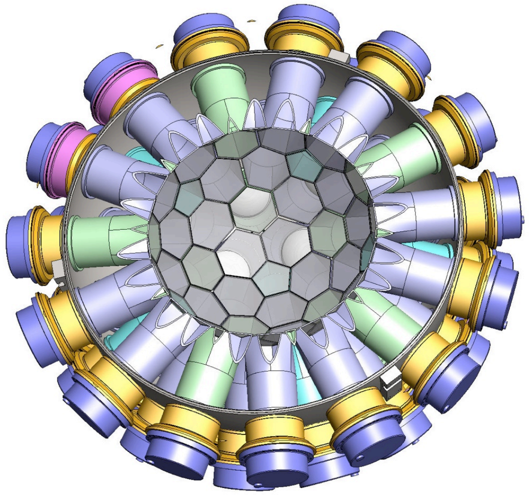
Taking Inventory of the Universe:

Searching for Dark Matter with the MiniCLEAN Experiment

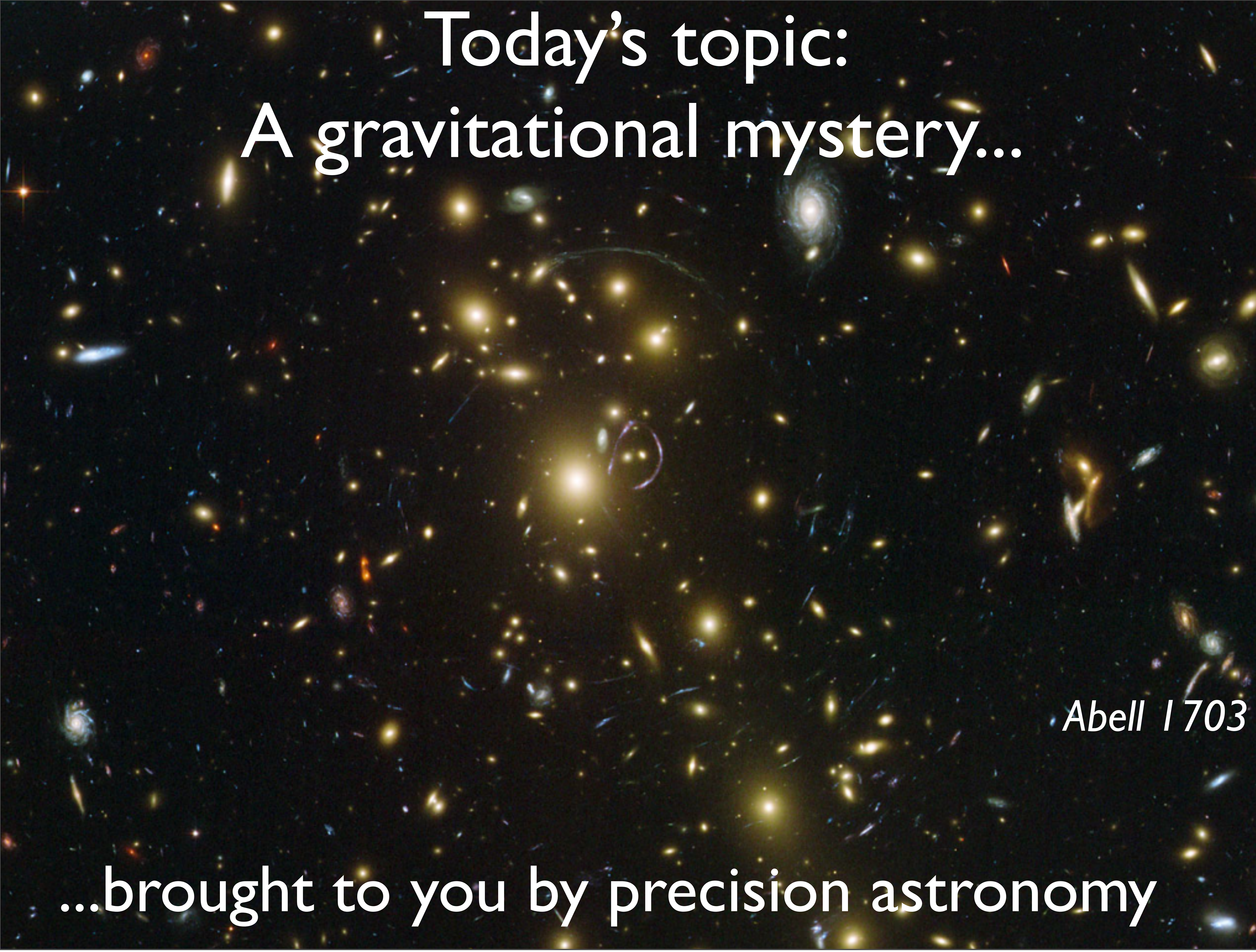
Stanley Seibert

University of Pennsylvania

March 1, 2011

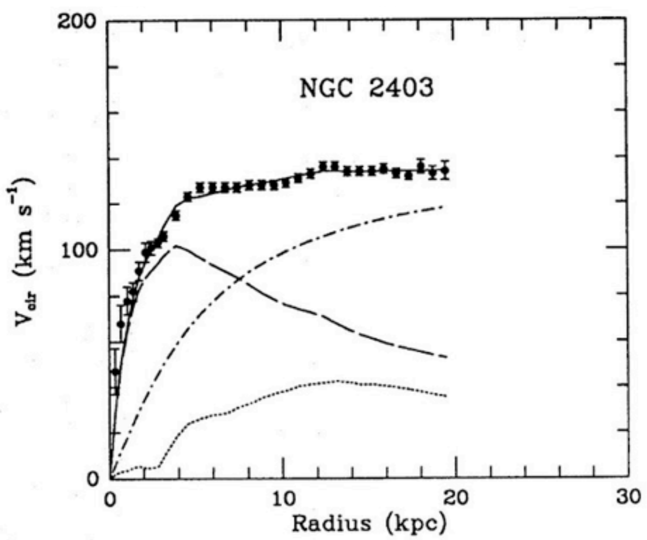


Today's topic:
A gravitational mystery...

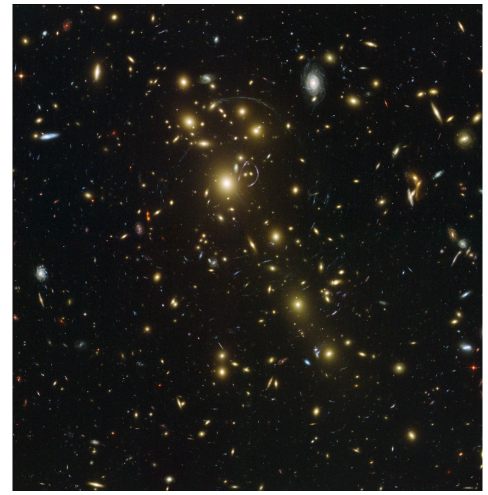


...brought to you by precision astronomy

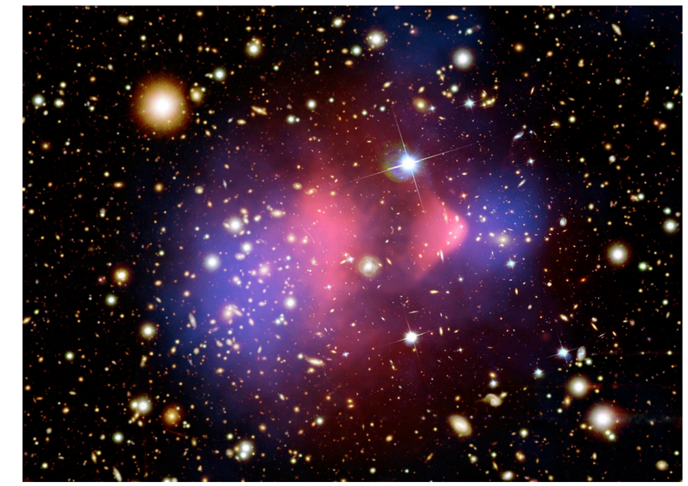
Seven Decades of "Excess Gravitation"



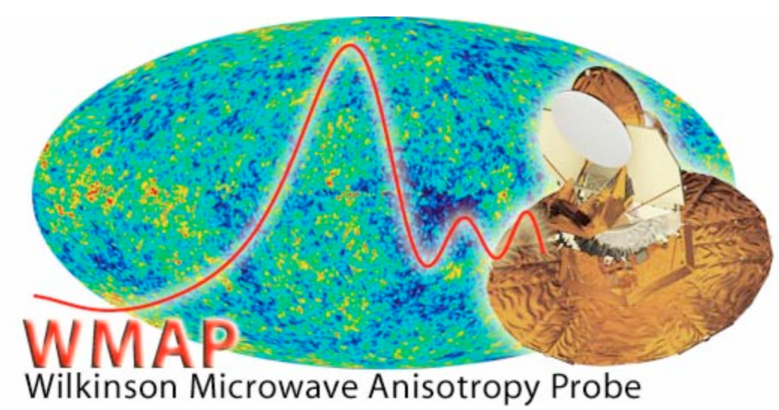
Rotation Curves



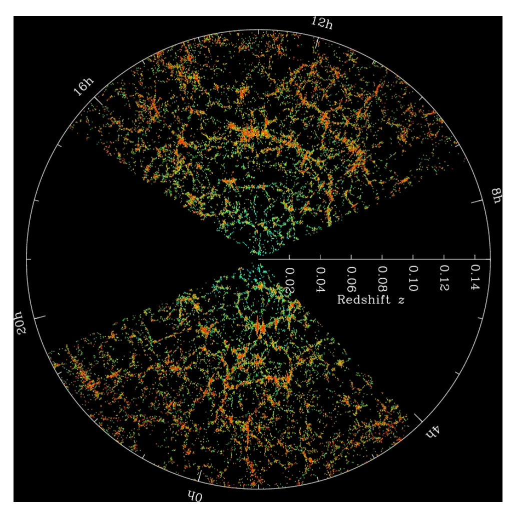
Gravitational Lensing



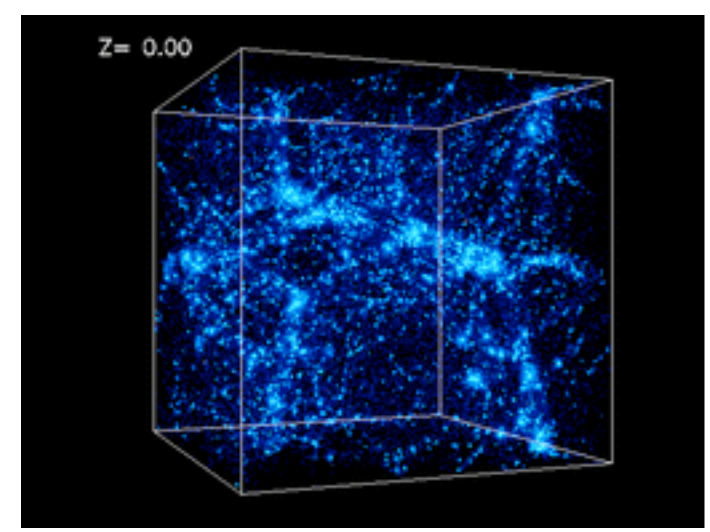
Cluster Collisions



CMB Power Spectrum



Baryon Acoustic Oscillations

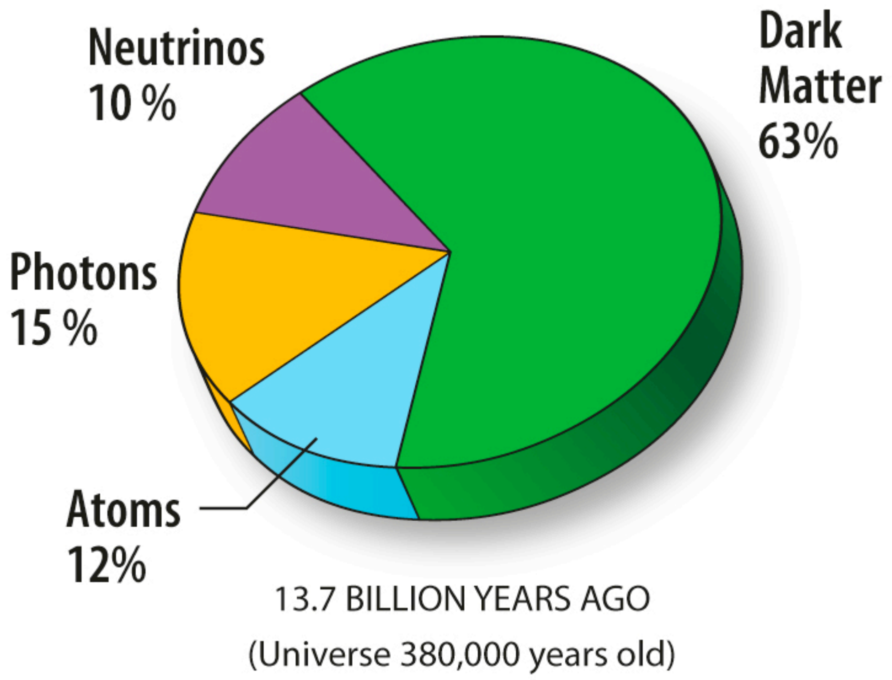


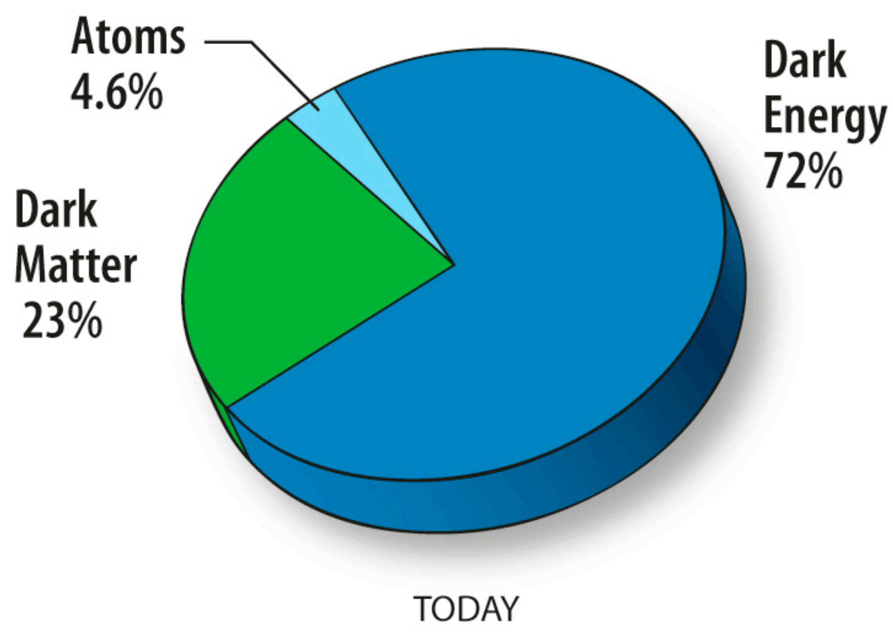
Simulations of Structure Formation

And many others!

The Dark Matter Hypothesis

A substantial fraction of the matter in the universe is in a form that does not interact with photons, rendering it invisible ("dark") to direct electromagnetic observation.





Dark Matter Candidates

- Light neutrinos:

  small fraction, too "hot" to be all of DM
- Weakly-Interacting Massive Particles
- Gravitinos
- Axions
- Sterile Neutrinos
- MACHOs
- ...

Dark Matter is Everywhere

Suppose you decide to search for "terrestrial" dark matter.
What do you know?

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- Cross-sections for interaction between dark matter and itself/other particles are very small.
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- Local density near Earth is around 0.3 GeV/cm^3
  (within a factor of 2 or 3)
- There is a ~230km/sec "WIMP wind" coming from the direction of Cygnus modulated by the yearly variation in the Earth's orbital velocity around the Sun.

Direct Dark Matter Searches

("looking for your lost keys under the street light")

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1. Anomalous nuclear recoils
   (WIMP scattering)
2. Primakoff interactions
   (axion-photon coupling)
3. Periodicity/Directionality
   (the 21st century search for the "aether wind")
4. [Insert your clever idea here]

Direct Dark Matter Searches

("looking for your lost keys under the street light")

1. Anomalous nuclear recoils (WIMP scattering) — XENON, CDMS, CoGeNT, DEAP/CLEAN, LUX, PICASSO, COUPP, CRESST, XMASS, EDELWEISS, ...
2. Primakoff interactions (axion-photon coupling) — ADMX, CAST, ...
3. Periodicity/Directionality (the 21st century search for the "aether wind") — DAMA/LIBRA, DRIFT, DMTPC, ...
4. [Insert your clever idea here]

Hunting for WIMPs

The expected properties of weakly interactive massive particles dictate the search methodology.

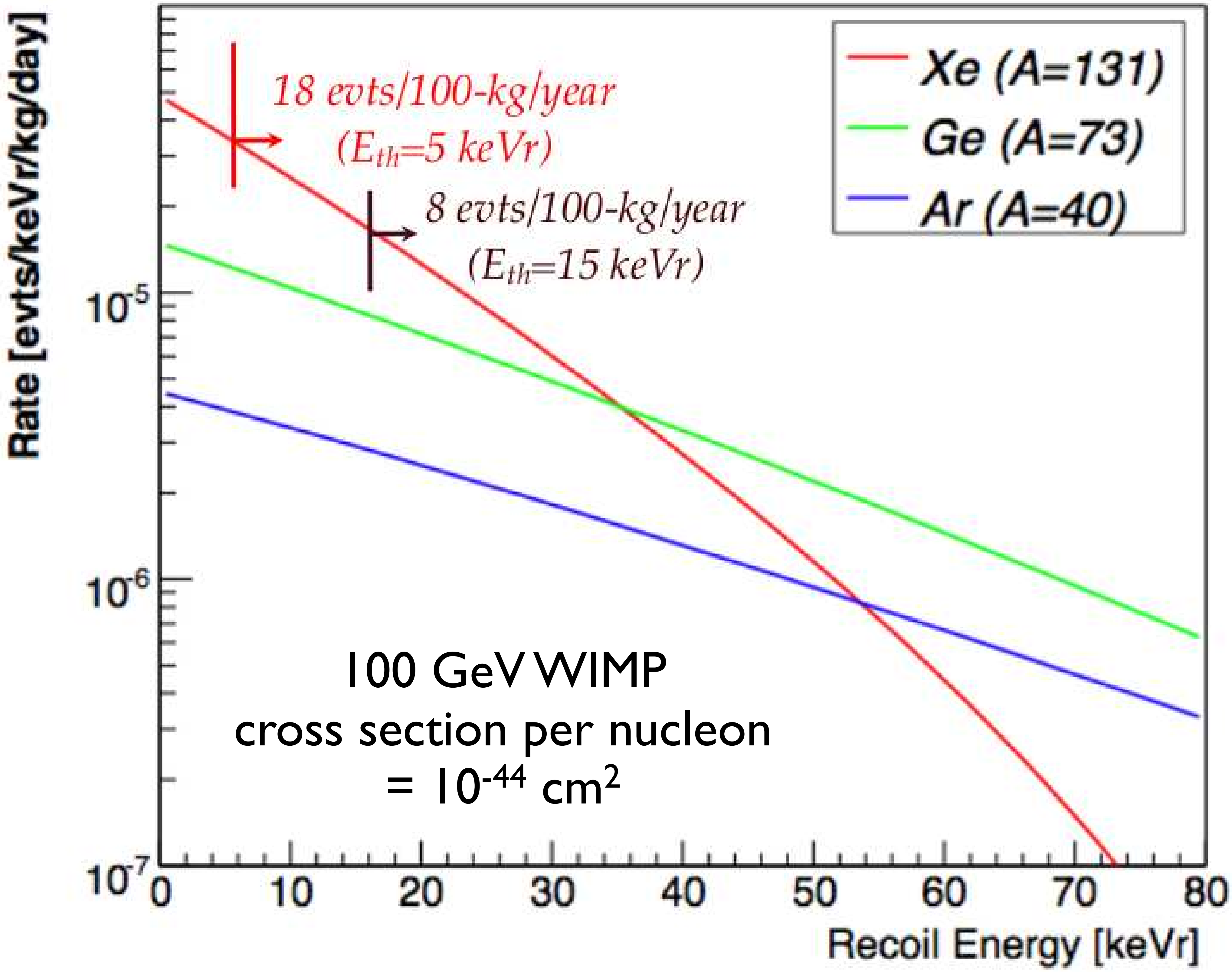
Low momentum transfer:

- High atomic mass target material to maximize coherent enhancement of nuclear recoil cross section.
- Sensitivity to low energy recoil events, with thresholds as low as a few keV of detectable energy.

Extremely low cross-sections:

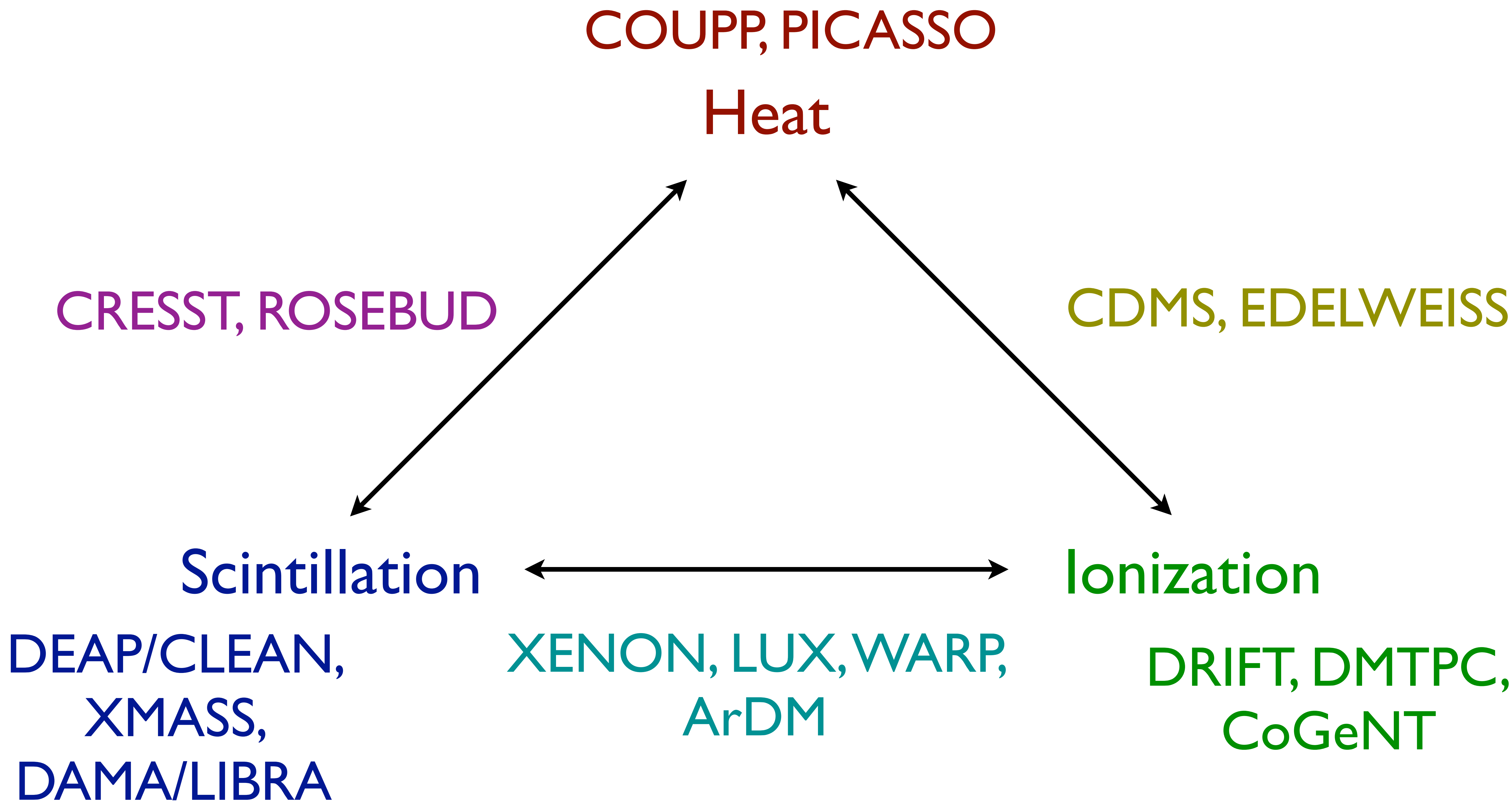
- Large mass of target material.
- Low background detector construction.
- Underground operation to shield cosmic rays.
- Excellent particle ID to allow rejection of background events, especially α, β, γ decays and neutrons.

