Flavor Physics and *CP* Violation

**FP*CP* 2016**

# Neutrinoless Double Beta Decay

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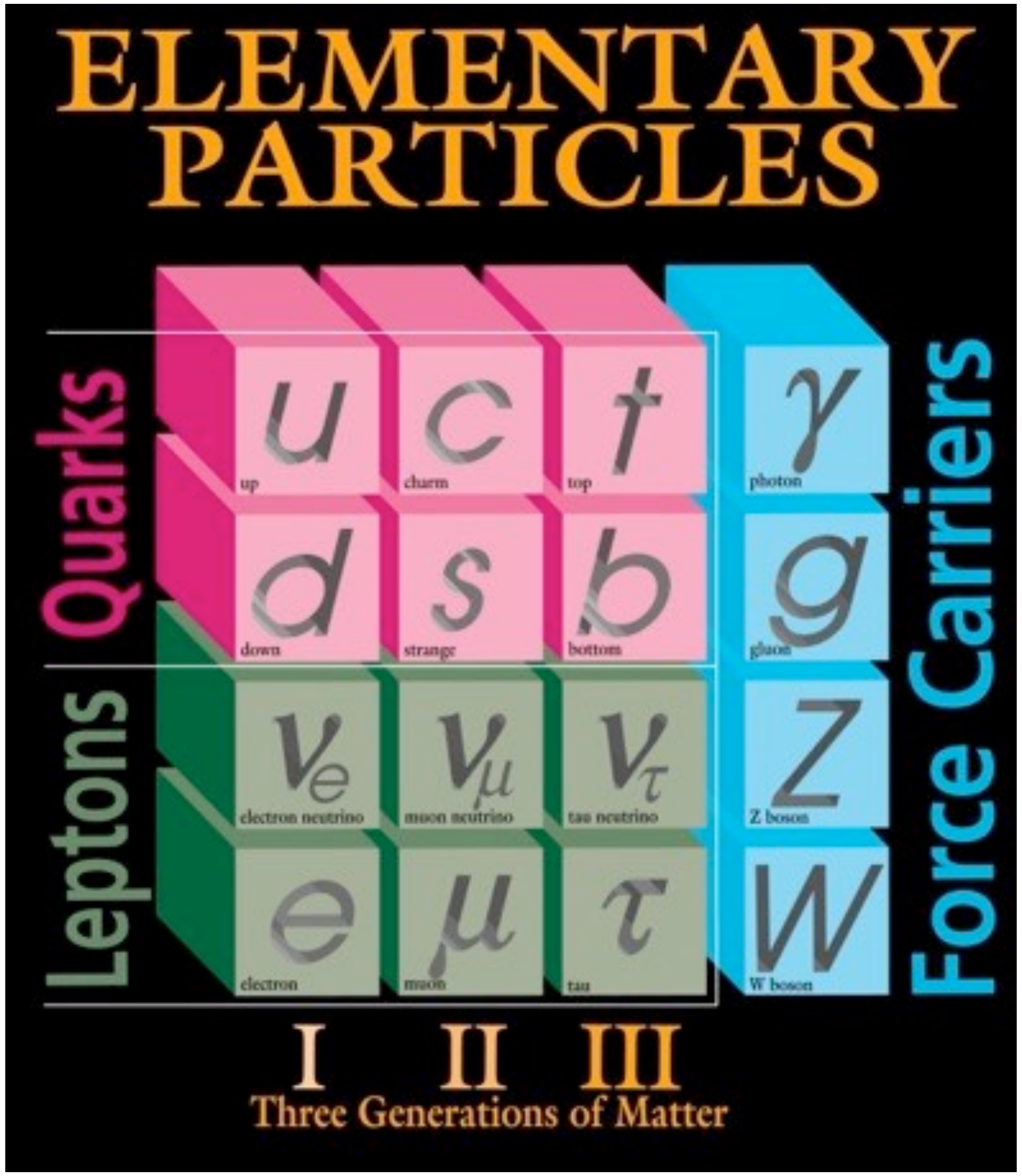
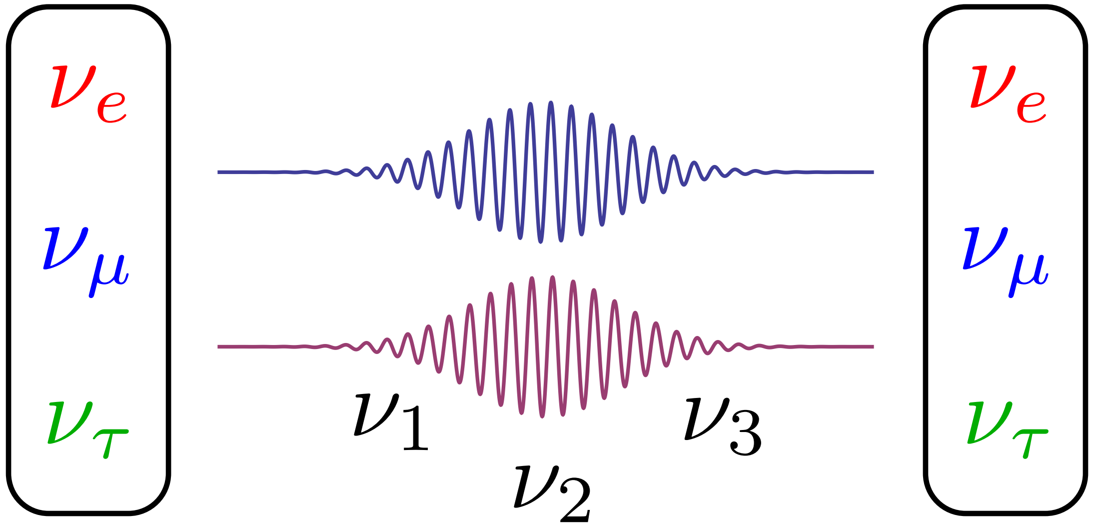
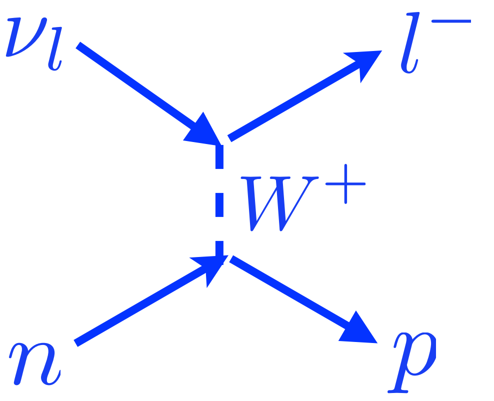
Indiana University
June 8, 2016

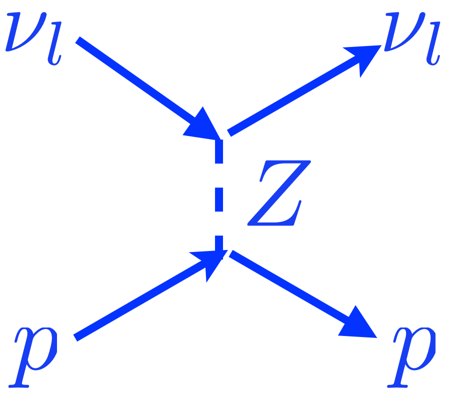
# Neutrino knowledge (today)

- Spin 1/2, low mass, fermions
- Interact only by weak interaction (and gravity)
- All observed neutrinos are left-handed, all observed anti-neutrinos are right-handed
- 3 neutrino mass eigenstates, 3 flavor eigenstates, all real oscillation angles non-zero









# What We Don't Know

## (Ignoring, for now, sterile νs and other BSM* phenomena)

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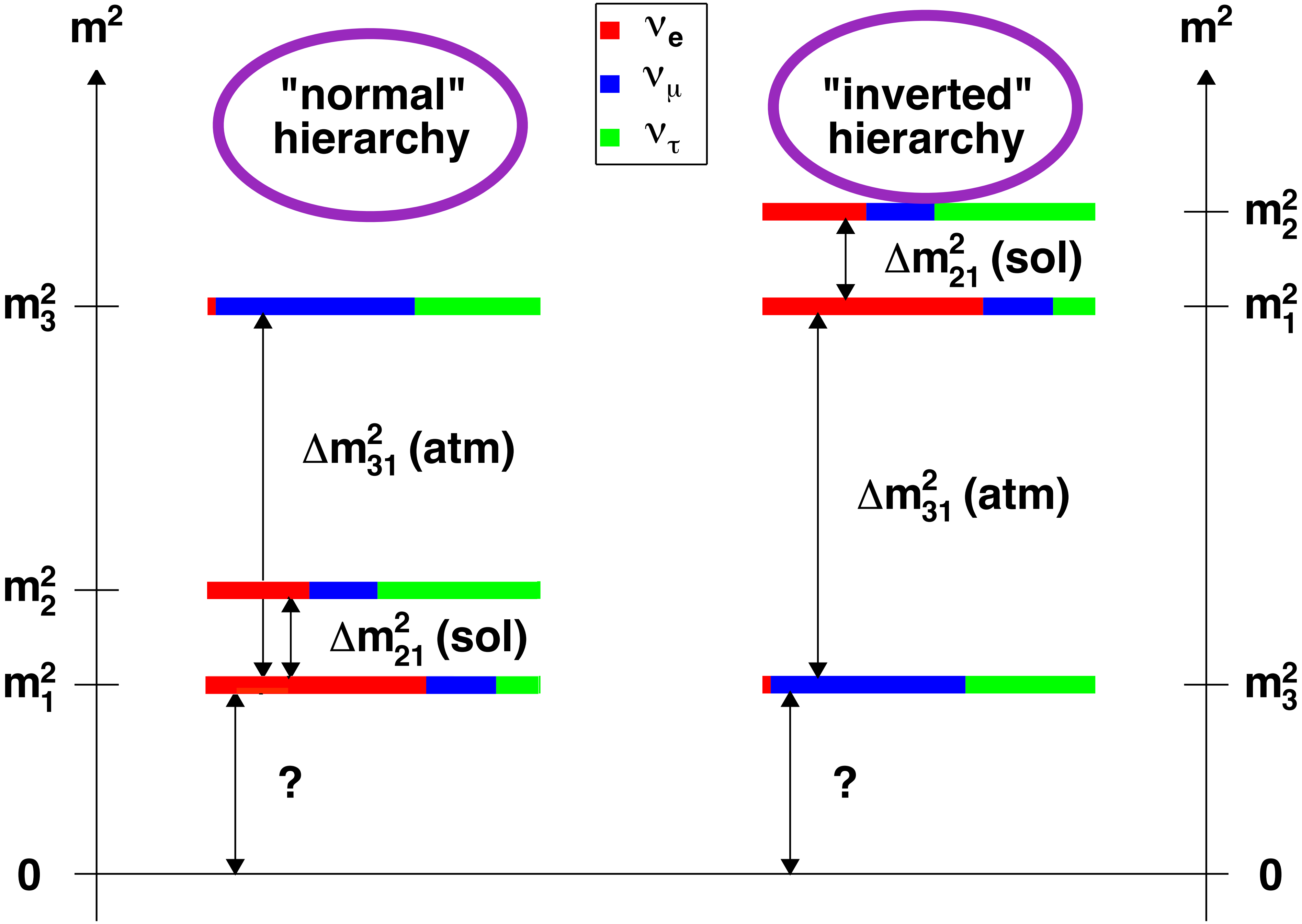
- Neutrino mass hierarchy



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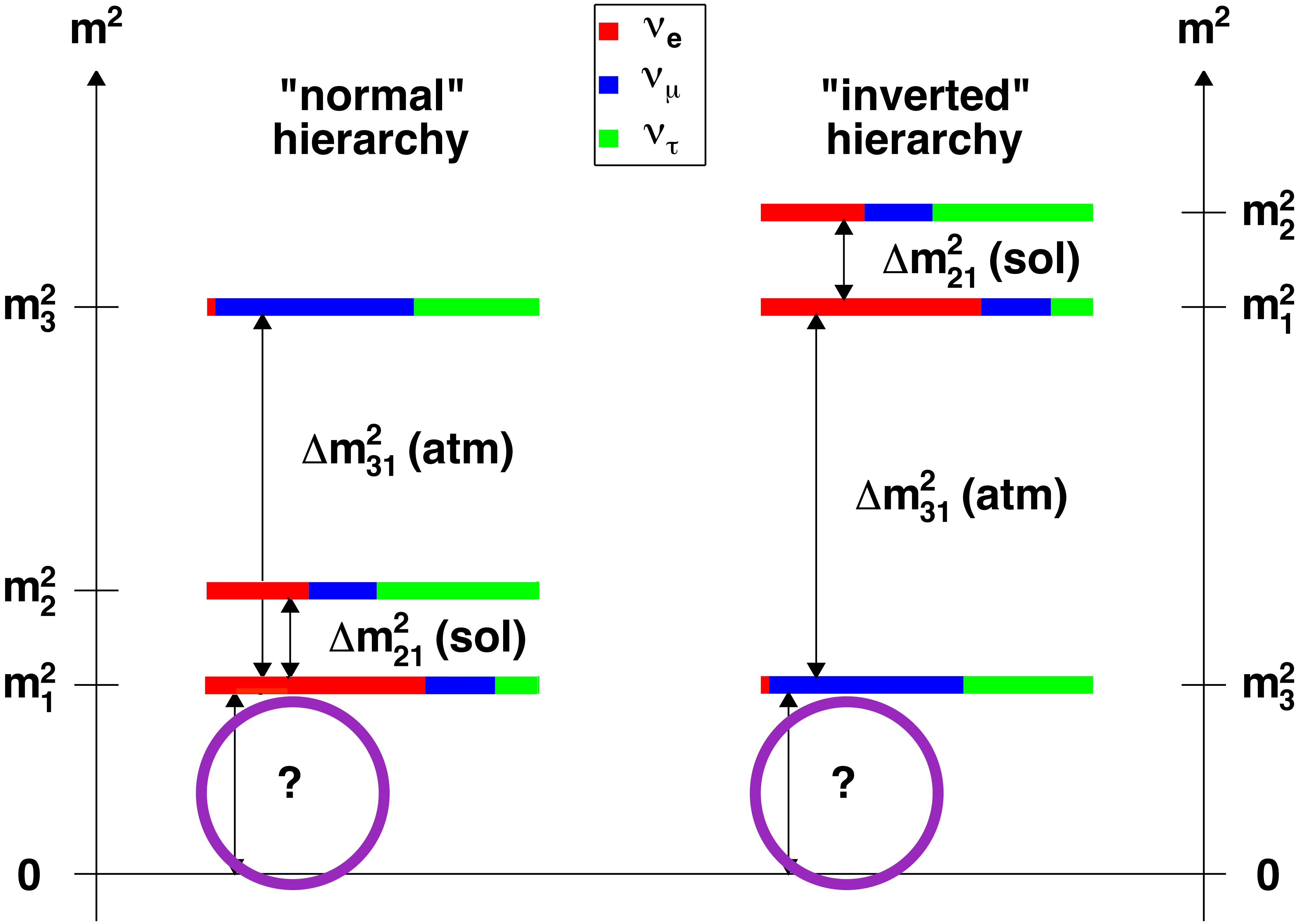
- Neutrino mass hierarchy
- Absolute neutrino mass



# What We Don’t Know

(Ignoring, for now, sterile νs and other BSM* phenomena)

- Neutrino mass hierarchy
- Absolute neutrino mass
- CP-violating behavior?

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$$

$$\overset{\text{Flavor}}{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{Atmospheric Oscillations}} \begin{pmatrix} c_{13} & 0 & \overset{\downarrow}{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar Oscillations}} \overset{\text{Mass}}{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}$$

$c_{23} = \cos\theta_{23}$ etc...

# What We Don't Know

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- CP-violating behavior?
- Dirac or Majorana nature?

$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu_\mu} \to \overline{\nu_e})$$

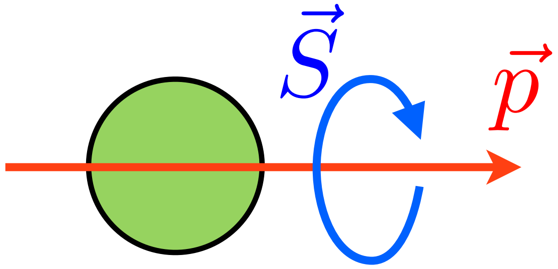
$$\nu \underset{?}{=} \overline{\nu}$$

$\nu_L$ $\overline{\nu_L}$ $\nu_L$ $\overline{\nu_L}$

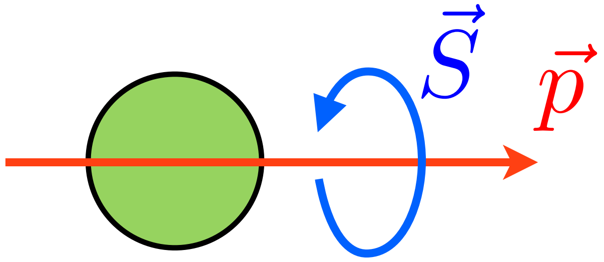
$\nu_R$ $\overline{\nu_R}$ $\nu_R$ $\overline{\nu_R}$

Paul Dirac

Ettore Majorana



left-handed $\nu$



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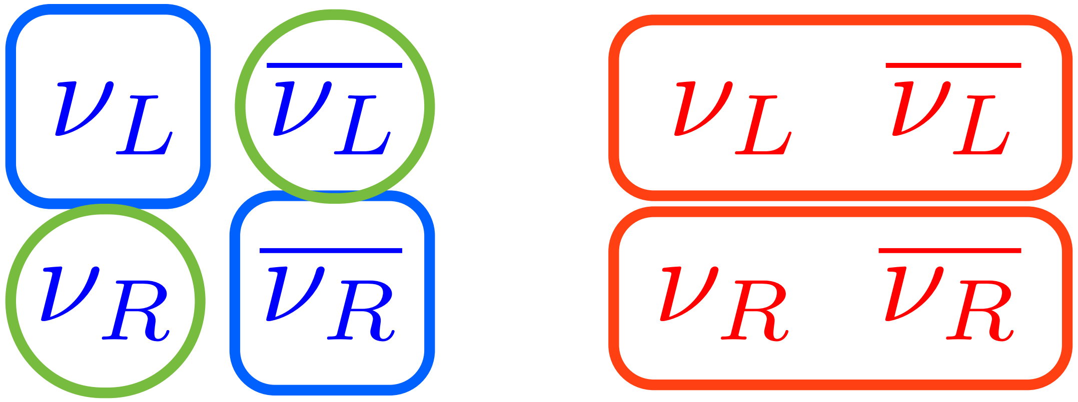

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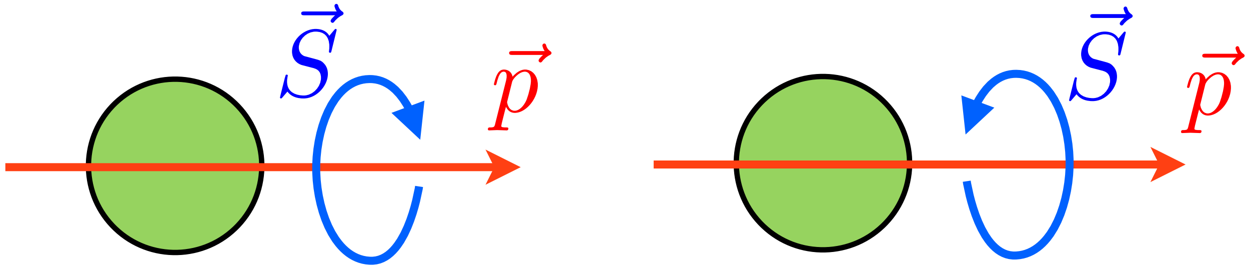

left-handed $\nu$ right-handed $\overline{\nu}$

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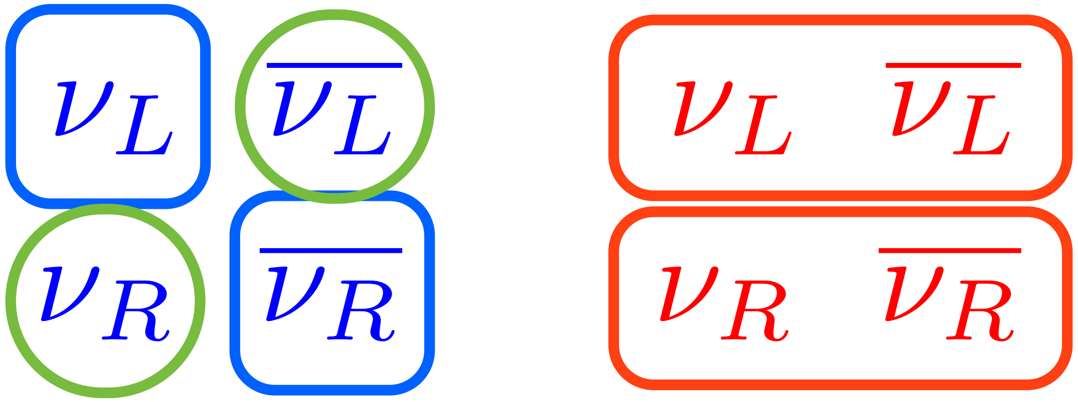
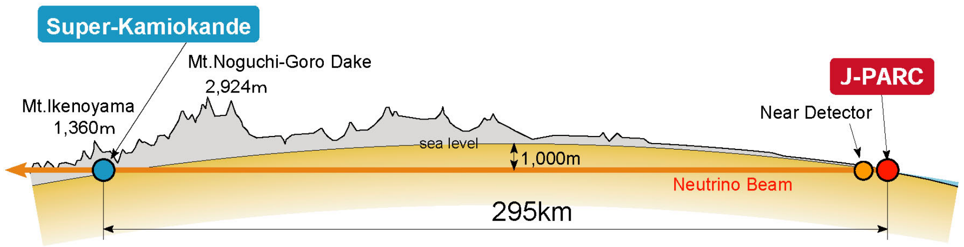


Solvable by neutrino beam experiments



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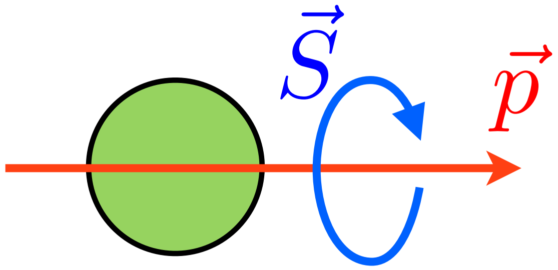
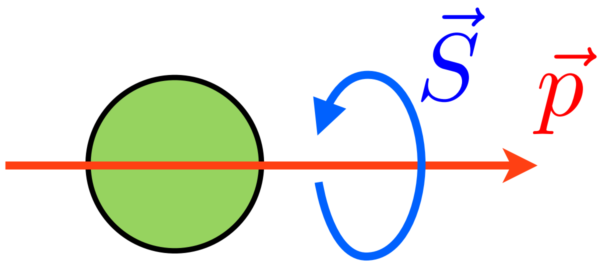


left-handed $\nu$



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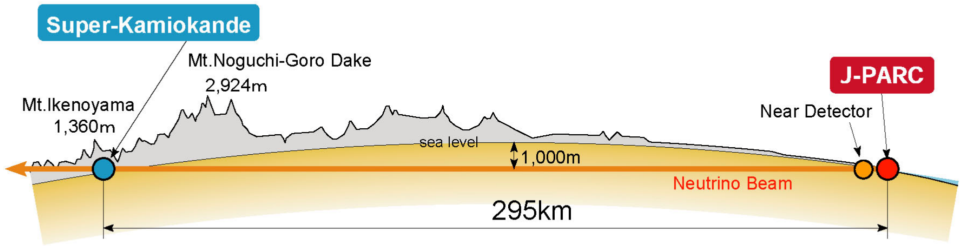

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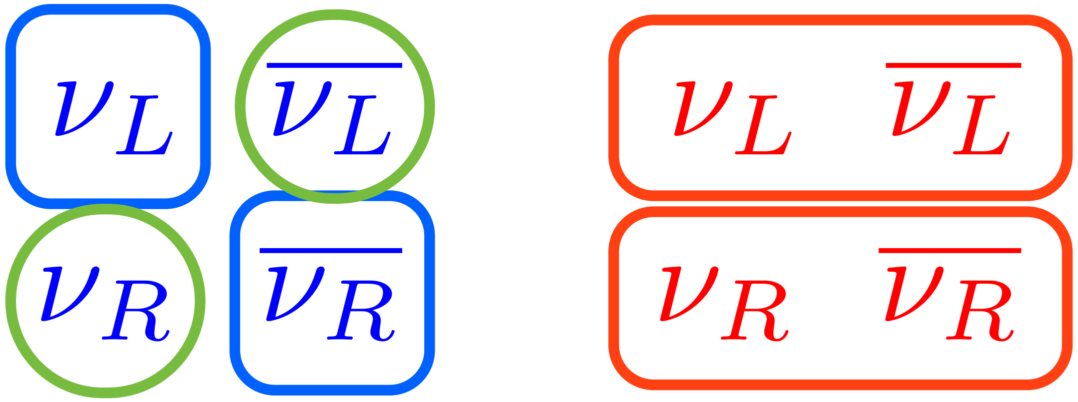
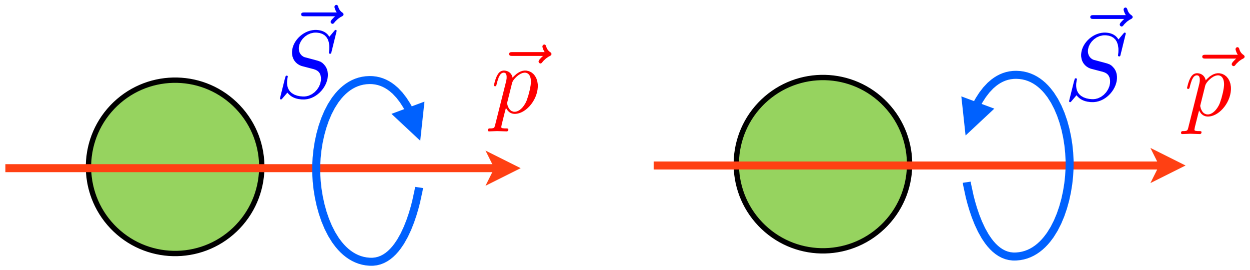
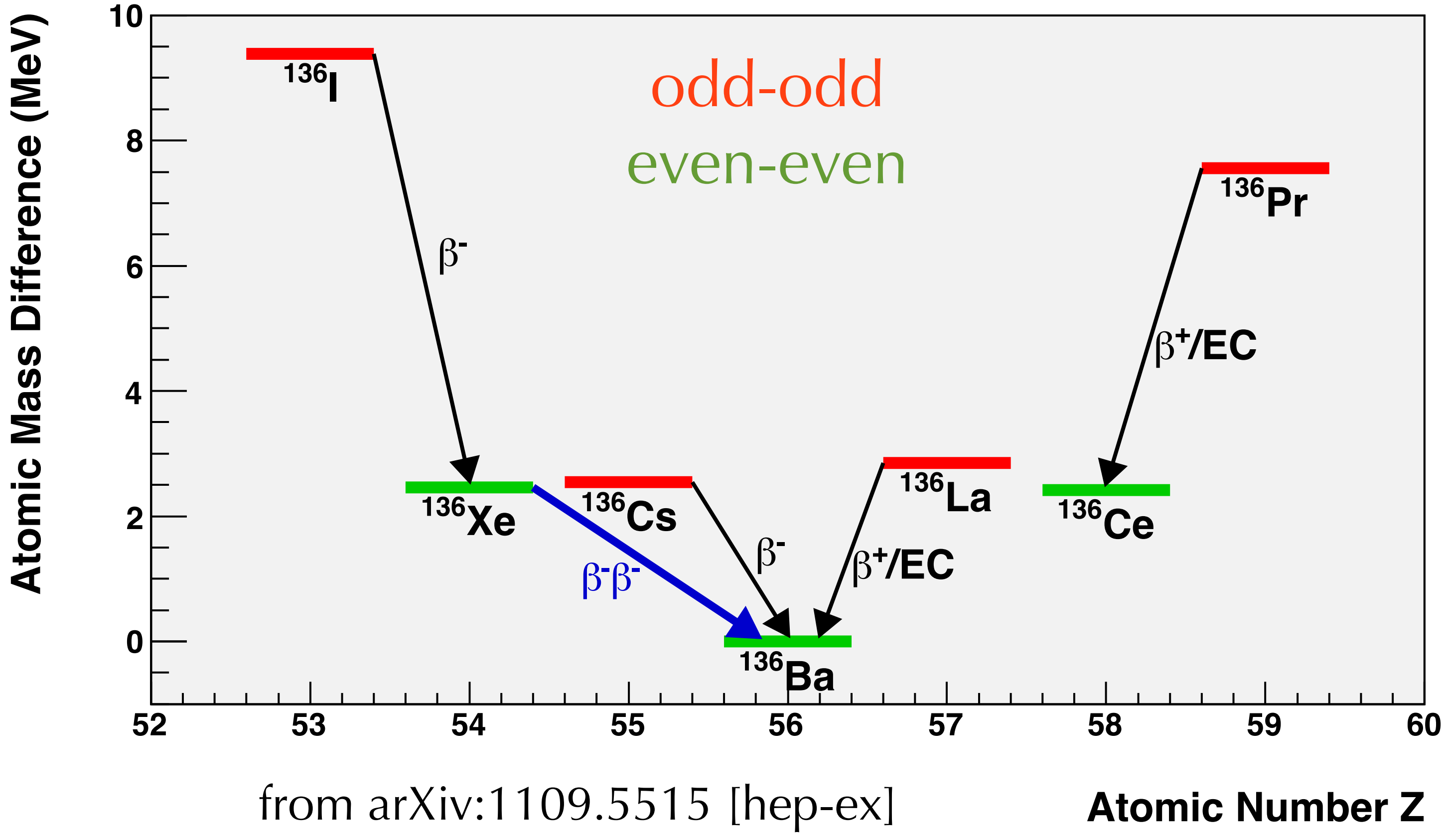




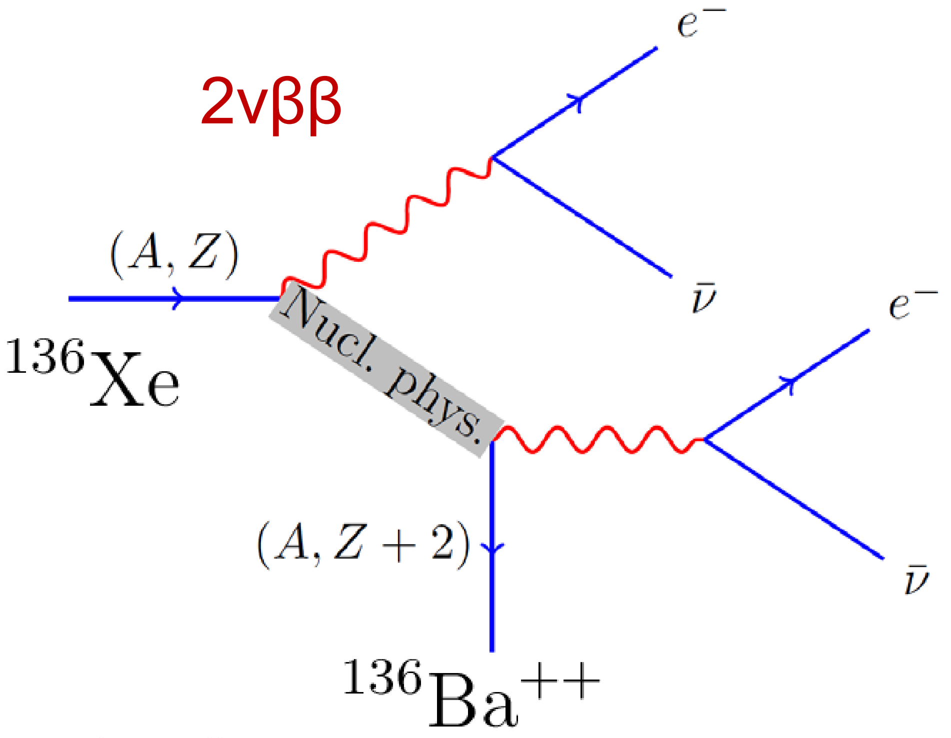
left-handed $\nu$ right-handed $\overline{\nu}$

# Double-Beta Decay

- Second order weak interaction
- Possible for some even-even nuclei



from arXiv:1109.5515 [hep-ex]

