KamLAND-Zen and the MAJORANA DEMONSTRATOR

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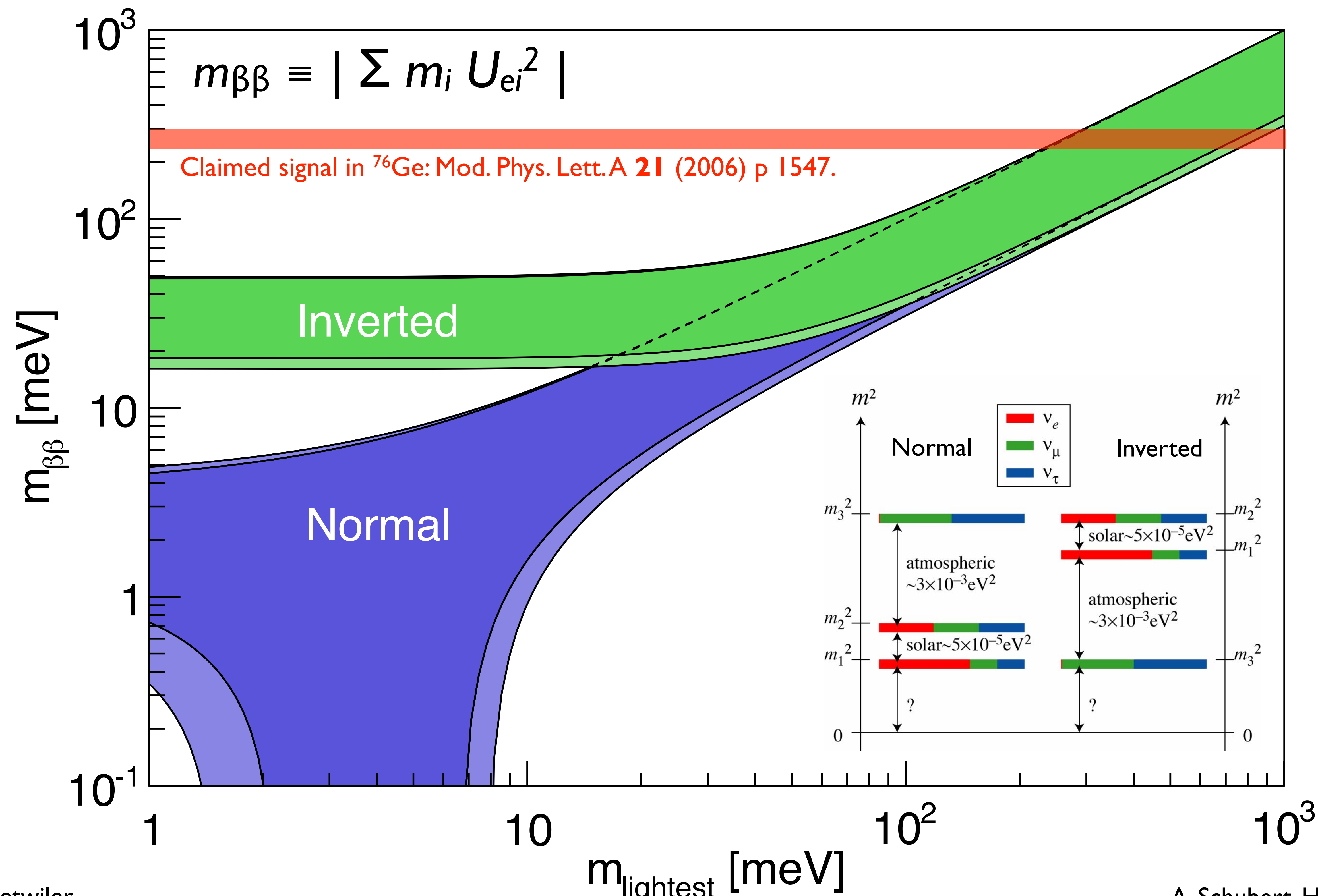
University of Washington

Nuclei and Fundamental Symmetries (INT-13-2b)
Seattle, Aug. 21 2013

Outline

- Recent motivations for large mass, low background experiments
- Large Mass: KamLAND-Zen
- Low-Background: MAJORANA DEMONSTRATOR

Double-Beta Decay



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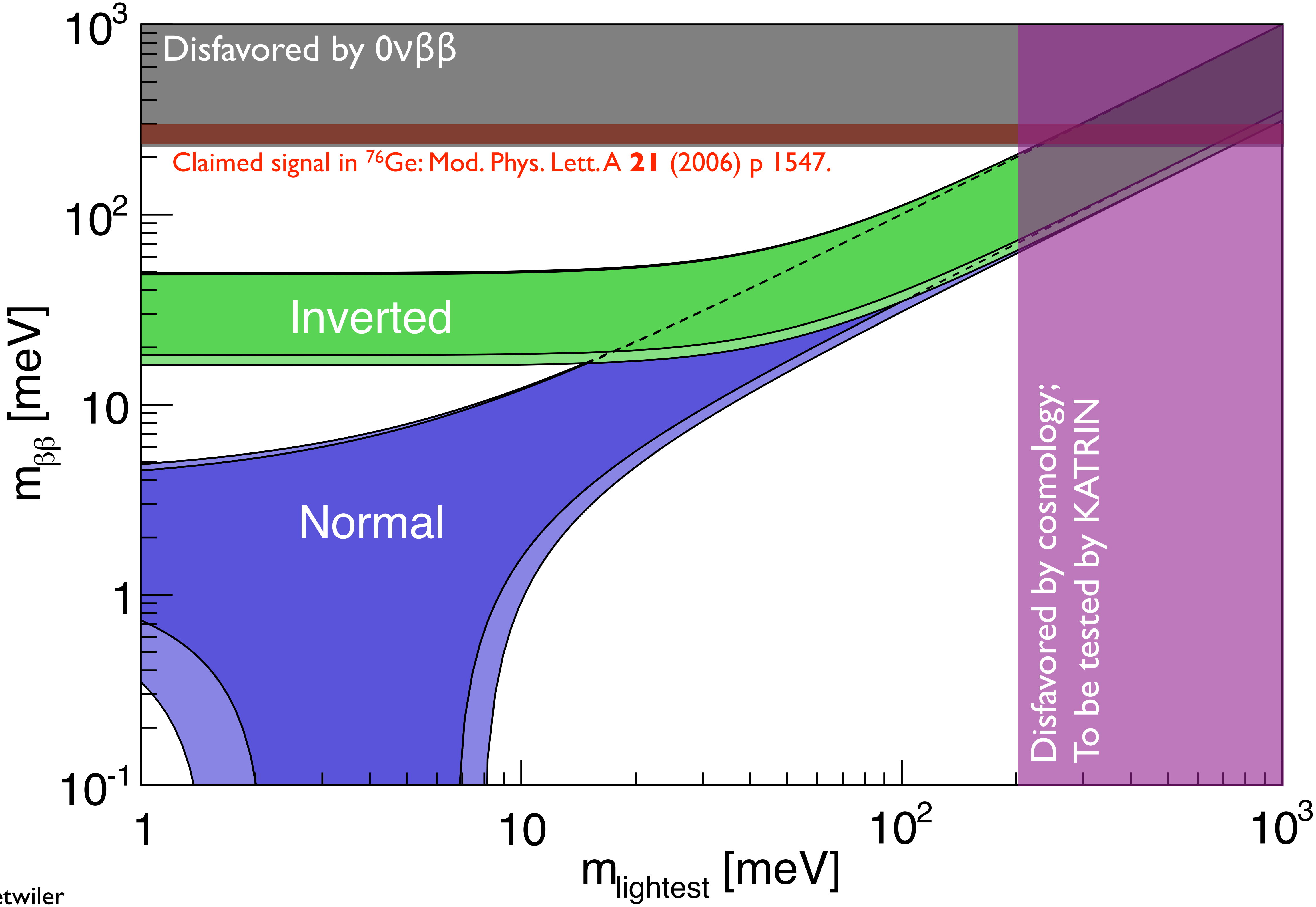
A. Schubert, H. Murayama

Double-Beta Decay



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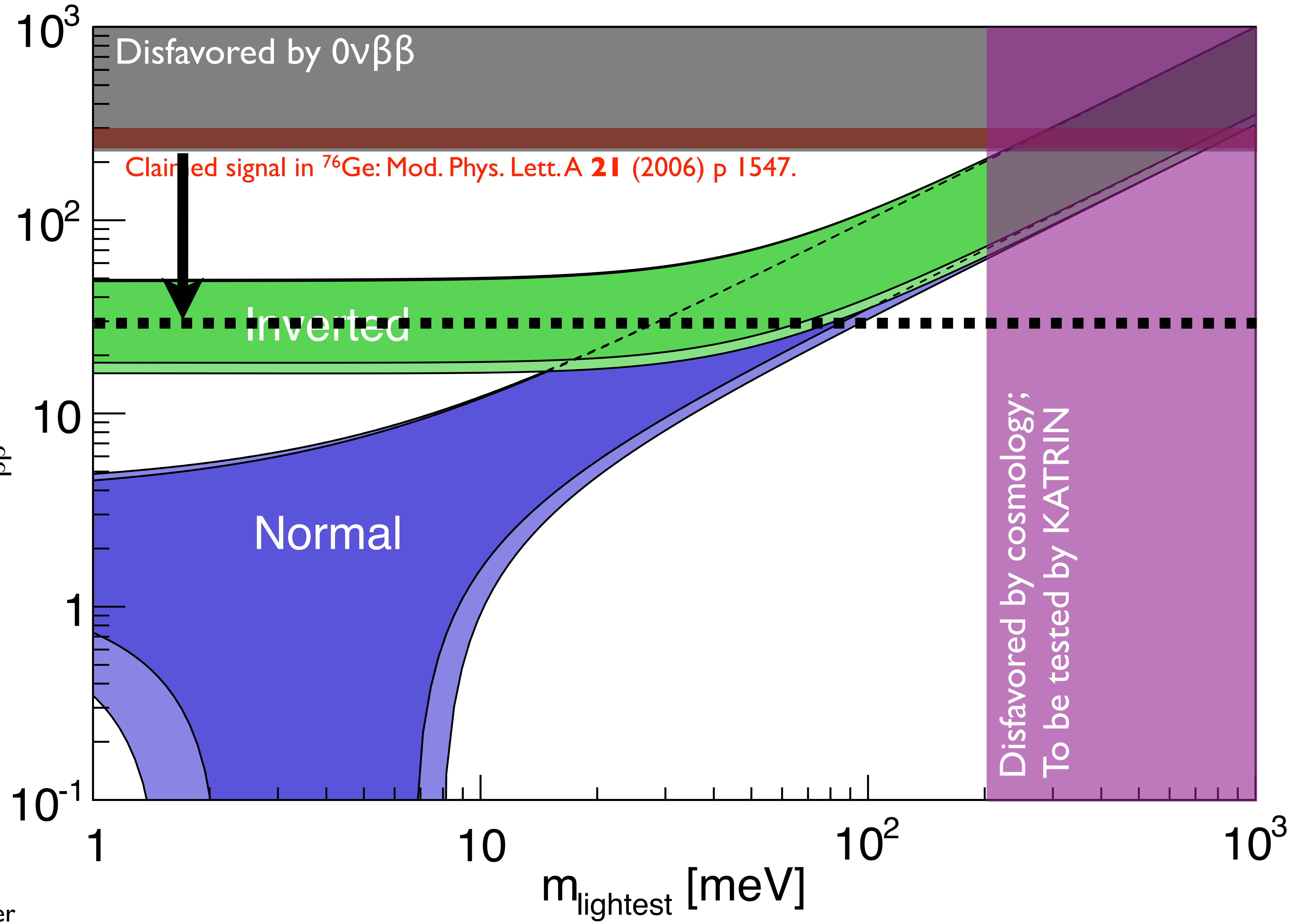
Double-Beta Decay



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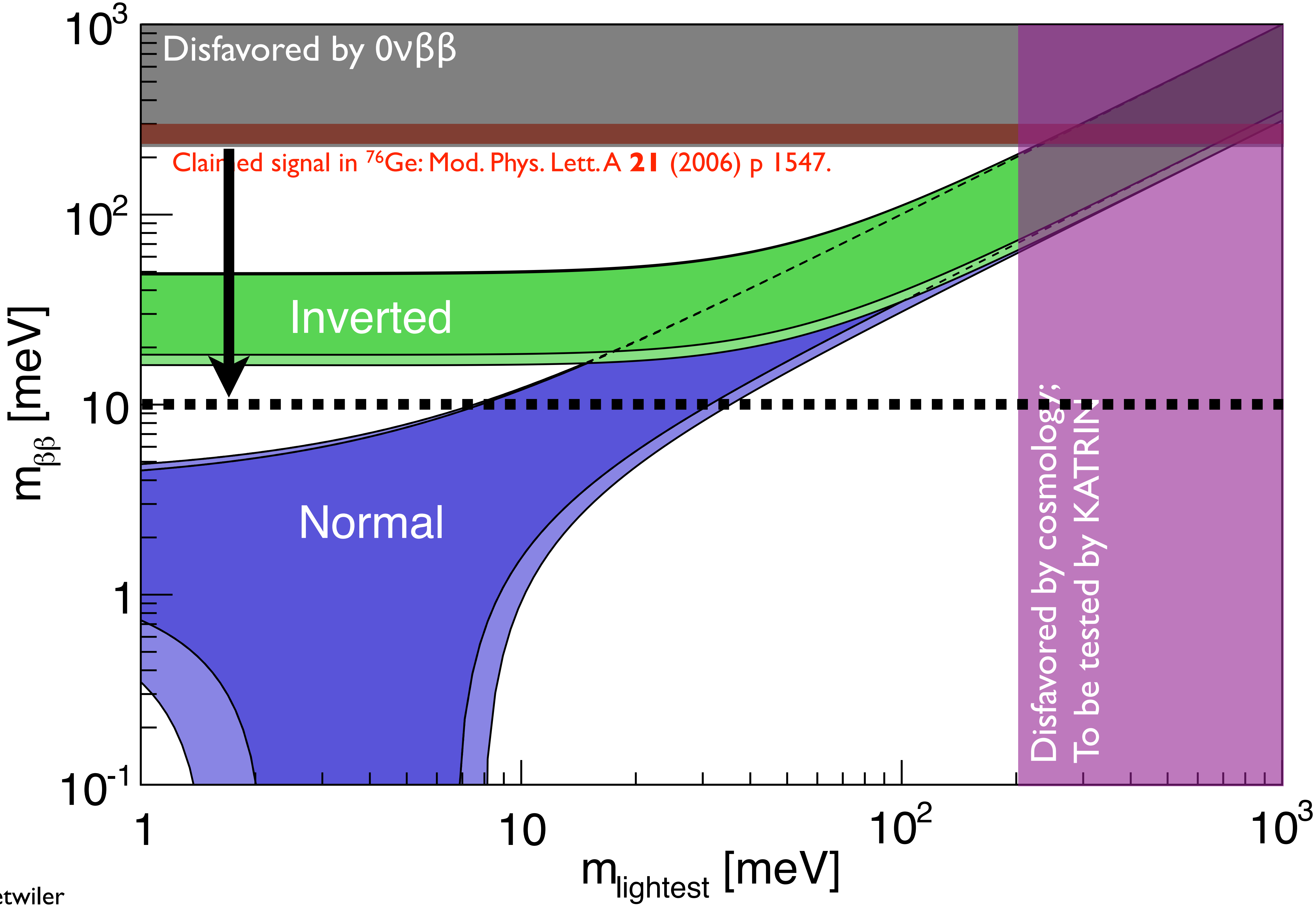
Double-Beta Decay



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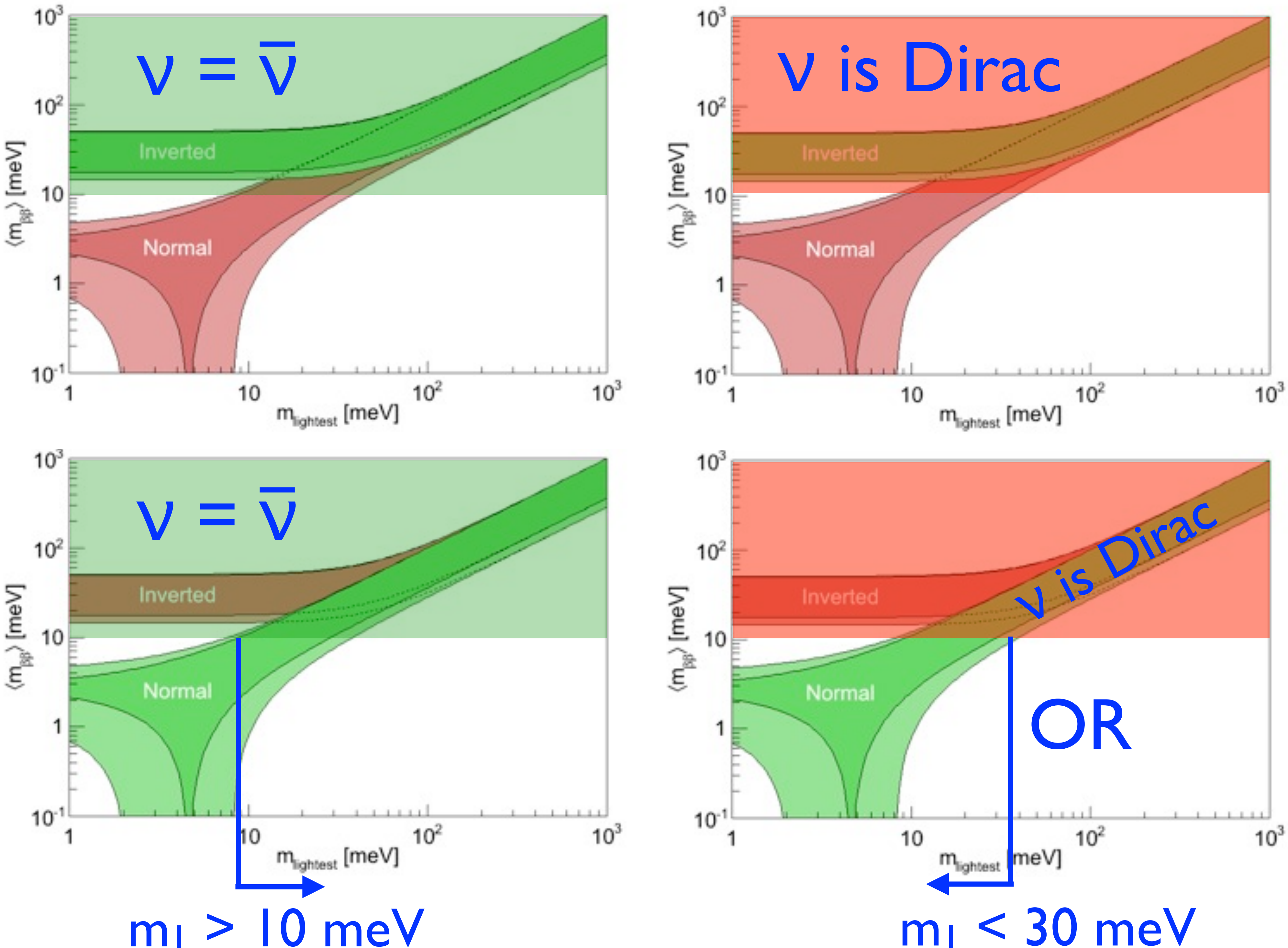
Combination with ν Oscillation

Next-Generation 0νββ Decay

Observed — Not observed

ν Oscillation: Hierarchy — Inverted / Normal



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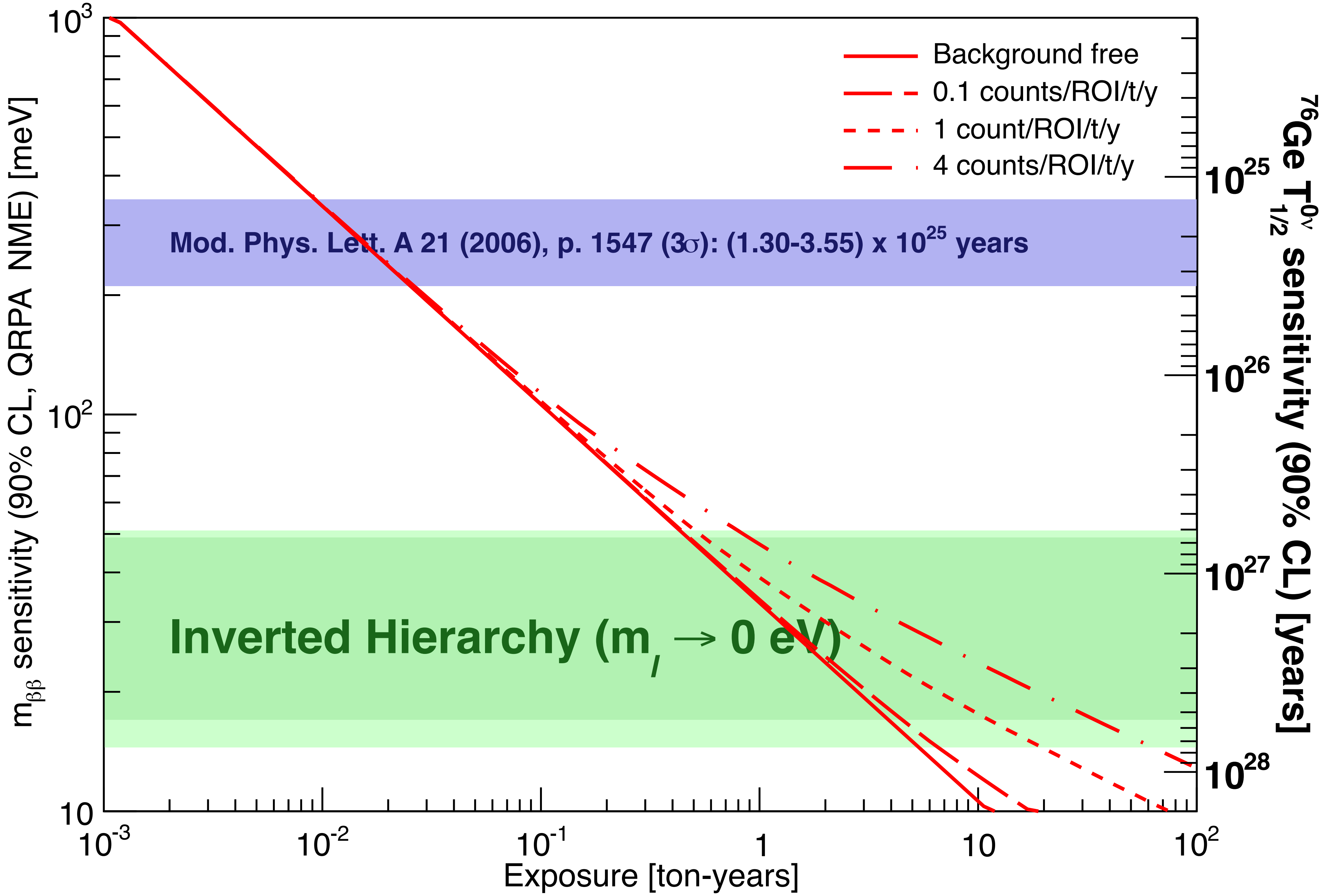
Inverted Hierarchy Sensitivity



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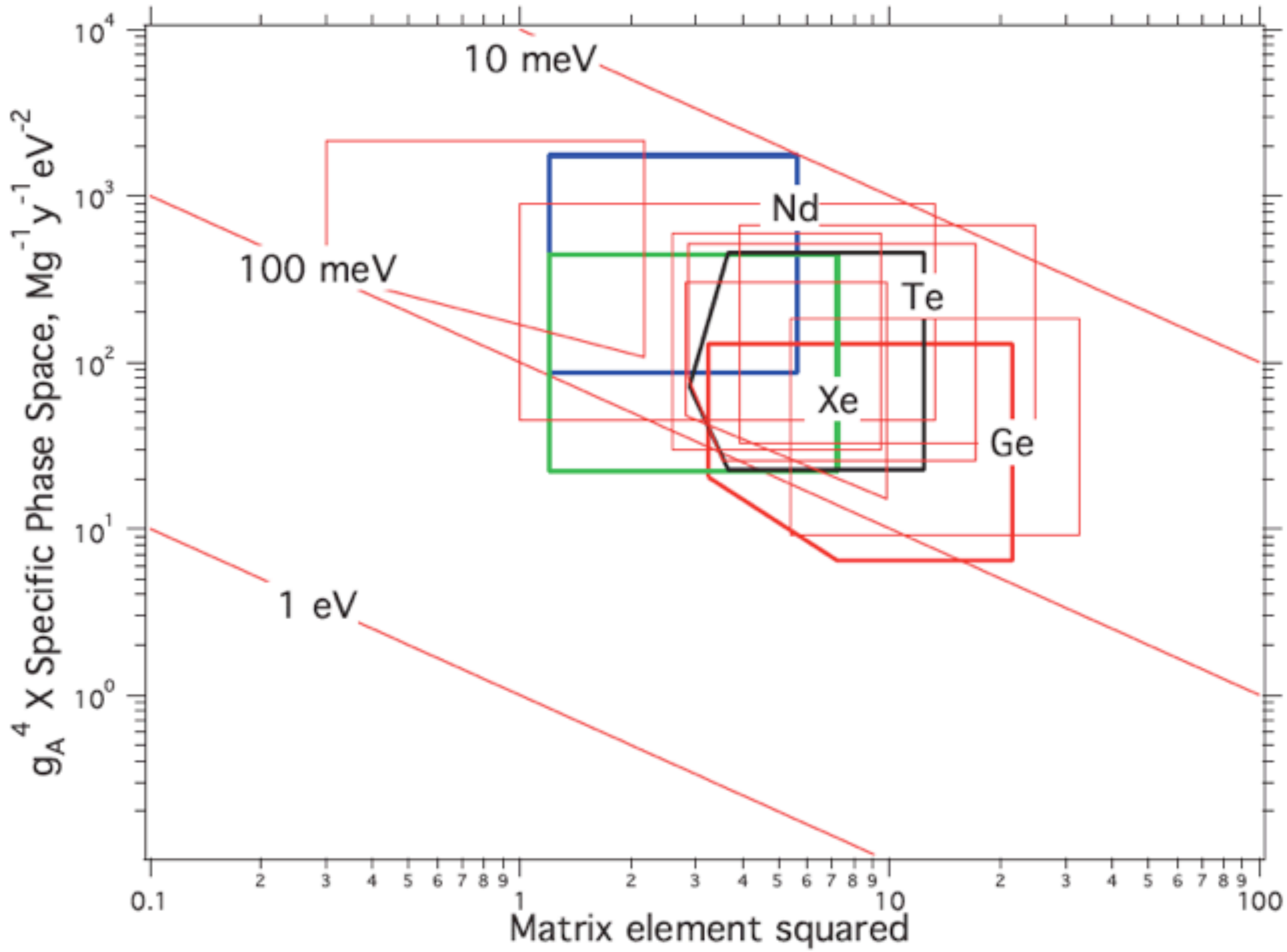
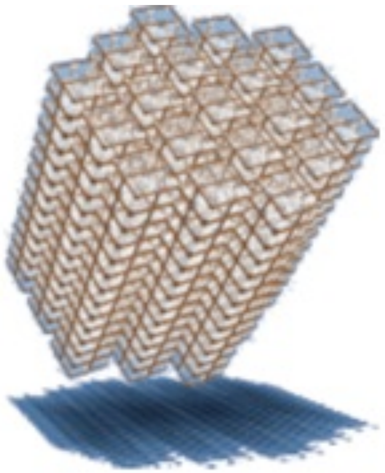
All isotopes are created equal...



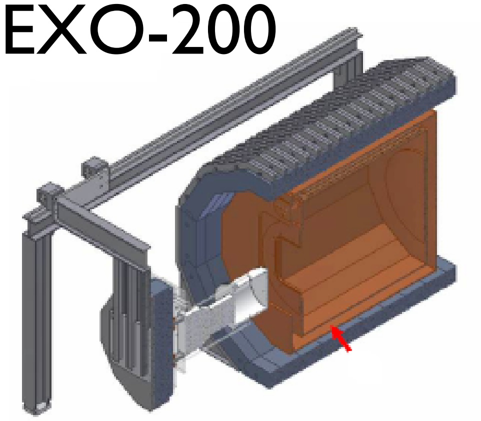
 R.G.H. Robertson, Mod. Phys. Lett. A **28**, 1350021 (2013).

0νββ Decay Experiments

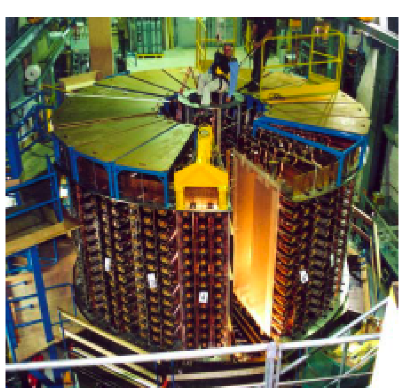
CUORE



EXO-200



NEMO3

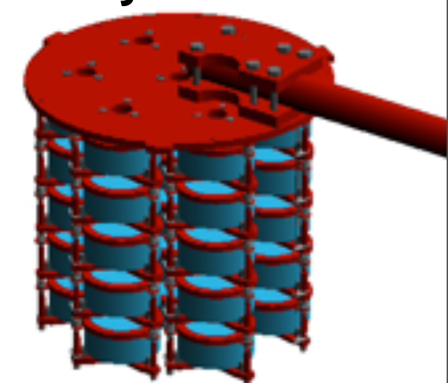


Collaboration	**Isotope**	**Technique**	**mass (0νββ isotope)**	**Status**
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
GERDA II	Ge-76	Point contact Ge in LAr or LN	30-35 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	26 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
CAMEO	Cd-116	$CdWO_4$ crystals	21 kg	R&D
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUORICINO	Te-130	TeO_2 Bolometer	11 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
SNO+	Te-130	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	370 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	R&D
EXO-200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	5 tonnes	R&D
DCBA	Nd-150	Nd foils & tracking chambers	32 kg	R&D

Complete | Construction | Operating

GERDA

MAJORANA



CANDLES

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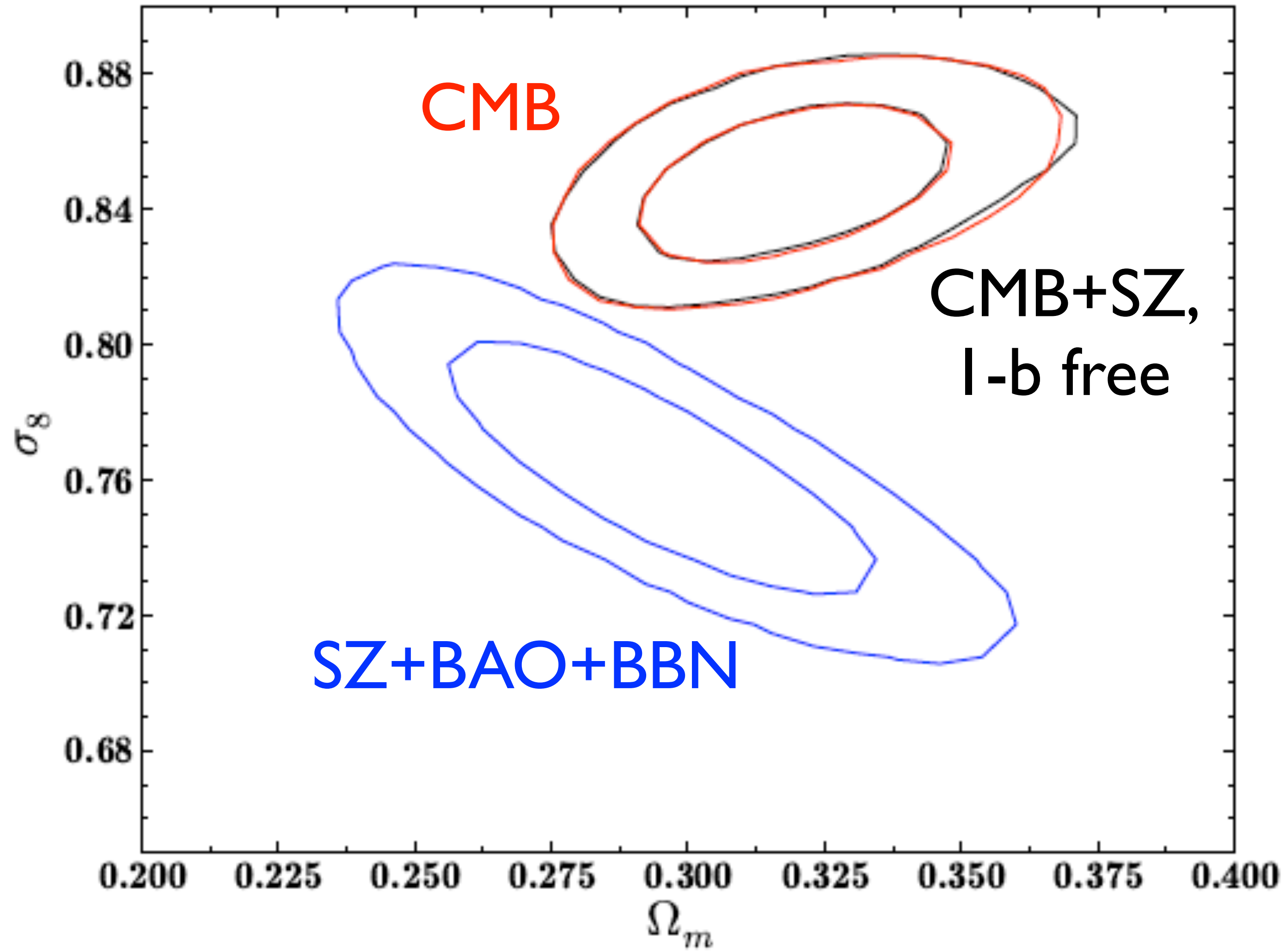
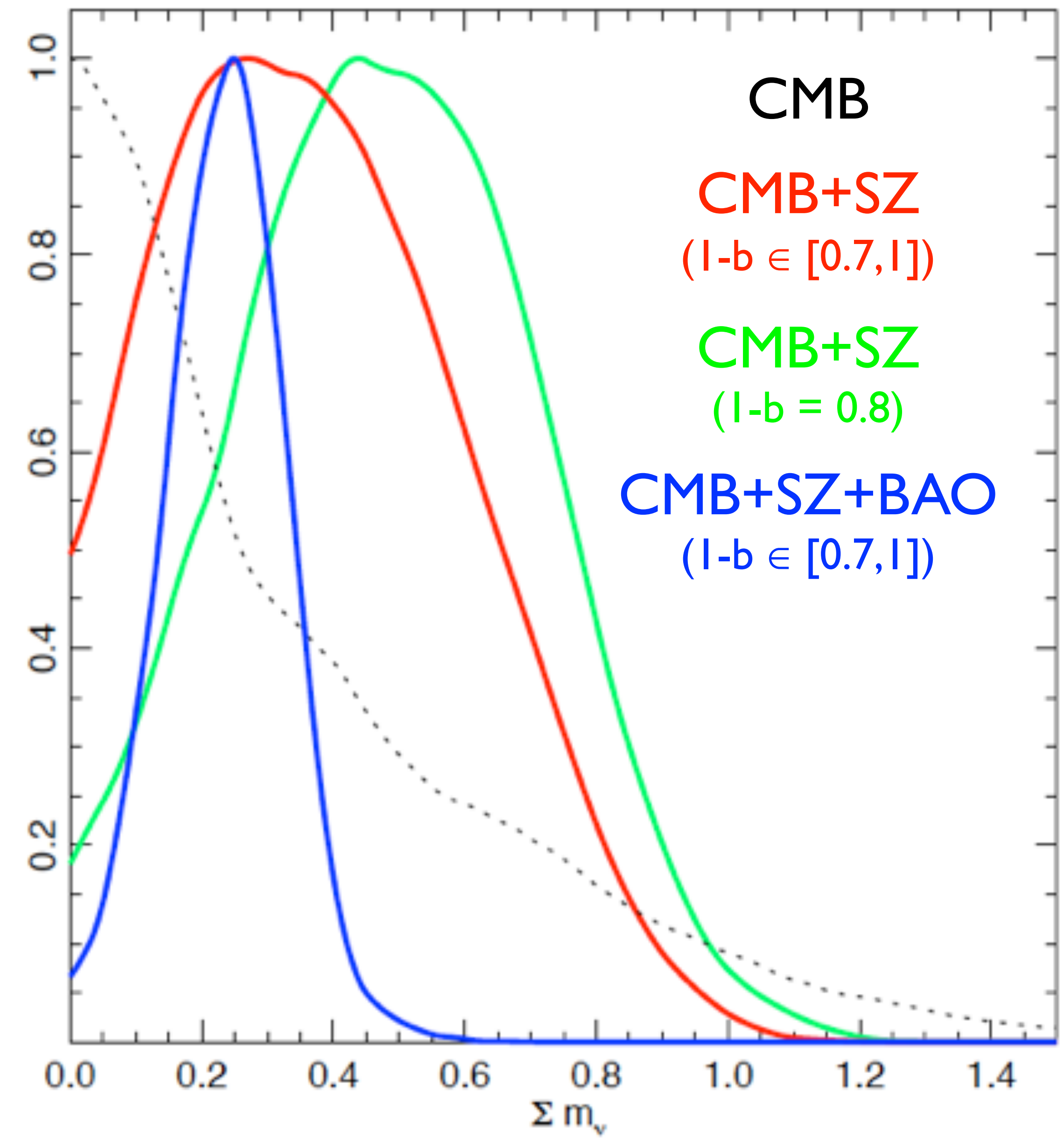
From J. F. Wilkerson

Hints from Planck?

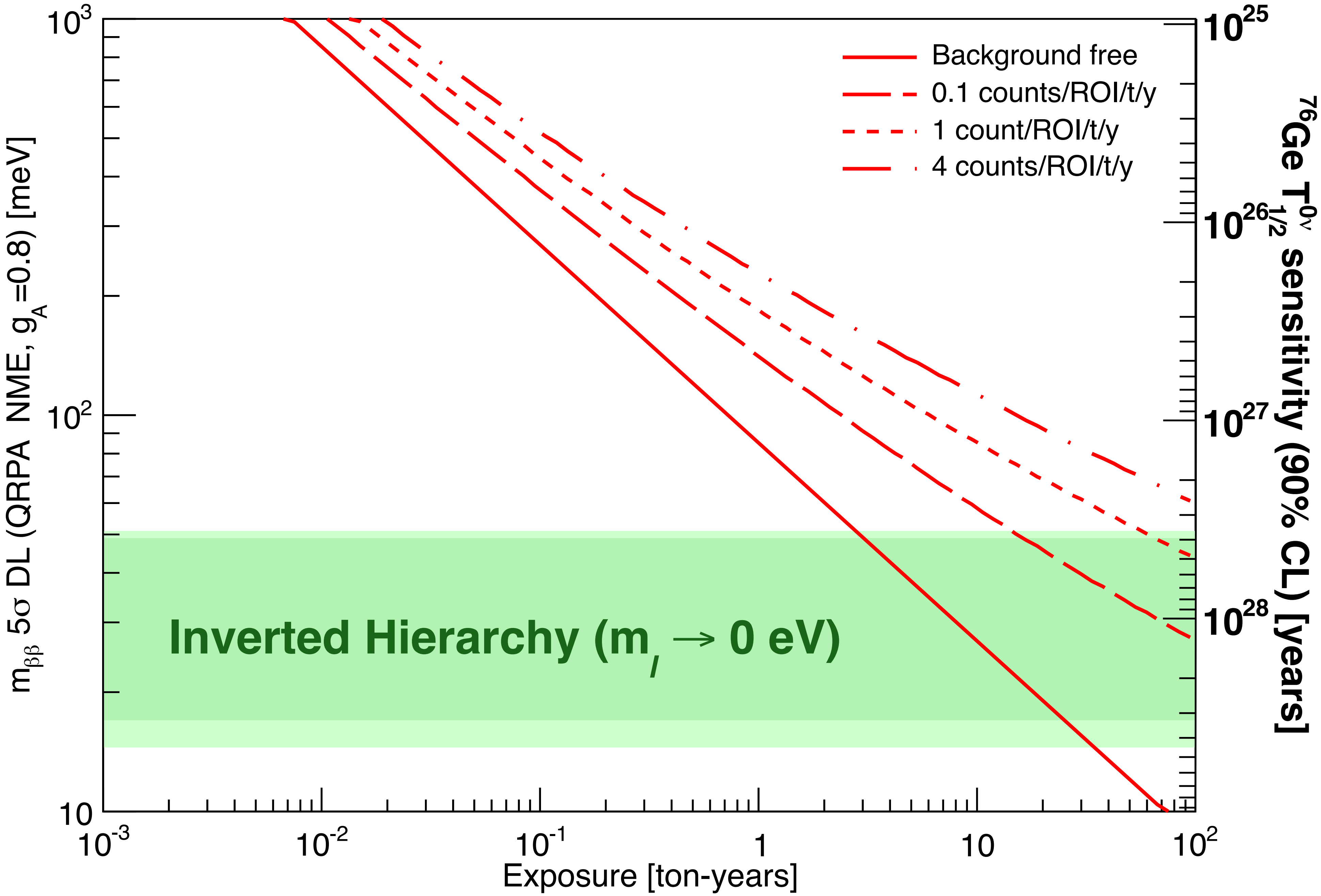




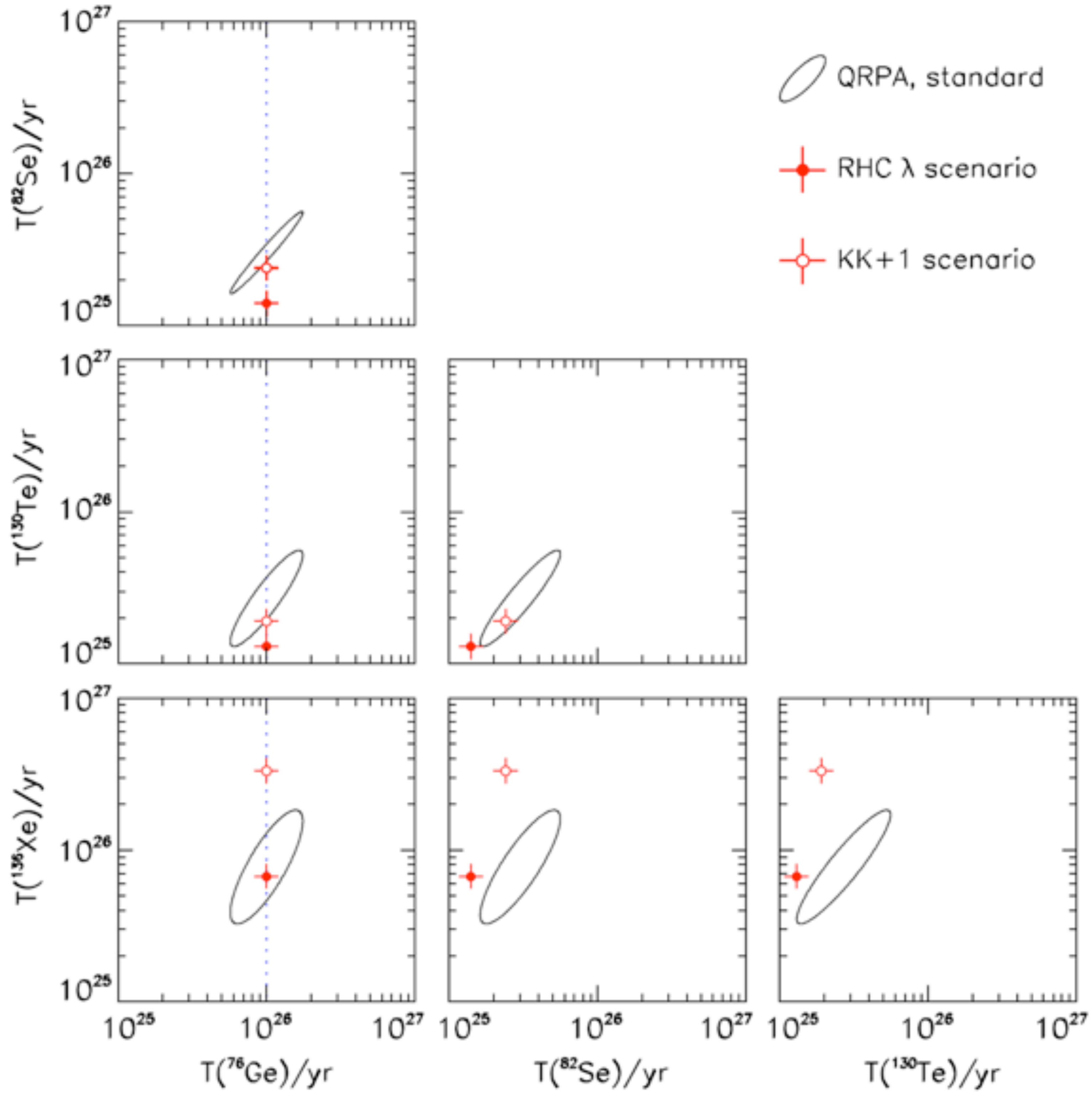
Tension relieved by
Σm_ν ~ 200-500 meV at 2-3σ
Stay tuned in 2014...