Hunting for WIMPs



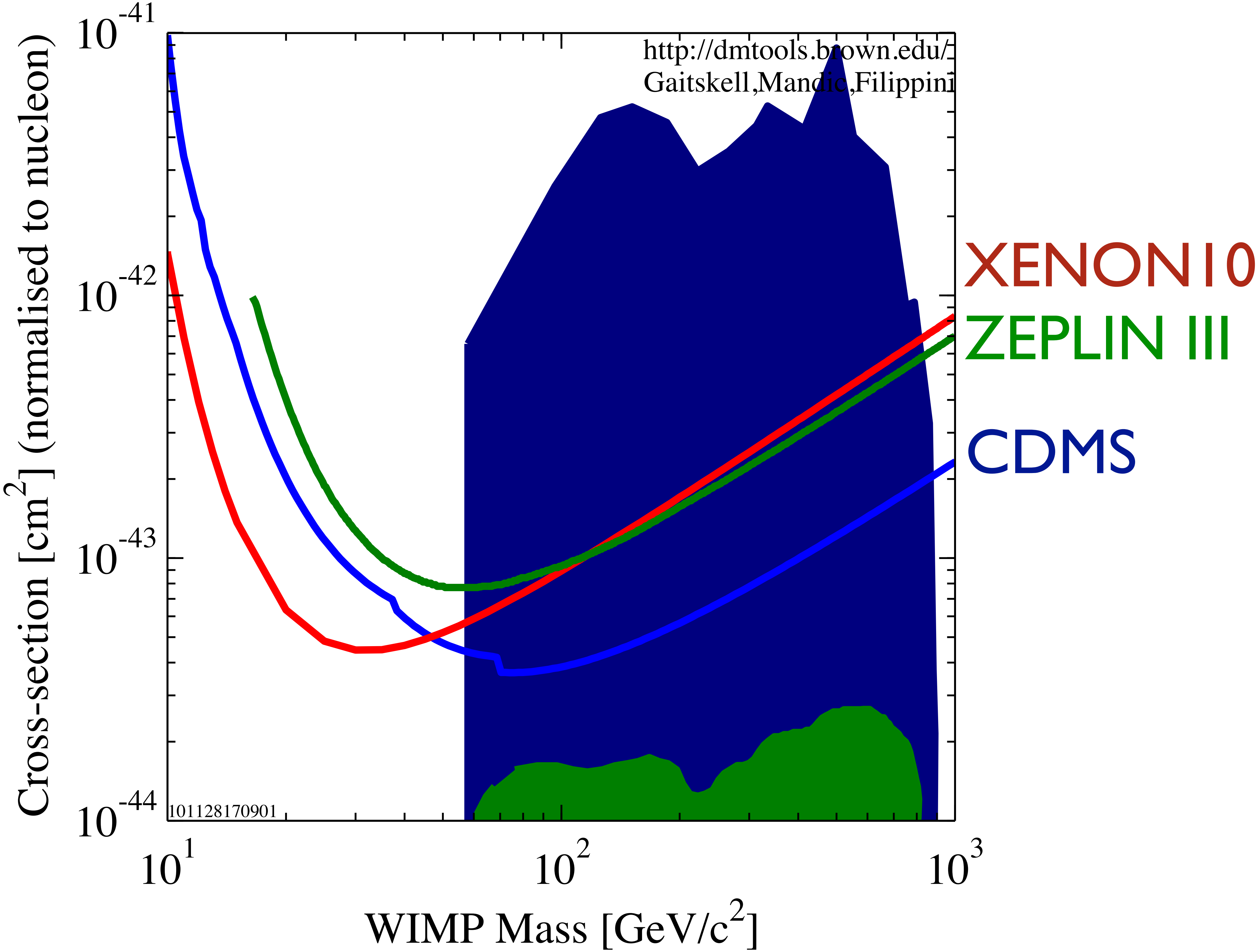
E. Aprile, http://www.slac.stanford.edu/econf/C080625/pdf/0018.pdf

Background Discrimination

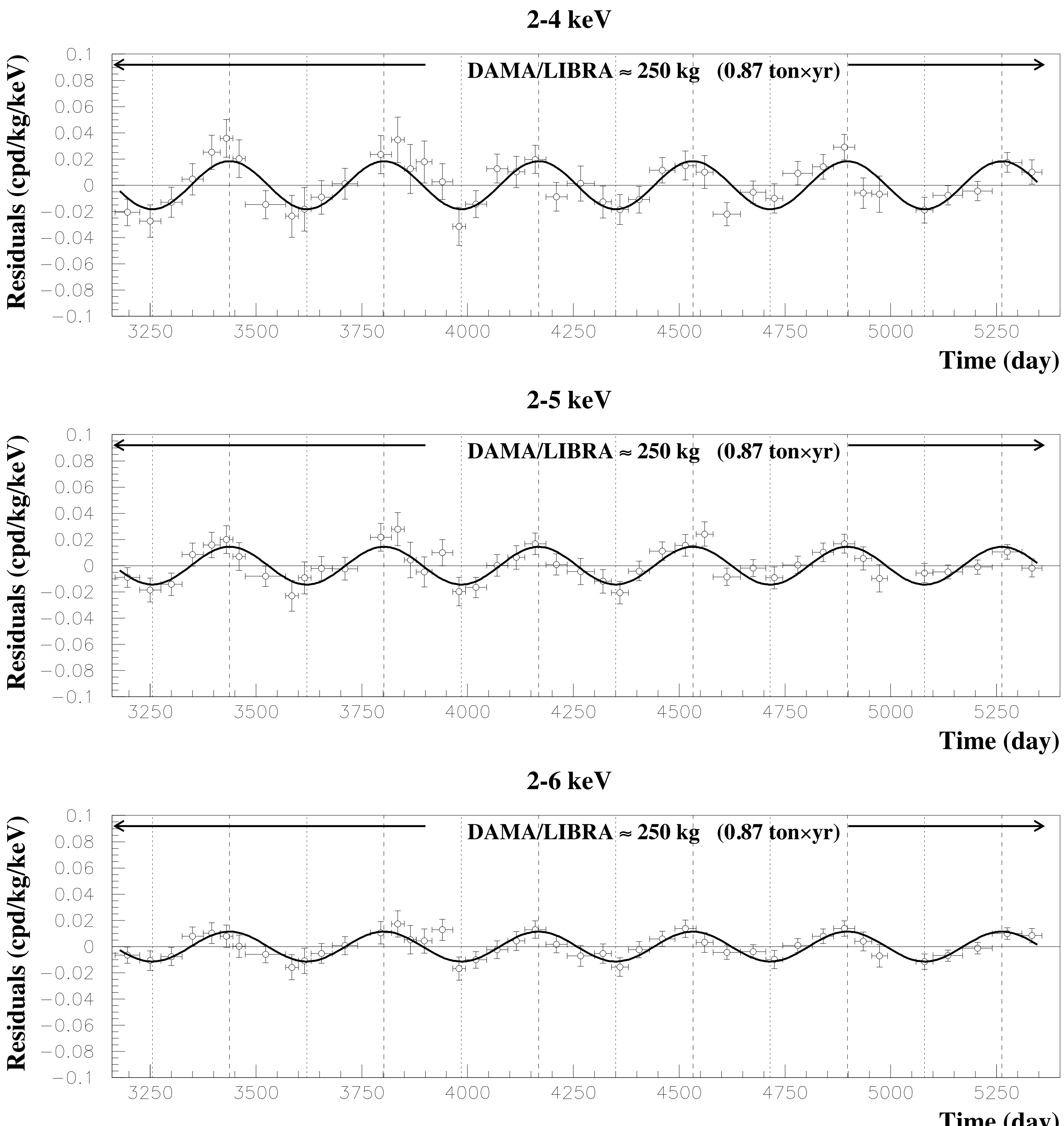


Experimental Results:
How are we doing so far?

Null Results



DAMA/LIBRA: Data



As of 2010, an annual modulation in the 2-6 keV energy window has been observed in NaI detectors underground at Gran Sasso with 8.9σ C.L. over 13 annual cycles.

But, is it dark matter?

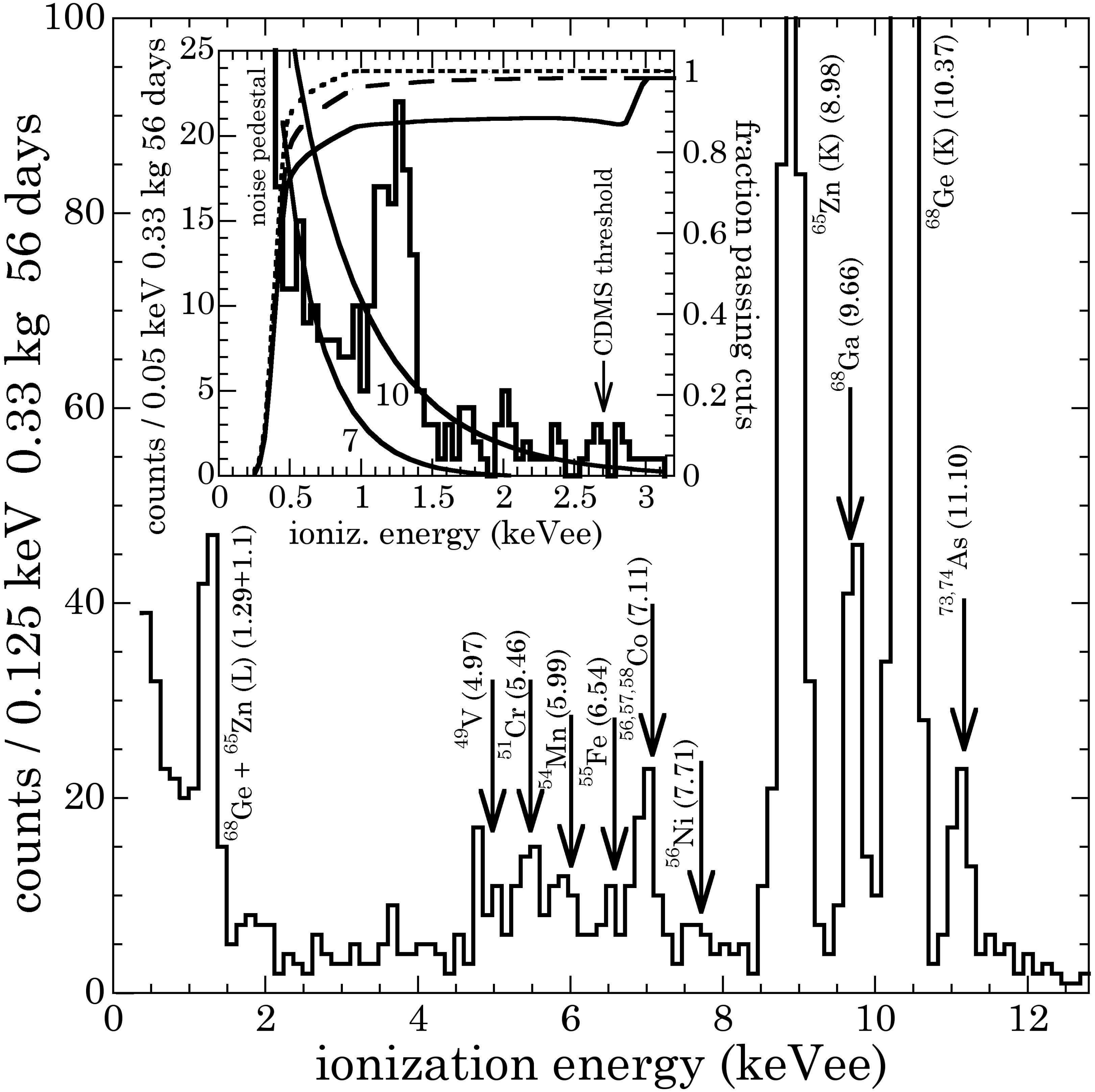
arXiv:1002.1028

DAMA/LIBRA Interpretation

- Due to presence of backgrounds, cannot identify dark matter in the NaI detectors on an event by event basis.
- Annual modulation is predicted in detector rates due to relative motion of Earth through local dark matter cloud.

- Modulation period of 1 year could be result of many things.
- Need confirmation with another target!

CoGeNT: Data

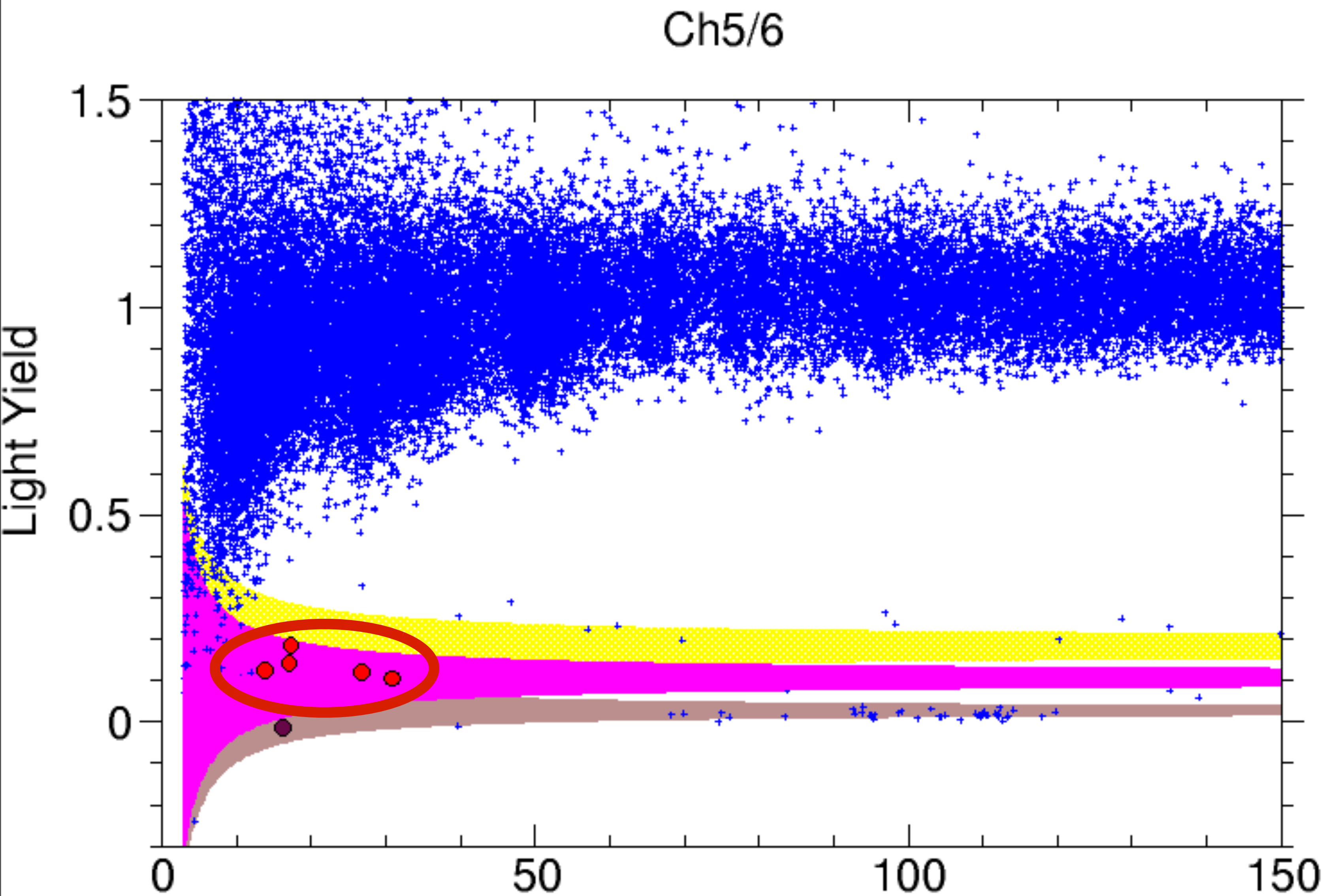


Extremely low threshold germanium detectors in the Soudan Mine see a slight excess of events (90% C.L.) below 3.2 keV that could be "light WIMPs", in the ~10 GeV mass range.

But it also could be noise or other backgrounds...

arXiv:1002.4703v2

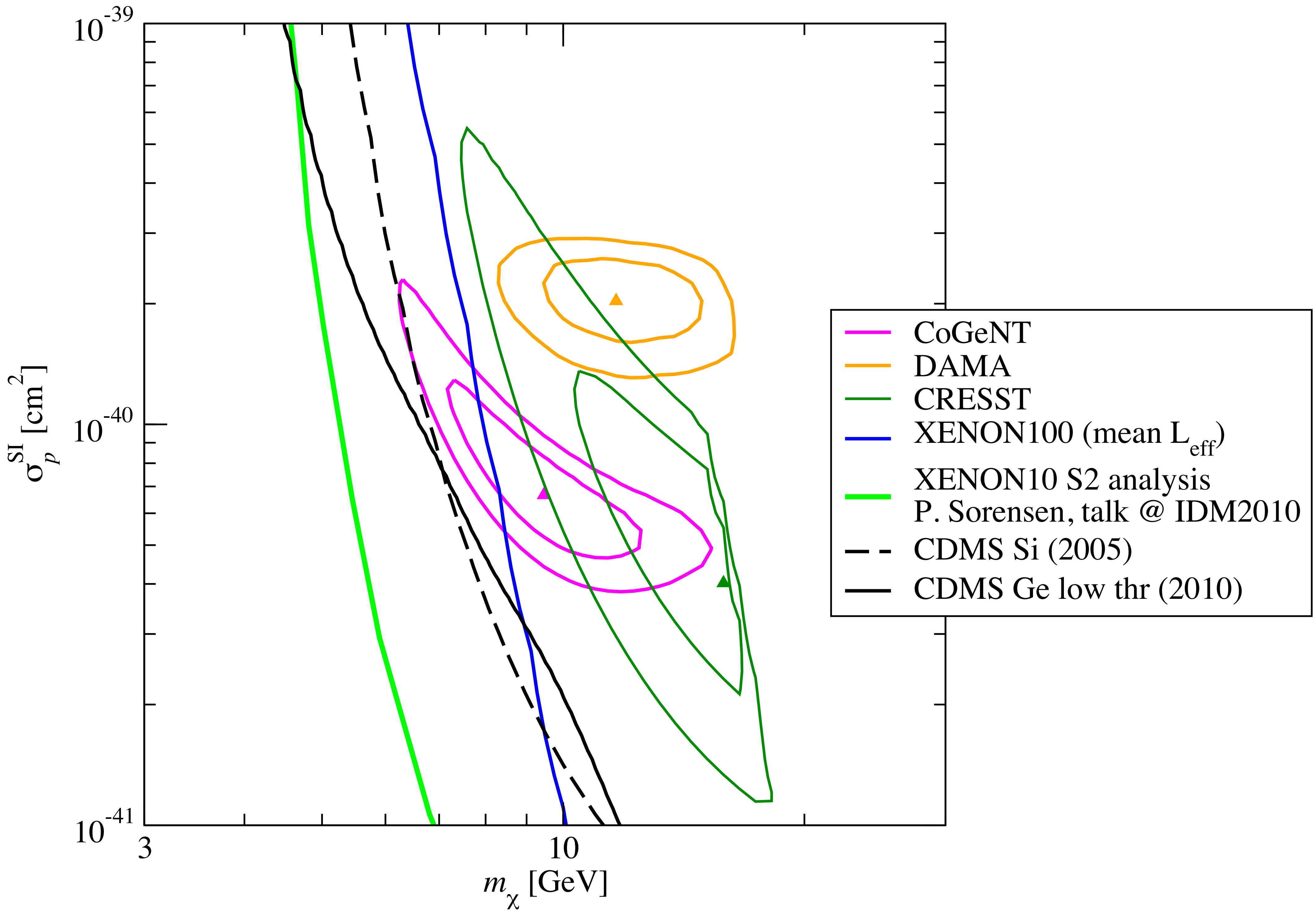
CRESST



$CaWO_4$ crystals held near the superconducting transition (~15 mK) observe 32 oxygen recoils with an estimated background of 8.7±1.4 events.

http://indico.in2p3.fr/contributionDisplay.py?sessionId=9&contribId=195&confId=1565

Tension with Null Results



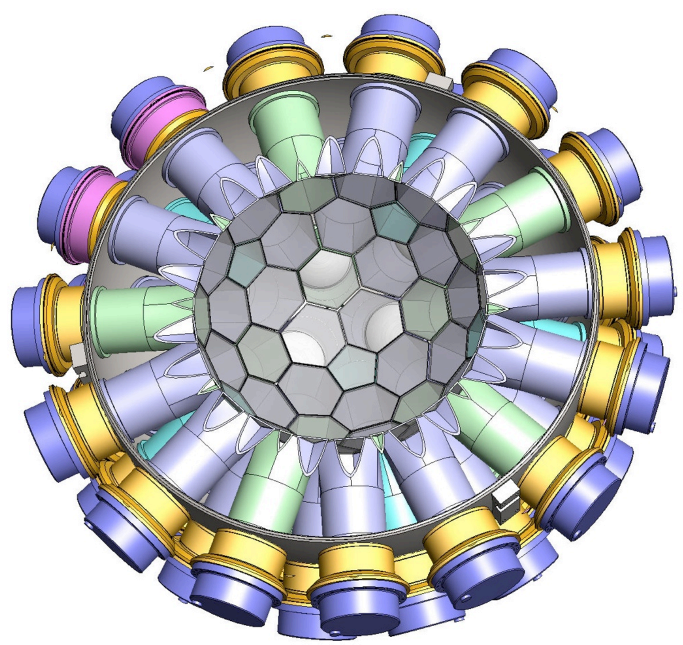
arXiv:1011.5432

Current state of play:

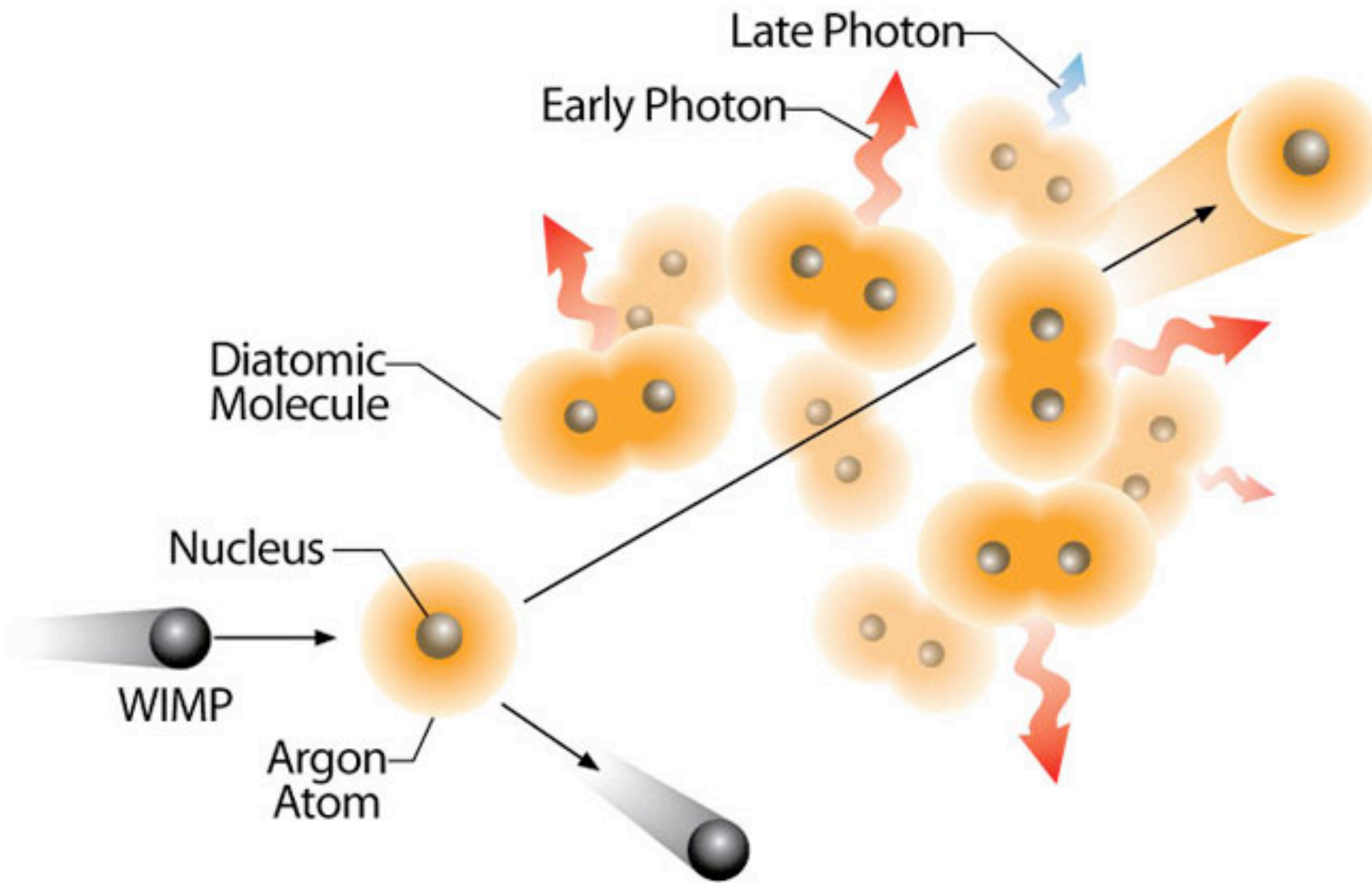
Existing positive results are both in tension with each other and with the null results of other experiments.

Clearly, more data would be useful....

DEAP/CLEAN: A Highly Scalable Search for Dark Matter with Argon and Neon



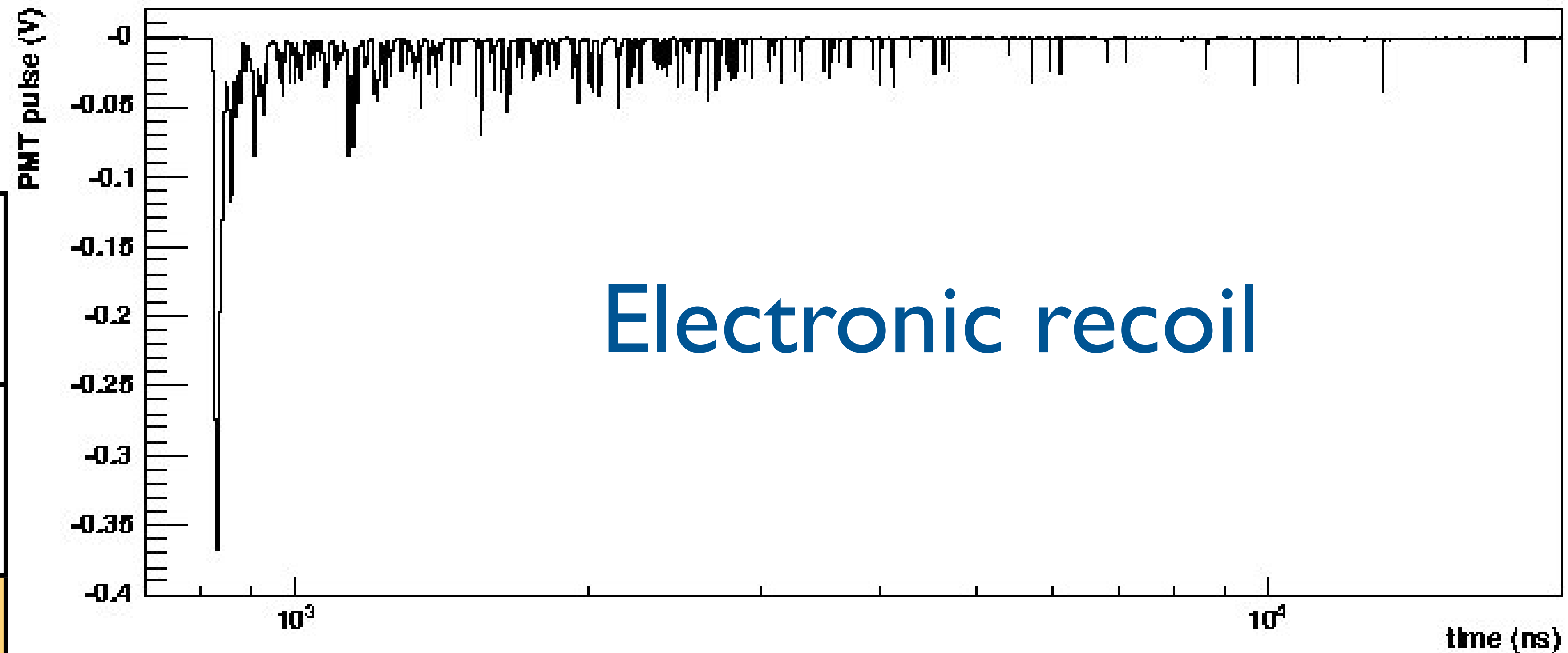
Scintillation in Noble Liquids

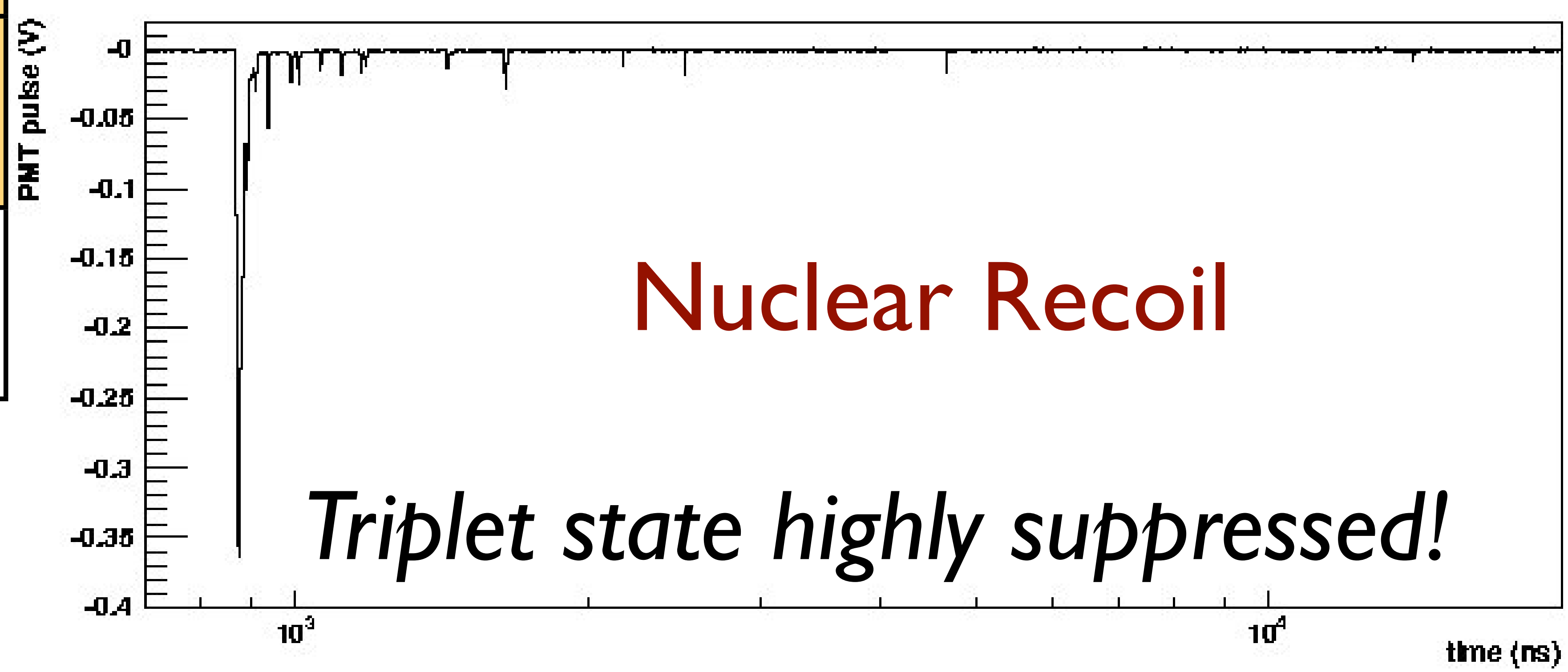


Energy deposition in noble liquids produces short lived excited diatomic molecules in singlet and triplet states.

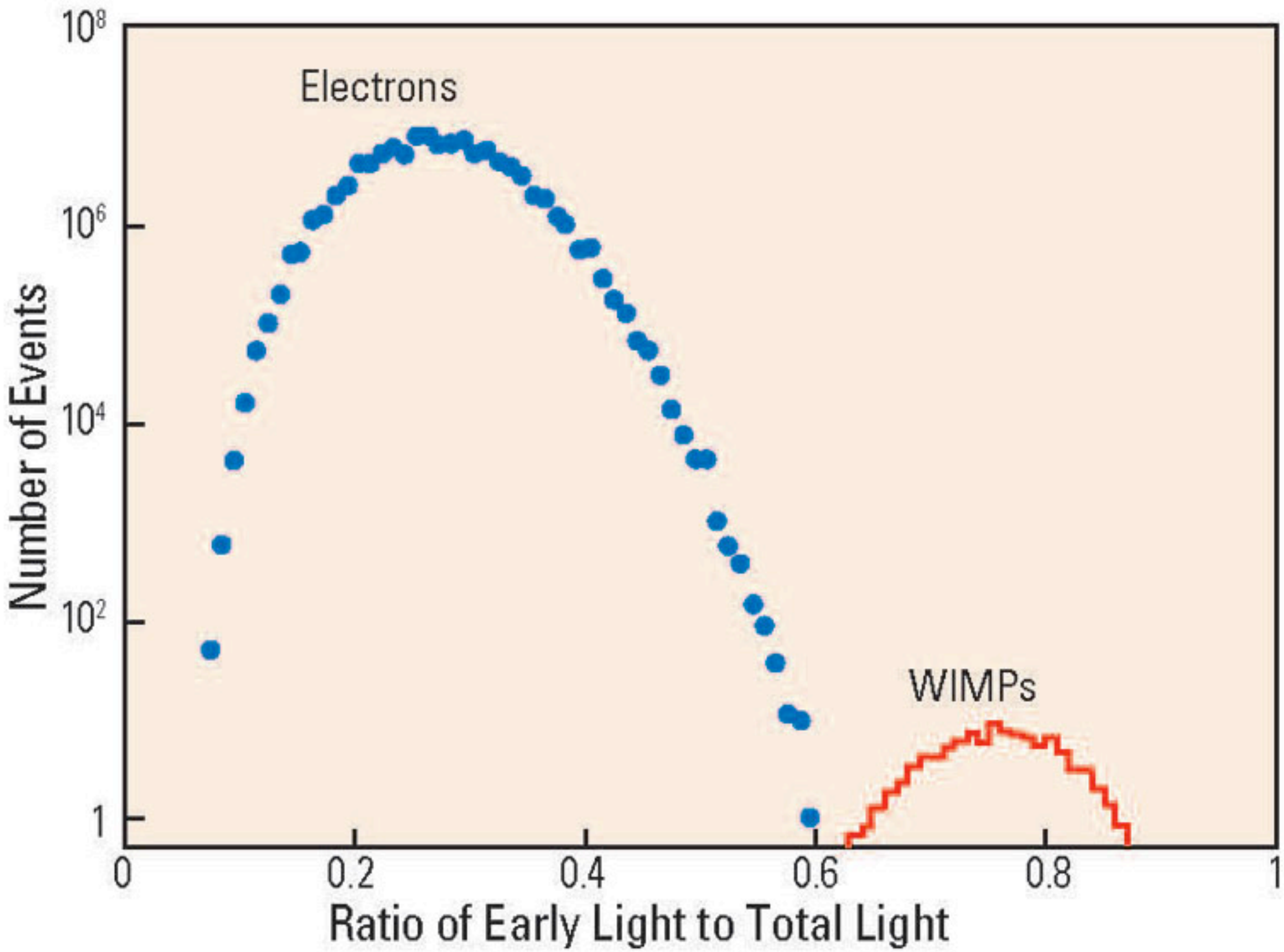
Pulse Shape Analysis

	Singlet	Triplet
He	~10ns	13 s
Ne	<18.2 ns	14.9 μs
Ar	7 ns	1.60 μs
Xe	4.3 ns	22 ns





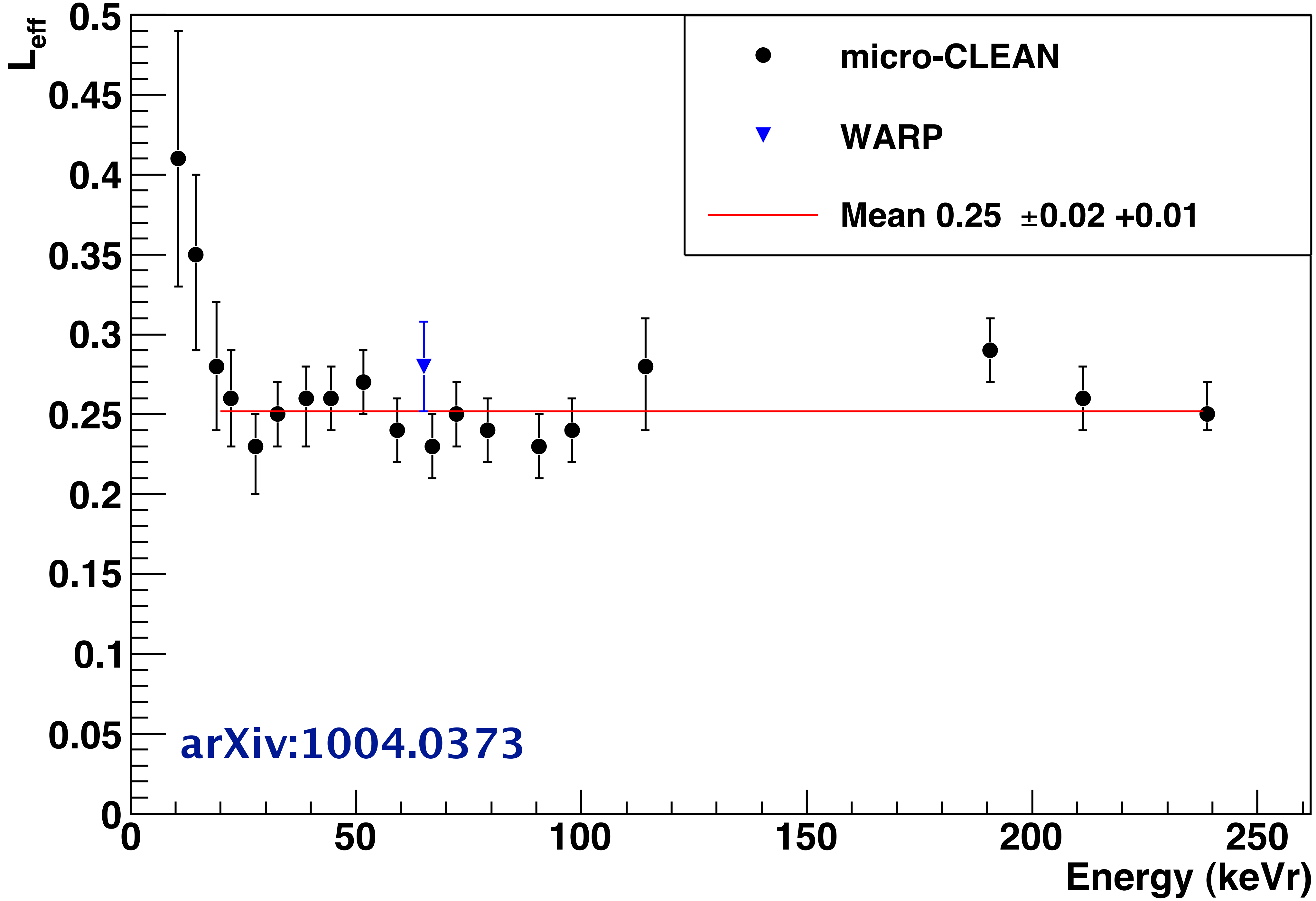
Rejecting Electron-like Events in Argon



Discriminate with ratio of prompt to total light

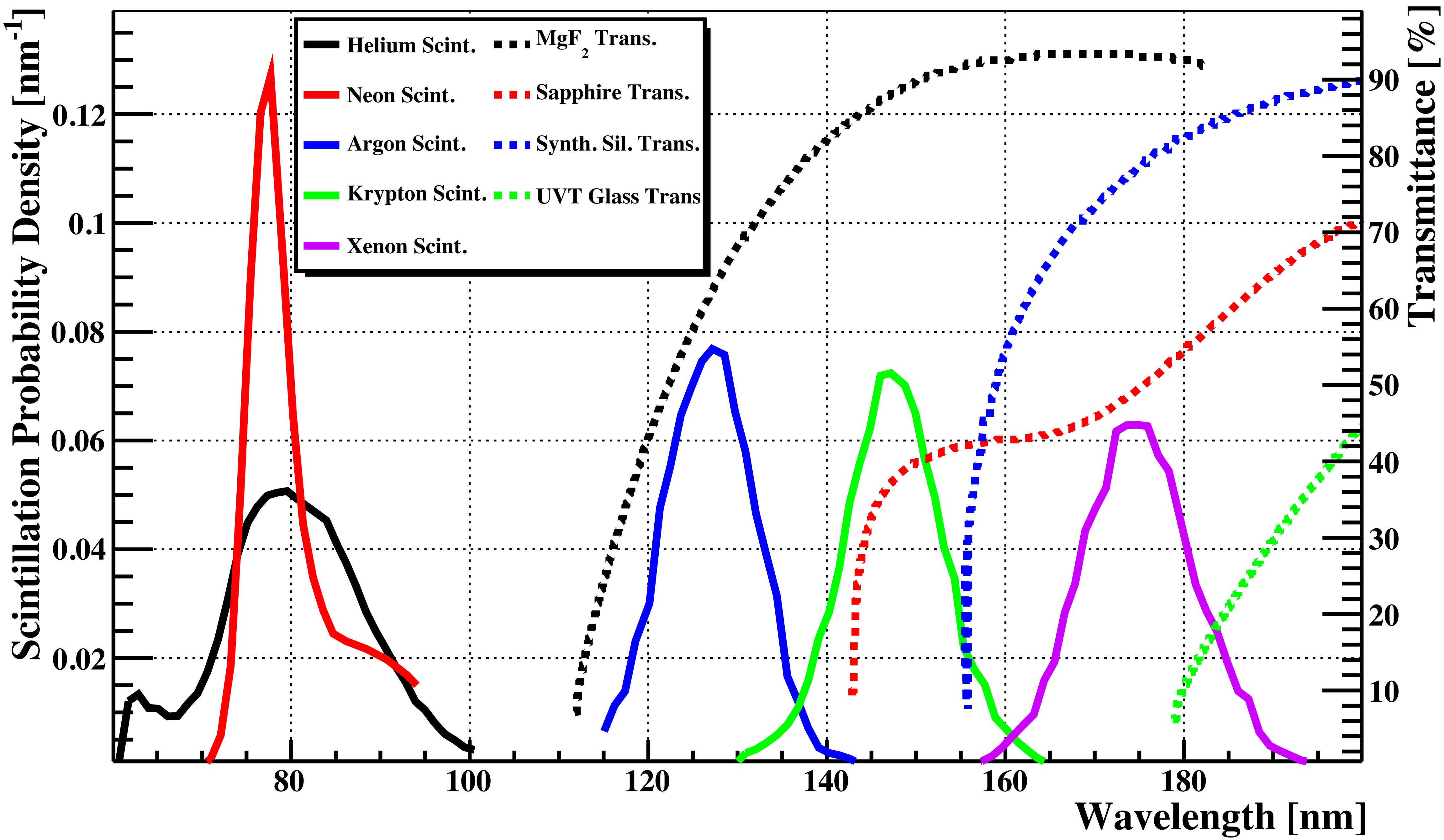
Reject beta and gamma backgrounds with greater than 10^8 efficiency

Quenching



Nuclear recoils produce less light per keV than electrons.

