RARE EVENT SEARCHES: WINDOWS INTO THE WORLD OF NEUTRINOS AND DARK MATTER

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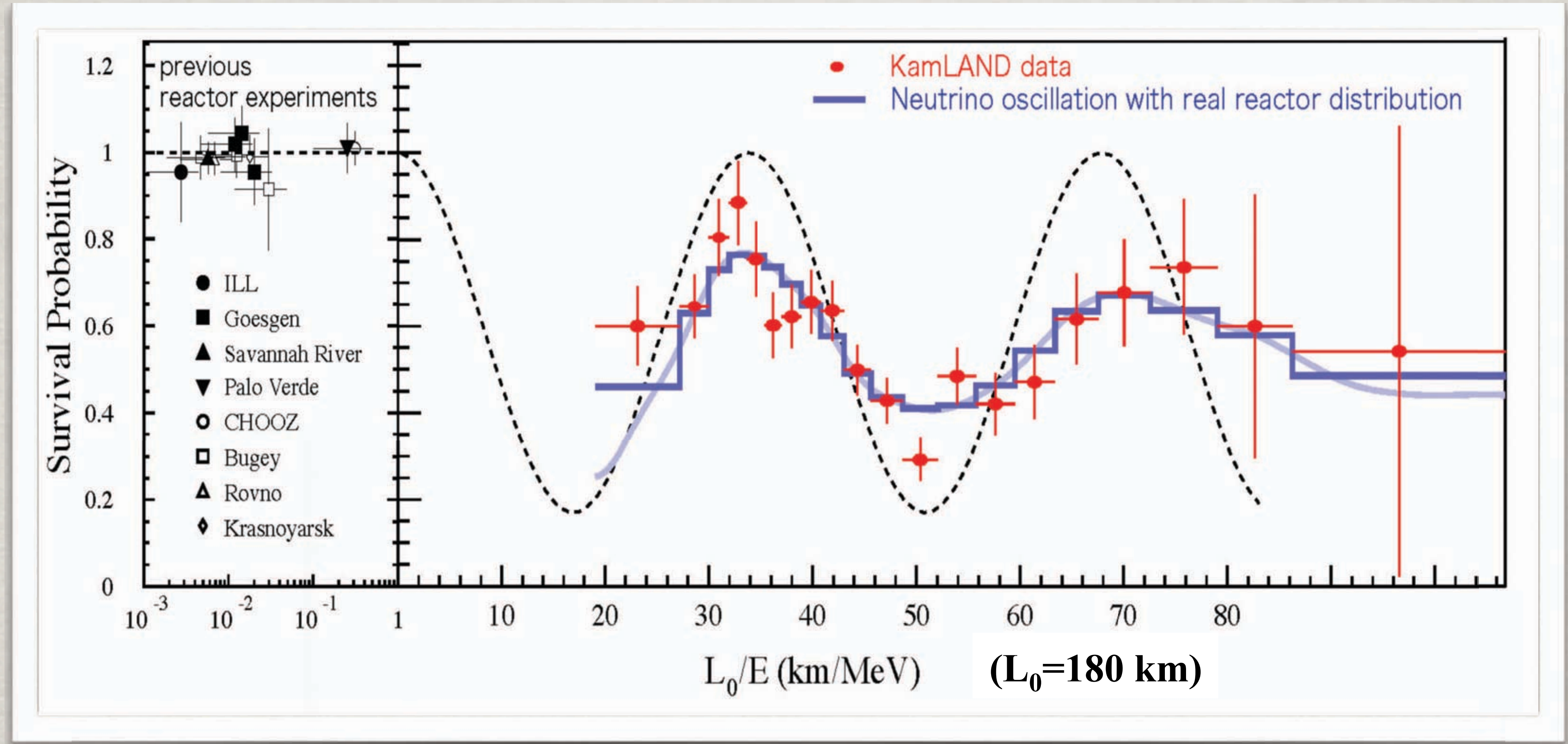
Enriched Xenon Observatory
EXO
for double beta decay

Lets get things started with EXO

- What we know about neutrino masses
- $0\nu\beta\beta$ decay
- Experimental approaches
- Status: The EXO-200 experiment
- First observation of ^{136}Xe $2\nu\beta\beta$ decay!
- Plans: EXO & Barium tagging

WHAT WE KNOW ABOUT NEUTRINOS



ν's oscillate (they have mass!)
mixing angles: relate mass and flavor eigenstates
~ 3 ν's from Z linewidth
3 ν flavors were active in Big Bang Nucleosynthesis
ν's emitted from the Sun & Supernovae

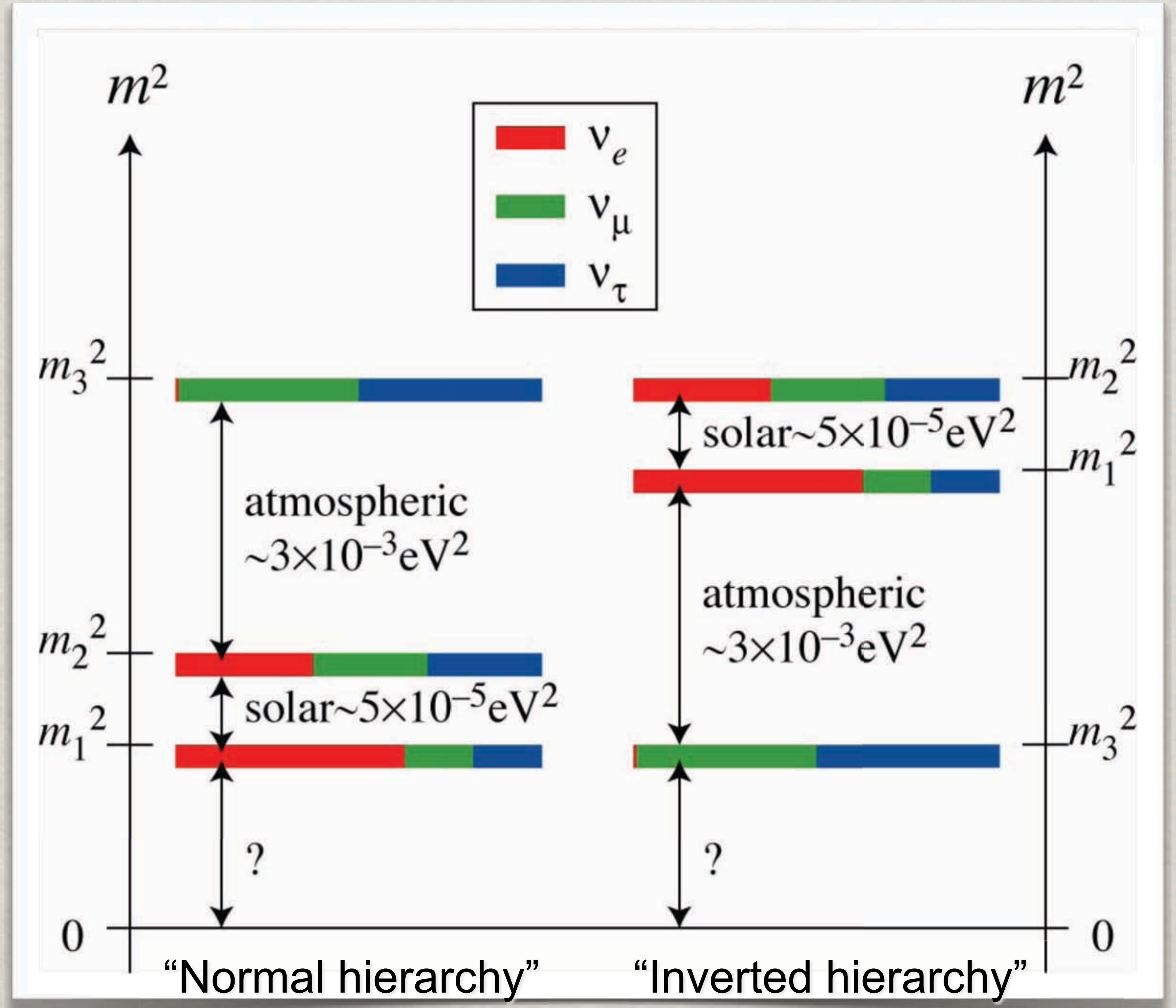
υ MASS SCALE & HIERARCHY

<2.3 eV

Tritium EndPoint

<0.3 eV

From $0\nu\beta\beta$, Majorana Neutrino



"Normal hierarchy" "Inverted hierarchy"

<1.7 or
<0.68 eV

Cosmology

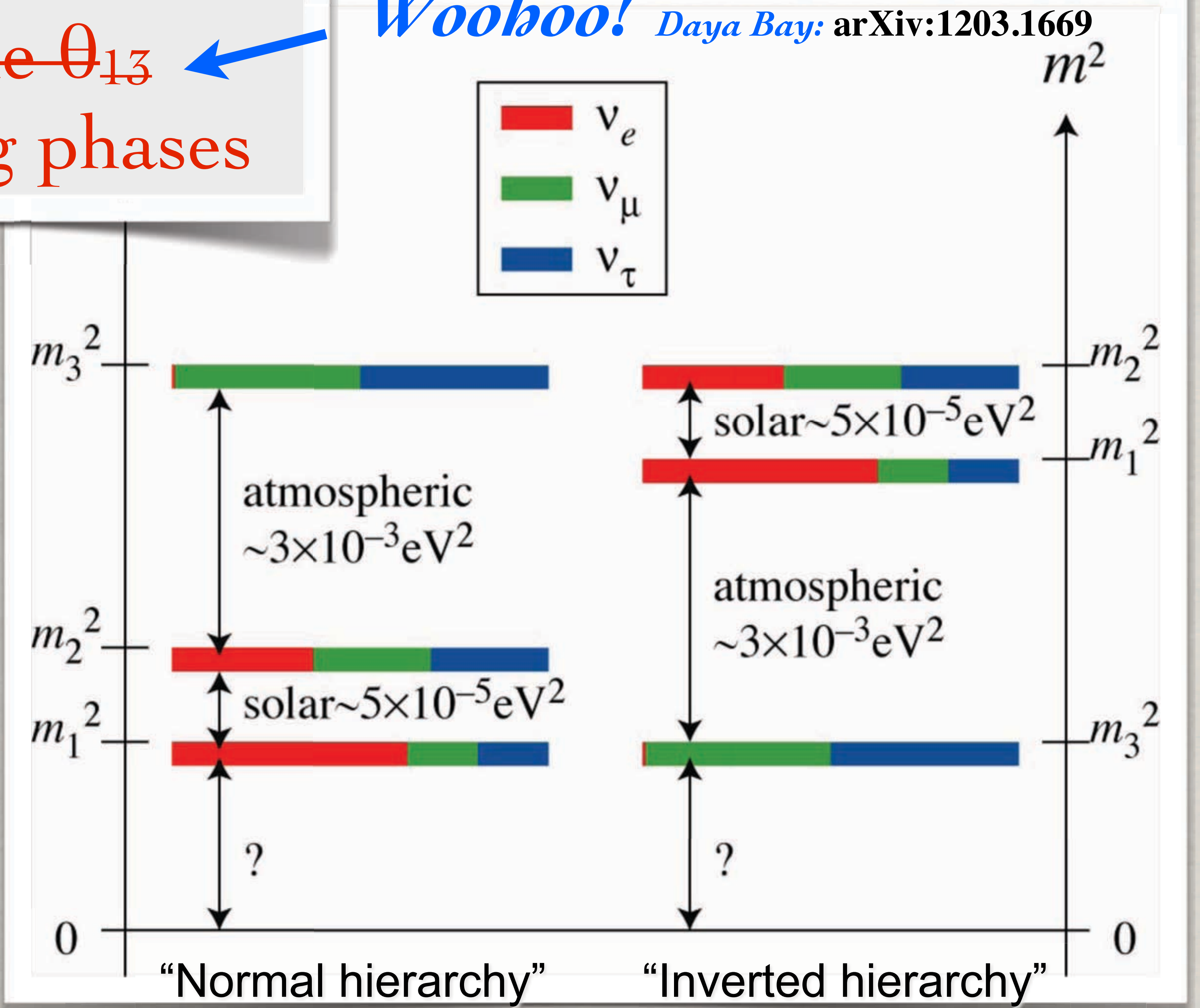
Cosmology
WMAP + SN +
Galaxy clustering

What we don't know:

-Majorana nature
-absolute mass scale
-mass hierarchy
~~-mixing angle θ_{13}~~
-CP violating phases

CALE & HIERARCHY

Woohoo! *Daya Bay:* **arXiv:1203.1669**



"Normal hierarchy" "Inverted hierarchy"

<0.3 eV

From 0νββ, Majorana Neutrino

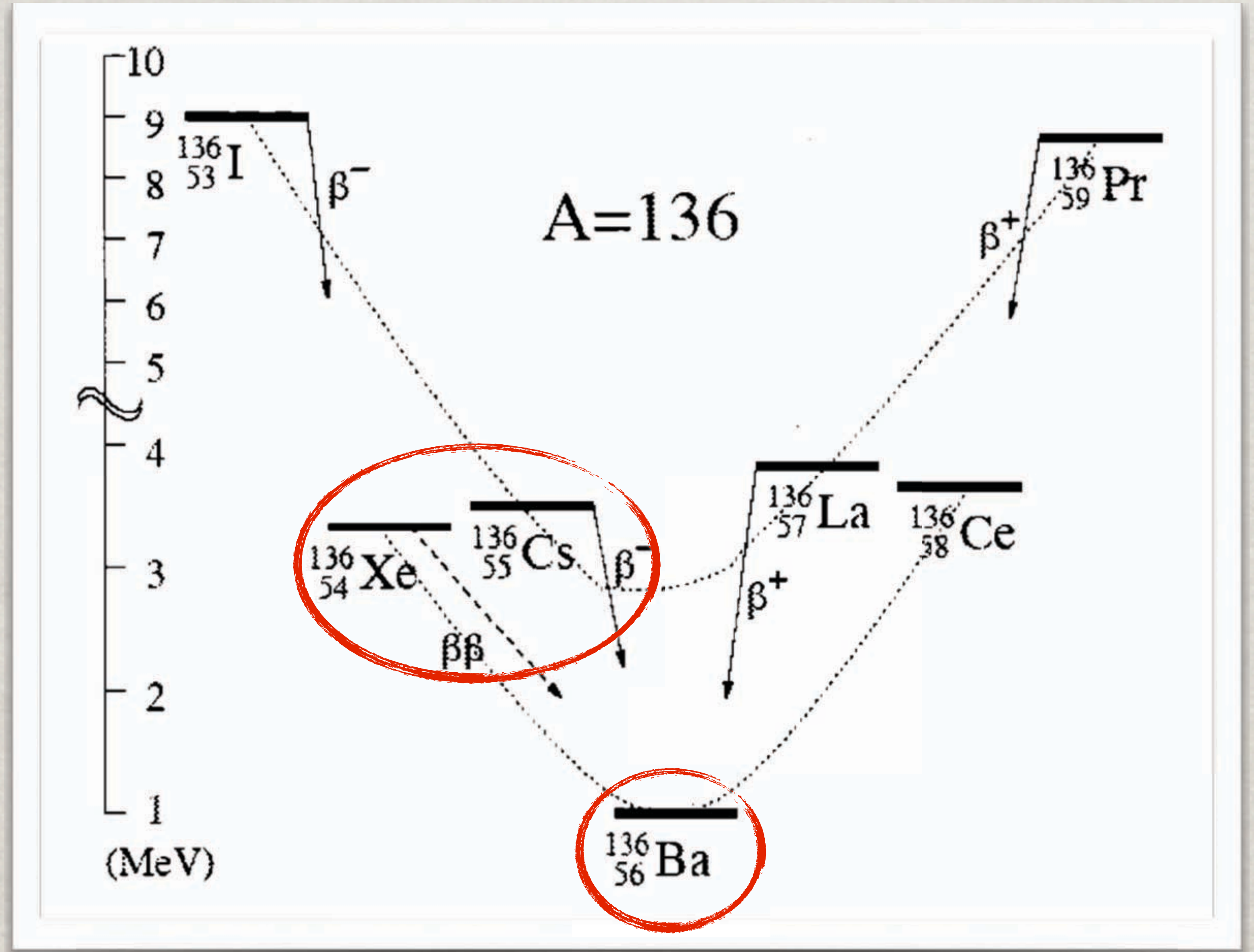
Tritium EndPoint

<1.7 or
<0.68 eV

Cosmology

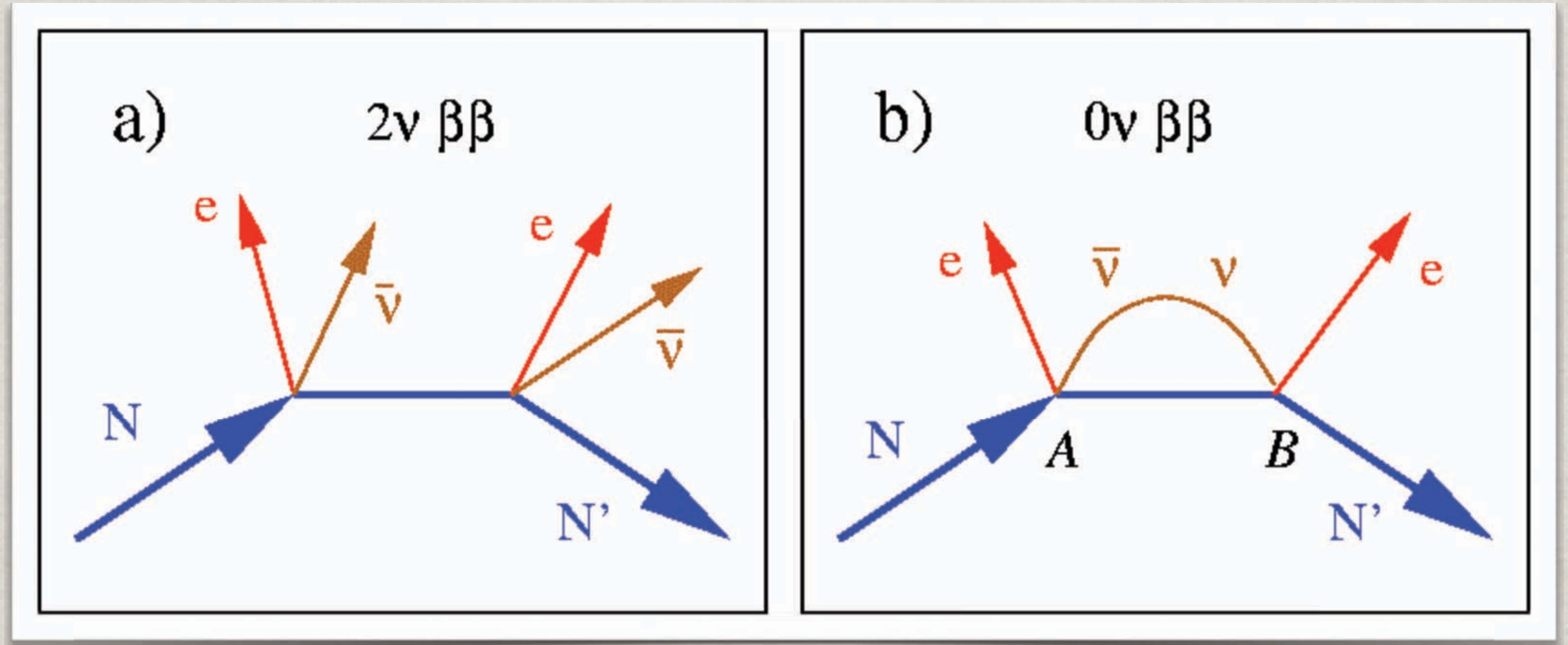
Cosmology
WMAP + SN +
Galaxy clustering

NATURE MAY PROVIDE A CONVENIENT TEST



- $\beta\beta$ decay: 2nd order process detectable if 1st order process is energetically forbidden

NEUTRINOLESS DOUBLE BETA DECAY



2νββ: Standard Model Process

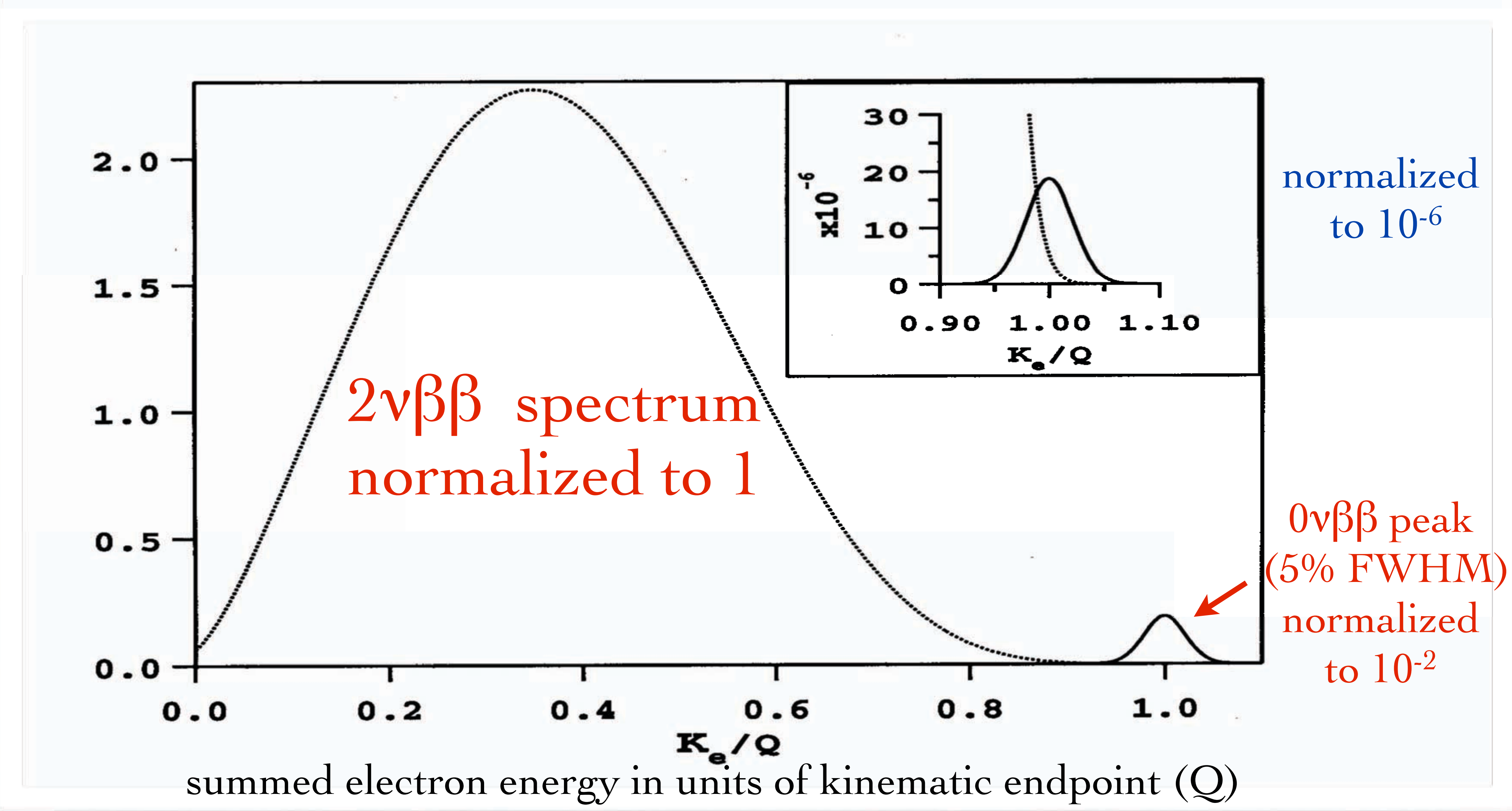
0νββ: Hypothetical

$M_\nu \neq 0 \quad |\Delta L| = 2$

$\bar{\nu} = \nu \quad |\Delta(B-L)| = 2$

Majorana nature

THE DIFFERENCE IS IN THE PEAK



2νββ spectrum normalized to 1

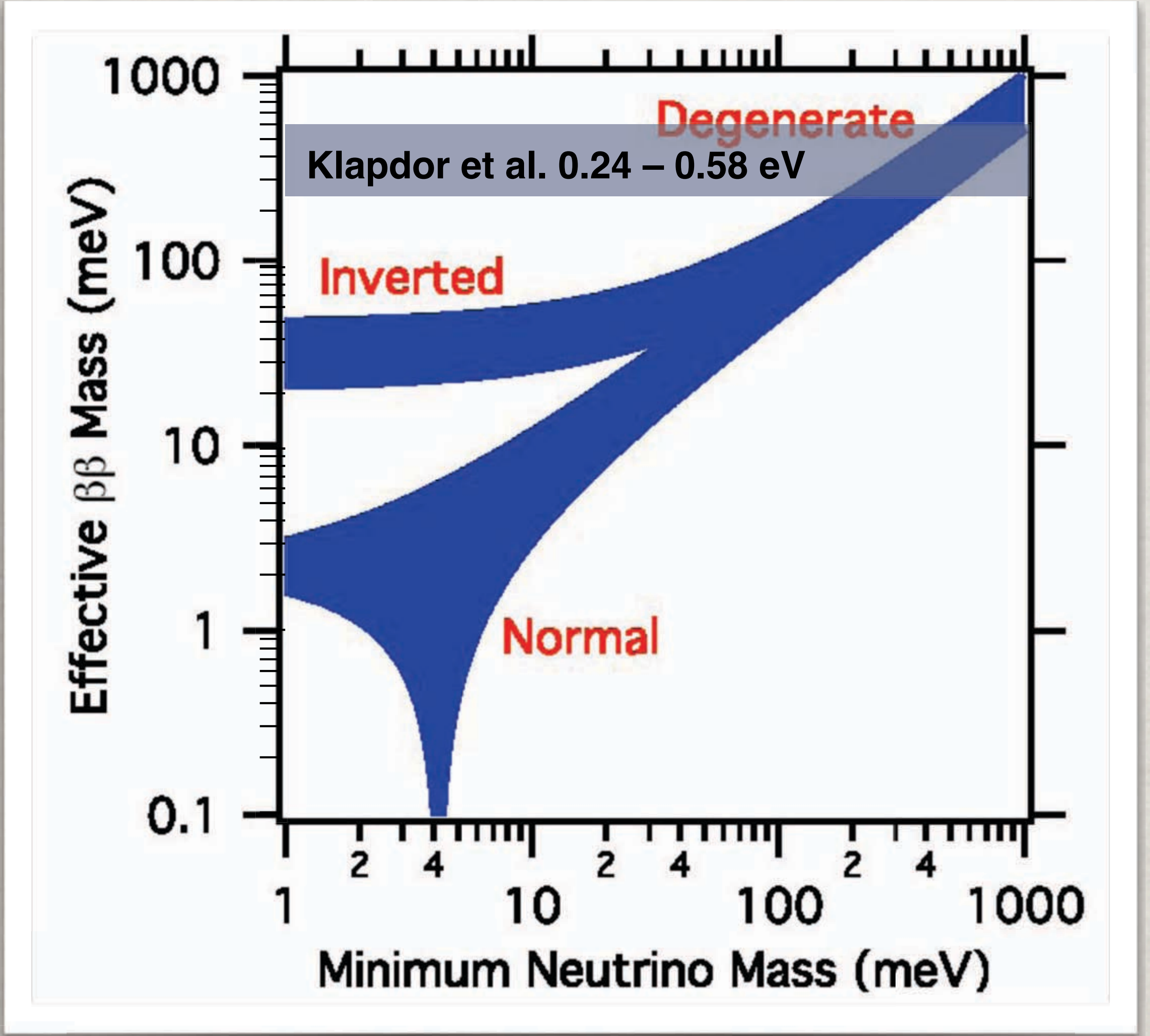
normalized to 10^{-6}

0νββ peak (5% FWHM) normalized to 10^{-2}

summed electron energy in units of kinematic endpoint (Q)

Most experimental approaches use enriched isotopes as both source and detector

EFFECTIVE MAJORANA MASS



measured half-life

phase space factor

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\ G_{0\nu\beta\beta}(E_0, Z)\ |M_{0\nu\beta\beta}|^2 \right)^{-1}$$

matrix element calculations have some model dependence

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_i \varepsilon_i \right|$$

F. Simkovic, Neutrino 2010

Nuclear structure approaches

In ***NSM*** ***(Madrid-Strassbourg group)*** *a limited valence space is used but all configurations of valence nucleons are included. Describes well properties of low-lying nuclear states. Technically difficult, thus only few $0\nu\beta\beta$-decay calculations*

In ***QRPA*** ***(Tuebingen-Caltech-Bratislava and Jyvaskula-La Plata groups)*** *a large valence space is used, but only a class of configurations is included. Describe collective states, but not details of dominantly few particle states. Relative simple, thus more $0\nu\beta\beta$–decay calculations*

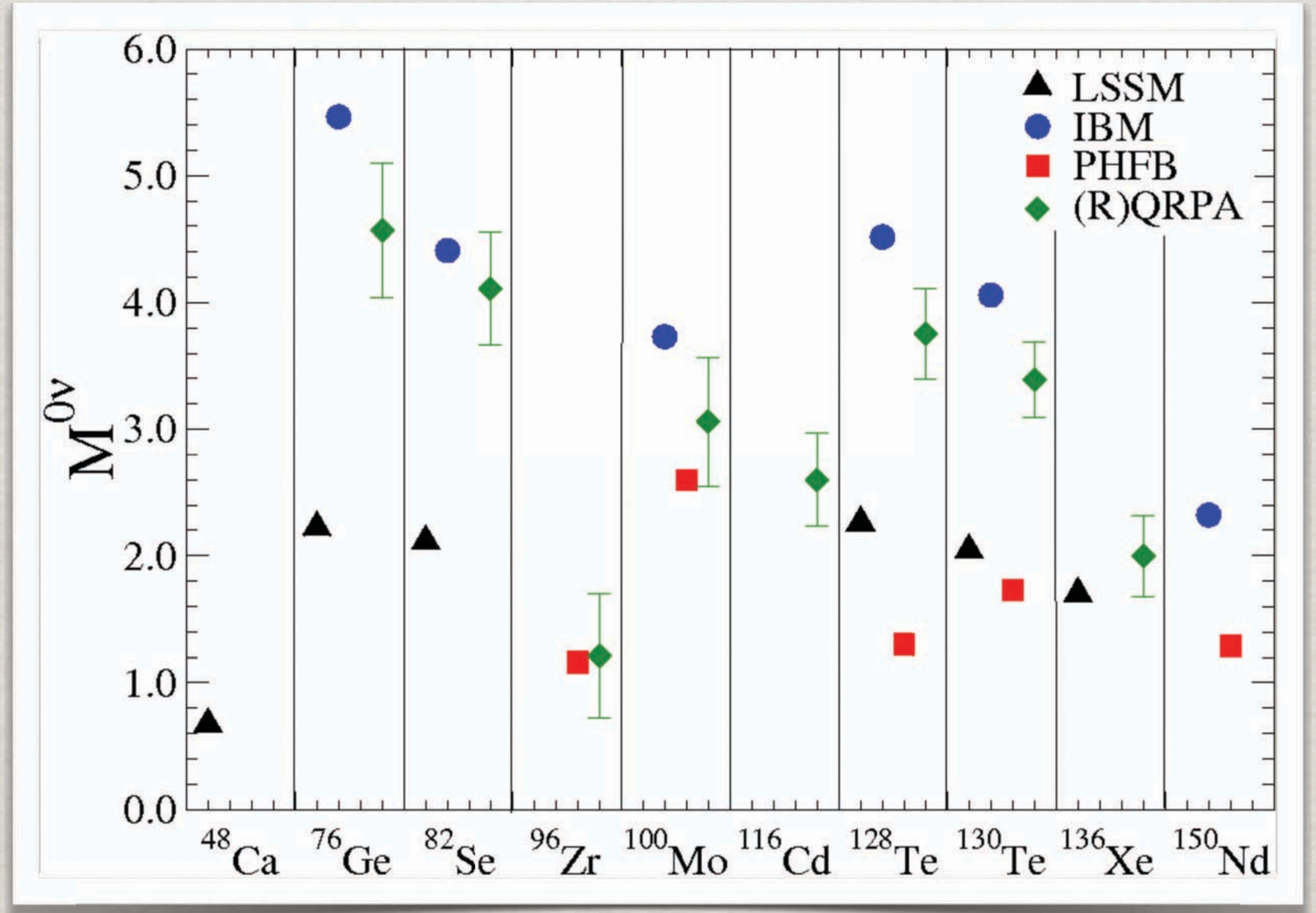
In ***IBM*** ***(Iachello, Barea)*** *the low lying states of the nucleus are modeled in terms of bosons. The bosons have either L=0 (s boson) or L=2 (d boson). The bosons can interact through one and to body forces giving rise to bosonic wave functions.*

In ***PHFB*** ***(India/Mexico groups)*** *w.f. of good angular momentum are obtained by making projection on the axially symmetric intrinsic HFB states. Nuclear Hamiltonian contains only quadrupole interaction.*

Differences: *i) mean field; ii) residual interaction; iii) size of the model space iv) many-body approximation*

CALCULATIONS FOR DIFFERENT ISOTOPES

F. Simkovic, Neutrino 2010

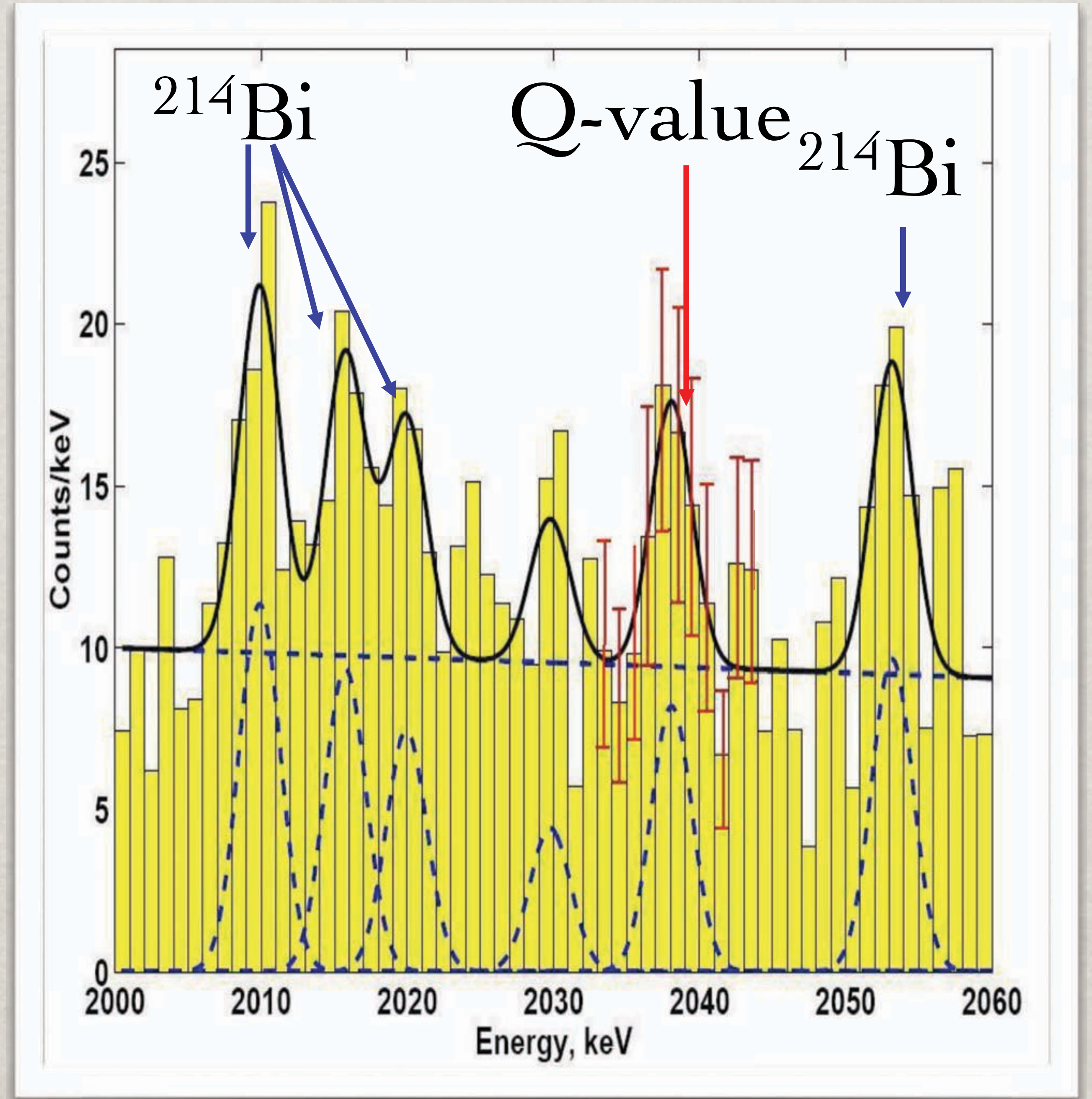


recent input from nuclear structure measurements for ^{76}Ge:
Phys. Rev. C 79, 021301(R) (2009), Phys. Rev. Lett. 100, 112501 (2008)

CONTROVERSIAL 0νββ DISCOVERY CLAIM

$$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24}\,yr$$

$$\langle m_\nu \rangle = 0.32 \pm 0.03\,eV$$

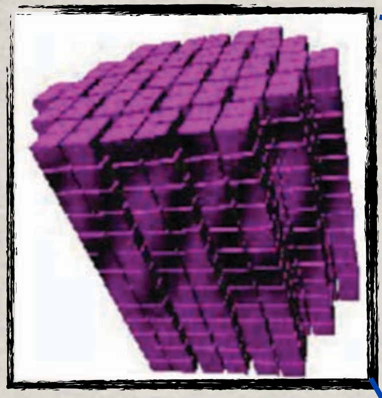


^{76}Ge HPGe semiconductor detectors

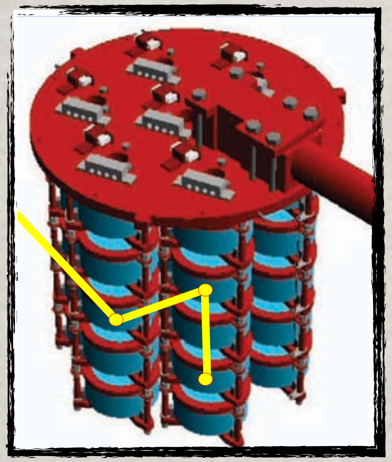
[H.V.Klapdor-Kleingrothaus and I.Krivosheina, Mod.Phys.Lett. A21 (2006) 1547]

THE GAME: INCREASE SIGNAL & REDUCE BACKGROUND

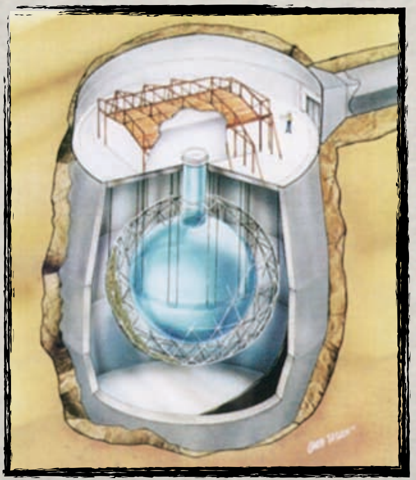
COURE



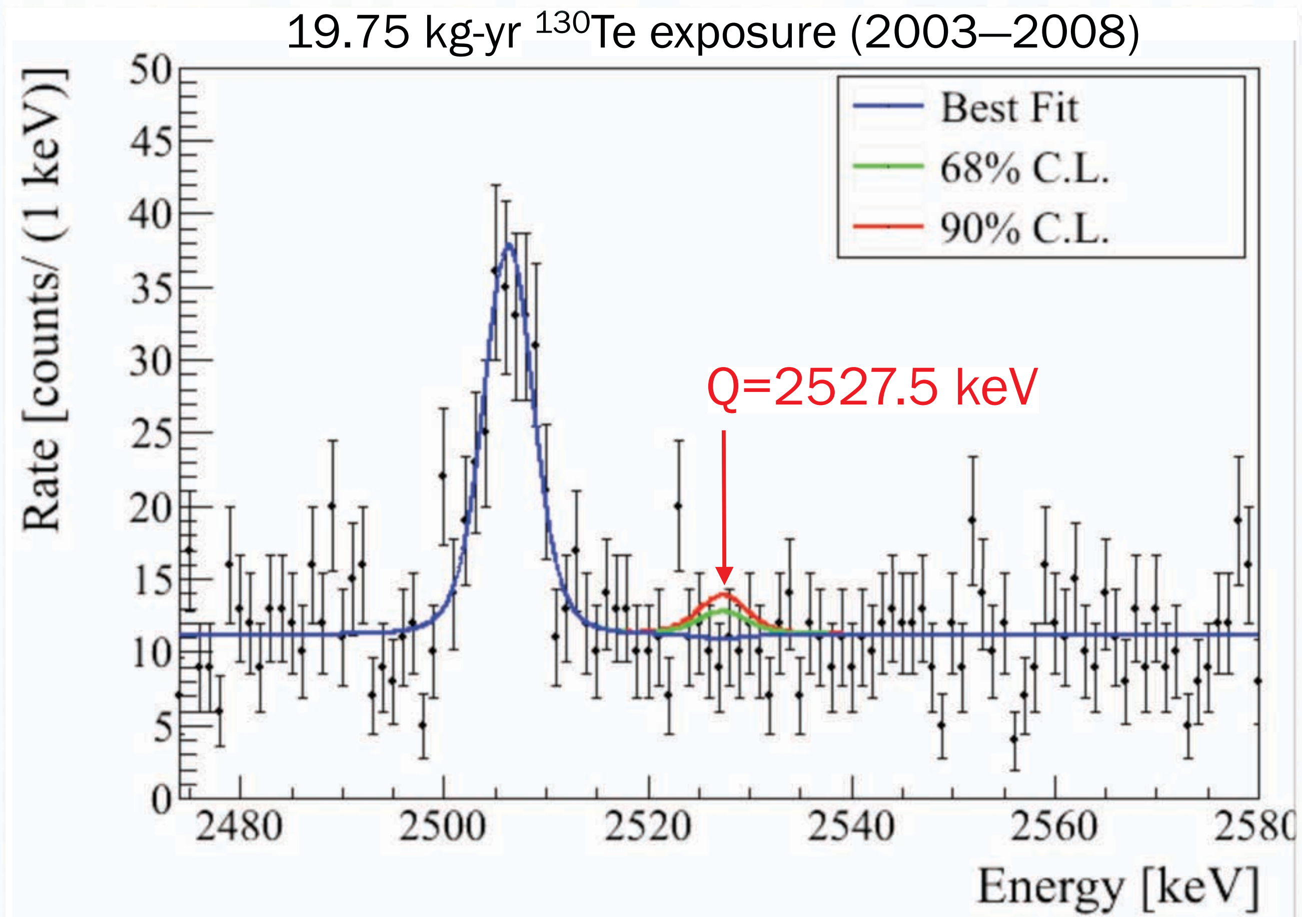
MAJORANA



SNO+



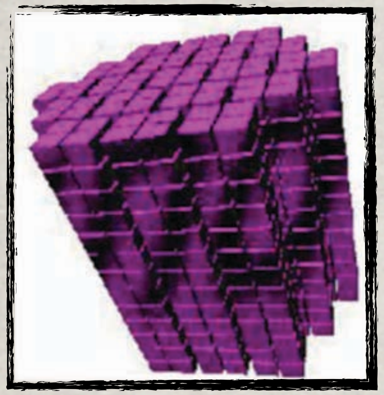
Bolometers



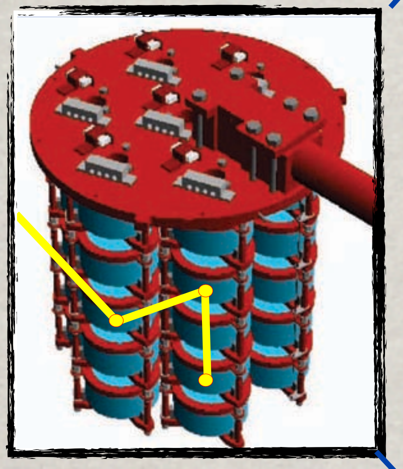
* E. Andreotti et al. (CUORICINO collaboration), Astropart. Phys. 34: 822-831 (2011)