Planck XX, arXiv:1303.5080

Would cure g_A woes:



Mechanism Determination

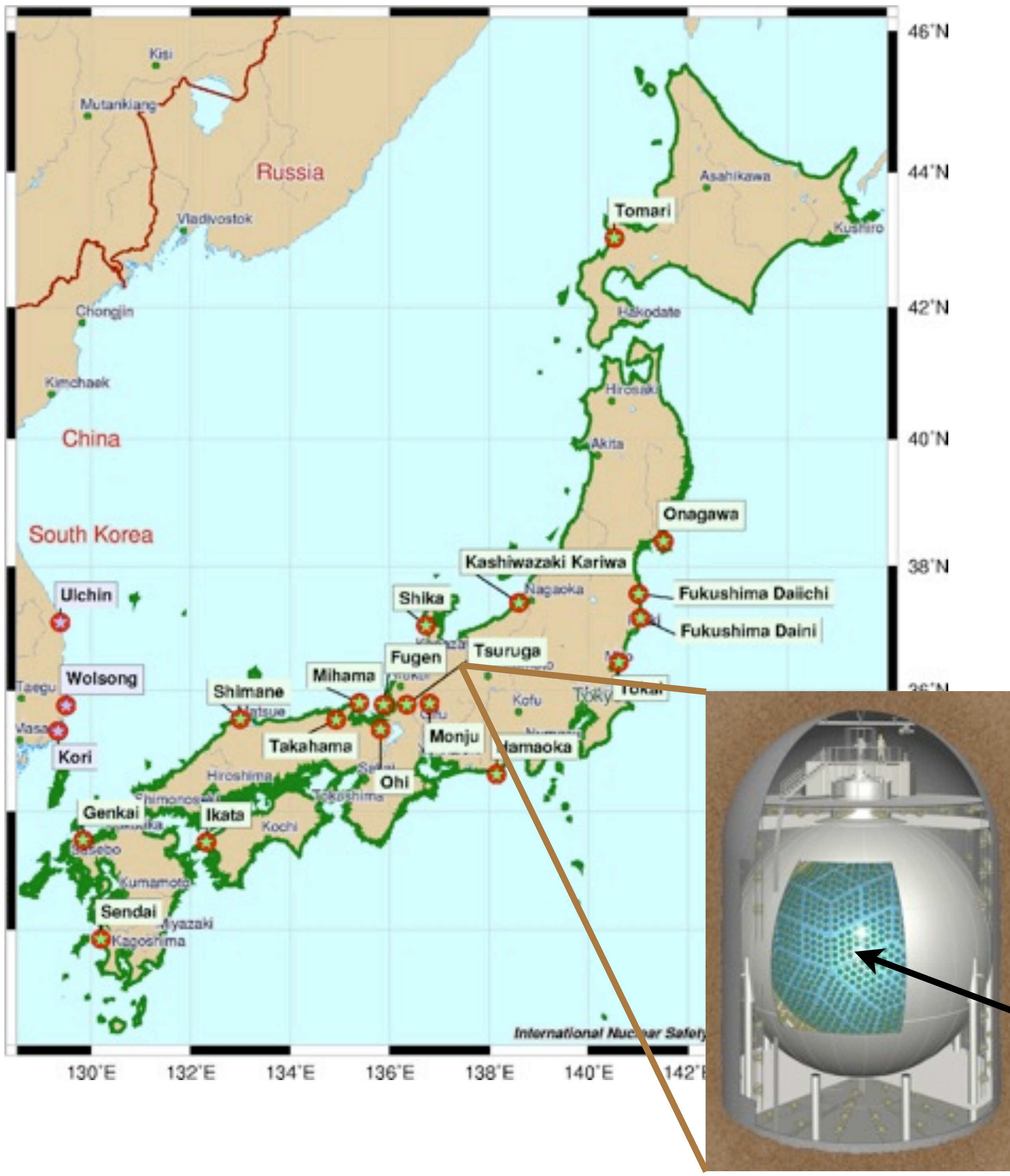


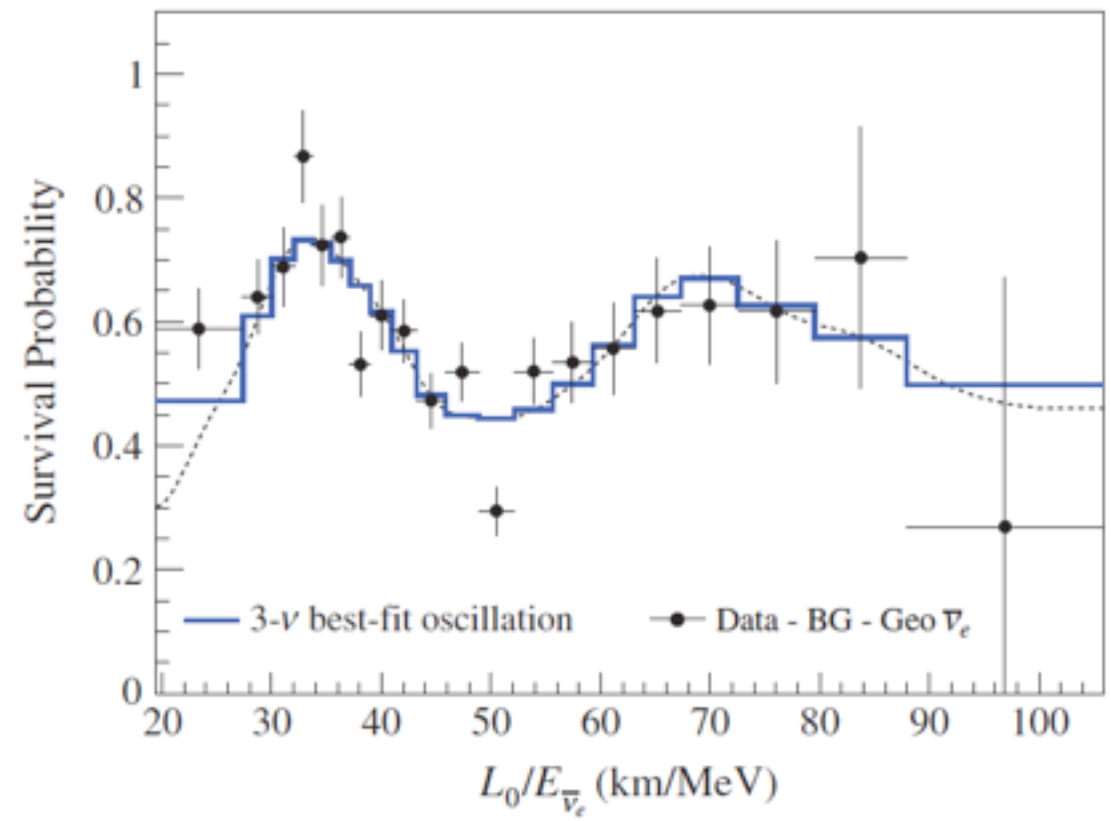
Fogli, Lisi and Rotunno, Phys. Rev. D **80**, 015024 (2009).

Outline

- Recent motivations for large mass, low background experiments
- Large Mass: KamLAND-Zen
- Low-Background: MAJORANA DEMONSTRATOR

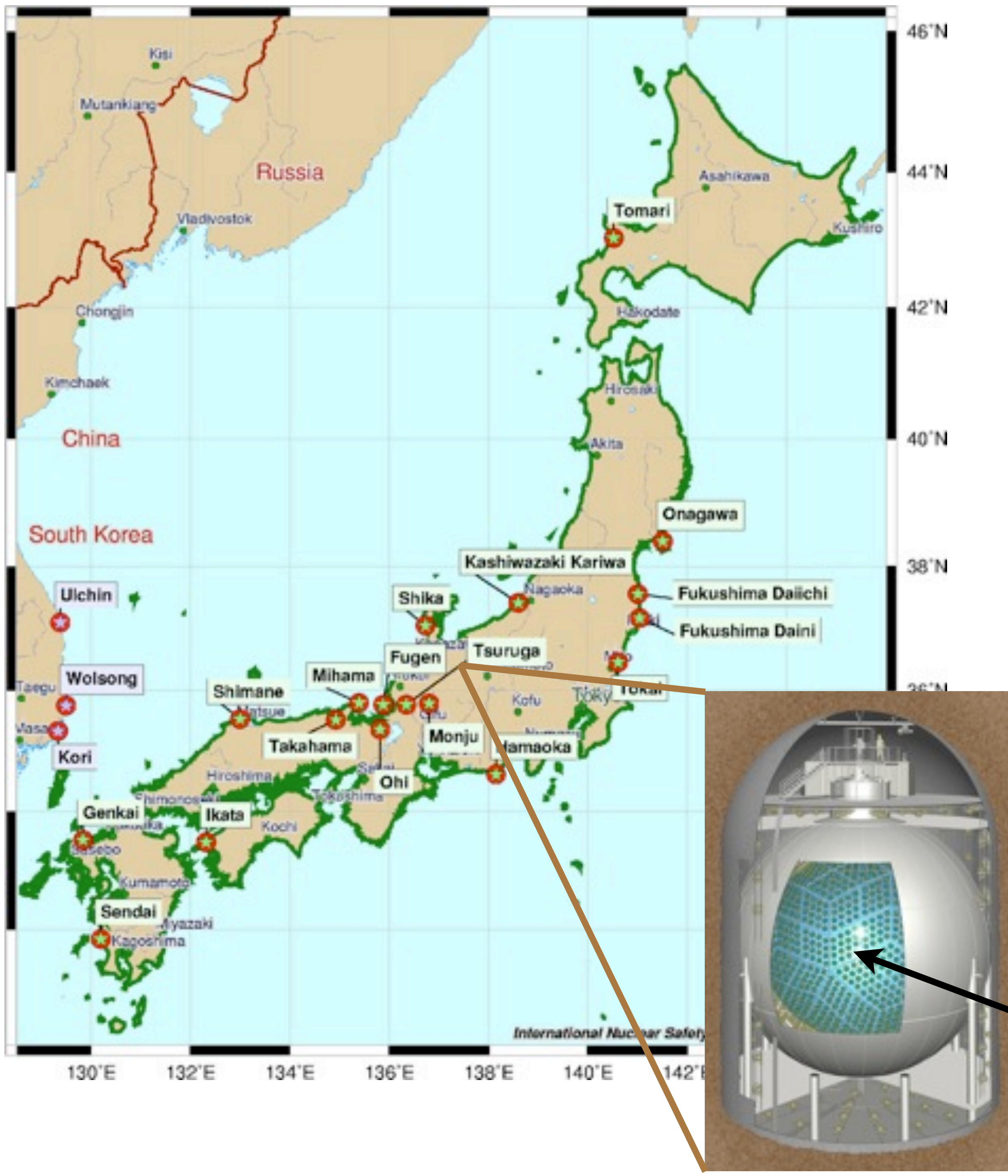
KamLAND

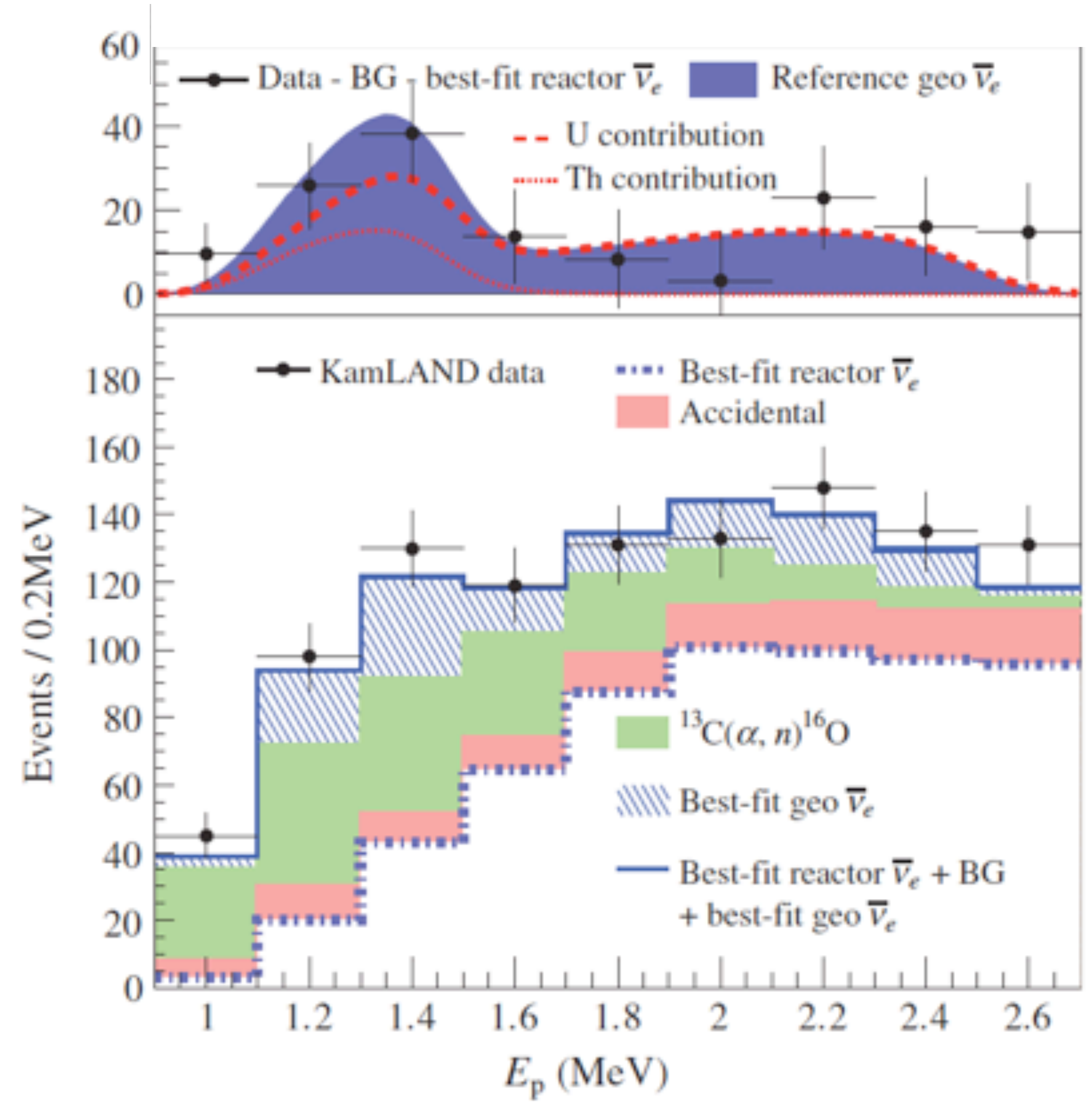




~1 kton liquid scintillator

KamLAND





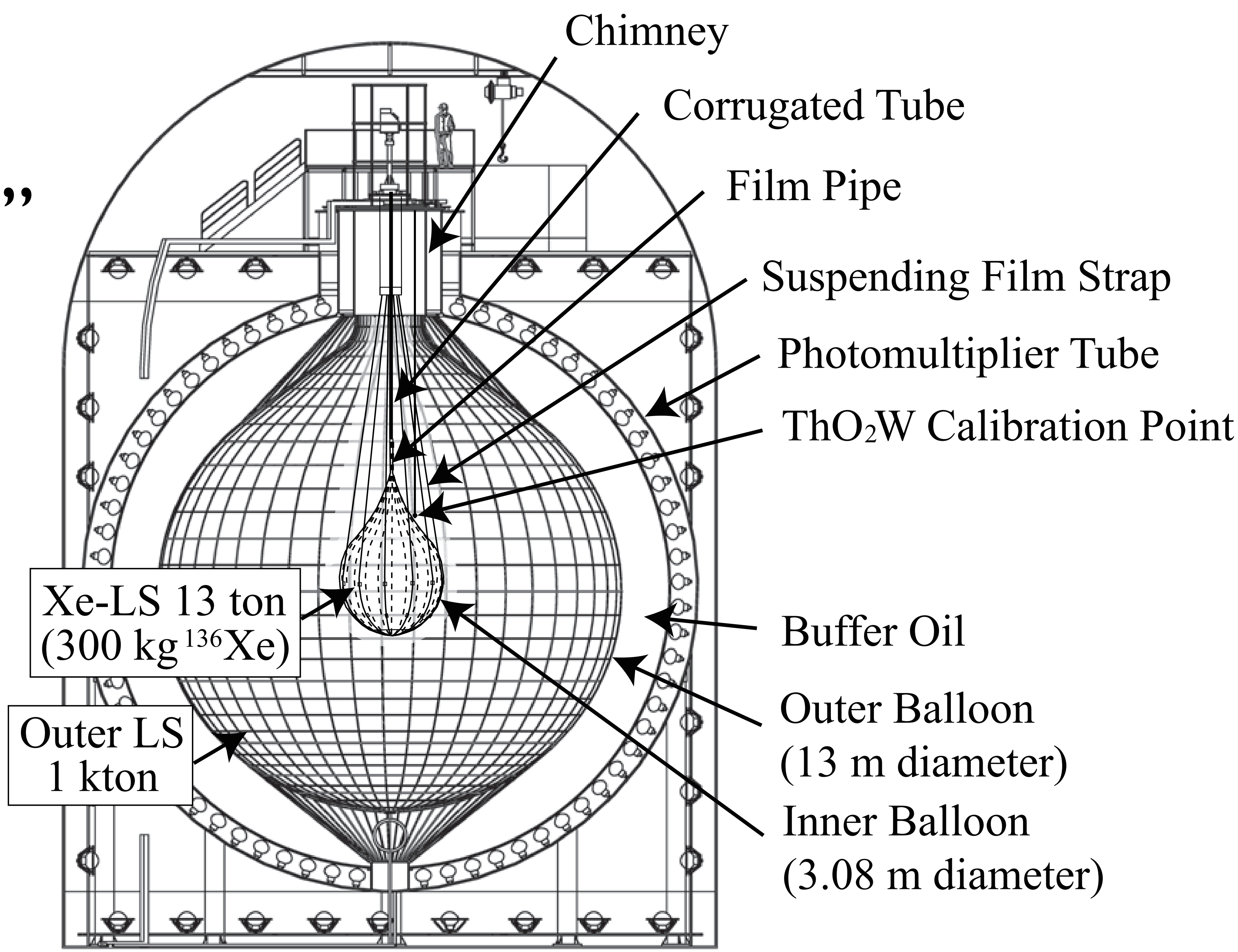
~1 kton liquid scintillator

Phys. Rev. D **88**, 033001 (2013).

KamLAND-Zen Upgrade

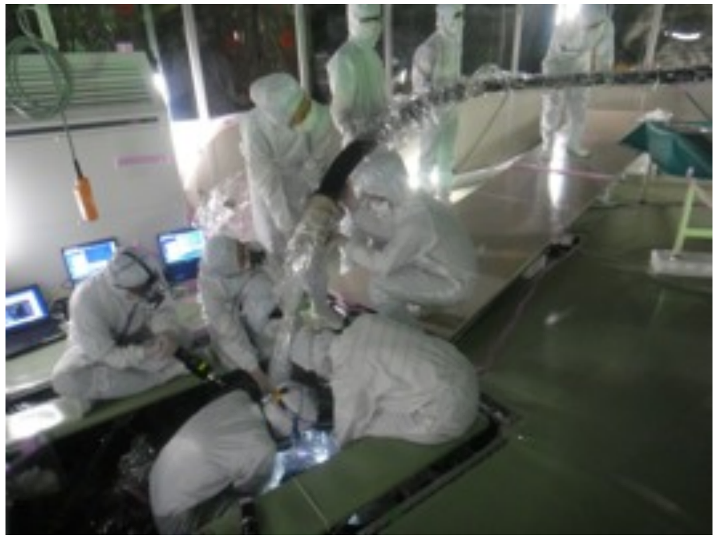
Zen =
" Zero-Neutrino"

but also:
"Xenon"
"Then"
"禅"



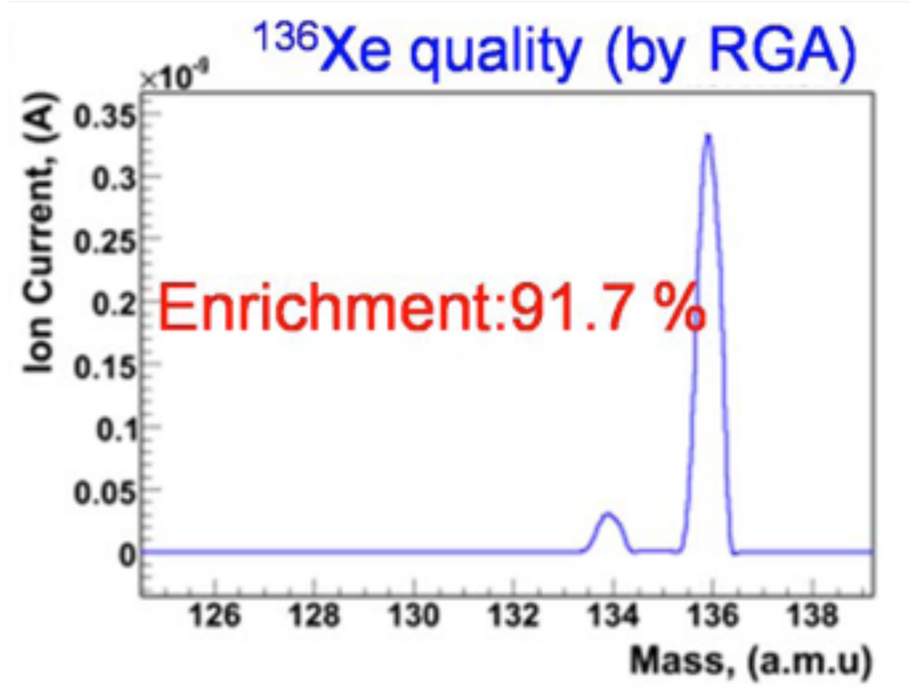
Inner Balloon Construction

- Ultra-low contamination heat-welded nylon film
  - ~25 μm thick
  - Straps made of identical material
  - U/Th/K ≲ 10^{-13} g/g



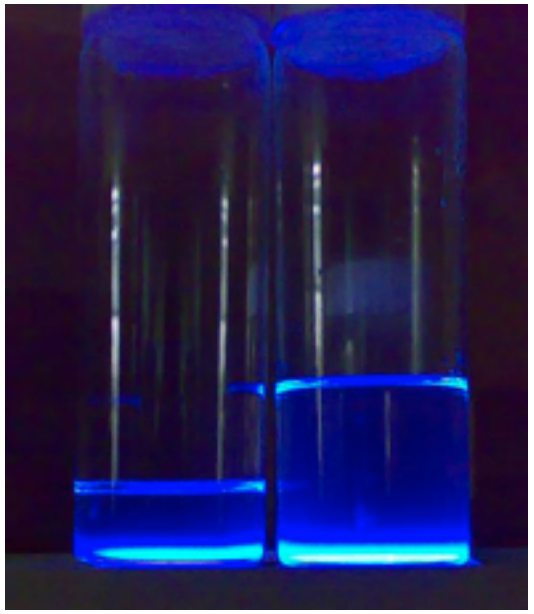
Xe Procurement

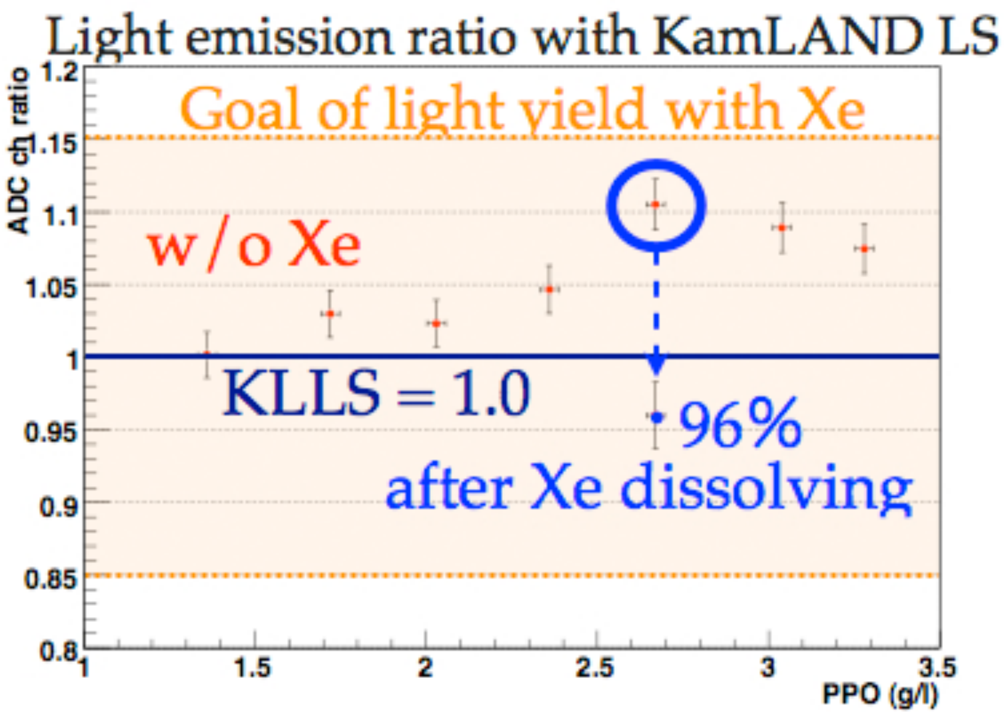
- Enrichment by gas centrifuge in Russia
- 190 kg purchased in 2009
- 210 kg purchased in 2010
- 400 kg more now in hand

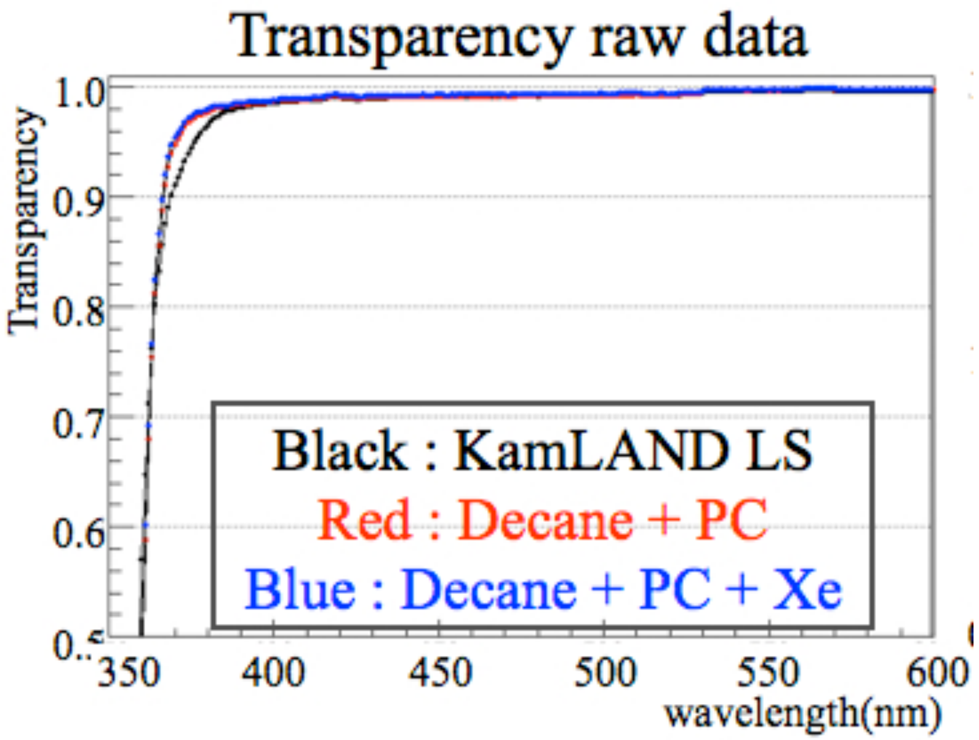


Xe-LS R&D

- Maximize Xe mass in LS, but maintain light yield and transparency
- Must also match density of KamLAND LS for balloon integrity
- Increase PPO with Xe: optimal point at 2.7 g/L PPO = 2.5% ^{enr}Xe (by weight)



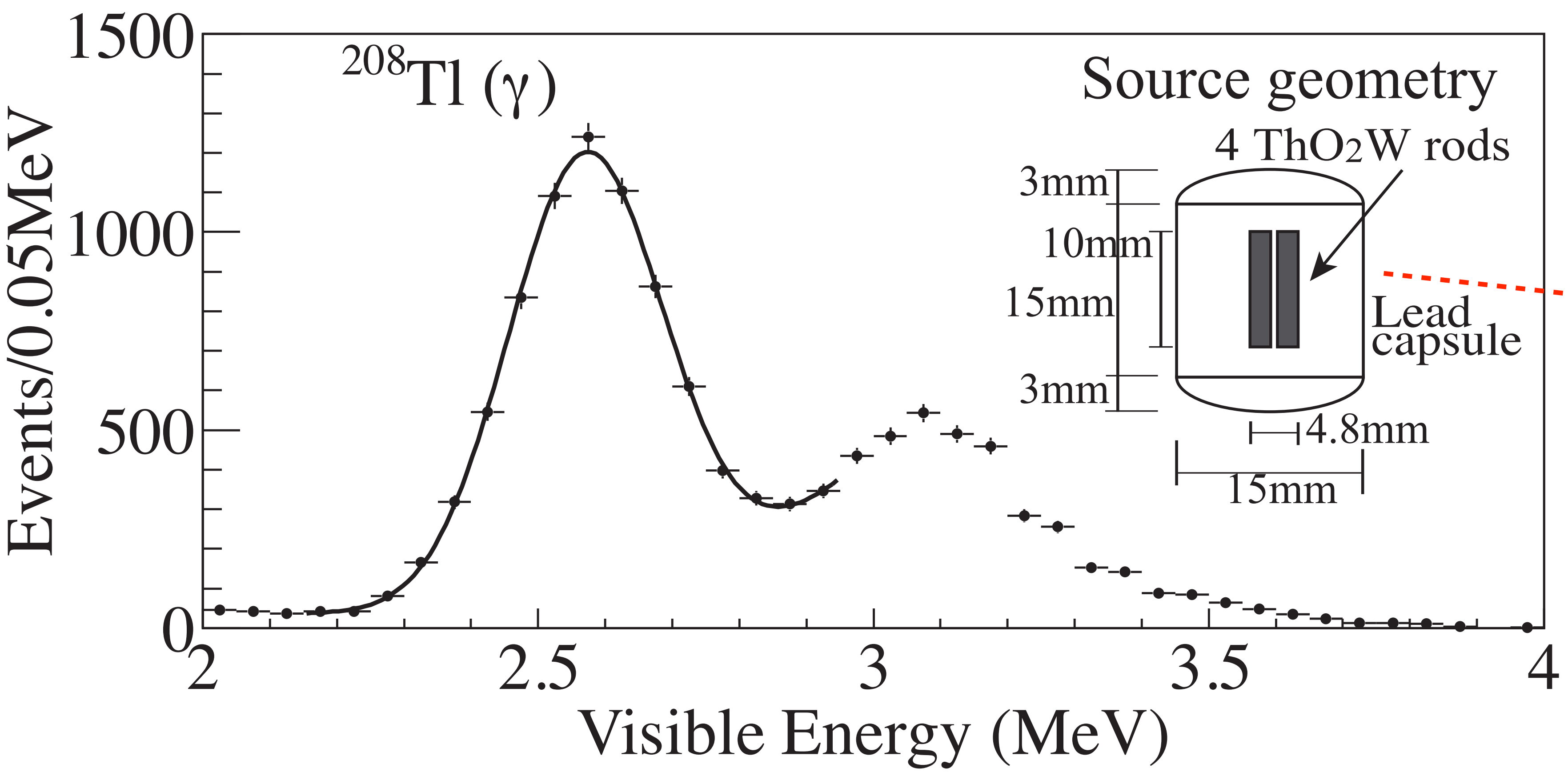


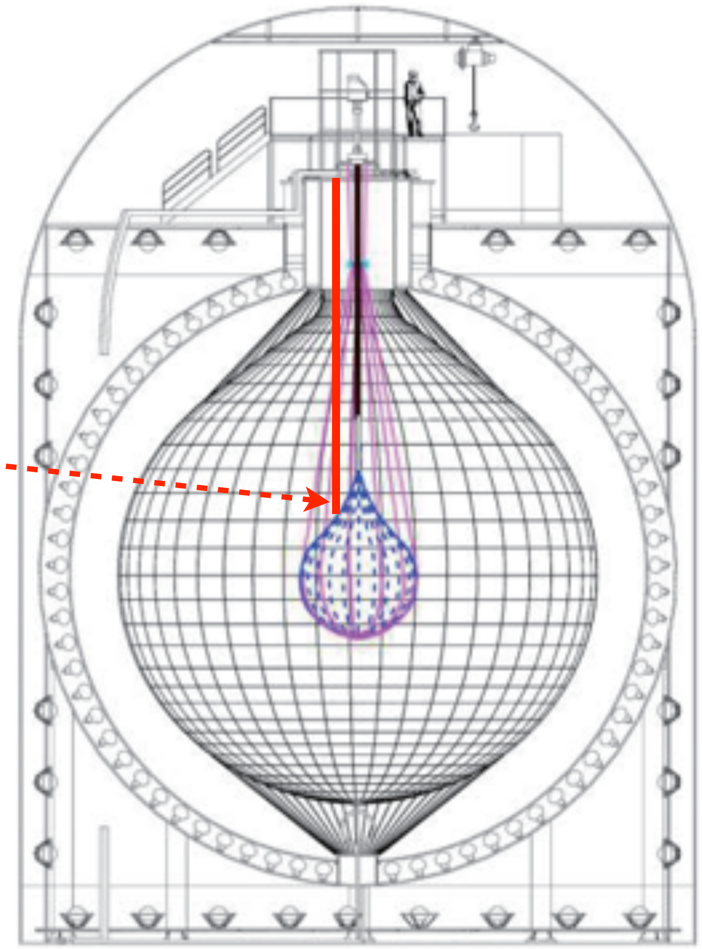


KamLAND-Zen Timeline

- ~2008-2011: R&D, ^{enr}Xe procurement, installation of new infrastructure
- March 2011: Tohoku earthquake and tsunami, and Fukushima nuclear disaster
- Summer 2011: Inner balloon fabrication and installation, Xe-LS filling, commissioning
- Oct 2011 - Jan 2012: First data set, published in PRC **85**, 045504 (2012)
- Feb 2012: Stop for filtration (DS-1), published Majorana emission mode result - PRC **86** 021601 (2012) (best $2\nu\beta\beta$ result)
- June 2012: Stop data taking (DS-2) for distillation, see PRL **110**, 062502 (2013) (best $0\nu\beta\beta$ result, this talk)

ThO_2W Calibration

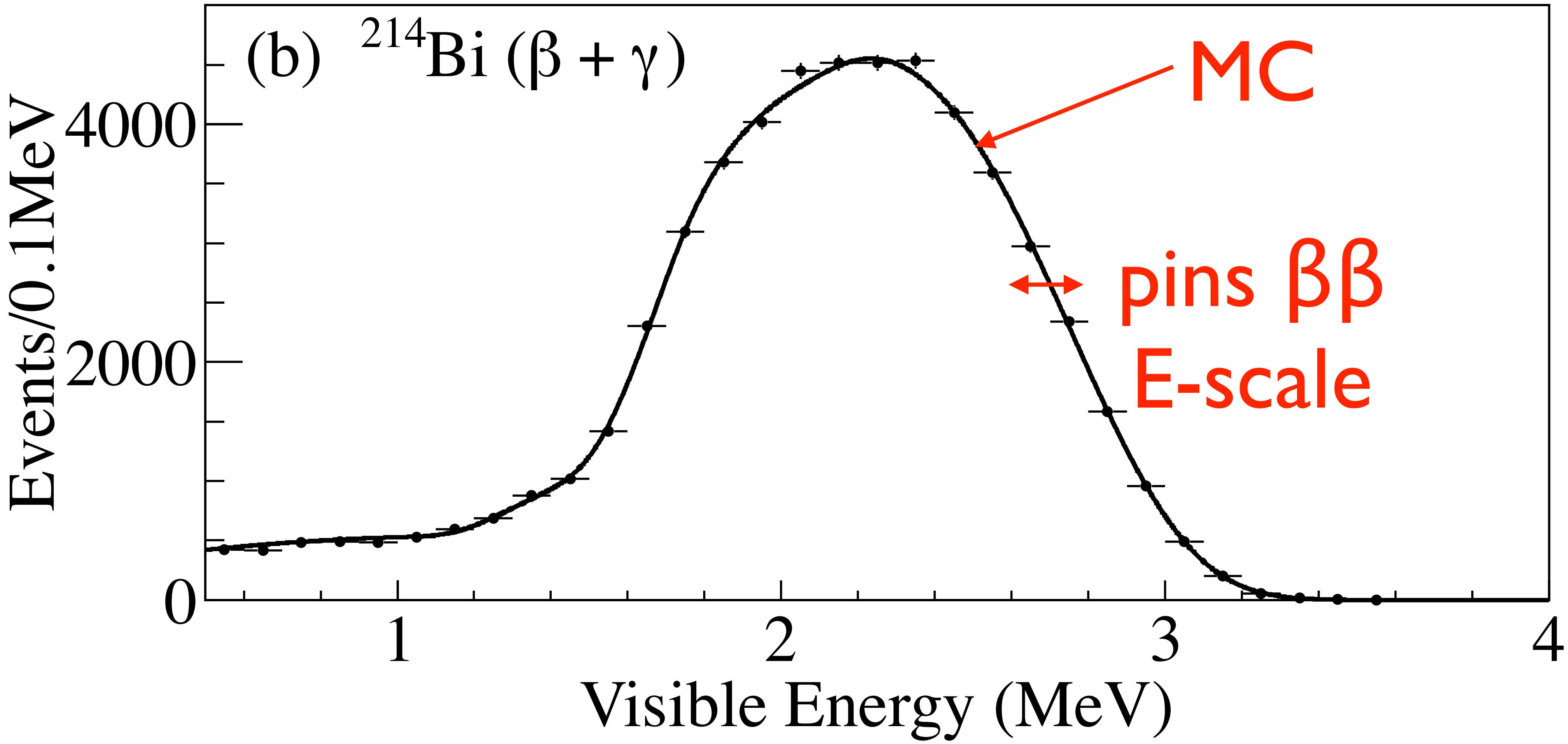




$\sigma = (6.6 \pm 0.3)\% / \sqrt{\text{MeV}}$

In-situ ^{214}Bi Fit

from ^{222}Rn (τ = 5.5 days)



