PAVI 2011

From parity violation to hadronic structure and more ...

Rome, 5-9 September 2011

EXO and DarkSide: double beta decay and dark matter searches with noble liquid detectors

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outline

1. ***two searches to probe fundamental symmetries of nature***

    - 0ν ββ decay (lepton number violation, particle/antiparticle symmetry)
    - non-baryonic particle dark matter (WIMPs) (supersymmetry?)

2. ***detection techniques and experiments***

    - use of large noble liquid detectors
    - common threads and challenges (not a review talk)

3. ***the Enriched Xenon Observatory (EXO) for double beta decay***

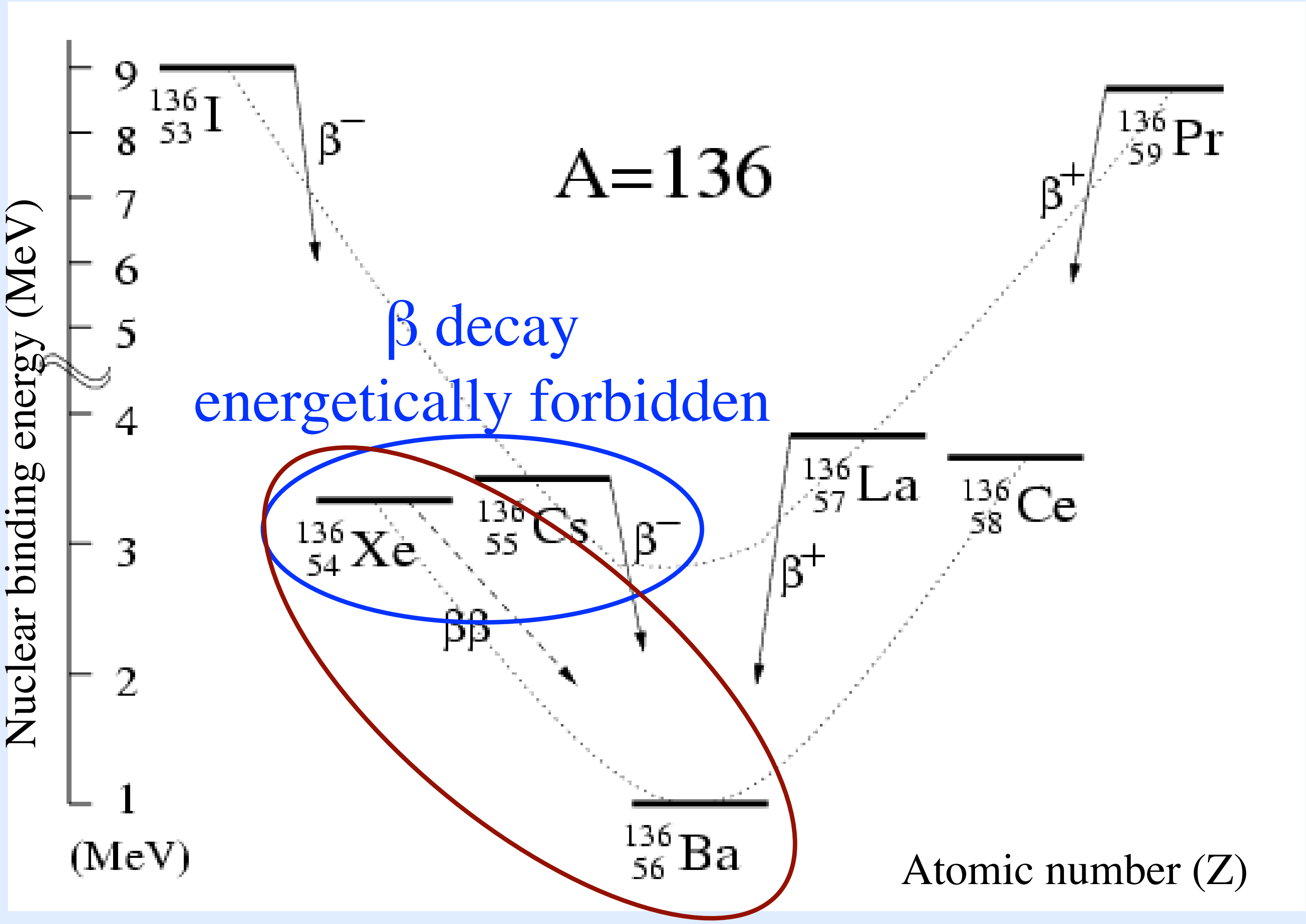
    - EXO-200 (first physics result)
    - ton-scale EXO (briefly)

4. ***the DarkSide program***

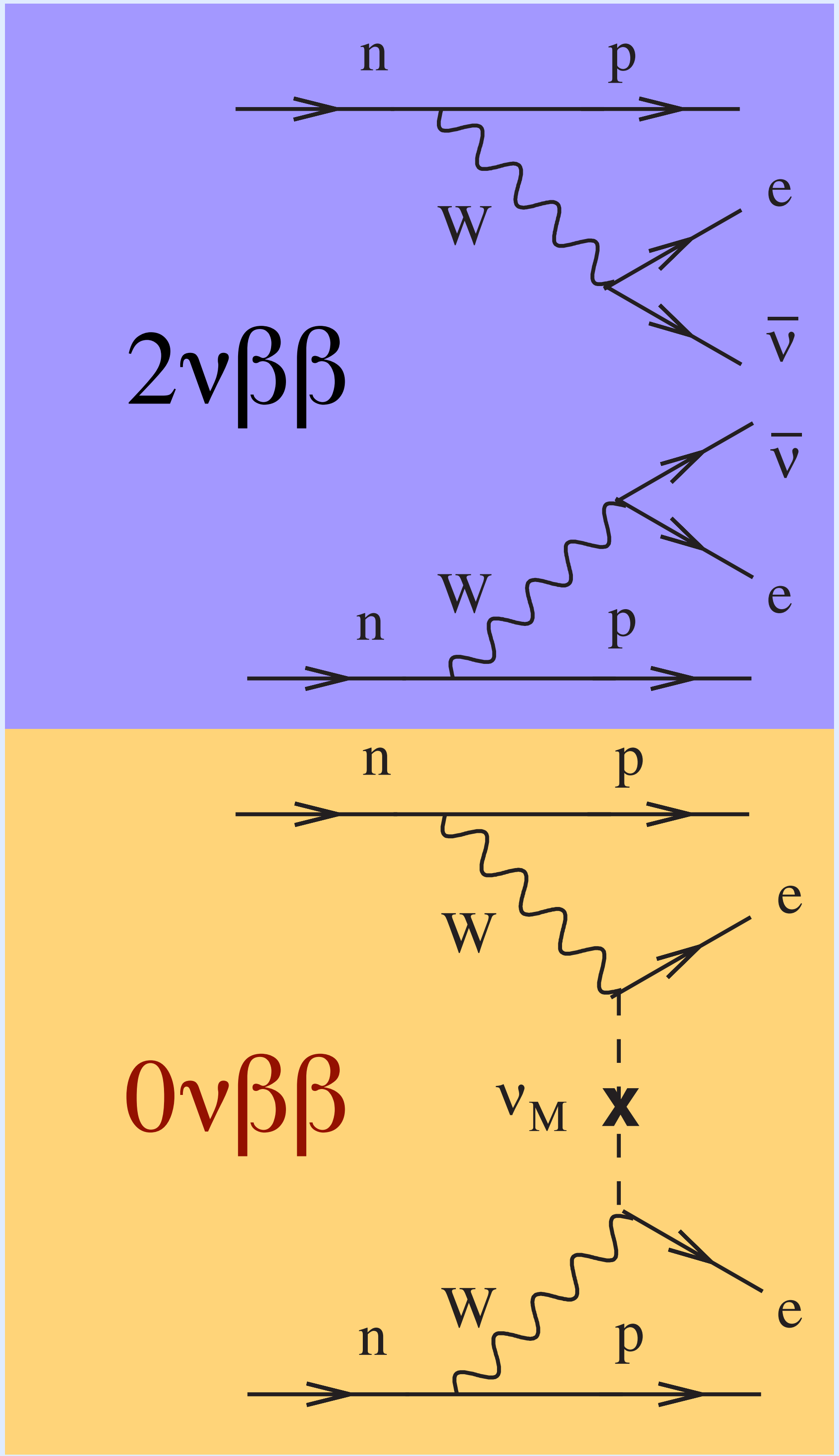
    - DS-10 prototype
    - DS-50 and ton-scale DS (briefly)

double beta decay

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



possibility of non-standard 0νββ process



why study $0\nu\beta\beta$ decay?

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:

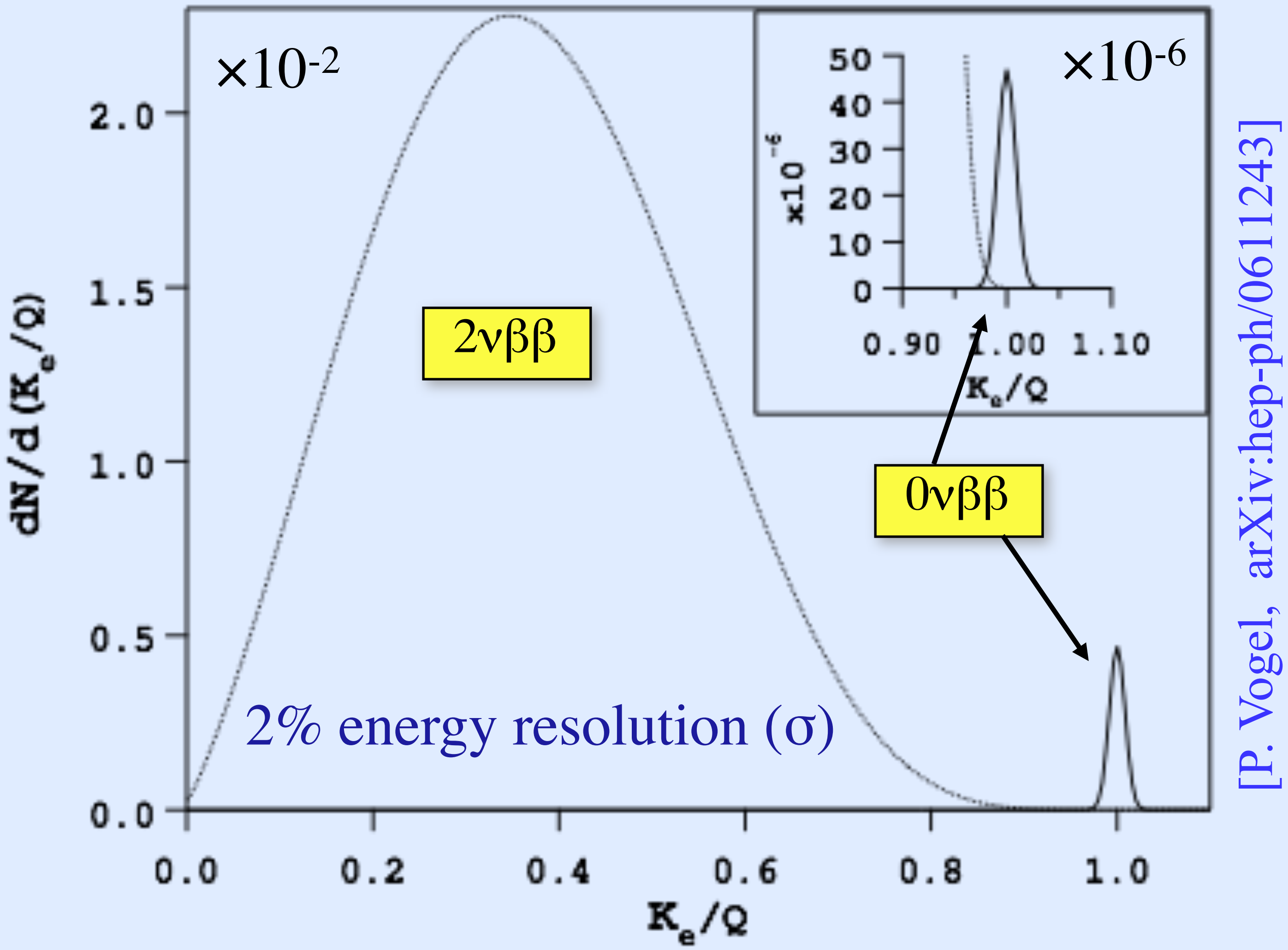
- measure the absolute mass scale of neutrinos
- define the mass ordering of neutrinos
- shed light on the matter/antimatter asymmetry (leptogenesis, ...)

how is 0νββ measured in the laboratory?

- very rare events: need to suppress non-ββ background with low radioactivity detectors (γ's in particular)

- large mass: large source, isotope enrichment

- energy resolution: separate 0νββ mono-energetic peak in the 2-electron energy spectrum and fewer non-ββ background events in the peak



- tracking: identify individual electron tracks to discriminate between single- and 2-electron events (discrimination of β and γ background radiation)

- multi-isotope: measure different isotopes with the same detector to cross-check results and reduce systematic and theoretical uncertainties

- decay product identification: unambiguously from ββ events

measured quantity: half life (rate)

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

directly measured quantity

calculable phase space factors

nuclear matrix elements
(calculated within particular nuclear models)

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

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

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)

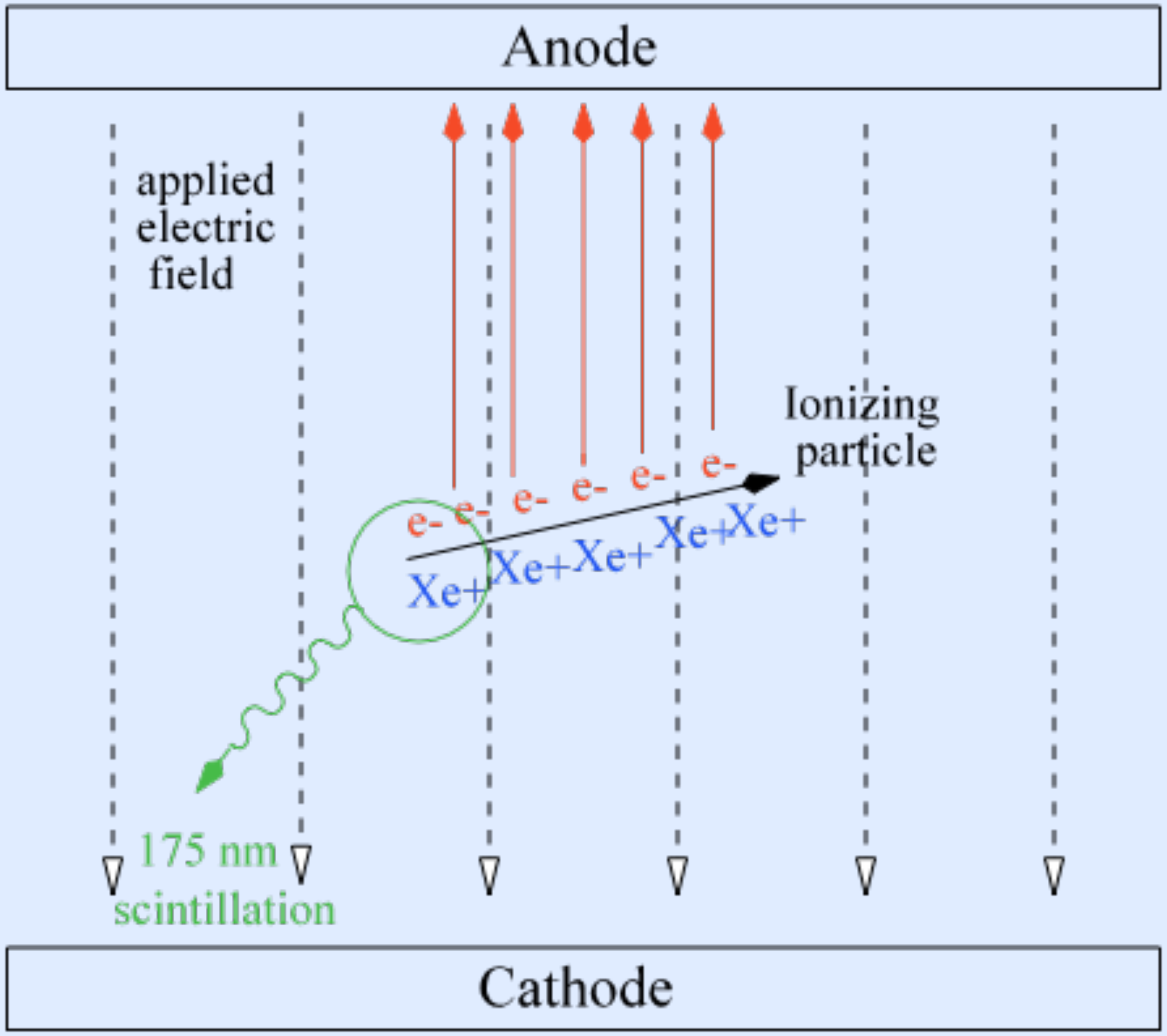
✓ standard $2\nu\beta\beta$ (just observed!) is very slow

($T^{0\nu}_{1/2} = 2.11 \times 10^{22}$ y) [Ackerman et al.., arXiv:1108.4193]

✳ energy resolution: GXe > LXe > scintillator

LXe TPC design

dual readout of ionization and scintillation for position and energy measurement



Ionizing radiation interacting with liquid (or gaseous) xenon locally separates charge along it's path

Electric field drifts some of it away
The rest recombines producing scintillation (175 nm), via Xe_2 dimer de-excitation

Event energy: ionization and scintillation light (used as t=0 for z)

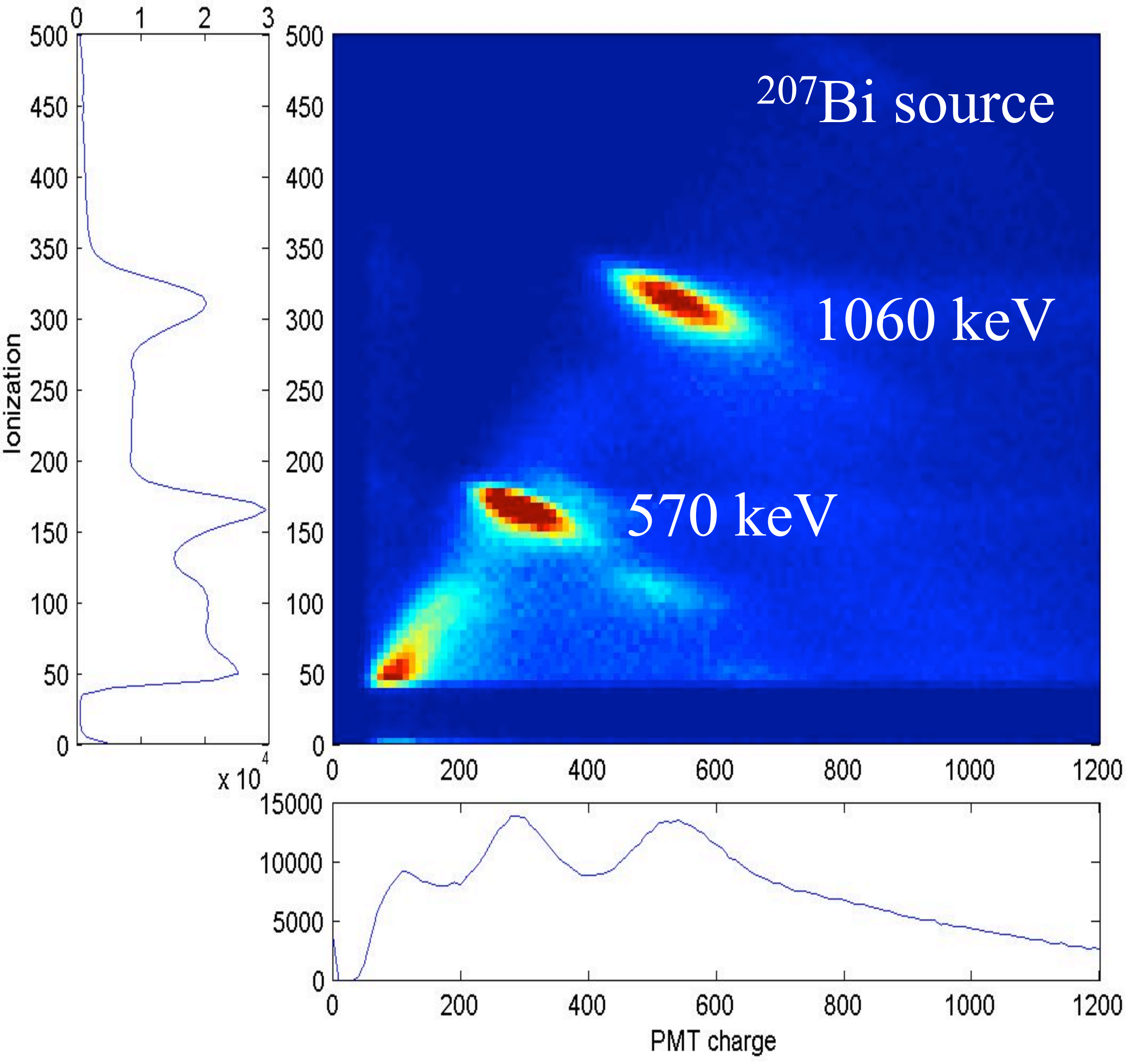
Position of the event: crossed wires at the anode (x-y) and drift time (z)

