Neutrinoless Double-Beta Decay: Experimental Review

Yury Kolomensky
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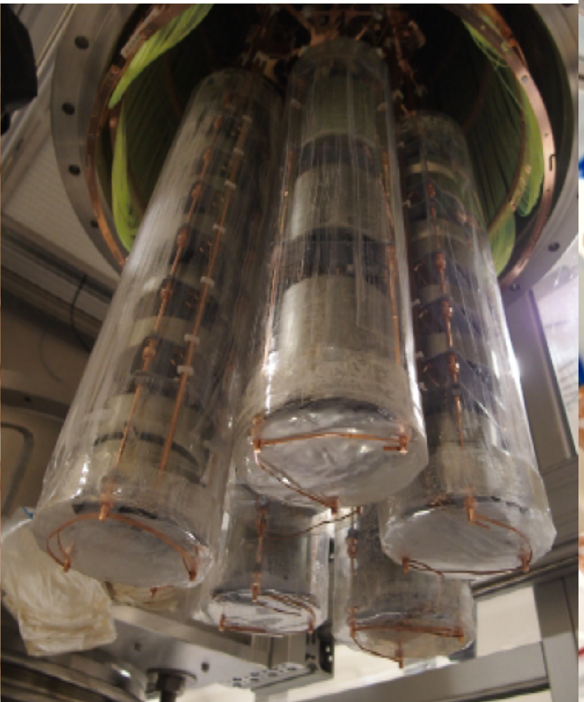
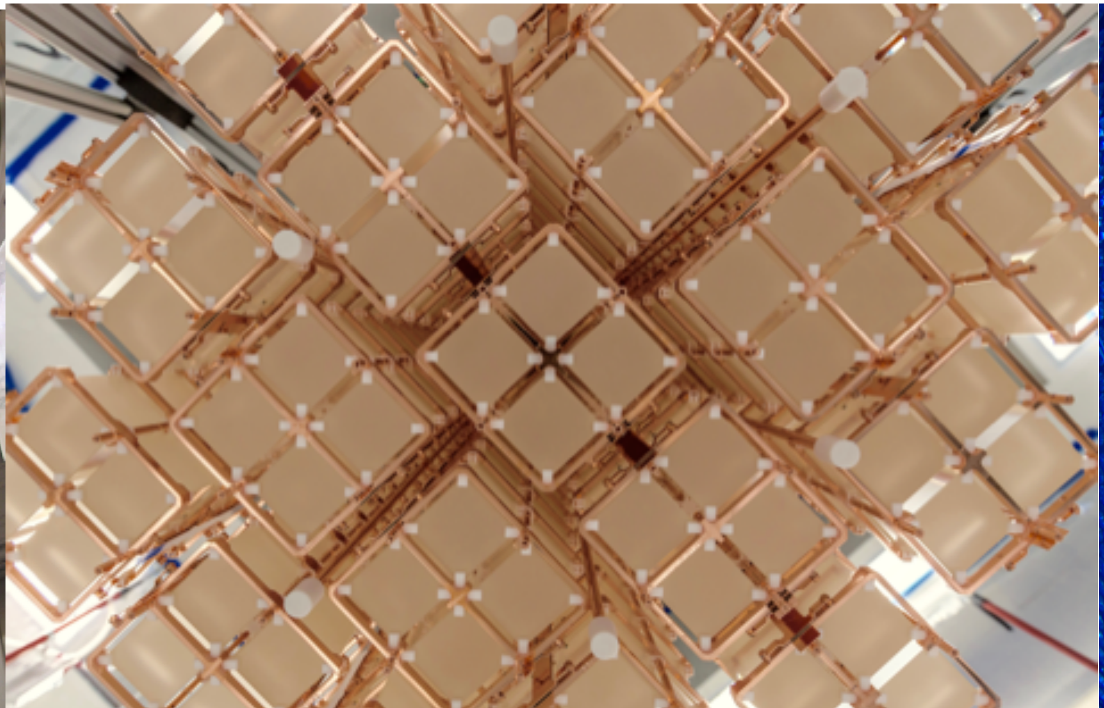
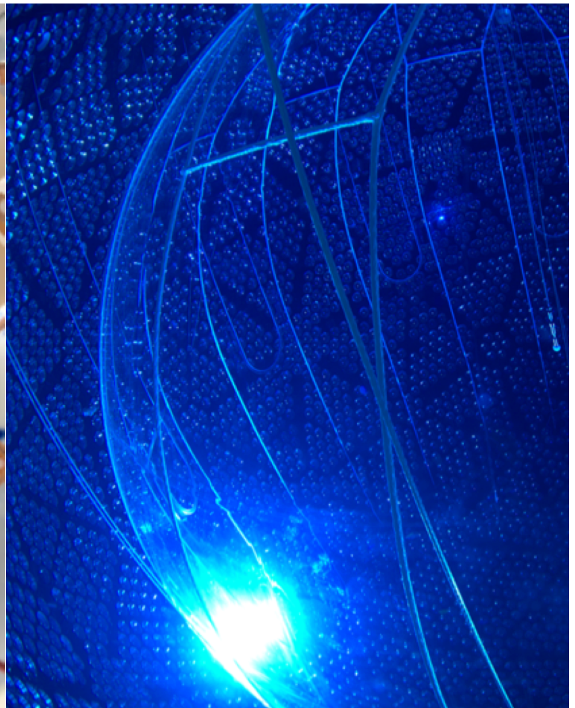
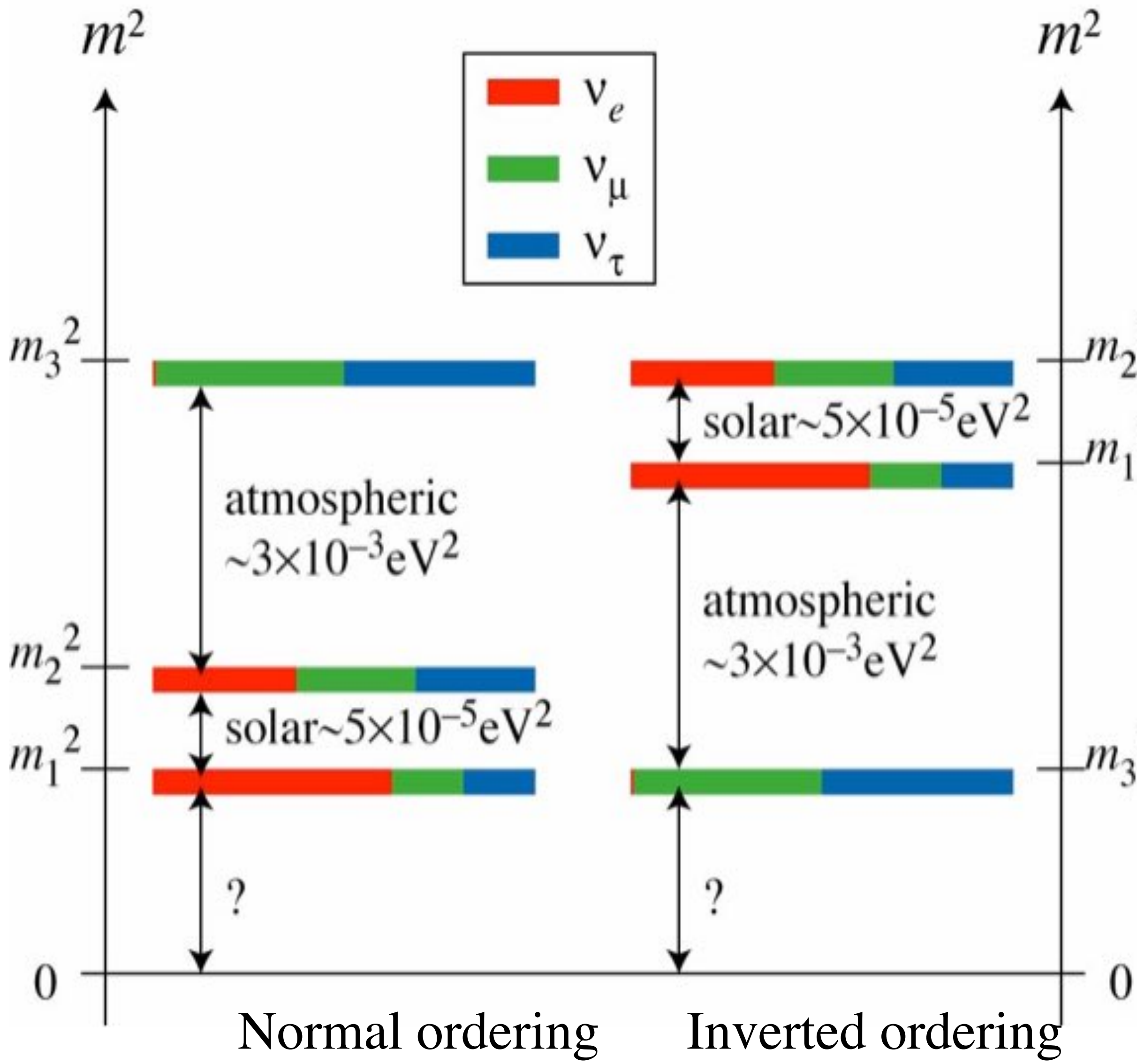
FPCP 2022

Neutrino Physics Landscape

Neutrino mass hierarchy

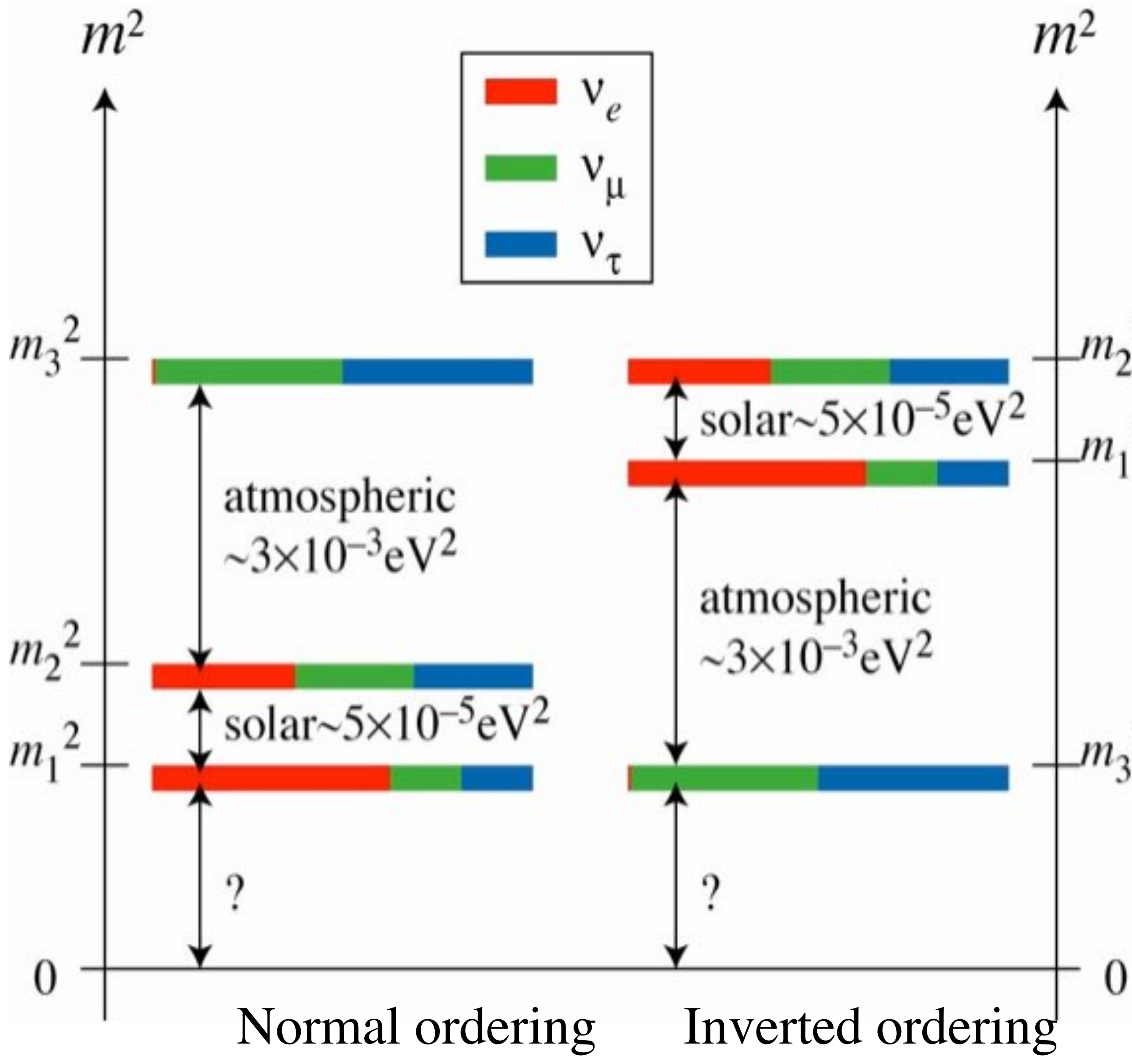


At least one ν has m > 55 meV

Neutrino Physics Landscape

- Compelling evidence for
  - Neutrino flavor-changing oscillations
  - (therefore) finite neutrino masses
  - Mixing angles are well measured

Neutrino mass hierarchy

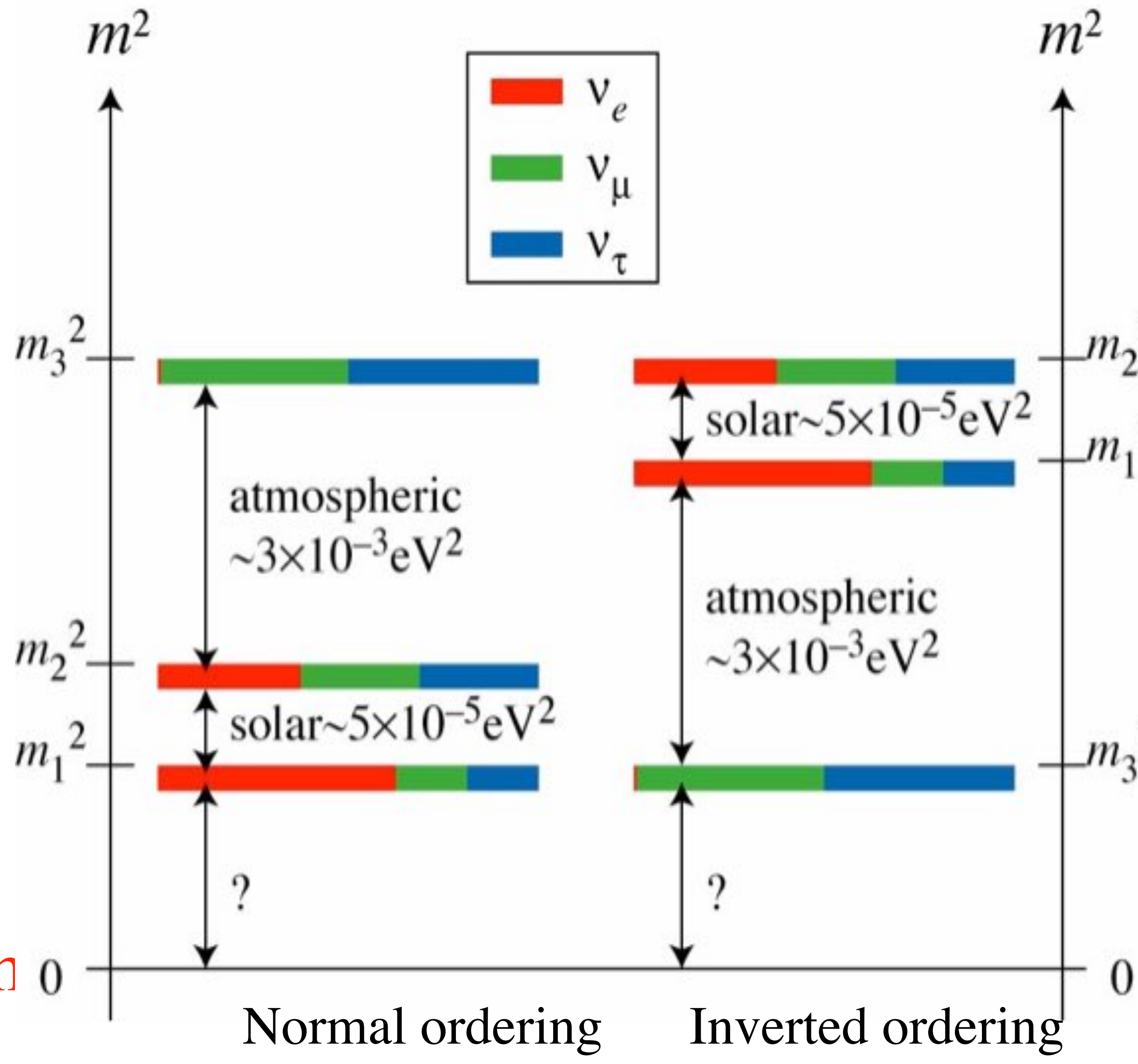


At least one ν has m > 55 meV

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 asym
  - 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
    - ☞ New physics ?
    - ☞ Potentially sensitive to very high mass scales (see-saw mechanism)
    - ☞ Can generate matter⇔antimatter transitions

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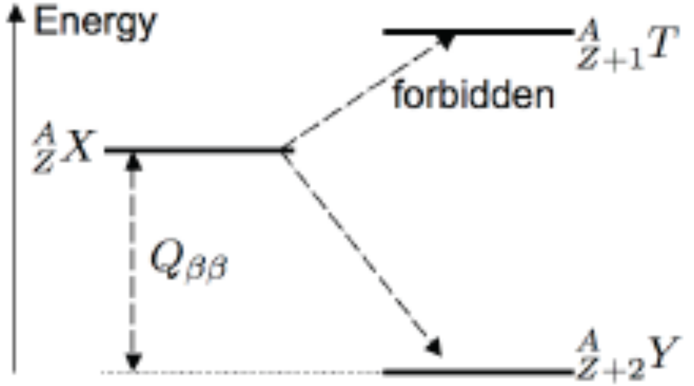
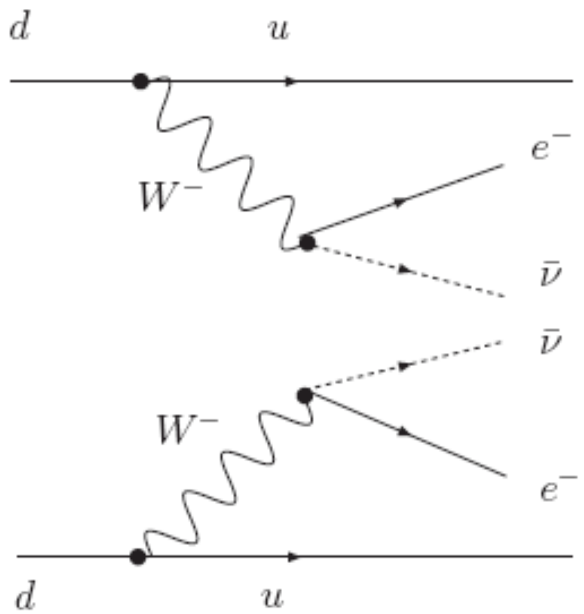
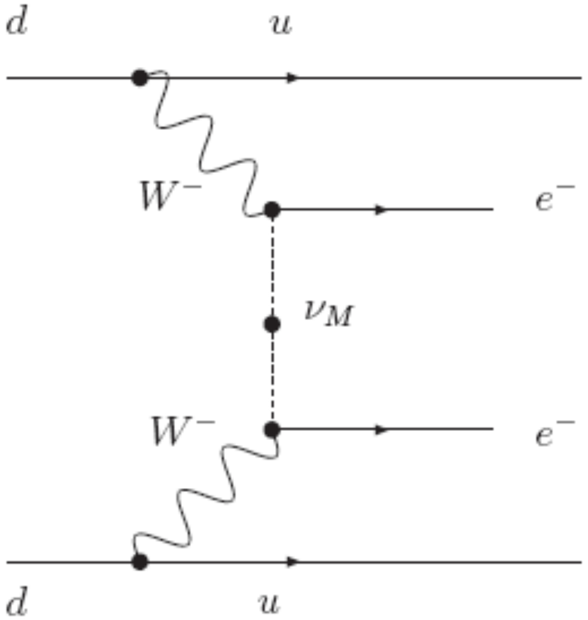
Neutrinoless Double-Beta Decay

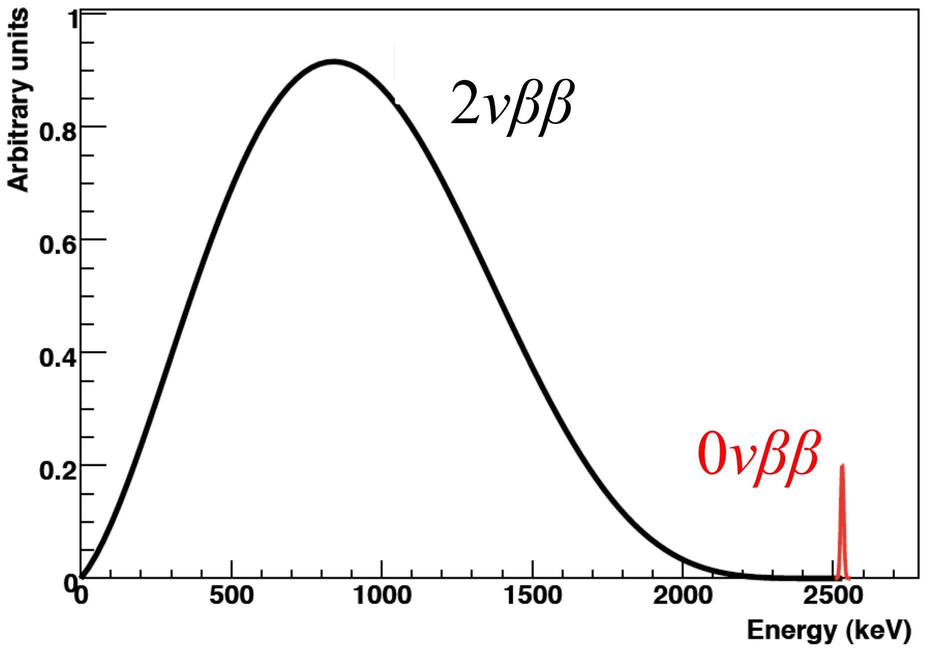




SM $2\nu\beta\beta$ decay $\tau \geq 10^{19}$ y



$0\nu\beta\beta$ $\tau \geq 10^{25}$ y



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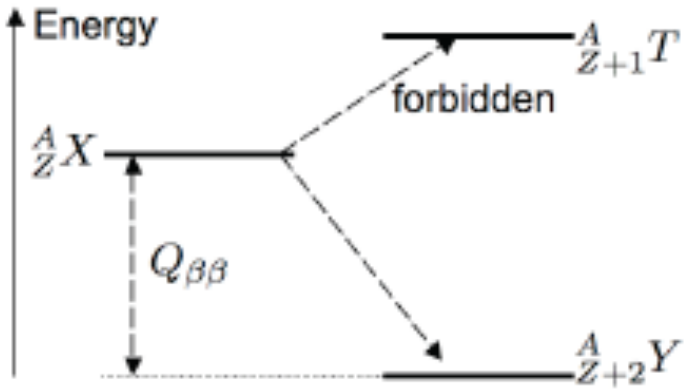