Candidate Selection

- Fiducial volume: R < 1.35 m (DS-2: cut out siphoning hardware)
- Detector vetos:
  - Muons (>10k p.e. or >5 OD hits) and the 2 ms following them
  - Bi-Po coincidences (Δt < 3 ms, 0.35 MeV < E_{prompt} < 1.5 MeV)
  - Antineutrinos (Δt < 1 ms, E_{prompt} > 1.5 MeV)
- Cuts: Vertex-time-charge goodness-of-fit

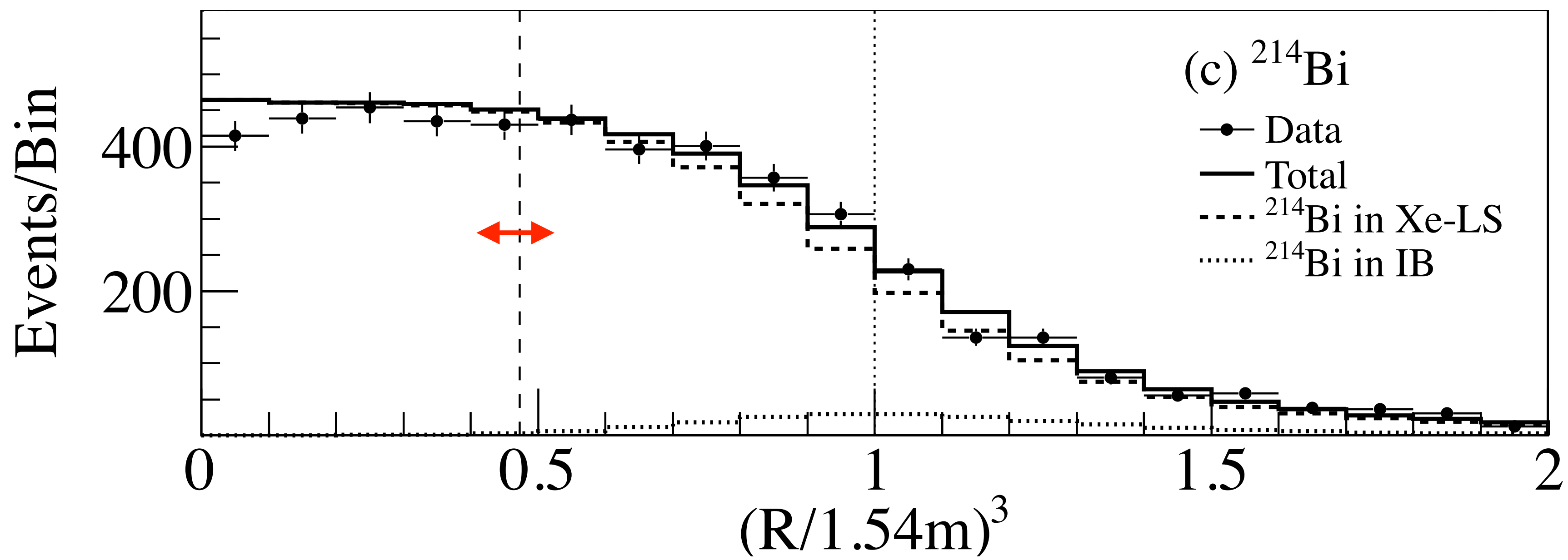
Fiducial mass (DS-1 / DS-2): 179 kg / 125 kg ^{136}Xe

Livetime (DS-1 / DS-2): 112.3 days / 101.1 days

ε > 99.9%

Systematic Uncertainties

- Uniformity of ^{214}Bi in early data + total mass of Xe-LS filled gives FV uncertainty of 3.9% / 4.1% (DS-1 / DS-2)



- Enrichment, E-scale, efficiency, livetime, Xe concentration, Xe-LS edge effect uncertainties all <0.4%

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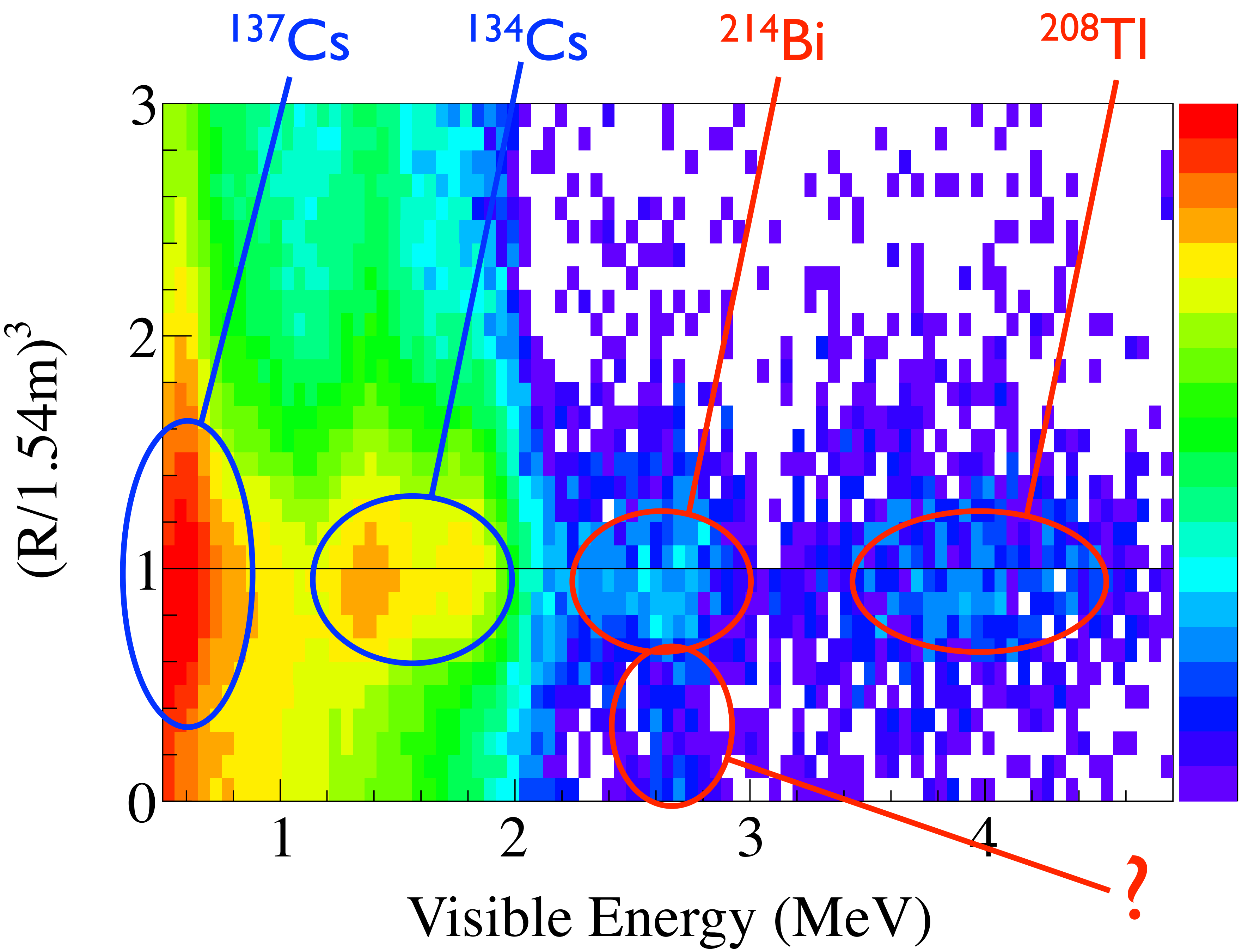
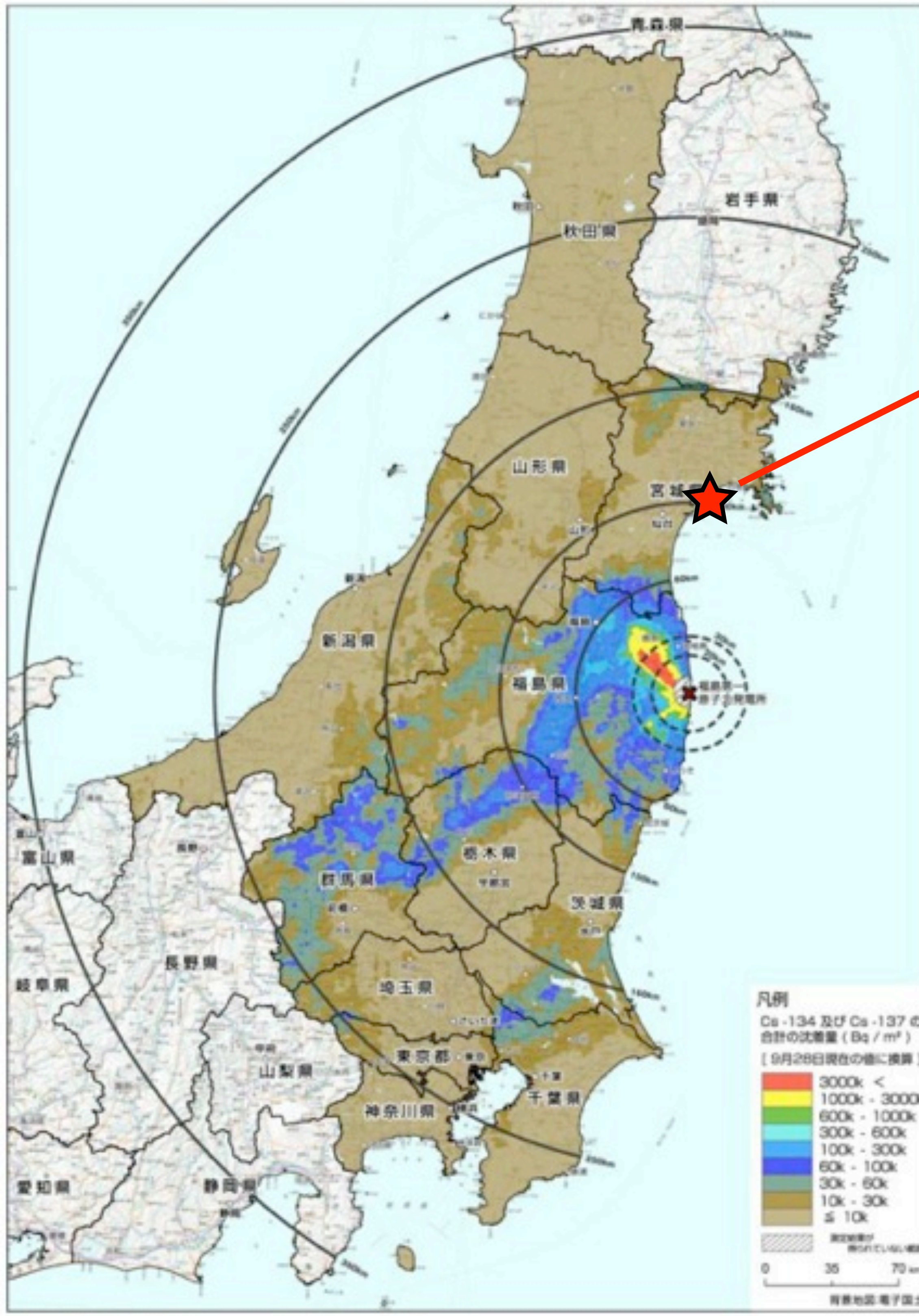
ββ Candidate R vs E



Fukushima Disaster



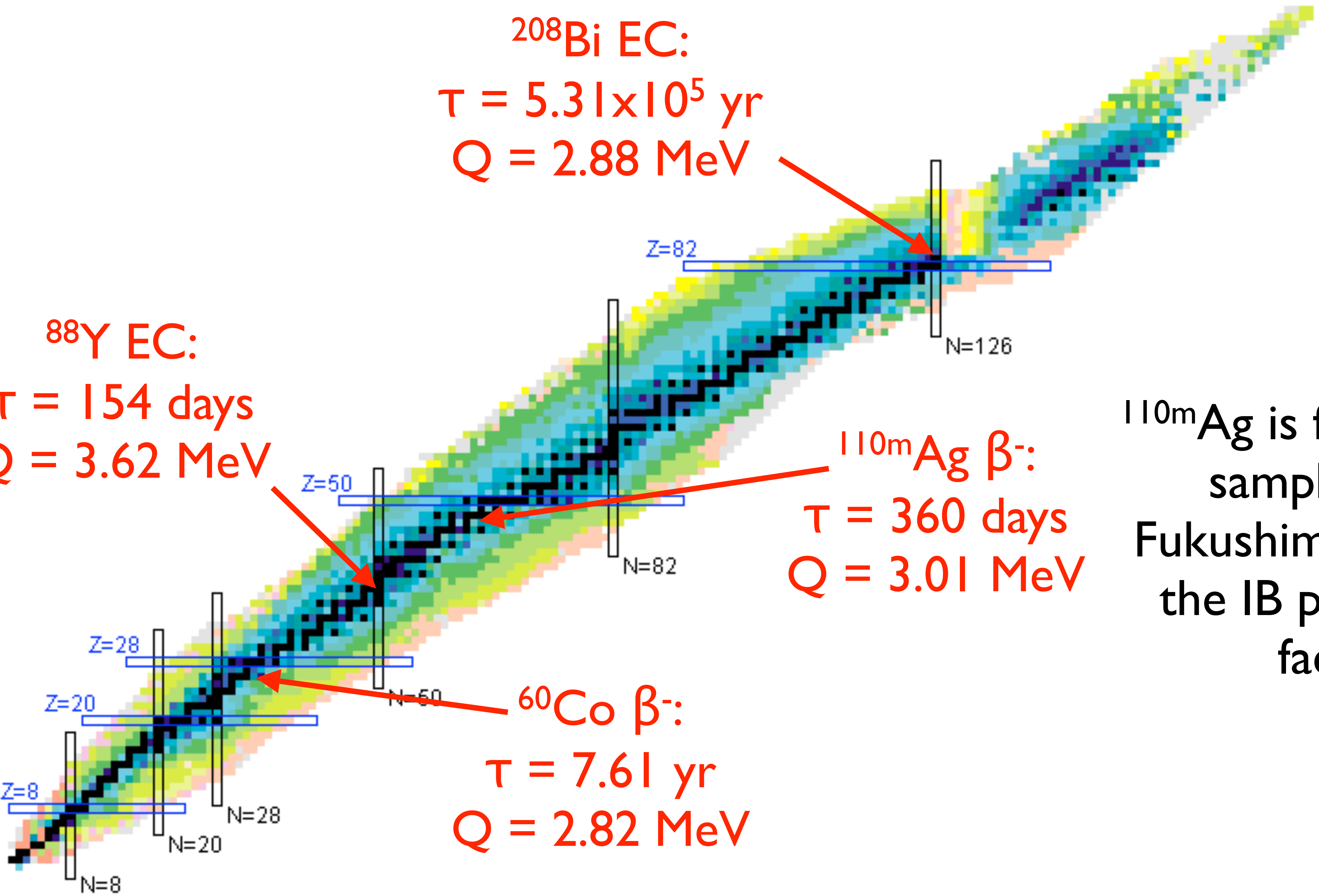
Tohoku U and Inner Balloon fabrication lab

Exhaustive Search for $0\nu\beta\beta$-like Backgrounds

- Search ENSDF for decays that can give a peak in KLZ between 2.4 and 2.8 MeV
- Account for all particle-dependent energy non-linearities
- Require $\tau > 30$ days, or $100\ \mathrm{s} < \tau < 30$ days if production cross section not too small

 Phys. Rev. C **76**, 064609 (2007).

Exhaustive Search for 0νββ-like Backgrounds



^{208}Bi EC:
τ = 5.31x10^{5} yr
Q = 2.88 MeV

^{88}Y EC:
τ = 154 days
Q = 3.62 MeV

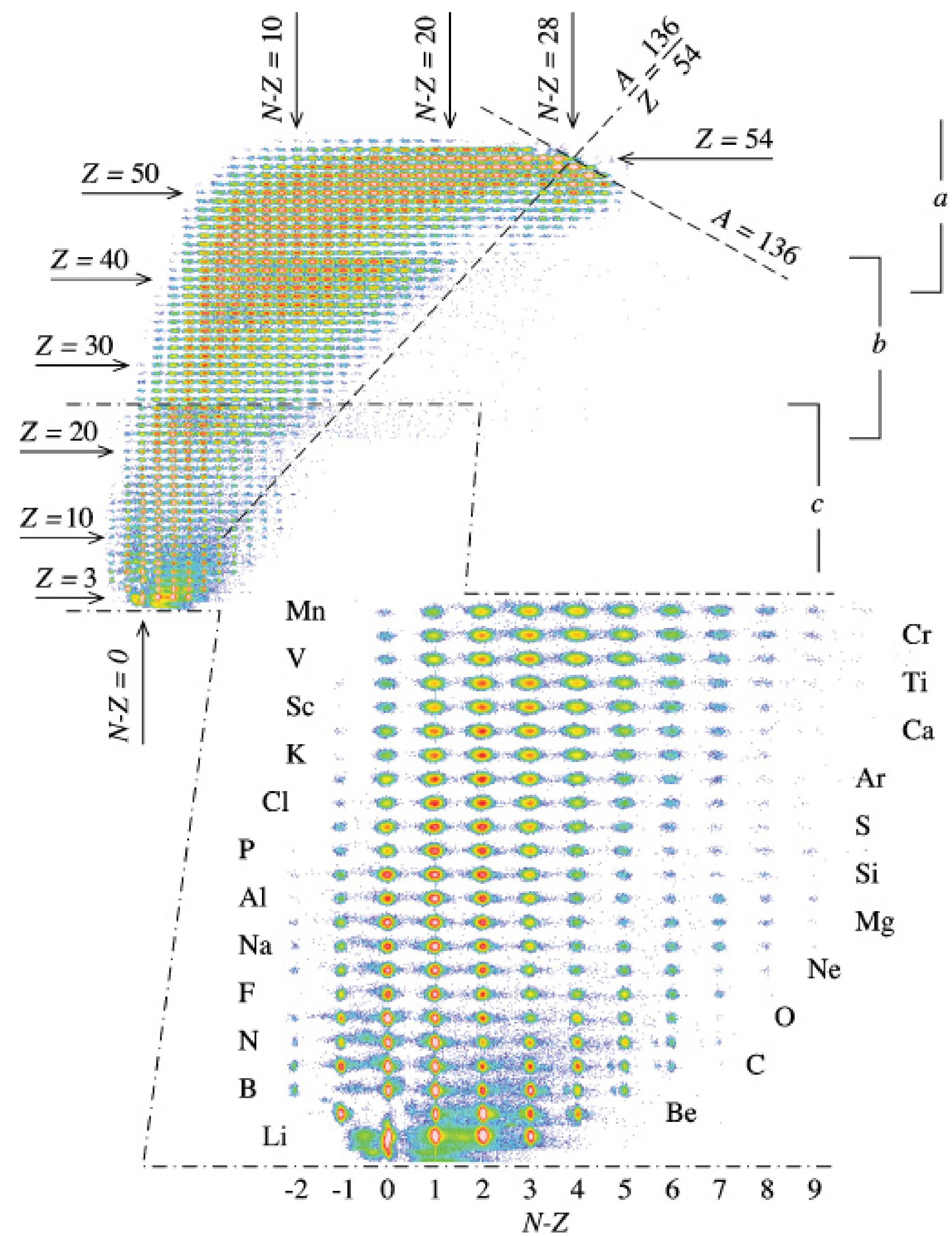
^{110m}Ag β^{-}:
τ = 360 days
Q = 3.01 MeV

^{60}Co β^{-}:
τ = 7.61 yr
Q = 2.82 MeV

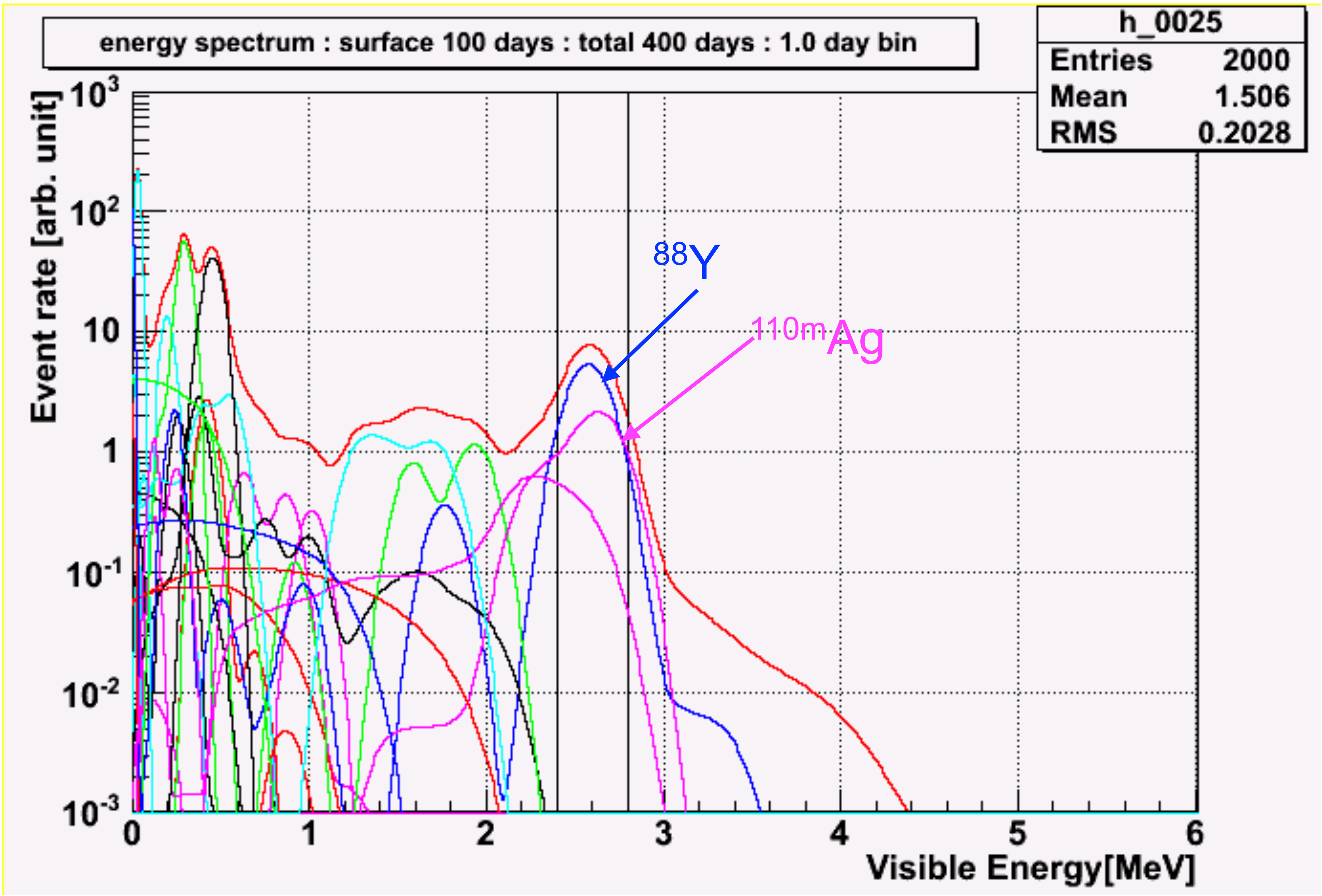
^{110m}Ag is found in soil samples near Fukushima, and near the IB production facility

Exhaustive Search for 0νββ-like Backgrounds

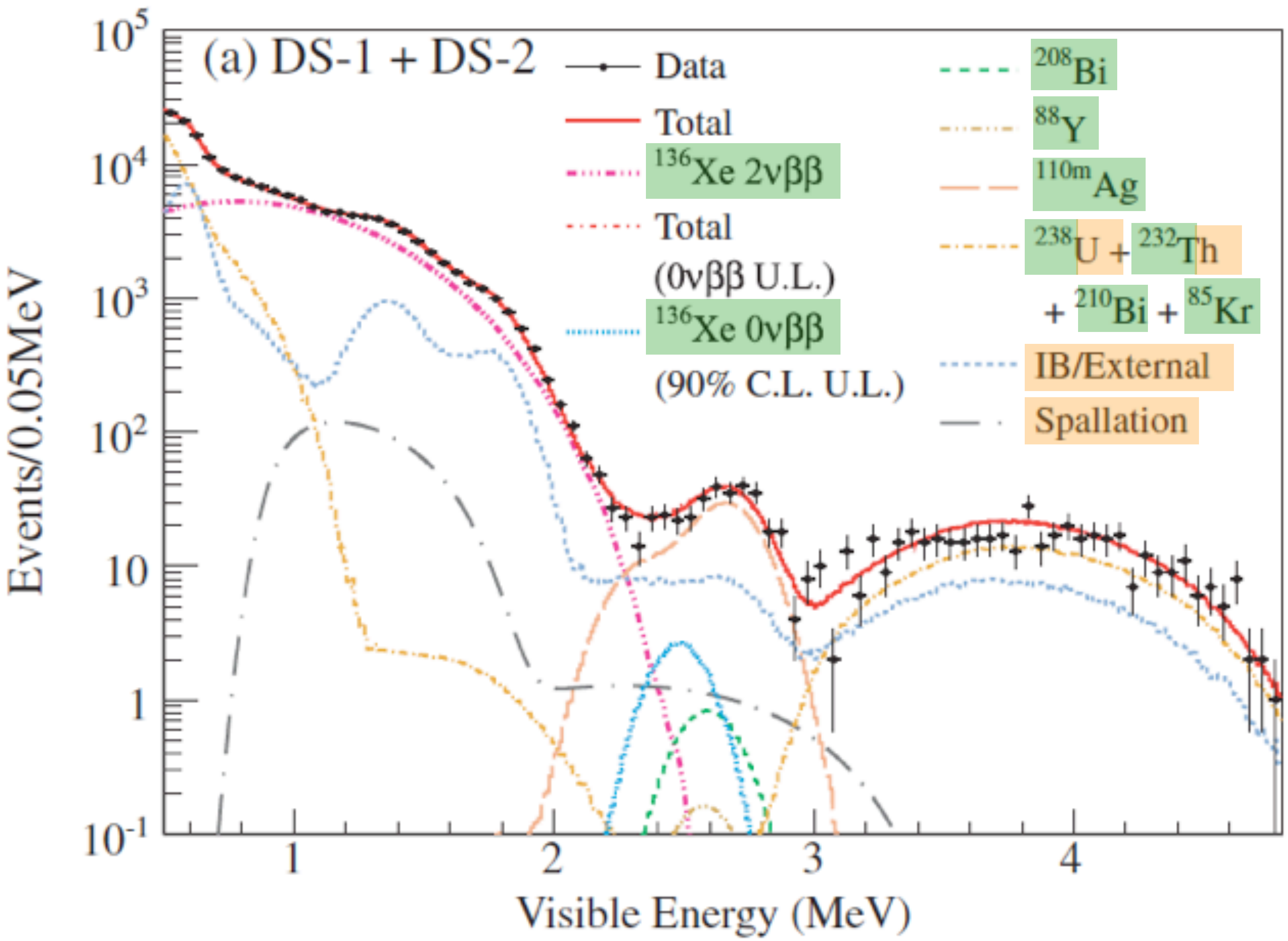
^{136}Xe spallation in 1 GeV$_{eq}$ p beam



Exhaustive Search for 0νββ-like Backgrounds



Energy Spectrum



free parameter

constrained

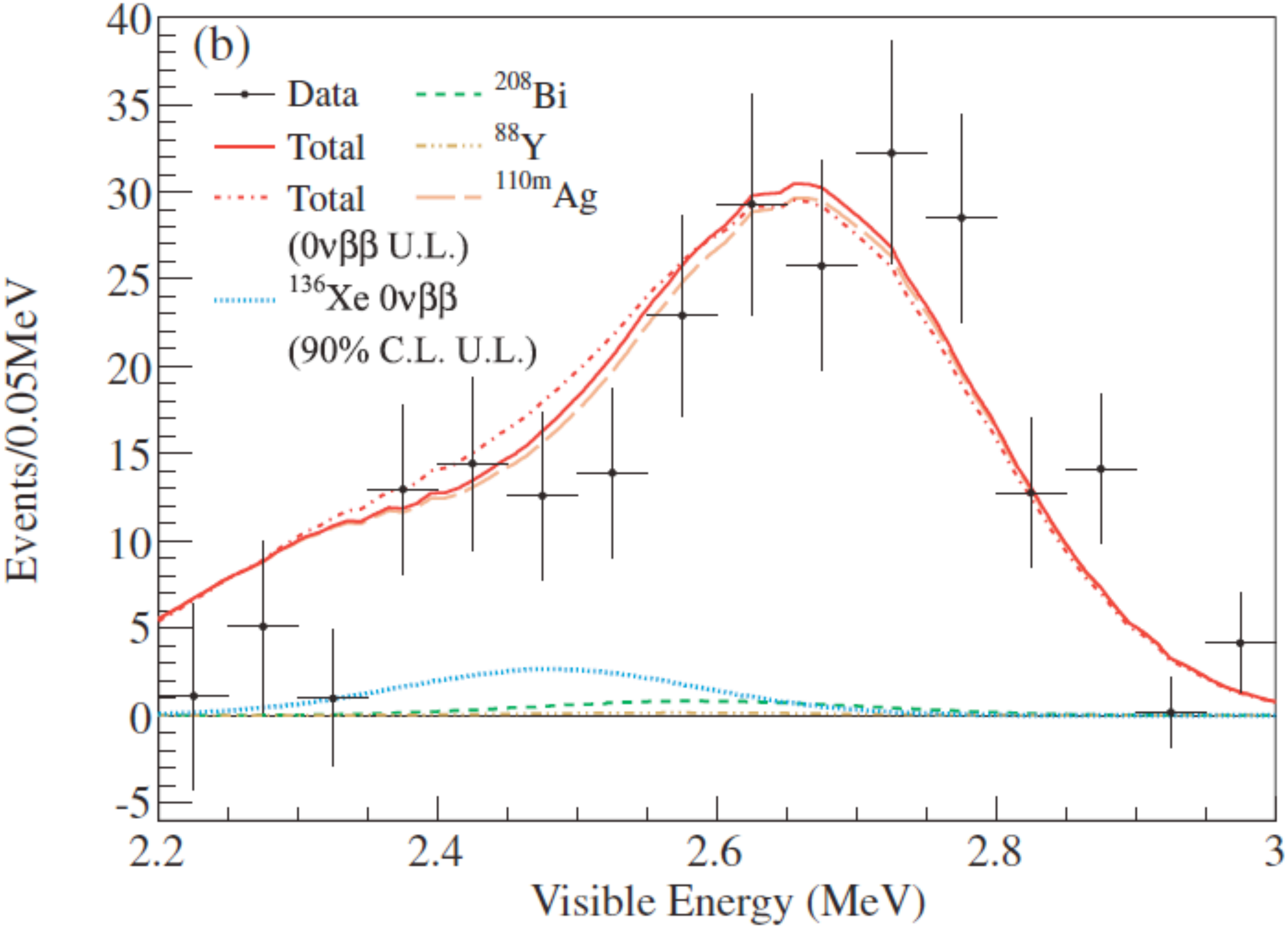
Components not shown have best fit = 0

Peak in the 0νββ window prefers to be ^{110m}Ag

$T_{1/2}^{2\nu}$ = [2.30 ± 0.02 (stat) ± 0.12 (syst)] x 10^{21} yr

(consistent with EXO-200)

$0\nu\beta\beta$ Region



90% CL Limit:

$T^{0\nu}_{1/2} > 1.9\times10^{25}$ years

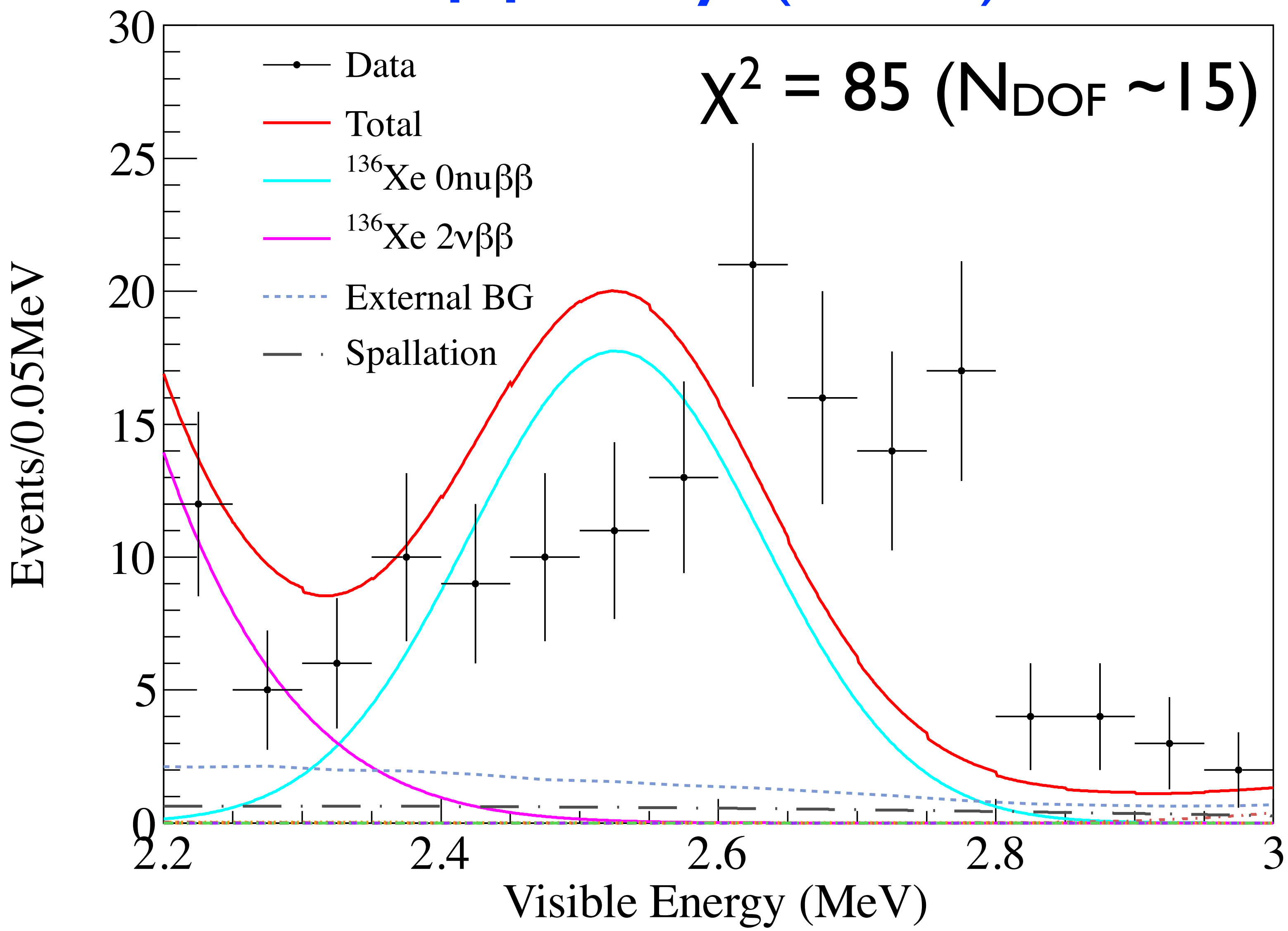
Sensitivity: $1.0\text{x}10^{25}$ y

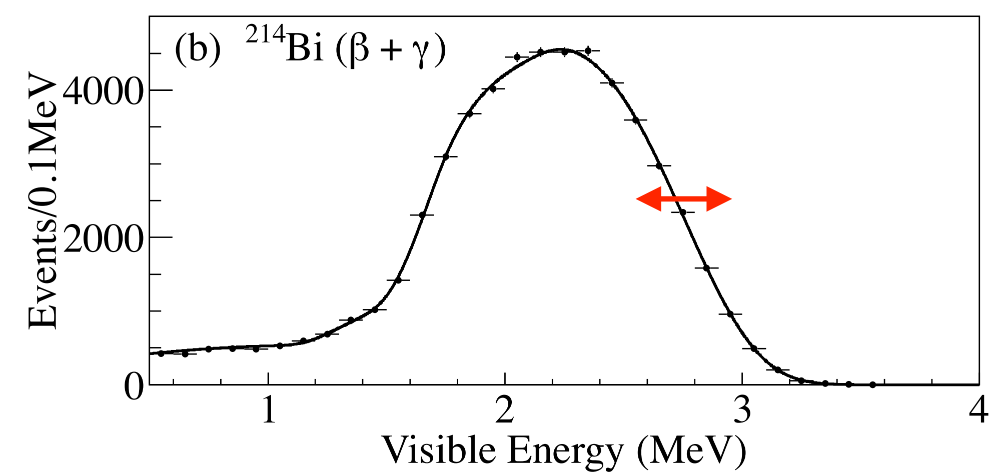
P(stronger limit) = 12%

Alternative Hypotheses

$0\nu\beta\beta$ only (DS-1):

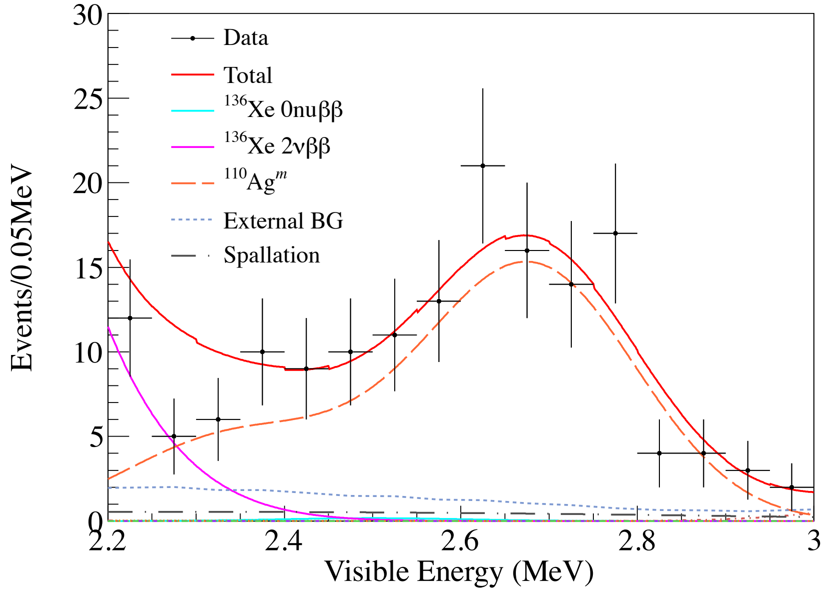
$\chi^2 = 85$ (N_{DOF} ~15) → It's *NOT* $0\nu\beta\beta$ decay



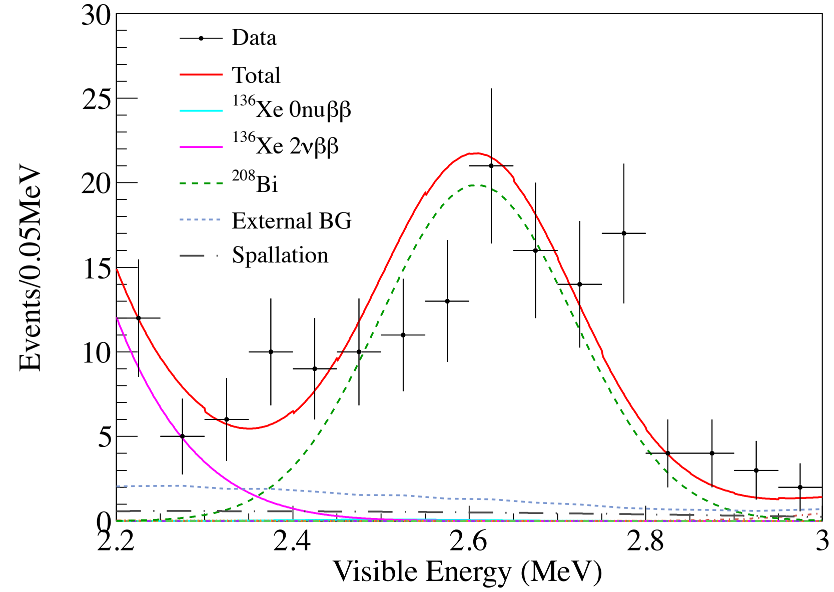


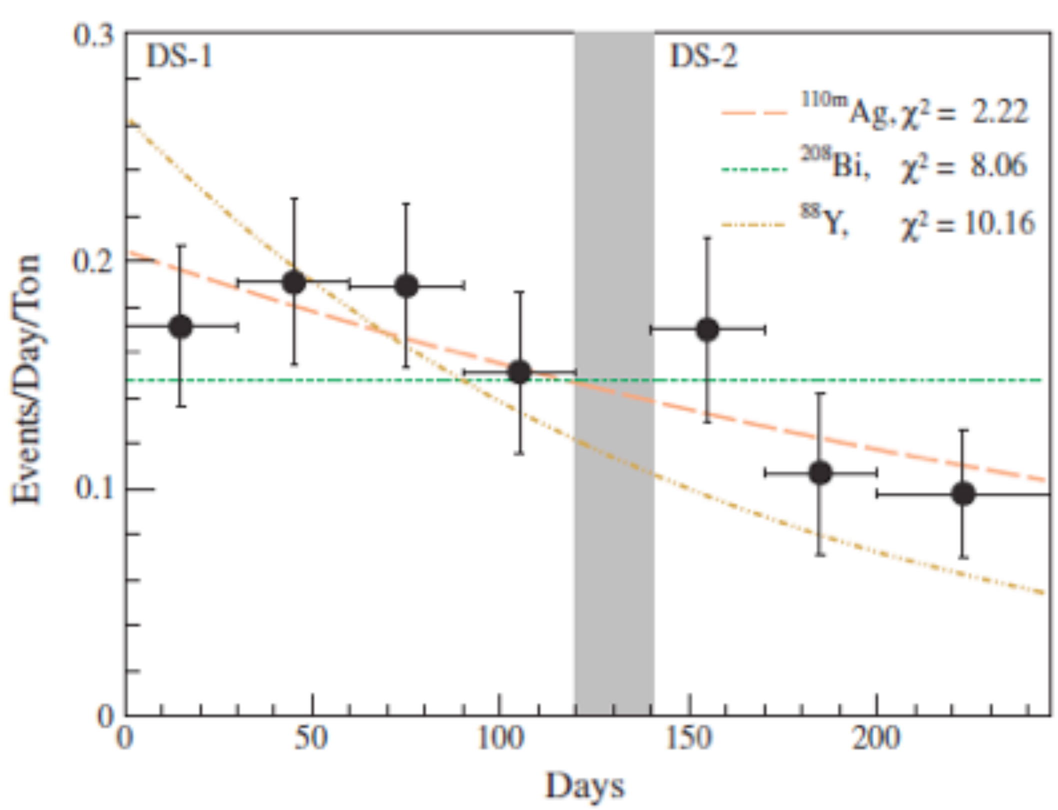
Alternative Hypotheses

^{110m}Ag + 0νββ (DS-1)



