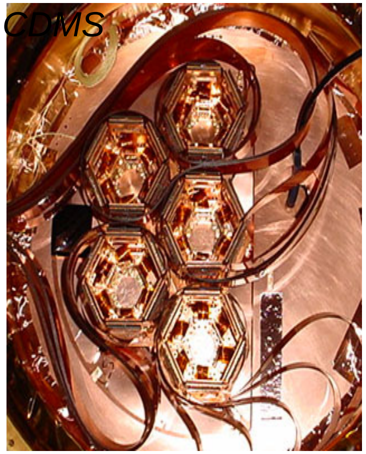
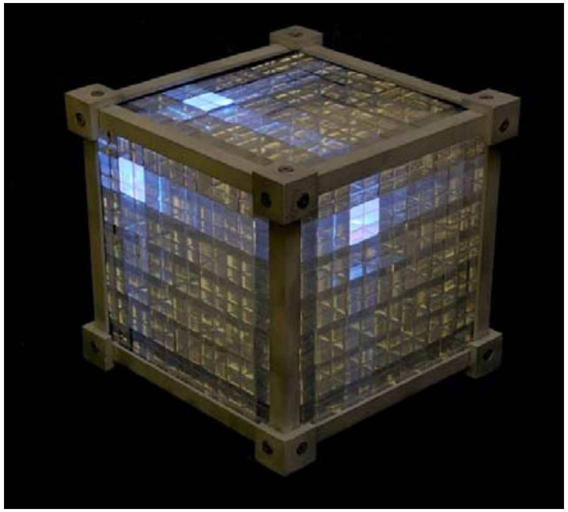
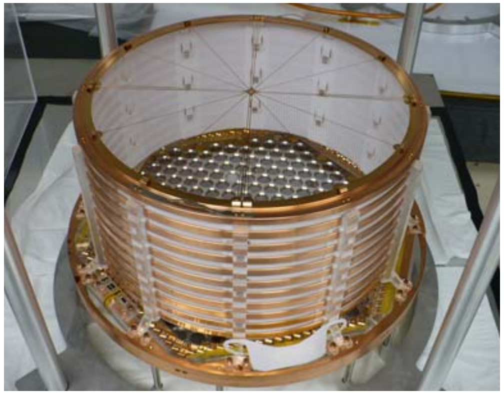


Non-accelerator Experiments: Physics Goals and Challenges

Carter Hall,
University of Maryland





Detecting galactic WIMP dark matter

Dark matter "Halo" surrounds all galaxies, including ours.

Density at Earth:

$$\rho \sim 300\ m_{proton}/\text{liter}$$

$$m_{wimp} \sim 100\ m_{proton}.$$

3 WIMPS/liter!

Typical orbital velocity:

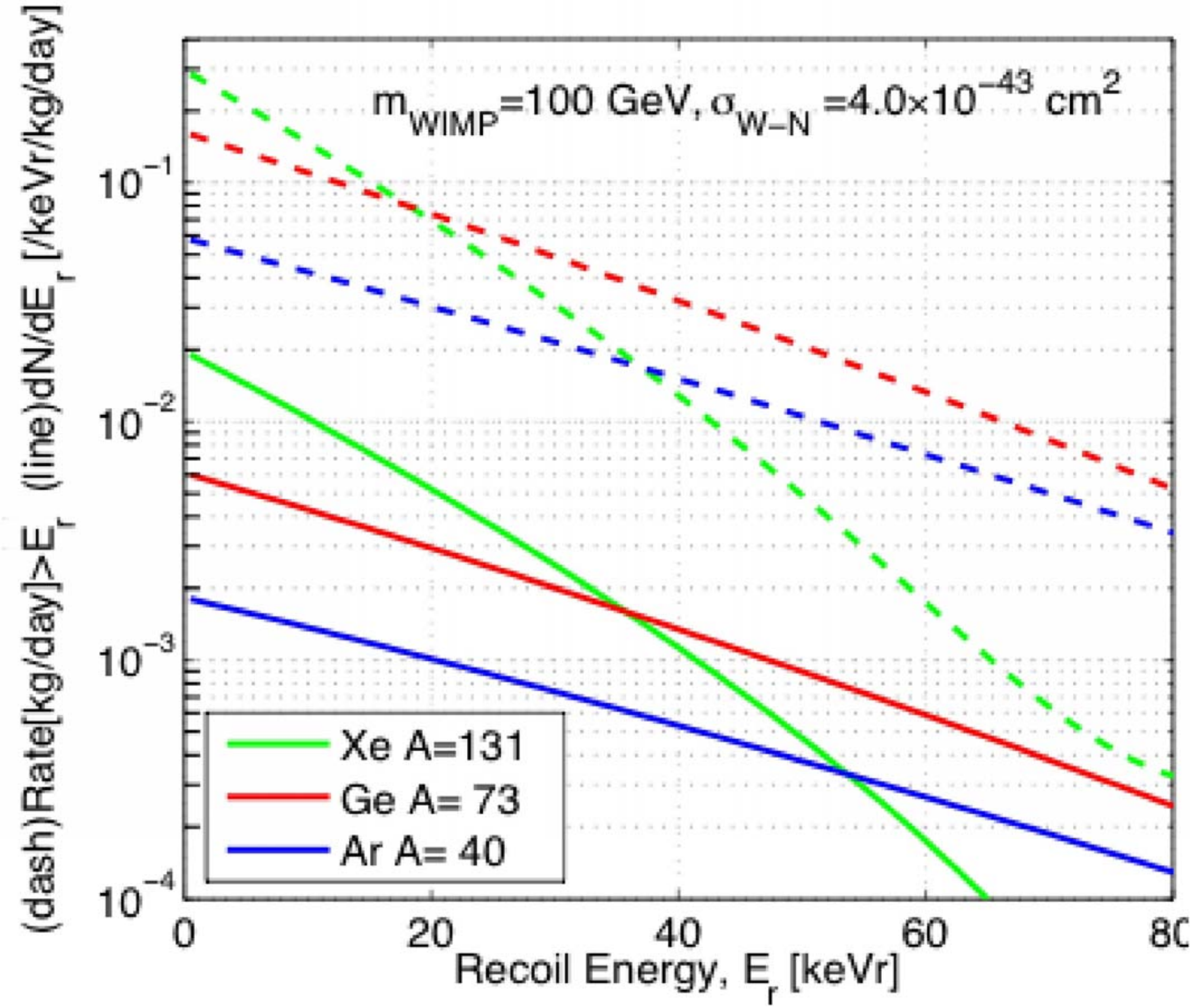
$v \approx 230$ km/s

~ 1/1000 speed of light

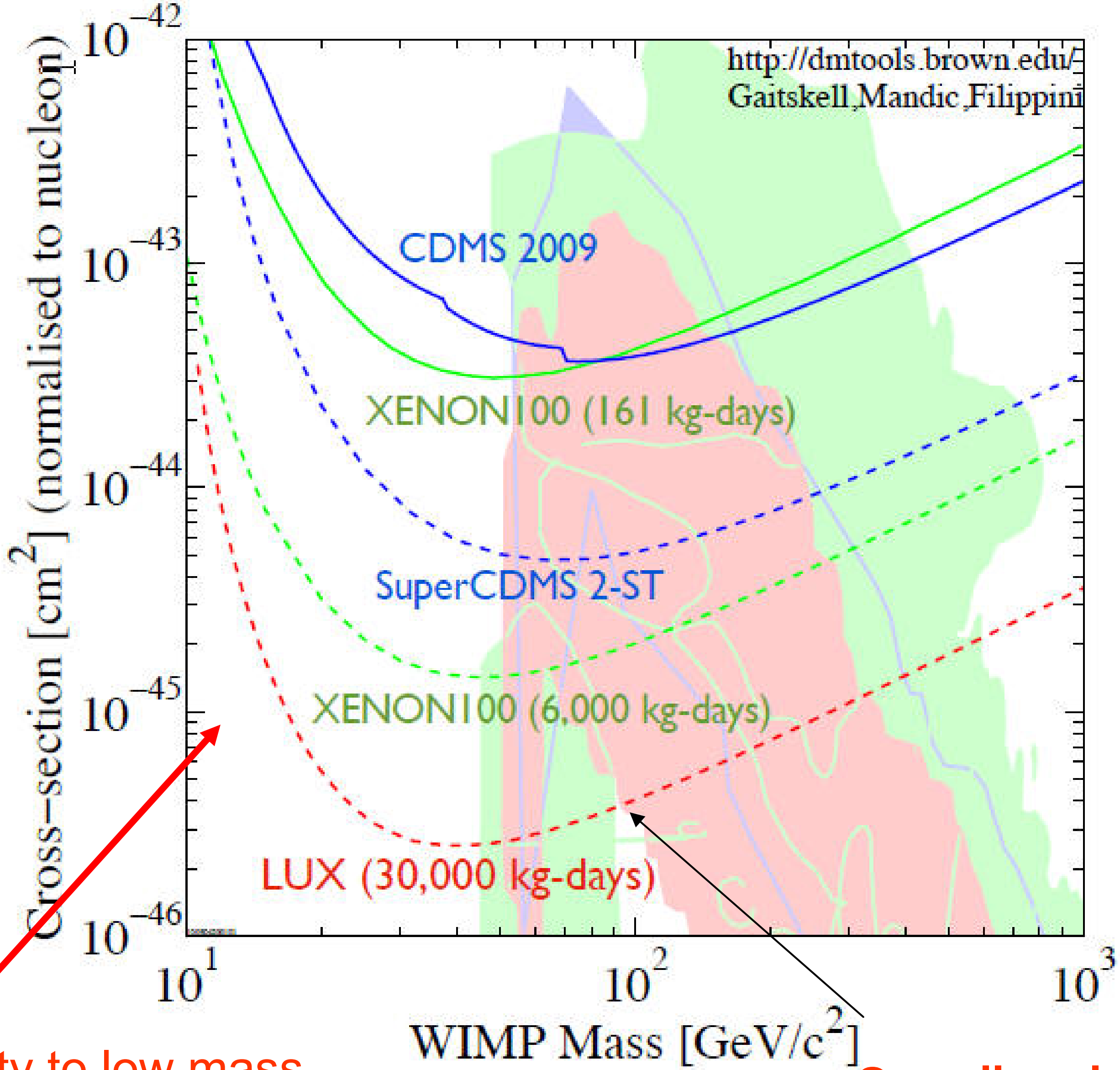
Coherent scalar interactions: A^2

Rate: < 1 event/kg/100day, or much lower

Nuclear Recoil Spectra from WIMP scattering



Dark matter search results



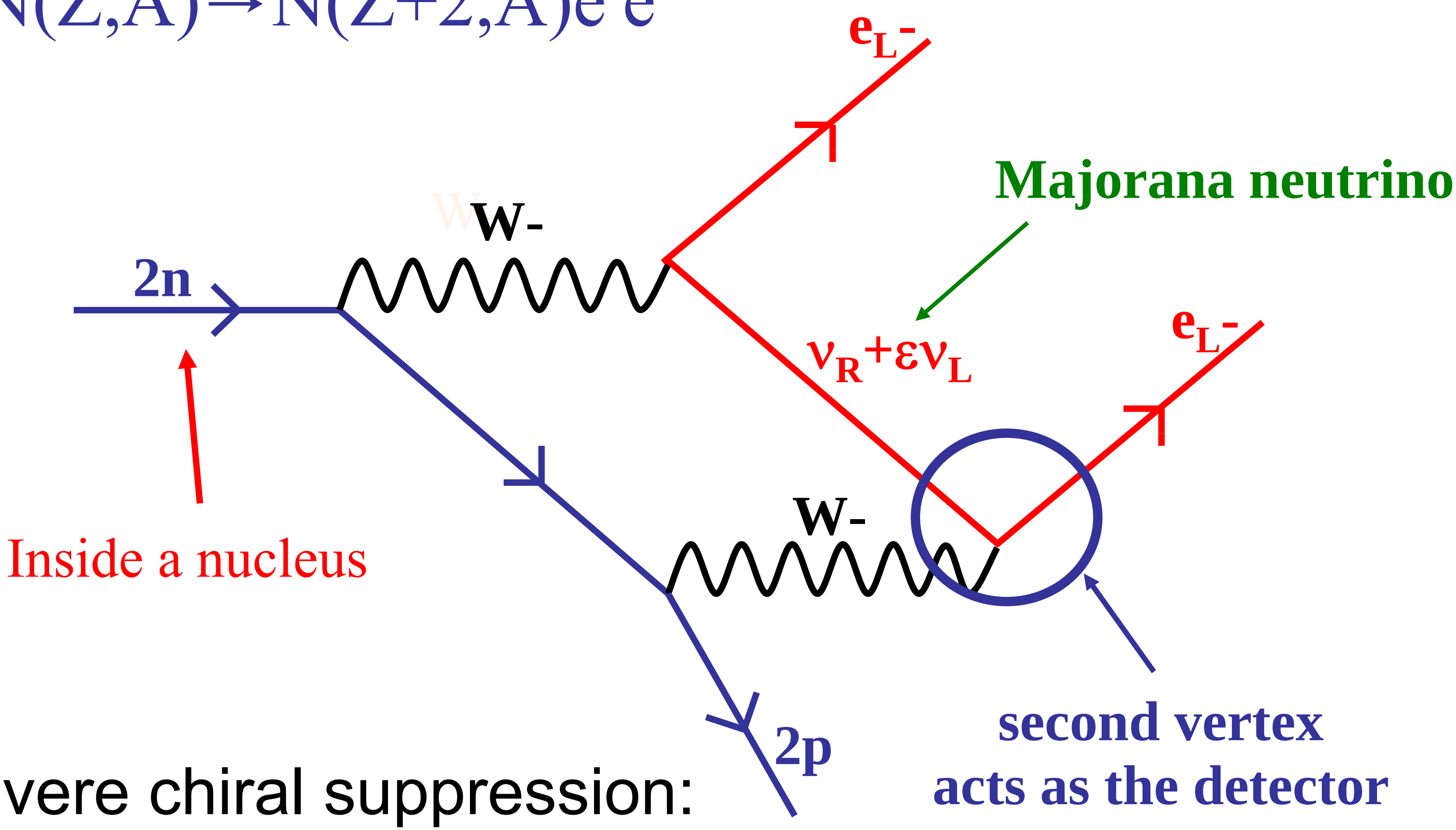
Sensitivity to low mass WIMPS determined by detector threshold

Overall scale determined by detector size, run time, and background rates.

Neutrinoless Double Beta Decay ($\beta\beta0\nu$)

Forbidden if neutrino mass is Dirac only

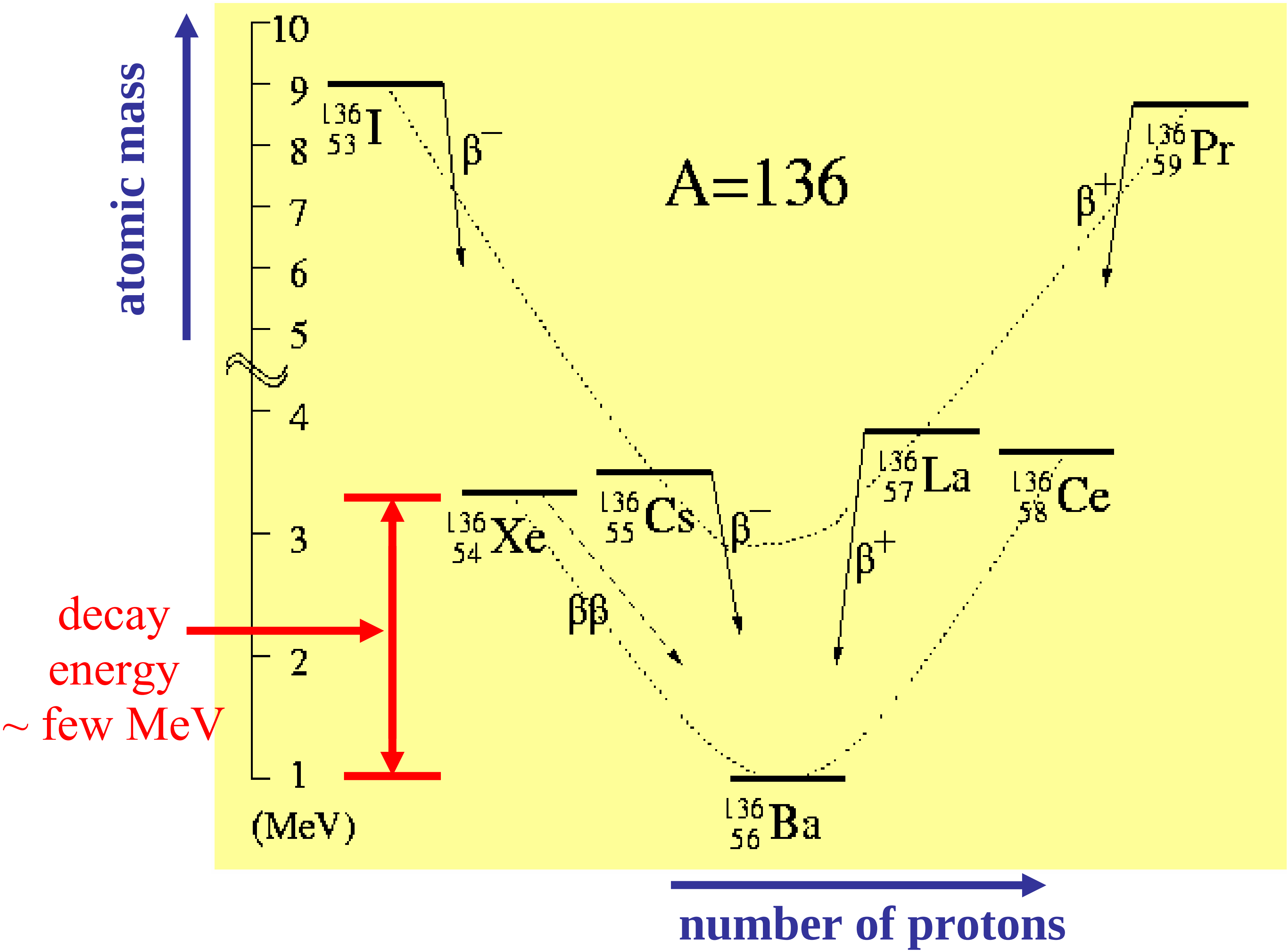
$$N(Z,A) \rightarrow N(Z+2,A)e^- e^-$$



Severe chiral suppression:

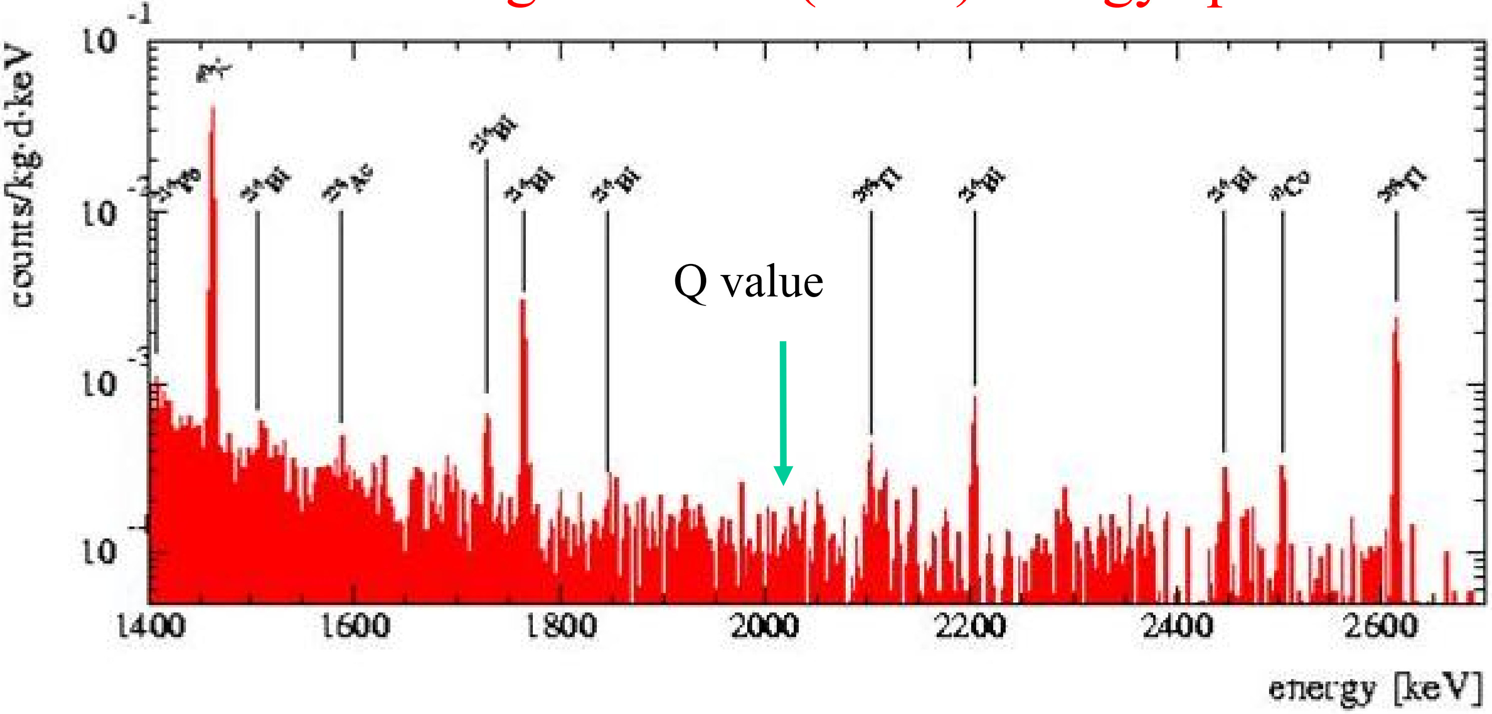
$T_{1/2} > \sim 10^{25}$ years

What nuclei are ββ candidates?



The most sensitive double beta decay experiments to date are based on 76-Germanium.

Heidelberg-Moscow (76Ge) energy spectrum

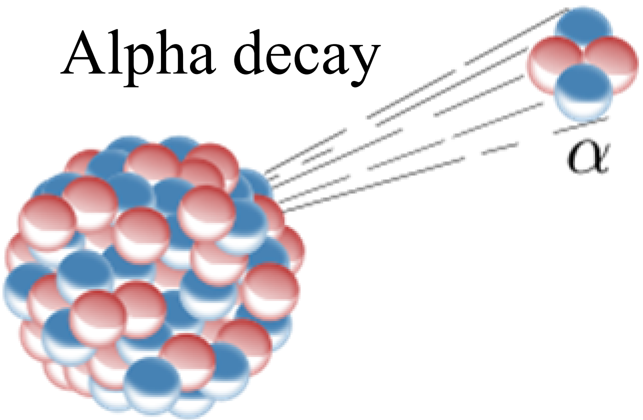


Half-life limit: 1.9 x 10^{25} years (H-M and IGEX)

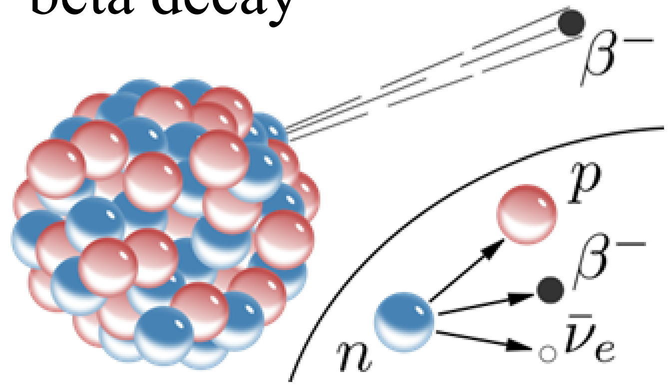
Majorana neutrinos ruled out for masses greater than ~0.35-1.0 eV

