Neutrinoless Double Beta Decay

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TAUP Summer School
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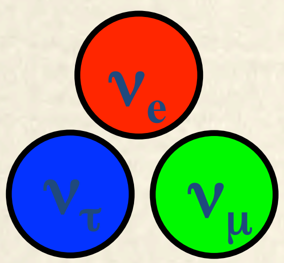
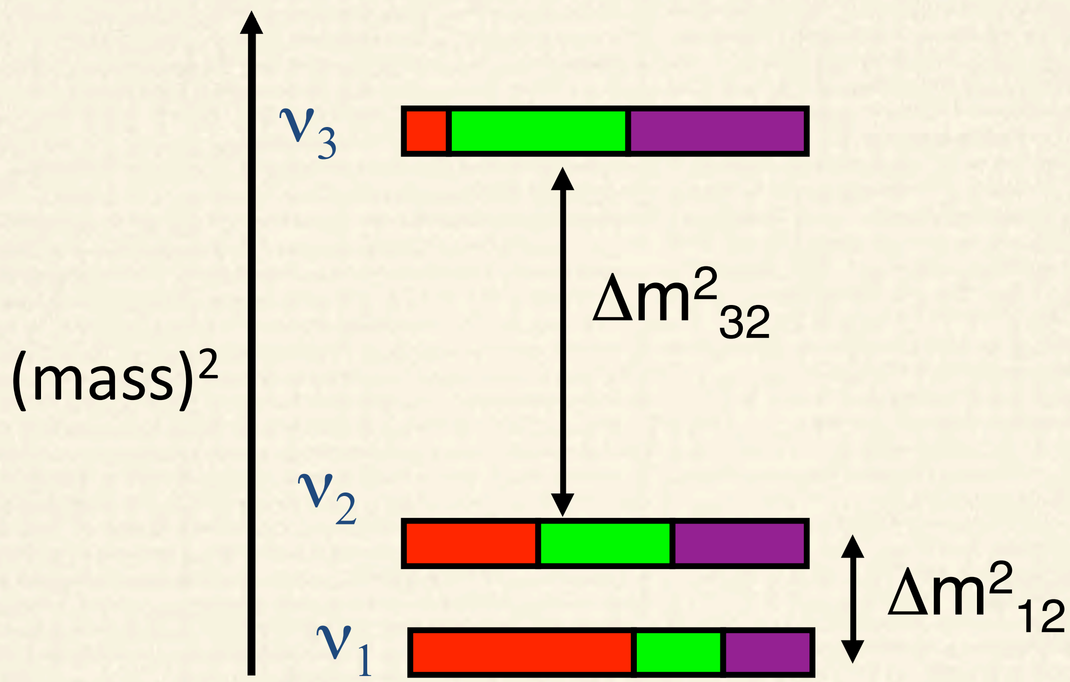
Overview

- Neutrino mixing
- The nature of neutrinos: why does it matter?
- Neutrino (-less) double beta decay
  - *Matrix elements, phase space and lifetime*
- Experimental techniques
  - *SNO+: the large-scale liquid scintillator approach*
  - *A word on sensitivity calculations*
- Status of the field ⇒ future goals (probing MH)

Neutrino Mixing

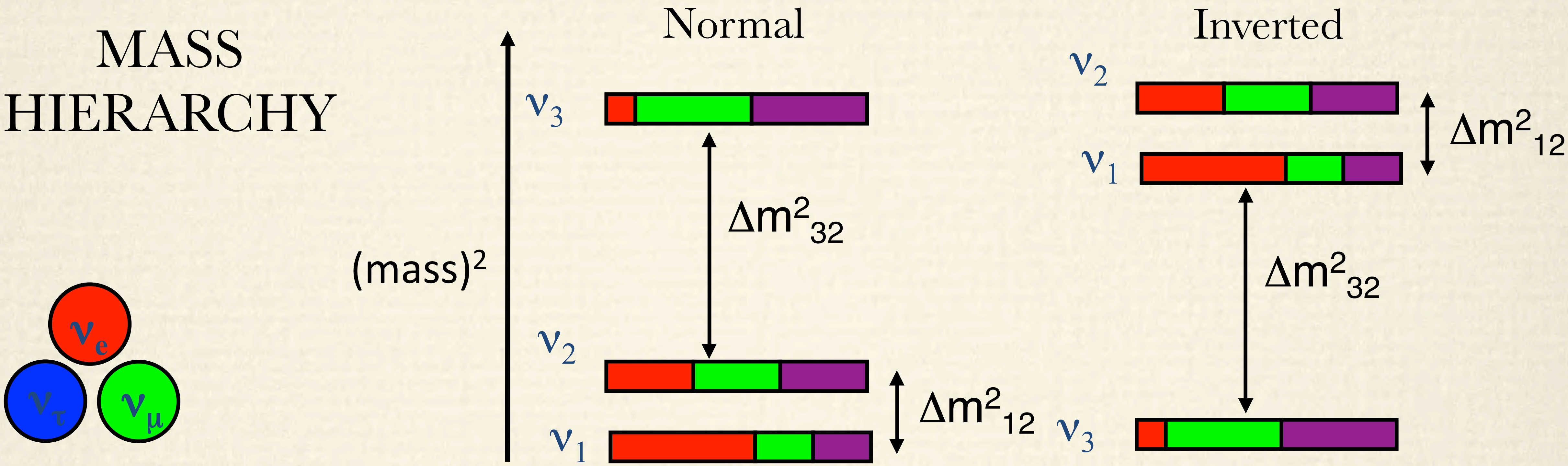




Parameters:
3 mixing angles
2 mass differences
1 phase

Neutrino Mixing

MASS HIERARCHY



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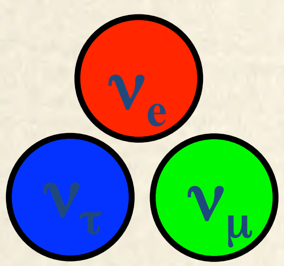

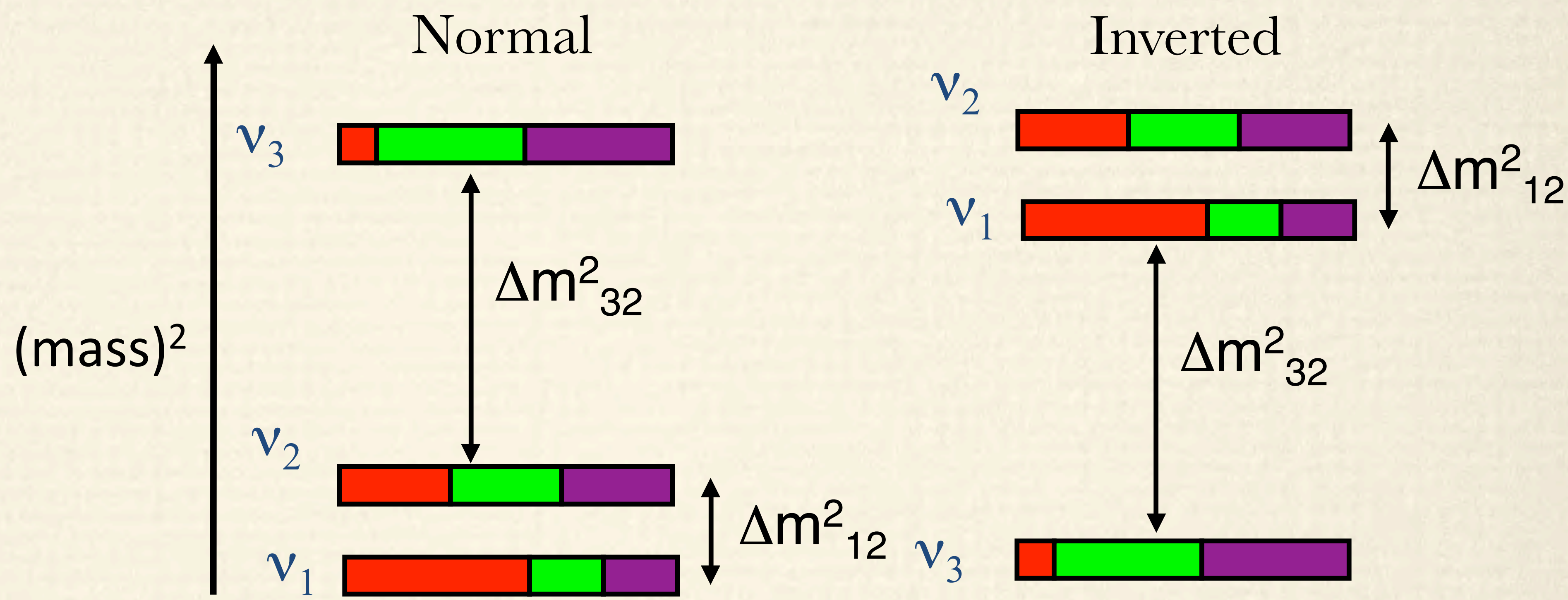

MIXING

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{\rm CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{\rm CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U^{\rm diag}_{\rm Maj}$$

Neutrino Mixing

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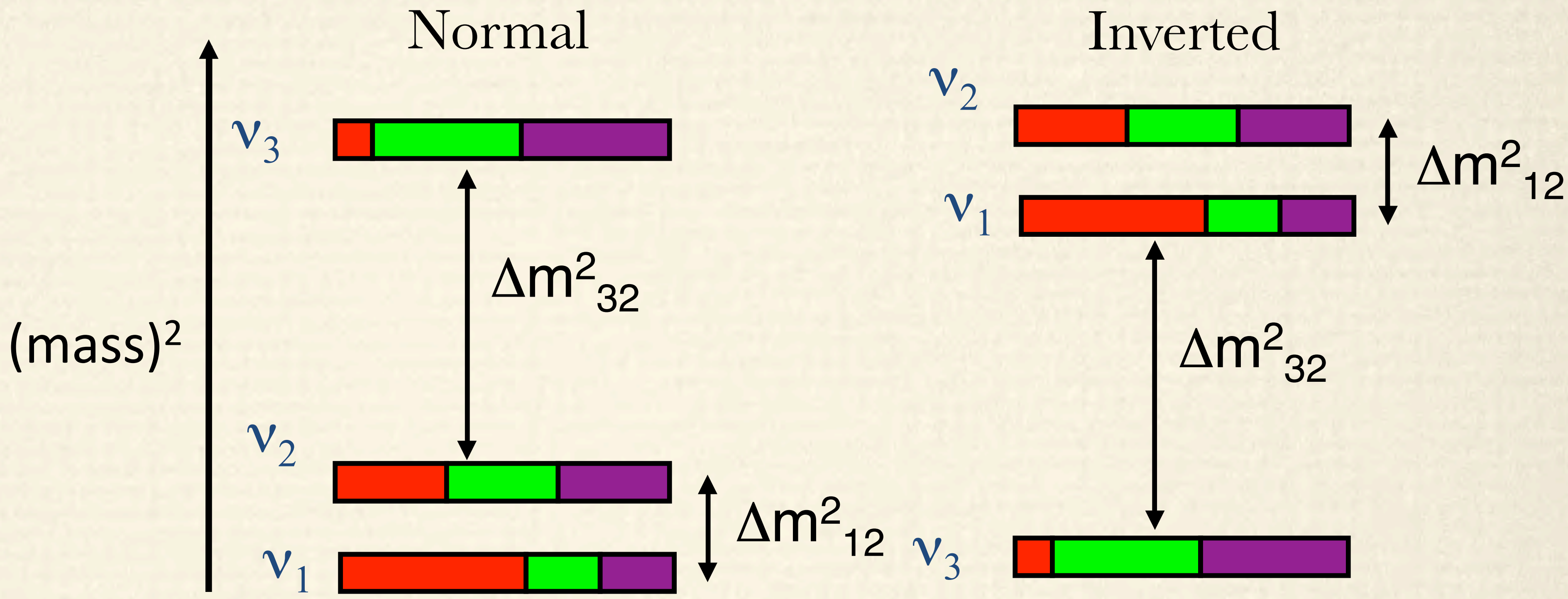

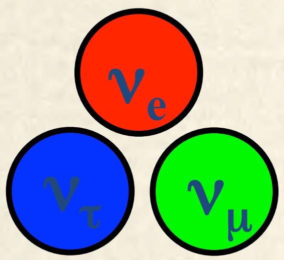

MIXING

Atmospheric
well measured

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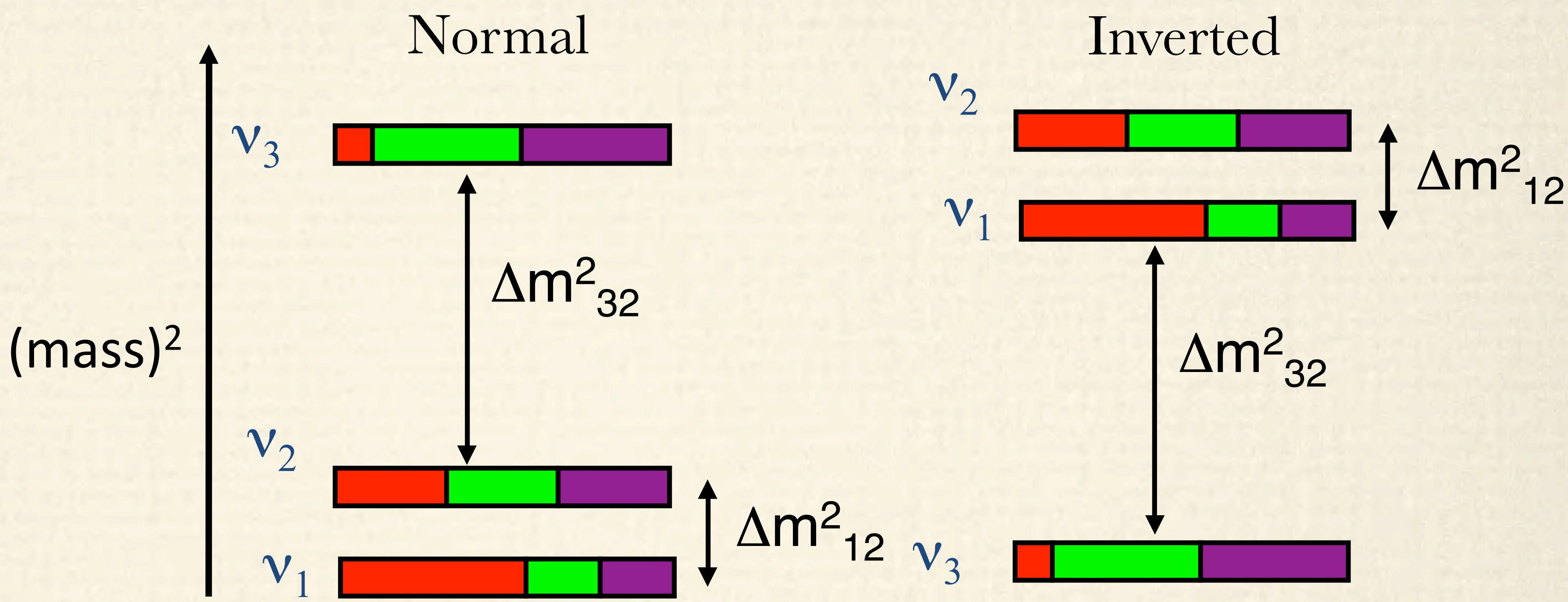

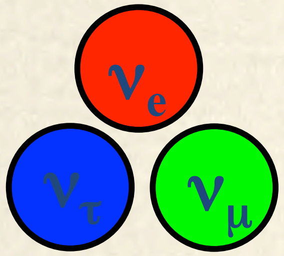

MIXING

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Measured as of Mar 2012!

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Neutrino Mixing

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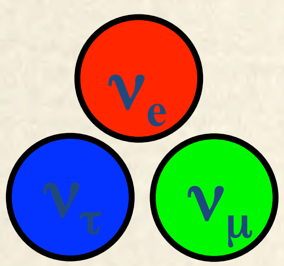

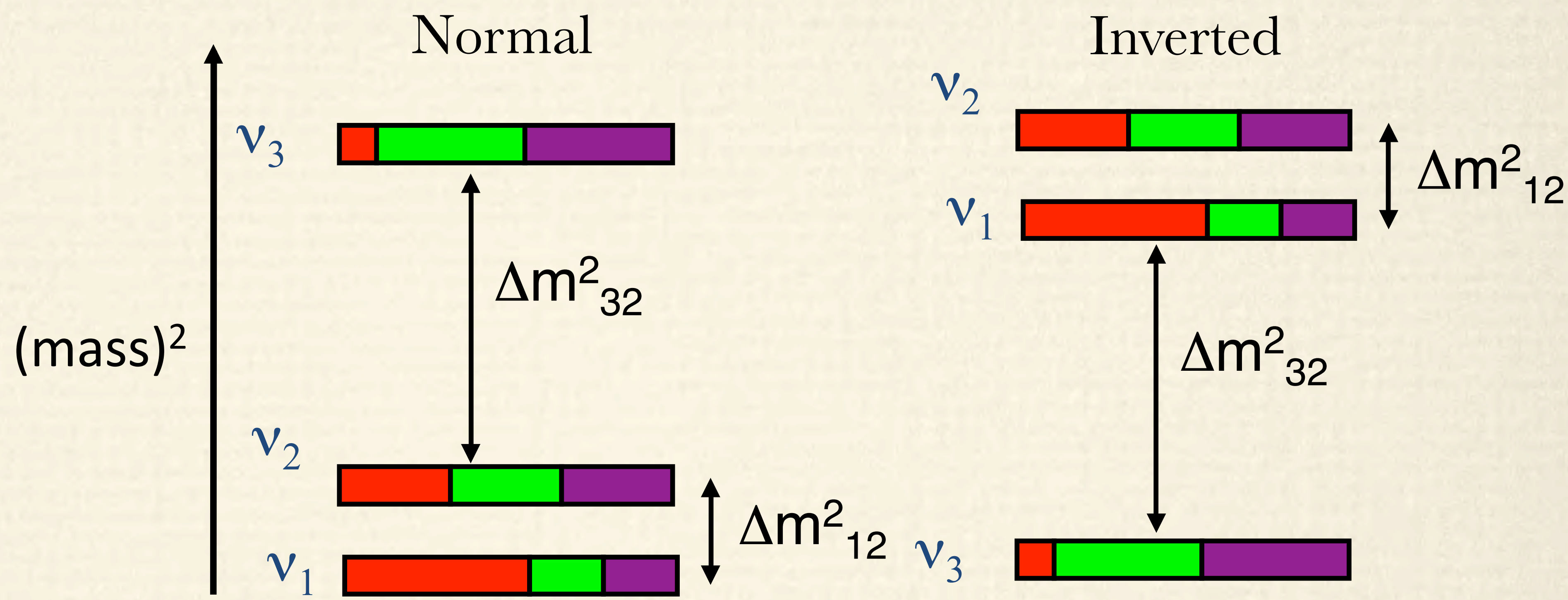

MIXING

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Measured as of Mar 2012!

Solar
well measured

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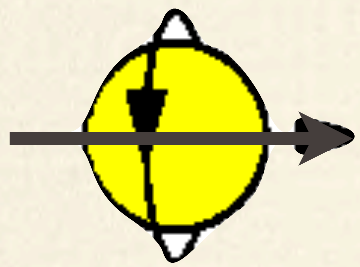
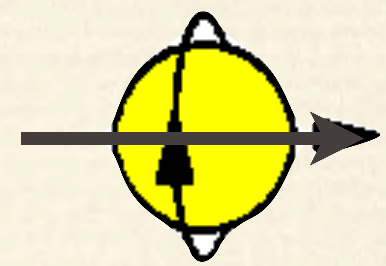
Helicity: a brief reminder



RH

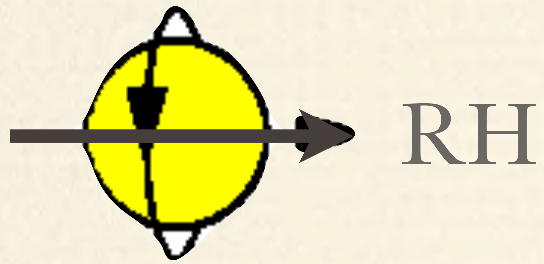
LH

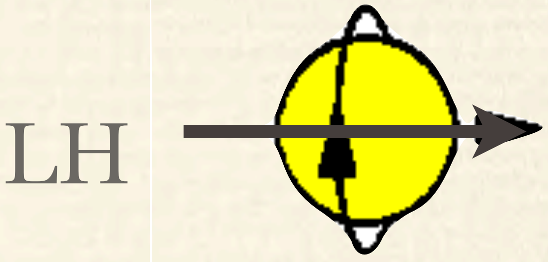


Thanks to J. Conrad &
L. Winslow for cartoons!

Helicity: a brief reminder

- Orientation of spin relative to momentum





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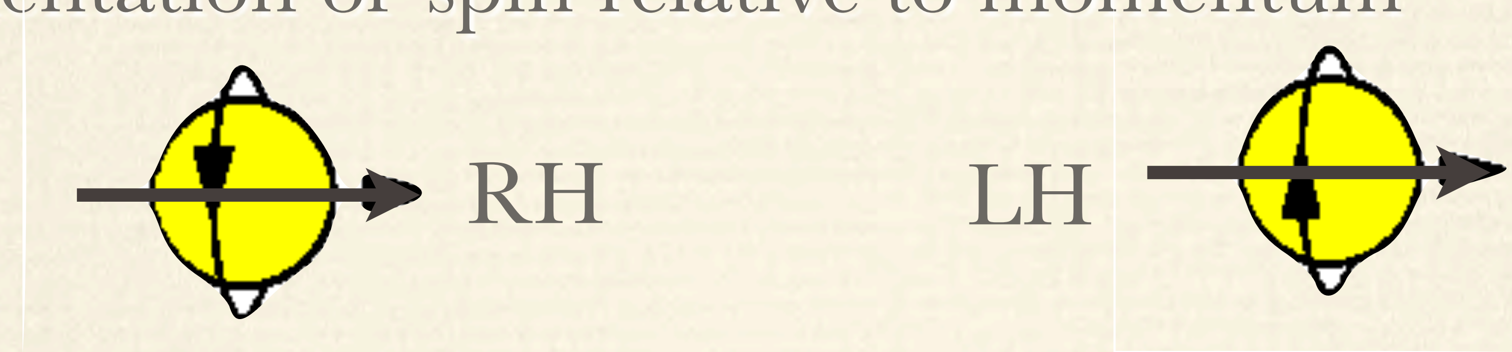
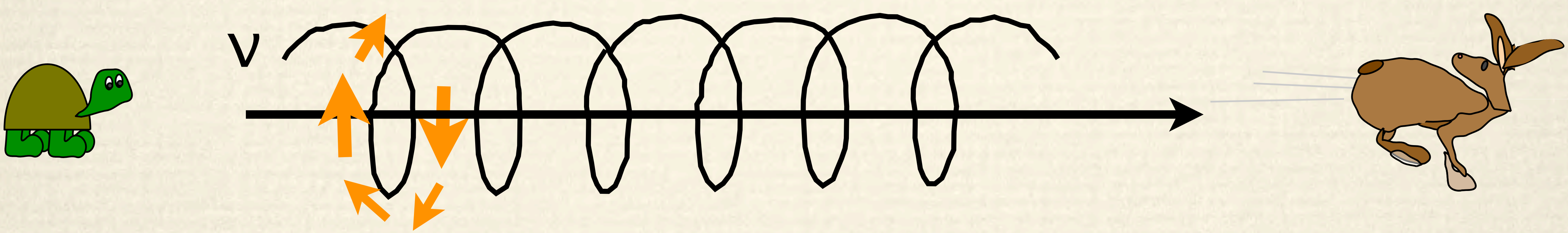


- If a particle has mass, can always boost to a frame in which helicity flips



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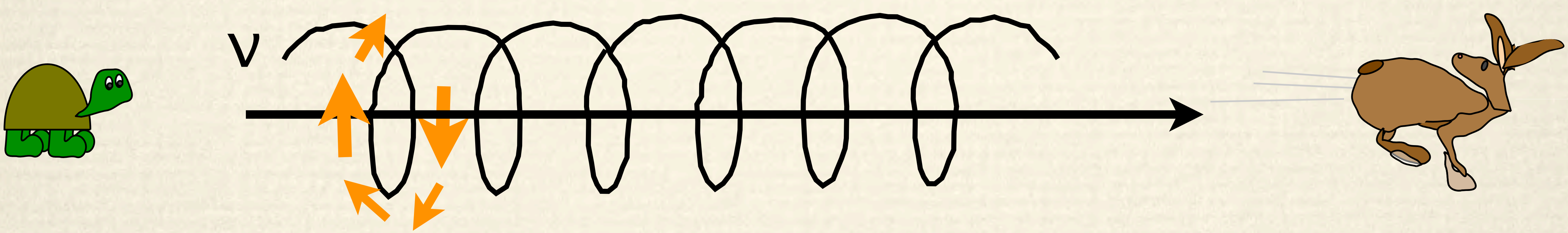

- Discovery of non-zero neutrino mass
  ⇒ can have a RH ν (or LH $\bar{\nu}$)

Thanks to J. Conrad &
L. Winslow for cartoons!

Neutrino Interactions

- **The only known fermion with the potential to be its own antiparticle**
- Define ν_e and $\overline{\nu}_e$ by interaction with charged leptons ($e^{\pm}$)
- Introduce a conserved 'charge' ⇒ lepton number

Lepton	Lepton number
e^-	+1
e^+	-1
ν_e	+1
$\overline{\nu}_e$	-1

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Majorana **vs** **Dirac**

Different helicity state of same particle

Different particles

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Majorana **vs** **Dirac**

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So what?

Dirac vs Majorana

- There is no Standard Model until we understand how neutrinos acquire mass

- **Dirac**

Requires global U(1) symmetry to be fundamental (lepton #)

Really?

⇒ matter and antimatter *fundamentally different*

- **Majorana**

Simplest M term is 5D

Cannot be explained by "standard" Yukawa Higgs coupling

Not renormalisable!

⇒ not the most fundamental theory

2ν Double Beta Decay

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

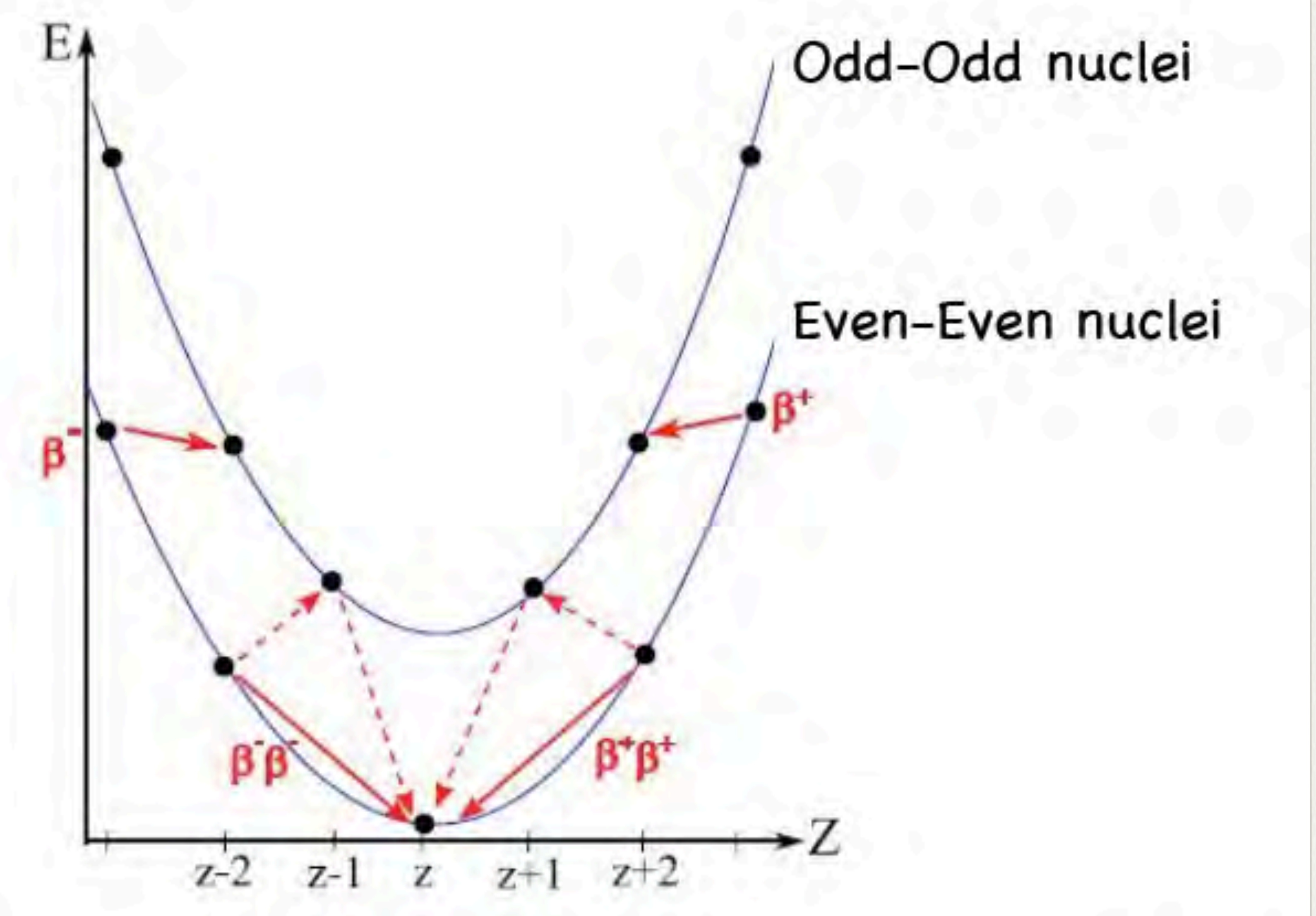
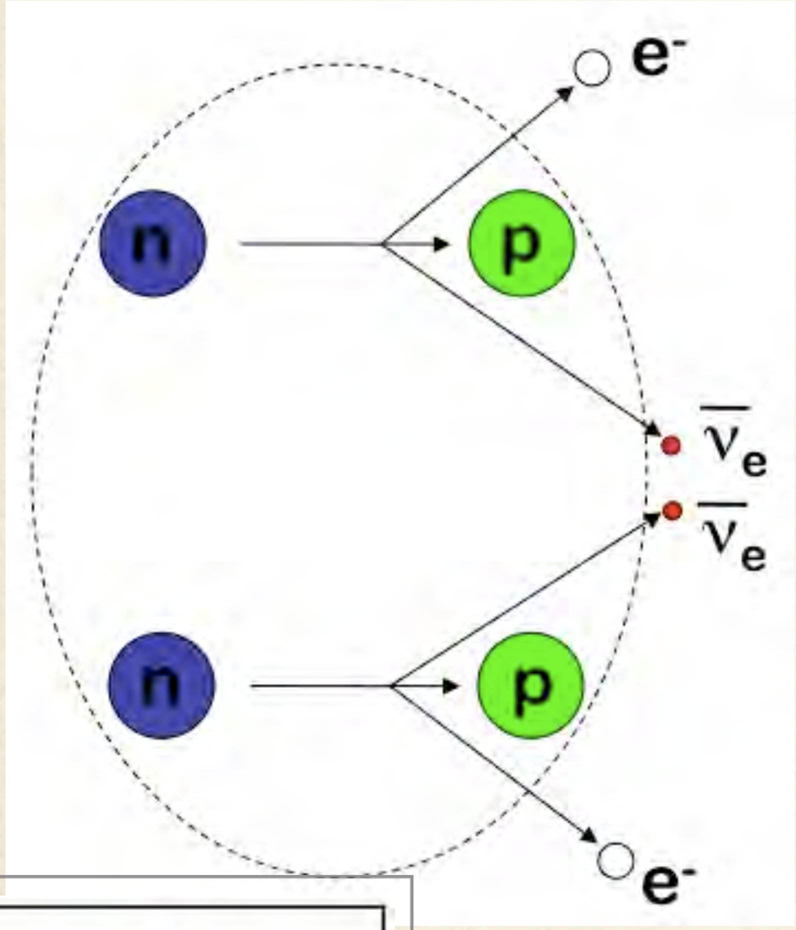
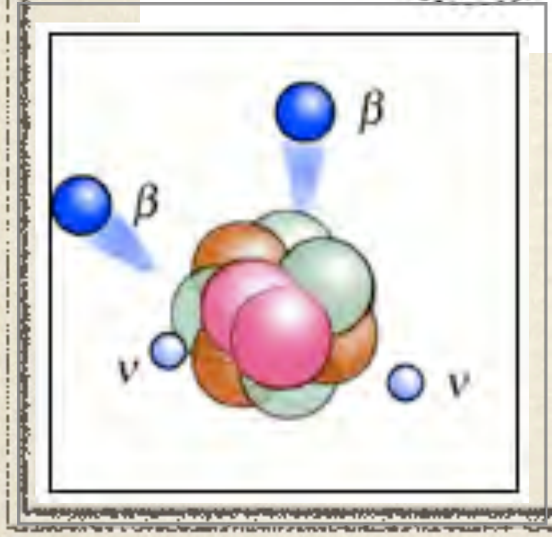


Figure adapted from: http://www.cobra-experiment.org/double_beta_decay/

2ν Double Beta Decay

Double Beta Decay

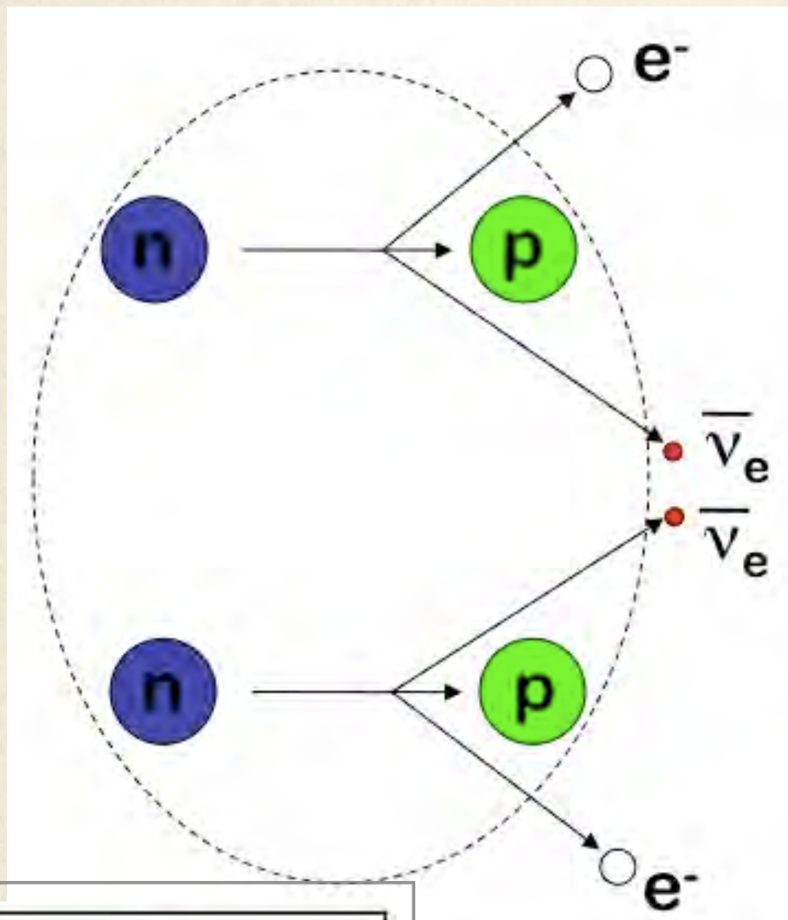


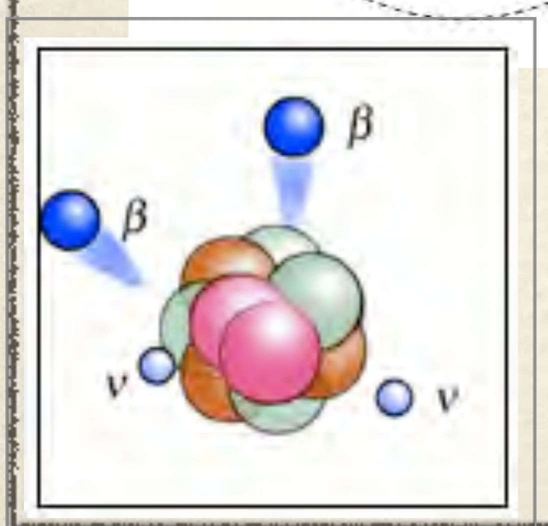


(A,Z) →
(A,Z+2) +2e$^-$ + 2$\overline{\nu}_e$

0ν Double Beta Decay

Double Beta Decay





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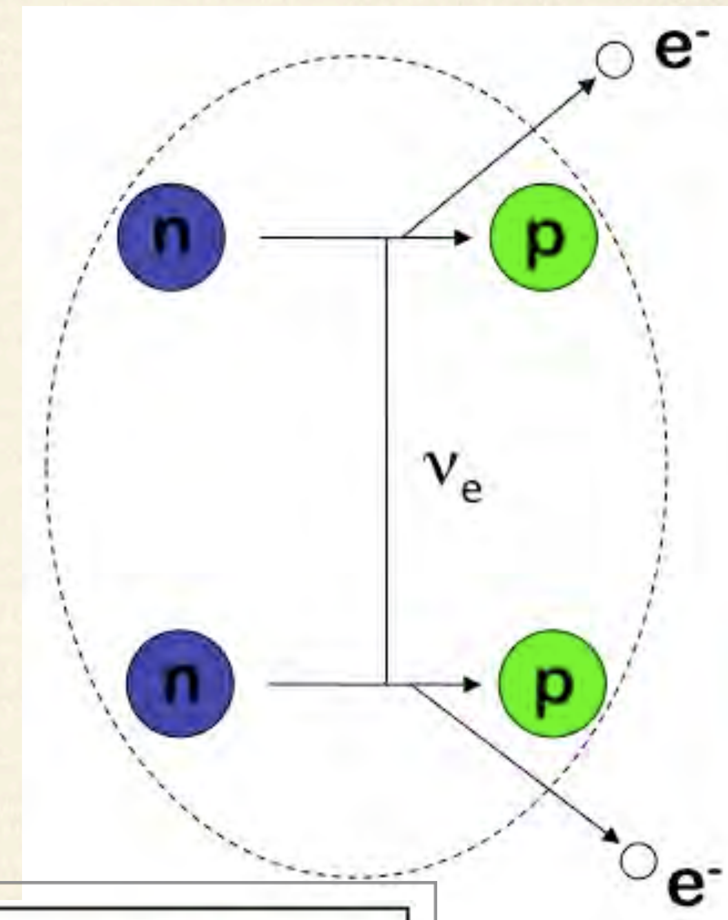

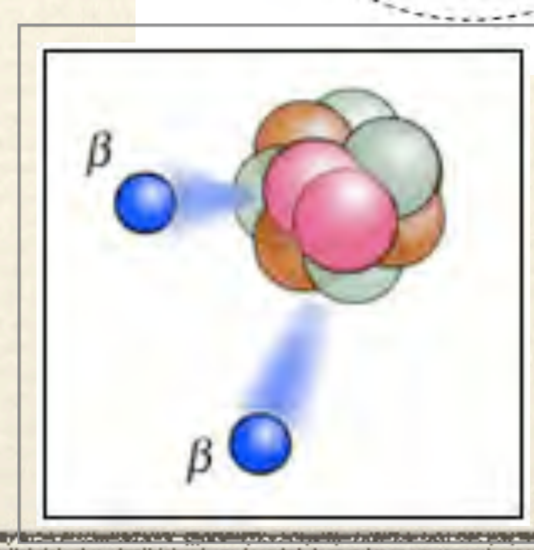

(A,Z) →
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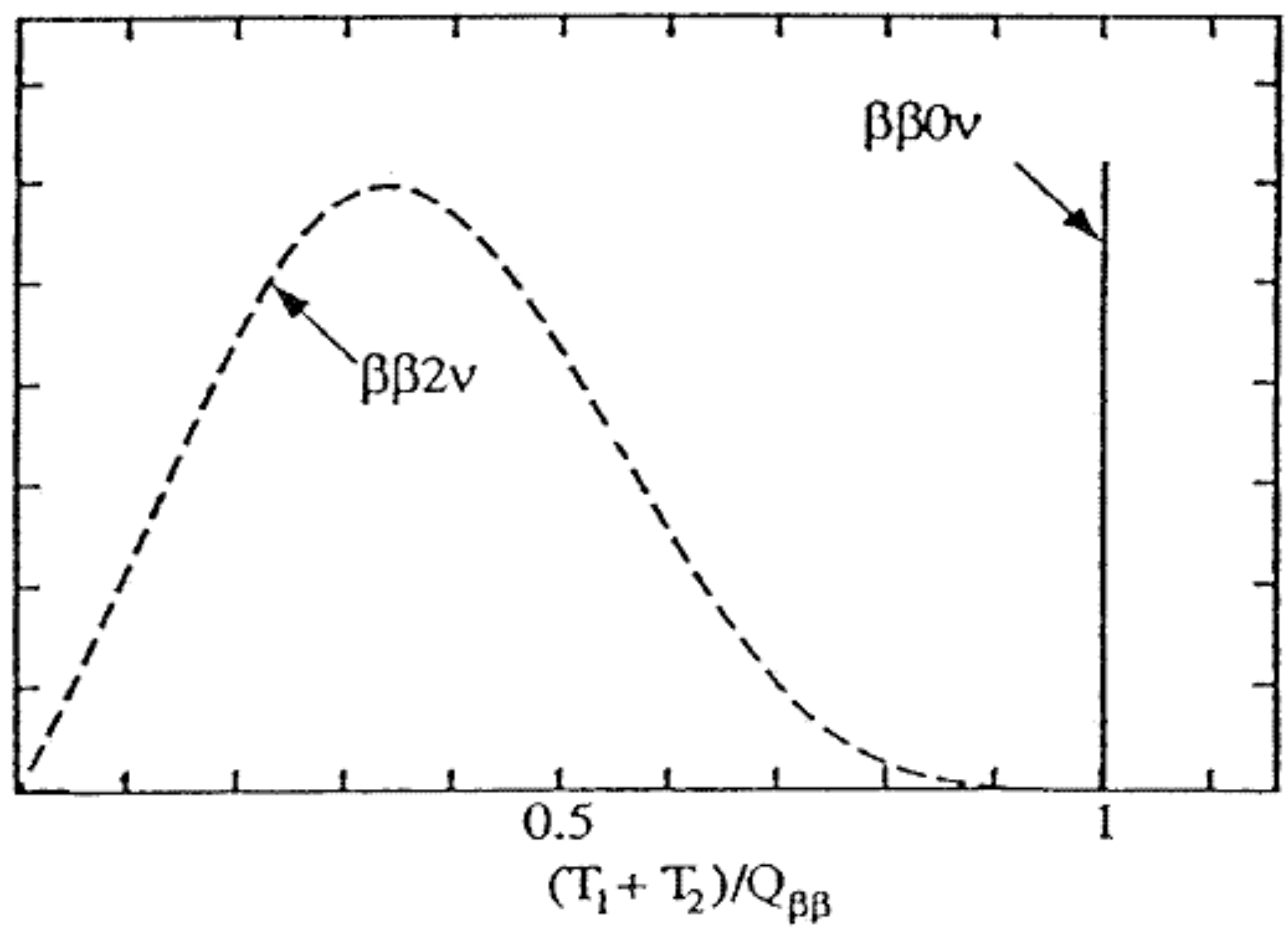
0νββ Signature

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

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

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Neutrino Mass

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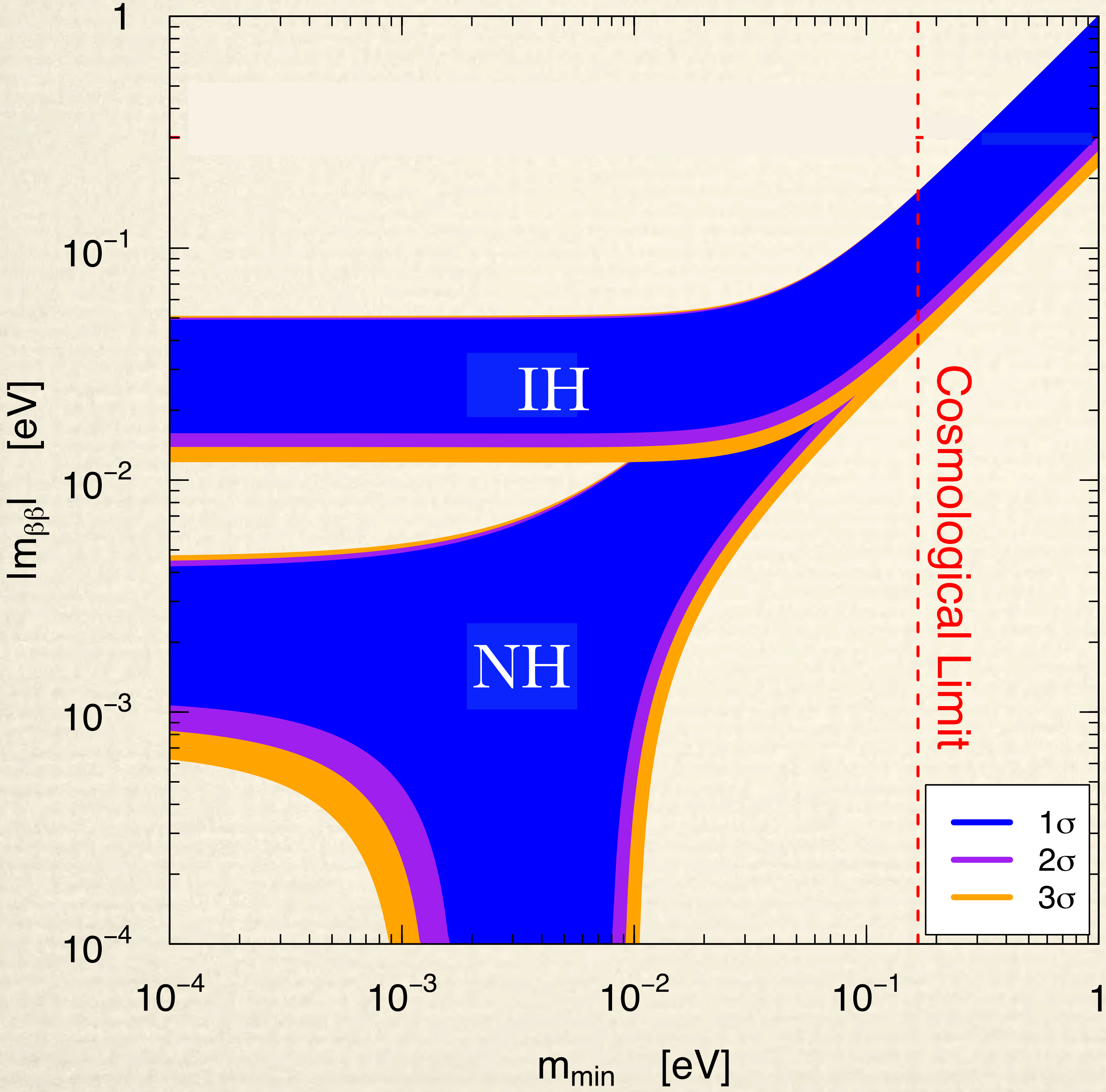
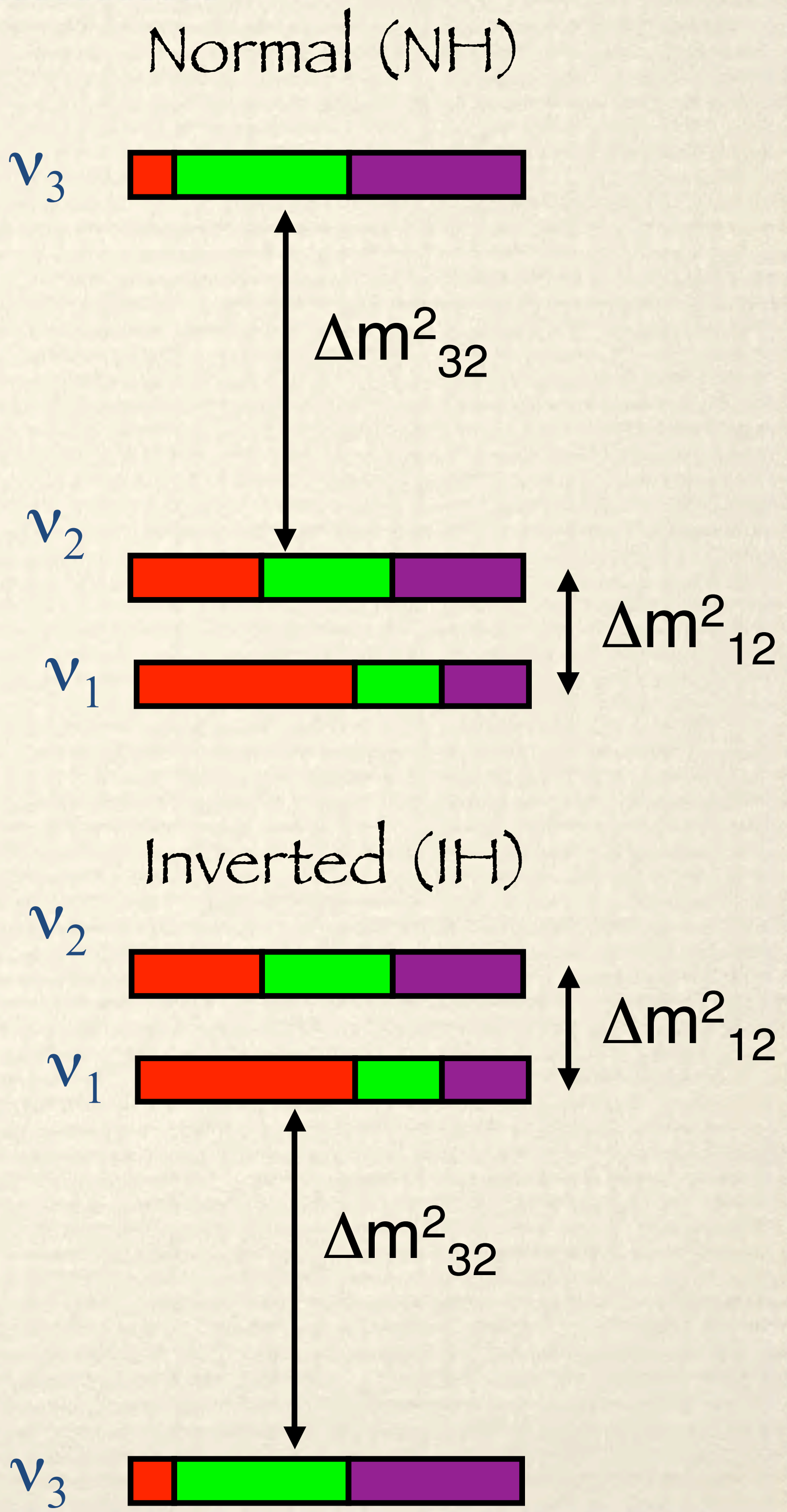
Probes absolute neutrino mass scale
Also sensitive to mass hierarchy

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

$$= \cos^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_1$$
$$+ \sin^2\theta_{12}\cos^2\theta_{13}e^{i\beta}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3$$