^{208}Bi + 0νββ (DS-1)



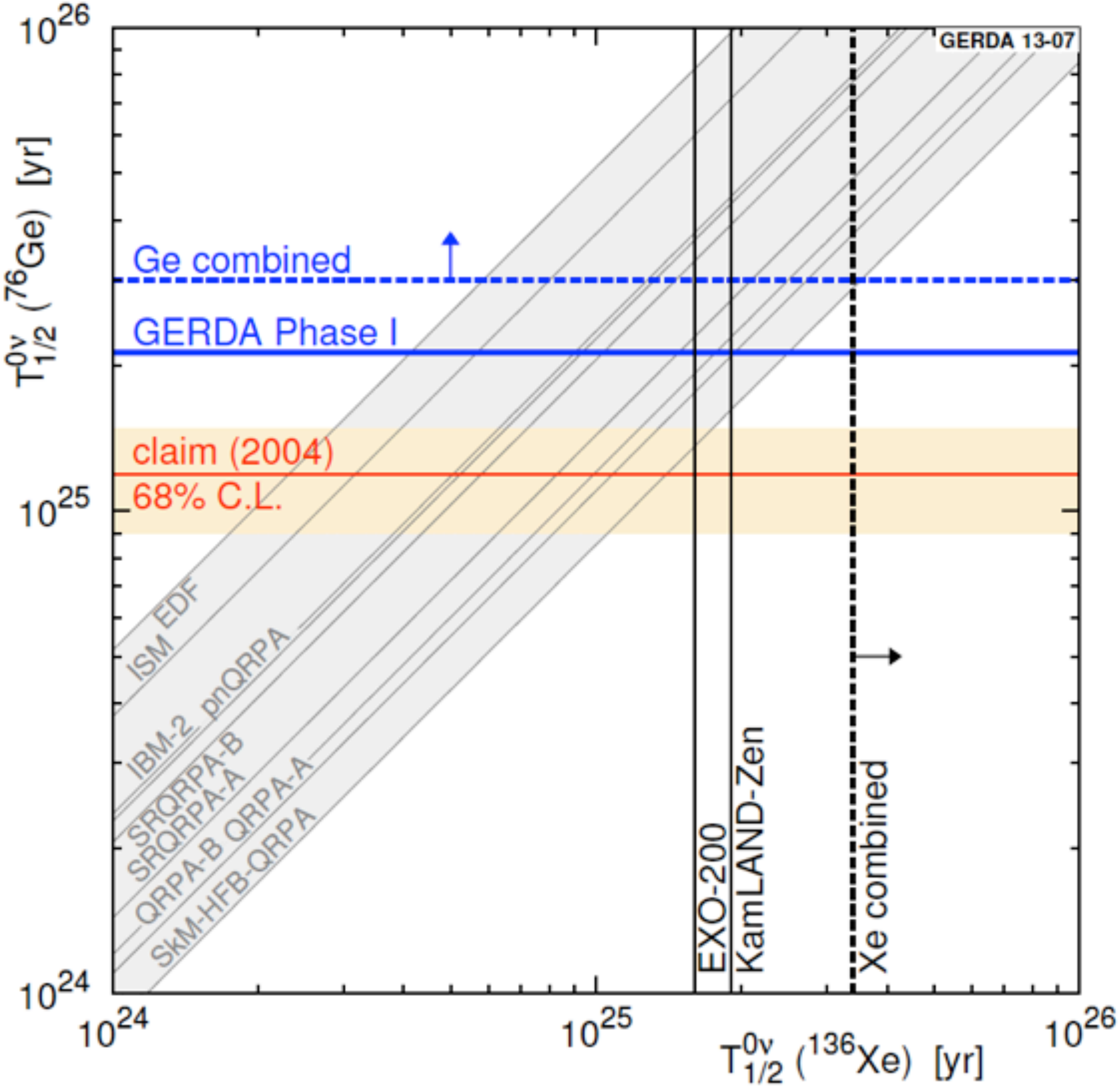


χ^2 for 2.2-3.0 MeV
112 days livetime
(DS-1)

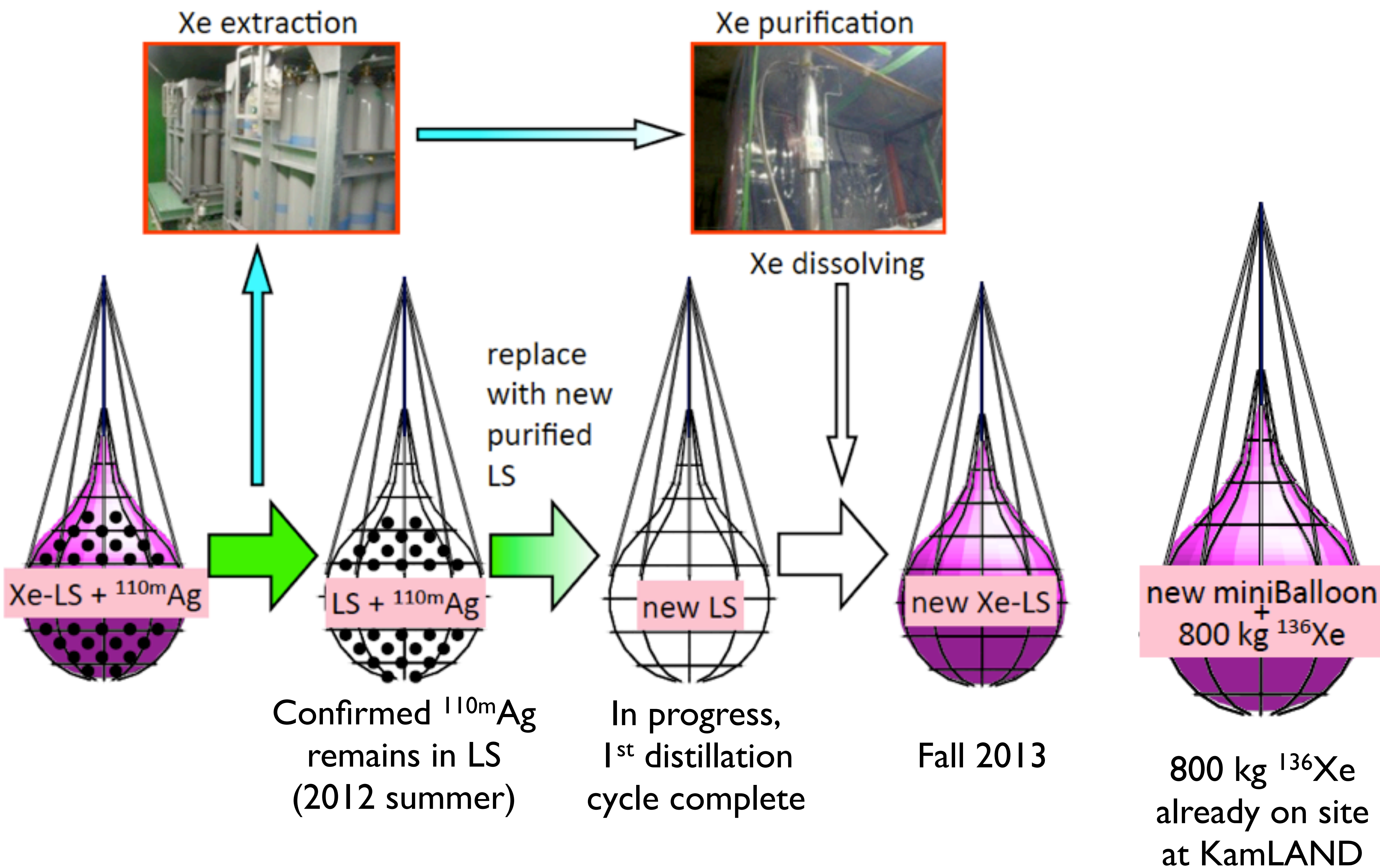
model	χ^2	d.o.f. (eff)
Full fit	11.6	12
0ν+^{110m}Ag	13.1	14
0ν+^{208}Bi	22.7	14
0ν+^{88}Y	22.2	14
0ν+^{60}Co	82.9	14
0ν only	85.0	15

BG is likely ~1000 atoms of ^{110m}Ag

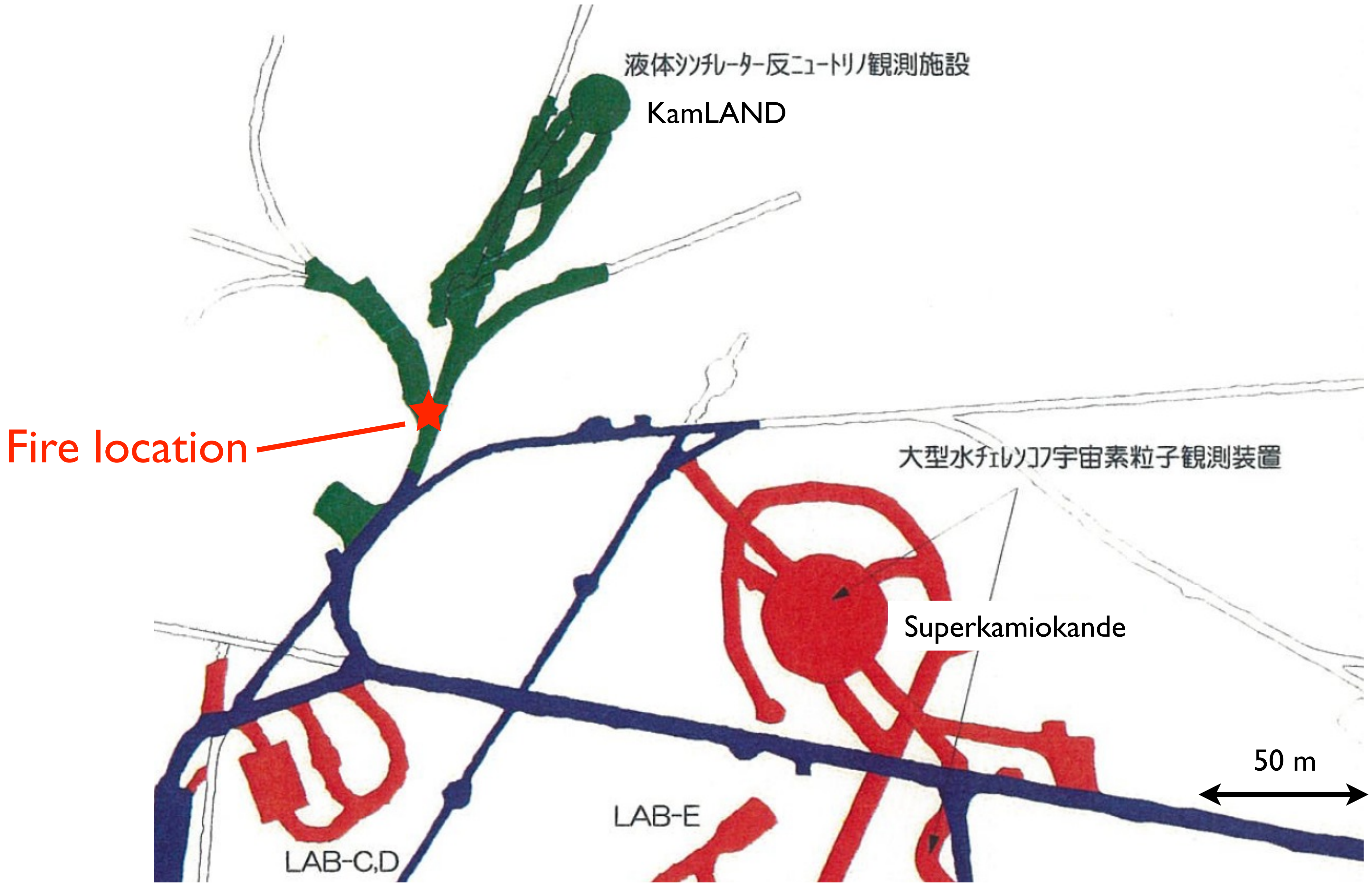
Comparison with ^{76}Ge



Purification / Upgrade Plan



Fire Accident, Nov. 20, 2012



Fire Accident, Nov. 20, 2012

Fire Accident, Nov. 20, 2012

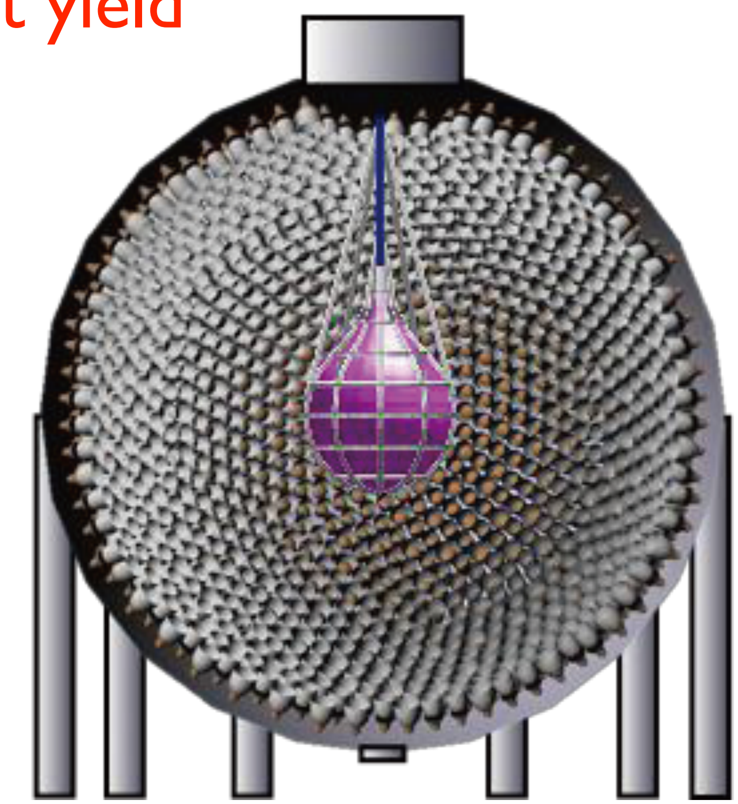
- Thankfully, no one was injured
- No major structural damage
- DAQ restarted within 1 month
- Purification system restarted after ~6 months

Feb 2013

The future: KamLAND2-Zen

- Upgrade options (>2016)
  - Winston cone reflectors
  - High-performance LS R&D
  - Pressurized Xe-LS
  - Scintillating film balloons
- May be able to cover the inverted hierarchy

up to x2 light yield



Outline

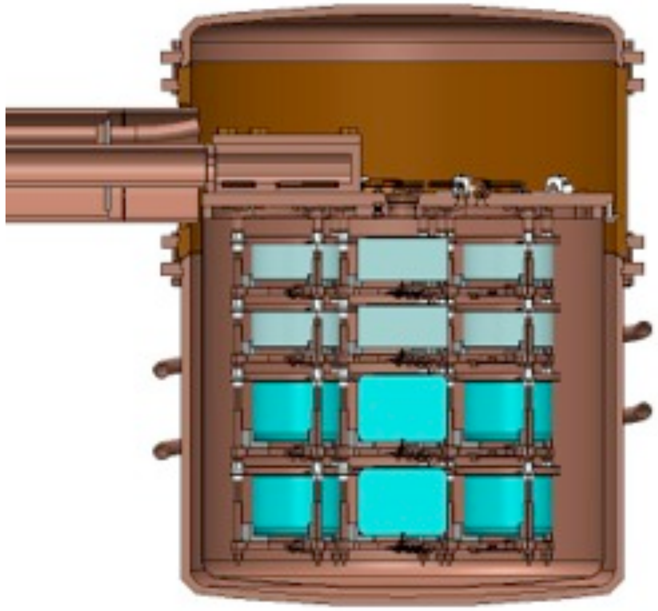
- Recent motivations for large mass, low background experiments
- Large Mass: KamLAND-Zen
- Low-Background: MAJORANA DEMONSTRATOR

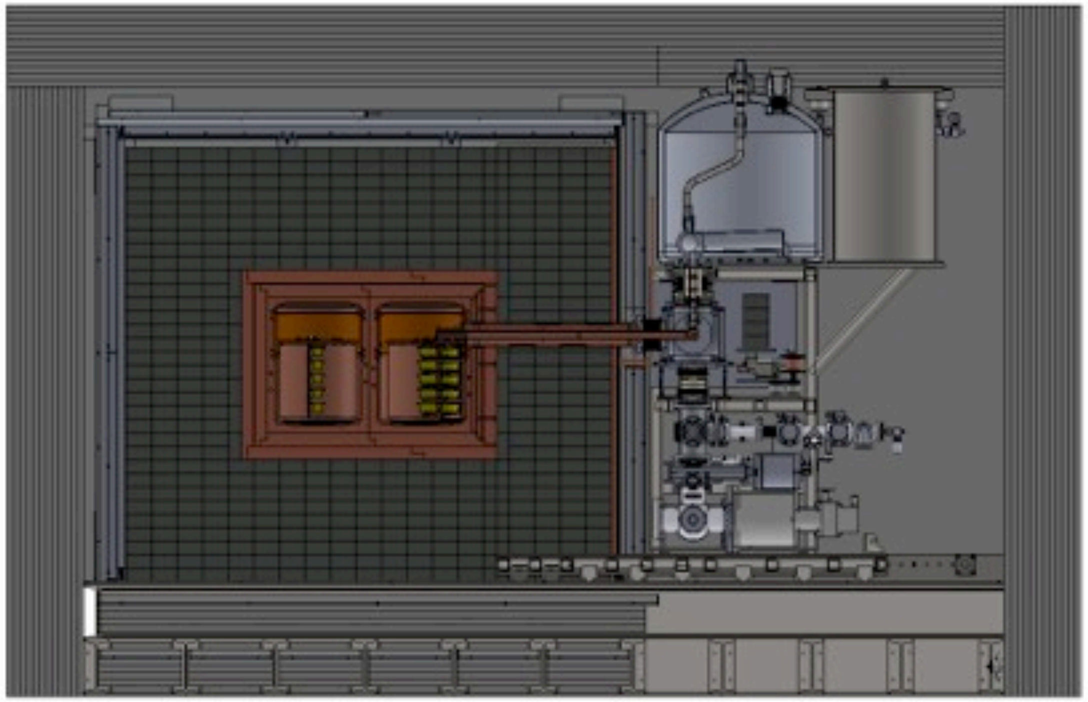
Advantages of ^{76}Ge

- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution: 0.16% at 2039 keV (4 keV ROI)
- Powerful background rejection: segmentation, timing, pulse-shape discrimination
- Demonstrated ability to enrich from 7.44% to ≥86%

The MAJORANA DEMONSTRATOR (MJD)

- Located 4850' underground at Sanford Underground Research Facility
- 40-kg of Ge detectors, 30-kg enriched to 86% in ^{76}Ge
- 2 independent cryostats made of ultra-clean, electroformed Cu
- Compact Pb and Cu shield + muon veto
- Background goal: 3 counts in the $0\nu\beta\beta$ peak region of interest in a one tonne-year exposure

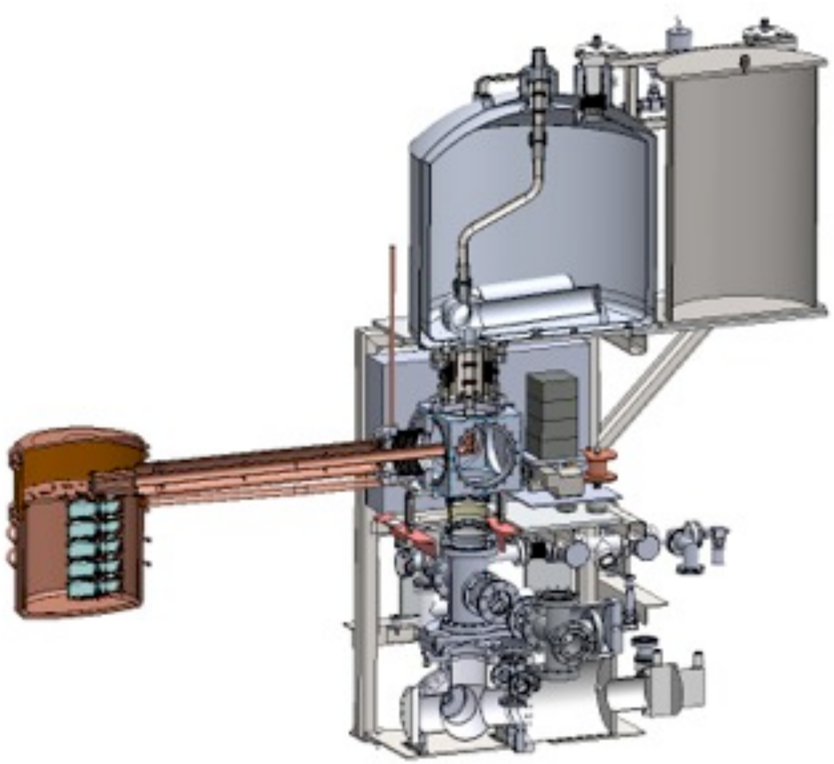


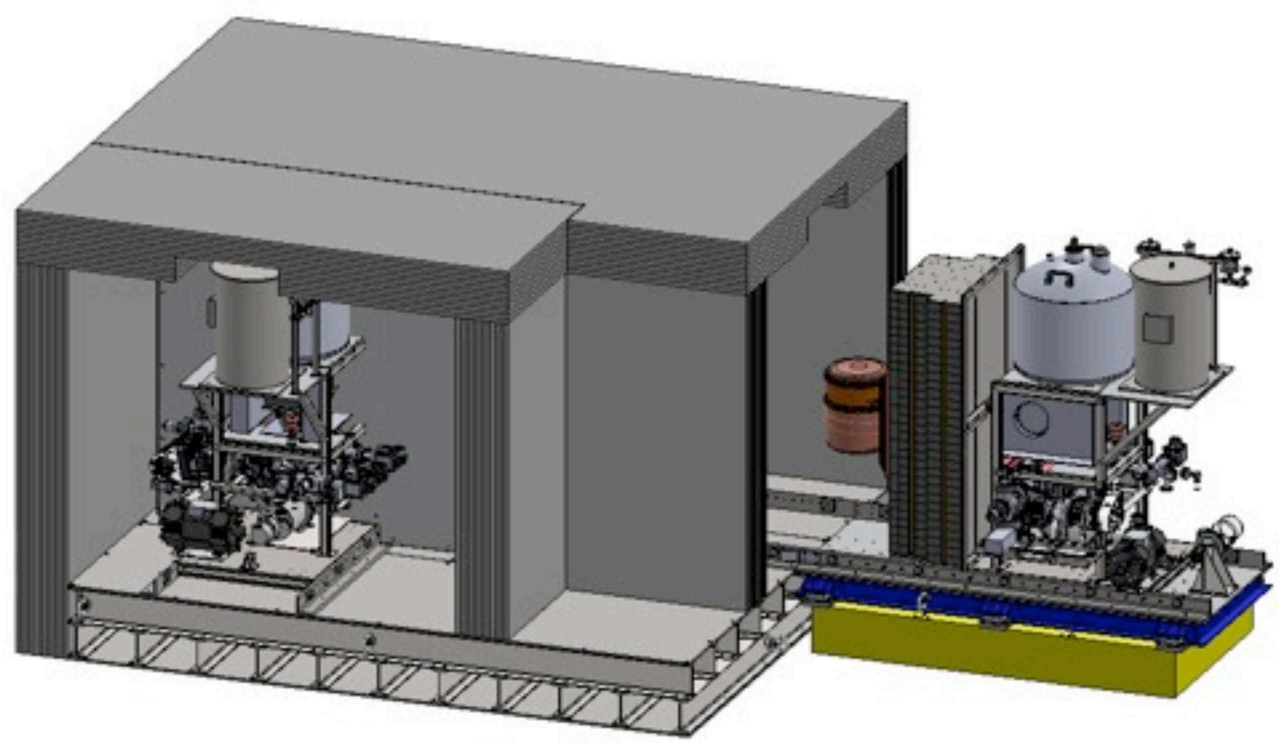


Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics, with additional contributions from international collaborators.

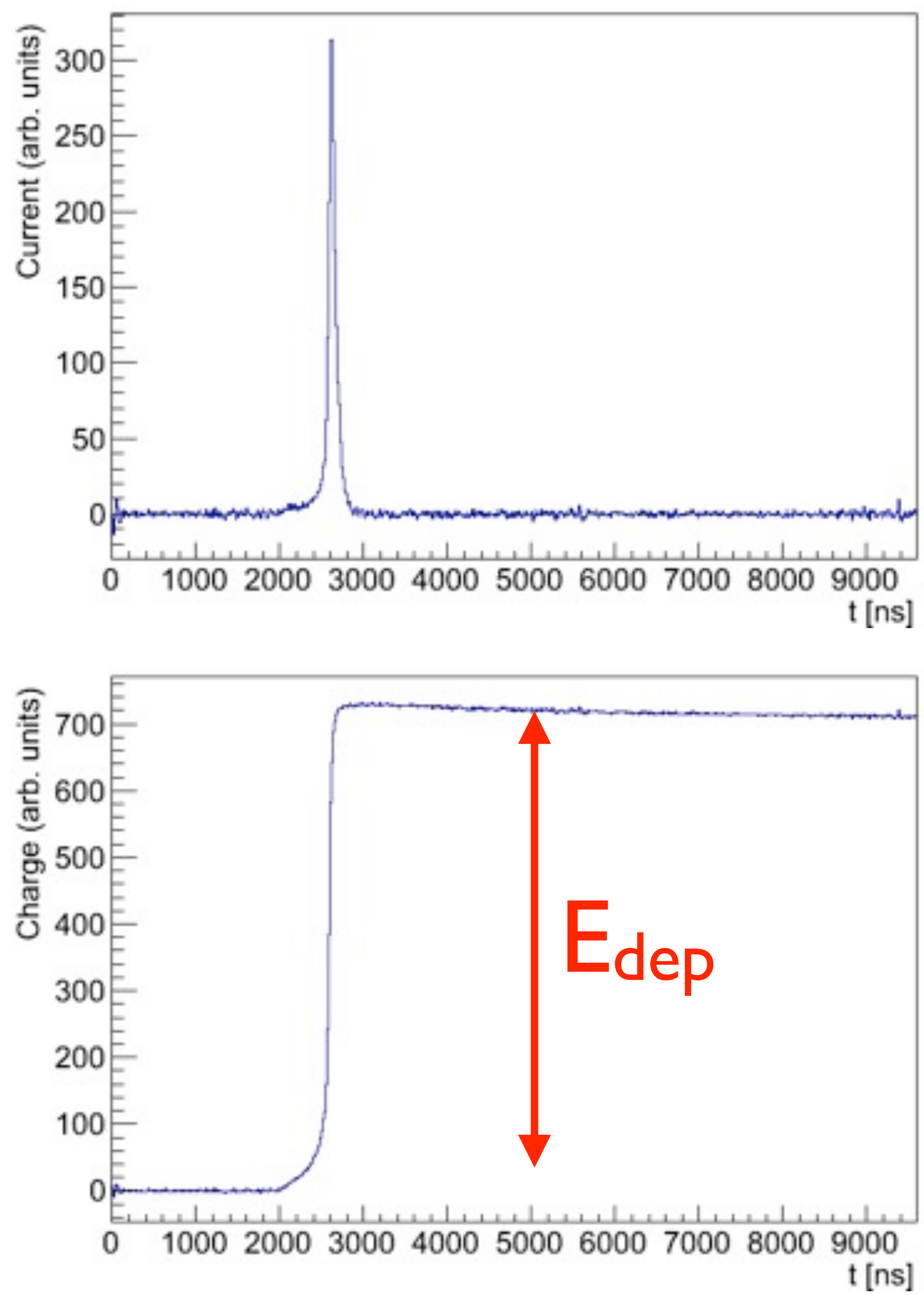
MJD Implementation

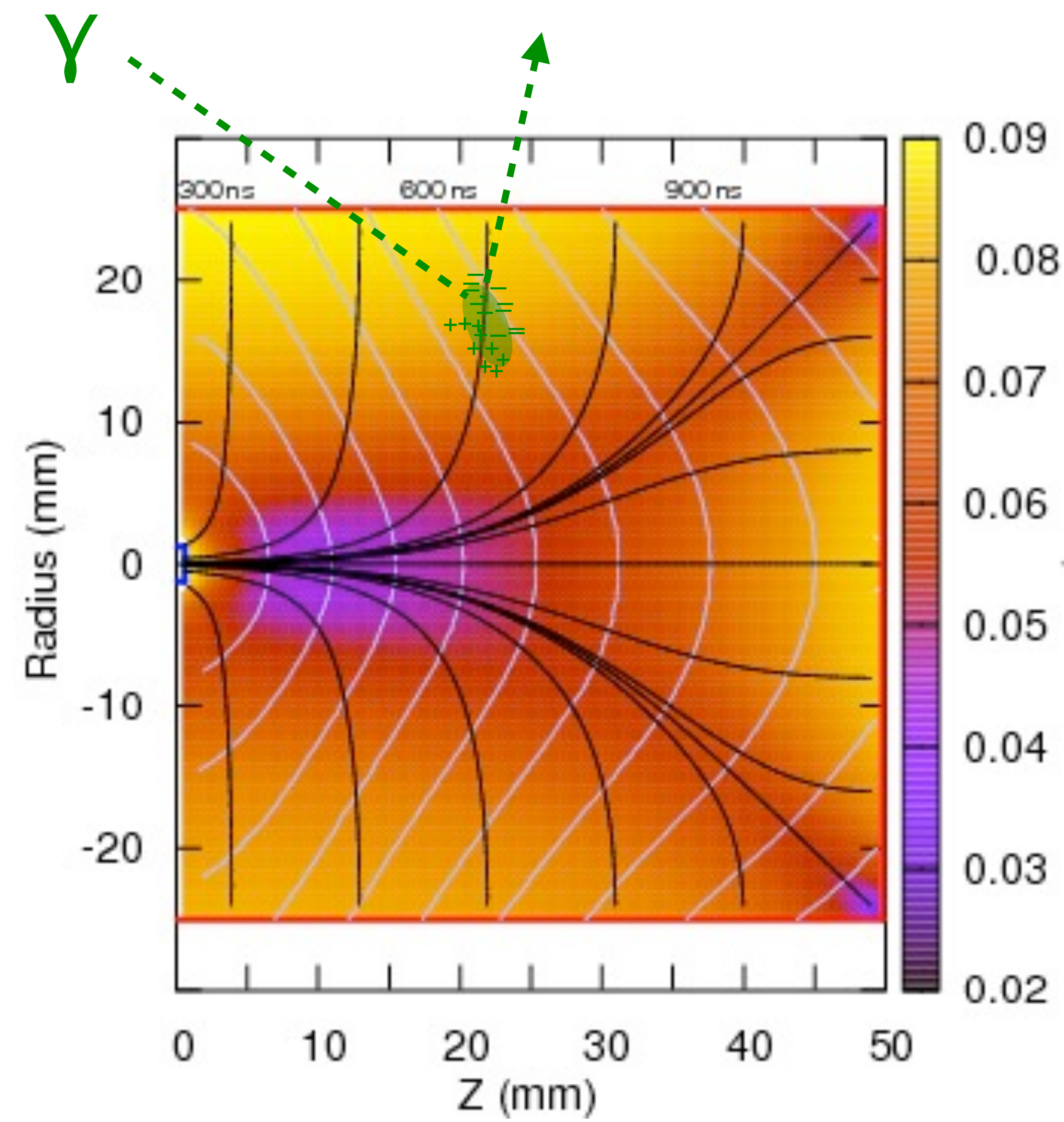
- Prototype Cryostat (2 strings, natGe): Summer 2013
- Cryostat 1 (3 strings enrGe & 4 strings natGe): Late 2013
- Cryostat 2 (7 strings enrGe): Fall 2014





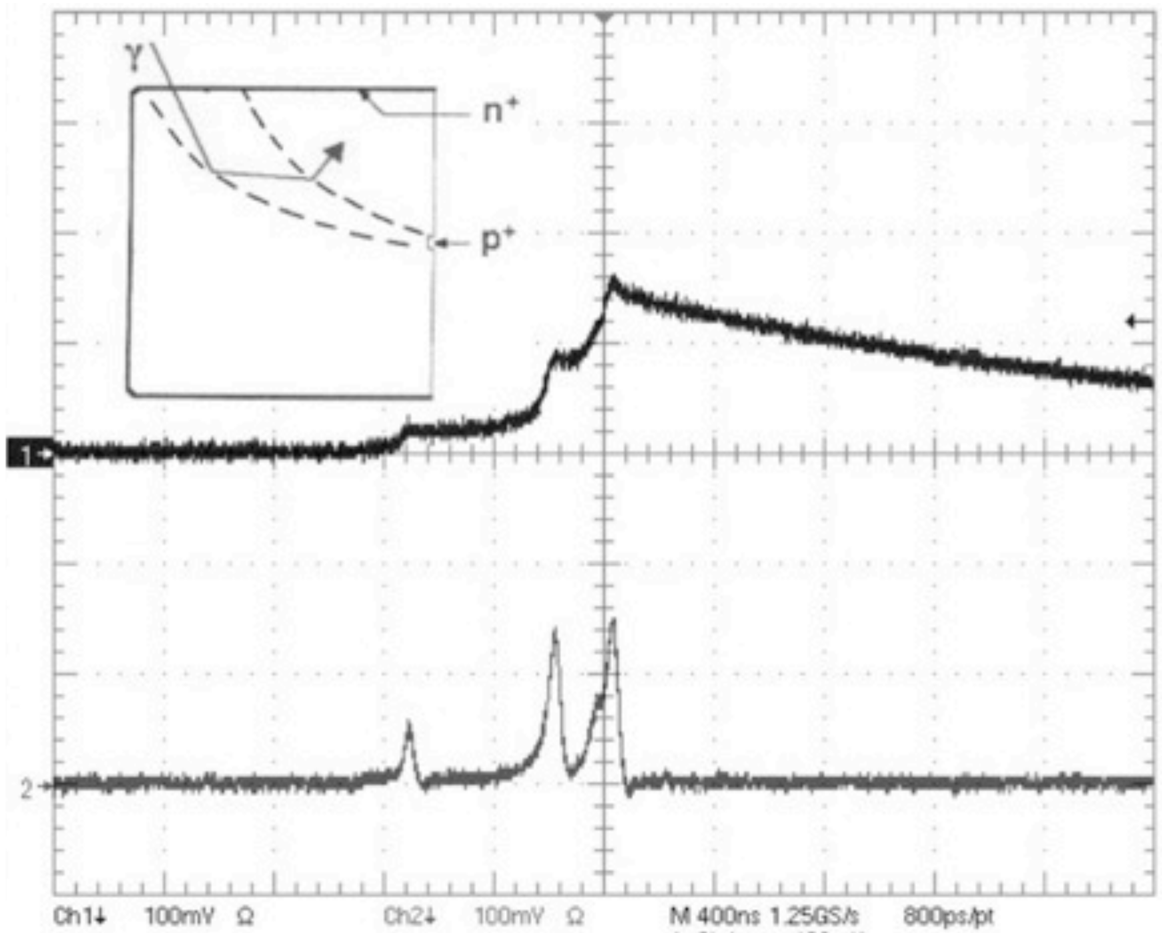
Point-Contact Ge Detectors

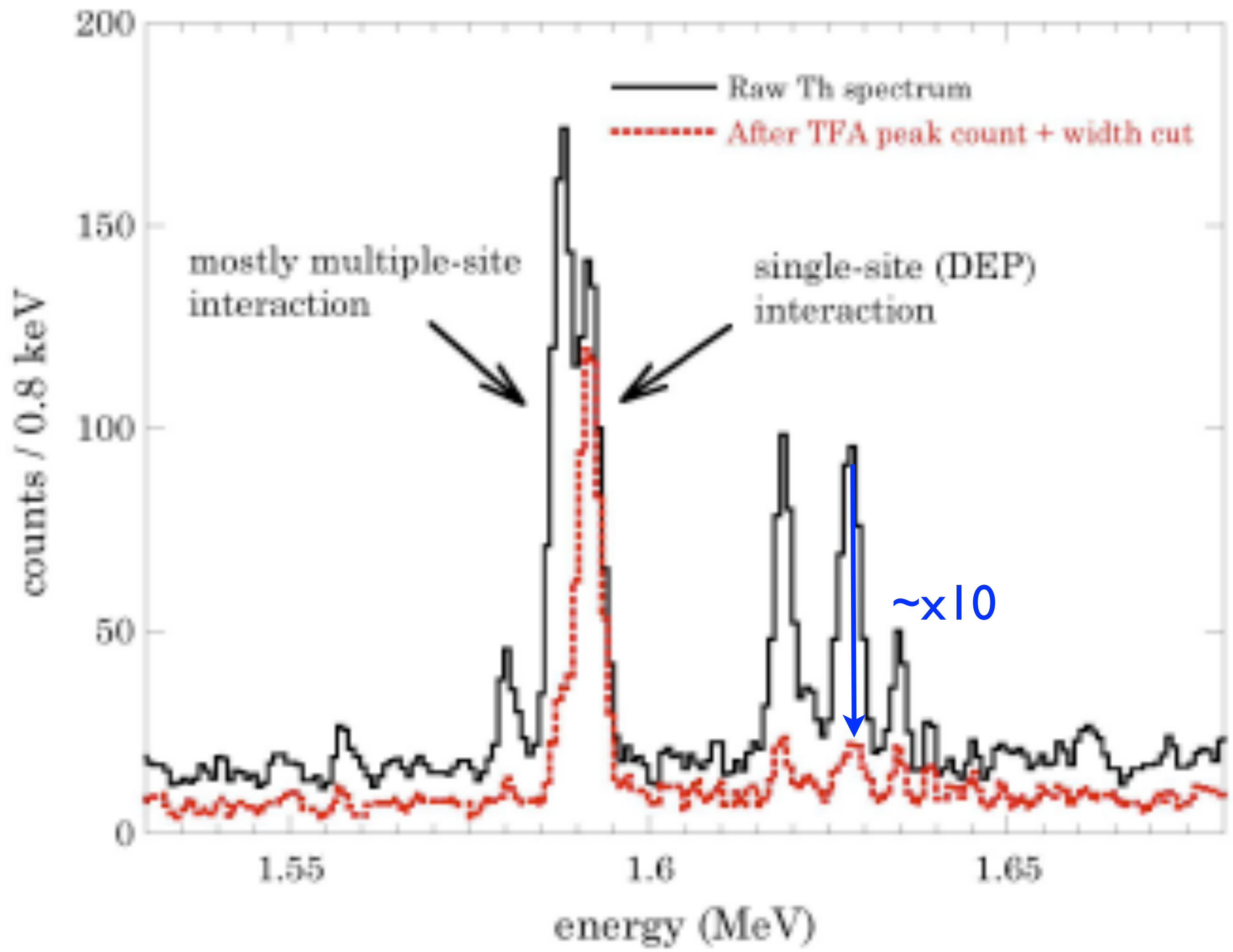




Hole v_{drift} (mm/ns) w/ paths, isochrones

Point-Contact Ge Detectors





Barbeau et al., JCAP 09, 009 (2007).