Ordinary radioactive decay

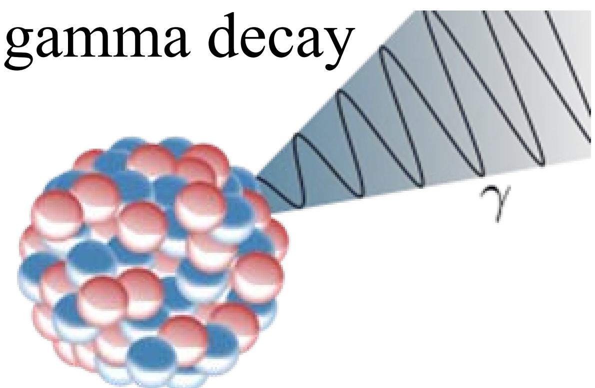
Alpha decay

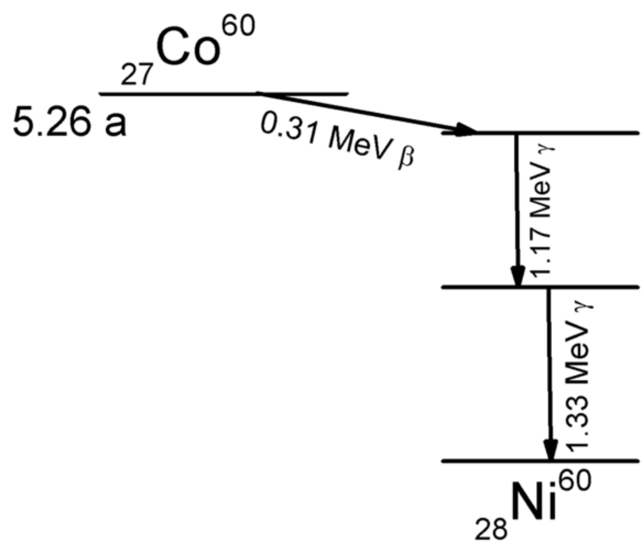


beta decay

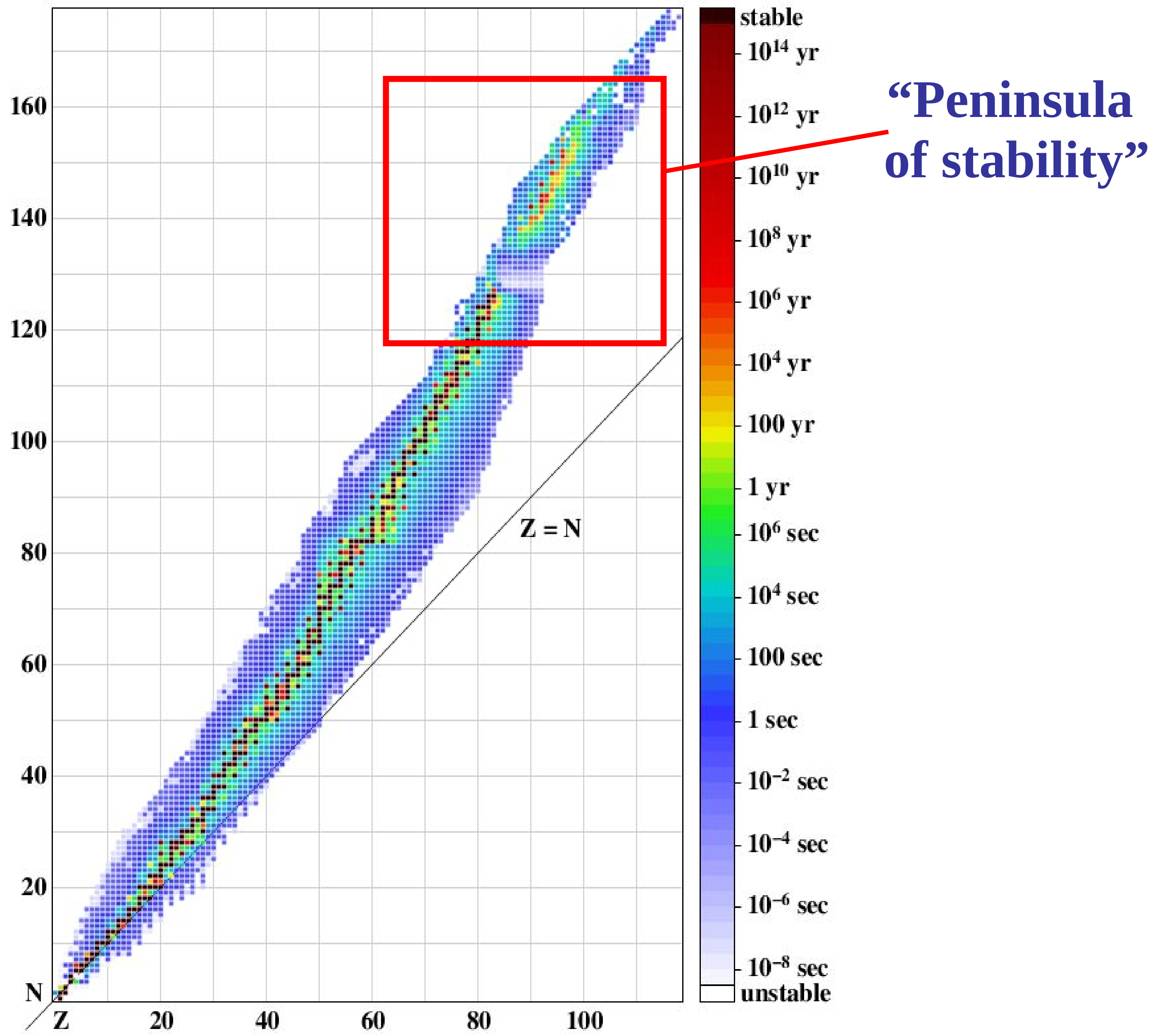


gamma decay

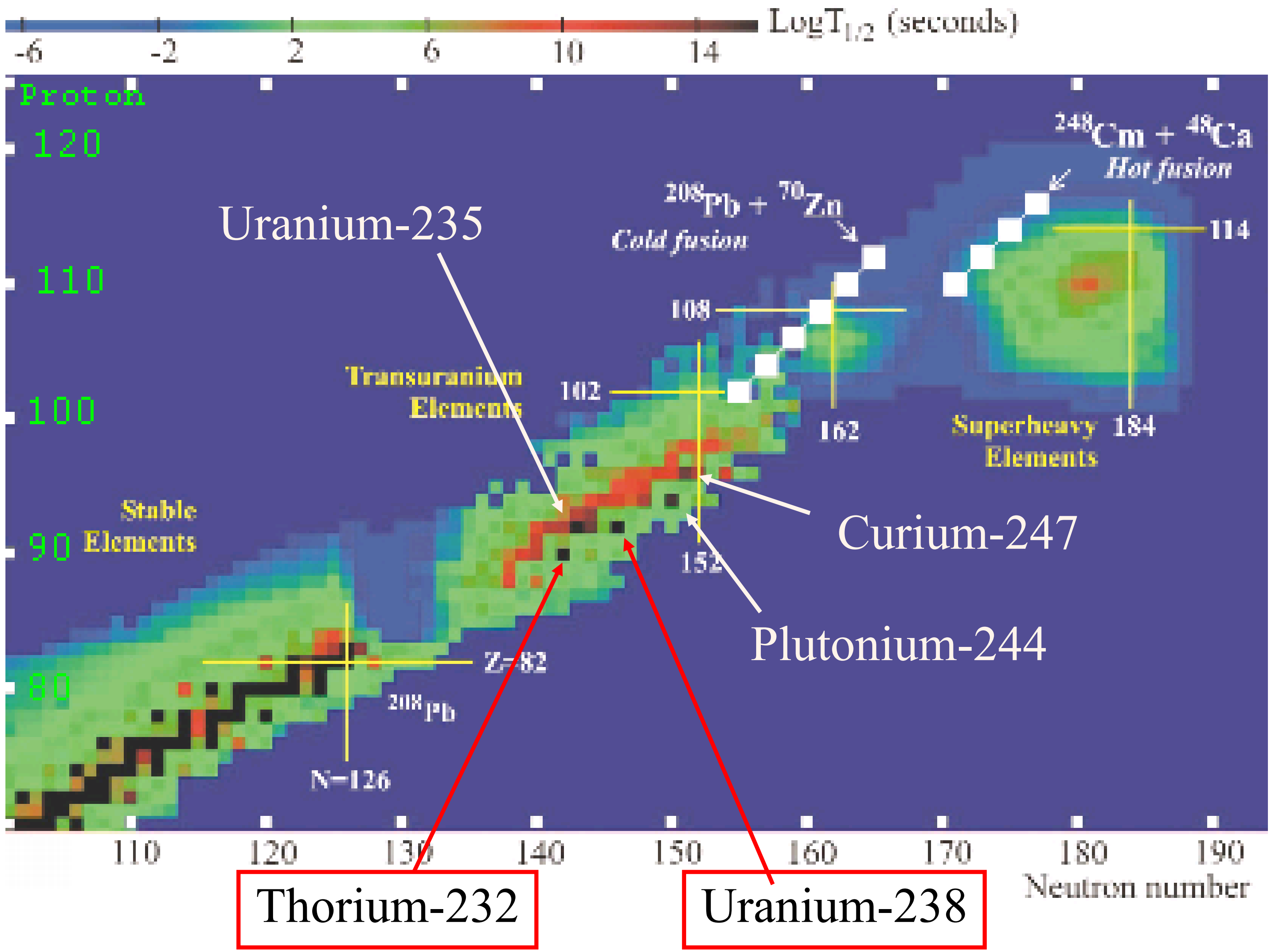




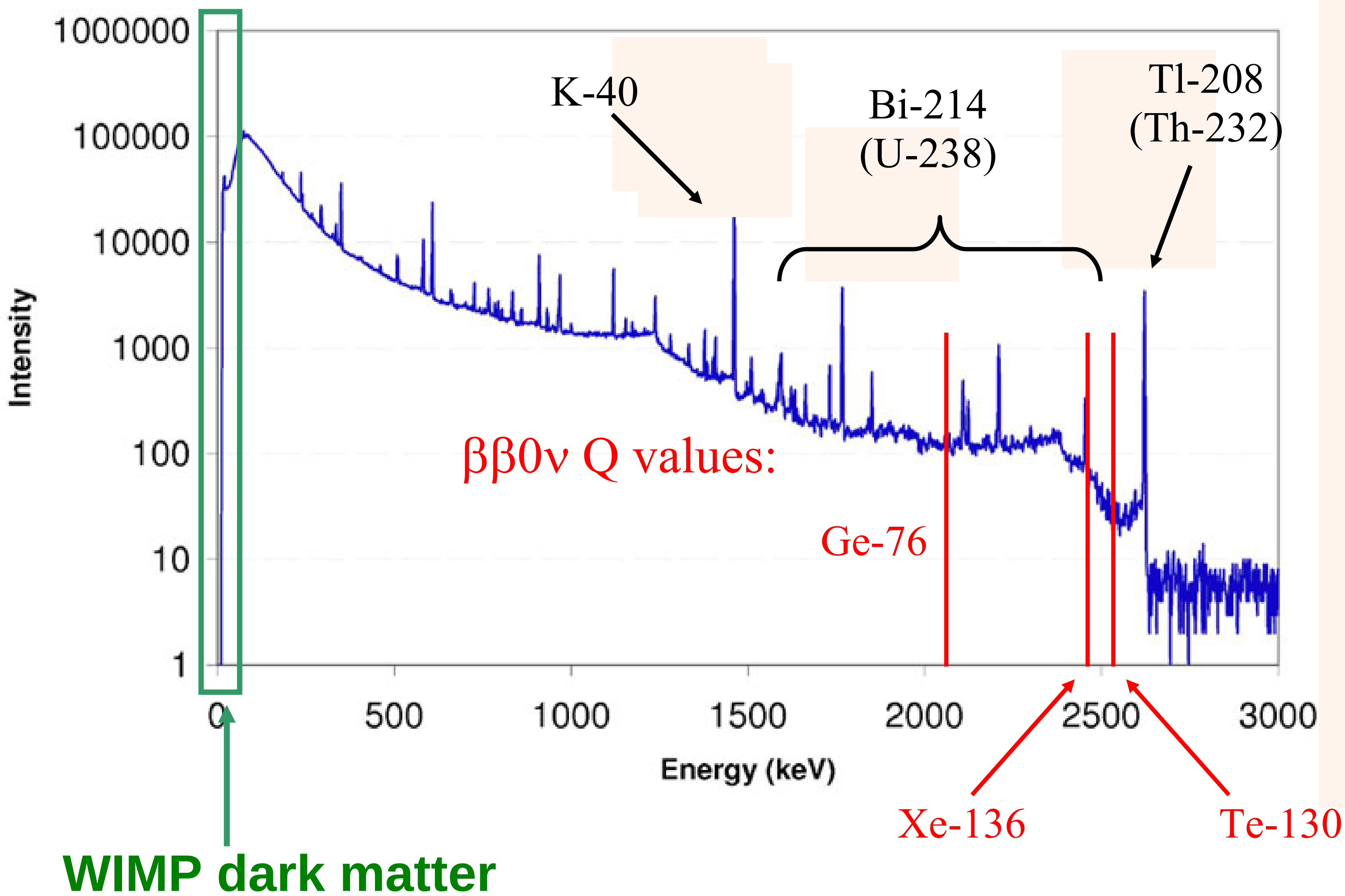
Nuclide half lives



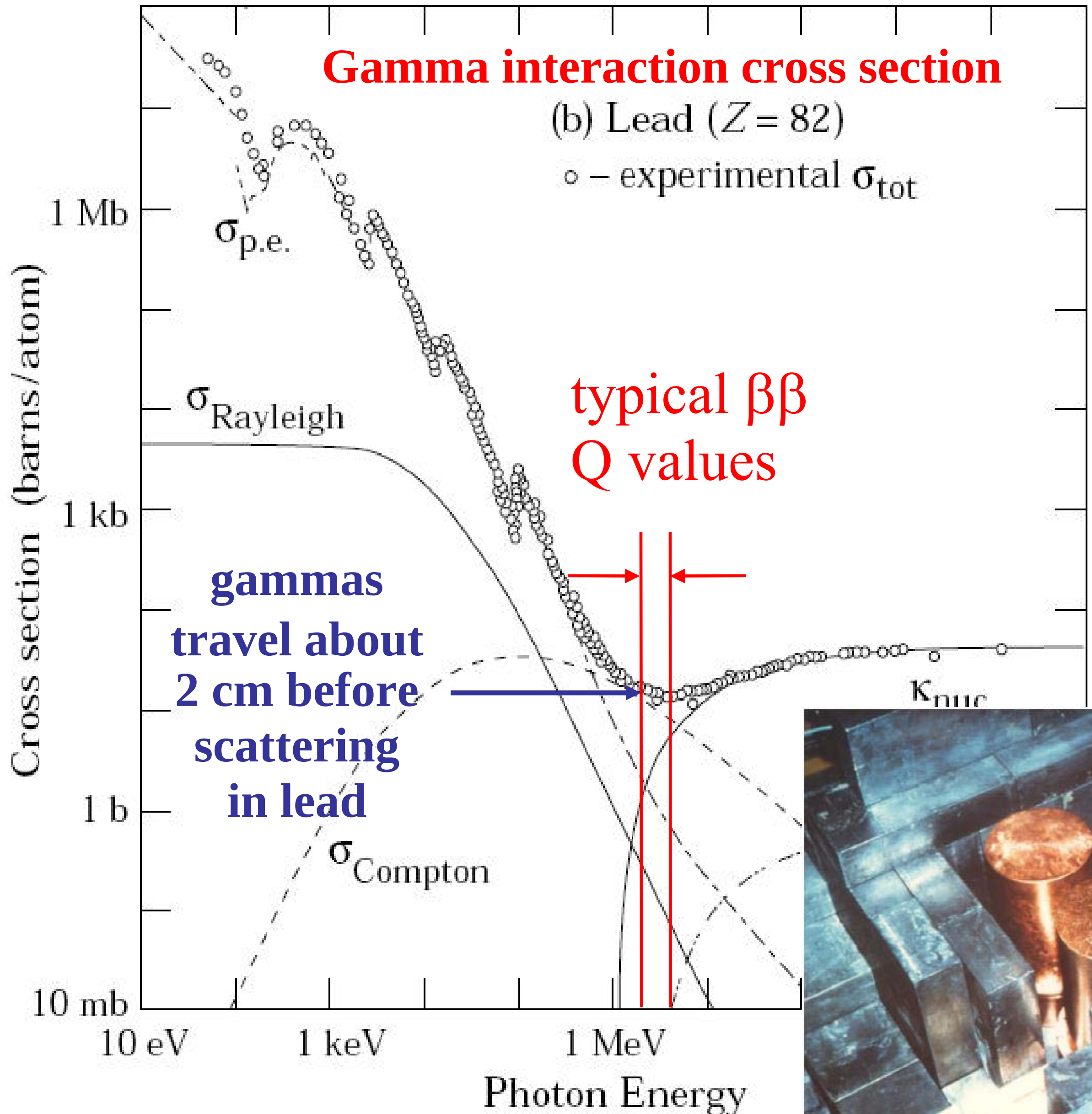
Peninsula of Stability

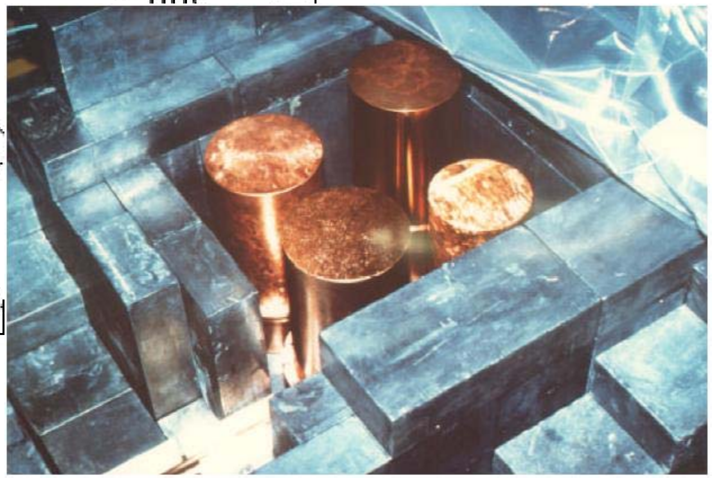


Ordinary radioactive decay here on earth



Shielding gammas is difficult!



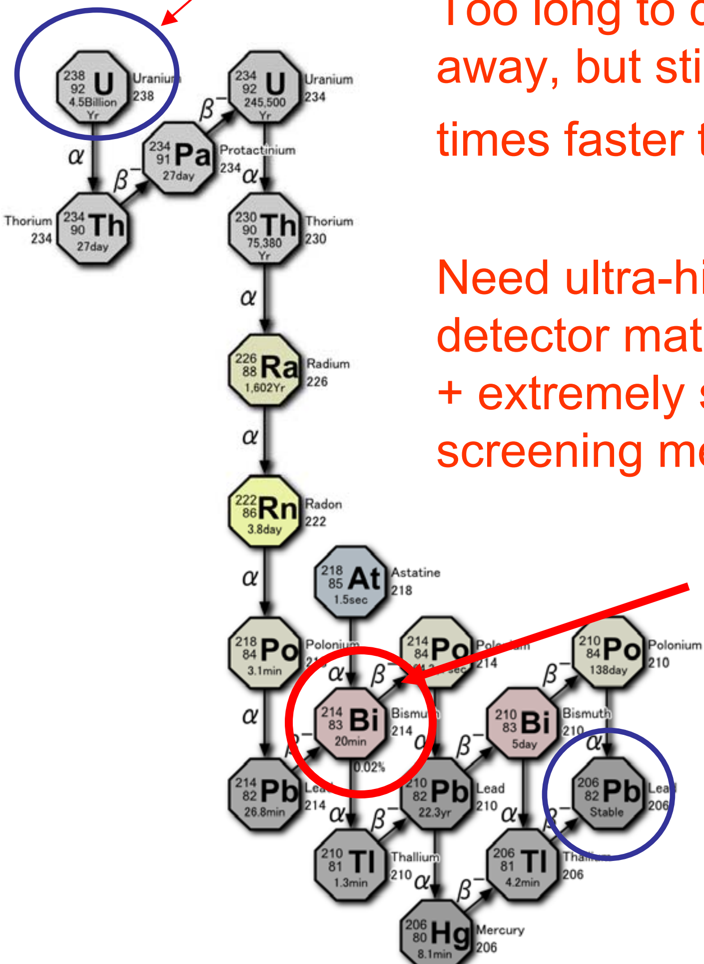


Uranium-238 decay chain

T(1/2)~10^9 years: the worst half-life in physics!

Thorium-232 decay chain

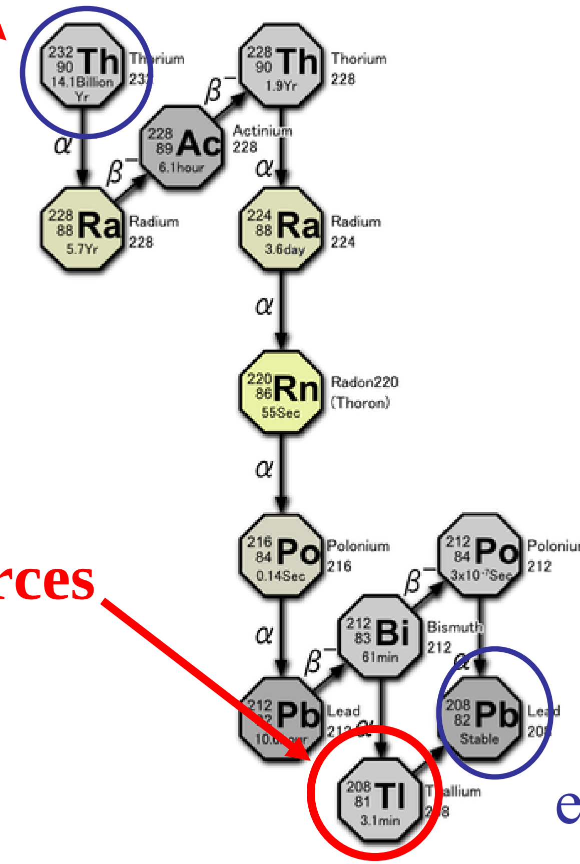
start



Too long to decay away, but still 10^{16} times faster than bb0ν!

Need ultra-high detector materials + extremely sensitive screening methods

start

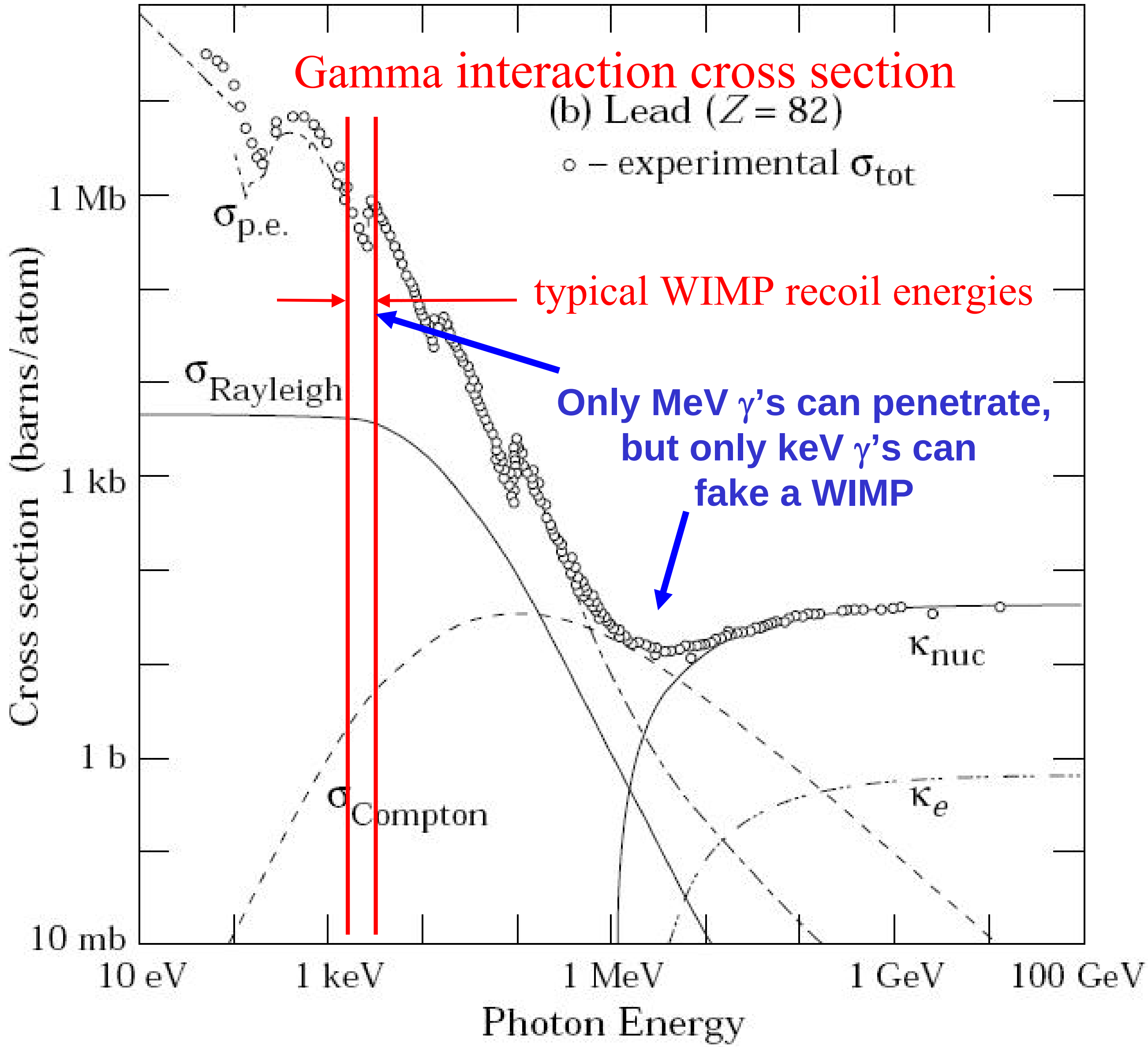


gamma sources

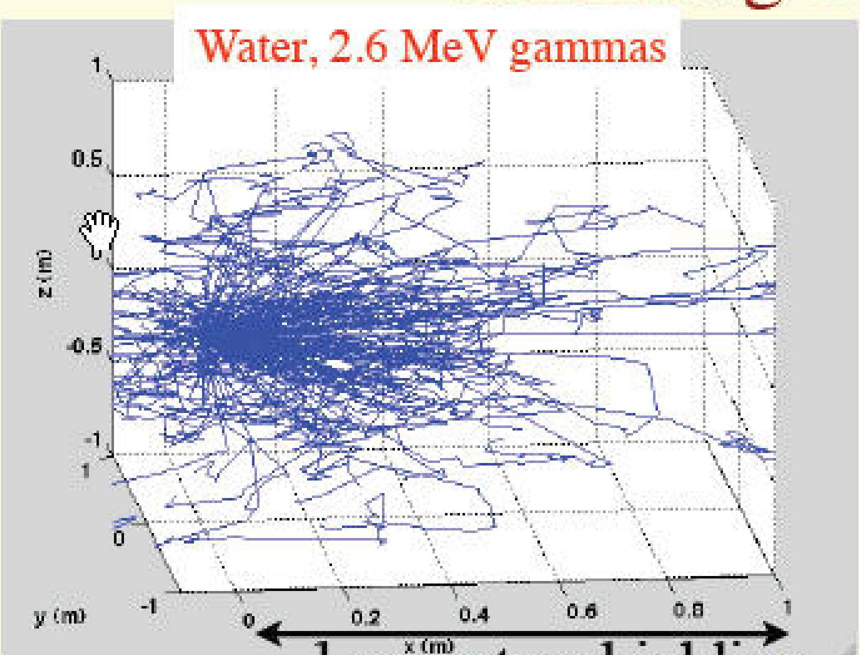
end

end

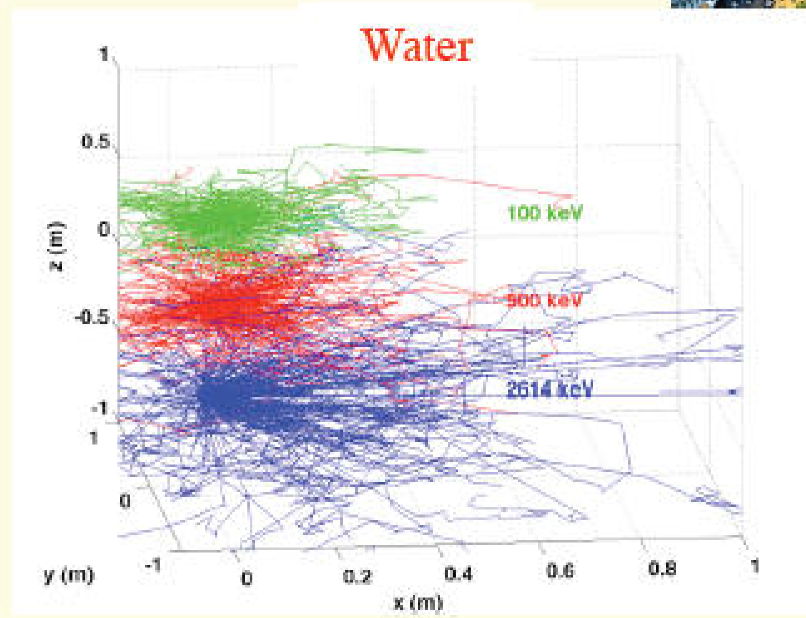
Dark matter: shielding is not so difficult @ 10 keV