THE GAME: INCREASE SIGNAL & REDUCE BACKGROUND

COURE



MAJORANA



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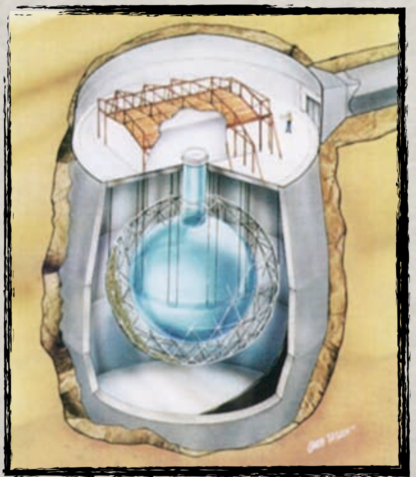
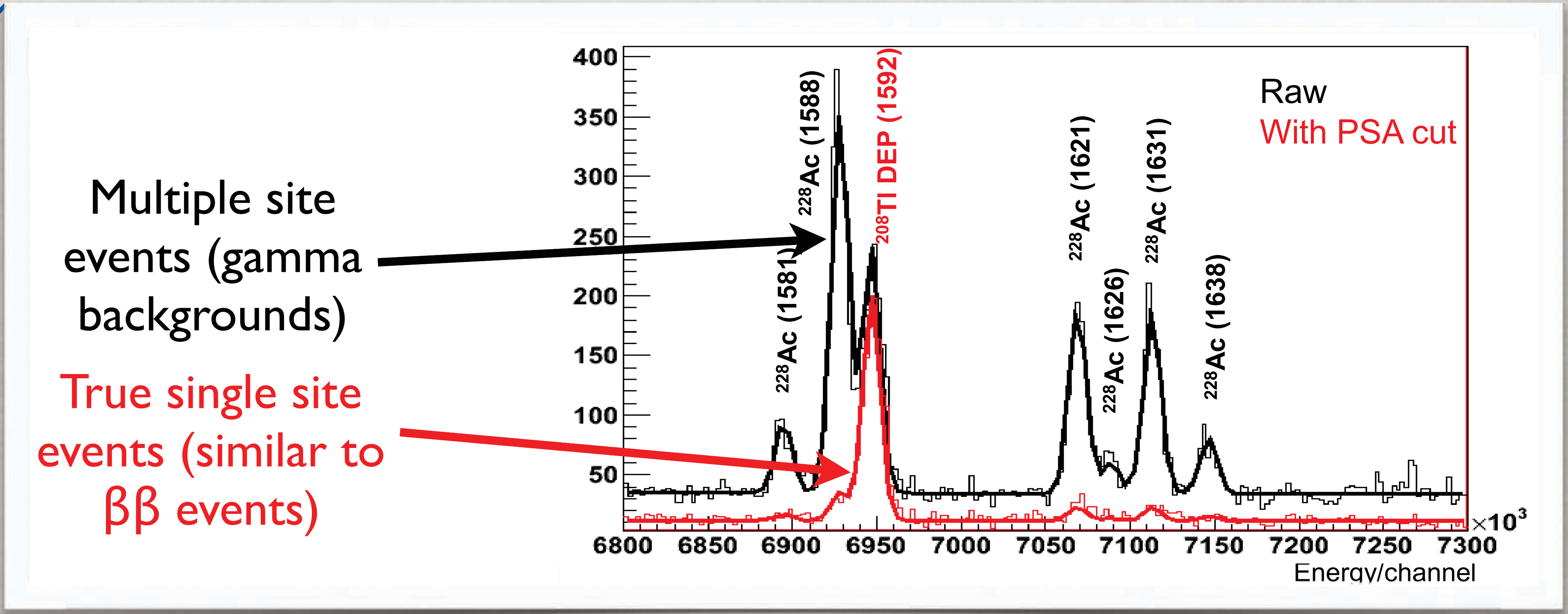


P-Type Point Contact HPGe detectors

P. S. Barbeau, J. I. Collar, and O. Tench., JCAP, 2007(09):009, 2007.



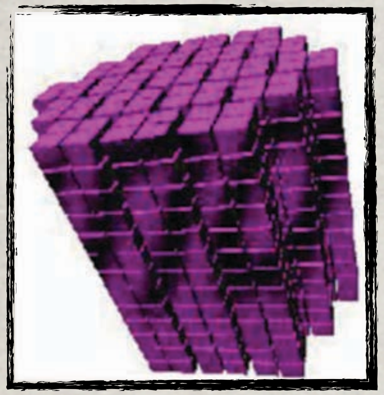
Multiple site events (gamma backgrounds)

True single site events (similar to ββ events)

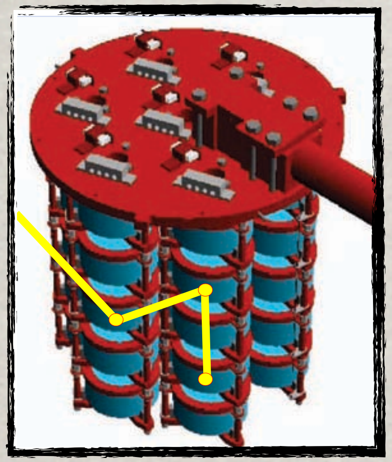
MAJORANA & GERDA using CoGeNT detectors

THE GAME: INCREASE SIGNAL & REDUCE BACKGROUND

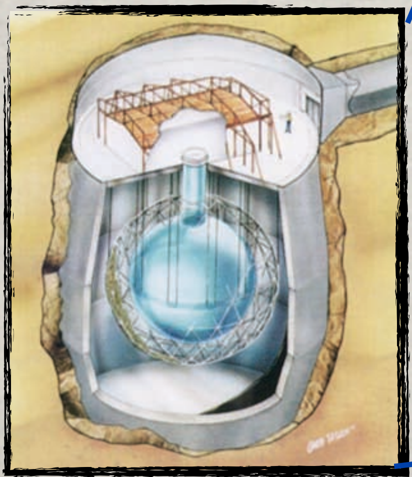
COURE



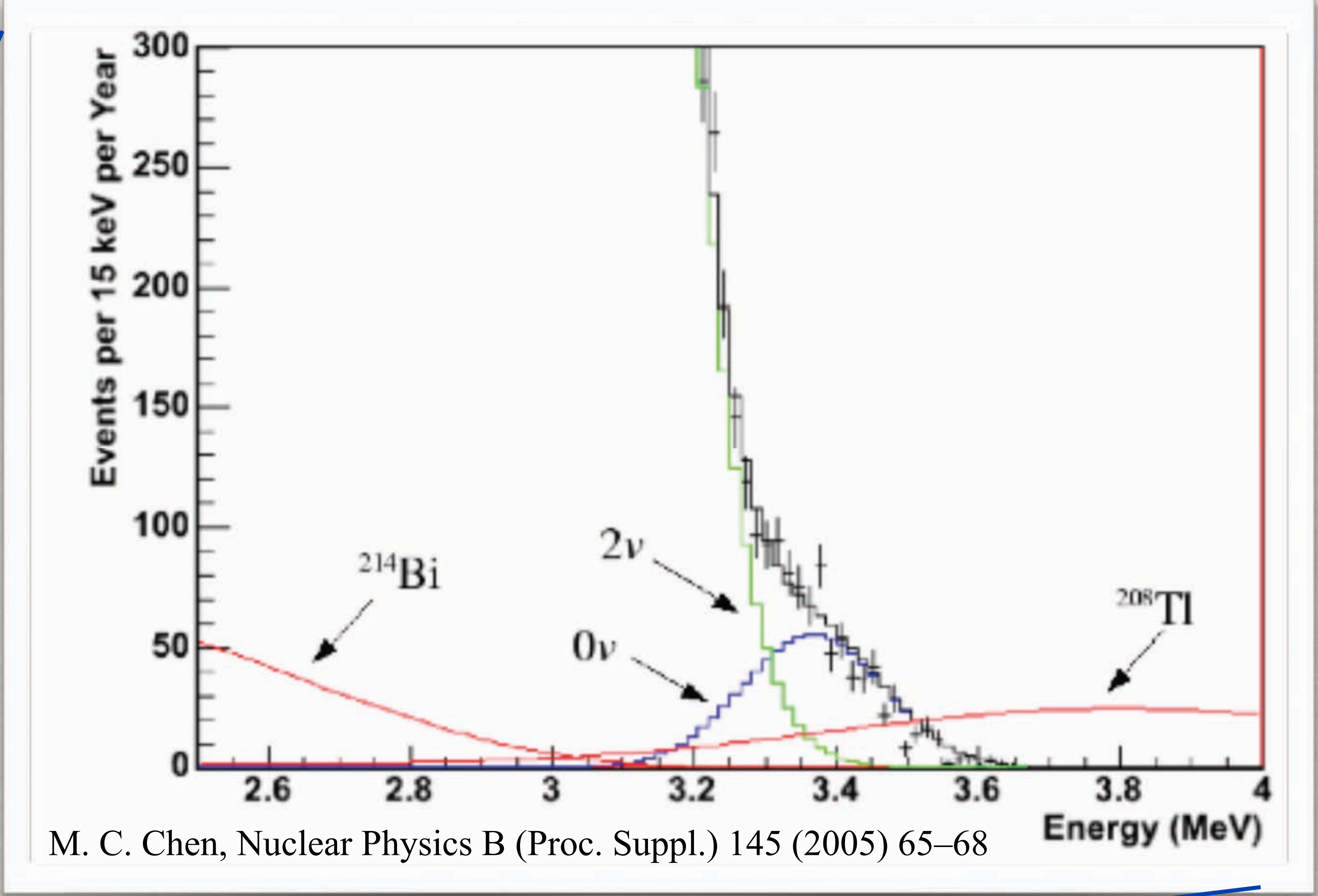
MAJORANA



SNO+



massive & well shielded scintillator



M. C. Chen, Nuclear Physics B (Proc. Suppl.) 145 (2005) 65–68

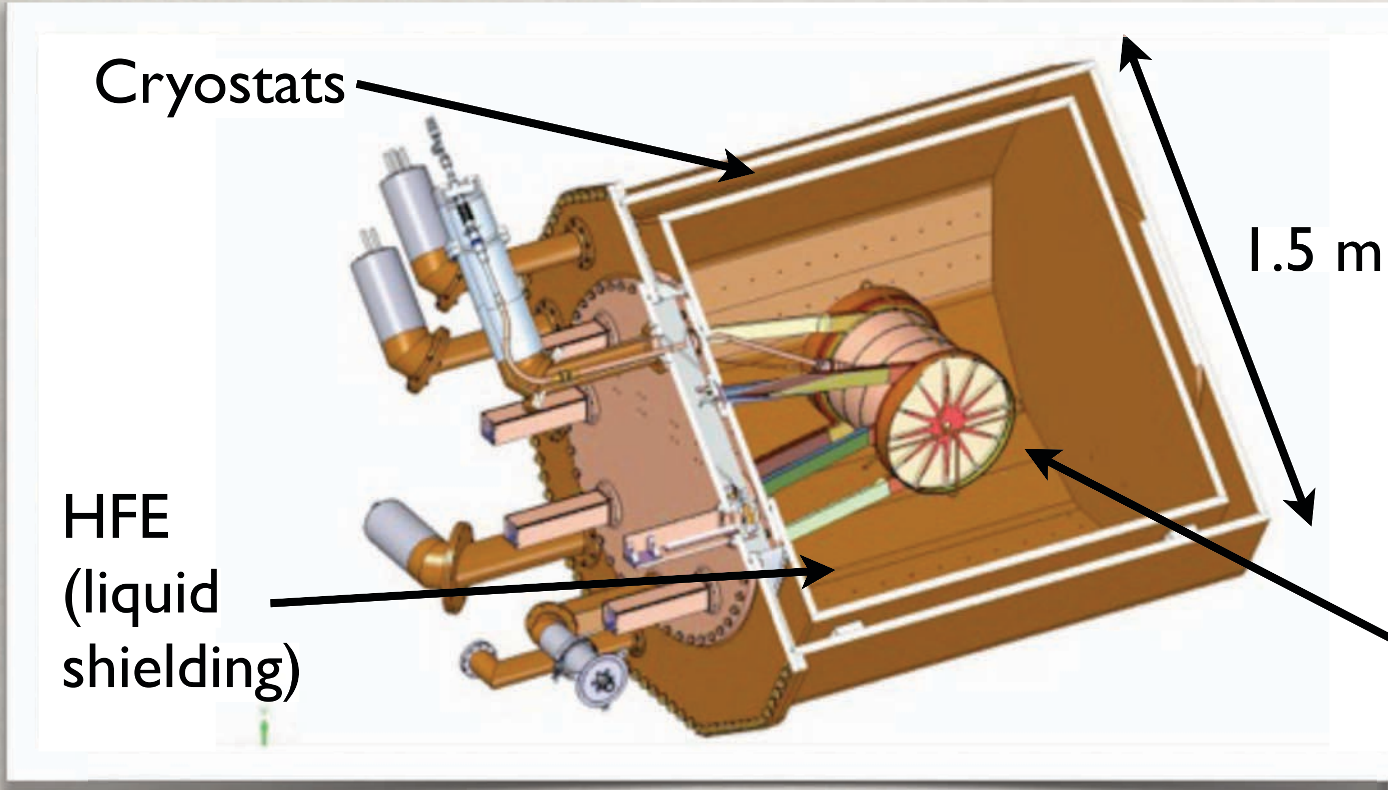
XENON IS AN EXCELLENT CANDIDATE FOR $0\nu\beta\beta$ SEARCH

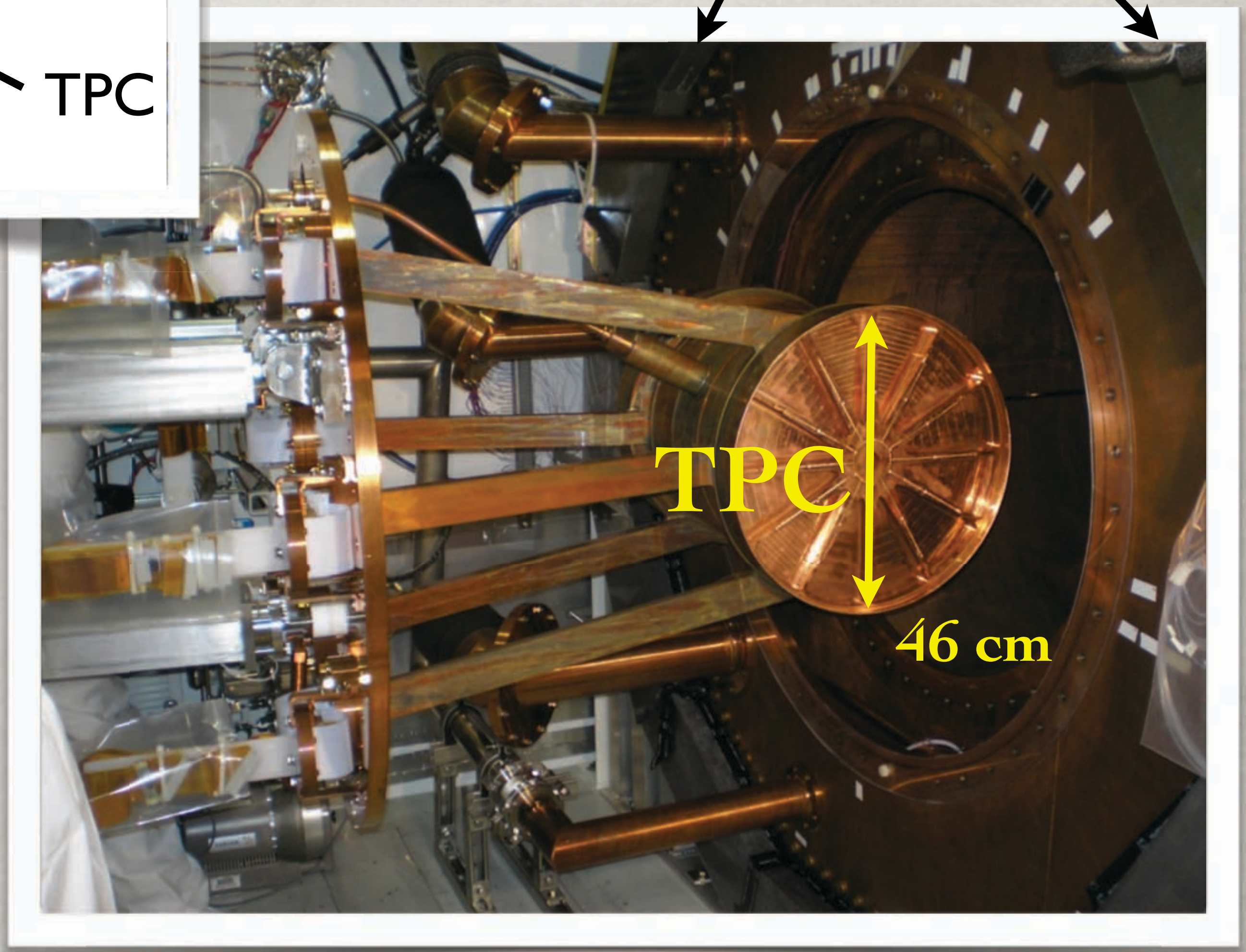
EXO-200

- *Poorer energy resolution than crystalline detectors*
- Xenon isotopic enrichment is easier: Xe already a gas. ^{136}Xe heaviest isotope.
- Xenon is "reusable": continuously purify-able & recyclable (no crystal growth).
- Monolithic detector: LXe is self shielding.
- Minimal Cosmogenic activation: No long lived radioactive isotopes of Xe.
- ***admits a novel coincidence technique:*** Background reduction by Ba daughter tagging.

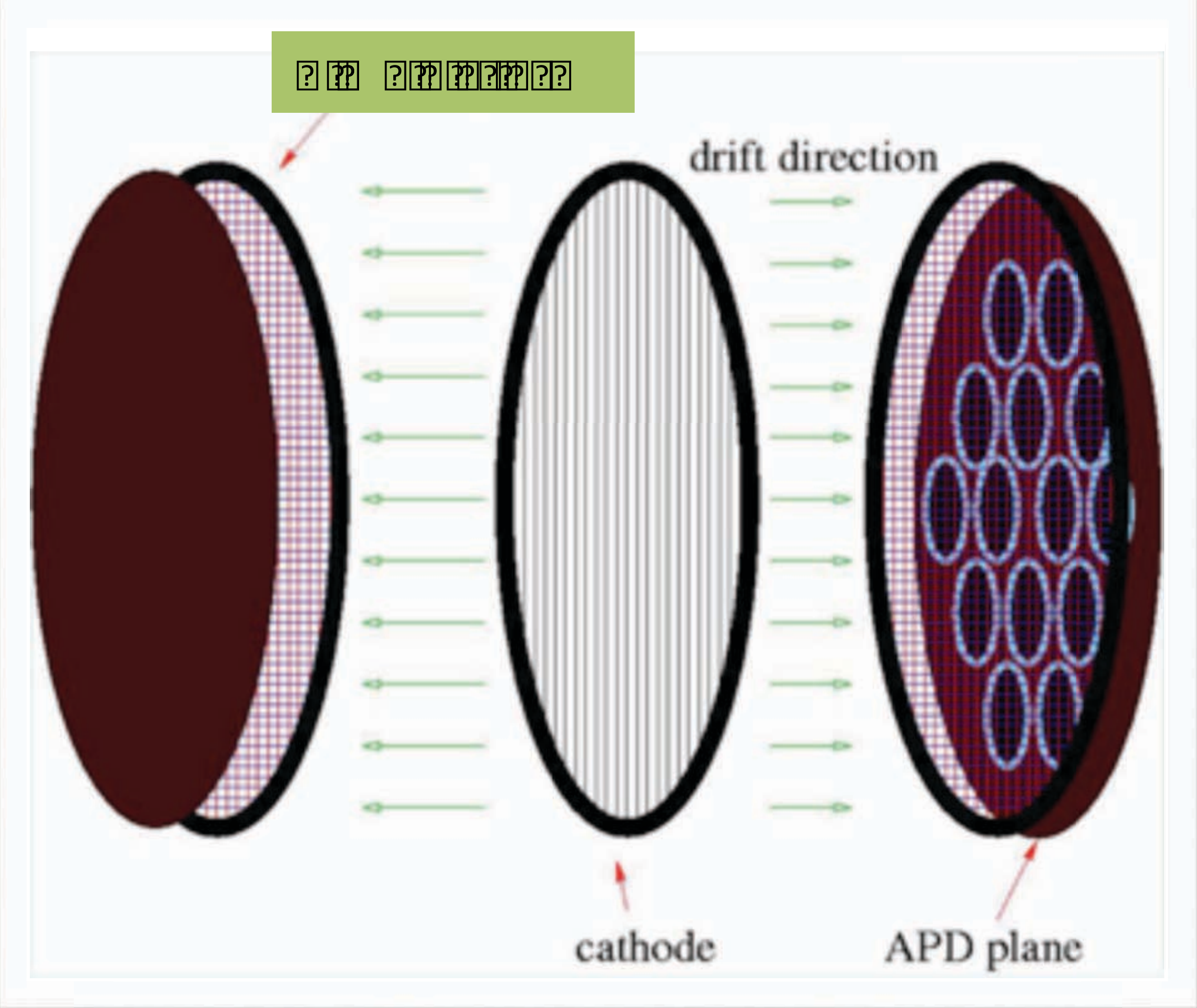
EXO

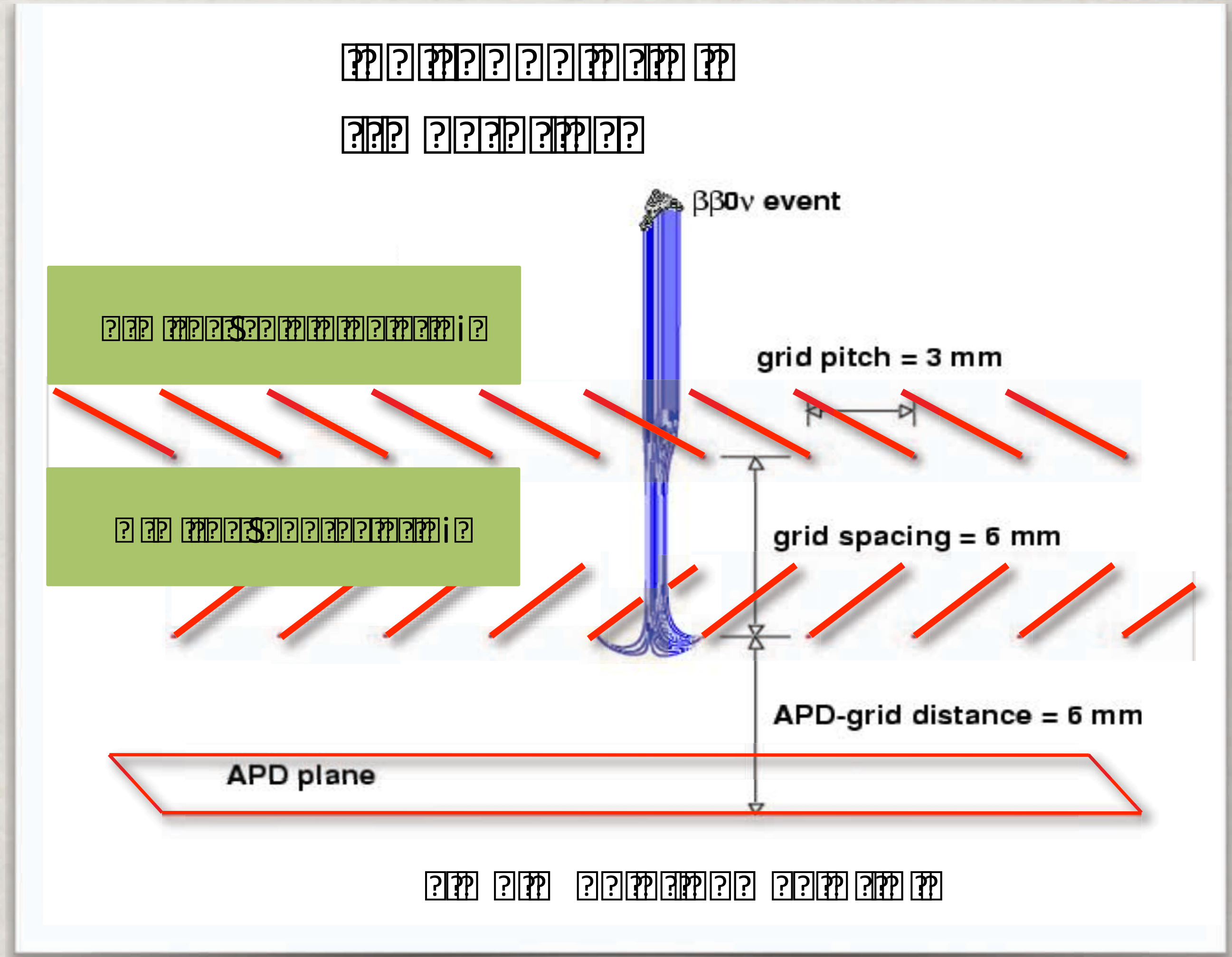
THE EXO-200 DETECTOR





EXO-200 Time Projection Chamber (TPC) Basics





Common cathode for 2 TPCs

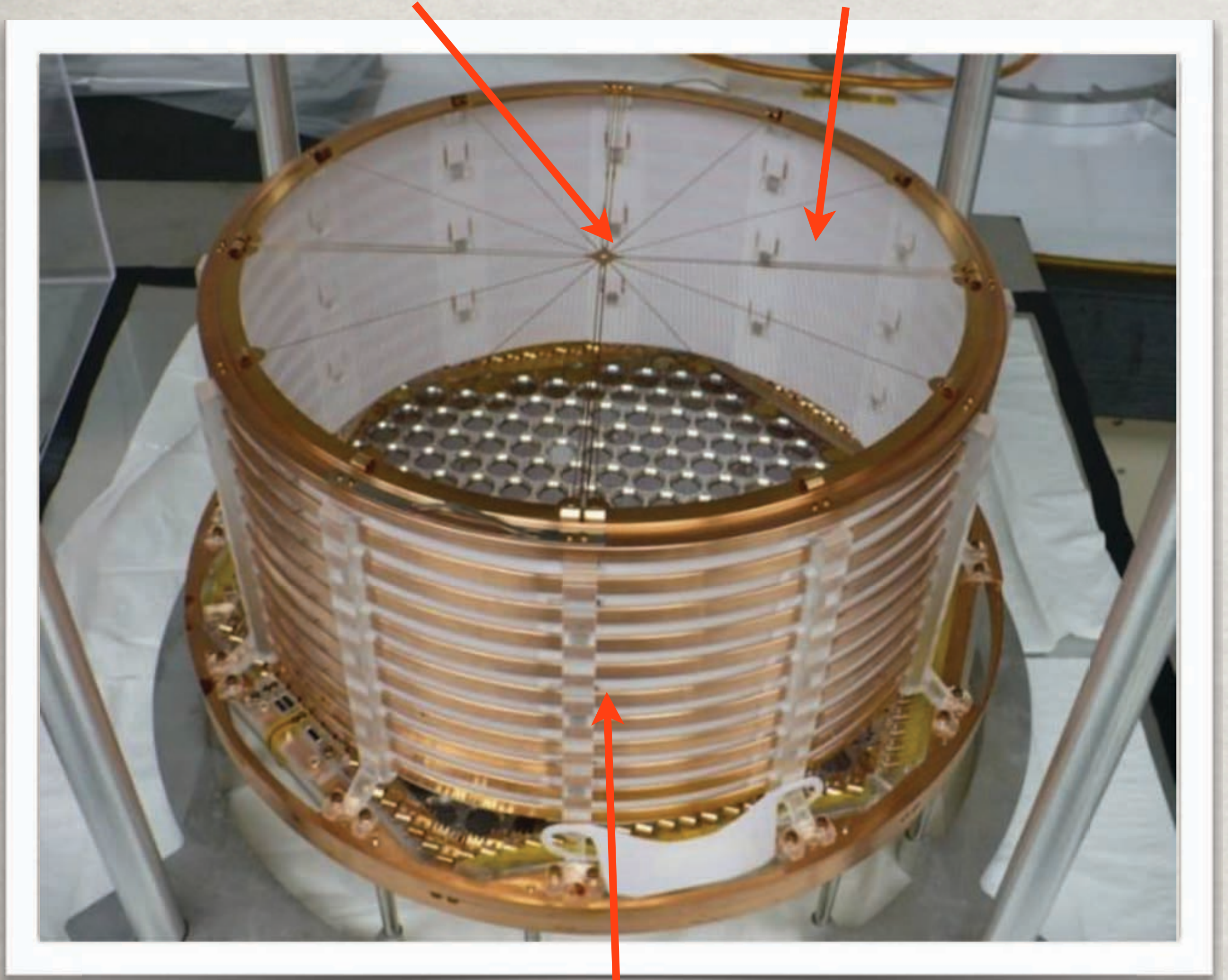
V: induction on shielding grid

APDs see prompt scintillation (t_0 for drift time)

U & ionization: charge on collection grid

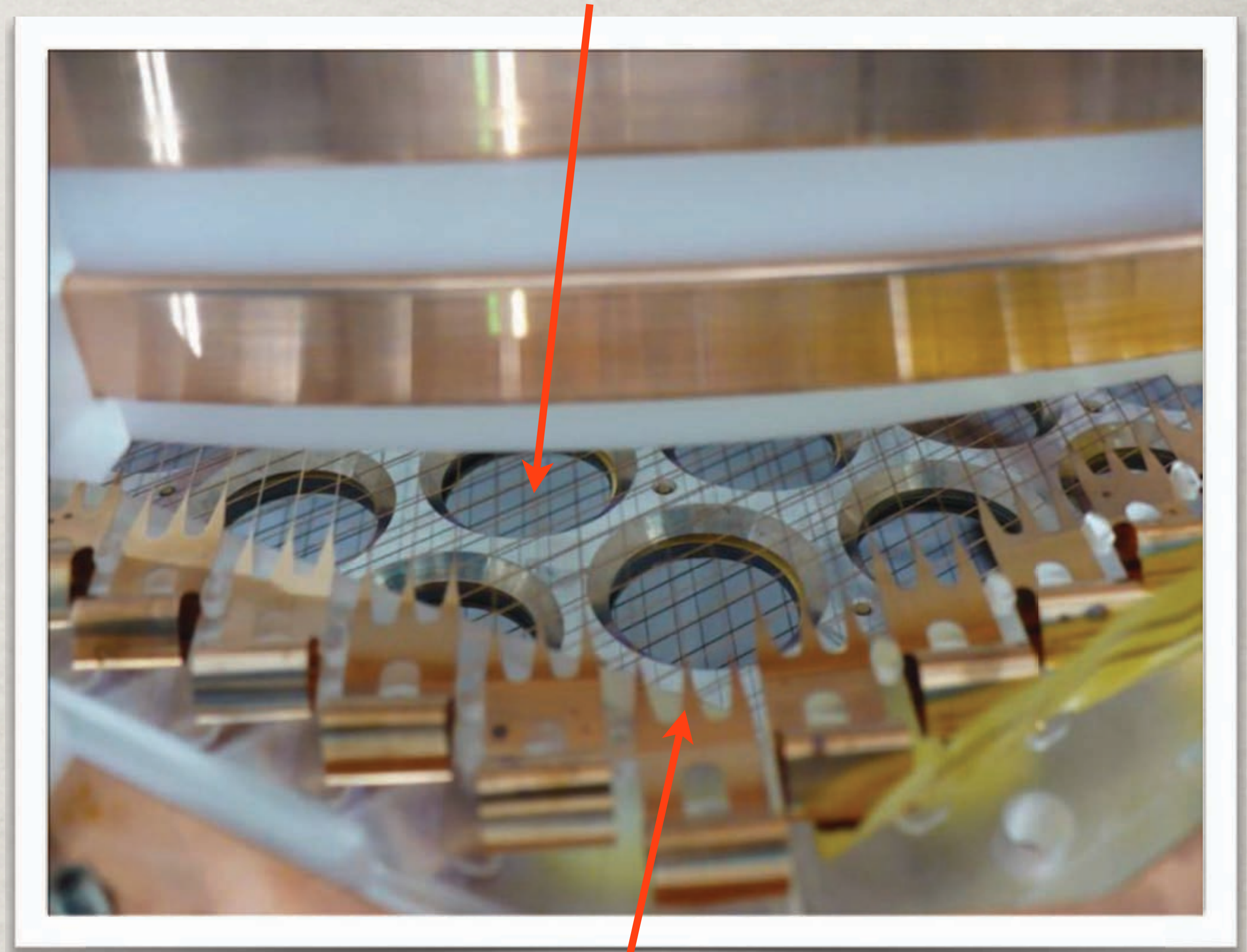
EXO-200 Internals

cathode Teflon Reflector



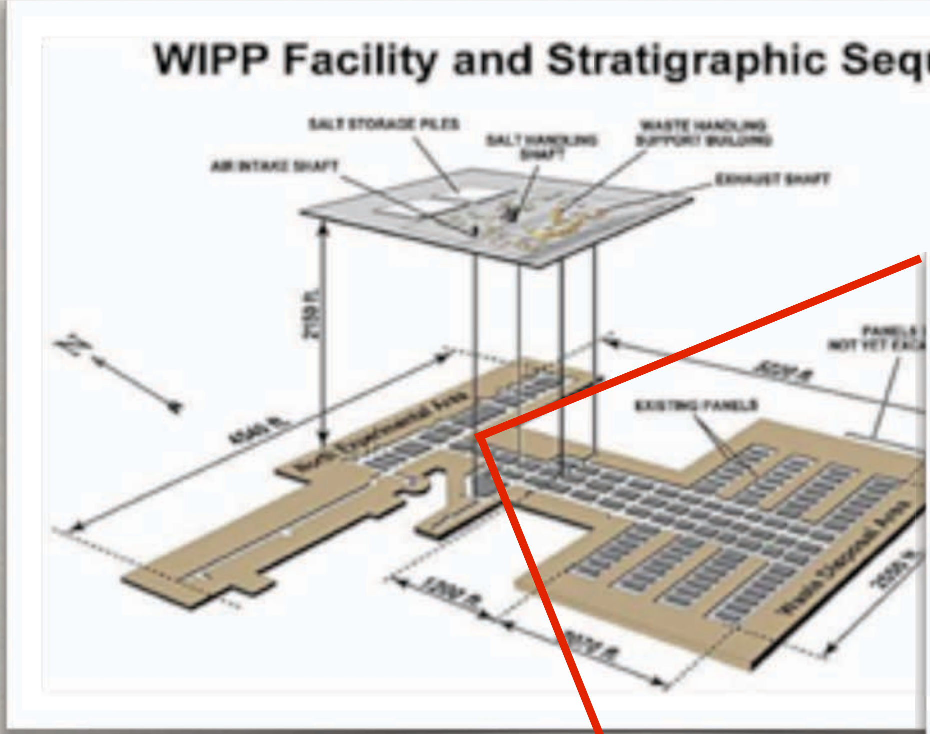
field shaping rings

APDs



charge detection wires

EXO-200 INSTALLATION SITE: WIPP



Waste Isolation Pilot Plant Carlsbad, NM
U.S. DOE Salt mine for radioactive waste storage

1600 mwe

Salt is low radioactivity compared to hard-rock mine

EXO-200 ENRICHED LOW BACKGROUND RUN (2011)

- Enriched Xe (~81% in ^{136}Xe) data taking begun Spring 2011
- Data used for immediate measurement of ^{136}Xe $2\nu\beta\beta$ $T_{1/2}$, & to begin energy resolution studies

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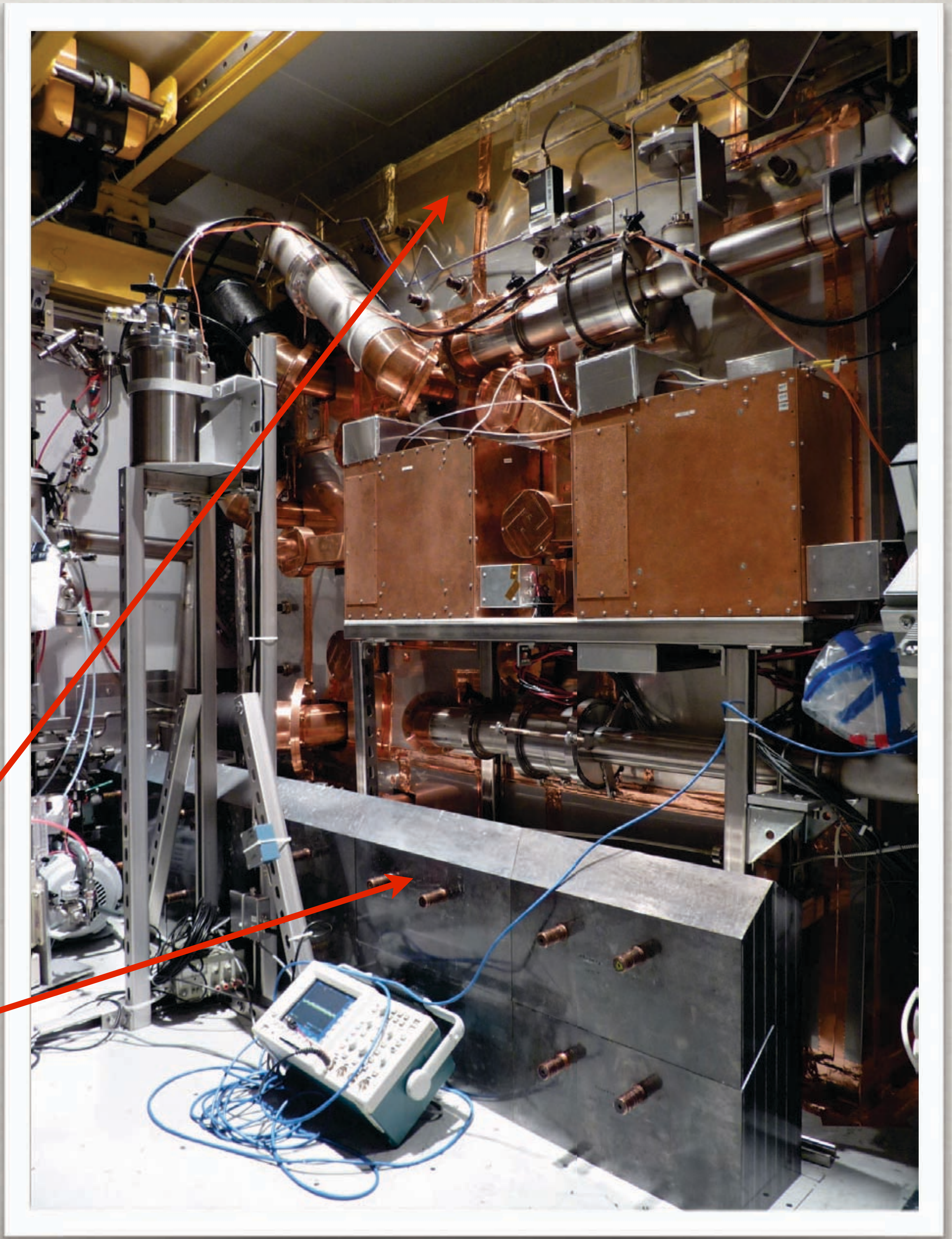
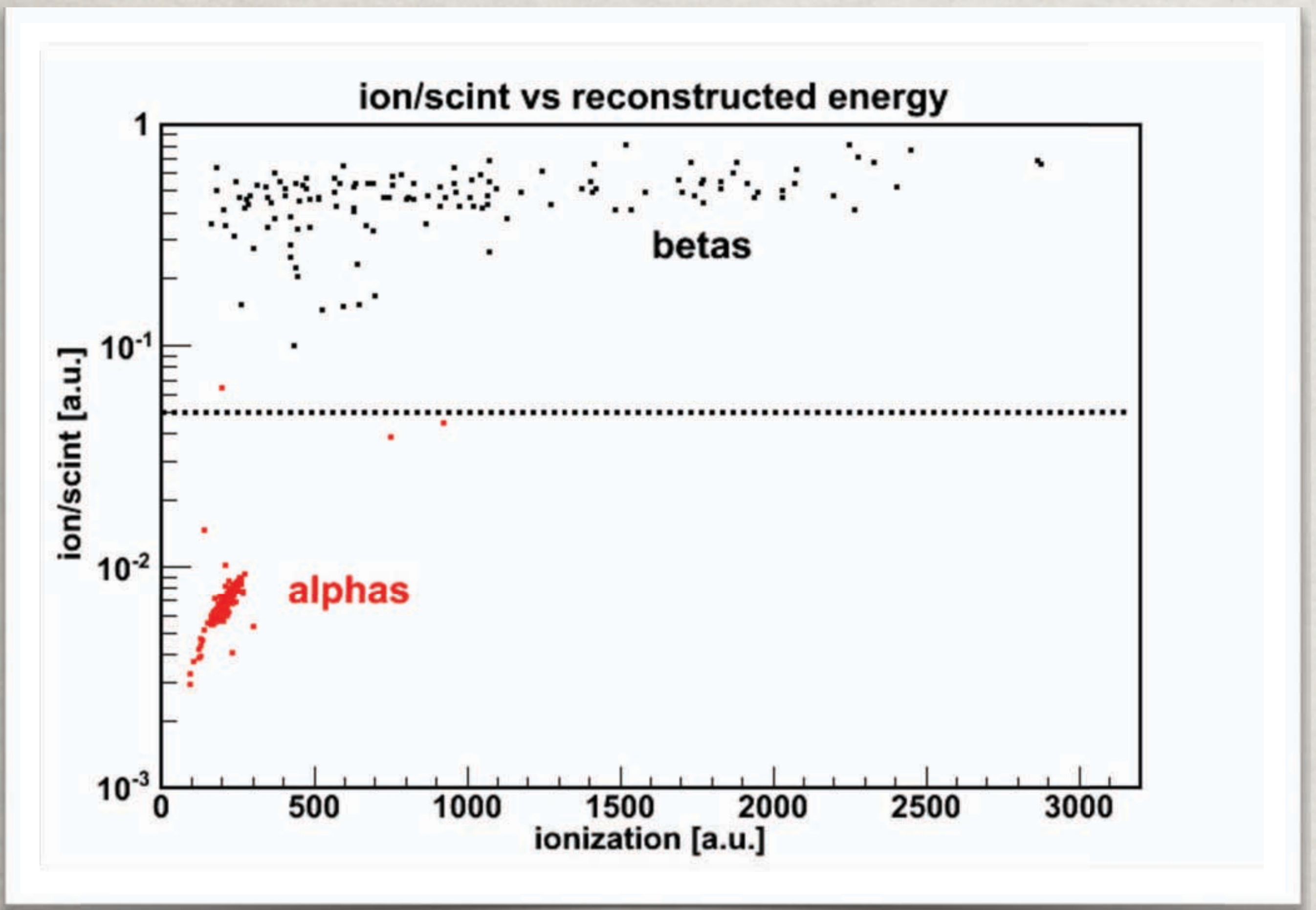
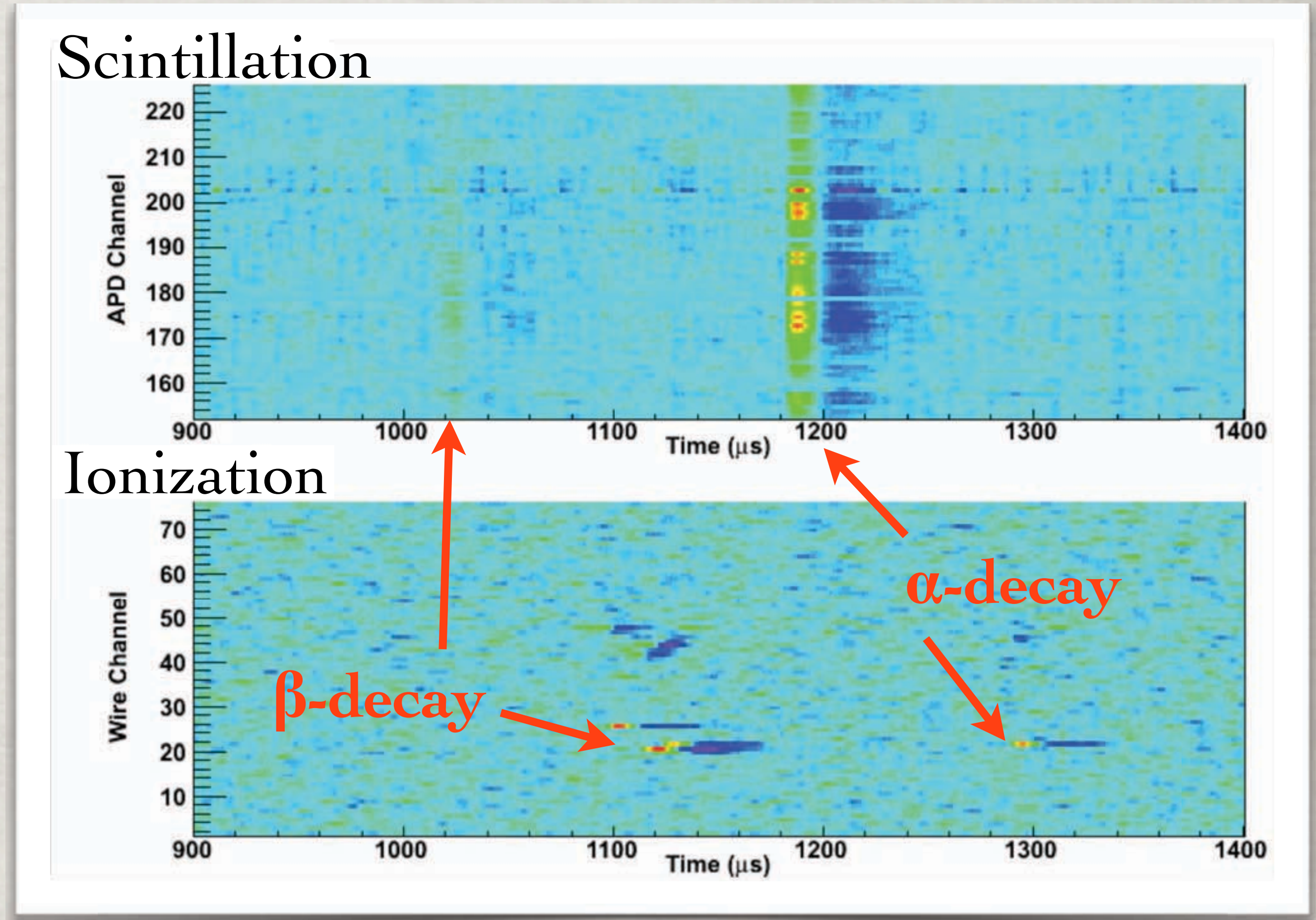
- No Rn trap on the system
- Recent: Rn enclosure in operation
- Recent: front Pb wall finished