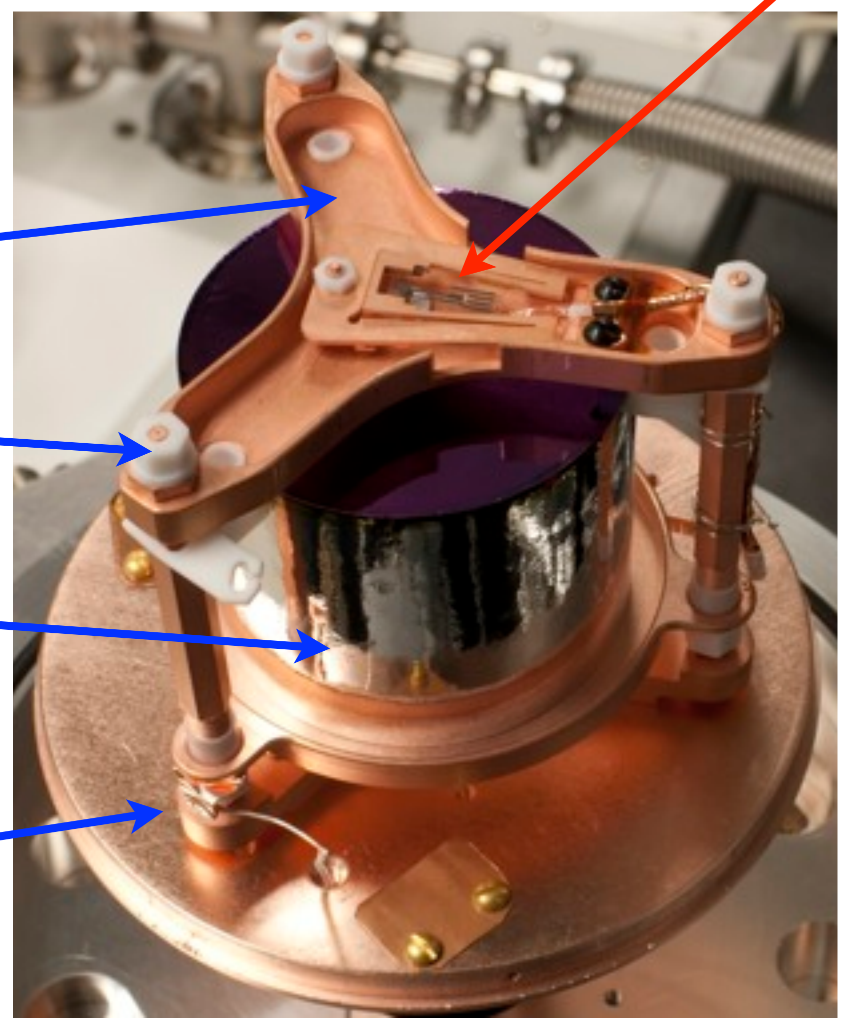
Ultra-Pure Materials

Electroformed Copper

clean PTFE

HPGe

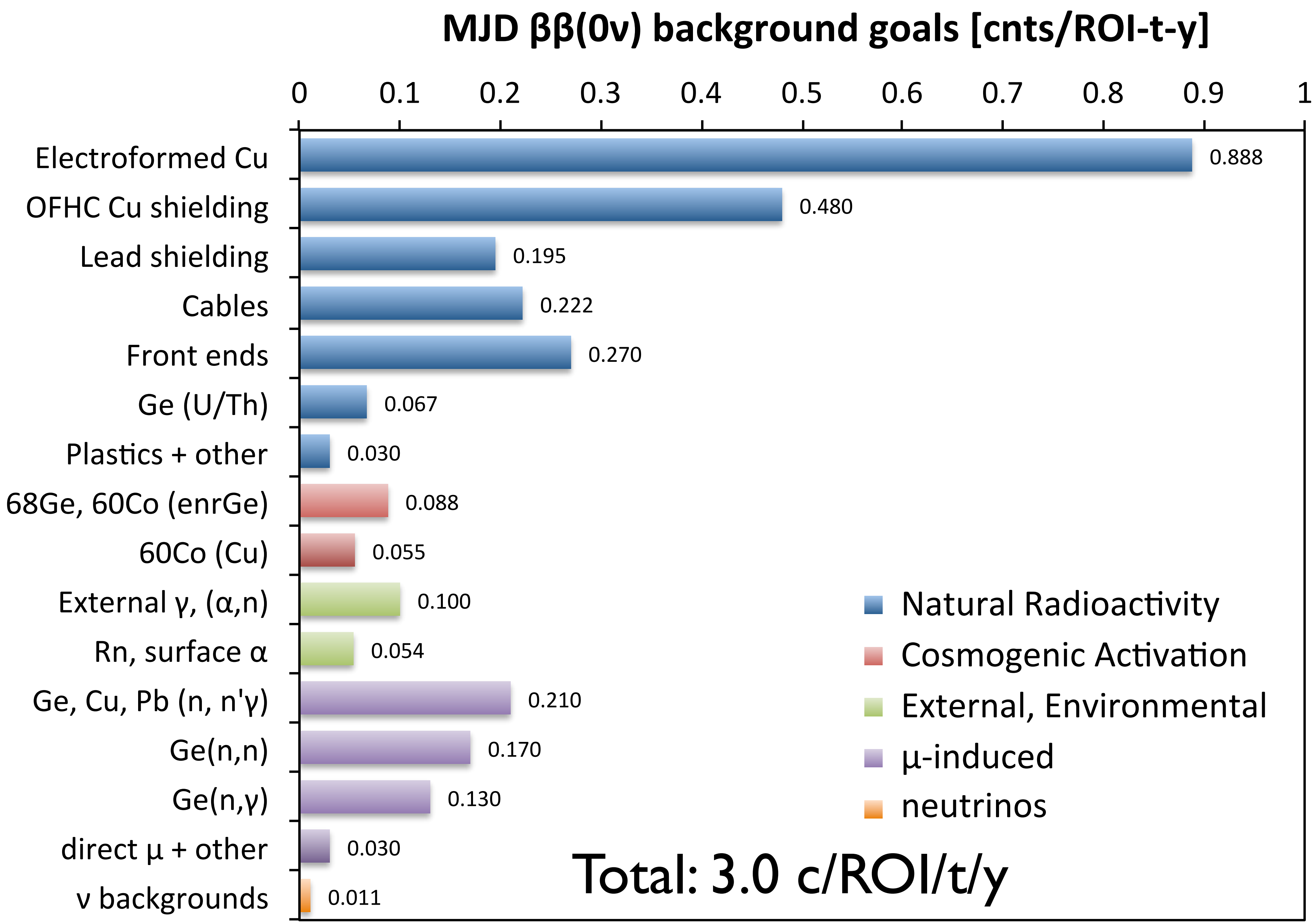
clean PFA + fine Cu coaxial cable



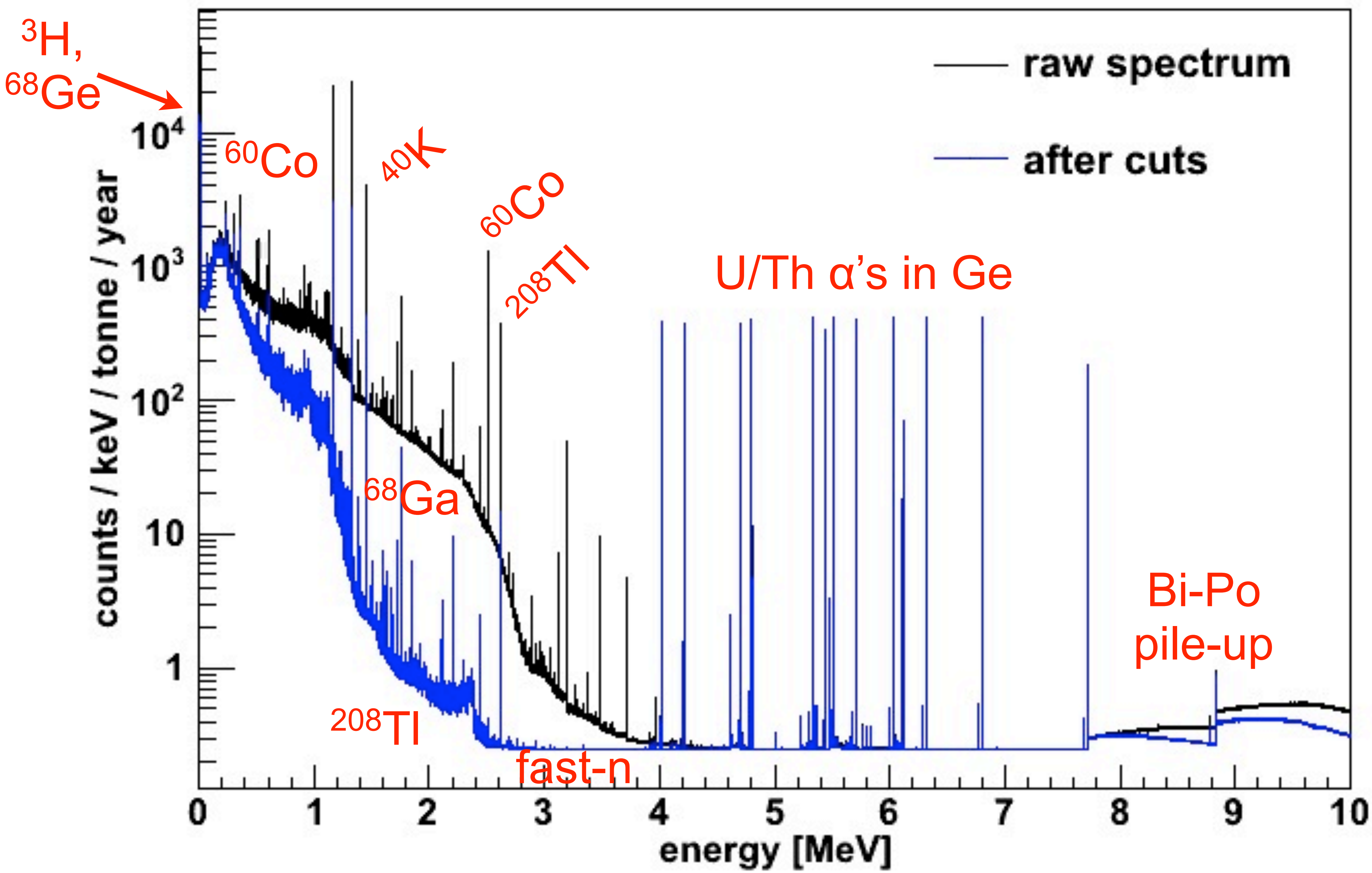
Custom Low-BG Electronics:
fused silica
clean Au+Ti traces
amorphous Ge resistor
FET w/clean silver epoxy
electroformed Cu spring clip
low-BG Sn contact pin

Also:
- Parylene coating / seals
- Vespel, PEEK supports
- Shields: Low-BG commercial Cu and Pb

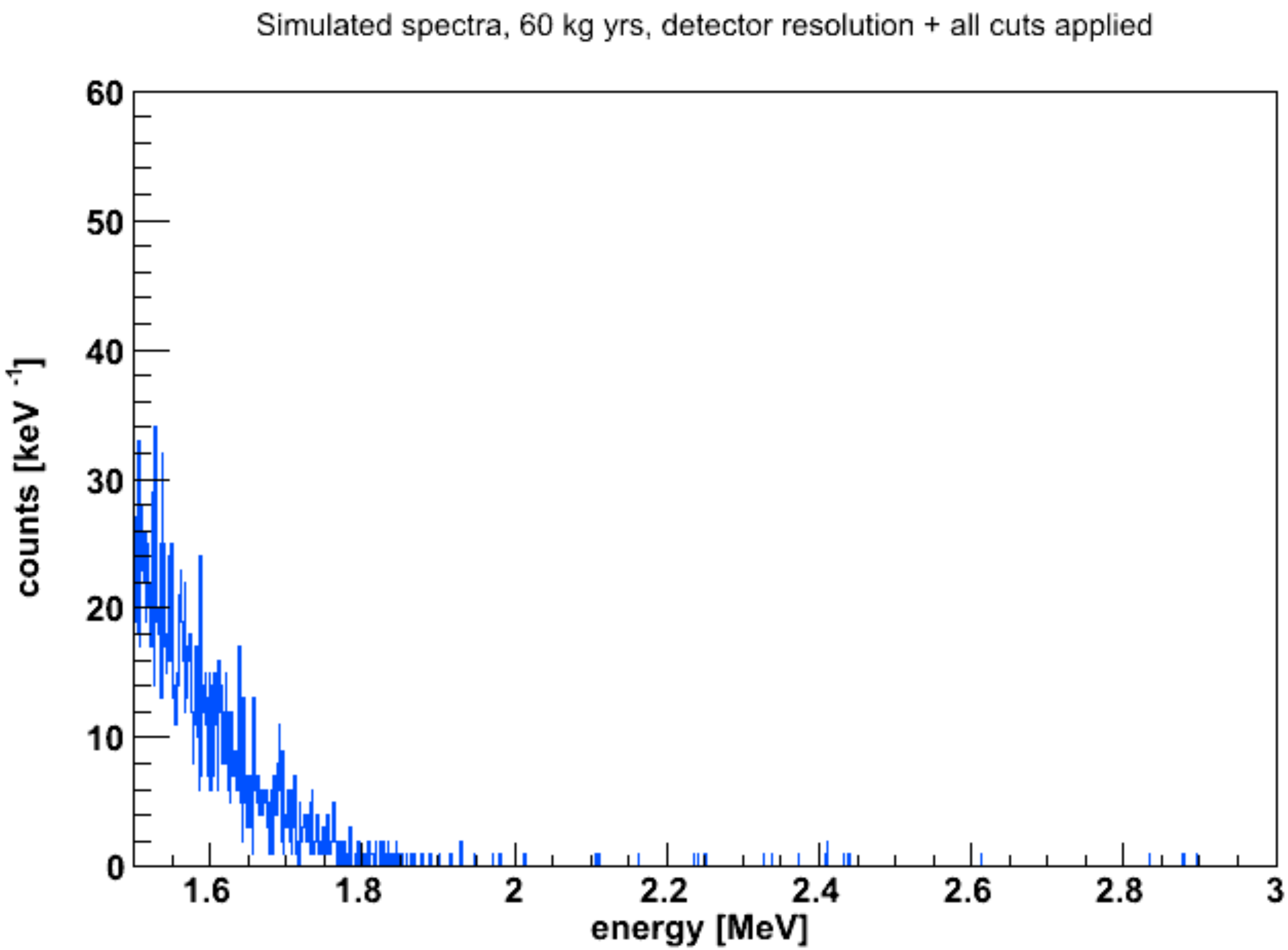
Background Budget



Expected Backgrounds



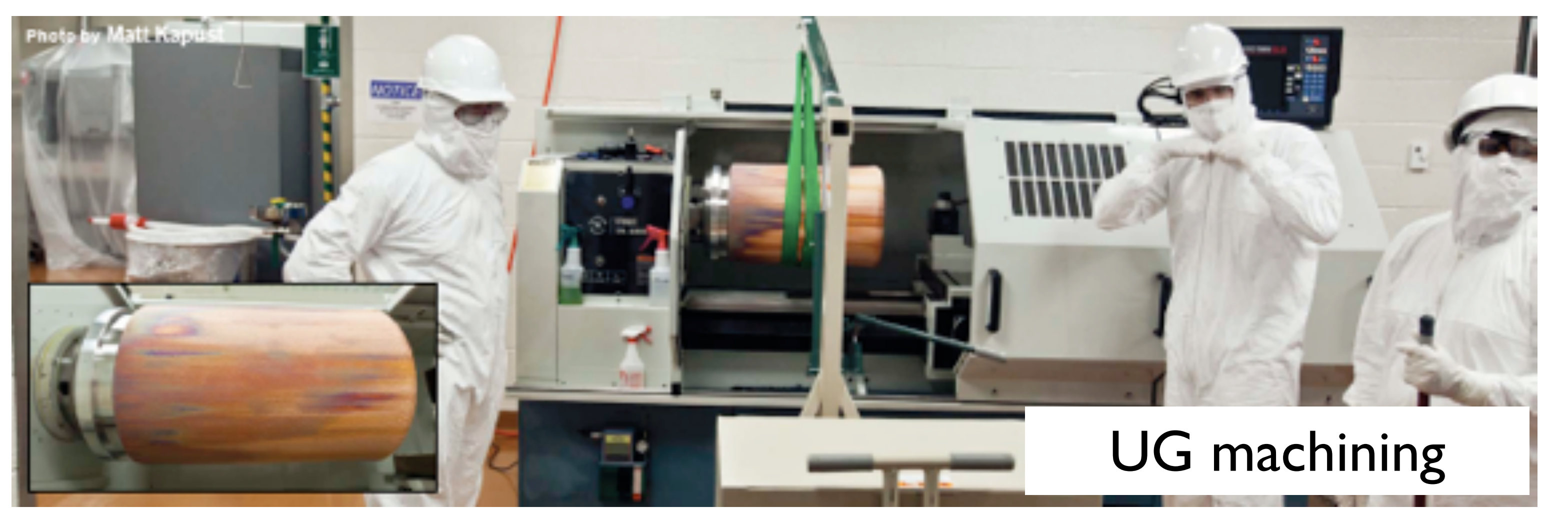
MJD Spectrum after 3 Years



MJD Progress

Site Infrastructure

- Under construction at 4850L of SURF
- Cu Electroforming facilities online since Spring 2011
- Beneficial occupancy of Davis Campus space since May 2012. Operational UG machine shop.
- Cleanliness exceeds specifications.



Materials and Assay

- Assay of all samples (gamma, NAA, ICPMS...)
- Significant improvements in Cu assay (sub μBq/kg)
- Operating 10 EFCu baths at SURF, 6 at PNNL.
- >75% of Cu production is complete

EFCu inspection during growth

Enriched Ge

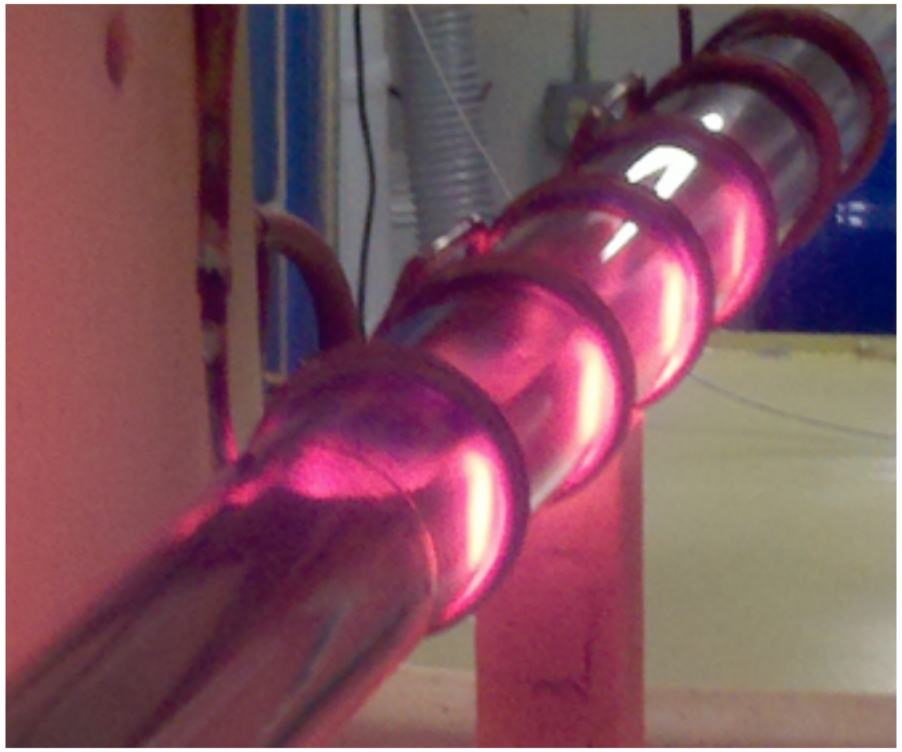
- 42.5 kg of 86% enriched Ge procured from Russia
- Shipped in shielded container
- Reduced to electronic grade Ge with 98% yield

Delivery to Oak Ridge

Enriched Ge

- 42.5 kg of 86% enriched Ge procured from Russia
- Shipped in shielded container
- Reduced to electronic grade Ge with 98% yield

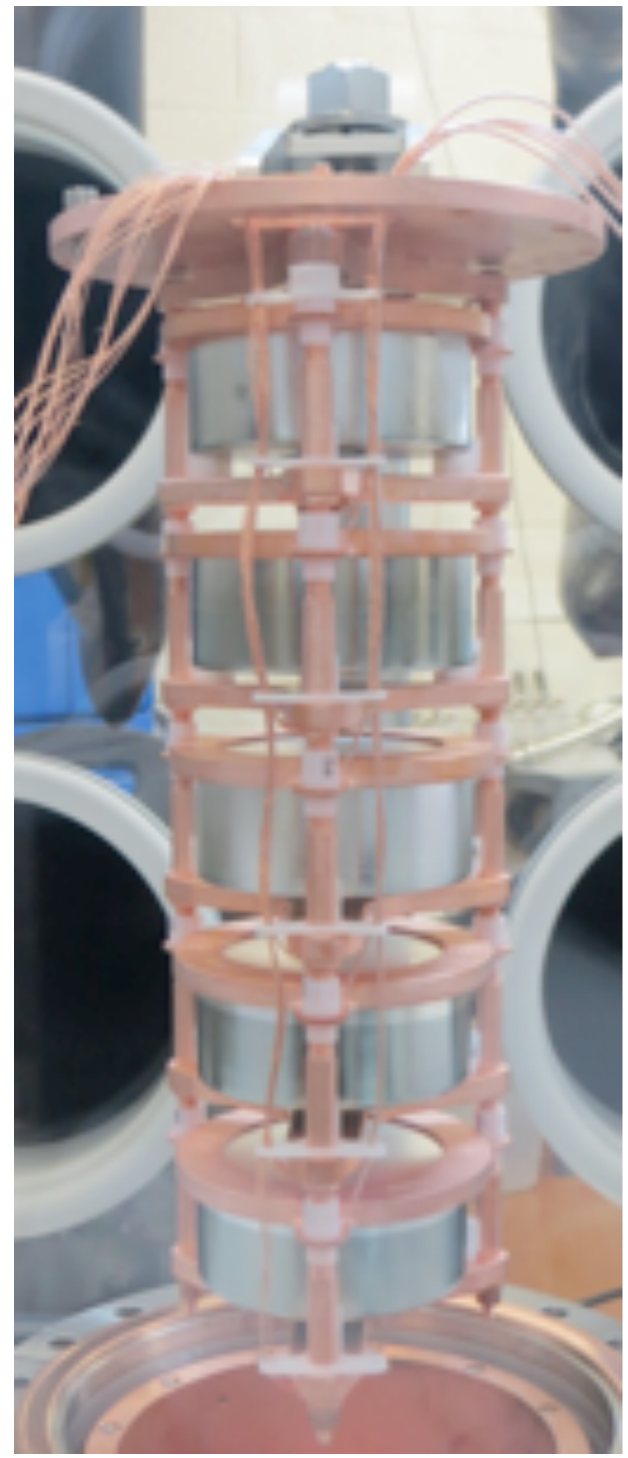
Zone refining ^{enr}Ge



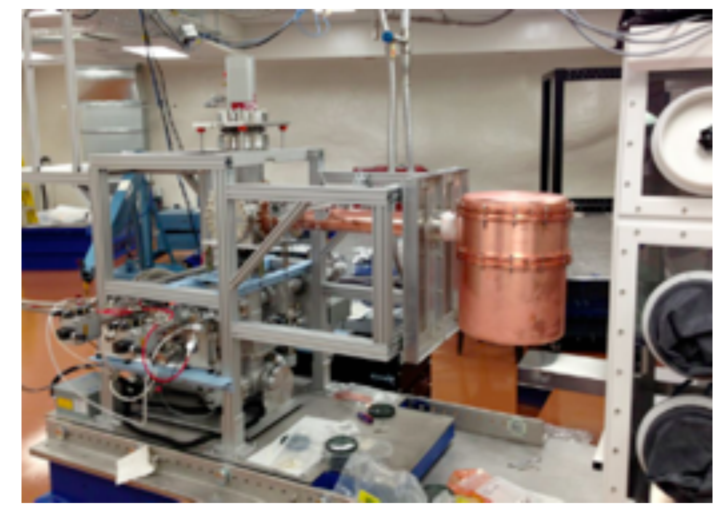
Electronic grade ^{enr}Ge

Detectors

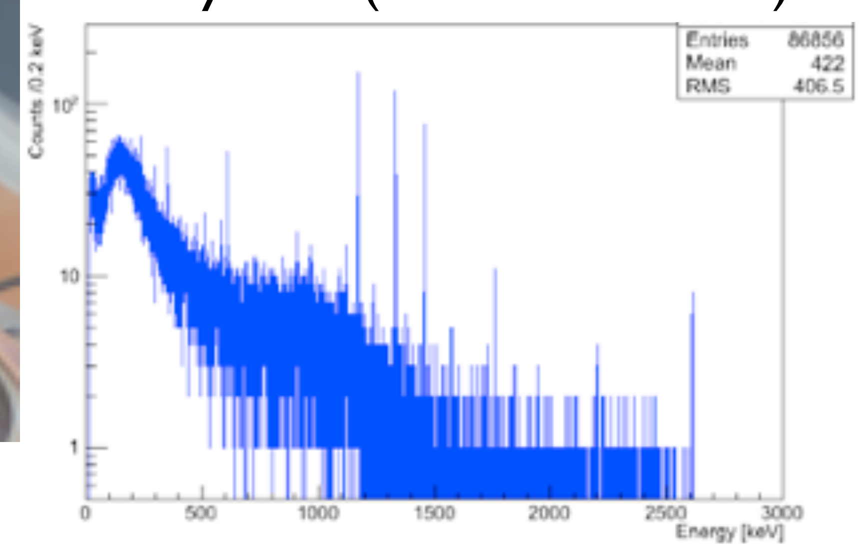
- 10 PPCs of ^{enr}Ge (9.5 kg) produced by ORTEC and UG at SURF
- Two strings of ^{nat}Ge built in UG glove boxes and under testing
- Prototype cryostat assembled and operated with pulse-tube cooler



Prototype Cryostat



^{Nat}Ge ORTEC PPC in String Test Cryostat (^{60}Co Calibration)



Shield

- Shield table and monolith carts in use
- Lead bricks cleaned, stacking about to start
- Veto panels delivered to site and ready for installation

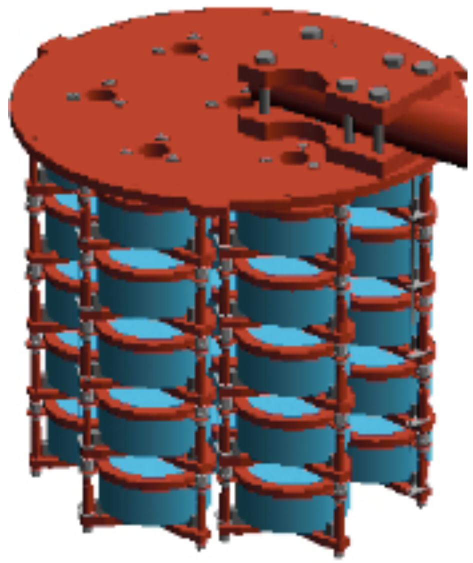
DAQ and Software

- Slow controls and monitoring running and stable since 2011
- ORCA DAQ implemented andin use
- Simulations co-developed with GERDA since 2004. Well-validated
- Analysis of characterization data in progress

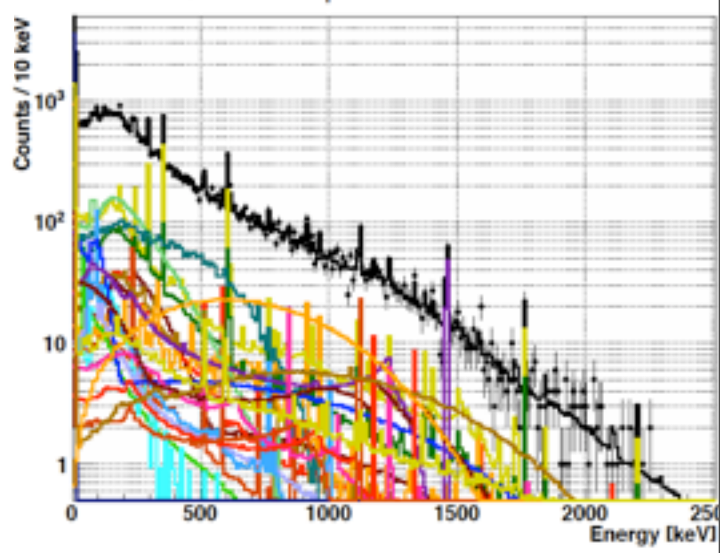
Vacuum monitoring/control

Slow controls web monitoring

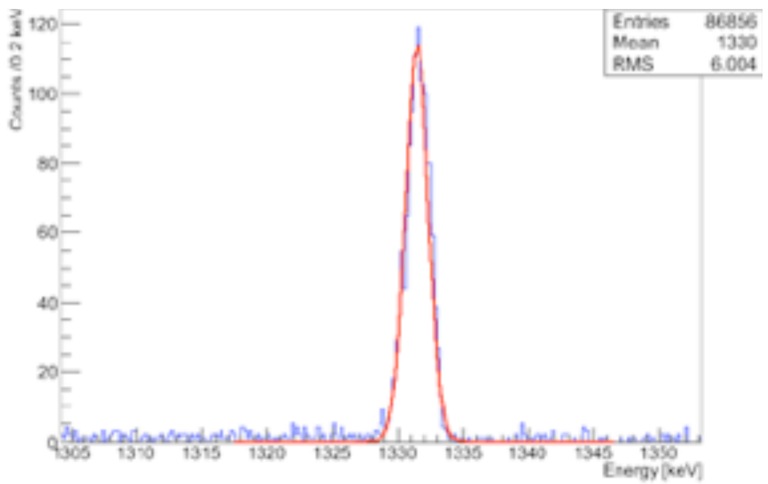
Geant4 model of cryostat



MALBEK Data compared to simulations



Fit to ^{60}Co 1332 keV for ORTEC PPC in string test cryostat



Upcoming Activities

2013-14

- Commission Cryostat 1, operate Prototype Cryostat and Cryostat 1 at MJD Davis Lab
  - detector operations
  - simulations with as built activities
  - data analysis
  - physics papers on Prototype Cryostat results
- Fabricate and assemble Cryostat 2 at MJD Davis Lab
  - underground machining
  - characterize enriched PPC detectors
  - build and test Cryostat 2 strings
- Assay of materials in Cryostat 2
- Complete manufacture of enriched PPC detectors, electroformed Cu, assembly of shield, lab infrastructure

2014-15

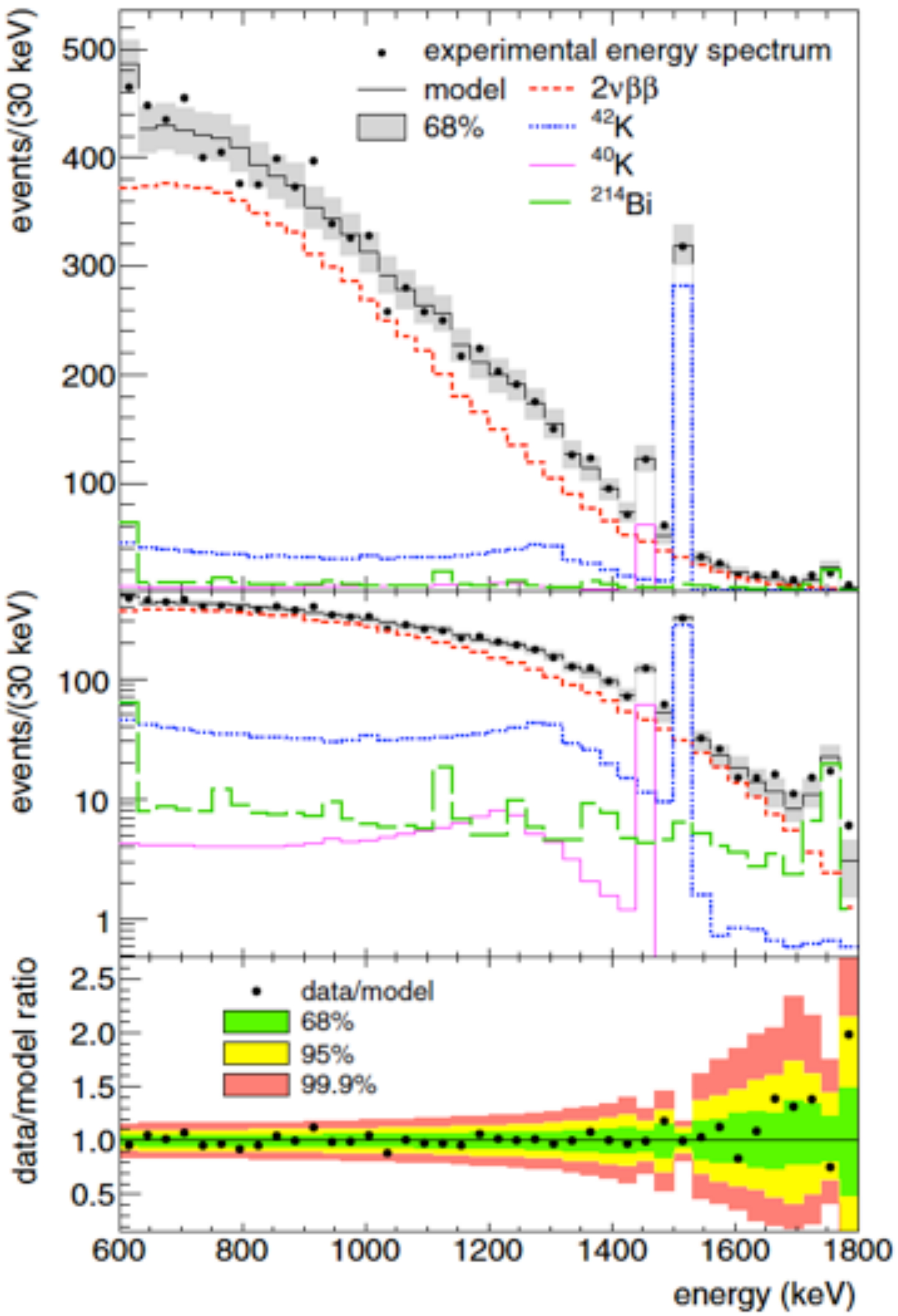
- Continue to operate Cryostat 1 at MJD Davis Lab
  - detector operations
  - simulations with as built activities
  - data analysis
- Commission Cryostat 2 at MJD Davis Lab
  - detector operations
  - simulations with as built activities
  - data analysis
- Operate the DEMONSTRATOR array.

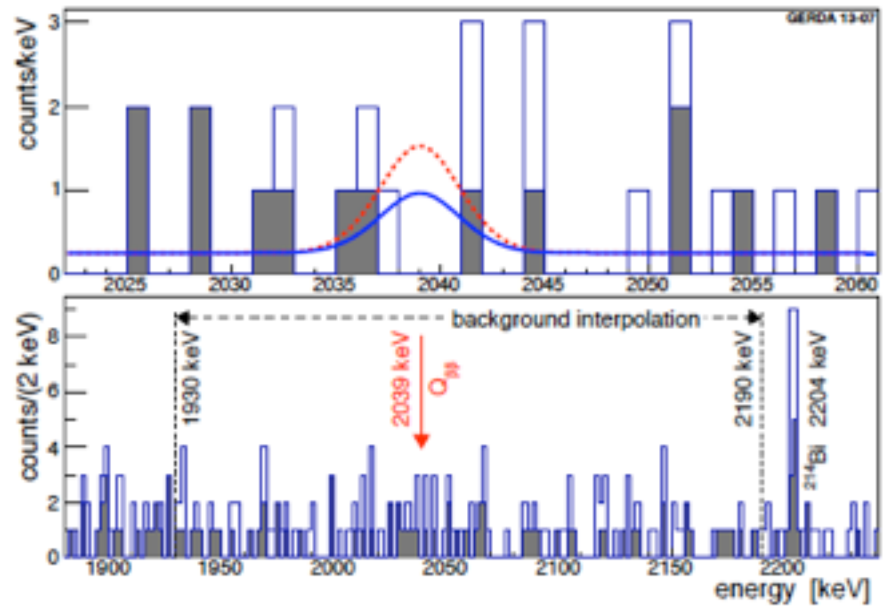
GERDA

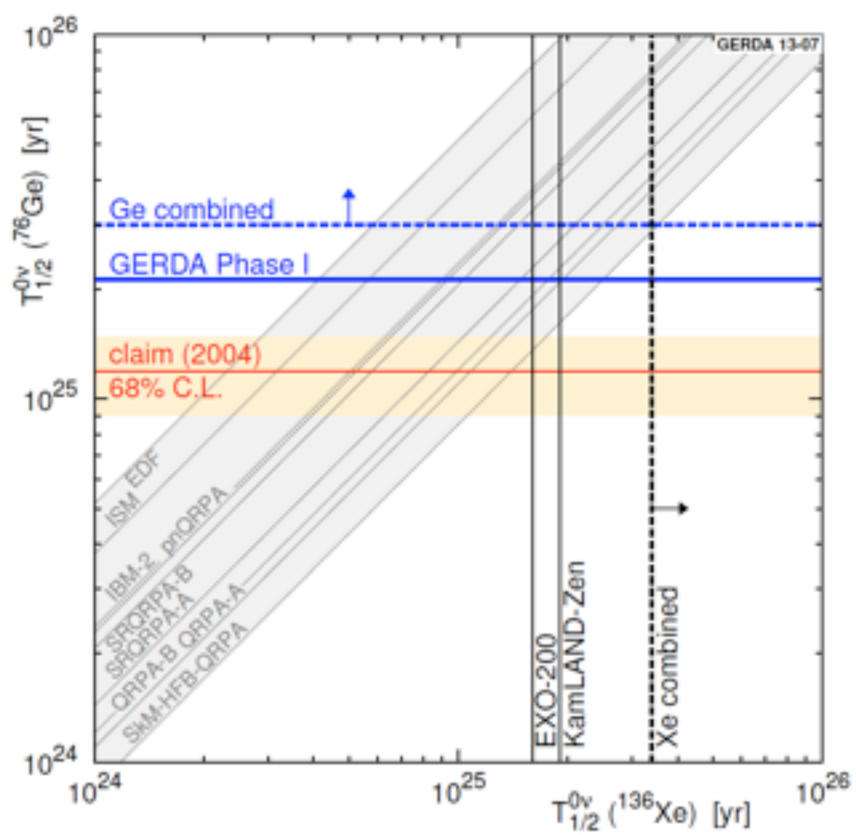
- Immerse detectors directly in liquid Ar
- Phase I: 15 kg at LNGS with H-M / IGEX detectors
- Phase II: 30-35 kg low-bg PPCs