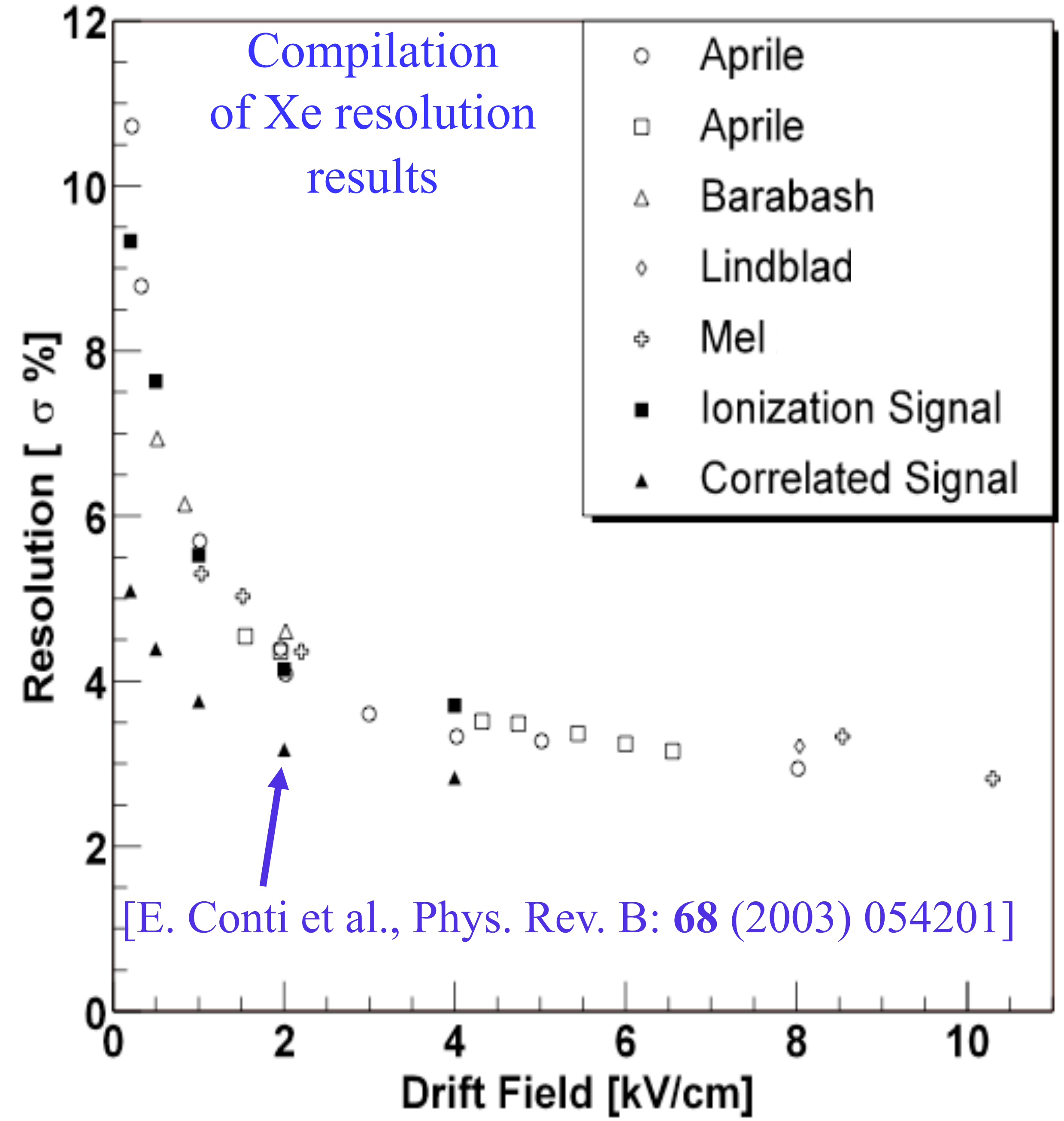
✓excellent technology for rare, low energy events!

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% @ $Q_{\beta\beta}$





the EXO program

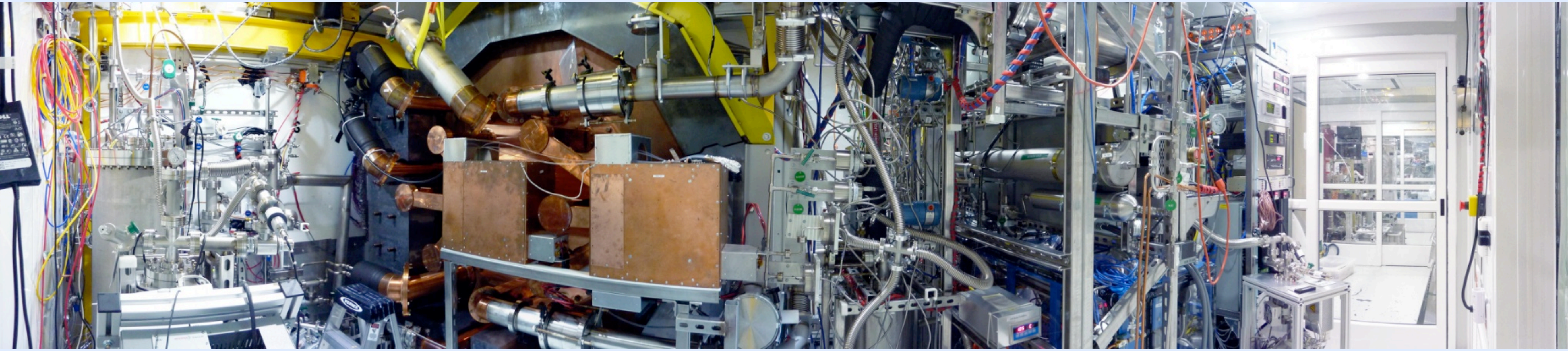
"EXO is a program aimed at building a xenon double beta decay experiment with a one or more ton ^{136}Xe source, with the particular ability to detect the two electrons emitted in the decay in coincidence with the positive identification of the ^{136}Ba daughter via optical spectroscopy for unprecedentedly low background"

EXO-200

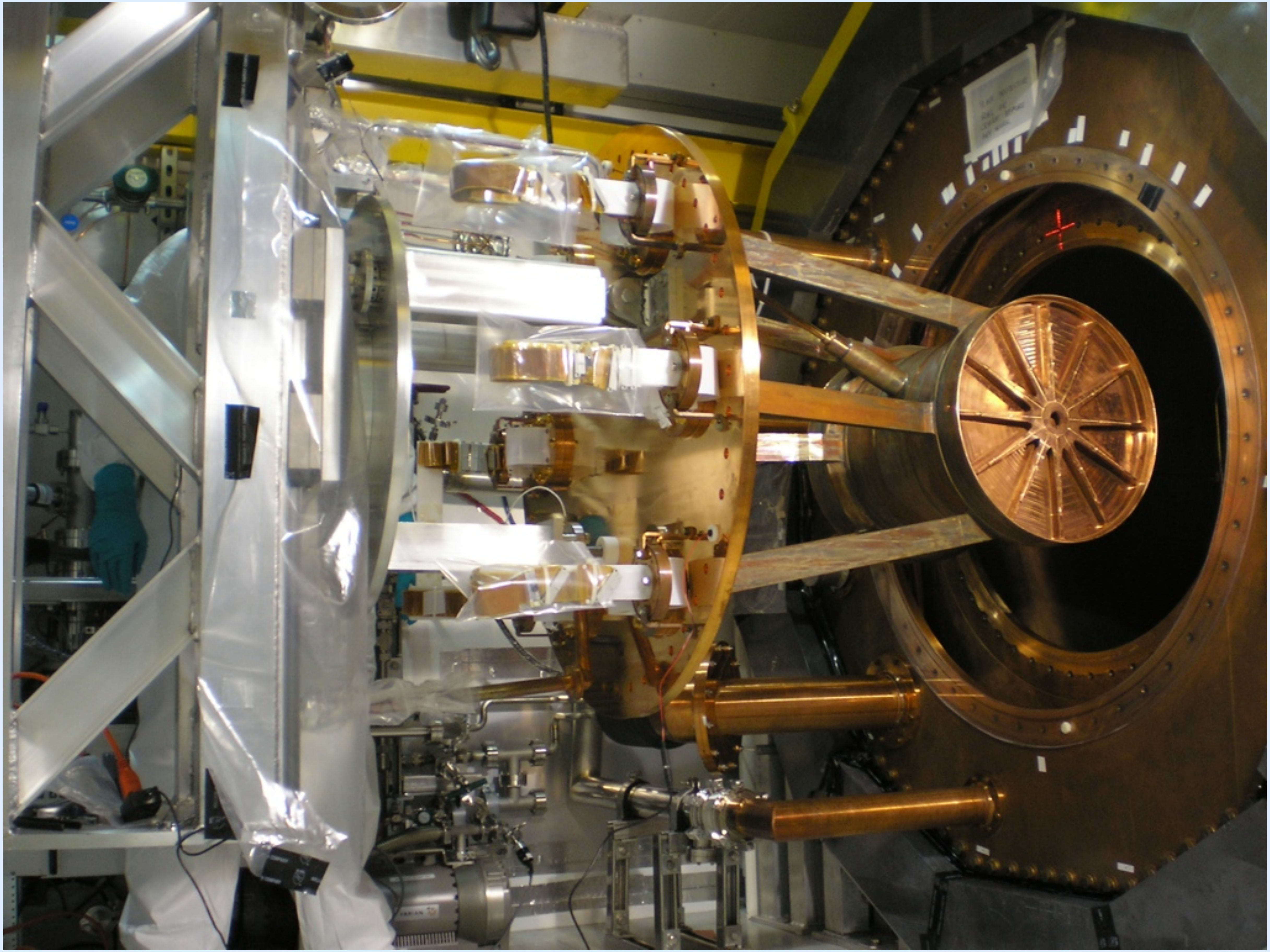
EXO-200 is a large single phase LXe TPC with scintillation light readout. It uses a source of 200 kg of enriched xenon (80% ^{136}Xe)

- measure the standard $2\nu\beta\beta$ decay of ^{136}Xe (done!) [Ackerman et al.., arXiv:1108.4193]
- look for $0\nu\beta\beta$ decay of ^{136}Xe with competitive sensitivity (current limit: $T^{0\nu}_{1/2} > 1.2 \times 10^{24}$ y) [R. Bernabei et al., Phys. Lett. B 546 (2002) 23]
- test backgrounds of large LXe detector at ~2000 m.w.e. depth
- test LXe technology and enrichment on a large scale
- test TPC components, light readout (~500 LAAPDs), and radioactivity of materials, xenon handling and purification, energy resolution