Observing Extreme UV



Almost everything absorbs 128 nm light!

TPB can wavelength shift EUV up to 440 nm with high efficiency.

Single Phase Ar/Ne Detectors

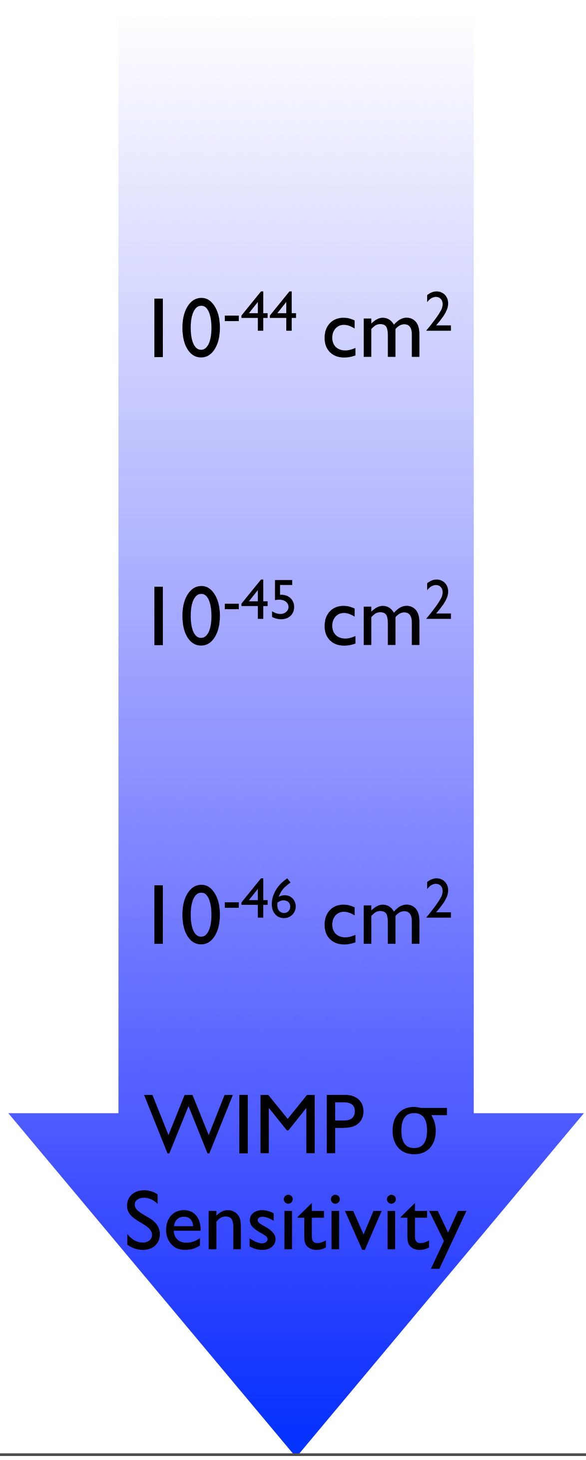
Advantages:

- Target material is very inexpensive.
- No need for electric fields to drift charge.
  - Simpler detector design
  - Able to use a spherical geometry
  - Does not require ^{39}Ar-depleted argon for large detectors
- Neon is clean enough to use for pp solar neutrinos

Disadvantages:

- Lower A^2 than Xe or Ge reduces coherent scattering enhancement
- Self-shielding from external backgrounds not as good as some other materials
- Atmospheric argon contains a high rate beta decay isotope, ^{39}Ar (1 Bq/kg, 270 year half-life)

The DEAP and CLEAN Family of Detectors



DEAP-0:
Initial R&D detector

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

picoCLEAN:
Initial R&D detector

microCLEAN:
4 kg LAr or LNe
2 cold PMTs
surface tests at Yale

MiniCLEAN:
500 kg LAr or LNe (150 kg fiducial mass)
92 cold PMTs
At SNOLAB 2011/2012

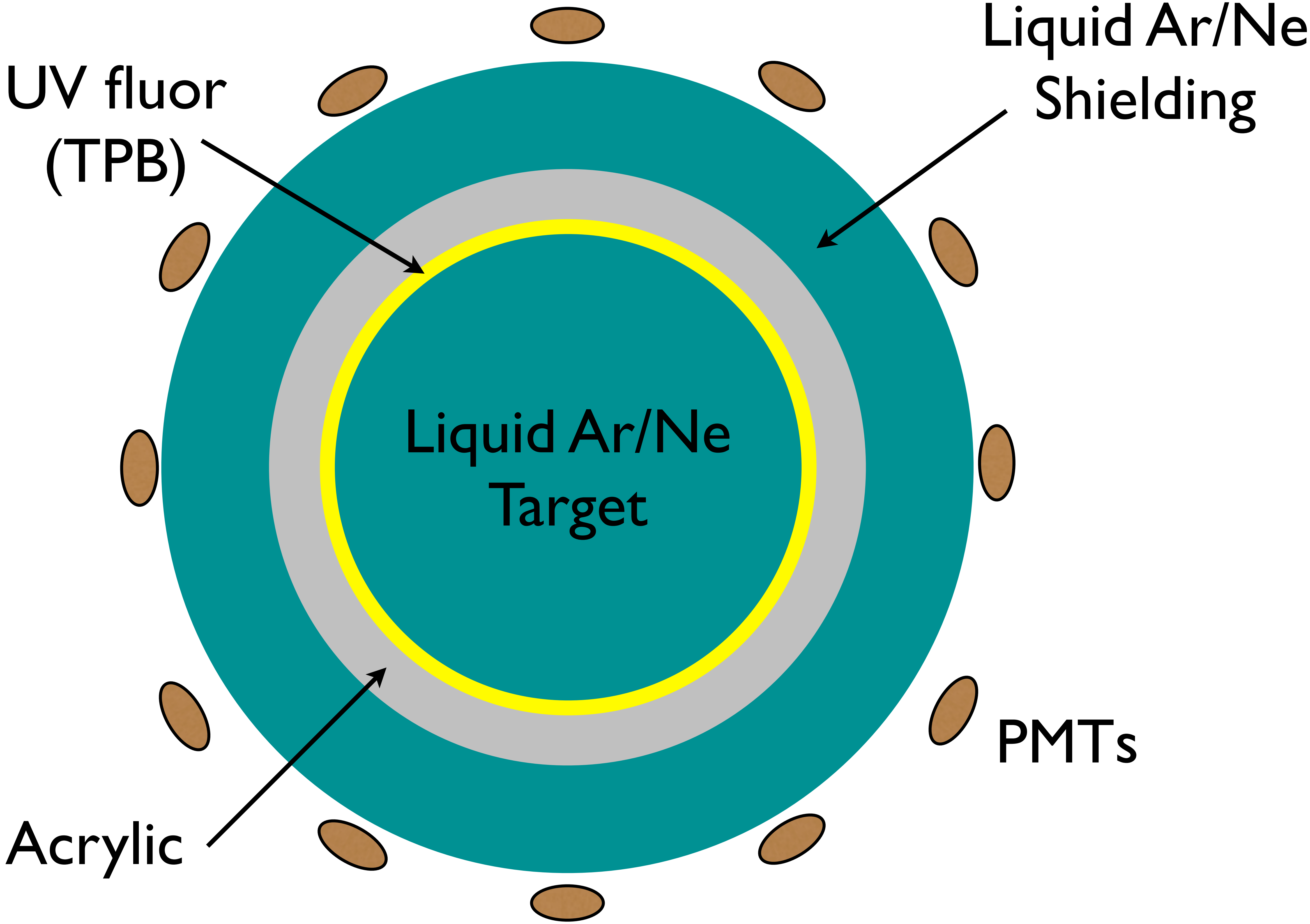
DEAP-3600:
3600 kg LAr (1000 kg fiducial mass)
266 warm PMTs
At SNOLAB 2012

50-tonne LNe/LAr Detector:
pp-solar ν, supernova ν, dark matter <10^{-46} cm^2
~2016?

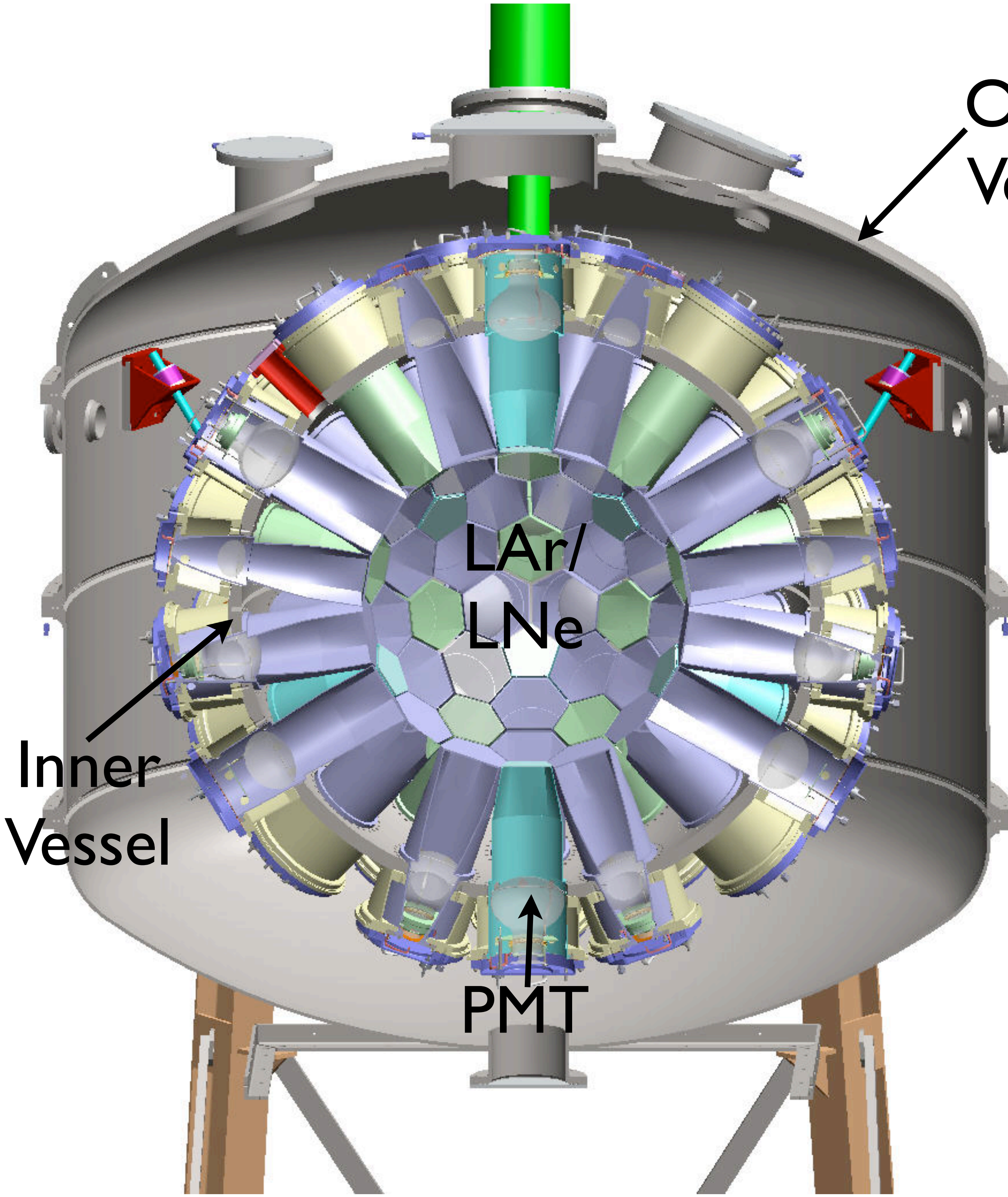
MiniCLEAN Goals

- Demonstrate the technical features of a 4π single-phase detector using both liquid argon and neon.
- Characterize detector response to produce signal and background distributions using combination of calibration and Monte Carlo. Leverage this knowledge in our analysis.
- Perform a WIMP dark matter search competitive with and complementary to next generation experiments with O(100 kg) fiducial mass.
- Develop the experience and verified simulation tools to design a 50 ton full-size CLEAN experiment.

Simplified View



A Less Simple View



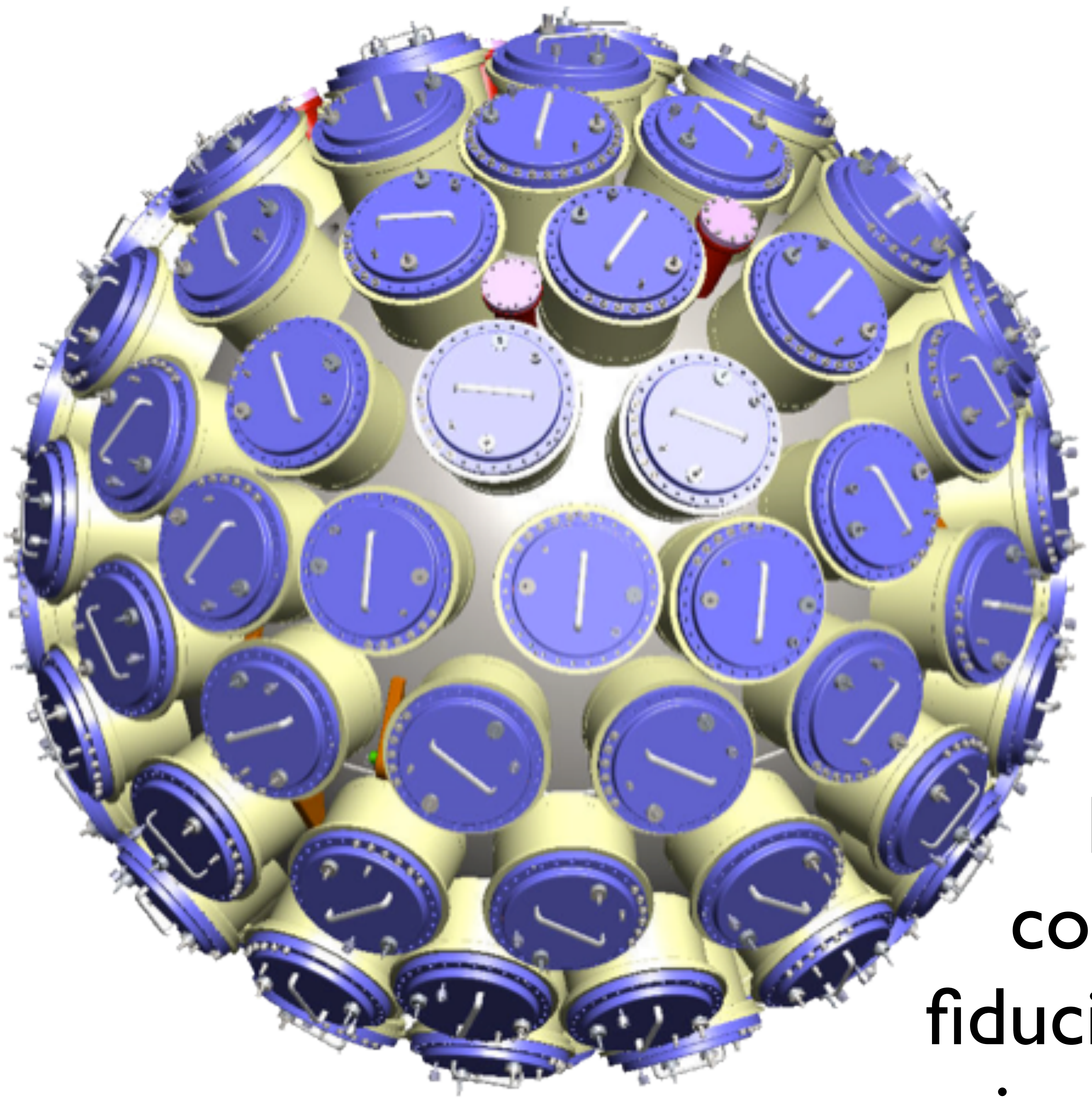
92 8" PMTs

TPB @ R=43 cm

PMTs @ R=81 cm

Courtesy J. Griego

Inner Vessel

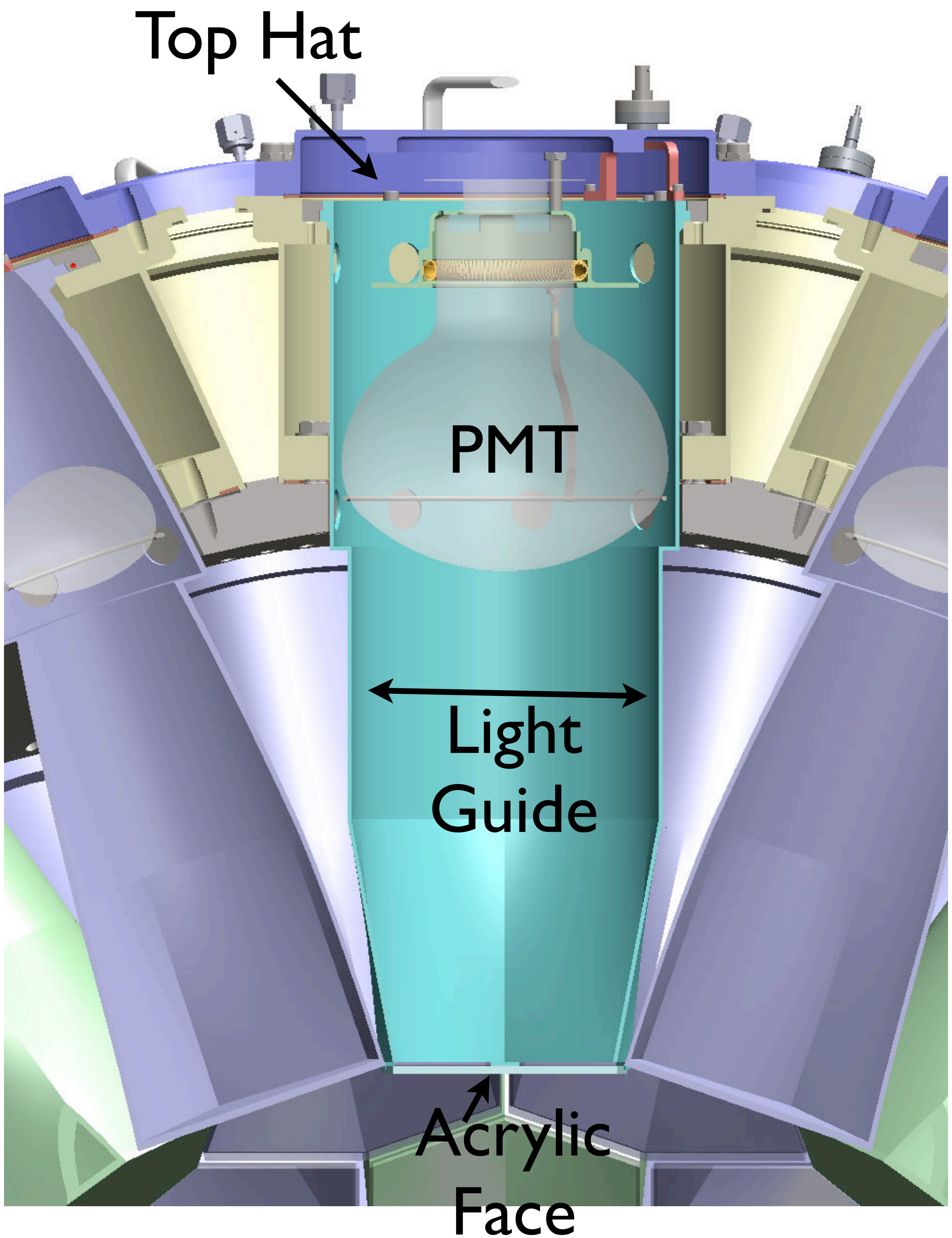


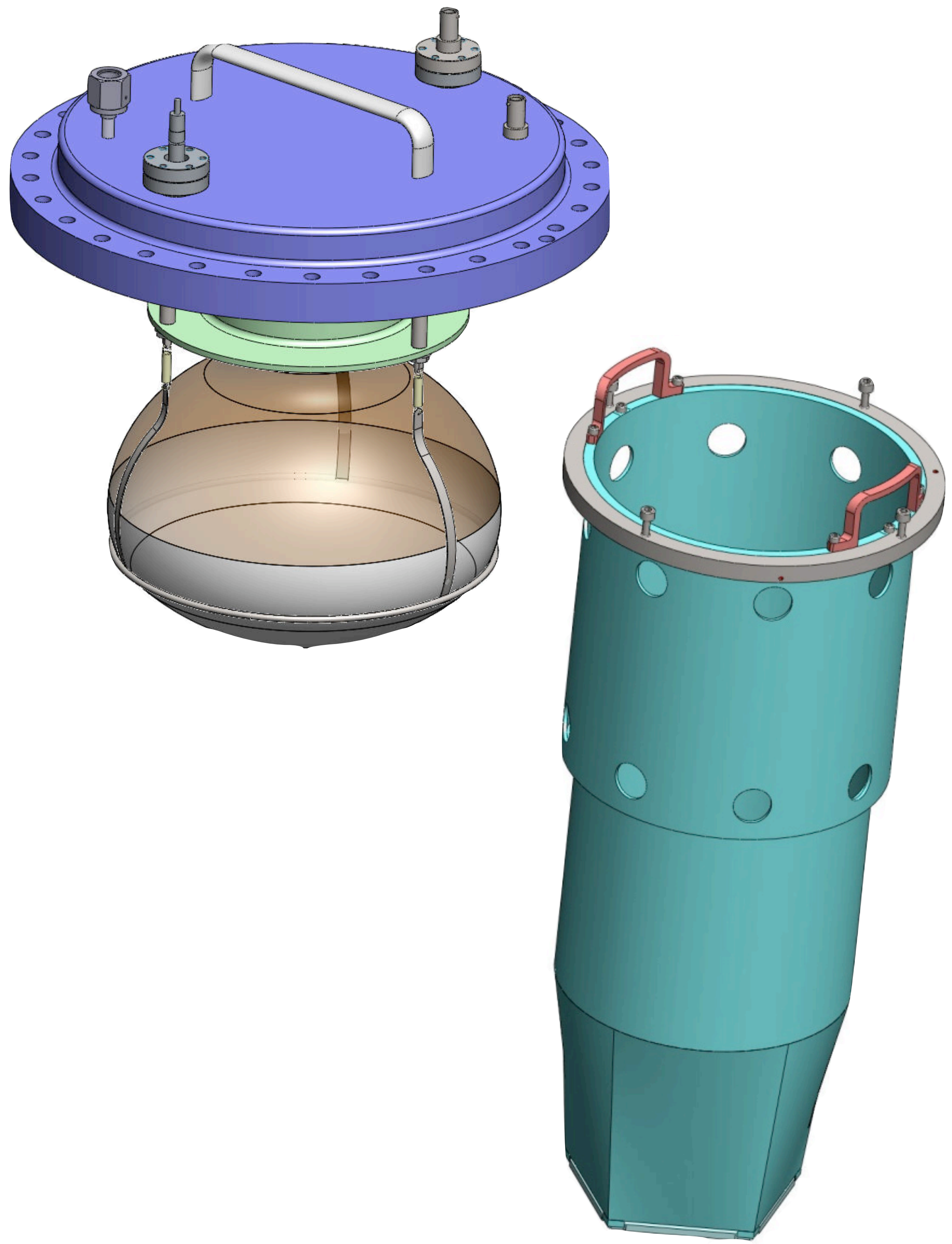
Cassettes are inserted through "portholes" in spherical inner vessel.