0νββ Phase Space





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

Isotope Choice

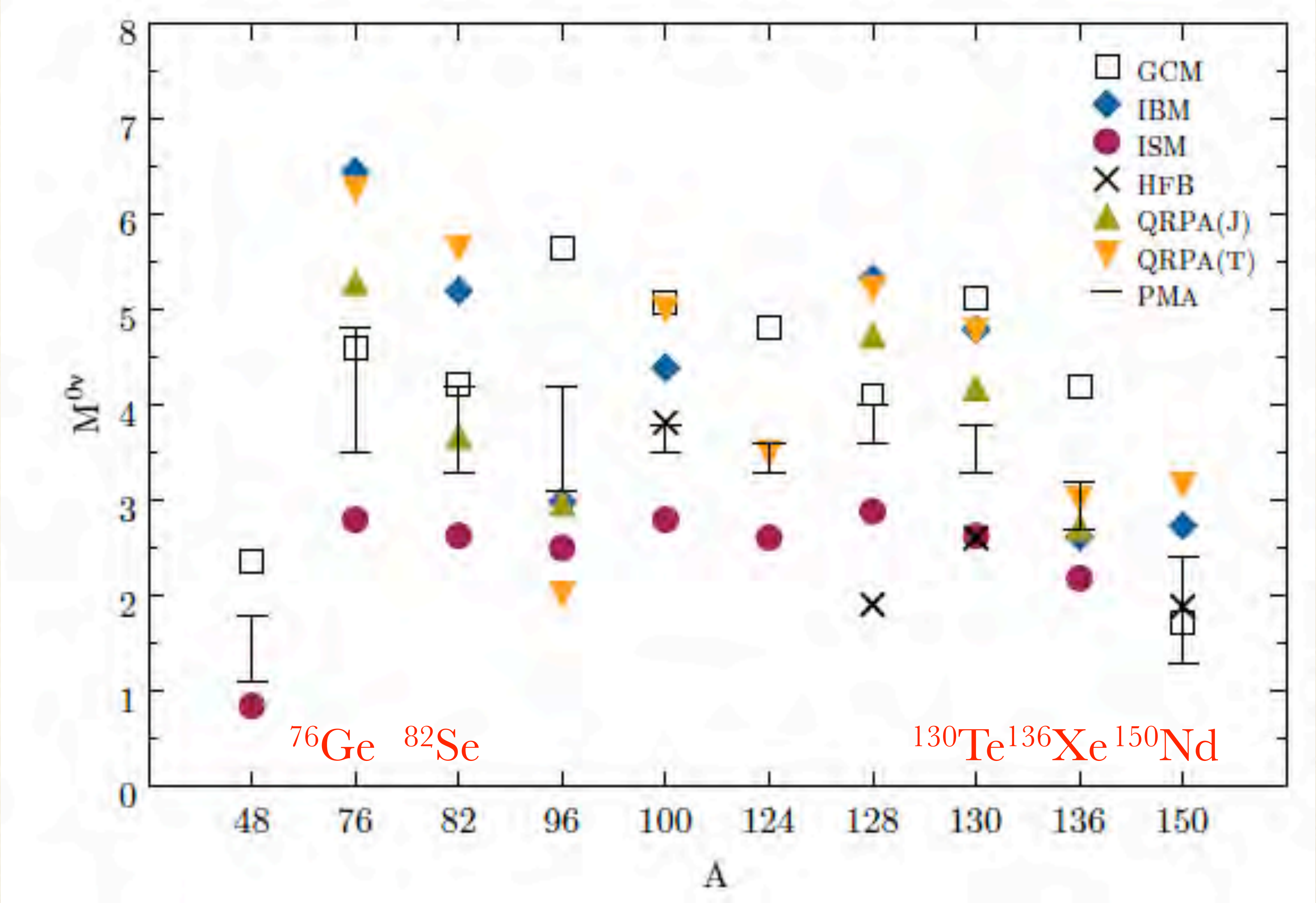
Isotope	$Q_{\beta\beta}$	Natural abundance	$\|M_{0\nu}\|$	$\|G_{0\nu}\|^{-1}$ (10^{25} y eV^2)	$T^{0\nu}_{1/2}$ (10^{27} y)	$N_{0\nu}$ / $N_{0\nu}(Ge)$
^{76}Ge	2.04 MeV	7.8%	4.15 ± 0.65	4.09	0.95	1.0
^{82}Se	3.00 MeV	9.2%	3.75 ± 0.45	0.93	0.26	3.3
^{130}Te	2.53 MeV	34.5%	3.65 ± 0.15	0.59	0.18	3.1
^{136}Xe	2.46 MeV	8.9%	2.95 ± 0.25	0.55	0.25	2.1
^{150}Nd	3.37 MeV	5.6%	1.85 ± 0.55	0.13	0.15	3.3

Sense and Sensitivity of ββ expts: arxiv/1010.5112

$$\Gamma = G^{0\nu} \left|M'^{0\nu}\right|^2 \left|m_{\beta\beta}/m_e\right|^2$$

NME

Different techniques can give quite different results for NME



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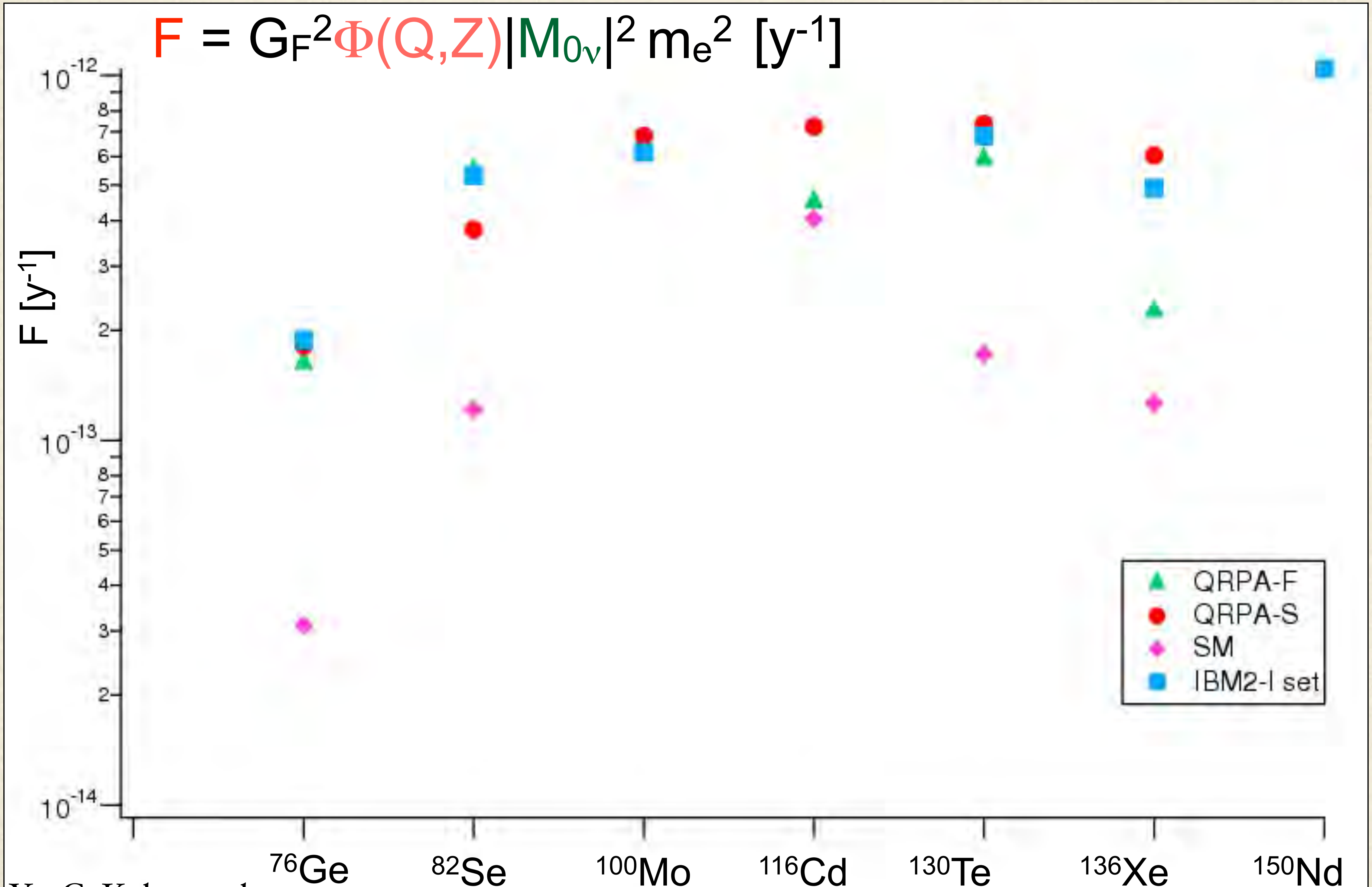
Combined Figure of Merit



Yu. G. Kolomensky

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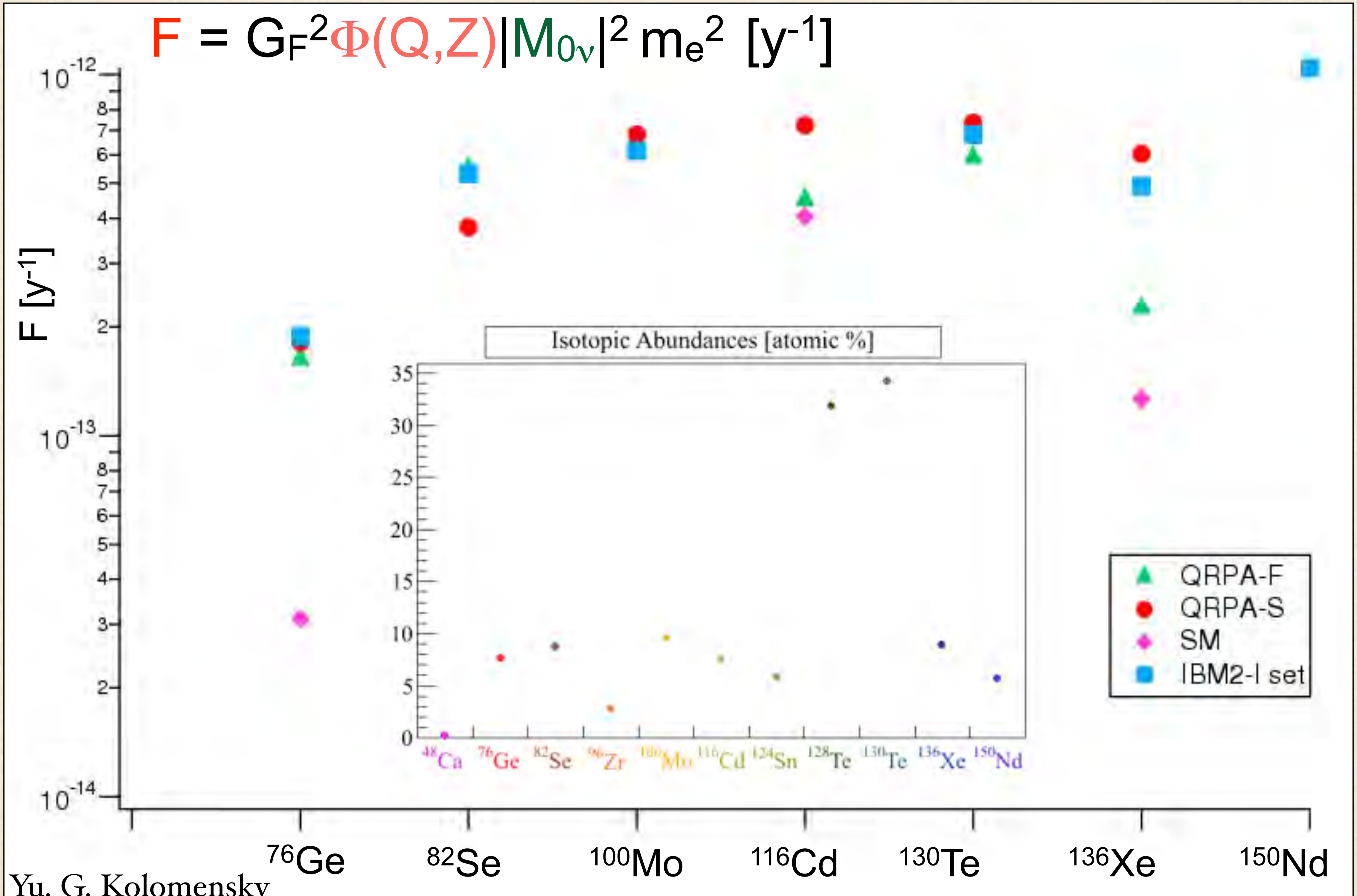

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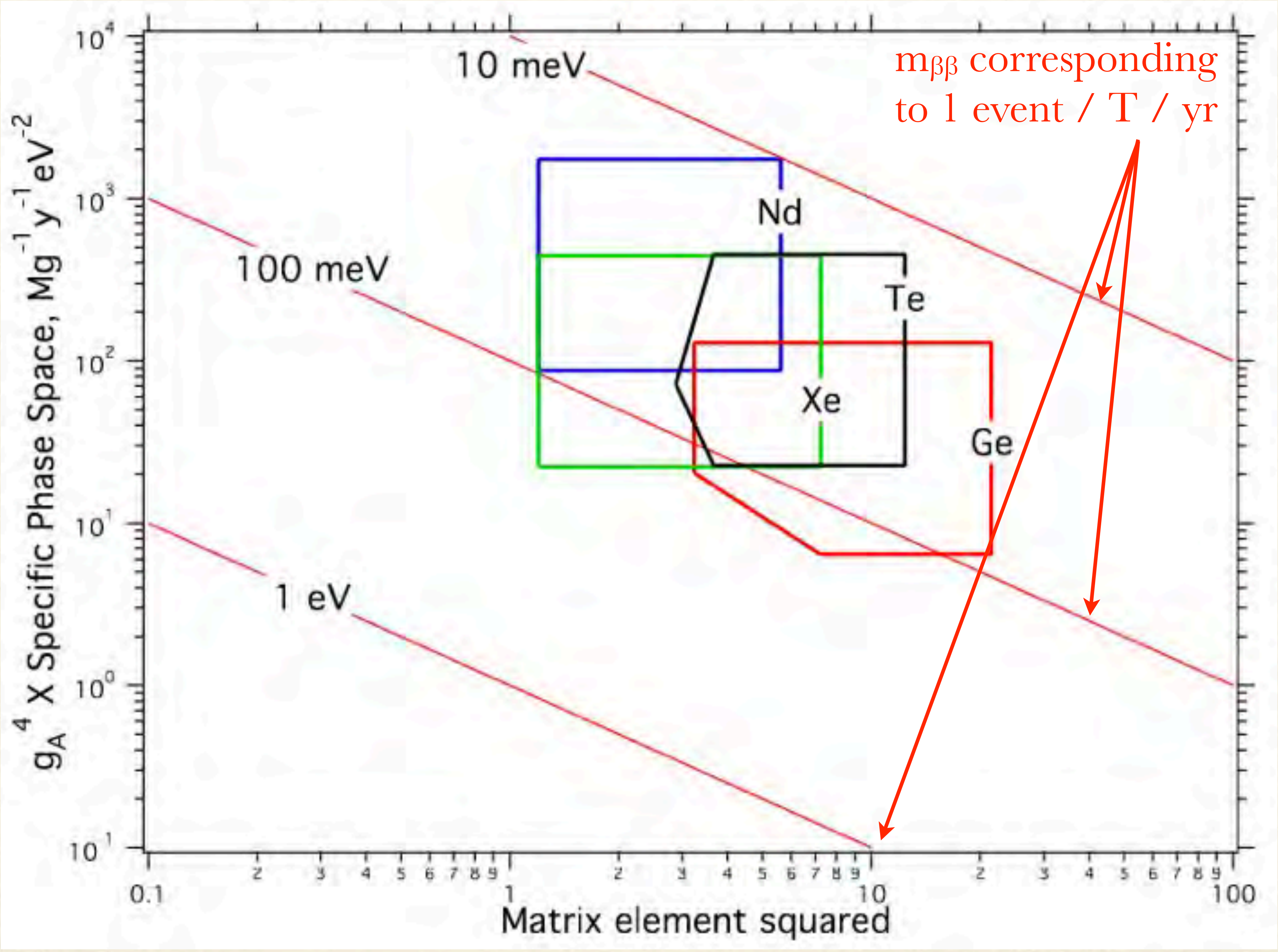
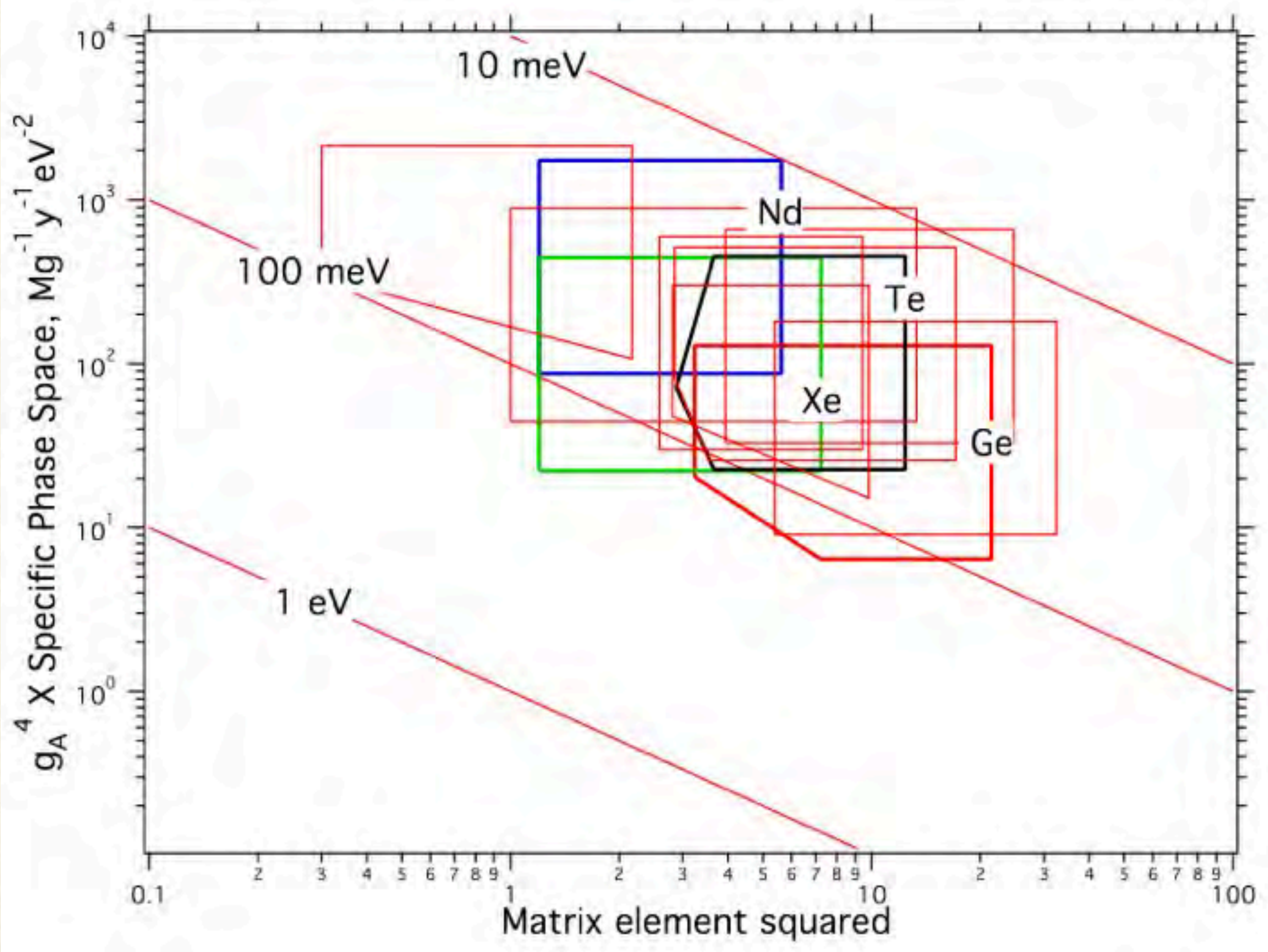
Isotope Comparison



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

Isotope Comparison



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

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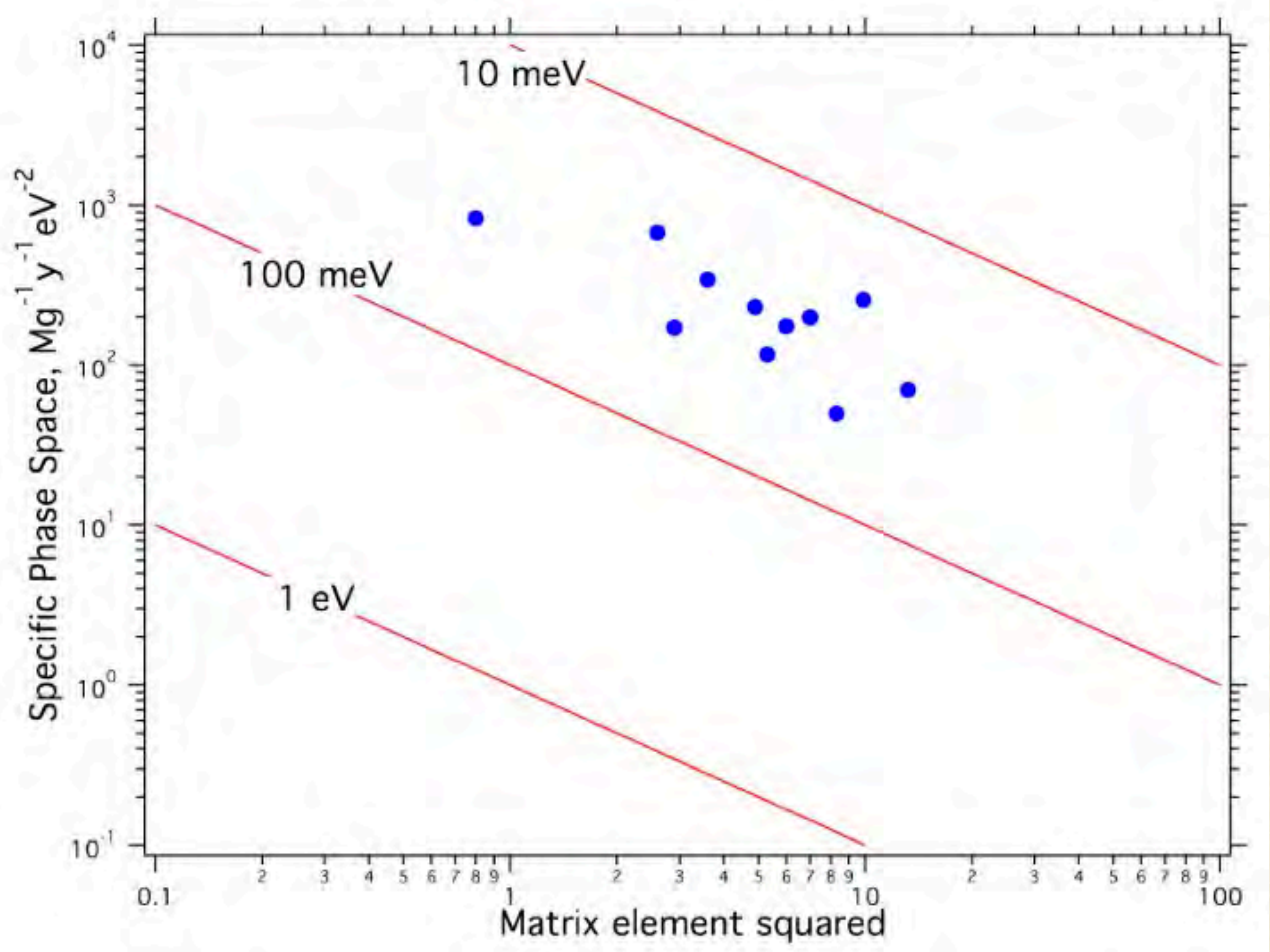
Isotope Comparison

Plot geometric mean of NME at g_A=1



Inc. abscissa: ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo, ^{110}Pd

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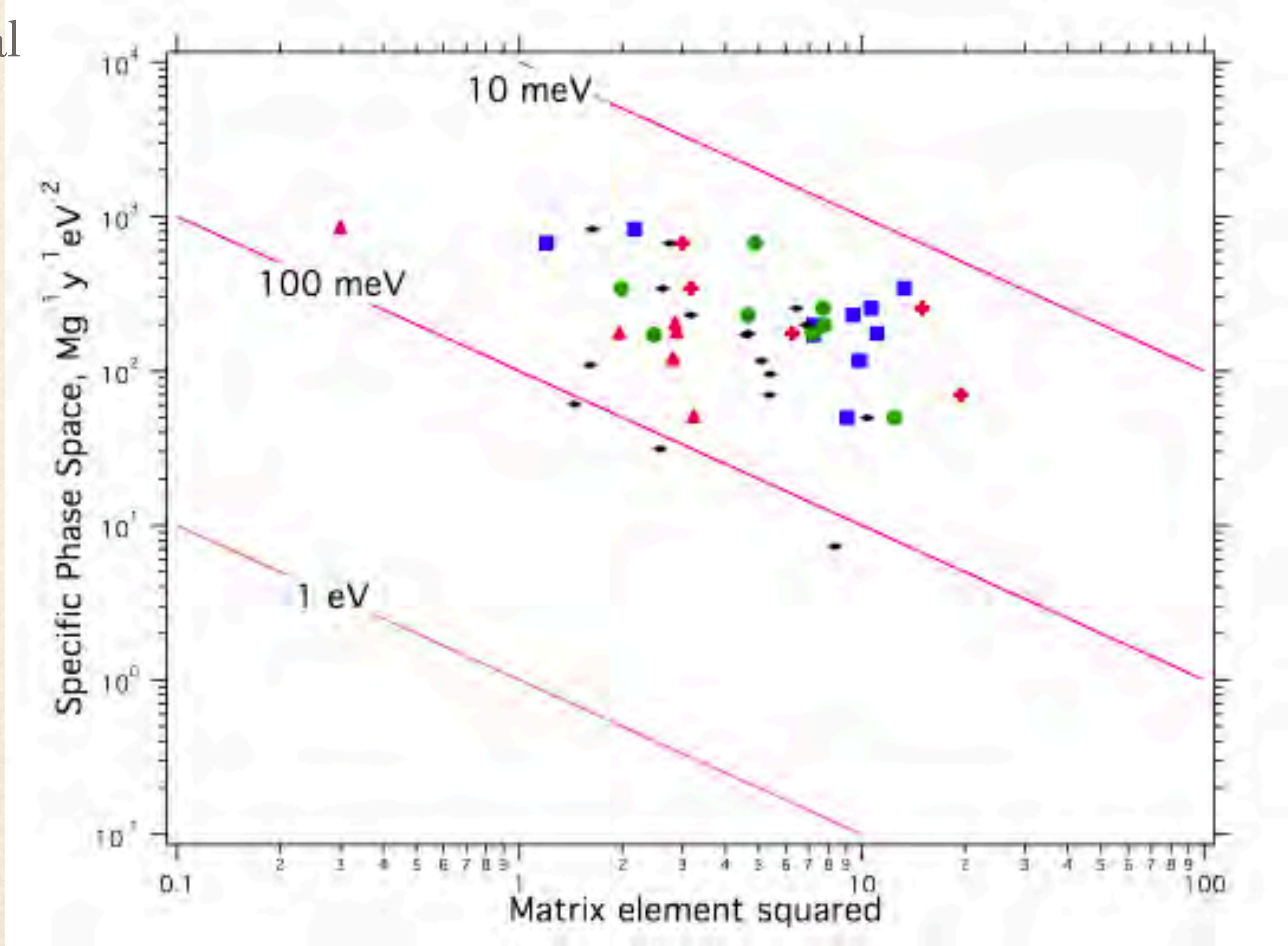
Isotope Comparison

Individual NMEs against specific phase space



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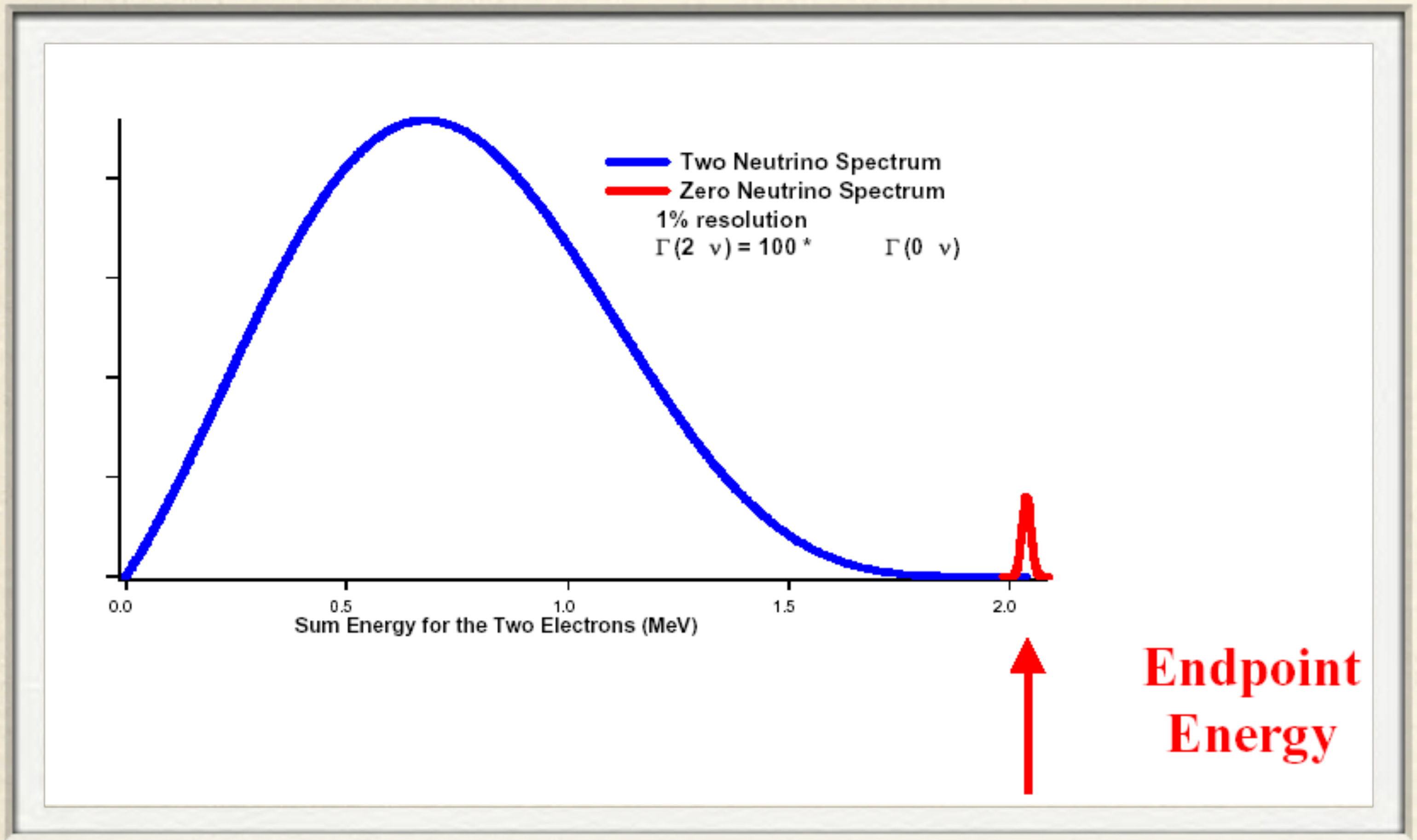
Experimental Challenges

Ultra small signal ⇒

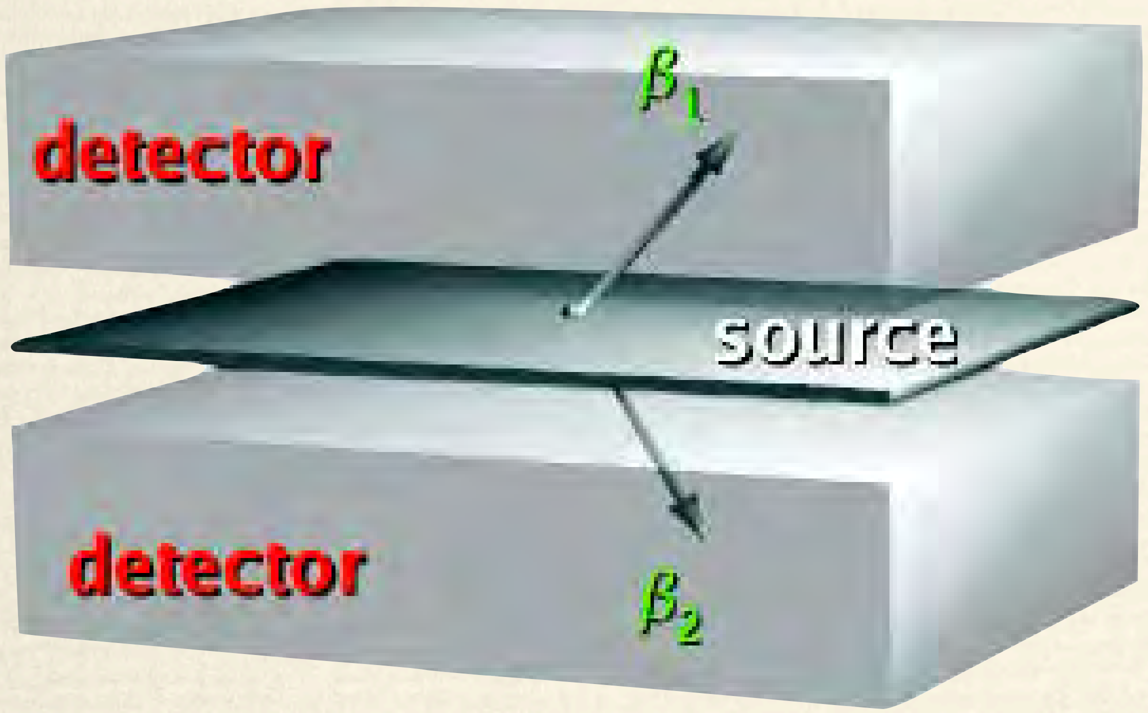


- Large mass (signal stats)
- Low bkg
  - Deep underground
  - Purification
  - Bkg ID methods
- Good E resolution
- Multiple isotopes
- Various technologies

Experimental Techniques

1. Source external to detector

e.g. SuperNEMO



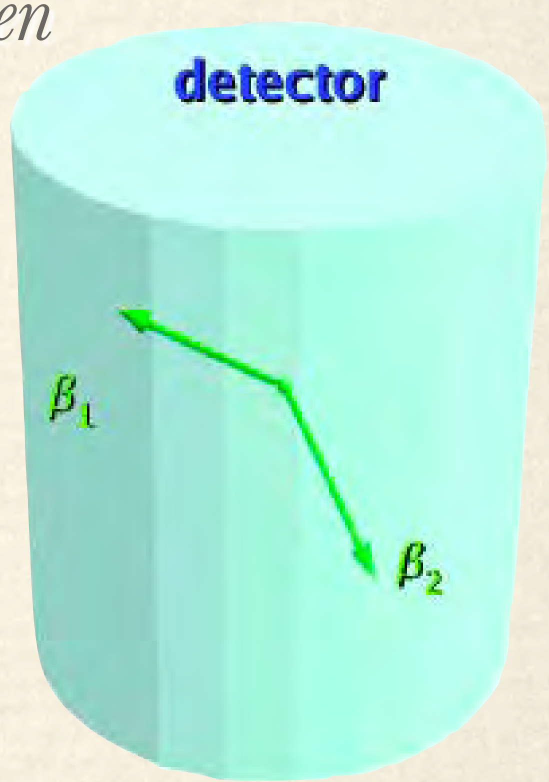
+ event topology, bkg ID

- detector M, resn, acceptance

Model testing

2. Source internal to detector

e.g. Gerda, MJ, CUORE, EXO, SNO+, KL-Zen



+ detector M, resn, acceptance

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Discovery

Experimental Techniques

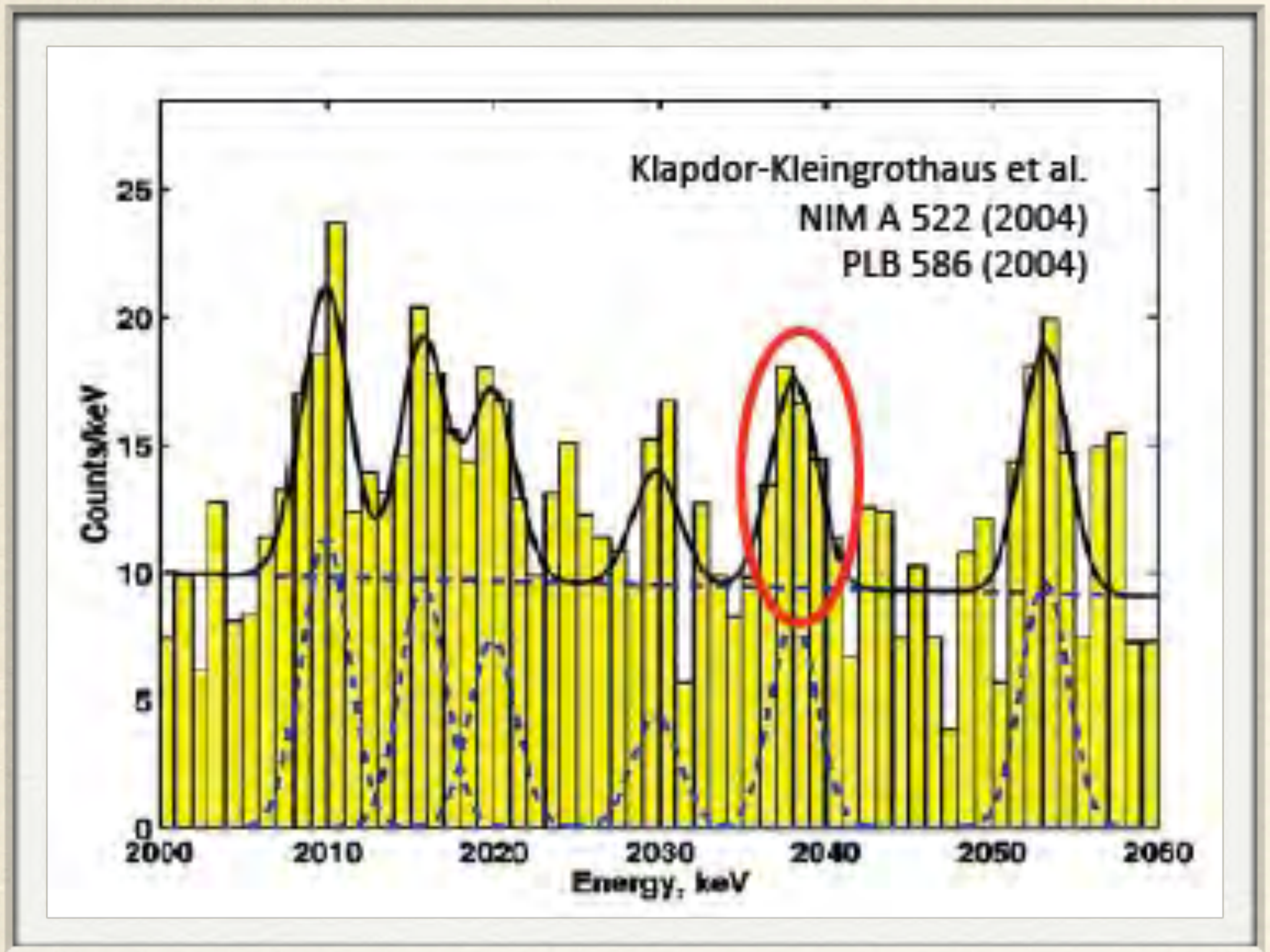
Approach	Pros	Cons
Large self-shielding calorimetry	• Self-shielding: low ext bkg • Easily scalable to large M • Source in / source out caln • High detection efficiency	• Relatively poor E resn
Xe TPC	• Relatively easy to enrich • No long-lived r/a isotopes • Scint + ionisation signals	• $Q_{\beta\beta}$ (2.46MeV) close to ^{208}Tl • %-level E resn
High-resolution calorimetry	• Excellent E resn • Simple, compact	• No tracking • Ltd bkg suppression (exc E) • Reduced self-shielding
Tracko-calo expt	• Good bkg rejection	• Low detection efficiency • Low E resn • Very hard to scale

Experiments

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

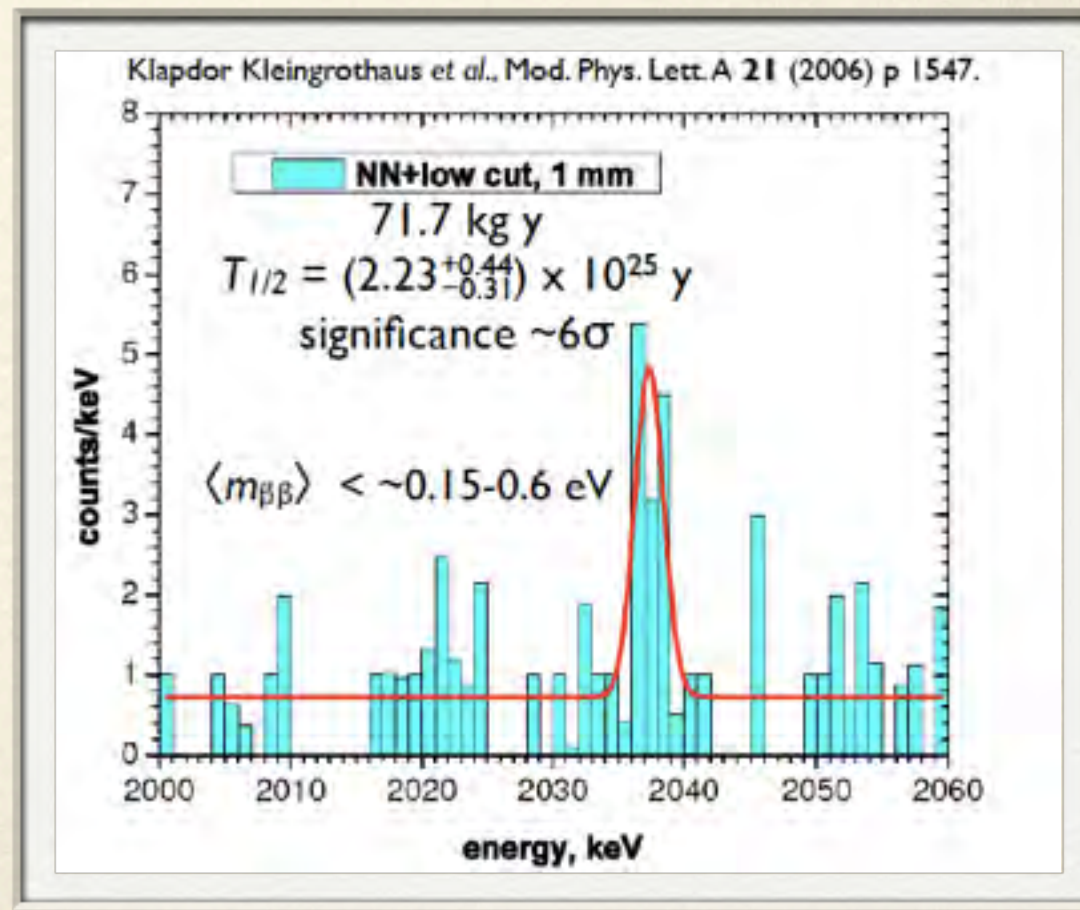
Controversial Signal

Heidelberg-Moscow ^{76}Ge experiment



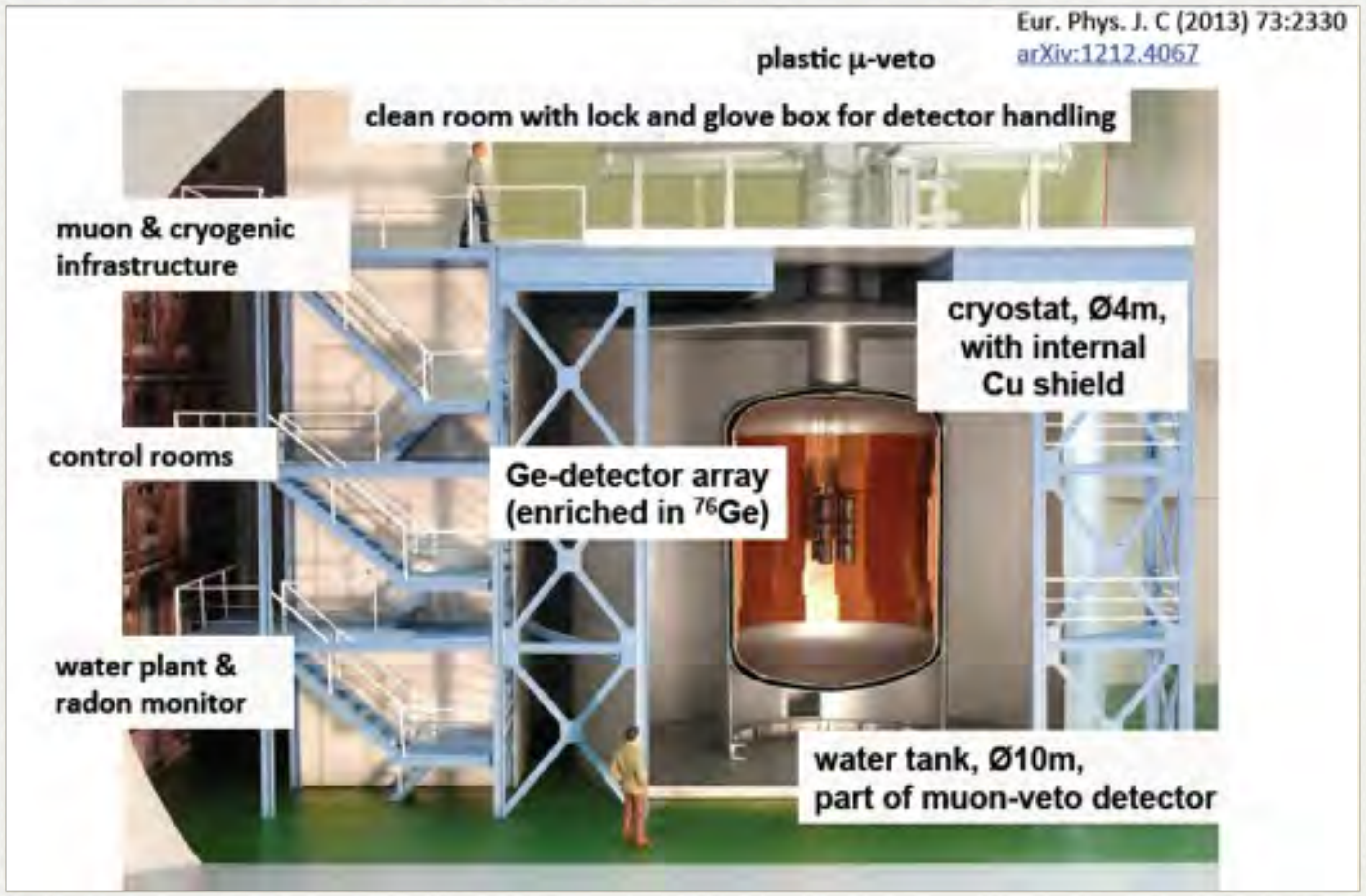
71.7 kg year

2004: 0.17 ct/kg-yr-keV
$T_{1/2} = 1.19 \times 10^{25}$yr,   4.2 σ



2006: "almost no γ background"
$T_{1/2} = 2.23 \times 10^{25}$yr,   >6 σ

GERDA



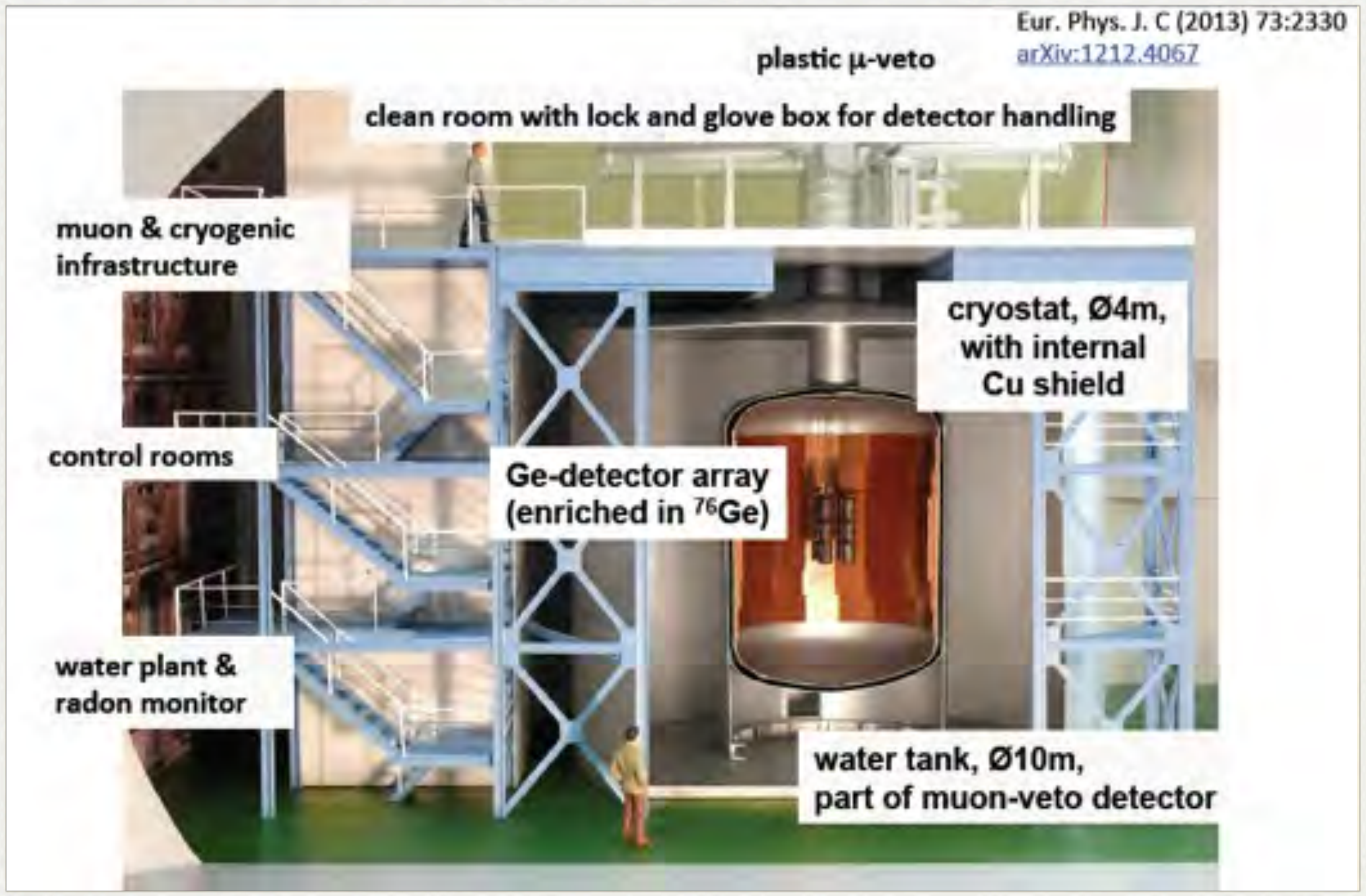
Enriched ^{76}Ge crystal array
LAr bath (shielding)
Refurbished Ge diodes from HdM / IGEX