^{222}RN CONTENT OF XENON



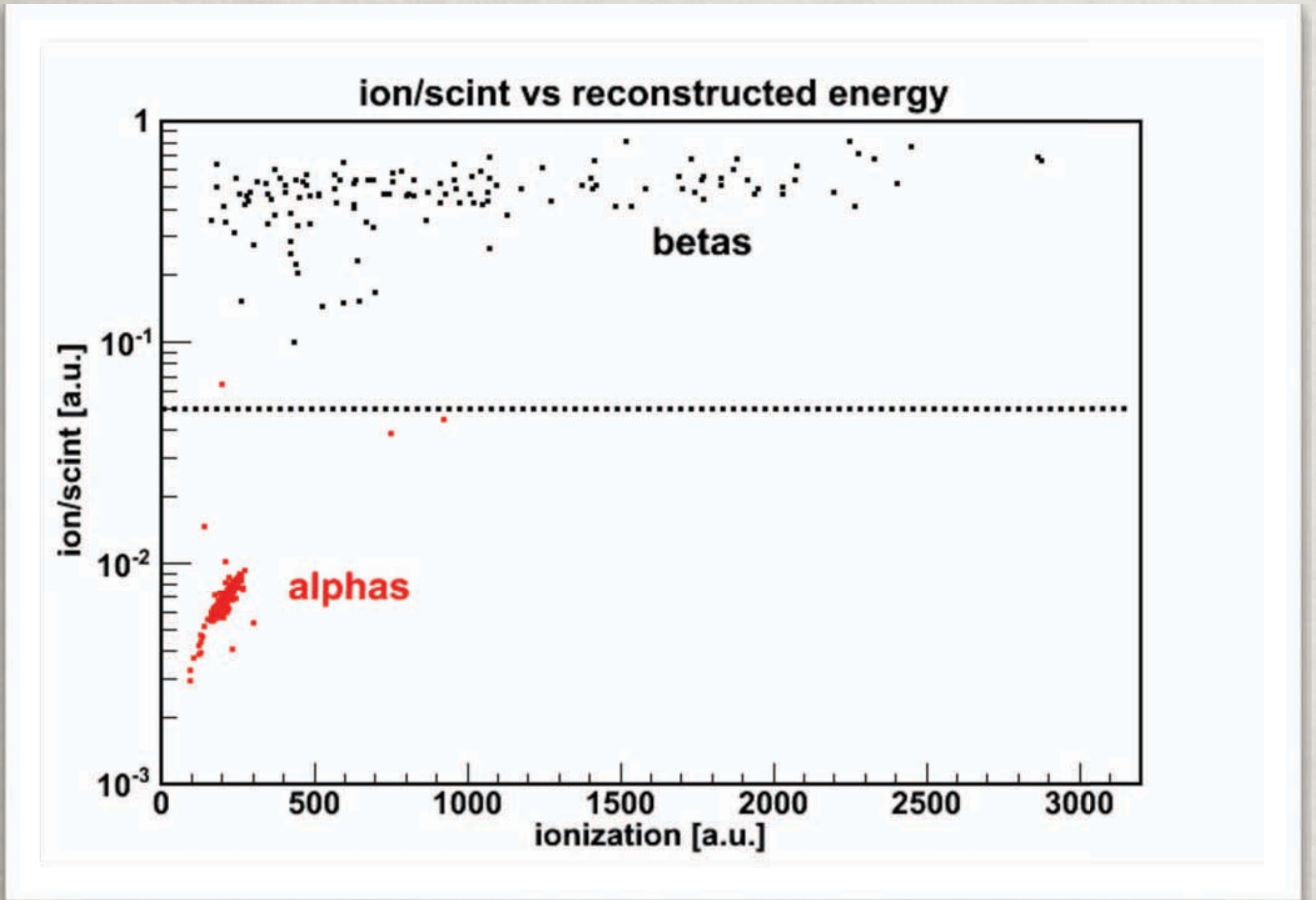
α: strong light signal; weak charge signal
β: weak light signal; strong charge signal

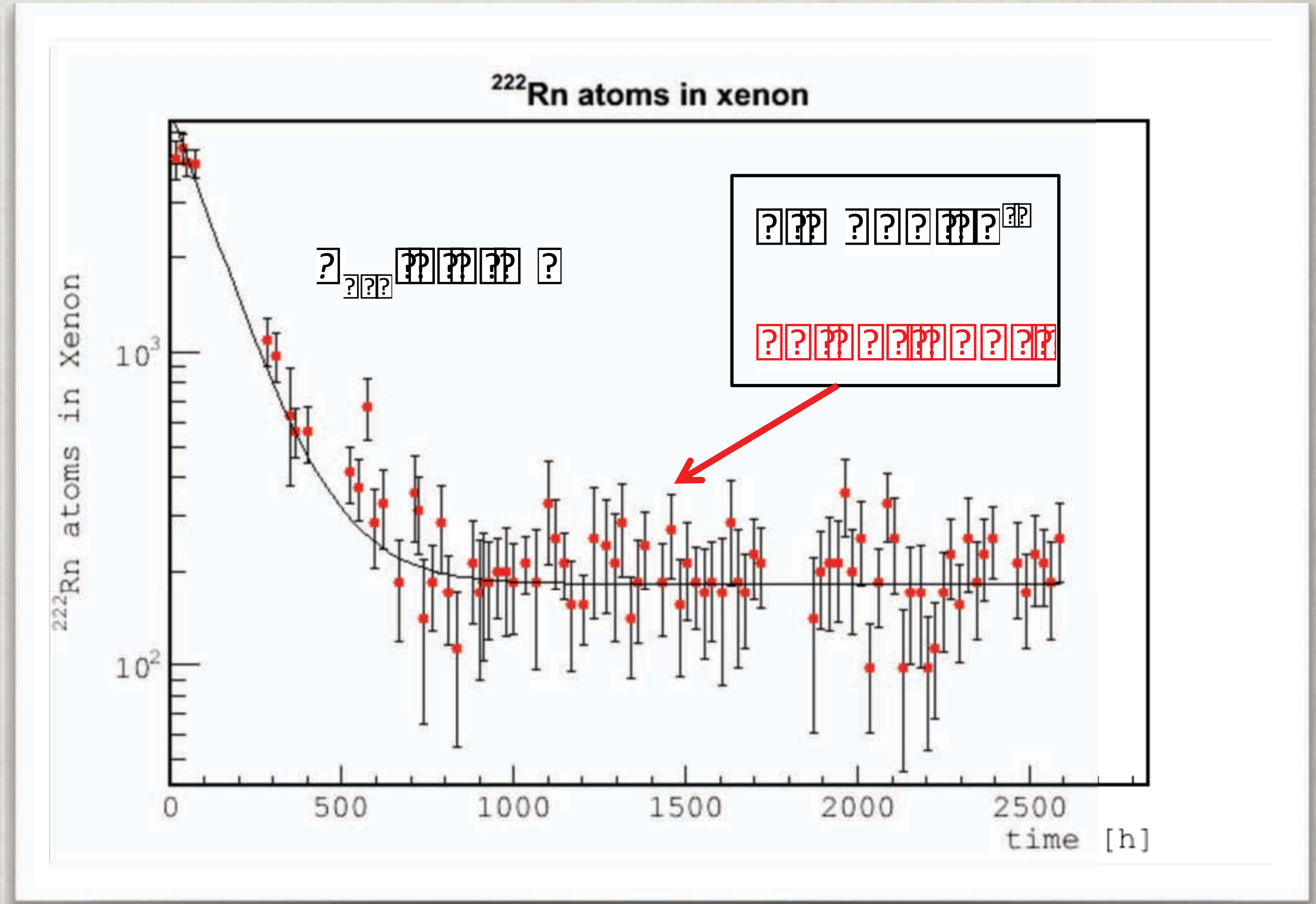


^{214}Bi-^{214}Po coincidences

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

^{222}Rn content of Xenon



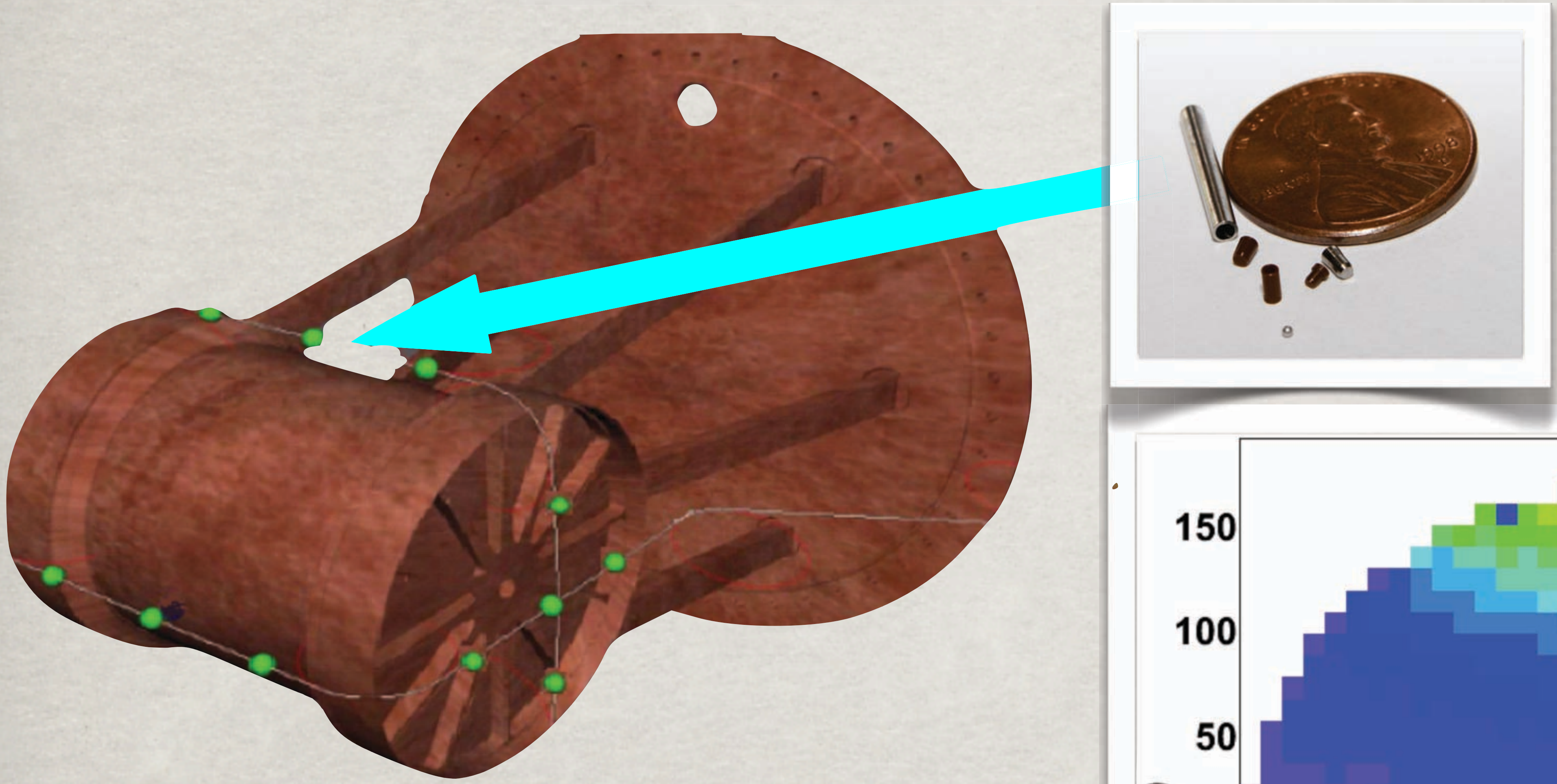


α: strong light signal; weak charge signal
β: weak light signal; strong charge signal

^{214}Bi-^{214}Po coincidences

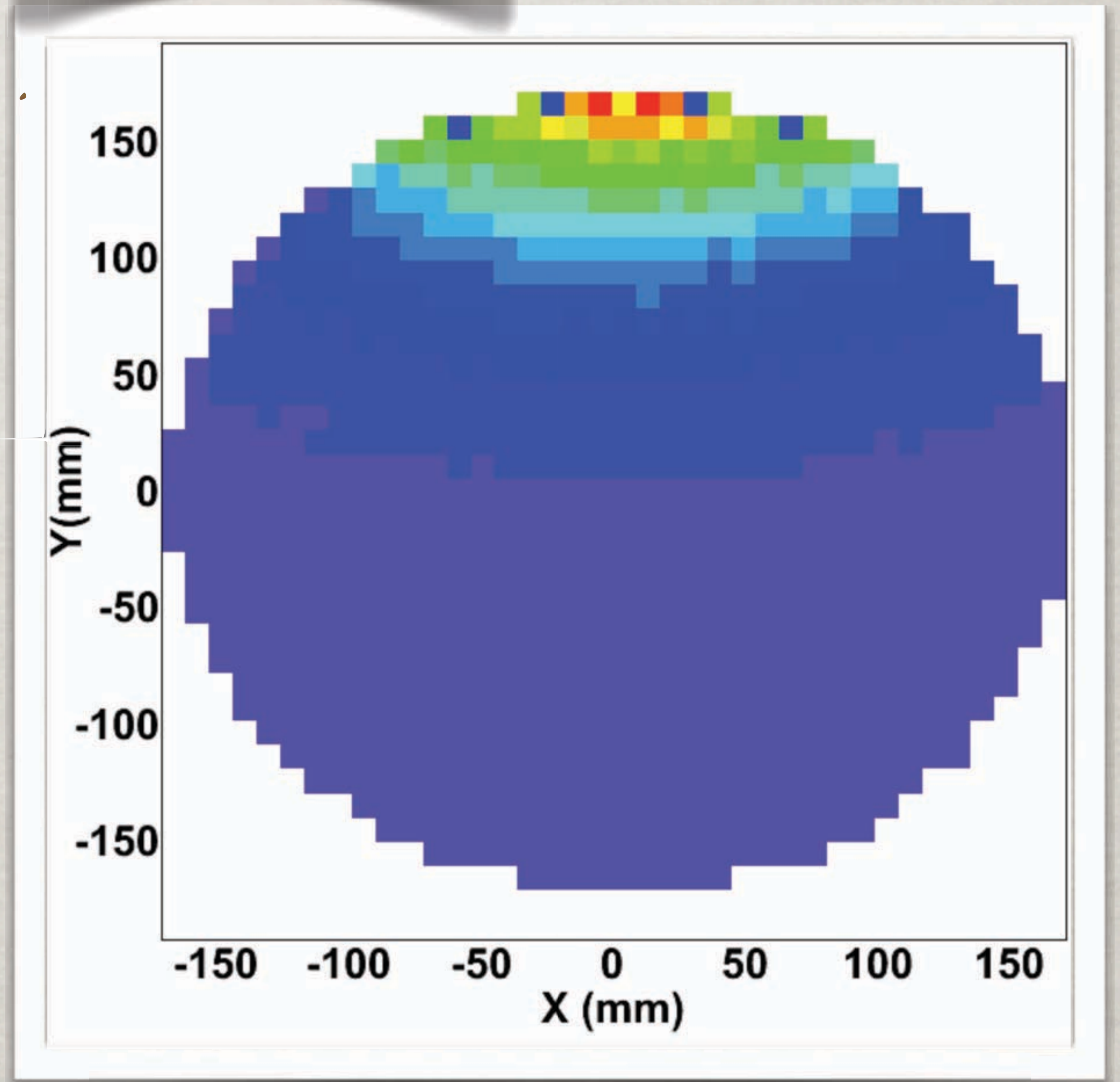
Using the Bi-Po (Rn daughter) coincidence technique, we can estimate the Rn content in our detector. The ^{214}Bi decay rate is consistent with measurements from alpha-spectroscopy and the expectation before the Rn trap is commissioned

CALIBRATION



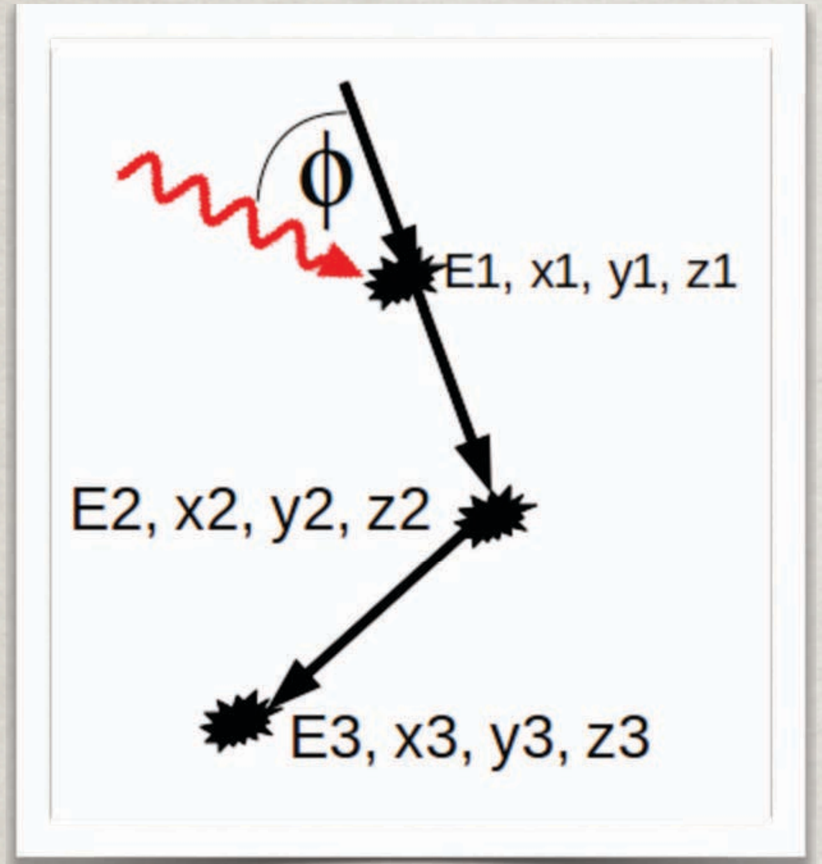
Sources:
^{137}Cs, ^{60}Co, ^{228}Th

Guide tube brings various sources to several positions outside detector



x-y distribution shows excess near source location

PINPOINT SOURCE LOCATION USING A COMPTON TELESCOPE TECHNIQUE

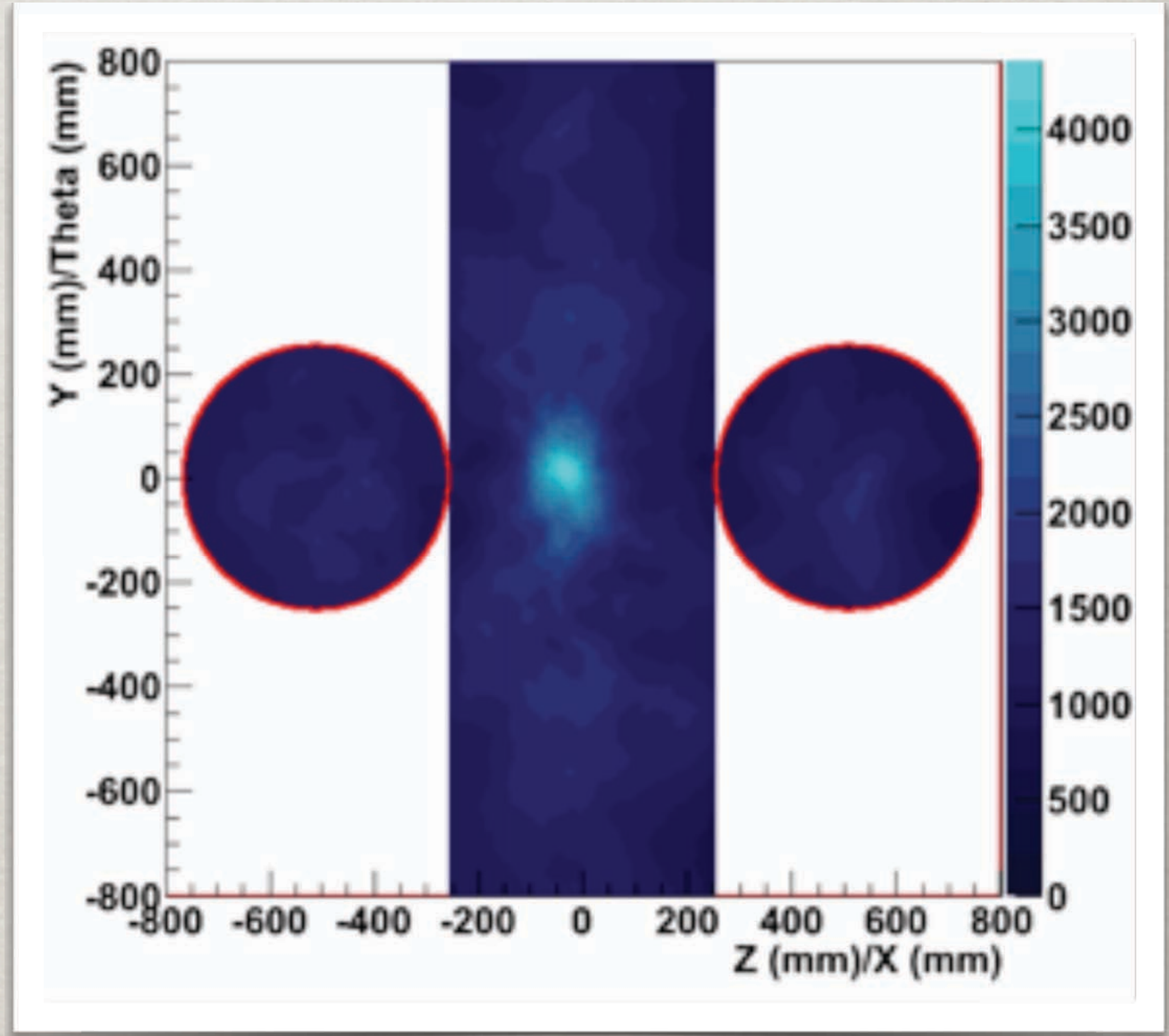


Detector measures E, x, y, z for each site
Use scattering formula

$$\phi = arccos\left[1 - m_e c^2 \cdot \left(\frac{1}{E_\gamma - E_1} - \frac{1}{E_1}\right)\right]$$

From each site a cone is drawn and adding up these cones produces the image to the right

500 events

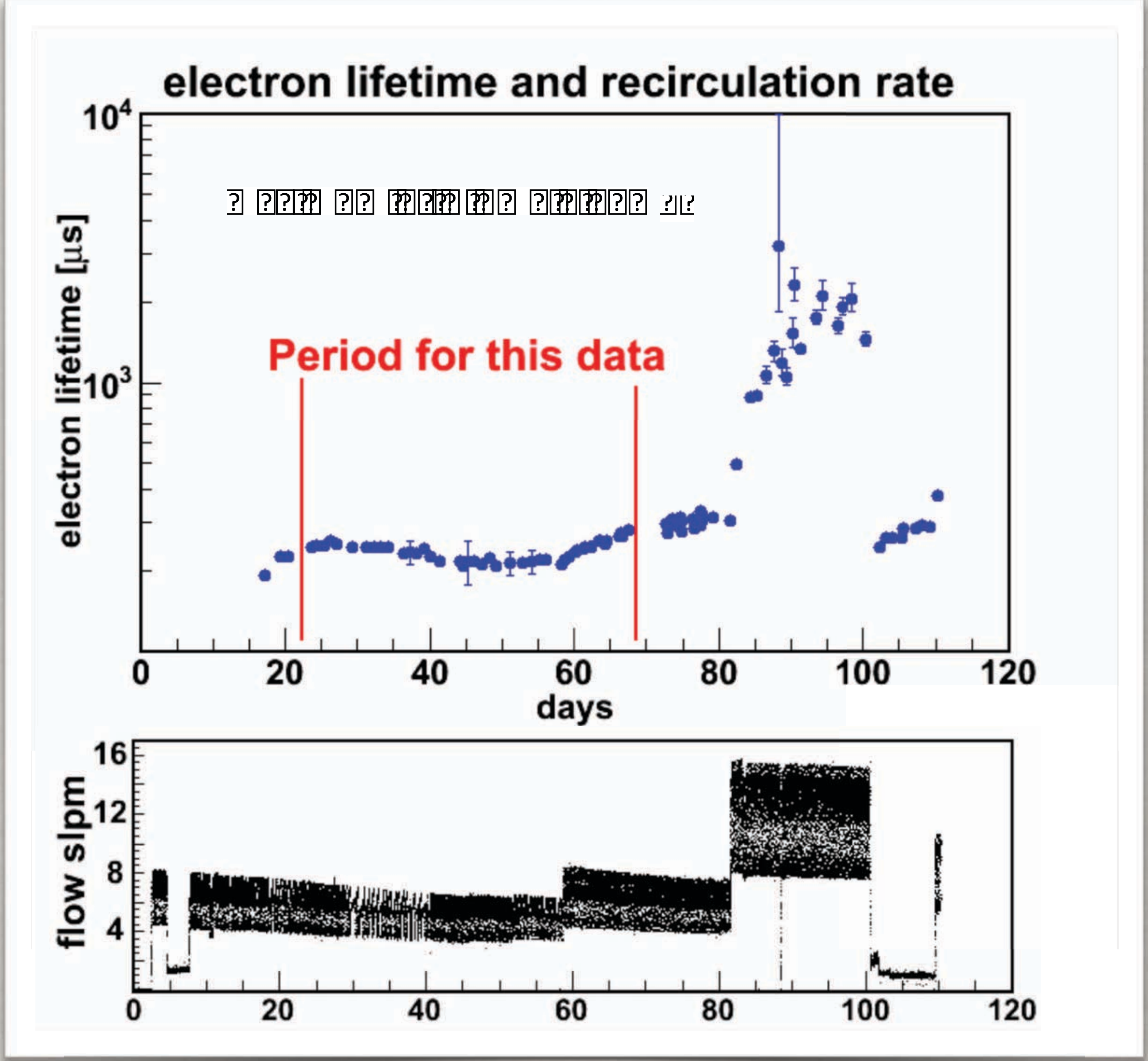


XENON PURITY

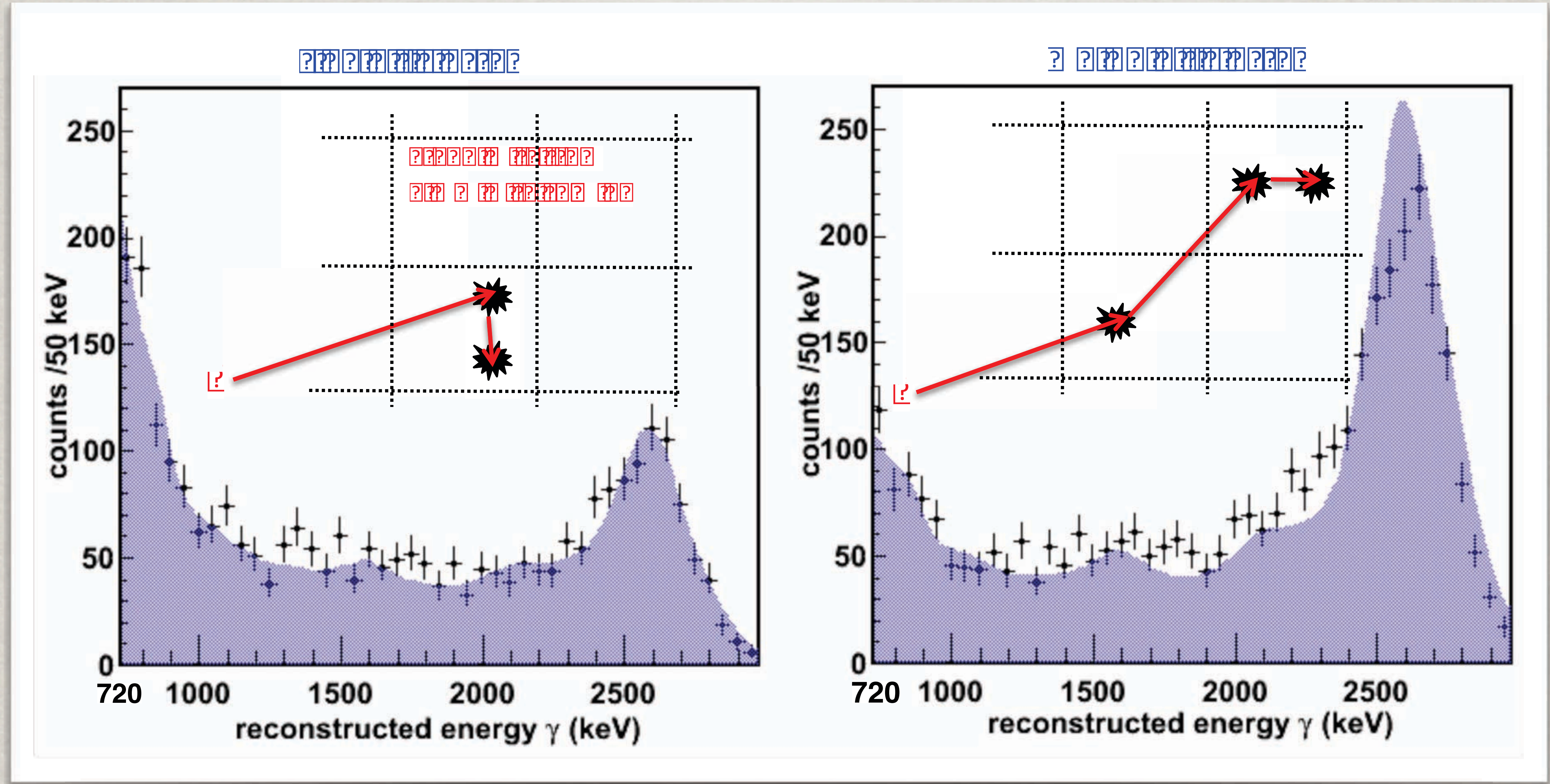
Use calibration sources to measure electro-negative purity

Extraordinarily rapid achievement of ~ms electron lifetimes due to recirculation!

This is great for energy resolution



^{228}Th Calibration

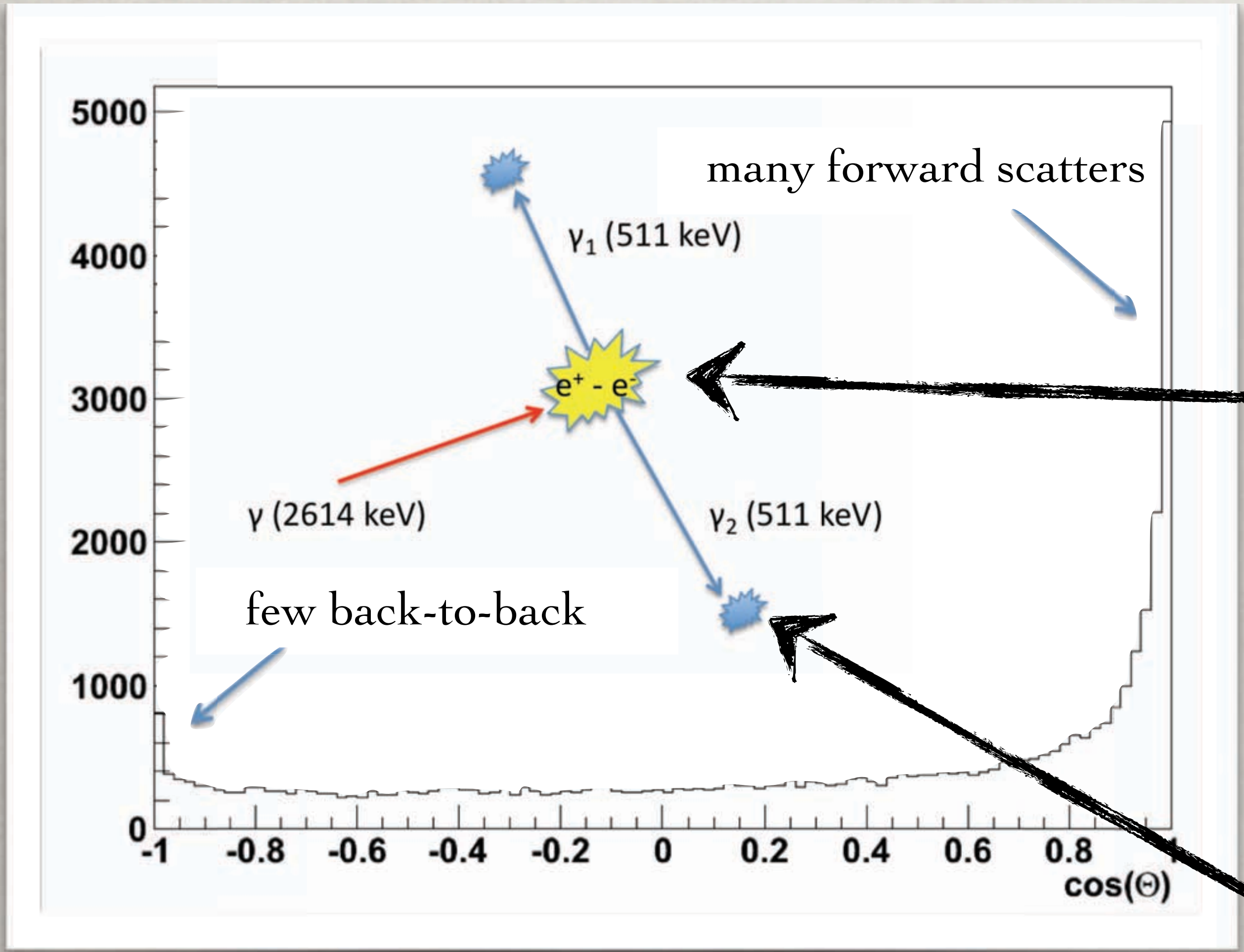


Rate is not a free parameter
poorest agreement is +8%

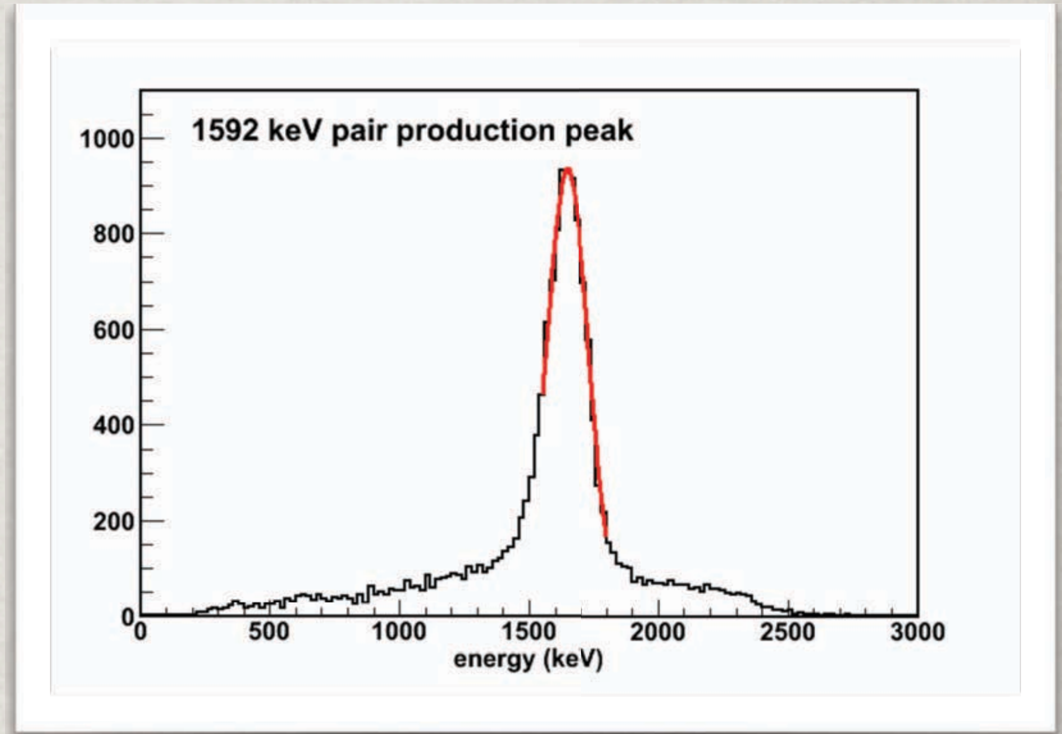
Calibration runs compared to simulation

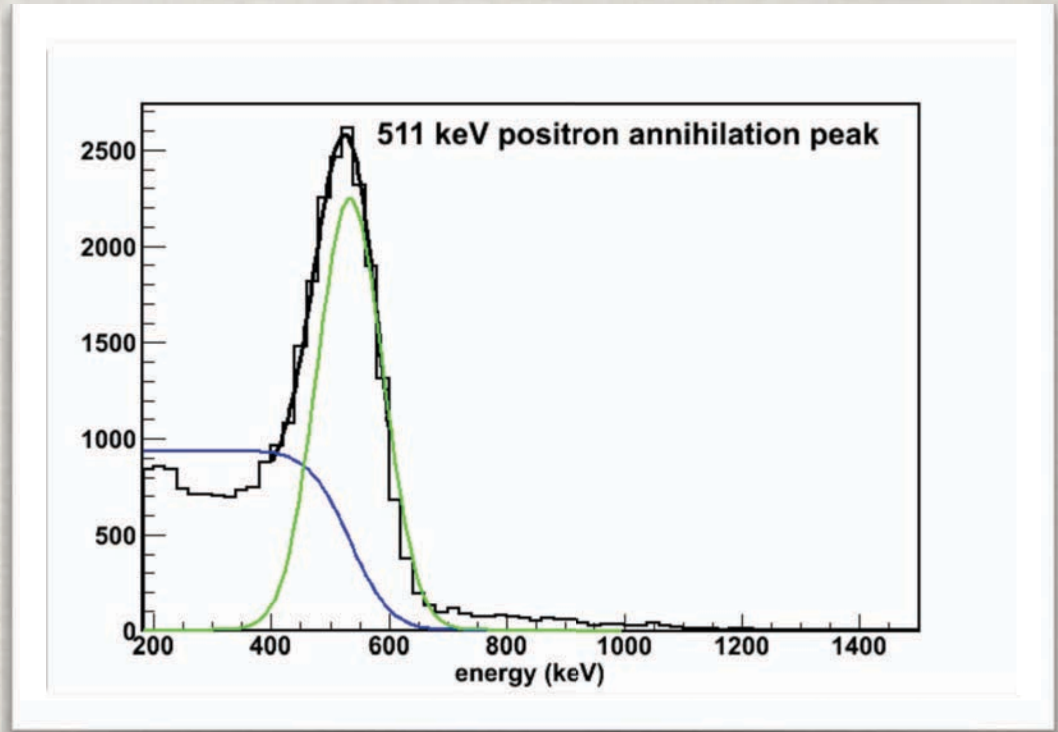
- -GEANT4 based simulation
- -charge & scintillation propagation
- -signal generation
- -energy resolution parameter is added from after the fact

