Status of ßß-decay in Xenon

(or *Back to the Future*)

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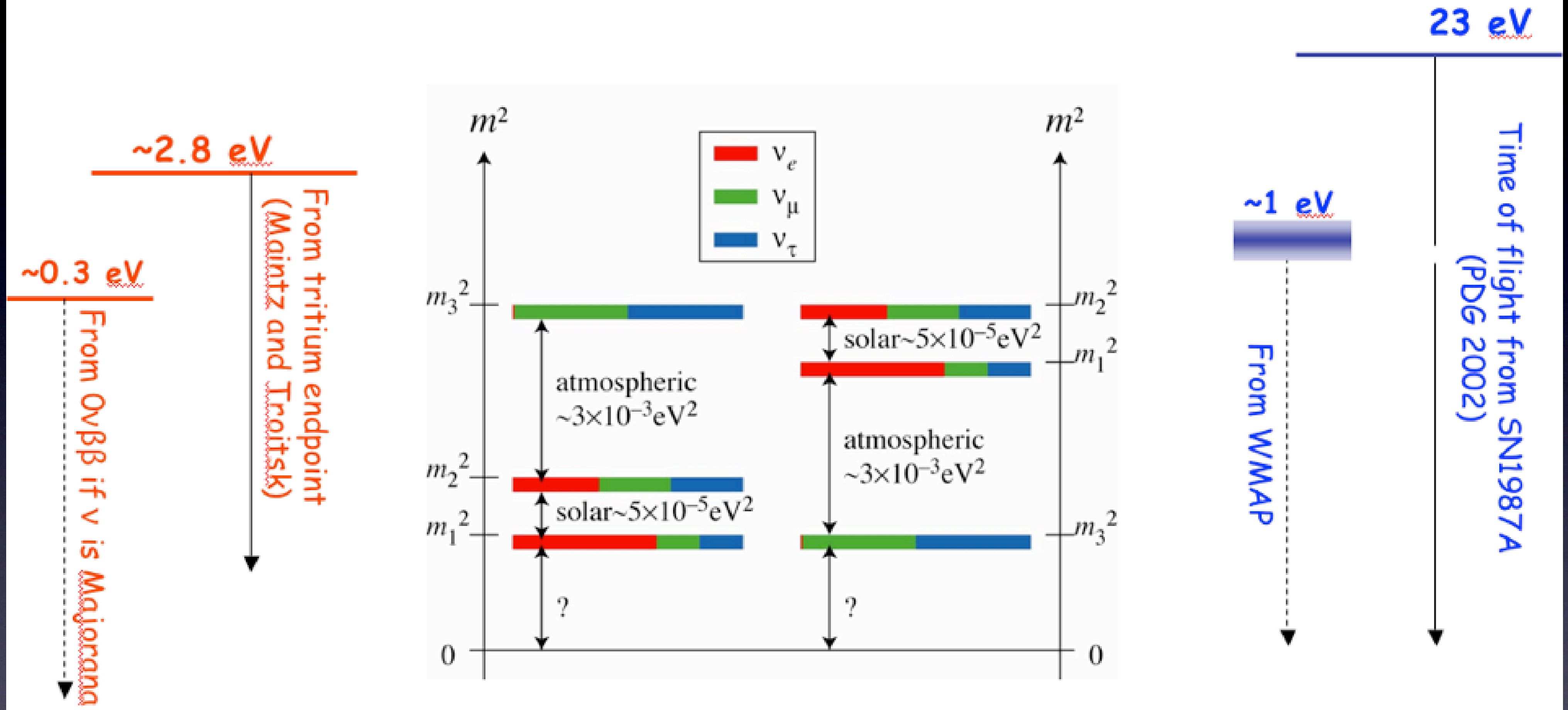
CCLRC/RAL

The most important question in neutrino physics: Neutrino mass scale

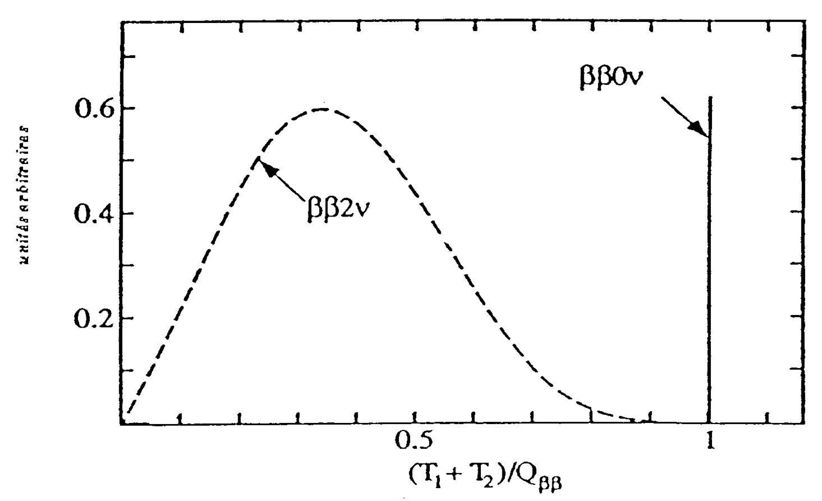


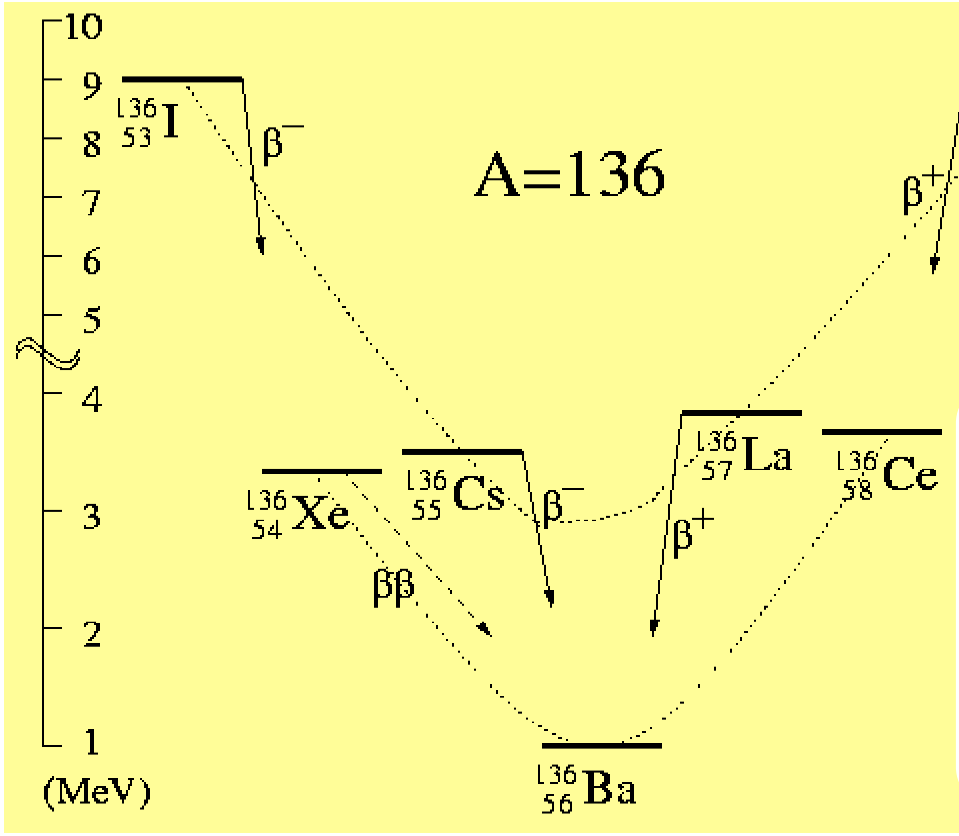
ie. need a ~10-200 meV sensitivity

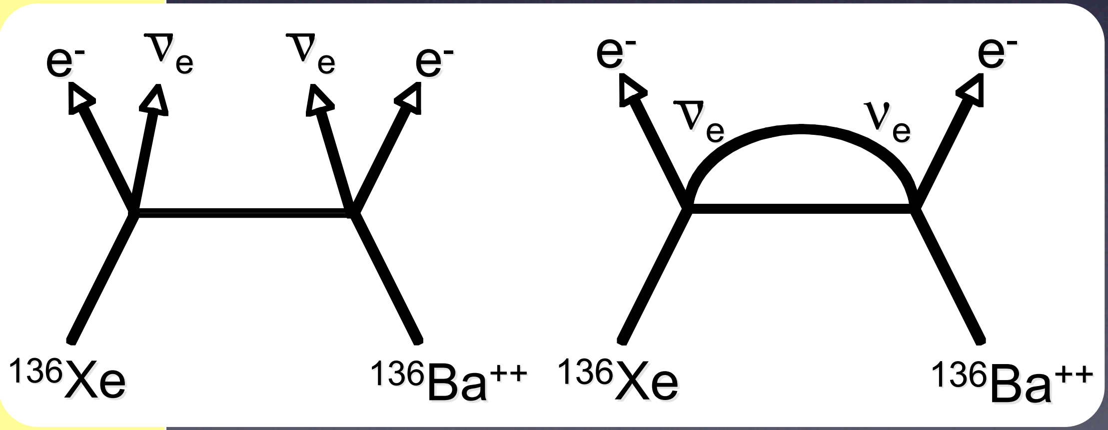
~1e27-1e28 yr in 136Xe

ßß-decay

- Second-order process, only observable when ß-decay is energetically forbidden
  (or strongly suppressed by angular momentum differences)







ßß-decay in Xenon

- 3 candidates to look at:
  - ^{136}Xe, with E_0 = 2.48 MeV, 8.9% natural abundance
  - ^{134}Xe, with E_0 = 0.85 MeV, 10.4% natural abundance
  - ^{124}Xe, with E_0 = 0.82 MeV, 0.1% natural abundance (ßß++ decay !!)

  - **neutrinoless-ßß rate, is going with E_0^5**

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta}\; G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

  - **World yearly production of enriched 124Xe is … 5 liters!**
  - -> 134Xe and mainly **136Xe**

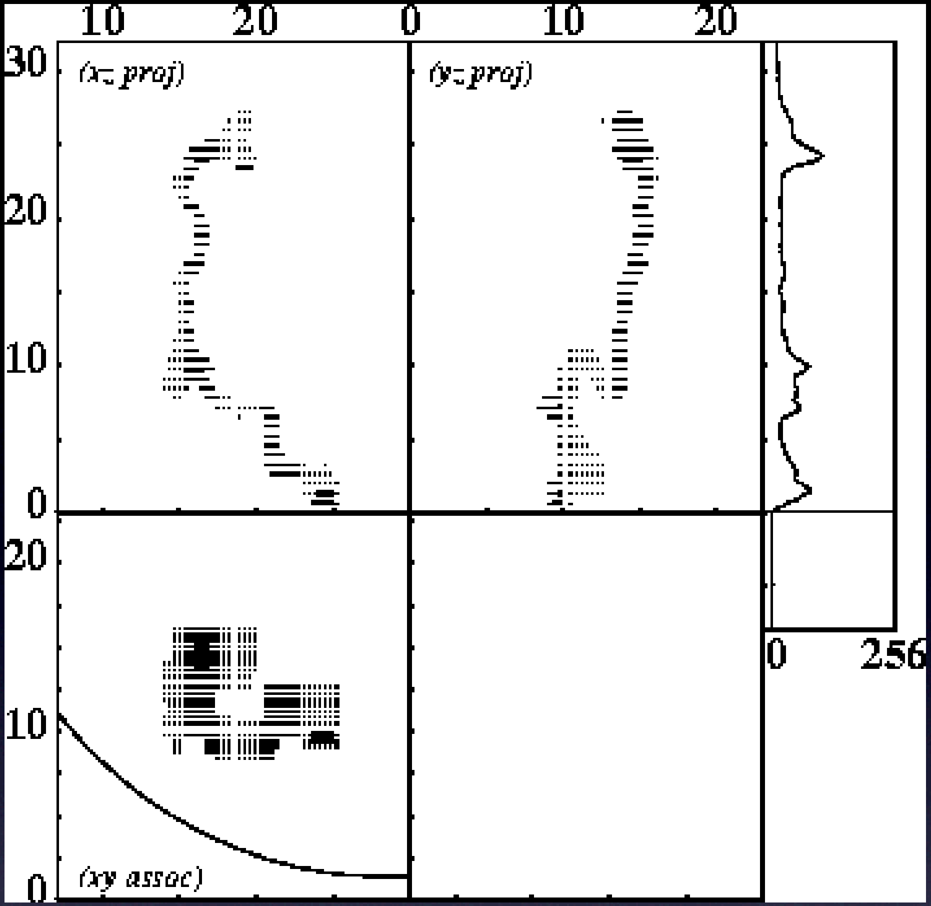
Why Xenon?

