Dark Matter Physics at SNOLAB: And Future Prospects

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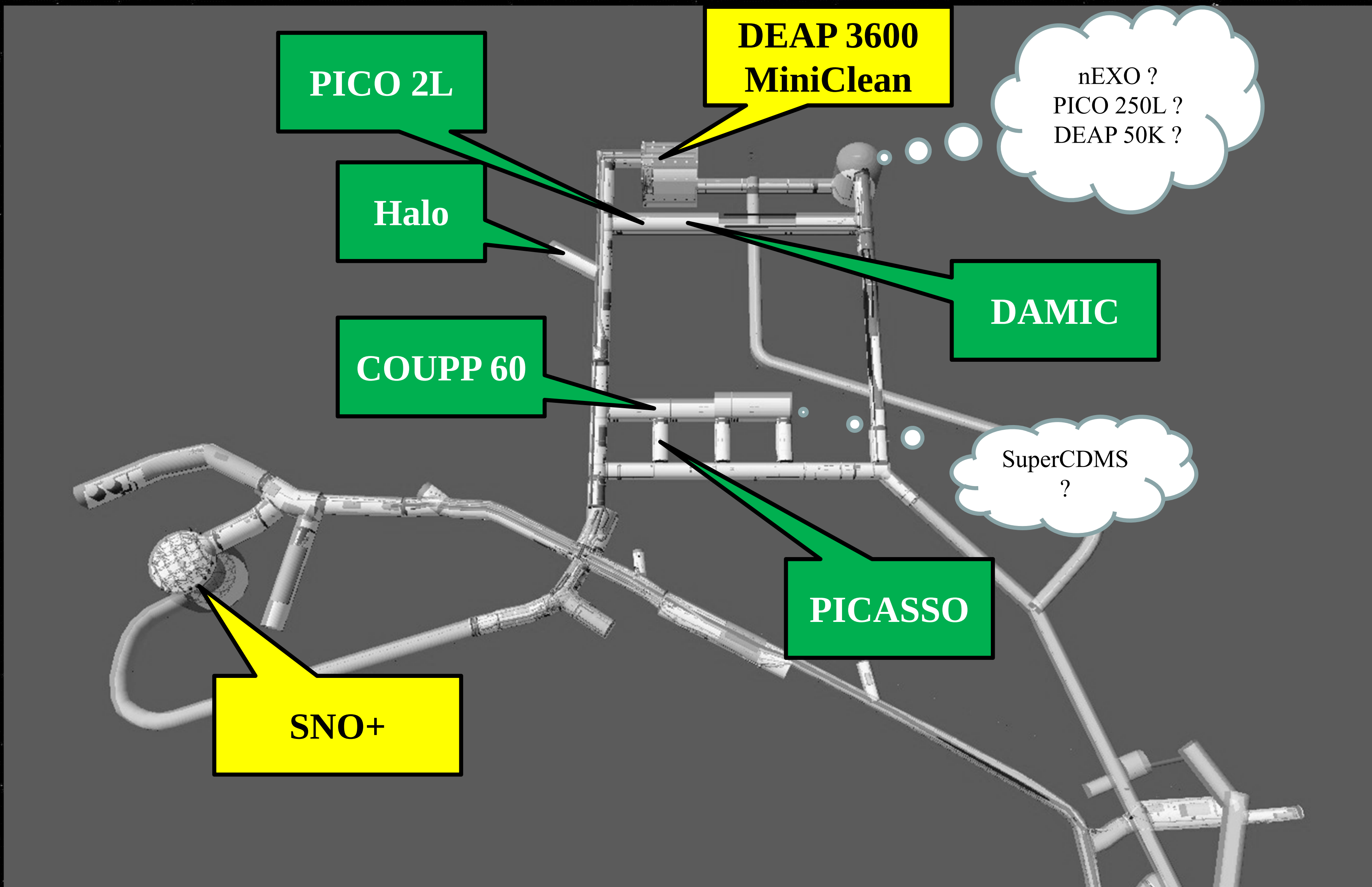
Outline

- Overview of SNOLAB DarkMatter Program
- Status of Current Experiments
- The G2 Down Select Process
- Crystal Ball Gazing … where will we be in 2020?

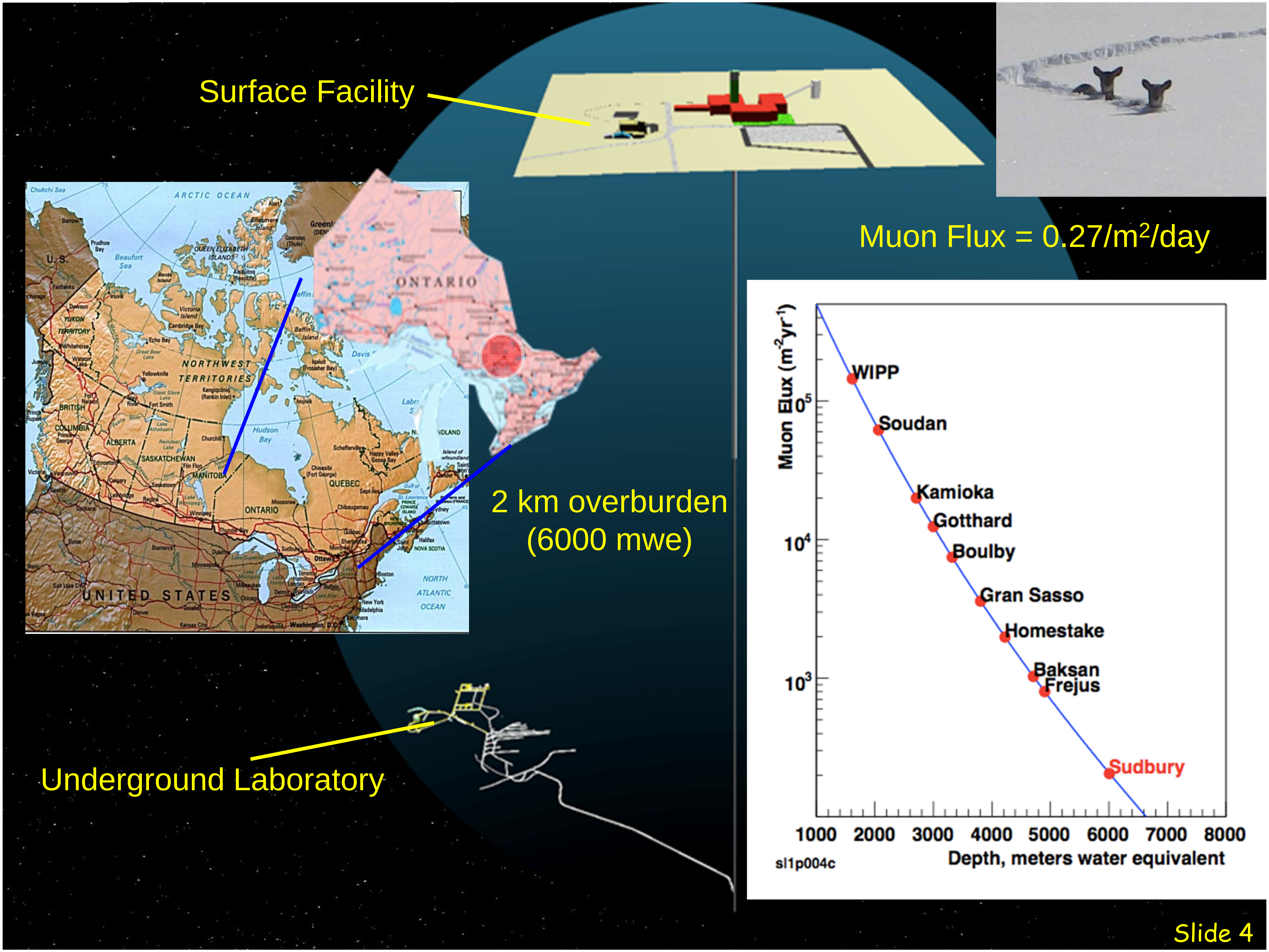
SNOLAB as of January 2013.



Dark Matter at SNOLAB

PICASSO 2.5kg	Superheated Droplet	C_4F_{10}	Completed Run
DEAP I 7kg	Scintillation	LAr	ProtoType Completed
COUPP 2kg	Superheated Bubble Ch.	CF_3I	Completed
COUPP 4kg	Superheated Bubble Ch.	CF_3I	Completed
DAMIC 10g	CCD	Si	Operational
COUPP 60kg	Superheated Bubble Ch	CF_3I	Operational
PICO 2L	Superheated Bubble Ch	C_3F_8	Operational
MiniClean 500 kg	Scintillation	LAr	Under Construction
DEAP 3600 kg	Scintillation	LAr	Under Construction

See following talk

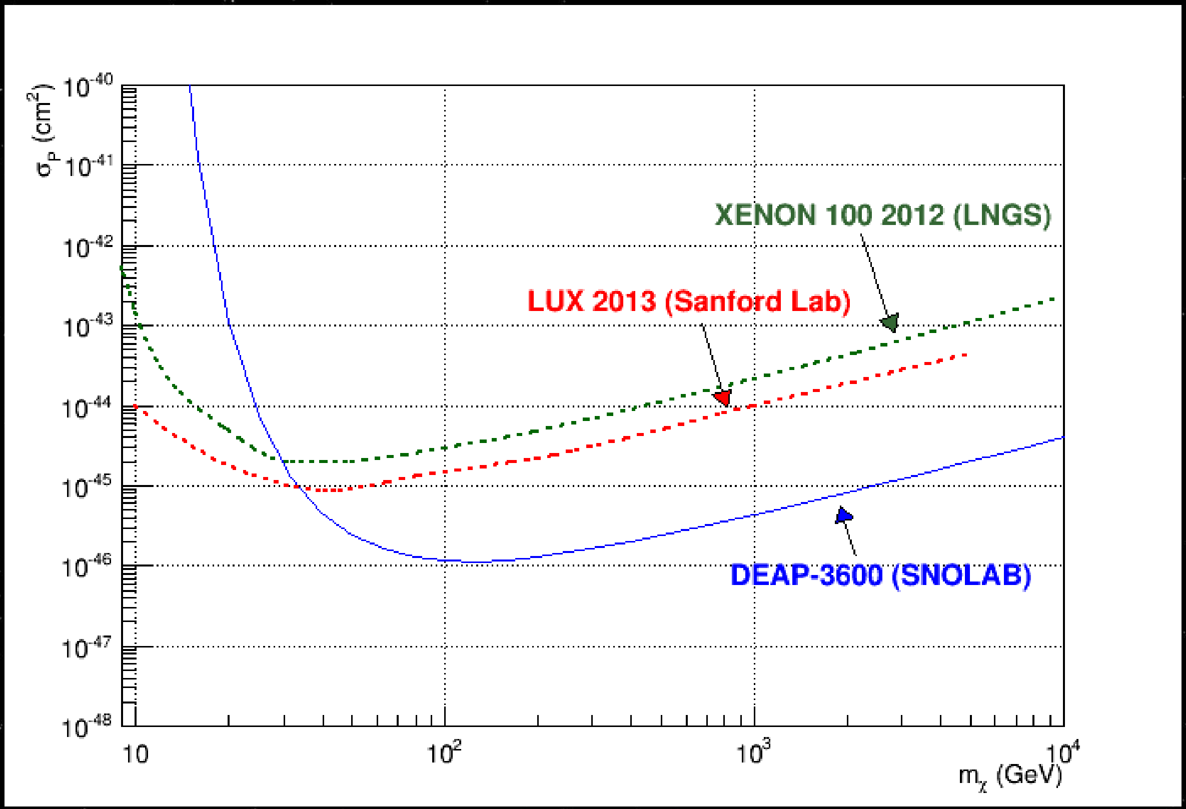


Surface Facility
Muon Flux = 0.27/m²/day
ONTARIO
2 km overburden
(6000 mwe)
Underground Laboratory
Muon Flux (m⁻²yr⁻¹)
WIPP
Soudan
Kamioka
Gotthard
Boulby
Gran Sasso
Homestake
Baksan
Frejus
Sudbury
1000 2000 3000 4000 5000 6000 7000 8000
Depth, meters water equivalent
sl1p004c
Slide 4

The DEAP 3600 Experiment

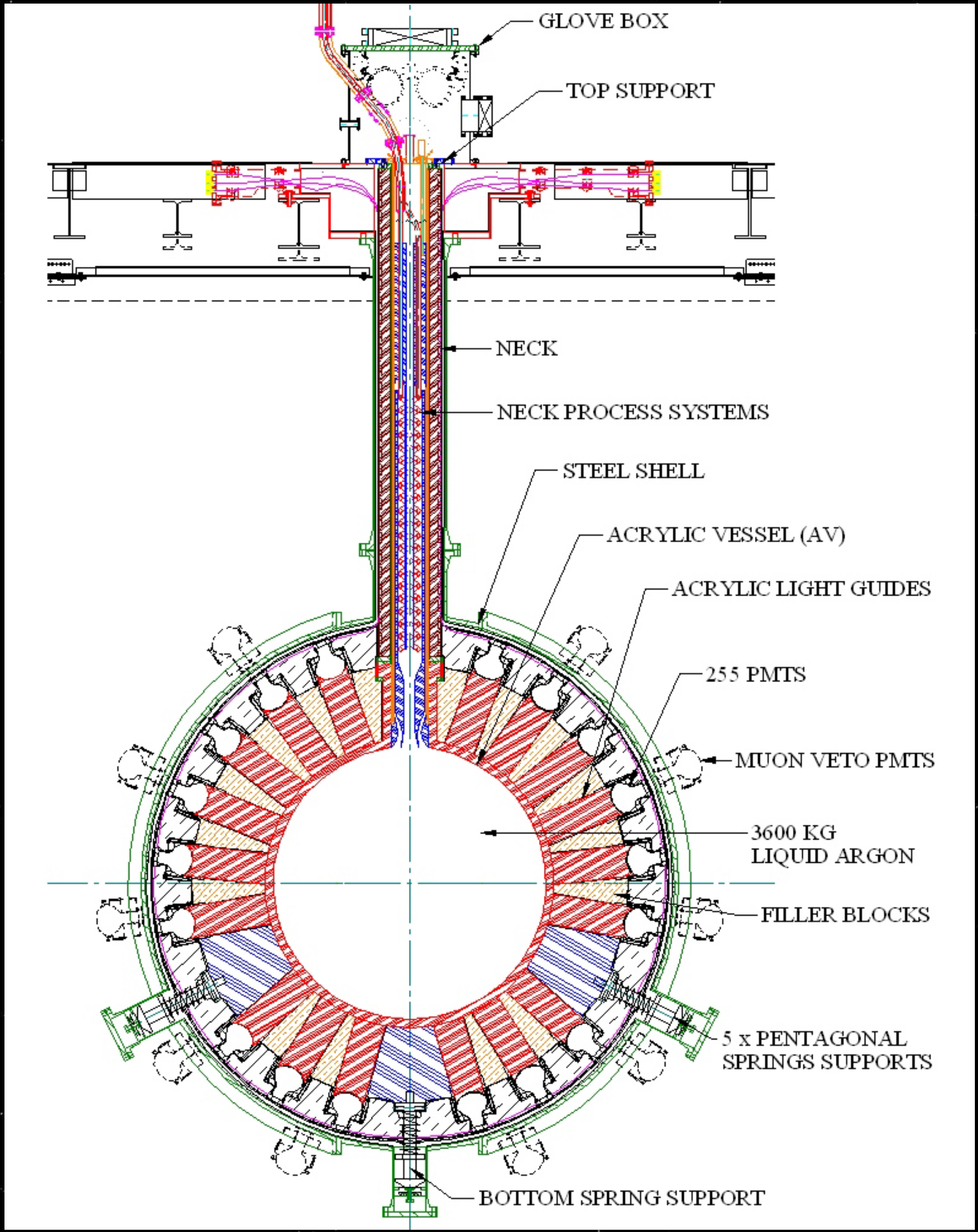
Goal: World leading sensitivity to Spin-Independent Dark Matter.