^{228}Th Calibration


many forward scatters

few back-to-back

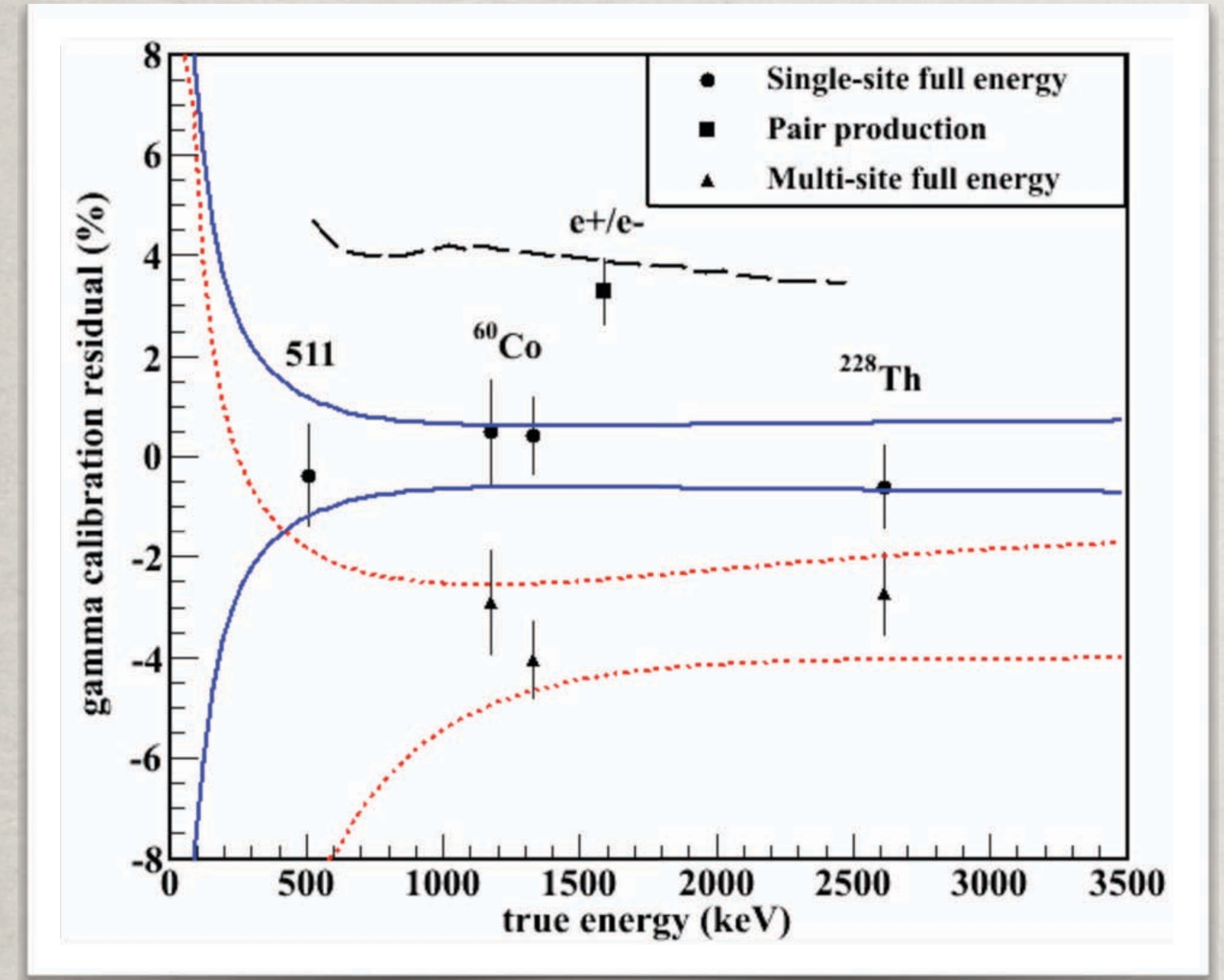


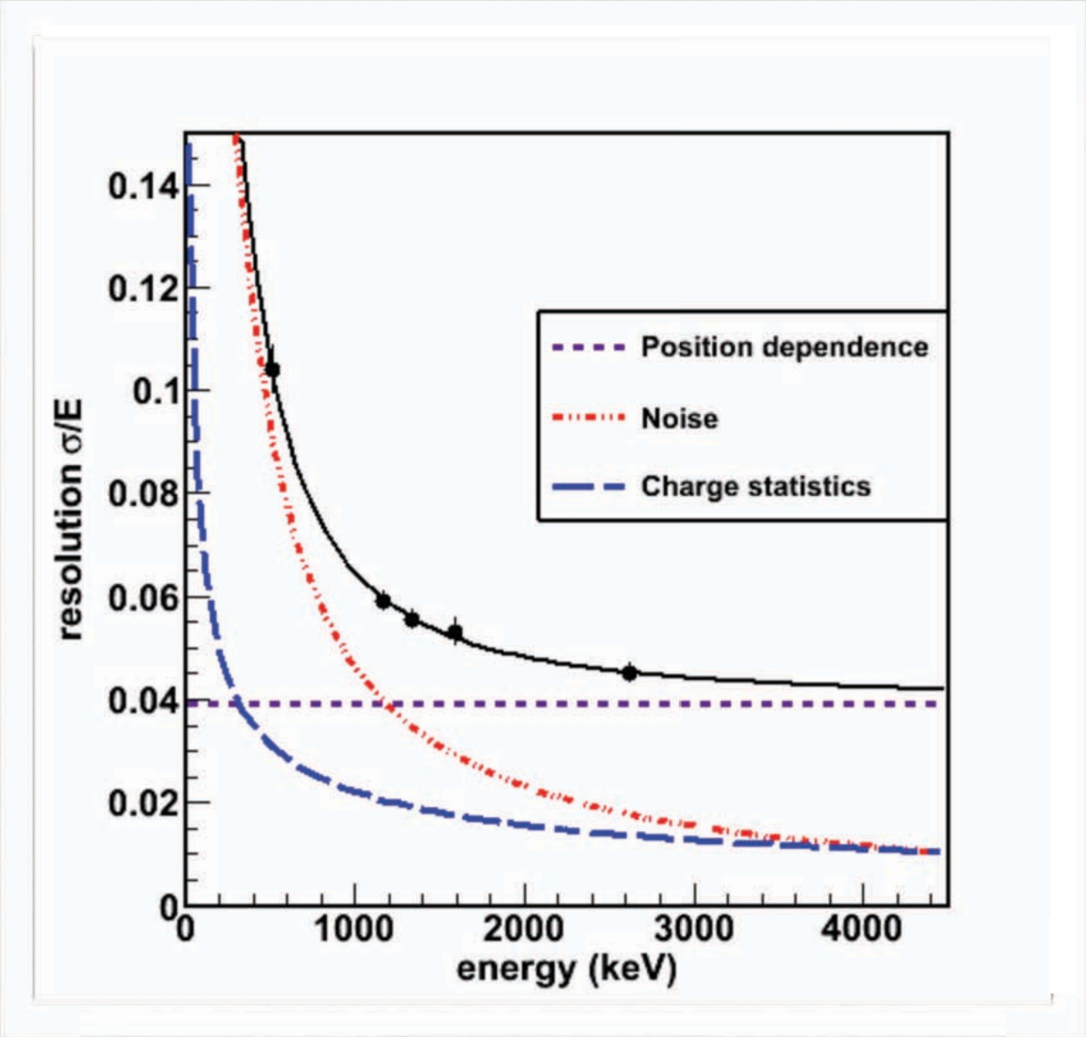


Identifying 3-site events from pair-production and annihilation provides 2 extra charge calibration peaks

- -511 keV gammas are our lowest energy calibration sources
- -1592 keV pair production very similar topology to ββ decays

ENERGY CALIBRATIONS





After purity correction, calibrated single and multiple cluster peaks across energy region of interest (511 to 2615 keV)

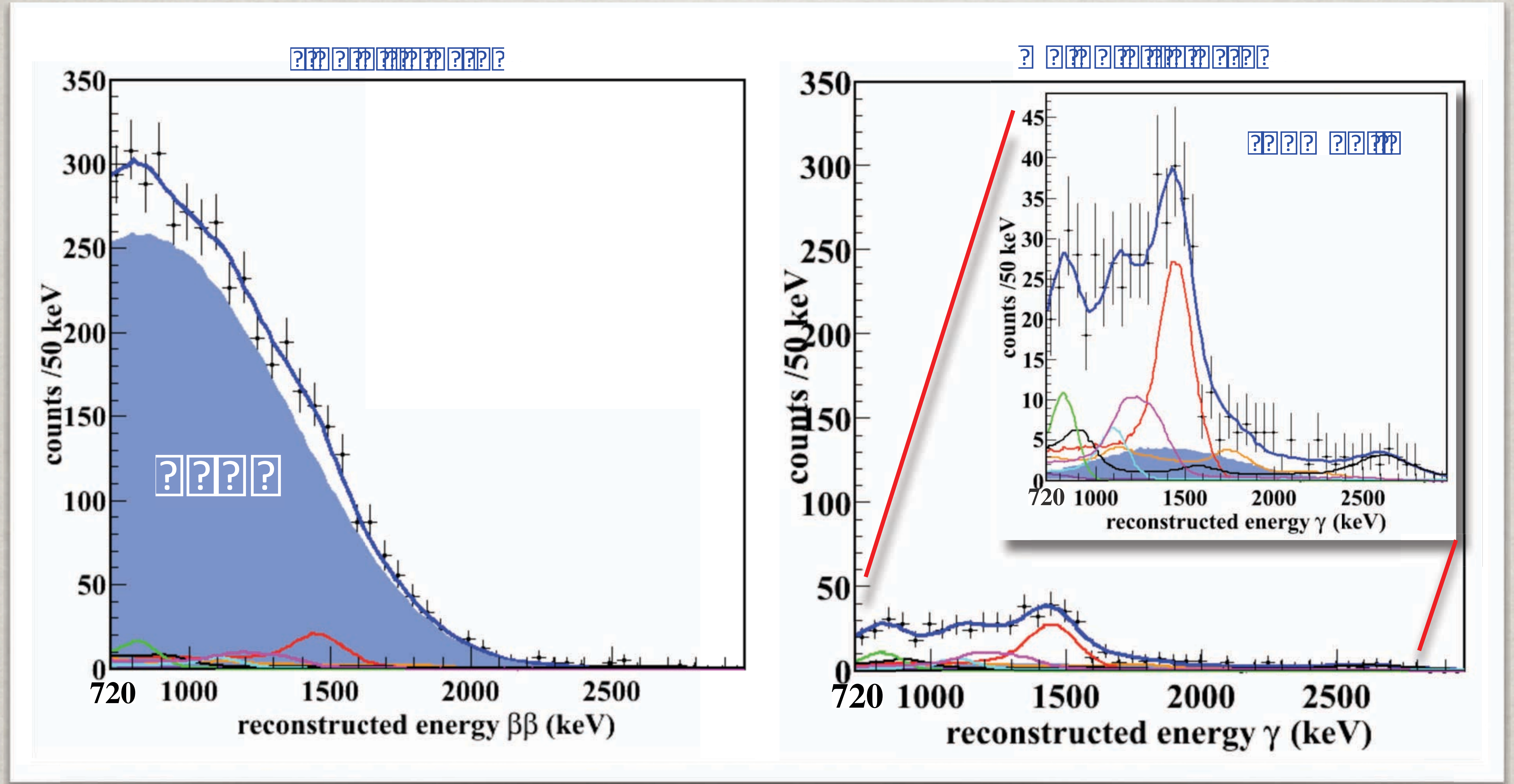
-uncertainty bands are systematic

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.

Low-background spectra



31 live-days of data

63 kg active mass

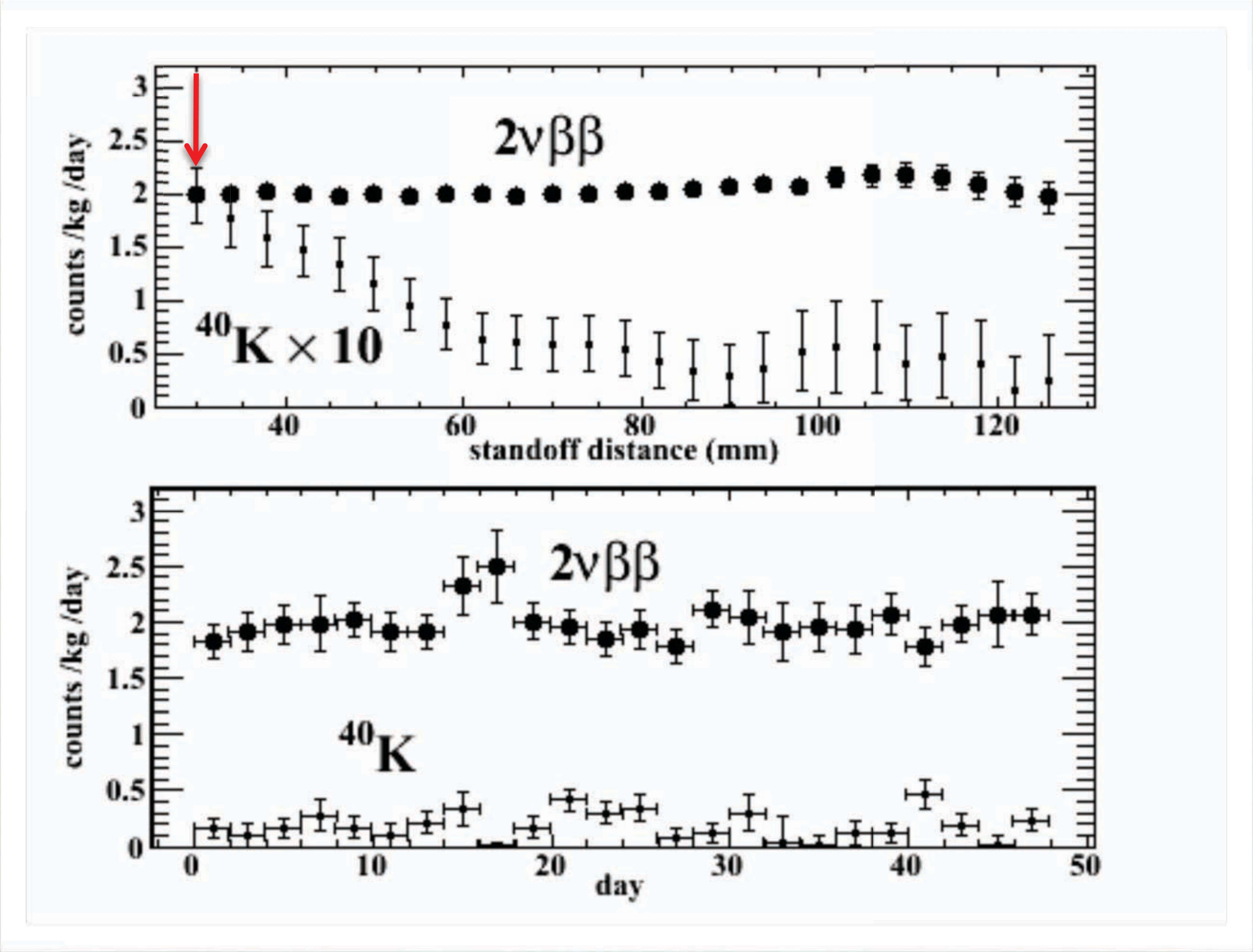
Signal / Background ratio 10:1

-as good as 40:1 for some extreme fiducial volume cuts

$T_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) yr (± 0.21 sys)

[PRL 107 (2011) 212501]

LOW-BACKGROUND SPECTRA



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

Also constant in time

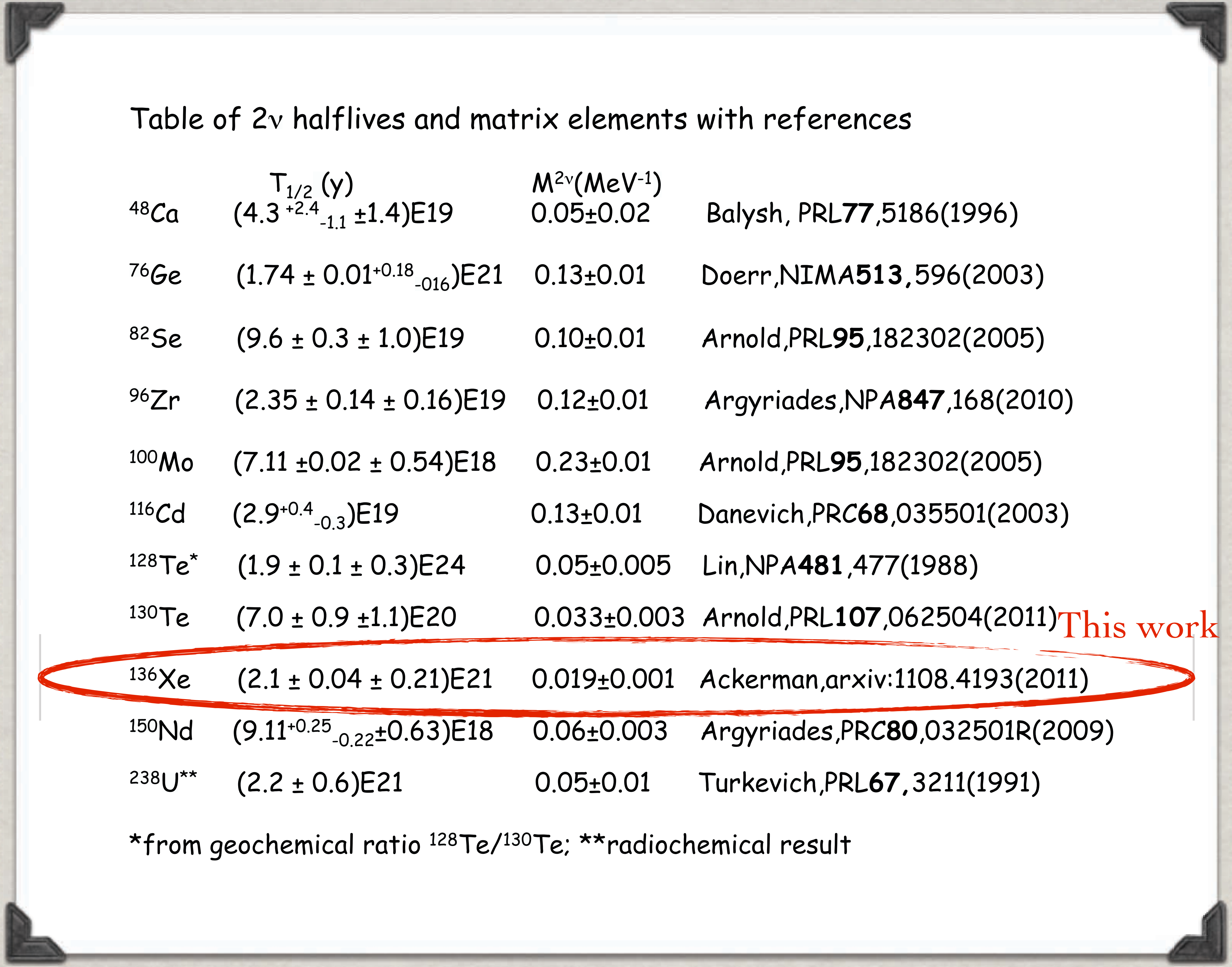


Table of 2ν halflives and matrix elements with references

	$T_{1/2}$ (y)	$M^{2\nu}(\mathrm{MeV}^{-1})$	
^{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)

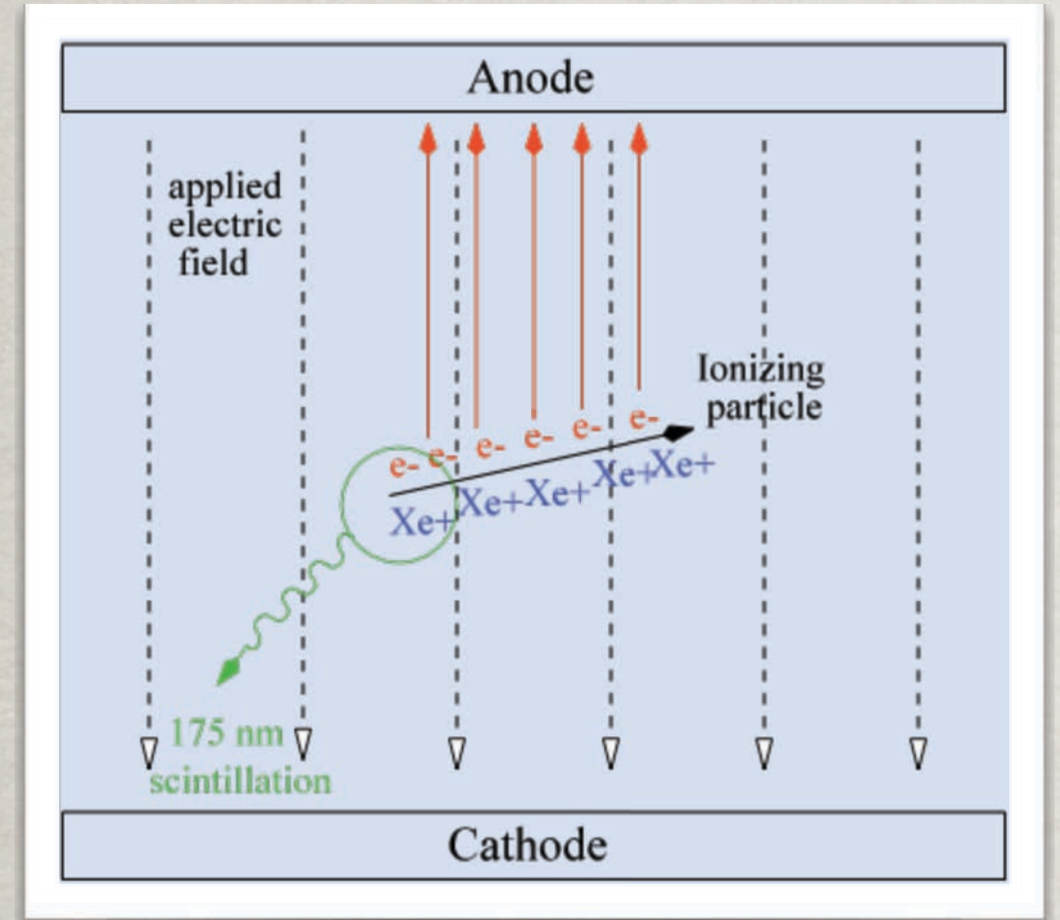
This work

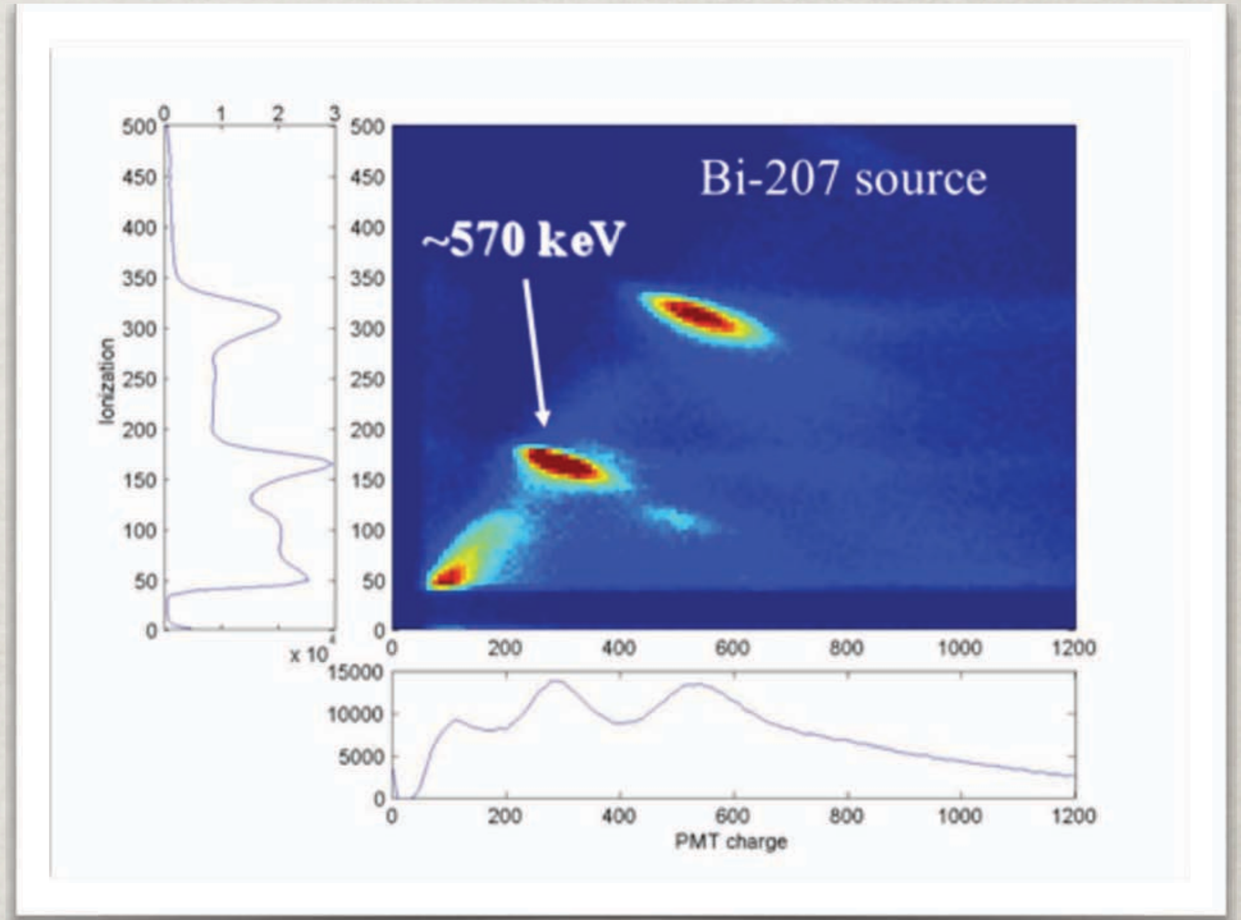
*from geochemical ratio ^{128}Te/^{130}Te; **radiochemical result

Significantly shorter than previous limits reported:
$T_{1/2} > 1.0 \cdot 10^{22}$ yr (90% C.L.) (R. Bernabei *et al*. Phys. Lett. B 546 (2002) 23)

and $T_{1/2} > 8.5 \cdot 10^{21}$ yr (90% C.L.) (Yu. M. Gavriljuk *et al.*, Phys. Atom. Nucl. 69 (2006) 2129)

WHAT'S NEXT: 0νββ WITH ANTI-CORRELATION





When ionizing radiation enters liquid xenon, it creates many Xe$^+$ and e$^-$ pairs and Xe*, some of the Xe$^+$ and Xe* undergo recombination and give off 175nm VUV photons or heat.

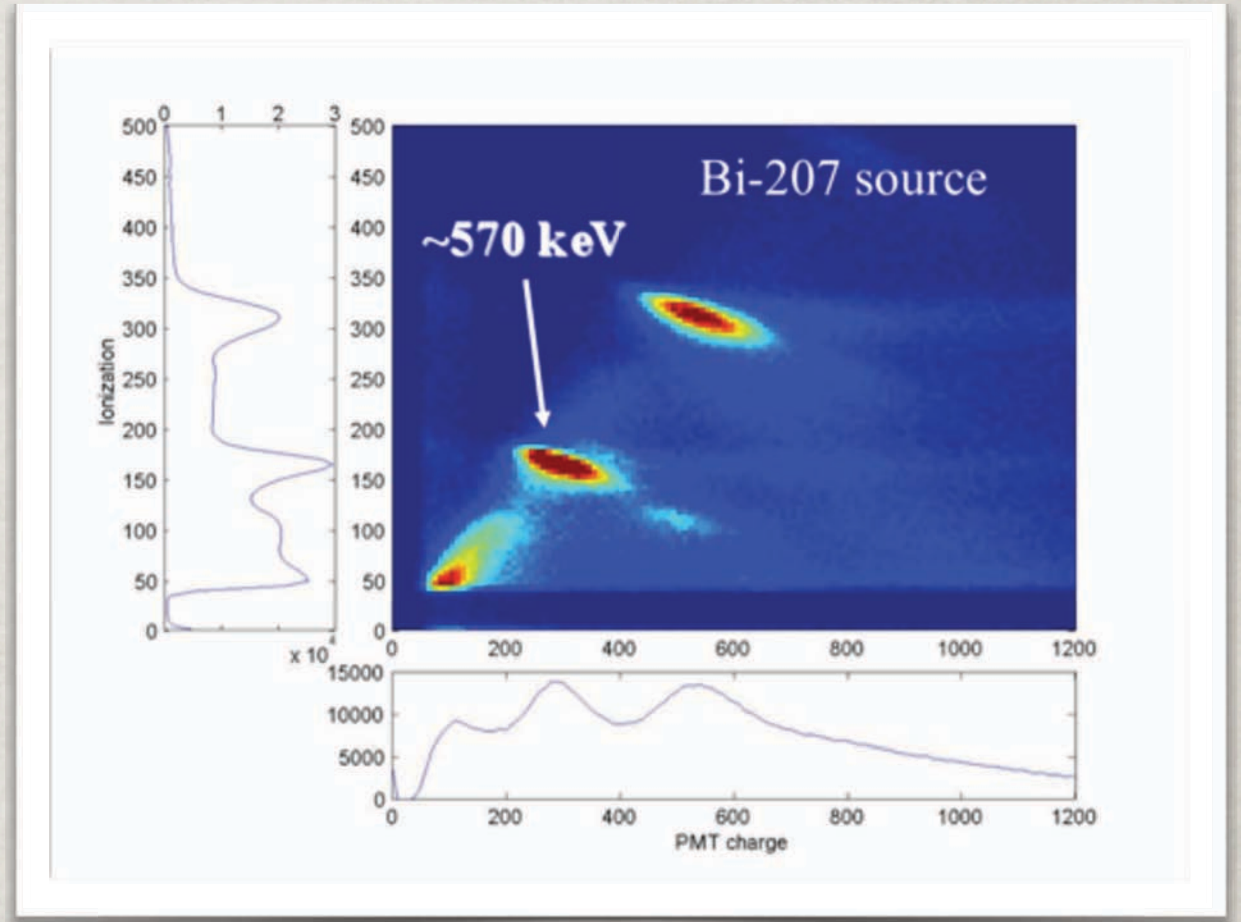
Ionization alone: 3.8% @ 570 keV or 1.8 % @ Q(ββ)

Ionization & Scintillation: 3.0% @ 570 keV or 1.4 % @ Q(ββ)

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

WHAT’S NEXT: 0νββ WITH ANTI-CORRELATION

- **New EXO-200 results**
- **0νββ**
- **More precise 2νββ**
- **Plus some extra-curricular physics**
  - **Search for Majoron**
  - **Nucleon decay into invisible channels**
  - **Pauli Exclusion Principle Violation**
  - **Charge Non-conservation**
  - **Cute light WIMP search with spare EXO APDs**



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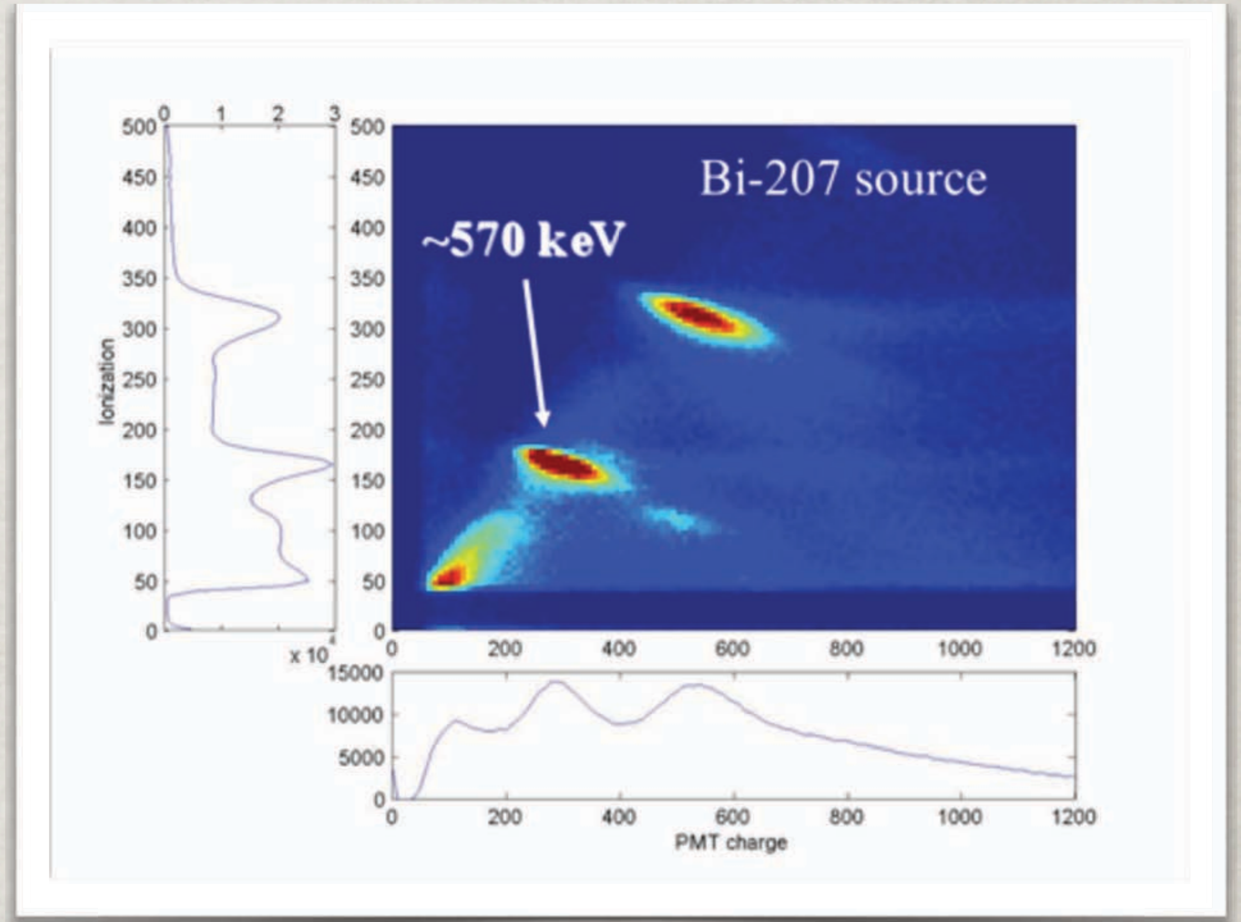

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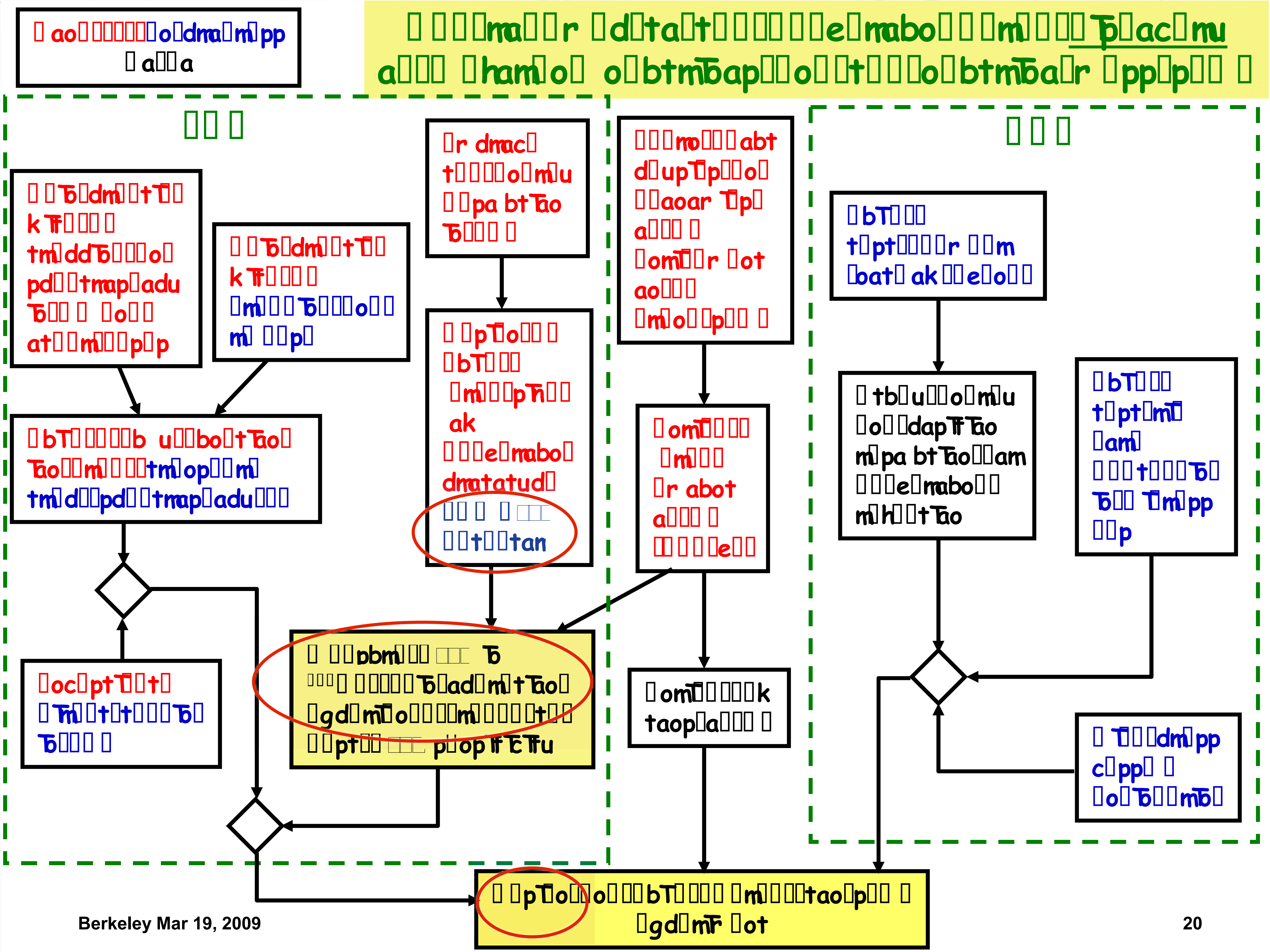
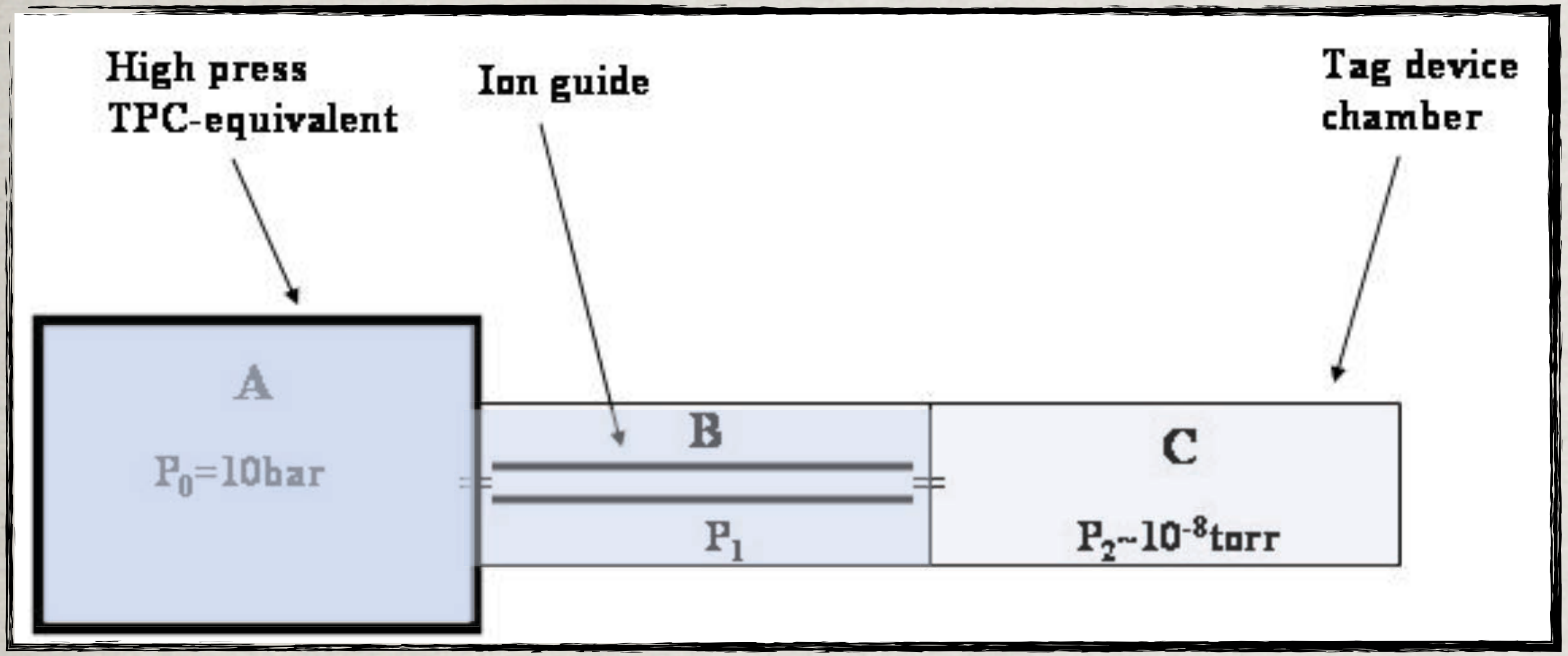
E.Conti et al., *Phys. Rev.* B **68** 054201 (2003)

