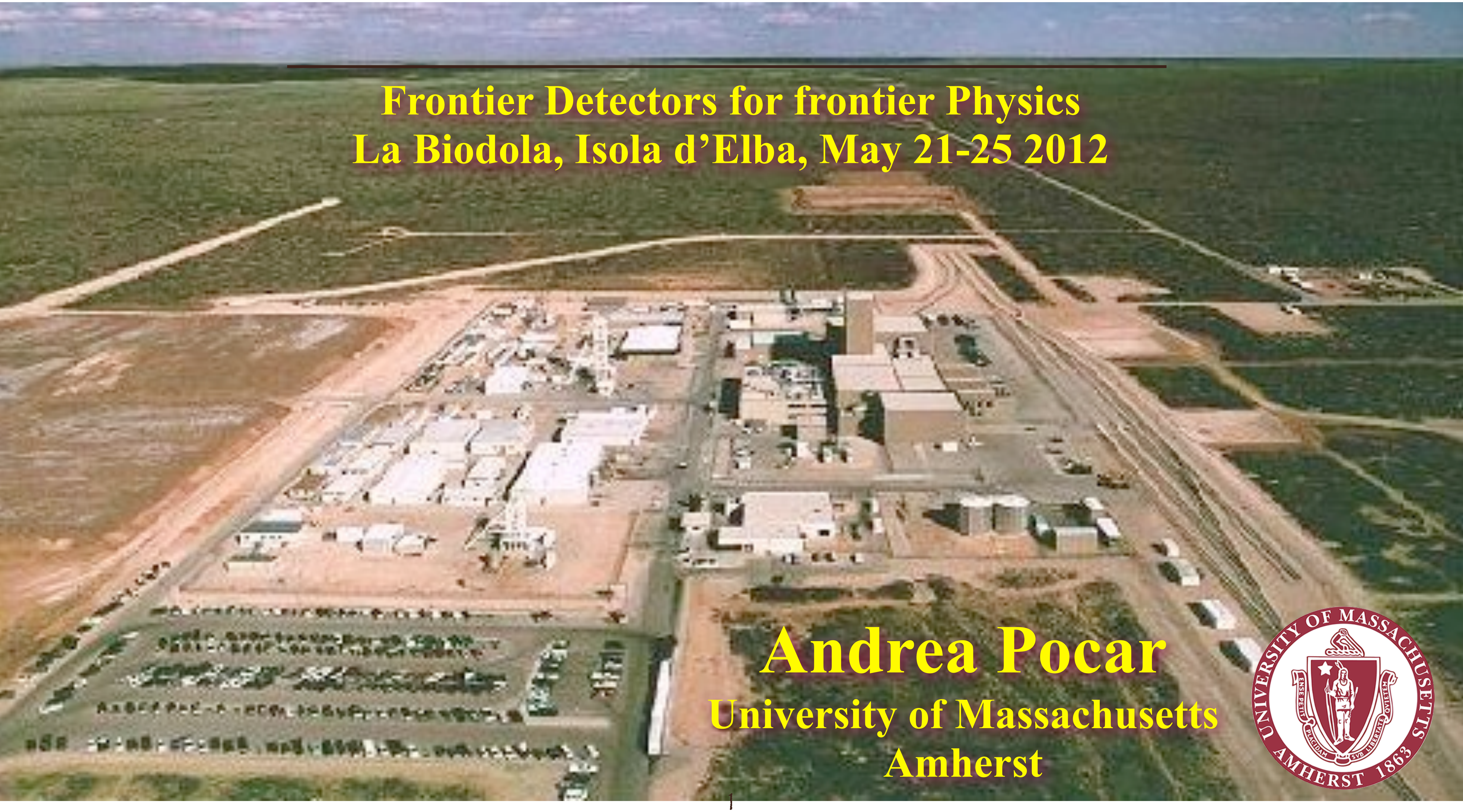
Enriched Xenon Observatory
EXO
for double beta decay

Neutrino-less double beta decay search with EXO-200



Frontier Detectors for frontier Physics
La Biodola, Isola d'Elba, May 21-25 2012

Andrea Pocar

University of Massachusetts
Amherst

outline

1. ***neutrino-less double beta decay***
   - *physics motivation, detection strategies (briefly)*
   - *the EXO-200 concept*

2. ***the EXO-200 experiment***
   - *first physics (2ν double beta decay of Xe-136)*
   - *backgrounds and detector challenges*

   - *performance*

(see Kirill Pushkin's poster on R&D for a possible future HPXe EXO detector)

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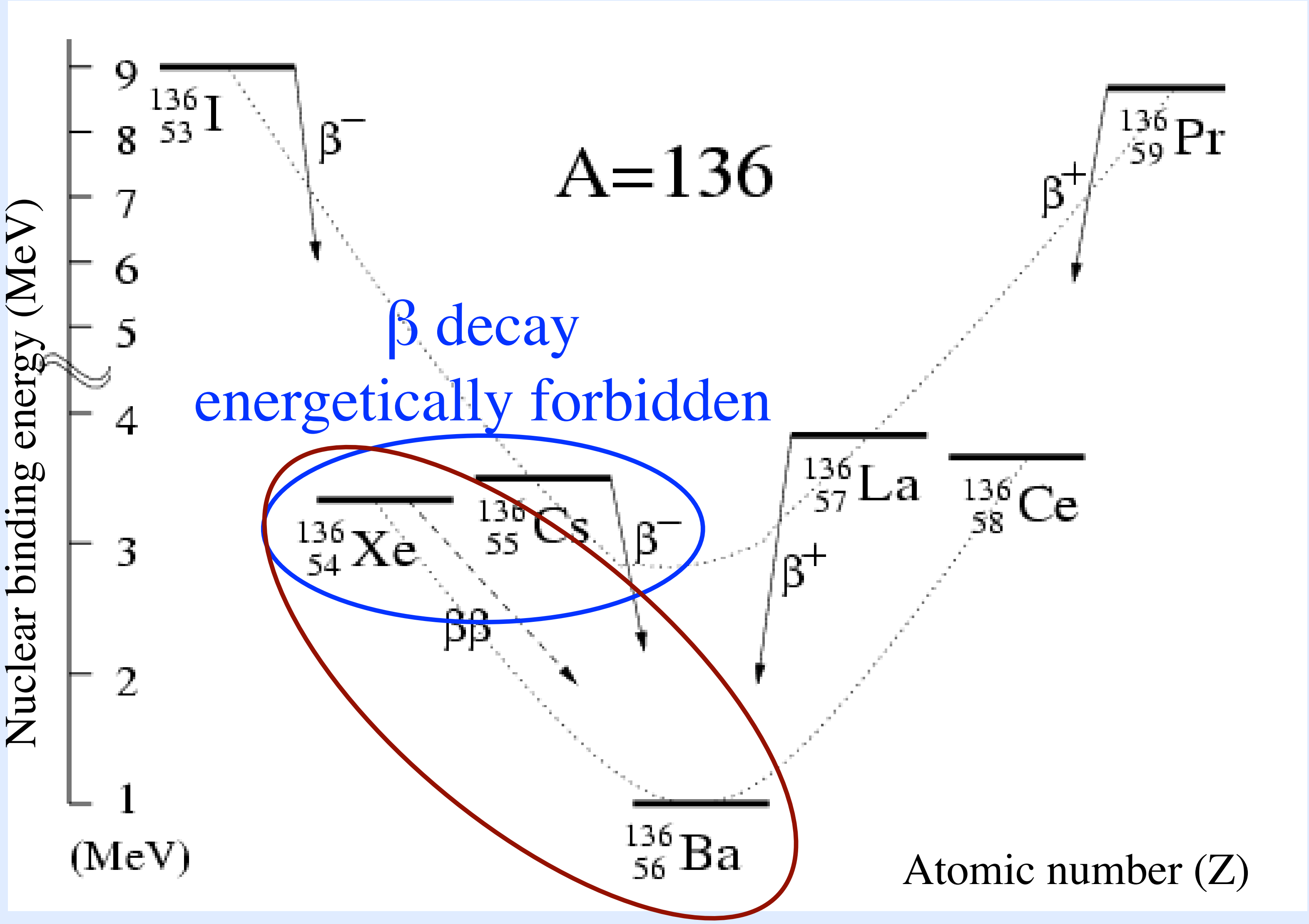
newly released data !

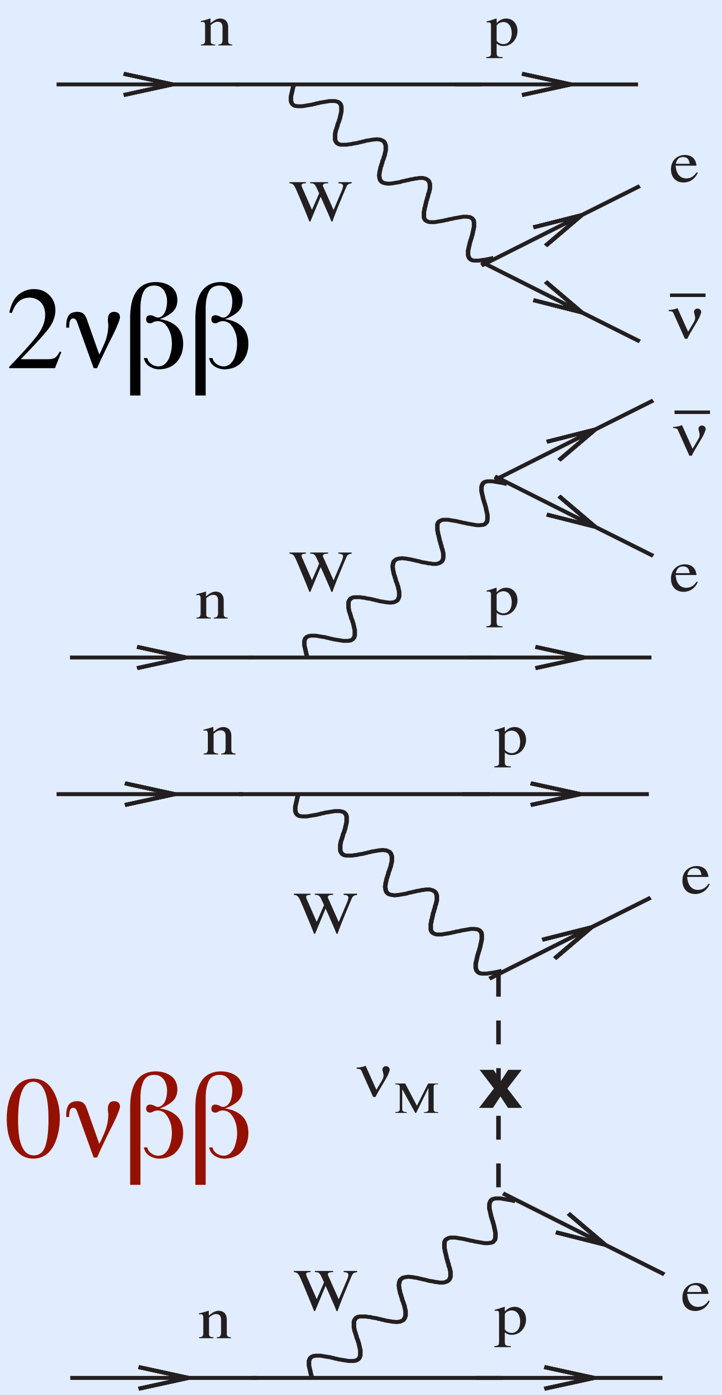
(see Kirill Pushkin's poster on R&D for a possible future HPXe EXO detector)

double beta decay

- second order weak process (even-even nuclei)
- predicted in 1935 by Göppert-Meyer
  after Wigner's suggestion (~10^{17} years!)



β decay
energetically forbidden



$2\nu\beta\beta$

$0\nu\beta\beta$

possibility of non-standard $0\nu\beta\beta$ process

why study 0νββ decay?

$$\bar{\nu}_i = \nu_i \qquad m_\nu \neq 0 \qquad \Delta L \neq 0$$

its observation is associated with the discovery of:

- lepton number violation
  - Majorana particles (neutrinos)

[Schechter and Valle, Phys. Rev. D 25 (1982) 2951]

and enables us to:

- measure the absolute mass scale of neutrinos
  - define the mass ordering of neutrinos
    - shed some light on the matter/antimatter asymmetry (leptogenesis, ...)

measured quantity: half life (rate)

$$[T^{2\nu}_{1/2}]^{-1} = G_{2\nu}(Q_{\beta\beta},Z)\left| M^{\mathrm{GT}}_{2\nu} - \frac{g_V^2}{g_A^2} M^{F}_{2\nu}\right|^2$$

directly measured quantity

calculable phase space factors

nuclear matrix elements
(calculated within particular nuclear models)

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Majorana neutrino mass
(can be zero !!)

$$\langle m_{\beta\beta}\rangle^2 = \left|\sum_i^N |U_{ei}|^2 e^{i\alpha_i} m_i\right|^2 \quad (\text{all } m_i \geqslant 0)$$

Nuclear physics is needed to connect different isotopes

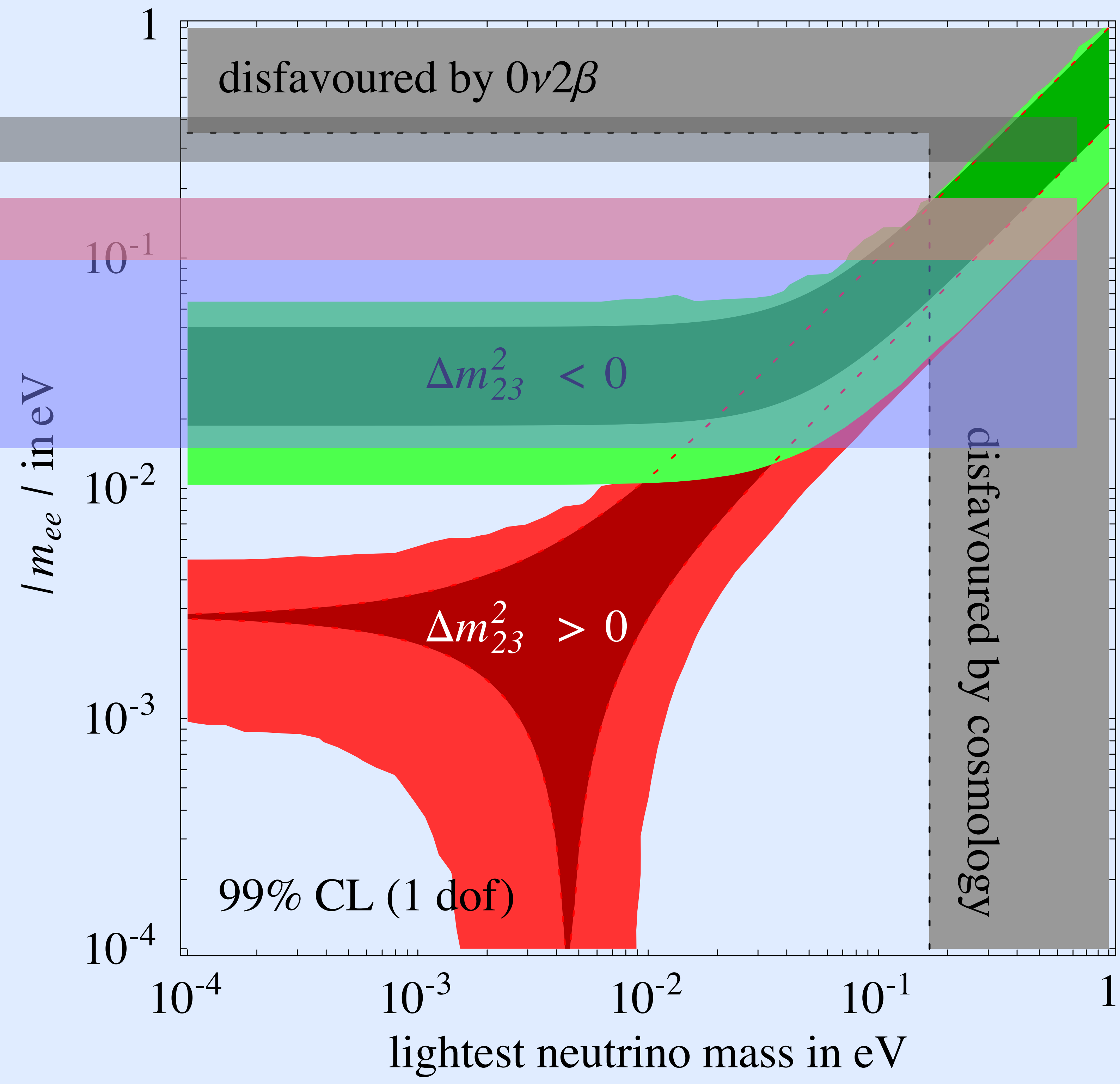
$0\nu\beta\beta$ and neutrino masses

[PLB 586(2004)198]

Klapdor et al.

EXO-200 (~100 meV)

current projects



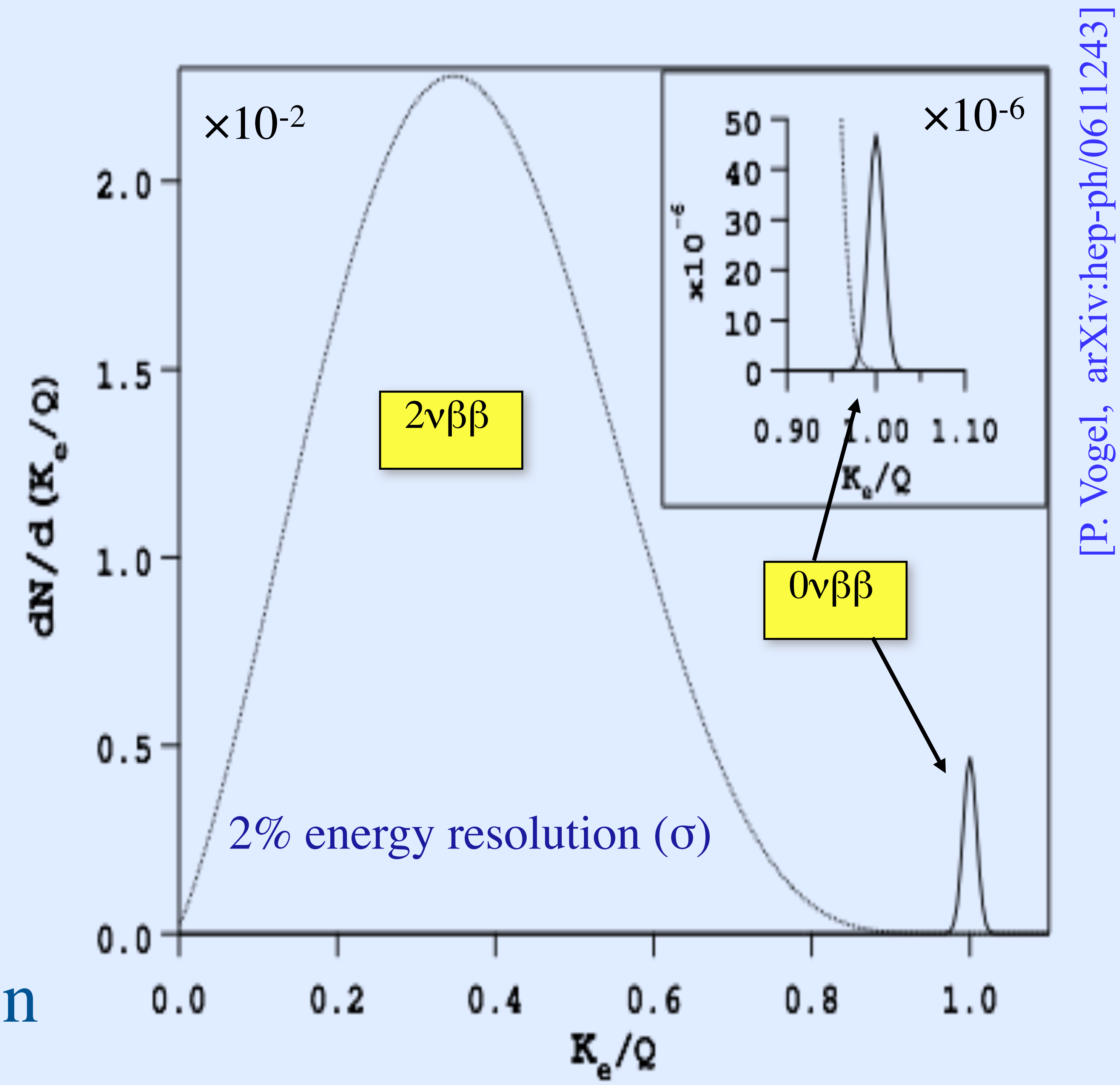
[Strumia and Vissani, hep-ph/0606054]

m_{eff} ~ 50 meV: ~ 10^{27} years

(10^{27} nuclei ~ 10^3 moles ~ 100 kg)

experimental handles

- ultra low radioactivity
- large source mass
- energy resolution
- tracking
- multi-isotope
- decay product identification



why xenon for EXO?

- ✓ known purification technology
- ✓ can be re-purified and transferred between detectors
- ✓ simplest enrichment (proven at the 100's kg scale)
- ✓ scalable technology (dark matter experiments help!)
- ✓ source = detector, high detection efficiency
- ✓ allows for particle ID (α/β, single/multiple cluster)
- ✓ (could allow for decay-daughter tagging)
- ✓ standard $2\nu\beta\beta$ is very slow

($T^{0\nu}_{1/2} = 2.11 \times 10^{21}$ y)

[Ackerman et al., PRL 107, 212501 (2011); arXiv:1108.4193]
[A. Gando et al., arXiv:1201.4664]

✳ energy resolution: GXe > LXe > liquid scintillator

The EXO Collaboration

Enriched Xenon Observatory
EXO
for double beta decay

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Colorado State University, Fort Collins CO, USA - S. Alton, C. Benitez-Medina, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold, T. Walton

University of Illinois, Urbana-Champaign IL, USA - D. Beck, J. Walton, L. Yang

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ITEP Moscow, Russia - D. Akimov, I. Alexandrov, V. Belov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich

Laurentian University, Sudbury ON, Canada - E. Beauchamp, D. Chauhan, B. Cleveland, J. Farine, B. Mong, U. Wichoski

University of Maryland, College Park MD, USA - C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Massachusetts, Amherst MA, USA - T. Daniels, S. Johnston, K. Kumar, A. Pocar, J.D. Wright

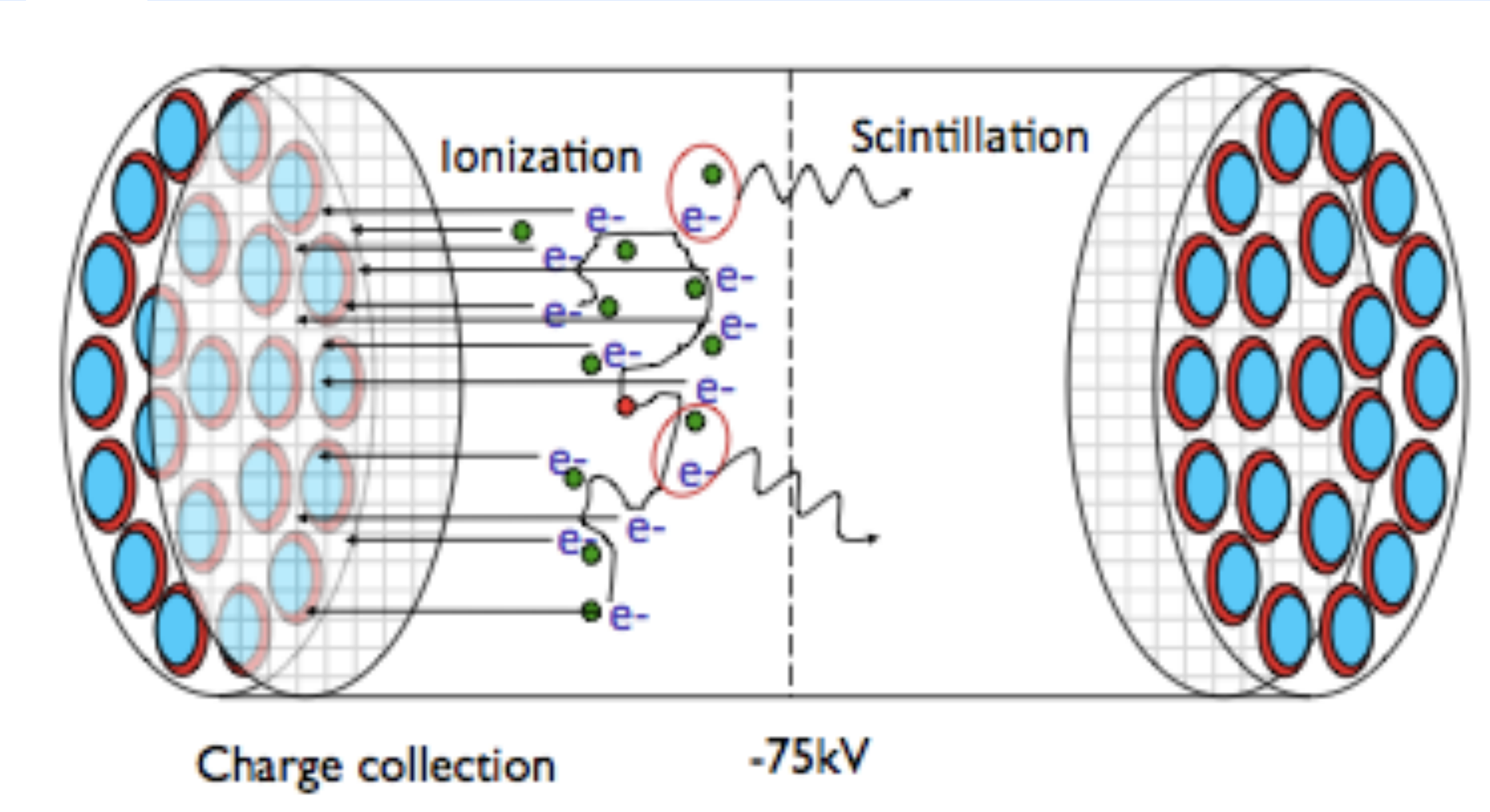
University of Seoul, South Korea - D. Leonard

SLAC National Accelerator Laboratory, Menlo Park CA, USA - M. Breidenbach, R. Conley, R. Herbst, S. Herrin, J. Hodgson, A. Johnson, D. Mackay, A. Odian, C.Y. Prescott, P.C. Rowson, J.J. Russell, K. Skarpaas, M. Swift, A. Waite, M. Wittgen, J. Wodin

Stanford University, Stanford CA, USA - P.S. Barbeau, T. Brunner, J. Davis, R. DeVoe, M.J. Dolinski, G. Gratta, M. Montero-Díez, A.R. Müller, R. Neilson, I. Ostrovskiy, K. O'Sullivan, A. Rivas, A. Sabourov, D. Tosi, K. Twelker

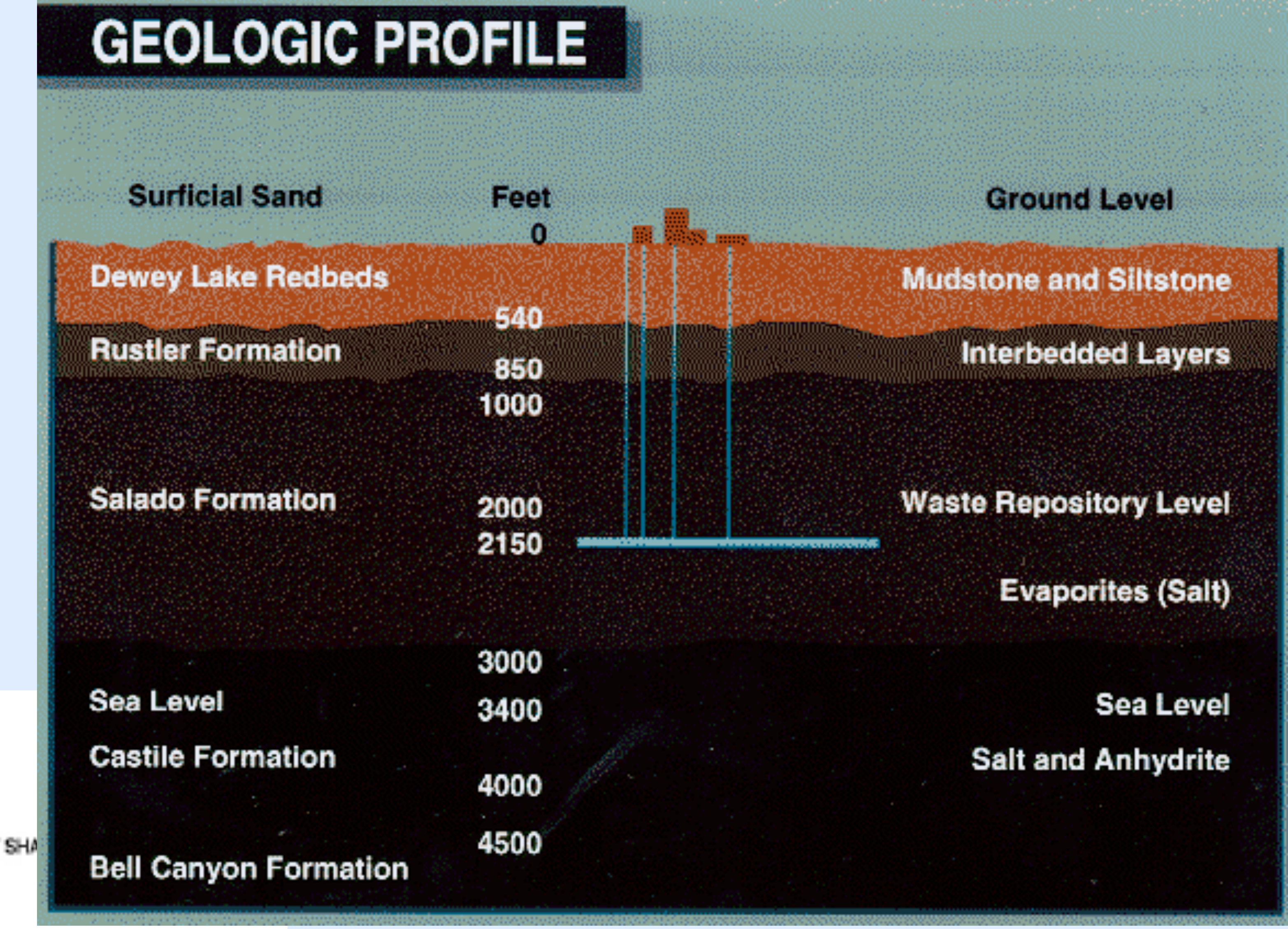
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

