Low-Background Searches for Rare Events:

The MAJORANA Neutrinoless Double-Beta Decay Experiment, and the CLEAN/DEAP Dark Matter Search

Victor M. Gehman

LA-UR: 10-00050

Los Alamos
NATIONAL LABORATORY

Low-Background Searches for Rare Events:

The Low-Intensity, Low-Energy Frontier...

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Outline

- Low-background searches and physics beyond the Standard Model
  - Neutrinoless double-beta decay
  - Direct dark matter detection
- MAJORANA and CLEAN/DEAP
  - Overview and strategy
  - Detector design
  - Recent R&D progress
- Conclusions

Rare Events and Physics BSM

- Departures from the standard model generally revolve around searches for small effects on top of a "sea of backgrounds"

The "Needle in a Haystack" Problem

Rare Events and Physics BSM

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- What to do?
  - Make the signal as big as you can...
  - Make the backgrounds as small as you can...
  - Find a special signature for the events you care about...

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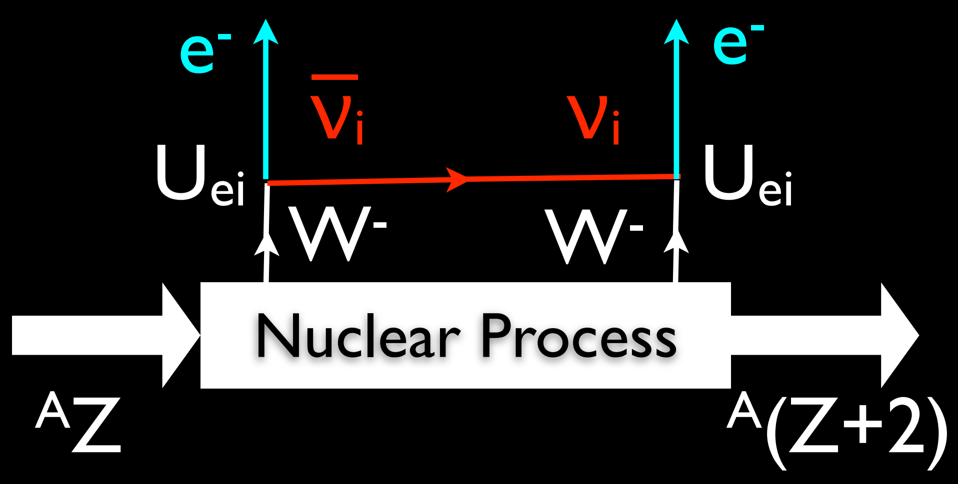
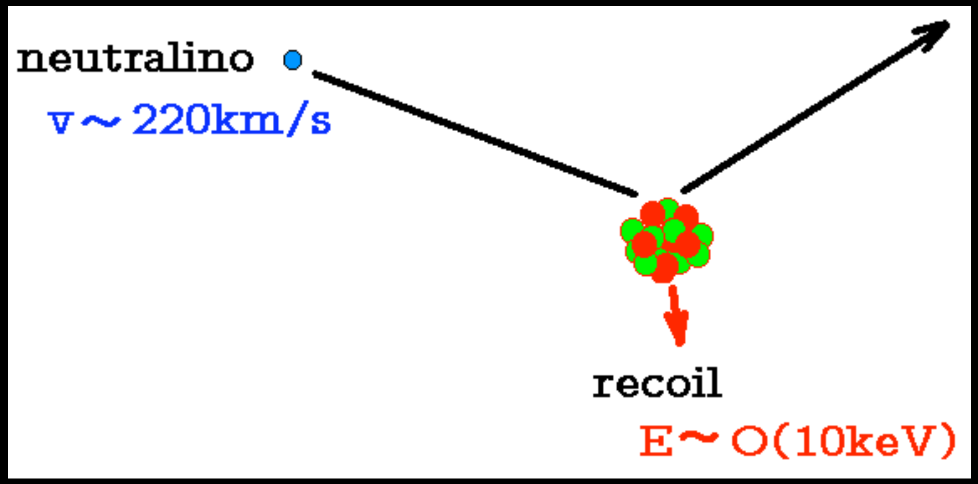
The "Low-Background Frontier"

- We will focus on two types of rare event searches
  - Neutrinoless double-beta decay
  - Direct dark matter detection





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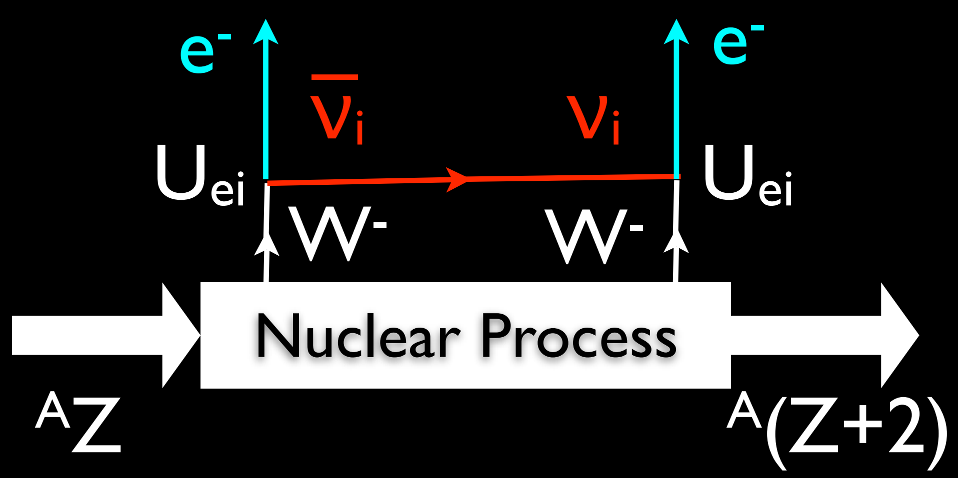
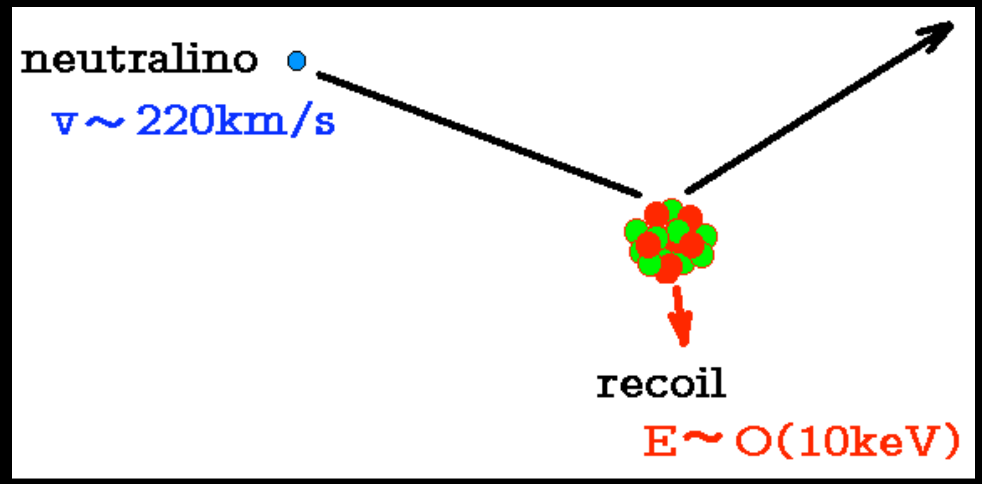
- …but there are A LOT more sub-fields of rare event searches





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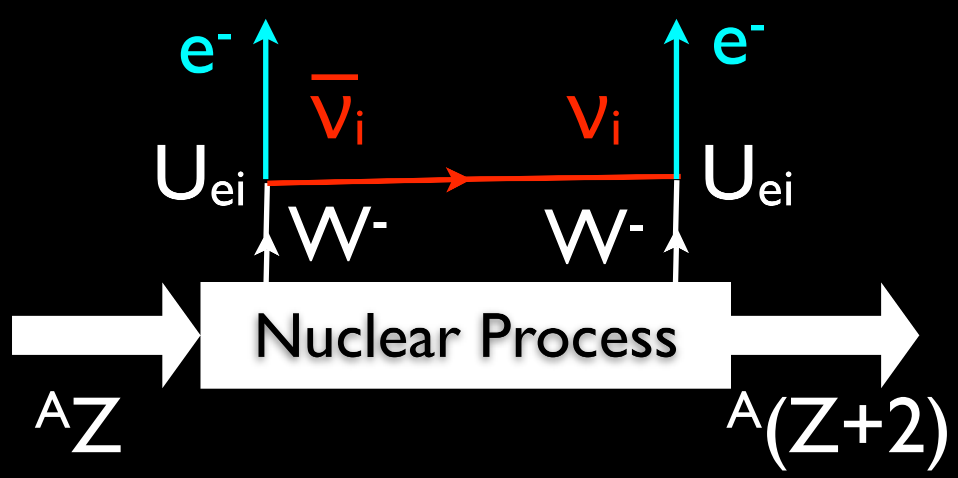
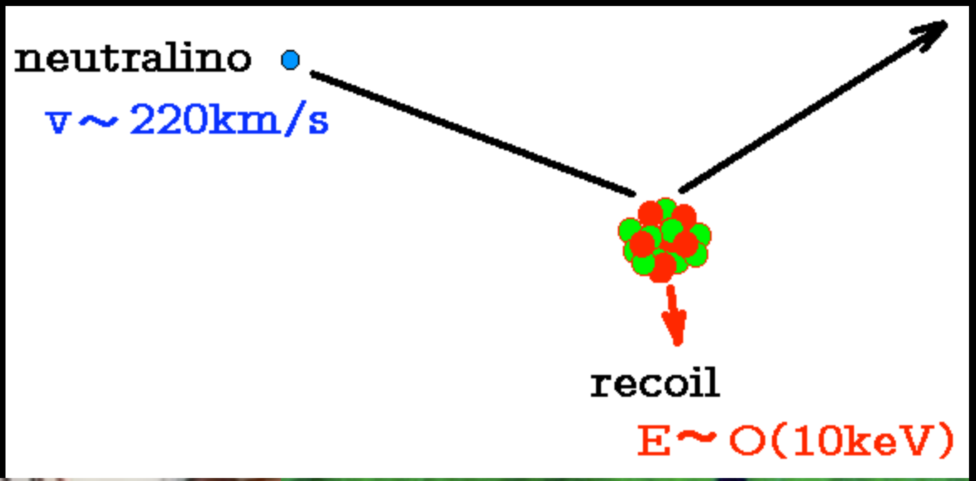
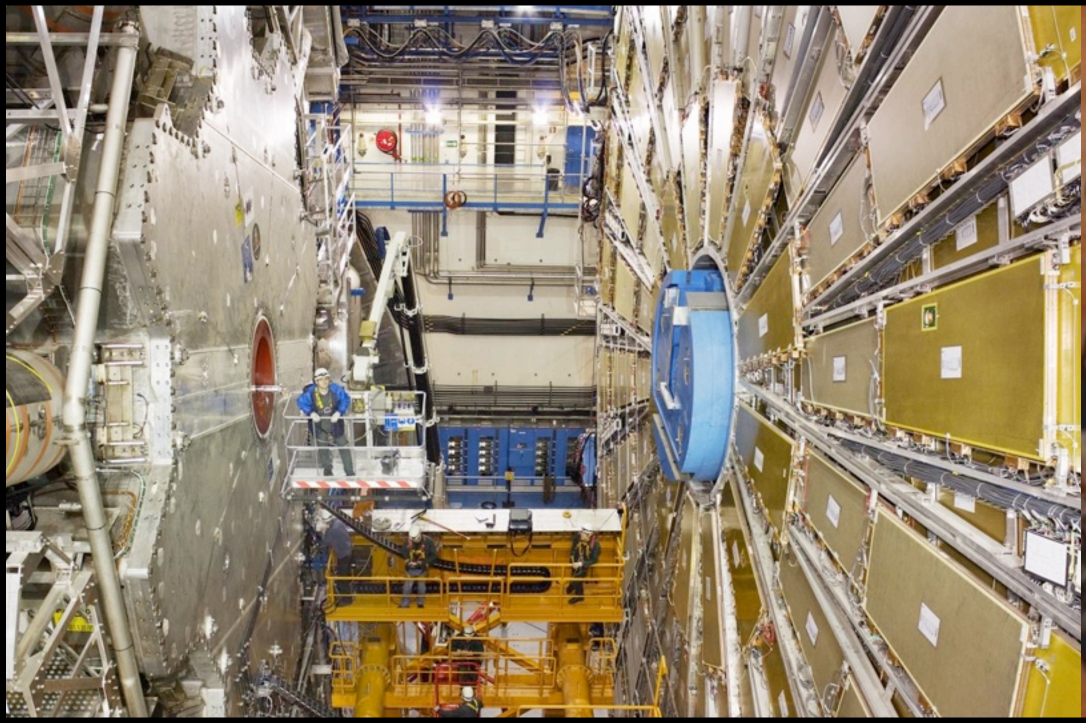
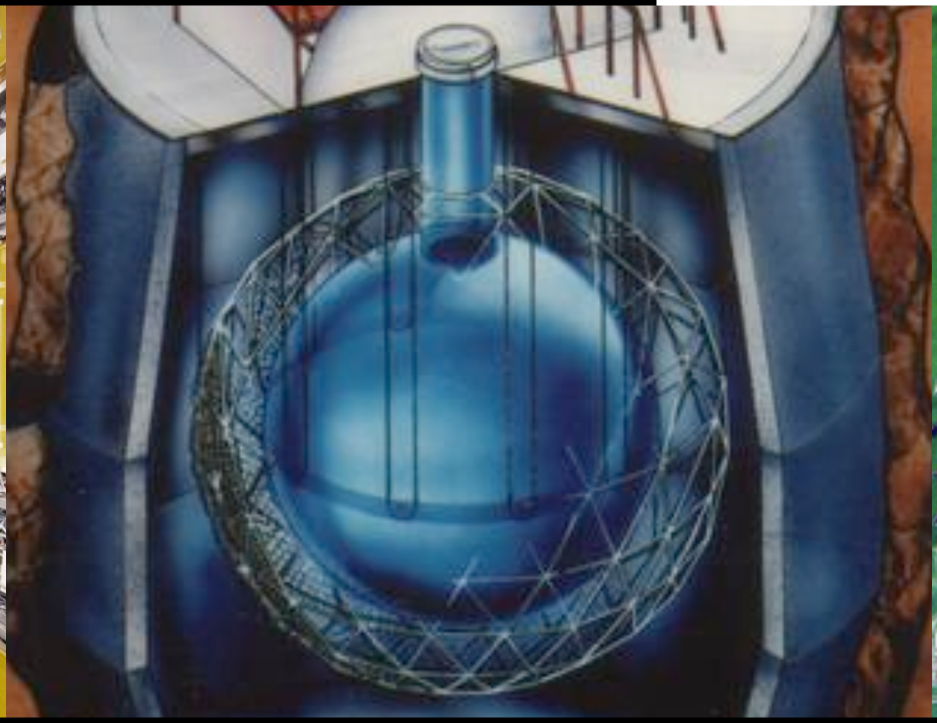


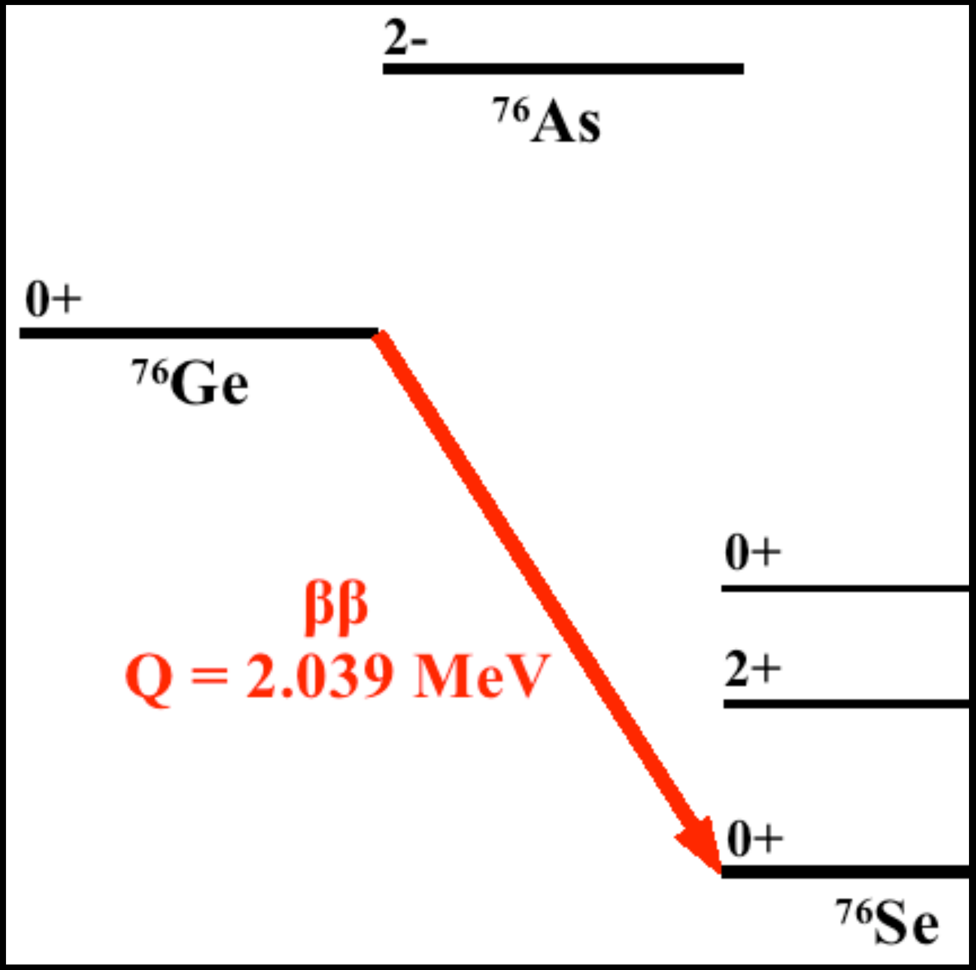


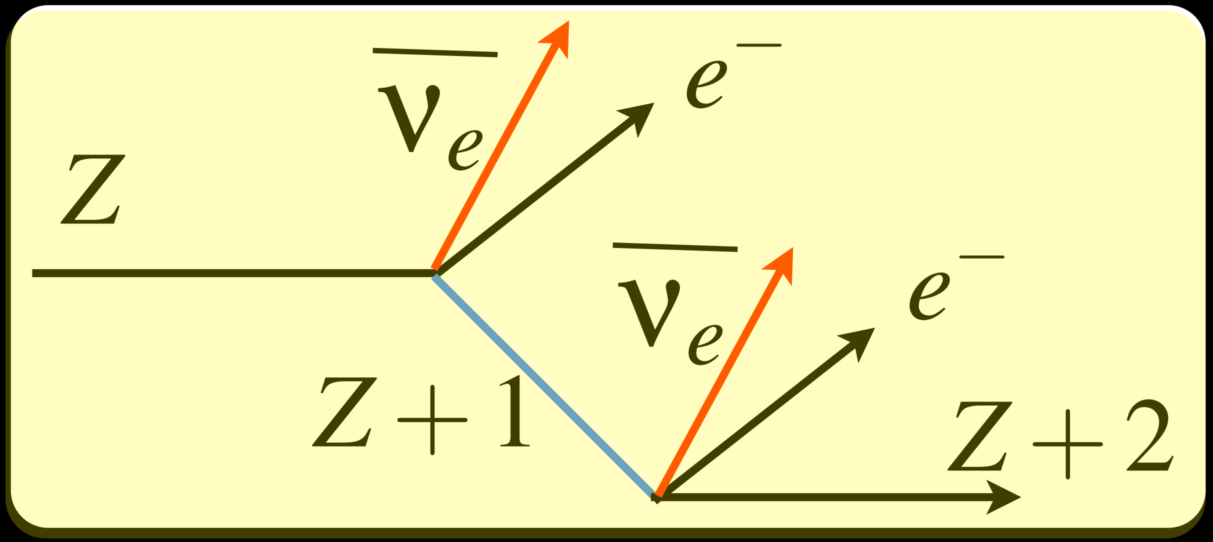


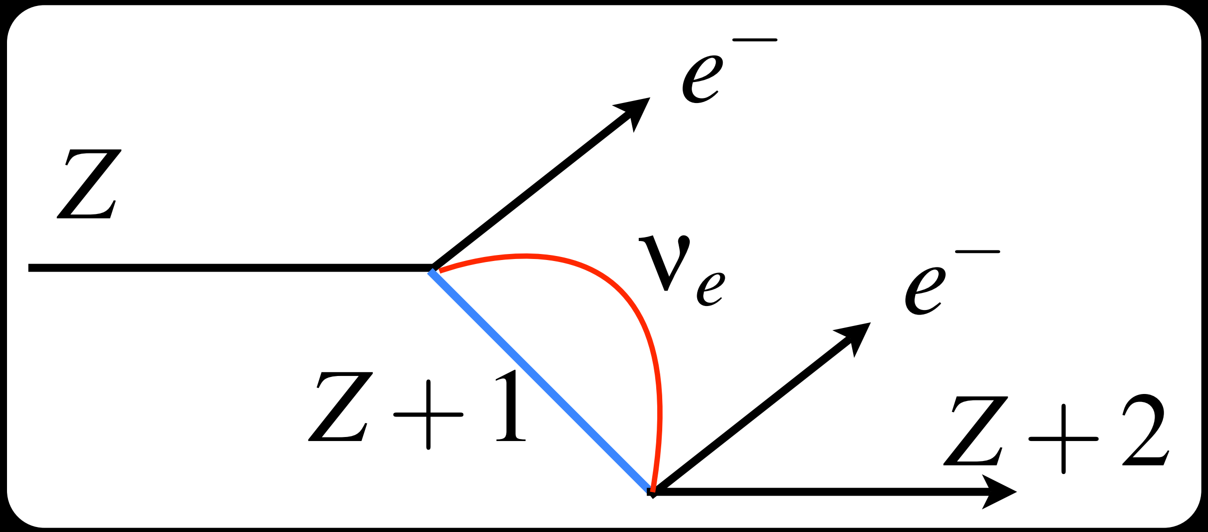


Neutrinoless Double-Beta Decay

- $2\nu\beta\beta$:
  - Slowest nuclear process allowed in SM
  - Observable when β decay forbidden
  - Observed in ≈10 isotopes

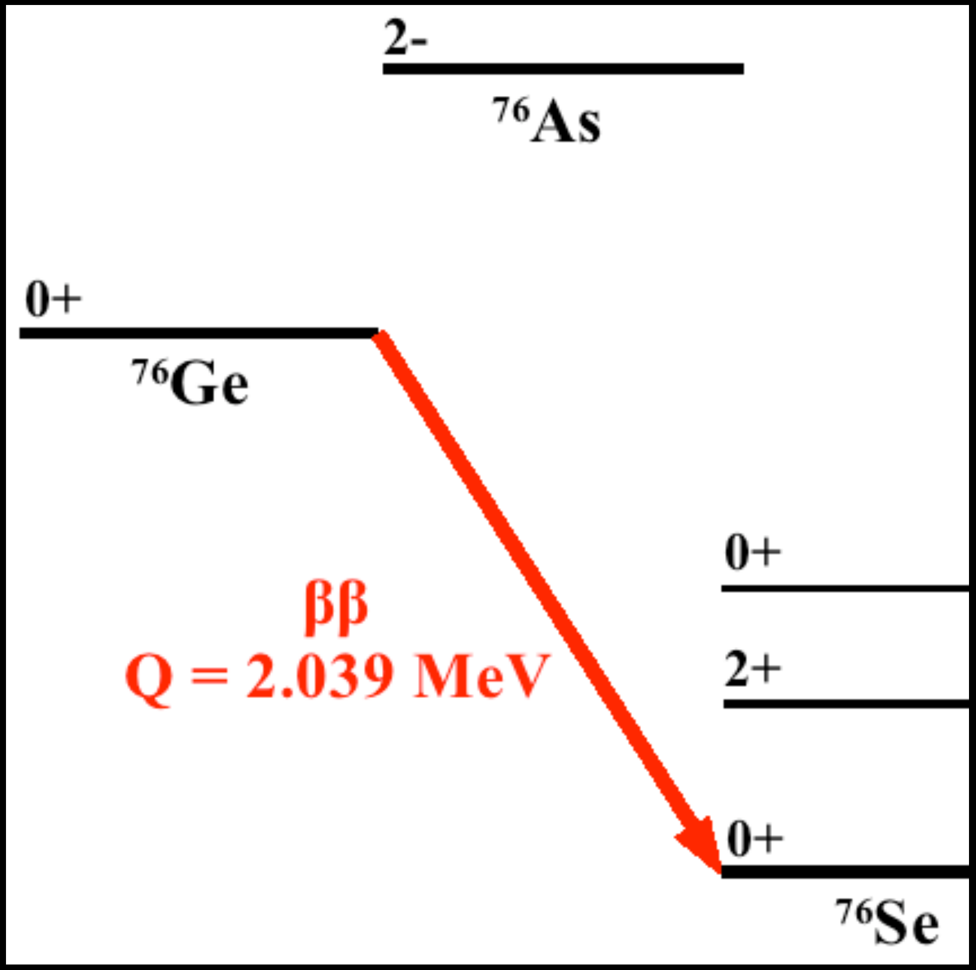


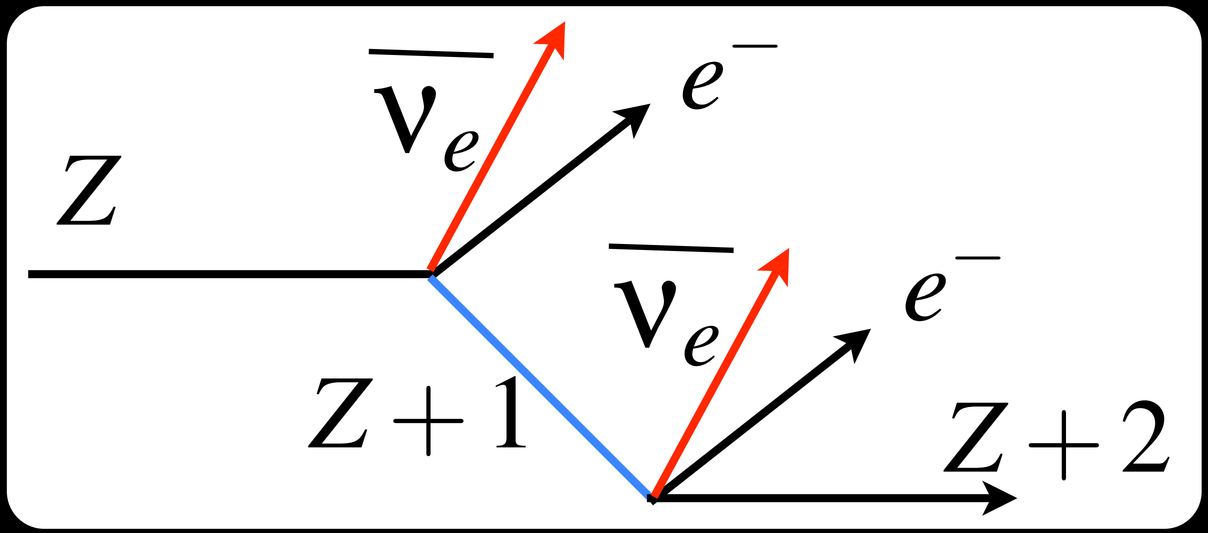


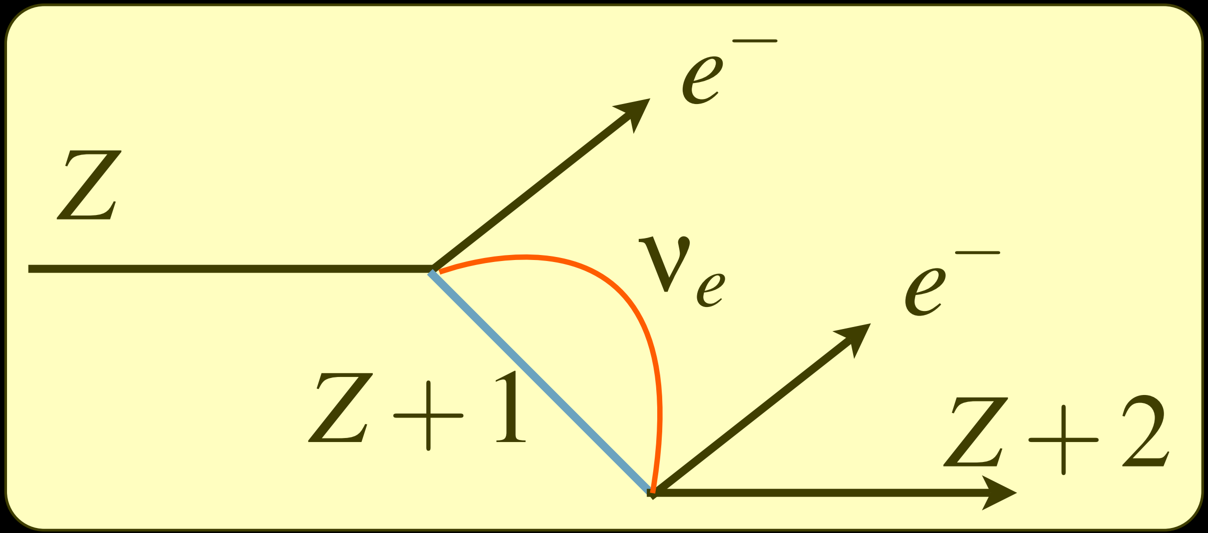


Neutrinoless Double-Beta Decay

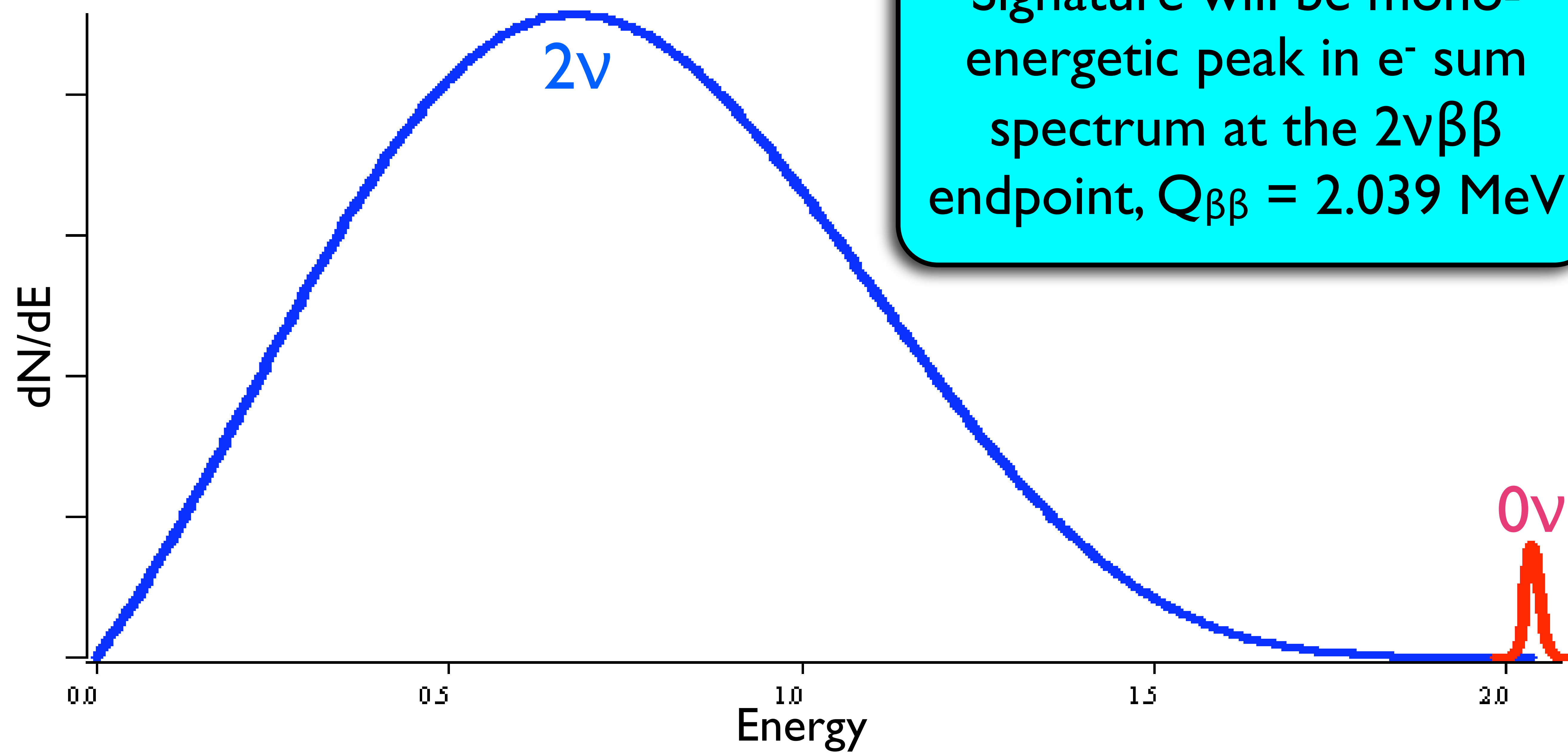
- $2\nu\beta\beta$:
  - Slowest nuclear process allowed in SM
  - Observable when β decay forbidden
  - Observed in ≈10 isotopes
- $0\nu\beta\beta$:
  - No emitted neutrinos!
  - Demands:
    - Majorana Neutrino
    - Lepton number non-conservation
    - Non-zero neutrino mass

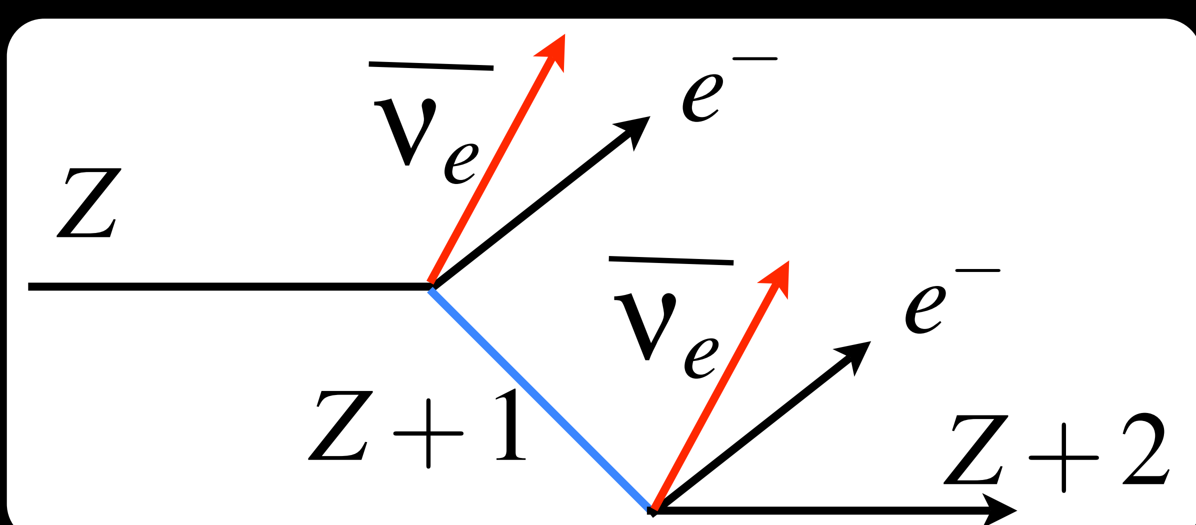


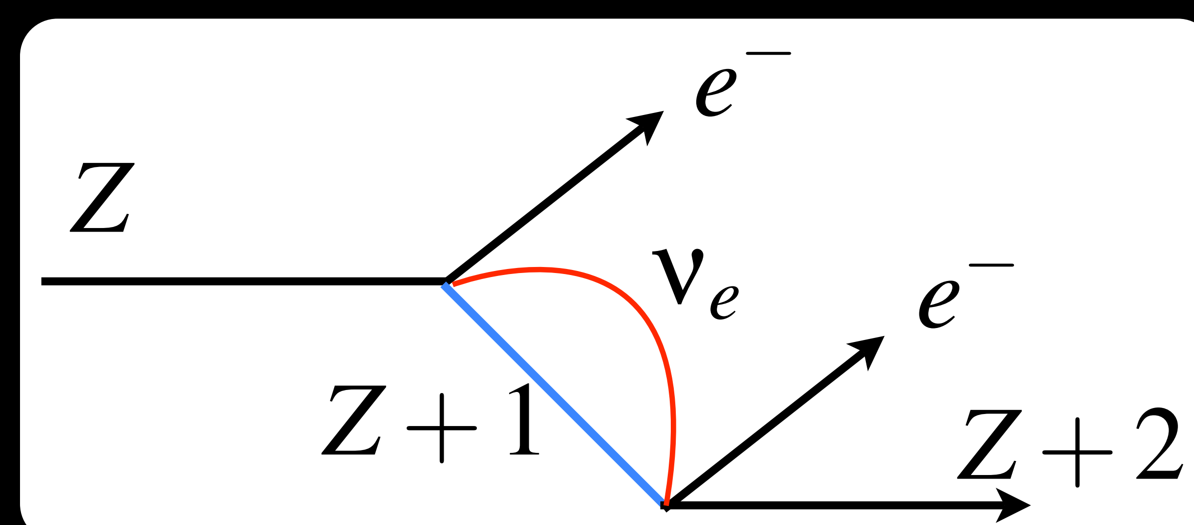




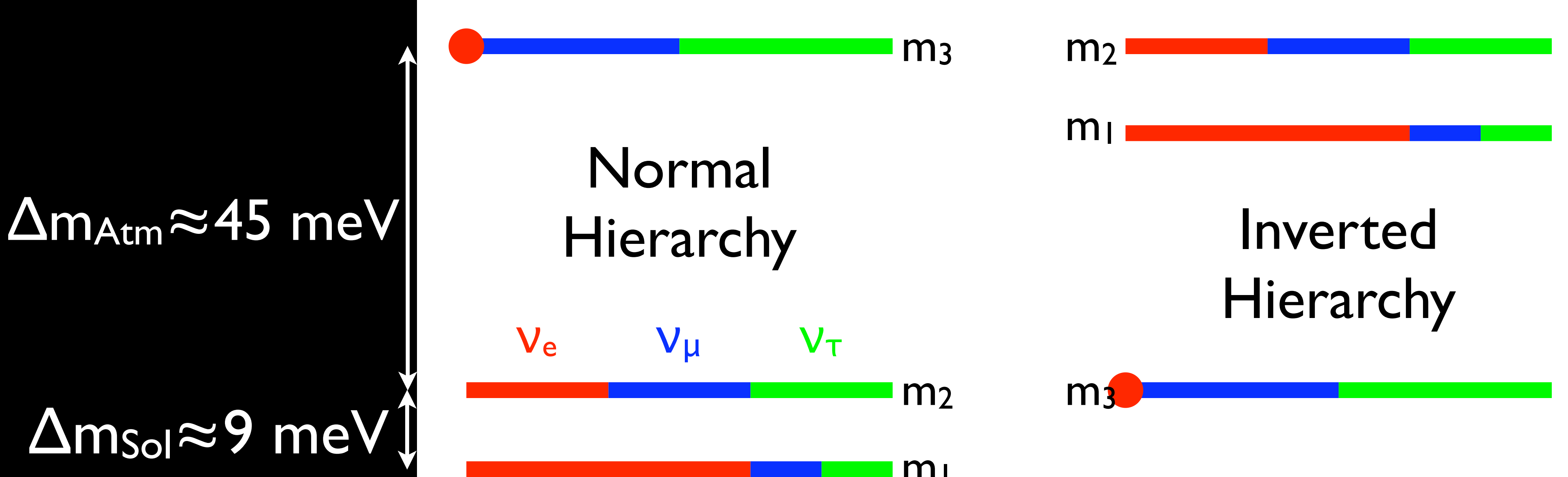
Signature will be mono-energetic peak in e^- sum spectrum at the $2\nu\beta\beta$ endpoint, $Q_{\beta\beta}$ = 2.039 MeV







Double-Beta Decay and Neutrino Mass

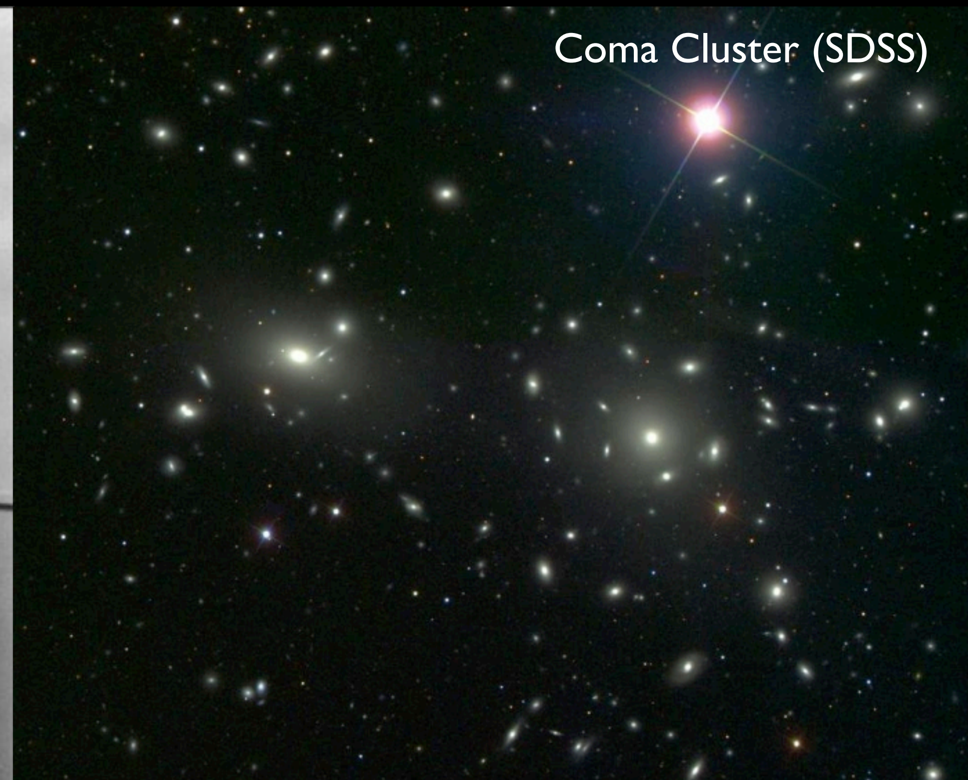


$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

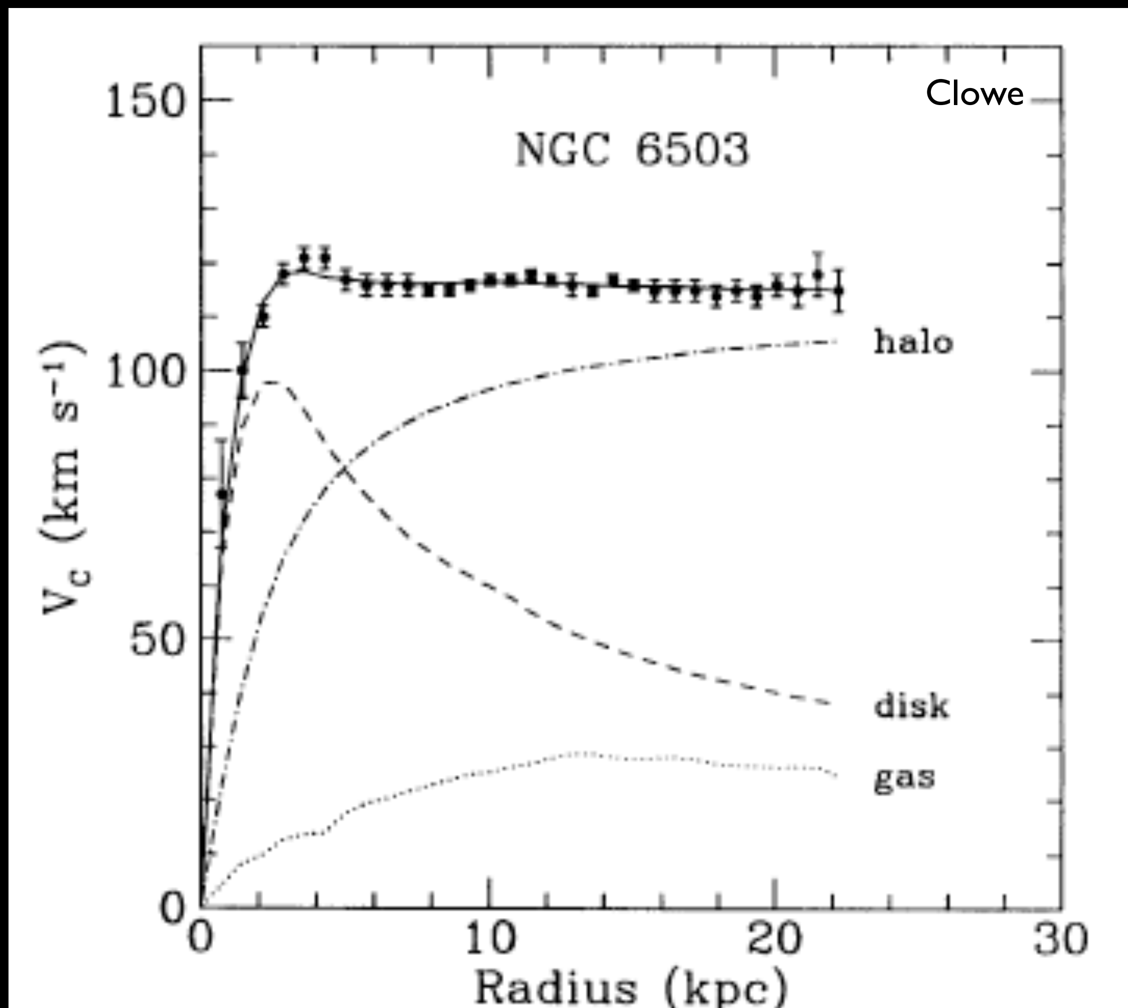
$0\nu\beta\beta$ is sensitive to $\langle m_{\beta\beta} \rangle$, and therefore the absolute masses, mixings and CP phases