Modular design allows components closest to the fiducial volume to be assembled in a glove box and stored in vacuum until installation

Courtesy J. Griego

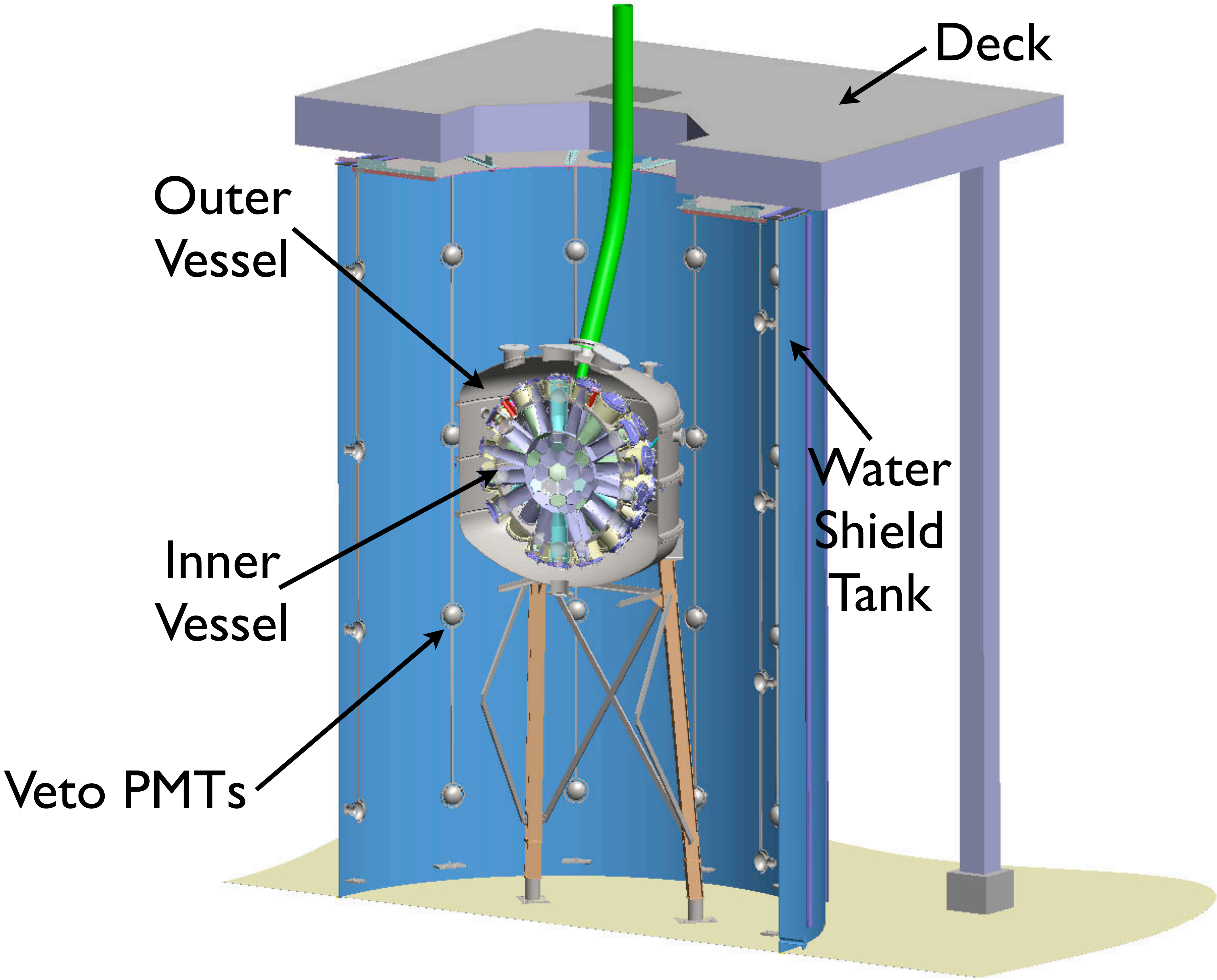
Optical Cassettes





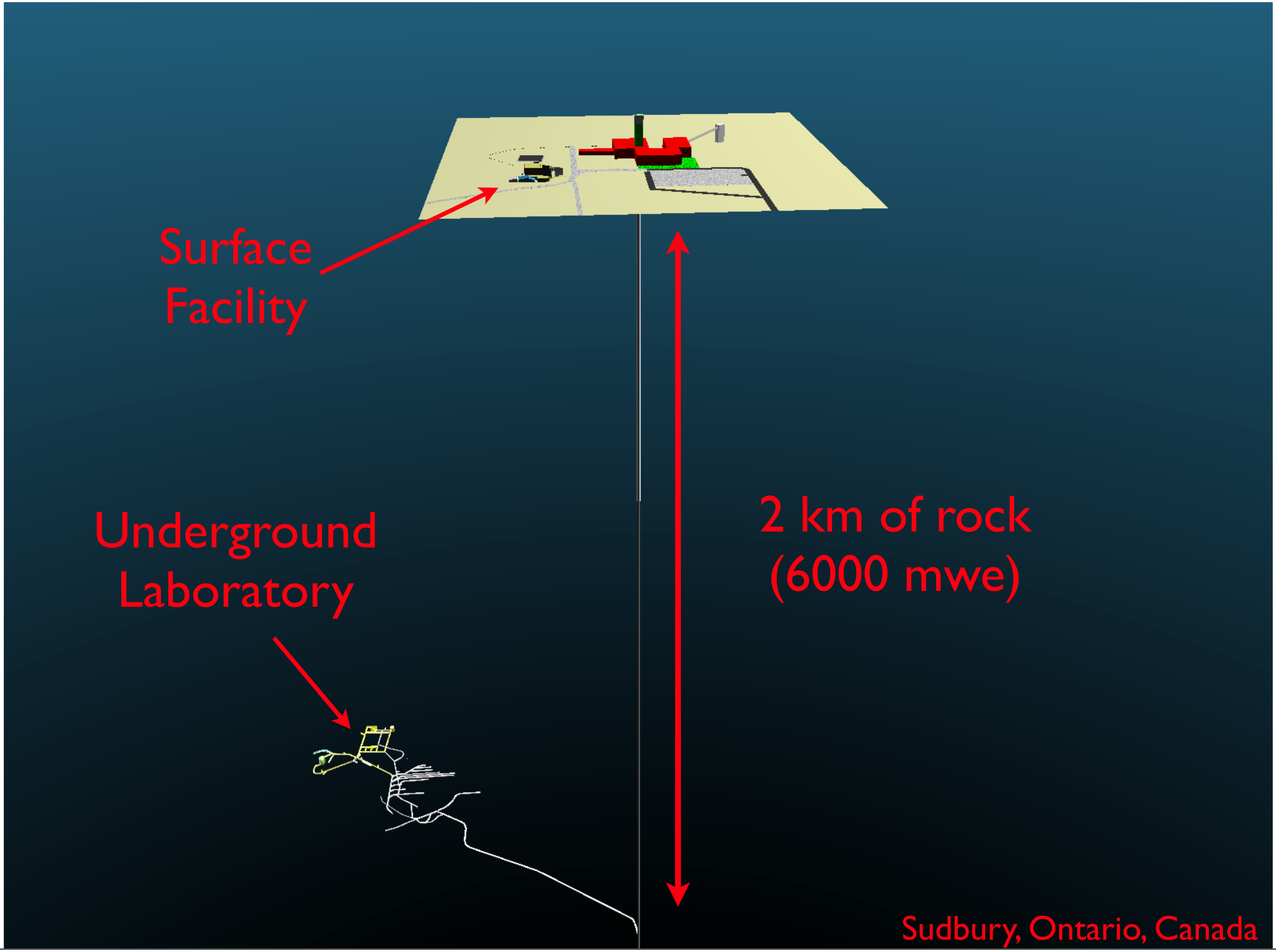
Courtesy J. Griego

Water Shielding

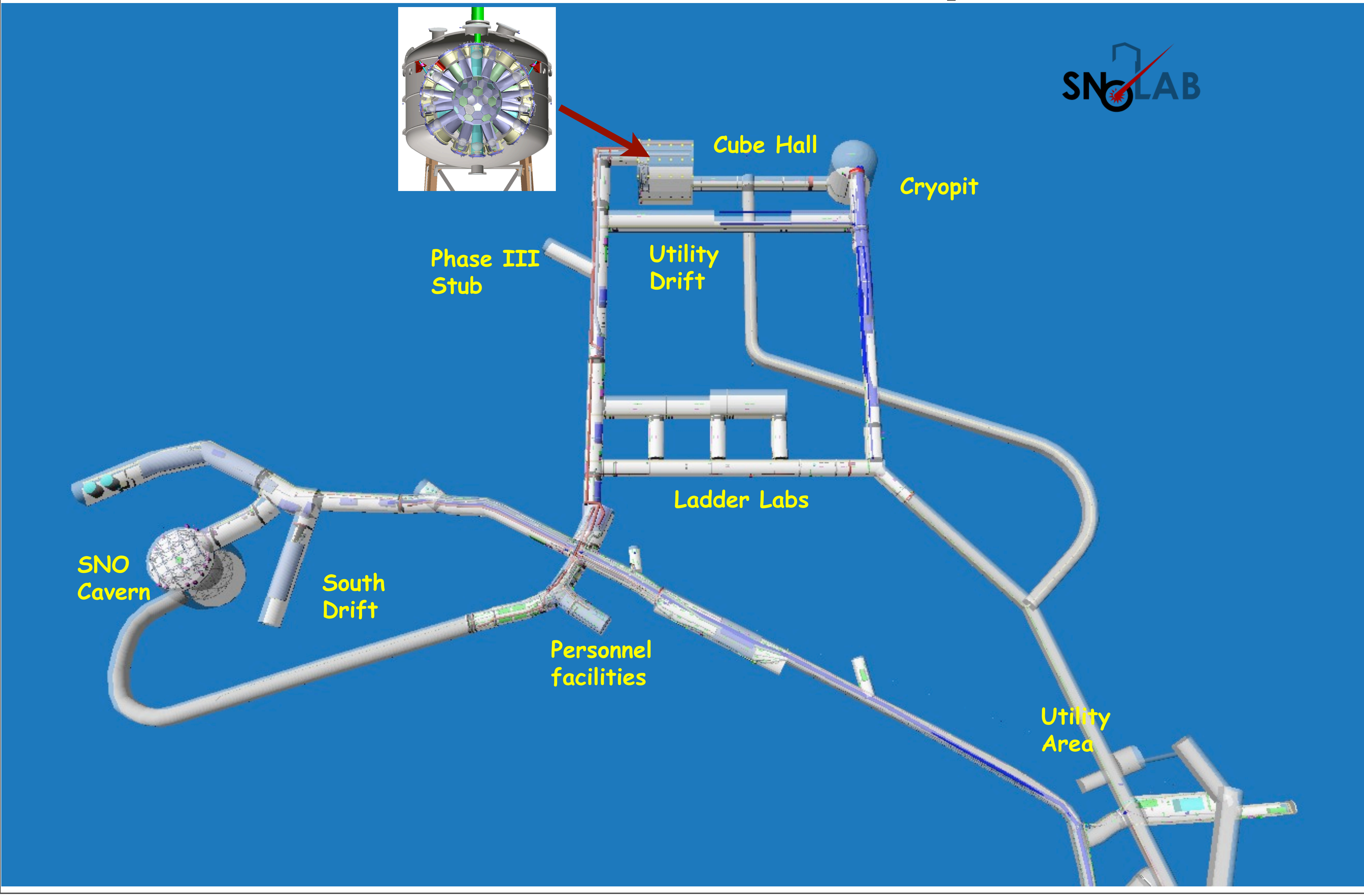


Courtesy J. Griego

SNOLAB


Surface
Facility
Underground
Laboratory
2 km of rock
(6000 mwe)
Sudbury, Ontario, Canada

SNOLAB Facility



Construction Progress: Cube Hall

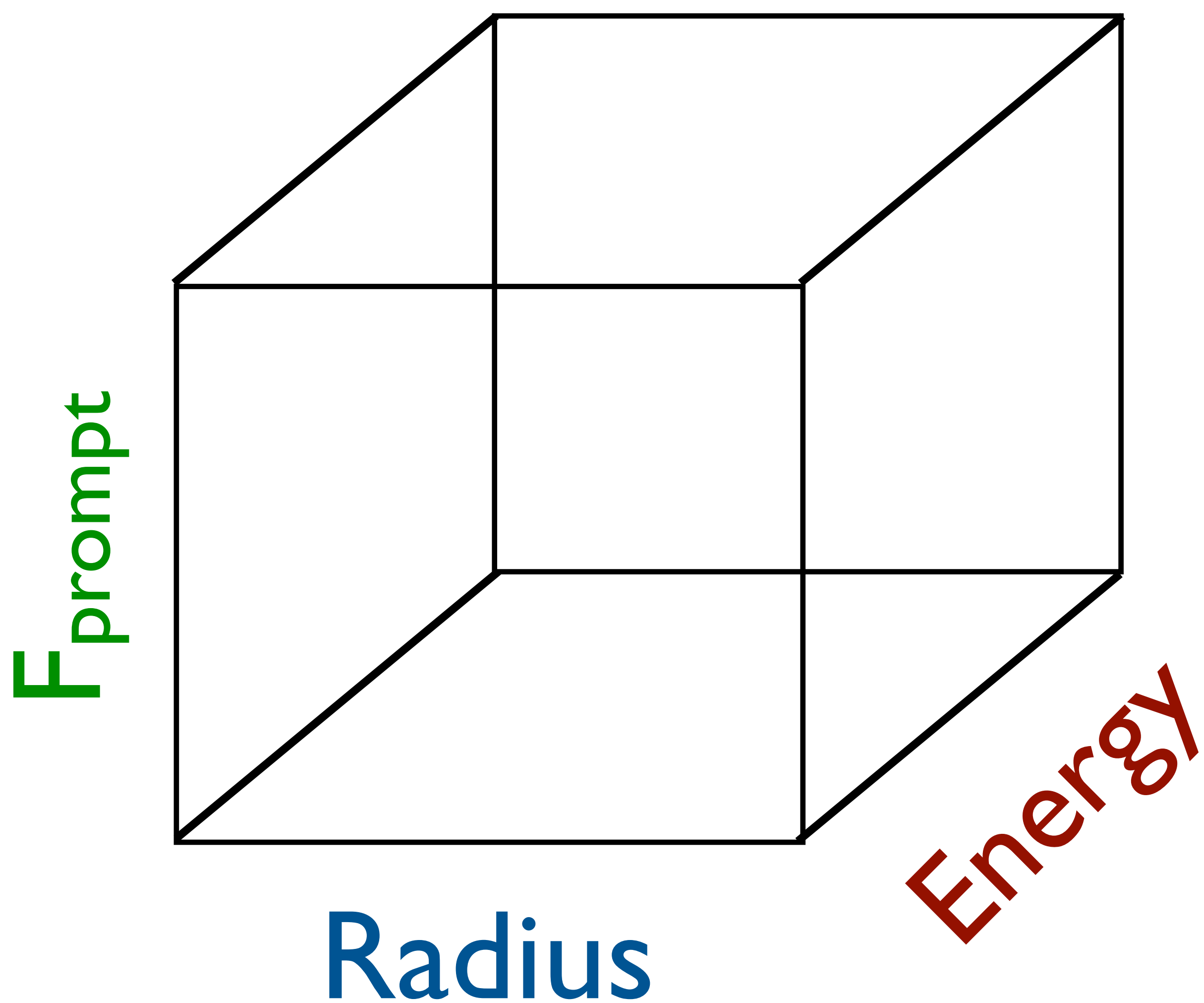
Courtesy F. Duncan

Construction Progress: Outer Vessel

Construction Progress: Inner Vessel

MiniCLEAN WIMP Analysis

Perform a blind analysis with signal box in three reconstructed observables:

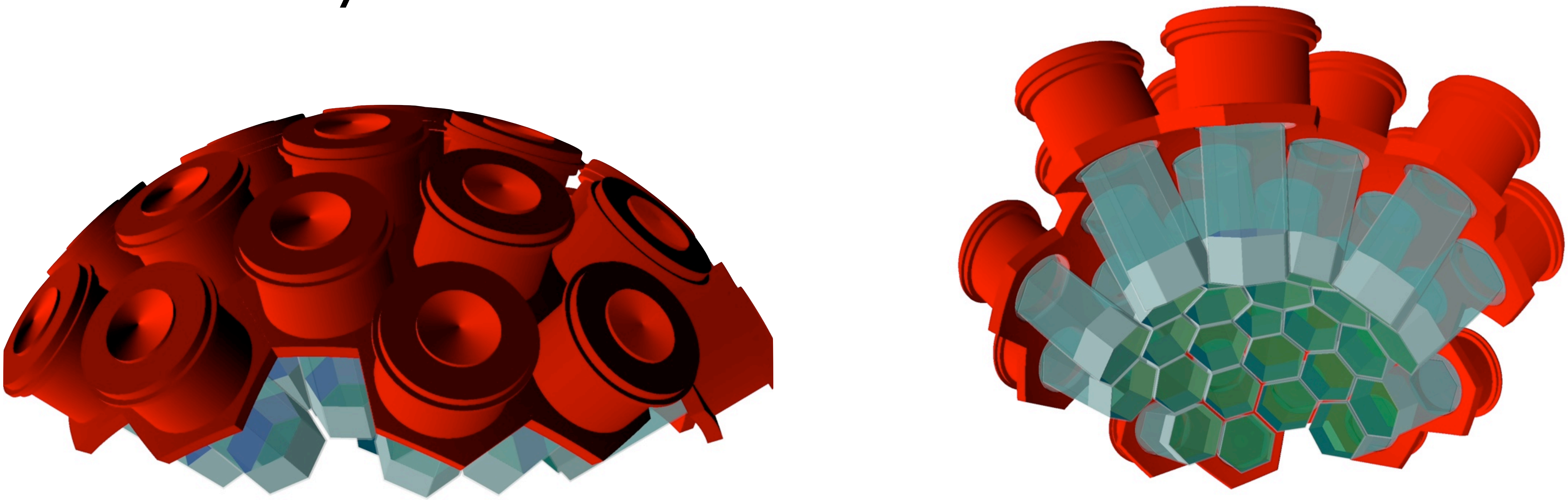


Use calibration data, simulation, and systematic uncertainties to optimize the final box.

Simulation

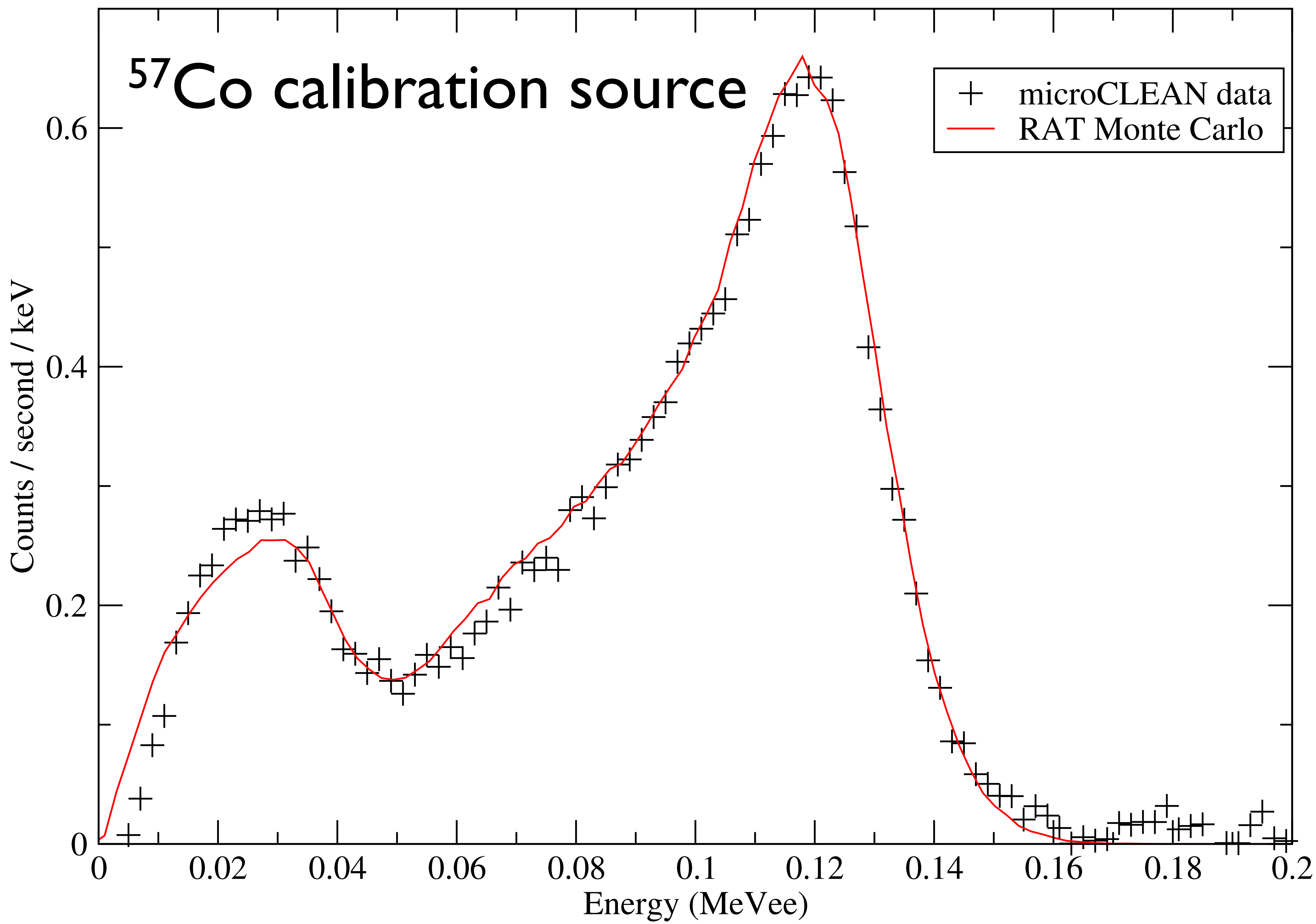
We are using our simulation and analysis tool, RAT, to:

- Optimize design of cassettes
- Develop position reconstruction algorithms
- Test cuts for different classes of backgrounds
- Stress-test the data acquisition software
- Analyze microCLEAN data!