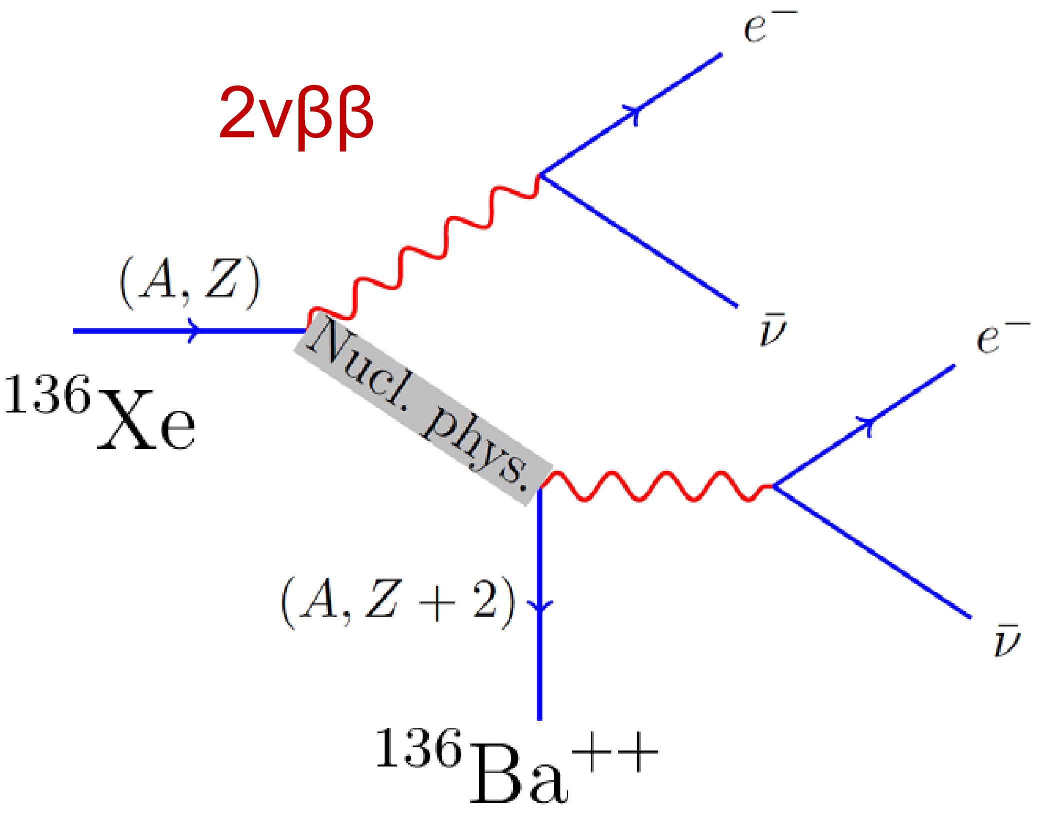


- Observable only where ordinary beta-decay is suppressed or forbidden

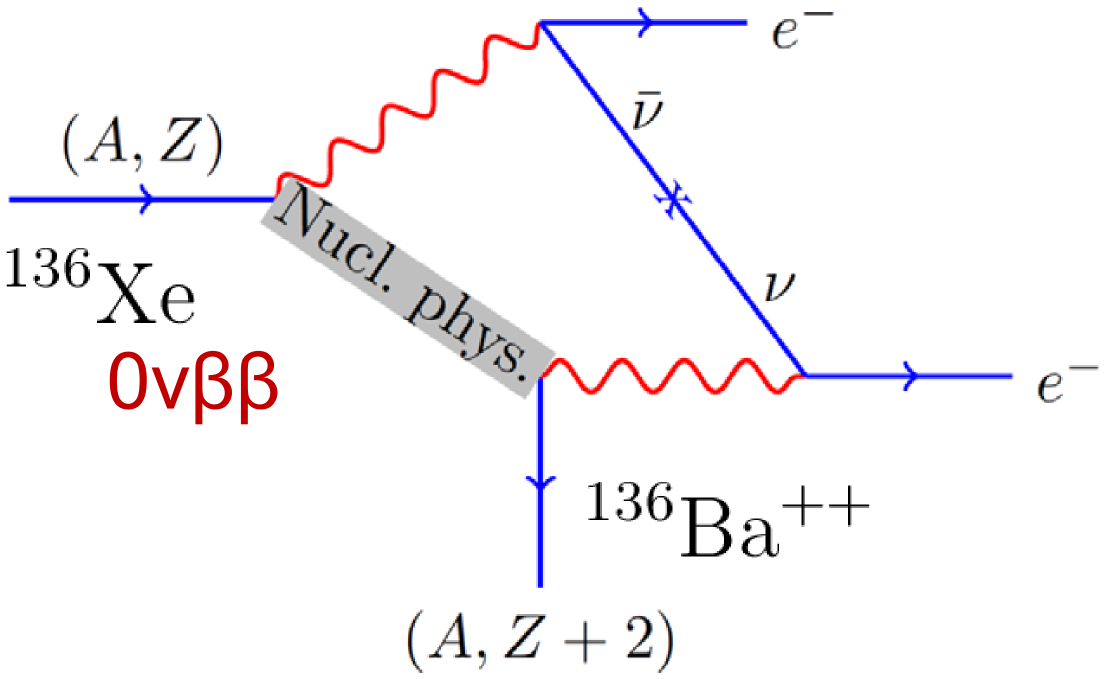
$$\cancel{n \rightarrow p + e^- + \overline{\nu}}$$

$$2n \rightarrow 2p + 2e^- + 2\overline{\nu}$$

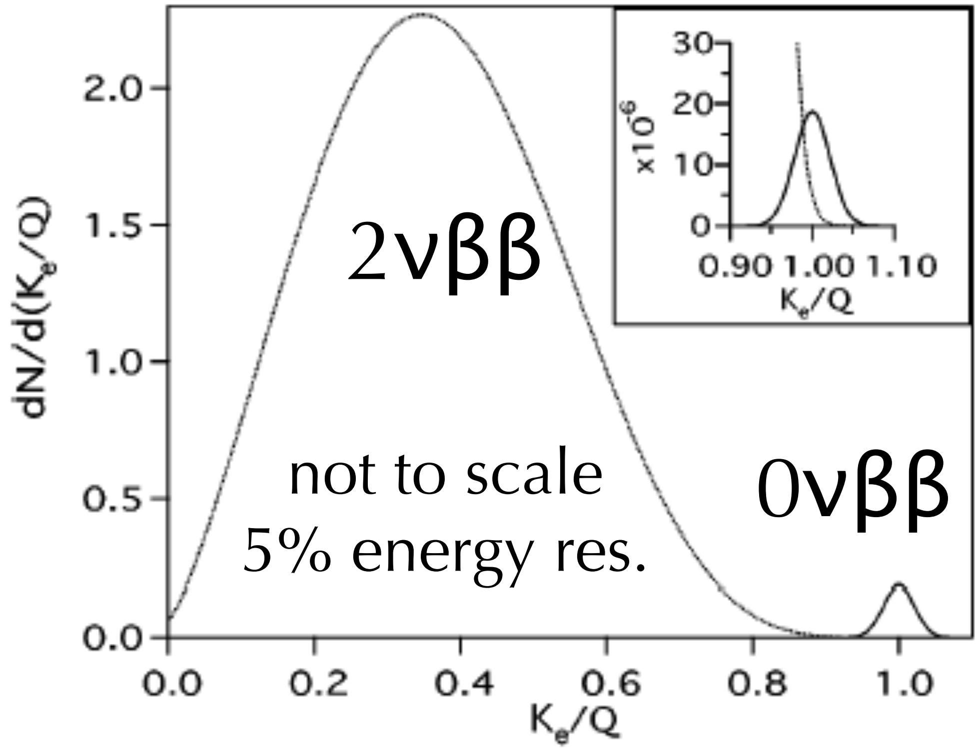
# Neutrinoless Double-Beta Decay



(simple 0νββ mechanism)



- Possible only if neutrinos are massive (yes) and Majorana (?)
- Majorana particles: are their own antiparticles
- Requires lepton number violation (implies new physics)
- Appears as peak at Q-value

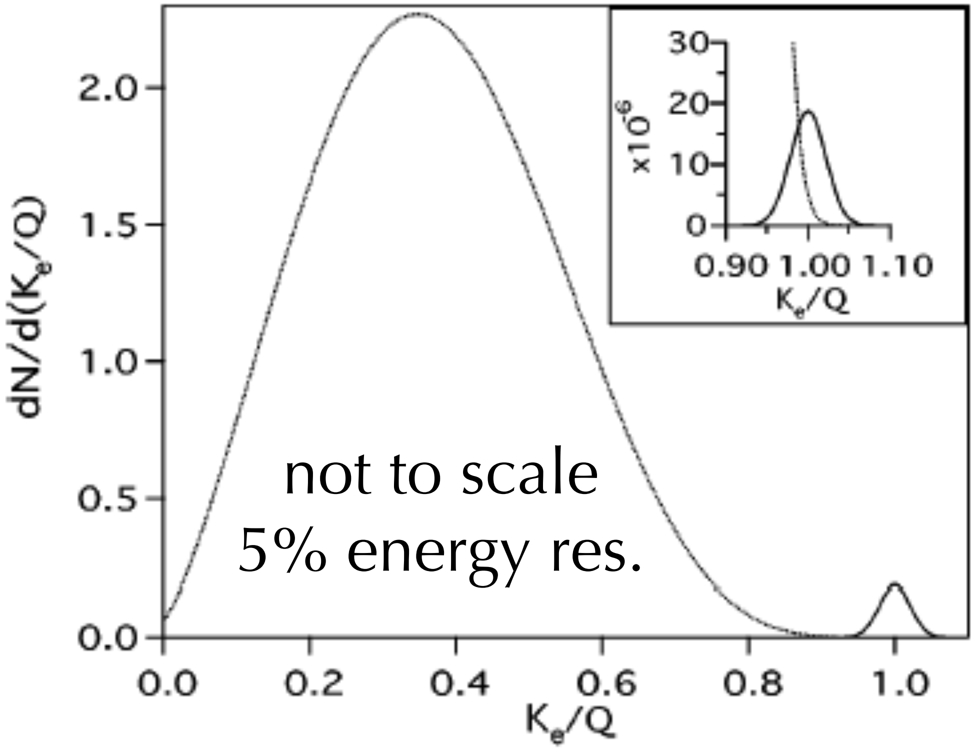


Elliot, S. et al., Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

# Searching for 0νββ

- Need very low backgrounds
  - Clean (radiopure) detector
  - Underground lab
  - Good energy resolution
  - Other discrimination techniques
- Large quantities of a candidate isotope

| Decay | Q-value | Abundance (%) |
|---|---|---|
| $^{48}\text{Ca}\rightarrow{}^{48}\text{Ti}$ | 4.271 | 0.187 |
| $^{76}\text{Ge}\rightarrow{}^{76}\text{Se}$ | 2.040 | 7.8 |
| $^{82}\text{Se}\rightarrow{}^{82}\text{Kr}$ | 2.995 | 9.2 |
| $^{96}\text{Zr}\rightarrow{}^{96}\text{Mo}$ | 3.350 | 2.8 |
| $^{100}\text{Mo}\rightarrow{}^{100}\text{Ru}$ | 3.034 | 9.6 |
| $^{110}\text{Pd}\rightarrow{}^{110}\text{Cd}$ | 2.013 | 11.8 |
| $^{116}\text{Cd}\rightarrow{}^{116}\text{Sn}$ | 2.802 | 7.5 |
| $^{124}\text{Sn}\rightarrow{}^{124}\text{Te}$ | 2.228 | 5.64 |
| $^{130}\text{Te}\rightarrow{}^{130}\text{Xe}$ | 2.528 | 34.5 |
| $^{136}\text{Xe}\rightarrow{}^{136}\text{Ba}$ | 2.458 | 8.9 |
| $^{150}\text{Nd}\rightarrow{}^{150}\text{Sm}$ | 3.367 | 5.6 |



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- Cost, availability, usability vary wildly.
- Many experimental technologies, very competitive field!
- Often similar to dark matter detectors, different optimization
- Approaching ton-scale era for 0νββ

# 0νββ vs Dark Matter

| | |
|---|---|
| Search for ββ decays | Search for WIMP nuclear recoils |
| Optimize for ~2 MeV energy (especially resolution) | Optimize for 100 keV energy (especially thresholds) |
| gamma shielding critical (neutron shielding important) | neutron shielding critical (gamma shielding important) |
| focus on electron recoils | focus on nuclear recoils |
| Slower iteration due to strict radiopurity requirements, enrichment | Iterate quickly to large mass |

- Synergy for technology development (xenon pumps, calibration, crystals), but not economical to build "jack of all trades" detector... yet

# Limits on <mββ>

$$\frac{1}{t^{0\nu}_{1/2}} = G^{0\nu} \left| M^{0\nu} \right|^2 m^2_{\beta\beta}$$

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} m_i U_{ei}^2 \right|$$

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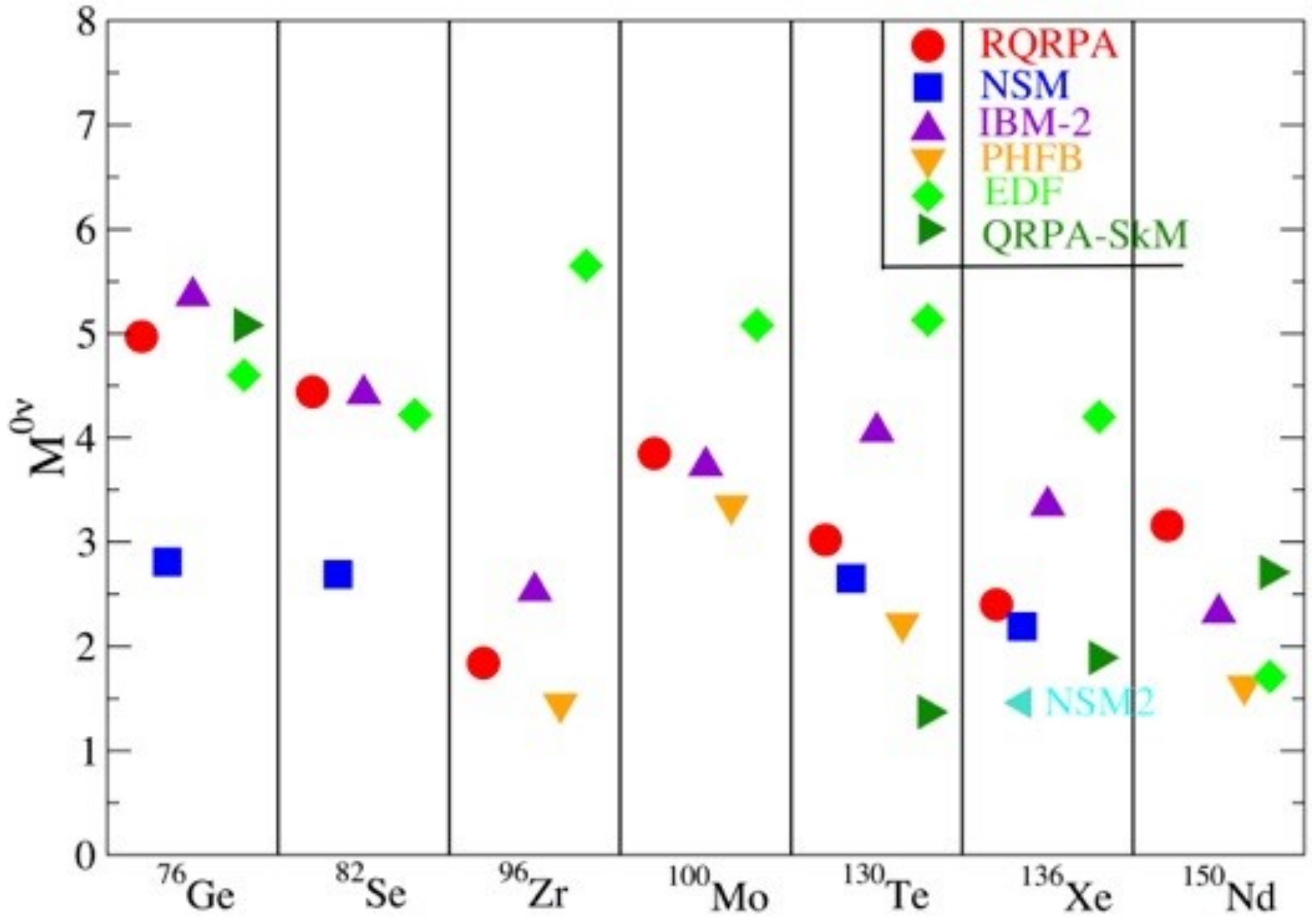
- Large uncertainties due to matrix elements
- Will improve as computational nuclear physics moves forward to heavier nuclei



Petr Vogel, 2014

# Limits on <mββ>

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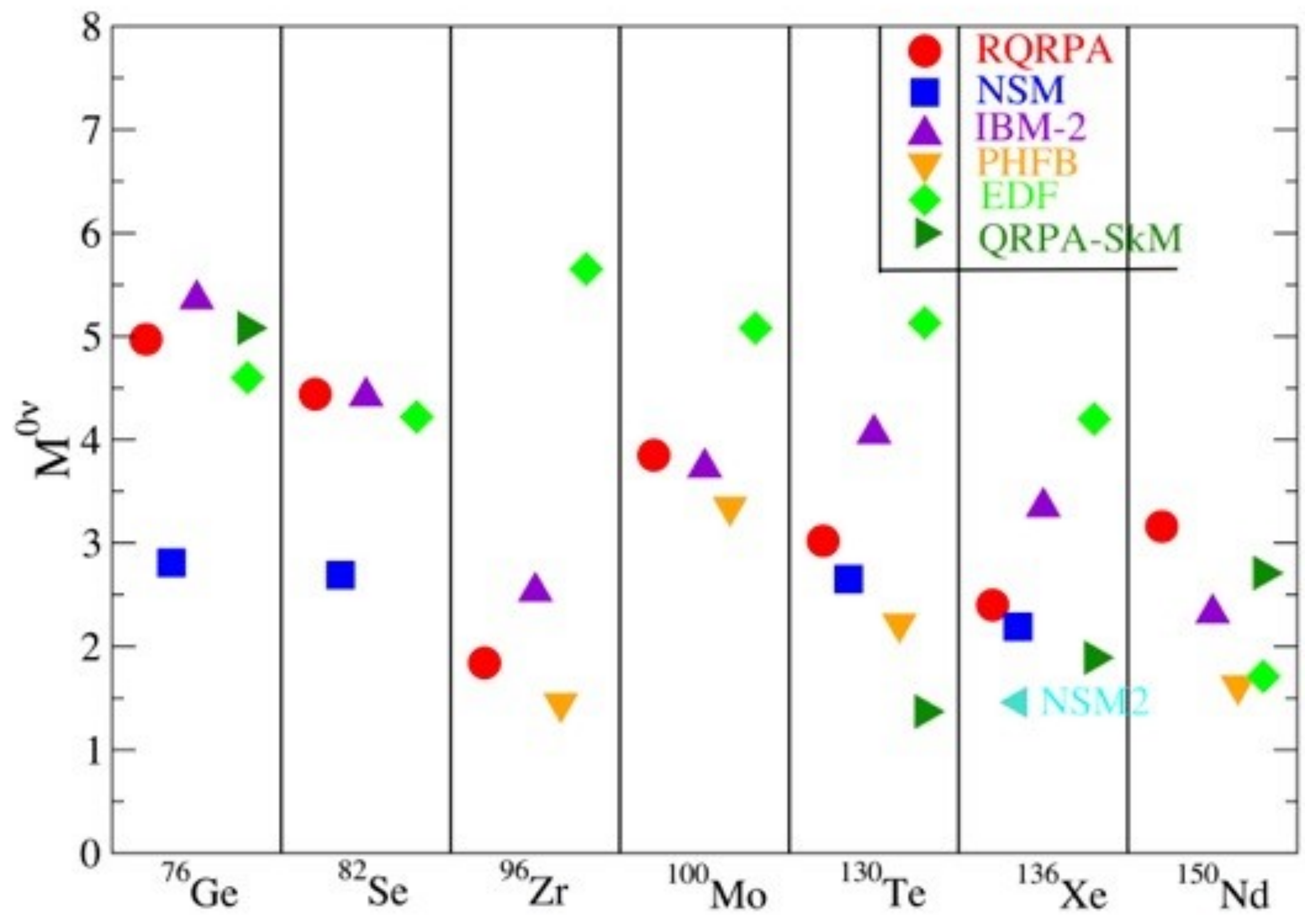
$$m_{\beta\beta} = \left|\sum_{i=1}^{3} m_i U^2_{ei}\right|$$

includes complex terms

- Large uncertainties due to matrix elements
- Will improve as computational nuclear physics moves forward to heavier nuclei
- Need to consider matrix elements and phase space factors for comparison



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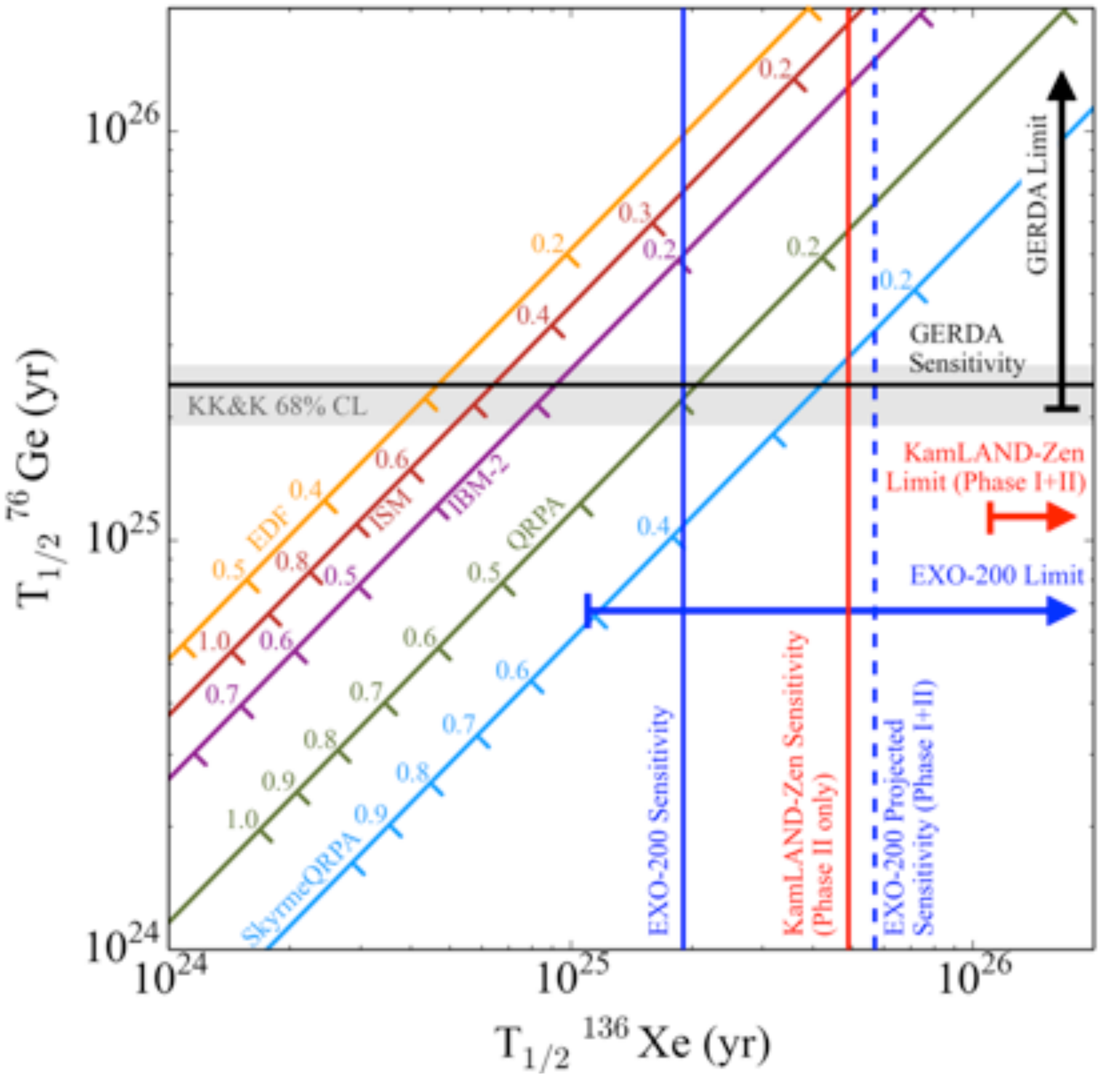
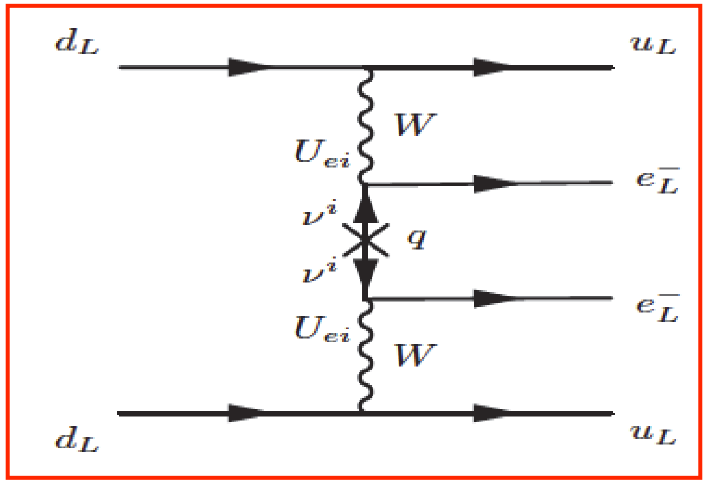
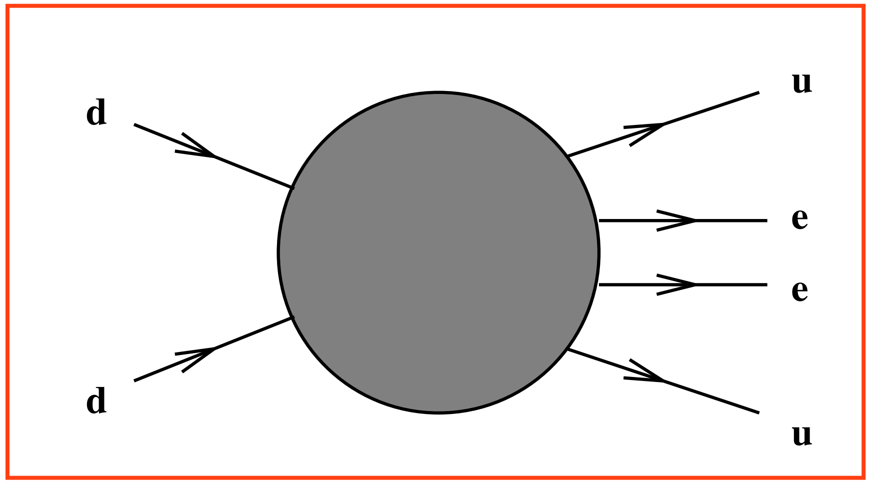


# 0νββ alternatives

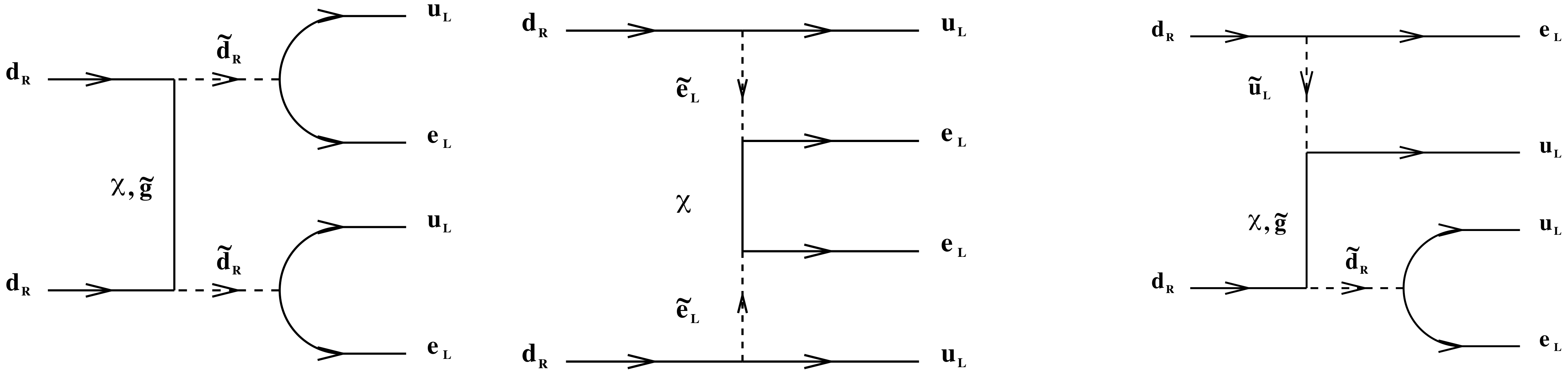
- Processes other than 0νββ mediated by light-ν exchange may be observed



standard



all we can see



Phys.Rev.D53:1329-1348,1996

http://arxiv.org/abs/hep-ph/9502385v1

- No matter what: Always lepton number non-conservation, Majorana neutrino, new physics!

# Three major metrics

- Sensitivity

*What limits can we set on <$m_{\beta\beta}$>, assuming no signal of 0νββ?*

- Discovery Potential

*If 0νββ happens, for what mass <$m_{\beta\beta}$> can we make a definite observation at the 3σ (5σ) level?*

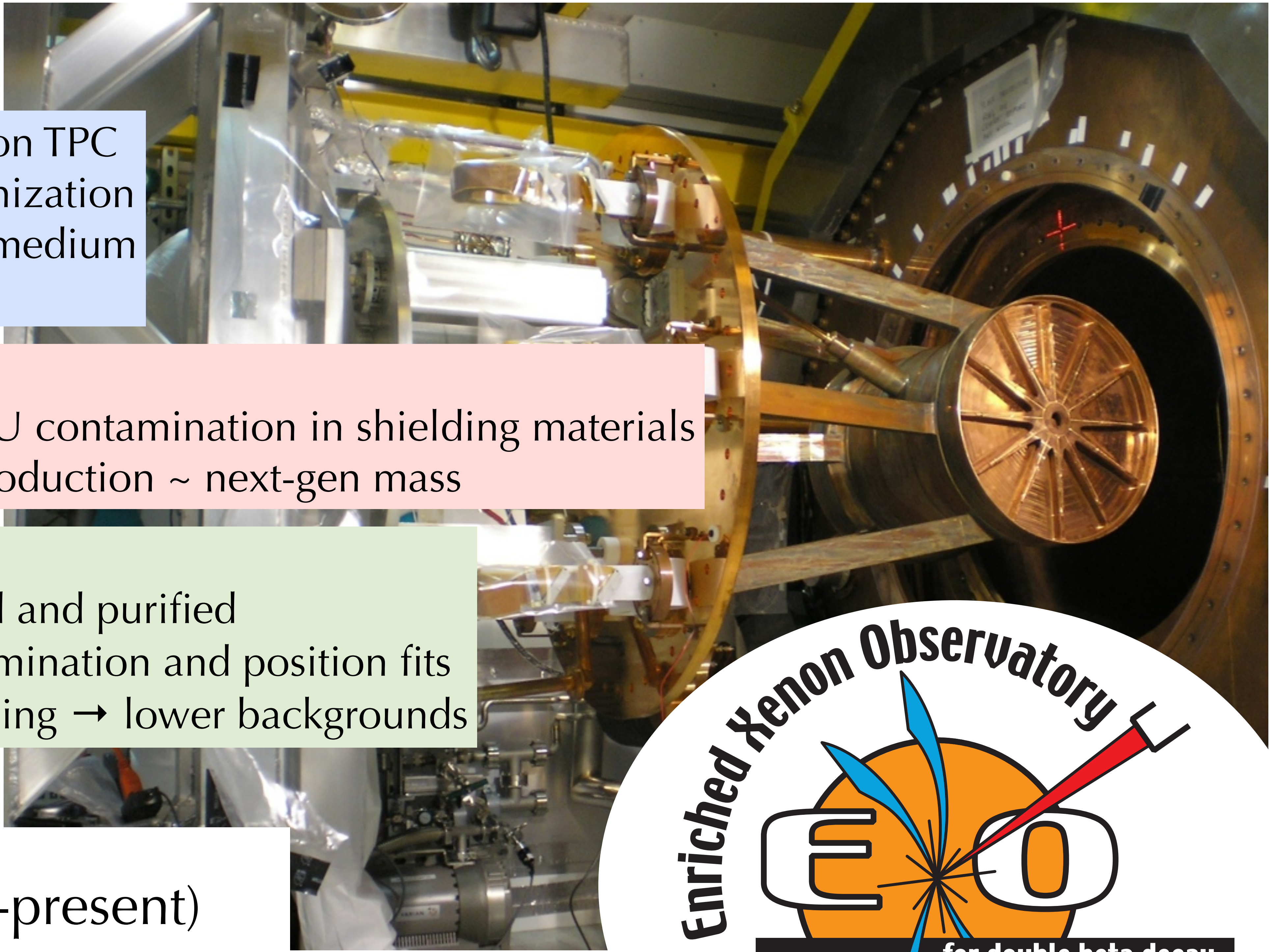
- Cost/Feasibility

*What is the total expense for the project, and how confident can we be that it will meet expectations?*

# Experimental Choices

- Detection type
    - gas tracking/liquid tracking/liquid scintillator/solid crystal
    - scintillation light/ionization charge/phonons
- Detection medium is the source?
- Isotope
- Shielding
    - Active←???→passive

# Enriched Xenon Observatory



Technology: Liquid xenon TPC
Signal from light and ionization
Source is the detection medium
Isotope: $^{136}$Xe