Dark Matter



- Fritz Zwicky's missing mass

Dark Matter



- Fritz Zwicky's missing mass
- Galaxy rotation curves

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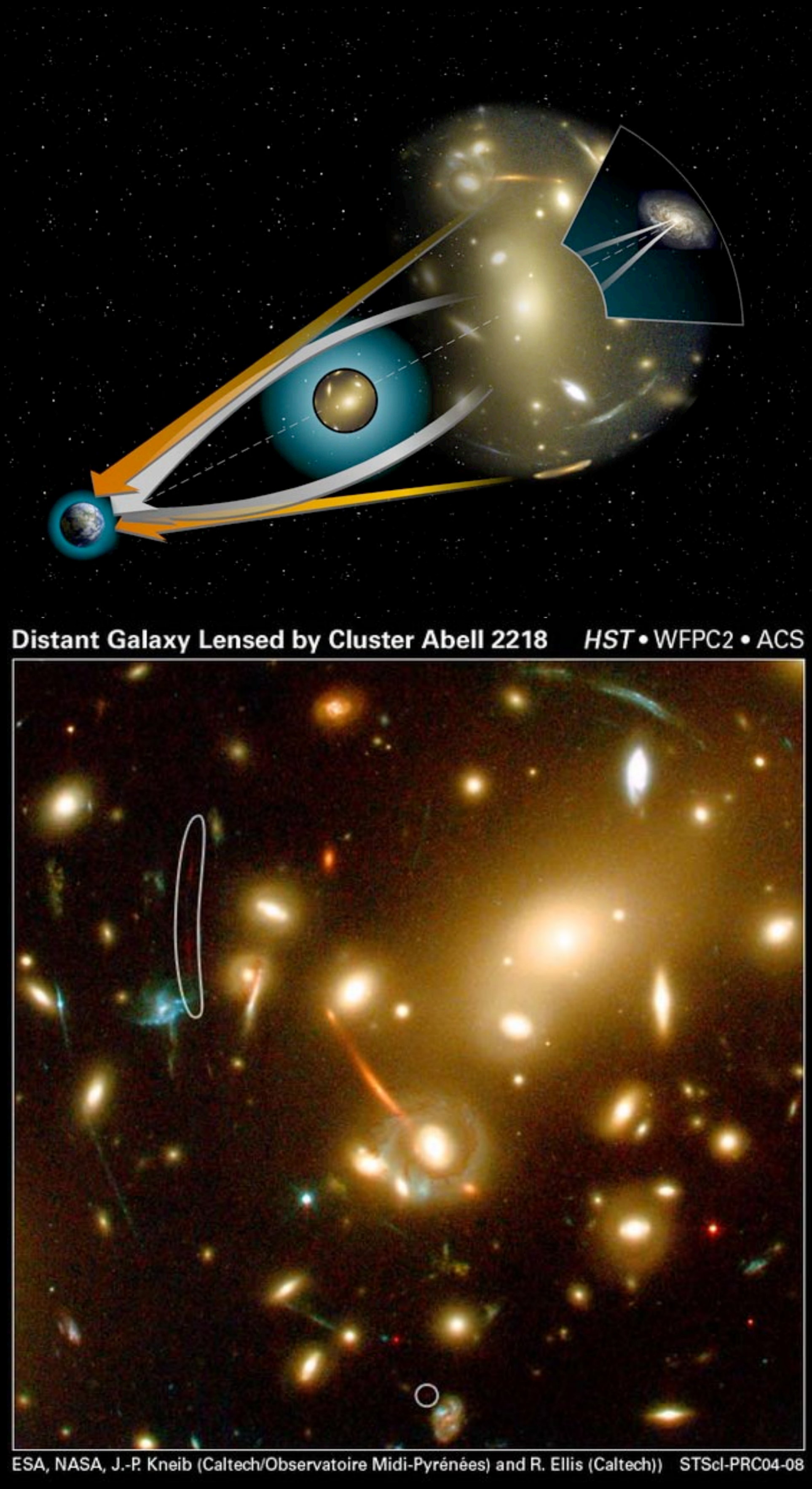

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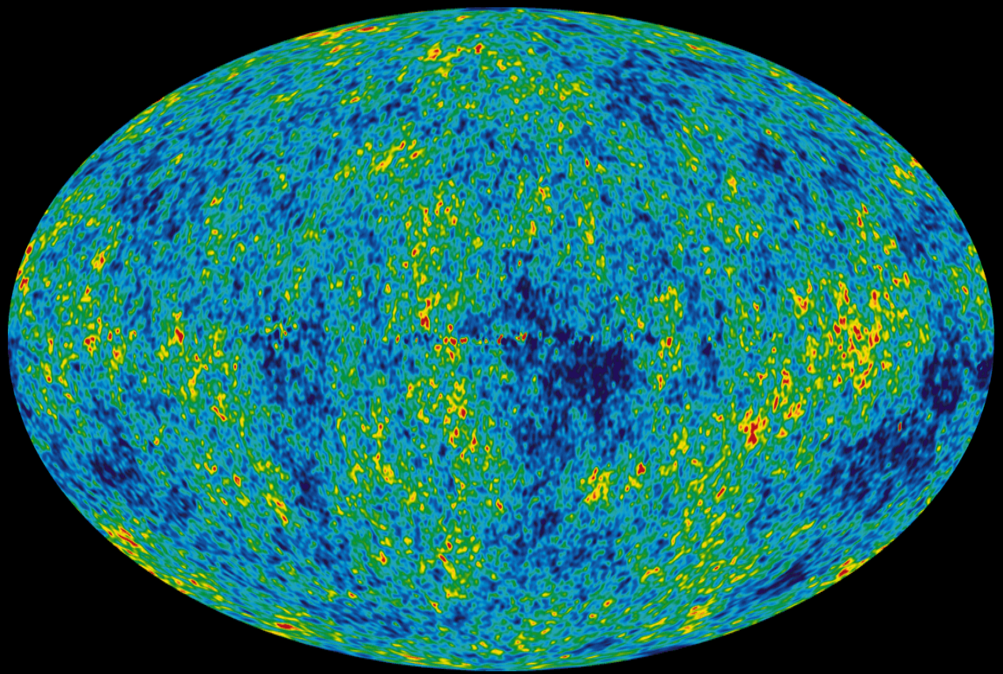
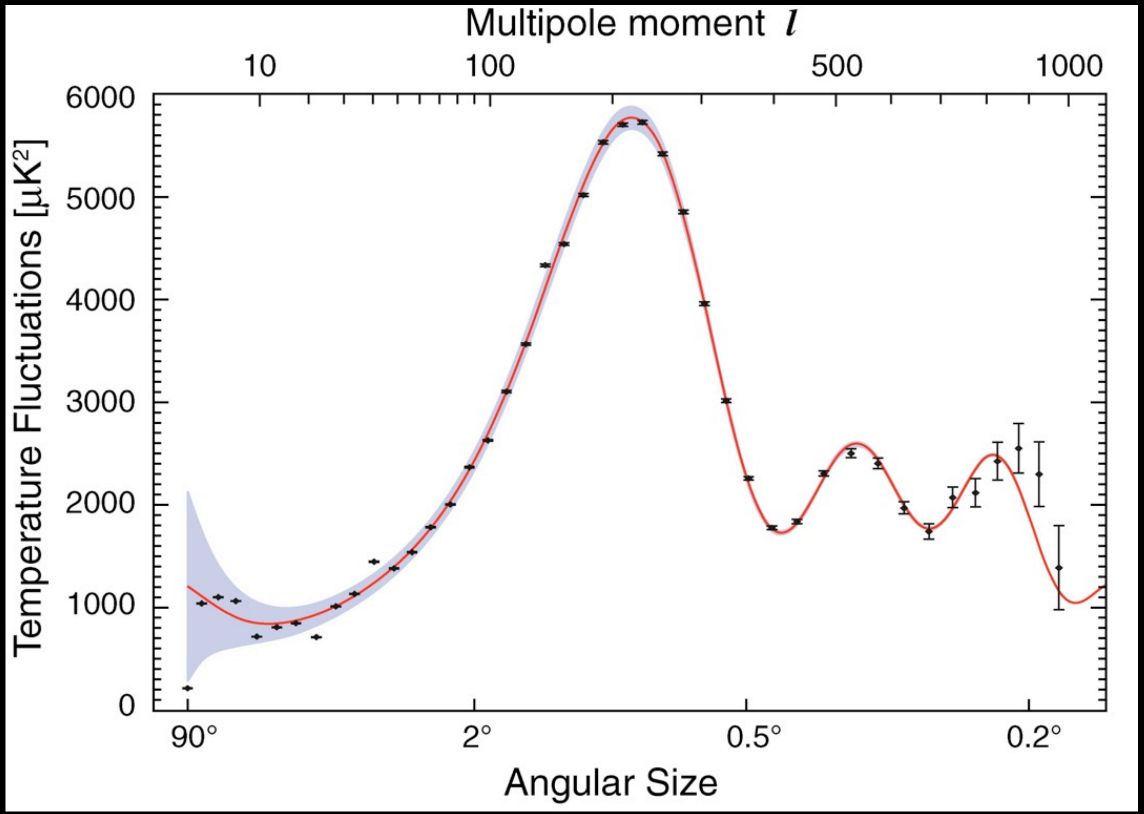
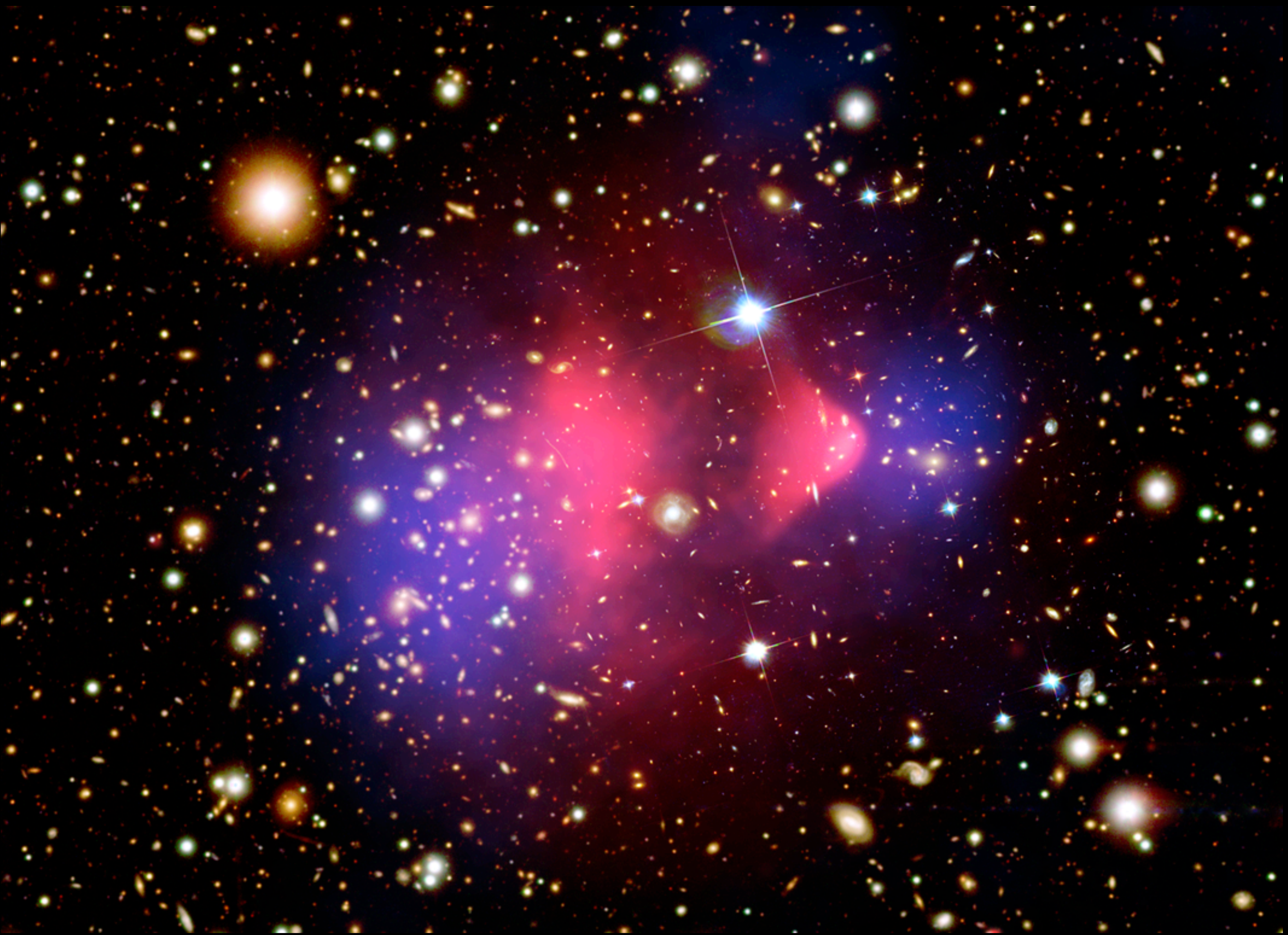




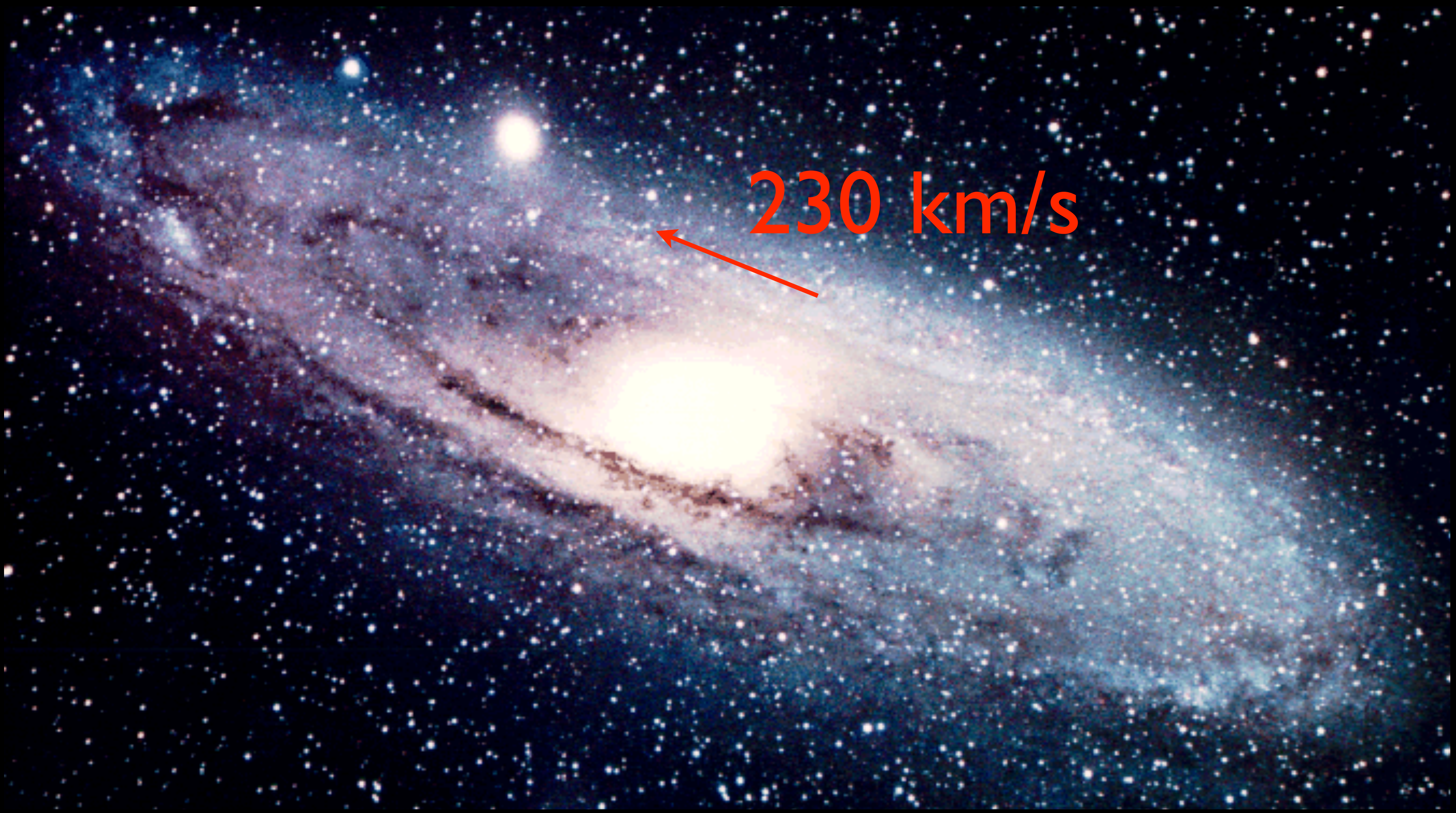
- Fritz Zwicky's missing mass
- Galaxy rotation curves
- Gravitational Lensing
- Cosmic microwave background

Dark Matter



- Fritz Zwicky's missing mass
- Galaxy rotation curves
- Gravitational Lensing
- Cosmic microwave background
- The Bullet Cluster

Challenges and Goals



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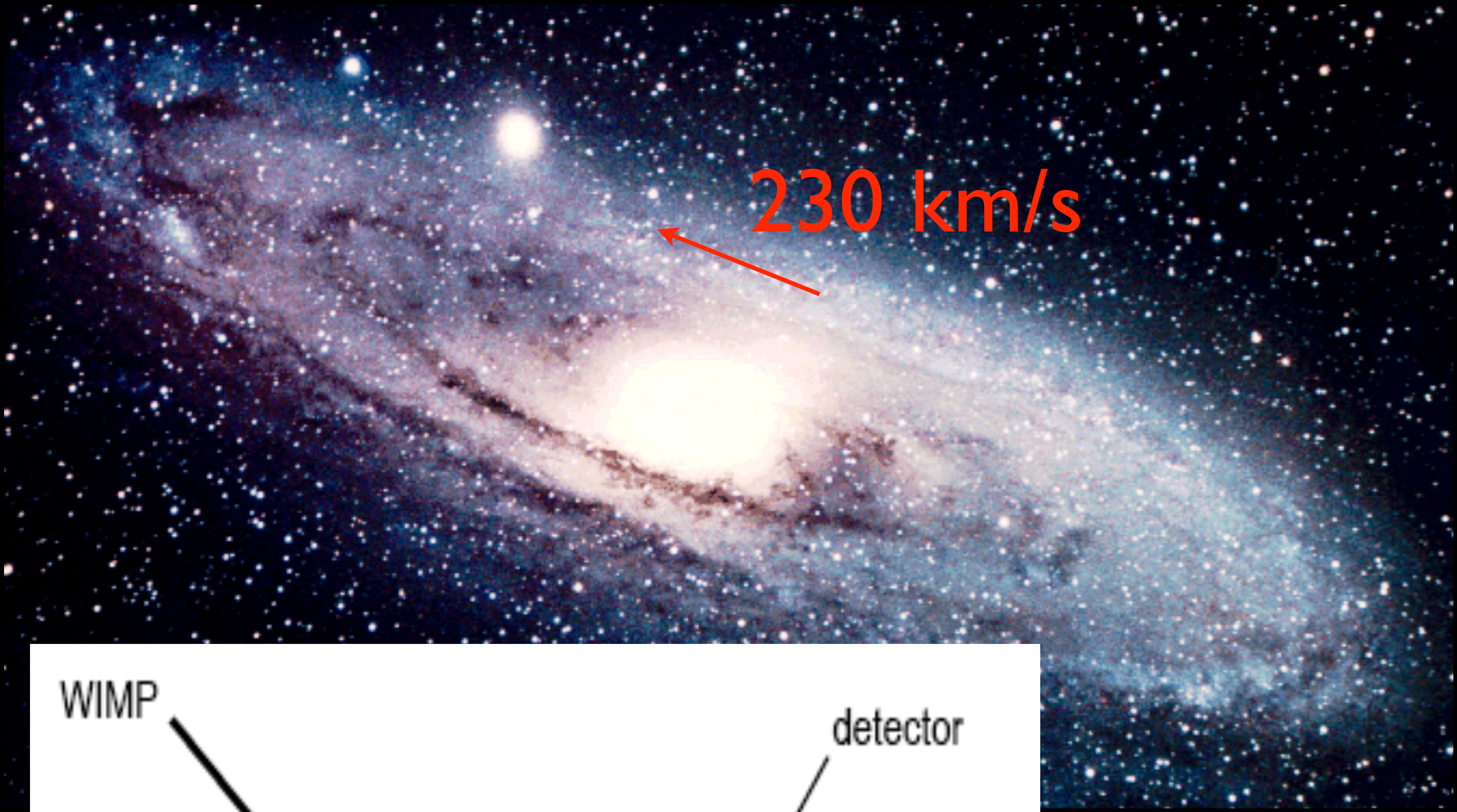
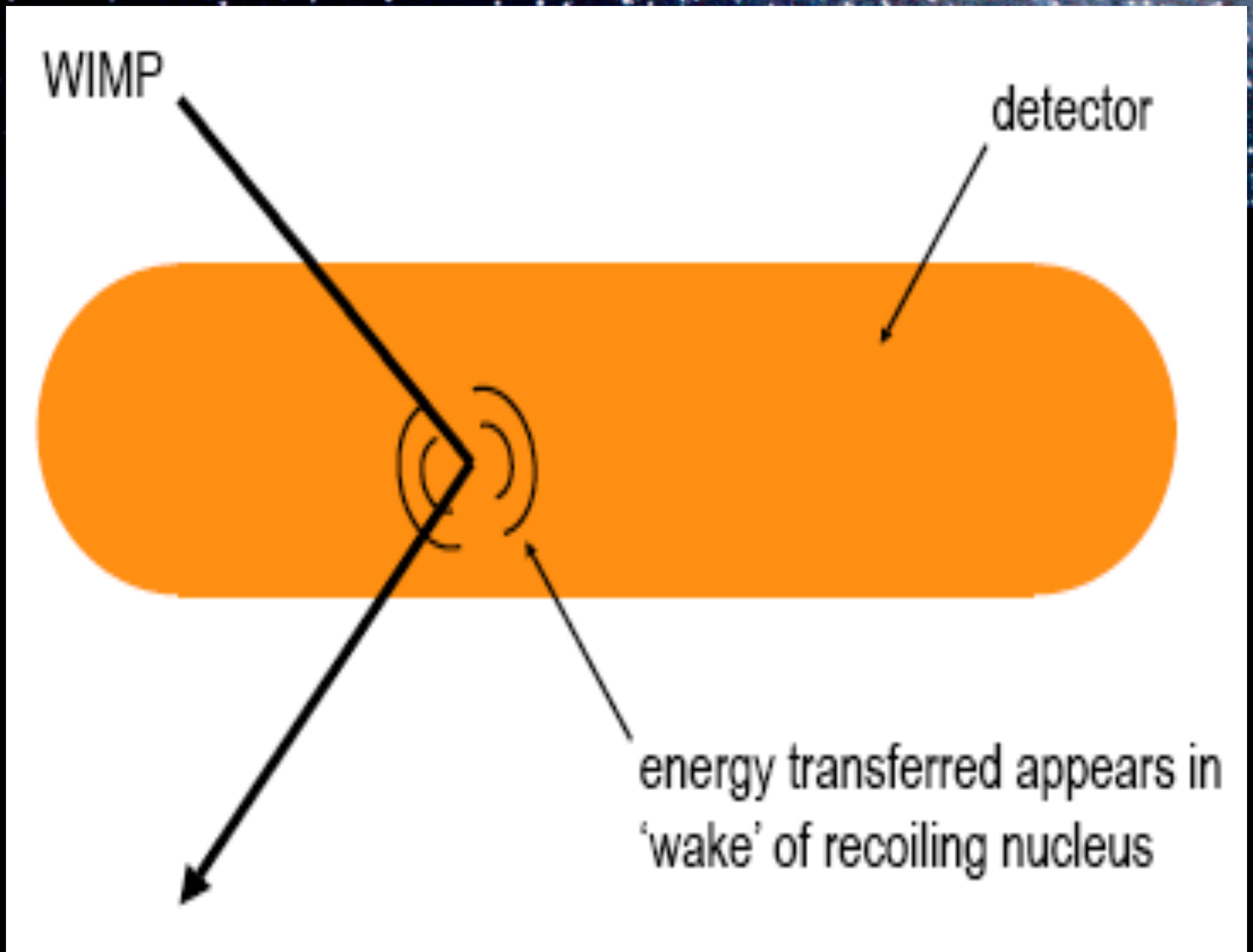
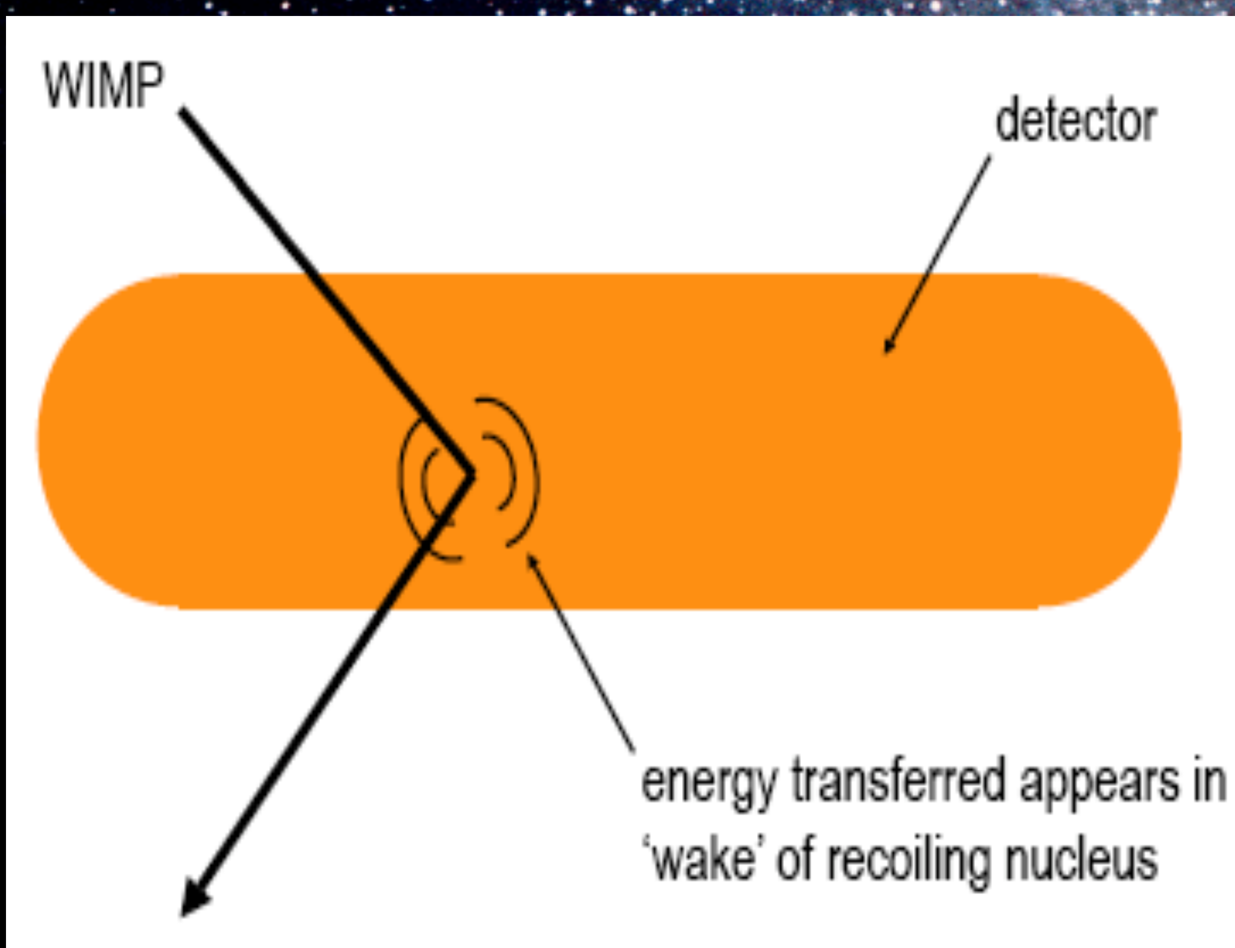
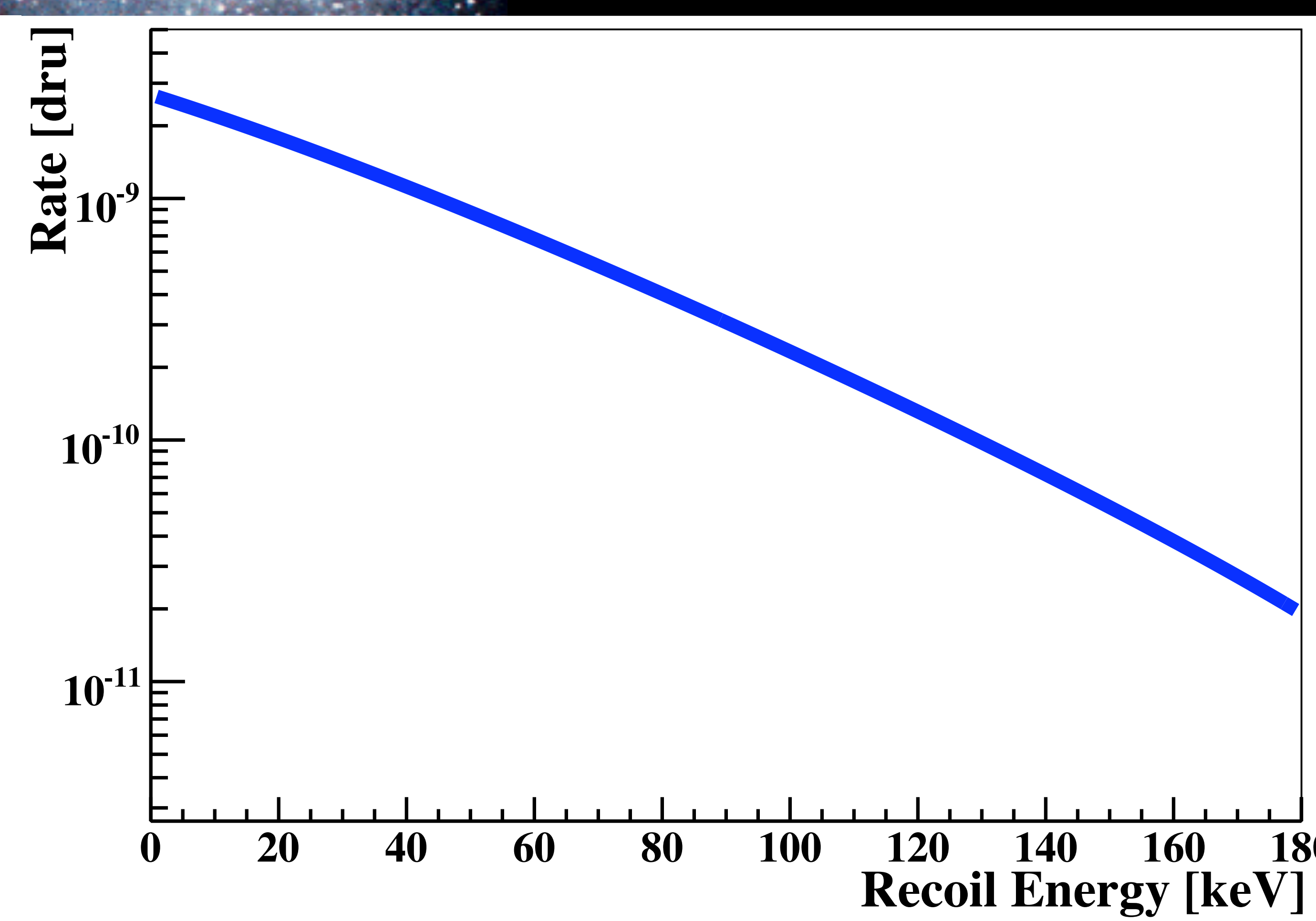




Challenges and Goals

- Low rates
- Low energies
- Background rejection





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Overview and Strategy

Why 0νββ ^{76}Ge?

- Intrinsic HPGe detectors are also the source
- Excellent energy resolution: 0.16% at 2039 keV (4 keV Region of Interest)
- Powerful background rejection: segmentation, timing, pulse-shape discrimination
- Demonstrated enrichment: 7.44% to ≥86%
- Matrix elements better understood than most
- ^{76}Ge has the current best limit:

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25} \text{ y (90\% CL)}$$

H.V. Klapdor-Kleingrothaus et al., Eur. Phys. J. A 12, 147, (2001)

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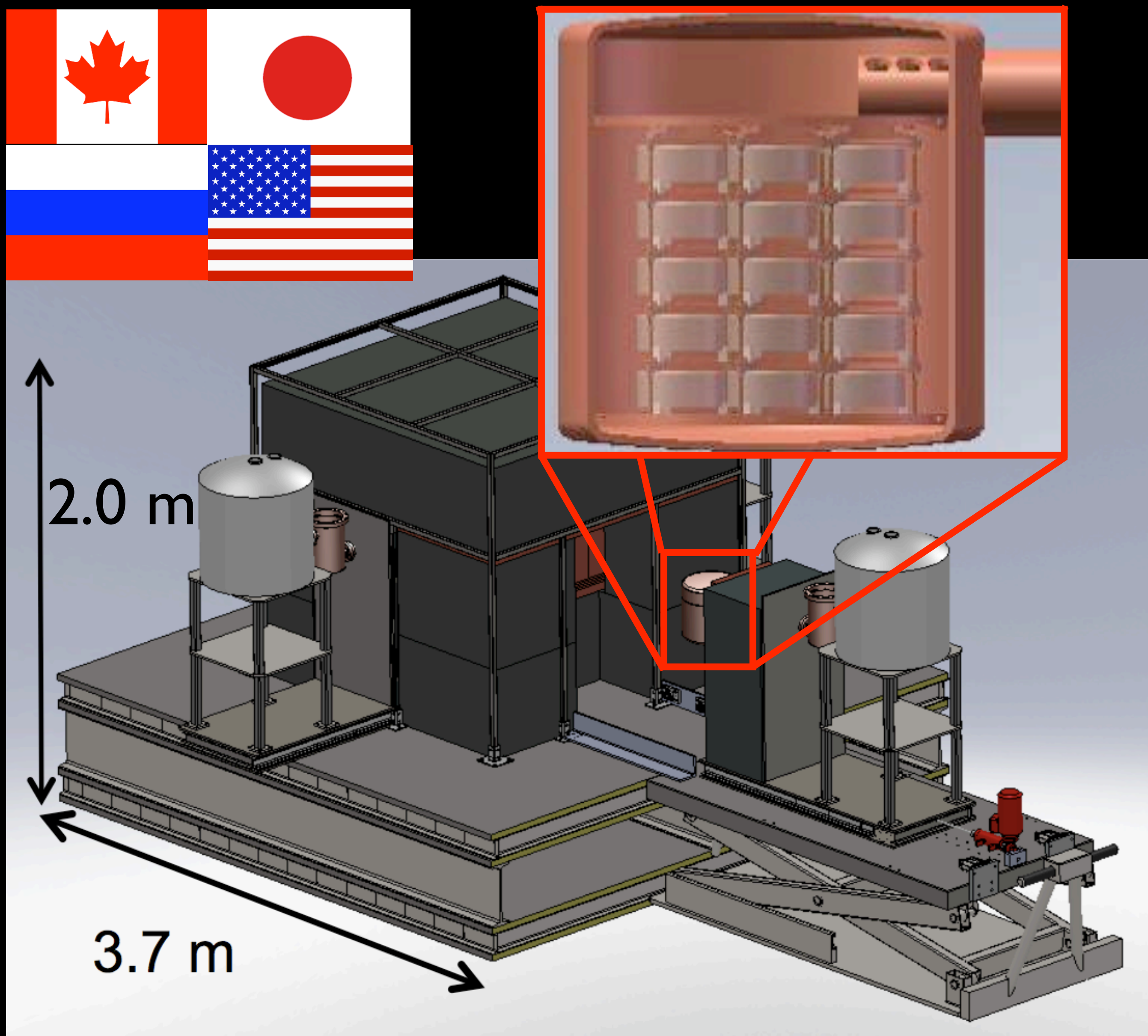

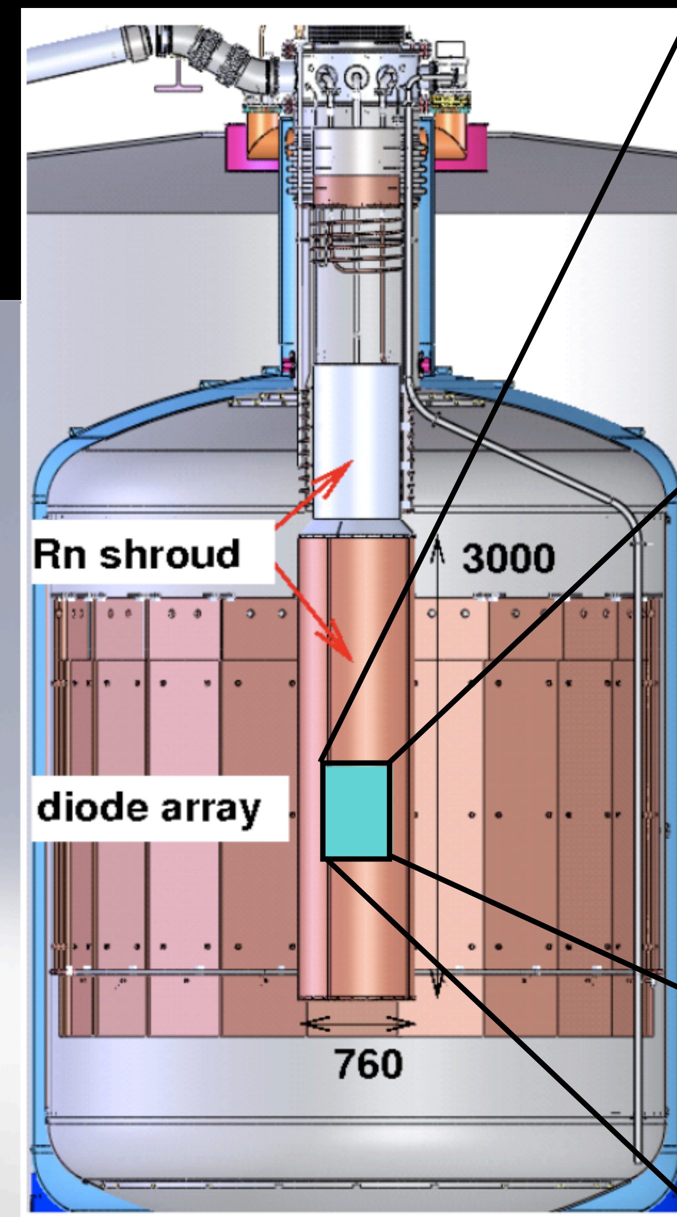

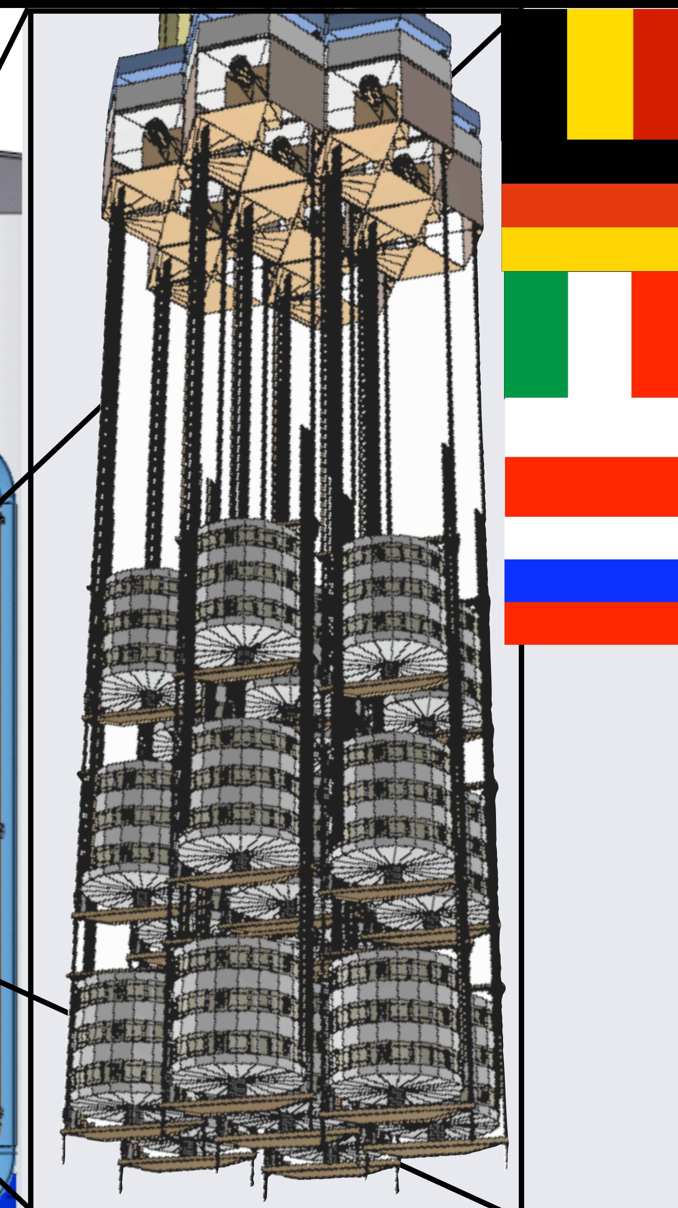

- Modular ^{enr}Ge arrays in electro-formed Cu Cryostats
- E-formed Cu/Pb passive shielding
- 4π plastic scintillator μ veto

- ^{enr}Ge in LAr
- Water cherenkov μ veto
- Phase I: ~18 kg (H-M/IGEX xtals)
- Phase II: +20 kg segmented xtals

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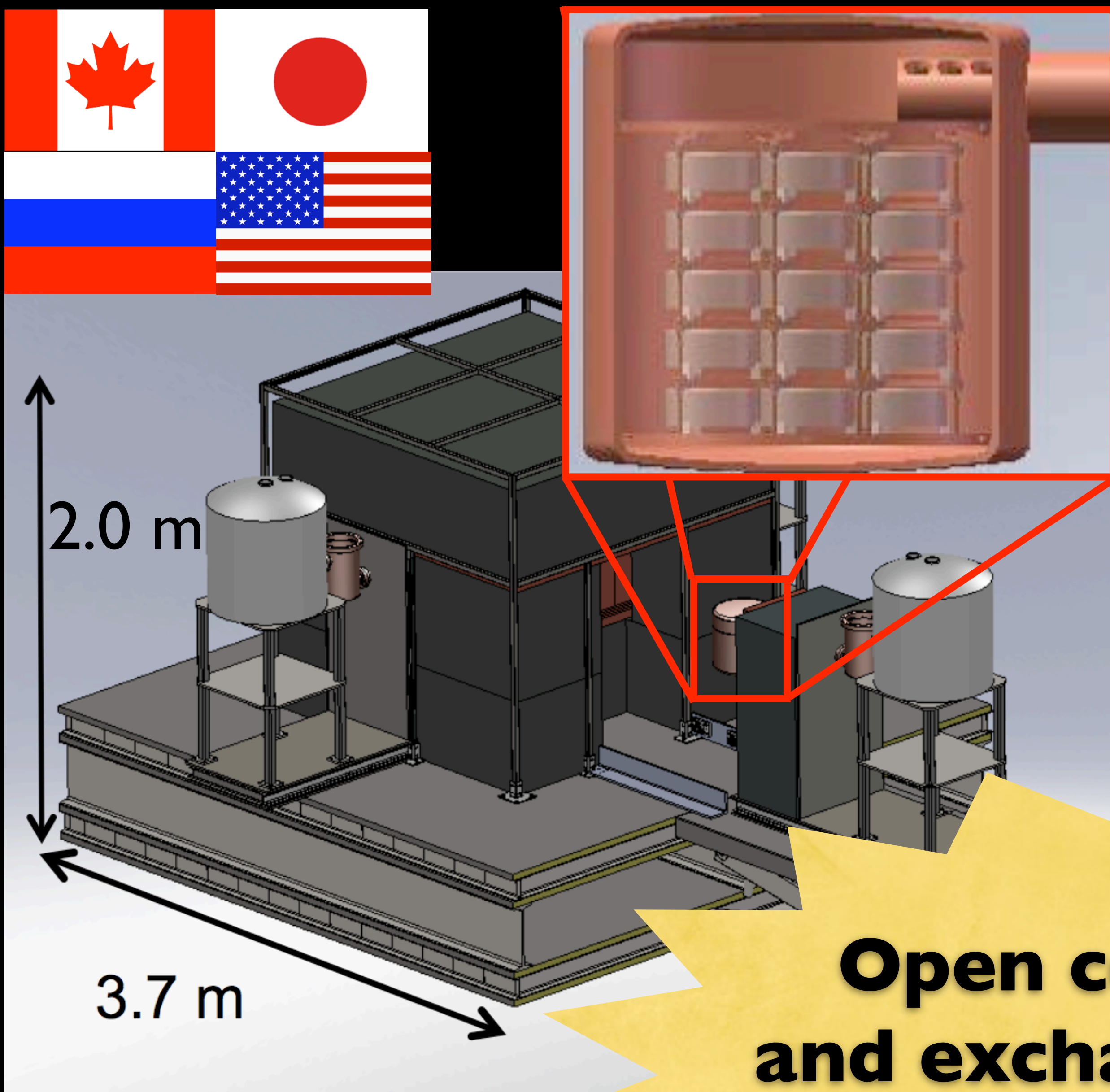

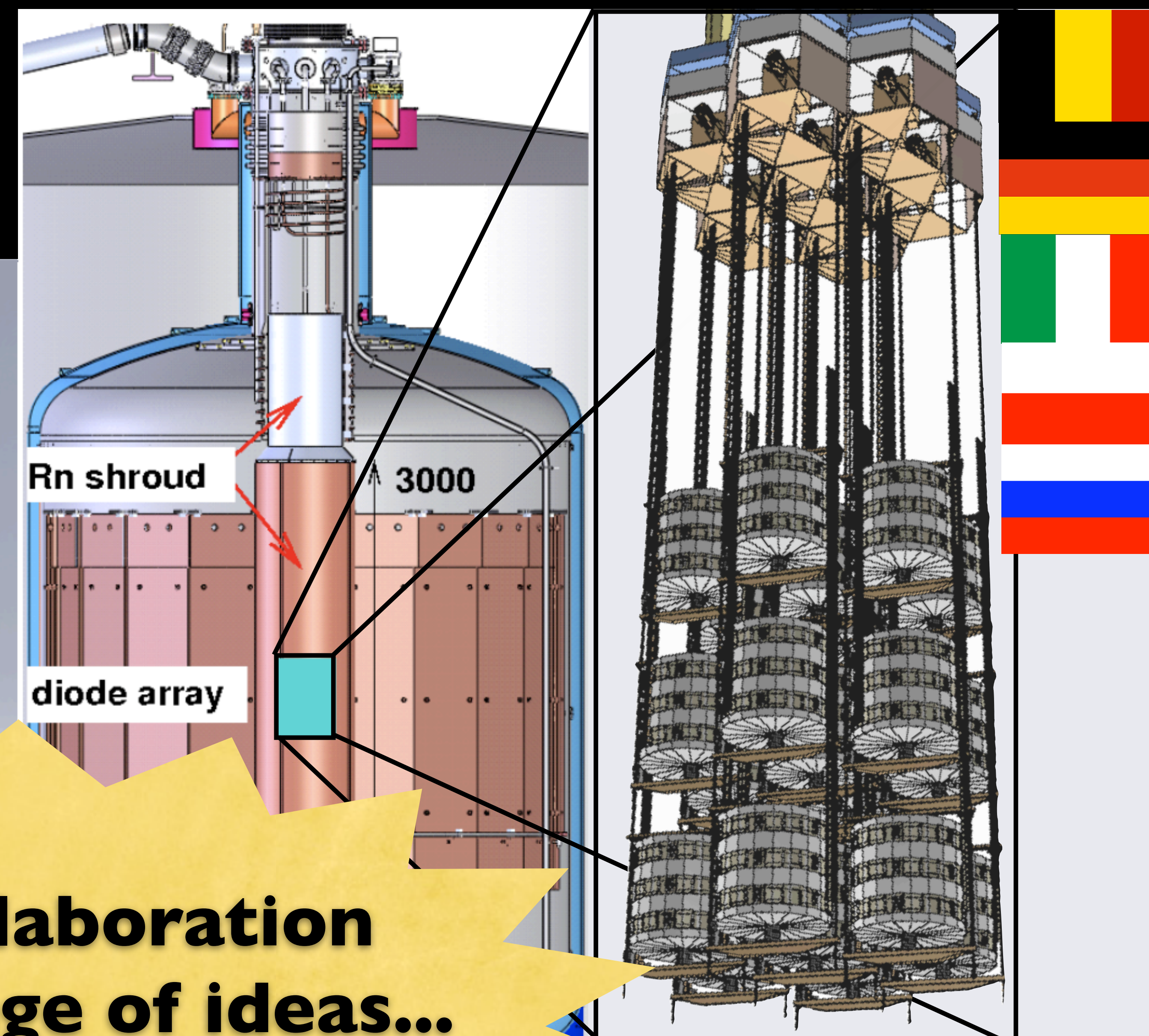

Open collaboration and exchange of ideas... Plans to merge for ton-scale experiment!!!