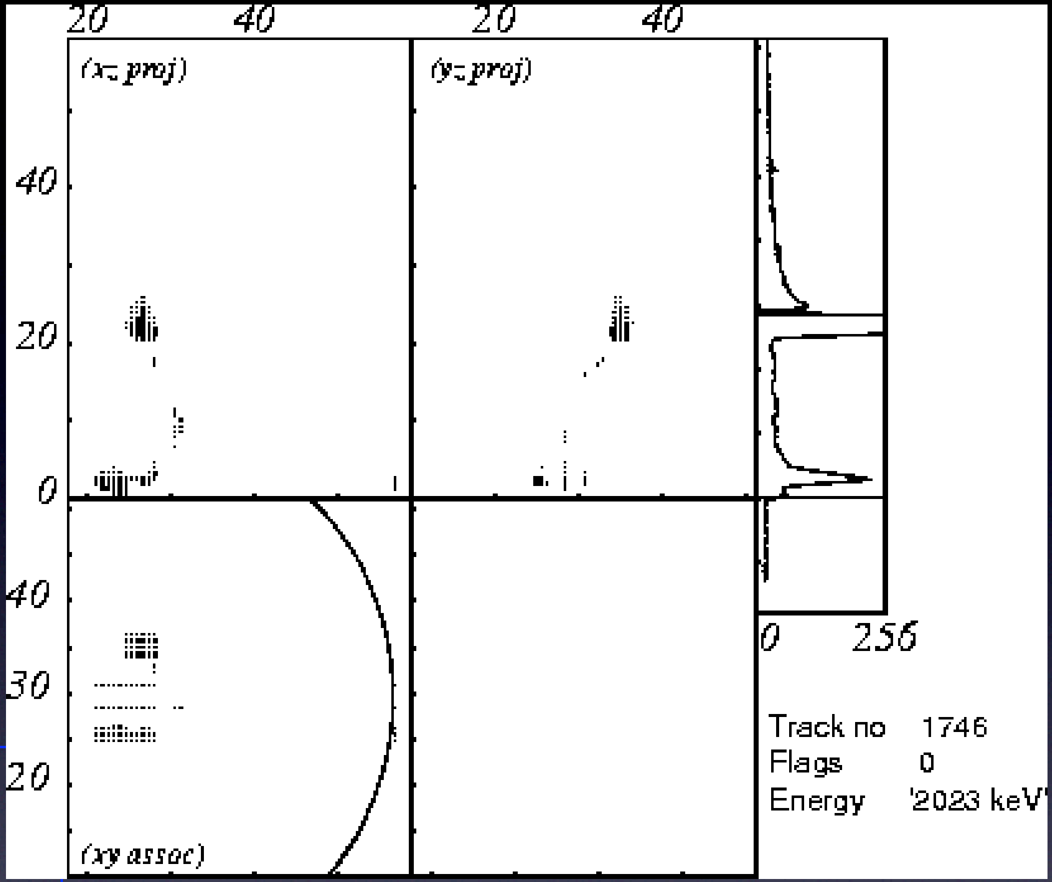
- Low background - once 85Kr removed
  (and can be cleaned without ‘re-crystallising’)
- ‘easy’ enrichment
  (Noble gas = no chemistry needed, centrifuging rate ~ g/s).
- Scintillation properties enables **Pulse-Shape Discrimination** (PSD) between background (electron recoil) and nuclear recoil events.
- **Ionisation** properties …
- Scale up possibilities - up to 1 or 10 tons
  (World yearly production: 36t)

Typical Problems with Xe

- Energy Resolution - not a solid state detector
- Gas-Xe allows tracking, but large mass takes large volume
- Liquid-Xe is very dense but looses tracking capability

Gas Xenon





Advantage:

Tracking background discrimination

Disadvantage:

Large detector for small source mass

Limited energy resolution

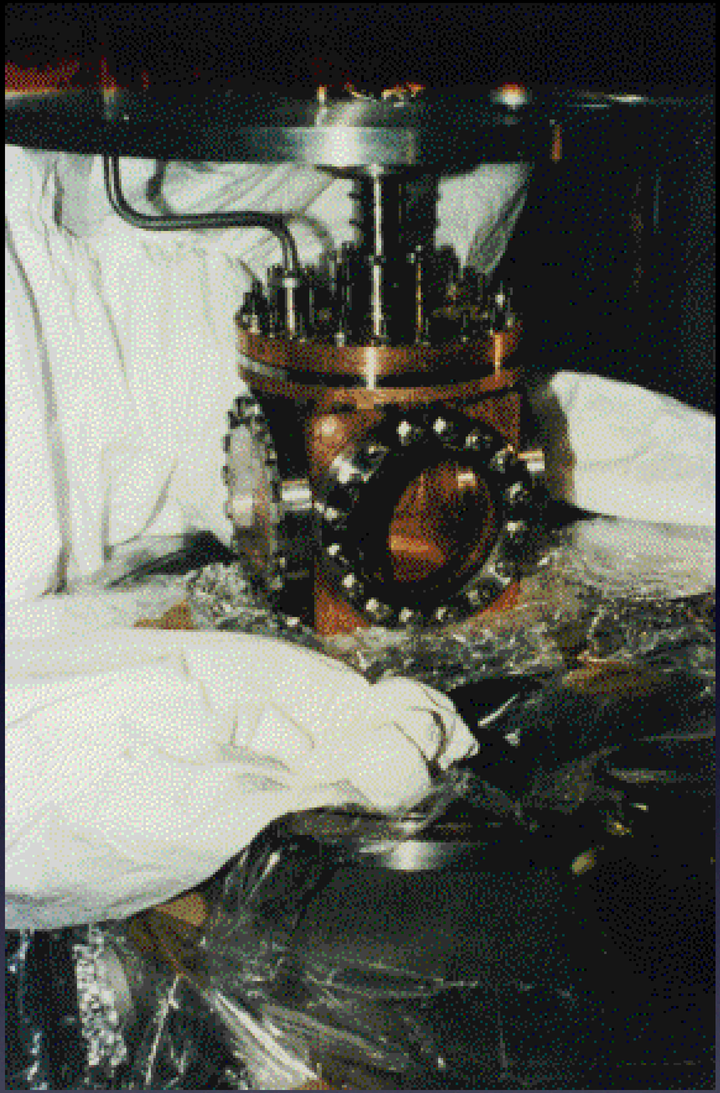
(σ(E)/E = 2.8% at 2480keV)

The Gotthard TPC

Volume: 180l

3.3 kg of ^{136}Xe (62.5% enrichment)

Liquid Xenon



The Dama LXe chamber

Volume: 1.5l

4.5 kg of ^{136}Xe (68.8% enrichment)

Gotthard:
DAMA:

Advantage:

Higher density -> smaller detector

Potentially Improved energy resolution

(Zeplin1: $\sigma(E)/E = 2.3\%$ at 2480keV
Dama: $\sigma(E)/E = 8.8\%$)

Disadvantage:

'Only' pulse shape discrimination

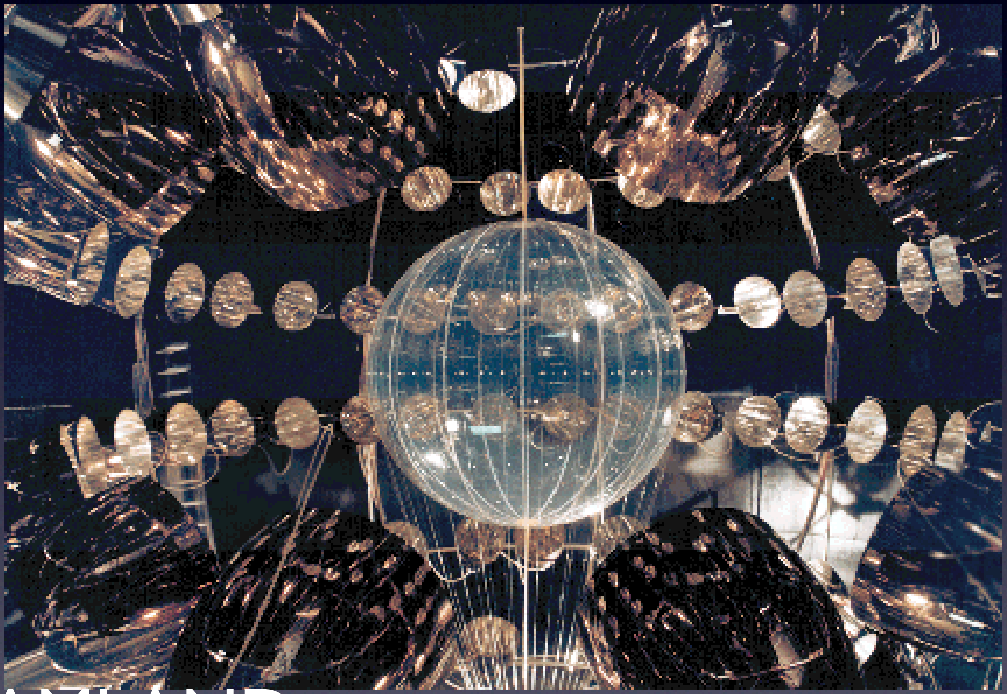
Detector response non-uniformity?

Current status

- Gotthard GXe TPC
  $T_{1/2} > 4.4 \times 10^{23}$ yr, <m> < 1.8-5.2 eV
  Luscher, PLB, 434 (1998) 407
- DAMA LXe scintillation detector
  $T_{1/2} > 1.2 \times 10^{24}$ yr, <m> < 1.1-3.1 eV
  Bernabei, PLB, 546 (2002) 23
- ...

Dissolved Xenon

- The third solution: dissolve Xenon in a large scintillation detector (Raghavan, PRL 72 1411 (1994))
- BOREXINO: 300t scintillator
  1.565t of Xe (enriched to 80%)
  sensitivity: 1.14e27 yr
  backgnd: 0.003 /kev/kg/yr
  (Caccianiga, Giammarchi,
  Astopart Phys 14 15 (2000))



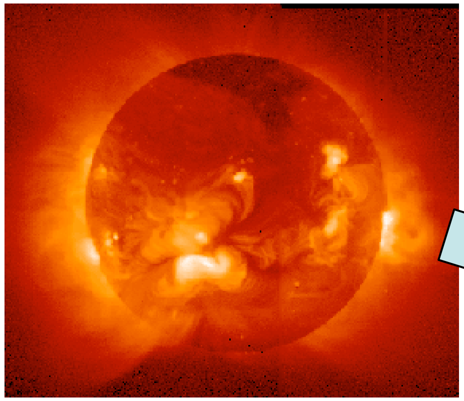
- Also evoked for SNO and KAMLAND ...

... but unlikely to happen in either 3!

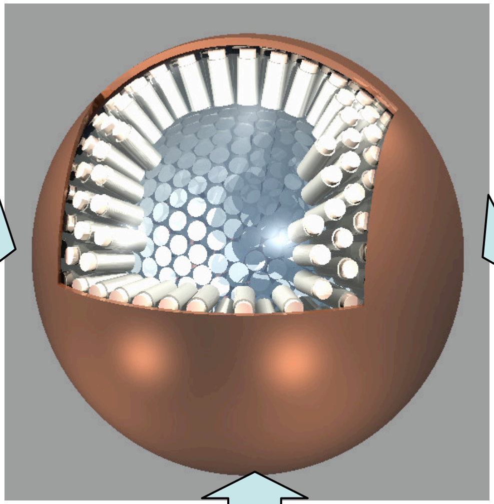
XMASS

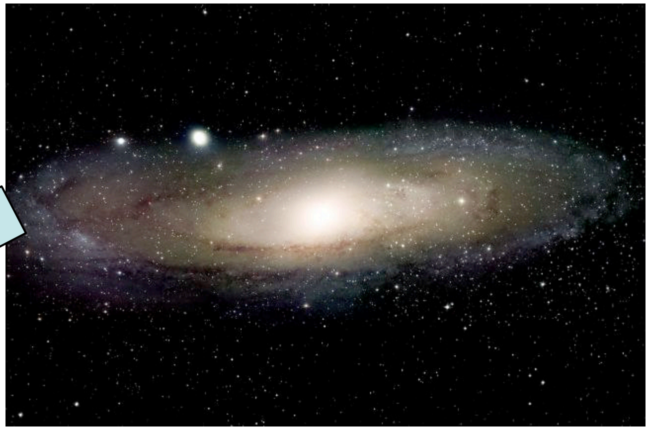
Multi purpose low-background experiment with liq. Xe

- **X**enon **MASS**ive detector for solar neutrino (**pp/^{7}Be**)
- **X**enon neutrino **MASS** detector (**ββ decay**)
- **X**enon detector for Weakly Interacting **MASS**ive Particles (**DM search**)

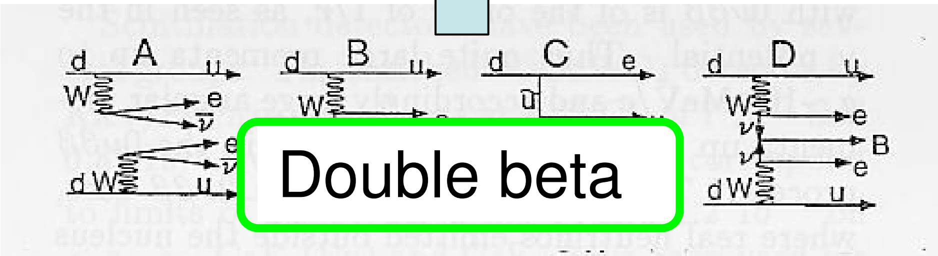


Solar neutrino





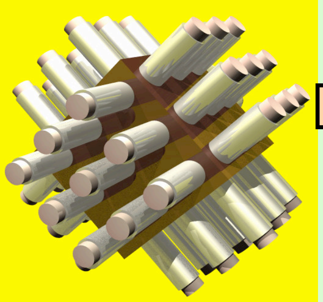
Dark matter



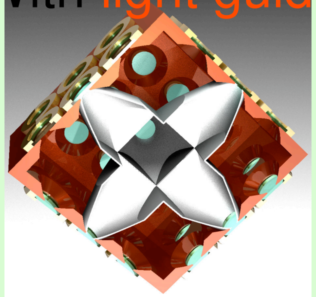
Double beta

➢ Strategy of the scale-up

100kg Prototype

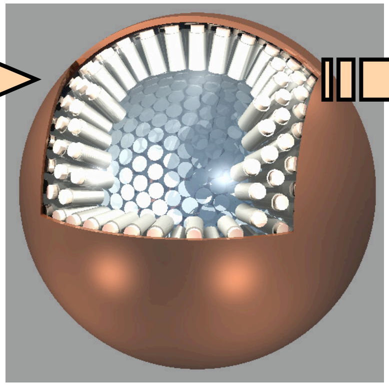


With light guide



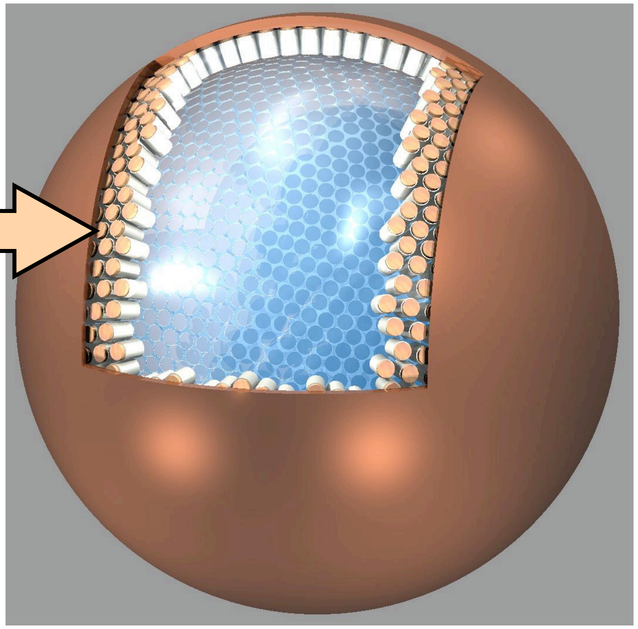
～30cm

800kg detector



～80cm

10 ton detector



～2.5m

R&D

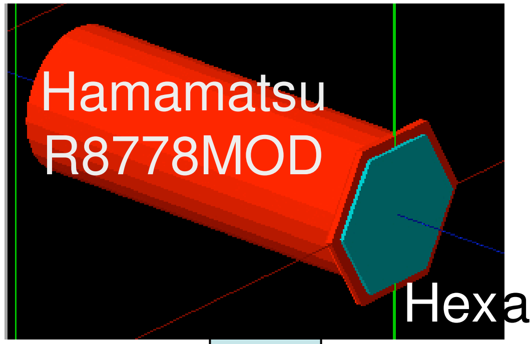
- ✓ Vertex & energy reconstruction
- ✓ Self shielding power
- ✓ BG level

We are here !