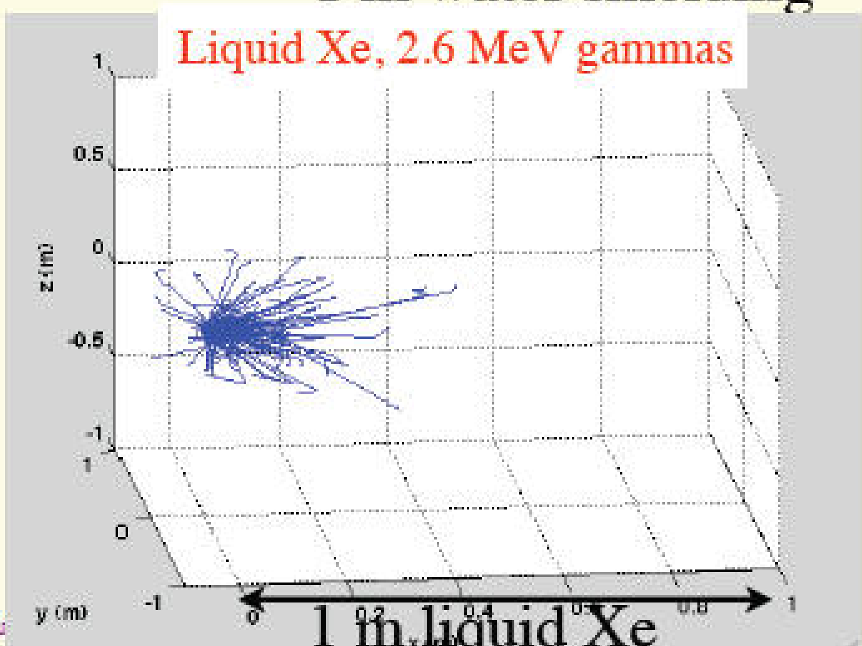


Shielding Gamma Rays

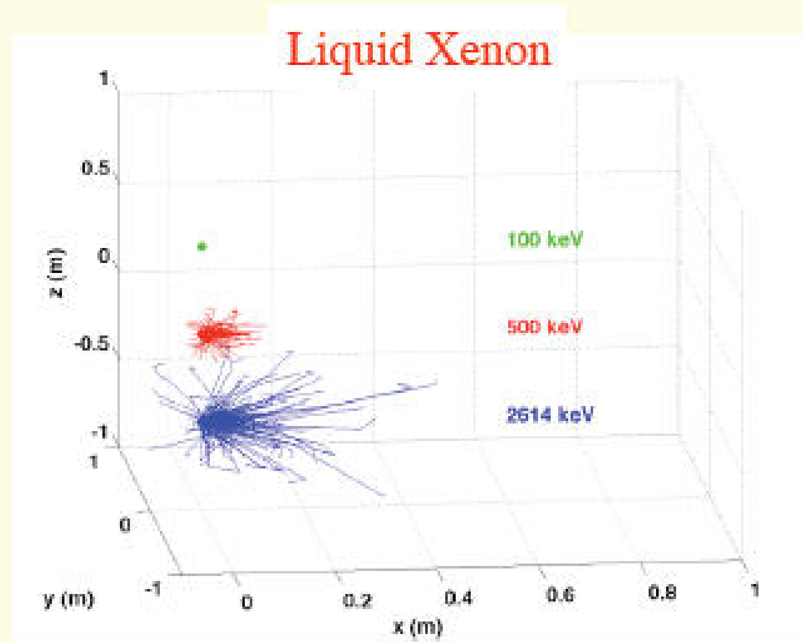


1 m water shielding



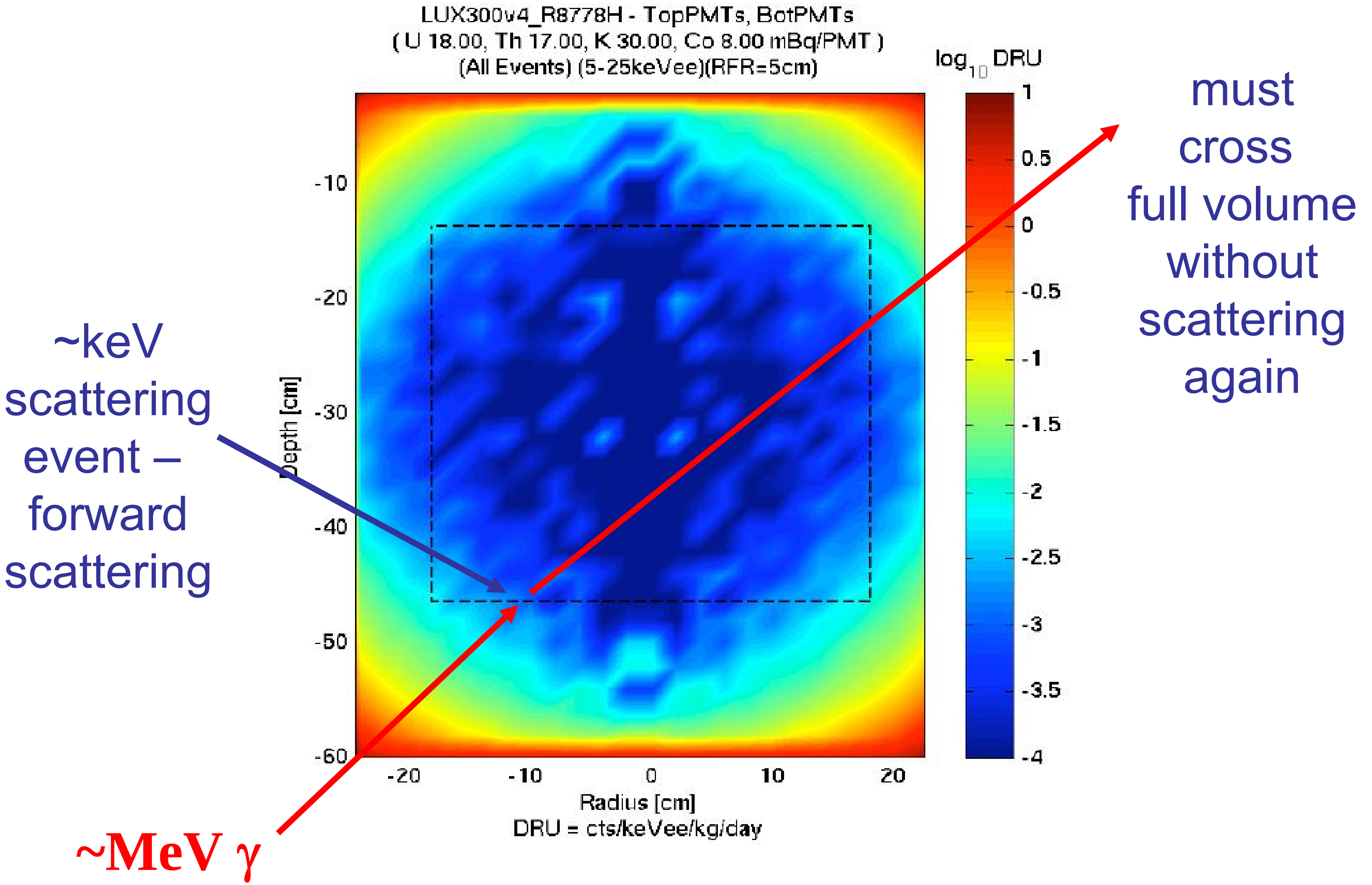


1 m liquid Xe

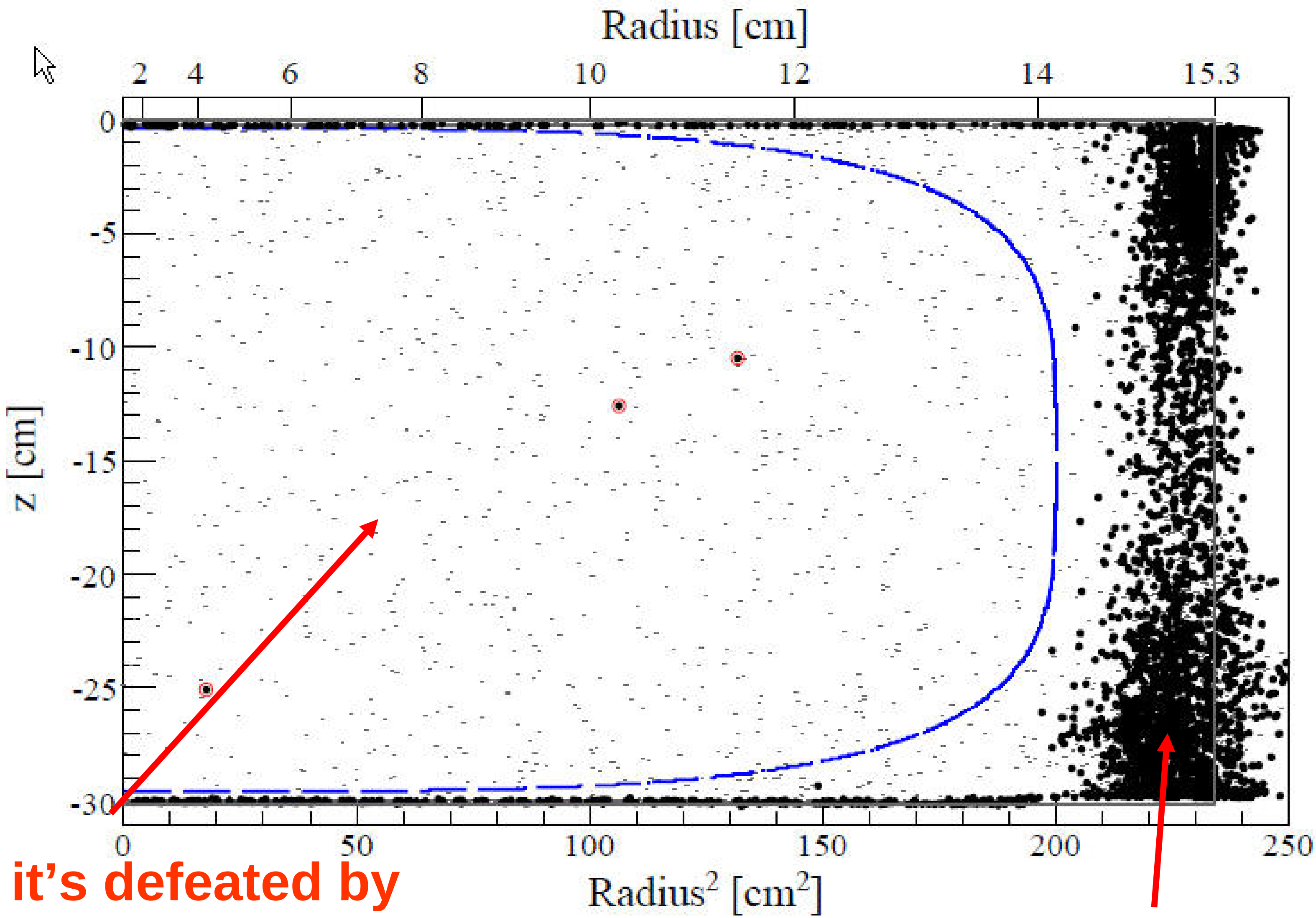


Self-shielding effect

Sensitivity improves quickly as target mass increases due to geometry!



Event location in XENON100 - 2011

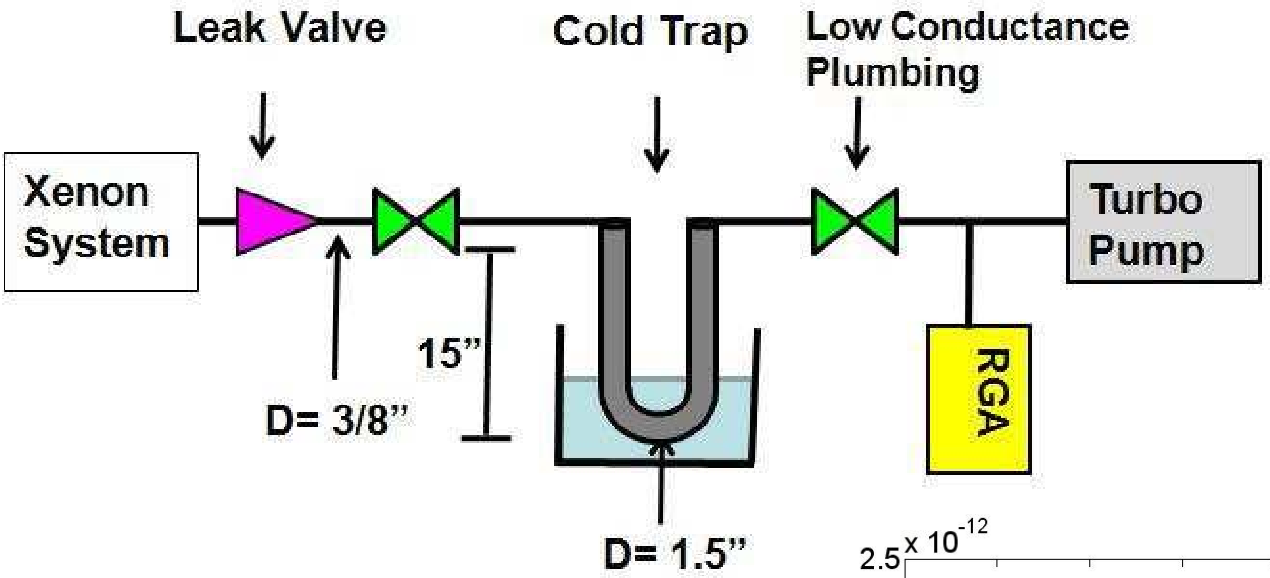


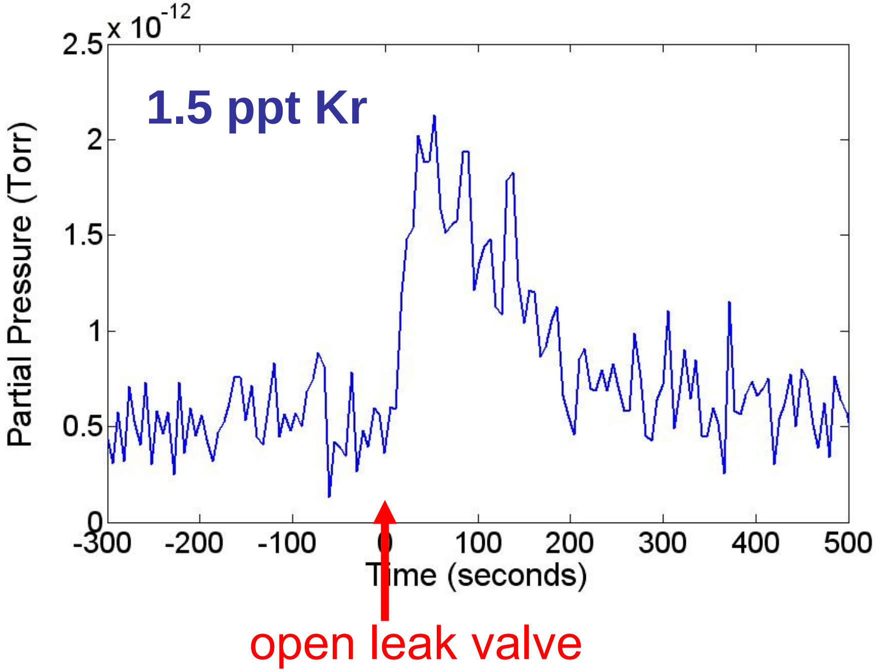
but it's defeated by Kr-85 dissolved in the bulk.

Self-shielding works....

New screening technique to detect krypton at the part-per-trillion level

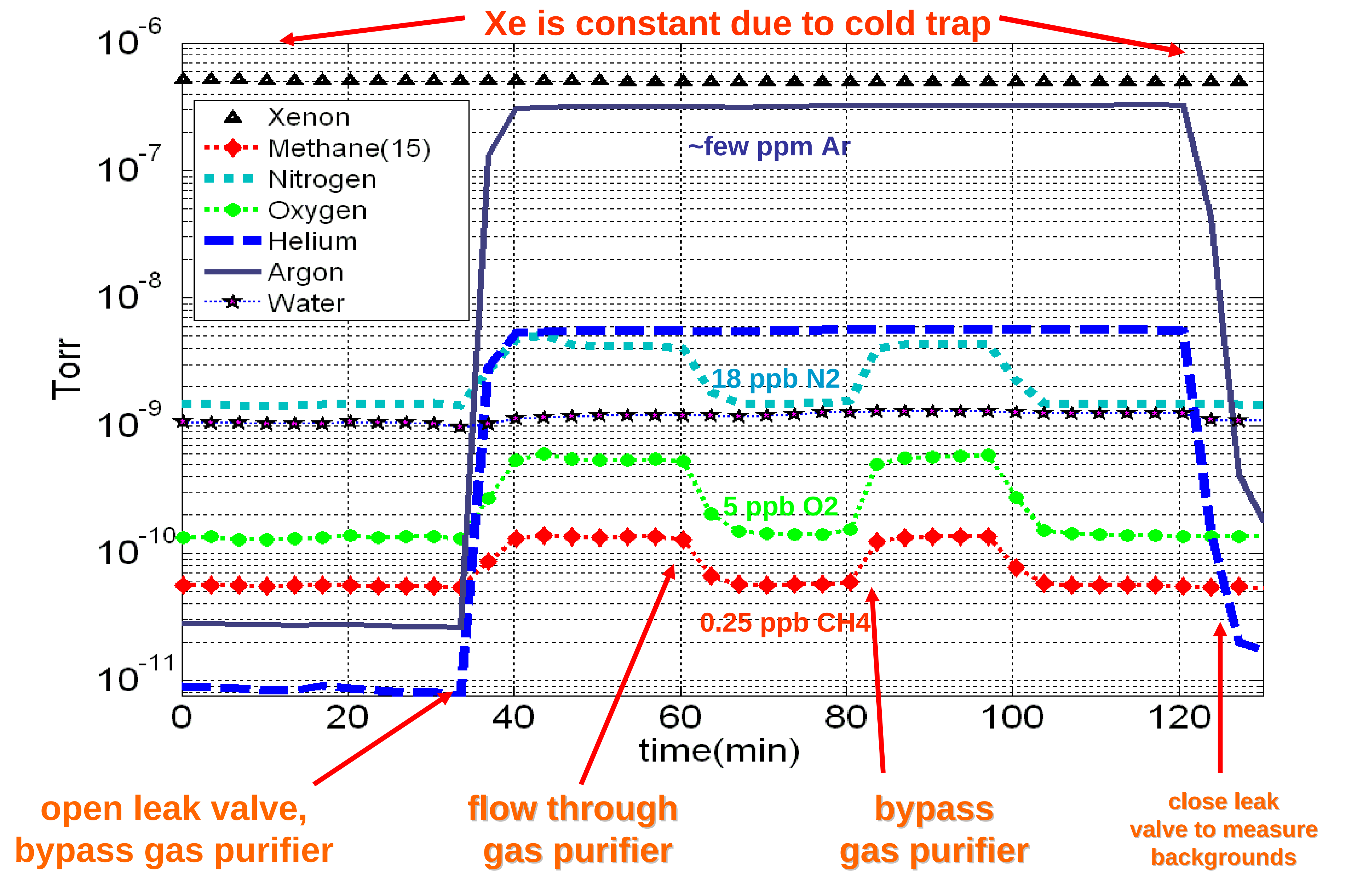
arXiv:1103.2714v1



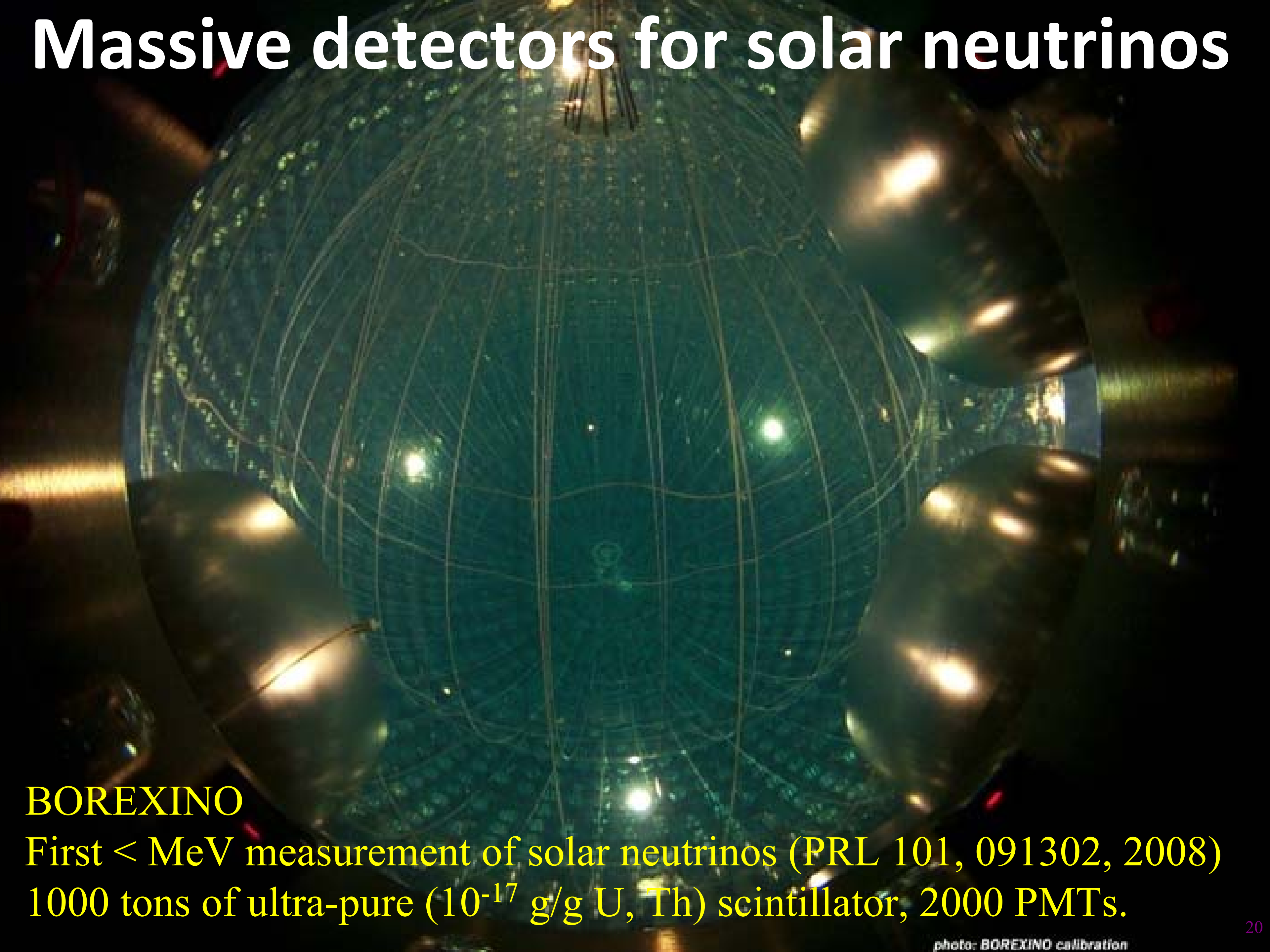


Detect electronegative impurities at less than a part-per-billion

NIM 621 678 (2010)



Massive detectors for solar neutrinos



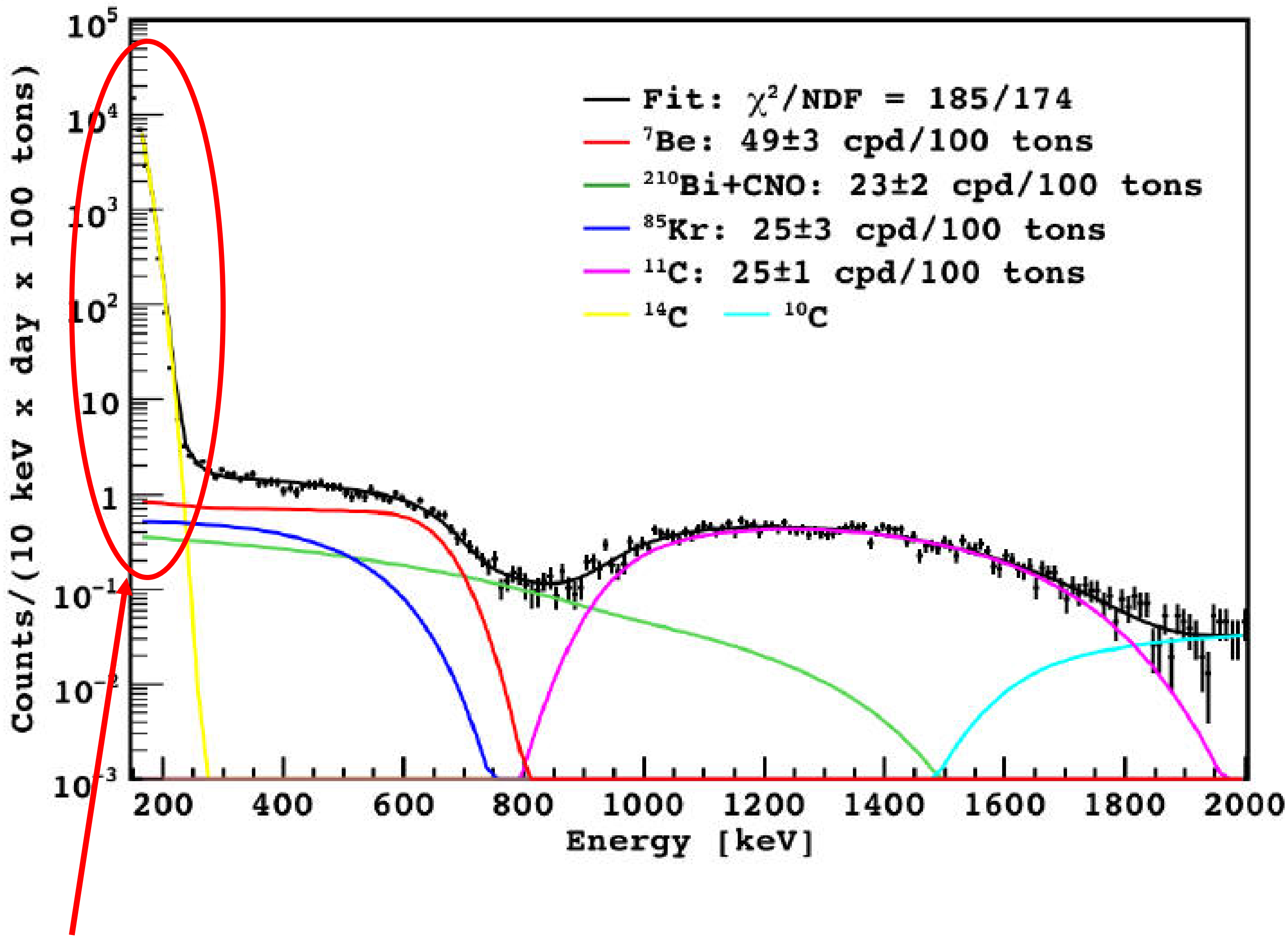
BOREXINO

First < MeV measurement of solar neutrinos (PRL 101, 091302, 2008)

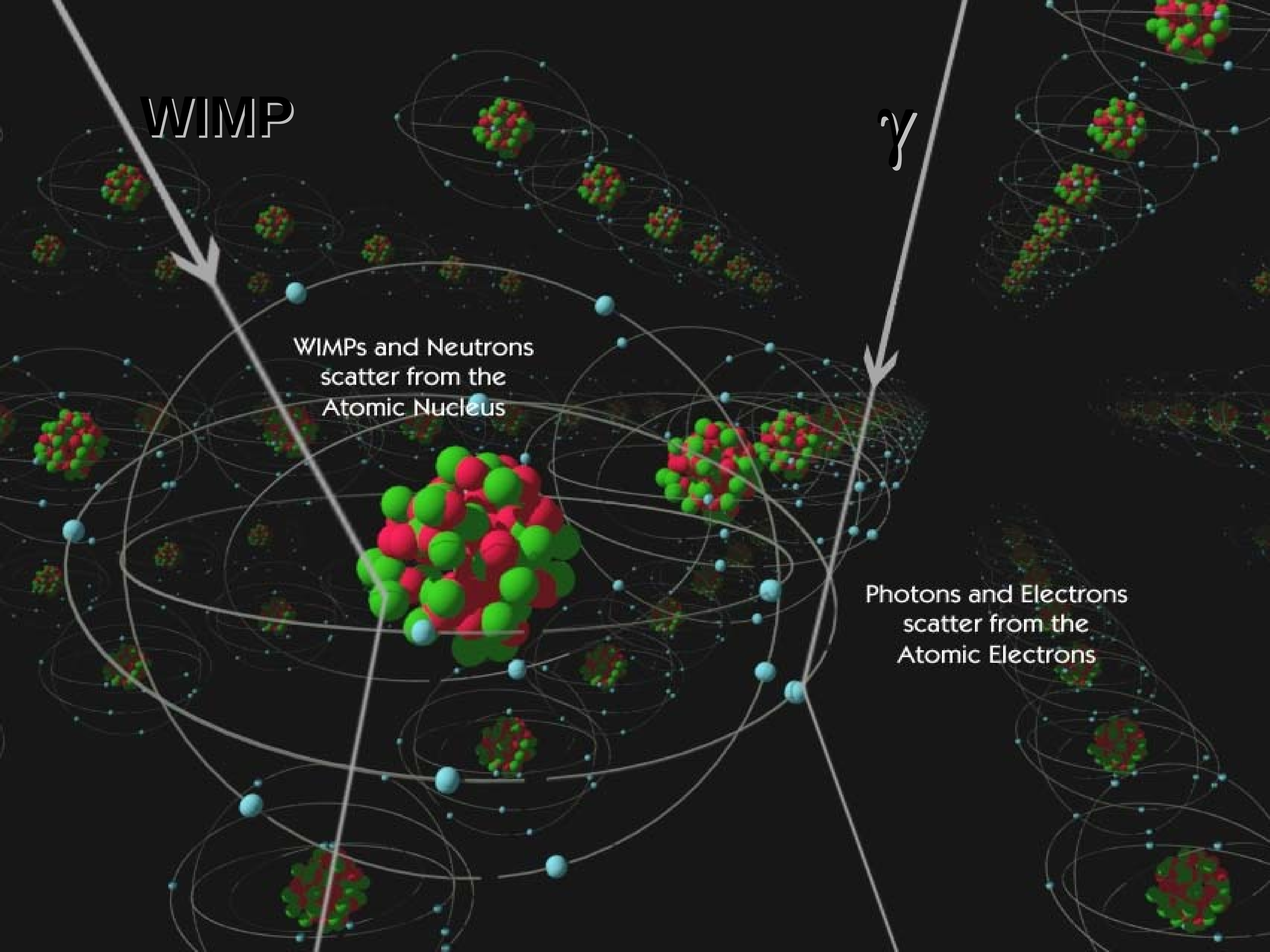
1000 tons of ultra-pure (10^{-17} g/g U, Th) scintillator, 2000 PMTs.

photo: BOREXINO calibration

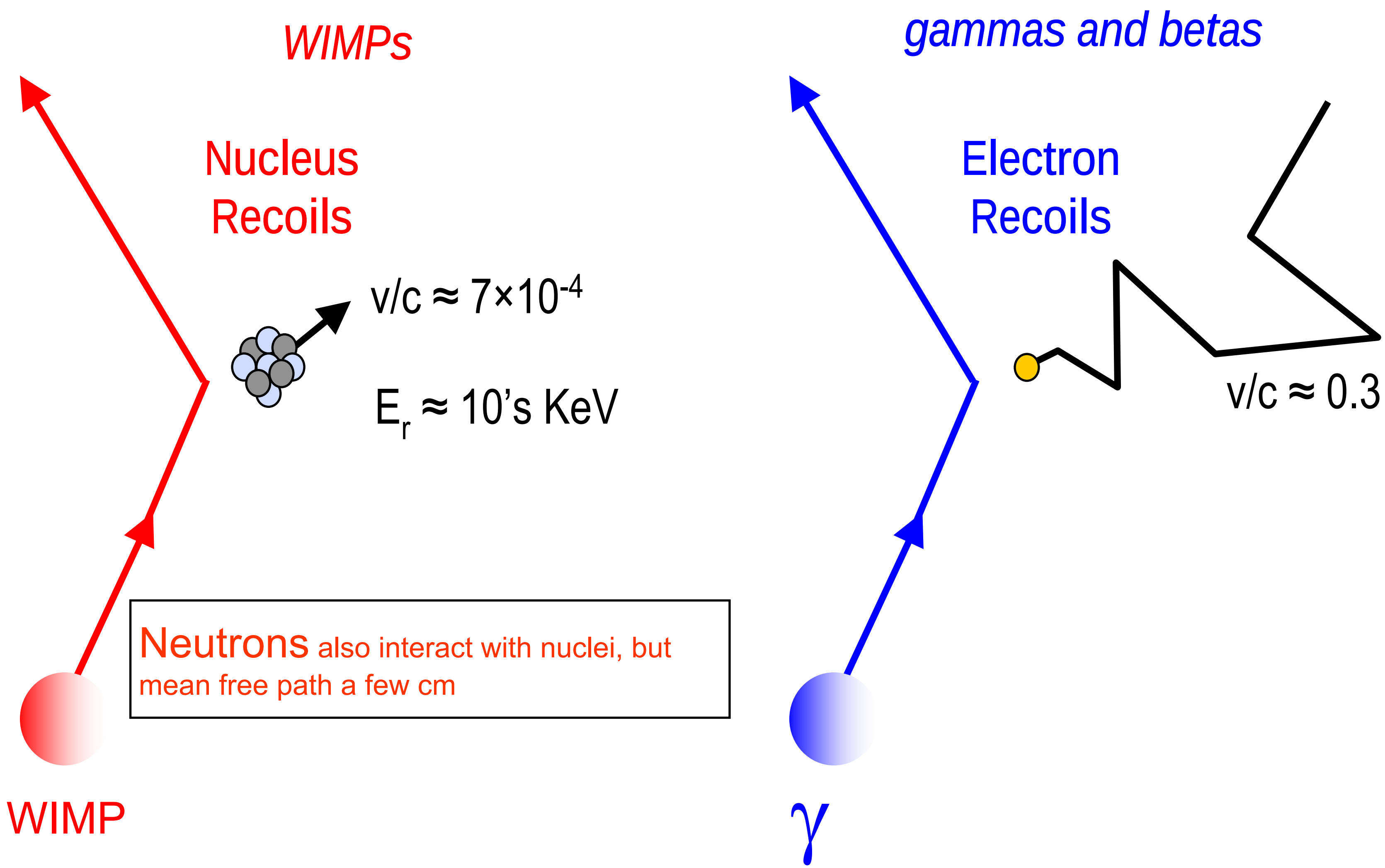
Borexino Solar Neutrino Spectrum – 192 days of exposure