AND AFTER THAT?
FULL SCALE EXO

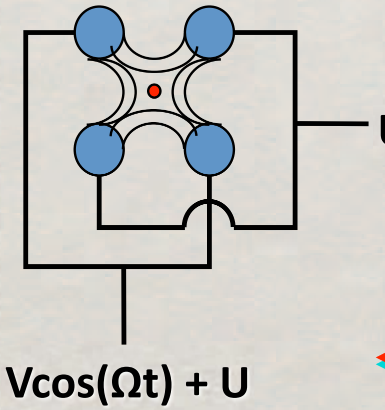


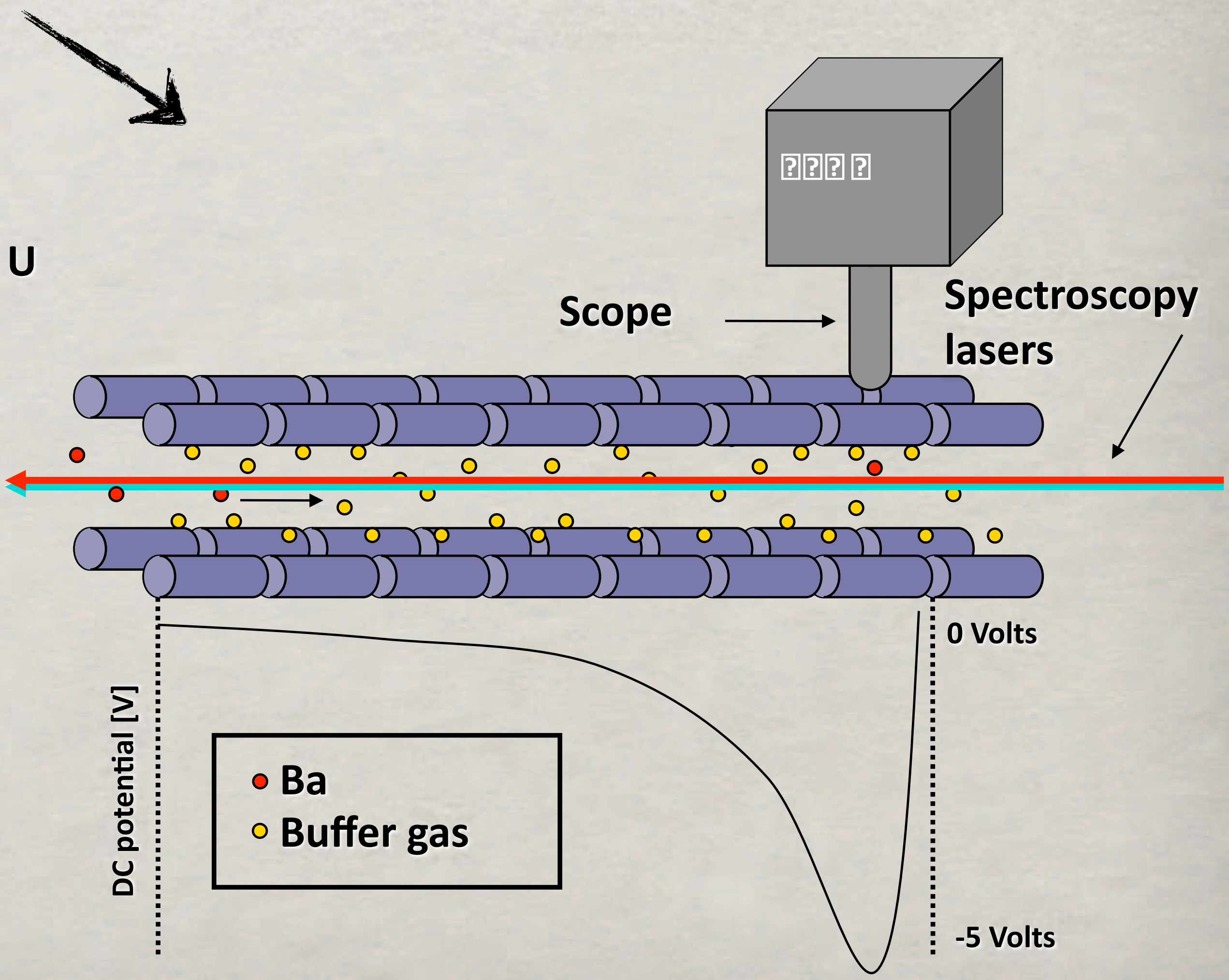
EXAMPLE: GAS-EXO BARIUM TRANSFER AND TAGGING

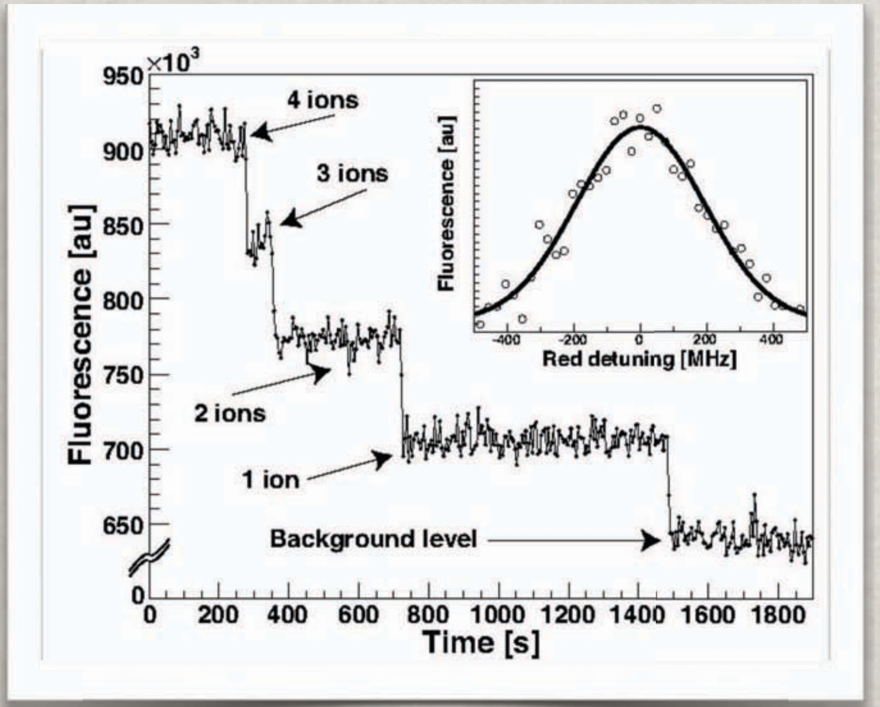


Transfer to RF Paul Trap:
single ion detection

Ba^+

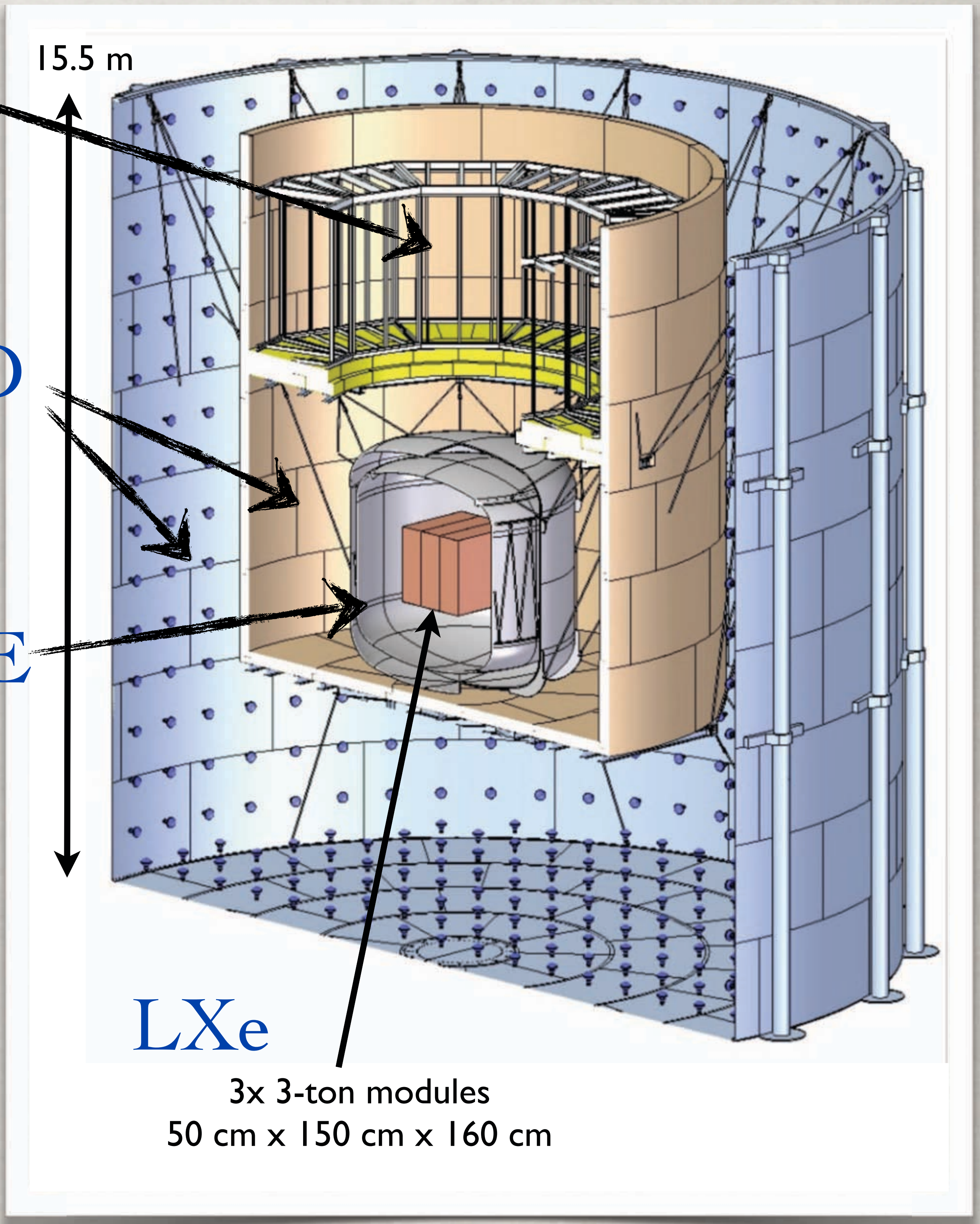




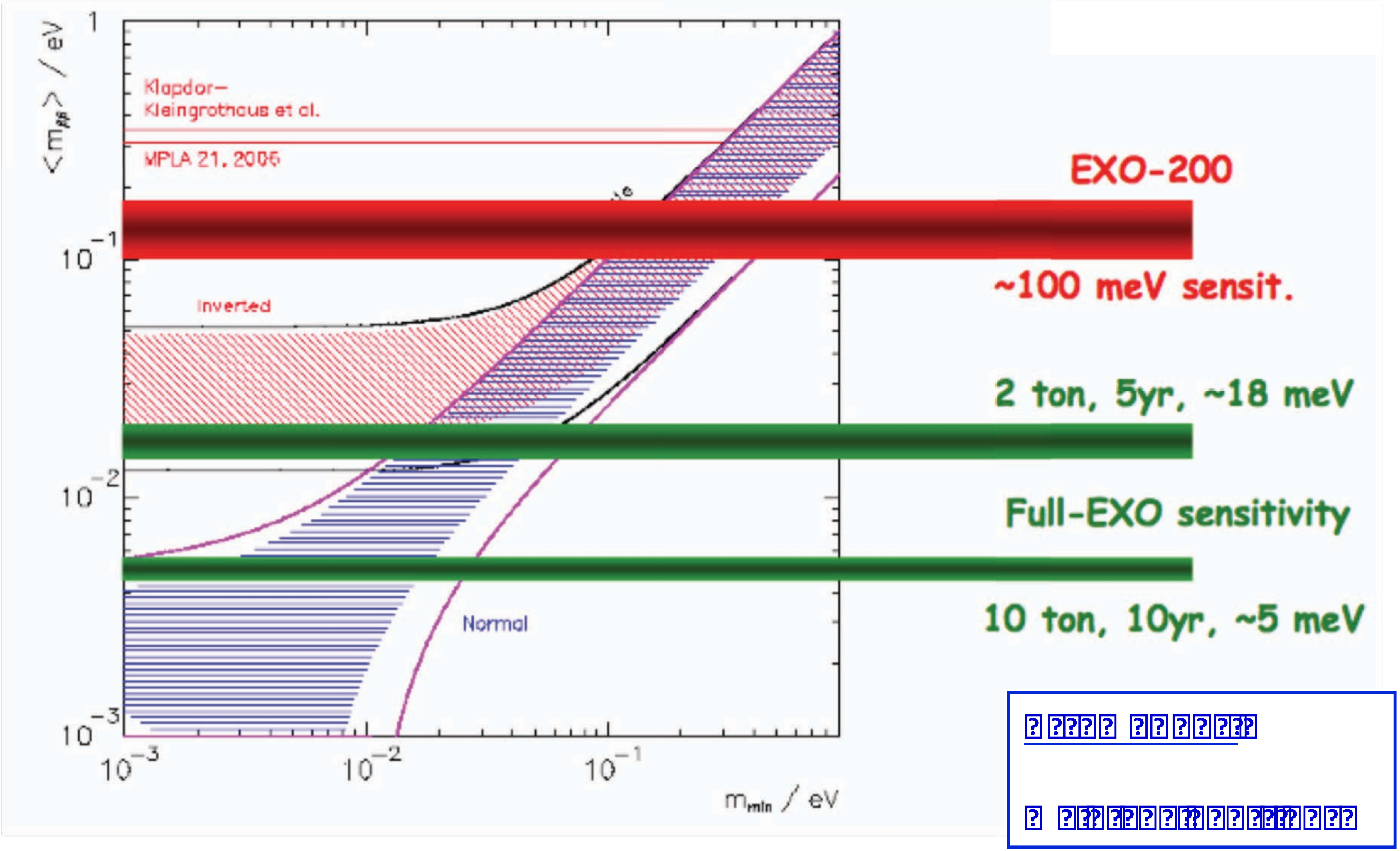


EXO (2-10 TON)

- Simulating different shielding configurations from this baseline
- Next: include gas phase concepts
- Goal: only backgrounds from 2νββ



EXO SENSITIVITY



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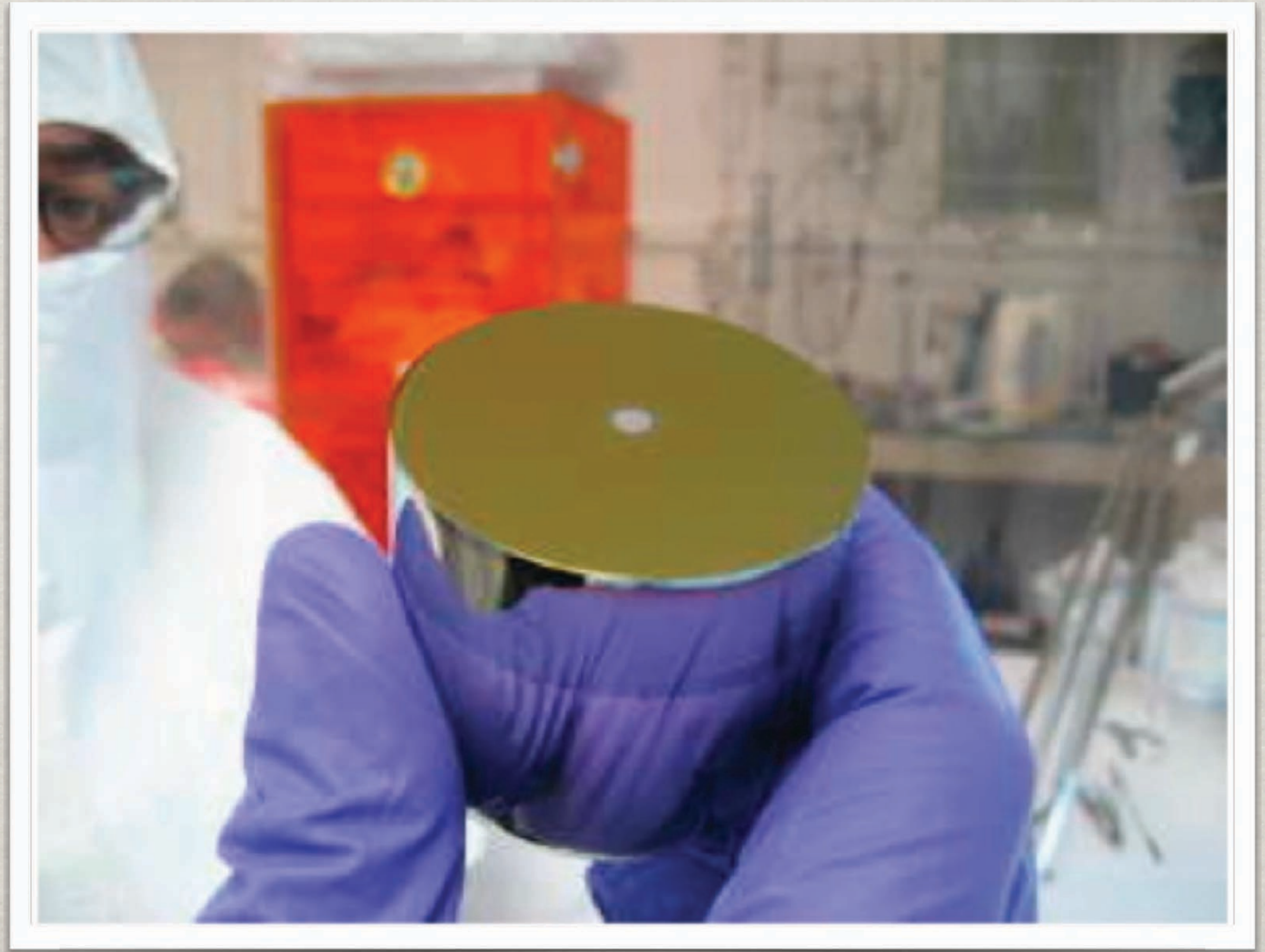
EXO SUMMARY

- All important EXO-200 subsystems working
- Low background running with enriched xenon already producing physics results
- $T_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) yr (± 0.21 sys) [PRL 107 (2011) 212501]
- Stay tuned: improved energy resolution & upgraded pattern recognition

A CoGeNT transition:

AN EXAMPLE OF THE ROLE OF DETECTOR DEVELOPMENT IN LOW BACKGROUND PHYSICS



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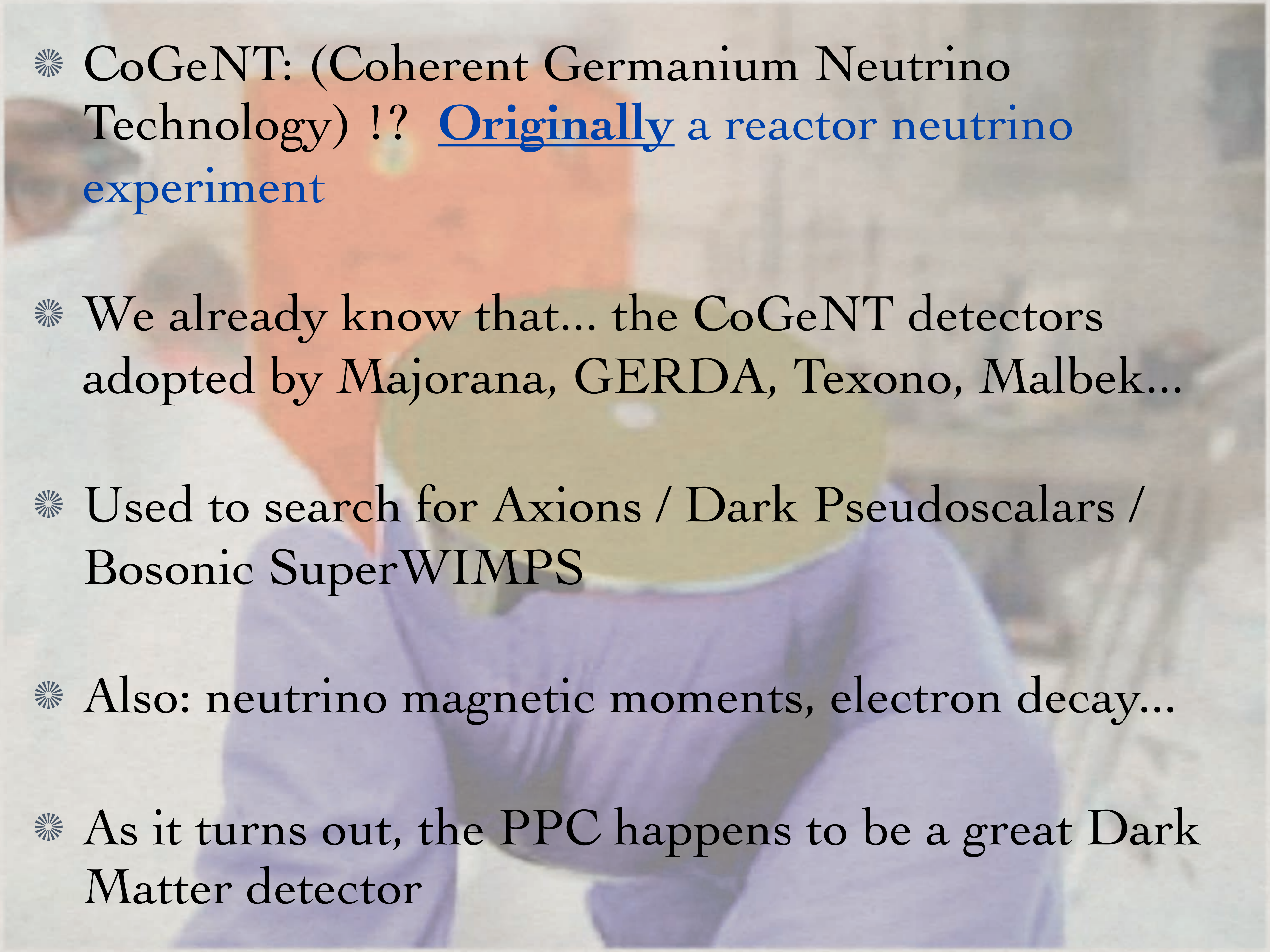


- CoGeNT: (Coherent Germanium Neutrino Technology) !? <u>**Originally**</u> a reactor neutrino experiment
- We already know that... the CoGeNT detectors adopted by Majorana, GERDA, Texono, Malbek...
- Used to search for Axions / Dark Pseudoscalars / Bosonic SuperWIMPS
- Also: neutrino magnetic moments, electron decay...
- As it turns out, the PPC happens to be a great Dark Matter detector

A Quick and Dirty Introduction to Dark Matter

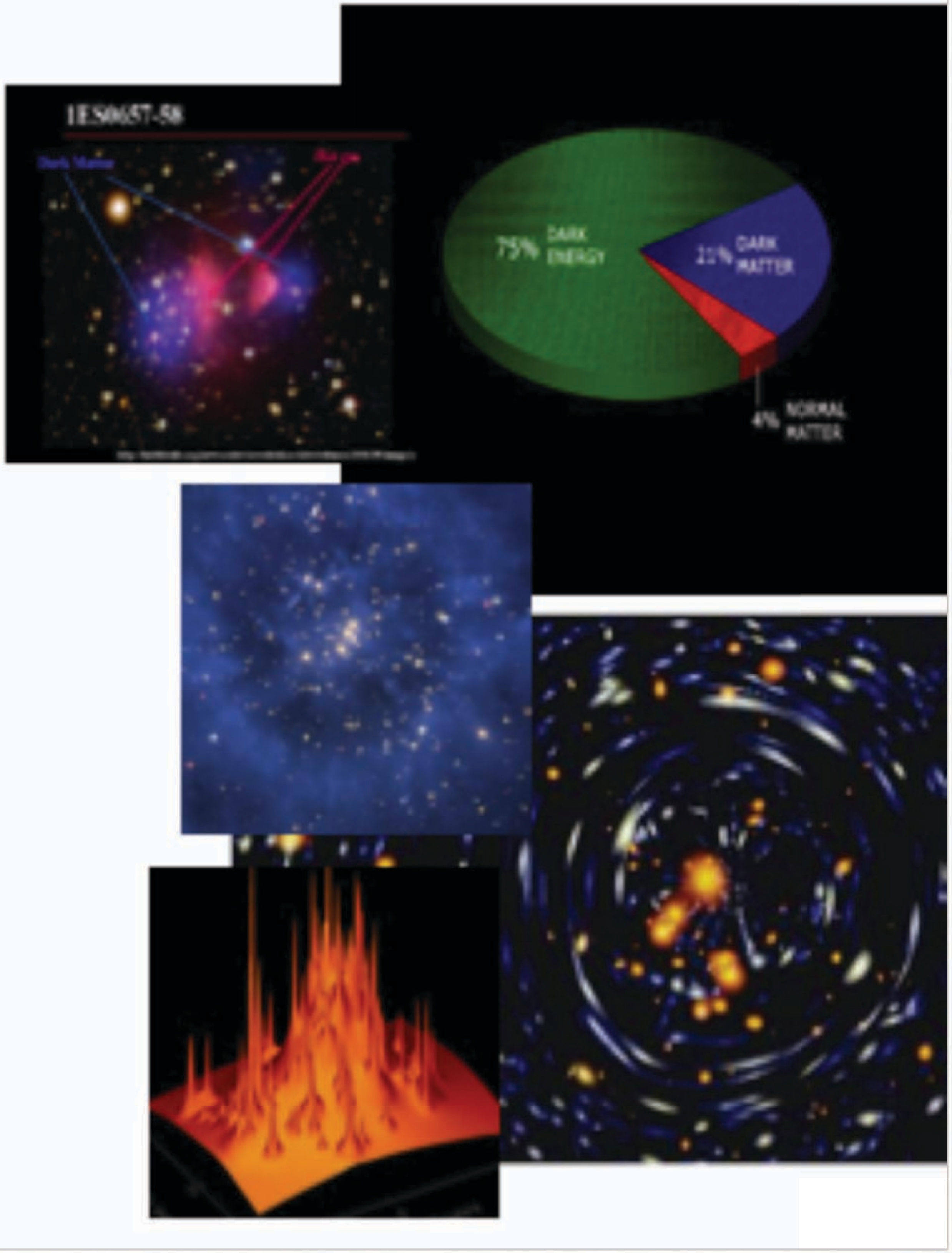
- Non-baryonic Galactic Dark Matter close to a paradigm (certainly in the minds of many), but yet to be detected.

- ~20-30% Cold (non-relativistic) DM presently favored

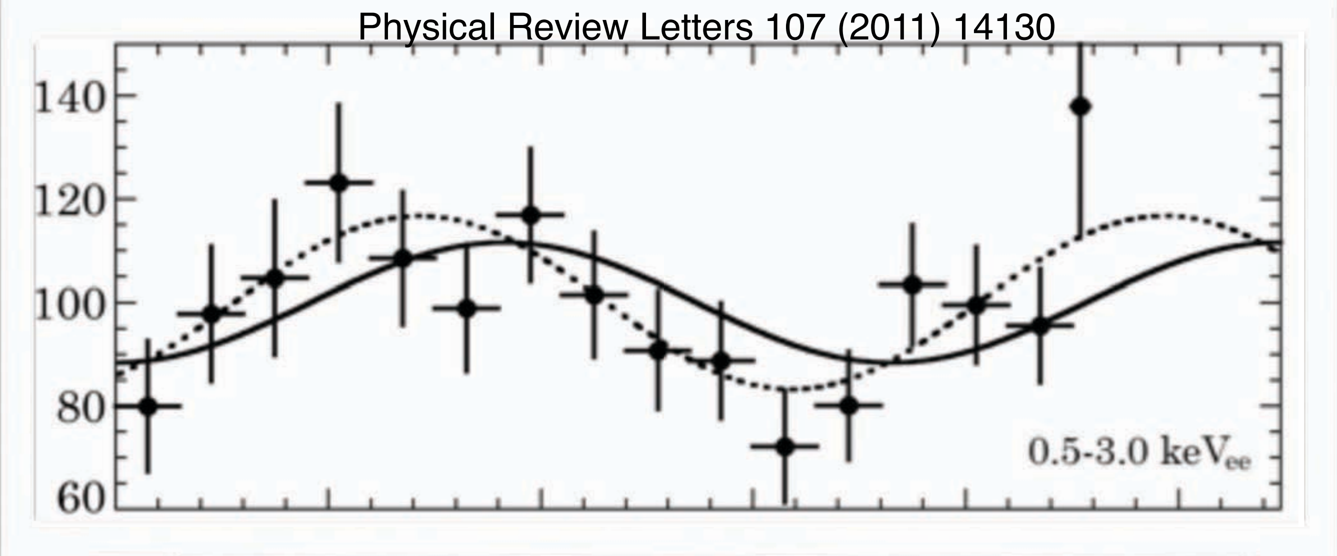
- Evidence: Coma cluster, galactic rotation curves, gravitational lensing, bullet cluster, CMB measurements

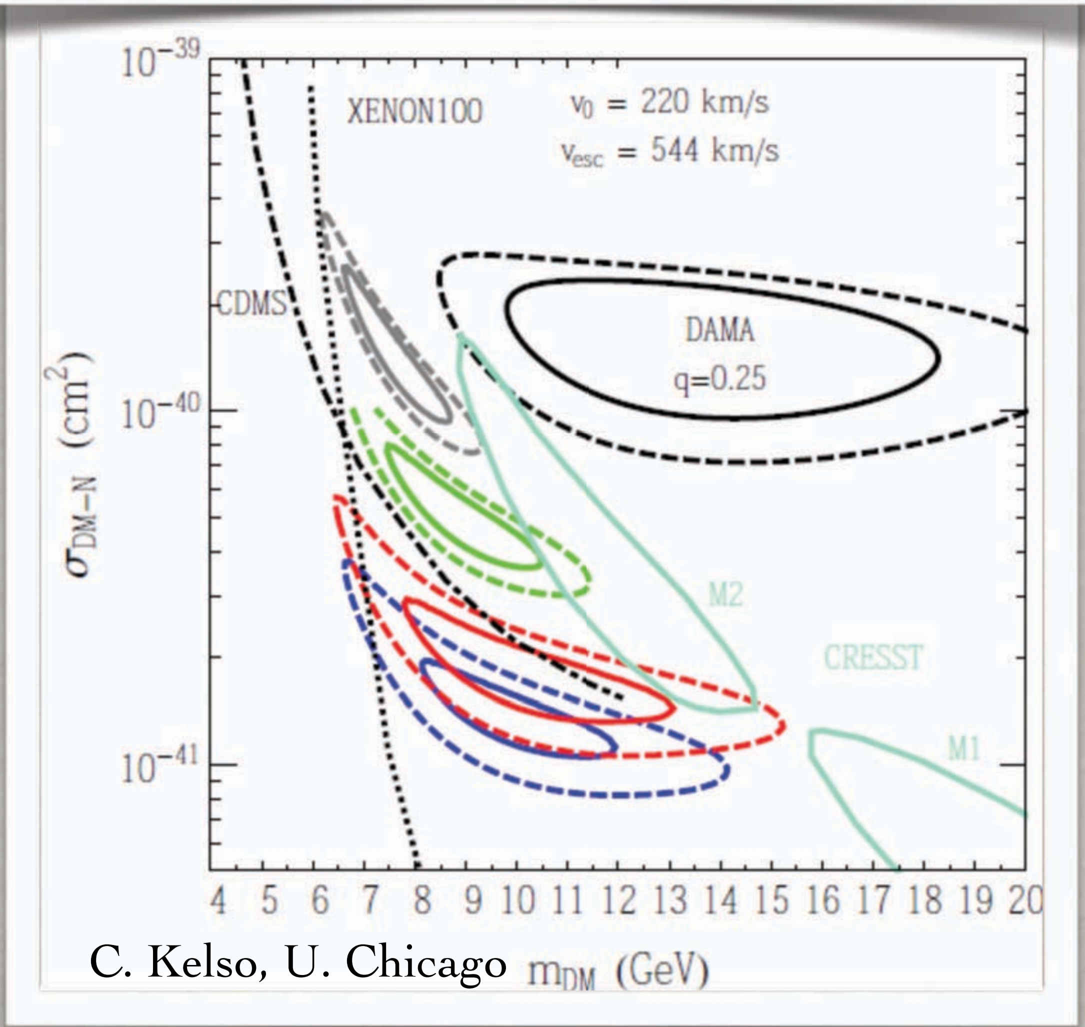
- Cautious strategy: start by looking first for non-ad hoc particle candidates, i.e., those already invoked by particle theories (e.g., neutralino <-> MSSM, axions <-> strong CP problem)

- WIMPs: dominant interaction via low-energy nuclear elastic scattering, expected rates << 1 per kg of target per day in keV region. (local ρ~0.3-0.4 GeV/cm^3, <v>~2-300 km/s, σ ~< 10^{-44} cm^2). Supersymmetric WIMPS can have rates as low as 1 recoil/ton/yr!



CoGeNT (DM) sees hints of an annual modulation


Physical Review Letters 107 (2011) 14130



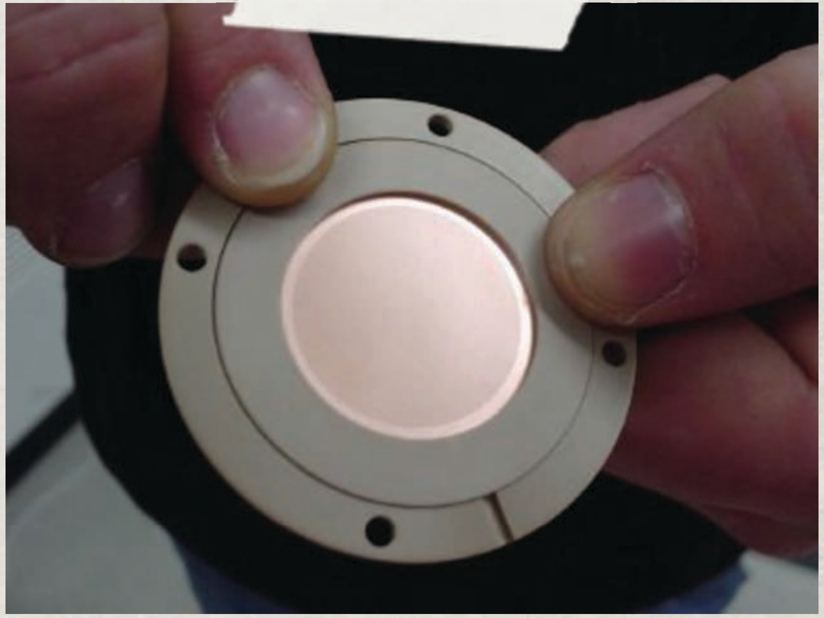
C. Kelso, U. Chicago

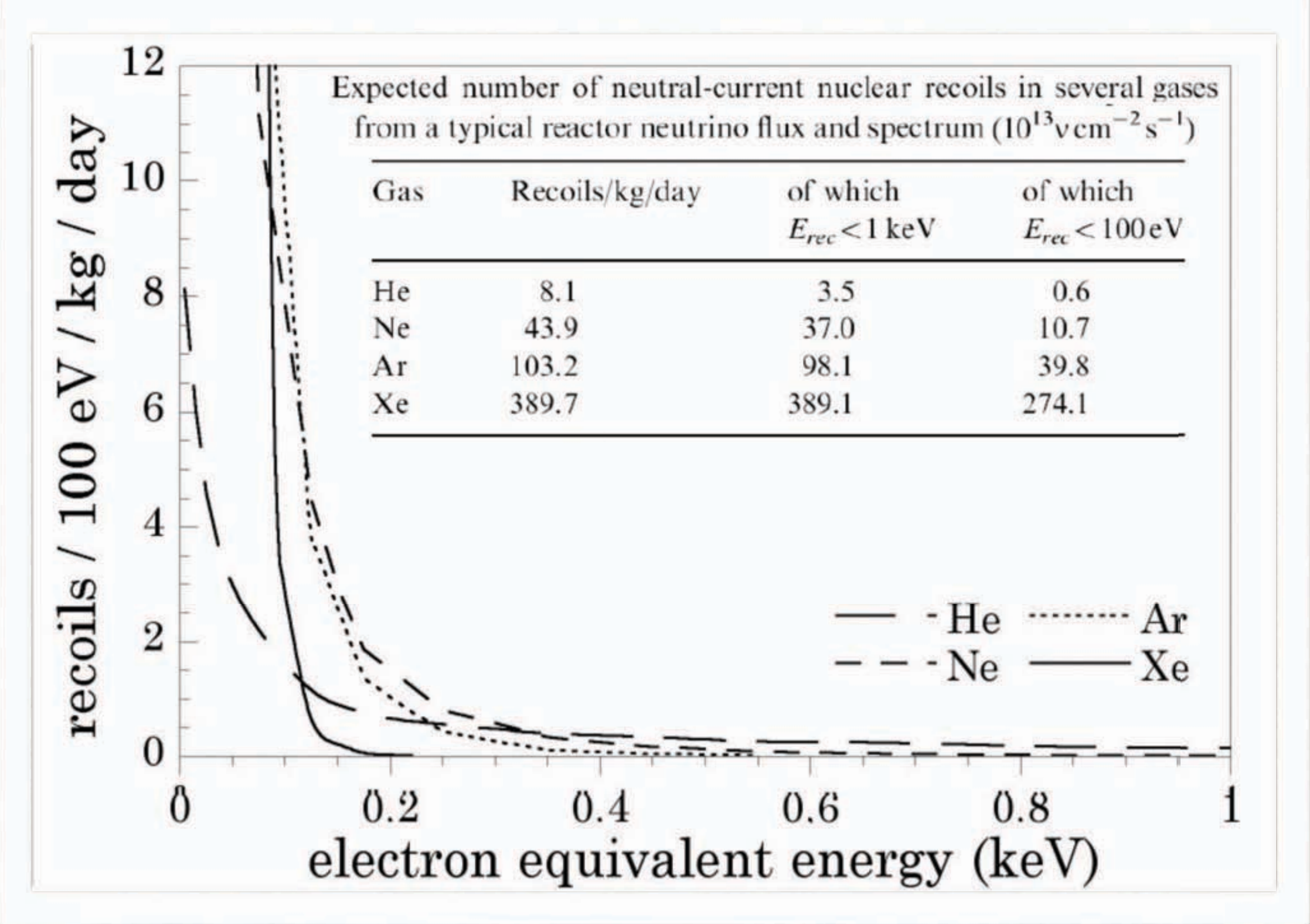
- We have a “light WIMP crisis”: 3 potential experimental signatures all over the place. (DAMA, CoGeNT, CRESST)
- Plus: lots of detector response, astrophysical & WIMP interaction uncertainties. Reconciliation is a mess.

Solution: revert to old CoGeNT concept ca. 2003

MAGνeT

- Gas detectors (years of experience in HEP)
- CoGeNT-like threshold (sub keV)
- CoGeNT-like mass (~ kg)
- Build with EXO-like Purity and Backgrounds

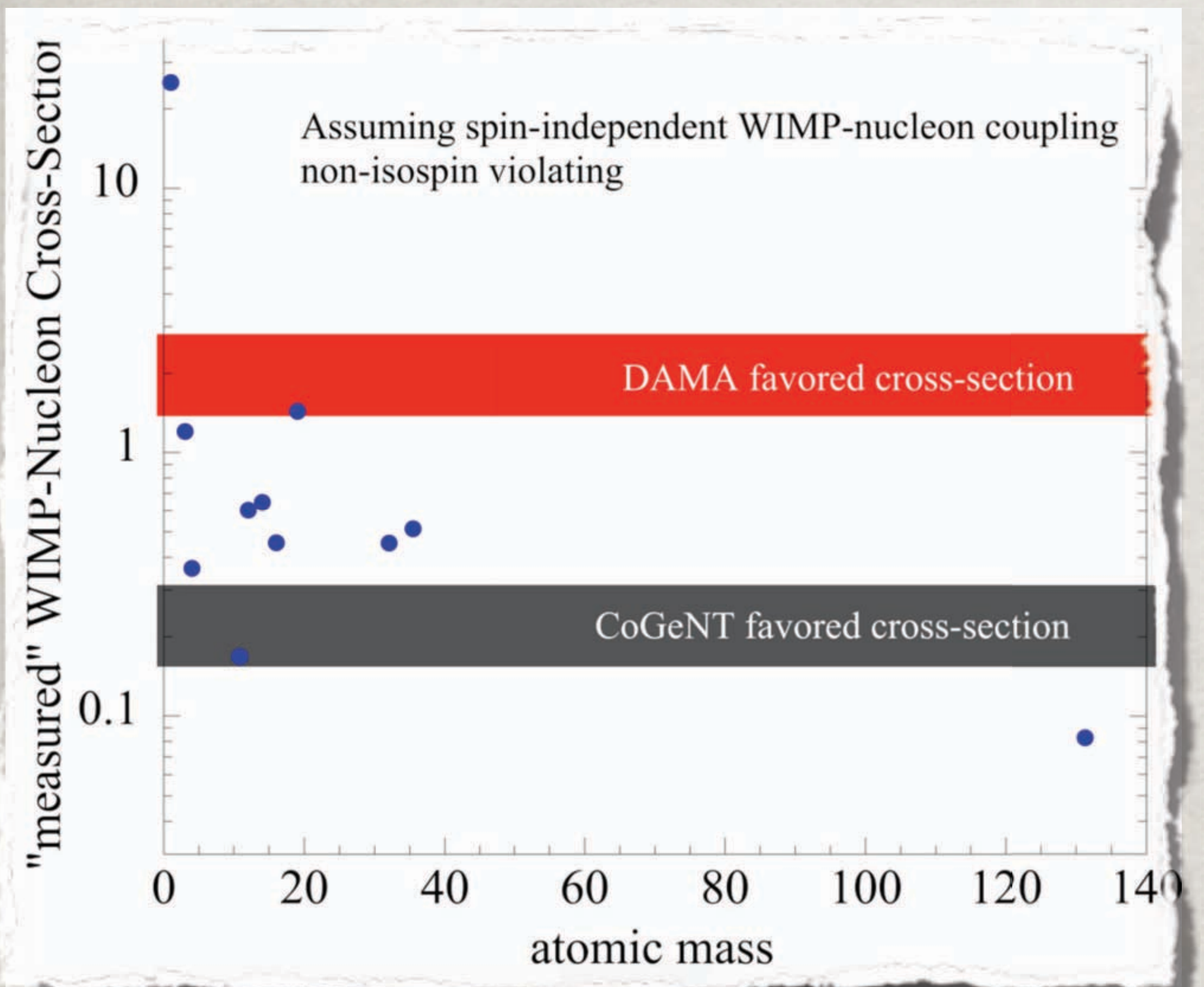




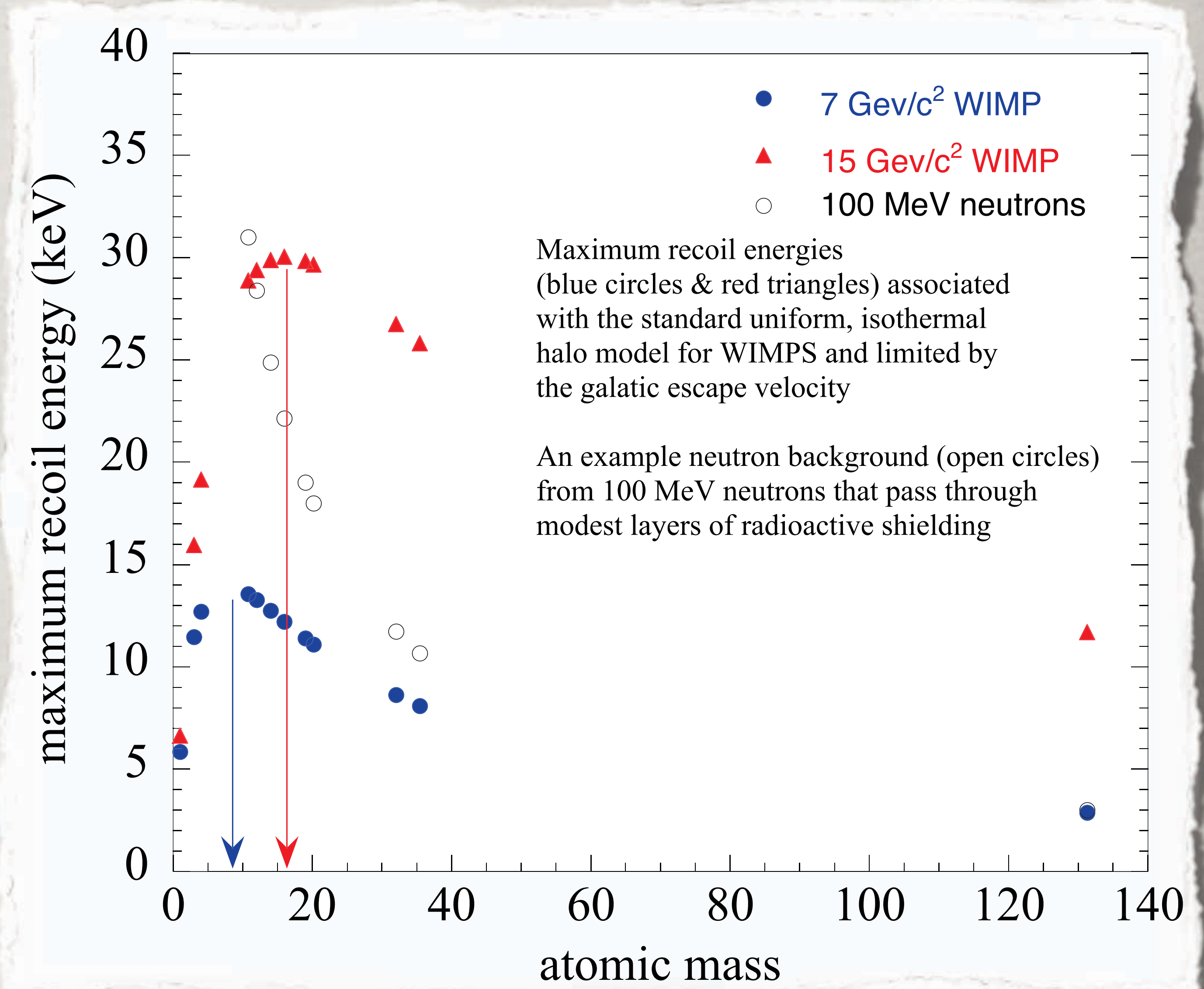
Expected number of neutral-current nuclear recoils in several gases from a typical reactor neutrino flux and spectrum ($10^{13}\nu\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)

Gas	Recoils/kg/day	of which $E_{rec} < 1$ keV	of which $E_{rec} < 100$ eV
He	8.1	3.5	0.6
Ne	43.9	37.0	10.7
Ar	103.2	98.1	39.8
Xe	389.7	389.1	274.1

MAGνeT (WIMPS)



Assuming spin-independent WIMP-nucleon coupling
non-isospin violating



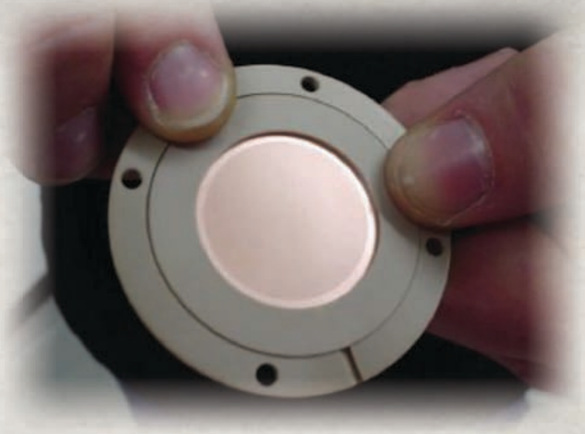
Maximum recoil energies
(blue circles & red triangles) associated
with the standard uniform, isothermal
halo model for WIMPS and limited by
the galatic escape velocity

An example neutron background (open circles)
from 100 MeV neutrons that pass through
modest layers of radioactive shielding

Cross-section cancelations can occur if we have isospin-violating WIMP interactions.