- Modular ^{enr}Ge arr
  formed Cu Cryostats
- E-formed Cu/Pb passive sh
- 4π plastic scintillator μ veto

- renkov μ veto
- Phase I: ~18 kg (H-M/IGEX xtals)
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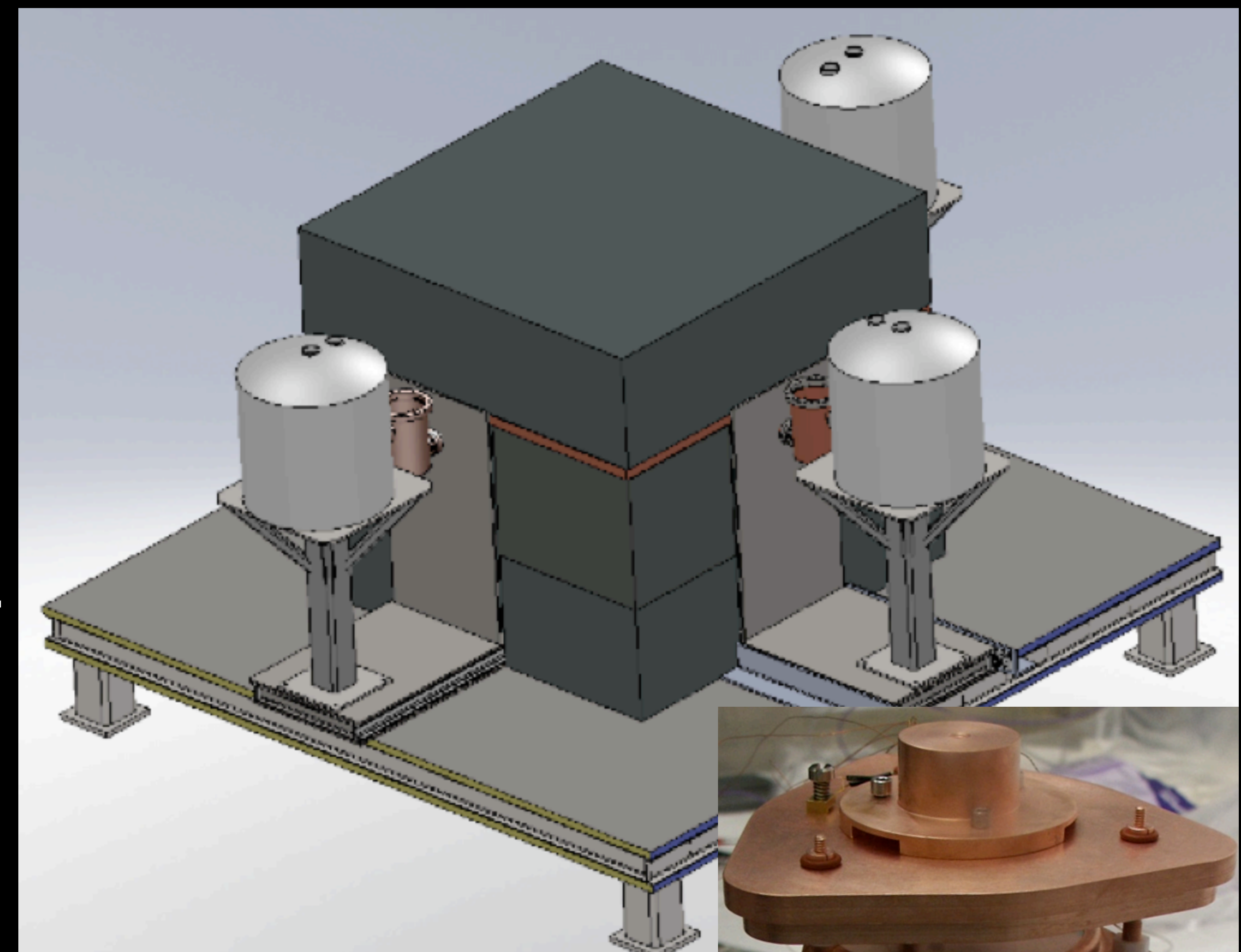
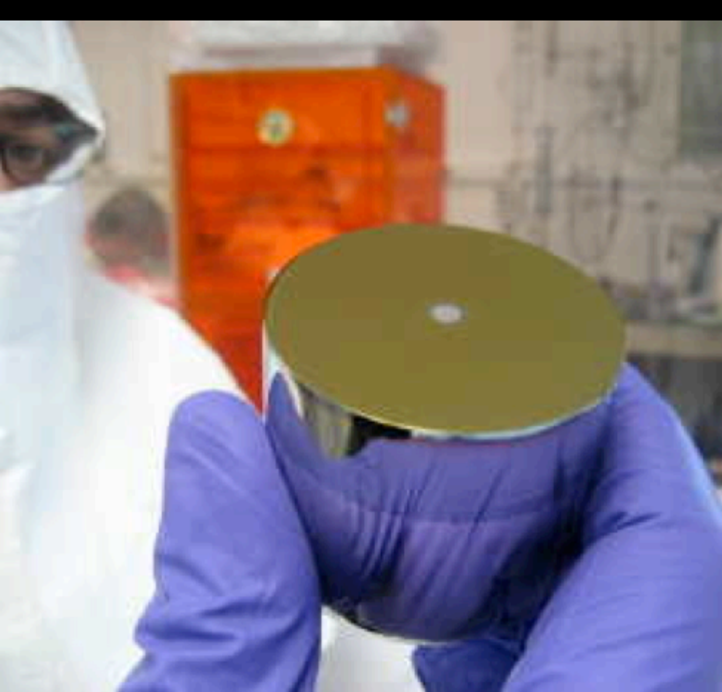
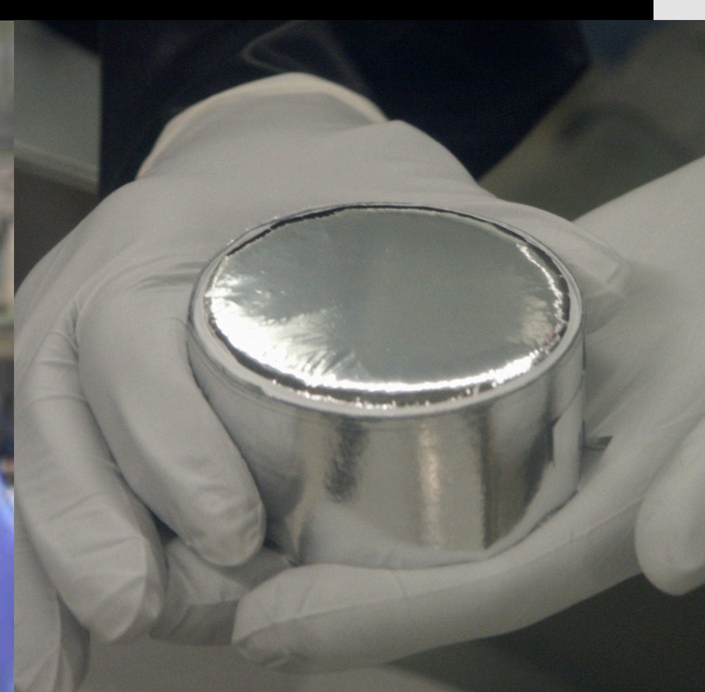
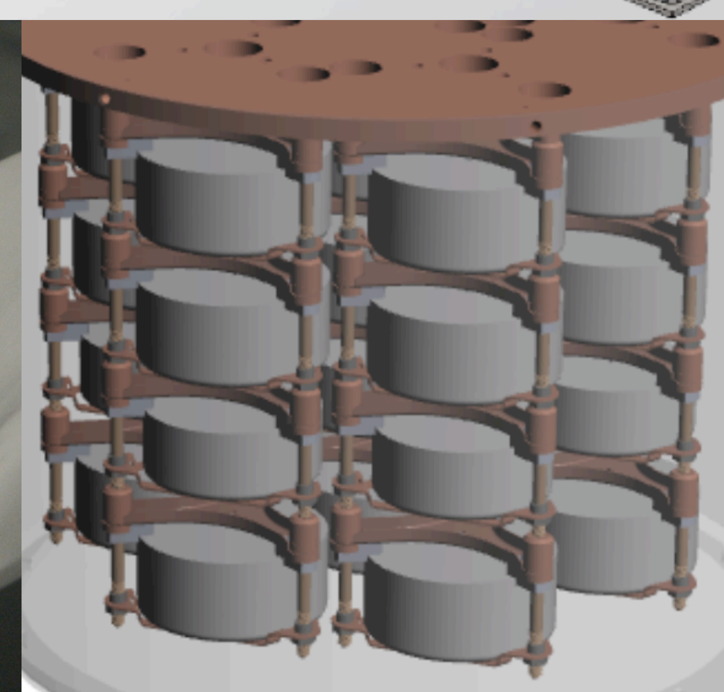
Majorana Demonstrator

- Primary goal: show background levels for ton-scale Majorana
- 60-kg HPGe detectors (~half enriched)
- Focus on p-type point-contact detectors
- Located at Sanford Lab (4850 level of Homestake mine)

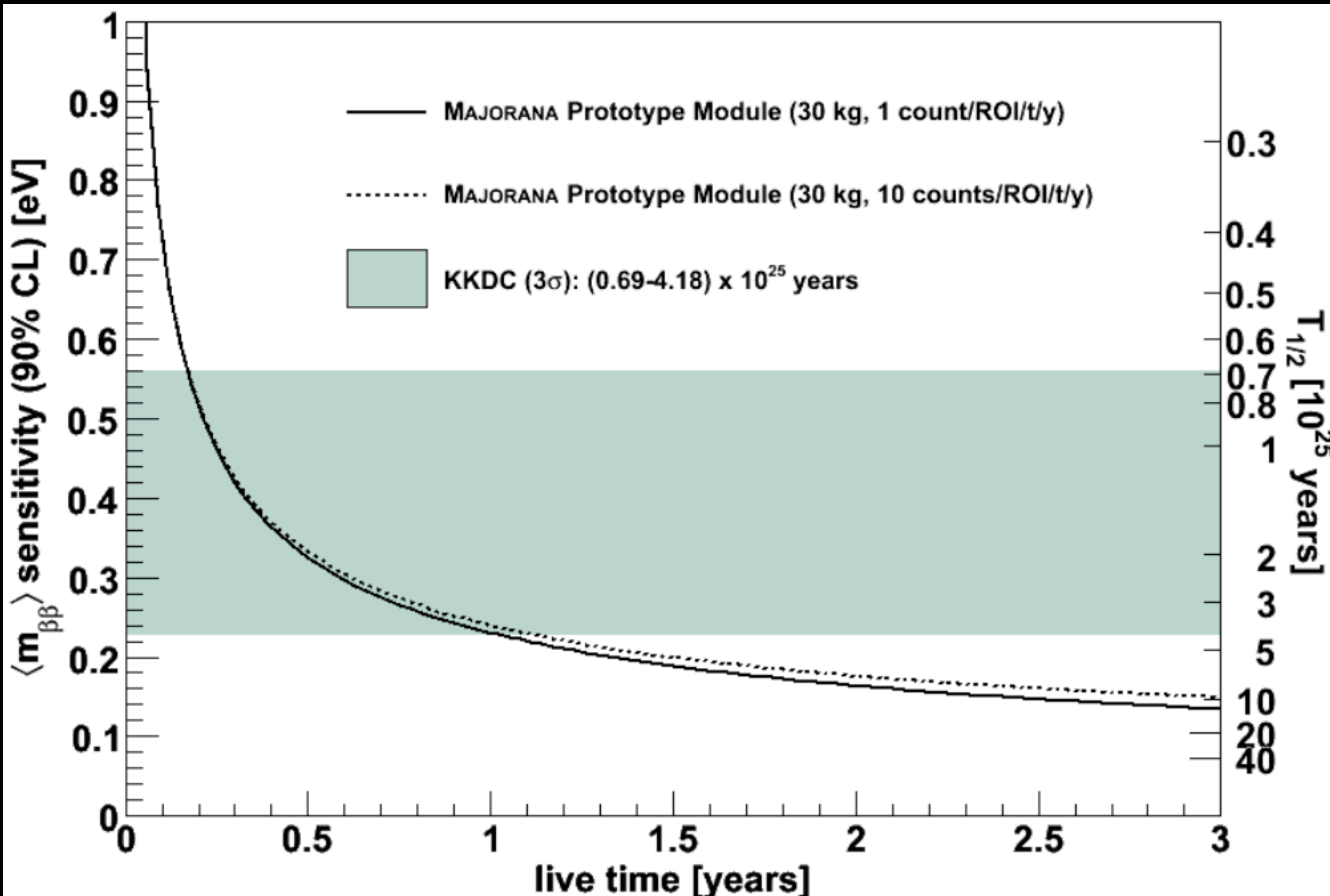








MAJORANA Sensitivity



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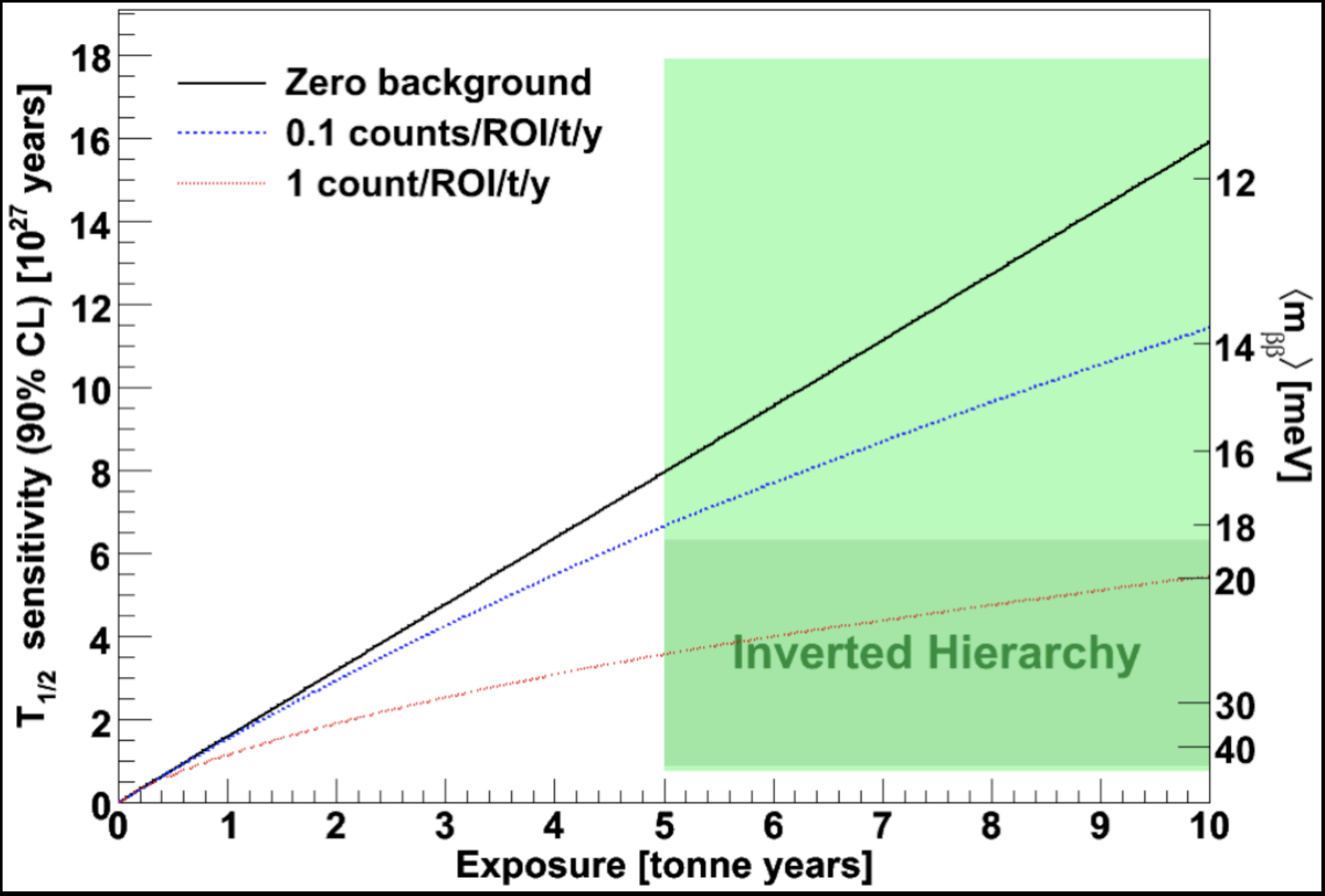

Different Models!

- What do I mean by "Models???"
  - A particular combination of M and η for a set of $\beta\beta$ isotopes that predict a a rate $\Gamma^{0\nu}$

Different Models!

- What do I mean by "Models???"

If the uncertainty on these predictions is good enough, we can tell these models apart!

- This work focused on seven models...
  - Light neutrino exchange, matrix elements from Nucl. Phys. A, **766**, 107
  - Light neutrino exchange, matrix elements from Nucl. Phys A, **729**, 867
  - Light neutrino exchange, matrix elements calculated from in shell model (various references)
  - Heavy neutrino exchange, matrix elements from Phys. Rev. C, **60**, 055502
  - SUSY, matrix elements from Phys. Rev. D, 58, 115004
  - Two right-handed current models from Z. Phys. 334, 187

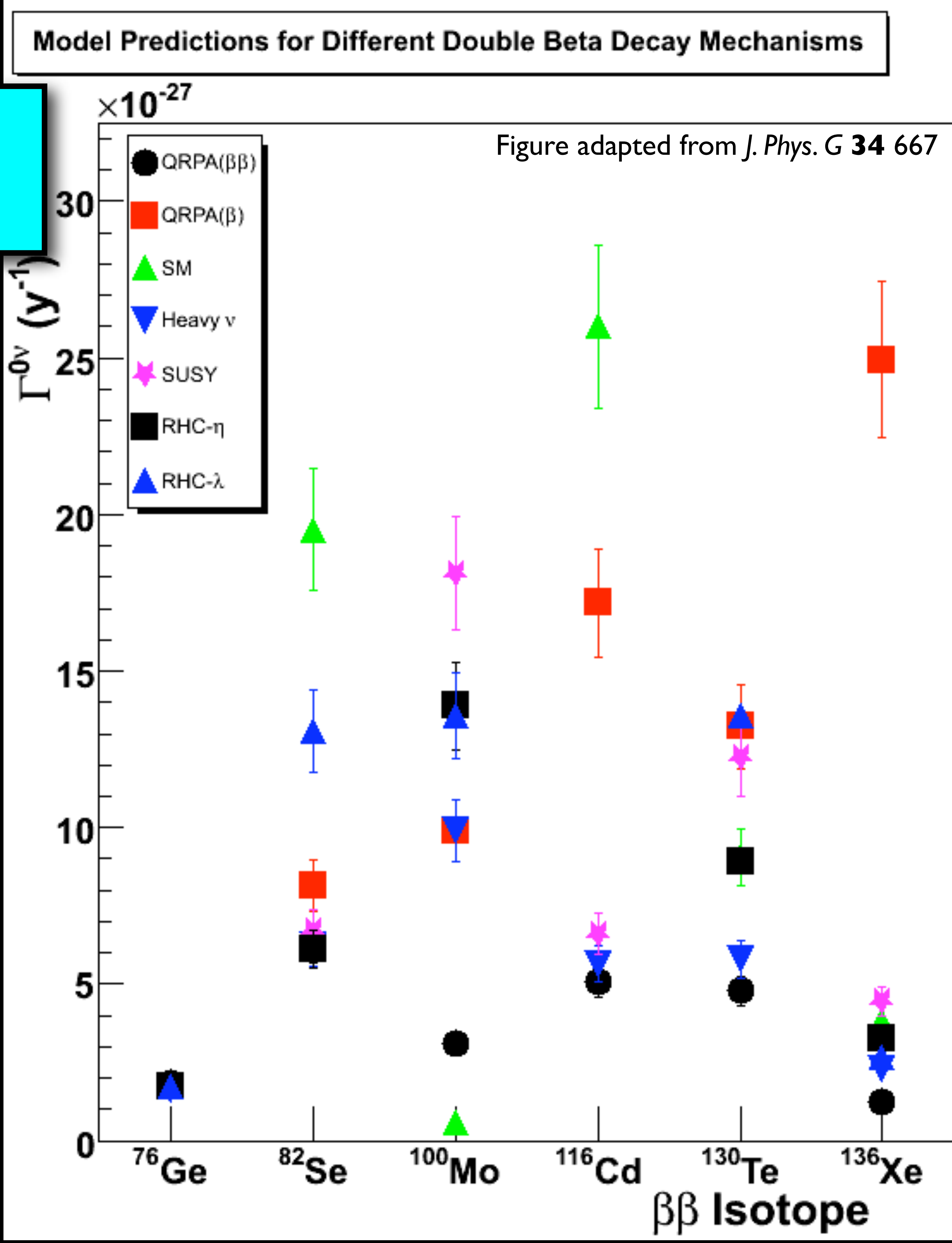

Figure adapted from *J. Phys. G* **34** 667

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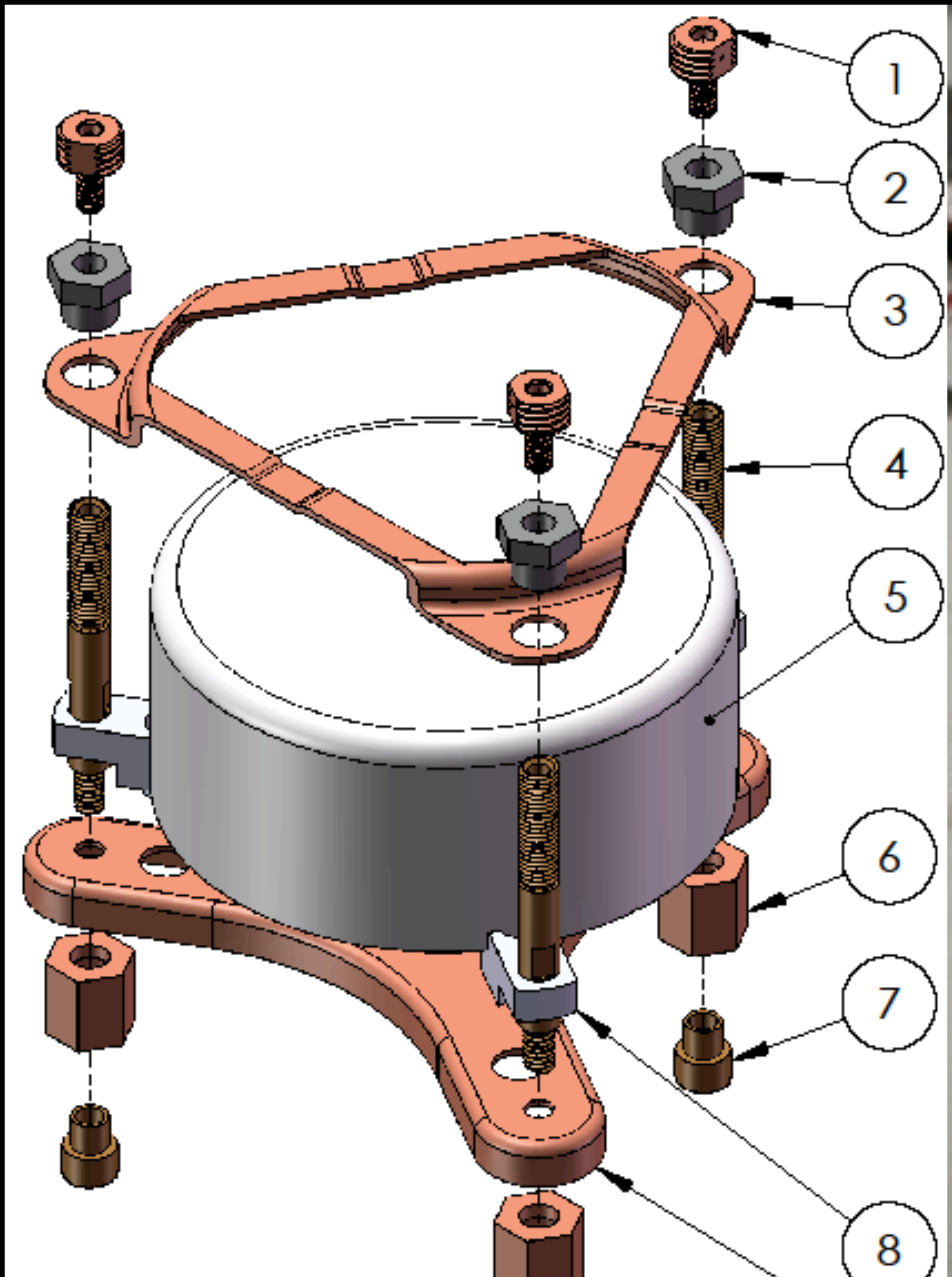
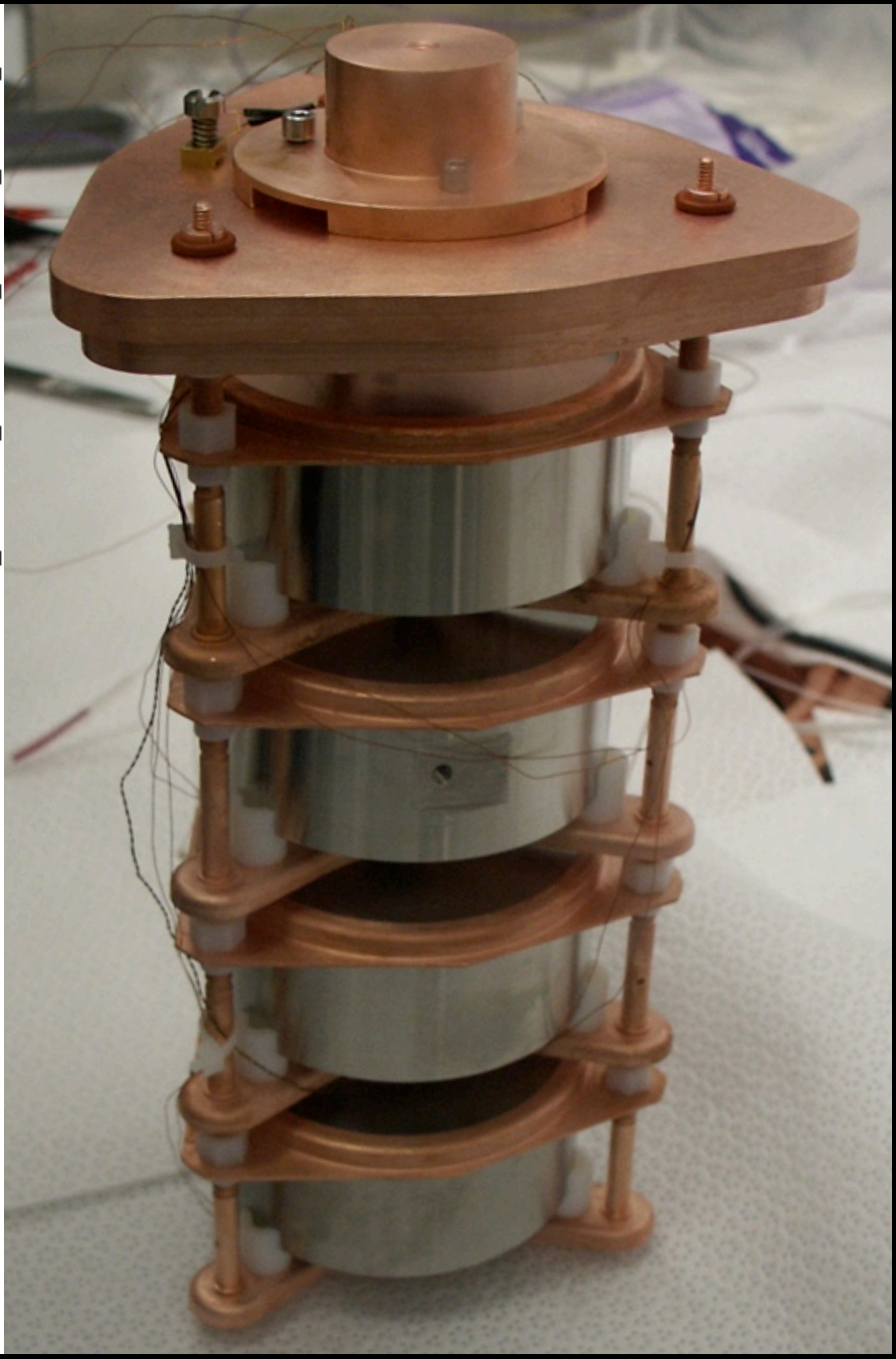
Detector design

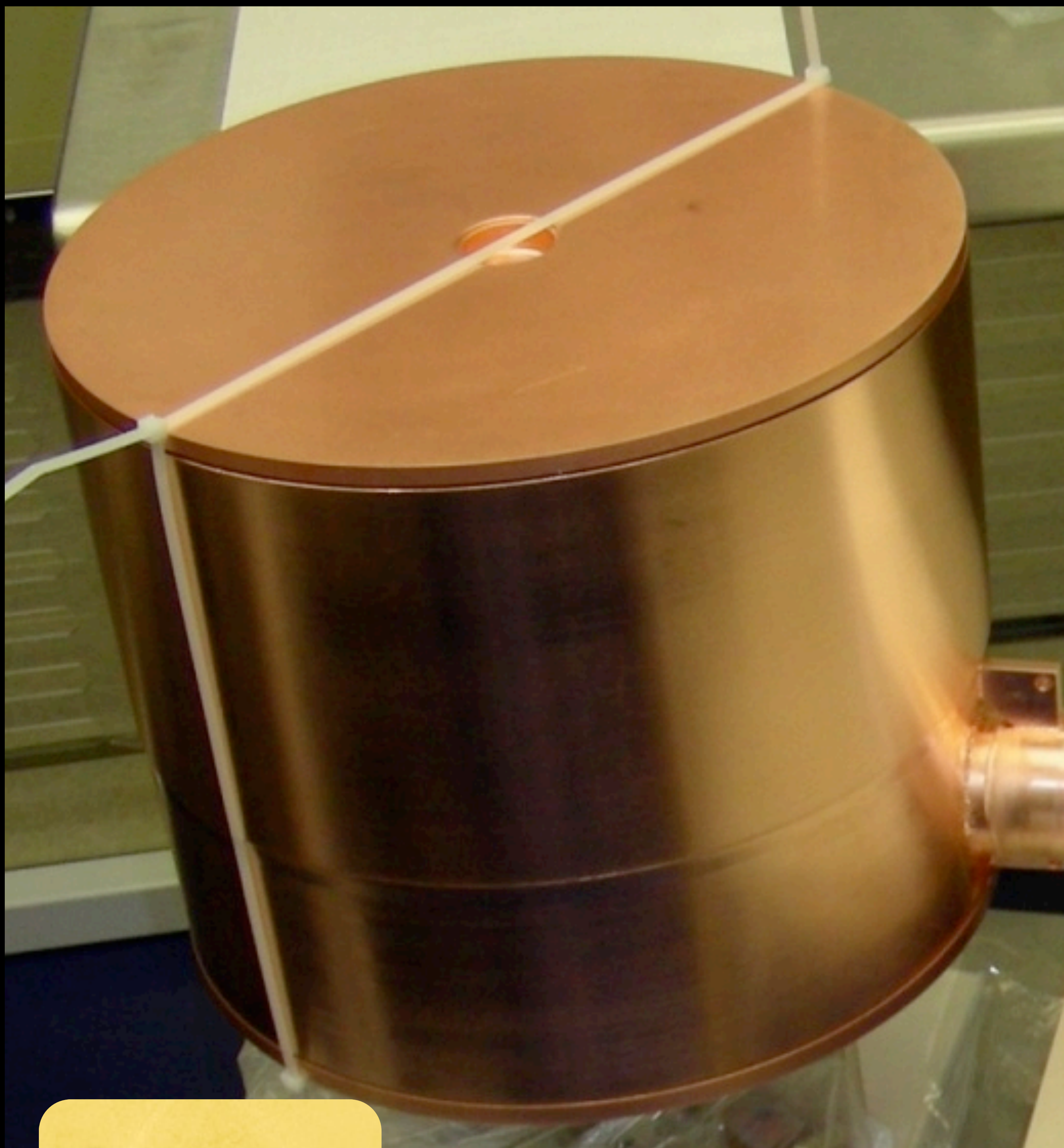
Majorana Design





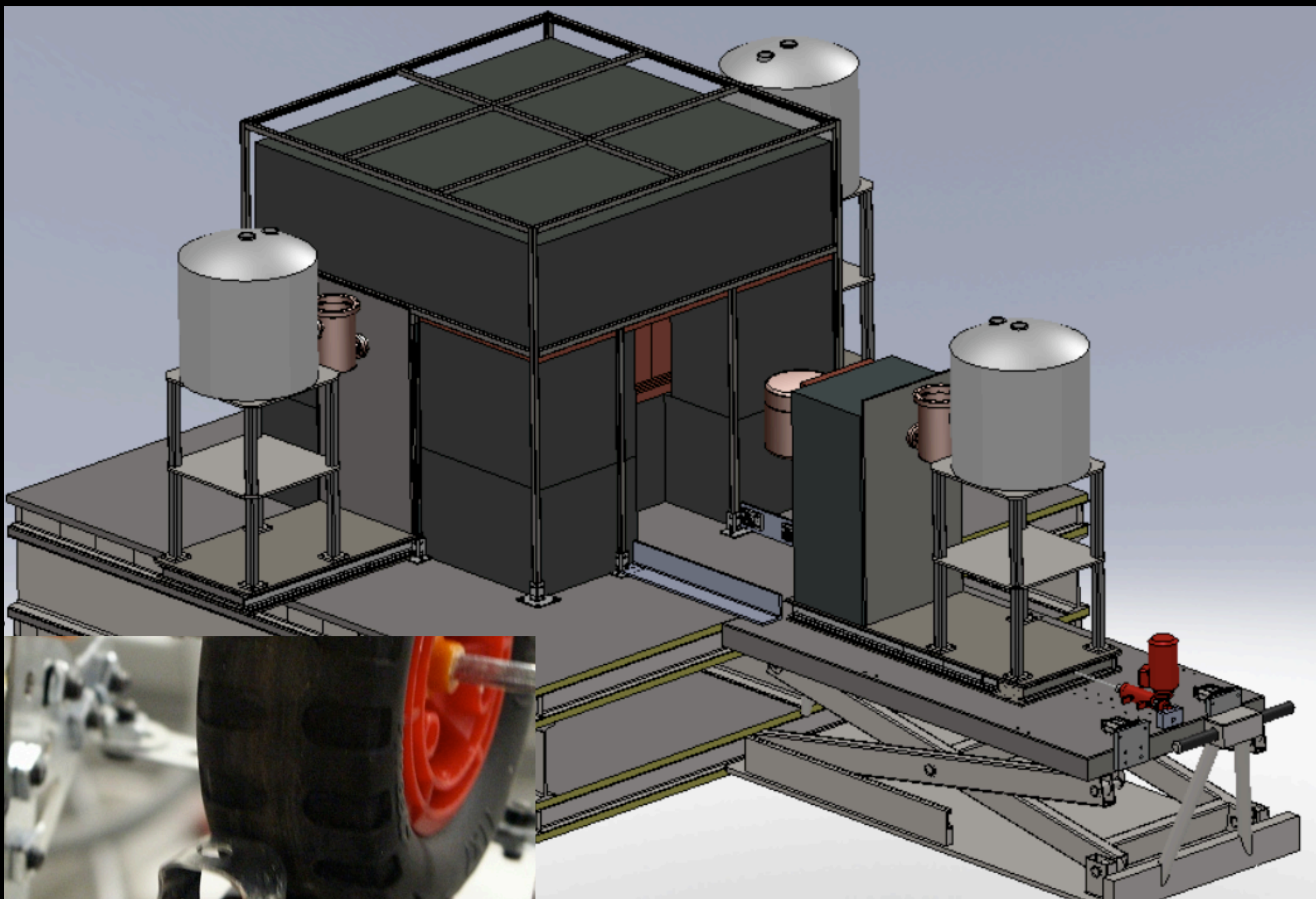
Detector Mounts and Strings

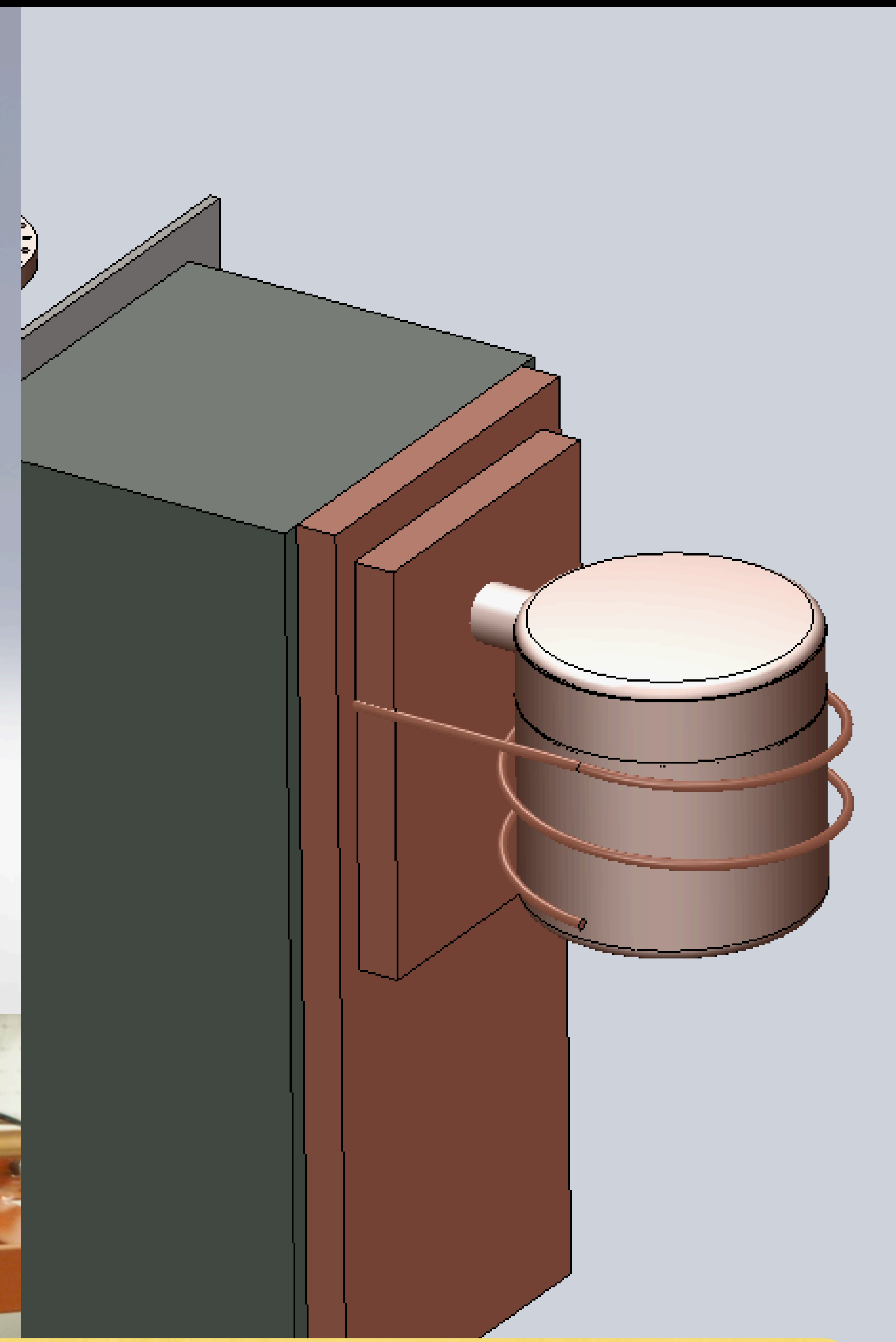
MAJORANA Design

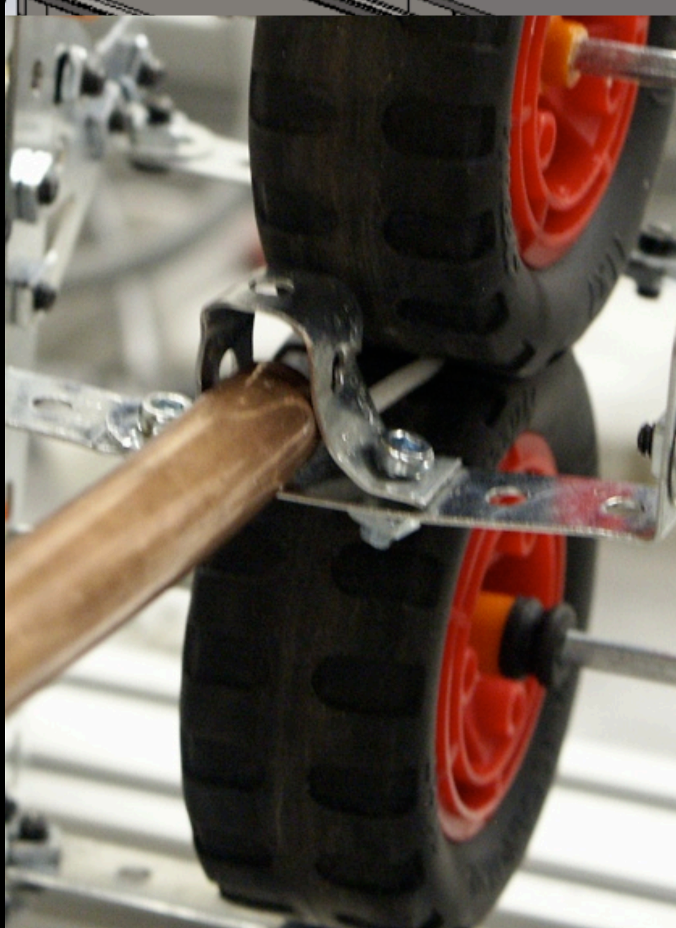


Cryostats

Majorana Design



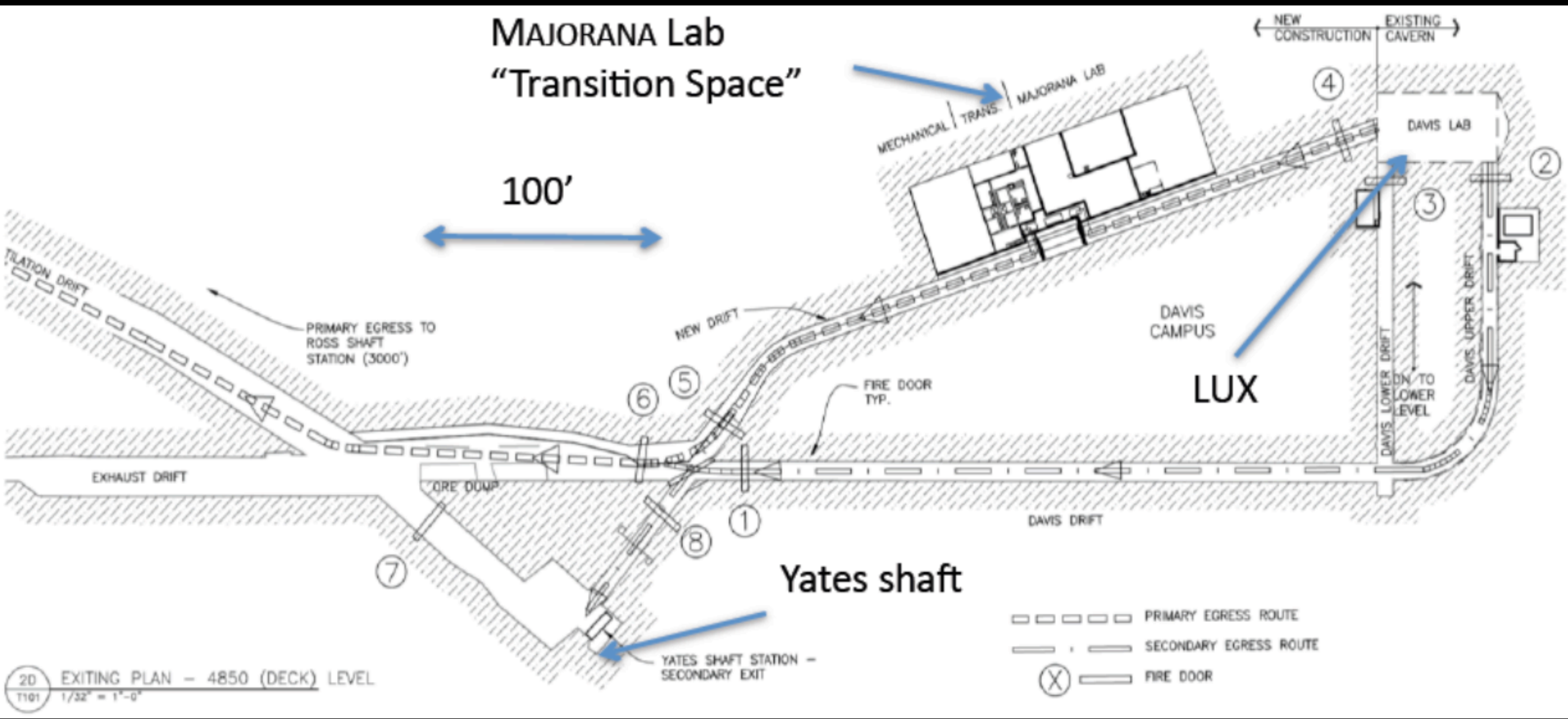




Shielding and Calibration

MAJORANA Site Facilities

- Copper Electro-forming, detector facilities, and machine shop in one campus at 4850' level (new drift to Davis cavity for LUX)
- Excavation underway--beneficial occupancy soon!
- Temporary lab for Copper Electro-forming near Ross Shaft



The Majorana Collaboration

Black Hills State University - Spearfish, SD
Kara Keeter

Duke University and TUNL - Durham, North Carolina
Matthew Busch, James Esterline, Mary Kidd, Gary Swift, Werner Tornow

Institute for Theoretical and Experimental Physics, Moscow, Russia
Alexander Barabash, Sergey Konovalov, Igor Vanushin, Vladimir Yumatov

Joint Institute for Nuclear Research - Dubna, Russia
Viktor Brudanin, Slava Egorov, K. Gusey, Oleg Kochetov, M. Shirchenko, V. Timkin E. Yakushev