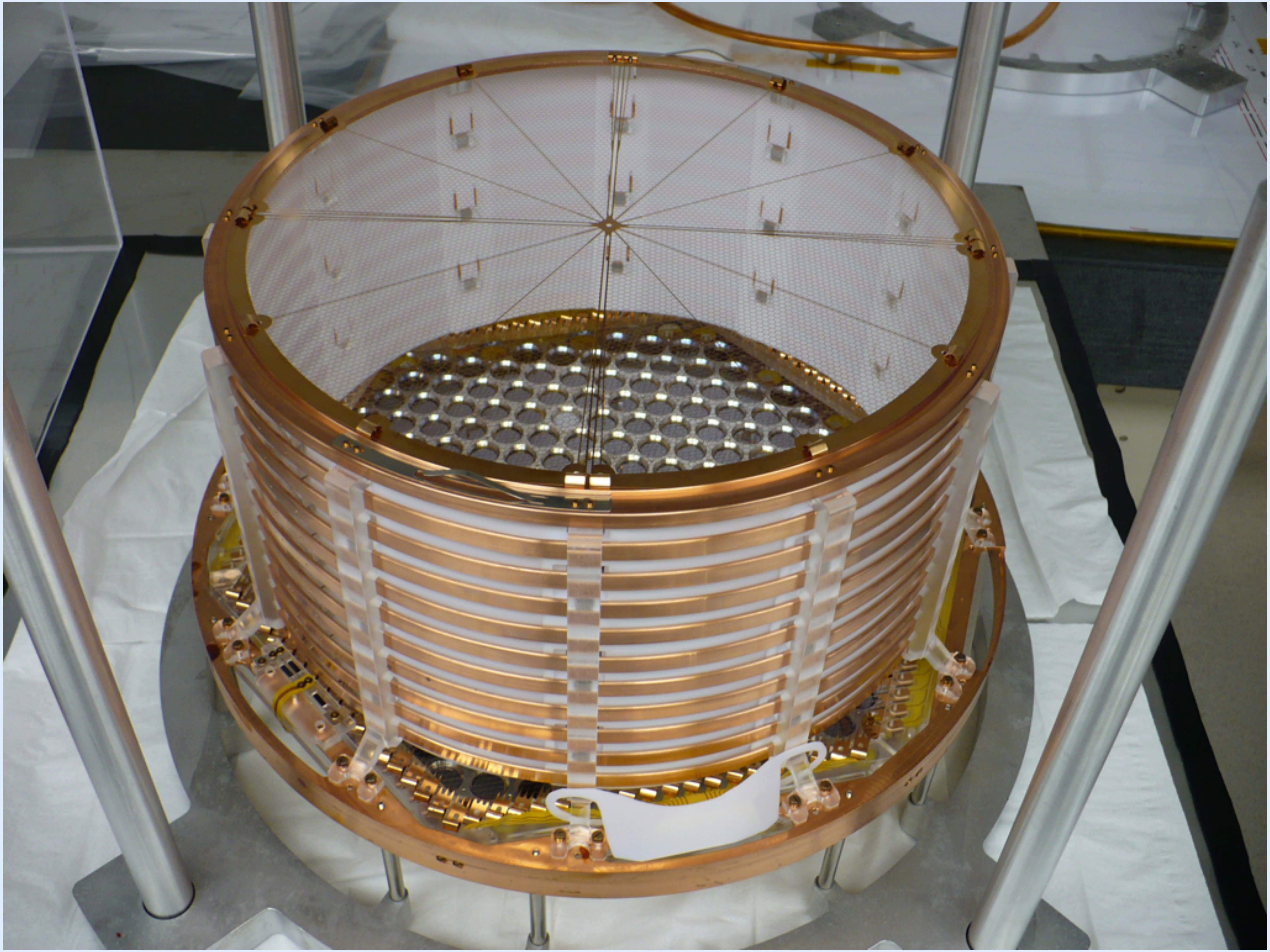
EXO-200 @ WIPP



EXO-200

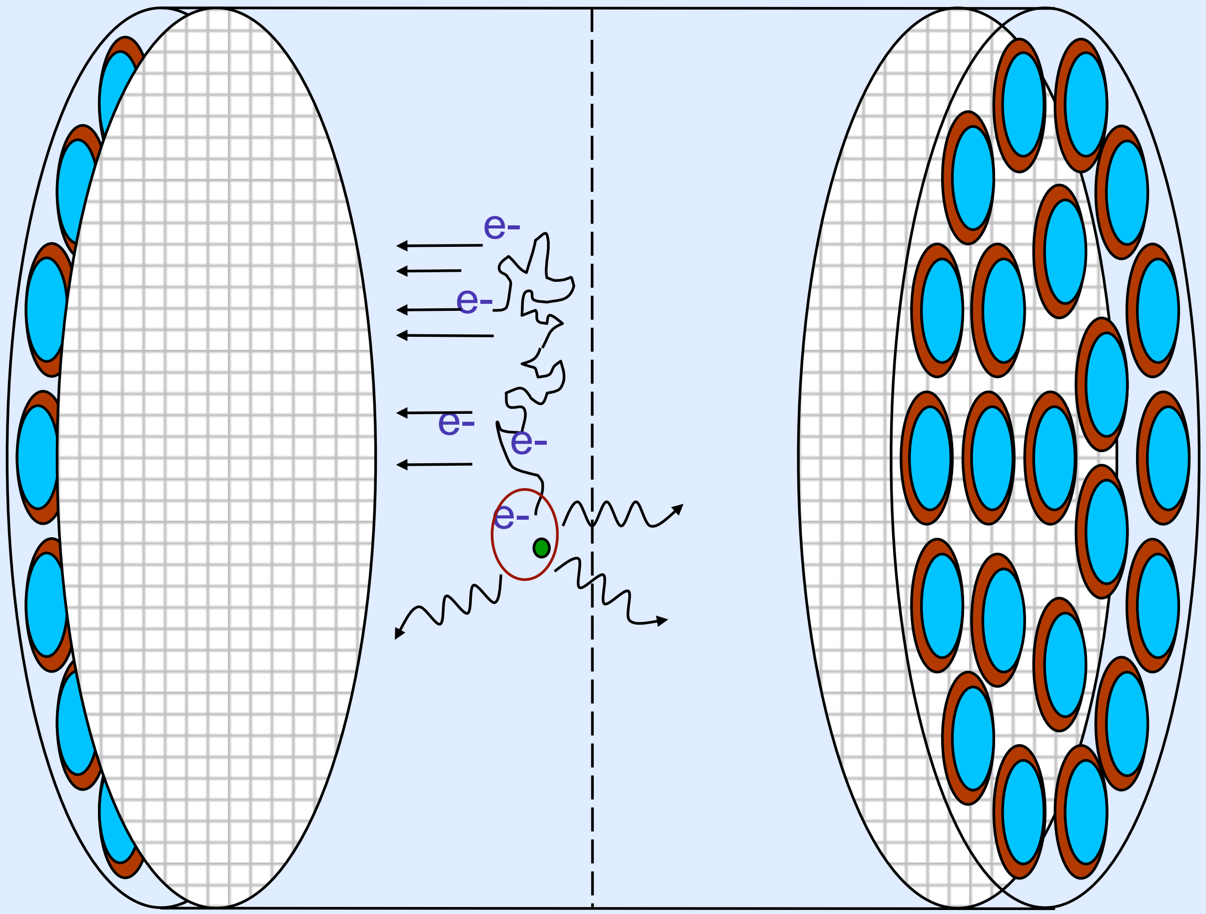


the EXO-200 TPC

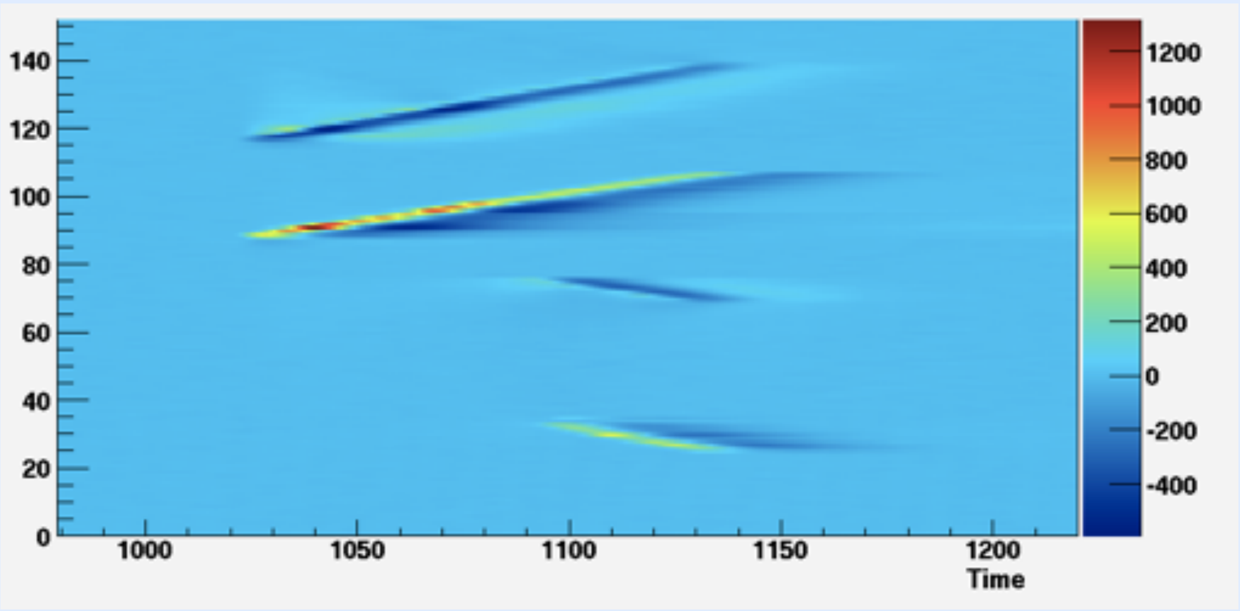


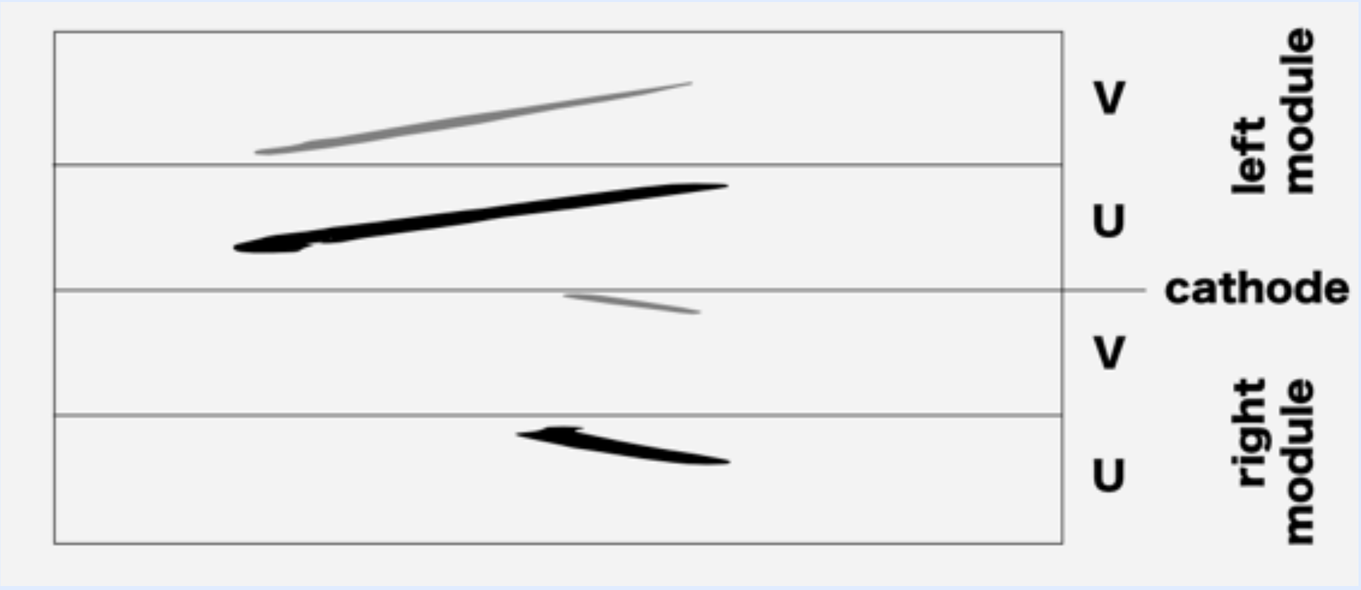
EXO-200 engineering run (Dec 2010)

✓ 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



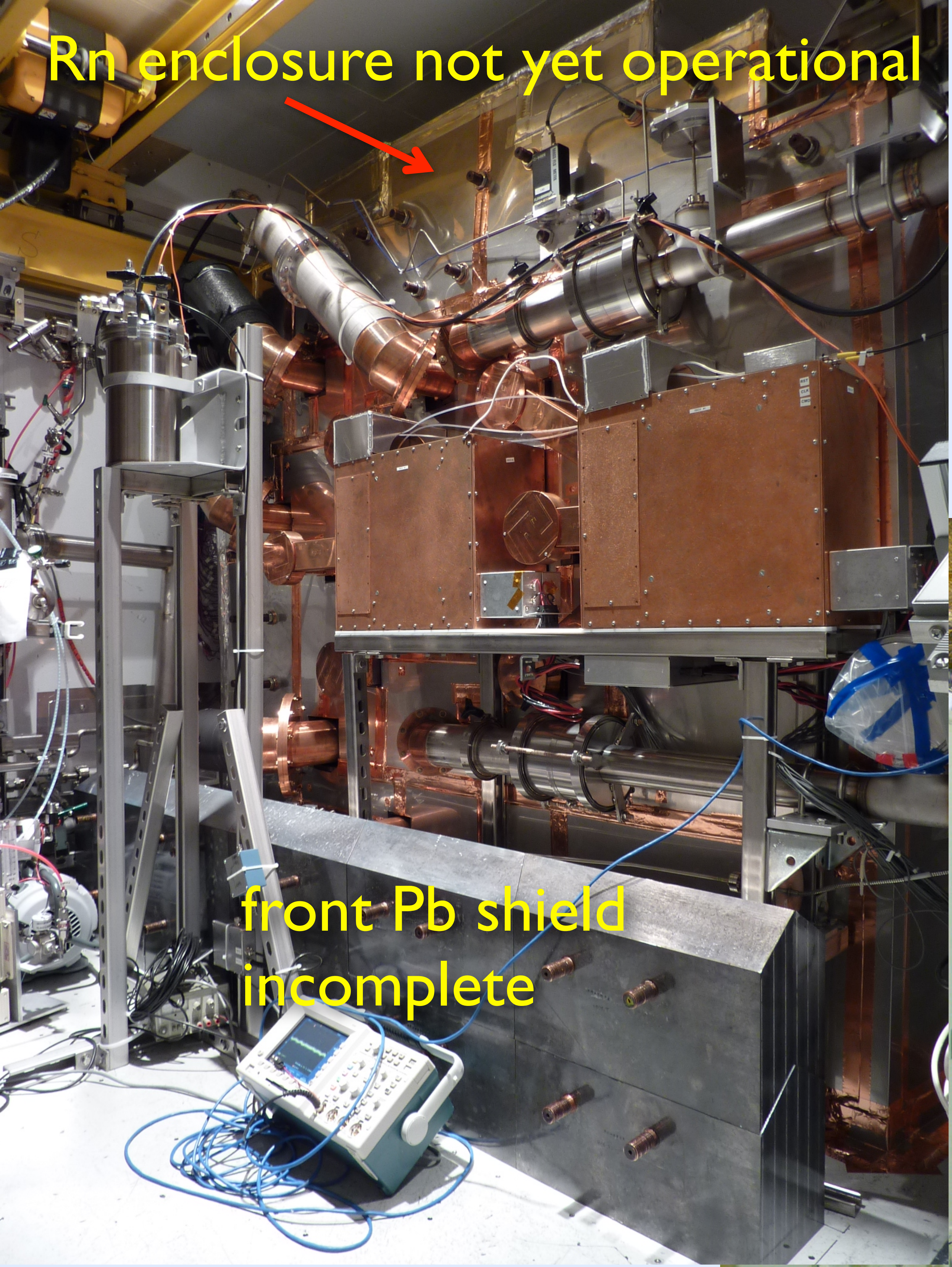
a muon event:





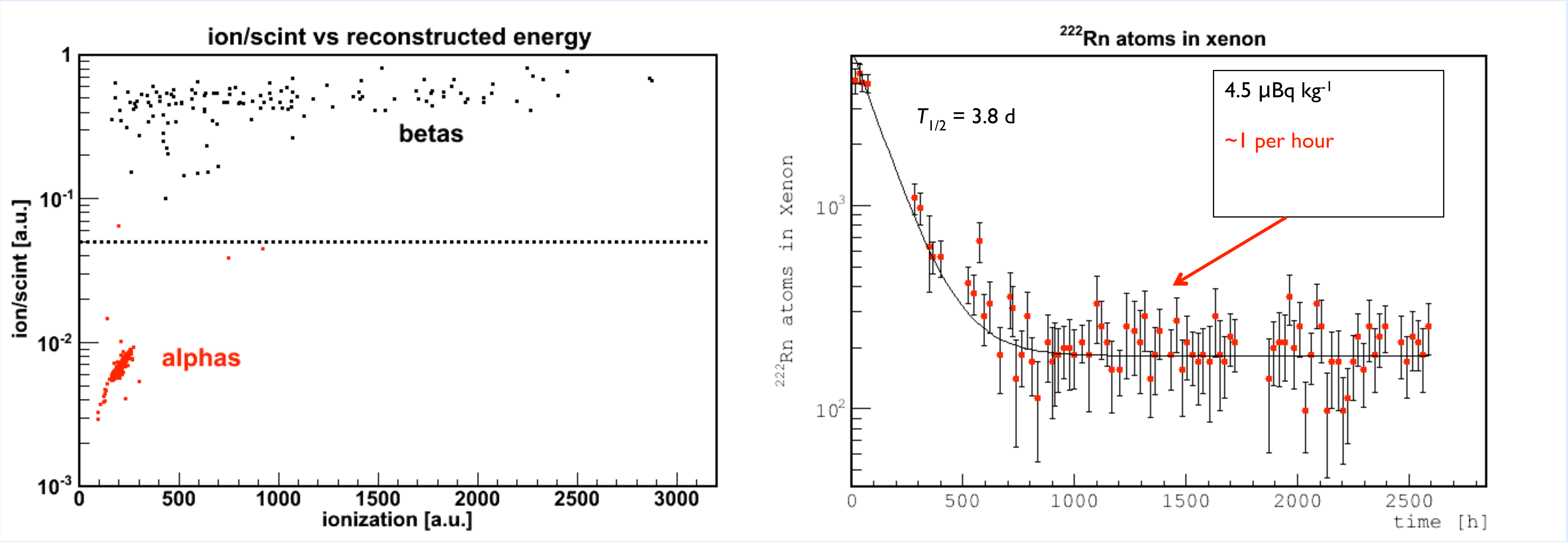
status of EXO-200

running with enriched xenon since spring 2011



no Rn trap in Xe system

Rn content and alpha discrimination

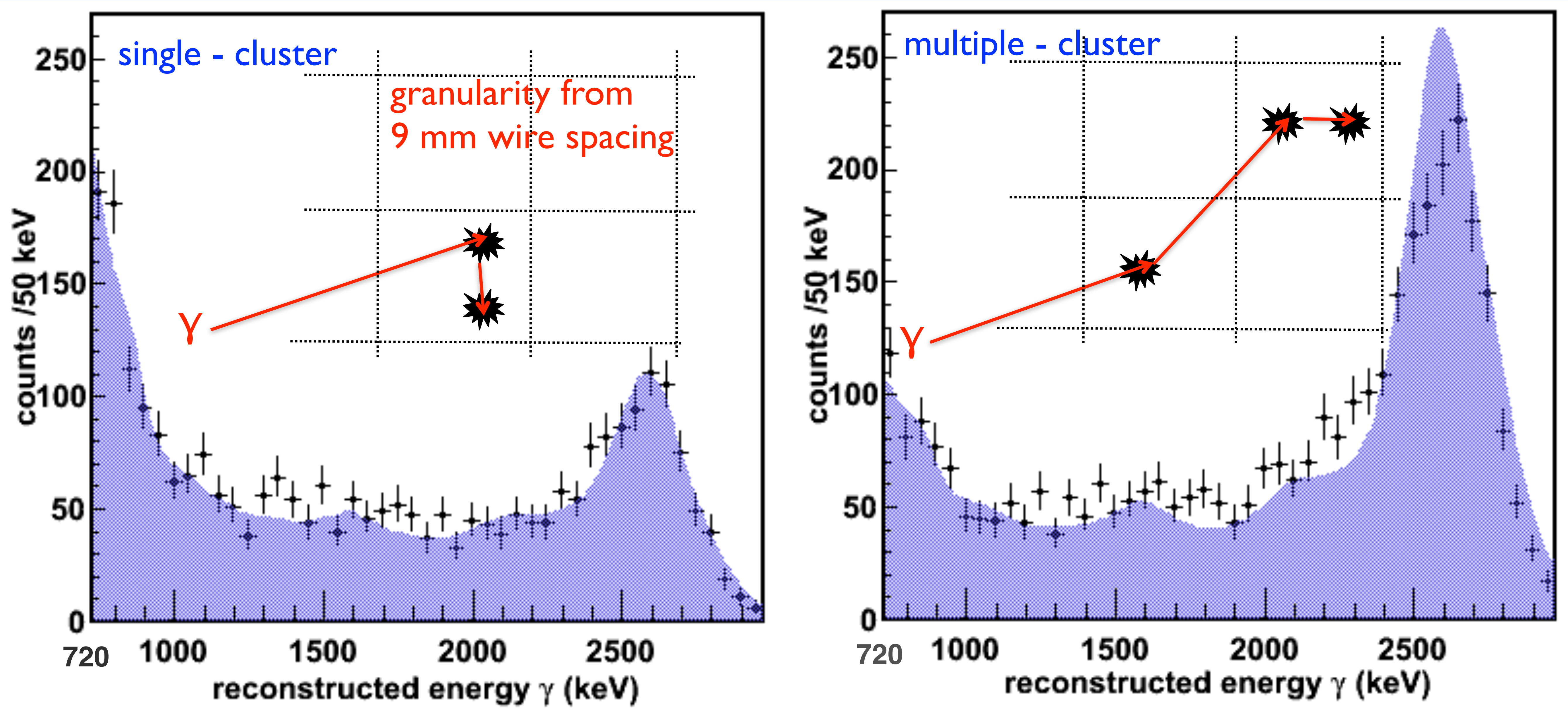


α: strong light signal, weak charge signal
β: weak light signal, strong charge signal

^{214}Bi–^{214}Po correlations in the EXO-200 detector

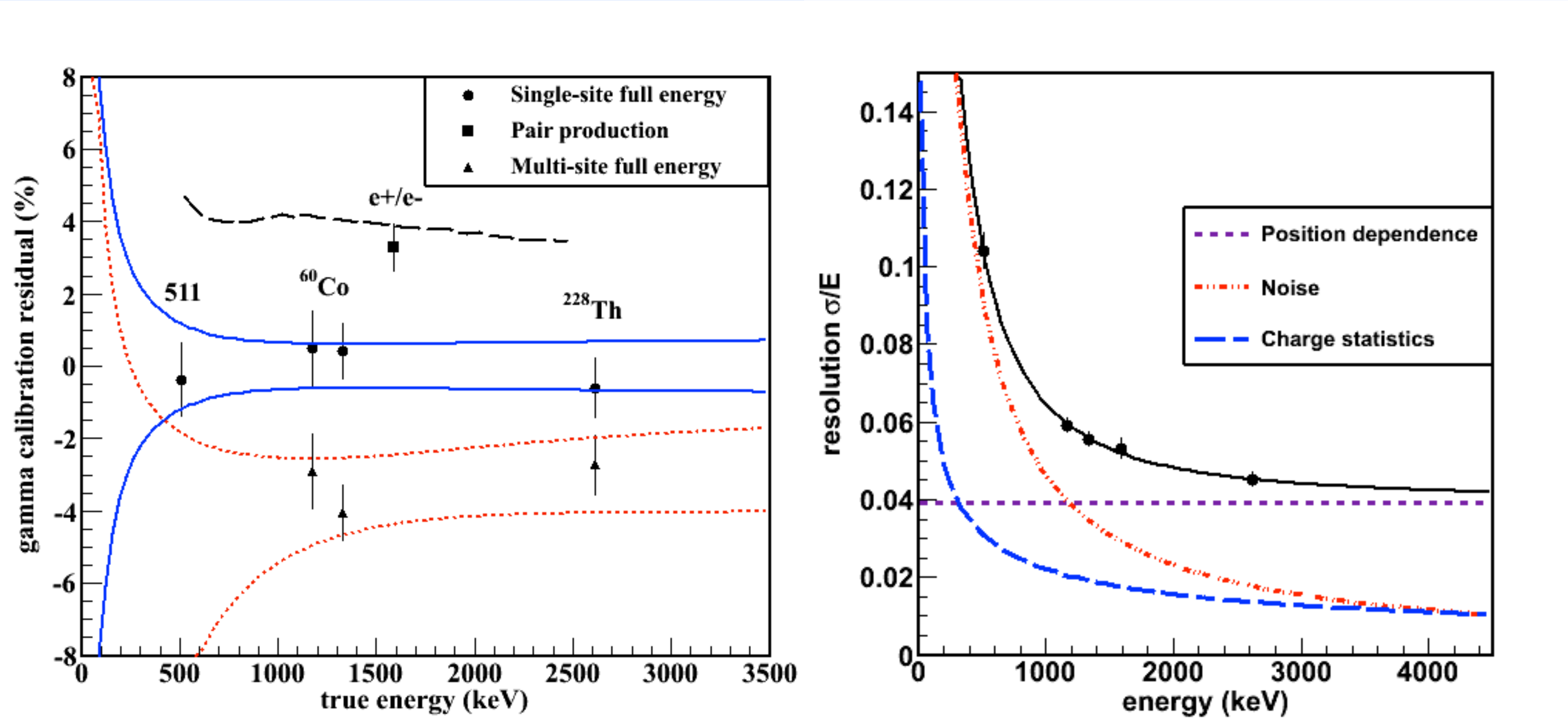
Using the Bi-Po (Rn daughter) coincidence technique, we can estimate the Rn content in our detector. The ^{214}Bi decay rate is consistent with measurements from alpha-spectroscopy and the expectation before the Rn trap is commissioned.