^{14}C overwhelms dark matter in organic scintillator

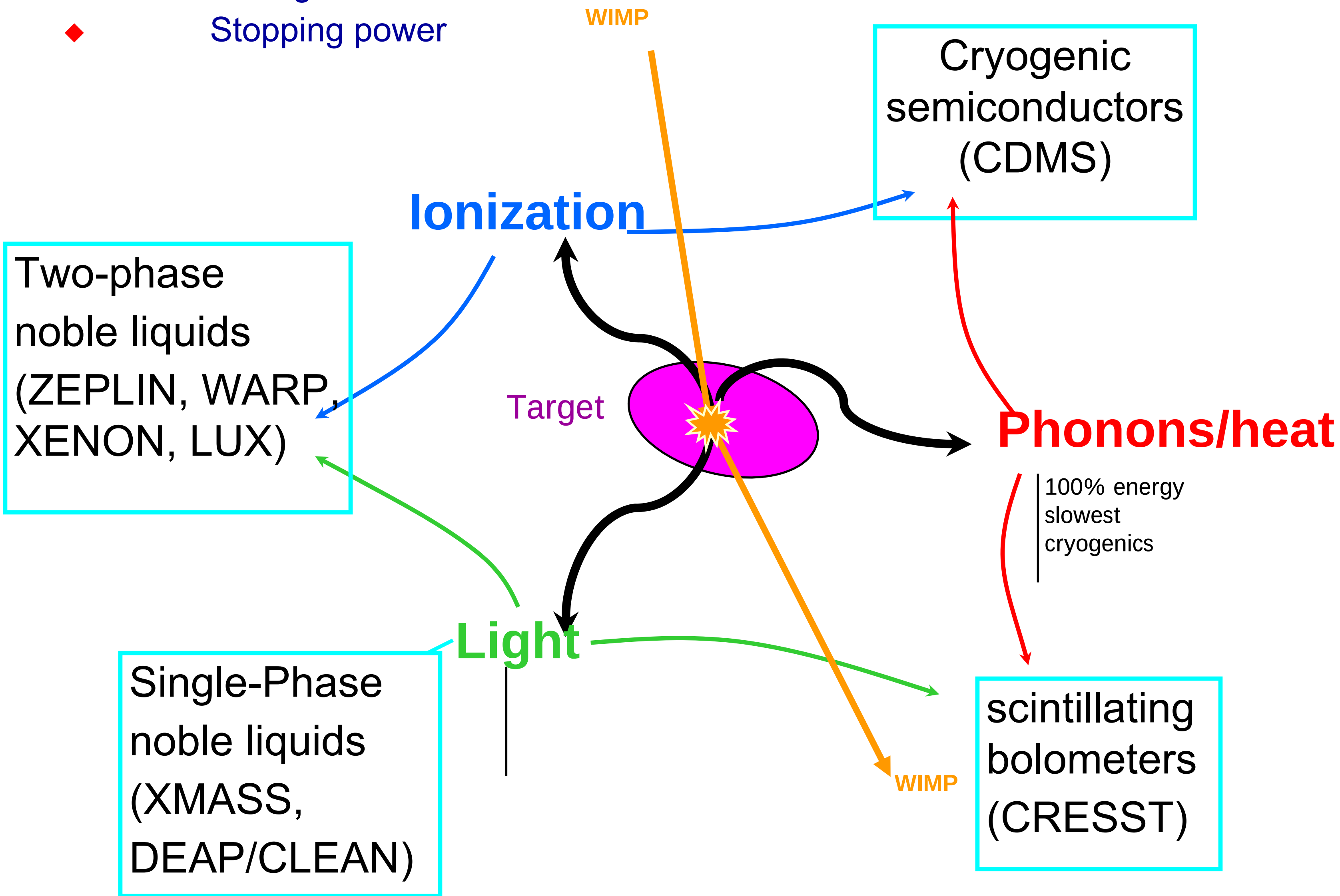

WIMP
γ
WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons

The Signal ... and Backgrounds

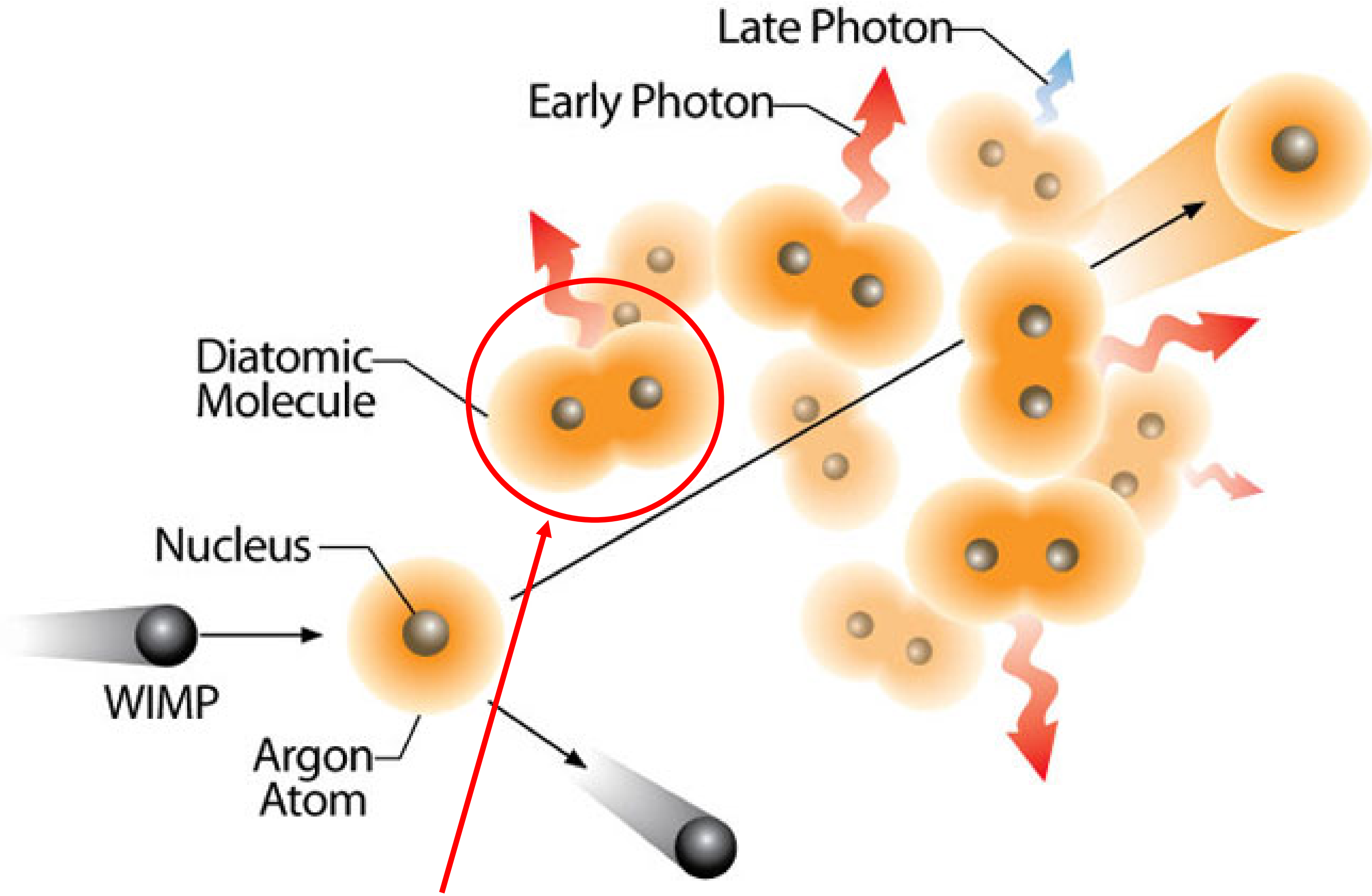


Background rejection through Particle ID

- Nuclear recoils vs. electron recoils
  - Division of energy
  - Timing
  - Stopping power

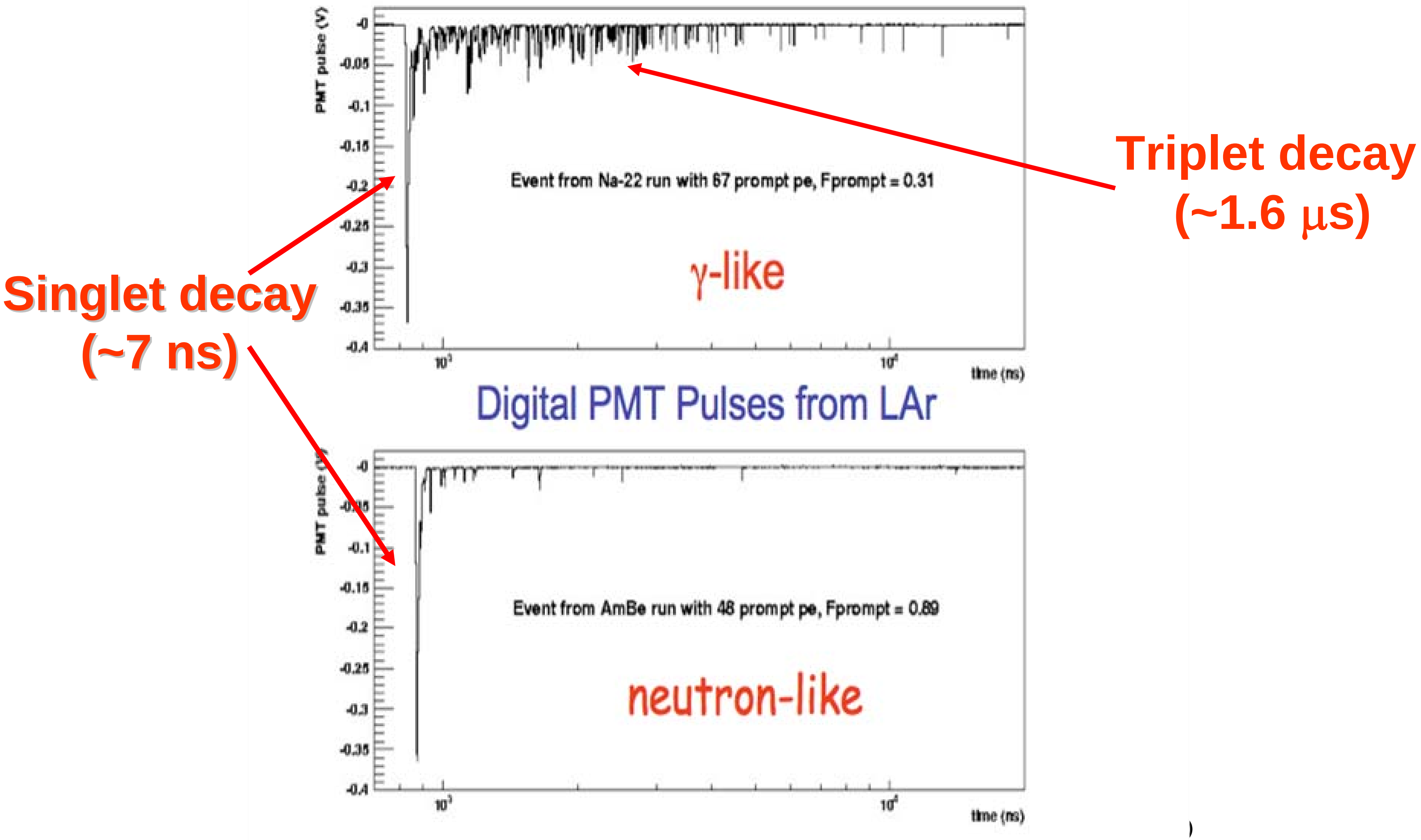


Scintillation pulse shape as particle ID

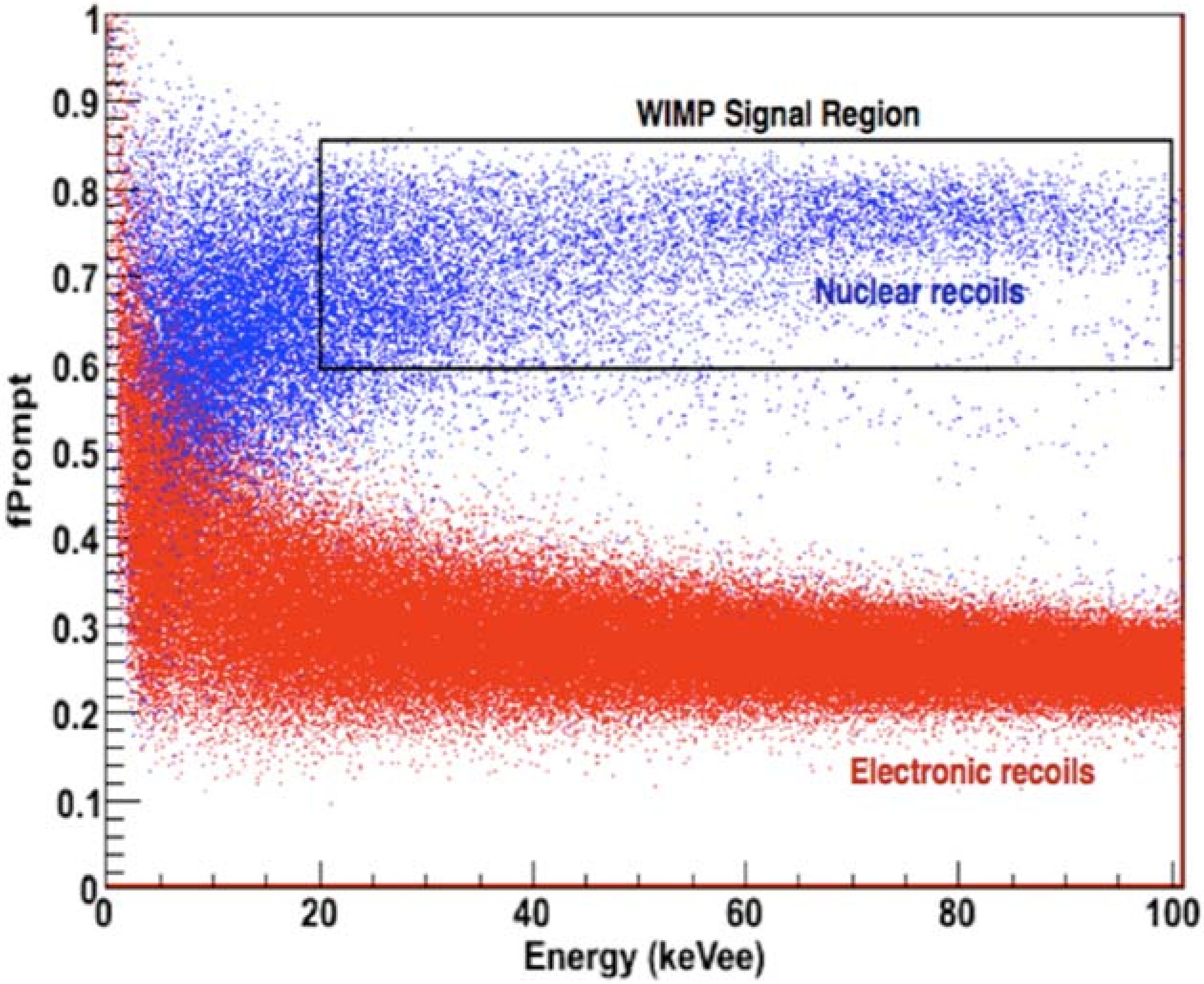


Excimer Molecules – (Ar)(Ar)* molecule has triplet and singlet states.

Scintillation pulse-shape-discrimination (PSD) in Liquid Argon



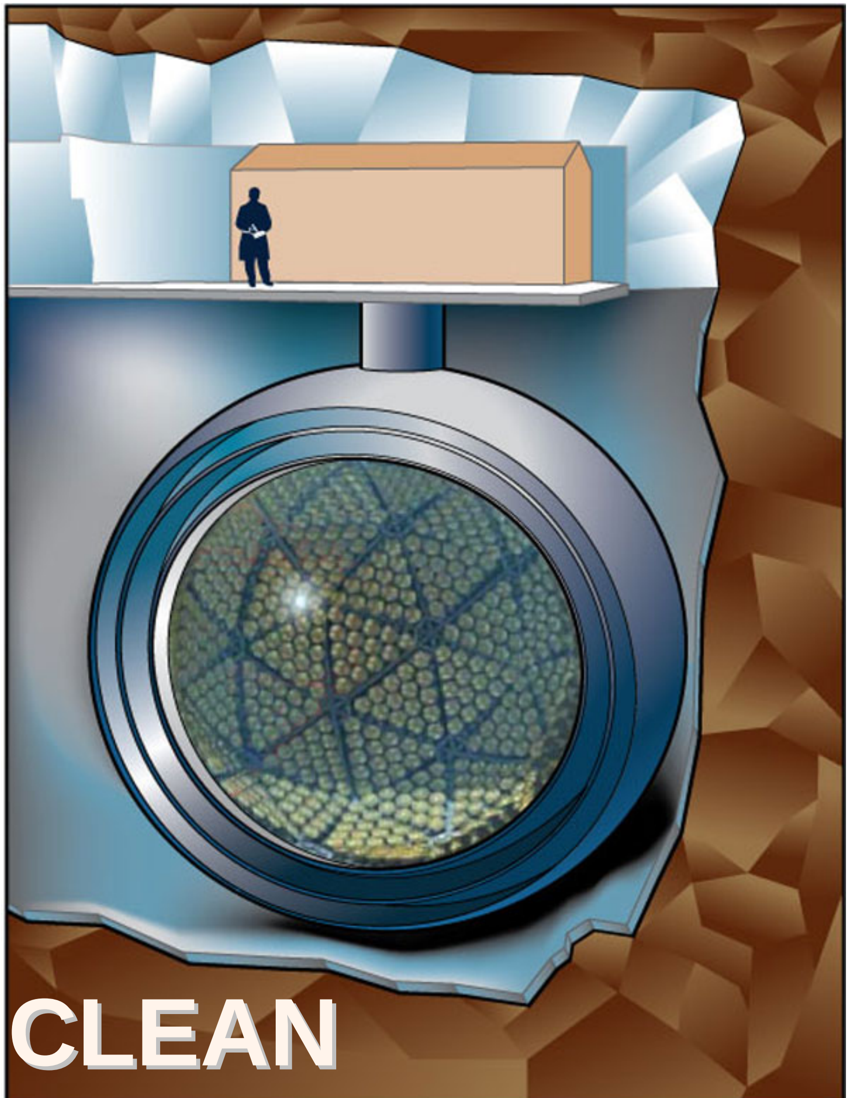
Scintillation pulse shape discrimination (PSD) in Argon



Data: Mini-Clean (McKinsey/Yale)

Discrimination is very powerful....... >10^6

CLEAN proposal:
Liquid Argon and Neon dark matter search

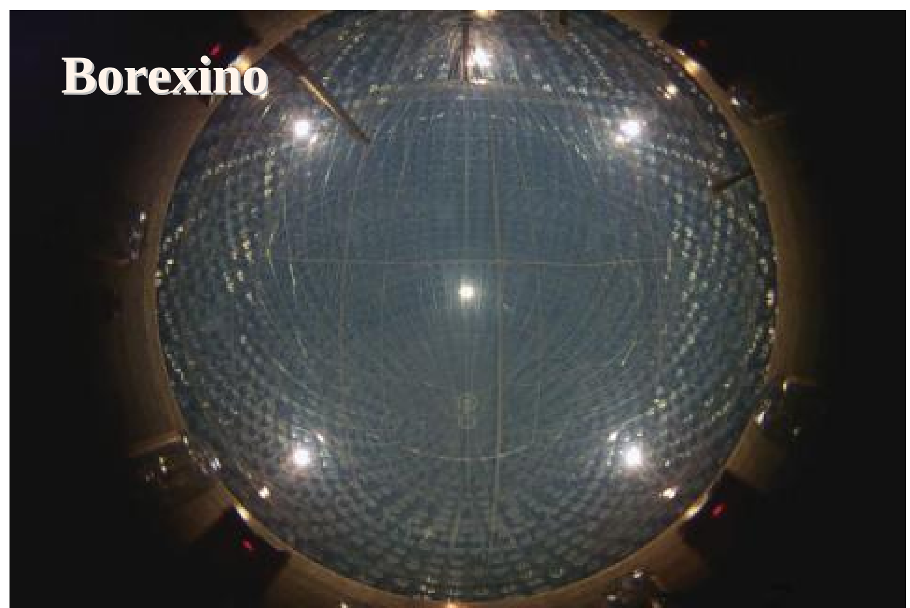


artist rendition courtest of LANL

- No ^{14}C background (Borexino)

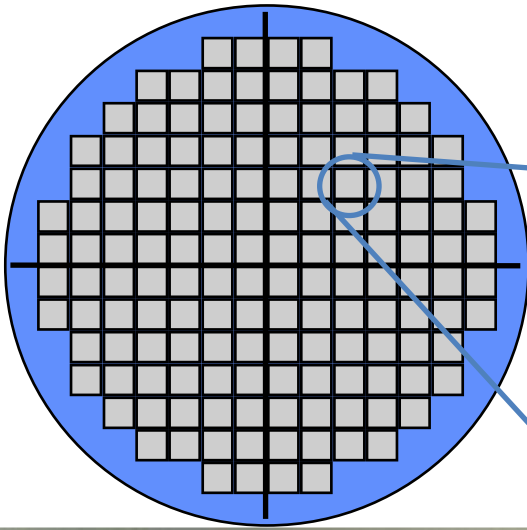
- Exquisite pulse shape rejection of common b & g backgrounds

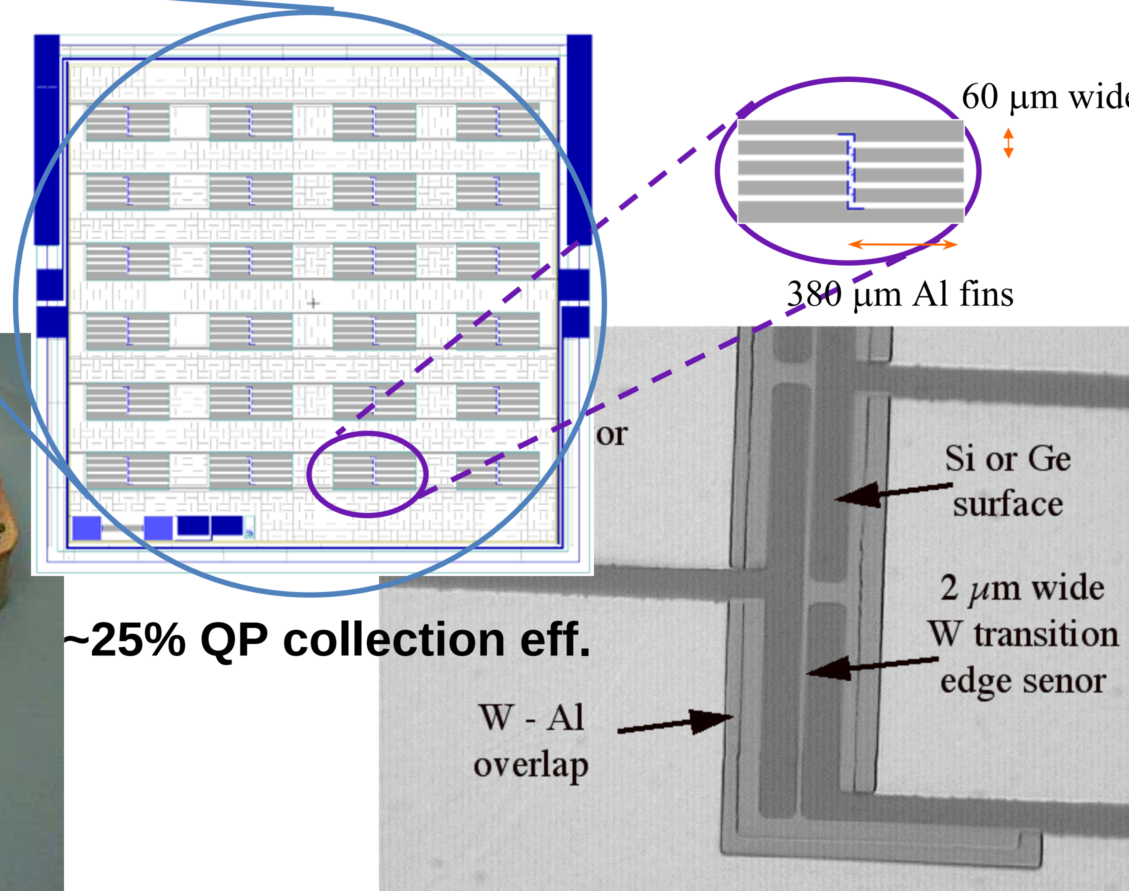
- BUT.....natural argon has its own problem – 39Ar (use depleted Argon instead)



CDMS - ZIP detector phonon sensor technology

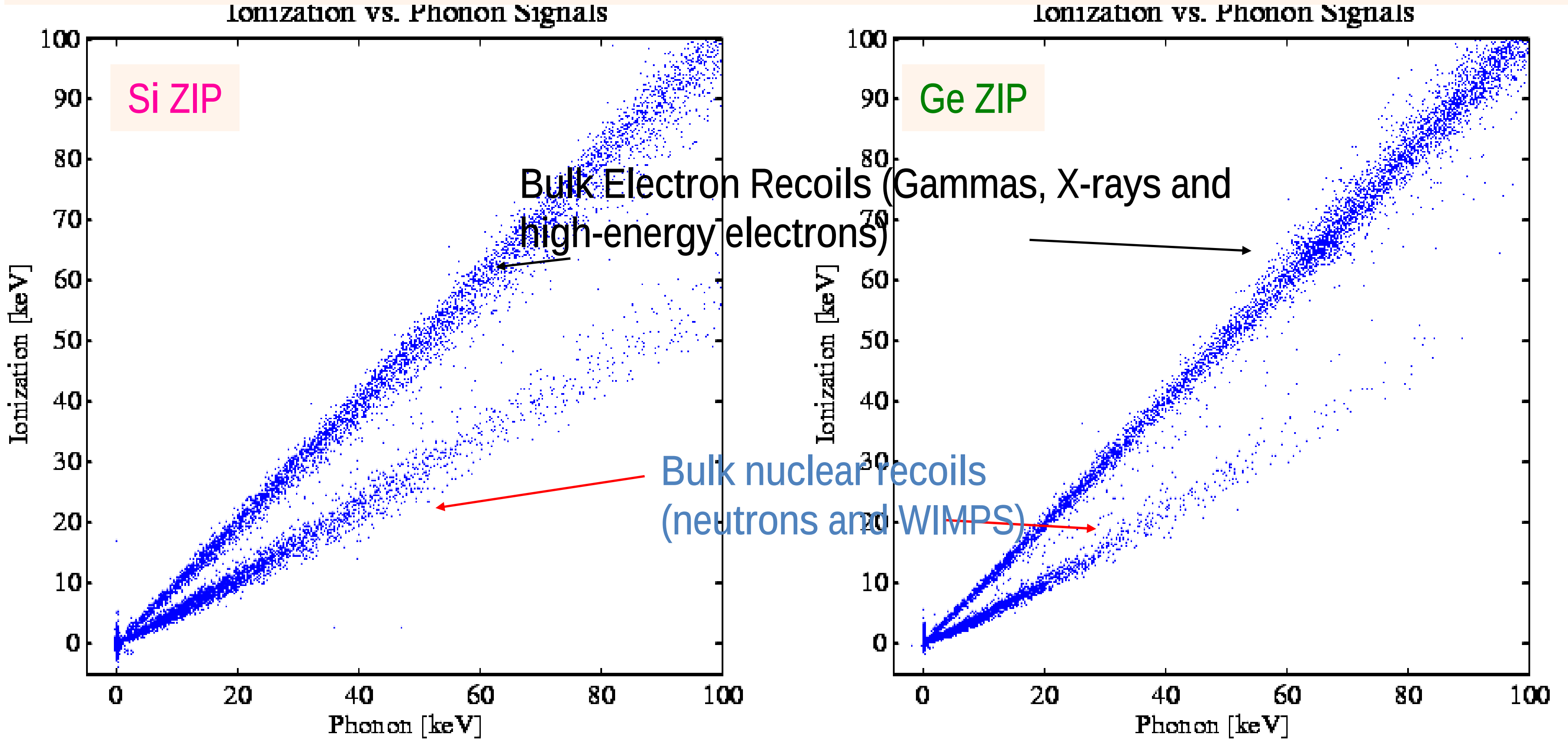
- TES's patterned on the surface measure the full recoil energy of the interaction
- Phonon pulse shape allows for rejection of surface recoils (with suppressed charge)
- 4 phonon channels allow for event position reconstruction





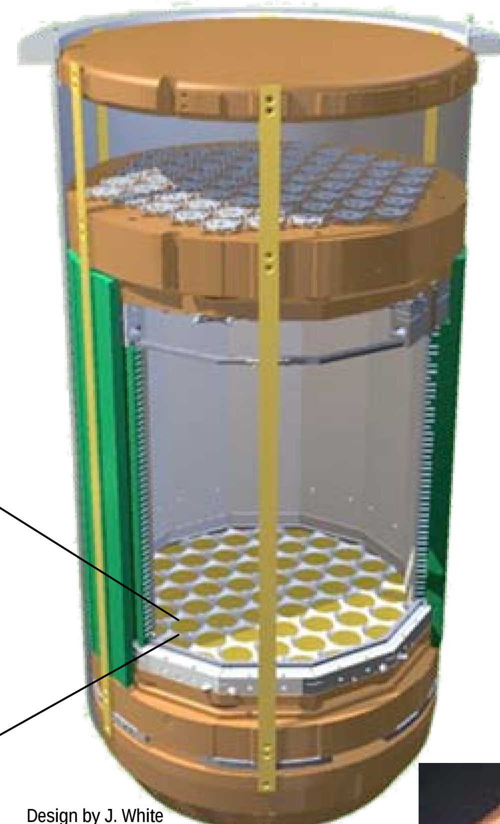
Photon and Neutron Calibration

- The response of the detectors is best demonstrated with in-situ calibration photon and neutron sources.
- Complete charge collection (after crystal neutralization) at 3V/cm.



