Advanced Instrumentation Techniques at SNOLAB

Nigel Smith
SNOLAB

Advanced Instrumentation

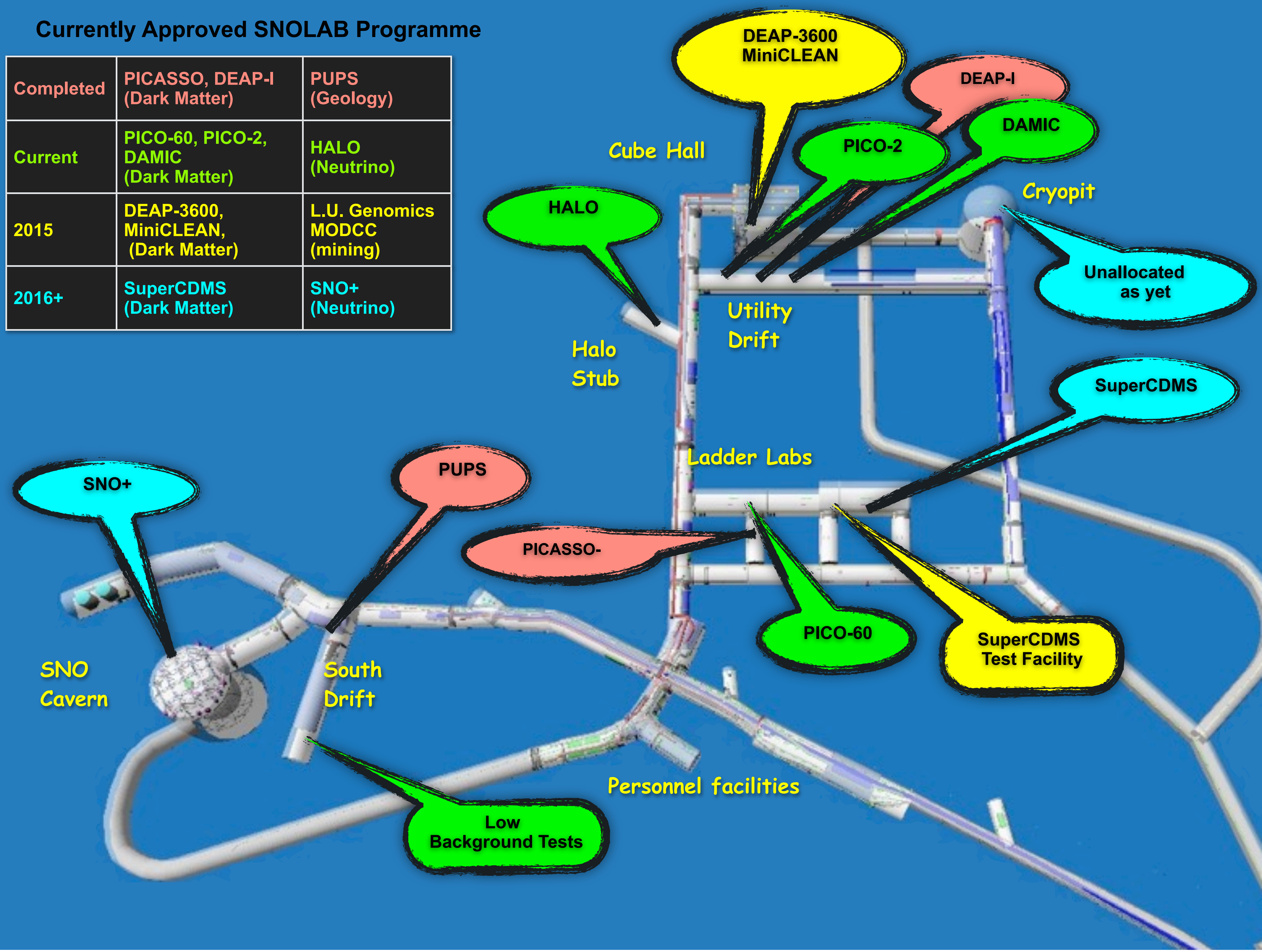
- The SNOLAB science programme requires advanced instrumentation to search for rare interactions and weak processes
  - Will focus on dark matter detector systems
- Challenges include
  - Minimal radiation backgrounds in detectors
  - High efficiency detection (single photon/phonon)
  - Particle discrimination (esp. neutrons and alphas)
- Techniques developed include
  - High light yield liquid noble gas
  - Low threshold solid state
  - Low threshold bubble chamber
- Common requirements for the programme include
  - Low radiological background assay capabilities (Ian Lawson)
  - Low radiological background environments (Chris Jillings)

SNOLAB Science programme

Experiment	Neutrino	Dark Matter	Other	Space allocated	Status
CEMI			Mining Data Centre	Surface Facility	In Construction
COUPP-4		√		"J"-Drift	Completed
DAMIC		√		"J"-Drift	Operational
DEAP-1		√		"J"-Drift	Completed
DEAP-3600		√		Cube Hall	In Construction
DEAP-50T/CLEAN		√		Cube Hall	Letter of Intent
DMTPC		√		Ladder Labs	Letter of Intent
Ge-1T	√			Cryopit	Letter of Intent
nEXO	√			Cryopit	Concept Phase
HALO	√			Halo Stub	Operational
MiniCLEAN		√		Cube Hall	In Construction
NEWS		√		Cryopit?	Letter of Intent
PICASSO-III		√		Ladders Labs	Completed
PICO-2L		√		"J"-Drift	Operational
PICO-60		√		Ladder Labs	Operational
PICO-250		√		Ladder Labs	Letter of Intent
PINGU			Test facility	Ladder Labs	Letter of Intent
PUPS			Seismicity	Various	Completed
SNO+	√			SNO Cavern	In Construction
SuperCDMS		√		Ladder Labs	In Preparation
U-Laurentian			Genomics	External Drifts	Operational