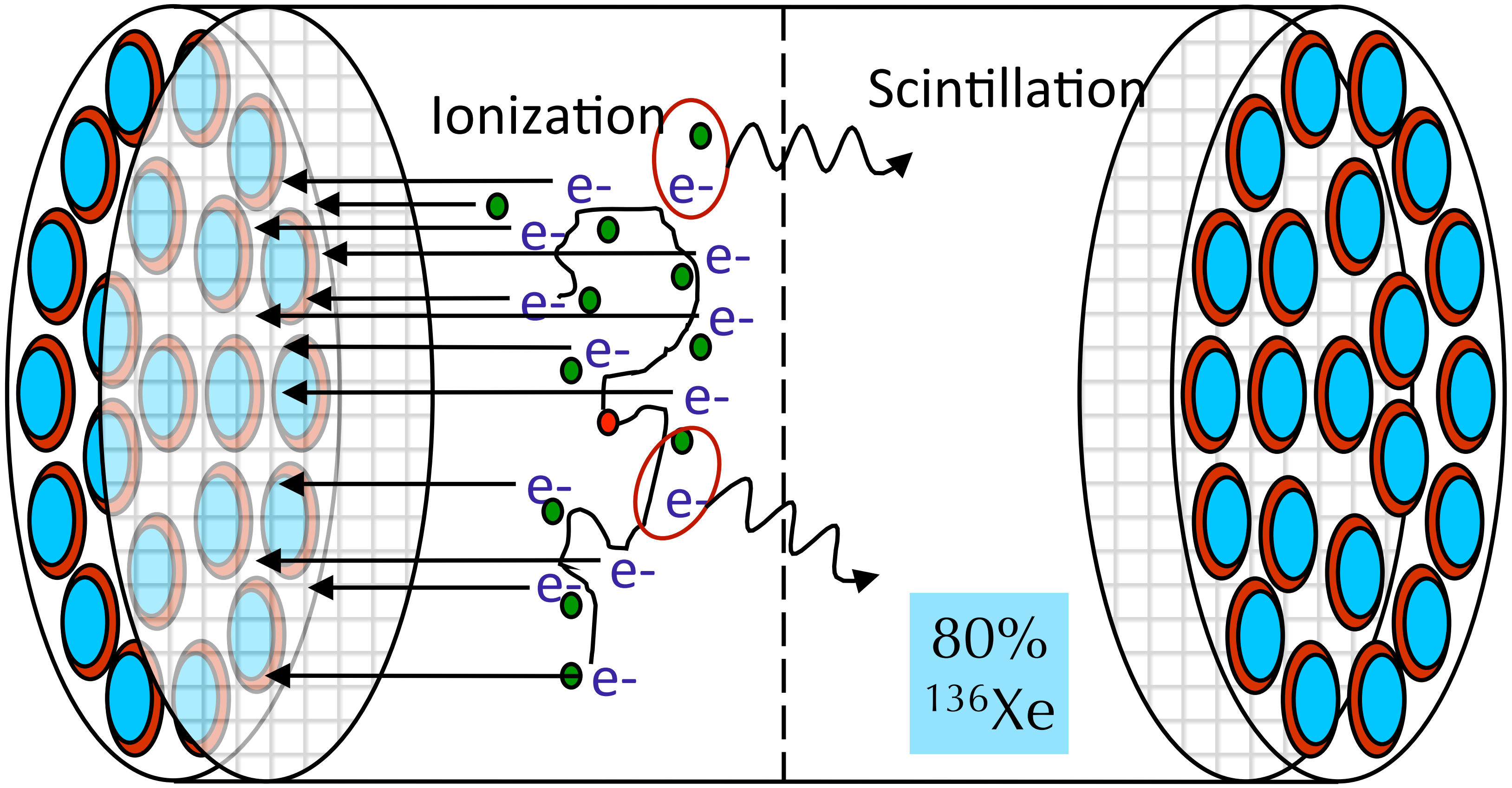
Challenges:
Need extremely low $^{238}$U contamination in shielding materials
Annual global xenon production ~ next-gen mass

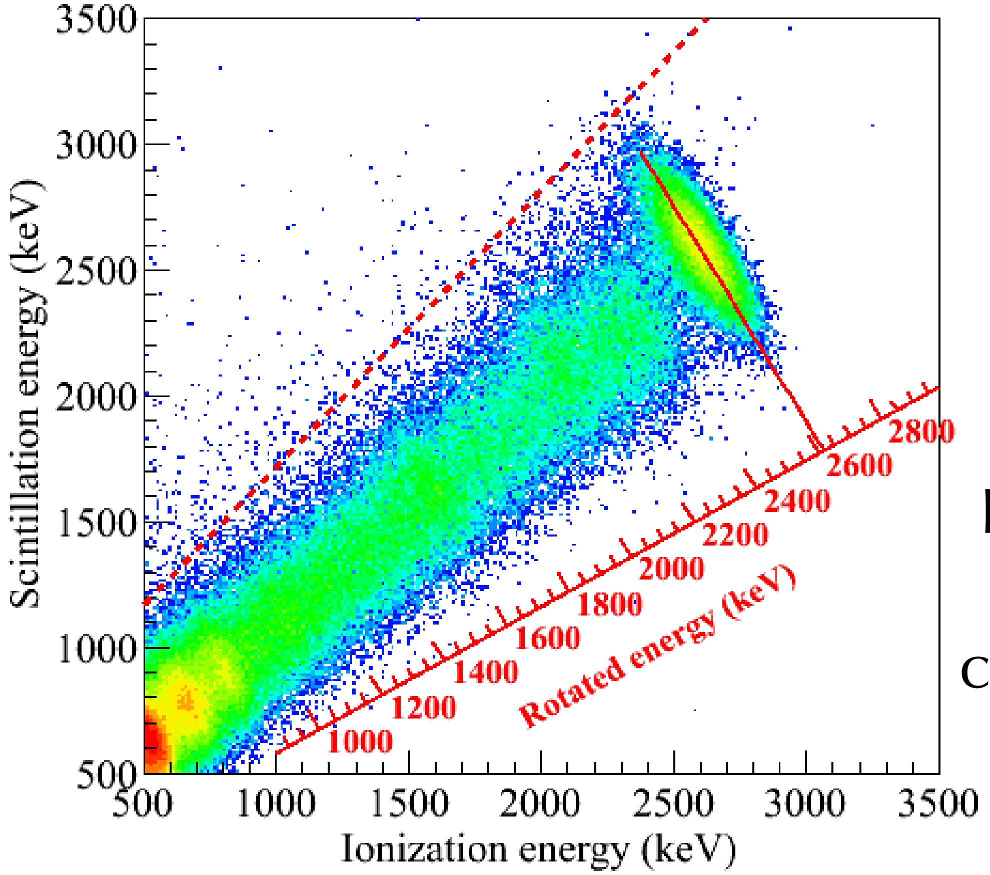
Highlights:
Xenon is easily enriched and purified
TPC allows α/β/γ discrimination and position fits
Scaling up → self-shielding → lower backgrounds

- EXO-200 (2011-present)
- nEXO (future)

# LXe Time Projection Chamber

- Xenon under high electric field
- Moving charged particles ionize LXe atoms, charge will recombine (scintillation light) or drift to anode (charge)



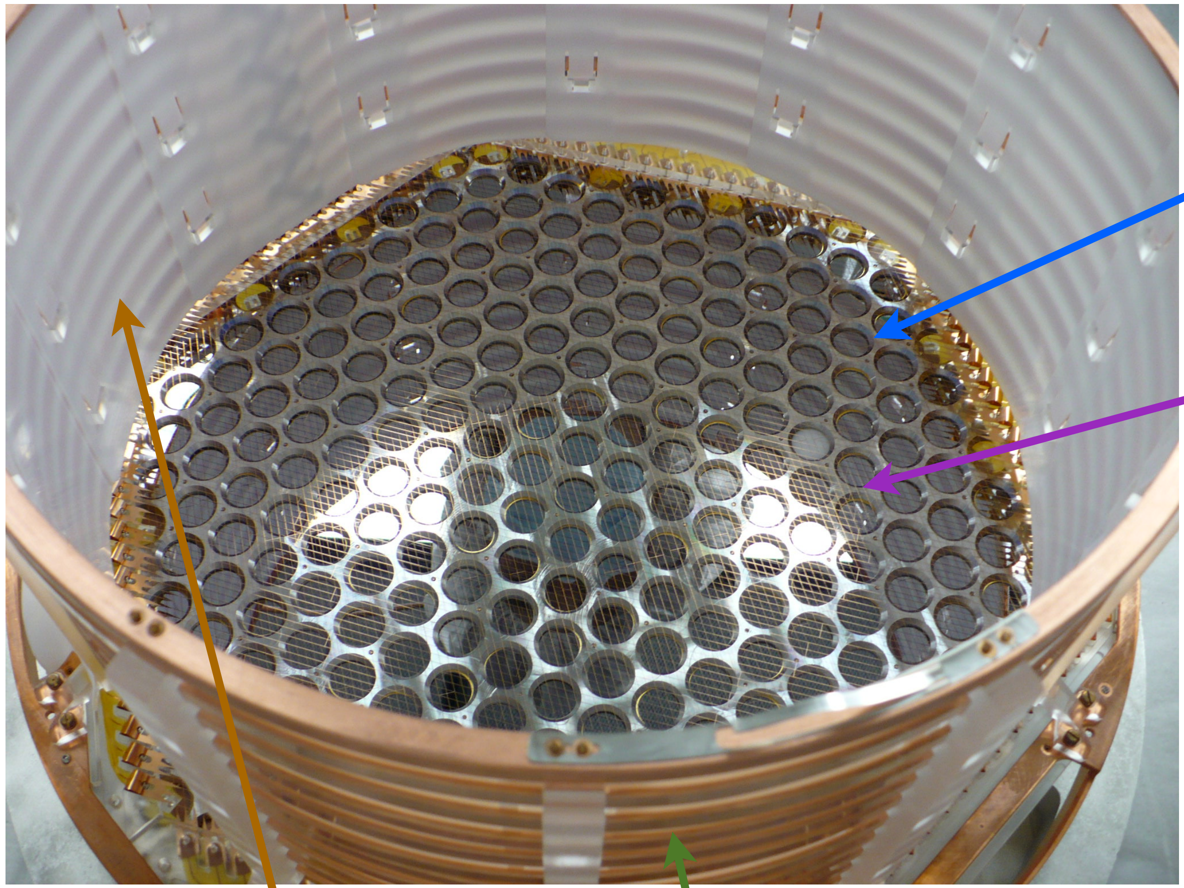


EXO-200
$^{228}$Th
calibration
data

- 2D readout at anode + scintillation time → 3D tracking
- Combine charge and light to optimize energy resolution (rotated energy)

# EXO-200

40 cm

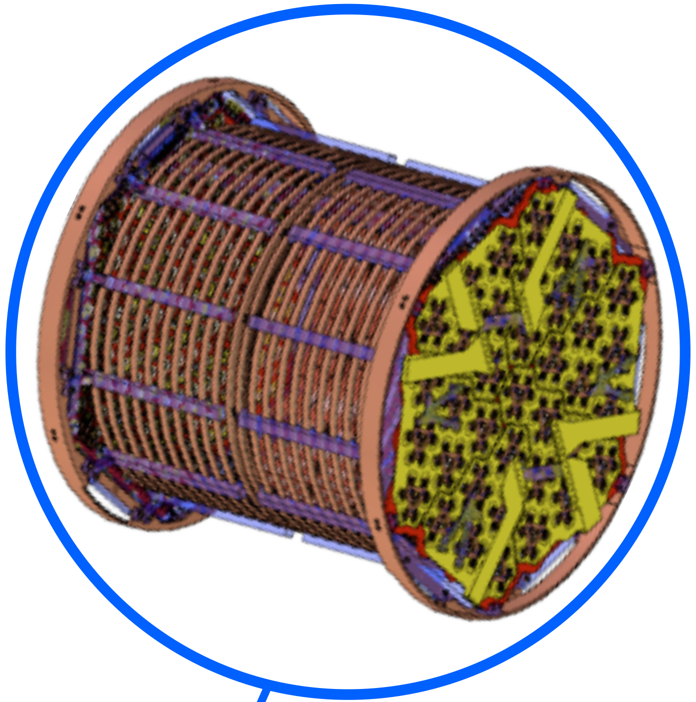


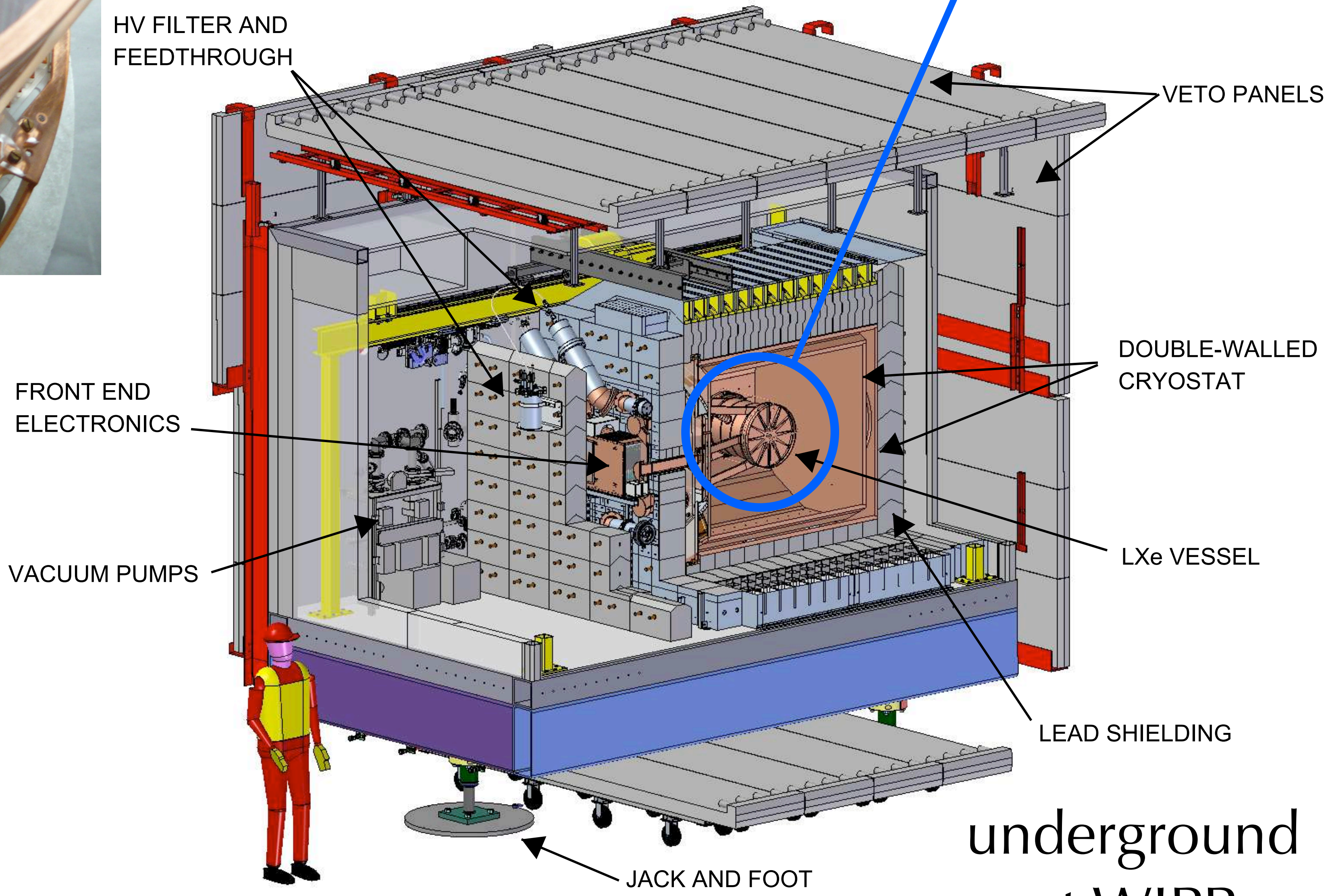
Avalanche photodiodes (APDs)

crossed induction and collection wires

Teflon reflector

Field rings (374 V/cm)



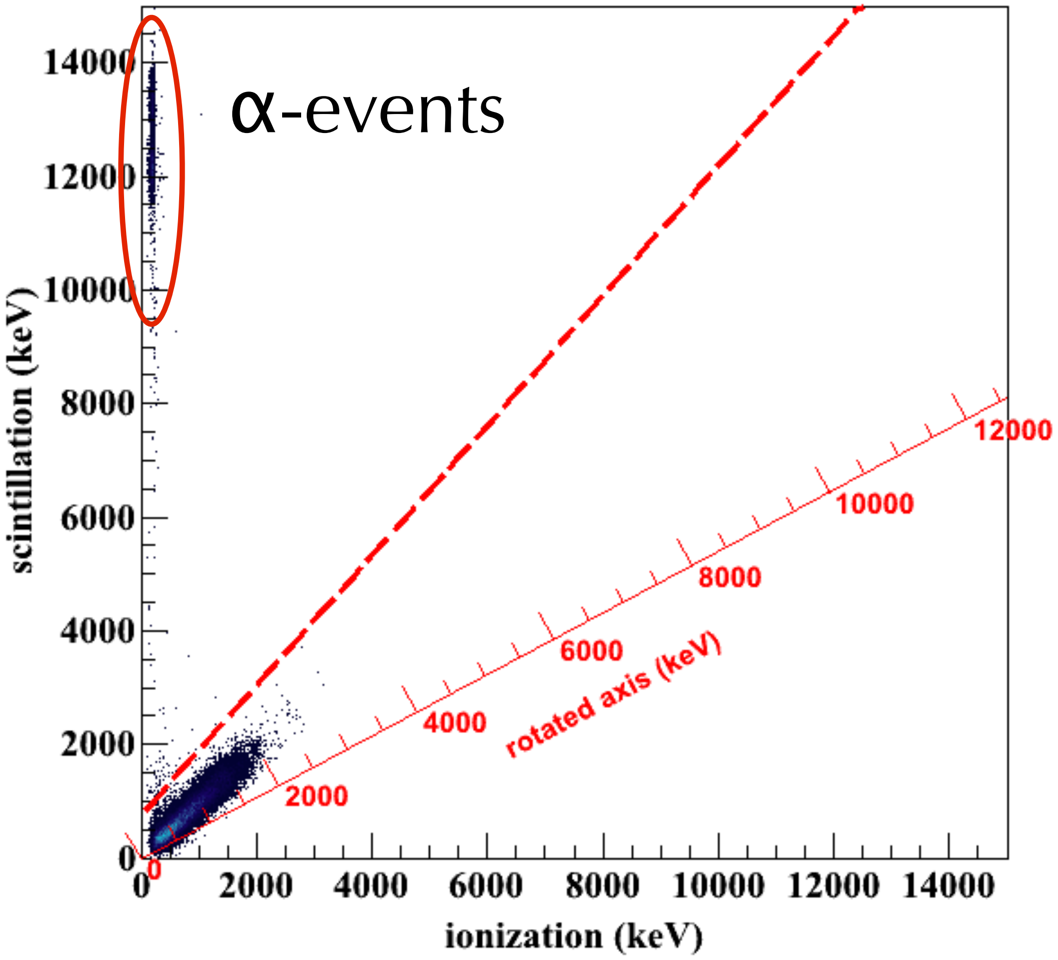


- Every component (down to the screws) within Pb shielding has been screened and selected for radiopurity

underground at WIPP

# Signal/background discrimination

(beyond energy)



- Scint/Ionization ratio

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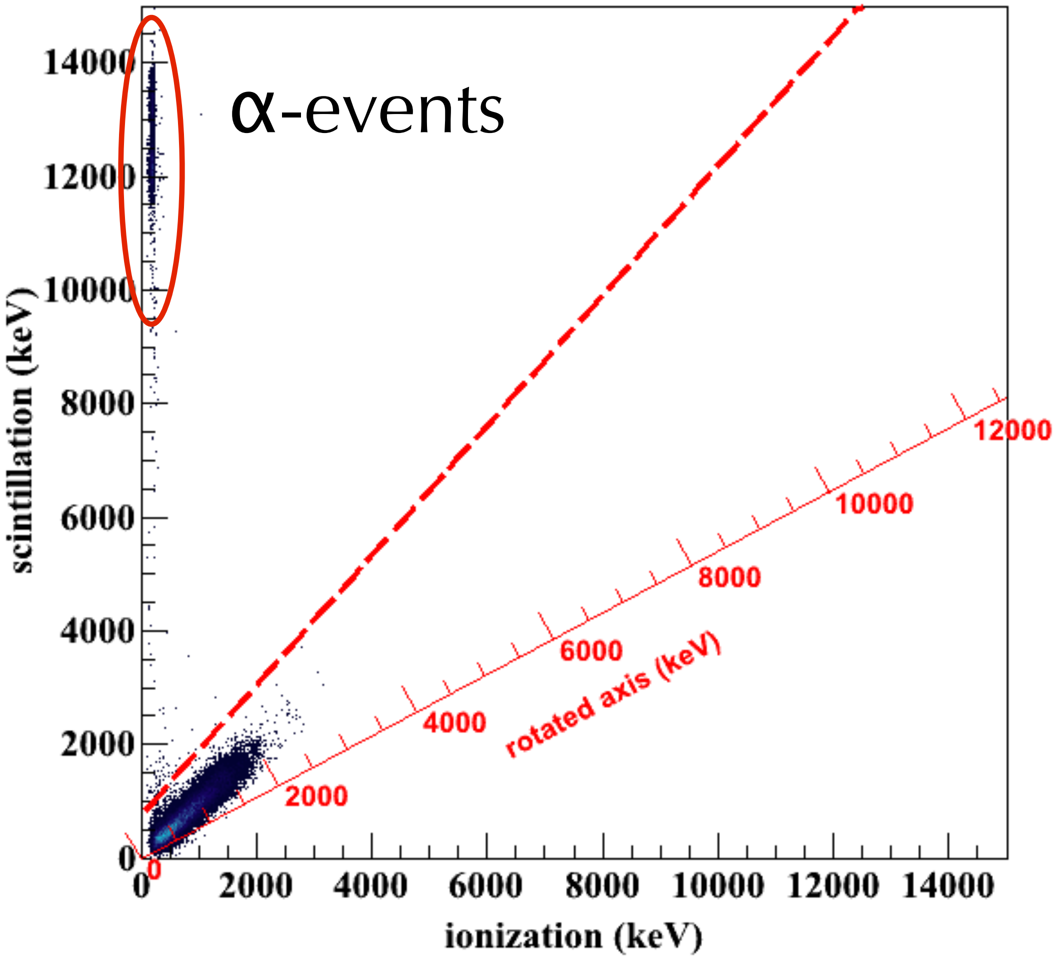
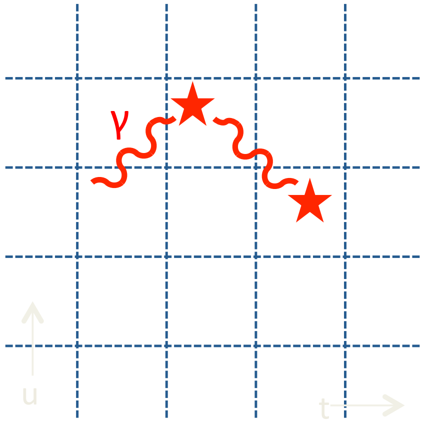
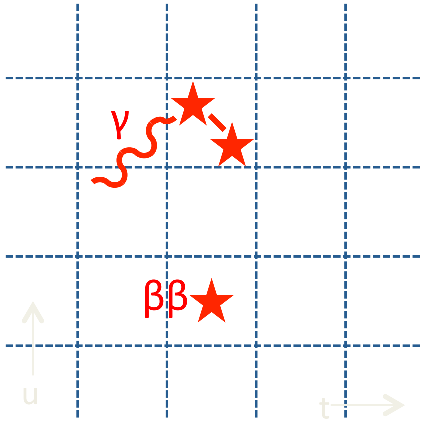
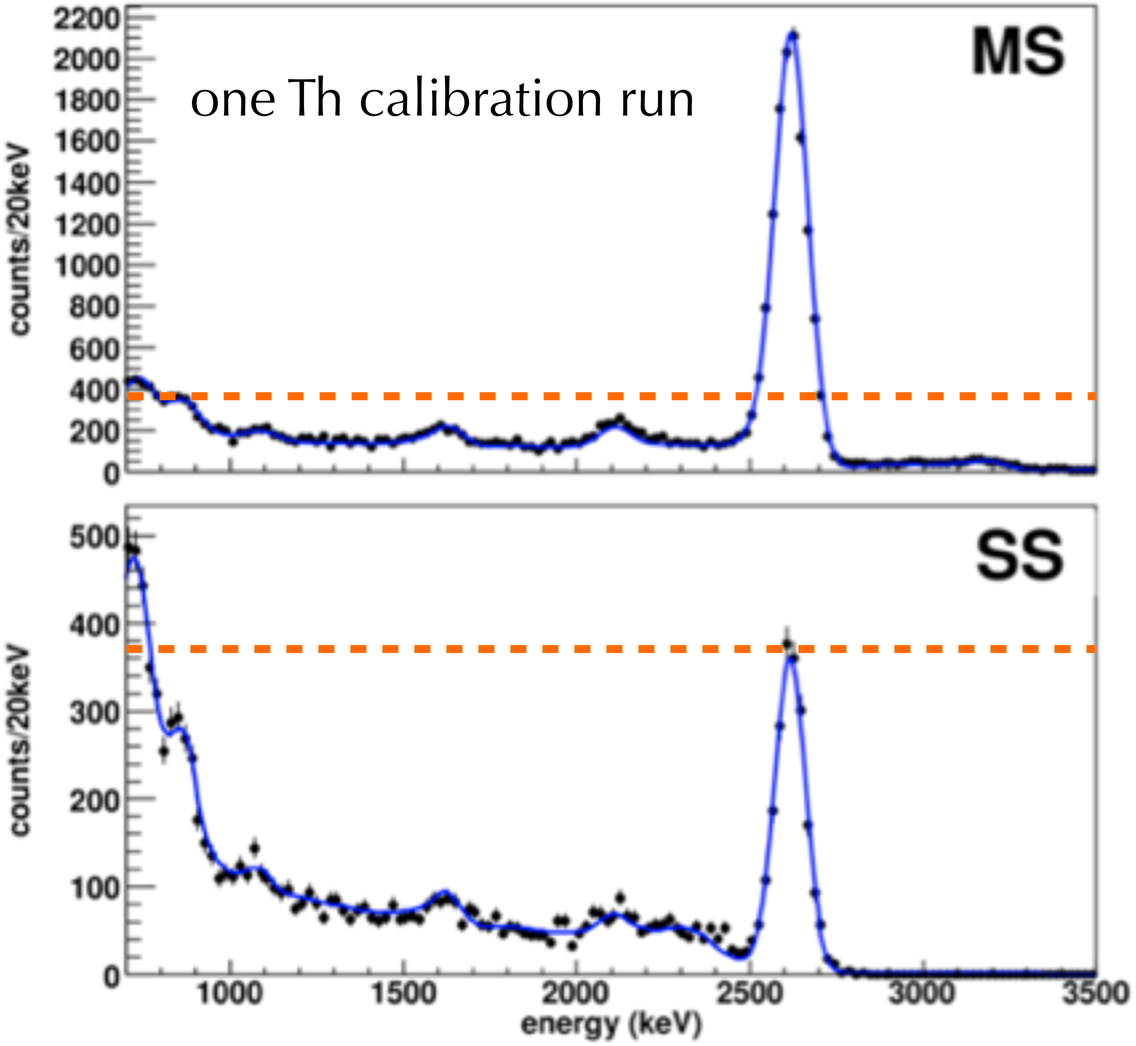


Multiple Site Events (MS)



Single Site Events (SS)





- Scint/Ionization ratio
- Single/Multi-site

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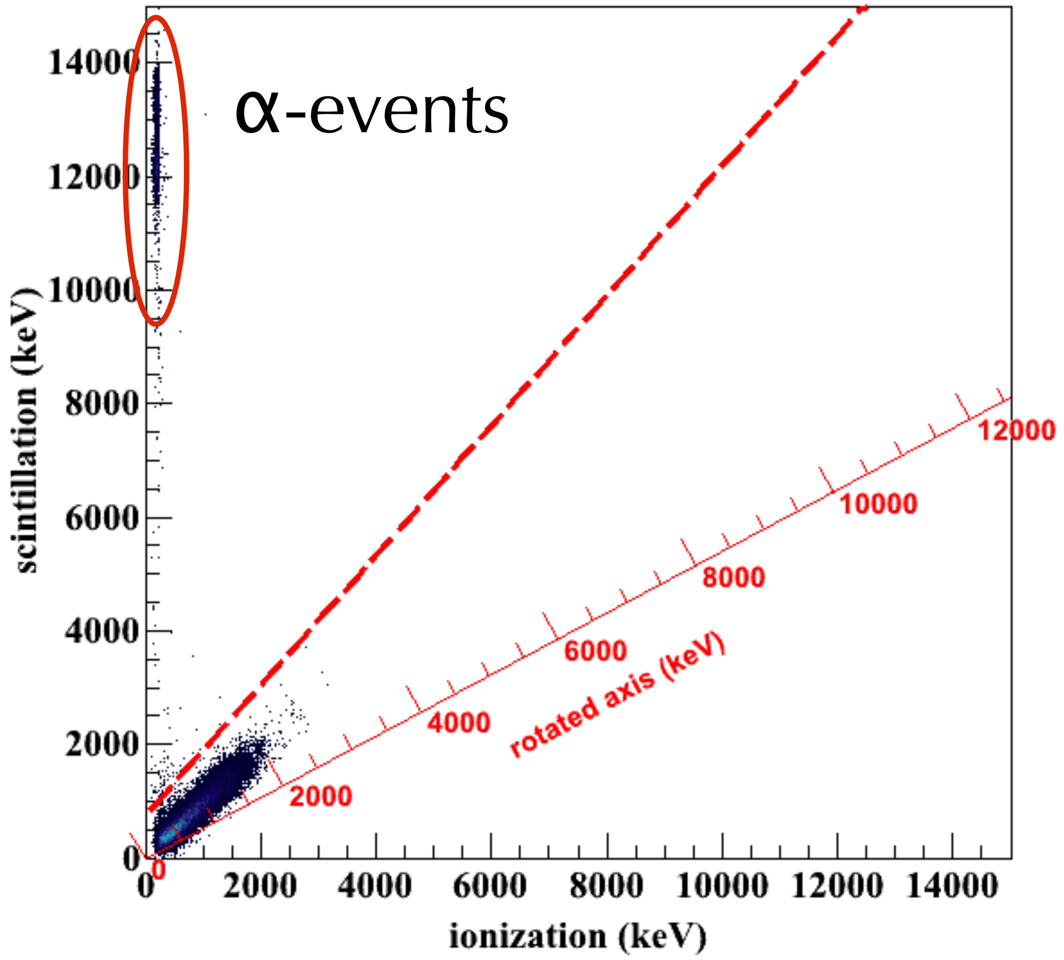
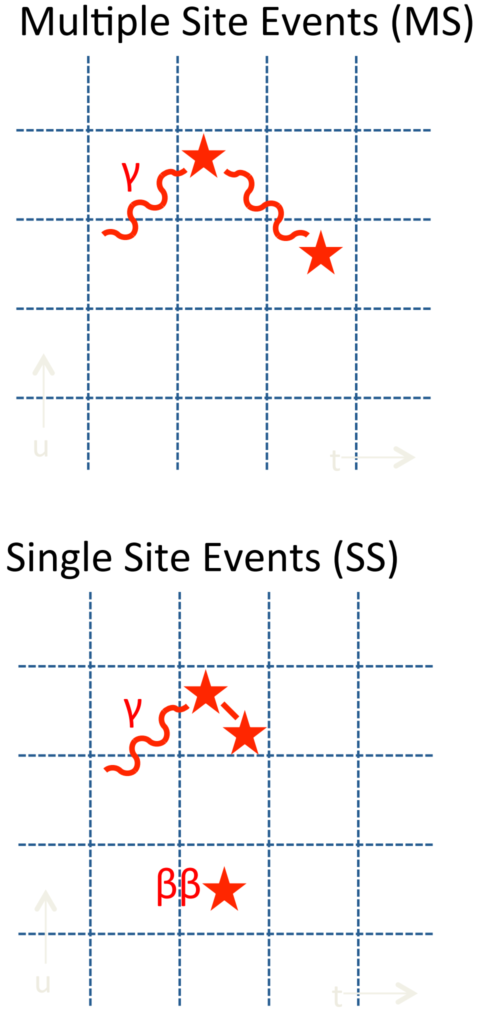
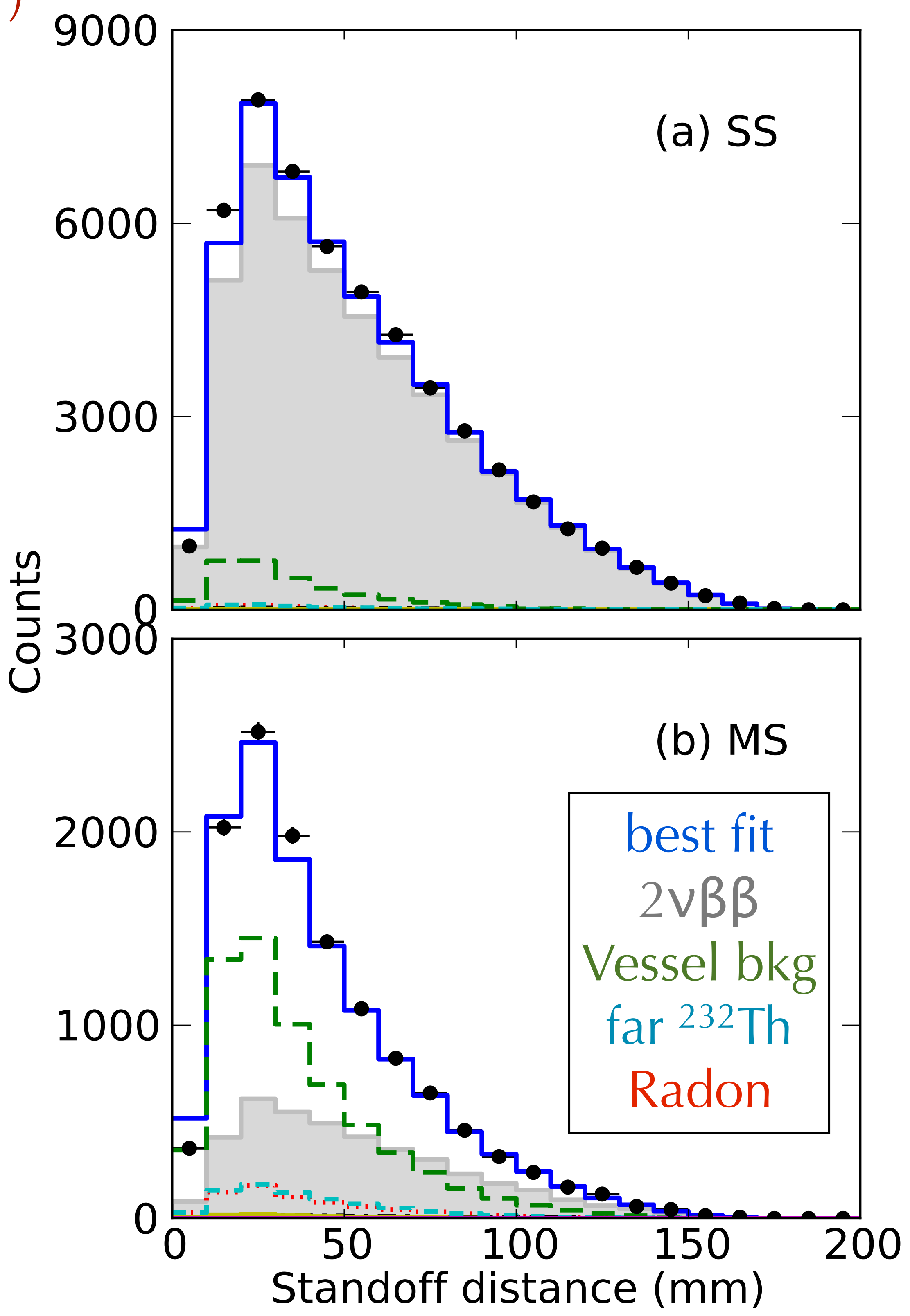
(beyond energy)