^{228}Th source calibrations



- 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%)

energy calibration

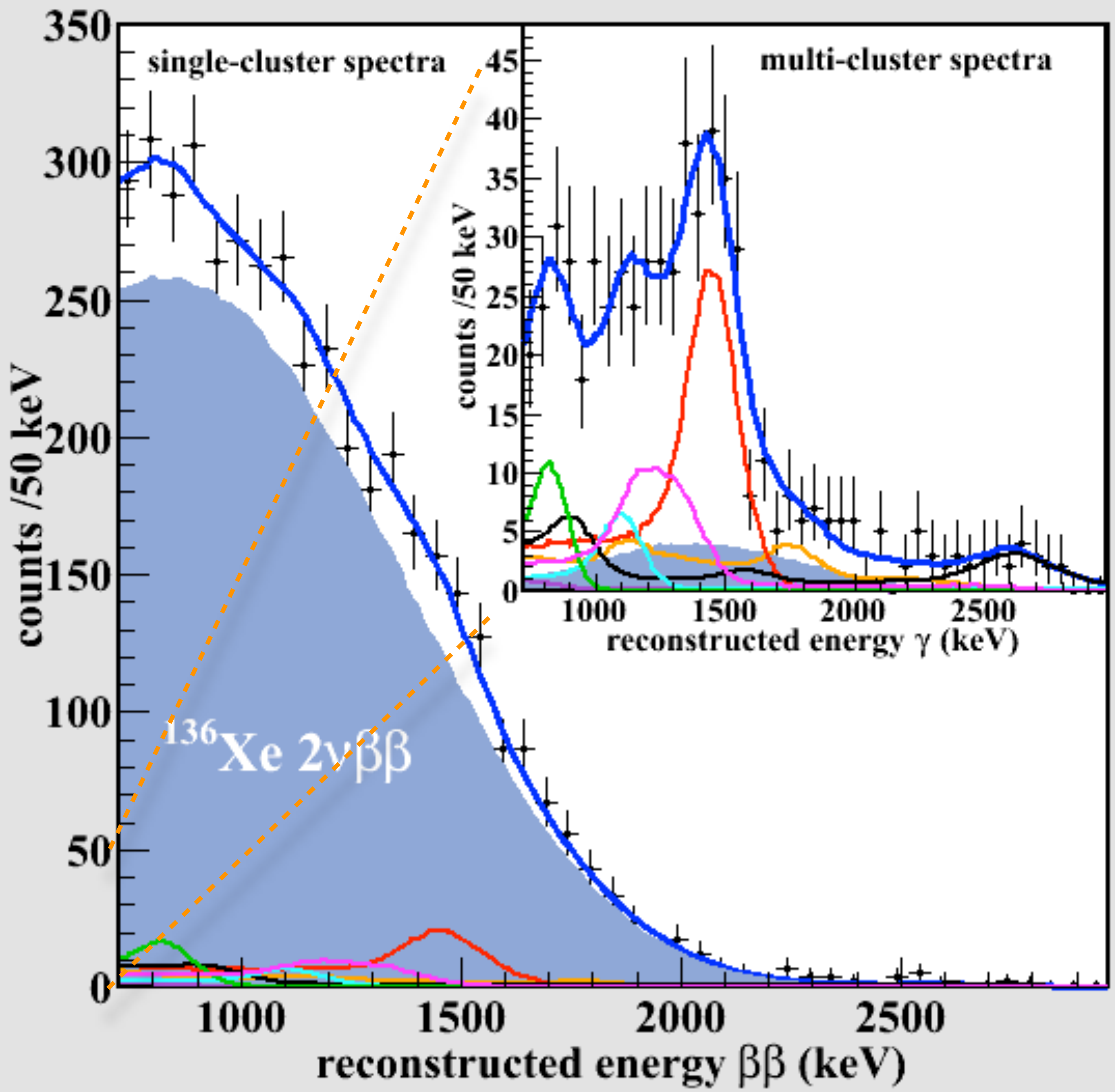


- After purity correction, calibrated single and multiple cluster peaks across energy region of interest (511 to 2615 keV)
  - -uncertainty bands are systematic
- Point-like depositions have large reconstructed energies due to induction effects
  - observed for pair-production site (similar to β and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

first observation of 2νββ of ^{136}Xe

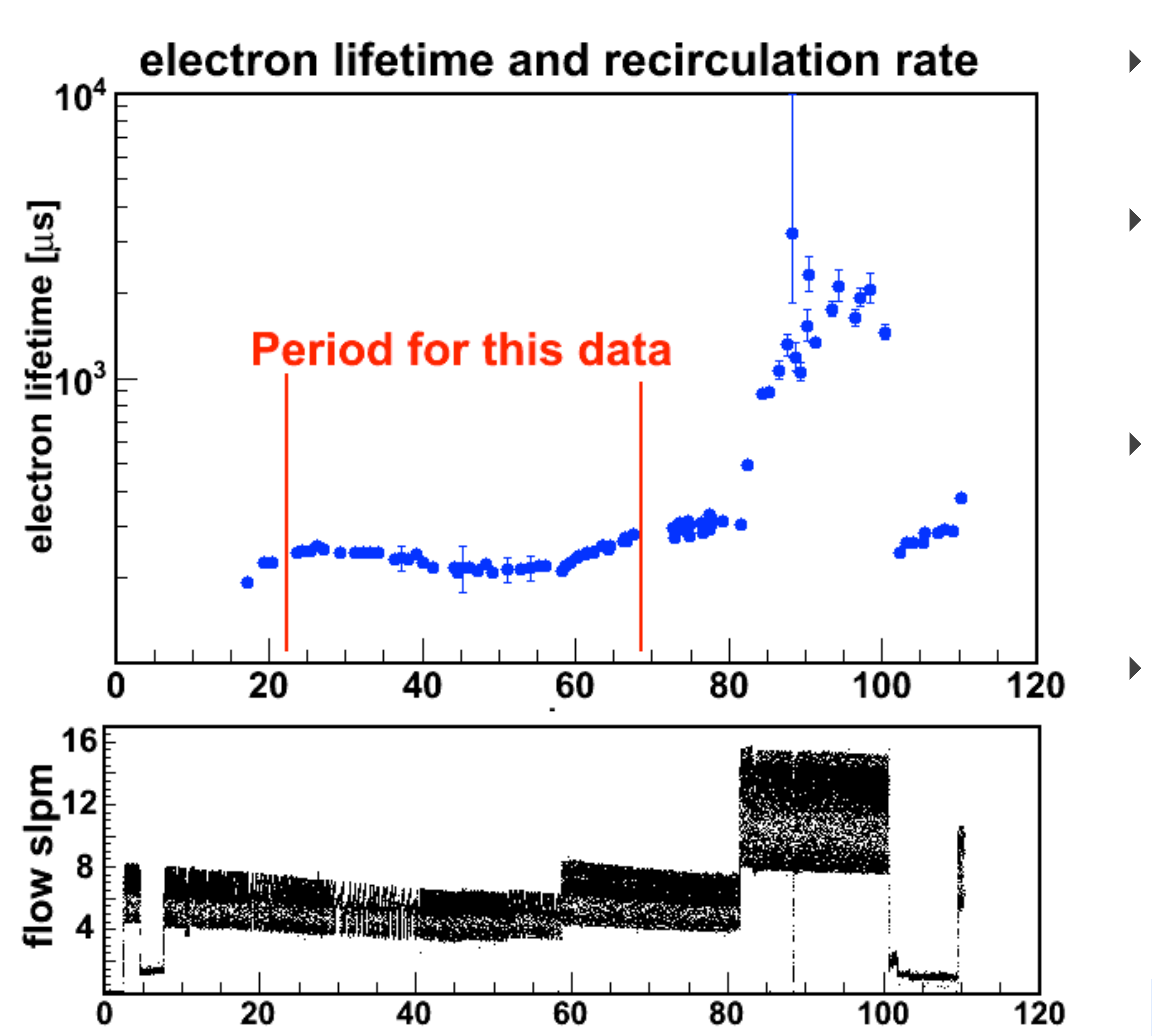
$$T_{1/2} = (2.11 \pm 0.04(\text{stat}) \pm 0.21(\text{syst})) \times 10^{21} \text{ years}$$

[arXiv:1108.4193]



- simultaneous fit to single- and multi-cluster energy spectra (un-binned maximum likelihood fit)
- 31 days of live-time
- 63 kg fiducial mass
- 376 V/cm drift field
- ionization charge spectrum only
- S/N ~ 10 (up to 40 for some extreme fiducial volume cuts)

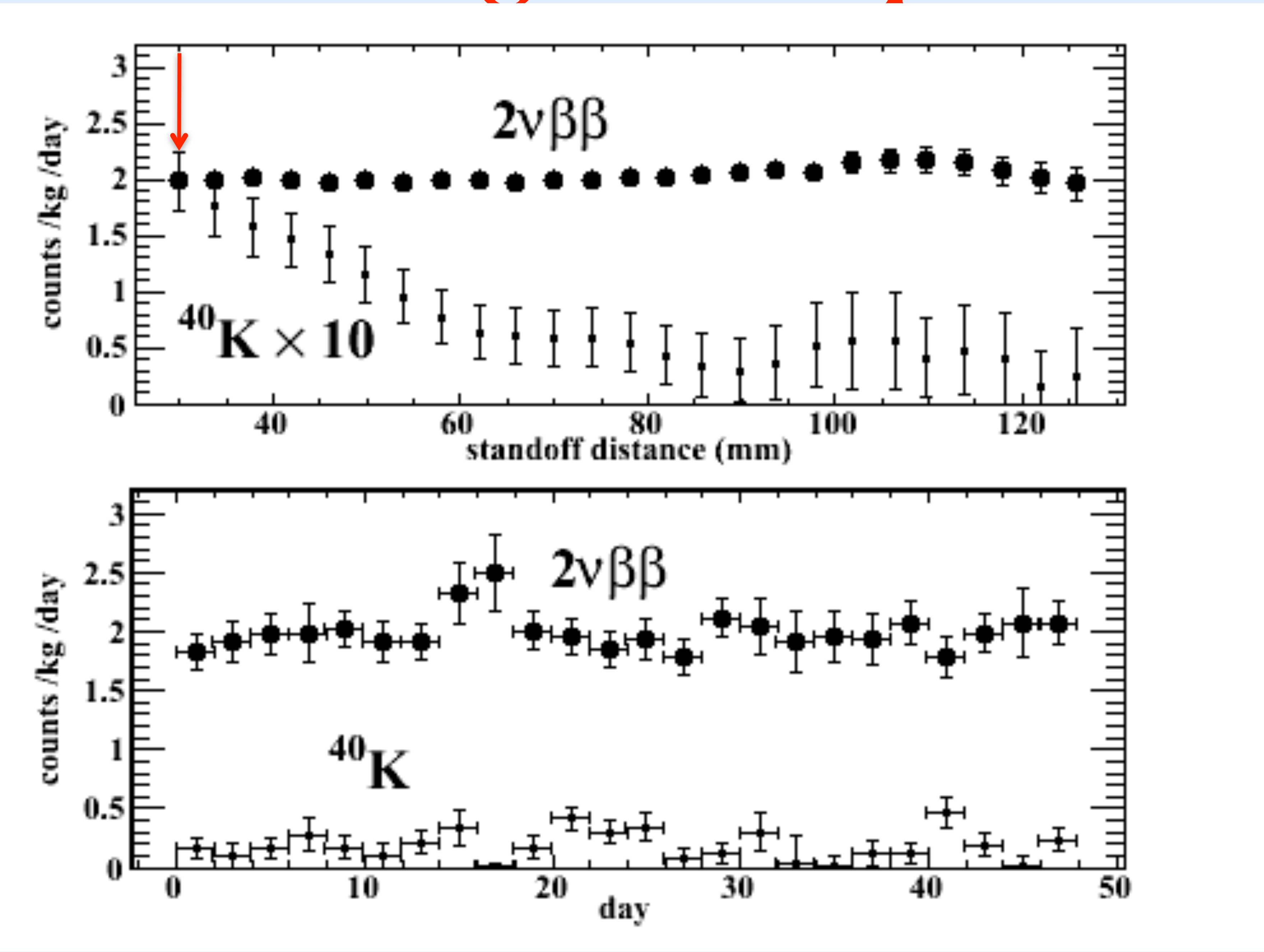
xenon purity



- deployed γ sources around the TPC
- measured the purity of LXe during continuous recirculation
- determined the energy scale in the relevant range of interest
- also used ^{60}Co source

• Use sources to measure purity of LXe in TPC
• Rapid achievement of ms lifetimes results is a clear benefit of recirculation.

low background spectra



- constant in time
- 2νββ signal is clearly in the LXe bulk, while other gamma background contributions decrease with increasing distance from the walls.

$T_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) yr (± 0.21 sys) **[arXiv:1108.4193]**

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 $0\nu\beta\beta$ by one order of magnitude

detected $2\nu\beta\beta$ 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: $T_{1/2} = 2.23^{+0.44}_{-0.31}\times10^{25}$y

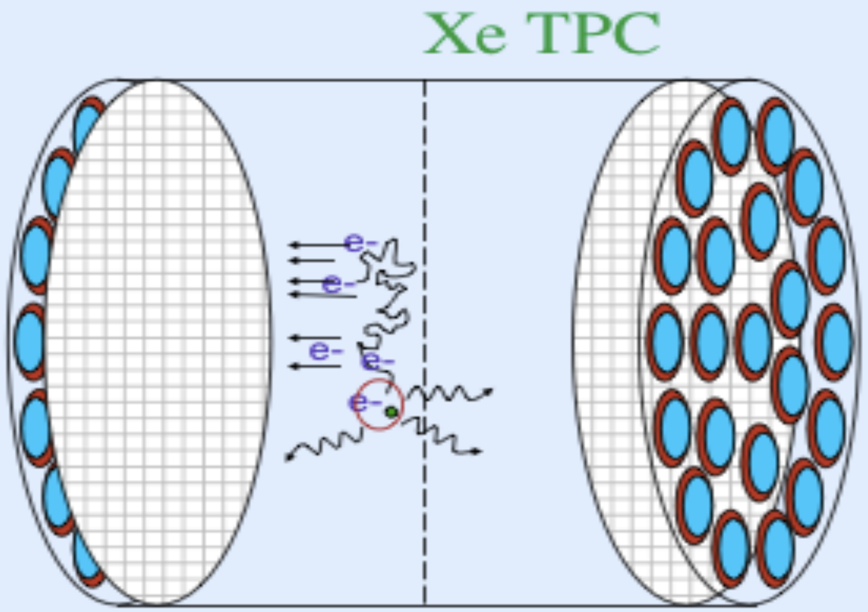
46/170 (QRPA/NSM) events above 40 bg: confirm or rule out at 5/11.7 σ

a ton-scale EXO

xenon admits a novel coincidence technique:
drastic background reduction by Ba daughter tagging!

detect the 2 electrons
(ionization + scintillation in xenon detector)

$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-} \; (+ 2\nu_e)$



[M. Moe, Phys. Rev. C 44 (1991) R931]

a ton-scale EXO

xenon admits a novel coincidence technique:

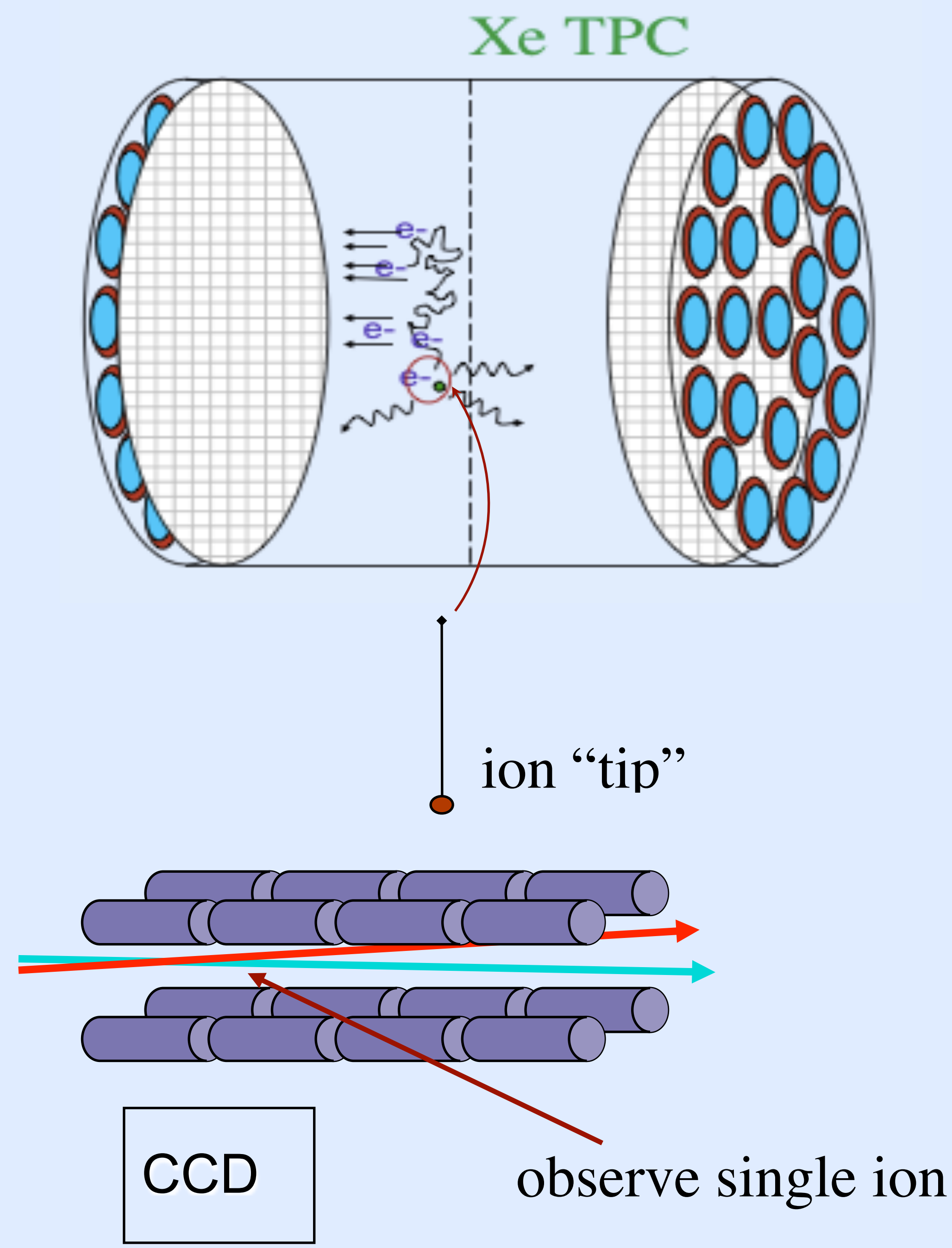
drastic background reduction by Ba daughter tagging!

detect the 2 electrons
(ionization + scintillation in xenon detector)

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^{-} \ (+\ 2\nu_e)$$

positively identify daughter via
optical spectroscopy of Ba^{+}

other Ba^{+} identification strategies are being
investigated within the EXO collaboration



[M. Moe, Phys. Rev. C 44 (1991) R931]

sensitivity of ton-scale EXO with barium tagging

Assumptions:

1. 80% enrichment in 136
2. Intrinsic low background + Ba tagging eliminate all radioactive background
3. Energy resolution only used to separate the 0ν from 2ν modes:
4. Select 0ν events in a ±2σ interval centered around the 2.458 MeV endpoint
5. Use for $2\nu\beta\beta$ $T_{1/2}=2.11\times10^{22}$yr (Ackerman et al., arXiv:1108.4193, 21 August 2011)

Case	Mass (ton)	Eff. (%)	Run Time (y)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ 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]

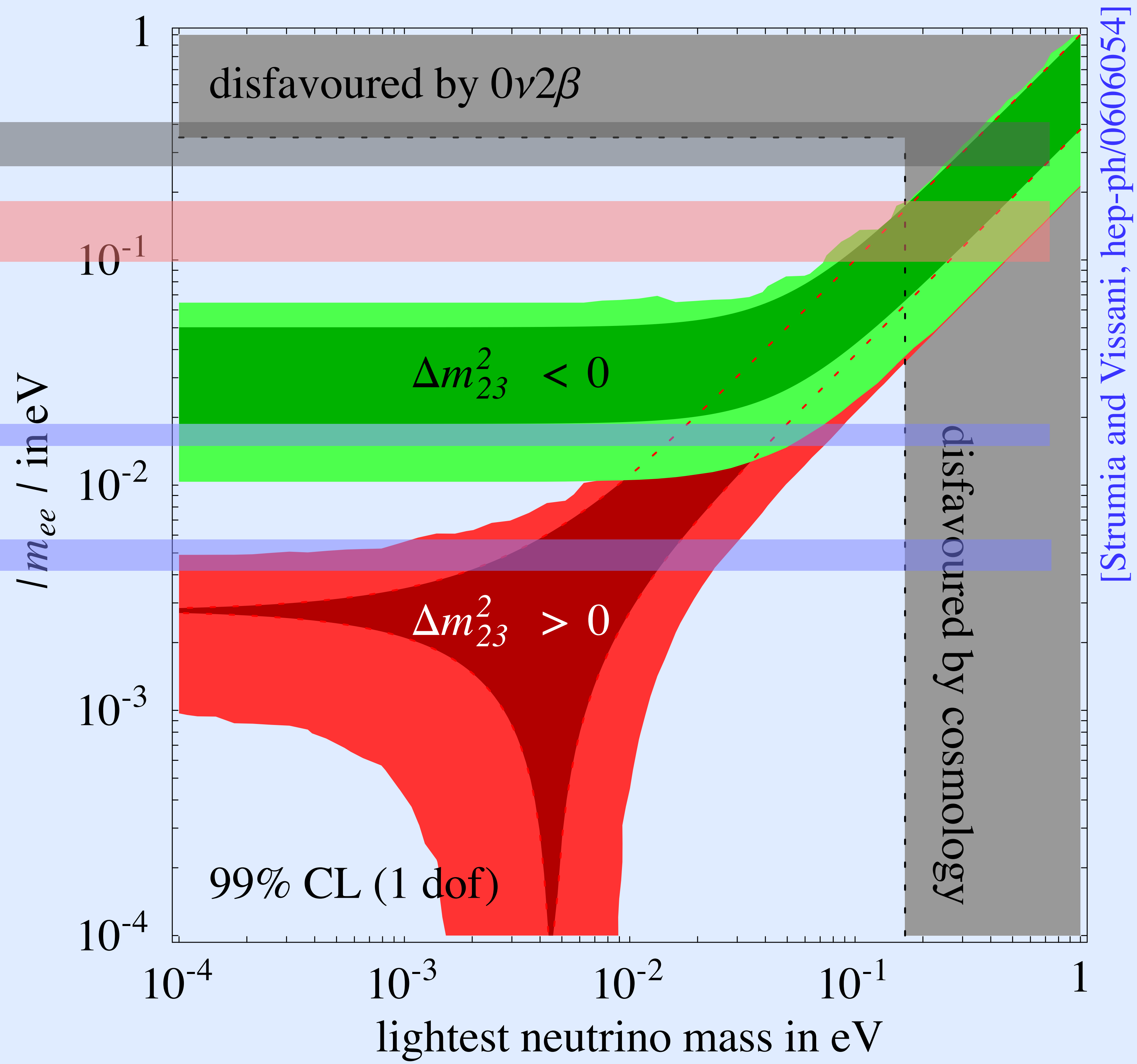
0νββ and neutrino masses

Klapdor et al. [PLB 586(2004)198]