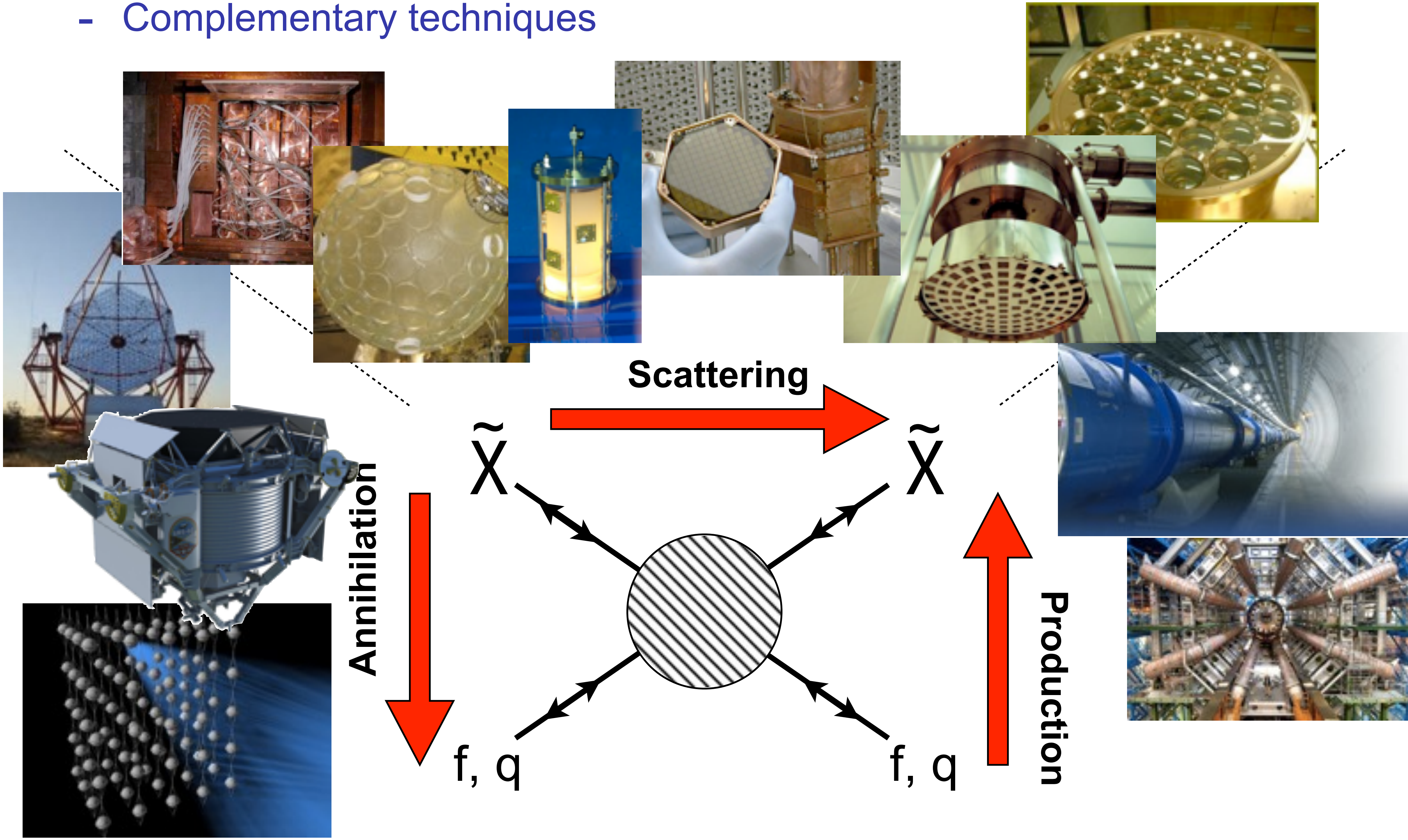
Currently Approved SNOLAB Programme

Completed	PICASSO, DEAP-I (Dark Matter)	PUPS (Geology)
Current	PICO-60, PICO-2, DAMIC (Dark Matter)	HALO (Neutrino)
2015	DEAP-3600, MiniCLEAN, (Dark Matter)	L.U. Genomics MODCC (mining)
2016+	SuperCDMS (Dark Matter)	SNO+ (Neutrino)



Ways to search for Dark Matter

- Complementary techniques



The challenges for direct searches

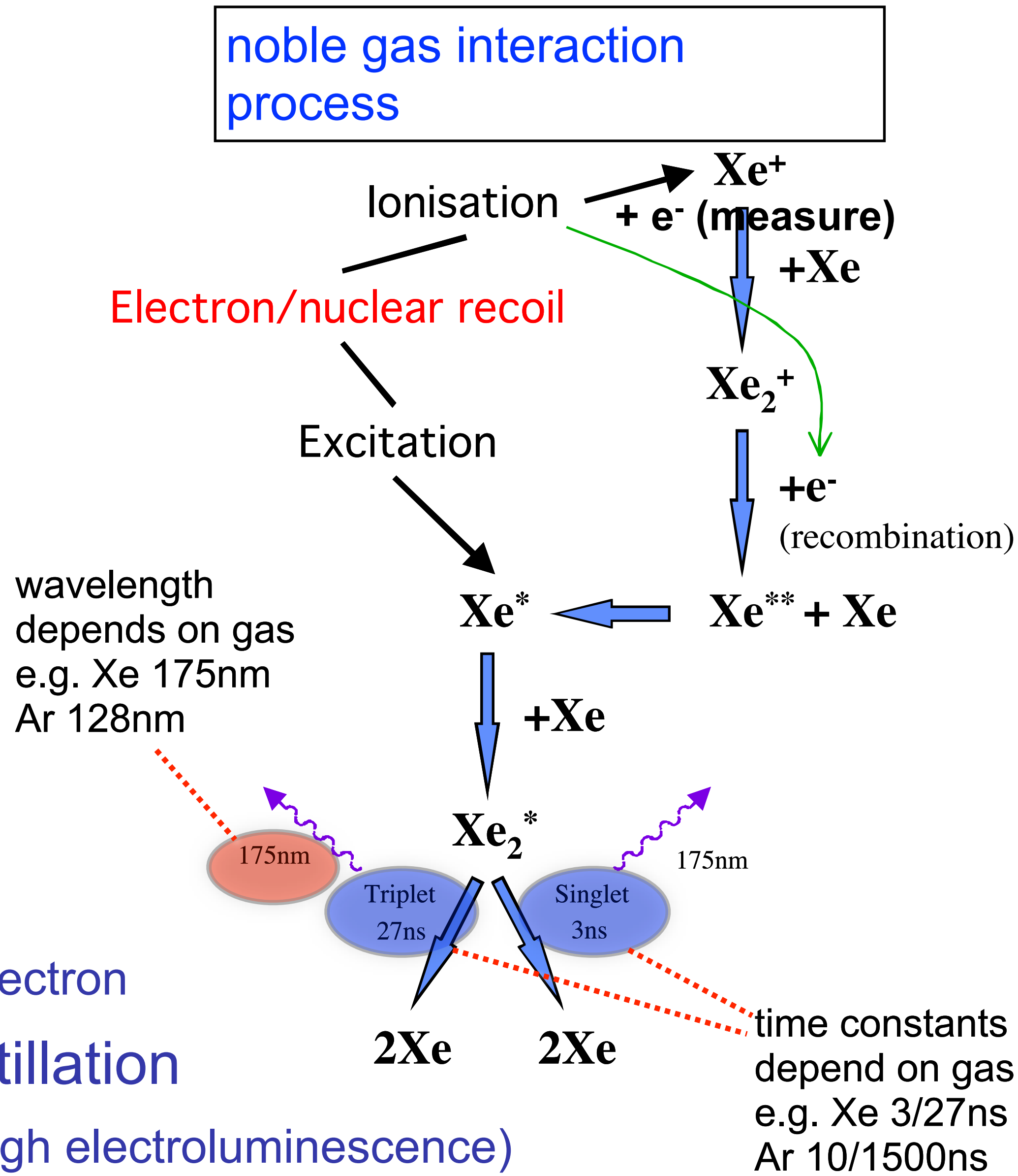
- WIMP nuclear recoil signal is:
  - Low rate (0.1 - 10^{-5} events/kg/day)
  - Small energy (1-100 keV actual: observed is less)
  - Similar observed exponential spectrum to many background signals (PMT, γ, etc.)
- Detection technique must be:
  - Low background
    - Gamma, beta: from U/Th/Co/Pb/etc radio-impurities
    - Neutron: from U/Th radio-impurities and c.r. μ spallation
  - Low threshold
    - To minimise form factor, maximise spectrum
  - Discriminating - Position sensitivity
    - Difference between WIMPs/n and γ/β, background rejection, directionality
  - Large massive