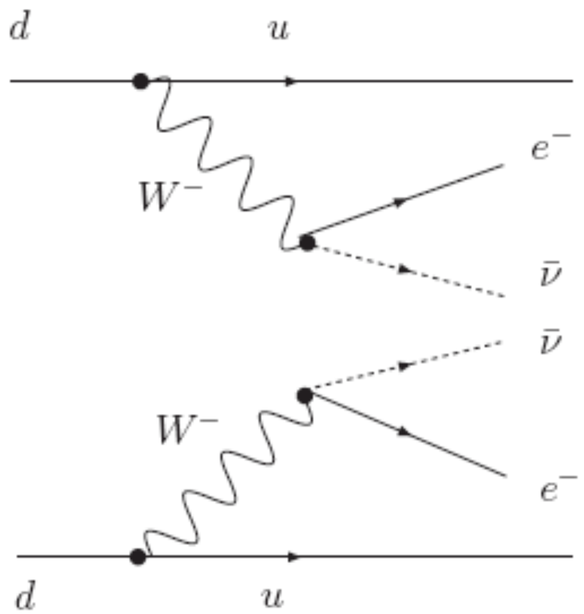

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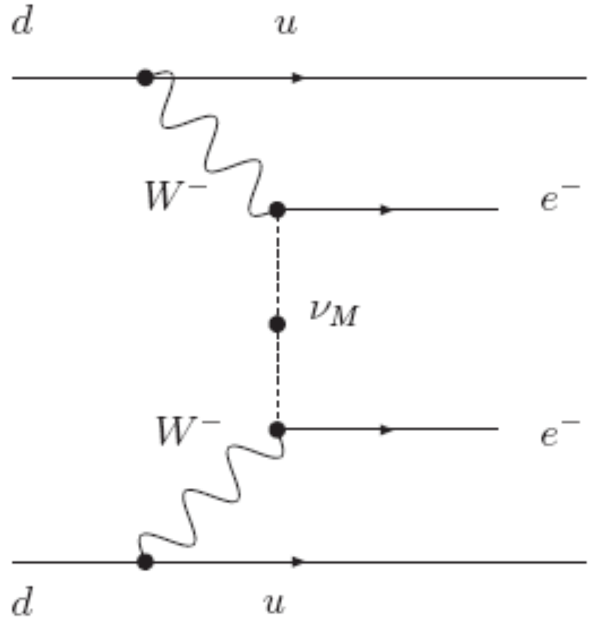
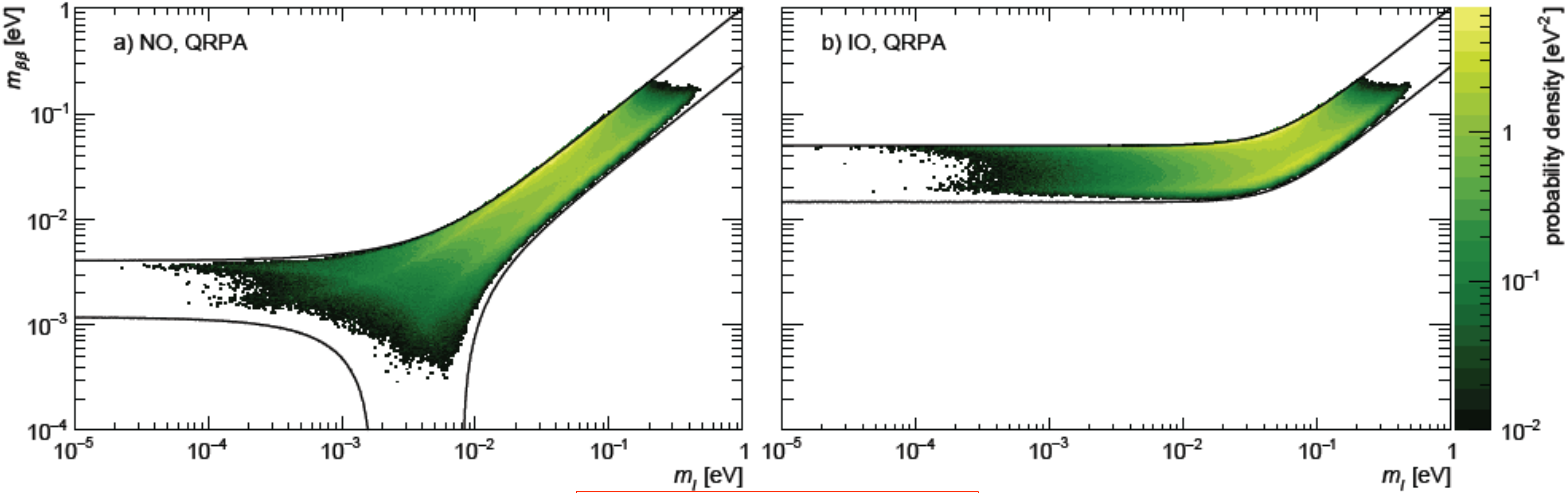


0νββ τ ≥ 10^{26} y

- 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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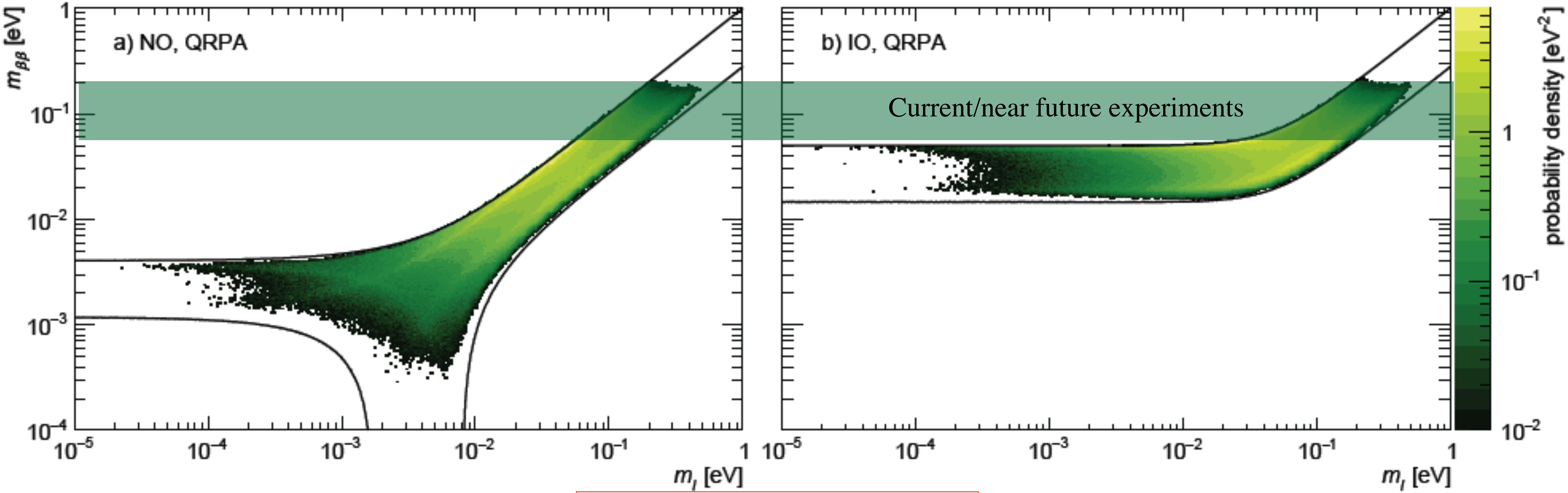

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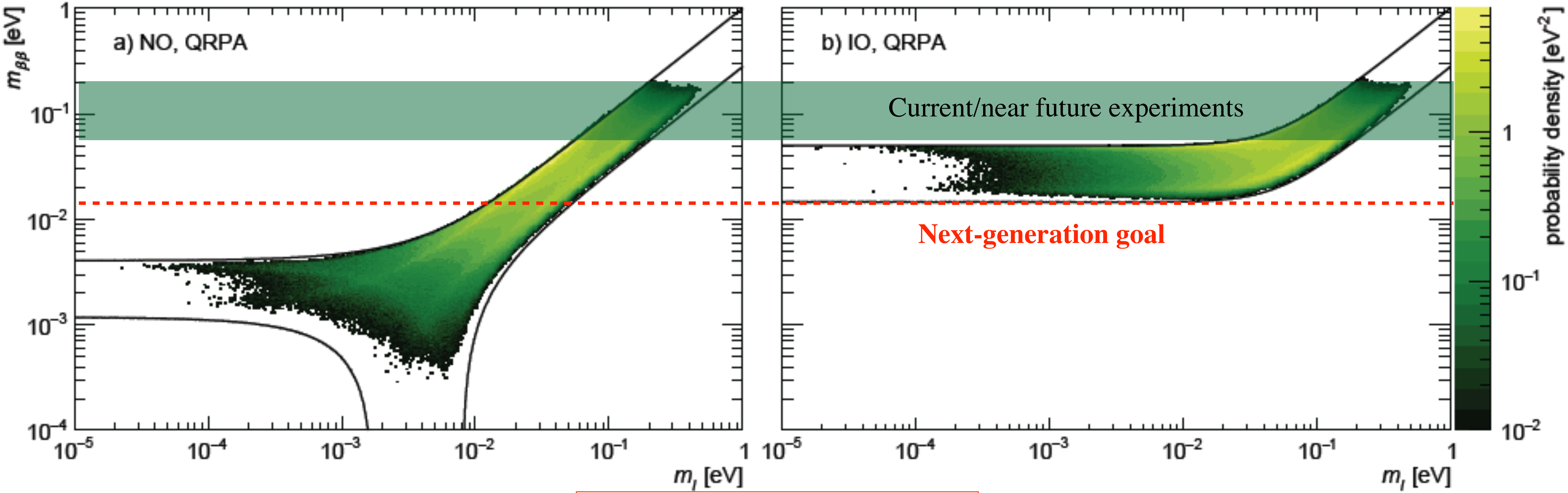

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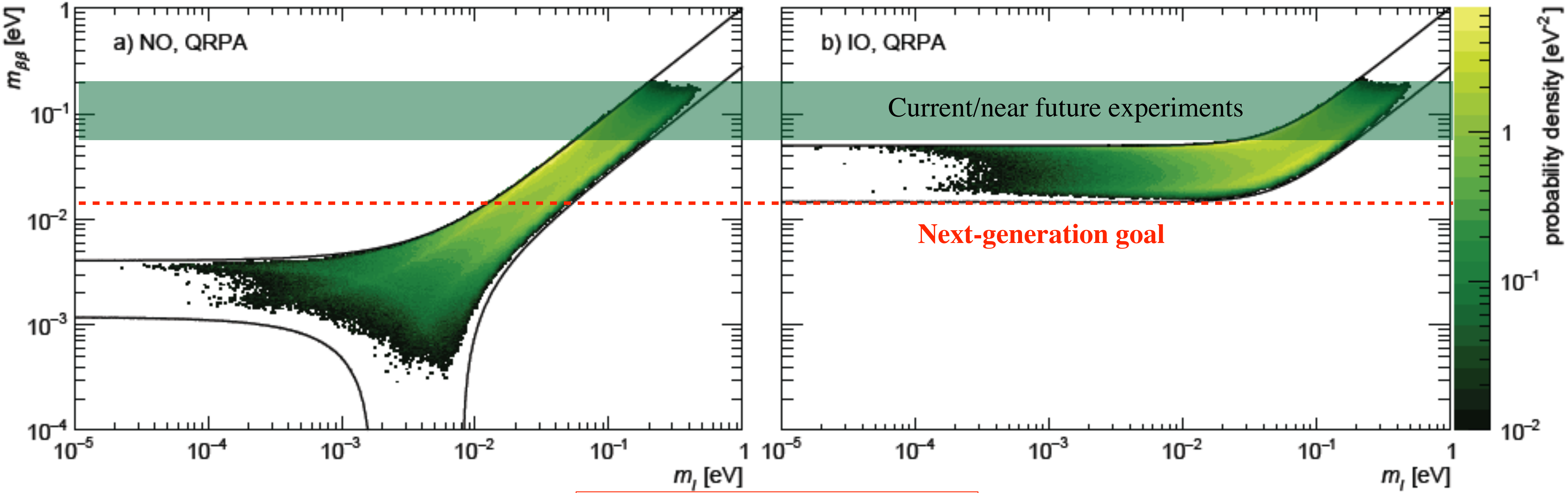

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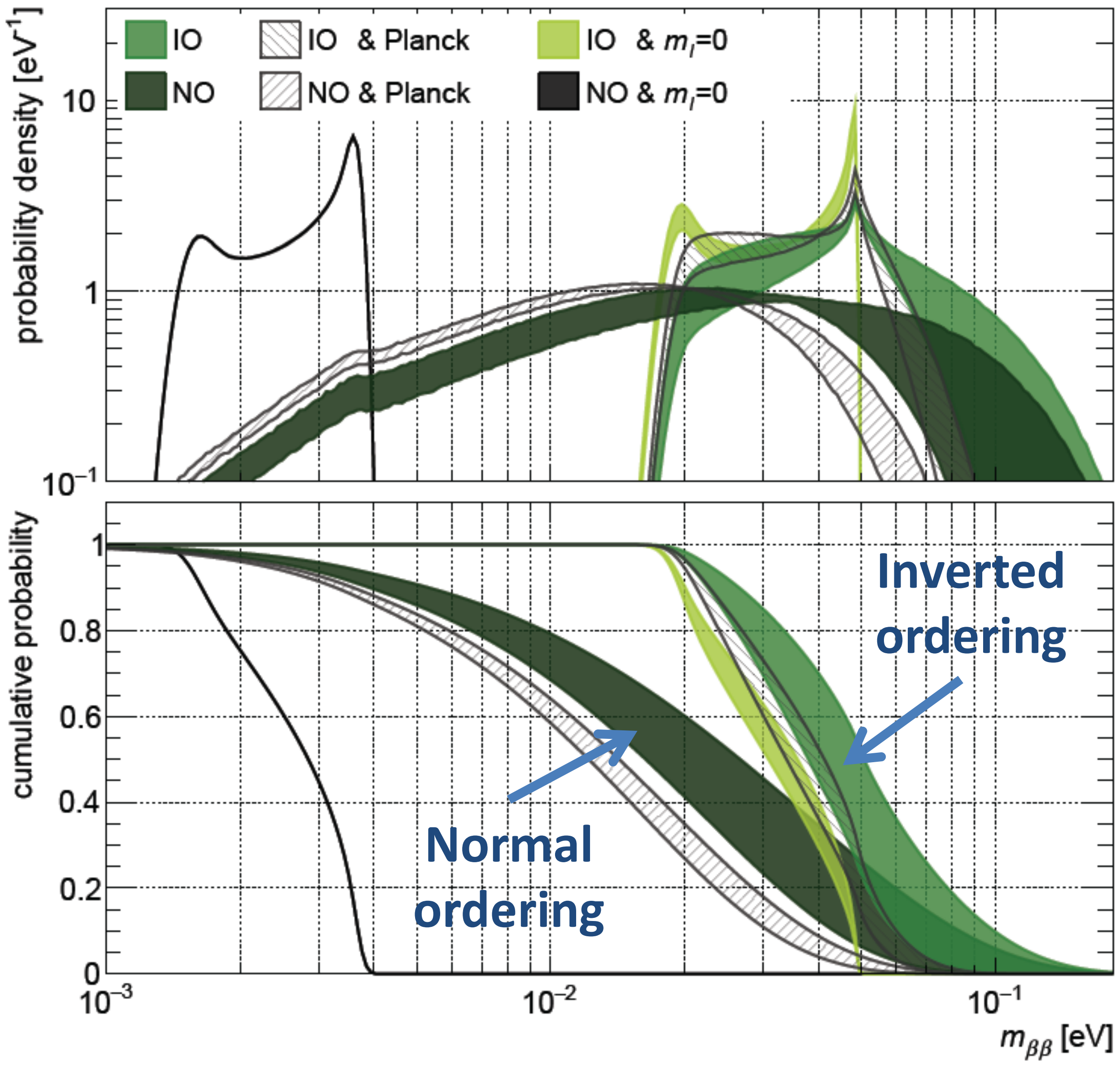
NB: simplest interpretation (3 light neutrinos). Sterile neutrinos or heavy new physics could change the interpretation dramatically !

Opportunities for the fundamental discovery



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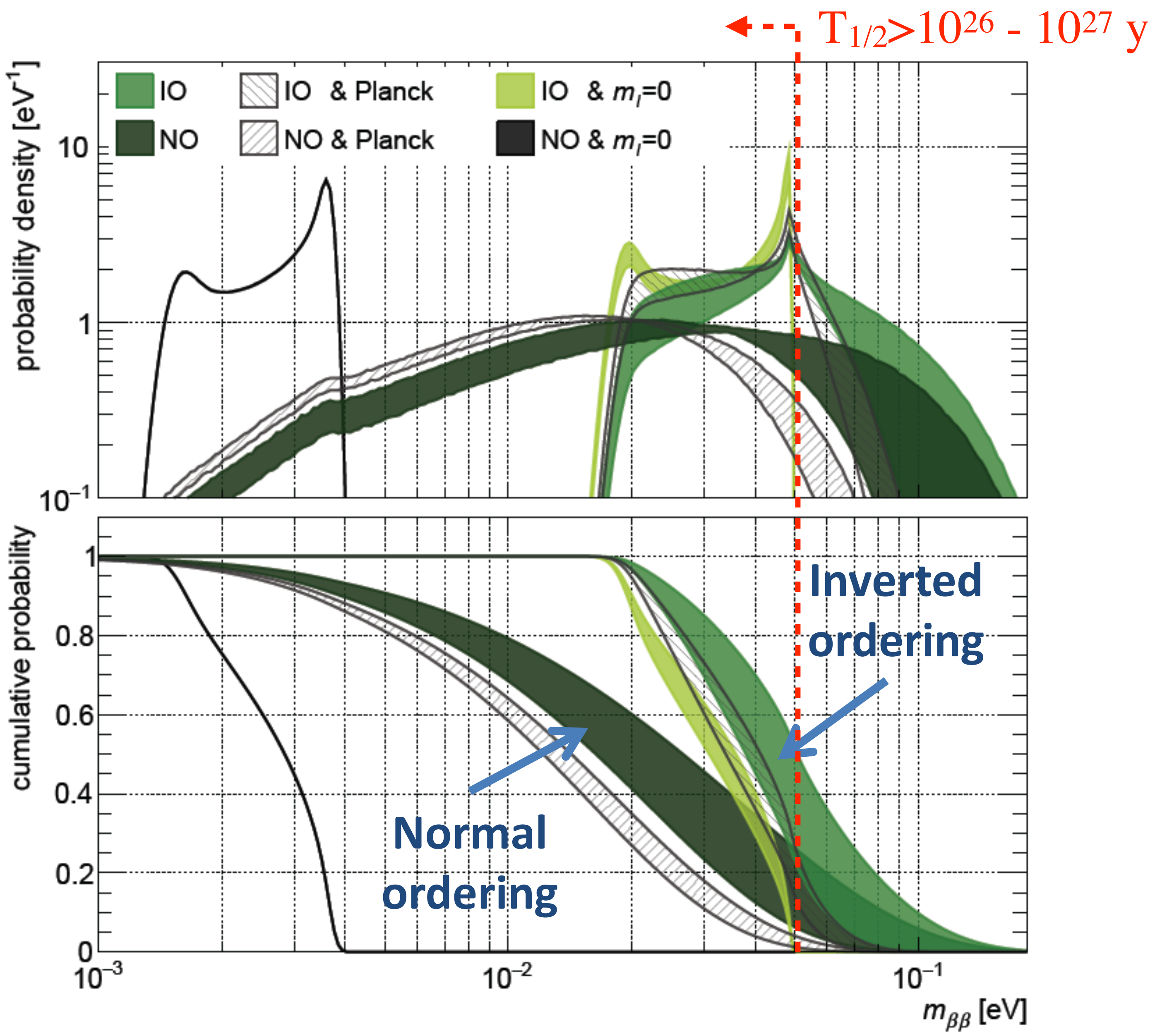

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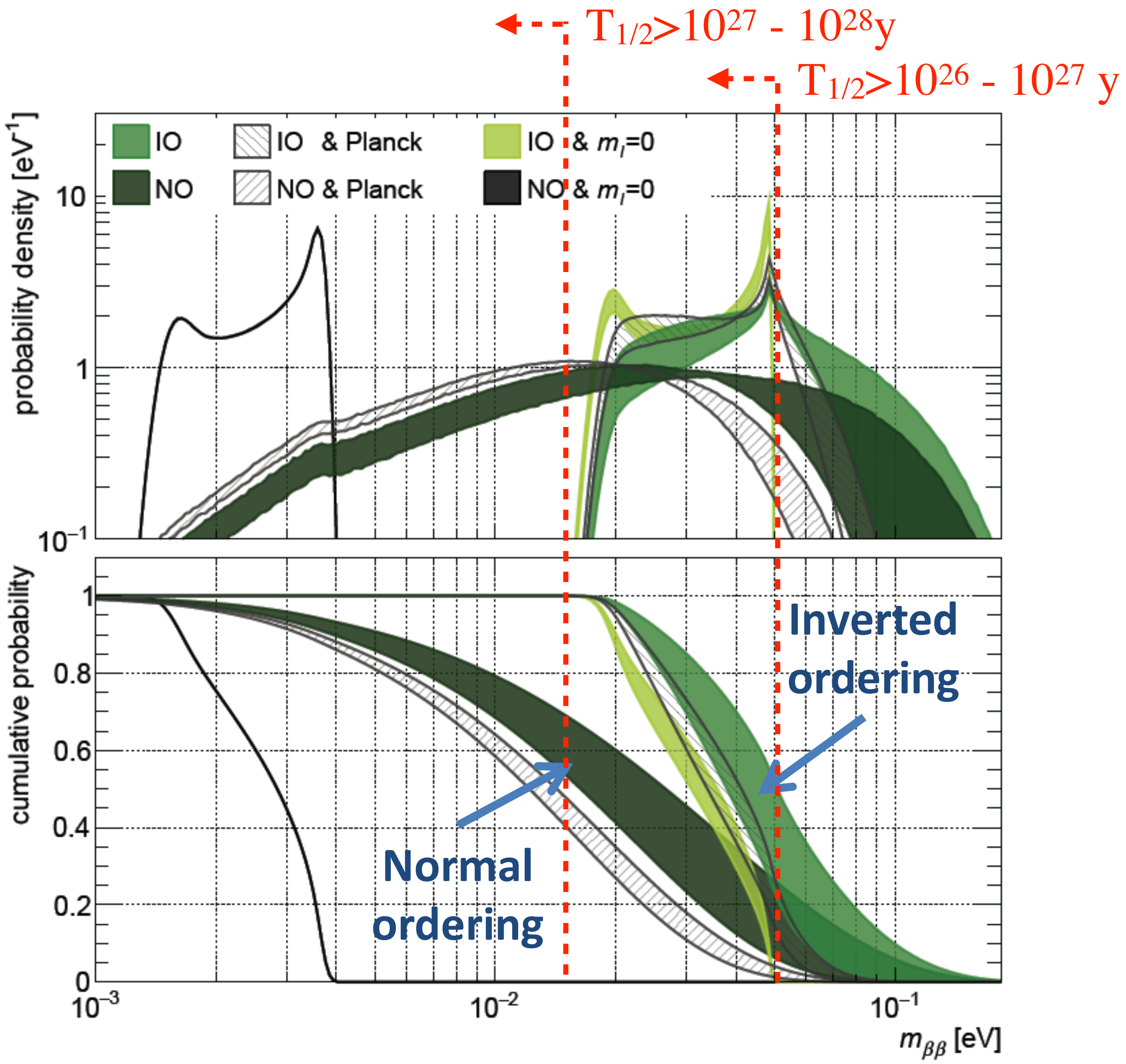