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)

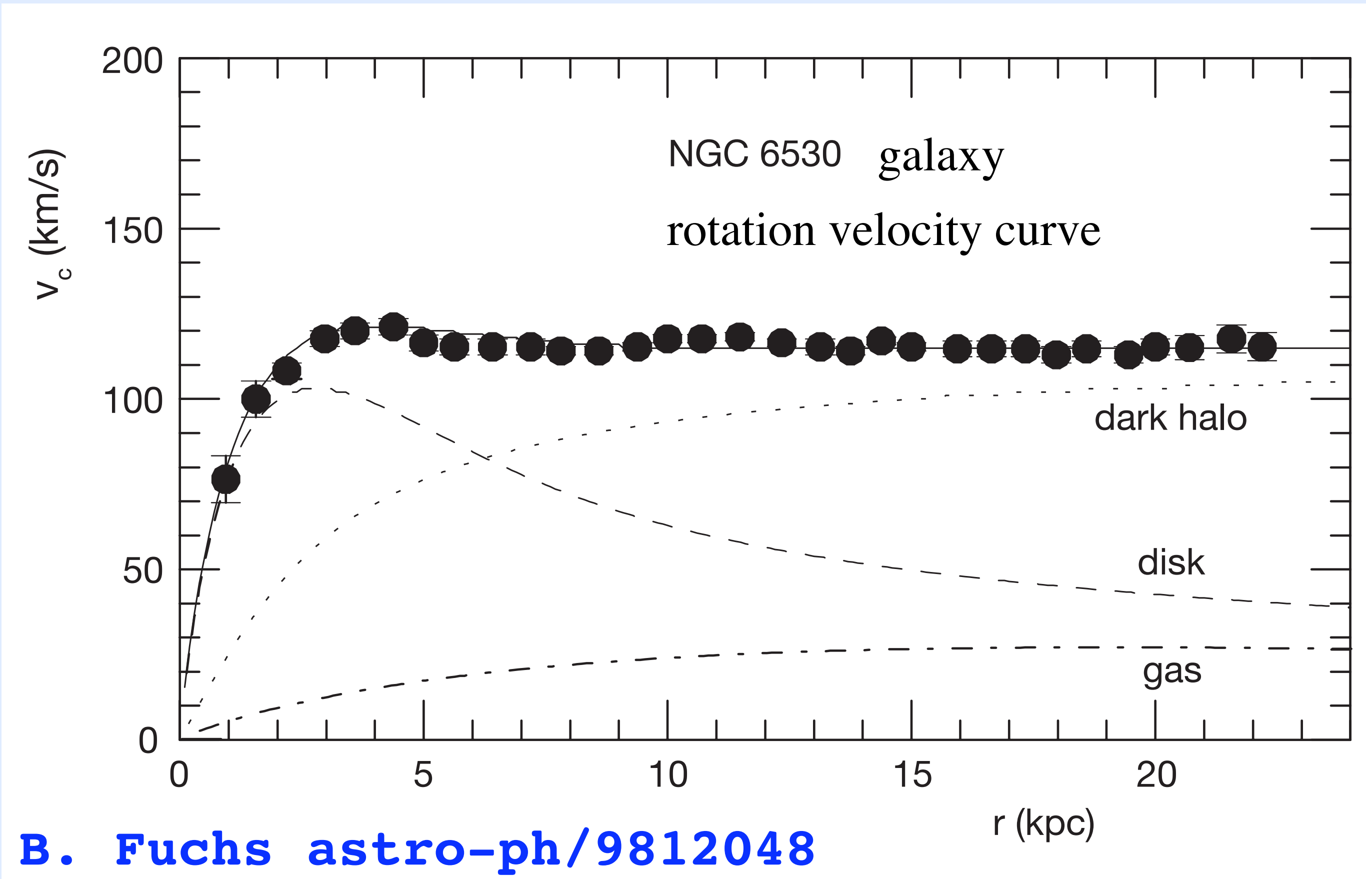
EXO and DarkSide

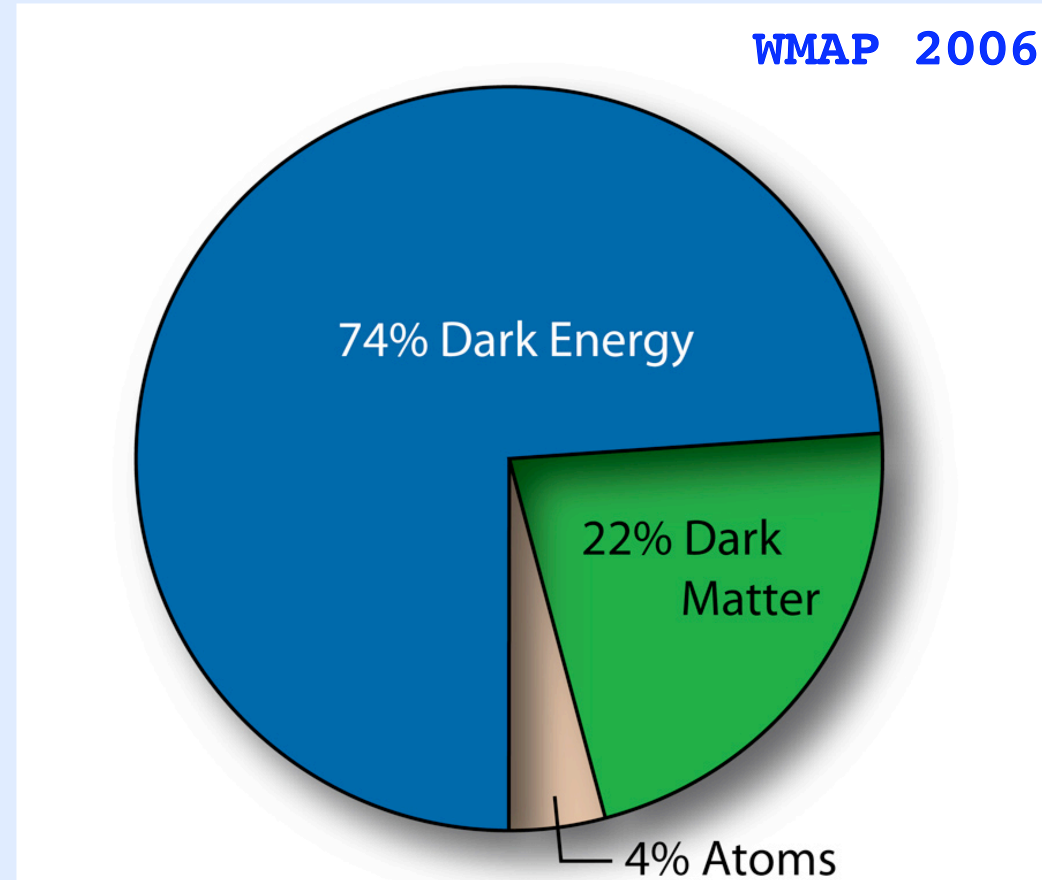
EXO:
single-phase, LXe TPC (enriched Xe)
searching for 0ν double beta decay

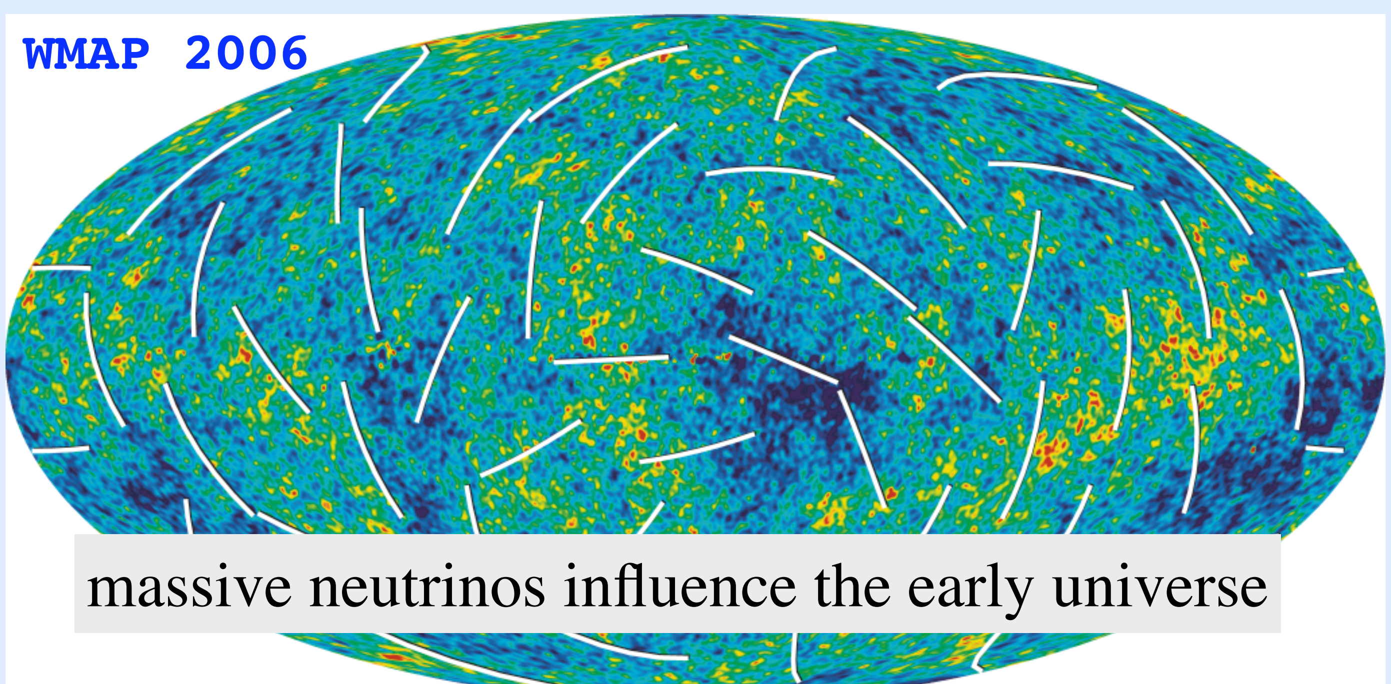
DarkSide:
dual-phase, LAr TPC (depleted Ar)
searching for galactic WIMPs

mass budget in the universe

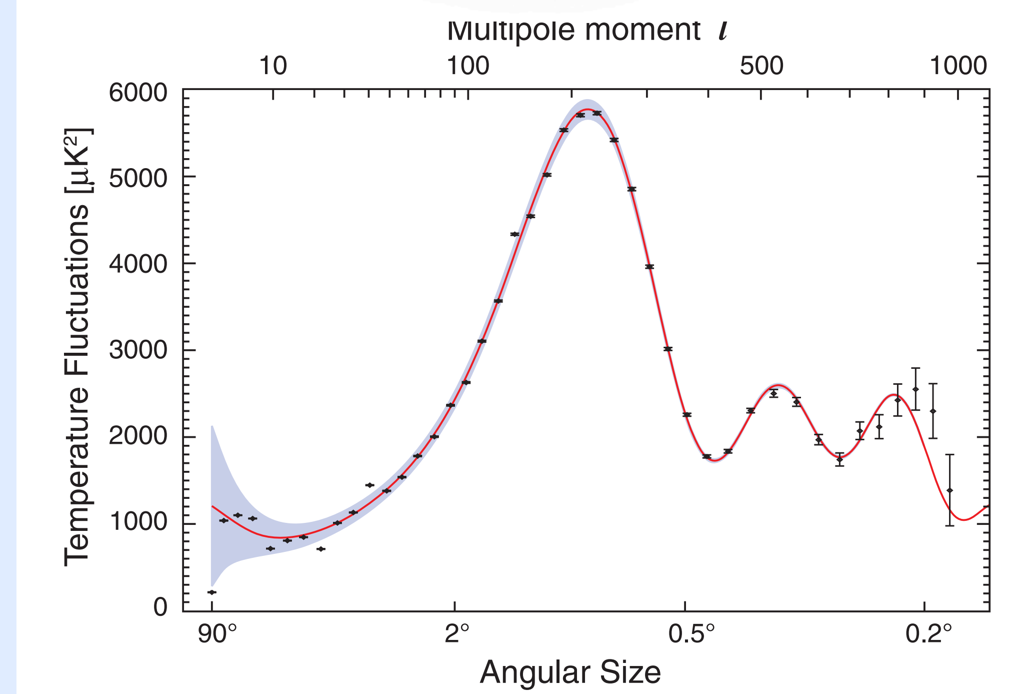
there is excellent evidence that most matter in the universe is dark (galaxy rotation velocity curves, cosmic microwave background)







massive neutrinos influence the early universe



evidence for dark matter (Bullet Cluster)

weak scale suggested by cosmology

the left-over abundance (WMAP) is inversely proportional to the annihilation cross-section:

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} = \frac{3 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_\mathrm{A} v \rangle_\mathrm{freezout}}$$

$$\langle \sigma_\mathrm{A} v \rangle_\mathrm{freezout} = 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

for weak-scale particles:

$$\langle \sigma_\mathrm{A} v \rangle \sim \alpha^2\, (100\ \mathrm{GeV})^{-2} \sim 10^{-25}\ \mathrm{cm}^3/\mathrm{s}$$

WIMP direct detection signature

Direct detection of the elastic scattering recoil of nuclei in a crystal or liquid, as the Earth 'sails' through the non-relativistic dark matter halo.

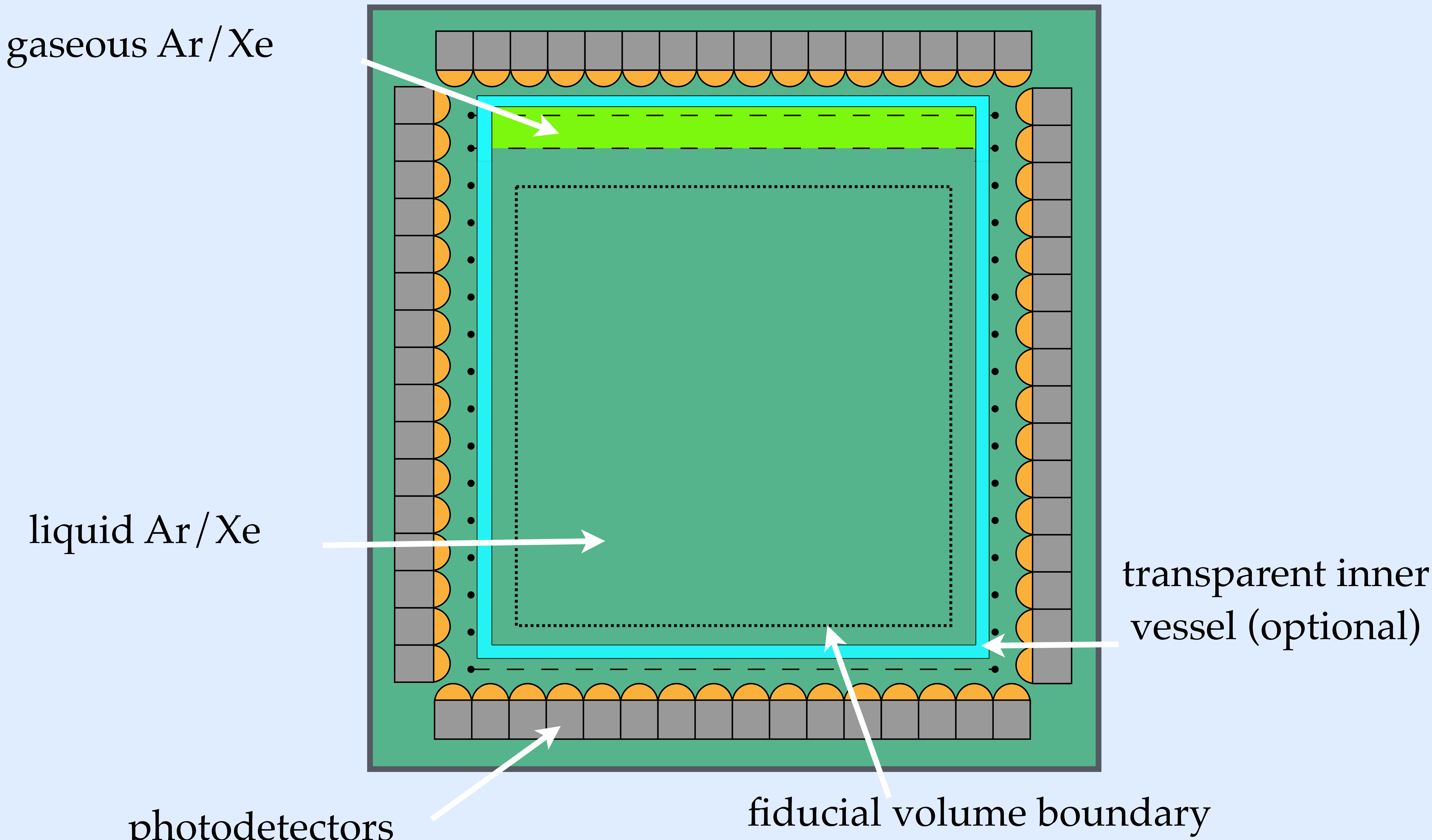
For a 100 GeV WIMP particle in the halo of our galaxy (300 m/s) on a ~100 amu target (Ar, Ge, I, Xe) the kinetic energy of the recoiling nucleus is few-to-tens keV:

$$\lambda = \hbar/(2mv) \approx 1 \text{ fm} \quad \Rightarrow \quad \sigma_0 \propto \sigma_n A^2 \text{ (coherent scattering)}$$

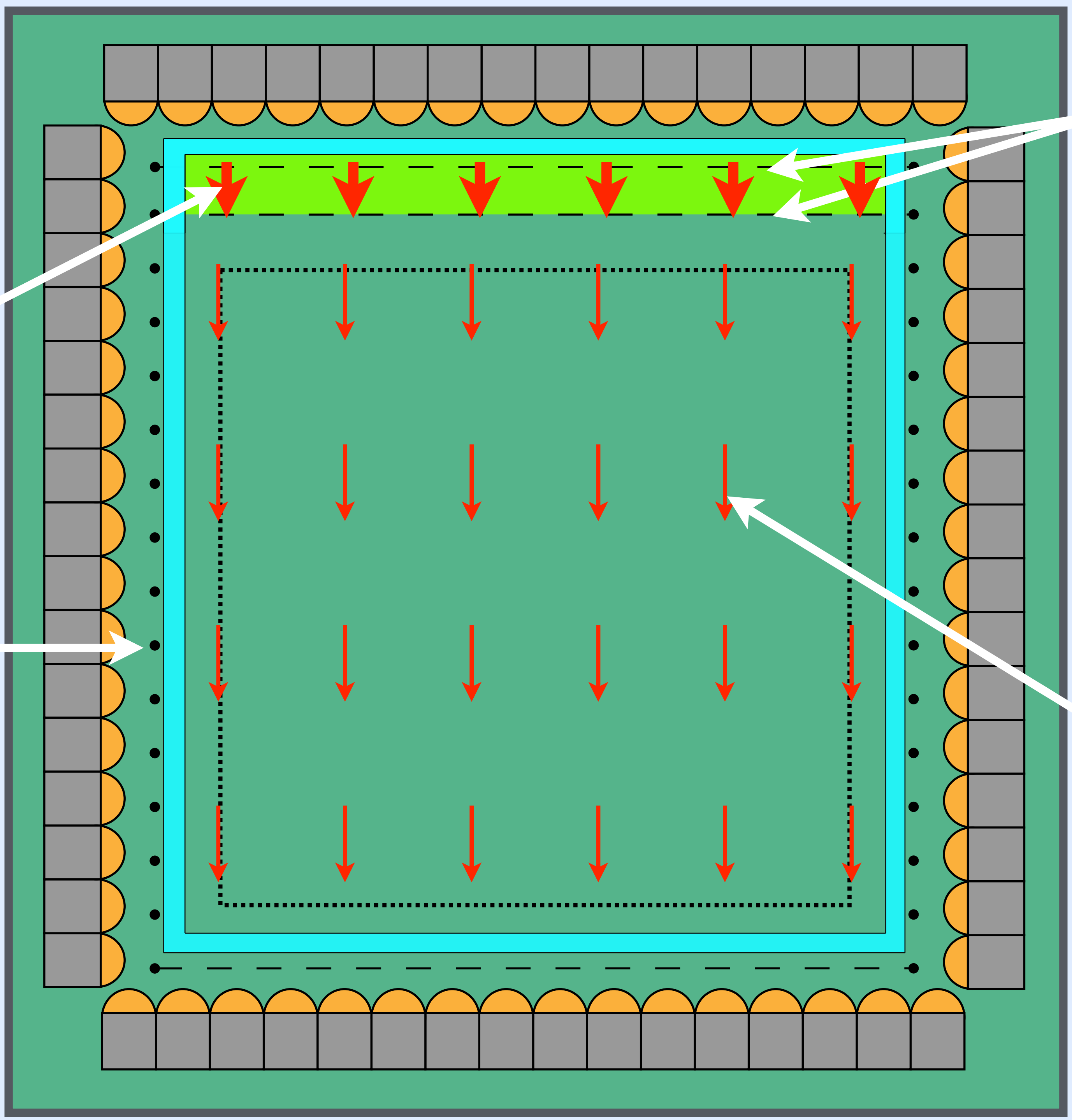
$$R_A = 1.0 \ x \ A^{1/3} \text{ fm}; \qquad E_{\text{kin}} = (2mv)^2/2M \approx 100 \text{ keV}$$