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

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr
90% CL (Bayesian)

arXiv:1307.4720 (2013) *07/2013*

GERDA



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Combine with other Ge:
$T^{0\nu}_{1/2} > 3 \times 10^{25}$ yr

arXiv:1307.4720 (2013) *07/2013*

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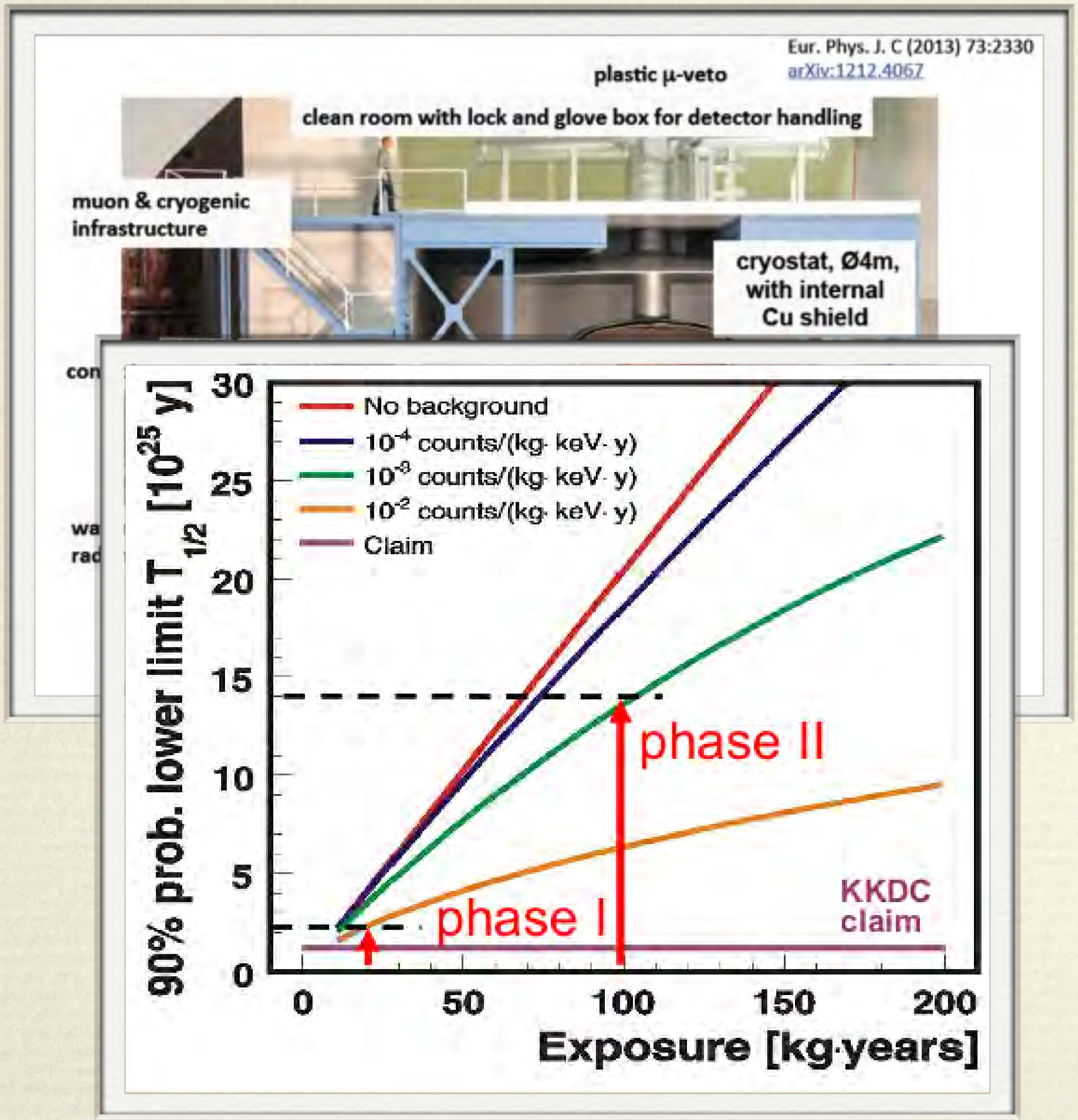

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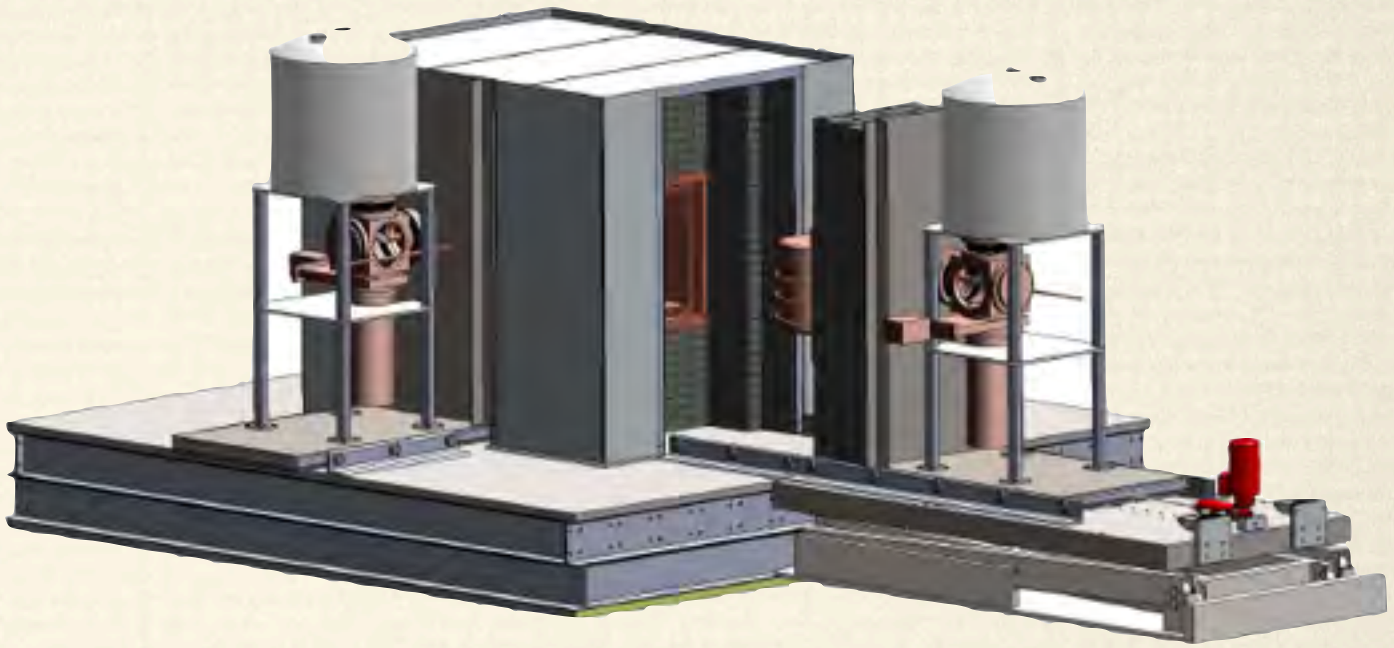
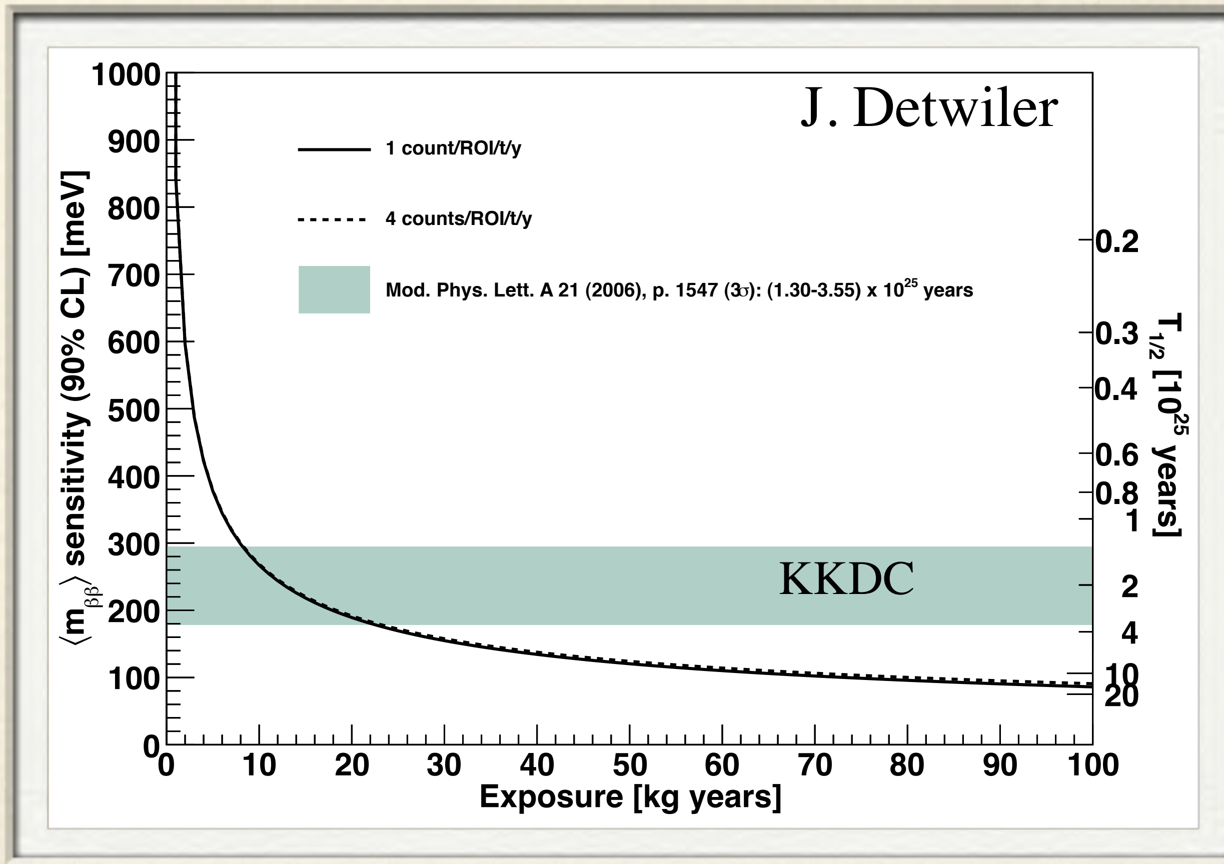
arXiv:1307.4720 (2013) *07/2013*

MAJORANA (Demonstrator)

- MJD: 40kg prototype
- 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





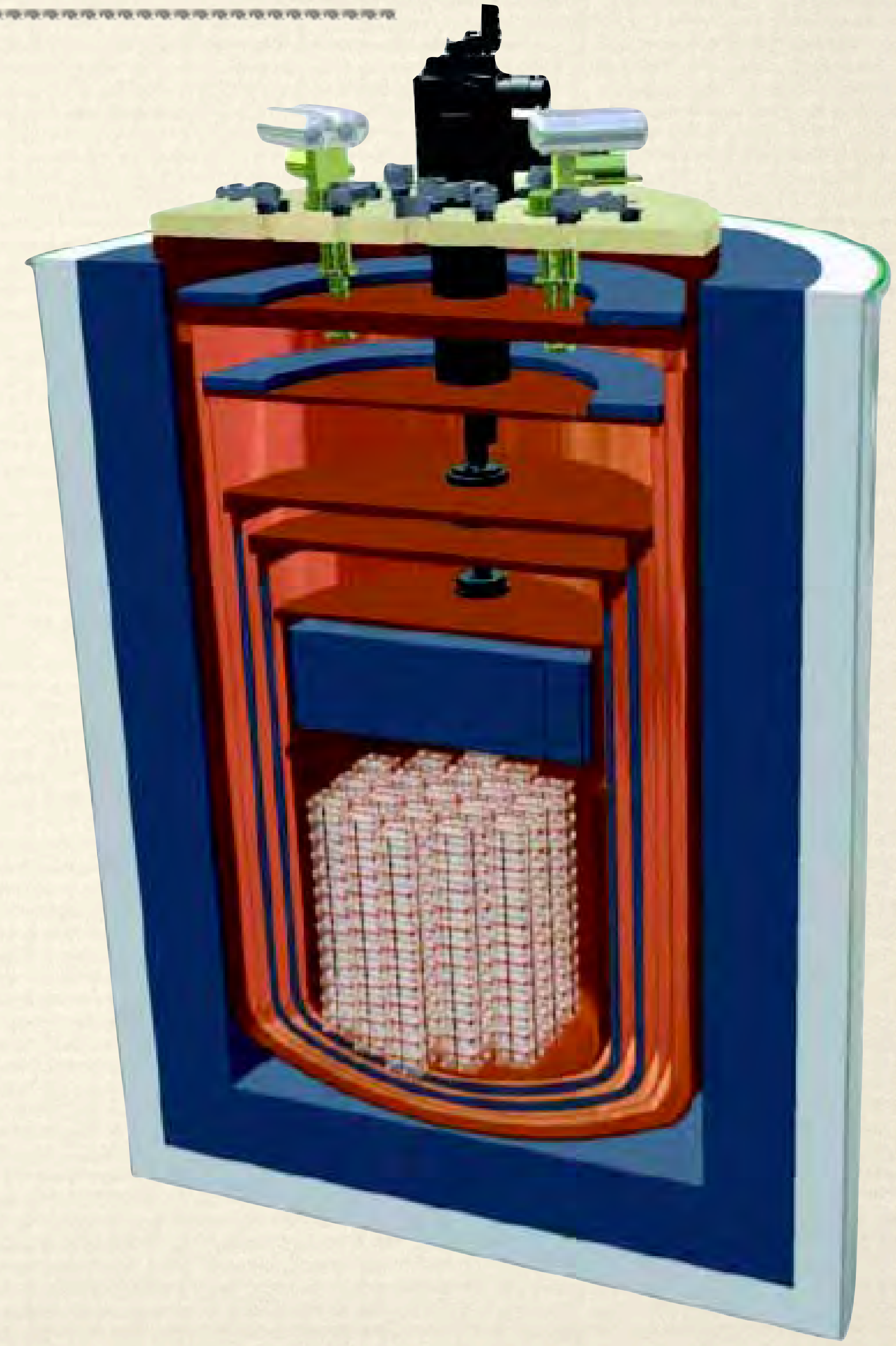
CUORE

Cryogenic Bolometry

- **19** towers suspended in a cylindrical structure
- **13** levels, **4** crystals each
- 5x5x5 cm^3 (750g each)
- ^{130}Te: 33.8% natural isotope abundance

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

- New pulse tube refrigerator and cryostat
- Radio-purity techniques and high resolution achieve low backgrounds
- Joint venture between Italy (INFN) and US (DOE, NSF)
- Under construction (expected completion by ~end of 2014)

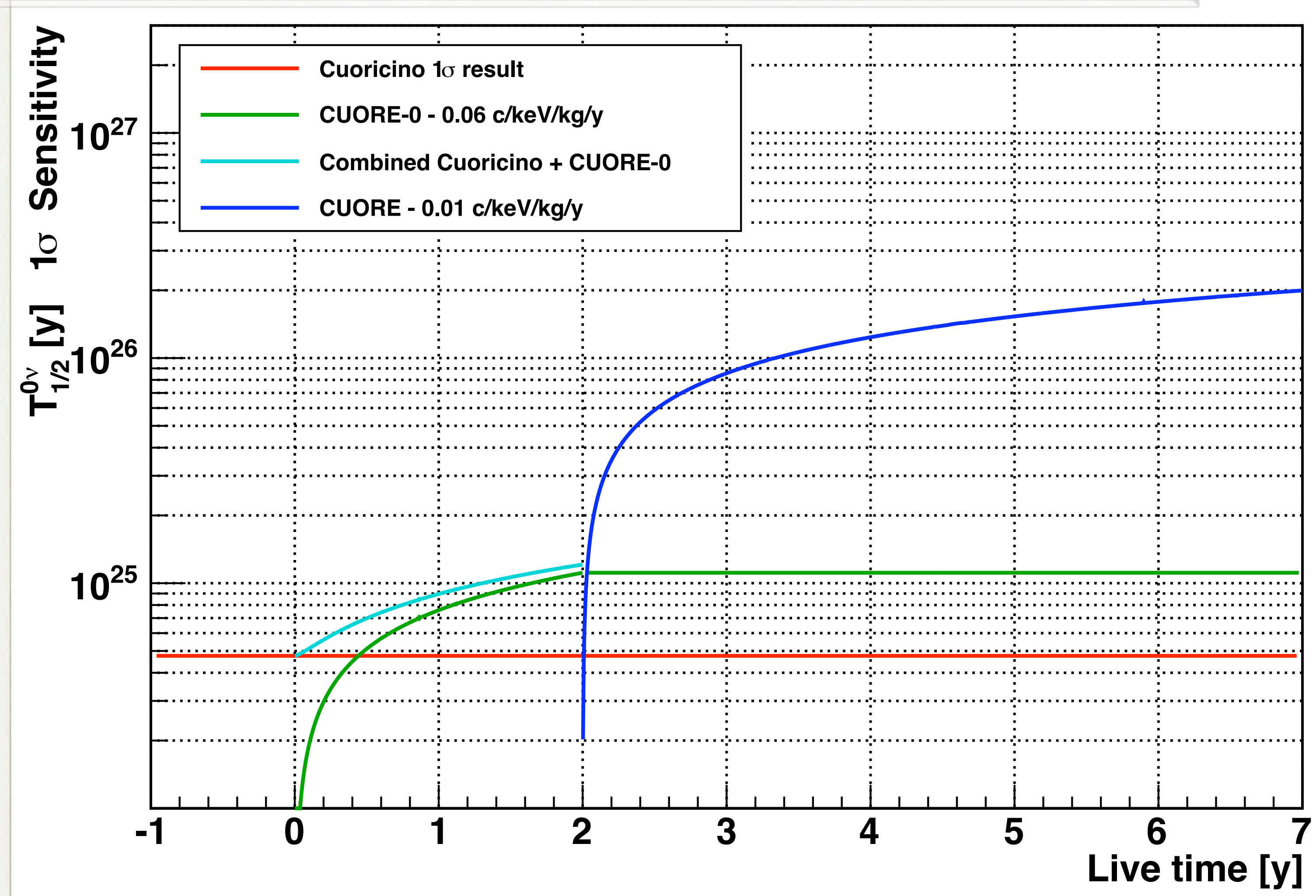


CUORE Sensitivity

Background [c/keV/kg/y]	ΔE_{FWHM} [keV]	$\tau_{1/2}^{0\nu}$ [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

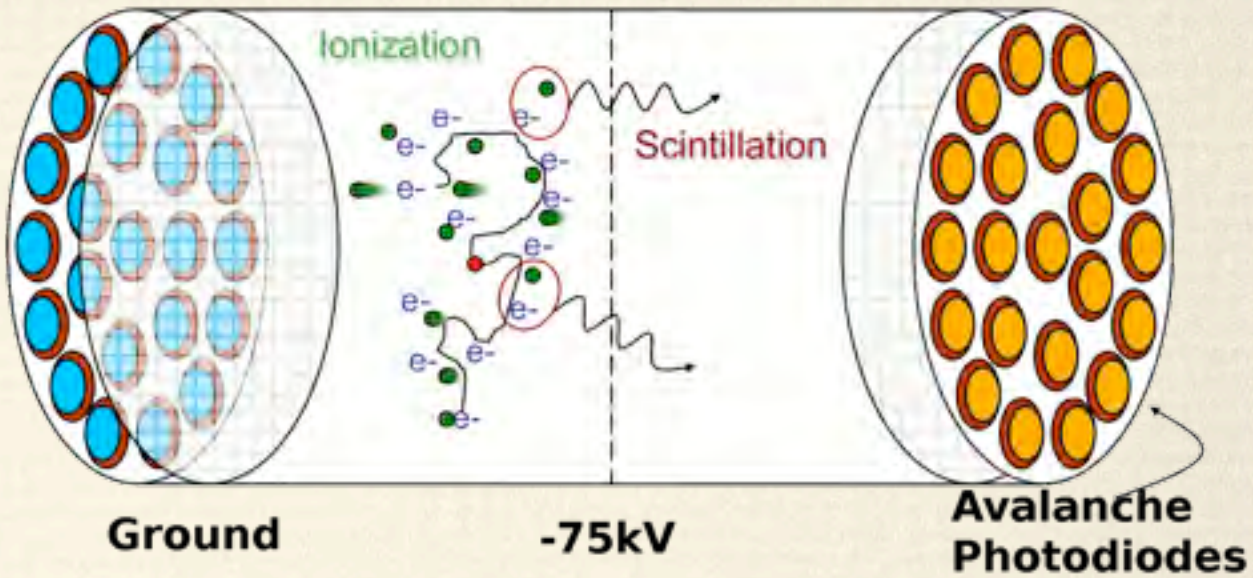
5-year sensitivity
Assumes 5keV FWHM resolution

First tower assembled in prototype (Cuoricino) cryostat
Taking data now (CUORE-0)
Will operate until start of CUORE



EXO-200

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



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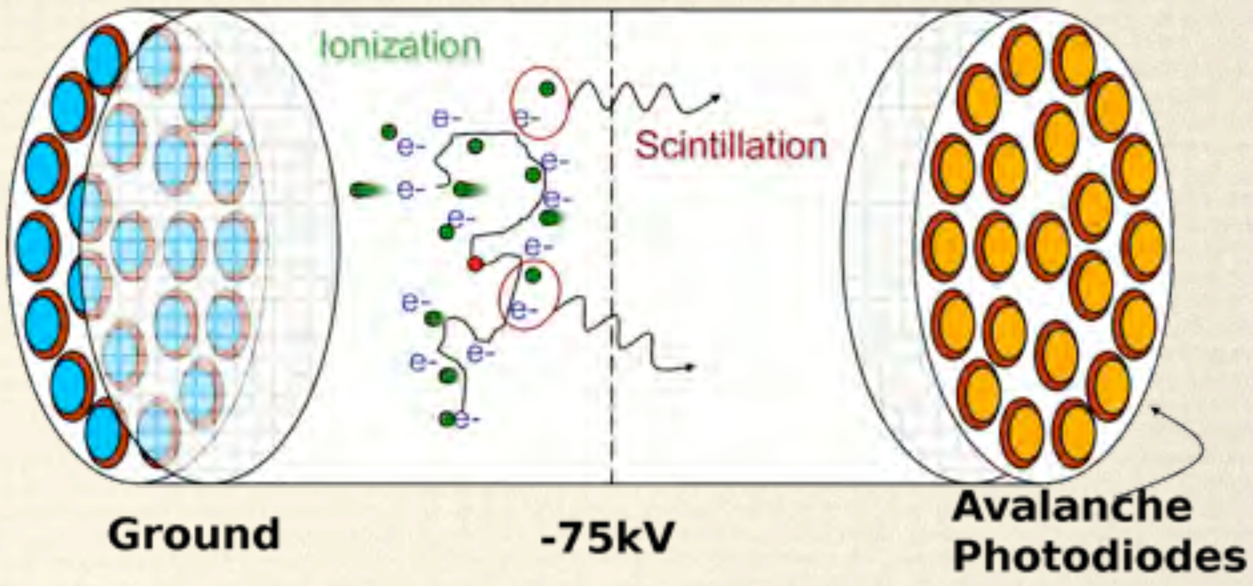
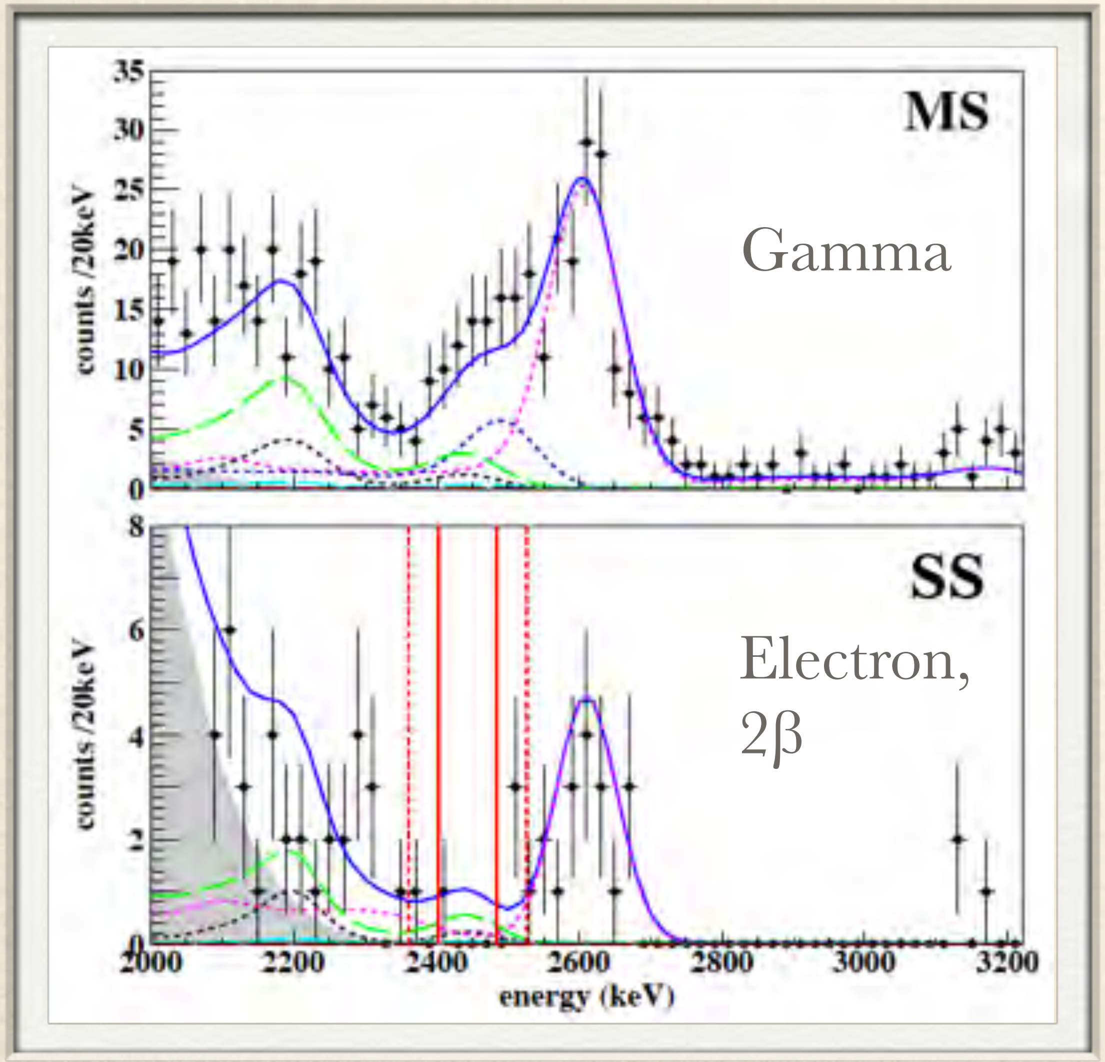




- Phase I: 120.69 days (32.5 kg-yr)

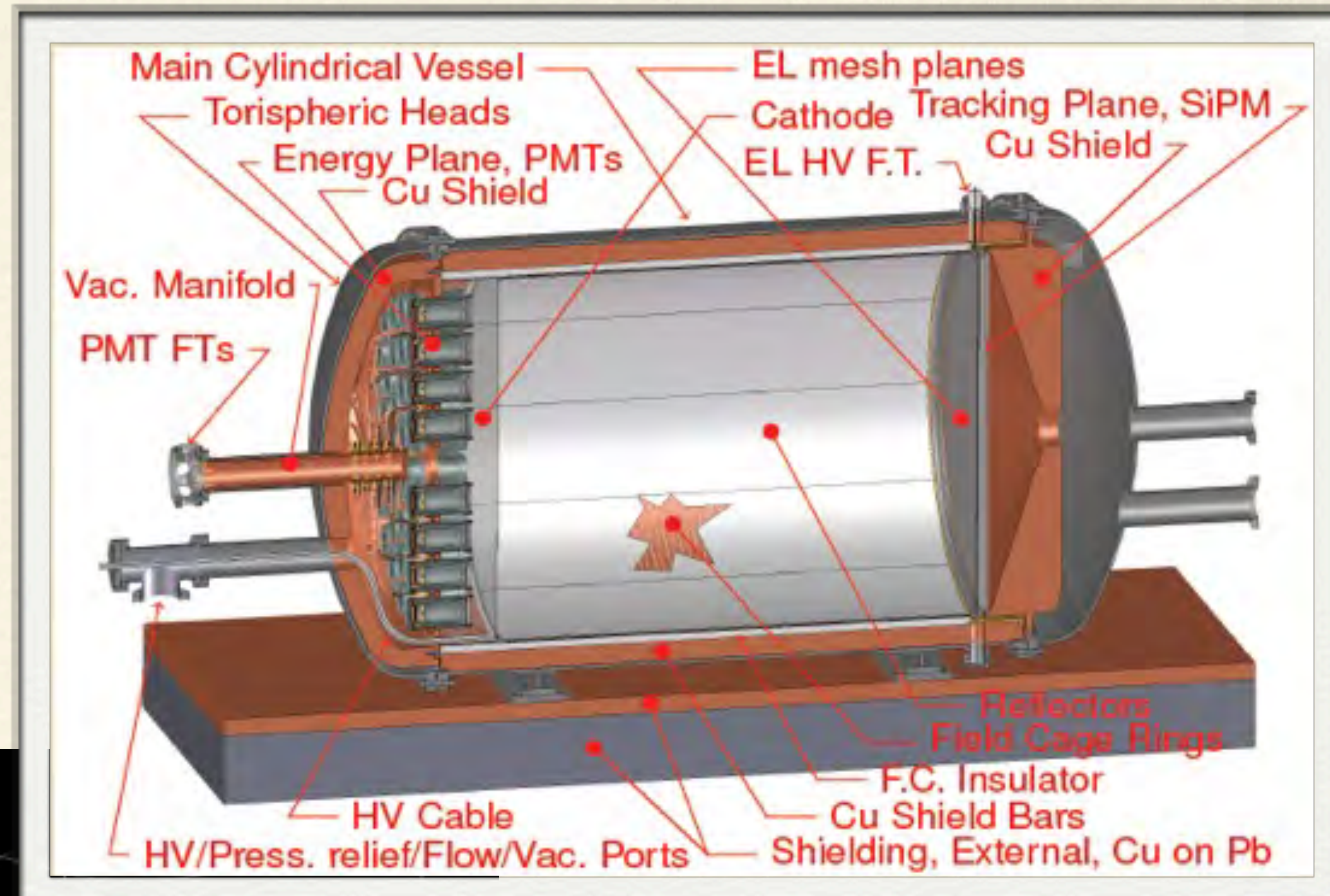
$$T_{\frac{1}{2}}^{0\nu\beta\beta}\left(^{136}\mathrm{Xe}\right) > 1.6 \times 10^{25}\,\mathrm{yr}$$

$$< m_{\beta\beta} > \; < [140, 380]\mathrm{meV}$$

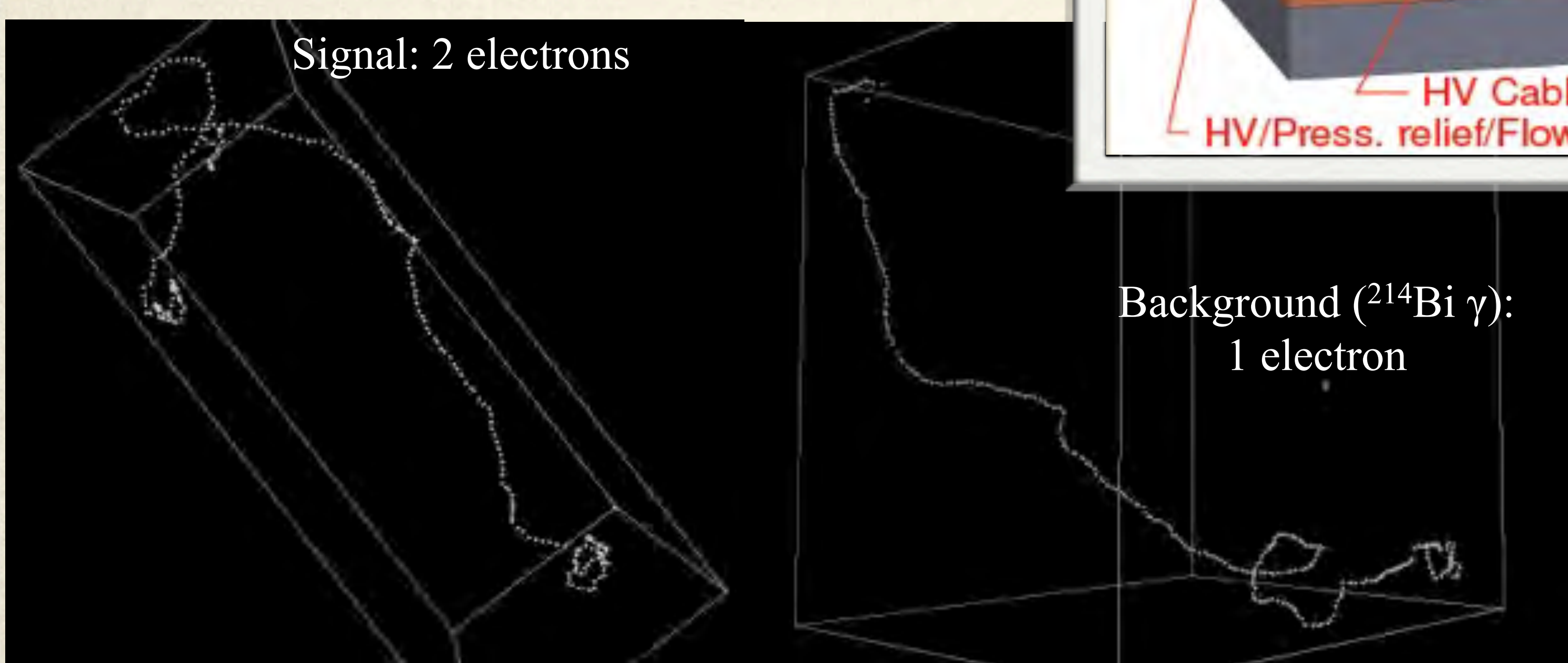
PRL 109 032505 (2012)

NEXT

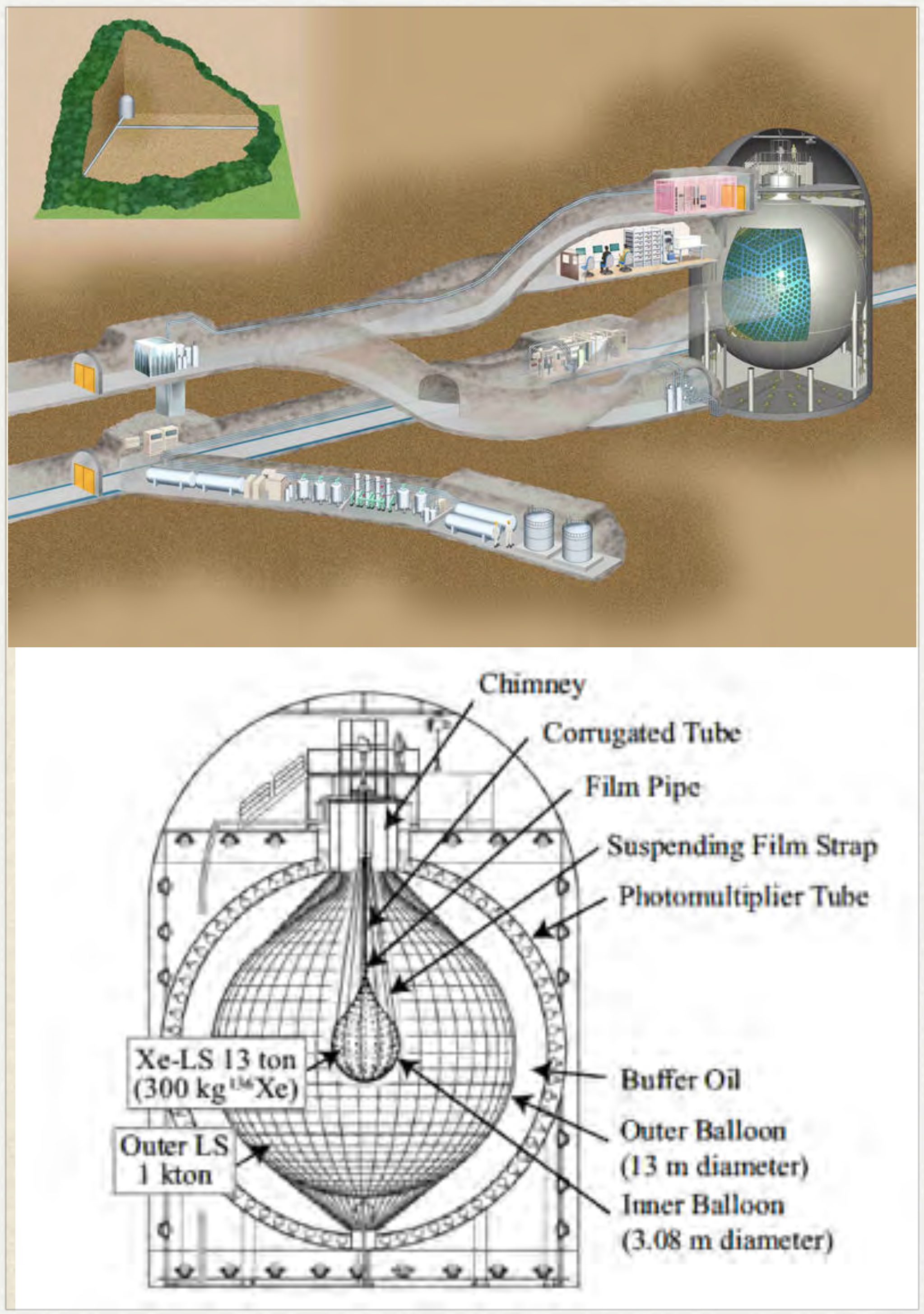
- Gaseous TPC: tracking
- 1% energy resolution
- Prototype for 100kg-scale in operation at LBNL



NEXT-100



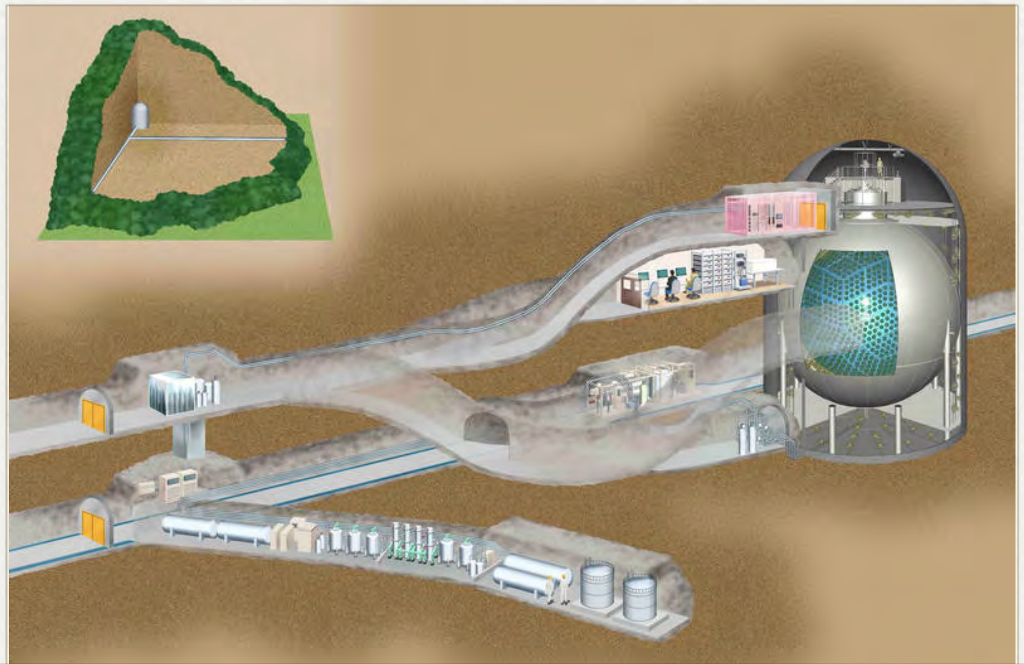
KamLAND-Zen



- Large-scale LS, LXe enriched to 91%
- 179kg, 112.3 days + 125kg, 101.1 days

PRL 110.062502 (2013)

KamLAND-Zen



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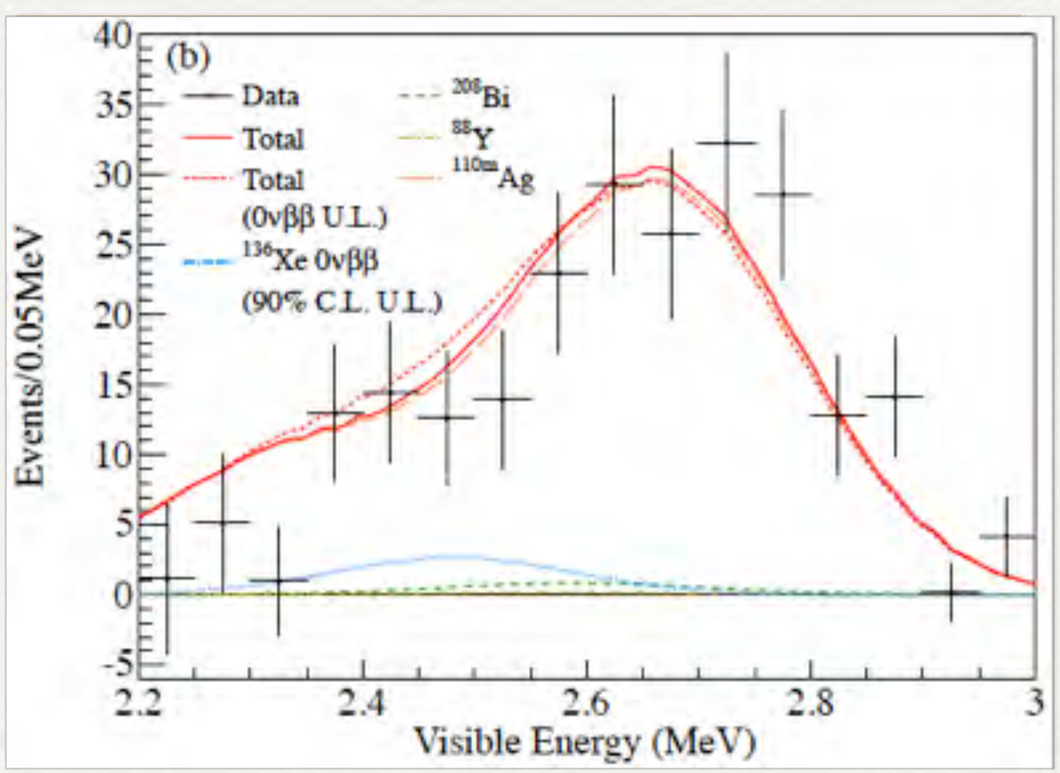
$$T_{\frac{1}{2}}^{0\nu\beta\beta}\left({}^{136}\mathrm{Xe}\right) > 1.9\times10^{25}\,\mathrm{yr}$$

NME:

KLZ $< m_{\beta\beta} > \; < [161, 334]\mathrm{meV}$

EXO-200 $< m_{\beta\beta} > \; < [128, 349]\mathrm{meV}$



PRL 110.062502 (2013)

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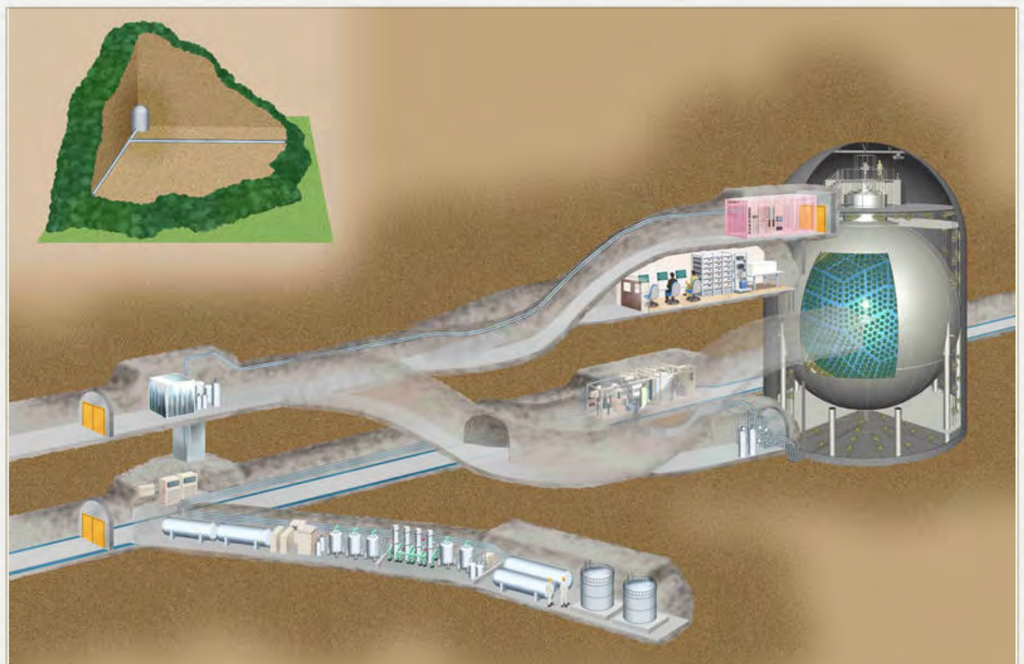

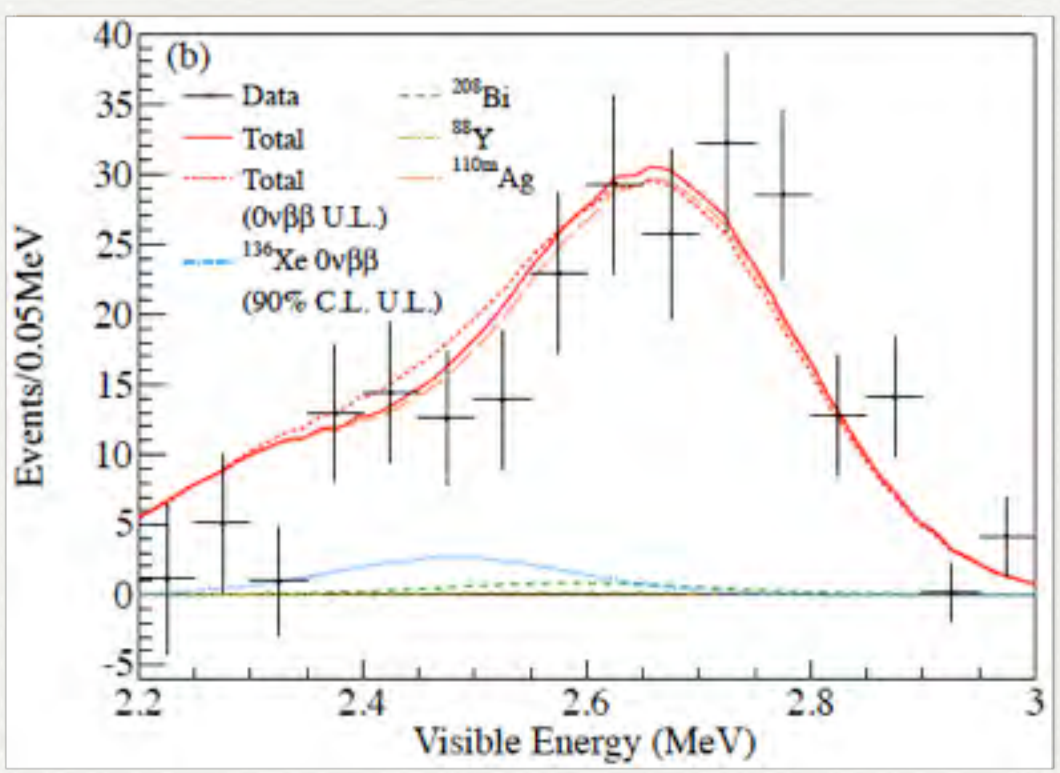

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KLZ $< m_{\beta\beta} > \; < [161, 334]\mathrm{meV}$

EXO-200 $< m_{\beta\beta} > \; < [128, 349]\mathrm{meV}$

KLZ + EXO-200

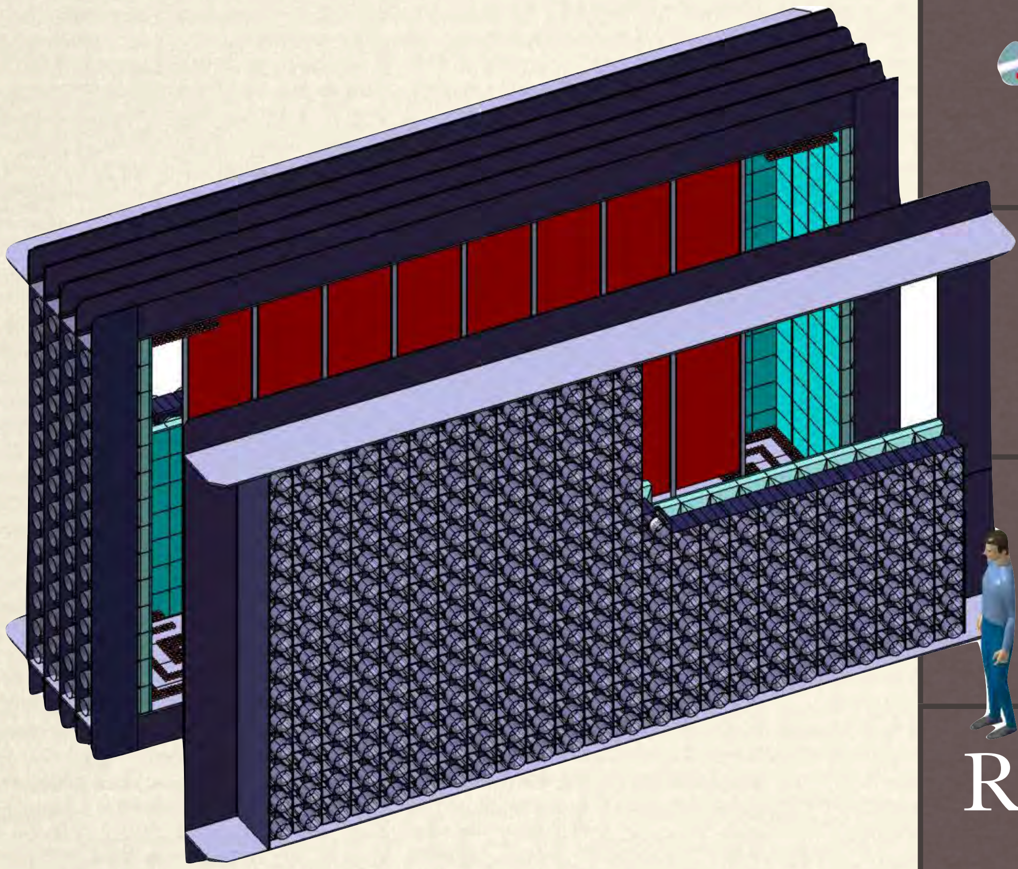
$$T^{0\nu\beta\beta}_{\frac{1}{2}}\left({}^{136}\mathrm{Xe}\right) > 3.4\times 10^{25}\,\mathrm{yr}$$

$$< m_{\beta\beta} > \; < [120, 250]\mathrm{meV}$$

$$< m_{\beta\beta} > \; < [96, 261]\mathrm{meV}$$

PRL 110.062502 (2013)

SuperNEMO

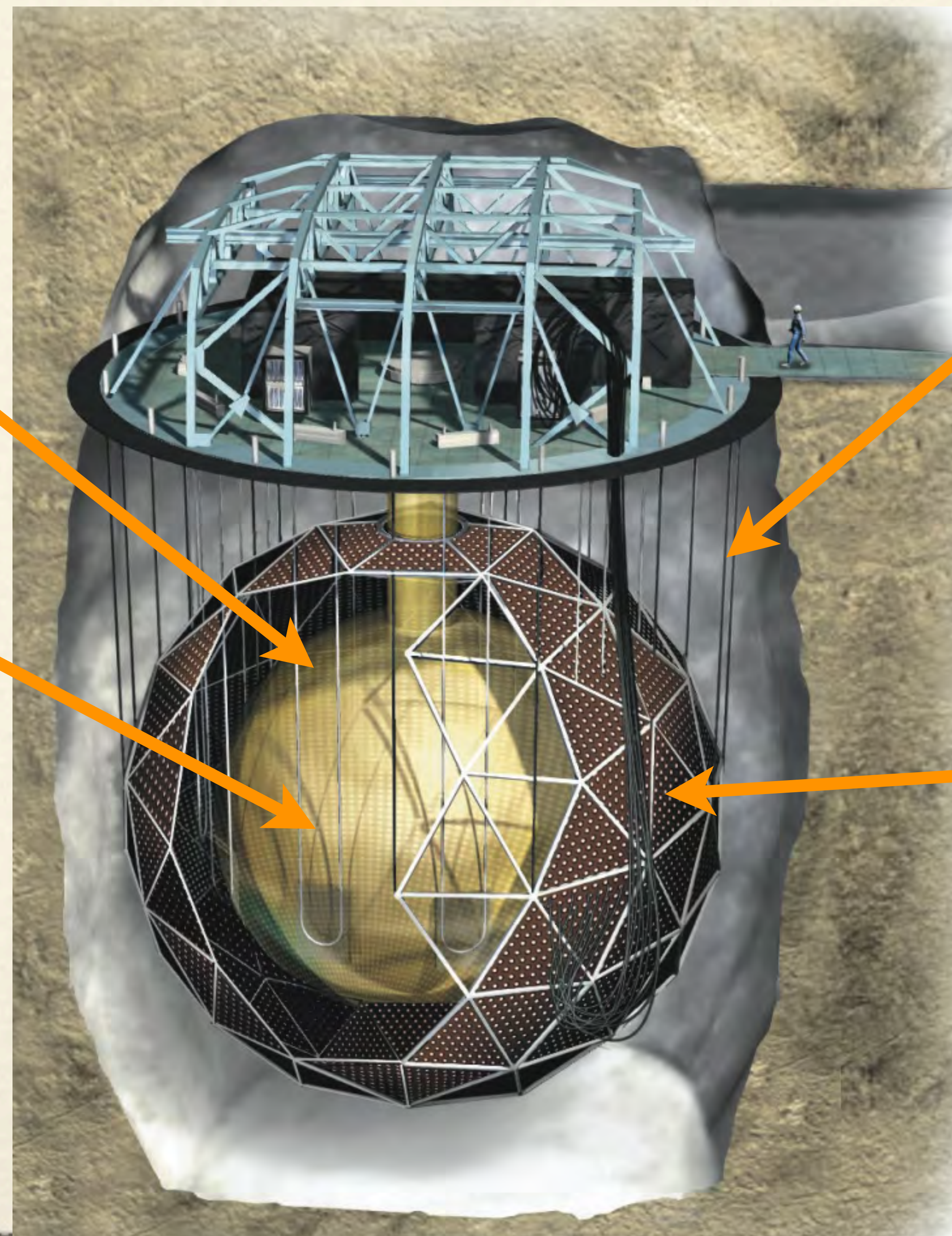


	NEMO-3	SuperNEMO
Isotope	100Mo	82Se, 100Mo
Mass	7kg	100-200kg
Resolution (3MeV)	8% (FWHM)	4% (FWHM)
Efficiency ($0\nu\beta\beta$)	18%	~30%
Sensitivity	> 2×10^{24} yr < 0.3-1.0 eV	> 1-2 x 10^{26} yr < 40-140 meV

20 modules
Event topology
⇒ model testing
Demonstrator ~2014

SNO

- 12m acrylic vessel
- 1kT D_2O
- 6800ft level
- 5890 m.w.e.