Dark Matter searches at SNOLAB

- Noble Liquids: DEAP-I, MiniCLEAN, & DEAP-3600
  - Single Phase Liquid Argon using pulse shape discrimination
  - High light yield detection required: single photon counting
  - Will measure Spin Independent cross-section.
- Superheated Liquid / Bubble chamber: PICASSO, COUPP => PICO
  - Superheated droplet detectors and bubble chambers.
  - Insensitive to MIPS radioactive background at operating temperature, threshold devices;
  - Requires strong alpha particle discrimination;
  - Measure Spin Dependent cross-section primarily, COUPP has SI sensitivity on iodine;
- Solid State: DAMIC, SuperCDMS
  - State of the art CCD (DAMIC) Si / Ge crystals with ionisation / phonon readout (SuperCDMS).
  - Low threshold devices, high efficiency
  - Mostly sensitive to Spin Independent cross-section.

(Liquid) Noble Gas detectors

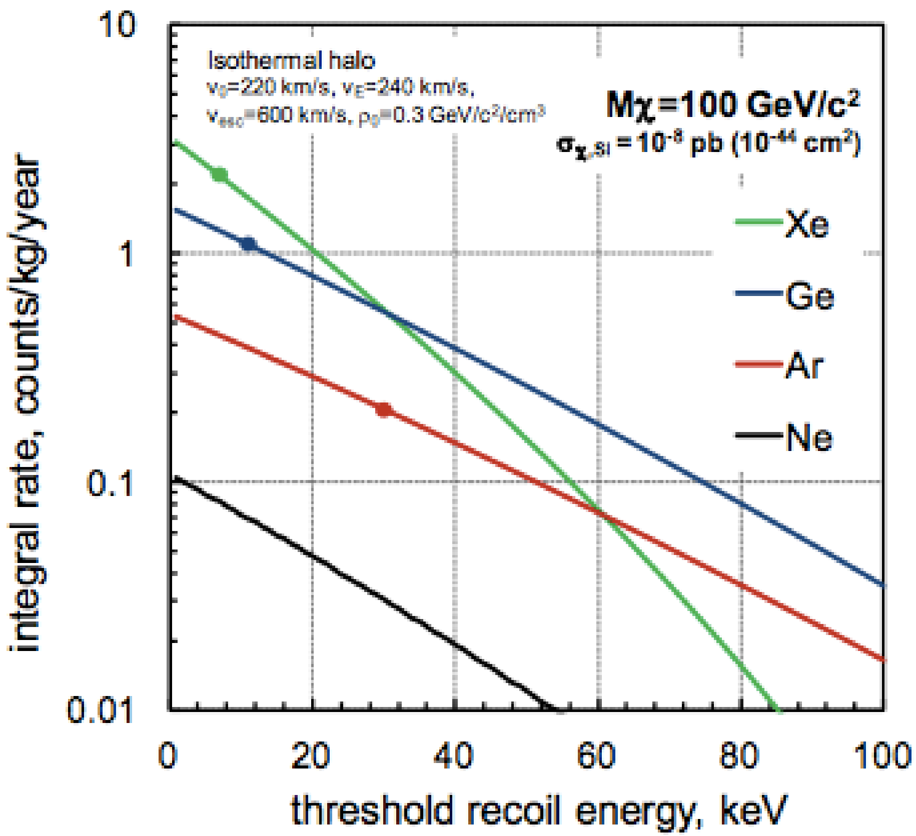
Gas	Single phase	Double phase
Xenon	ZEPLIN I, XMASS	ZEPLIN, XENON, LUX
Argon	DEAP, CLEAN	DarkSide, ArDM
Neon	CLEAN	-

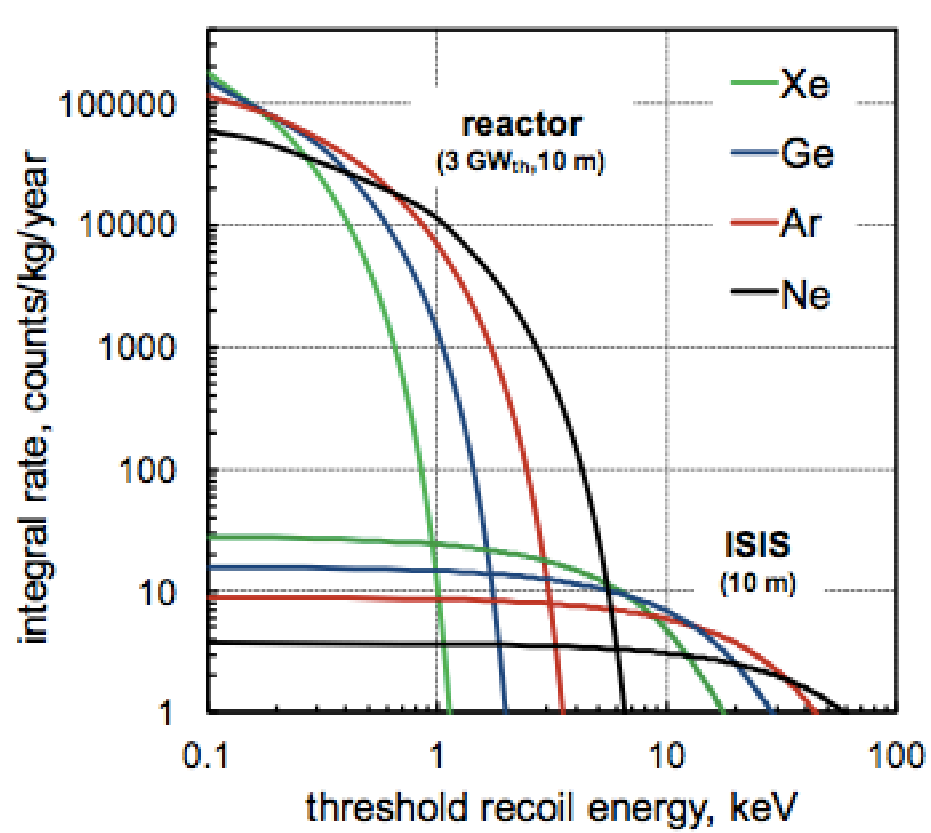


- Single phase - scintillation
  - recombination occurs
  - singlet/triplet ratio 10:1 nuclear:electron
- Double phase - ionisation/scintillation
  - measure ionisation directly (through electroluminescence)

