Neutrinoless Double Beta Decay

"A Whirlwind Tour"

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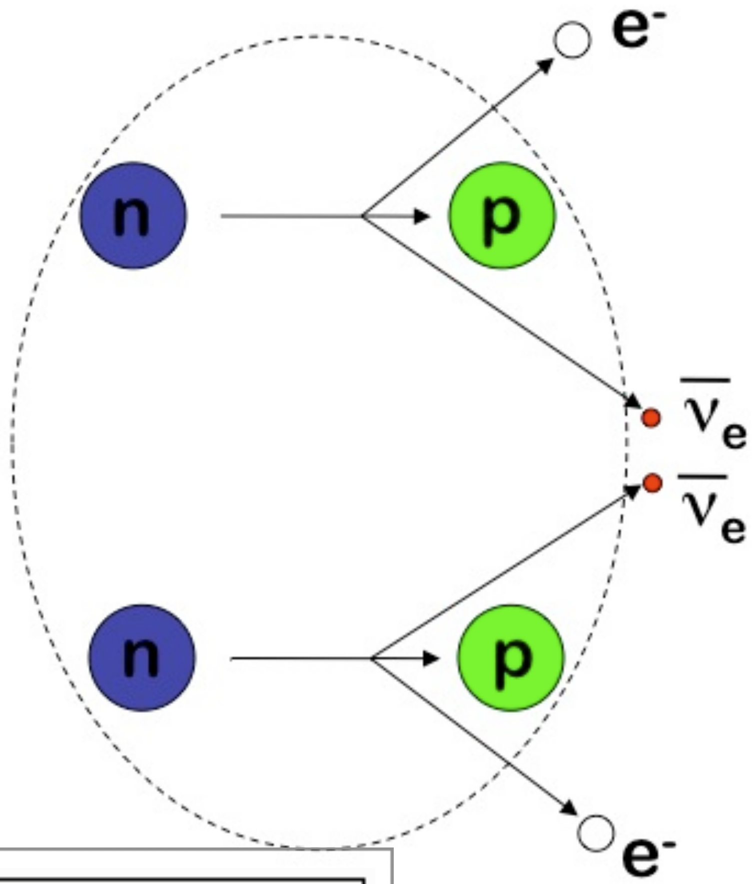
U. C. Berkeley / LBNL
NuFACT 2014
28th Aug 2014

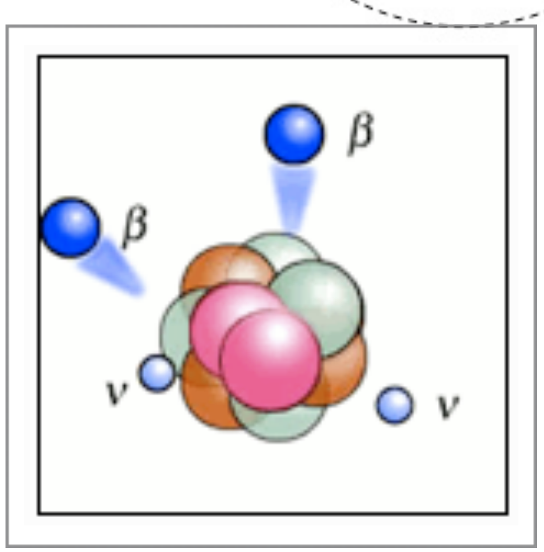
Overview

- Neutrino (-less) double beta decay
- Experimental techniques:
    - Current status & future prospects
    - *SNO+: the large-scale liquid scintillator approach*
- Status of the field ⇒ future goals (probing MH)

2ν Double Beta Decay

Double Beta Decay



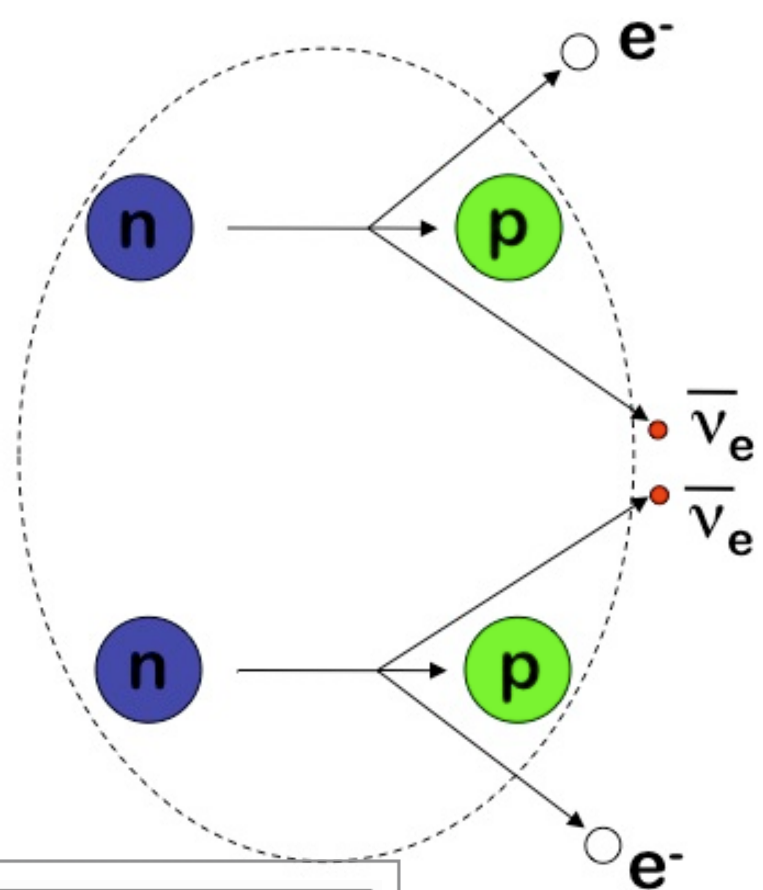


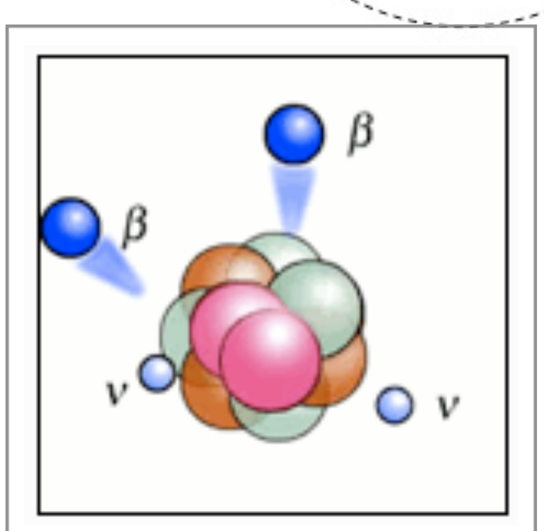
$(A,Z) \rightarrow$
$(A,Z+2) + 2e^- + 2\overline{\nu}_e$

- Rare process
- Occurs in ~50 nuclear isotopes
- Single-β decay energetically disfavoured

0ν Double Beta Decay

Double Beta Decay





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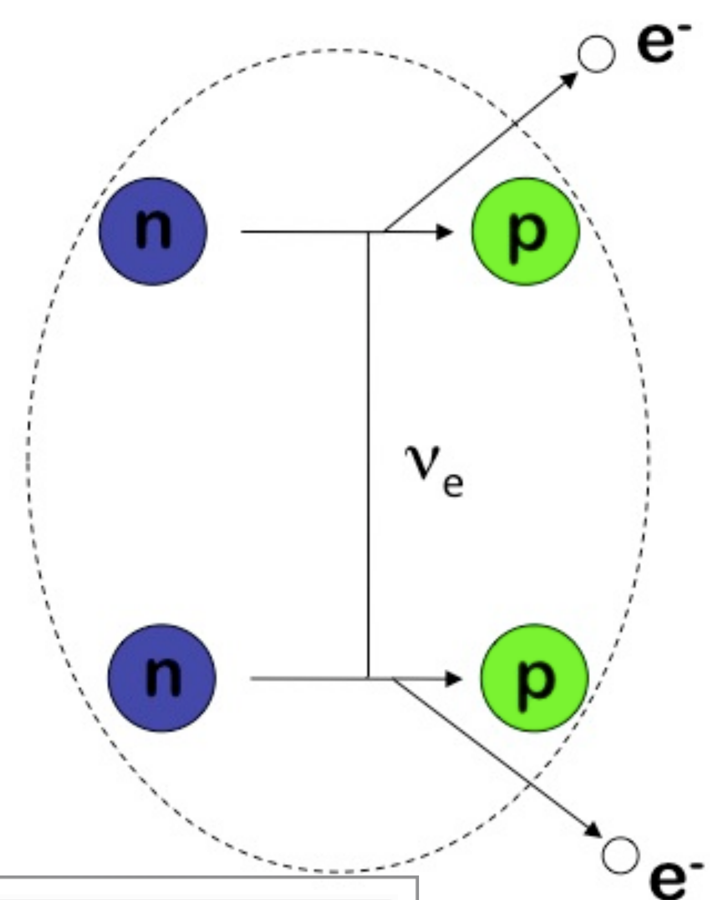
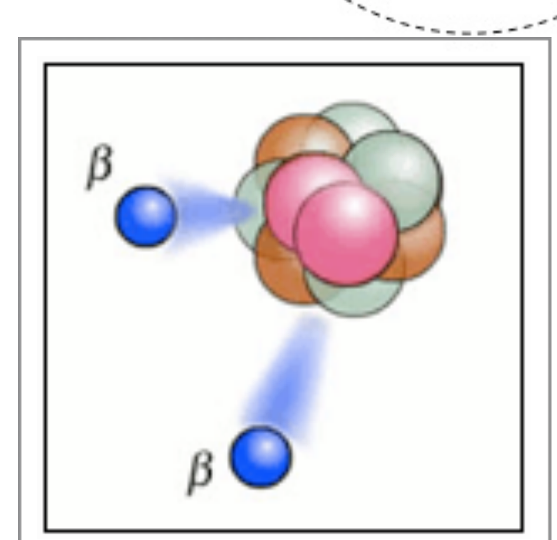
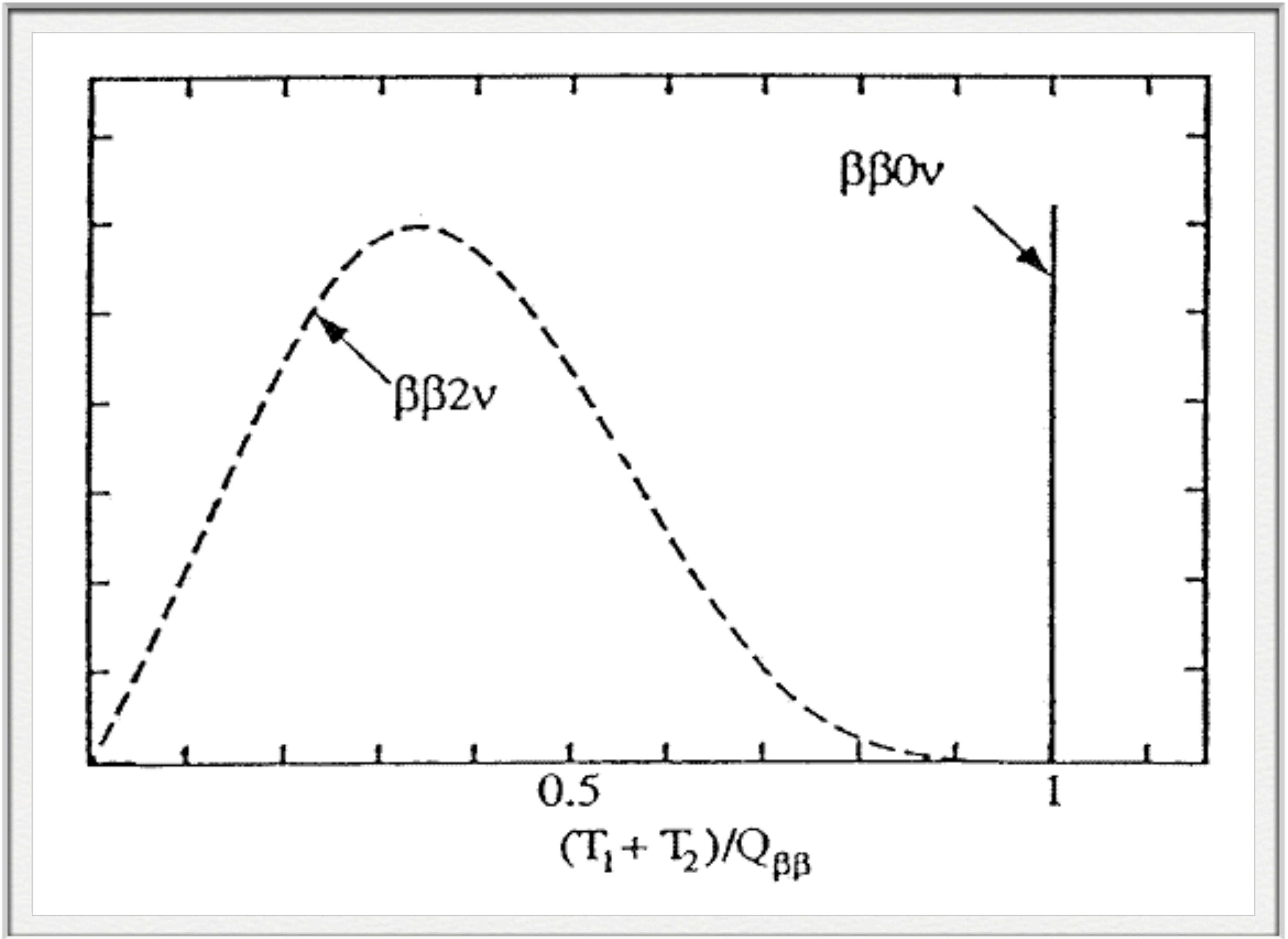




$(A,Z) \rightarrow$
$(A,Z+2) + 2e^-$

0νββ Signature

Energy Spectrum



0νββ Decay Rate

$$\Gamma = \left(T_{1/2}\right)^{-1} = G^{0\nu}\left|M'^{0\nu}\right|^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

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Phase space factor
Well defined

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Nuclear Matrix Element
Not so calculable

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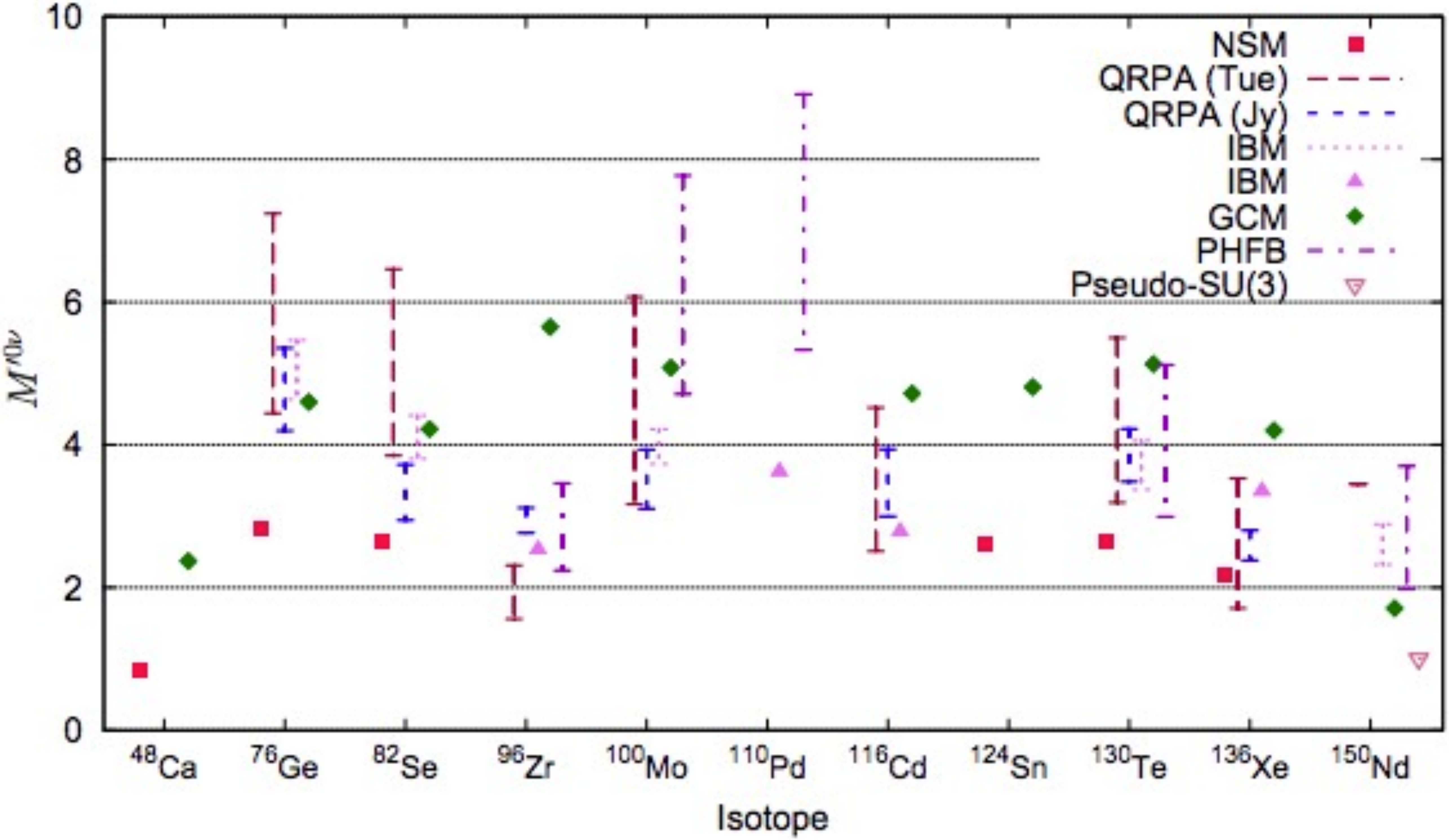
$$M'^{0\nu} = \left(\frac{g_A^{eff}}{g_A}\right)^2 M^{0\nu}$$

Phenomenological correction
Accounts for use of nuclear models
to estimate coupling
Taken from single-β decay
Some controversy over value

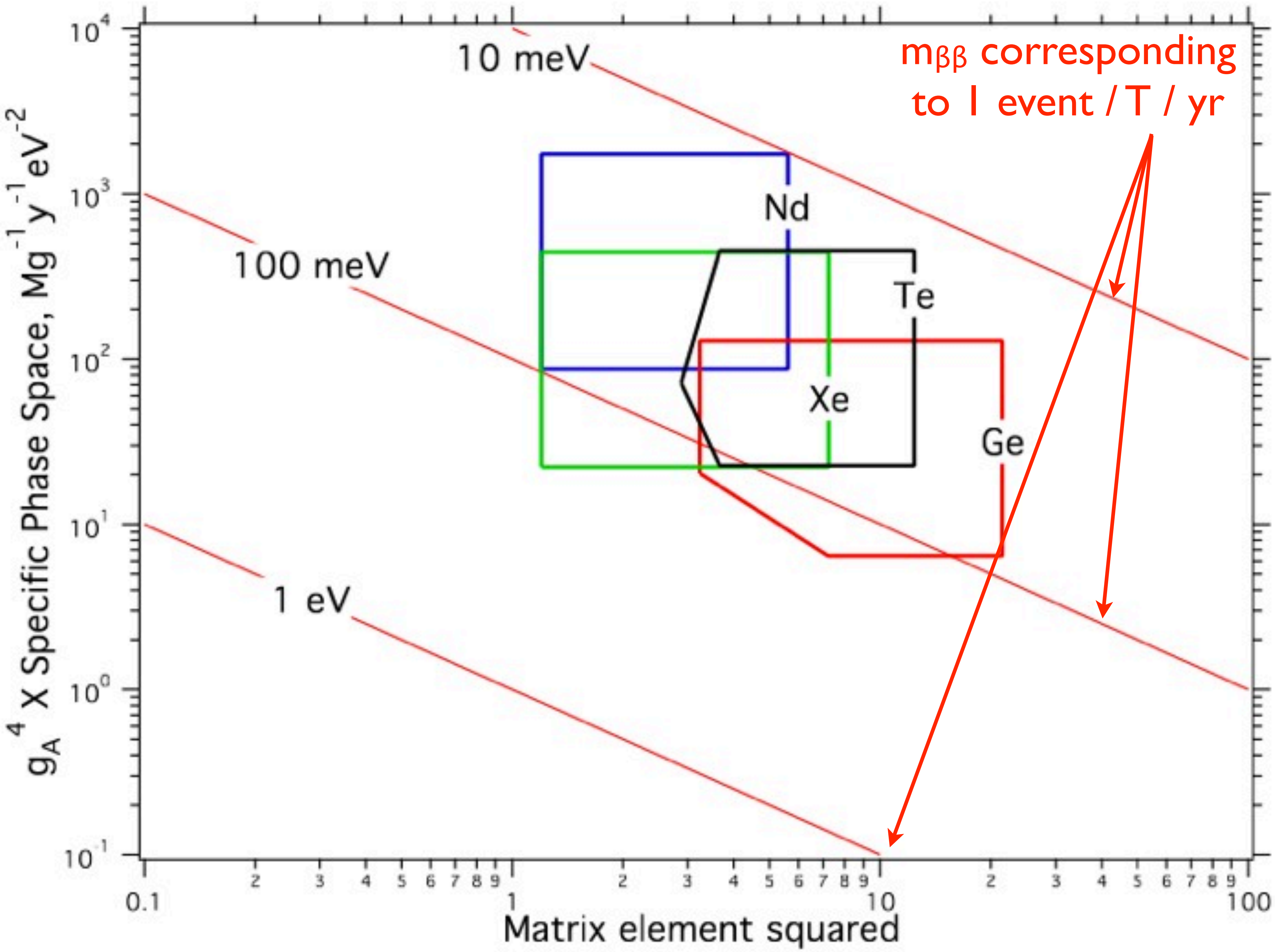
NME

Different techniques can give quite different results for NME



Dueck, Rodejohann, Zuber, Phys. Rev. D83:113010 (2011) (r_0 = 1.2fm, g_A = 1.25)

Isotope Comparison



R.G.H. Robertson Mod. Phys. Lett. A, Vol. 28, No. 8 (2013) 1350021

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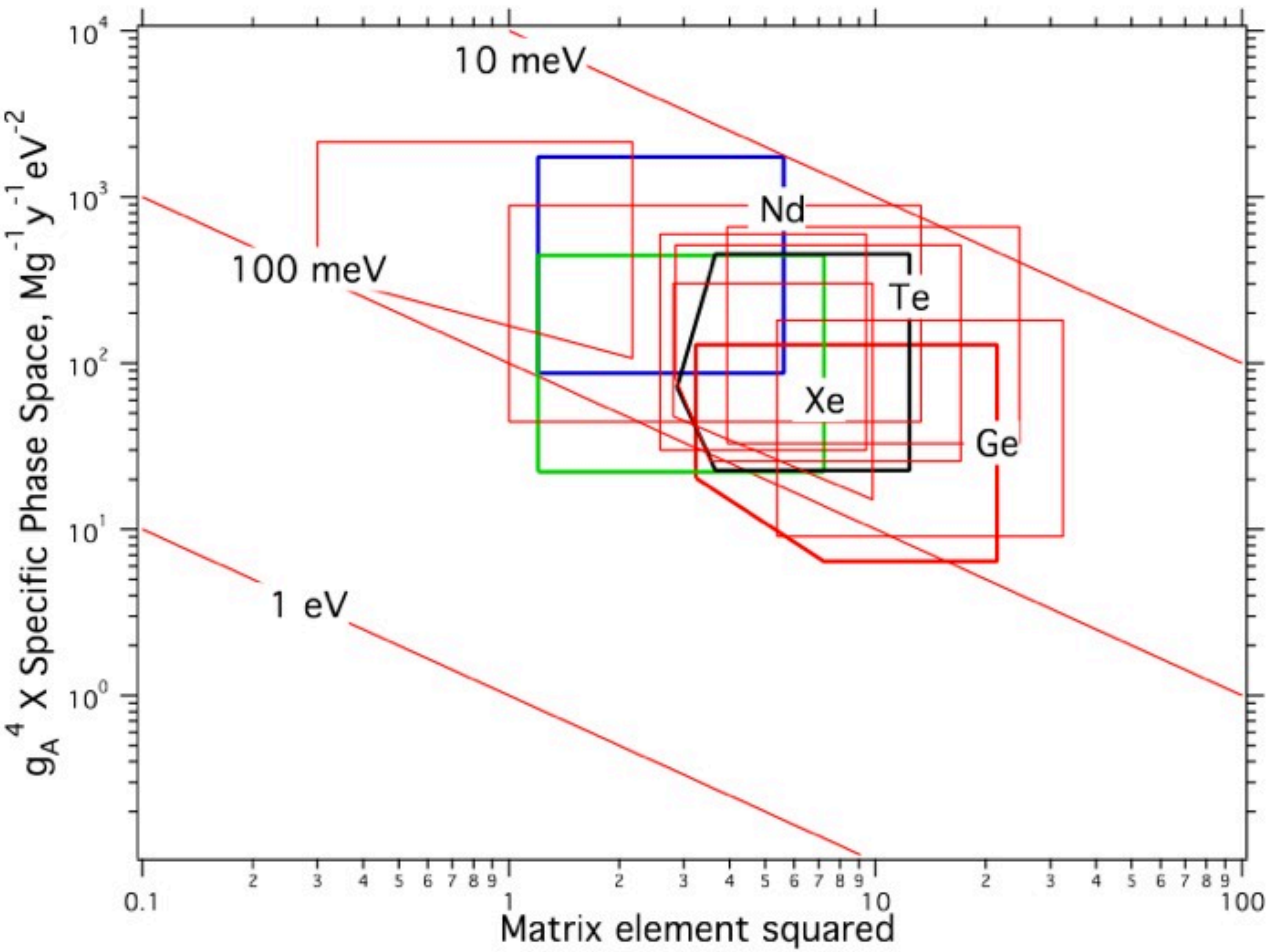

Include ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{110}Pd, ^{116}Cd, ^{124}Sn

R.G.H. Robertson Mod. Phys. Lett. A, Vol. 28, No. 8 (2013) 1350021

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Phase space factor
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Effective
Neutrino Mass

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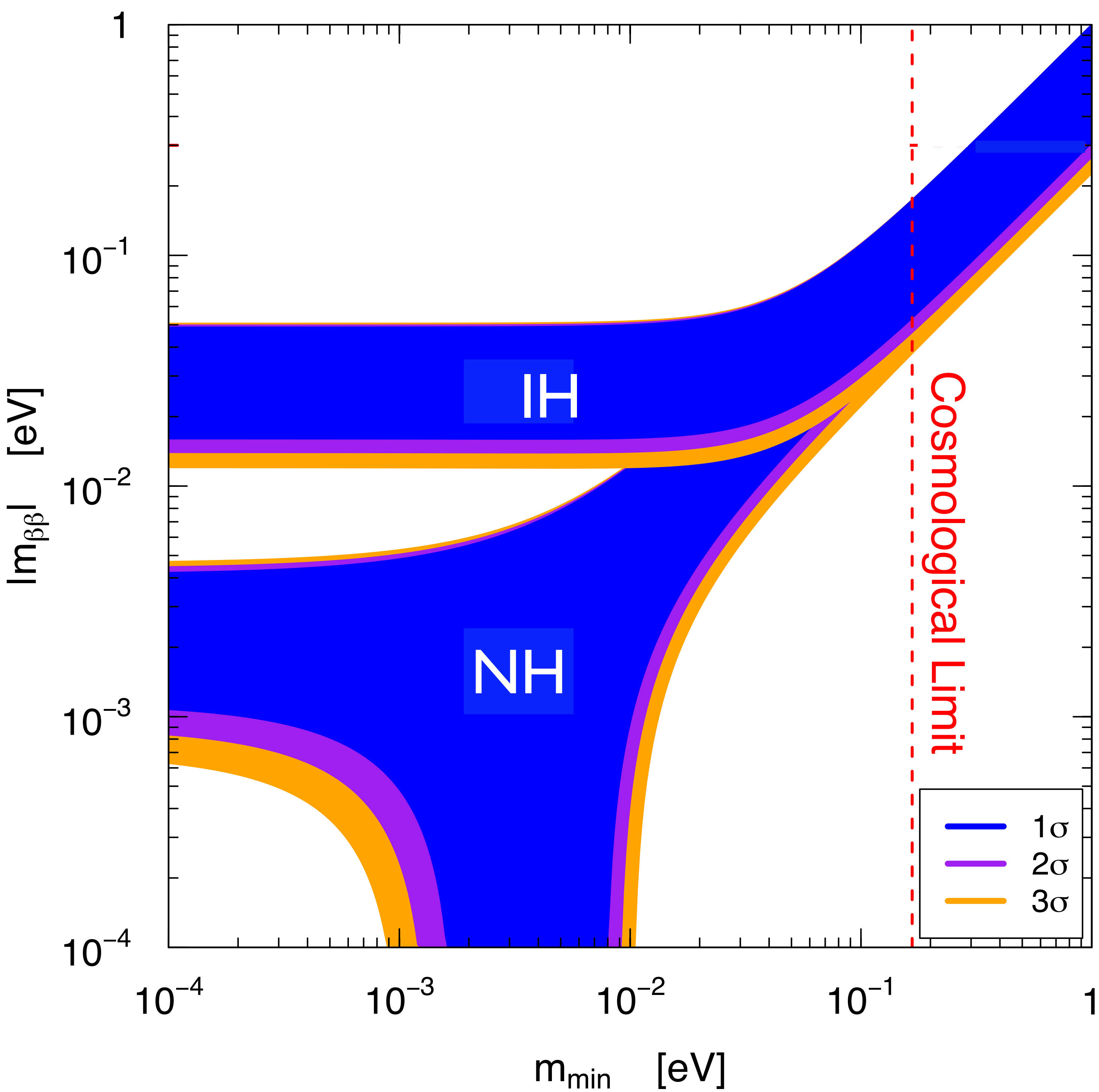
Probes absolute neutrino mass scale
Also sensitive to mass hierarchy

$$m_{\beta\beta} = \left|\sum_i m_i U_{ei}^2\right|$$

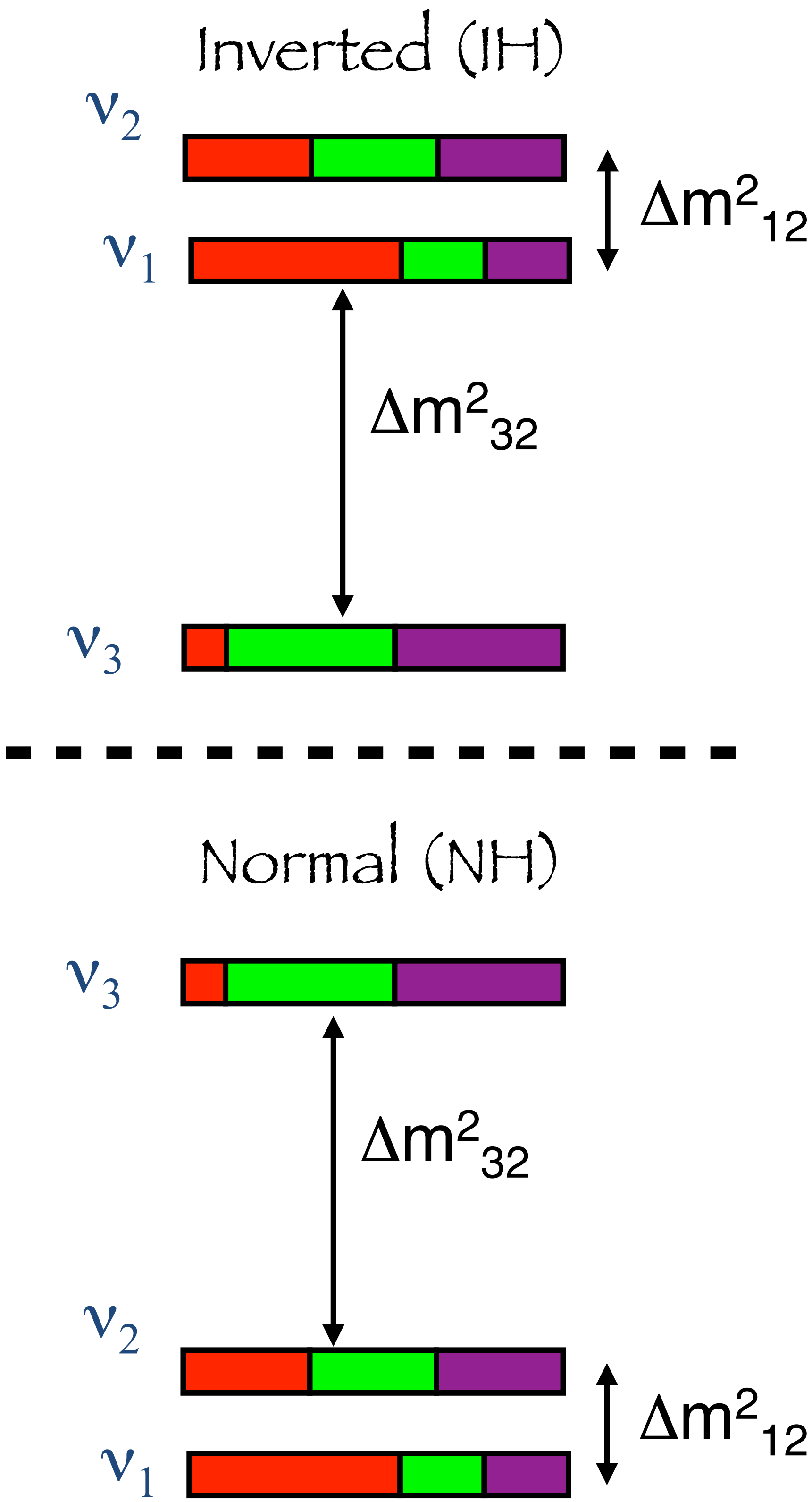
$$= \cos^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_1$$

$$+ \sin^2\theta_{12}\cos^2\theta_{13}e^{i\beta}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3$$