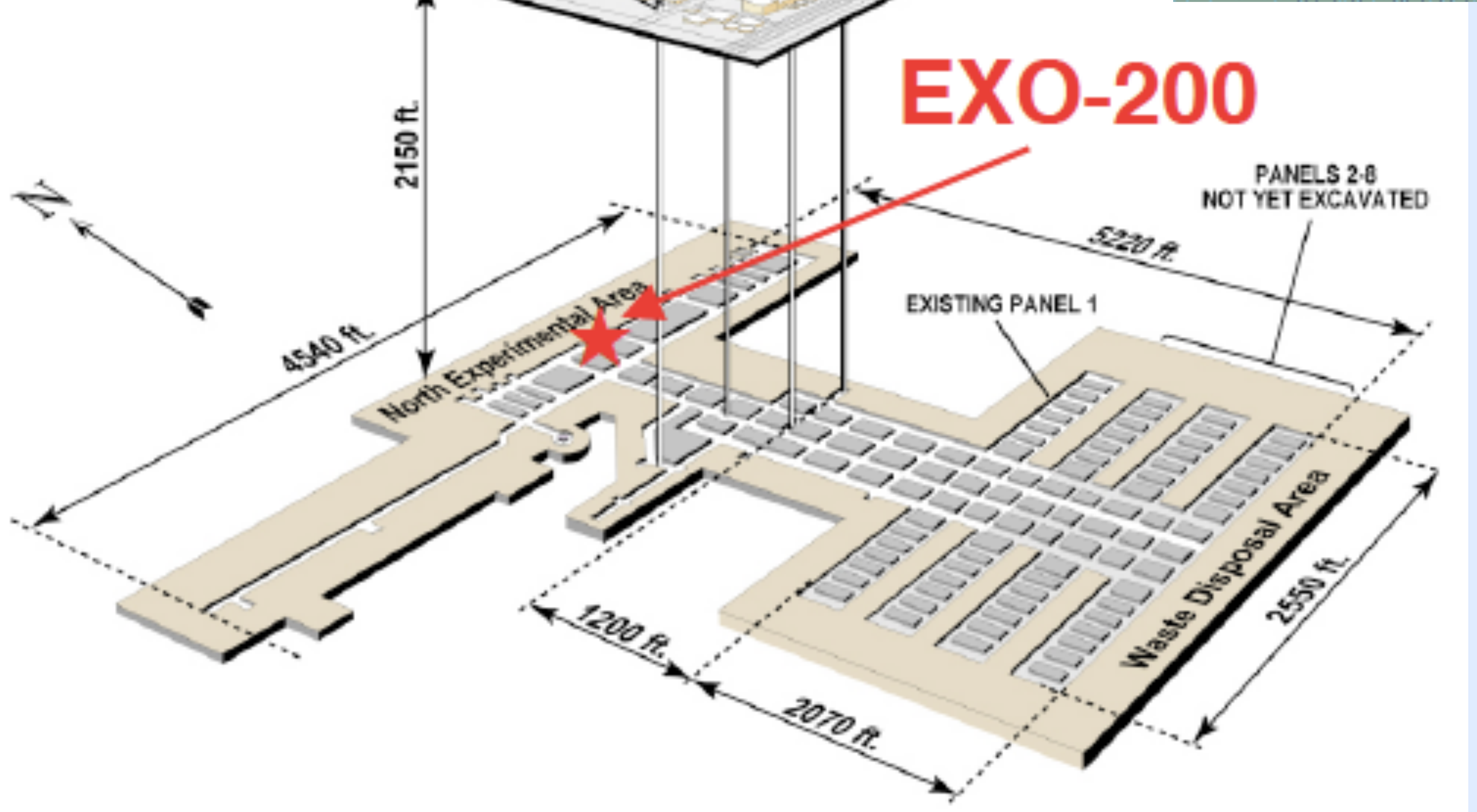
EXO-200 concept



- 200kg of xenon (80% enrichment in ^{136}Xe) liquid phase (~170 K)
- Ionizing events deposit energy as charge (slow) and scintillation (prompt)
- Collect scintillation on APDs
- Collect ionization on wires ---> charge preamplifiers
- Energy reconstruction, PID, from ionization+scintillation ($\Delta E/E = 1.4\%$ at $Q_{\beta\beta}$)

EXO-200 at WIPP



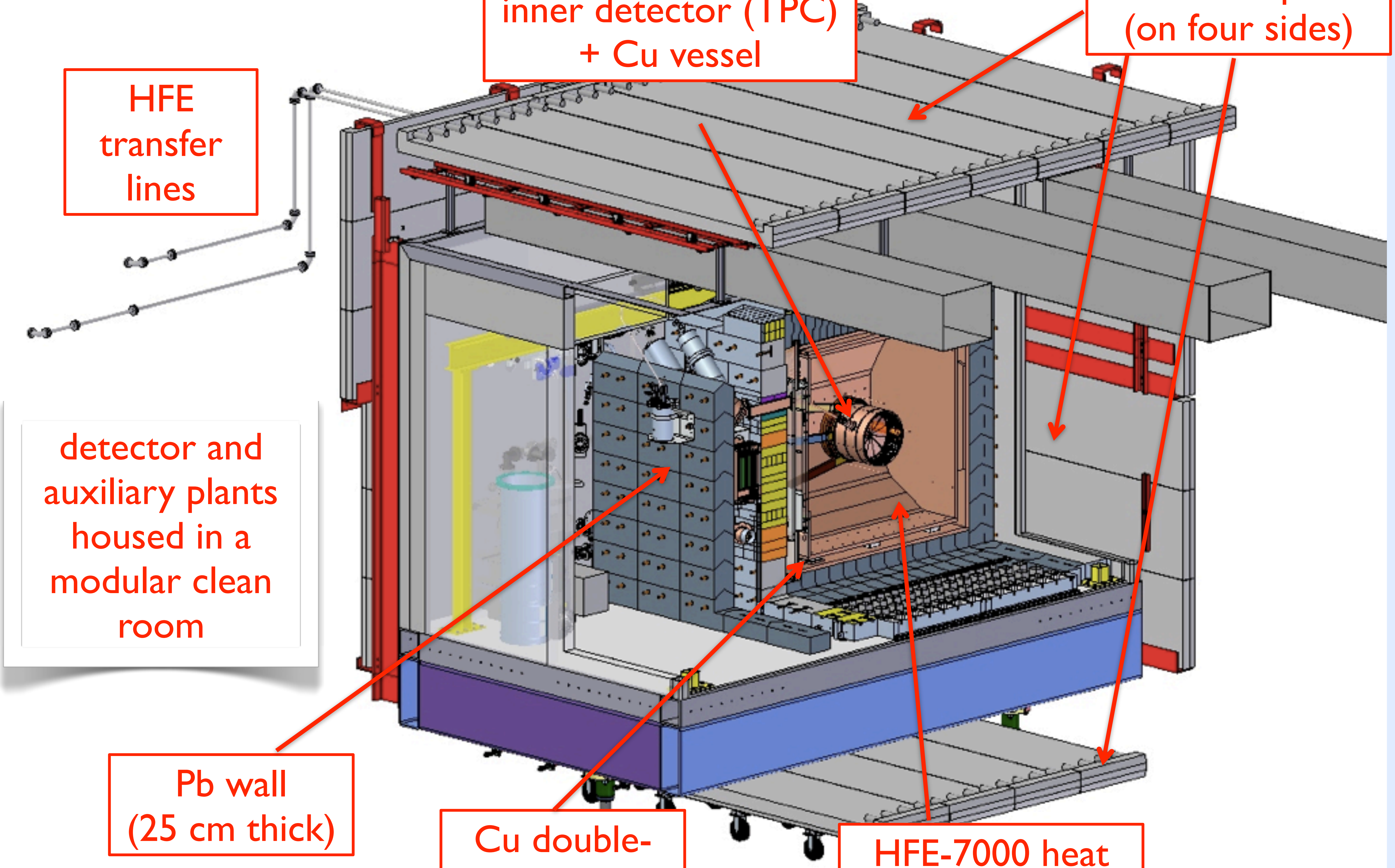


- ~1600 m.w.e. overburden (650 meters or rock + salt)

  [Esch et al., NIM A 538, 516 (2005)]

- <100 ppb U,Th
- ~20 Bq/m^3 radon

EXO-200



HFE transfer lines

inner detector (TPC) + Cu vessel

muon veto panels (on four sides)

detector and auxiliary plants housed in a modular clean room

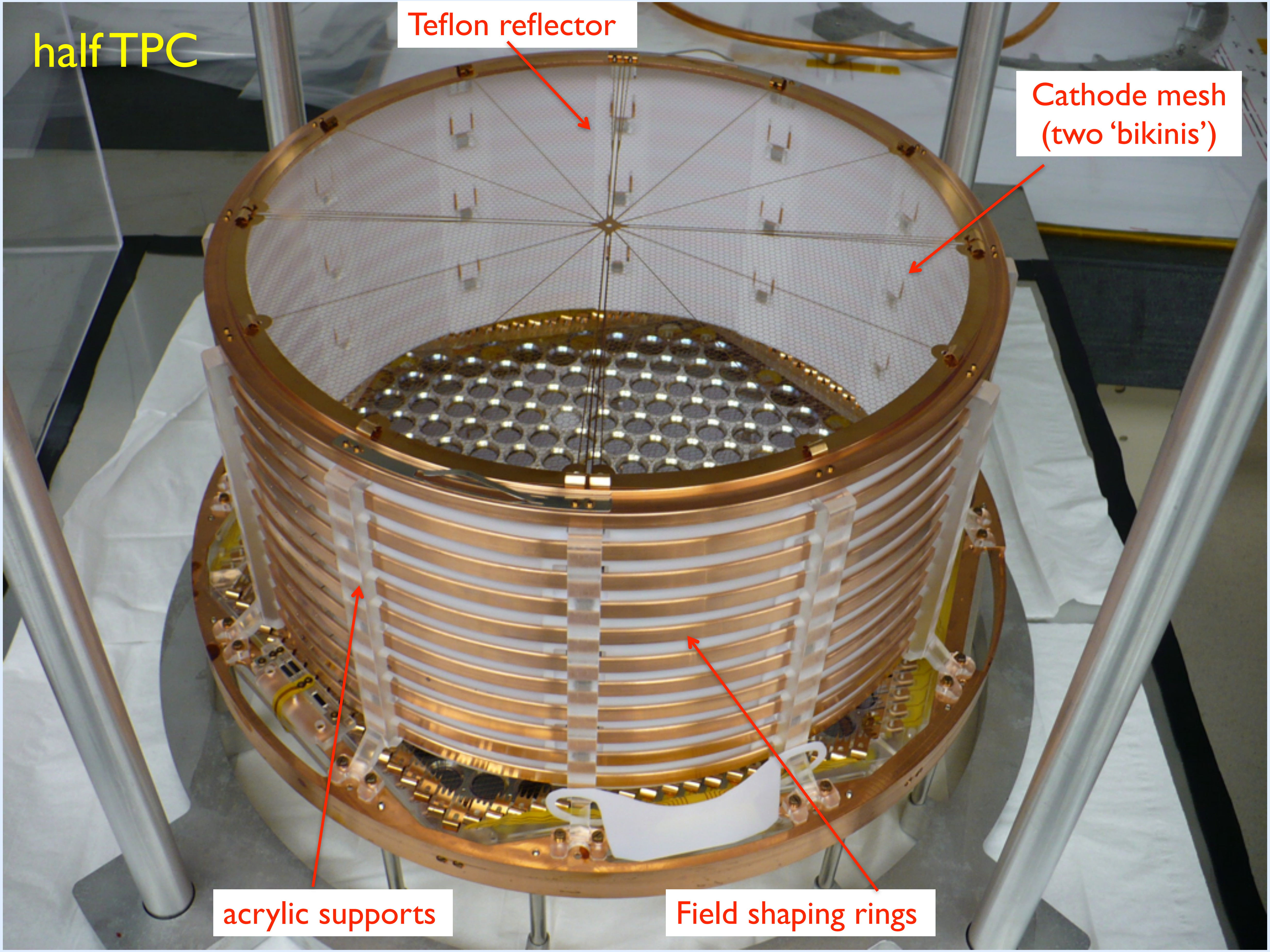
Pb wall (25 cm thick)

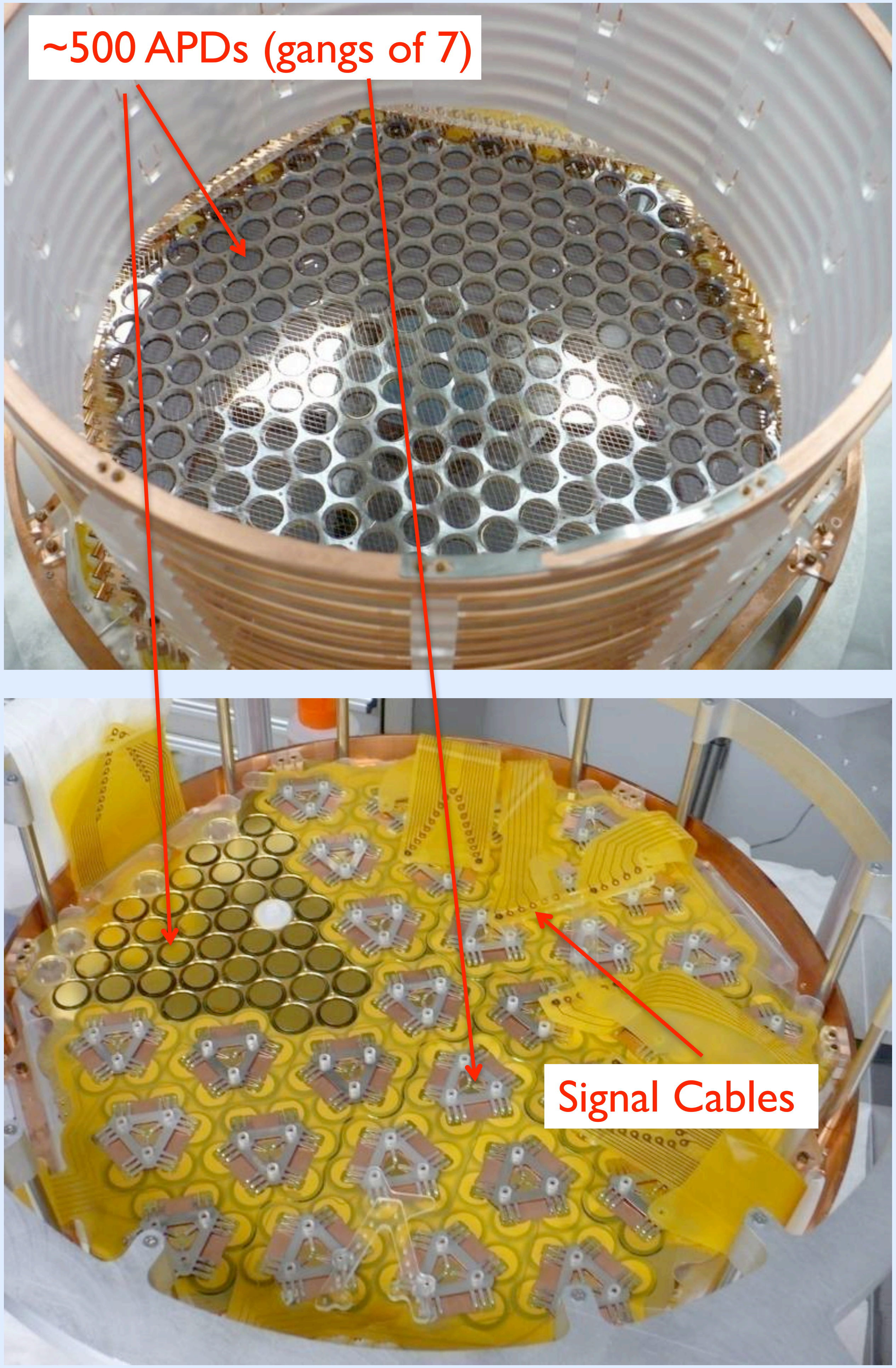
Cu double-walled cryostat

HFE-7000 heat transfer fluid (~4 tonnes)

EXO-200 @ WIPP

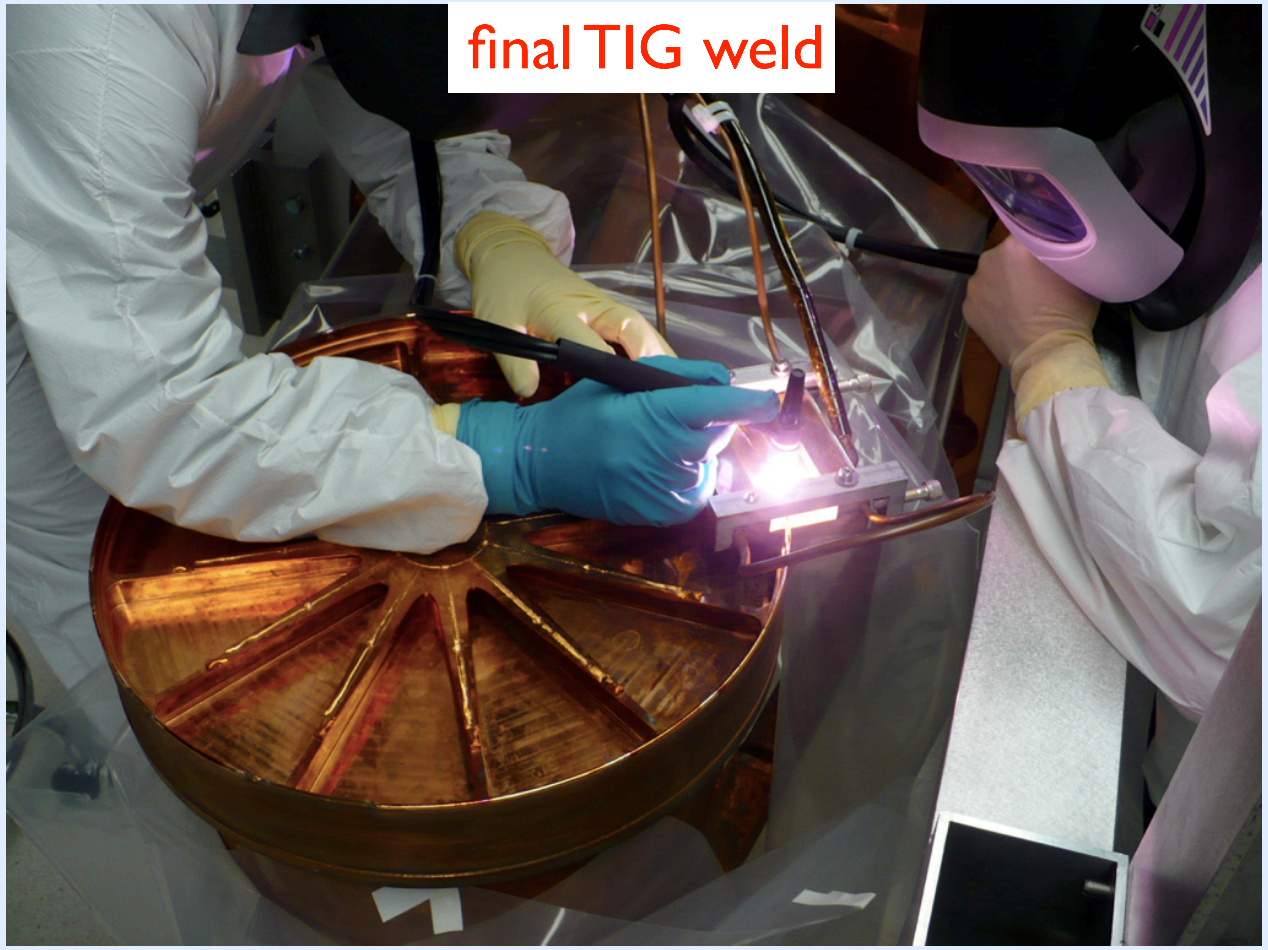
the EXO-200 TPC



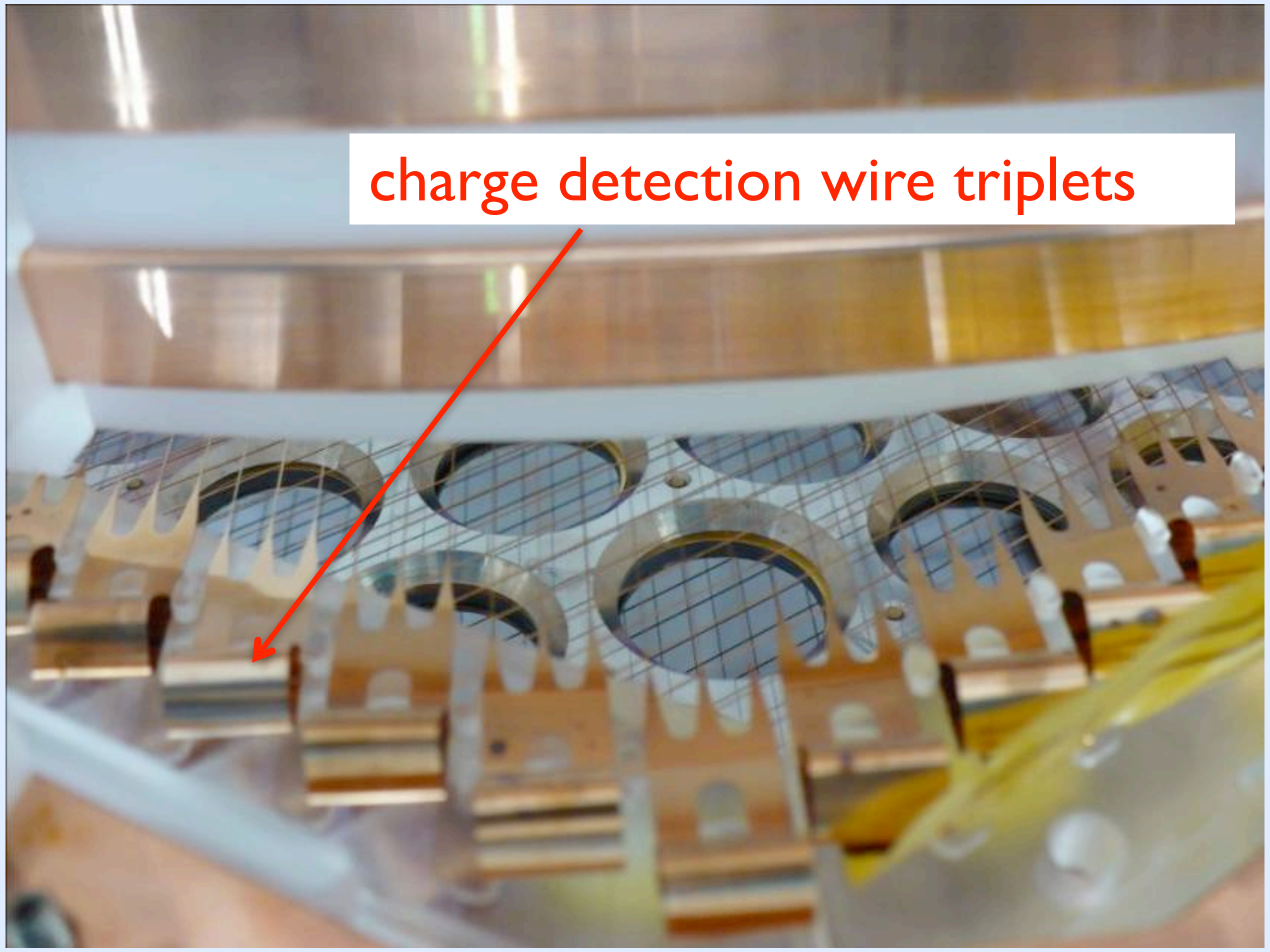


~500 APDs (gangs of 7)