Max Sensitivity at 100 GeV/c^2



The DEAP 3600 Detector

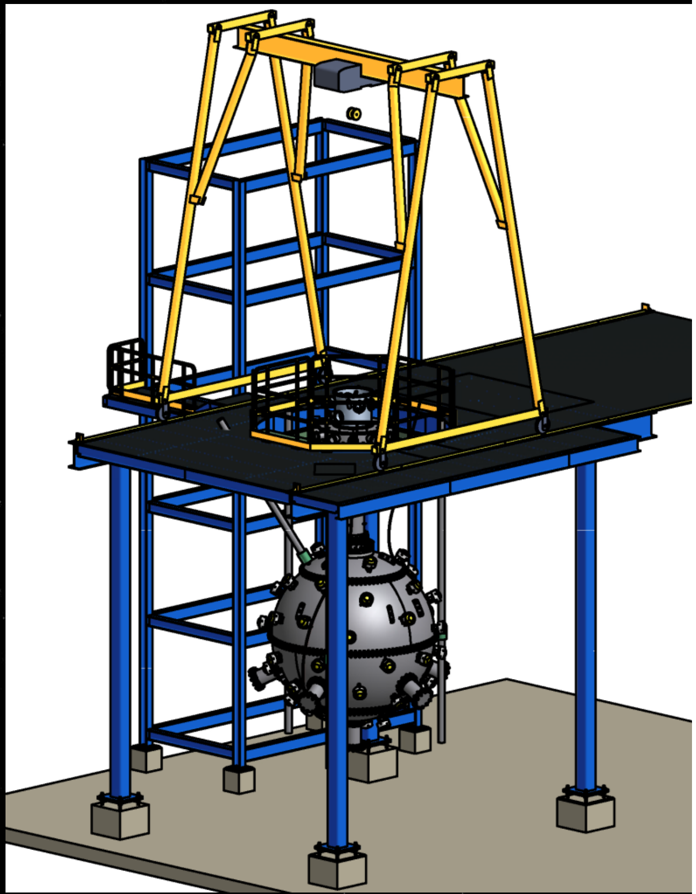
- Acrylic vessel contains 3600 kg liquid argon. (Temperature of -200 C)
- WIMP interactions in LAr produce scintillation light.
- Layer of TPB converts light from 128 nm to visible.
- Light is observed by array of photomultipliers.



Of course, in reality it is a bit more complicated….

Why Liquid Argon ?

- Easily purified and has a high light-yield
- Well suited to pulse shape discrimination with two distinctly different time components for scintillation
- Well-understood, allows for very simple scintillation detector and argon is inexpensive.
- Has an easily accessible temperature (85K)
- Allows a very large detector mass (~tonne) with uniform response and long light attenuation length



DEAP-3600 Background Budget (3 year run)

Background	Raw No. Events in Energy ROI	Fiducial No. Events in Energy ROI
Neutrons	30	<0.2
Surface α's (^{210}Po)	150	<0.2
^{39}Ar β's (nat. argon)	1.6×10^{9}	<0.2
^{39}Ar (depleted Ar)	8.0×10^{7}	<0.01
Total		**<0.6**

Acr+H_2O shield

Resurfacer

PSD

Need to resurface inner vessel and ensure purity of acrylic.

- removal of 1 mm acrylic
- $^{210}Pb < 1.1\times10^{-19}$ g/g for 0.1 events/3 years (strict control of Rn exposure)

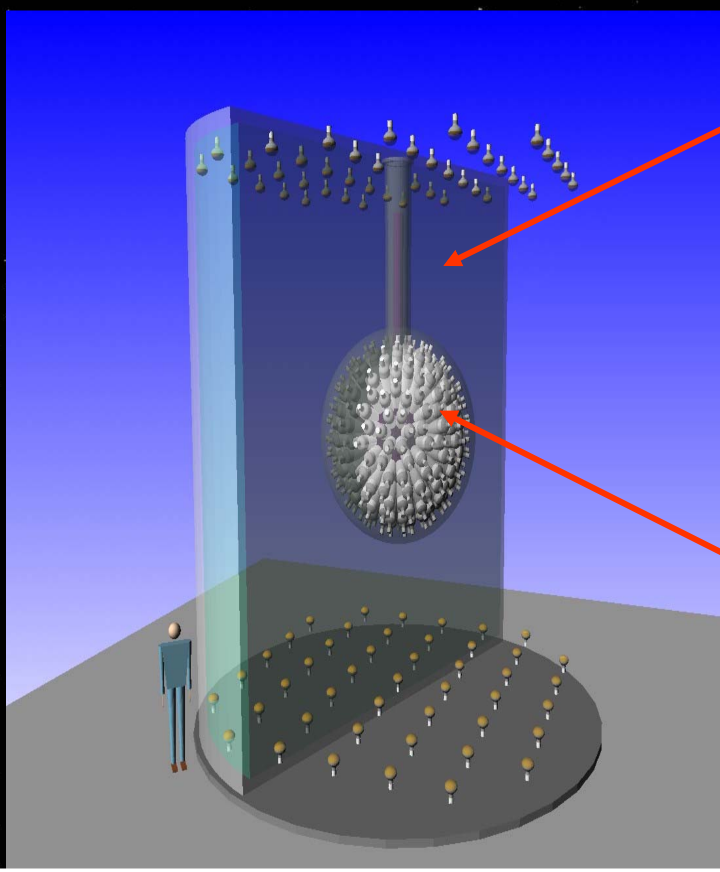
All materials have been assayed/controlled (2007-2013)

Neutrons

→ go deep underground. Veto residual muons in active water shield.

→ shield locally for (α,n). Main concern is the PMT base. Strategy is to move PMT away with long light-guide, and fill in remaining space with neutron absorber.

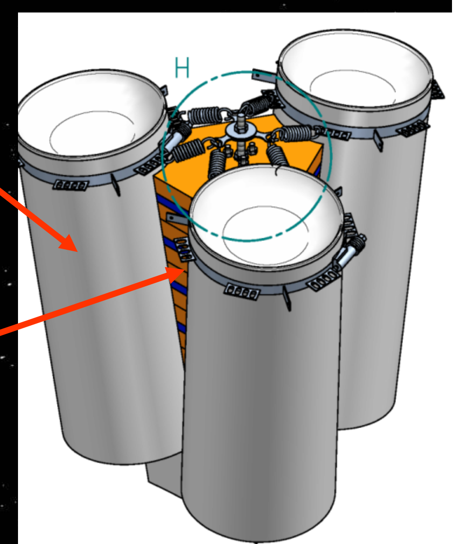
→ External neutrons absorbed in water.

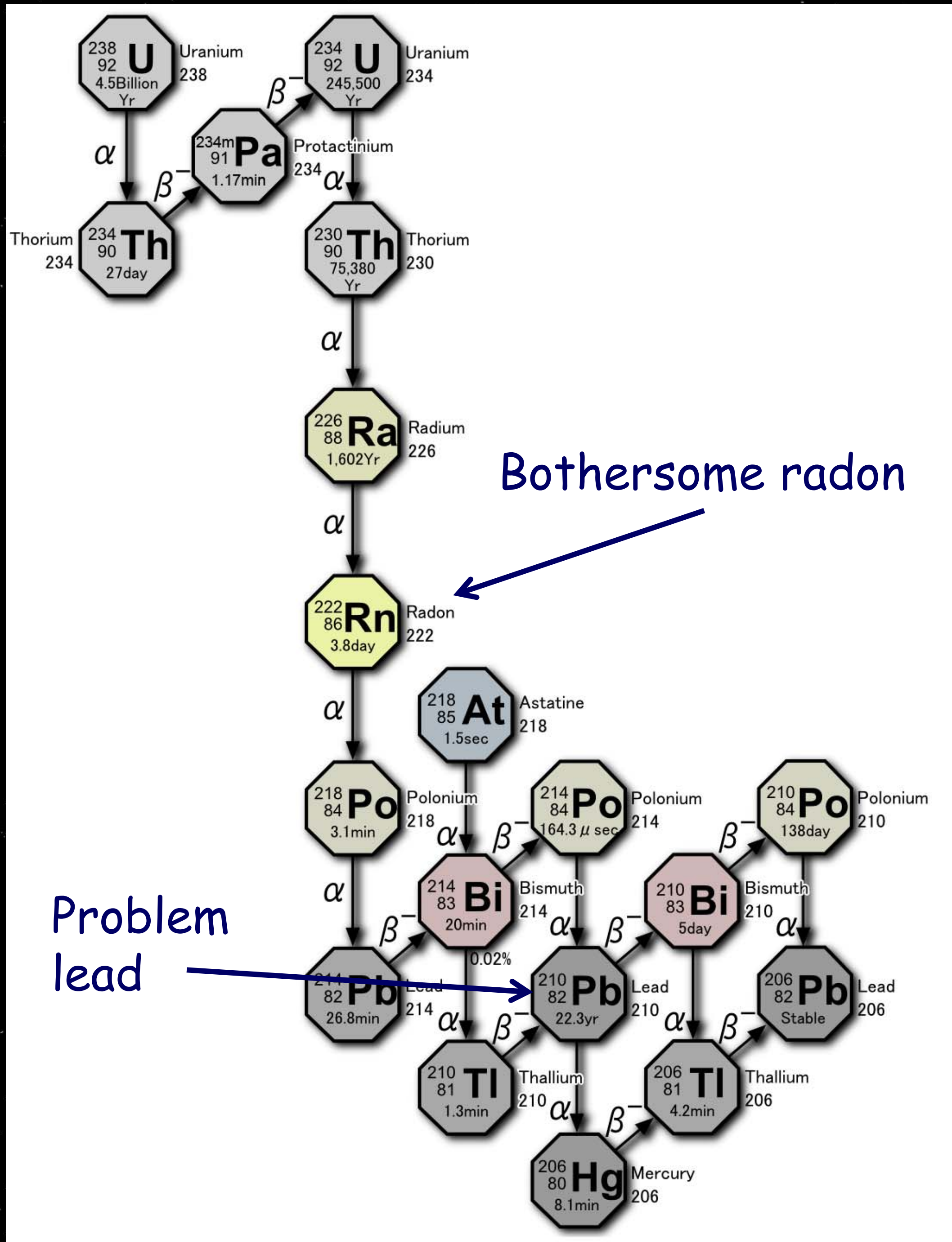


Active water shield

PMT Light guide

Clean filler between PMT lightguides





Background Radiation. Eg: Uranium chain.

The parent ^{238}U is long lived

8 α`s, 6 β`s, numerous γ`s

Even worse, it releases radon gas, which lives 4 days, giving ample time to migrate into detector components.

Also, ^{210}Pb is long lived, and often embedded in materials after radon decays. Exposure to room air (radon) during manufacture must be limited.

DEAP will deal with this by:

- Minimizing exposure to radon from the first steps of manufacture
- Sanding off the surface before beginning operation.

Sanding heads on long arm which spiral around inside of vessel

Acrylic sheets thermoformed into “orange slices” then bonded together to form ball

Ball is machined to make light guide stubs.

Always sealed to keep radon out !

This is the current state of the acrylic vessel.

As of Jan 2014.

Next major step: Attach photomultipliers. This is underway. PMT’s ready to attach. Some sanding/cleaning of vessel being completed first.

Then bond the light guides to vessel ….

Then it will be installed in steel vessel

Steel vessel, suspended in water tank for neutron shielding.