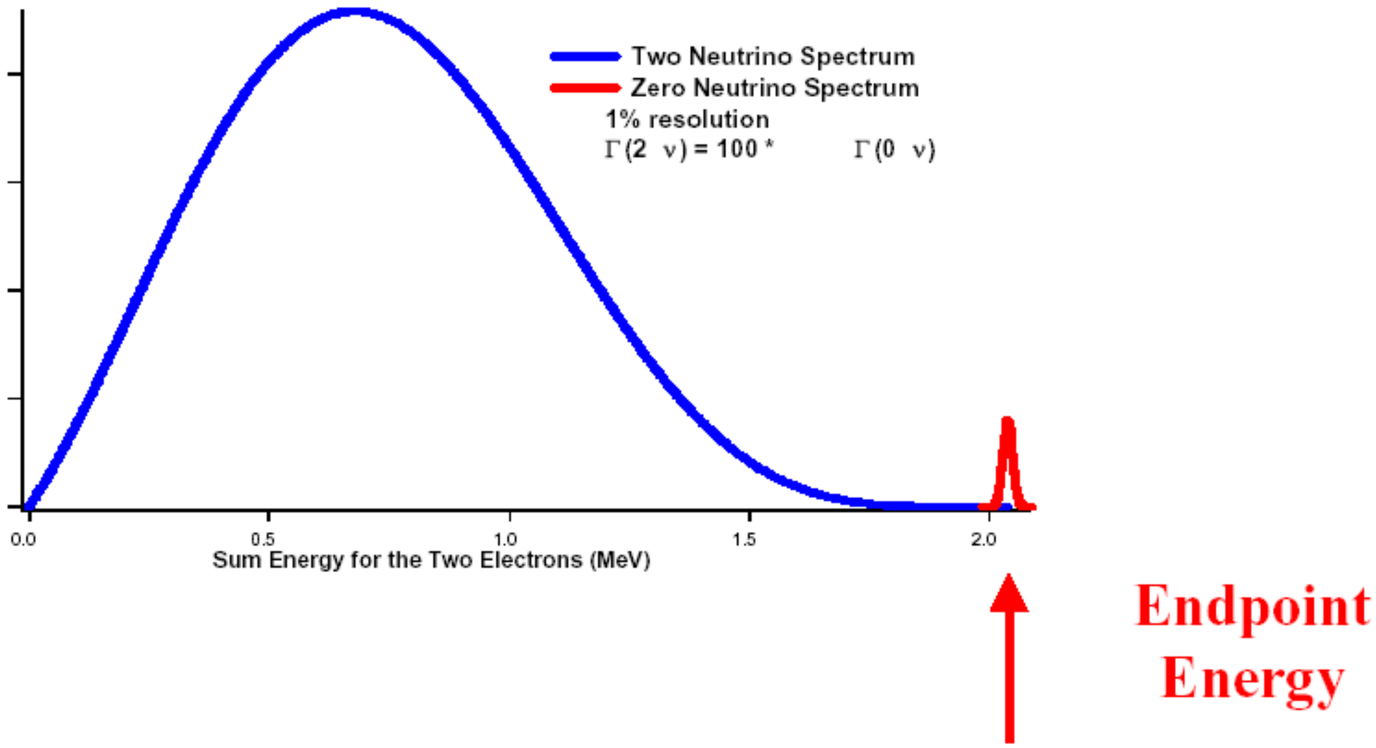
0νββ Phase Space



S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)



Requirements for 0νββ Sensitivity



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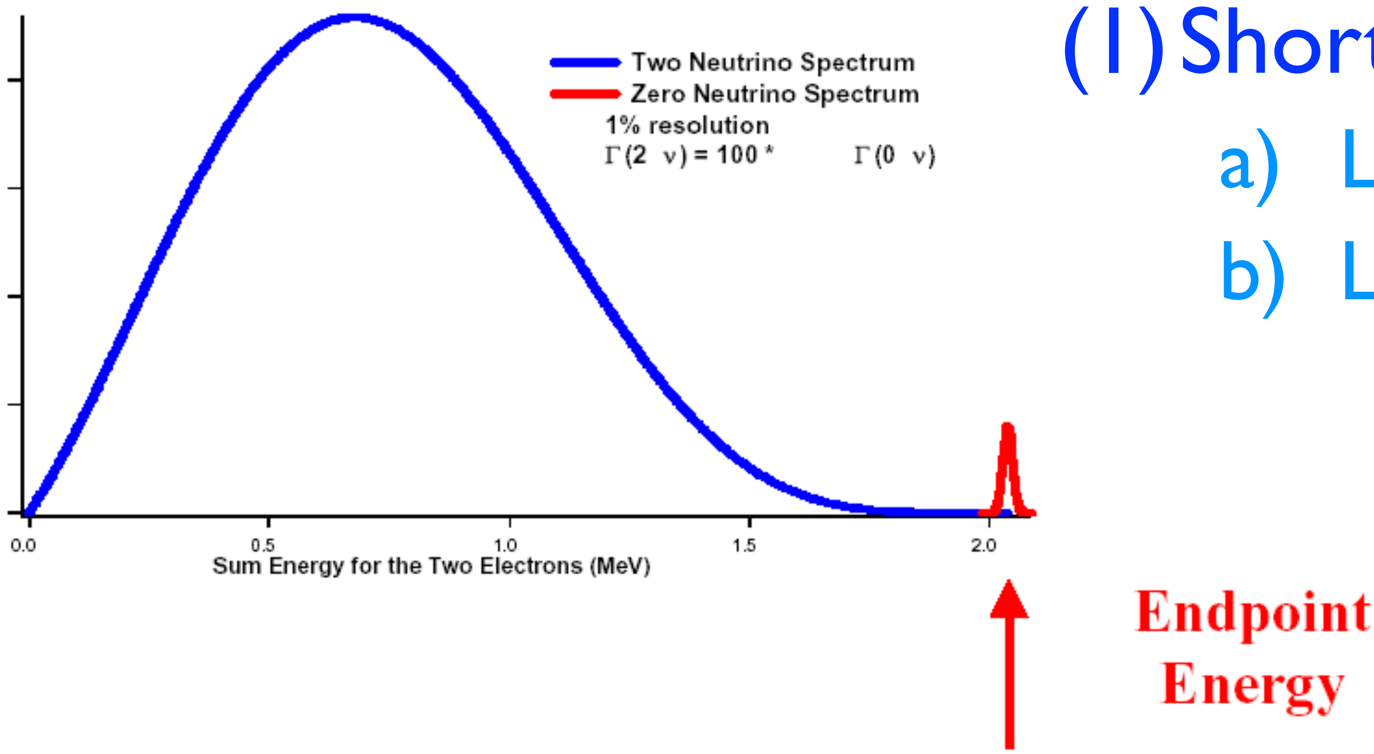

(1) Short half-life for given neutrino mass

a) Large phase space factor

b) Large NME

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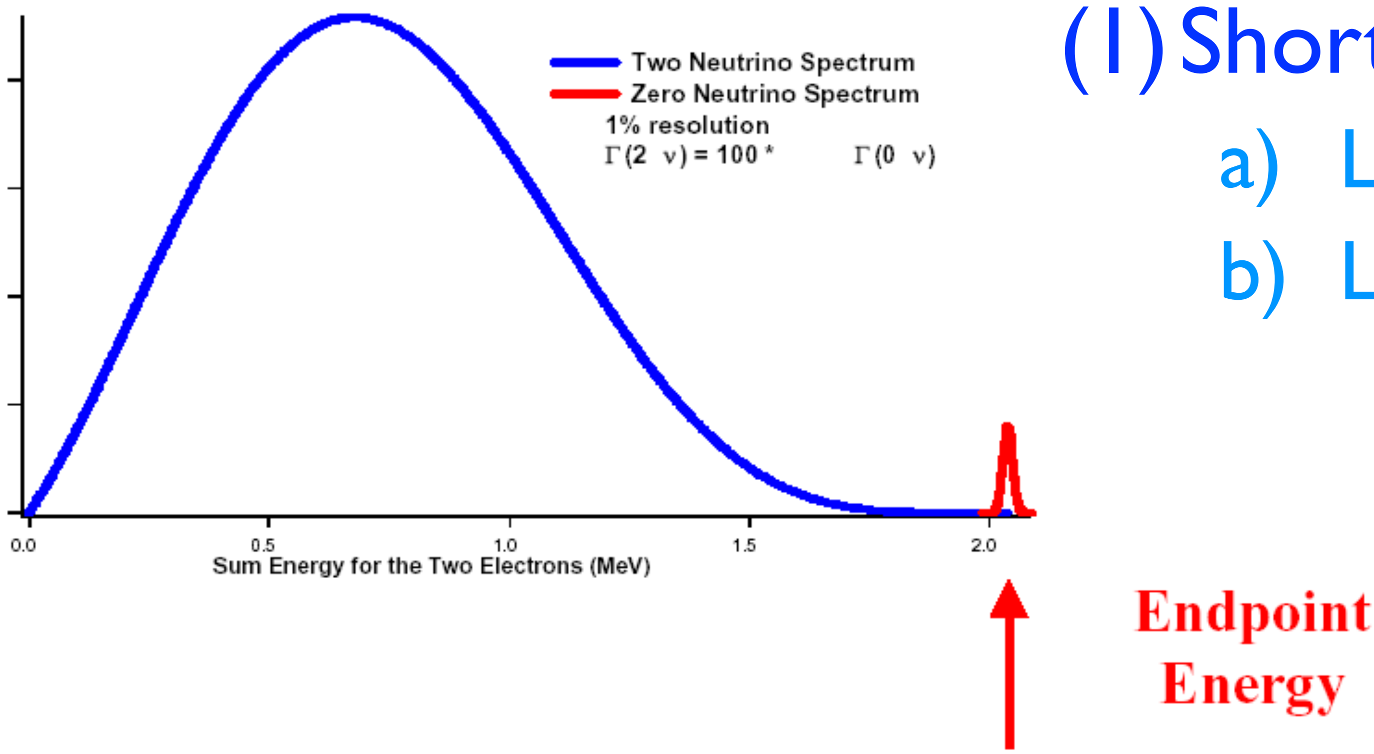

(1) Short half-life for given neutrino mass
   a) Large phase space factor
   b) Large NME

(2) Low background in ROI
   a) High Q value (above bkg)
   b) High 0ν/2ν ratio and/or good E resolution
   c) Deep location
   d) Background rejection techniques

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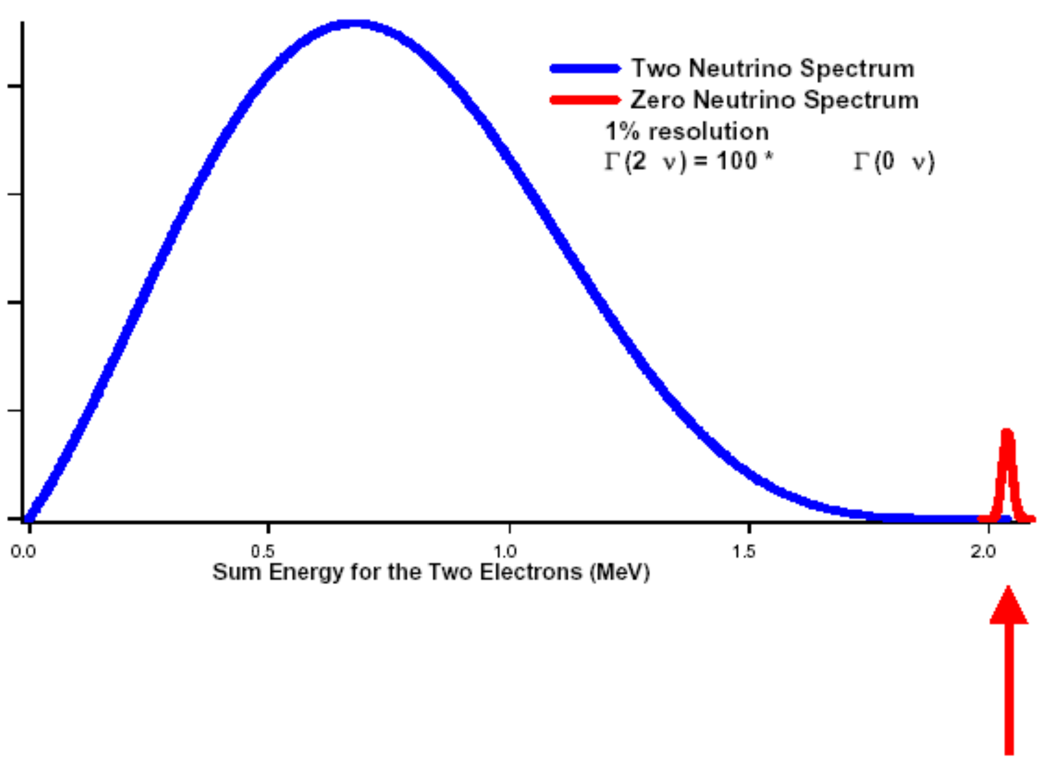


Endpoint Energy

(1) Short half-life for given neutrino mass
   a) Large phase space factor
   b) Large NME

(2) Low background in ROI
   a) High Q value (above bkg)
   b) High 0ν/2ν ratio and/or good E resolution
   c) Deep location
   d) Background rejection techniques

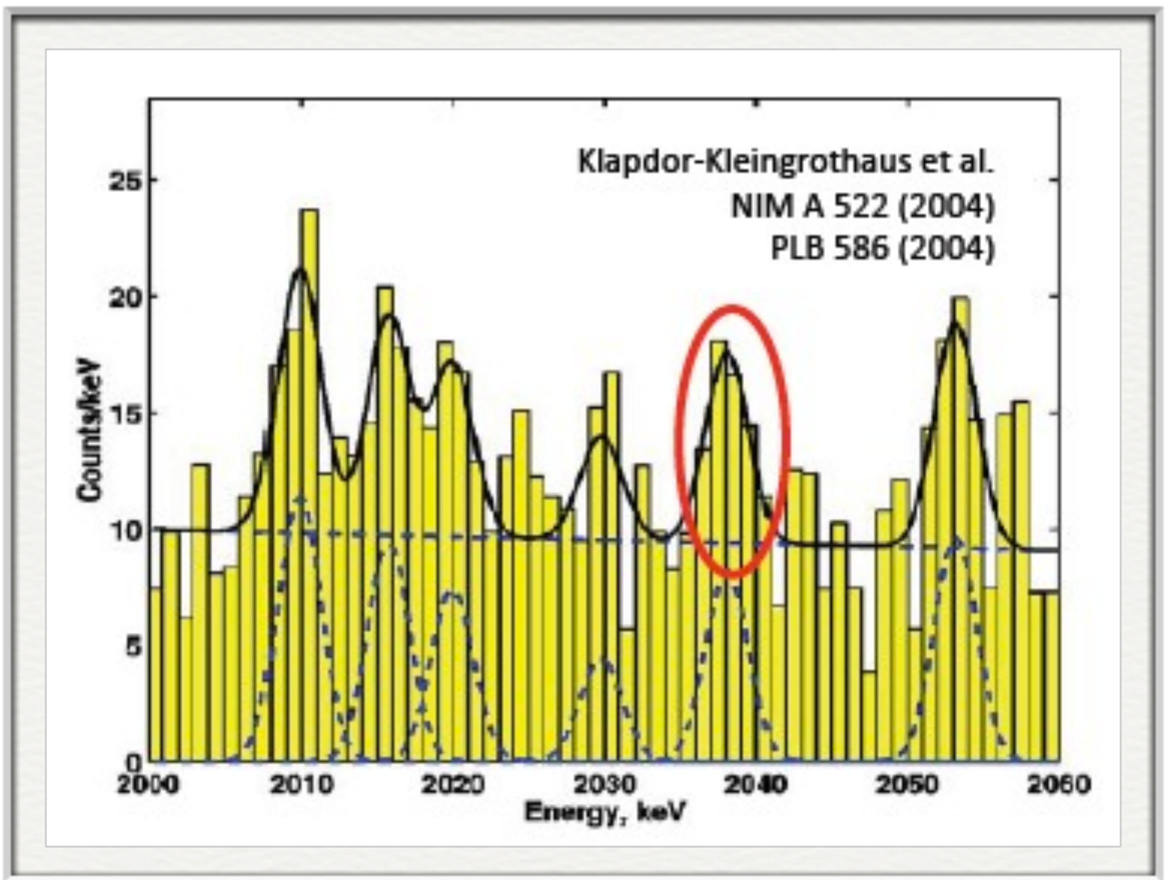
(3) Large # atoms of target isotope
   a) Low cost per mol
   b) High nat. abundance
      or low enrichment cost
      or low detector cost (iff detector is source)
      or detector unaffected by large quantity of isotope

Experiments

Approach	Technology	Experiment	Isotope
High-resolution calorimetry	• Ionisation • Bolometers	• **MAJORANA**, **GERDA,** COBRA • **CUORE**	76Ge 76Ge 130Te, 116Cd 130Te
Xe TPC	• Liquid Xe • High-pressure gas	• **EXO-200,** nEXO • **NEXT**	136Xe 136Xe 136Xe
Tracko-calo expt	• Tracking with external source	• **SuperNEMO**, MOON	Multiple
Large self-shielding calorimetry	• Isotope-loaded liquid scintillator	• **KamLAND-Zen, SNO+**, XMASS, CANDLES	136Xe 130Te 136Xe 48Ca

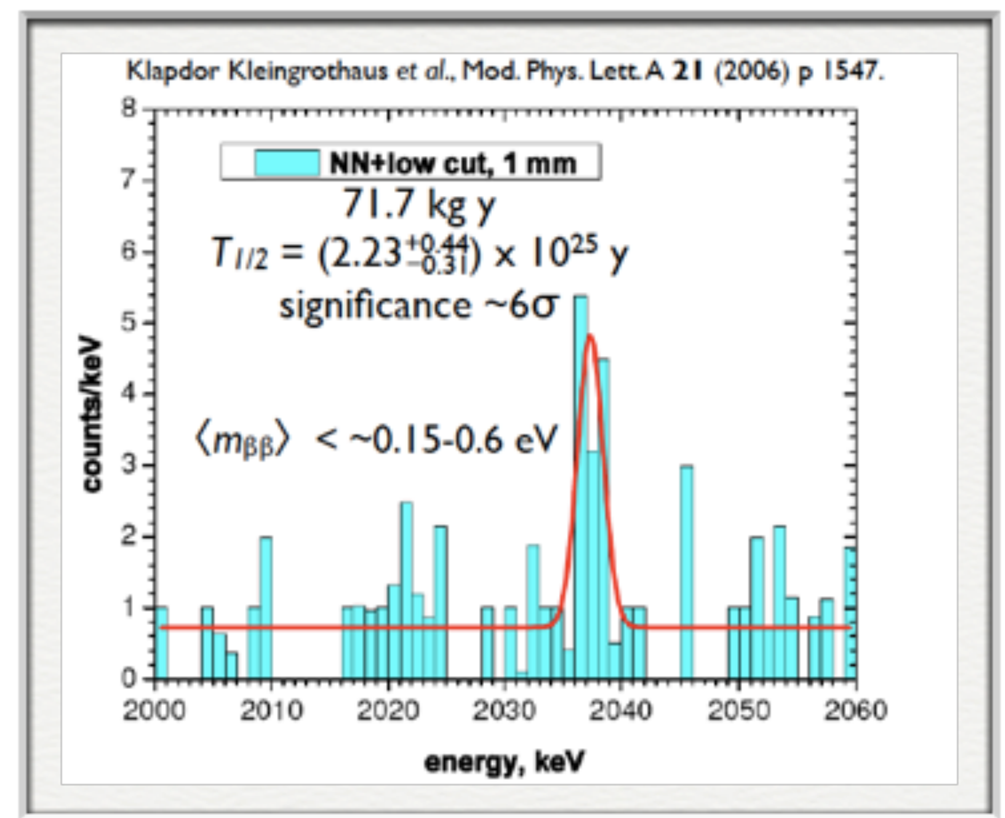
Controversial Signal

Heidelberg-Moscow ^{76}Ge experiment



71.7 kg year

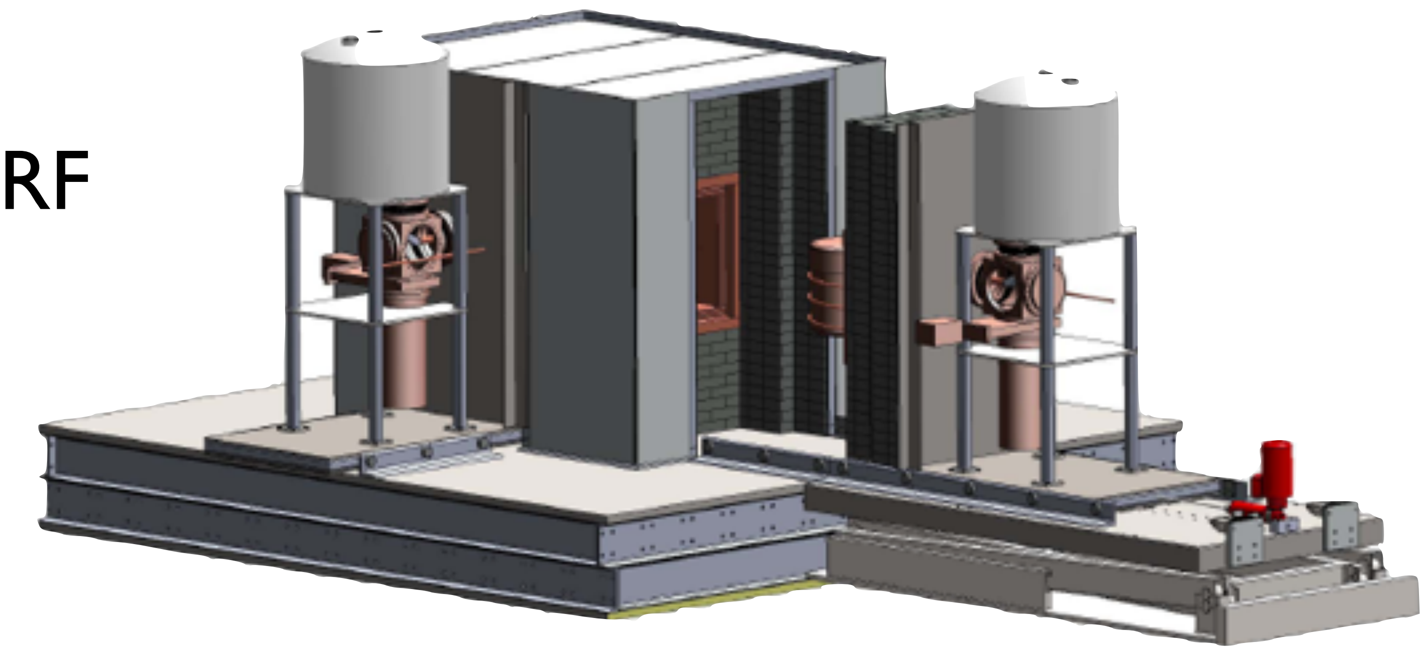
2004: 0.17 ct/kg-yr-keV
$T_{1/2}$ = 1.19x10^{25}yr, 4.2 σ

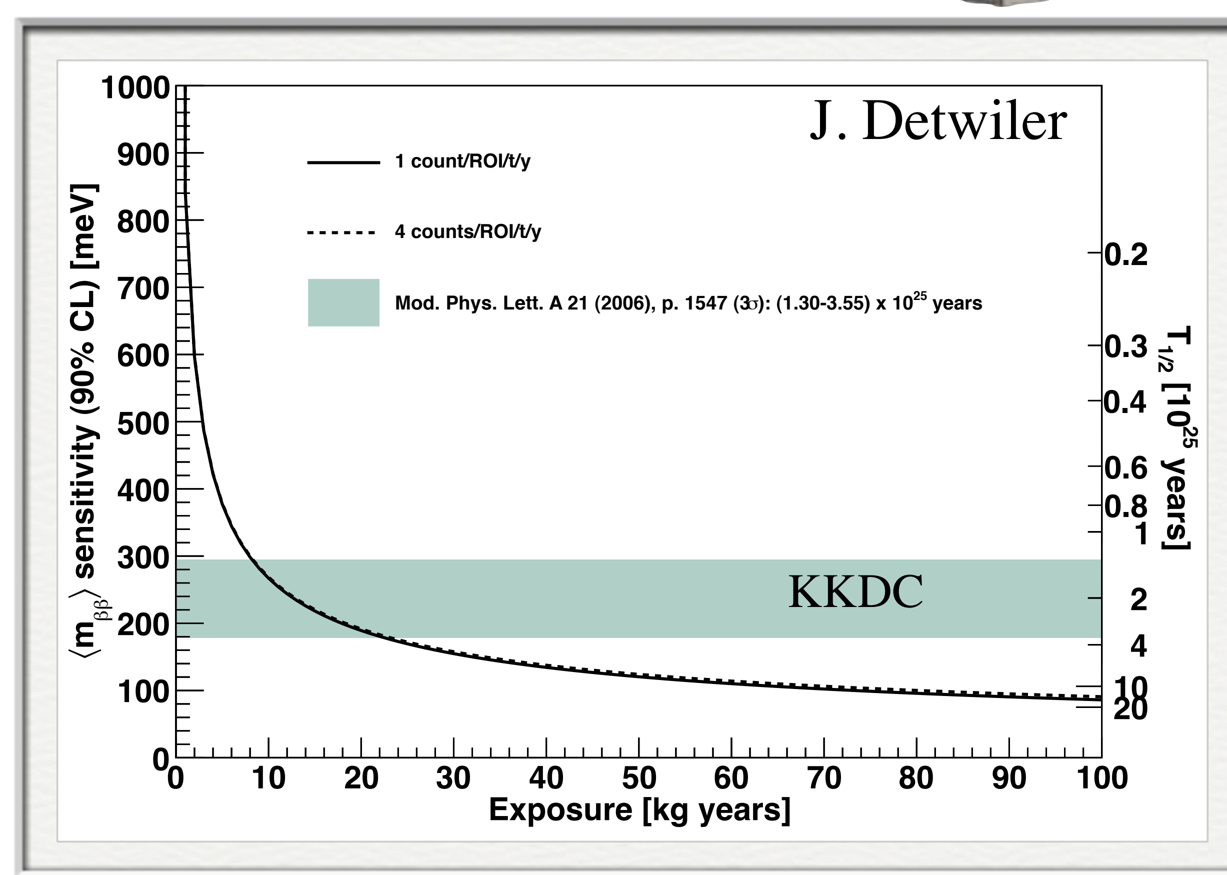


2006: "almost no γ background"
$T_{1/2}$ = 2.23x10^{25}yr, >6 σ

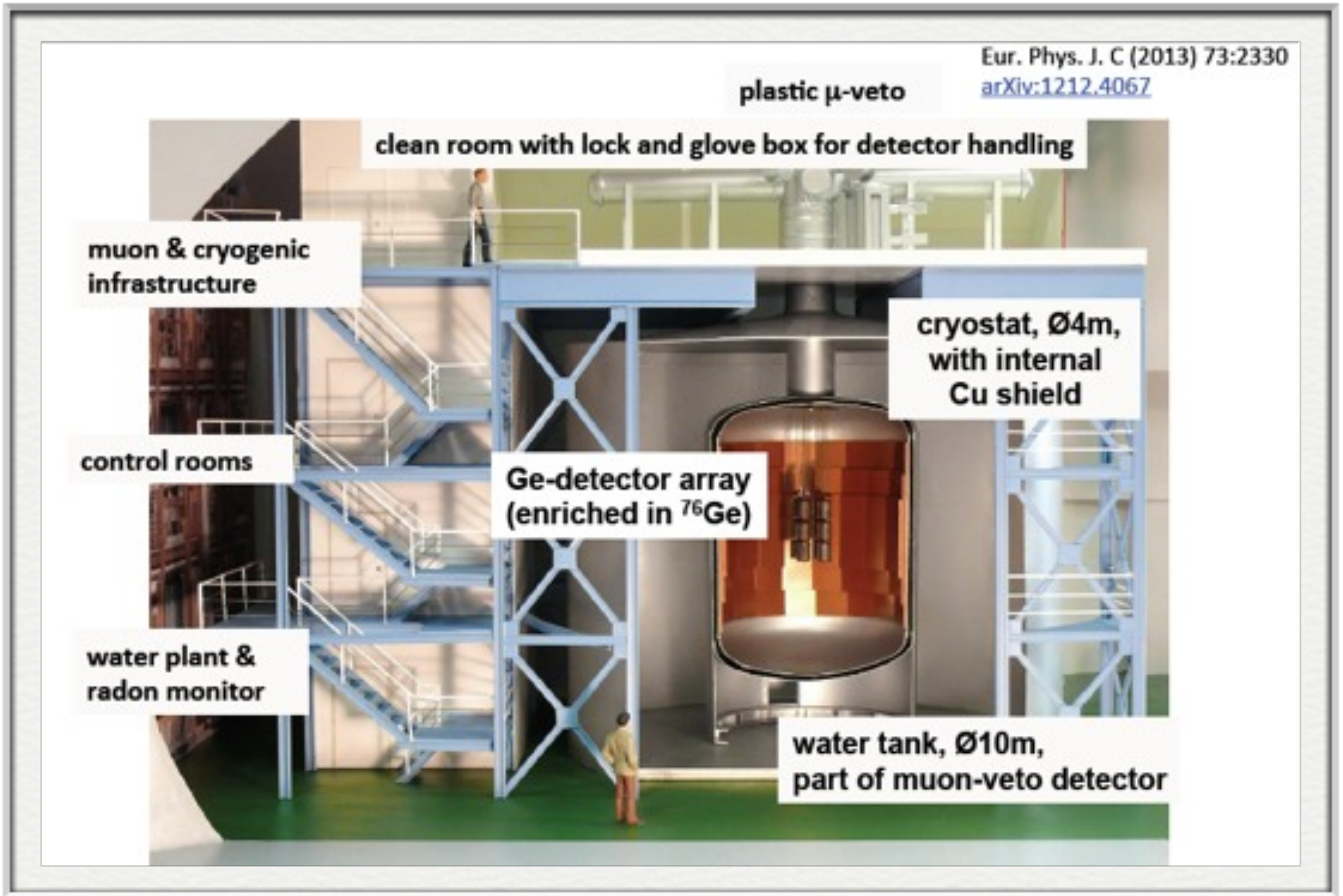
MAJORANA (Demonstrator)

- MJD: 40kg prototype @ SURF
- Goal: tonne-scale
- Advanced High-purity Ge detector
- Electroformed Cu cryostat
- Electroformed Cu/Pb shield
- Under construction in SURF
- Goal: 1 bkg/ton-keV-yr
- Data this year





GERDA



Enriched ^{76}Ge crystal array
LAr bath (shielding)
Refurbished Ge diodes from HdM / IGEX