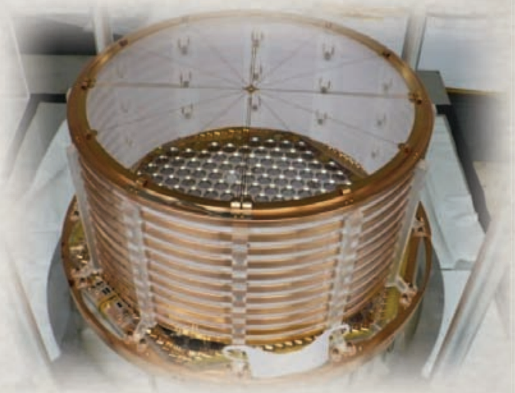
non-thermal DM halo's/ streams-> larger E_{max}

MAGνeT



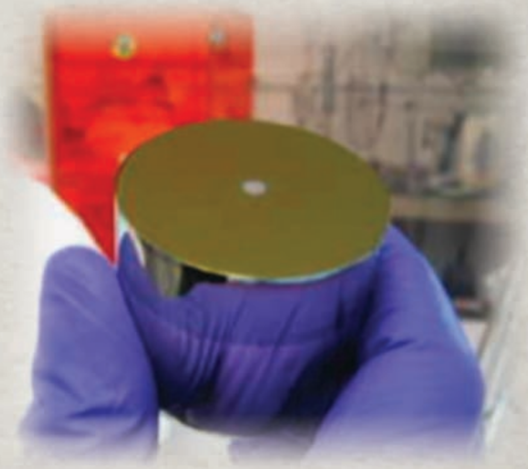
- Aim is to resolve the "light WIMP crisis"
- Low background gas detector technology *synergistic* with EXO-Gas.
- also: coherent neutrino-nucleus scattering
- also: neutrino magnetic moment search
- also: non-standard neutrino interactions (NSI)

Summary



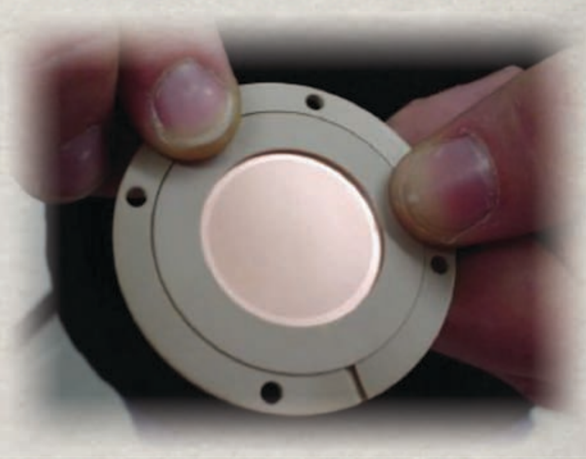
- EXO-200 producing great data. Stay tuned for more results!

- Full scale EXO moving forward: gas and liquid versions with Ba tagging



- CoGeNT continuing to take data

- MAGνeT concept. Synergistic work with both CoGeNT and EXO calibration facilities, low background techniques, low threshold experience, low Rn & electronegative techniques...



C.E. Aalseth,[1] P.S. Barbeau,[2] J. Colaresi,[3] J.I. Collar,[2] J. Diaz Leon,[4] J.E. Fast,[1] N. Fields,[2]
T.W. Hossbach,[1,2] M.E. Keillor,[1] J.D. Kephart,[1] A. Knecht,[4] M.S. Kos,[1] M.G. Marino,[4]
H.S. Miley,[1] M.L. Miller,[4] J.L. Orrell,[1] D.C. Radford,[5] J.F. Wilkerson,[6] and K.M. Yocum[3]
(CoGeNT Collaboration)

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[5]*Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[6]*Department of Physics and Astronomy, University of North Carolina, NC 27599, USA*

CoGeNT Collaboration

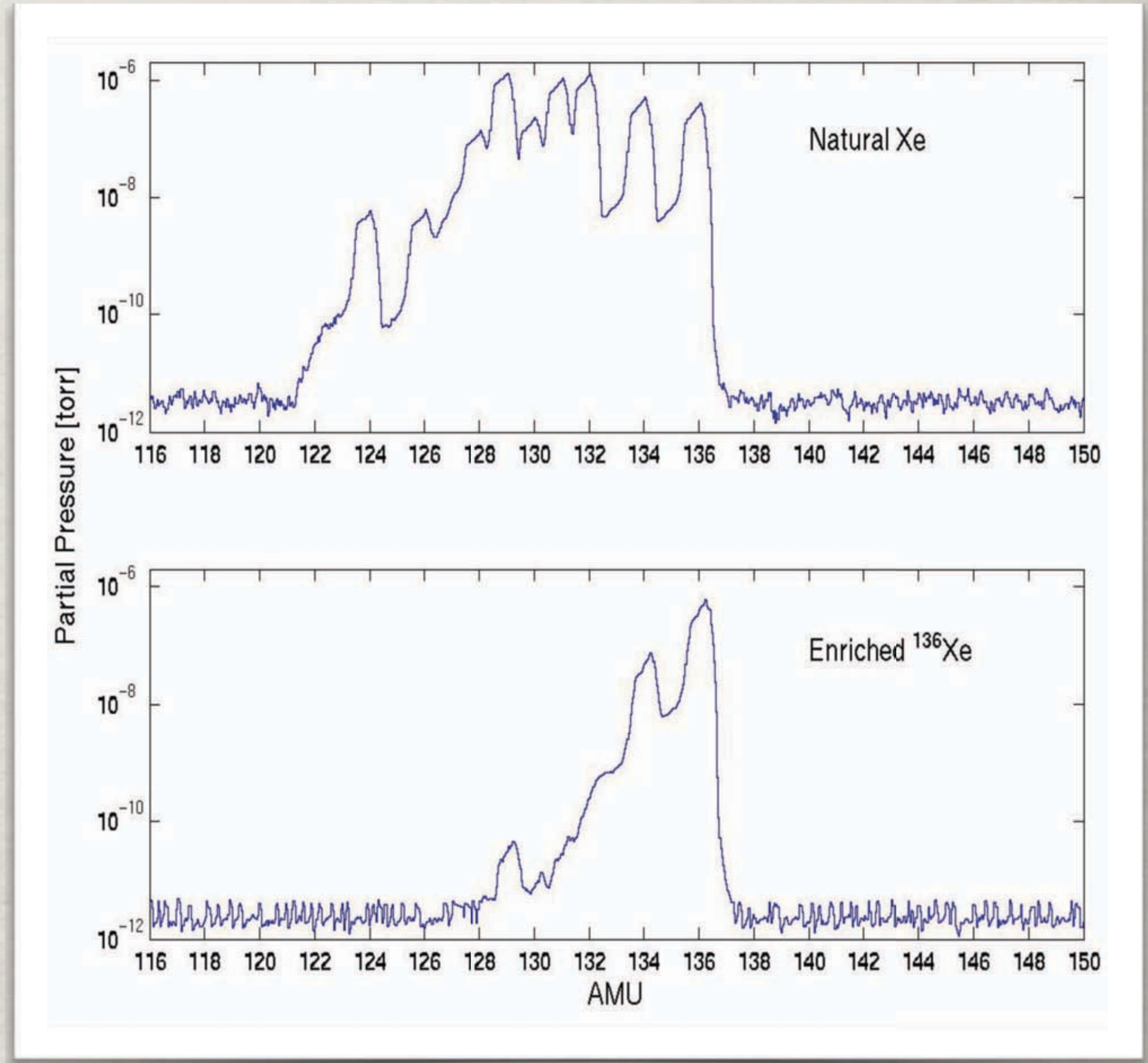
Backup Slides

PMNS NEUTRINO MIXING MATRIX

$$\begin{pmatrix} & & & & & {}^{-\ \delta} \\ - & - & {}^{\delta} & - & {}^{\delta} & \\ & - & {}^{\delta} \quad - & - & {}^{\delta} & \end{pmatrix}\begin{pmatrix} {}^{\alpha} & 3 & 3 \\ 3 & {}^{\alpha} & 3 \\ 3 & 3 & 4 \end{pmatrix}$$

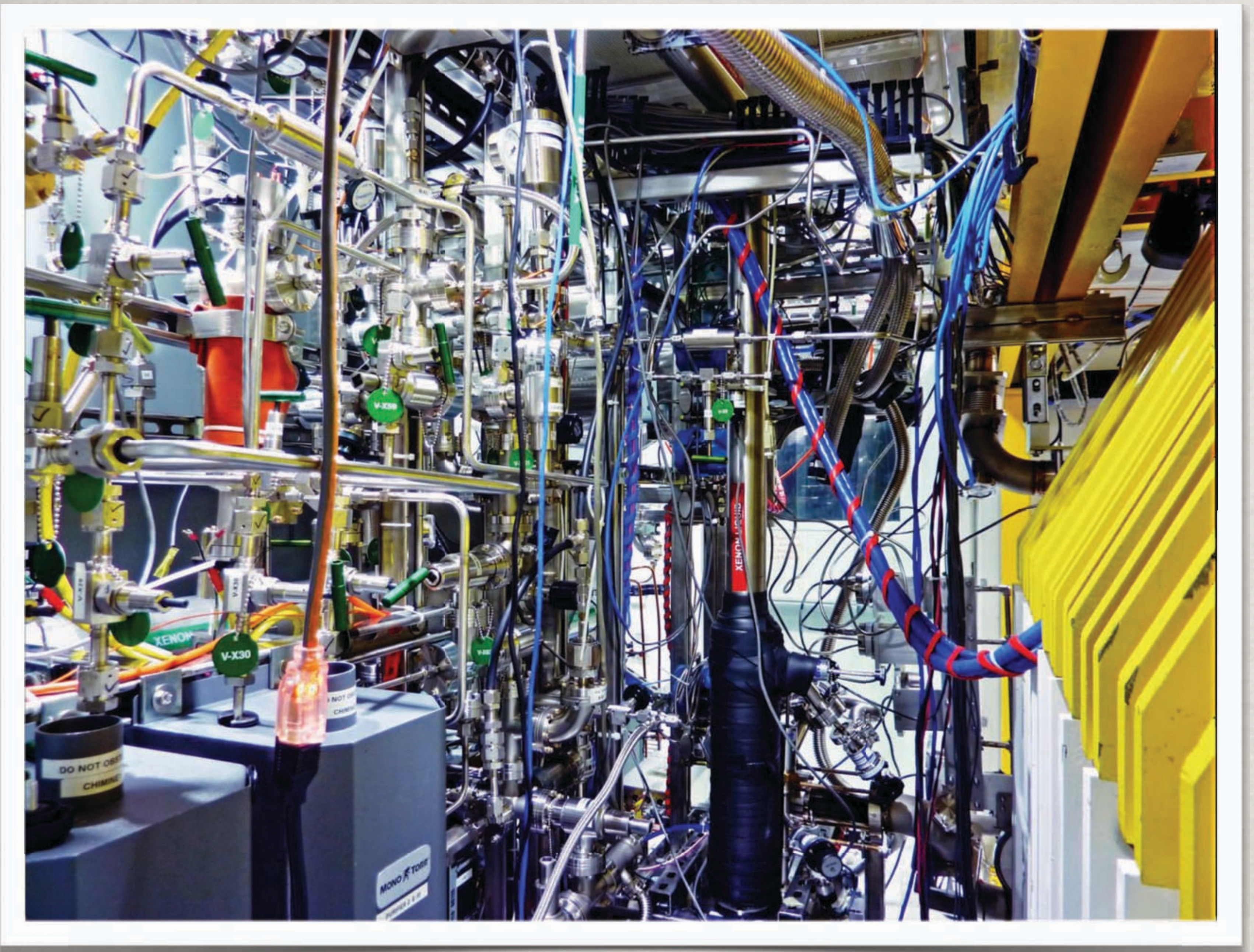
ENRICHED XE

Centrifuge facility in Russia



RGA mass scan of xenon samples

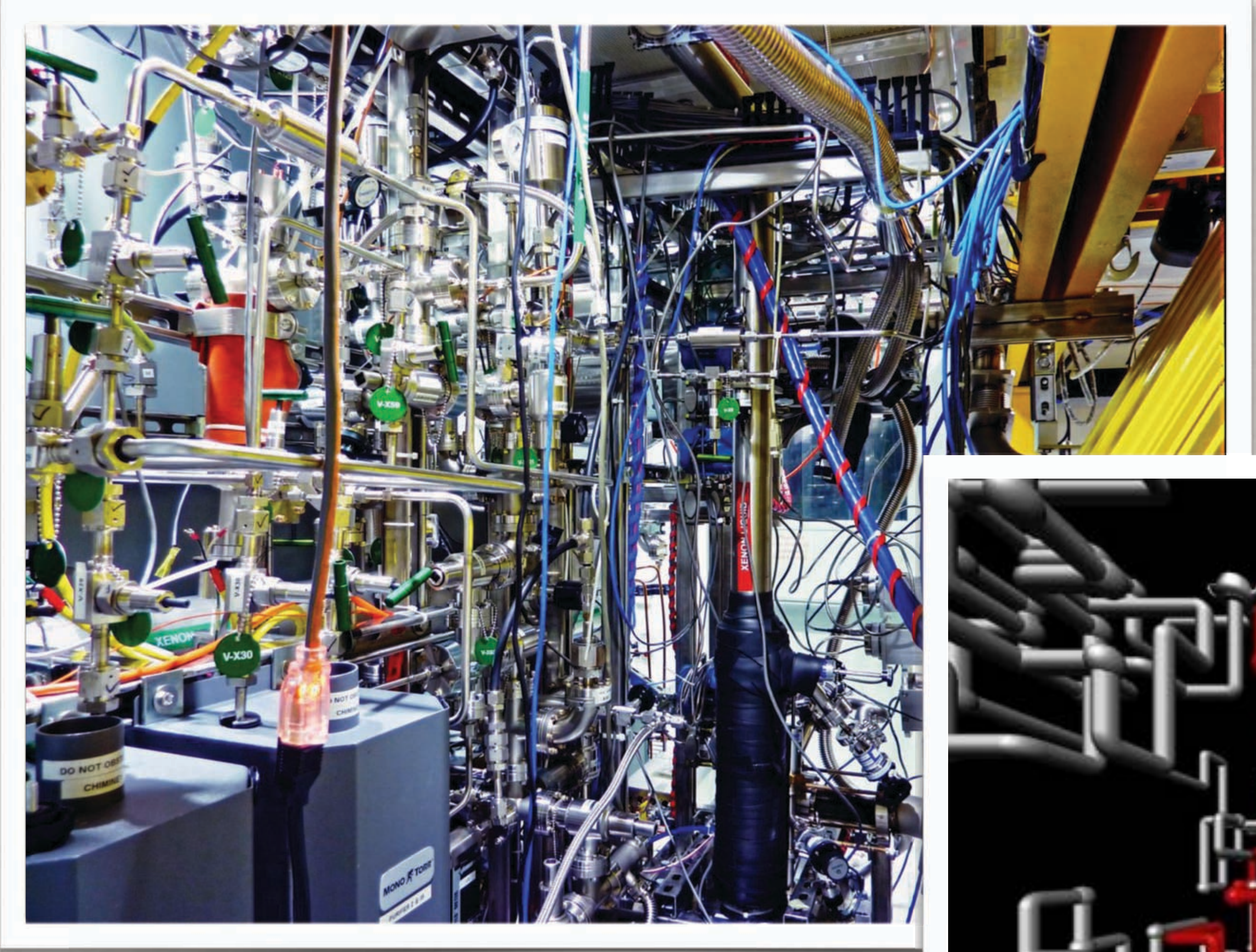
XENON SYSTEM



What does it take to maintain purity, control differential pressure, minimize Rn level, keep 200 kg enriched Xe safe, etc.

System probably looks very familiar

XENON SYSTEM

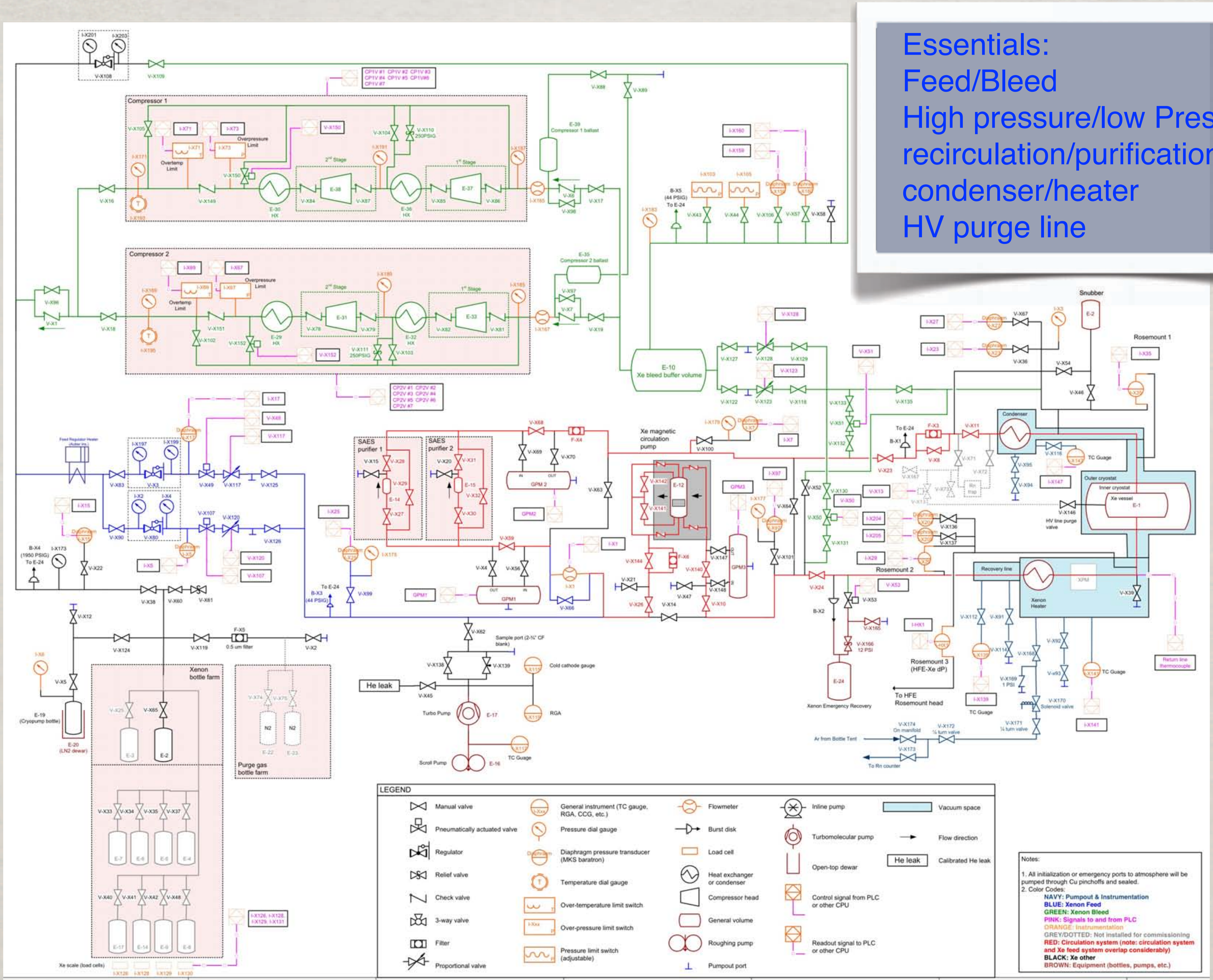


What does it take to maintain purity, control differential pressure, minimize Rn level, keep 200 kg enriched Xe safe, etc.

System probably looks very familiar

XENON SYSTEM

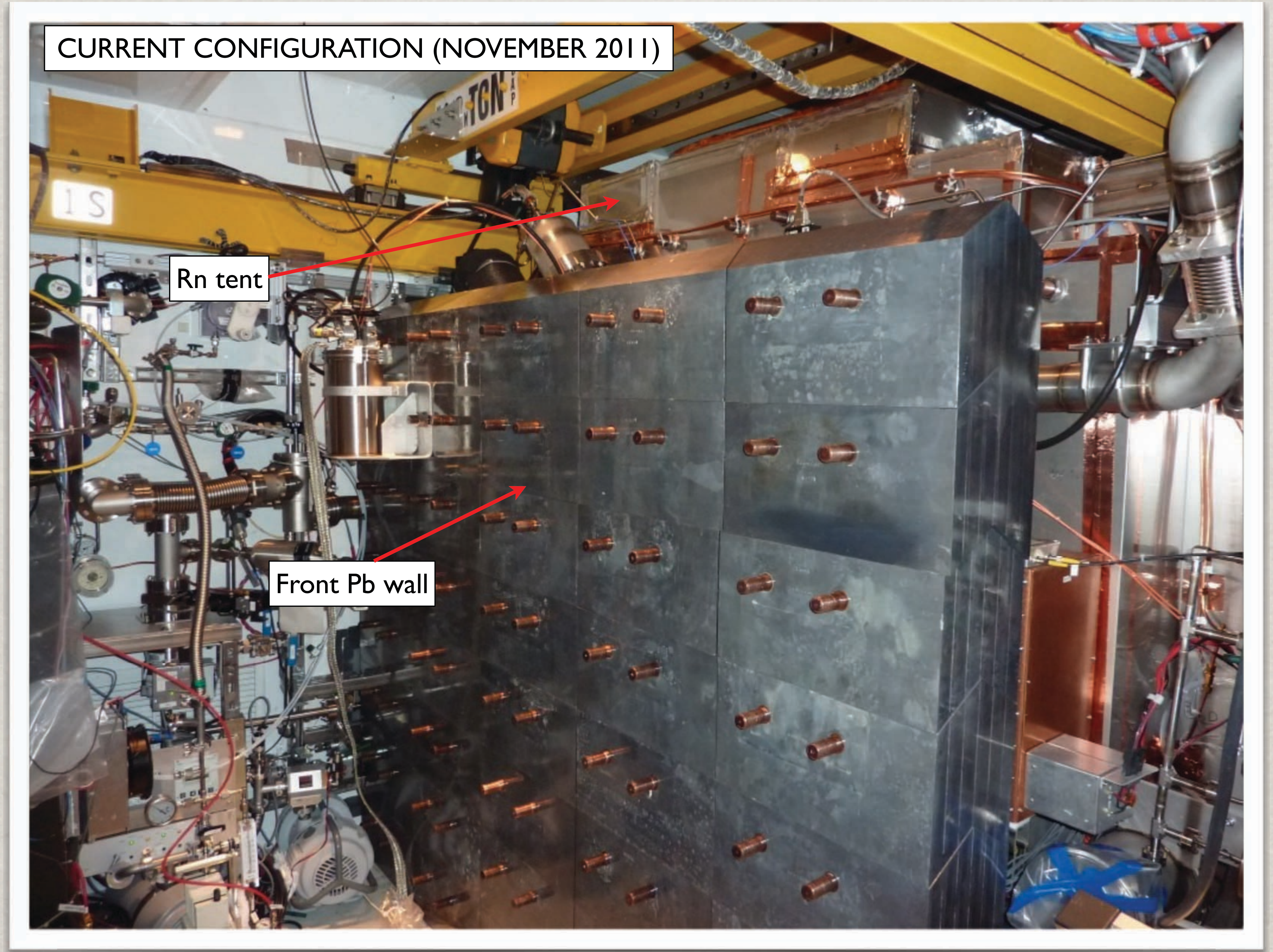
Essentials:
Feed/Bleed
High pressure/low Pressure
recirculation/purification loop
condenser/heater
HV purge line



Notes:

1. All initialization or emergency ports to atmosphere will be pumped through Cu pinchoffs and sealed.
2. Color Codes:
    - NAVY: Pumpout & Instrumentation
    - BLUE: Xenon Feed
    - GREEN: Xenon Bleed
    - PINK: Signals to and from PLC
    - ORANGE: Instrumentation
    - GREY/DOTTED: Not installed for commissioning
    - RED: Circulation system (note: circulation system and Xe feed system overlap considerably)
    - BLACK: Xe other
    - BROWN: Equipment (bottles, pumps, etc.)

FRONT PB WALL



CURRENT CONFIGURATION (NOVEMBER 2011)

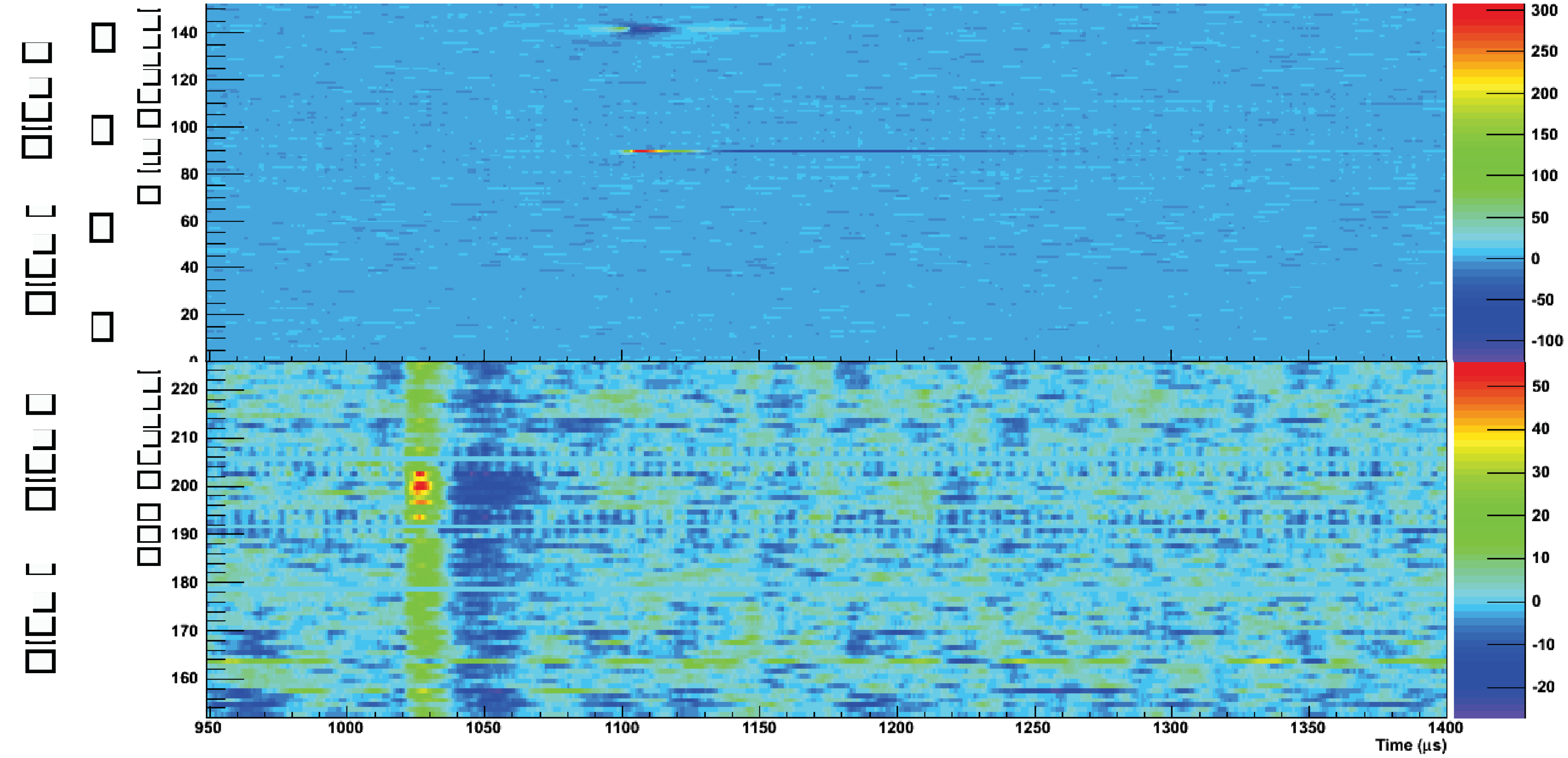
Rn tent

Front Pb wall

[illegible]

[illegible]

[illegible]



140
120
100
80
60
40
20
0
300
250
200
150
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50
0
-50
-100
220
210
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190
180
170
160
50
40
30
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Time (µs)

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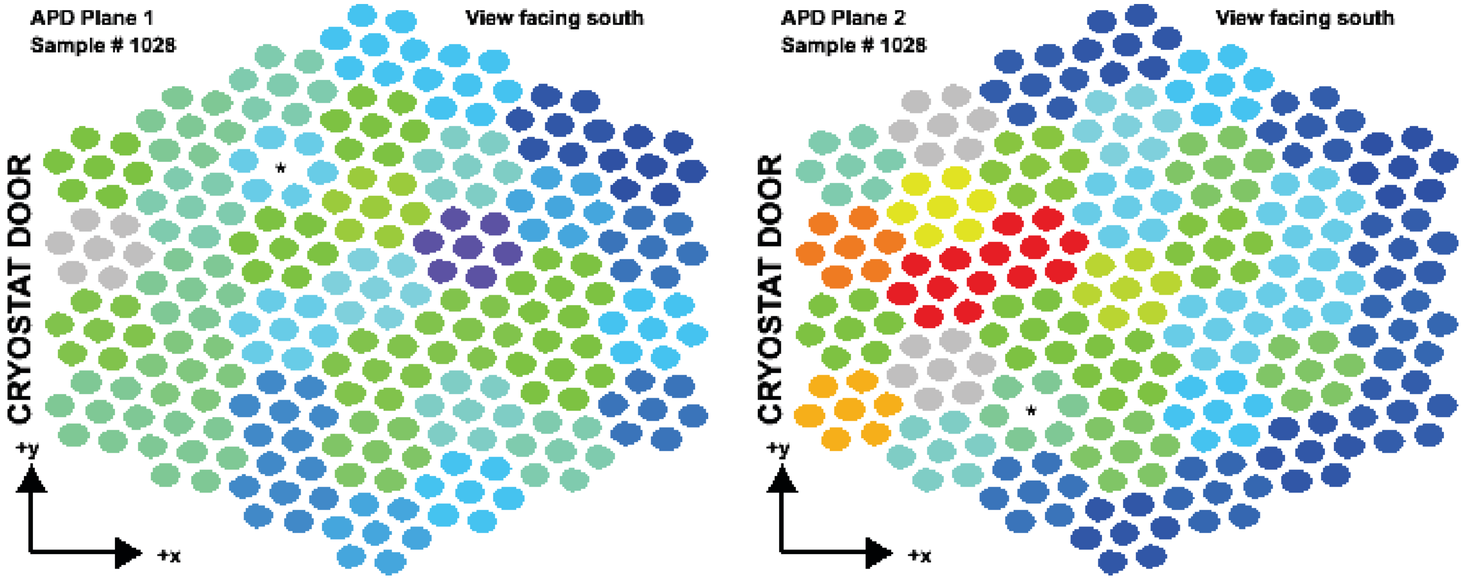


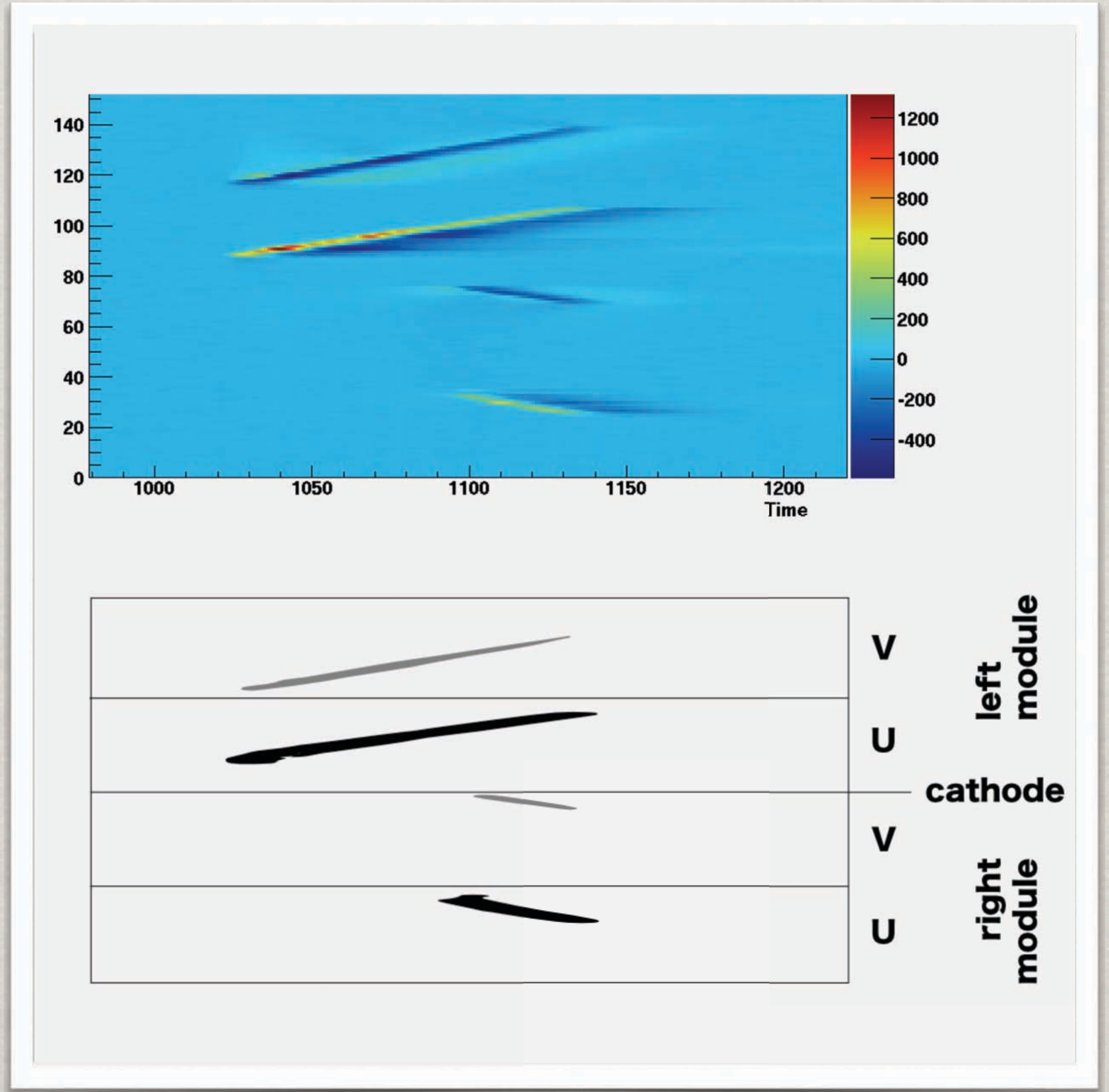
APD Plane 1
Sample # 1028
View facing south
CRYOSTAT DOOR
+y
+x
APD Plane 2
Sample # 1028
View facing south
CRYOSTAT DOOR
+y
+x