Dark matter search

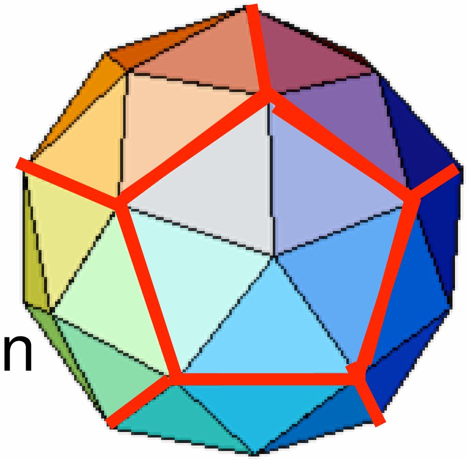
Multipurpose detector
(solar neutrino, $\beta\beta$ …)

Structure of 800 kg detector

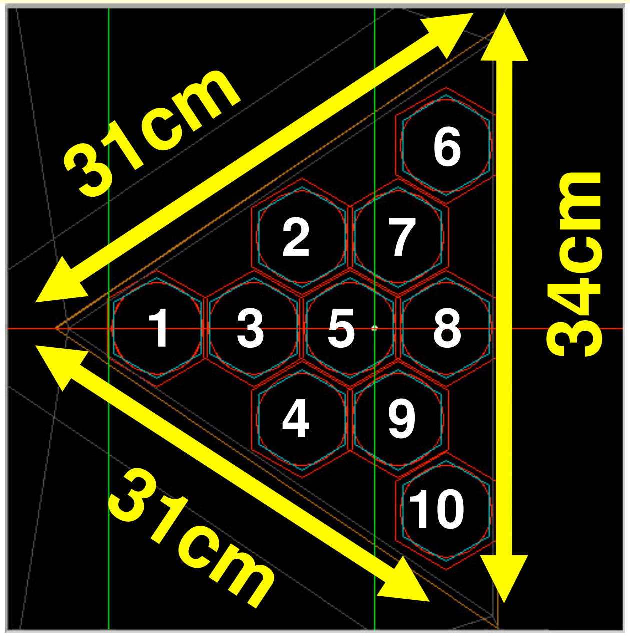


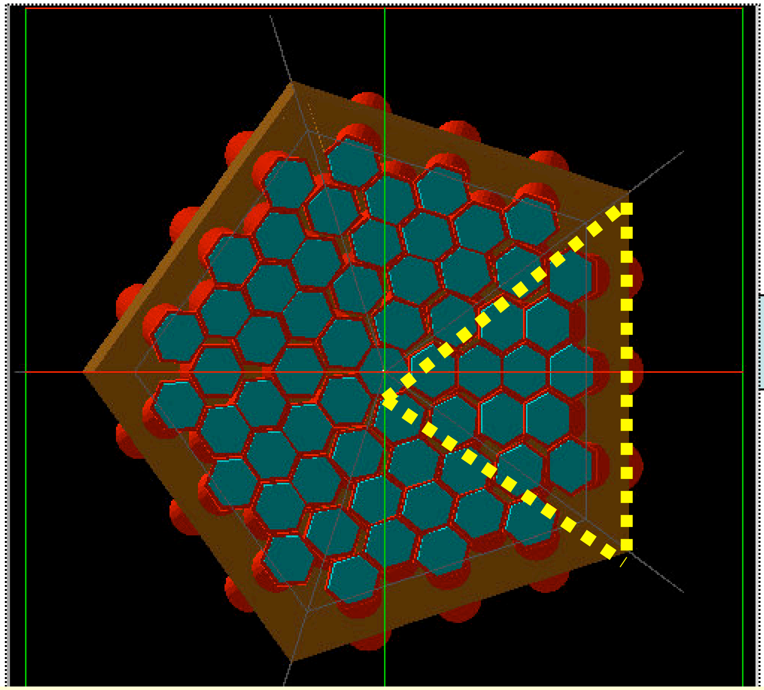
Hexagonal
quarts window

12 pentagons /
pentakisdodecahedron

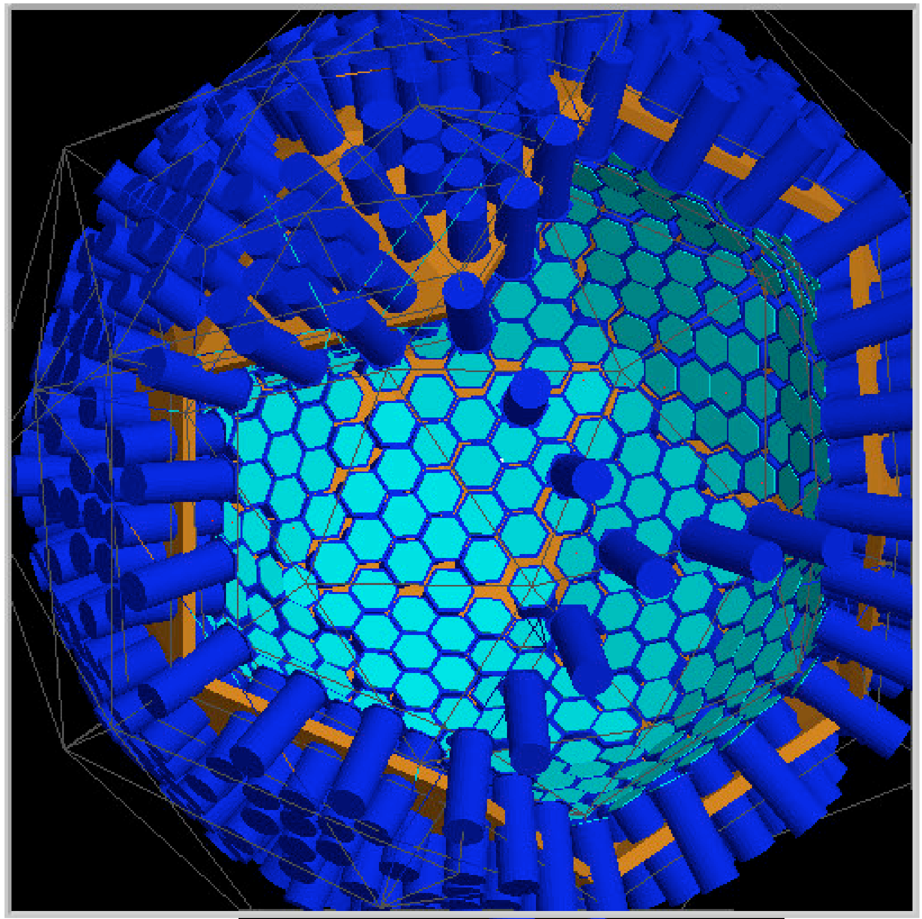


10 PMTs per 1 triangle

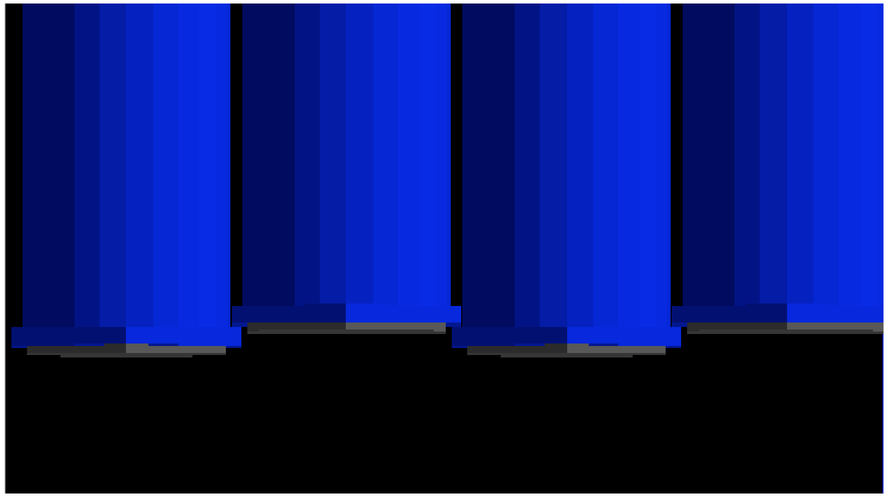




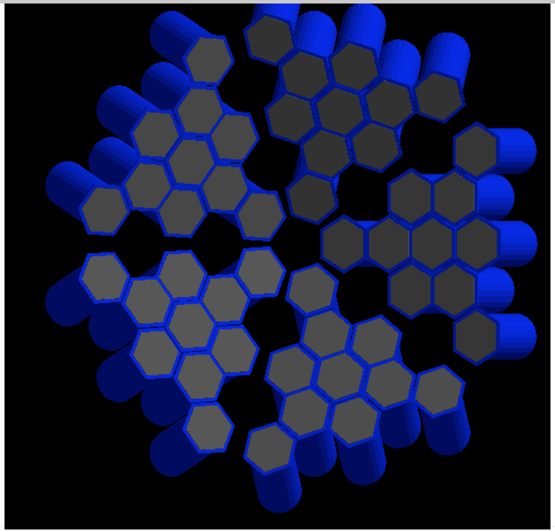
5 triangles make pentagon

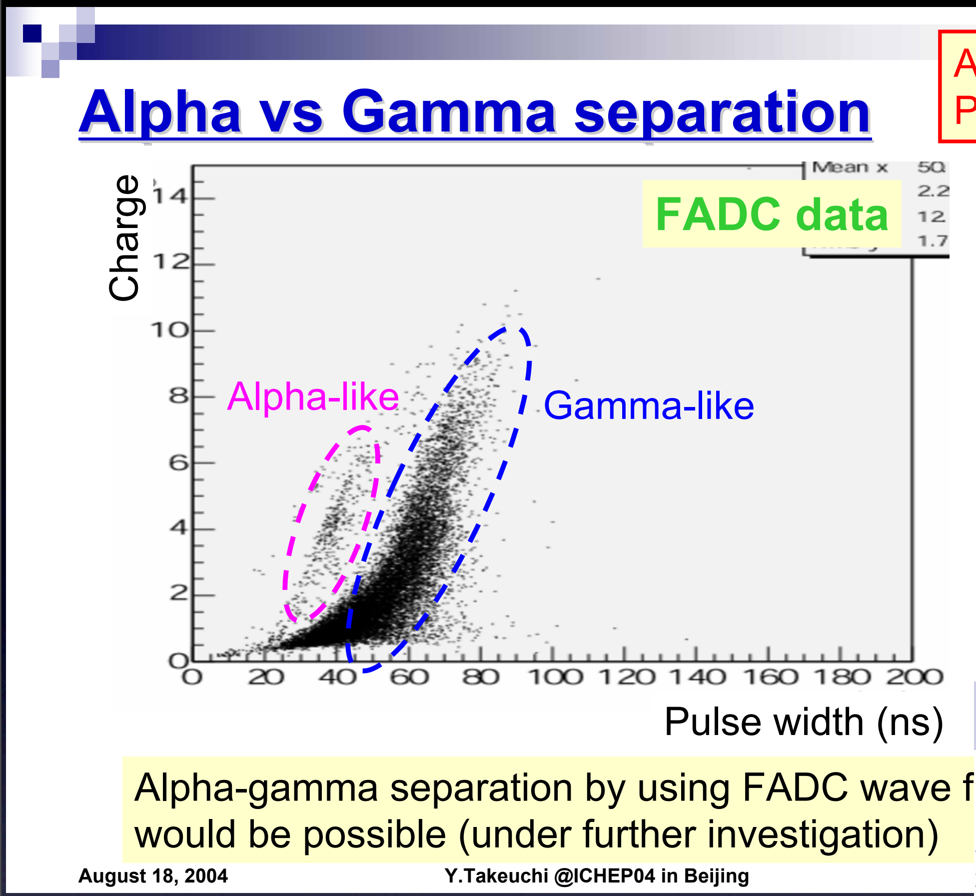


- Total **812** hex **PMTs** (10PMTs/triangle × 60 + 212 @gap) immersed into liq. Xe
- **~70%** photo-coverage
- Radius to inner face **~44cm**