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T$_{1/2}$>10^{27} - 10^{28}y

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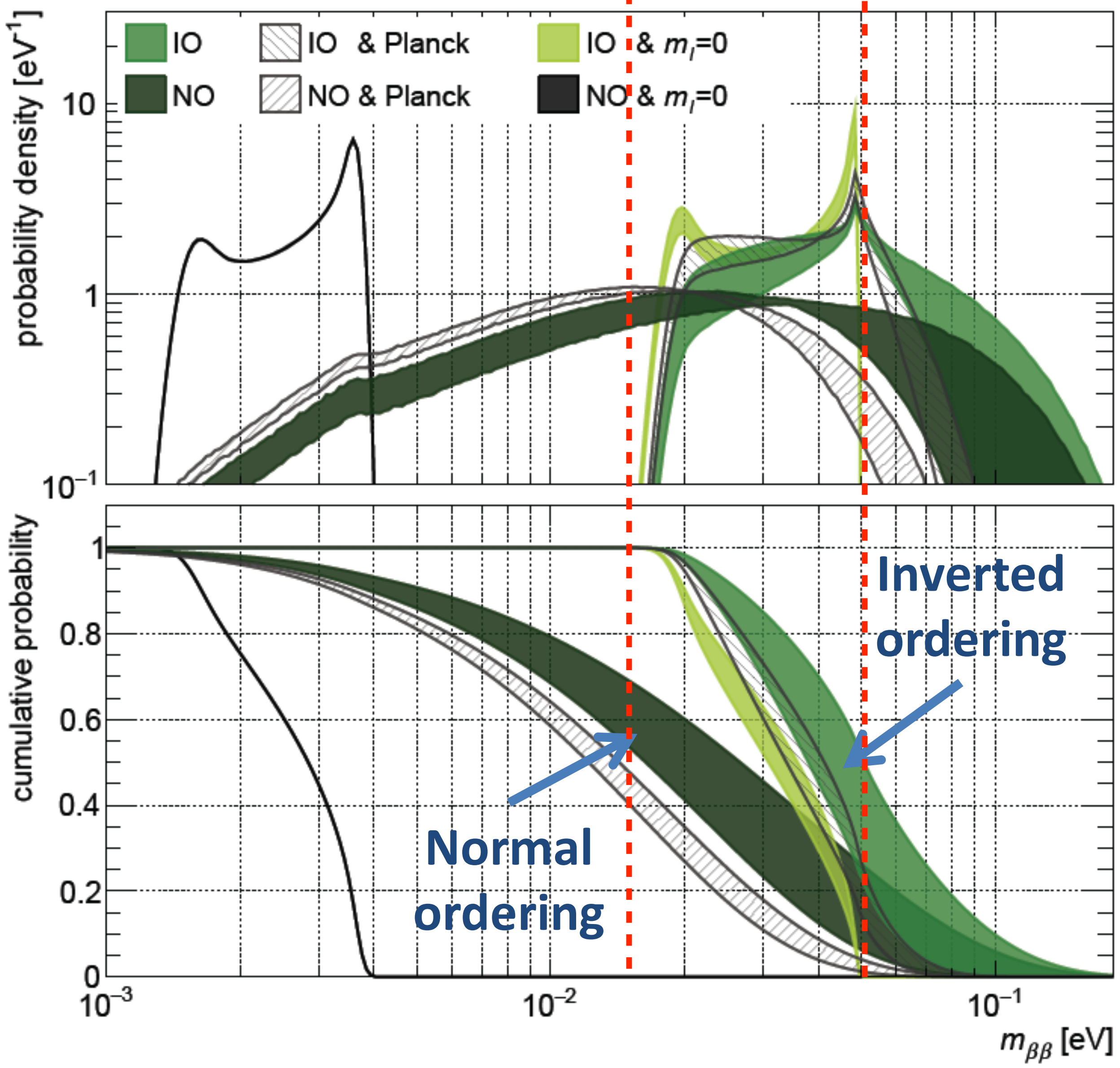

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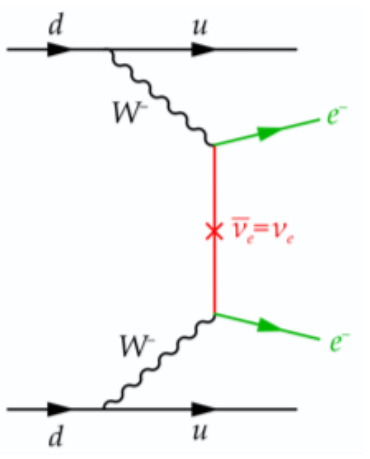
If the neutrino hierarchy is inverted, the light neutrino exchange is dominant.

Next-generation experiments with sensitivity $T_{1/2}>10^{27}$ years have a definite target



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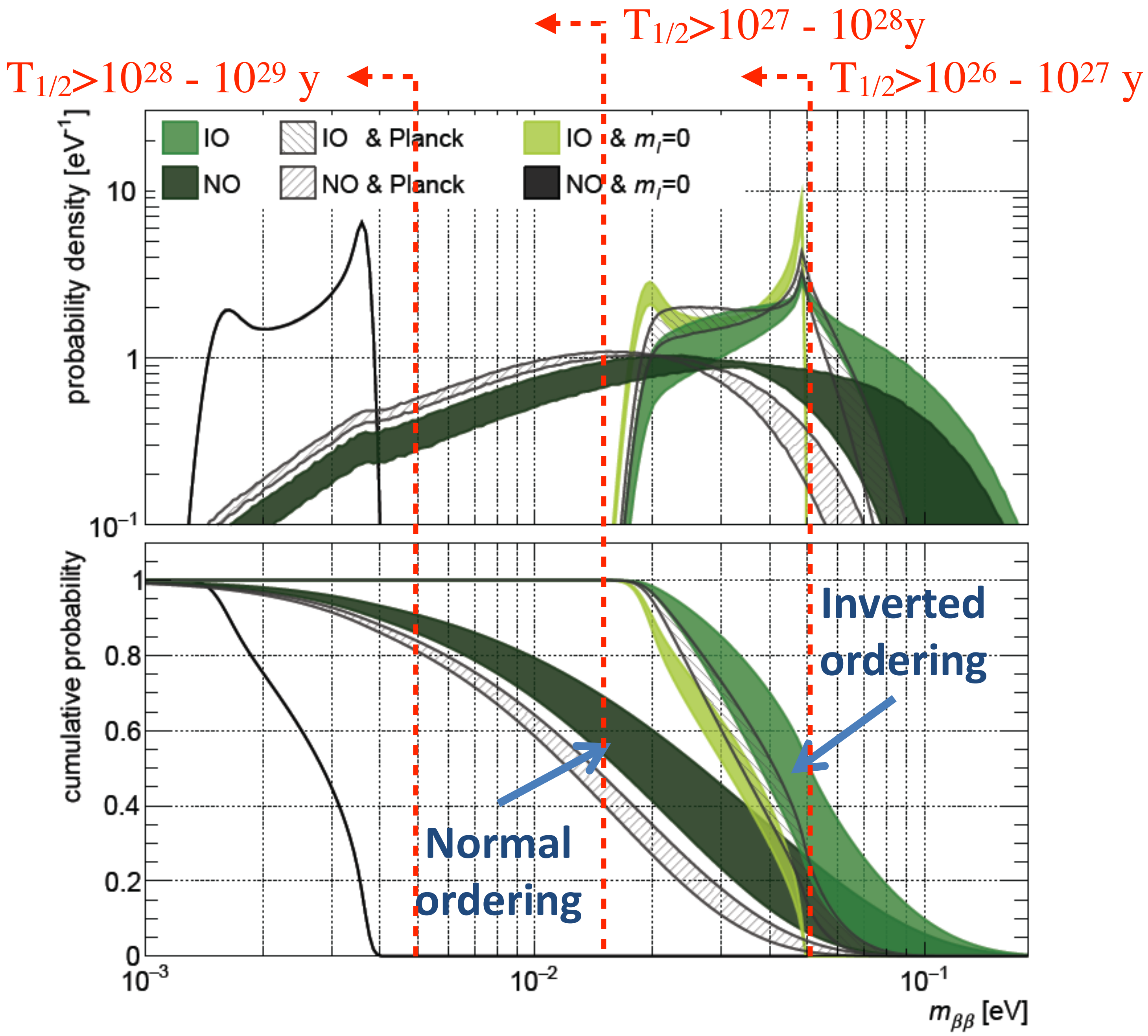

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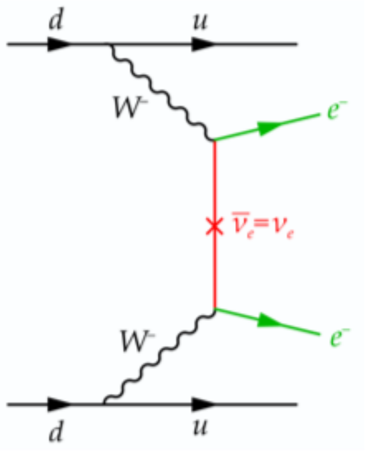

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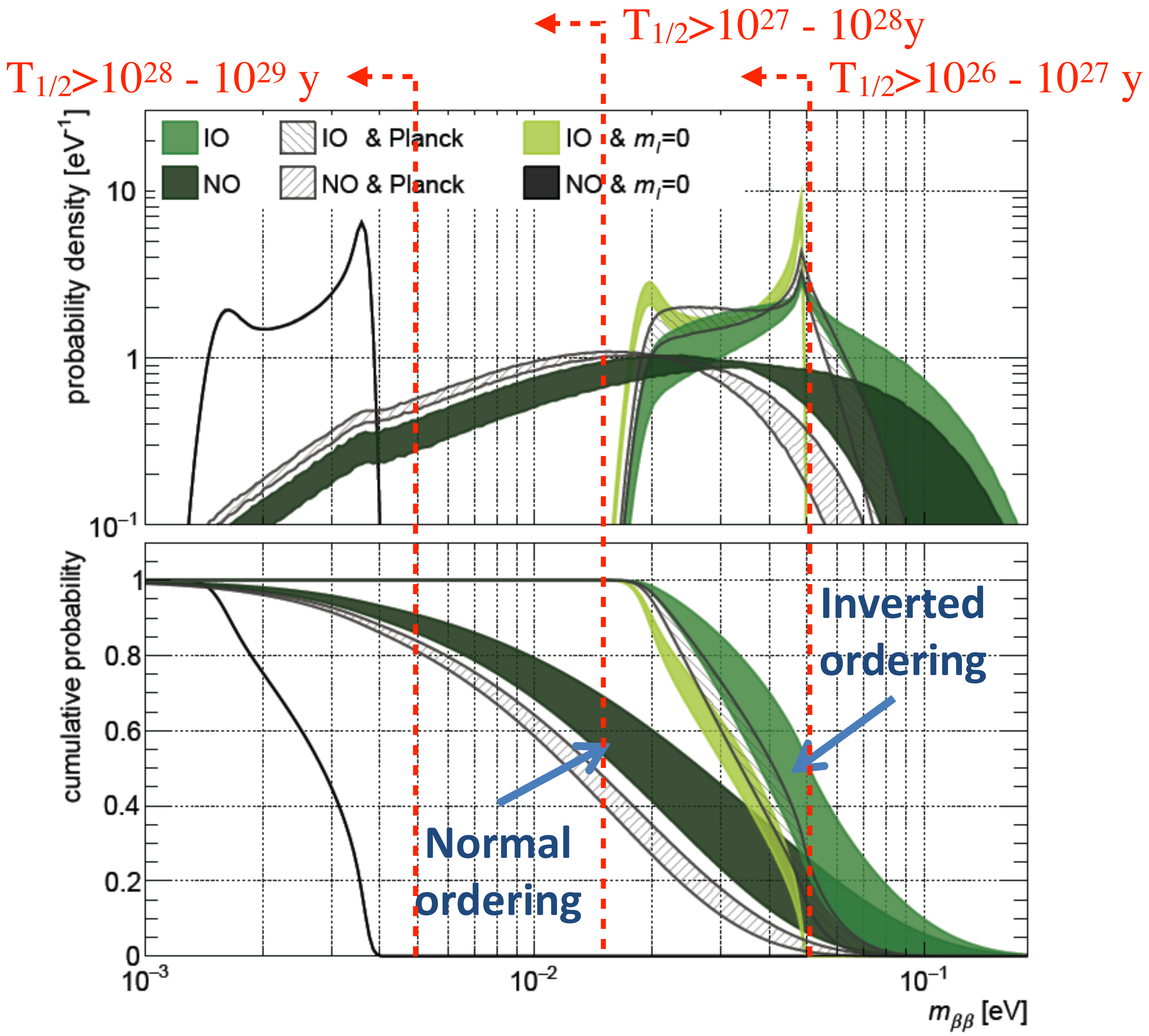

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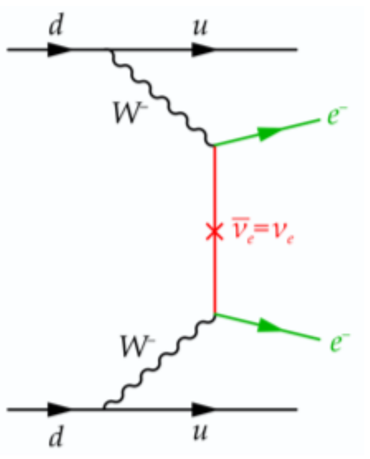
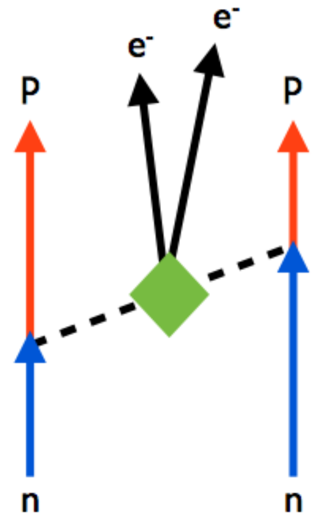


In NO case the leading contribution could come from short-range new physics effects.

Factor of 10-100 improvement in sensitivity next decade.



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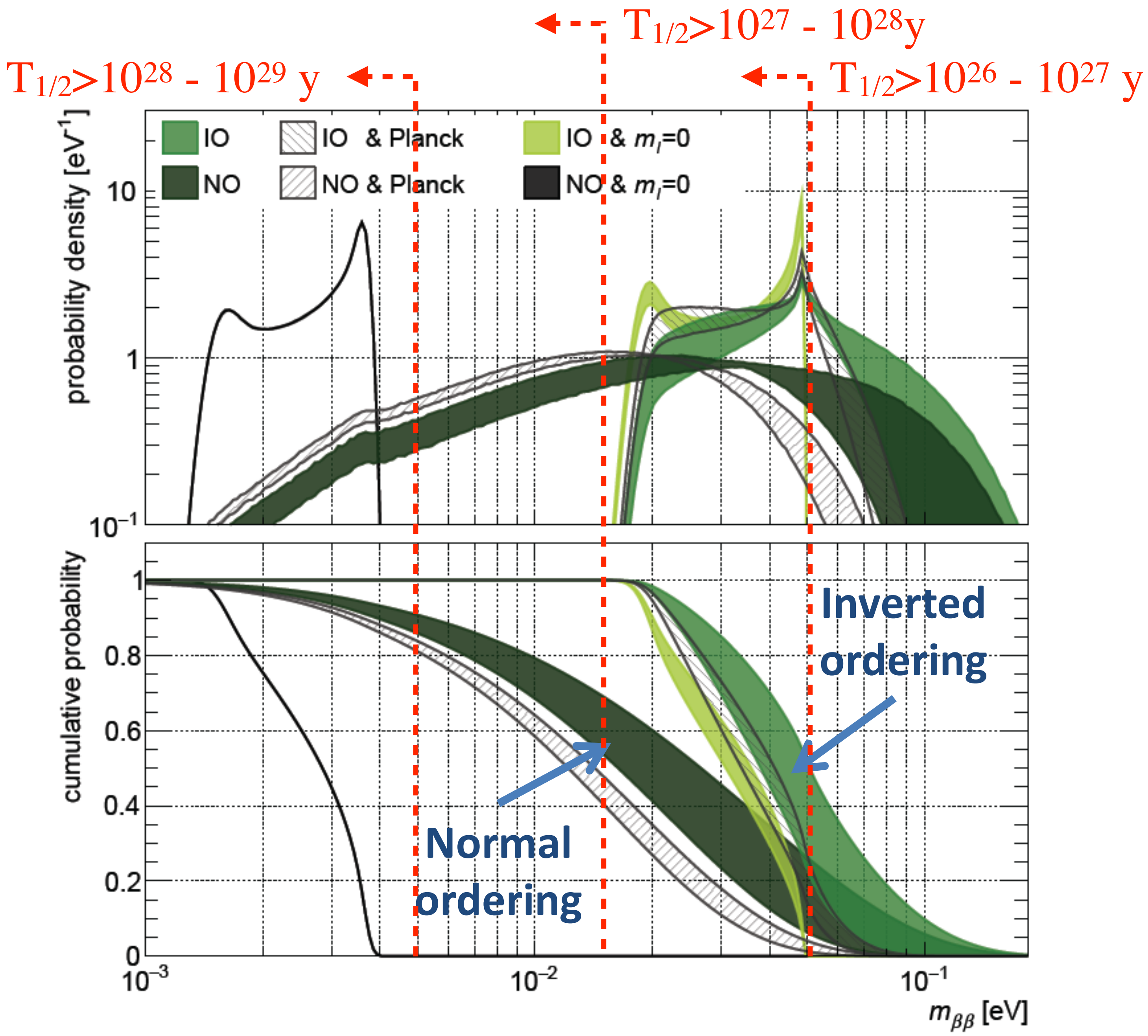

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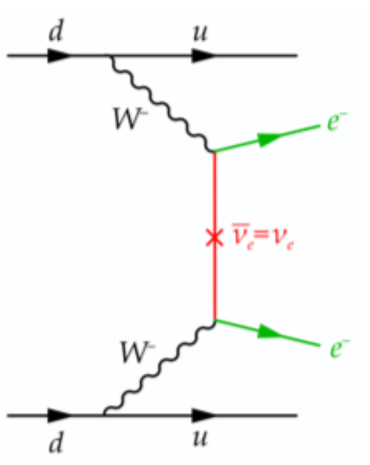

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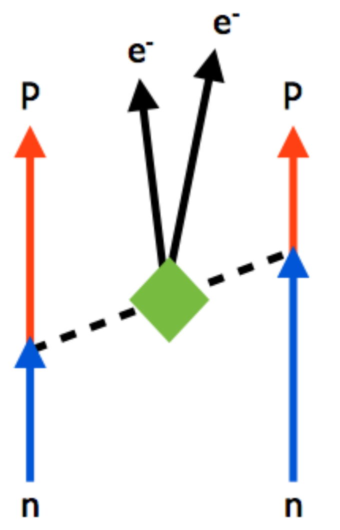

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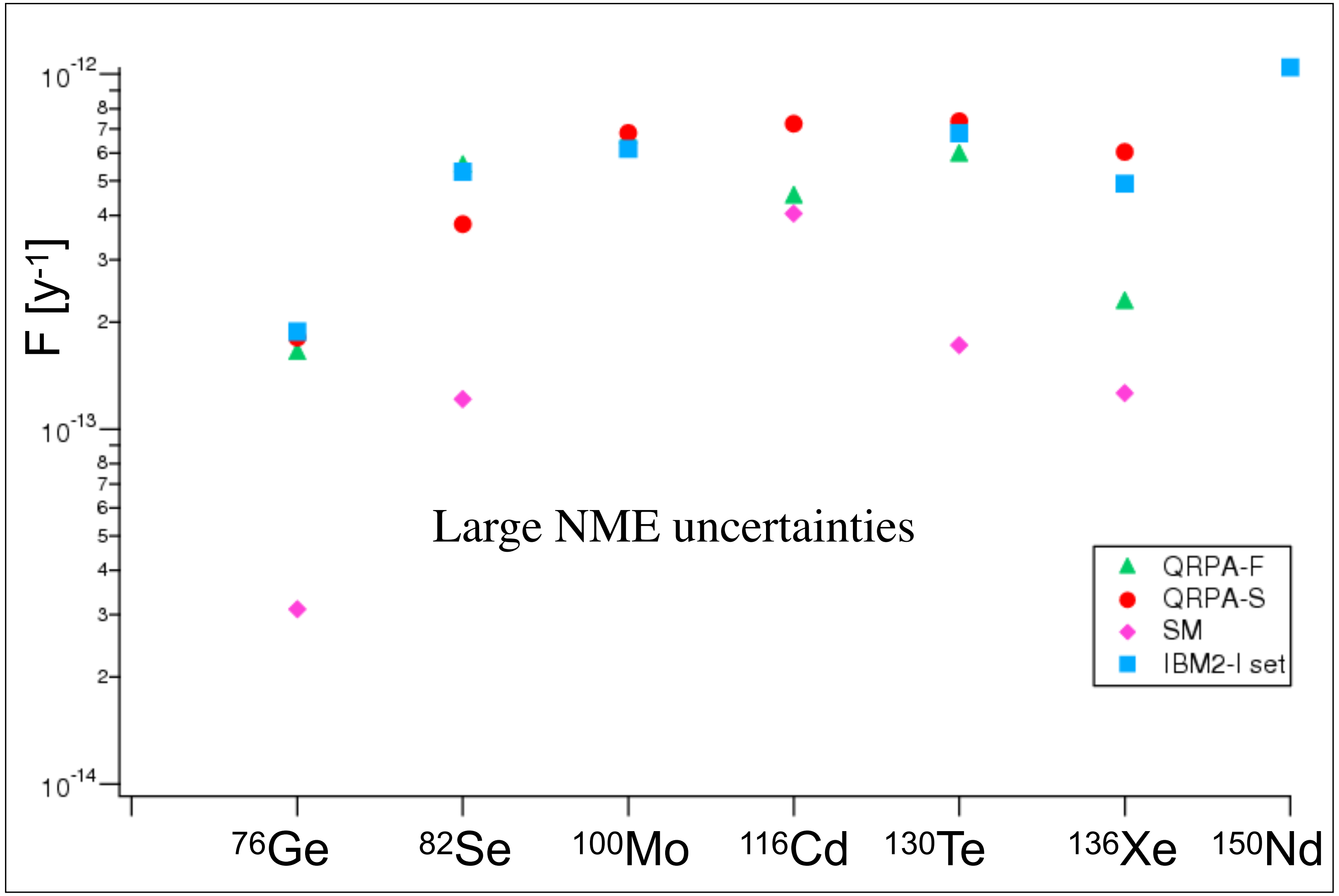
High discovery potential independently of neutrino mass ordering