Phase I: 18kg (14.6kg), 21.6 kg yr

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

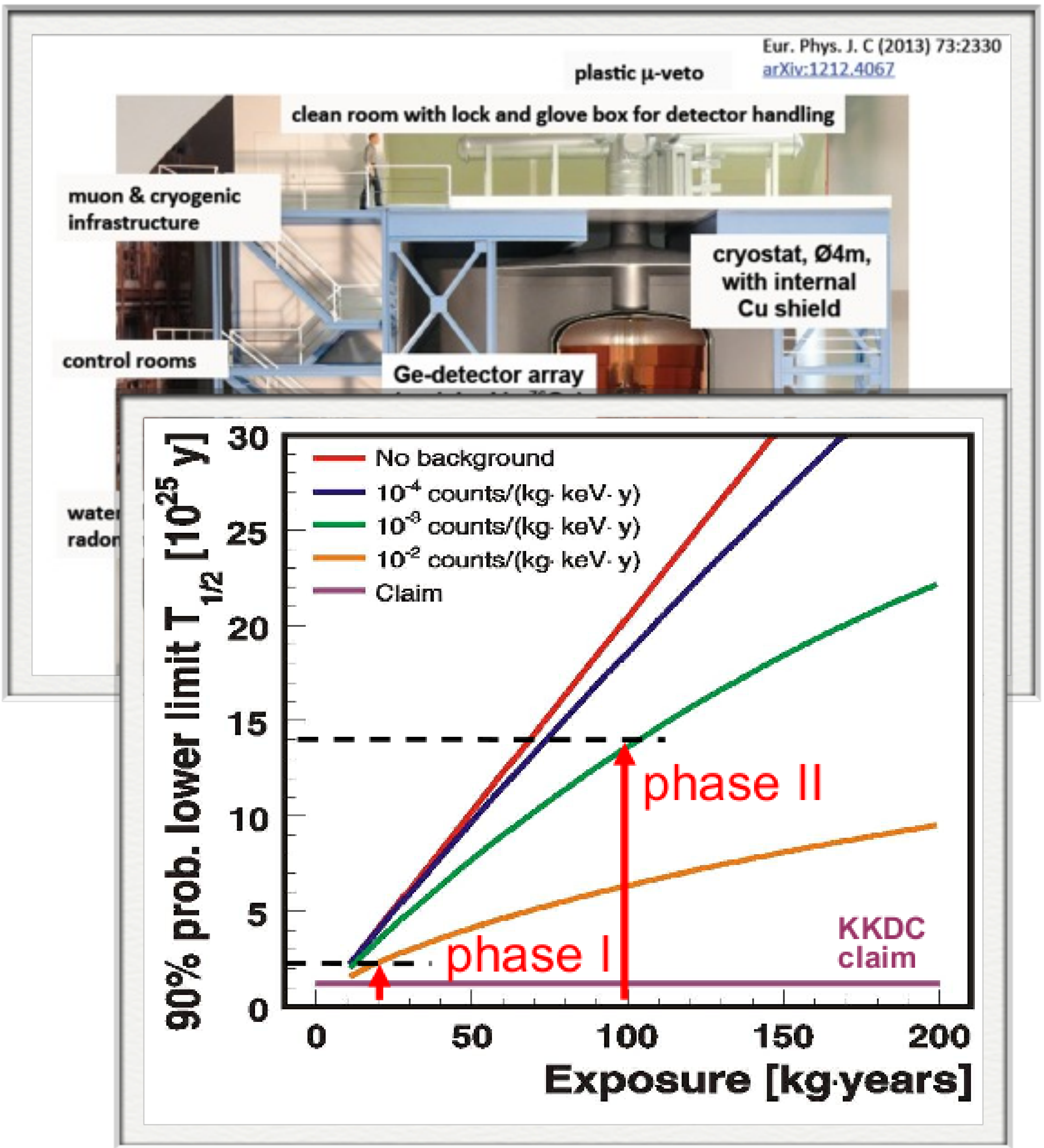
90% CL (Bayesian)

Combined: $T^{0\nu}_{1/2} > 3 \times 10^{25}$ yr

$<m_{\beta\beta}> < [0.2,0.4]$ eV

PRL 111 (2013) 122503

GERDA



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Phase II (40kg)

Advanced PSD

Instrument LAr veto

⇒ *Reduce bkg by 10*

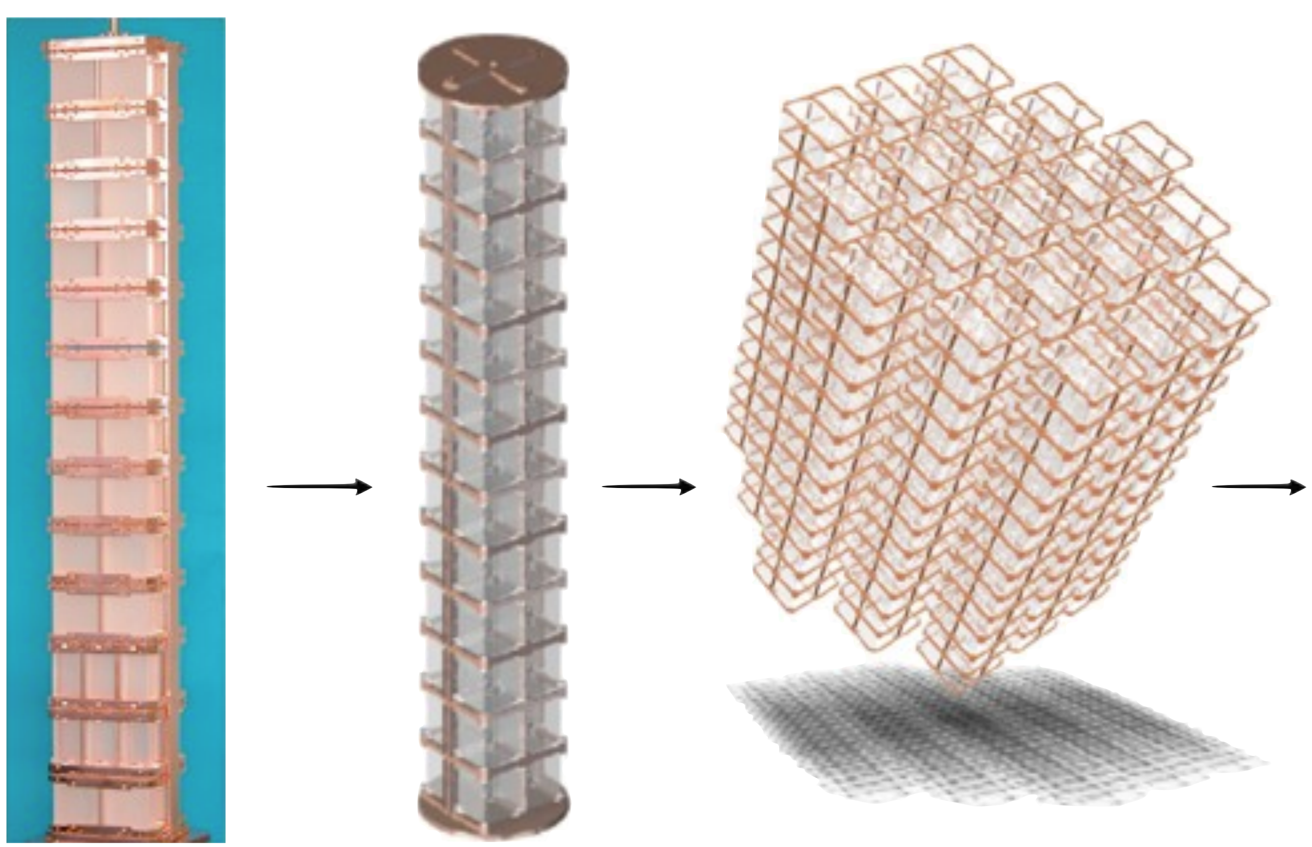
CUORE: cryogenic bolometry

- 988 crystals in a tower structure

  (19 towers, 13 levels, 4 crystals per)

750 kg TeO_2 => 200 kg ^{130}Te

CUORICINO 2003-08 | CUORE-0 2013-15 | CUORE 2015+

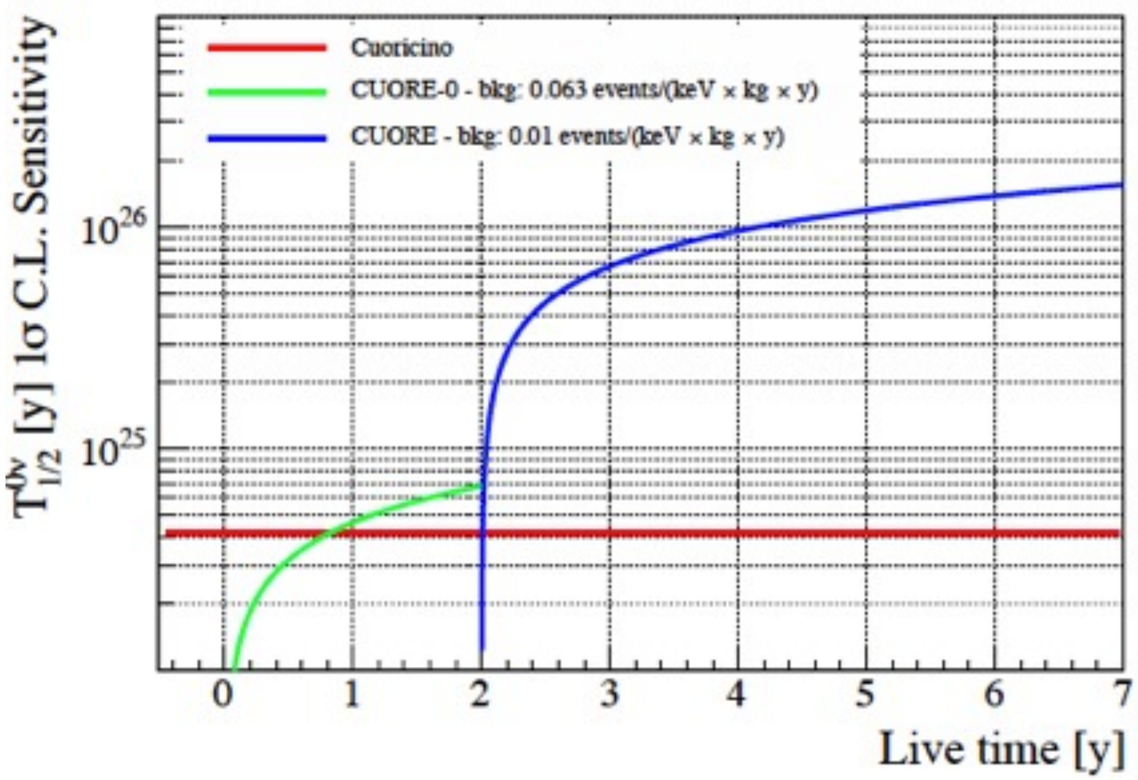


	$0\nu\beta\beta$ region cnts/(keV kg y)	2700-3900 keV	ε(%)
Cuoricino	0.153 ± 0.006	0.110 ± 0.001	83
CUORE-0	0.063 ± 0.006	0.020 ± 0.001	78

- Radio-purity techniques and high resolution achieve low backgrounds
- Data taking ~2015

CUORE: sensitivity & R&D

Background [c/keV/kg/y]	ΔE_{FWHM} [keV]	$\tau_{½}^{0\nu}$ [y] @ 68%C.L.	m_{ee} [meV] R(QRPA)[1]	pn(QRPA)[2]	ISM[3]	IBM-2[4]
0.01	5	**2.1×10^{26}**	35÷66	41÷67	65÷82	41
0.001	5	**6.5×10^{26}**	20÷38	23÷38	37÷47	23



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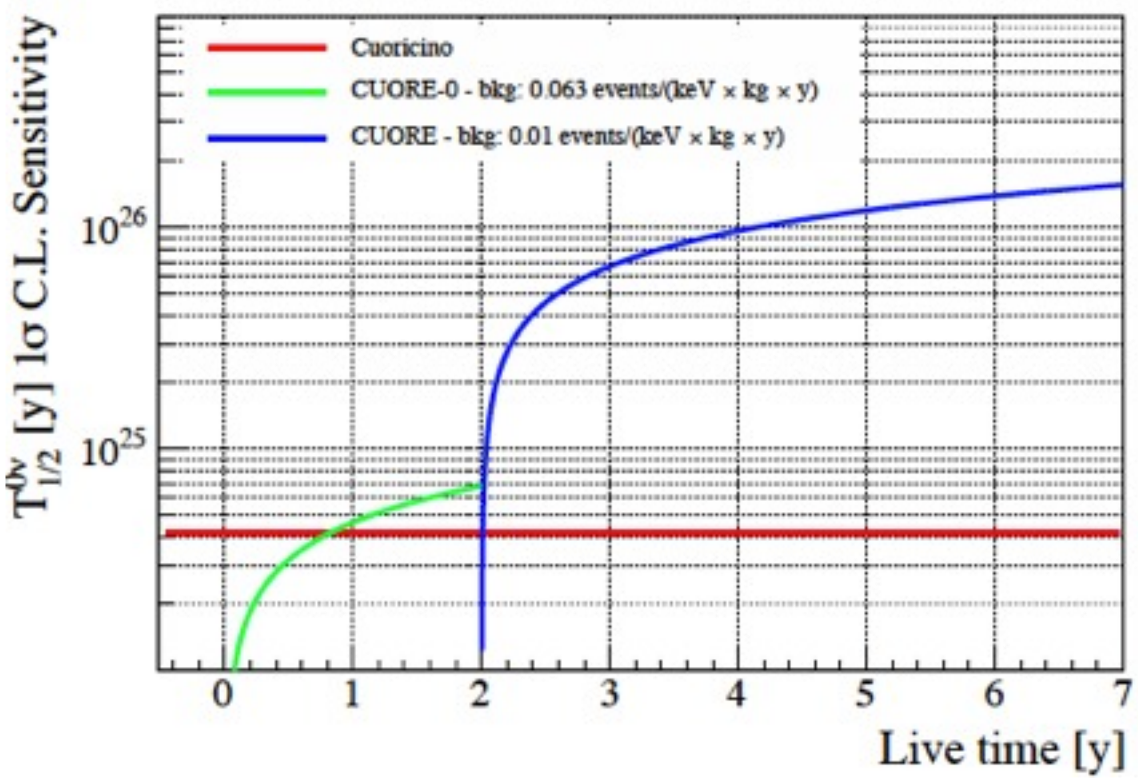

- CUORE-IHE: scintillating bolometers
  - TeO_2 (Cher) (Q = 2528 keV)
  - ZnSe (Q=2996 keV)
  - $ZnMoO_4$ (Q=3034 keV)
  - $CdWO_4$ (Q = 2814 keV)

R&D ongoing for stable crystal production & background reduction

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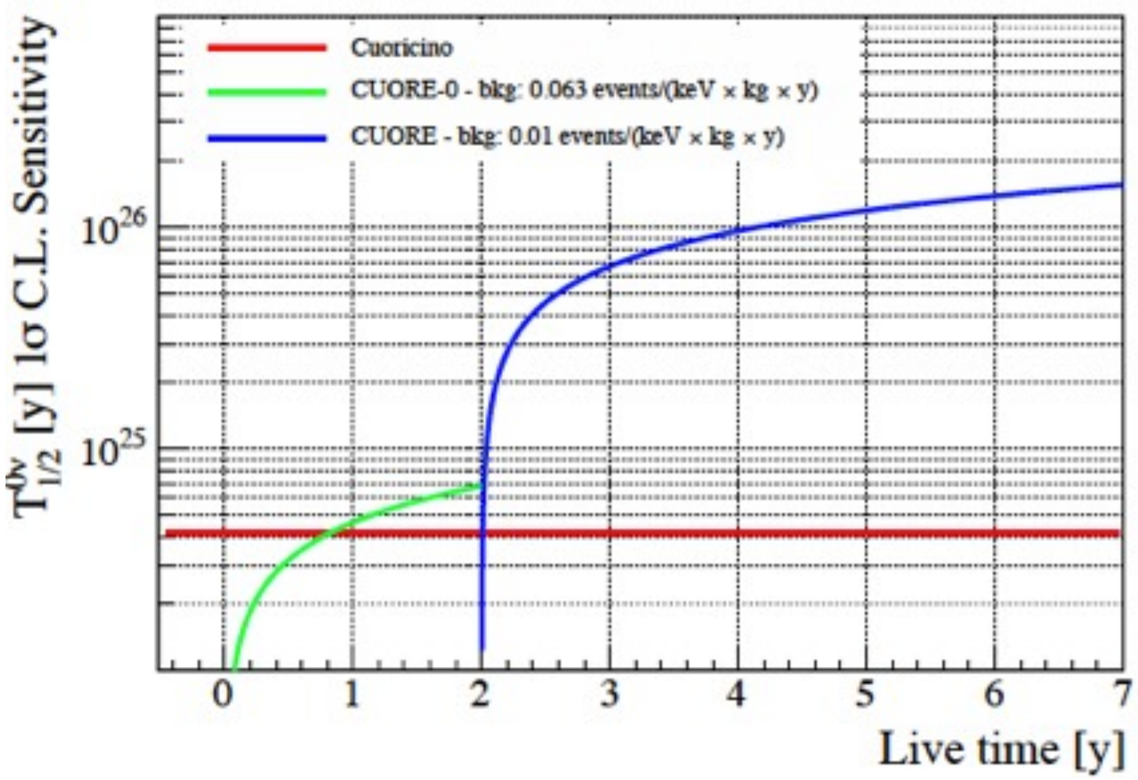

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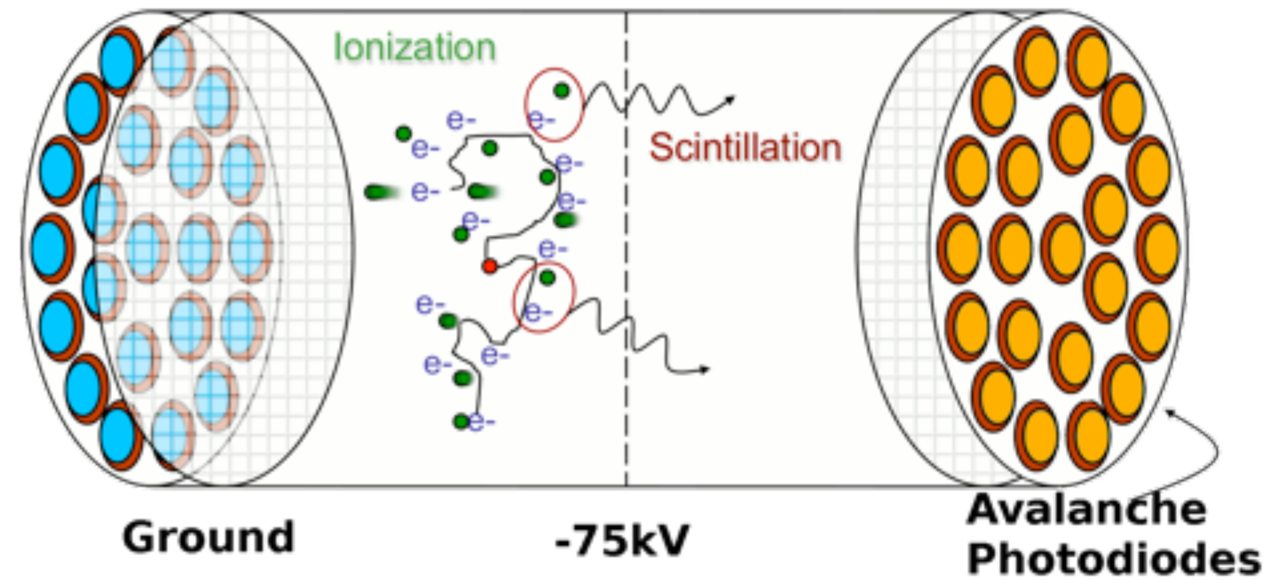
"Next-generation bolometric experiment has the potential to convincingly discover, or rule out, $0\nu\beta\beta$ in the entire Inverted Hierarchy region"

Cremonesi, Neutrino '14 presentation

EXO-200

- TPC: ionisation + scintillation
- 200kg enriched LXe (80.6%)
- Prototype for 1T-scale



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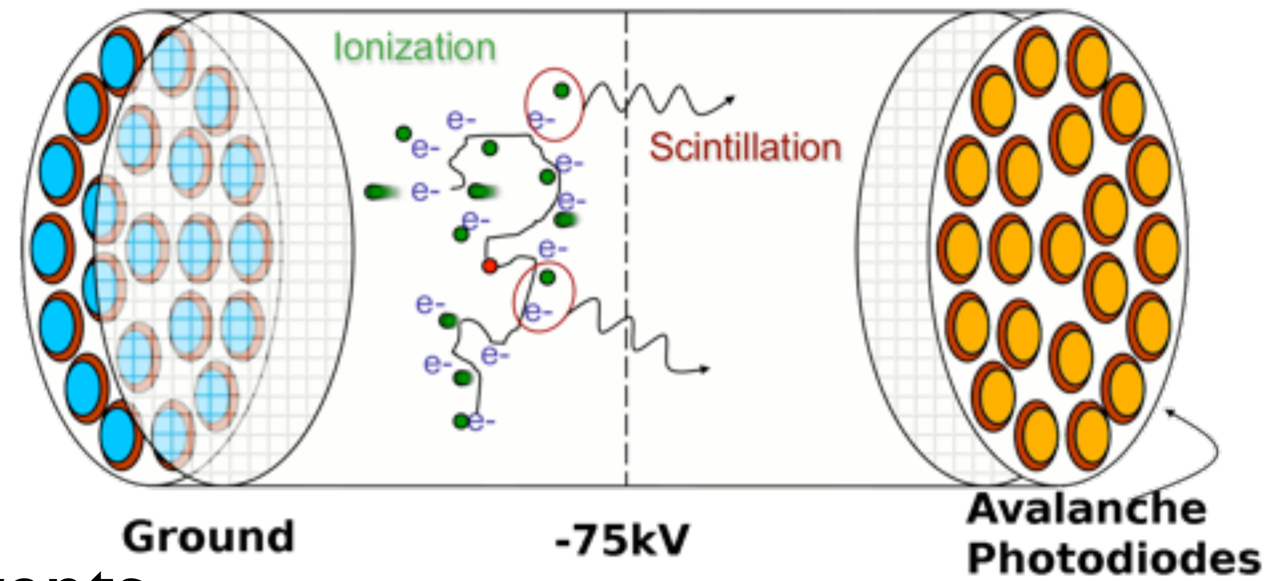

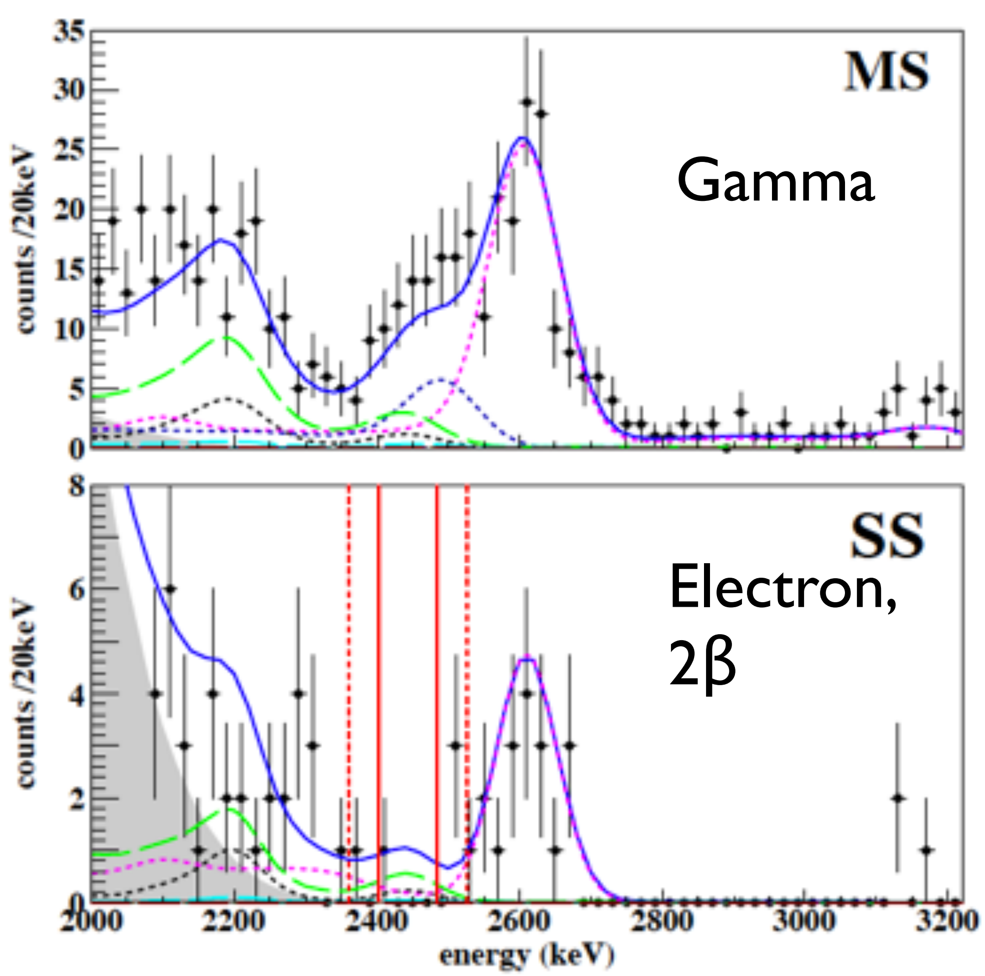

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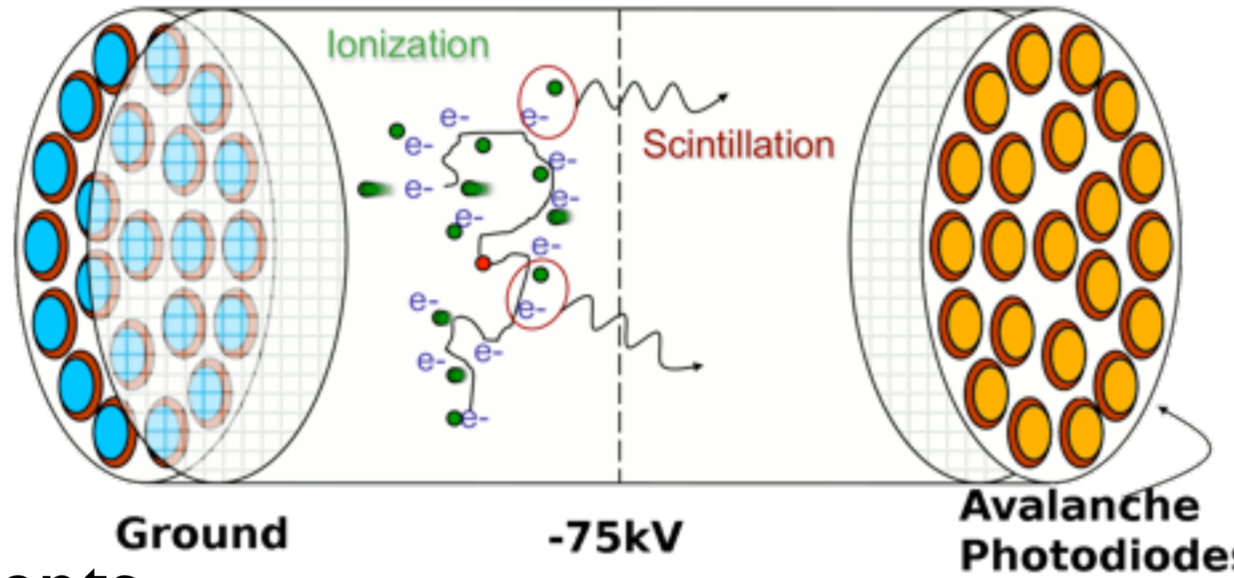

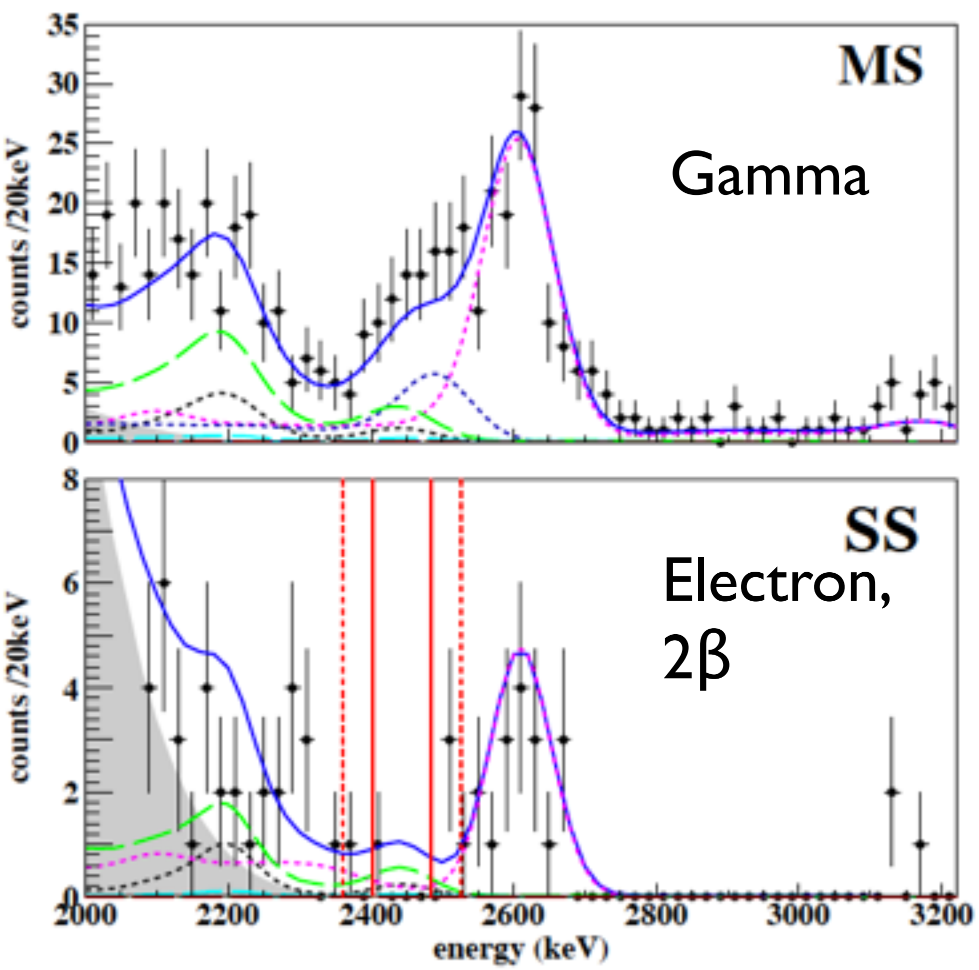

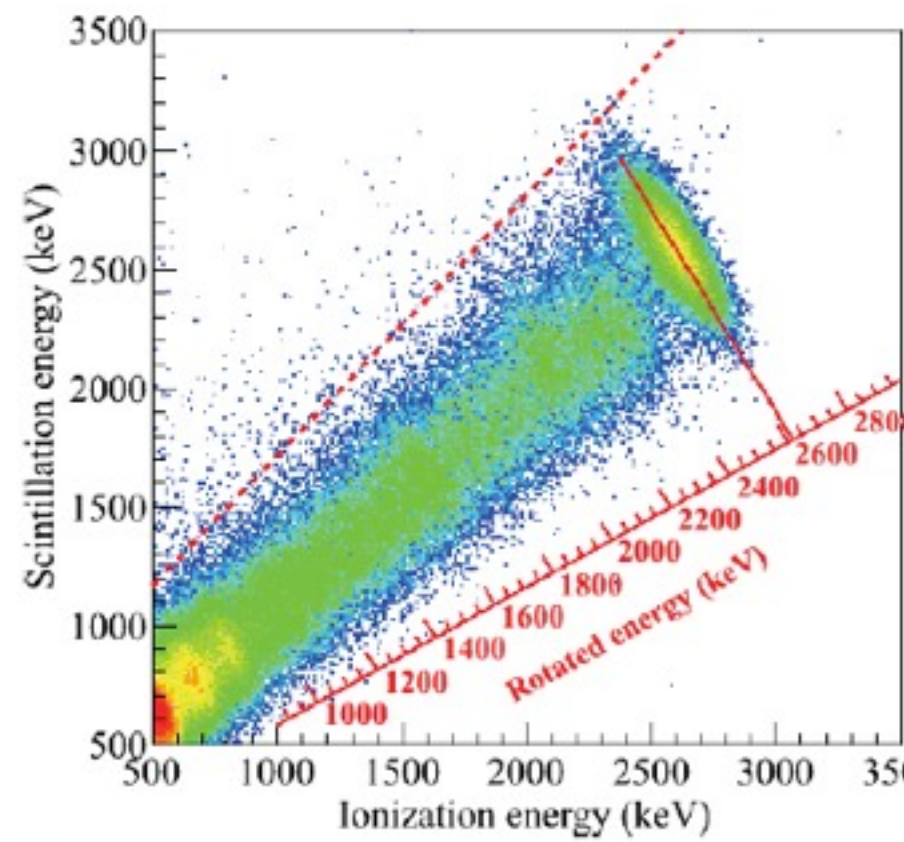

- Energy reconstruction uses scint + ionisation signals (σ = 1.4%)

EXO-200 Results & nEXO

- Phase I: (32.5 kg-yr) $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ yr PRL 109 032505 (2012)

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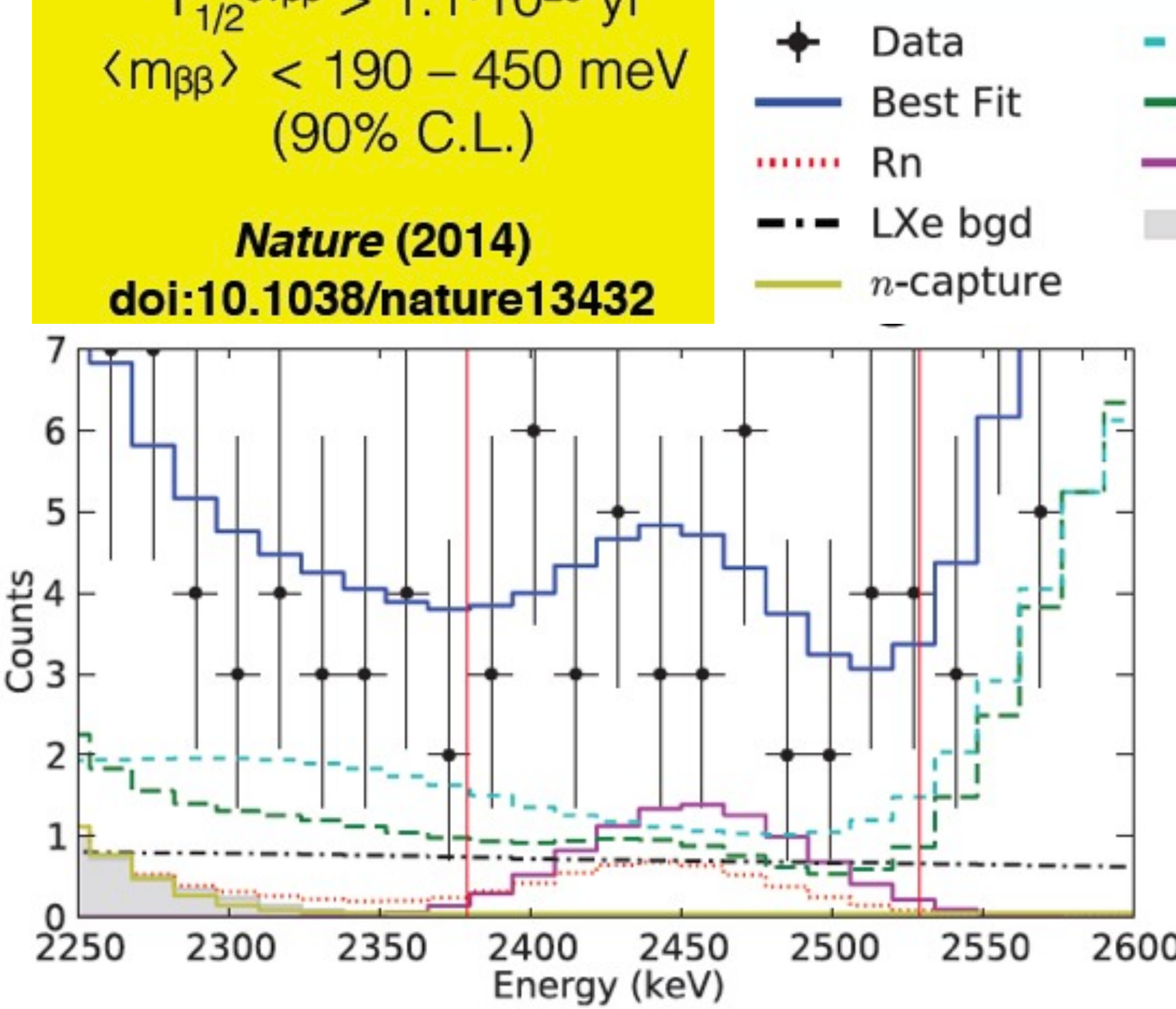
- Phase II: (100 kg-yr)

$T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}$ yr
$\langle m_{\beta\beta}\rangle < 190 - 450$ meV
(90% C.L.)