Response to elastic scattering

- Principle technique for WIMPs and neutrino detection is coherent elastic scattering off target nucleii
- For WIMP detection
  - low threshold required in xenon to maximise signal
  - higher threshold in argon for discrimination

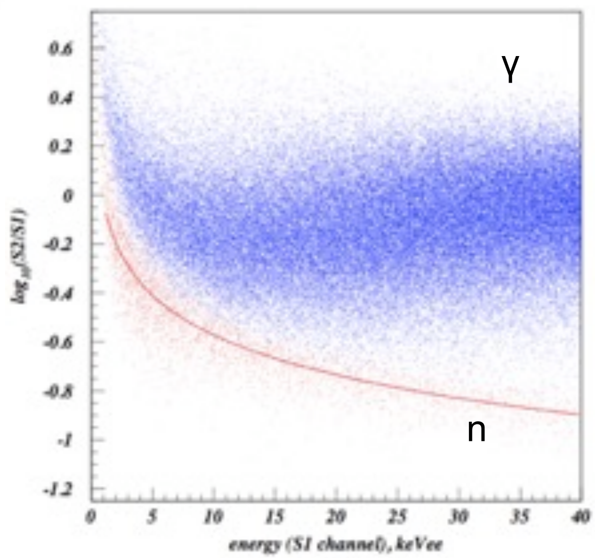




Chepel/Araújo

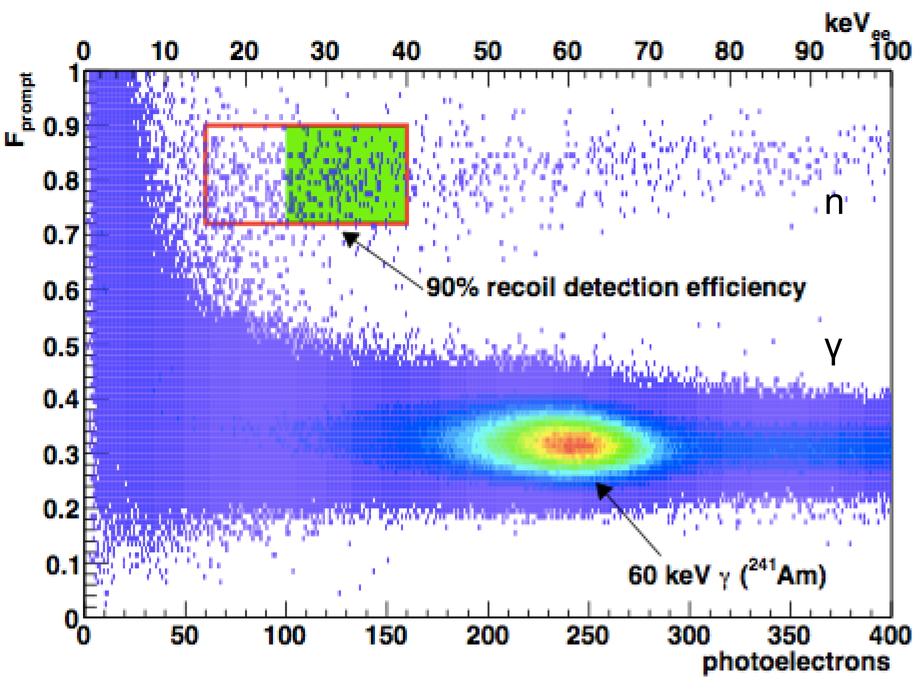
Particle identification

- Discrimination between nuclear and electron recoils
- Single phase detectors use pulse shape discrimination
- Double phase use ratio ionisation to scintillation (+PSD for LAr)