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

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



$F = G_F^2 \Phi(Q,Z) |M_{0\nu}|^2 m_e^2$ [y^{-1}]

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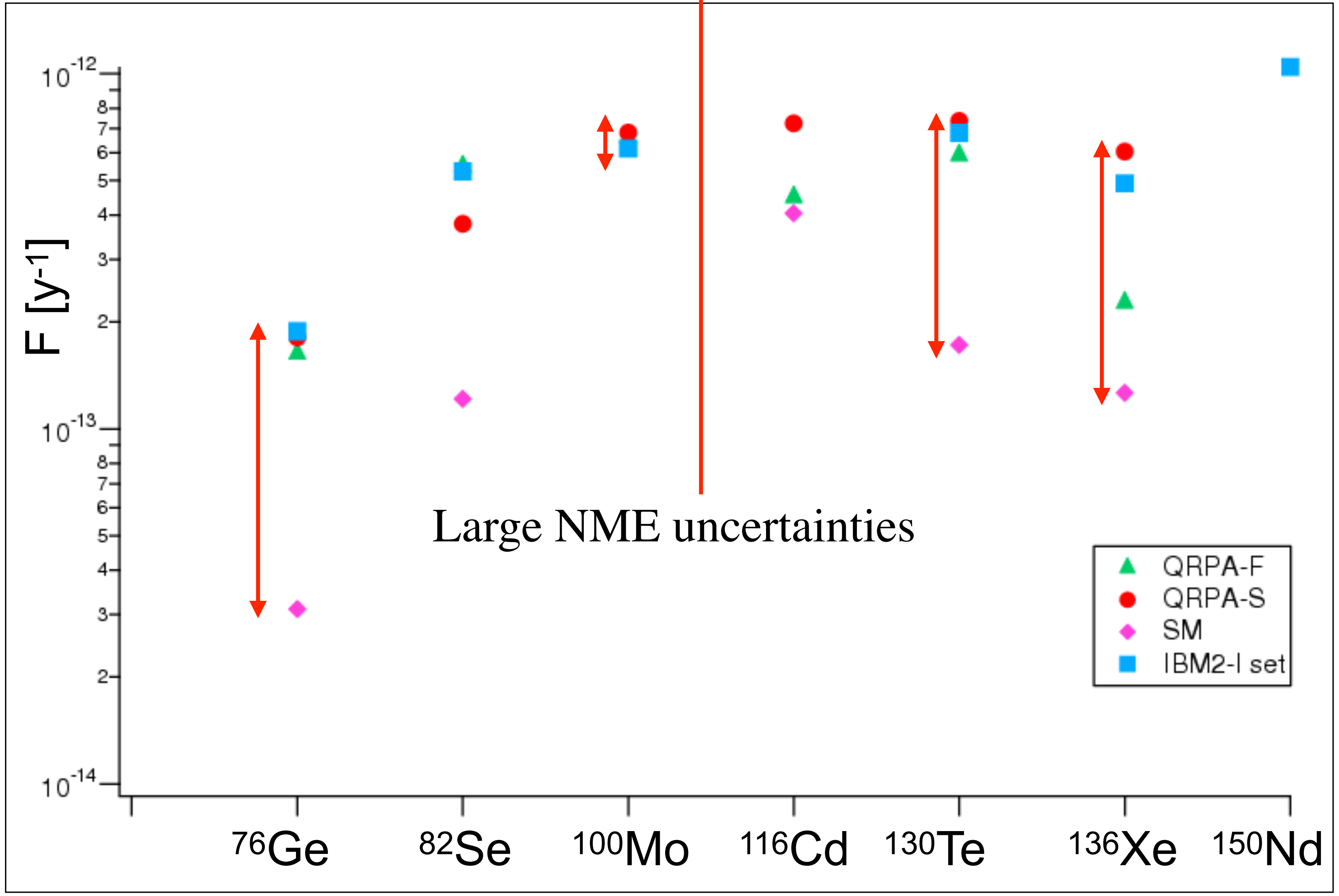

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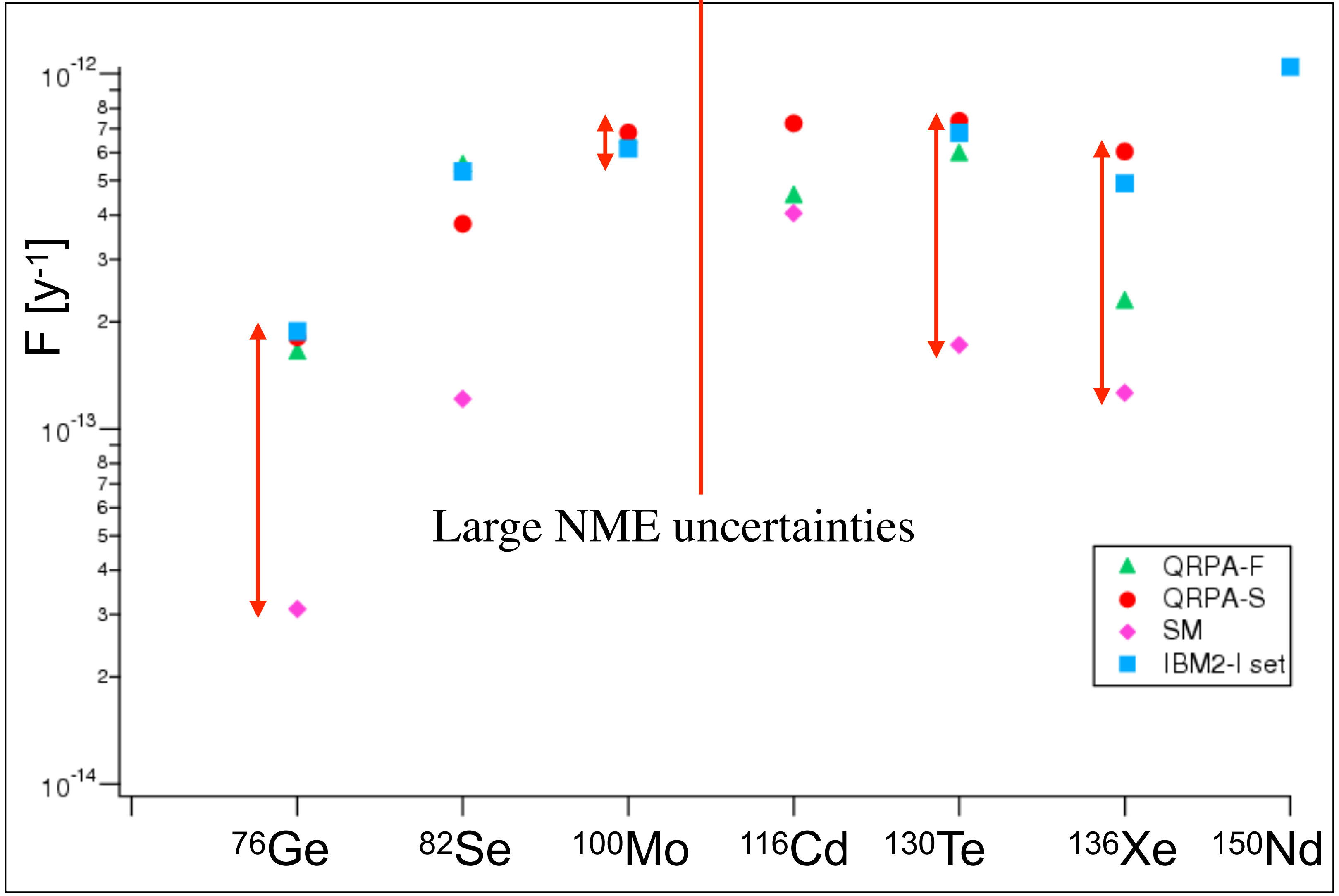
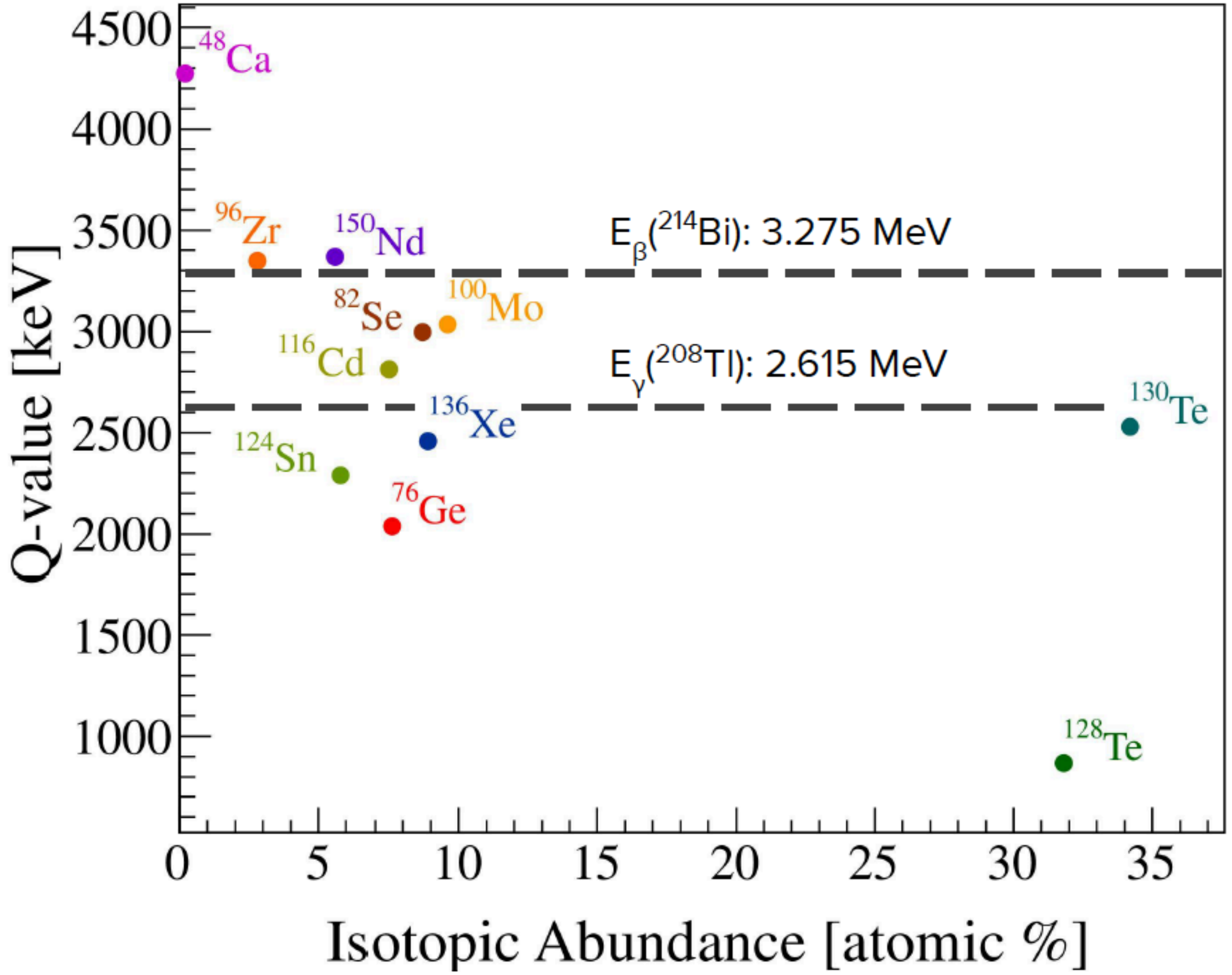


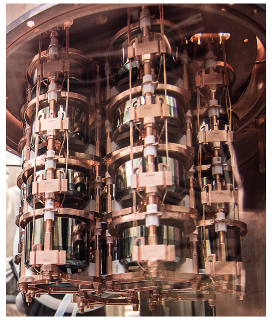
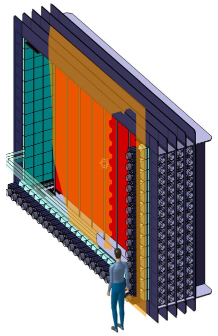
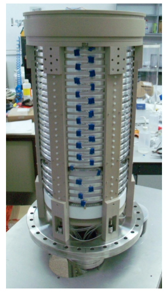
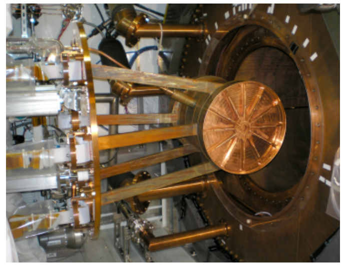
F = $G_F^2 \Phi(Q,Z) |M_{0\nu}|^2 m_e^2$ [y^{-1}]

Experimental constraints:

- Detector technology
- Backgrounds
- Isotopic abundance



Diverse Worldwide Experimental Program

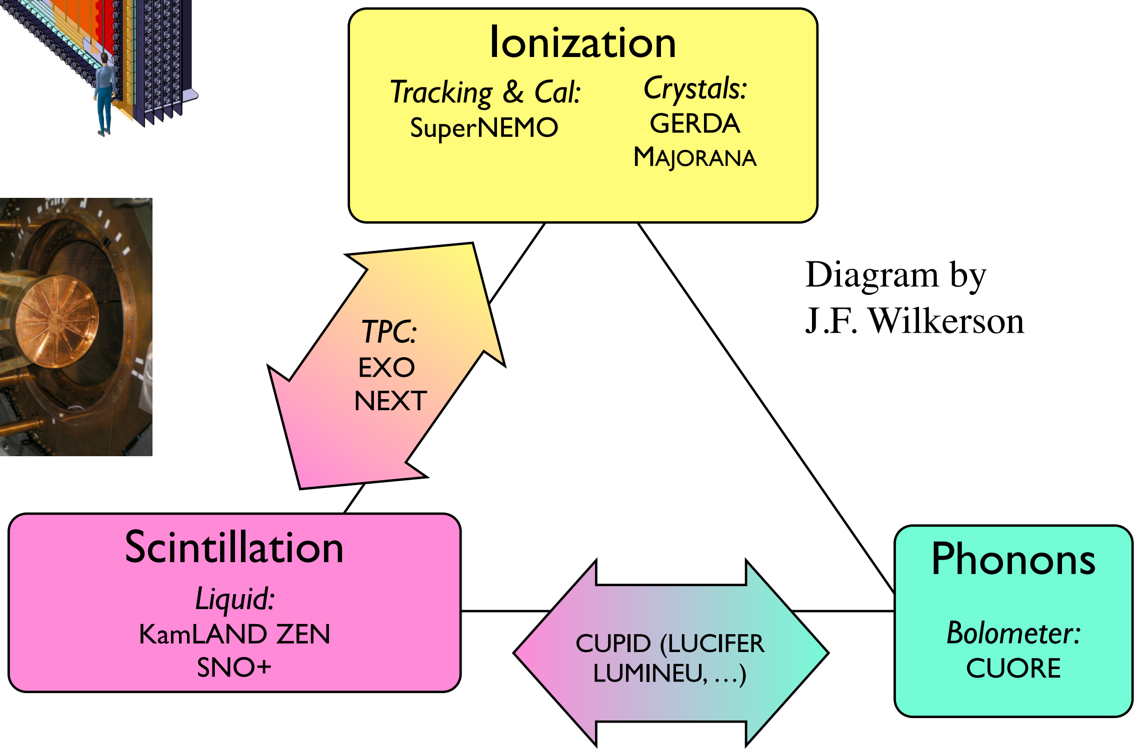
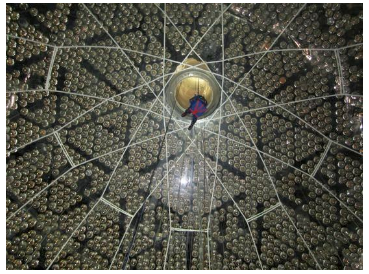
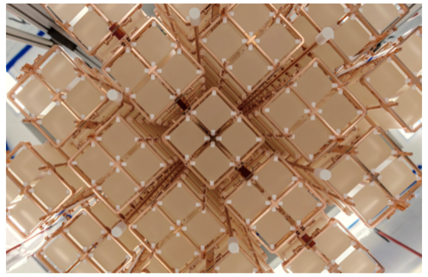


Diagram by
J.F. Wilkerson





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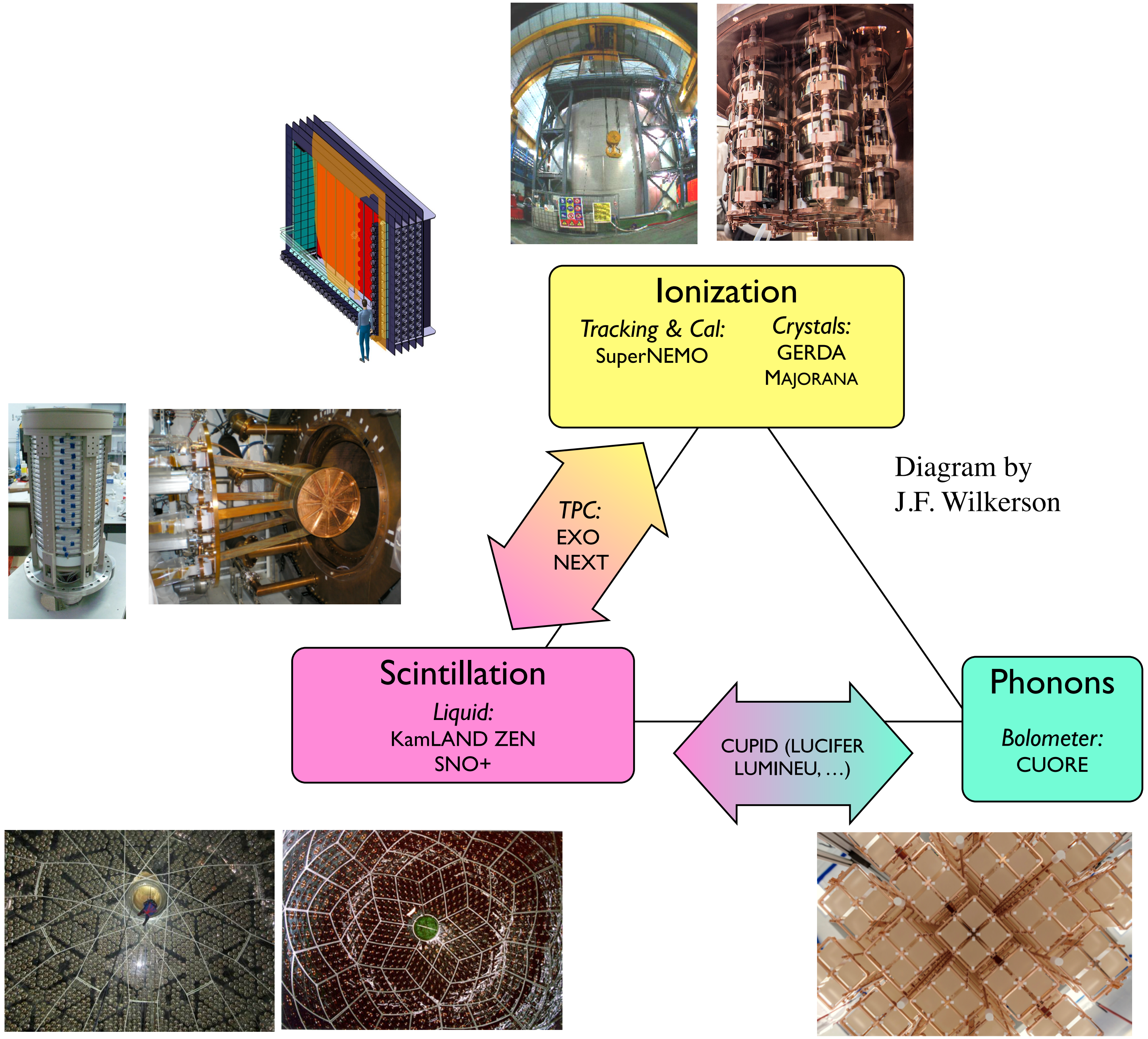


Important to maintain:

Multiple isotopes
Technological tradeoffs
Different systematics

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

Challenges

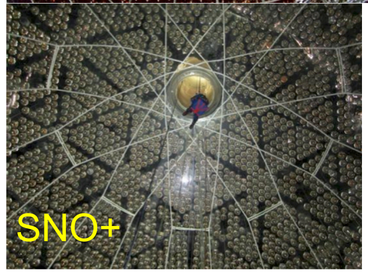
Practical challenge: very rare process !

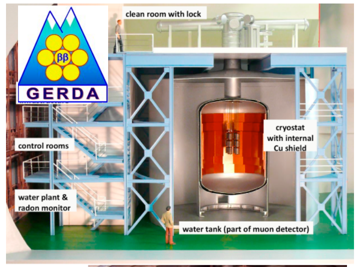
Half-life	Expected Signal (counts/tonne-year)	
10^{26} years	~50	current gen
10^{27} years	~5	next gen
10^{28} years	~0.5	next-next gen

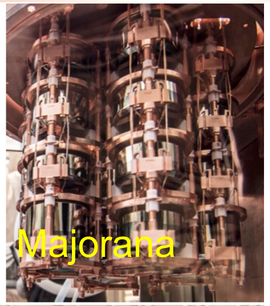
Experimental challenge -- sensitivity scaling:

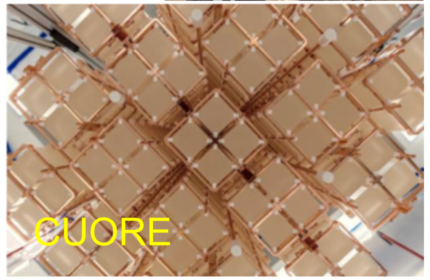
Non-zero backgrounds (most current experiments):

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









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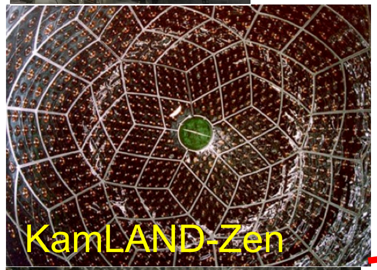

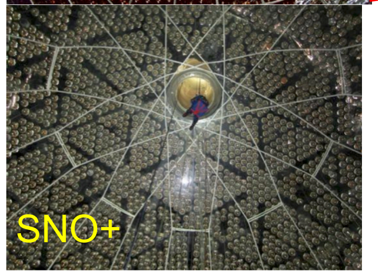

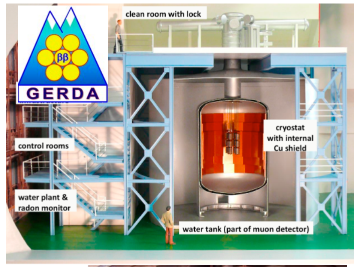

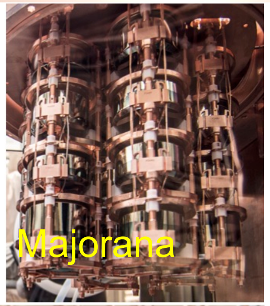

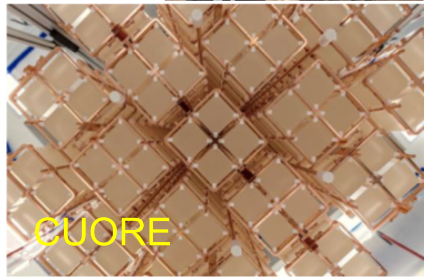

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current gen

next gen

next-next gen

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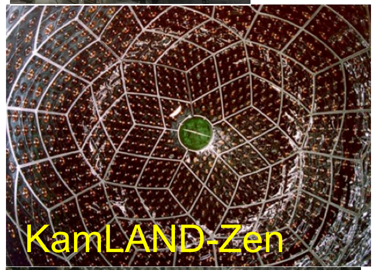

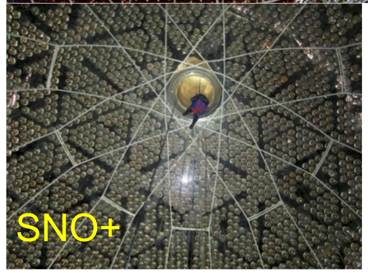

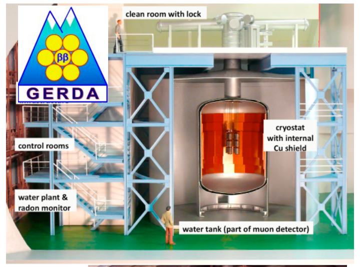

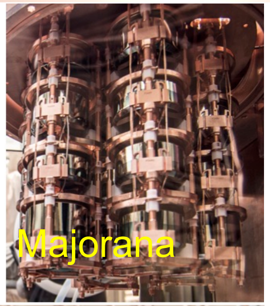

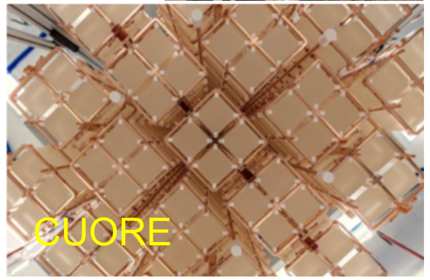

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Practical challenge: very rare process !