Intend to merge GERDA + MJD for tonne-scale experiment

GERDA Phase I



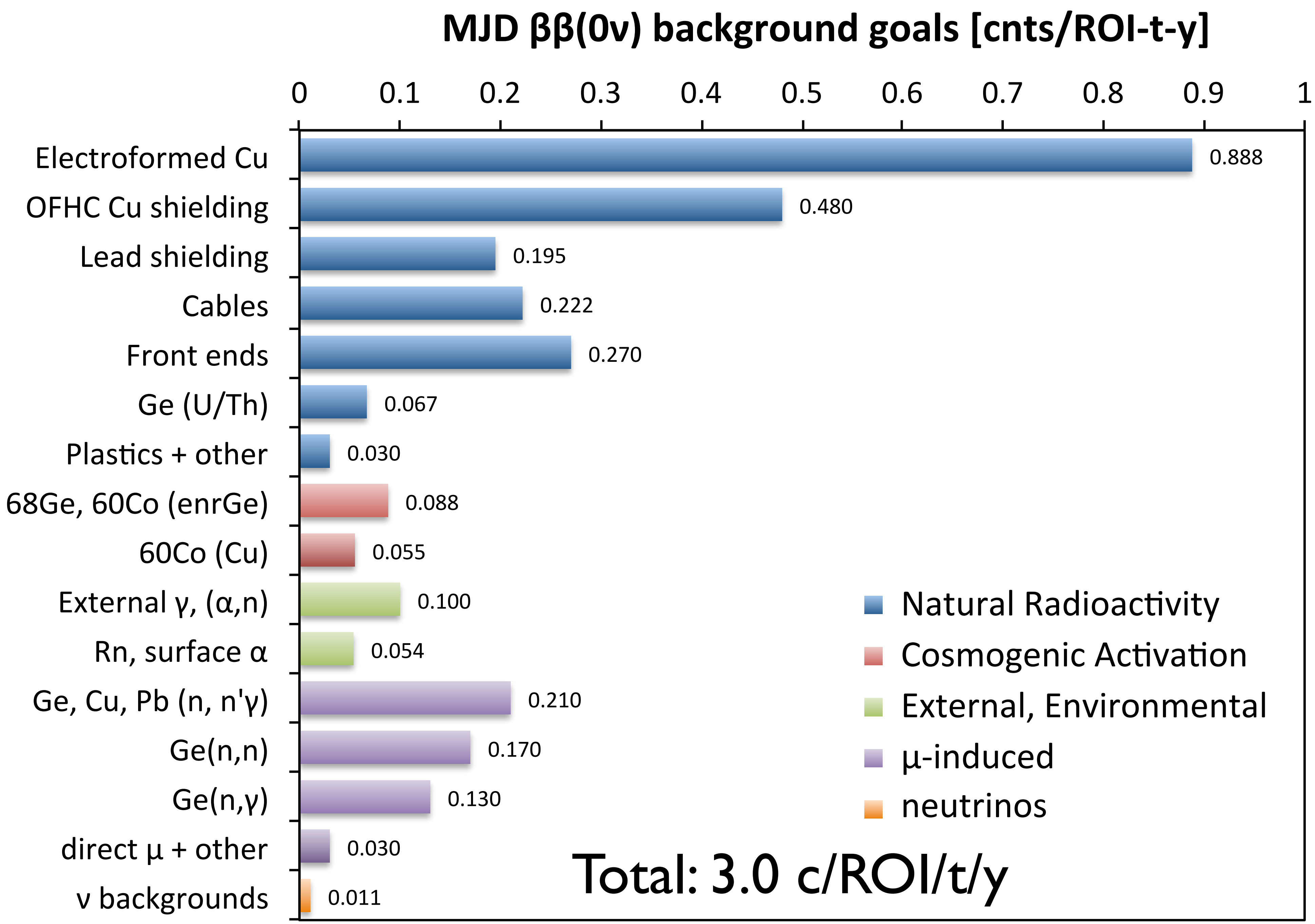




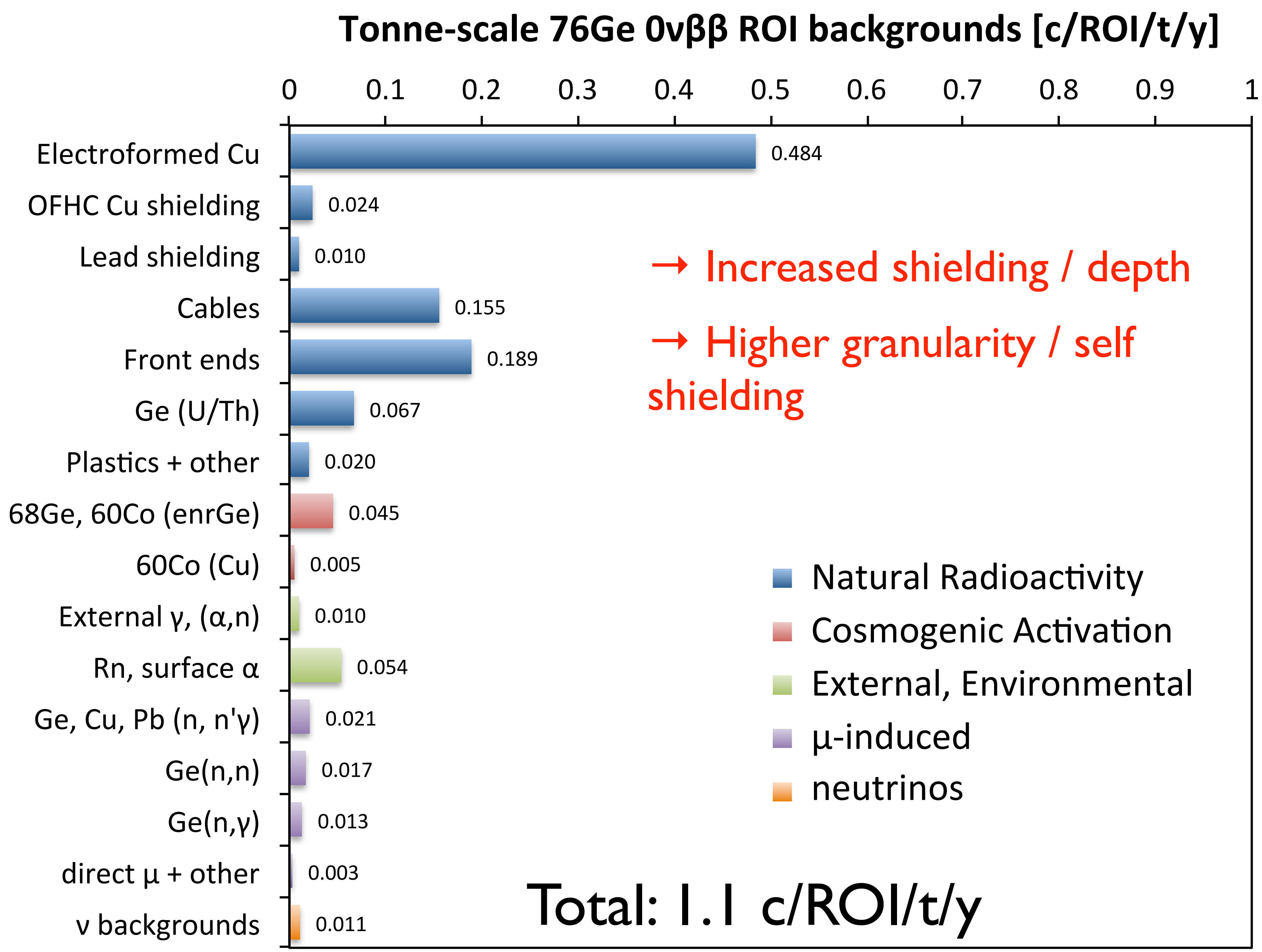
Background:
~40 counts/ROI/t/y,
meets Phase I goal

Phase II bg goal
similar to MJD

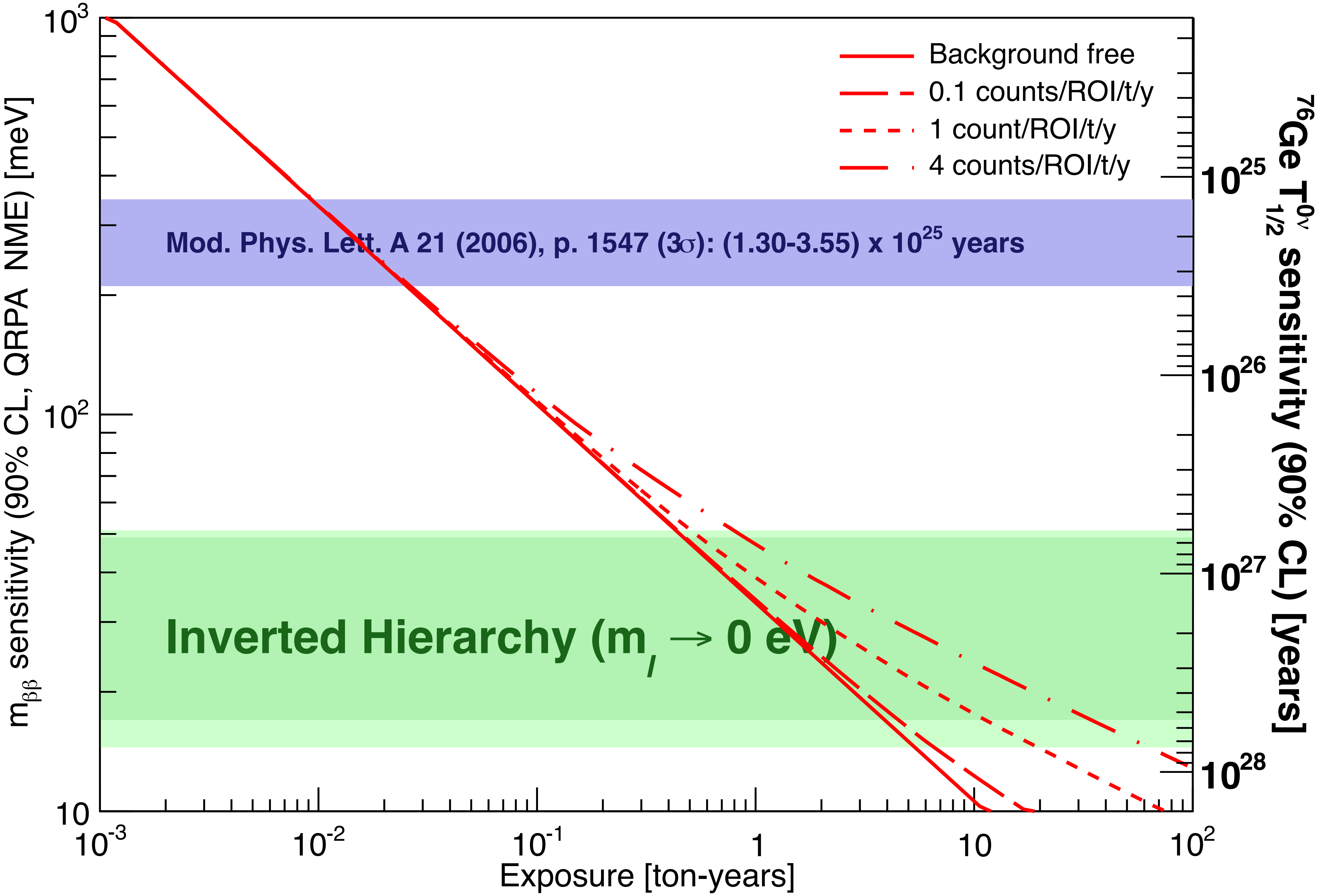
MJD Background Budget



Tonne-Scale Projection



Inverted Hierarchy Sensitivity



Jason Detwiler

Summary

- Low background is essential for IH sensitivity.
- Discovery may be just around the corner!
- If the $0\nu\beta\beta$-region background can be removed, KamLAND-Zen could cover much of the available space
- MJD and GERDA are aiming for the lowest background levels in the *current* generation: 3-4 c/ROI/t/y, projecting to <1 c/ROI/t/y without requiring new reduction techniques

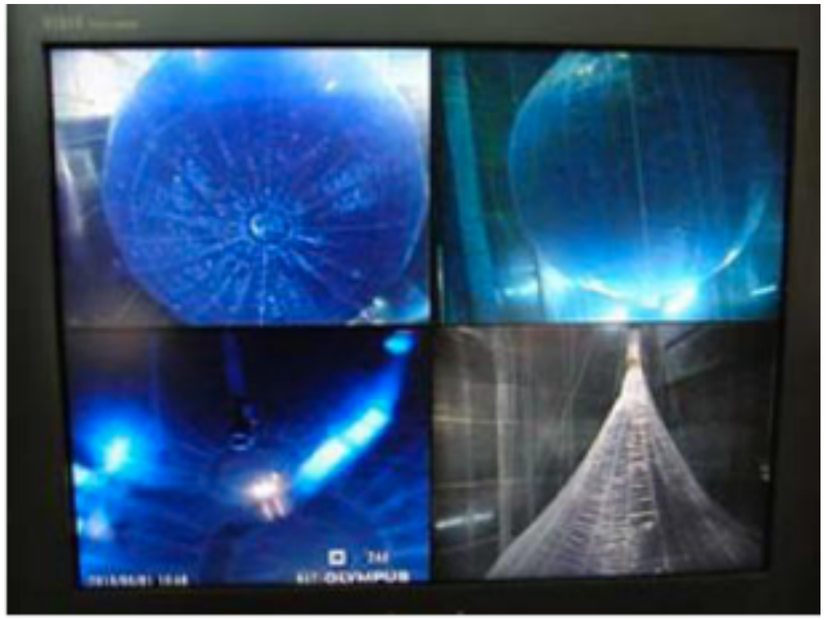
Spare Slides

MJD Collaboration

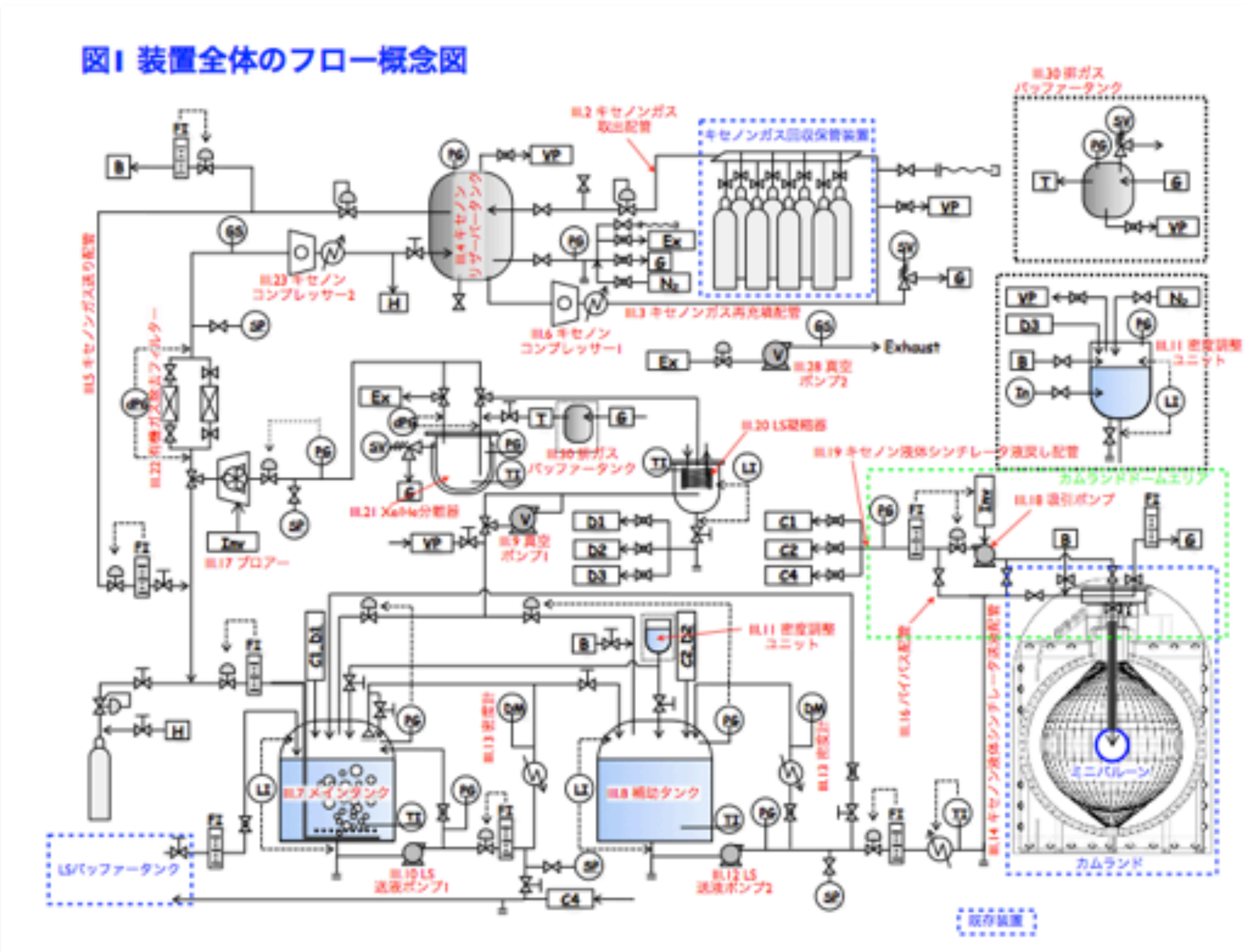
Black Hills State University · Duke University · ITEP · Joint Institute for Nuclear Research · Berkeley Lab · Los Alamos National Laboratory · Oak Ridge National Laboratory · University of Alberta · Osaka University · North Carolina State University · Pacific Northwest National Laboratory · Sanford Underground Research Facility · TUNL · The University of North Carolina at Chapel Hill · University of South Carolina · Tennessee Tech University · Shanghai Jiao Tong University · M · University of South Dakota · The University of Tennessee · W

Inner Balloon R&D

- Ultra-low contamination heat-welded nylon film
  - ~25 μm thick
  - Straps made of identical material
  - U/Th/K ≲ 10^{-13} g/g

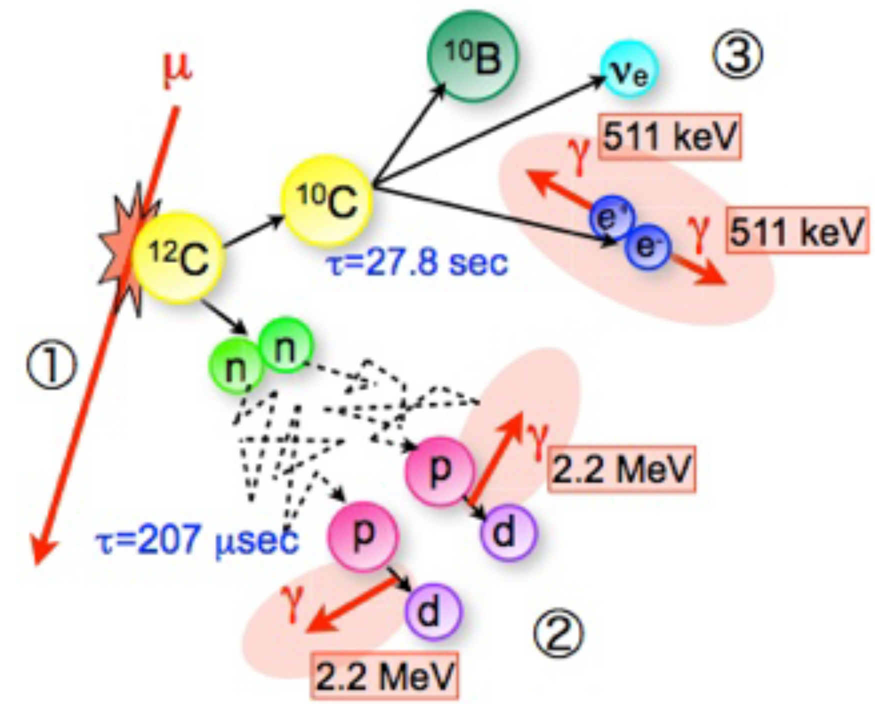


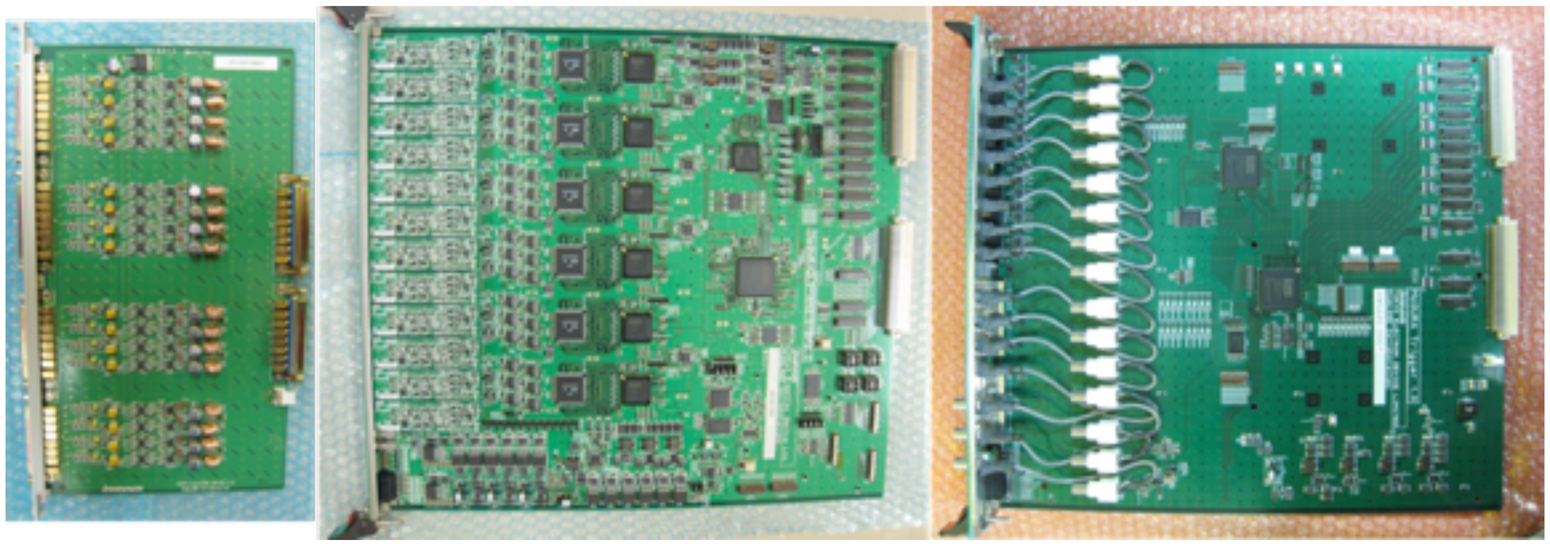
Xe-LS Handling System



Electronics Upgrade

- 1 GHz flash ADCs
- Eliminate post-muon dead time to remove >90% ^{11}C, ^{10}C
- Fully operational and in use, data analysis underway
- Not used for first results



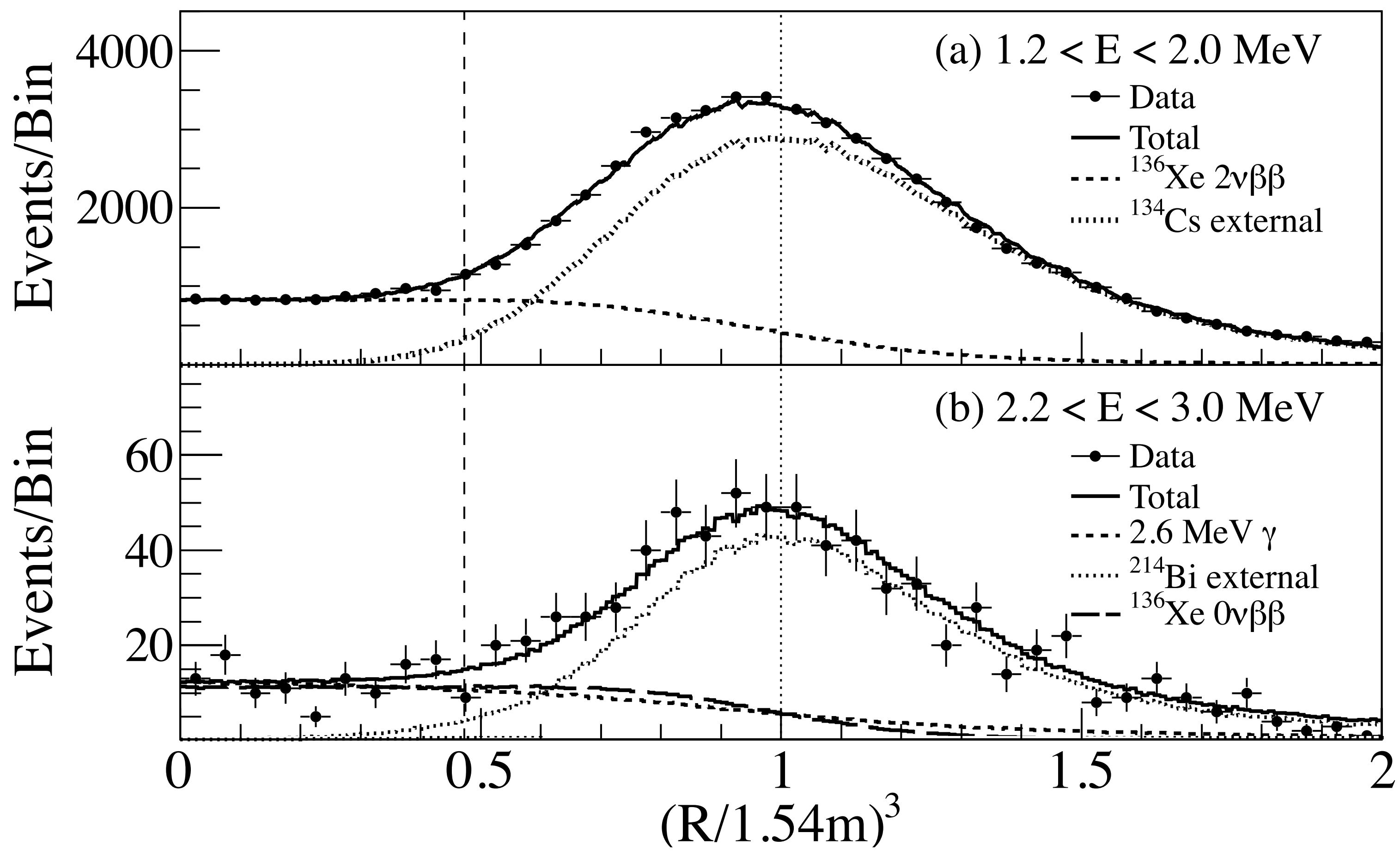


Balloon and Xe-LS Backgrounds

(other than U/Th/K)

FV cut

Inner Balloon radius



2νββ window

LS: 2νββ

Balloon: ^{134}Cs, ^{137}Cs

0νββ window

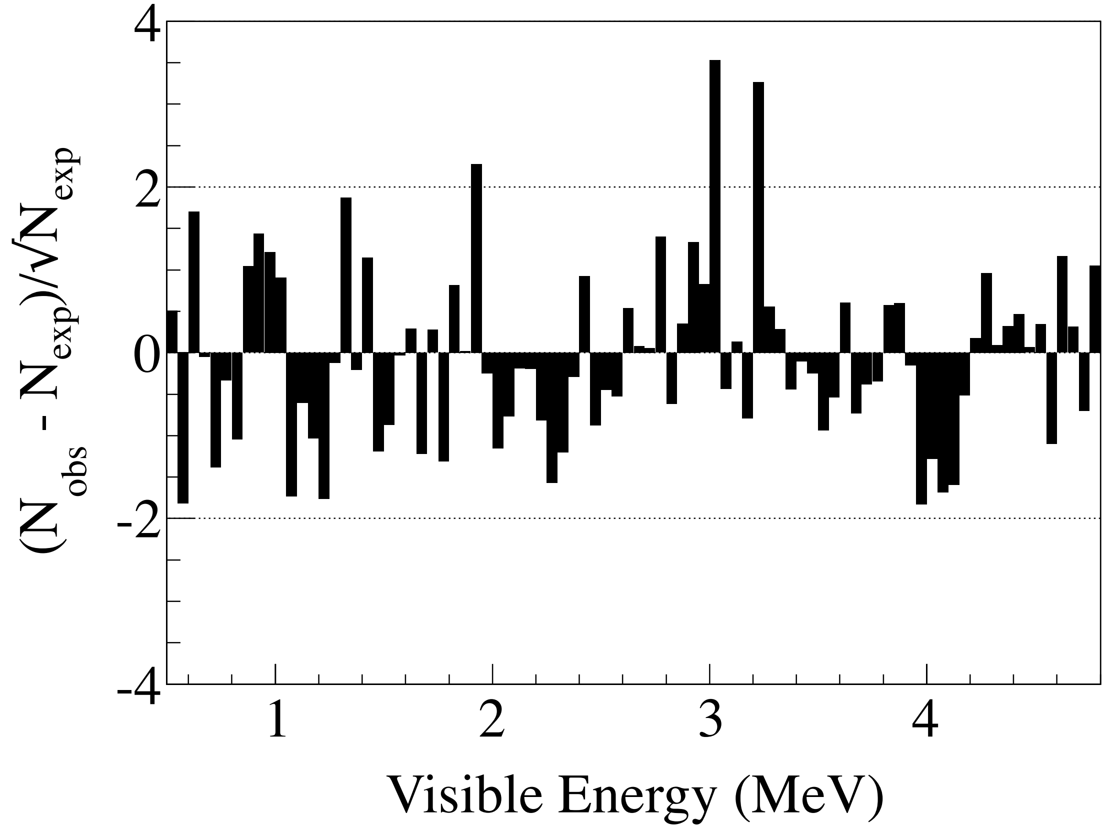
LS: "something"

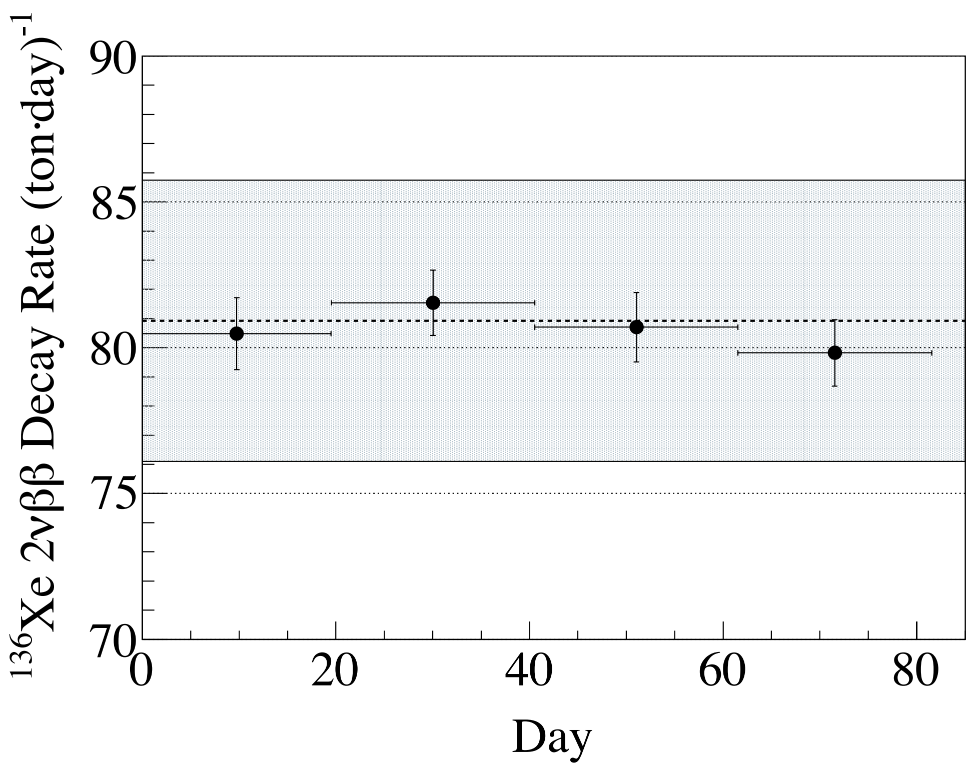
Balloon: ^{214}Bi (supported)

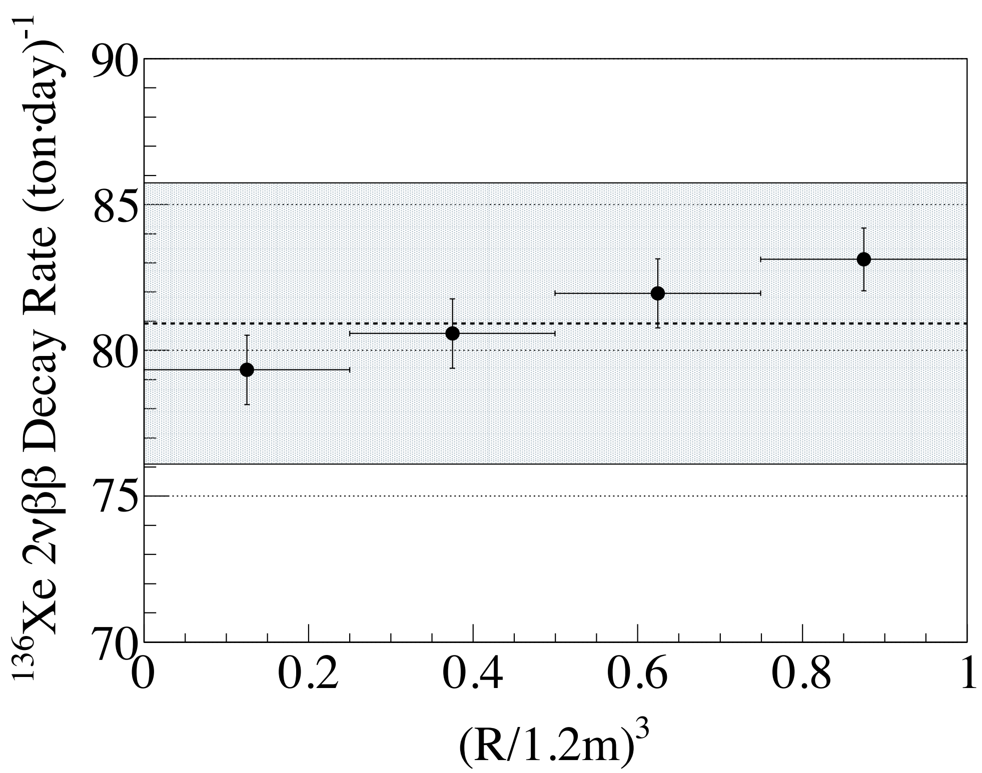
Spallation Products

- ^{11}C: 1.11 ± 0.28 a/t/d
- ^{10}C: (0.0211 ± 0.0044) a/t/d
- Spallation neutron yield 13±6% higher (absorb in yield systematics)
- n capture on H, C; no evidence of n capture on Xe
- No evidence of muon followers with τ < 100s

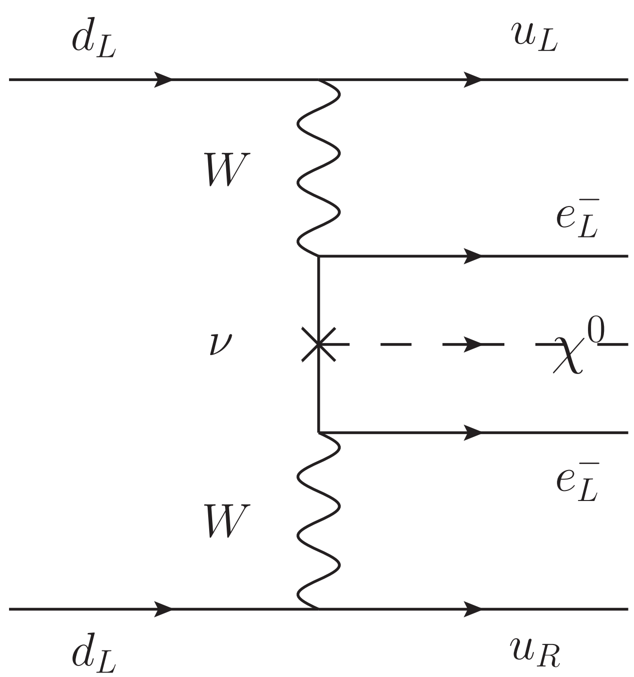
Fit Residuals and Stability





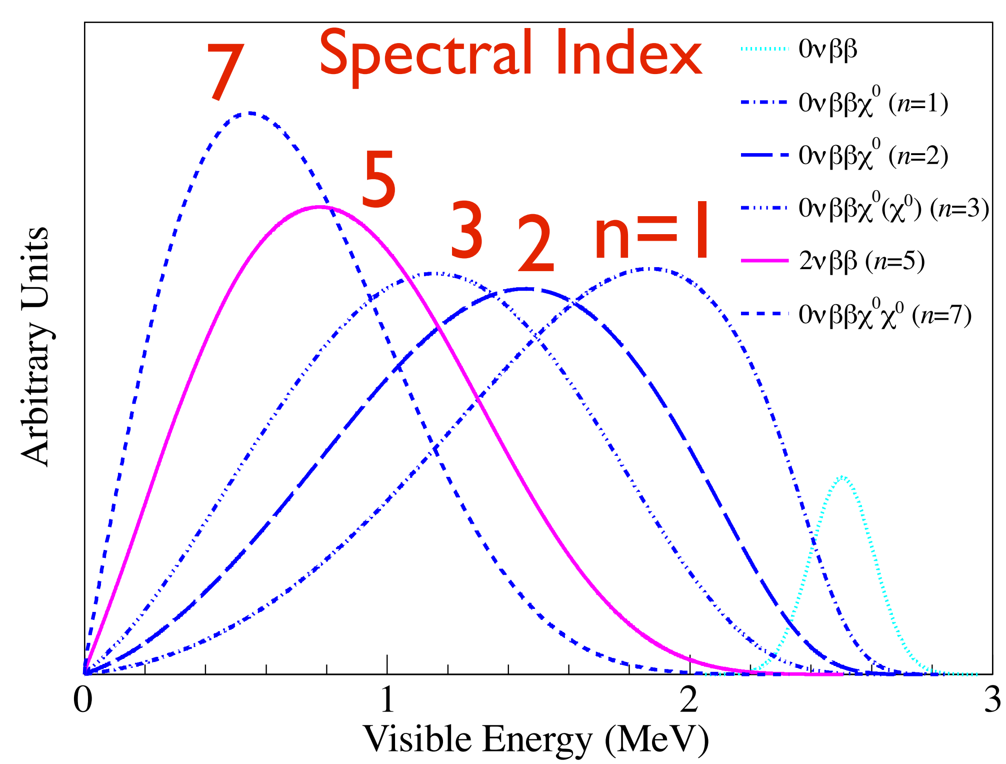


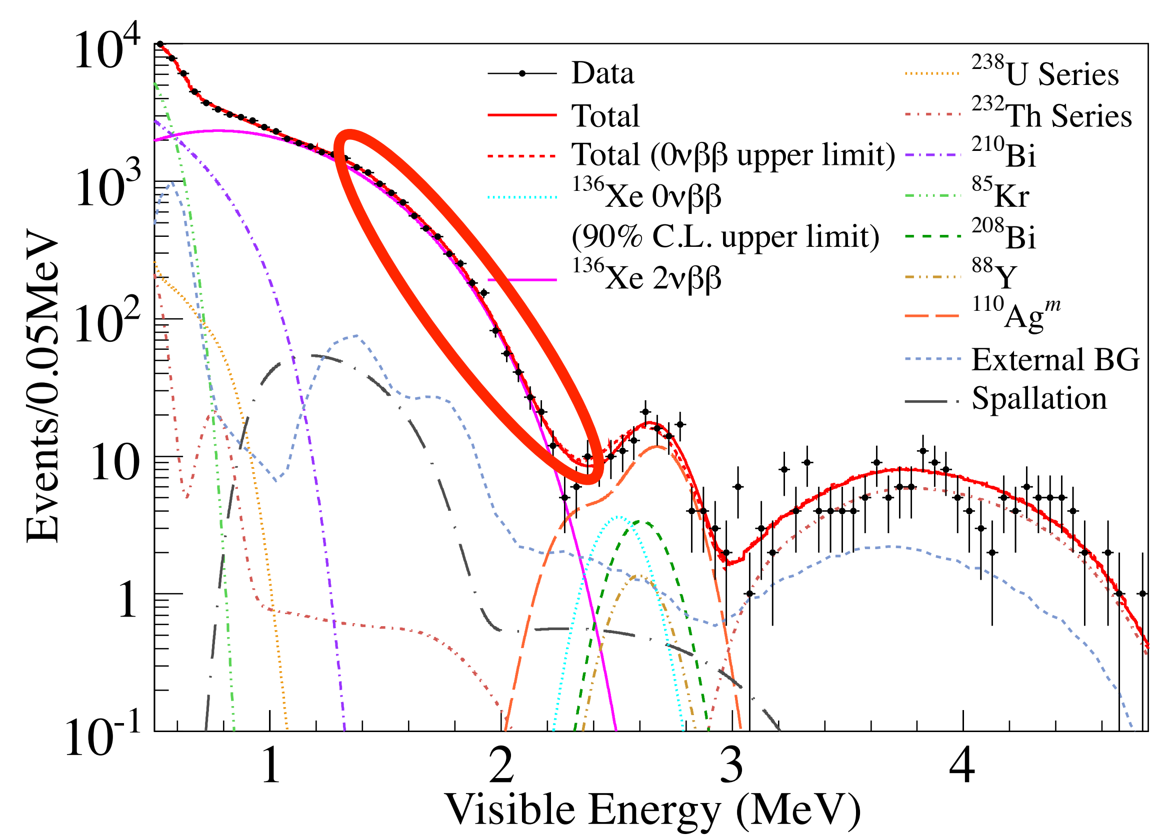
Majoron Emission



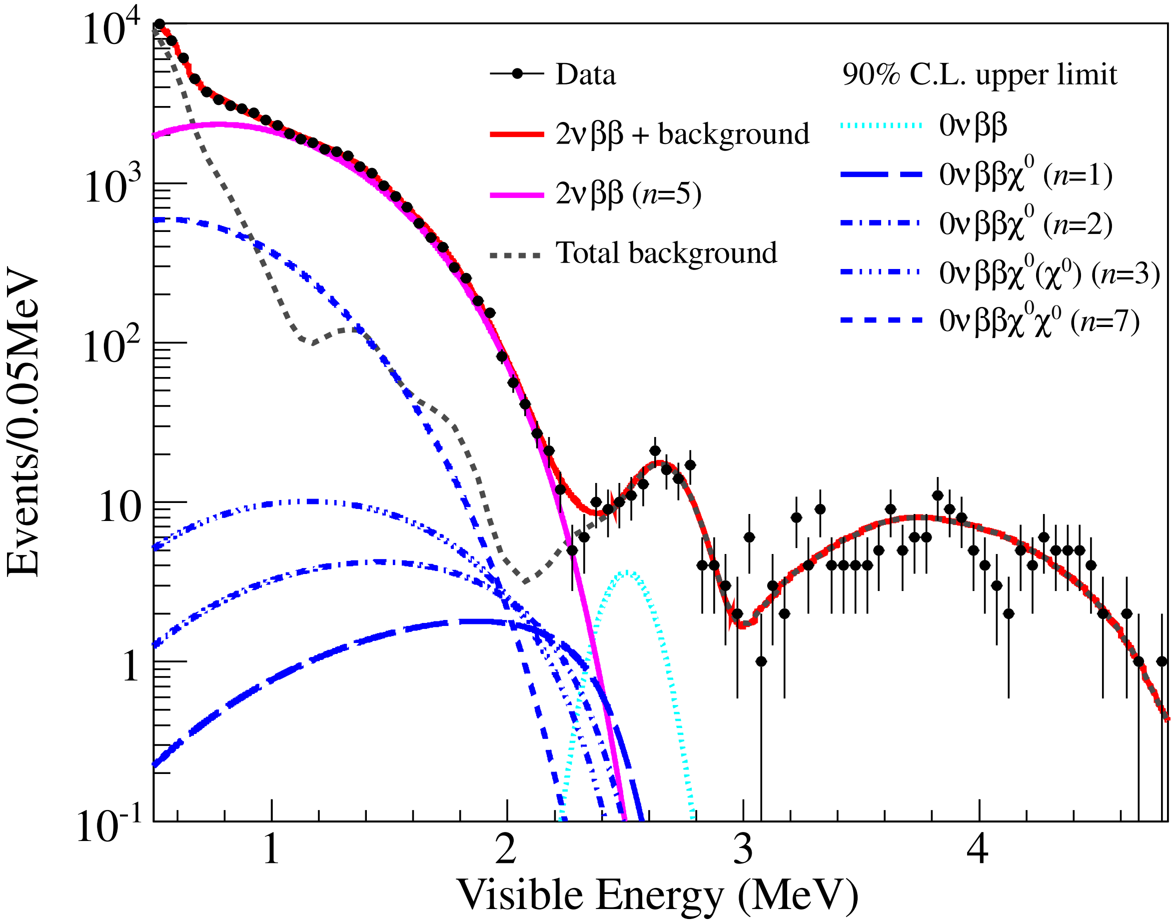
NG-Boson from SSB of L conservation

Model	Decay Mode	NG boson	L	n
IB	$0\nu\beta\beta\chi^0$	no	0	1
IC	$0\nu\beta\beta\chi^0$	yes	0	1
ID	$0\nu\beta\beta\chi^0\chi^0$	no	0	3
IE	$0\nu\beta\beta\chi^0\chi^0$	yes	0	3
IIB	$0\nu\beta\beta\chi^0$	no	-2	1
IIC	$0\nu\beta\beta\chi^0$	yes	-2	3
IID	$0\nu\beta\beta\chi^0\chi^0$	no	-1	3
IIE	$0\nu\beta\beta\chi^0\chi^0$	yes	-1	7
IIF	$0\nu\beta\beta\chi^0$	gauge boson	-2	3
"bulk"	$0\nu\beta\beta\chi^0$	bulk field	0	2