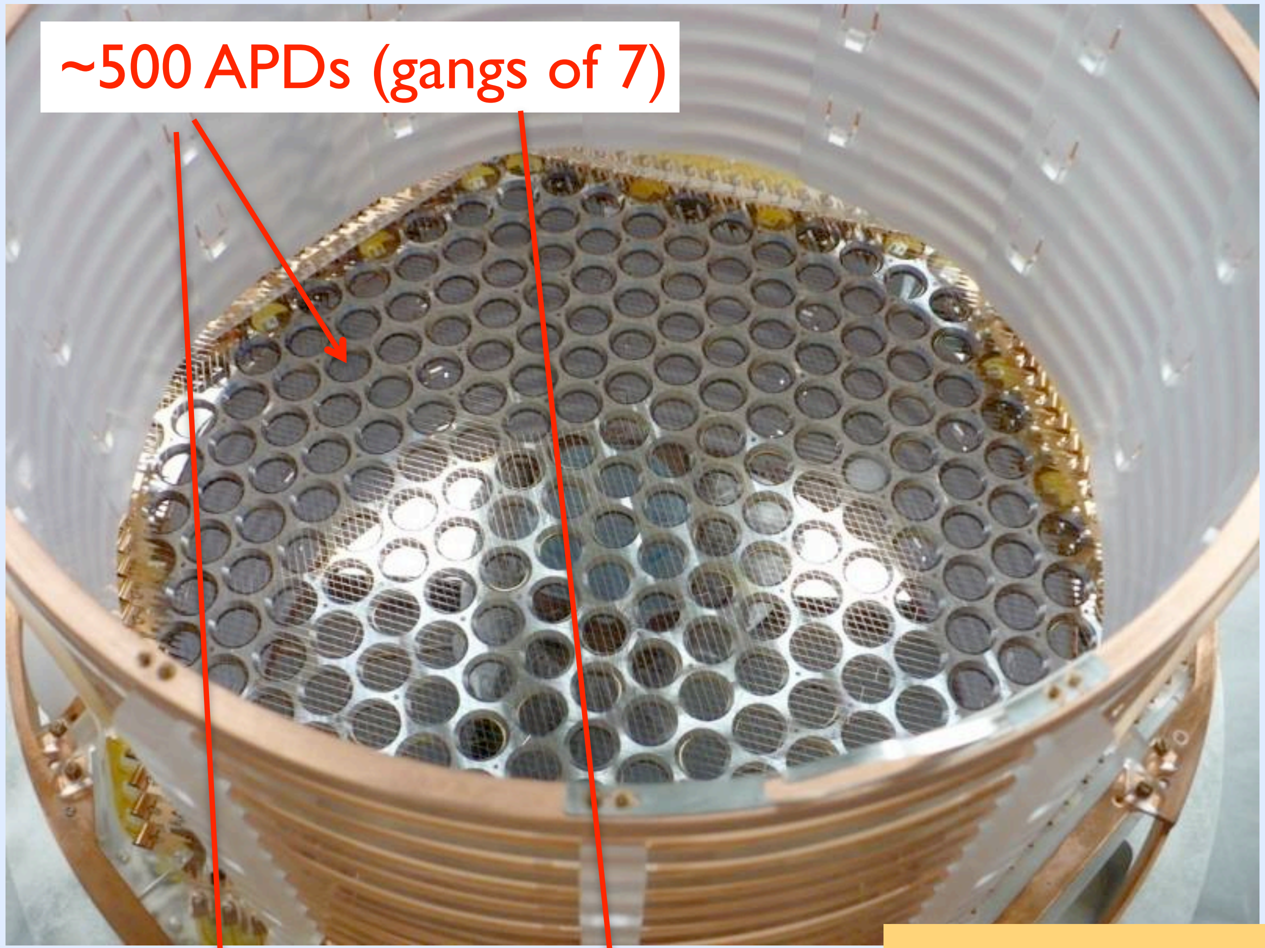
Signal Cables



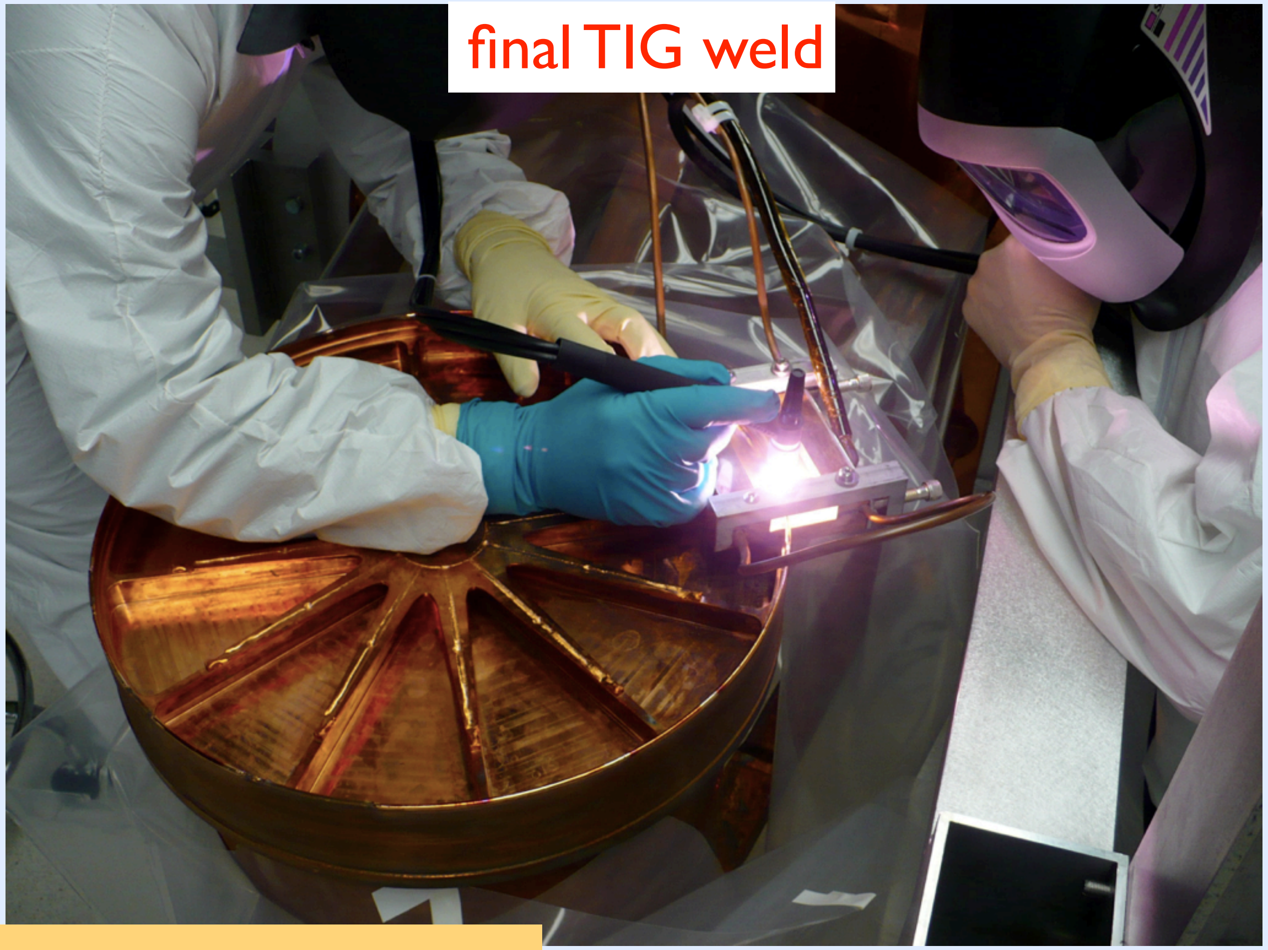
final TIG weld



charge detection wire triplets

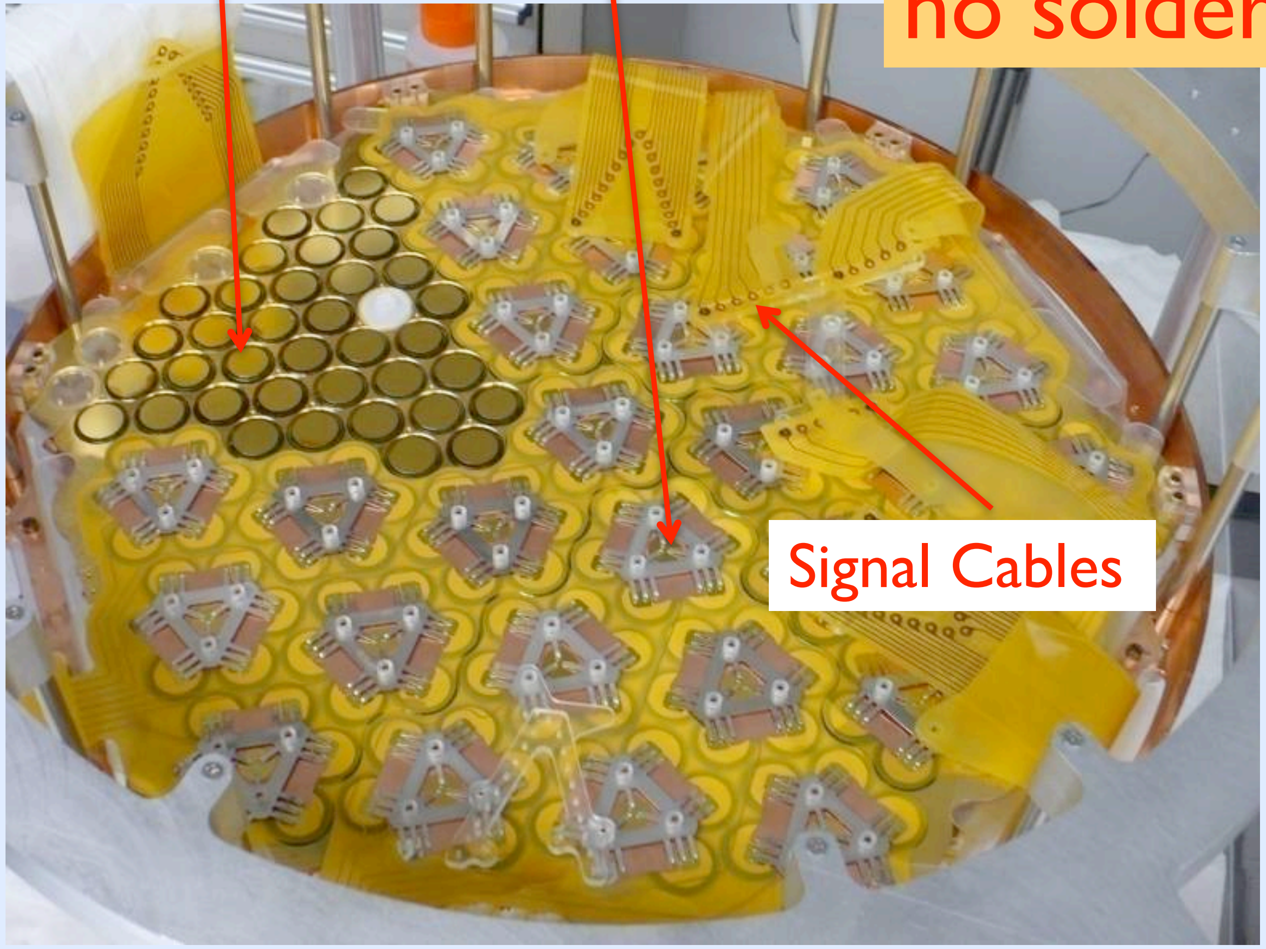


~500 APDs (gangs of 7)

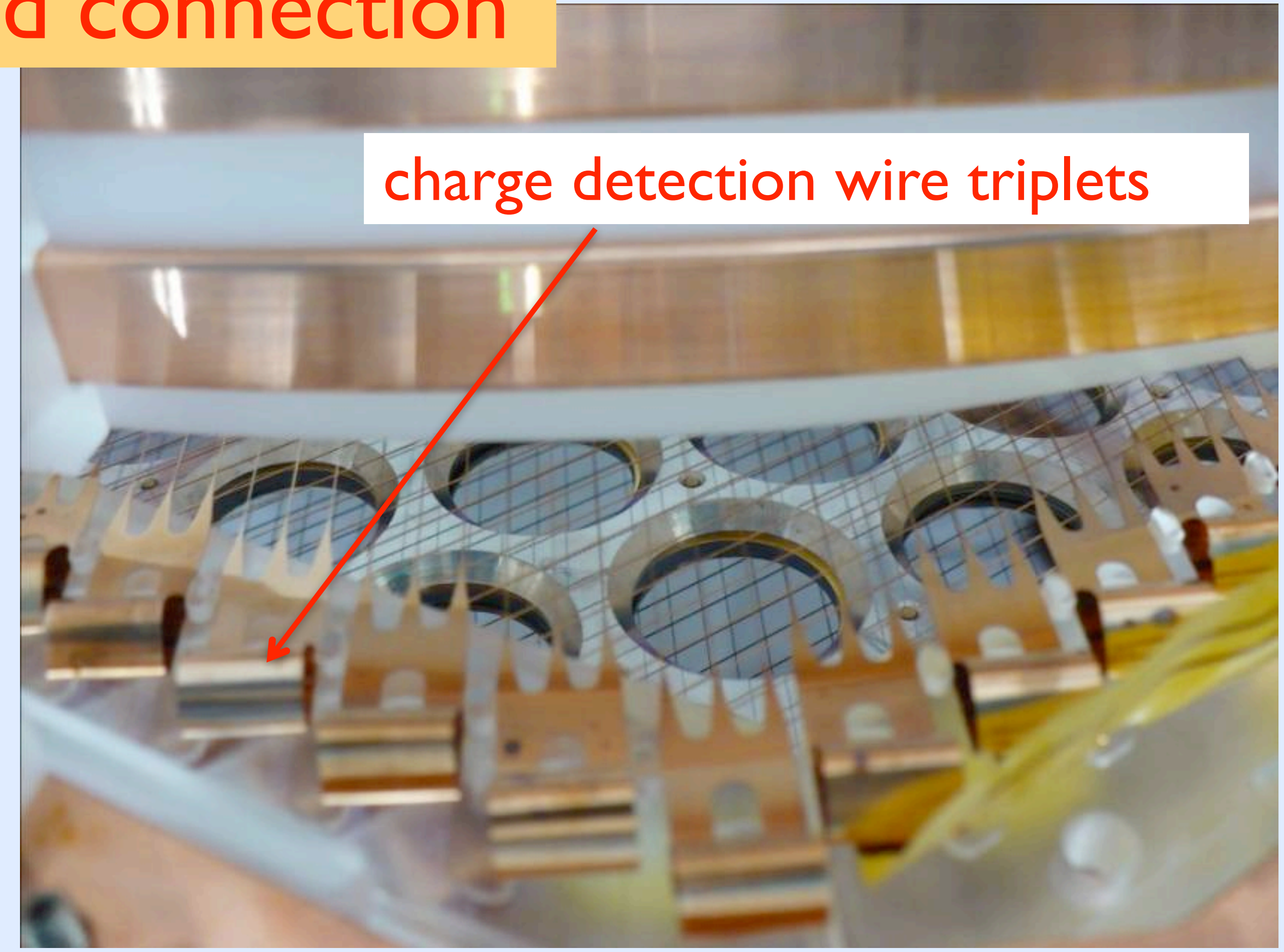


final TIG weld

no soldered connection

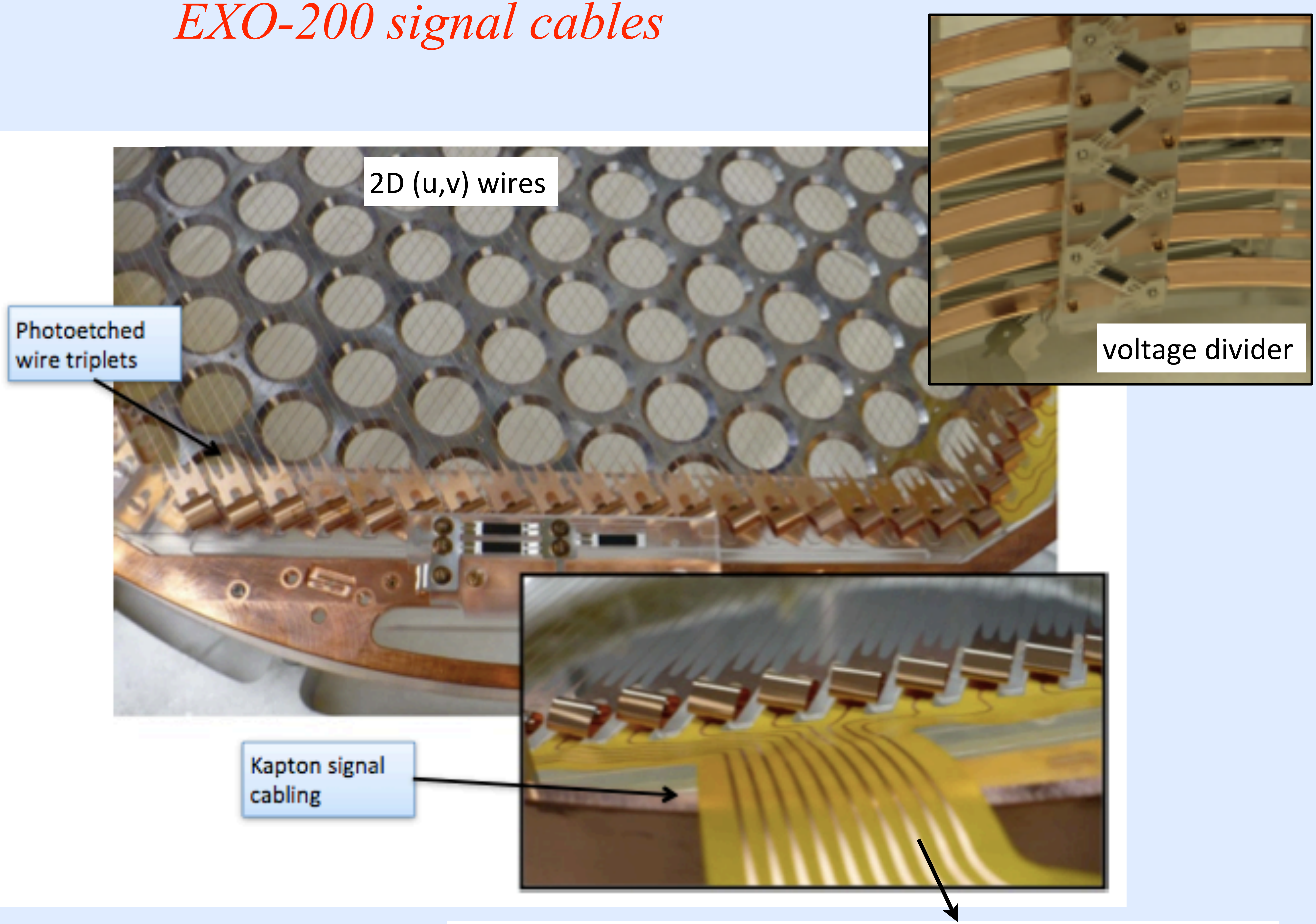


Signal Cables



charge detection wire triplets

EXO-200 signal cables



2D (u,v) wires

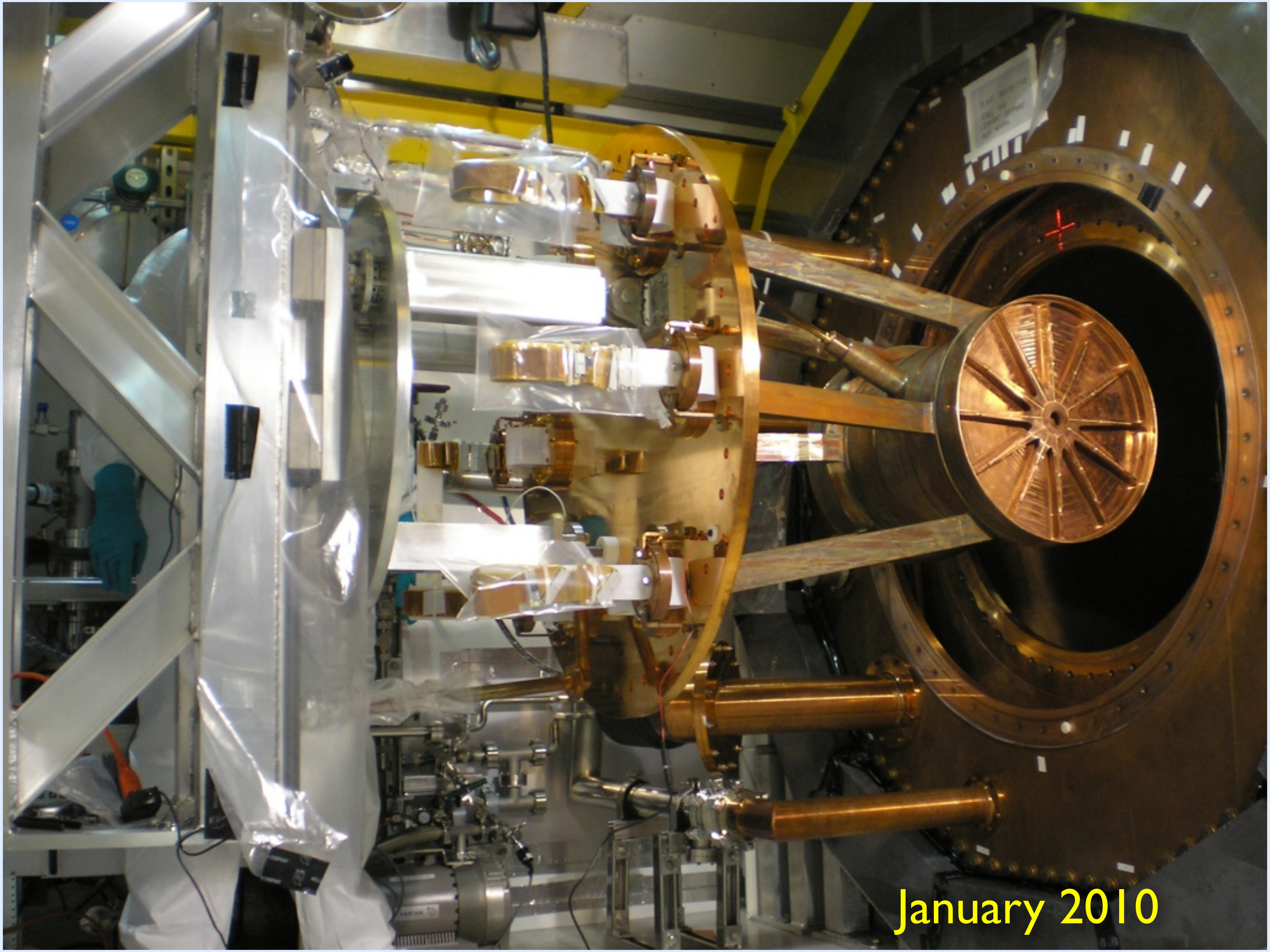
Photoetched wire triplets

voltage divider

Kapton signal cabling

Signal cabling penetrates TPC and cryostat (no “feedthroughs”)

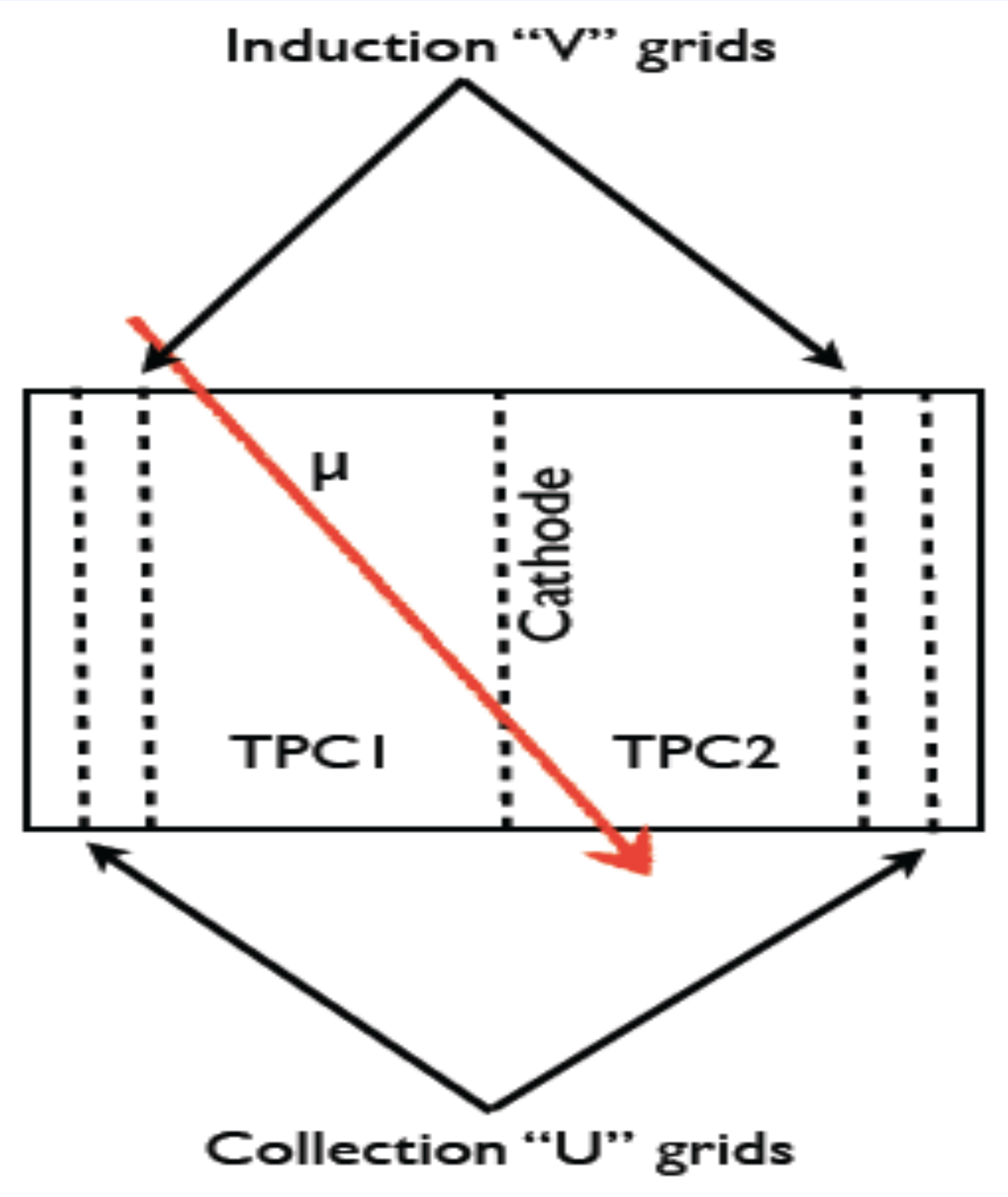
EXO-200



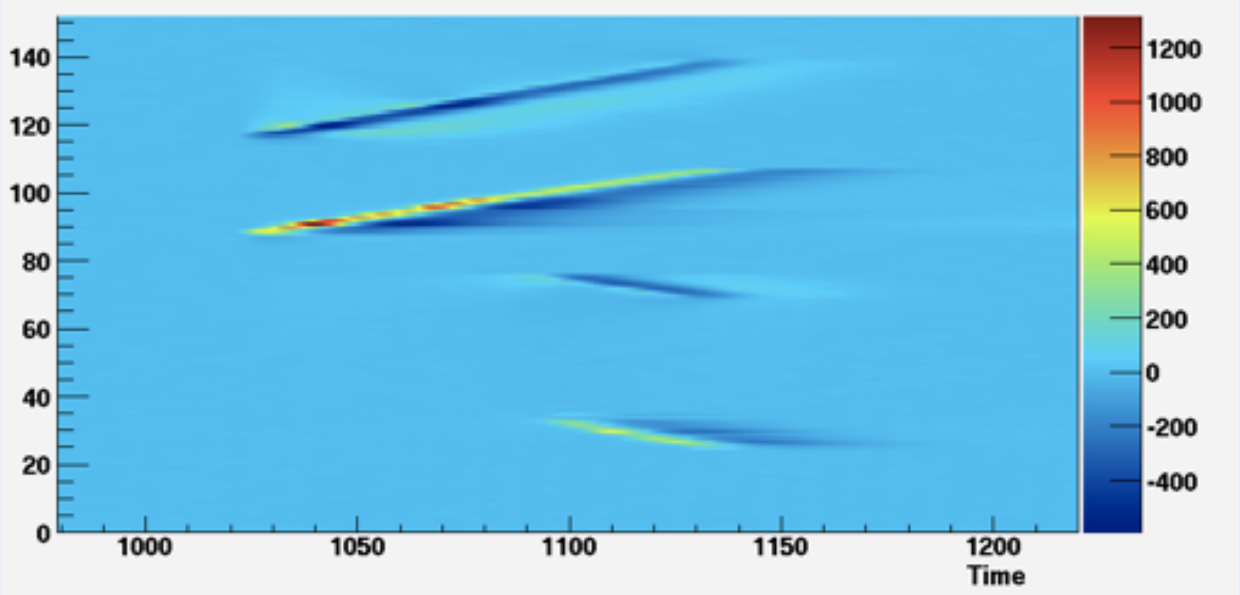
January 2010

EXO-200 engineering run (Dec 2010)

- ✓ natural xenon
- ✓ test stability of LXe/GXe systems
- ✓ measure Xe purity
- ✓ generally test detector performance
- ✓ test source calibration system
- ✓ test Xe emergency recovery
- ✳ no front Pb shield
- ✳ no Rn-suppressed enclosure
- ✳ no Rn trap in Xe system
- ✳ no muon veto



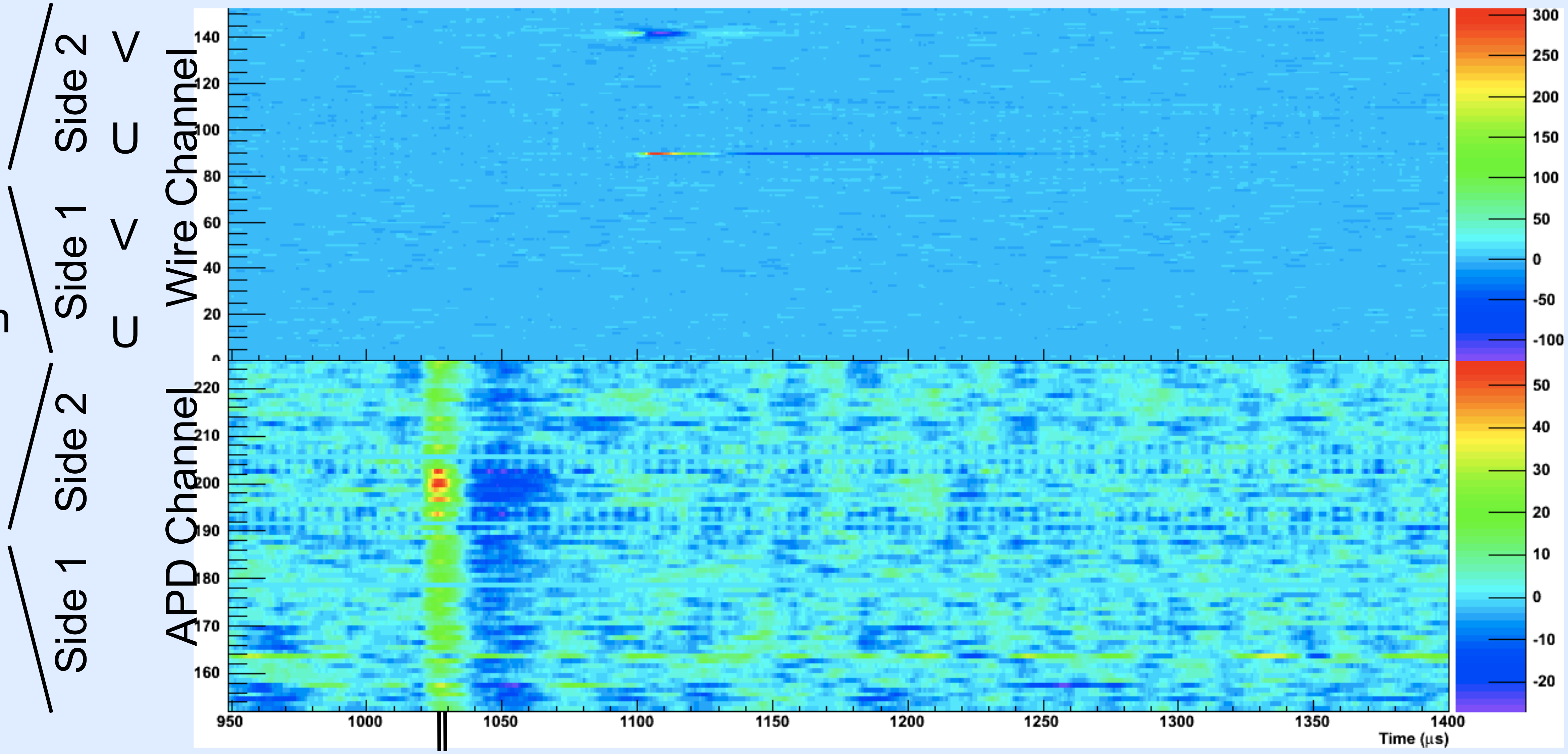
a muon event:



Charge readout

V: Induction
U: Collection

Light readout

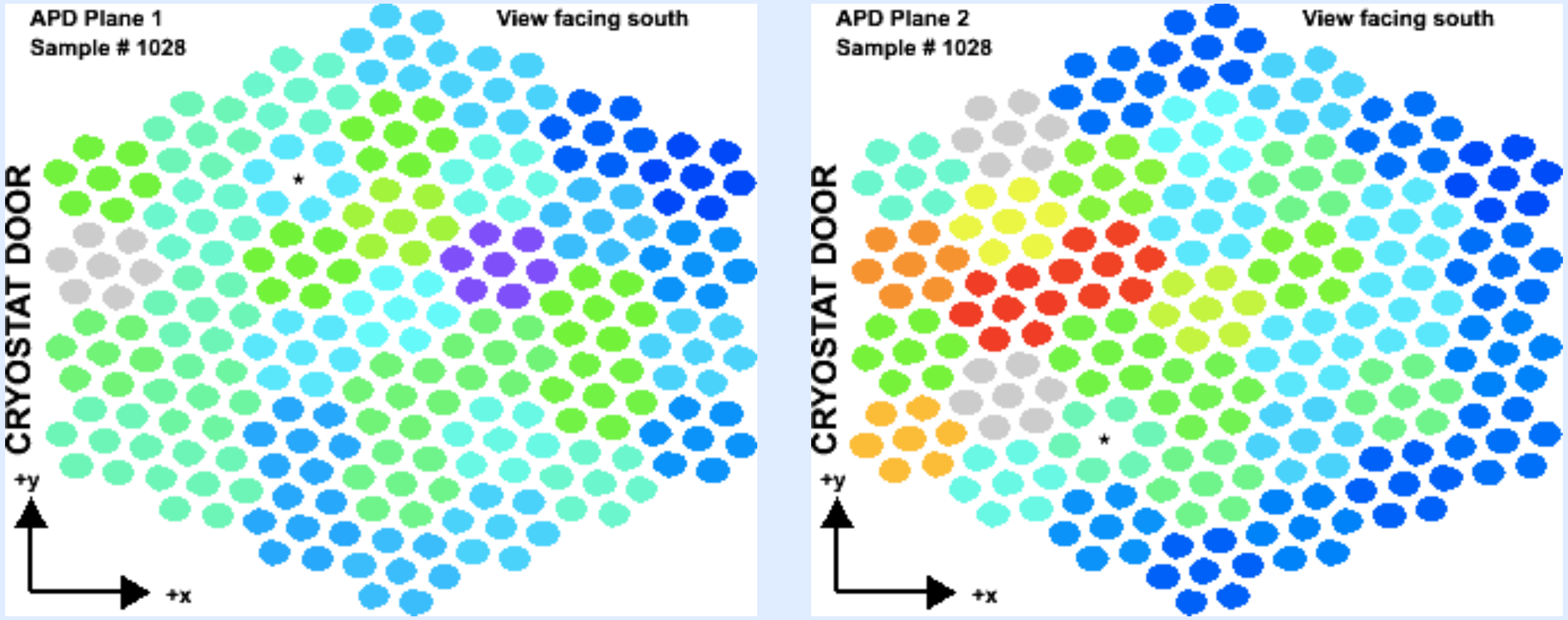


A single-site energy deposition in EXO-200

Scintillation light is seen at both sides. The light is more diffuse on side 1 and more localized on side 2, where the event occurred.

