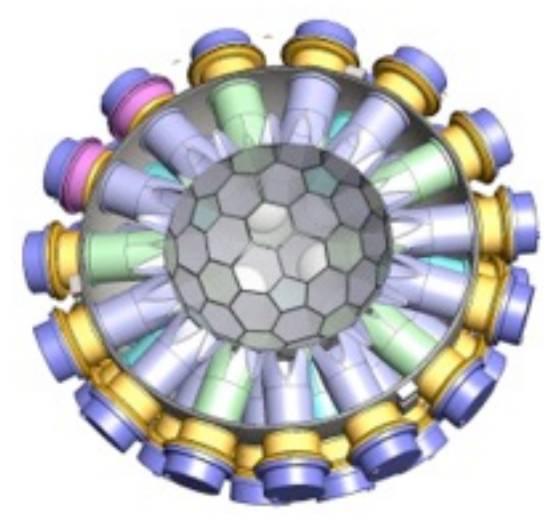
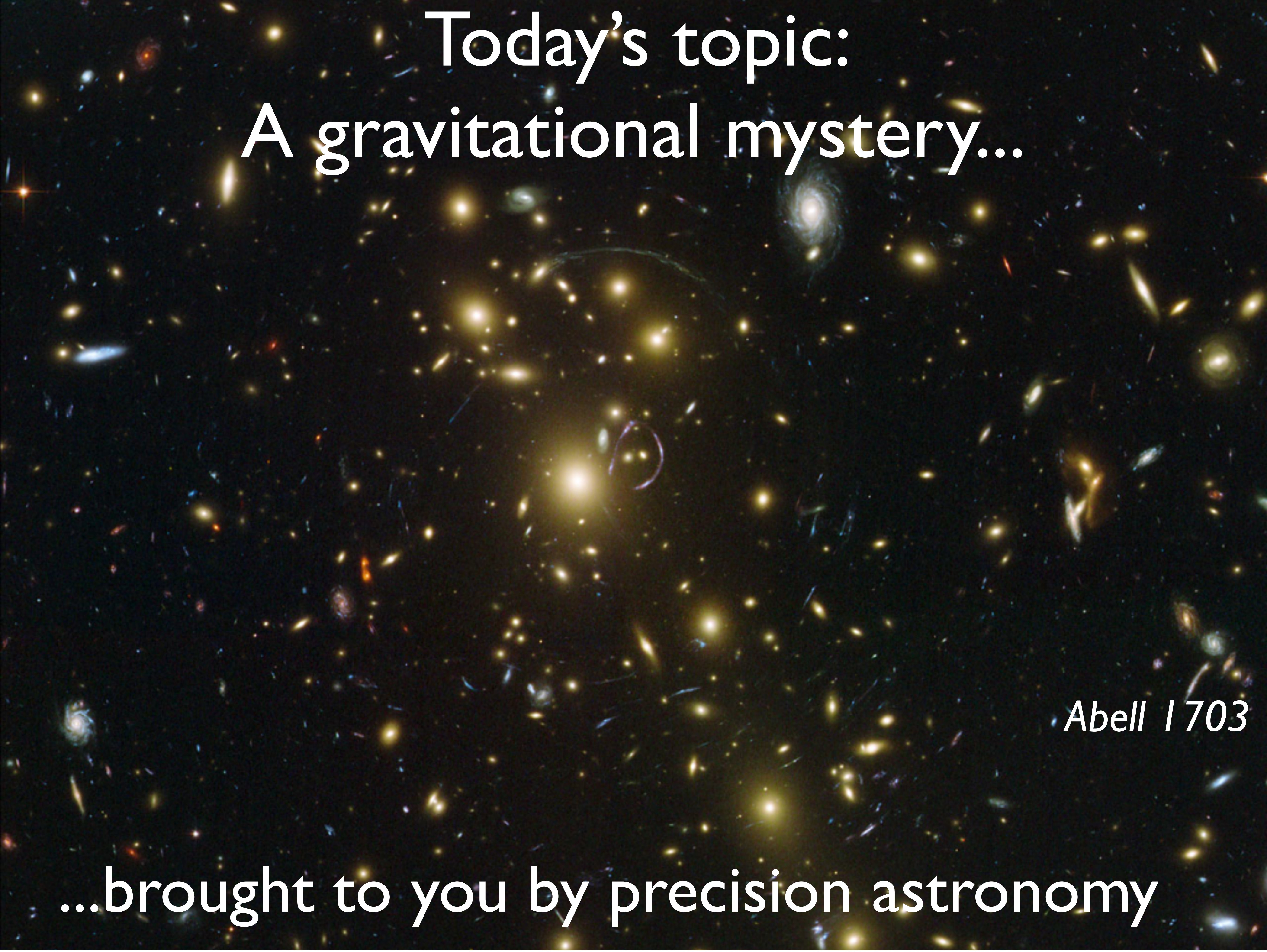
Taking Inventory of the Universe: The Mystery of Dark Matter

Stanley Seibert
University of Pennsylvania
UC Davis, April 11, 2013

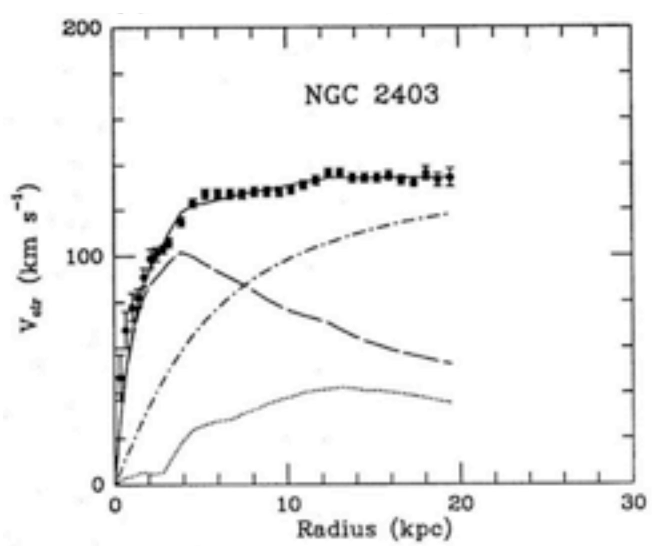


Today's topic:
A gravitational mystery...



...brought to you by precision astronomy

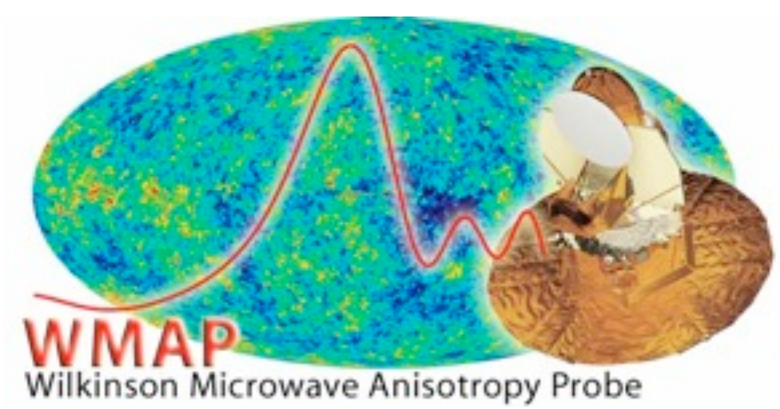
Seven Decades of "Excess Gravitation"



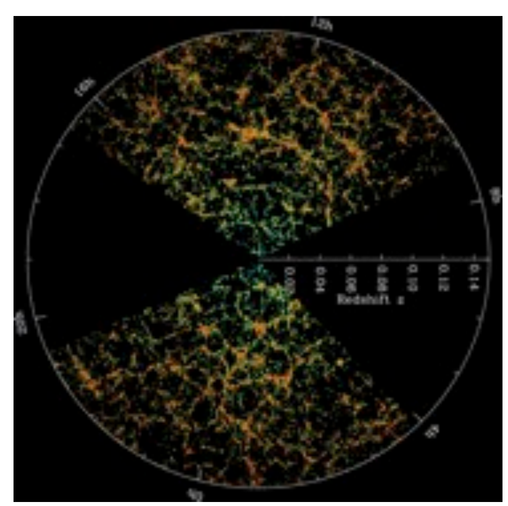
Rotation Curves

Gravitational Lensing

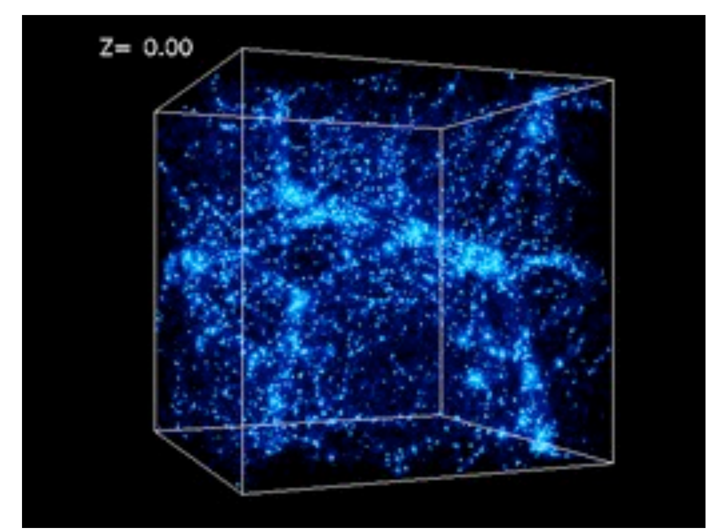
Cluster Collisions



CMB Power Spectrum



Baryon Acoustic Oscillations



Simulations of Structure Formation

And many others!

Responses to the Unexpected

1. "Observational" error.

2. Interpretation or modeling error.

3. New or modified interaction between matter.

4. New material constituent. (usually a new particle)

Pick any combination of all 4!

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“Are you really sure you know where all the baryons are?”
(Black holes, neutron stars, brown dwarfs, etc.)

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   Modified Newtonian Dynamics (MOND), TeVeS

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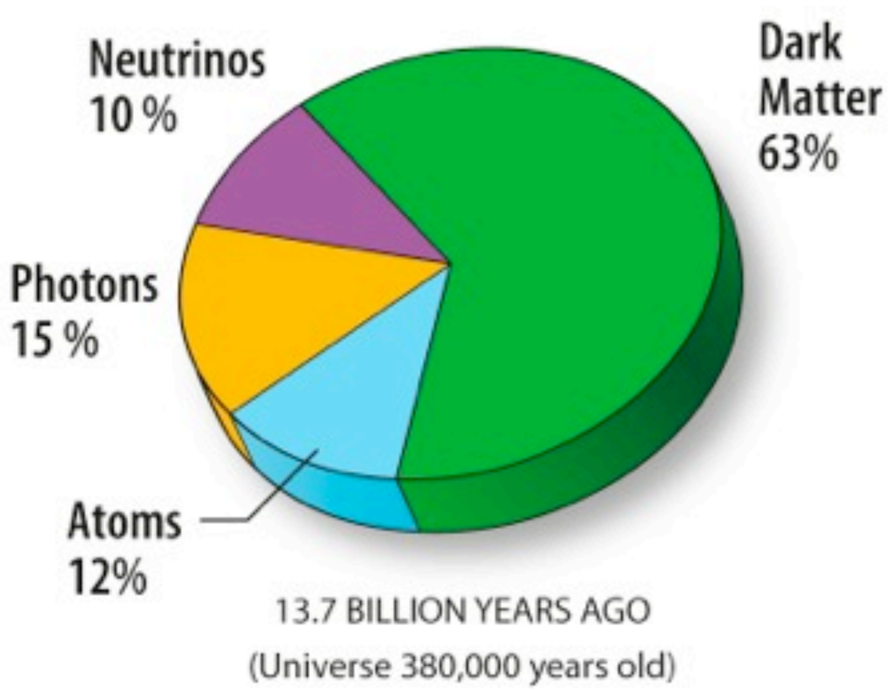
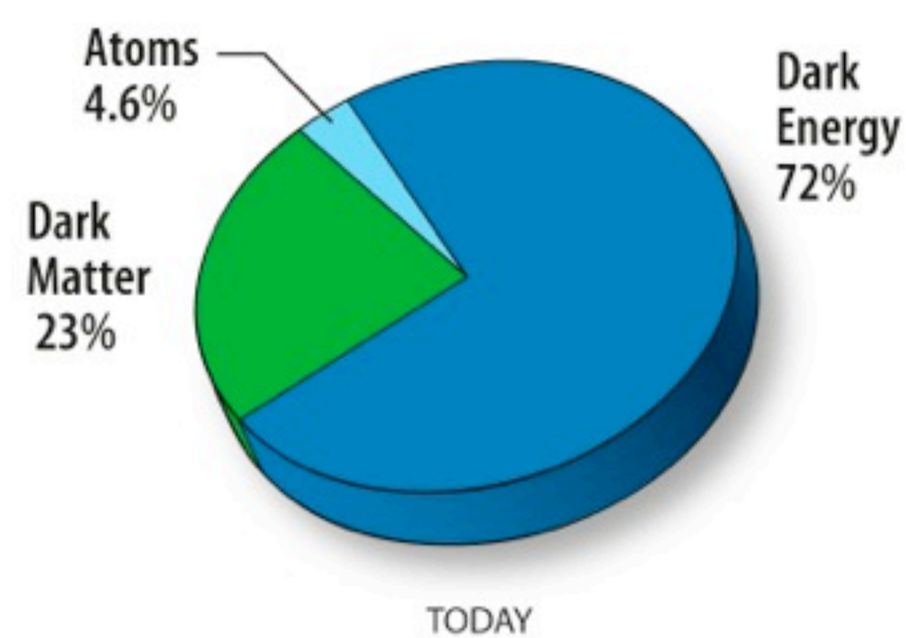
Neutralinos, axions, Kaluza-Klein states, ...

Pick any combination of all 4!

The Dark Matter Hypothesis

A substantial fraction of the matter in the universe is in a form that rarely (or never) interacts with photons, rendering it invisible ("dark") to direct electromagnetic observation.





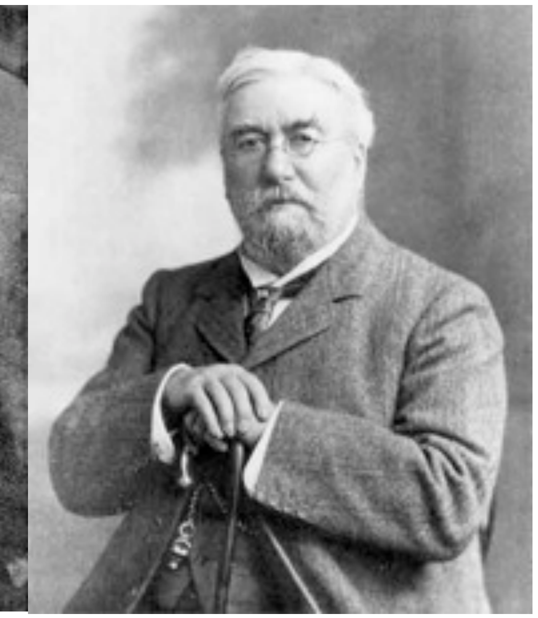
But, isn't proposing a new form of matter based purely on astronomical evidence preposterous?

We've Been Here Before...

We've Been Here Before...

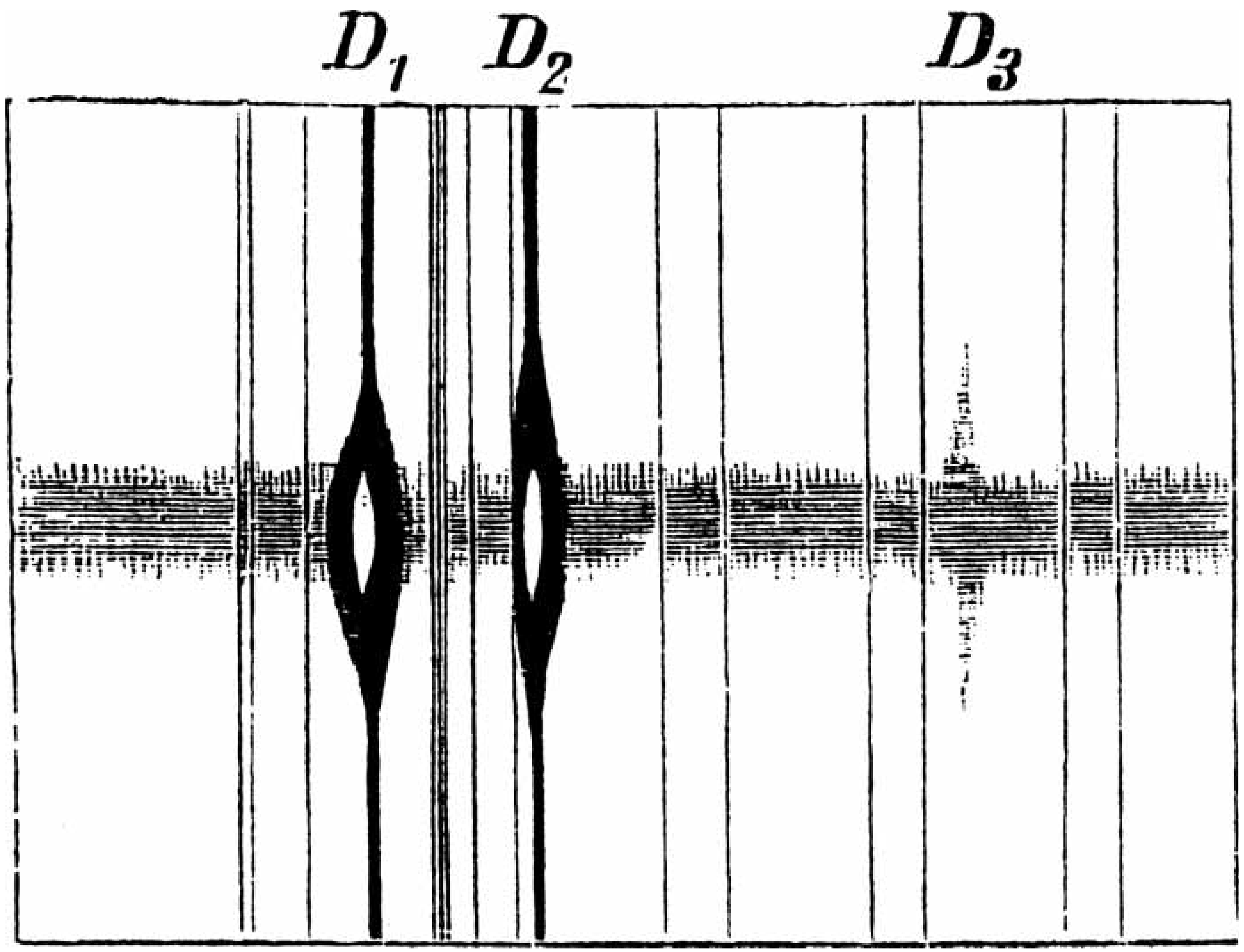
N. Lockyer

We've Been Here Before...

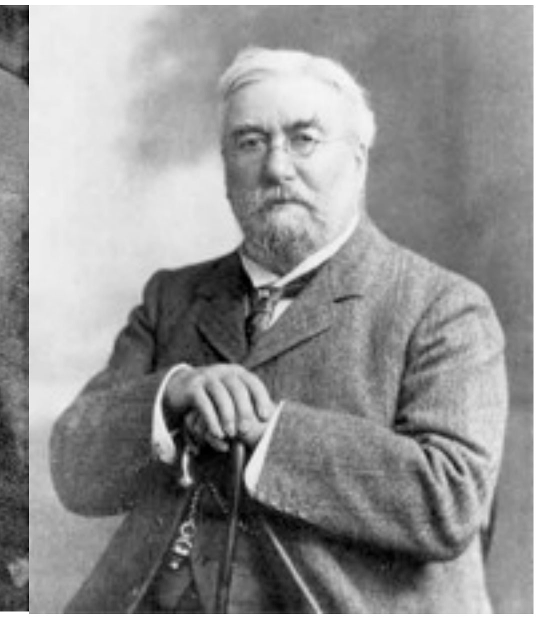



E. Frankland N. Lockyer

We've Been Here Before...



E. Frankland



N. Lockyer

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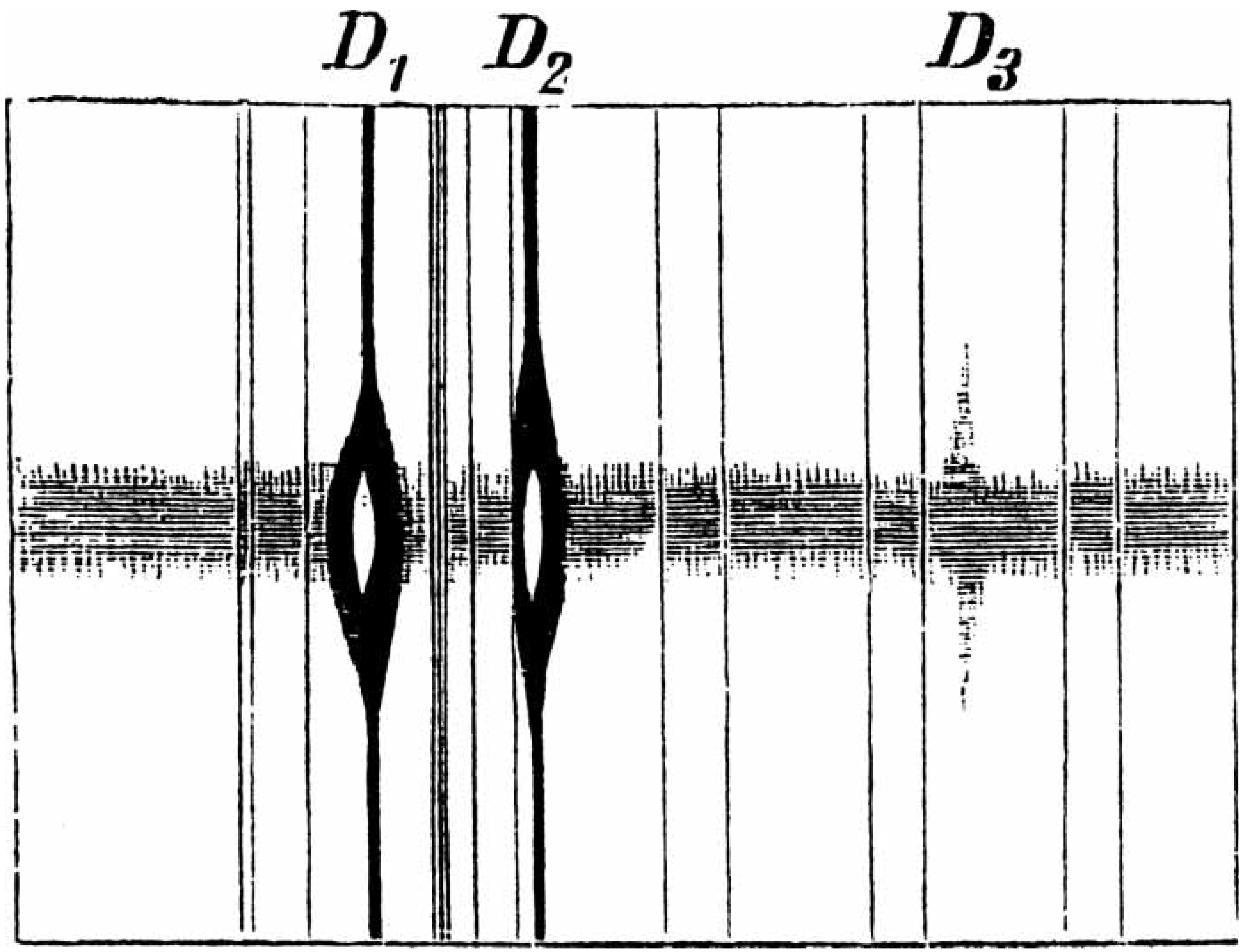

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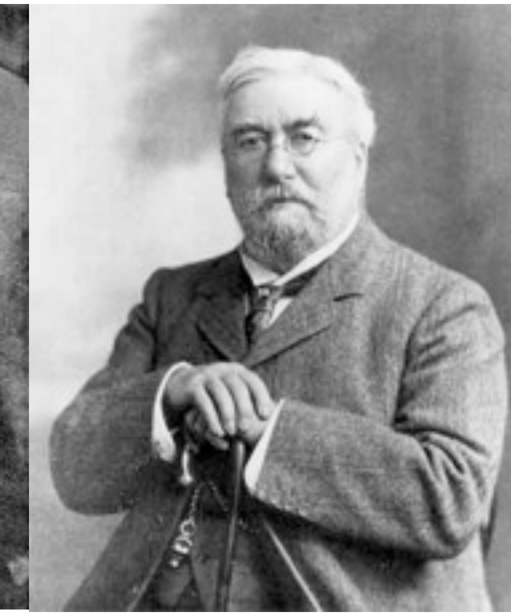
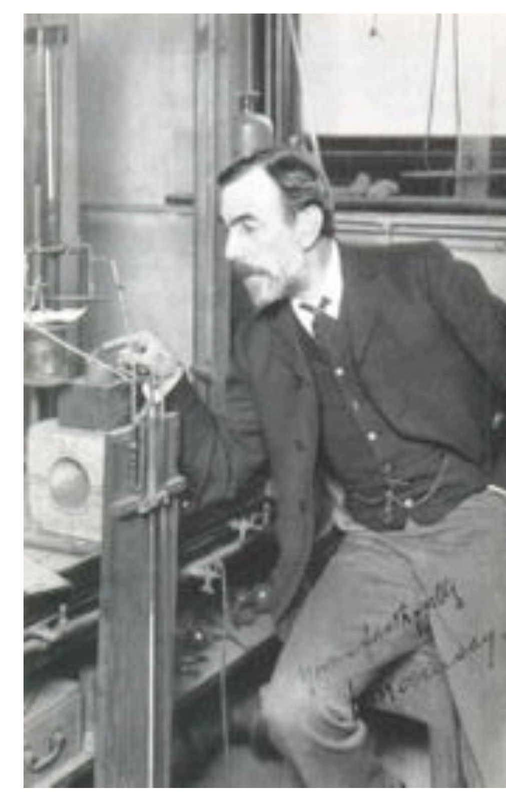


N. Lockyer

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



W. Ramsay

What is Dark Matter?

