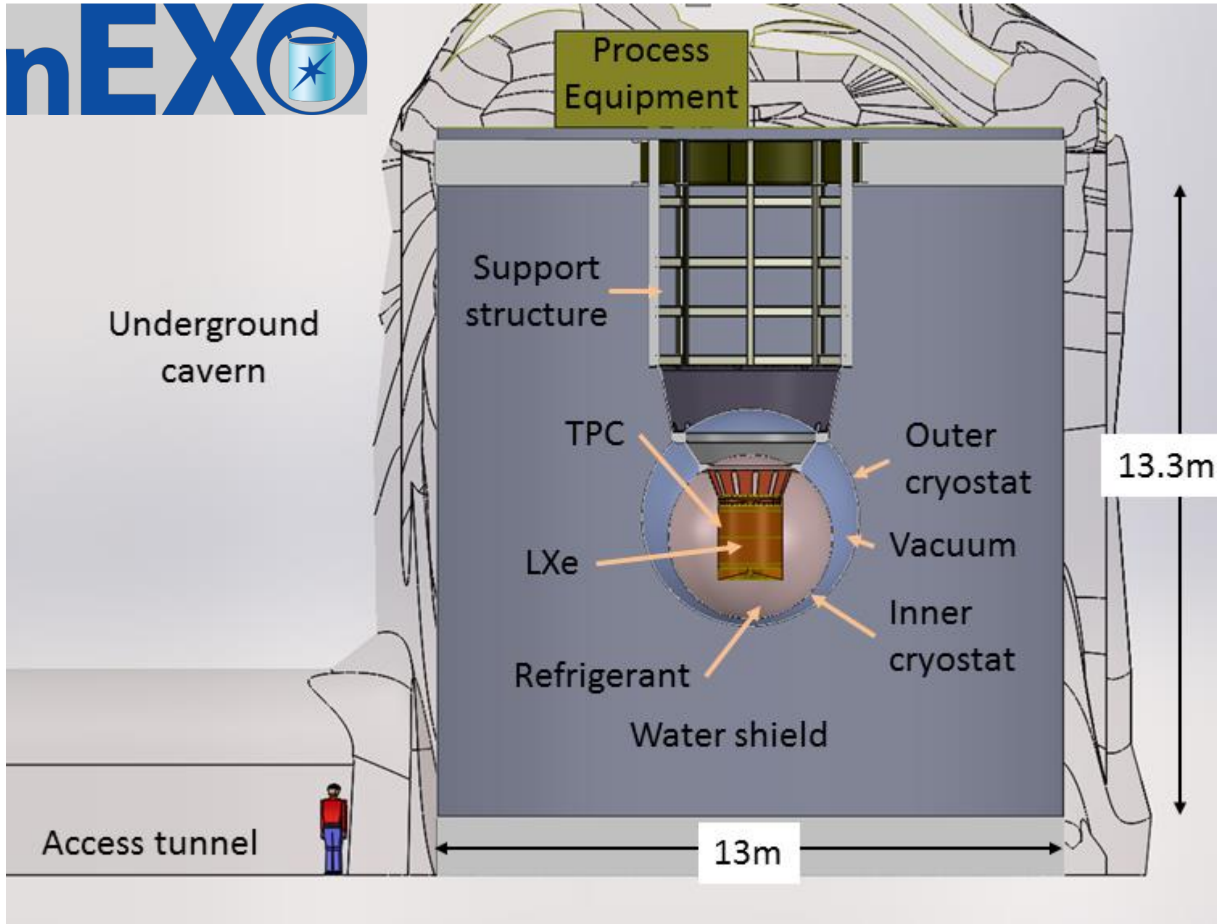
Goal: $0\nu\beta\beta$ discovery if $m_{\beta\beta}$ is above ~10-20 meV in the next decade



CUPID



LEGEND-1000



Complemented by a world-wide suite of efforts developing technologies for ton-scale and beyond, with comparable scientific sensitivities

Next Generation: LEGEND (LNGS)

*L*arge *E*nriched *G*ermanium *E*xperiment for *N*eutrinoless ββ *D*ecay

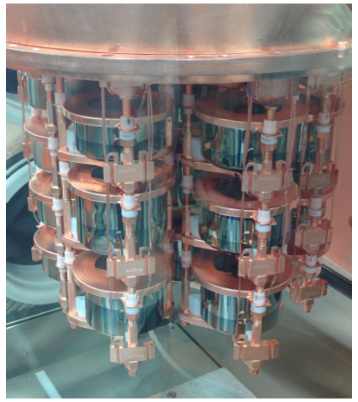
Phased ^{76}Ge-based 0νββ program with discovery potential at a half-life beyond 10^{28} years

Enriched ^{76}Ge diodes (HPGe detectors): best energy resolution

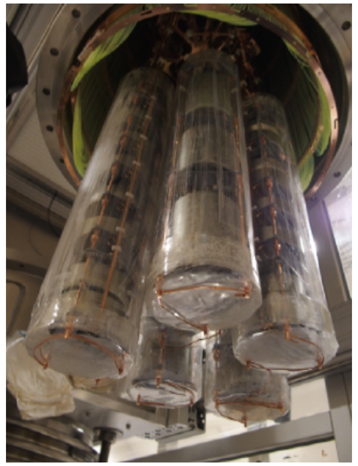
LEGEND combines the best aspects of GERDA and MJD:

- Ultra-low background materials, FEE (MJ)
- Low-Z active veto (GERDA)

Majorana Demonstrator

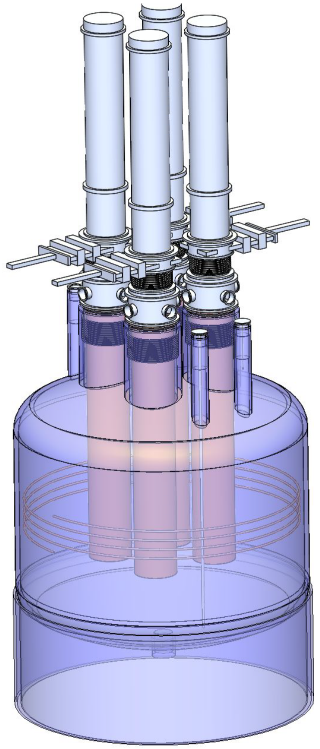


GERDA



LEGEND-200

- Use existing GERDA infrastructure at LNGS
- Up to 200 kg
- BG goal: 1/5 of GERDA
- Started in 2021



LEGEND-1000

- LNGS or SNOLab
- UG LAr
- Phased implementation
- BG goal: 1/100 of GERDA (0.025 c/FWHM t y)

LEGEND-200 (LNGS)

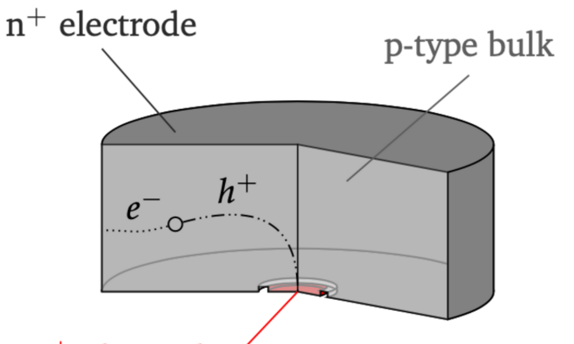


Image: C. Wiesinger

142 kg of enriched HPGe detectors submerged in LAr

Mesh shroud around detector towers to protect from ^{42}K

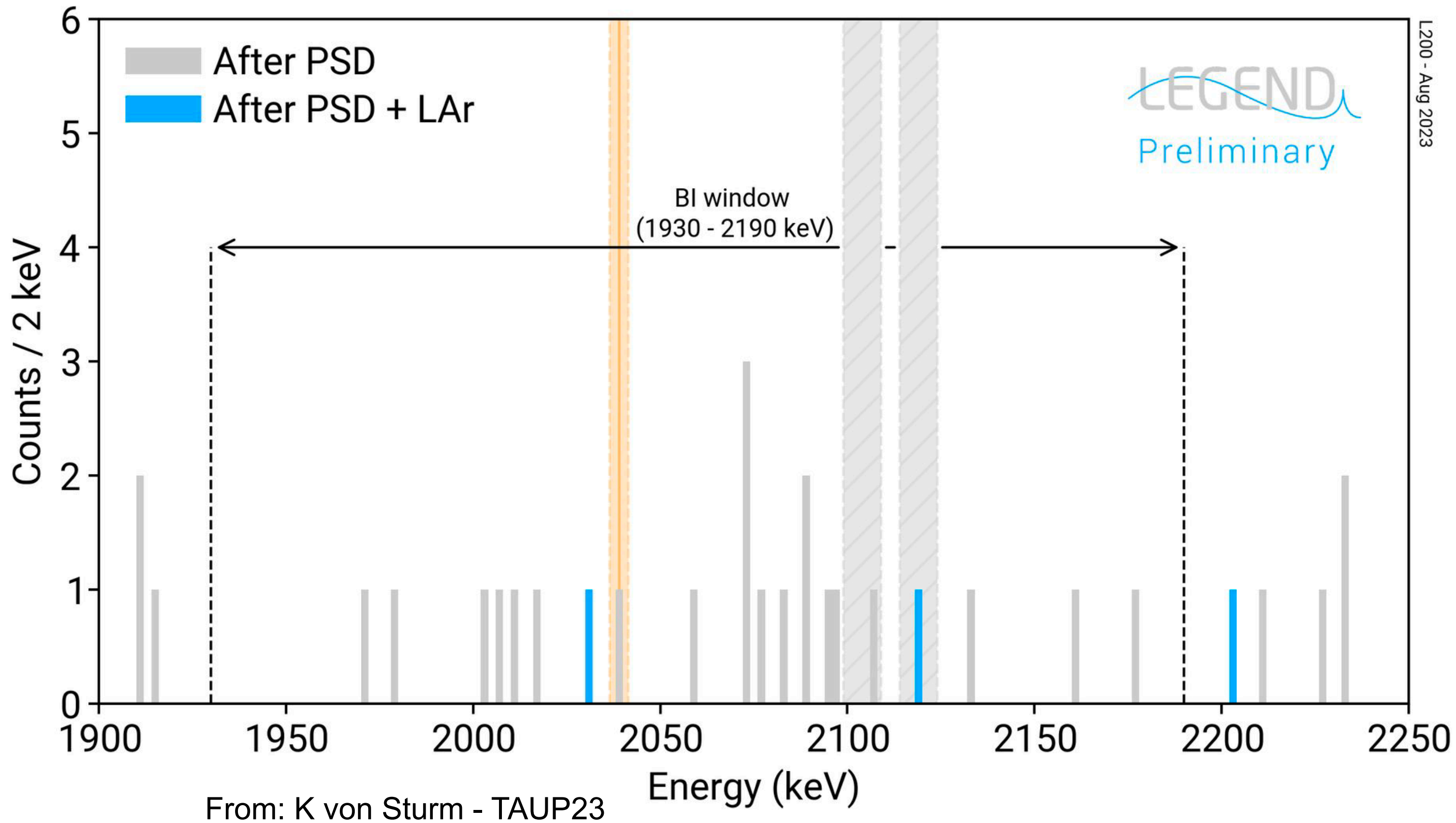
Science data taking since 2023; expect new results at Neutrino 2024