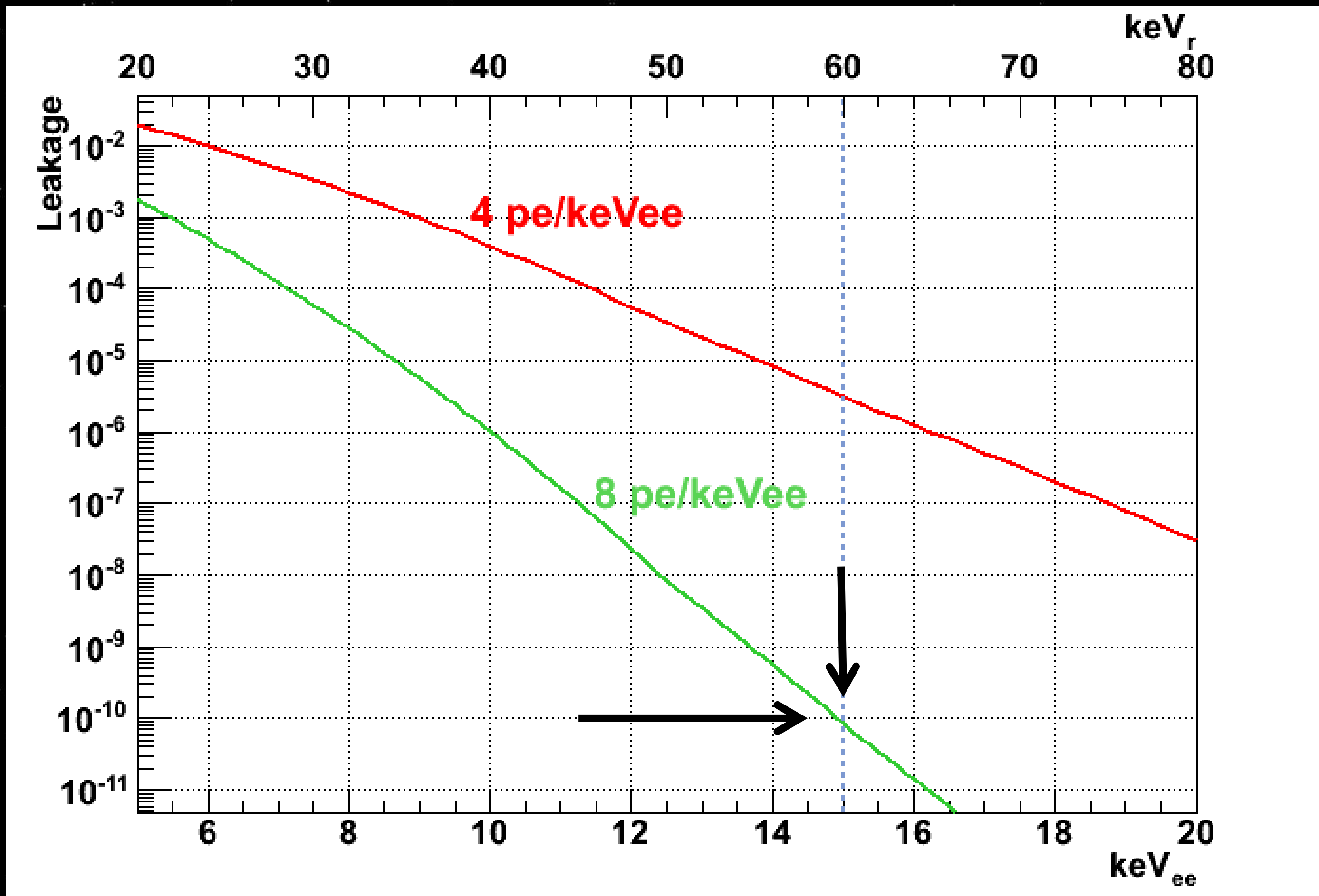
DEAP Experimental Challenge: ^{39}Ar

- On earth 99.6% of argon is ^{40}Ar (produced in the decay of ^{40}K)
- There is however a small amount of radioactive ^{39}Ar on earth.
  - ~8.1 x 10^{-16} g^{39}Ar / g^{40}Ar
  - long half life… 269.2 years
  - Decays by $^{39}Ar \rightarrow {}^{39}K + \beta^- + \nu$ which is a problem for DEAP.
  - This gives an activity of about ~1 Bq/kg of argon. Huge !

Solutions:

- Rely on Pulse Shape Discrimination capability in liquid argon. Need to get discrimination at 10^{-9} level
- In future, get source of argon depleted in ^{39}Ar

Pulse shape discrimination in Liquid Argon



Need good PMT coverage (high light yield) to obtain full discrimination

How does Pulse shape discrimination work?

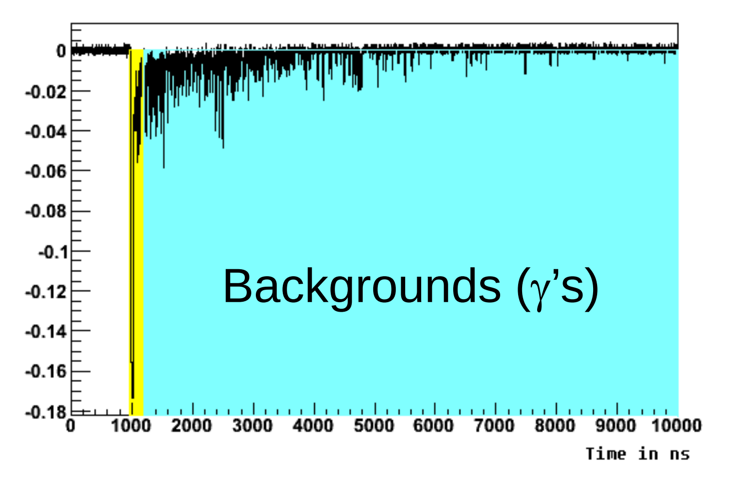
- A recoiling nucleus is slow and heavy, and deposits all its energy in a small localized region.

- An electron is fast and light and deposits its energy along a long track.

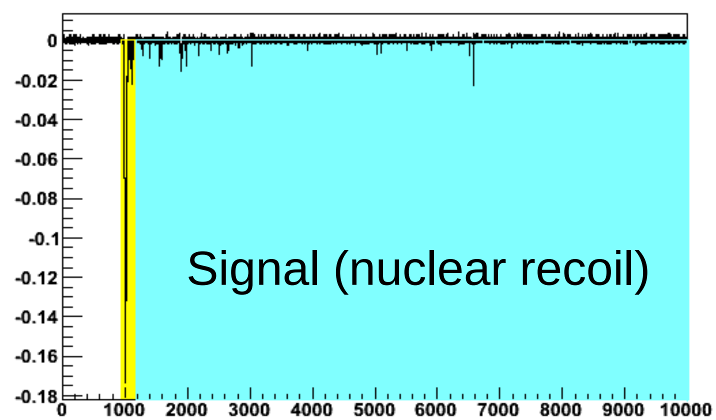
- The interactions create argon dimers in singlet and triplet states (with different live-times). The number in each state depends on collision induced transfers, which because of the charge density, are different for electrons and recoils.

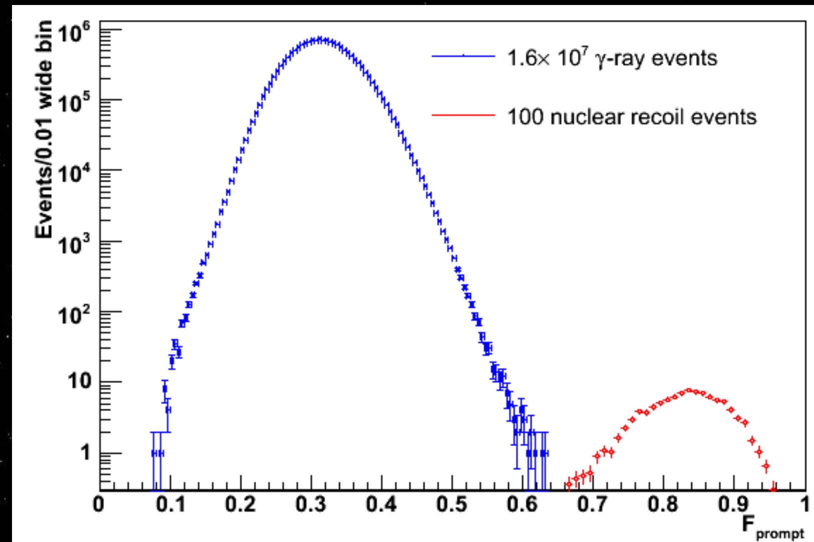
Strategy: use pulse shape discrimination to distinguish between a recoil like event and an electron like event. (need factor of 10^9 rejection).

Background suppression with PSD in DEAP prototype



Yellow: Prompt light region
Blue: Late light region





$$F_{prompt} = \frac{PromptPE(150ns)}{TotalPE(9\mu s)}$$

Depleted ^{39}Ar Source ?

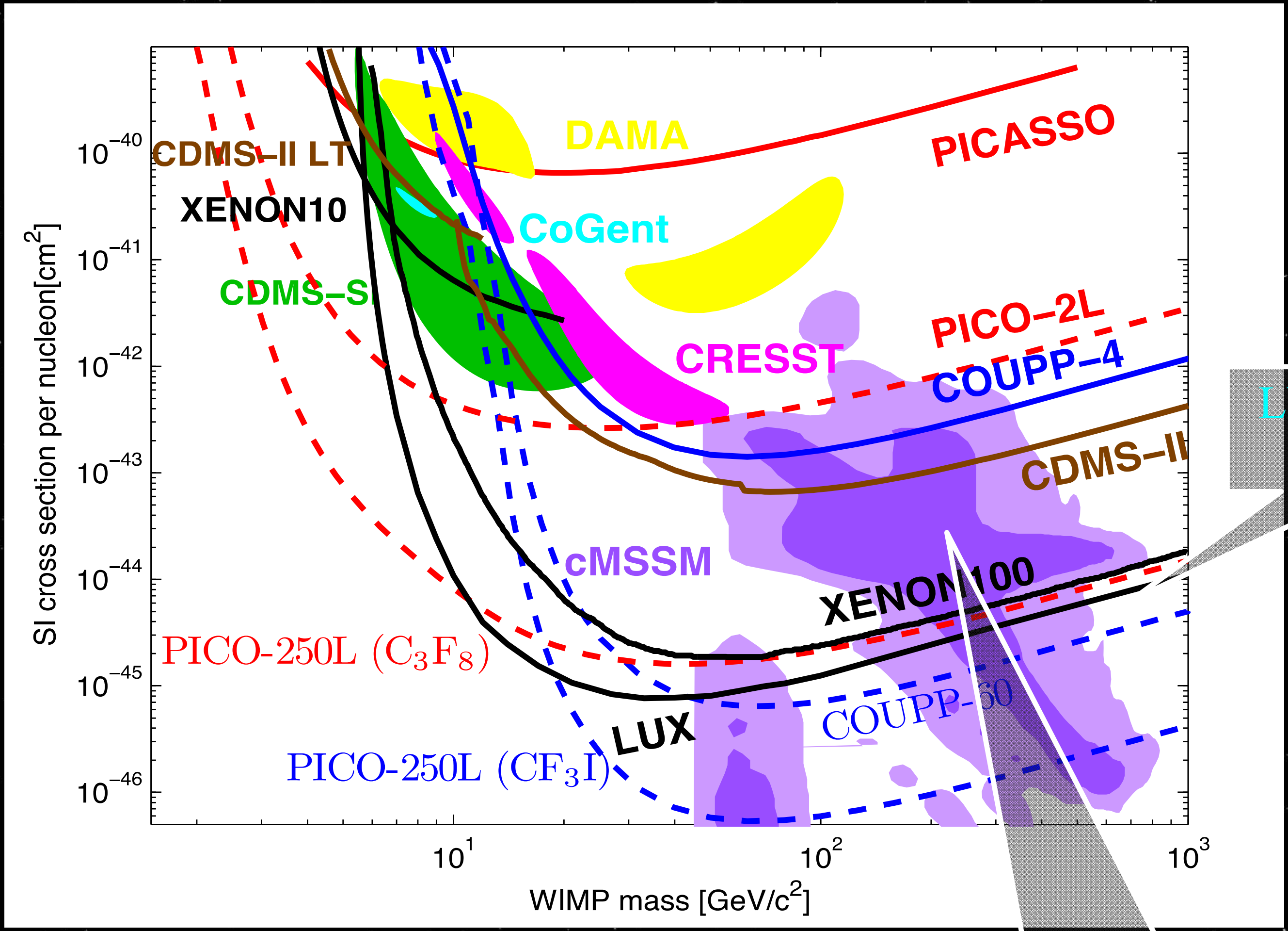
- Production of ^{39}Ar in the atmosphere is via $^{40}Ar + n \rightarrow {}^{39}Ar + n + n$ where the neutrons are produced by cosmic rays.
- Underground, can get away from cosmic rays, and in underground gas and water reservoirs there is little neutron activity. Hence:
- By extracting argon from deep gas wells, one can get natural argon with low levels of ^{39}Ar.
- Pilot program is currently in place. It is working well. Plans to upgrade capacity to ~ 25 kg per day are underway.

Status of DEAP-3600

- fully funded
- being installed underground at SNOLAB
- pulse shape discrimination demonstrated in prototype
- all major components are being installed or commissioned:
  - Acrylic vessel complete
  - Shielding tank in place.
  - Steel vessel in place
  - PMT's ready to be installed on Acrylic vessel
  - Electronics installed and being tested
  - Resurfacer being commissioned

Results expected in about a year will be world leading

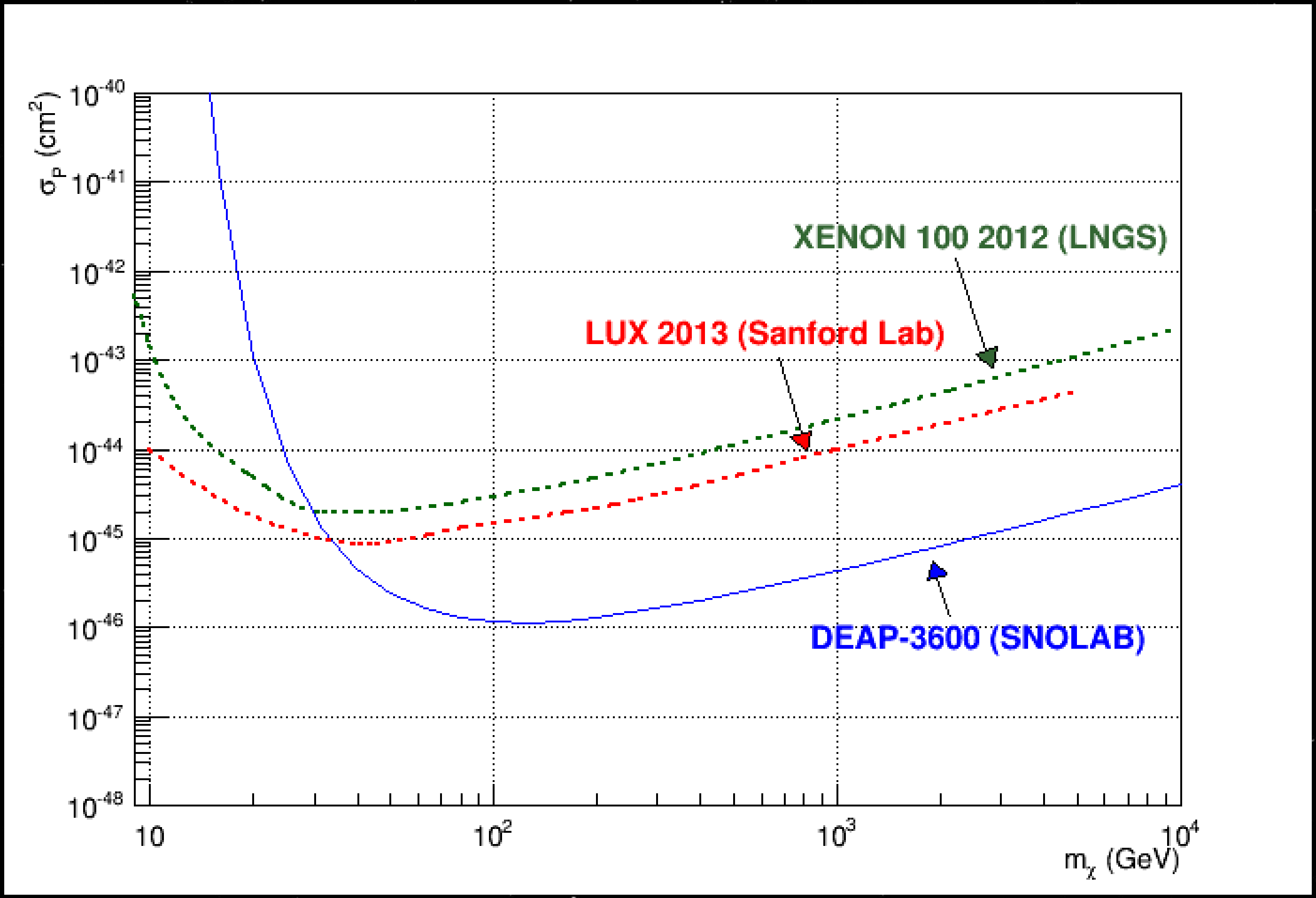
Overview of current status in SI.