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

If you explain the astronomy data with dark matter, then you know:

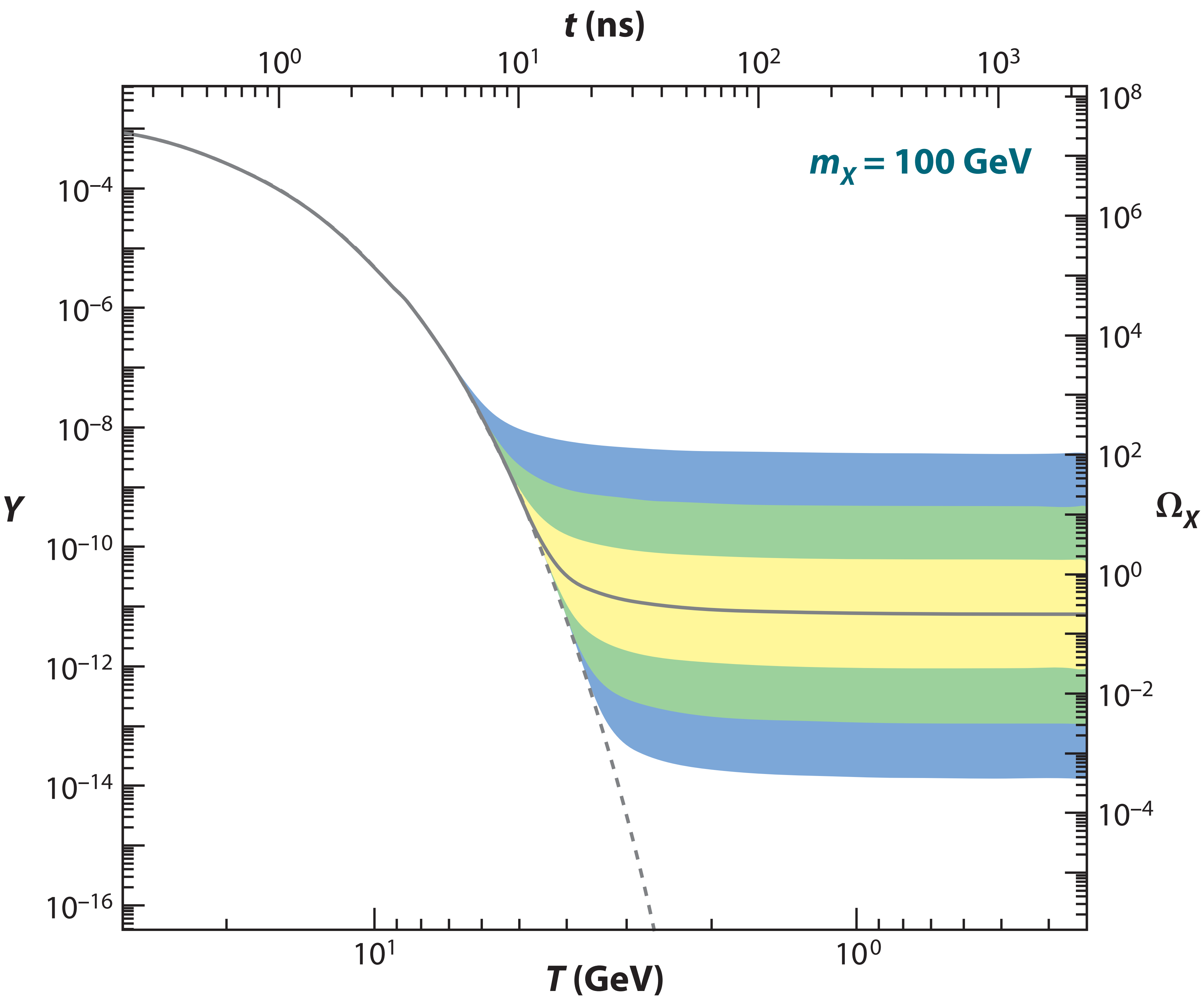
- Cross-sections for interaction between dark matter and itself/other particles are very small. (or you would have seen it already)
- Local density near Earth is around 0.3 GeV/cm^3 (within a factor of 2 or 3)
- Solar system moves through dark matter halo at 220 km/sec

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]

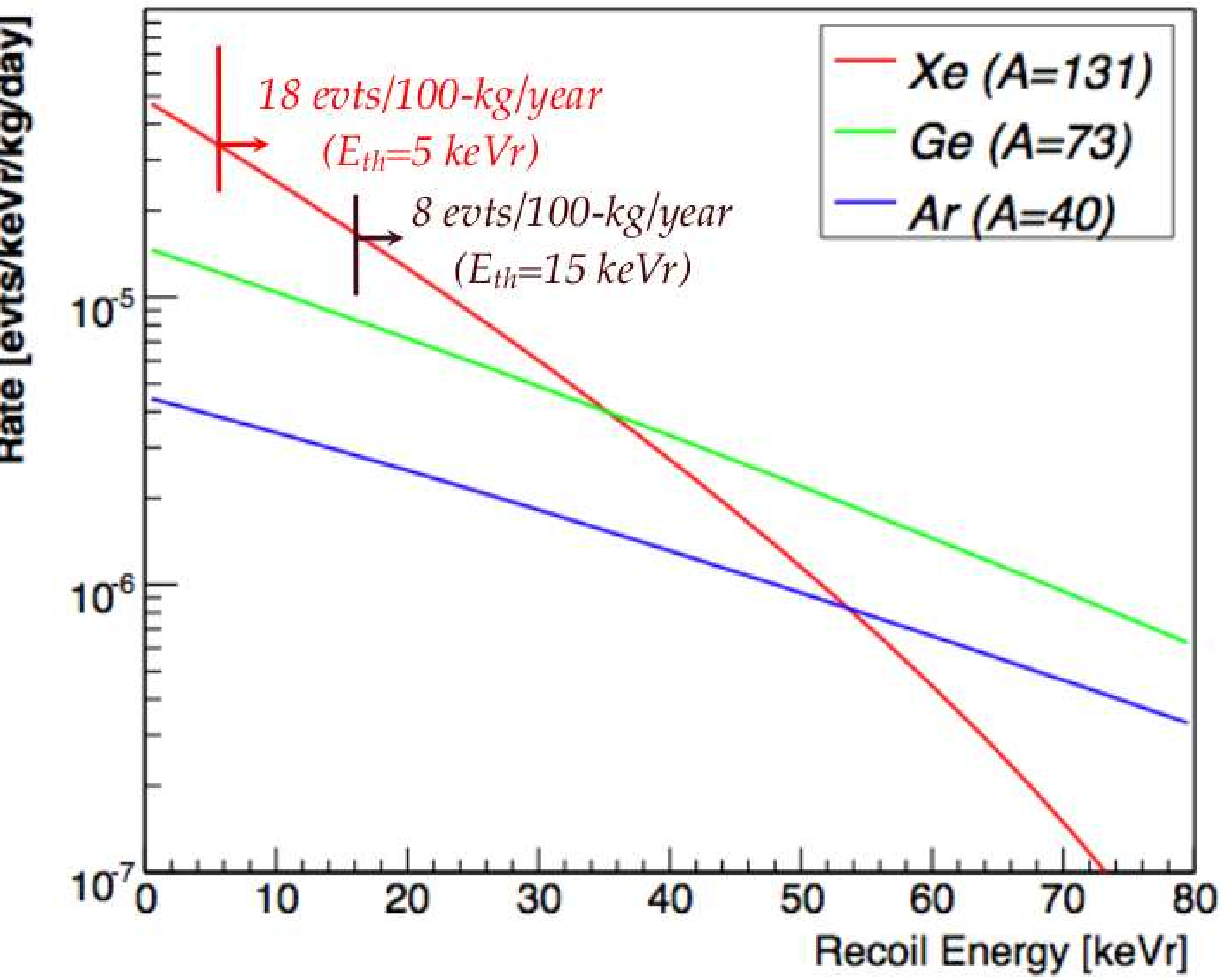
Why WIMPs?



A new particle with mass near the EW symmetry-breaking scale and weak force gauge couplings produces the right thermal relic density.

Annu. Rev. Astron. Astrophys. 2010. 48:495–545

Hunting for WIMPs



Want:

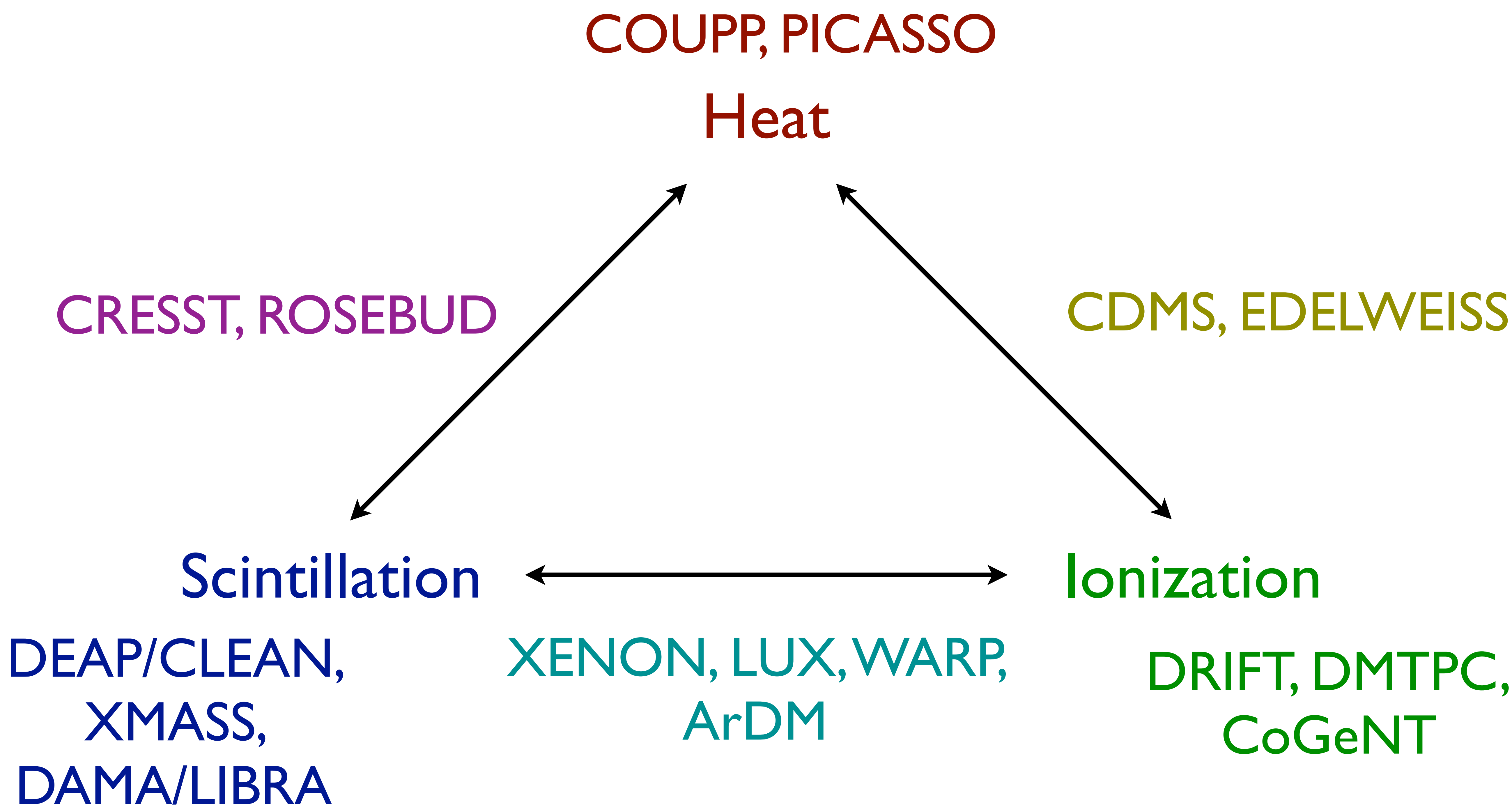
Low energy threshold

Large, "cheap," and clean target material

Excellent separation of nuclear recoils (induced by WIMPs) from other backgrounds

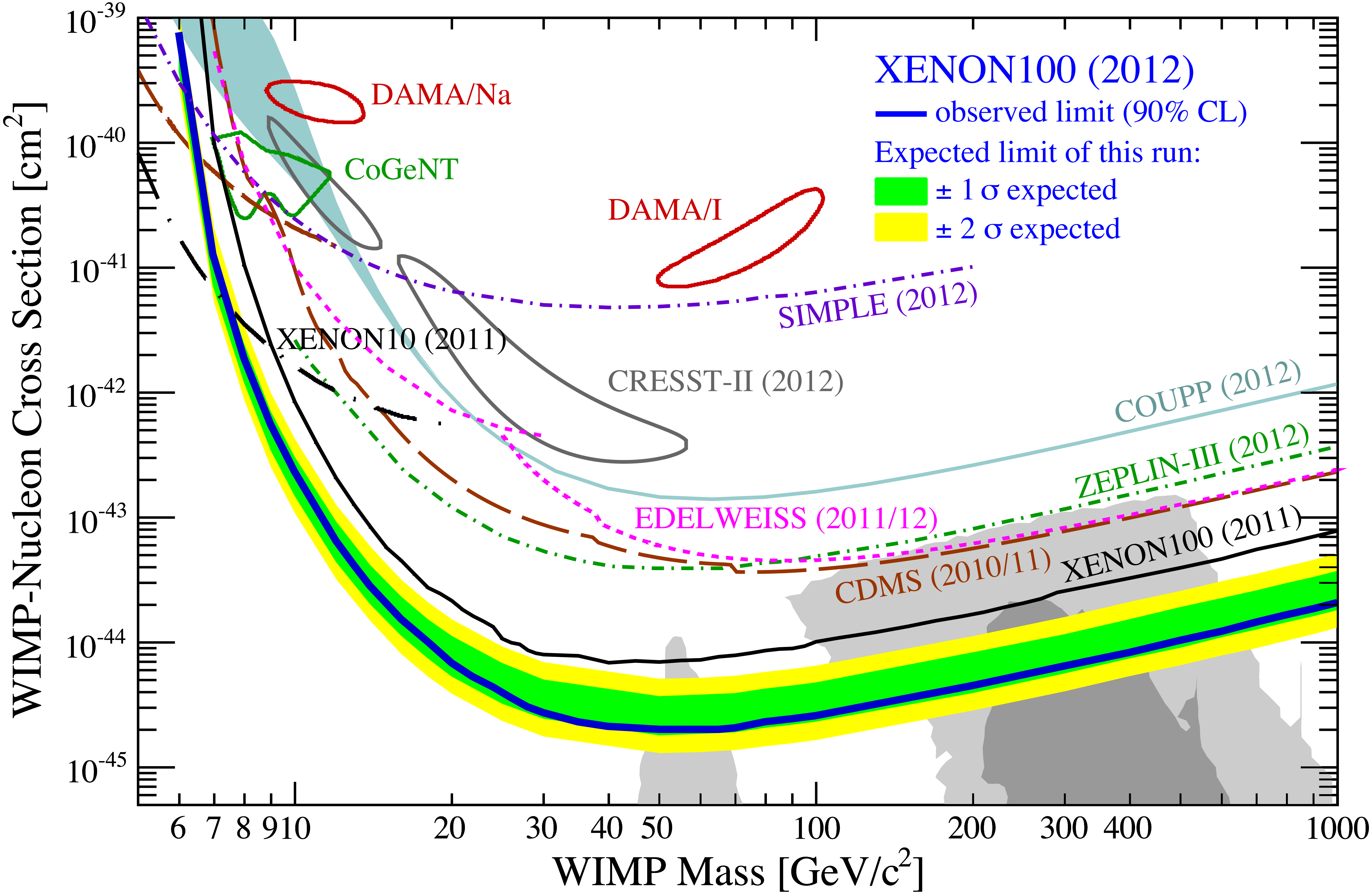
E. Aprile, http://www.slac.stanford.edu/econf/C080625/pdf/0018.pdf

Background Discrimination



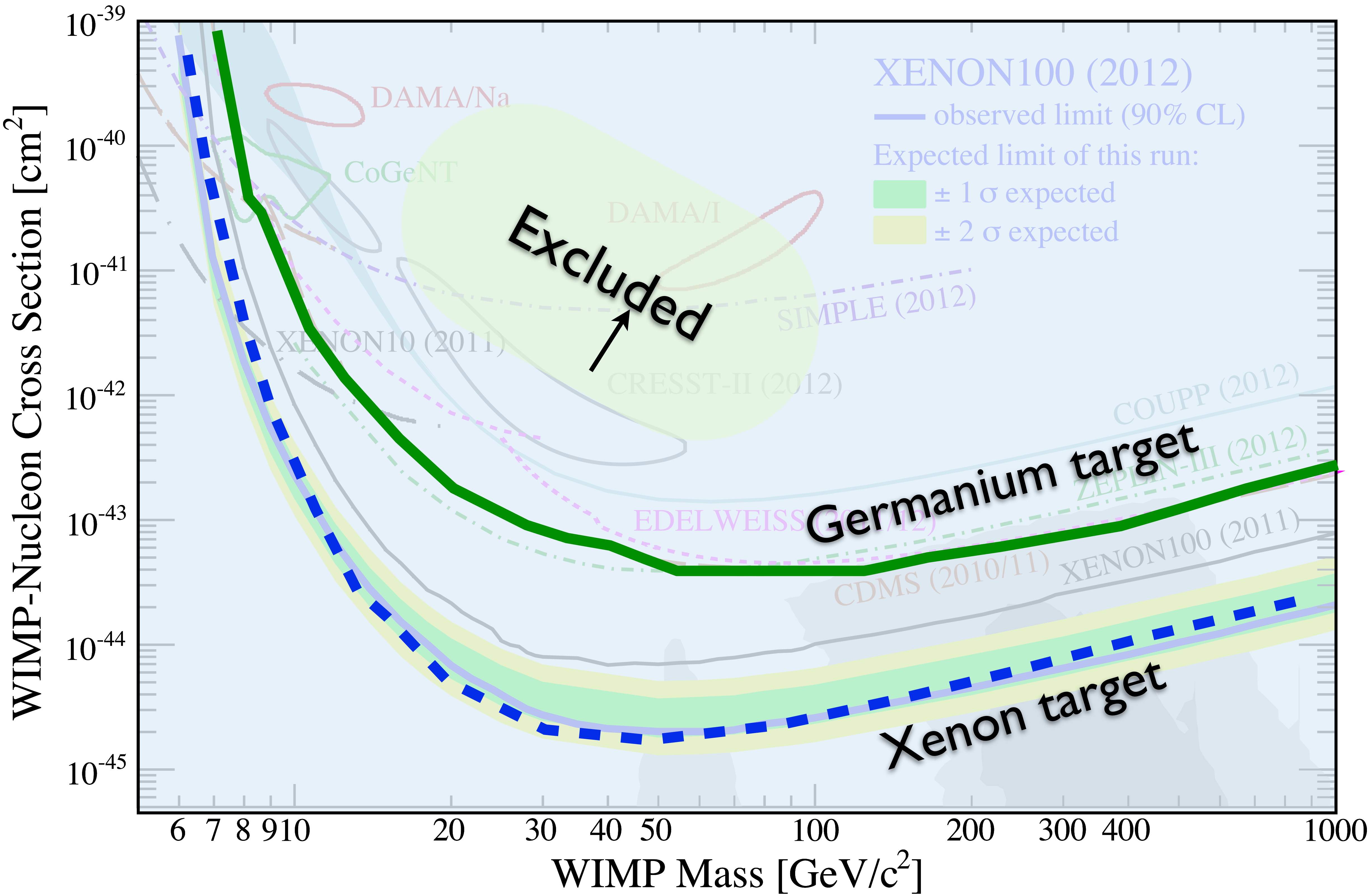
Experimental Results:
How are we doing so far?