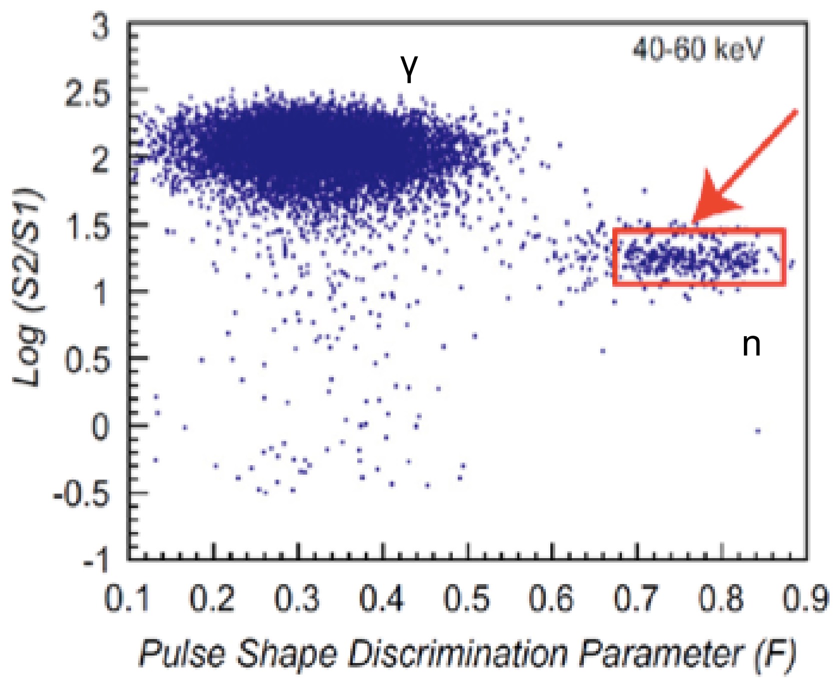


ZEPLIN-III - LXe

DEAP - LAr

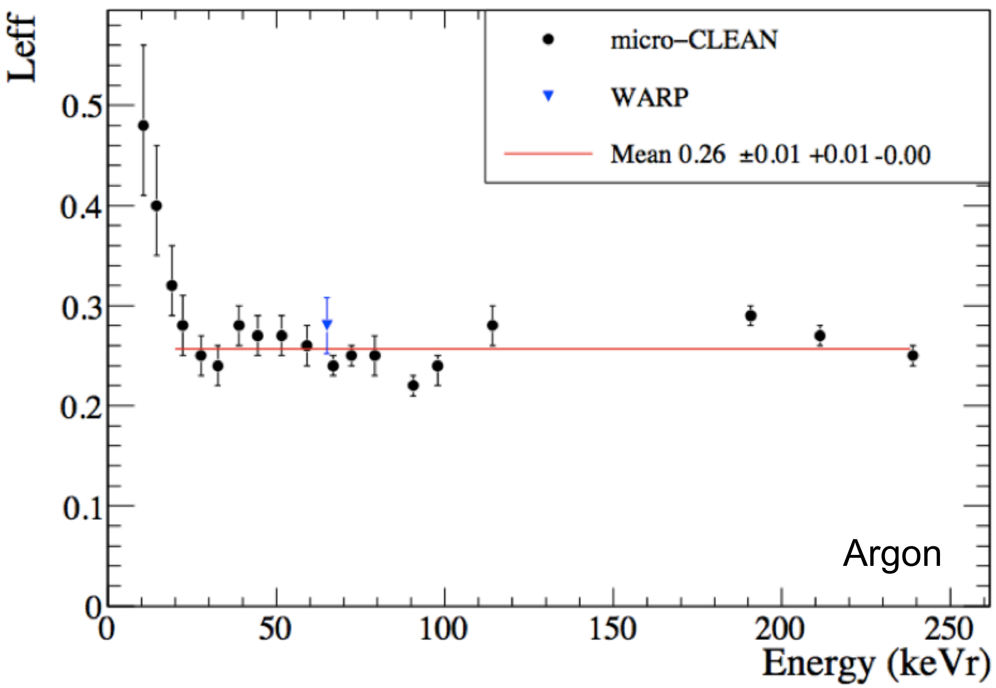


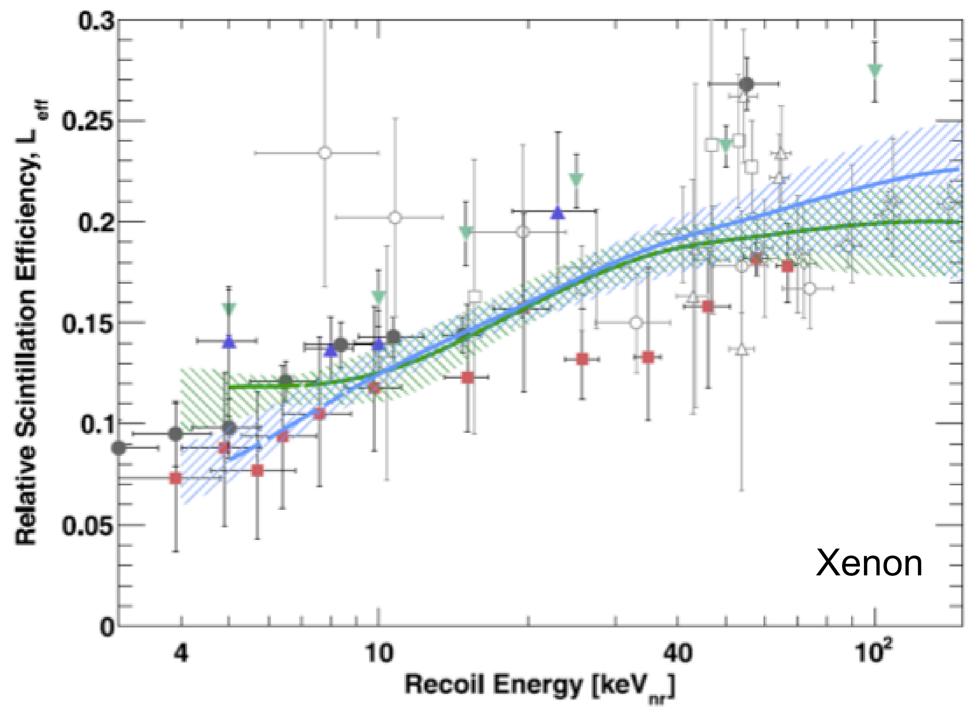
WARP - LAr



Liquid Noble Physics

- Relative scintillation yield measures quenching of scintillation in nuclear recoils compared to electron recoils
  - measured directly through dedicated mono-energetic neutron beam scattering tests, compared to gamma rays
  - also extracted from poly-energetic neutron source calibrations, compared to simulations



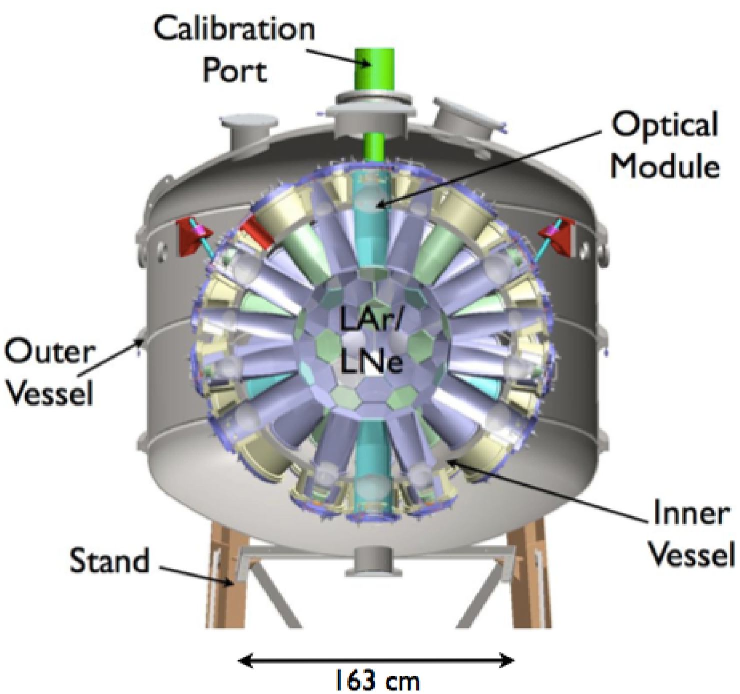


Properties of Noble Gas detectors

- Large mass targets possible
- Re-purification of target possible
- Fiducialisation against surface backgrounds
- High primary scintillation yield (40 photons/keV)
  - transparent to own light
- High ionisation yield (WLXe = 15 eV, WLAr = 24 eV)
- Position reconstruction capability
  - cm in single phase
  - mm in TPC mode, better in z
- Good particle identification
  - PSD & Ionisation/Scintillation ratio