- Scint/Ionization ratio
- Single/Multi-site
- Interaction position

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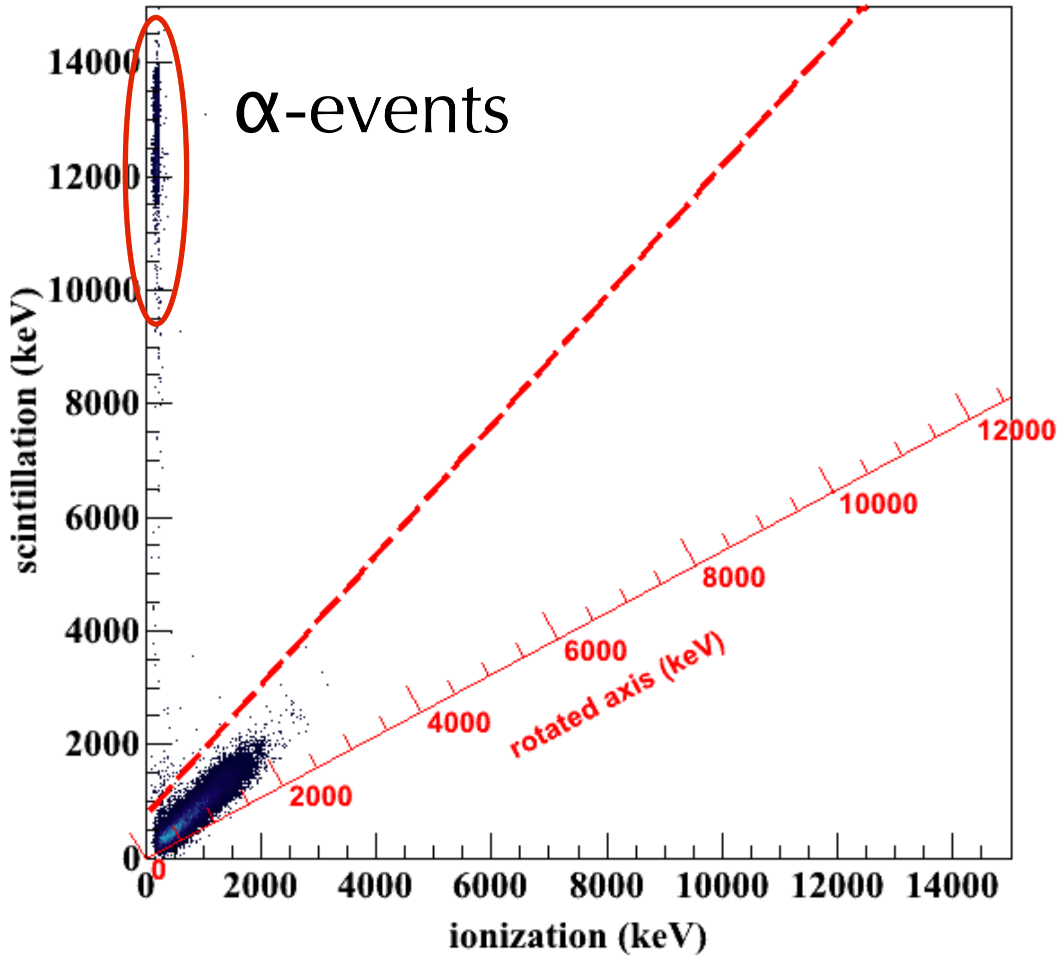
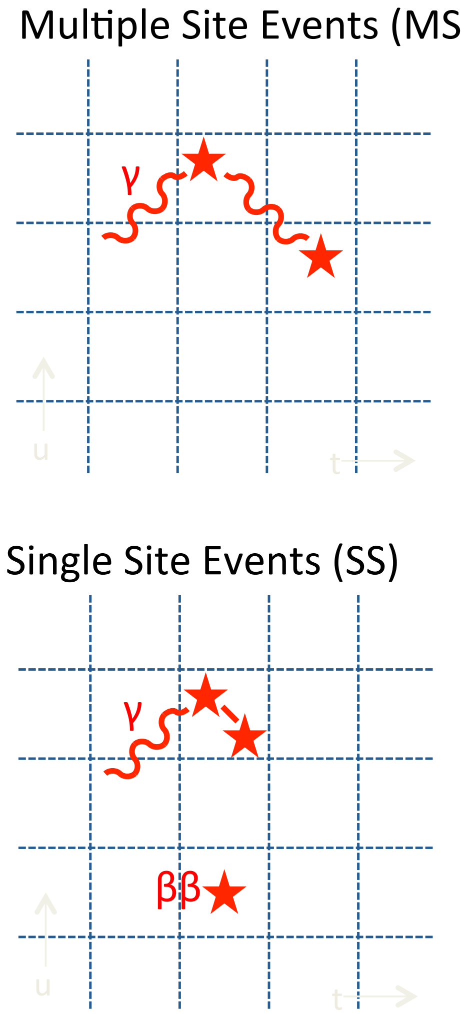
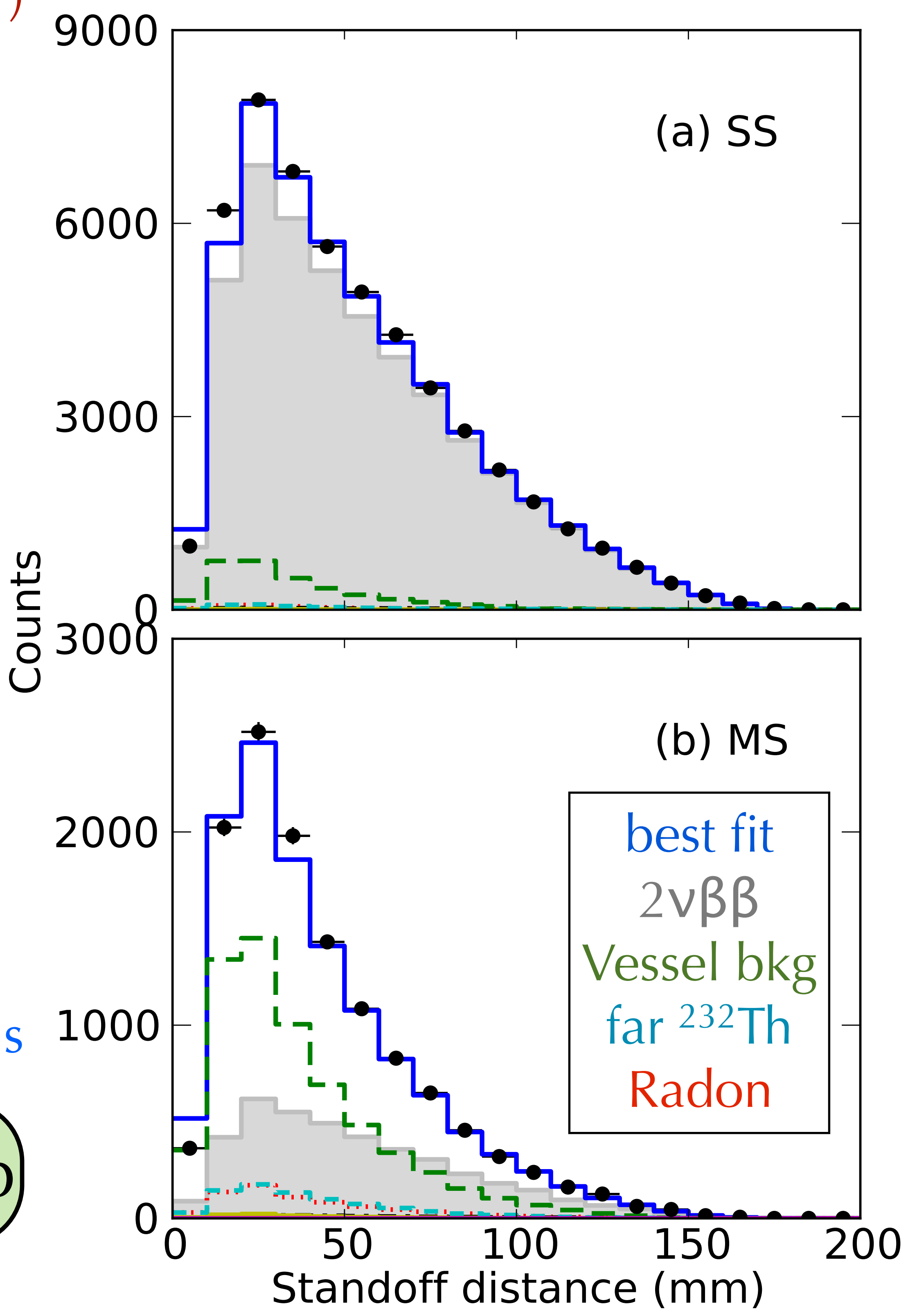
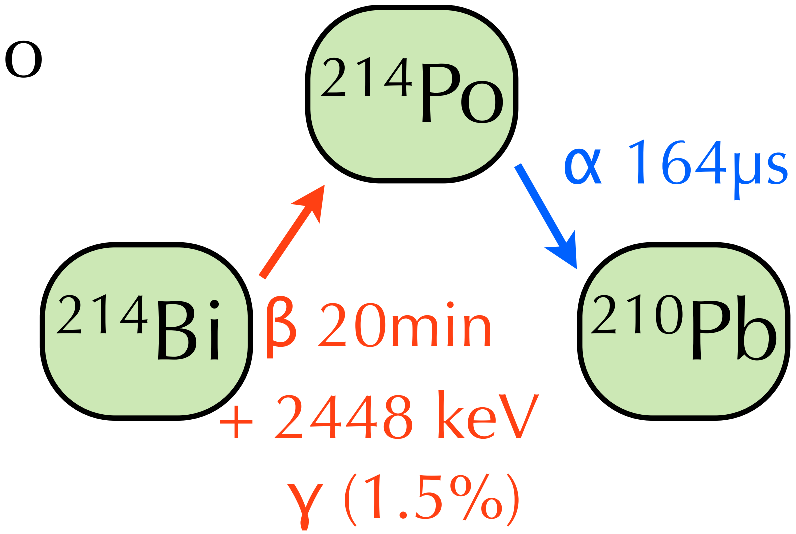
(beyond energy)



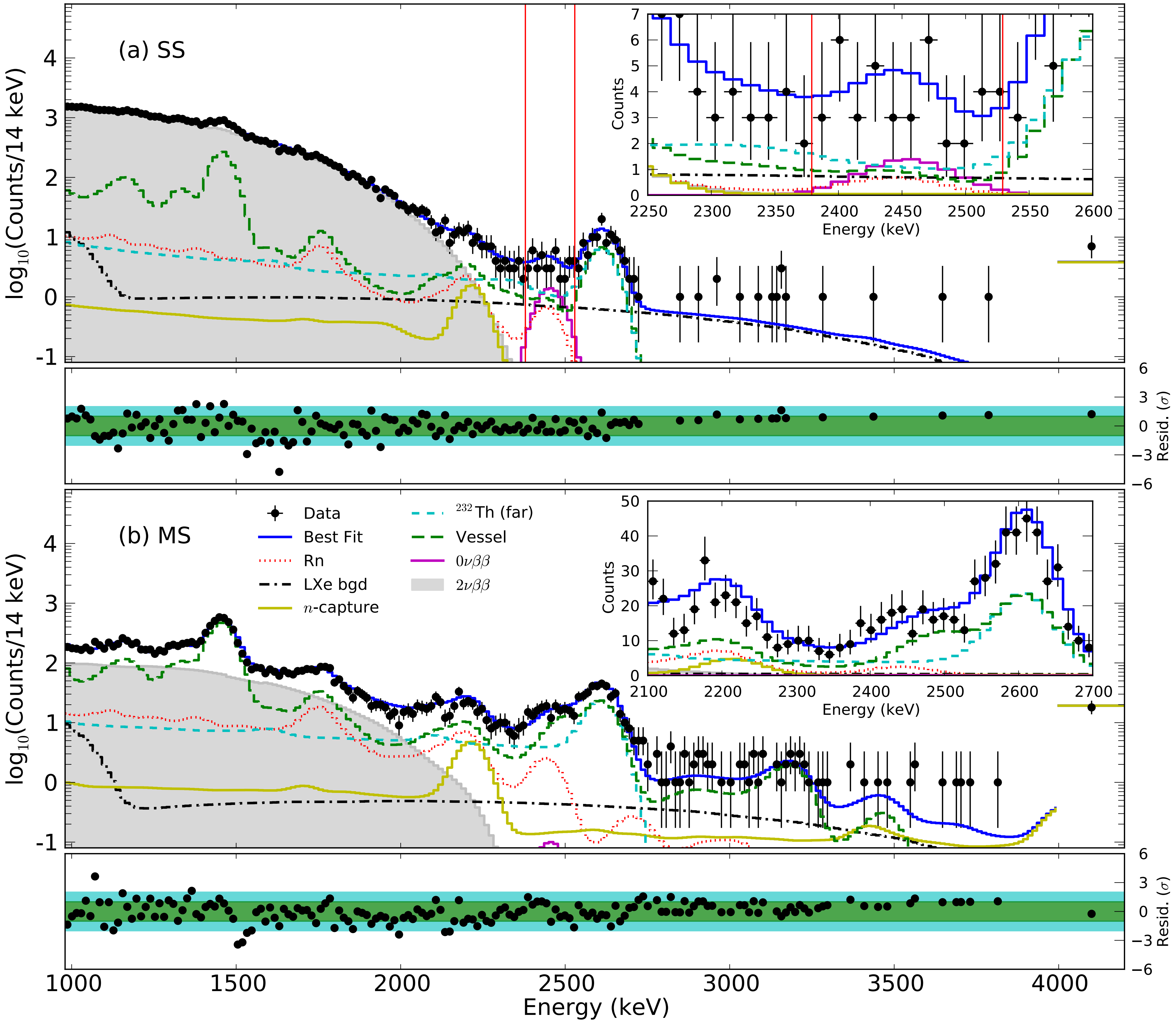






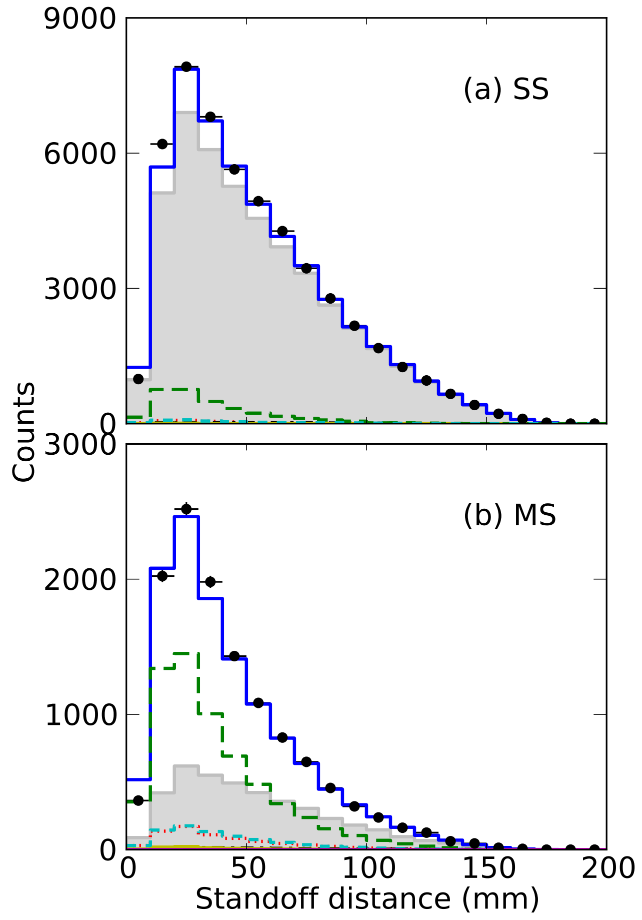
- Scint/Ionization ratio
- Single/Multi-site
- Interaction position
- Time coincidence

# Phase I results

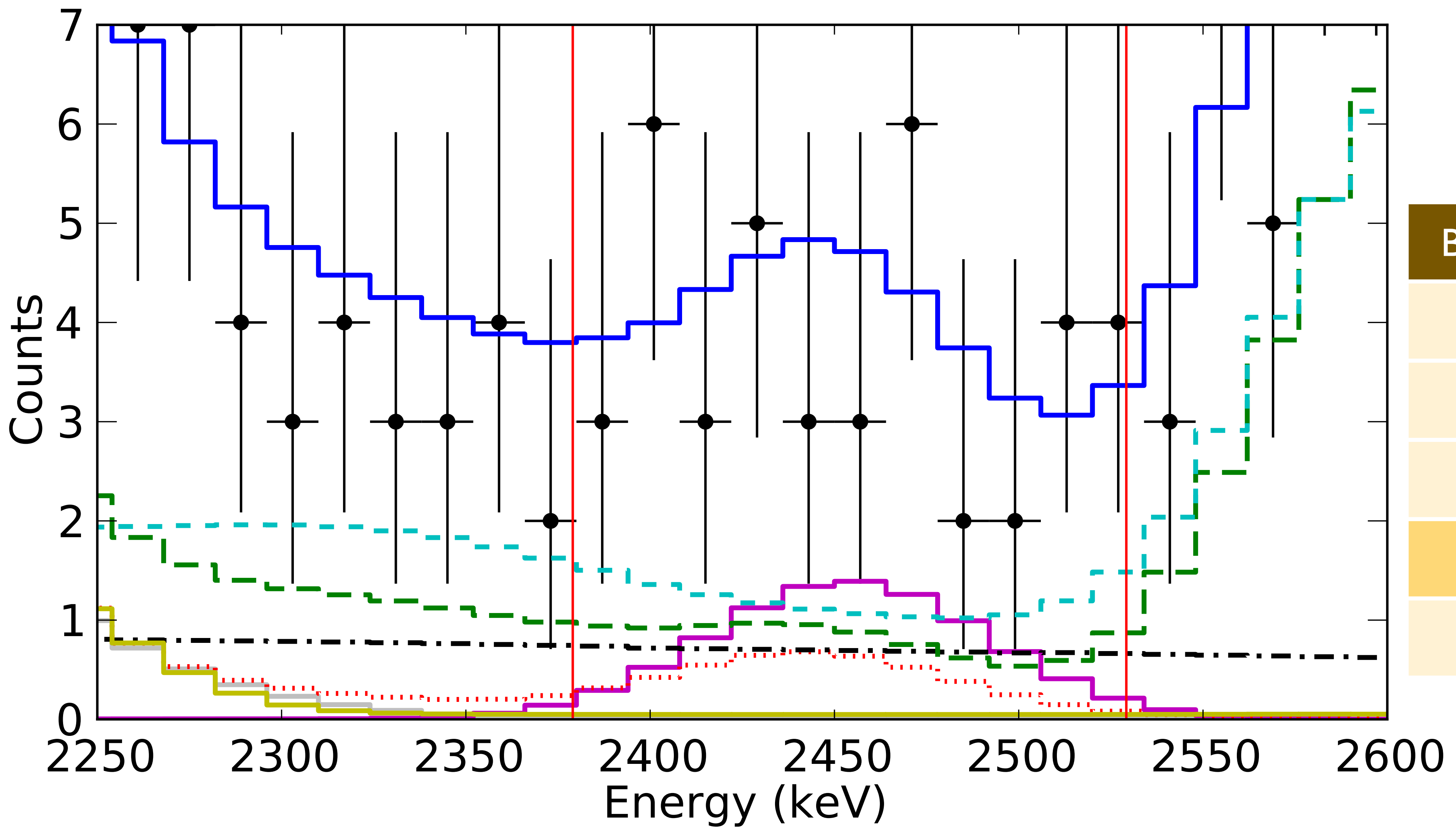


J. B. Albert et al.
(EXO-200 Collaboration),
Nature 510, 229 (2014)

- Final fit to 477.6 days data (full run 2 dataset, 123.7 kg-yr)



# Phase I results

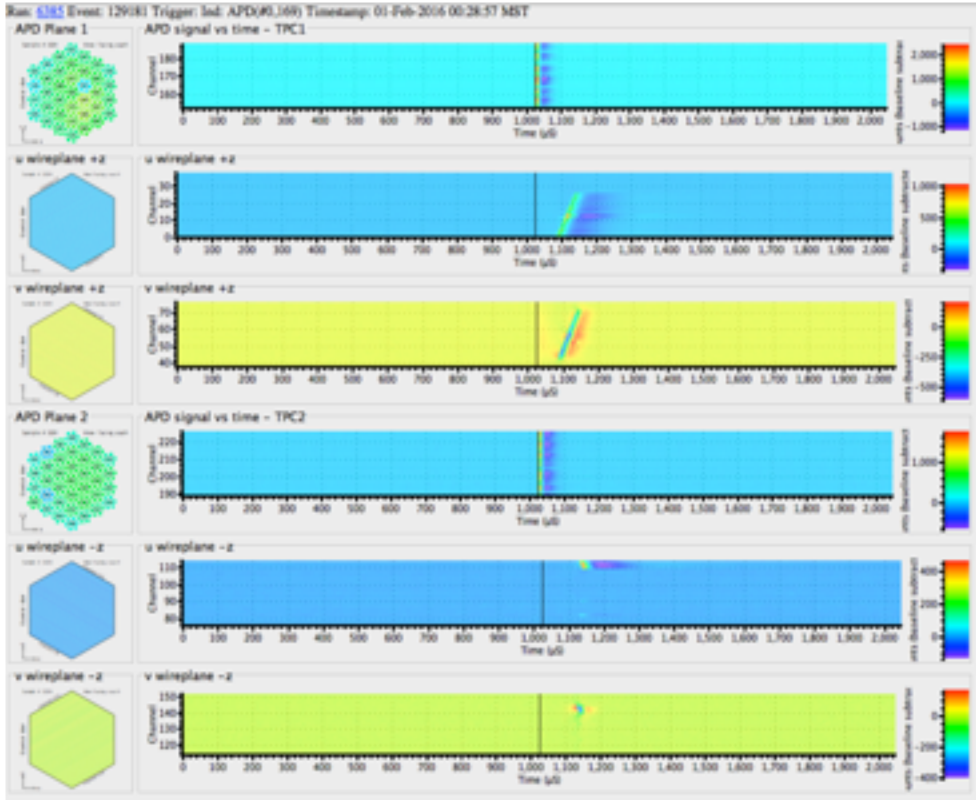


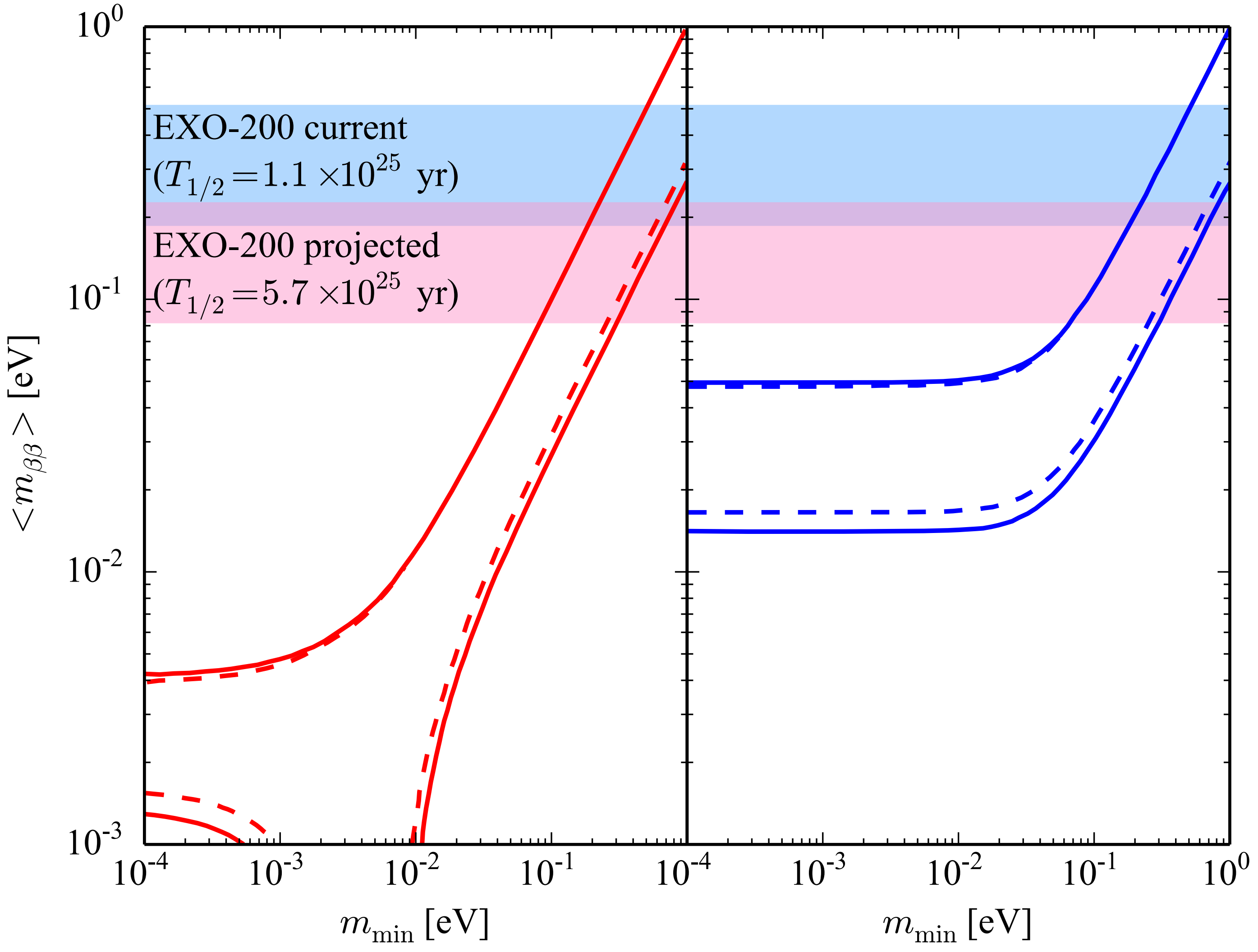
| | Fitted events |
|---|---|
| Background type | ±2σ |
| $^{238}$U chain | 8.1 |
| $^{232}$Th chain | 16.0 |
| $^{137}$Xe | 7.0 |
| Total | 31.1±3.8 |
| Observed | 39 |

- 0νββ best fit 9.9 events, consistent with zero at 1.2σ
- Limit: $t_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}$ years
- Sensitivity: $t_{1/2}^{0\nu\beta\beta} > 1.9 \times 10^{25}$ years
- Mass limit: $\langle m_{\beta\beta} \rangle < 190\text{–}450$ meV

# EXO-200 Phase II

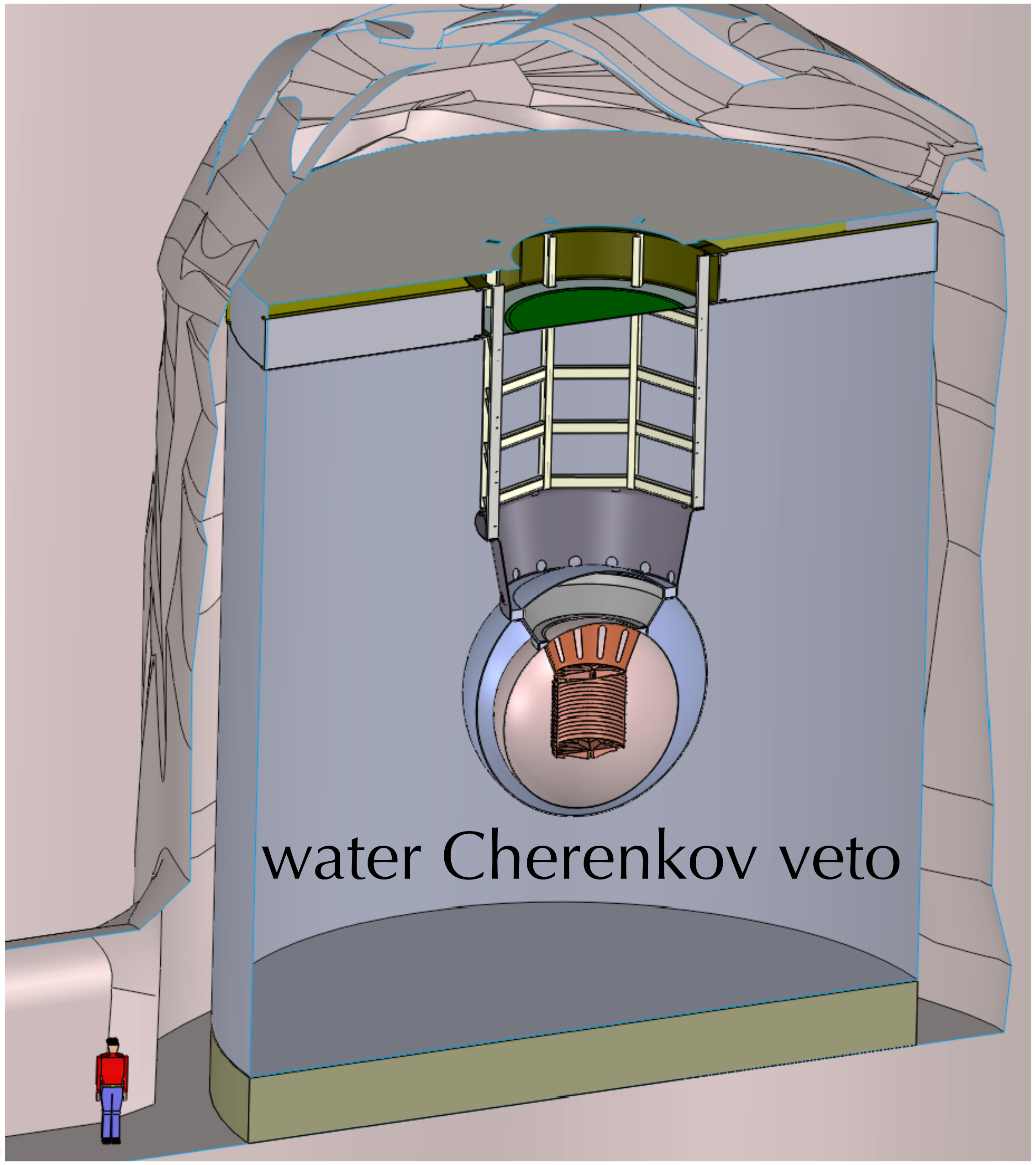
- After ~2 year hiatus due to underground access issues, EXO-200 has returned to data taking. Plan for 3-year run.
- Upgraded electronics will allow for better energy resolution (1.53%→~1%?)
- New analysis techniques will allow for further background reduction.
- Radon reduction system.