The light signal always precedes both charge signals. The induction (V) signal precedes the collection (U) signal.

one sample



Charge readout

V: Induction
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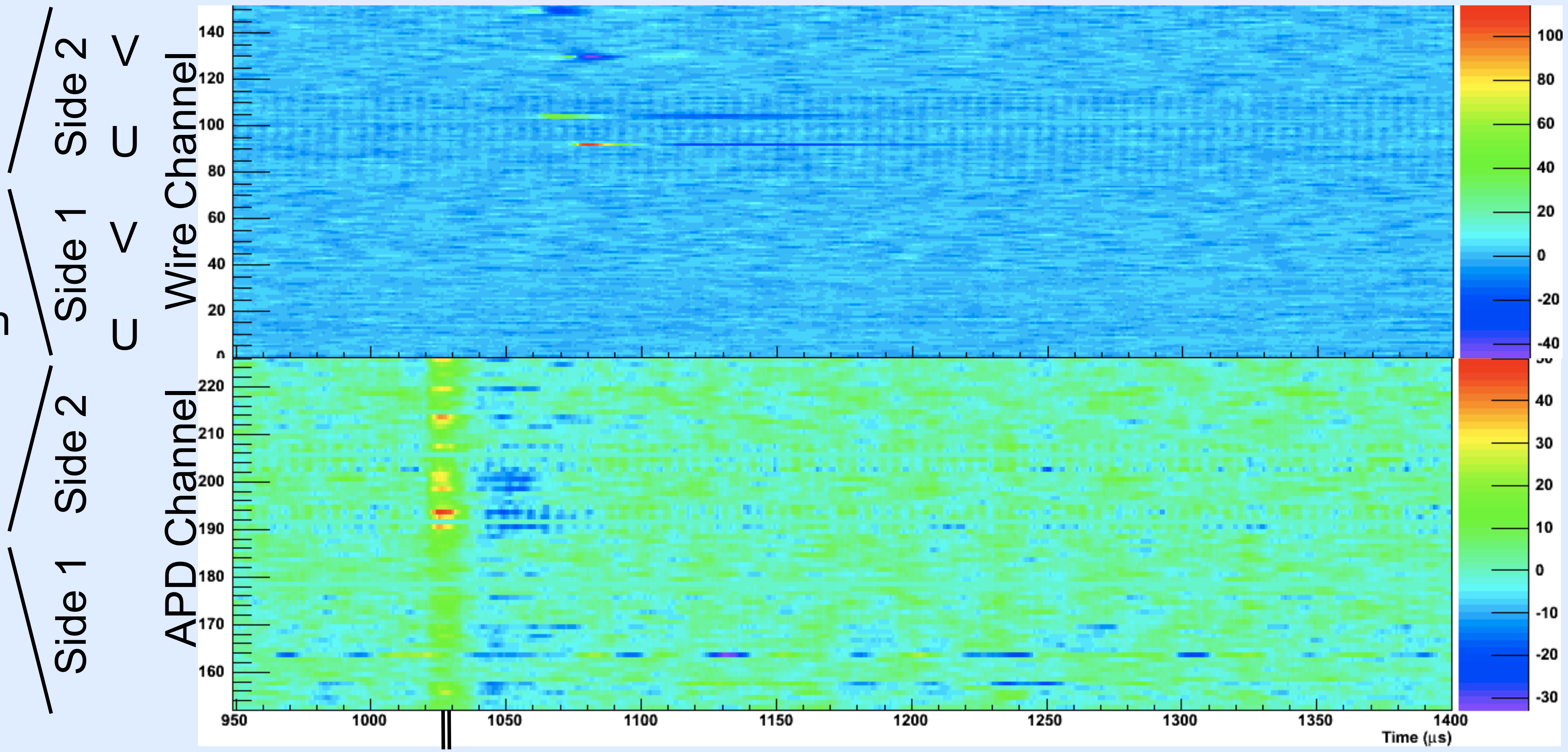
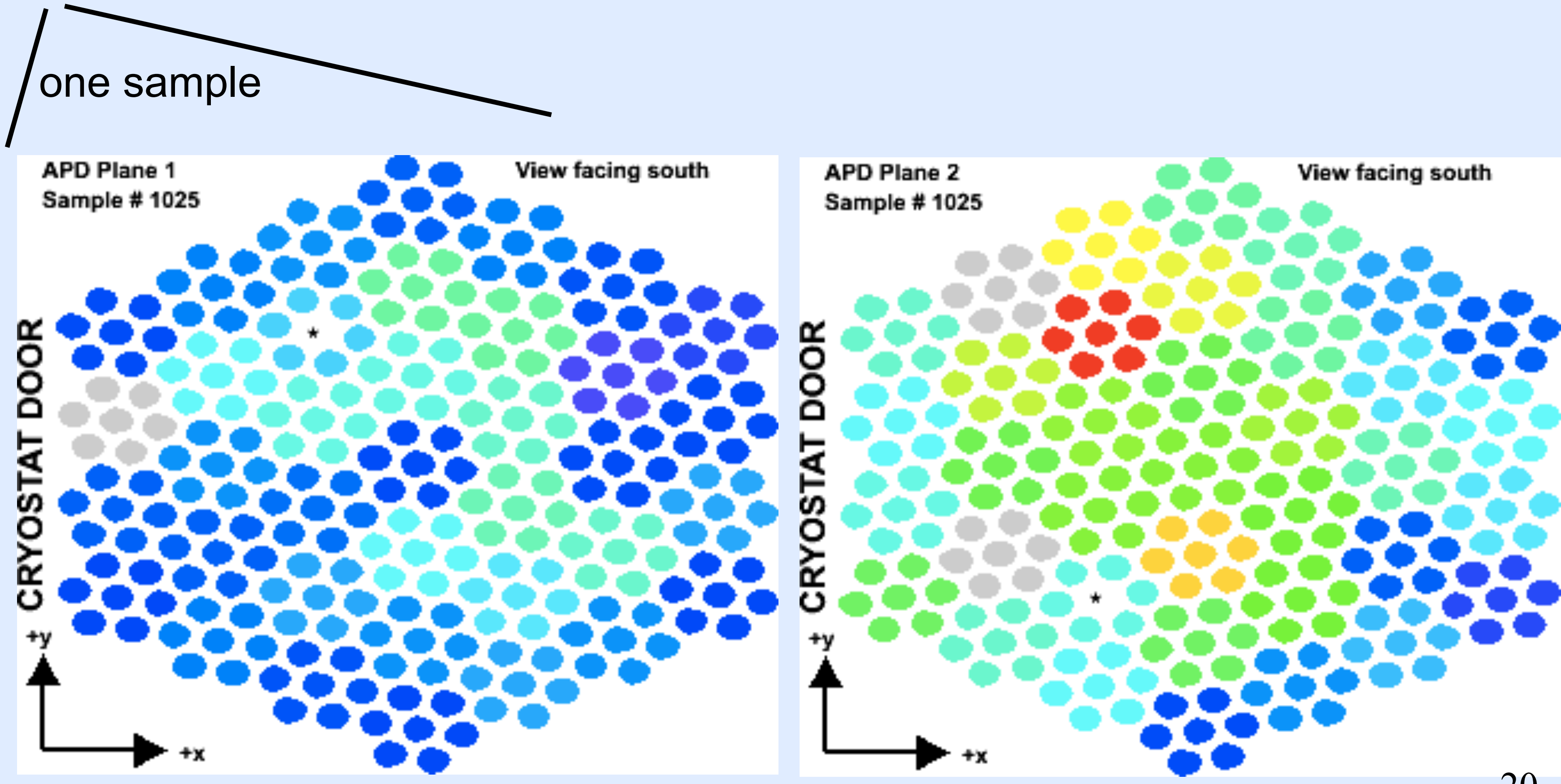
Light readout



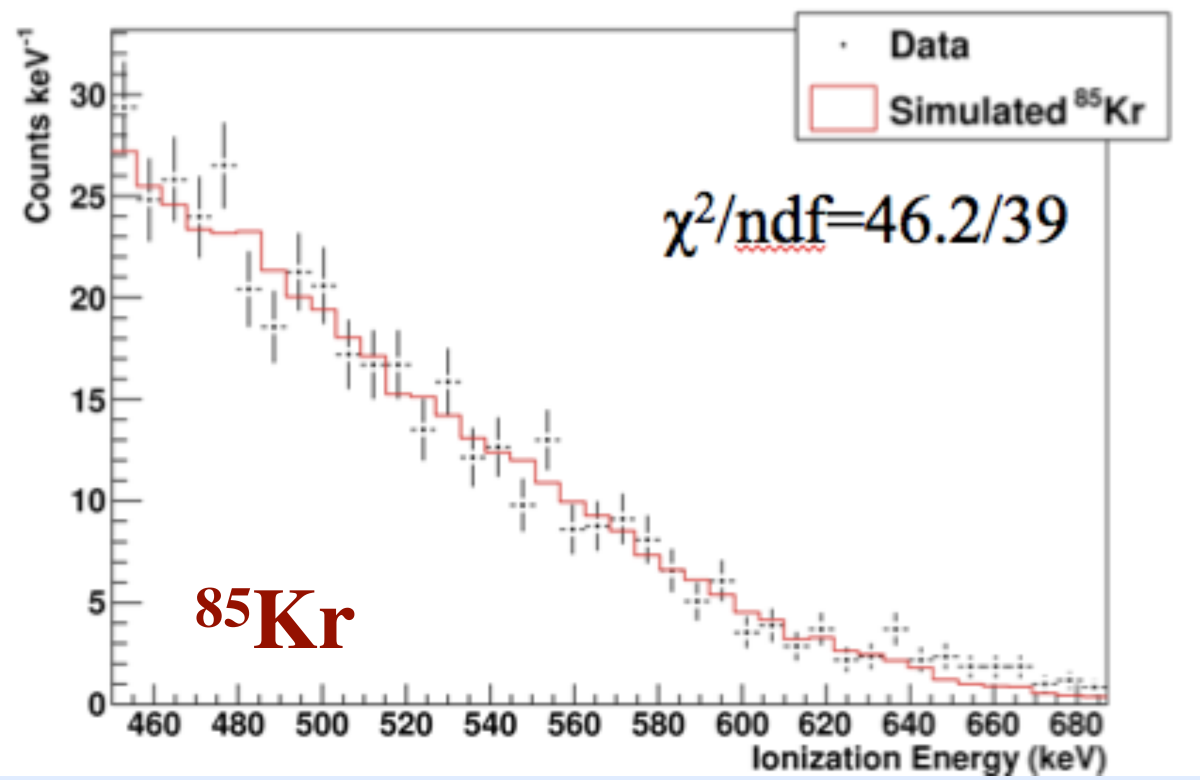
A two-site Compton scattering event

All scintillation light arrives at the same time, indicating that the two energy depositions are simultaneous.

In this case, the gamma ray occurred on side 2. The light hitting side 2 is more localized, while the light hitting side 1 is more diffuse across the plane.



known offenders (in ^{nat}Xe, Dec ’10)



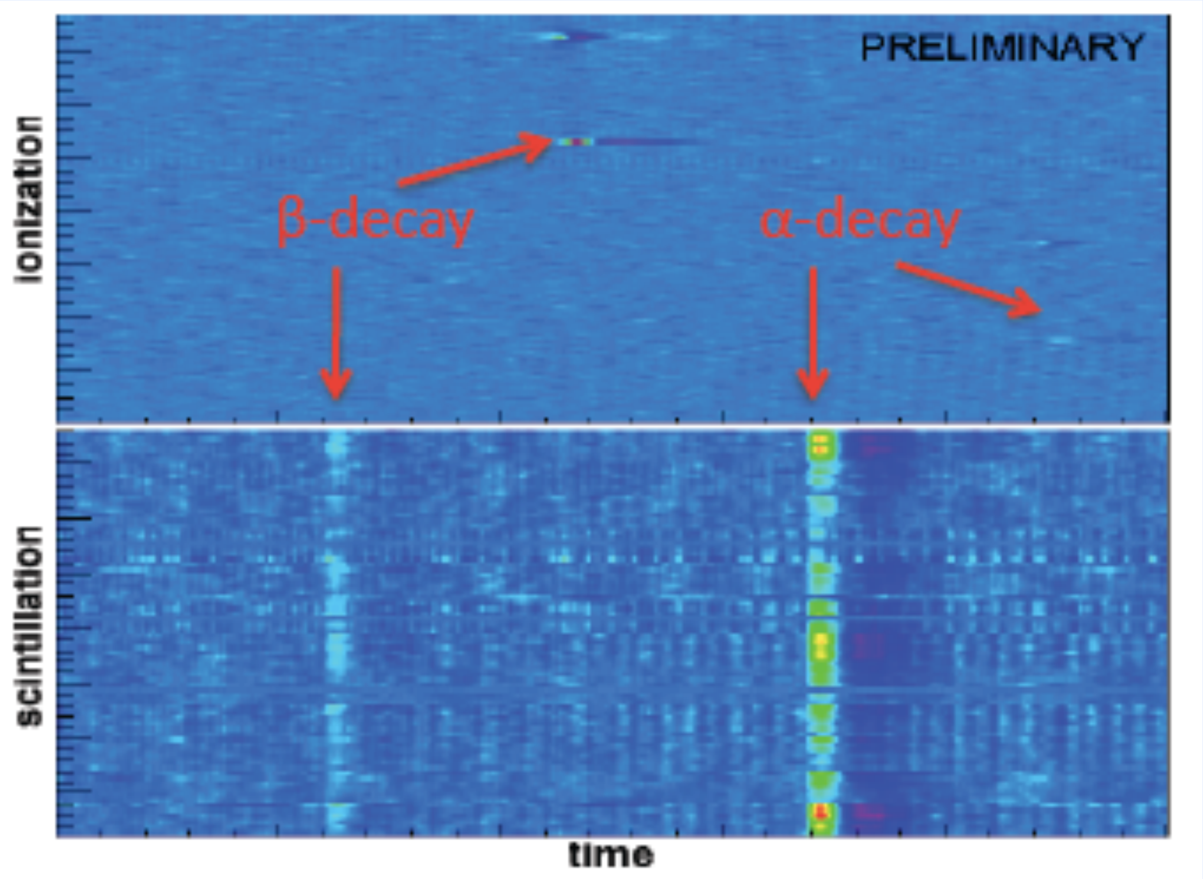
^{85}Kr

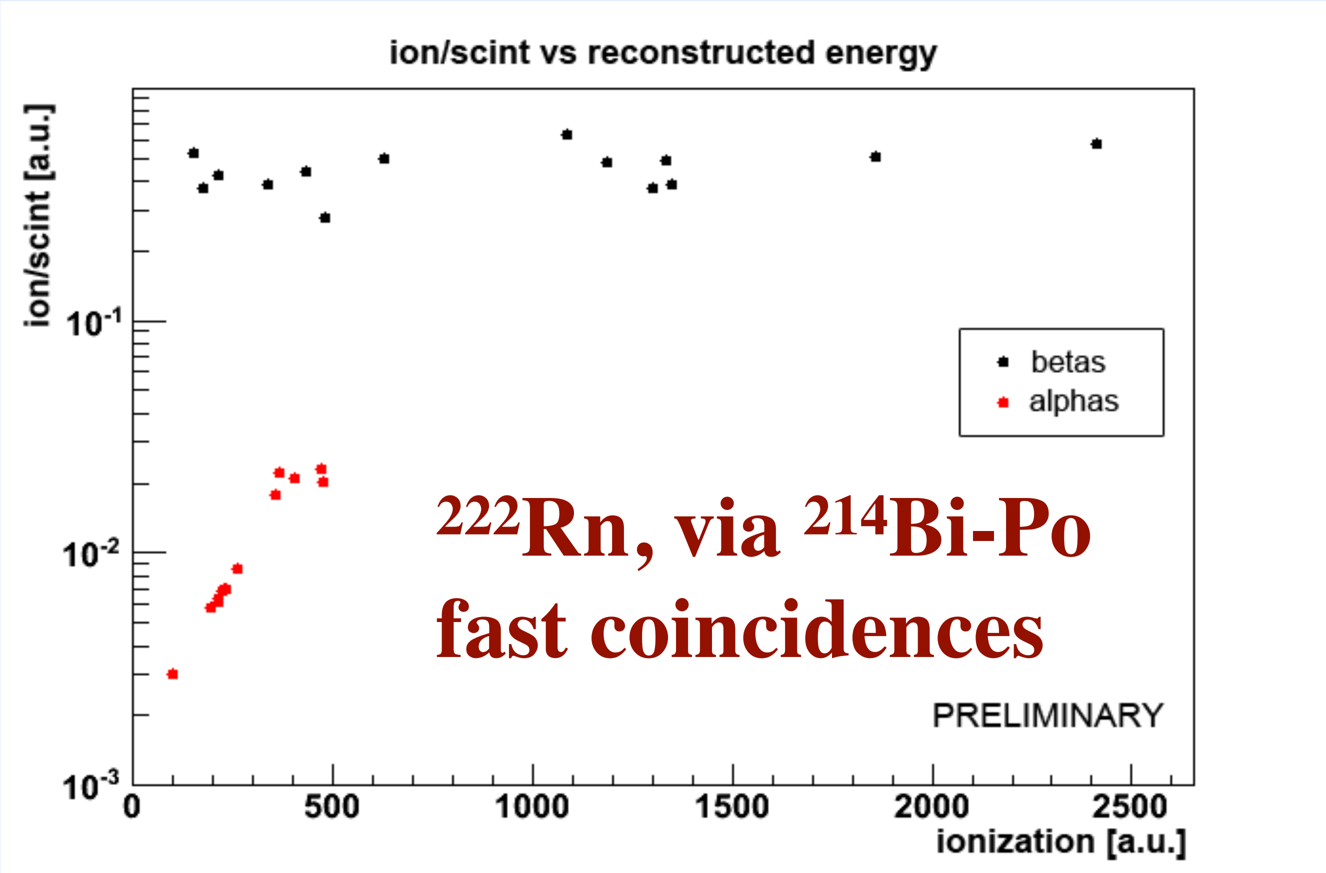
the total Kr concentration in the ^{nat}Xe was measured to be, using a special technique involving mass-spectroscopic analysis in the gas phase,

$$(42.6\pm5.7)\cdot10^{-9}\ \text{g/g}$$

[A. Dobi et al., arXiv:1103.2714v1]

→ consistent with Mass Spec result assuming standard ^{85}Kr/Kr concentration of ~10^{-11}

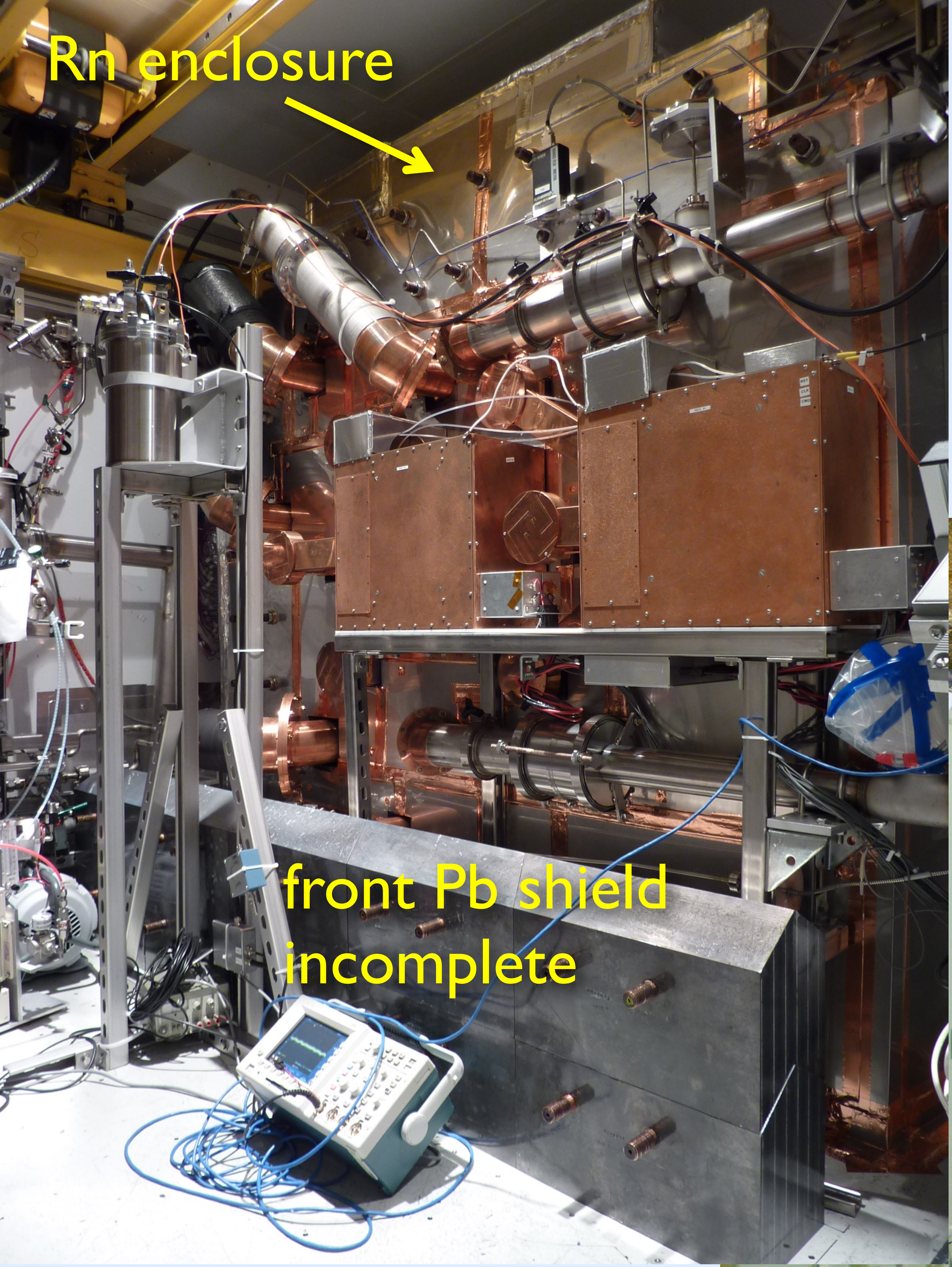




^{222}Rn, via ^{214}Bi-Po fast coincidences

low bg run

running with enriched xenon since spring 2011

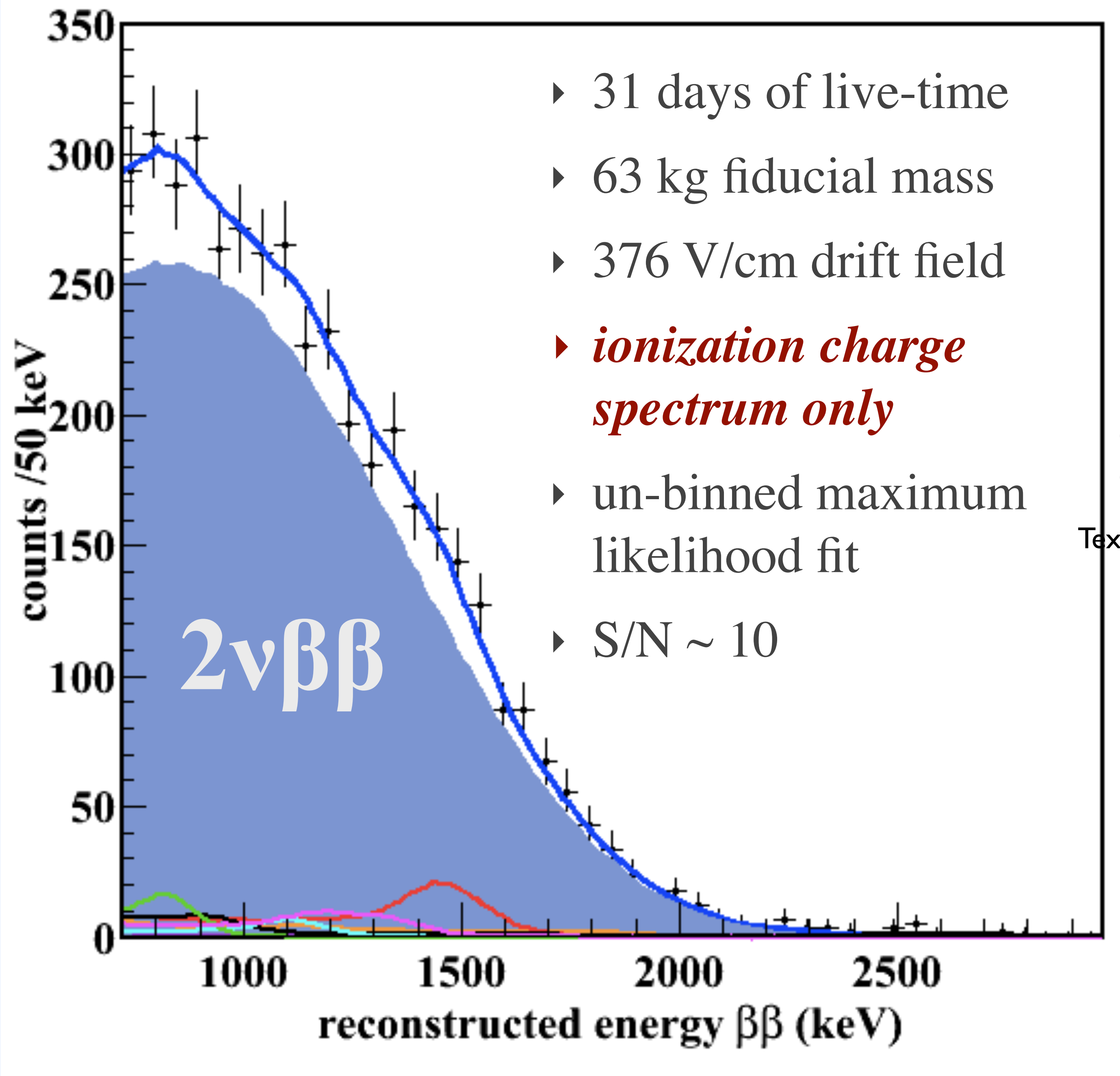


Rn enclosure

front Pb shield incomplete

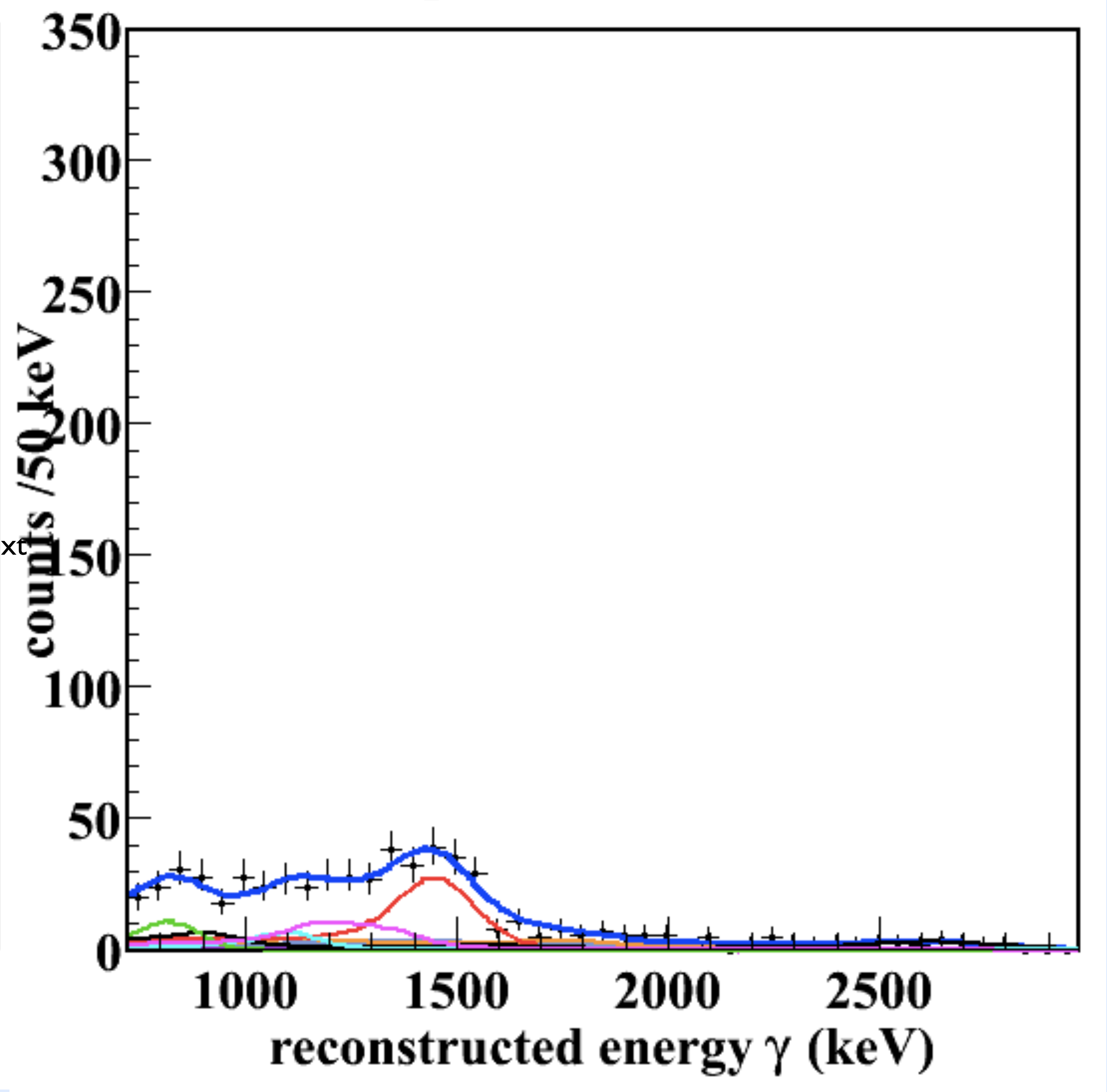
first observation of 2νββ of ^{136}Xe

single cluster events



- 31 days of live-time
- 63 kg fiducial mass
- 376 V/cm drift field
- ***ionization charge spectrum only***
- un-binned maximum likelihood fit
- S/N ~ 10