MUON TRACK SIGNALS

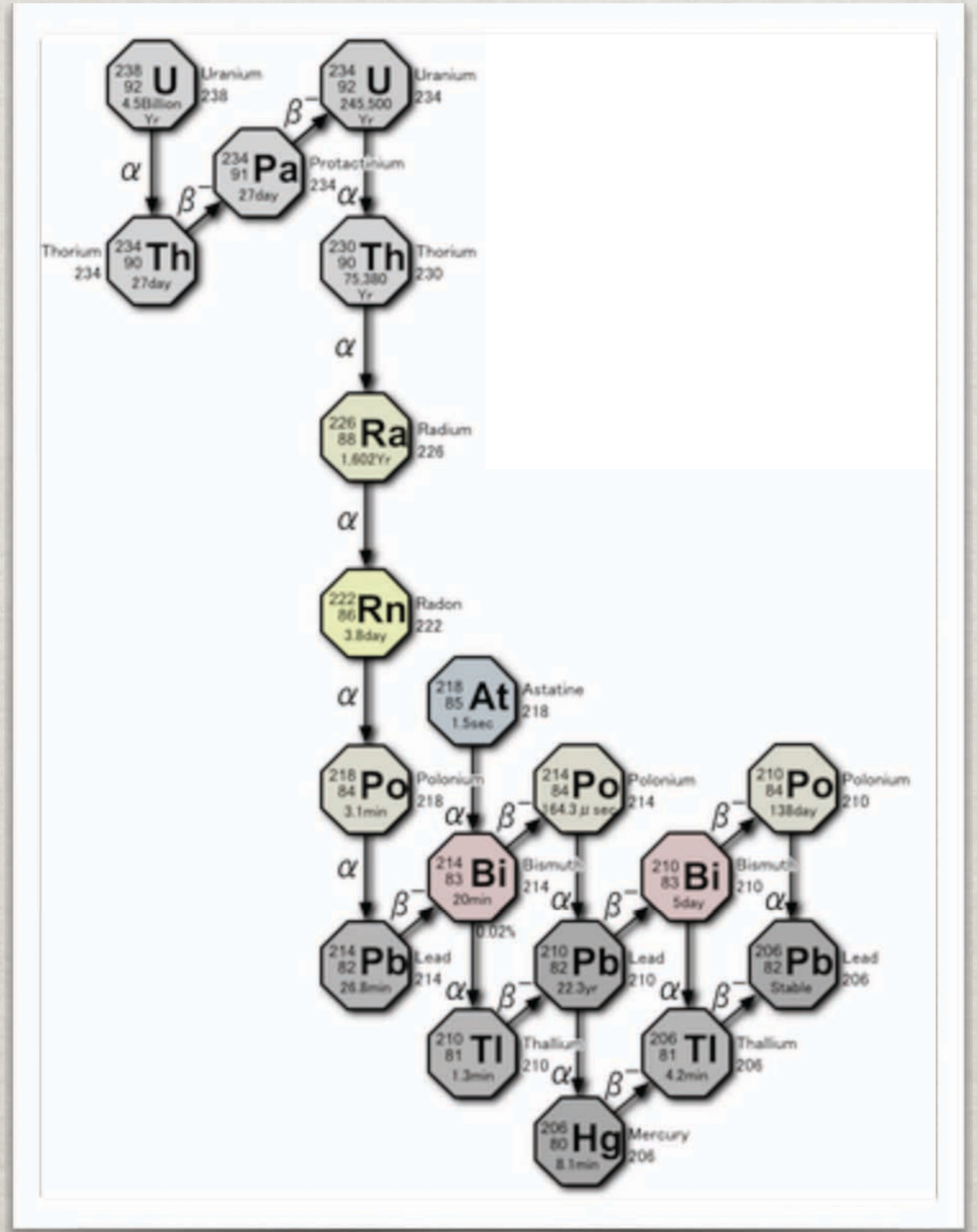
collection

induction

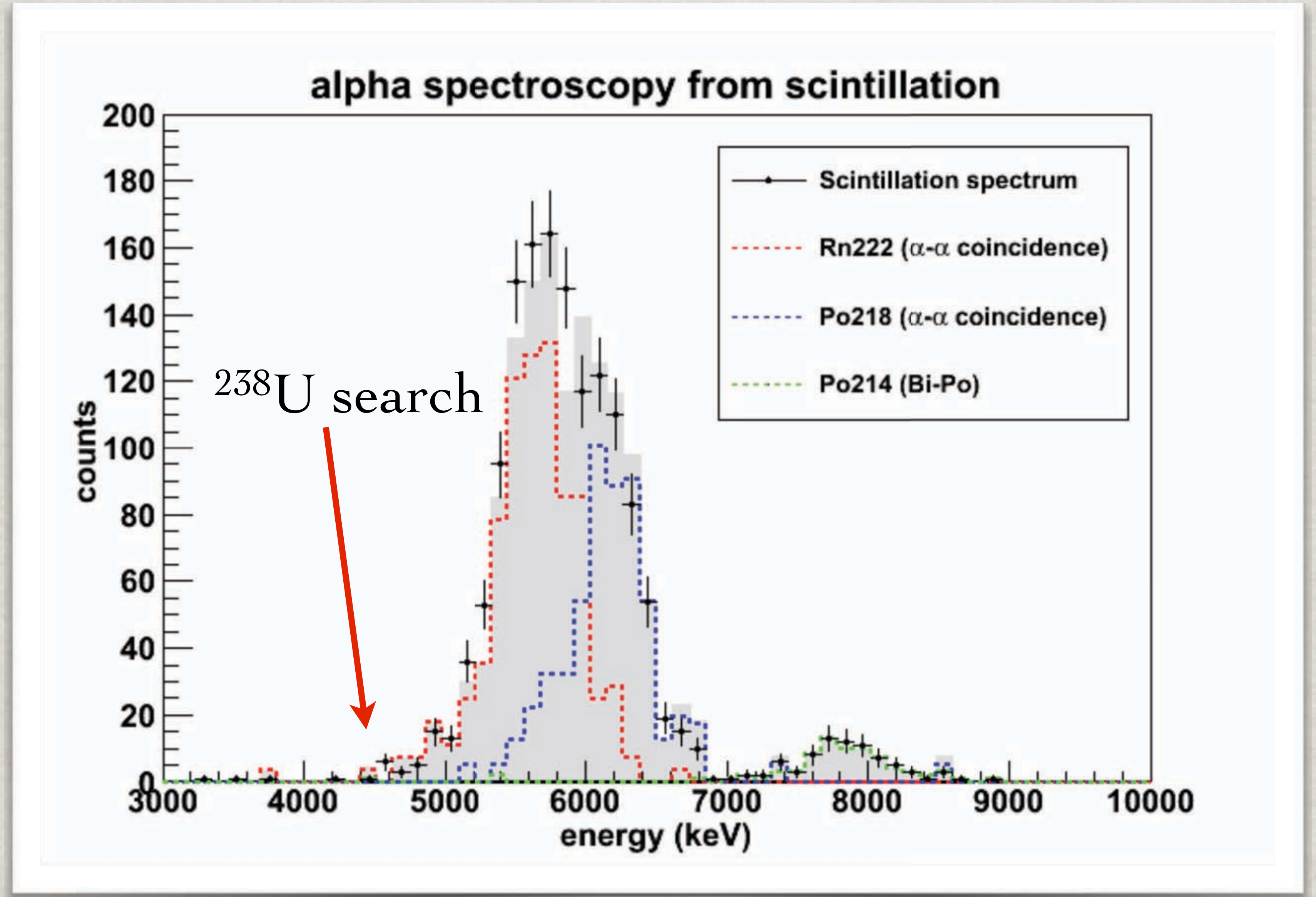
Muon traverses
both TPCs



^{222}Rn DECAY CHAIN



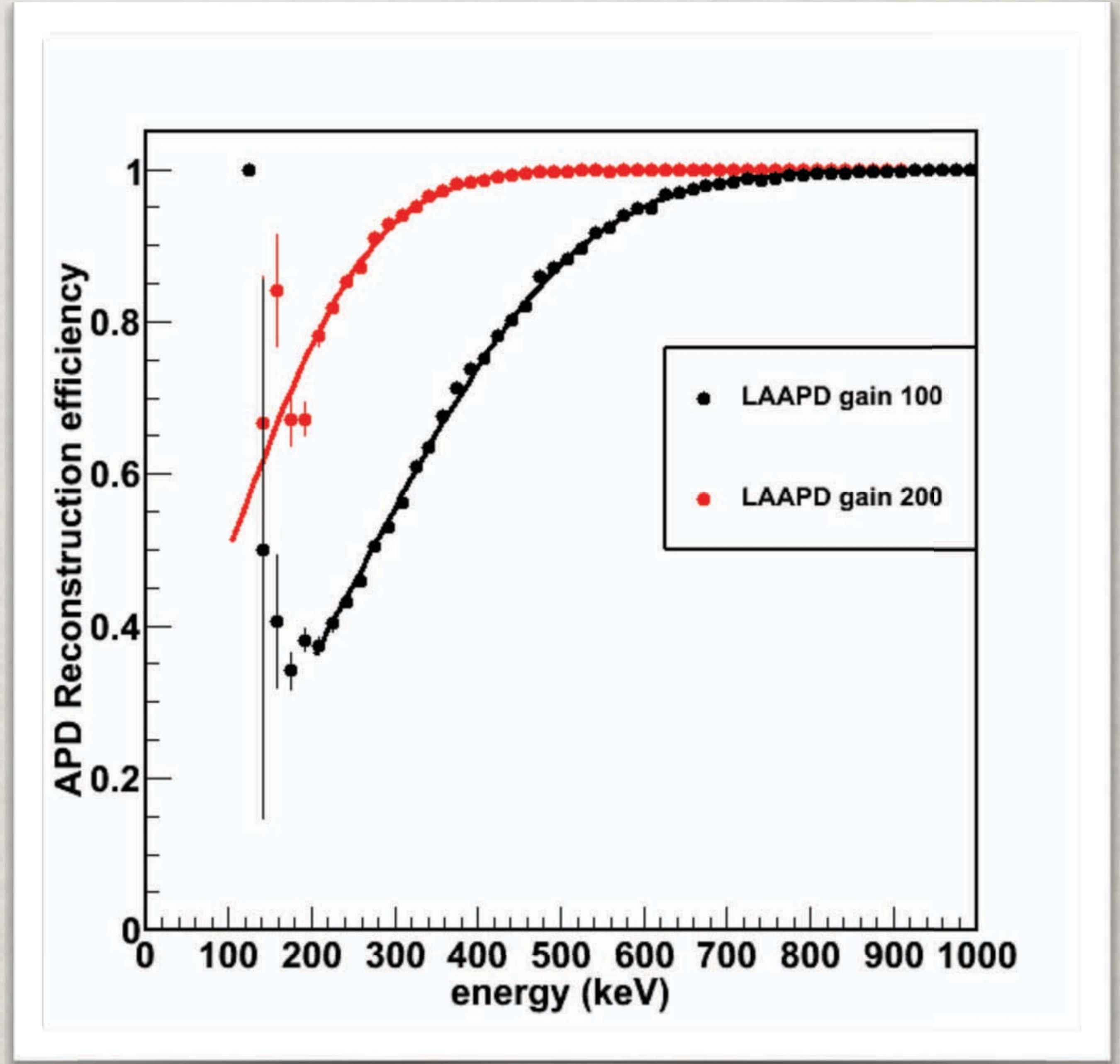
CONSTRAINTS FROM ALPHA-SPECTROSCOPY



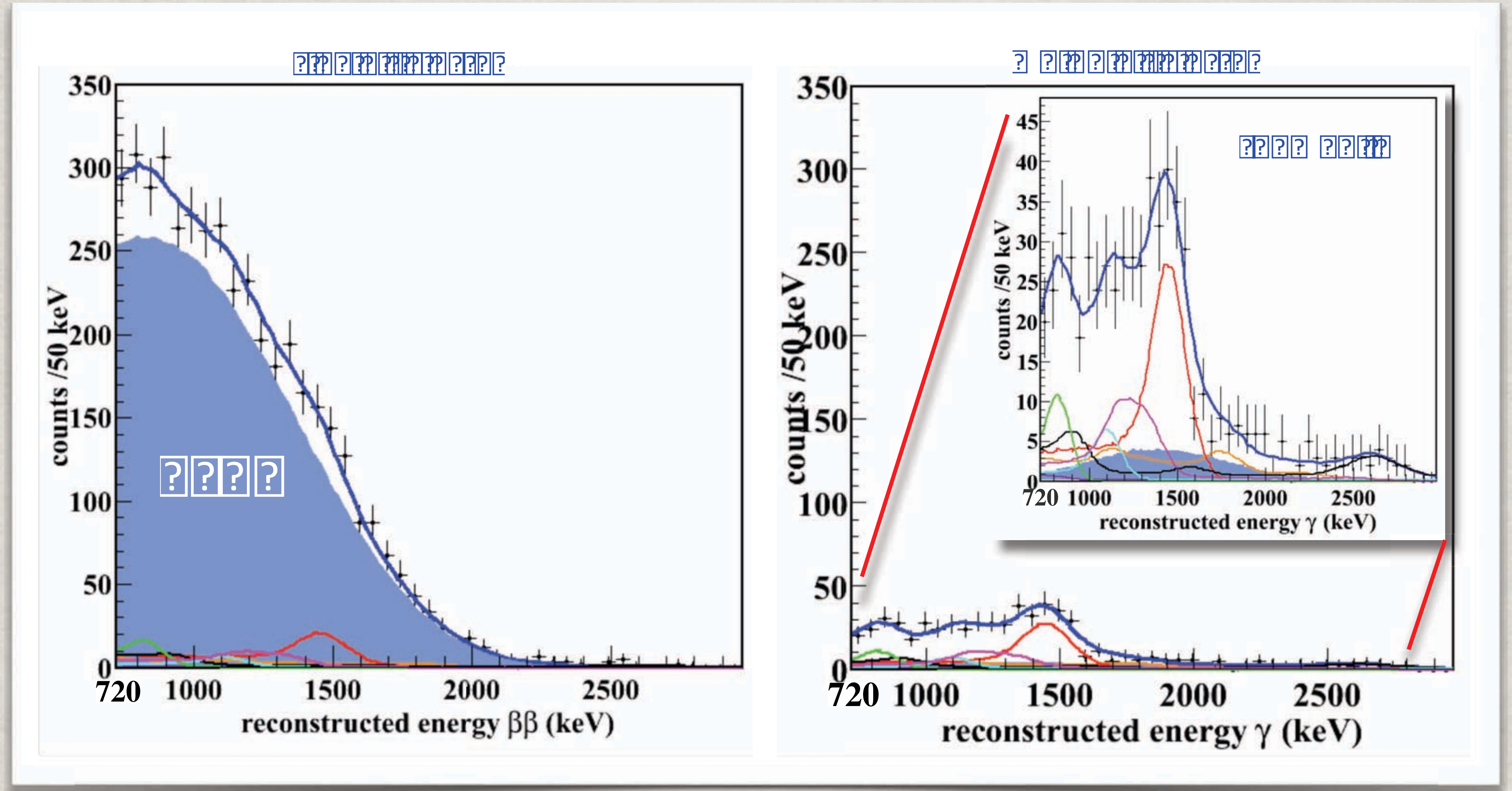
-Investigate alpha spectrum for scintillation signals from ^{238}U
-Calibrate spectrum with alphas in Rn chain
-Can constrain contamination of ^{238}U in bulk LXe by searching for 4.5 MeV alphas
(< 0.3 counts per day in our fiducial volume)
-The same limit applies to its daughter ^{234m}Pa which β decays with a Q-value of 2195 keV, which cannot then explain our LXe bulk signal

3D RECONSTRUCTION THRESHOLD

- Events >100 keV well above charge detection threshold
- 3D reconstruction still requires t_0 from scintillation signal
- Compare ratio of fully reconstructed events to triggered events to determine reconstruction efficiency
- Early software threshold ~700 keV
- Recent dramatic increase with change in APD bias voltages ~300 keV

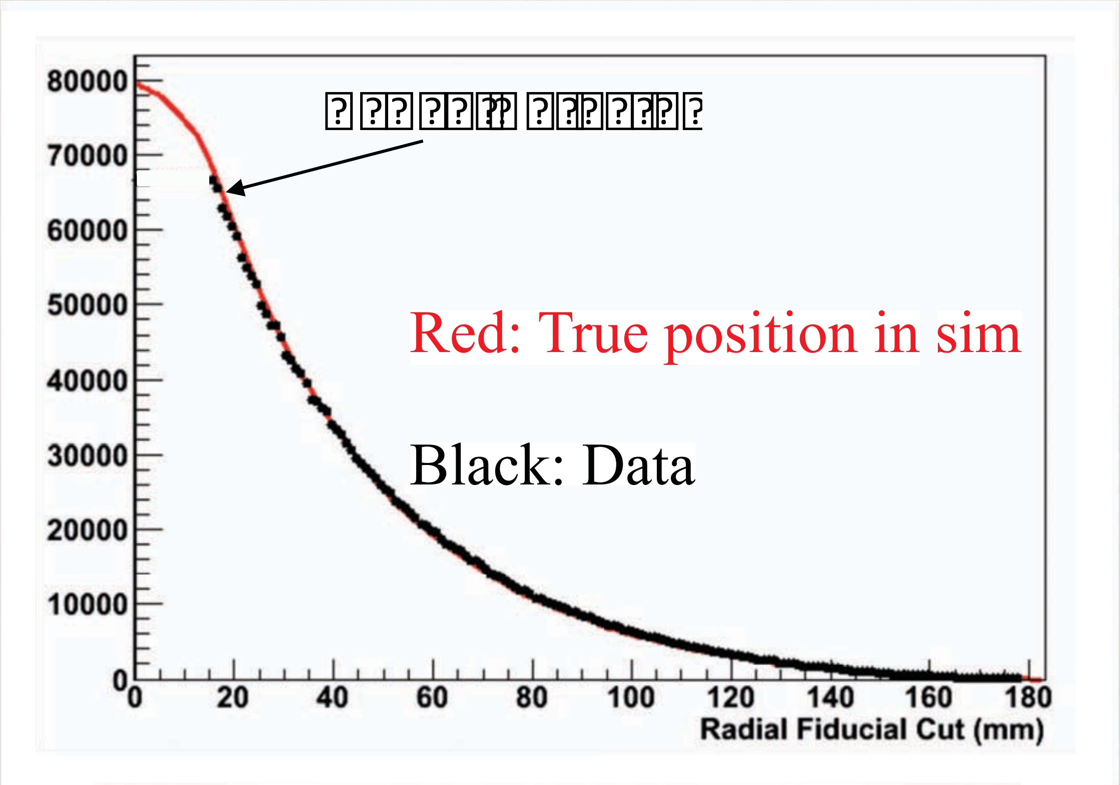


SYSTEMATIC UNCERTAINTIES



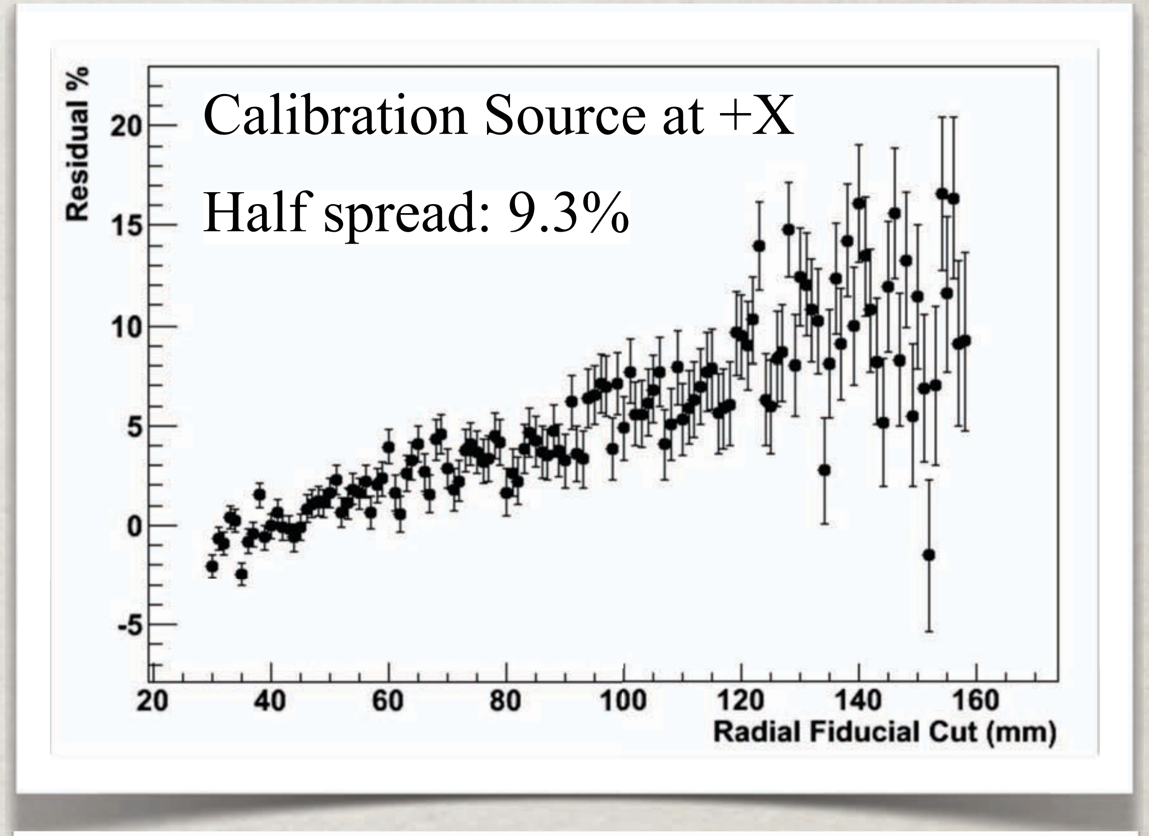
- Fiducial volume: 9.3%
- Multiplicity assignment: 3%
- Energy calibration: 1.8%
- Background models: 0.6%

FIDUCIAL VOLUME UNCERTAINTY



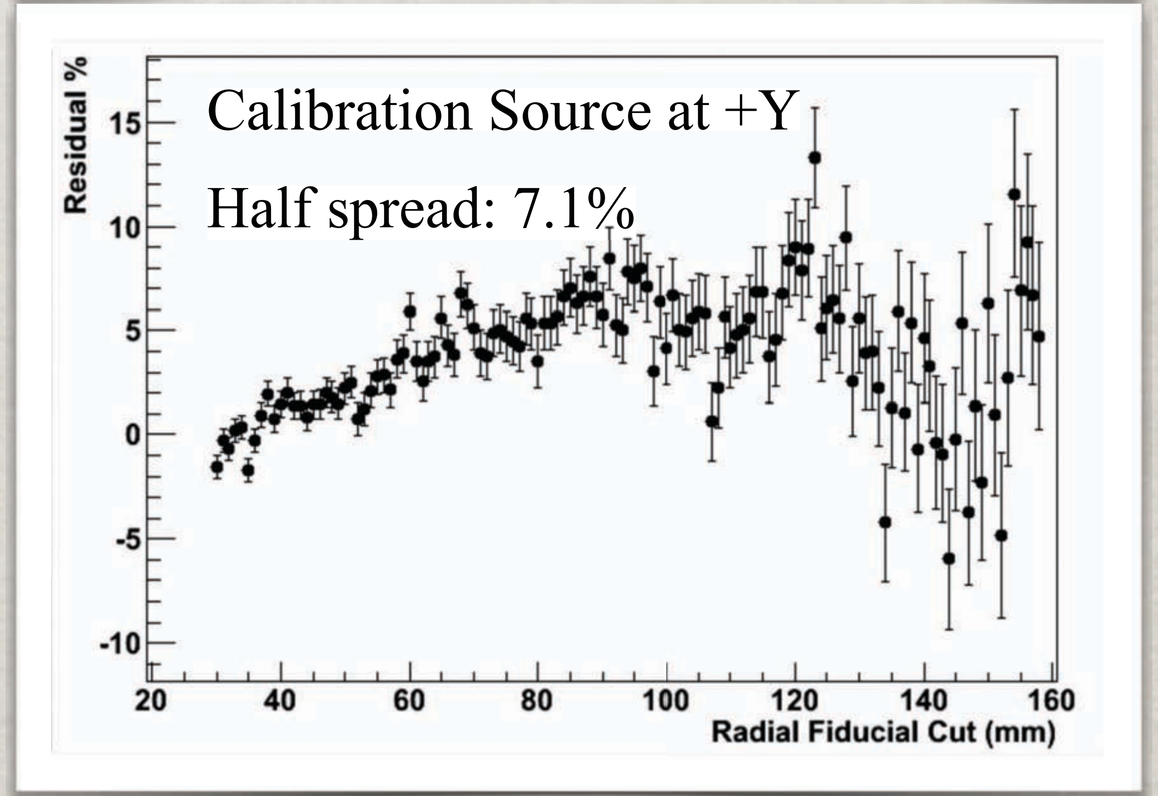
Red: True position in sim

Black: Data



Calibration Source at +X

Half spread: 9.3%



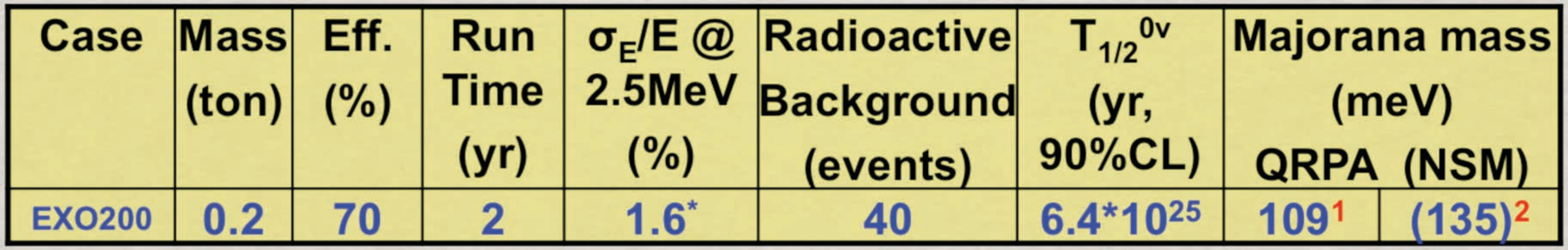
Calibration Source at +Y

Half spread: 7.1%

Uncertainty determined from the fidelity with which calibration events are reconstructed within a chosen volume as compared to simulation

EXO-200 SENSITIVITY

- Expect 20 events/yr in +- 2σ window around 2.458 MeV
- $2\upsilon\beta\beta$ background negligible ($T_{1/2}$ = 2.2· 10^{21})
- Expected energy resolution $\sigma(E)/E$ = 1.6%



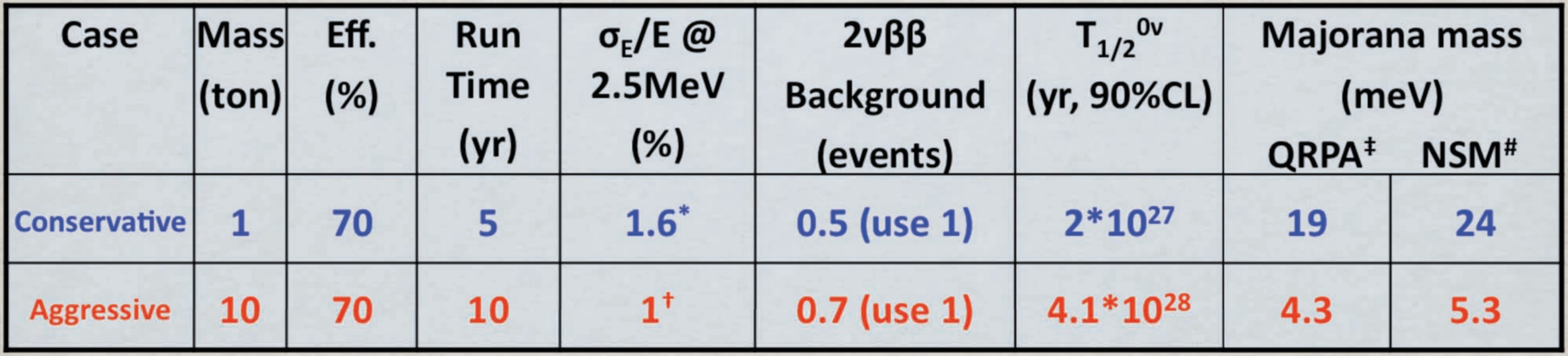
Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0v}$ (yr, 90%CL)	Majorana mass (meV)	
							QRPA	(NSM)
EXO200	0.2	70	2	1.6^{*}	40	$6.4*10^{25}$	109[1]	(135)[2]

---

[1] F.Simkovic et al., *Phys. Rev.* C79, 055501 (2009)
[2] Menendez et al., *Nucl. Phys.* A818, 139 (2009)

EXO SENSITIVITY

- 80% ^{136}Xe enrichment
- Intrinsic low radioactivity + Ba tagging to eliminate backgrounds
- Energy resolution only needed to separate 2υ and 0υ modes



Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA‡	NSM#
Conservative	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	19	24
Aggressive	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	4.3	5.3

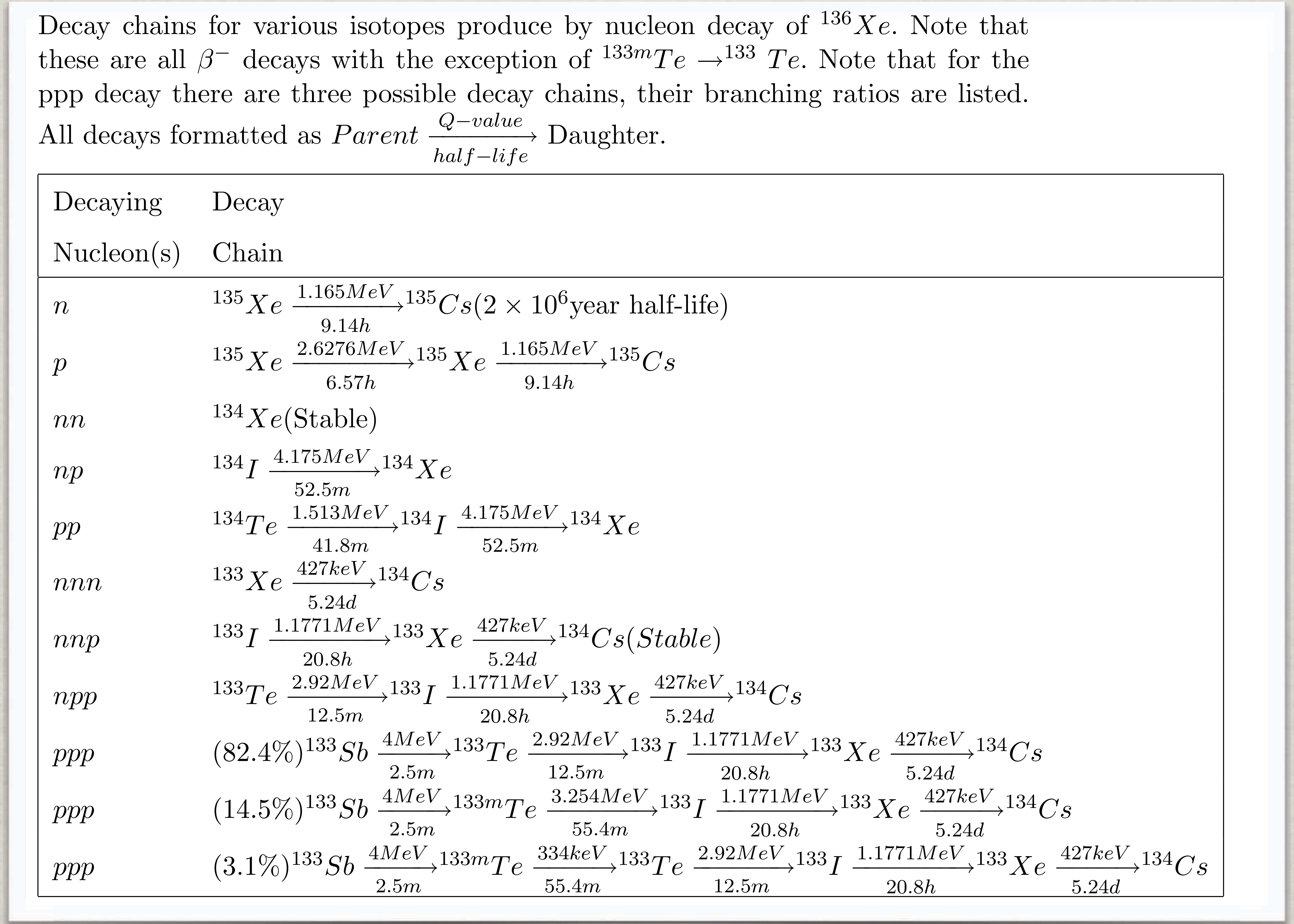
[*] σ(E)/E = 1.4% obtained in EXO R&D, Conti et al Phys Rev B 68 (2003) 054201

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

[‡] F. Simkovic et al., Phys. Rev. C79, 055501 (2009)

[#] Menendez et al., Nucl. Phys. A818, 139 (2009)

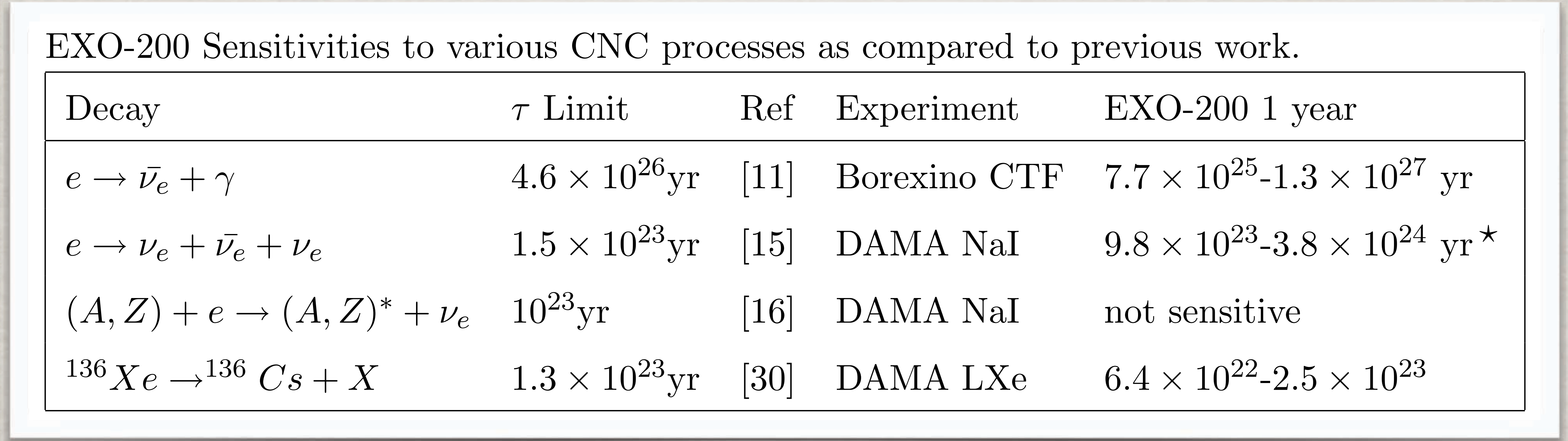
Nucleon Decay



Decay chains for various isotopes produce by nucleon decay of ^{136}Xe. Note that these are all β^- decays with the exception of $^{133m}Te \rightarrow^{133} Te$. Note that for the ppp decay there are three possible decay chains, their branching ratios are listed. All decays formatted as $Parent \xrightarrow[half-life]{Q-value}$ Daughter.

Decaying Nucleon(s)	Decay Chain
n	$^{135}Xe \xrightarrow[9.14h]{1.165MeV} {}^{135}Cs$(2 × 10^6year half-life)
p	$^{135}Xe \xrightarrow[6.57h]{2.6276MeV} {}^{135}Xe \xrightarrow[9.14h]{1.165MeV} {}^{135}Cs$
nn	^{134}Xe(Stable)
np	$^{134}I \xrightarrow[52.5m]{4.175MeV} {}^{134}Xe$
pp	$^{134}Te \xrightarrow[41.8m]{1.513MeV} {}^{134}I \xrightarrow[52.5m]{4.175MeV} {}^{134}Xe$
nnn	$^{133}Xe \xrightarrow[5.24d]{427keV} {}^{134}Cs$
nnp	$^{133}I \xrightarrow[20.8h]{1.1771MeV} {}^{133}Xe \xrightarrow[5.24d]{427keV} {}^{134}Cs(Stable)$
npp	$^{133}Te \xrightarrow[12.5m]{2.92MeV} {}^{133}I \xrightarrow[20.8h]{1.1771MeV} {}^{133}Xe \xrightarrow[5.24d]{427keV} {}^{134}Cs$
ppp	(82.4%)$^{133}Sb \xrightarrow[2.5m]{4MeV} {}^{133}Te \xrightarrow[12.5m]{2.92MeV} {}^{133}I \xrightarrow[20.8h]{1.1771MeV} {}^{133}Xe \xrightarrow[5.24d]{427keV} {}^{134}Cs$
ppp	(14.5%)$^{133}Sb \xrightarrow[2.5m]{4MeV} {}^{133m}Te \xrightarrow[55.4m]{3.254MeV} {}^{133}I \xrightarrow[20.8h]{1.1771MeV} {}^{133}Xe \xrightarrow[5.24d]{427keV} {}^{134}Cs$
ppp	(3.1%)$^{133}Sb \xrightarrow[2.5m]{4MeV} {}^{133m}Te \xrightarrow[55.4m]{334keV} {}^{133}Te \xrightarrow[12.5m]{2.92MeV} {}^{133}I \xrightarrow[20.8h]{1.1771MeV} {}^{133}Xe \xrightarrow[5.24d]{427keV} {}^{134}Cs$

CHARGE NON-CONSERVATION



EXO-200 Sensitivities to various CNC processes as compared to previous work.

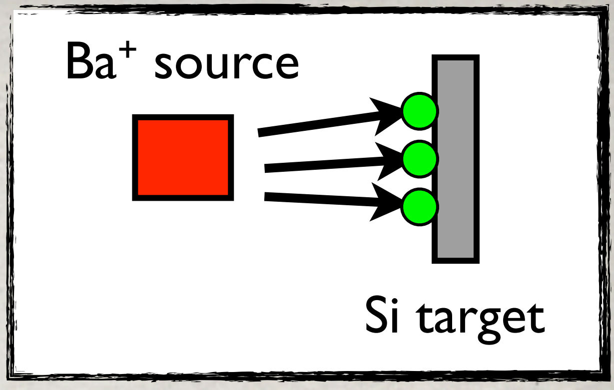
Decay	τ Limit	Ref	Experiment	EXO-200 1 year
$e \rightarrow \bar{\nu_e} + \gamma$	4.6×10^{26}yr	[11]	Borexino CTF	7.7×10^{25}-1.3×10^{27} yr
$e \rightarrow \nu_e + \bar{\nu_e} + \nu_e$	1.5×10^{23}yr	[15]	DAMA NaI	9.8×10^{23}-3.8×10^{24} yr*
$(A, Z) + e \rightarrow (A, Z)^* + \nu_e$	10^{23}yr	[16]	DAMA NaI	not sensitive
$^{136}Xe \rightarrow ^{136}Cs + X$	1.3×10^{23}yr	[30]	DAMA LXe	6.4×10^{22}-2.5×10^{23}

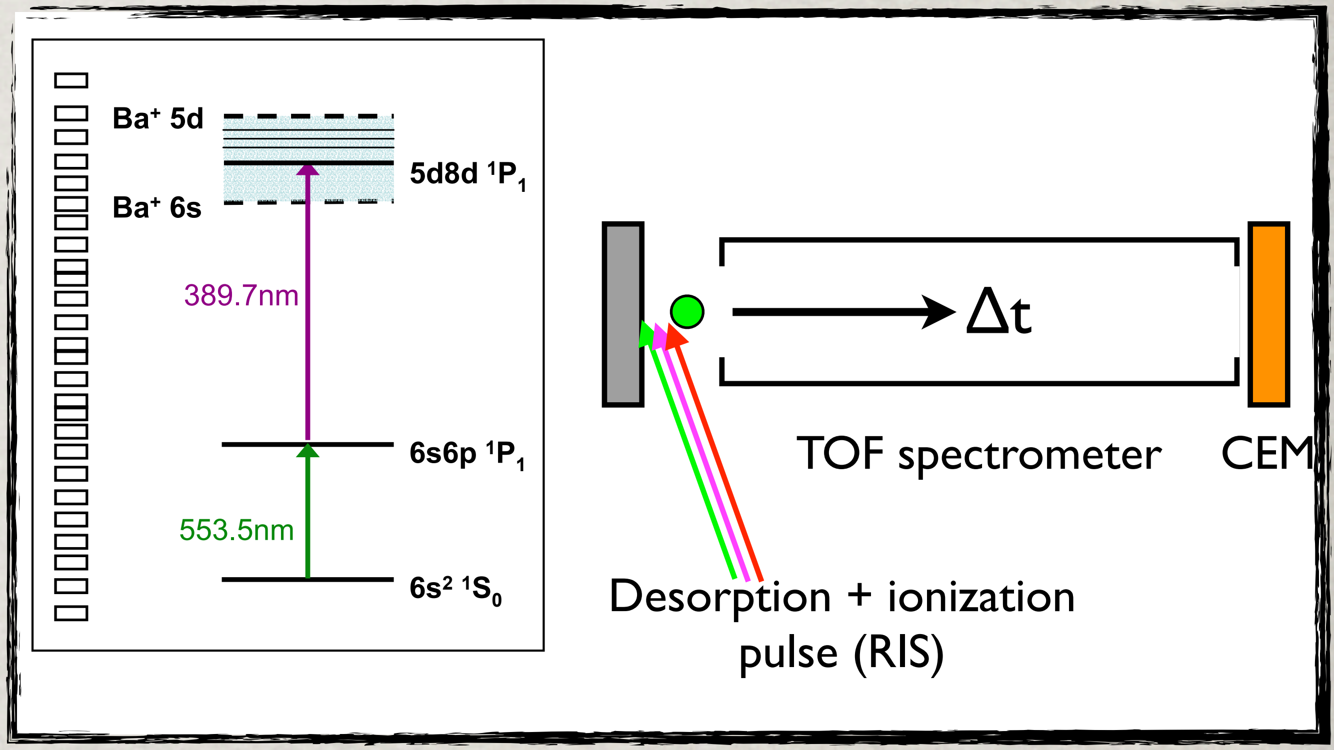
BARIUM TAGGING (RIS)

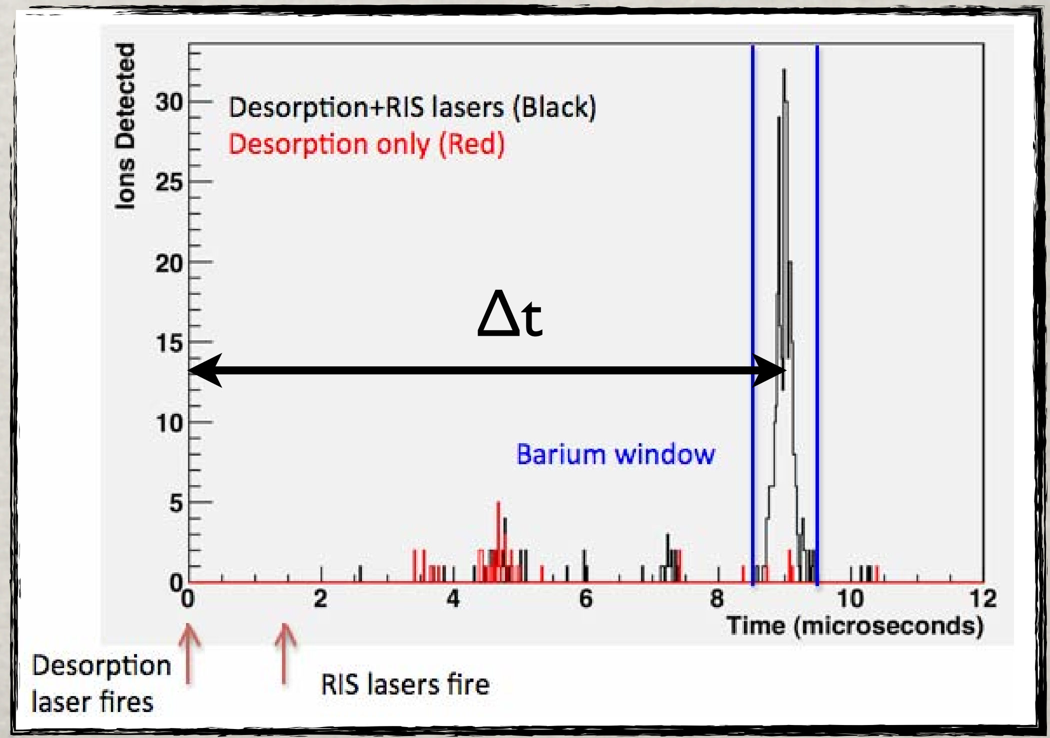
Identify ββ via final state nucleus (M. Moe, PRC44, 1991, 931)

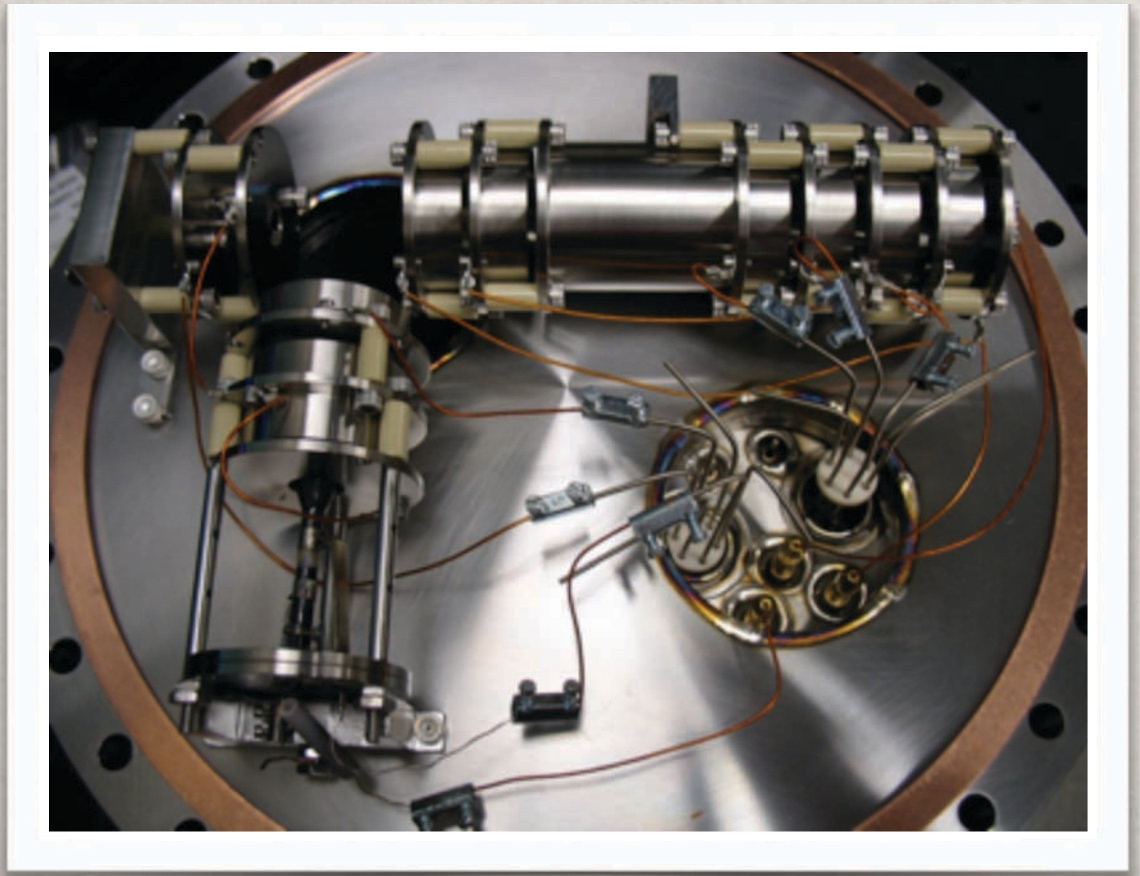
$^{136}Xe \rightarrow {}^{136}Ba + 2e^-$