- 1.7kT + 5.3kT H_2O buffer
- 9500 PMTs, 60% coverage

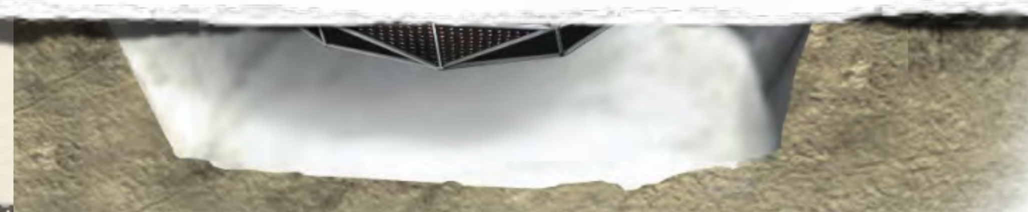
SNO

- 1…
  a…
  v… …fer
- 1…
  …Ts,
  …erage
- 6…
- 5890 m.w.e.

CLASSIFIEDS

AVAILABLE

Basement space! Six million cubic ft., large deck, showers. Laundry facilities and a/c. Just 10 min. walk to elevator access. V. low radon, shielding from dangerous `cosmic' radiation.

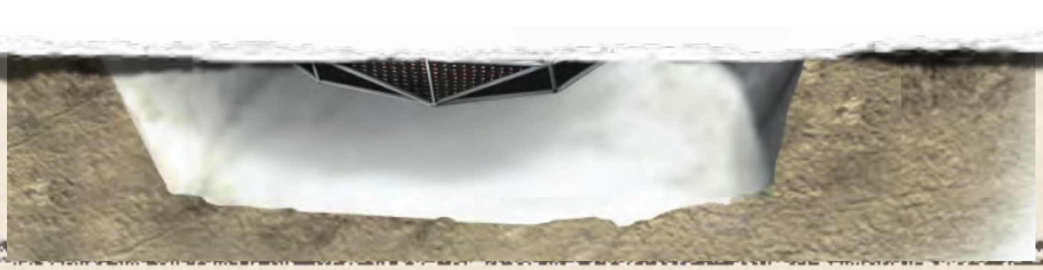


SNO ⇛ SNO+

Re-use SNO detector
Replace D_2O with liquid scintillator
+ minor upgrades

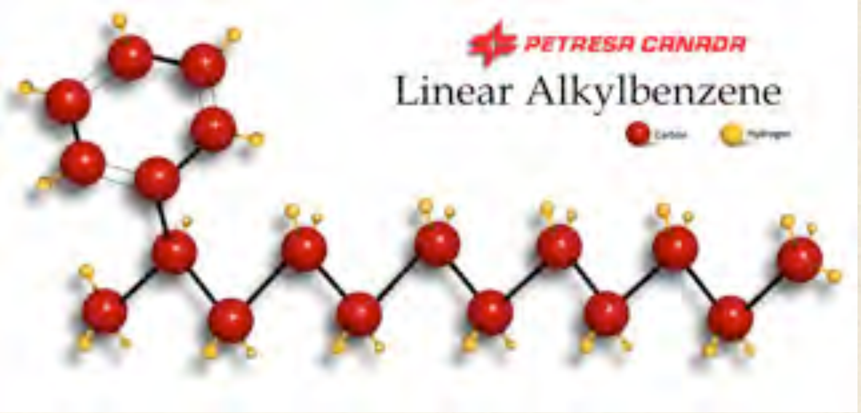
Basement space! Six million cubic ft., large deck, showers. Laundry facilities and a/c. Just 10 min. walk to elevator access. V. low radon, shielding from dangerous `cosmic' radiation.

- 5890 m.w.e.

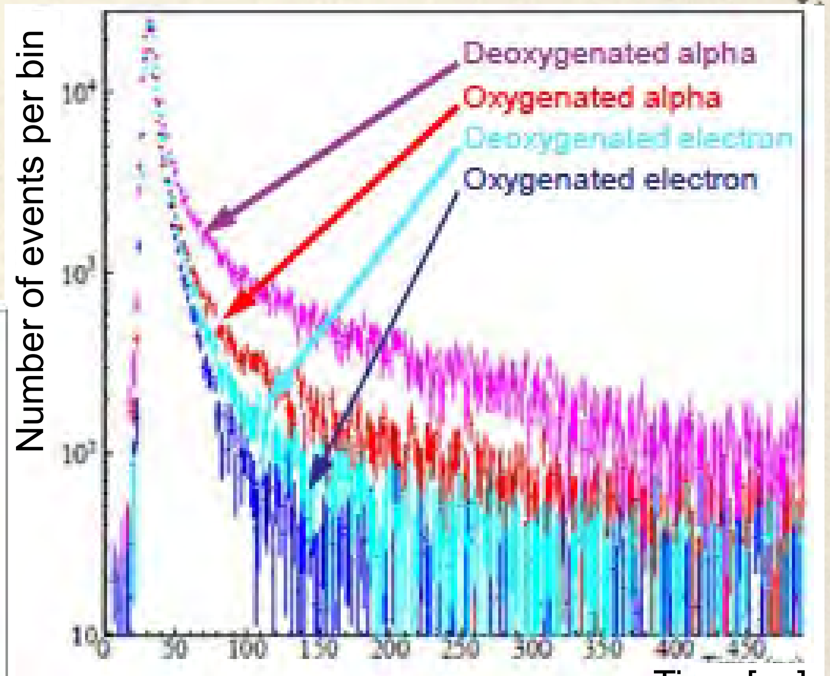


Scintillator Development

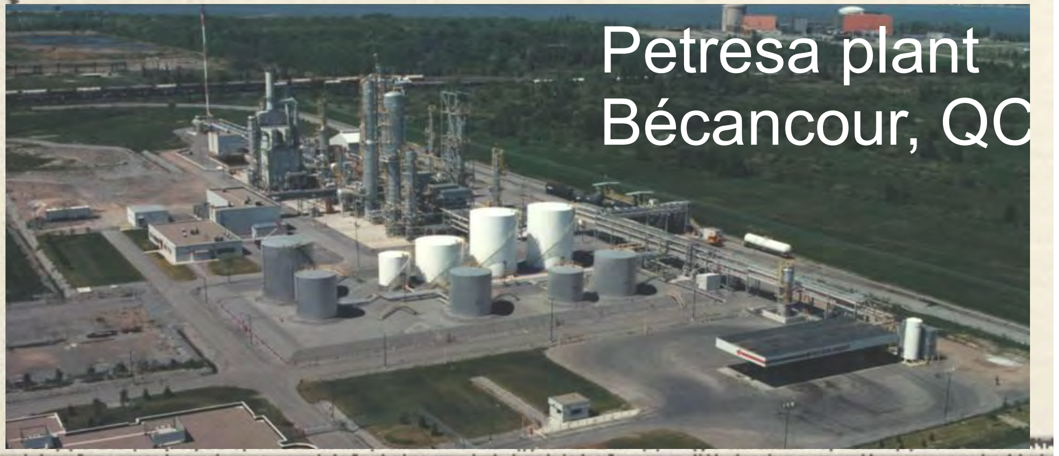
- In use in reactor & other experiments
- Chemically compatible with acrylic
- High flash point, low toxicity
- Readily available (used in detergent production)
- Loading of metallic ions to few %, stable for 3+ yrs
- High light yield (10,000 γ / MeV)
- Decay times: α-β separation

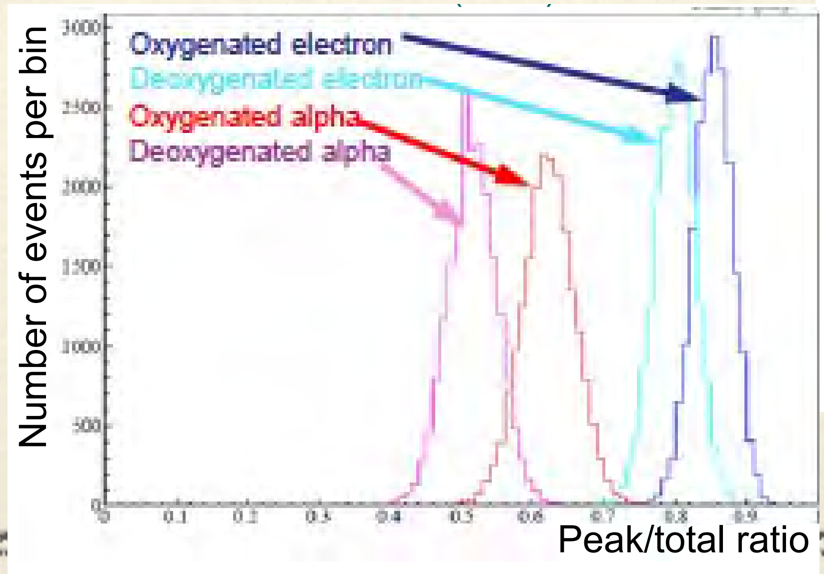


NIM A 578 (2007) 329-339

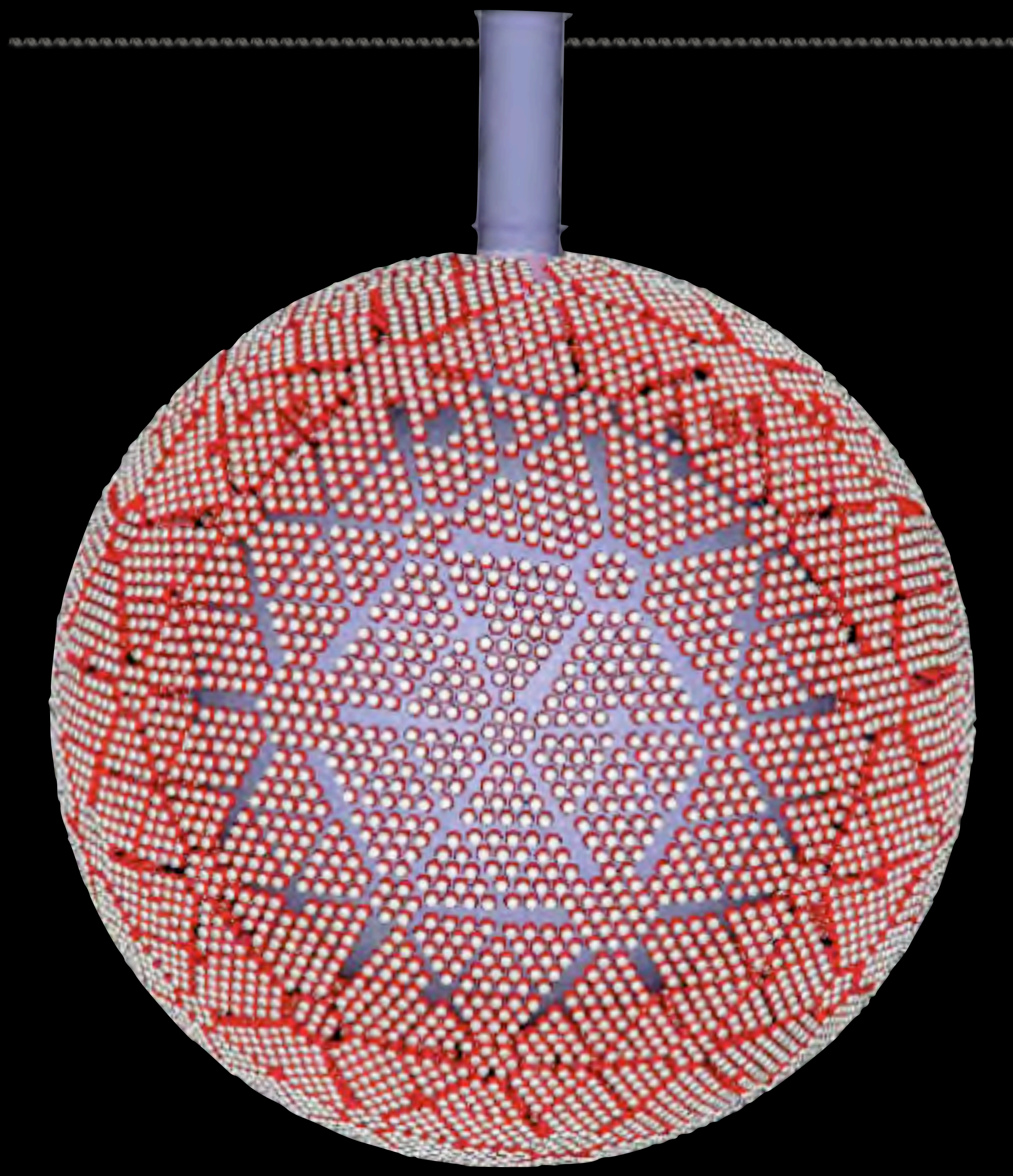


NIM **A640**, 119-122 (2011)





World's Largest Spherical Lens?



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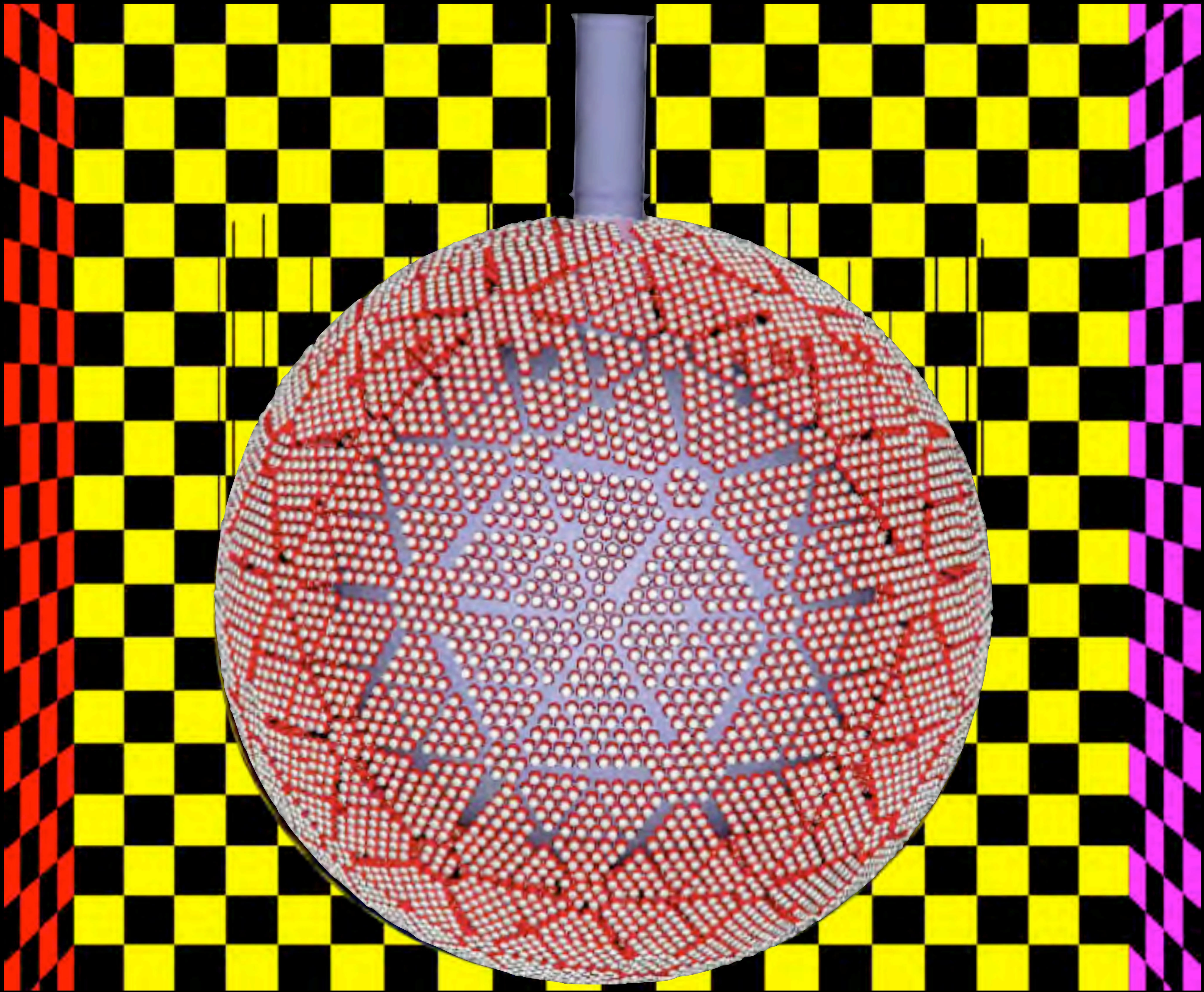

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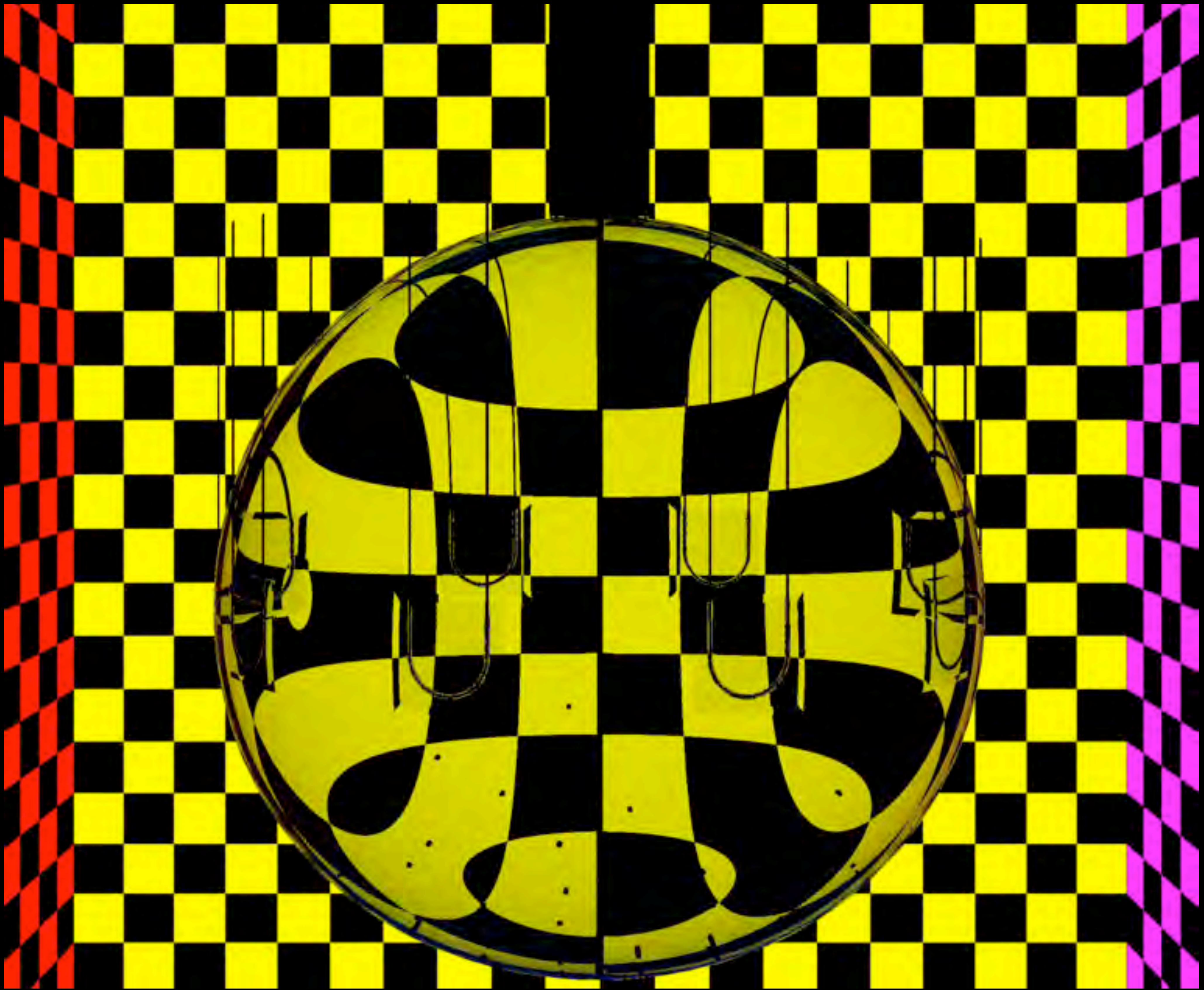
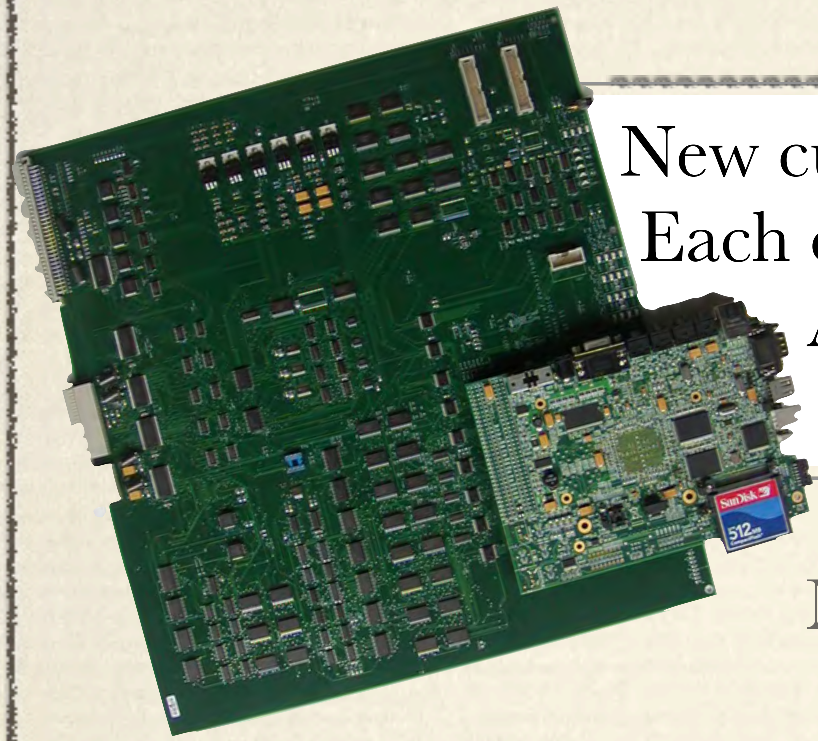


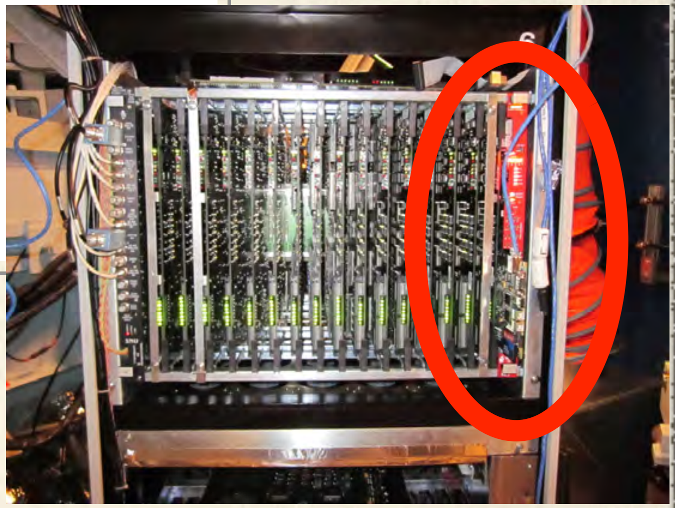
Electronics & DAQ



New custom crate-readout cards in each crate

Each crate now has **local** intelligence

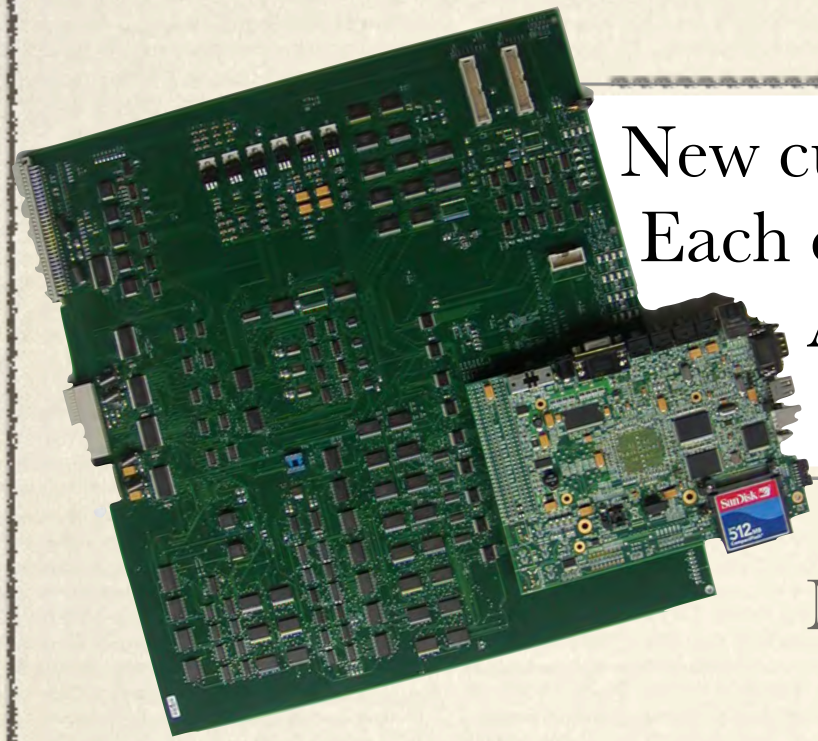
Autonomously push data to central switch via TCP/IP



Max data rate for SNO: 2.4MBits/s

SNO+: **250** MBits/s

Electronics & DAQ



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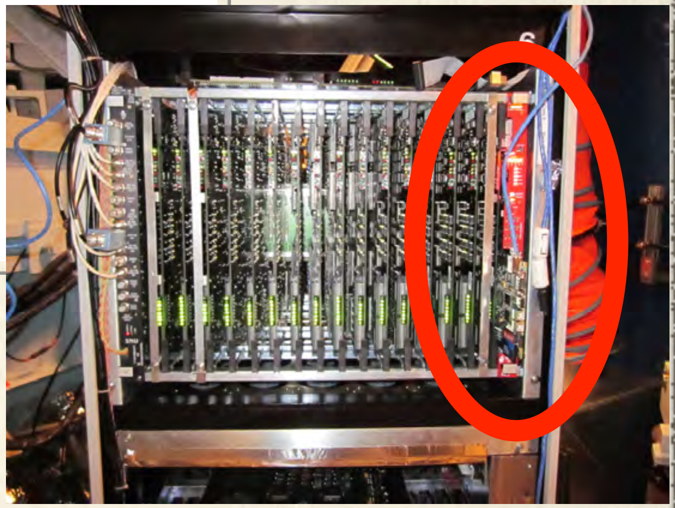

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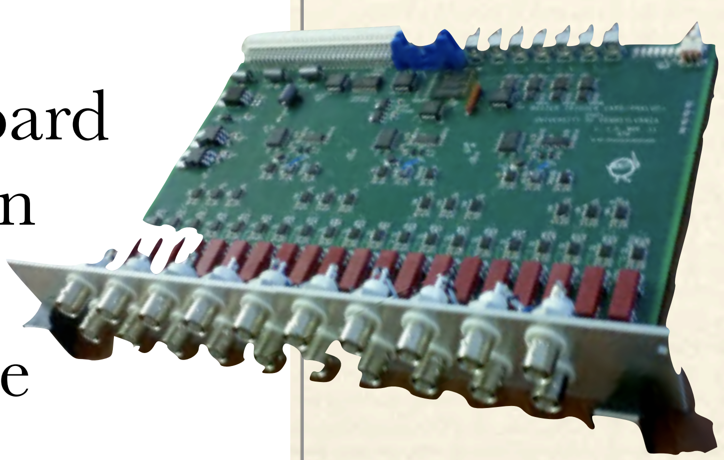
SNO+: **250** MBits/s

High rate/occupancy

=> need new trigger board

- Low power dissipation
- Reduce deadtime
- Larger dynamic range
- + Auto retrigger
- + Remote crate disconnects



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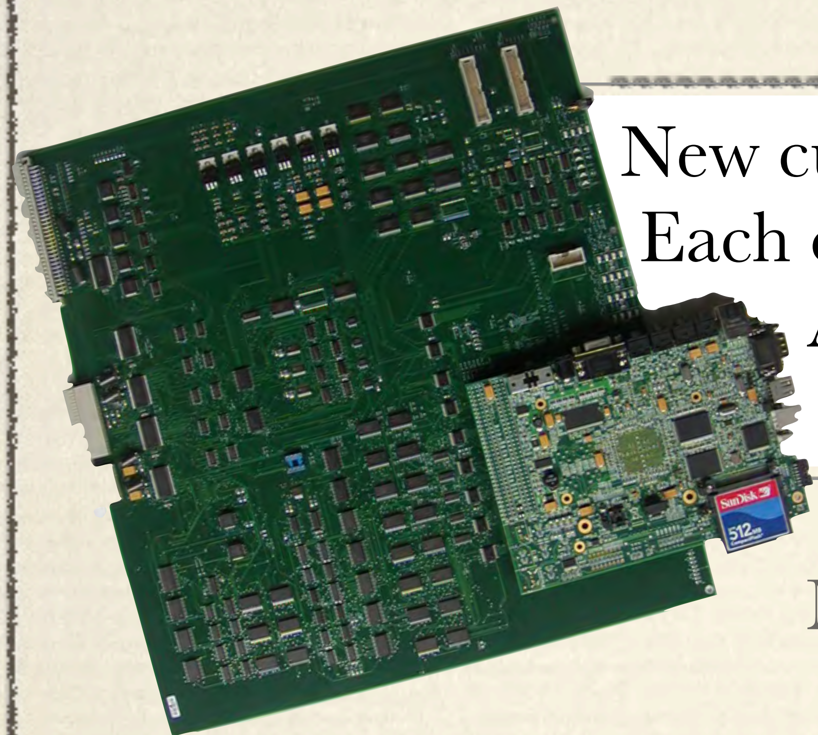

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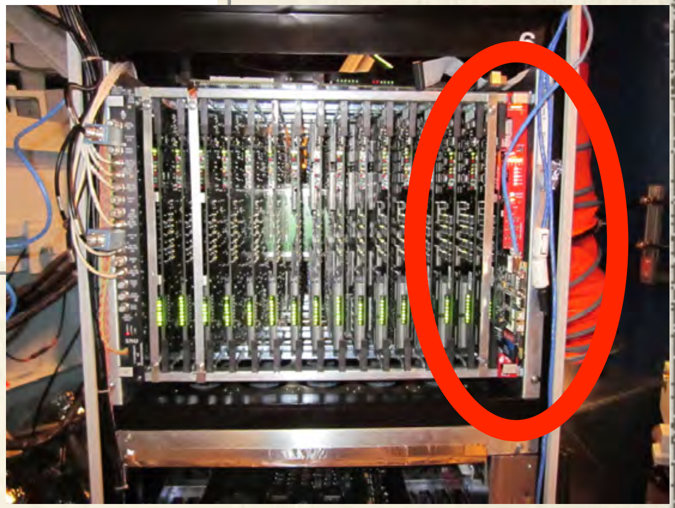

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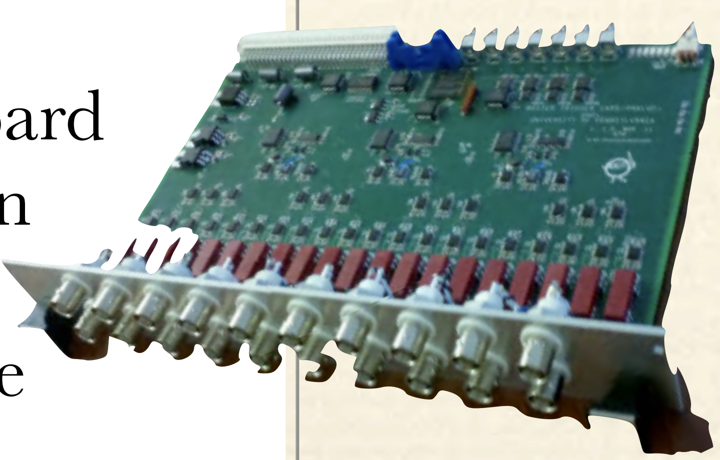
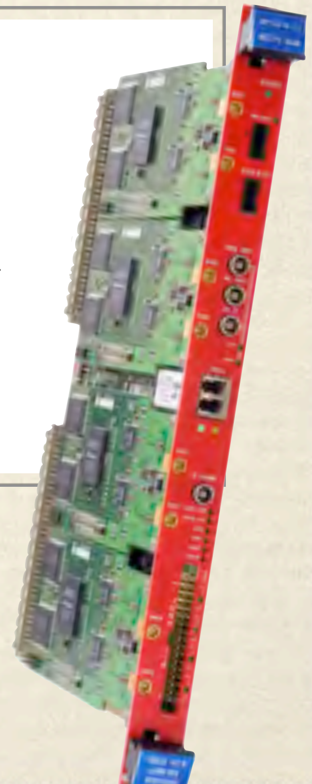


Plus:

New interface board

CAEN digitizer board

New GPS receiver



SNO+

A Diverse Instrument for Neutrino Research within the SNOLAB Underground facility

New underground facility

Image from www.northernontariobusiness.com


6800 ft down...


SNOLAB
BOOT WASH STATION


SNOLAB


SNOLAB


SNOLAB



SNOLAB



JM



SNOLAB





SNOLAB


SNOLAB

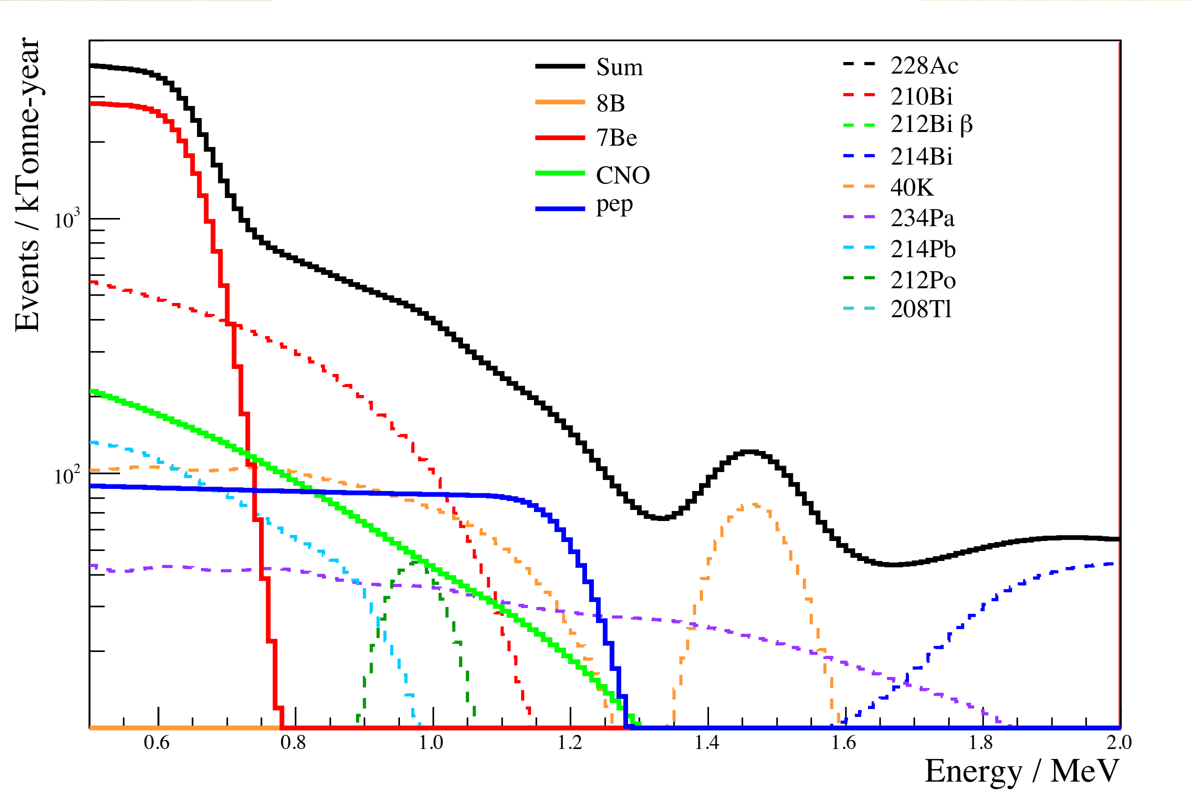

SNOLAB

Start of Clean conditions for the new SNOLAB: Feb. 2009


Start of Clean conditions for the new SNOLAB: Feb. 2009
Lunch
Room
Tim Hortons

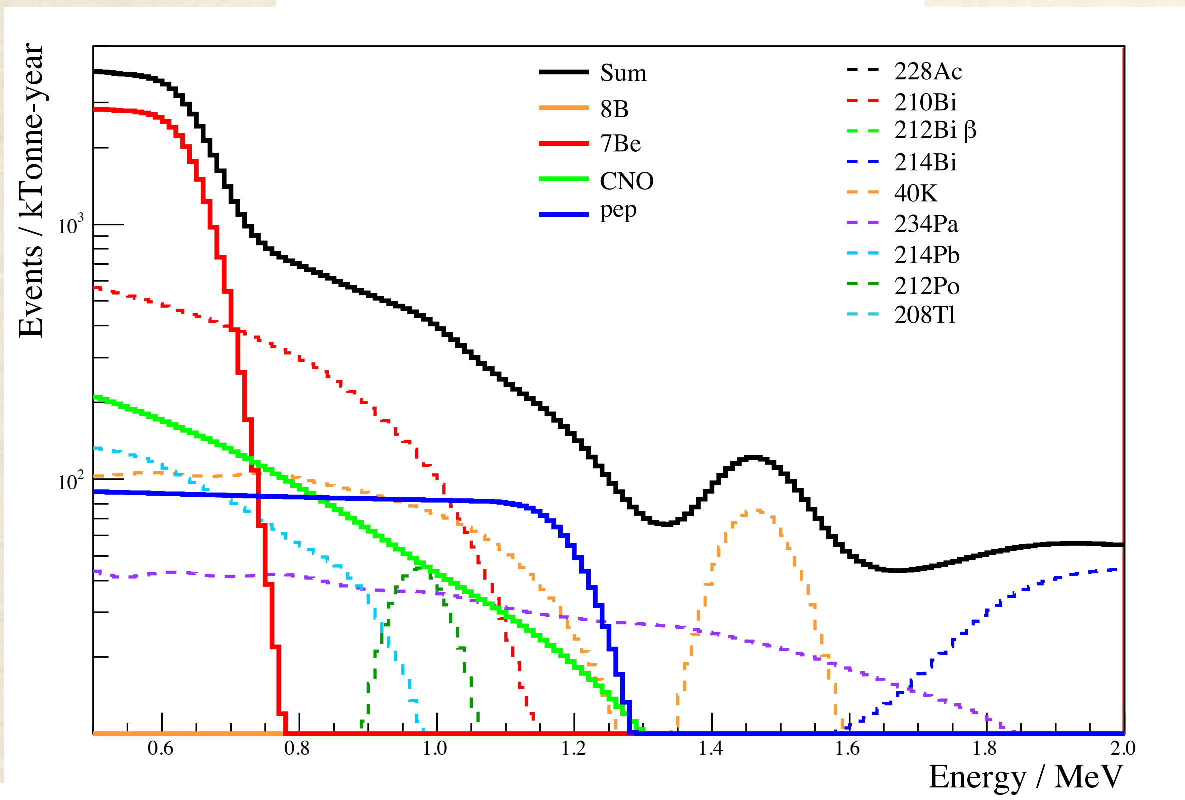
Multi-Faceted Physics Program

Solar neutrinos

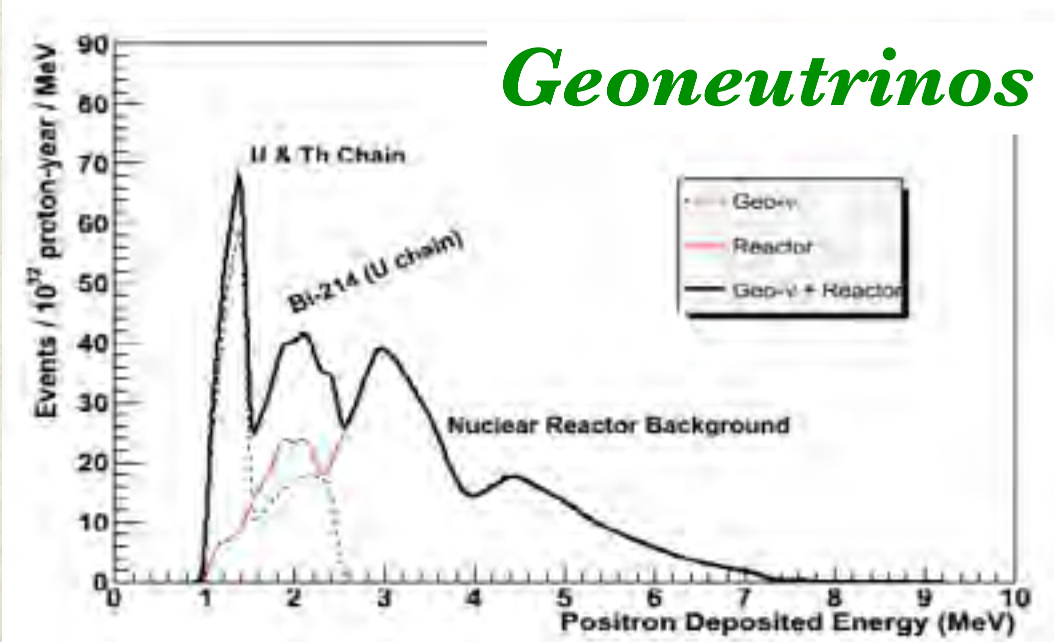


Multi-Faceted Physics Program

Solar neutrinos



Geoneutrinos



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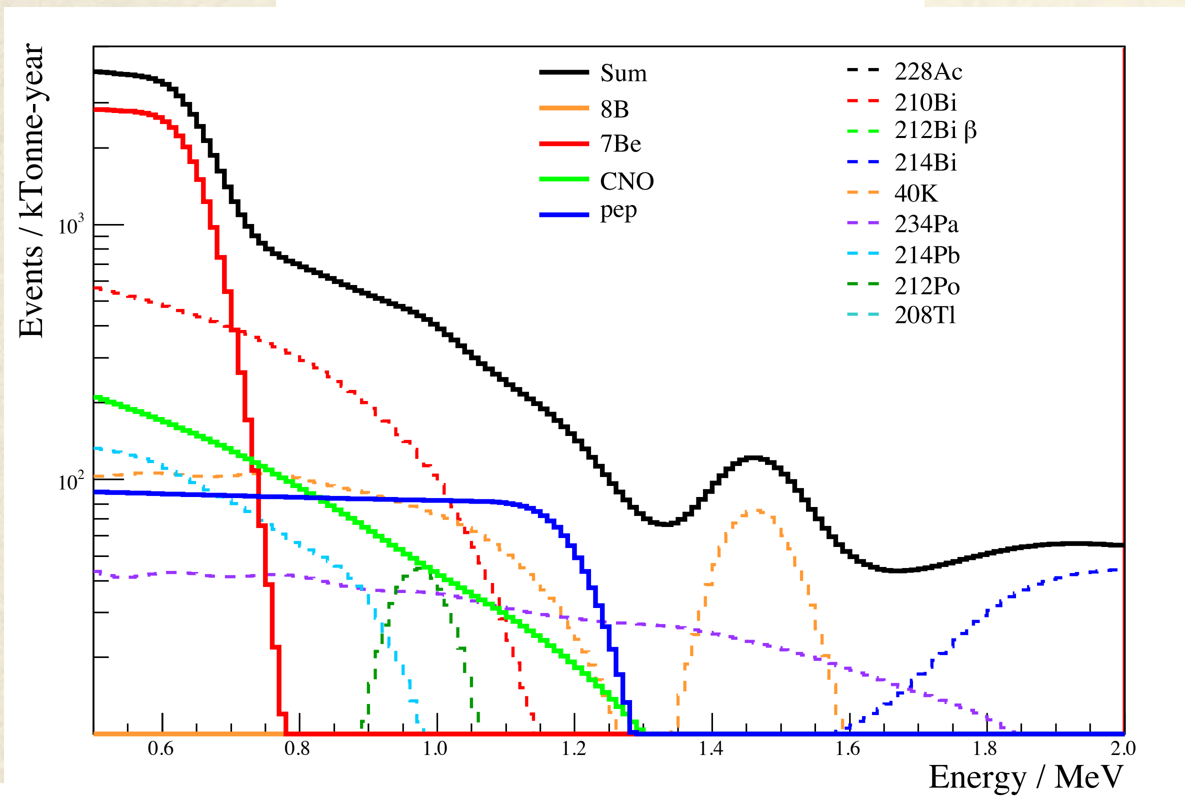
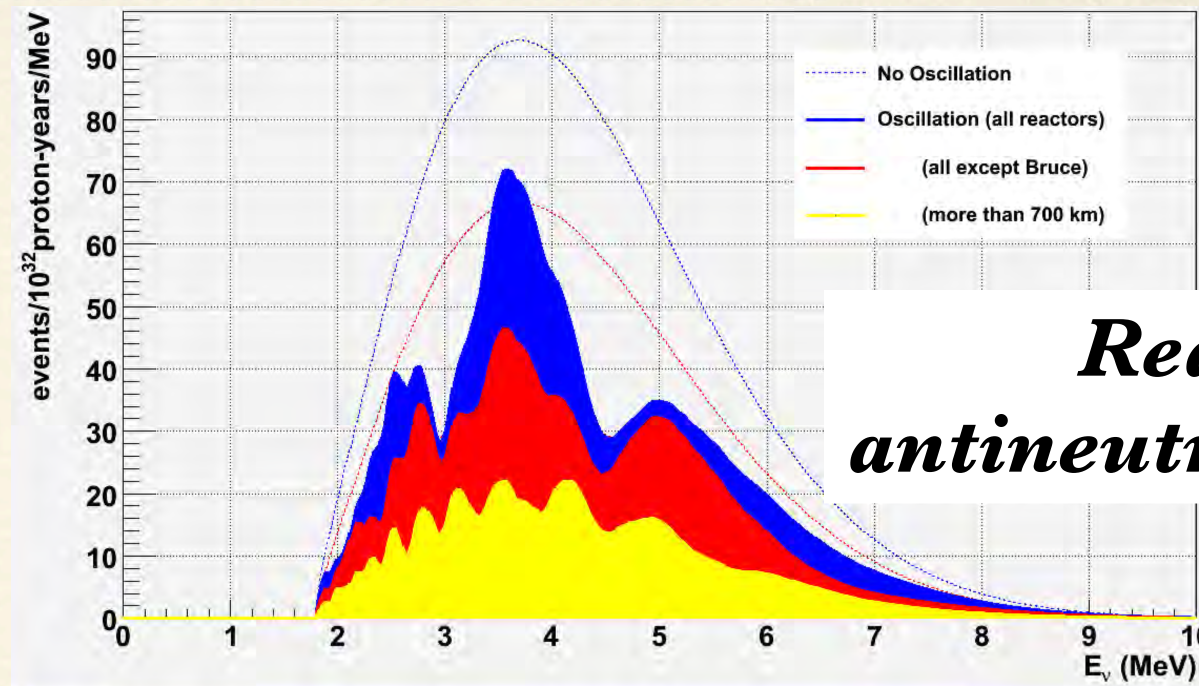