In the Thick of It



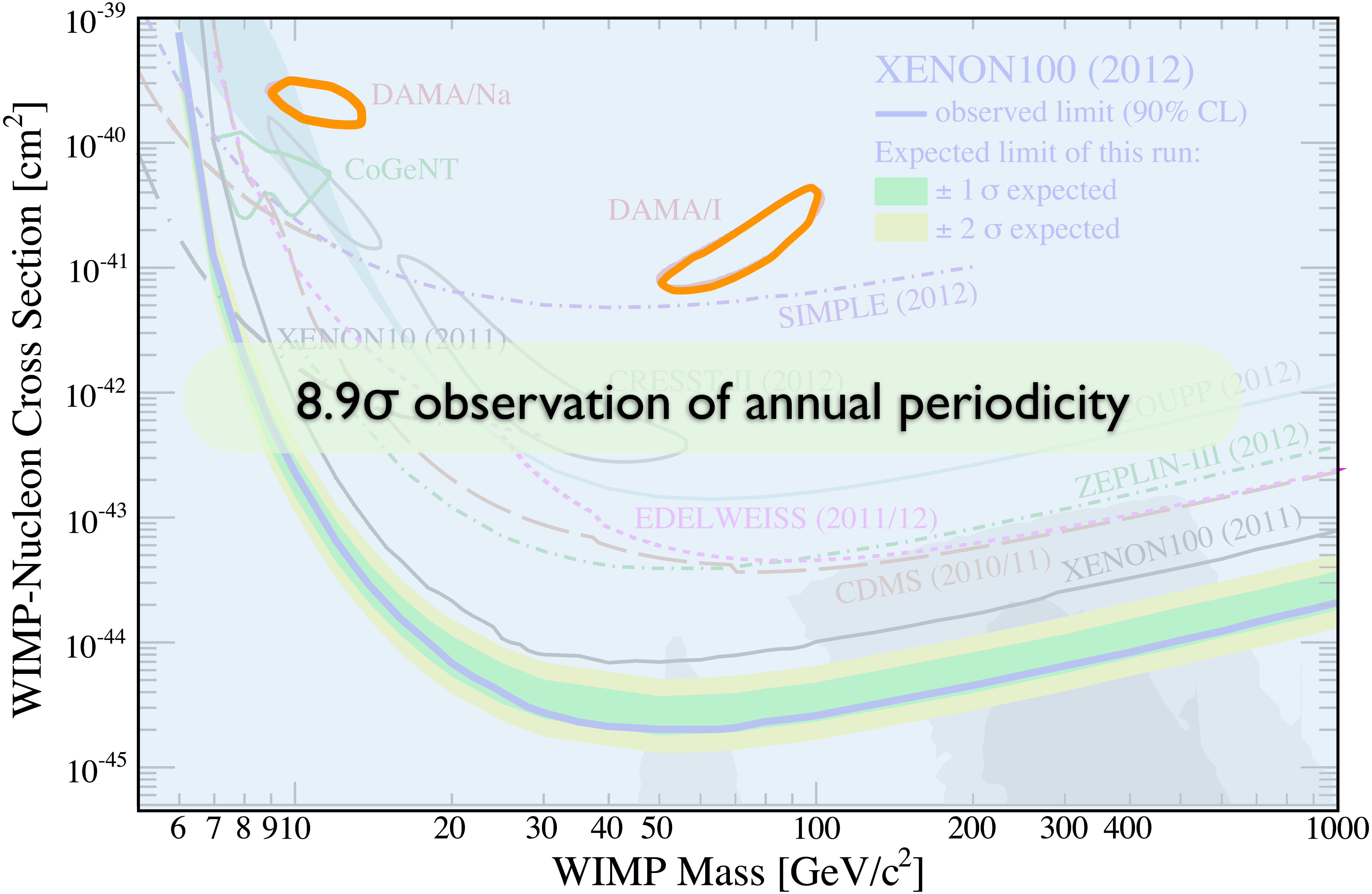
arXiv:1207.5988

Null Results: CDMS & XENON100



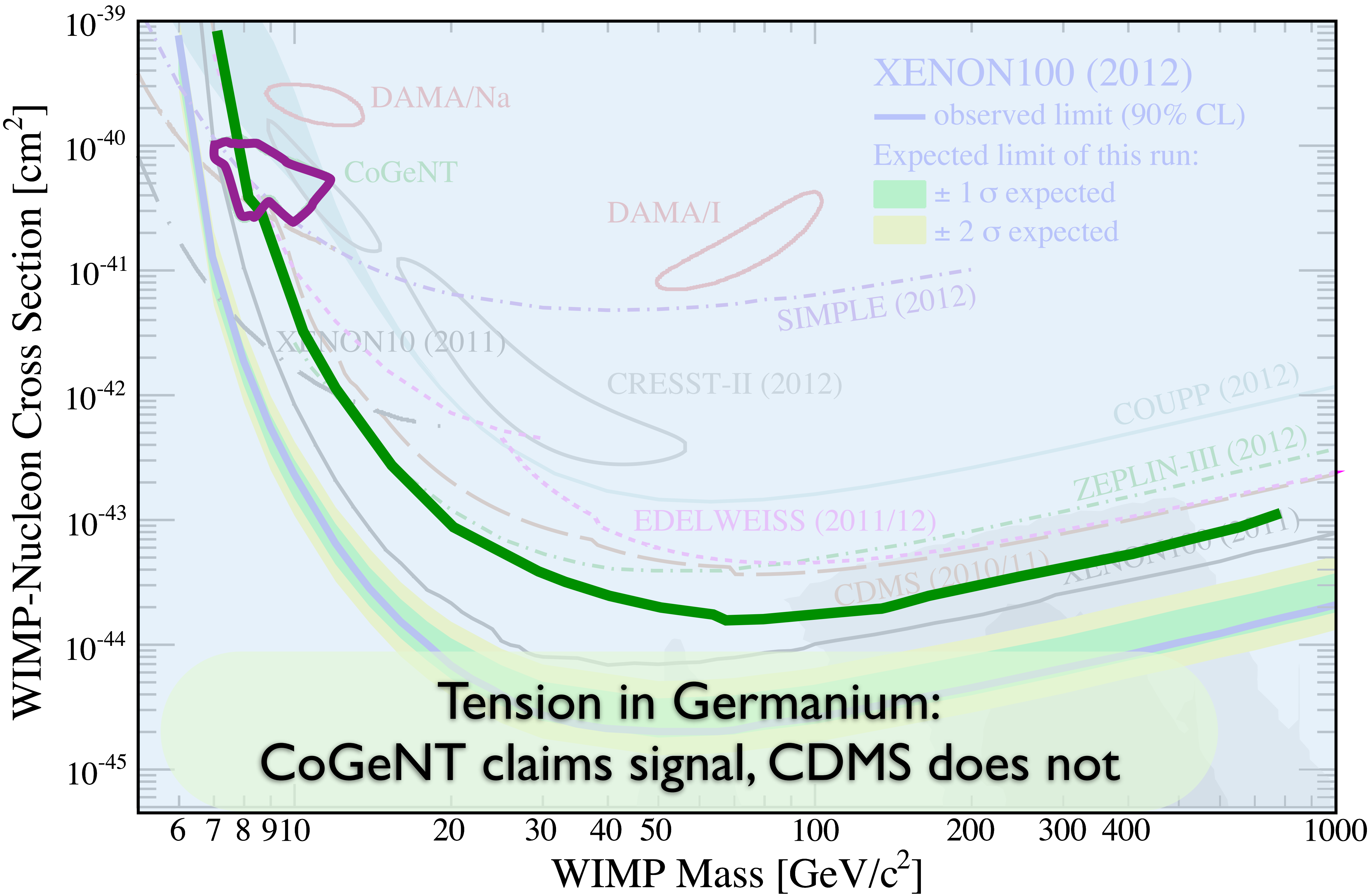
arXiv:1207.5988

DAMA



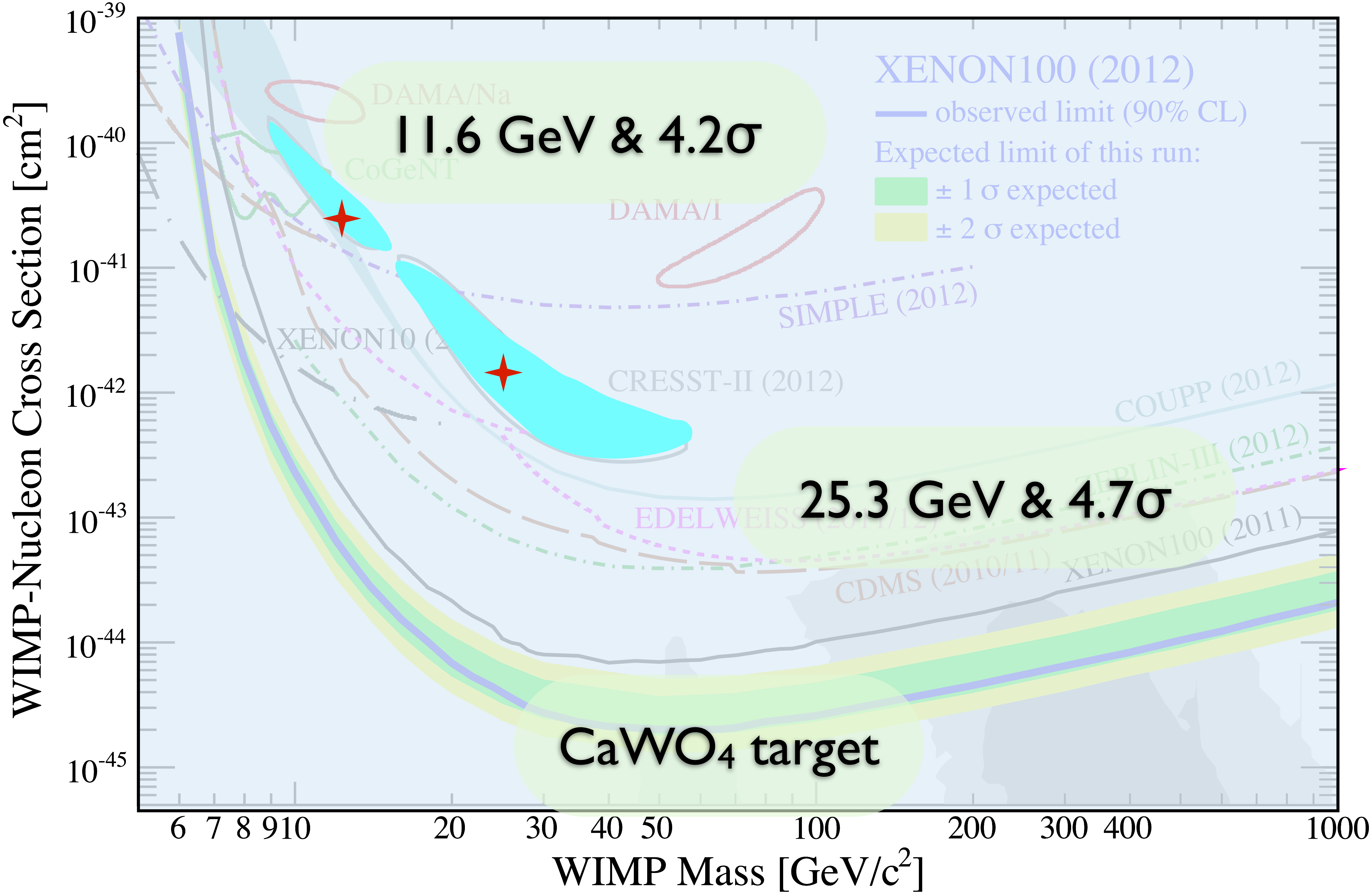
arXiv:1207.5988

CoGeNT vs. CDMS



arXiv:1207.5988

CRESST



arXiv:1207.5988

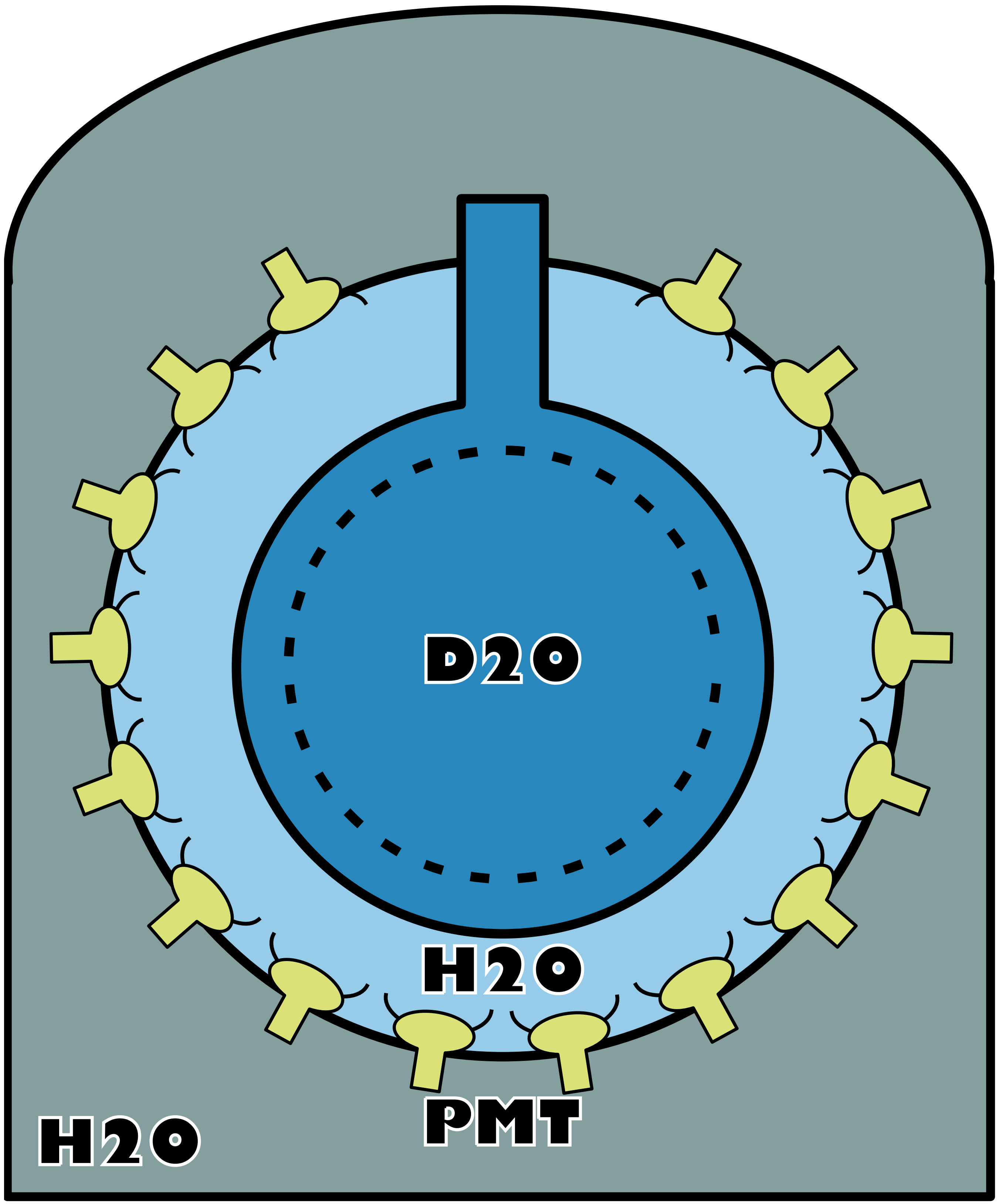
Summary of the data so far:

It took astronomers many decades to sort out evidence for dark matter.

Particle physicists are still very early in the process, and there is plenty of room for other approaches....

Can we look to past successes for inspiration?

Lessons From Neutrino Experiments



Sudbury Neutrino Observatory

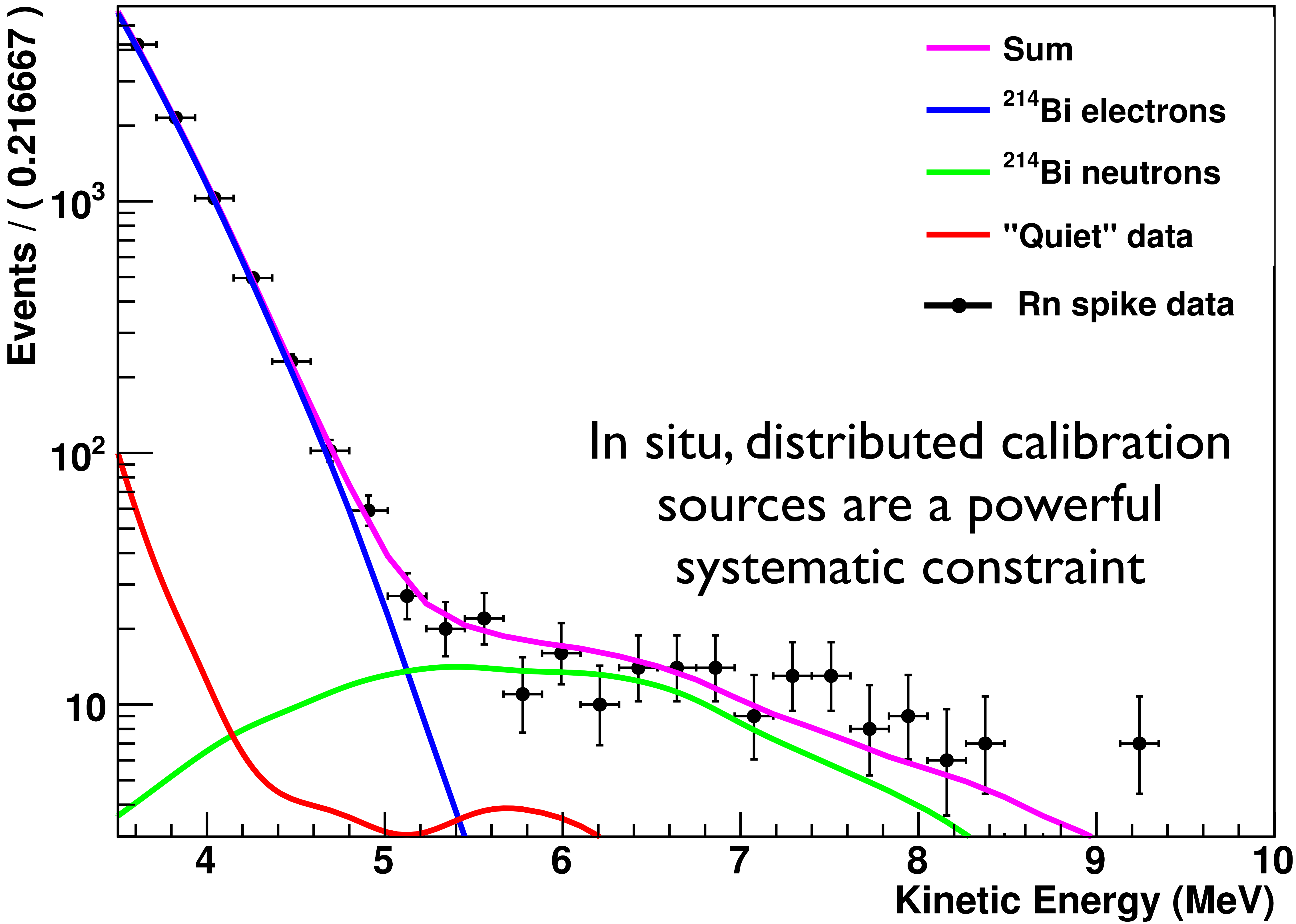
Low energy neutrino detection demands large, clean, and deep underground experiments, *much like dark matter.*

Scaling requires a detector that can be composed from "simple" repeatable structures.

Percent-level calibration is possible, especially when you start with a well-modeled detector.

Careful modeling of backgrounds allows for low threshold signal extraction.

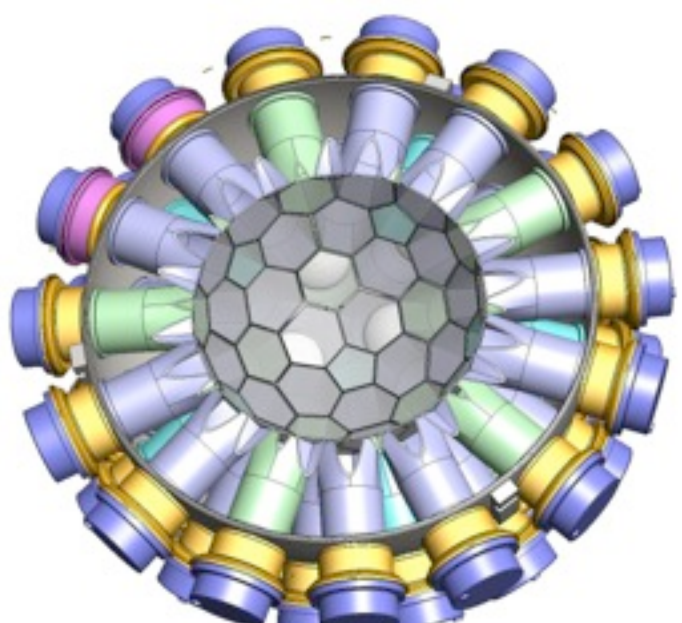
Ex: SNO Radon Spike



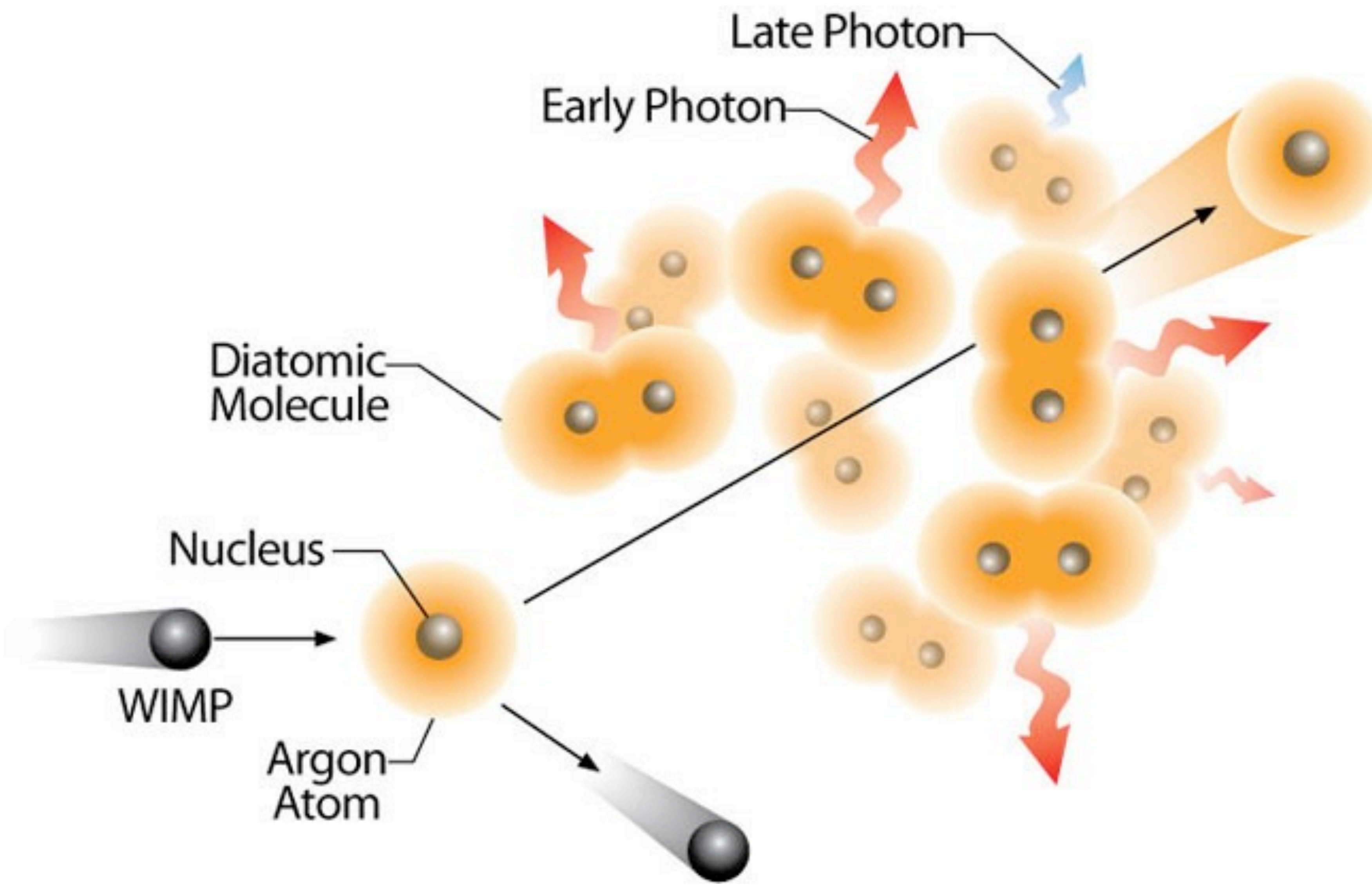
In situ, distributed calibration sources are a powerful systematic constraint

Best fit convolution of Monte Carlo by ~0.1 MeV

MiniCLEAN:
Searching for Dark Matter with Argon and Neon Scintillation



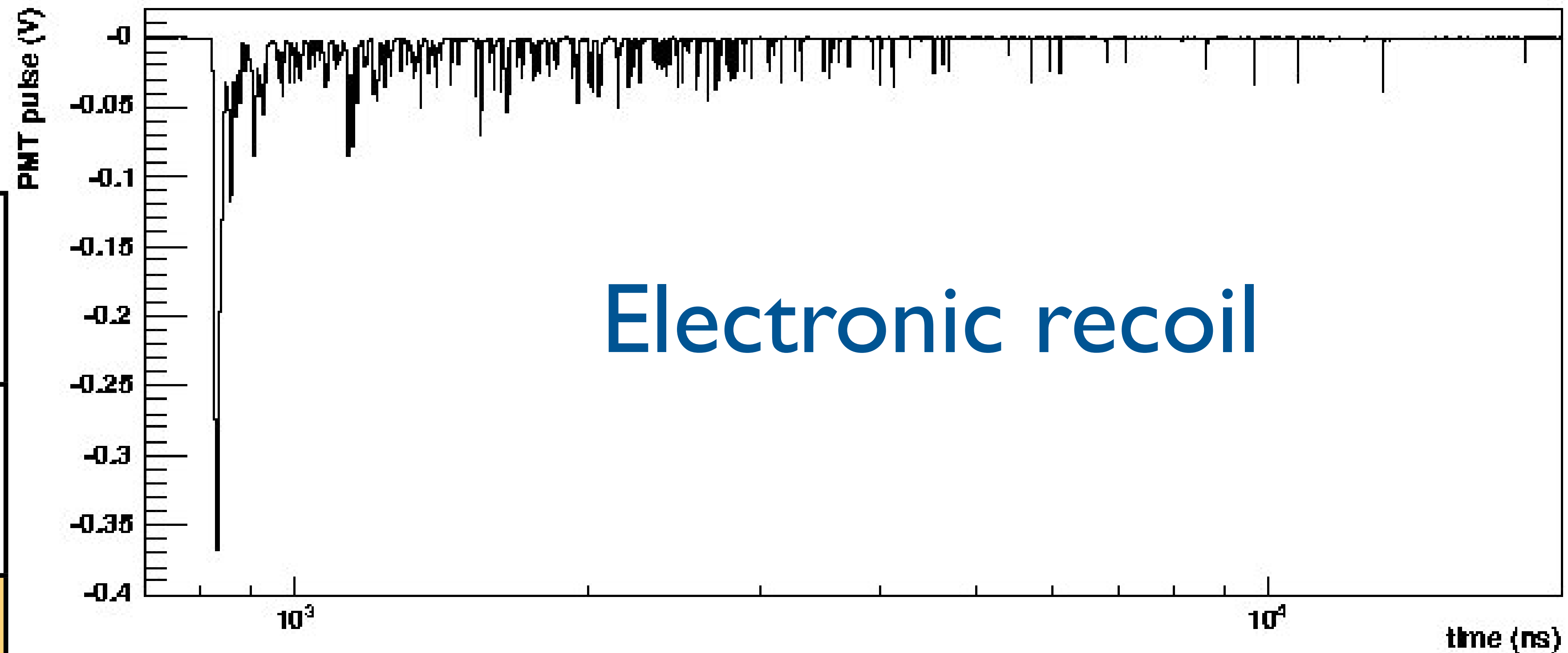
Scintillation in Noble Liquids

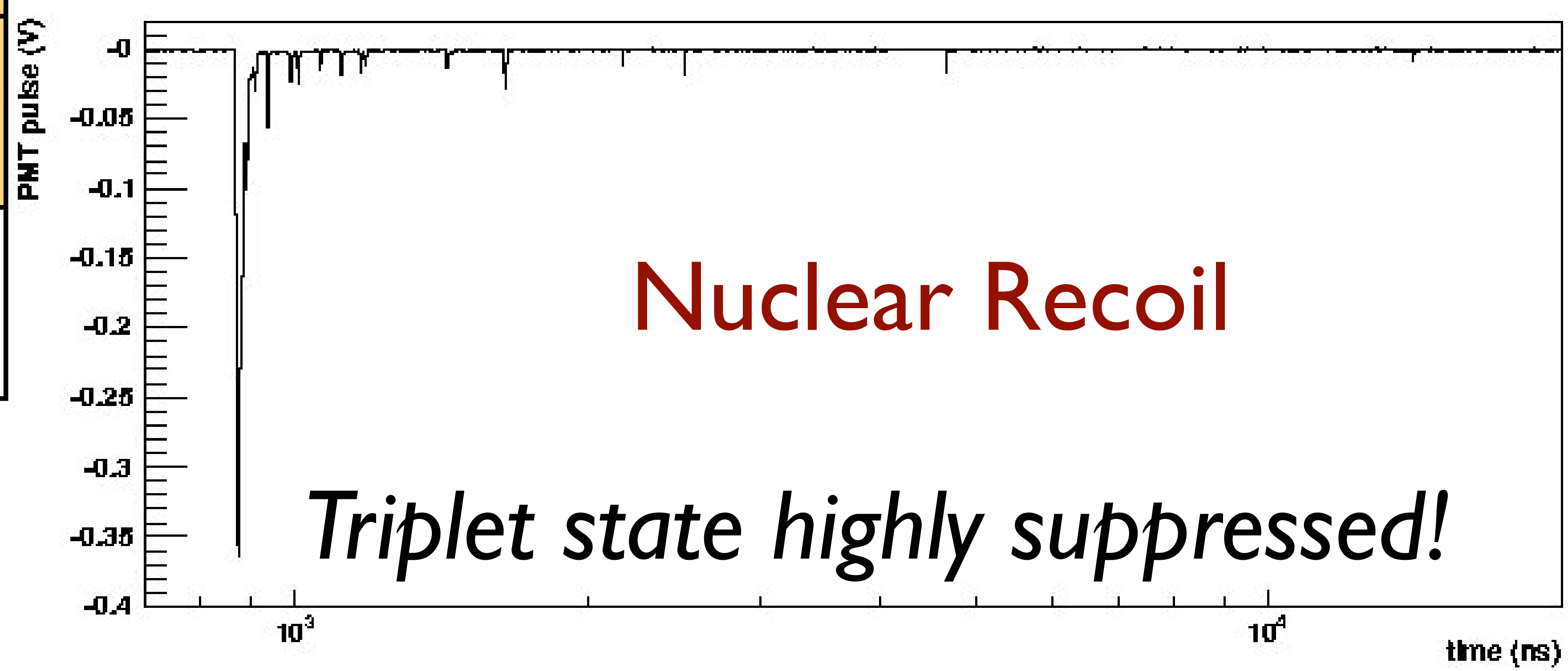


Energy deposition in noble liquids produces short lived excited diatomic molecules in singlet and triplet states.