Low background index $4.1^{+11.4}_{-1.5} \times 10^{-4}$ counts/kg/keV/year

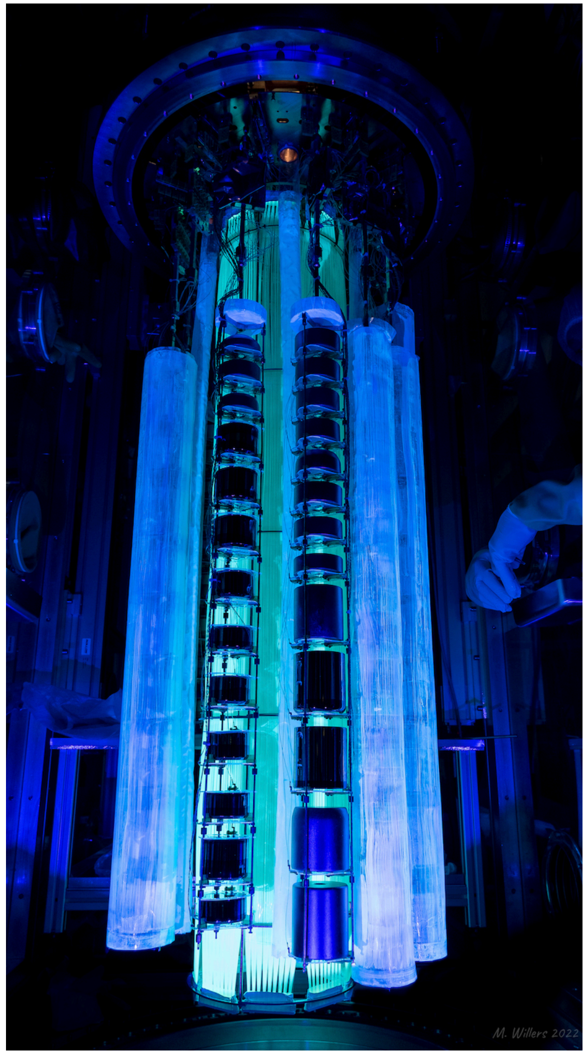
Projected limits (5 years):

$T^{0\nu}_{1/2} > 1.5 \times 10^{27}$ years

$m_{\beta\beta} < 34 - 78$ meV



From: K von Sturm - TAUP23



M. Willers TAUP2023

CUORE Upgrade with Particle ID (CUPID): LNGS

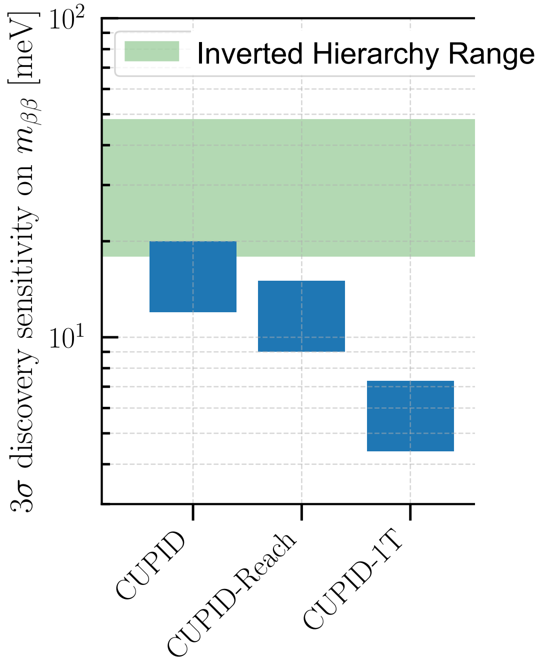
^{100}Mo

R. Artusa et al., Eur.Phys.J. **C74**, 3096 (2014)
pre-CDR: arXiv:1907.09376

Next-generation bolometric ton-scale experiment at LNGS

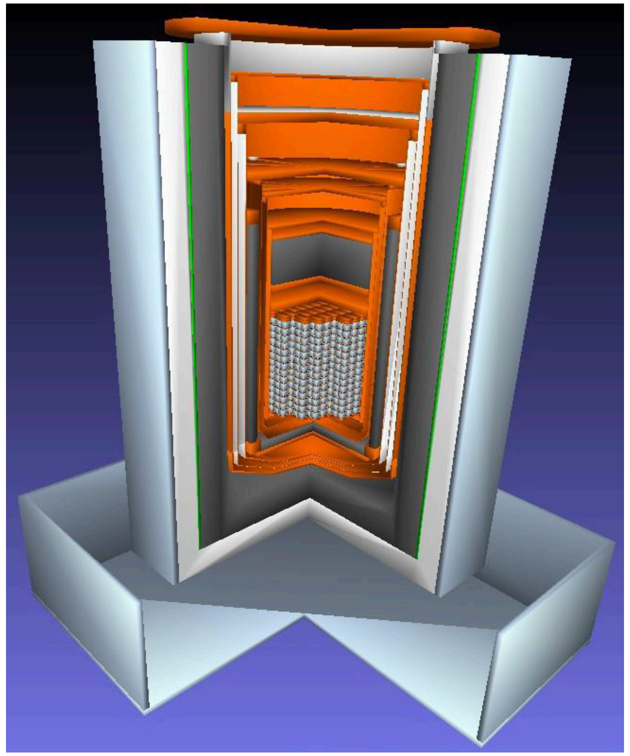
Mission: Discover $0\nu\beta\beta$ if $m_{\beta\beta}$ > 10 meV (half-life in ^{100}Mo>10^{27} years)

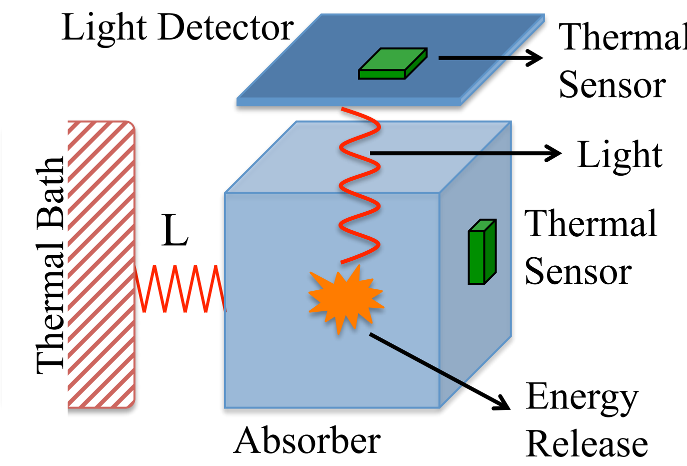
- 1500 enriched Li_2MoO_4 crystals (~240 kg of ^{100}Mo)
- Demonstrated radio-purity, active background rejection
- Energy resolution ~5 keV
- Total background of <0.1 counts/(ton*kev*year)
- Phased deployment options up to 1 ton of ^{100}Mo (CUPID-1T)