***Nature* (2014)**
doi:10.1038/nature13432



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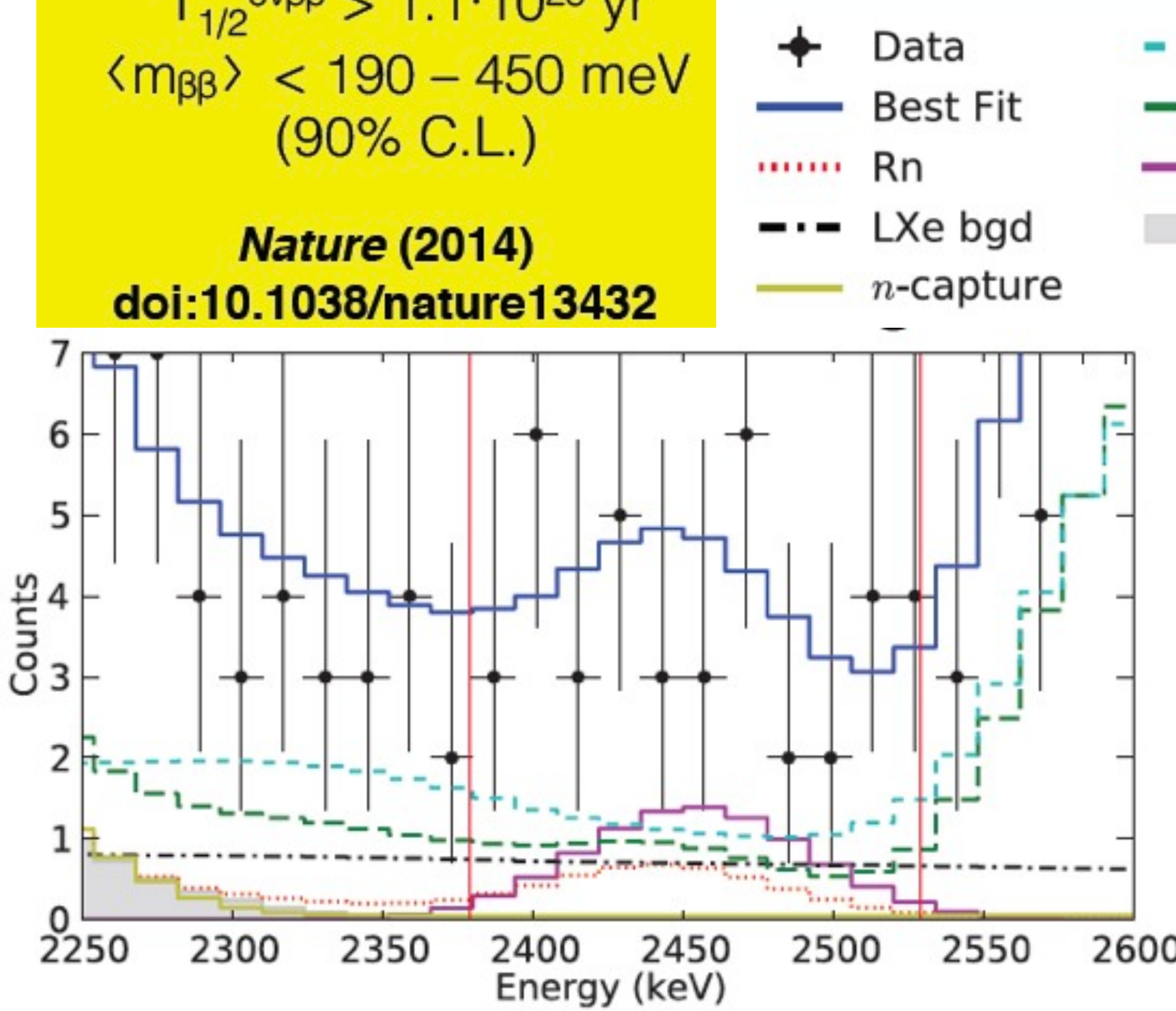
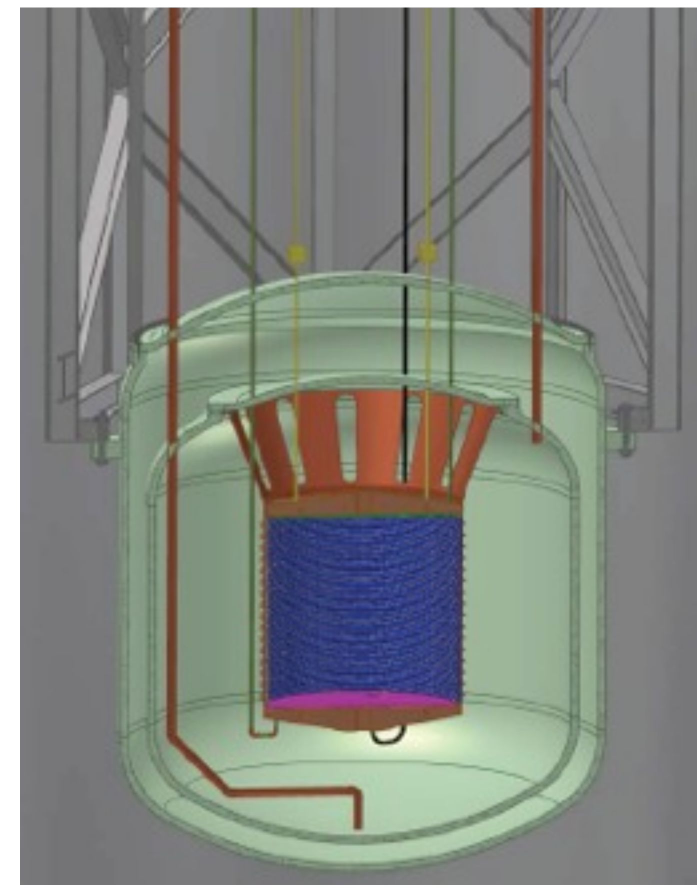
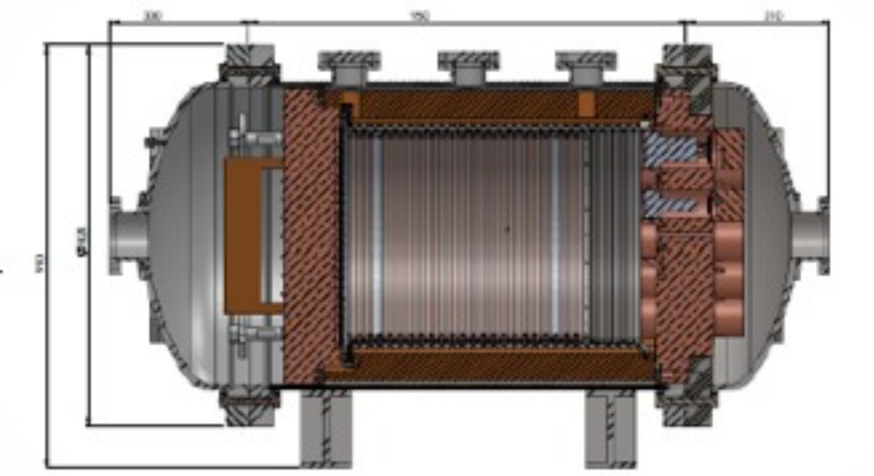


- nEXO

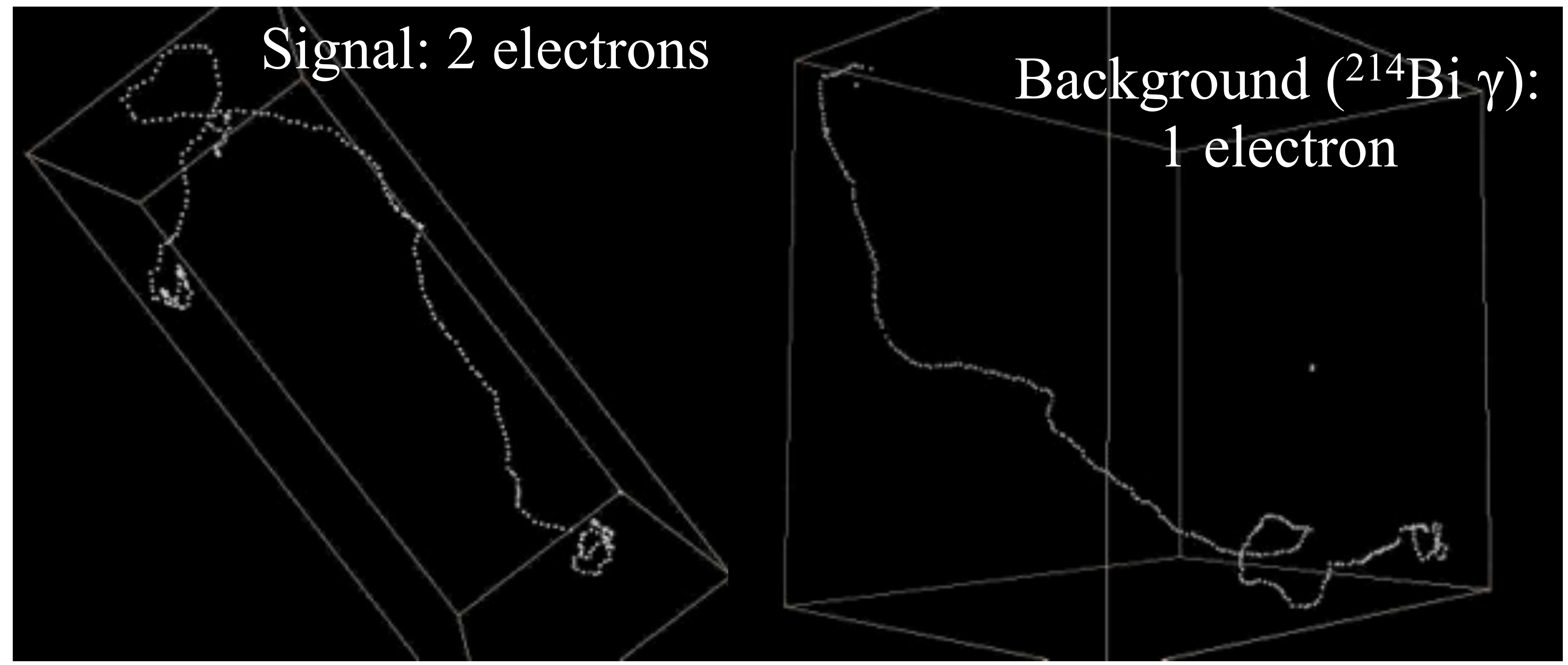


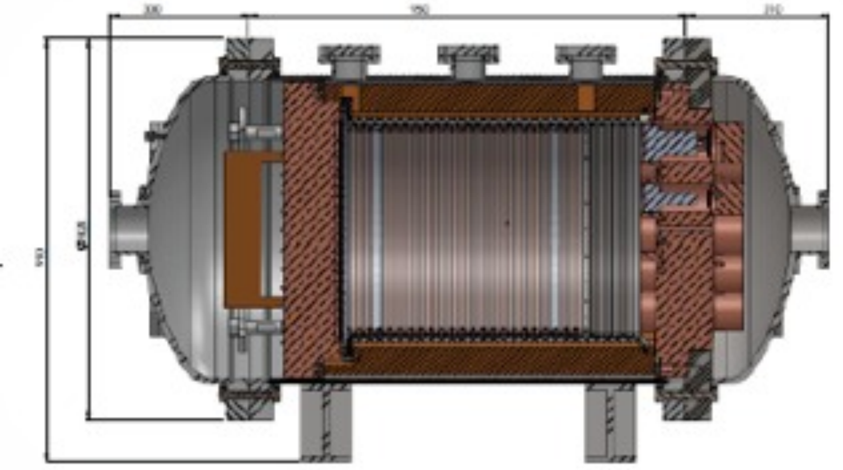
- tracking power increases with size (containment)
- self shielding from ext bkg
- Ba tagging could enable NH?



NEXT

- Gaseous TPC: tracking





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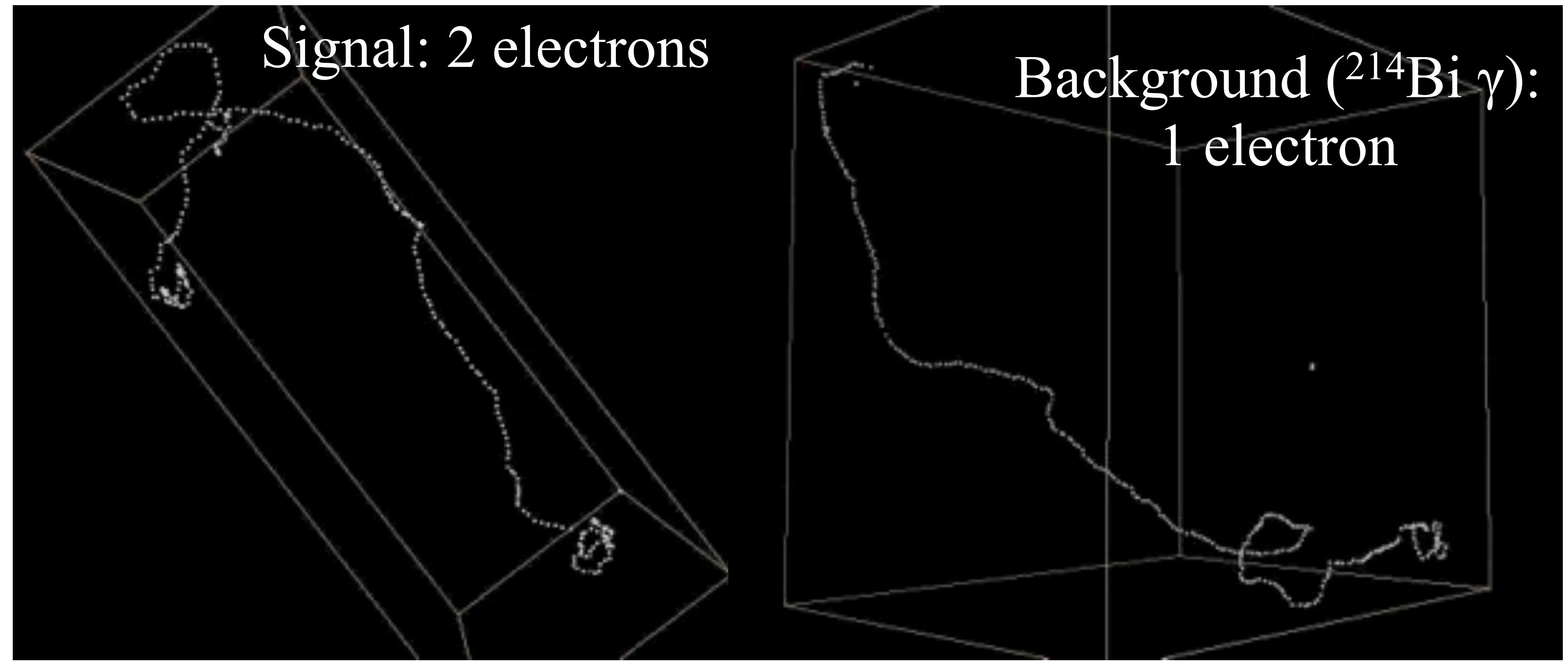
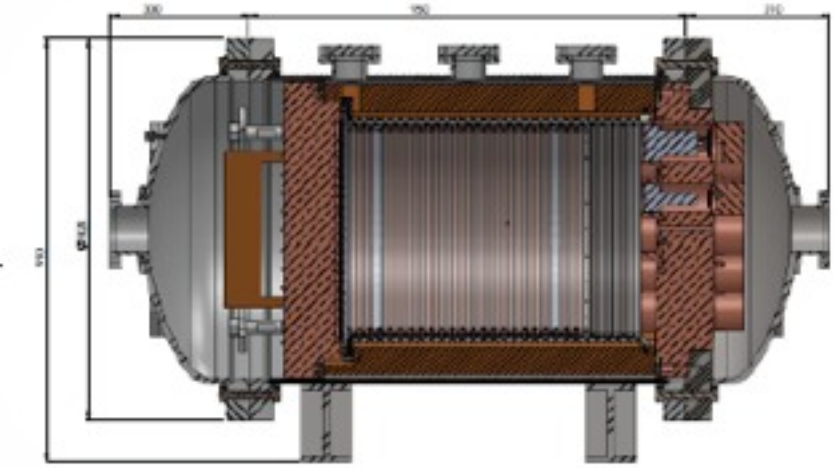
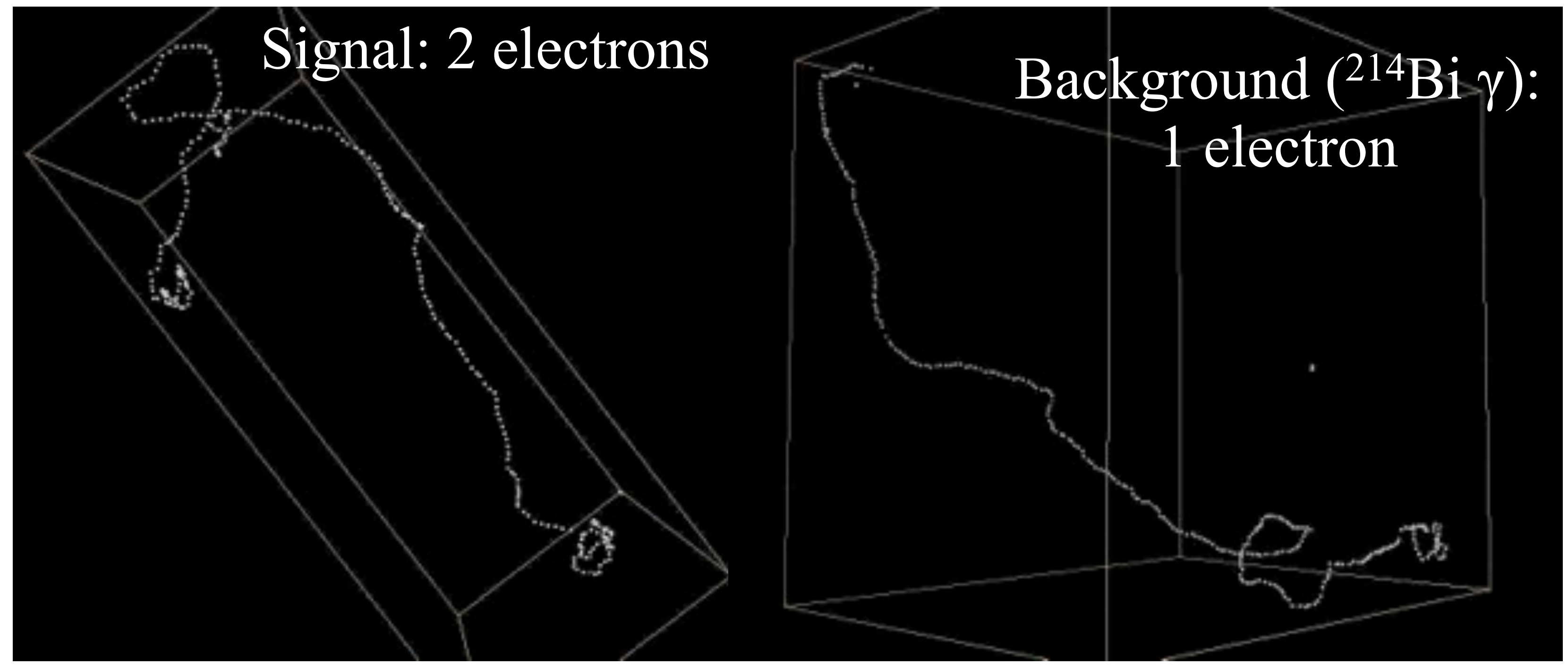


- Gaseous TPC: tracking
- Prototype for 100kg-scale in operation at LBNL

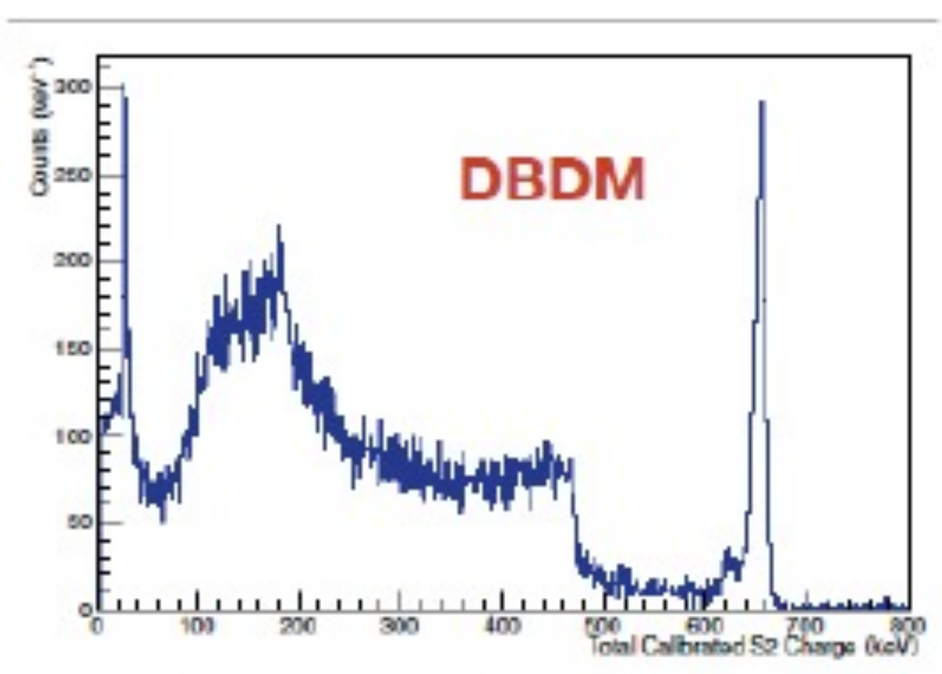
(2008-13) (2014-16) (2016-20?) (2020?)

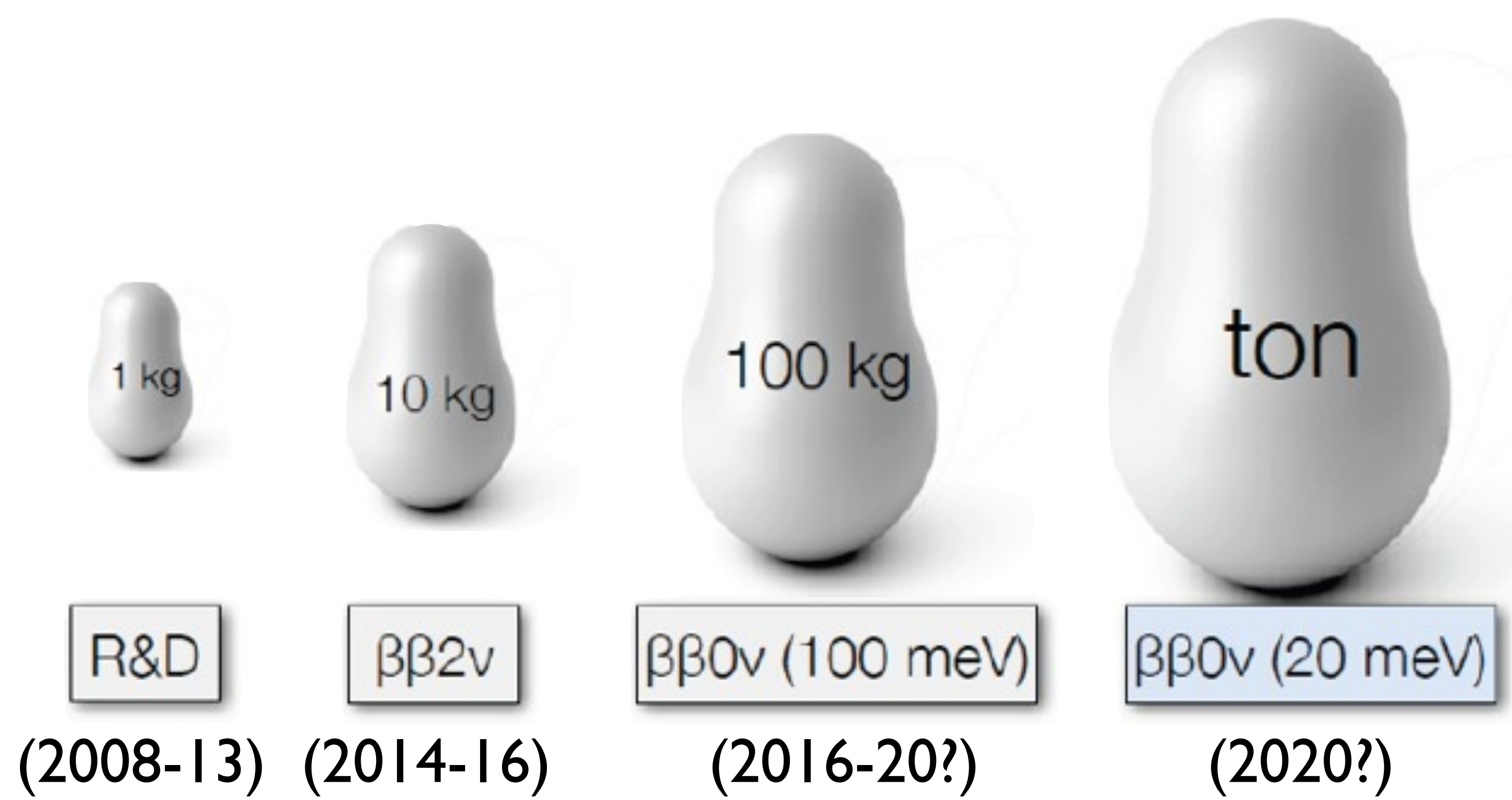


NEXT



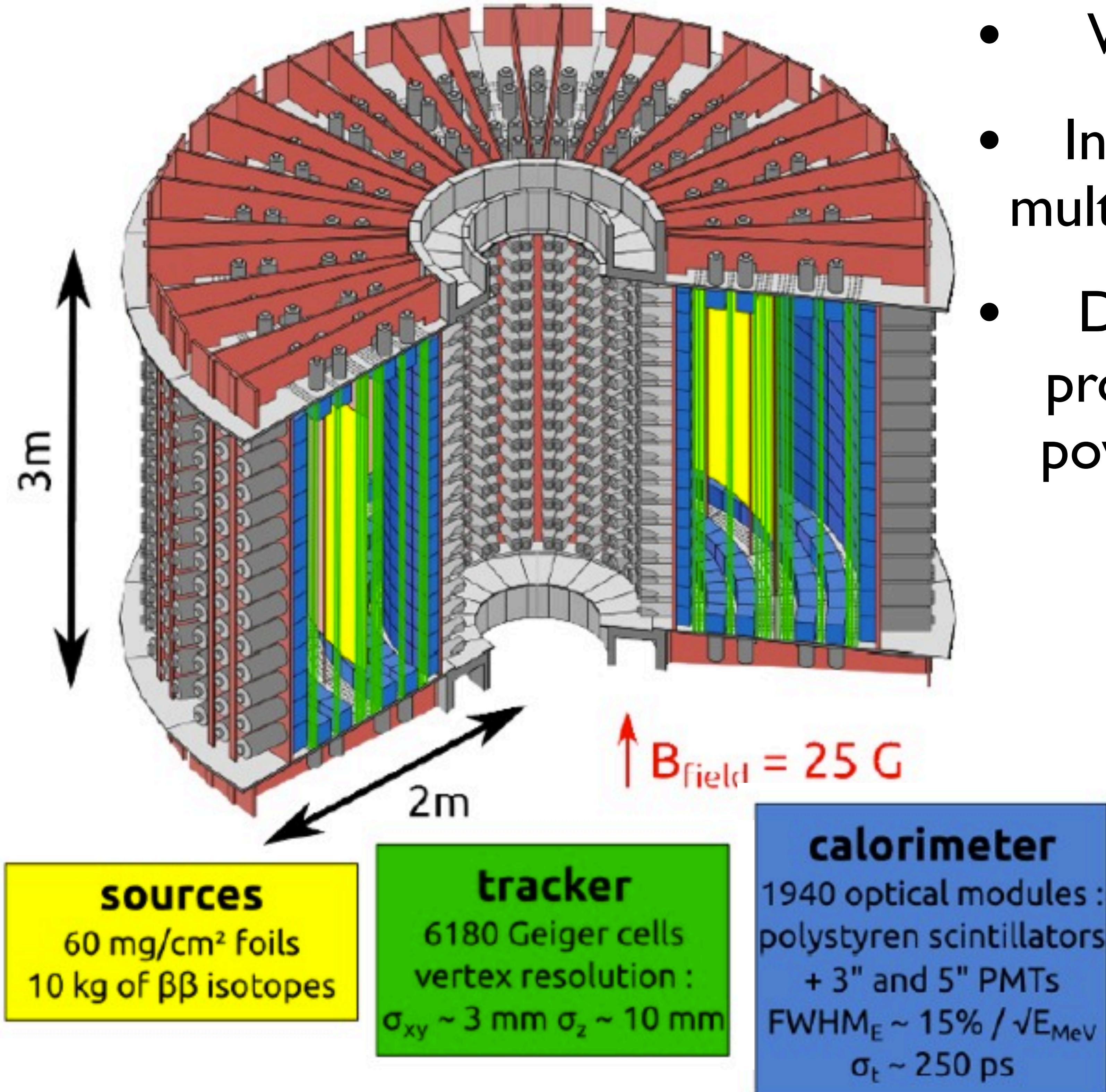
- Gaseous TPC: tracking
- Prototype for 100kg-scale in operation at LBNL
- ~0.5% energy resolution extrapolated from ^{137}Cs electron calibration