Each rim of a PMT overlaps to maximize coverage



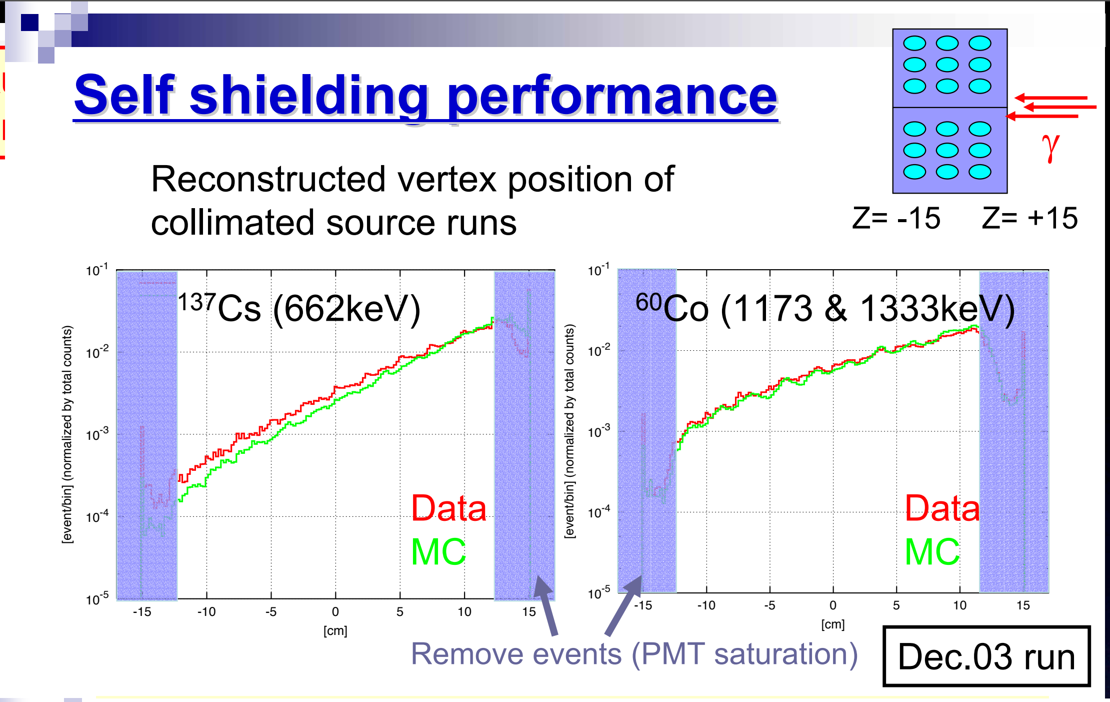


Alpha vs Gamma separation

Au
Pr

Alpha-gamma separation by using FADC wave f
would be possible (under further investigation)

August 18, 2004 Y.Takeuchi @ICHEP04 in Beijing



Self shielding performance

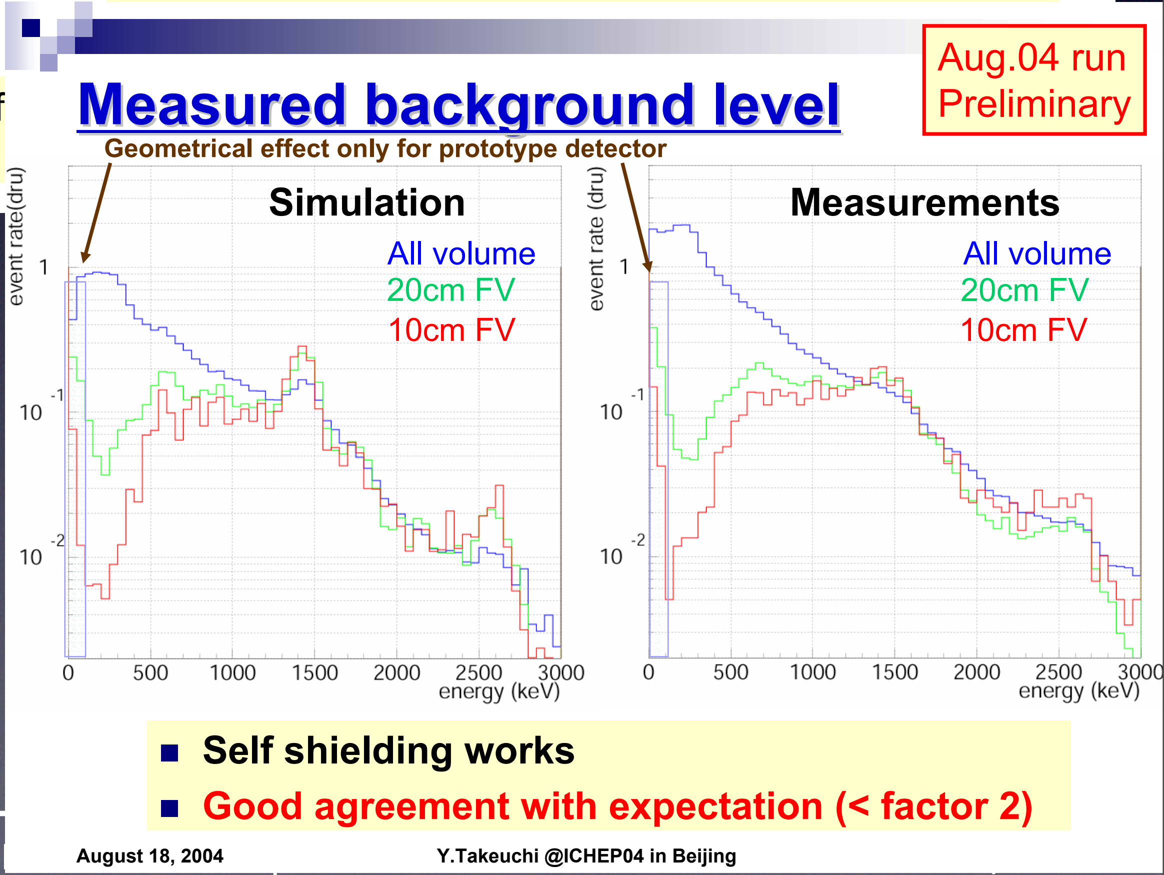
Reconstructed vertex position of collimated source runs

Remove events (PMT saturation)

Dec.03 run

100kg Prototype measurements

- Good position reconstruction
- background 11 c/kev/kg/yr !!!!



Measured background level

Aug.04 run
Preliminary

Geometrical effect only for prototype detector

- Self shielding works
- Good agreement with expectation (< factor 2)

August 18, 2004 Y.Takeuchi @ICHEP04 in Beijing

XMASS prospects

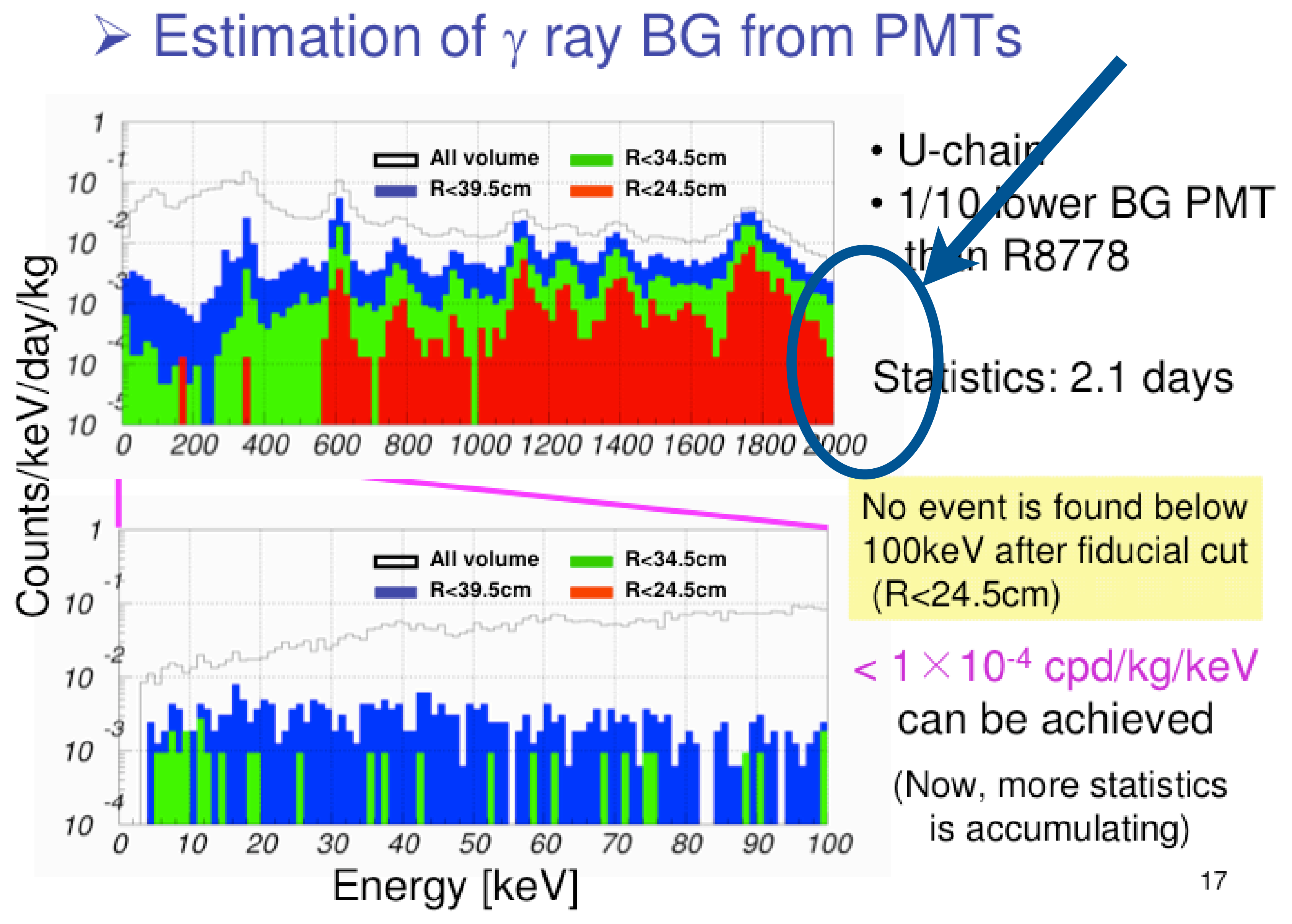
100kg prototype: 11 c/kev/kg/yr background
By comparison :
Zeplin1 had 0.05 c/kev/kg/yr at 2.5MeV
Zeplin2 has <0.06 c/kev/kg/yr at 2.5MeV
(limit extracted from 2 days realtime of monitoring runs)

800kg detector:
100kg fiducial mass for ßß-search

Extrapolating ΔE from prototype and photocathode coverage: ΔE/E ~ 0.05

To be competitive: reduction by a factor 10e5
to ~1e-4 c/kev/kg/yr

Background estimate for DM search !!



➢ Estimation of γ ray BG from PMTs

- U-chain
- 1/10 lower BG PMT than R8778

Statistics: 2.1 days

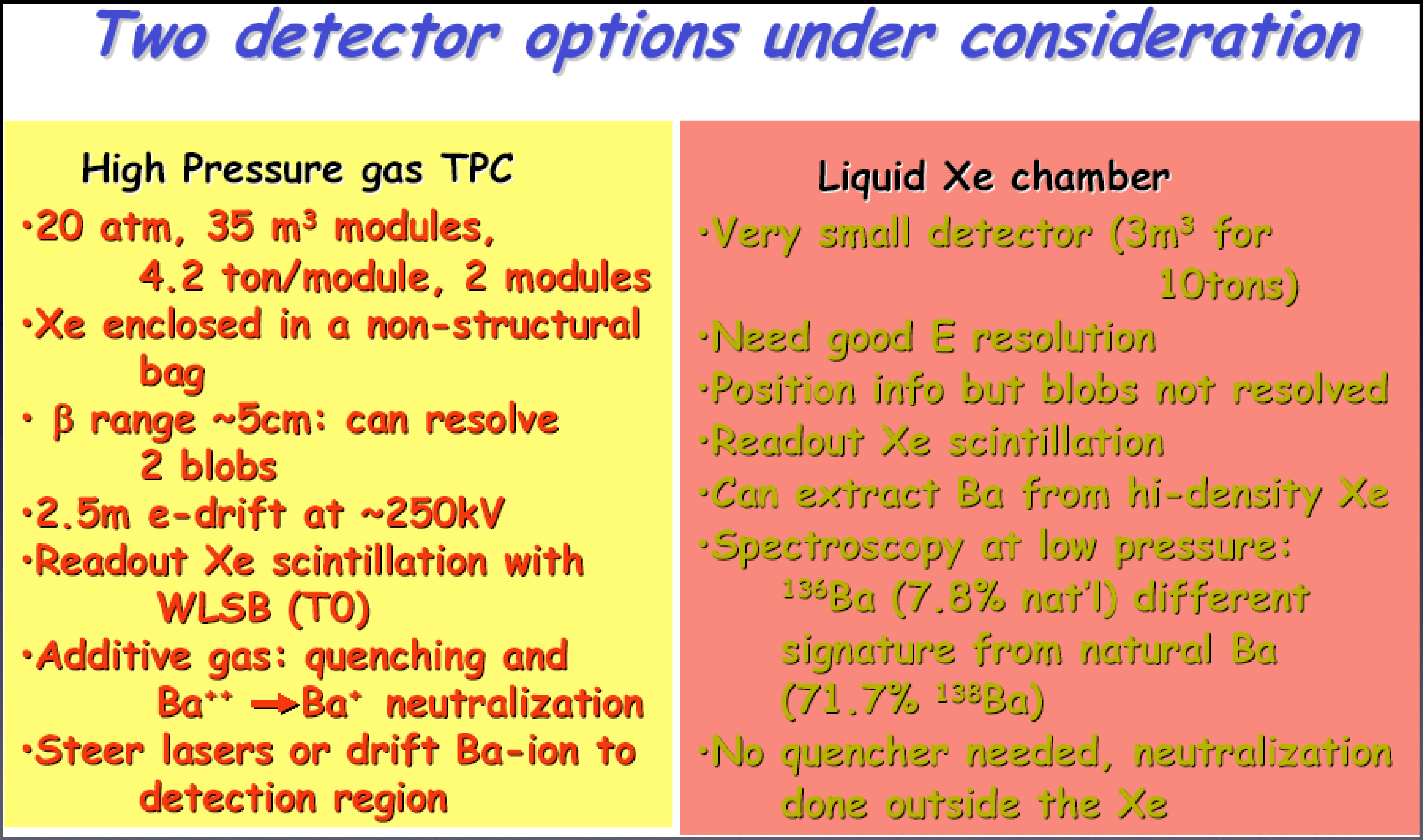
No event is found below 100keV after fiducial cut (R<24.5cm)

$< 1 \times 10^{-4}$ cpd/kg/keV can be achieved

(Now, more statistics is accumulating)

17

EXO



Two detector options under consideration

High Pressure gas TPC

- 20 atm, 35 m^3 modules, 4.2 ton/module, 2 modules
- Xe enclosed in a non-structural bag
- β range ~5cm: can resolve 2 blobs
- 2.5m e-drift at ~250kV
- Readout Xe scintillation with WLSB (T0)
- Additive gas: quenching and $Ba^{++} \rightarrow Ba^{+}$ neutralization
- Steer lasers or drift Ba-ion to detection region