MiniCLEAN Detector

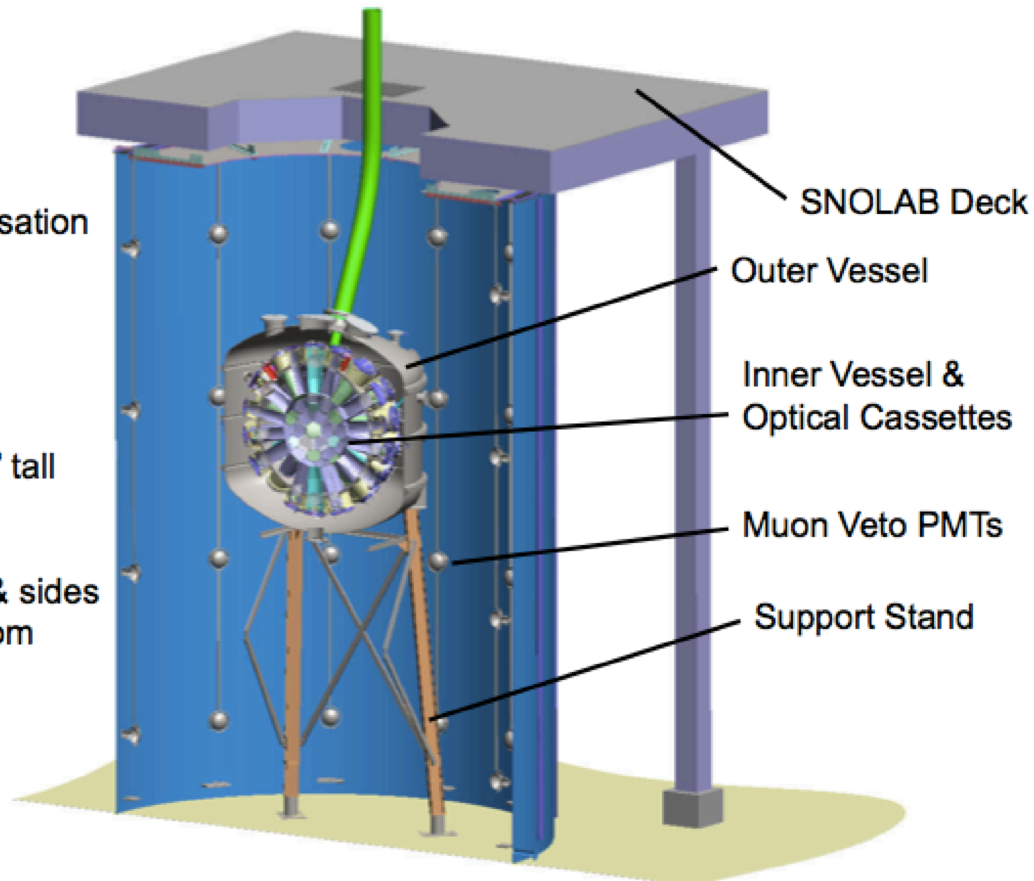
- Single phase LAr/LNe (solar neutrino capability)
- 180kg fiducial volume; PSD discrimination for background rejection
- Wavelength shifter on acrylic plugs
- PMT Cassette into steel vessel



Not Shown:
Magnetic Compensation
Process Systems
Cable Bundles

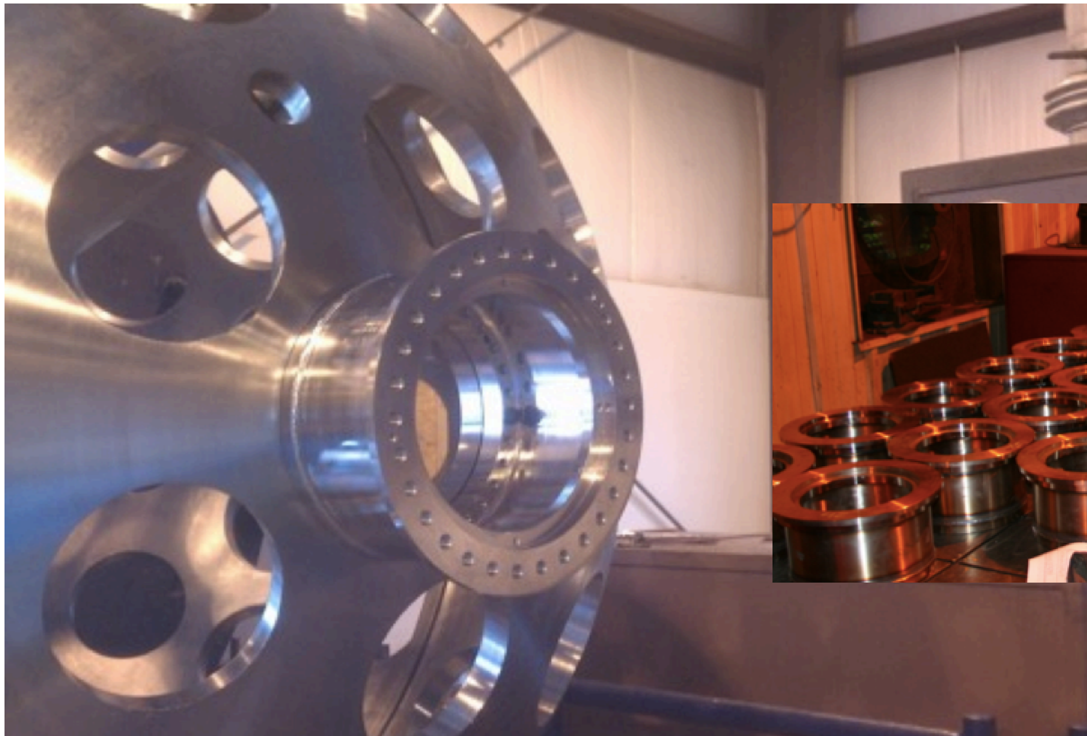
Tank 18' dia. x 25' tall
47,600 gallons

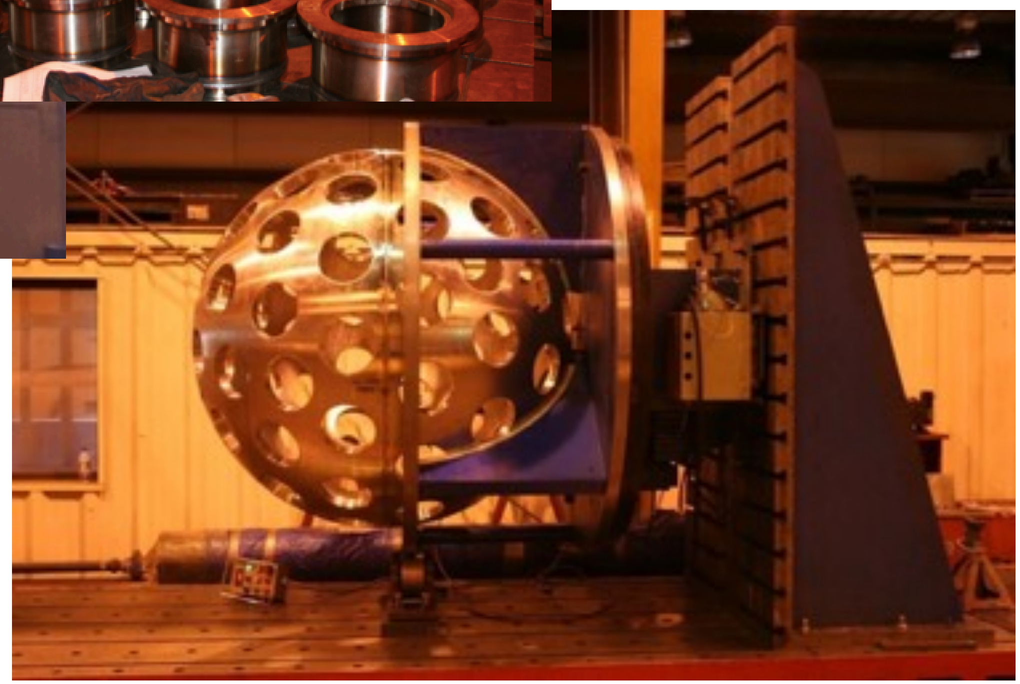
~1.5m water top & sides
~3.5m water bottom