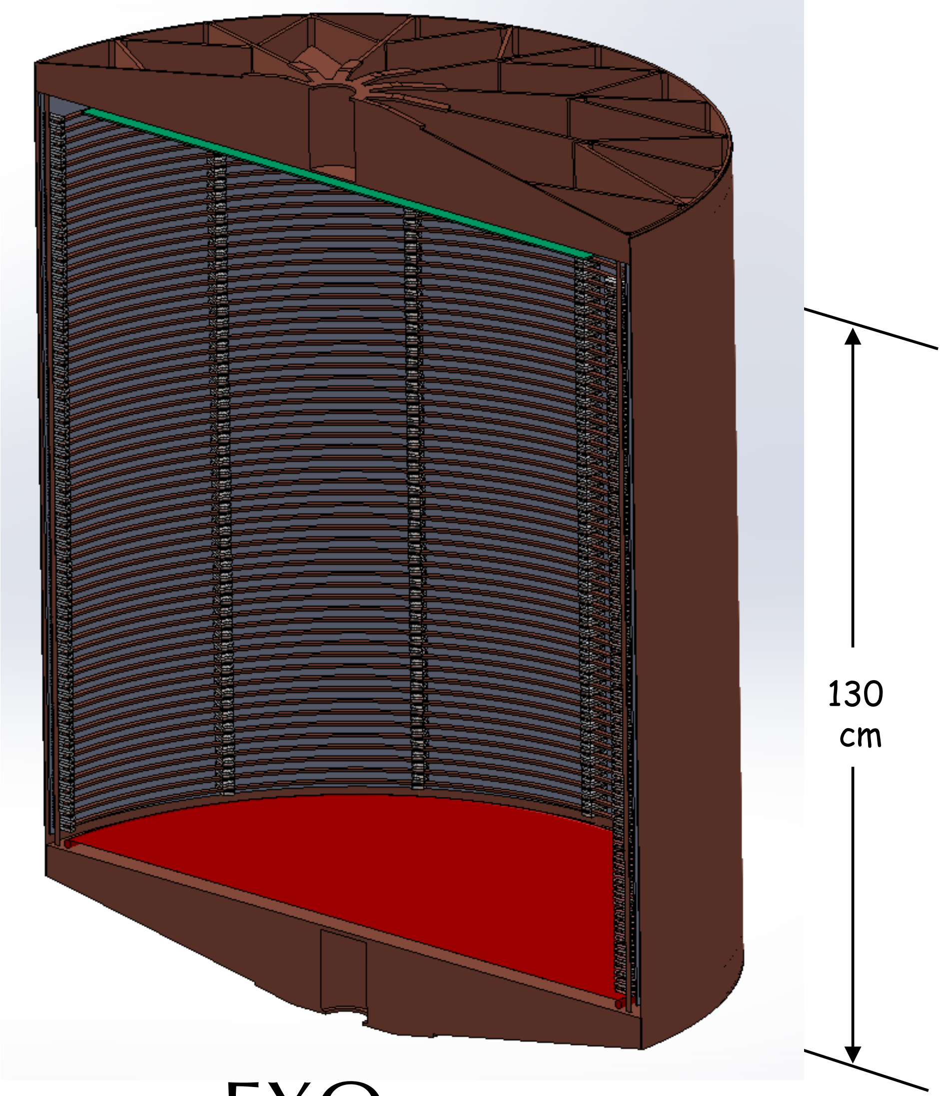




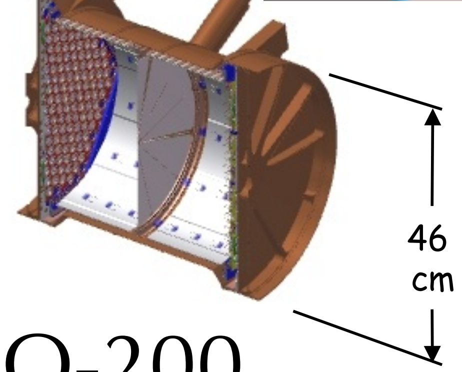
# EXO future: nEXO

- 5000 kg LXe TPC
- Tentatively at SNOlab cryopit



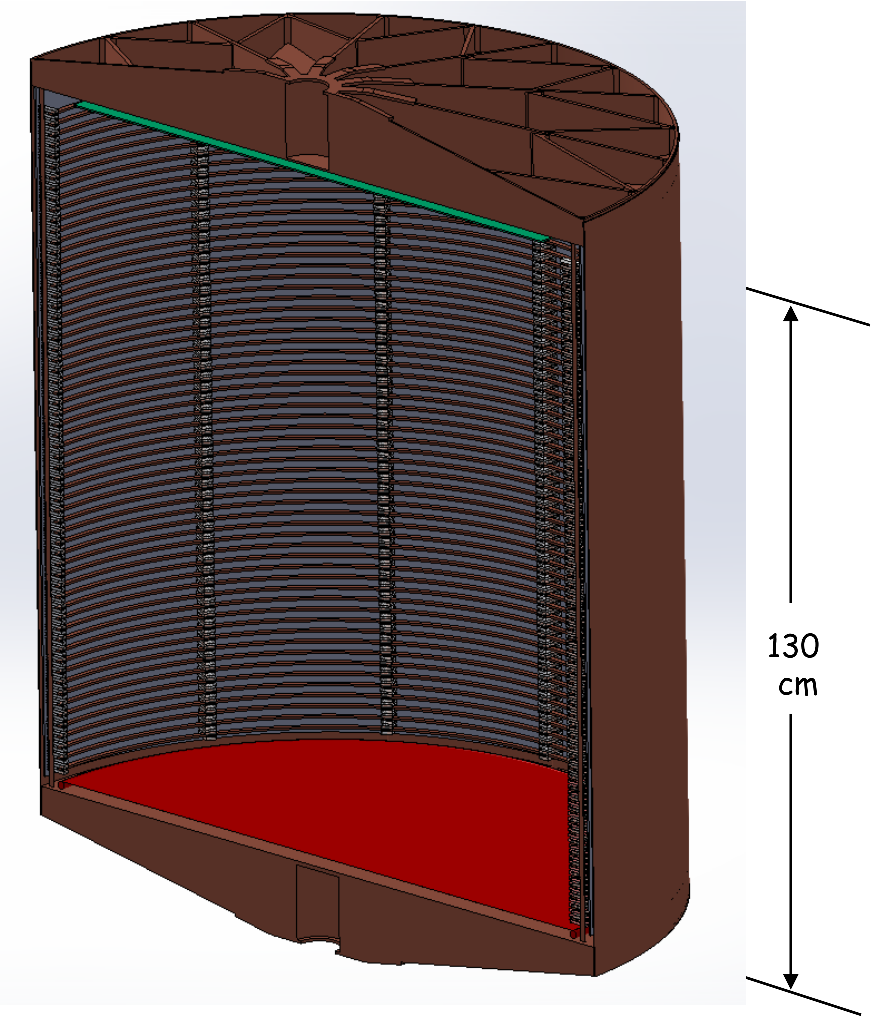


nEXO

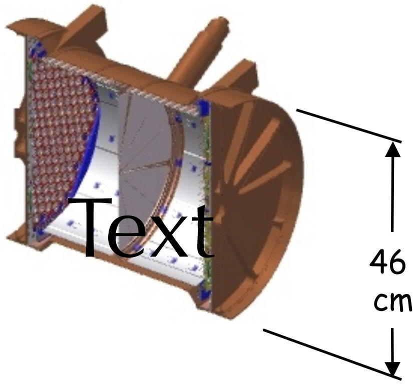


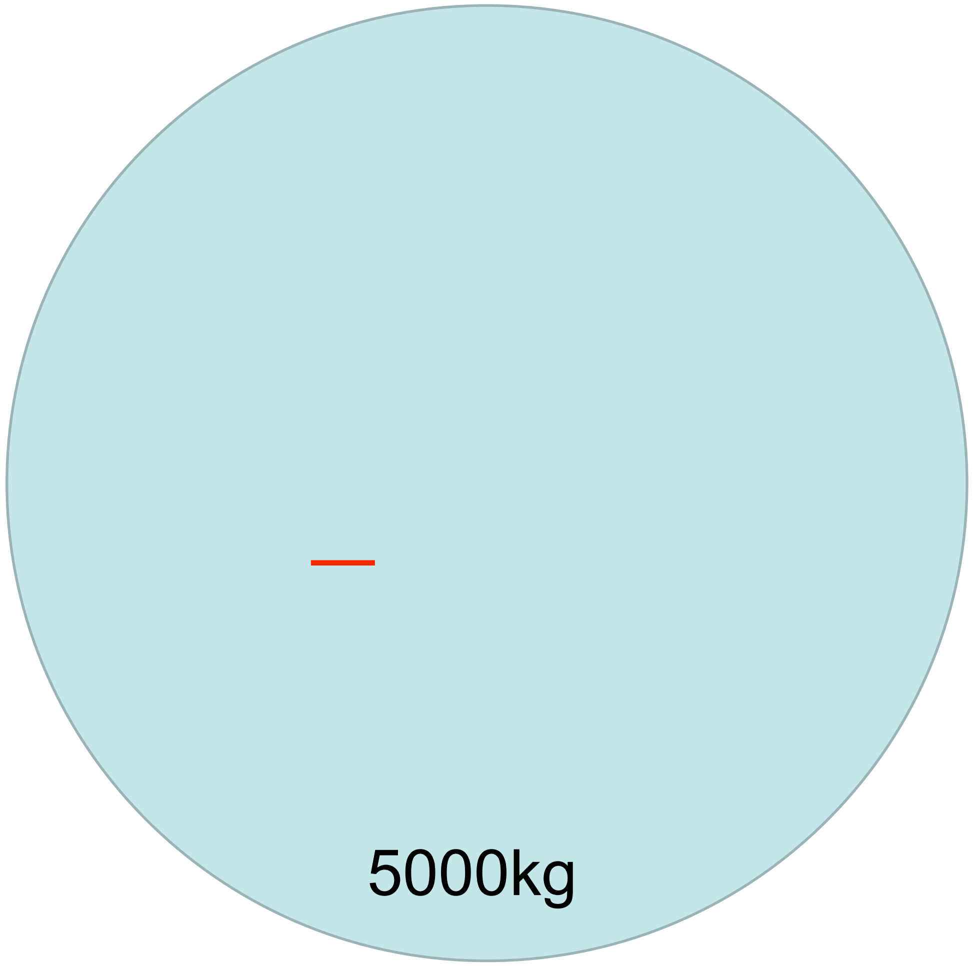
EXO-200

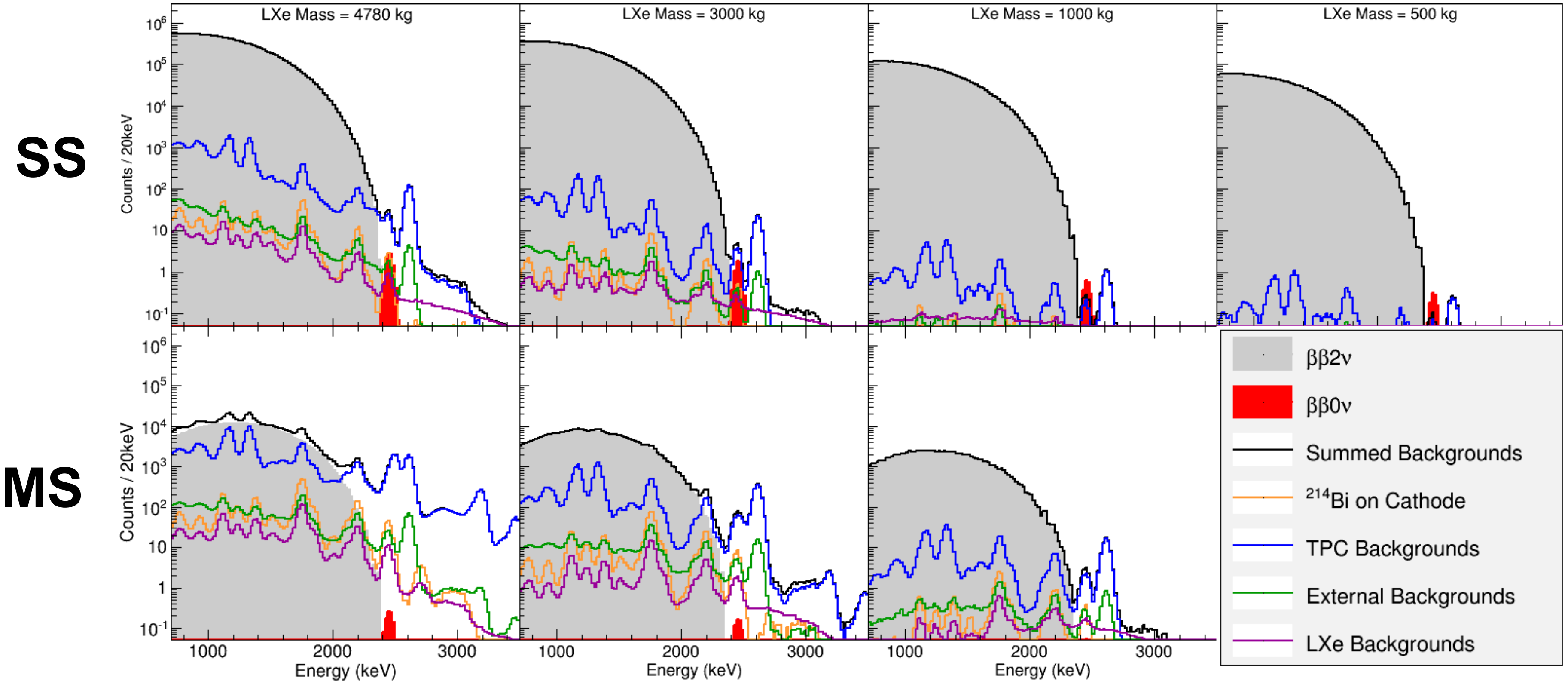
# nEXO



2.5MeV γ
attenuation length
8.5cm = —





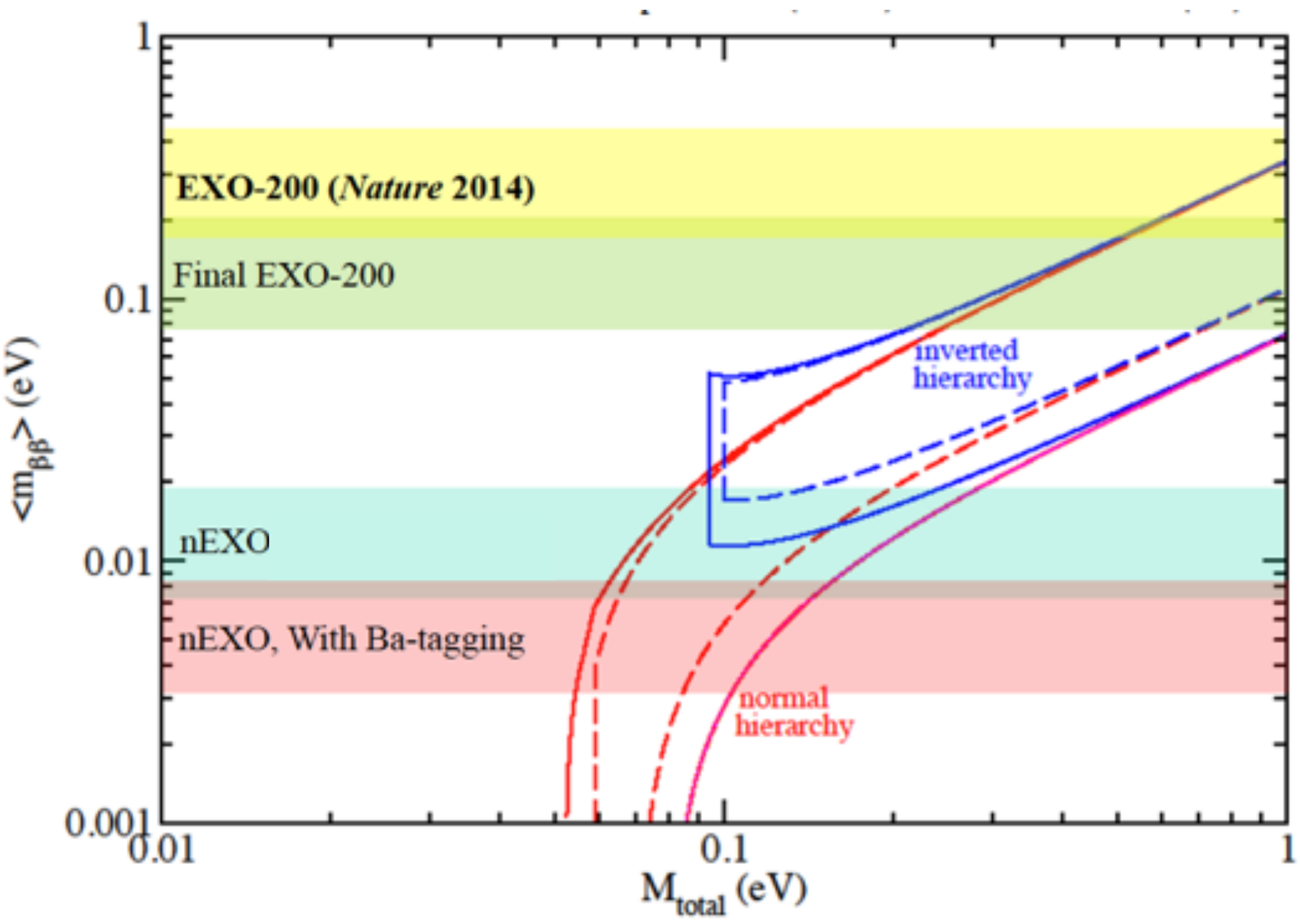


- Huge gains from self-shielding, monolithic detector
- No mystery γs
- Simultaneous fit

5 yr simulated data, 0νββ corresponds to $T^{1/2}=6.6\text{x}10^{27}$ yr

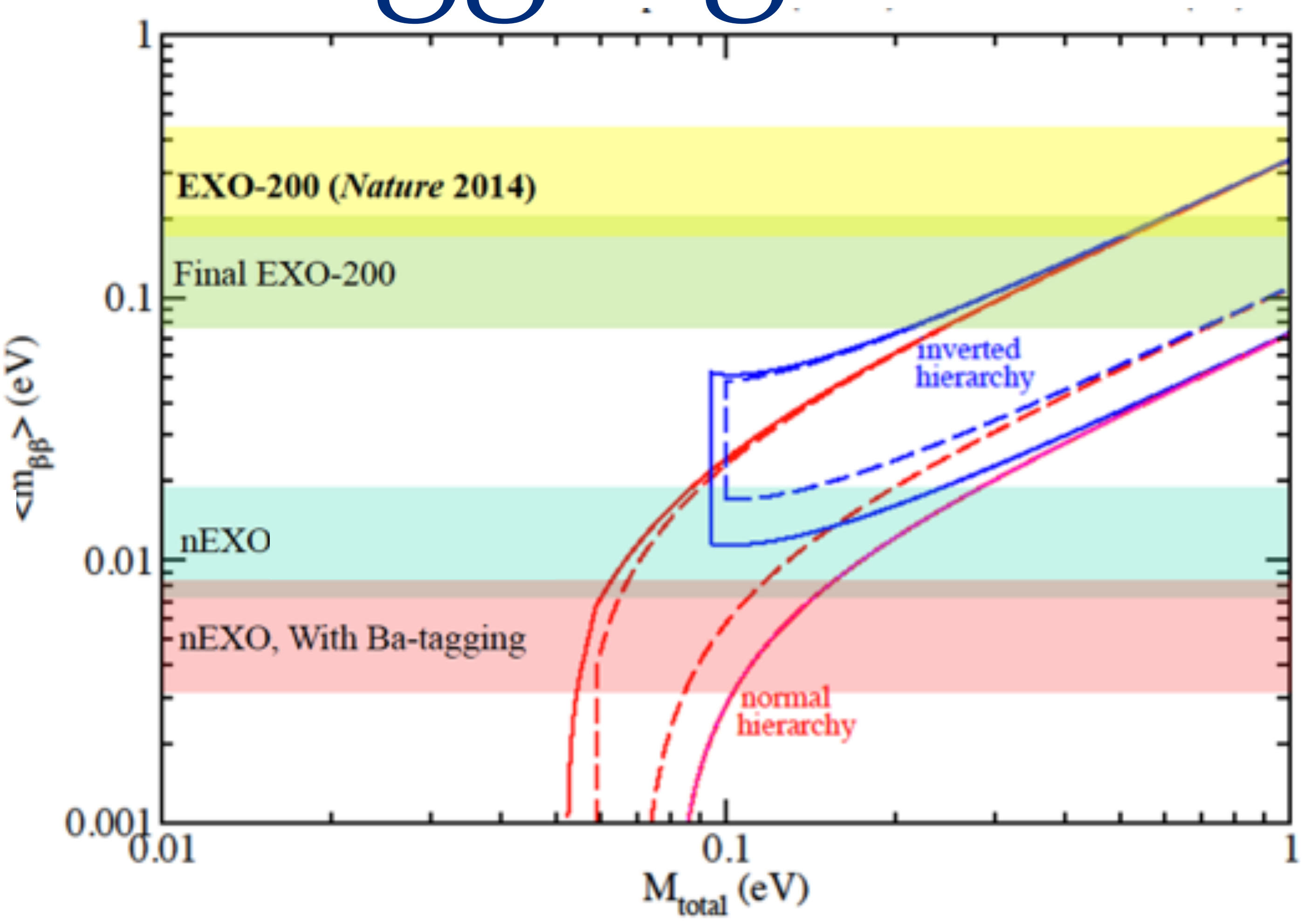
# nEXO

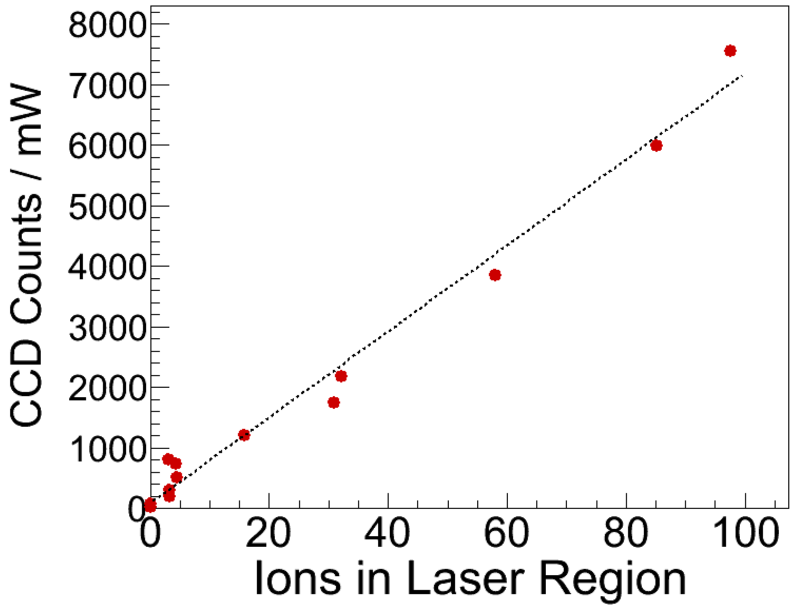
- SNOlab → negligible cosmogenics
- Improved energy and position resolution
- Cover inverted hierarchy, or beyond
- Large R&D effort

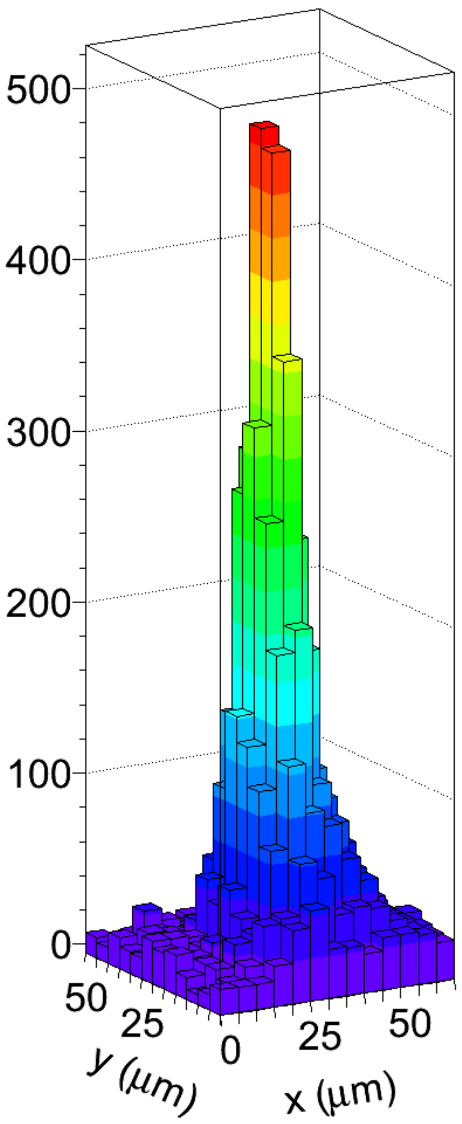


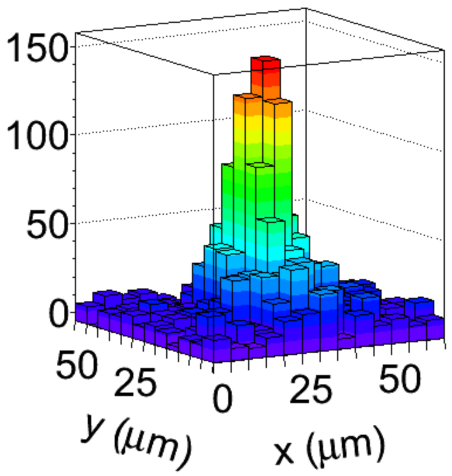
# nEXO + Ba tagging

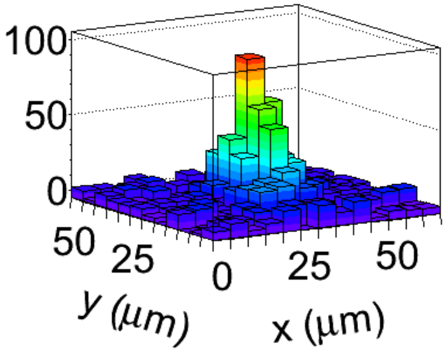
- SNOlab → negligible cosmogenics
- Improved energy and position resolution
- Cover inverted hierarchy, or beyond
- Large R&D effort
- Barium tagging?

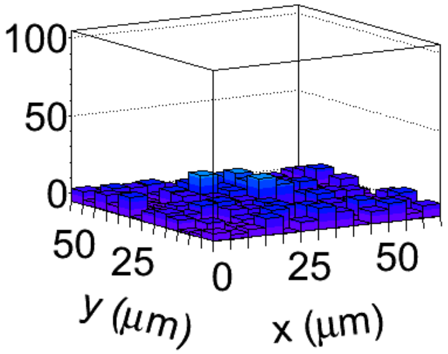





**≤ 58-atom**


**≤ 15-atom**


**≤ 4-atom**

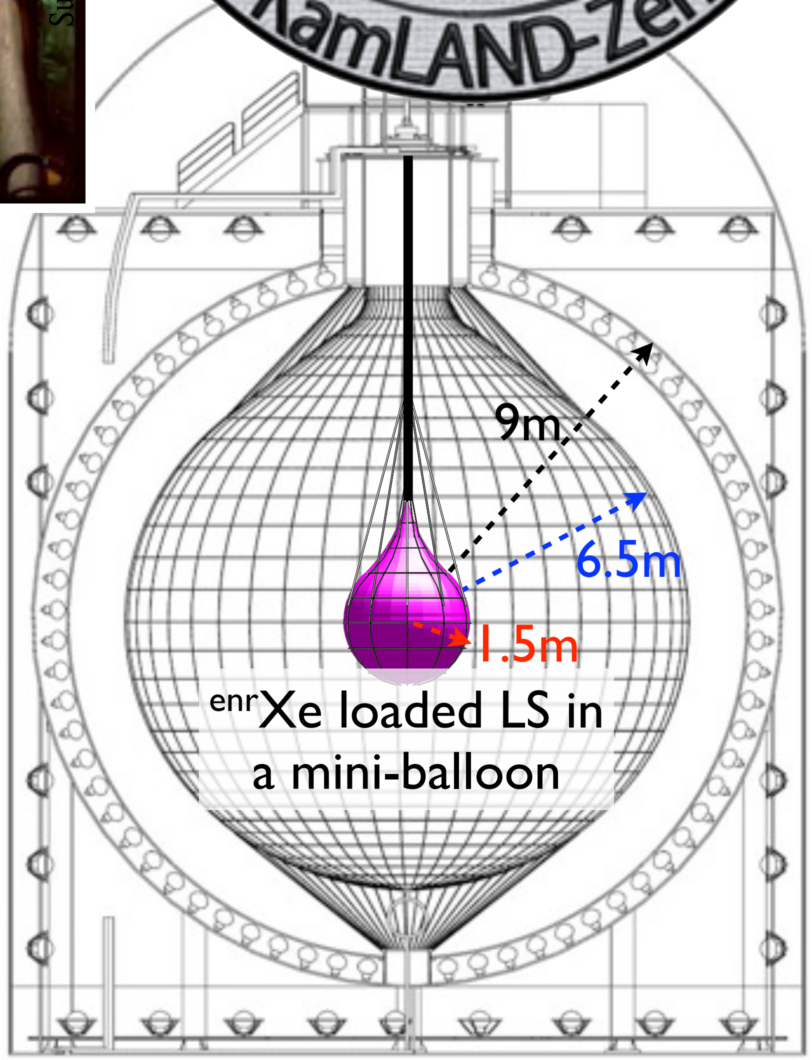

**0-atom**

# KamLAND-Zen

Technology: Liquid scintillator with PMTs
Signal from scintillation
Source is dissolved in detection medium
Isotope: $^{136}$Xe

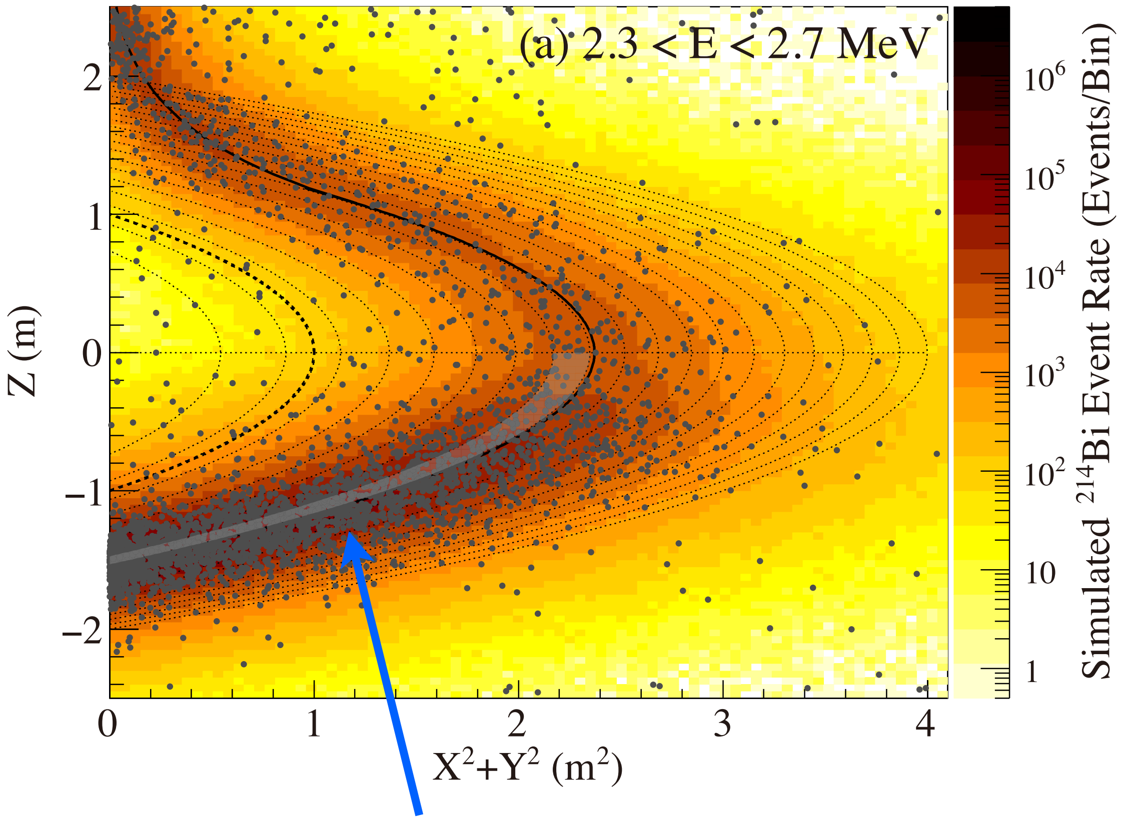
Challenges:
Relatively poor energy resolution
Currently no topological discriminators
Need extremely clean balloon

Highlights:
Very large detector gives a large active shield
Currently largest xenon mass, best limit
Well-understood detector (KamLAND)

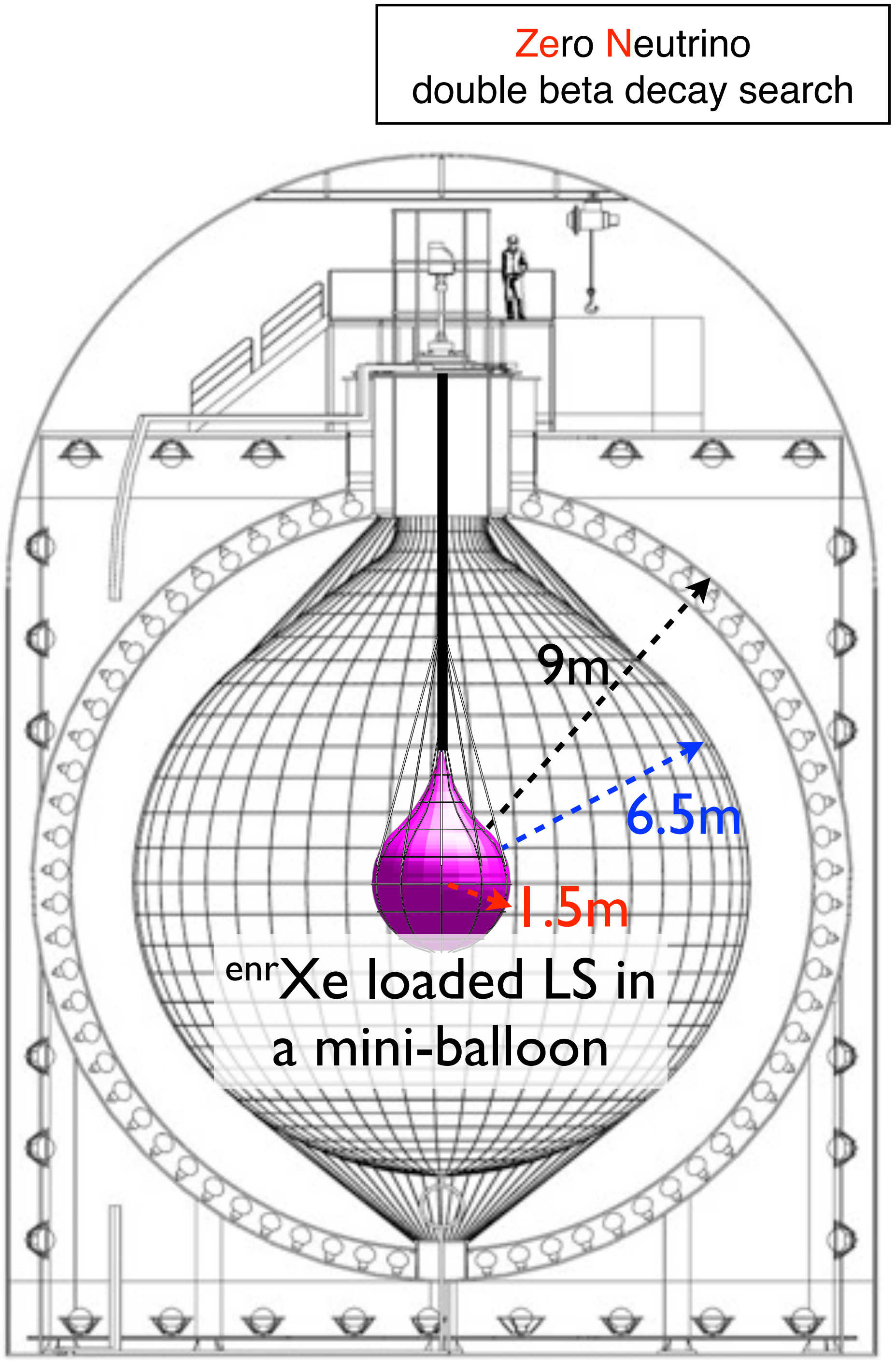


- A new mission for the KamLAND detector
- 2011-present, with significant upgrades planned
- 380 kg 90% $^{enr}$Xe so far, will run with 750 kg soon