Liquid Xe chamber

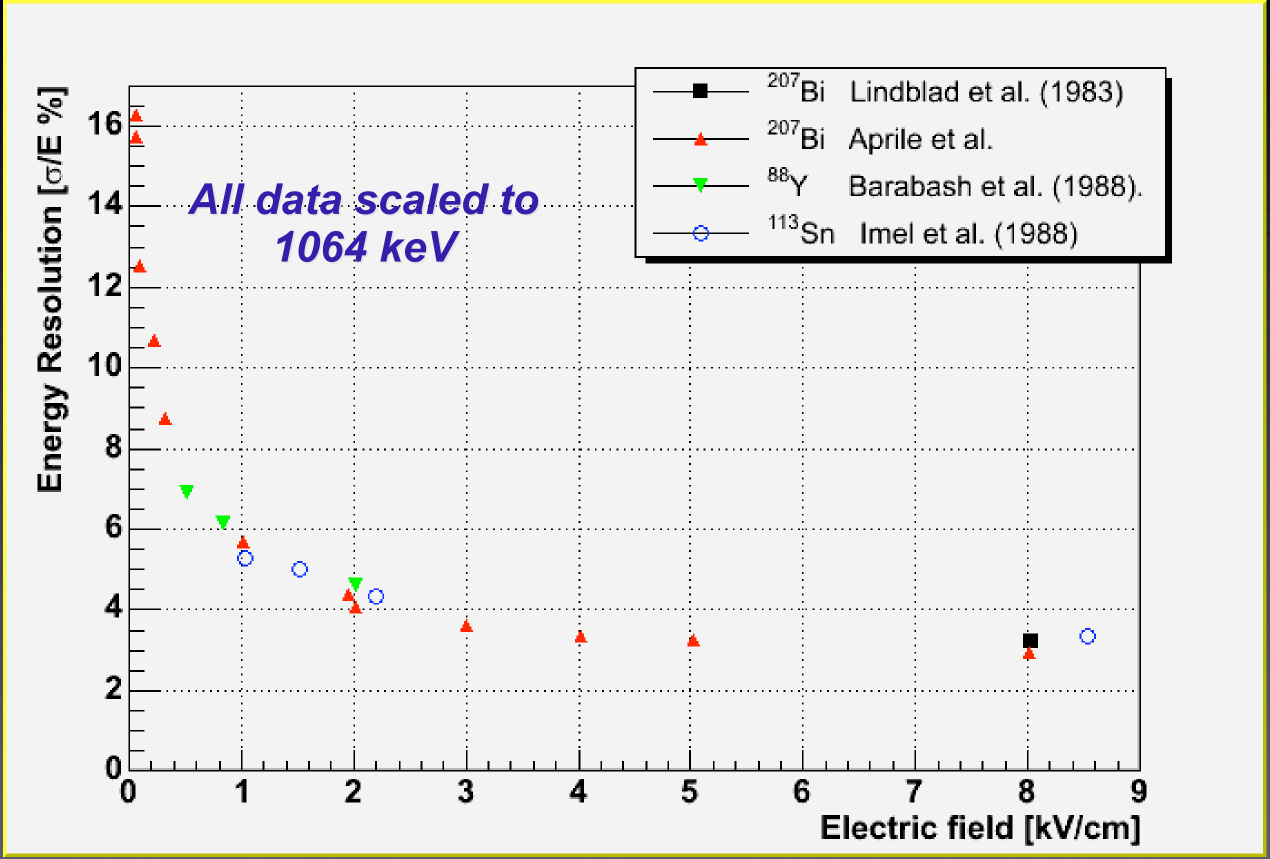
- Very small detector ($3m^3$ for 10tons)
- Need good E resolution
- Position info but blobs not resolved
- Readout Xe scintillation
- Can extract Ba from hi-density Xe
- Spectroscopy at low pressure: ^{136}Ba (7.8% nat'l) different signature from natural Ba (71.7% ^{138}Ba)
- No quencher needed, neutralization done outside the Xe

EXO

- Main problems to address:
  - Energy resolution - not least to disentangle 2-neutrinos from 0-neutrino mode
  - Background rejection - ßß signature

EXO- energy resolution

Highly non–Poisson statistics limit calorimetric resolution in LXe



$$\sigma \sim \sqrt{FN_e}$$

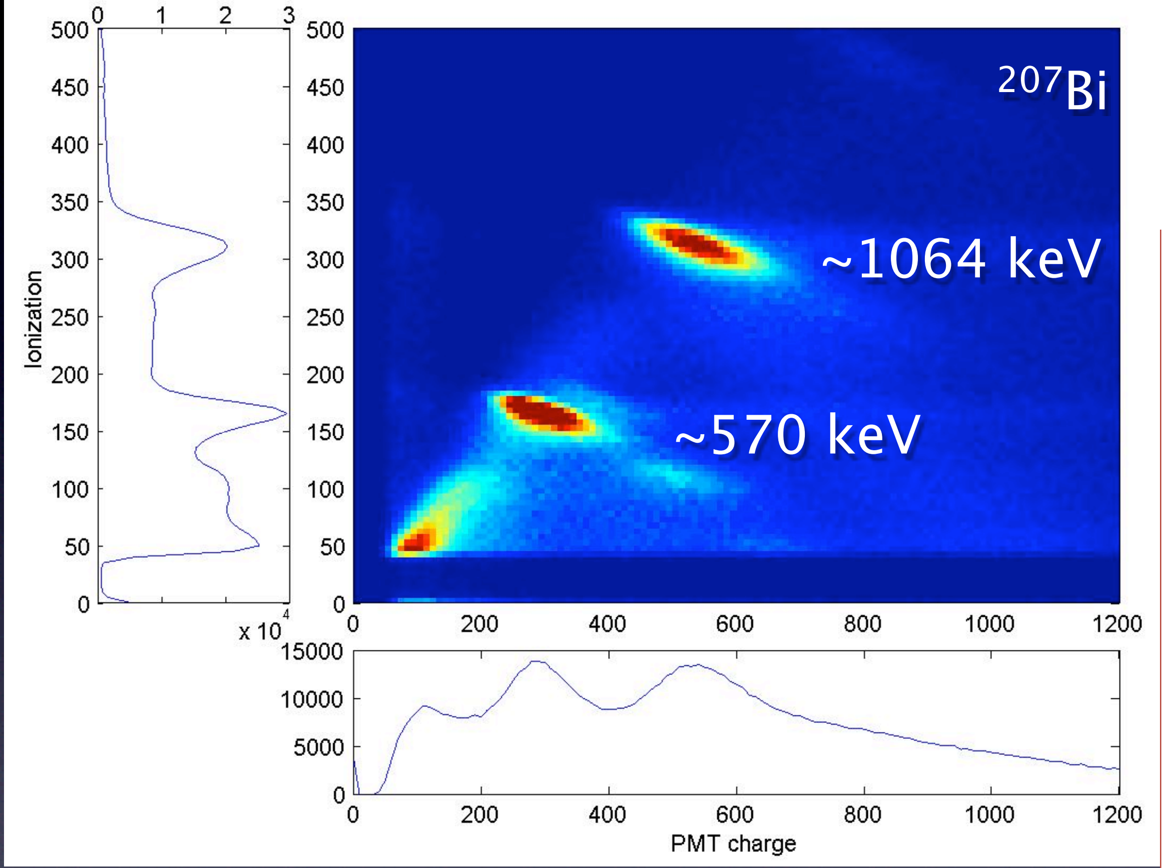
$$F_{\text{Pred.}} \sim 0.05^{a}$$

$$F_{\text{Meas.}} > 20^{b}$$

[a] T. Doke, et. al, Nucl. Instrum. Methods Phys. Res. 134, 353 (1976)

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

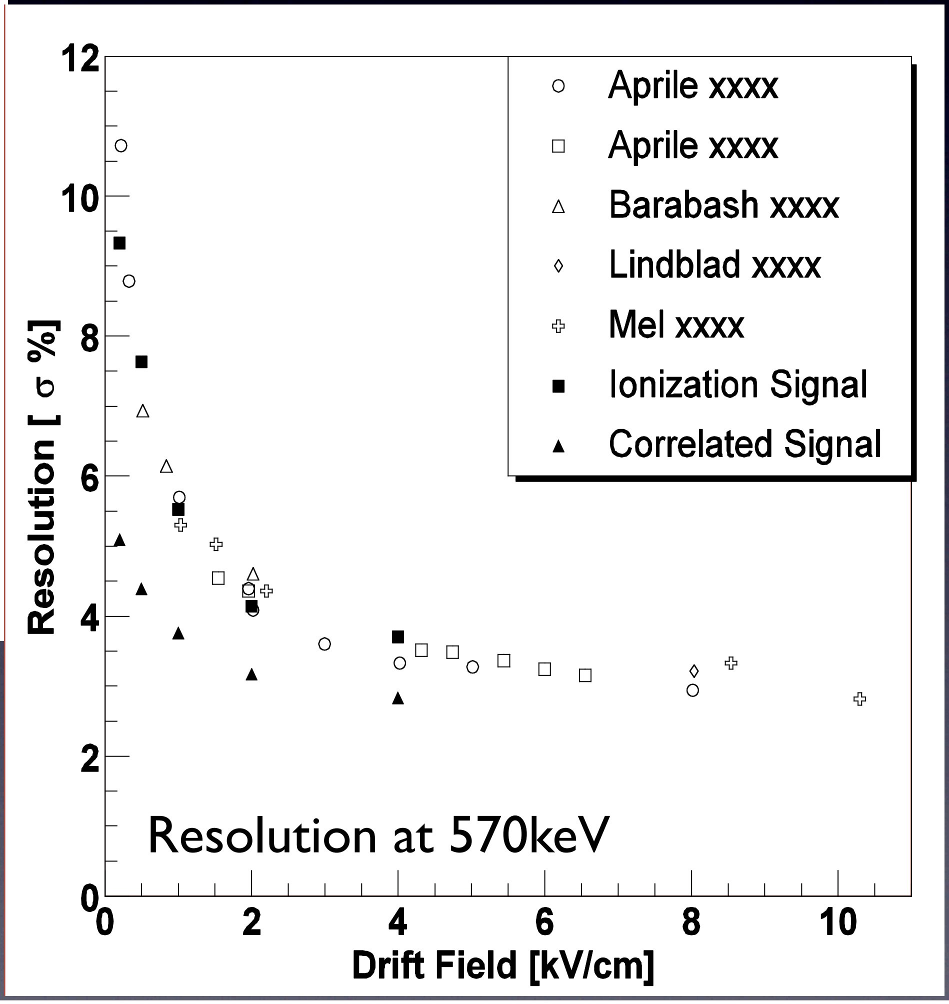
EXO- energy resolution



Using anti-correlation:

$\Delta E/E \sim 0.014$ @ 2.48MeV

(0.018 with ionisation only)



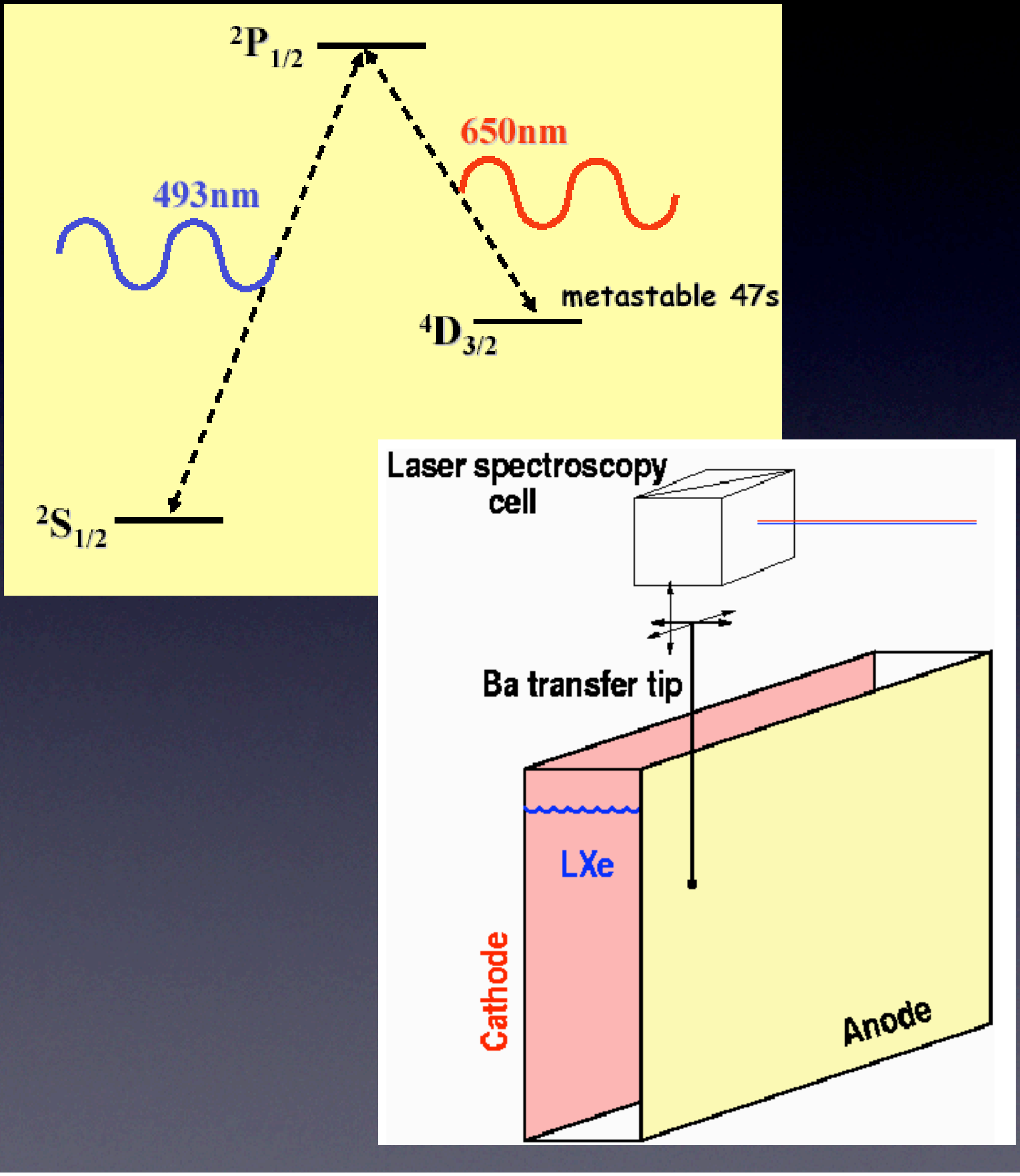
Small test chamber results

(EXO-200 will collect 3 times more light - ie further improvement possible)