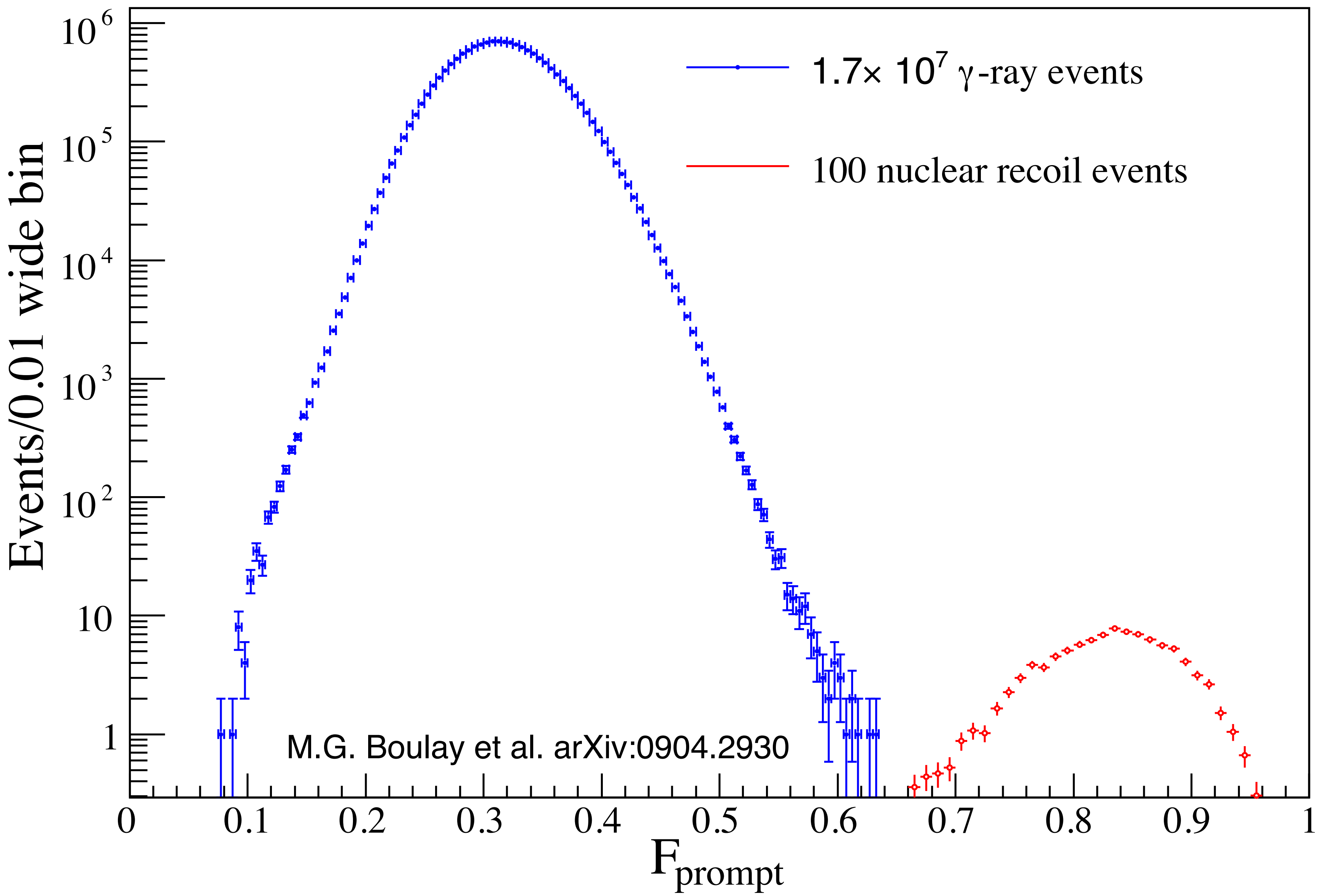
Pulse Shape Analysis

	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

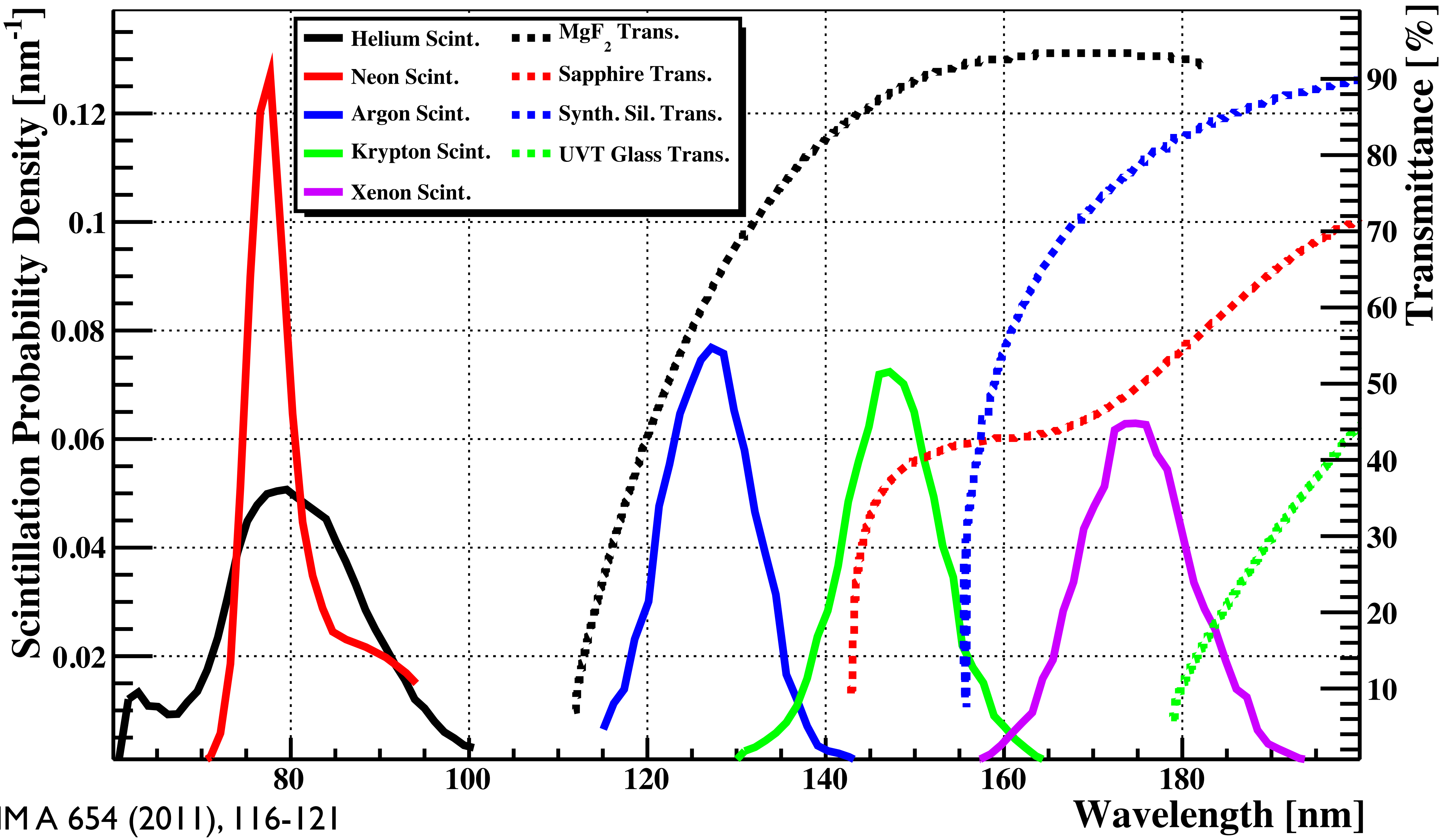


Discriminate with ratio of prompt to total light

Reject beta and gamma backgrounds with less than 10^{-8} leakage

Important to reject intrinsic ^{39}Ar background

Observing Extreme UV

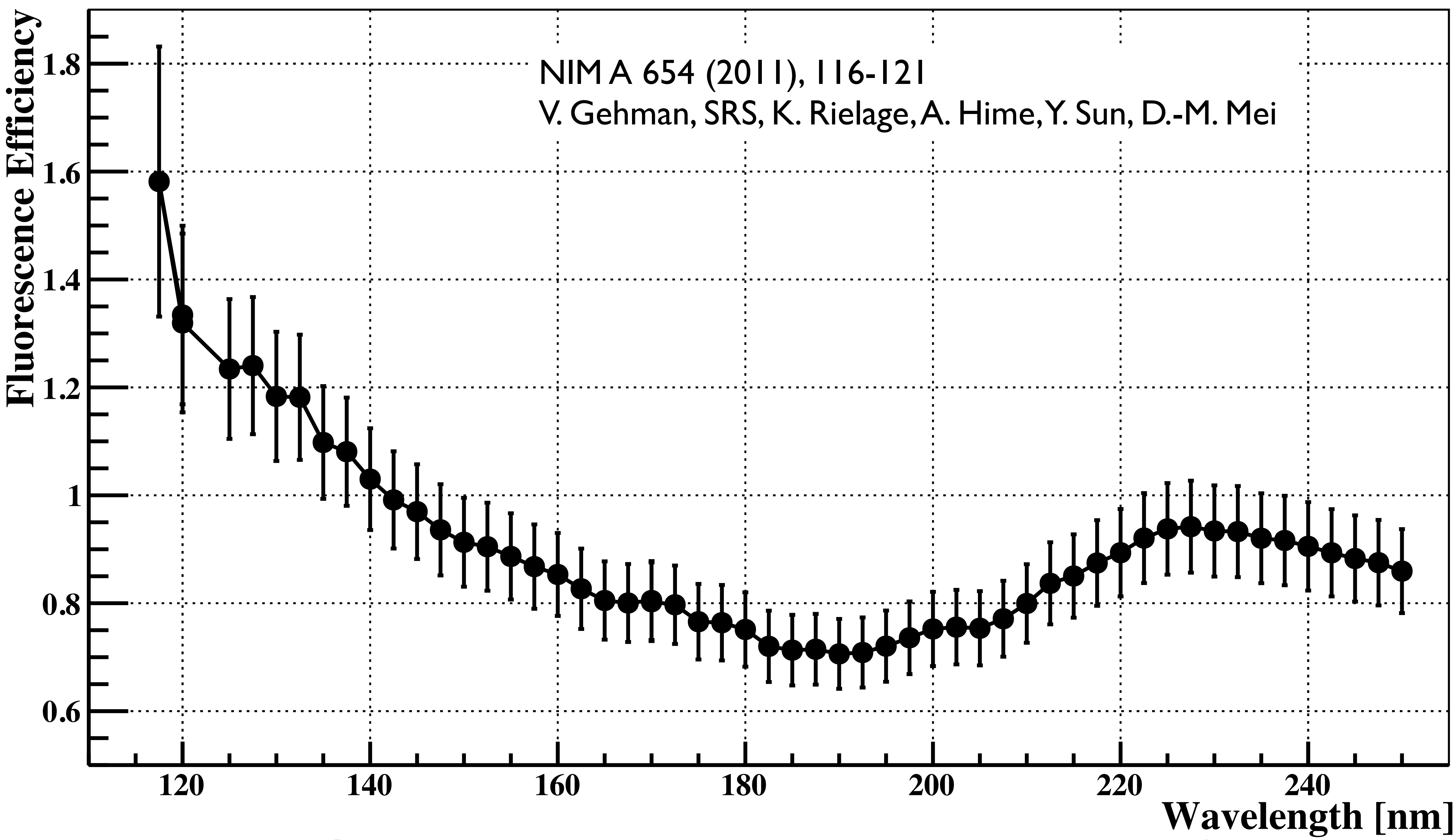


NIM A 654 (2011), 116-121
V. Gehman, SRS, K. Rielage, A. Hime, Y. Sun, D.-M. Mei

Almost everything absorbs 128 nm light!

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

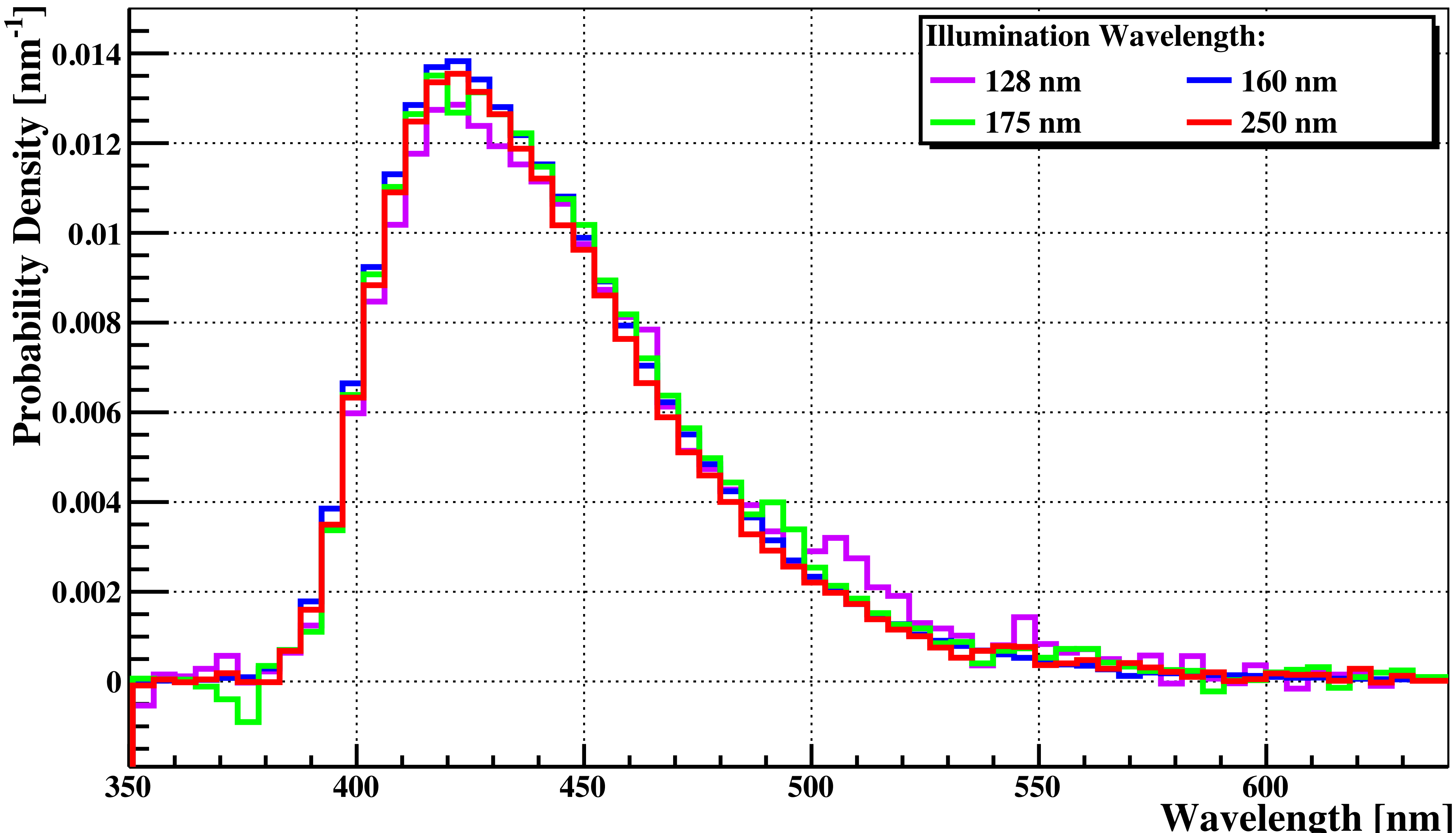
TPB Re-emission Efficiency



10% measurement resolves factor of 3 ambiguity in the literature

→ Disentangles TPB and argon scintillation efficiency, useful for other noble liquids

TPB Re-emission Spectrum



NIM A 654 (2011), 116-121
V. Gehman, SRS, K. Rielage, A. Hime, Y. Sun, D.-M. Mei

Discovered that re-emission spectrum independent of illumination wavelength and has cutoff near 400 nm.

→ Direct impact on choice of optical materials

Single Phase Ar/Ne Detectors

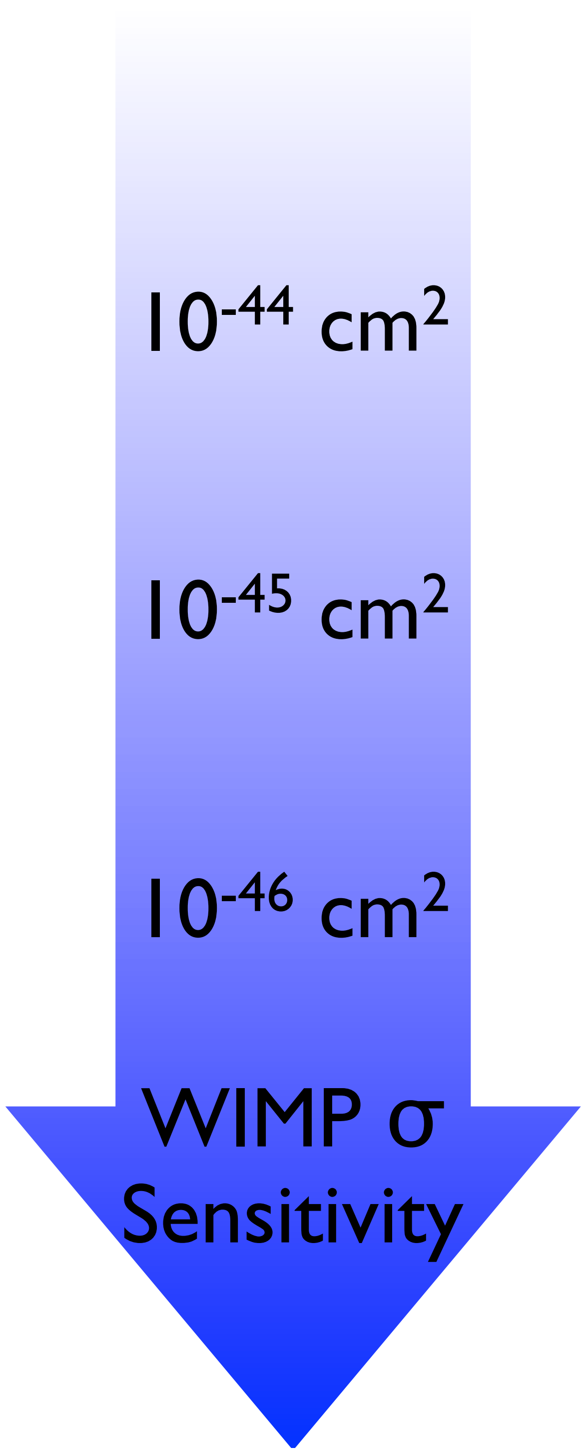
Advantages:

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

Disadvantages:

- Lower A^2 reduces coherent scattering enhancement
- Self-shielding from external backgrounds worse than other materials
- Atmospheric argon contains a high rate beta decay isotope, ^{39}Ar @1 Bq/kg *(also a fantastic calibration!)*

The DEAP and CLEAN Family of Detectors



DEAP-0:
Initial R&D detector

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

DEAP-3600:
3600 kg LAr (1000 kg fiducial mass)
266 warm PMTs
SNOLAB 2014

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
SNOLAB 2013

40-140 tonne LNe/LAr Detector:
pp-solar ν, supernova ν, dark matter $<10^{-46}$ cm^2
~2018?