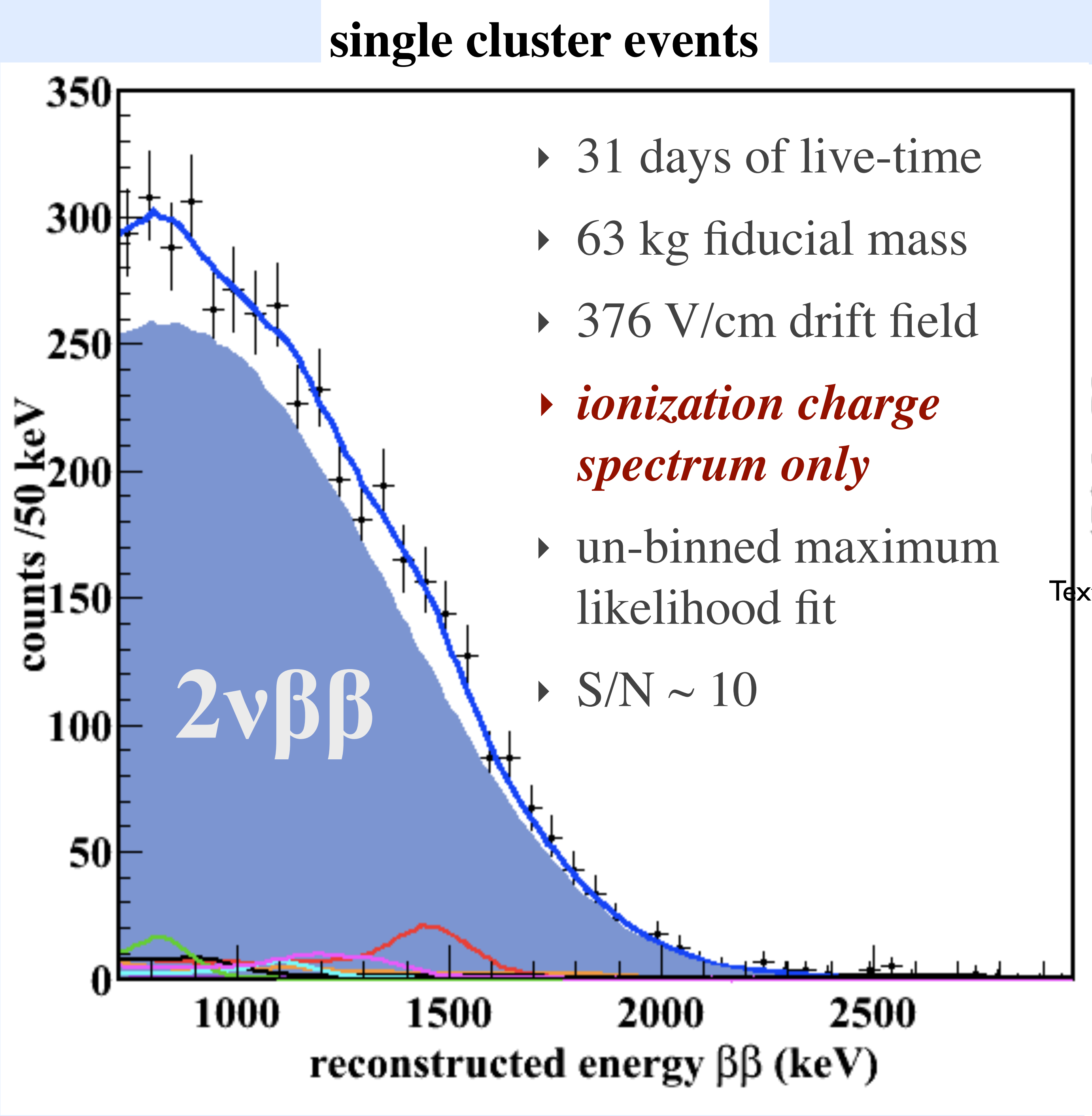
multiple cluster events



$$T^{2\nu}_{1/2} = (\mathbf{2.11} \pm \mathbf{0.04}(\mathbf{stat}) \pm \mathbf{0.21}(\mathbf{syst})) \times \mathbf{10^{21}}\ \text{years}$$

[PRL 107, 212501 (2011); arXiv:1108.4193]

first observation of $2\nu\beta\beta$ of ^{136}Xe



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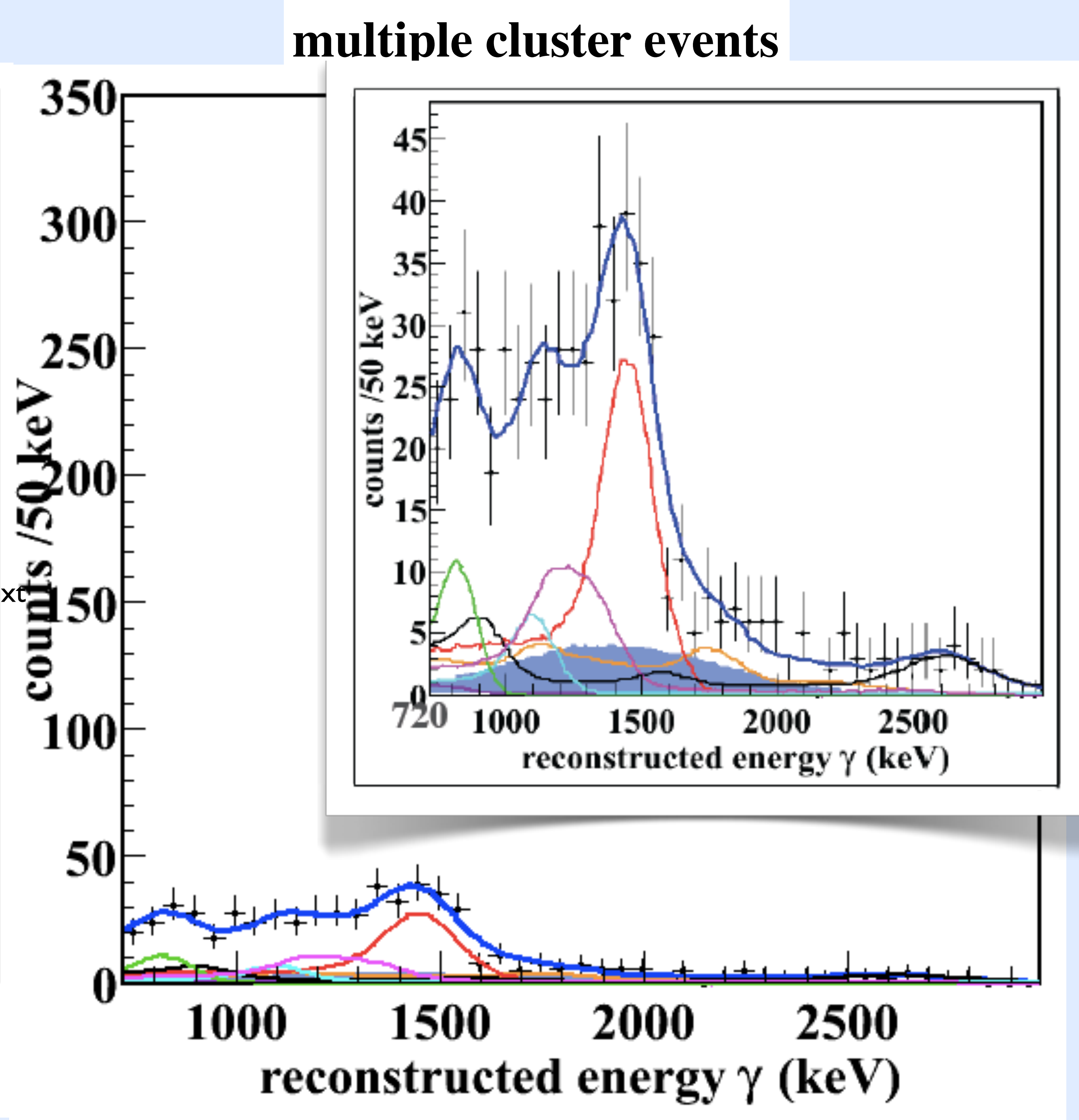

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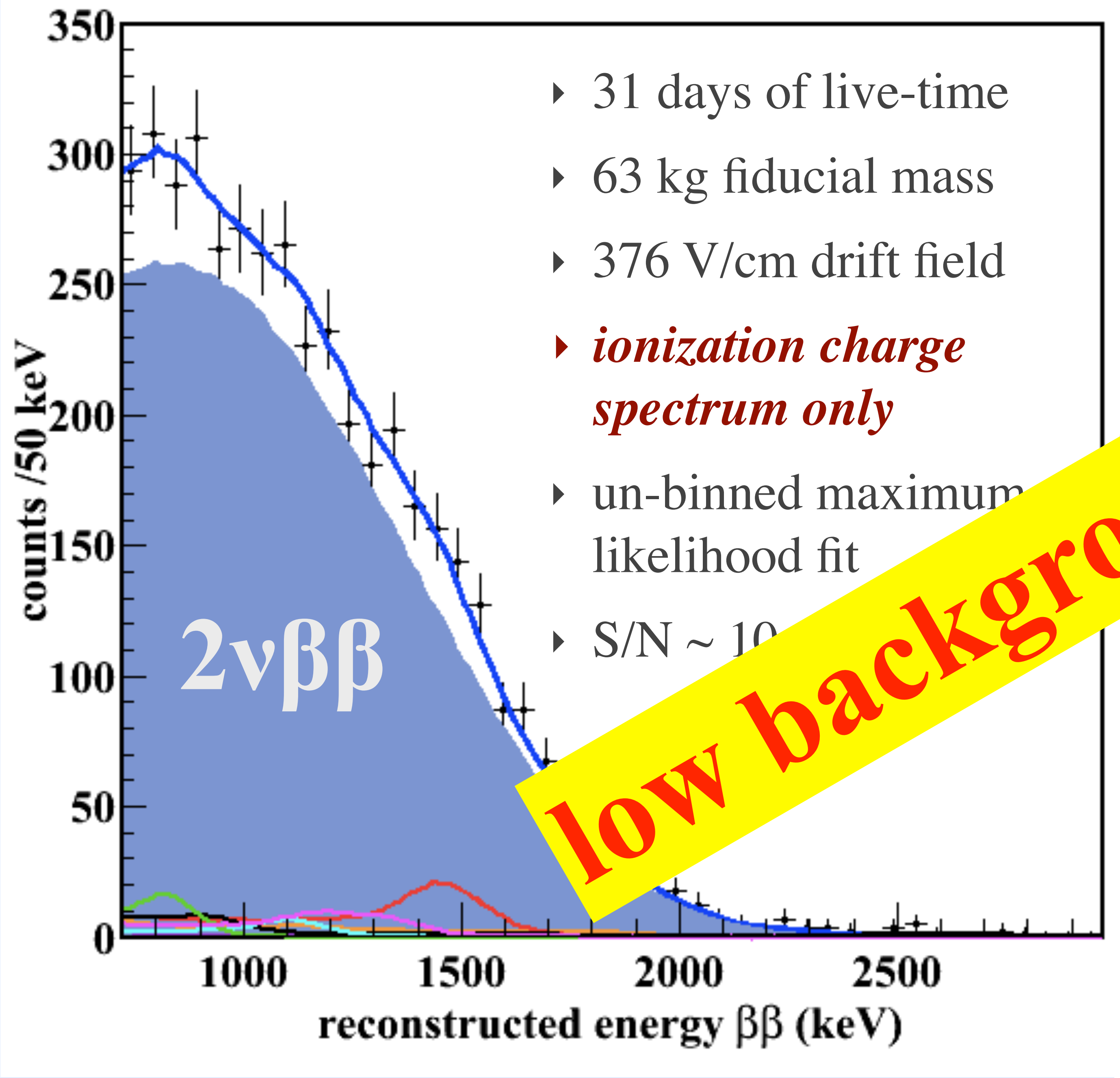

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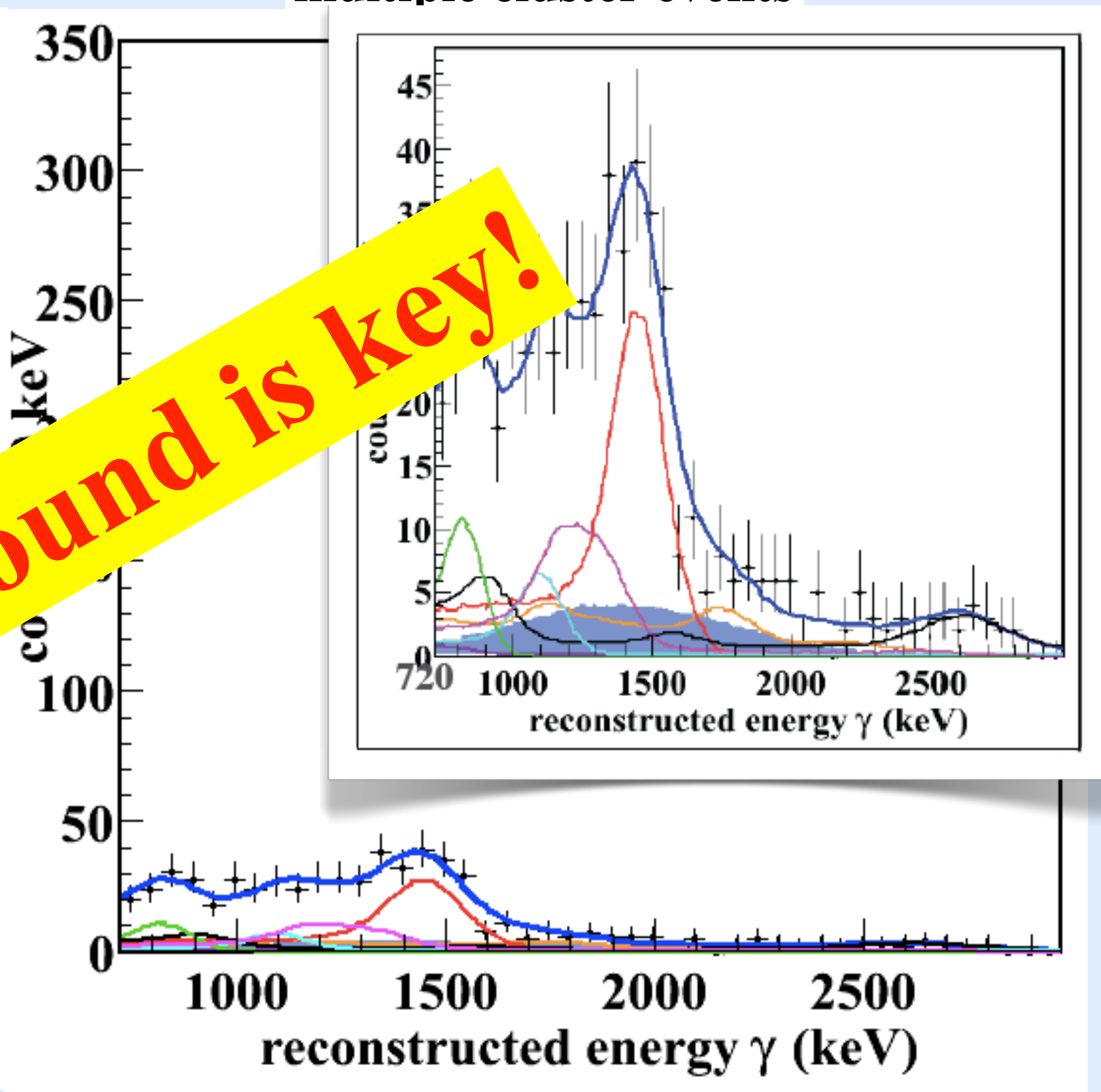
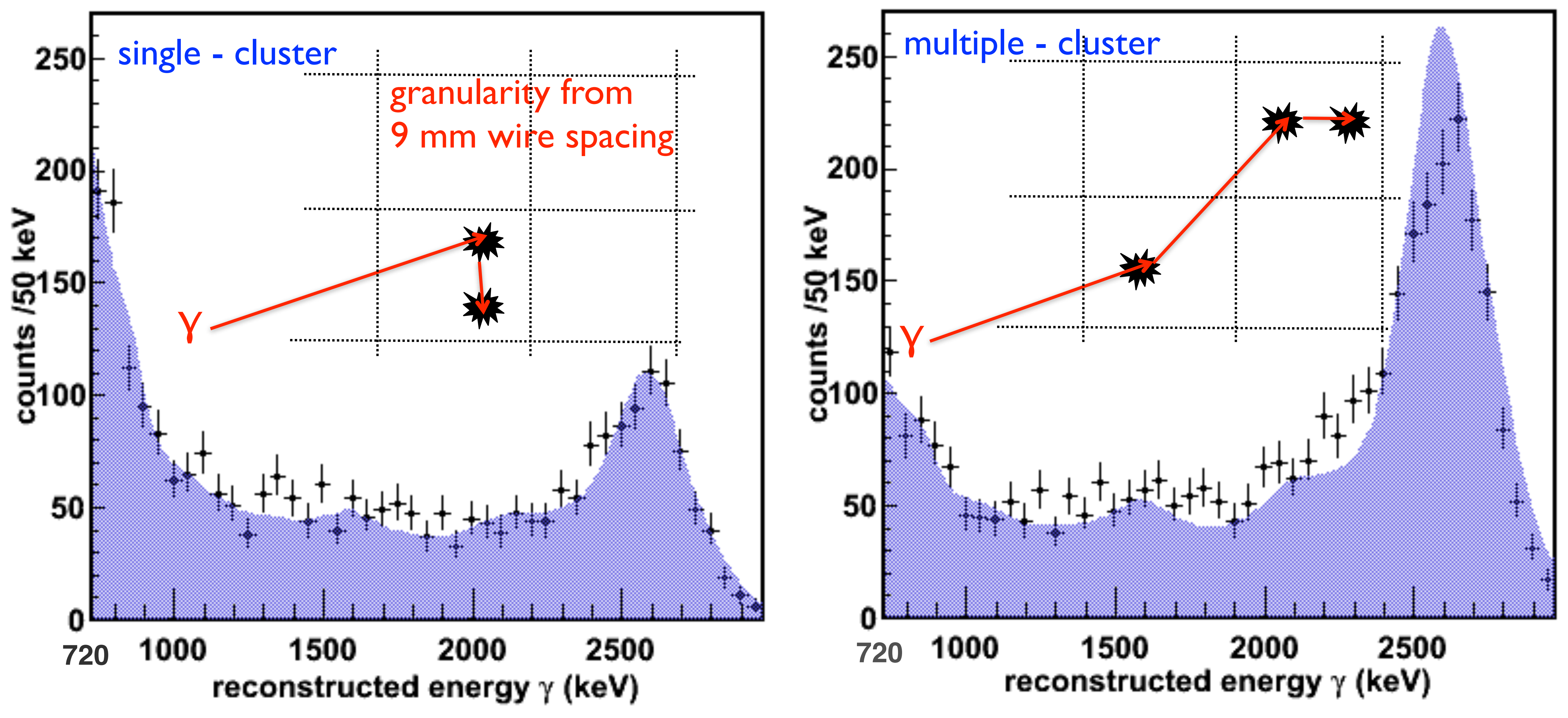


low background is key!

$$T^{2\nu}_{1/2} = (\mathbf{2.11} \pm \mathbf{0.04}(\mathbf{stat}) \pm \mathbf{0.21}(\mathbf{syst})) \times \mathbf{10^{21}}\ \text{years}$$

[PRL 107, 212501 (2011); arXiv:1108.4193]

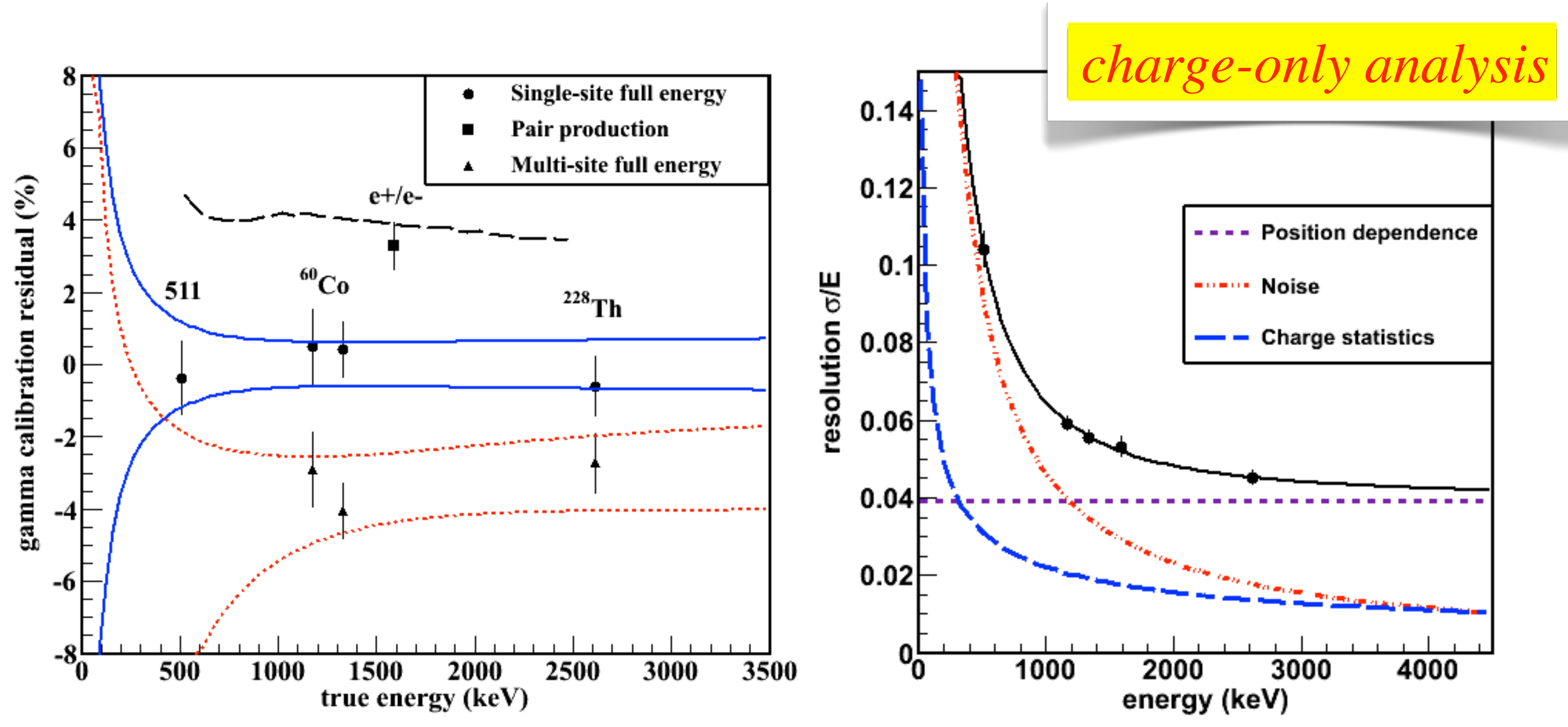
^{228}Th source calibrations (Run 1)



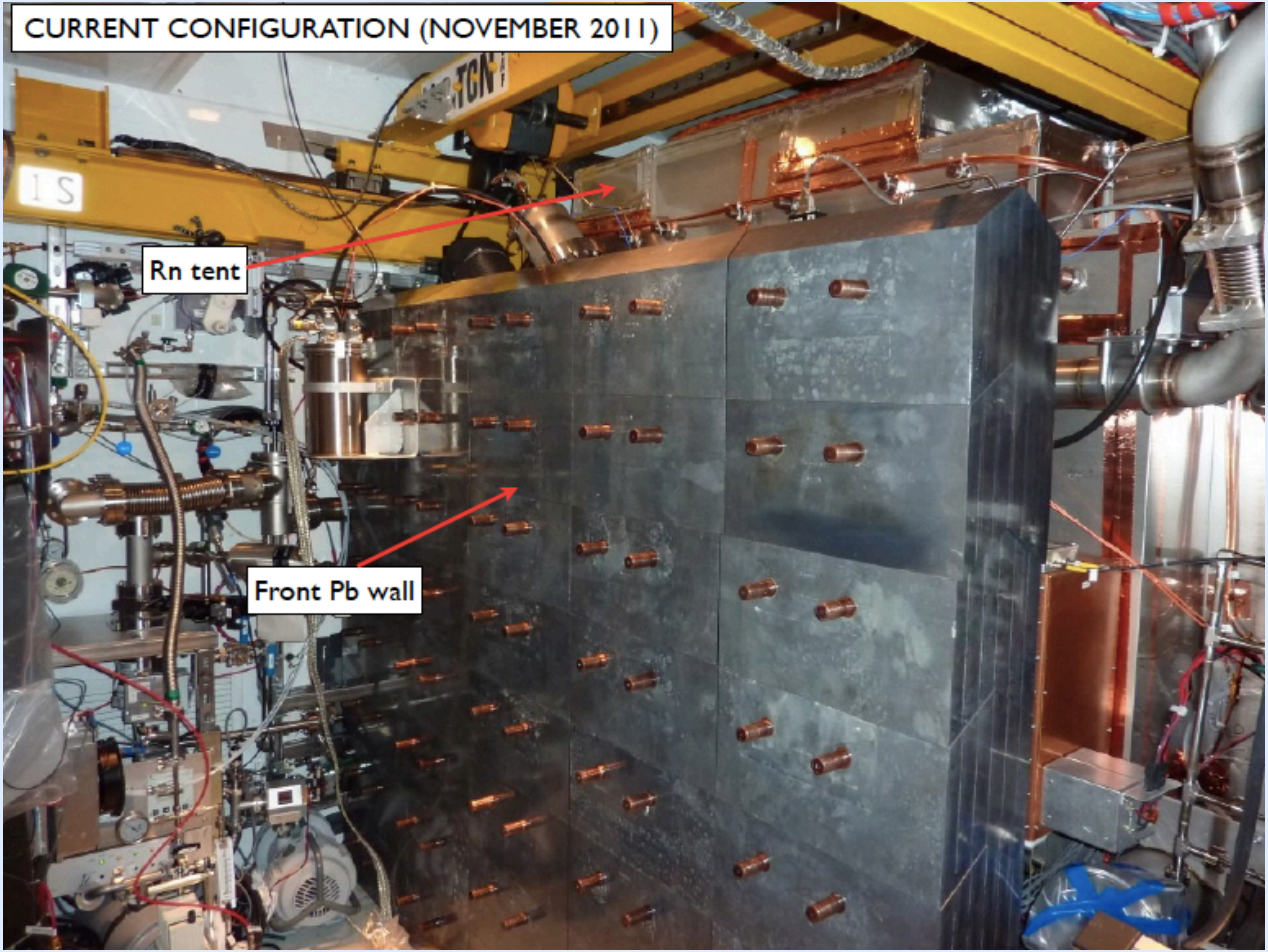
- Calibration runs compared to simulation
  - GEANT4 based simulation
  - charge propagation
  - scintillation propagation
  - signal generation
  - energy resolution parameterization is added in after the fact
- There are no free parameters for these comparisons (worst agreement is +8%)

charge-only analysis

energy calibration (Run 1)



- After purity correction, calibrated single and multiple cluster peaks across energy region of interest (511 to 2615 keV)
  - -uncertainty bands are systematic
- Point-like depositions have large reconstructed energies due to induction effects
  - - observed for pair-production site (similar to β and ββ decays)
  - - reproduced in simulation
- Peak widths also recorded and their dependence on energy is parameterized.