Lawrence Berkeley National Laboratory and the University of California at Berkeley - Berkeley, California
Mark Amman, Marc Bergevin, Yuen-Dat Chan, Mario Cromaz, Jason Detwiler, Brian Fujikawa, Donna Hurley, Kevin Lesko, James Loach, Paul Luke, Ryan Martin, Alan Poon, Gersende Prior, Jing Qian, Kai Vetter, Harold Yaver, Sergio Zimmerman

Los Alamos National Laboratory - Los Alamos, New Mexico
Melissa Boswell, Steven Elliott, Victor M. Gehman, Andrew Hime, Adam Montoya, Kieth Rielage, Larry Rodriguez, David Steele, Jan Wouters

North Carolina State University and TUNL - Raleigh, North Carolina
Henning Back, Lance Leviner, Albert Young

Oak Ridge National Laboratory - Oak Ridge, Tennessee
Jim Beene, Fred Bertrand, Greg Capps, Ren Cooper, David Radford, Chang-Hong Yu

Osaka University - Osaka, Japan
Hiroyasu Ejiri, Ryuta Hazama, Masaharu Nomachi, Shima Tatsuji

Pacific Northwest National Laboratory - Richland, Washington
Craig Aalseth, James Ely, Jim Fast, Aaron Fuller, Todd Hossbach, Eric Hoppe, Marty Keillor, Jeremy Kephart, Richard T. Kouzes, Harry Miley, Alan Myers, John Orrell

Queen's University - Kingston, Ontario
Art McDonald

University of Alberta - Edmonton, Alberta
Aksel Hallin

University of Chicago - Chicago, Illinois
Phil Barbeau, Juan Collar, Nicole Fields

University of North Carolina and TUNL - Chapel Hill, North Carolina
Padraic Finnerty, Graham Giovanetti, Reyco Henning, Mark Howe, Sean MacMullin, Dave Phillips, Jacquie Strain, John F. Wilkerson

University of South Carolina - Columbia, South Carolina
Frank Avignone, Richard Creswick, Horatio A. Farach, Leila Mizouni

University of South Dakolta - Vermillion, South Dakota
Vincente Guiseppe, Tina Keller, Dongming Mei, Keenan Thomas, Chao Zhang

University of Tennessee - Knoxville, Tennessee
William Bugg, Yuri Efremenko

University of Washington - Seattle, Washington
John Amsbaugh, Tom Burritt, Peter J. Doe, Robert Johnson, Michael Marino, Michael Miller, R. G. Hamish Robertson, Alexis Schubert, Tim Van Wechel

Note: Red text indicates students

MAJORANA and CLEAN/DEAP

Overview and Strategy

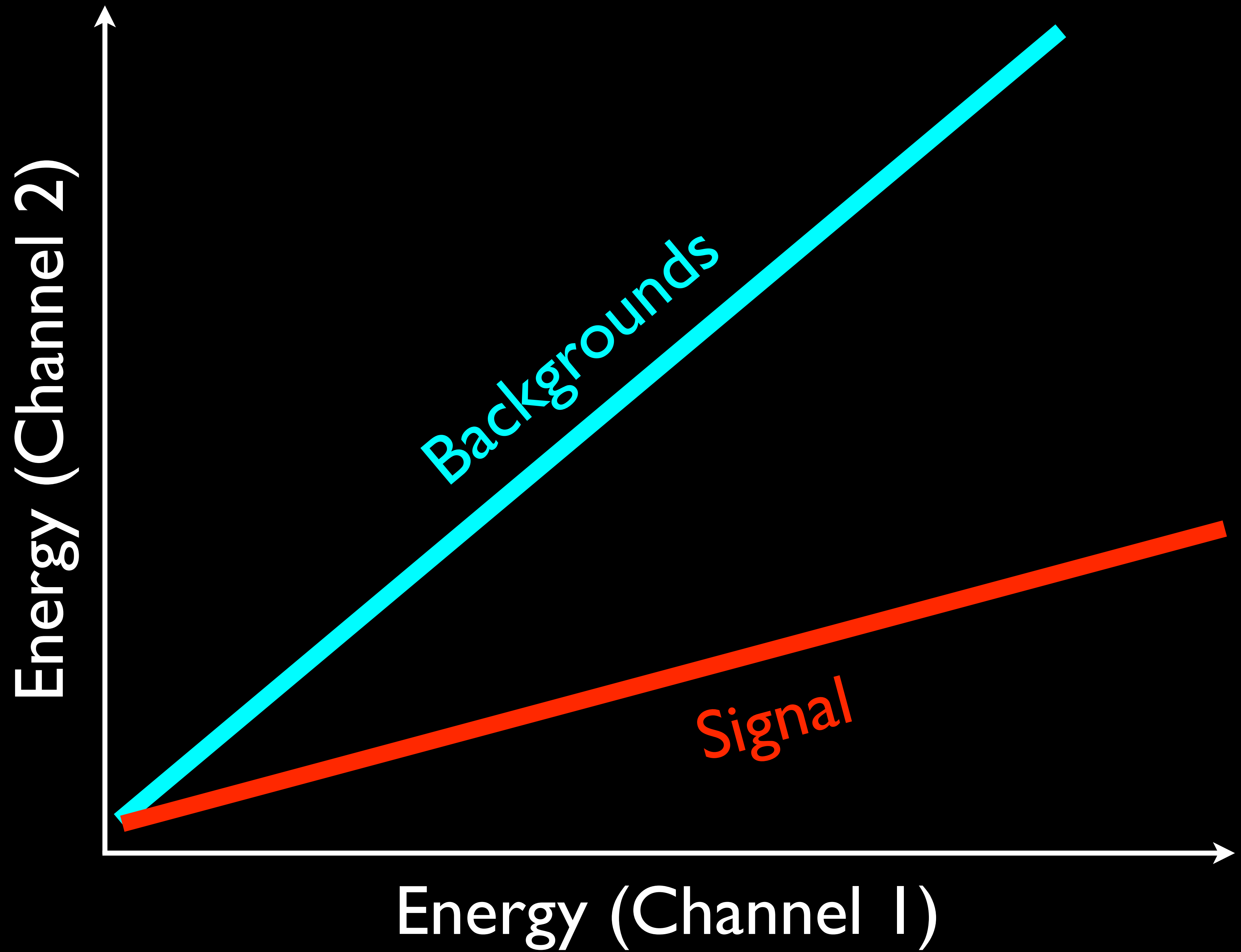
WIMP Dark Matter

- No particle in the Standard Model of Particle Physics explains dark matter
- Supersymmetric models predict a Lightest Supersymmetric Particle -- also known as a Weakly Interacting Massive Particle (WIMP)
- Could be a neutralino (mixture of the Z, γ and Higgs super-partners)
    - Thermal relics, Mass ~ 10 GeV - 1 TeV
    - σ_A ~ Electroweak scale

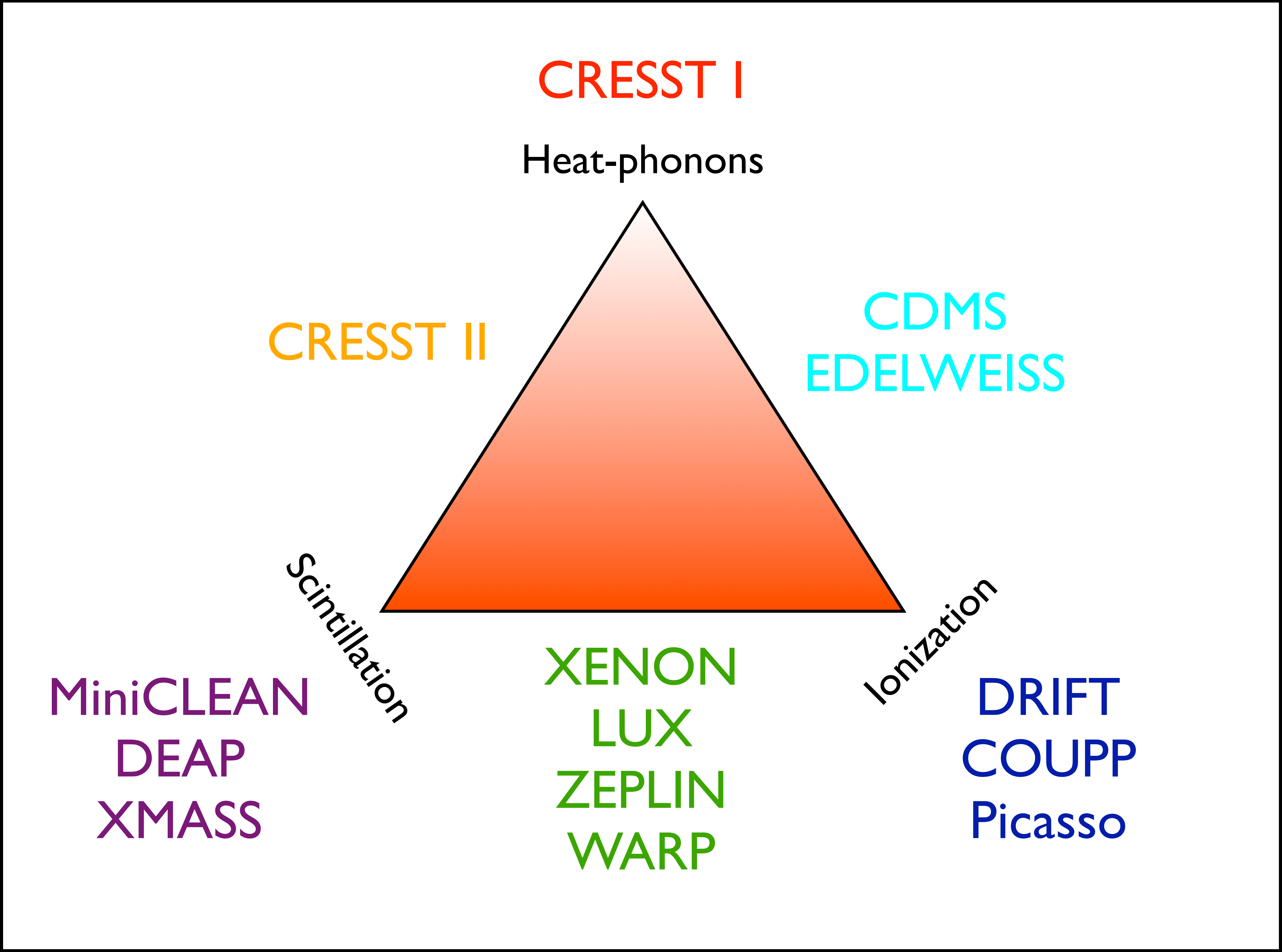
WIMP Dark Matter

We have realized a novel approach for the direct detection of dark matter using scintillation light from single phase detectors of LAr and LNe. We have developed a conceptually simple and economic means to achieve the multi-ton scale necessary to detect and study WIMP dark matter.

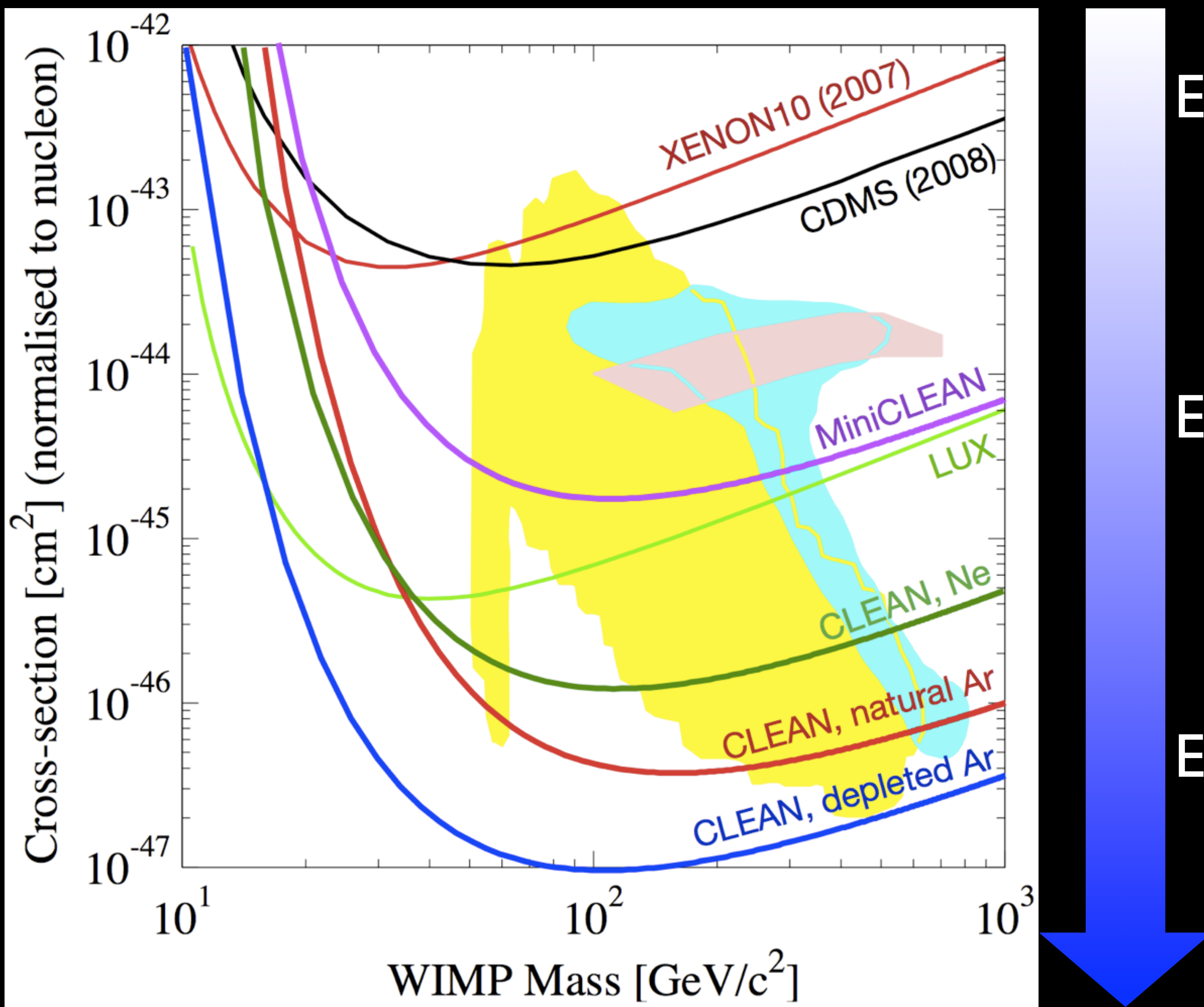
What to do?



What to do?


CRESST I
Heat-phonons
CRESST II
CDMS
EDELWEISS
Scintillation
Ionization
MiniCLEAN
DEAP
XMASS
XENON
LUX
ZEPLIN
WARP
DRIFT
COUPP
Picasso

Progress Requires Scalable, "Background-Free" Detectors

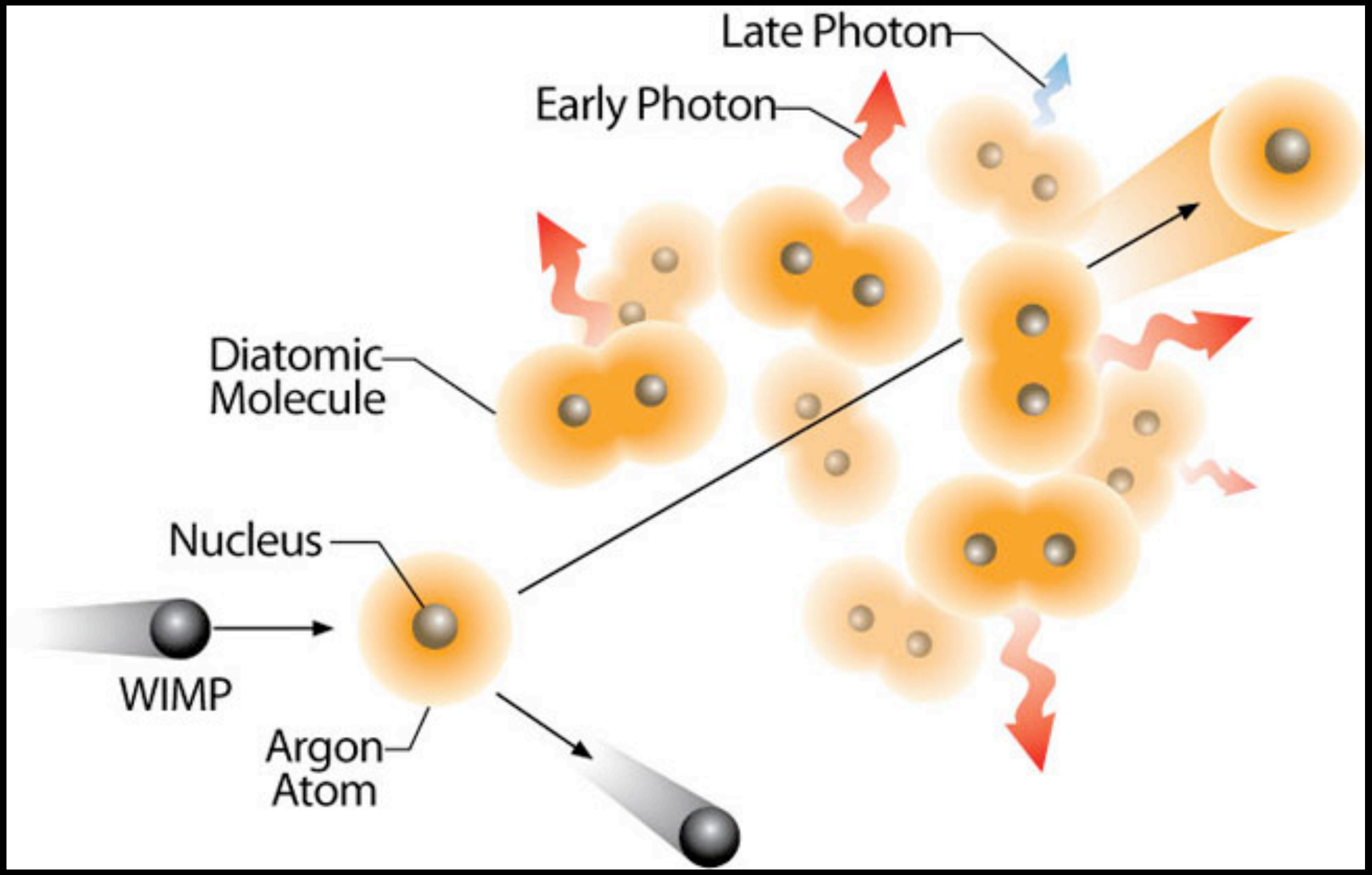


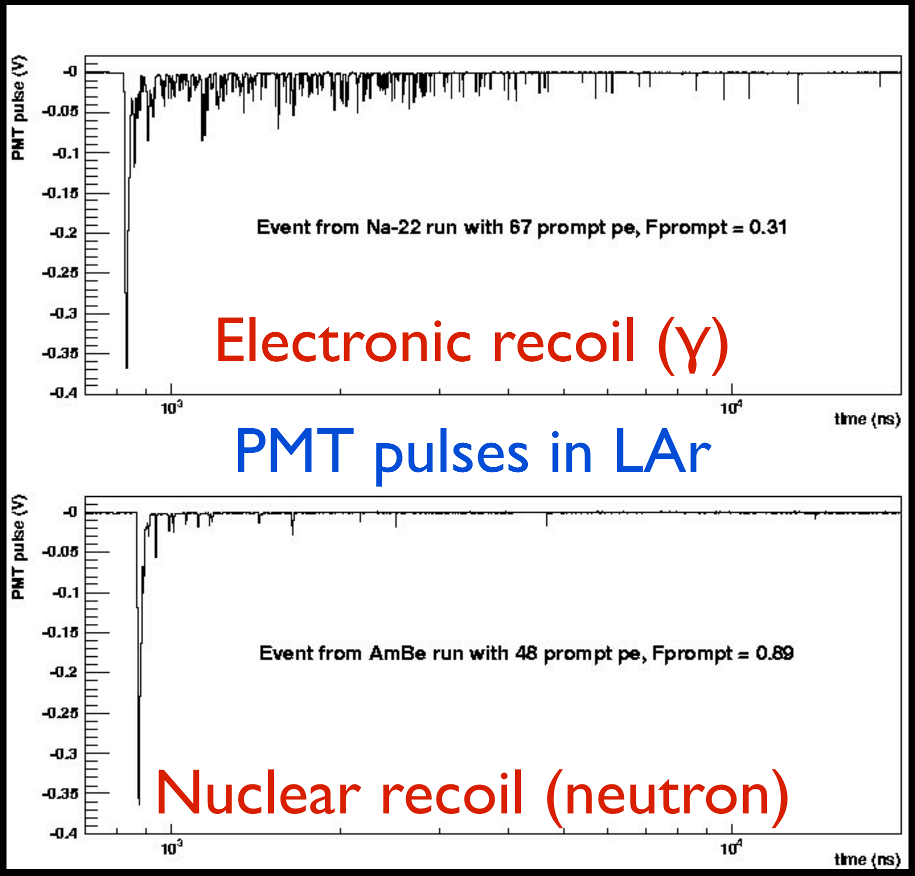
Events / 10 kg year

Events / 100 kg year

Events / 1000 kg year

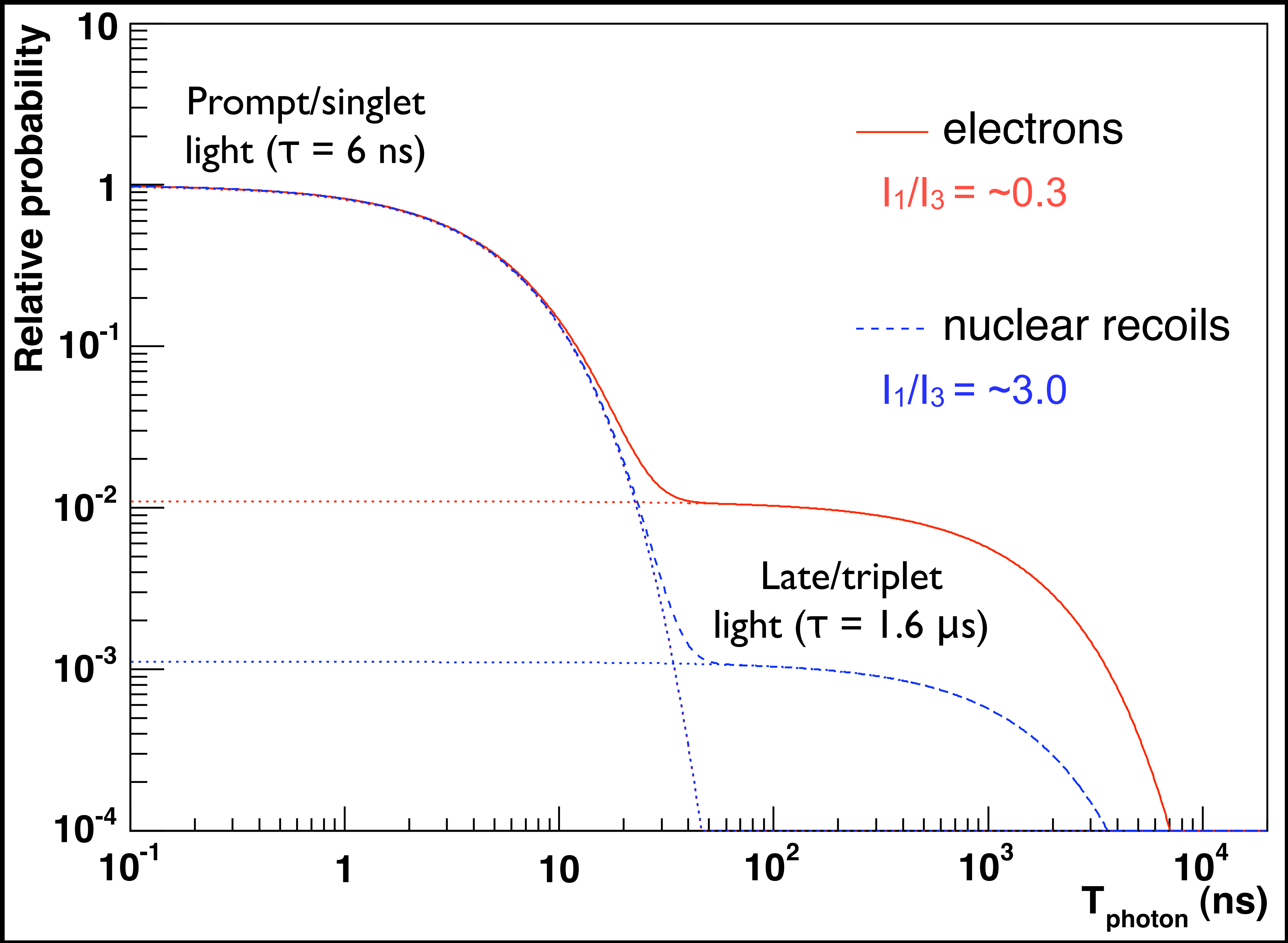
Single-Phase Noble Liquid





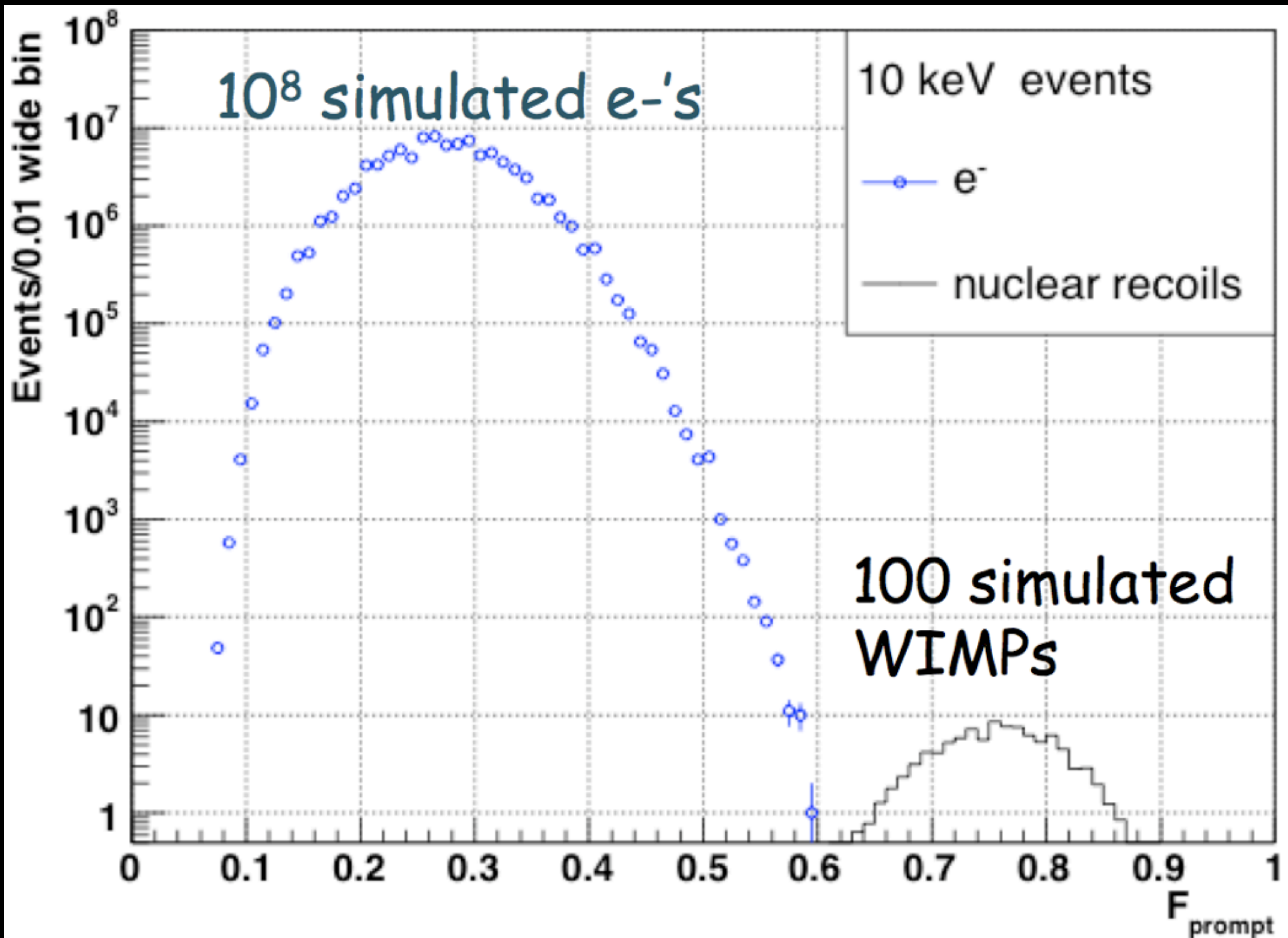
- Noble liquids have singlet and triplet excited states
- For argon and neon, decay times for these states are different and long enough to provide discrimination between electronic and nuclear recoils
- Electronic recoils result in more triplet states so more late light

Background Discrimination

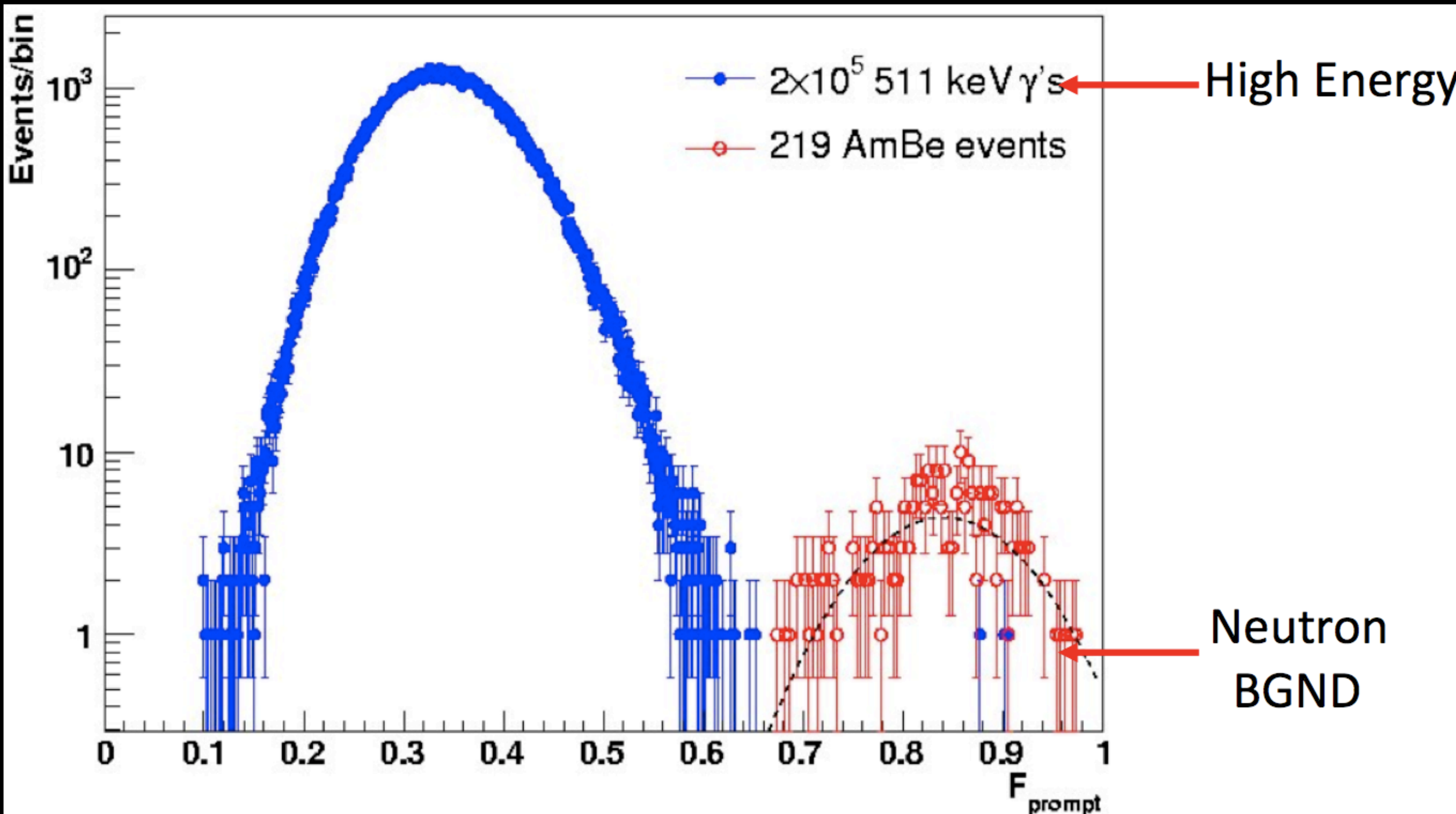


M.G.Boulay and A.Hime, *Astroparticle Physics* **25**, 179 (2006)

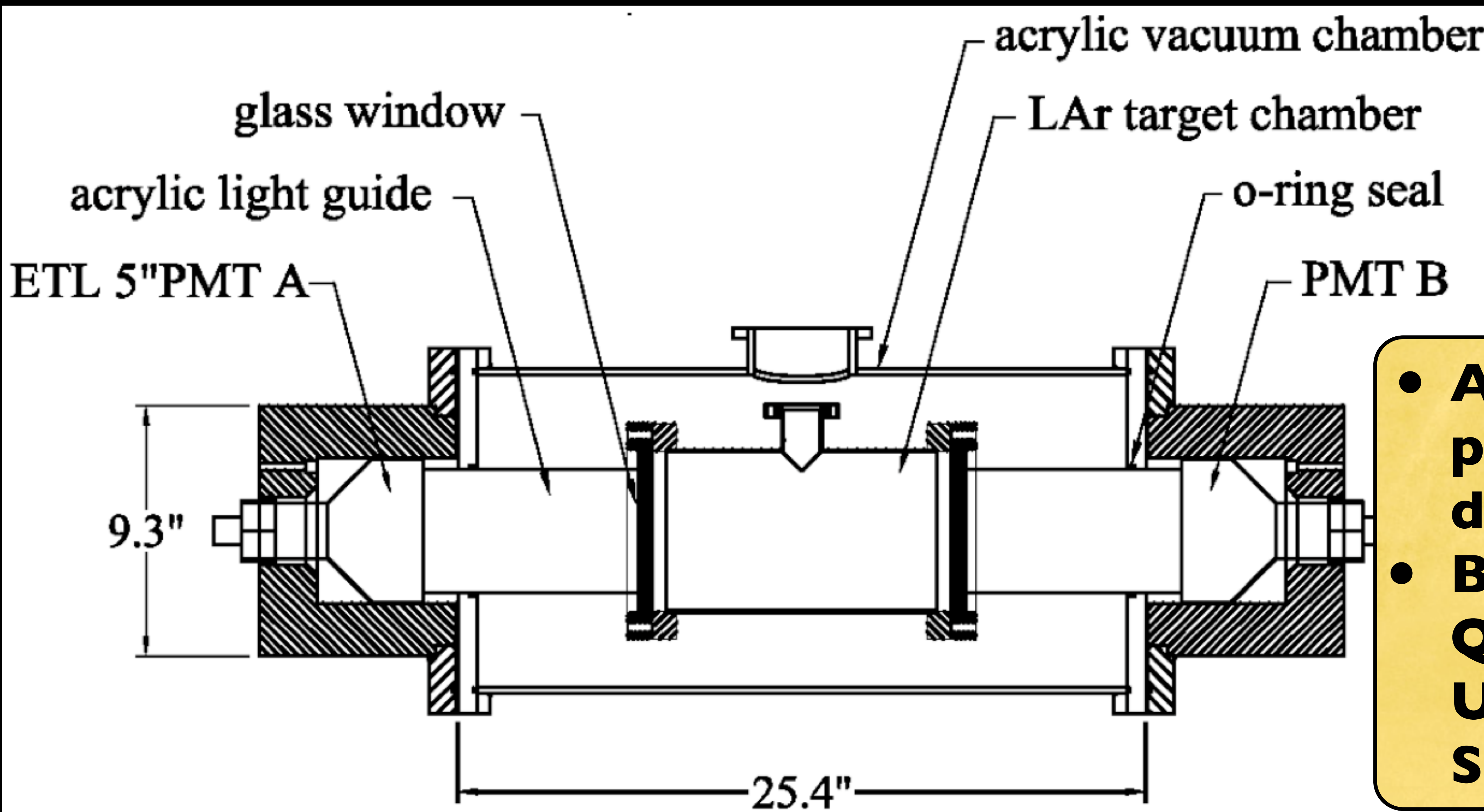
Background Discrimination



Background Discrimination



So we built DEAP-1...



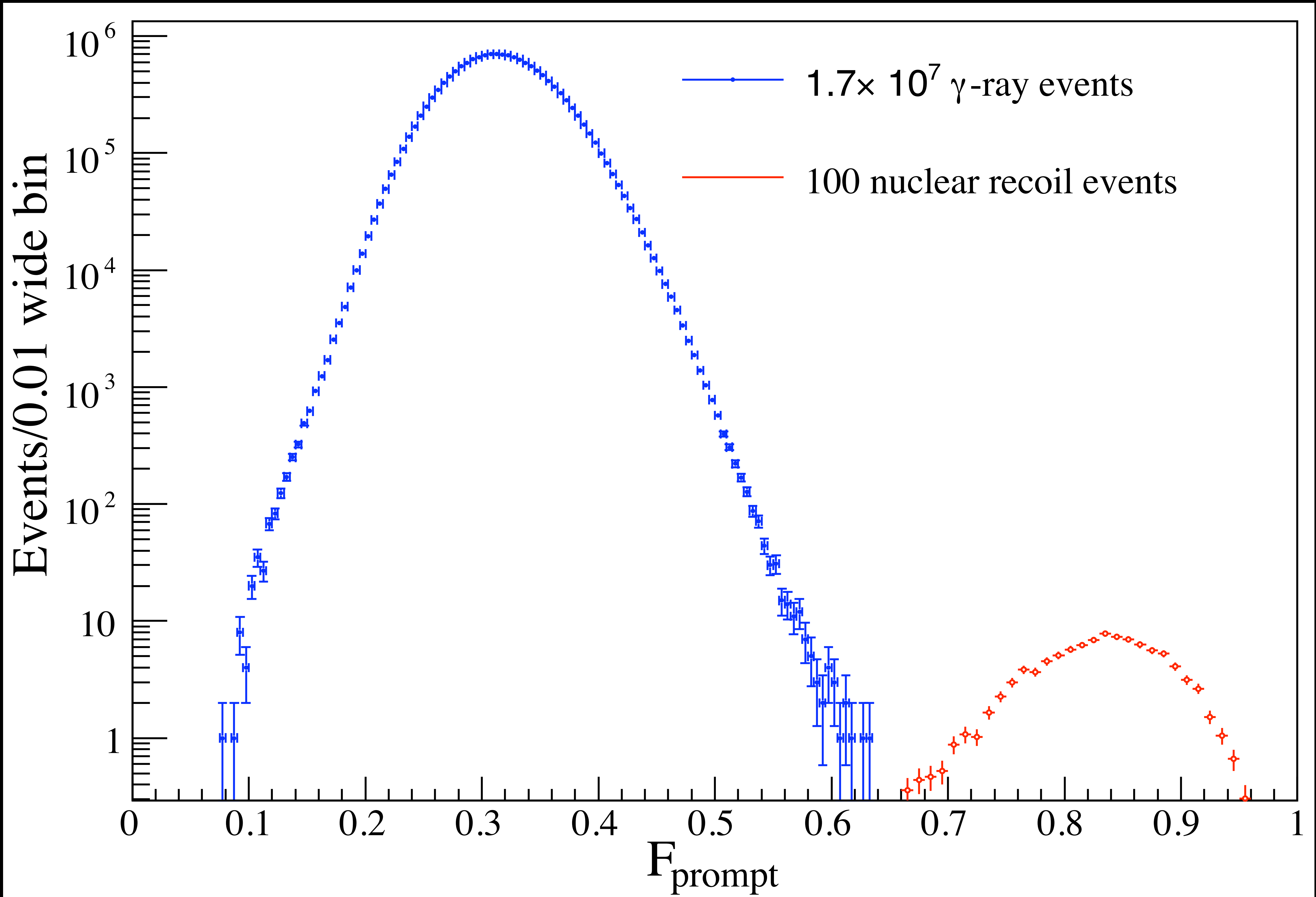
- **A 7-kg, single-phase LAr detector**
- **Built and run at Queen's University then SNOLab**

- Development of liquid Argon methods
- Demonstrate pulse shape discrimination experimentally
- Develop background reduction techniques
- Dark matter sensitivity to $\approx 10^{-44}$ cm^2 at 100 GeV


5 GAL/20L
5 GAL/20L
5 GAL/20L
5 GAL/20L
EMPTY
IN SERVICE
Nov 10/08
1900 psi
DEAP-1 and Pulse-Shape Discrimination in Liquid Argon
DEAP-1


Roughing pump will
not start under vacuum
PFEIFFER
VACUUM
5 GAL/20 L

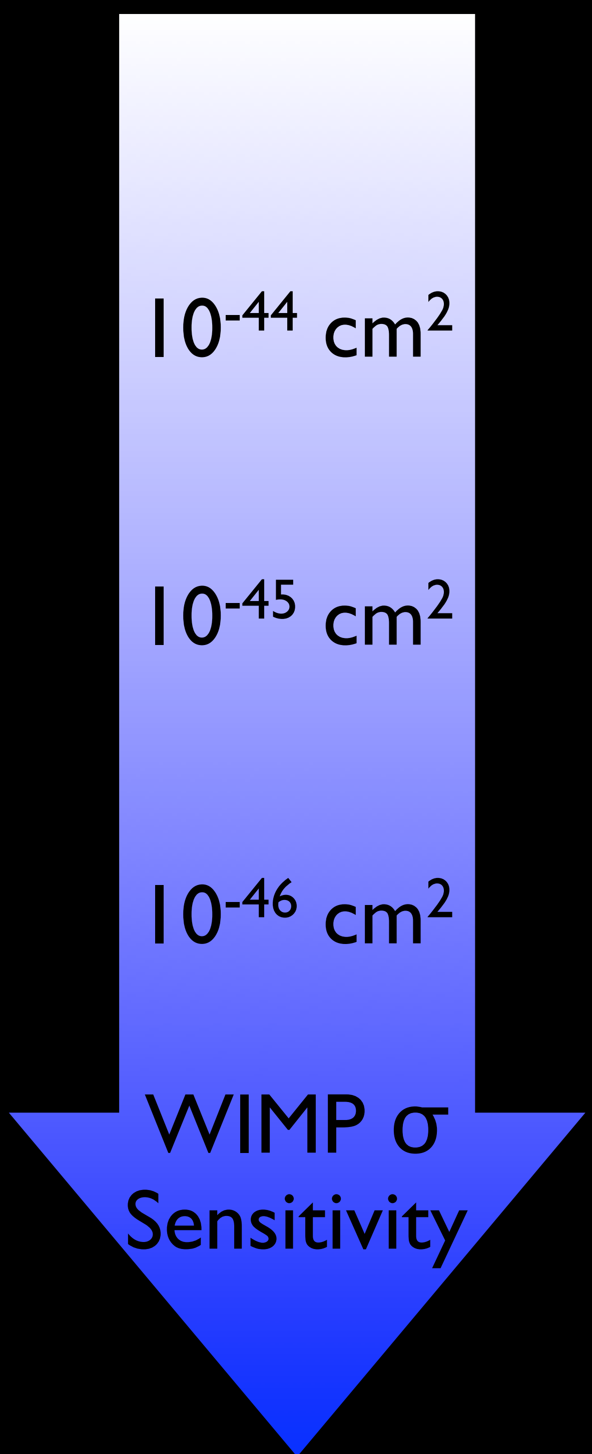
So we built DEAP-1...