MiniCLEAN Collaboration

Boston University

D. Gastler, E. Kearns, S. Linden

UC Berkeley

G.D. Orebi Gann

Los Alamos National Laboratory

M. Akashi-Ronquest, K. Bingham, R. Bourque, J. Griego, A. Hime, F. Lopez, J. Oertel, K. Rielage, L. Rodriguez

Massachusetts Institute of Technology

J.A. Formaggio, S. Jaditz, J. Kelsey, K. Palladino

National Institute Standards and Technology

K. Coakley

University of New Mexico

M. Bodmer, F. Giuliani, M. Gold, D. Loomba, J. Matthews, P. Palni, J. Wang

University of North Carolina/TUNL

R. Henning

University of Pennsylvania

T. Caldwell, J.R. Klein, A. Mastbaum, S. Seibert

Royal Holloway University of London

A. Butcher, J. Monroe, J.A. Nikkel, J. Walding

University of South Dakota

V. Guiseppe, D.-M. Mei, G. Perumpilly, C. Zhang

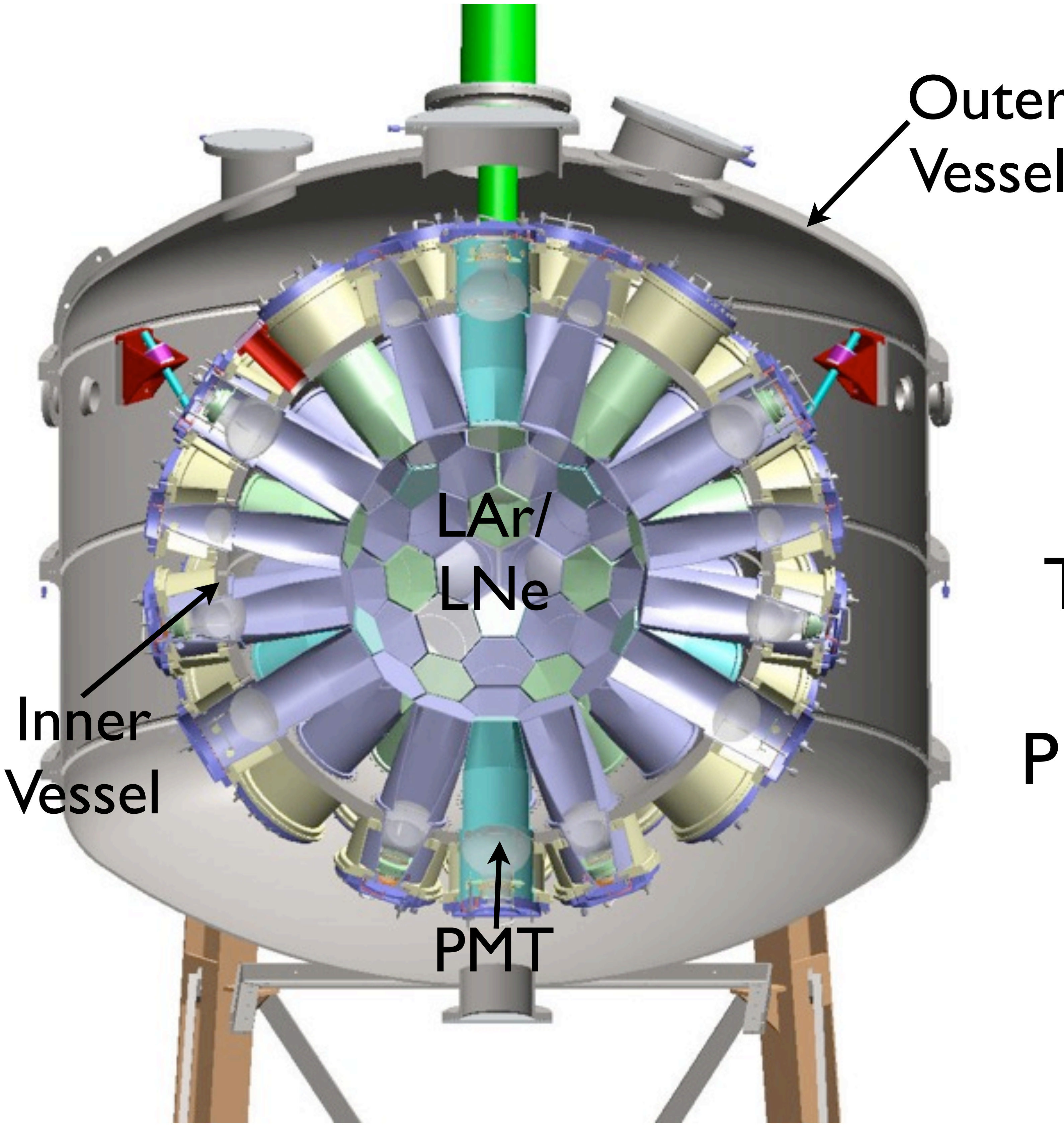
Syracuse University

R.W. Schnee, B. Wang

Yale University

D.N. McKinsey

The MiniCLEAN Detector



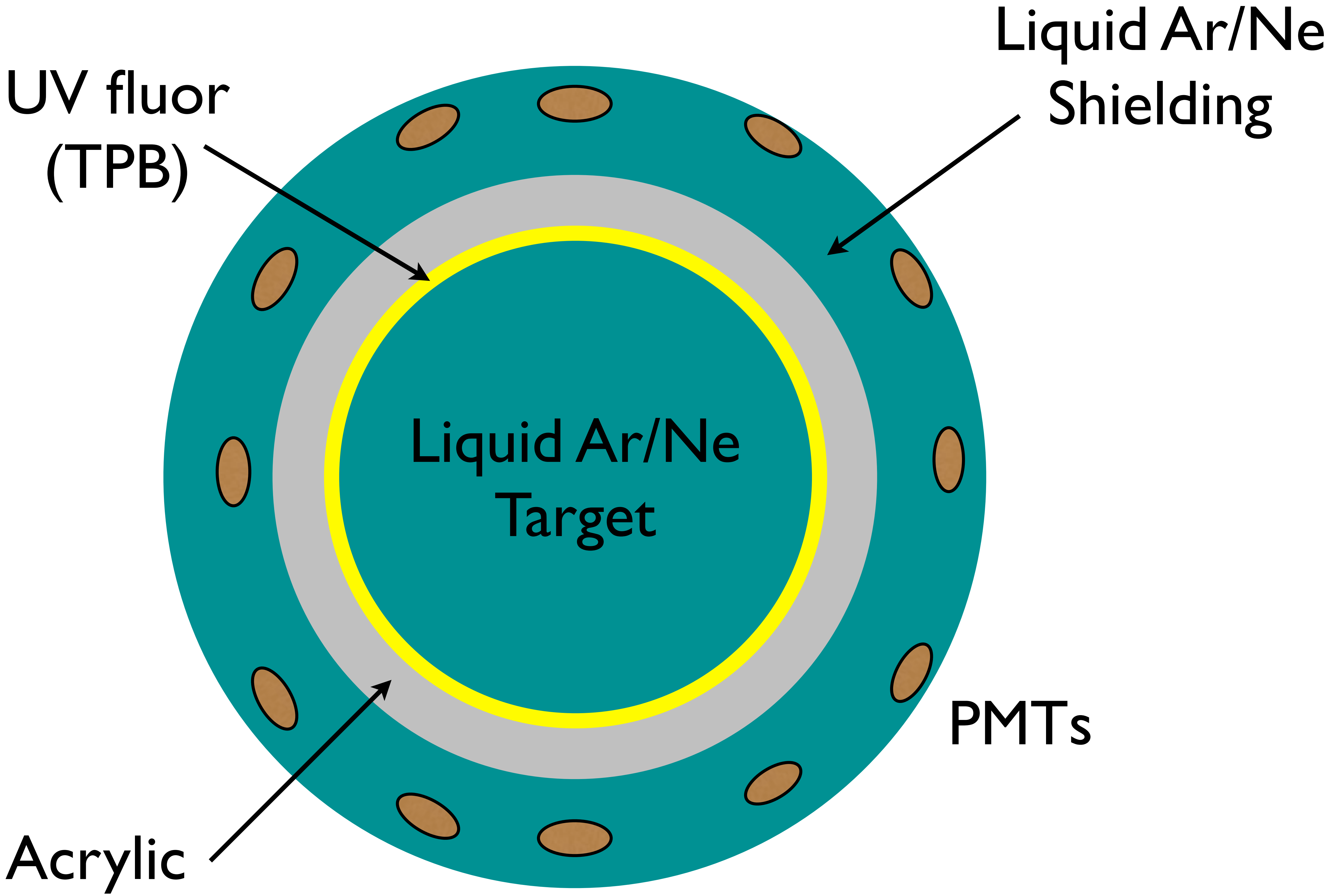
92 8" PMTs

TPB @ R=43 cm

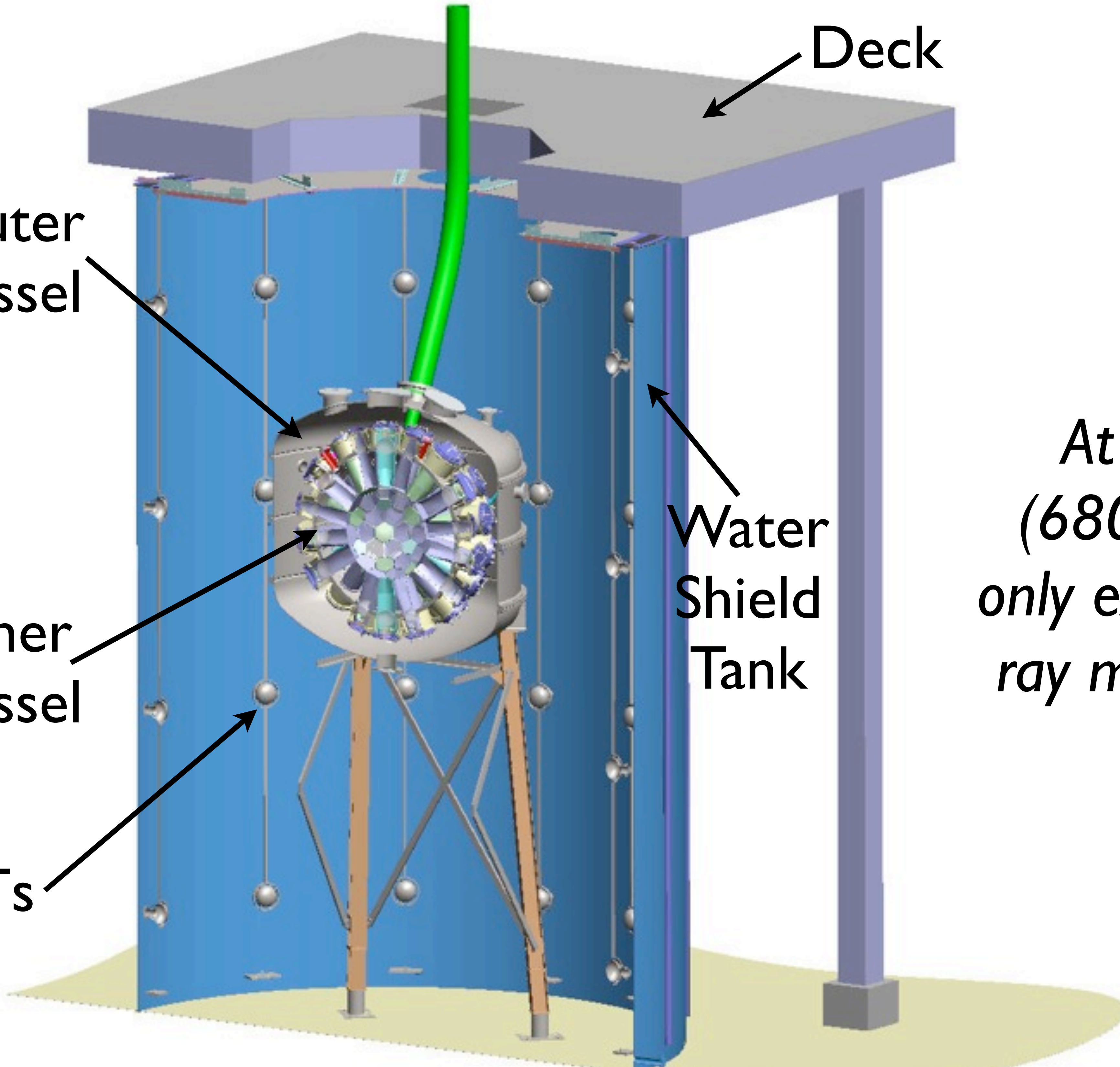
PMTs @ R=81 cm

Courtesy J. Griego

Simplified View



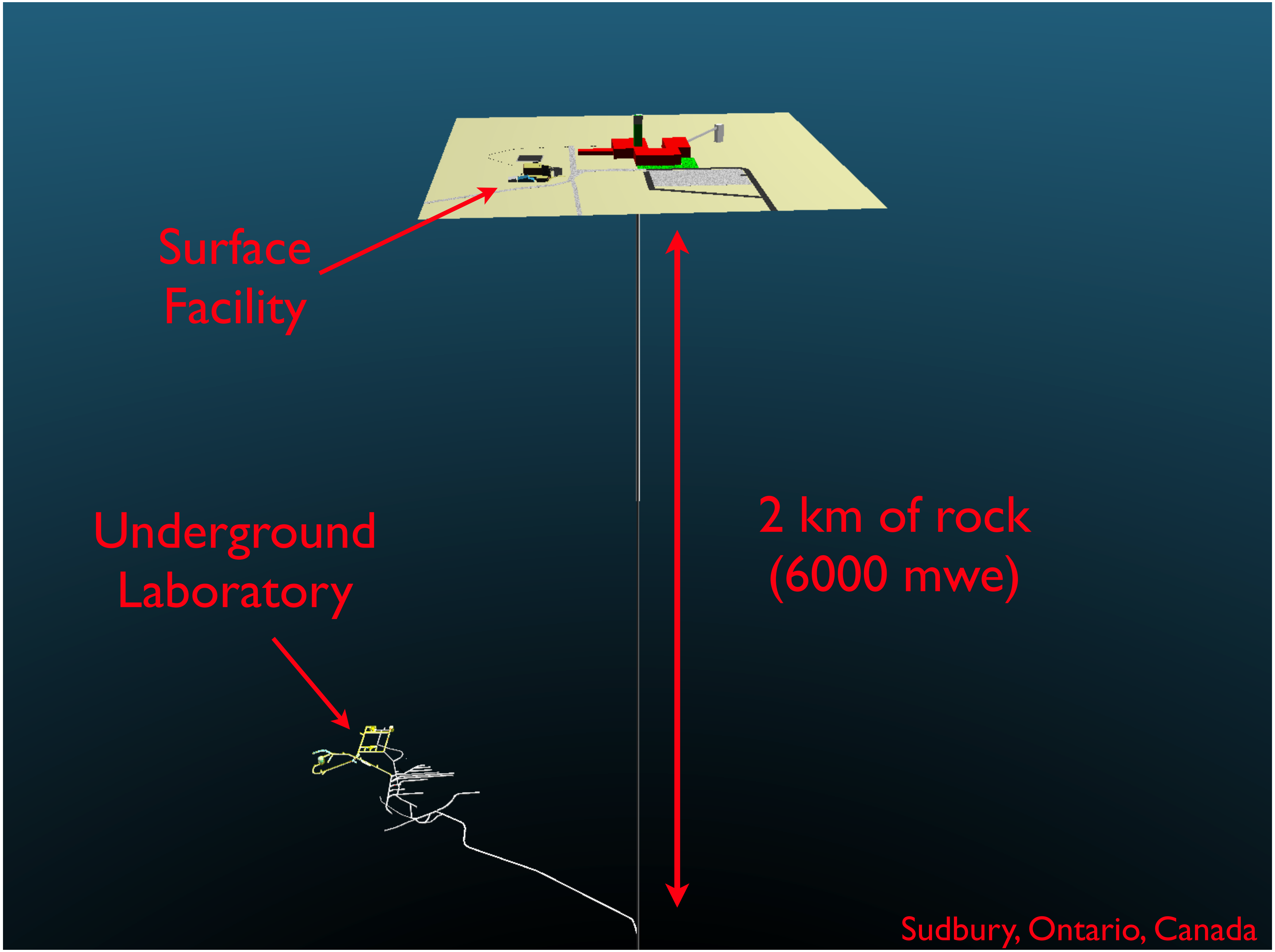
Water Shielding



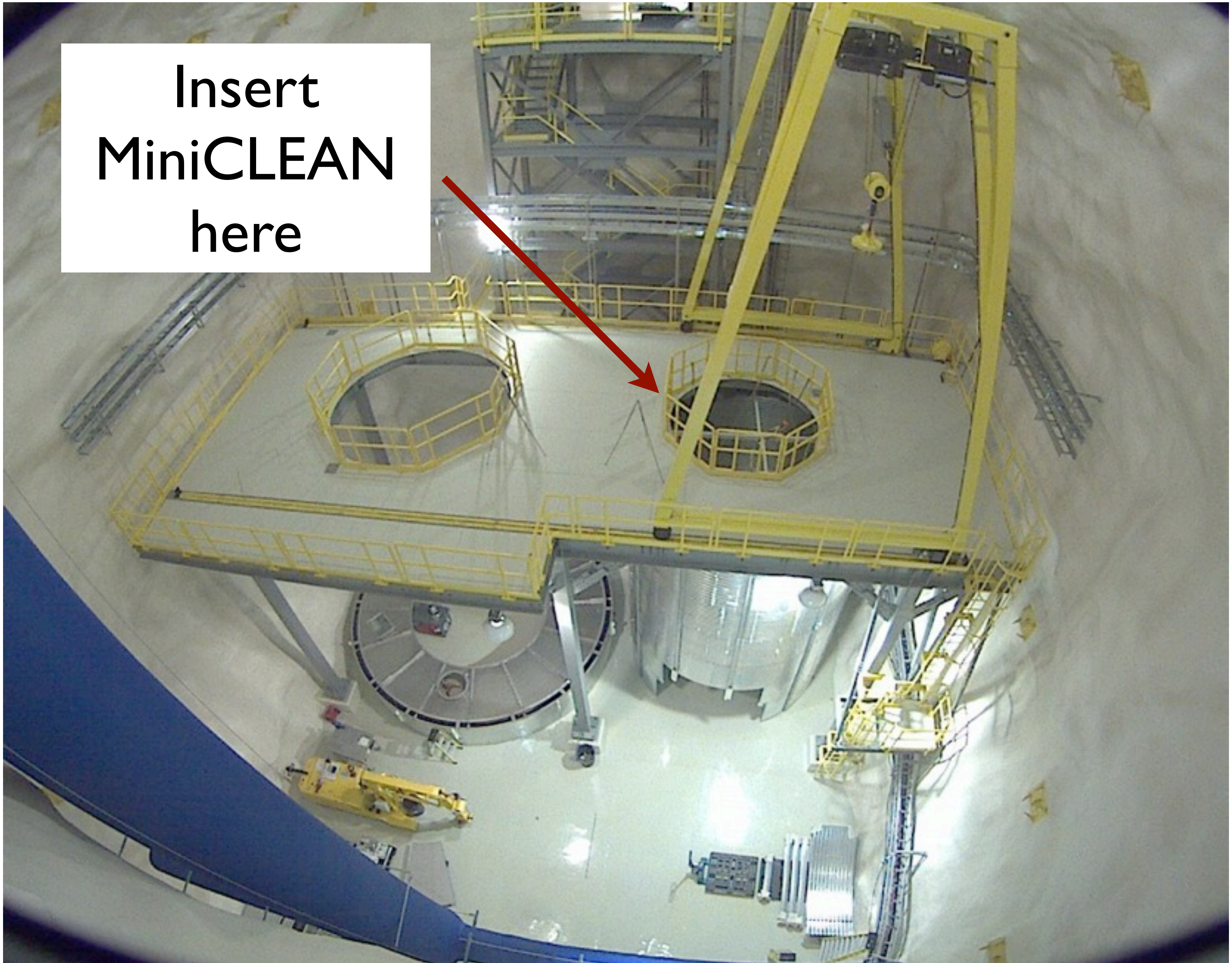
At 6000 mwe (6800 ft of rock), only expect 3 cosmic ray muons per day!

Courtesy J. Griego

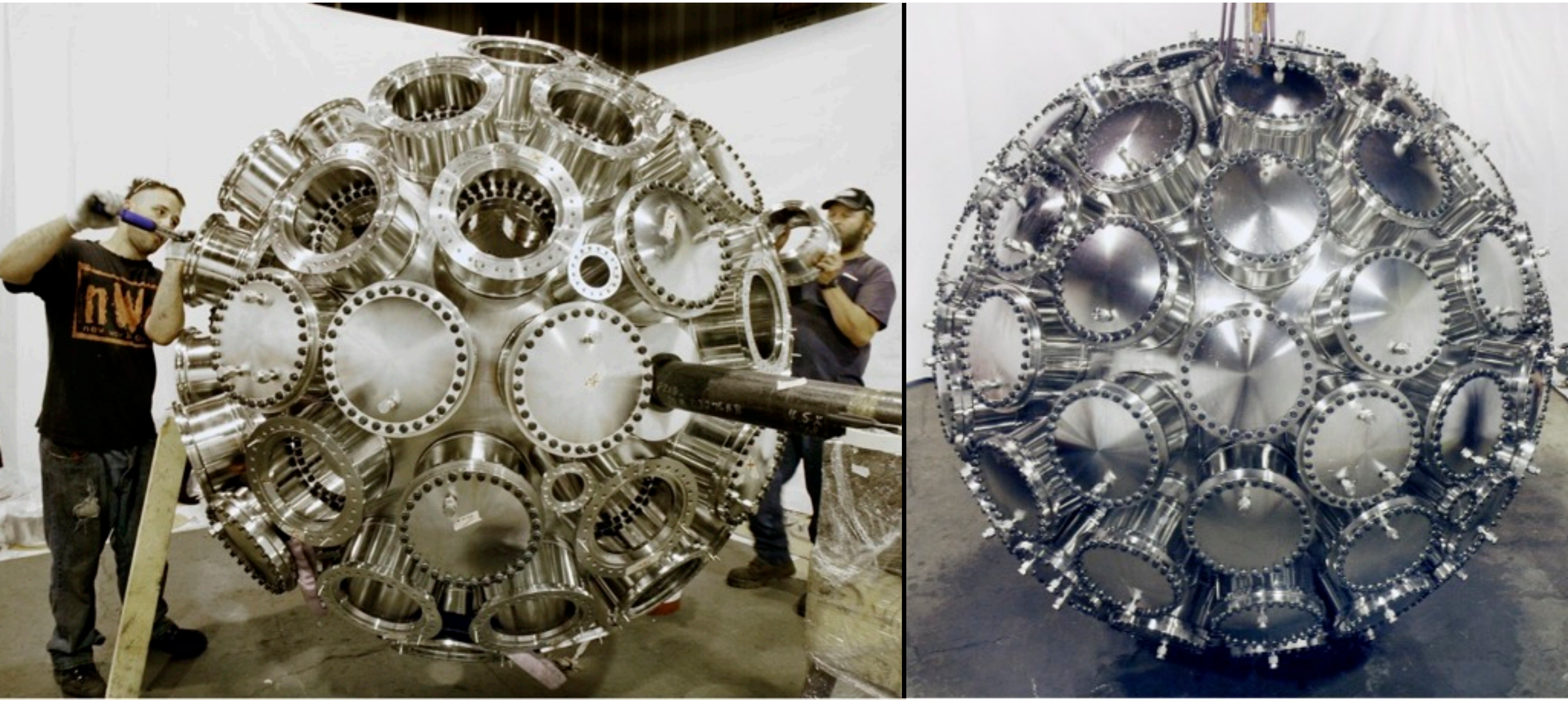
SNOLAB


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

Lab Area



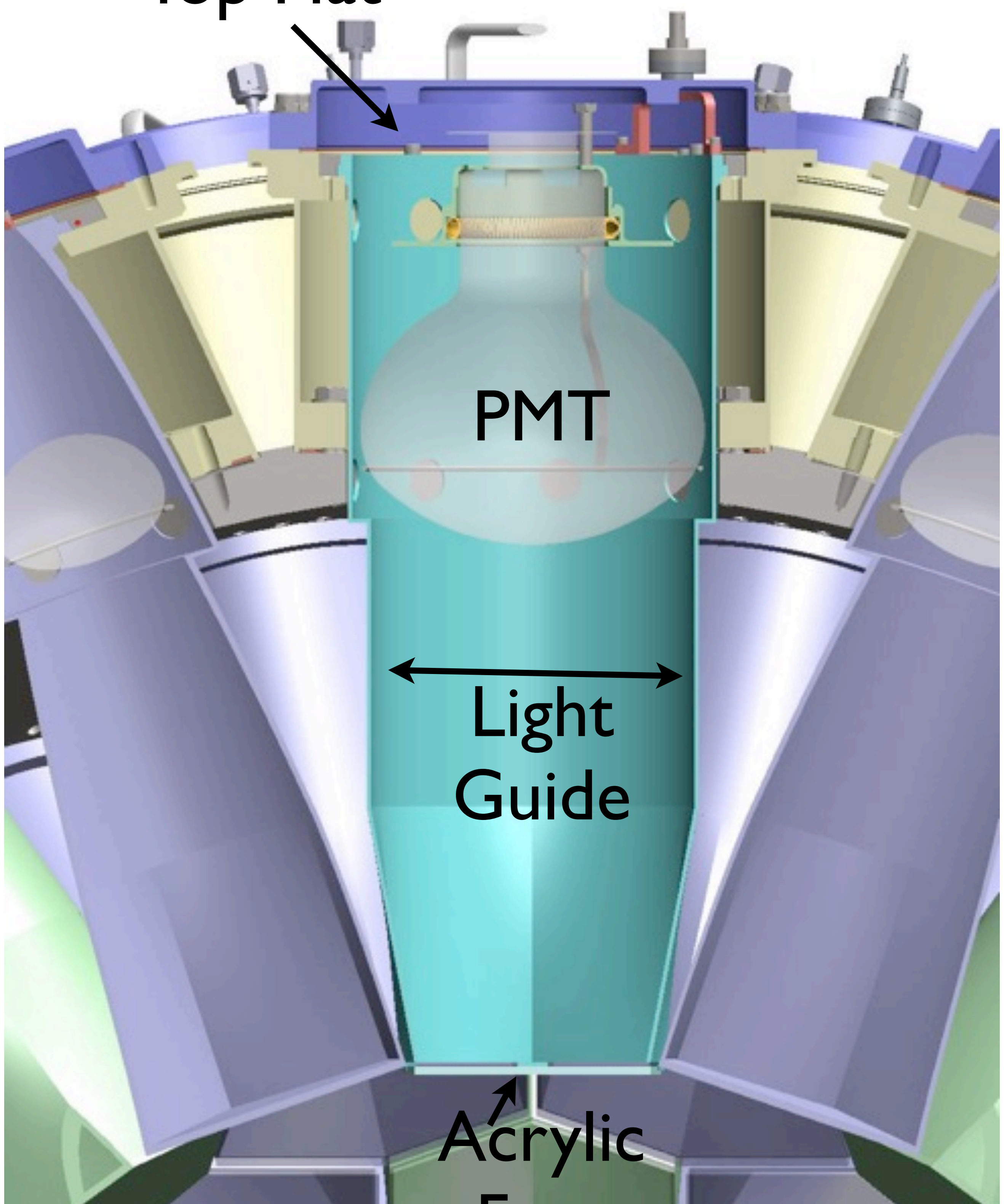
Inner Vessel

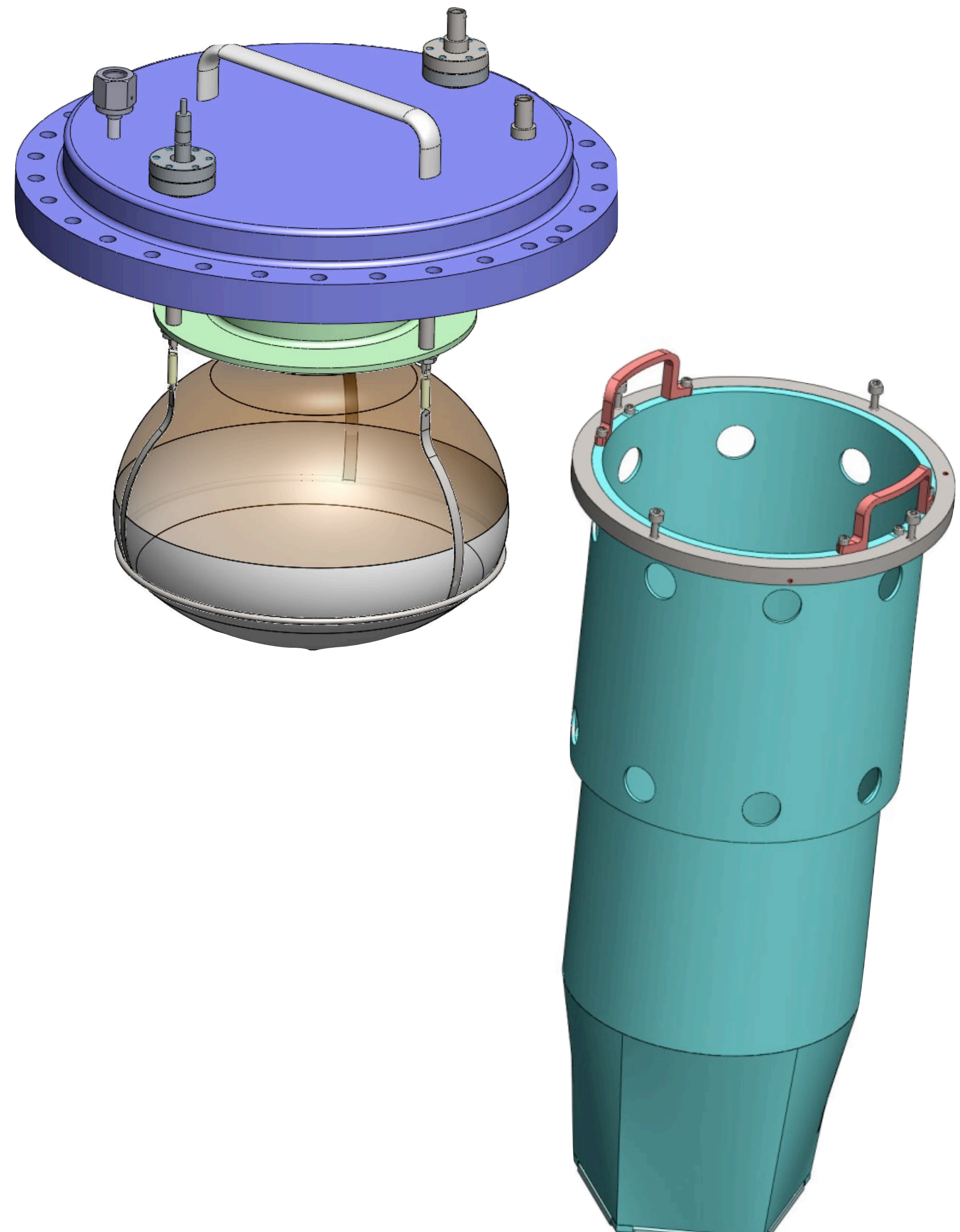


Manufacturing completed, pressure and leak tested in Sept. 2012

Inner Vessel Underground

Optical Cassettes



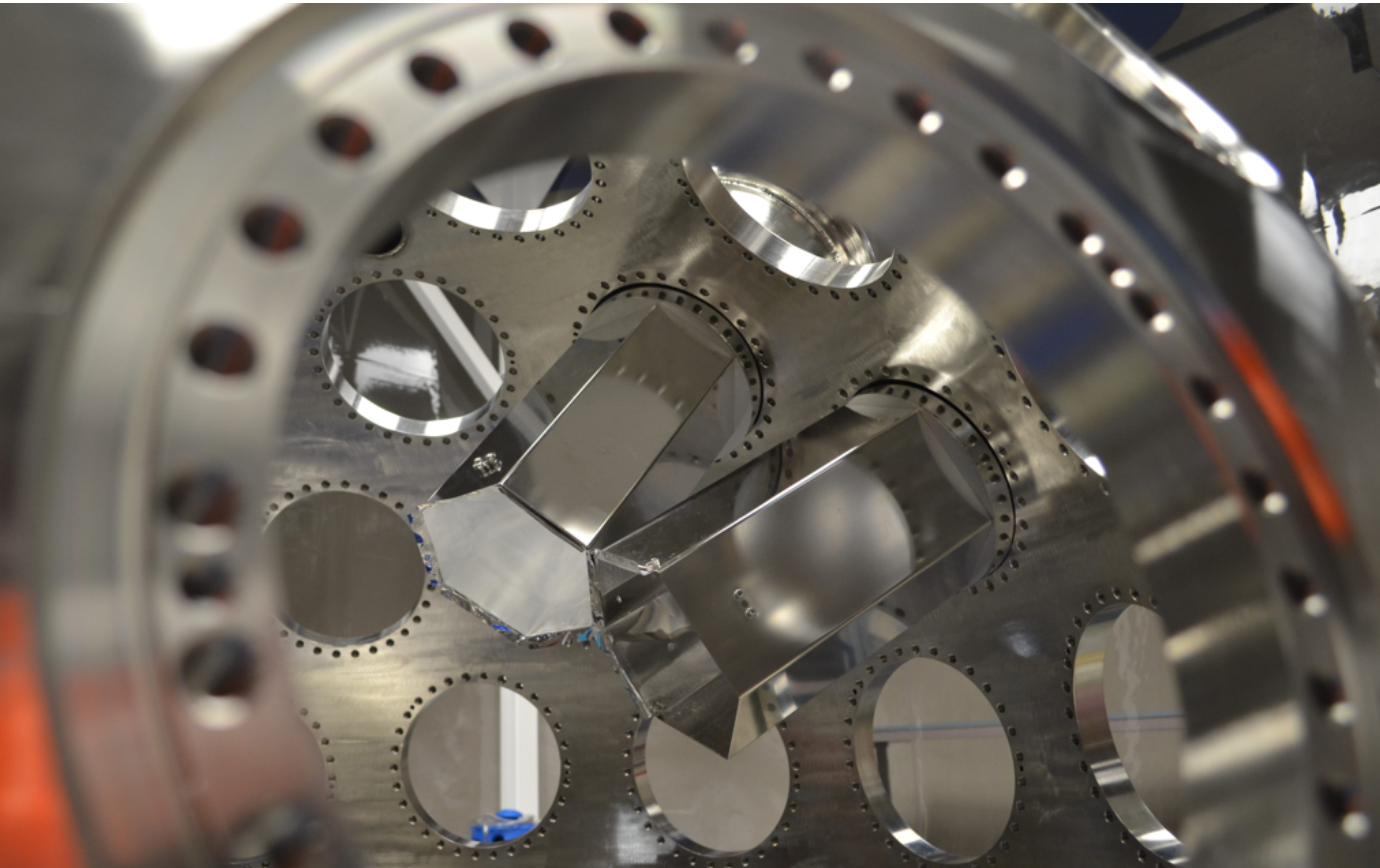


Courtesy J. Griego

Construction Progress: Cassettes

All stainless steel parts delivered to SNOLAB and underground!