CURRENT CONFIGURATION (NOVEMBER 2011)

Rn tent

Front Pb wall

what’s ahead

our background at $Q_{\beta\beta}$ = 2458 keV for this analysis was
~0.005 counts/(kg keV y)

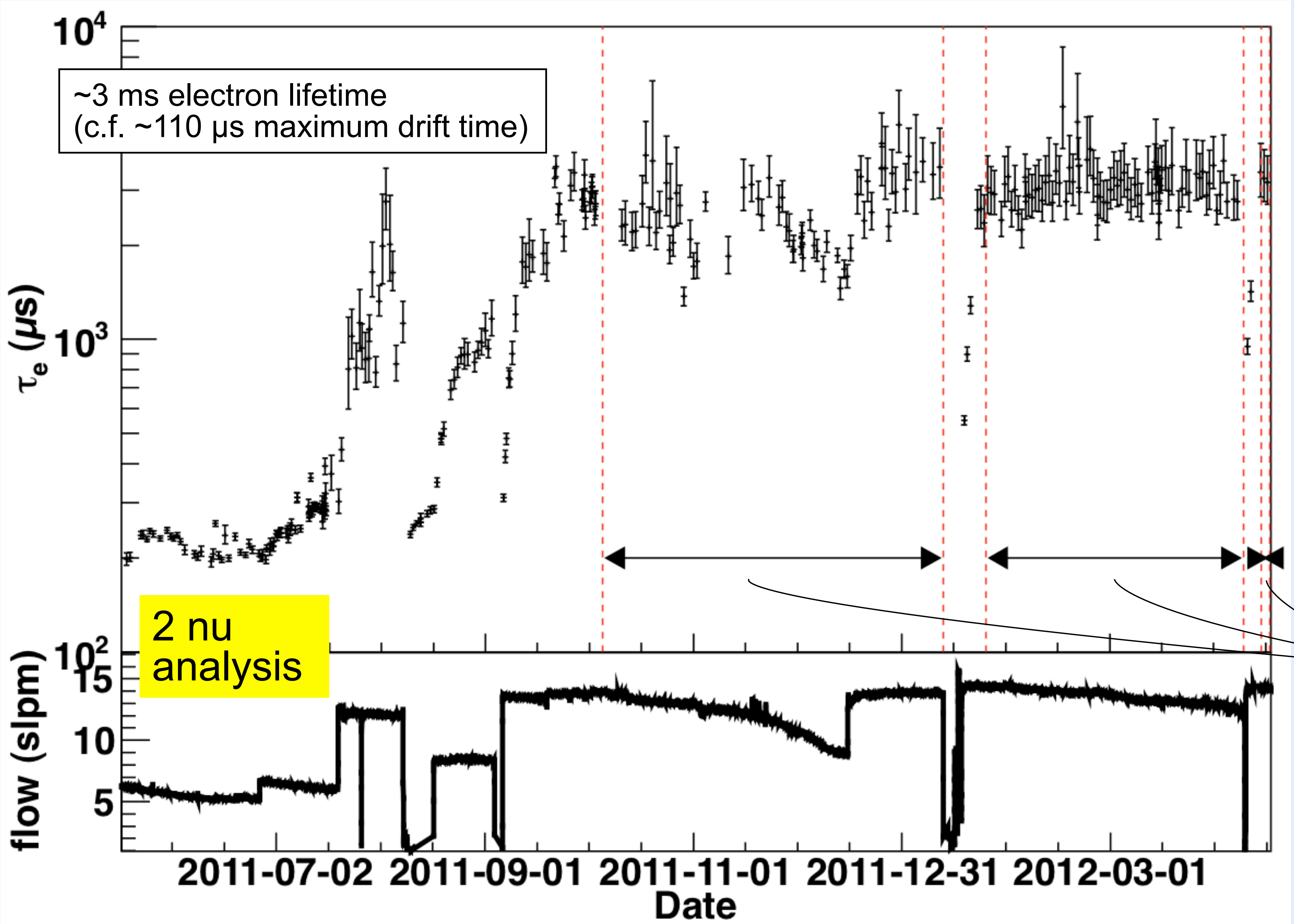
done

- upgraded electronics, improve clustering
- increase LAAPD gain, reduce energy threshold

in progress

- flush radon-suppression tent around cryostat
- 3D multiple site discrimination
- ionization + scintillation anticorrelation
- design energy resolution

xenon purity

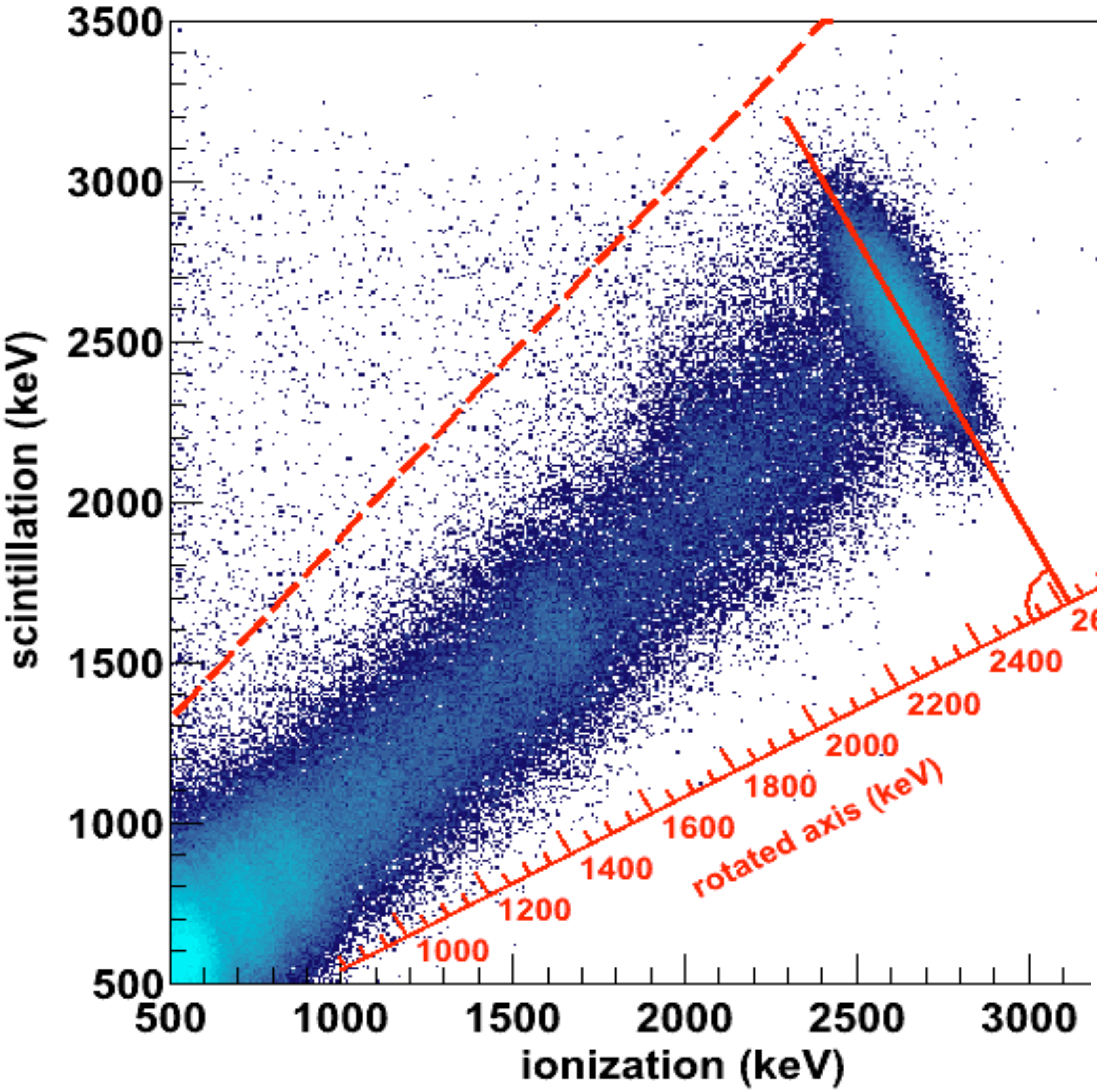


Electron lifetime was determined by measuring the attenuation of the ionization signal as a function of drift time for the full-absorption peak of gamma ray sources

Xenon gas is circulated through a heated zirconium getter using a custom-built ultraclean pump†. For this analysis, the recirculation rate was increased to 14 slpm, leading to long electron lifetimes in the TPC. Occasional stops for maintenance, etc. resulted in temporary reductions in electron lifetime, followed by quick recovery.

† Rev Sci Instrum. 82,105114 (2011)

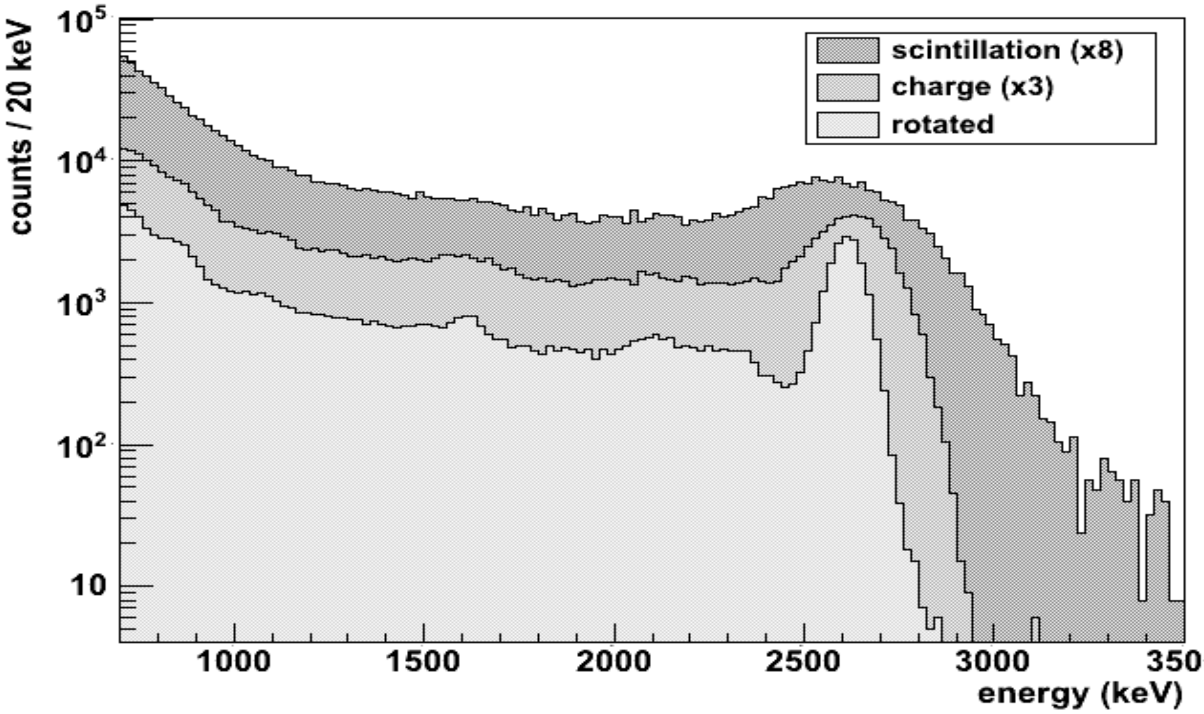
^{228}Th calibration



Ionization and scintillation are microscopically anti-correlated processes (conservation of energy)

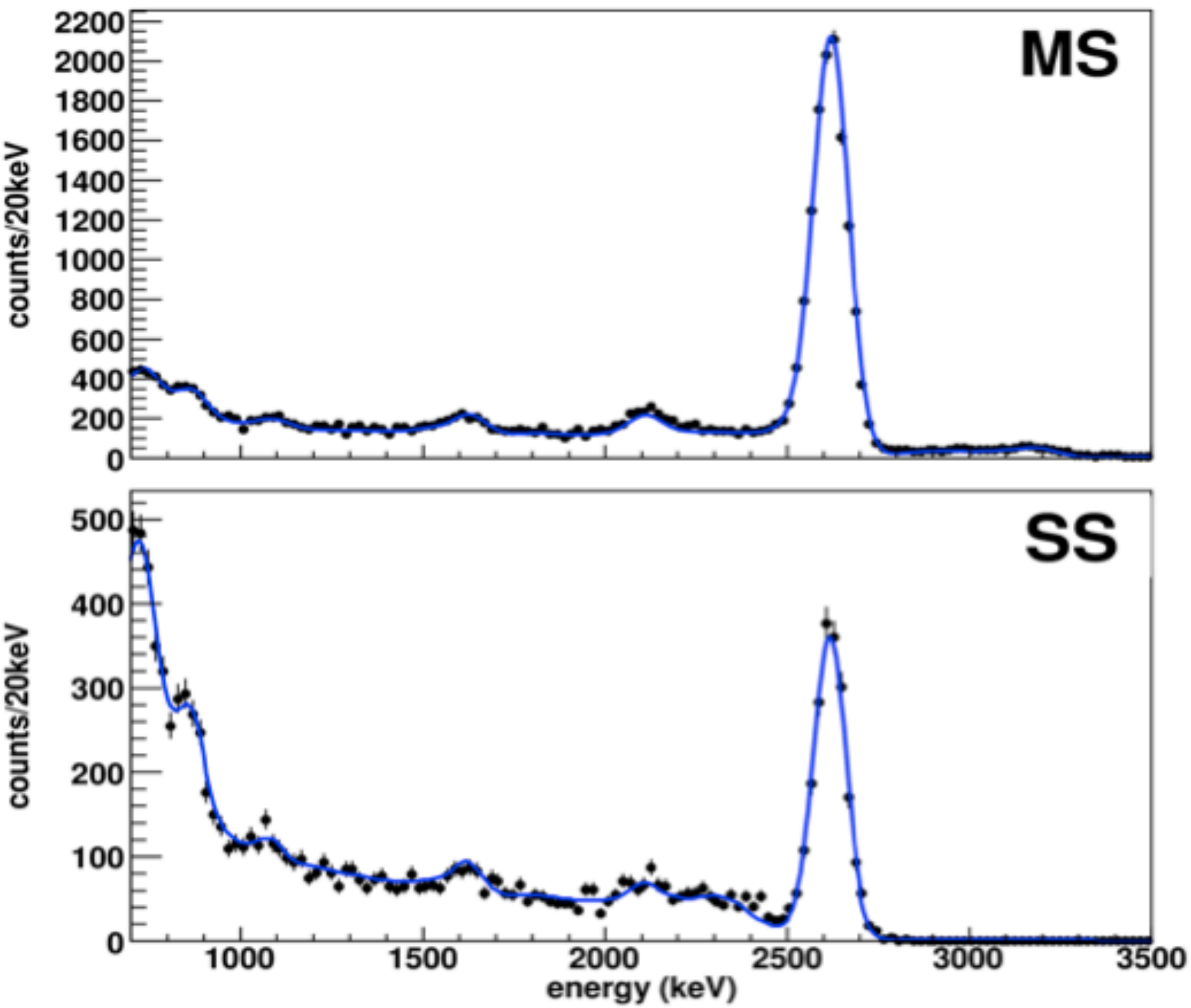
[E. Conti et al., Phys. Rev. B: **68** (2003) 054201]

charge+light analysis



Use projection onto a rotated axis to determine event energy

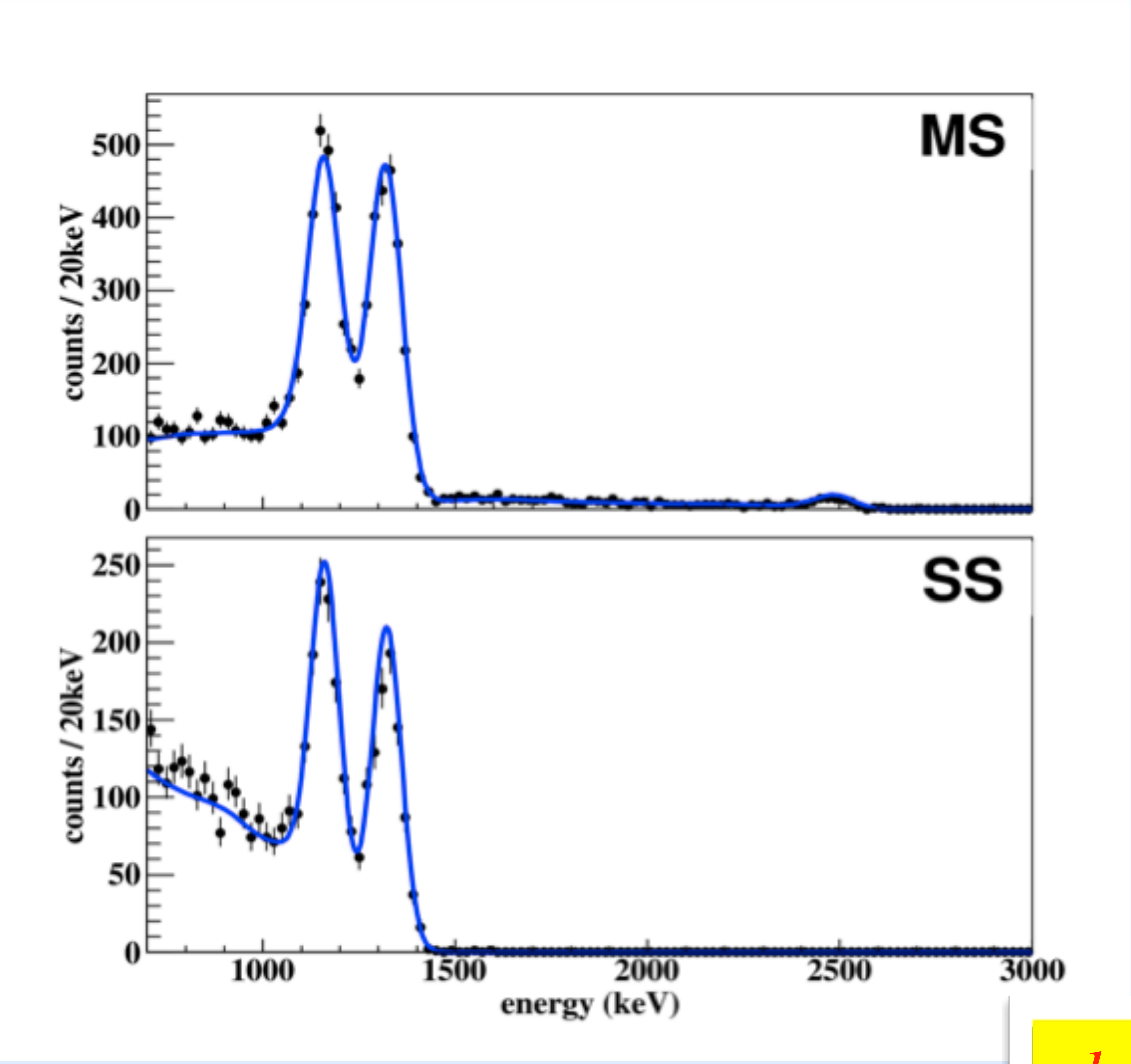
^{228}Th calibration



- Multi site (MS) and single site (SS) data (black points) are compared to model (blue curve)
- Single site fraction agrees to within 8.5%
- Can measure source activities to within 9.4%

charge+light analysis

^{60}Co calibration

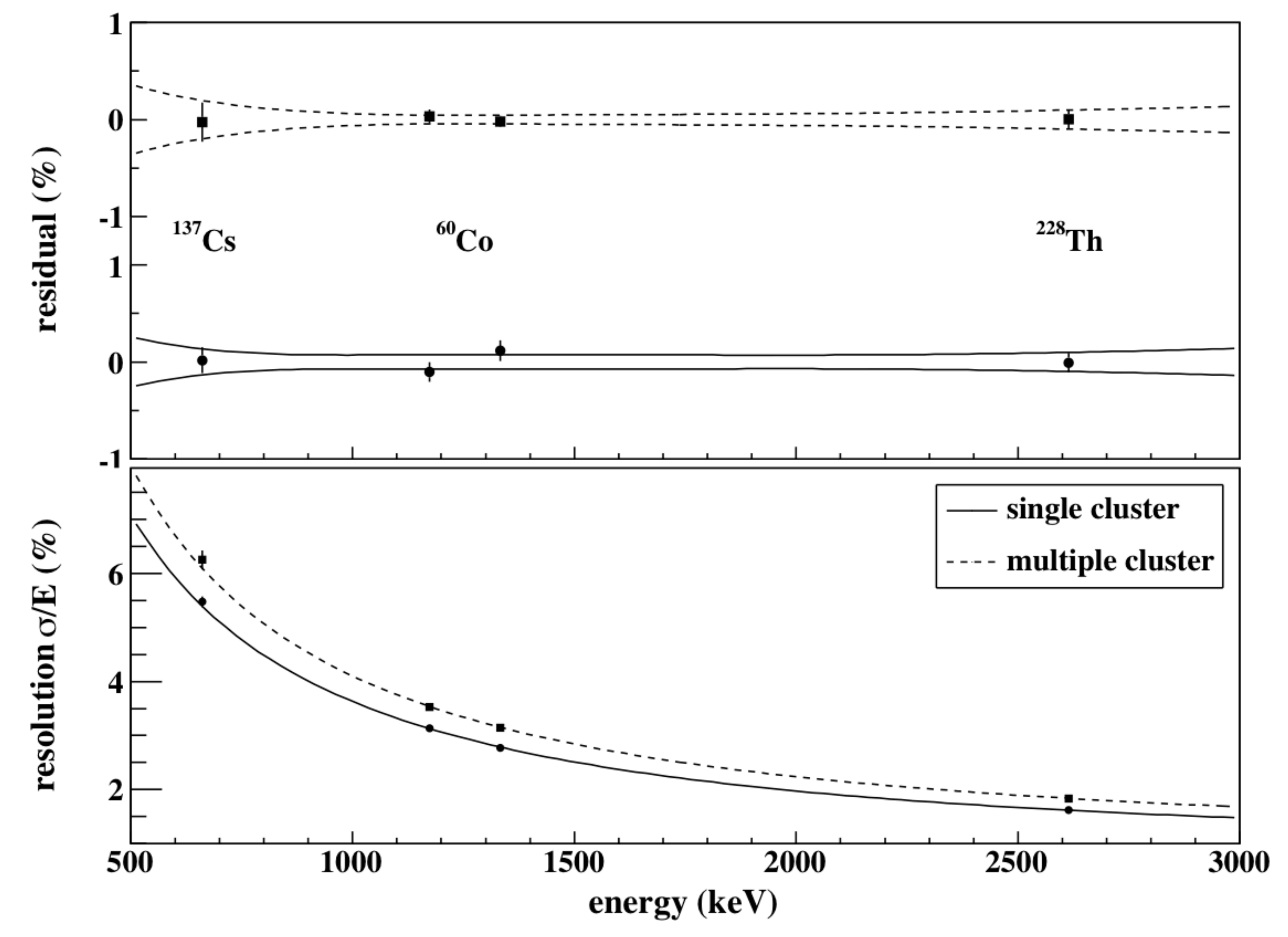


- Multi site (MS) and single site (SS) data (black points) are compared to model (blue curve) for ^{60}Co source
- This is used to verify the detector simulations

charge+light analysis

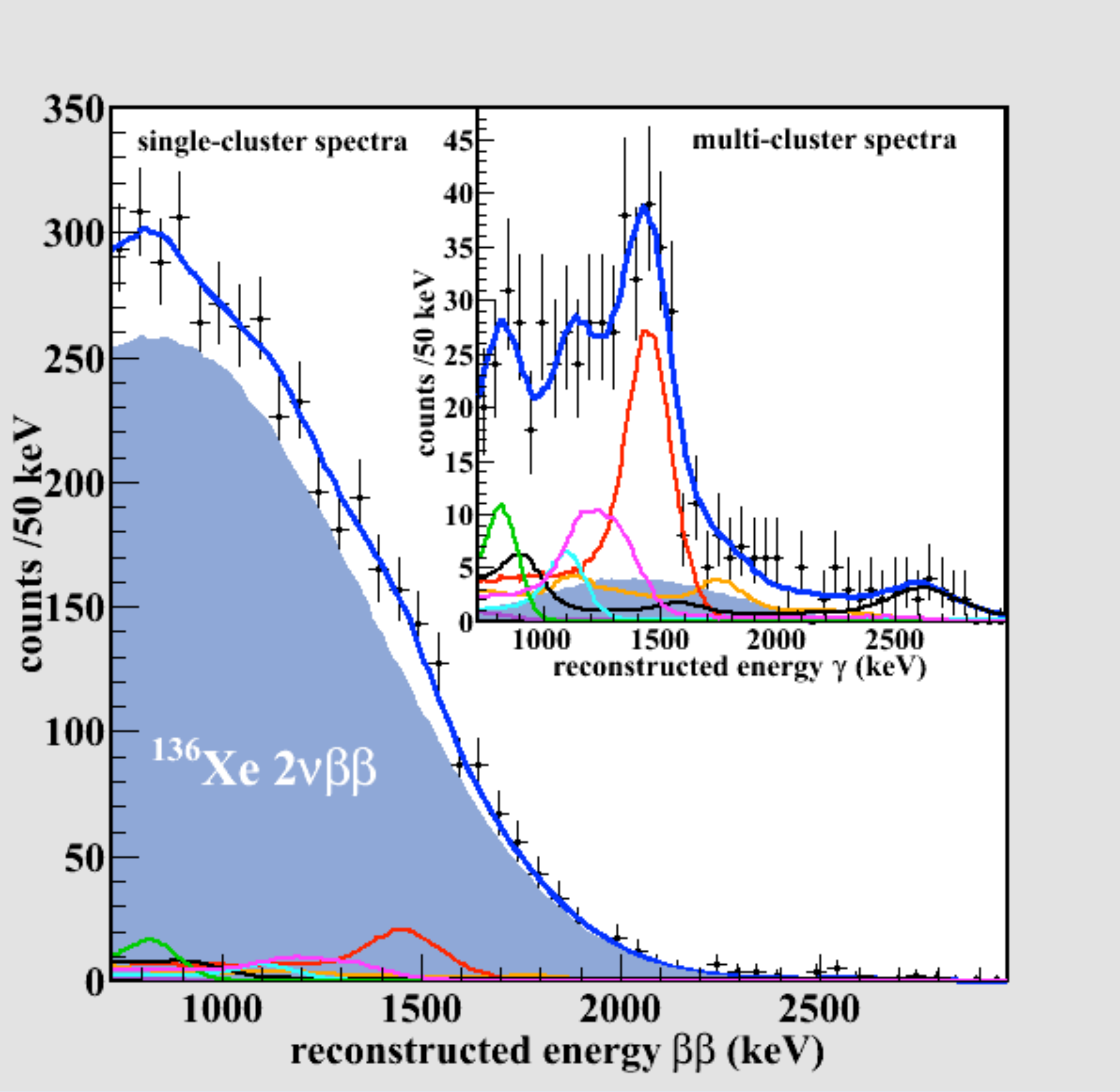
energy calibration

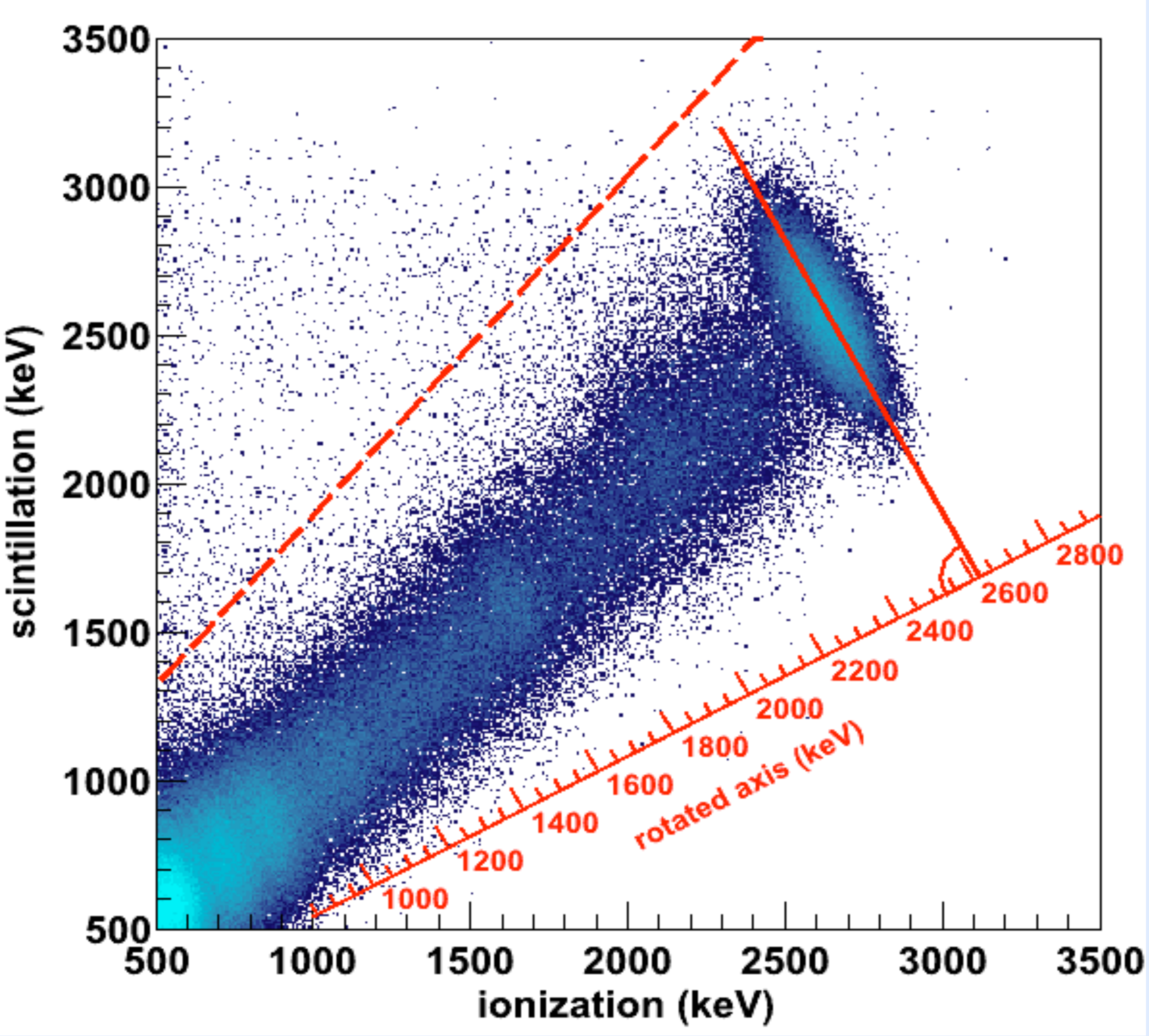
charge+light analysis



- Energy calibration residuals uncertainties constrained to be less than 0.1%
- Energy resolution at Q-value (2458 keV) is 1.67% (1.84%) in SS (MS) spectrum