# KamLAND-Zen



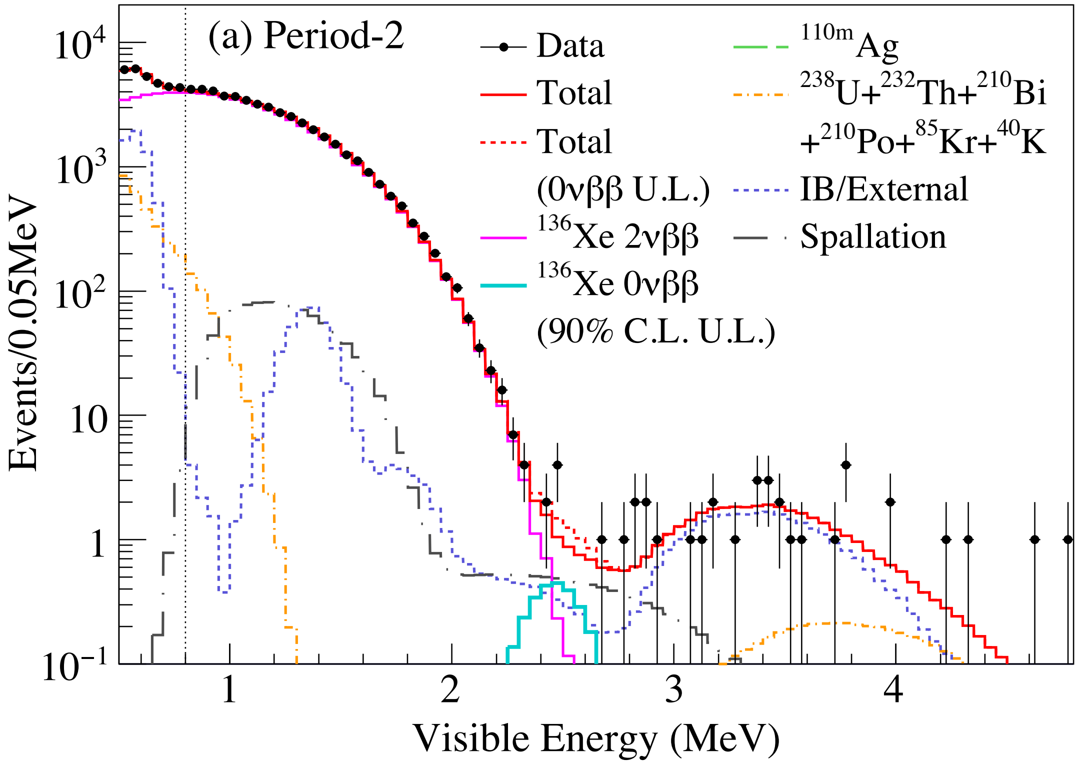
25-μm thick transparent nylon balloon

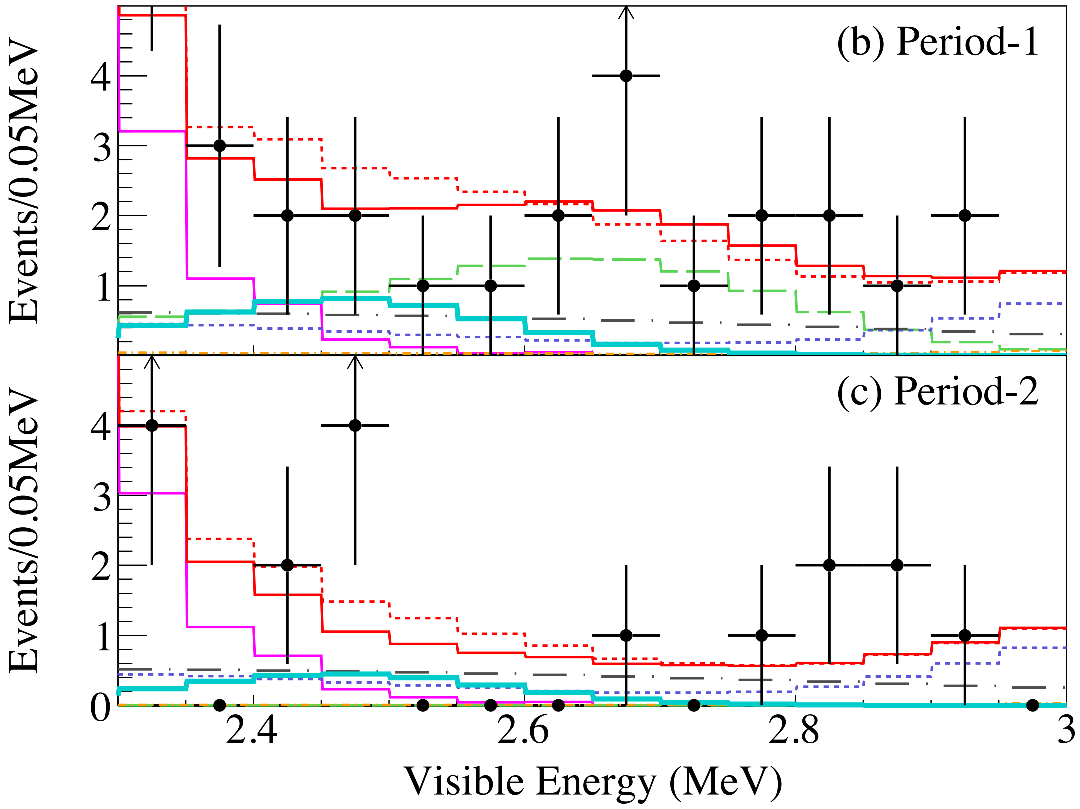


$^{enr}$Xe loaded LS in a mini-balloon

- Ultra-pure liquid scintillator, ultra-thin balloon, and large buffer volume → low backgrounds
- Position-based analysis greatly improves background identification and suppression
- Spallation backgrounds reduced through coincidence cuts

# KZ backgrounds



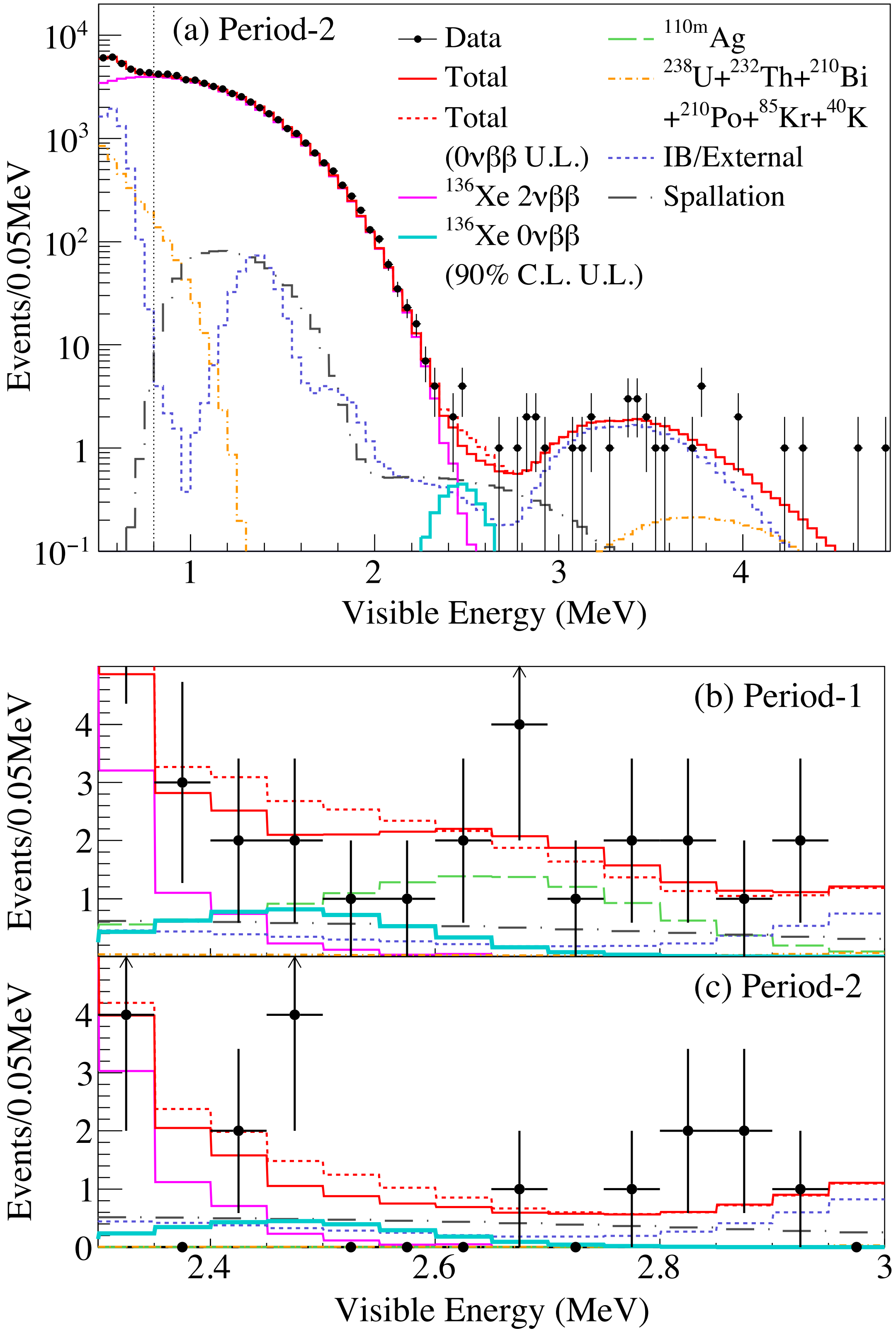


- Initial run hampered by $^{110m}$Ag contamination
- After cleaning and re-purification, much lower backgrounds
- $^{214}$Bi on balloon, 2νββ, and cosmogenic $^{10}$C dominate

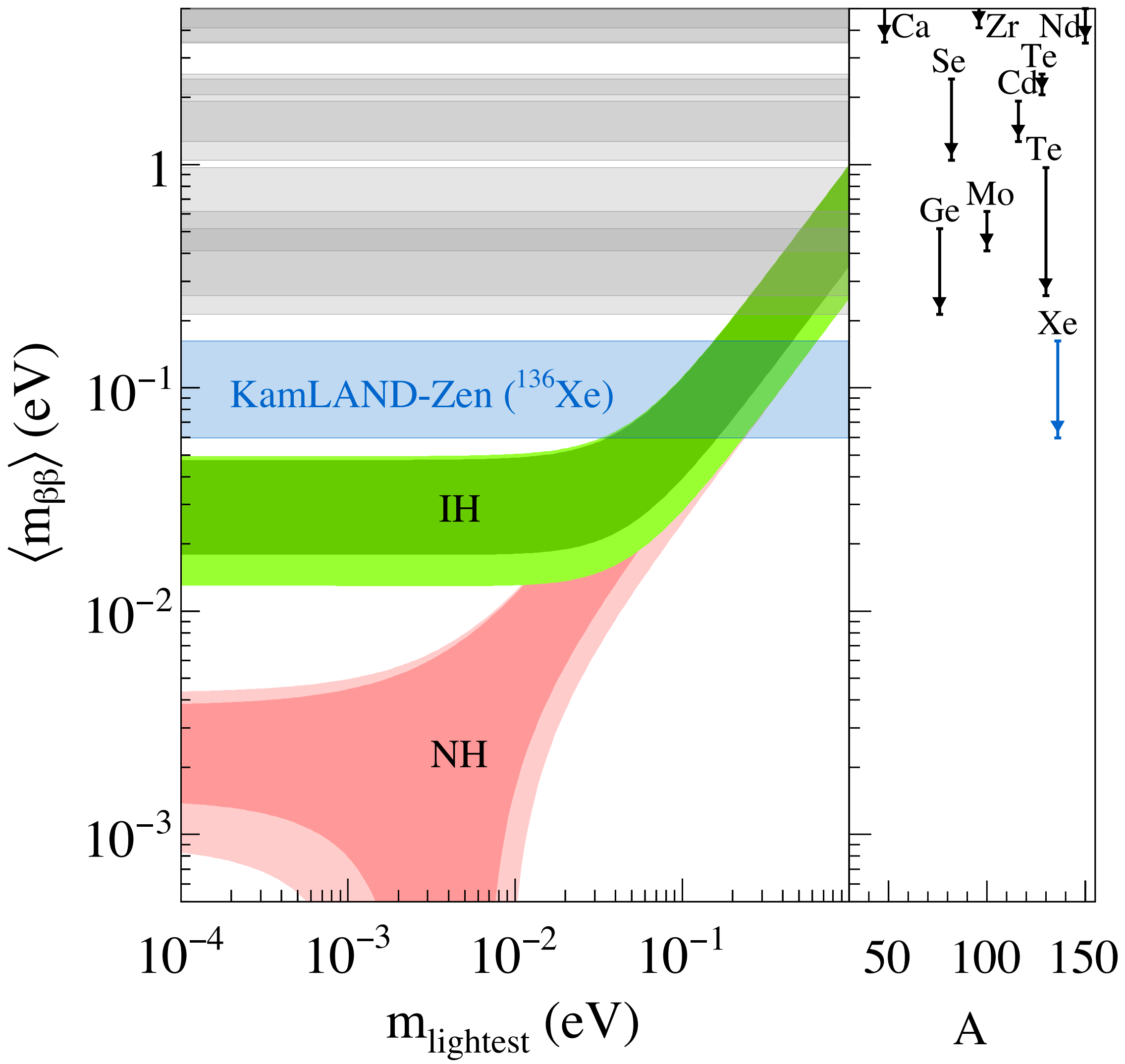
Event summary $2.3 < E < 2.7$ MeV, $R < 1$ m

| | Period-1 (270.7 days) | | Period-2 (263.8 days) | |
|---|---|---|---|---|
| Observed events | 22 | | 11 | |
| Background | Estimated | Best-fit | Estimated | Best-fit |
| $^{136}$Xe $2\nu\beta\beta$ | - | 5.48 | - | 5.29 |
| Residual radioactivity in Xe-LS | | | | |
| $^{214}$Bi ($^{238}$U series) | $0.23 \pm 0.04$ | 0.25 | $0.028 \pm 0.005$ | 0.03 |
| $^{208}$Tl ($^{232}$Th series) | - | 0.001 | - | 0.001 |
| $^{110m}$Ag | - | 8.0 | - | 0.002 |
| External (Radioactivity in IB) | | | | |
| $^{214}$Bi ($^{238}$U series) | - | 2.55 | - | 2.45 |
| $^{208}$Tl ($^{232}$Th series) | - | 0.02 | - | 0.03 |
| $^{110m}$Ag | - | 0.002 | - | 0.001 |
| Spallation products | | | | |
| $^{10}$C | $2.7 \pm 0.7$ | 3.2 | $2.6 \pm 0.7$ | 2.7 |
| $^{6}$He | $0.07 \pm 0.18$ | 0.08 | $0.07 \pm 0.18$ | 0.08 |
| $^{12}$B | $0.15 \pm 0.04$ | 0.16 | $0.14 \pm 0.04$ | 0.15 |
| $^{137}$Xe | $0.9 \pm 0.5$ | 1.1 | $0.9 \pm 0.5$ | 0.8 |

# KZ results



- Downward fluctuation→ stronger limit
- Limit: $t_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{26}$ years
- Sensitivity: $t_{1/2}^{0\nu\beta\beta} > 4.9 \times 10^{25}$ years
- Mass limit: $\langle m_{\beta\beta} \rangle < 60 - 121$ meV



# KZ Future

- Larger balloon, 750 kg Xenon →KamLAND-Zen 800
  - Cleaner, larger balloon

# KZ Future

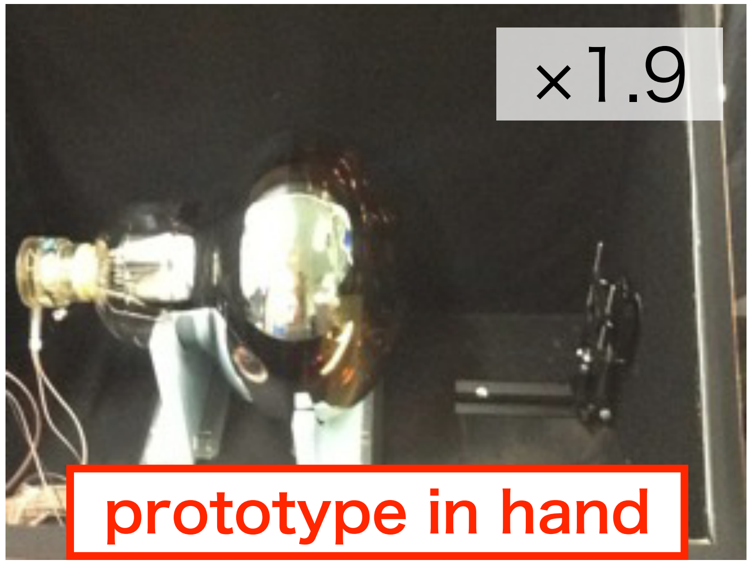
- Larger balloon, 750 kg Xenon
→KamLAND-Zen 800
  - Cleaner, larger balloon
- Improve energy resolution (4.5% → ~2%)
  - HQE PMT, winston cones
  - decane/pseudocumene
→linear alkylbenzene

○ winston cone

×1.8

succeeded with prototype

○ HQE-PMT



×1.9

prototype in hand

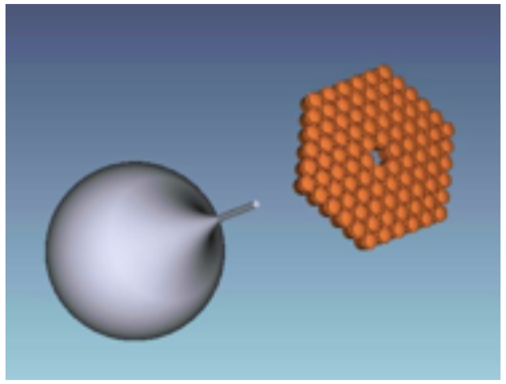
# KZ Future

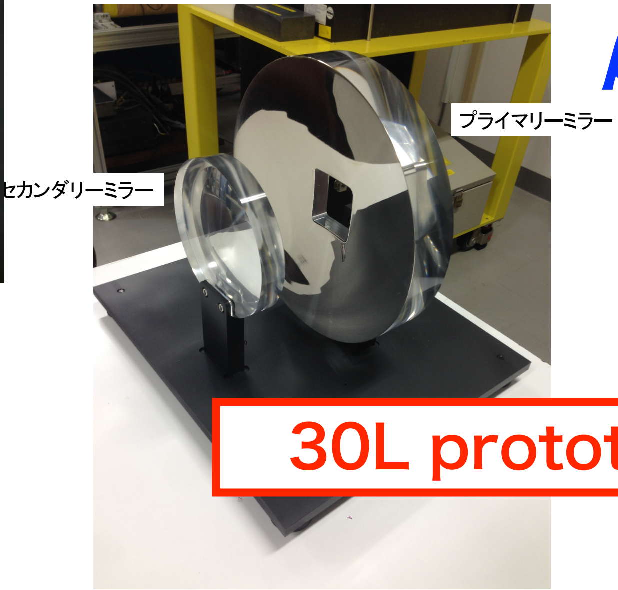
- Larger balloon, 750 kg Xenon →KamLAND-Zen 800
    - Cleaner, larger balloon
- Improve energy resolution (4.5% → ~2%)
    - HQE PMT, winston cones
    - decane/pseudocumene →linear alkylbenzene
- Scintillating balloon film
- Denser xenon
- Imaging system (for SS/MS)
- Target sensitivity for KamLAND2-Zen: $m_{\beta\beta} < 20$ meV

○ winston cone

succeeded with prototype

○ imaging





$\beta$ / $\gamma$ id.

30L prototype

# MAJORANA/GERDA

Technology: Cryogenic germanium crystals
Signal from ionization
Source is detection medium
Isotope: $^{76}$Ge

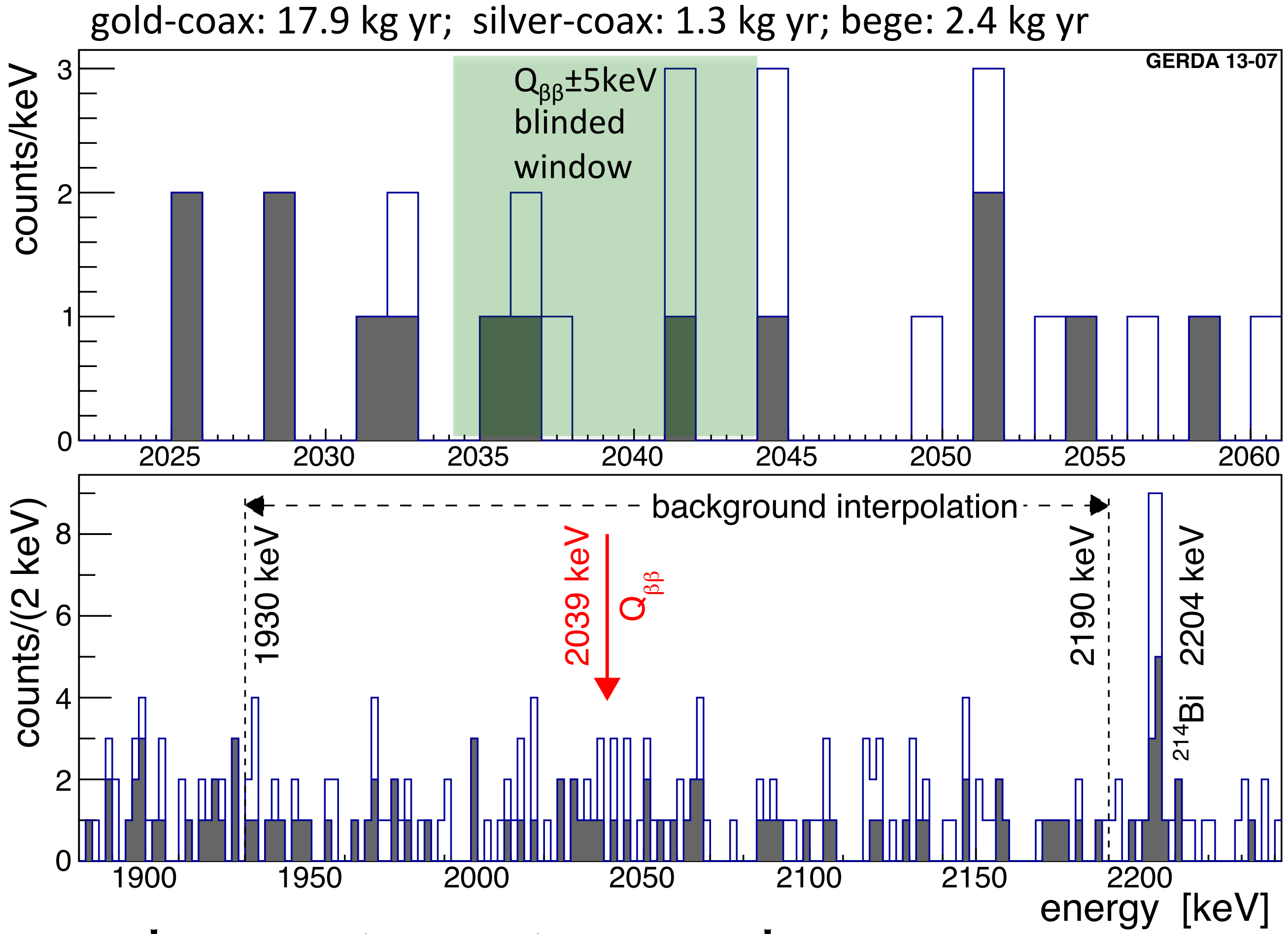
Challenges:
Fabrication of enriched germanium crystals very expensive
Need ultra-low radioactivity in crystals, supports, shielding

Highlights:
Excellent energy resolution (~0.06%)
Innovative shielding (Argon and ultra-pure copper)

- Experiments in US and Italy
- Collaborations will merge for next generation

# GERDA

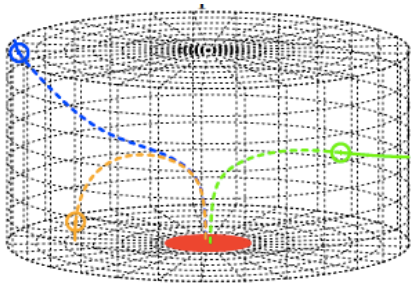
PRL 111 (2013) 122503



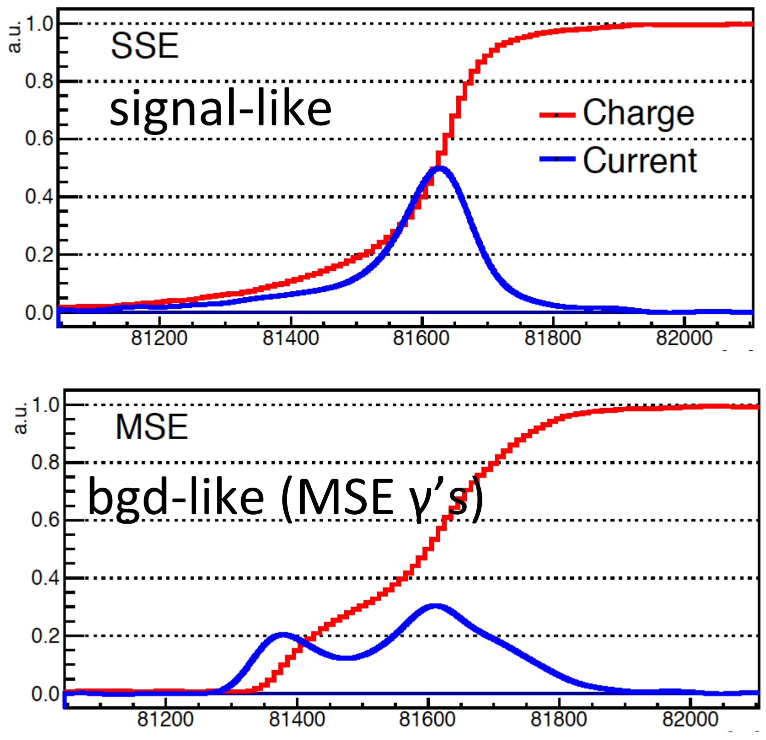
☐ before PSD

▨ after PSD

Phase I



BEGe



Pulse shape discrimination (SS/MS)

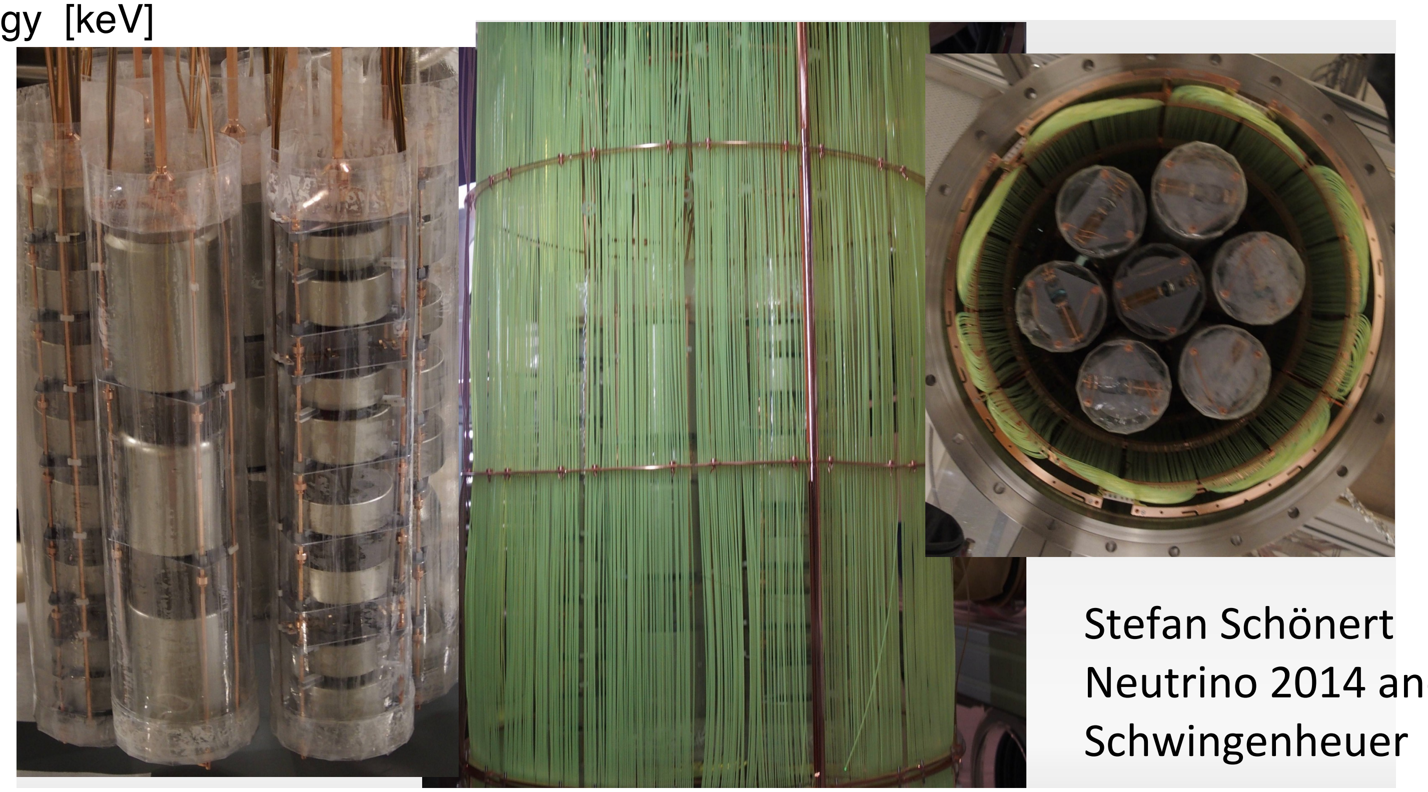
- Phase I (2013): 21.6 kg-yr $^{enr}$Ge (86%) analyzed,

$$t^{0\nu\beta\beta}_{1/2} > 2.1 \times 10^{25} \text{ years}$$

$$\langle m_{\beta\beta}\rangle < 0.2 - 0.4 \text{ eV}$$

(Ge combined)

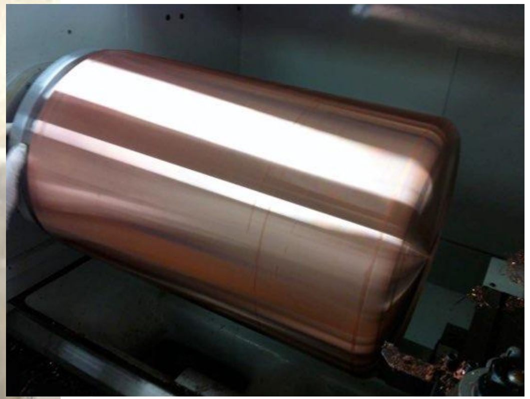
- Phase II (taking data): ~35 kg $^{enr}$Ge, instrumented active LAr shield, BEGe



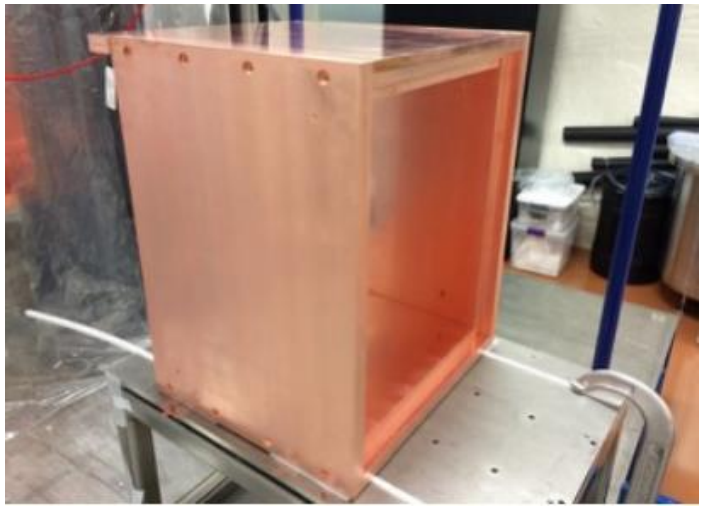
Stefan Schönert Neutrino 2014 and Schwingenheuer