MAJORANA and CLEAN/DEAP

Detector design

The CLEAN and DEAP Family of Detectors



DEAP-0:
Initial R&D detector

DEAP-1:
7 kg LAr
2 warm PMTs
At SNOLab 2008

DEAP-3600:
3600 kg LAr (1000 kg fiducial mass)
266 cold PMTs
At SNOLab late 2010

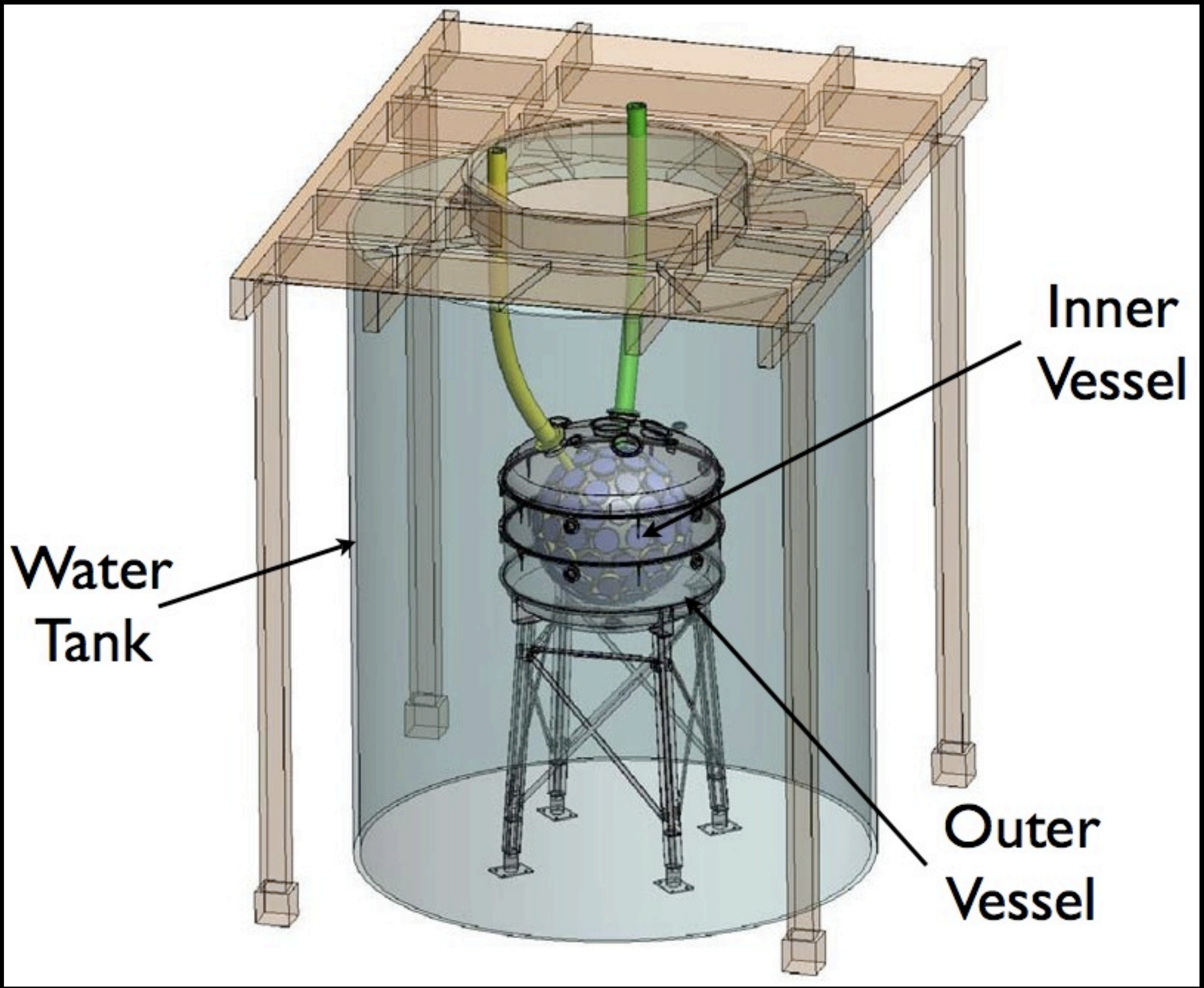
pico-CLEAN:
Initial R&D detector

Micro-CLEAN:
4 kg LAr or LNe
2 cold PMTs
surface tests at Yale

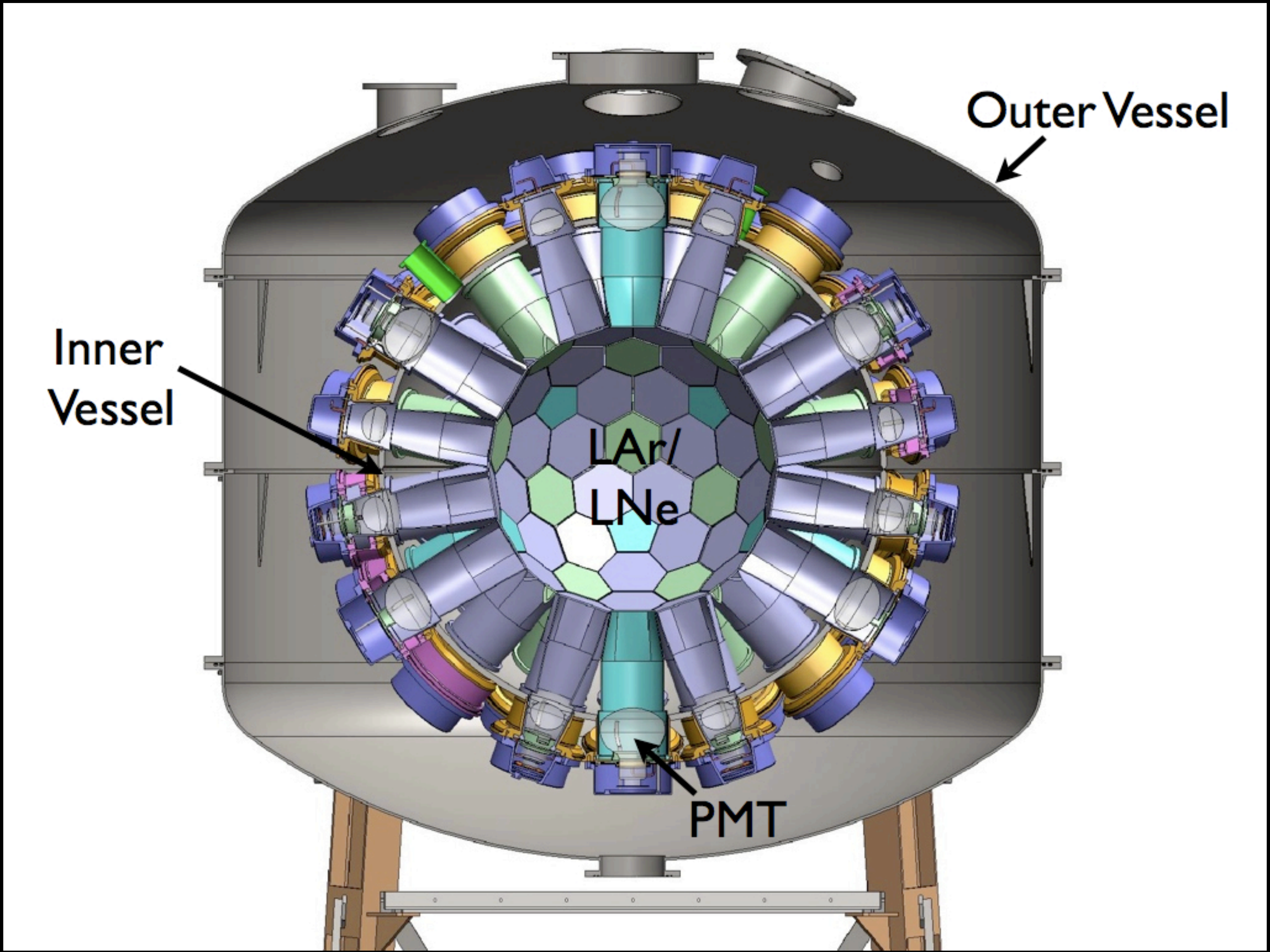
Mini-CLEAN:
400 kg LAr or LNe (150 kg fiducial mass)
92 cold PMTs
At SNOLab mid-2010

50-tonne LNe/LAr Detector:
pp-solar ν, supernova ν, dark matter $<10^{-46}$ cm^2
At DUSEL ~2012

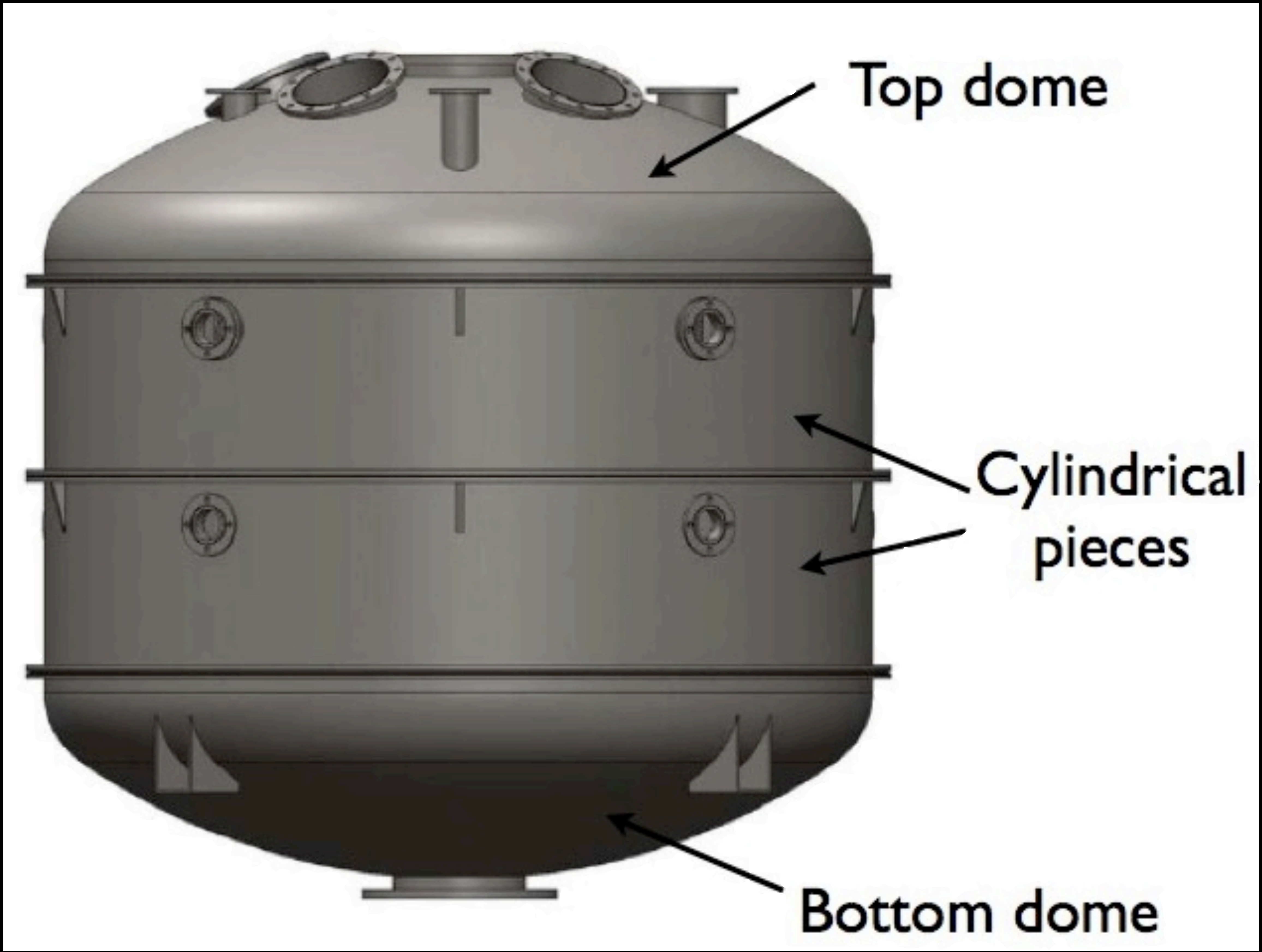
Building Mini-CLEAN



Building Mini-CLEAN



Building Mini-CLEAN



Building Mini-CLEAN

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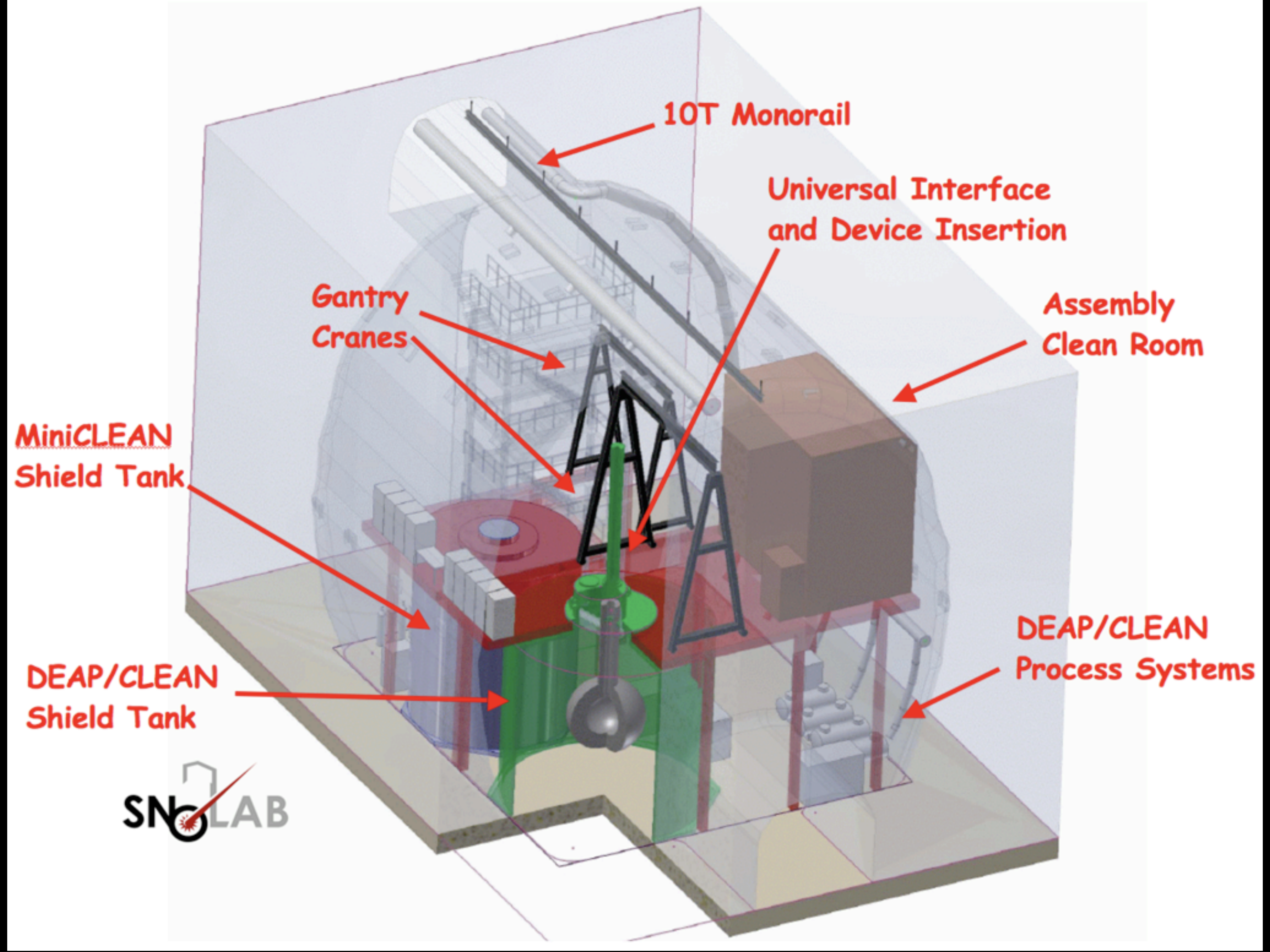
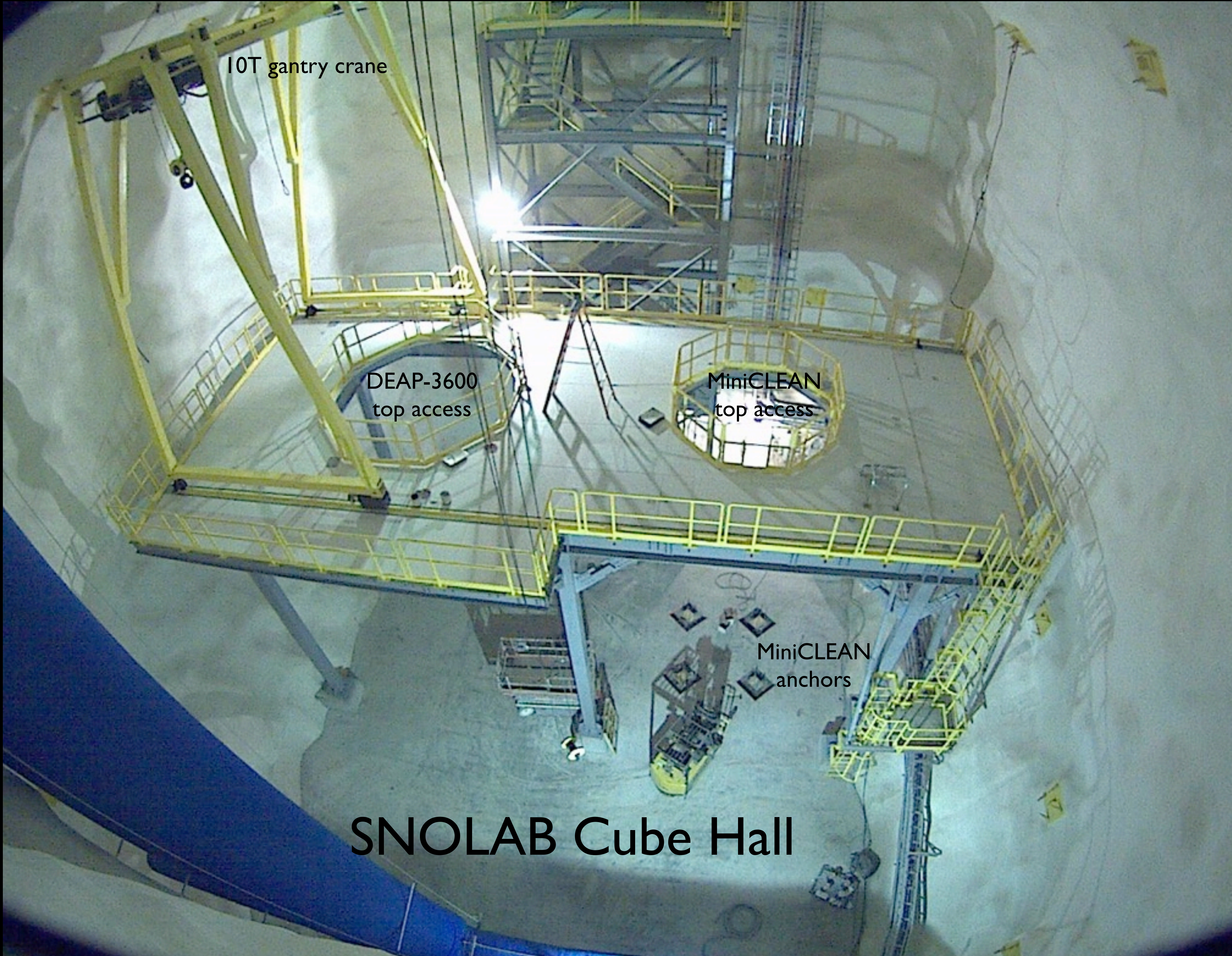
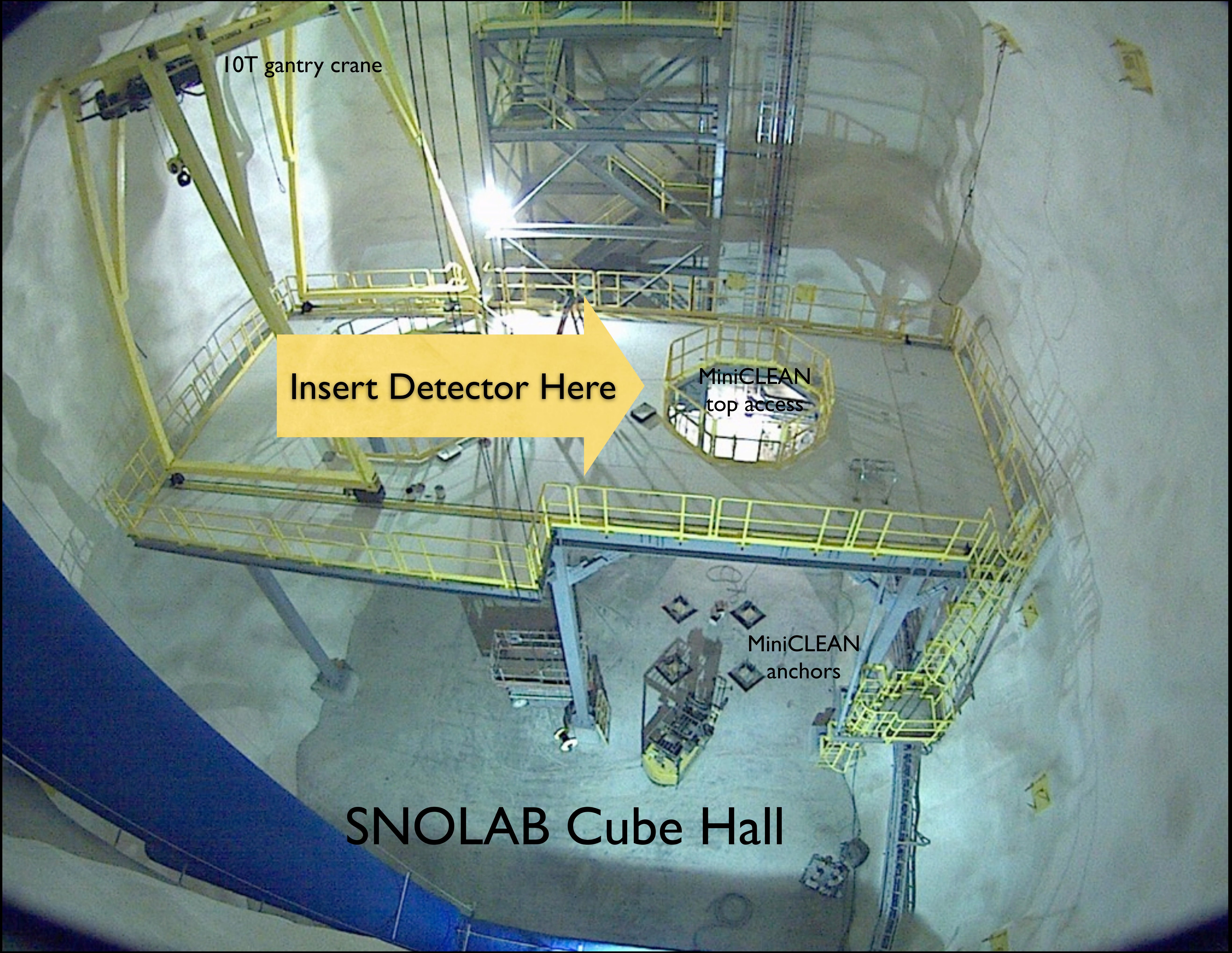
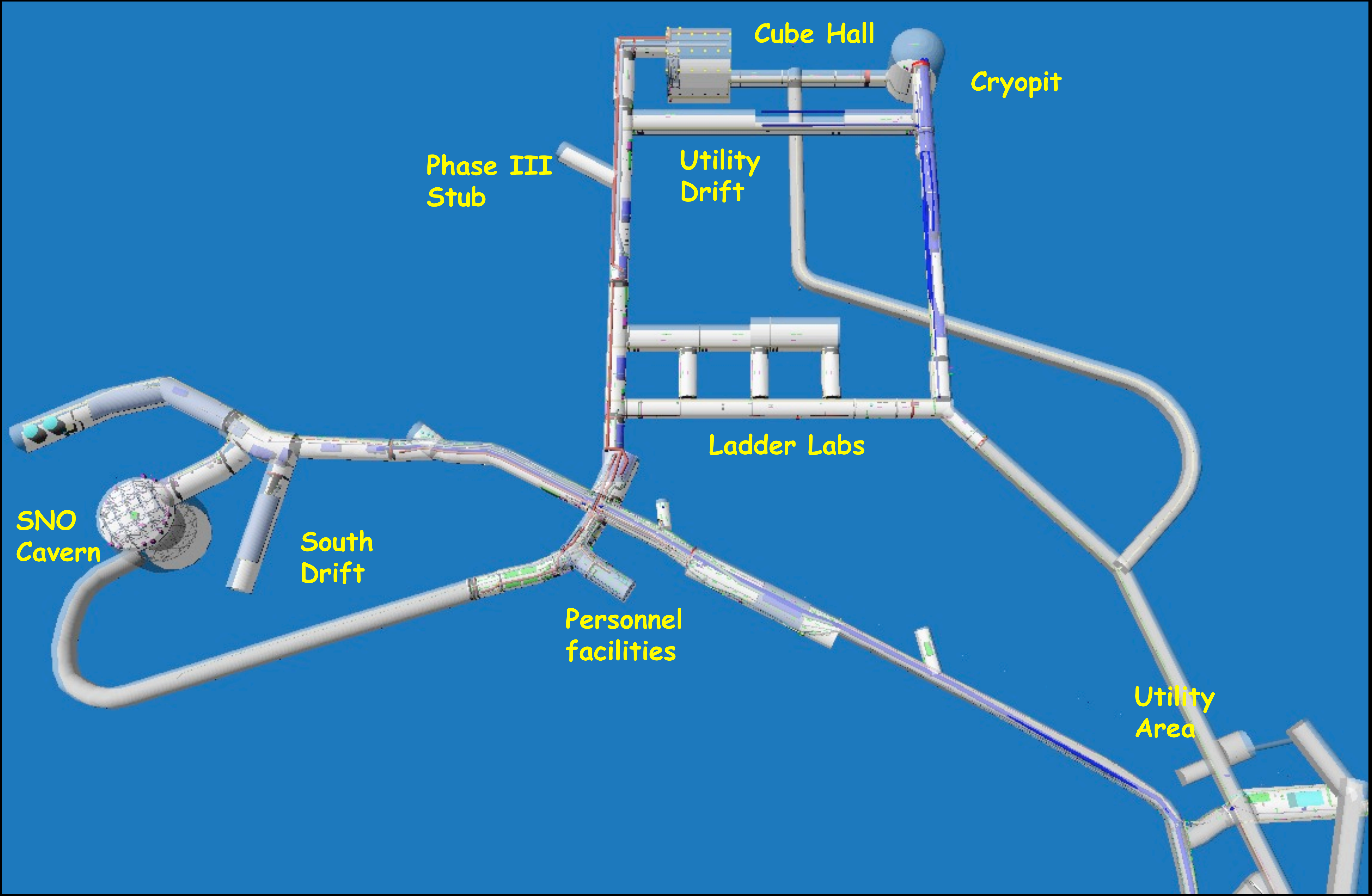

10T Monorail
Universal Interface
and Device Insertion
Gantry
Cranes
Assembly
Clean Room
MiniCLEAN
Shield Tank
DEAP/CLEAN
Shield Tank
DEAP/CLEAN
Process Systems
SNOLAB


Cube Hall at SNOLAB


10T gantry crane
DEAP-3600
top access
MiniCLEAN
top access
MiniCLEAN
anchors
SNOLAB Cube Hall


10T gantry crane
Insert Detector Here
MiniCLEAN
top access
MiniCLEAN
anchors
SNOLAB Cube Hall


Cube Hall
Cryopit
Phase III Stub
Utility Drift
Ladder Labs
SNO Cavern
South Drift
Personnel facilities
Utility Area

CLEAN/DEAP Collaboration

University of Alberta
Aksel Hallin
Boston University
Ed Kearns
Carleton University
Kevin Graham
Harvard University
John Doyle
Los Alamos National Laboratory
Andrew Hime
MIT
Joe Formaggio and Jocelyn Monroe
NIST - Boulder
Kevin Coakley
University of New Mexico
Dinesh Loomba

University of North Carolina
Reyco Henning
University of Pennsylvania
Josh Klein
Queens University
Mark Boulay and Art McDonald
University of South Dakota
Dongming Mei
SNOLab
Fraser Duncan
Syracuse University
Richard Schnee
TRIUMF
Fabrice Retrieve
Yale University
Dan McKinsey

16 Institutions with ~80 Participants
Institutional Representitives, Scientists (Postdocs and Students), Engineers and Technicians

MAJORANA and CLEAN/DEAP

Recent R&D Progress

MAJORANA R&D

- Background Modeling: Alexis Schubert (B8.00003)
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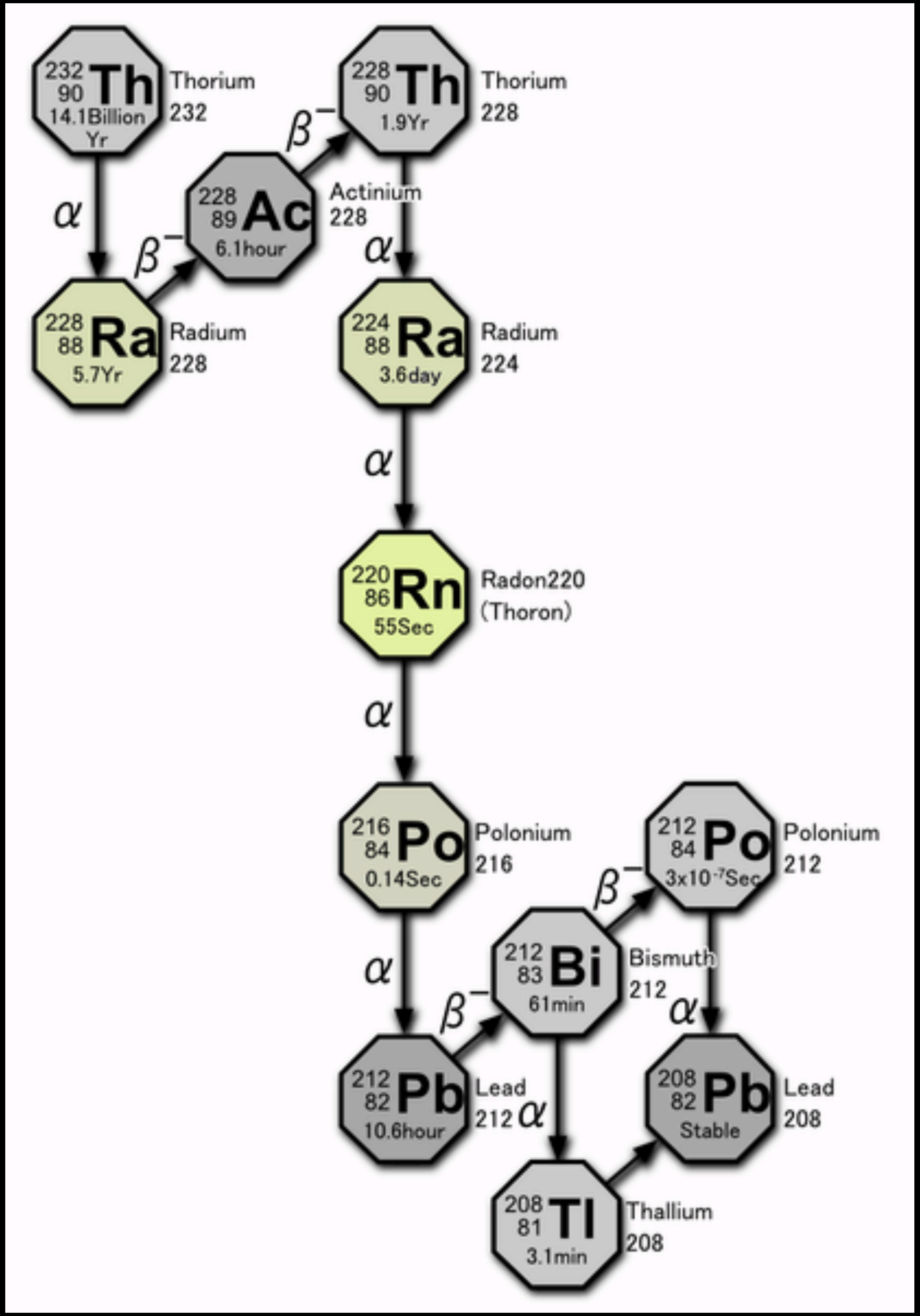

From my APS talk ~2 weeks ago...

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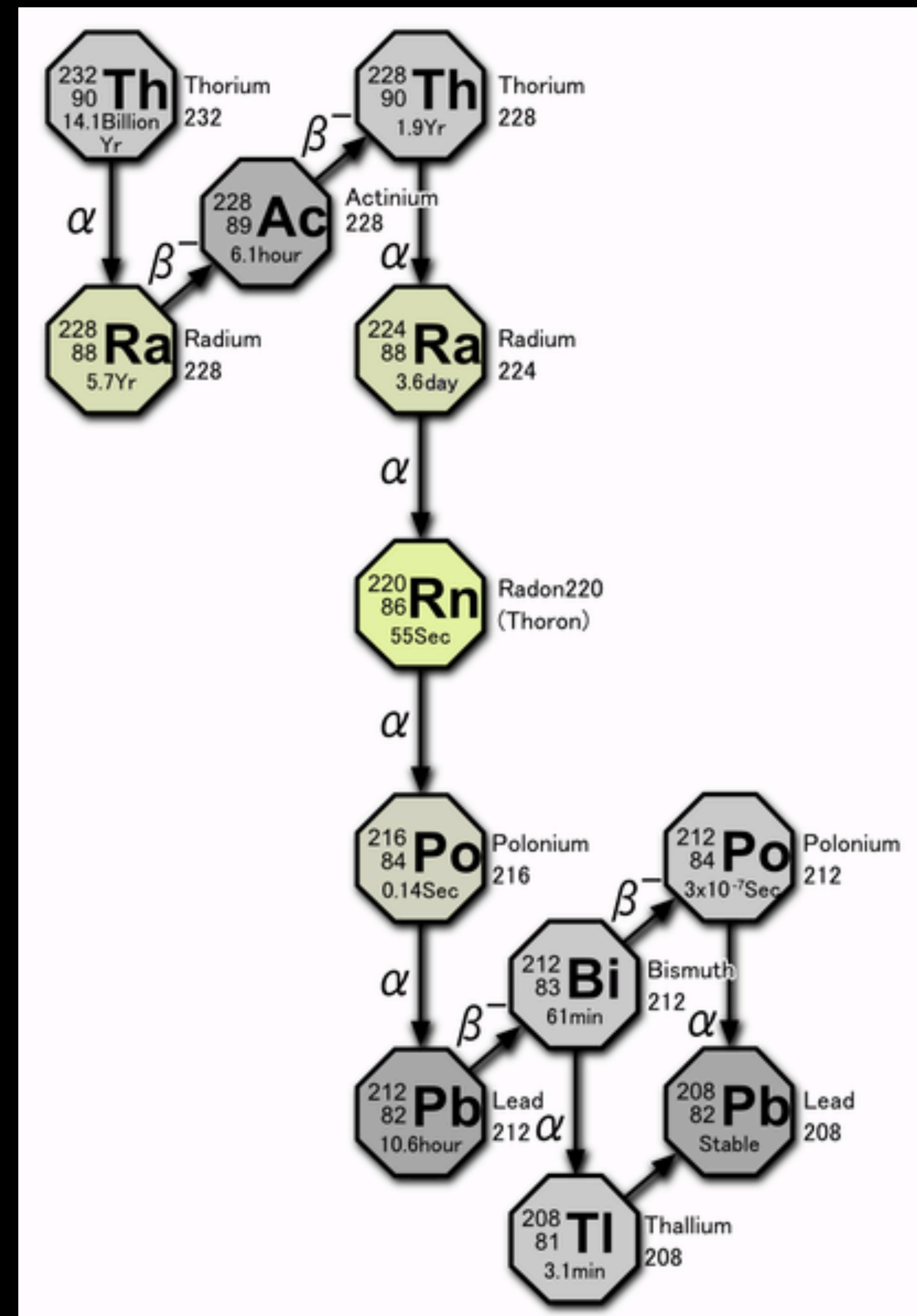

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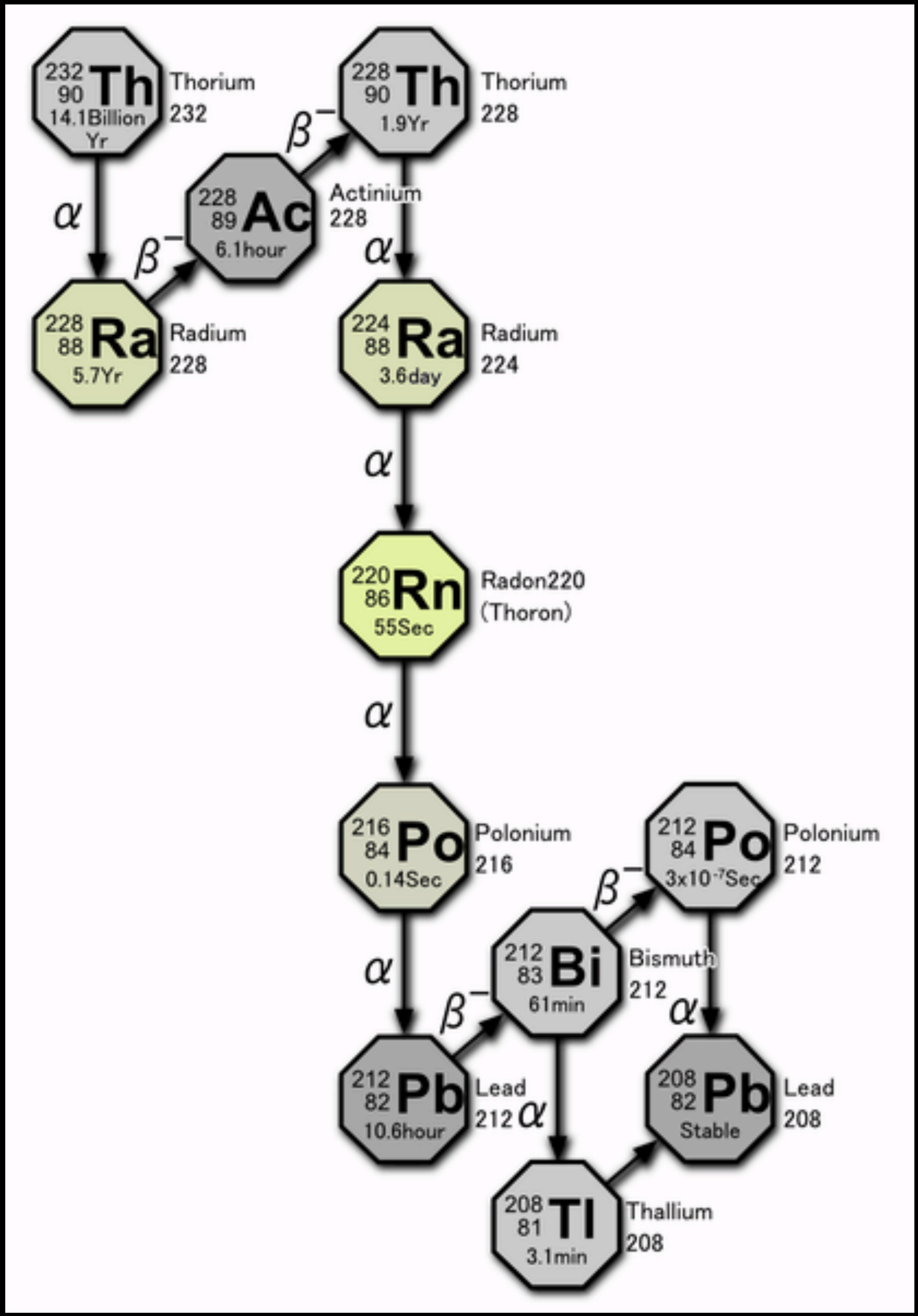

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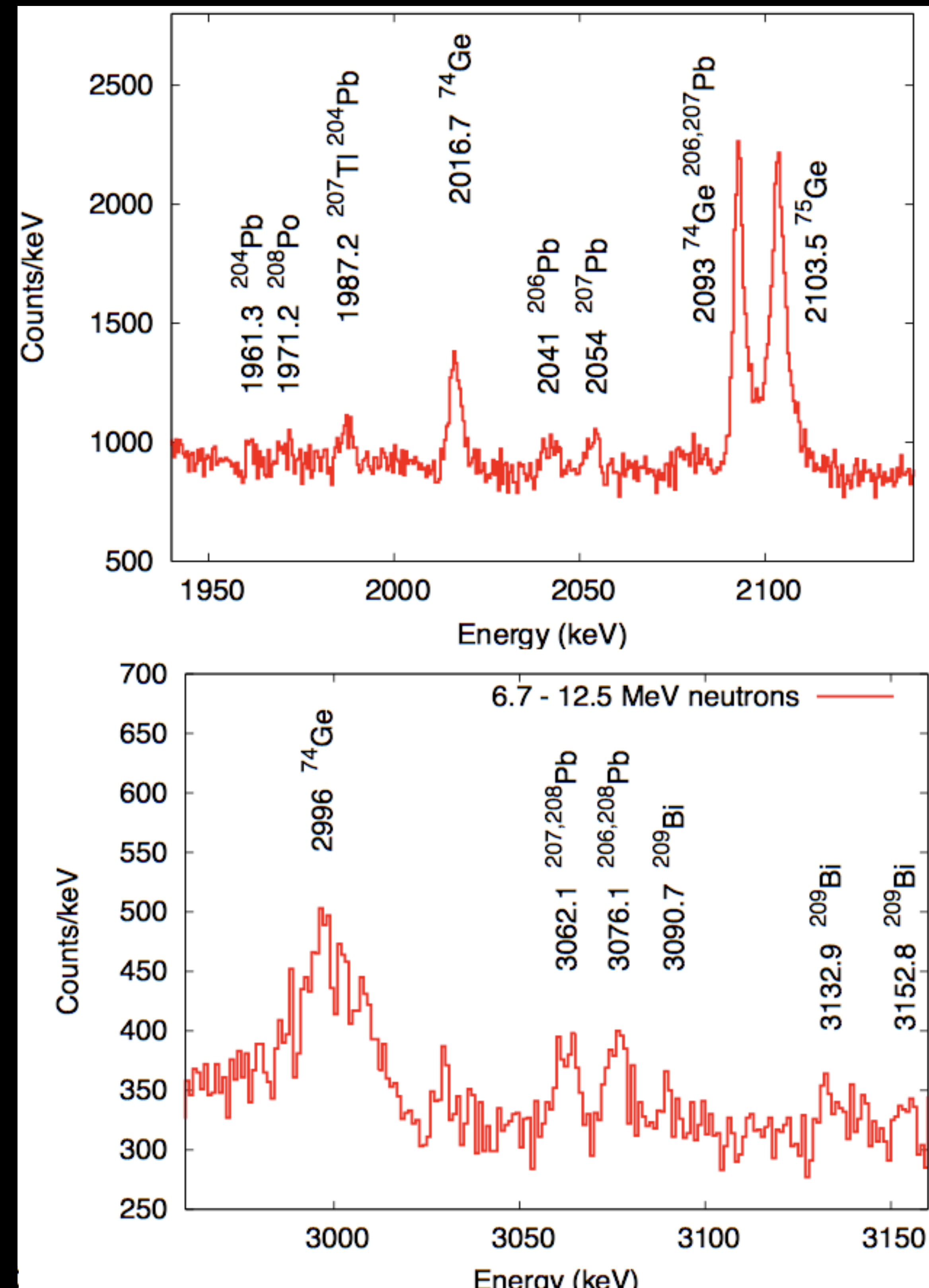

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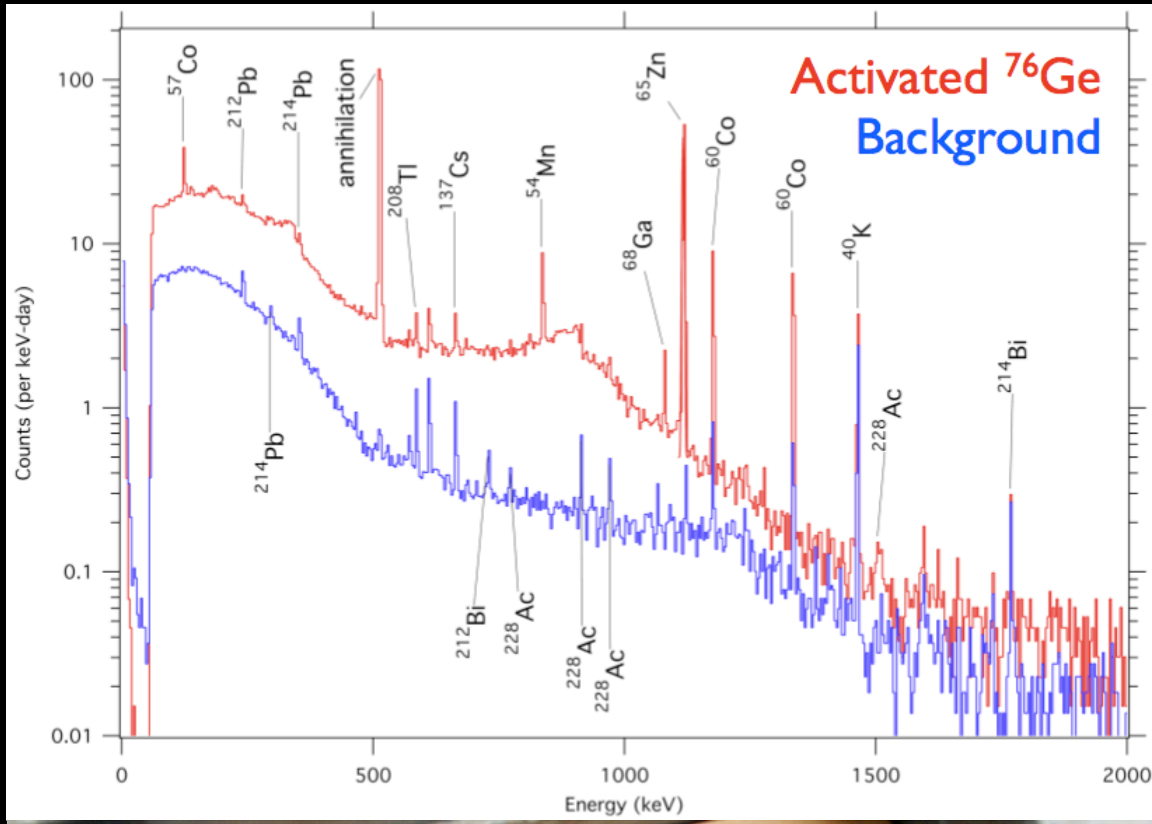

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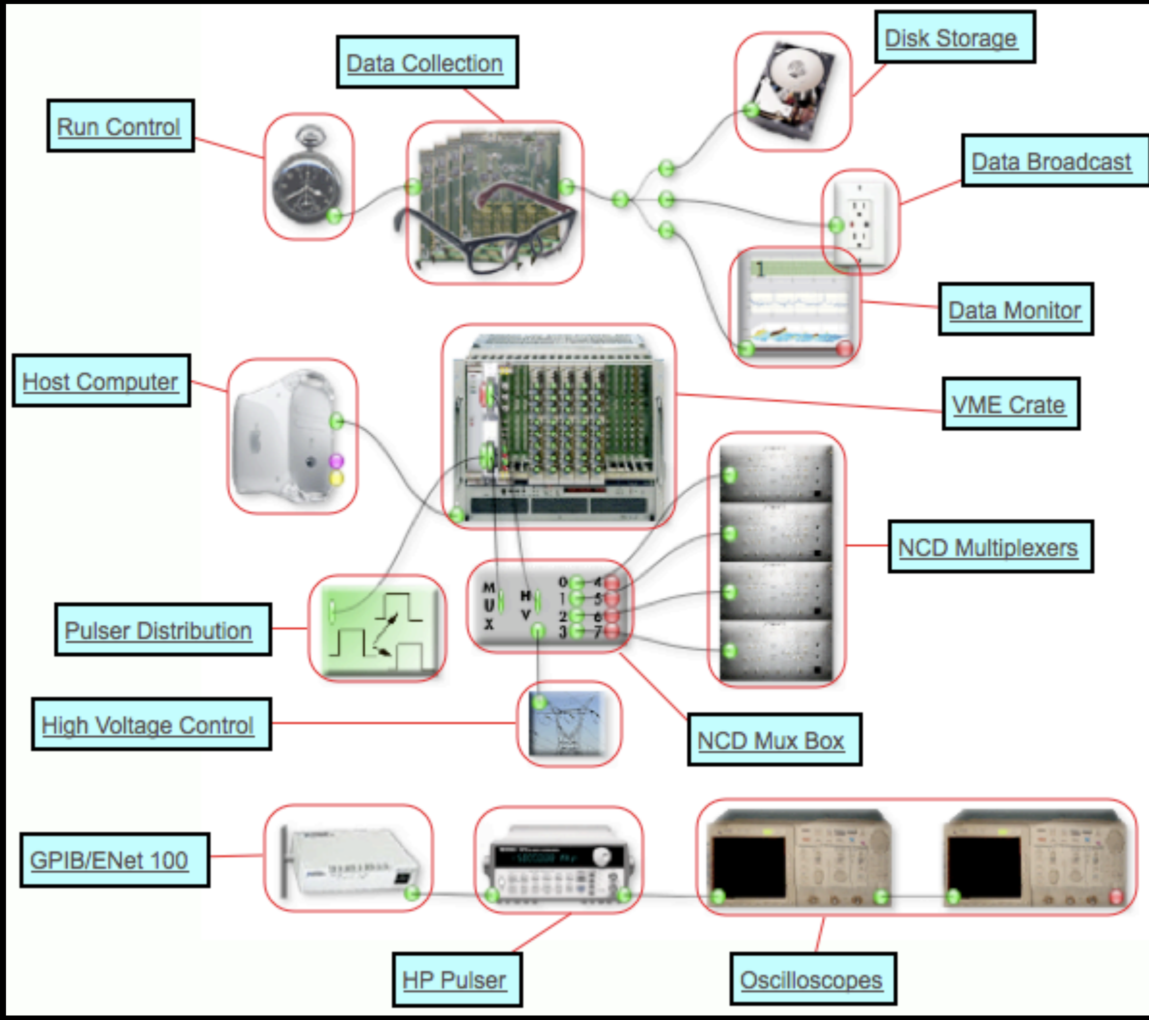