LUX. Current best result

Supersymmetry predictions favour these areas.

DEAP 3600 is projected to have sensitivity an order of magnitude higher than LUX, the current leader, for higher WIMP masses



Will explore much of the parameter space allowed by current theory.

The MiniClean Experiment

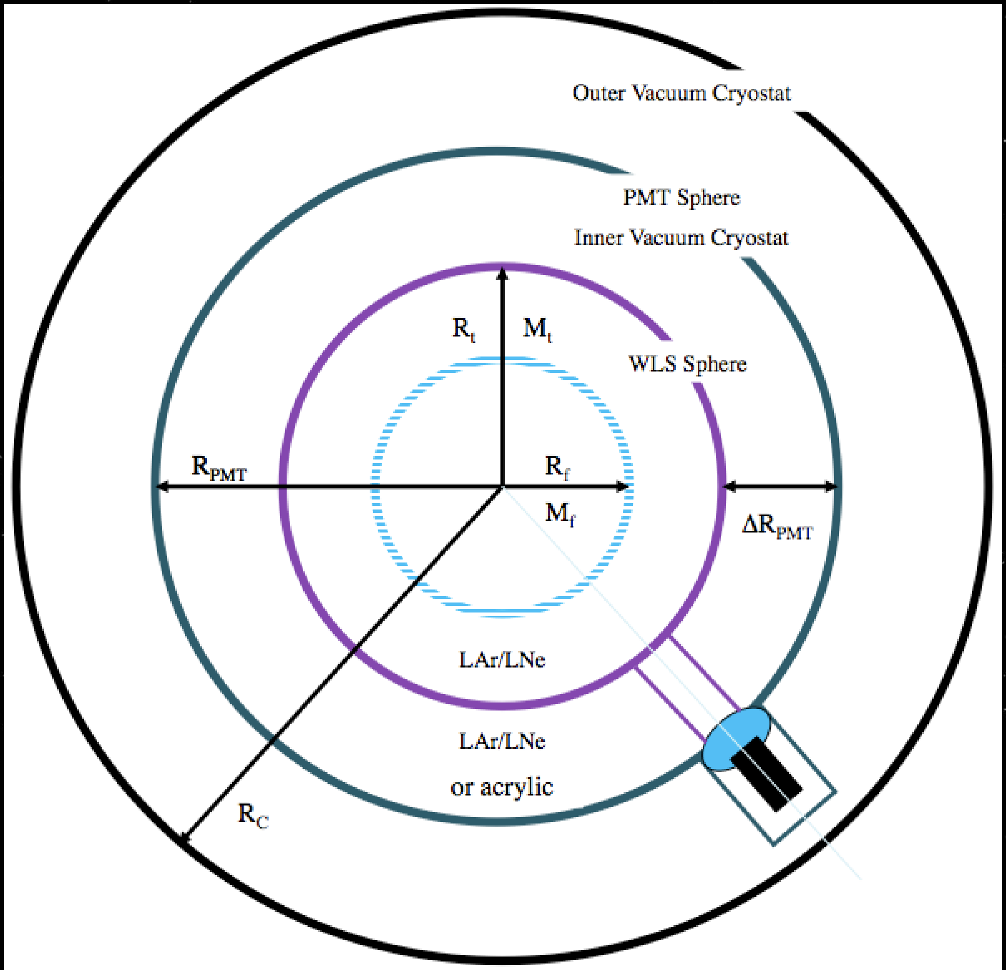
Goal: Engineering test of LAr technology

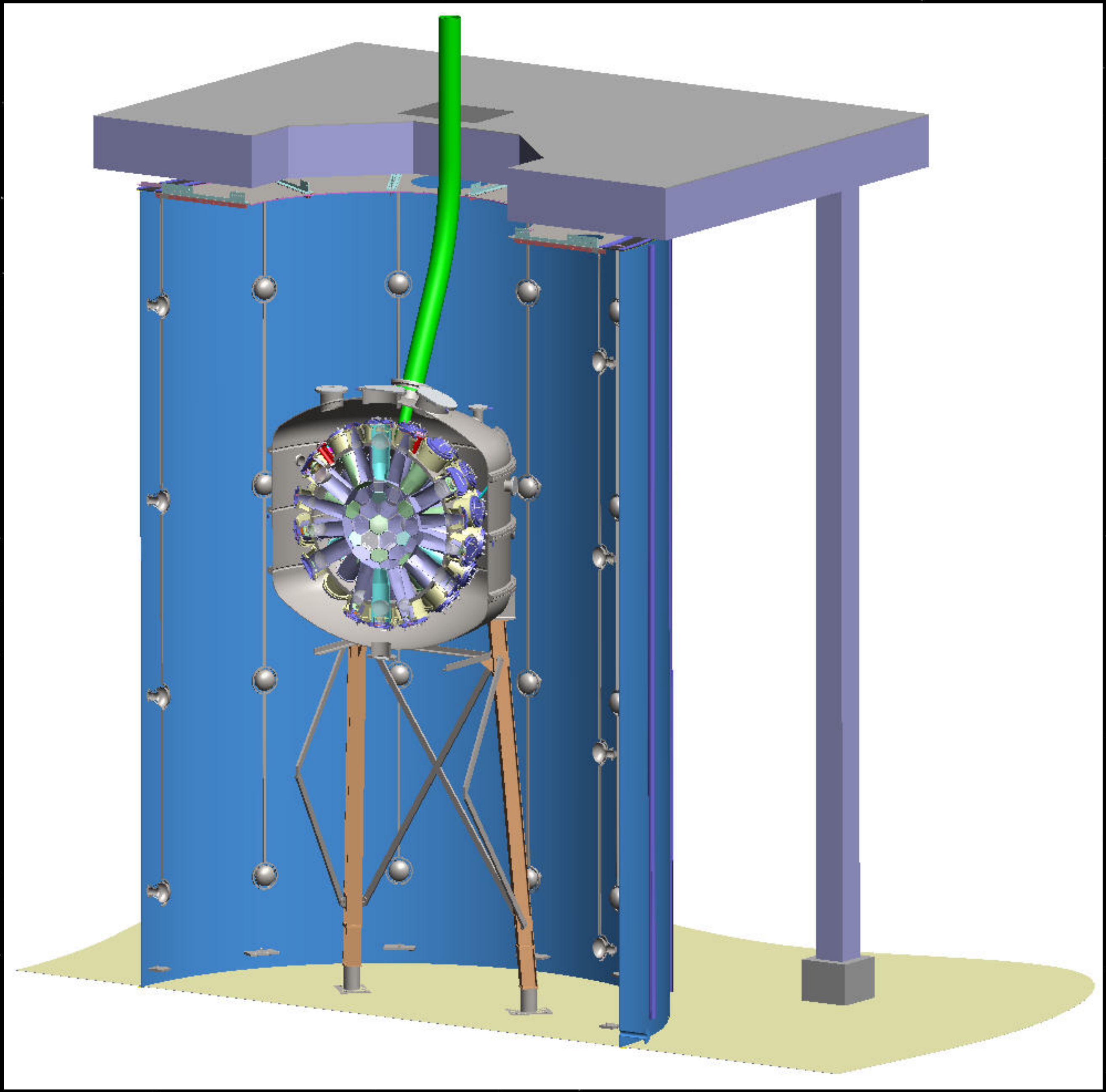
- Measure light yield compared to expectations
- Demonstrate position reconstruction
- Measure backgrounds
- Use ^{39}Ar spike to demonstrate pulse shape discrimination in LAr
- If additional funding is procured, also fill with LNe to make solar neutrino measurement.

The MiniClean Experiment

General Features

- 350 kg LAr,
- ~150 kg LAr fiducial
- In contrast to DEAP, entire system, including PMTs is at LAr temperature.
- Otherwise technologies are very similar.

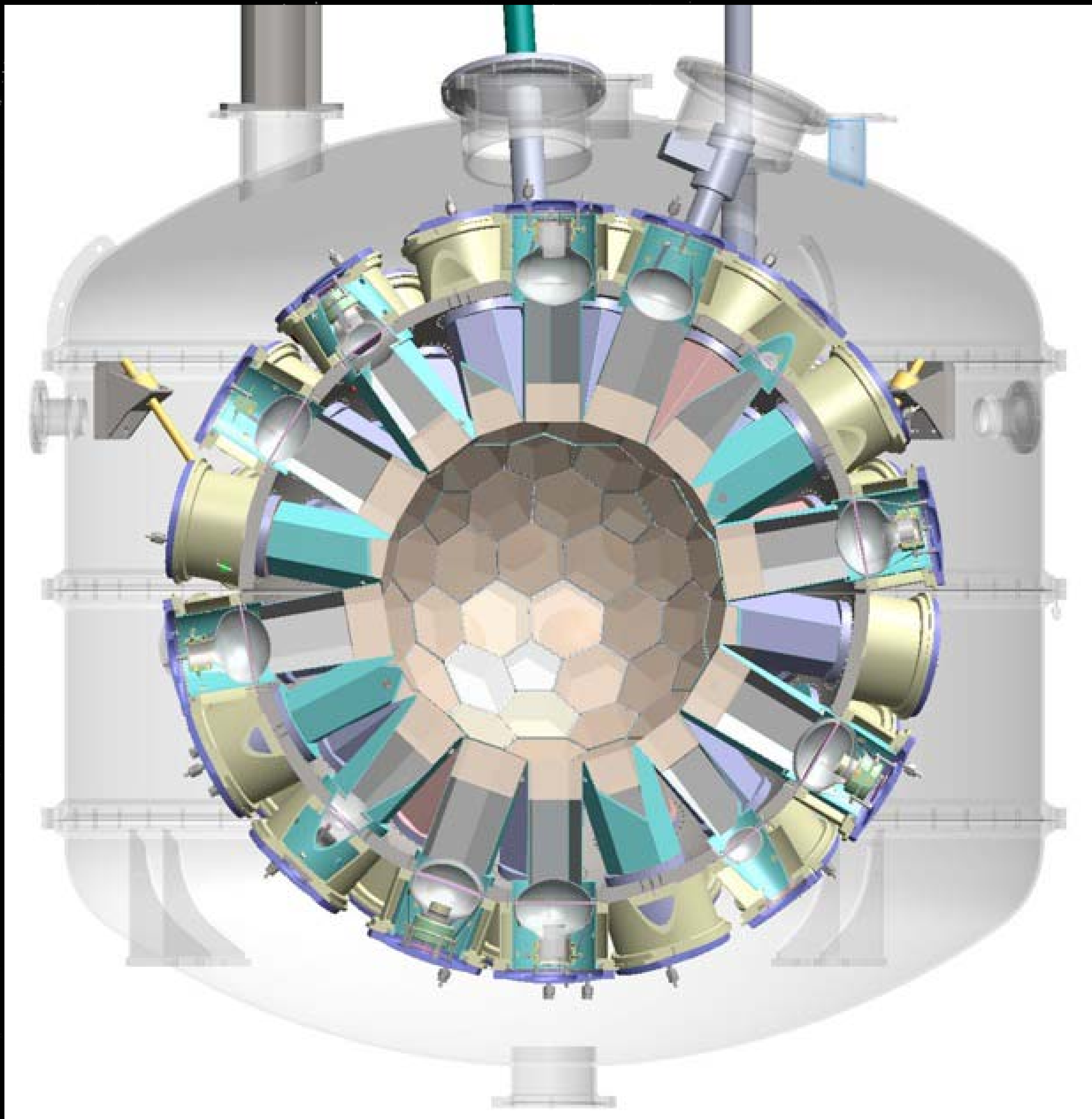




Conceptual Design

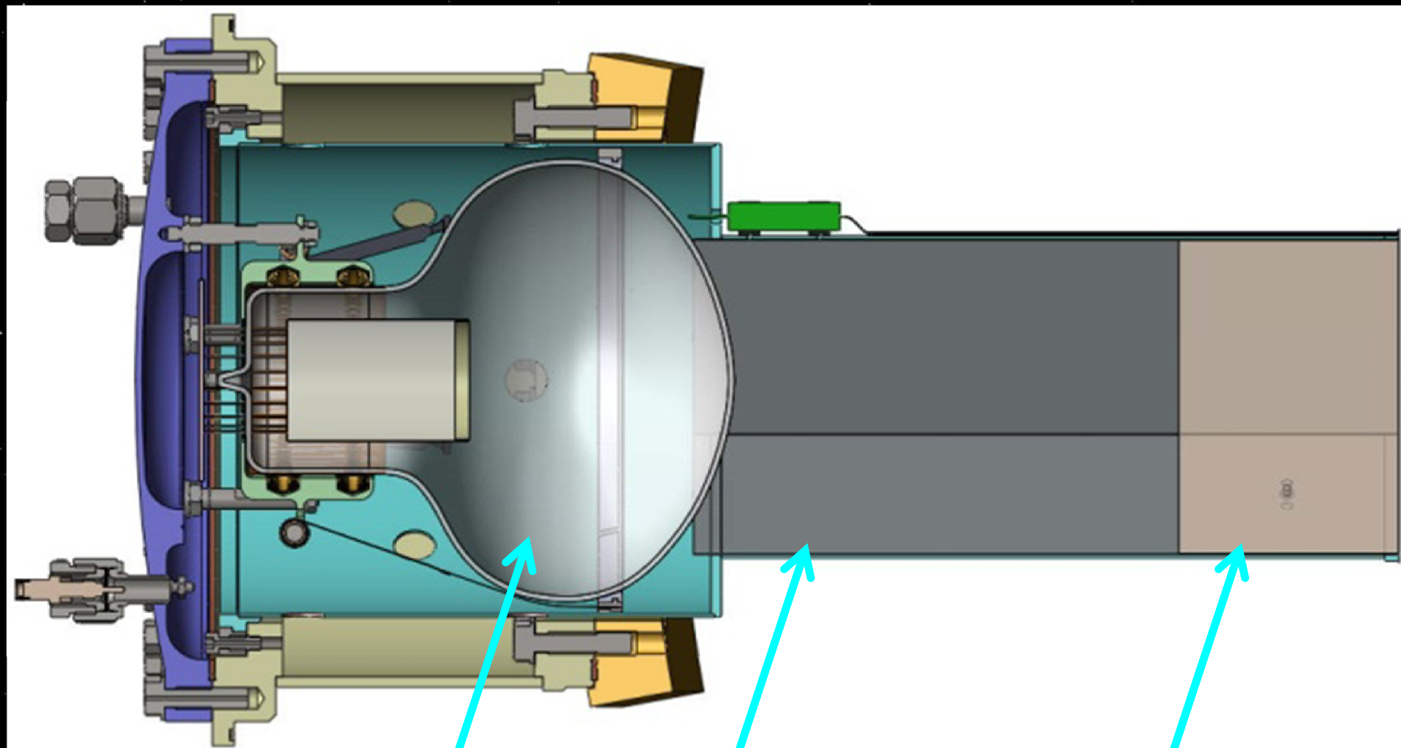
Vacuum vessel mounted inside water shielding tank.