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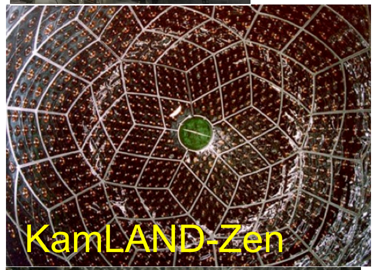

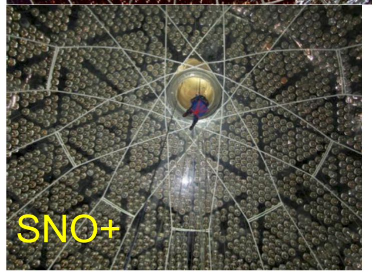

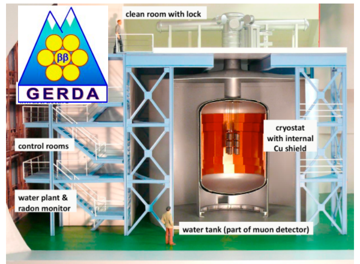

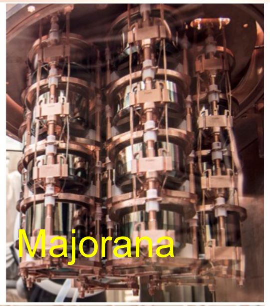

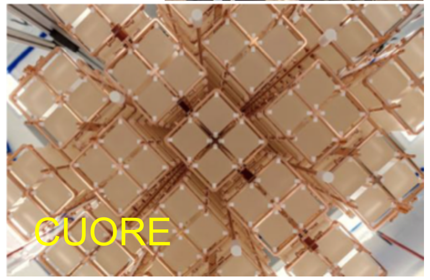

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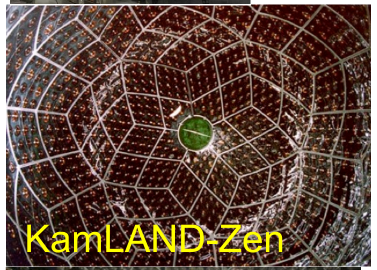

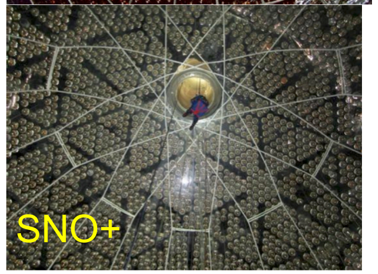

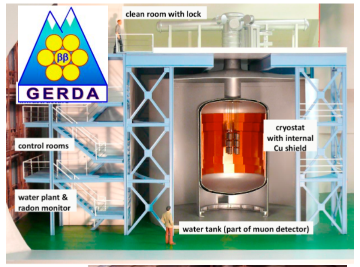

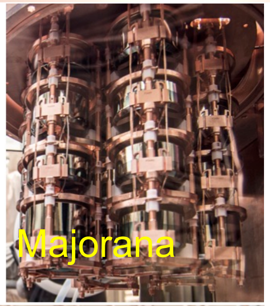

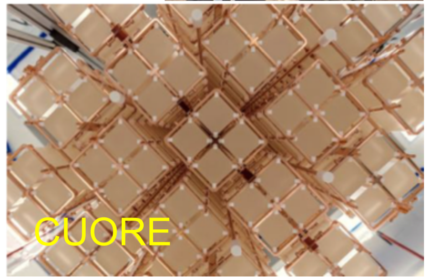

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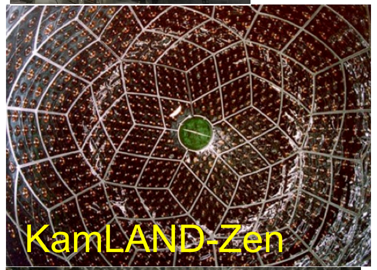

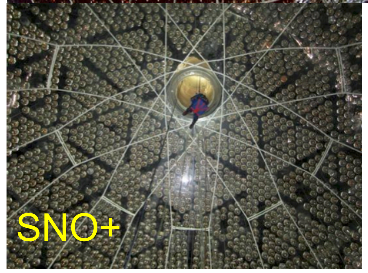

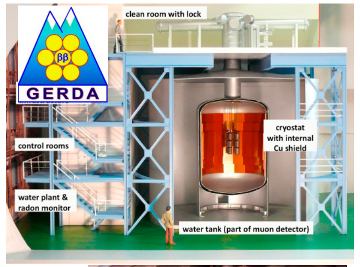

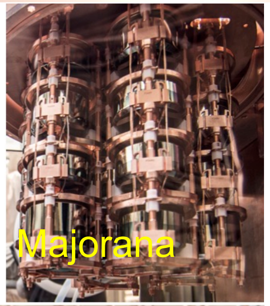

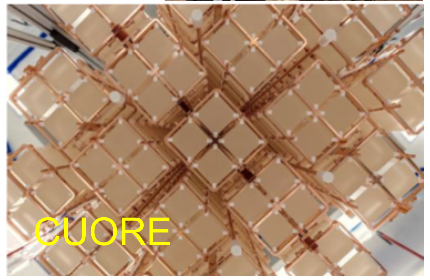

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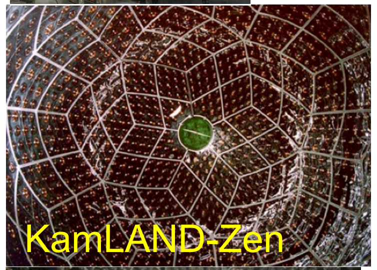

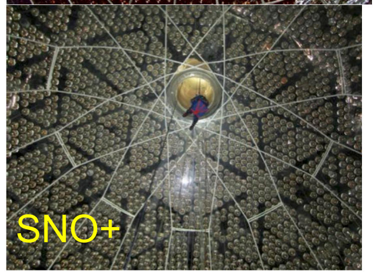

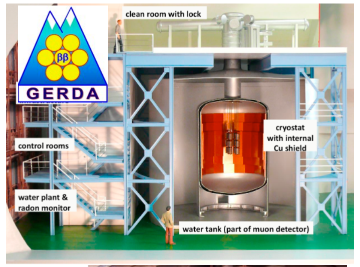

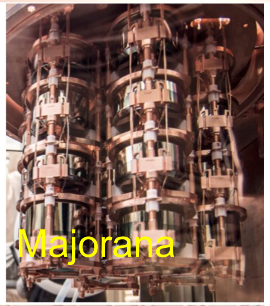

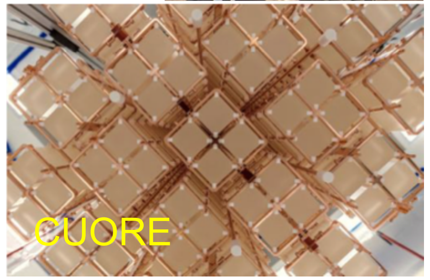

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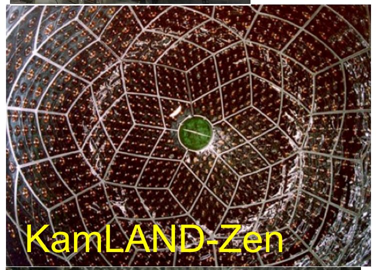

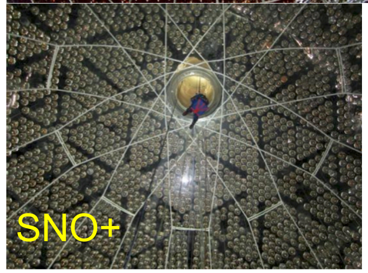

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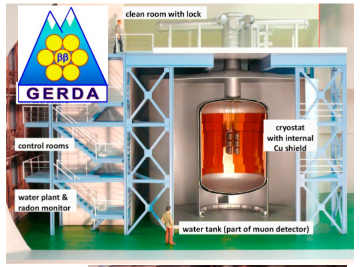
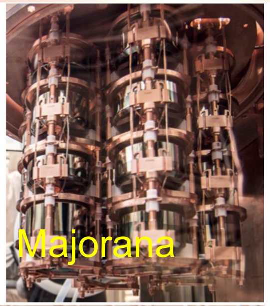
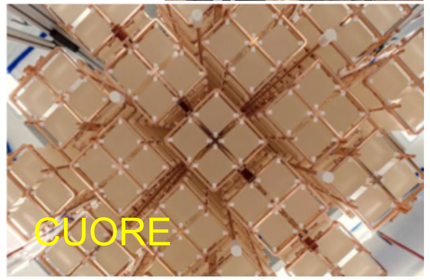
(background-free, next generation)







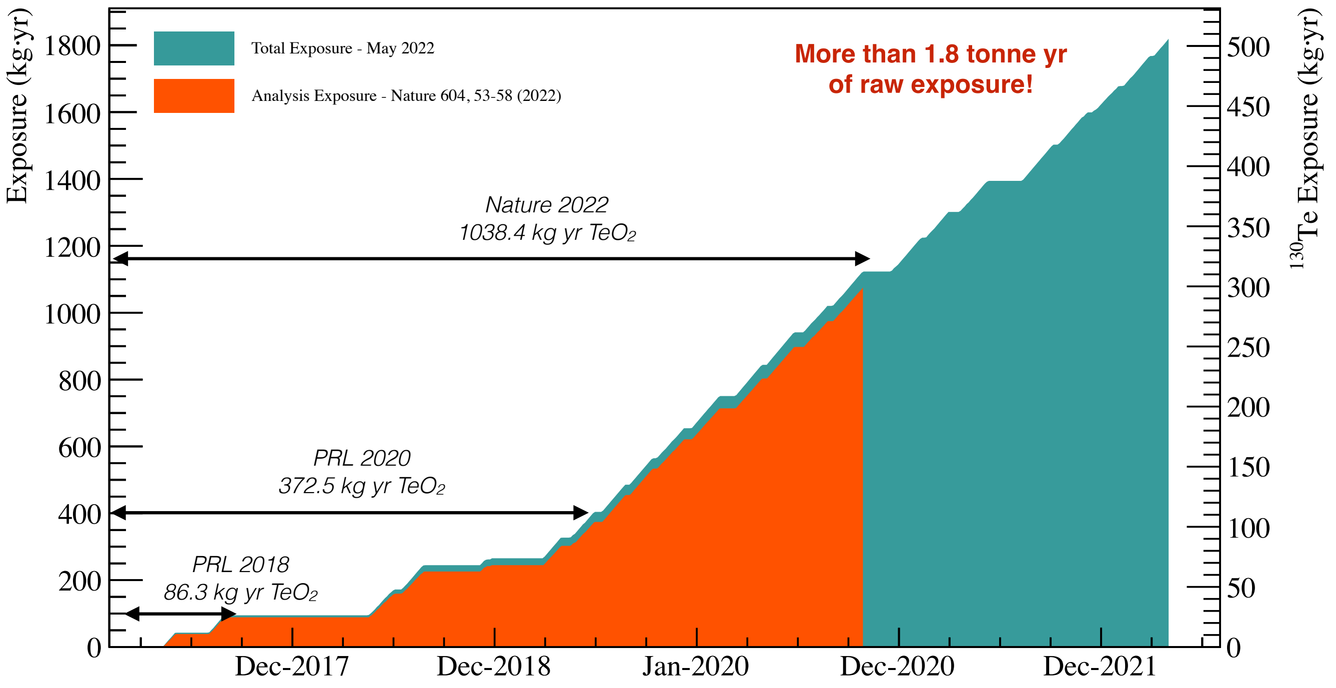
Most Recent Results: CUORE

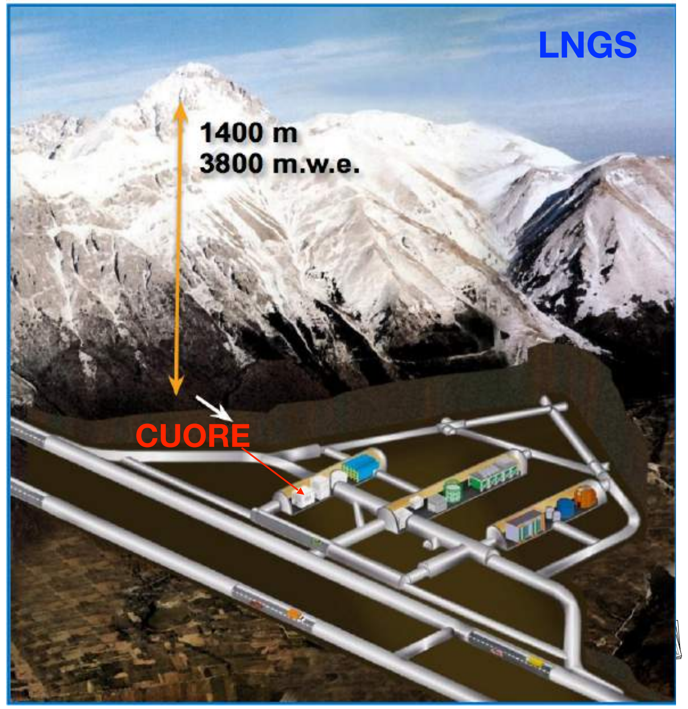
Array of 988 TeO_2 crystals

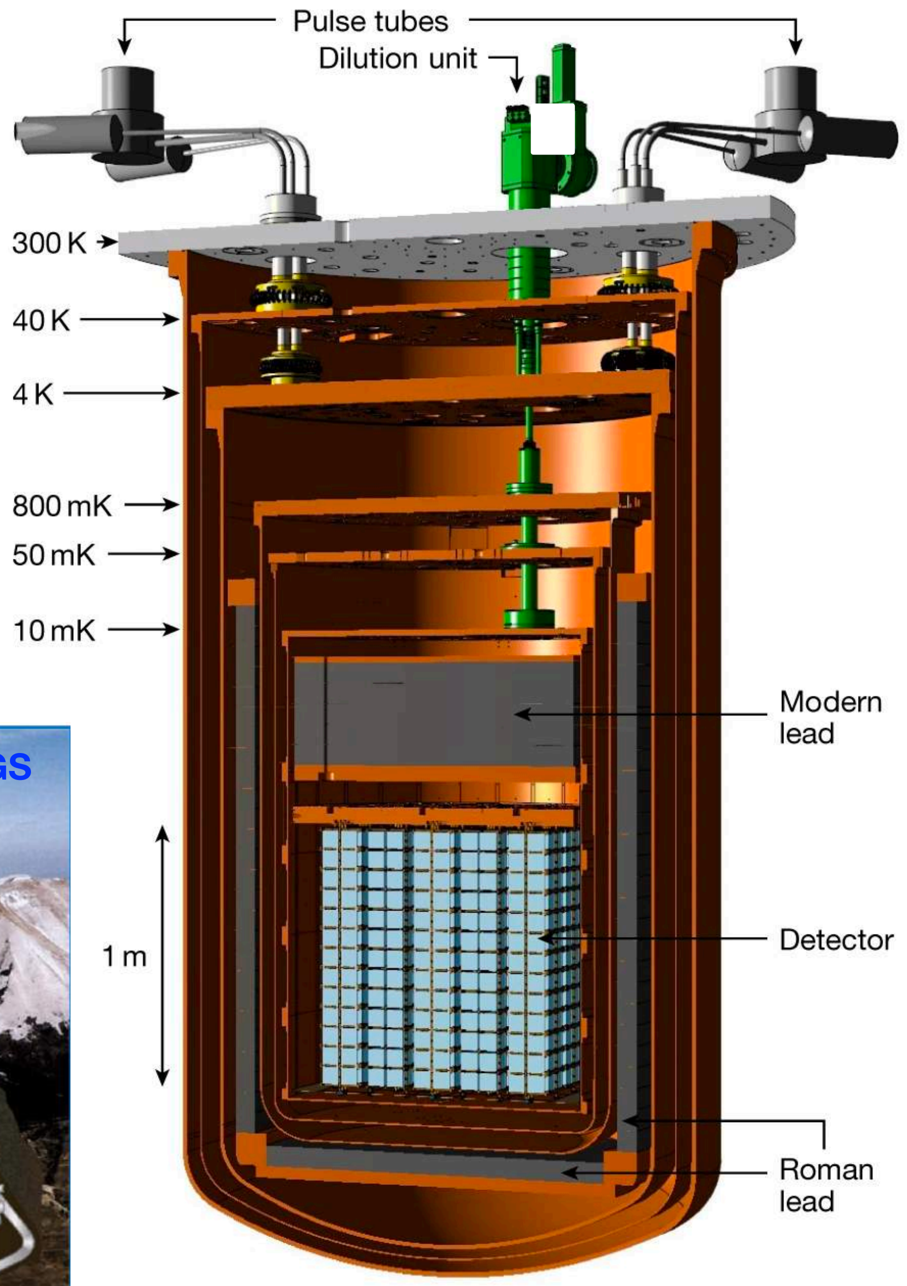
- **19** towers suspended in a cylindrical structure (**13** levels, **4** crystals each)
- 5x5x5 cm^3 (750g each); ^{130}Te: 34.1% natural isotope abundance

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





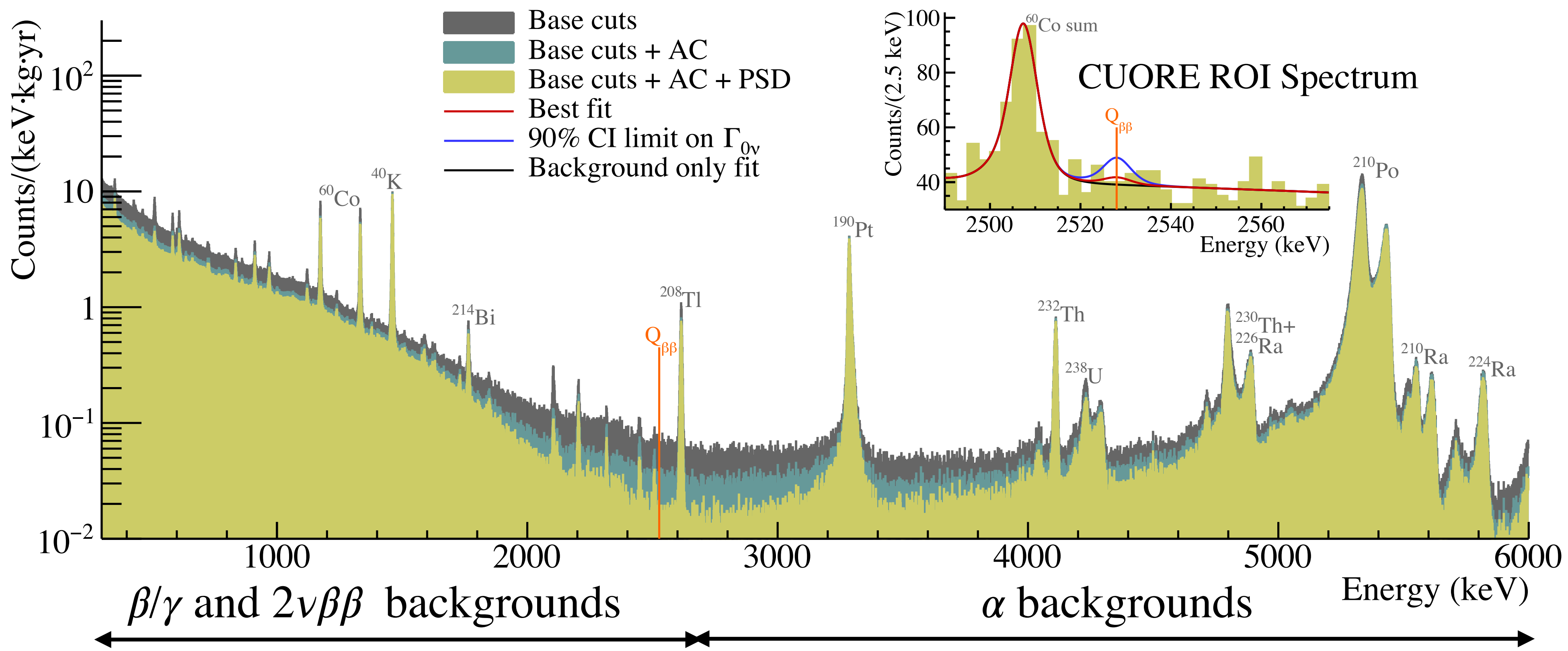


Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011

Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902,
https://doi.org/10.1016/j.ppnp.2021.103902

^{130}Te

CUORE results with 1 ton-year of exposure



- No evidence for 0νββ decay

$T_{1/2}^{0\nu} > 2.2 \times 10^{25}$ years (90 % CI)

- Interpretation in context of light Majorana neutrino exchange

$m_{\beta\beta} < 90 - 305$ meV

Nature **604**, 53 (2022)