EXO ßß signature

Xe offers a qualitatively new tool against background:

$^{136}Xe \rightarrow {}^{136}Ba^{++}\, e^{-}\, e^{-}$ final state can be identified using optical spectroscopy (M. Moe, Phys. Rev. C 44 (1991) 931)



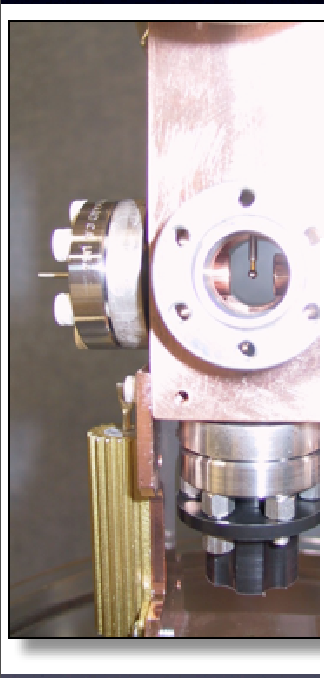
GXe: laser brought to event

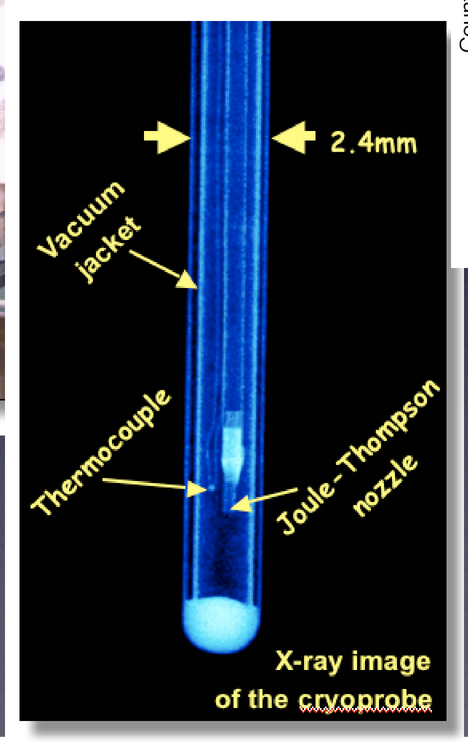
LXe: ion extracted, moved to quadripole and analysed
Important additional constraint

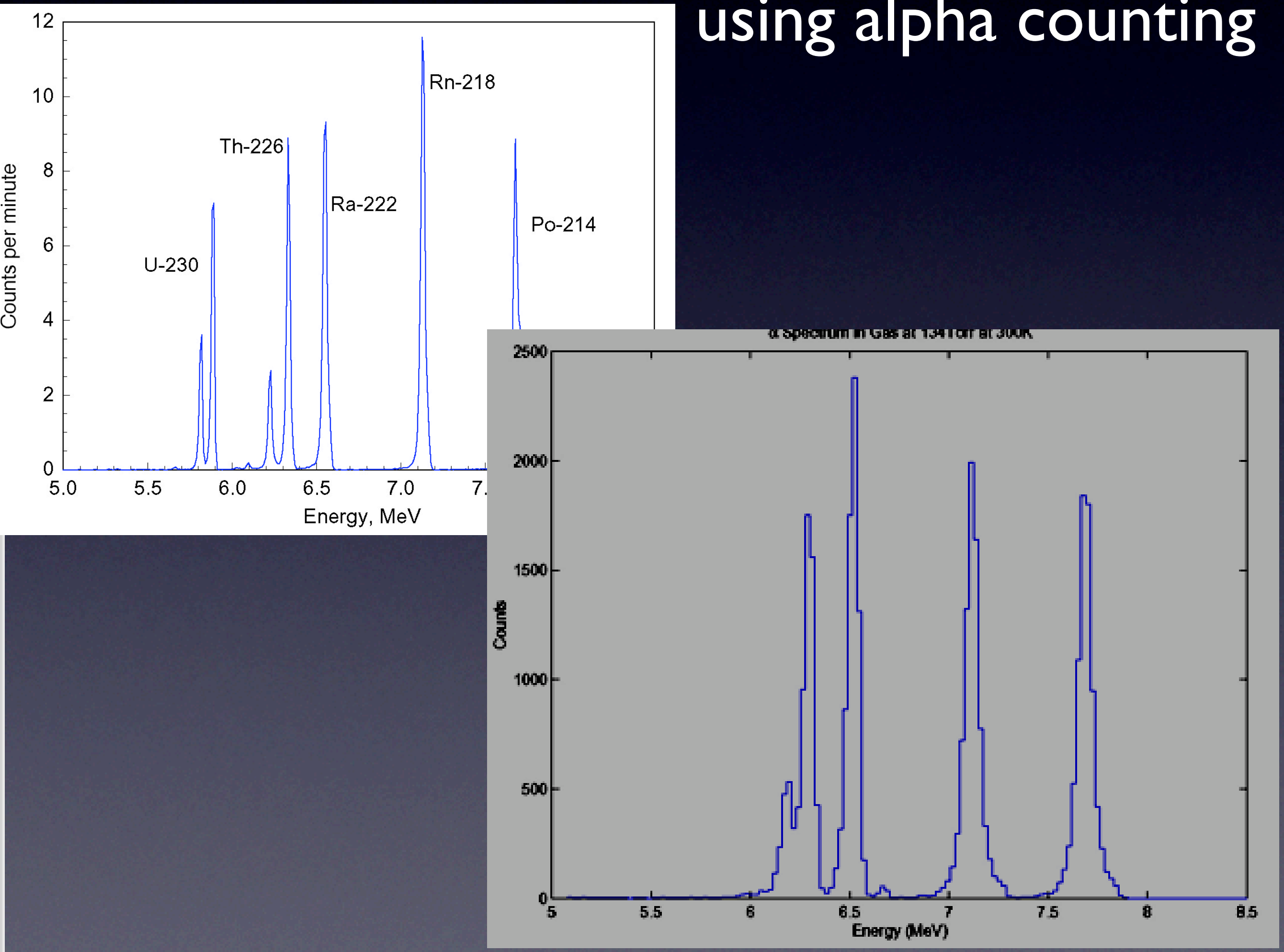
Laser tagging - how it works

1. grabbing of 136Ba+ ion

Tested with 230U ions:
similar chemistry, but easier signature
using alpha counting

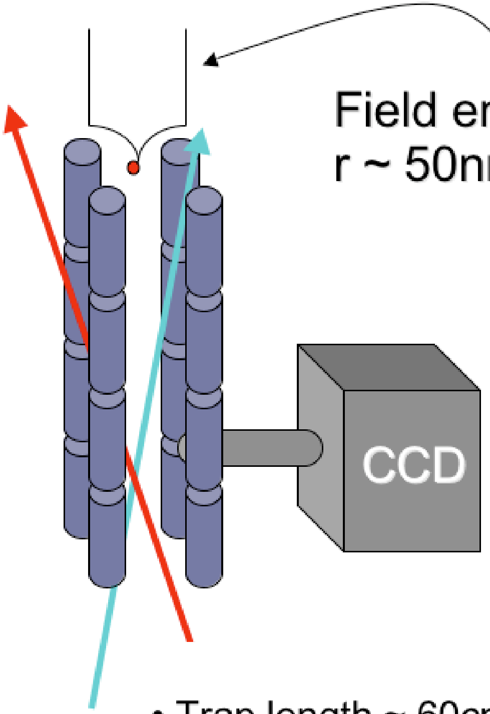






2. release of 136Ba+ in quadripole

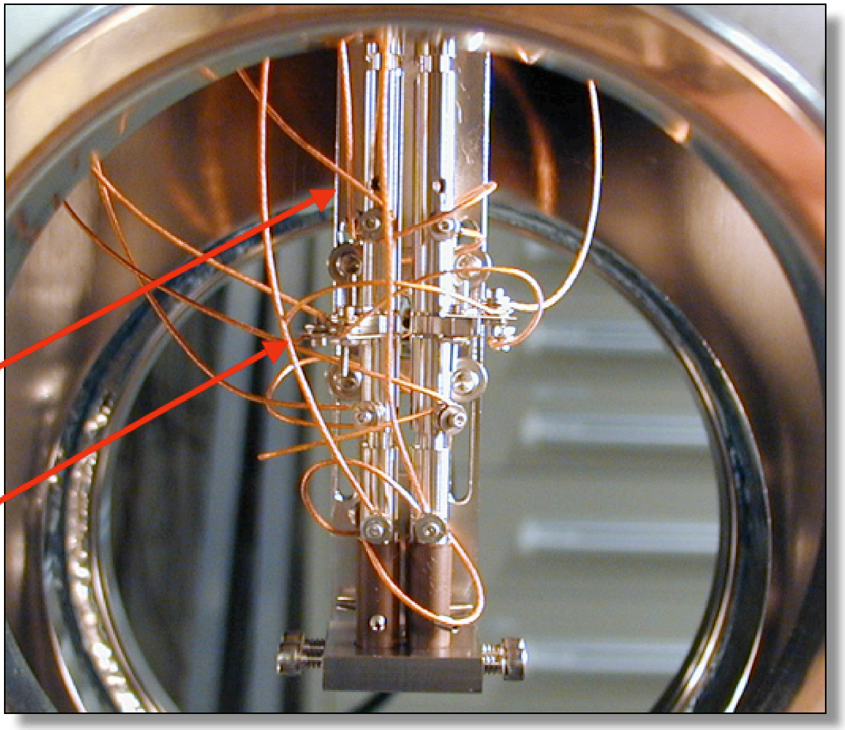
- Load ion into trap with oven
- Observe in trapping region
- Field *adsorb* ion onto tip
- Field *desorb* ion from tip into trap and observe



- Trap length ~ 60cm (no limiting factor on length)
- 16 independently computer-controlled segments (real time)
- RF low (no breakdown in buffer gas)

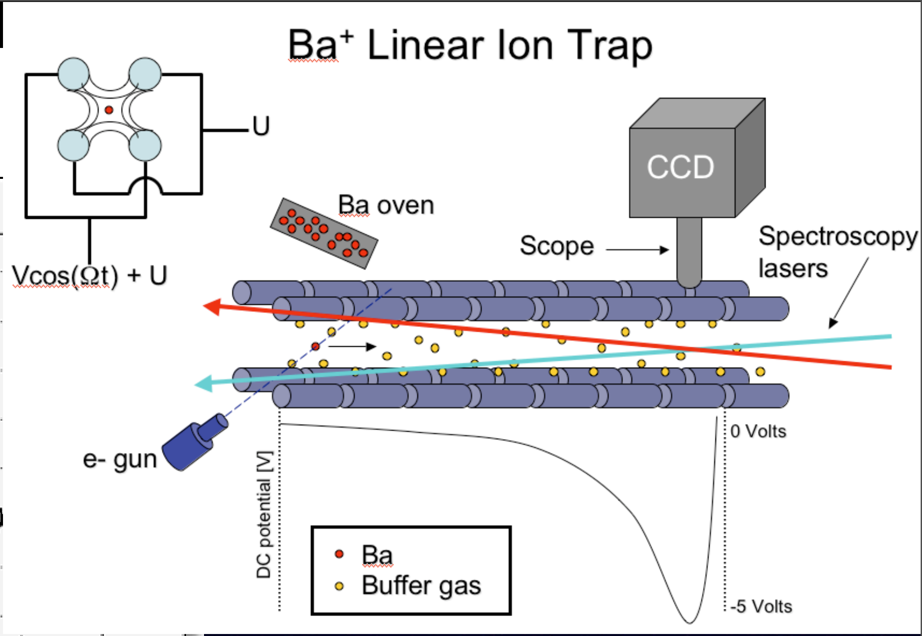
Transport segments (~3 cm length)

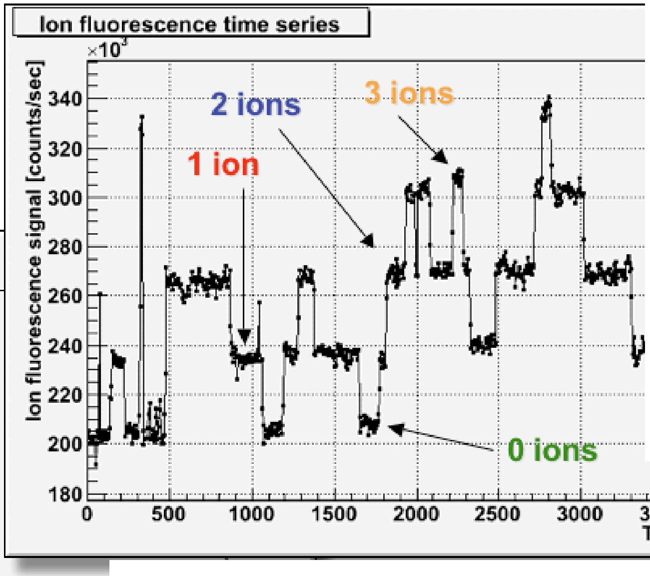
Trapping segments (~3 mm length)