Sections of inner vessel from RAT

MicroCLEAN Comparison



Backgrounds

Major:

- ^{39}Ar: 1 Bq per kg of atmospheric argon
- PMT Neutrons
- Rn daughters on surfaces

Sub-dominant:

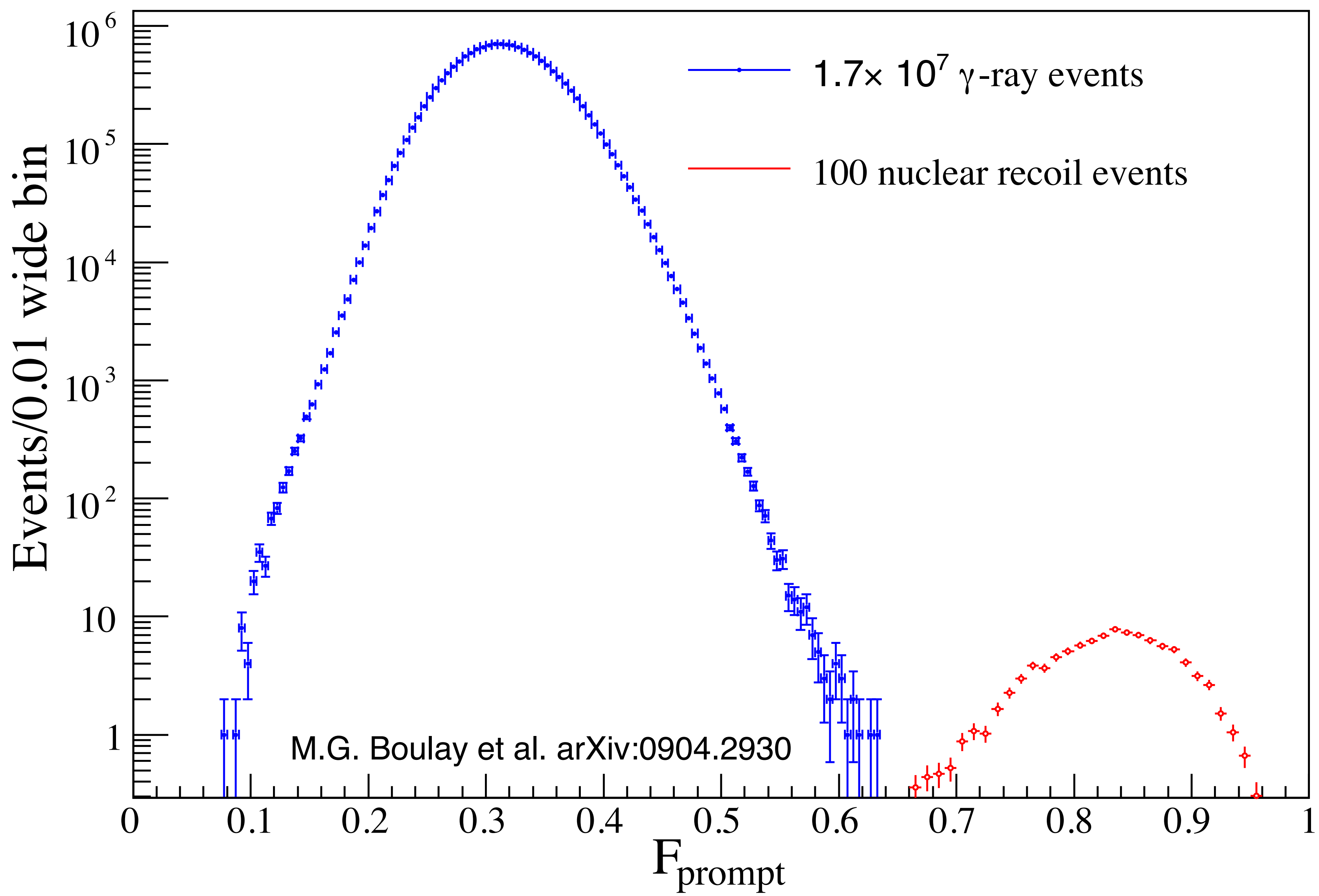
- External gammas from steel and rock
- External neutrons from rock and cosmic ray spallation

Mitigating Backgrounds

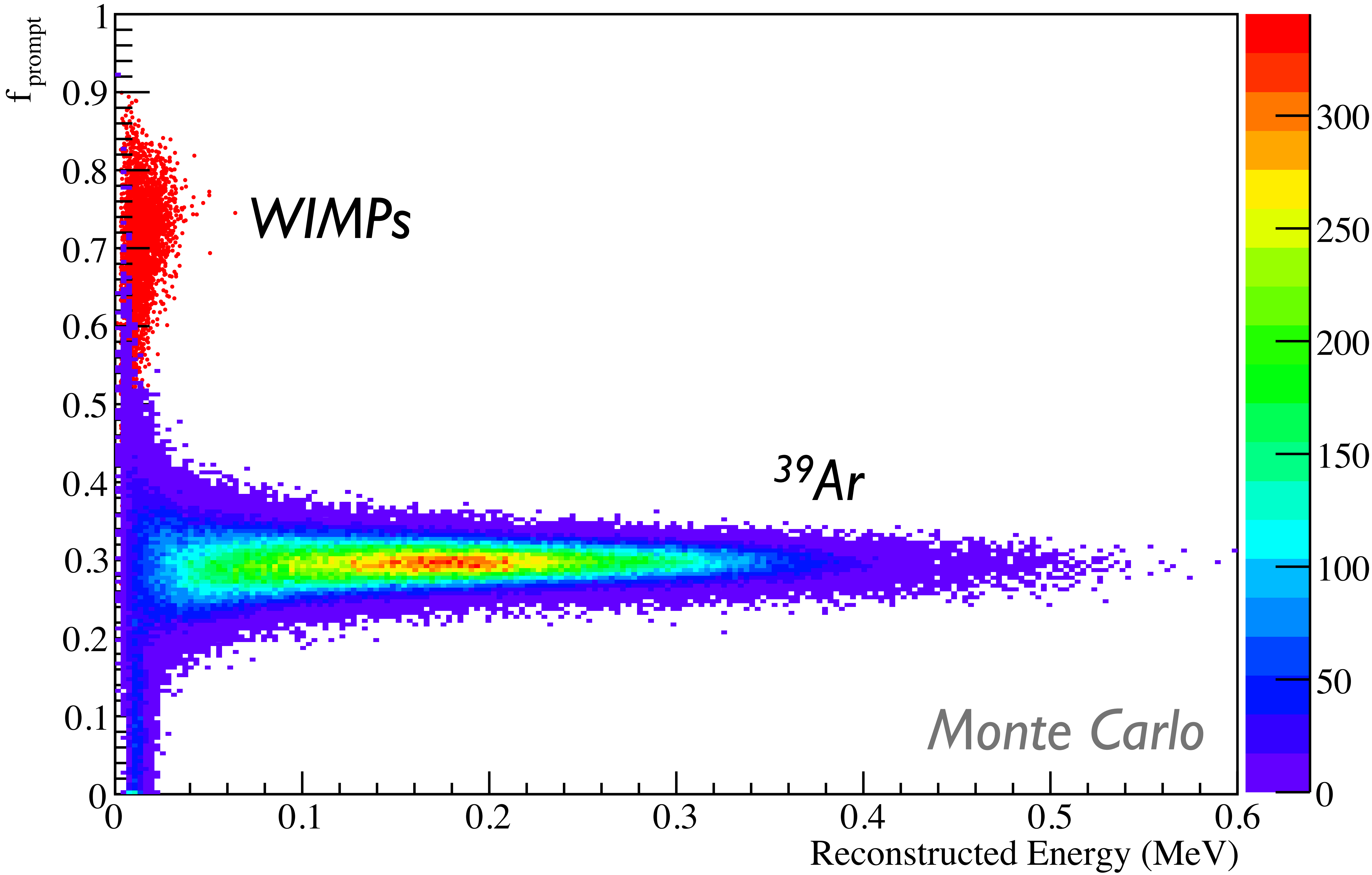
- ^{39}Ar: Cut with Fprompt
- PMT Neutrons: Low activity glass, pull PMTs back from fiducial volume, acrylic shielding, position reconstruction, timing distribution
- Rn daughters on surfaces: Modular design to assemble cassettes in gloveboxes, position reconstruction
- External gammas from steel and rock: Low activity steel, water shield, cut with F_{prompt}
- External neutrons from rock and cosmic ray spallation: Water shield, active cosmic ray veto in water shield.

F_{prompt}

- Designed to be the simplest possible pulse shape discriminant.
- F_{prompt} = Charge in prompt window (~100 ns) divided by total charge. Ranges from 0 to 1.



F_{prompt} vs. Energy

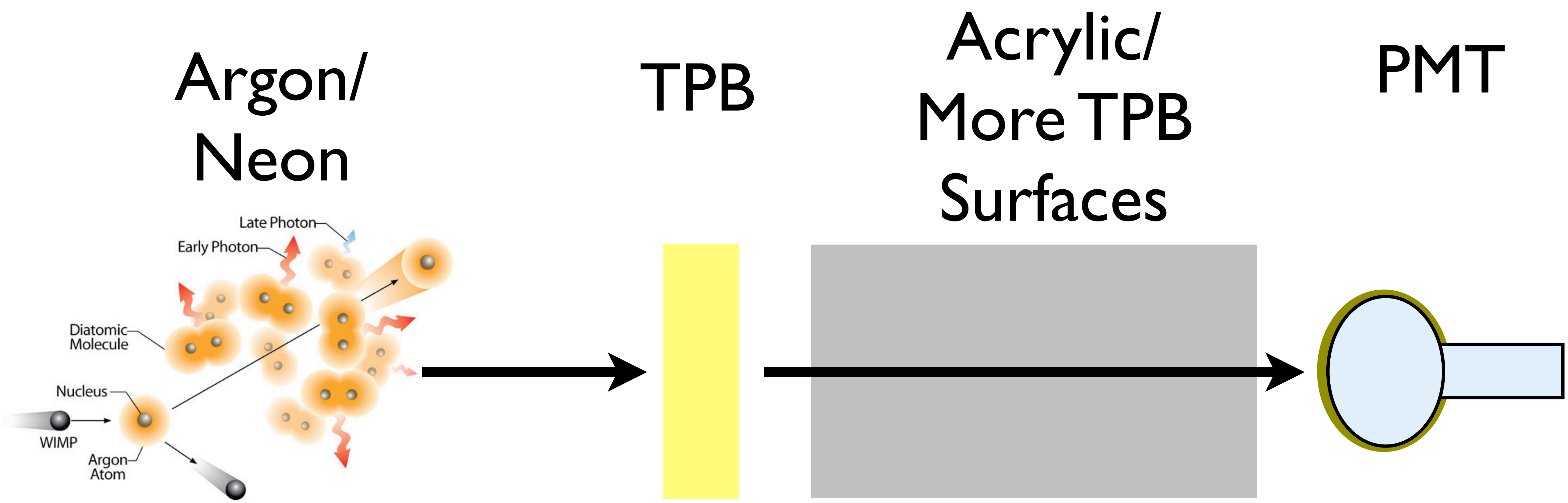


Position Reconstruction

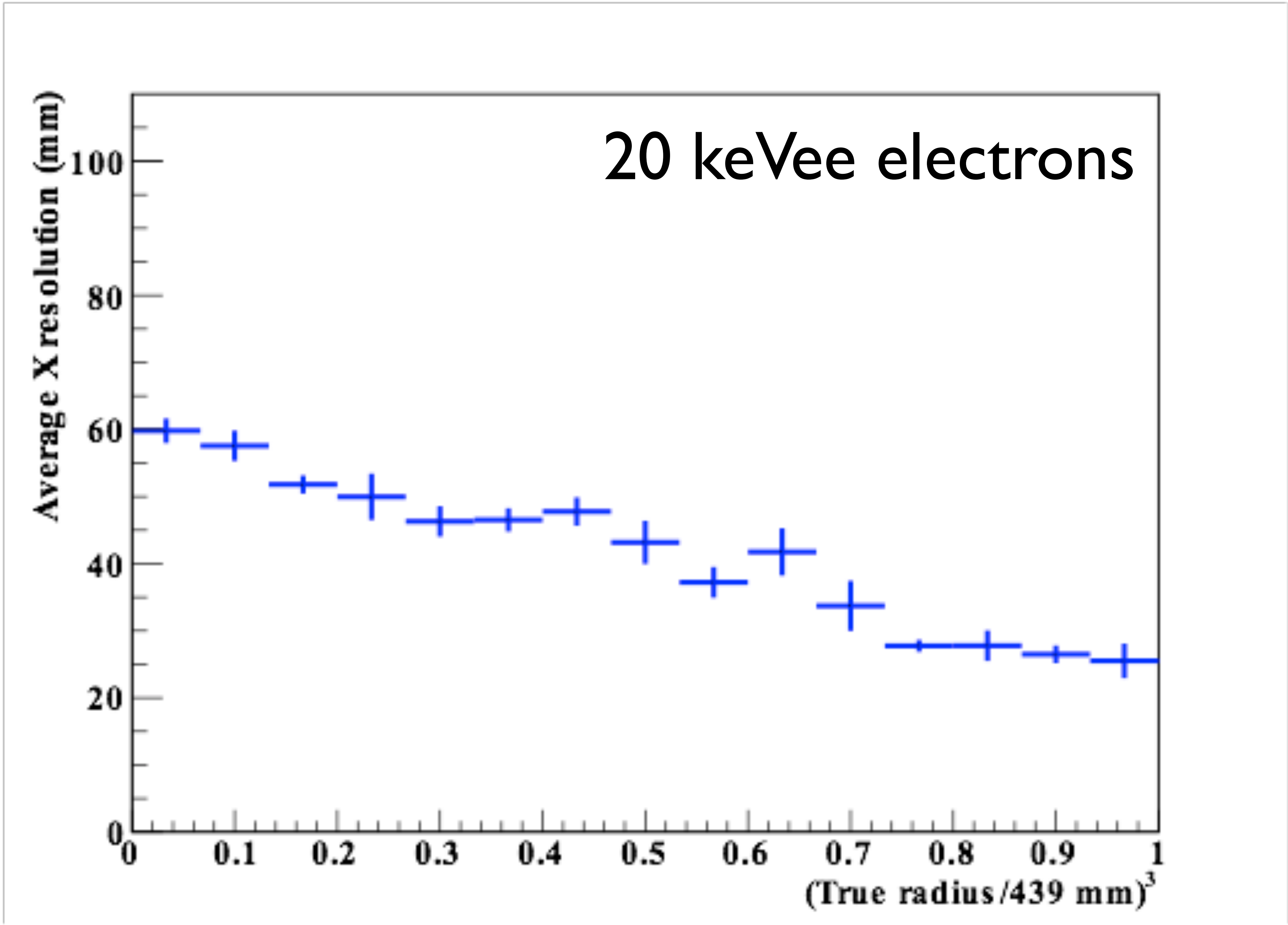
No photon in MiniCLEAN can travel directly from the event vertex to a PMT!

Position Reconstruction

- We use a hybrid analytic/Monte Carlo based maximum likelihood position reconstruction called *ShellFit*.
- Sum over possible photon histories to produce probability distributions for number of detected photons at each PMT.



Position Reconstruction

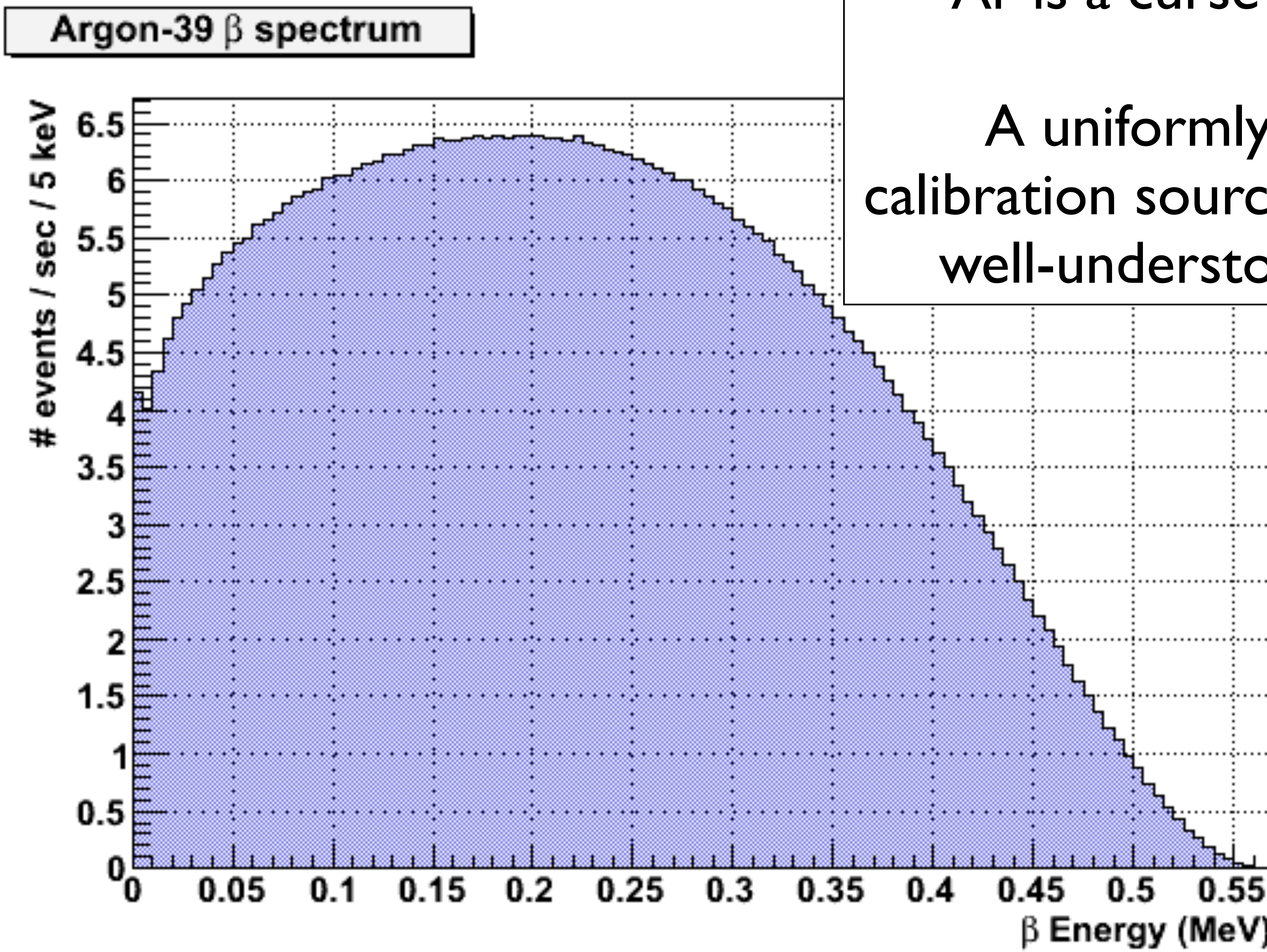


Calibration

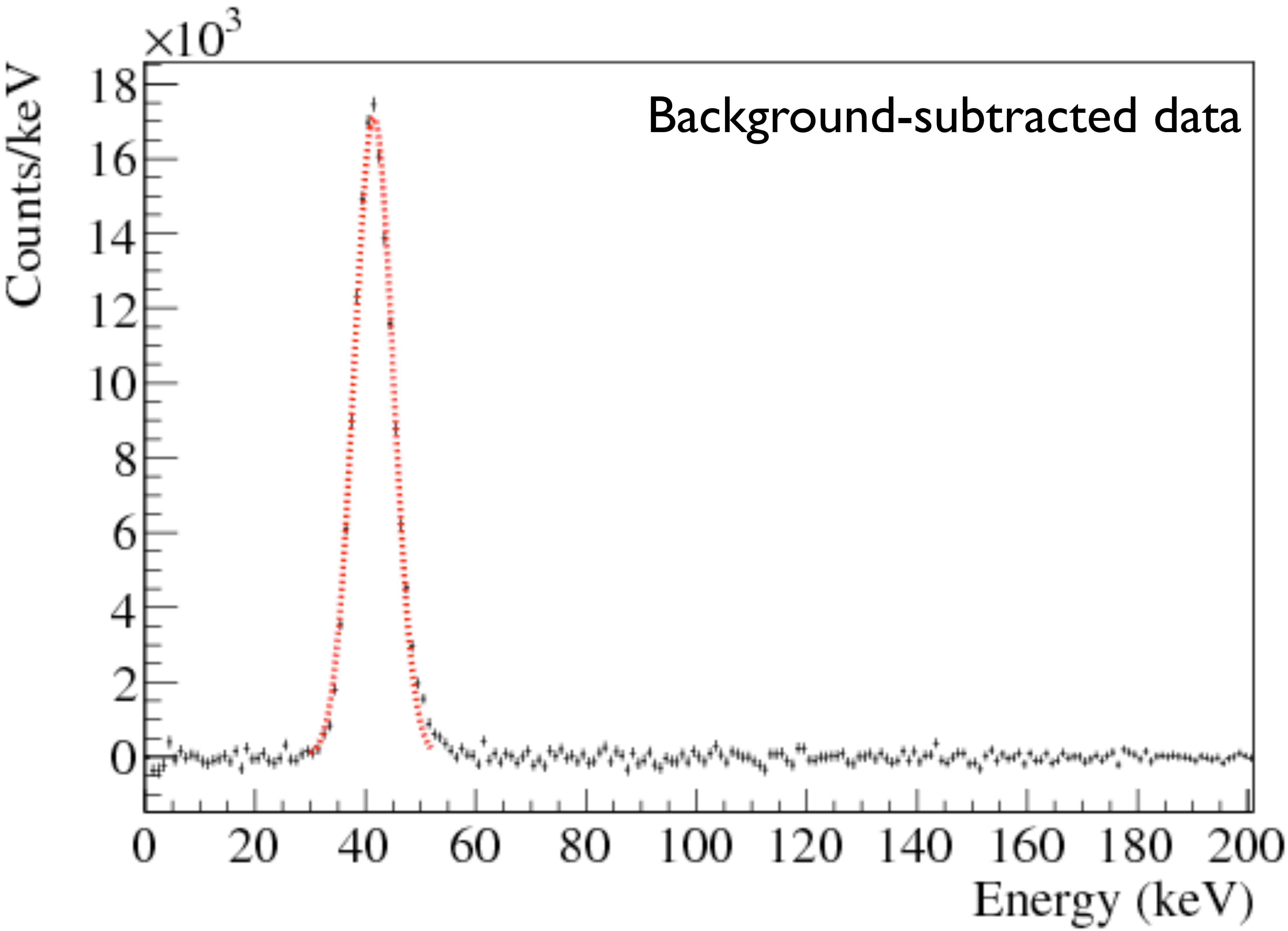
- ^{39}Ar: Constant rate source, always present!
- ^{57}Co: External source of 122 & 136 keV gammas
- $^{83}Kr^{m}$: Distributed source of 32.1 + 9.4 keV internal conversion electrons
- d-d neutron generator: Pulsed neutron source
- UV and Visible pulsed LEDs: Low activity steel, water shield, cut with Fprompt
- ^{39}Ar spike: Introduce up to 10x the natural activity of ^{39}Ar at end of argon run to test particle ID

^{39}Ar is a curse and a blessing!