Detector Performance Parameters

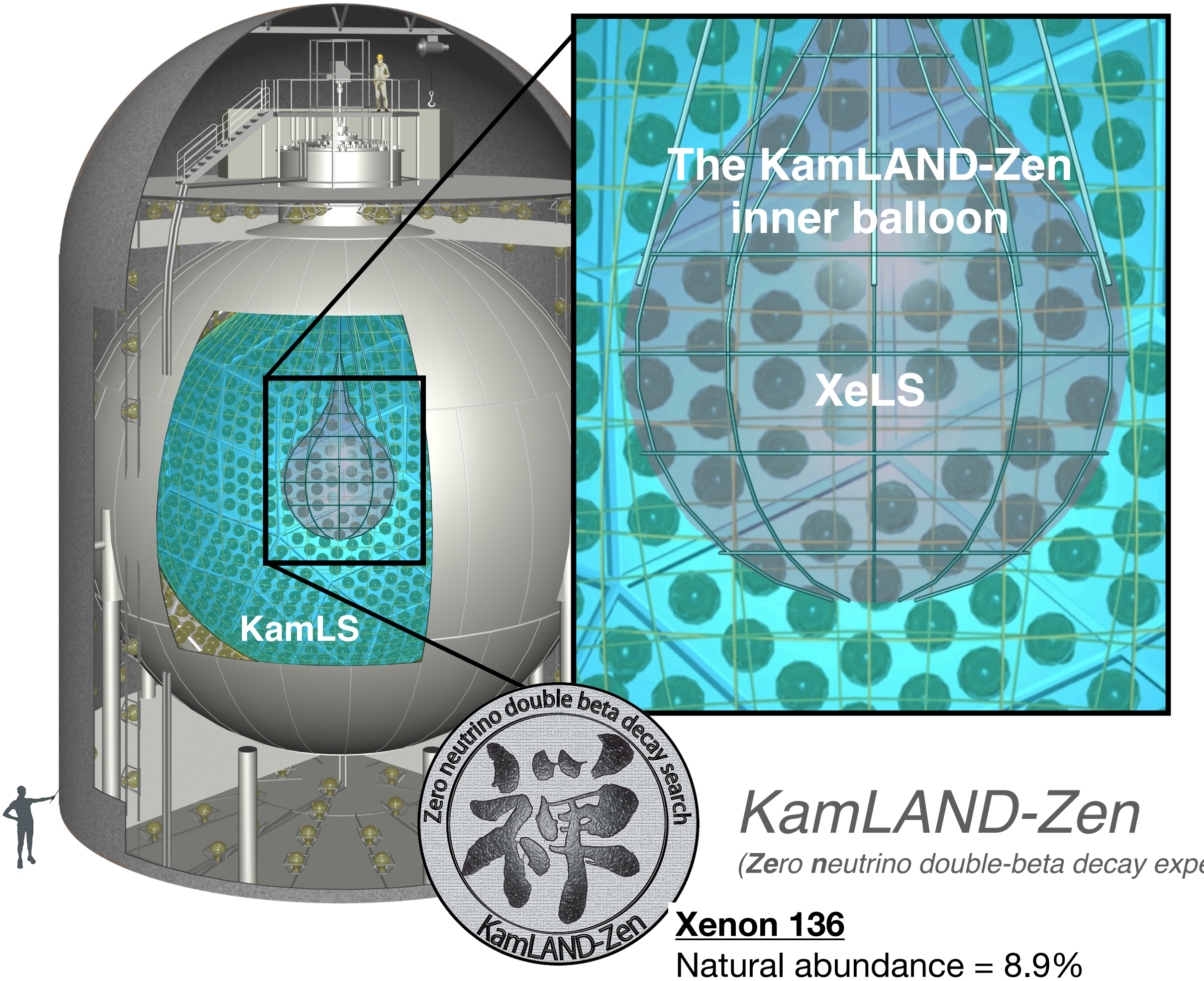
Background Index
$(1.49 \pm 0.04) \cdot 10^{-2}$ counts/(keV·kg·yr)

Characteristic FWHM *ΔE* at $Q_{\beta\beta}$
7.8(5) keV

- Total exposure in TeO_2: 1038.4 kg*y
- Bayesian Analysis (BAT)
- Likelihood model: flat continuum (BI), posited peak for 0νββ (rate), peak for ^{60}Co (rate + position)
- Unbinned fit on physical range (rates non-negative), uniform prior on $\Gamma_{0\nu}$
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

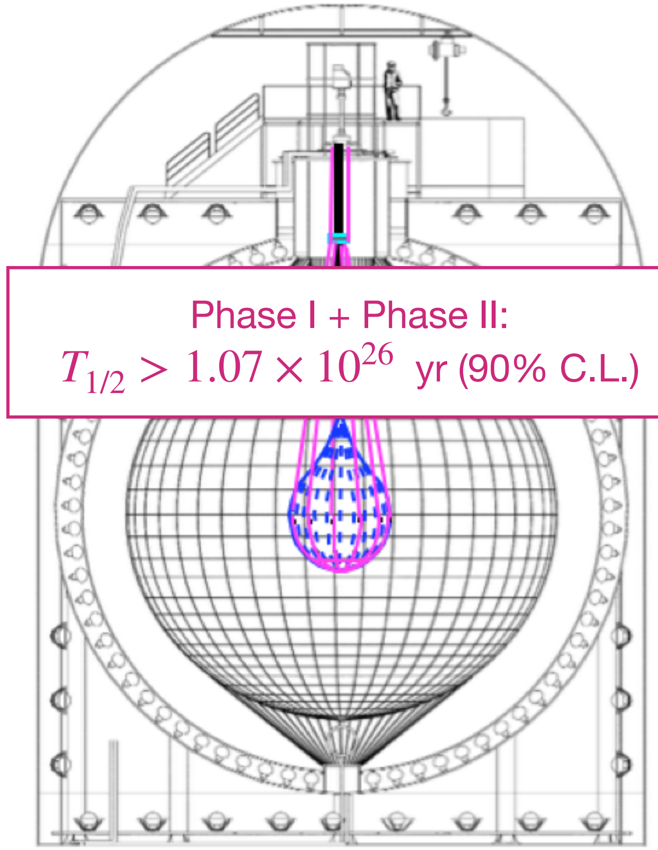
Most Recent Results: KamLAND-Zen

C. Grant

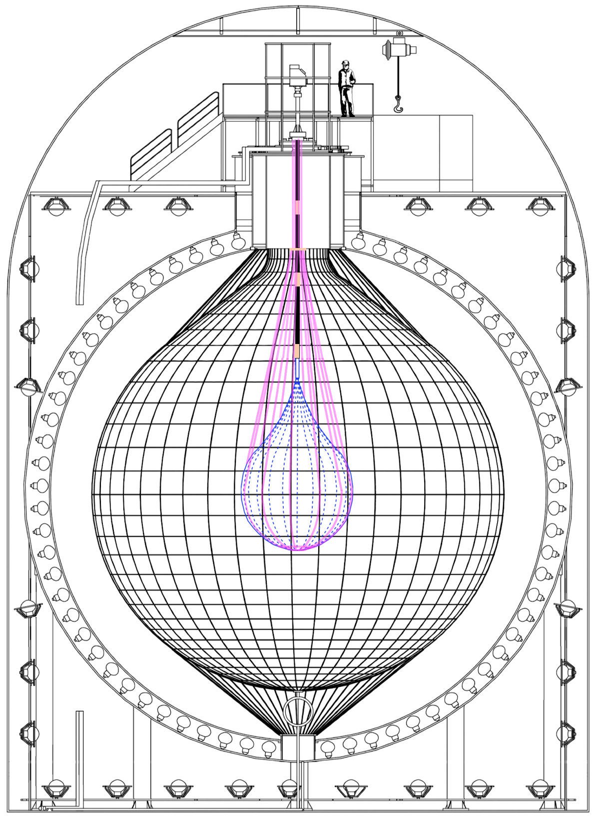


KamLAND-Zen

*(**Zer**o neutrino double-beta decay experiment)*



Phase I + Phase II:
$T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)



Xenon 136
Natural abundance = 8.9%
Isotopic enrichment = 90.86%
3% wt soluble in Liquid Scintillator

KamLAND-Zen 400:

- Mini-balloon Radius = 1.54 m
- Xenon mass = 320 ~ 380 kg
- Duration: 2011 ~ 2015

KamLAND-Zen 800:

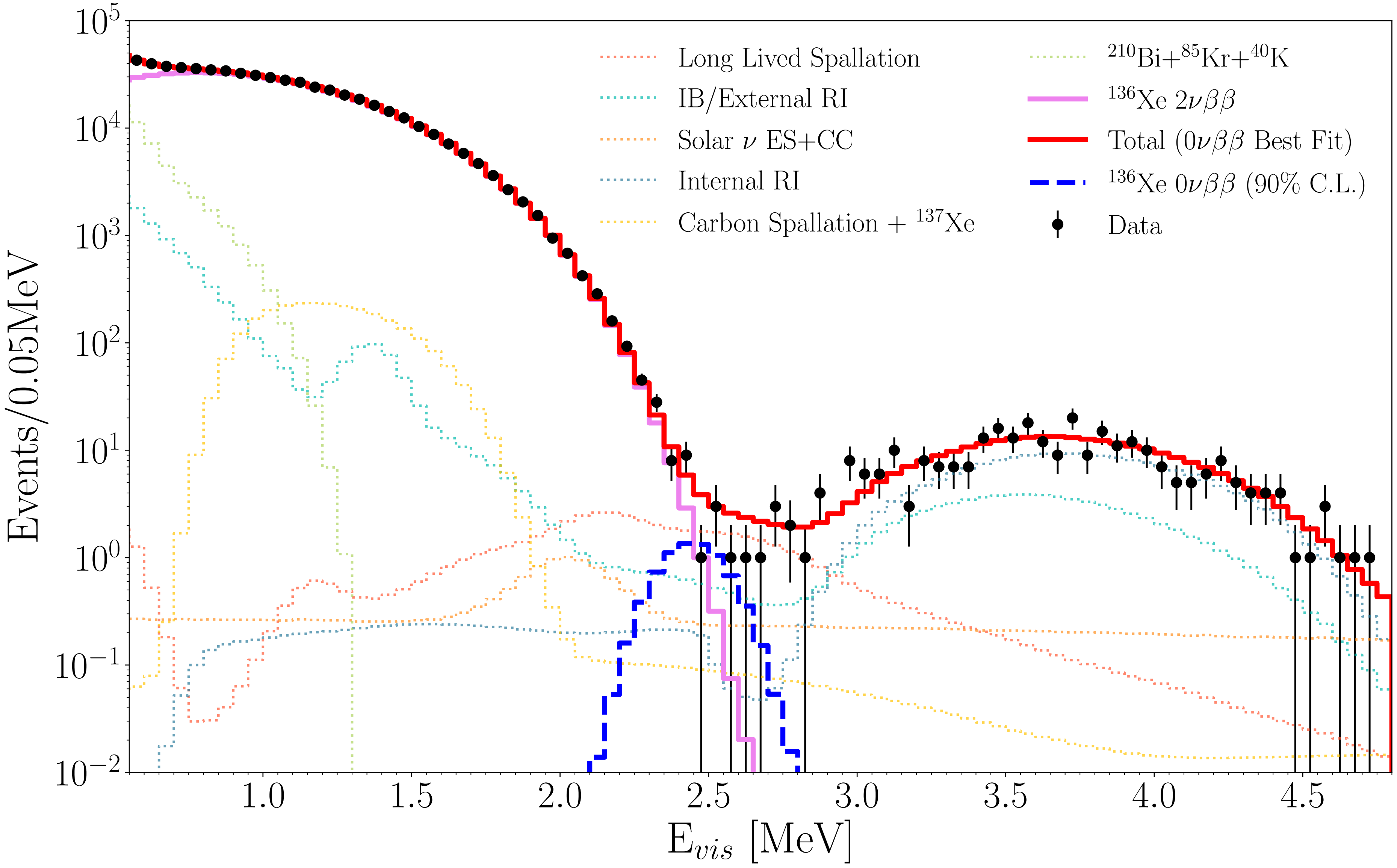
- Mini-balloon Radius = 1.90 m
- Xenon mass = 745±3 kg
- Data taking started Jan. 2019

New results from KLZ-800: arXiv:2203.02139

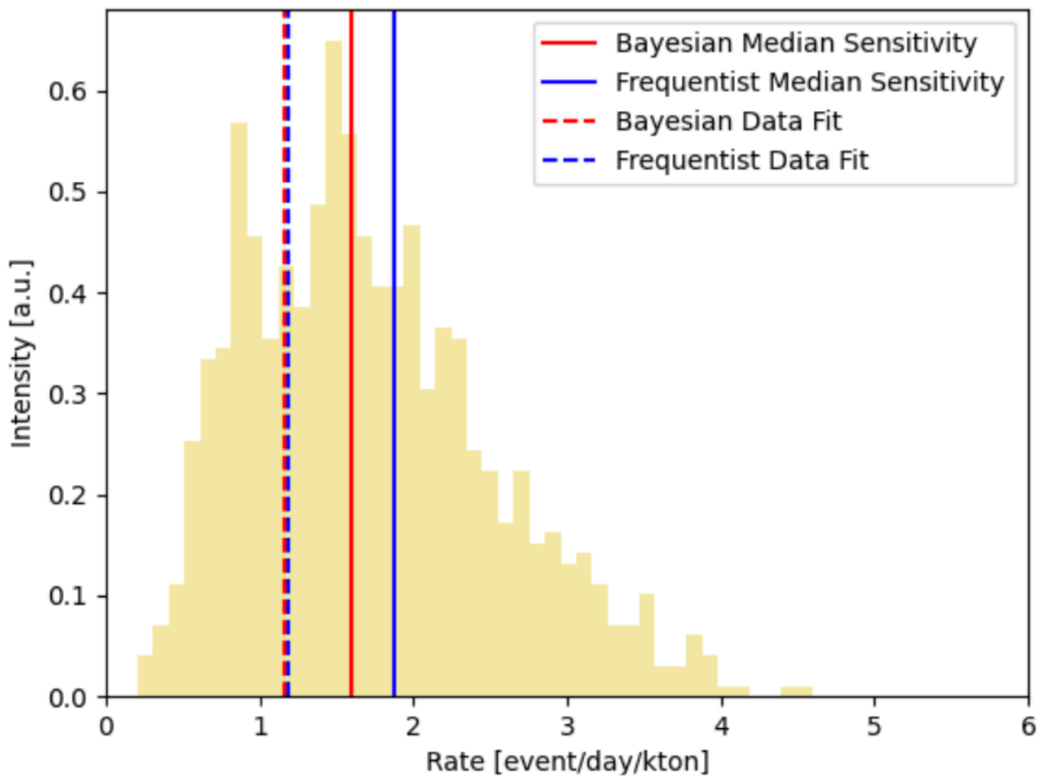
KamLAND-Zen Results with ~1 ton-year of ^{136}Xe exposure

Total Livetime = 523 days Exposure = 970 kg·yr

C. Grant



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



Median Sensitivity:

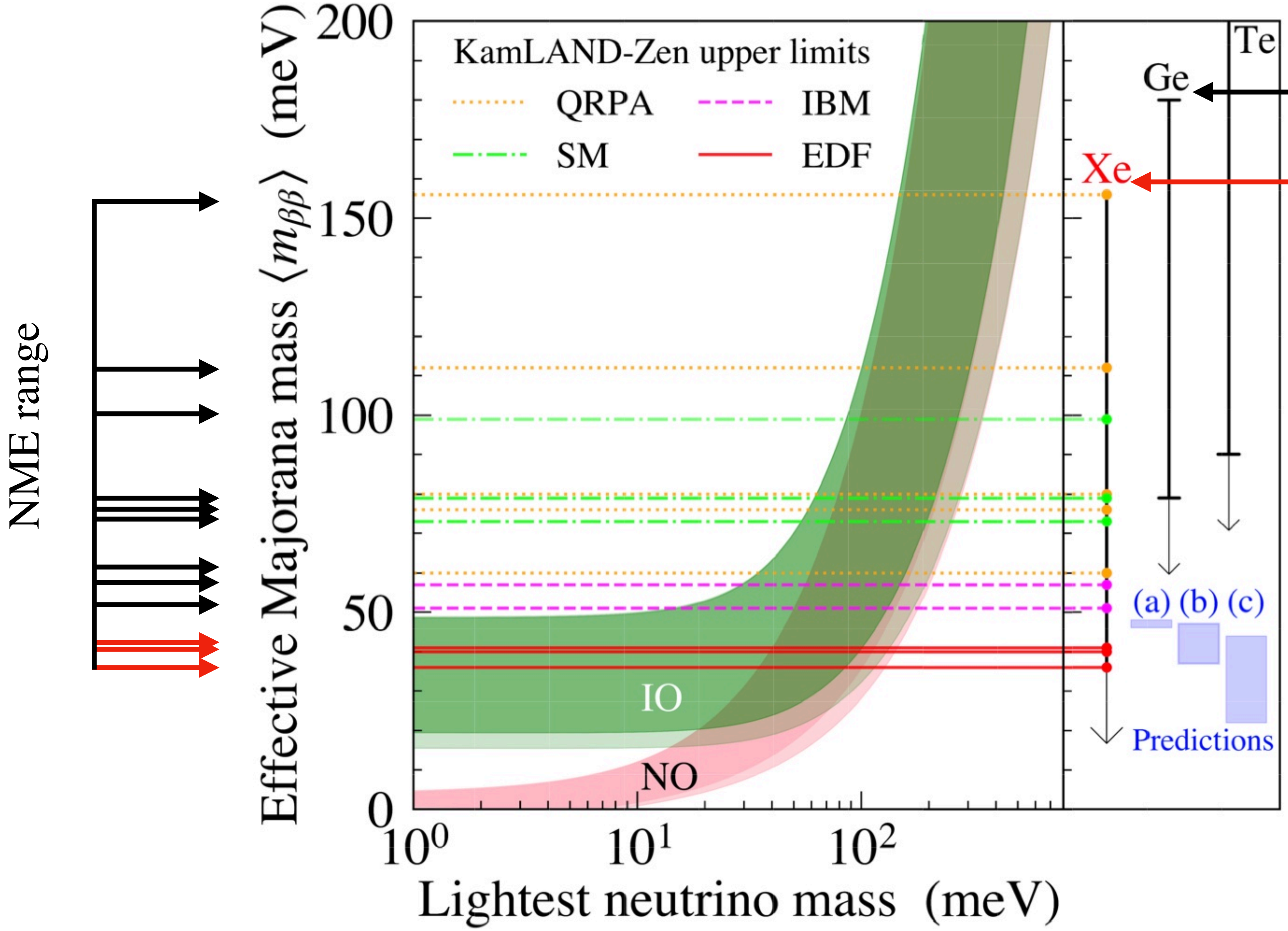
$T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{26}$yr (90 % C.I.)

Combination of KLZ-400 and KLZ-800

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

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

Current Constraints on $m_{\beta\beta}$



CUORE: Nature **604**, 53 (2022)
GERDA: PRL **125**, 252502 (2020)
KamLAND-Zen: arXiv:2203.02139

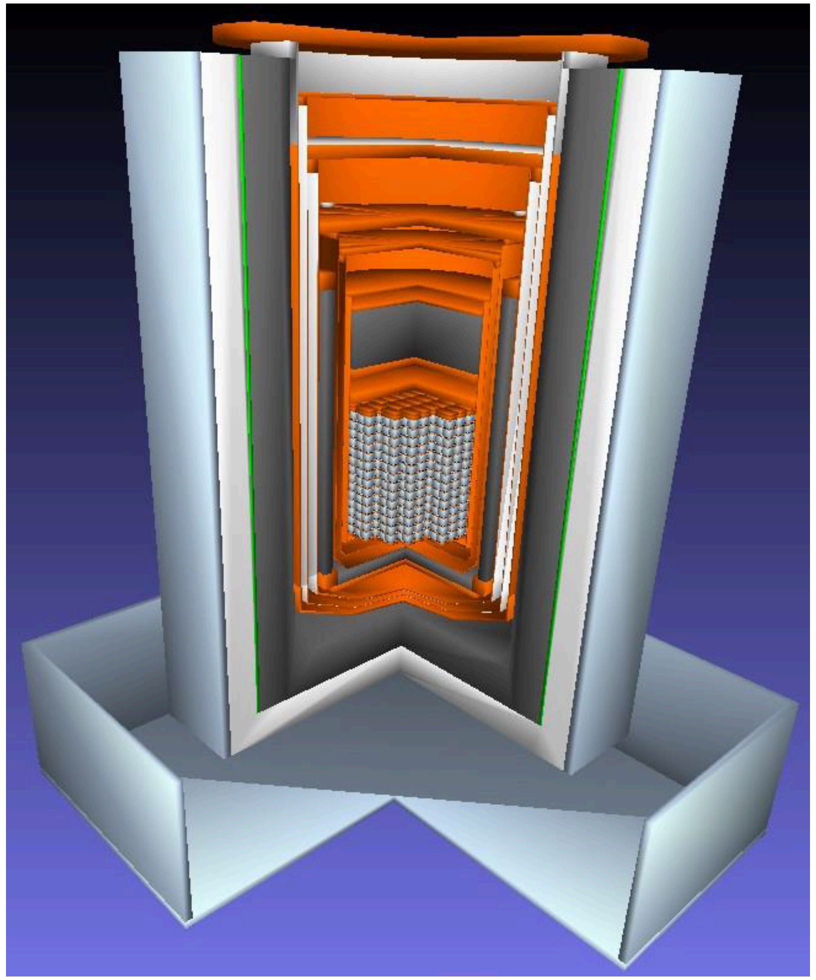
Current experiments starting to approach IO range

Next-generation target: $m_{\beta\beta}$<15-209 meV

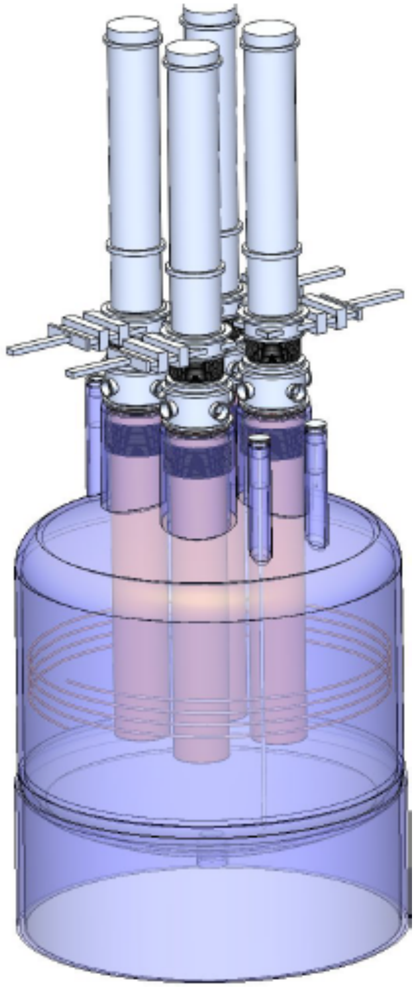
(Select) theory predictions

(a) Phys. Rev. D 86, 013002
(b) Phys. Lett.B 811, 135956
(c) Euro.Phys.J.C 80, 76