summary

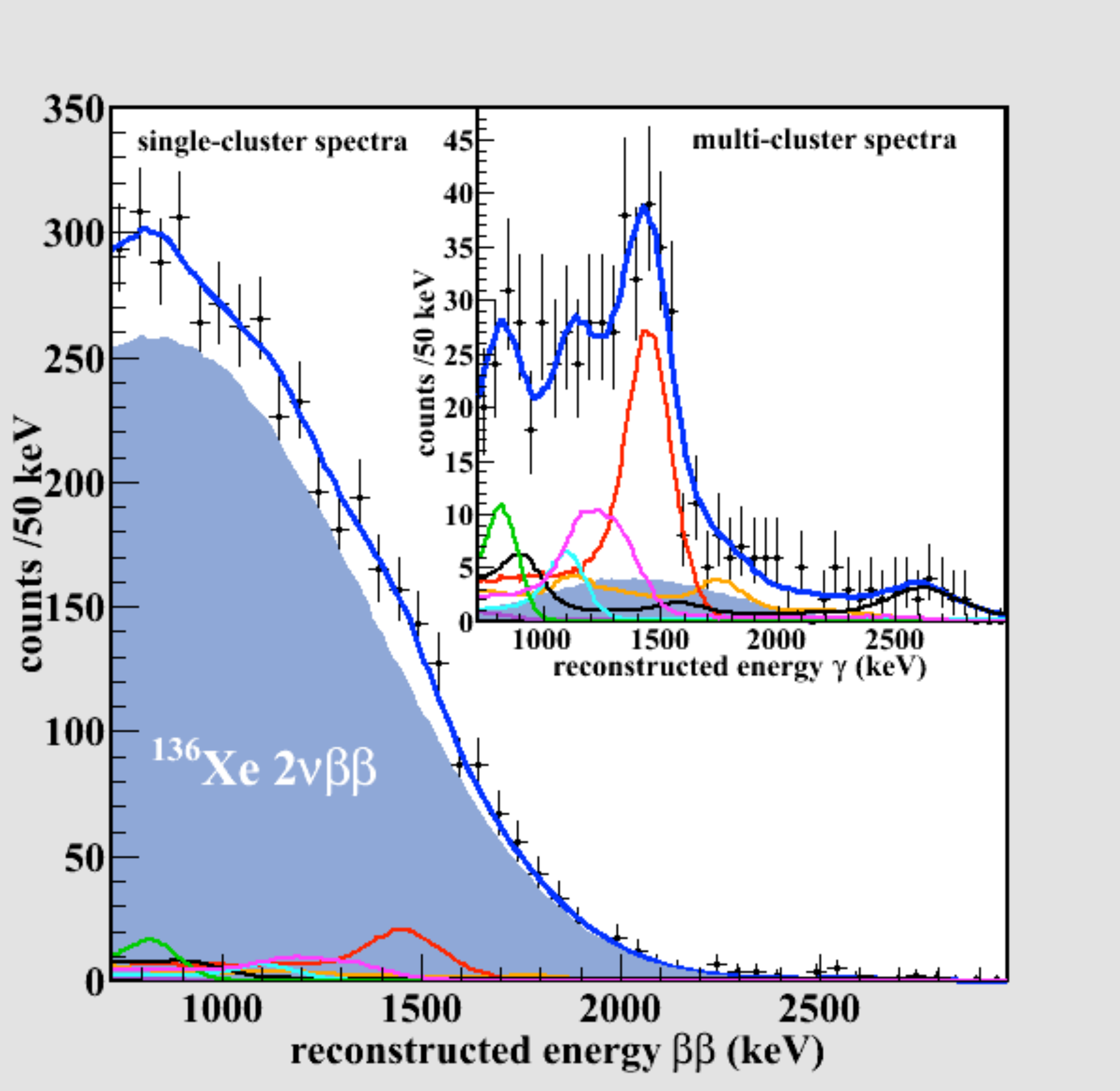


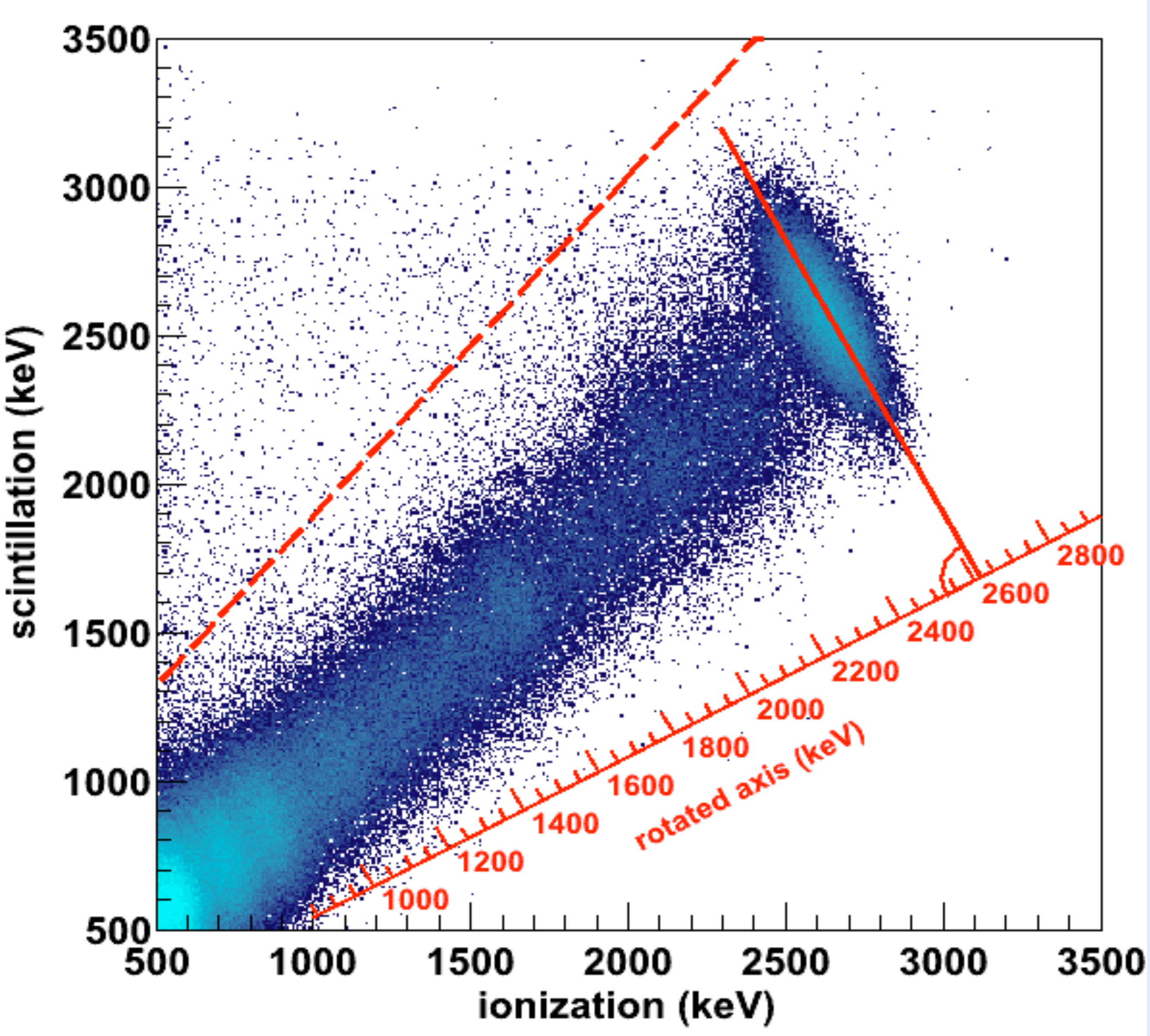


“ two nu’s is good news but no nu’s is even better! ”

- Roger Blandford (Stanford University) -

stay tuned!





“ two nu’s is good news but no nu’s is even better! ”

- Roger Blandford (Stanford University) -

The Final State(ment)

THANK YOU

extra slides

Anti-correlated ionization and scintillation improves the energy resolution in LXe

Ionization alone:

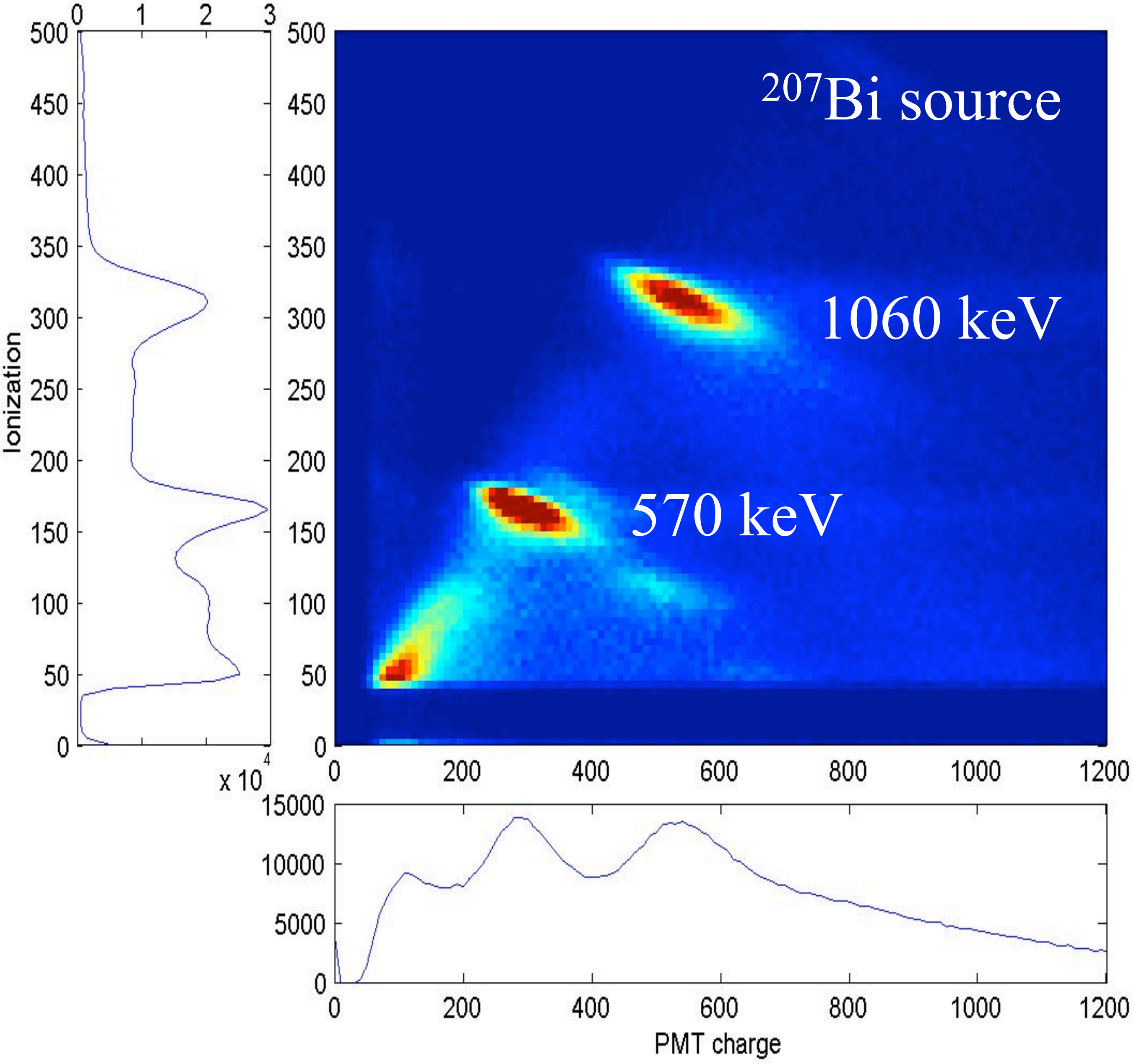
$\sigma(E)/E = 3.8\%$ @ 570 keV

or 1.8% @ $Q_{\beta\beta}$

Ionization + Scintillation:

$\sigma(E)/E = 3.0\%$ @ 570 keV

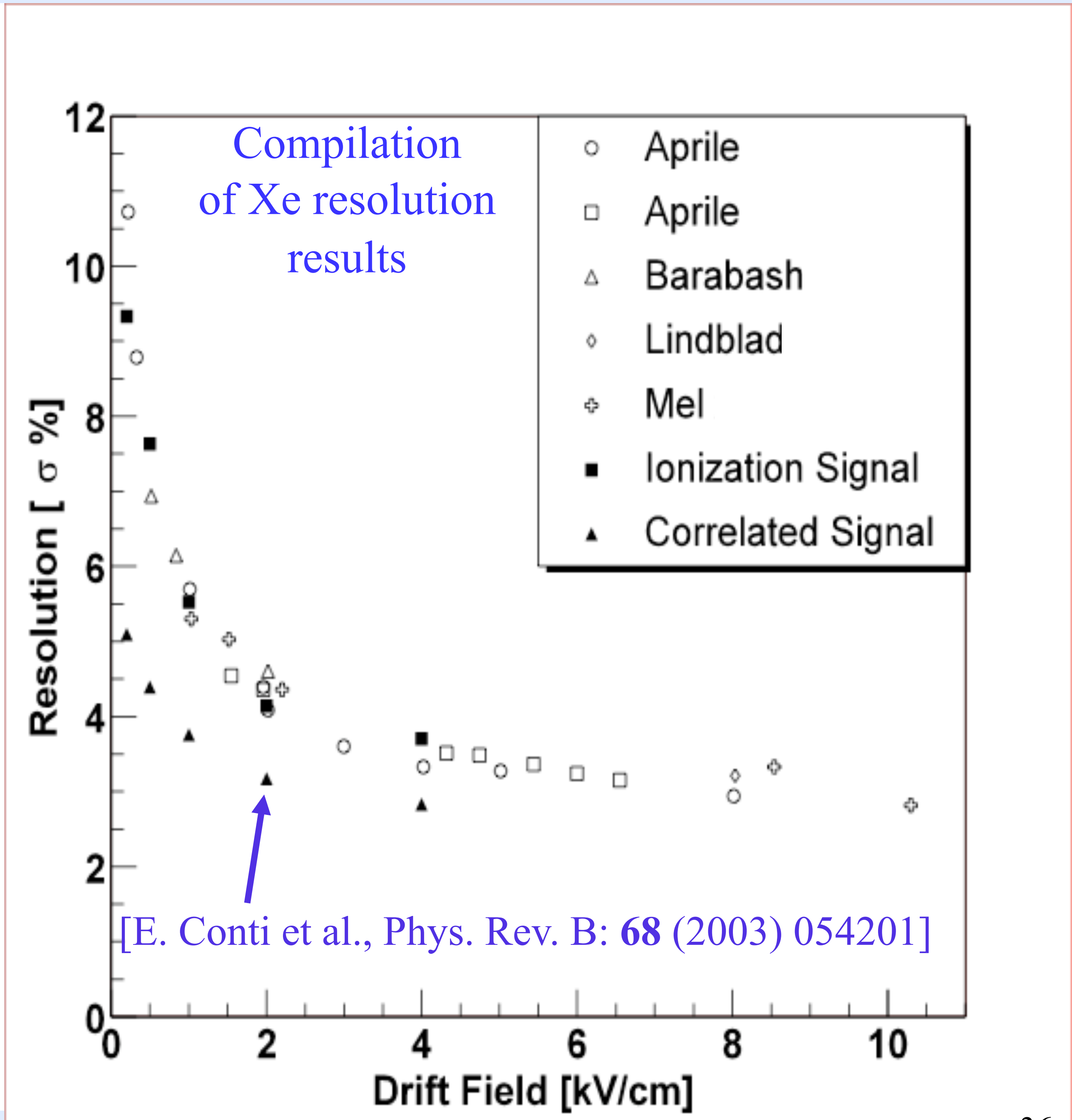
or 1.4% @ $Q_{\beta\beta}$



^{207}Bi source

1060 keV

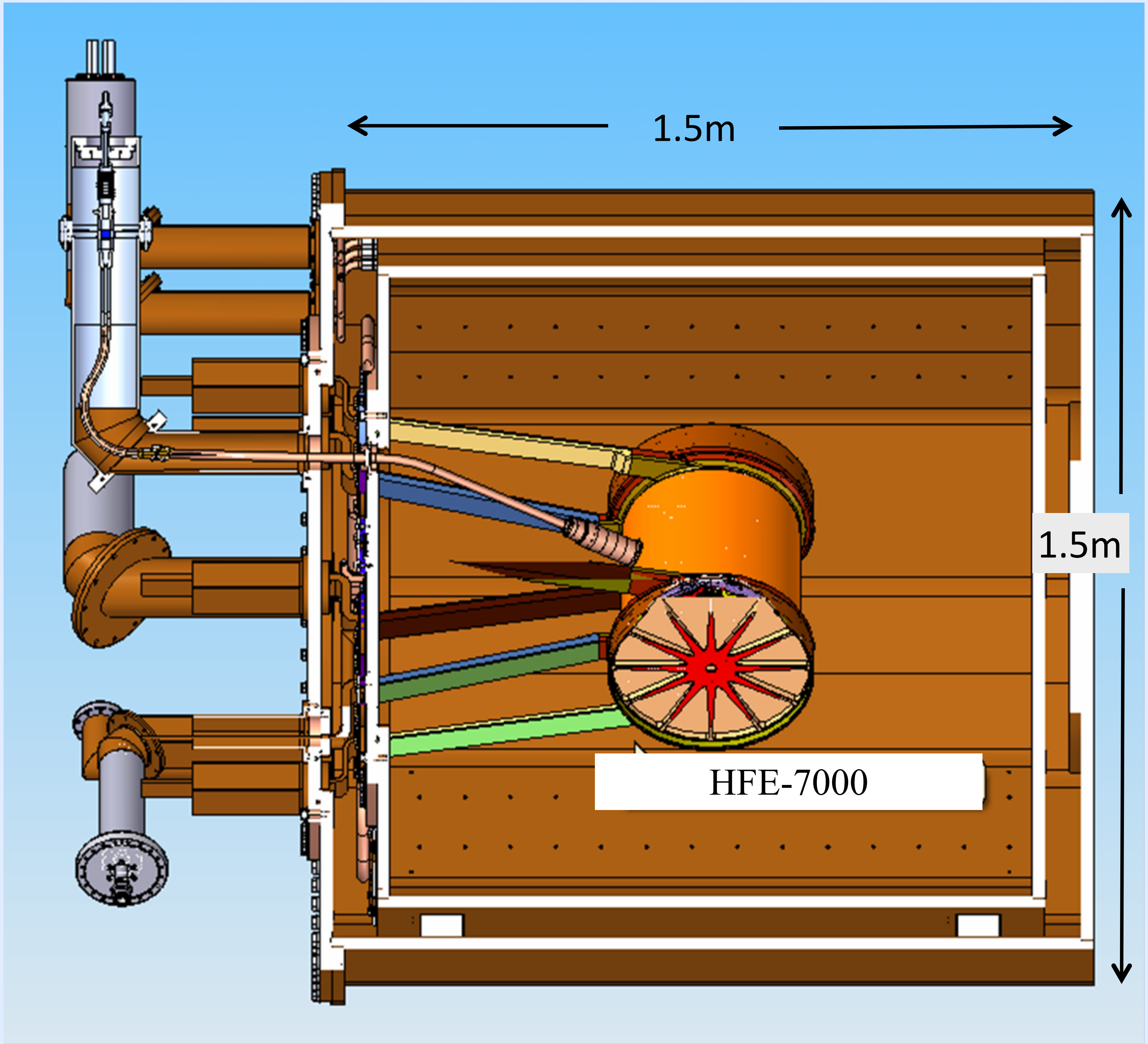
570 keV



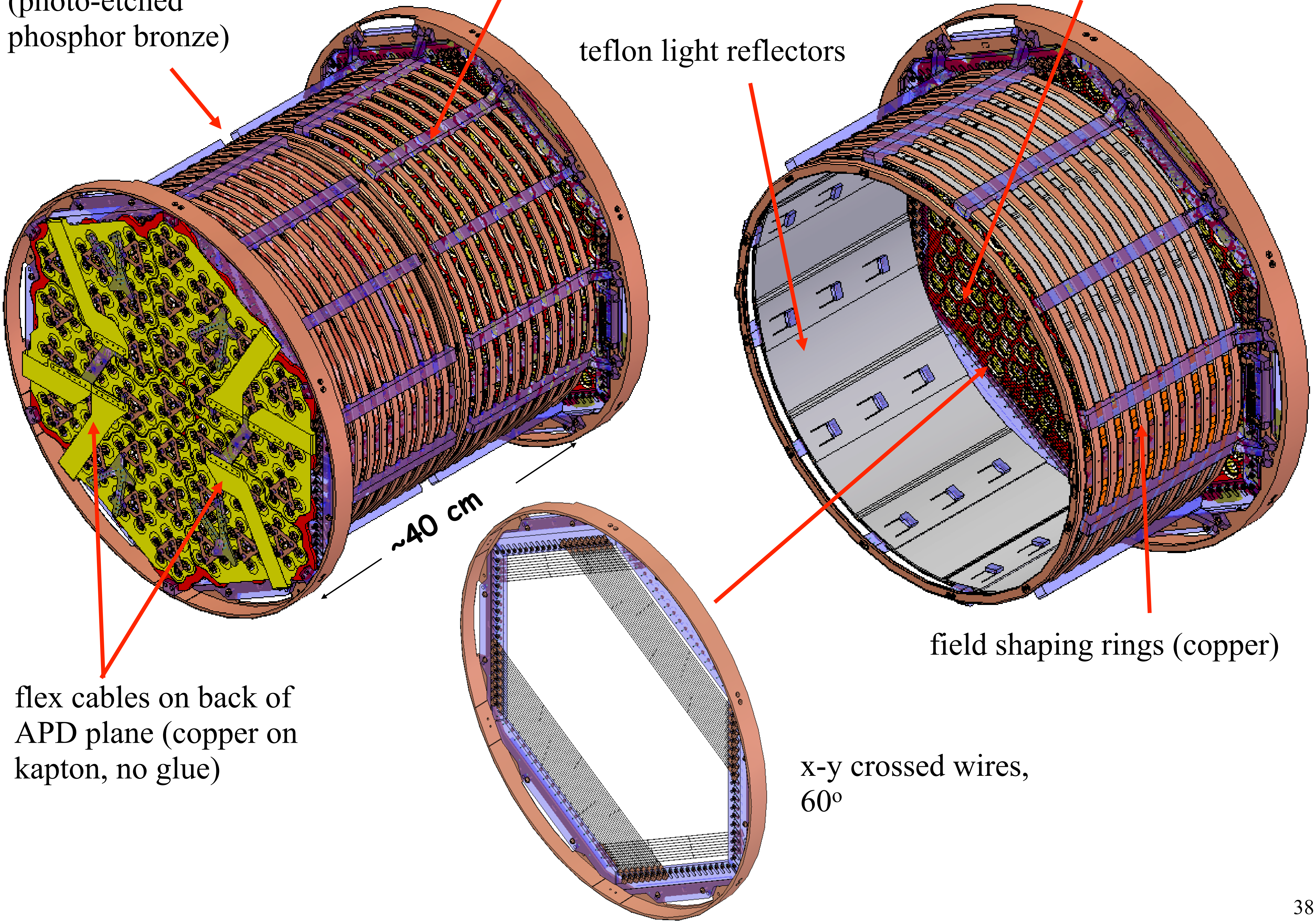
Compilation of Xe resolution results

[E. Conti et al., Phys. Rev. B: **68** (2003) 054201]

The EXO-200 detector



HFE-loaded cryostat is cooled via closed-loop refrigerant chilled by external refrigerators and circulating in heat exchangers



Central HV plane
(photo-etched
phosphor bronze)

acrylic supports

LAAPD plane (copper) and x-y wires
(photo-etched phosphor bronze)

teflon light reflectors

field shaping rings (copper)

flex cables on back of
APD plane (copper on
kapton, no glue)

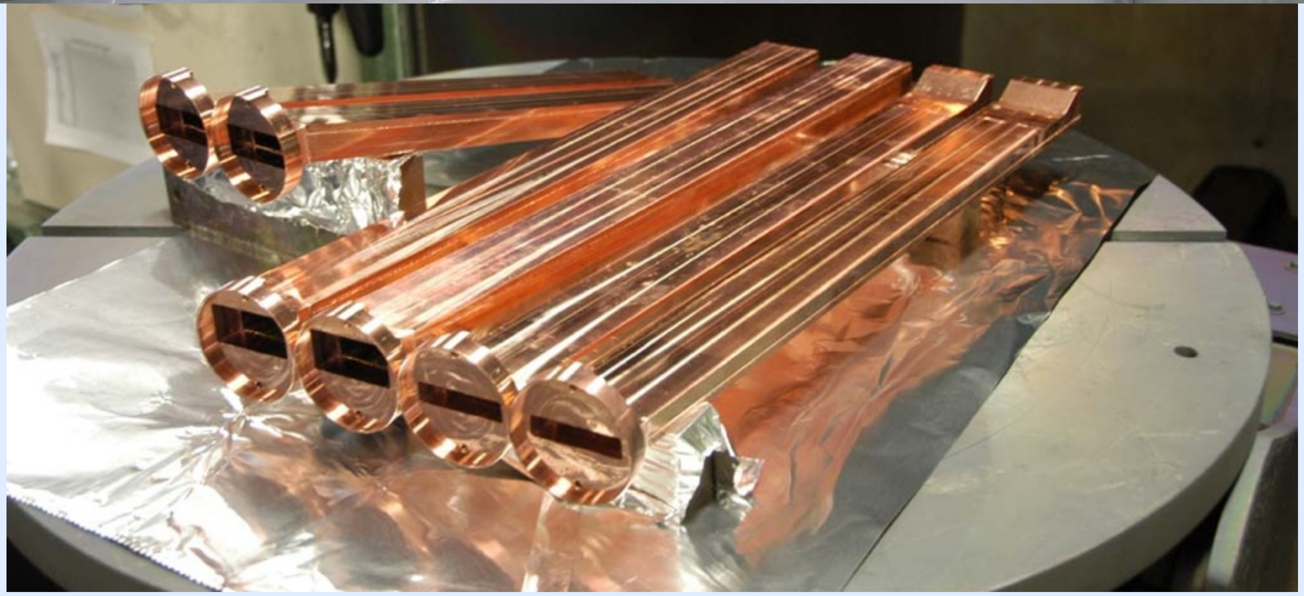
x-y crossed wires,
60^o

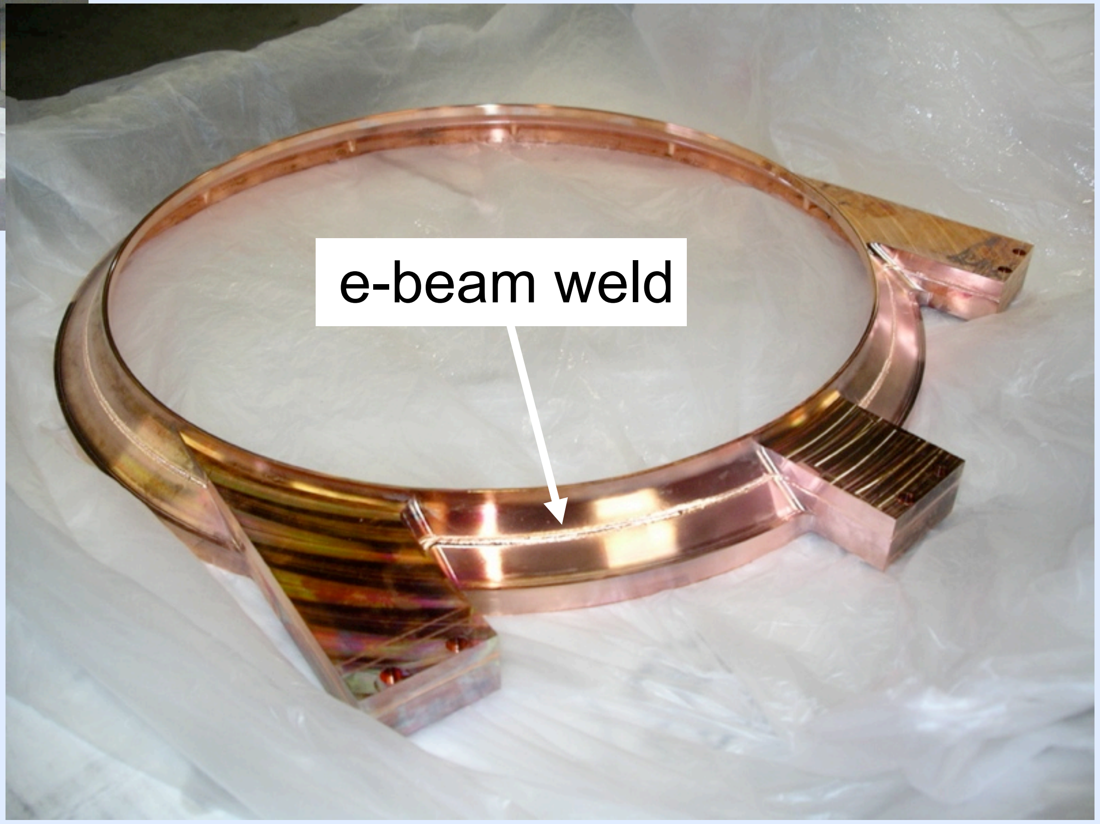
EXO-200 xenon vessel

self-shielding is poor for ~MeV gamma rays

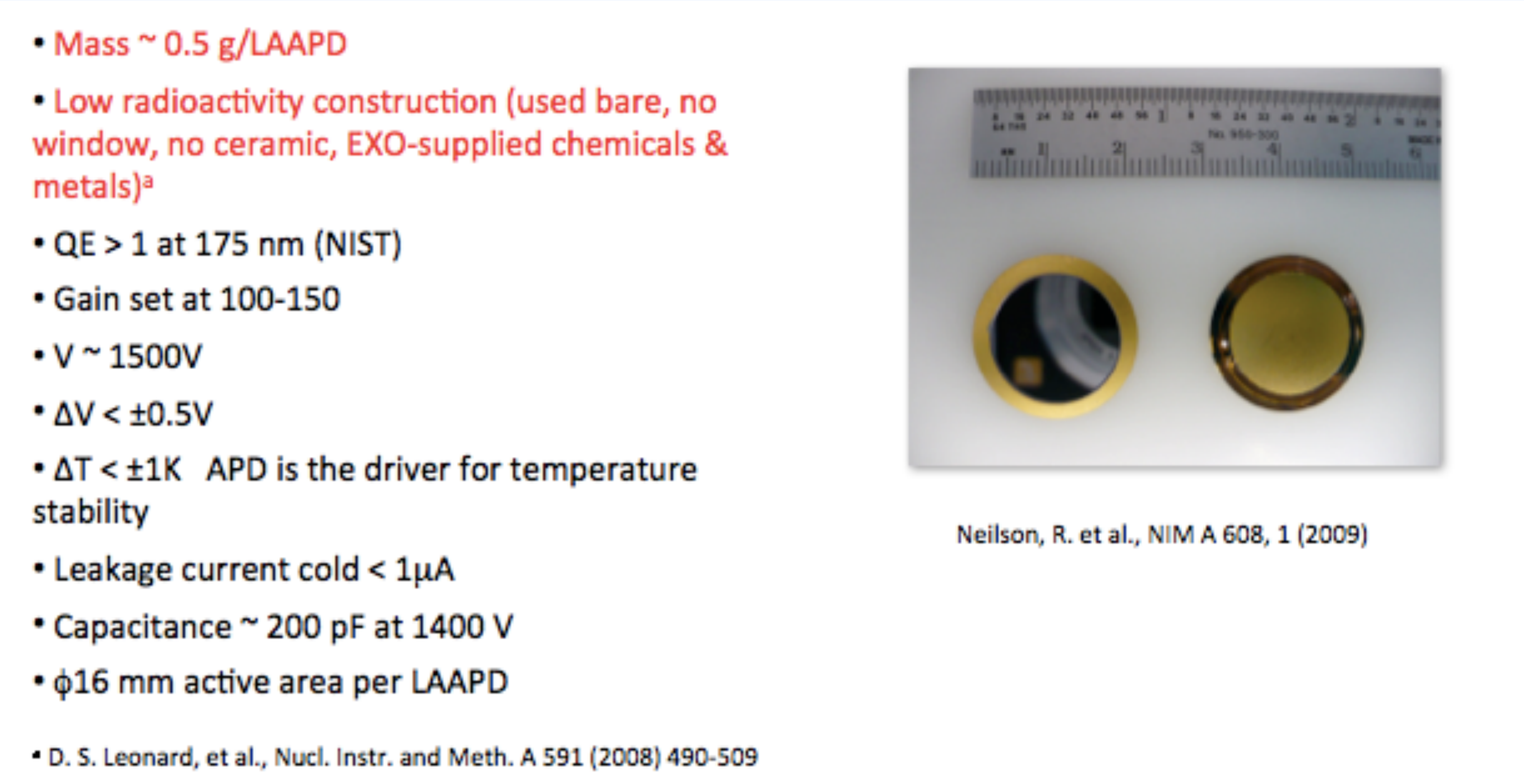
- ultra-pure copper
- 1.4 mm thick
- mostly e-beam welded