Reactor antineutrinos



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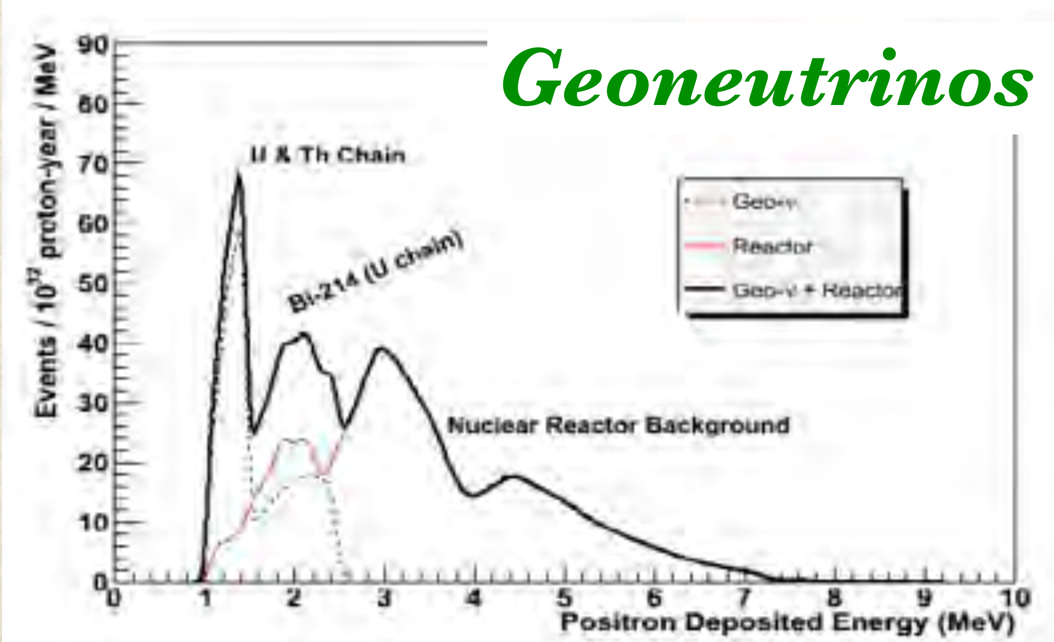
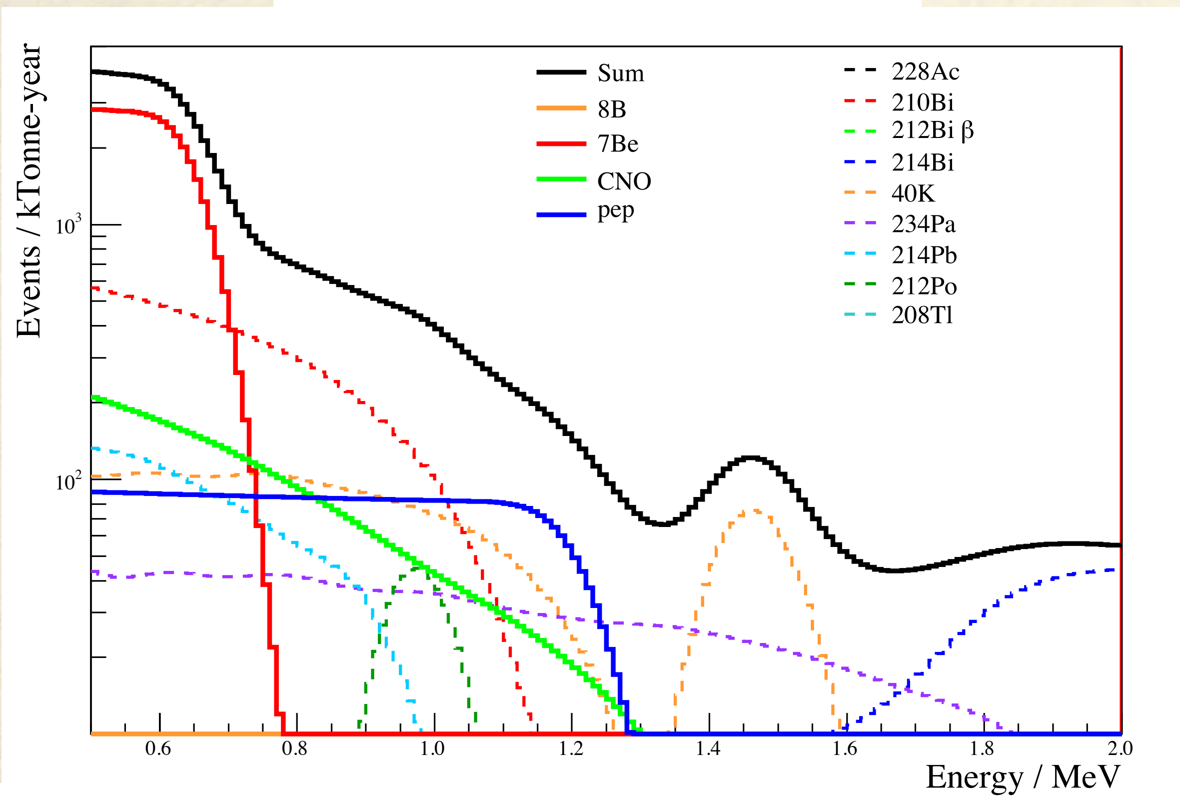
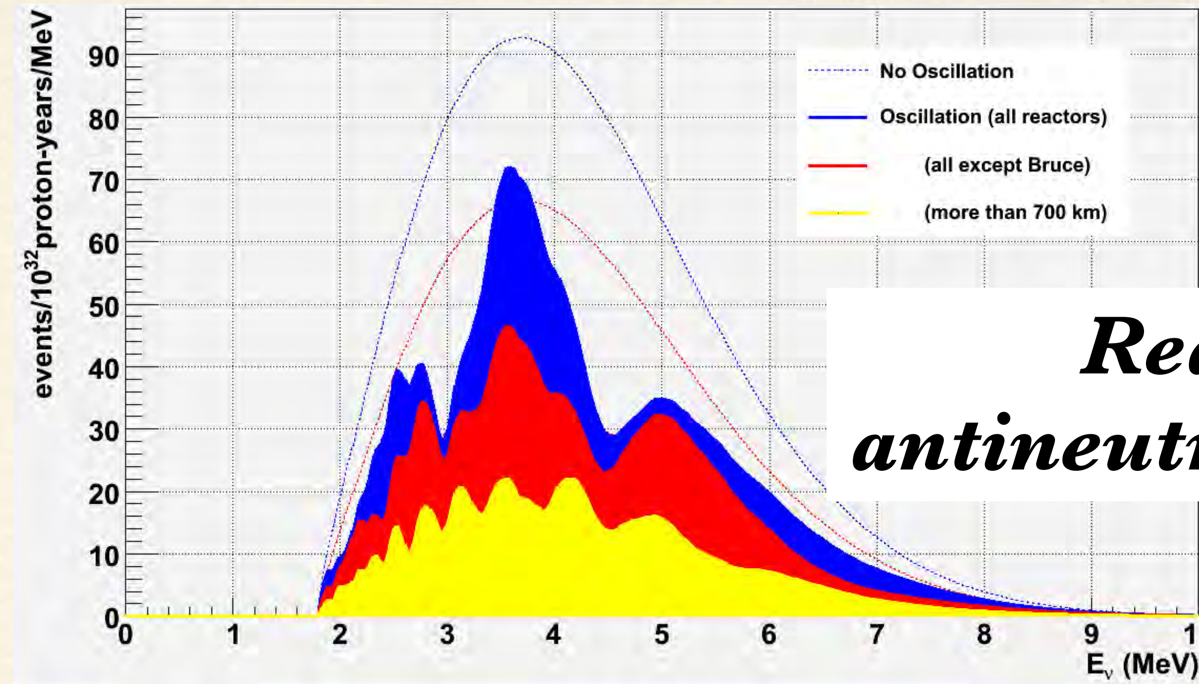


Multi-Faceted Physics Program

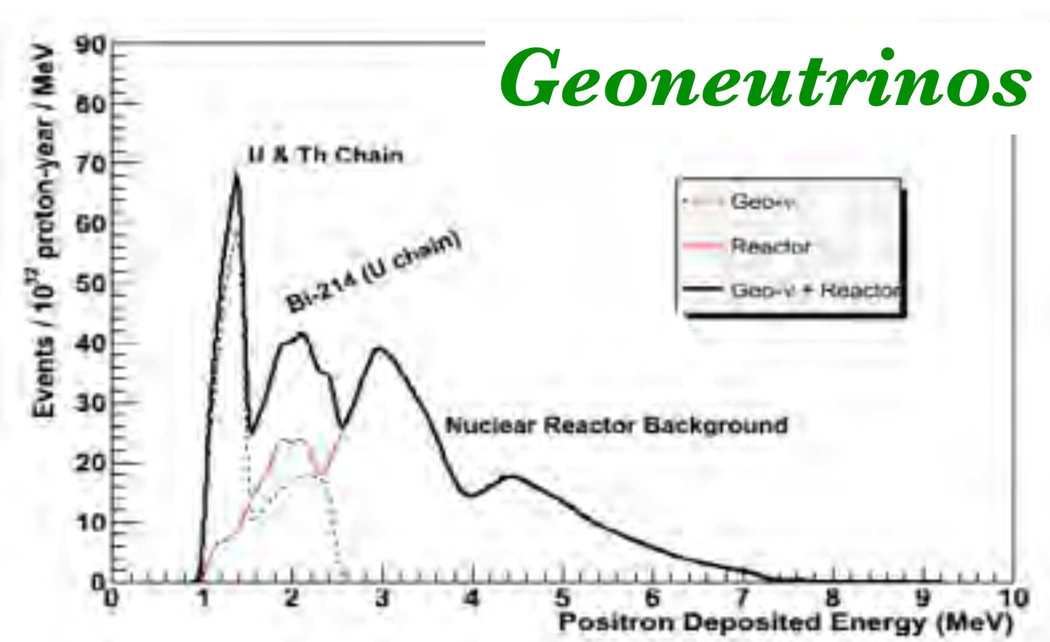
Solar neutrinos



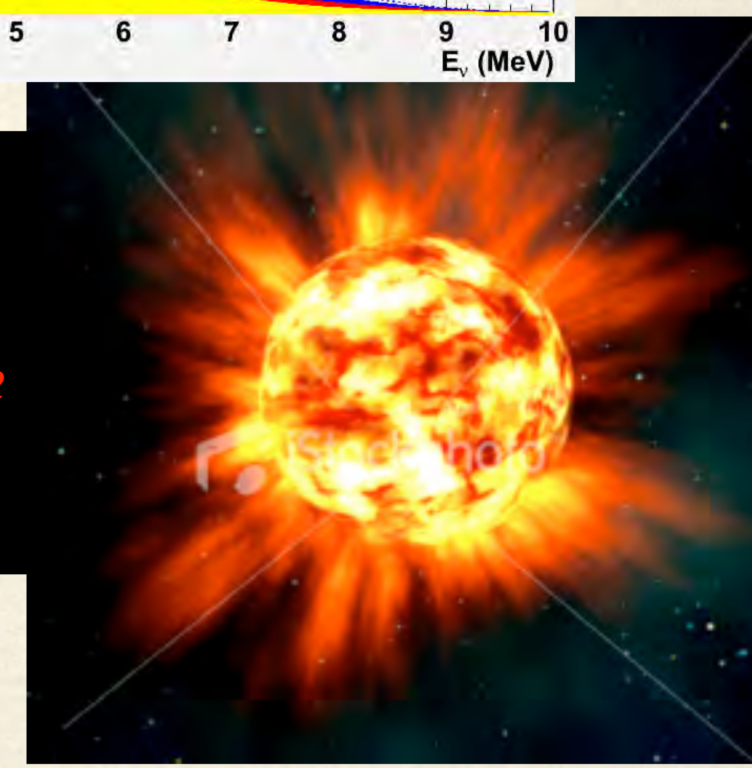


Reactor antineutrinos

Geoneutrinos

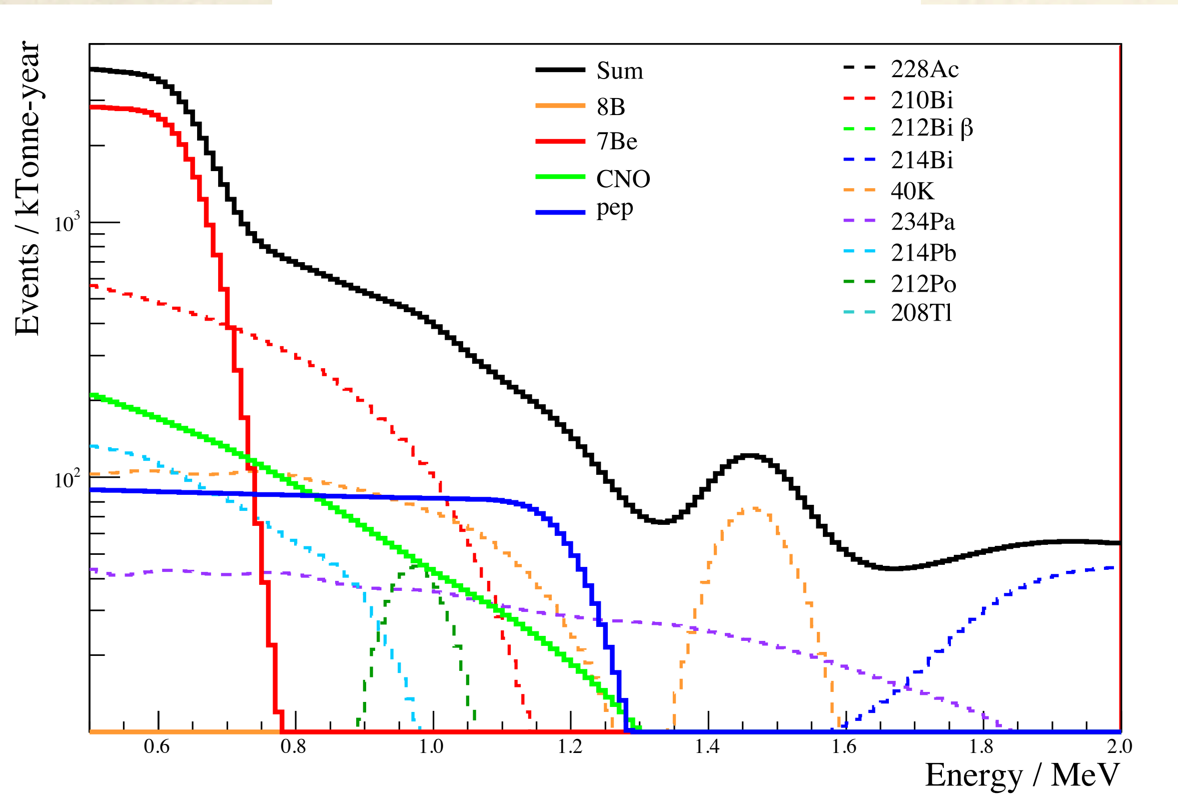


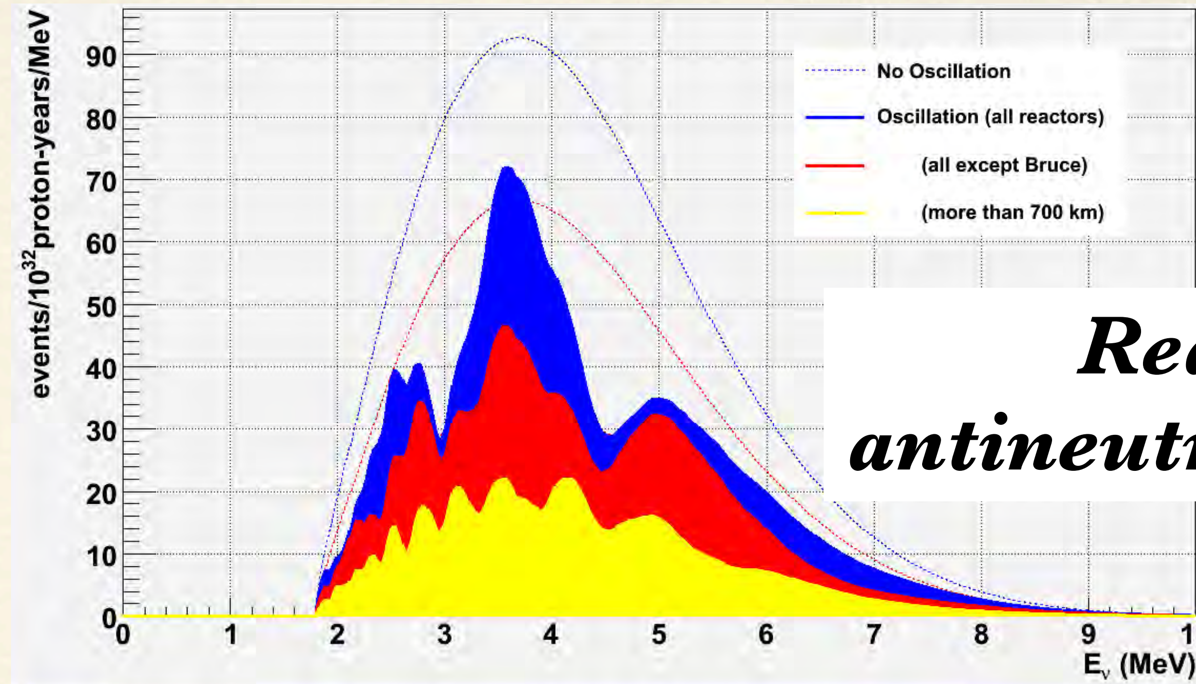
Neutrino probes of supernovae



Multi-Faceted Physics Program

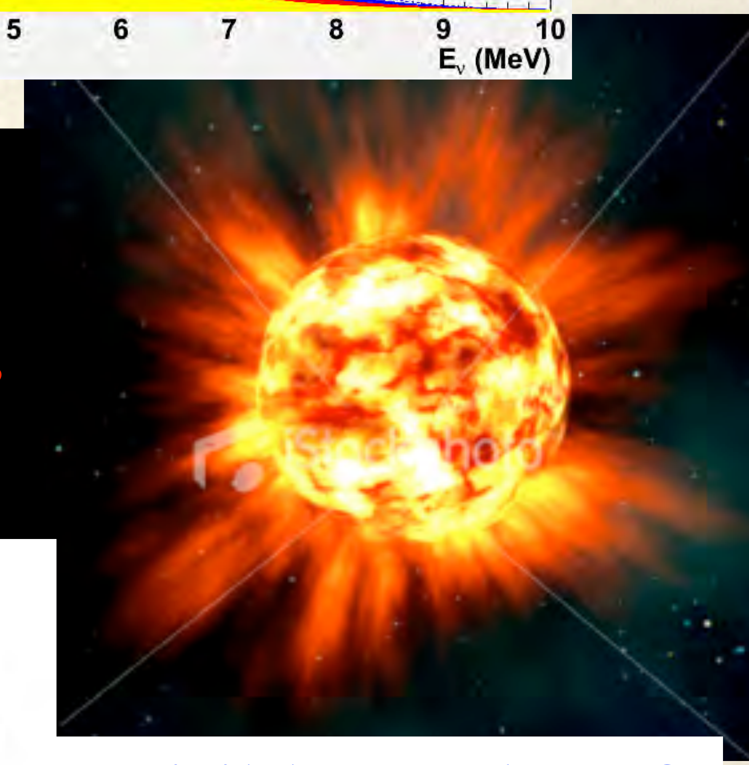
Solar neutrinos



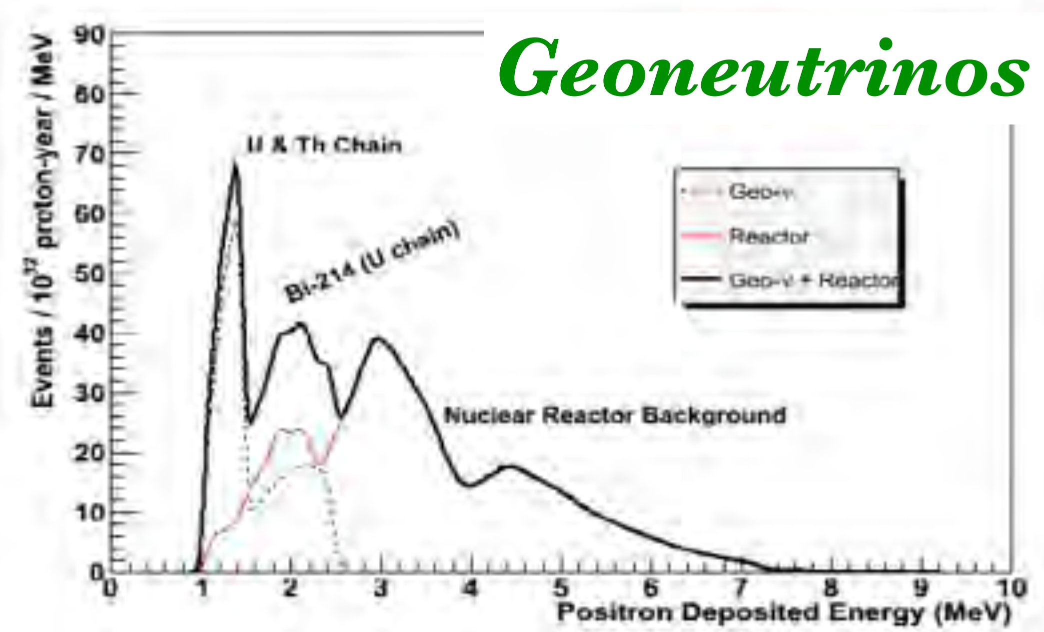


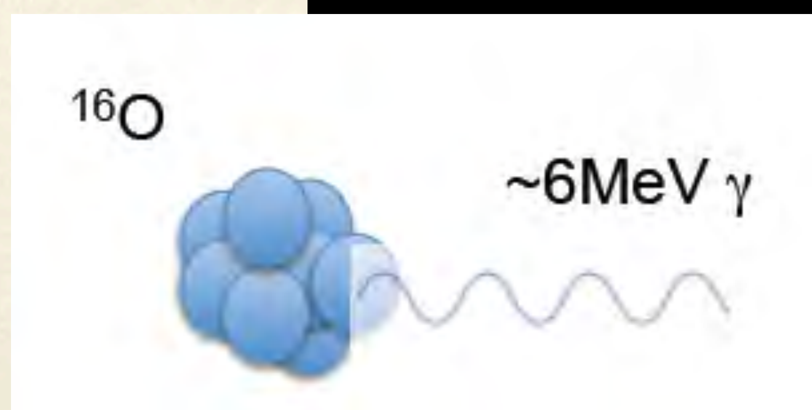
Reactor antineutrinos

Neutrino probes of supernovae



Geoneutrinos



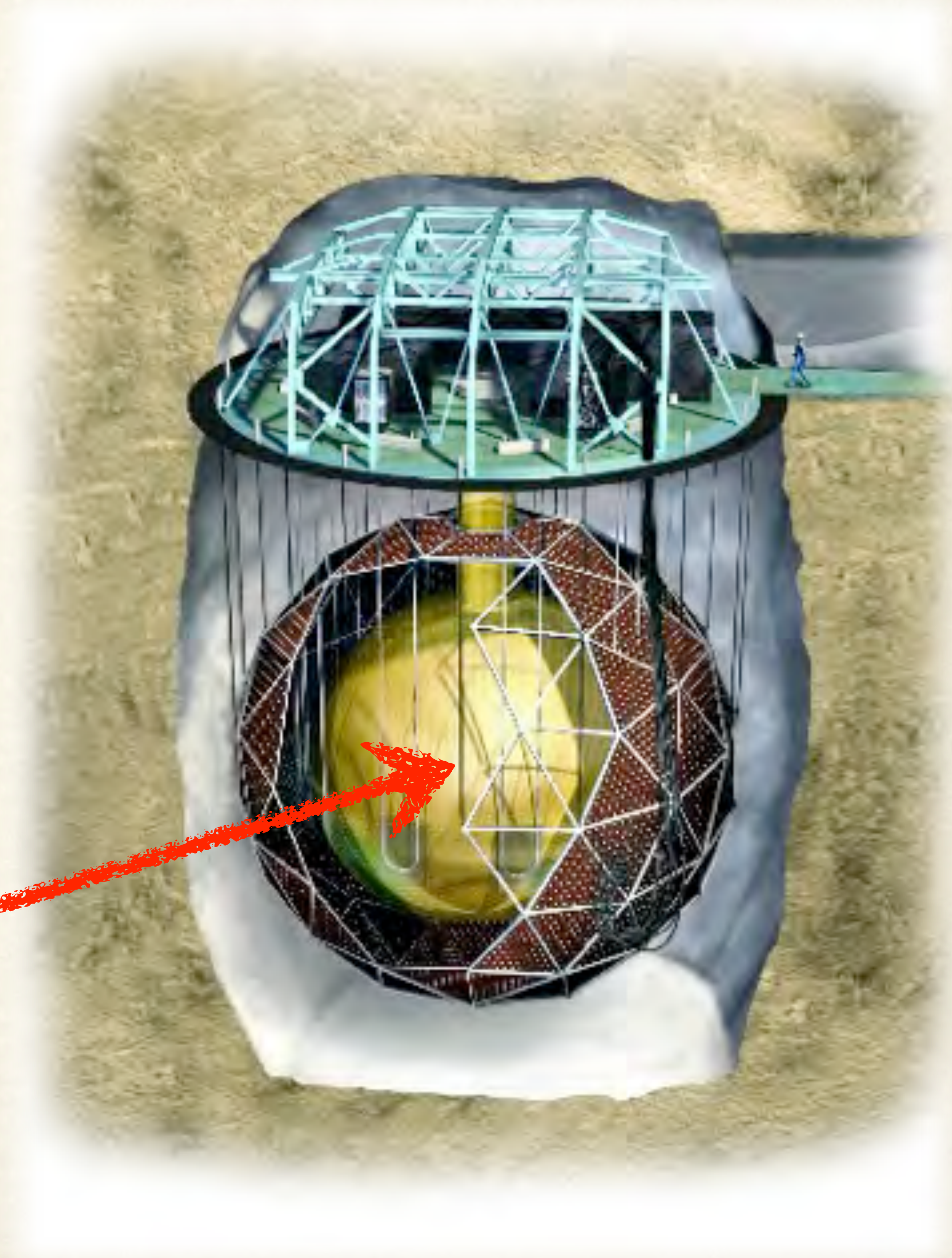


Invisible modes of nucleon decay

0νββ with SNO+

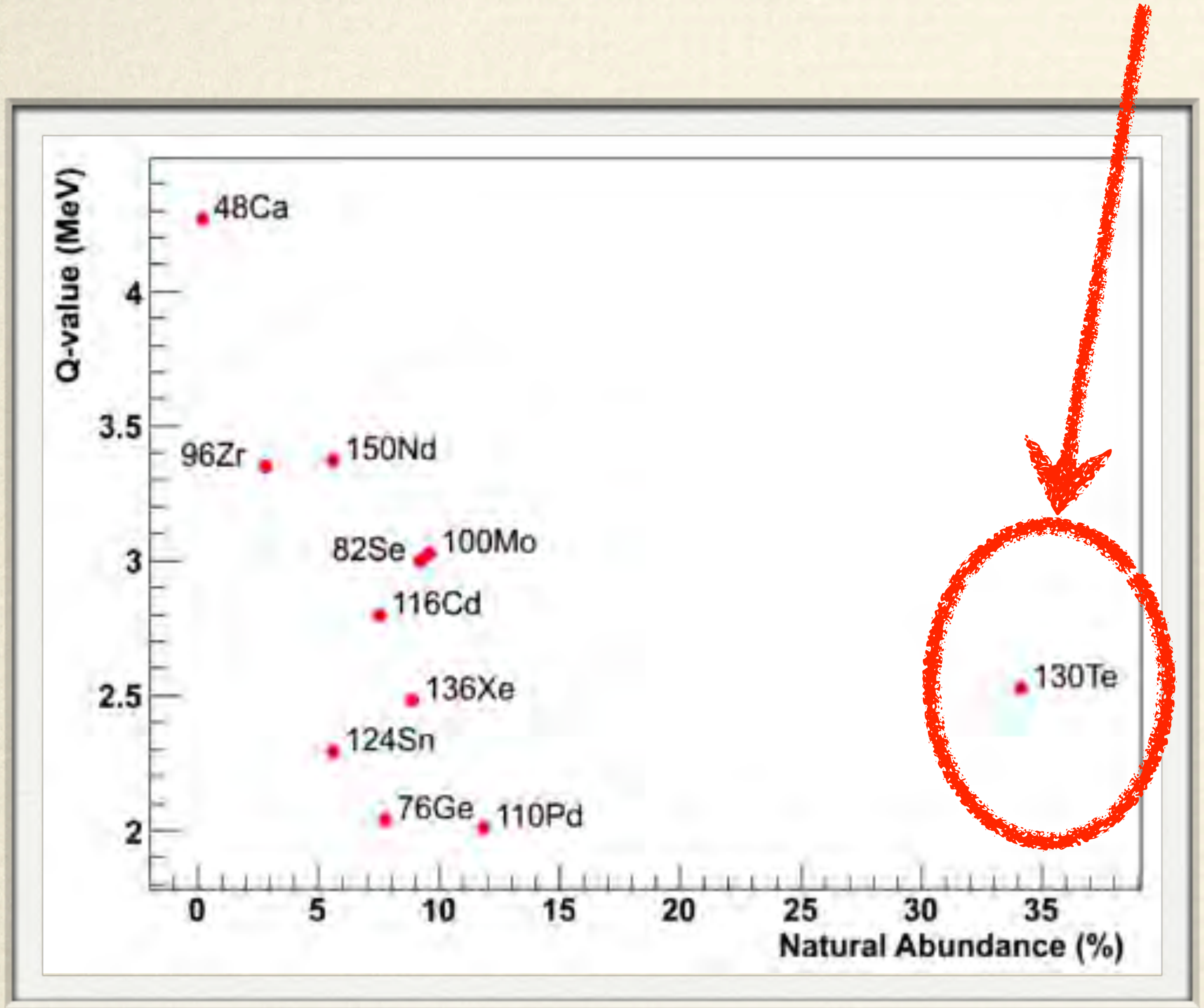
- Large target mass, easy scaling
- Fiducialisation ⇒ self-shielding
- Low backgrounds (dominated by 8B solar neutrinos)
- Spectral fitting improves sensitivity
- High detection efficiency
- Source in / out calibration

Isotope goes here



^{130}Te vs ^{150}Nd

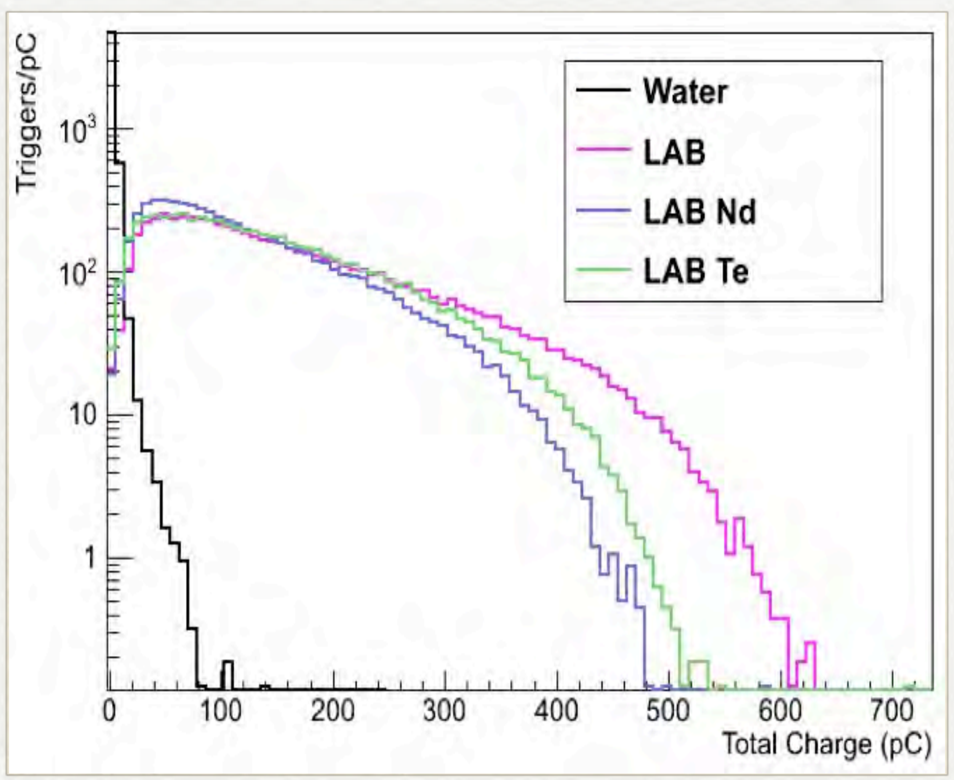
- Load 780T with 0.3% natural Te (34%) ⇒ ~800kg 130Te



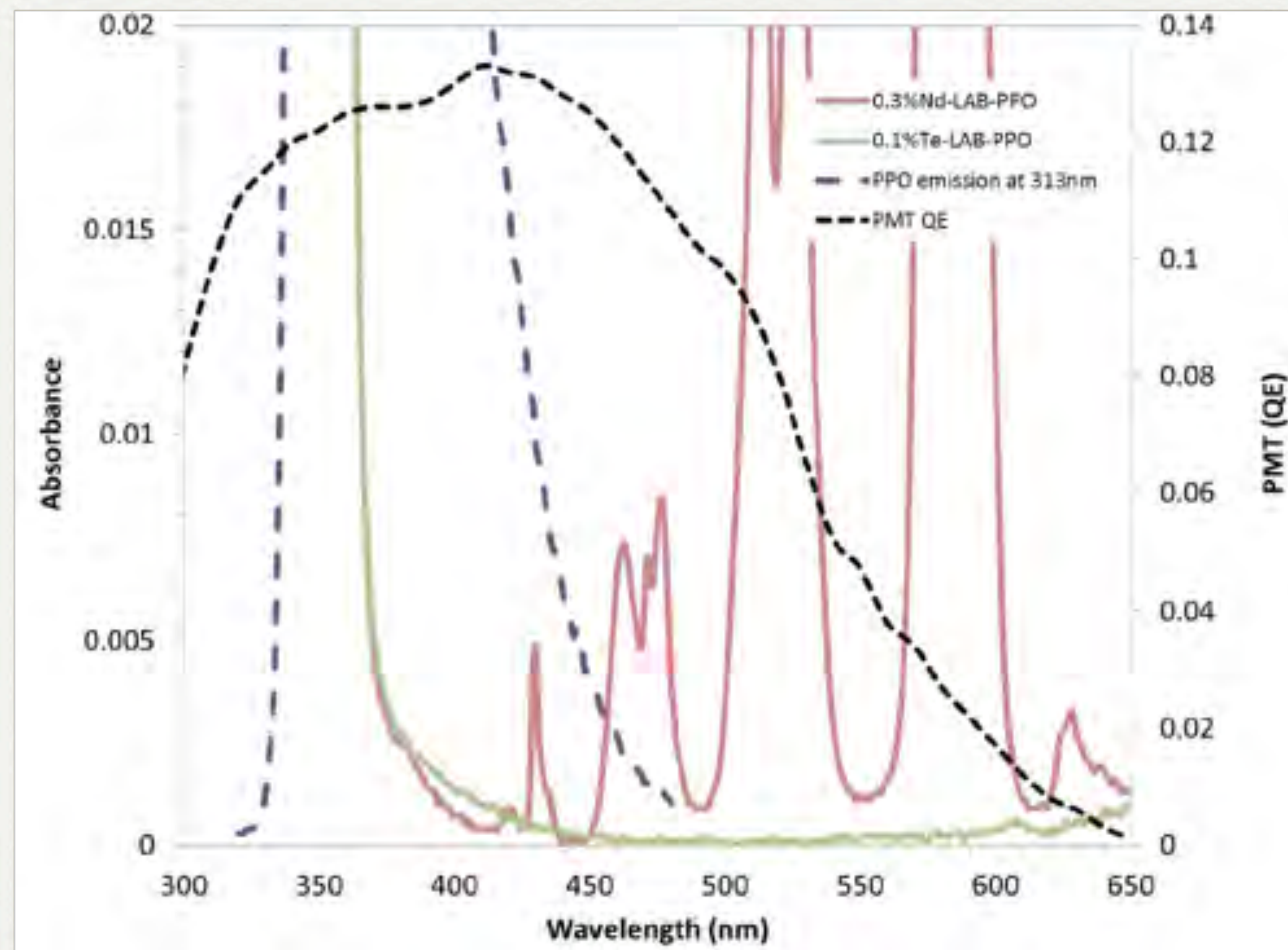
- High natural abundance ⇒ high loading w/o enrichment
- 2ν rate 100x lower ⇒ lower bkg, less sensitive to poor energy resn
- R/A background rejection at 99.9% (coincidence tag)
- Improved optical properties

SNO+ Optics

- Higher intrinsic light yield
  Nd-LS (0.5%): 8400 γ / MeV
  Te-LS (0.5%): 9400 γ / MeV
- Optically clear: no abs peaks
- Use of WLS to shift to high-λ

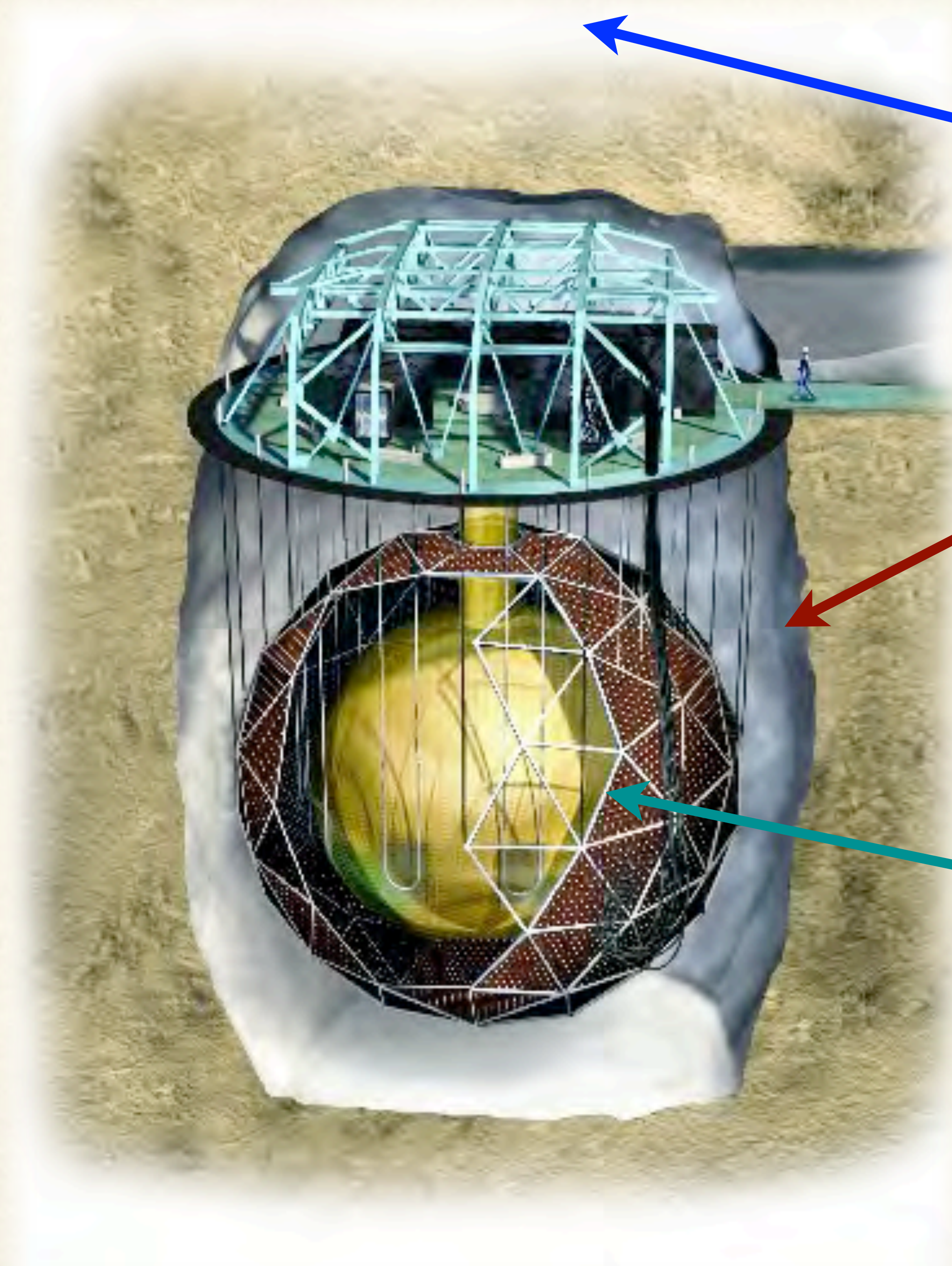


Nd-LAB
Te-LAB
PPO emission
PMT QE



SNO+ Backgrounds

- ^{39}Ar
- ^{210}Bi
- ^{11}C
- ^{14}C
- ^{40}K
- ^{85}Kr
- ^{210}Pb
- ^{210}Po
- U chain
- Th chain

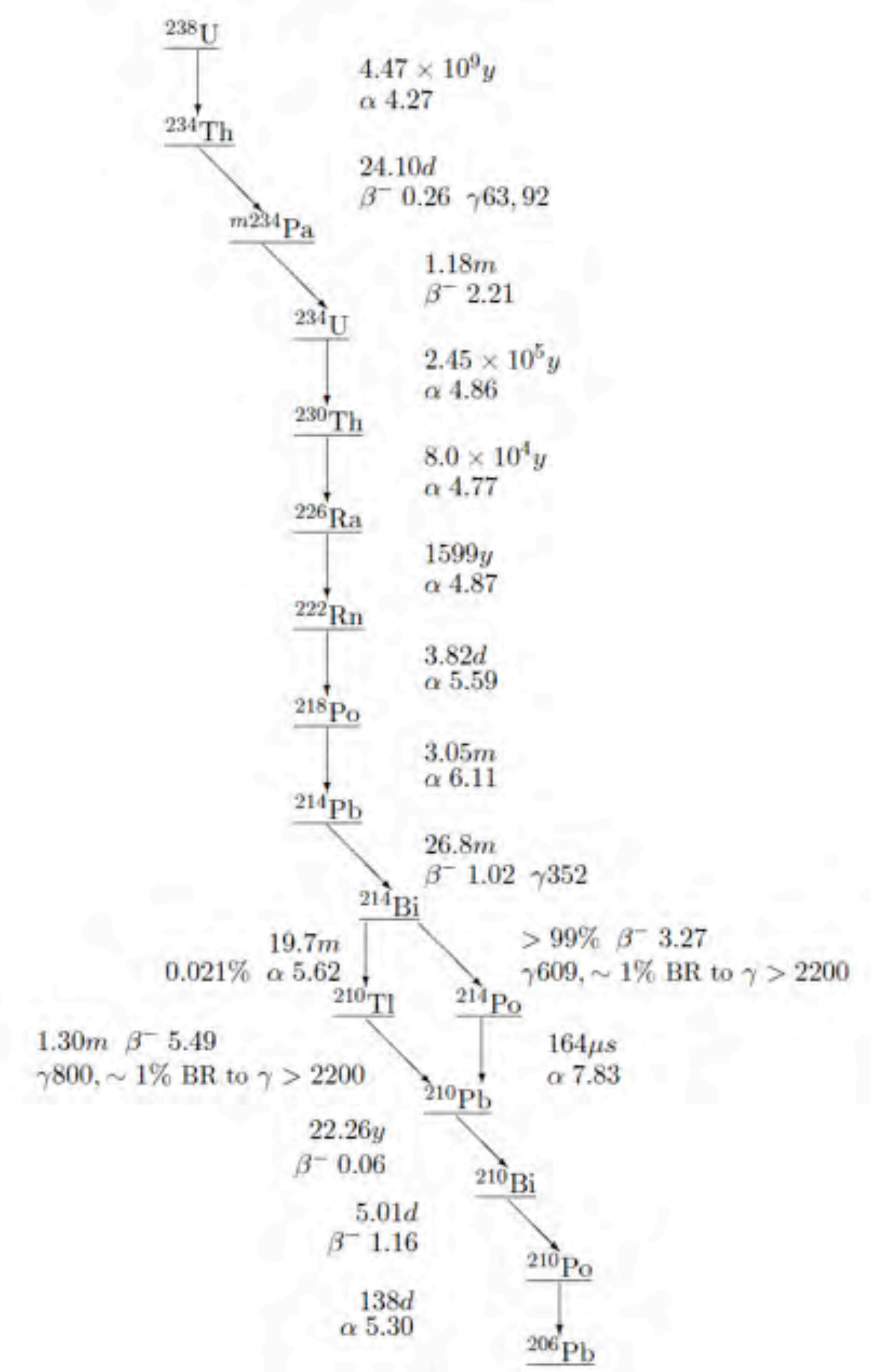


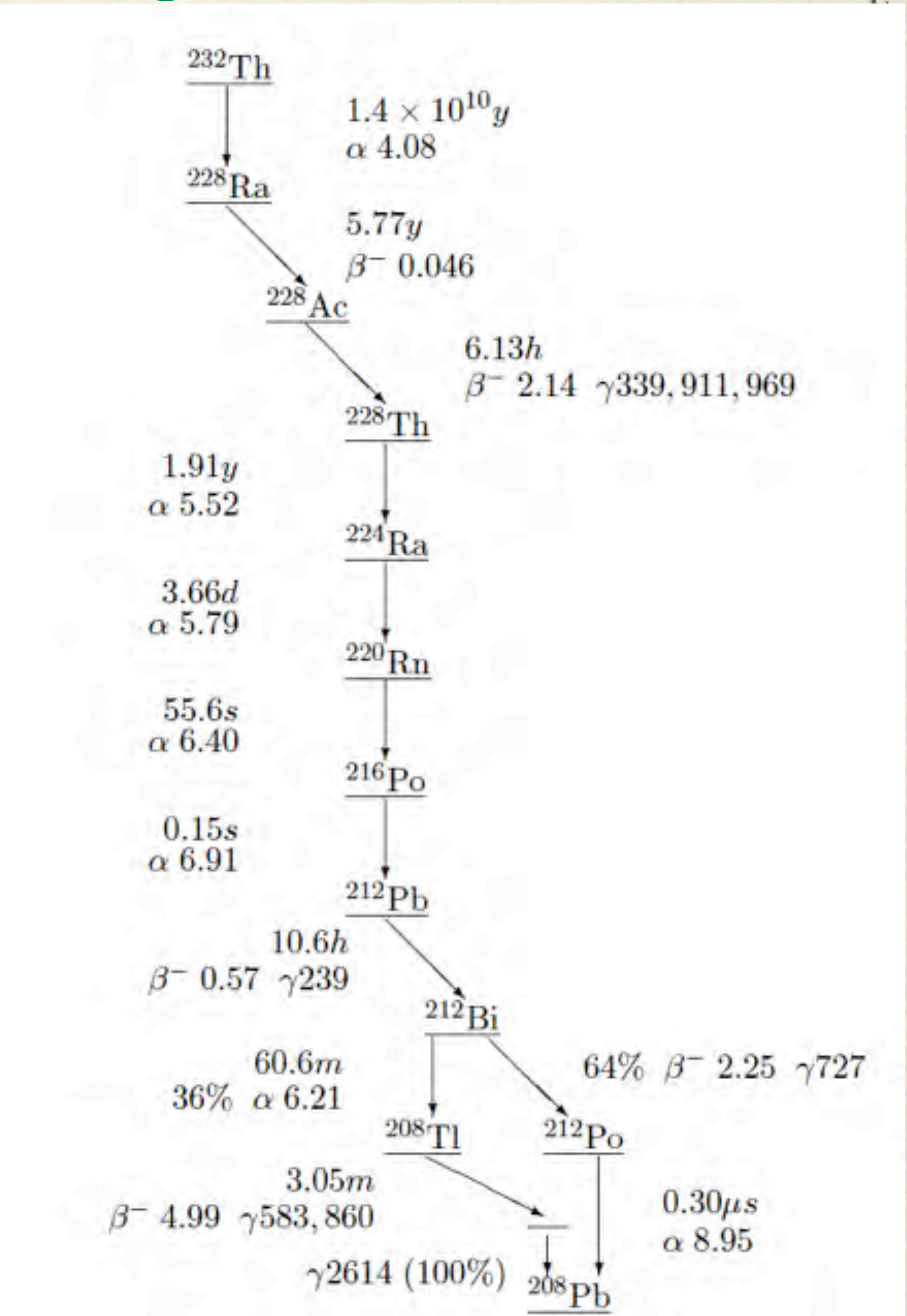
Cosmogenic
e.g. ^{11}C

External
AV, PMTs, H_2O, ropes

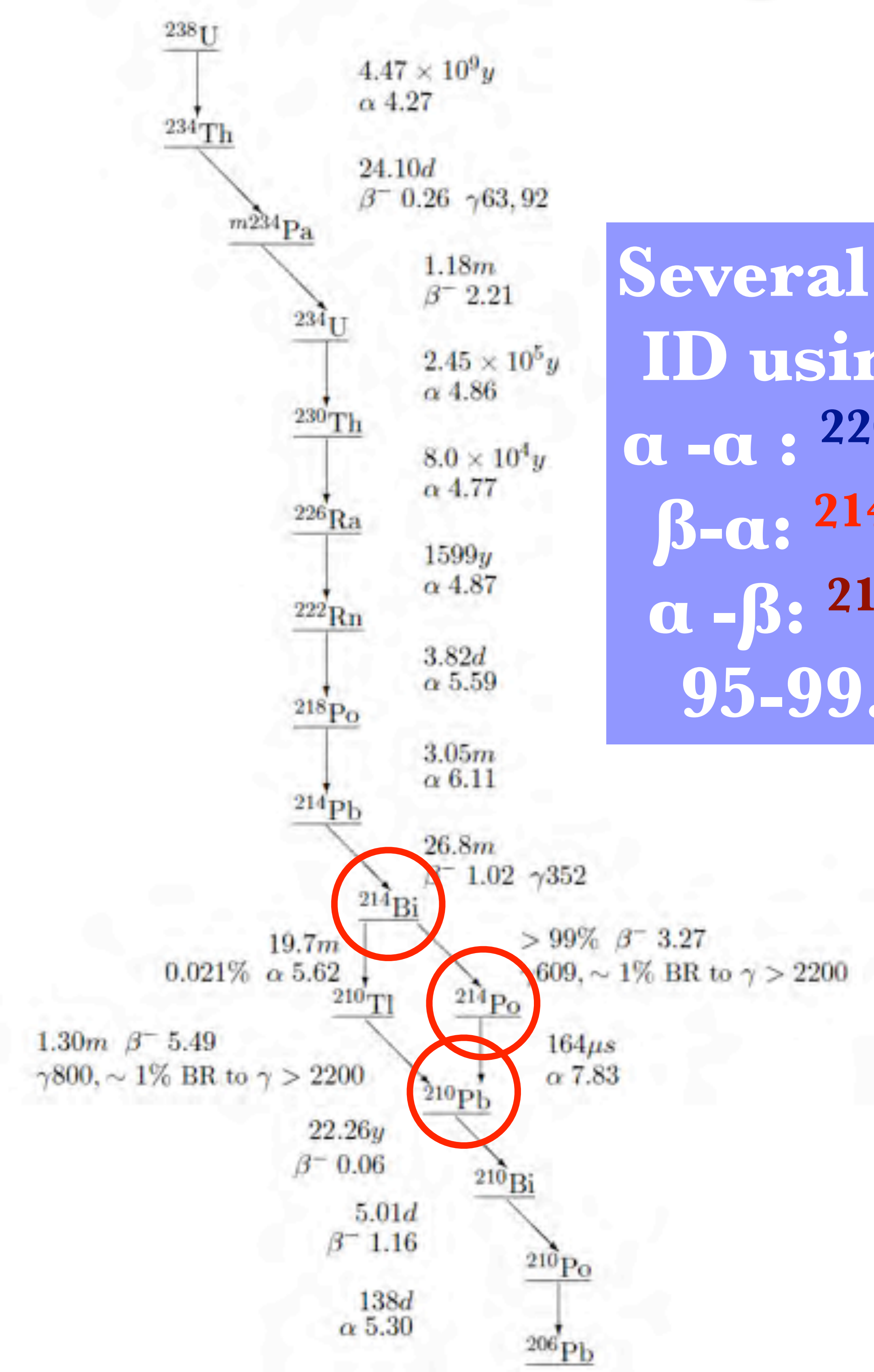
Internal
LS, AV leaching, internal ropes