Active veto in water tank.



95% solid angle coverage with close packed faces.

PMTs at LAr temperature need platinum underlay for photocathode conductivity.

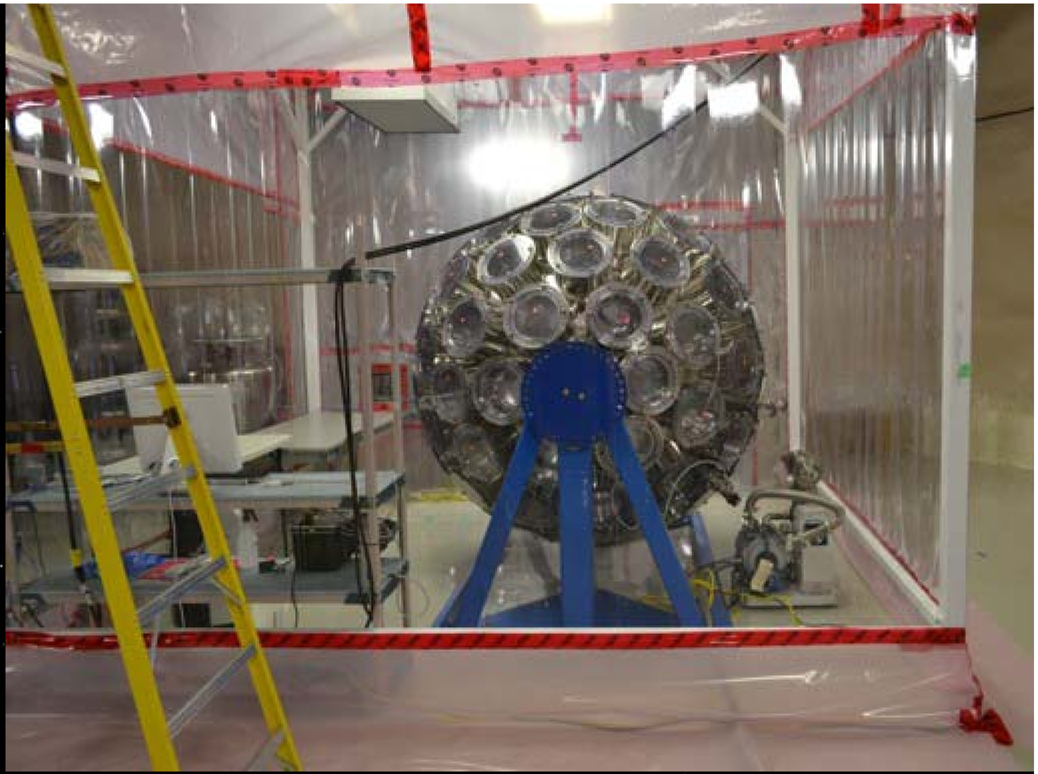


PMT Cassettes: PMT and light guide and acrylic plug assembly

Acrylic plug has TPB wavelength shifter.

Preparing the Optical cassettes

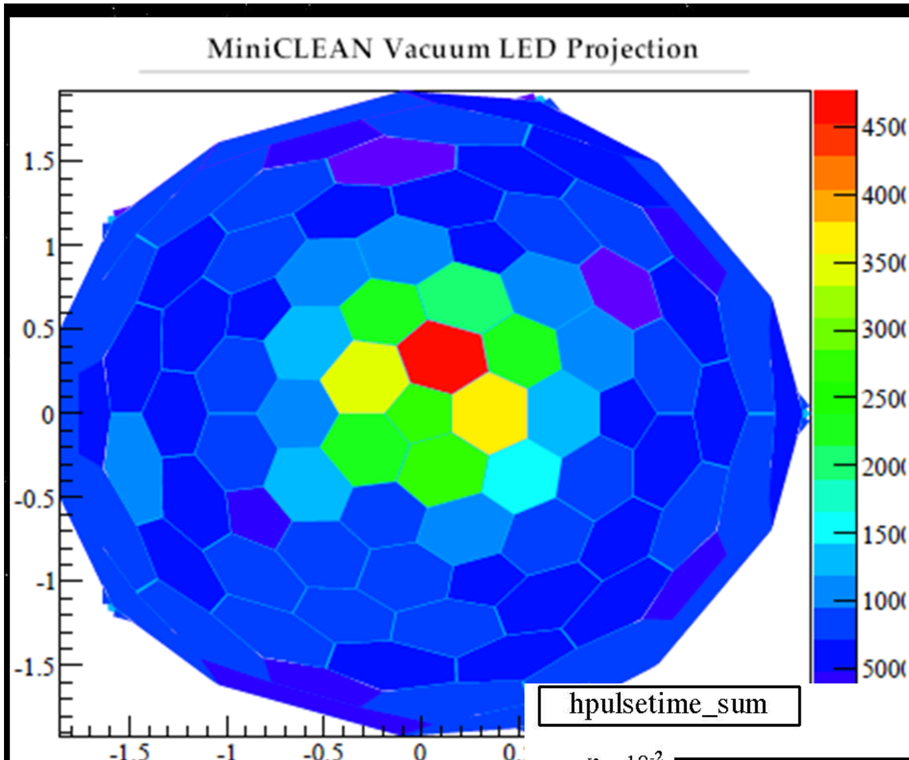
Inserting the Optical cassettes



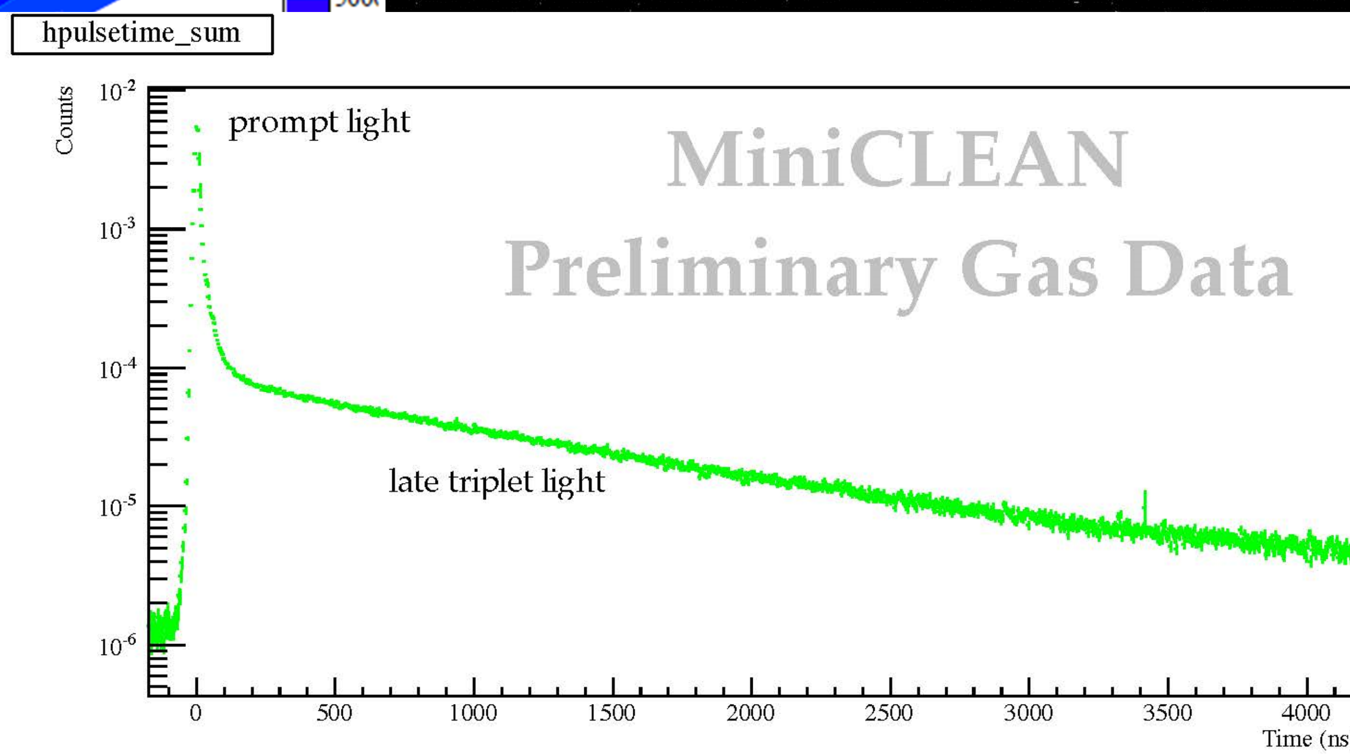
Cassette loading is now complete.
Testing underway with Argon gas.

Next steps will be to insert into
vacuum vessel in cube hall.

Testing with LED flashers.



First Argon Light. January 29th, 2014



Rough schedule (~as reported at TAUP 2013)

- Assembly and initial commissioning complete in late 2013
- 4-5 weeks to condense argon gas into LAr
- ~8 weeks of calibration and running:
  - Energy scale
  - Position reconstruction
  - Neutron calibration
  - Preliminary PSD
- Then ~100 days of enriched argon running
- Produce at least 1010 39Ar events in the fiducial volume
- Use PSD run to compare to DEAP-3600, Darkside-50, etc
- Pursue addition of LNe

The PICO Experimental Program

Uses Superheated Liquids to Search for WIMPs

(Use PICASSO to explain Physics of Technique)

What is special about COUPP/PICASSO?

- One of only a few experiments sensitive to spin dependent interactions.

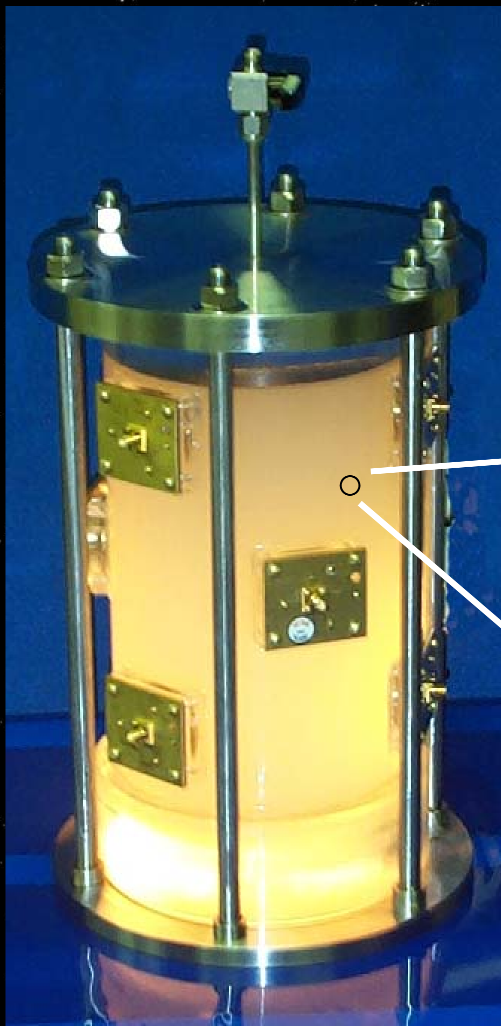
Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

$$\sigma = \frac{32 G_F^2 m_r^2}{\pi} \underbrace{\frac{J+1}{J} \left[a_p \left\langle s_p \right\rangle + a_n \left\langle s_n \right\rangle \right]^2}_{\lambda^2}$$

- Fluorine one of the more favourable targets

- Sensitive to low mass region in both SI and SD interactions, due to smallness of ^{19}F
- Capable of very low thresholds. ~ a few keV
- Very different technique from other experiments. Very complementary.
- Very different background behavior …. Not sensitive to β, γ radiation

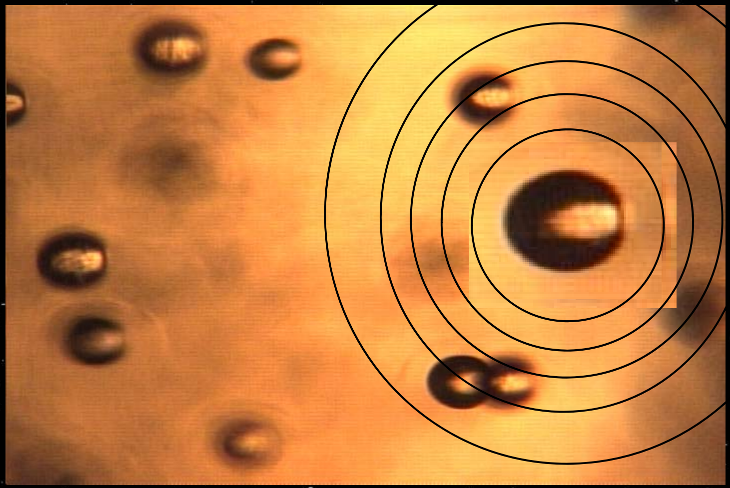
The Picasso Dark Matter Search Experiment

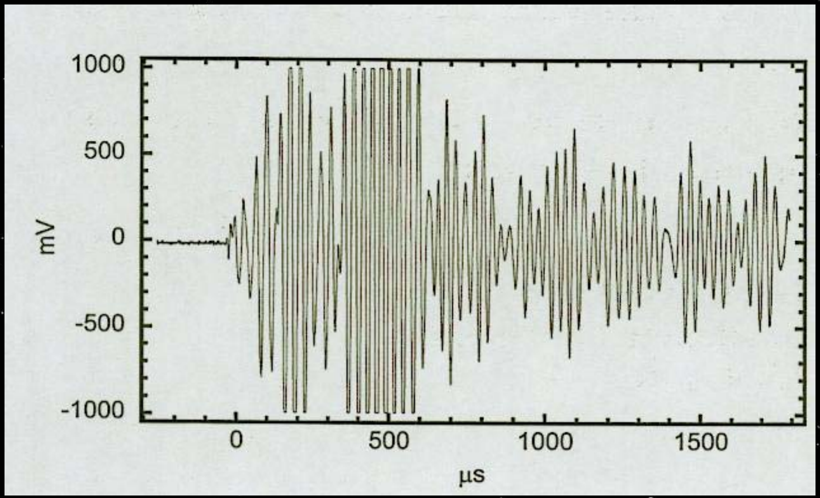


- Detector consists of tiny (~100 μm) halocarbon liquid droplets (C_4F_{10}) embedded in a gel.
- The droplets are superheated - maintained at a temperature higher than their boiling point.