Inverted Hierarchy Probes

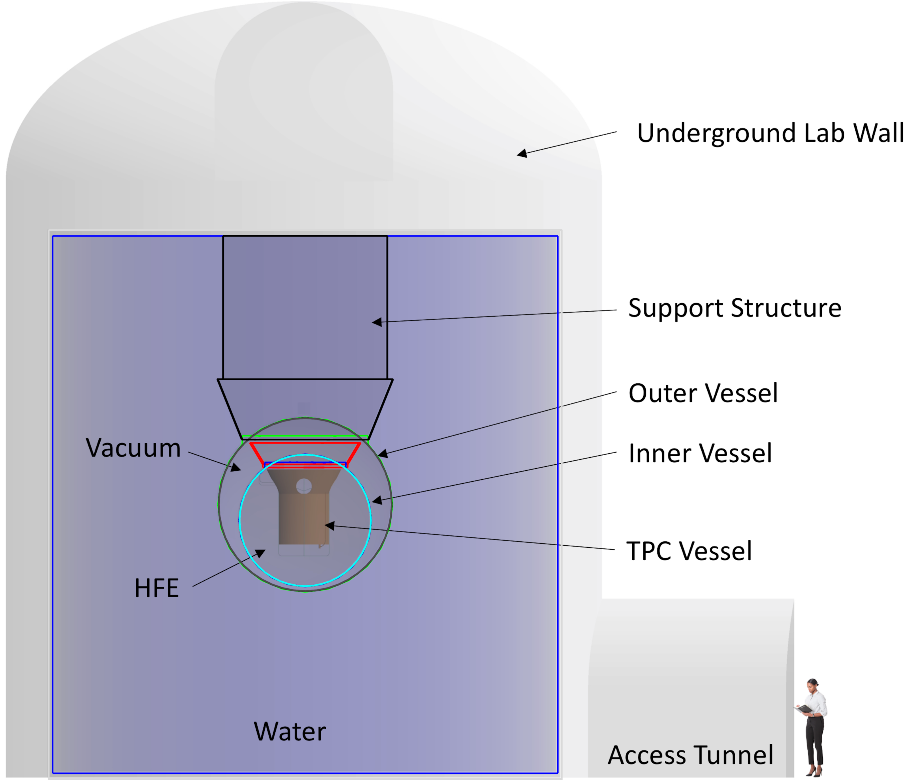
- **CUPID:** Baseline, Technically ready
- **CUPID-reach:** Same Cryostat really mitigate background to $1x10^{-5}$
- **CUPID-1T:** 1000 kg of ^{100}Mo, new cryostat, BI of $5x10^{-6}$ ckky

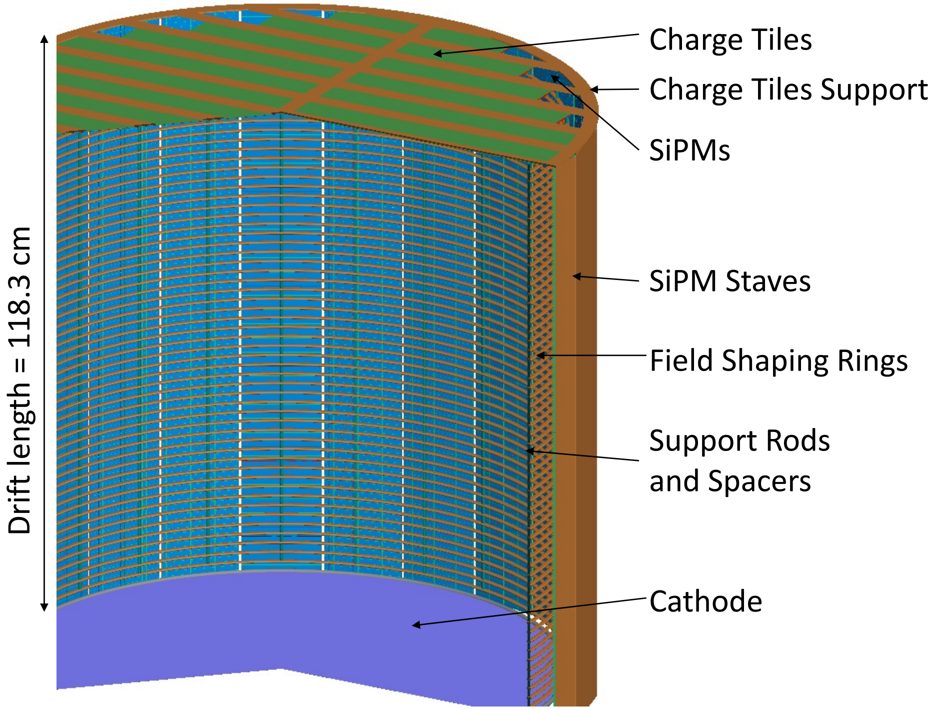




nEXO (SNOLab)

^{136}Xe





Large monolithic LXe TPC

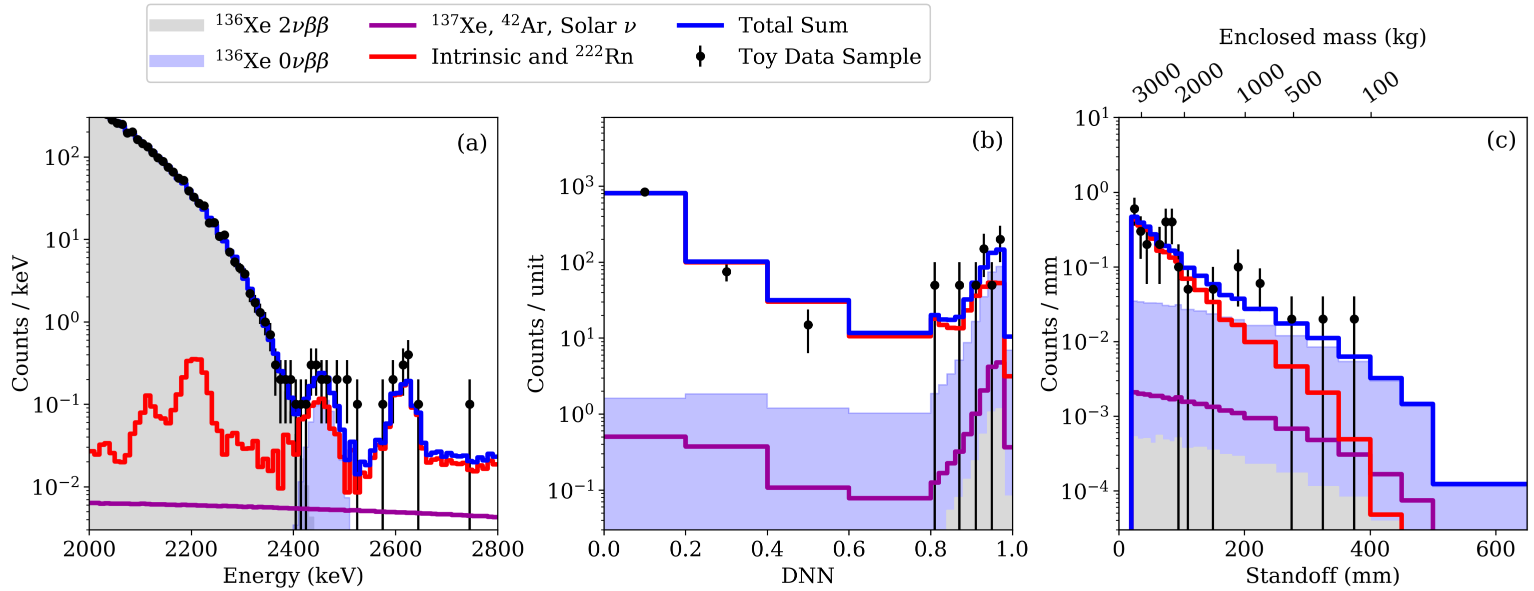
5000 kg of liquid ^{136}Xe

(90% enrichment)

Resolution $\sigma_E/E \sim 0.8\%$

Self-shielding, active background discrimination (topology, vertex reconstruction)

Multi-dimensional fit to constrain backgrounds



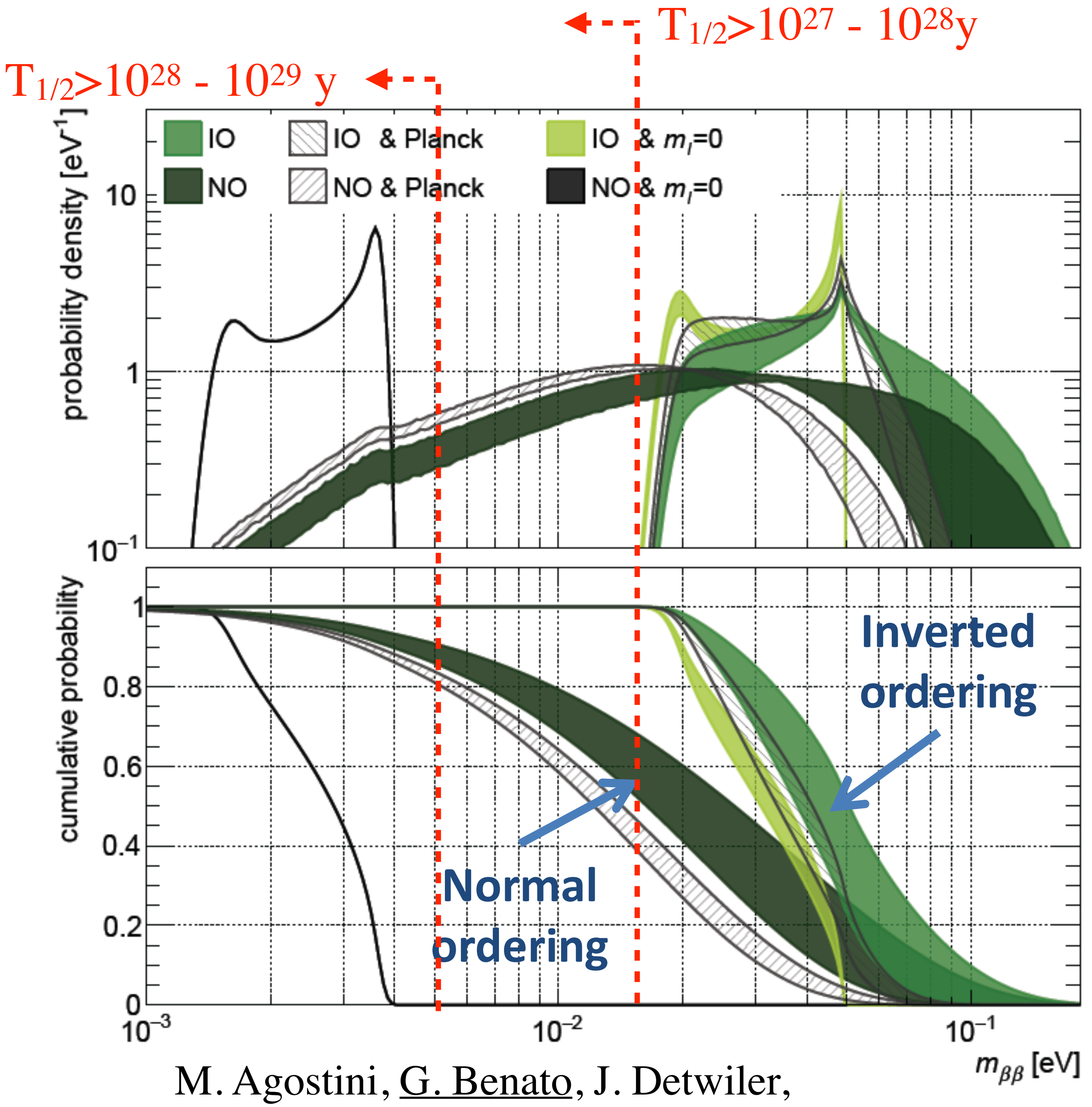
Discovery sensitivity (3σ): $T_{1/2} = 7.4\times10^{27}$ years