# MAJORANA Demonstrator

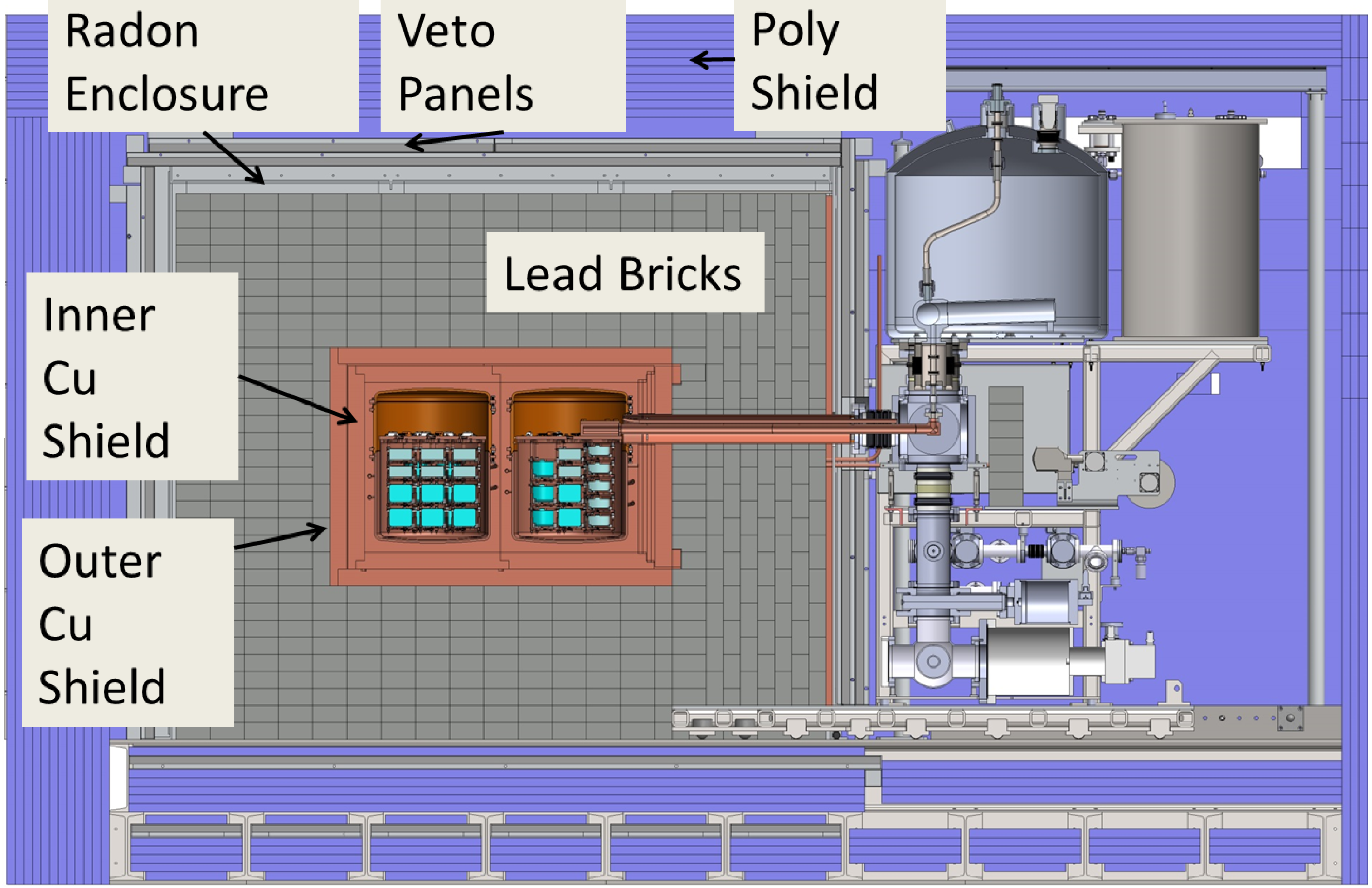
Outer copper + lead shield



- Underground electroformed copper shielding
- Data being taken now, ~30 kg $^{enr}$Ge



Inner electroformed copper shield



# Future large Ge experiment

- Will “cherry-pick” best aspects of MJD and GERDA
- Aim for 1T $^{enr}$Ge
- Cover entire inverted hierarchy (this is effectively the goal of each major 0νββ project for the early-mid 2020s)
- Crystals unlikely to be made larger, so simple scaling with more crystals
- Need lower backgrounds, some gains from crystal-crystal anti-coincidence

Fig: Courtesy M. Kapust

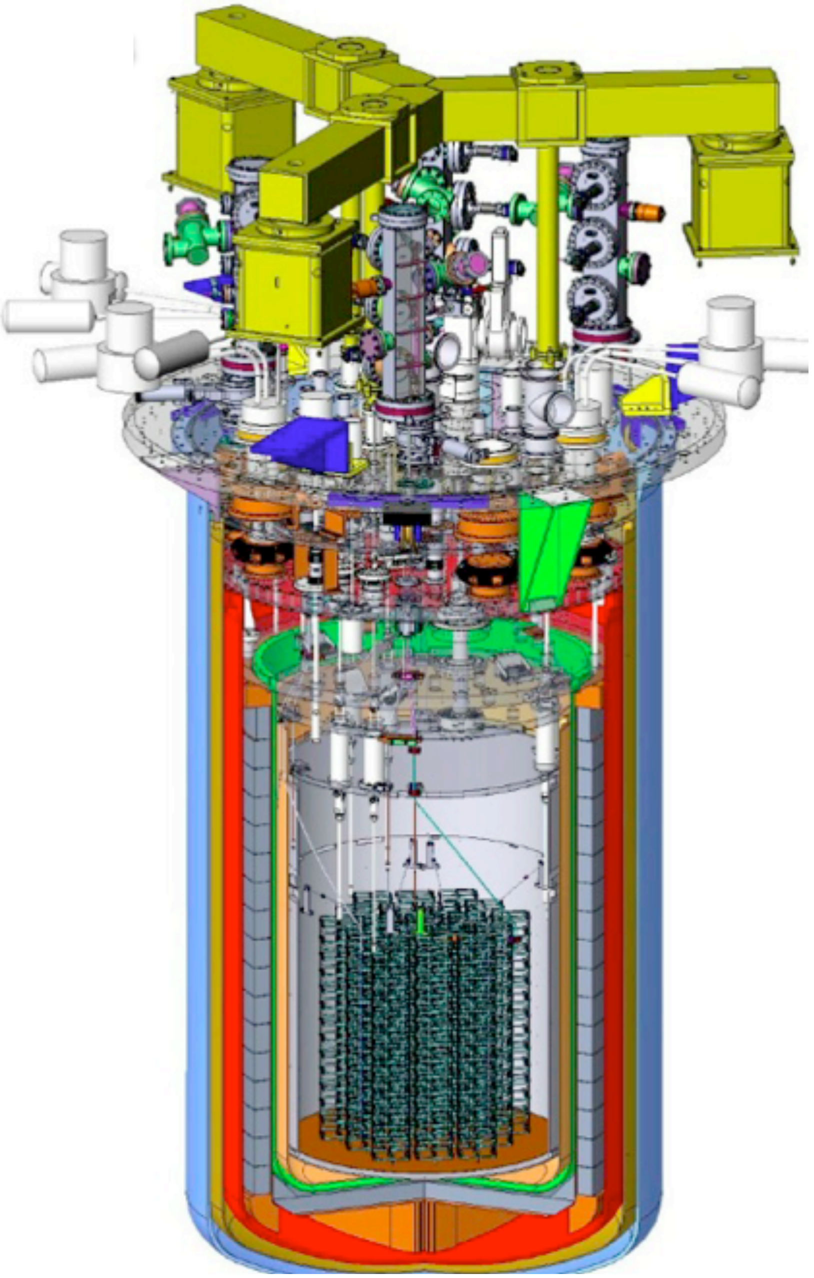
# CUORE

Technology: Cryogenic $TeO_2$ bolometer
Signal from phonons
Source is detection medium
Isotope: $^{130}Te$

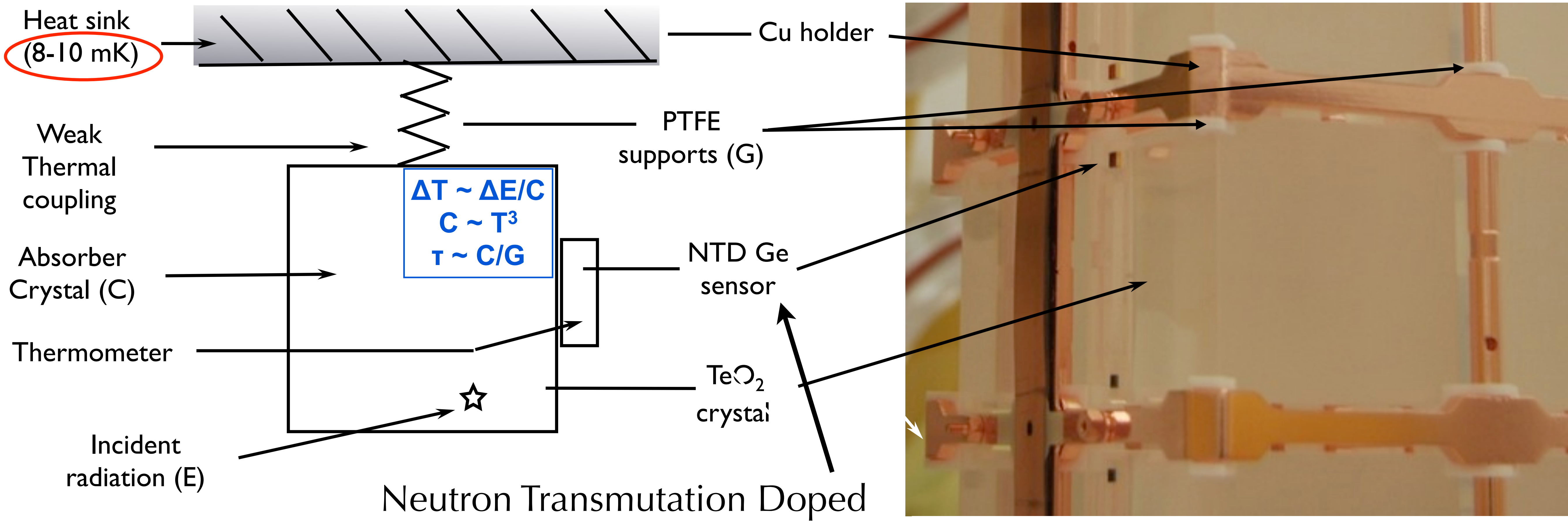
Challenges:
Presently no second channel for α/β discrimination

Highlights:
Excellent energy resolution
No enrichment necessary

- Cryogenic Underground Observatory for Rare Events (CUORE)
- Creating the coldest cubic meter (<10 mK) in the known universe at LGNS



# CUORE Method

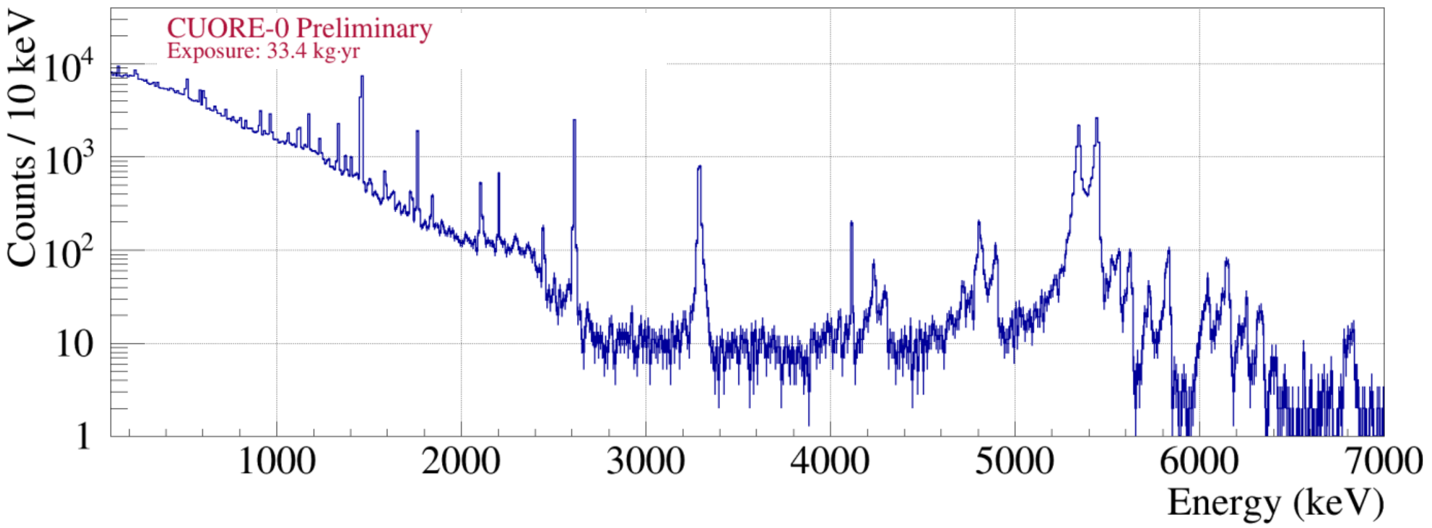


Neutron Transmutation Doped Ge thermistor

from Cremonesi Neutrino 2014

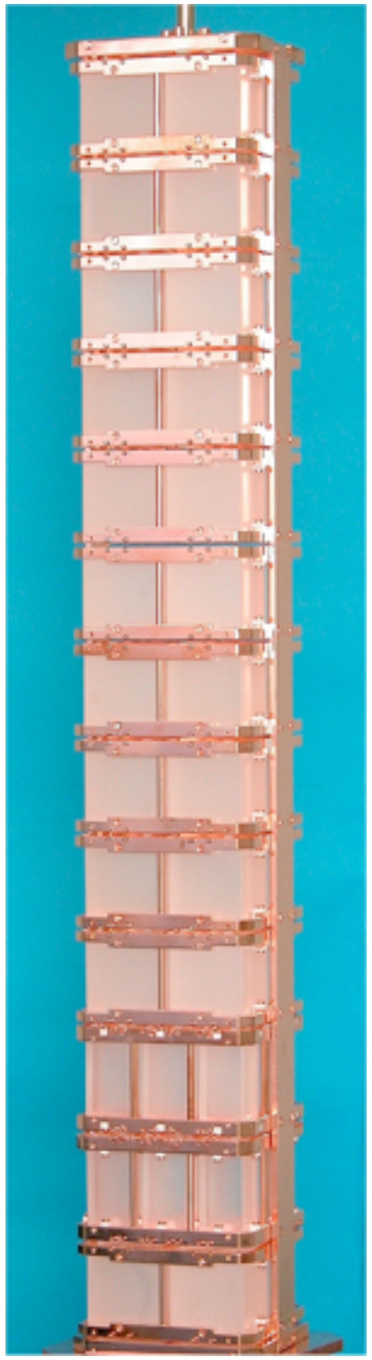
- Energy resolution comparable to Ge crystal detectors (0.085% at Q-value)

- Each crystal is a calorimeter, no discrimination for α/β



# CUORE roadmap

CUORICINO
2003



19.75
kg-yr

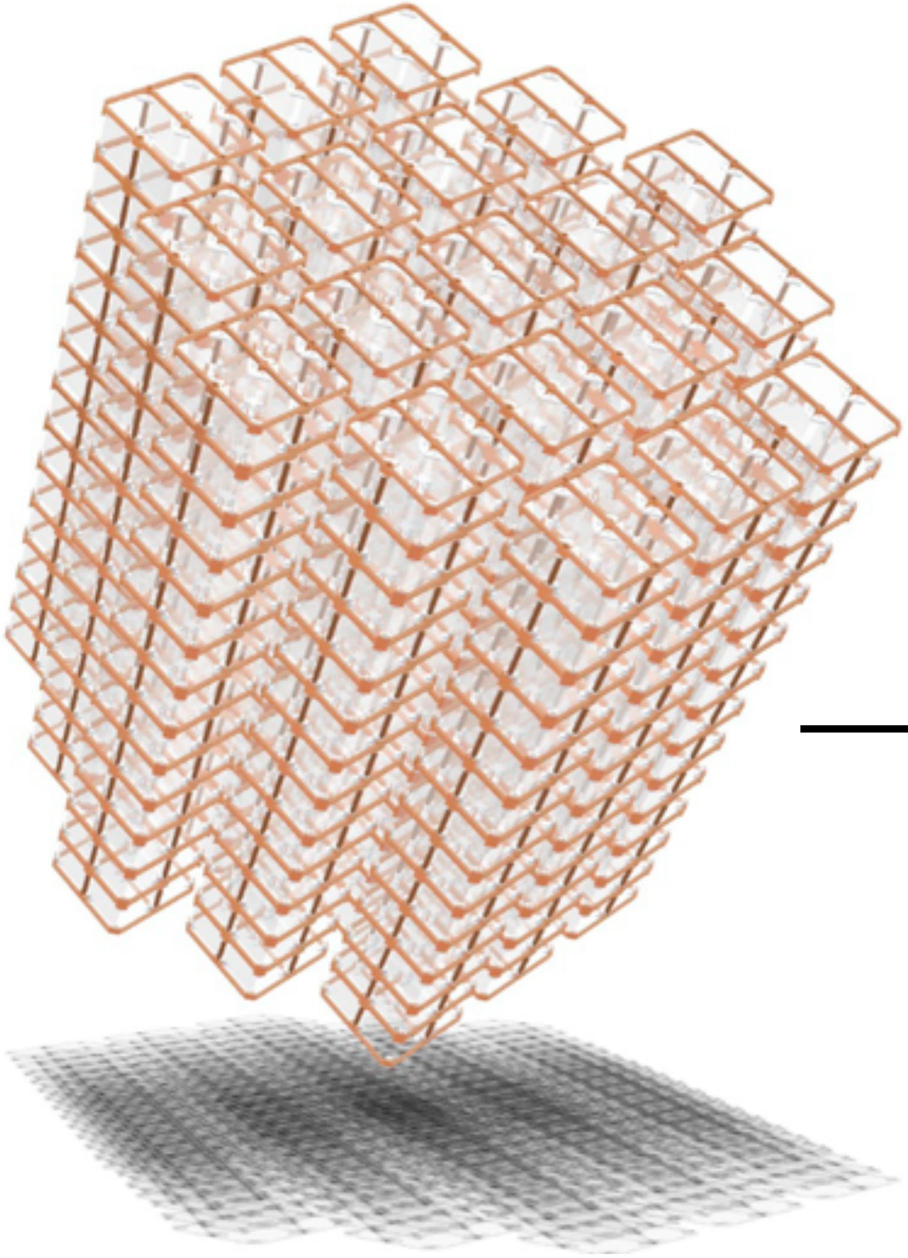
→

CUORE-0
2013-15

9.8
kg-yr

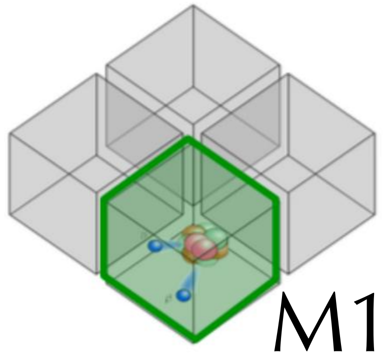
→

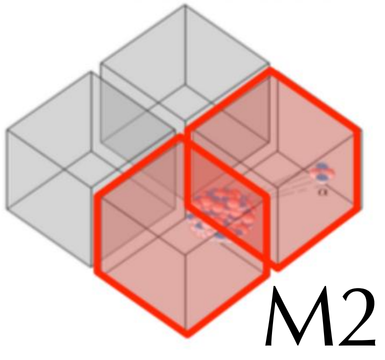
CUORE
2016-?

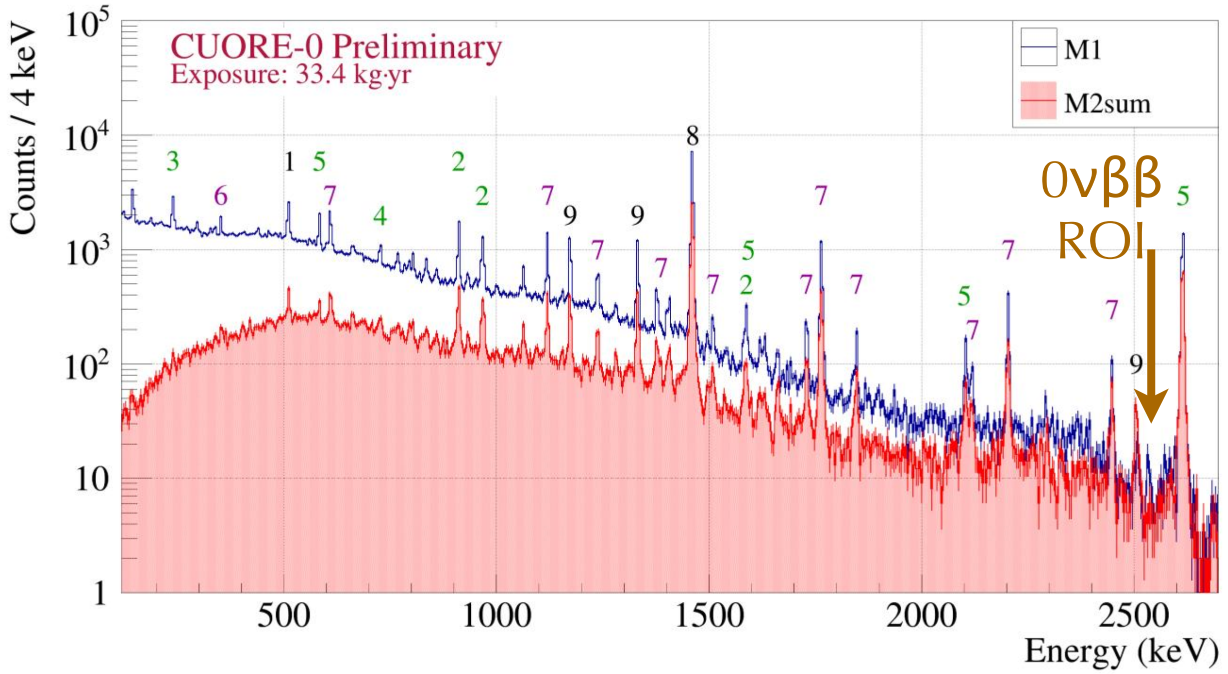


→ ?

# CUORE-0 results







1) $e^+e^-$ annihilation
2) $^{228}$Ac
3) $^{212}$Pb
4) $^{212}$Bi
5) $^{208}$Tl
6) $^{214}$Pb
7) $^{214}$Bi
8) $^{40}$K
9) $^{60}$Co

$^{232}$Th decay chain

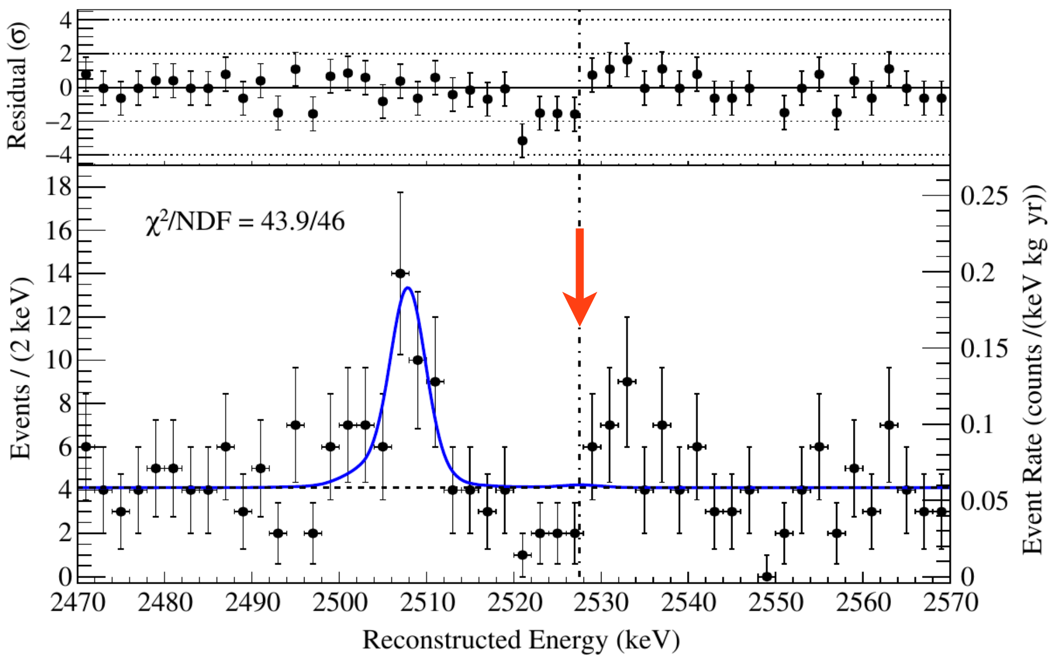
$^{238}$U decay chain

- CUORE-0 is the first tower, 52 $TeO_2$ crystals
- 39 kg $TeO_2$, 10.9 kg $^{130}$Te (no enrichment needed)
- CUORE-0 + CUORICINO:

$$t_{1/2}^{0\nu\beta\beta} > 4.0 \times 10^{24} \text{ years}$$

$$\langle m_{\beta\beta} \rangle < 270 - 760 \text{ meV}$$

arXiv:1504.02454v2



# CUORE and CUPID

- CUORE has 19 towers, 740 kg $^{nat}TeO_2$, aiming for $\langle m_{\beta\beta} \rangle < 40 - 100 \text{ meV}$, detector is cold, stay tuned for results.
- For future upgrades
    - Reuse cryostat
    - Use enriched crystals
- Cuore Upgrade with PID ($\alpha/\beta$)
    - Need second channel, probably Cherenkov or scintillation light
    - Various R&D projects underway, may require new crystal, isotope

Some ideas

$TeO_2$, $ZnMoO_4$,
ZnSe, $CdWO_4$

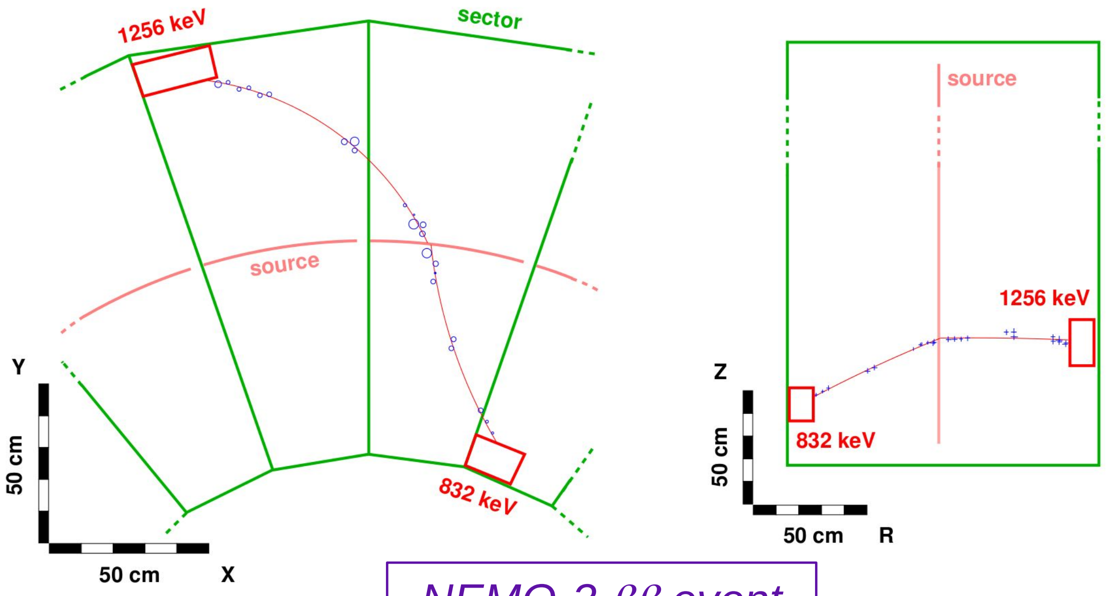
Scintillating crystal,
Cherenkov light readout

Isotopes with Q-values above 2615 keV in scintillating crystals may offer exceptionally low background

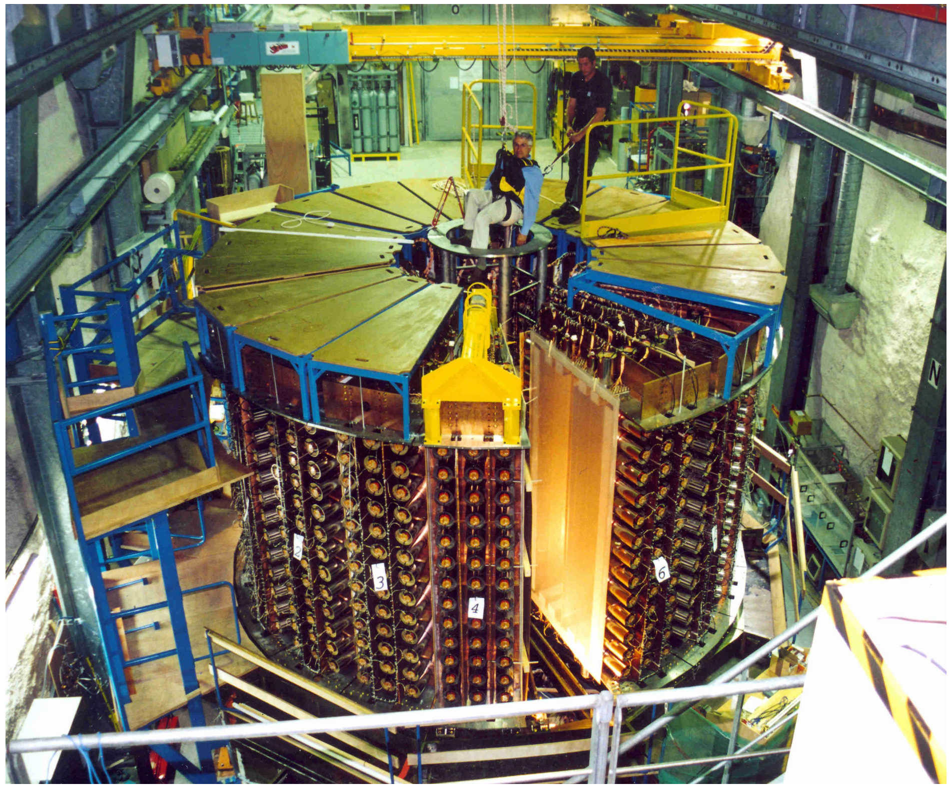
# NEMO-3/SuperNEMO

- Neutrino Ettore Majorana Observatory
- Source foils and tracker volumes to fully reconstruct both βs
- Flexible, multi-isotope, but low mass
- NEMO-3 (2003-2011), $^{100}$Mo, $^{82}$Se, $^{130}$Te, ...
- SuperNEMO demonstrator (commissioning, ~5 kg $^{82}$Se)
- SuperNEMO (future, ~100 kg $^{82}$Se)

supernemo collaboration

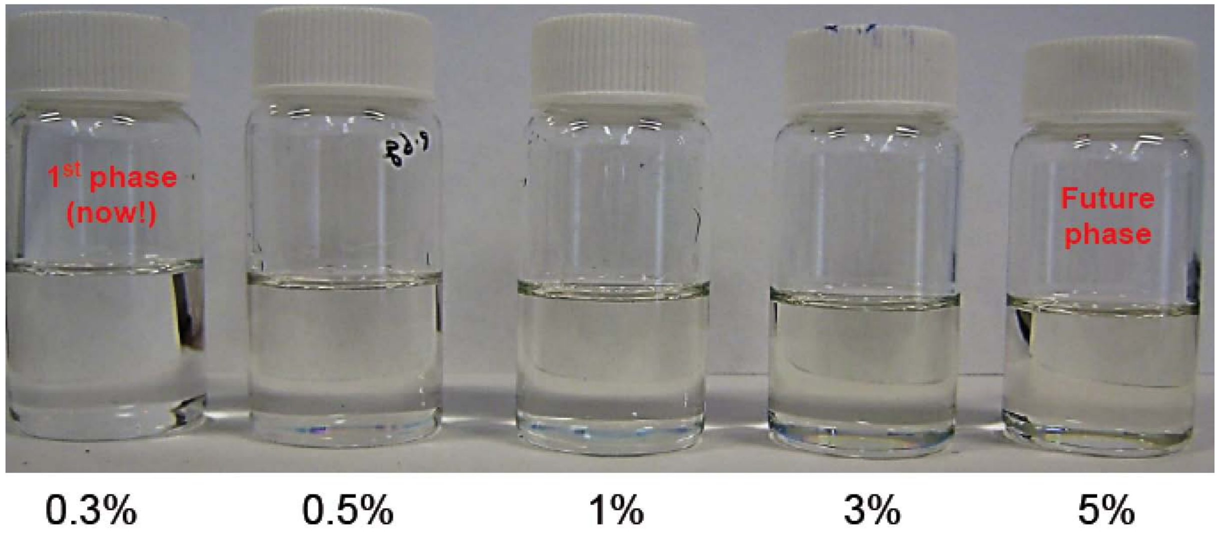


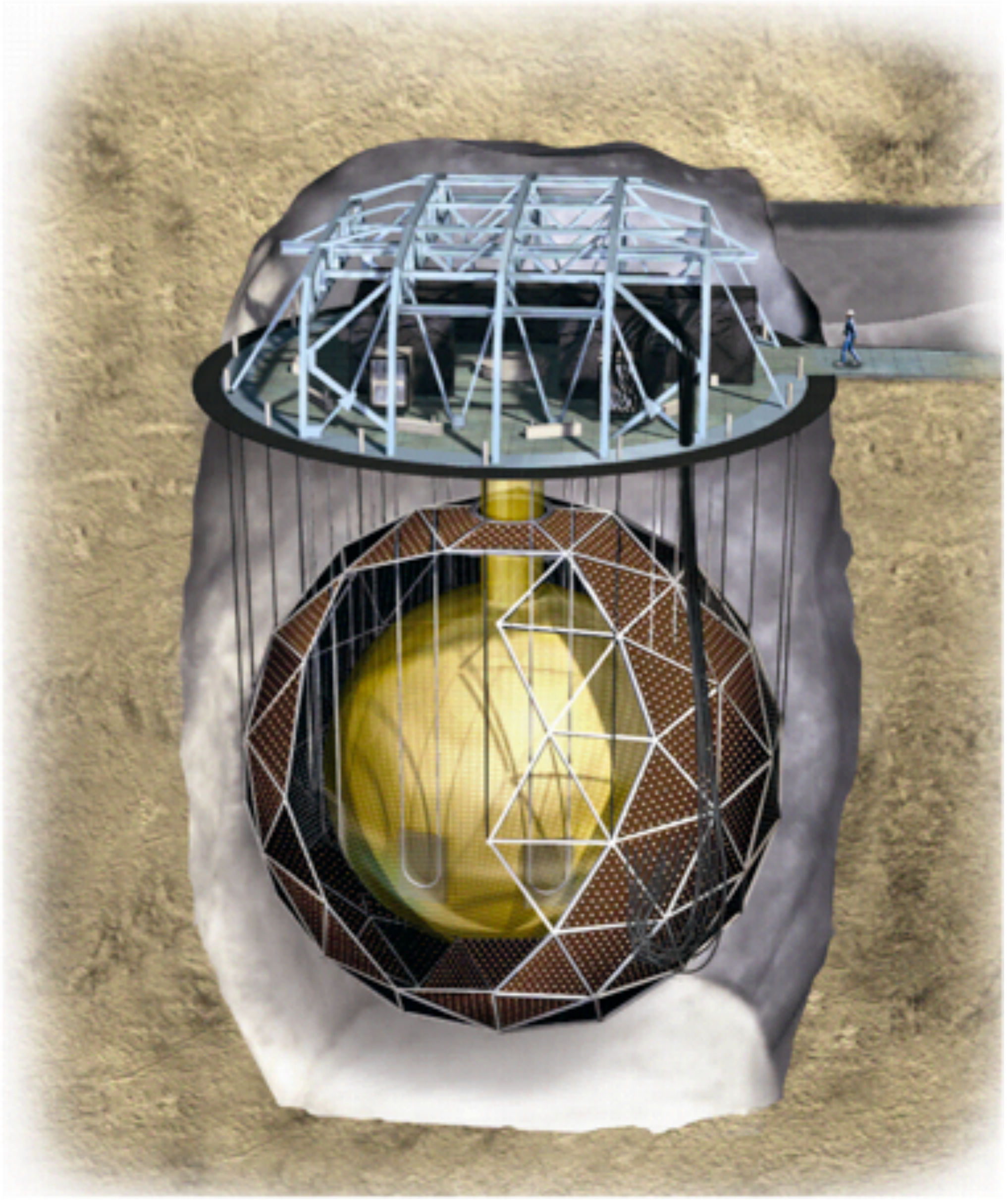
NEMO-3 ββ event



# SNO+

- Repurpose SNO with $^{130}$Te-loaded liquid scintillator
- Very large mass possible at modest cost
- Energy resolution (~4.5%) is a challenge, future upgrades may help
- Detector preparing for water-fill, scintillator and loaded scintillator to follow