Detector Operation

- When a nuclear recoil (from WIMP, or neutron interaction, or alpha) deposits a spike of heat into droplet, it rapidly changes phase.
- The expanding bubble creates an acoustic shock wave, which can be recorded by a sensitive piezo-electric transducer

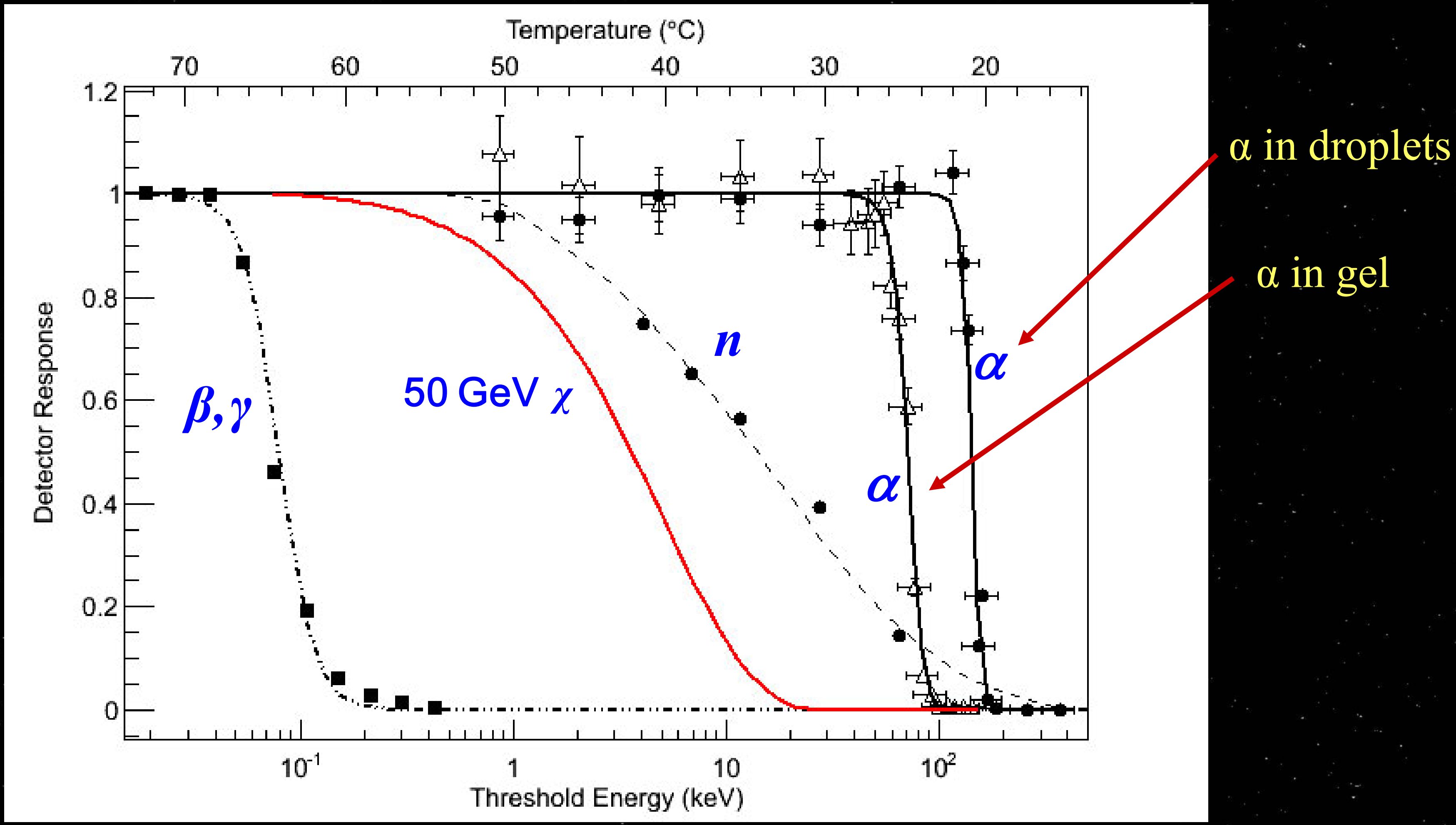




A bubble forms iff the particle creates a heat spike

- with enough energy E_{min}
- deposited within R_{min}

Mainly sensitive to heavily ionizing particles. Alphas are main background



Detector Response very well mapped by calibration.

We determine the WIMP interaction rate by collecting data as a function of temperature, then fitting the spectra to see how much WIMP signal there can be.

Bubble Dynamics allow for alpha ↔ nuclear recoil discrimination

10^{-14} | 10^{-13} | 10^{-10} | 10^{-9} | 10^{-3} | time (s)

Interaction with electrons

Local heating

Phase transition at nucleation site (10 nm)

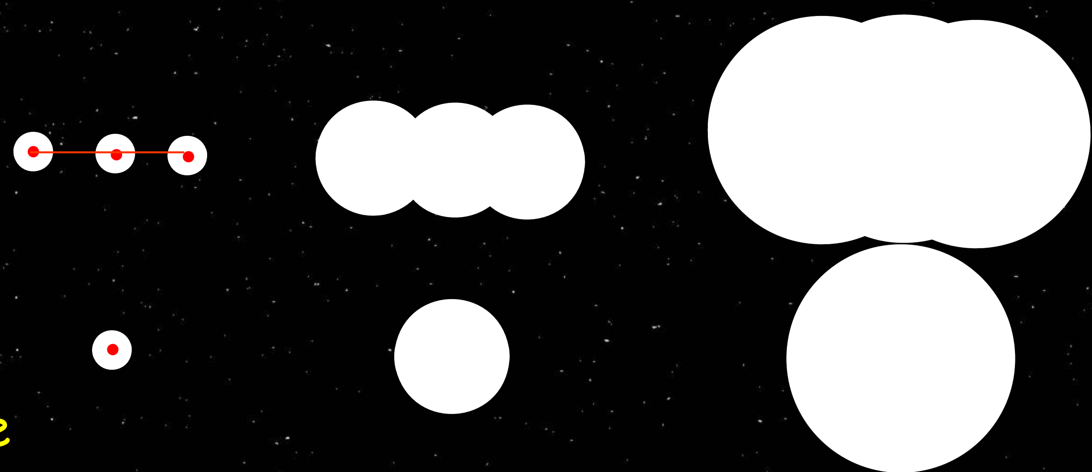
Rapid expansion of protobubble with strong acoustic emission

Intensity of acoustic signal: $I = \dfrac{\rho \ddot{V}^2}{4\pi c}$

Depends on volume acceleration

a track ~35 μm

recoil track ~pointlike



$\ddot{V}_\alpha \gg \ddot{V}_{Recoil}$

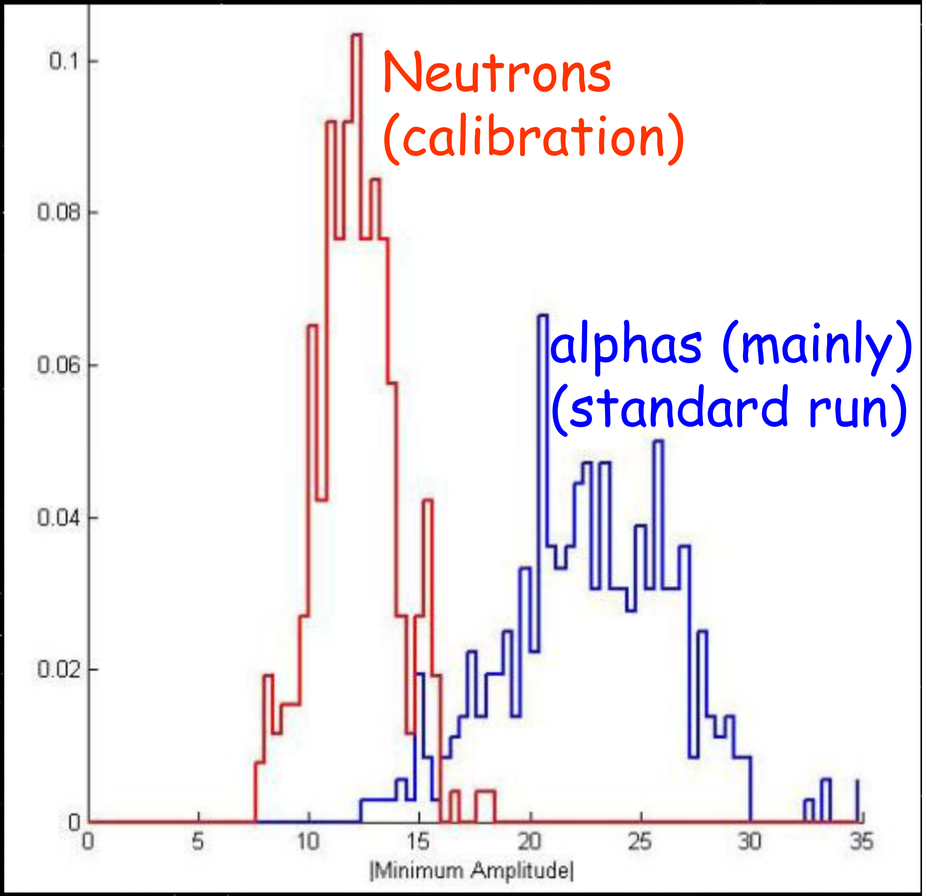
Especially during first 100 μs

Background from alpha particles II

- Pulse Shape discrimination.

This has been made possible recently by significant upgrades to the PICASSO DAQ:

- New preamps with better gain control to avoid signal saturation (and loss of signal information)
- DAQ Clock speed doubled to get better sampling of early signal
- 3-D event localization algorithms optimized to allow compensation for path length dependent accoustic attenuation.



> 99% α-rejection @ 80% WIMP acceptance

4 Picasso Detectors located in a temperature/pressure controlled unit:

Each with 9 piezo-electric transducers

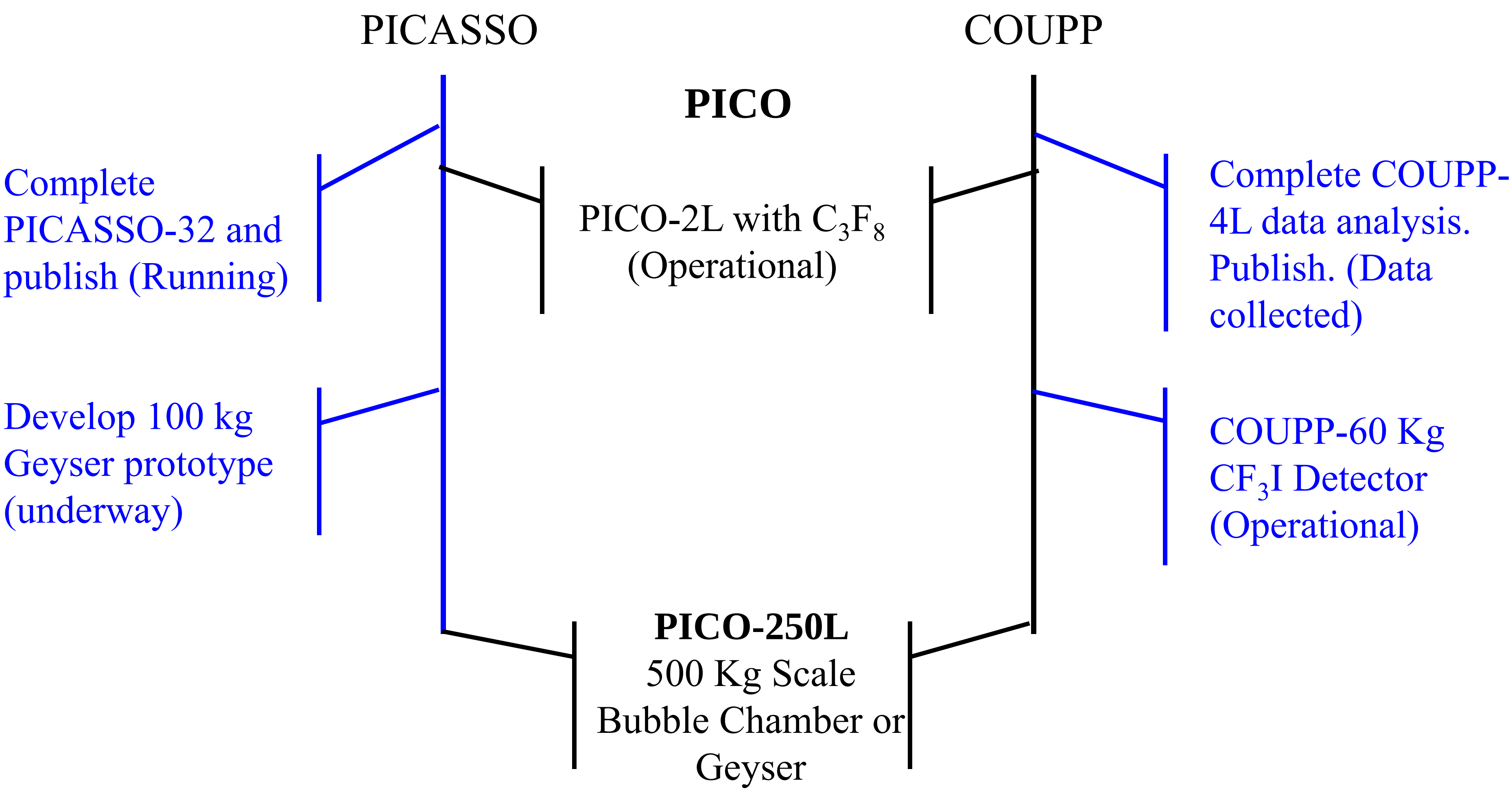
8 such units now in operation (32 detectors total).