$m_{\beta\beta}$ discovery sensitivity: 5-27 meV

(arXiv:2106.16243; J.Phys.G **49**, 015104 (2022))

NLDBD Beyond Ton-Scale Experiments

- Long-term world-wide experimental effort
- Discovery reach of the next-generation experiments covers IO region of (light) neutrino masses
- Next-next generation:
  - In case of discovery: precision measurements of NLDBD mechanism
  - If no discovery: probe NO region
- Vibrant R&D towards next-next generation experiments



M. Agostini, G. Benato, J. Detwiler, Phys. Rev. **D96**, 053001 (2017)

Going Beyond the Inverted Hierarchy

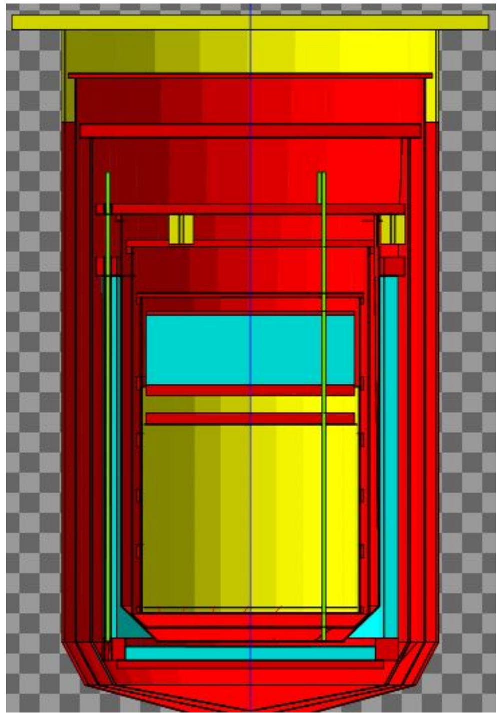
Half-life	Expected Signal (counts/tonne-year)	
10^{26} years	~50	current gen
10^{27} years	~5	next gen
10^{28} years	~0.5	next-next gen

Detectors need to be:

- Bigger (more isotope)
- Better (lower backgrounds, higher resolution, topological info)

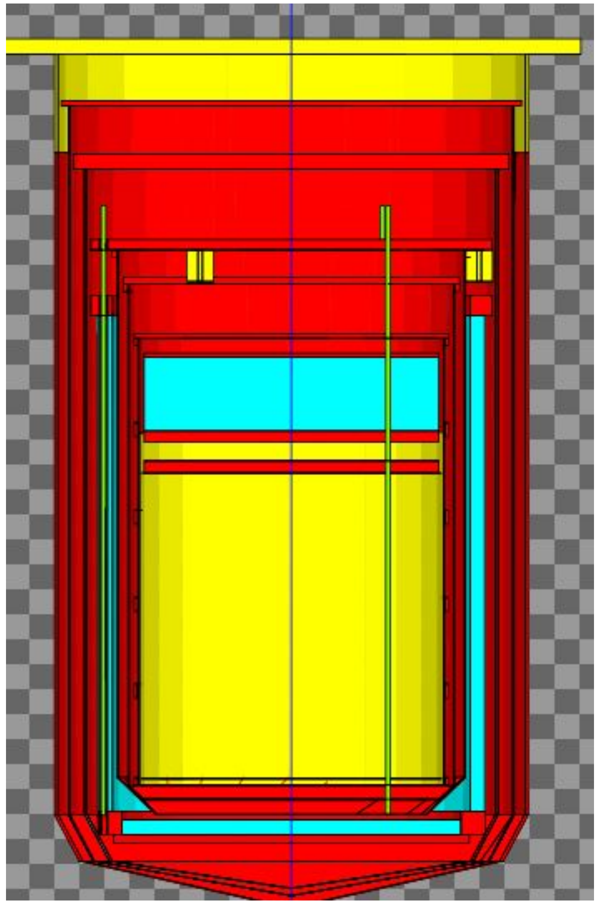
Large Bolometric Detector: CUPID-1T

CUPID Baseline

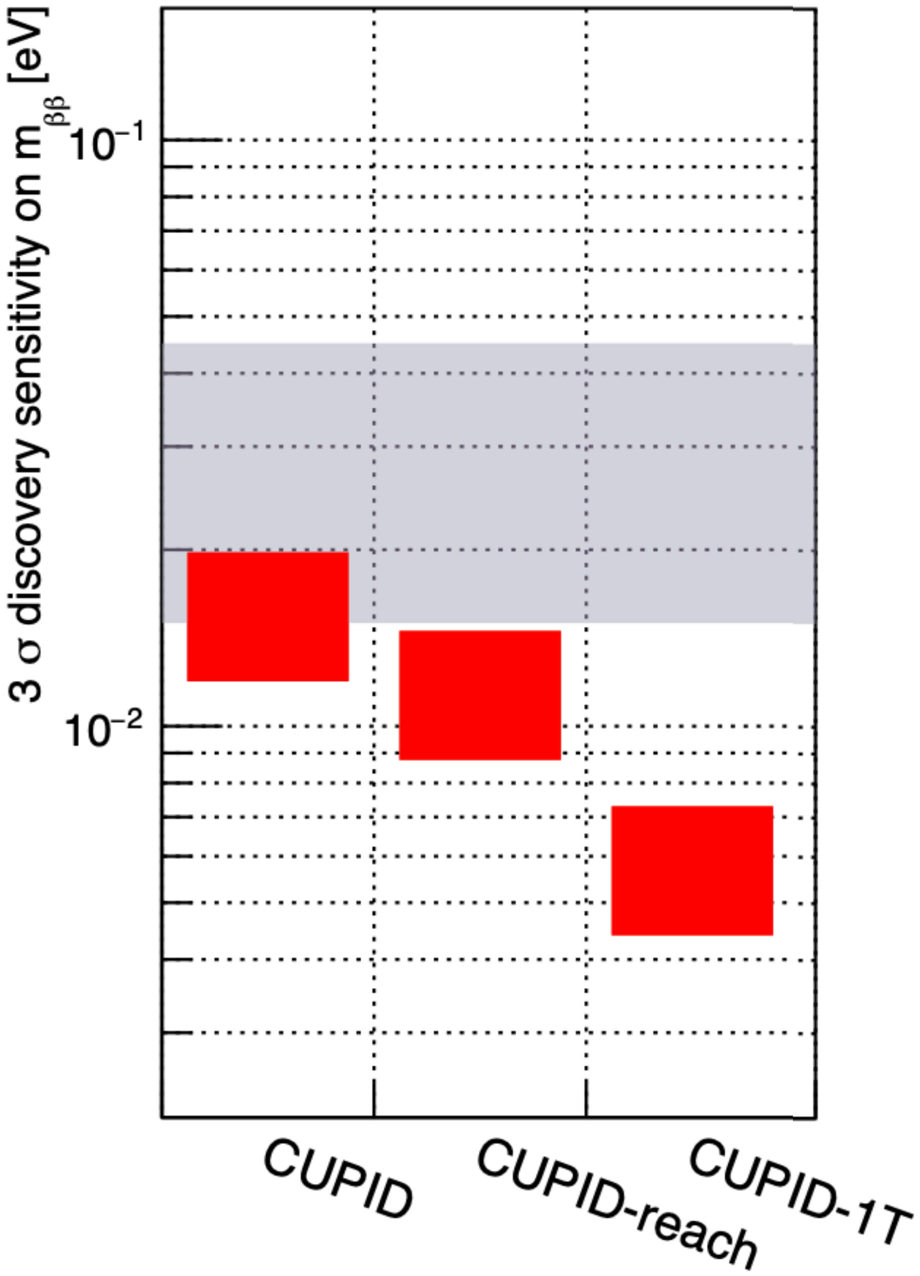


Li_2MoO_4 crystals
250 kg of ^{100}Mo
CUORE cryostat
Sensitivity:
$T_{1/2} > 1.5\times10^{27}$ years (IH)