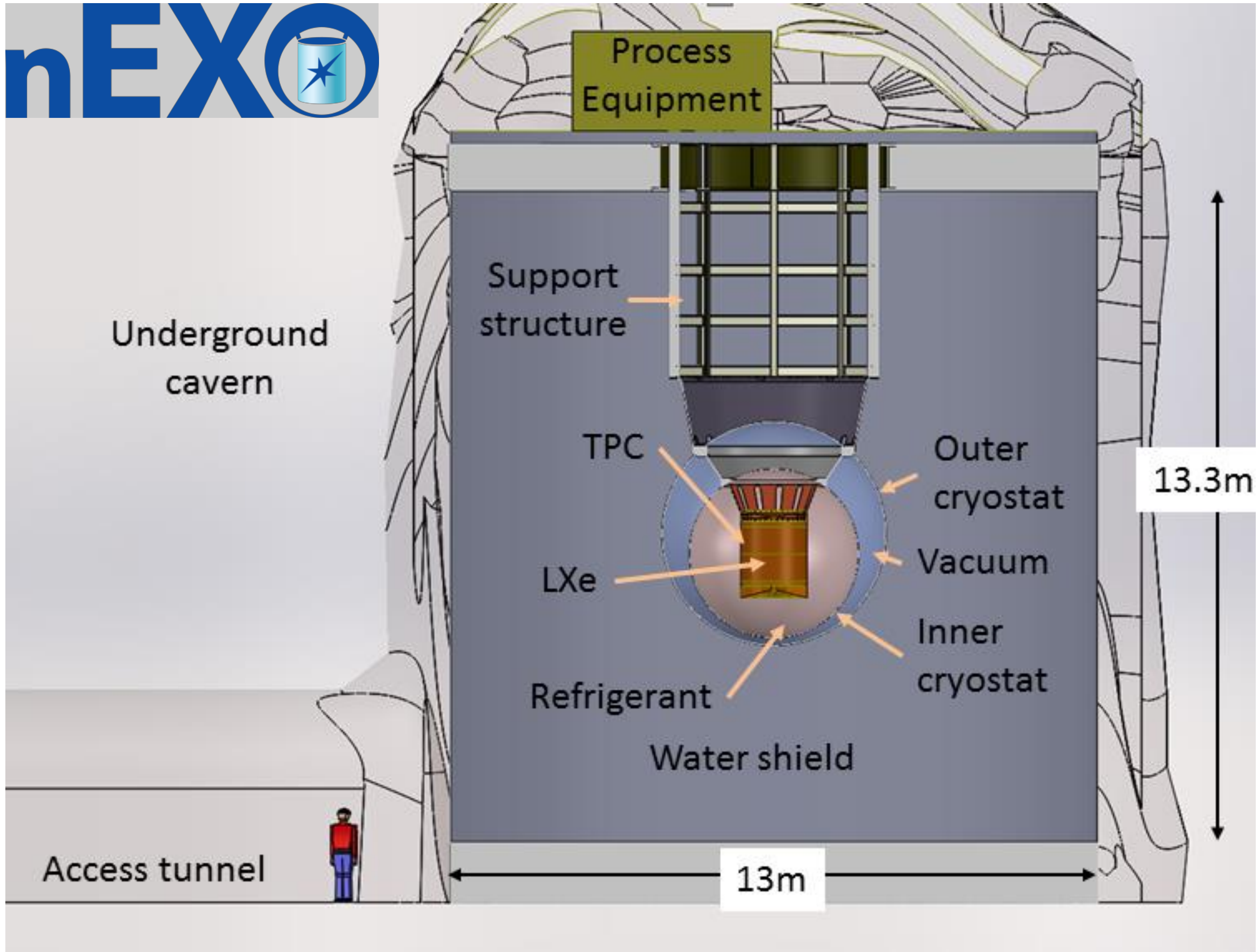
Next-Generation (Ton-Scale) Program (US-centric view)



CUPID



LEGEND-1000



Aim for $0\nu\beta\beta$ discovery if neutrino masses are above ~10-20 meV in the next decade

Highest priority new experiments in the 2015 Long Range Plan for Nuclear Science

Next Generation: LEGEND

***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

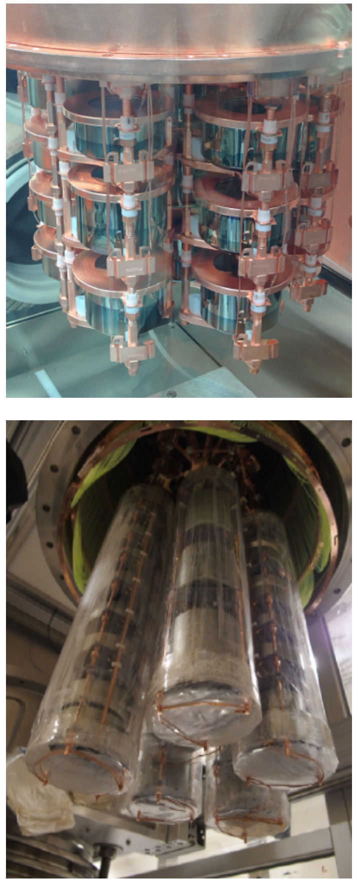
Enriched ^{76}Ge diodes (HPGe detectors): best energy resolution

LEGEND combines the best aspects of GERDA and MJD:

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

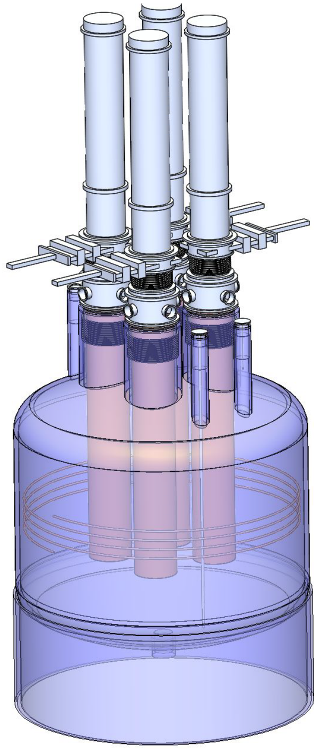
Majorana Demonstrator

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)

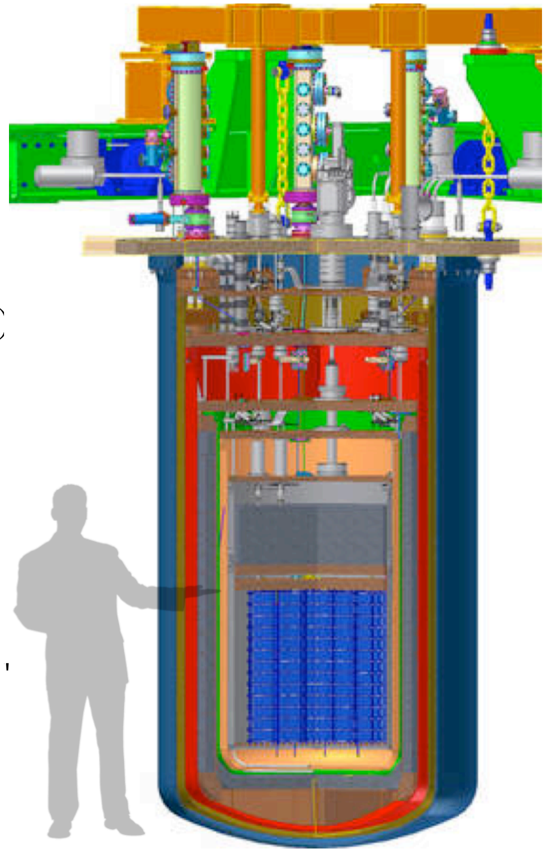
CUORE Upgrade with Particle ID (CUPID): LNGS

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)

Mature concept based on:

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

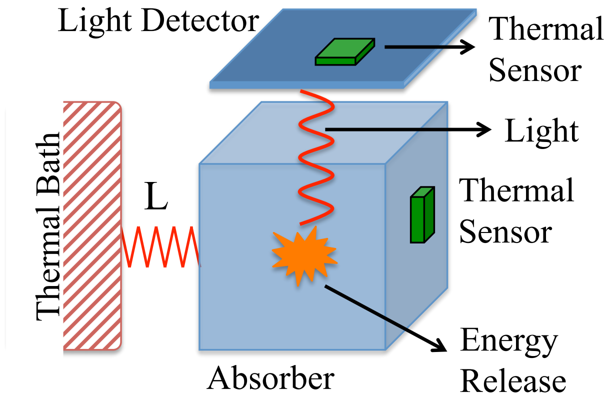


CUORE Achievements:

- Ton-scale bolometric detector is technically feasible
- Operation and analysis of 1000 bolometers demonstrated
- Reliable data-driven background model constructed
- Infrastructure for next-generation experiment exists

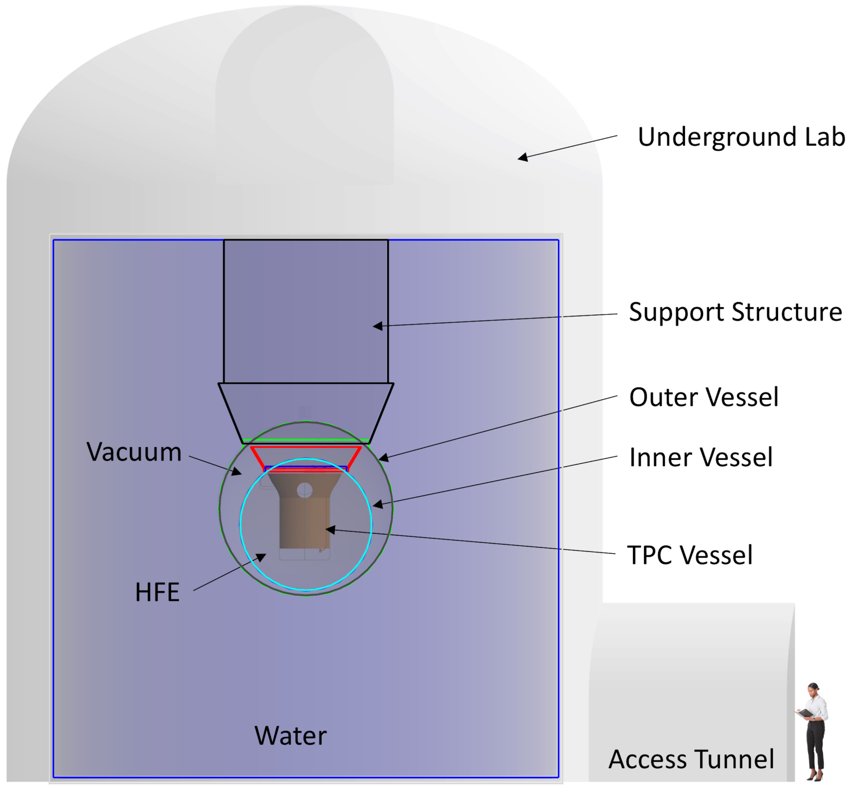
Scintillating Bolometer technology based on R&D by Lucifer/CUPID-0, LUMINEU, CUPID-Mo

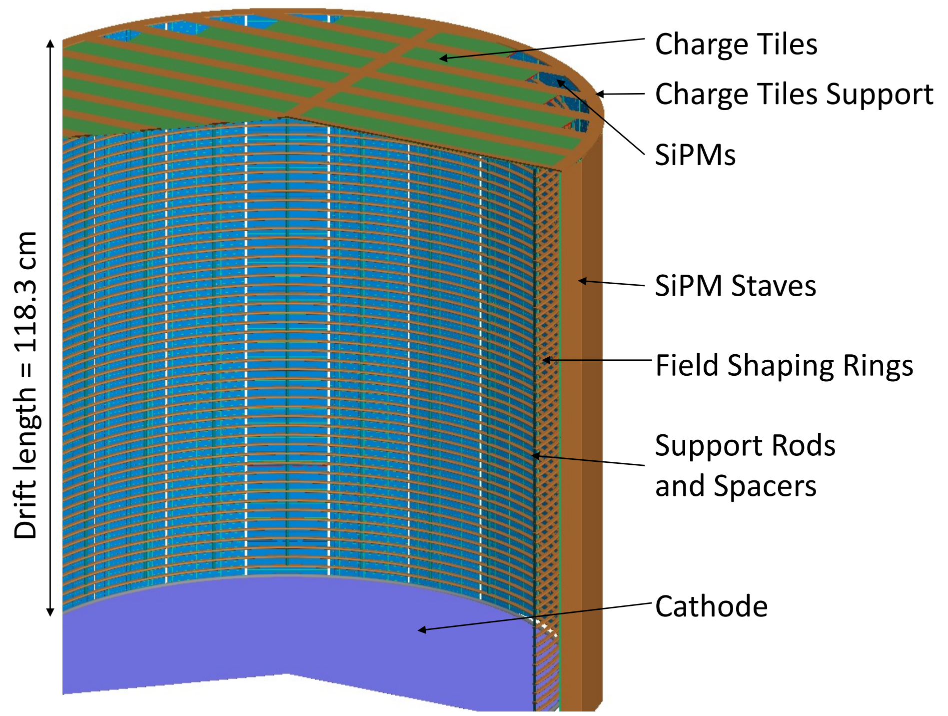
- Baseline: 1500 enriched Li_2MoO_4 crystals (~240 kg of ^{100}Mo)
- Demonstrated radio-purity, active background rejection
- Energy resolution ~5 keV demonstrated
- Total background of <0.1 counts/(ton*kev*year)
- Phased deployment options up to 1 ton of ^{100}Mo (CUPID-1T)



^{136}Xe

nEXO (SNOLab)





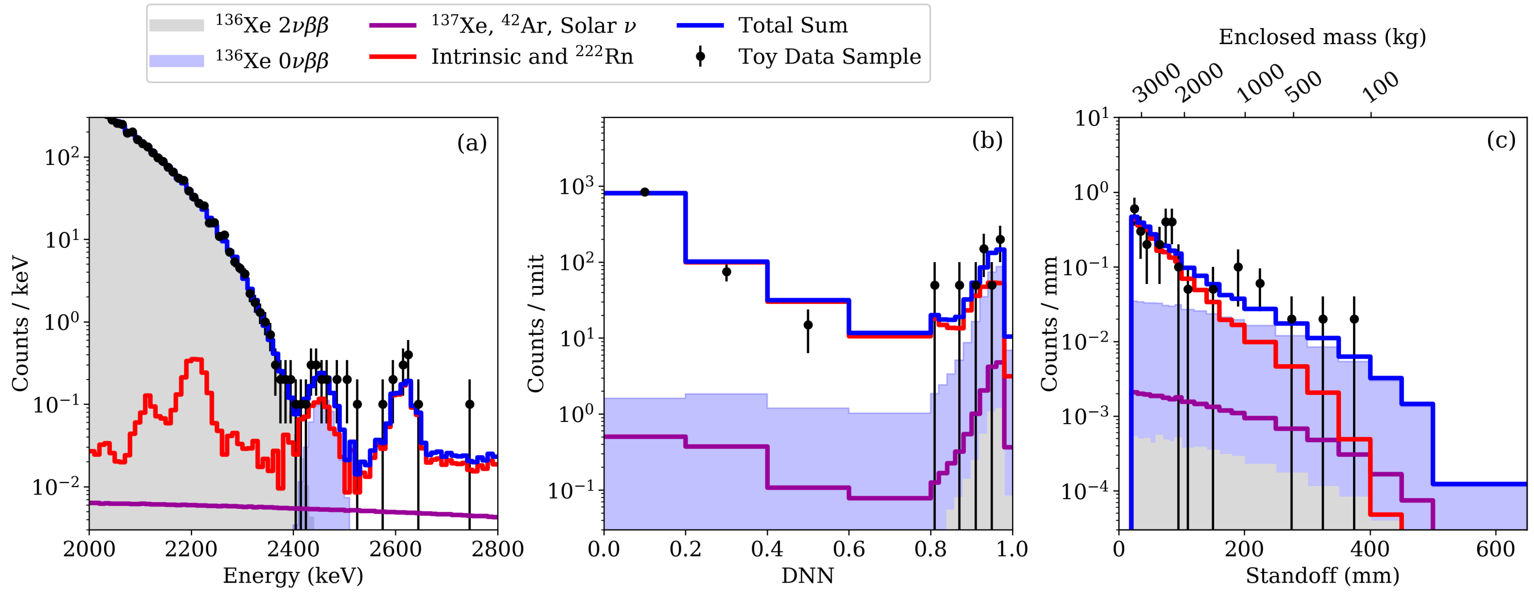
Large monolithic LXe TPC

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



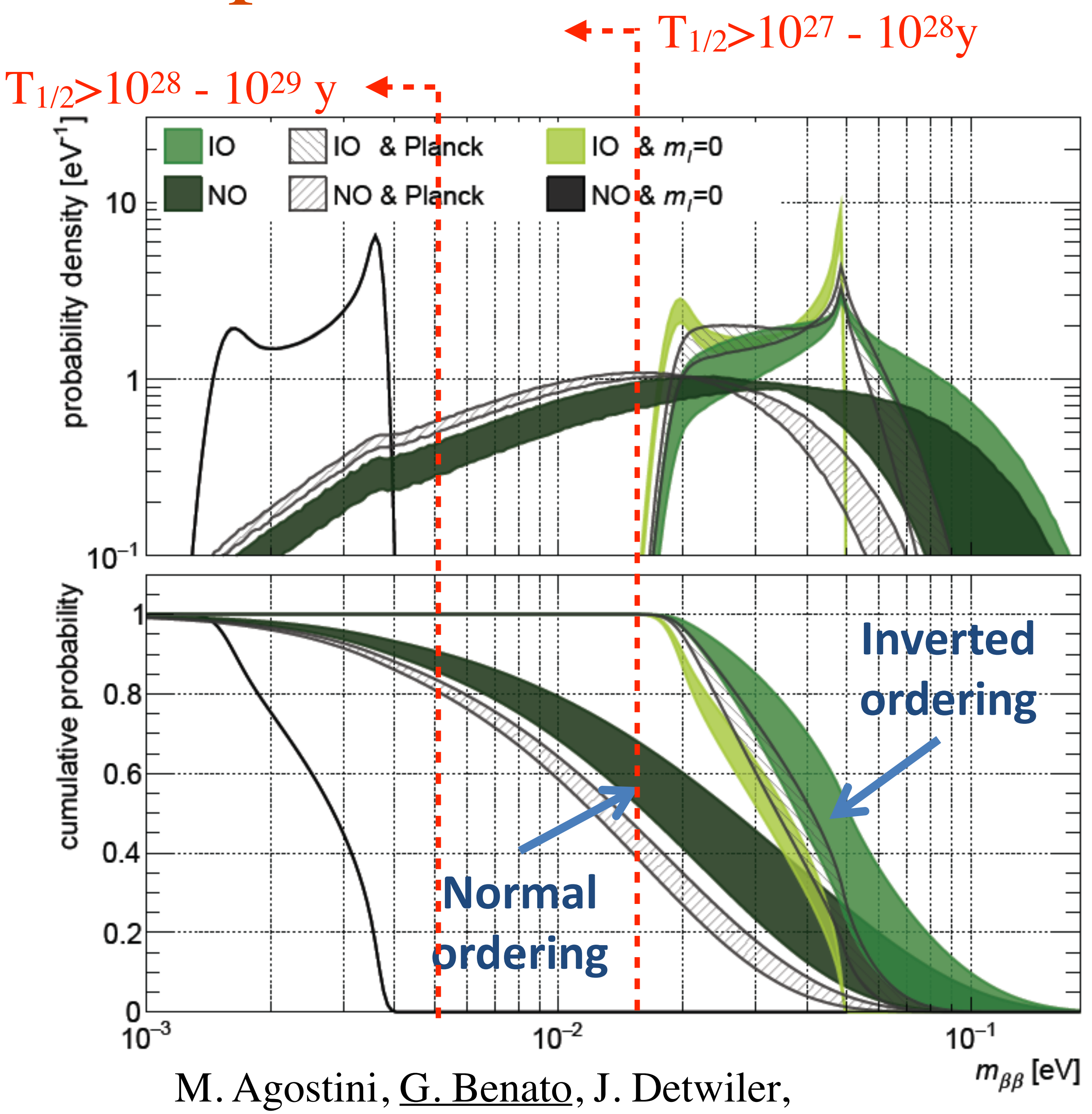
Discovery sensitivity (3σ): $T_{1/2} = 7.4\times10^{27}$ years

$m_{\beta\beta}$ 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

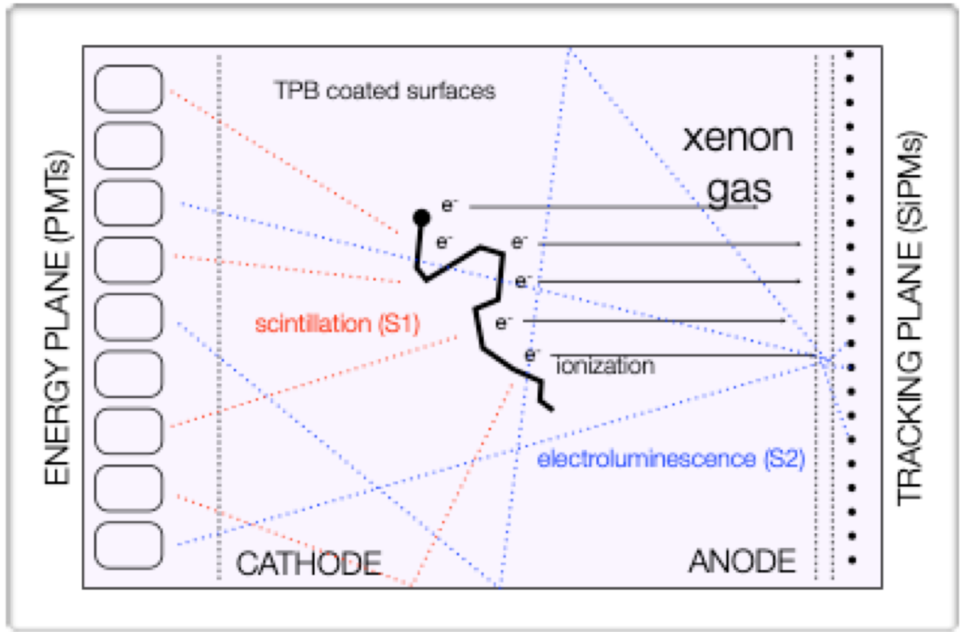


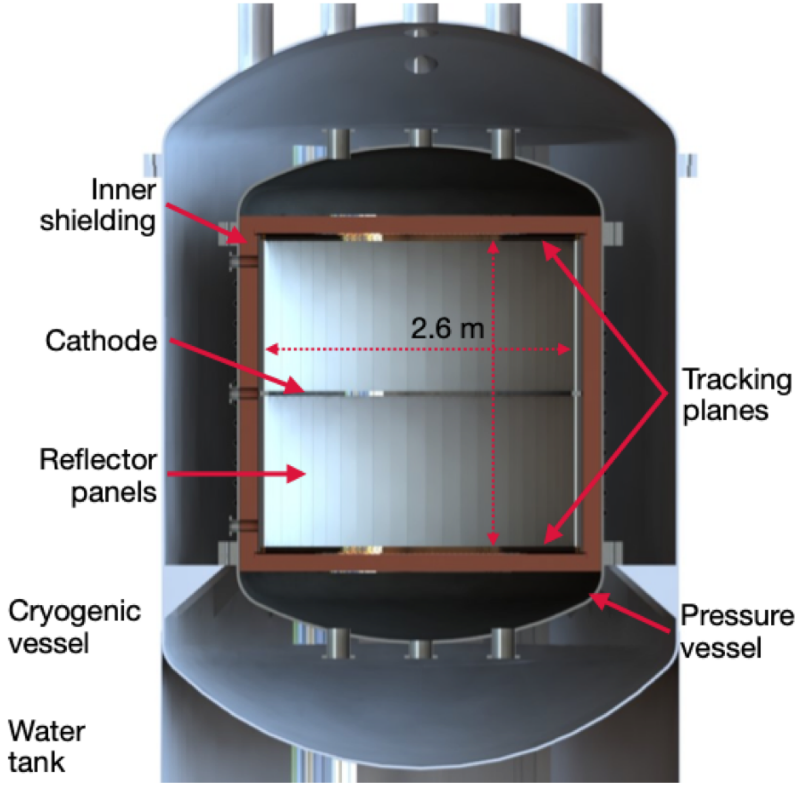
M. Agostini, G. Benato, J. Detwiler, Phys. Rev. **D96**, 053001 (2017)