In new area of SNOLAB with:

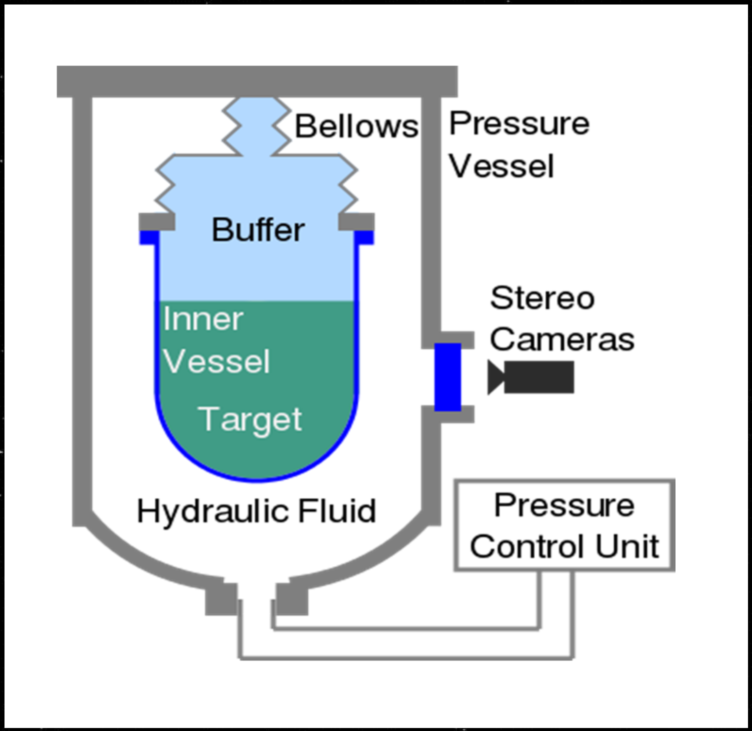
- Improved neutron shielding
- Improved electronics and DAQ to exploit discrimination
- Improved calibration

- UPW shielding (30 cm → 50 cm)
- Ambient neutron flux < 1/400 !

Physics Program of PICO

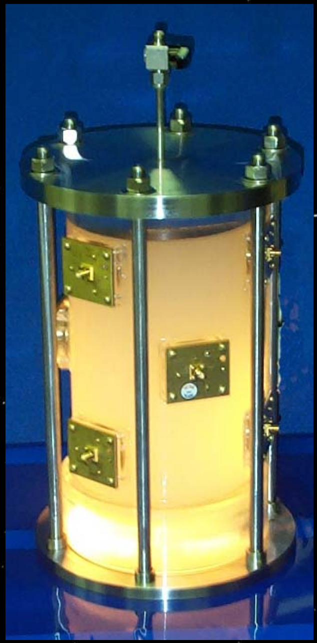


Operation of Bubble Chamber



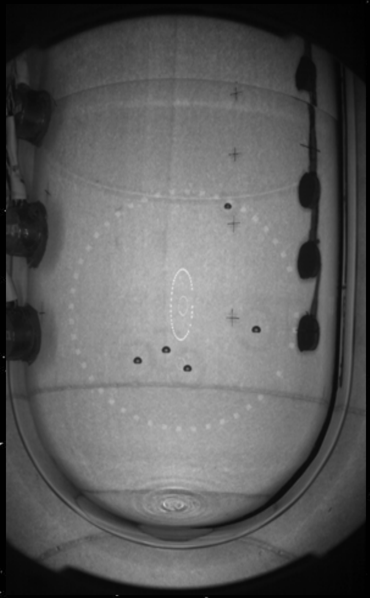
- Target is a superheated fluid
- When a bubble is produced, cameras photograph it, and trigger the pressure control system. Acoustic sensors record event.
- Rapid application of pressure puts bubble back to vapour state
- Expansion of chamber resets it to superheated state.
- Pressure transmitted to inner fluid via dual bellows system

Prior Superheated Liquids Program



PICASSO: C_4F_{10} Superheated Droplet Detectors:

- Reached world leading limits in SD
- Discover acoustic discrimination
- Developed method to determine thresholds precisely. Min is < 2 keV
- Not competitive on larger scales



COUPP: Large Volume CF_3I Bubble Chambers

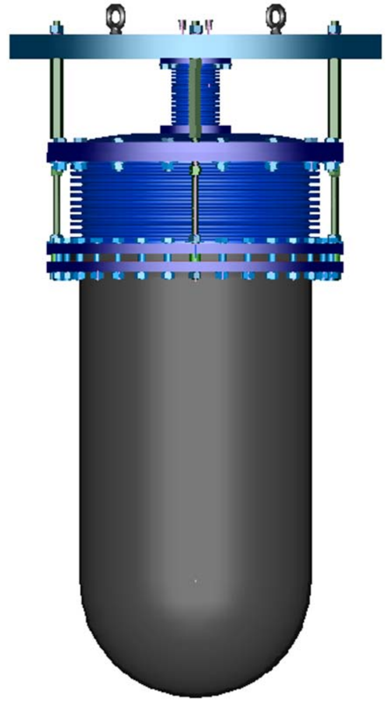
- Demonstrated large scale capability
- Verified acoustic discrimination
- Had some mystery events, possibly due to CF_3I chemistry or bubble chamber operation
- Threshold limited to ~ 15 keV

Current/Future Superheated Liquids Program

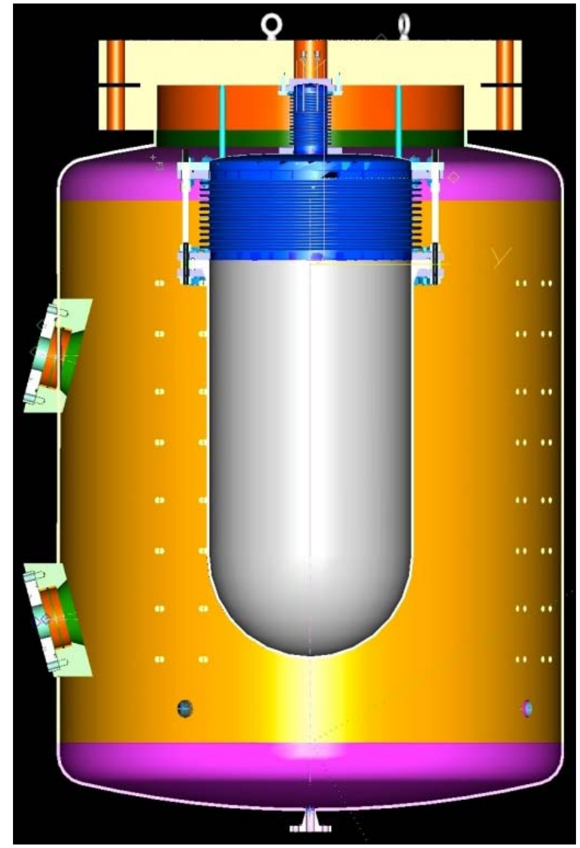
PICO Joint Future Program:
Scale to 500 kg size, with workable liquid and chamber technology.

- PICO-2L is testing C_3F_8 in bubble chamber. See if mystery events go away and low threshold can be achieved. If CDMS-Si result is due to WIMPs, should see ~ 1 WIMP per day.
- COUPP-60 kg is operational with CF_3I and will determine origin of mystery events while also setting very good physics limit.
- PICO-250L is large scale "ultimate" detector currently planned as C_3F_8 bubble chamber. Will own the SD sector, and have good sensitivity for SI as well, especially at low masses.
- Geyser 100 kg R&D   To test alternate chamber operation mode if mystery events are due to compression method or materials involved. Will also test suitability of acrylic over quartz (easier to scale up)

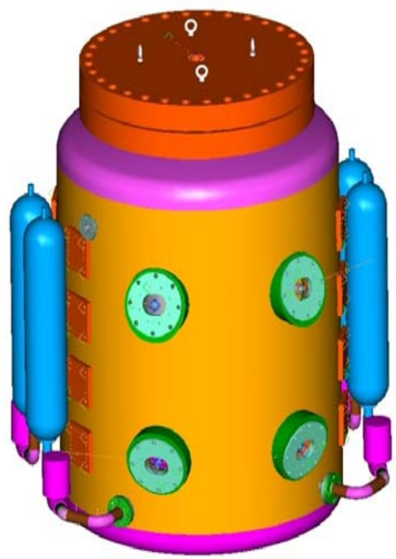
COUPP 60 Installation



PICO 250L
Inner Vessel Design

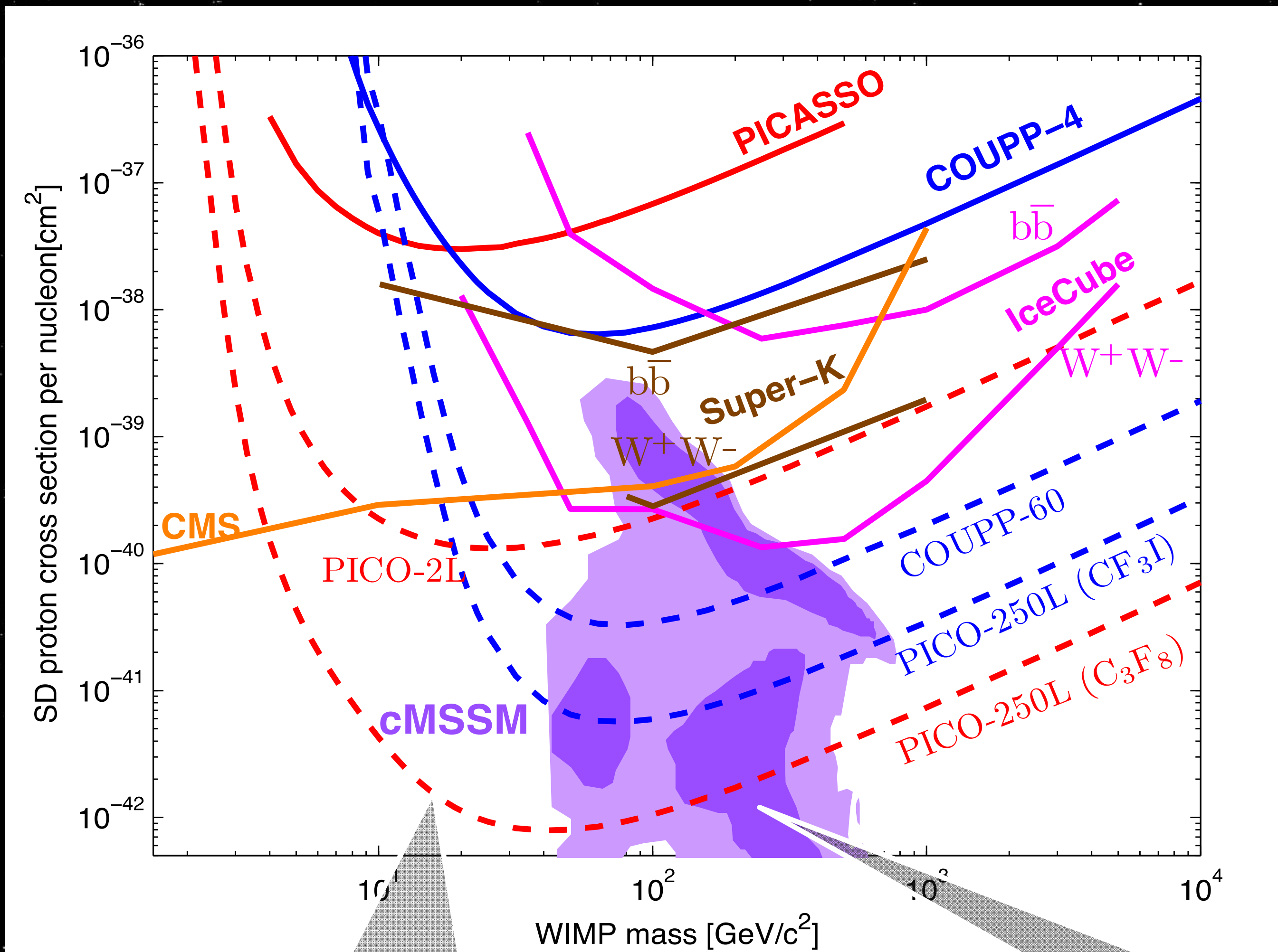


PICO 250L
Outer Vessel Design



PICO 250L
Fast Compression
System

Where will this take us?