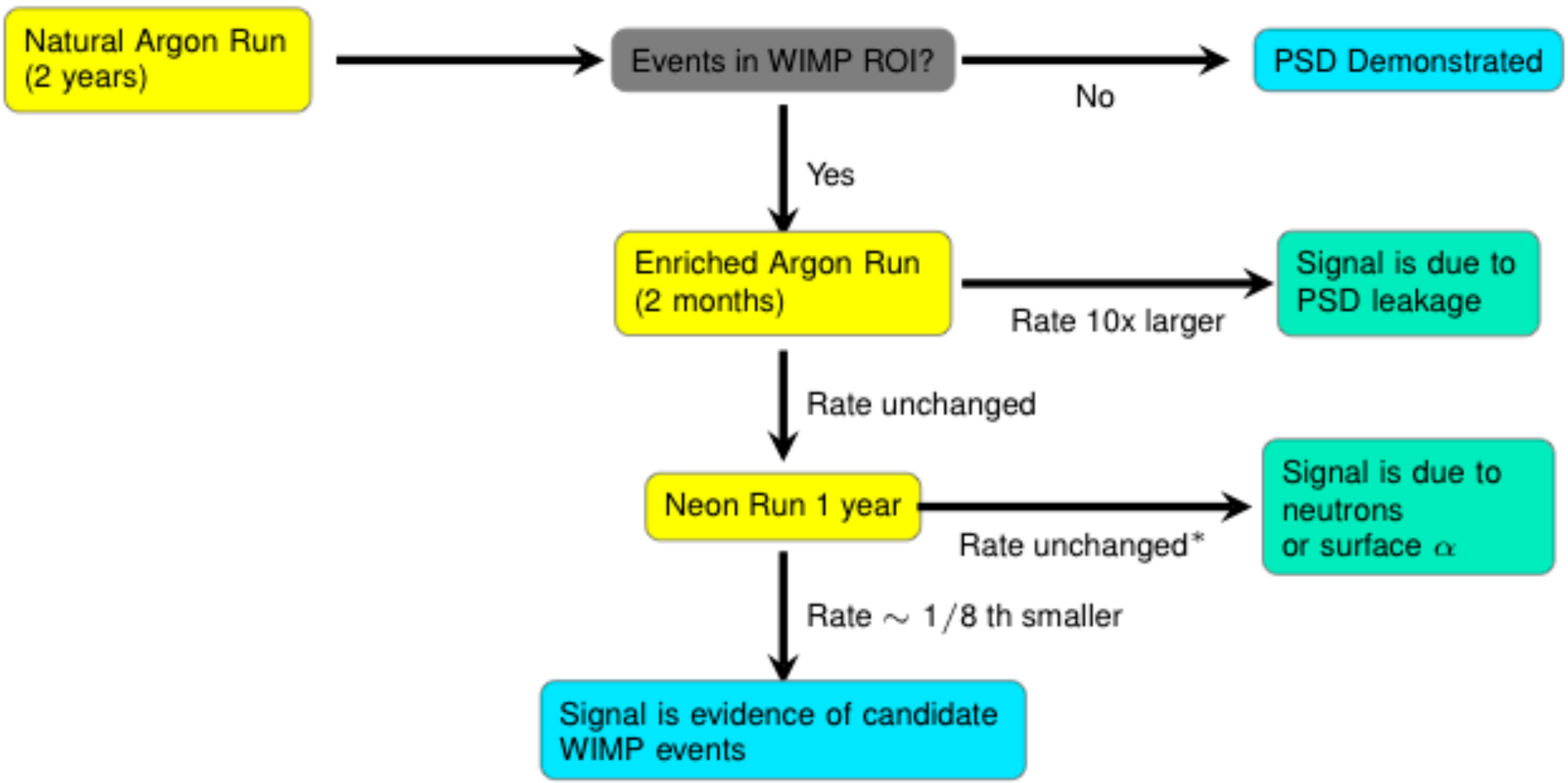
A uniformly distributed calibration source of betas with a well-understood spectrum.



$^{83}Kr^m$ in MicroCLEAN

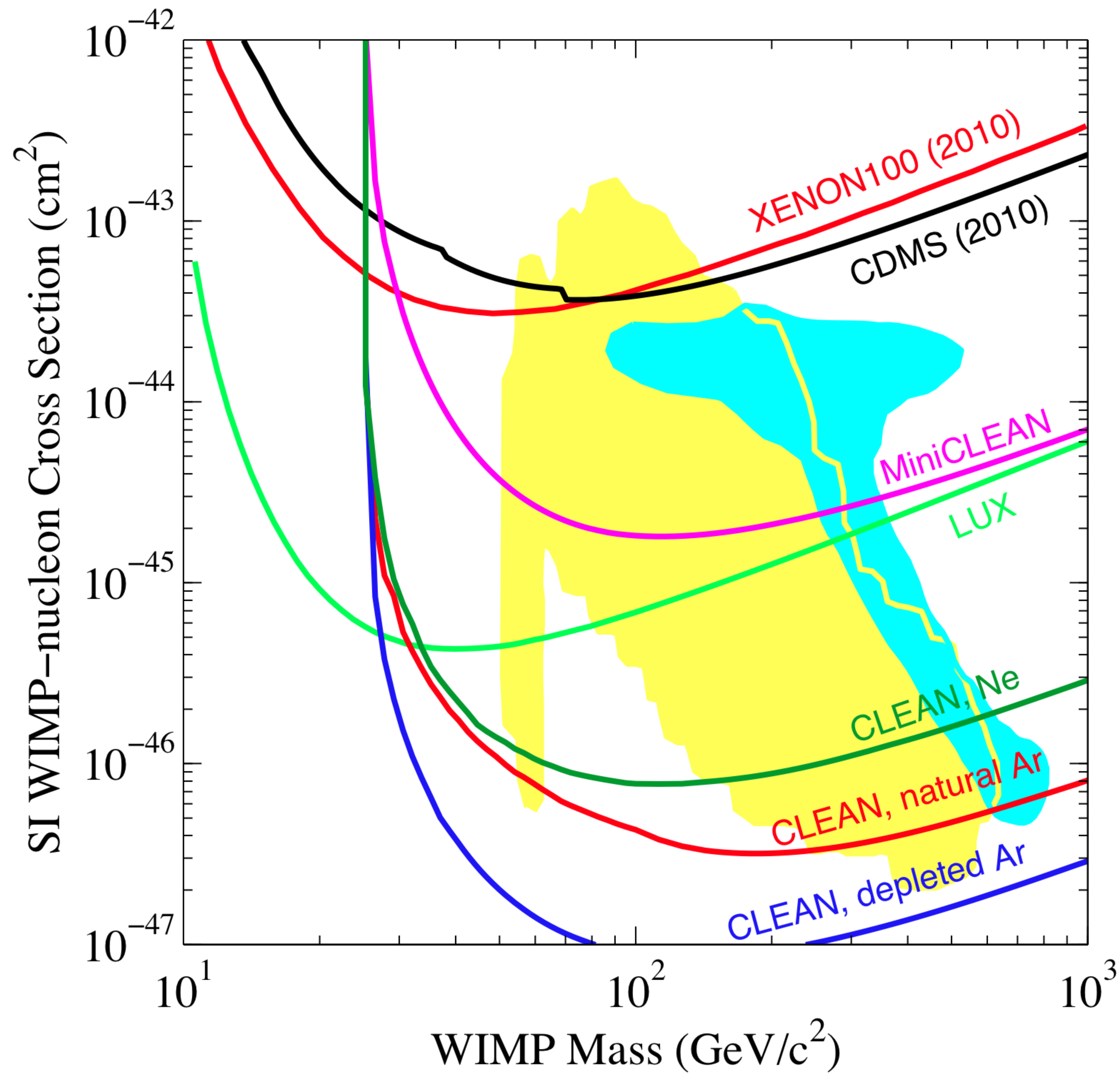


WIMP Discovery Flowchart

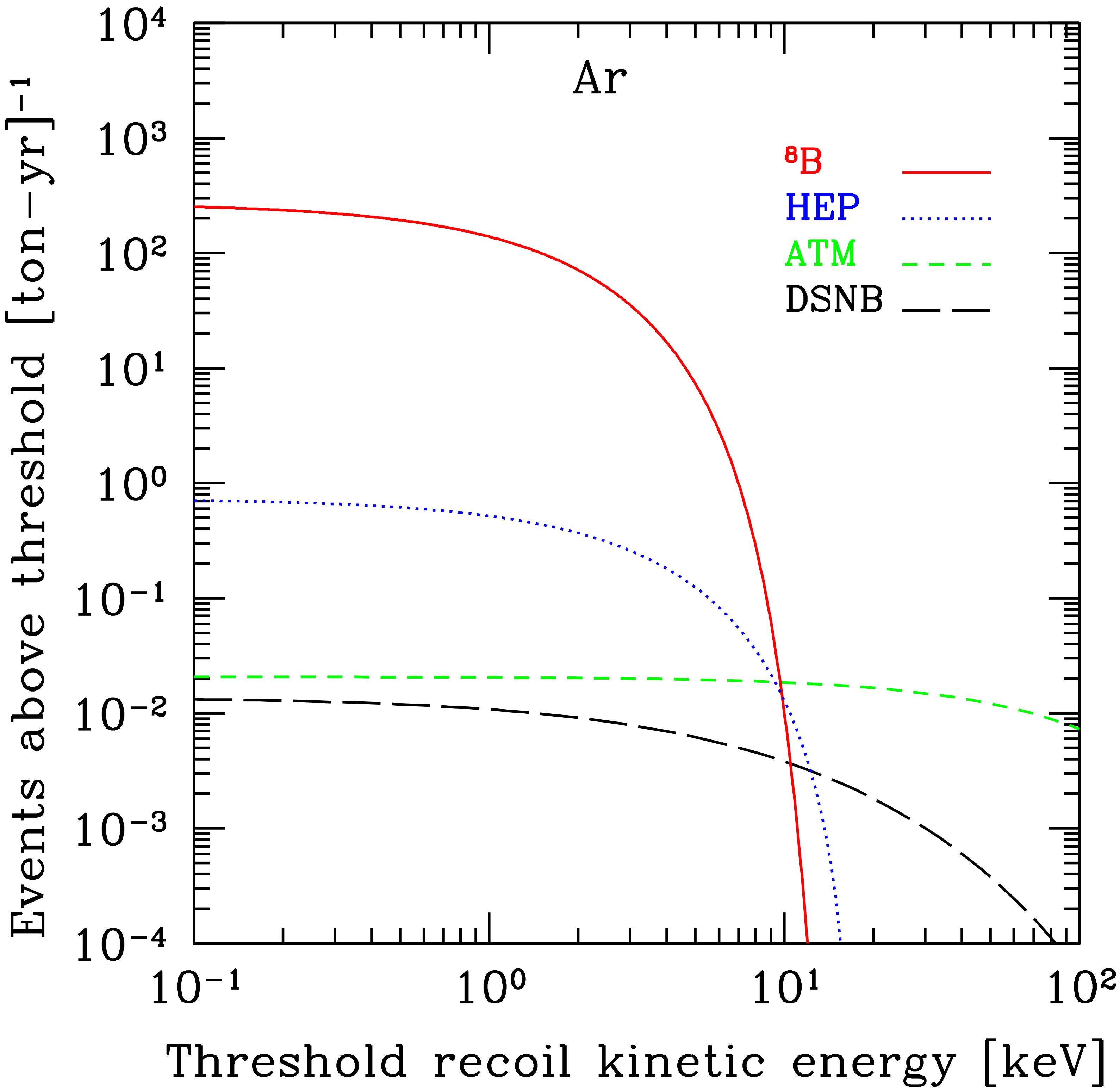


* work is ongoing towards full understanding of neutron propagation in neon, including neutron scattering measurements @ TUNL and LANL

WIMP Sensitivity



Neutrino Background to WIMPs



One physicist's signal is another's background.

Coherent neutrino scattering will interfere with WIMP sensitivity below 10^{-48} cm^2/nucleon

Monroe & Fisher, arXiv:0706.3019
Strigari, arXiv:0903.3630

DEAP/CLEAN Collaborators

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National Institute Standards and Technology
K. Coakley

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Syracuse University
M.S. Kos, R.W. Schnee, B. Wang

TRIUMF
P.-A. Amaudruz, A. Muir, F. Retiere

Yale University
W.H. Lippincott, D.N. McKinsey, J.A. Nikkel, Y. Shin

Conclusion

- *Something is out there,* and it might be dark matter!
- We've seen hints of direct detection, but you should continue to be skeptical.
- Single phase noble liquid detectors offer a highly scalable option for dark matter and neutrino detection.
- MiniCLEAN extends the DEAP/CLEAN series of detectors to 150 kg fiducial volume with liquid argon and neon.
- Construction is underway, with detector commissioning scheduled for late 2011, followed by two years of argon running.

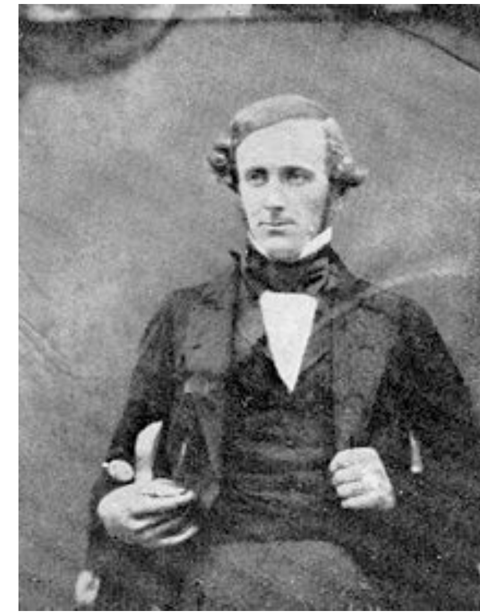
Backup Slides

We've Been Here Before...

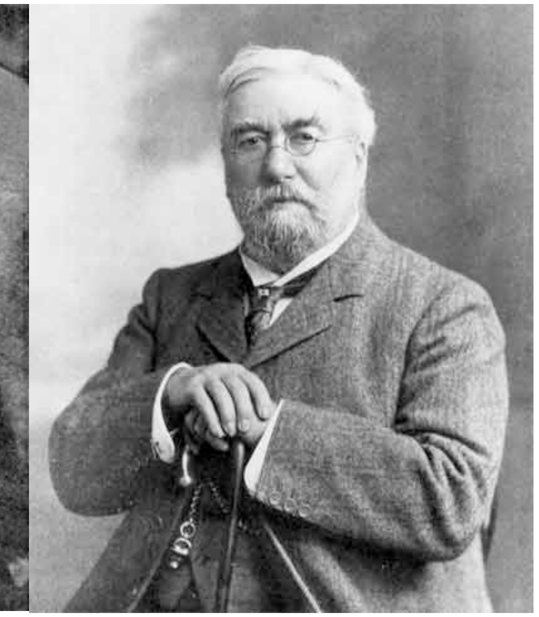
We've Been Here Before...

Lockyer

We've Been Here Before...



Frankland



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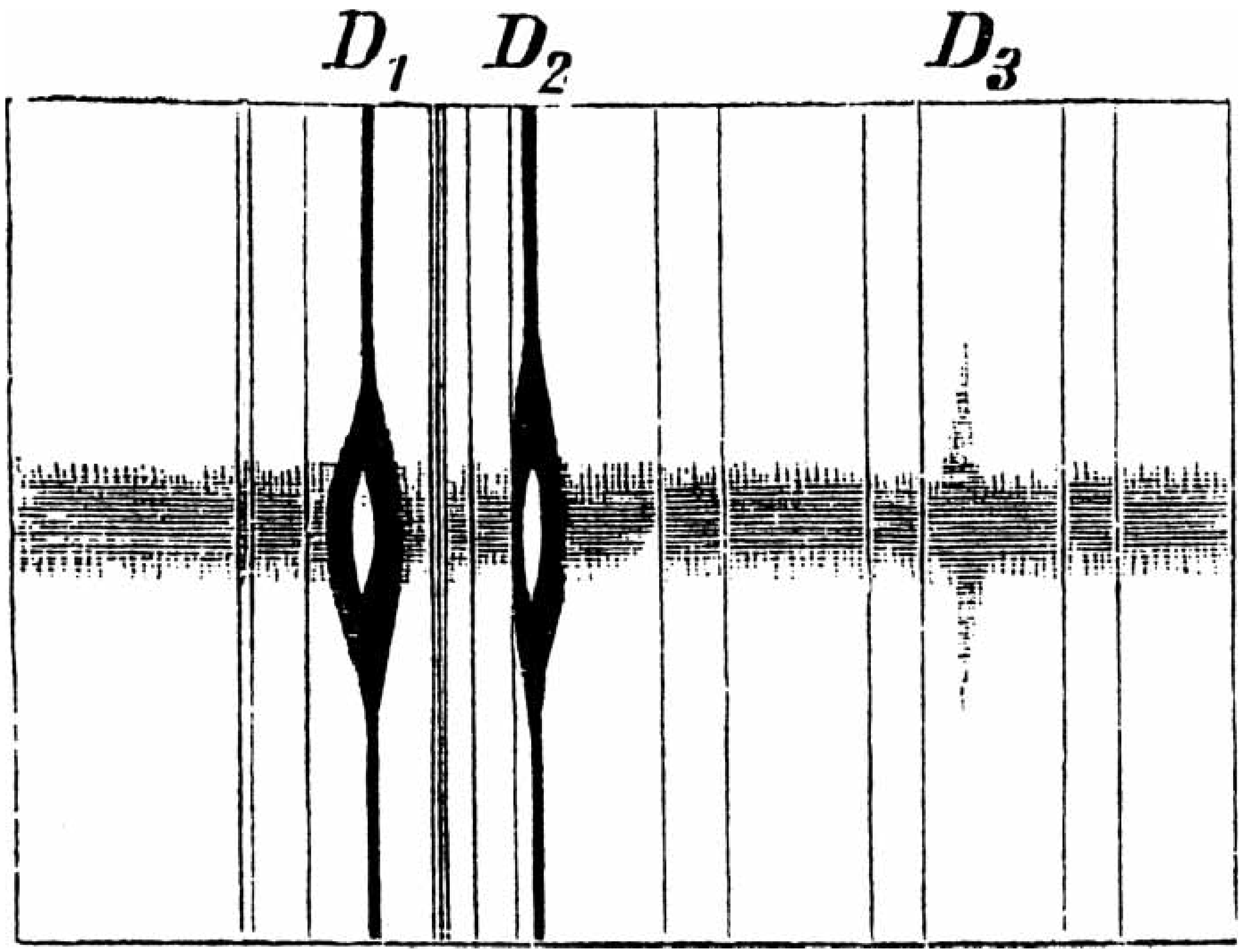
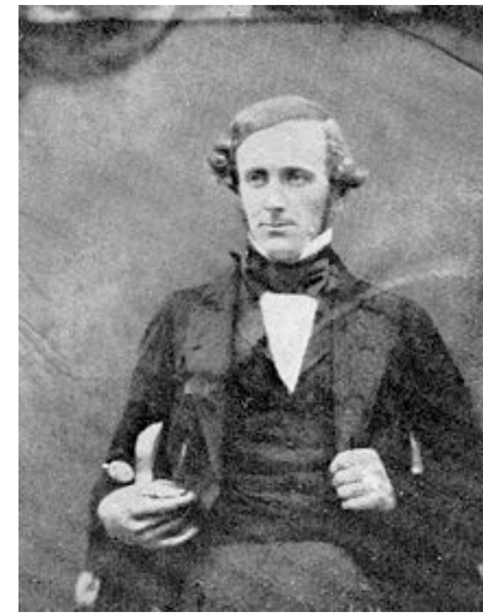
We’ve Been Here Before...