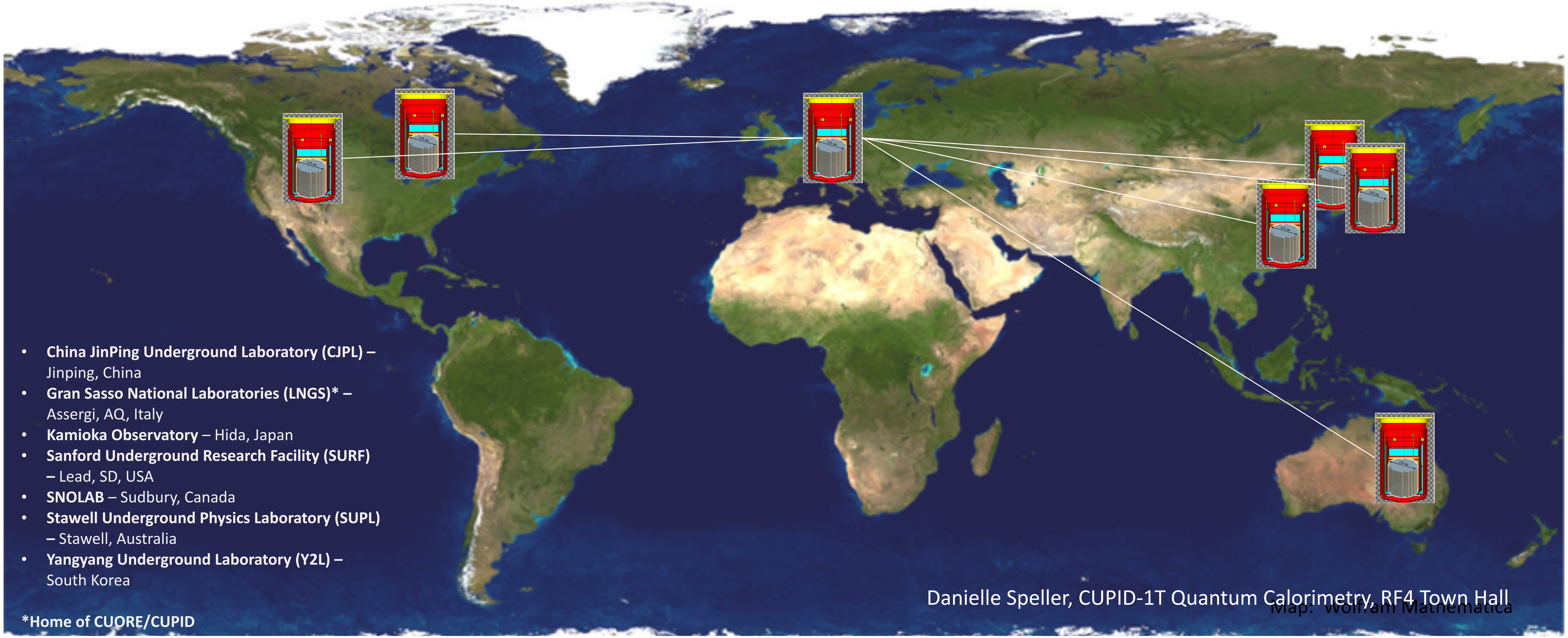
CUPID-1T



Li_2MoO_4 crystals
1000 kg of ^{100}Mo
New cryostat or 4 CUORE-sized
Sensitivity:
$T_{1/2} > 9.2\times10^{27}$ years (NH)



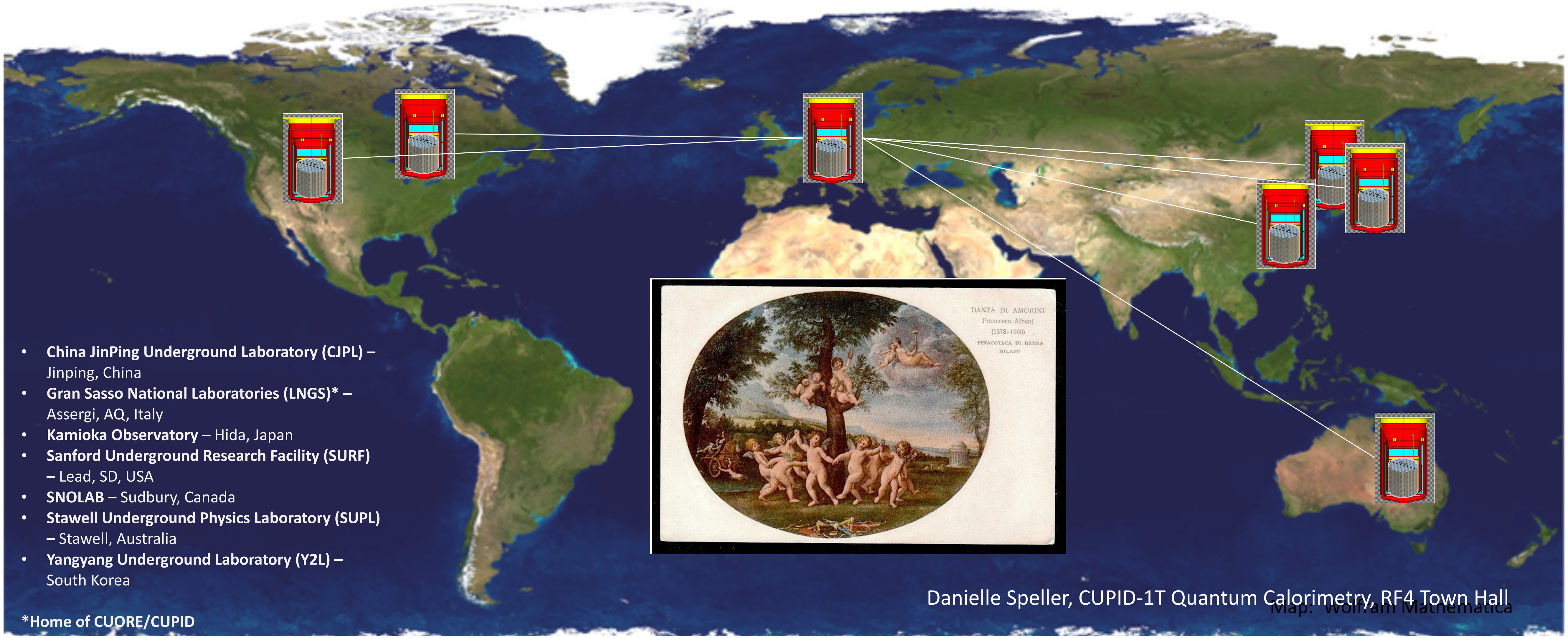
Possible Multi-Site Deployment



Leverage worldwide interest in NLDBD physics, R&D opportunities, and complementarity with QIS

Multi-isotope deployment possible: key in case of a discovery

Possible Multi-Site Deployment



- **China JinPing Underground Laboratory (CJPL) –** Jinping, China
- **Gran Sasso National Laboratories (LNGS)* –** Assergi, AQ, Italy
- **Kamioka Observatory** – Hida, Japan
- **Sanford Underground Research Facility (SURF)** – Lead, SD, USA
- **SNOLAB** – Sudbury, Canada
- **Stawell Underground Physics Laboratory (SUPL)** – Stawell, Australia
- **Yangyang Underground Laboratory (Y2L) –** South Korea