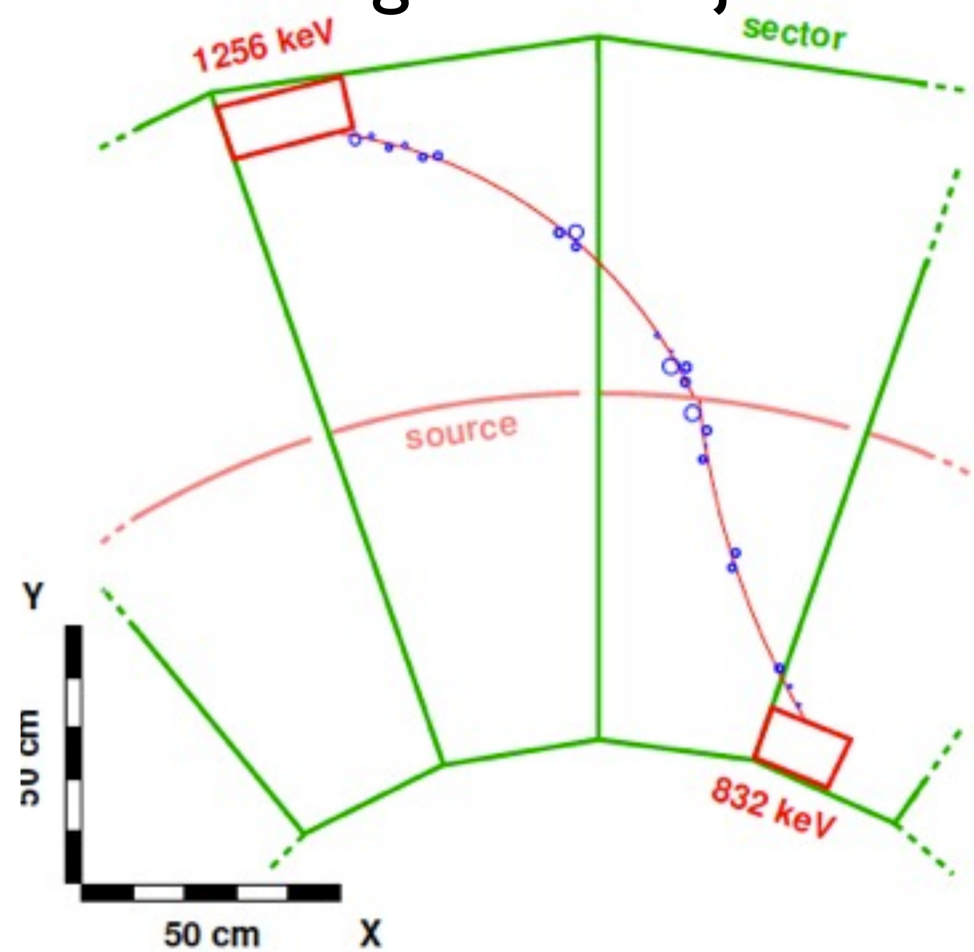




NEMO-3

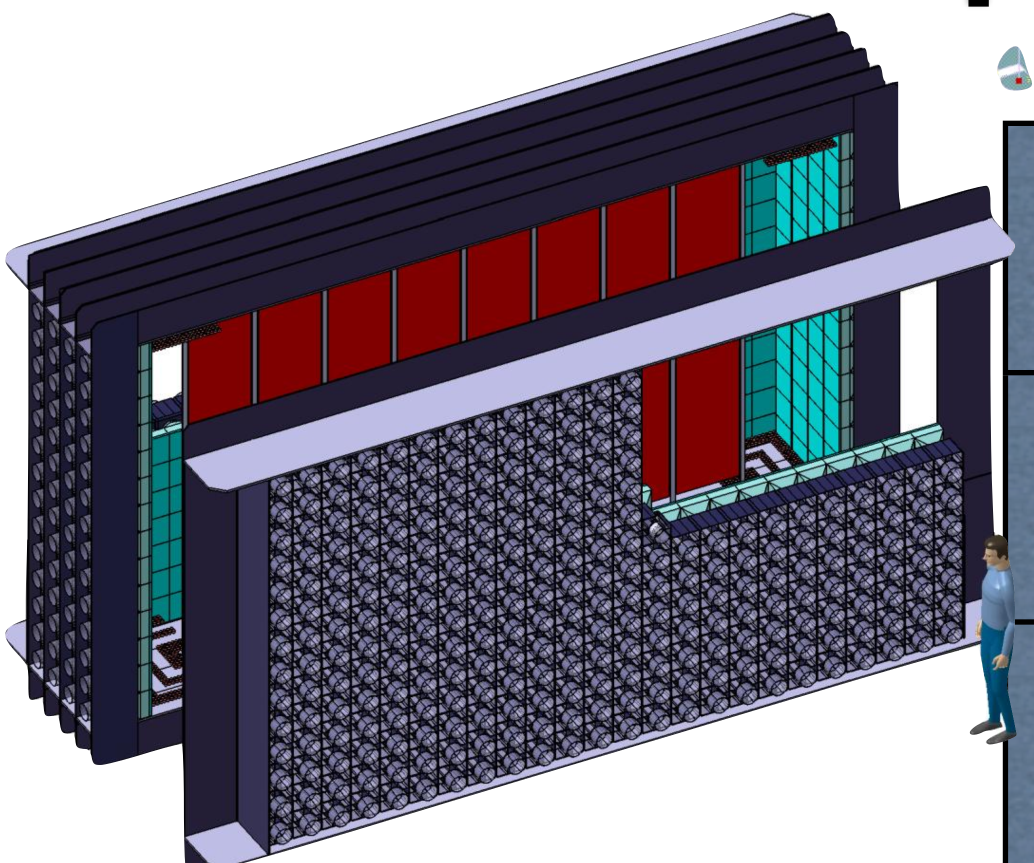
- Wire chamber + scintillator
- Interchangeable foils allow for multiple isotopes (^{100}Mo, ^{150}Nd...)
- Direct reconstruction of 2 e^- provides full $0\nu\beta\beta$ signature & powerful background rejection





From M. Bongrand, Nu2014 slides

SuperNEMO

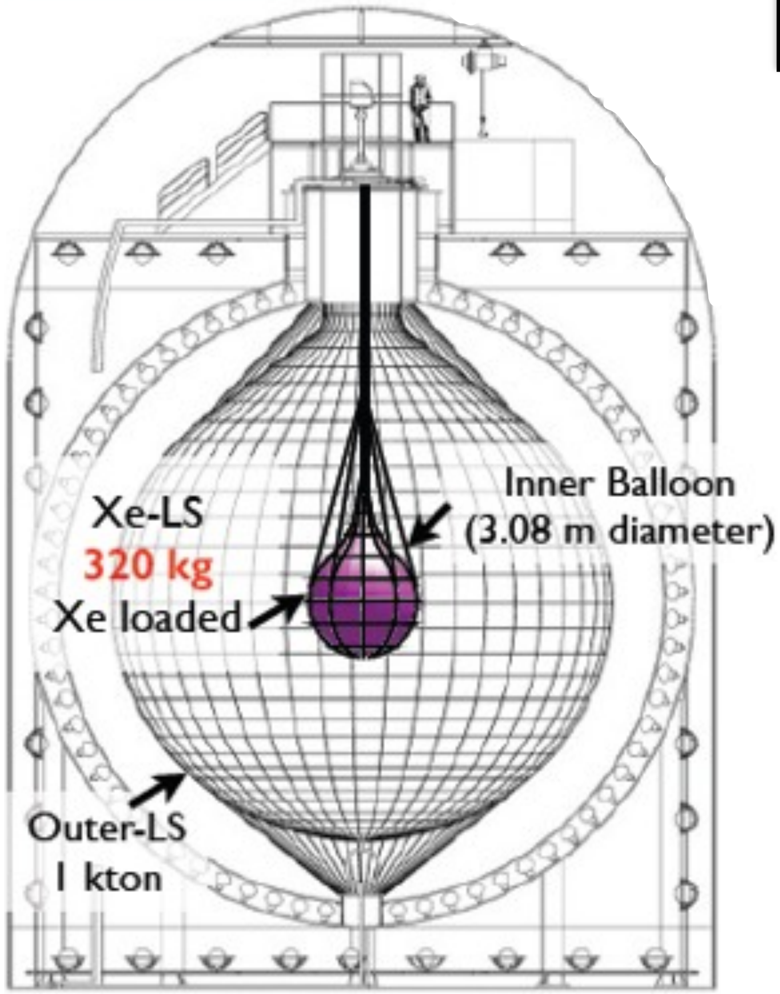


Demonstrator commissioning & physics data taking summer 2015

Zero bkg expected in 2.5 yrs with 7kg ^{82}Se
⇒ 0.2-0.4 eV mass limit

	NEMO-3	SuperNEMO
Isotope	^{100}Mo+	^{82}Se, ^{150}Nd, ^{48}Ca
Mass	7kg	100kg
Resolution (3MeV)	8% (FWHM)	4% (FWHM)
Total bkg cts/keV/kg-yr	1.3×10^{-3}	5×10^{-5}
Sensitivity	$> 1.1 \times 10^{24}$ yr < 0.33-0.87 eV	$> 1 \times 10^{26}$ yr < 40-100 meV

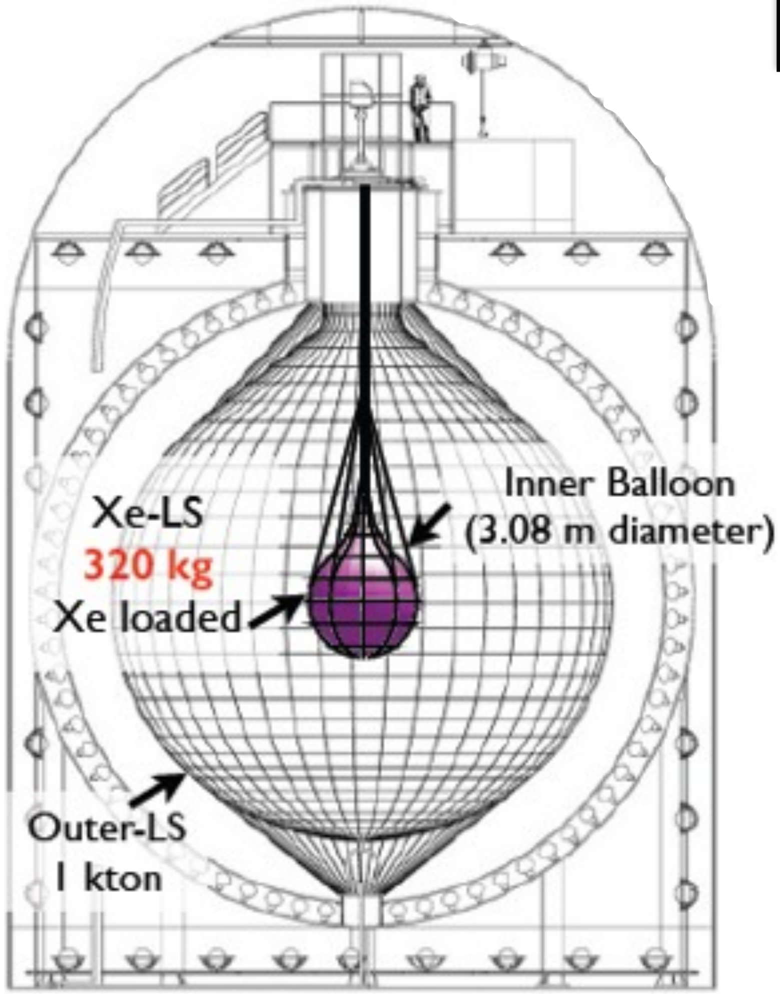
KamLAND-Zen



- Large-scale Xe-loaded LS (enriched to 91%)
- Phase I: $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)

PRL 110.062502 (2013)

KamLAND-Zen



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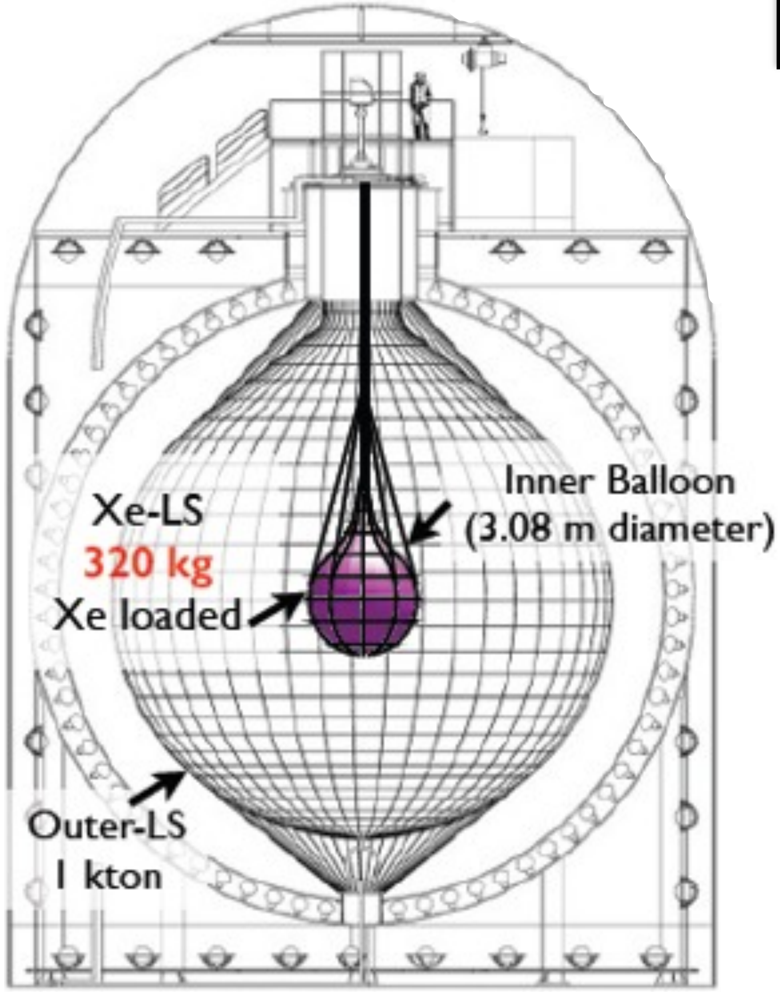

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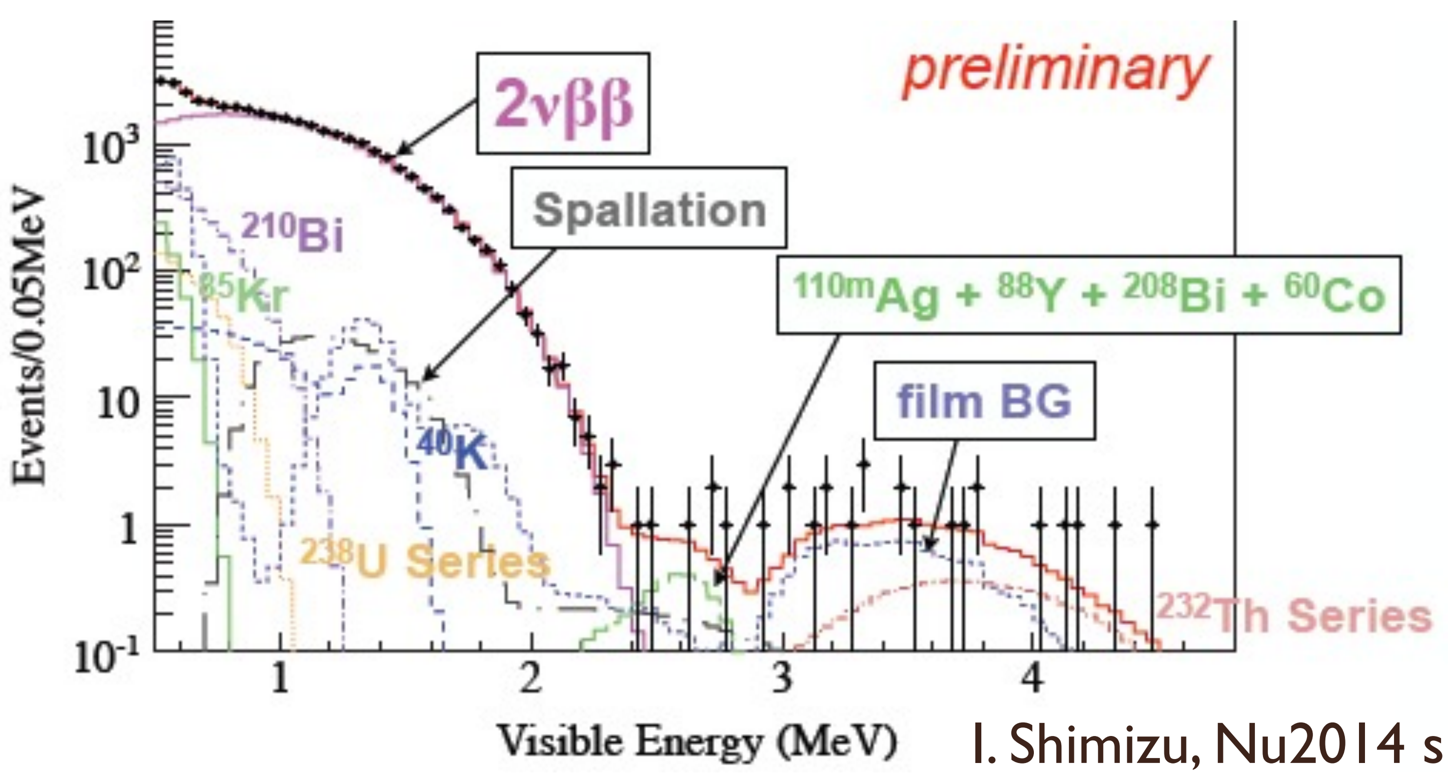
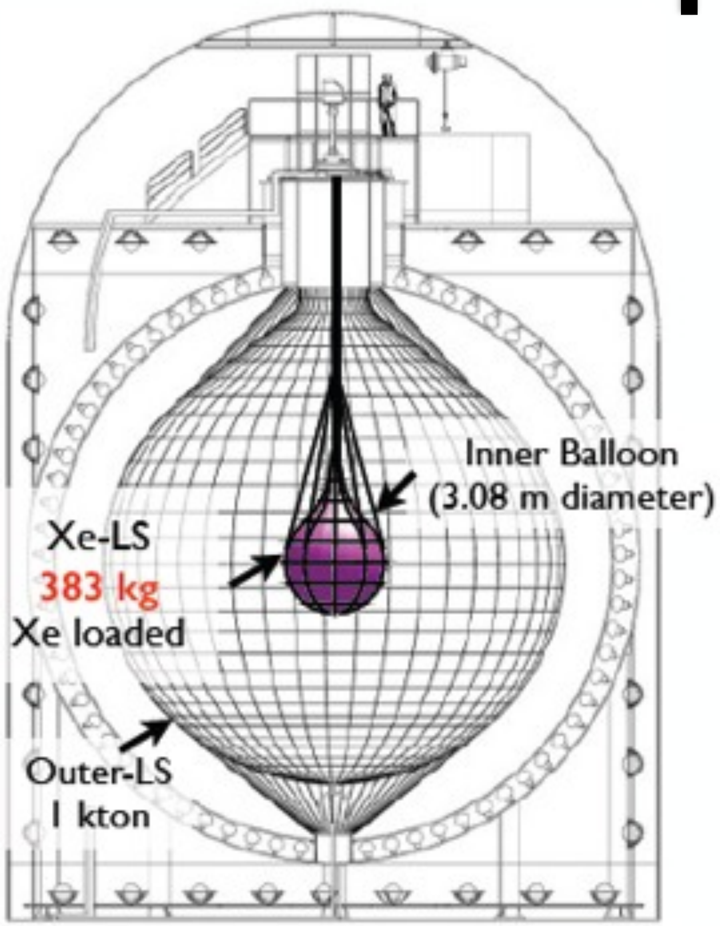


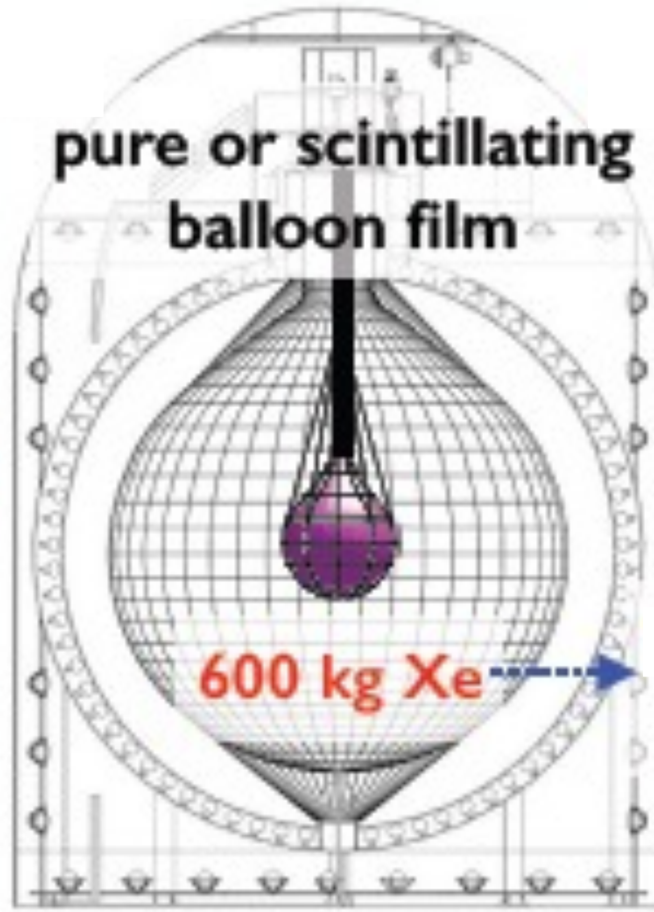
I. Shimizu, Nu2014 slides

- Phase II:
  $T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr (90% CL)
- Combined:
  $T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr (90% CL)
  $\langle m_{\beta\beta} \rangle < [0.14,0.28]$ eV

KamLAND2-Zen

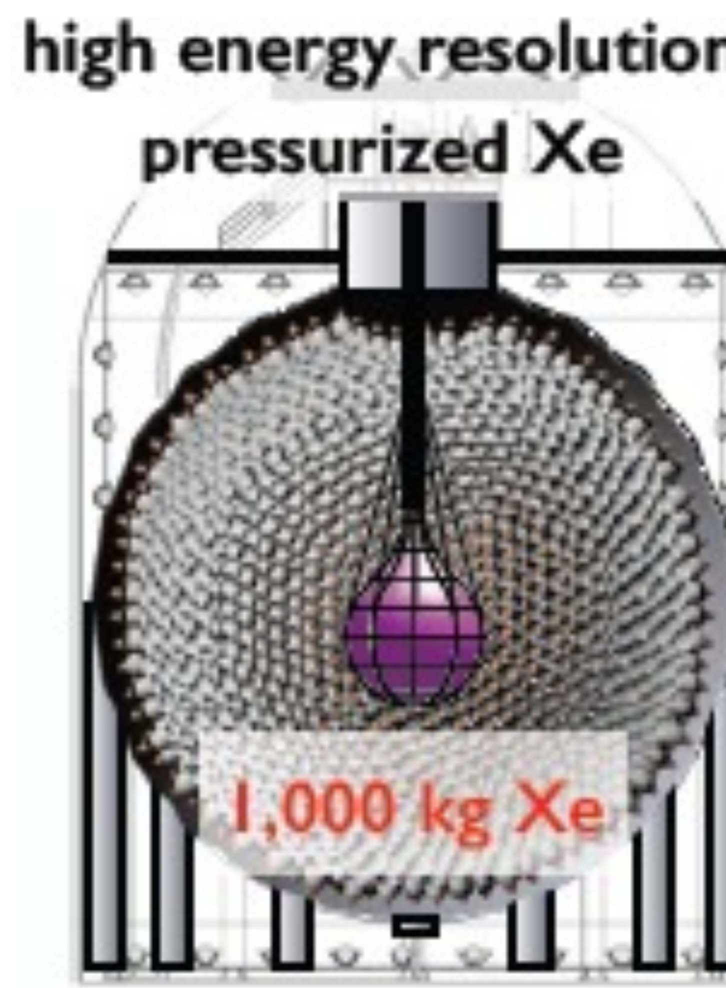


Phase II
Continued operation
~2014-16



Phase III
600-800kg Xe
~2014-16
Reach IH

KamLAND2-Zen
1T Xe
~2018-20?
Goal: 20meV



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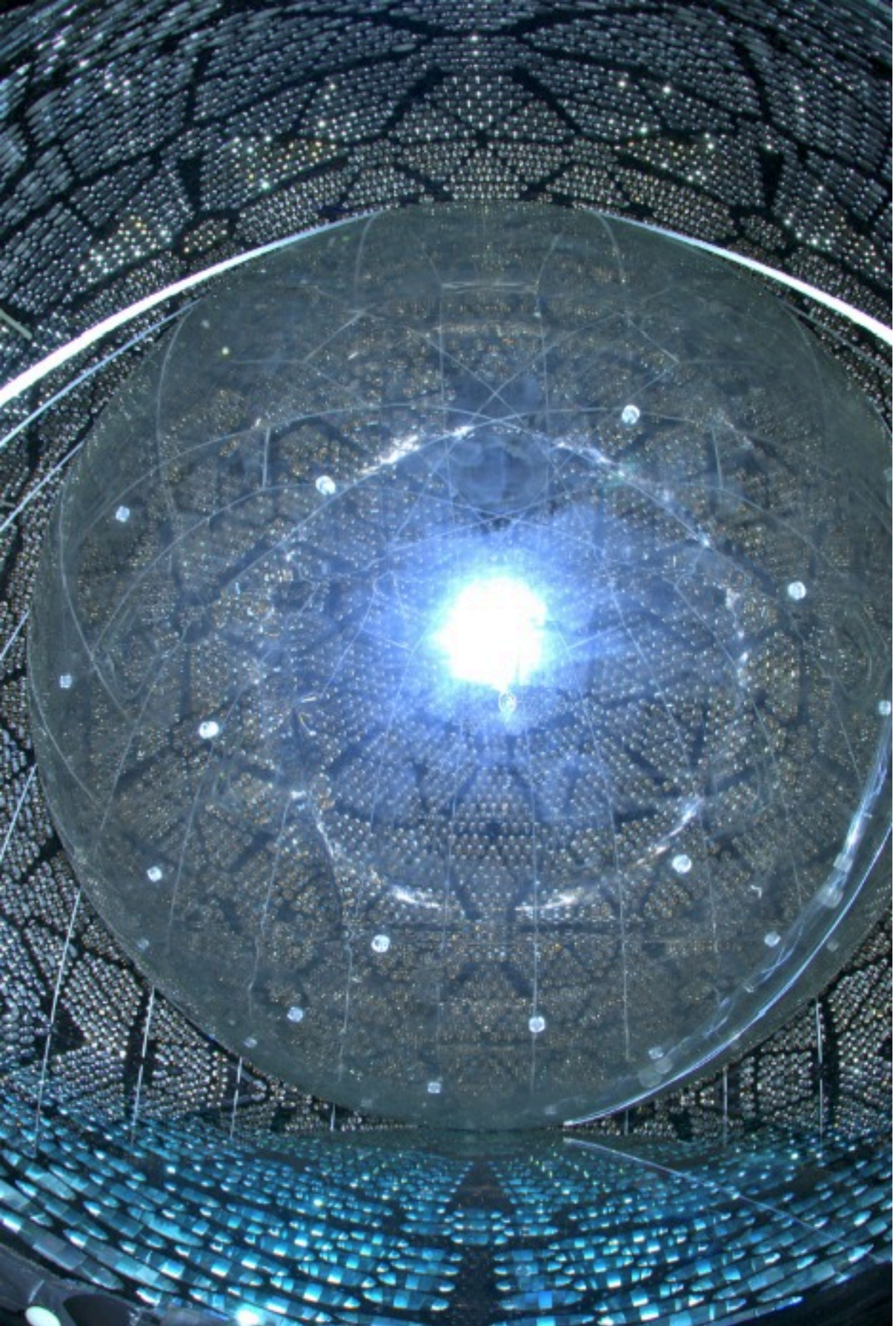
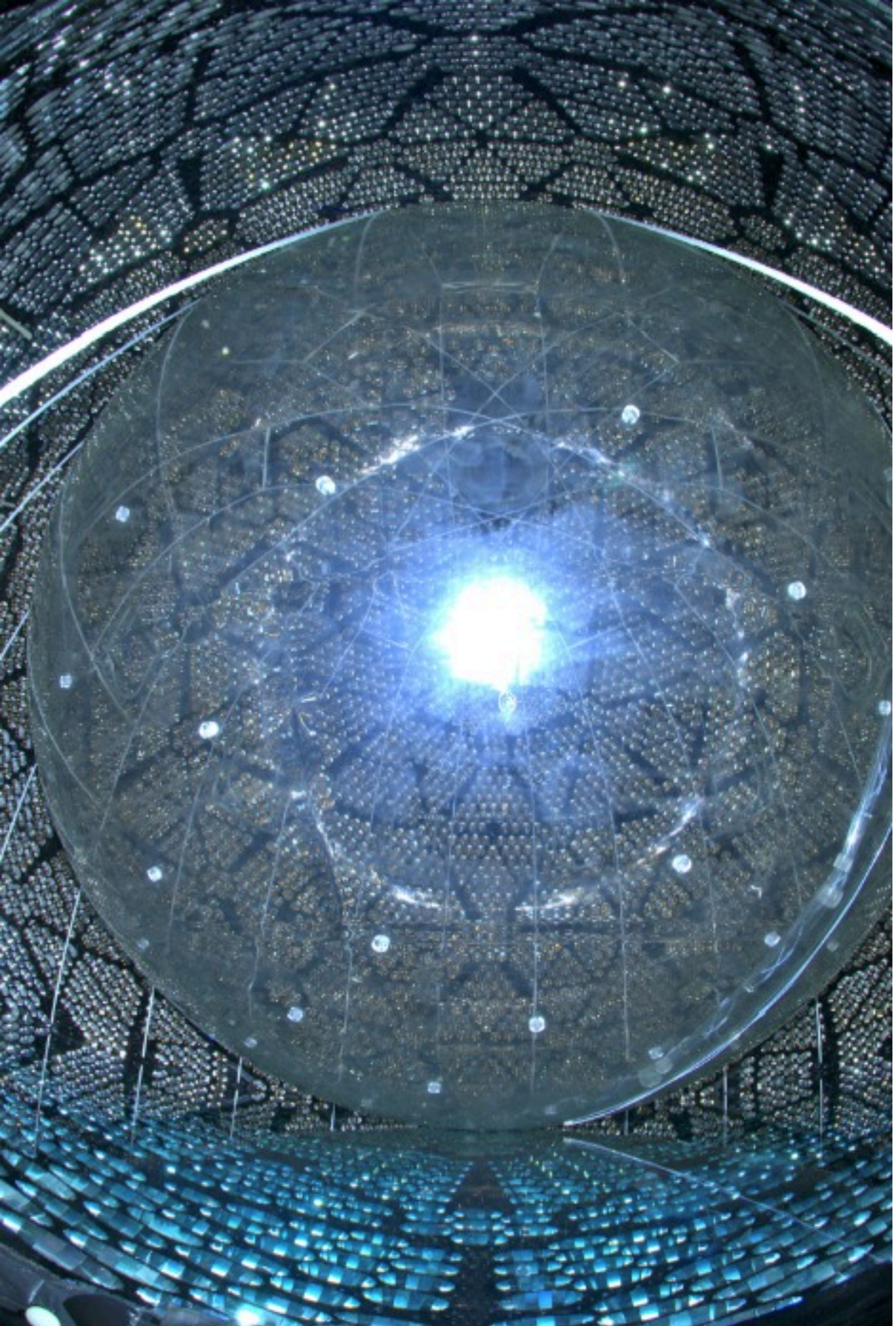
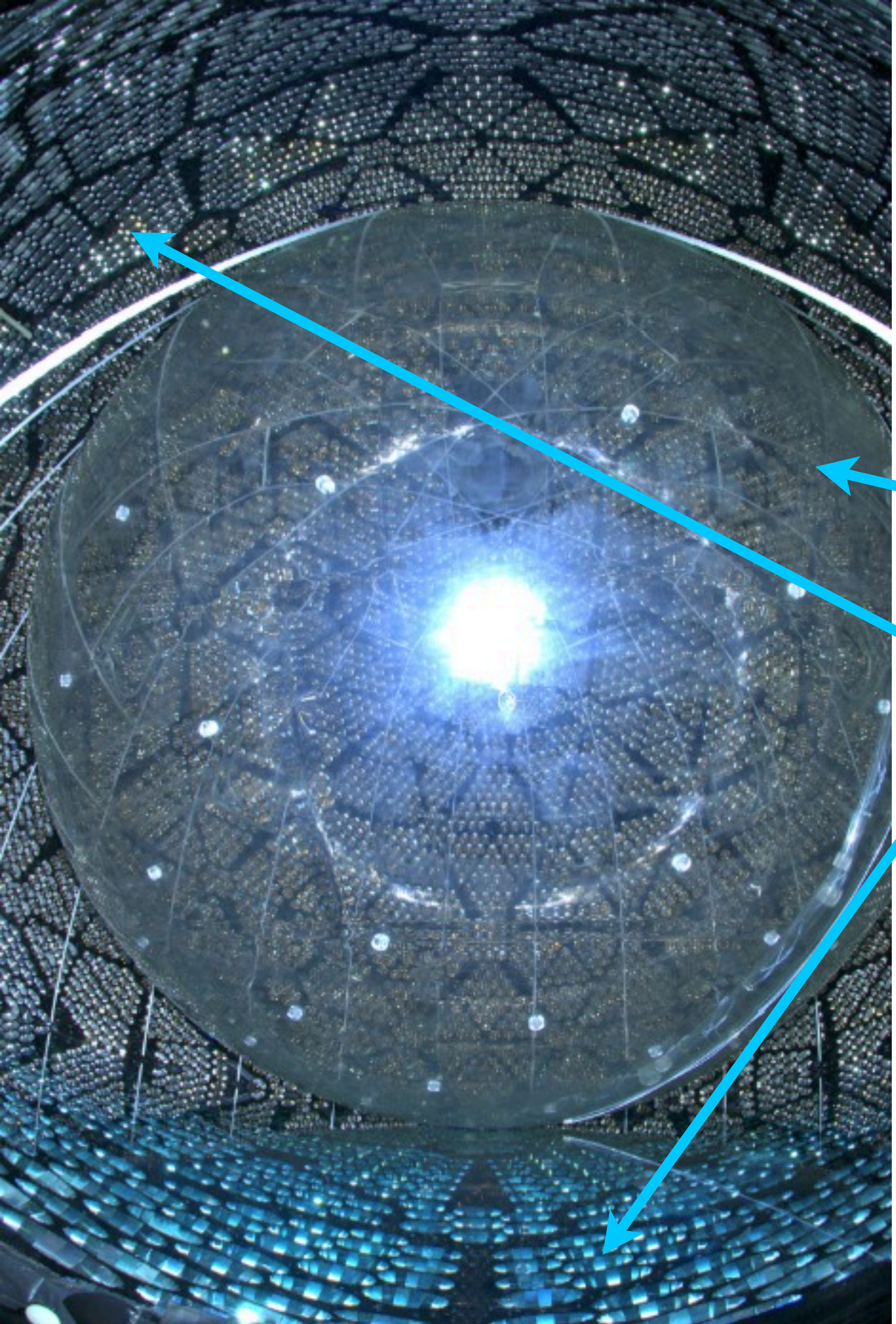