LUX Design – Active Volume

- 350 kg of liquid Xe
  - Active volume: h=59cm, d=49cm
- Light collection ~2.0 phe/keVr
  - 2x better than Xe10
  - Analysis threshold down to < 3 keVr

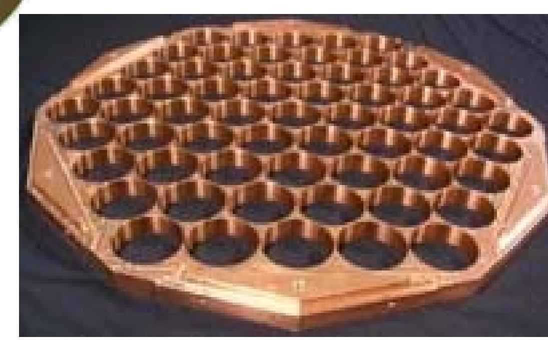


Design by J. White

- Dodecagonal field cage + PTFE reflectors

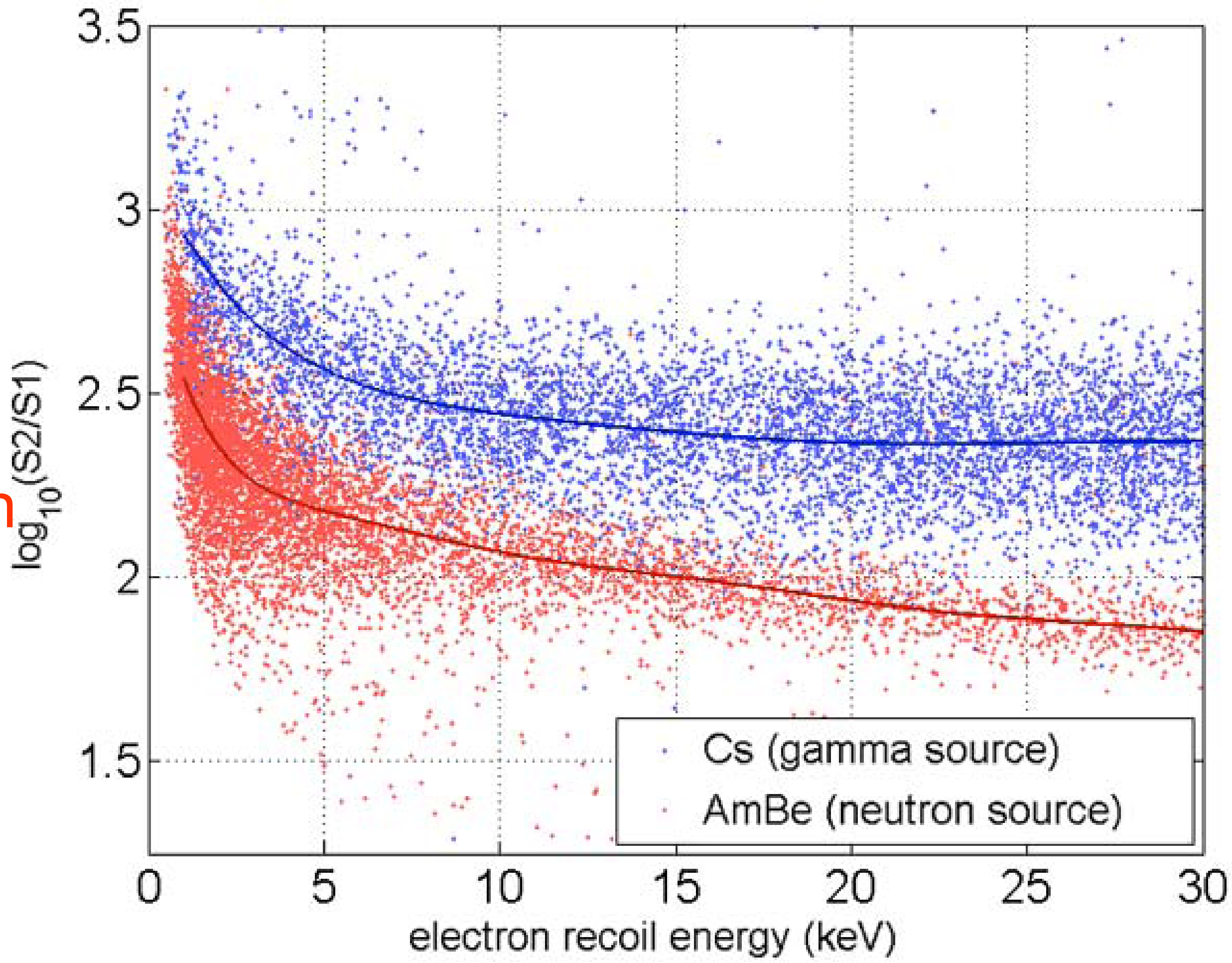
- 122 PMT R8778
  - 2" diameter
  - 175 nm, QE > ~30%
  - U/Th ~9/3 mBq/PMT

- Cu PMT holding plate



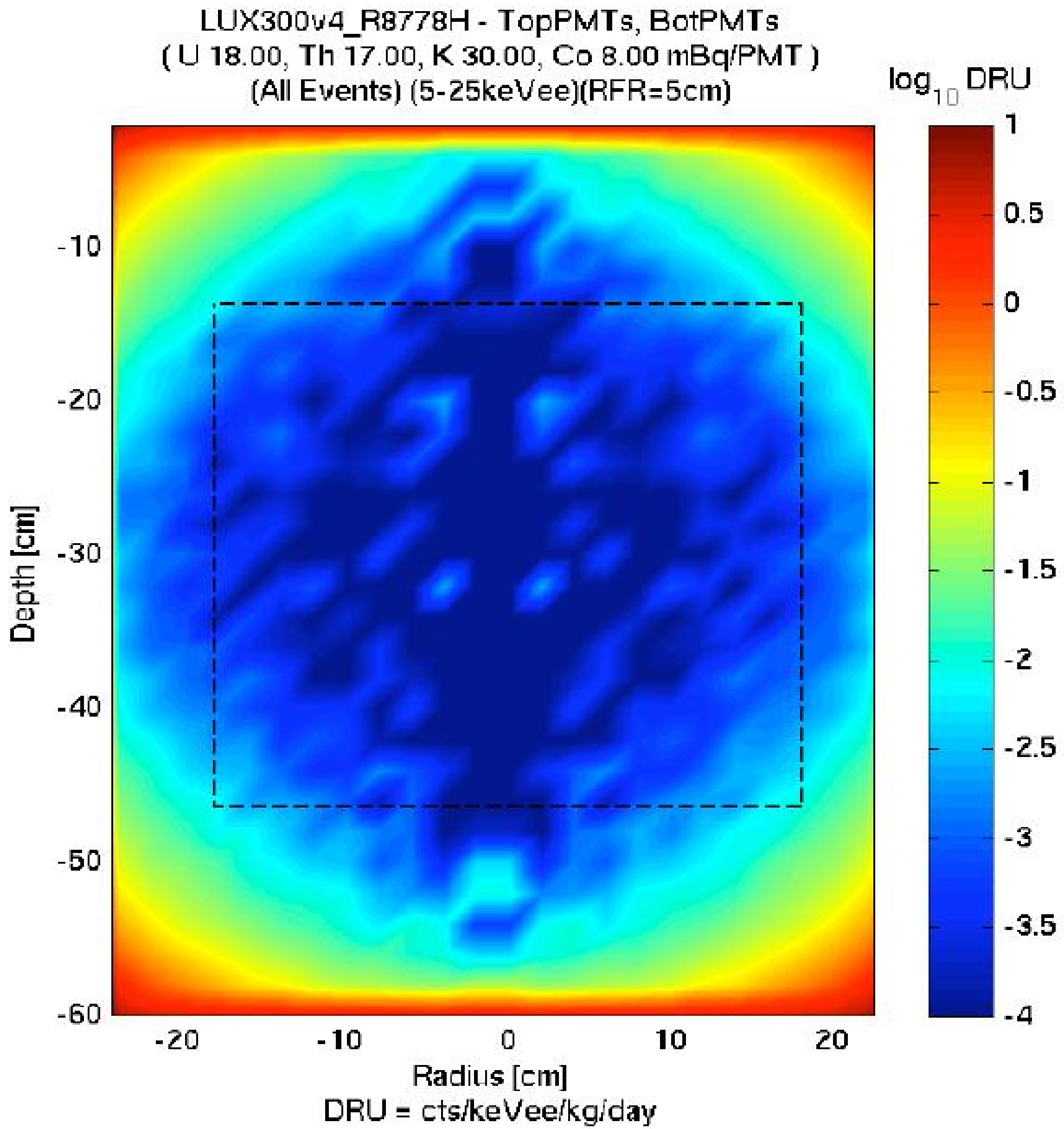
Photons vs neutrons with liquid xenon

Ionization to Scintillation ratio



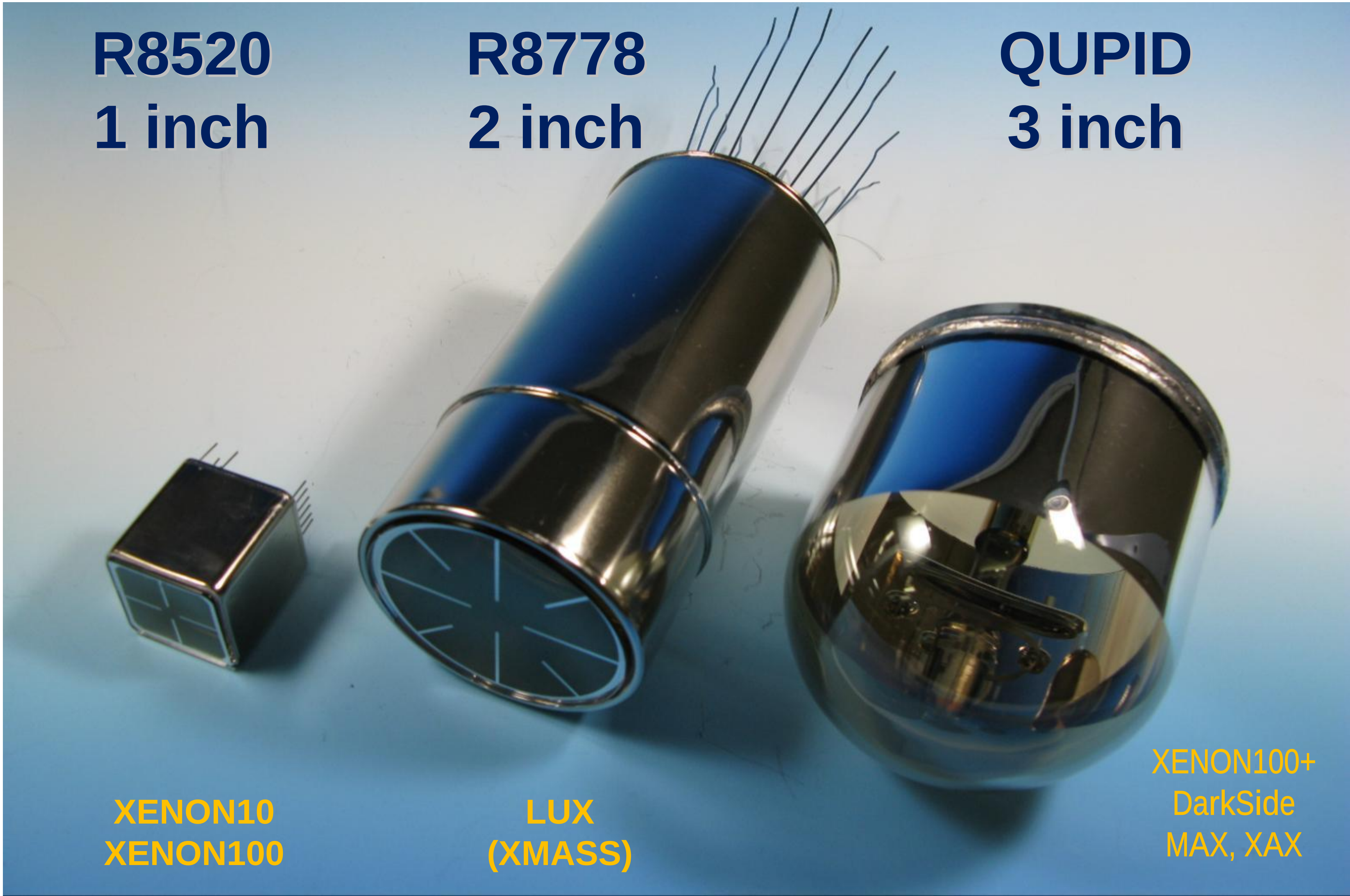
Allows discrimination between common radioactivity and WIMP events.
Background rejection factor of ~180

Detector self-shielding –
absorption of naturally occurring radioactivity

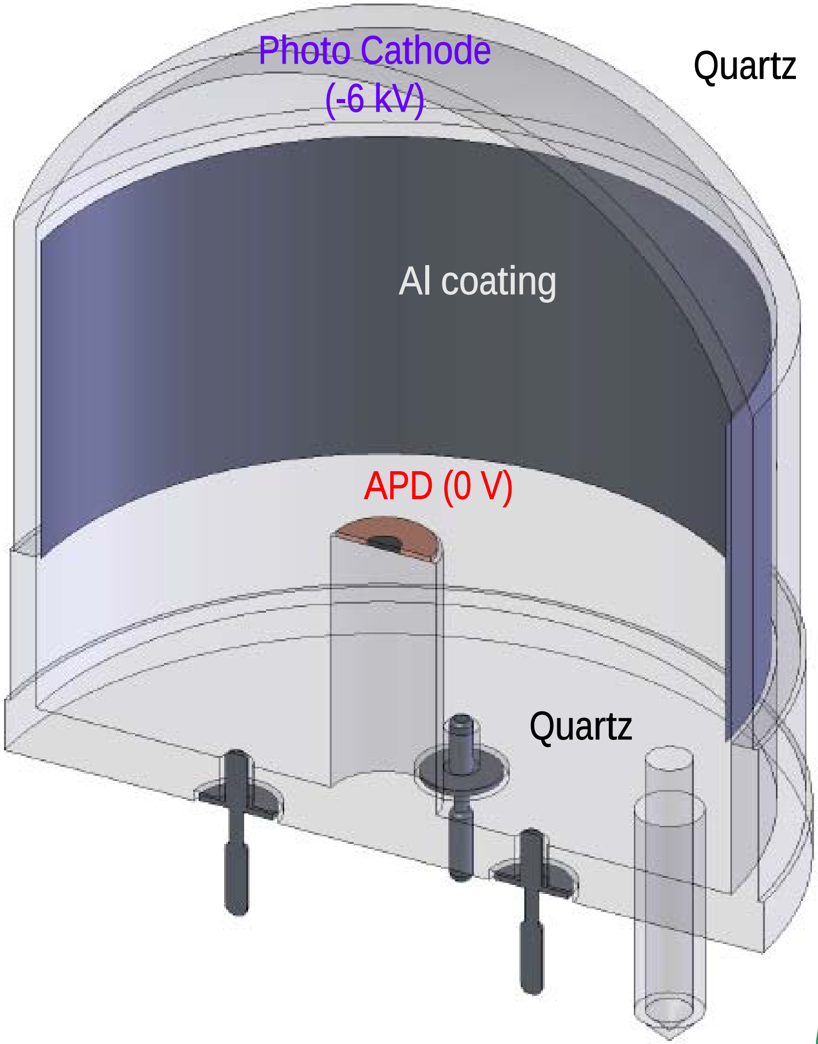


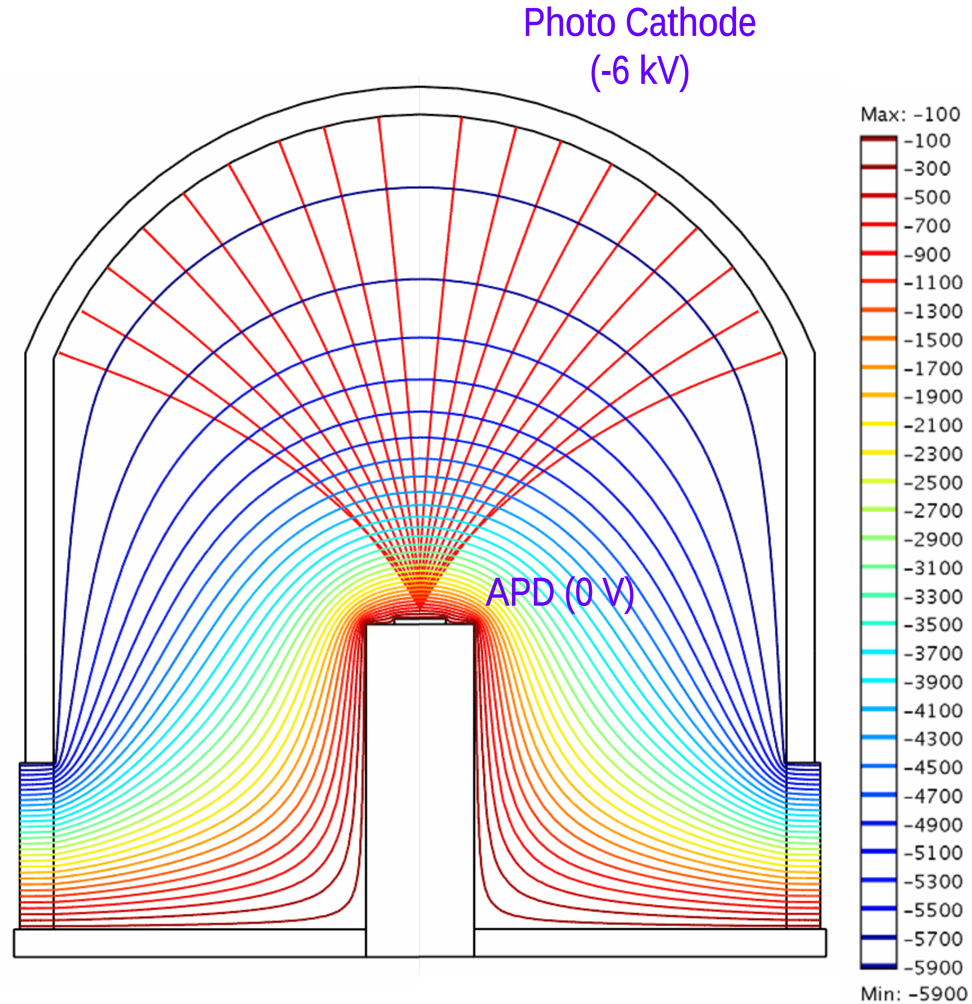
PMT radioactivity dominates

Comparison of Low-radioactive Photon Detectors from Hamamatsu



QUPID (QUartz Photon Intensifying Detector)

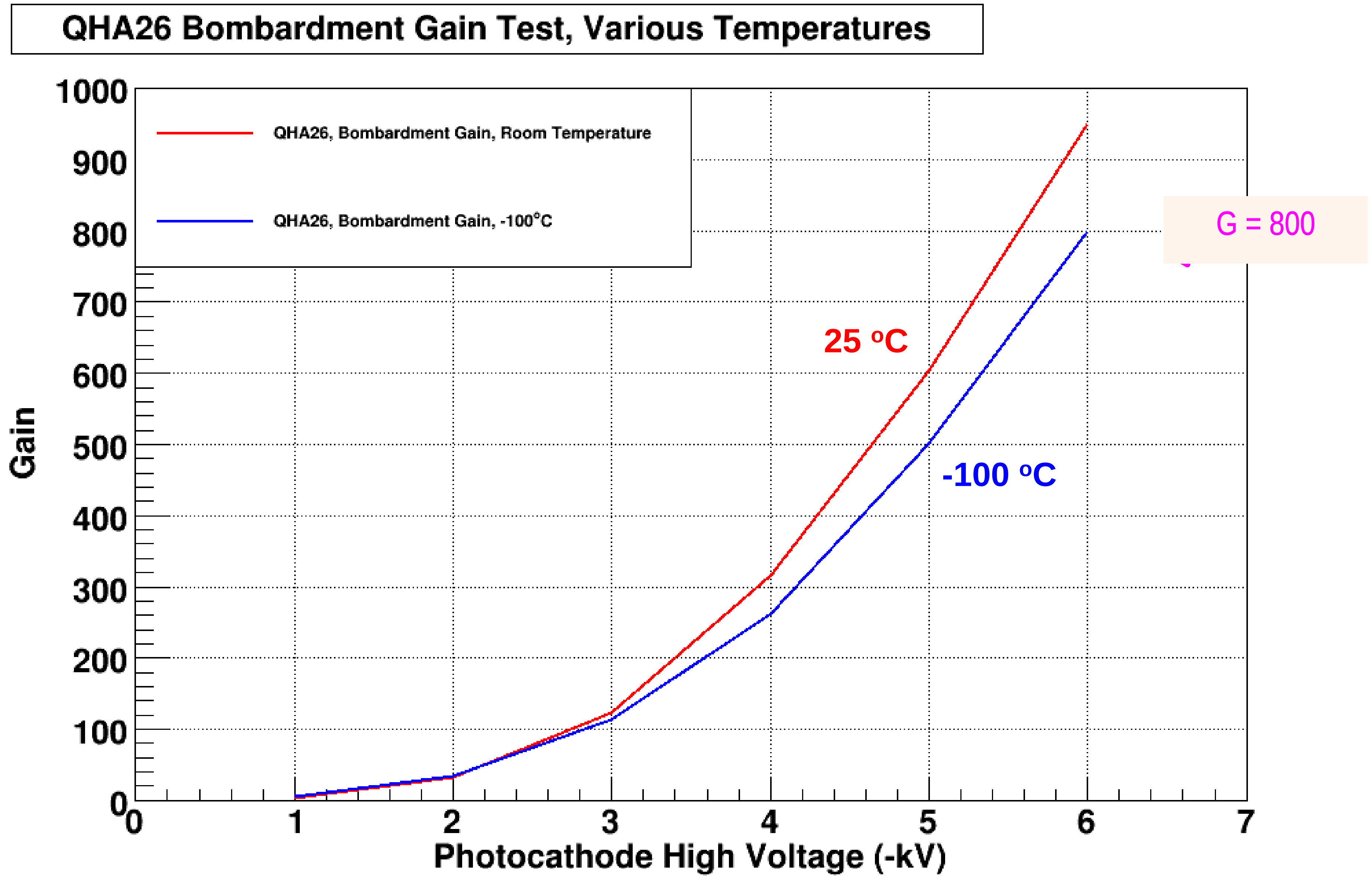




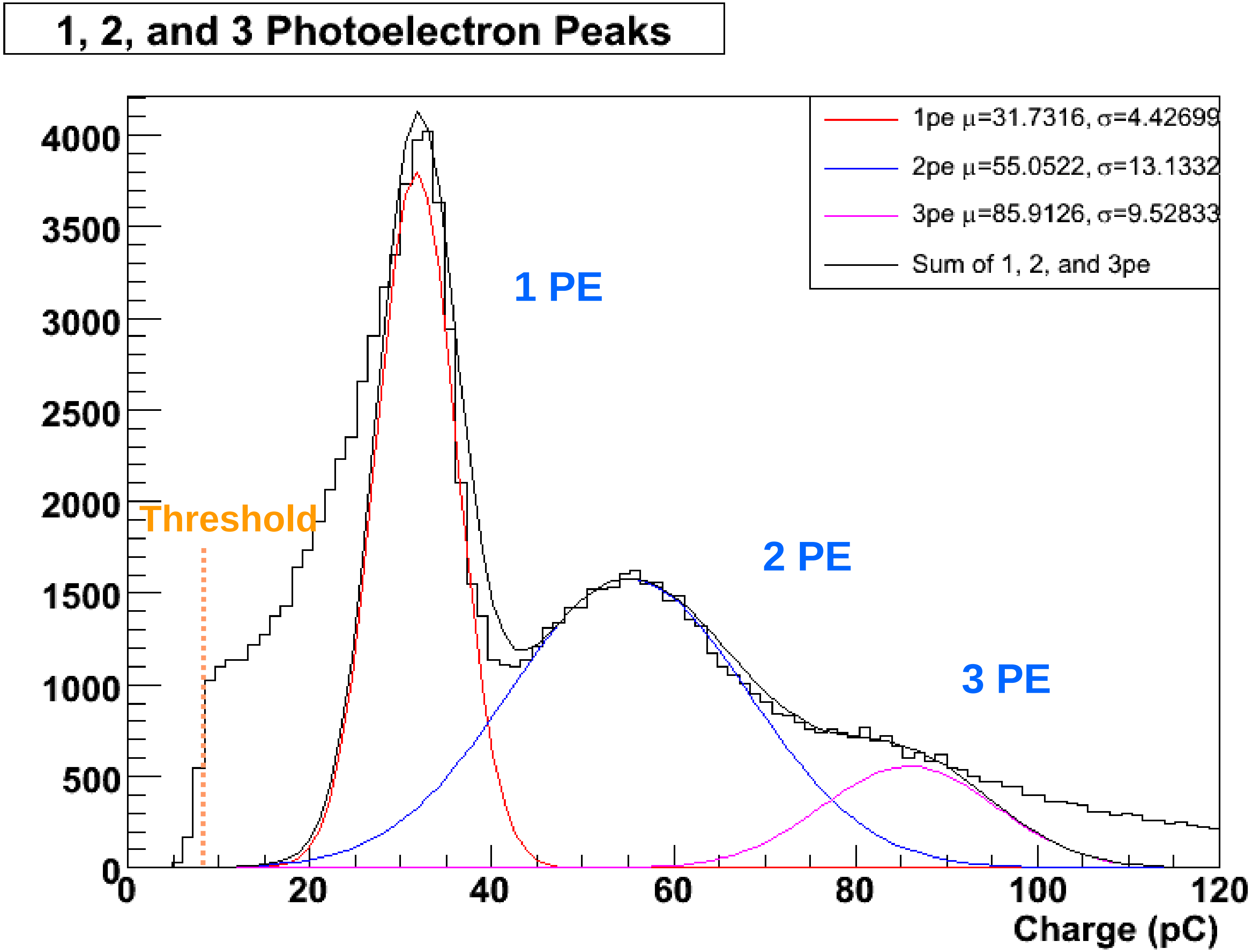
Made by Synthetic Silica only.
US Patent (No. 5374826) pending.