Background Mitigation

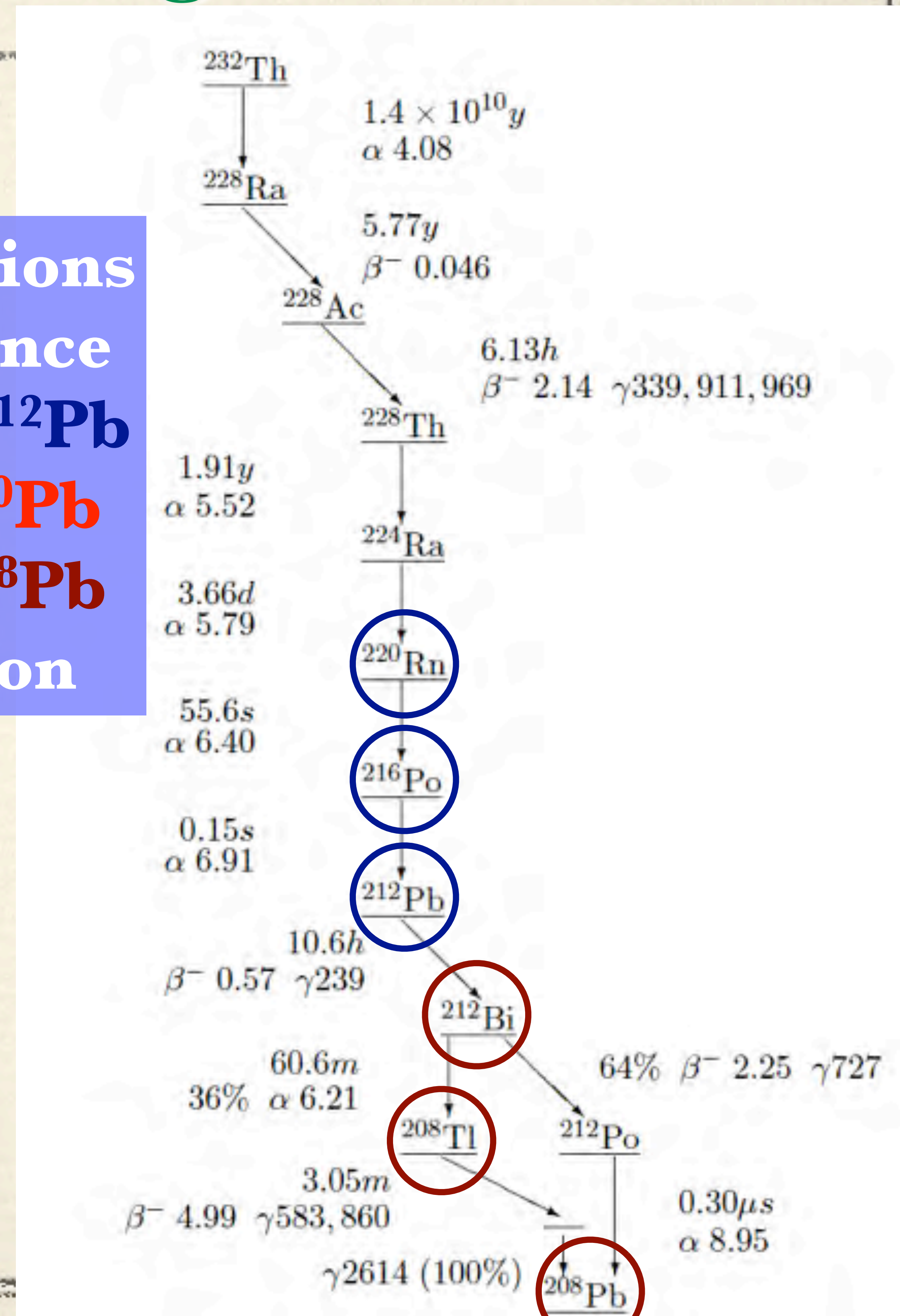




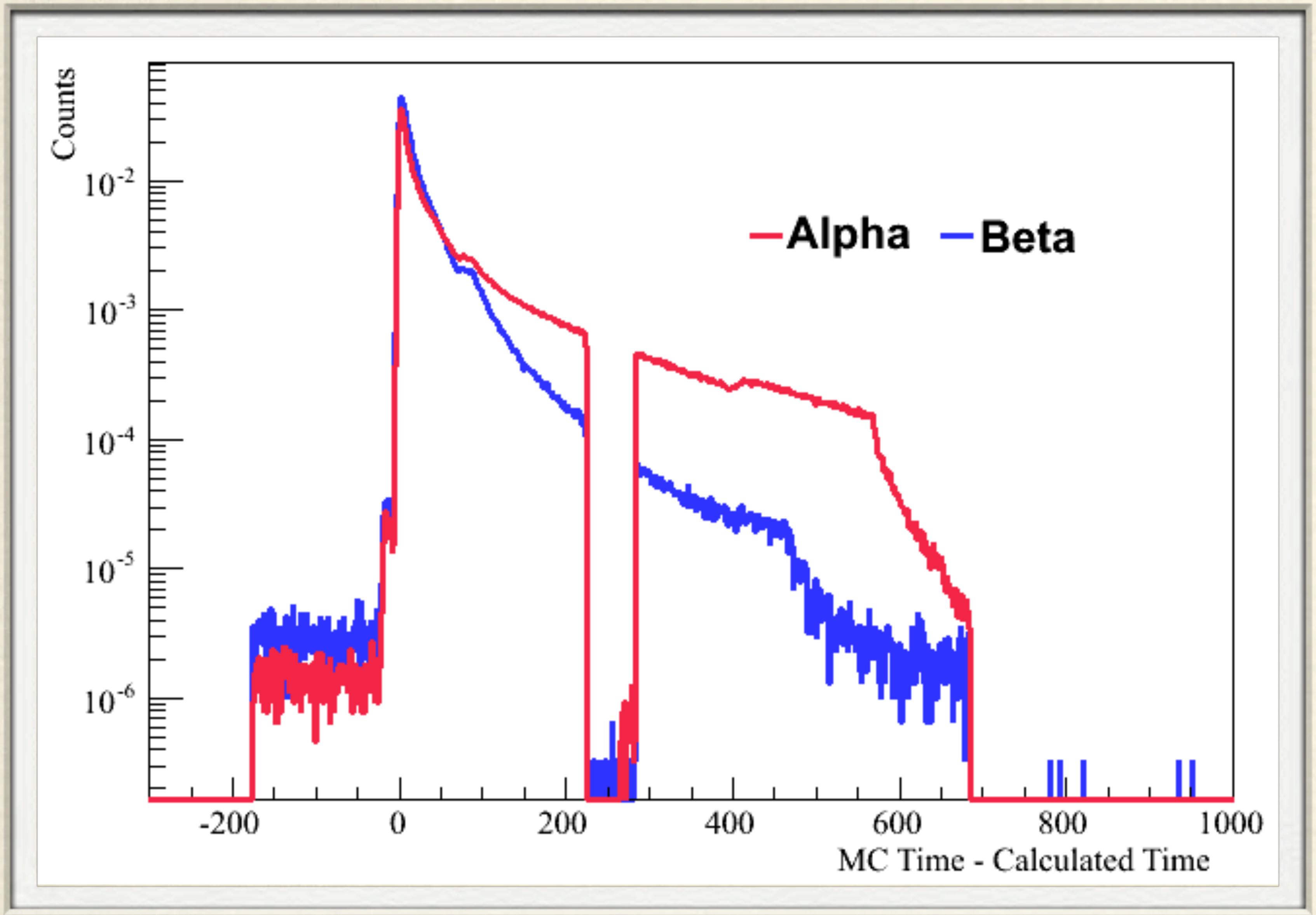
Background Mitigation



Several α, β emissions
ID using coincidence
α -α : ^{220}Rn-^{216}Po-^{212}Pb
β-α: ^{214}Bi-^{214}Po-^{210}Pb
α -β: ^{212}Bi-^{208}Tl-^{208}Pb
95-99.9% rejection



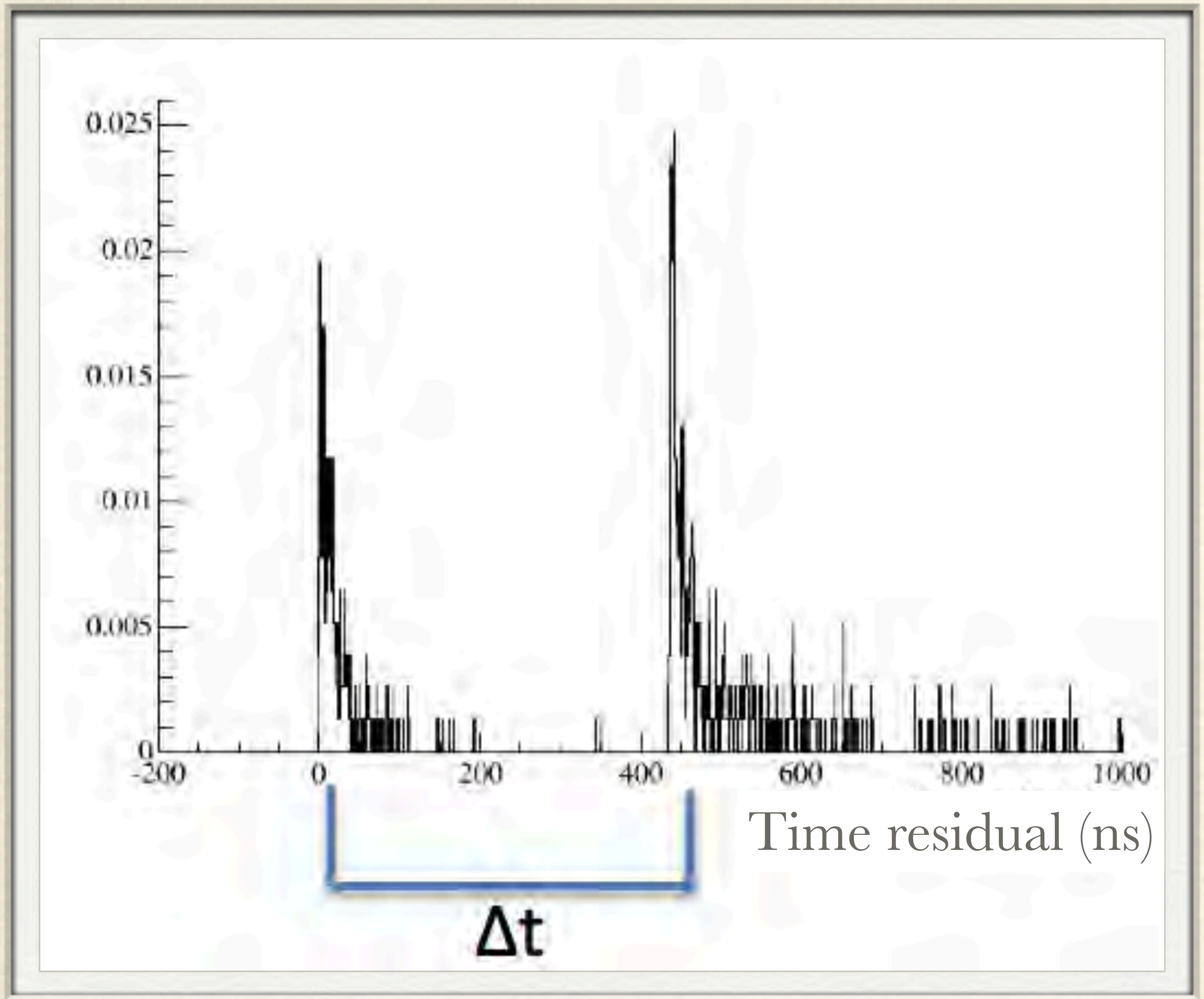
Particle Identification



Determine particle ID from PMT hit-time residual distribution

>99.9% α-β separation from Likelihood ratio test

Coincidence Rejection



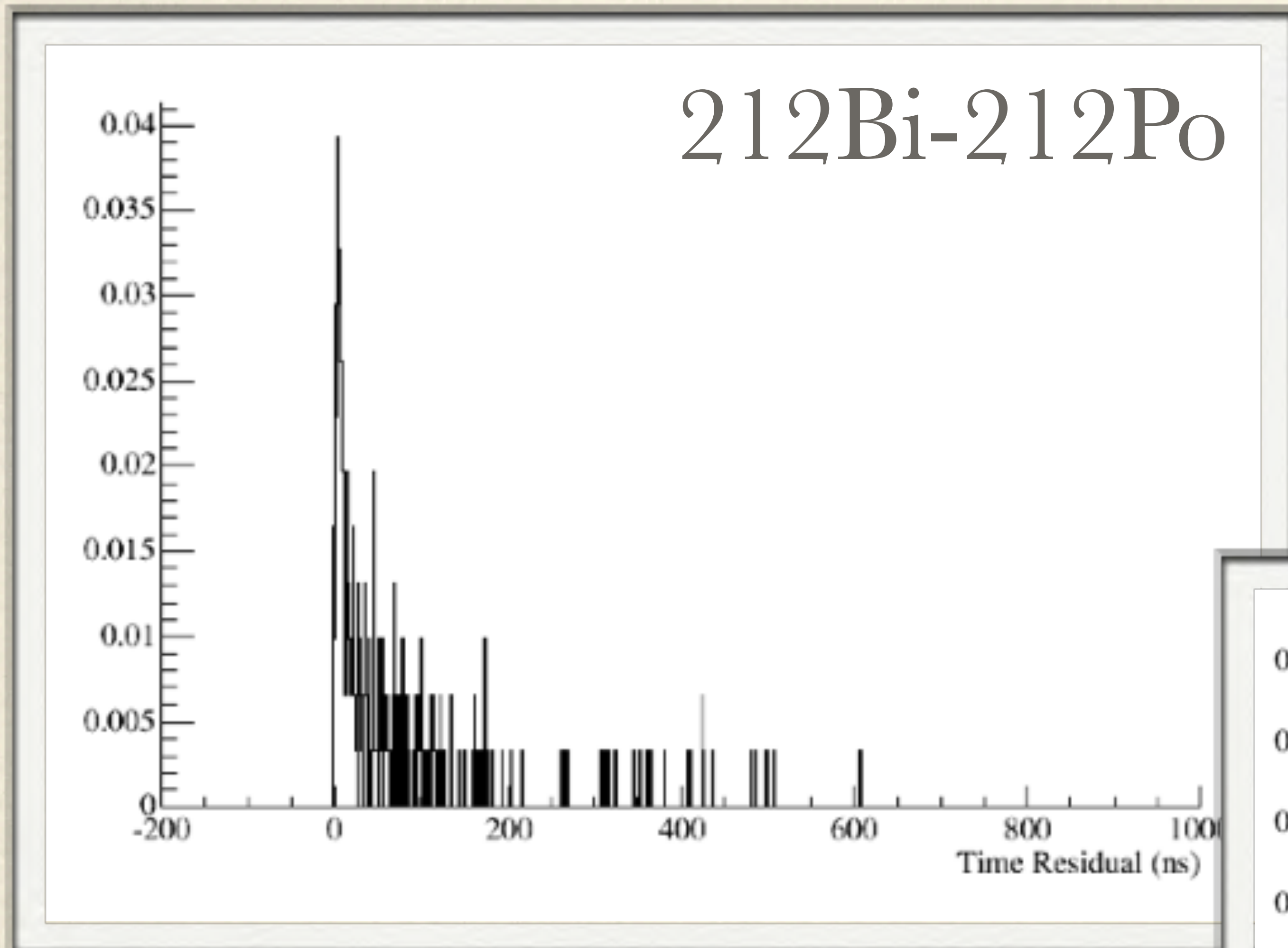
Identify coincidences by timing

212Bi
→ 212Po + β
→ 208Pb + α τ = 300ns

Simplest case:
α and β fall in separate event windows

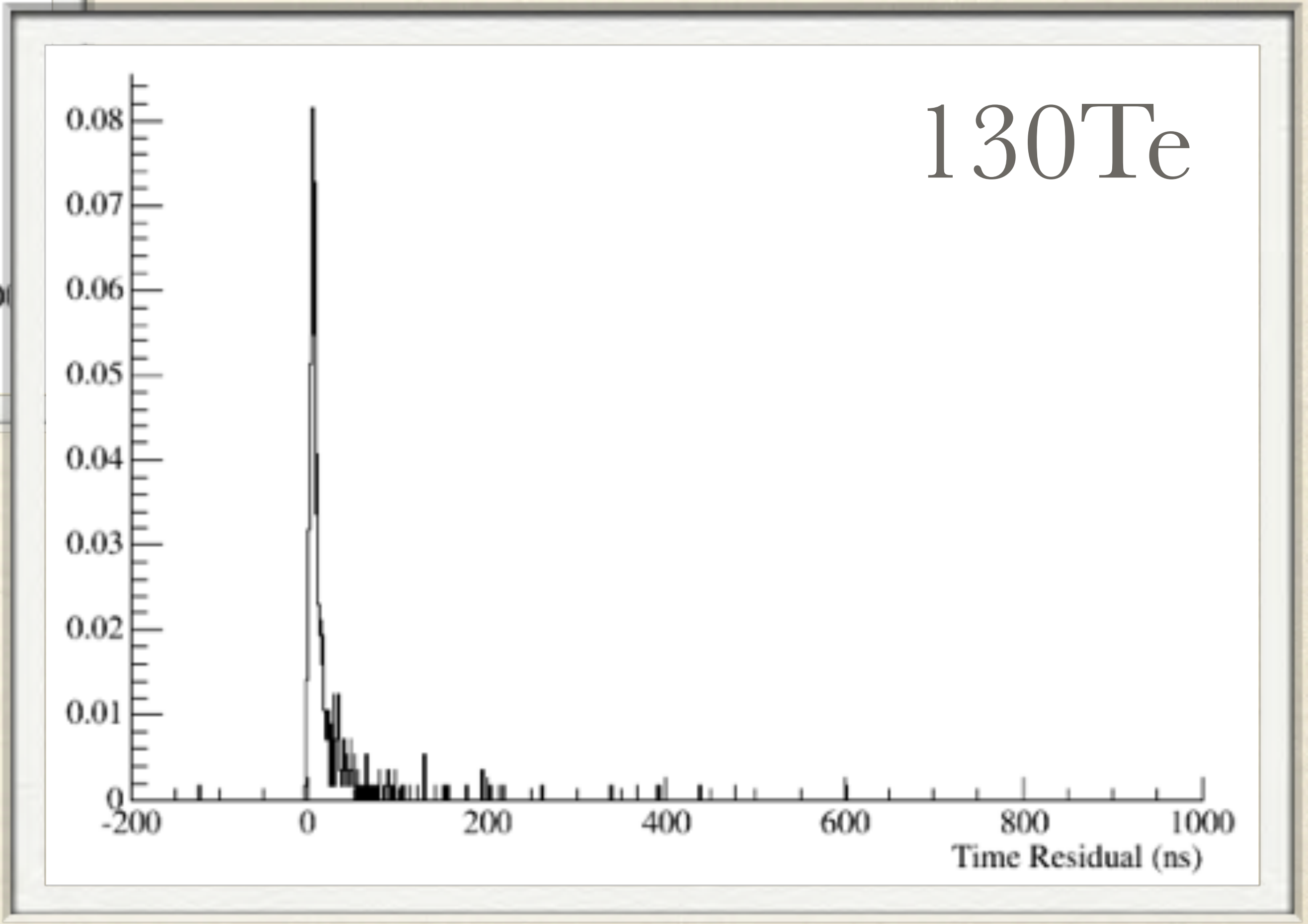
⇒ 100% β rejection purely by coincidence tag

Pile-Up Rejection



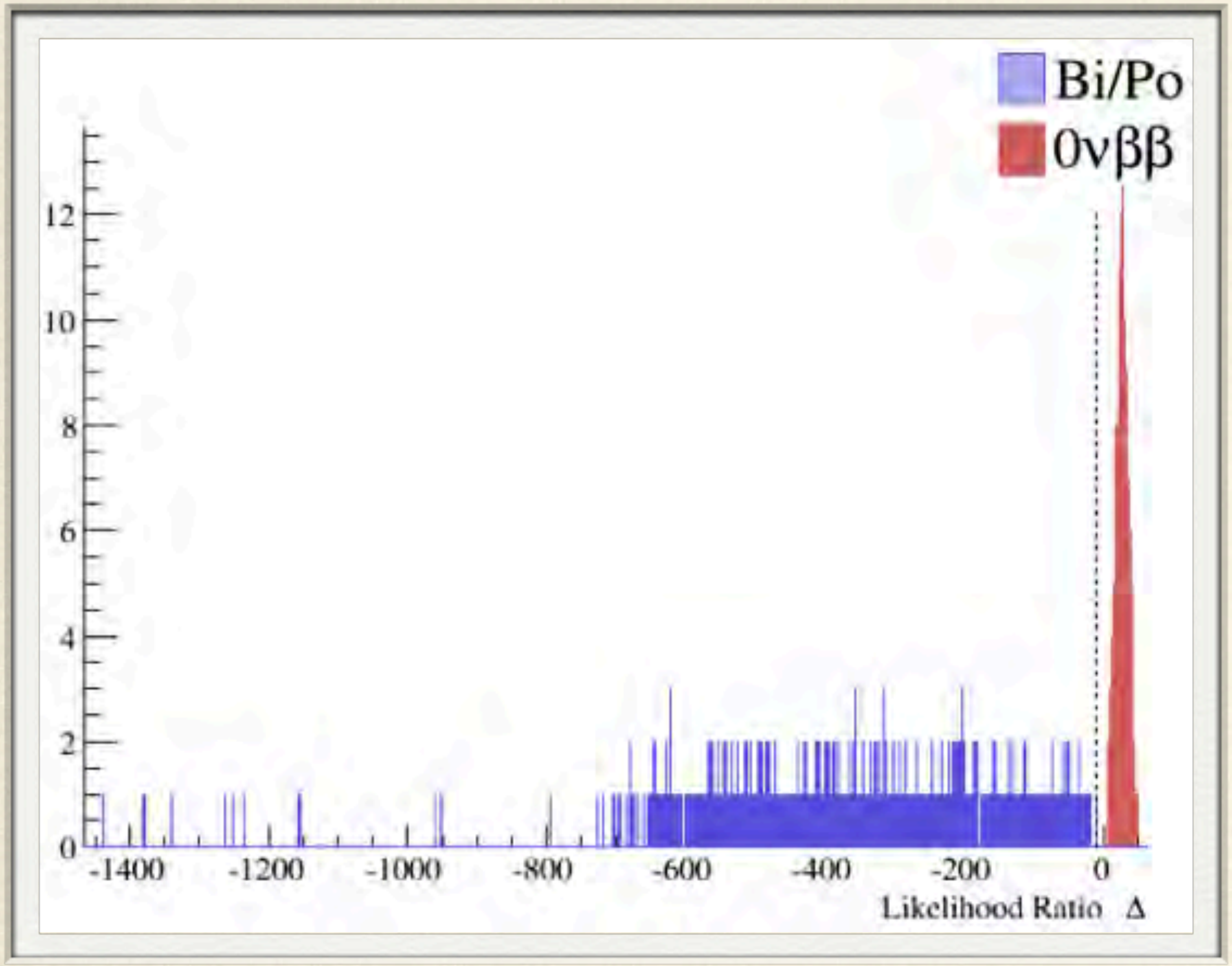
Determine particle ID from PMT hit time distribution

Instead of α vs β
Consider α+β vs 2β

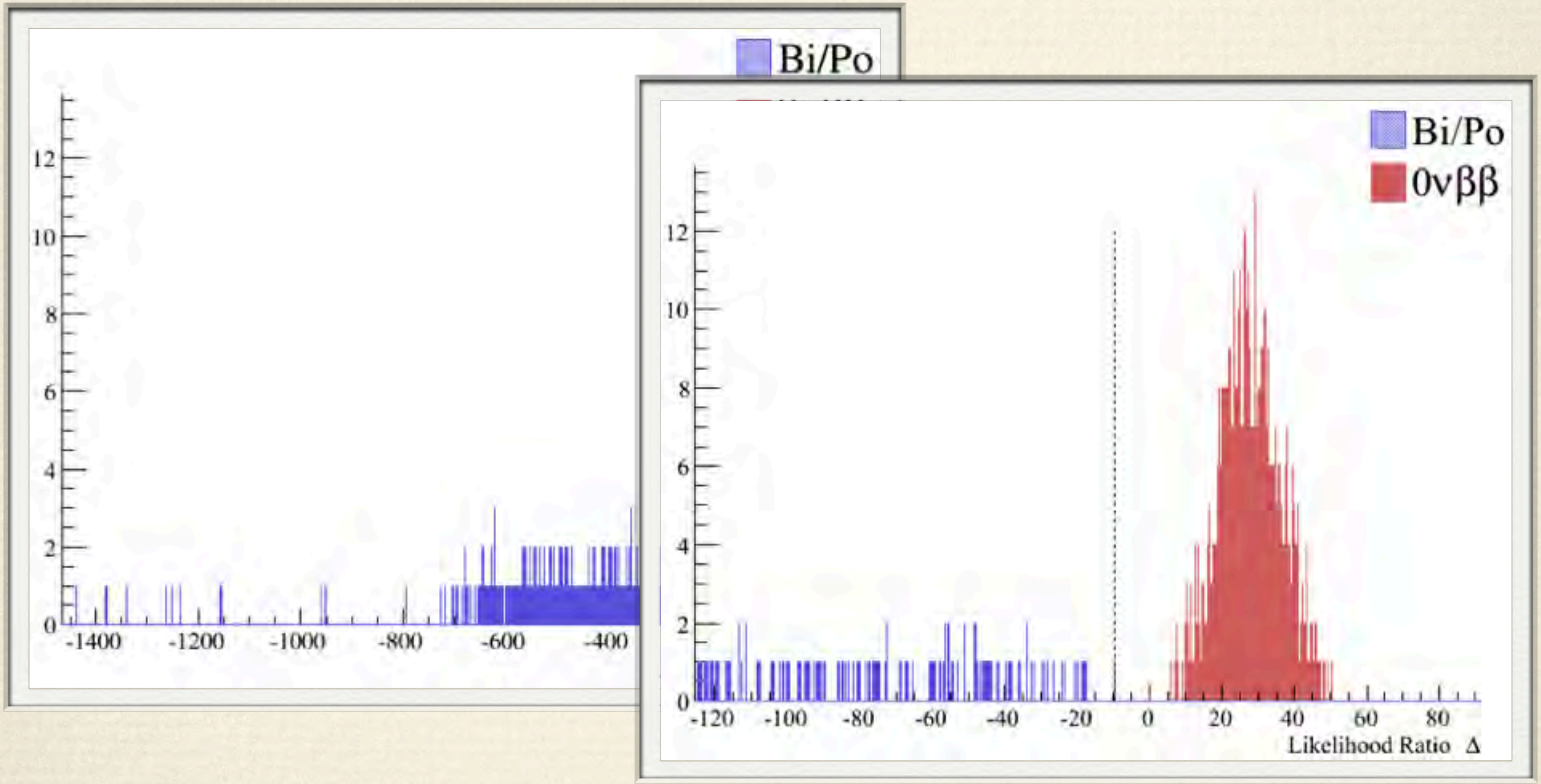


Likelihood ratio in hit-time residuals
Constrain fit with known α/β energy ratio

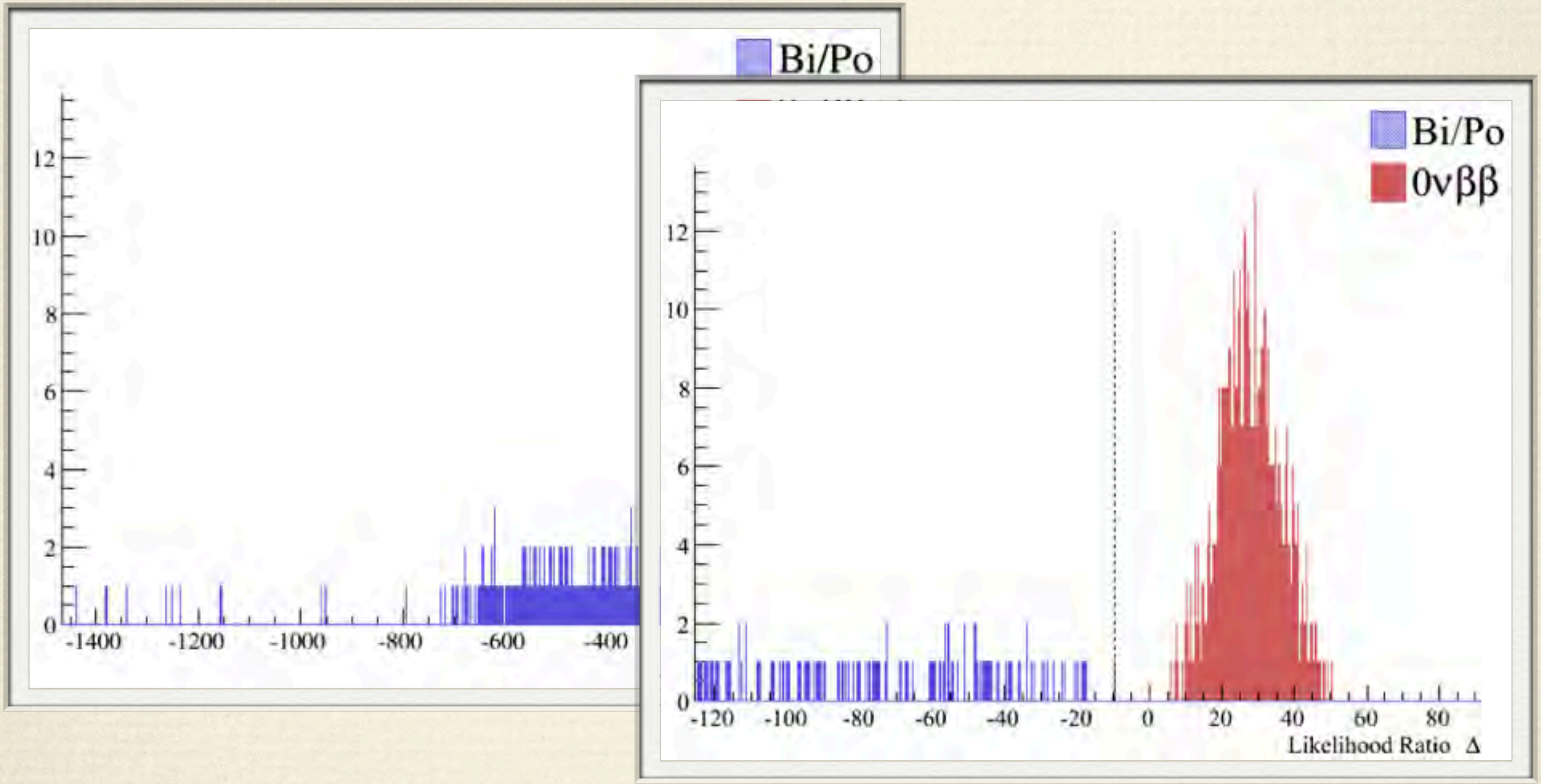
Pile-Up Rejection



Pile-Up Rejection



Pile-Up Rejection



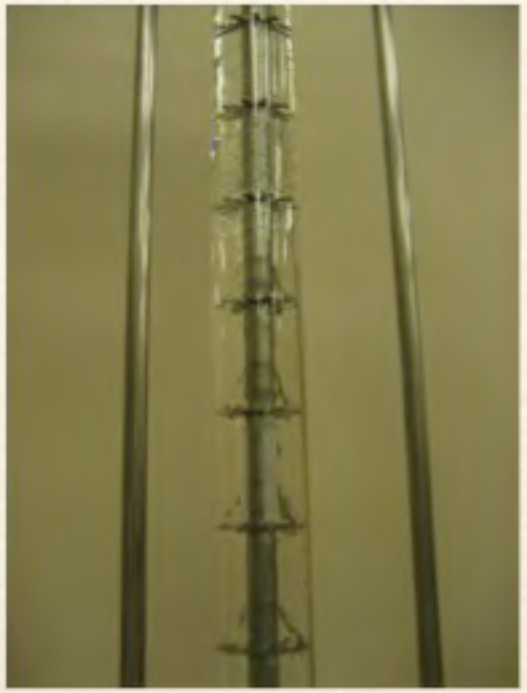
100% rejection of 100,000 BiPo pile-up events
0% sacrifice of 10,000 Te events

Purification

- Multi-stage distillation
  - *Removes heavy metals*
  - *Improves UV transparency*
  - *Dual-stream PPO distillation*

Distillation

Water extraction



- N_2 / steam stripping
  - *Removes Rn, Kr, Ar, O_2*
- Water extraction
  - *Removes Ra, K, Bi*
- Metal scavenging
  - *Removes Bi, Pb*
- Microfiltration
  - *Removes dust*

e.g. ^{60}Co reduced to 2.7×10^{-6}

Calibration Programme

Source	AmBe	^{90}Y	^{65}Zn	^{60}Co	^{57}Co	^{24}Na	^{48}Sc	^{8}Li	^{16}N
Particle	n, γ	β	γ	γ	γ	γ	γ	β	γ
Energy(MeV)	$4.4(\gamma)$	2.2	1.1	2.5	0.122	4.1	3.3	10	6.1

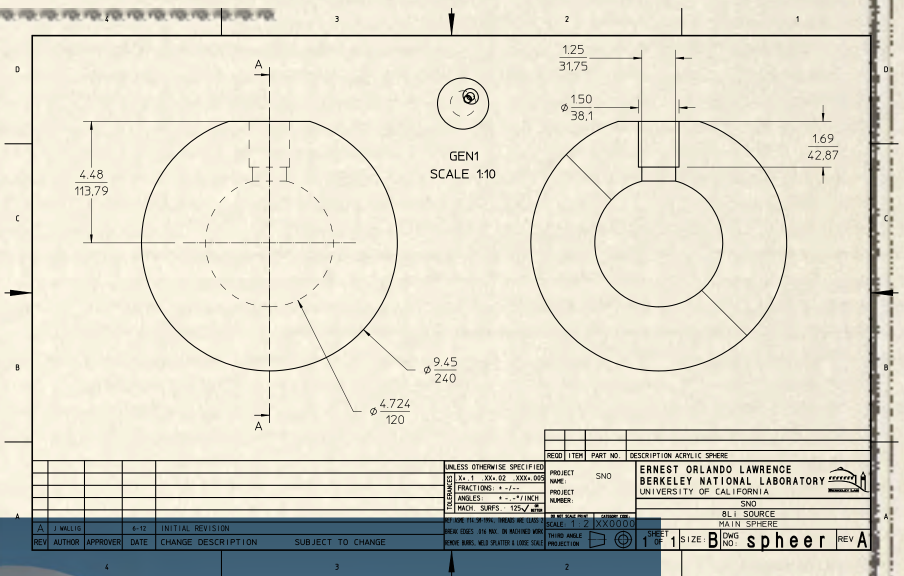
- Comprehensive source list
- Minimalist deployment plan (risk 222Rn contam)
- Camera system for source positioning
- Plus optical sources

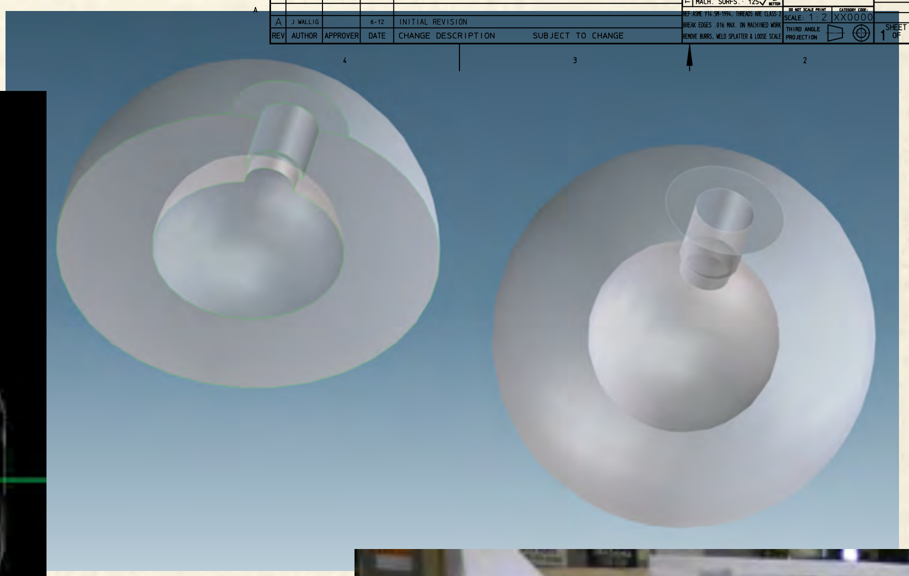
Cherenkov Source

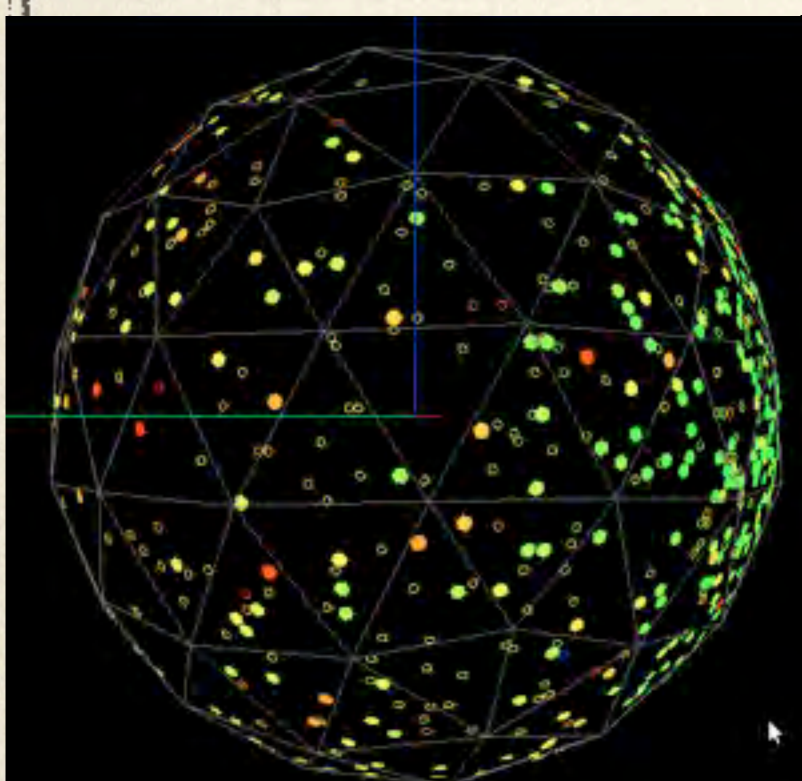
Cherenkov-light source

⇛ Measure PMT optical response

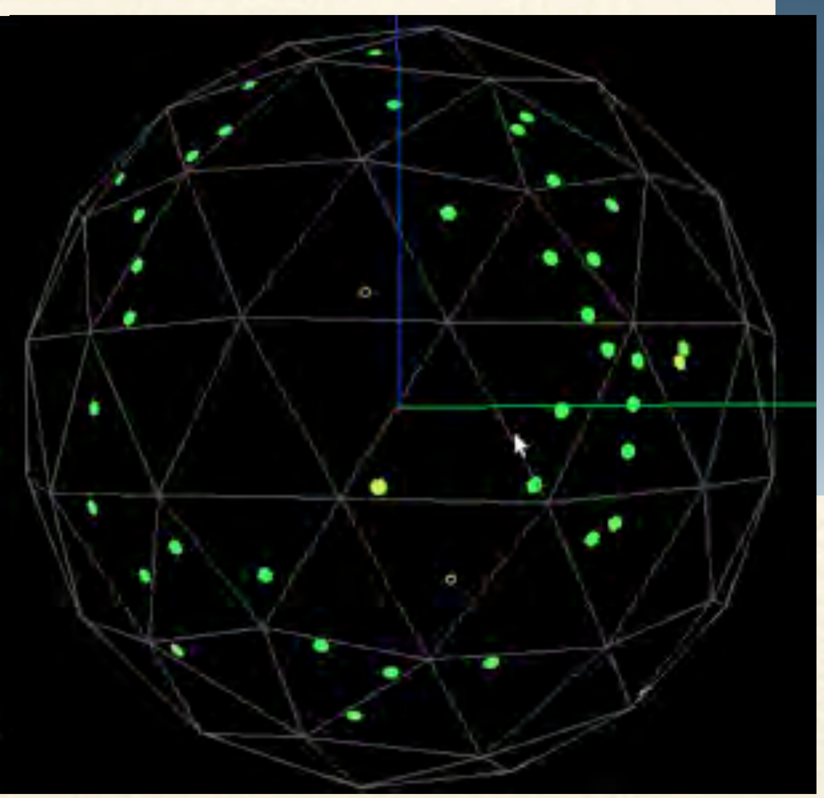
Independently of scintillator properties