2-phase TPC's with noble liquids are a compact, scalable technology which can be made very low background and offer excellent discrimination between nuclear and electron recoils

2-phase TPC

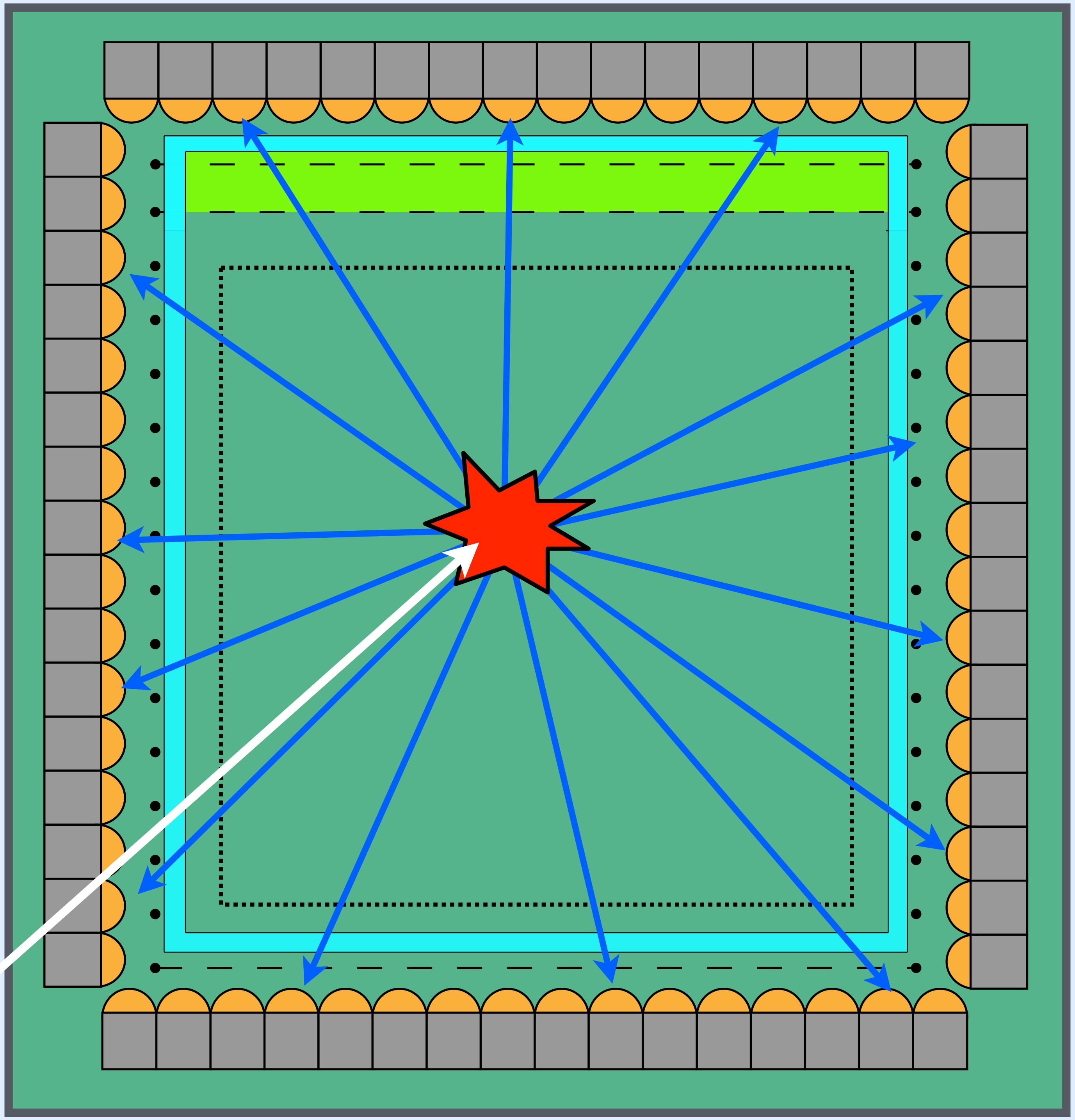

gaseous Ar/Xe
liquid Ar/Xe
transparent inner vessel (optional)
photodetectors
fiducial volume boundary

2-phase TPC


extraction and acceleration grids
multiplication field (~3 kV/cm)
field-shaping rings
drift field (~1 kV/cm)

2-phase TPC

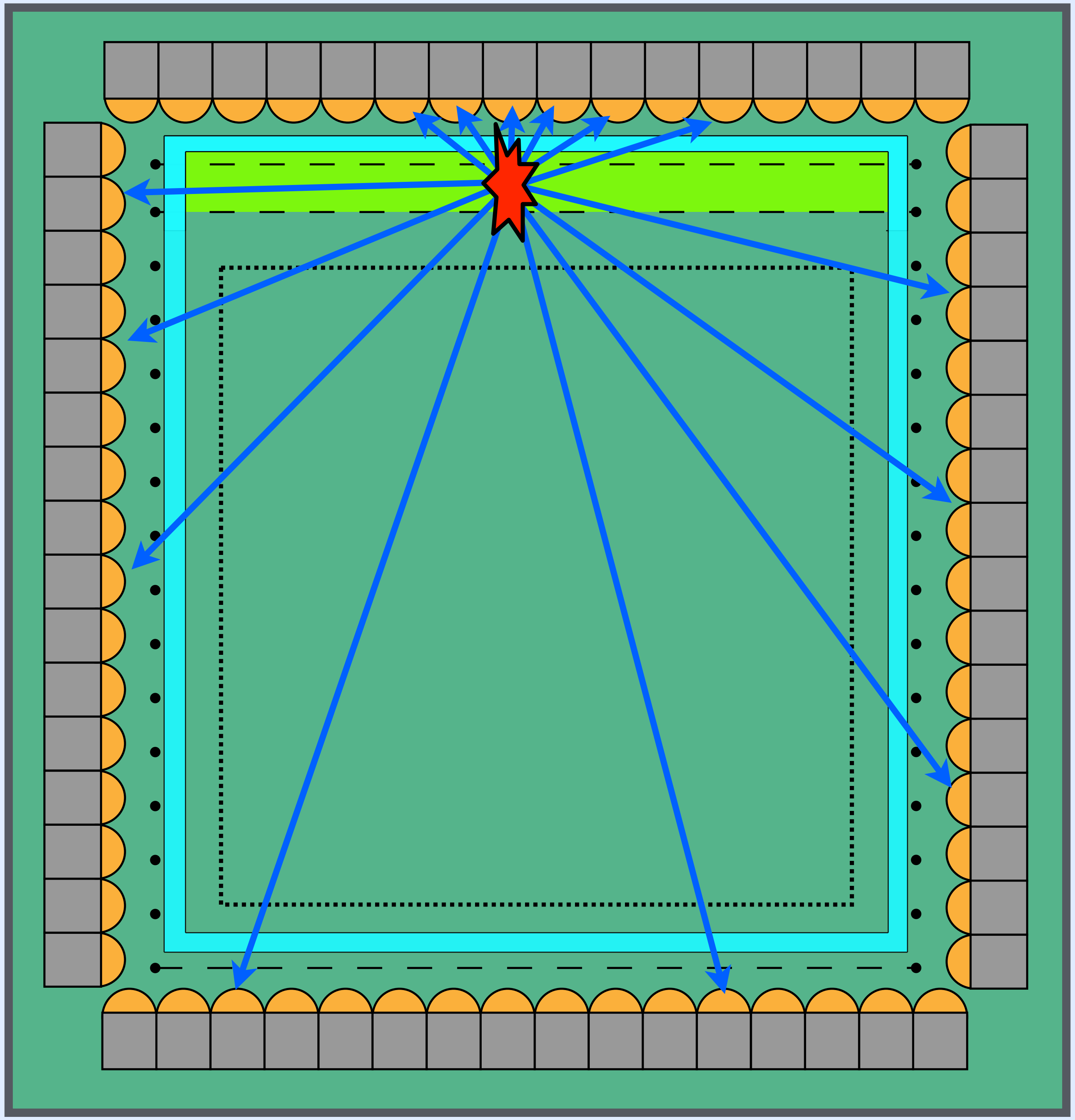
primary scintillation photons
emitted and detected (S1)



WIMP scatter
deposits
energy in FV

2-phase TPC

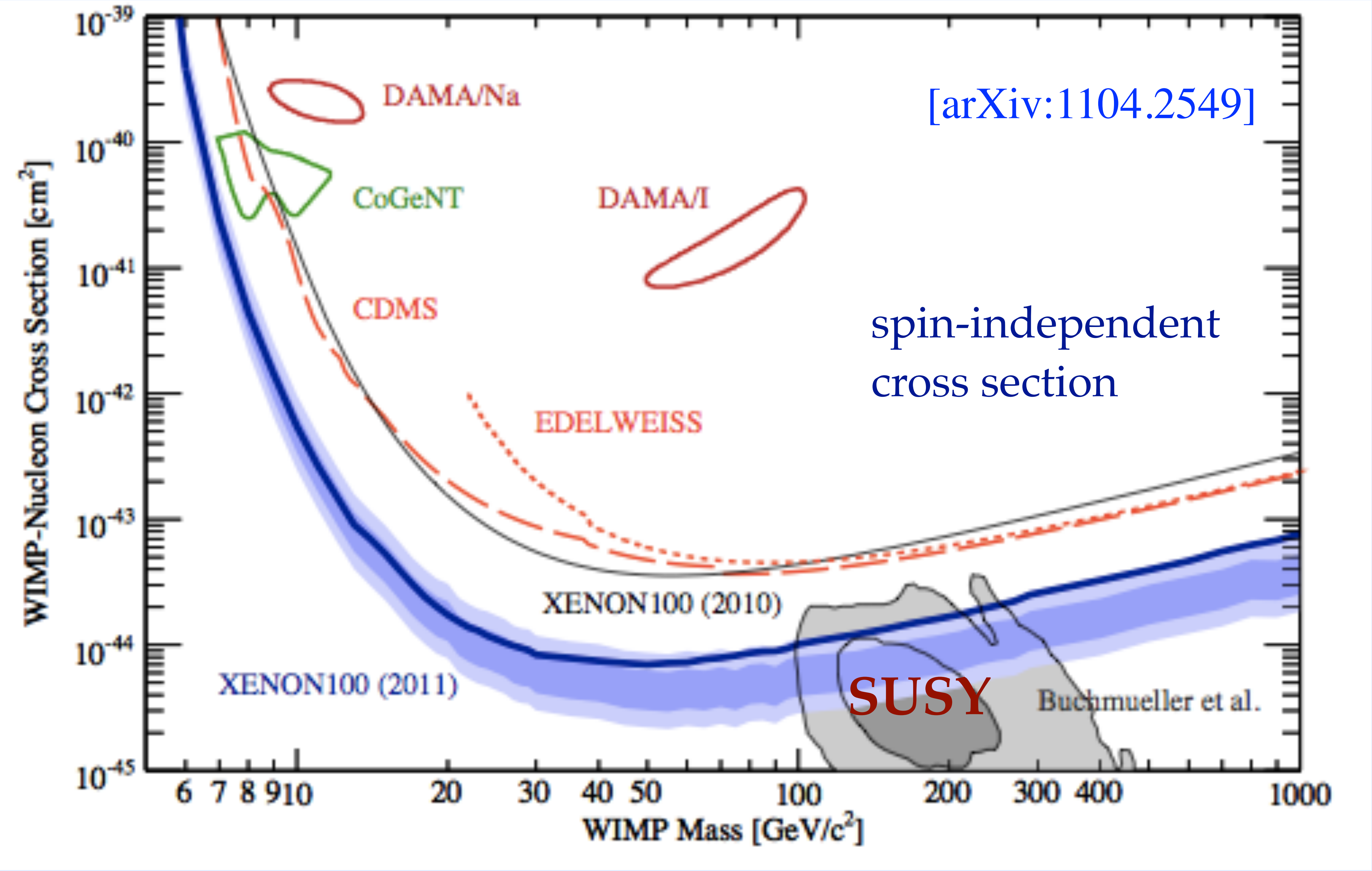
secondary photons emitted by multiplication in gas region (S2)



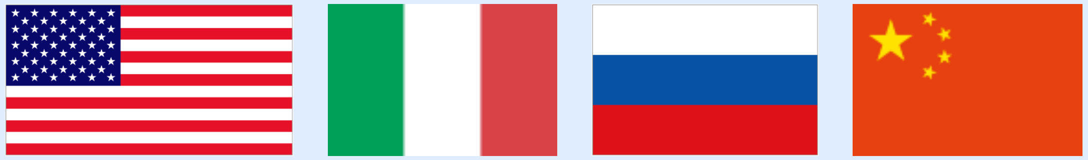
ionized electrons drifted to gas region (~2 mm/μs))

XENON100 results

- the S2/S1 is much smaller for nuclear recoils: ~100-fold discrimination
- wonderful self-shielding from γ radiation



the DarkSide program

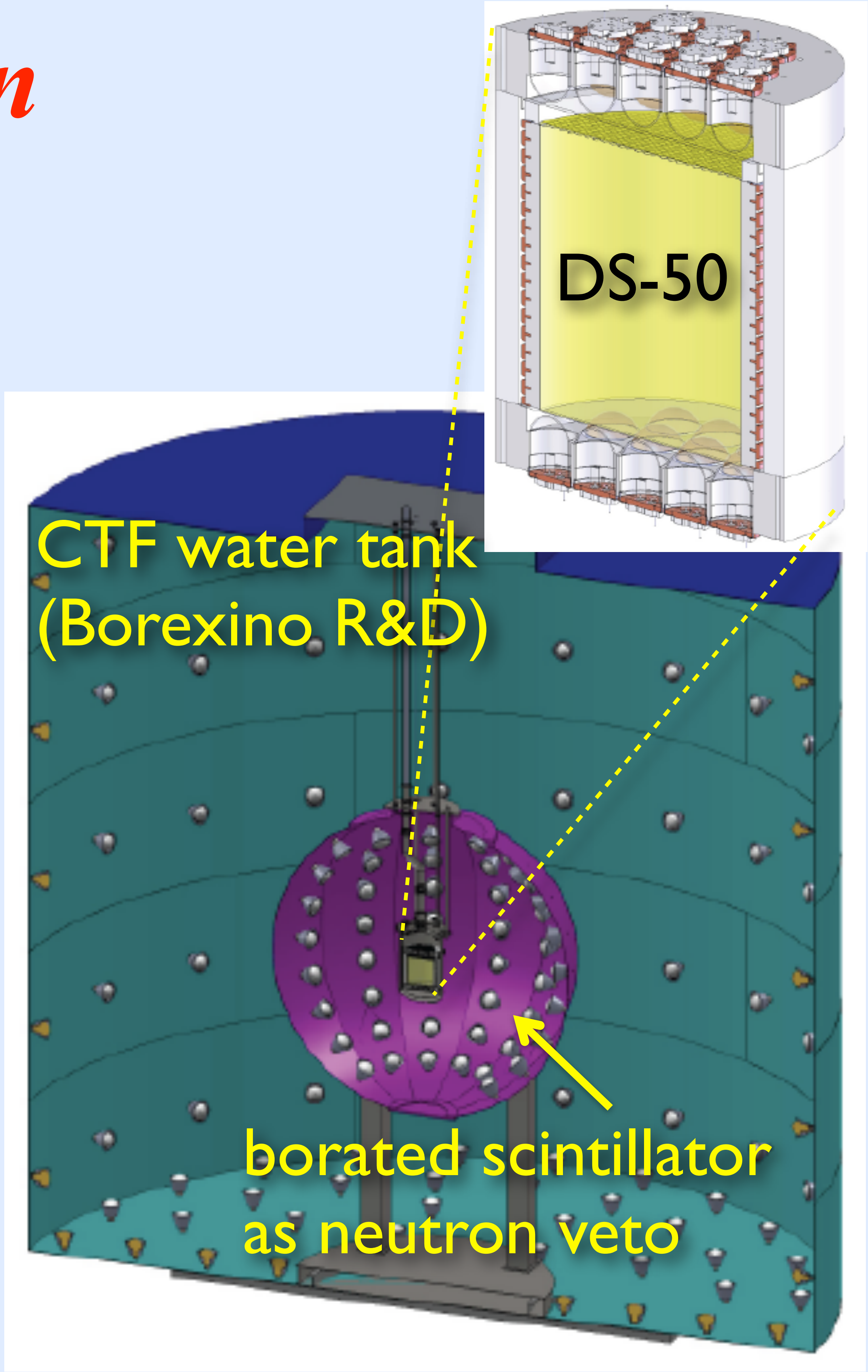


"DarkSide is a program aimed at searching for particle dark matter with large dual-phase, depleted argon TPCs"

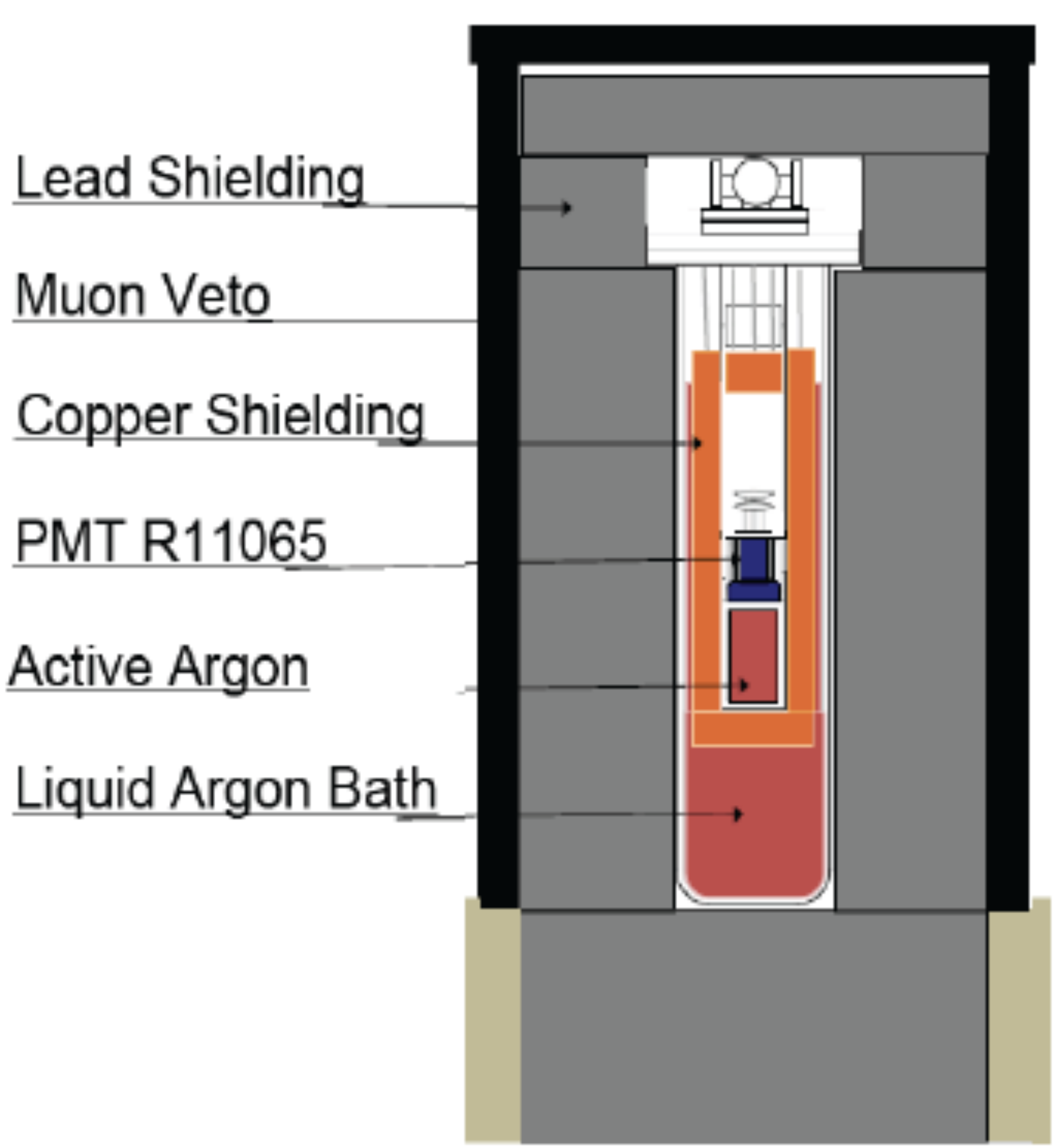
- argon TPC with readout of both primary scintillation light and ionization, for accurate 3D position reconstruction
- pulse-shape discrimination of primary scintillation for powerful discrimination of nuclear recoils (poor in xenon)
- 2-phase design allows for amplification of electronic signal (gain)
- low ^{39}Ar (i.e. depleted in this radioactive isotope) argon from underground in view of a very large (several tons) detector
- ultra-low background detector design
- high efficiency, compact neutron shield