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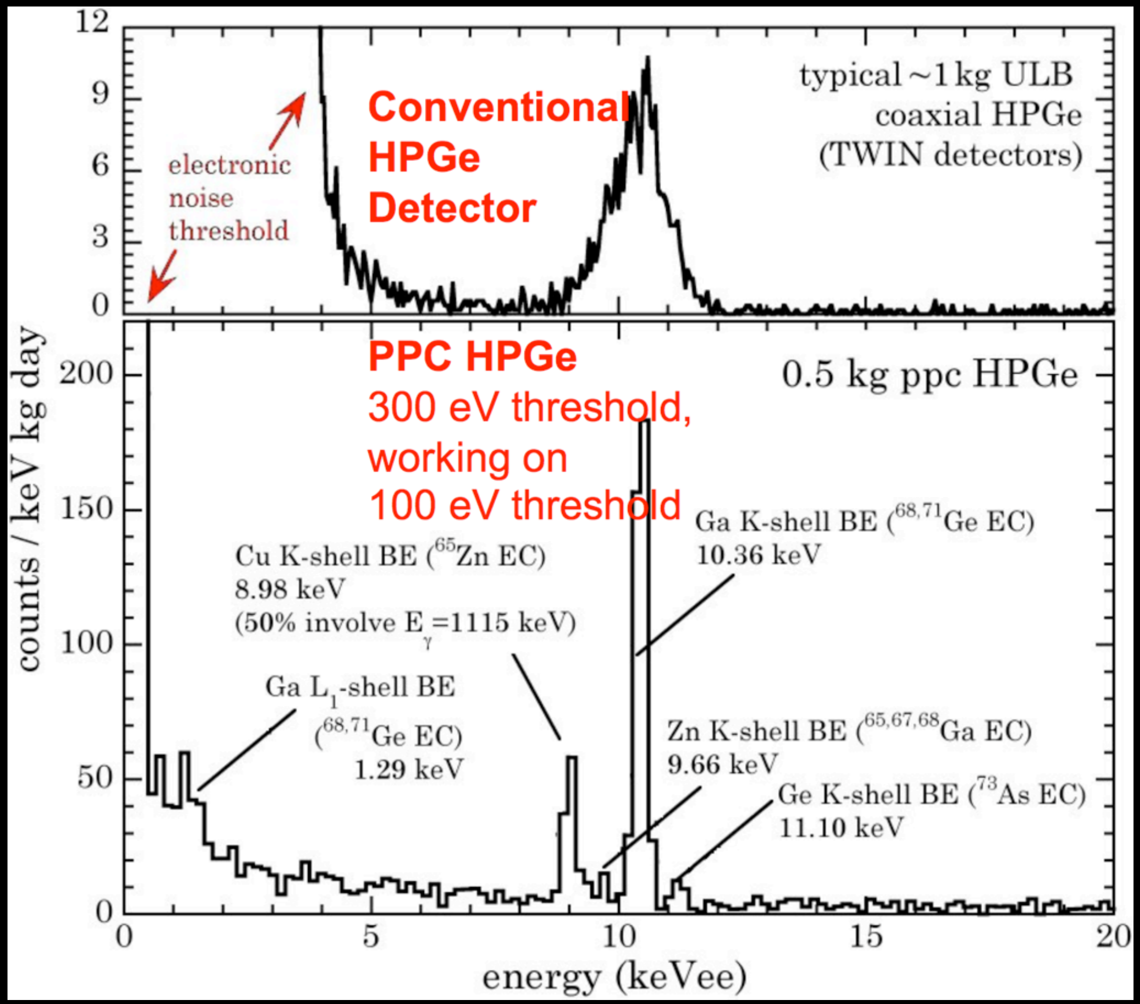

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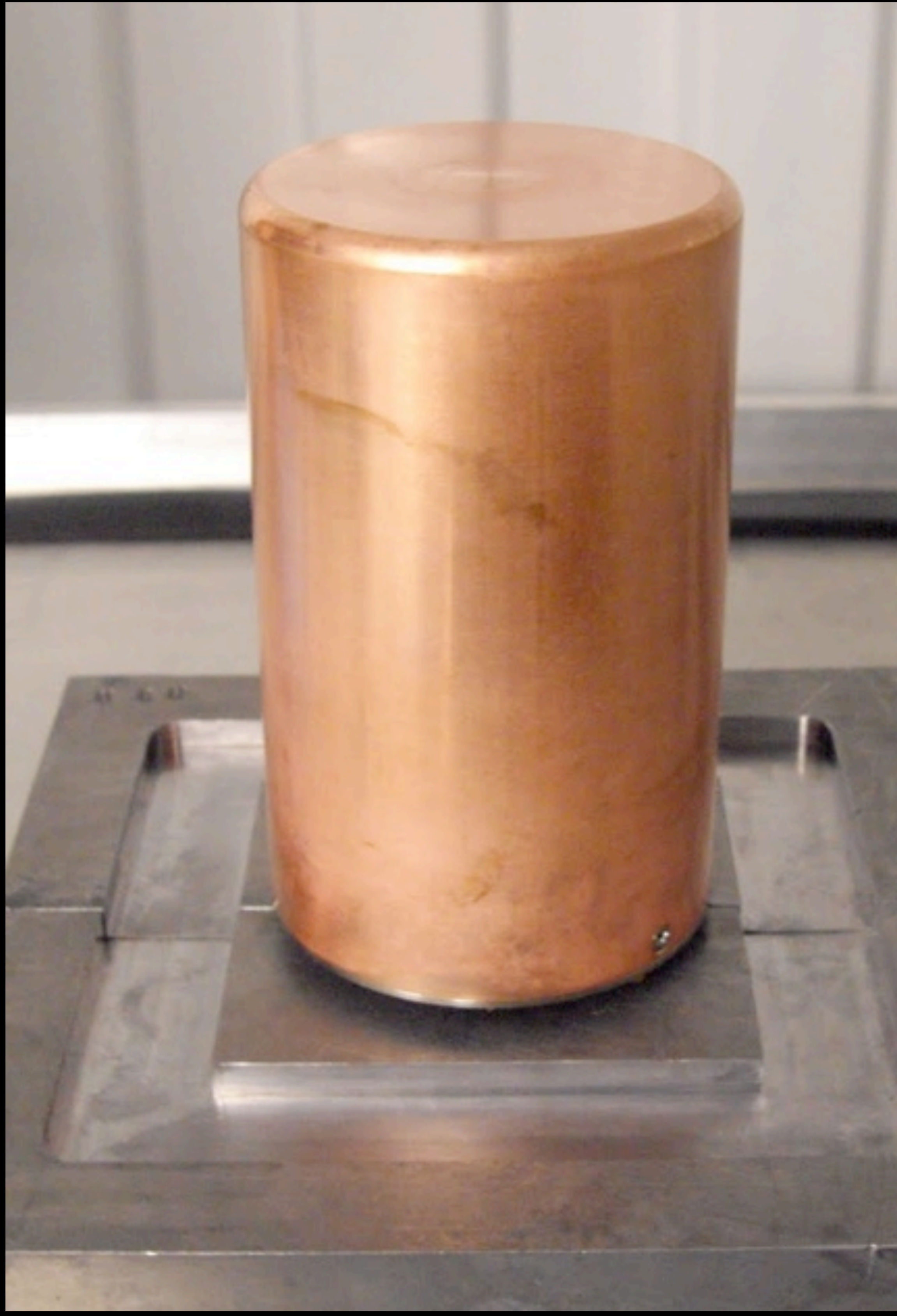
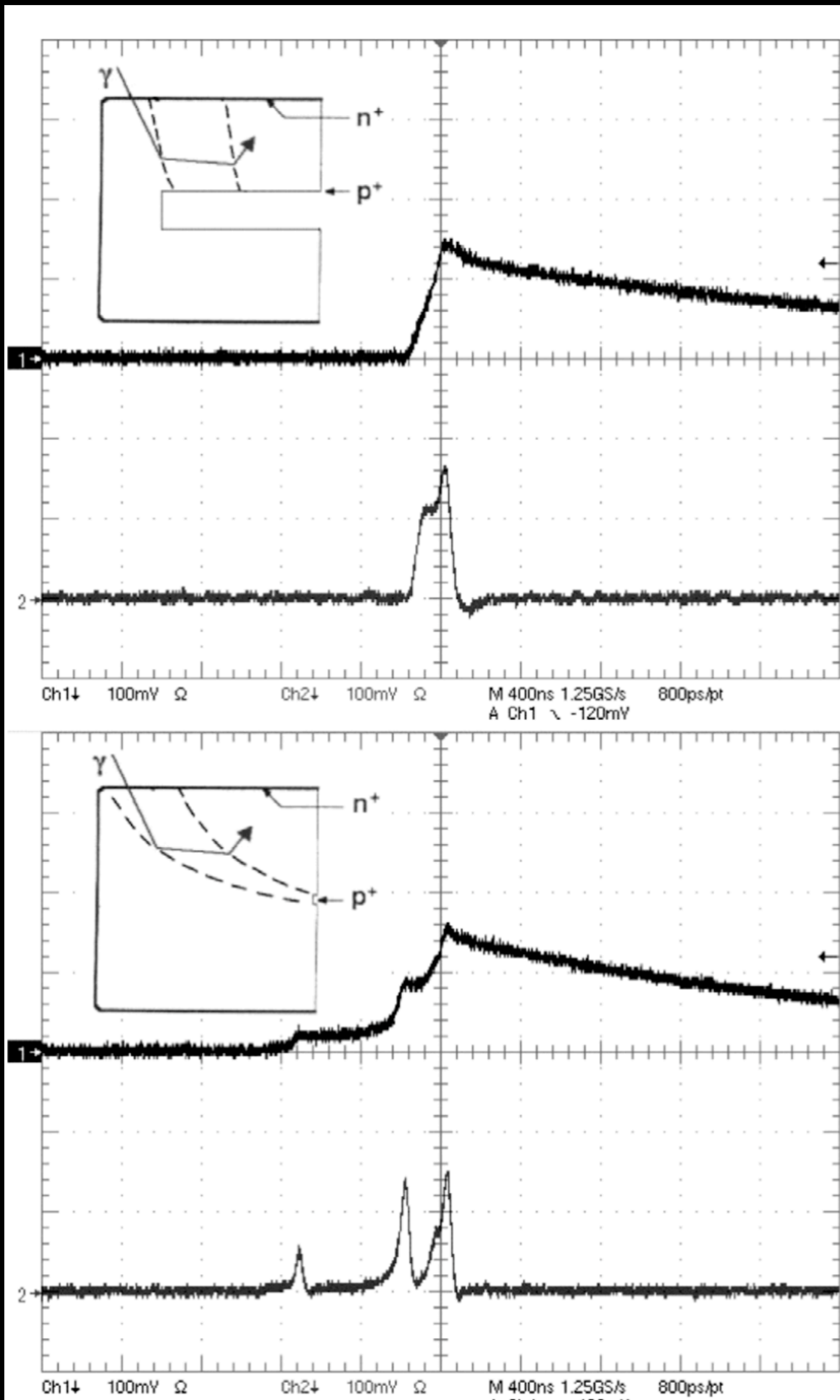


MAJORANA Detectors: PPC



- P-type = simpler to fabricate/handle/instrument
- Compact electrode geometry increases drift times--clearly indicates multiple-site events

MAJORANA Detectors: PPC

Barbeau et al., JCAP **09** (2007) 009
Luke et al., IEEE trans. Nucl. Sci. **36** , 926 (1989)

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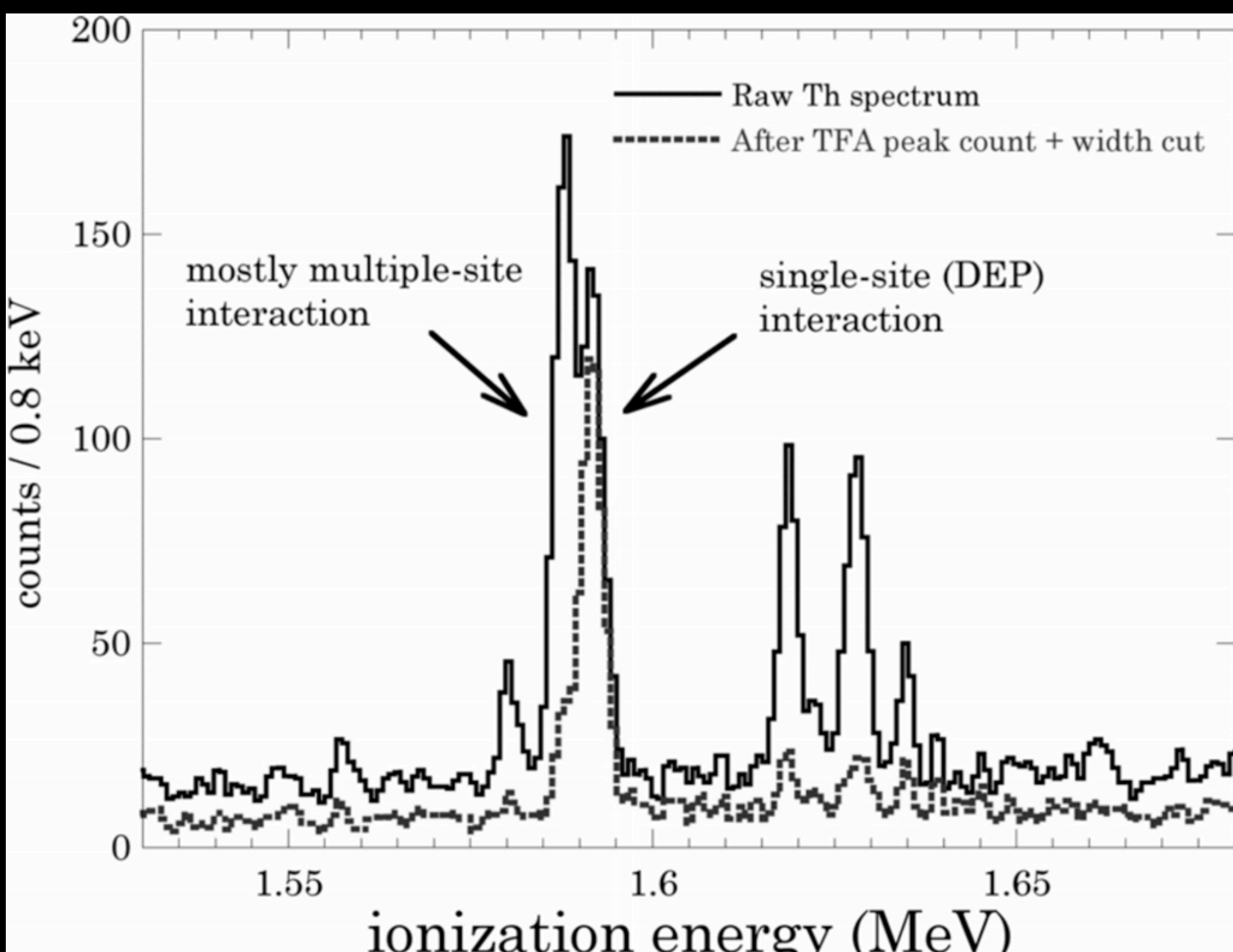

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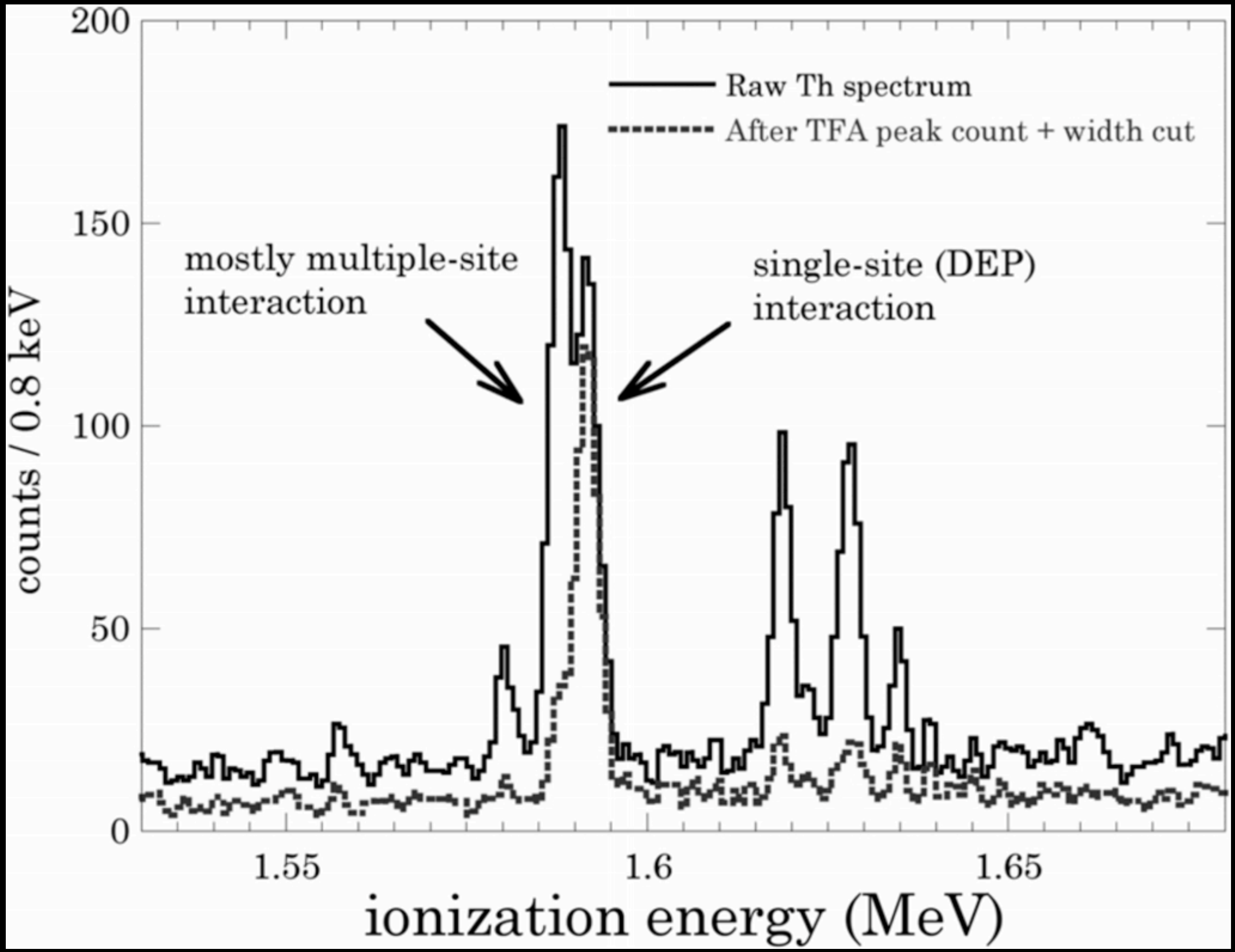
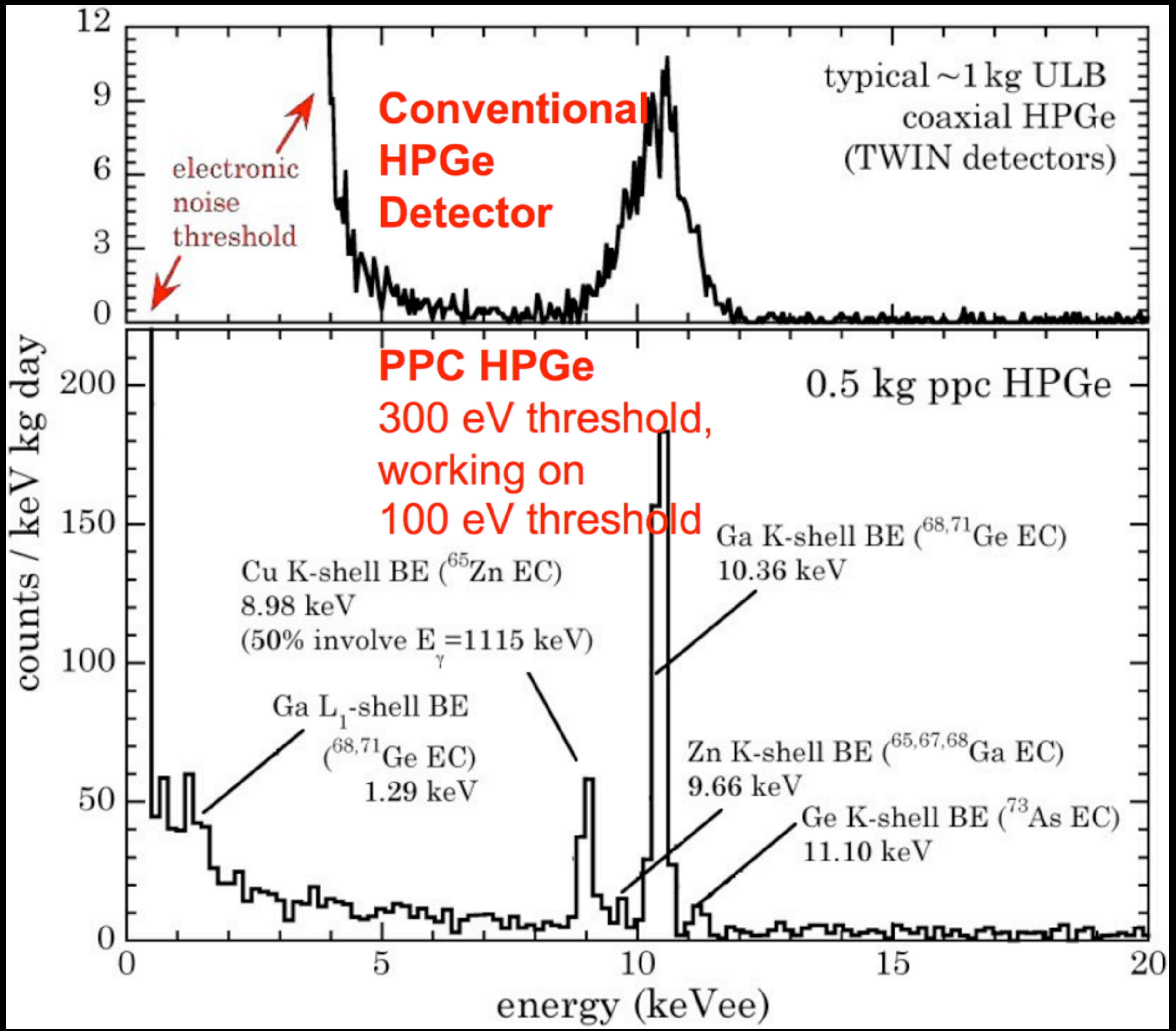
- P-type = simpler to fabricate/handle/instrument
- Compact electrode geometry increases drift times--clearly indicates multiple-site events
- Similar background rejection to highly-segmented detectors without added complexity/backgrounds
- Very low energy threshold (sub keV) allows for additional physics reach (e.g. dark matter, axions)





The BEGe's

- Broad Energy Ge (BEGe) detectors
- PPC-like detectors, 7 cm (dia.) x 3 cm
- Our BEGes have some modifications from standard

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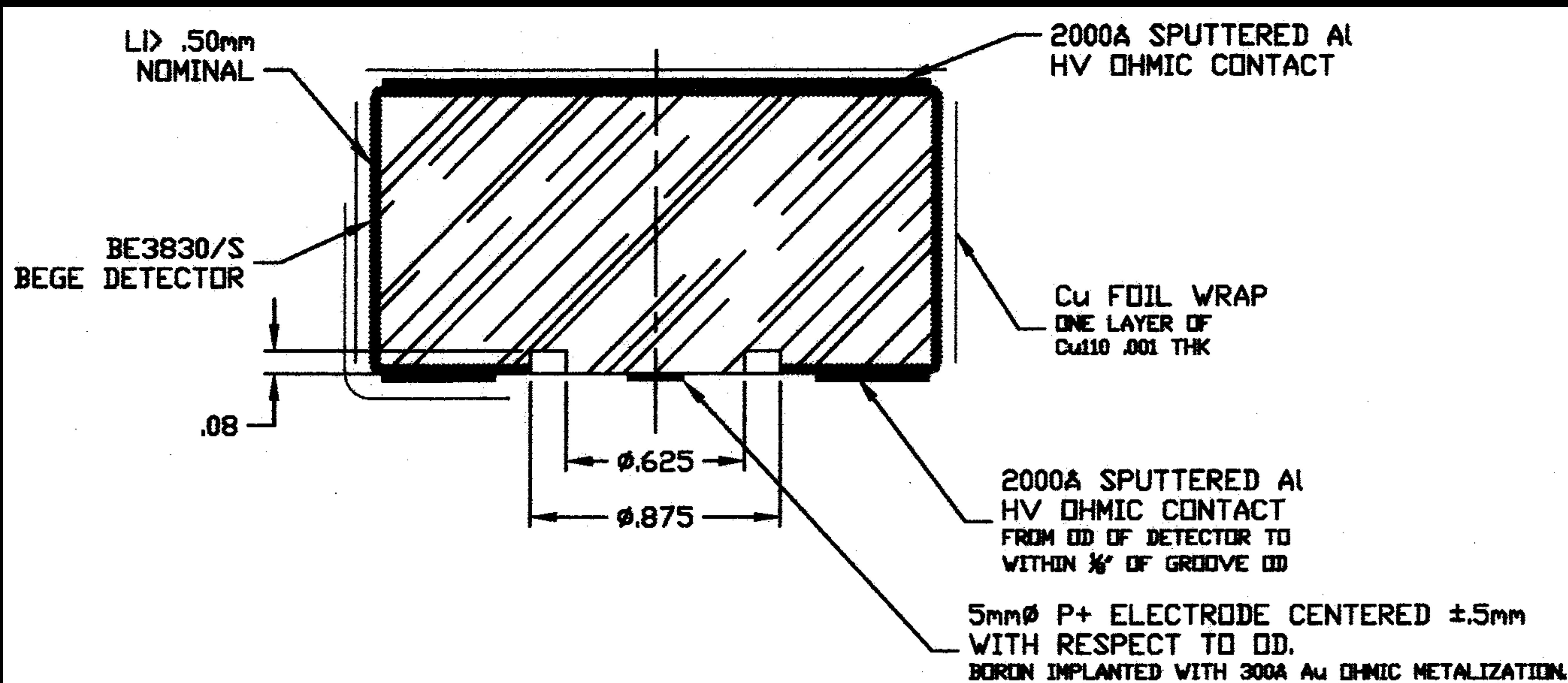

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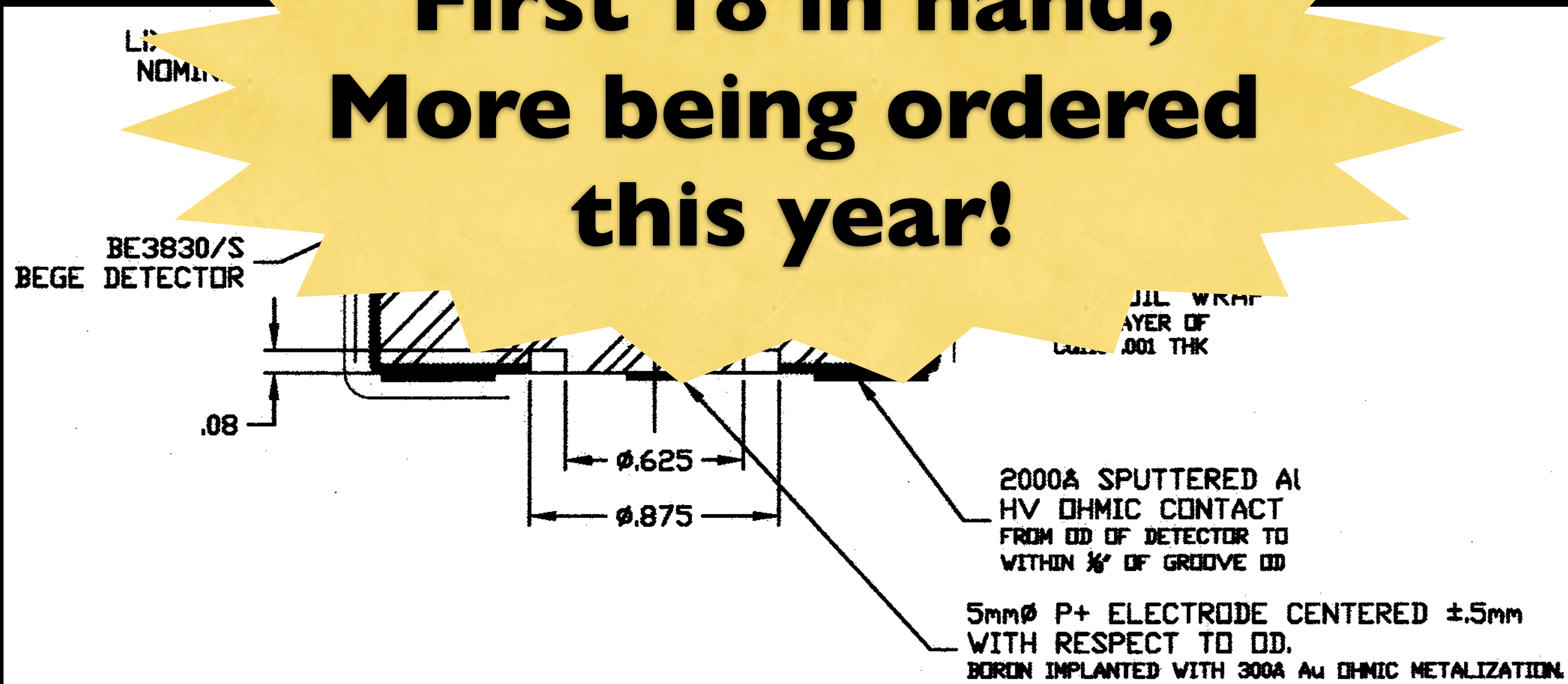
First 18 in hand,
More being ordered
this year!



Good Results

All detectors are in hand and have been examined for acceptance!

Good Results

- Leakage currents vary from: 0.5 - 17.0 pA
- Capacitances from: 1.0 - 1.8 pF
- FWHM at 1332.5 keV from: 1.6 - 2.5 keV
- First nine detectors out of their cryostats in storage

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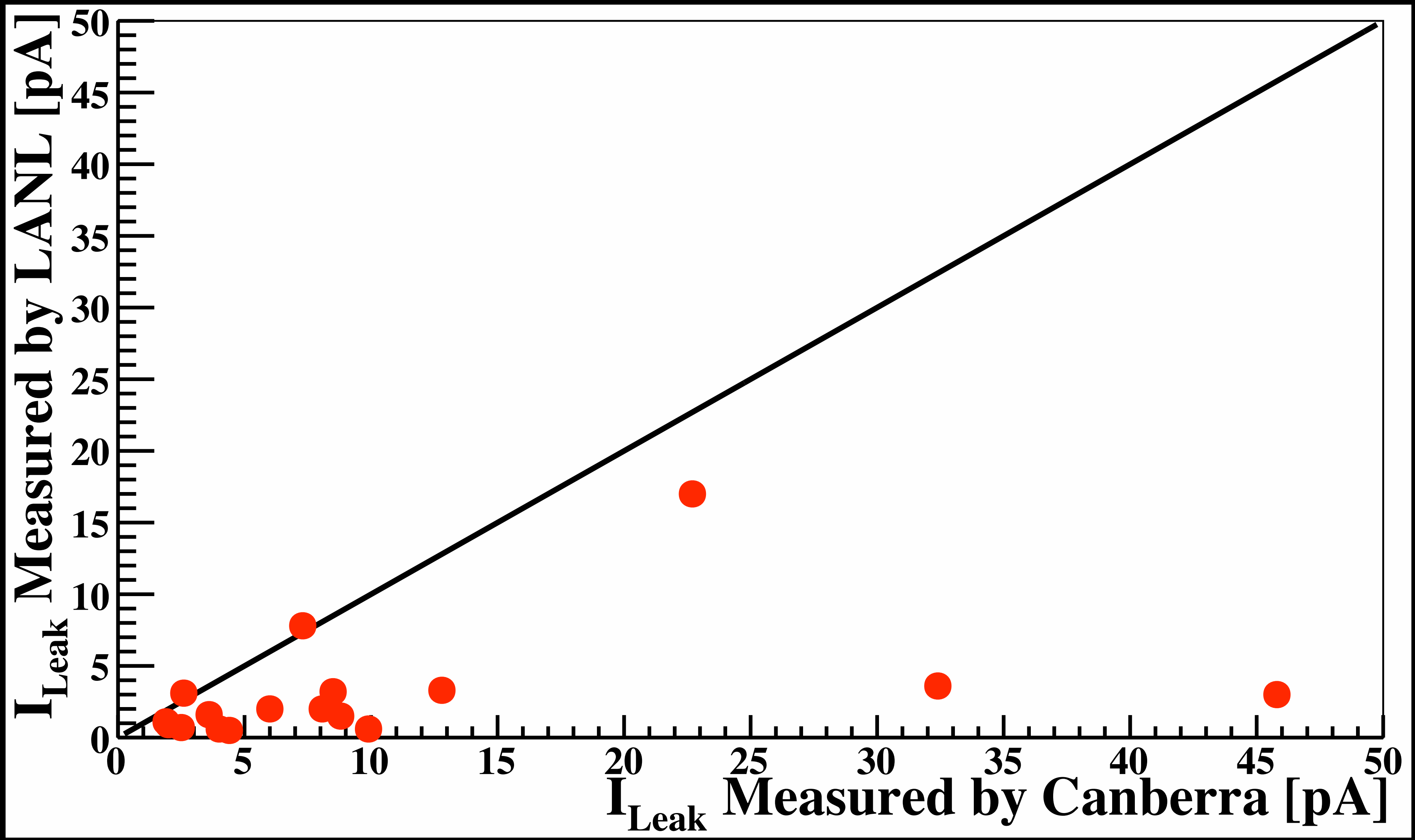

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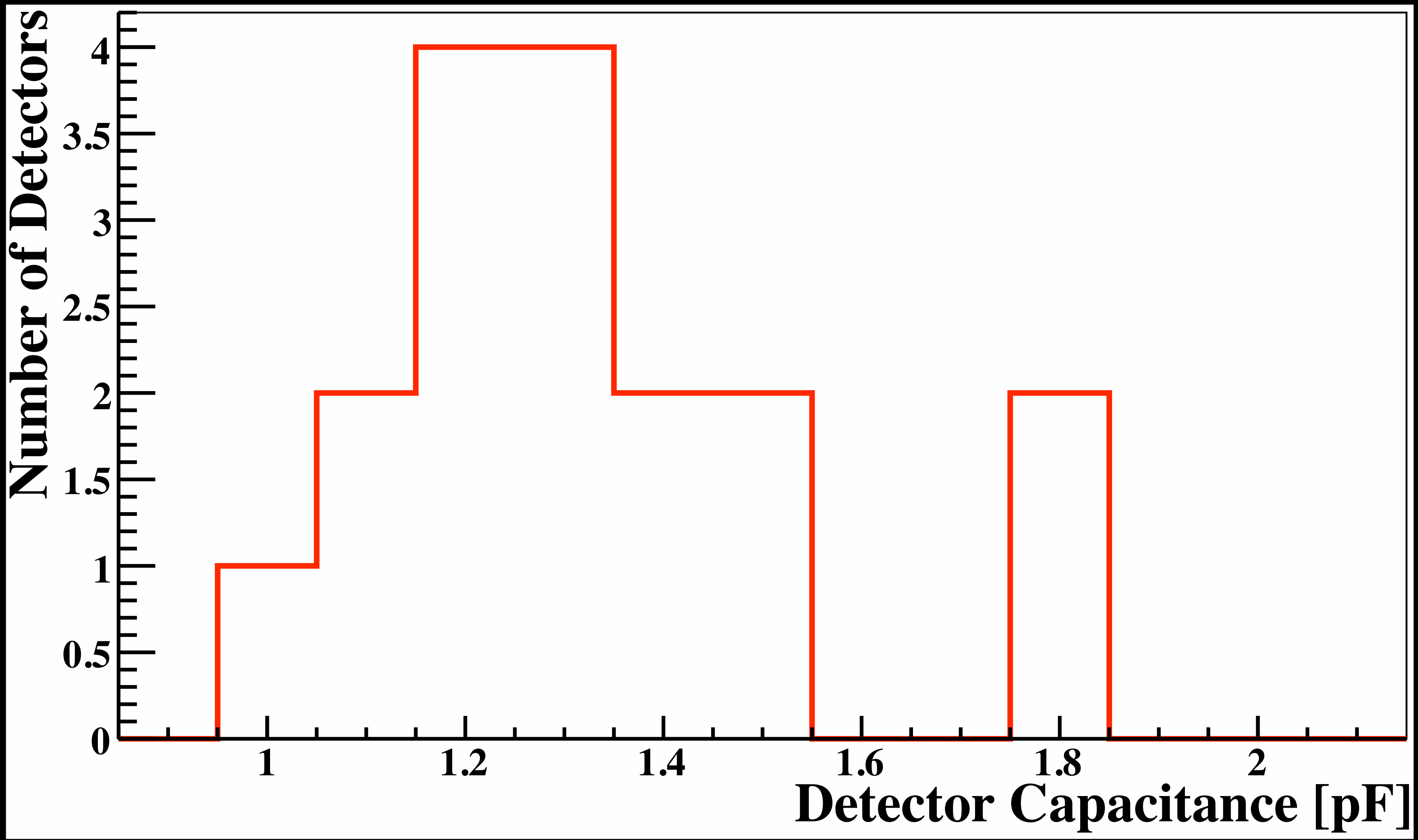

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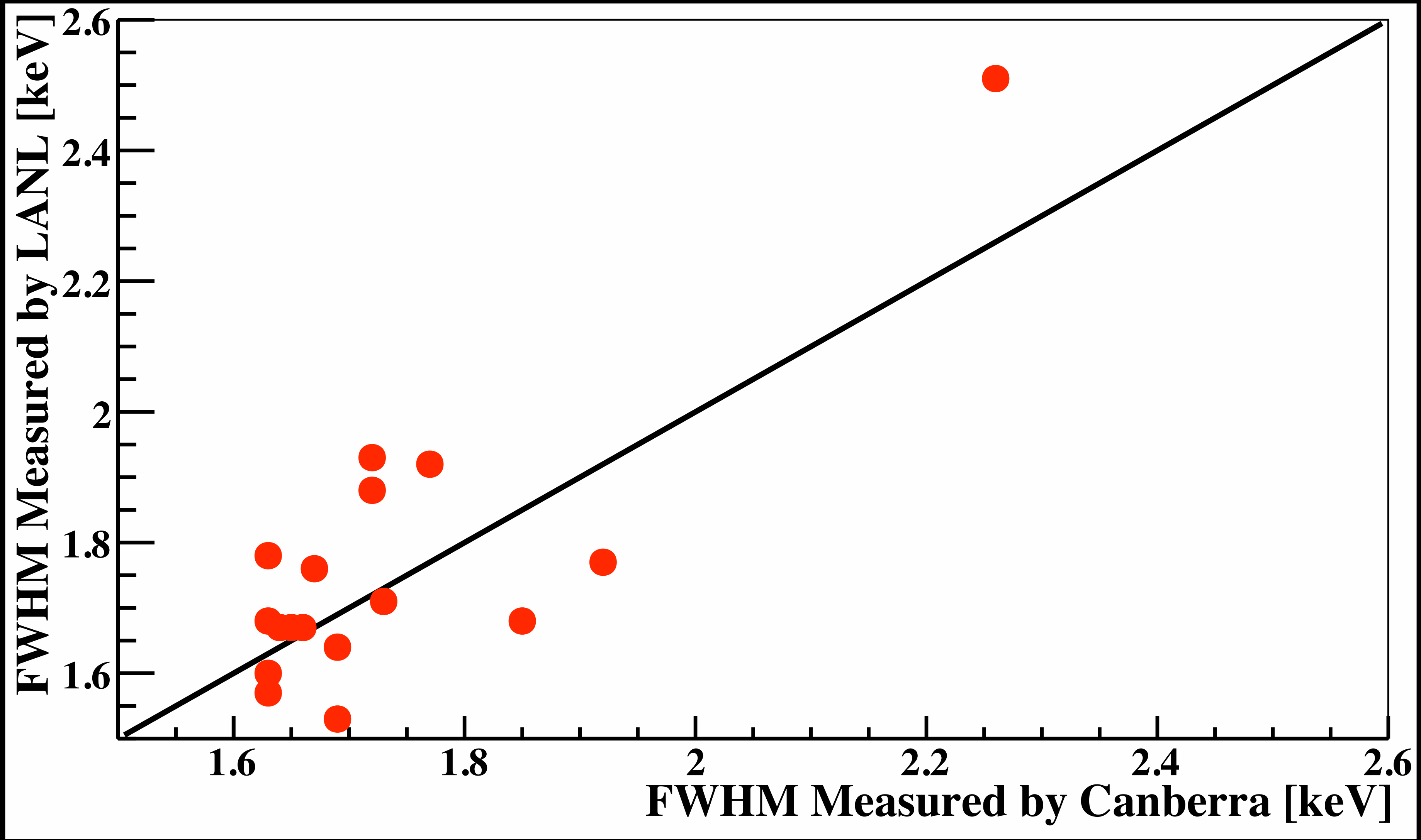
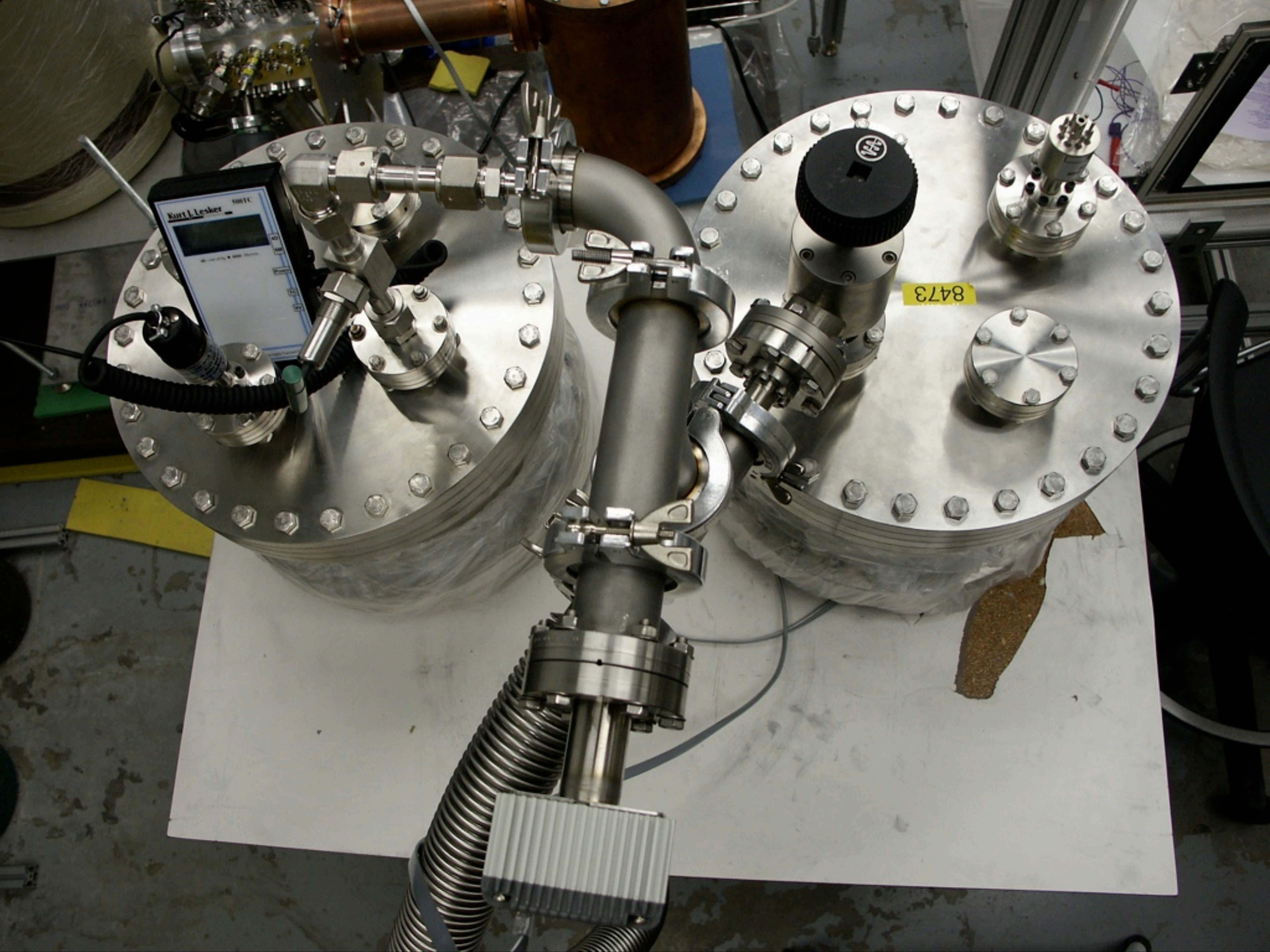
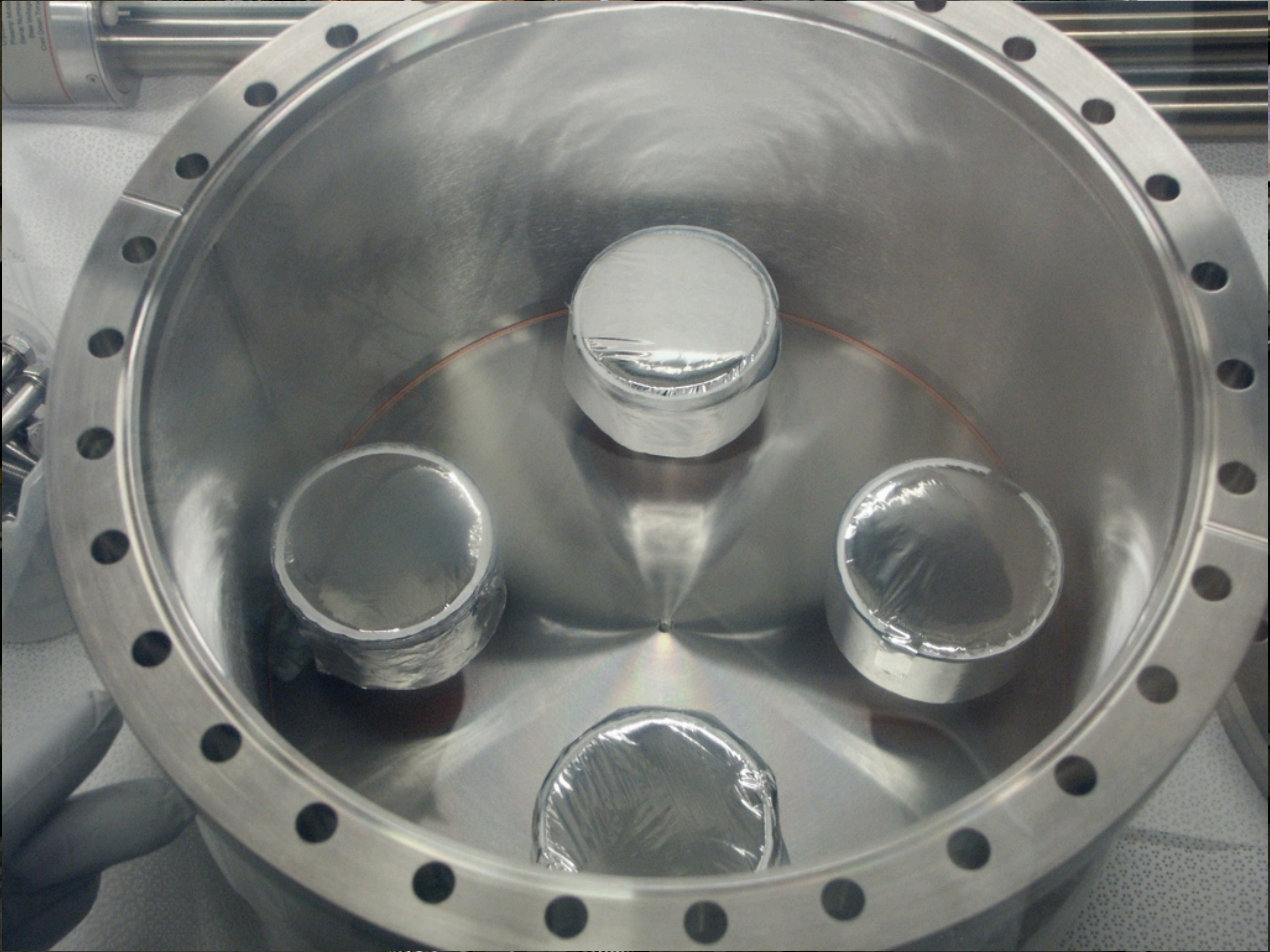


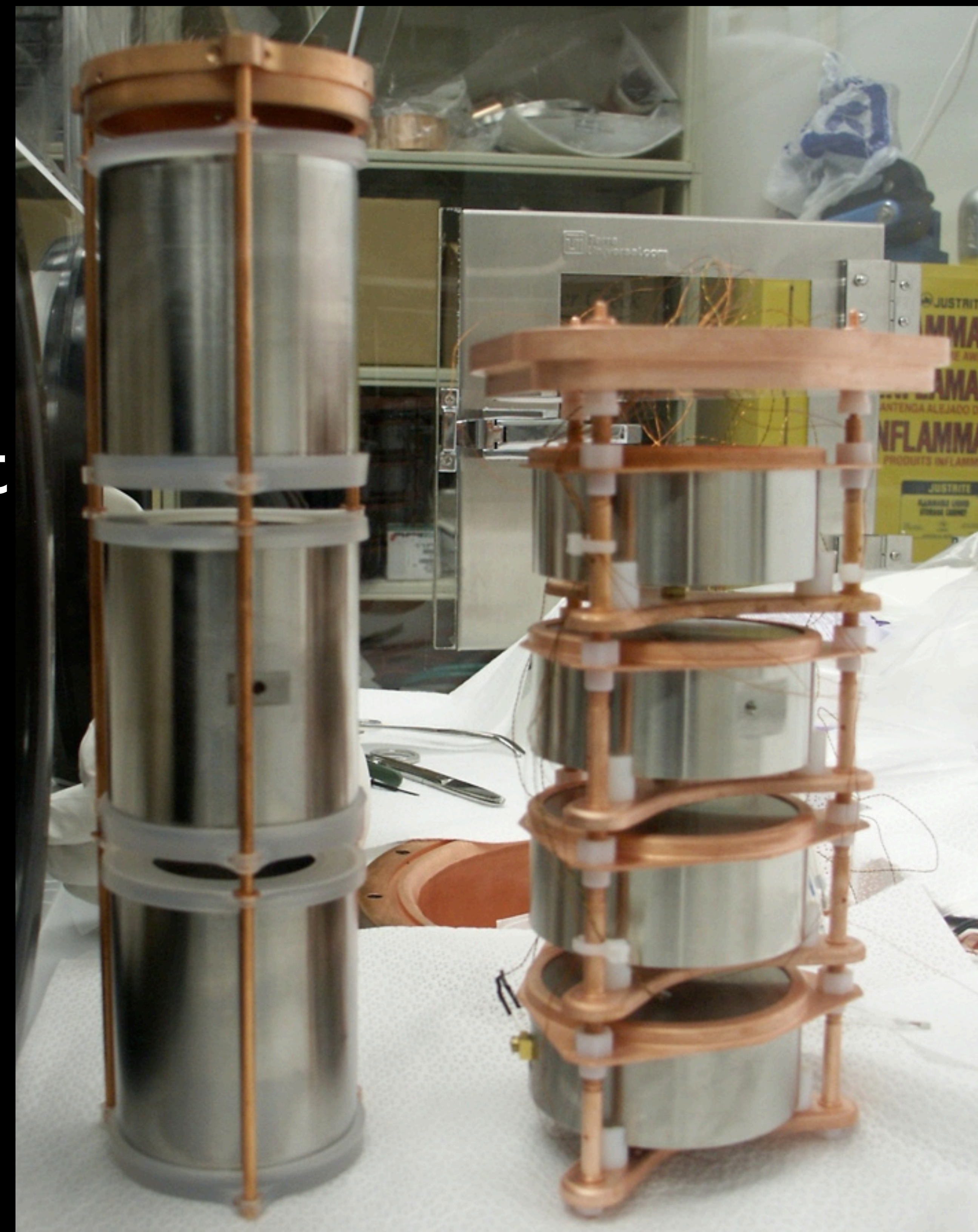

Kurt J. Lesker


8455
8463
JUSTRITE
PRODUITS INFLAMMABLES



Cryostat R&D

- We came into some older detectors and use them frequently in test stands
- Built a MAJORANA test cryostat for mechanical and electrical tests: **The Canary Cage**
- Using it to test detector string designs...