Isotropic scintillation event

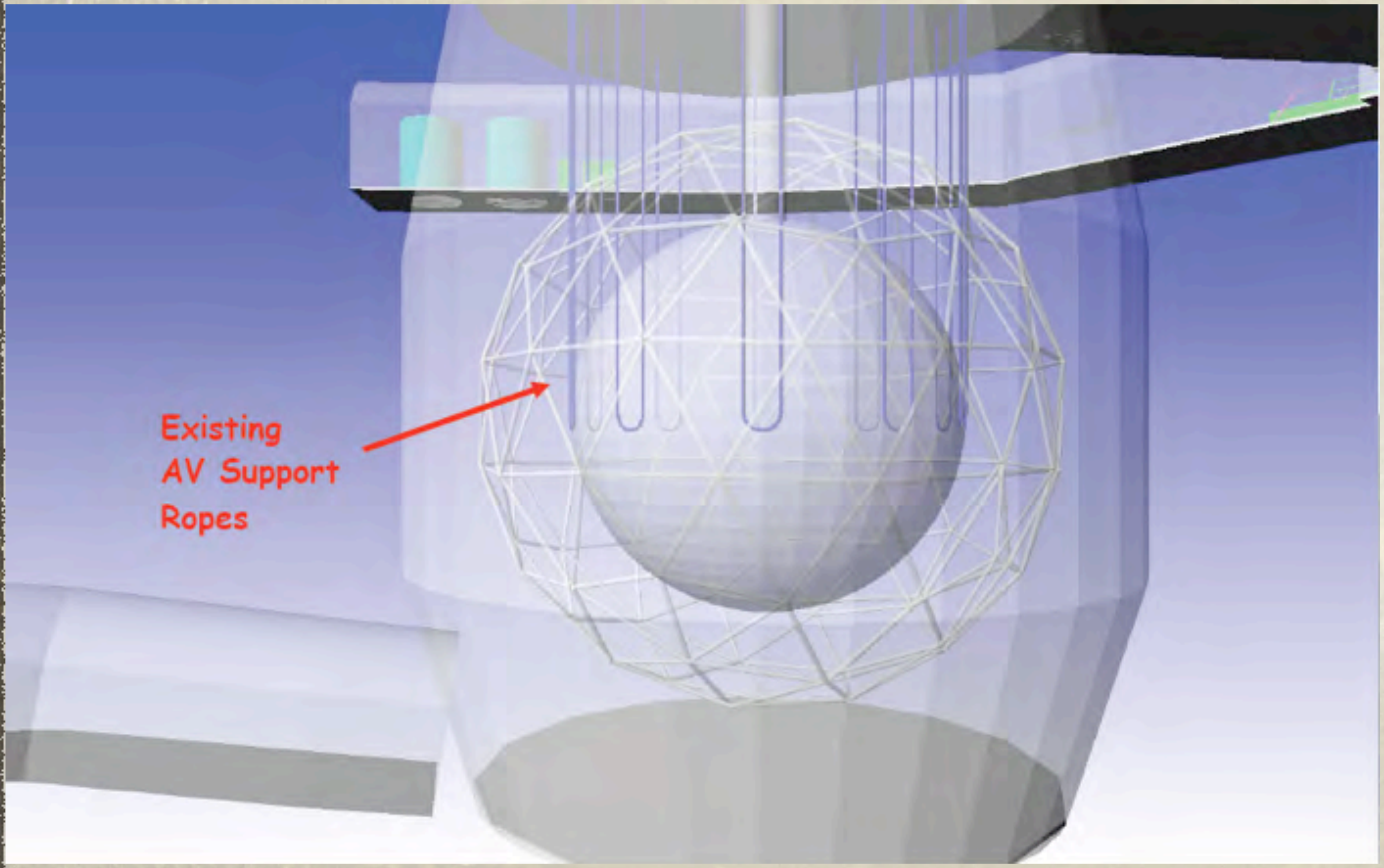


Clean, clear, fast Cherenkov ring

SNO+ Status

SNO+ Status

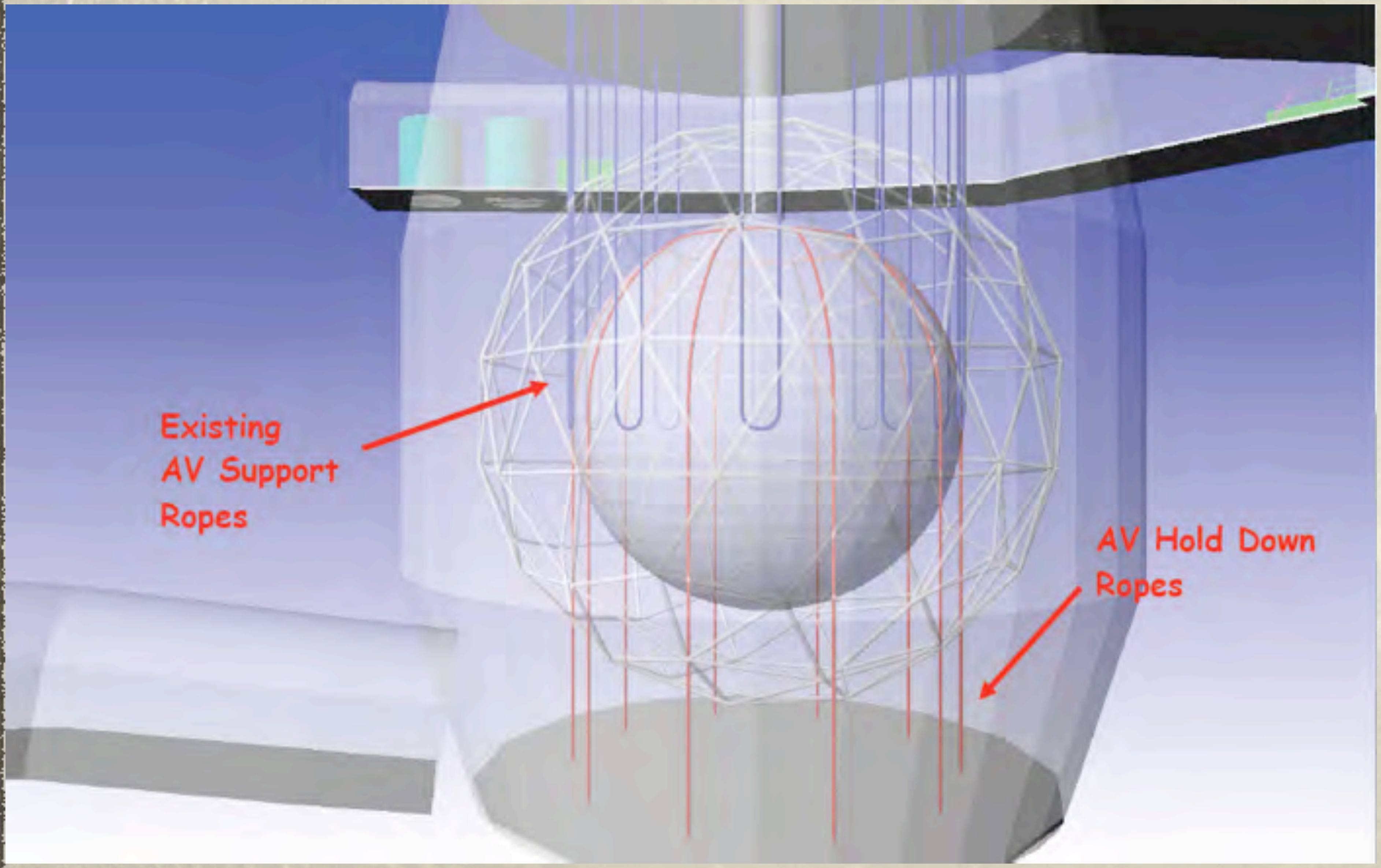
- Rope net installation



Highlights

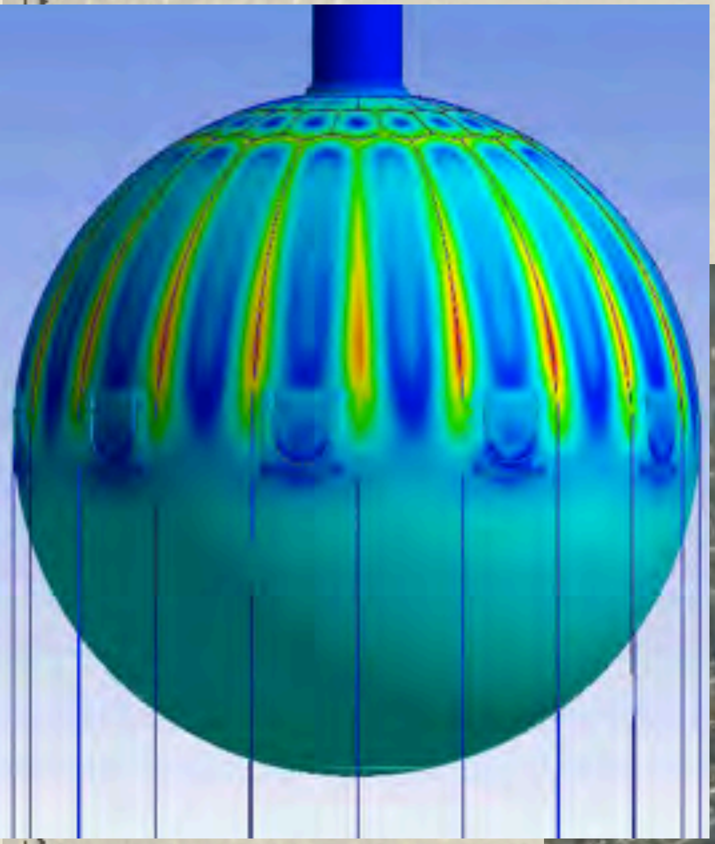
SNO+ Status

- Rope net installation



SNO+ Status

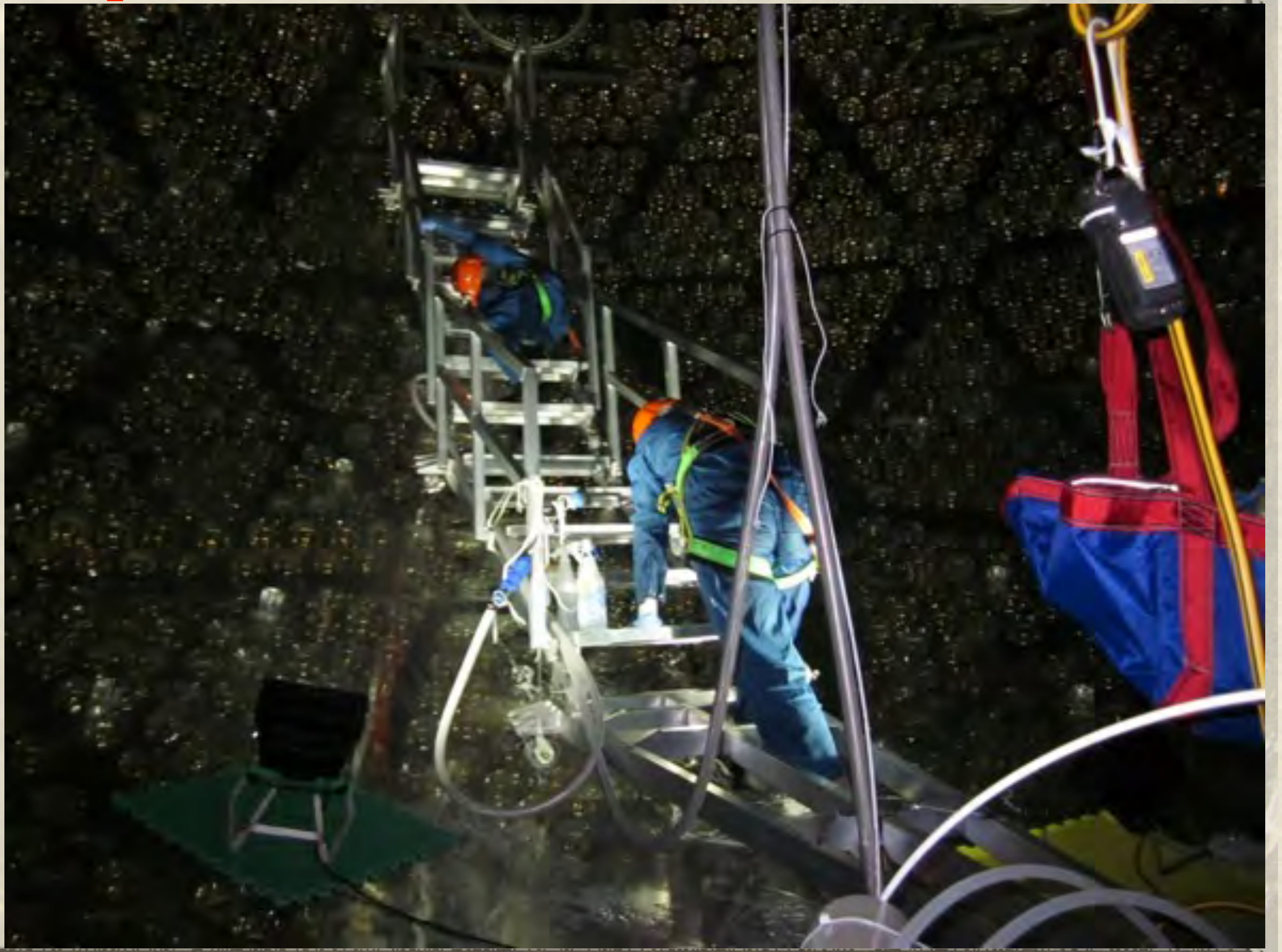
- Rope net installation complete

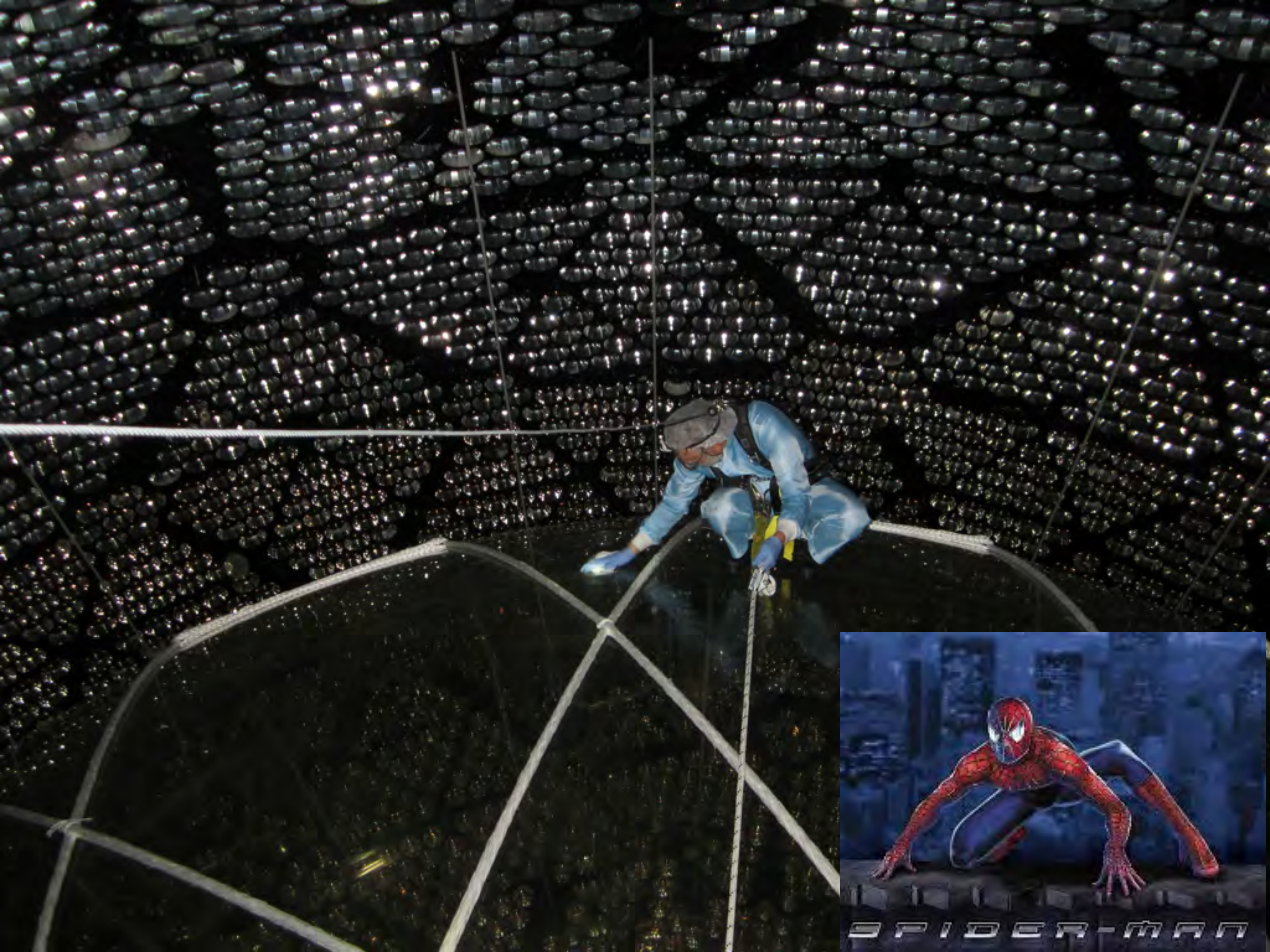


Highlights

SNO+ Status

- Rope net installation complete
- Cleaning complete: the superheroes of SNO+

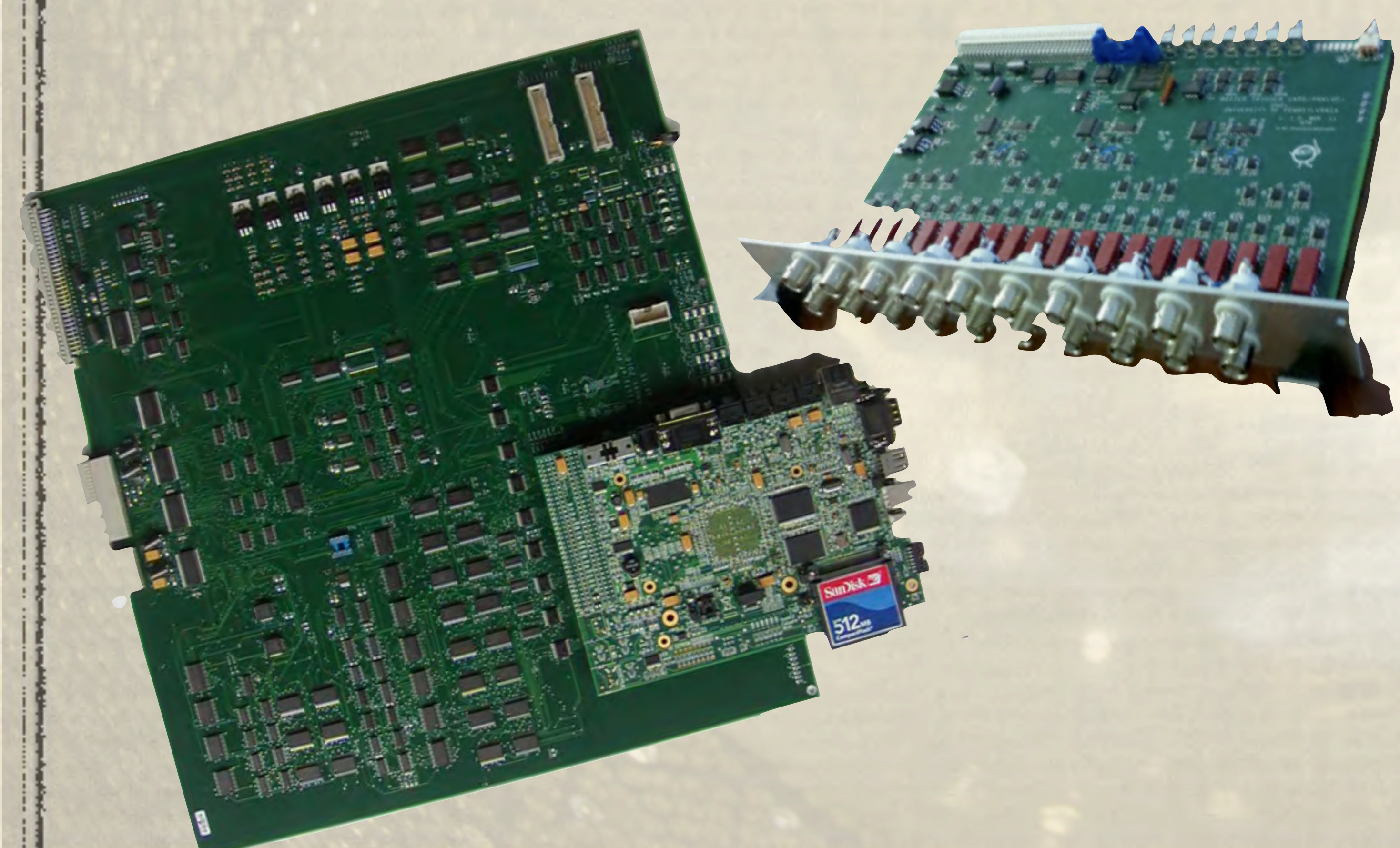



SPIDER-MAN

Highlights

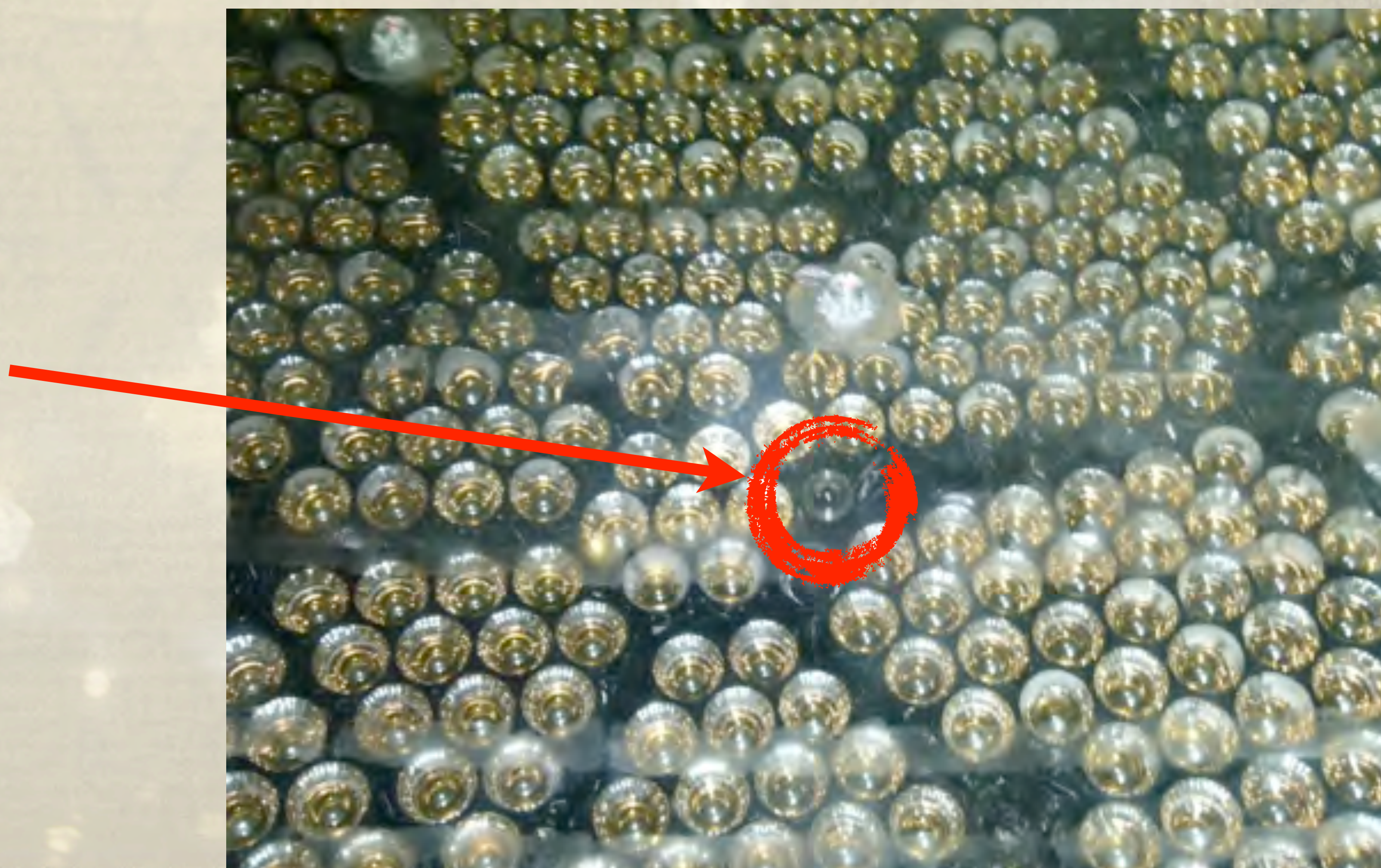
SNO+ Status

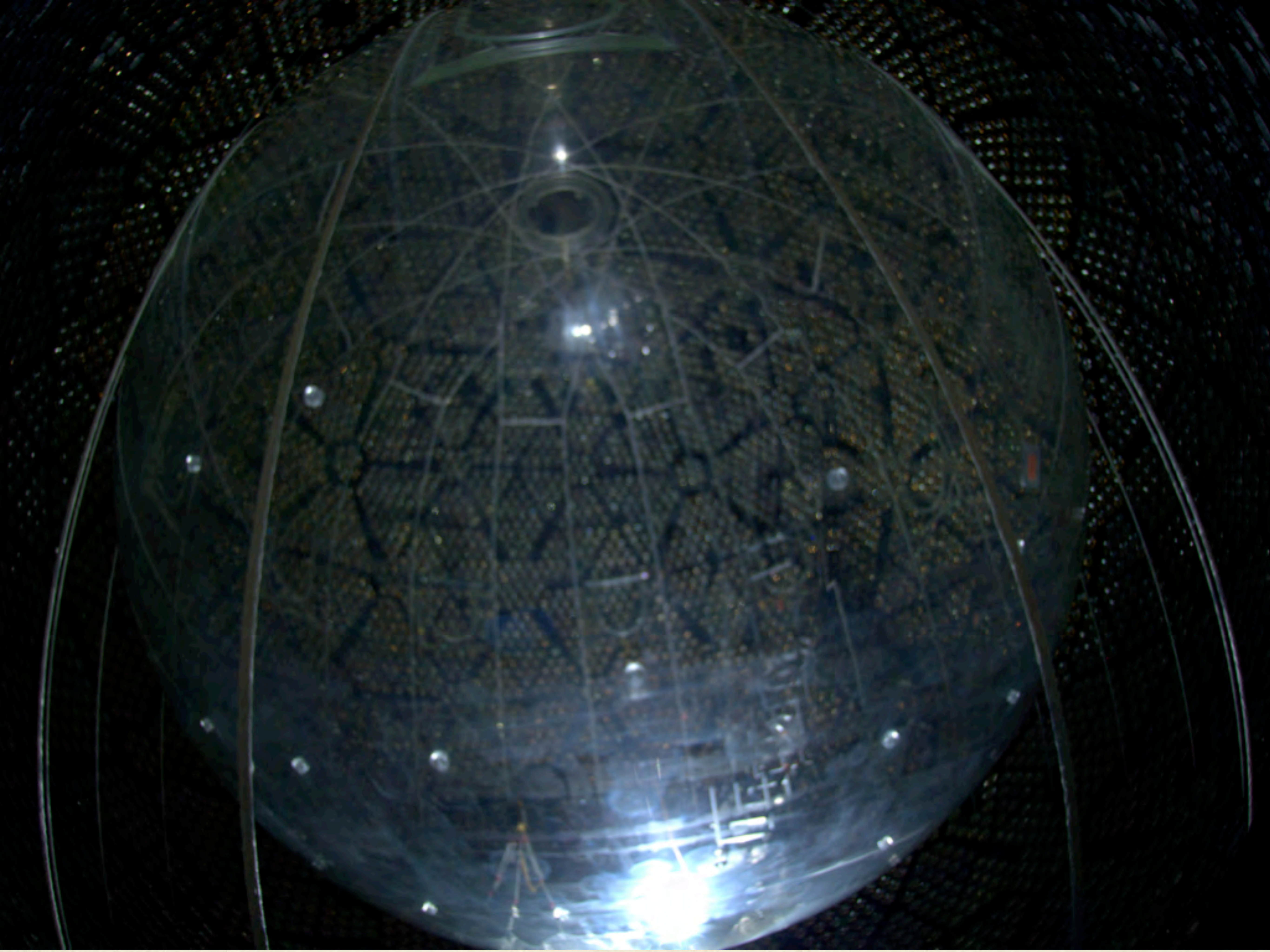
- Rope net installation complete
- Cleaning complete
- Electronics upgrade complete



SNO+ Status

- Rope net installation complete
- Cleaning complete
- Electronics upgrade complete
- Cameras installed



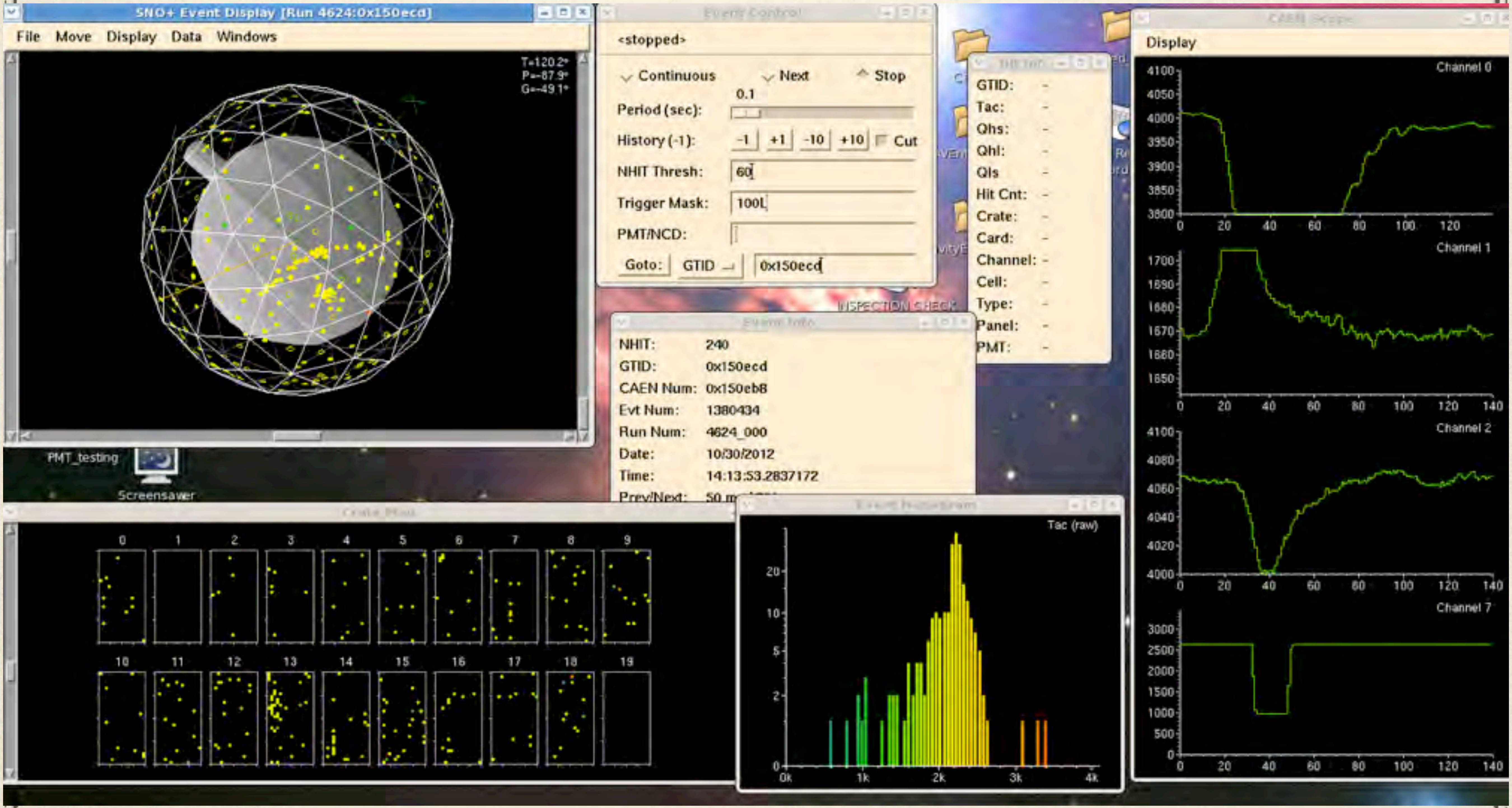


Highlights

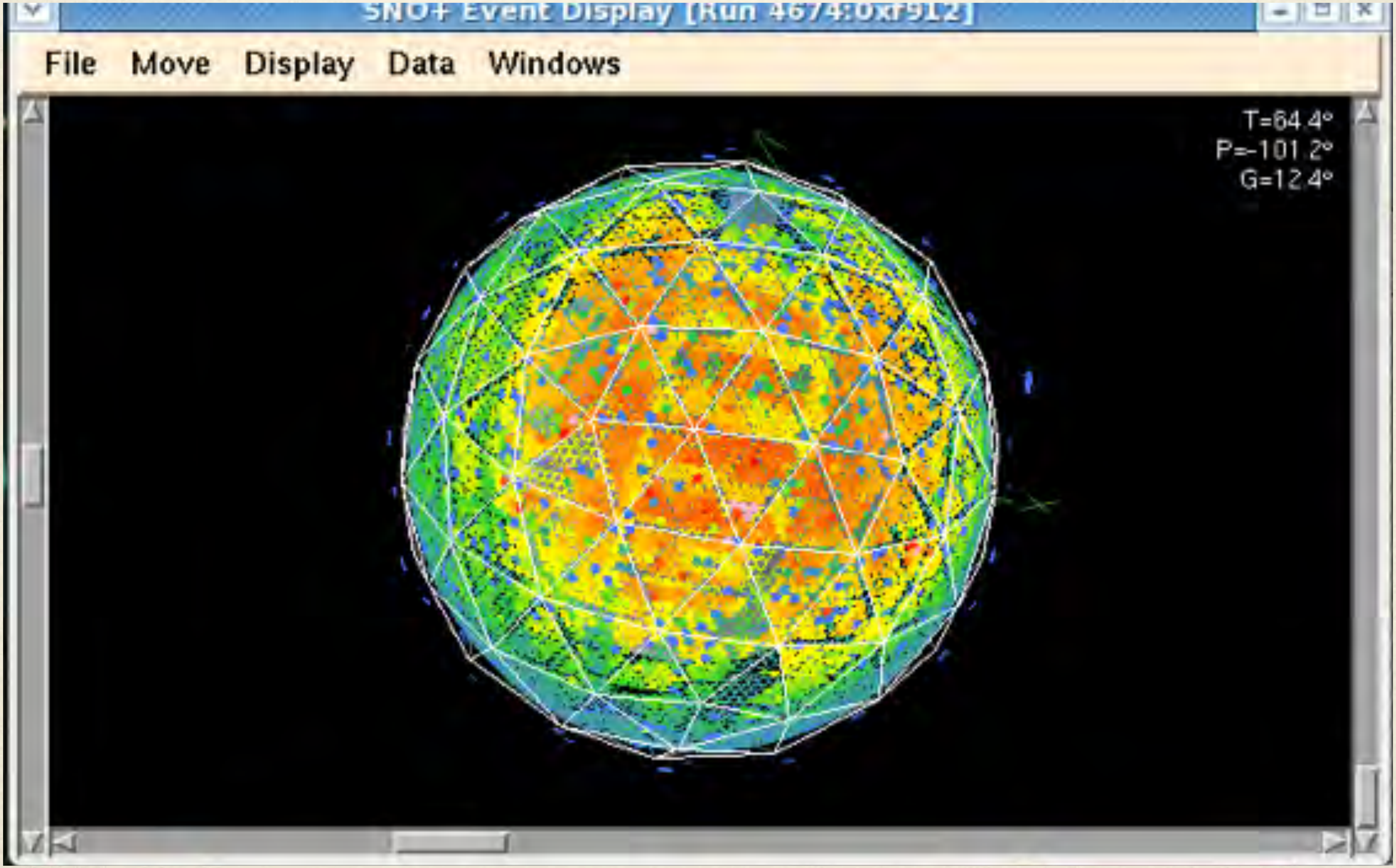
SNO+ Status

- Rope net installation complete
- Cleaning complete
- Electronics upgrade complete
- Cameras installed
- Successful `air-fill' running

Air-Fill Data: Our First Muon



Air-Fill Data: Richie finds a ladder



Air-Fill Data: Day Shift, Oct 31st

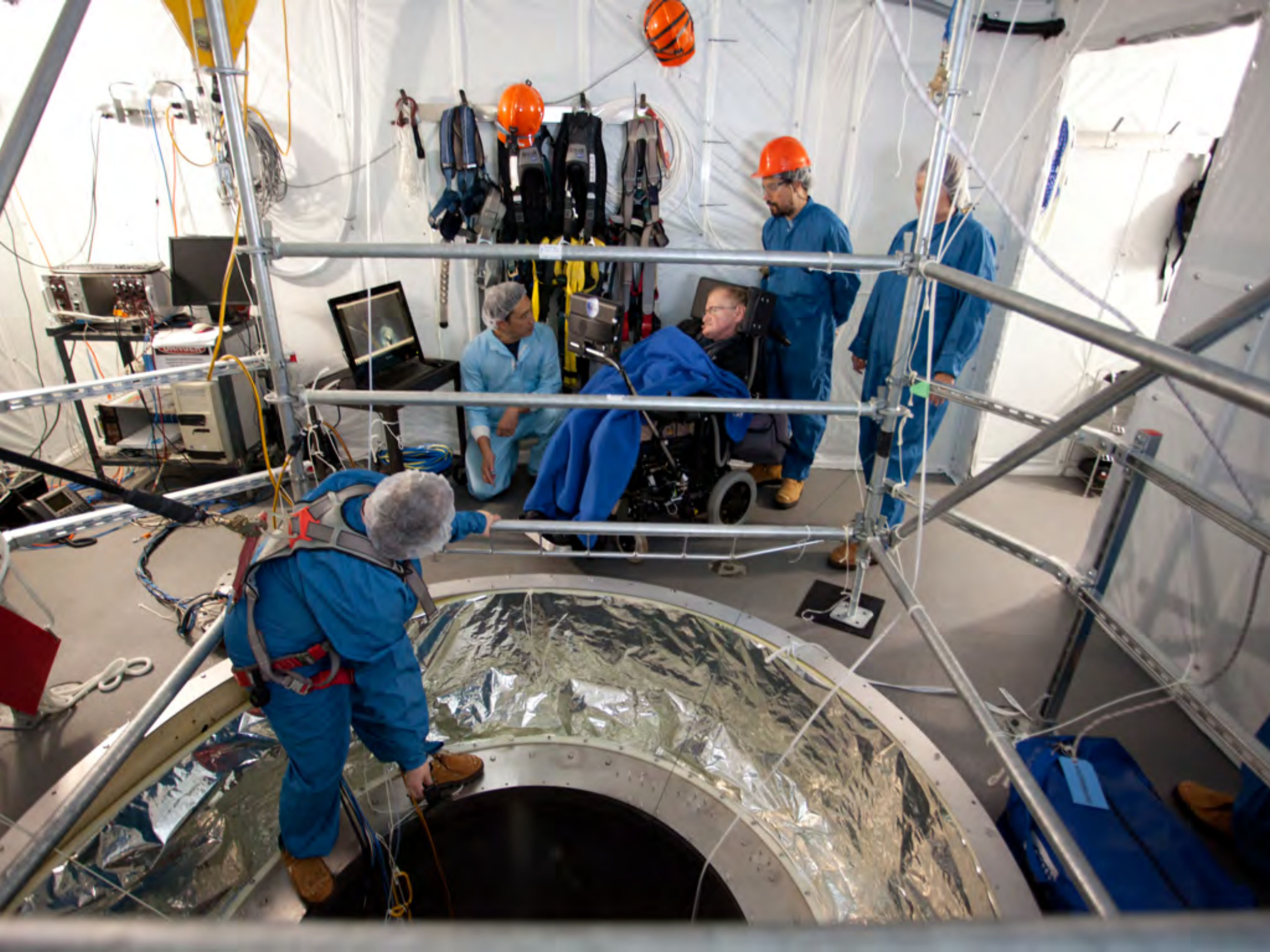
SNO+ Status

- Rope net installation co
- Cleaning complete
- Electronics upgrade co
- Cameras installed
- Successful `air-fill' runn
- Water in the cavity!

Highlights

SNO+ Status

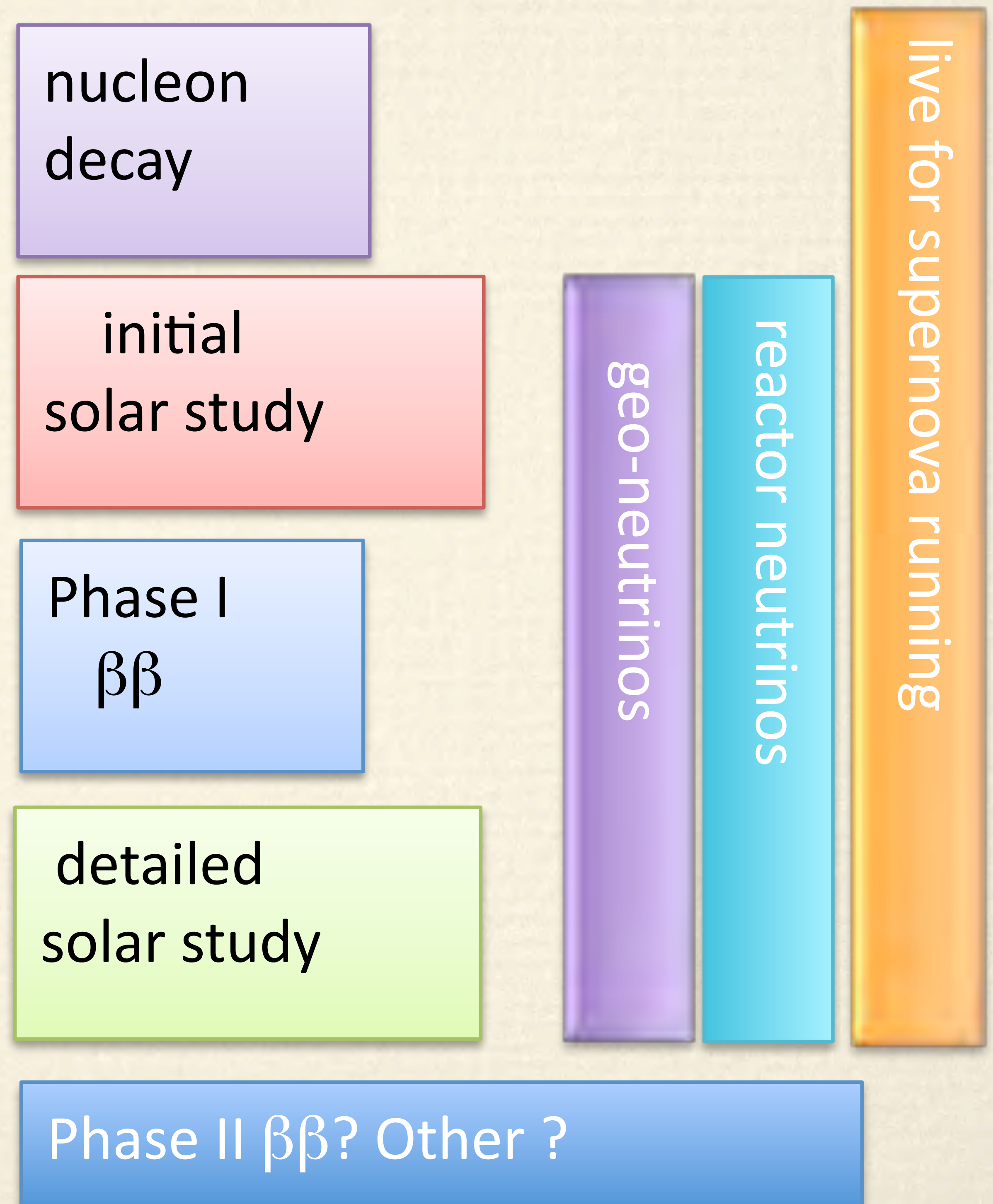
- Rope net installation c
- Cleaning complete
- Electronics upgrade co
- Cameras installed
- Successful `air-fill’ run
- Water in the cavity!
- Stephen Hawking comes to visit



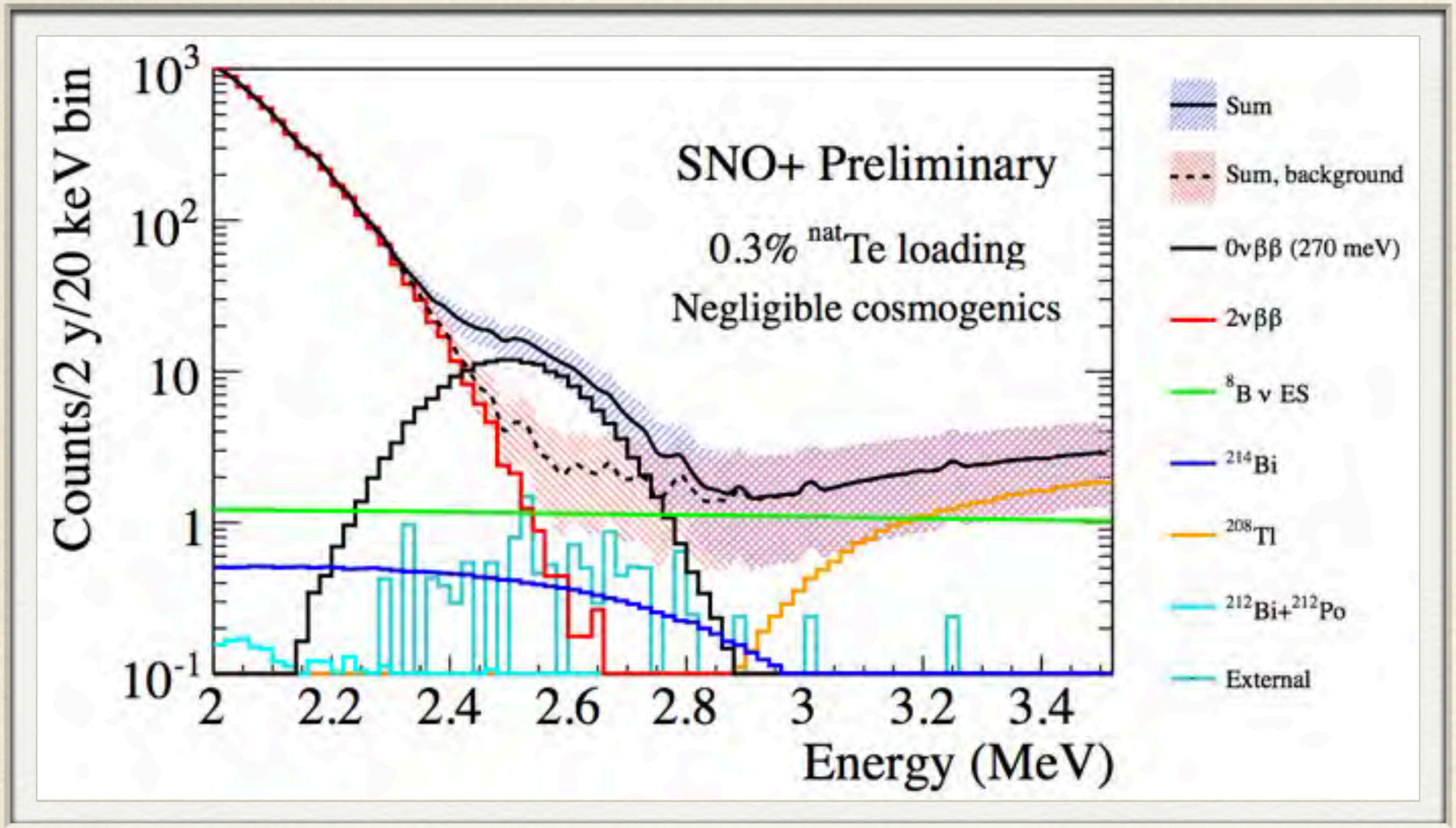

X-MEN

Physics Plan

- Light Water fill
  (Now!)
- Scintillator fill
  (Summer 2014)
- Te-loaded scintillator
  (Late 2014)
- Pure scintillator (II)
  (2017?)



SNO+ Sensitivity



Assumptions:

- 100% detection efficiency
- Background rejection efficiencies
- AV/PMT r/a at SNO-proposal levels

- **Input parameters:**
  - $m_{\beta\beta}$ = 270meV
  - NME = 4.03 (IBM-2)
  - G = 3.69 x 10^{-14} /y (g_A =1.269)
- 0.3% natural Te
- 2 years live time
- Optics from ex-situ (Penn/BNL)
- 3.5m fiducial volume (20%)

Requirements for 0νββ Sensitivity

Requirements for $0\nu\beta\beta$ Sensitivity

(1) Short half-life for given neutrino mass

a) Large phase space factor

b) Large NME

Requirements for 0νββ Sensitivity

(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 r/a bkg)
  b) High 0ν/2ν ratio and/or good E resolution
  c) Background rejection techniques

Requirements for 0νββ Sensitivity

(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 r/a bkg)
  b) High 0ν/2ν ratio and/or good E resolution
  c) Background rejection techniques

(3) Large number of 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

Sensitivity Calculations

$$T^{0\nu}_{1/2} = \frac{ln(2)}{n_\sigma} \frac{N_A \; a \; \eta \; \epsilon}{W} \sqrt{\frac{M \; t}{b \; \delta E}} \; f\,(\delta E)$$

Sensitivity Calculations

- Standard sensitivity calculation:

$$T^{0\nu}_{1/2} = \frac{ln(2)}{n_\sigma} \frac{N_A \; a \; \eta \; \epsilon}{W} \sqrt{\frac{M \; t}{b \; \delta E}} \; f\left(\delta E\right)$$

Sensitivity Calculations

- Standard sensitivity calculation:

Exposure time

$$T^{0\nu}_{1/2} = \frac{ln(2)}{n_\sigma} \frac{N_A \, a \, \eta \, \epsilon}{W} \sqrt{\frac{M \, t}{b \, \delta E}} \, f\,(\delta E)$$

Number of sigma

1. *Fixed factors*

Sensitivity Calculations

- Standard sensitivity calculation:

Isotopic abundance

Exposure time

$$T^{0\nu}_{1/2} = \frac{ln(2)}{n_\sigma} \frac{N_A \, a \, \eta \, \epsilon}{W} \sqrt{\frac{M \, t}{b \, \delta E}} \, f(\delta E)$$

Number of sigma

Molecular weight

1. *Fixed factors*
2. *Isotope-dependent*

Sensitivity Calculations

- Standard sensitivity calculation:

Isotopic abundance

Total mass (target e.g. TeO2)

Detector efficiency

Exposure time

$$T^{0\nu}_{1/2} = \frac{ln(2)}{n_\sigma} \frac{N_A \, a \, \eta \, \epsilon}{W} \sqrt{\frac{M \, t}{b \, \delta E}} \, f\,(\delta E)$$

Signal acceptance

Number of sigma

Molecular weight

Energy ROI

Background rate

1. *Fixed factors*
2. *Isotope-dependent*
3. *Experimental technique*

Sensitivity Calculations

- Standard sensitivity calculation:

$$T^{0\nu}_{1/2} = \frac{ln(2)}{n_\sigma} \frac{N_A \, a \, \eta \, \epsilon}{W} \sqrt{\frac{M \; t}{b \; \delta E}} \; f\left(\delta E\right)$$

Isotopic abundance (a)
Detector efficiency (ϵ)
Total mass (target e.g. TeO2) (M)
Exposure time (t)
Signal acceptance ($f(\delta E)$)
Number of sigma (n_σ)
Molecular weight (W)
Energy ROI (δE)
Background rate (b)

1. *Fixed factors*
2. *Isotope-dependent*
3. *Experimental technique*

Assumes backgrounds scale with target mass

Sensitivity Calculations

$$B(\delta E) = b\ M\ \delta E\ t$$

Sensitivity Calculations

- If backgrounds scale with mass: $B(\delta E) = b\ M\ \delta E\ t$

Sensitivity Calculations

- If backgrounds scale with mass: $B(\delta E) = b\ M\ \delta E\ t$
- If backgrounds do not scale with mass:

$$B(\delta E) = (b\ M\ +\ c)\ \delta E\ t$$

Sensitivity Calculations

- If backgrounds scale with mass: $B(\delta E) = b\ M\ \delta E\ t$
- If backgrounds do not scale with mass:

$$B(\delta E) = (b\ M\ +\ c)\ \delta E\ t$$

- $\Rightarrow$ more accurate formula:

$$T^{0\nu}_{1/2} = \frac{ln(2)\ N_{isotope}}{n_\sigma} \frac{t}{\sqrt{(b\ M\ +\ C)\ \delta E\ t}}\ f\,(\delta E)$$

Sensitivity Calculations

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b: 2ν, cosmogenics, LS cocktail

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b: 2ν, cosmogenics, LS cocktail
c: 8B, external γs (AV, PMTs), LAB $\Leftarrow$ ***dominant!***

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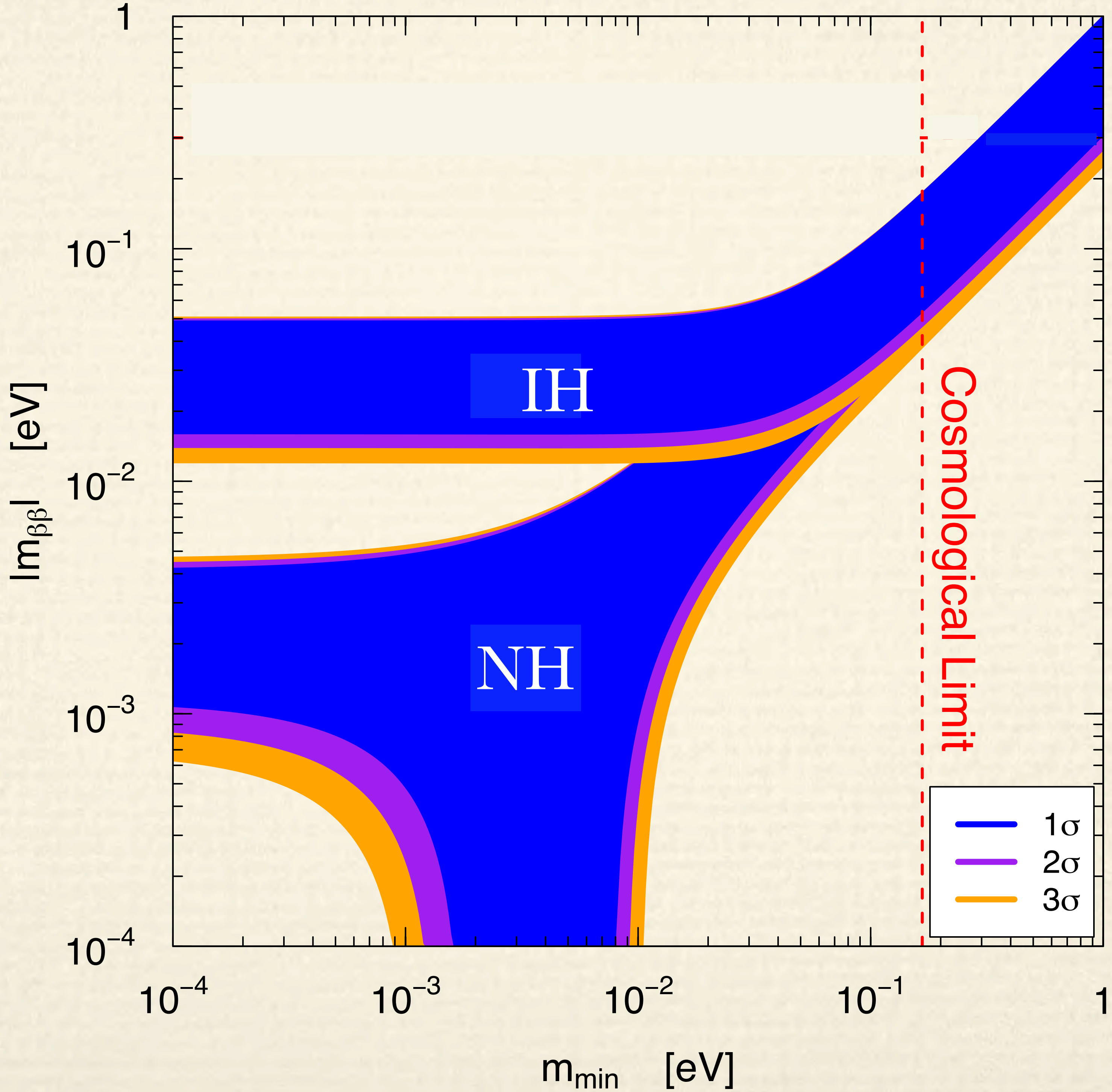
b: 2ν, cosmogenics, LS cocktail
c: 8B, external γs (AV, PMTs), LAB $\Leftarrow$ ***dominant!***

bM < C $\Rightarrow$ **$m_{\beta\beta}$ scales with $M^{1/2}$** NOT $M^{1/4}$

Status of the Field



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

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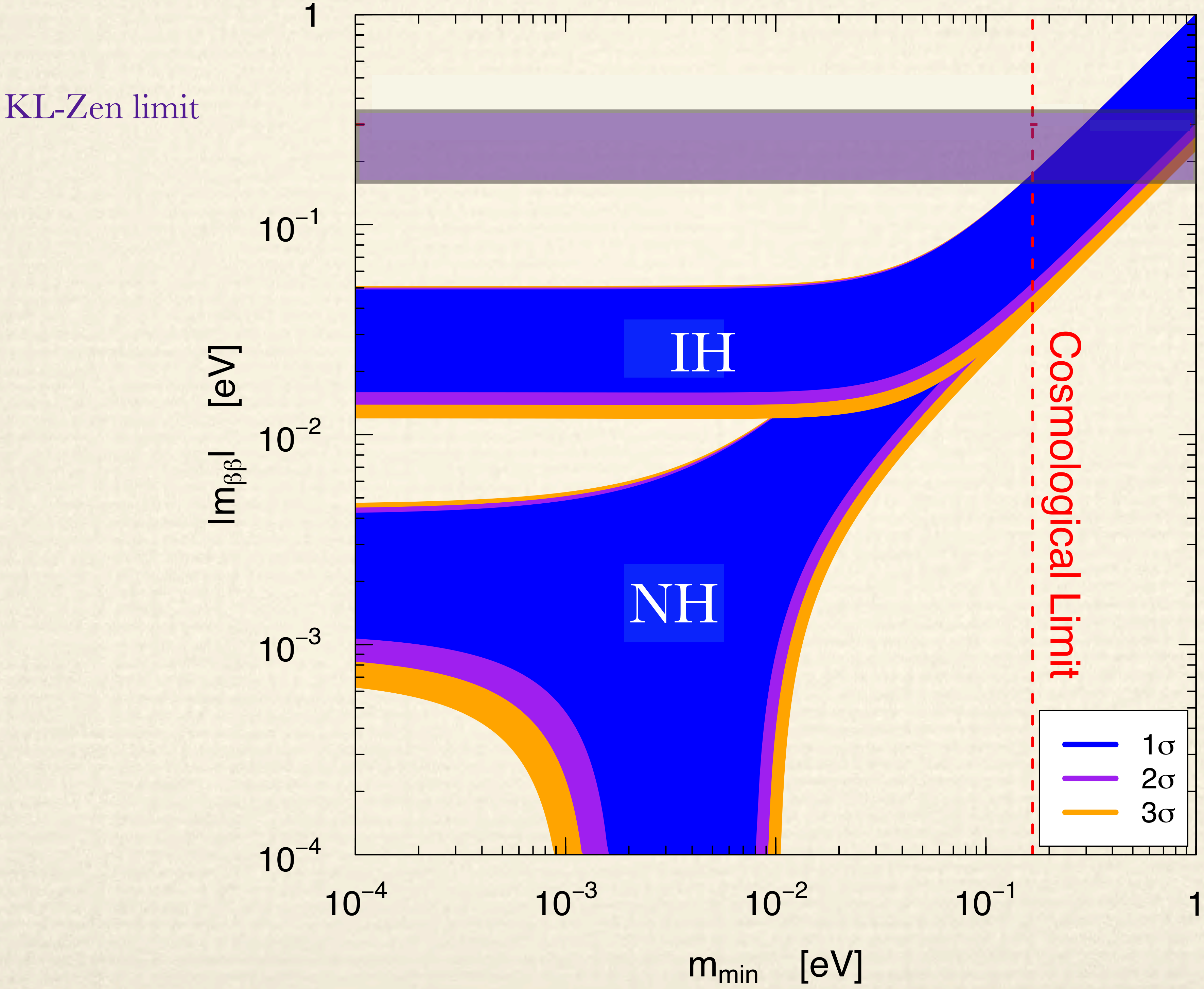