MiniCLEAN Construction

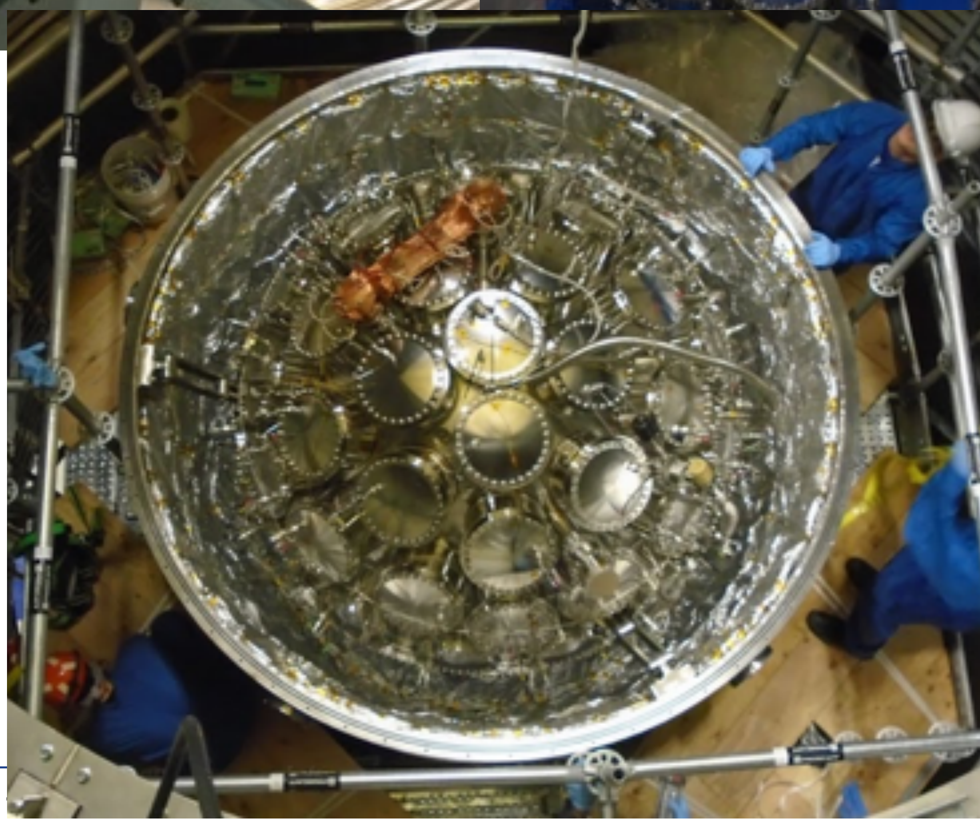
Flange assemblies for PMT cassette connections being produced and welded onto inner vessel