2% efficiency with this setup

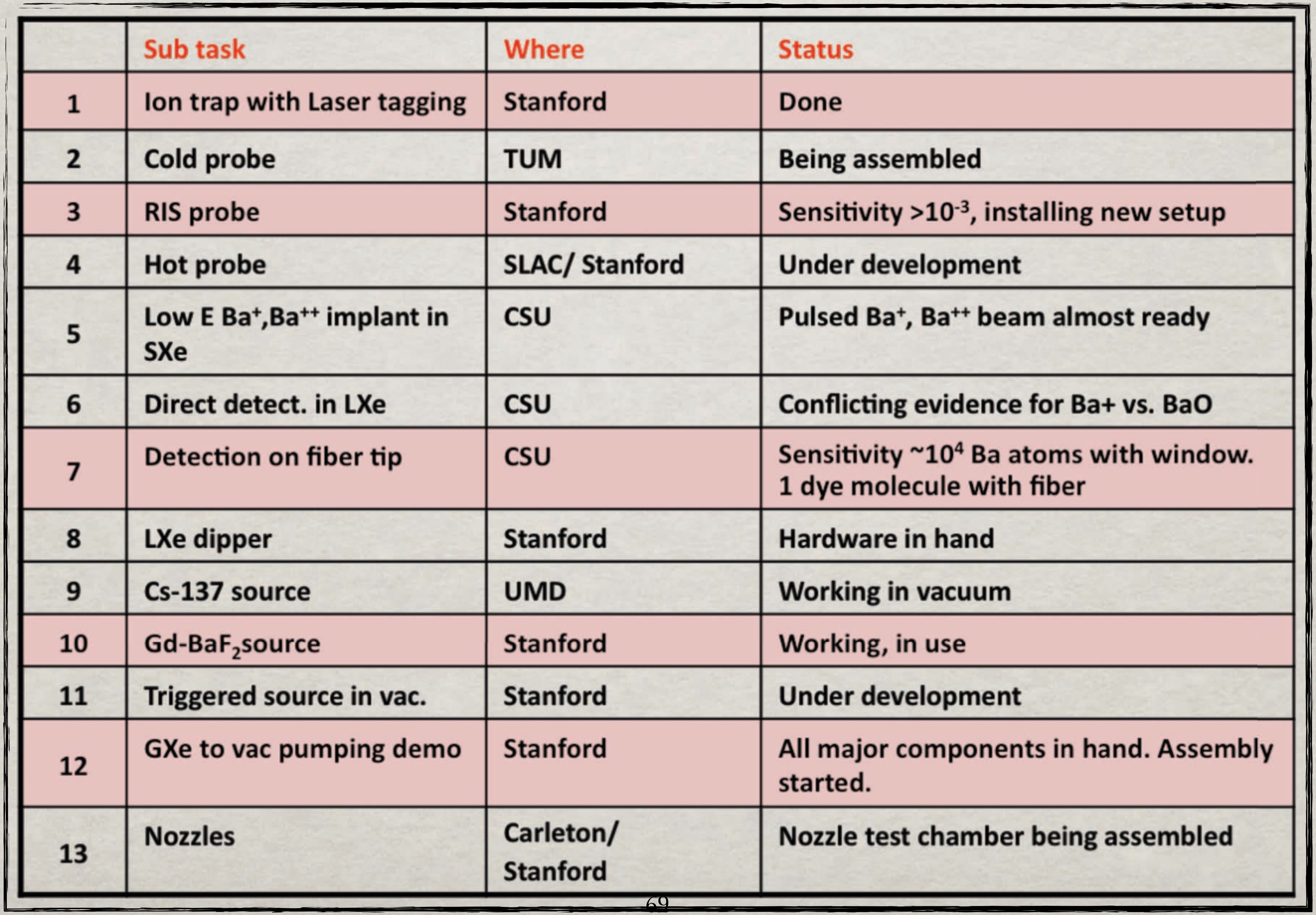






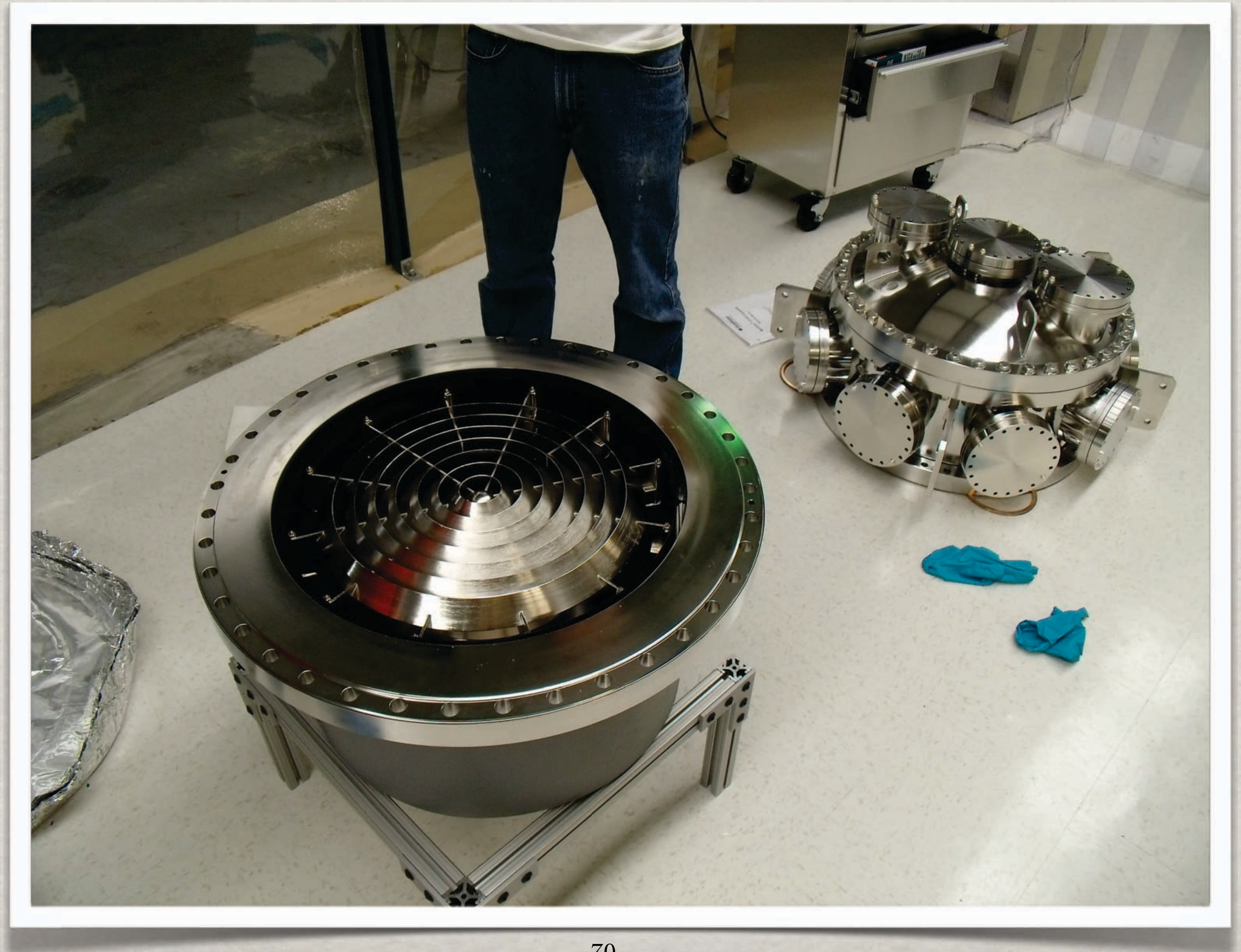


Tagging effort

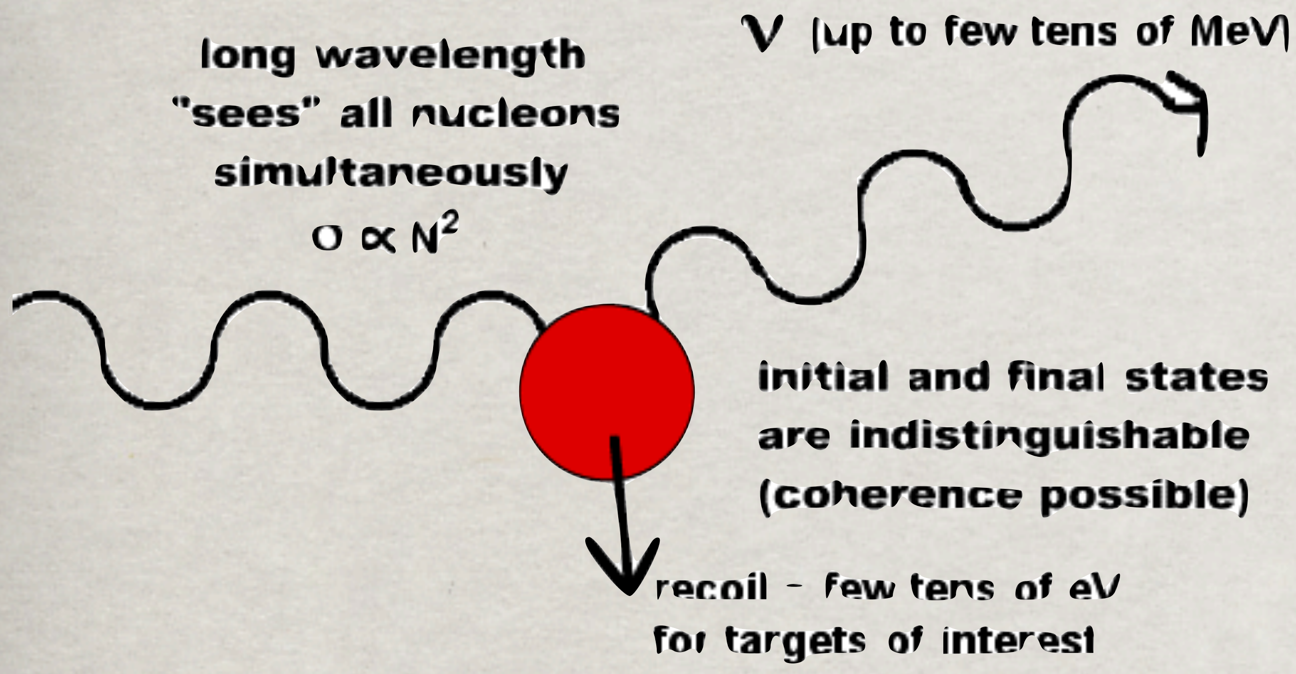


	Sub task	Where	Status
1	Ion trap with Laser tagging	Stanford	Done
2	Cold probe	TUM	Being assembled
3	RIS probe	Stanford	Sensitivity $>10^{-3}$, installing new setup
4	Hot probe	SLAC/ Stanford	Under development
5	Low E Ba$^+$,Ba^{++} implant in SXe	CSU	Pulsed Ba$^+$, Ba^{++} beam almost ready
6	Direct detect. in LXe	CSU	Conflicting evidence for Ba+ vs. BaO
7	Detection on fiber tip	CSU	Sensitivity ~10^4 Ba atoms with window. 1 dye molecule with fiber
8	LXe dipper	Stanford	Hardware in hand
9	Cs-137 source	UMD	Working in vacuum
10	Gd-BaF$_2$source	Stanford	Working, in use
11	Triggered source in vac.	Stanford	Under development
12	GXe to vac pumping demo	Stanford	All major components in hand. Assembly started.
13	Nozzles	Carleton/ Stanford	Nozzle test chamber being assembled

HIGH CAPACITY XE CRYOPUMP



INITIAL COGENT MOTIVATION: COHERENT NEUTRINO-NUCLEUS SCATTERING



- non-controversial SM process
- $\sigma \sim N^2$ for neutral currents, $E_\nu <$ few MeV
- need sub-keV threshold
- and low backgrounds (~ c $\mathrm{keV}^{-1}\ \mathrm{kg}^{-1}\ \mathrm{day}^{-1}$)
- and large mass (~ kg)

- Has been tried before, without success: Cabrera, Krauss & Wilczek, PRL 55 (1985), 25-28

- Largest σ in SN dynamics: measurements validates models. J.R. Wilson, PRL 32 (74) 849
- Large detector can measure total E and T of nearby SN, $\nu_\mu\ \nu_\tau$ measurement allows determination of oscillation pattern. (J.F. Beacom, W.M. Far & P. Vogel, PRD 66 (02) 033011)
- Search for sterile neutrinos (A. Drukier & L. Stodolsky, PRD 30 (84) 2295)
- Sensitive probe of weak nuclear charge (L.M. Krauss, PLB 269, 407)
- NSI and effective ν charge radius tests (J. Barranco et. al, hep-ph/0508299, hep-ph/0512029)
- σ critically dependent on μ_ν (A.C. Dodd et. al, PLB 266 (91) 434)
- Neutrino Technology: Reactor Monitoring
- Also: light WIMP searches
- Solar Bound WIMPS

EXO: LIGHT WIMP & LOW ENERGY NEUTRINOS

~468 APDs in the EXO detector.
(~180 spares left over)

~0.5 g/APD, though active mass with amplification is less.

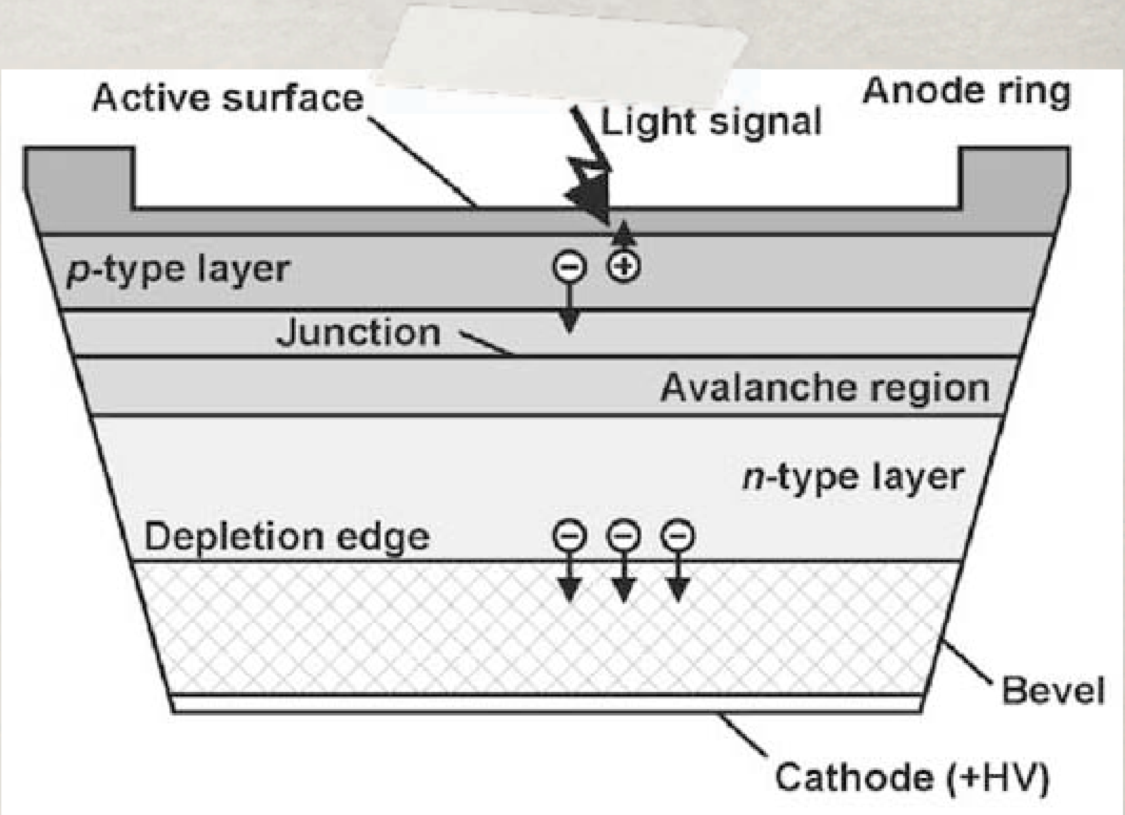
The internal gain (100-400 at LXe temps) amplifies very tiny signals.

Low background materials.

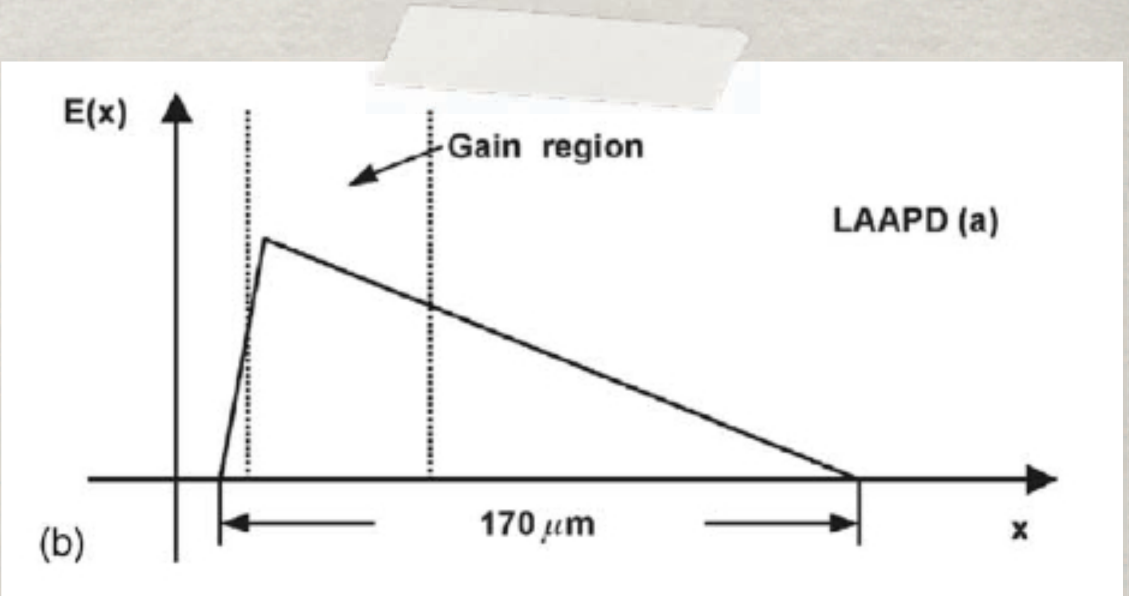
Well shielded from gammas, neutrons and cosmogenic activation.

Potential to use the LXe as an active veto for Compton scattered photons.

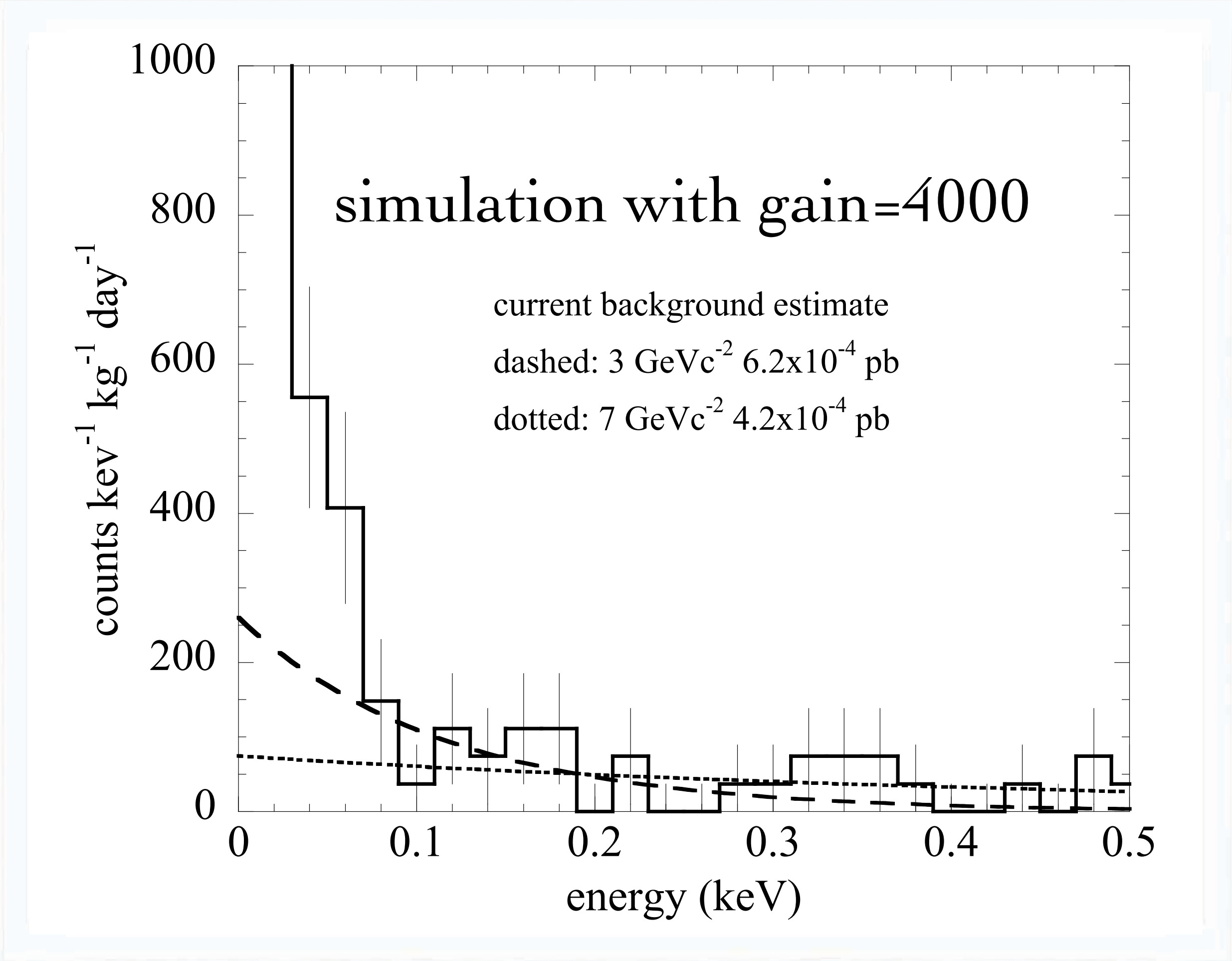
The tagline:
There is a unique opportunity to perform a dark matter search with a large ensemble of ultra-low threshold, low background detectors.

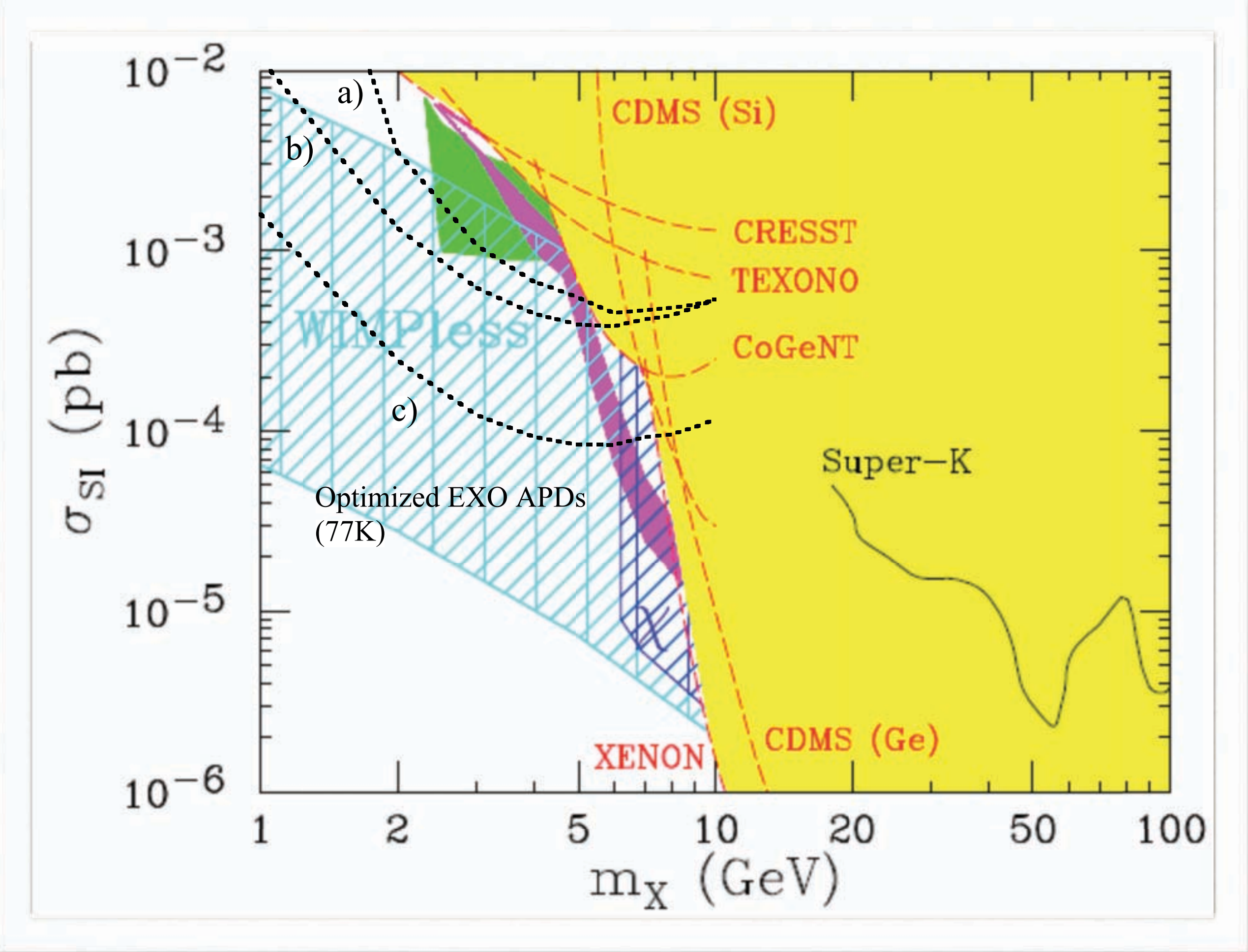


M. Moszylnski et al., NIM A, 485 (2002) 504–521



EXO: Light WIMP & low energy neutrinos



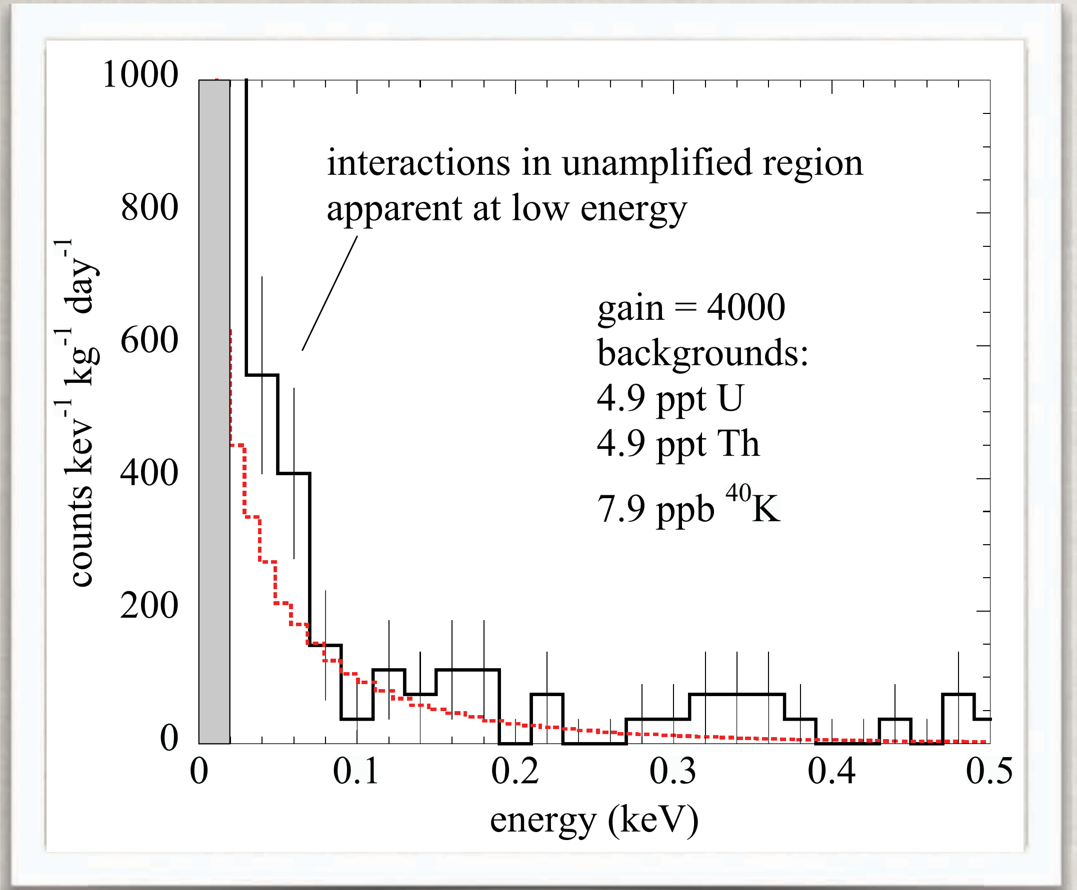


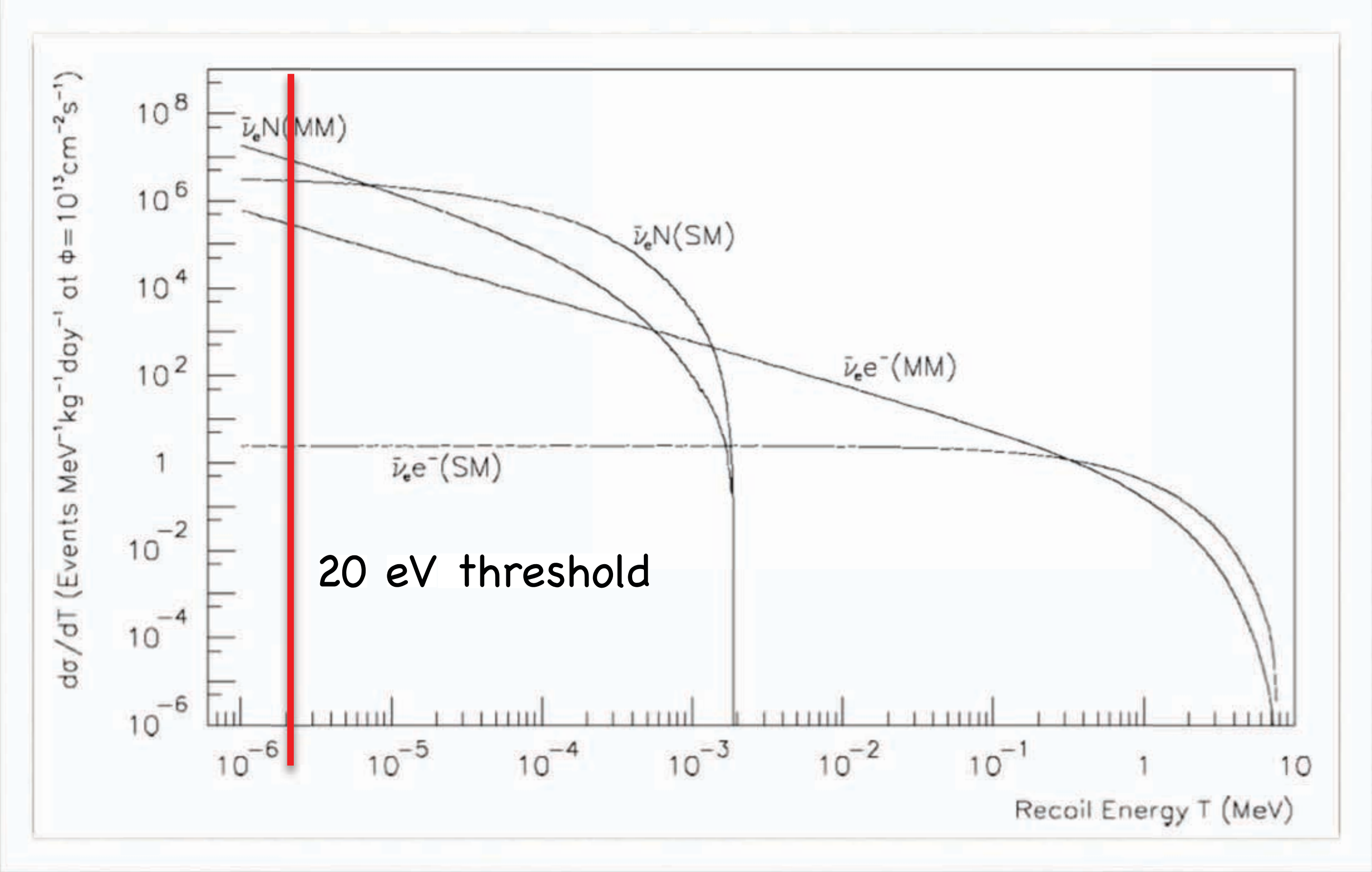
background estimate U. L.: <100 ckkd

reasonable expectation of lower backgrounds: several other low threshold semiconductors <10 ckkd

C. E. Aalseth et al. Phys. Rev. Lett., 101:251301, 2008.
S.-T. Lin, H. T. Wong, and f. t. T. Collaboration. 2008.
A. Morales et al. Phys. Lett., B489:268–272, 2000.
Z. Ahmed et al. arXiv:0902.4693 [hep-ex], 2009.

EXO: Light WIMP & low energy neutrinos





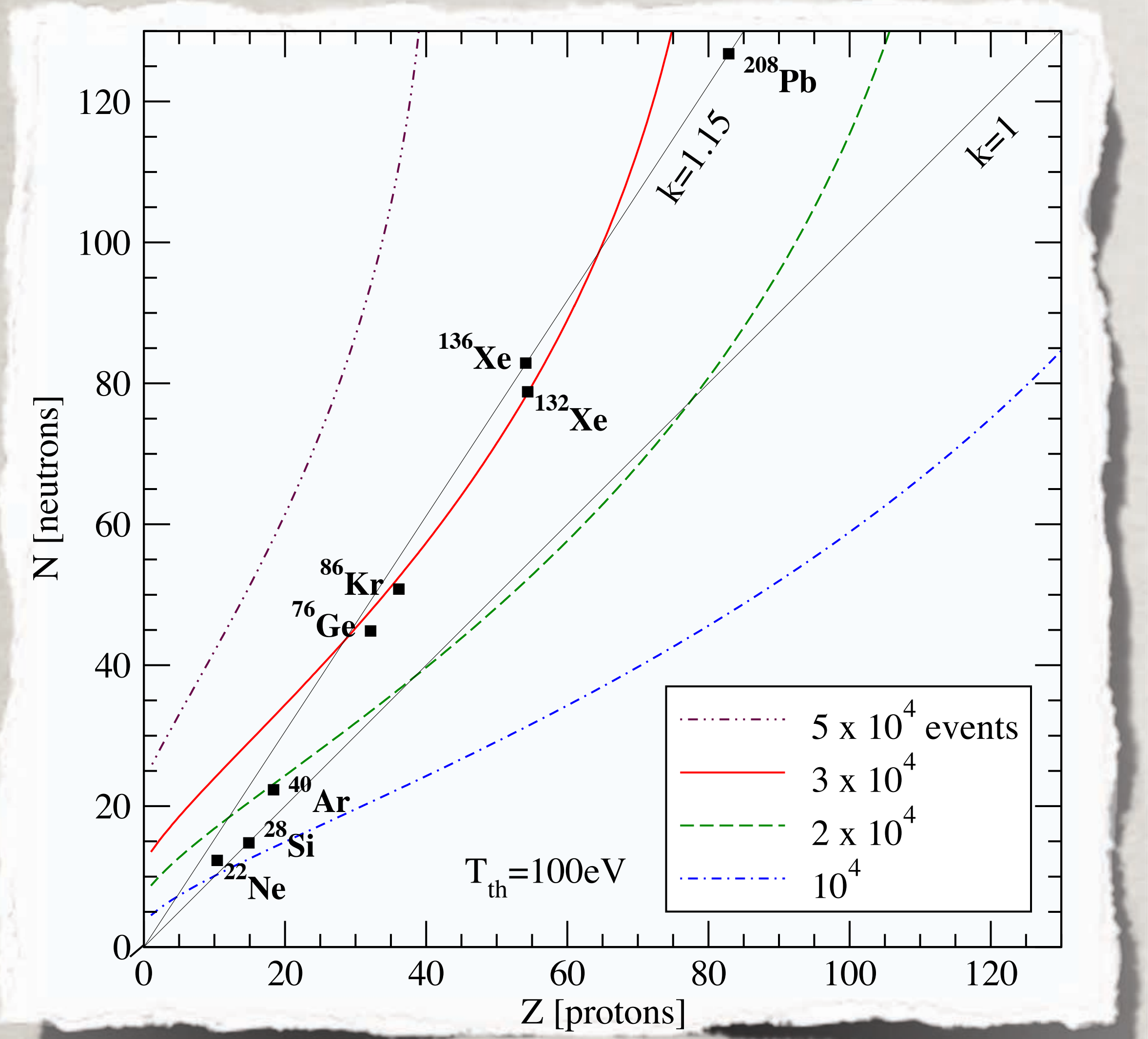
H. T. Wong and H.-B. Li. Mod. Phys. Lett., A20:1103–1117, 2005.

Coherent neutrino scattering

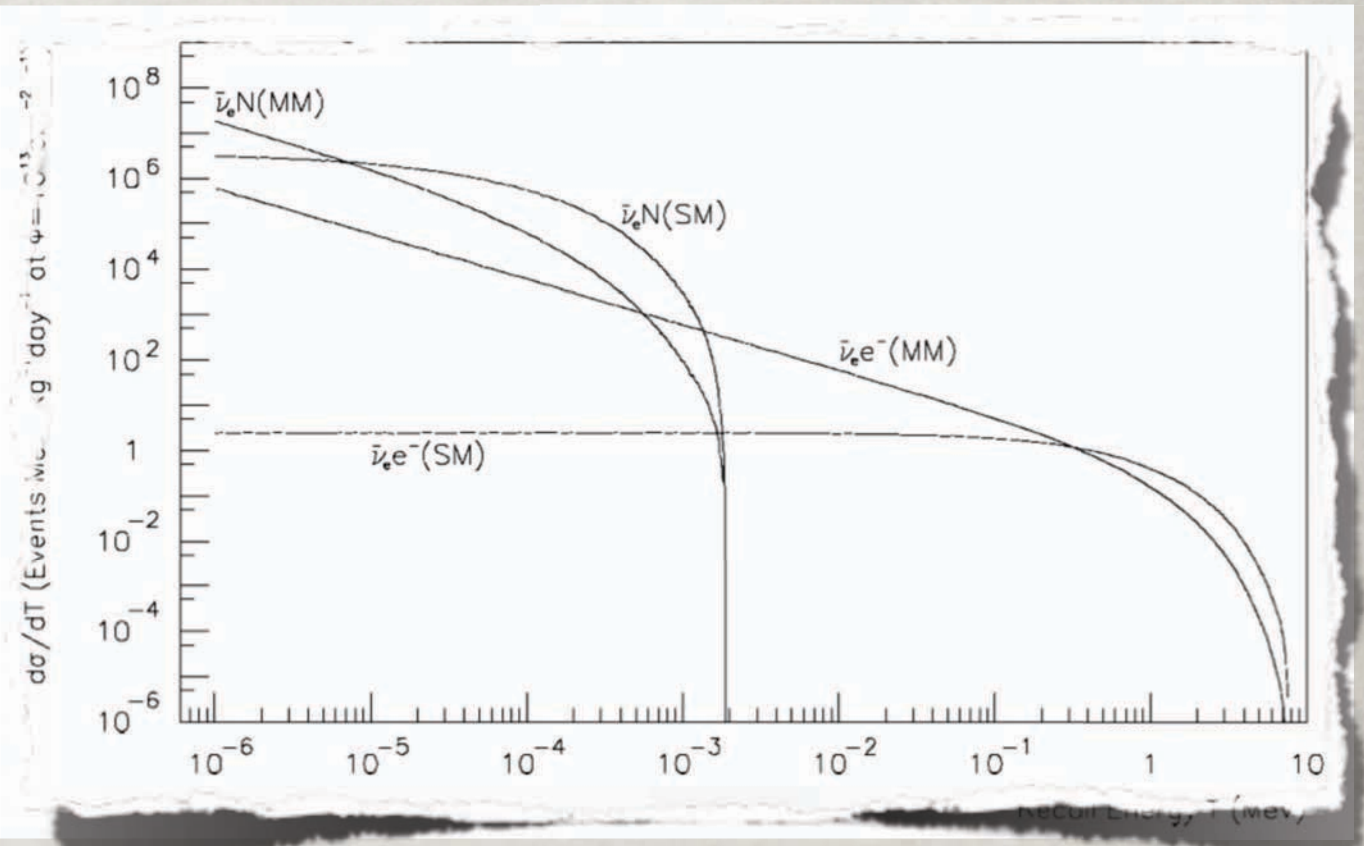
Neutrino magnetic moment search ($< 10^{-11}\ \mu_B$?)

MAGνeT (neutrinos)

Barranco, J., Miranda, O. G., & Rashba, T. I. 2005, JHEP, 12, 021



Wong, H. T. 2005, Nucl. Phys. Proc. Suppl., 138, 333



$$\frac{d\sigma_{EM}}{dT} = \frac{\pi\alpha_{em}^2\mu_\nu^2}{m_e^2}\left[\frac{1}{T} - \frac{1}{E_\nu}\right]$$

$$\frac{\sigma}{} \quad \nu \quad . \quad \frac{}{\pi}\left(- \; - \frac{}{\nu}\right) \times$$

$$\times \Big\{\Big[\quad (\quad \varepsilon \quad (\; \varepsilon \quad (\qquad (\; \varepsilon \quad (\quad \varepsilon \quad \Big] \; ($$

$$(\quad \sum_{\alpha \qquad \tau} \Big[\quad \varepsilon_\alpha \; (\; \varepsilon_\alpha \; (\quad \varepsilon_\alpha \; (\; \varepsilon_\alpha \quad \Big] \quad \Big\}$$