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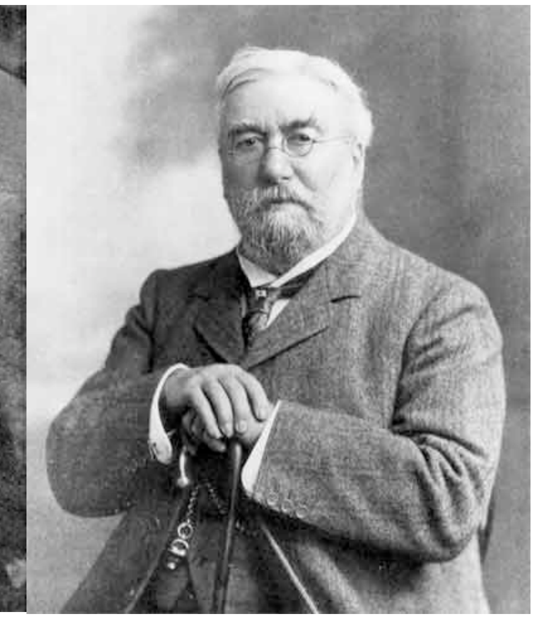
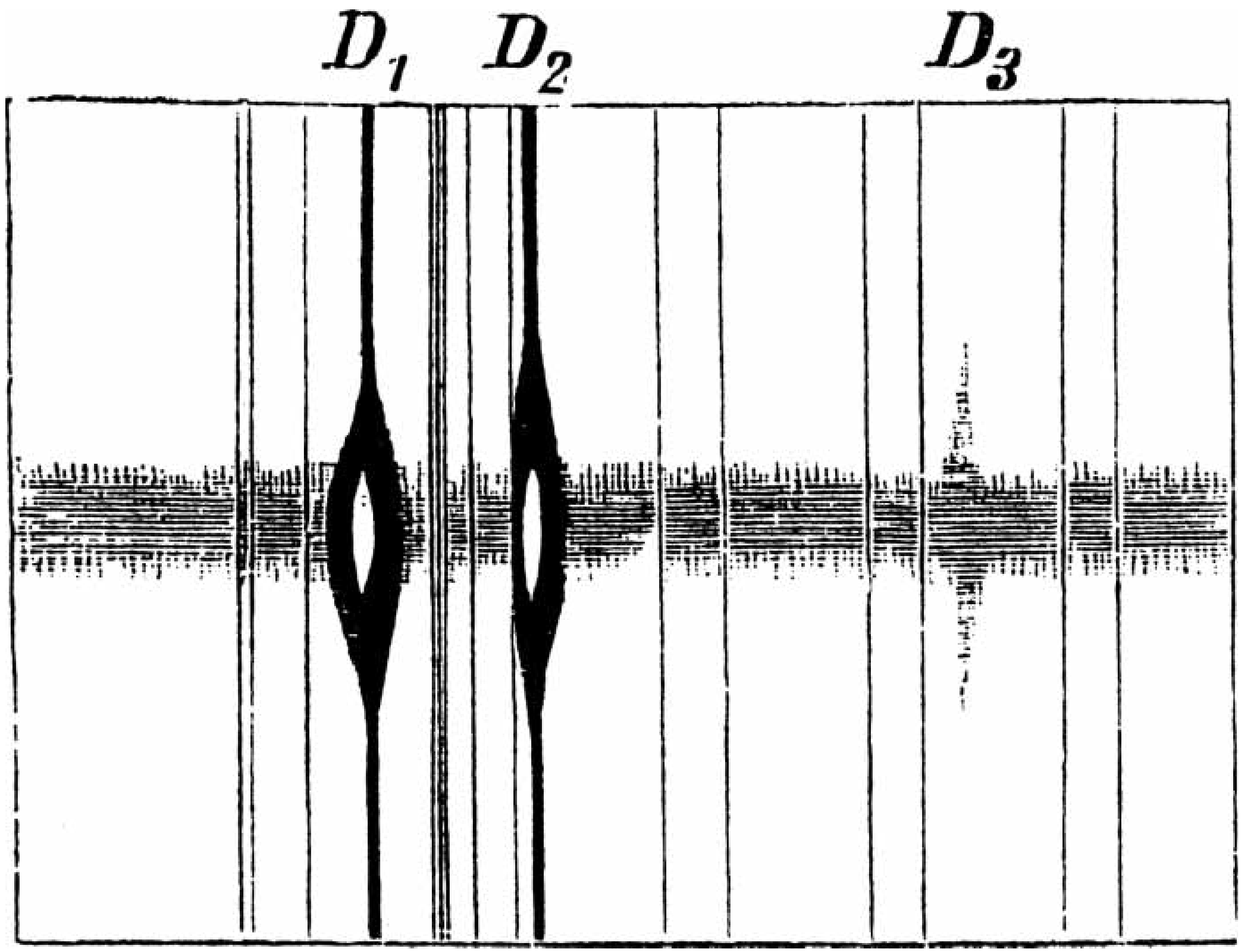
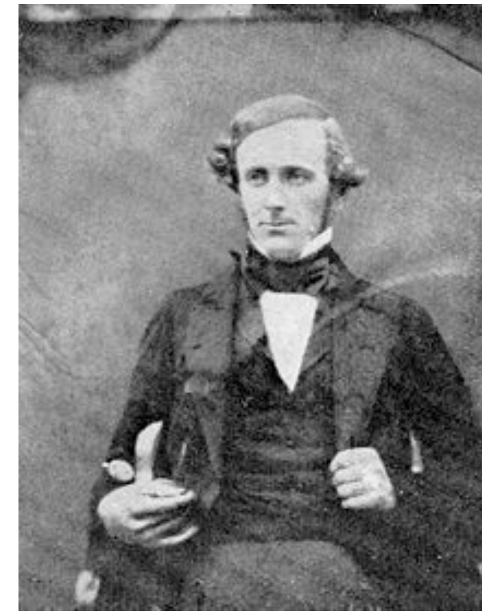

Lockyer

We've Been Here Before...





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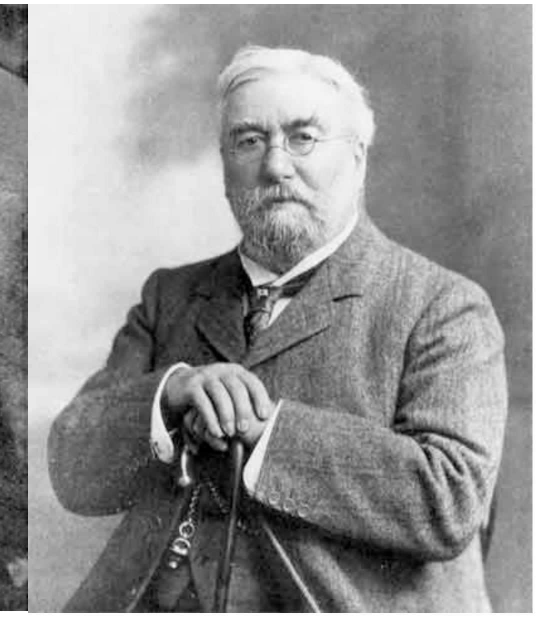

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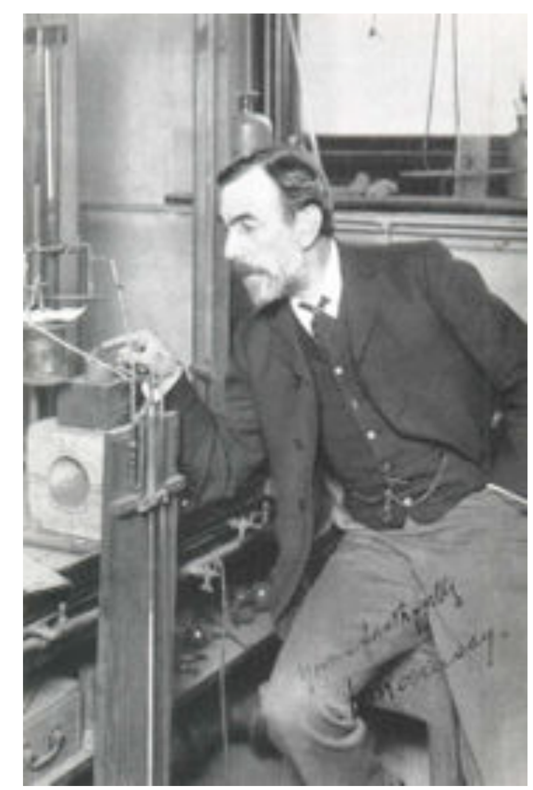
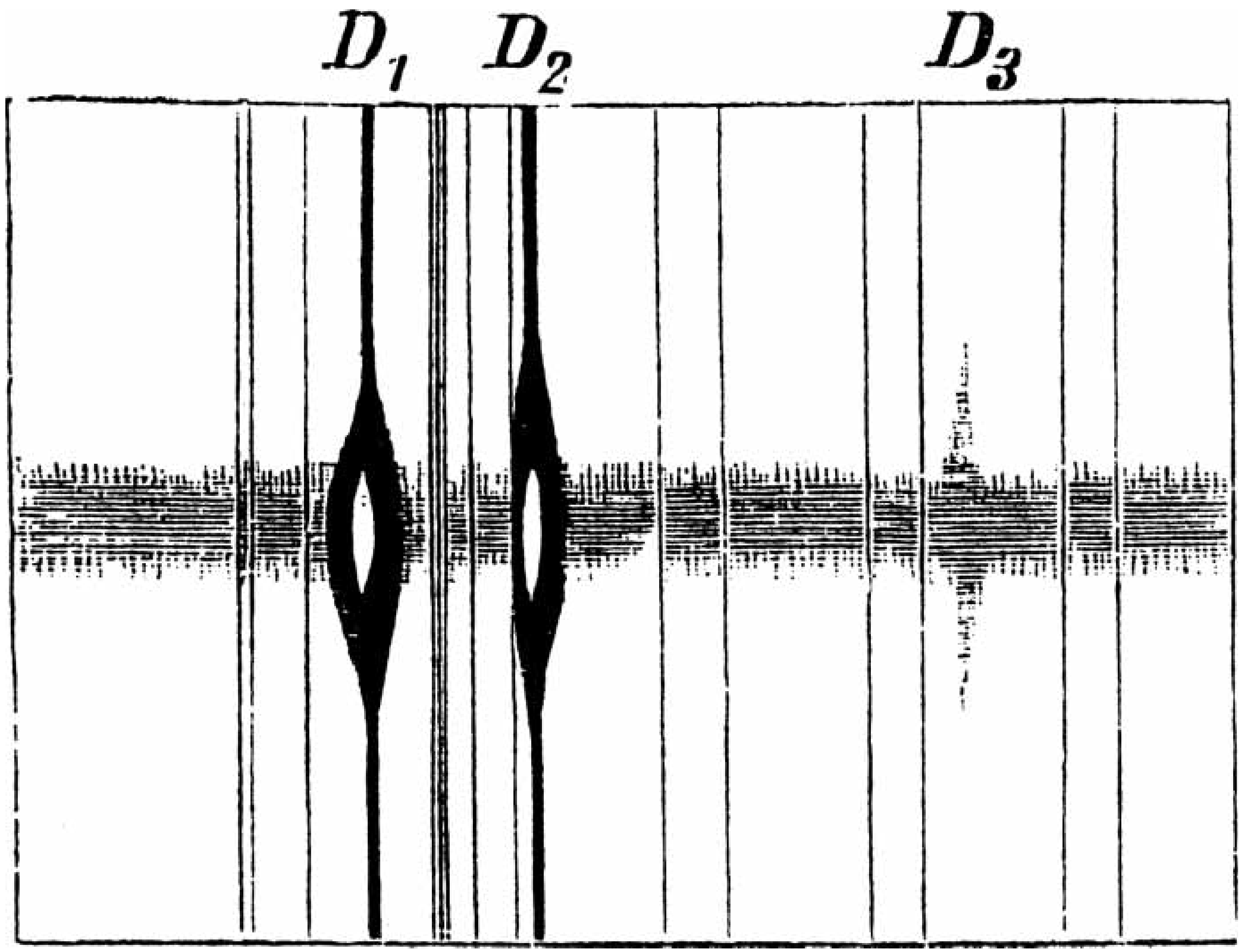
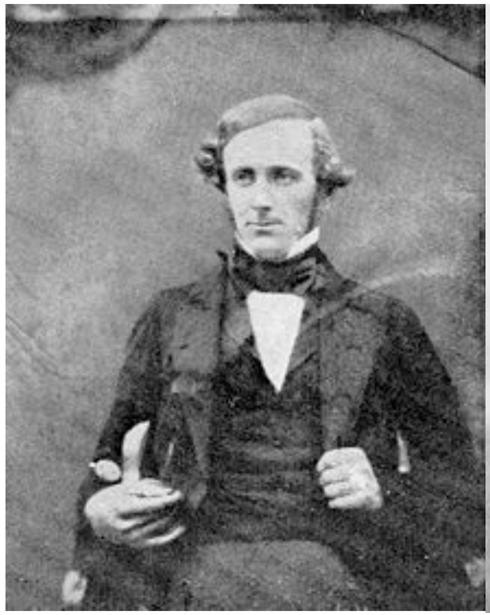


Ramsay

We've Been Here Before...





Frankland

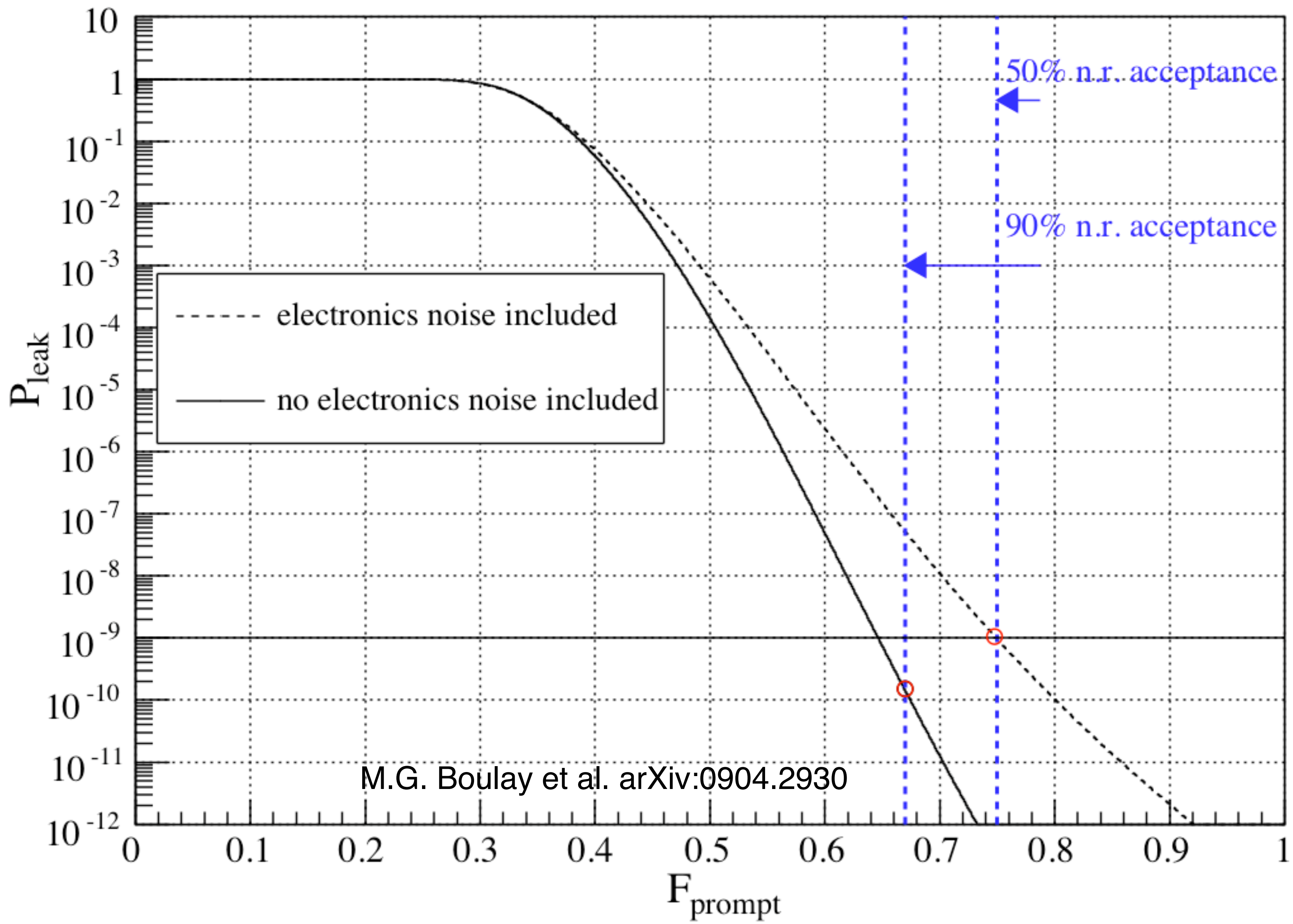
Lockyer

Ramsay

Helium was first discovered by astronomers in the solar chromosphere in 1868, but not by chemists in the lab until 1895!

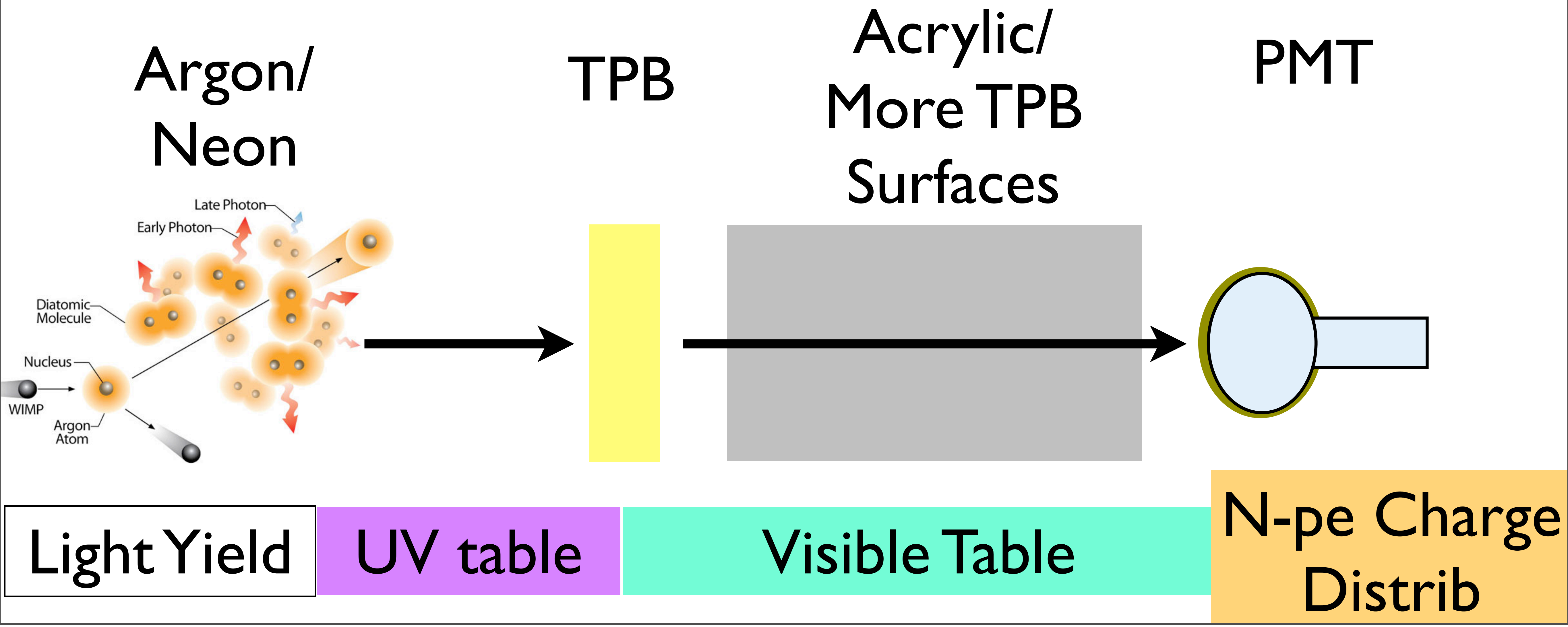
Fprompt

- Designed to be the simplest possible pulse shape discriminant.
- Fprompt = Charge in prompt window (150 ns) divided by total charge. Ranges from 0 to 1.



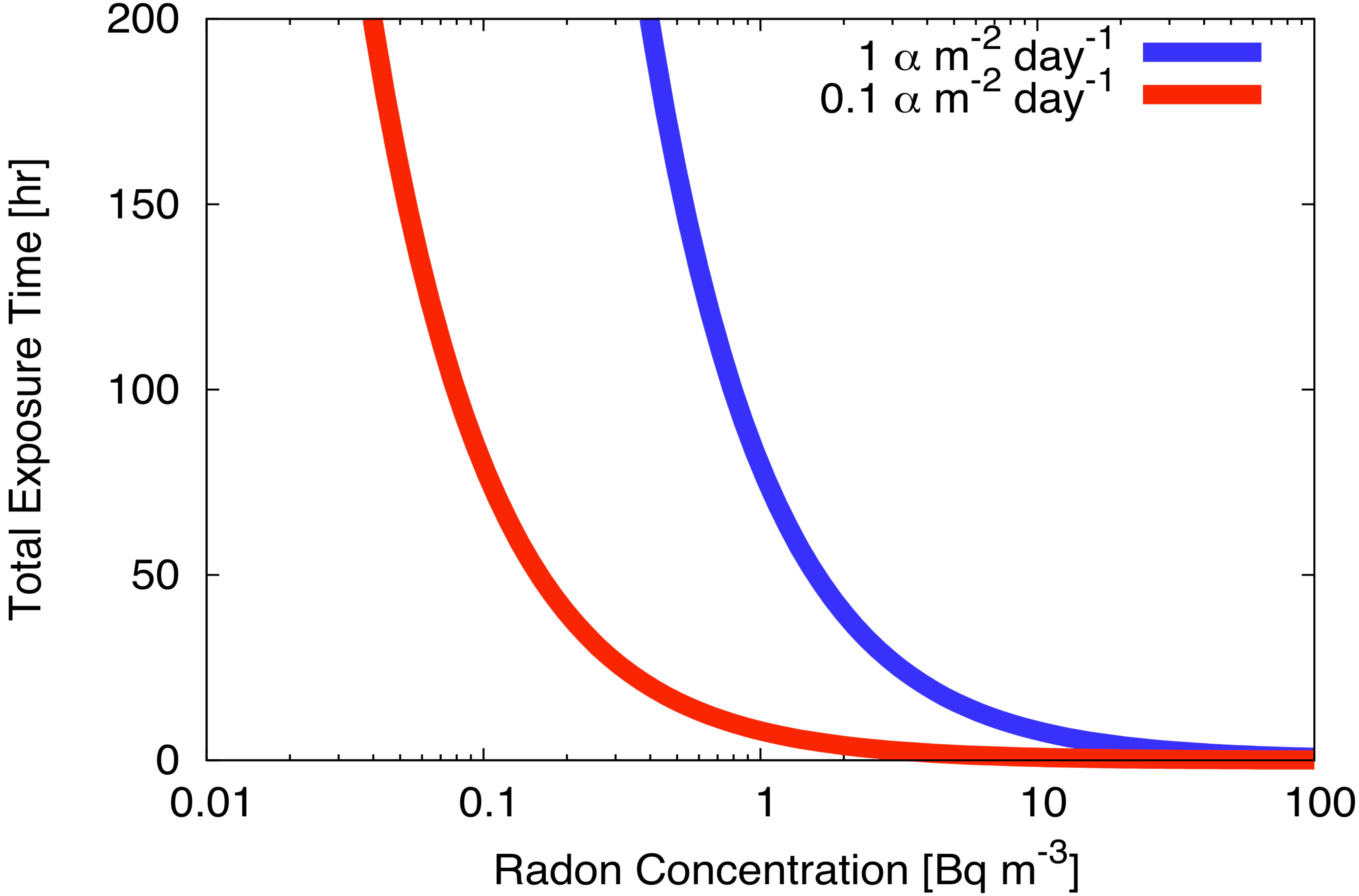
Position Reconstruction

- No photon in MiniCLEAN can travel from event vertex to a PMT!
- We have developed a hybrid analytic/Monte Carlo based maximum likelihood position reconstruction called *ShellFit*.
- Includes all major optical effects.



Controlling Radon

- Goal of 1 decay per m^2 per day on the TPB surface.
- Creating a model of Rn deposition to understand how to achieve this goal during assembly.



Neutron Cross-Sections

- Modeling of neutrons is important for detector design and optimization
- Carefully studying GEANT4 neutron simulations in argon/neon and making new measurements.