Testing Assembly

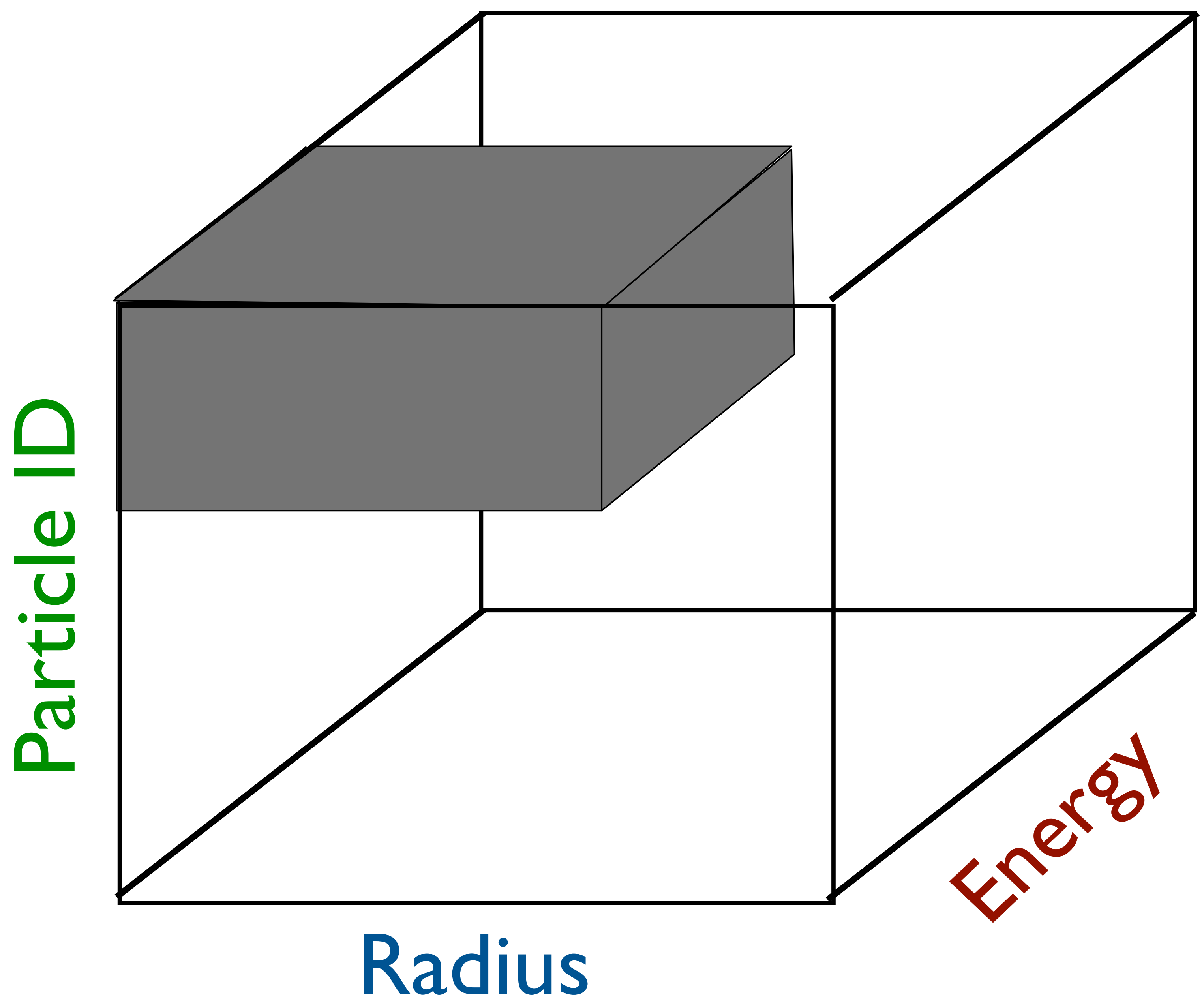


Acrylic and Wavelength Shifter

Coated acrylic from IntlVac completed and delivered

MiniCLEAN WIMP Analysis

Will perform a maximum likelihood analysis with a blind signal box in three reconstructed observables:



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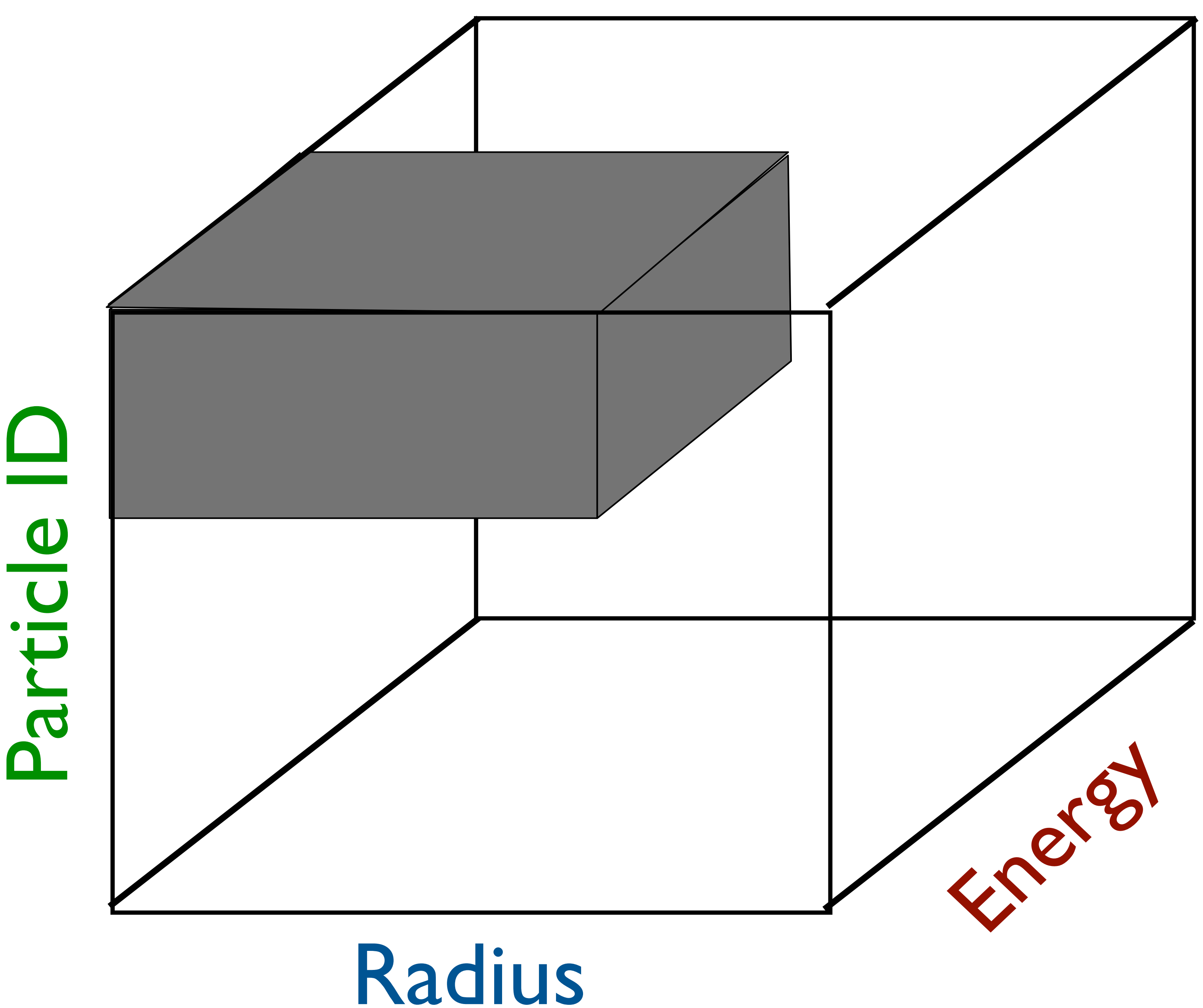
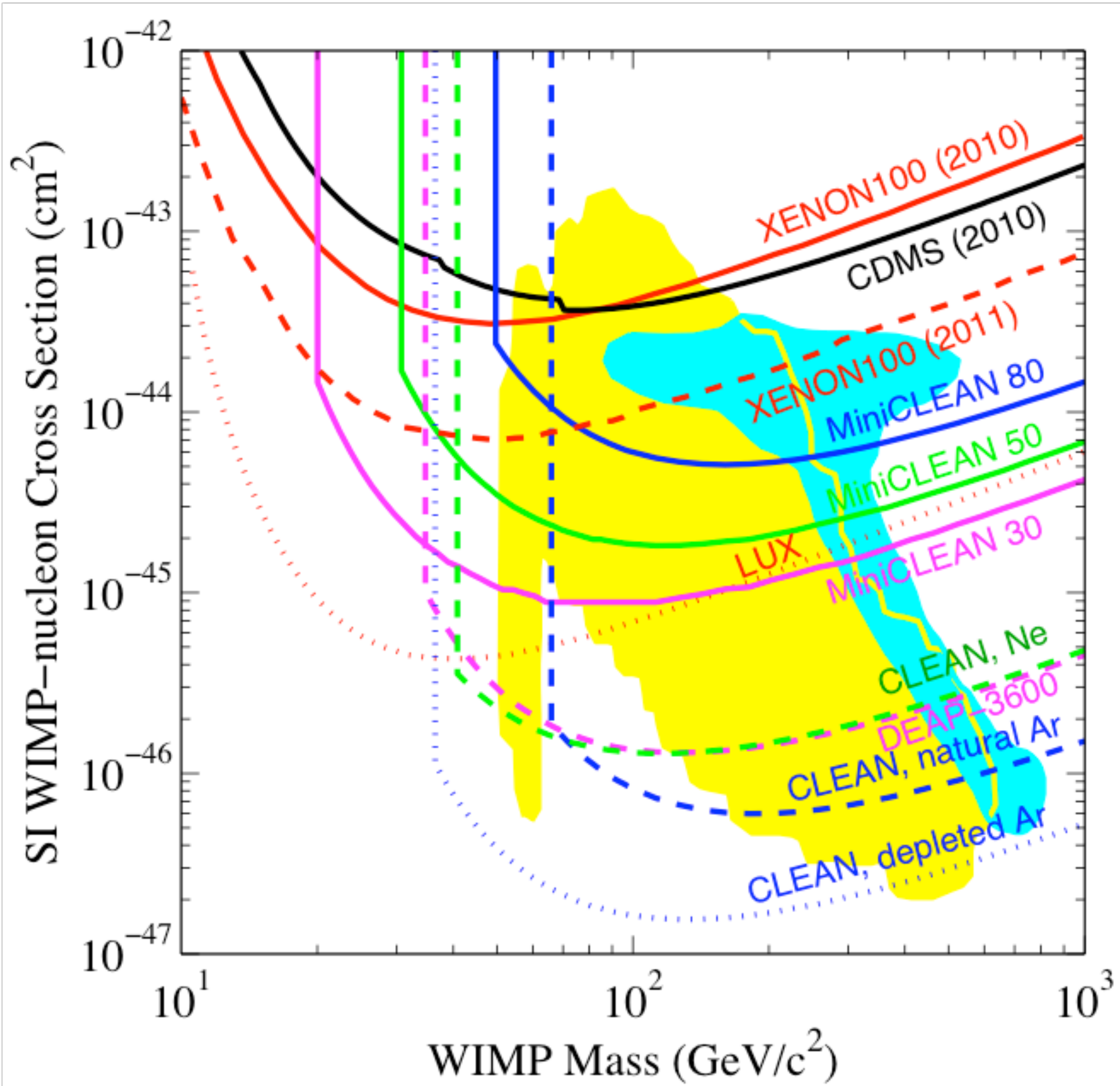


Particle ID:
- Reject ^{39}Ar, TPB scintillation from alphas, external gammas, neutrons

Radius:
- Reject surface events and neutrons

Energy:
- Reject all backgrounds at high energies

WIMP Sensitivity



MiniCLEAN w/ 150 kg fiducial volume

80 = 80 keVr threshold

50 = 50 keVr threshold

30 = 30 keVr threshold

Small change in energy threshold equivalent to large change in fiducial volume!

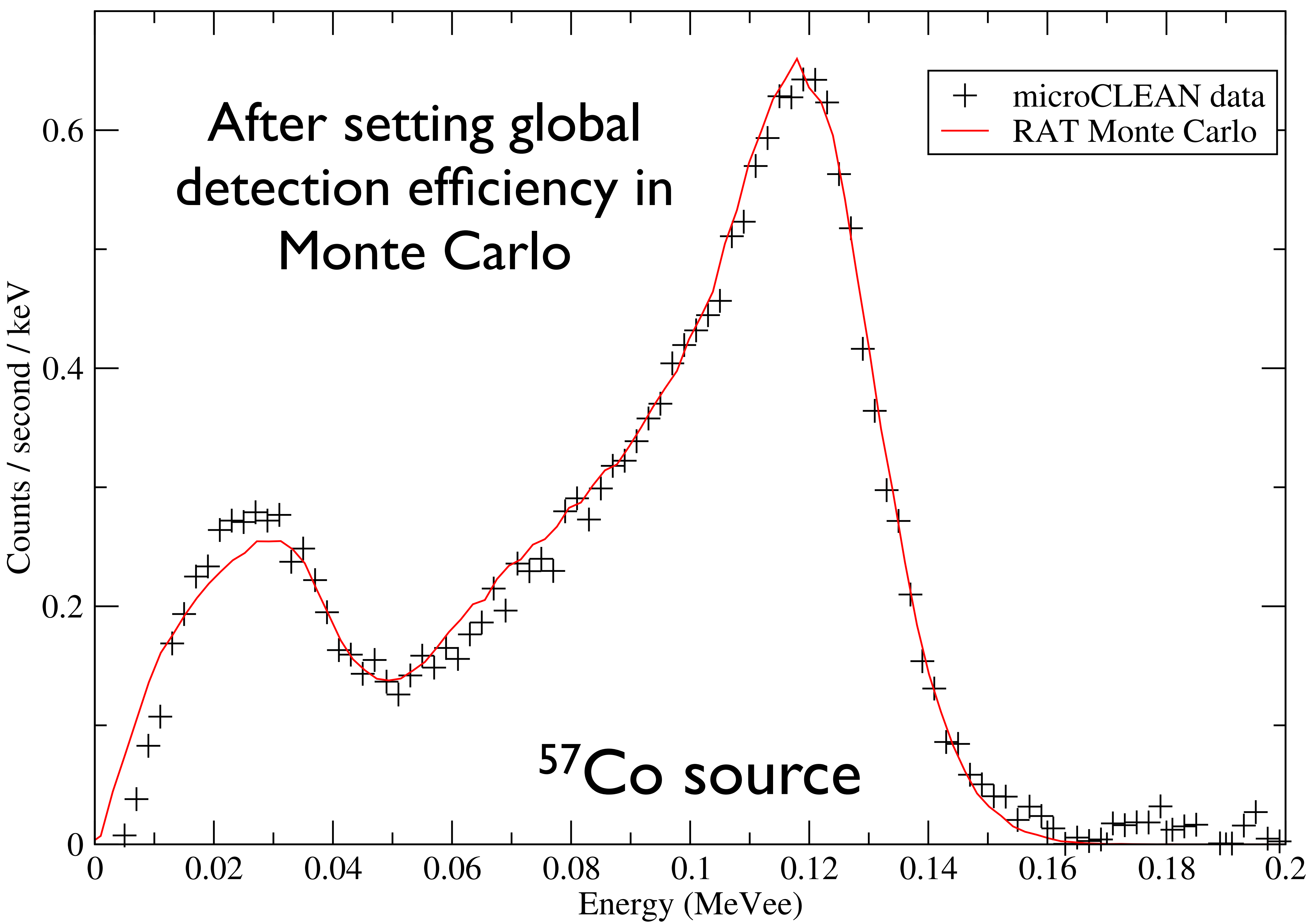
Lowering the Energy Threshold

- Rejection of ^{39}Ar beta decay events sets the energy threshold in single-phase argon.
- ^{39}Ar is the only background that scales like volume, rather than surface area, so it also limits detector size.
- Important to maximize the performance of our pulse-shape rejection algorithms.
- Prior to construction, we have done this with a detailed simulation...

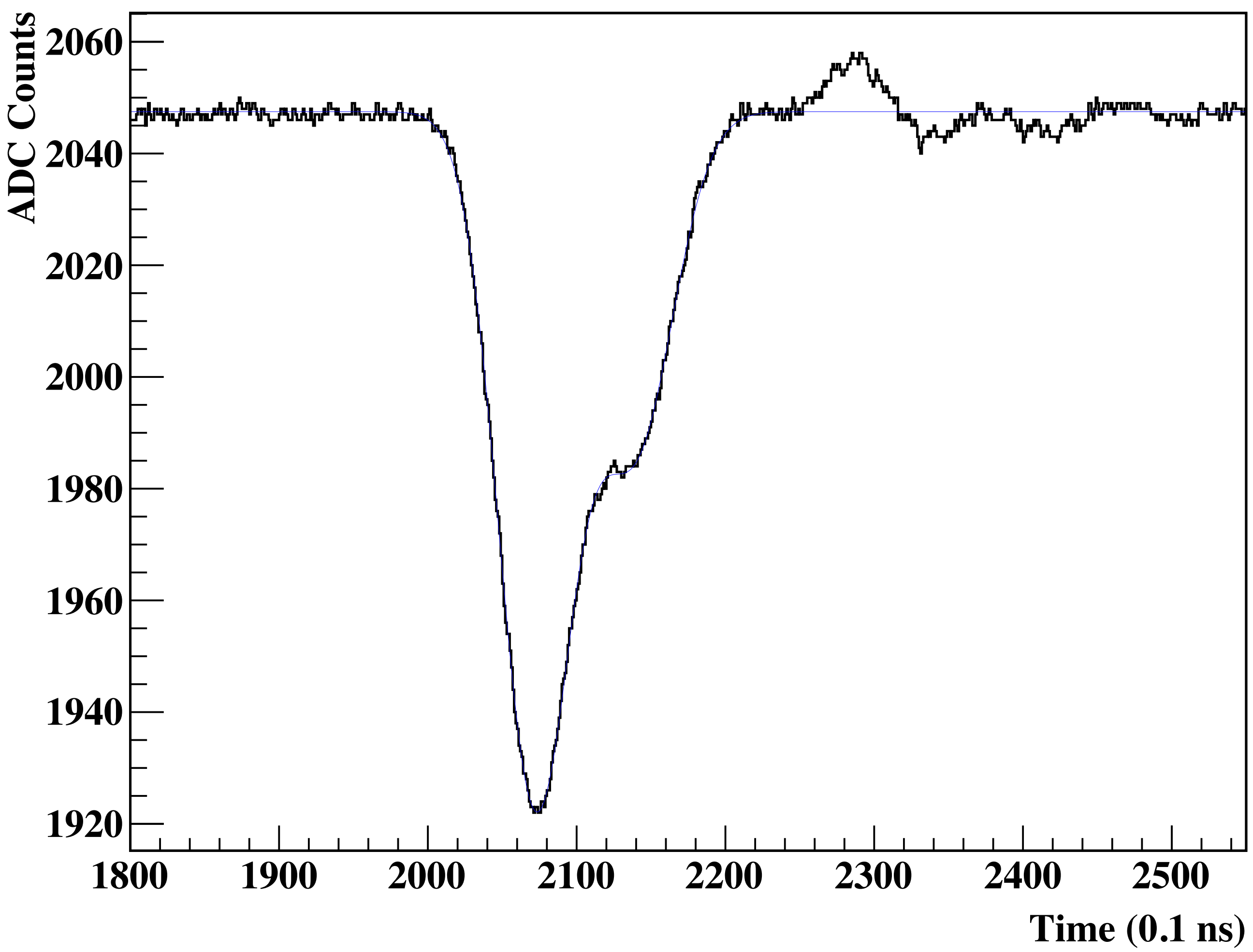
MiniCLEAN Simulation: RAT

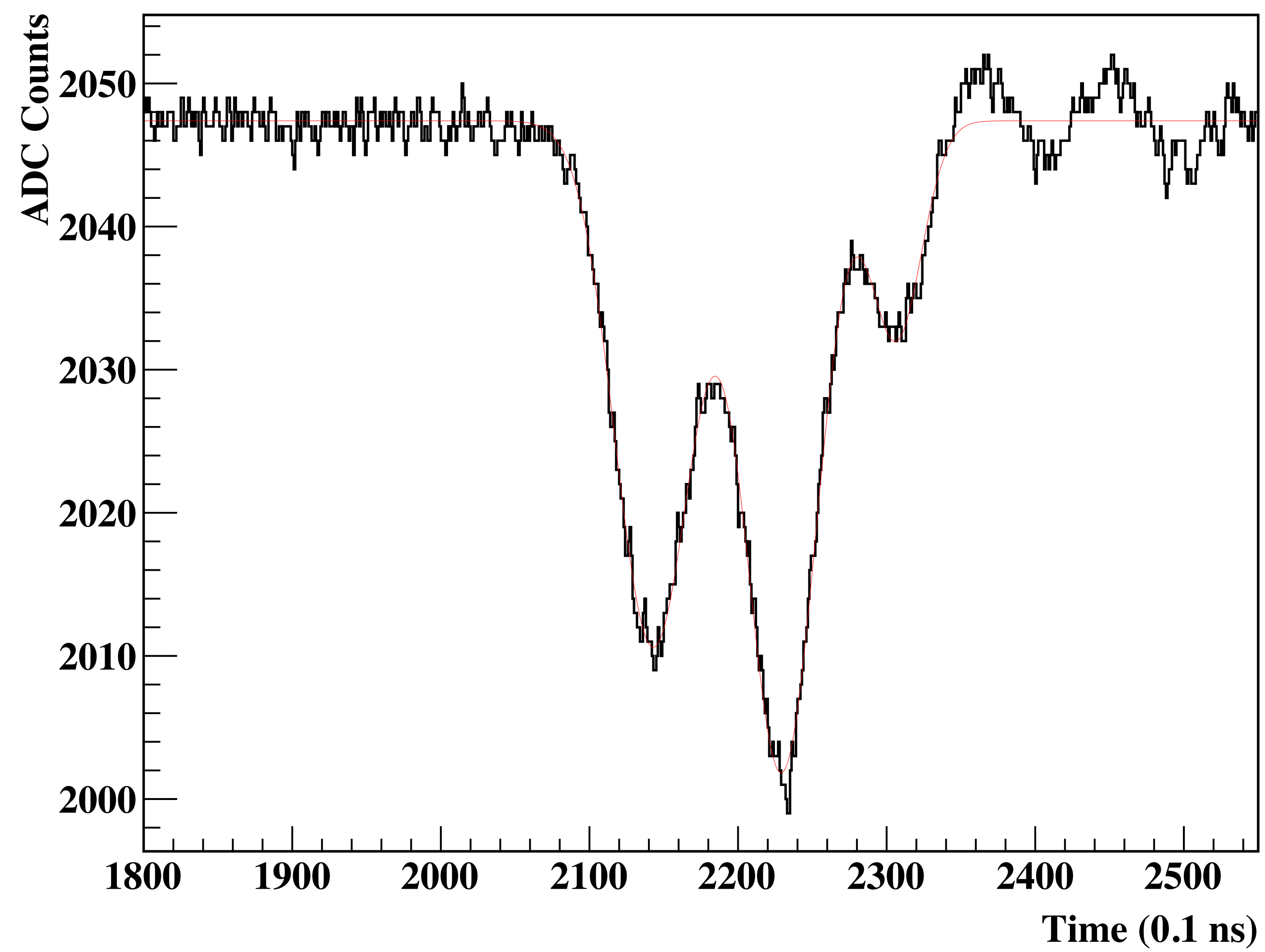
- Developed for Braidwood (SRS), now used by SNO+ and DEAP/CLEAN.
- Wraps together GEANT4, ROOT, and GLG4sim (KamLAND) into full simulation and analysis package.
- Fully propagates optical photons, including PMT response and digitizer / DAQ simulation
- Includes pulse shape analysis tools, maximum likelihood position reconstruction