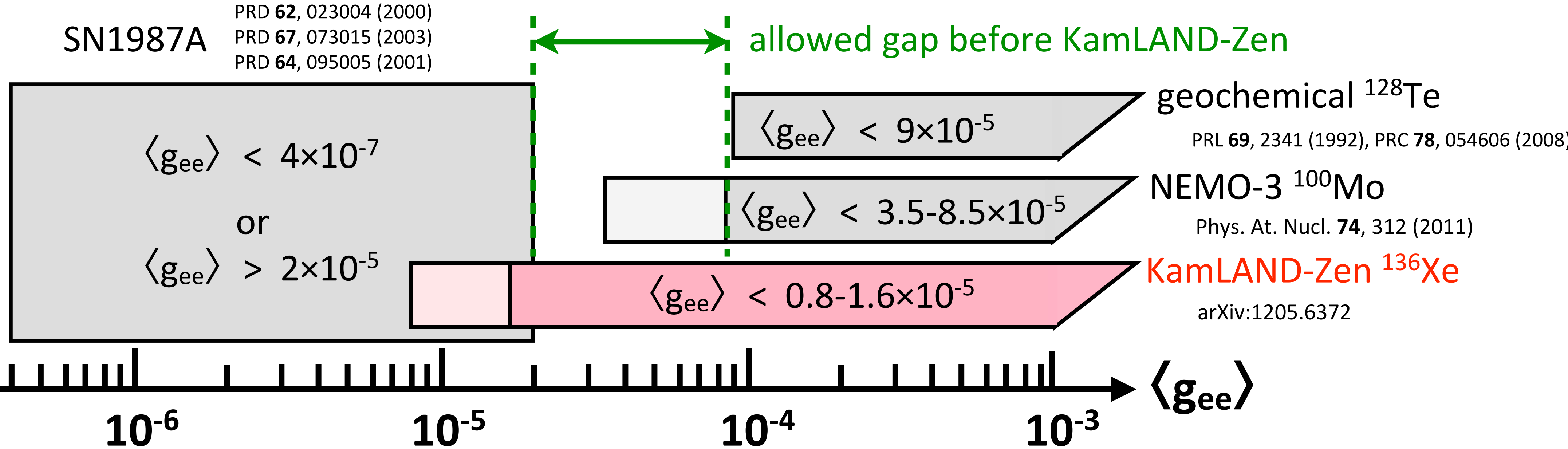
Majoron Emission Mode Limits



Model	Decay Mode	Results from this measurement $T_{1/2}$ (yr)	$\langle g_{ee} \rangle$
IB	$0\nu\beta\beta\chi^0$	$> 2.6 \times 10^{24}$	$< (0.8 - 1.6) \times 10^{-5}$
IC	$0\nu\beta\beta\chi^0$	$> 2.6 \times 10^{24}$	$< (0.8 - 1.6) \times 10^{-5}$
ID	$0\nu\beta\beta\chi^0\chi^0$	$> 4.5 \times 10^{23}$	< 0.68
IE	$0\nu\beta\beta\chi^0\chi^0$	$> 4.5 \times 10^{23}$	< 0.68
IIB	$0\nu\beta\beta\chi^0$	$> 2.6 \times 10^{24}$	$< (0.8 - 1.6) \times 10^{-5}$
IIC	$0\nu\beta\beta\chi^0$	$> 4.5 \times 10^{23}$	< 0.013
IID	$0\nu\beta\beta\chi^0\chi^0$	$> 4.5 \times 10^{23}$	< 0.68
IIE	$0\nu\beta\beta\chi^0\chi^0$	$> 1.1 \times 10^{22}$	< 1.2
IIF	$0\nu\beta\beta\chi^0$	$> 4.5 \times 10^{23}$	< 0.013
"bulk"	$0\nu\beta\beta\chi^0$	$> 1.0 \times 10^{24}$	–

$$\Gamma_{N\chi^0} = |\langle g_{ee} \rangle|^{2N} |M|^2 G$$

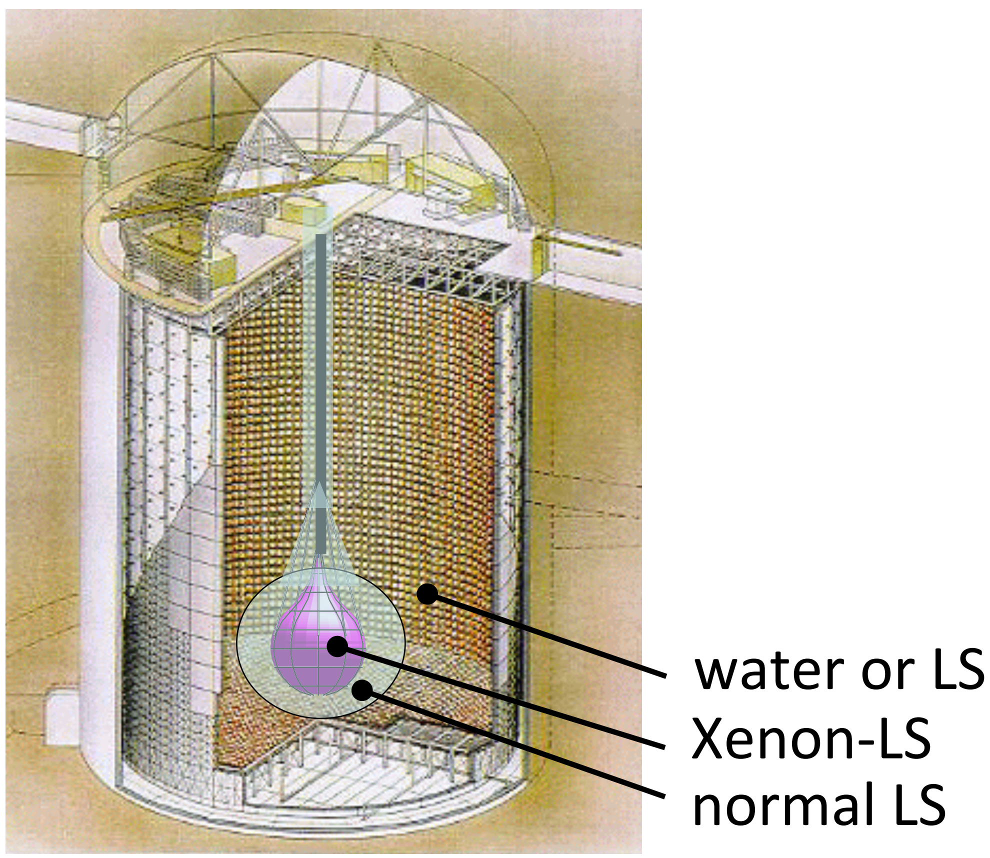
"ordinary" Majoron emission (IIB):



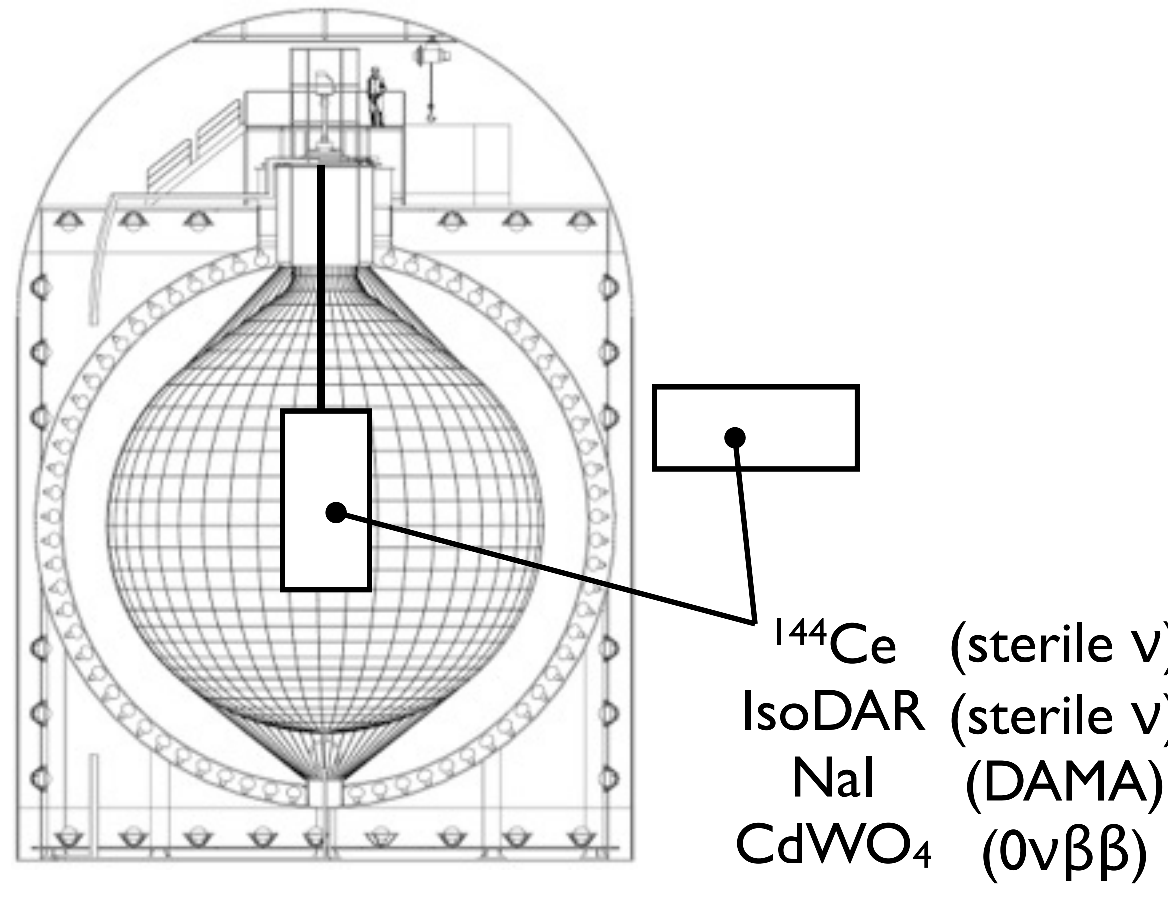
⟸ ordinary Majoron emission slower than light ν for $m_{\beta\beta}$ above 20 meV

Future Options

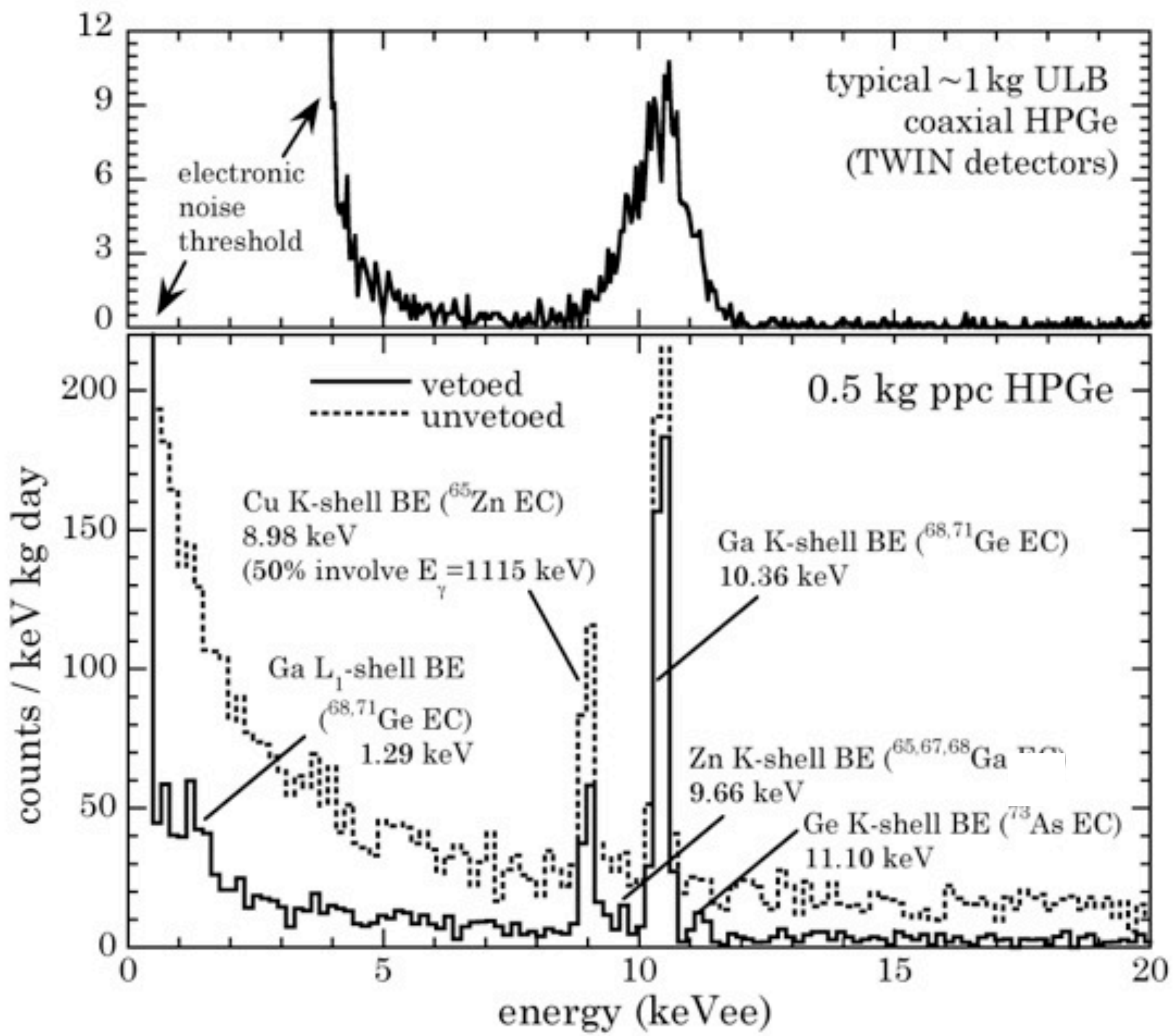
Super-KamLAND-Zen

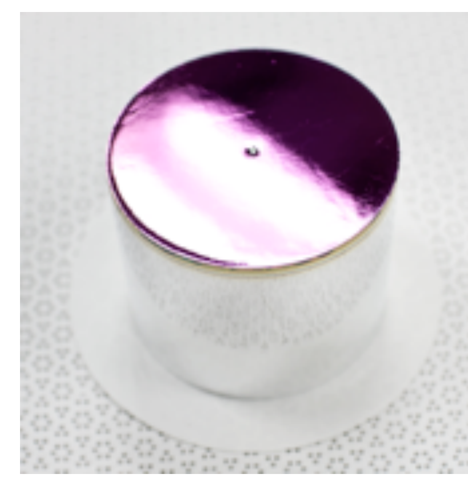


Low-background Laboratory



Low-Energy Performance

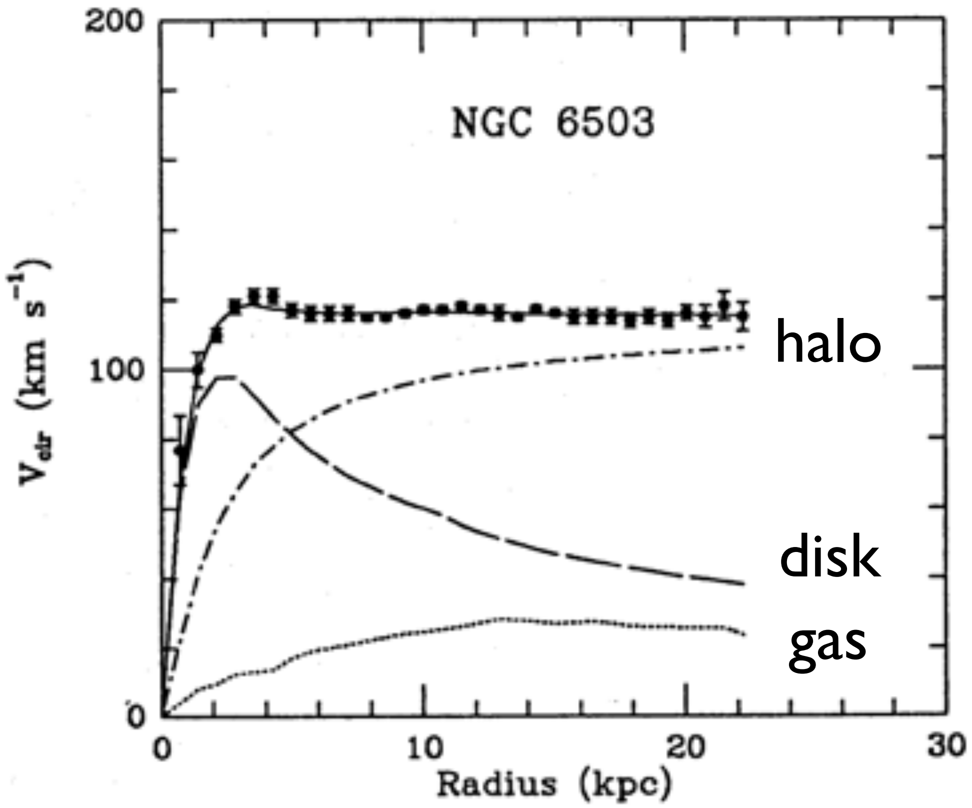




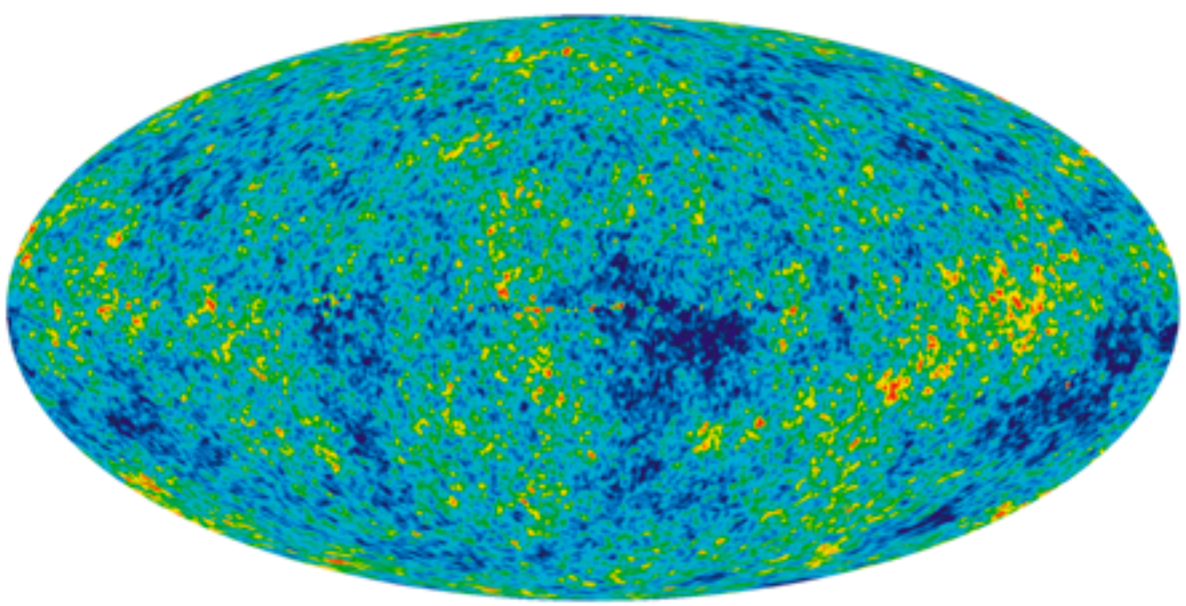
C. E. Aalseth *et al.*, Phys. Rev. Lett. **101**, 251301 (2008).

Dark Matter

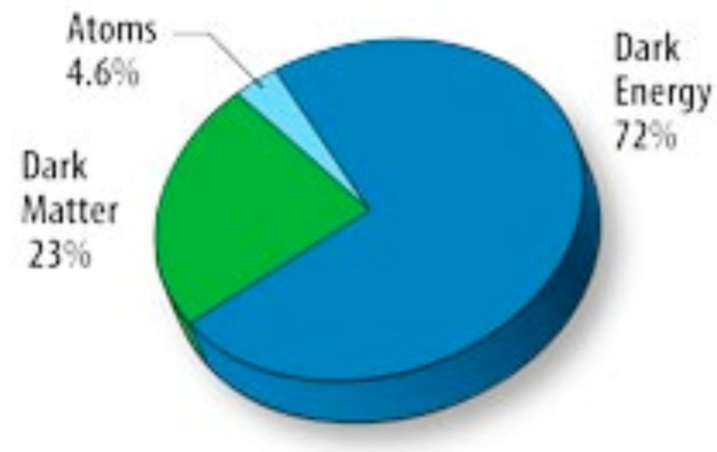
Galactic rotation curves



CMB

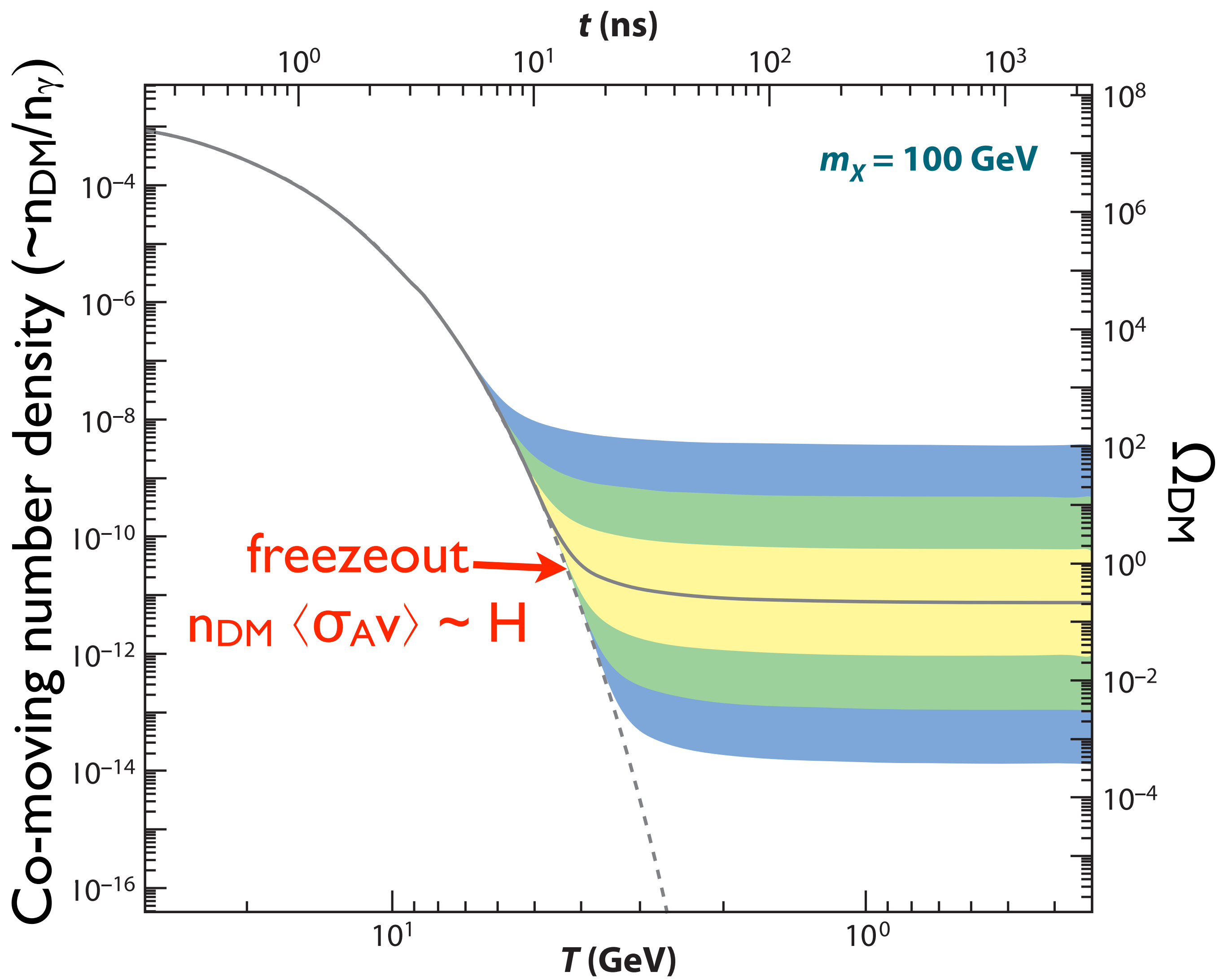


Our Universe



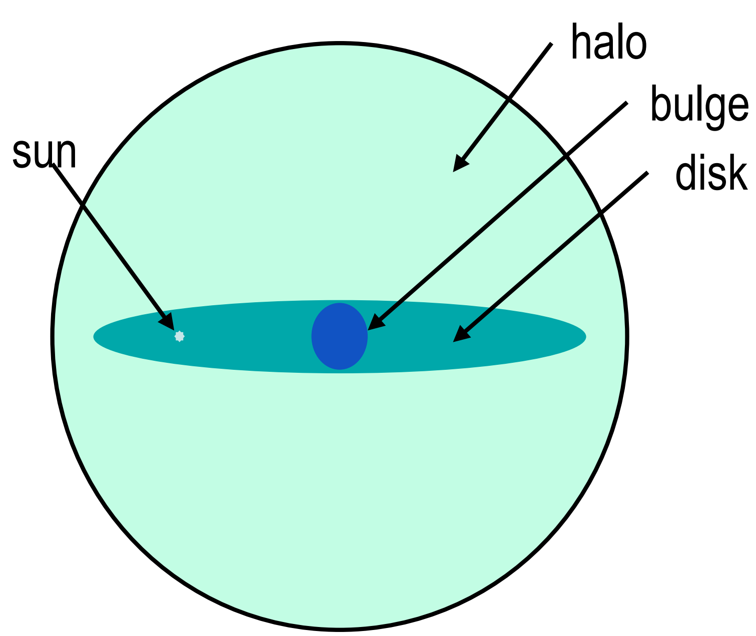
K. G. Begeman *et al.*, MNRAS **249**, 523 (1991).
http://chandra.harvard.edu/photo/2006/1e0657/more.html
http://wmap.gsfc.nasa.gov/media/101080/

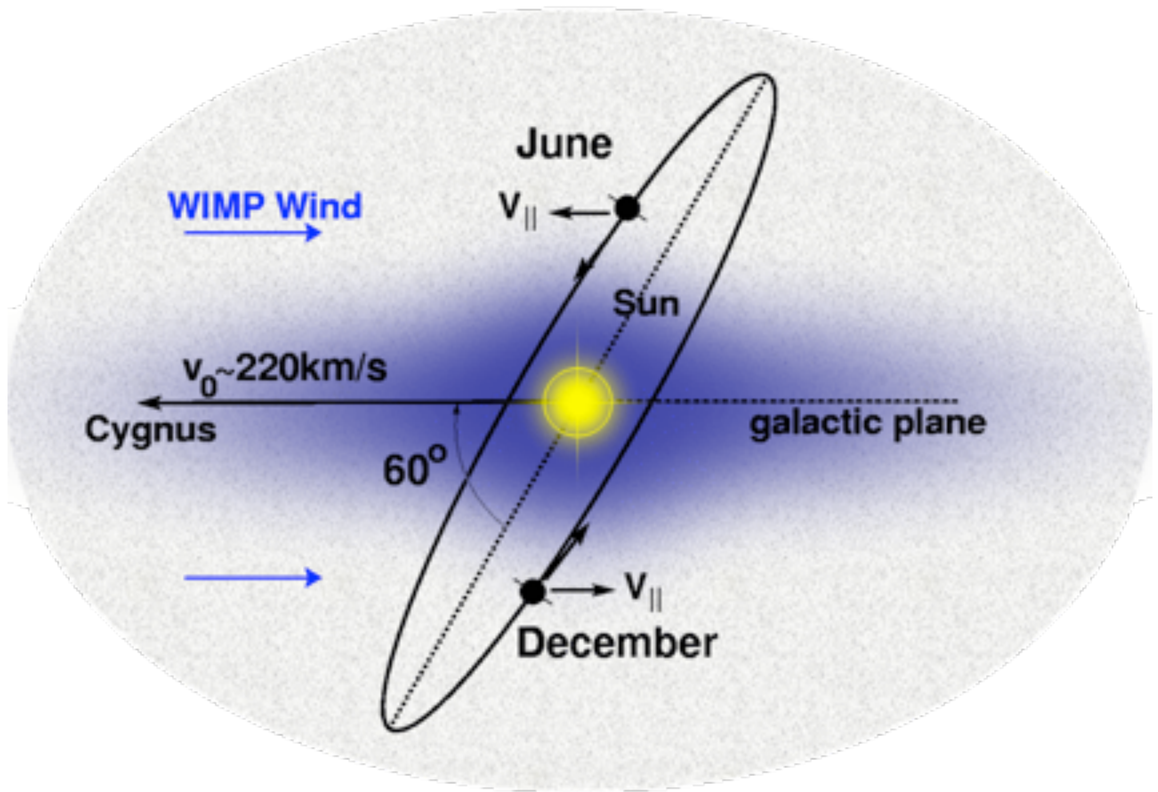
"The WIMP Miracle"

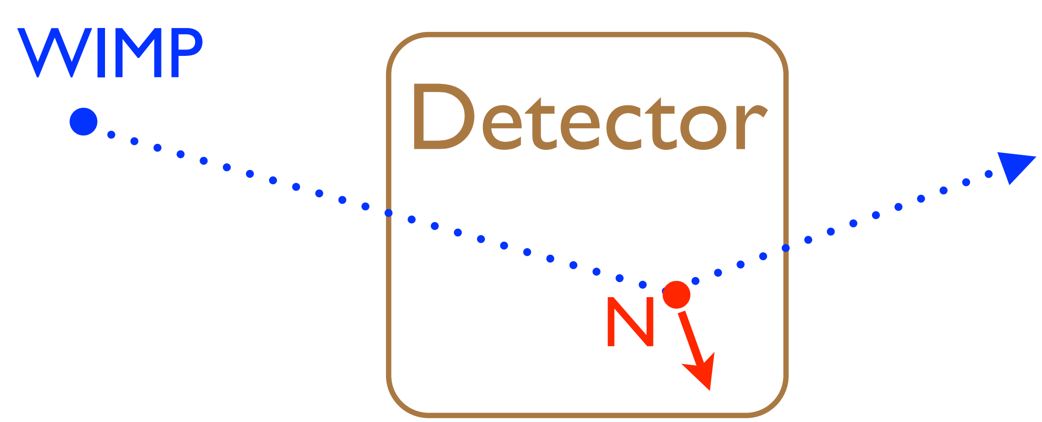


σ_A ~ weak scale for
m_{DM} ~ 10 GeV - few TeV

WIMP Detection

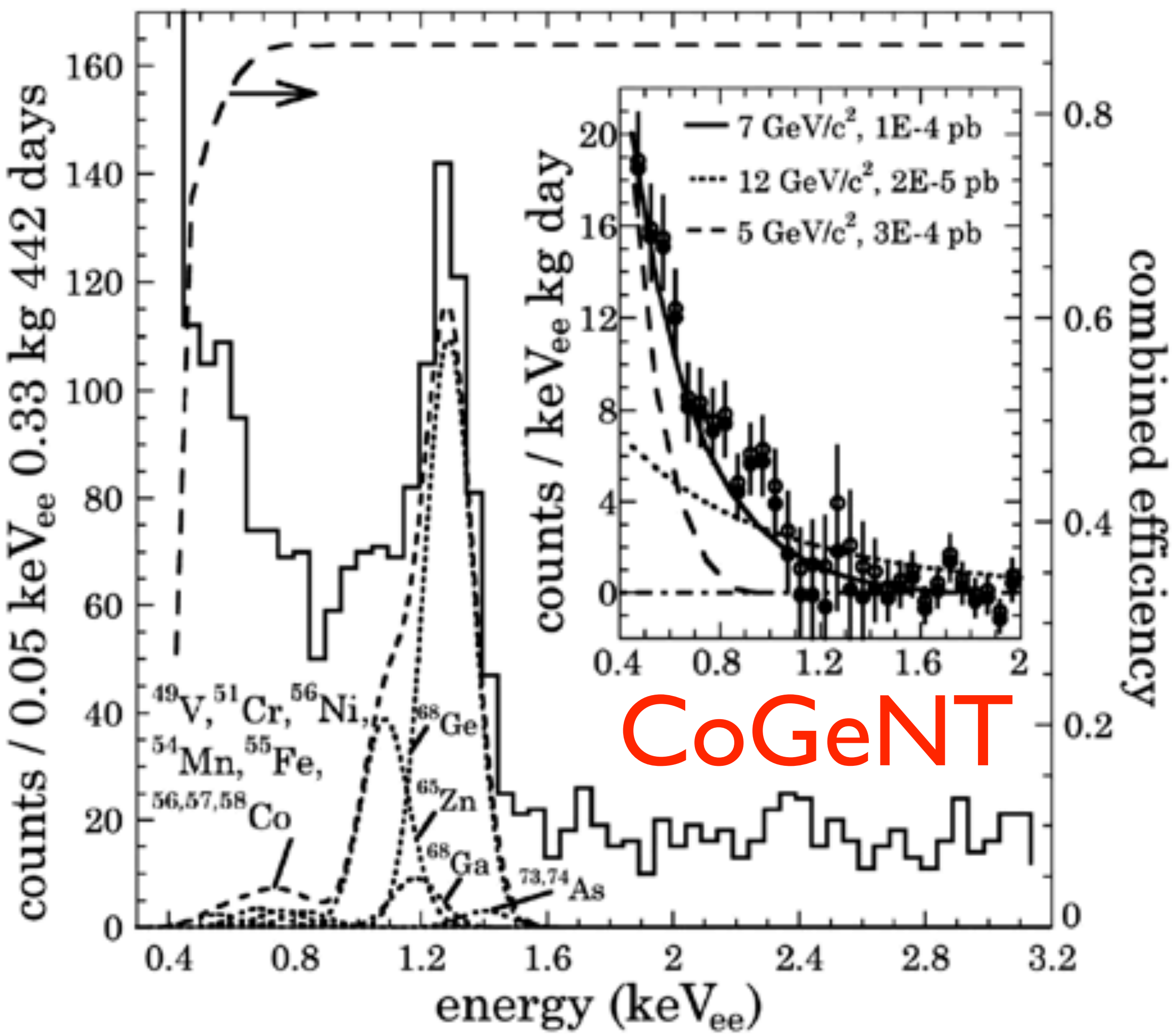


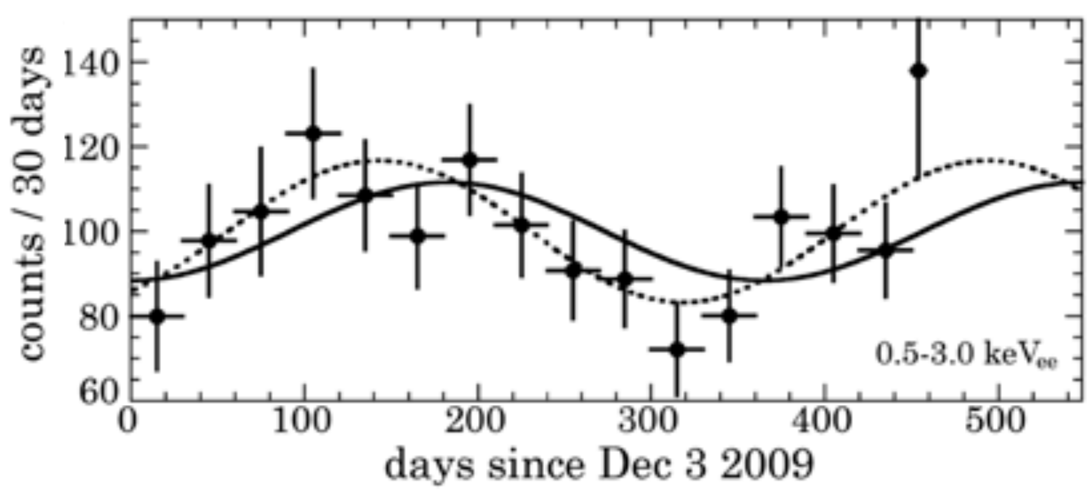


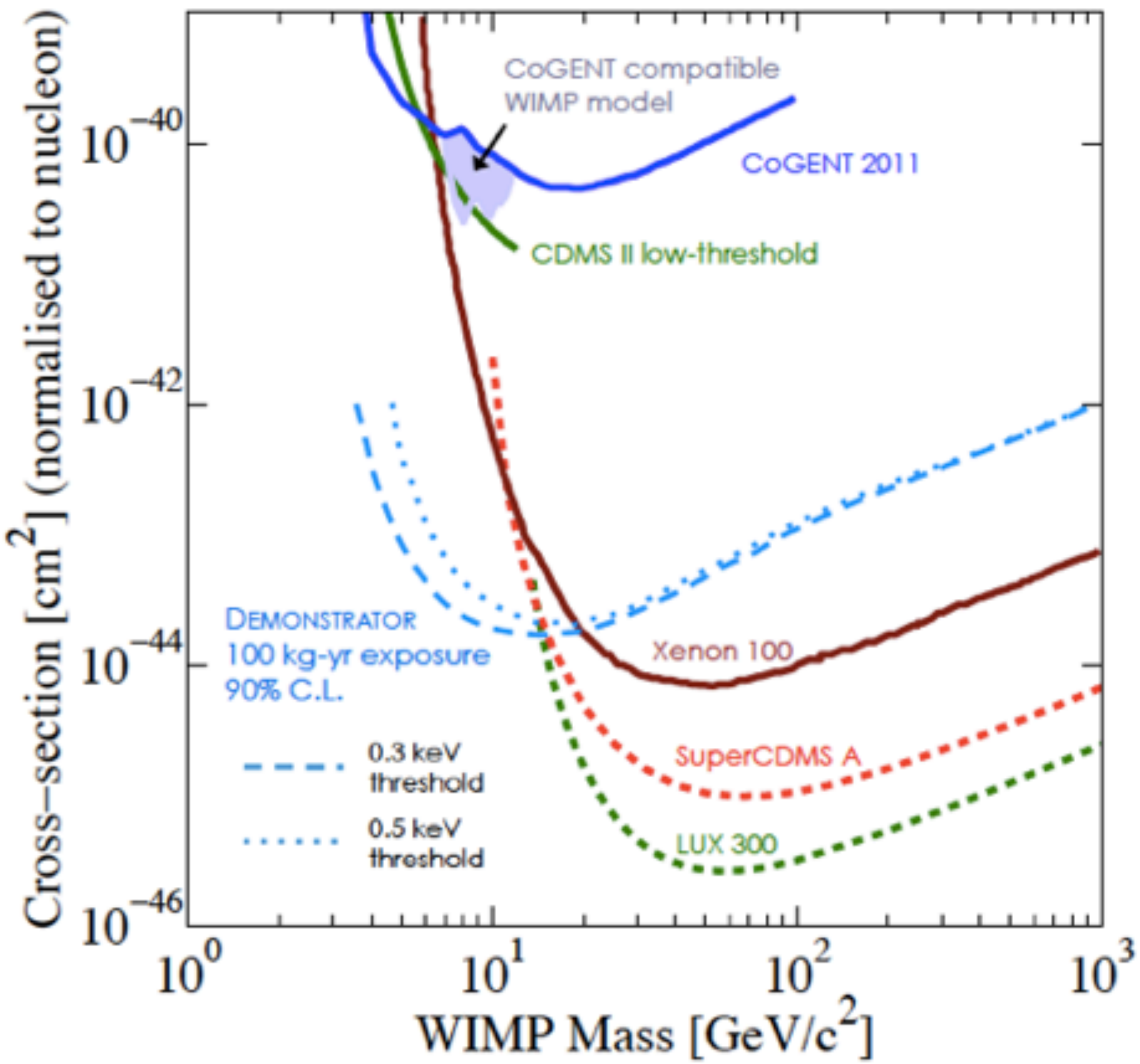


J. Feng, Annu. Rev. Astron. Astrophys. **48**, 495 (2010).

WIMP Searches with PPCs



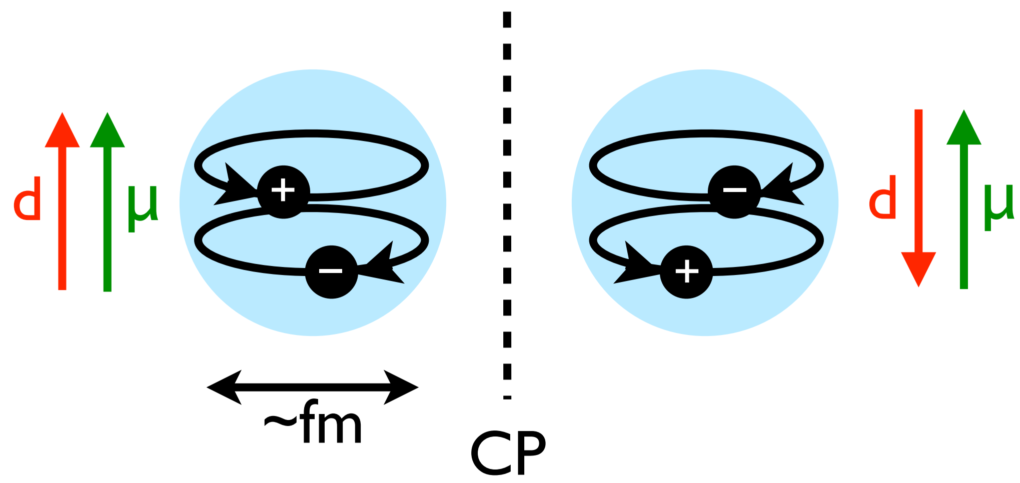




C.E. Aalseth *et al.*, Phys. Rev. Lett. **107**, 141301 (2011).
G. Giovanetti, TAUP 2011.