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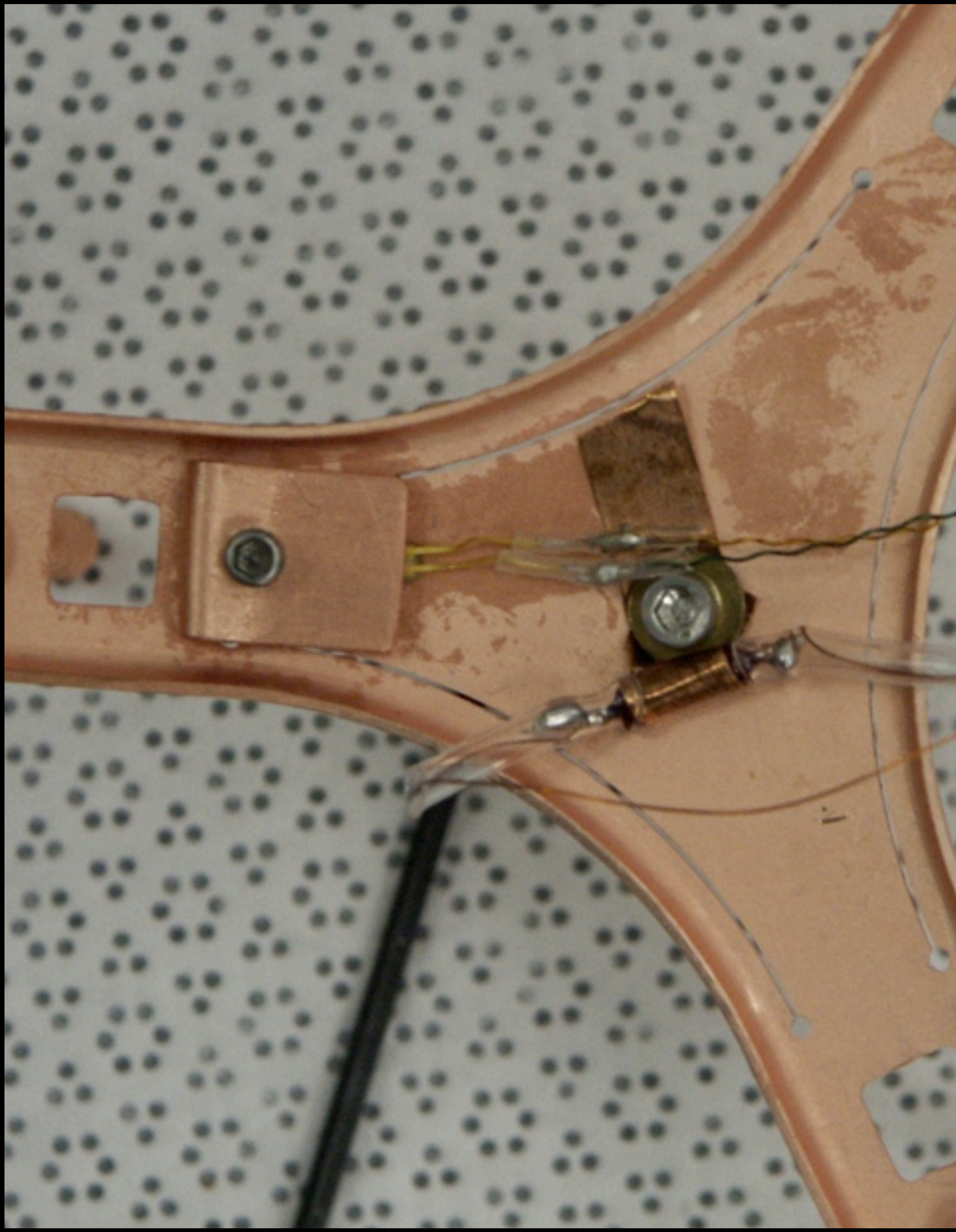

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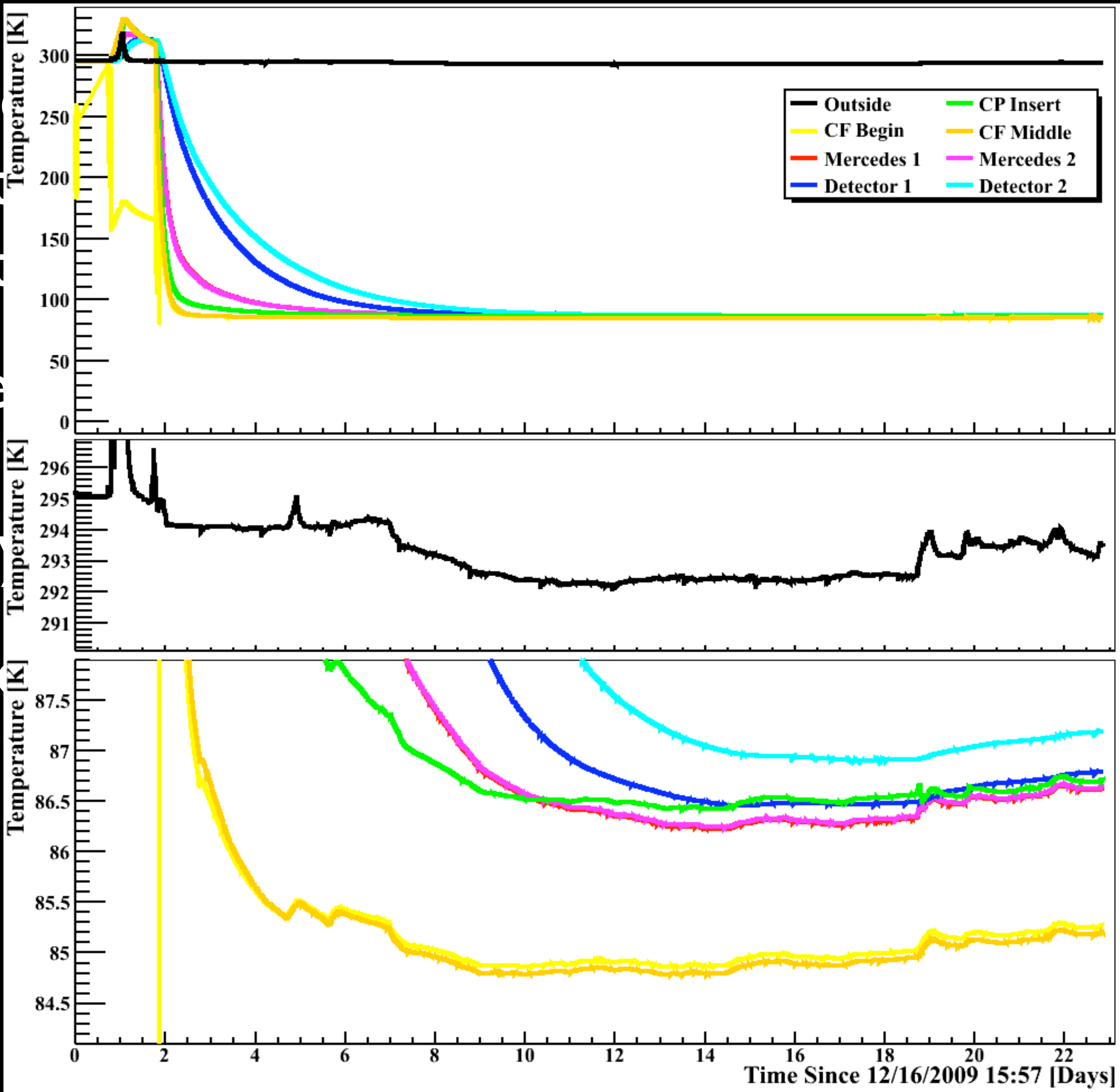

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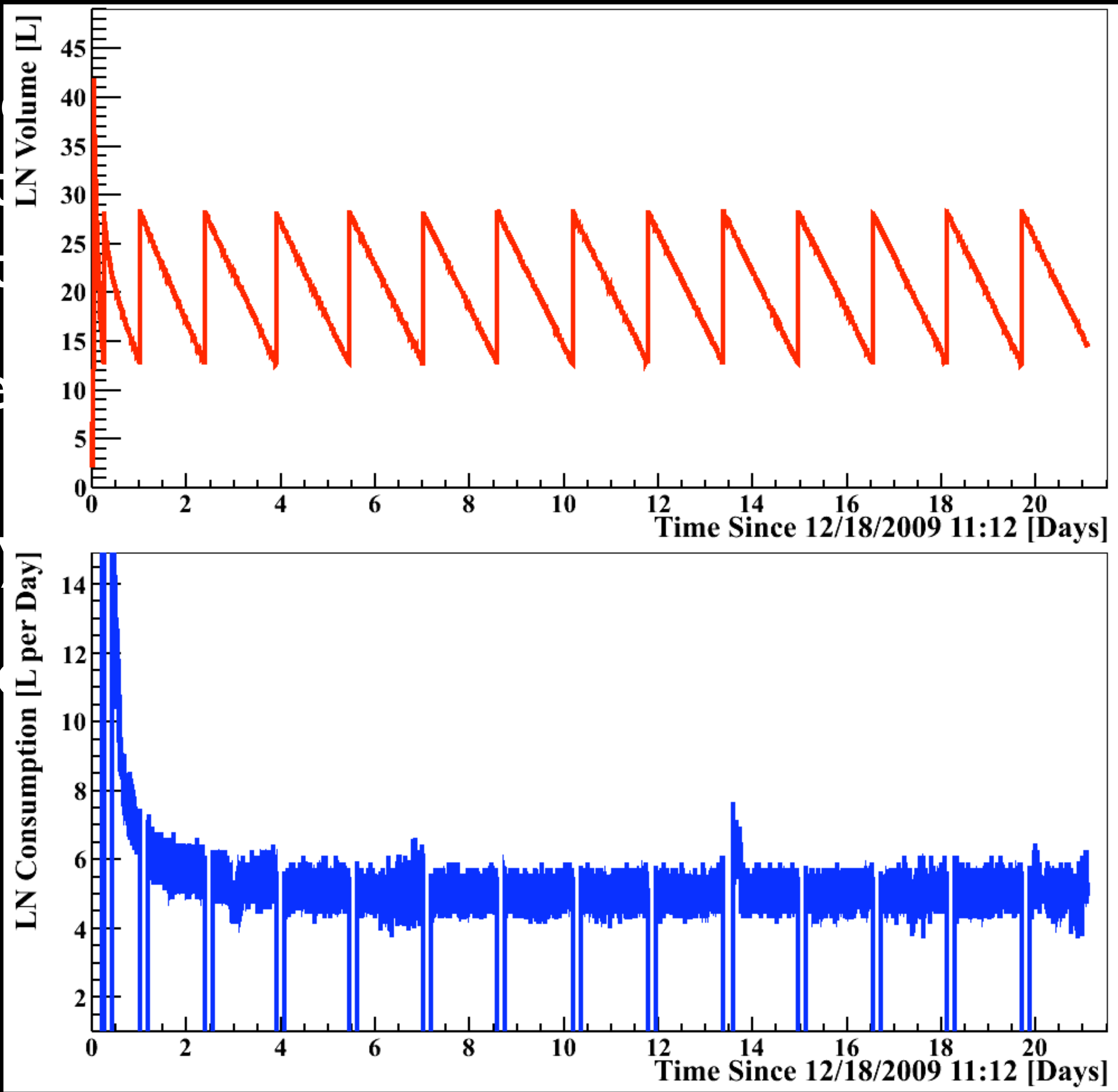
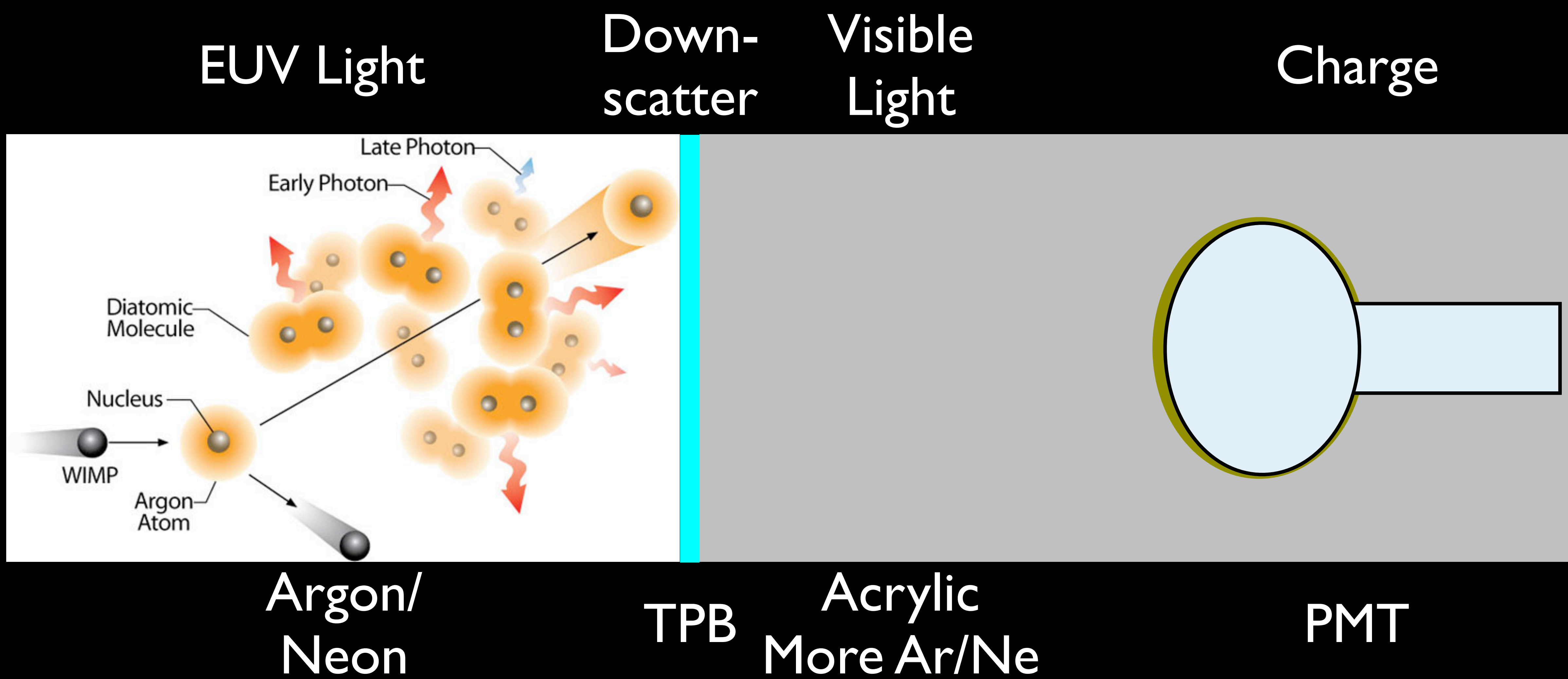


MAJORANA and CLEAN/DEAP

Recent R&D Progress

Detector Response R&D



- PMT tests: dark current, gain, QE vs. Temperature
- TPB tests: fluorescence efficiency, emission spectrum vs. EUV wavelength
- Optical Module Tests: mechanical and integration

Cold PMT Tests

- These tubes have already been tested down to 29K...

Journal of Instrumentation,
2 (2007), P11004
doi: 10.1088/1748-0221/2/11/P11004

Cold PMT Tests

- These tubes ha tested down to 29K...
- We will be able to carefully control the temperature of the PMT!

Cold PMT Tests

- These tubes have already been tested down to 29K...
- We will be able to carefully control the temperature of the PMT!
- This will allow us to do an extensive gain and efficiency vs. bias curve for several temperatures

Cold PMT Tests

You should probably test your PMTs cold too...

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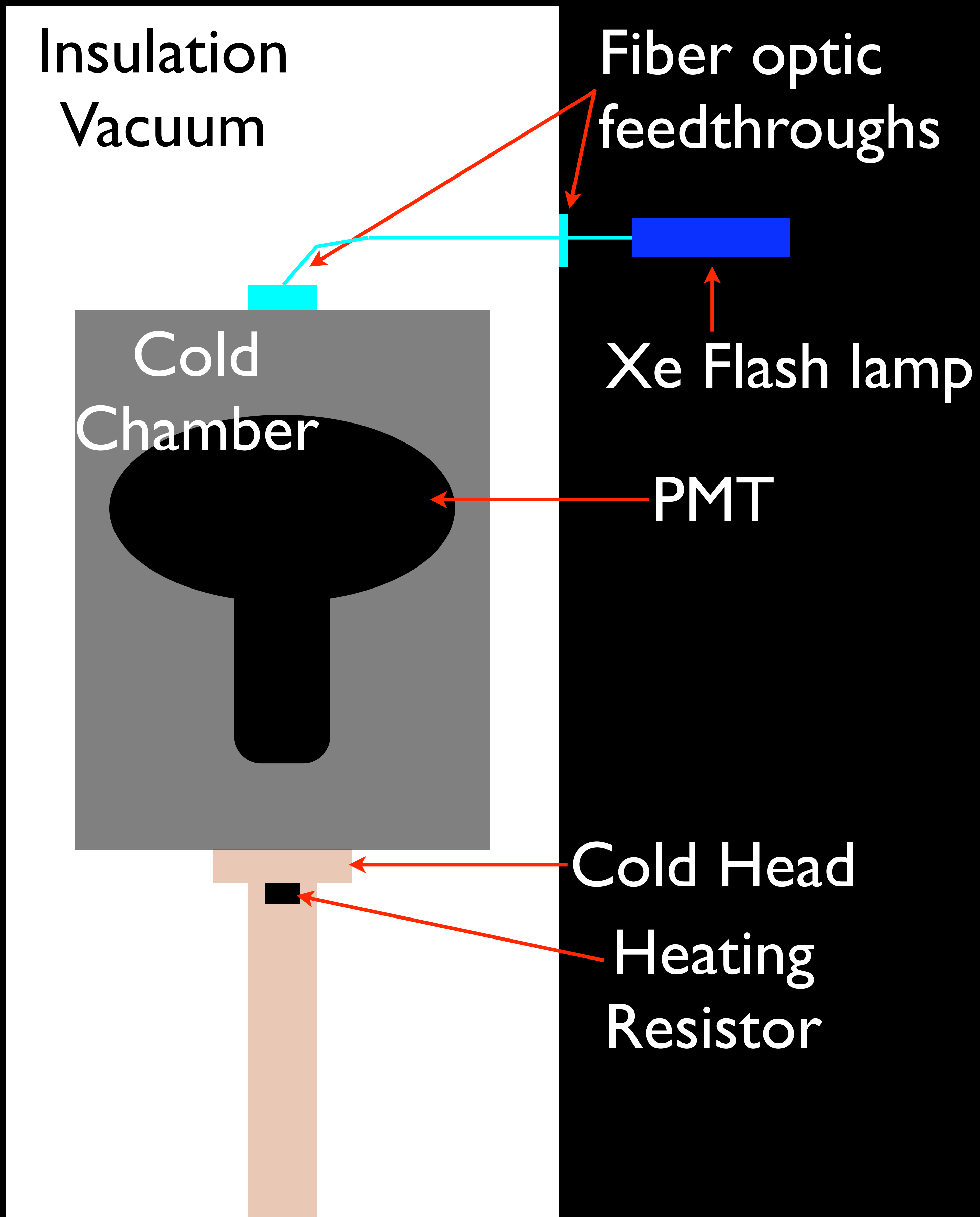
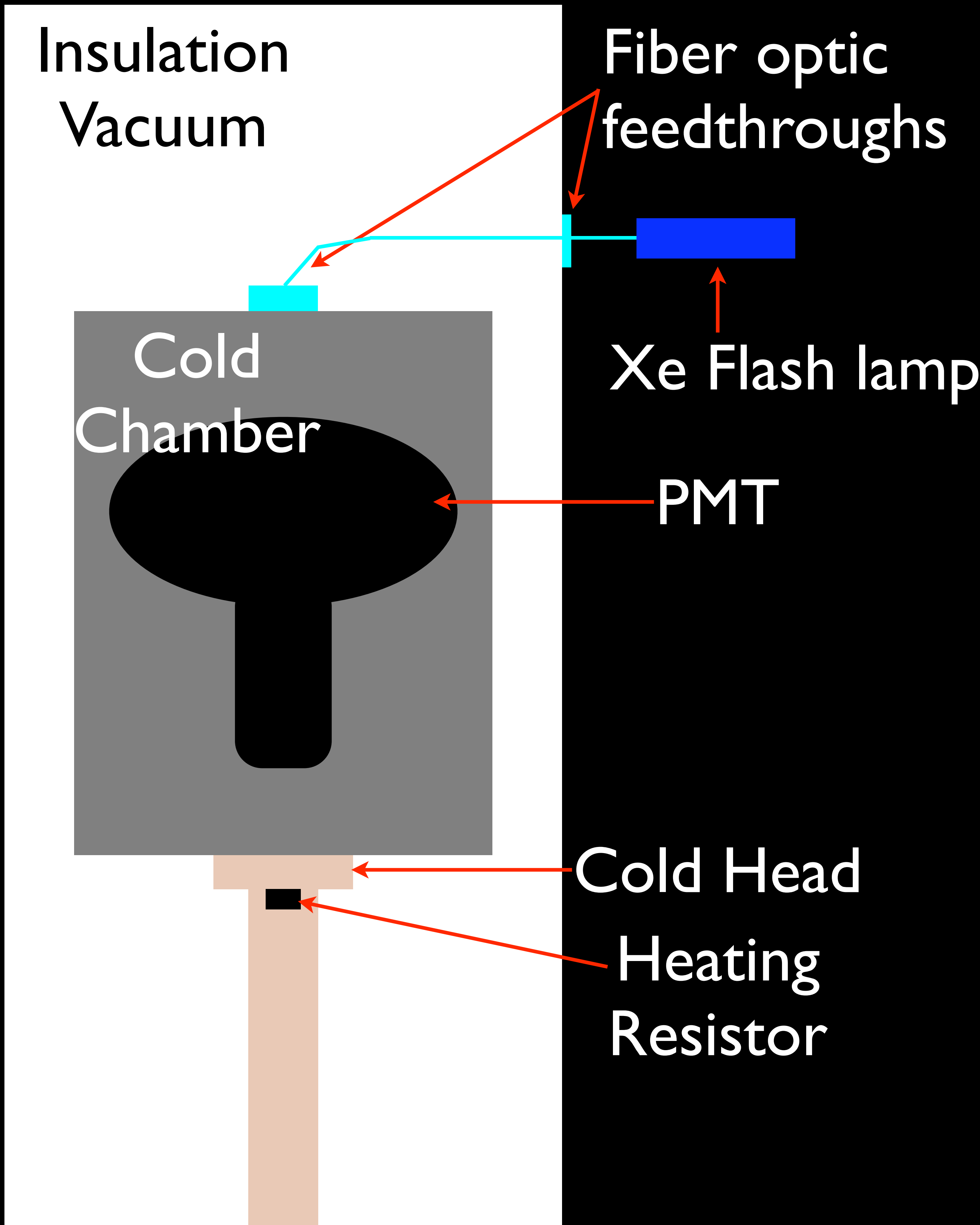
    - One or two every ~10-20 K from 50-300 K

The Plan...


Insulation
Vacuum
Fiber optic
feedthroughs
Xe Flash lamp
Cold
Chamber
PMT
Cold Head
Heating
Resistor

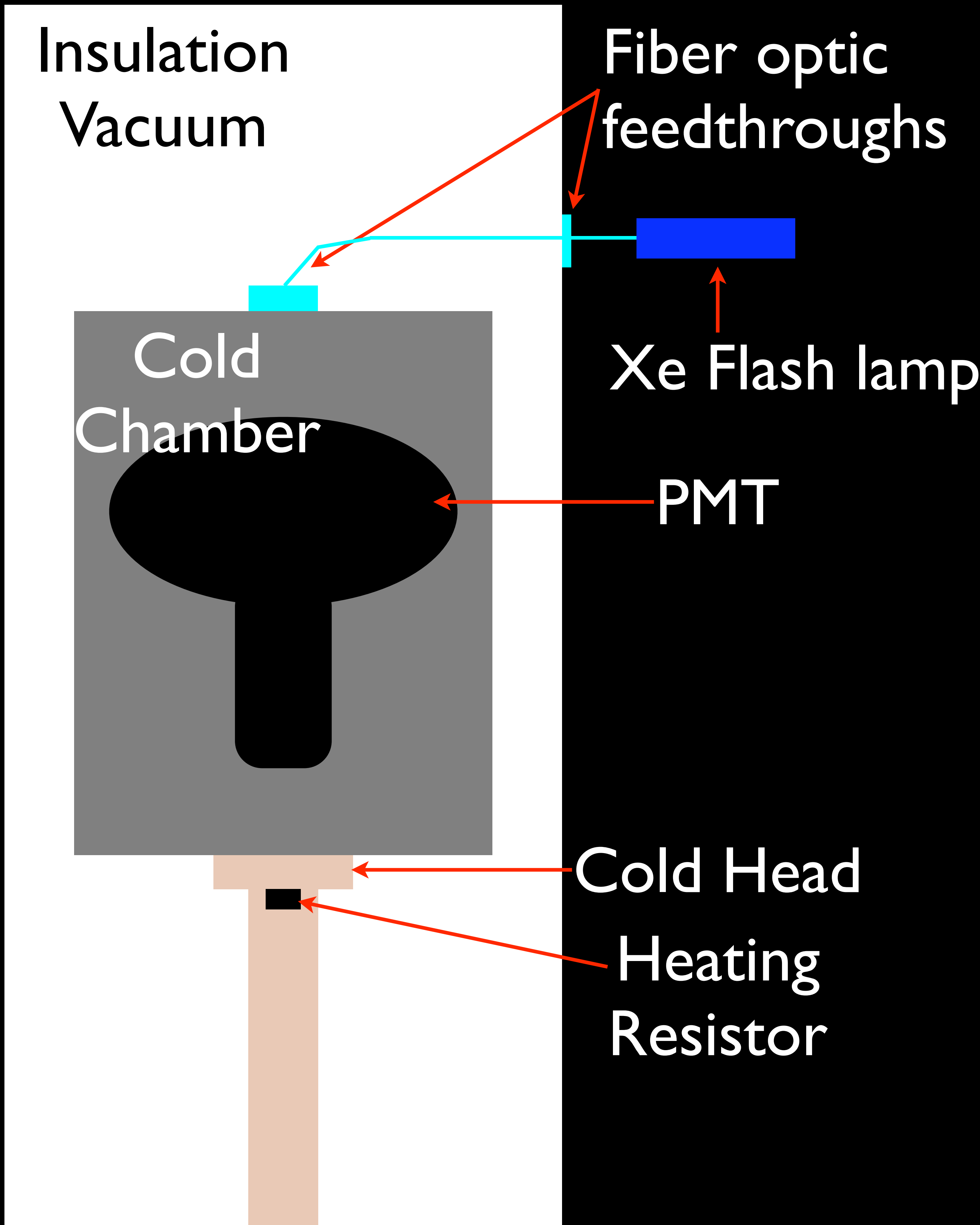
The Plan...

1. Pump out insulation vacuum and cold chamber



The Plan...

1. Pump out insulation vacuum and cold chamber
2. Fill cold chamber with cover gas



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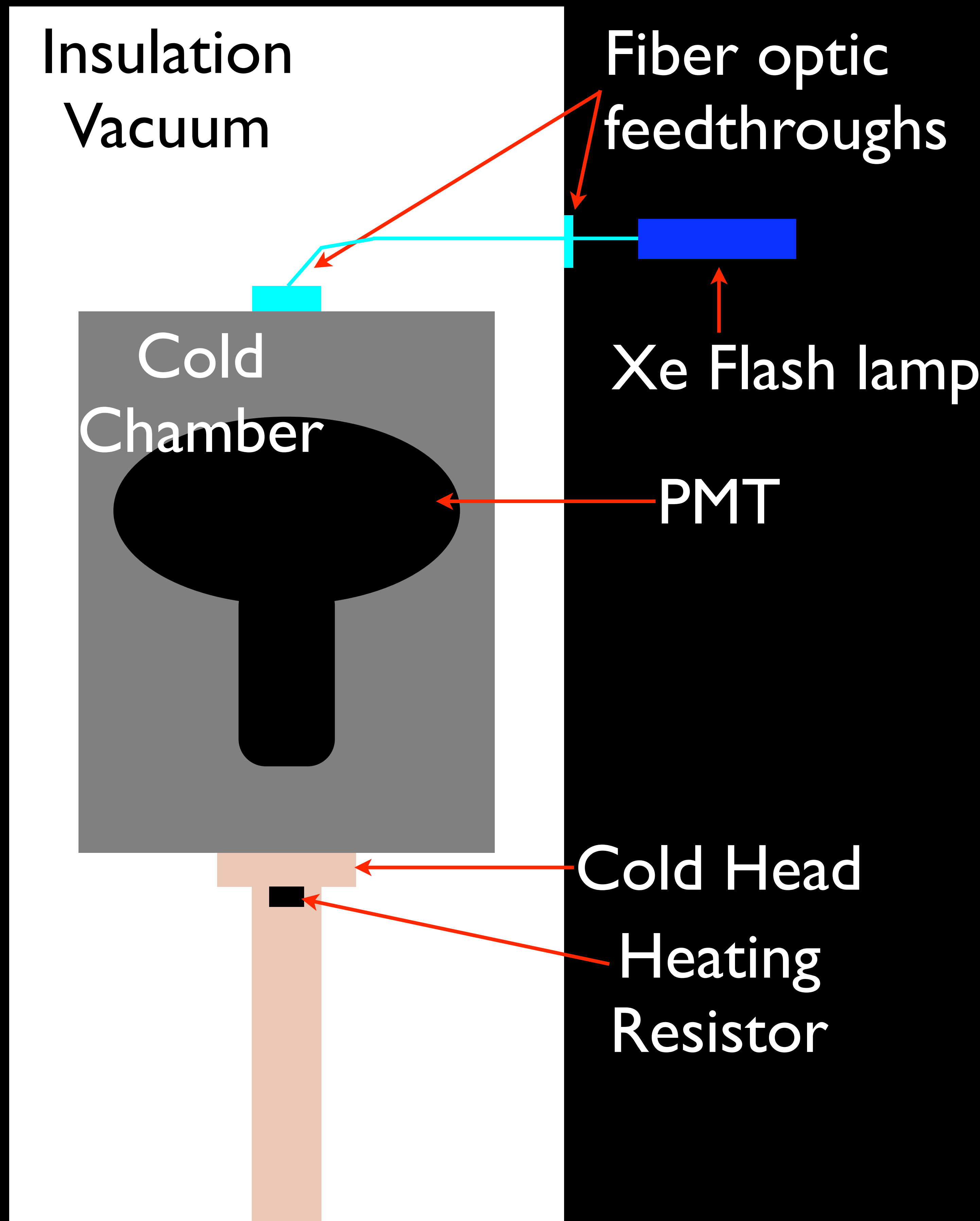

The Plan...

1. Pump out insulation vacuum and cold chamber
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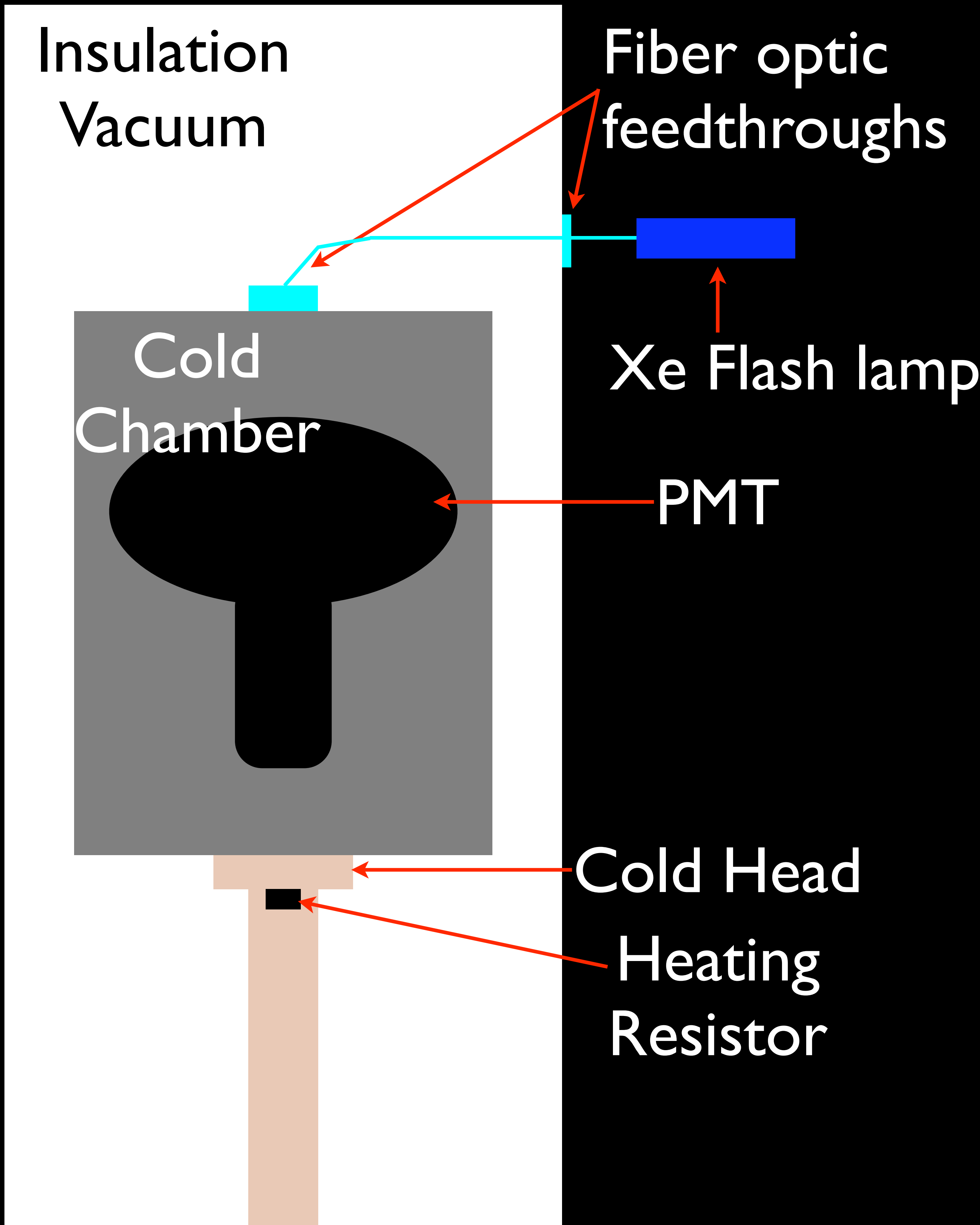
4. Adjust heating resistor to set temperature



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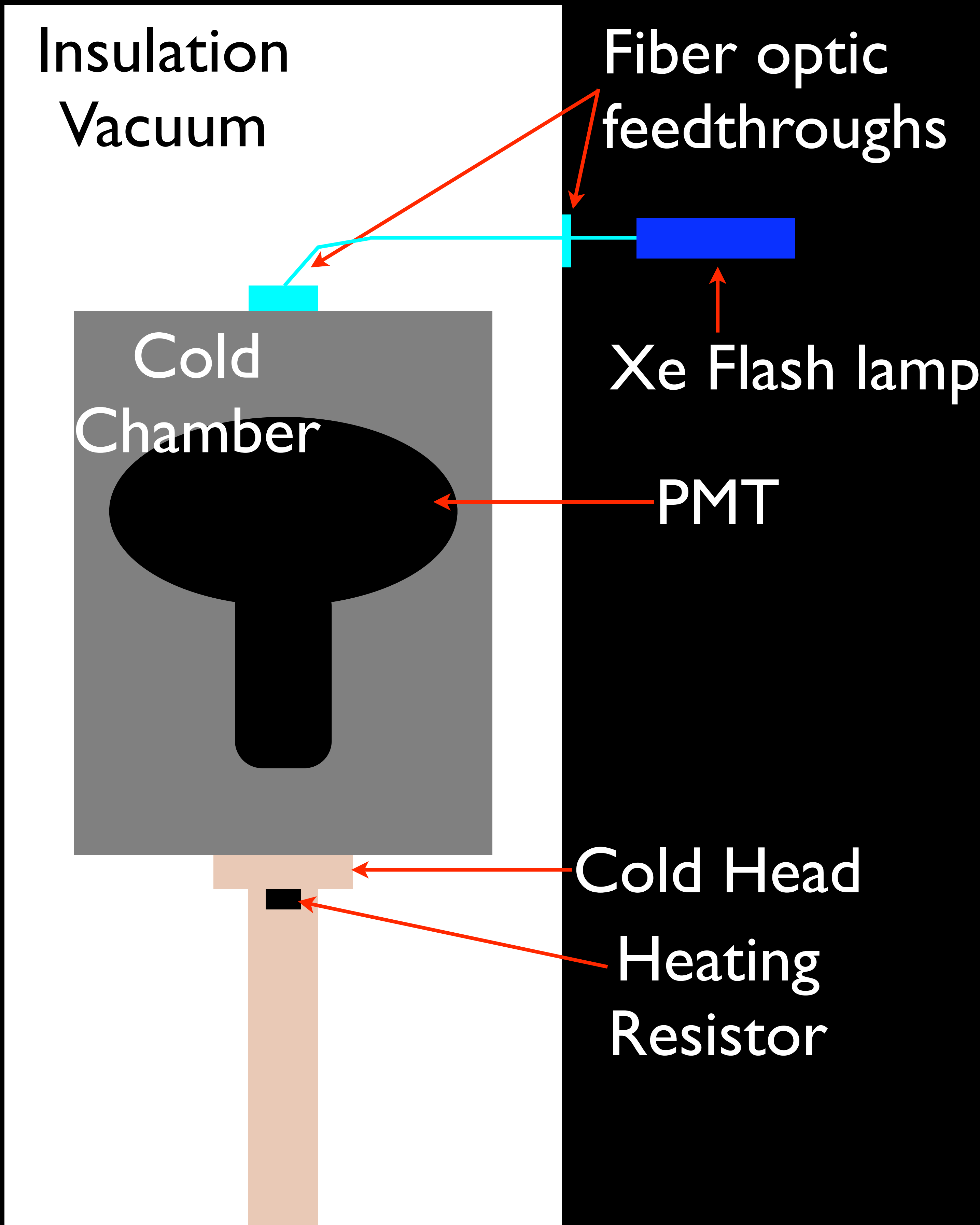
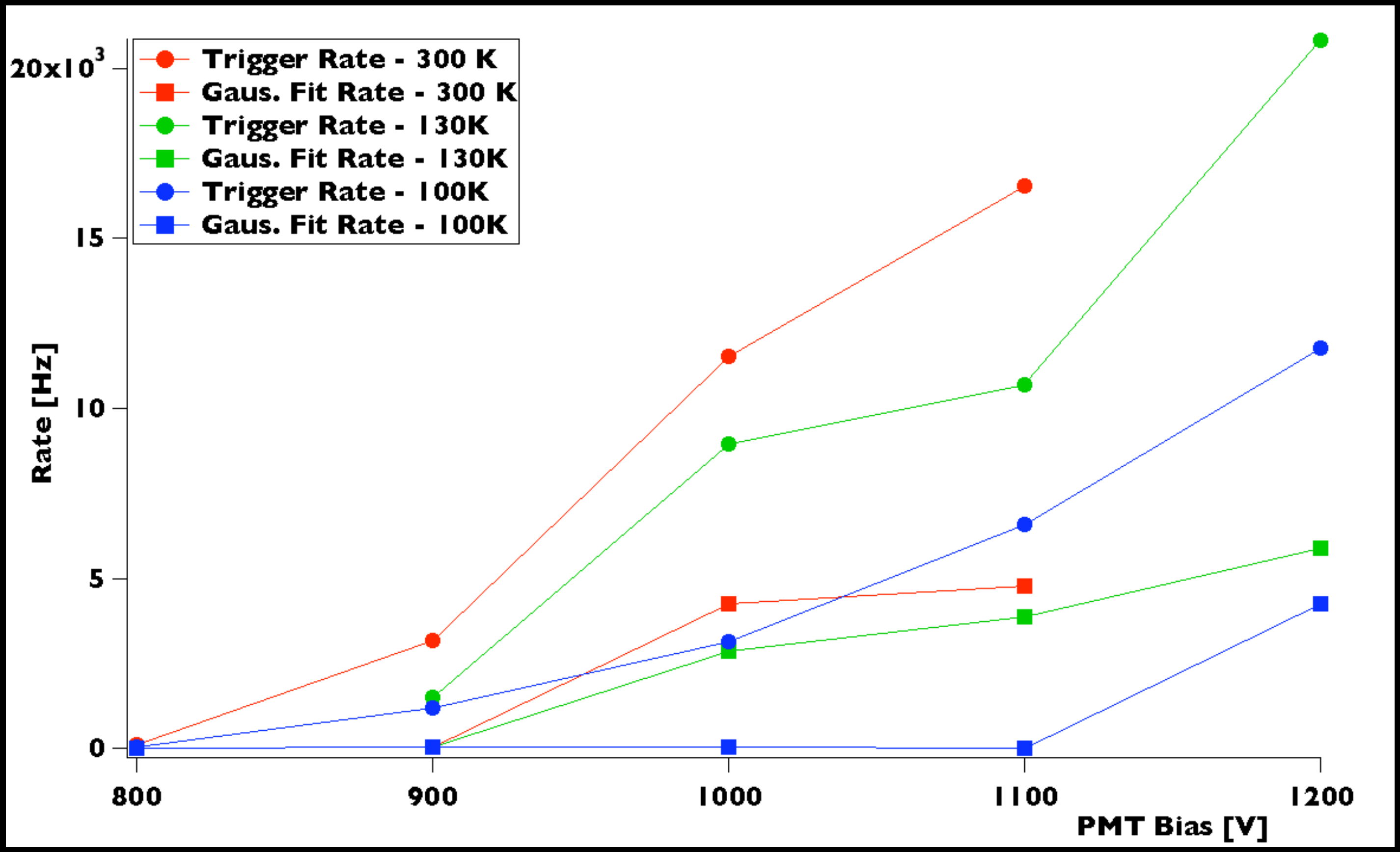
3. Cool down cold chamber with cold head
4. Adjust heating resistor to set temperature
5. Bias PMT and take data



Initial Dark Current Measurements

- Can cool down to ~100 K with ~ 1 Atm. N2 cover gas, bias PMT's take data-- **DARK CURRENT!**



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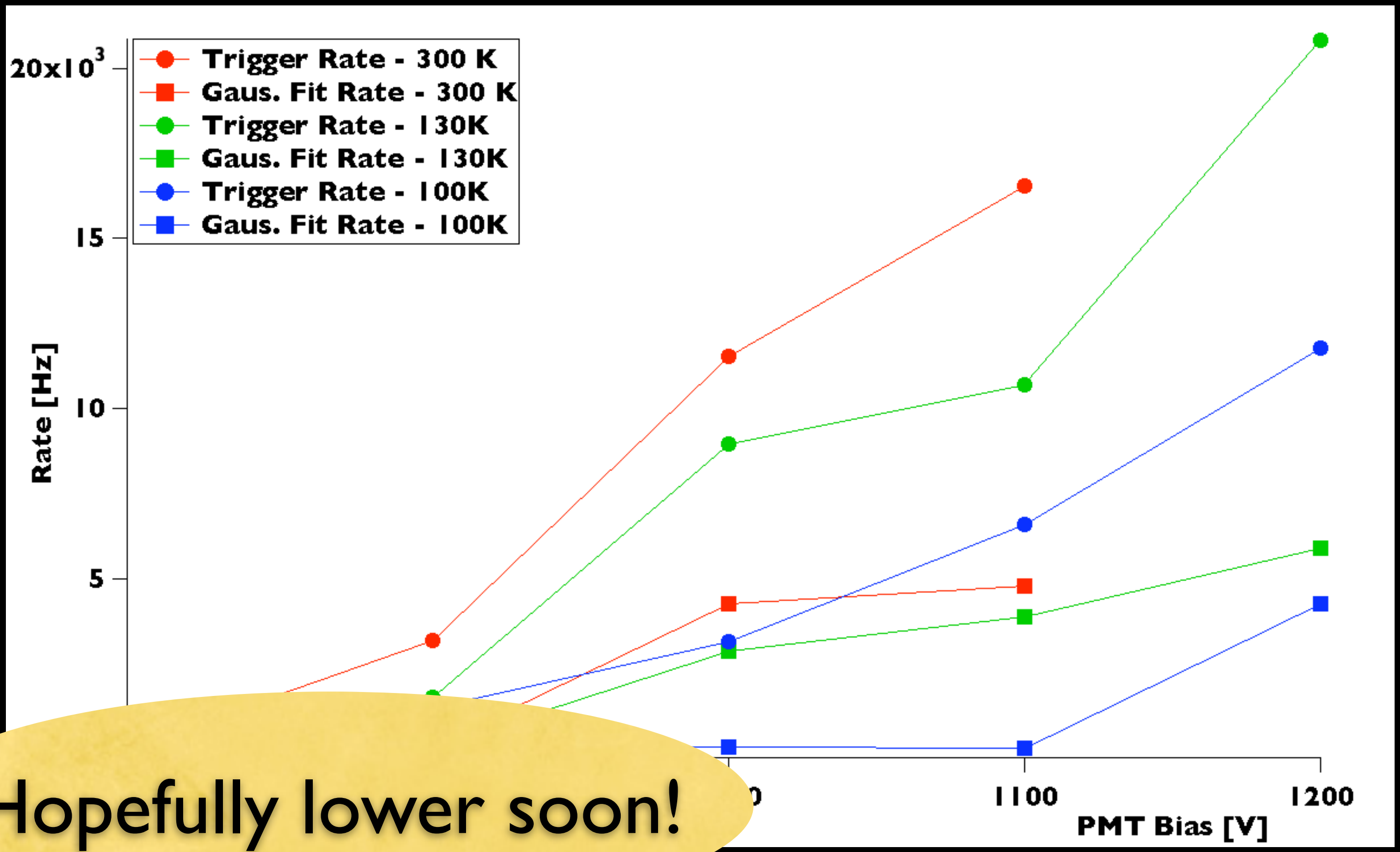

Hopefully lower soon!