Comparison with MicroCLEAN



Modeling of Cryogenic PMT Response





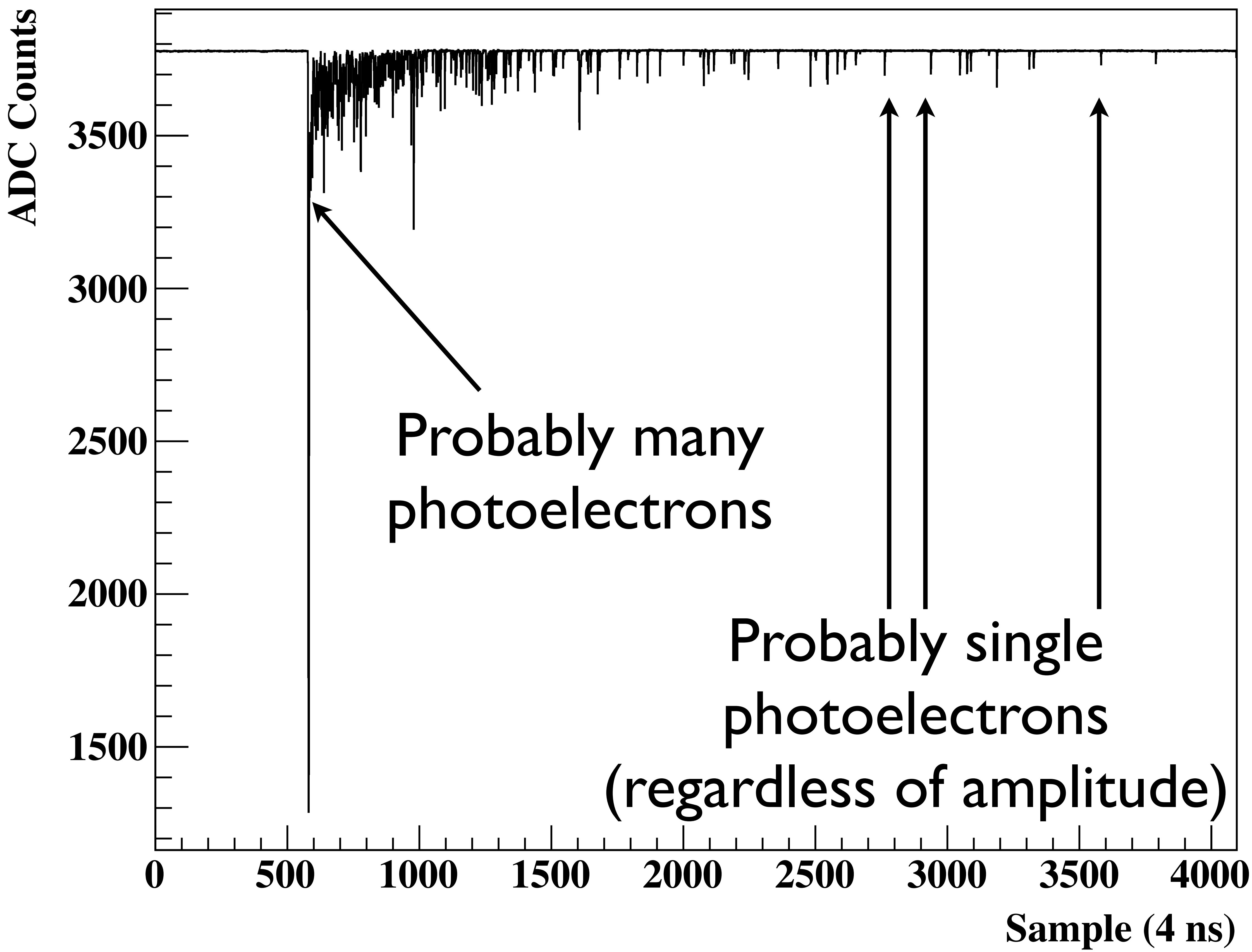
MiniCLEAN uses Hamamatsu R5912-02-MOD 8” PMTs, tested for use at temperatures down to 25K.

T. Caldwell

Photoelectron (PE) Counting

- Counting the number of PE on a channel is fundamental to energy and position estimation.
- PMTs produce variable size, finite width (~20ns) pulses for each PE.
- Counting peaks in a waveform is biased low when there is pulse pileup.
- Integrating charge is unbiased, but higher variance.
- How to get best of both worlds?
- (Side note: This is one of many instances where single phase detectors get better as they get bigger and add channels...)

Bayesian PE Counting



Bayesian PE Counting

Chop up waveform for each PMT into regions with pulses, and for each region, compute:

n-PE charge distribution

$$P_N(n|q,t_1,t_2) = \frac{P_Q(q\,|\,n)P_N(n\,|\,t_1,t_2)}{\sum_{i=0}^{\infty} P_Q(q\,|\,i)P_N(i\,|\,t_1,t_2)}$$

Probability of *n*-PE given pulse integral *q*, and pulse ranging from t_1 to t_2

Poisson probability of observing *n* (or *i*) photons between t_1 and t_2 *in this PMT.*

This is where we insert our knowledge of argon scintillation time structure and event position & energy

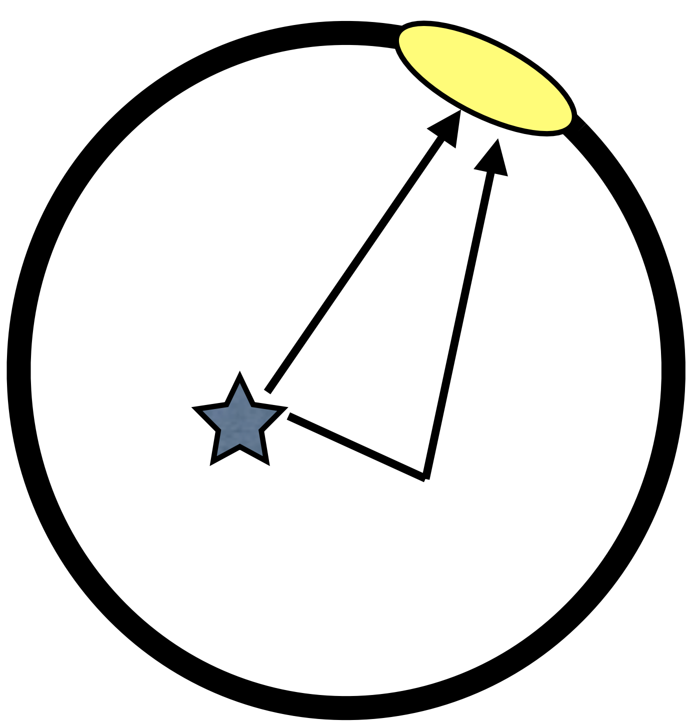
Position & Energy Reconstruction

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

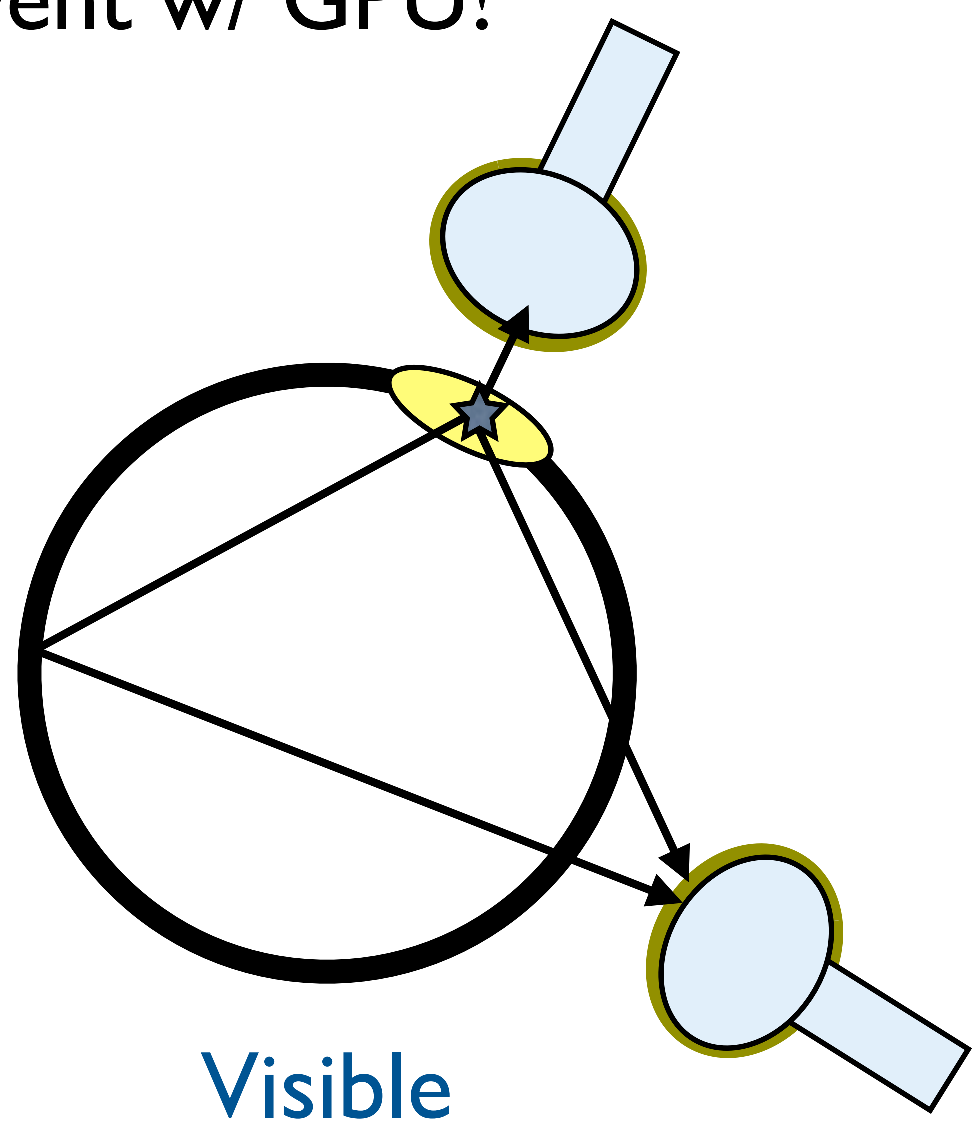
- Rayleigh scattering length in argon is ~90 cm (or 66 cm?).
- TPB further randomizes photon paths.
- Estimating PMT hit probability based simply on solid angle tends to bias the fit inward.
- The actual light pattern is more isotropic than a direct propagation model would predict.

ShellFit: Self-Tuning Maximum Likelihood Fitting

- Automatically use Monte Carlo simulation to collapse complete space of photon histories to before and after wavelength shifting.
- Integrate over TPB surface using a GPU to compute likelihood.
- 4 sec/event w/ CPU and 0.2 sec/event w/ GPU!

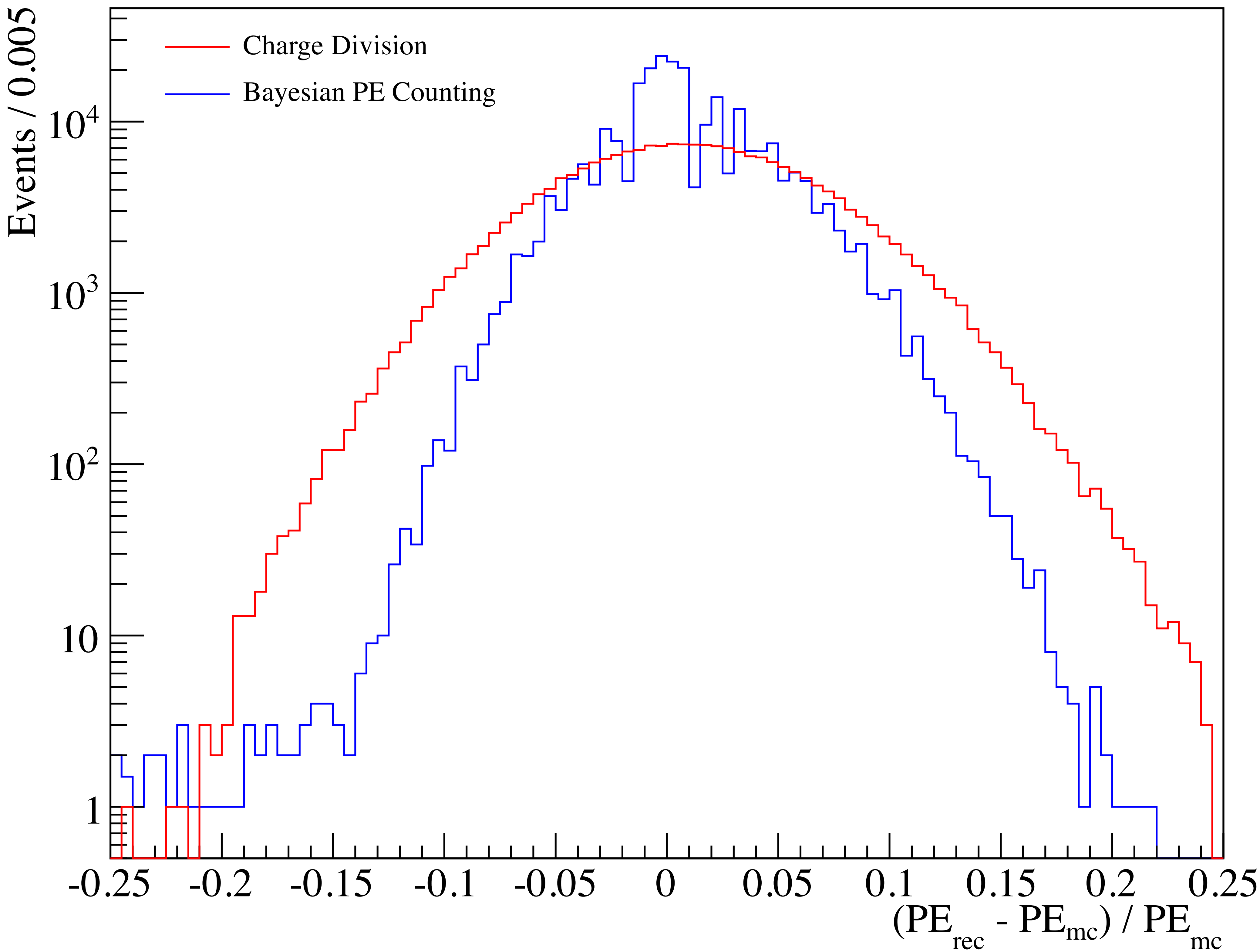


UV transmission to TPB



Visible

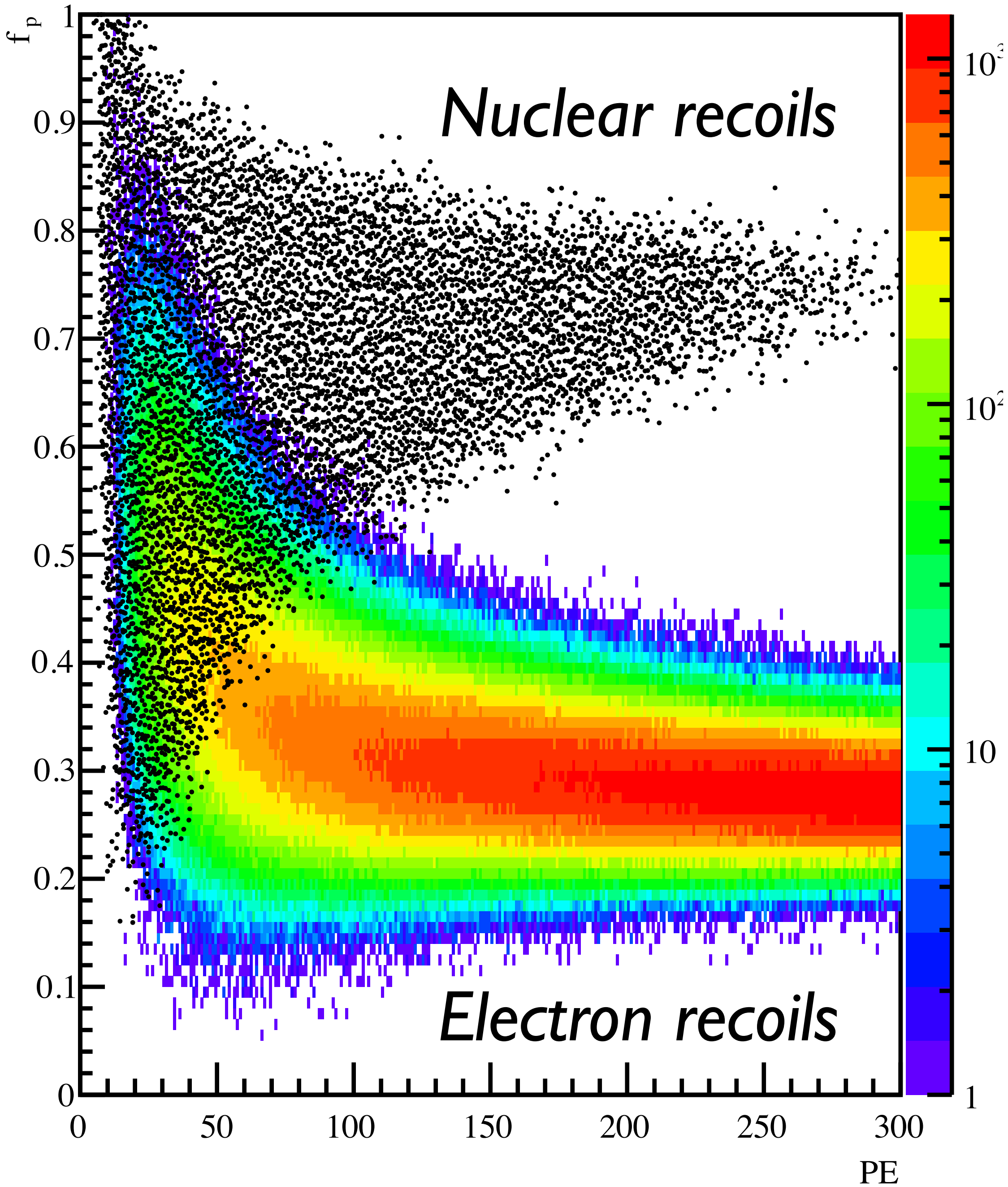
Energy resolution after iterating PE counting



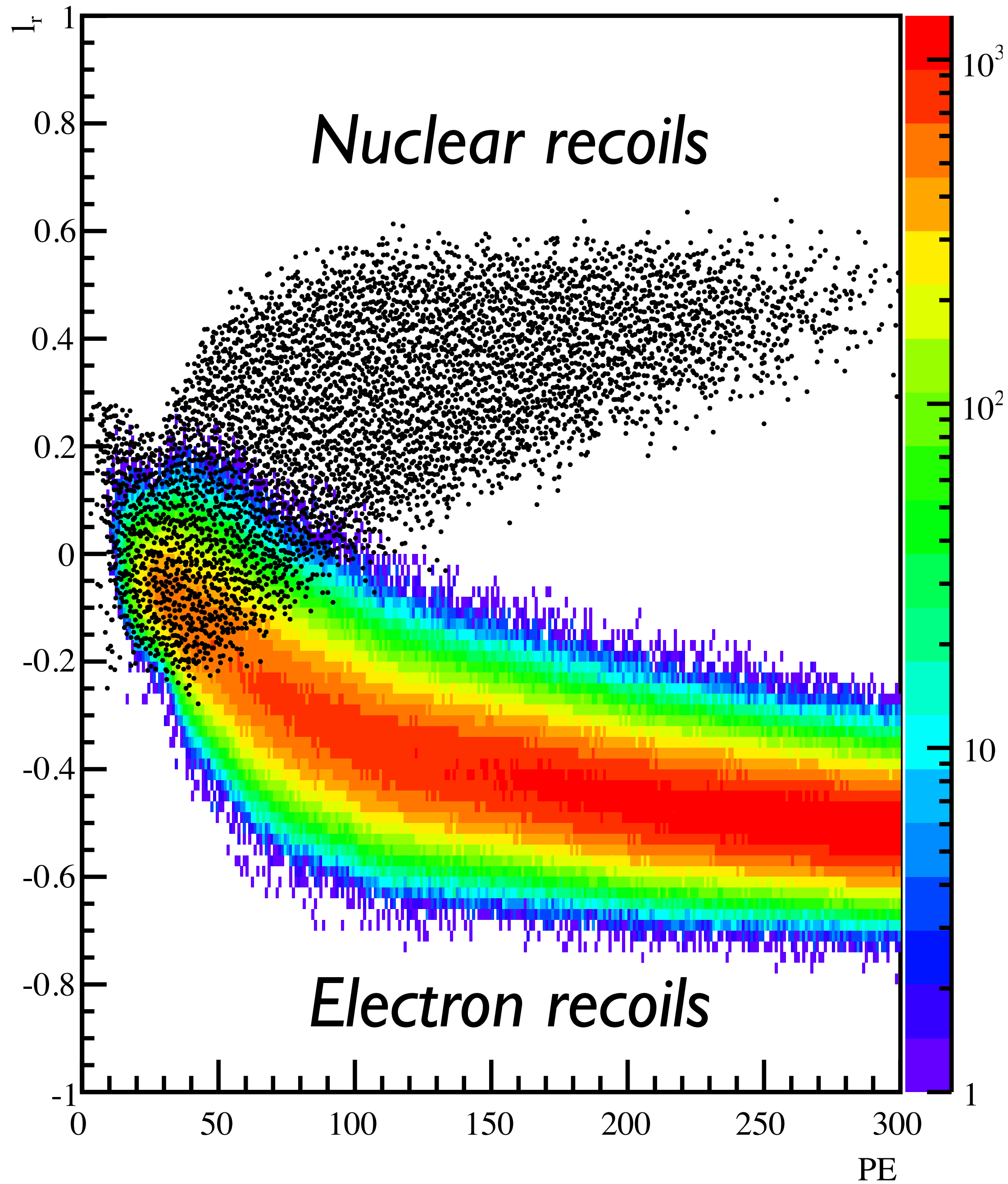
MiniCLEAN simulation, ^{39}Ar, 75-100 PE, inside fiducial volume

Particle ID Techniques

Prompt ratio (standard)



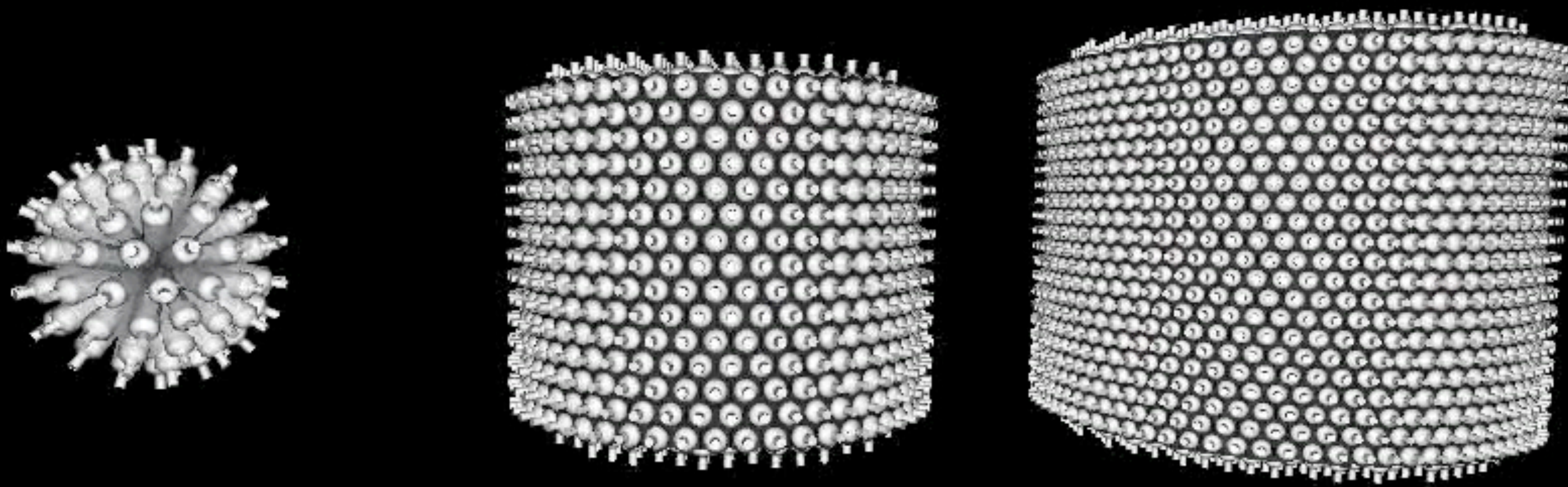
Likelihood ratio (new)



MiniCLEAN simulation

The Future

- The next generation concept for single phase liquid argon and neon is the CLEAN experiment.