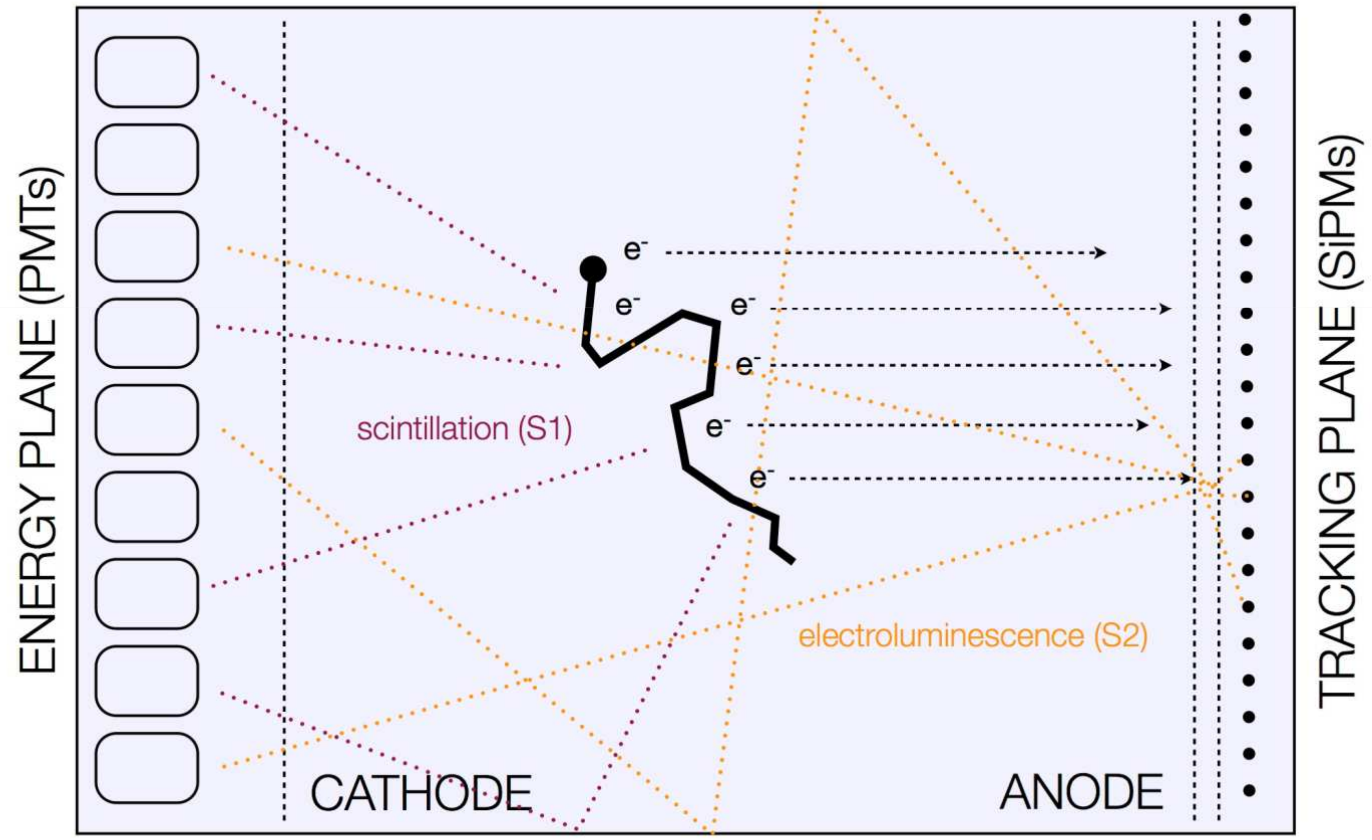
# NEXT

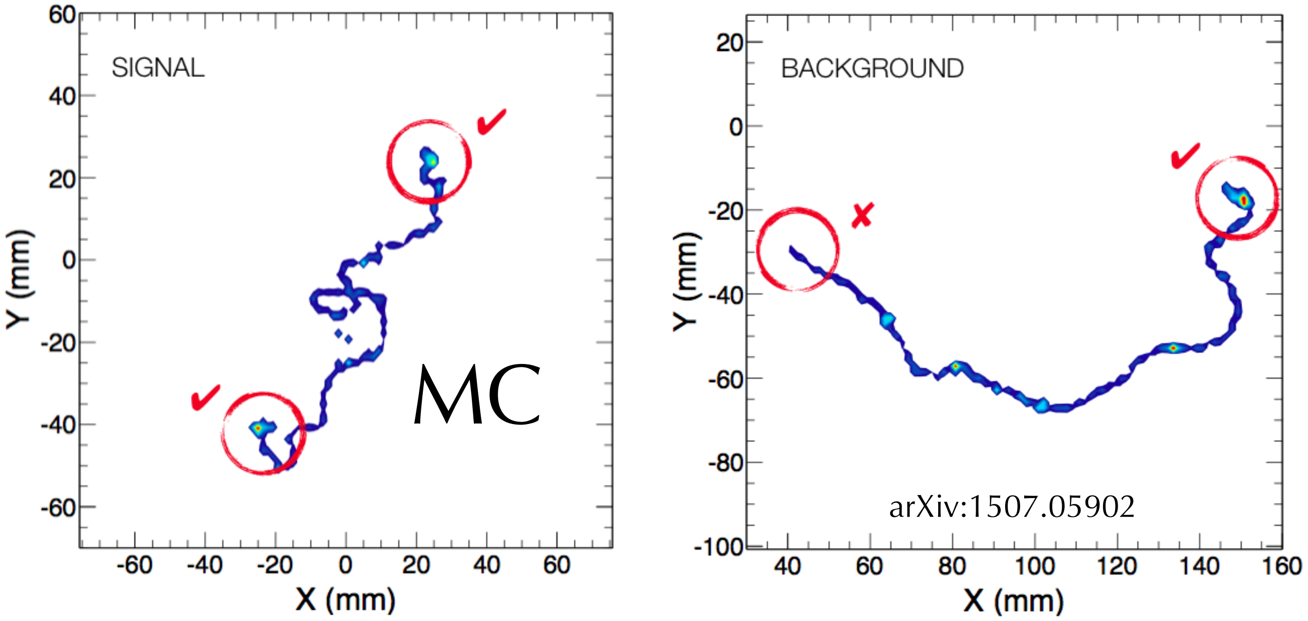
- Neutrino Experiment with a Xenon Time projection chamber
- 15 bar gas TPC: good energy resolution (~0.4%), long tracks
- Topological identification!

NEXT-DEMO: 2014, 1.5 kg Xe

NEXT-NEW: 2016, 10 kg Xe

NEXT-100: next, 100 kg $^{enr}$Xe





arXiv:1507.05902

NEXT-NEW at Canfranc

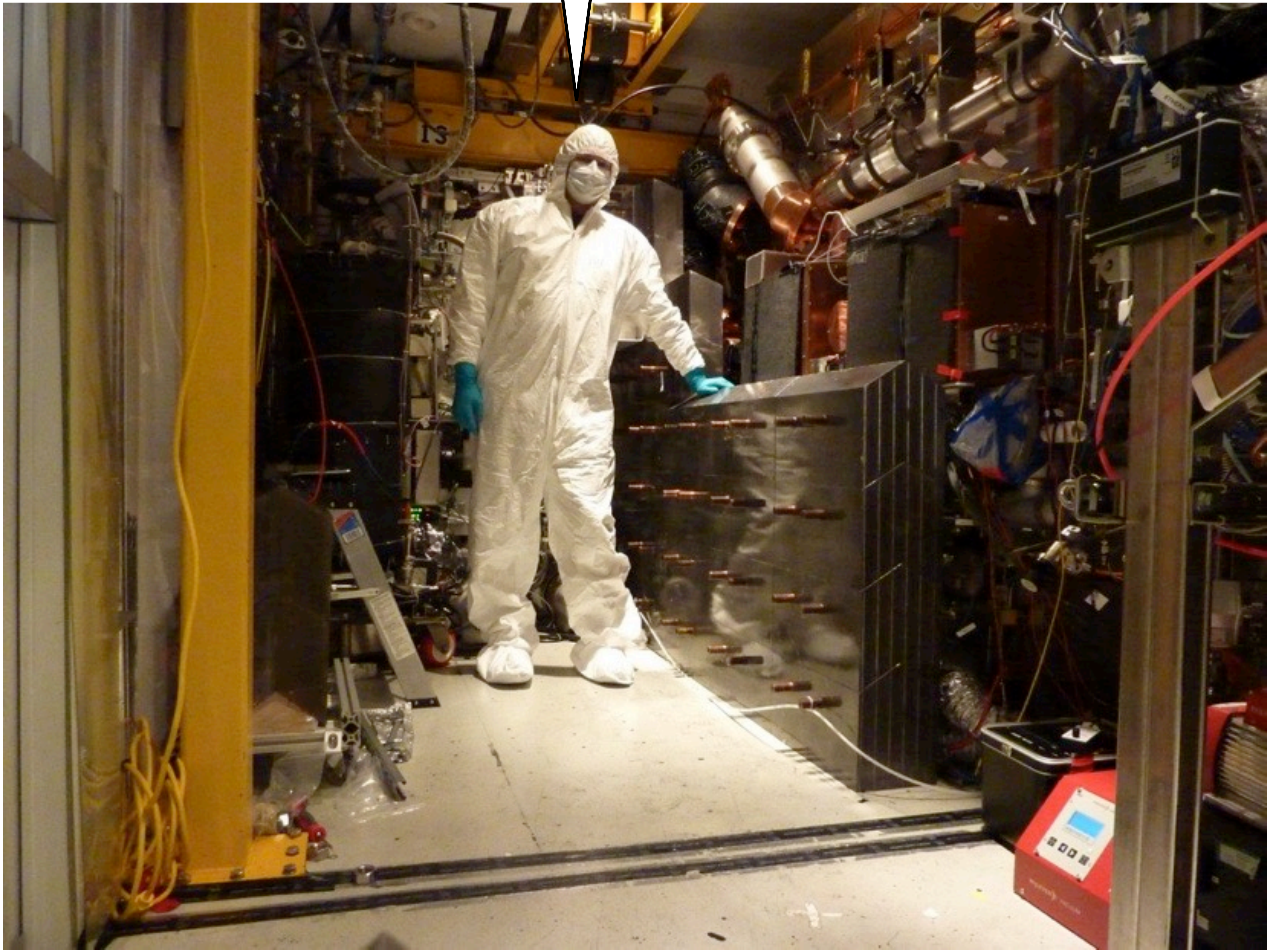
# Apologies for incompleteness

- The list of small projects and planned projects gets very large.
- Incomplete list of additional projects:
    - COBRA
    - PandaX-III
    - AMoRE
    - Lucifer
    - LUMINEU
    - CANDLES

# Conclusions?

- How will the search for 0νββ conclude?
  - Determination that neutrinos are in the inverted hierarchy
    → Majorana/Dirac determination in next-generation
  - Measurement of absolute neutrino mass
    → Majorana/Dirac determination eventually
  - Discovery of 0νββ
    → Also a measurement of neutrino mass, possibly next-gen?
  - Nothing but limits
- Impressive progress in background reduction techniques along the way
- Any of these outcomes will require verification from multiple experiments before outcome is settled.

# Thanks!



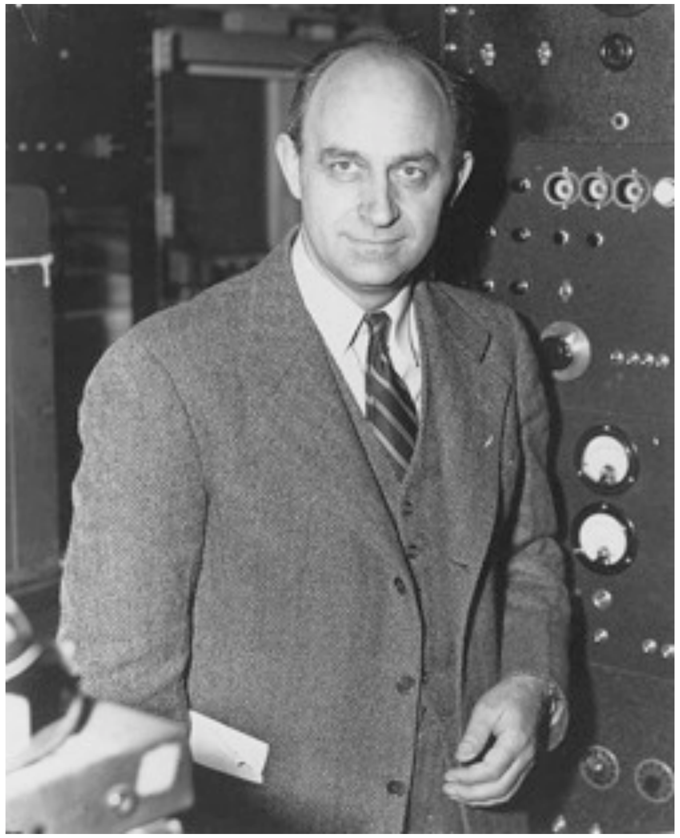
# Backup Slides

# Special Thanks

- Giorgio Gratta (EXO)
- Kunio Inoue (KZ)
- Bernhard Schwingenheuer (GERDA)
- Steve Elliott (MAJORANA)
- Oliviero Cremonesi (CUORE)

# Early Neutrino Physics

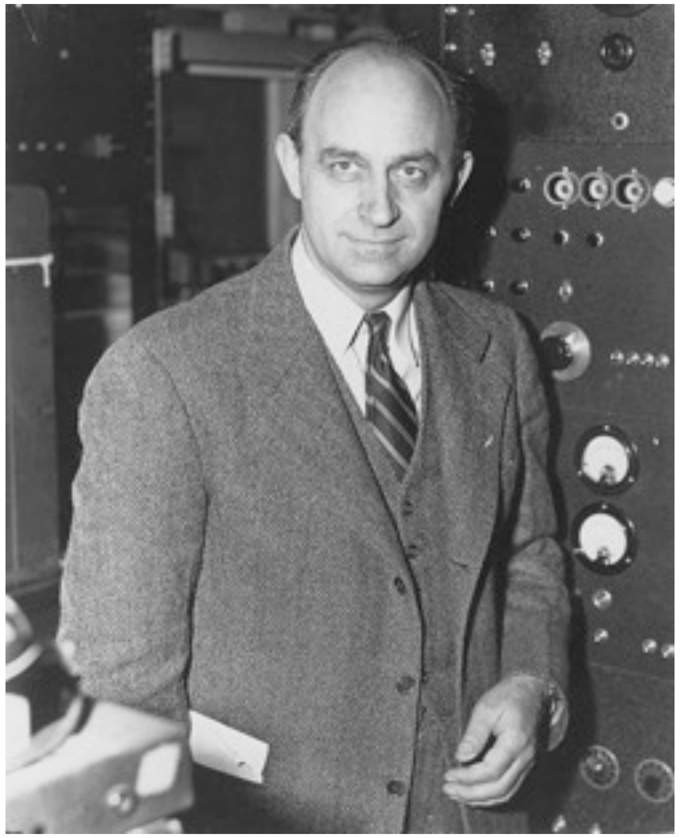
*1934*



- Enrico Fermi develops Pauli's idea
- "neutrinos", little neutrons

# Early Neutrino Physics

*1934*



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- "neutrinos", little neutrons

*1956*

- Frederick Reines and Clyde Cowan at Savannah River

$$\overline{\nu} + p \to n + e^+$$

# Early Neutrino Physics

*1934*

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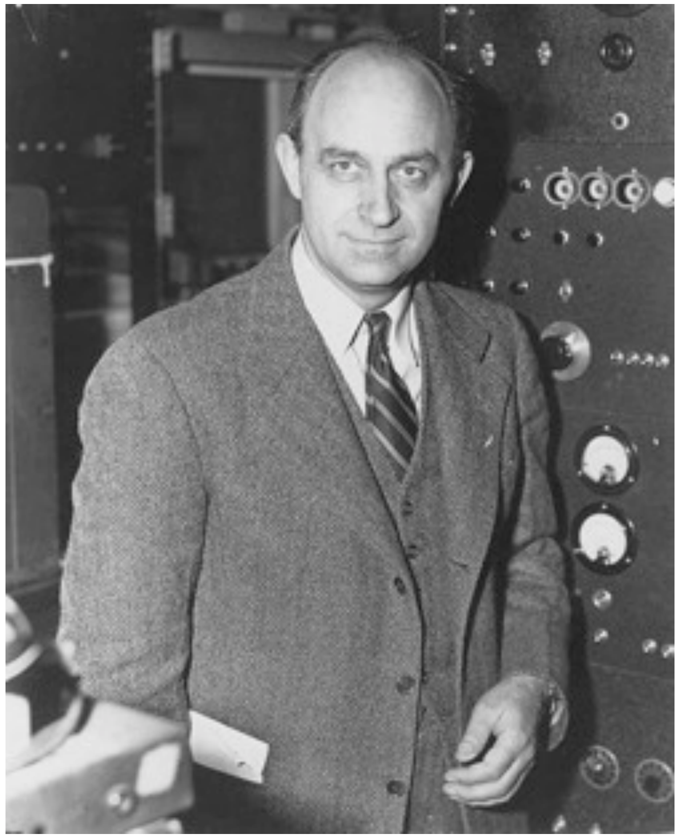


*1956*

- Frederick Reines and Clyde Cowan at Savannah River

$$\overline{\nu} + p \rightarrow \boxed{n} + e^{+}$$

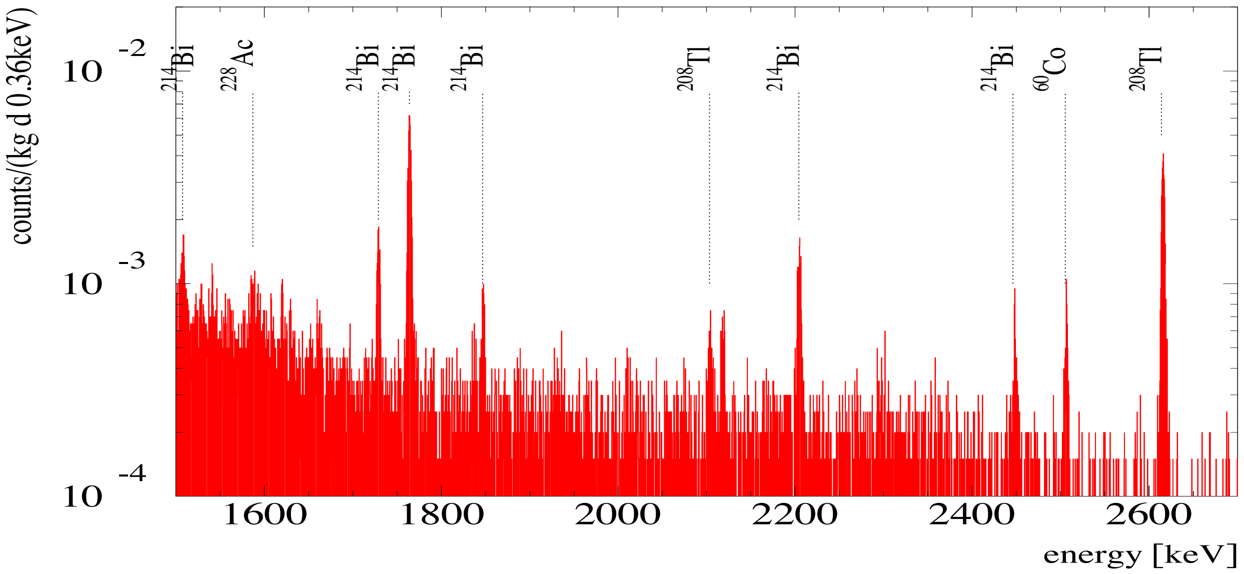
# Sensitivity

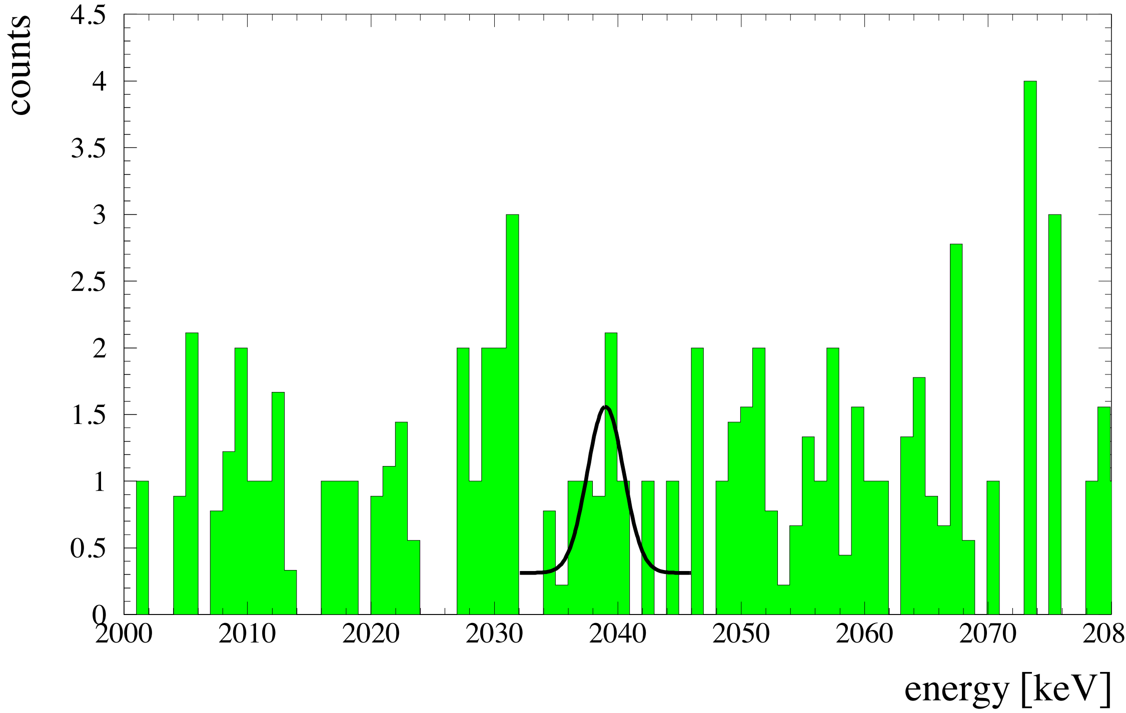
- Low backgrounds
    - Radiopure materials
    - Shielding
    - Good energy resolution
    - Large pure volumes
    - Additional discrimination techniques
    - Vetos and depth
- Large masses of isotopes
- Isotopic matrix elements
- High signal efficiency

# Discovery Potential

- Everything required for sensitivity, plus excellent background suppression and characterization.
- To make a discovery, it is necessary to demonstrate that no unidentified background could be causing a false signal.
- A previous discovery claim (Klapdor et. al) failed this test, and has since been solidly refuted by $^{136}$Xe measurements.

from doi:10.1023/A:1019722802931

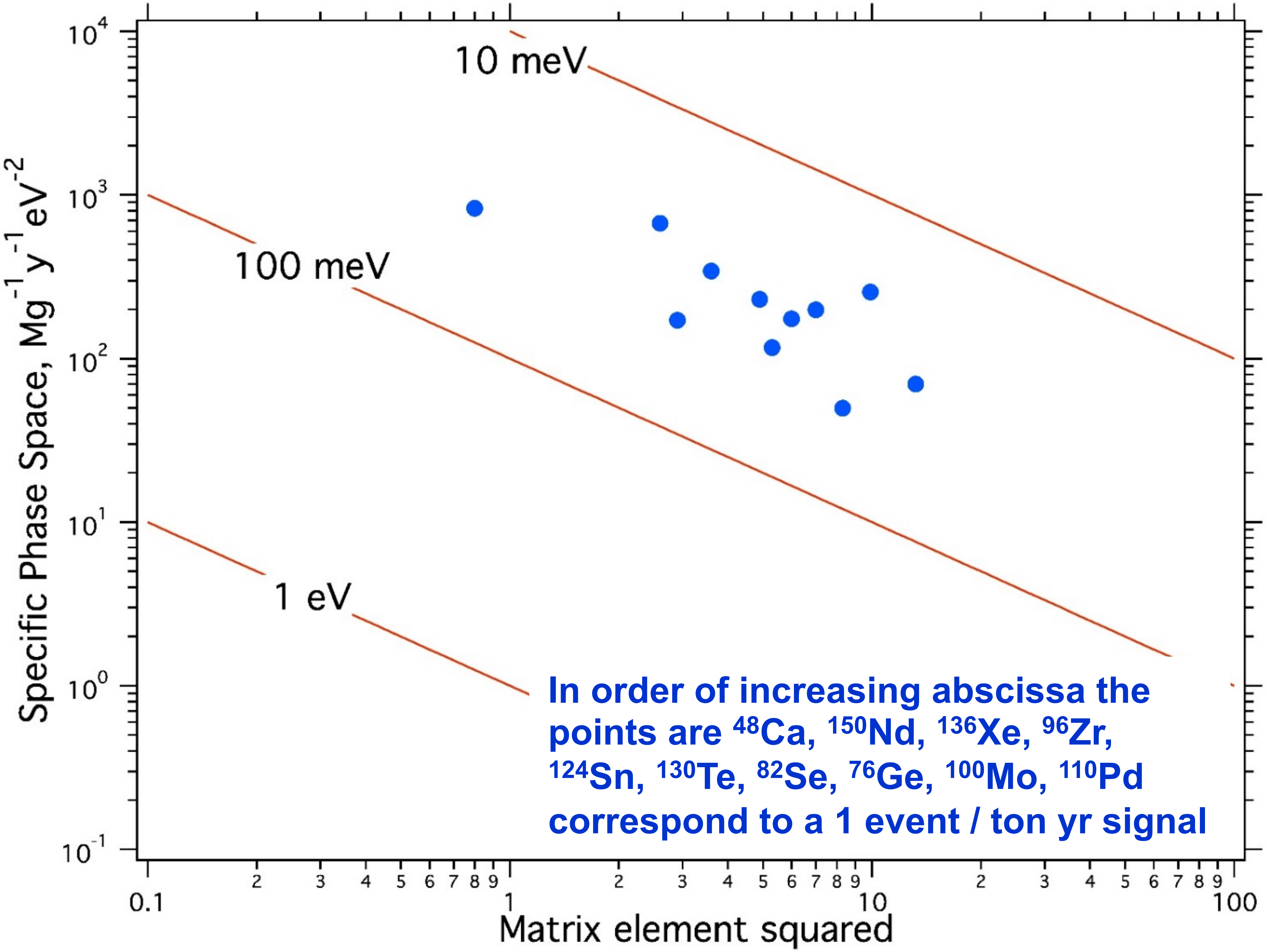




# Cost/Feasibility?

- Cost of isotope (including enrichment, if necessary)
- Availability of isotope
- Cost of detector and shielding
- Cost and reliability for radiopurity of detector and shielding
- Time necessary to build and commission detector
- Tolerance for problems (can it be fixed?)
- R&D status (new technologies?)

# From G. Gratta



**In order of increasing abscissa the points are $^{48}$Ca, $^{150}$Nd, $^{136}$Xe, $^{96}$Zr, $^{124}$Sn, $^{130}$Te, $^{82}$Se, $^{76}$Ge, $^{100}$Mo, $^{110}$Pd correspond to a 1 event / ton yr signal**

R.G.H. Robertson, MPL A 28 (2013) 1350021

# EXO-200 site

- Waste Isolation Pilot Plant, near Carlsbad, NM
- 650m flat overburden, ~1620 mwe
- Salt relatively low in $^{238}$U and $^{232}$Th

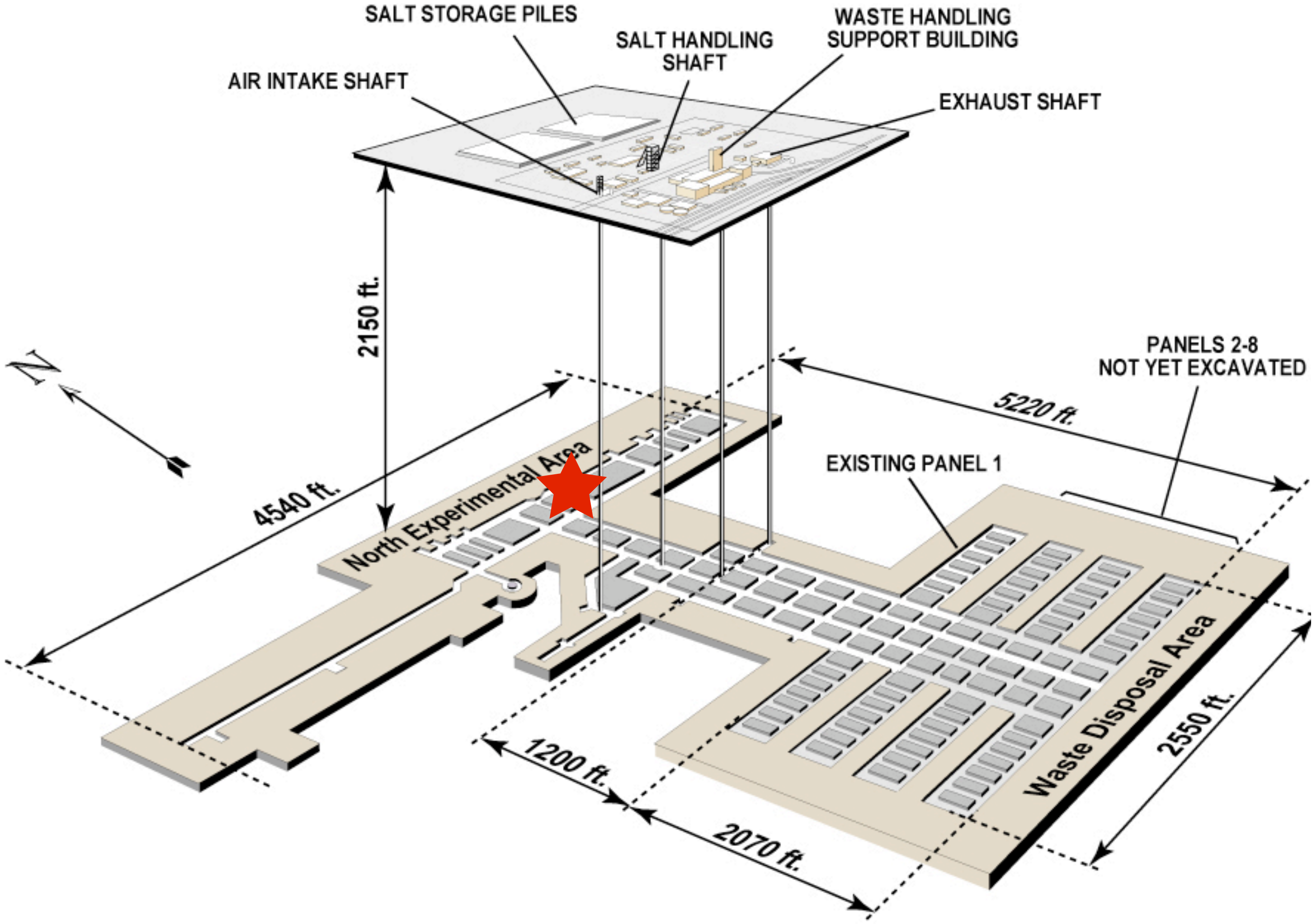
$\Phi_{\mu} \sim 1.5 \times 10^{5} yr^{-1} m^{-2} sr^{-1}$

$U \sim 0.048\, ppm$

$Th \sim 0.25\, ppm$

$K \sim 480\, ppm$

Esch et al., arxiv:astro-ph/0408486 (2004)



# About resolutions

- I am reporting resolutions in terms of σ, multiply by 2.355 to get to FWHM resolutions.