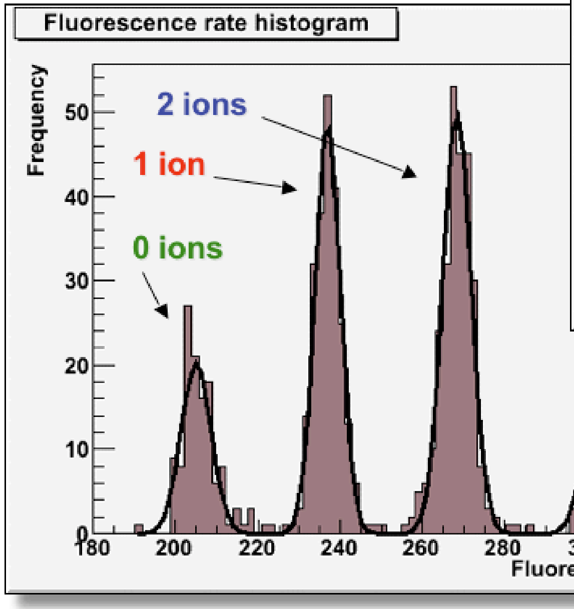


Ion quantization in Helium

- P_{buffer} ~ 10^{-3} torr Helium
- 5 sec integration per point
- Peak separation ~ 8.7σ







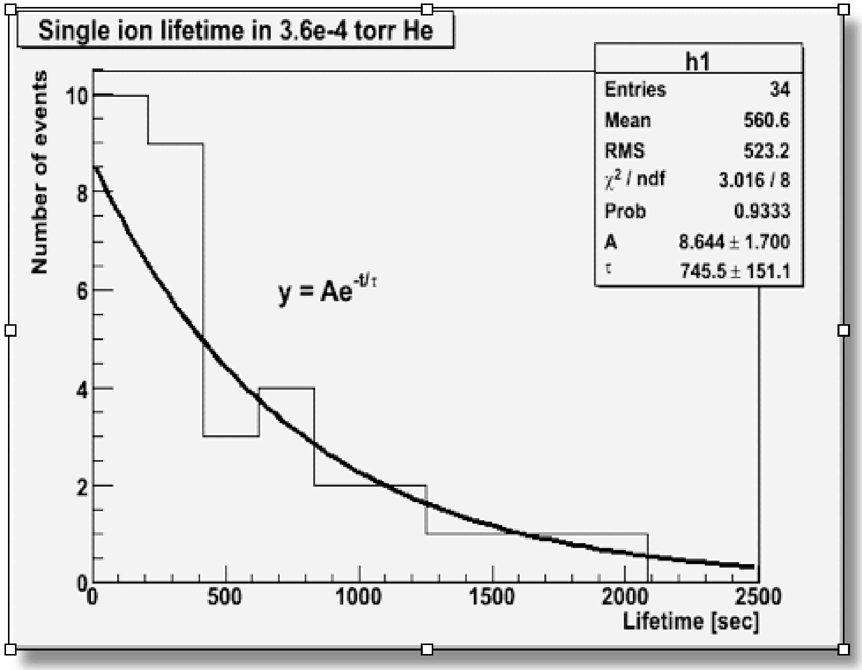
3. evidence of 136Ba+ ion

been tested in He and Argon

- P_{buffer} ~ 3.6×10^{-4} torr He
- Single ion is loaded, and timed until ejection from trap
- Ion lifetimes histogrammed and fit to exponential
- Lifetime follow exponential distribution with

τ ~ 746 ± 151 sec

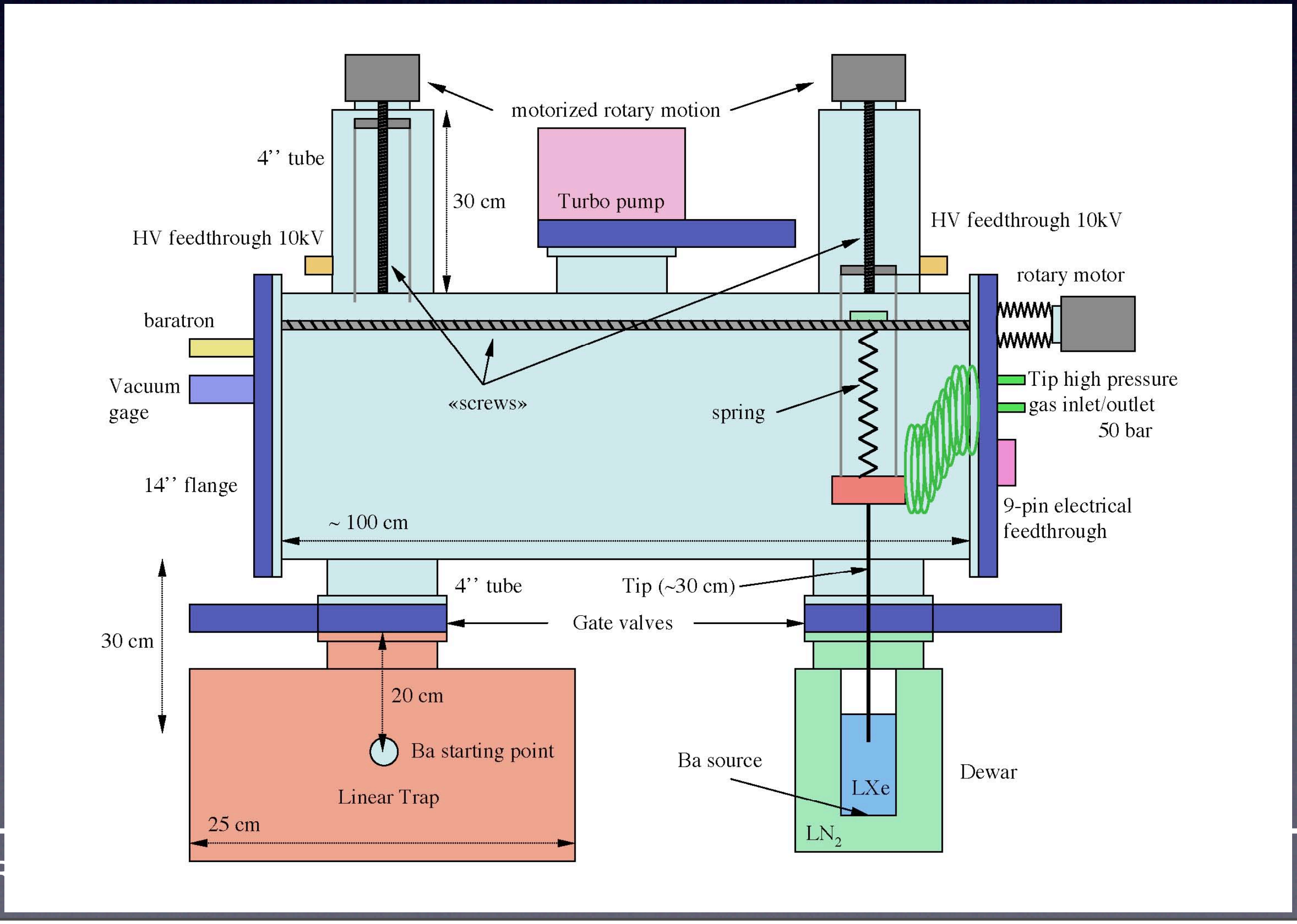
→ Probably capture on impurities in trap (O_2, NO, CO_2, etc.)

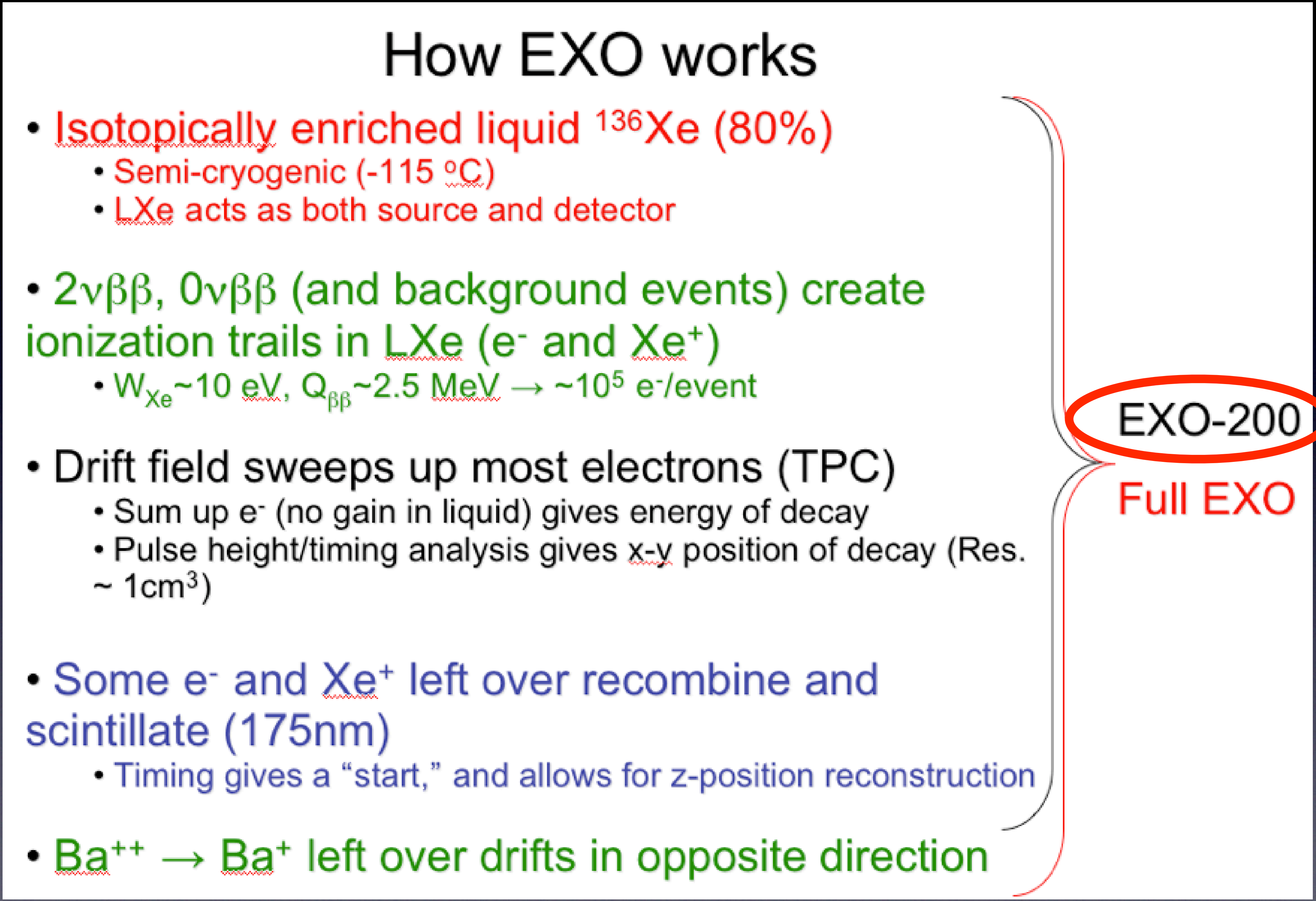


3.6×10^{-4} torr He → λ_{mfp} ~ 31cm → $R_{collision}$ ~ 740 Hz → *2 ppm impurities*

Laser tagging - R&D

- Choice of grabbing tip
  - QCM tip; FE tip (field emission); RIS tip (resonant ionisation spectroscopy)
- Proof of grabbing/releasing/measure all-in-one in a ‘real’ detector
  - build of an R&D 100kg LXE TPC