SNO+



SNO+

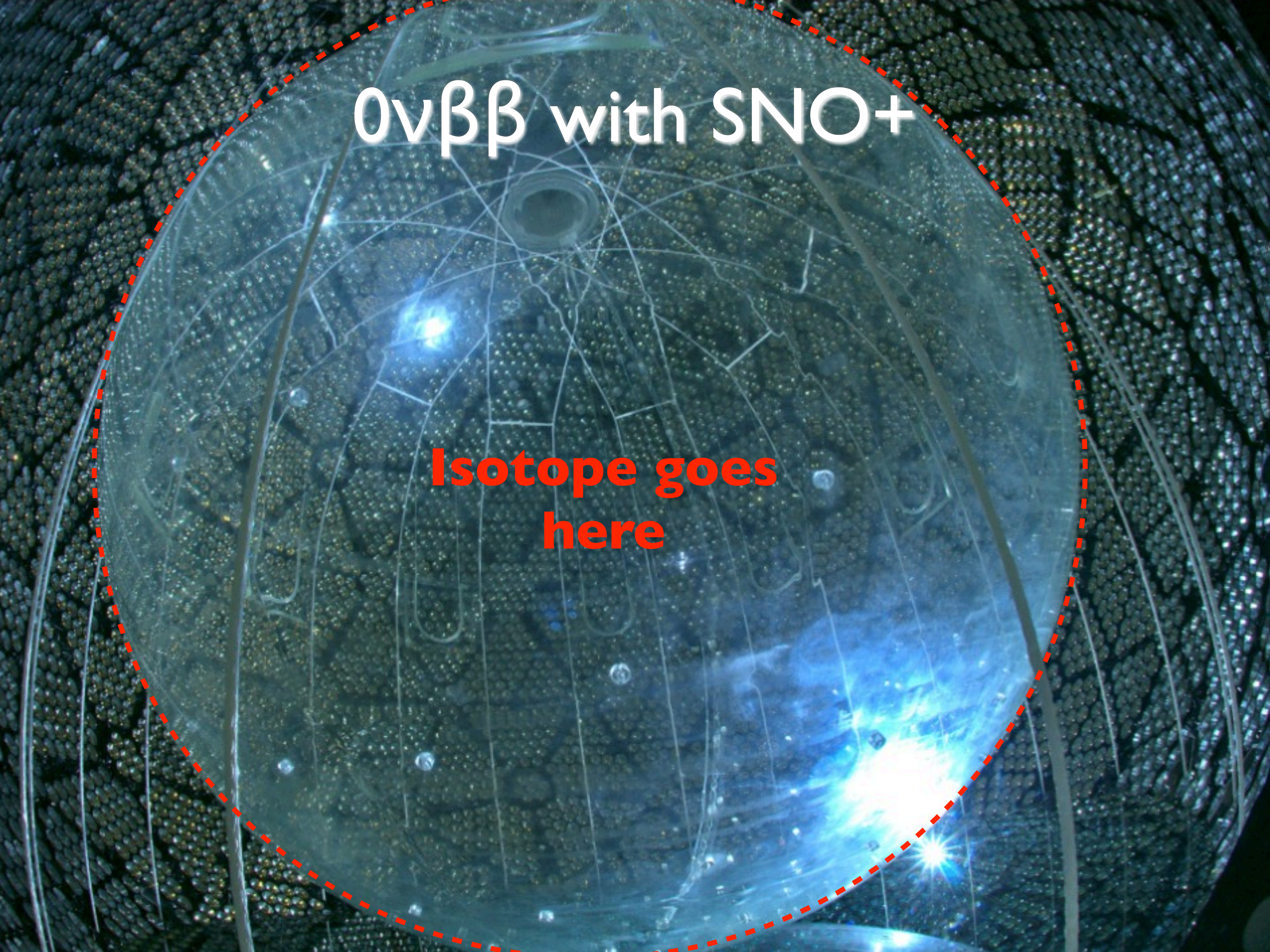
- Re-use SNO detector



SNO+

- Re-use SNO detector
  - 12-m diameter acrylic vessel
  - ~9500 PMTs
- 7kT H_2O buffer
- Replace D_2O with liquid scintillator (LAB)
- New hold-down rope net

$0\nu\beta\beta$ with SNO+


0νββ with SNO+
Isotope goes here

^{130}Te Loading

- Loading hydrophilic atoms into organic LS is challenging...

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- BNL develop new loading technique

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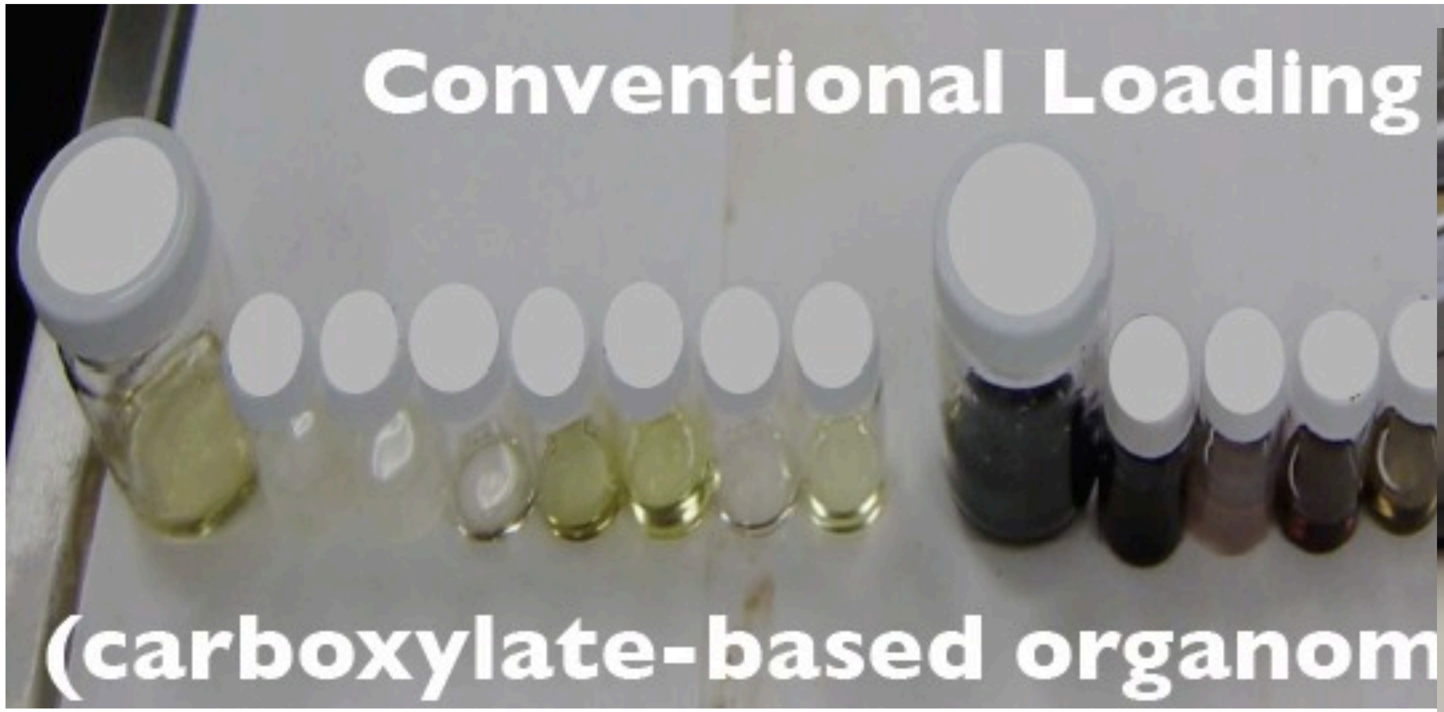

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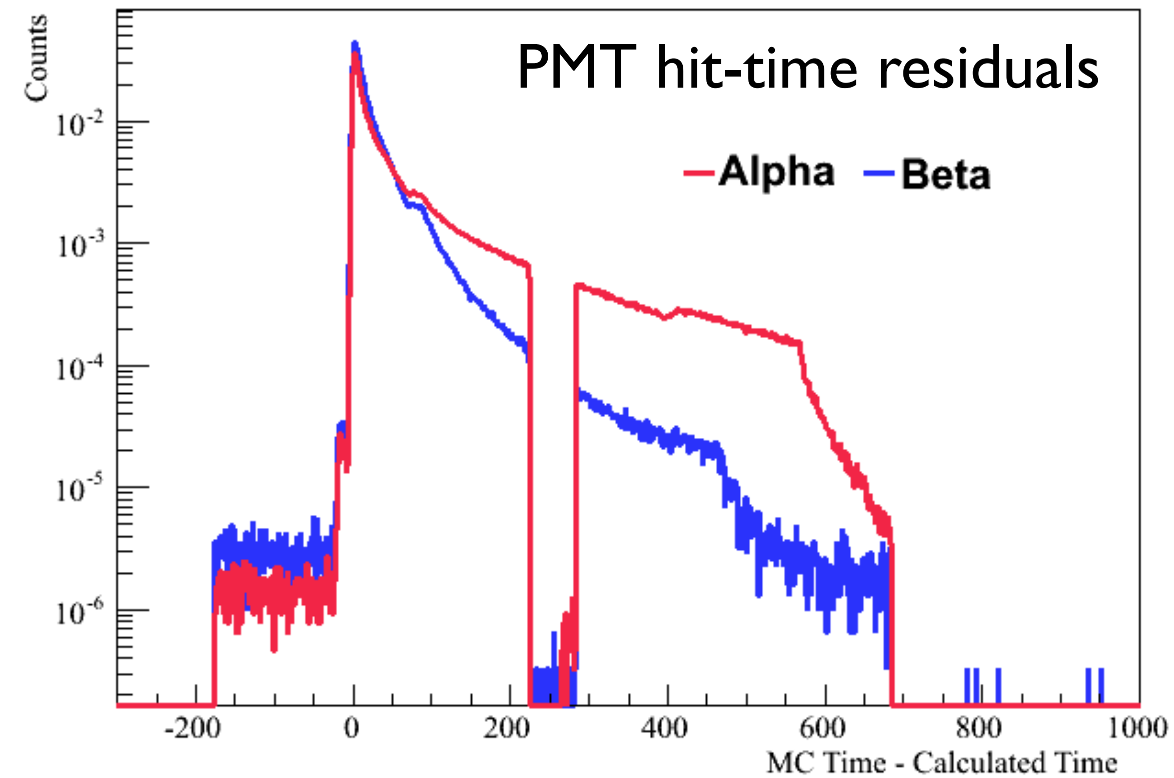

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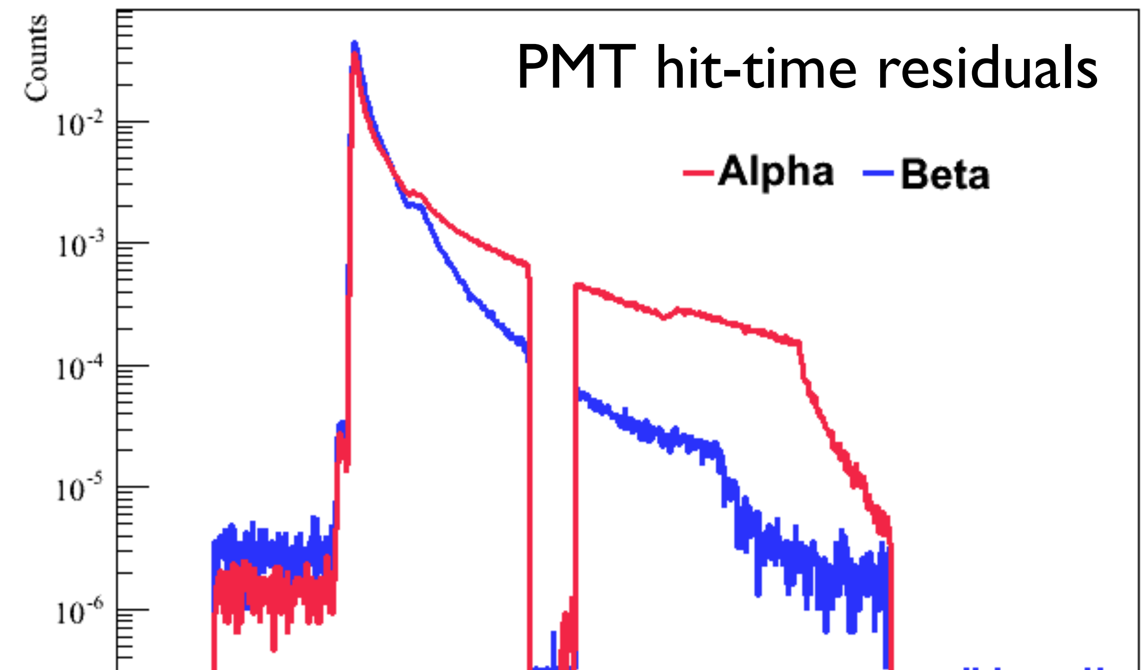

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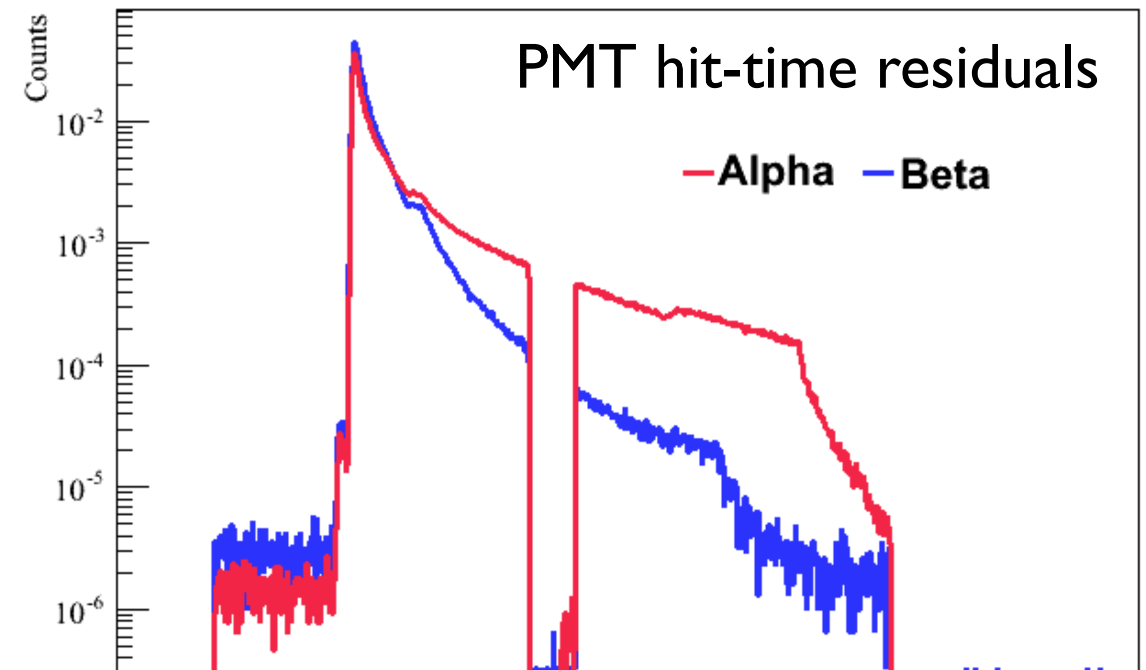

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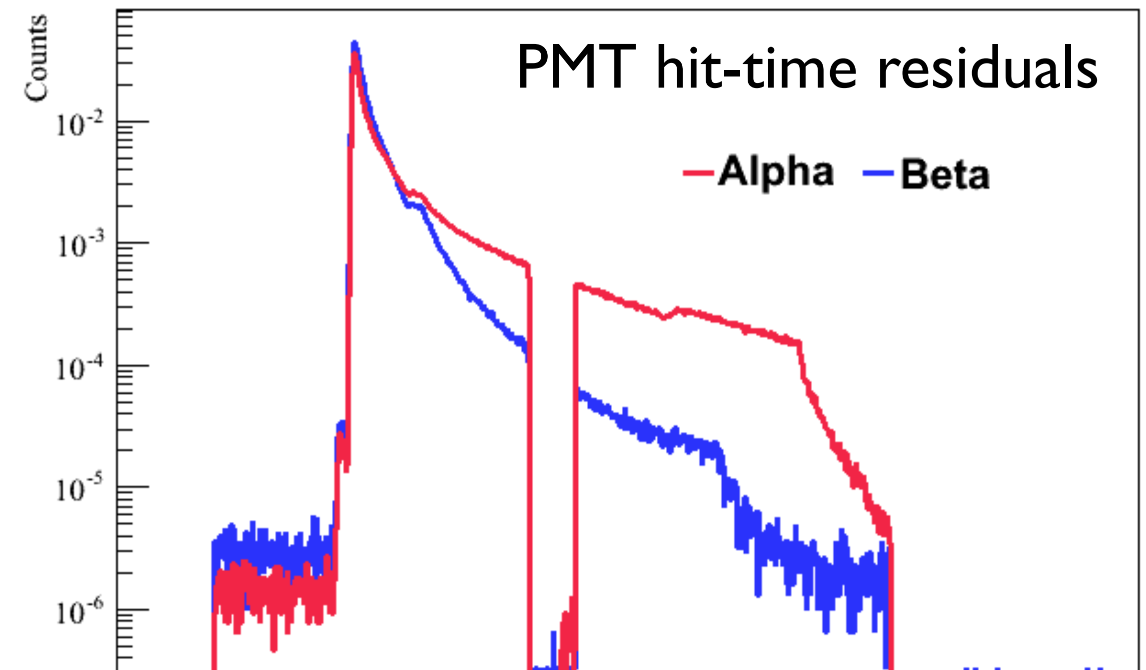

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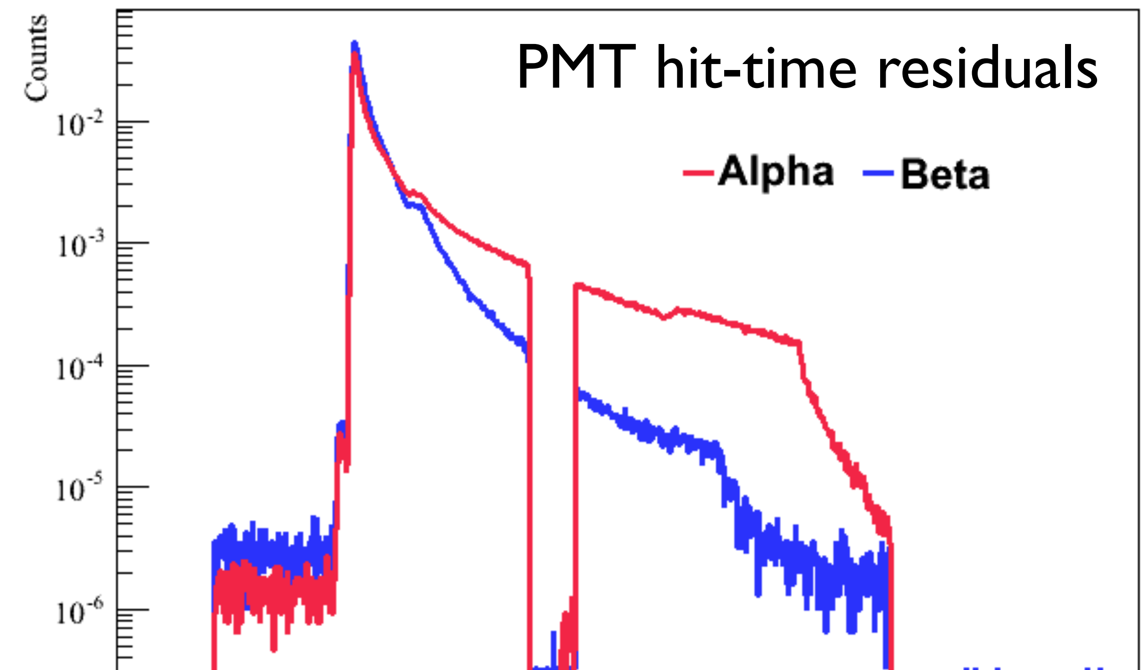
- *Bonus: broad program includes solar, geo, reactor, supernova ν & nucleon decay*

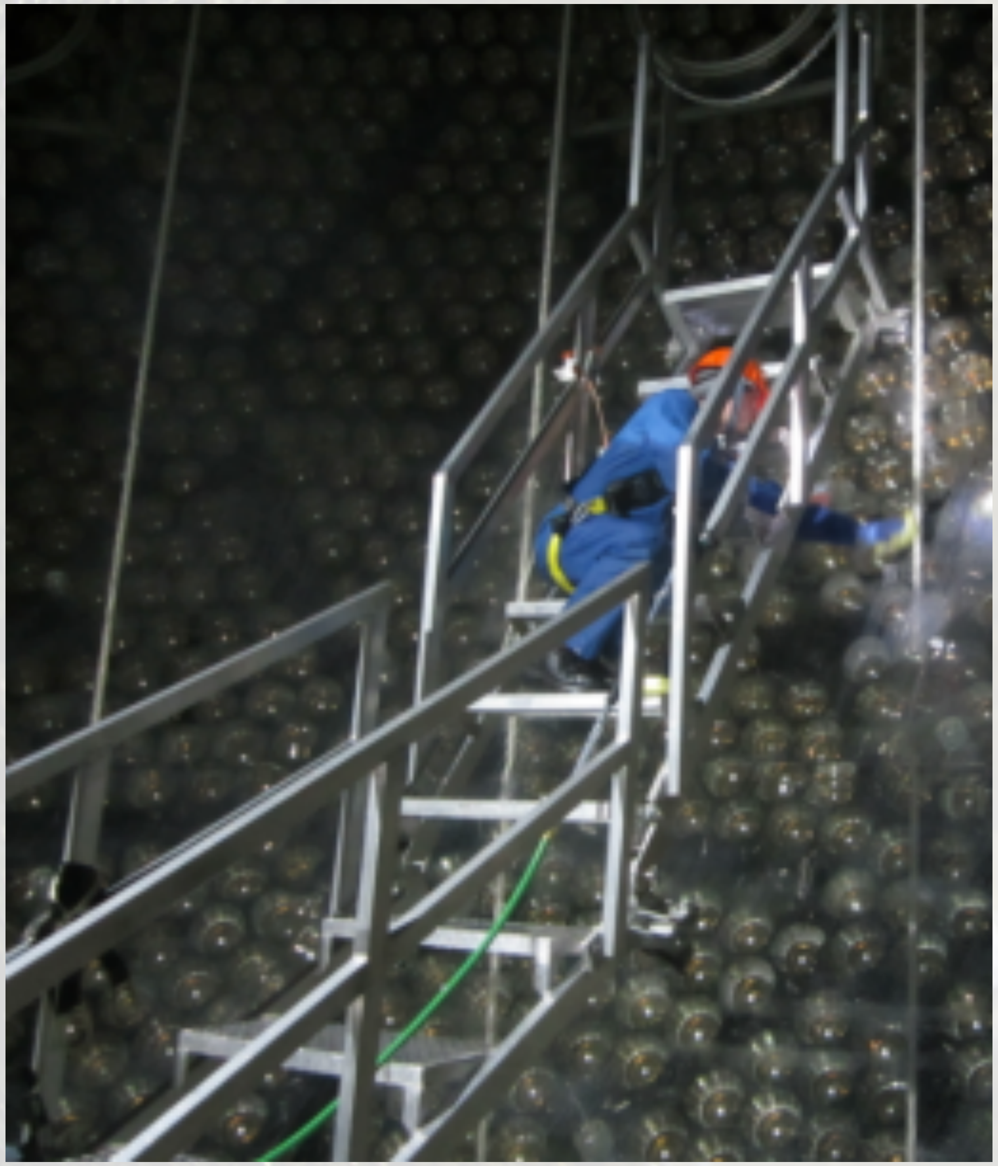


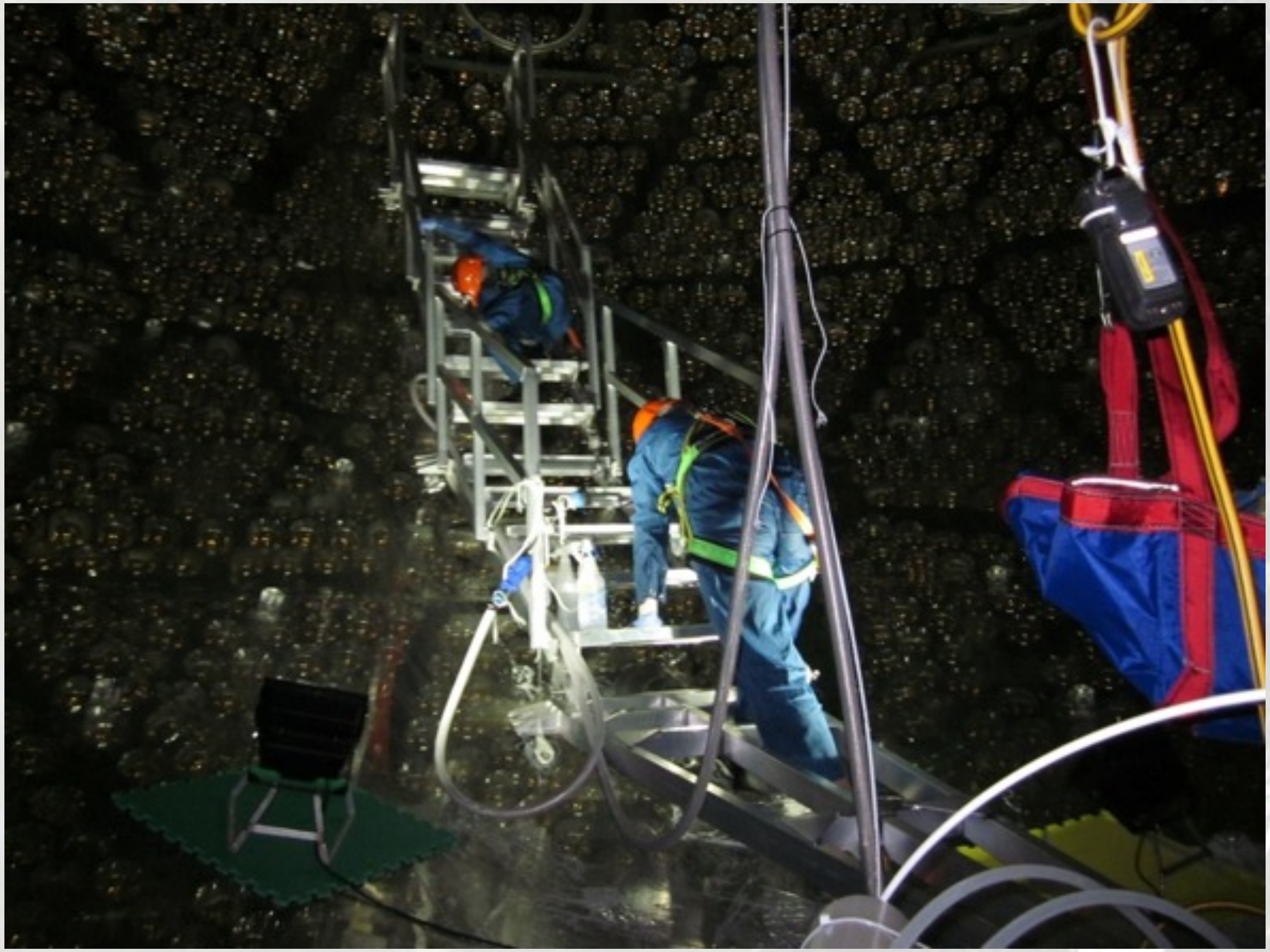
SNO+ Status

Highlights

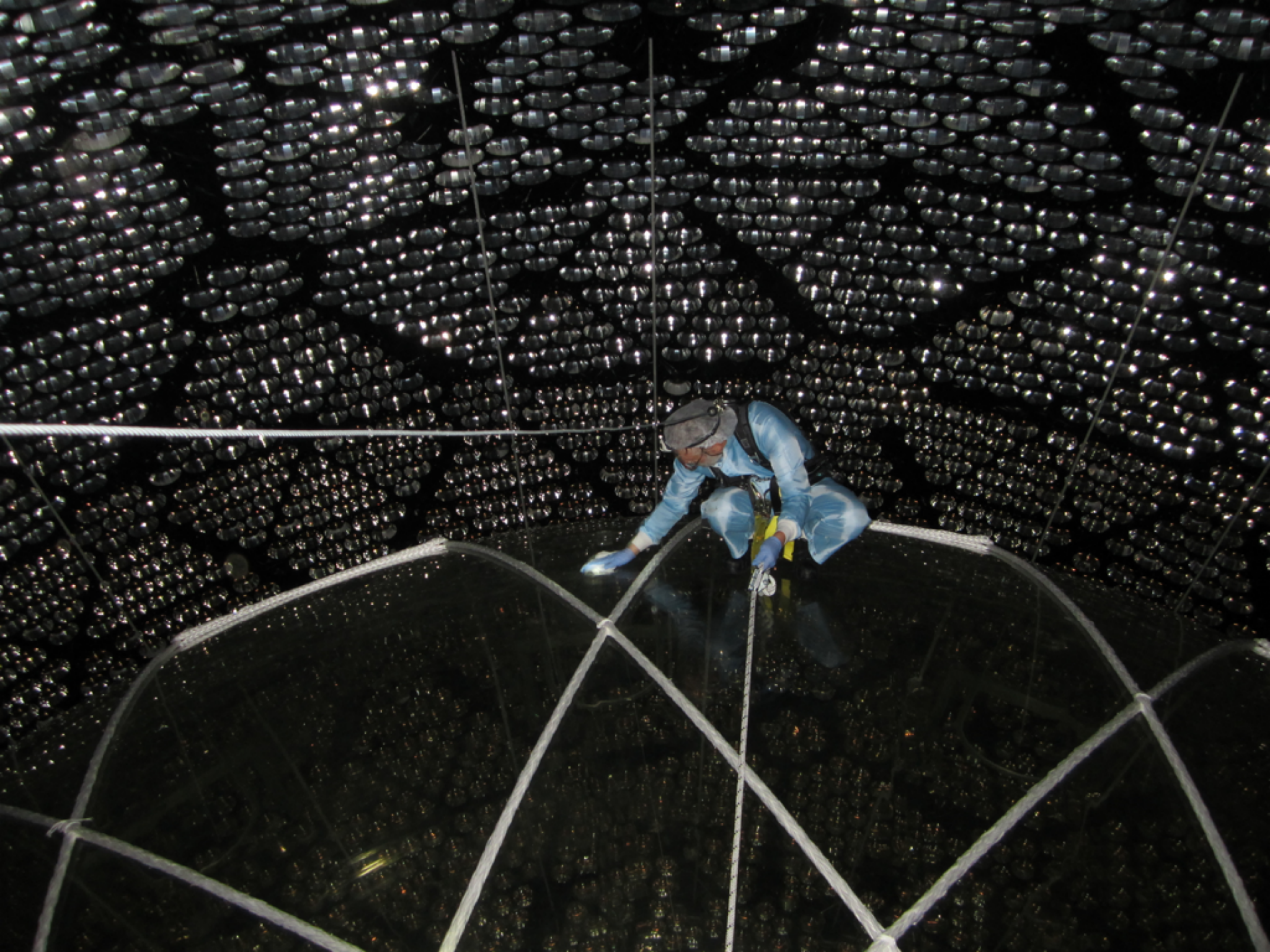
SNO+ Status

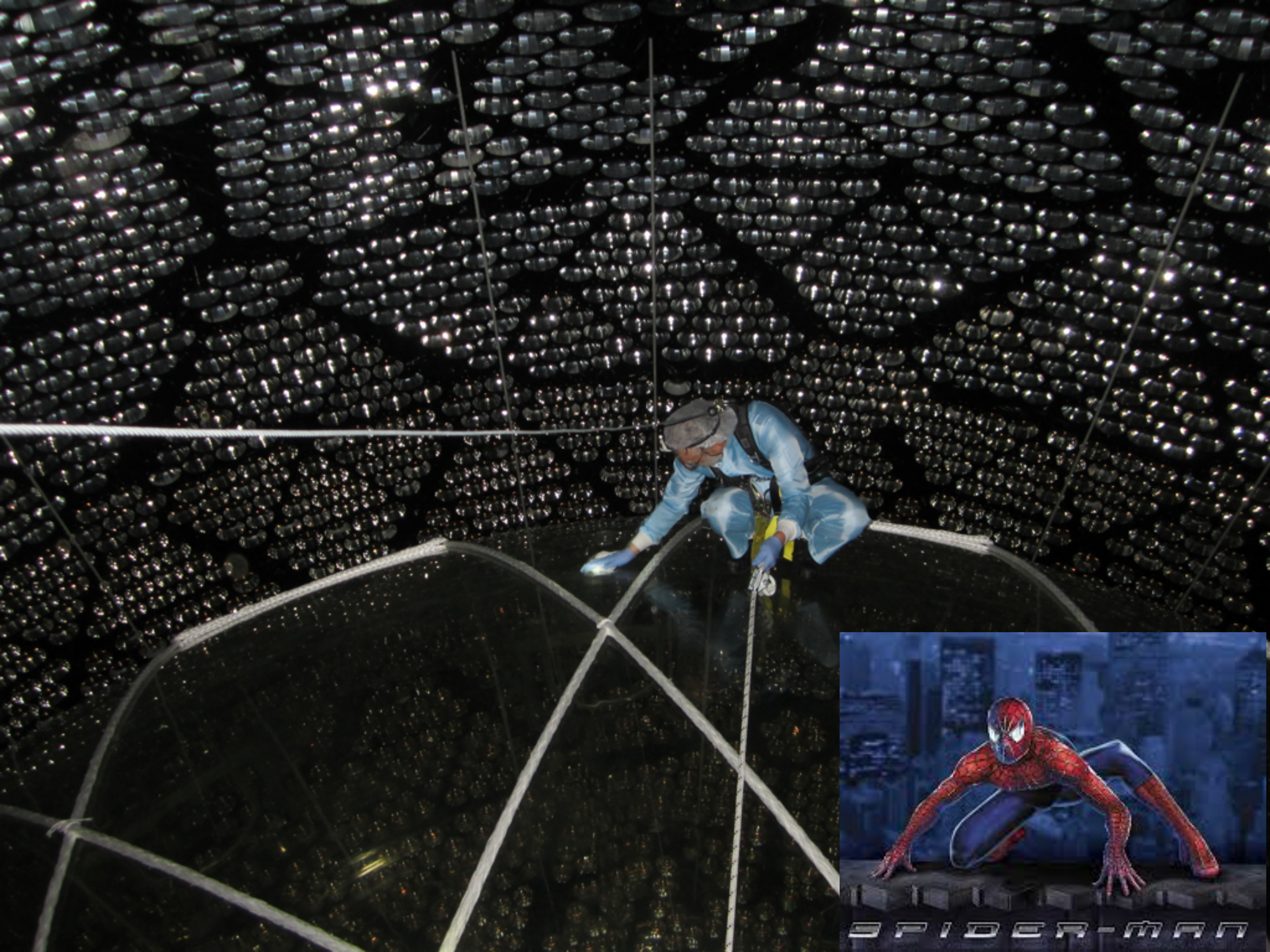
- Cleaning complete: the superheroes of SNO+





Cleaned the AV, both inside and out...