New 3” QUPID (Production Version)

Electron Bombardment Gain (QHA26)



The first Scintillating lights detected by QUPID from ^{57}Co in Liquid Xenon

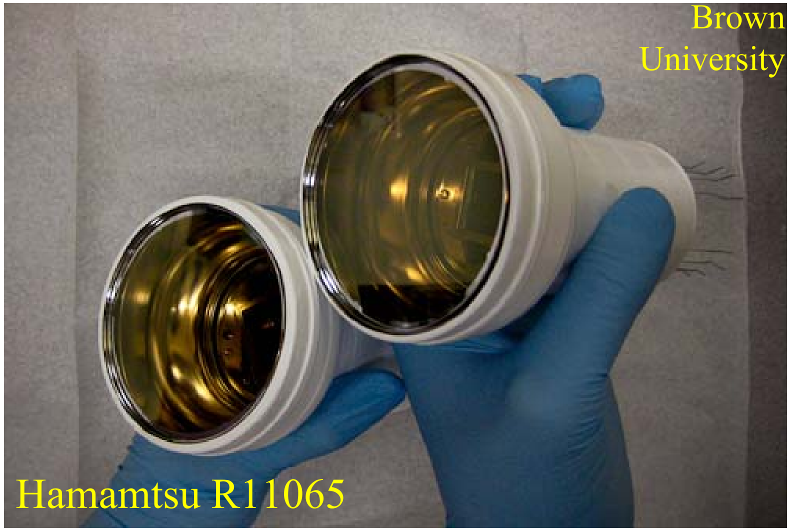


PMTs (LZS and LZD 20 tonne LXe)

- Current LUX 350 Experiment: Using 122 x 2” R8778 Hamamatsu
  - Production yields high/very stable - long track record with technology
  - U/Th 10/2 mBq/PMT
    - There has been tremendous progress in reducing PMT backgrounds
    - The level of radioactivity already achieved in these PMTs would be an acceptable baseline for the LZS and LZD experiments
  - Demonstrated QE: average=33%, max 39% at 175 nm
    - Permits factor 3 better phe/keV response in LUX than in XENON100

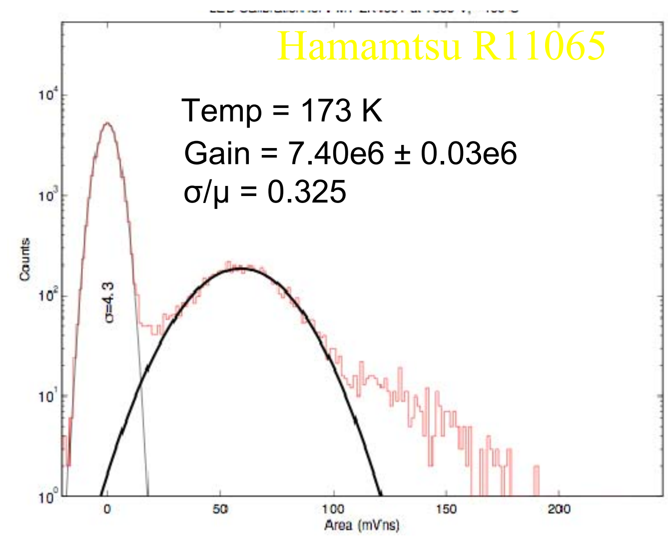
PMTs (LZS and LZD 20 tonne LXe)

3” Diameter PMT for LXe



3” Testing in LXe

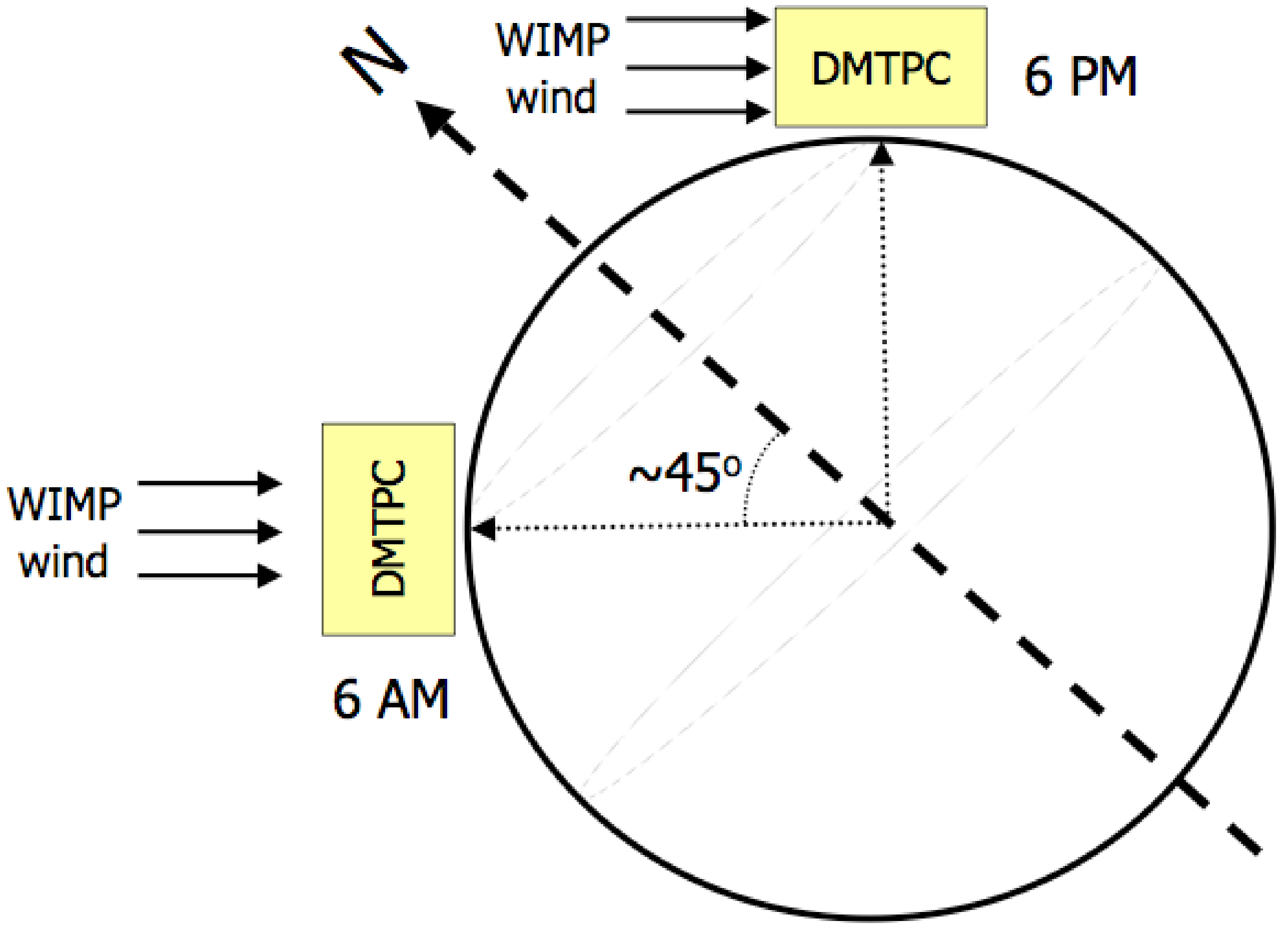
Single phe calibration, -100 C, -1500 V



- Under LZ S4 development program: DUSEL R&D
  - Larger diameter - twice collection area. Radioactivity further reduced.
  - In 2009 initially fab of and tested Hamamatsu 3” R11065 in LXe
    - Tested QE/LXe operation - all PMTs performed identically to those of same as R8778
    - Well understood performance. Stable performance.
    - High gains >5x10^6 mean that no additional amplifiers required. Electronics within cryostat are limited to passive components with very low/well understood radioactive backgrounds
  - Developed new ultra low background 3” PMTs for LXe: R11410mod
    - Background measured U/Th <1/1 mBq/PMT (90% CL) - No U/Th signal seen
    - This comfortably exceeds background requirements for LZD detector
    - Upgraded Hamamatsu Super bialkali photocathodes will also be available to move QE above 40%
- Requirement is for 1000x3” PMT for LZD (20 tonne)
  - Production yields and cost well understood

DM wind signature #2: daily modulation

Spergel PRD 37,1353 (1988)



Only directional detection can correlate with Cygnus:
unambiguous positive observation of Dark Matter in presence of backgrounds

DMTPC: detector concept

Low-pressure CF_4 TPC

- 50 torr: 40 keV F recoil ~2mm

Optical readout (CCD)

- Image scintillation photons in amplification region
- 2D, $, proven technology, clean

PMT and charge readout

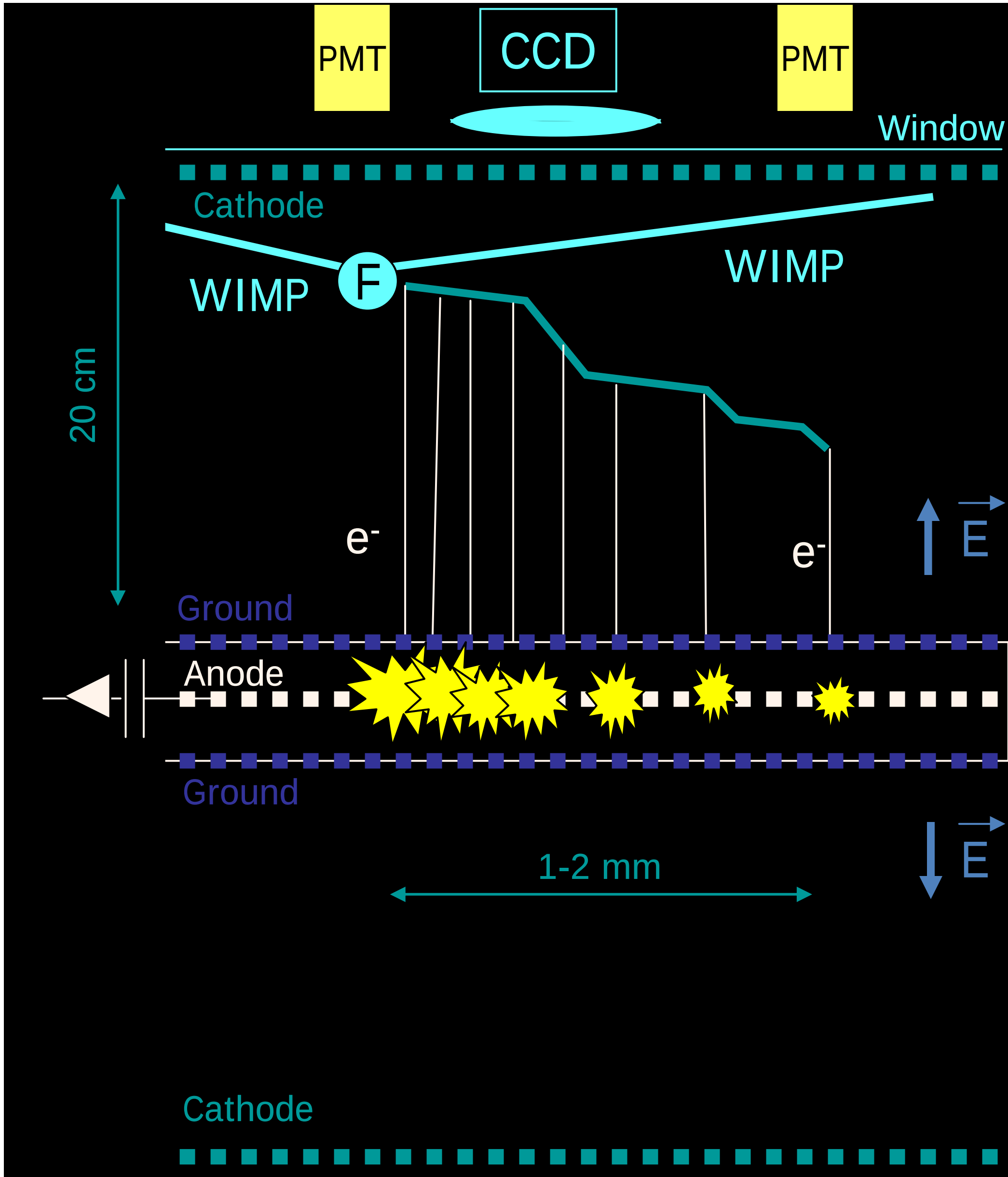
- Trigger and E measurement

Amplification region

- Woven mesh 250 μ m pitch

CF_4 is ideal gas

- F: spin-dependent interactions
- Good scintillation efficiency
- Low transverse diffusion
- Non flammable, non toxic

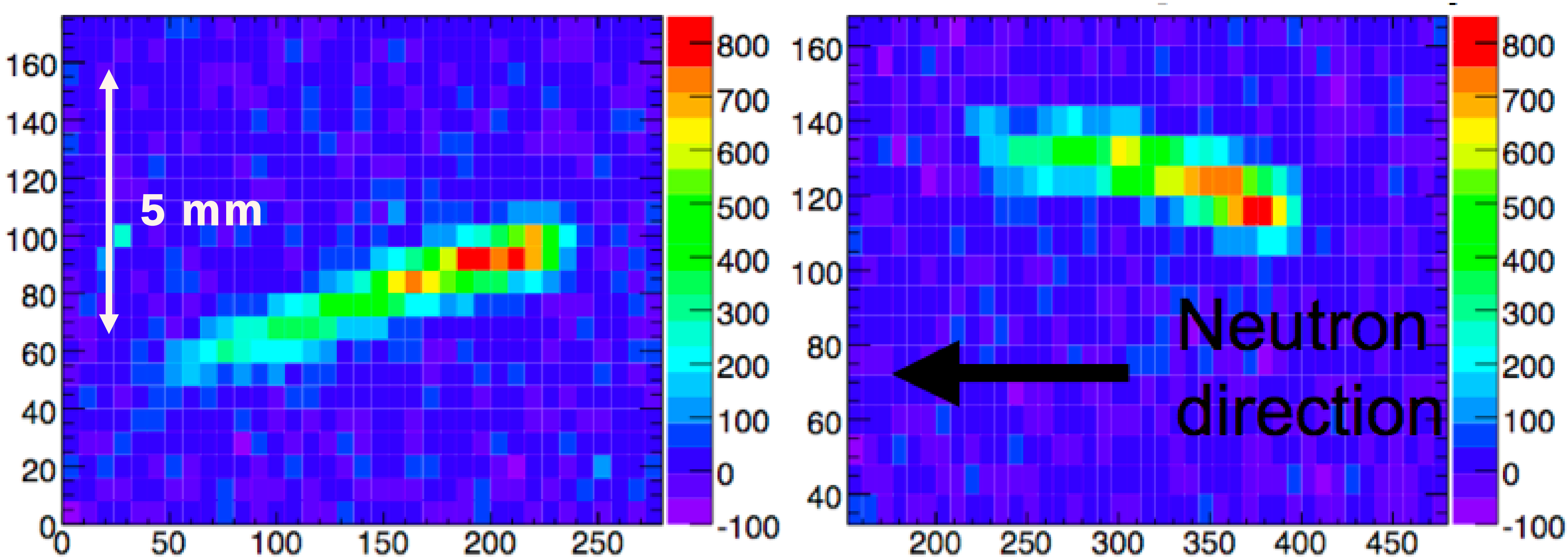


Astropart. Phys. 30 (2008) 58-64

Calibration with low-energy neutrons:

^{252}Cf run with mesh detector

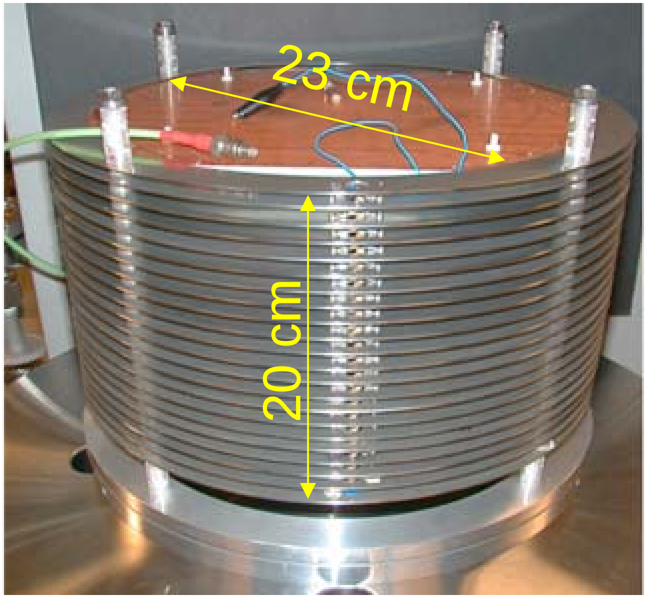
- Mesh-based detector: 1D → 2D projection of recoil
- Stable data-taking at 75 torr
  - "Head-tail" effect demonstrated down ~ 100 keV
- Excellent data-MC agreement
- Angular resolution: 15° at 100 keV

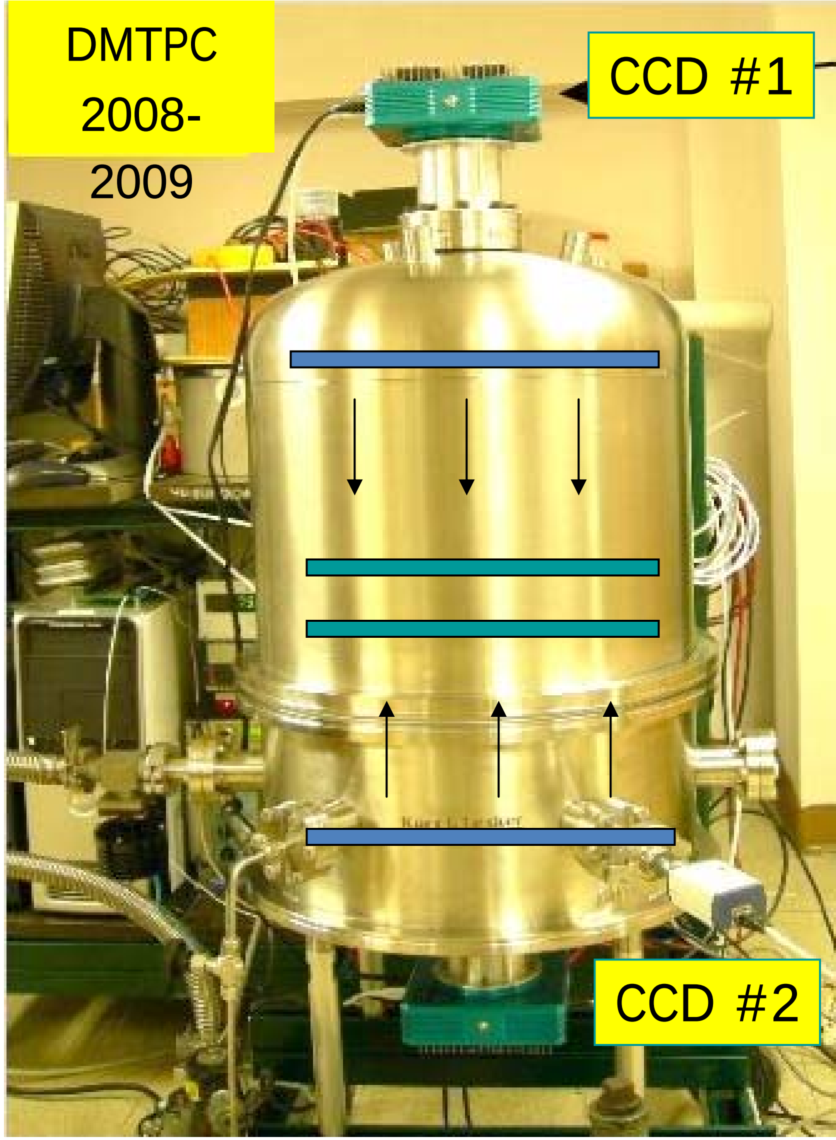


10-liter DMTPC detector

Second generation - DMTPC 10-ℓ

- Mesh-based amplification planes
- 23cm Ø and 20 cm drift/TPC
- 3.3g @75 torr
- 2 CCD cameras (top and bottom)





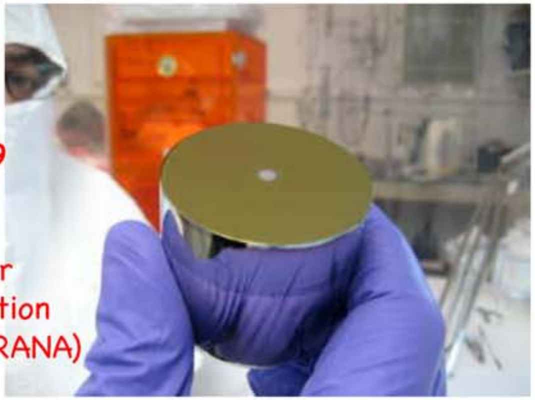
P-type Point Contact High Purity Germanium

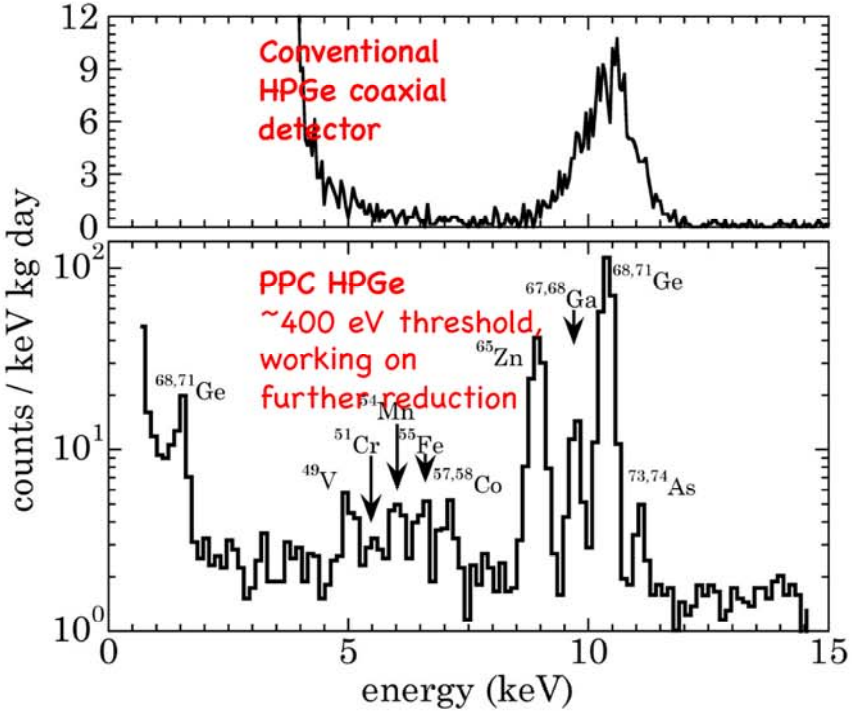
CoGeNT:
neutrino &
astroparticle physics
using large-mass,
ultra-low noise
germanium detectors
(CANBERRA, PNNL, ORNL, UC, UNC, UW)

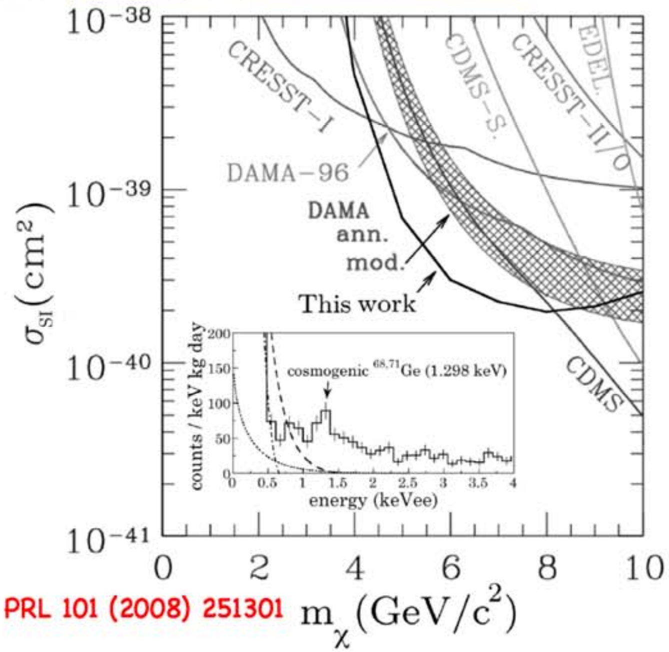
PPC HPGe

JCAP 09(2007)009

Applications:
- Light Dark Matter
- Coherent ν detection
- ββ decay (MAJORANA)







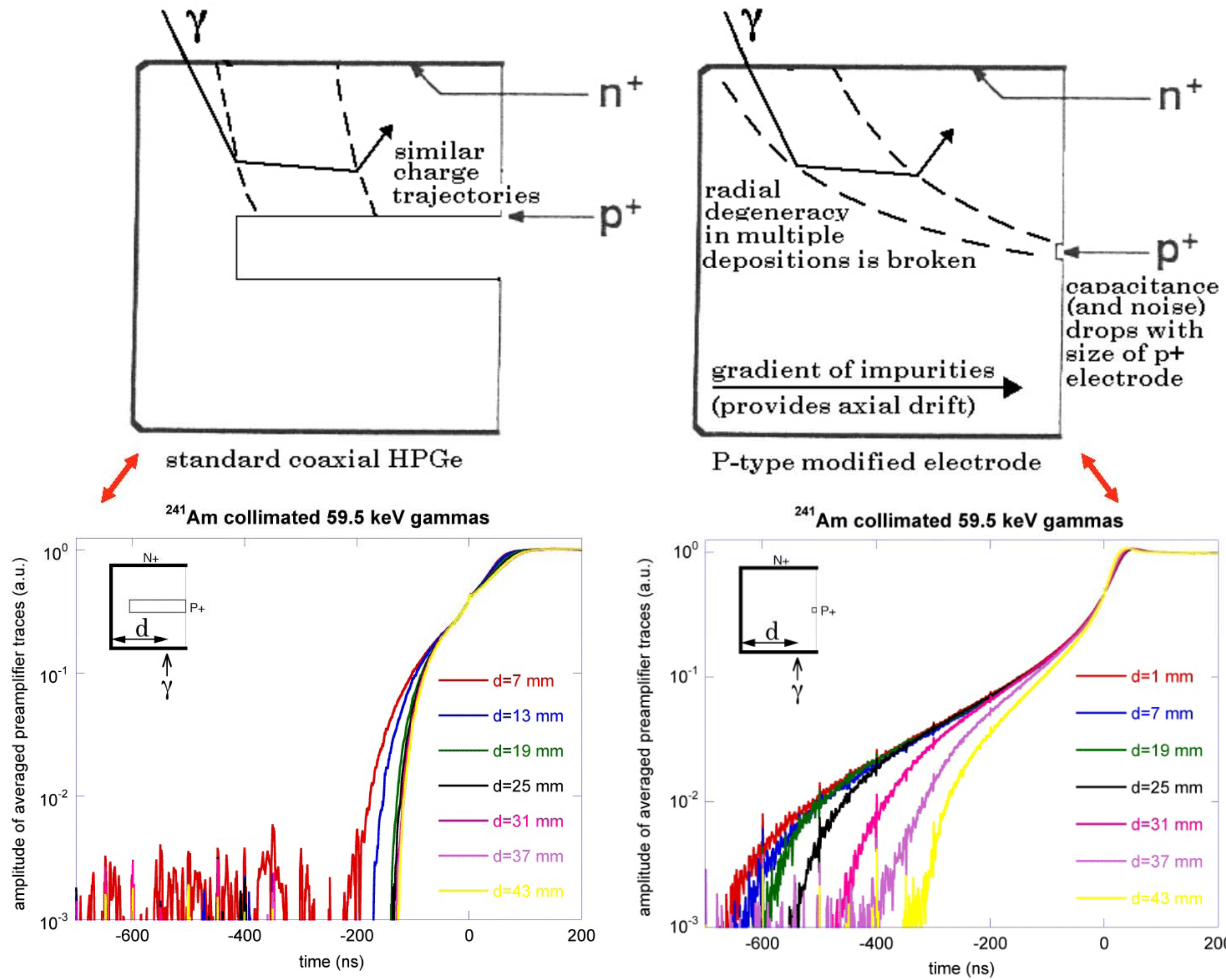
PRL 101 (2008) 251301

Extensive constraints on DAMA's claim:
- Light WIMPs
- Dark scalars
- Dark pseudoscalars

J. Collar, U. Chicago

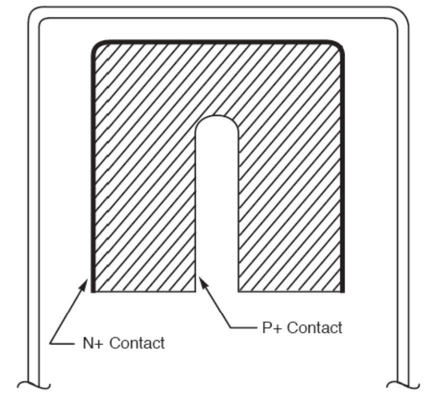
-type Point Contact High Purity Germanium

What is happening?