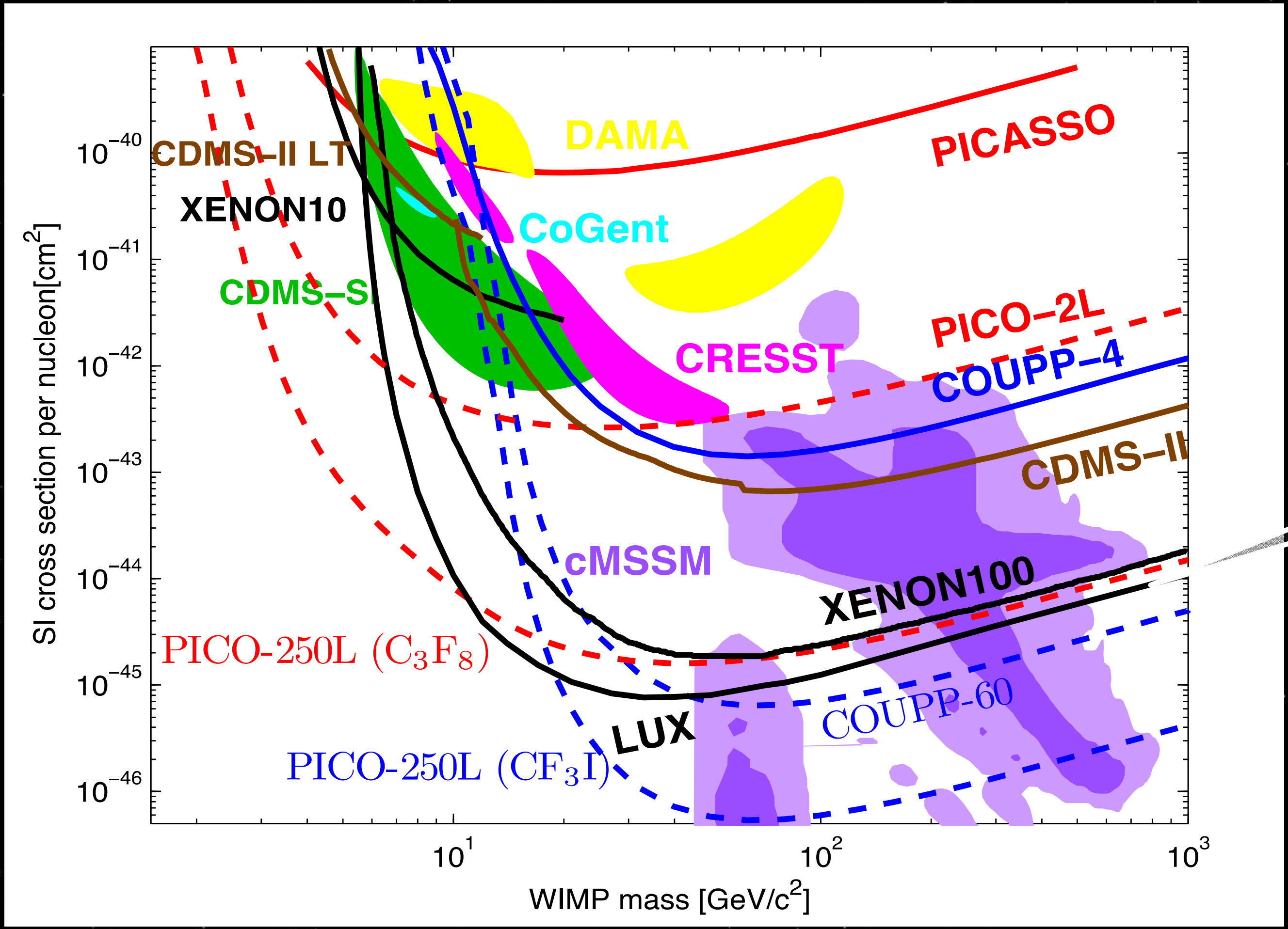


PICO 250L will be world best in SD

C_3F_8 sensitive to low masses

Cover most of theoretical parameter space for SUSY

And will have world leading sensitivity at low mass in SI with C_3F_8.



LUX. Current best result

And with change of gas to CF_3I or similar, will be world leading at high mass as well.

The G2 Down Select Process

(as I understand it)

Phase 1 (2013):

Provide R&D only funding to G2 candidates. 5 of 13 selected

ADMX, LZ, SuperCDMS_SNOLAB, DarkSide, PICO

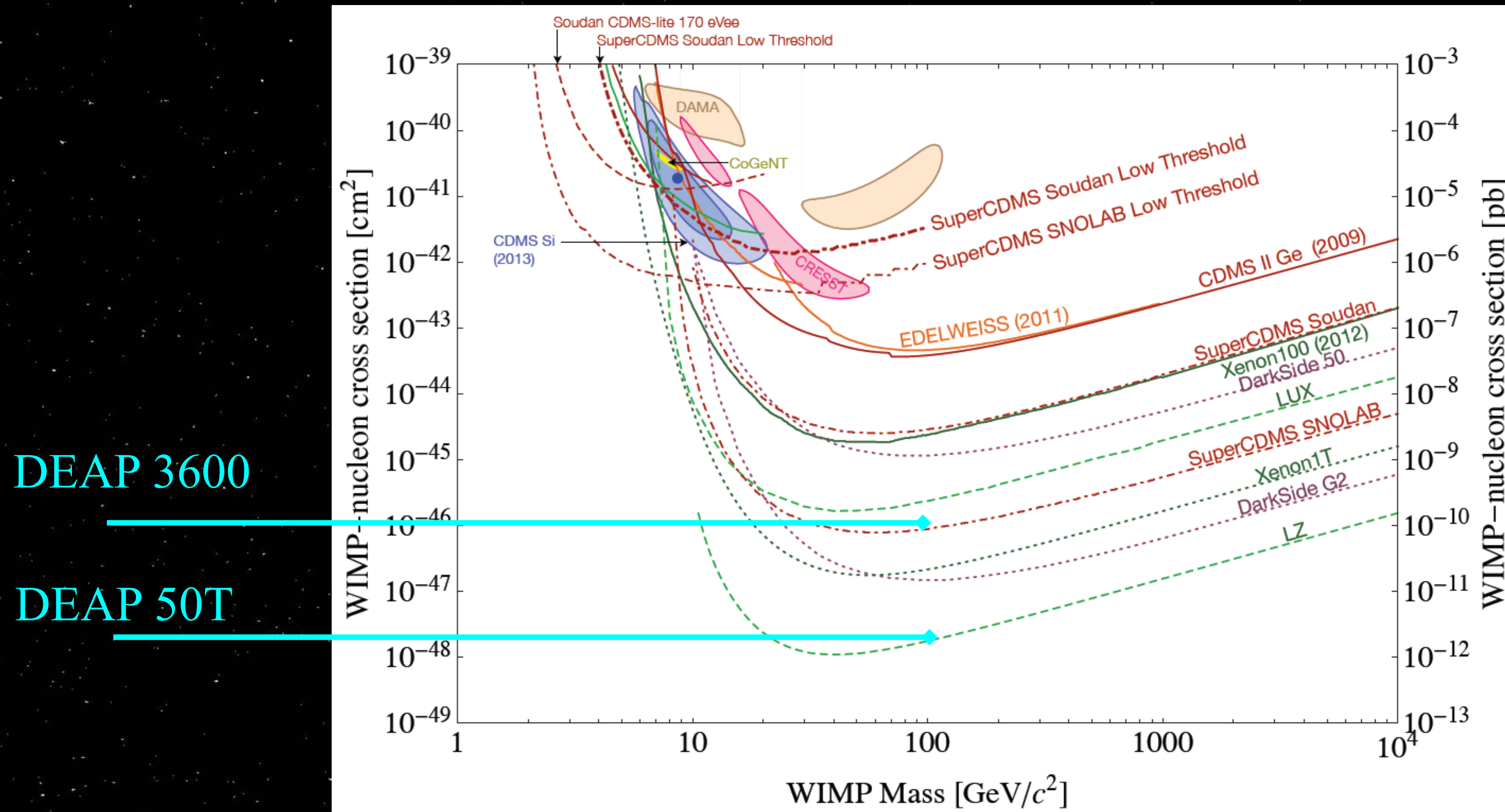
Phase 2:

- Proposals due to NSF and DOE in December 2013
- Selection in January 2014
- Announcement in Feb/March 2014

Rumour Mill:

- Requested amounts far exceed the available 31 M$
- Some possibility of more money
- Most likely scenario: One large, one axion, one small

Crystal Ball Gazing: Where will we be in 2020

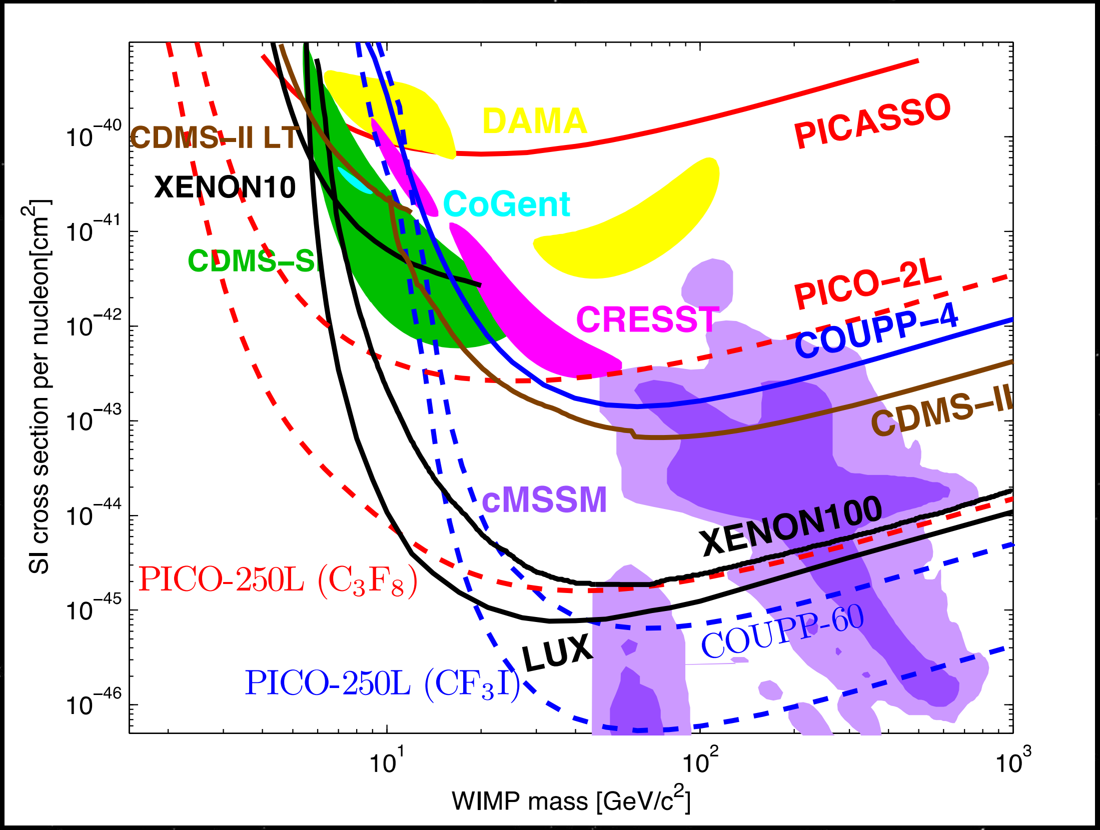


From SuperCDMS presentation TAUP 2013

DEAP 3600 (2014) …. Will be done. May be ramping up on DEAP 50 Tonne
LUX (2013)…. Will be done. Moving on to LZ if selected.
DarkSide 50 (2013) … will be done. Moving on to DarkSide G2 if selected
Xenon 1 tonne. ~2015 – 2018 … will be moving on to Xenon 8 tonne
SuperCDMS-SNOLAB…will be operational, if selected.

Will likely be numerous G2 sized detectors exploring the SI sector above 30 GeV/c^2

Crystal Ball Gazing: Where will we be in 2020



Only PICO 250L will be probing the SI sector below 30 GeV/c^2 and able to refute or confirm hints.

DAMIC 100 will have less sensitivity in cross-section, but lower mass coverage.

There is room here for more contributions….

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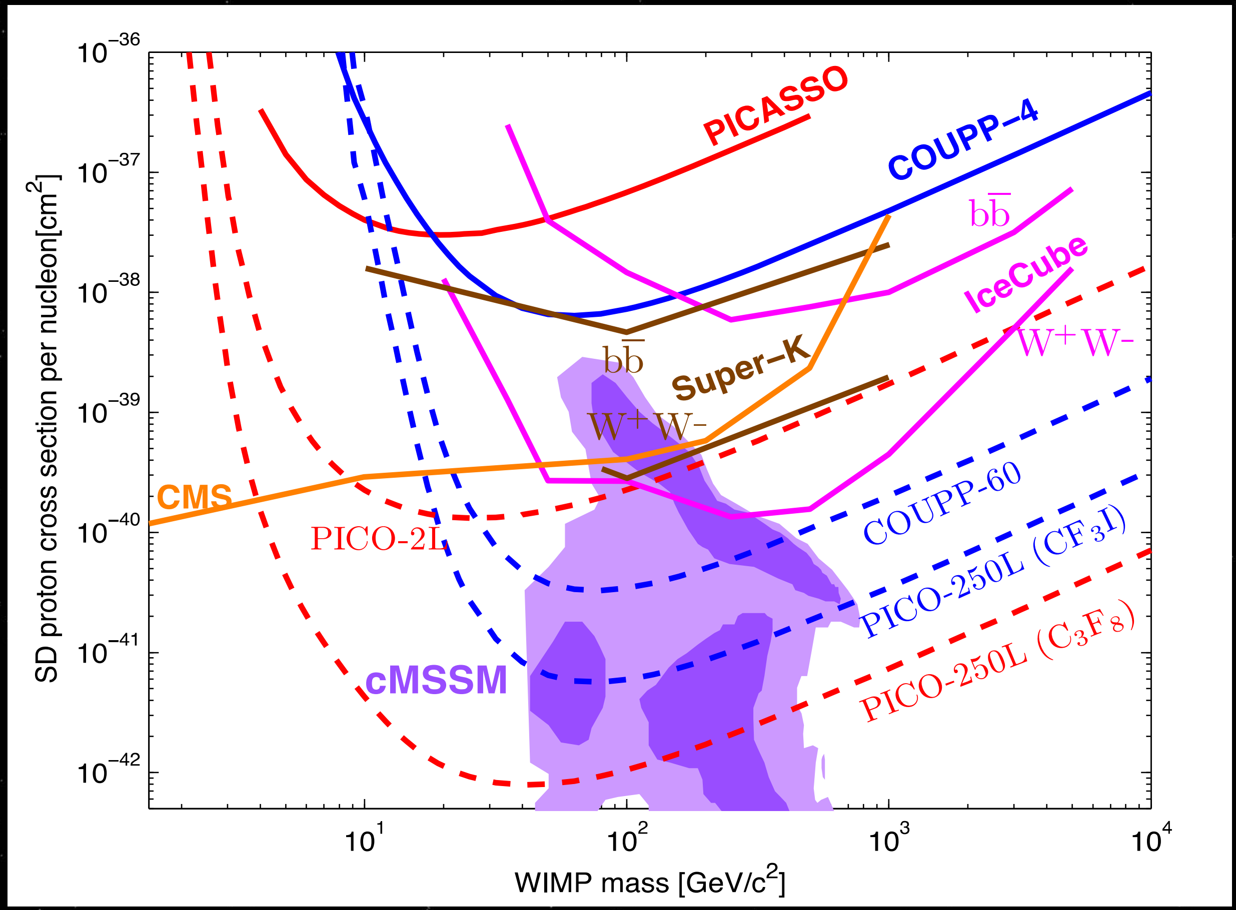

Only PICO 250L will be probing the SD sector (and perhaps SIMPLE).

There is lots of room here for more contributions….different technologies…

End