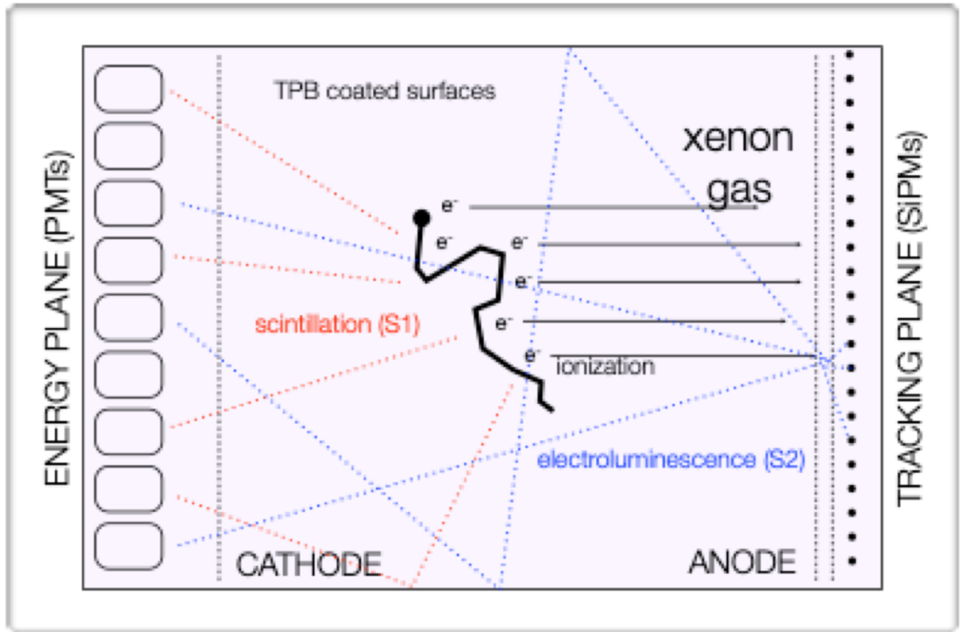
***Home of CUORE/CUPID**

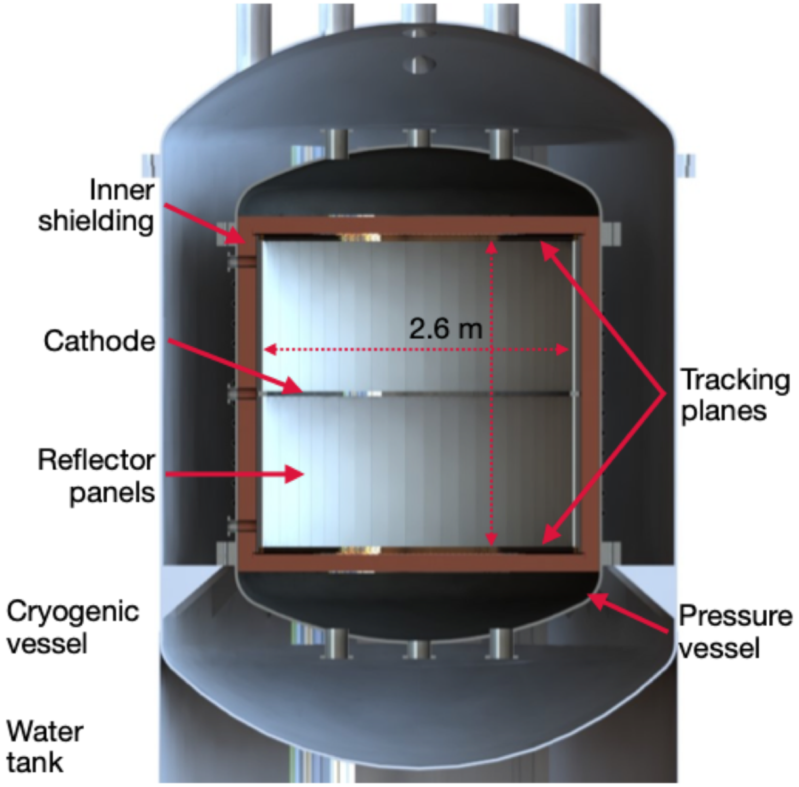
Leverage worldwide interest in NLDBD physics, R&D opportunities, and complementarity with QIS

Multi-isotope deployment possible: key in case of a discovery

Next Idea: High-Pressure ^{136}Xe TPC

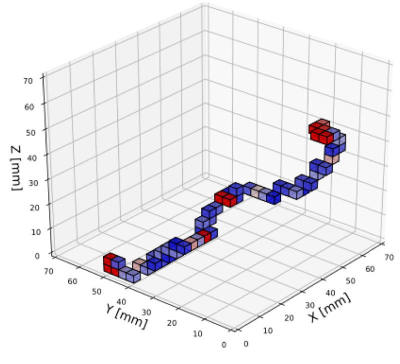
NEXT (Spain): Electro-luminescence HPXe TPC



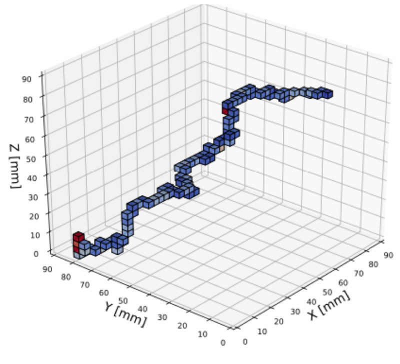


Key features:

- Event topology (background suppression, kinematics)
- Energy resolution: 0.5% FWHM
- Background: 4×10^{-3} counts/(ton*keV*year)



ββ Signal



e- Track Background

Demonstrator (NEXT-100): ~2024 at Canfranc

Ton-scale: NEXT-HD. Projected sensitivity (90% C.L.):

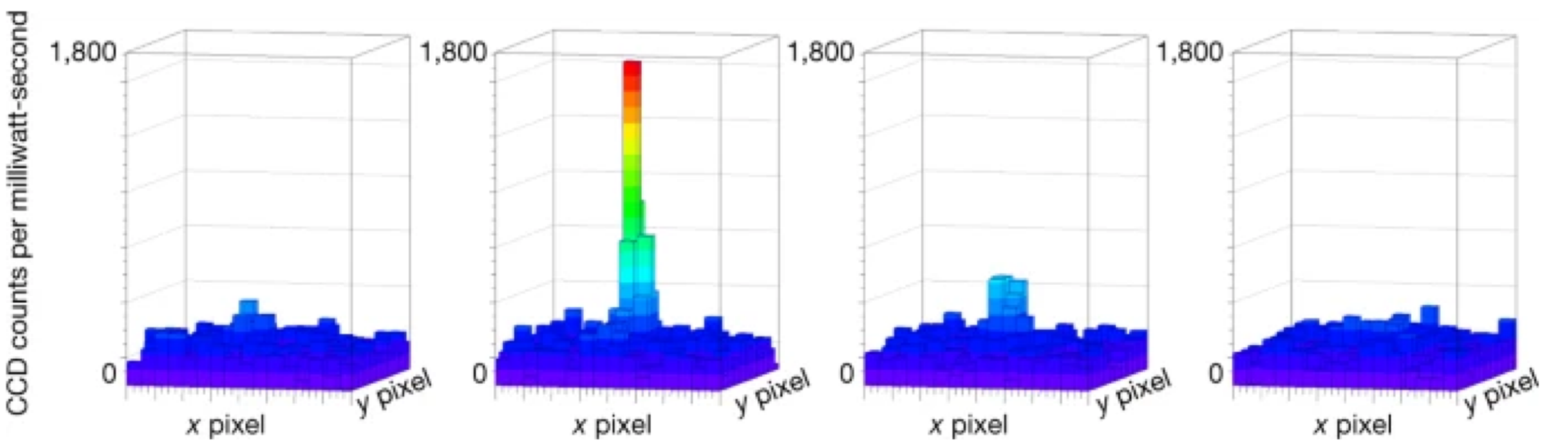
$T_{1/2}>2.7\times10^{27}$ years ($m_{\beta\beta}$=8-45 meV)

NEXT-BOLD concept with barium tagging

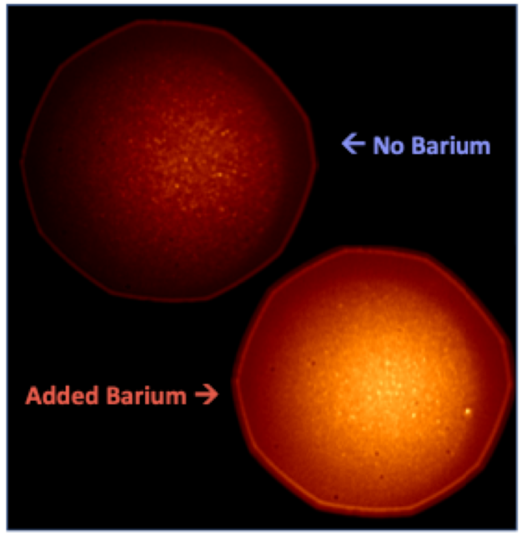
Barium Tagging ^{136}Xe Decays

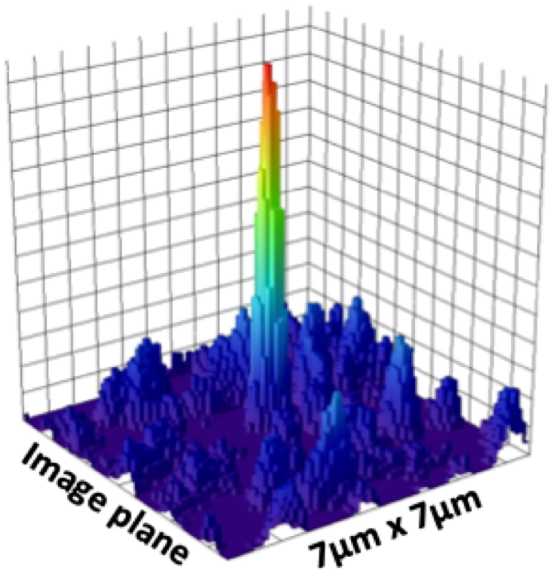
Tagging ^{136}Xe → ^{136}Ba++ transition with high efficiency would eliminate all non-DBD backgrounds
Significant improvement in sensitivity
Vibrant R&D effort for over 20 years, major recent breakthroughs
Demonstrated tagging single atoms in both LXe and GXe
Next steps: Ba capture and transport, scalability

J. Gruszko



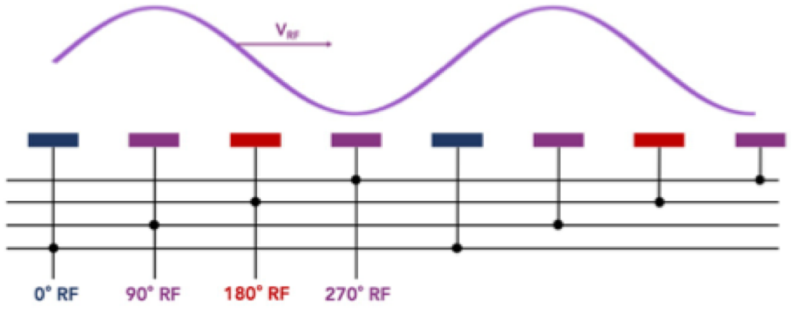
Laser-based ID in solid Xe for nEXO, *Nature 569, 203-207 (2019)*