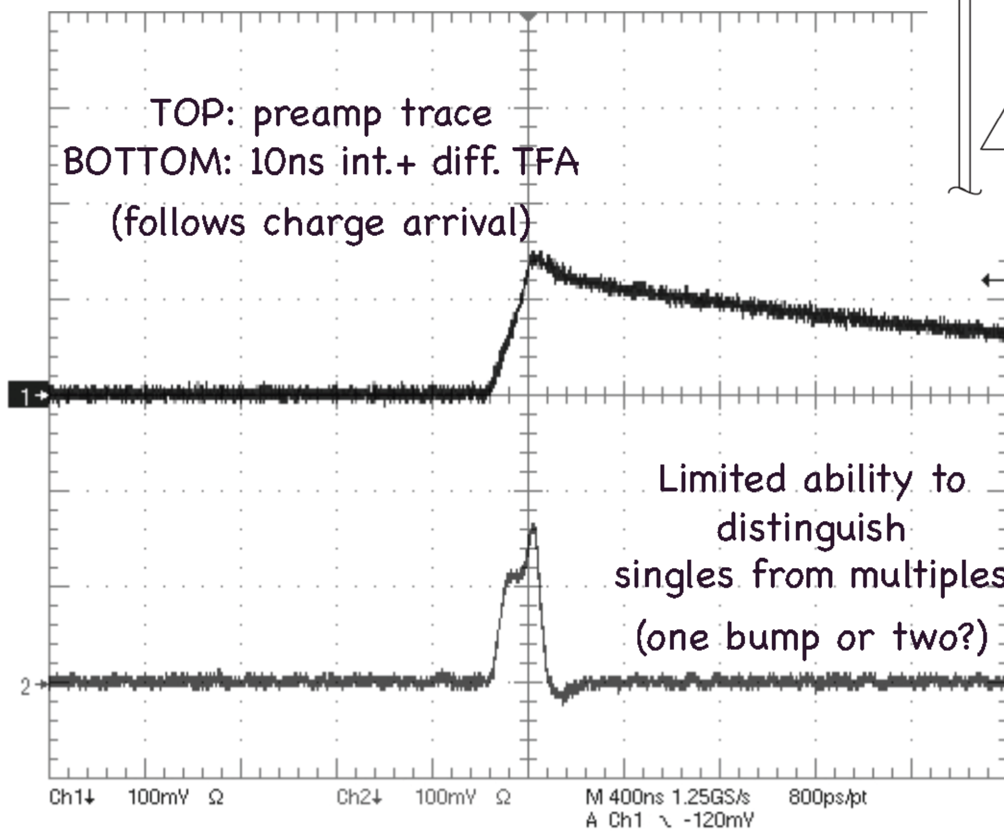
P-type Point Contact High Purity Germanium

Other nice features brought by the point contact:



Coaxial Ge Detector Configuration

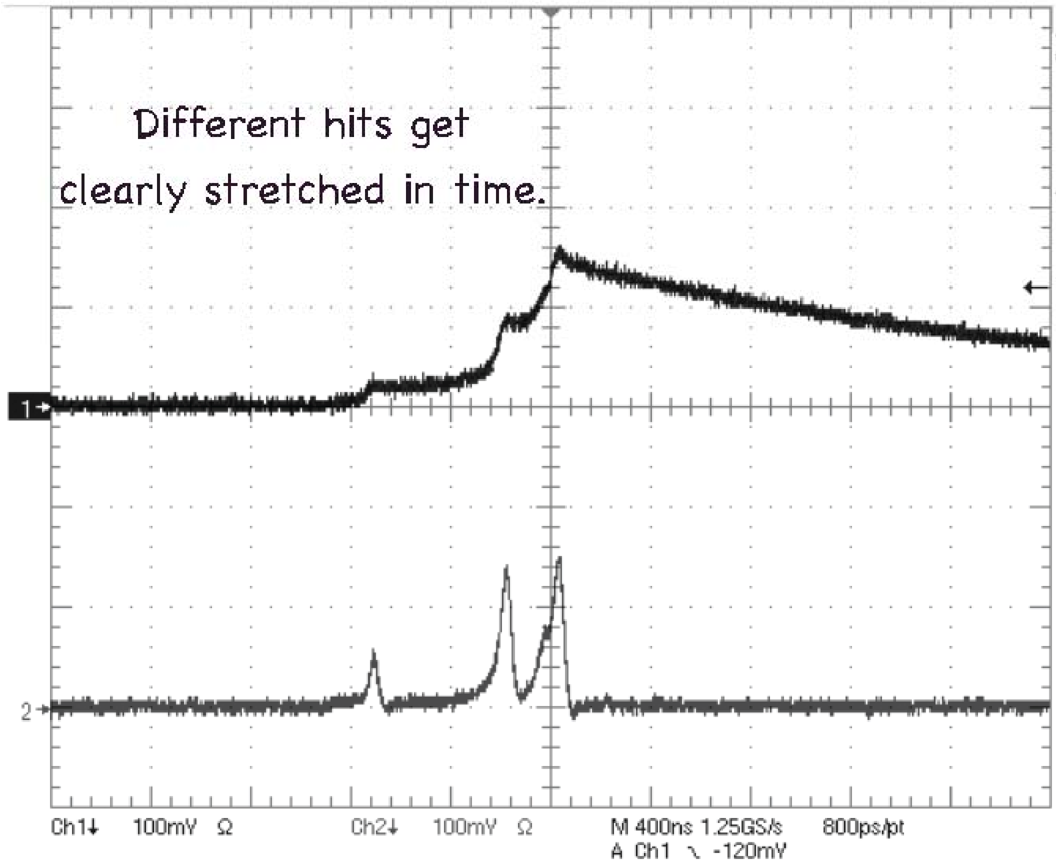
That was then...

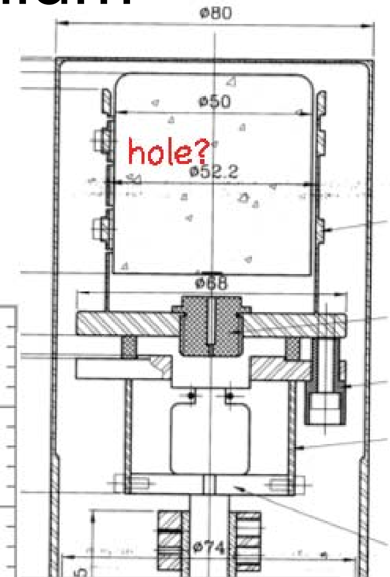


J. Collar, U. Chicago

P-type Point Contact High Purity Germanium

This is now.





All this with optimal energy resolution and charge collection (and one channel)

J. Collar, U. Chicago

Double beta decay: get smarter with single Ba^+ ion detection

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

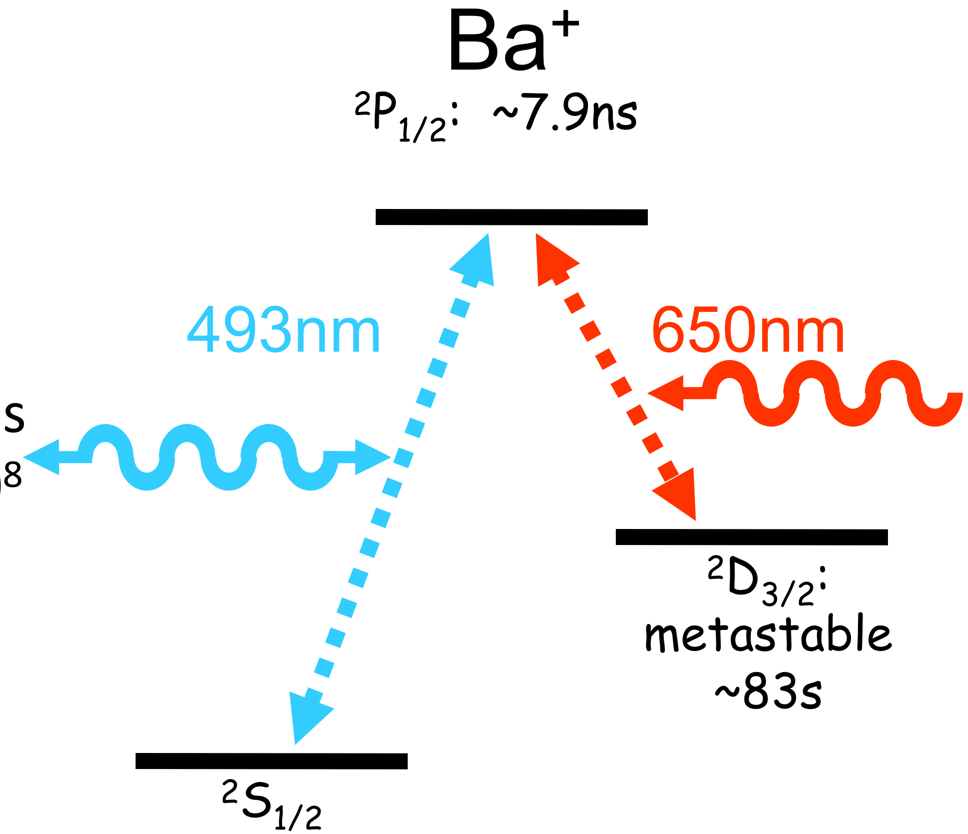
Daughter identified by optical spectroscopy of Ba^+, well studied in ion traps for more than 25 years

[Neuhauser, Hohenstatt, Toshek, Dehmelt, Phys. Rev. A 22 (1980) 1137]

- very specific signature ("Λ" shelving)

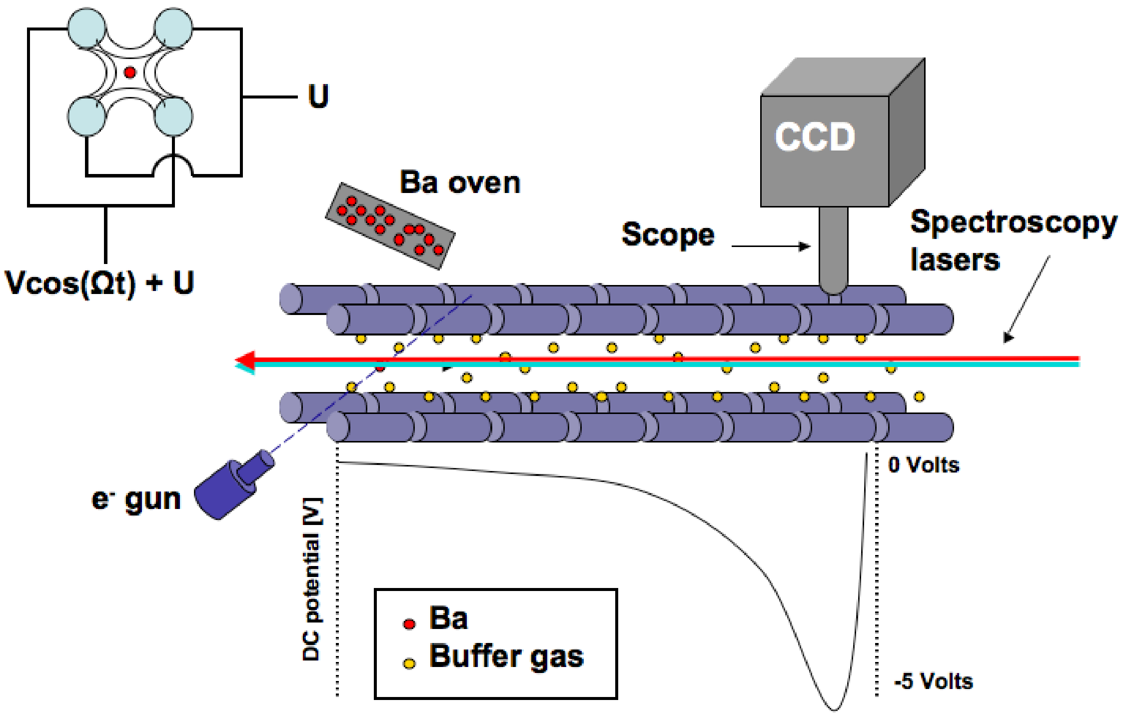
- cycling 493/650 nm transitions gives a fluorescence rate of ~10^8 Hz (in vacuum)

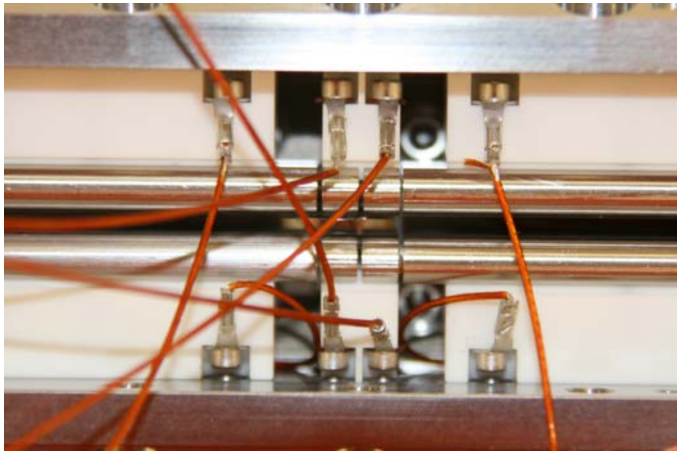
plenty of light!

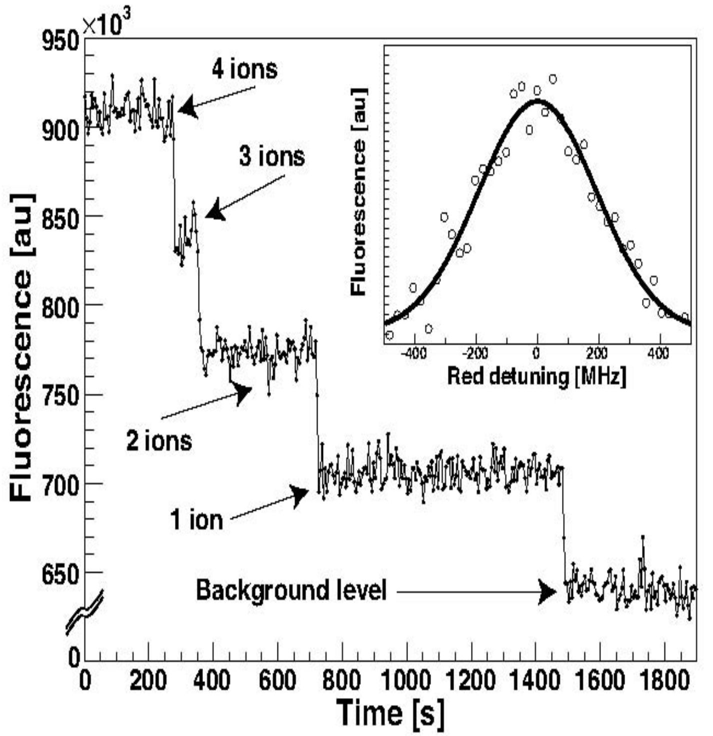


Ba+ Tagging: Ion Trap + fluorescence

QuickTime™ and a decompressor are needed to see this picture.





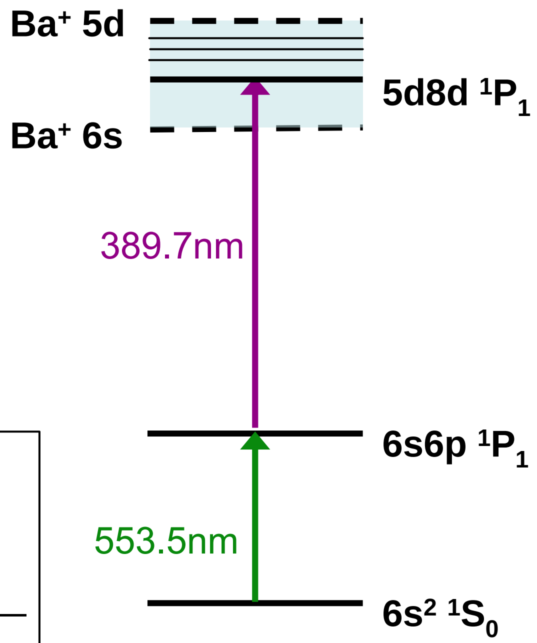


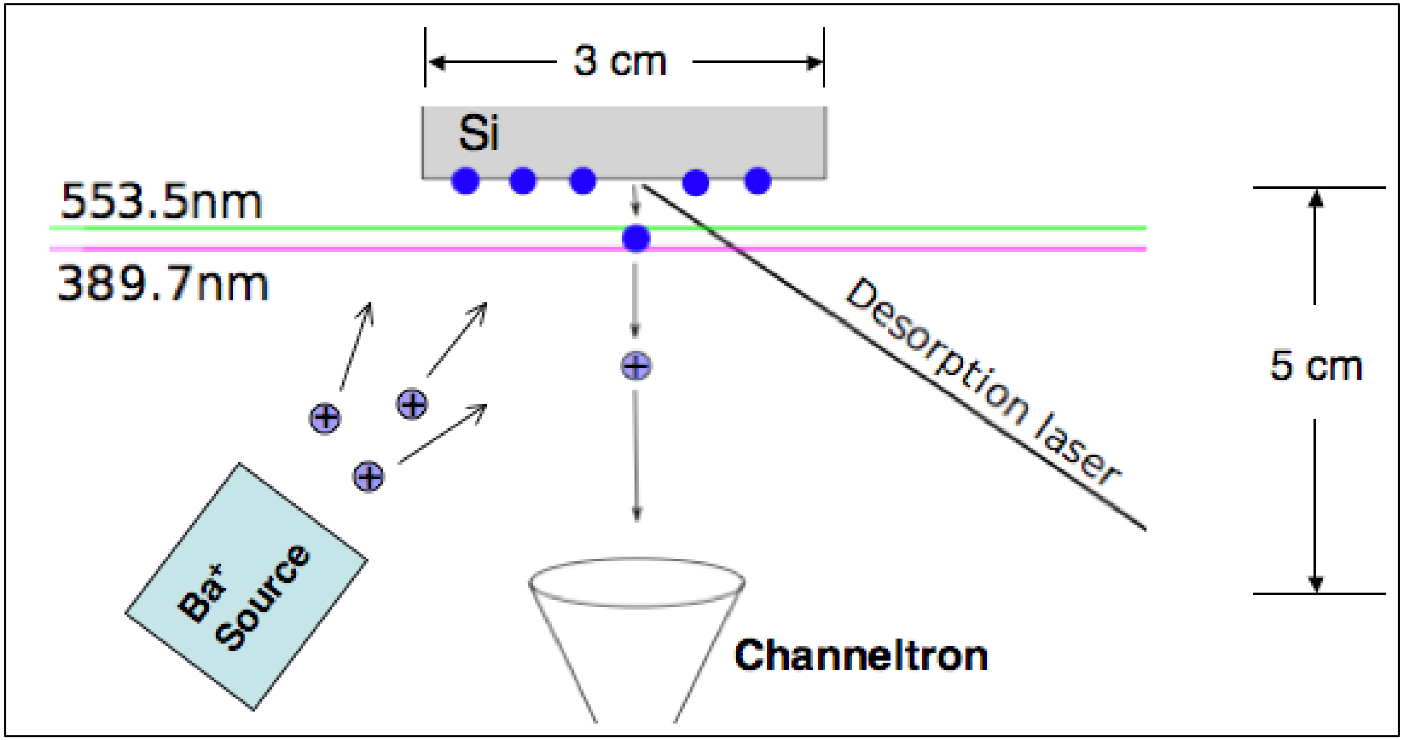
~9σ discrimination in 5s integration

M.Green et al., *Phys Rev* A**76** (2007) 023404
B.Flatt et al., *NIM* A**578** (2007) 409

Ba$^+$ Tagging: RIS

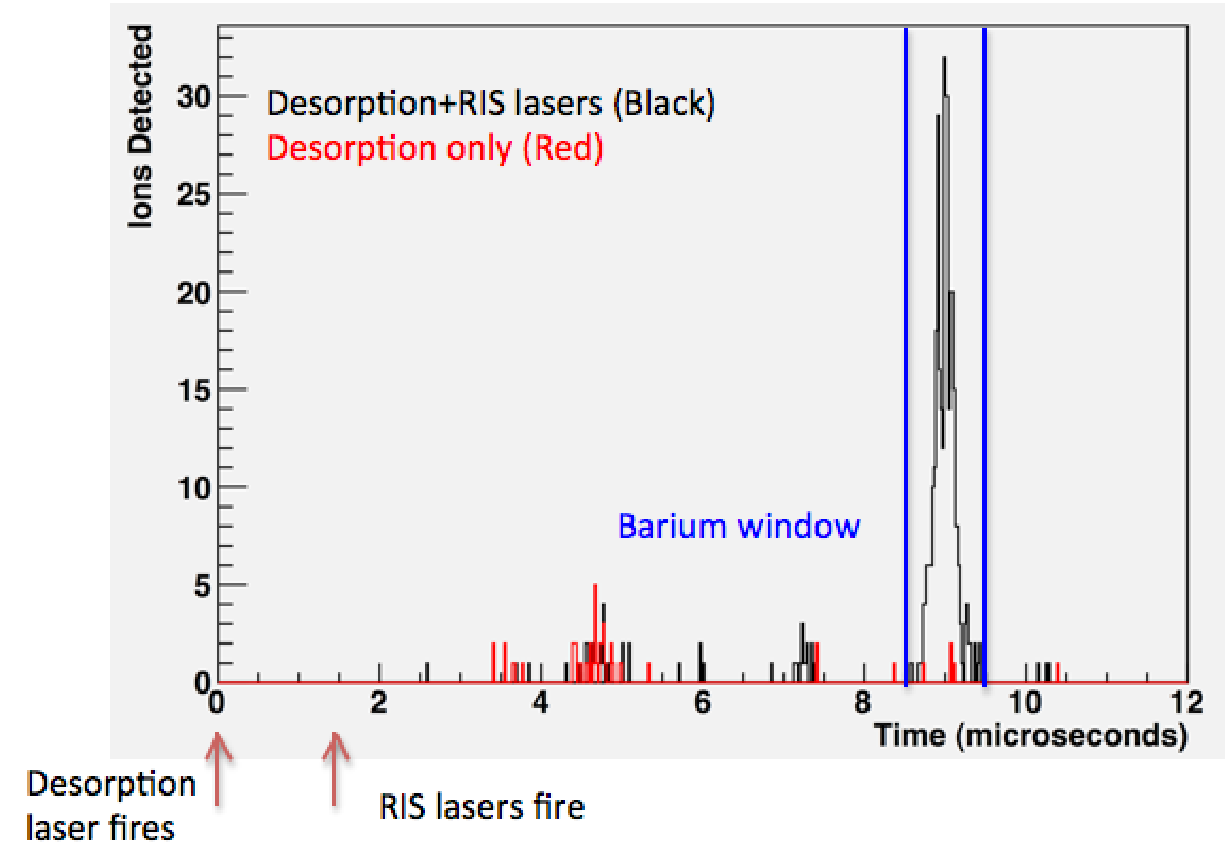
- Resonant Ionization Spectroscopy uses lasers tuned to atomic resonances to first *excite* and then *ionize* specific atoms.
- We use pulsed dye lasers at 553.5 nm and 389.7 nm.
- Autoionization: The 5d8d $^1P_1$ state decays to a lower energy ionized state, allowing use of the high cross section of the resonance to achieve ionization.

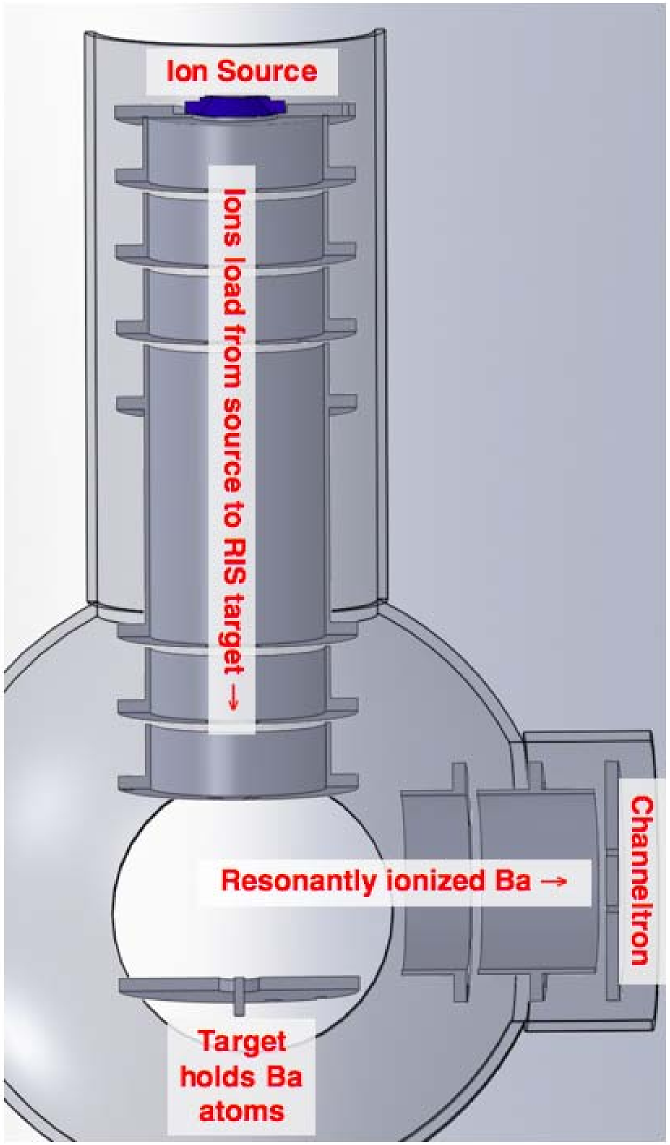




Ba$^+$ Tagging: RIS

QuickTime™ and a decompressor are needed to see this picture.

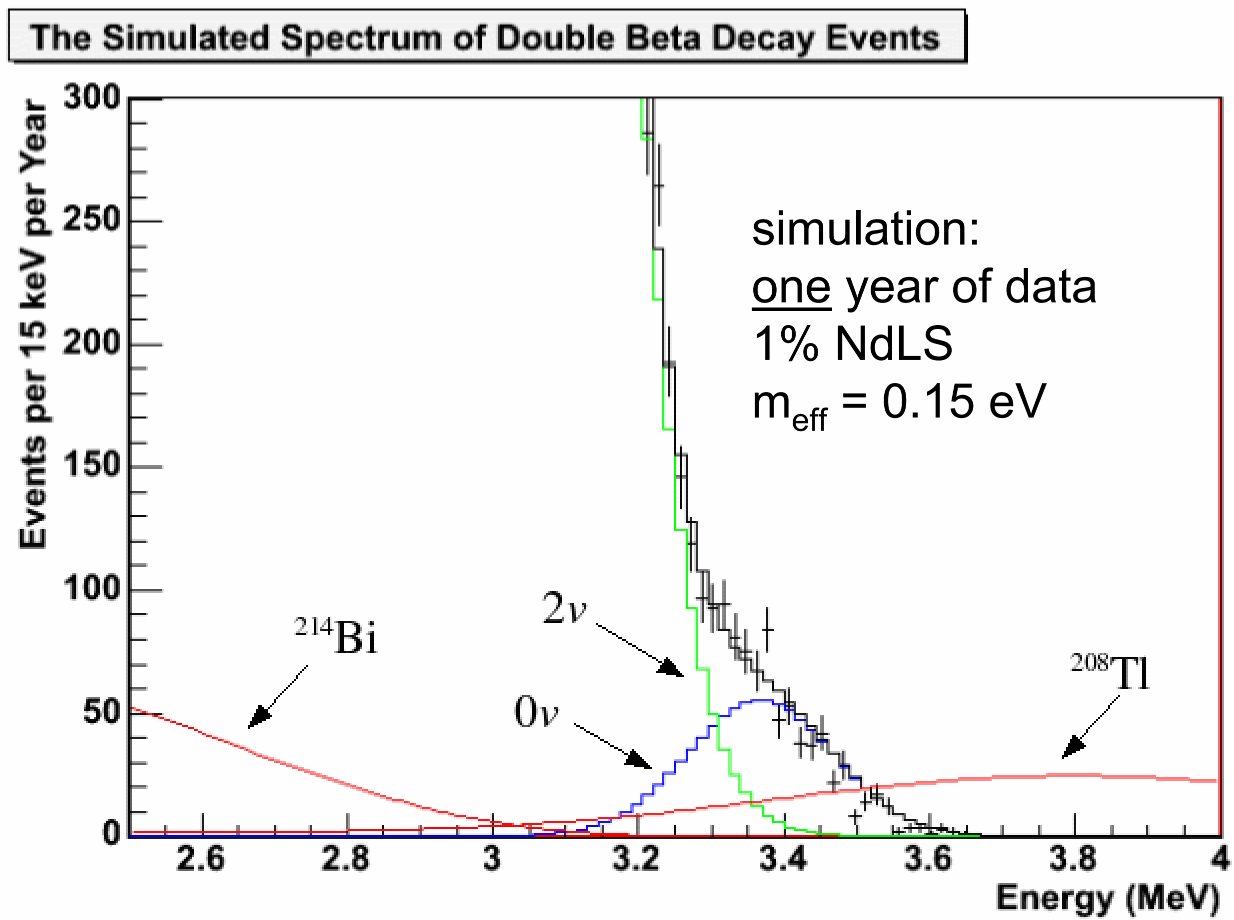




Efficiency of ~10^{-3} in "bulk mode" setup. New "single ion mode" setup about to start taking data.