- machined and stored shallow underground (2 m of concrete)





EXO-200 LAAPDs

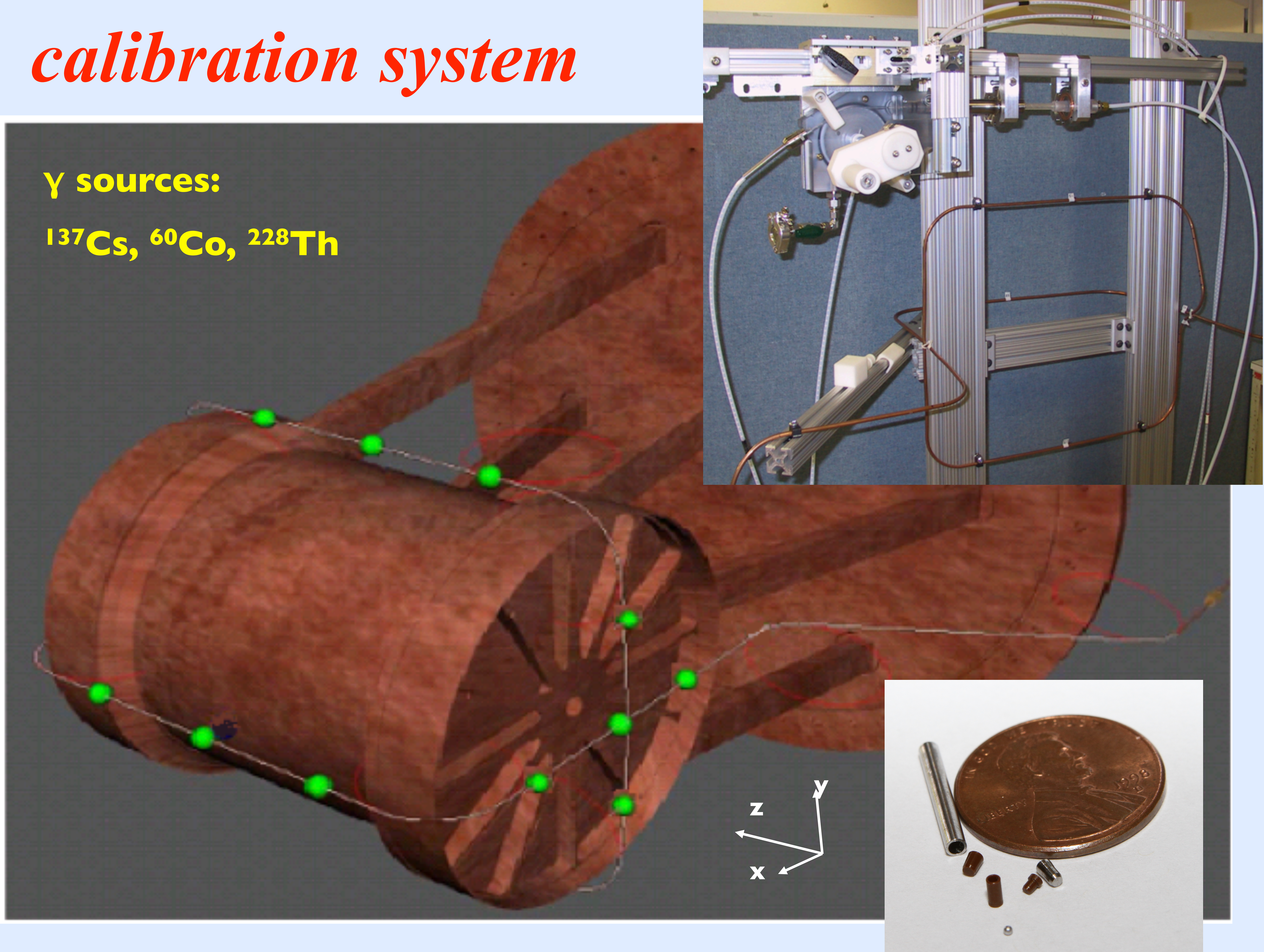


- Mass ~ 0.5 g/LAAPD
- Low radioactivity construction (used bare, no window, no ceramic, EXO-supplied chemicals & metals)[a]
- QE > 1 at 175 nm (NIST)
- Gain set at 100-150
- V ~ 1500V
- ΔV < ±0.5V
- ΔT < ±1K APD is the driver for temperature stability
- Leakage current cold < 1μA
- Capacitance ~ 200 pF at 1400 V
- ϕ16 mm active area per LAAPD

Neilson, R. et al., NIM A 608, 1 (2009)

- D. S. Leonard, et al., Nucl. Instr. and Meth. A 591 (2008) 490-509

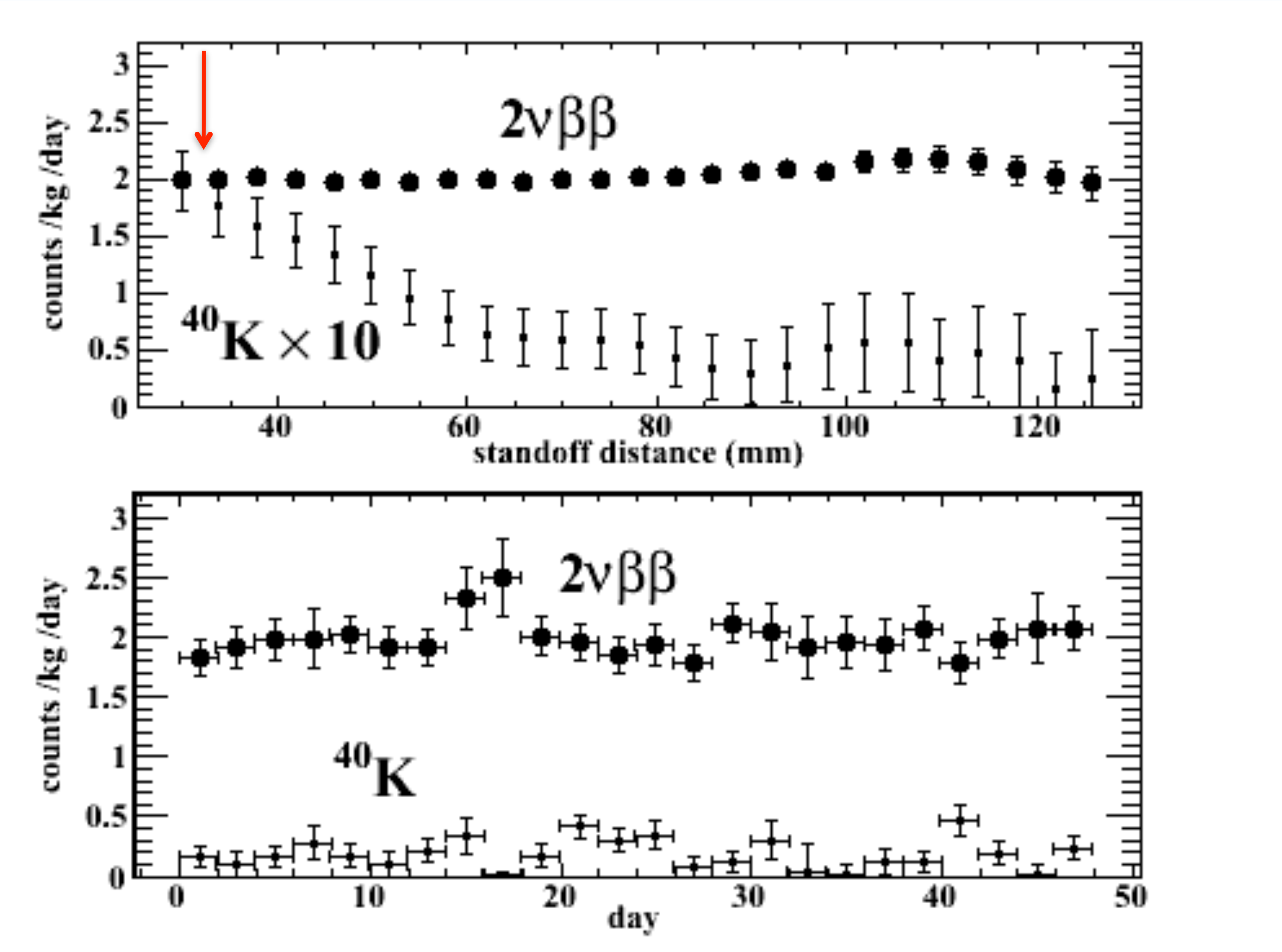
calibration system



γ sources:

^{137}Cs, ^{60}Co, ^{228}Th

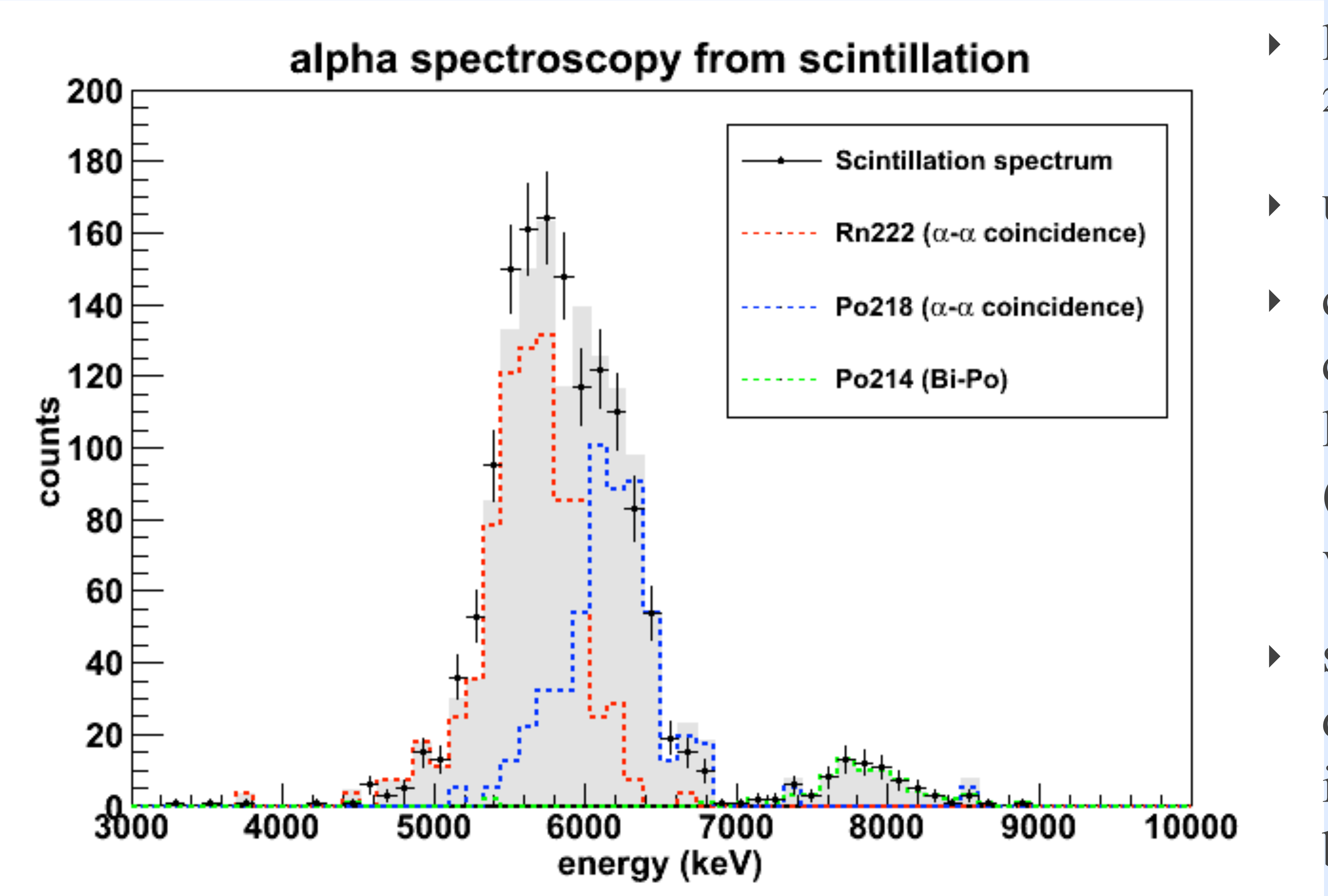
low background spectra



- signal constant in time
  - signal is uniform throughout the LXe bulk
    - gamma backgrounds are suppressed towards the center of the detector

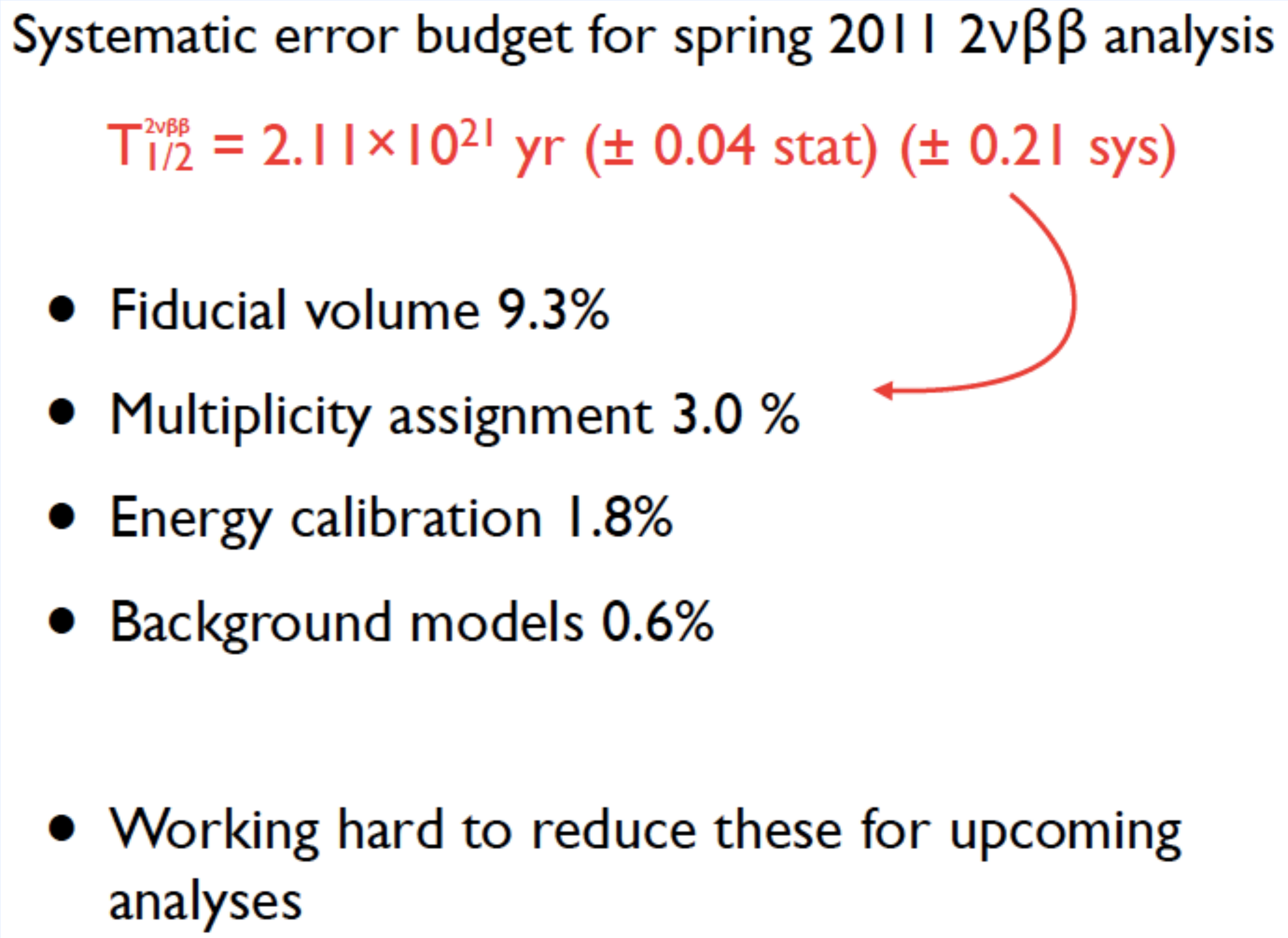
constraints from alpha spectroscopy

use well-identifiable α decays to constrain plausible backgrounds



- look for α decays in the ^{238}U chain, above ^{222}Rn
- use Rn alphas to calibrate
- can constrain ^{238}U contamination by setting a limit on 4.5 MeV α's (<0.3 counts/day in fiducial volume)
- same limit applies to its daughter ^{234m}Pa, which with its Q=2195 keV β's could be a background (but isn't)

steady state radon: 4.5 μBq kg^{-1} ~1 per hour



Systematic error budget for spring 2011 $2\nu\beta\beta$ analysis

$T^{2\nu\beta\beta}_{1/2} = 2.11\times10^{21}$ yr (± 0.04 stat) (± 0.21 sys)

- Fiducial volume 9.3%
- Multiplicity assignment 3.0 %
- Energy calibration 1.8%
- Background models 0.6%

- Working hard to reduce these for upcoming analyses

$2\nu\beta\beta$ decay matrix elements

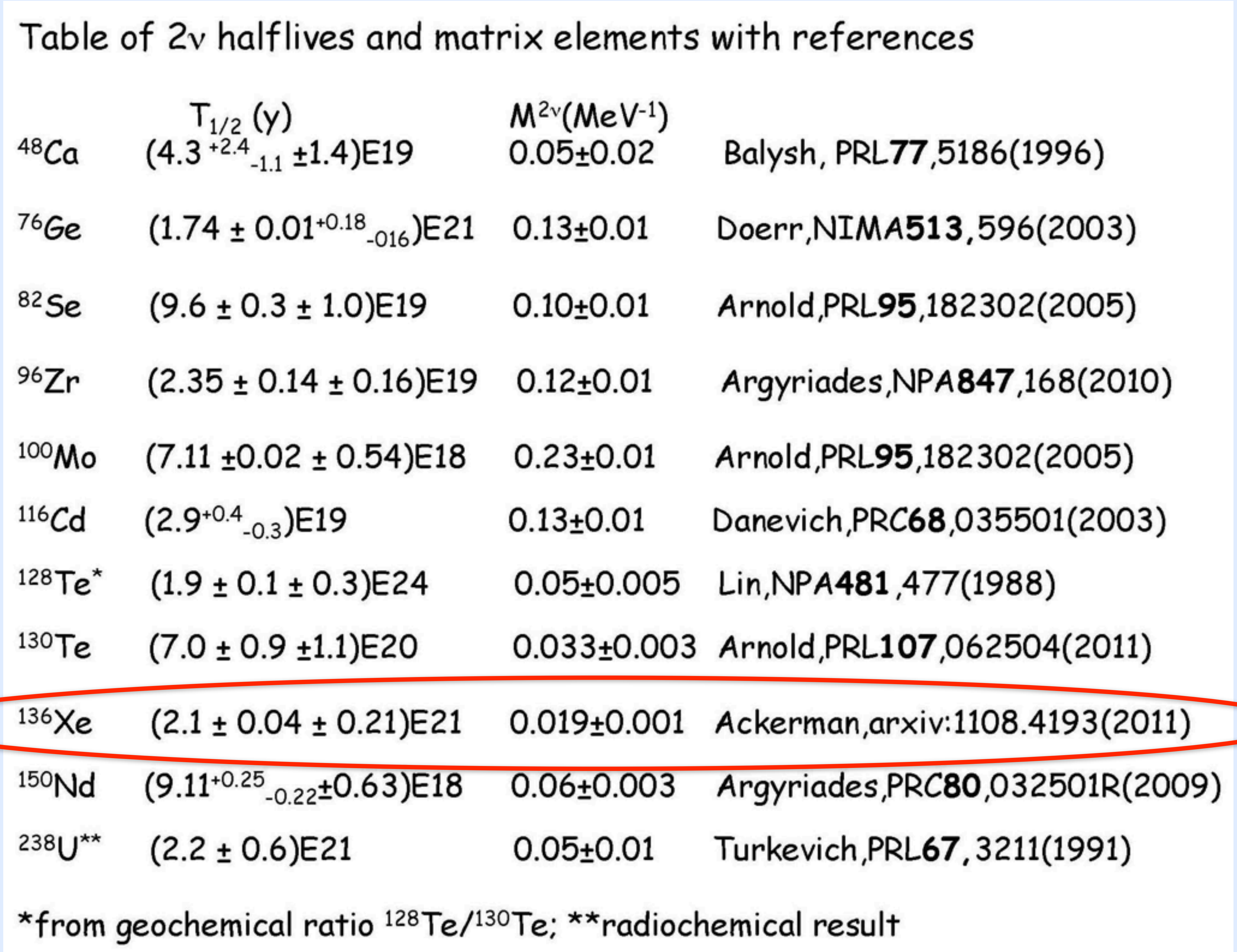


Table of 2ν halflives and matrix elements with references

	$T_{1/2}$ (y)	$M^{2\nu}$(MeV^{-1})	
^{48}Ca	$(4.3^{+2.4}_{-1.1} \pm 1.4)$E19	0.05 ± 0.02	Balysh, PRL**77**,5186(1996)
^{76}Ge	$(1.74 \pm 0.01^{+0.18}_{-016})$E21	0.13 ± 0.01	Doerr,NIMA**513**,596(2003)
^{82}Se	$(9.6 \pm 0.3 \pm 1.0)$E19	0.10 ± 0.01	Arnold,PRL**95**,182302(2005)
^{96}Zr	$(2.35 \pm 0.14 \pm 0.16)$E19	0.12 ± 0.01	Argyriades,NPA**847**,168(2010)
^{100}Mo	$(7.11 \pm 0.02 \pm 0.54)$E18	0.23 ± 0.01	Arnold,PRL**95**,182302(2005)
^{116}Cd	$(2.9^{+0.4}_{-0.3})$E19	0.13 ± 0.01	Danevich,PRC**68**,035501(2003)
^{128}Te*	$(1.9 \pm 0.1 \pm 0.3)$E24	0.05 ± 0.005	Lin,NPA**481**,477(1988)
^{130}Te	$(7.0 \pm 0.9 \pm 1.1)$E20	0.033 ± 0.003	Arnold,PRL**107**,062504(2011)
^{136}Xe	$(2.1 \pm 0.04 \pm 0.21)$E21	0.019 ± 0.001	Ackerman,arxiv:1108.4193(2011)
^{150}Nd	$(9.11^{+0.25}_{-0.22} \pm 0.63)$E18	0.06 ± 0.003	Argyriades,PRC**80**,032501R(2009)
^{238}U**	(2.2 ± 0.6)E21	0.05 ± 0.01	Turkevich,PRL**67**,3211(1991)

*from geochemical ratio ^{128}Te/^{130}Te; **radiochemical result

EXO-200 sensitivity

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA[1]	NSM[2]
EXO-200	0.2	70	2	1.6*	40	6.4×10^{25}	109	135

[*] σ(E)/E = 1.4% obtained in EXO R&D, Conti et al., Phys. Rev. B 68 (2003) 054201

[1] Simkovic et al. Phys. Rev. C79, 055501(2009) [use RQRPA and g_A= 1.25]

[2] Menendez et al., Nucl. Phys. A818, 139(2009), use UCOM results

improves sensitivity for ^{136}Xe 0νββ by one order of magnitude

detected 2νββ of ^{136}Xe ($|M^{2\nu}|=0.019\ \mathrm{MeV}^{-1}$)

(reference: 10^{25} years lifetime => 440 events/year/ton of ^{136}Xe)

discovery claim in ^{76}Ge: $T_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$y

46/170 (QRPA/NSM) events above 40 bg: confirm or rule out at 5/11.7 σ

0νββ and neutrino masses

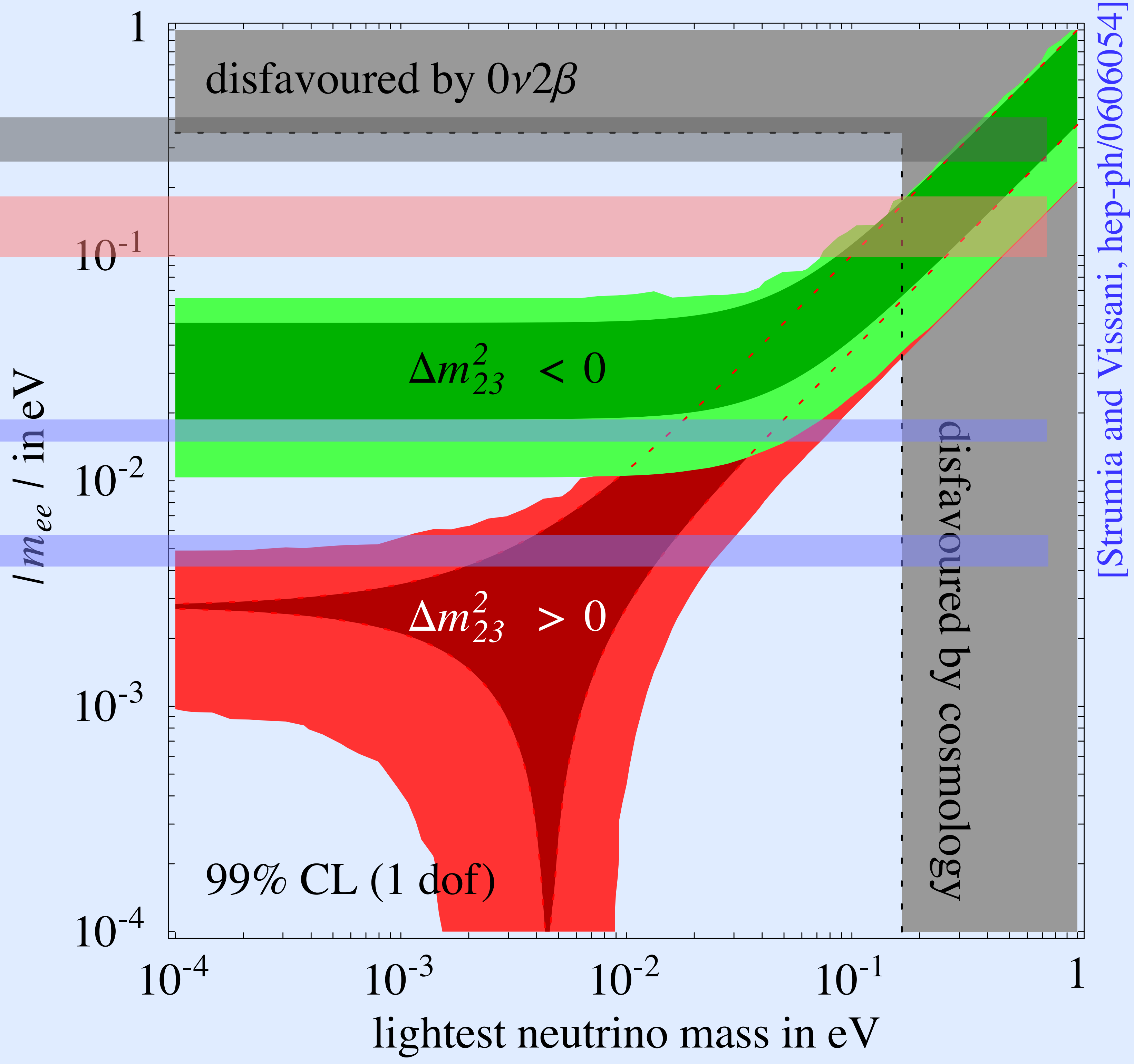
[PLB 586(2004)198]

Klapdor et al.

EXO-200 (~100 meV)

EXO (2 tons, 5 years, ~18 meV)

EXO (10 tons, 10 years, ~5meV)



m_{eff} ~ 50 meV: ~ 10^{27} years

(10^{27} nuclei ~ 10^3 moles ~ 100 kg)

sensitivity of ton-scale EXO with barium tagging

Assumptions:

1. 80% enrichment in Xe-136
2. 68% overall efficiency: 95% energy cut * 80% tracking effic * 90% lifetime fraction from EXO-200 analysis
3. Intrinsic low background + Ba tagging eliminate all radioactive background
4. Energy resolution only used to separate the 0ν from 2ν modes: select 0ν events in a ±2σ interval centered around the 2.458 MeV endpoint
5. Use for 2νββ $T_{1/2}$=2.11×10^{22}yr (Ackerman et al., arXiv:1108.4193, 21 August 2011)

Case	**Mass (ton)**	**Eff. (%)**	**Run Time (y)**	**σ_E/E @ 2.5MeV (%)**	**2νββ Background (events)**	**$T_{1/2}^{0\nu}$ (y) (90% CL)**	**Majorana mass (meV)**	
							QRPA[1]	**NSM[2]**
large	2	68	5	1.6*	5	2.4×10^{27}	16	20
very large	10	68	10	1†	3.4	3.5×10^{28}	4.7	5.8

* σ(E)/E = 1.6% obtained in EXO R&D, Conti et al Phys Rev B68 (2003) 054201

† σ(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area

[1] Šimkovic et al., Phys. Rev. C79 055501 (2009) [use RQRPA with g_A=1.25]

[2] Menendez et al., Nucl. Phys. A818 139 (2009) [use UCOM results]