Fluorescent molecule-based ID for NEXT, *ACS Sens. 2021, 6, 1, 192–202 (2021)*

Cryoprobe-based extraction for nEXO



RF carpet-based transport for NEXT, *arXiv:2111.11091 (2021)*

Large Hybrid Detector: Theia

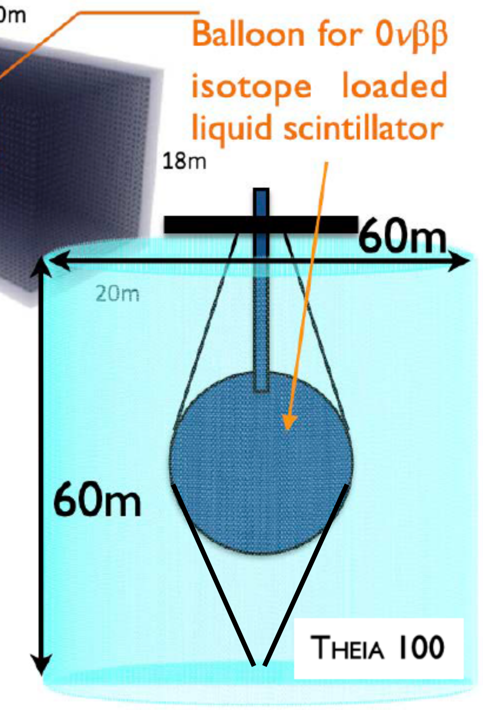
^{130}Te ^{136}Xe

G.D. Orebi Gann

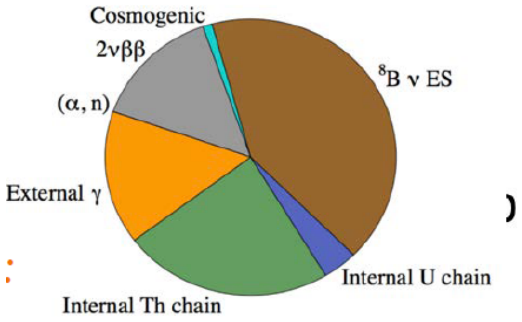
- Hybrid Cherenkov / scintillation detector improves background rejection via PID and event topology
- Scalable, ultra-clean liquid detector
- Potential to deploy a 25-kton THEIA module at LBNF, in a Module of Opportunity
- Mass sensitivity of ~4—22 meV
- Broad program of other physics

Background reduction via event imaging: PID, multi-site, directionality

Te or Xe

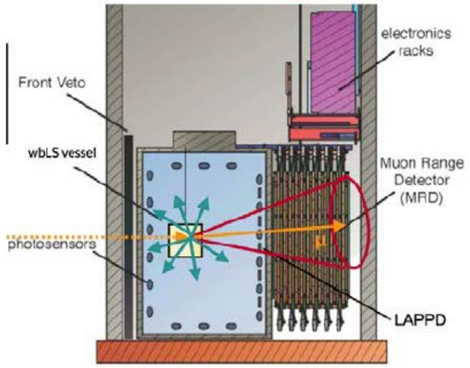


SNO+ Collaboration



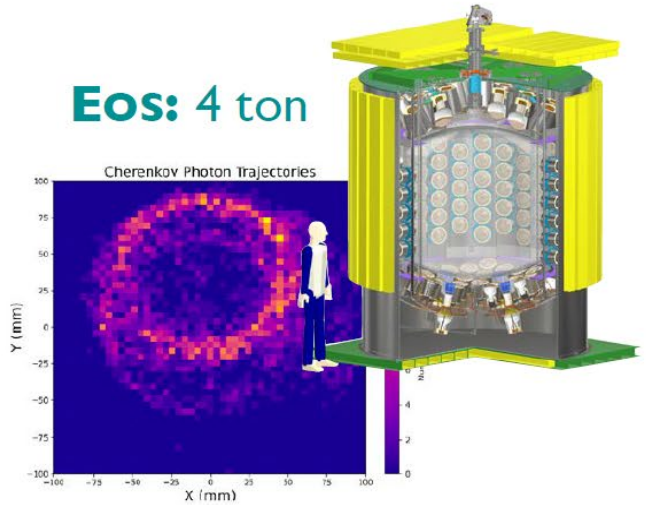
R&D into next-gen LS detectors

ANNIE: 365 kg



NuDot: 1 ton

Eos: 4 ton



BNL: 1- and 30-ton

Builds on critical developments by KLZ & SNO+ collaborations

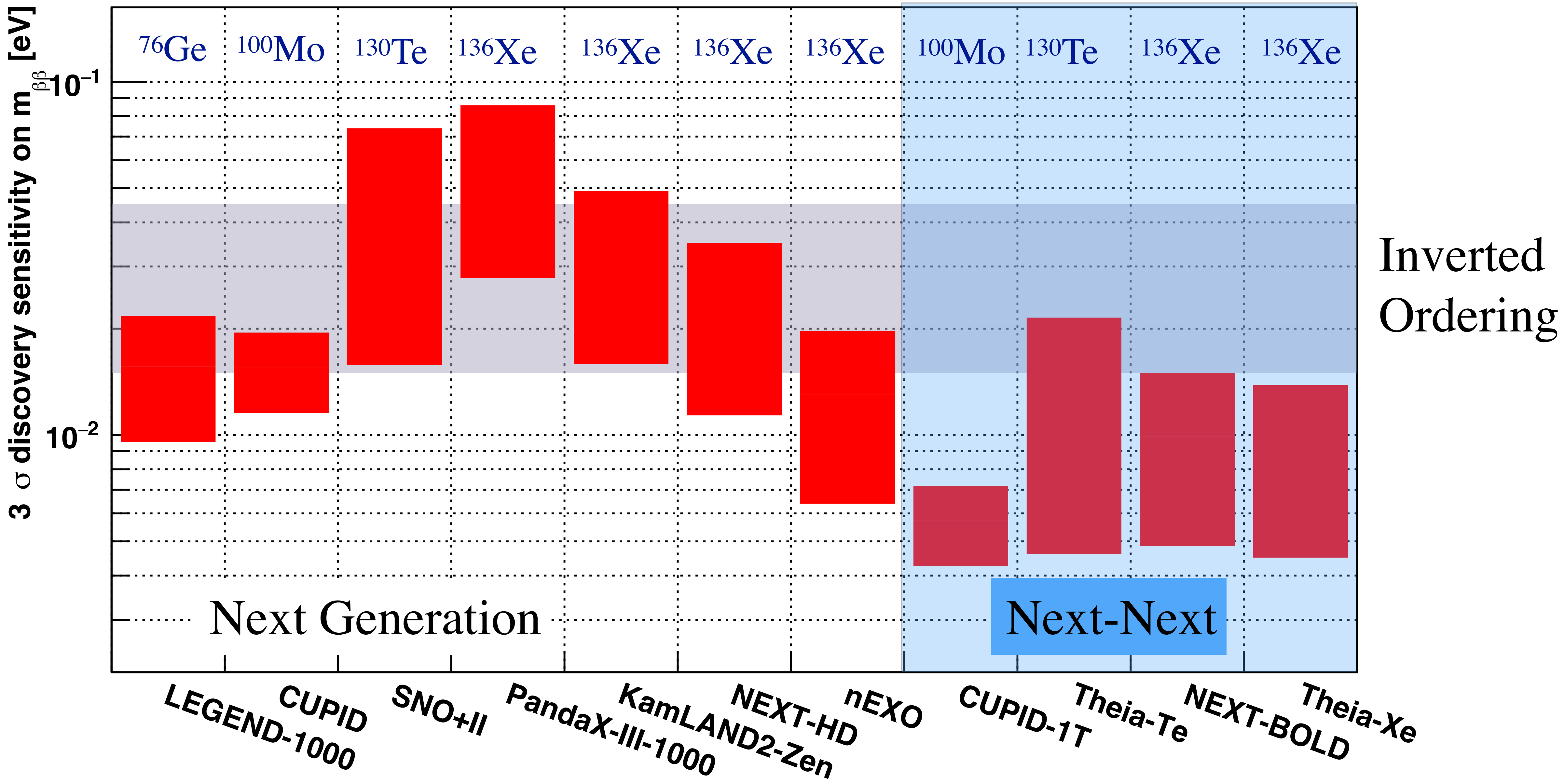
$T_{1/2} > 1.5 \times 10^{28}$ yrs (Te)

$T_{1/2} > 2.7 \times 10^{28}$ yrs (Xe)

(90% CL)

$m_{\beta\beta} < 5.4$ (4.8) meV Te (Xe)

Future $0\nu\beta\beta$ Discovery Potential



G. Benato, YGK

Methodology from Phys. Rev. **D96**, 053001 (2017)