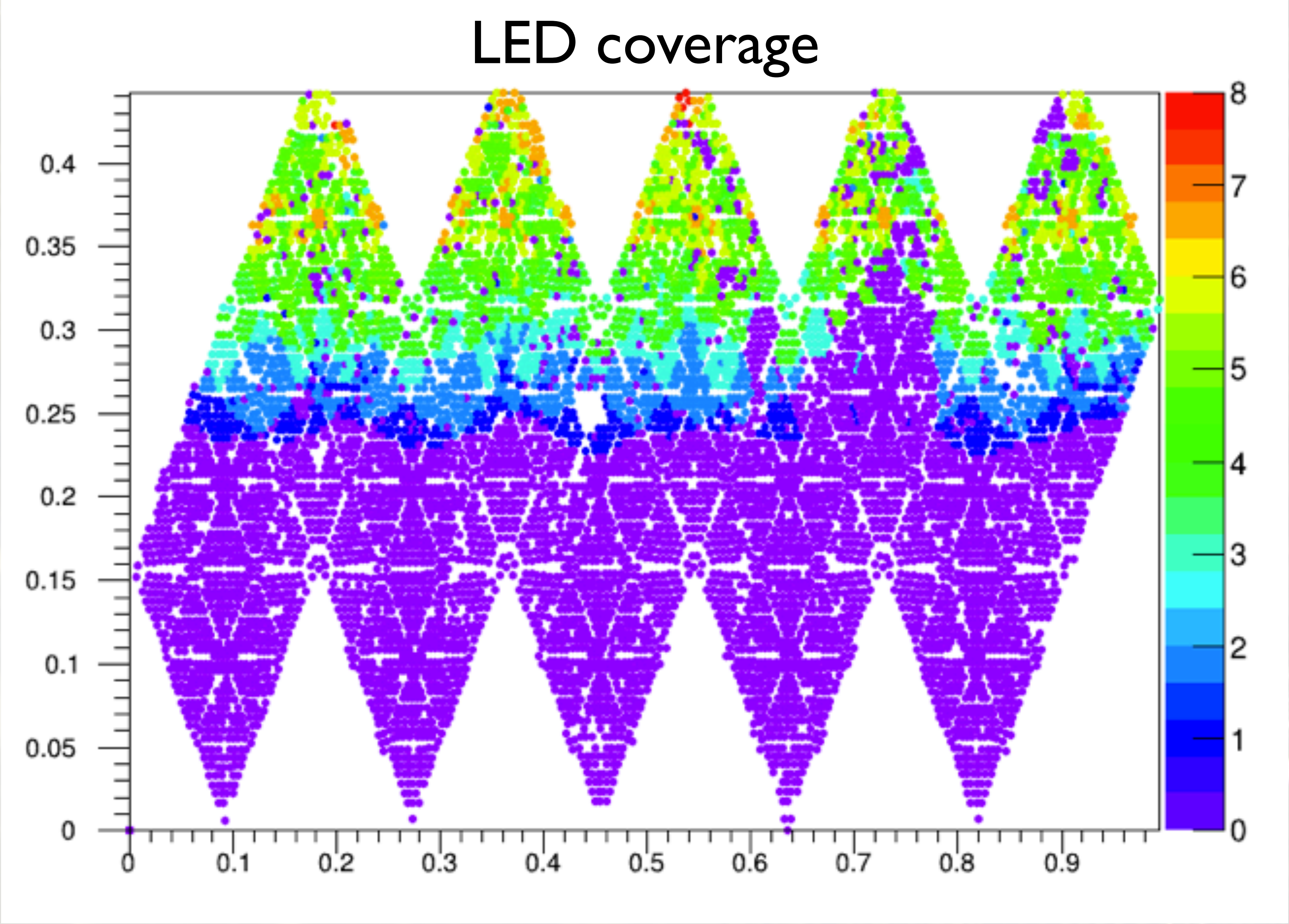



SPIDER-MAN

Highlights

SNO+ Status

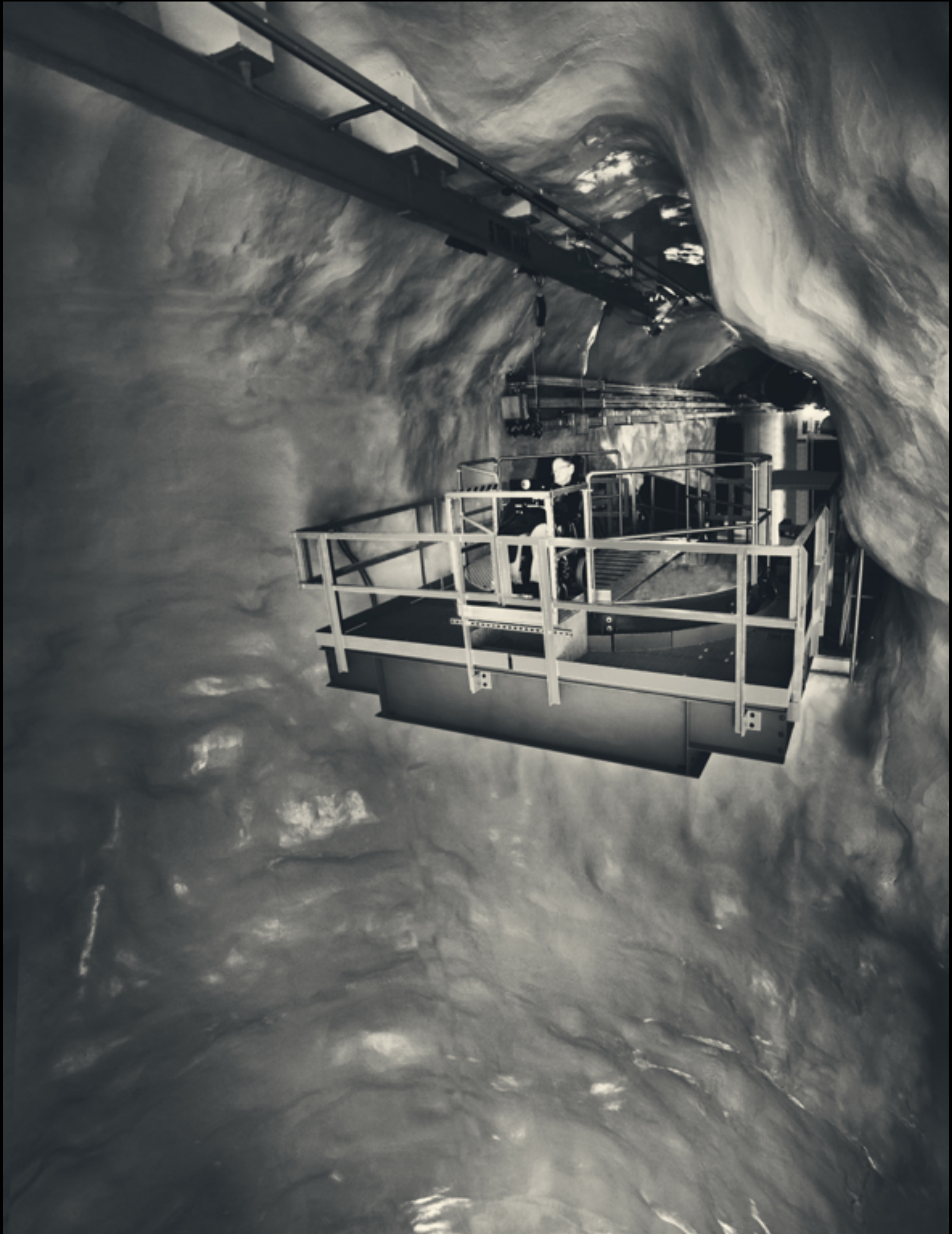
- Early commissioning data ("air-fill")



Highlights

SNO+ Status

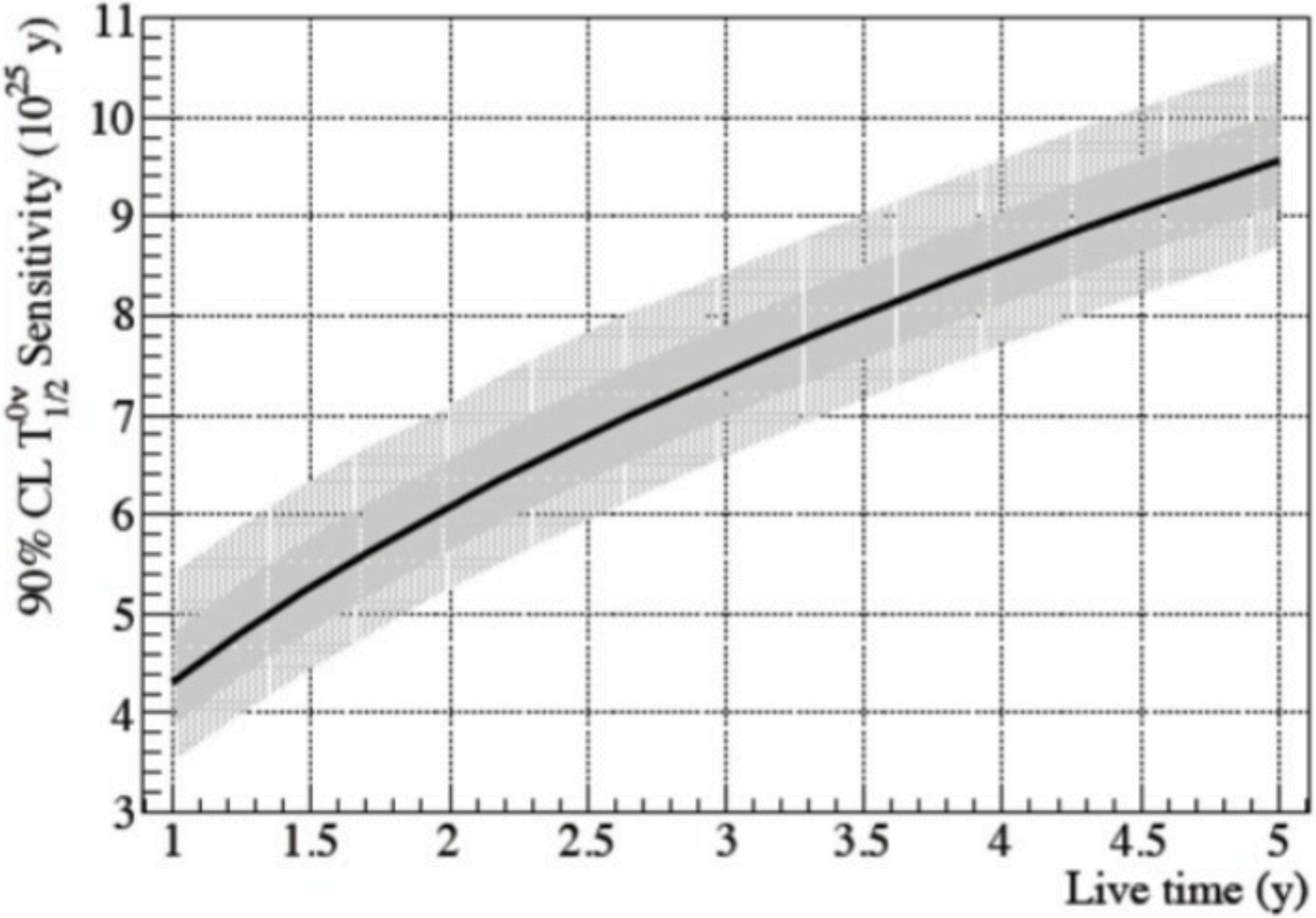
- Stephen Hawking comes to visit




X-MEN

SNO+ Sensitivity

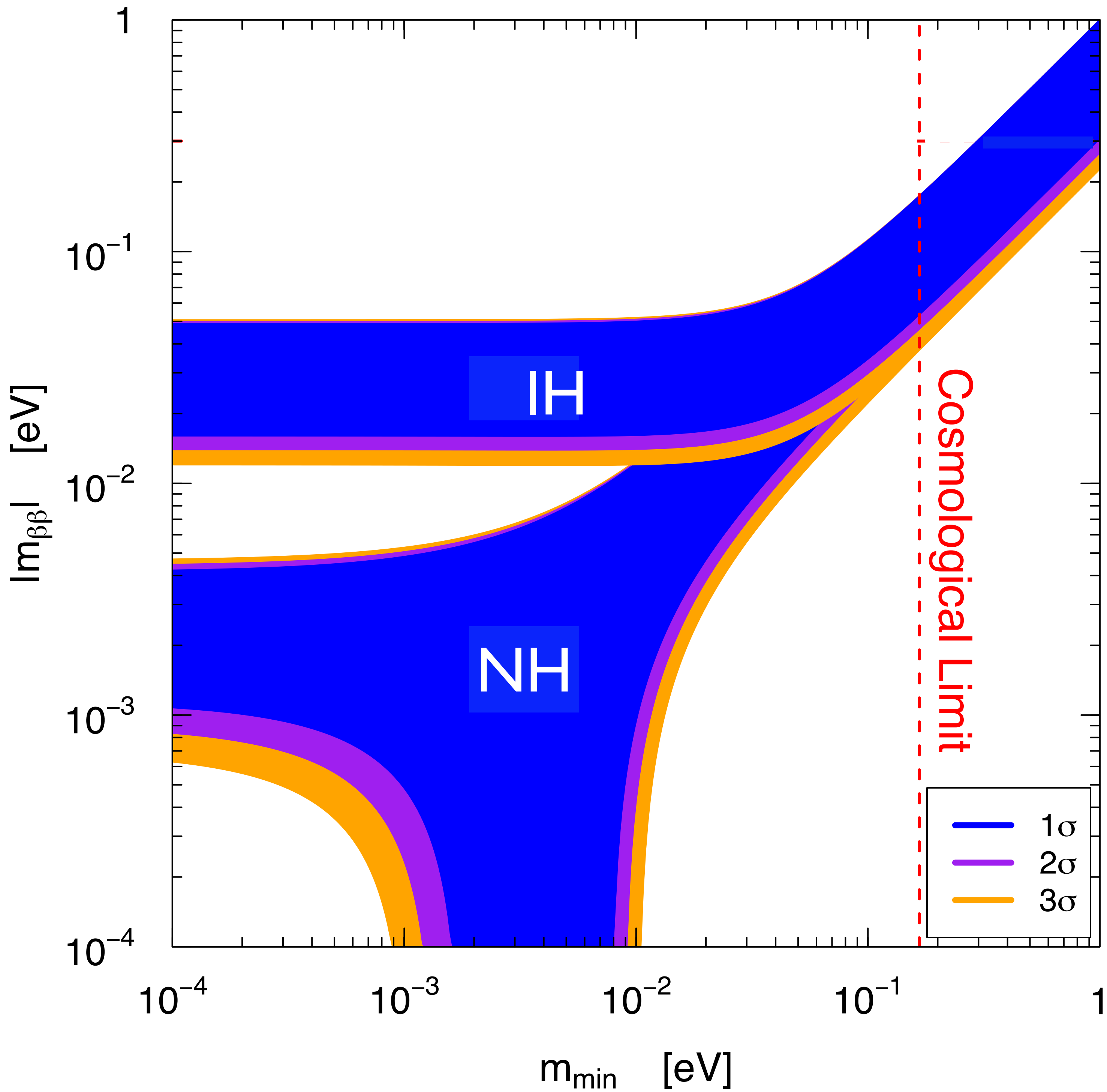
Half-life sensitivity at 90% CL with 0.3% loading



3 yrs @ 0.3% loading: ~7.5e25 yrs
5 yrs @ 0.3% loading: ~9.5e25 yrs

Cuoricino $T_{1/2}$>2.8×10^{24} years at 90% C.L -> <300-710meV, depending on the adopted nuclear matrix element evaluation
arXiv:1012.3266 [nucl-ex]

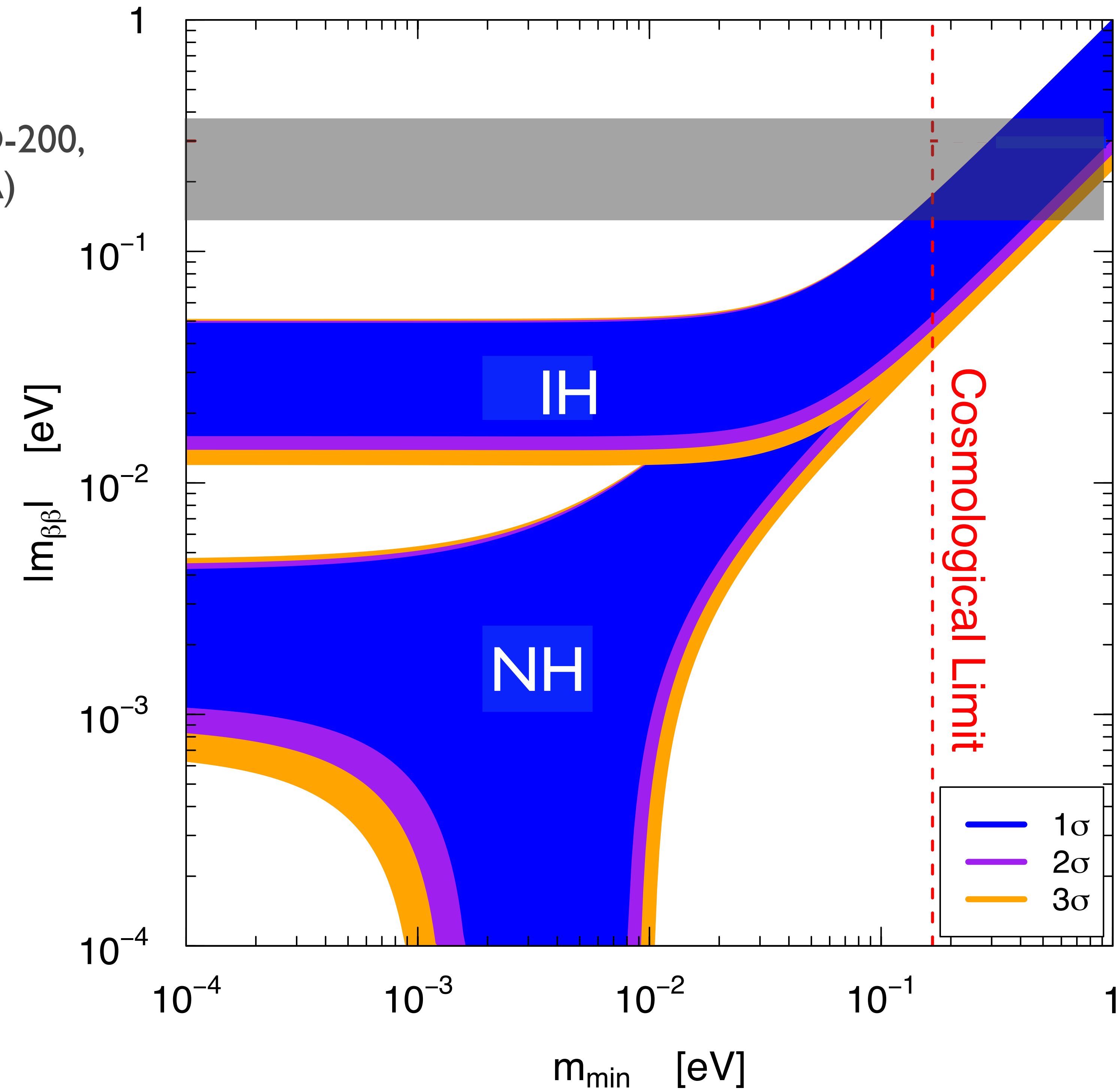
Status of the Field



S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

Status of the Field

Current limits (EXO-200, KL-Zen, GERDA)



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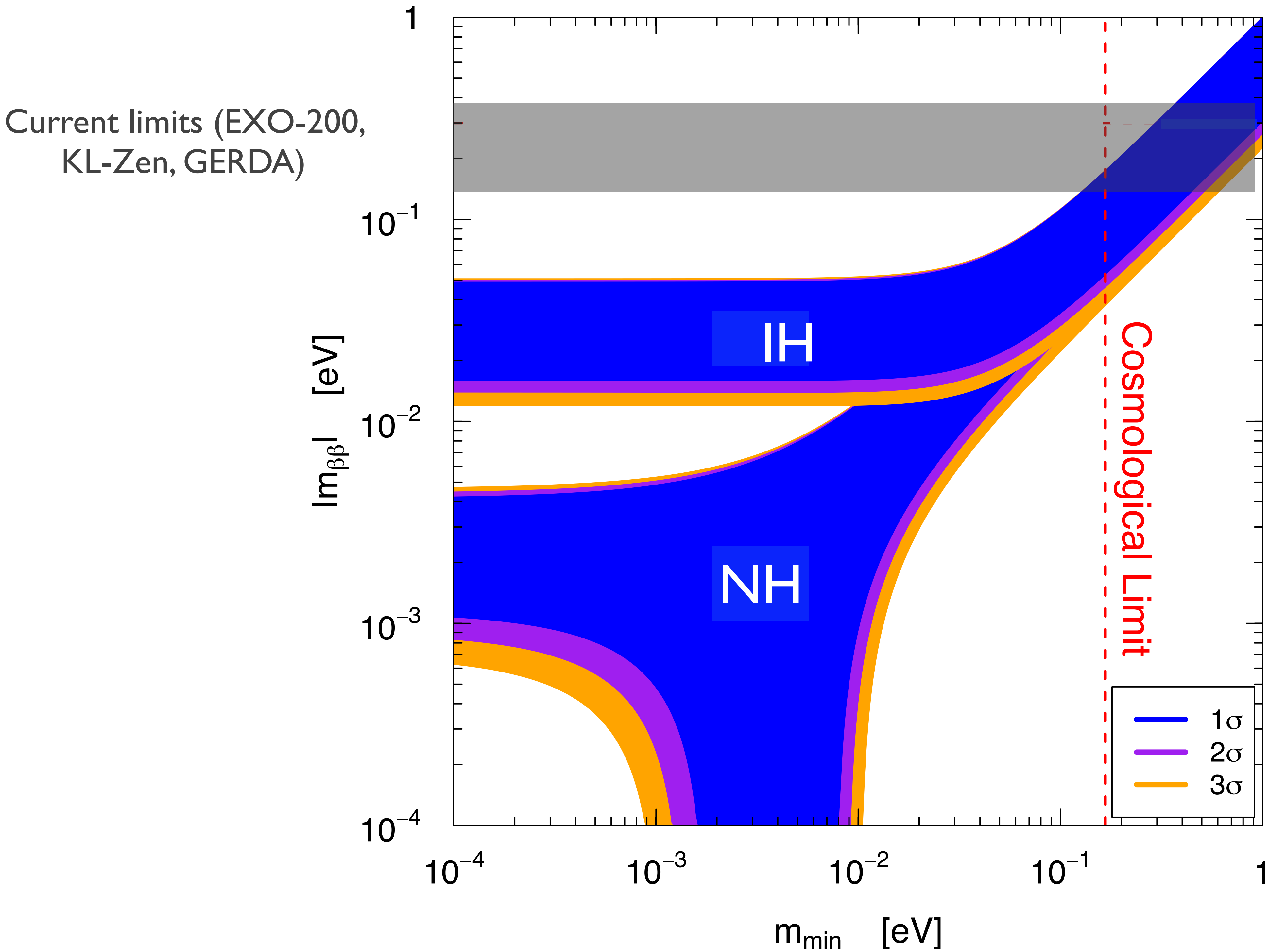
Future Plans: Probing the MH?



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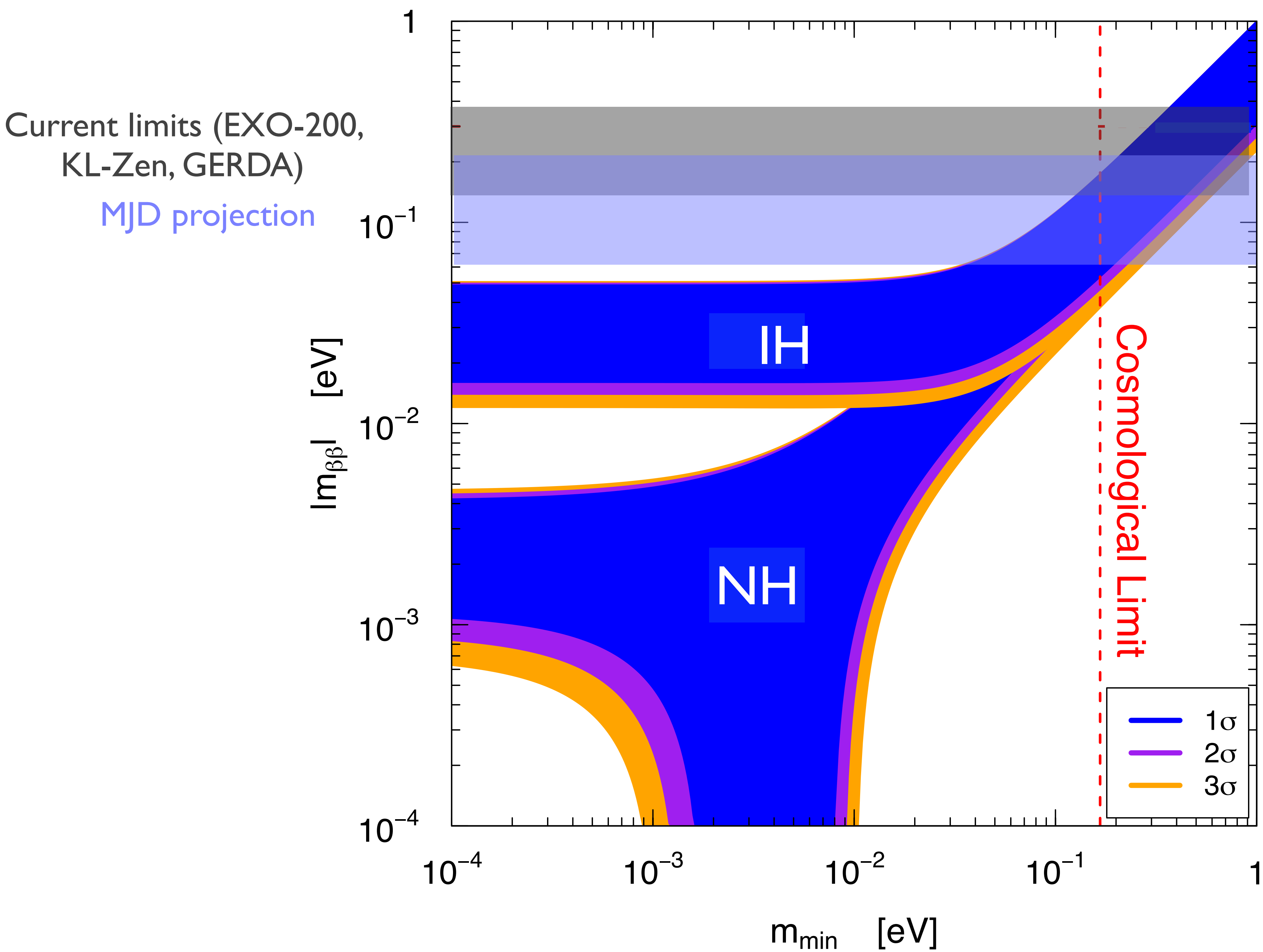