Axions

Neutron EDM



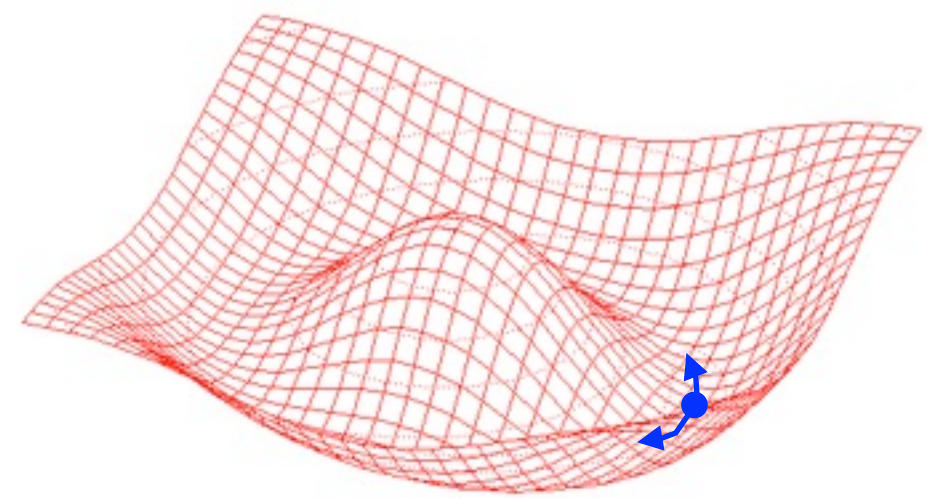
d ~ θ x 10^{-16} e cm

"Naturalness": $\theta \sim O(1)$

Experiment: $\theta < 10^{-10}$

"The Strong CP Problem"

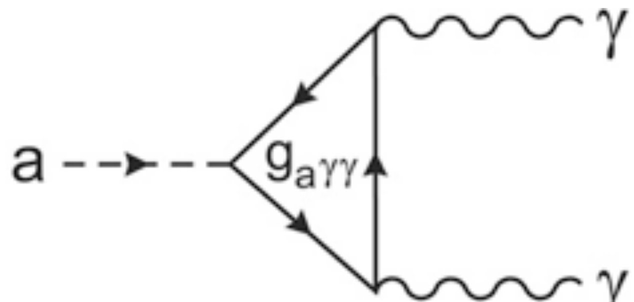
Solution: $U(1)_{PQ}$ symmetry spontaneously broken at scale f_a, explicitly broken by QCD vacuum:

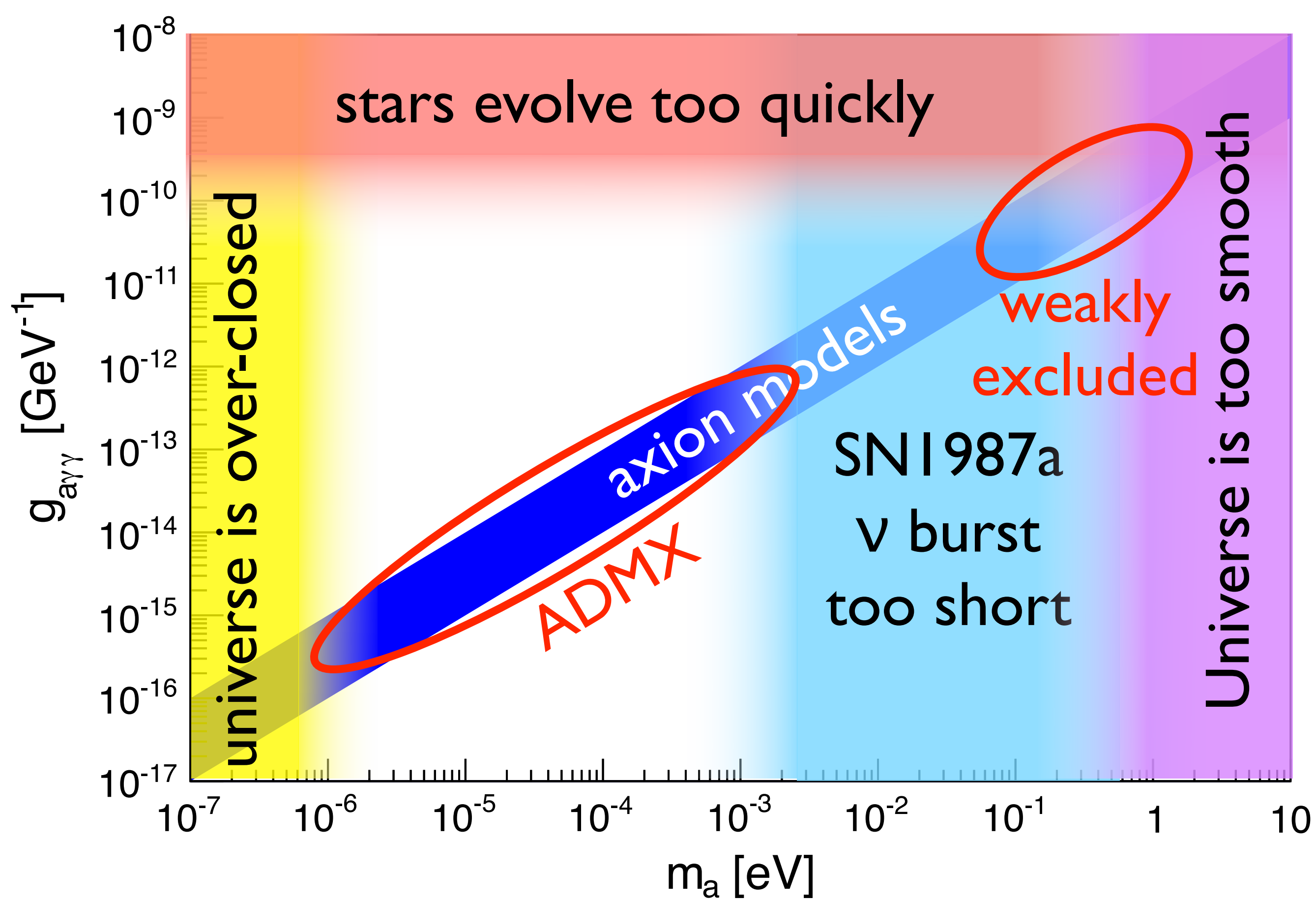


Massive pseudo-NG-boson: the axion!
mass & couplings ~ $1/f_a$

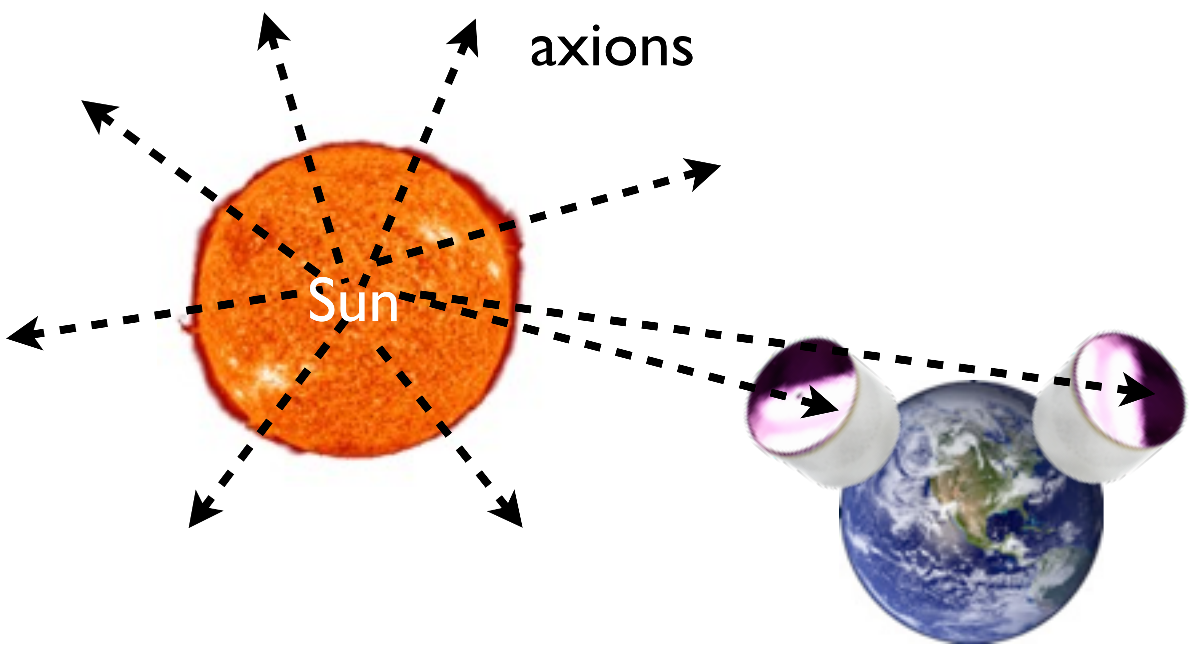
Axions

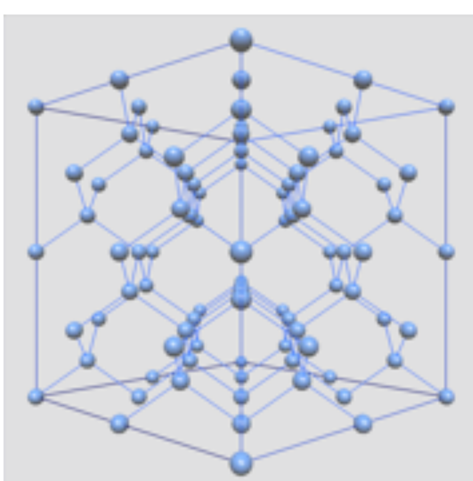
Axion coupling to quarks implies photon interaction:



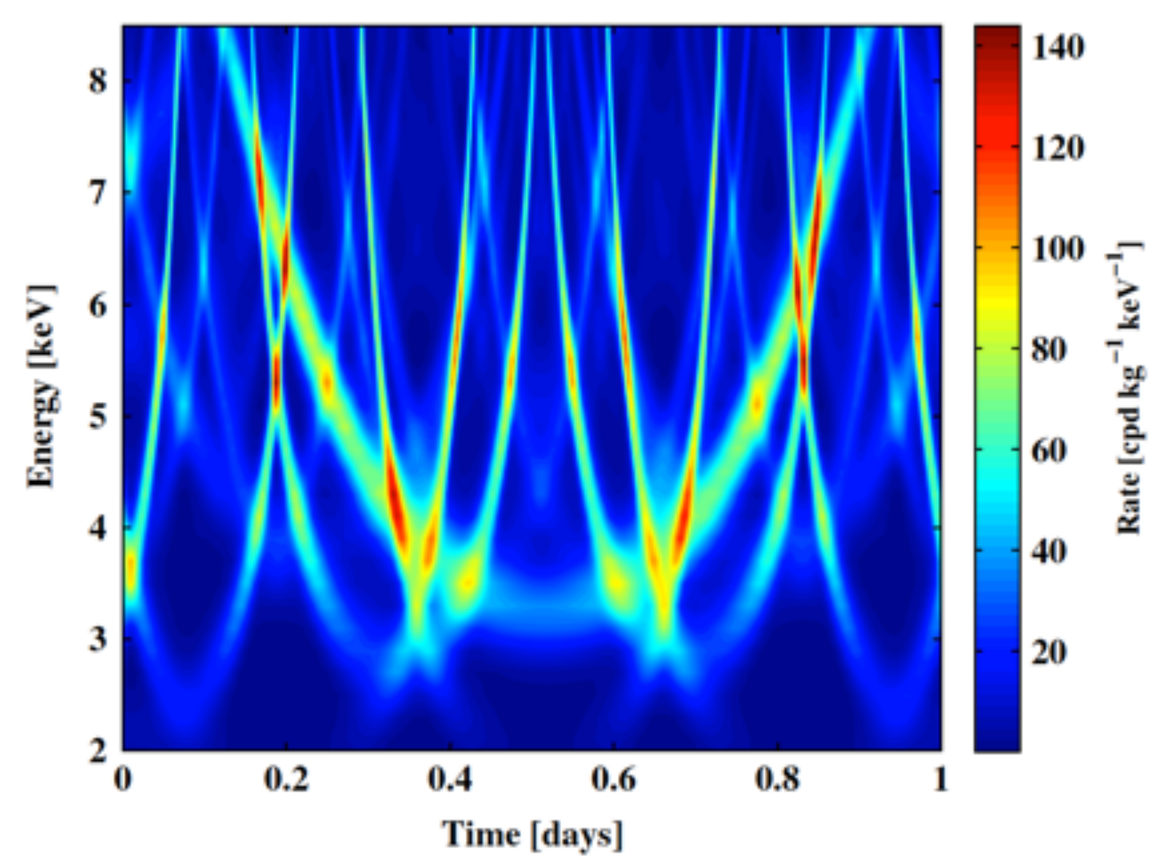


Axions



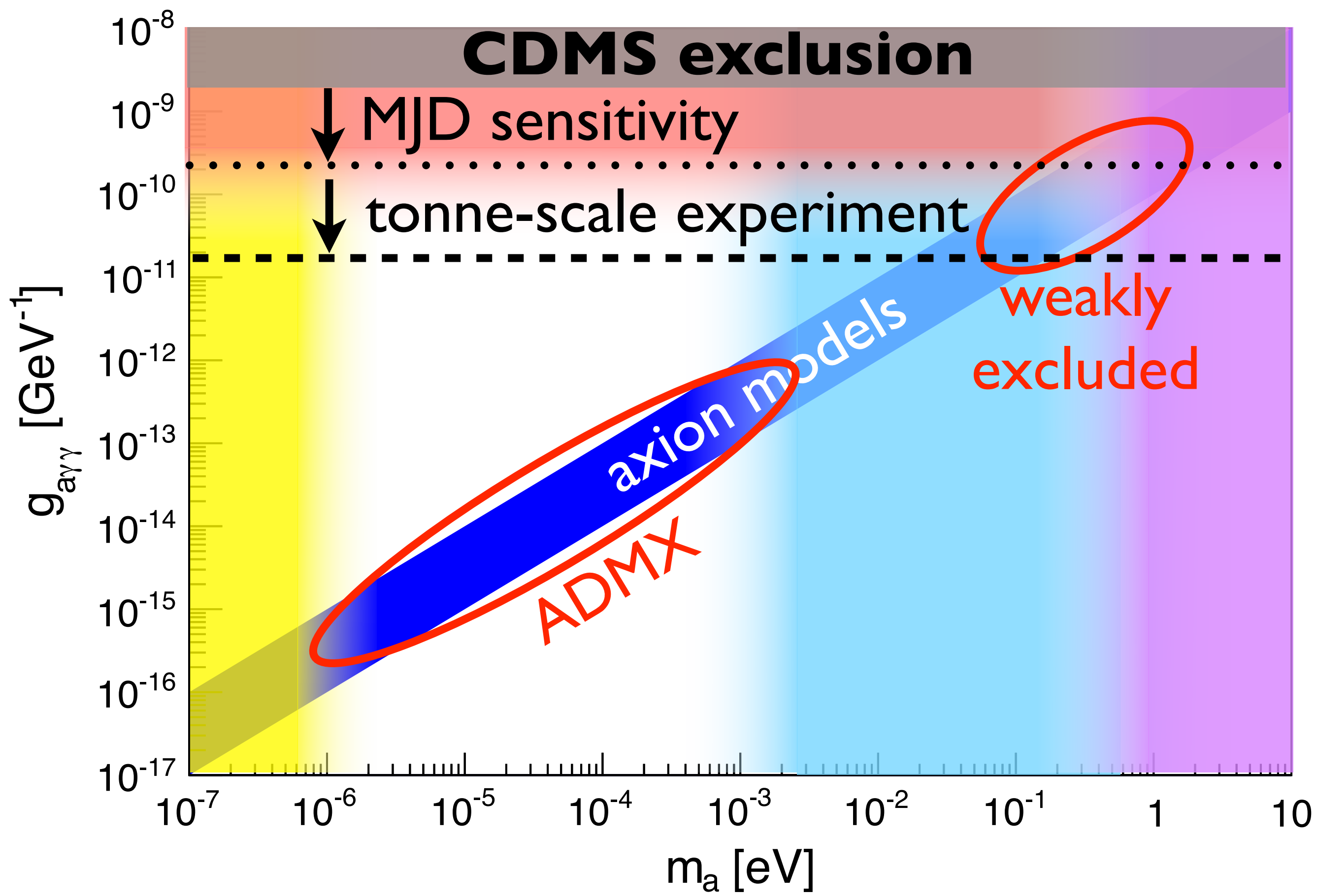


coherent inverse-Primakoff scattering off of Ge lattice



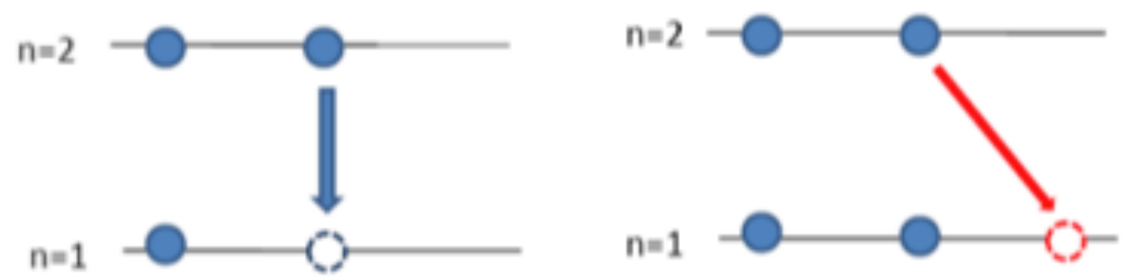
Z. Ahmed *et al.*, Phys. Rev. Lett. **103**, 141802 (2009).
http://phycomp.technion.ac.il/~nika/diamond_structure.html

Axions



Z. Ahmed *et al.*, Phys. Rev. Lett. **103**, 141802 (2009).
http://phycomp.technion.ac.il/~nika/diamond_structure.html

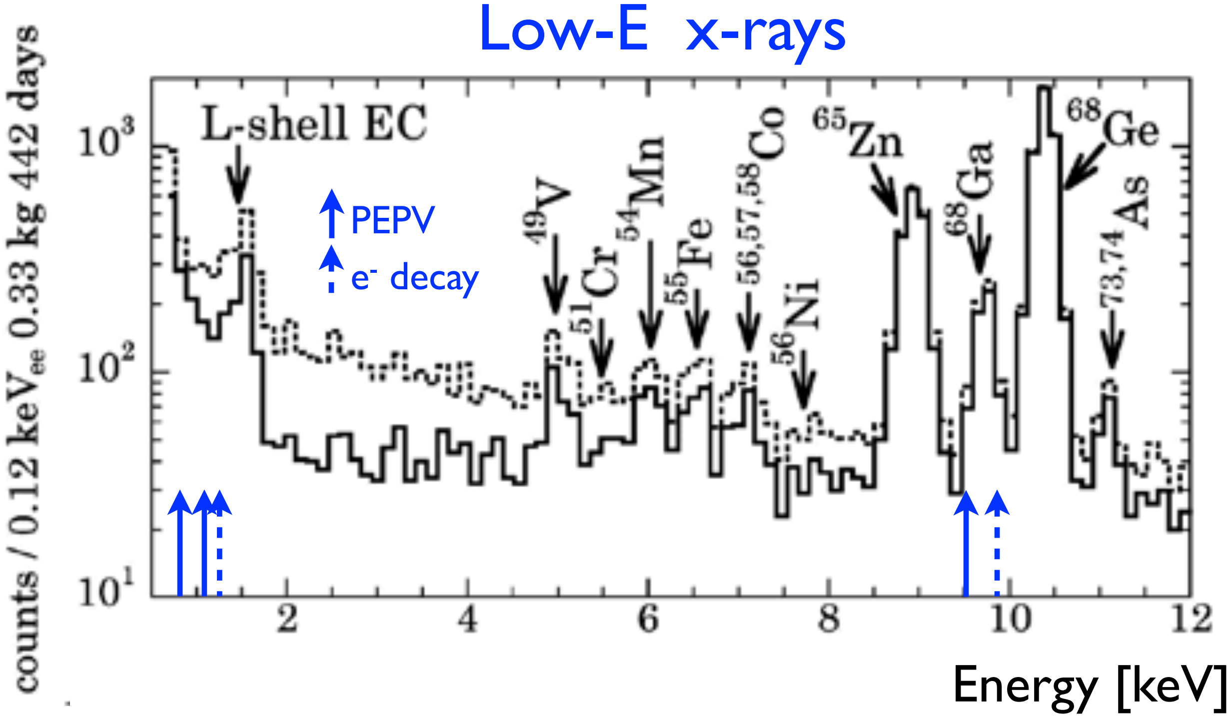
PEP-Violation, e⁻ Decay



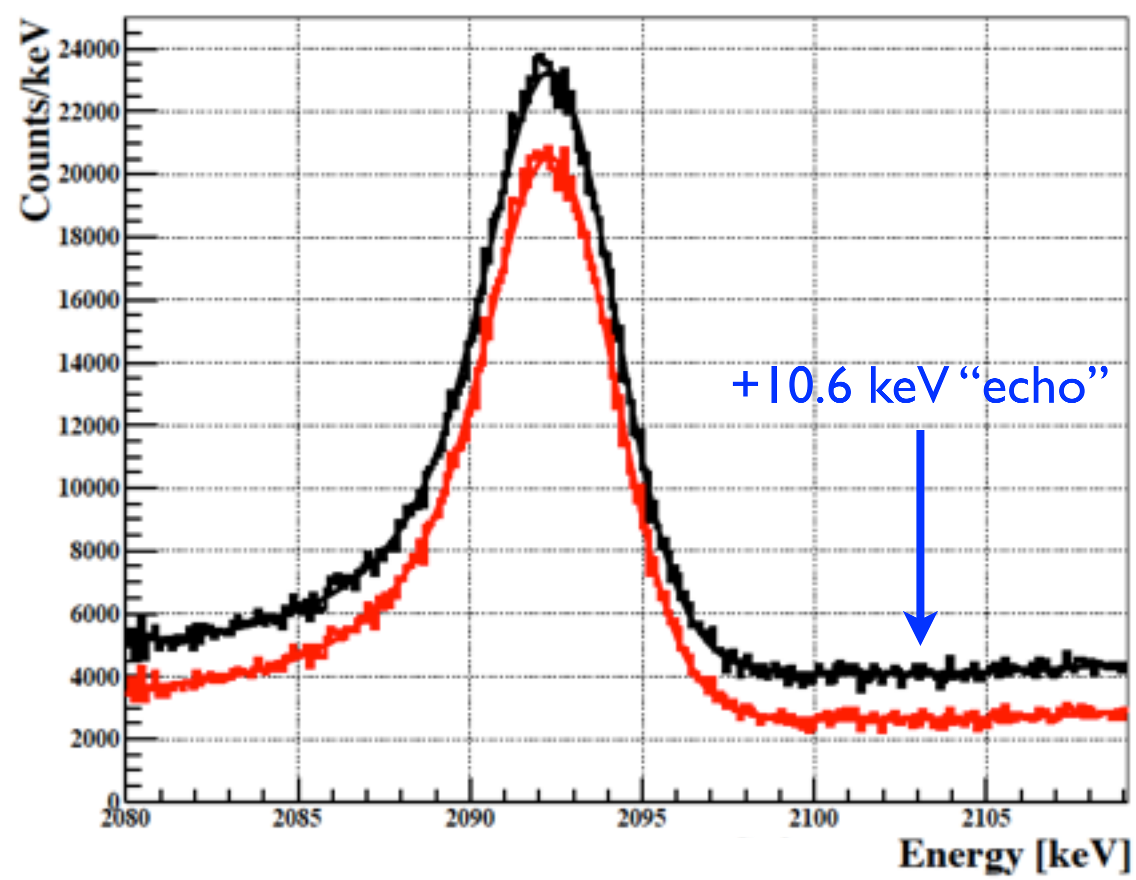
Normal 2p → 1s transition

PEP violating 2p → 1s transition

Low-E x-rays



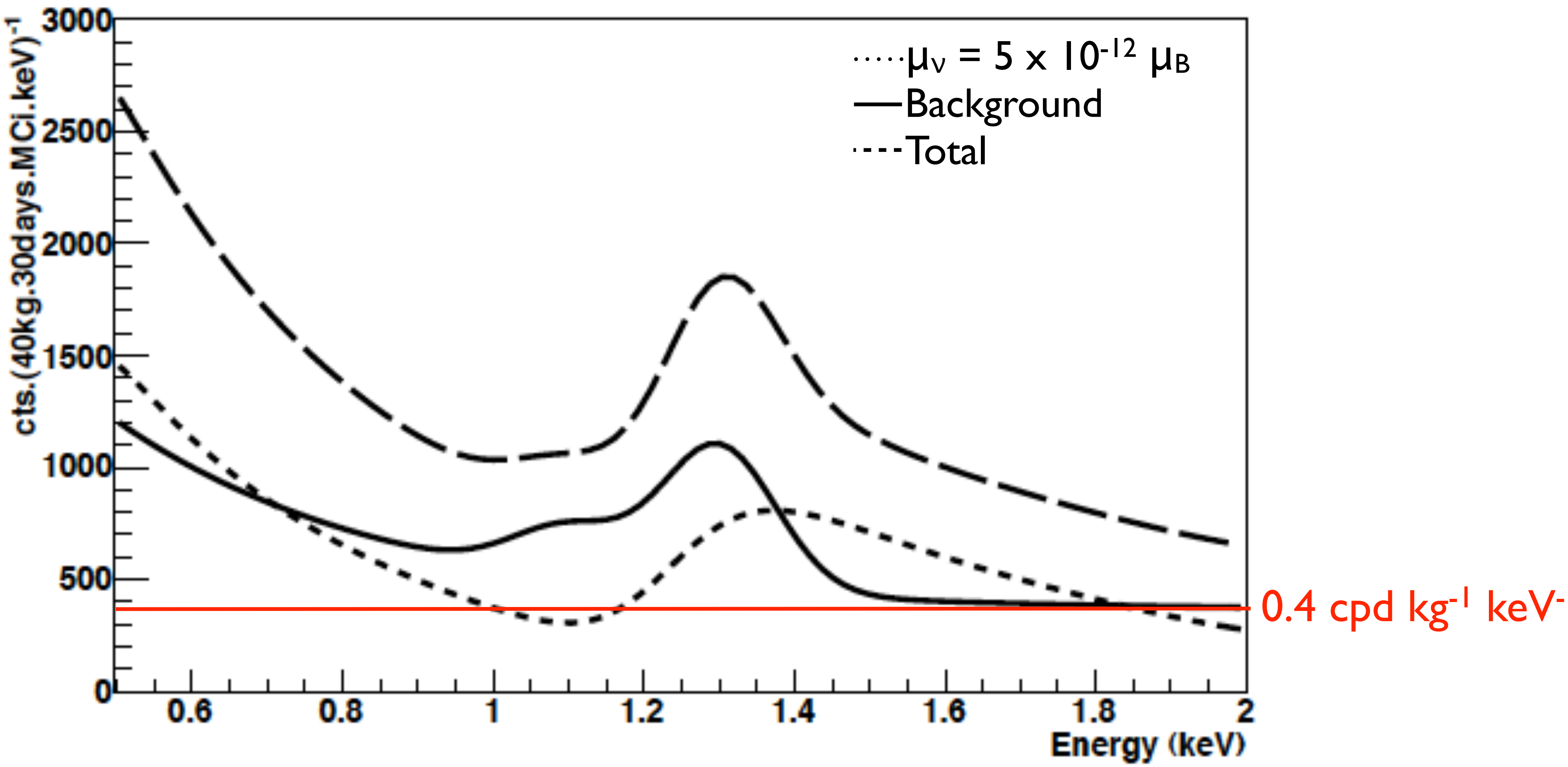
^{208}Tl SEP



J. Marton *et al.*, J. Phys. Conf. Ser. **35**, 012060 (2011).
C.E. Aalseth *et al.*, Phys. Rev. Lett. **107**, 141301 (2011).
S.R. Elliott *et al.*, arXiv:1107.3118v1 [nucl-ex] (2011).

Neutrino Magnetic Moment

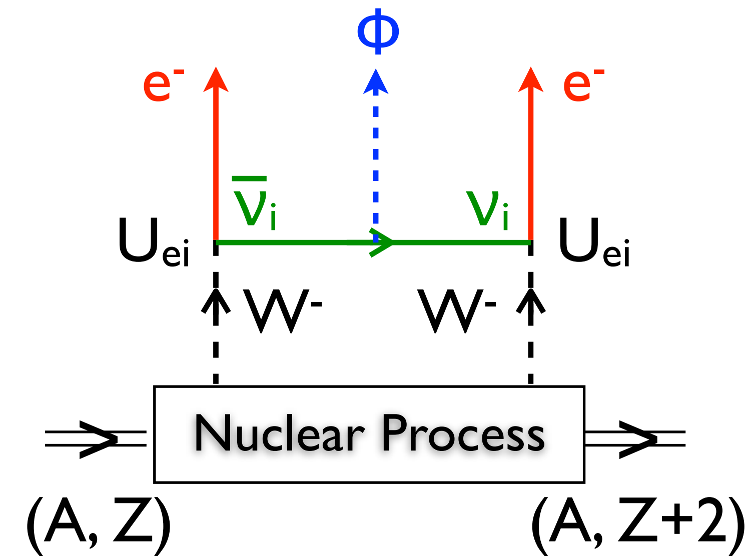
1 MCi ^{51}Cr source



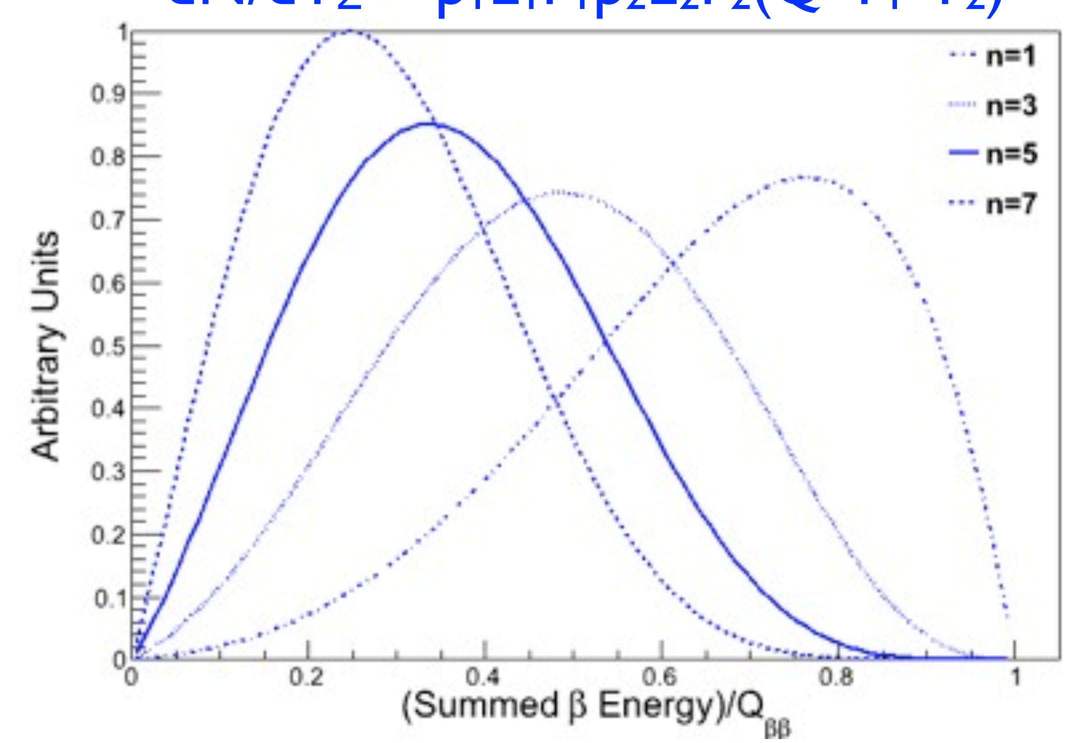
R. Henning, arXiv:1011.3811v1 (2010).

Other ββ Physics

- High-statistics 2νββ spectral measurement
  - Majoron emissions modes
  - Nuclear model tests
  - Bosonic ν mixing
- ββ decay to excited states
  - Constrain NME



$dN/dT_{\Sigma} \sim p_1 E_1 F_1 p_2 E_2 F_2 (Q-T_1-T_2)^n$



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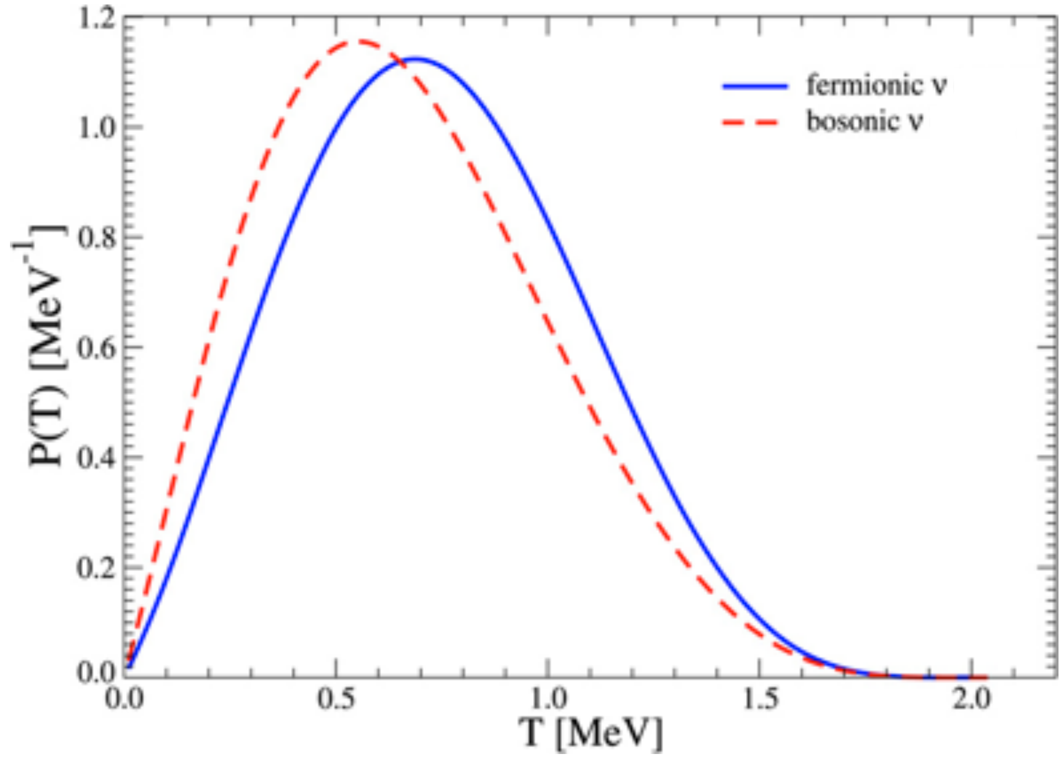
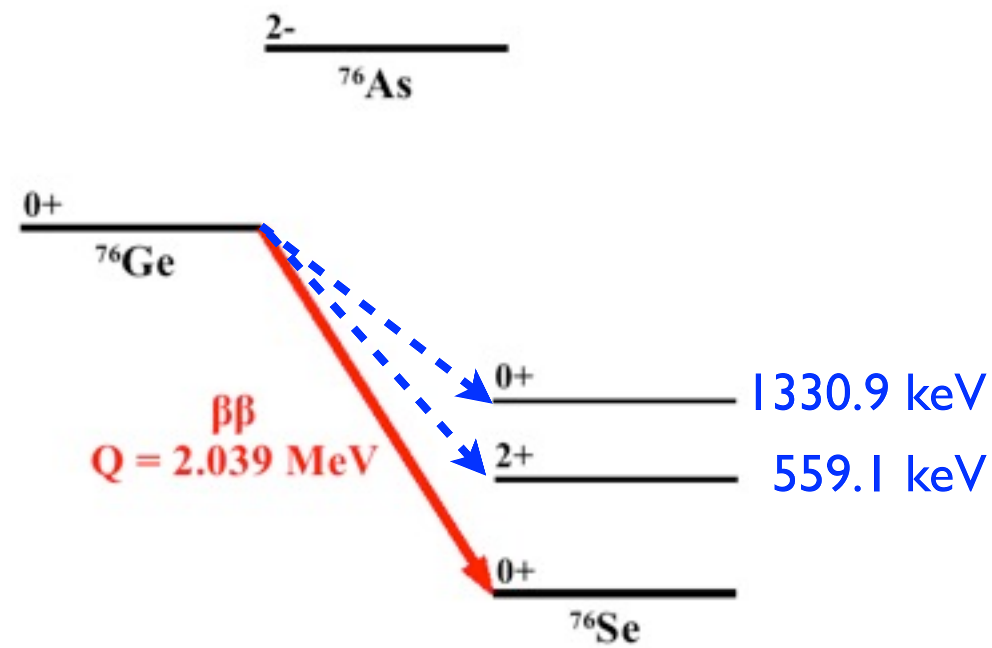
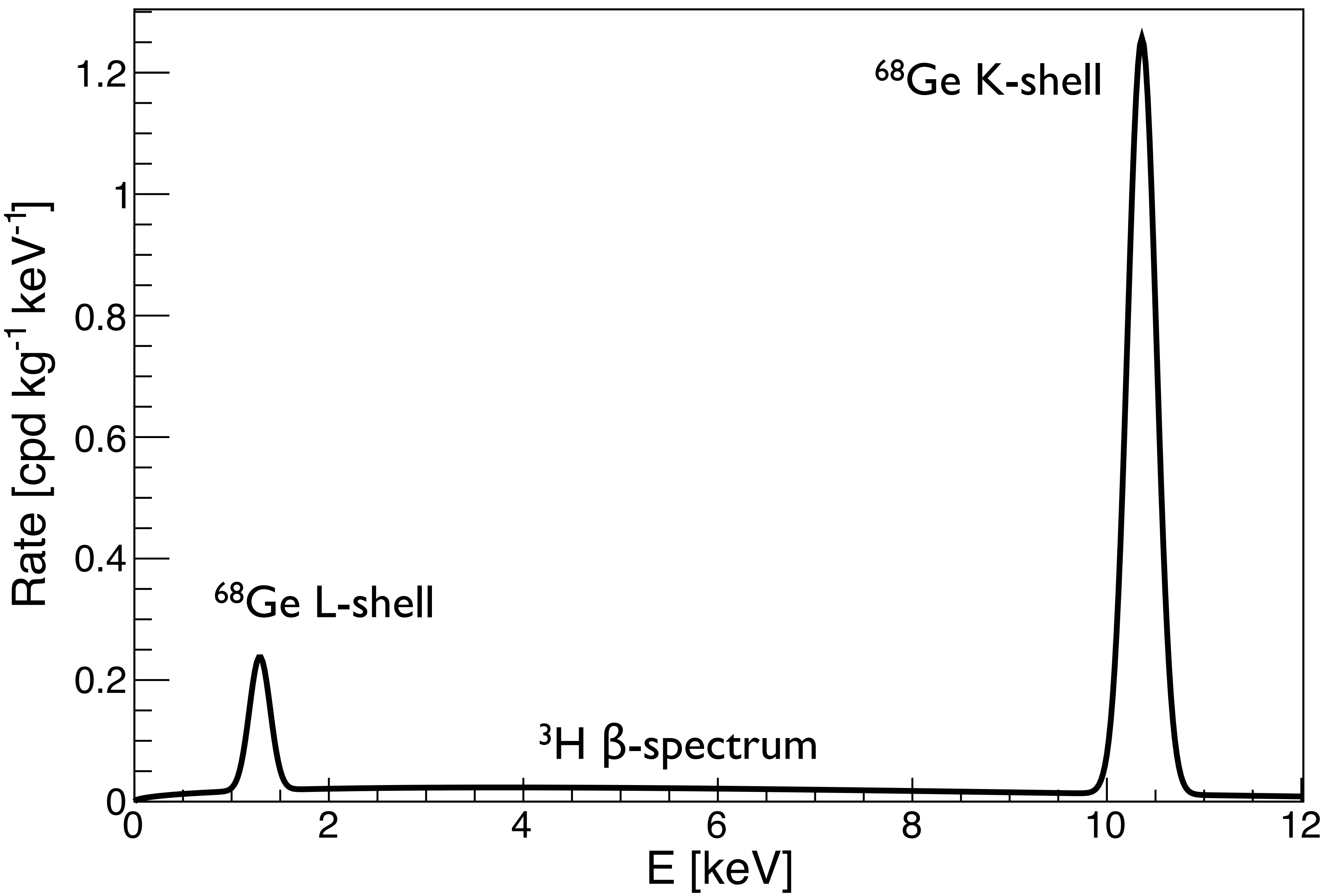




A.S. Barabash *et al.*, Nucl. Phys. B **783**, 90 (2007).

Low-E Backgrounds

MJD expectation: factor ~100 reduction



Z. Ahmed *et al.*, Phys. Rev. Lett. **103**, 141802 (2009).

Ton-Scale Design