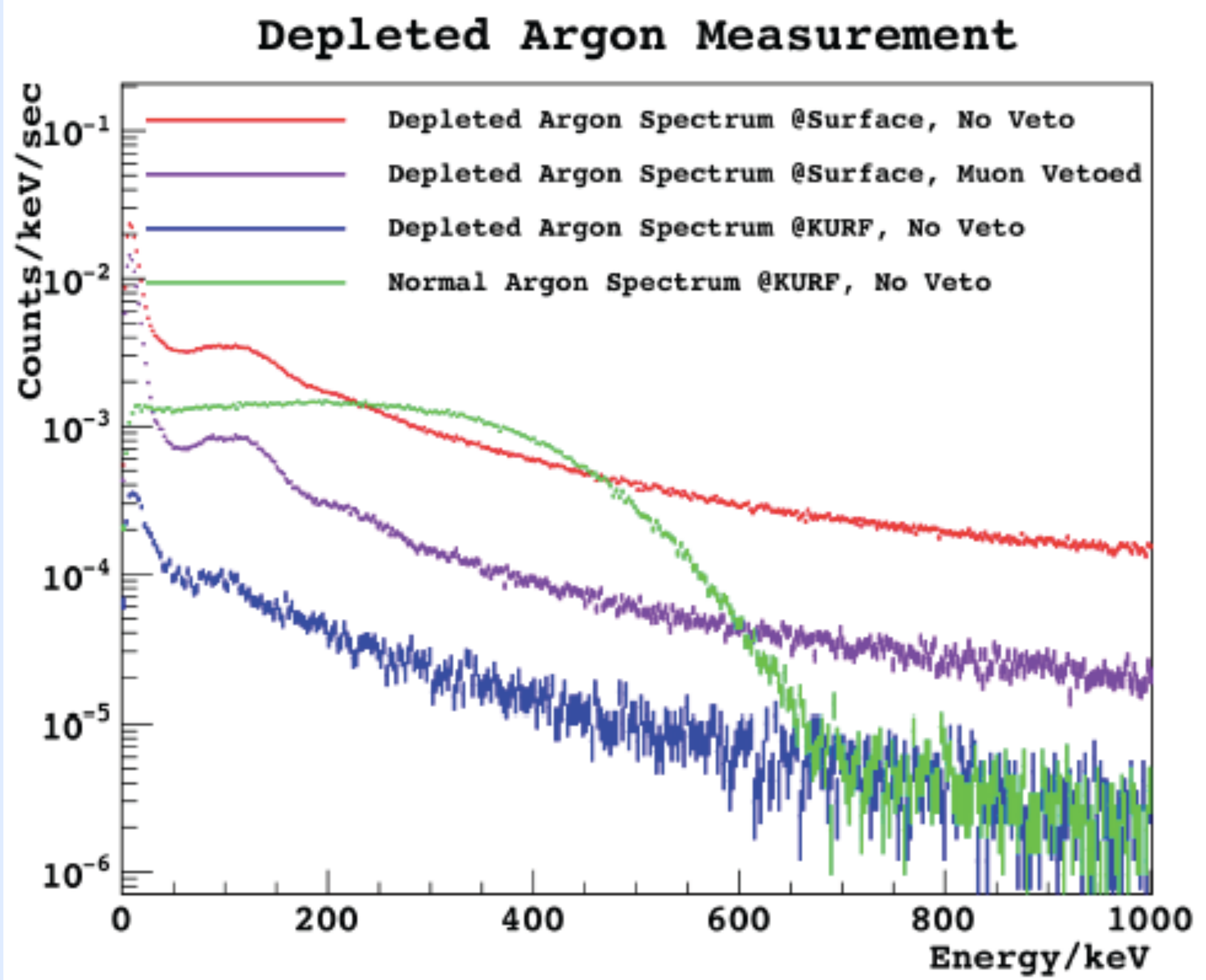
DarkSide design

- DS-10
  10 kg engineering prototype with regular argon. Has run at Princeton, now running at LNGS testing novel design features
- DS-50 (@LNGS)
  50 kg experiment with depleted argon (from underground natural gas wells), ~10^{-45} cm^2
- tonne-scale experiment (@LNGS)
  ~10^{-45}-10^{-46} cm^2



depleted argon

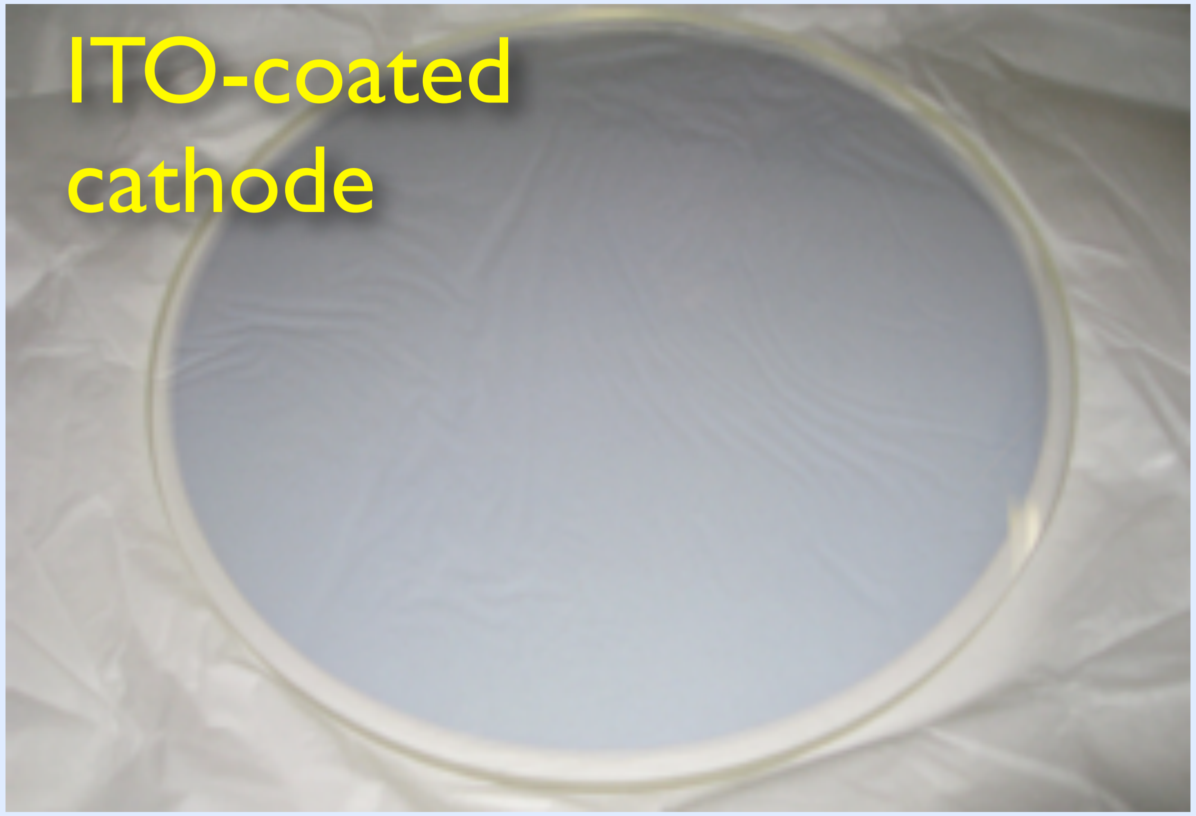


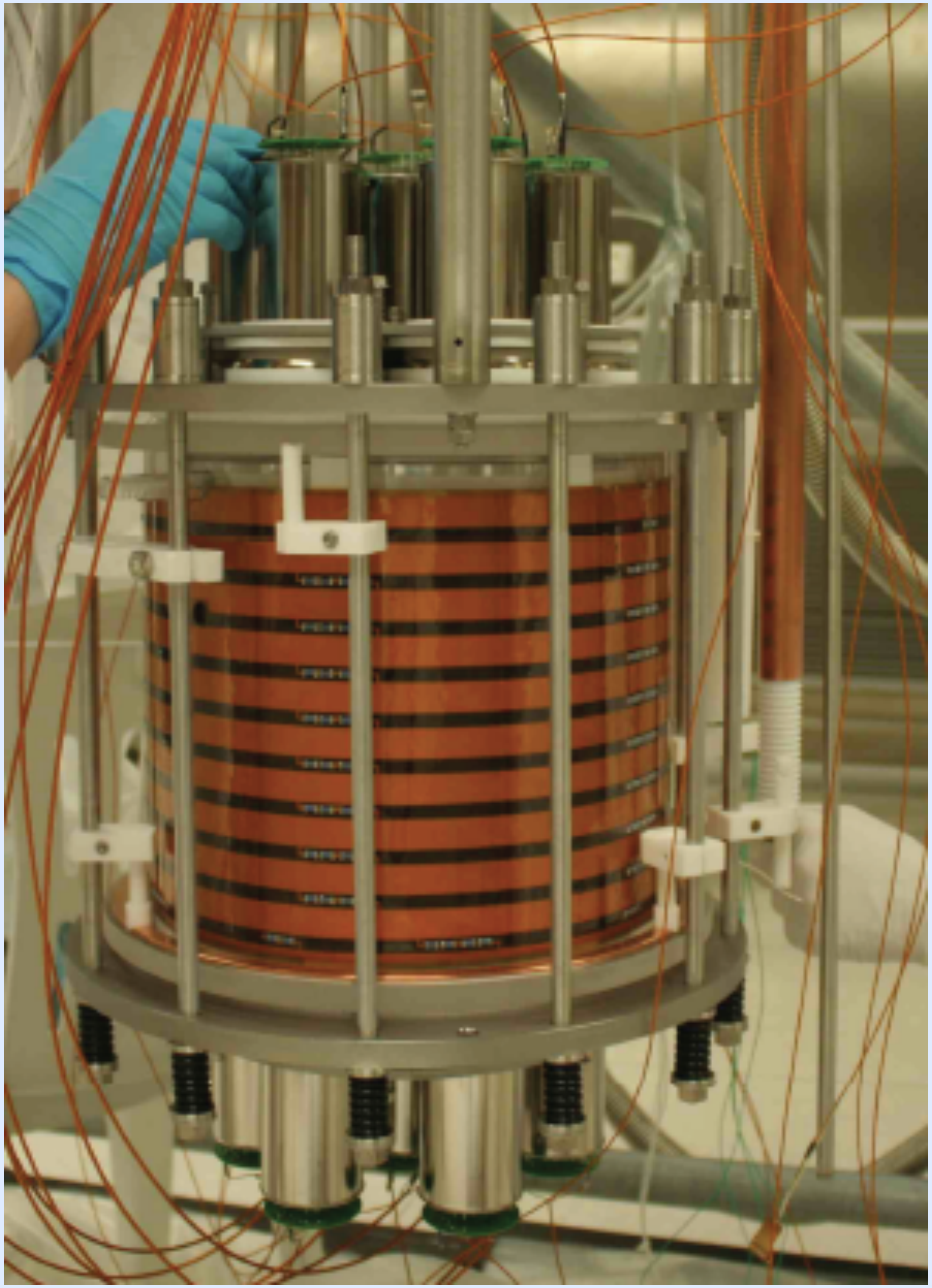


- ✓ **depletion factor >50**
- ✓ **^{39}Ar most likely not the main source of electron recoils in DS-50**

DarkSide-10

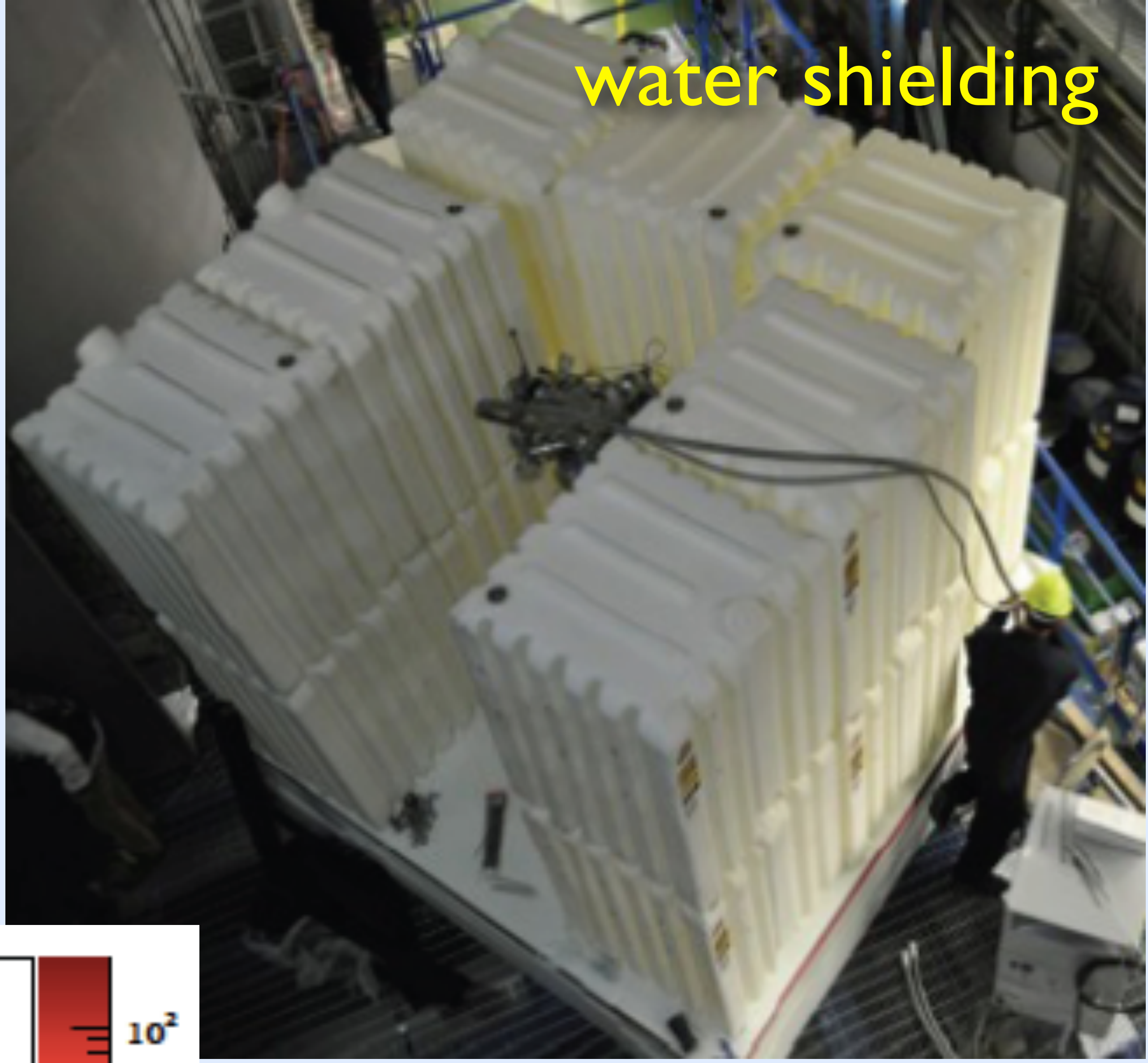
- test ‘gas pocket’ operation
- scintillation light yield
- charge drift, high voltage
- background discrimination
- surface backgrounds
- new design ideas