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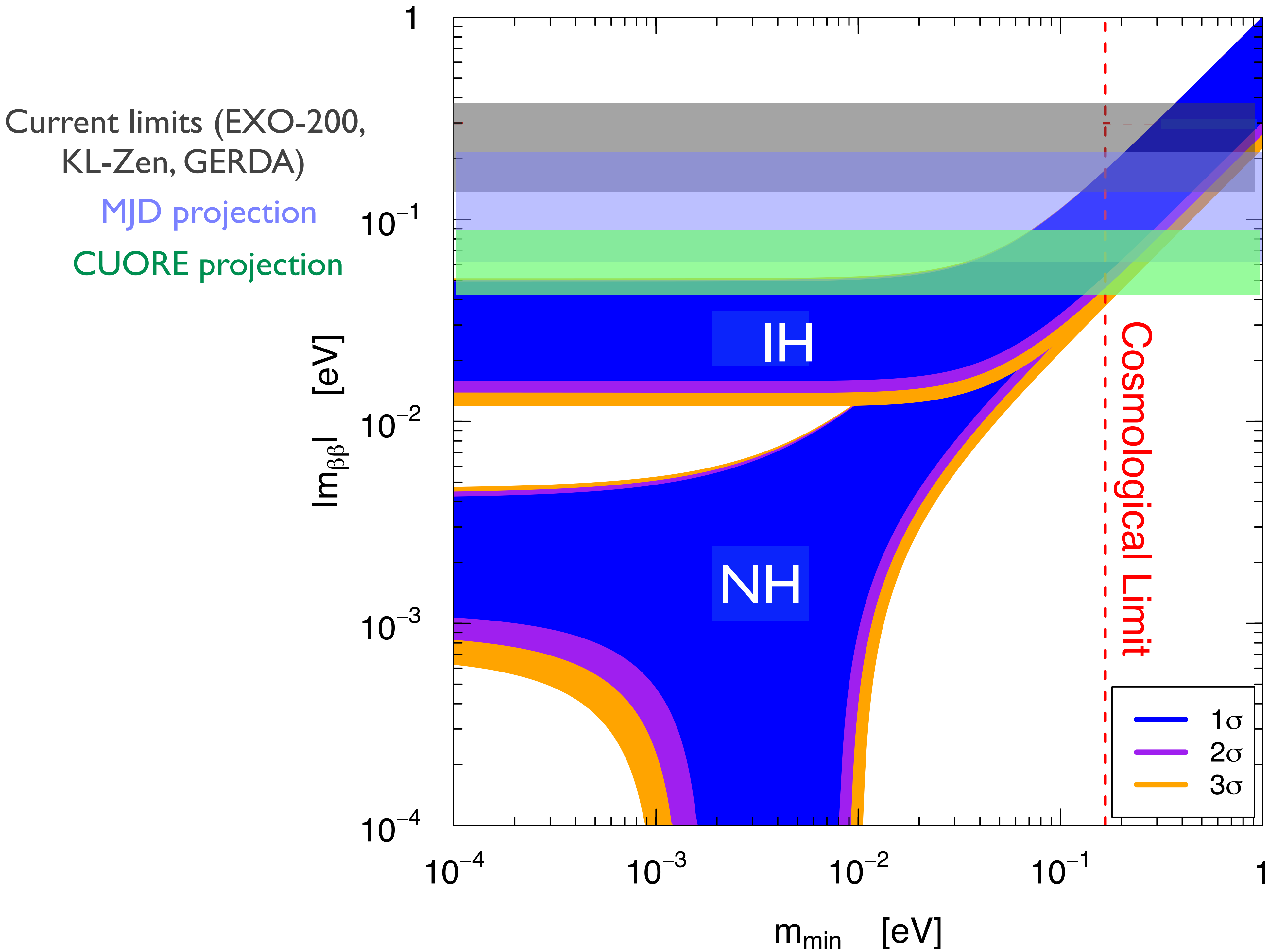

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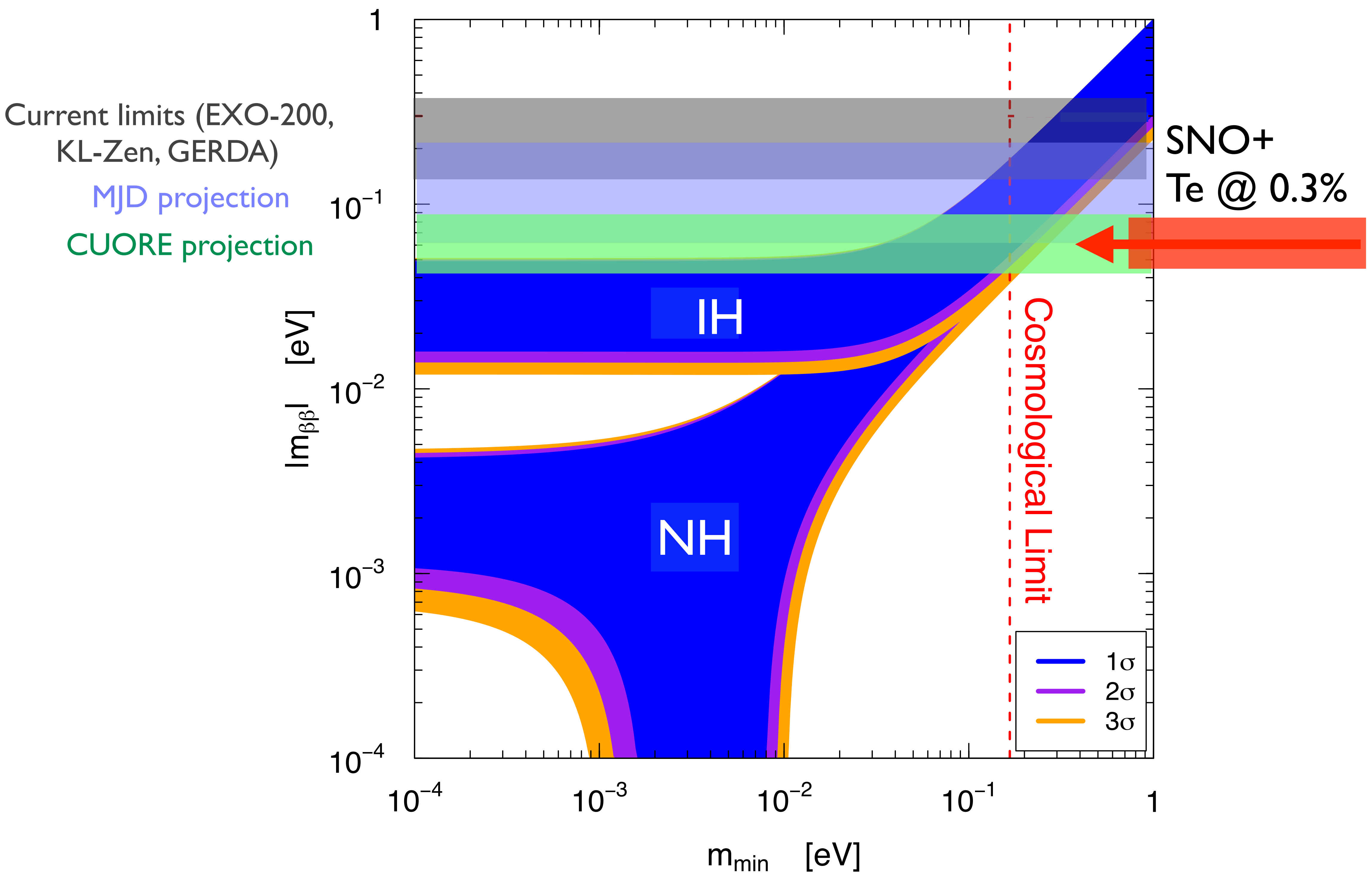

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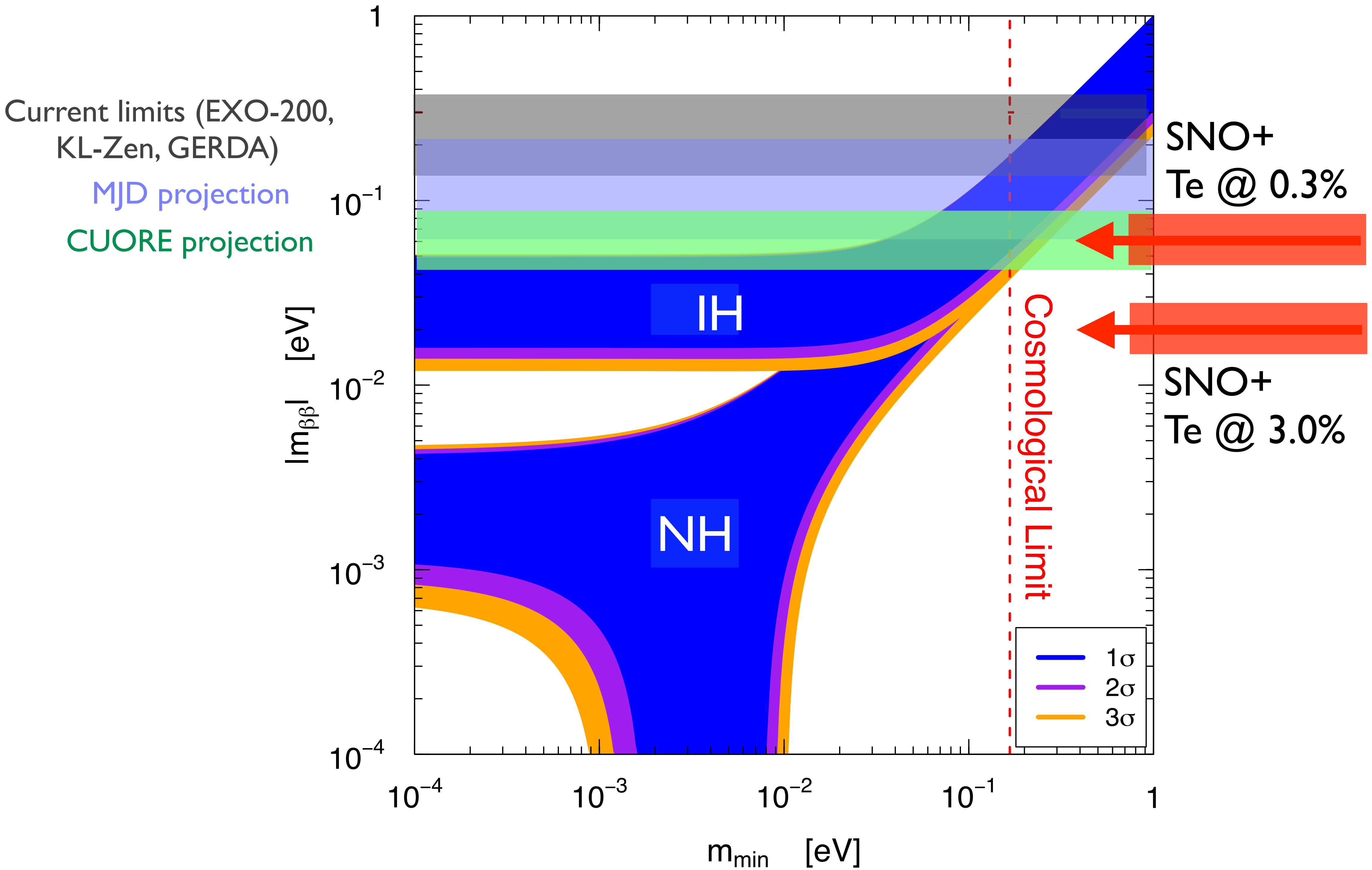

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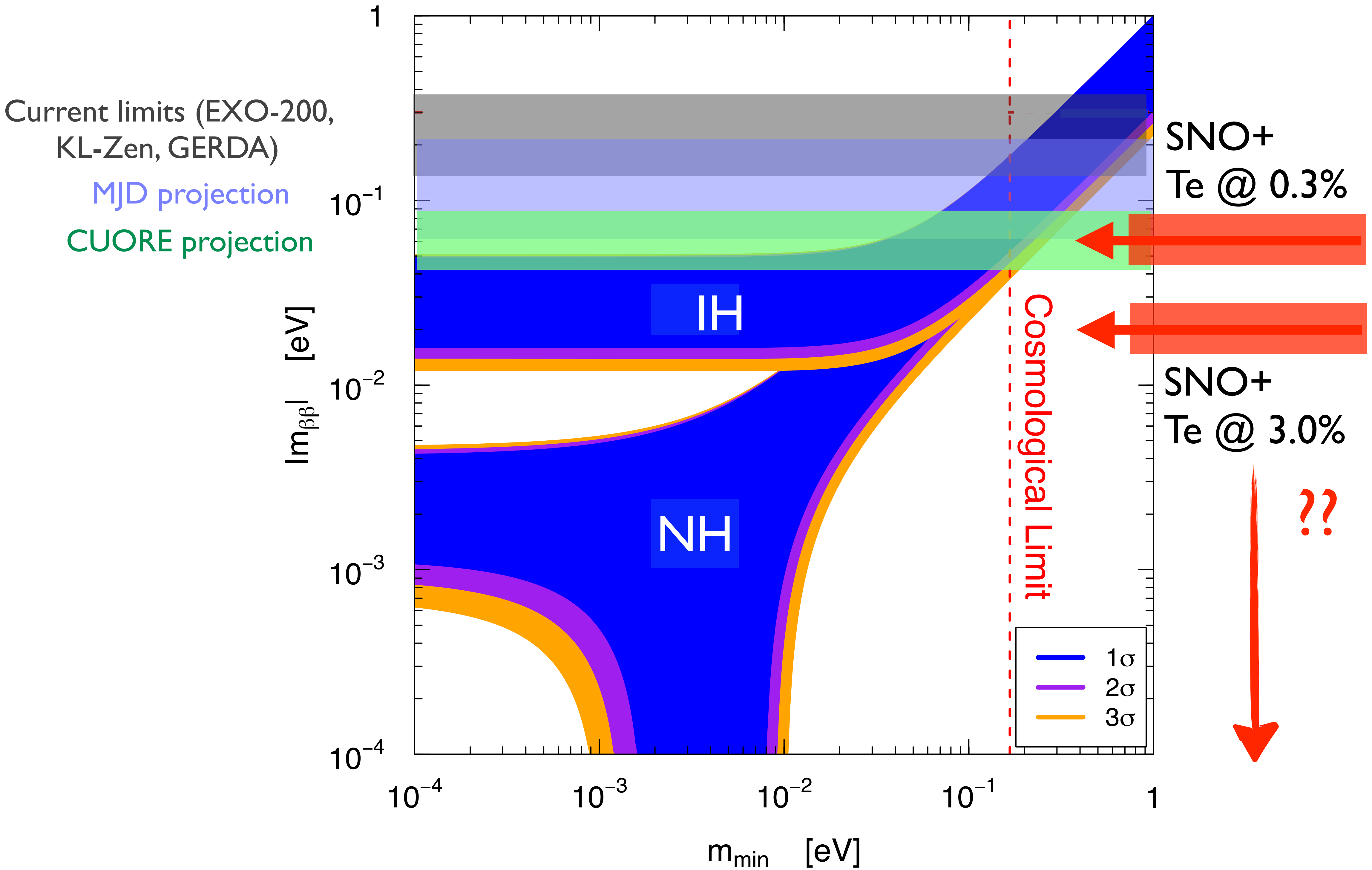

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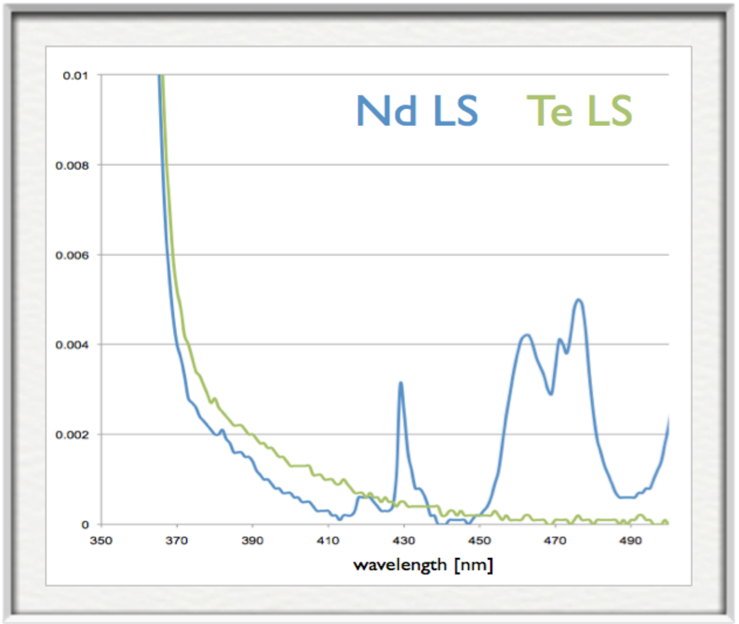

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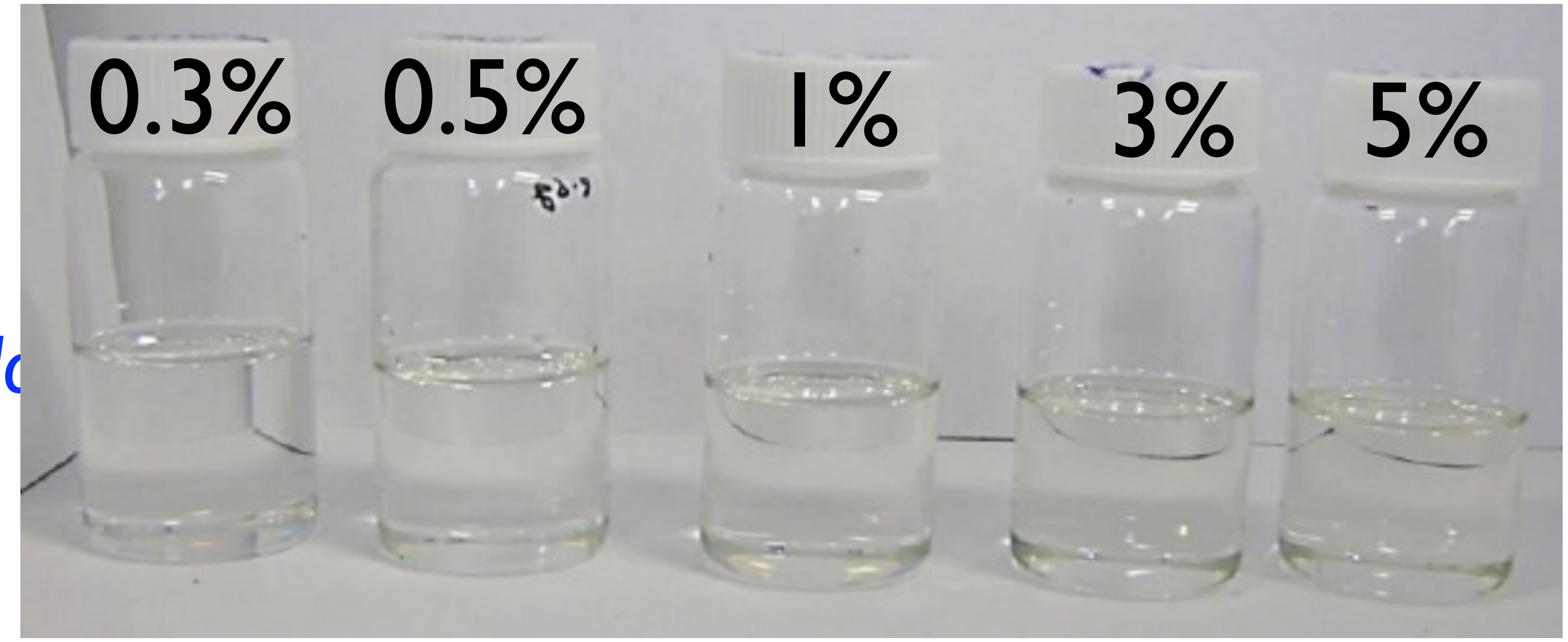

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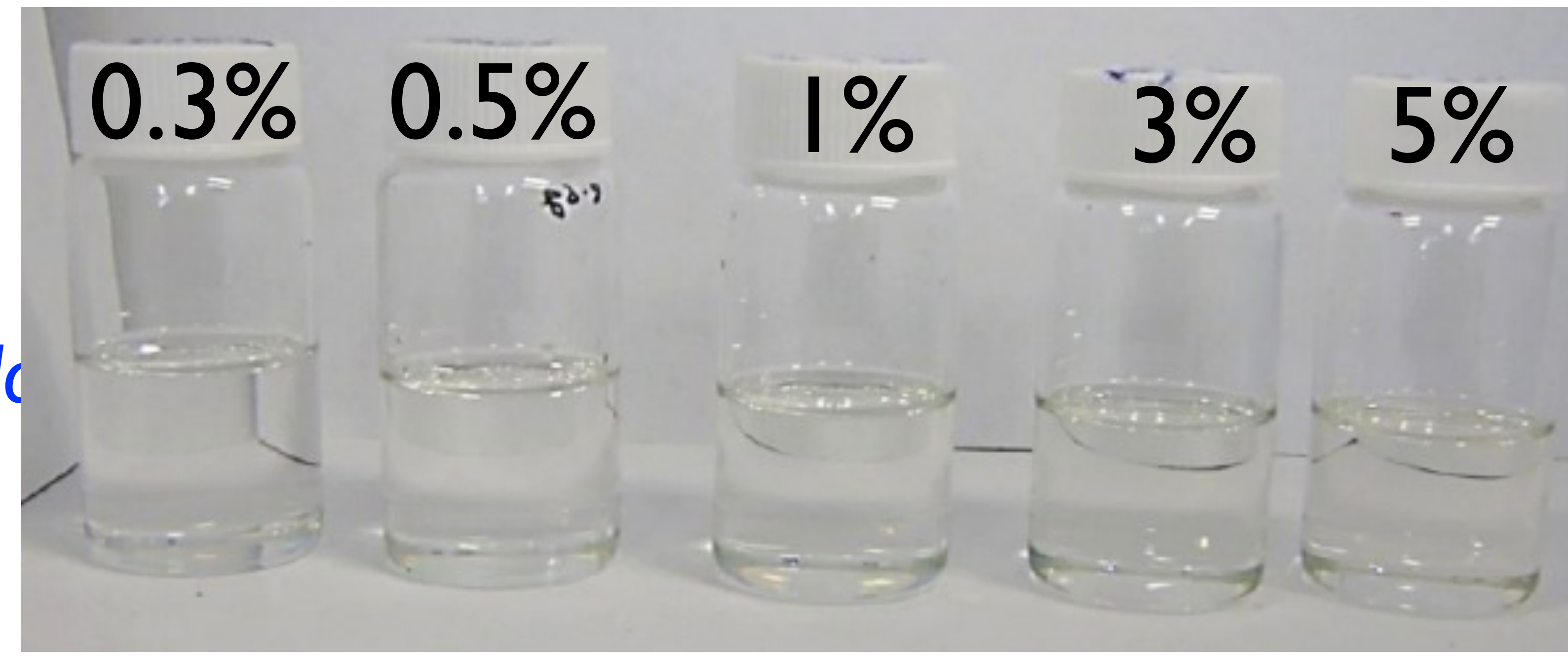

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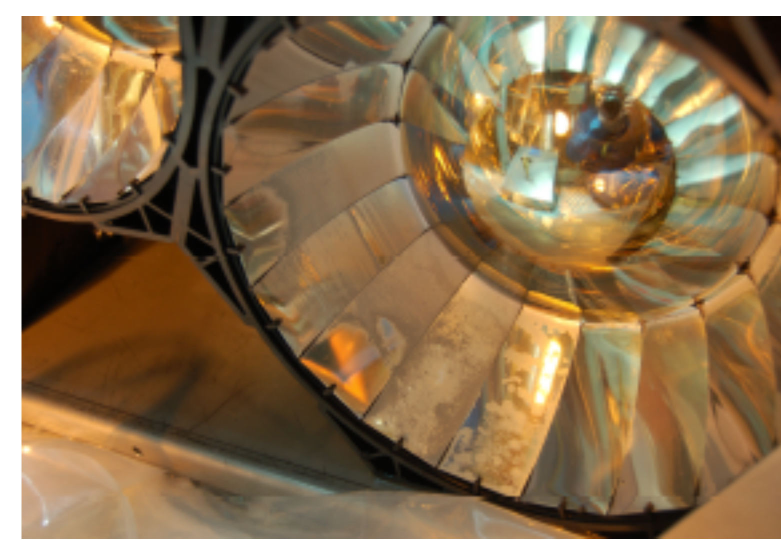

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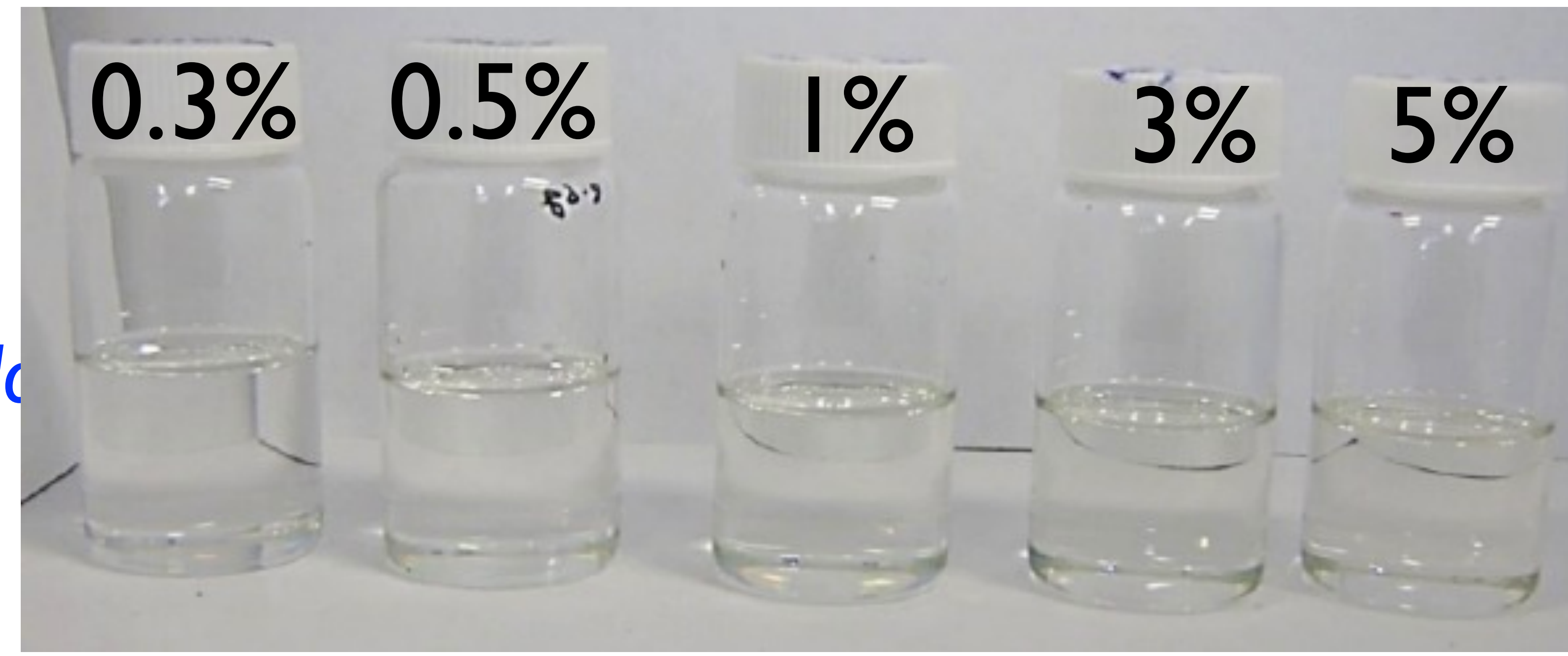

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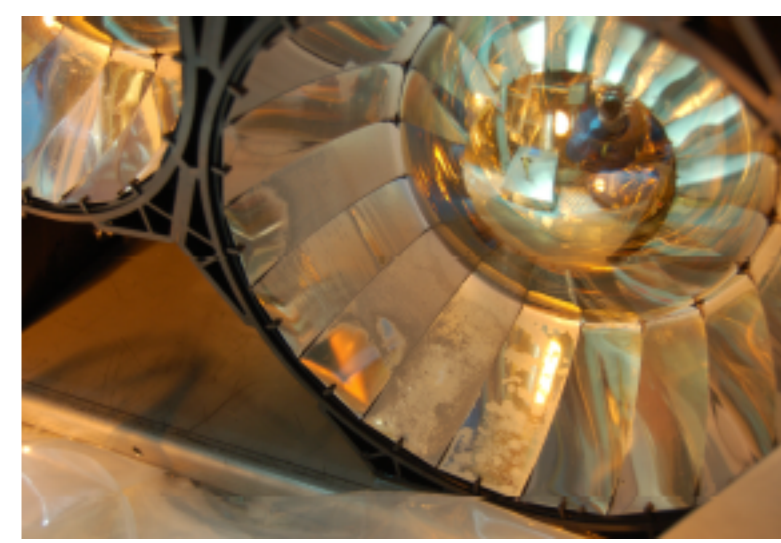
    - *Low attenuation, high light yield, directionality*



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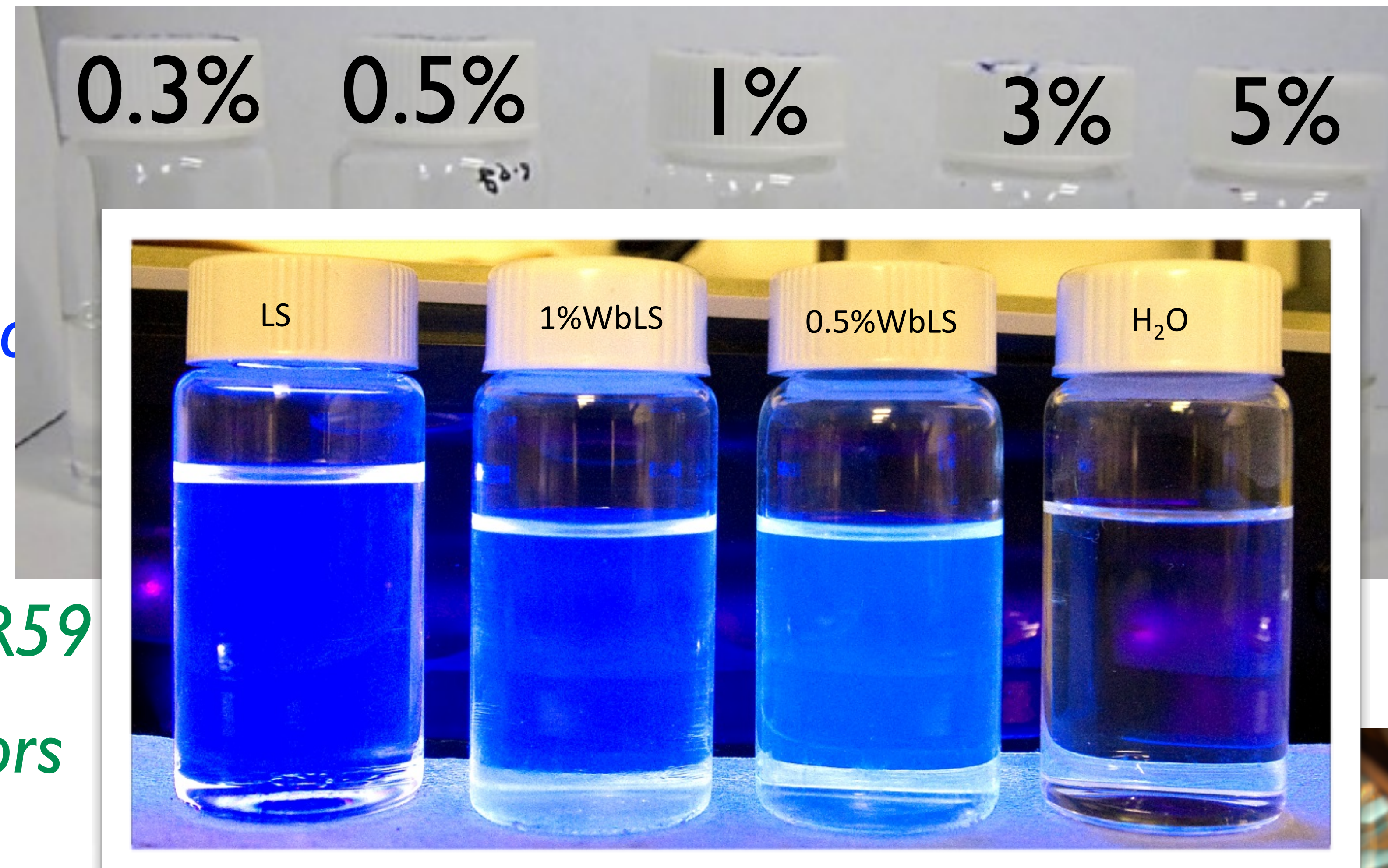

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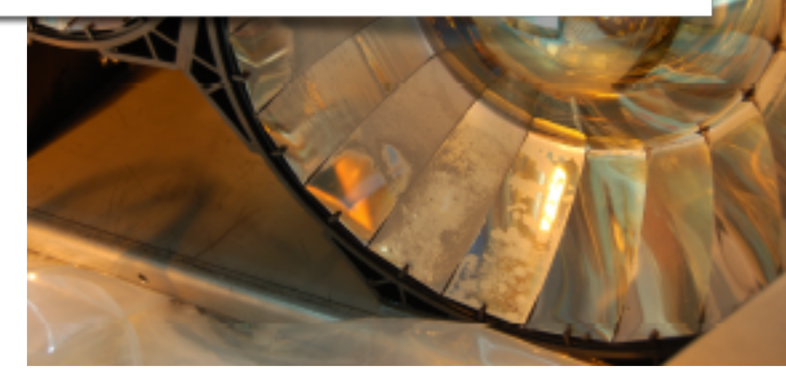

Courtesy M. Yeh, BNL

Neutrinoless Double Beta Decay

in summary

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What it could tell us about the neutrino:

Majorana vs Dirac

Absolute mass scale

Neutrino mass hierarchy

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What will it take for future discovery?

"Flavour Physics" @ NuFACT