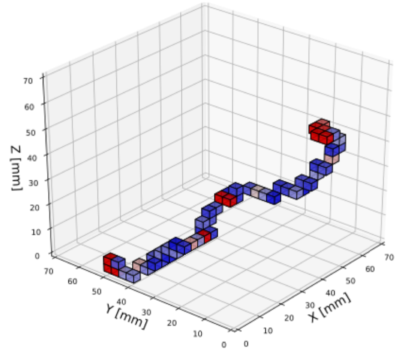
NEXT Idea: Gas $^{136}Xe/^{82}SeF_6$ TPC

^{82}Se ^{136}Xe

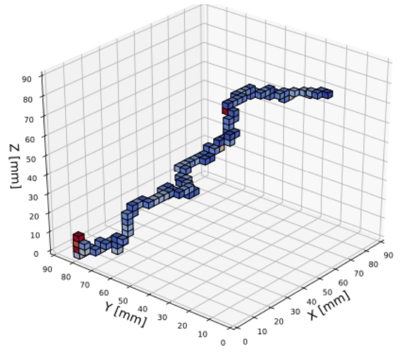
NEXT (Spain): Electro-luminescence HPXe TPC



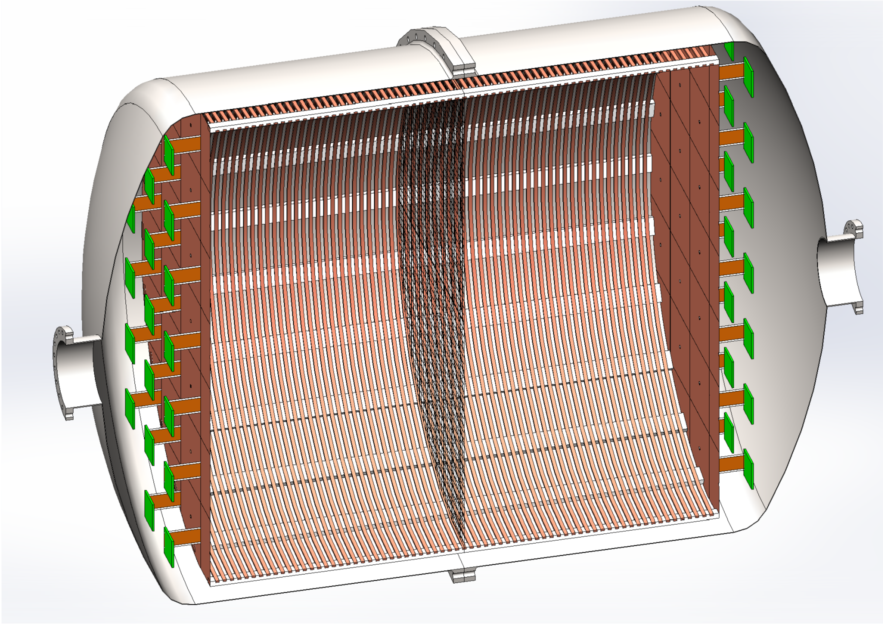




ββ Signal

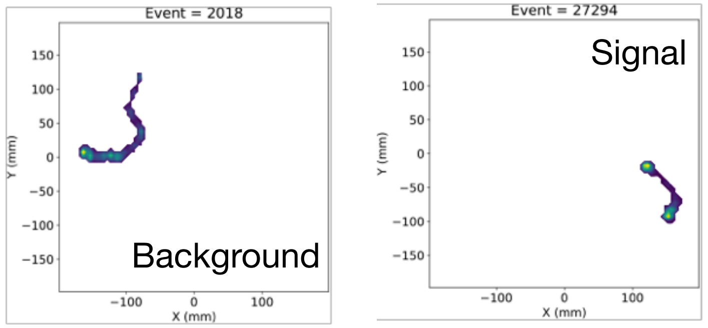


e- Track Background



PANDA-X III (China): Electron HPXe TPC

Also SeF_6 ion-drift TPC



Key features:

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

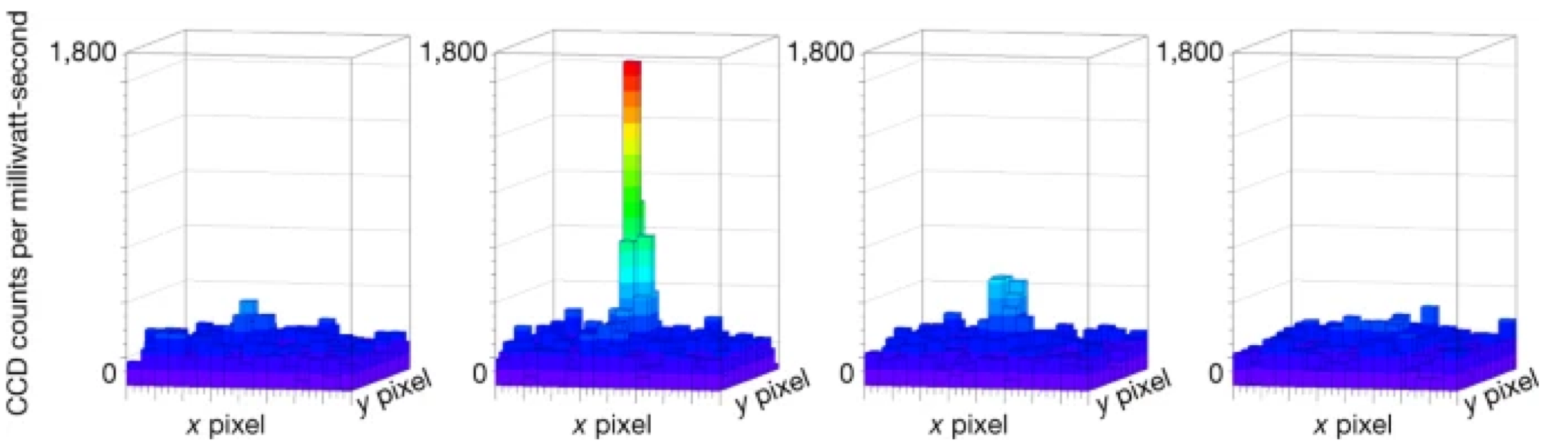
Demonstrator (NEXT-100): ~2022

Ton-scale: NEXT-HD. Projected sensitivity (90% C.L.) $T_{1/2}>2.7\times10^{27}$ years ($m_{\beta\beta}$=8-45 meV)

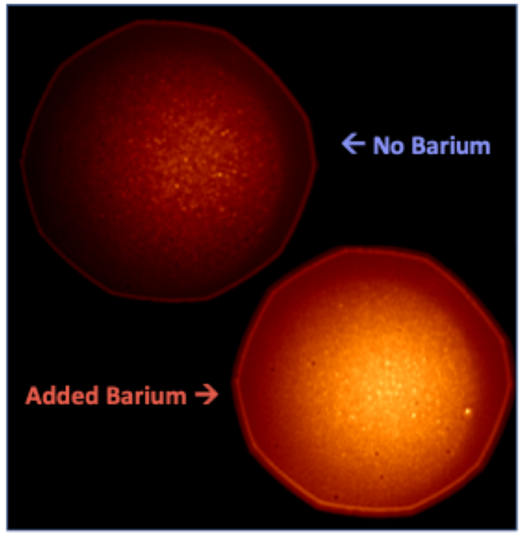
Barium Tagging ^{136}Xe Decays

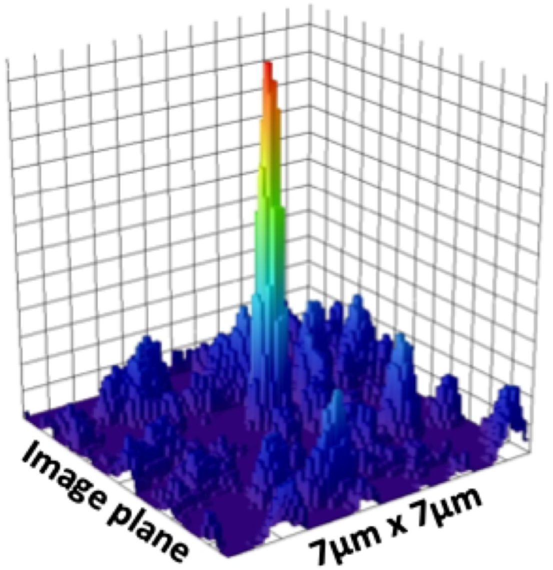
Tagging $^{136}Xe \rightarrow {}^{136}Ba^{++}$ transition with high efficiency would eliminate all non-DBD backgrounds
Significant improvement in sensitivity
Vibrant R&D effort for over 20 years, major recent breakthroughs
Demonstrated tagging single atoms in both LXe and GXe
Next steps: Ba capture and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

J. Gruszko



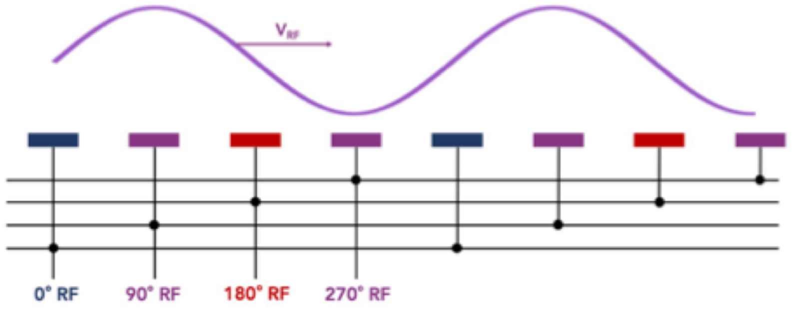
Laser-based ID in solid Xe for nEXO, *Nature 569, 203-207 (2019)*





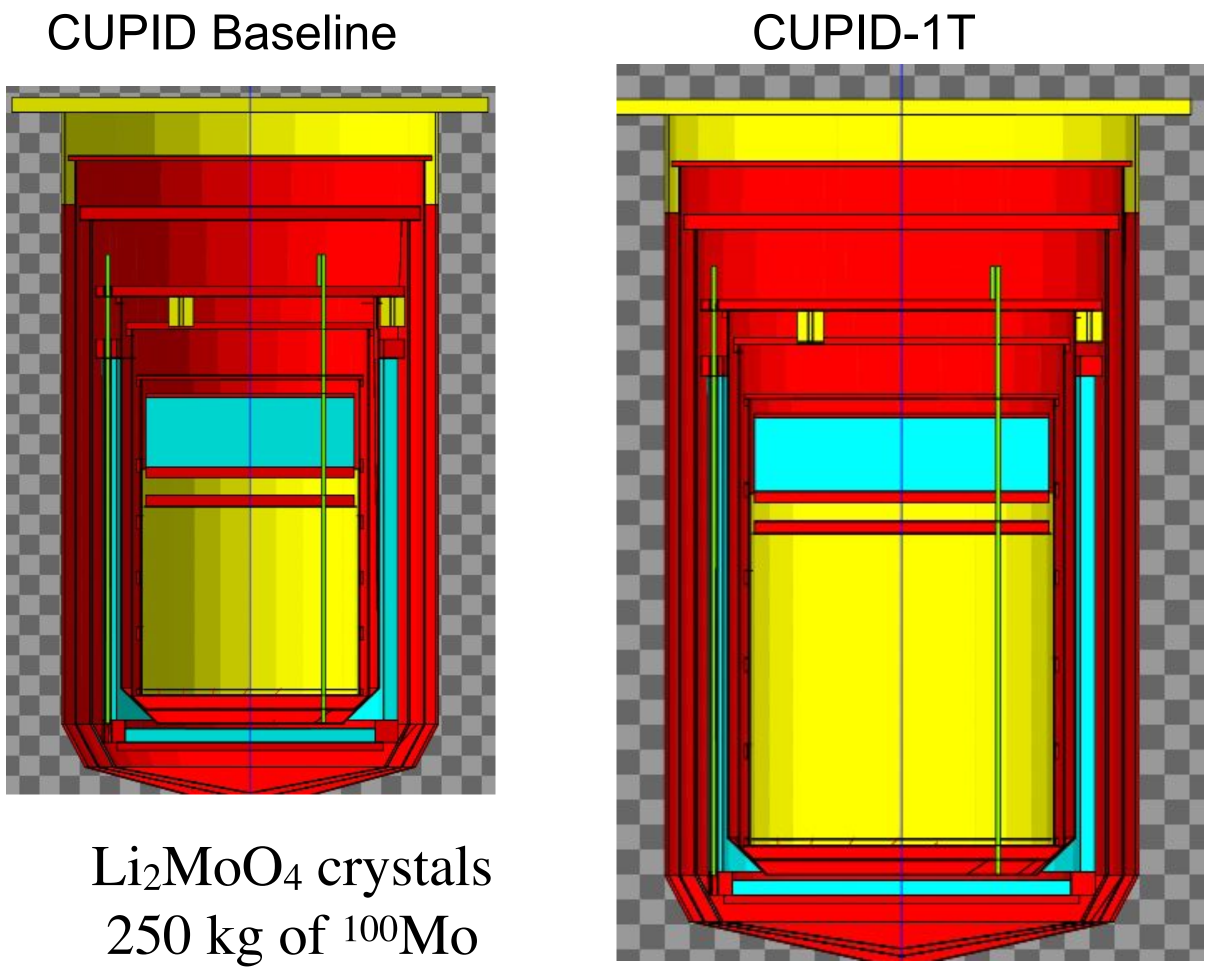
Fluorescent molecule-based ID for NEXT,
ACS Sens. 2021, 6, 1, 192–202 (2021)

Cryoprobe-based extraction for nEXO



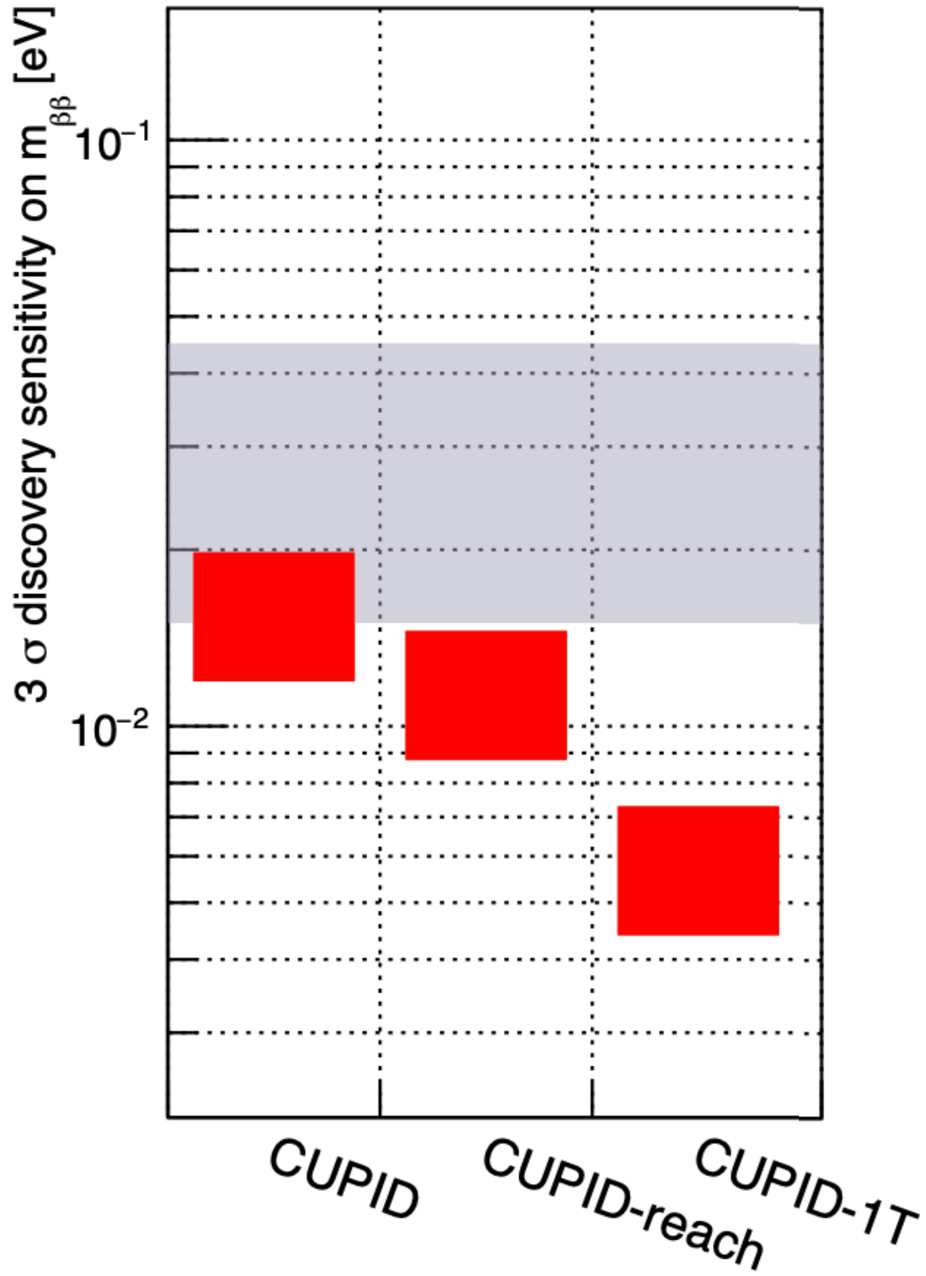
RF carpet-based transport for NEXT,
arXiv:2111.11091 (2021)

Large Solid-State Detector: CUPID-1T



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

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



^{130}Te ^{136}Xe

Large Hybrid Detector: Theia

G.D. Orebi Gann

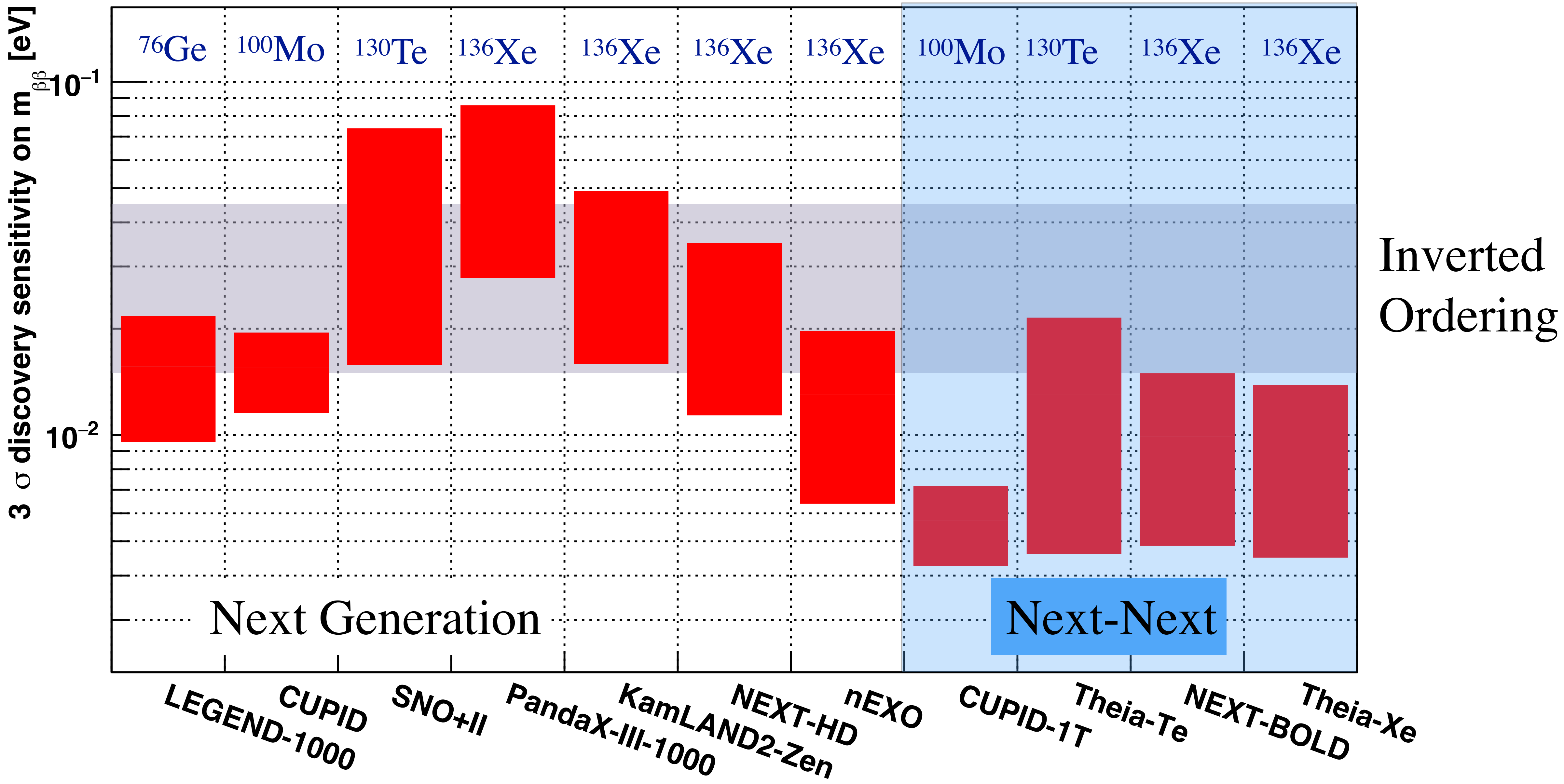
- Large-scale detector (50-100 kton)
- Water-based LS target (scintillation, Cherenkov)
- Fast, high-efficiency photon detection with high coverage
- Deep underground (e.g. Homestake)
- Isotope loading (Gd, Te, Xe, Li…)
- ***Flexible***! Target, loading, configuration

➡ **Broad physics program, including $0\nu\beta\beta$!**

8-m radius balloon with high-LY LS & isotope
7-m fiducial volume
5% ^{nat}Te or 3% ^{enr}Xe, 10 years
Normal hierarchy sensitivity

$T_{1/2} > 1.5 \times 10^{28}$ 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
  - Another order of magnitude in sensitivity with next-next generation experiments

Exciting future ahead !

Backup