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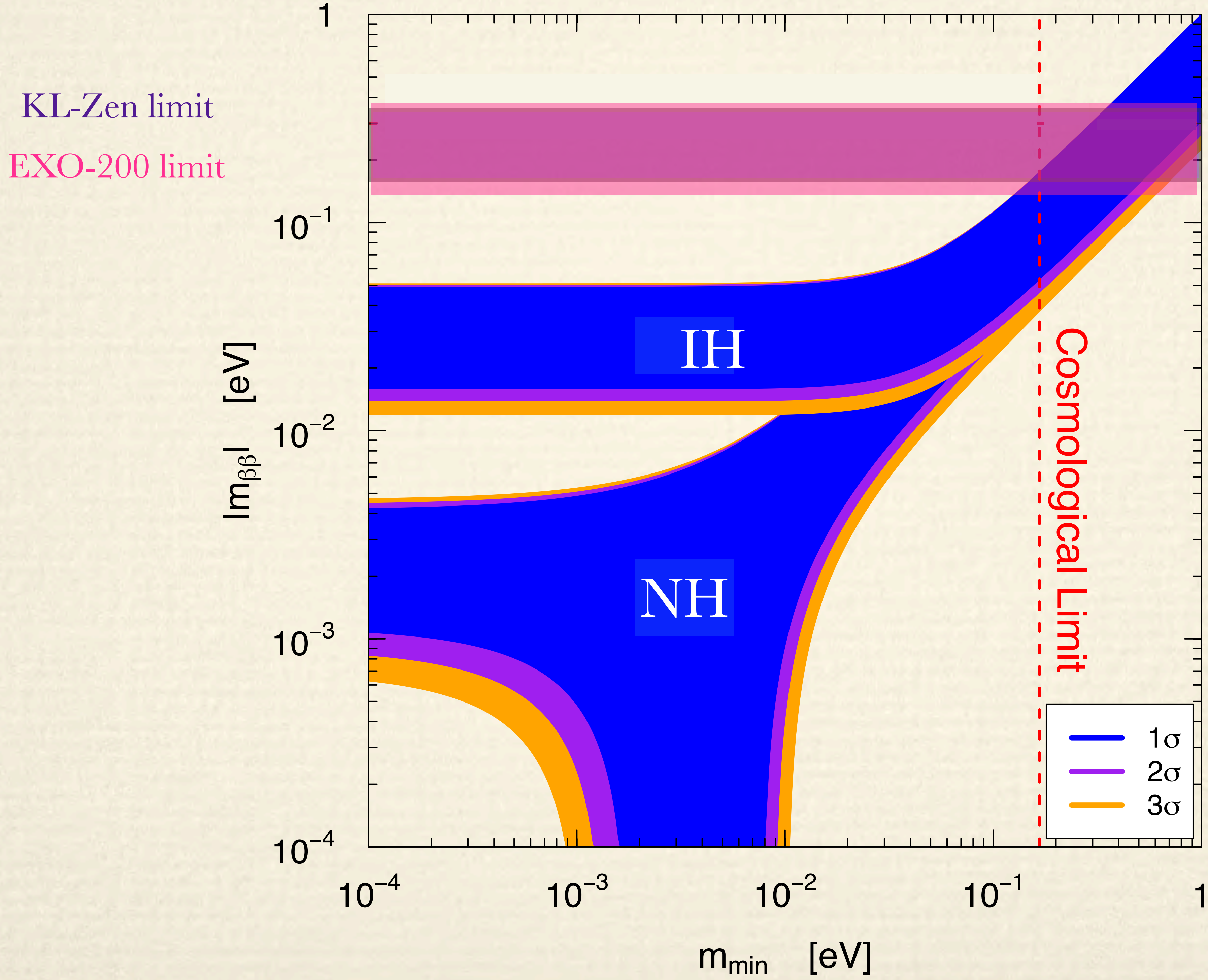

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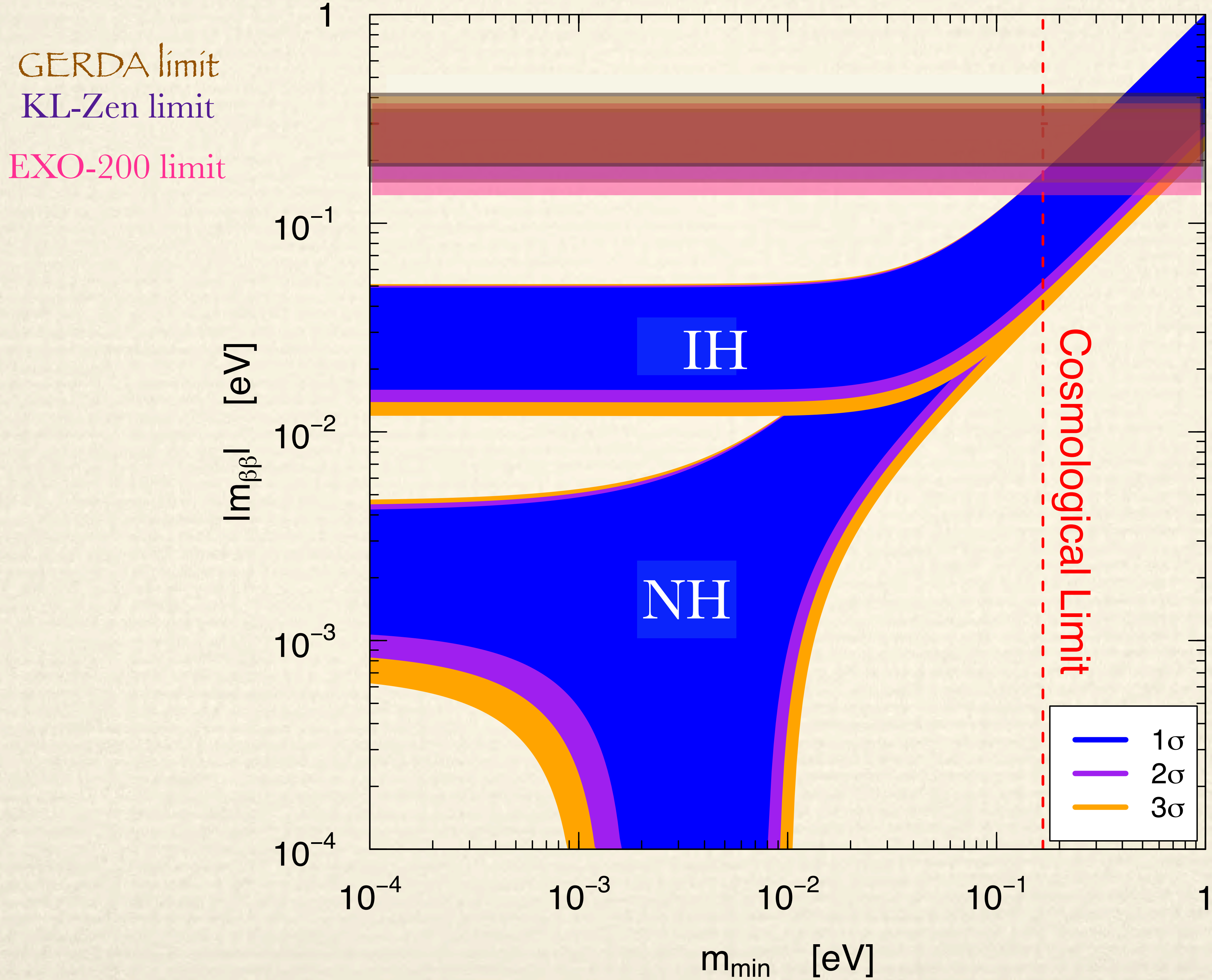
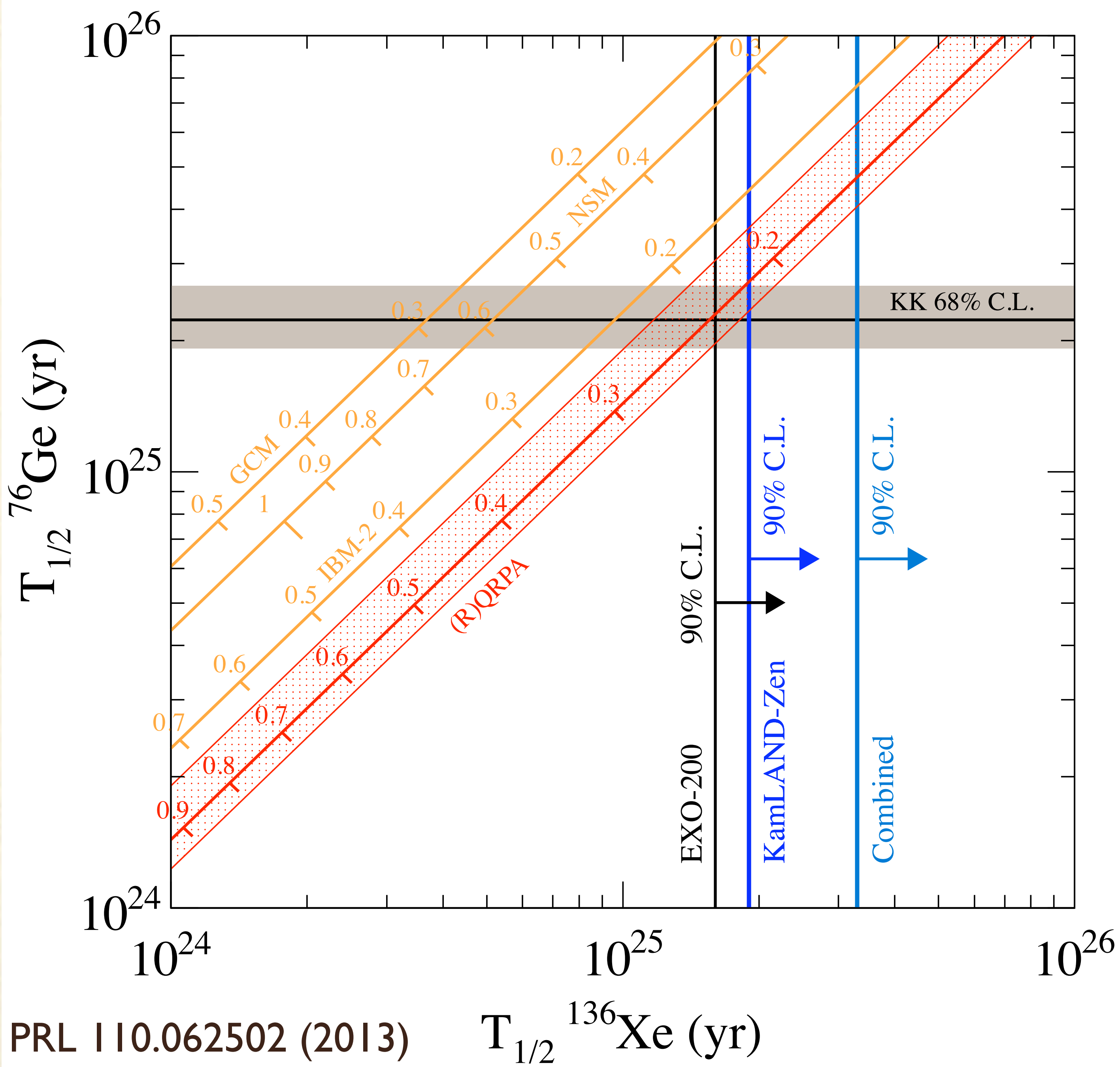


S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

An Alternative View

- More direct comparison of 2 isotopes
- Challenging when we have data from 3+...



PRL 110.062502 (2013)

An Alternative View

- More direct comparison of 2 isotopes
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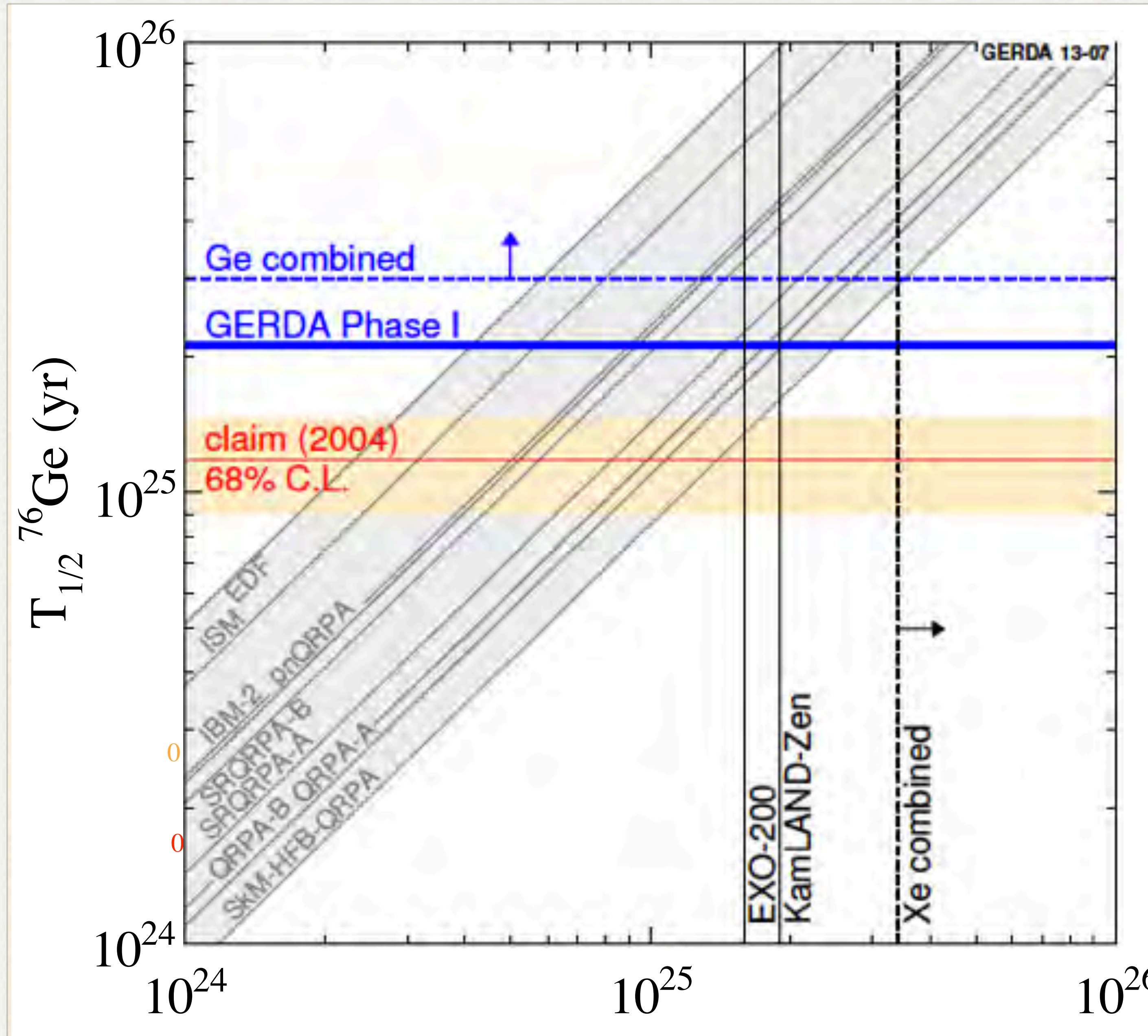

arXiv:1307.4720 (2013)

An Alternative View

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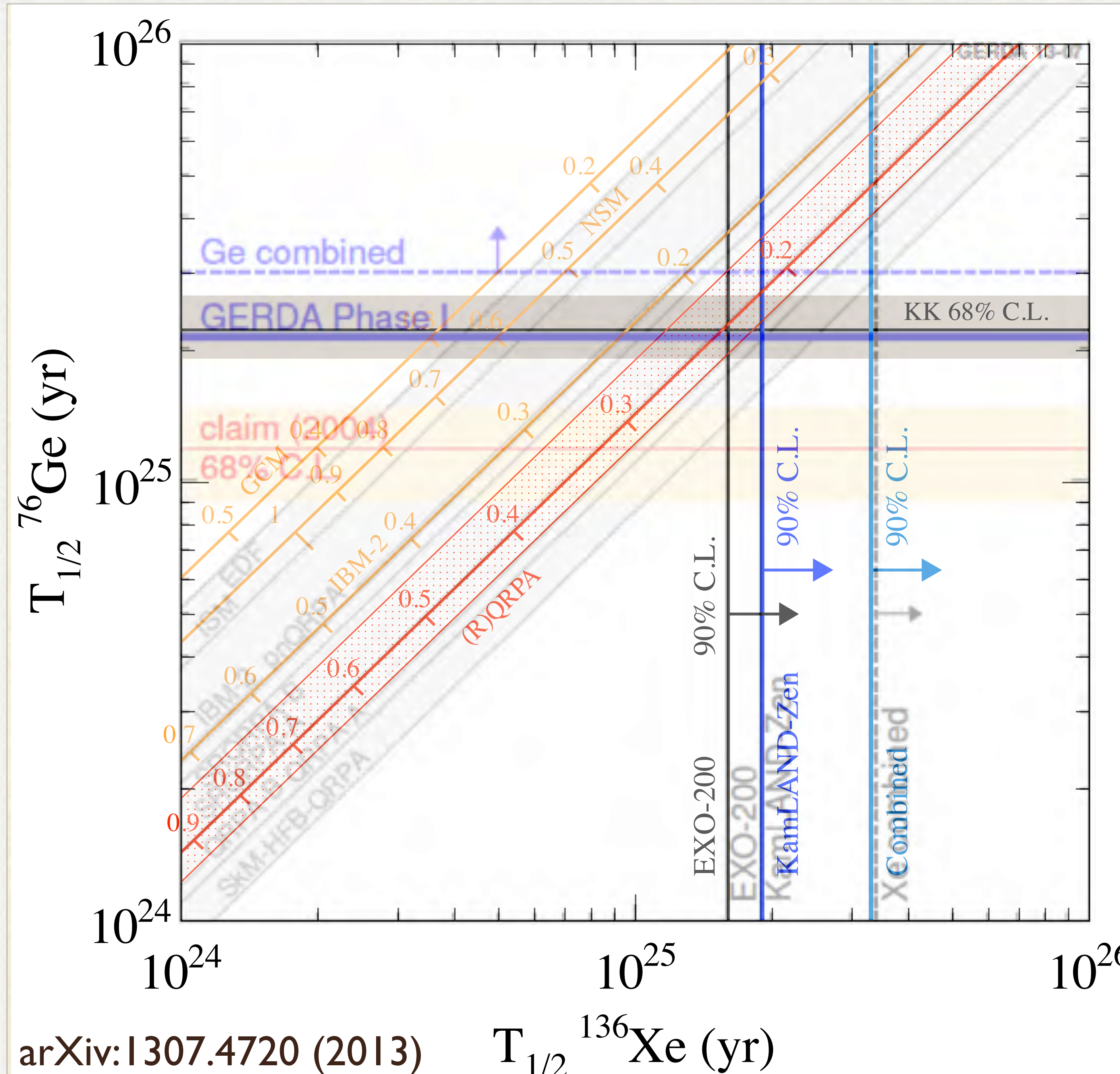

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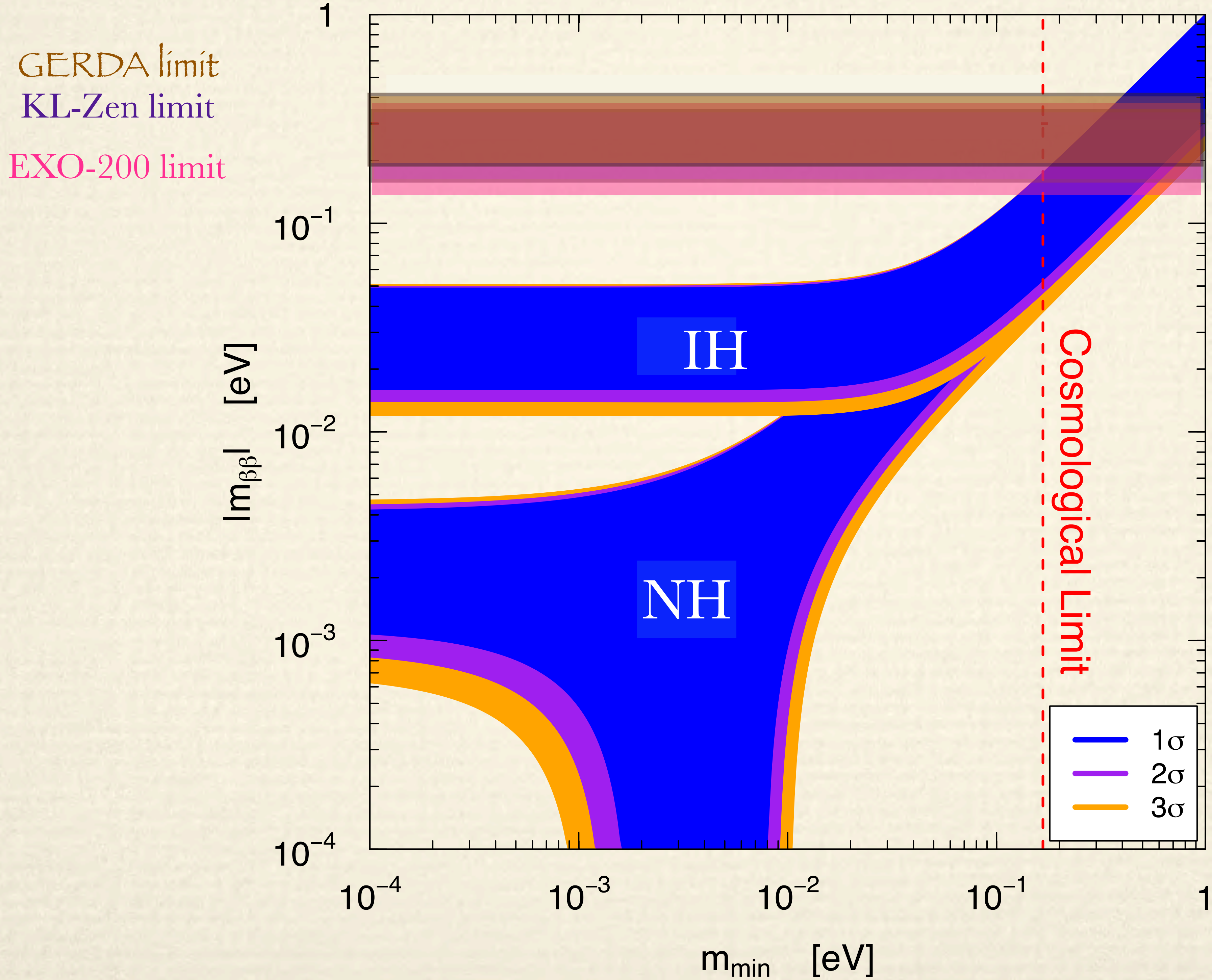
Future Plans: Probing the MH?



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

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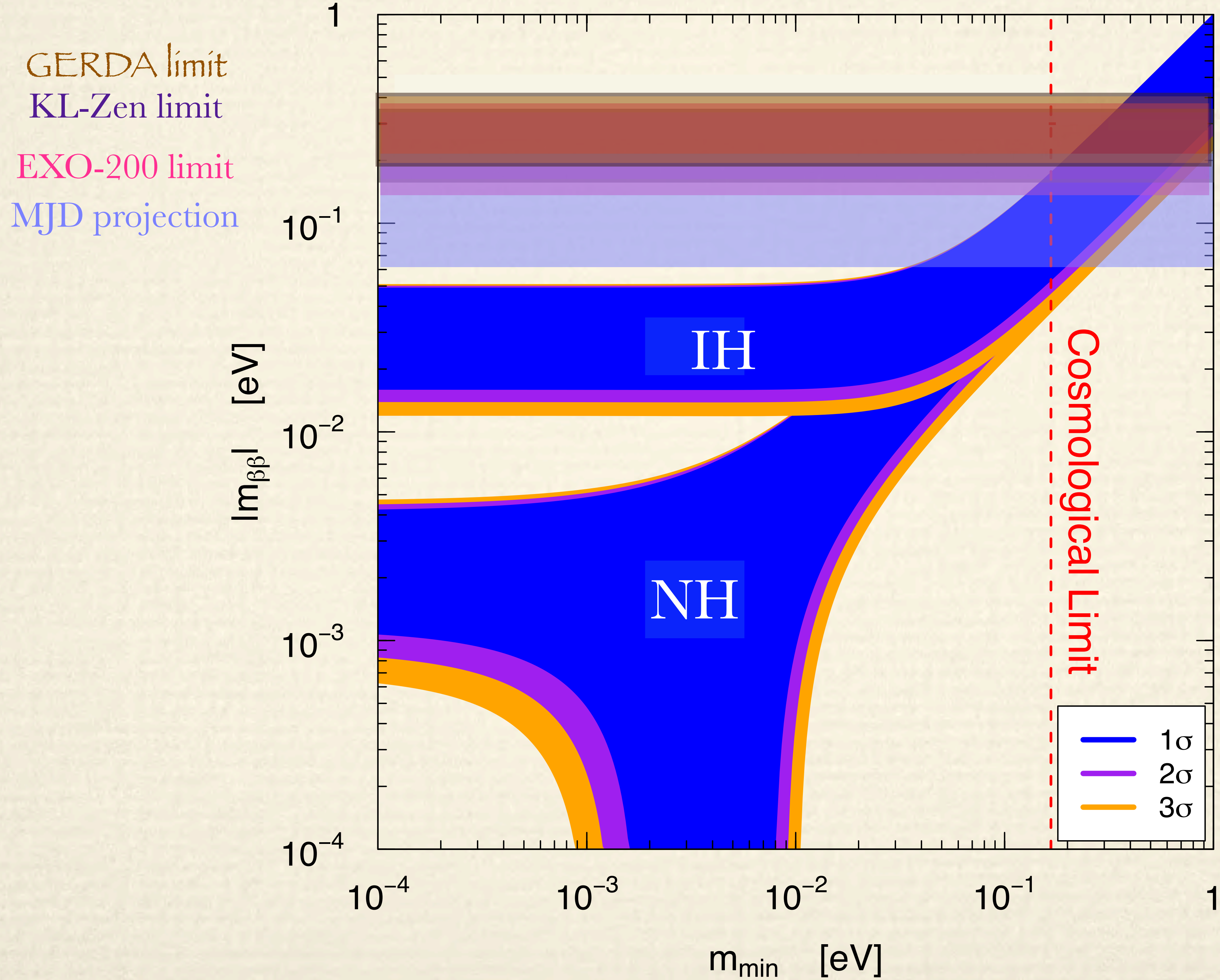

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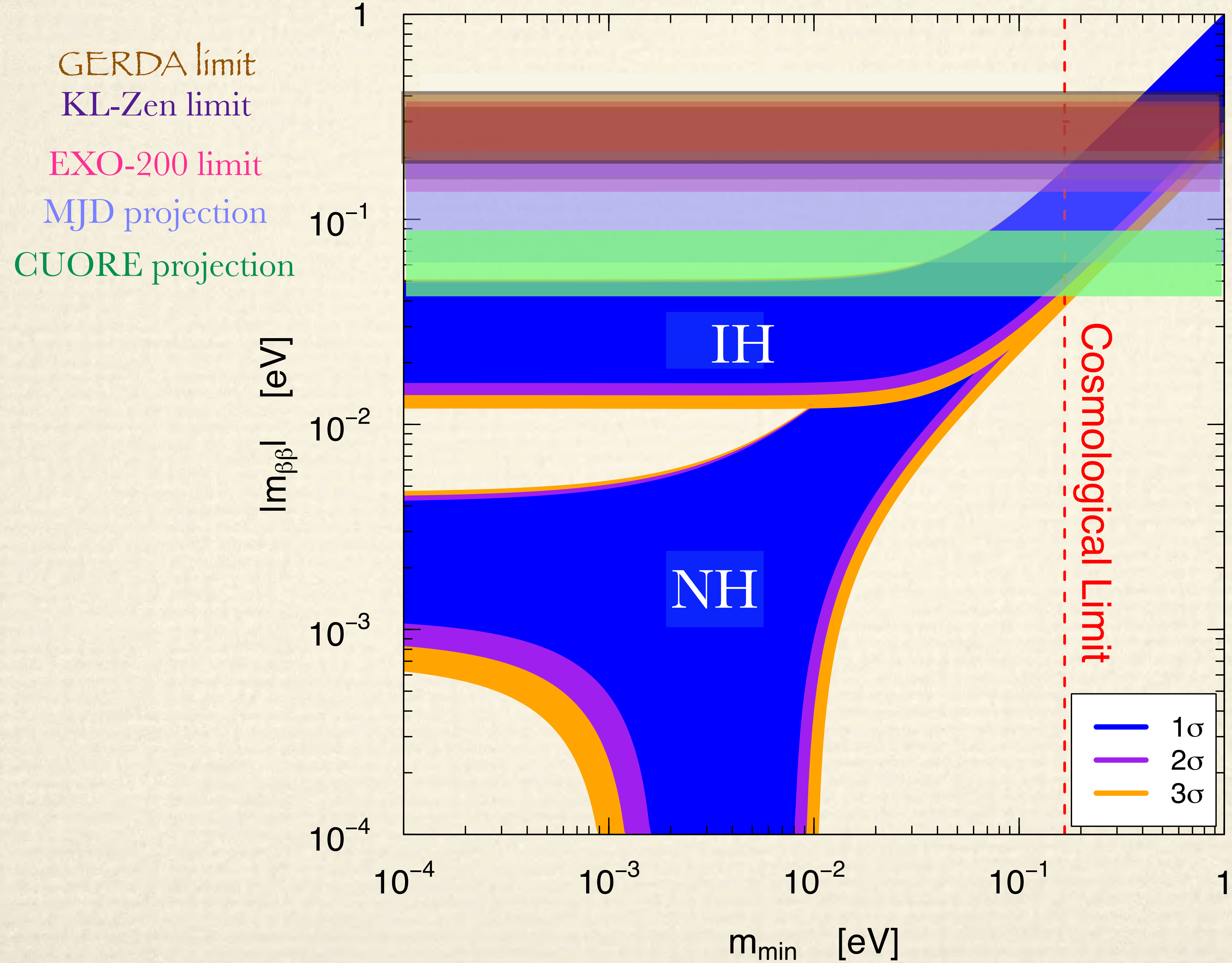

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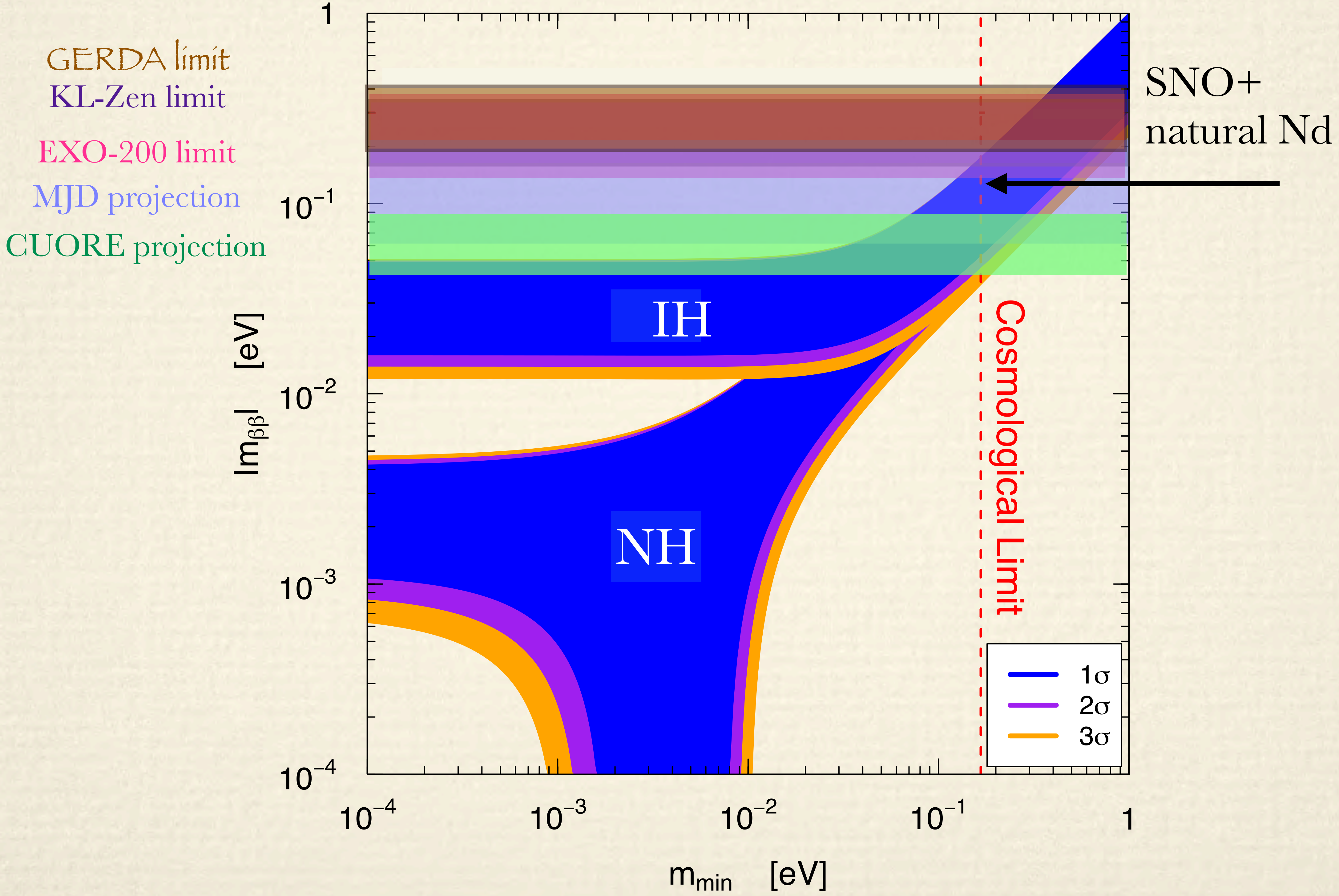

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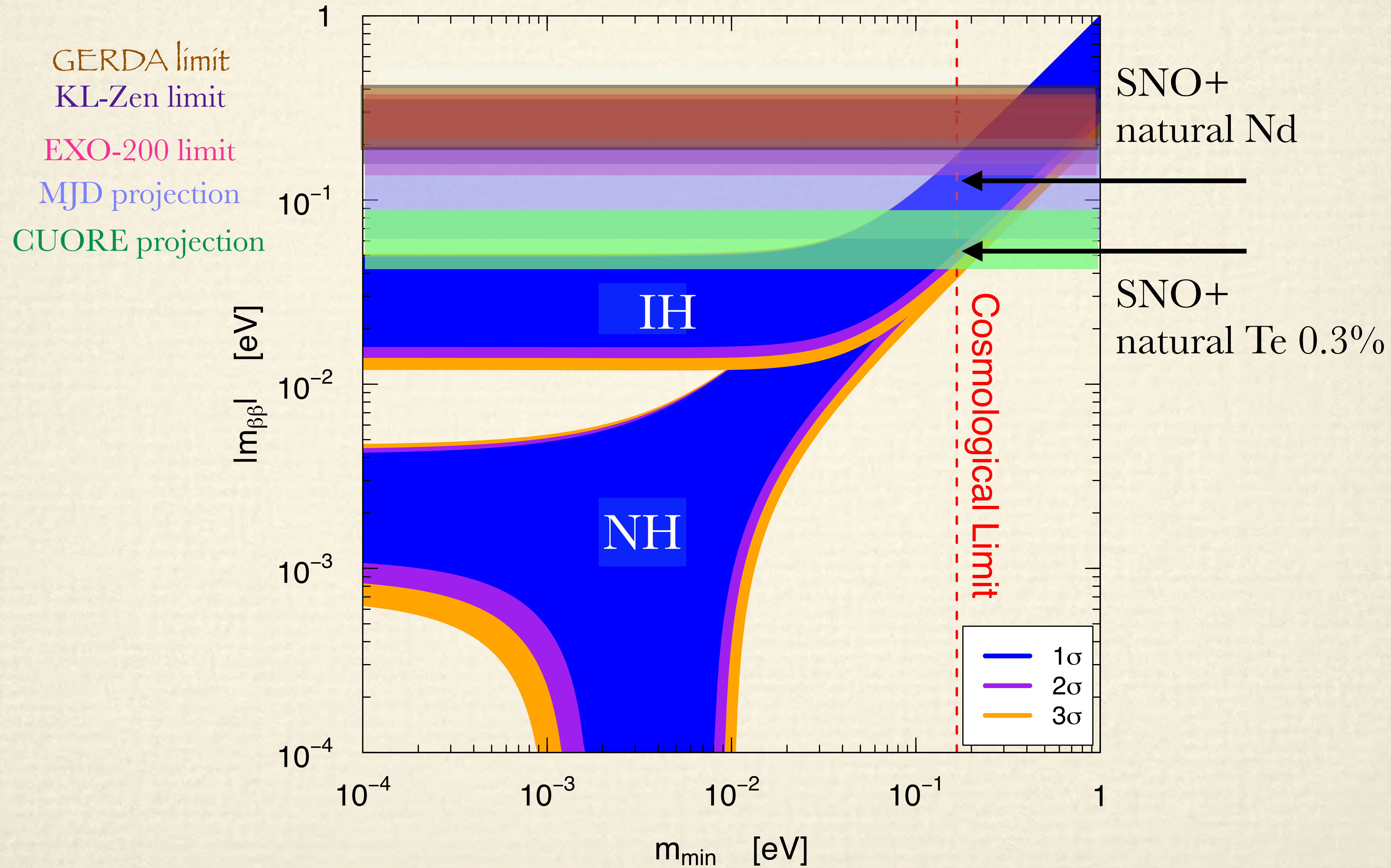

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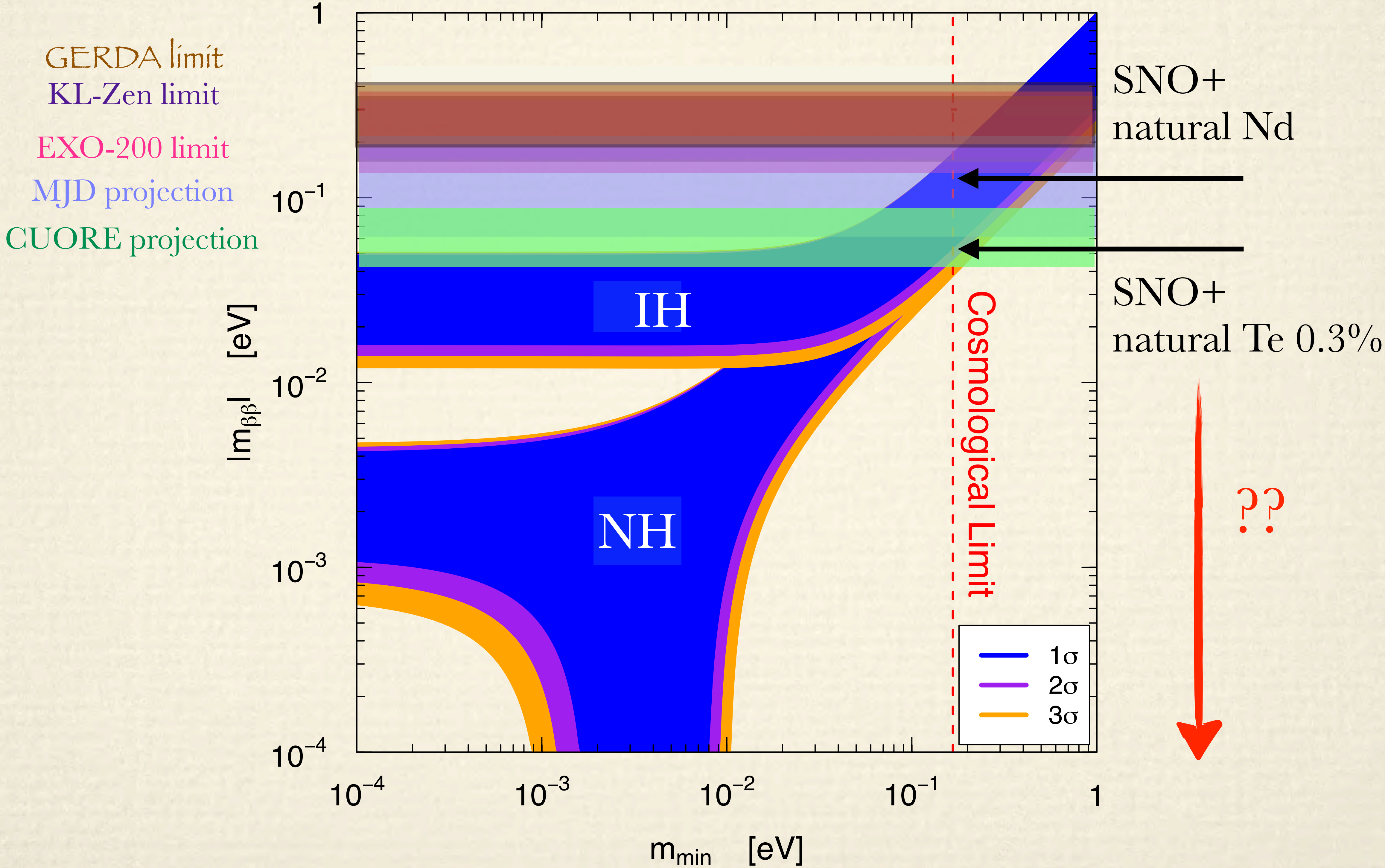
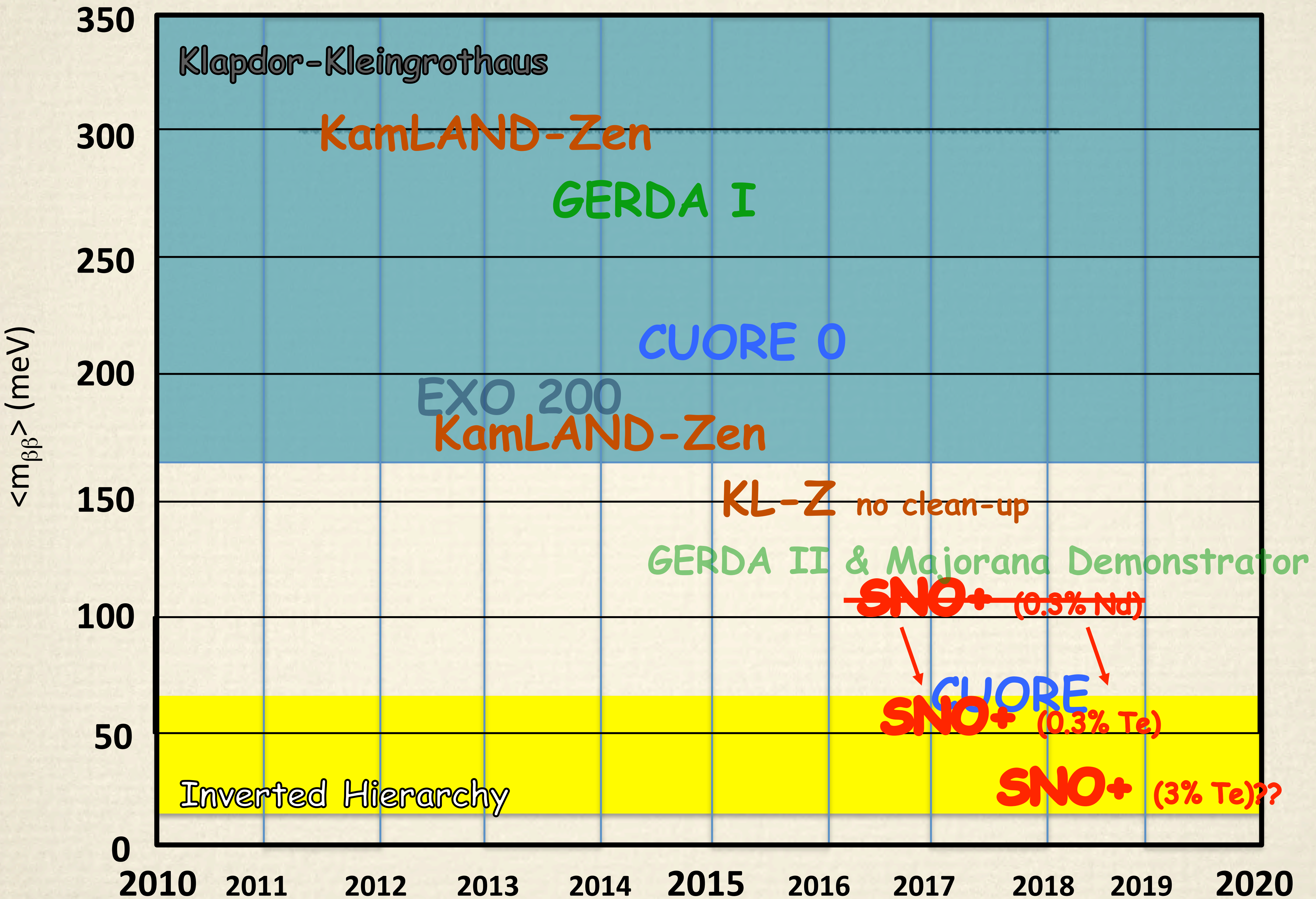


S. M. Bilenky & C. Giunti, Mod. Phys. Lett. A27, 1230015 (2012)

Running Approved R&D

Current / Proposed Experiments

Experiment	Isotope	Mass [kg]	$\Gamma^{0\nu}_{1/2}$ [y]	$m_{\beta\beta}$ [meV]	Timescale
CUORE-0 CUORE	^{130}Te	11 206	9×10^{24} 1×10^{26}	170-390 50-120	2013-2015 2014-2019
GERDA-I GERDA-II **GERDA-III	^{76}Ge	15 40 1000	2×10^{25} 2×10^{26} 6×10^{27}	200-650 65-200 10-40	2010-2013 2013-2015 2016-2025
MJD **MAJORANA	^{76}Ge	33 1000	9×10^{25} 6×10^{27}	94-300 10-40	2013-2014 2016-2025
EXO-200 nEXO	^{136}Xe	200 5000	6×10^{25} 2×10^{27}	130-190 11-30	2010-2014 2015-2025
SuperNEMO	^{82}Se	100-200	$(1\text{-}2)\times10^{26}$	40-140	2013-2019
KamLAND-Zen	^{136}Xe	400 1000	4×10^{26} $\sim10^{27}$	40-80 25-50	2011-2013 2014-2016
SNO+	^{130}Te	800 8000	~	~	2014-2017 2017-2020



Klapdor-Kleingrothaus
KamLAND-Zen
GERDA I
CUORE 0
EXO 200
KamLAND-Zen
KL-Z no clean-up
GERDA II & Majorana Demonstrator
SNO+ (0.3% Nd)
CUORE
SNO+ (0.3% Te)
SNO+ (3% Te)??
Inverted Hierarchy
$<m_{\beta\beta}>$ (meV)
350
300
250
200
150
100
50
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

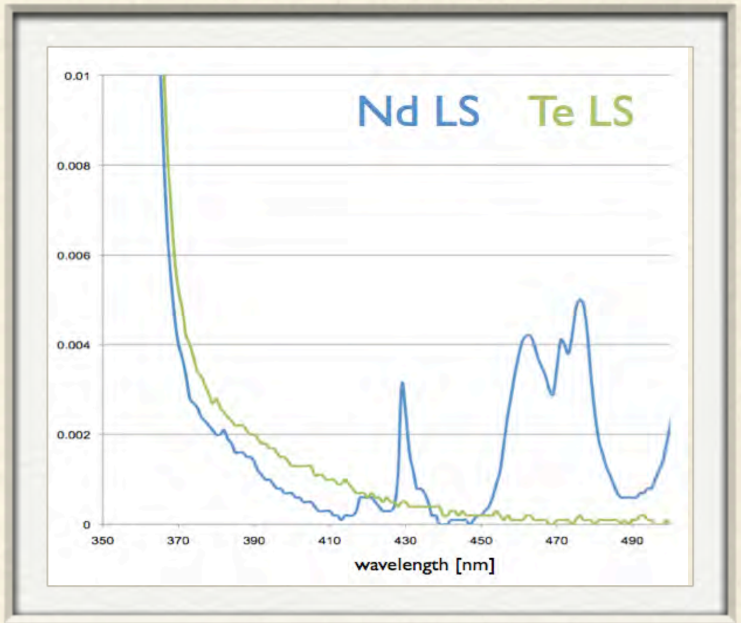
Open Questions

- Most current-generation experiments will ~reach the IH
- Next-gen experiments should aim to cover the IH
  - ★ *No demonstrated technique (need R&D)*
  - ★ *Hugely costly ~ O($50M - $500M)*
  - ★ *2020-2025*
  - ★ *Time pressure (correlated to other hierarchy expts)*
- We may need a plan for covering the NH
  - ★ *No suggested technique for achieving O(1meV)*
  - ★ *No guarantees ($m_{\beta\beta}$ can go to 0)*

PRD **87** 071301(R) (2013)

SNO+ Future Direction (?)

- 0.3% run: prototype for multi-T experiment
- WLS R&D:
  - *Increase light yield*
  - *Reduce correlation loading/optics*



- Upgrade path:
  - *Replace PMTs e.g. R5912-HQE plug-and-play (34%)*
  - *Replace concentrators*
- Pie in the Sky...
  - *Move PMTs to cavity walls*
    → 8kT volume "vessel"

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?

Thank you for your attention