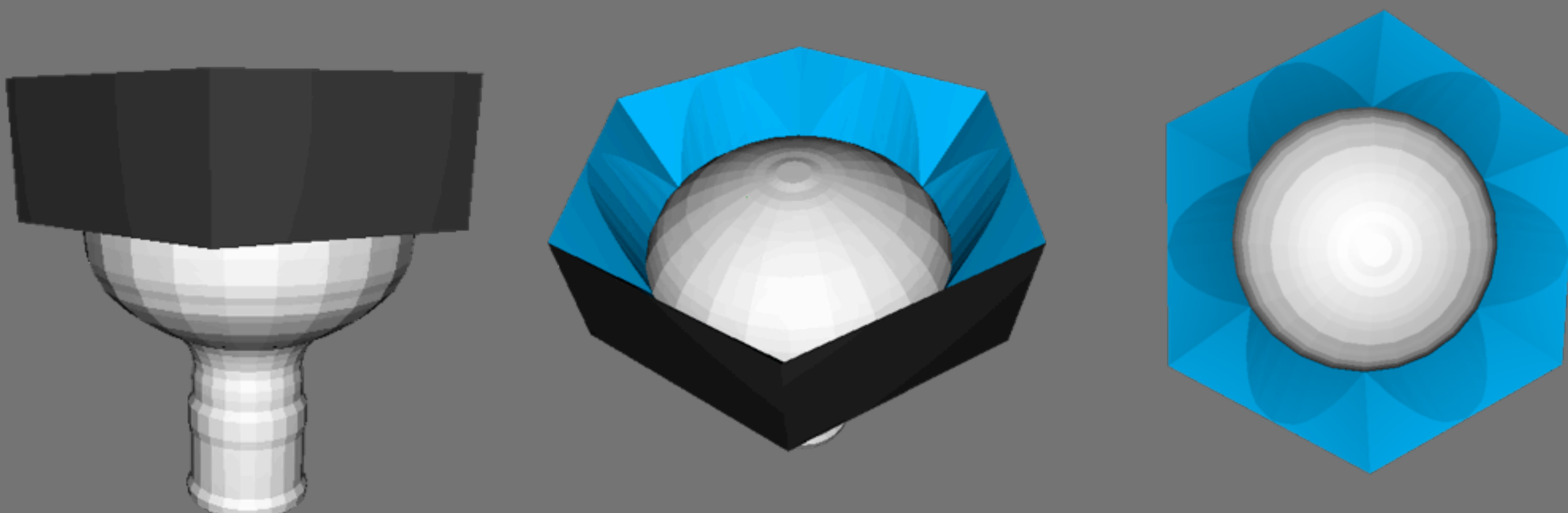
MiniCLEAN
(~500 kg total)

CLEAN-40
(44 tons total)

CLEAN-140
(140 tons total)

The Future

Simpler PMT modules
Better Cryogenic PMTs



(Front TPB plate removed)

The Future

- Between 40 and 140 tons total argon mass ($\geq$15 tons fiducial).
- Optimal size with natural argon limited by pulse-shape discrimination performance and pileup.
- At ~140 tons (total), a dual-use argon and neon detector can do a percent-level precision measurement of pp solar neutrinos and observe supernova neutrinos.
- With depleted argon, could go very large...

Conclusion

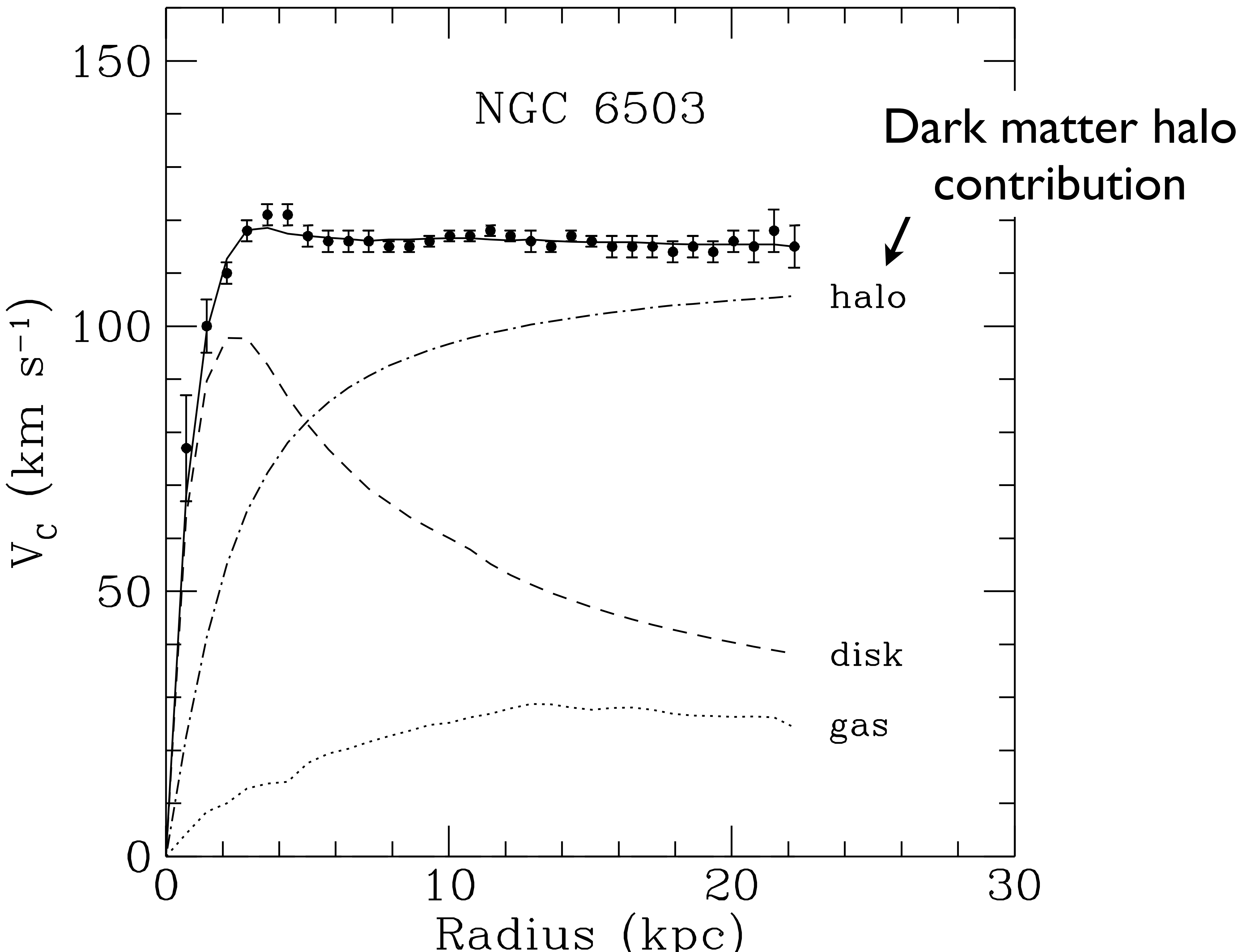
- *Something is out there*, and it might be WIMPs!
- We've seen claims of direct detection, but you should continue to be skeptical.
- Single phase noble liquid detectors offer a highly scalable option for dark matter and neutrino detection.
- MiniCLEAN extends the DEAP/CLEAN series of detectors to 150 kg fiducial volume with liquid argon and neon.
- Many analysis improvements ready to test on data as it arrives.
- Construction is underway, with detector commissioning scheduled for mid-2013.

"I often look at the bright yellow ray emitted from the chromosphere of the sun, by that unknown element, Helium, as the astronomers have ventured to call it. It seems trembling with excitement to tell its story, and how many unseen companions it has. And if this be the case with the sun, what shall we say of the magnificent hosts of the stars? May not every one of them have special elements of their own? Is not each a chemical laboratory in itself?"

John William Draper
Inaugural Address to the American Chemical Society
1876

Backup Slides

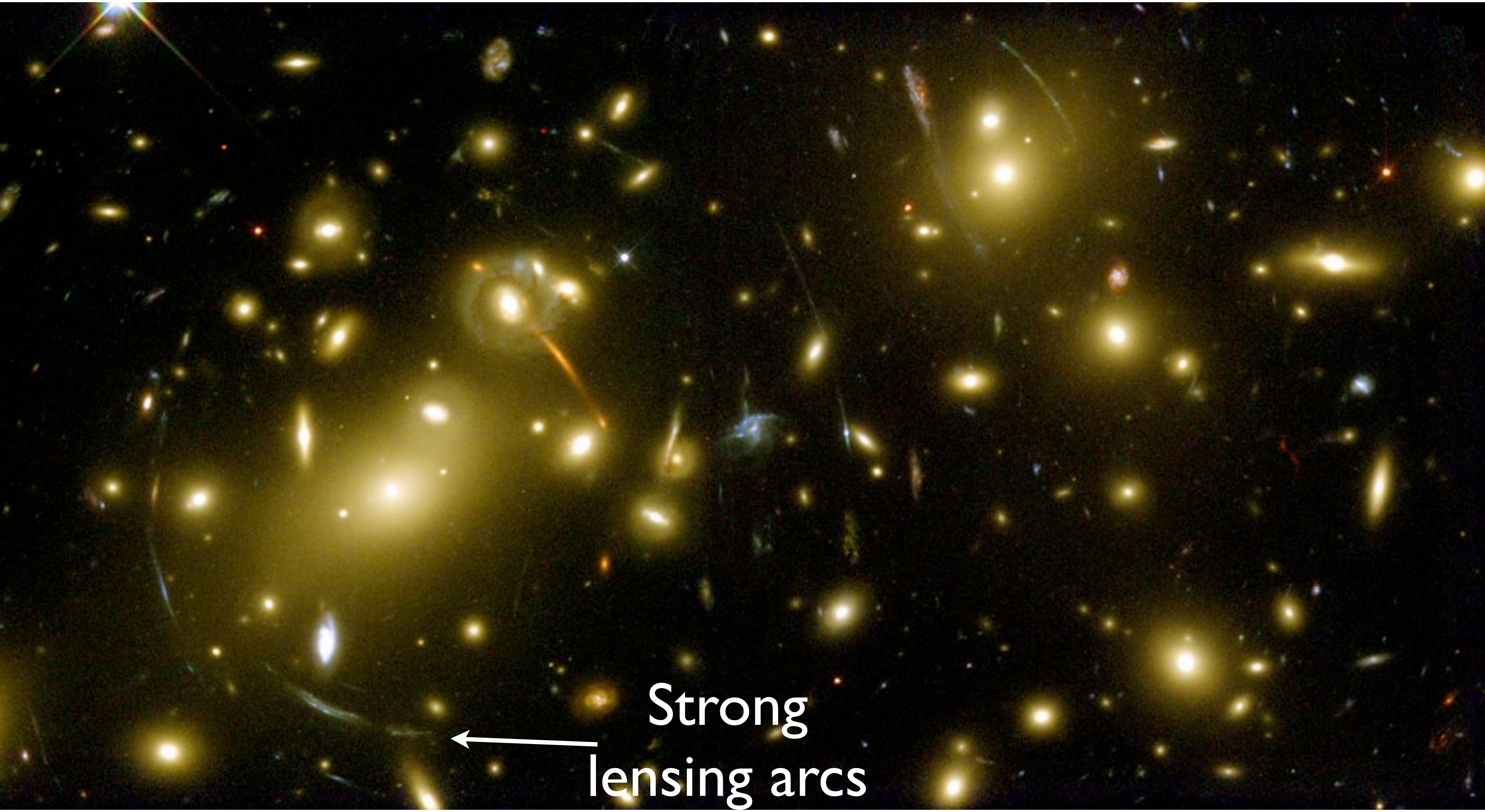
Rotation Curves



K. G. Begeman, et. al., Mon. Not. Roy. Astron. Soc. 249 (1991) 523.

Cluster Collisions

Gravitational Lensing



Abel 2218

Image credit: NASA, ESA, A. Fruchter and the ERO Team (STScI, ST-ECF)

Gravitational Lensing

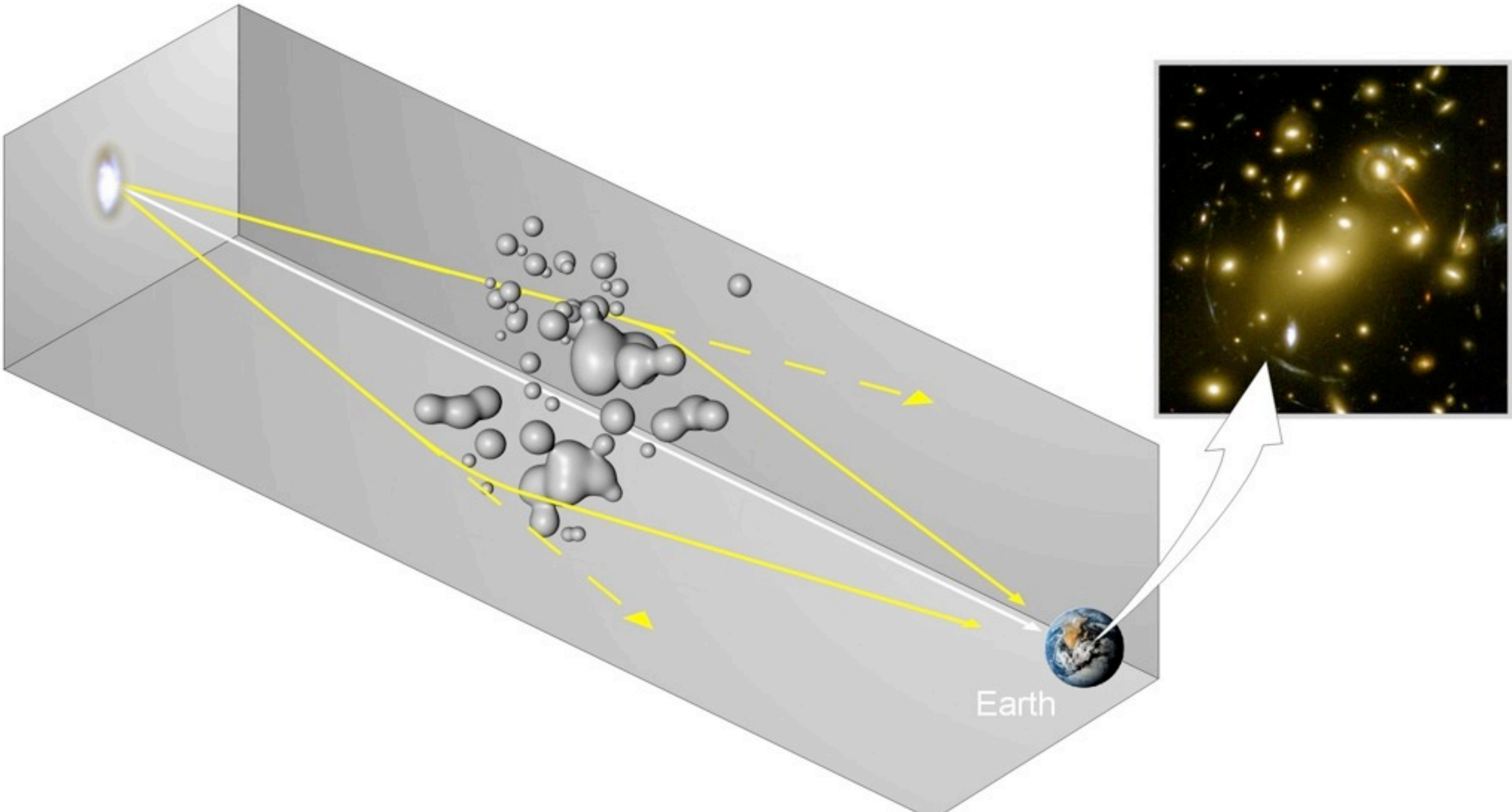
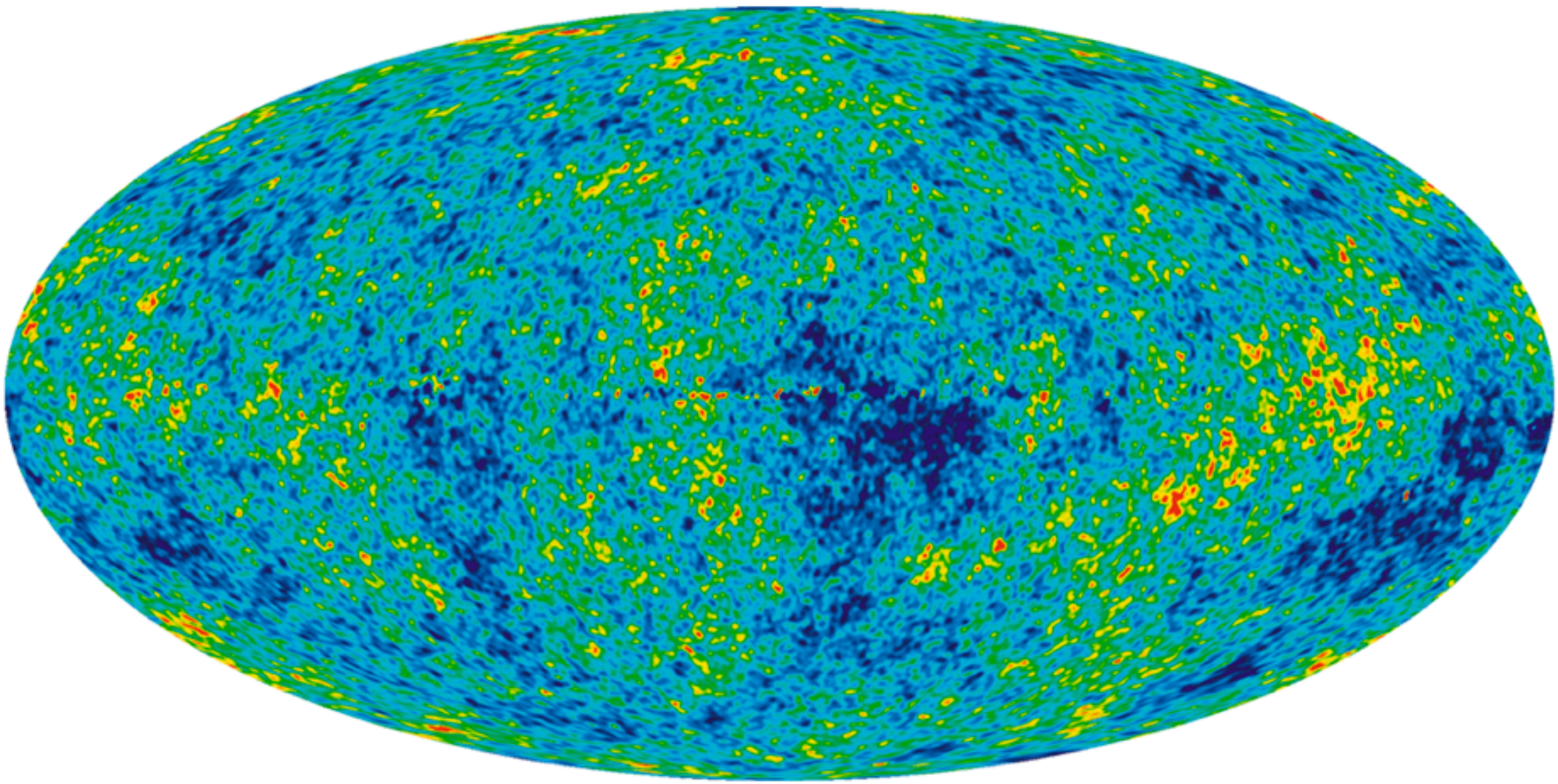


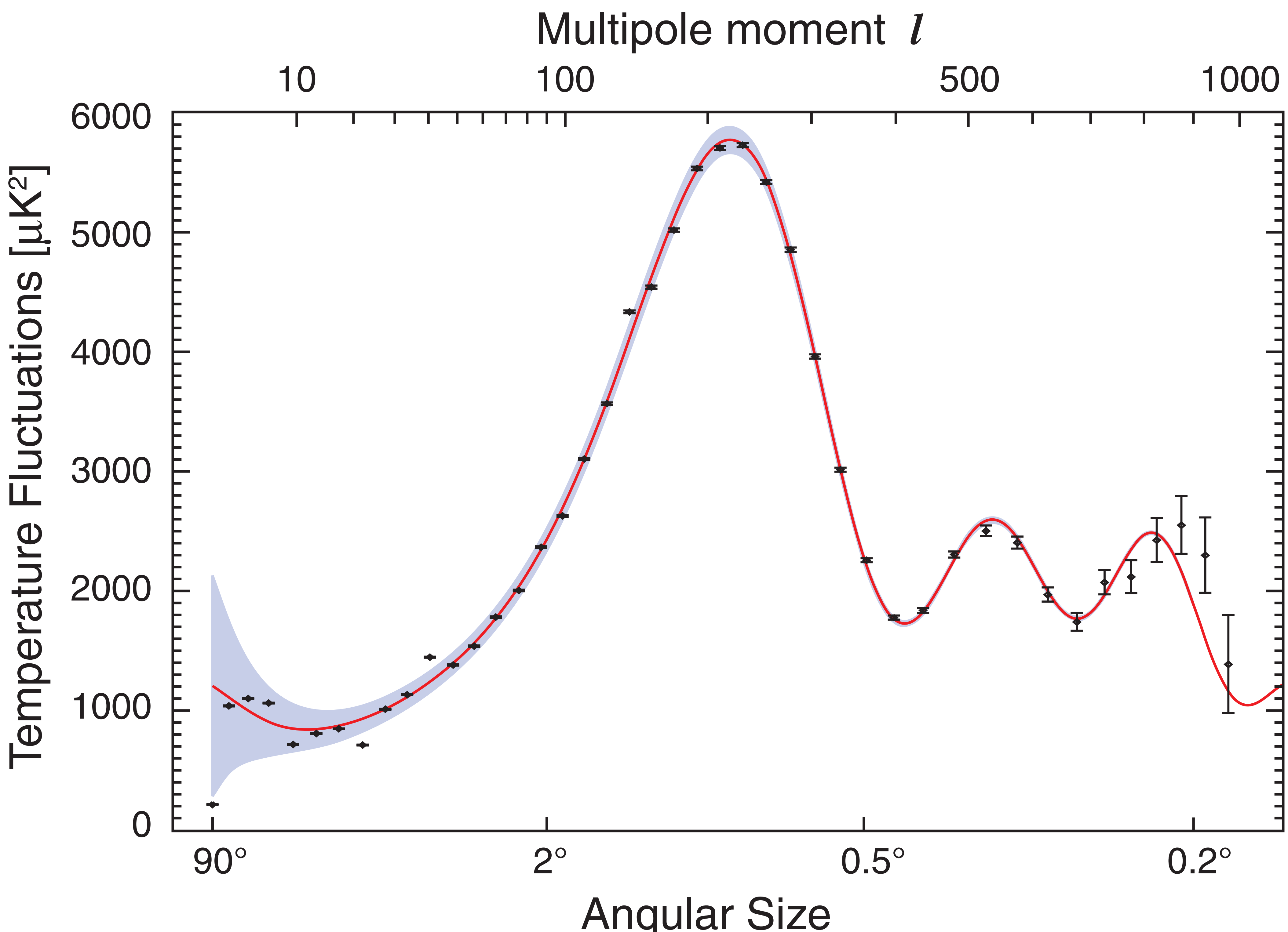
Image credit: ESA

Cosmic Microwave Background



WMAP 5 year dataset

Cosmic Microwave Background



WMAP 5 year dataset

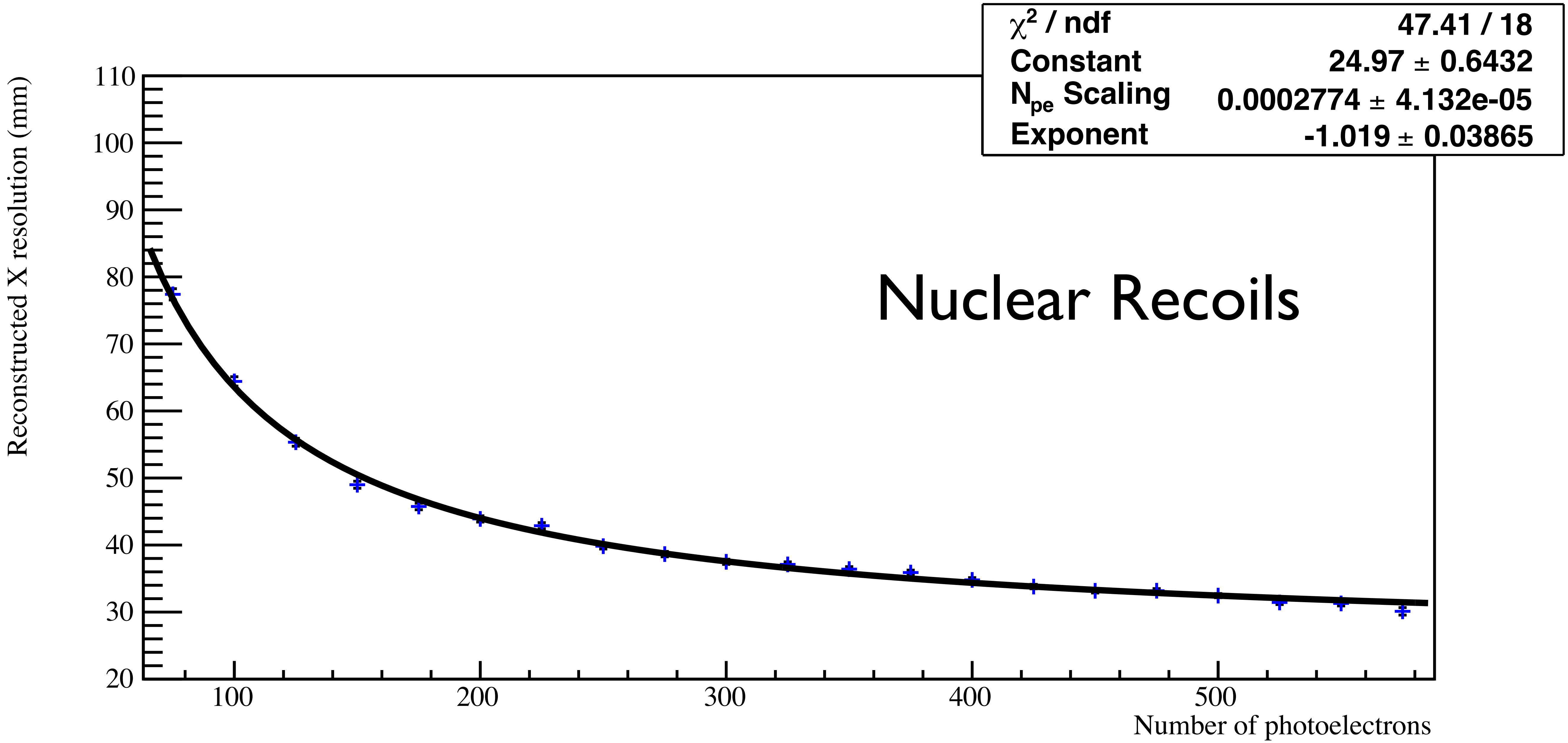
Construction Progress: Inner Vessel at SNOLAB

Delivered Oct. 2012

Construction Progress: Outer Vessel

Transported underground in 4 pieces

ShellFit Resolution



Volume-averaged resolution is less than 8 cm at 75 pe (12.5 keVee, 50 keVr)!

Removing Surface Backgrounds with ShellFit