Conclusions and Outlook

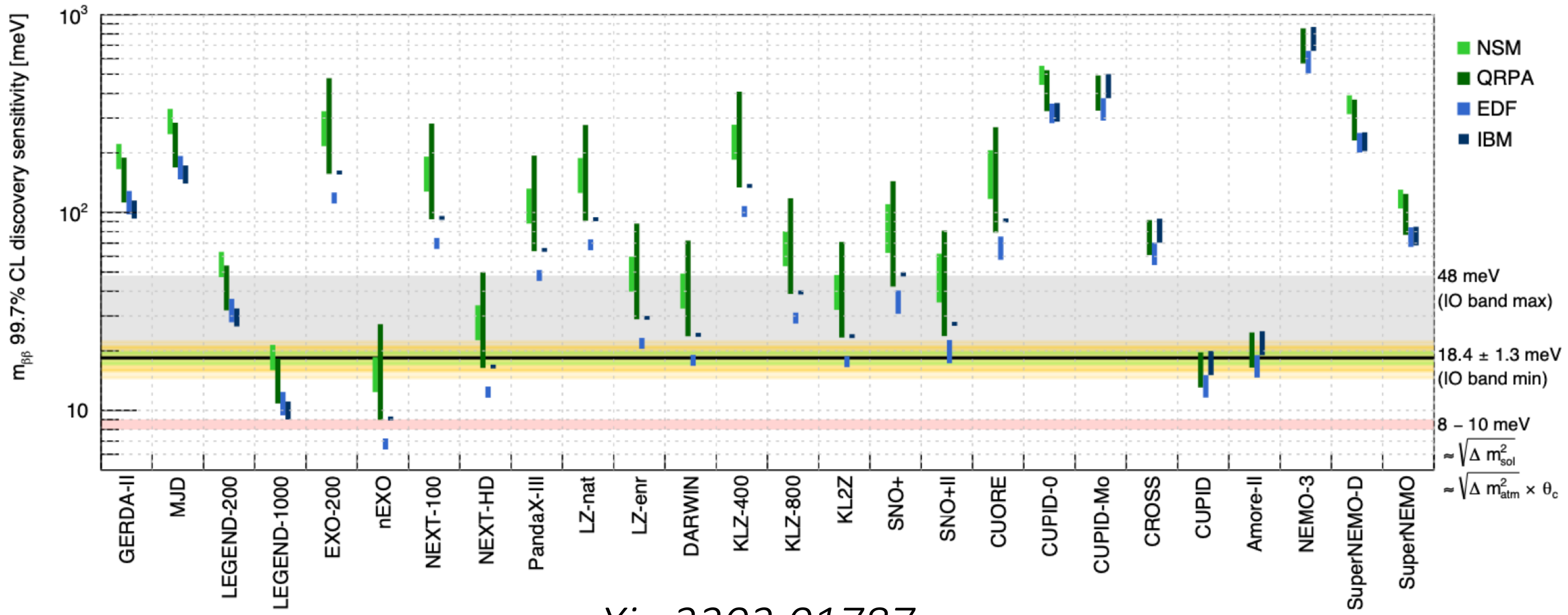
- Neutrinoless Double Beta Decay: discovery science
  - ❑ Lepton Number Violation from low to high mass scales
  - ❑ Current generation of experiments are approaching Inverted Ordering region.
    - ☞ More results this decade: AMoRE, CUORE, KamLAND-Zen, LEGEND-200, SNO+
  - ❑ Next-generation (ton-scale) projects will improve half-life sensitivity by 1-2 orders, probe IO region $m_{\beta\beta} \sim 10$ meV
  - ❑ Active R&D for beyond ton-scale experiments

Exciting future ahead !

Backup

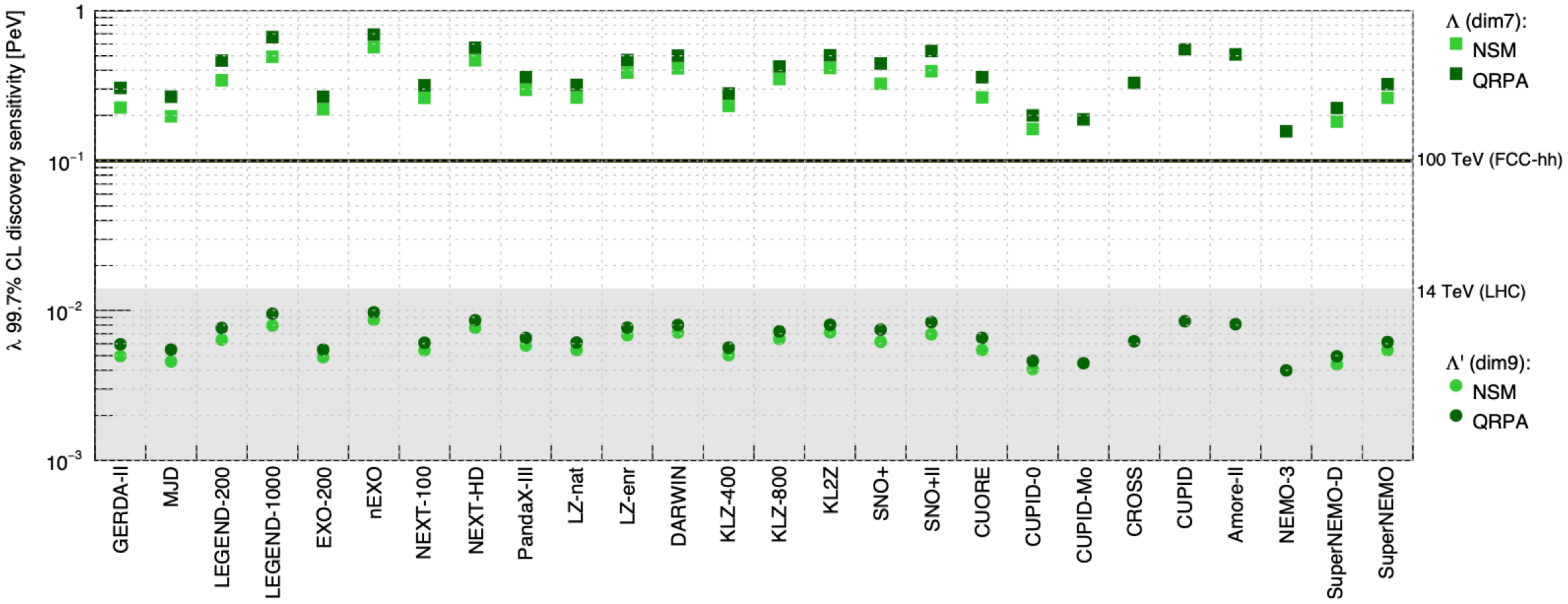
Discovery Sensitivity

Light Majorana neutrino exchange (dim 5):



arXiv:2202.01787

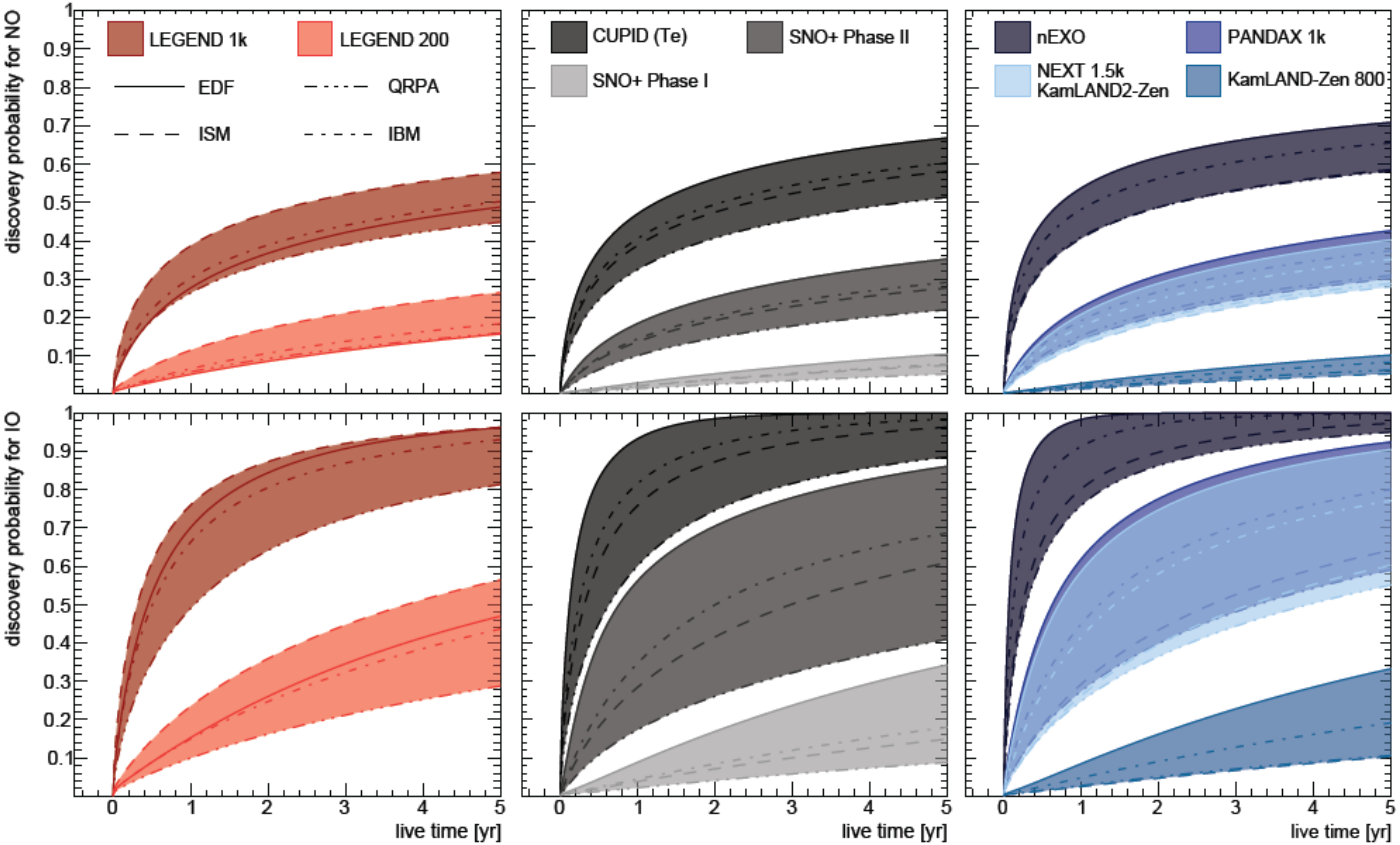
0νββ via dimension 7 and 9 operators:



Future Experiments: Discovery Probability

Bayesian probability for 3σ $0\nu\beta\beta$ discovery, folding current prior on $m_{\beta\beta}$

Phys. Rev. **D96**, 053001 (2017)



Normal Hierarchy

Inverted Hierarchy