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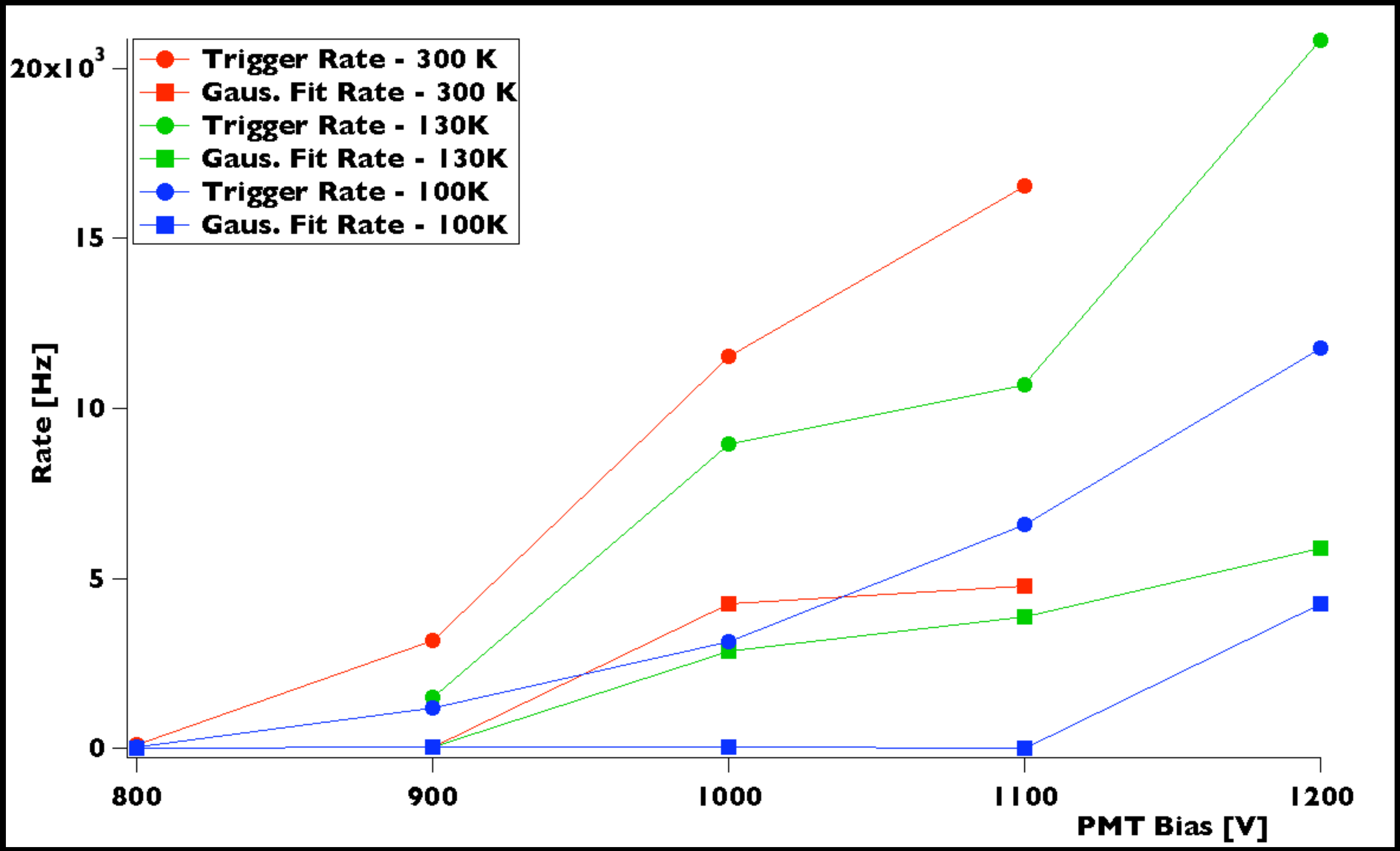

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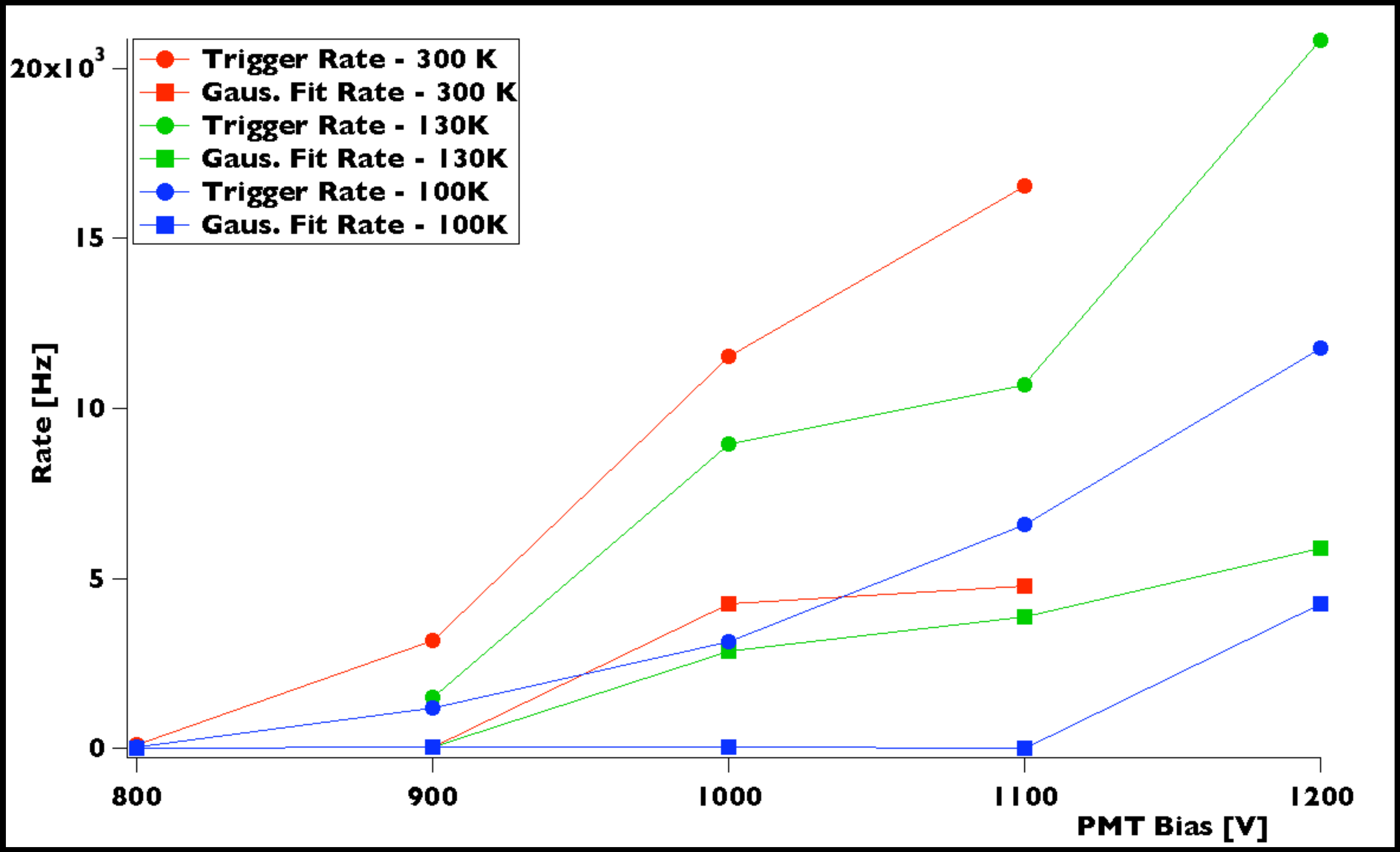

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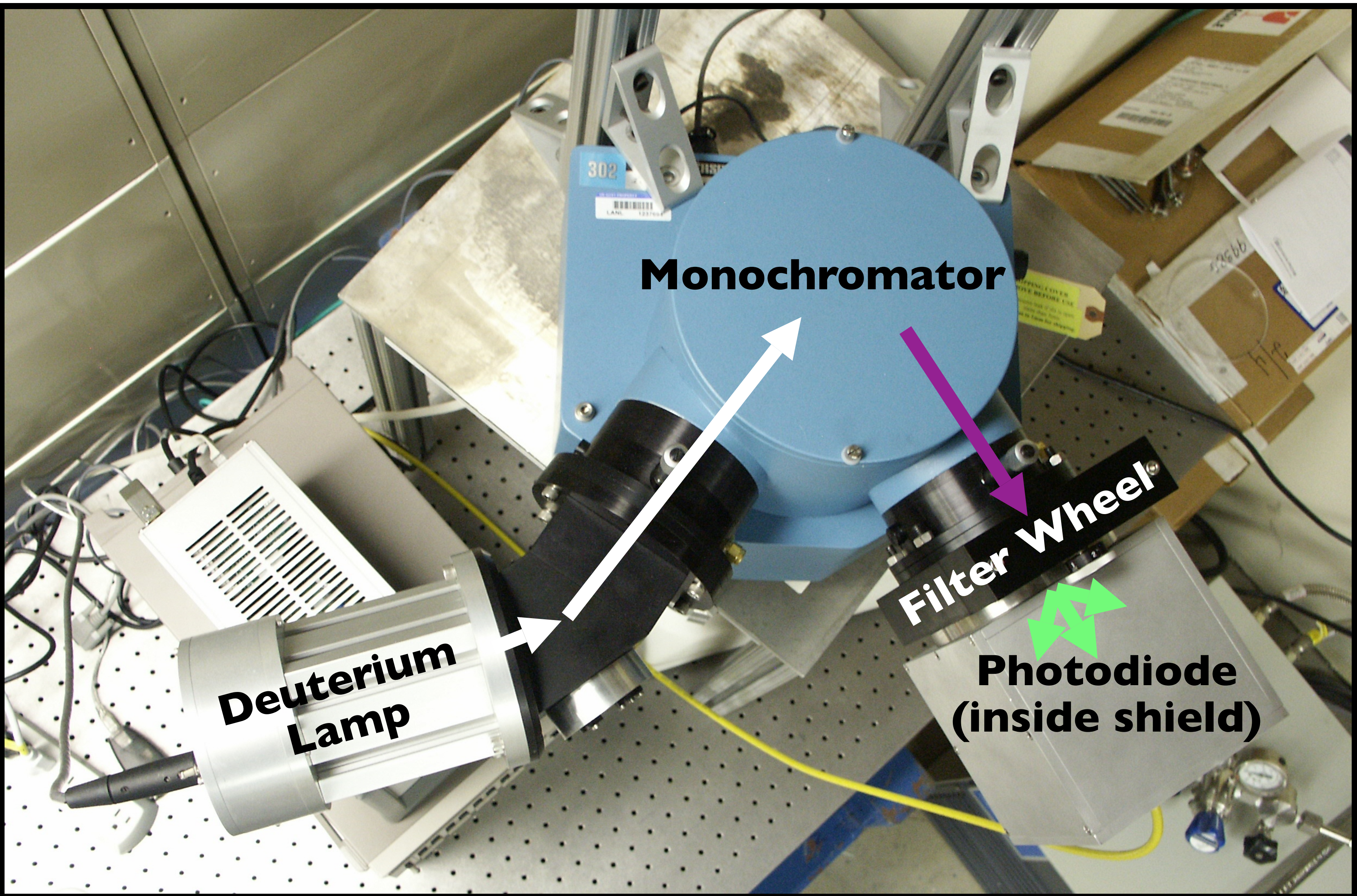
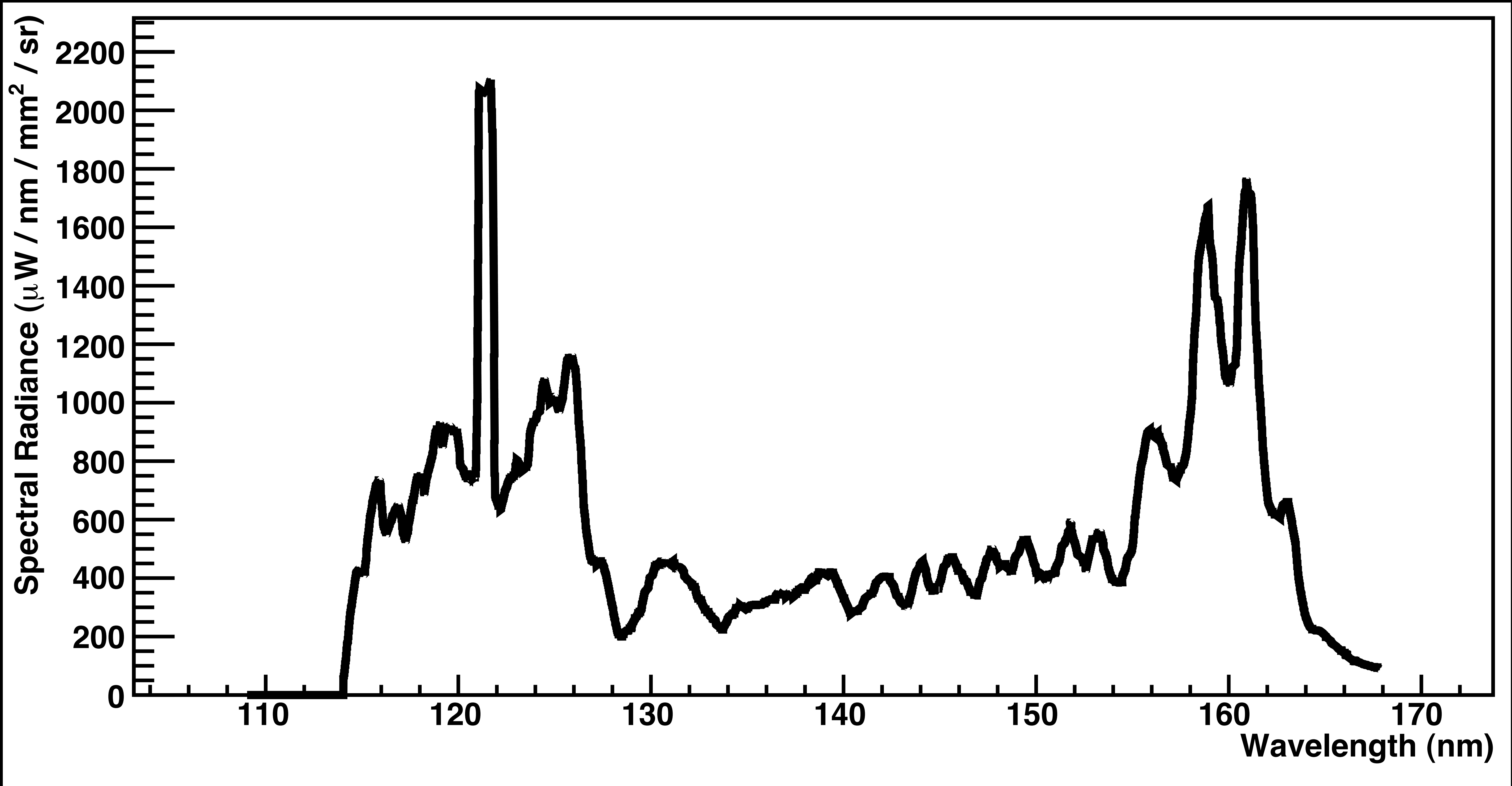
TPB Fluorescence

Since we are observing individual photons, we care about the efficiency as a ratio of photon rates.

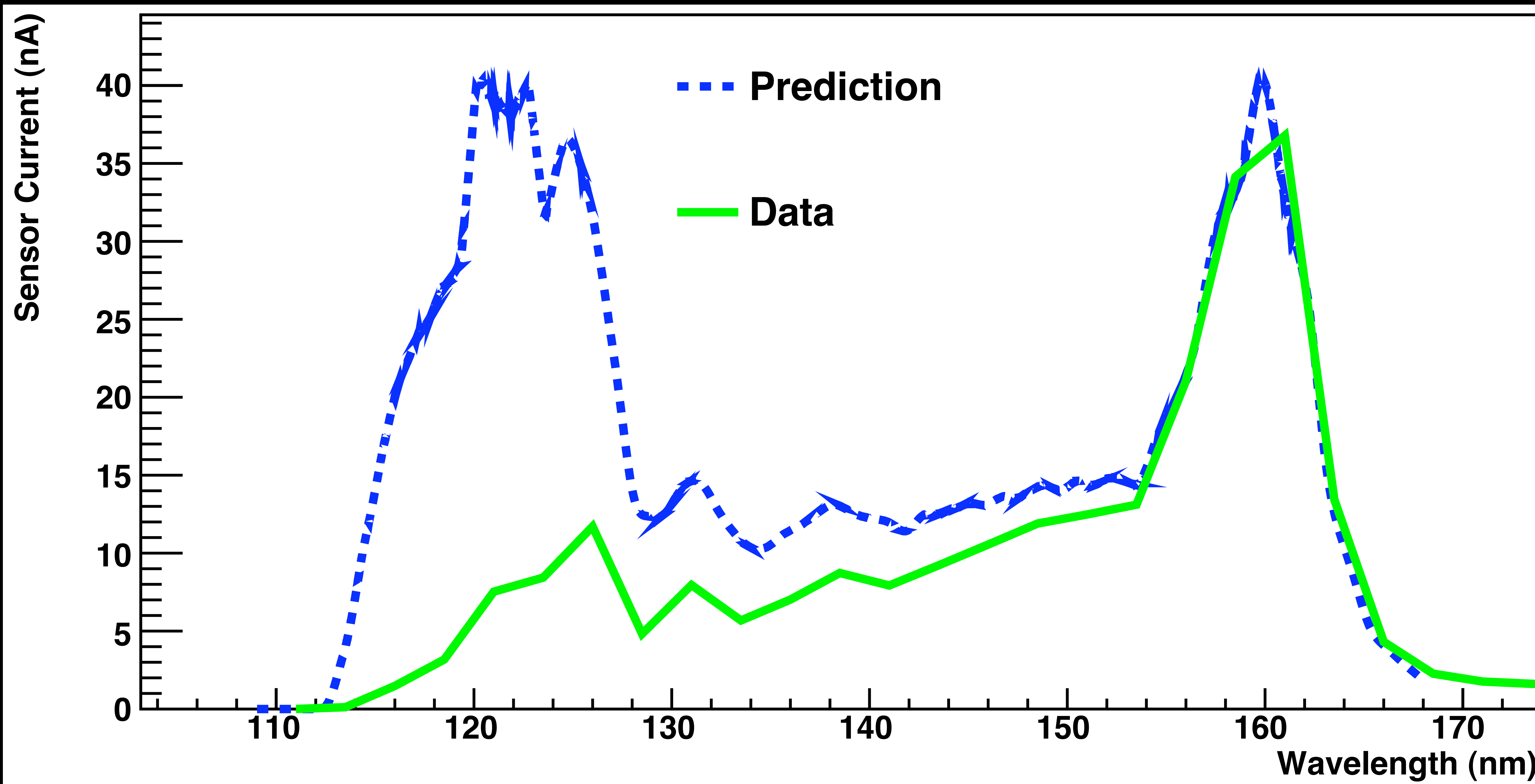
$$\epsilon(\lambda_{\mathrm{UV}}) = \frac{R_{\mathrm{vis}}}{R_{\mathrm{UV}}} = \frac{I_{\mathrm{vis}}(\lambda_{\mathrm{UV}})\ \frac{4\pi}{\Omega_{\mathrm{vis}}}\ \int d\lambda_{\mathrm{vis}}\ S_{\mathrm{TPB}} \frac{1}{C(\lambda_{\mathrm{vis}})hc/\lambda_{\mathrm{vis}}}}{I_{\mathrm{UV}}(\lambda_{\mathrm{UV}})\ \frac{4\pi}{\Omega_{\mathrm{UV}}}\ \frac{1}{C(\lambda_{\mathrm{UV}})hc/\lambda_{\mathrm{UV}}}}$$



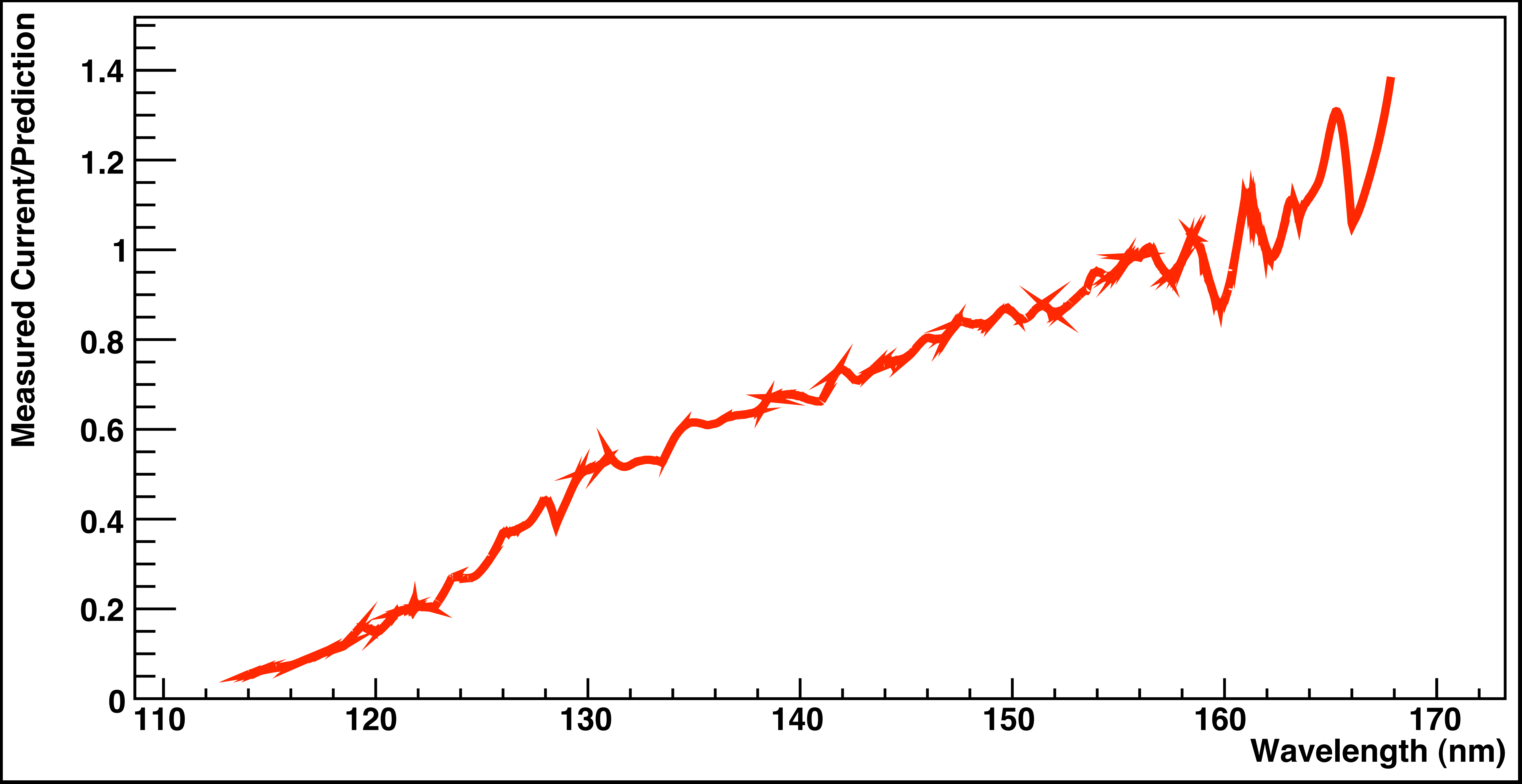
Raw Lamp Spectrum



Sensor Current

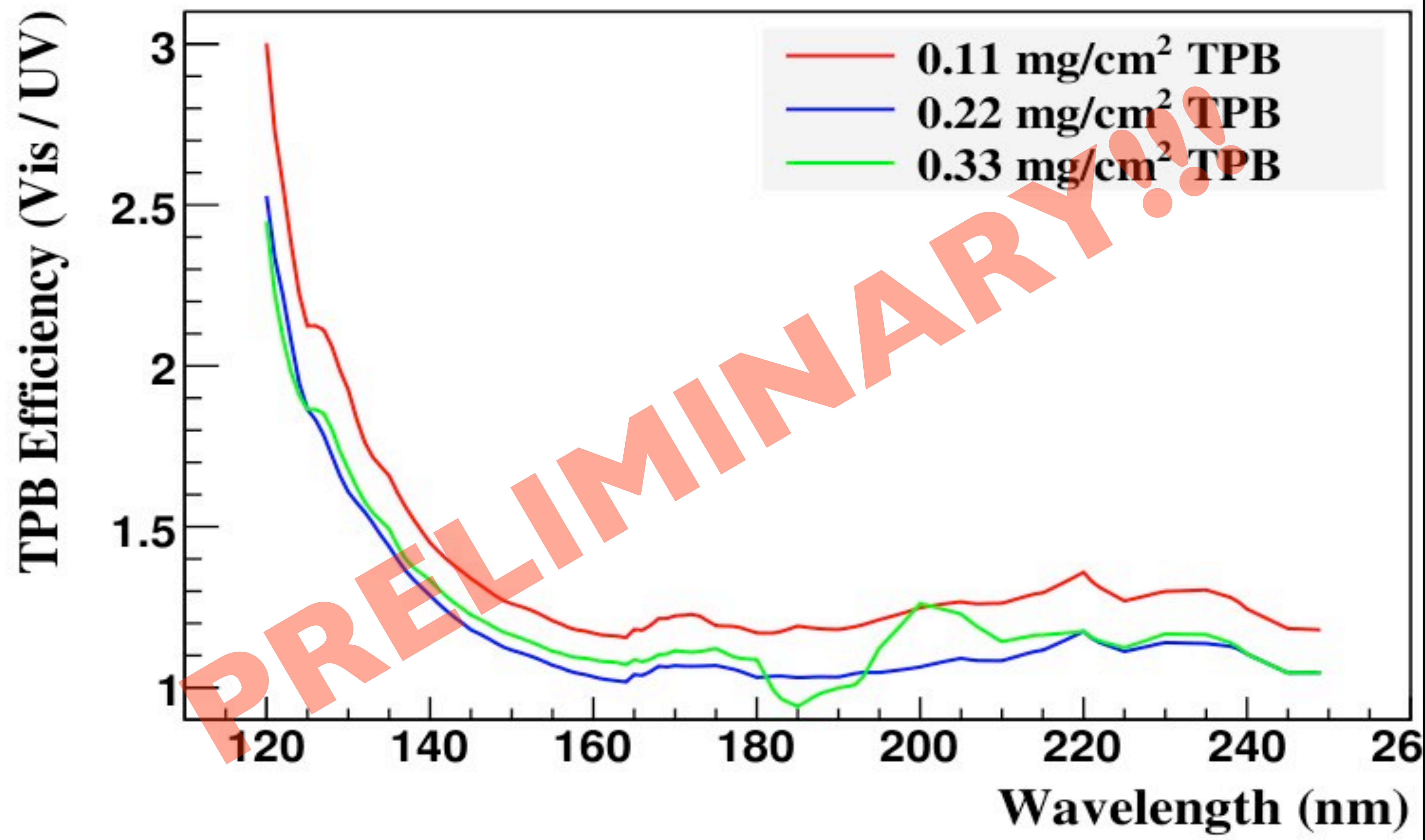


Lost UV



Measured Current/Prediction
1.4
1.2
1
0.8
0.6
0.4
0.2
0
110
120
130
140
150
160
170
Wavelength (nm)

Fluorescence Efficiency



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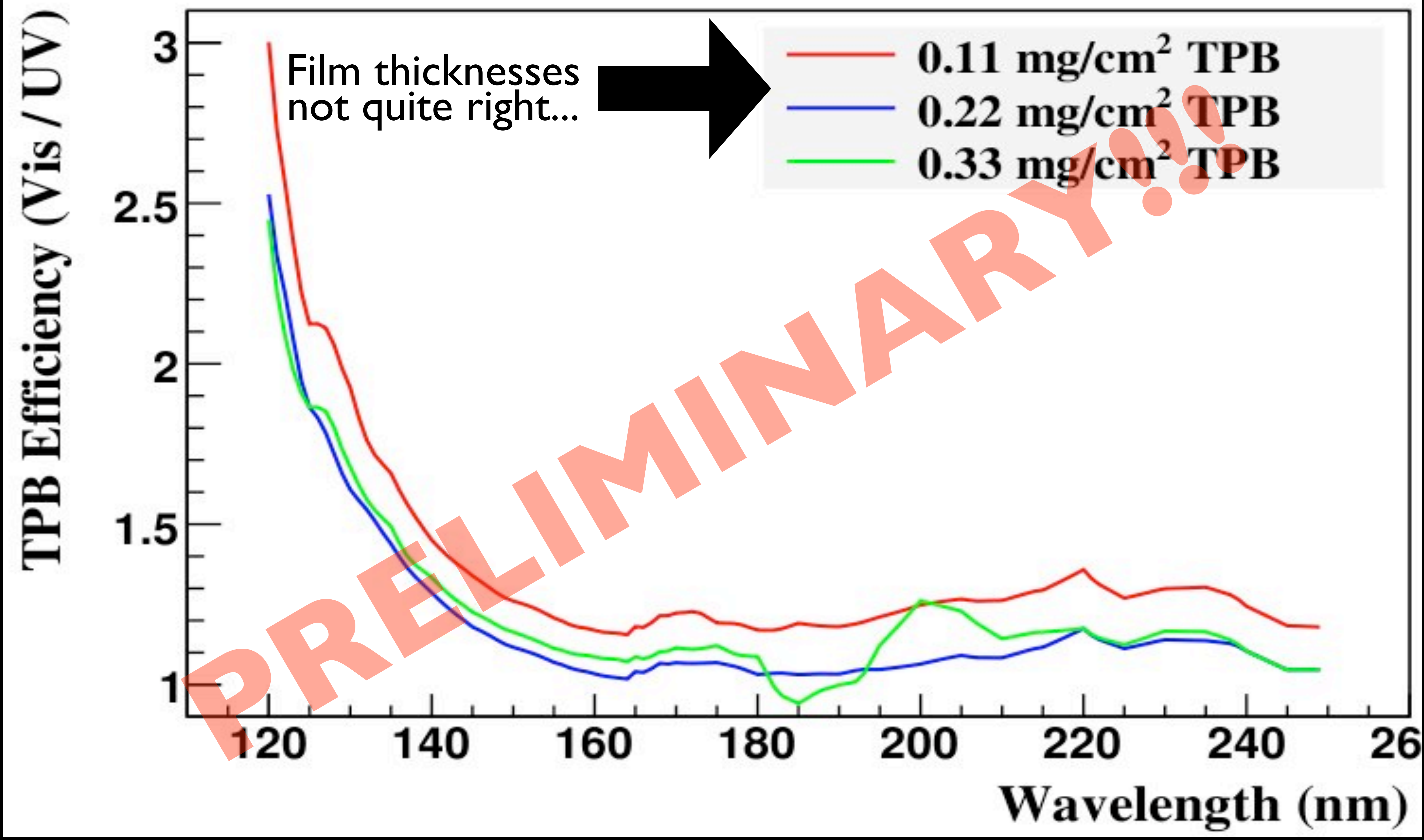

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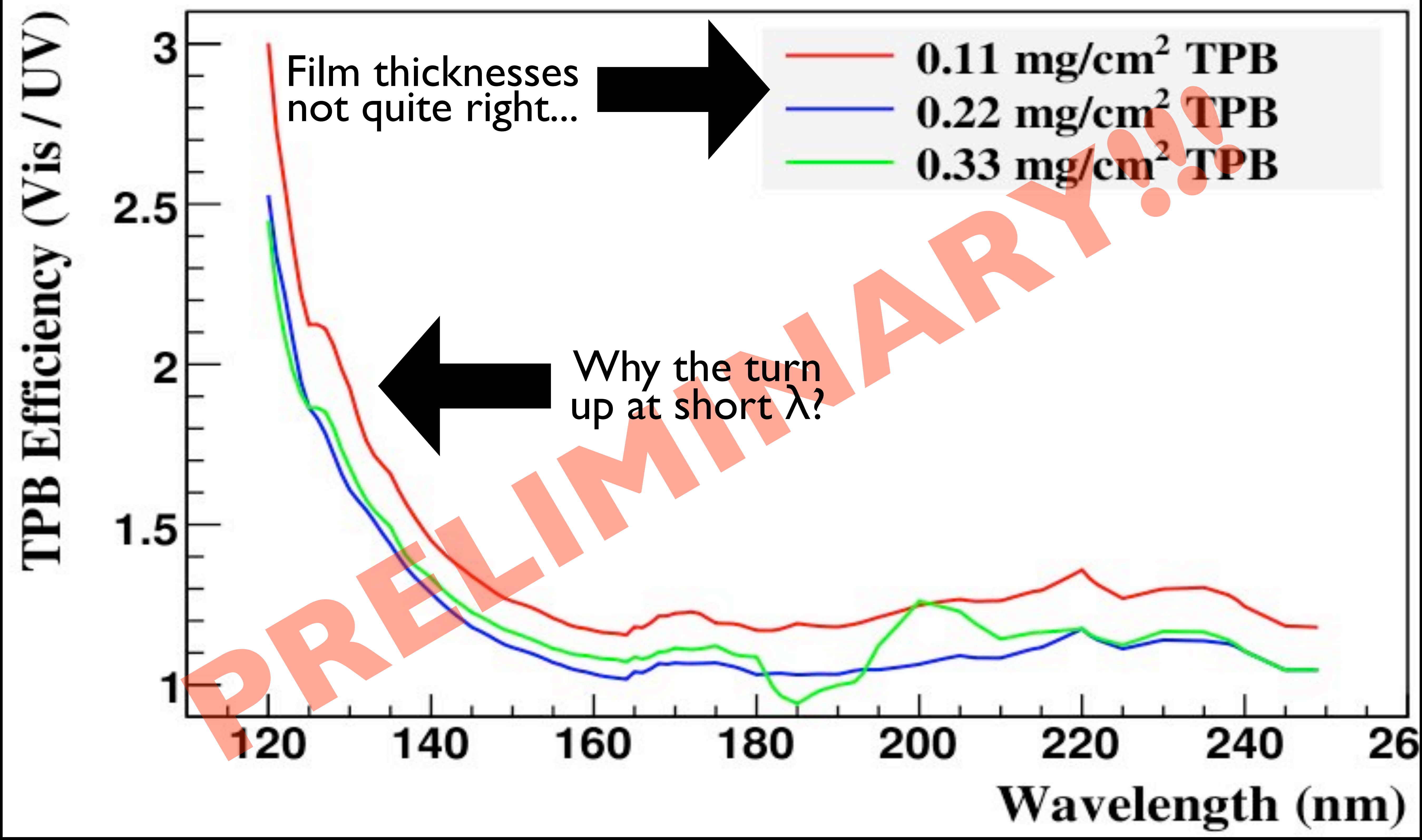
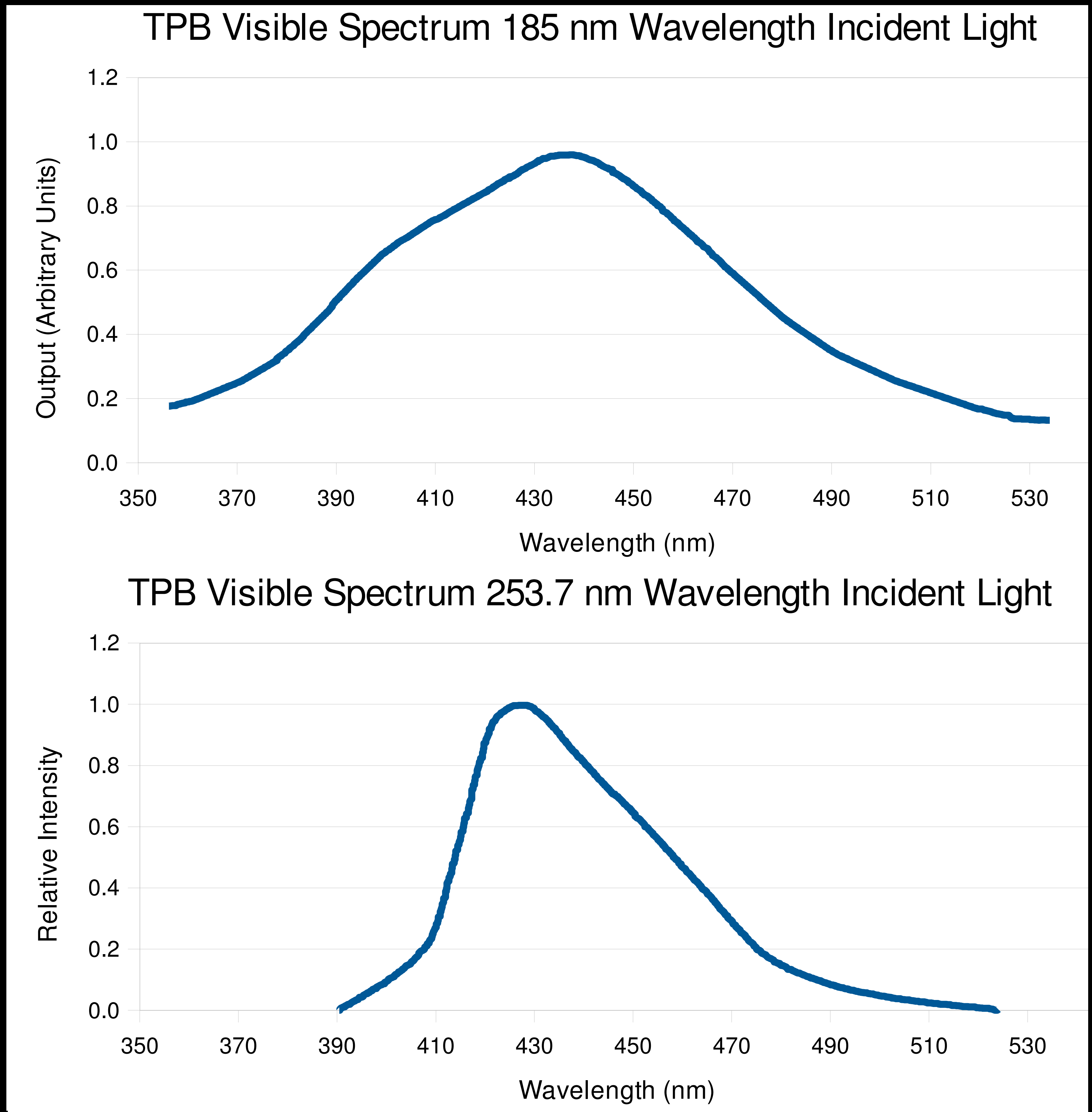


TPB Emission Spectrum



Applied Optics **12**, 87 (1973)

NIM-B **117**, 421 (1996)

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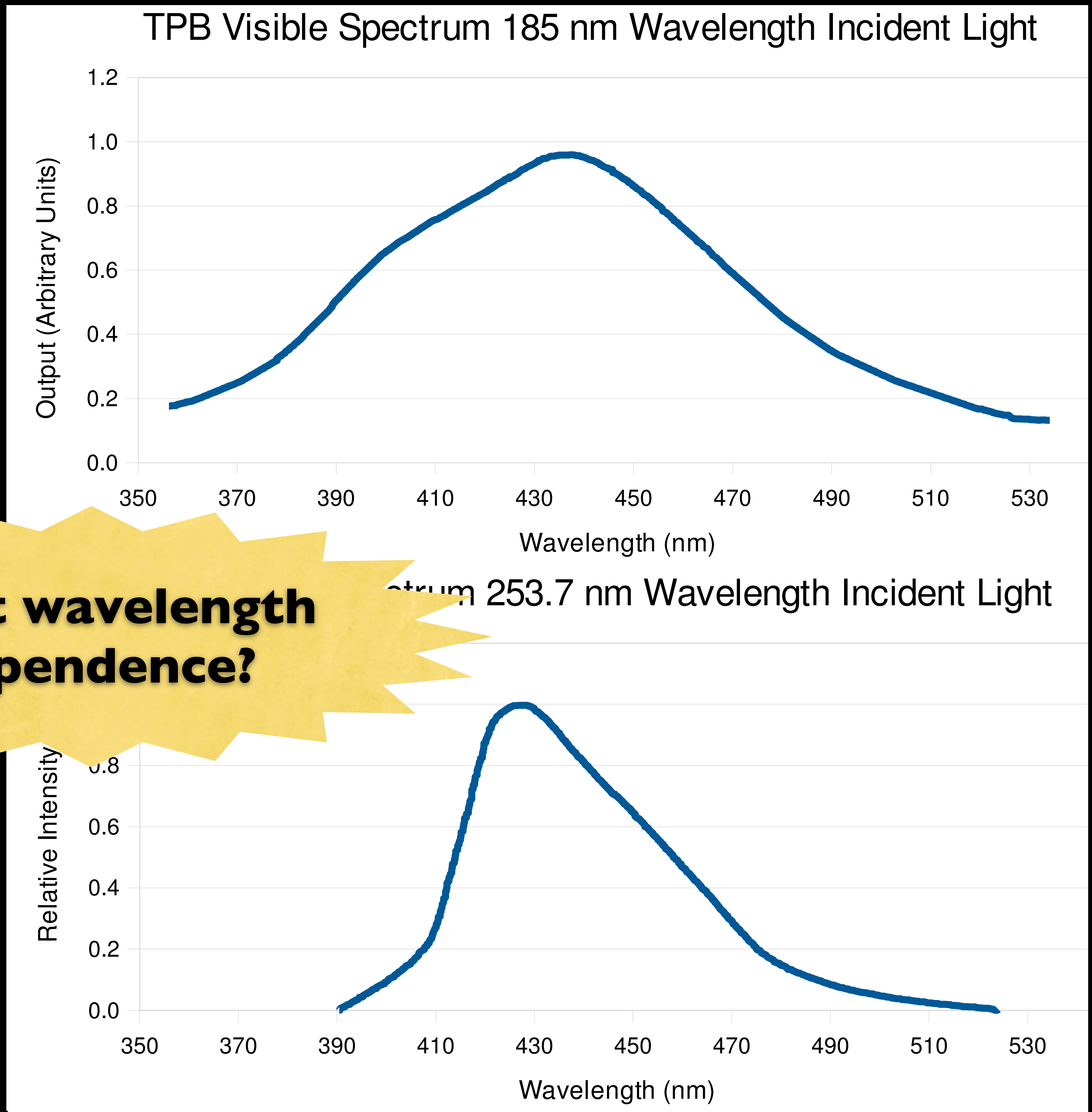

Input wavelength dependence?

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Conclusions

- There are LOTS of frontiers in particle physics!
- We've talked about a comparatively rare and quiet one today…
- MAJORANA and CLEAN are world-leading low-background experiments, with far-reaching physics implications
- This is a very exciting time for low-background physics


Thank you
for your attention!