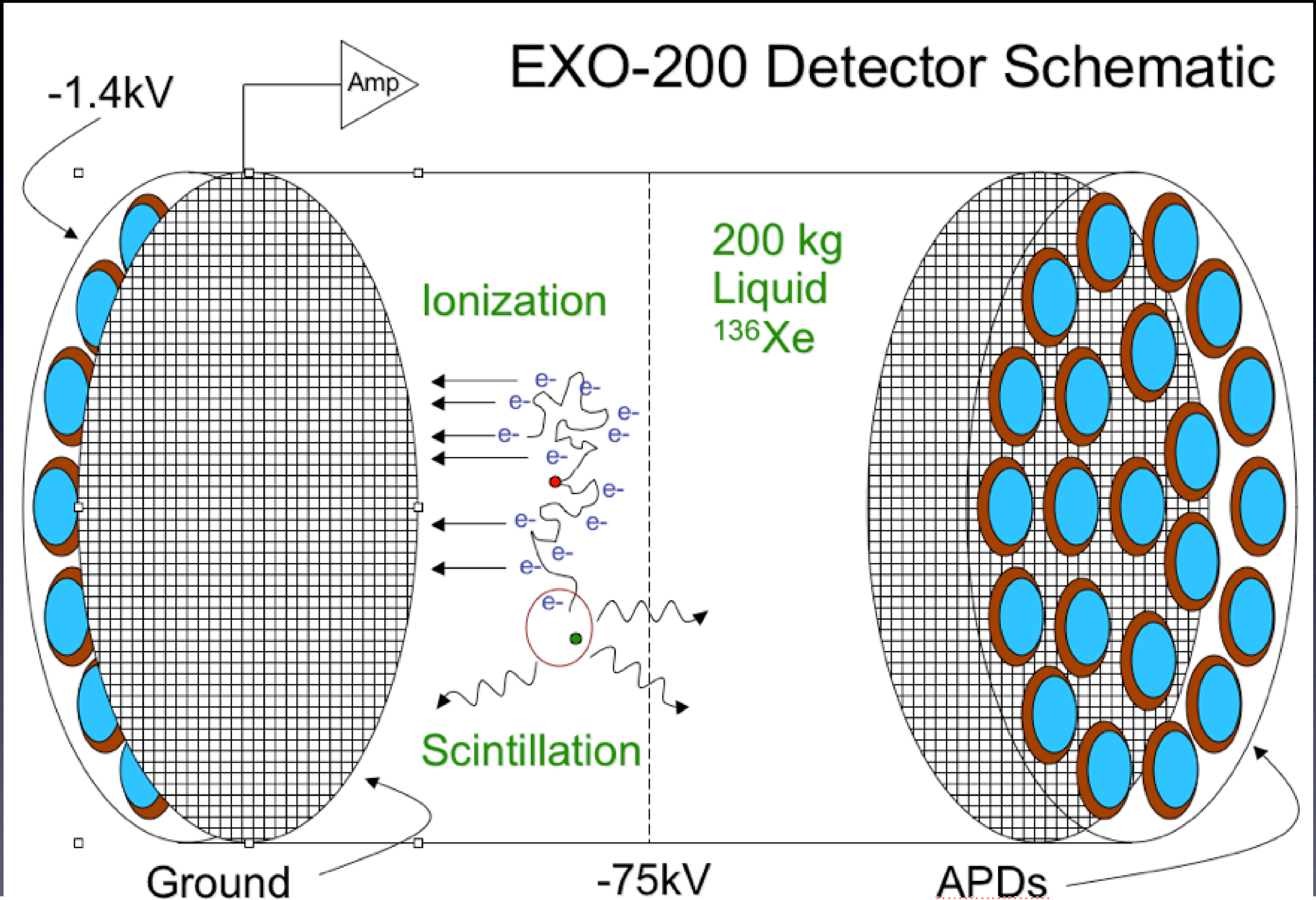
How EXO works

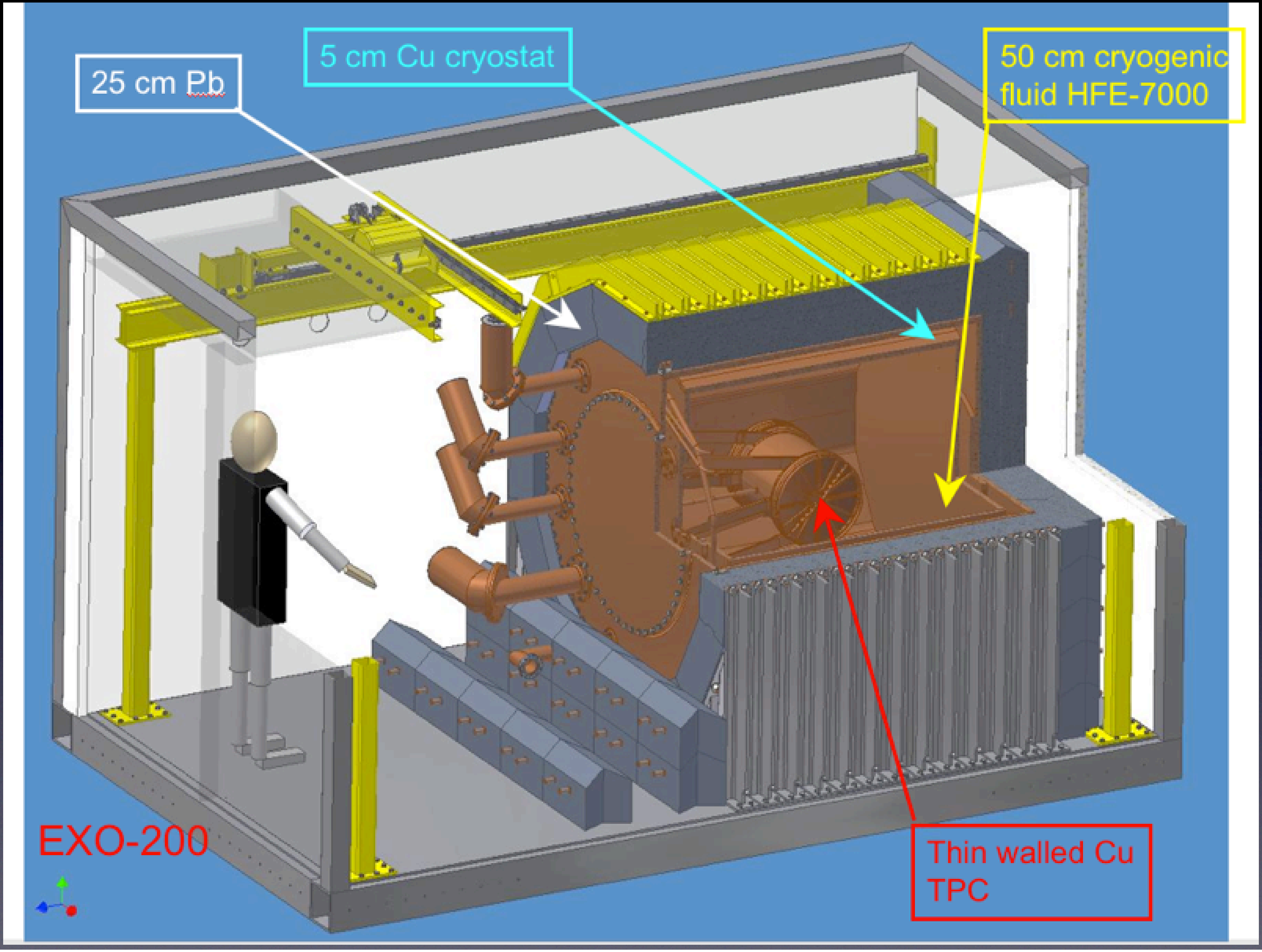
- Isotopically enriched liquid ^{136}Xe (80%)
  - Semi-cryogenic (-115 ºC)
  - LXe acts as both source and detector
- 2νββ, 0νββ (and background events) create ionization trails in LXe (e^- and Xe^+)
  - W_{Xe}~10 eV, $Q_{\beta\beta}$~2.5 MeV → ~10^5 e^-/event
- Drift field sweeps up most electrons (TPC)
  - Sum up e^- (no gain in liquid) gives energy of decay
  - Pulse height/timing analysis gives x-y position of decay (Res. ~ 1cm^3)
- Some e^- and Xe^+ left over recombine and scintillate (175nm)
  - Timing gives a "start," and allows for z-position reconstruction
- Ba^{++} → Ba^+ left over drifts in opposite direction

EXO-200

Full EXO

EXO-200 - LXe TPC

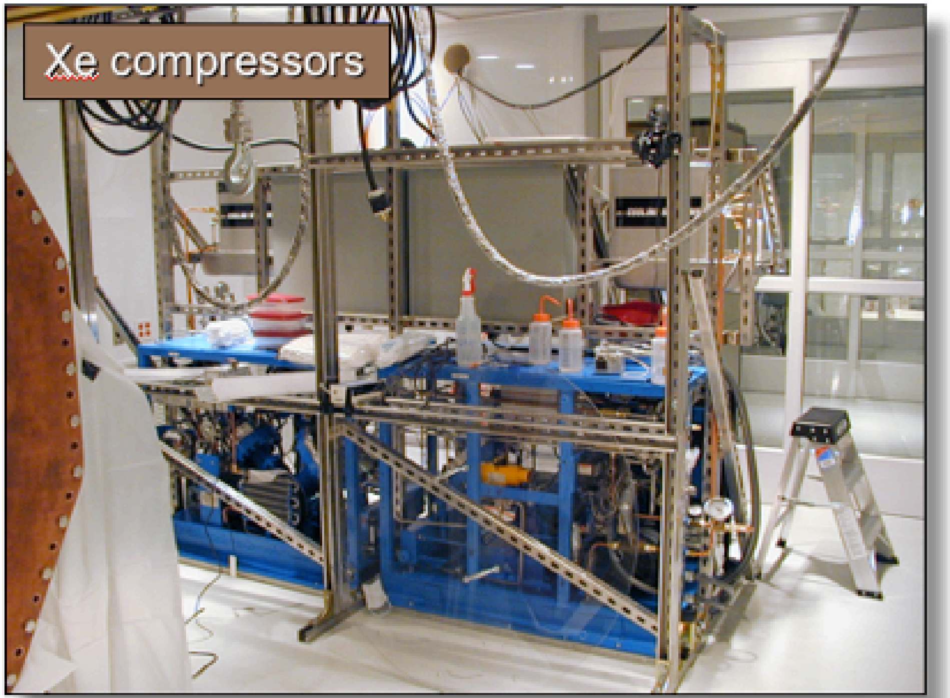



25 cm Pb
5 cm Cu cryostat
50 cm cryogenic fluid HFE-7000
Thin walled Cu TPC
EXO-200

EXO-200 commissioning at HEPL, Stanford

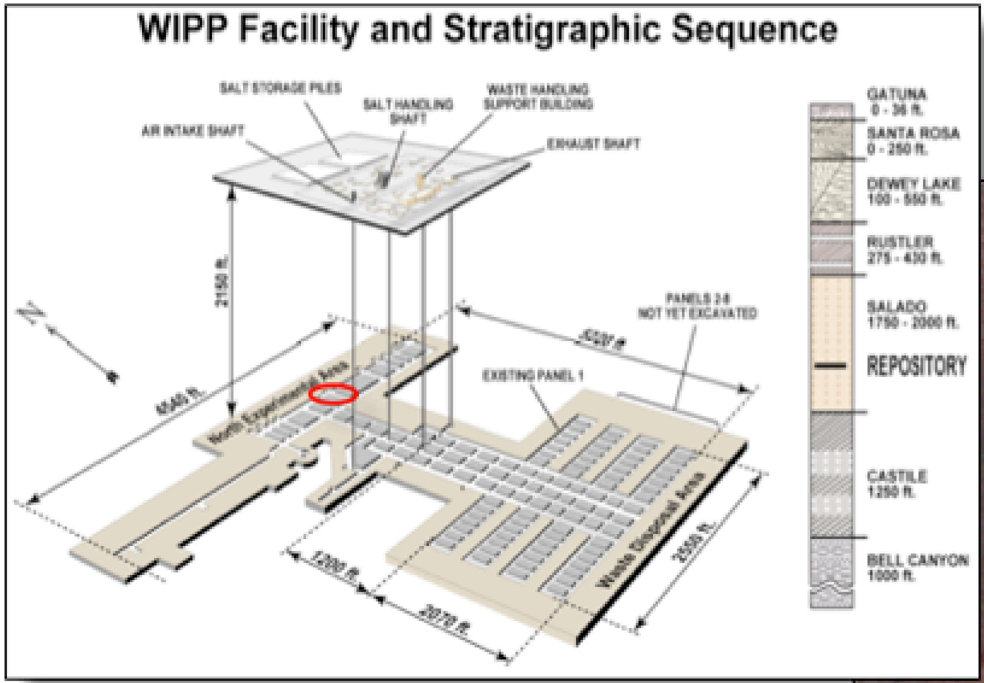

EXO-200 cleanrooms


Refrigeration systems


Xe compressors


Refrigerant storage

EXO-200 Experimental Site

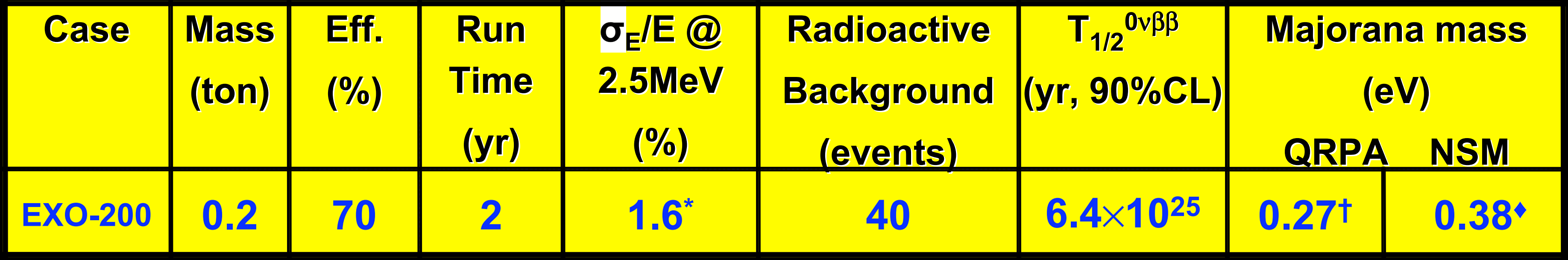


Installation ancillaries started
Installation of detector March 07

- 655 m underground (rock + salt), 1600 m.w.e
- vertical muon flux = 3.1 $\times 10^{-7}$ s^{-1} cm^{-2} sr^{-1}

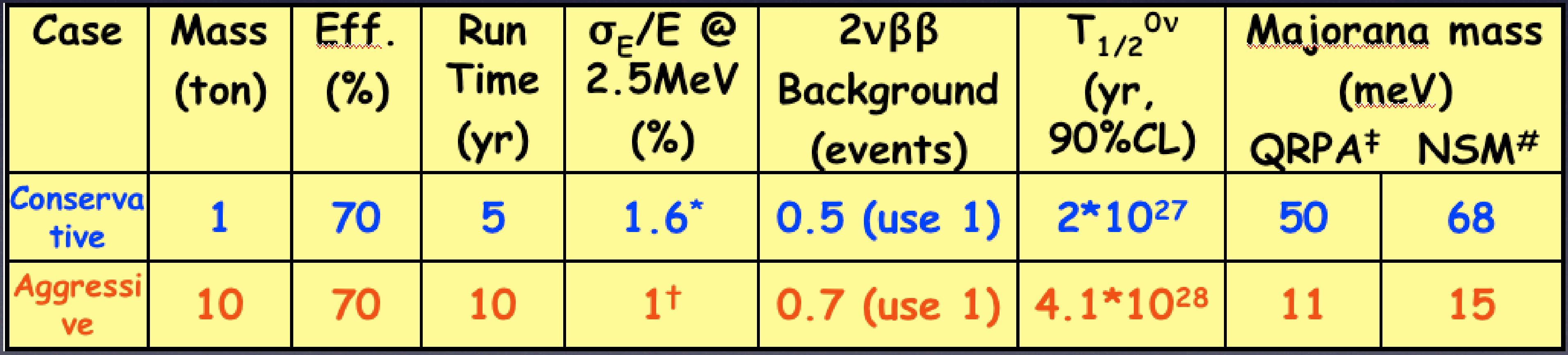
(NIMA 538 (2005) 516)

EXO - sensitivity



Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu\beta\beta}$ (yr, 90%CL)	Majorana mass (eV) QRPA	NSM
EXO-200	0.2	70	2	1.6^*	40	6.4×10^{25}	$0.27^\dagger$	0.38♦

Future - with laser tagging



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)	$2*10^{27}$	50	68
Aggressive	10	70	10	$1^\dagger$	0.7 (use 1)	$4.1*10^{28}$	11	15

Combining DM & ßß?

... as both fields seek ton-scale experiment?

- Bargain? Buy one get, one free?!?
- No really: cost for enriched Xe, essential for ßß
  = cost for rest of DM experiment

- WIMP spin independent/dependent cross section studies
  would anyway require some isotopic separation!

^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
1.9	26.4	4.1	21.2	26.9	10.4	8.9

Mainly odd: spin dependant
no ßß candidate

Mainly even: spin dependant
two ßß candidate

- ‘No waste’ enrichment, ie cheaper