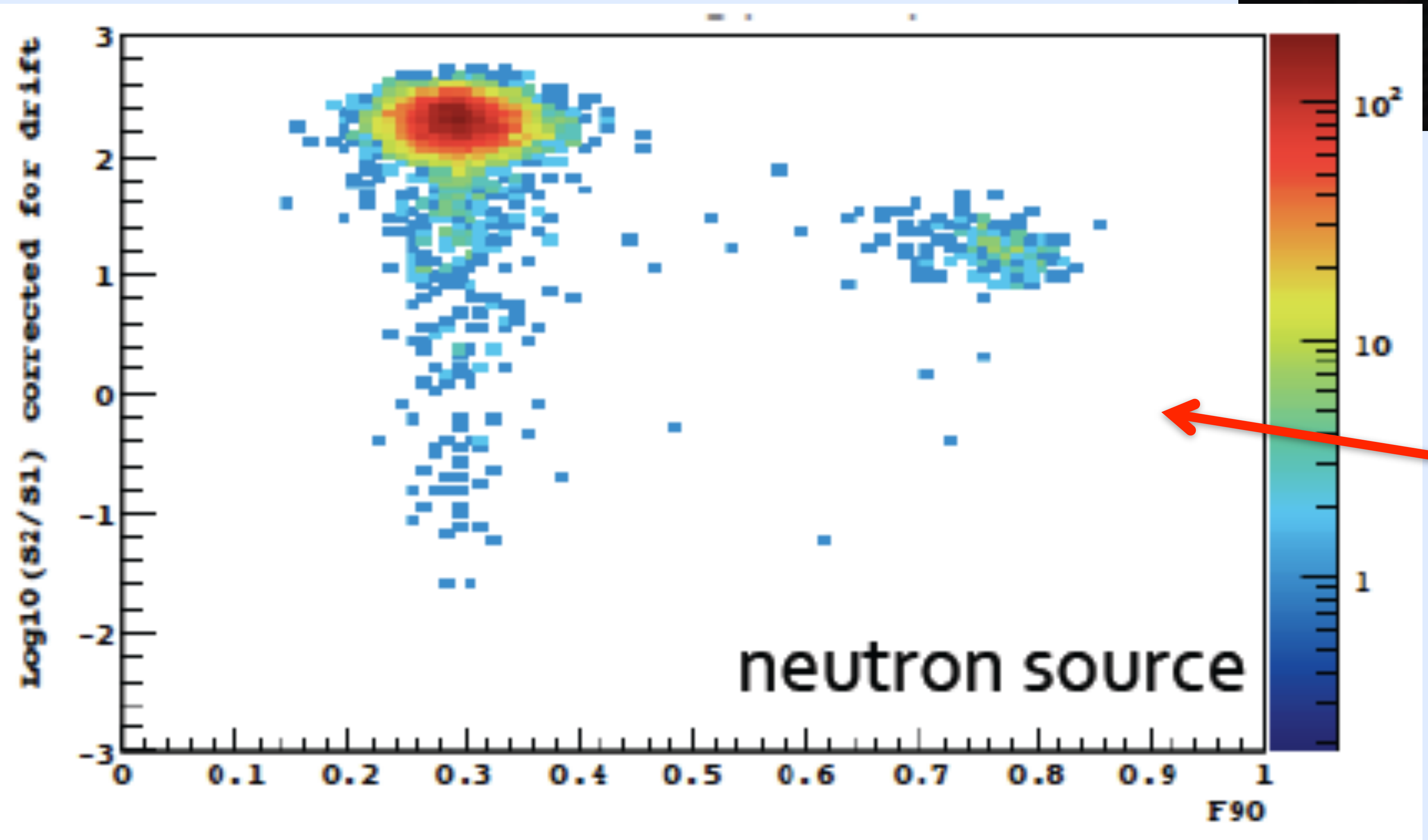




DarkSide-10

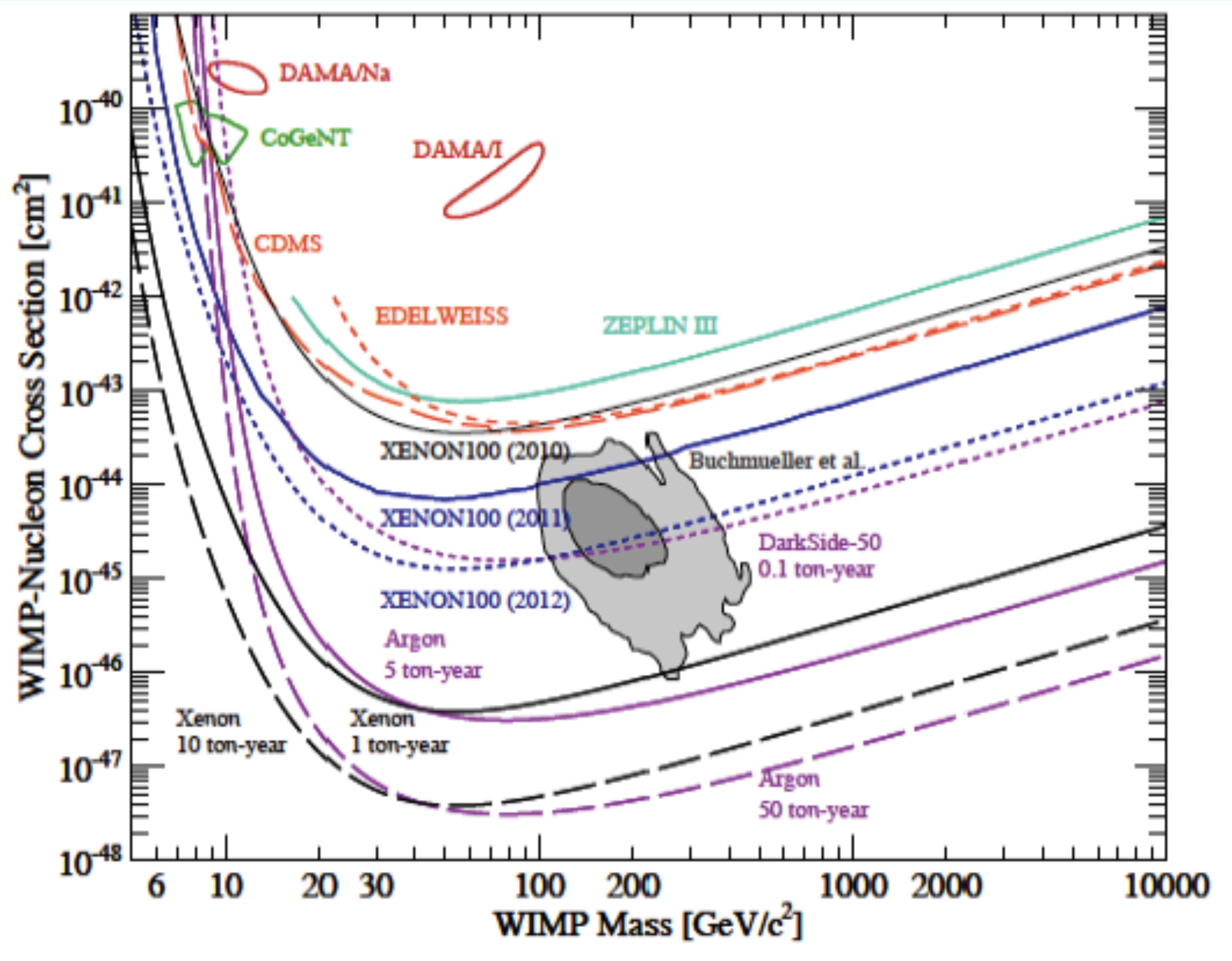
- basic operation successful at Princeton
- now commissioning at LNGS
- CTF tank being refurbished for DS-50





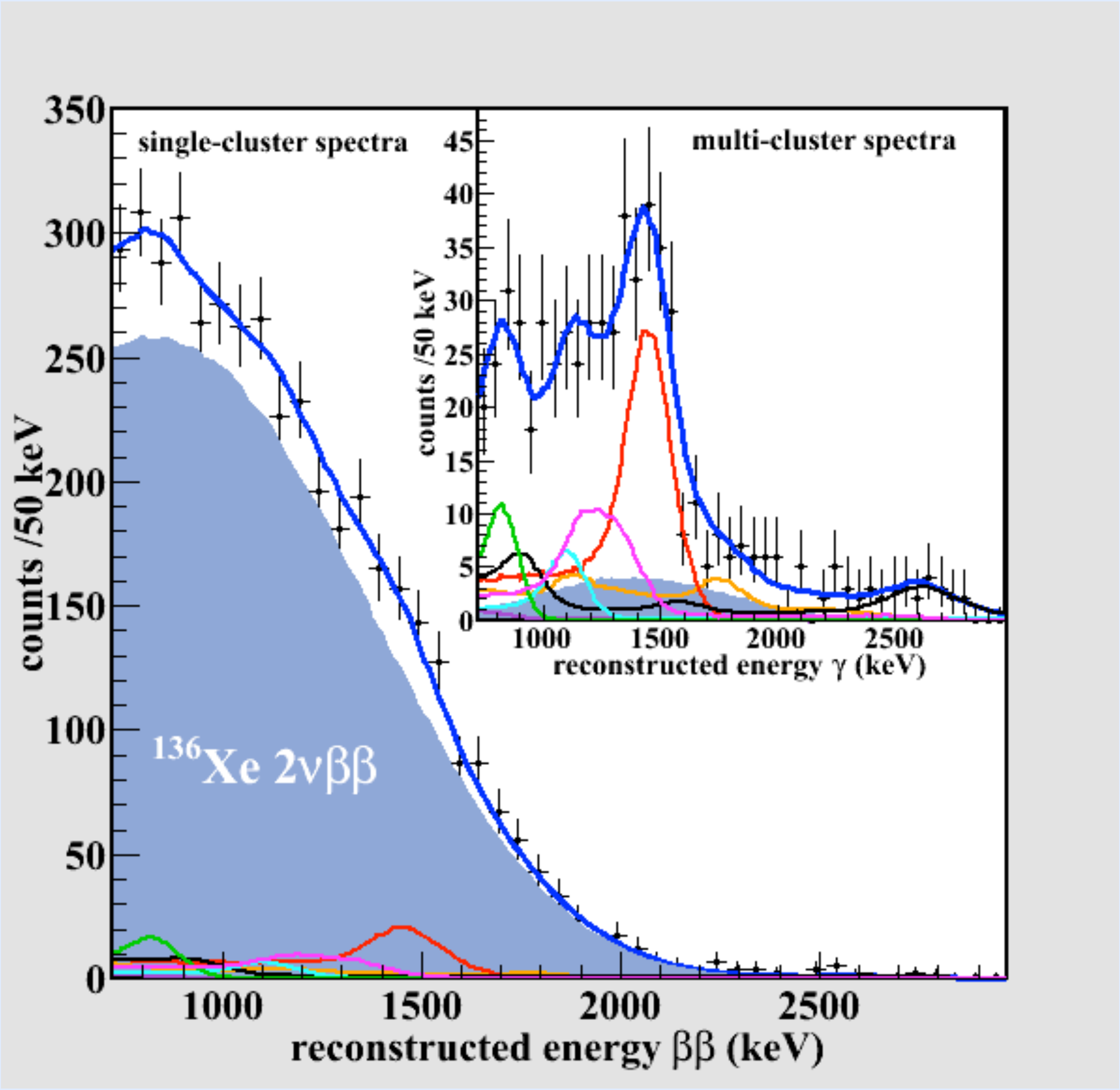
electron/nuclear recoil discrimination

the DarkSide horizon



summary

- $0\nu\beta\beta$ decay and WIMP searches probe the existence of fundamental symmetries of particle physics
- noble liquid detectors, now running at 100 kg scale, offer a very promising path towards tonne-scale experiments
- EXO ($\beta\beta$ decay) and DarkSide (dark matter) are designed to tackle bg's in qualitatively new ways, with a phased of ever larger detectors
- EXO-200 (200 kg of enriched xenon) has recently measured $2\nu\beta\beta$ decay and is performing very well



- DarkSide is running a 10 kg prototype and plans to "catch up" with the best sensitivity dark matter experiments within a couple of years

Thank you

discovery of 0νββ?

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

[Mod. Phys. Lett. A27(2001)2409]
[Mod. Phys. Lett. A27(2001)2409]

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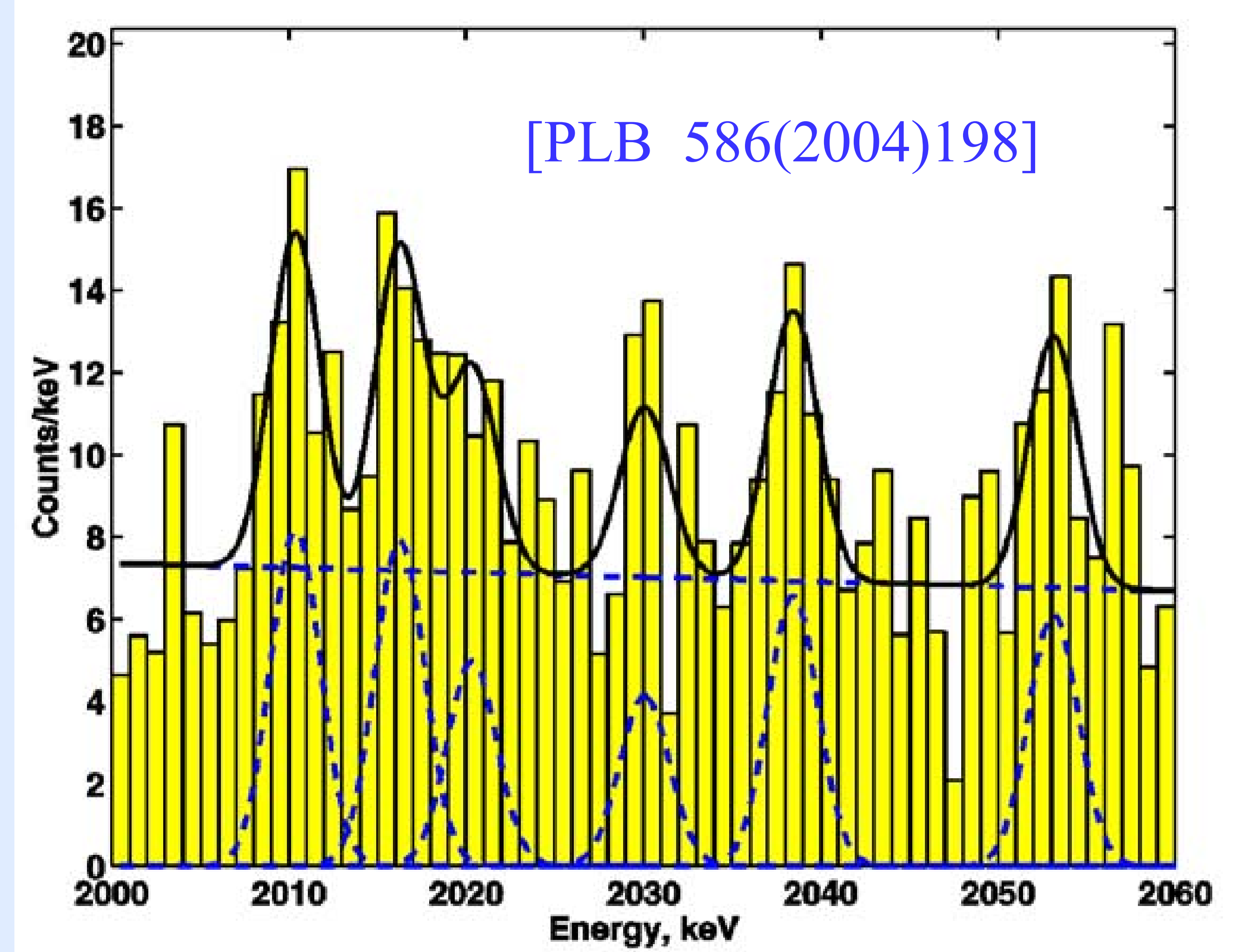
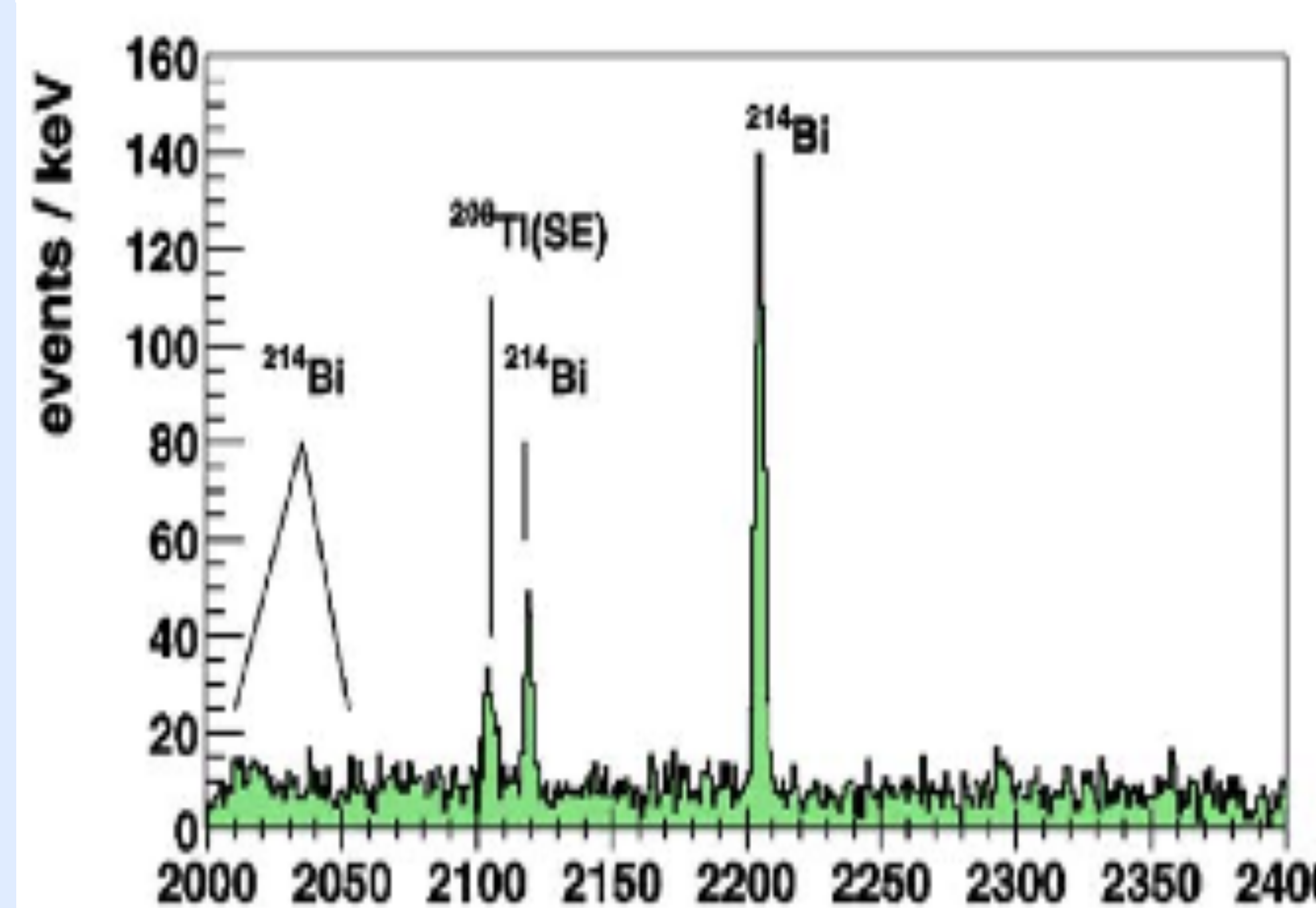
$T_{1/2}^{0\nu\beta\beta} = 2.23^{+0.44}_{-0.31}\ 10^{25}$ years
$m_\nu^{eff}=0.32\pm0.03$ eV

- enriched (86%) ^{76}Ge crystals
- excellent energy resolution
- if limit: $T_{1/2} > 1.9\times10^{25}$ y

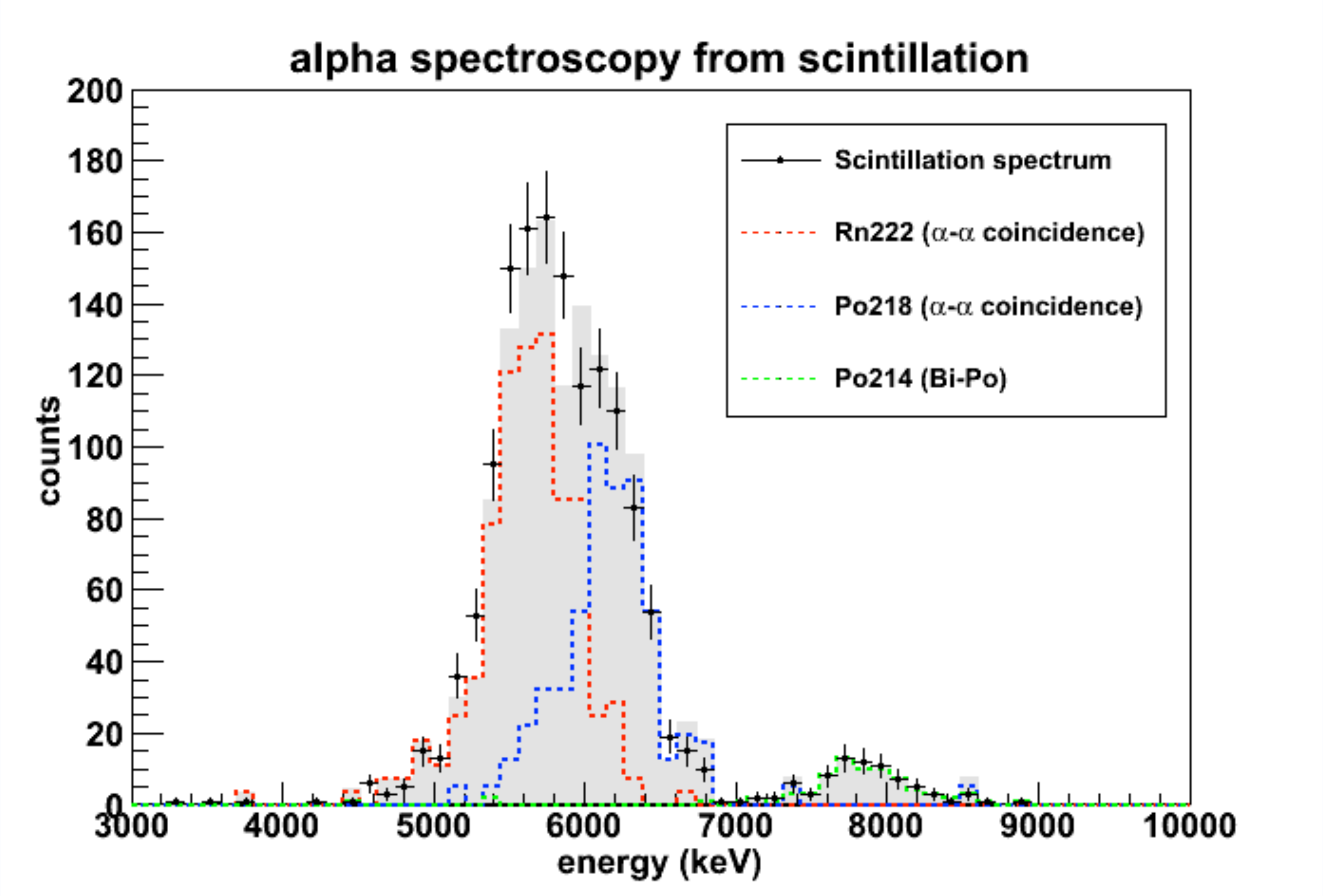




controversial issue:

C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345
Addendum-ibid. B659 (2003) 359
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
A.M.Bakalyarov et al. hep-ex/0309016
H.V.Klapdor-Kleingrouthaus et al. Phys. Lett. B 586 (2004) 198
H.V.Klapdor-Kleingrouthaus et al. Mod. Phys. Lett. 21 (2006) 1547

constraints from alpha spectroscopy



- Investigate alpha spectrum for scintillation signals from ^{238}U
- Calibrate spectrum with alphas in Rn chain
- Can constrain contamination of ^{238}U in bulk LXe by searching for 4.5 MeV alphas

  < 0.3 counts per day in our fiducial volume

  -The same limit applies to its daughter ^{234m}Pa which β decays with a Q-value of 2195 keV, which cannot then explain our LXe bulk signal

10 kg prototype