SNO+: ^{150}Nd Double Beta Decay Concept

- energy resolution in a liquid scintillator is relatively poor
- search for endpoint shape distortion at high Q-value above the gamma lines from natural radioactivity
- ^{150}Nd has highest phase space factor and NME, thus highest predicted rate



Nd Liquid Scintillator Synthesis

- the organometallic form is a carboxylate
- similar to Gd-loaded scintillator for Daya Bay
- solvent-solvent extraction method to transfer to the organic phase
- this method was used to make NdLS at both BNL and Queen's University

linear alkylbenzene (LAB)

(organic phase) **$Nd(RCOO)_3$**

(aqueous phase)

$$Nd^{3+}(Cl^{-})_3 + 3RCOO^{-} \rightarrow Nd(RCOO)_3$$

$$NH_3 + RCOOH \rightarrow NH^{4+} + RCOO^{-}$$

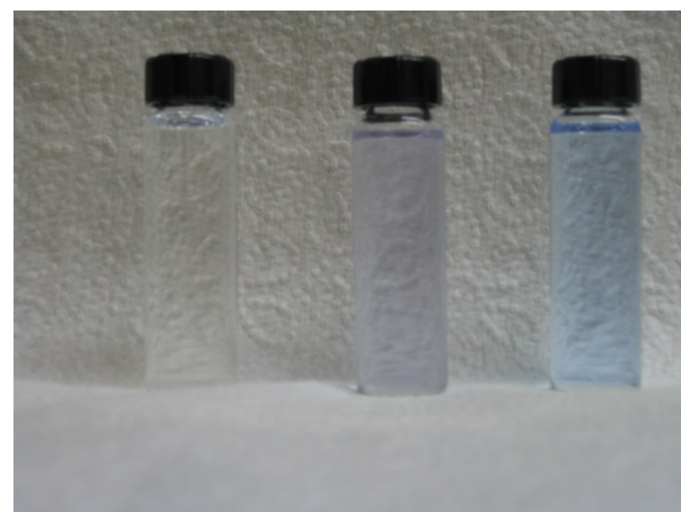
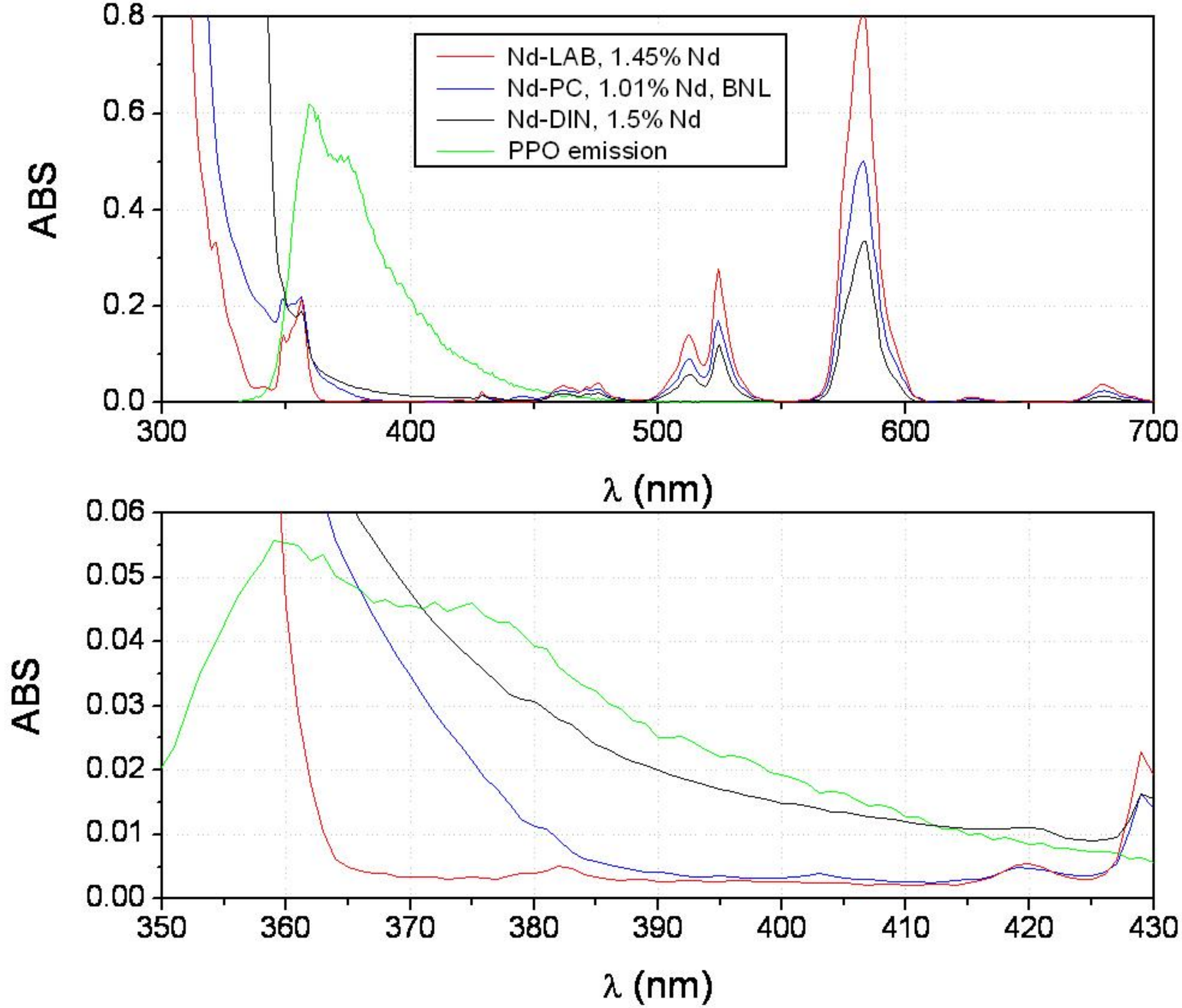


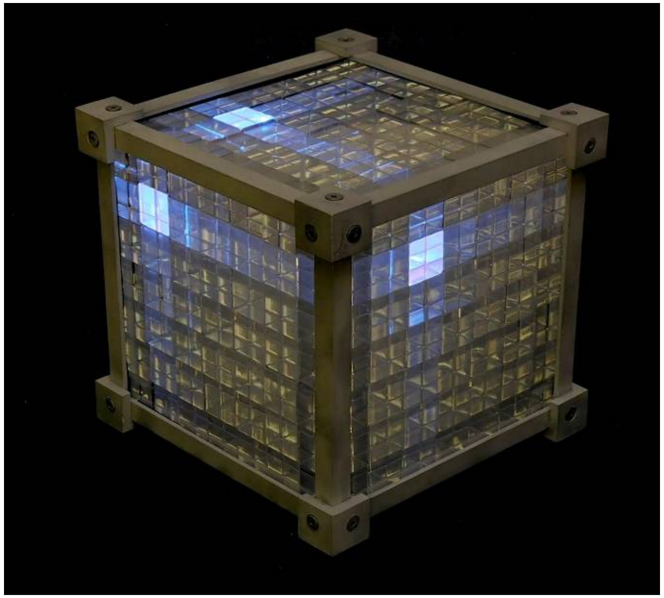
photo depicts NdLS in two different solvents and unloaded scintillator

Nd in Various Scintillation Solvents



Measuring the complete Solar neutrino spectrum

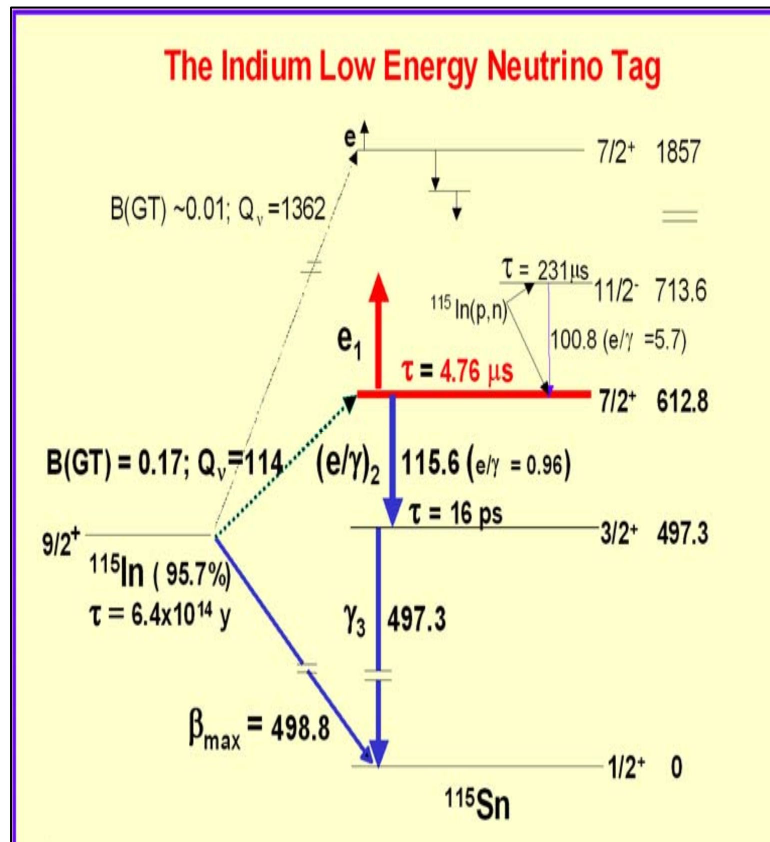
LENS



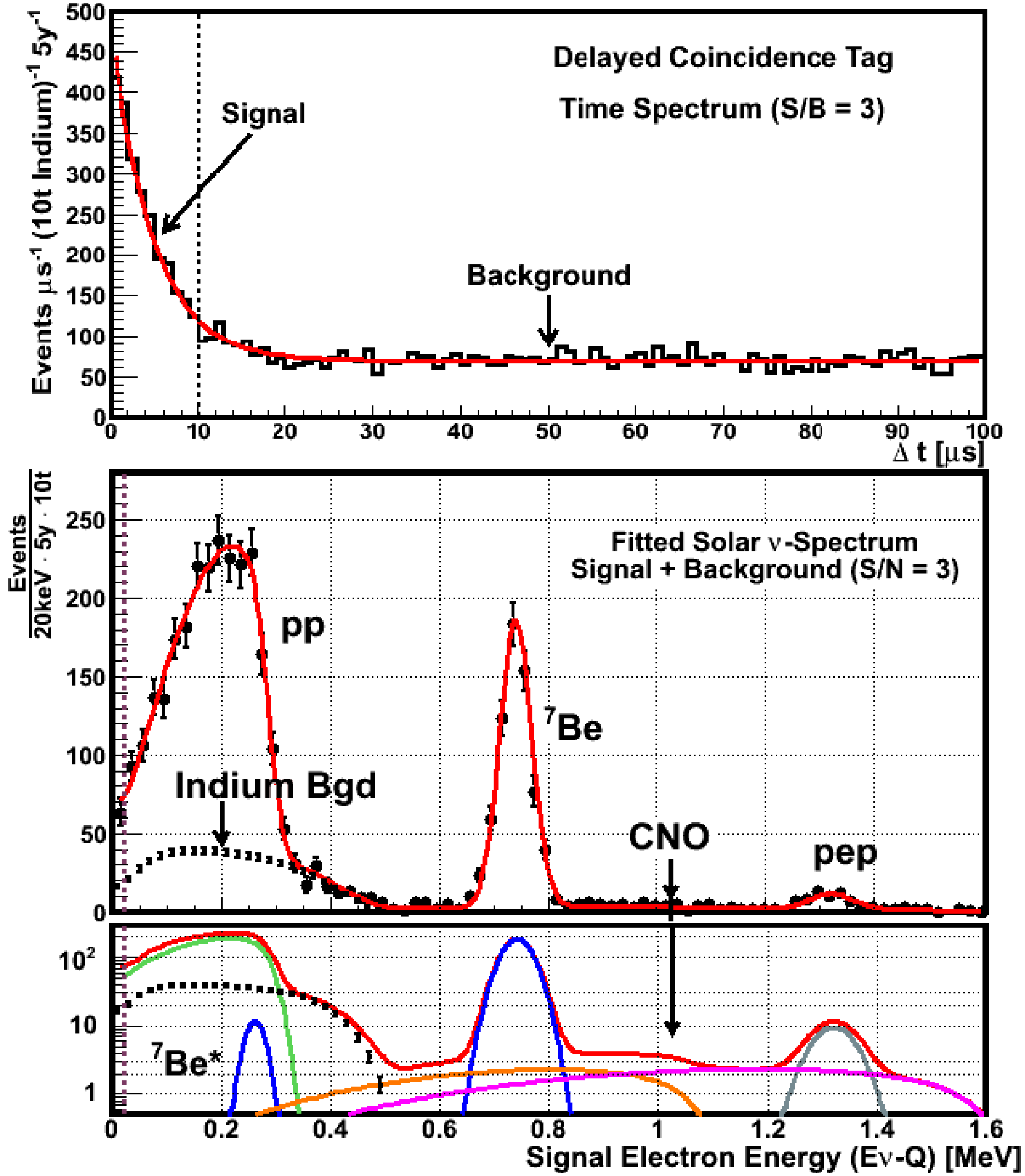
complementary use: sterile neutrinos

$$\nu_e + {}^{115}In \rightarrow \underbrace{e^-}_{\text{solar signal}} + \underbrace{\gamma + (\gamma / e^-)}_{\text{delayed tag } (\tau = 4.76\,\mu s)} + {}^{115}Sn$$

- E_{th}=114 keV (95% of pp spectrum)
- Measure pp-ν flux @ 3%
- Determine CNO-fraction
- Measure T_{sun} by change in mean energy of ^{7}Be line – maybe (hep-ph/9309292)
- needs separate calibration experiment –"LENS Sterile"

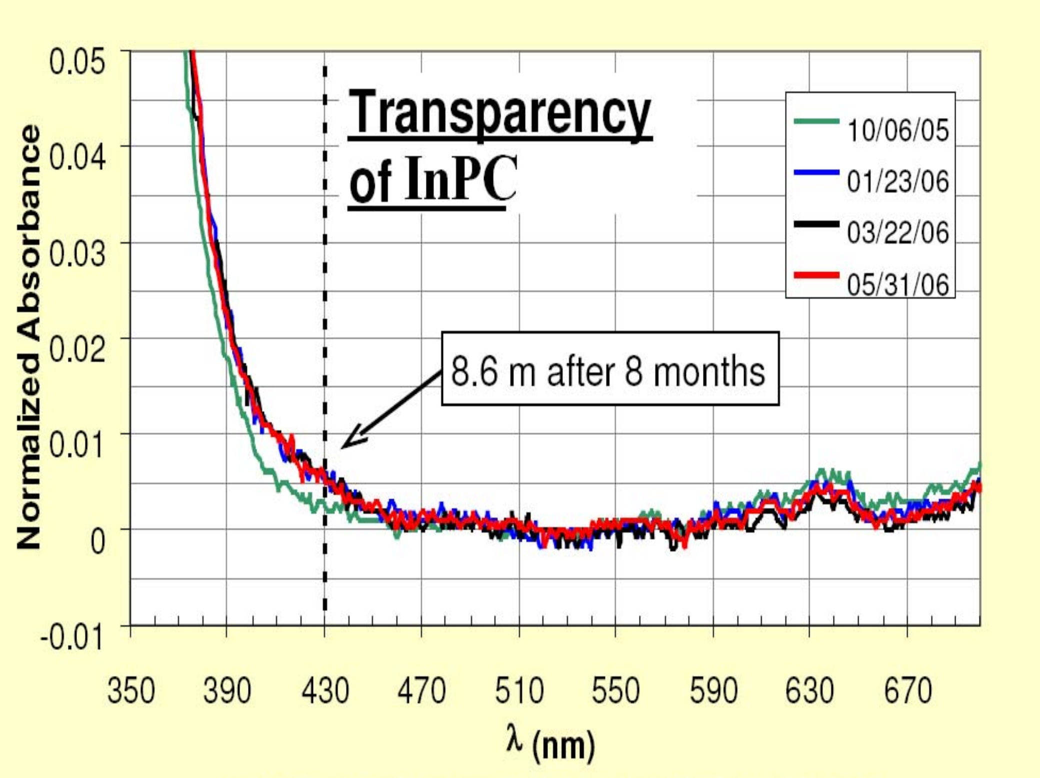


LENS proposal: real-time solar neutrino spectral measurement



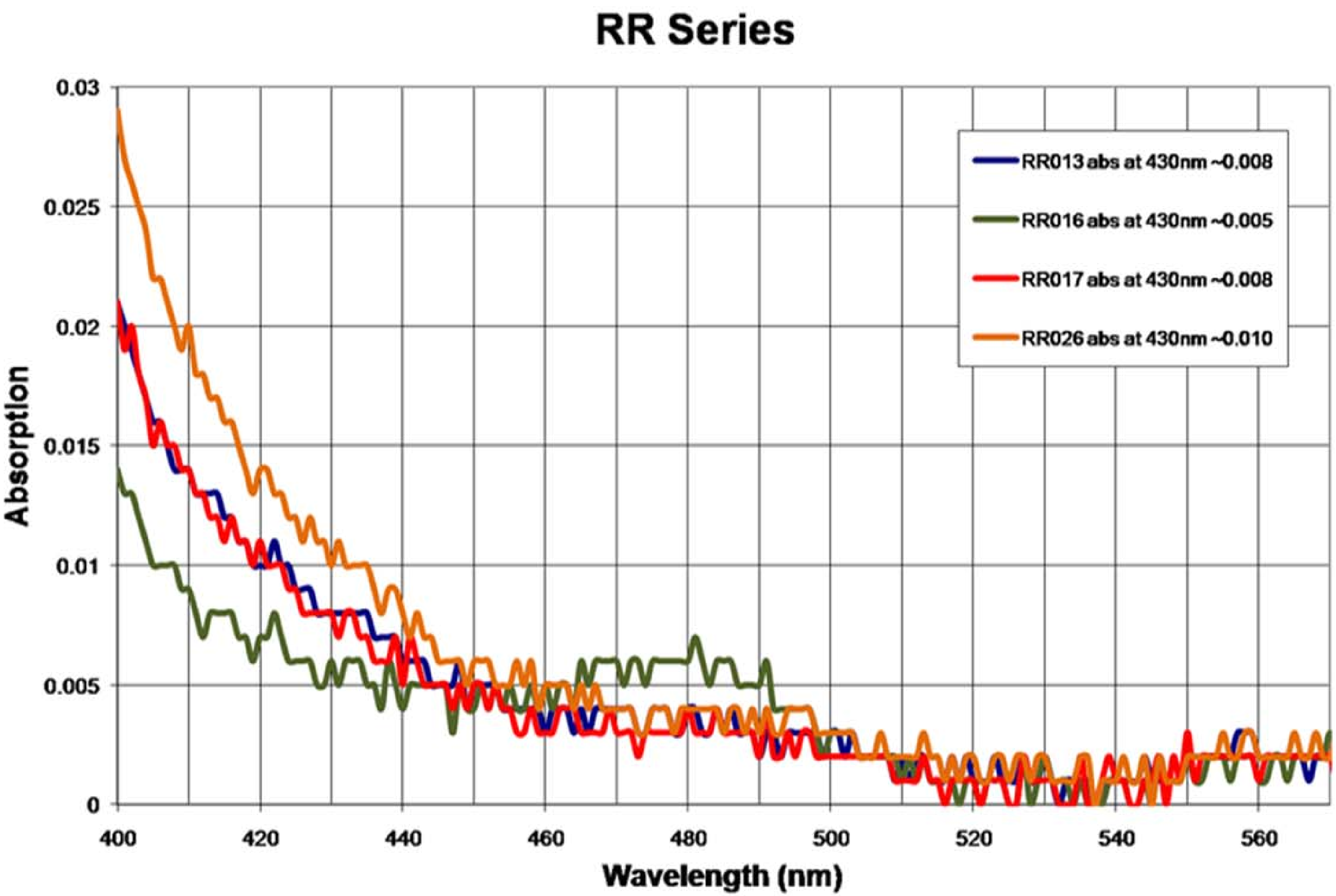
Indium Loaded Pseudocumene (PC) Scintillator Performance

Metal loaded LS status	InPC
1. Indium concentration	8%
2. Scintillation signal efficiency	~7000 hν/MeV
3. Transparency at 430 nm: L(1/e) (working value):	8m (long term)
4. Light yield (Y%pc) (working value):	55-60%
5. Chemical and Optical Stability:	Stable >1.5 yr with L(1/e)>8m
6. InLS Chemistry	Robust

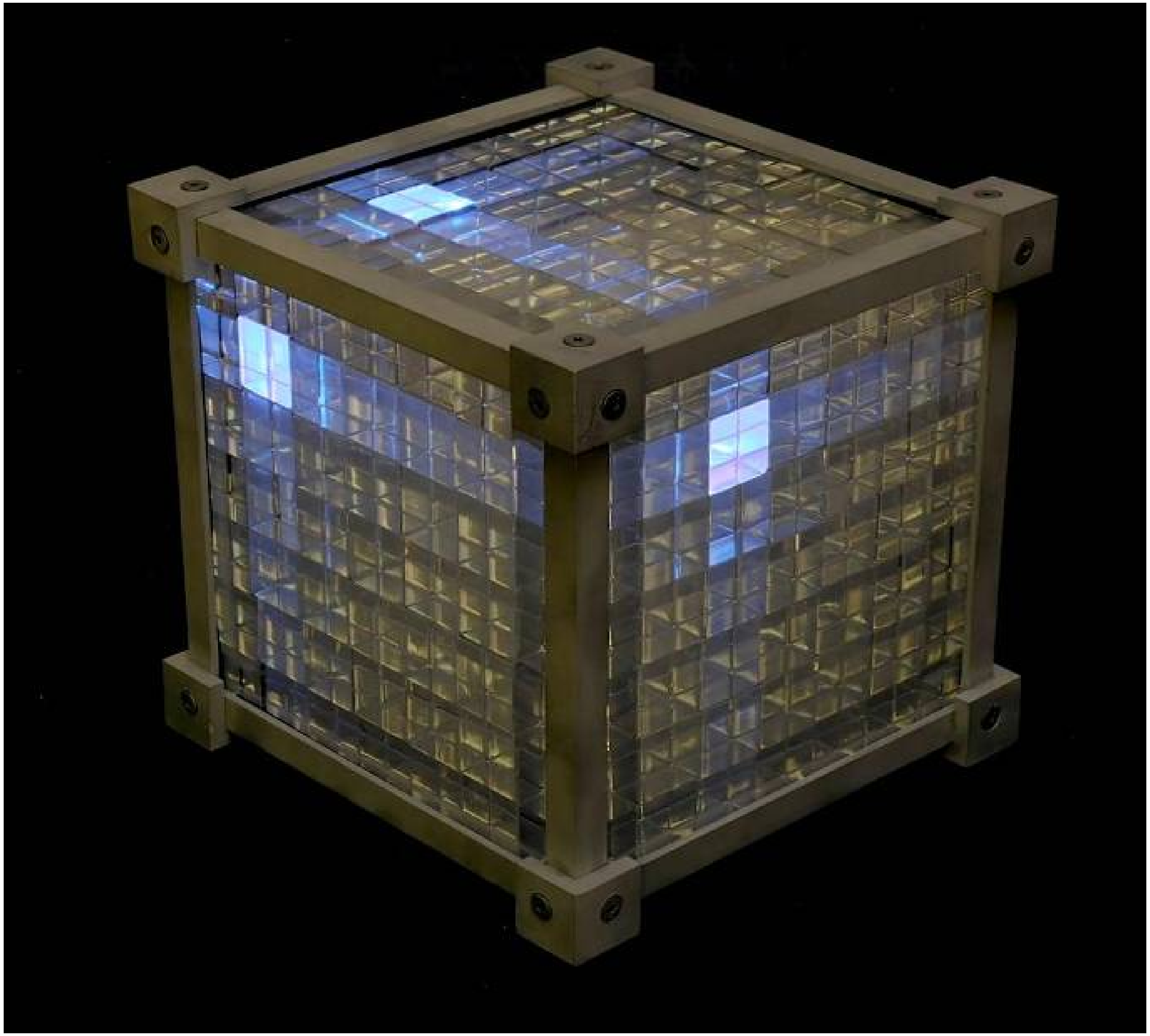


UV/Vis absorbance of zVt45 (pH 6.88) with time

Linear Alkyl Benzene as a alternative to Pseudocumene: Promising Absorbance Results for in InLAB



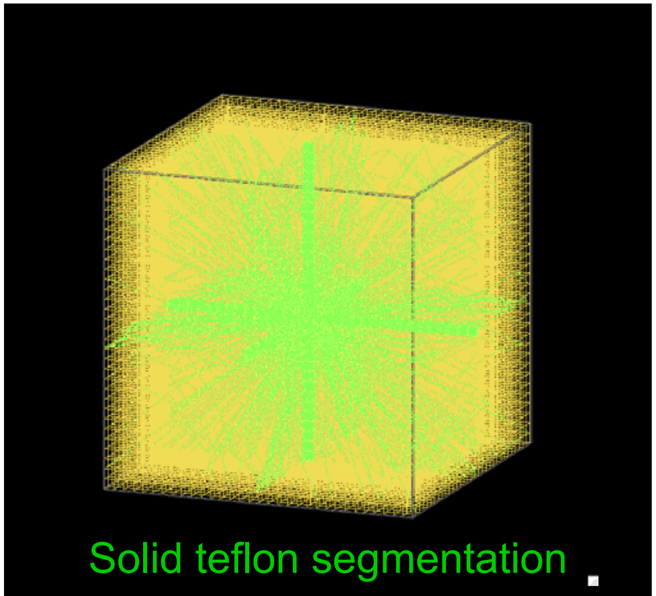
LENS: optical lattice for improved pattern recognition and background rejection

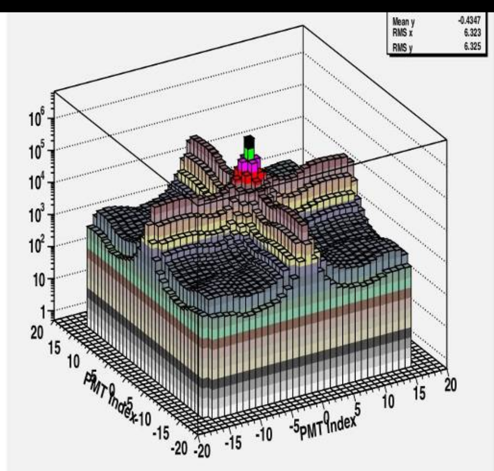


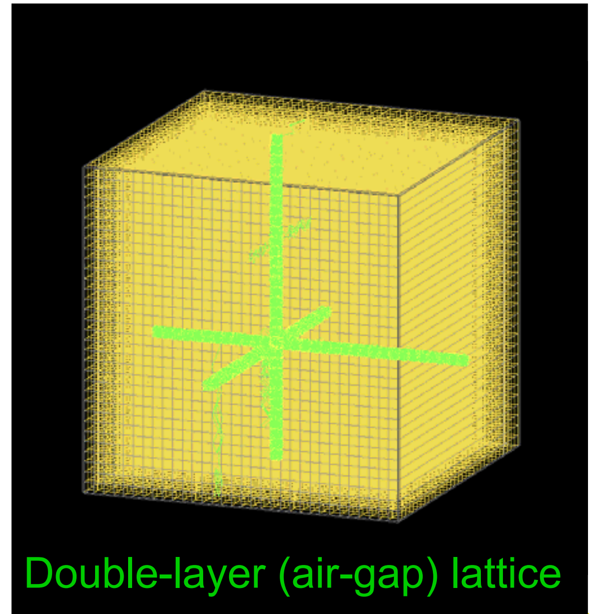
Lattice Structure

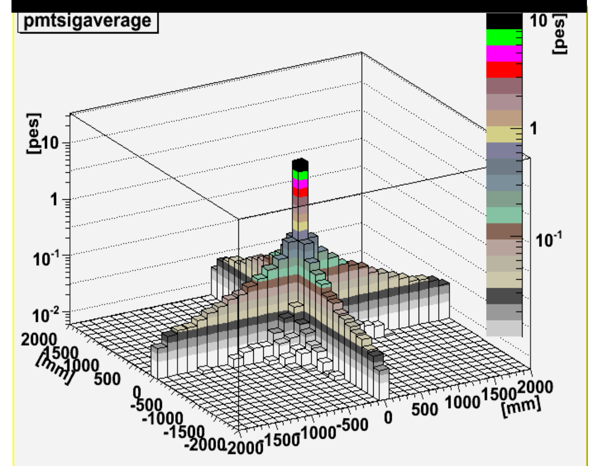
Single Foil

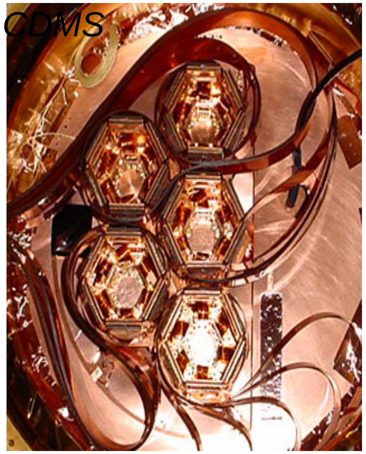
Double Foil











Thanks to: Paul Brink, Derek Roundtree, Mark Chen, Katsushi Arisaka, Rick Gaitskell, Gabriella Sciolla, Juan Collar