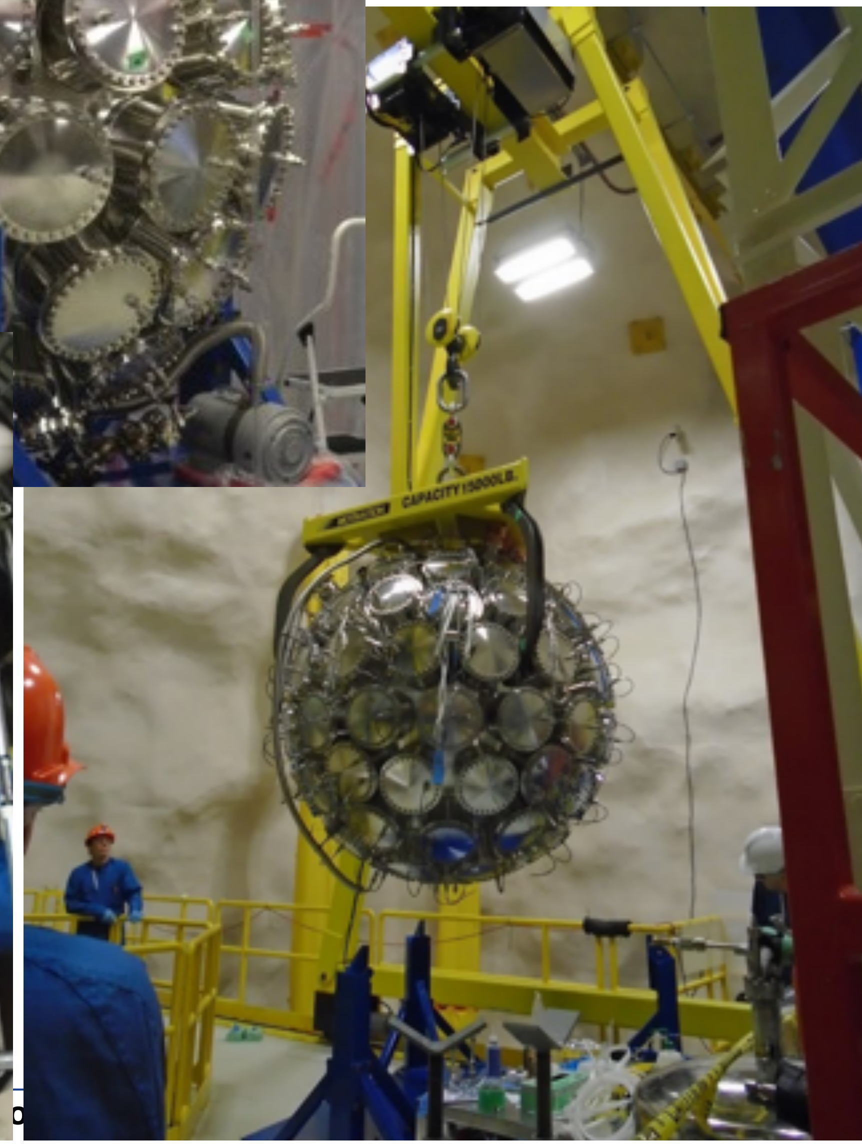




MiniCLEAN inner vessel final machining; PMT cassettes under construction

MiniCLEAN Construction

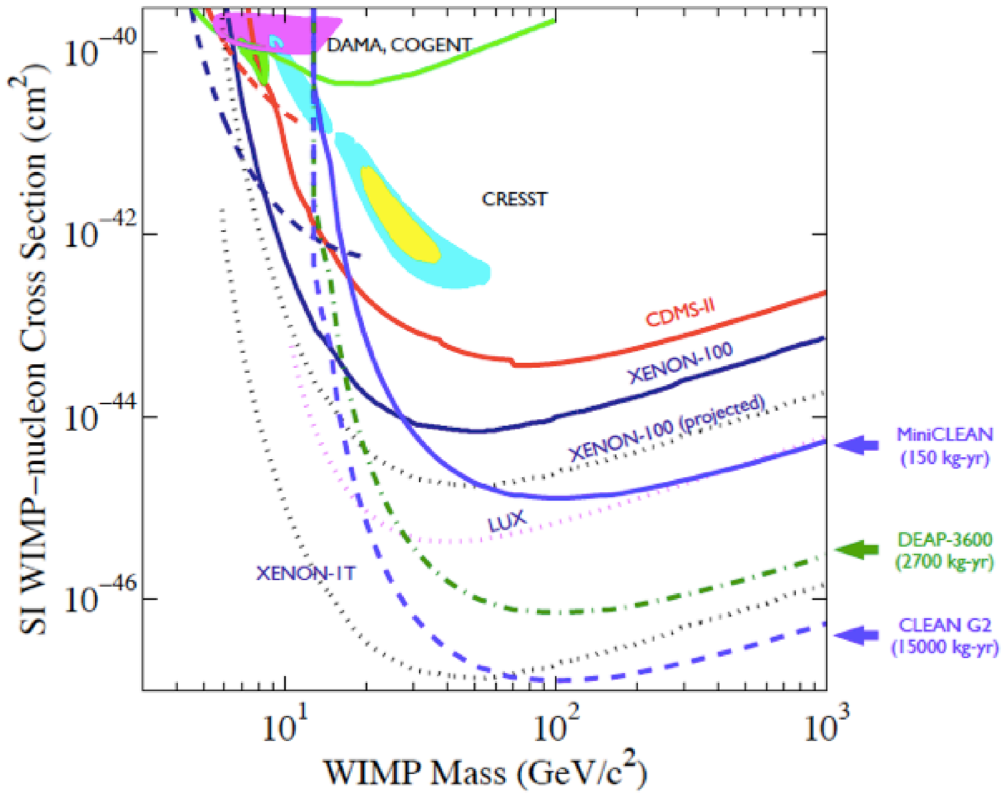




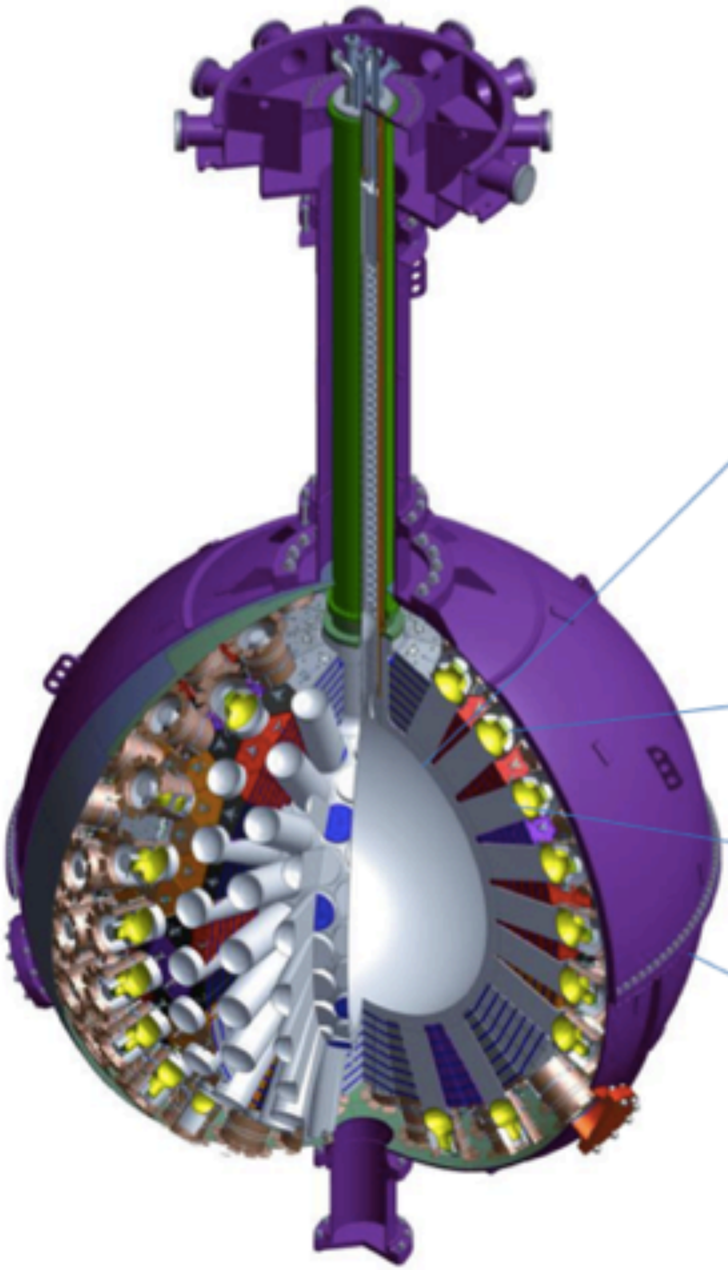
Backgrounds / Sensitivity

Event Selection	^{39}Ar	PMT (α, n)	Surface αs	γs
Raw rate	1 Bq/kg	42000 n/yr	10000 α/yr	1.4×10^{10} γ/yr
Energy between 12.5–25 keV_{ee}	4.2×10^8	352.2 ± 2.1	3360	6.0×10^6
Fiducial Volume Cut	1.2×10^8	91.6 ± 1.1	0.82 ± 0.09	3×10^5
F_{prompt} Cut	75 ± 1.1	7.1 ± 0.3	0.24 ± 0.05	<0.36
L_{recoil} or L_{alpha} Cut & KS test	0.3 ± 0.2	3.8 ± 0.2	0.14 ± 0.04	–
Tagging	–	0.9 ± 0.1		–
Total Background (events/year)	0.3 ± 0.2	0.9 ± 0.1	0.14 ± 0.04	< 0.36

- Upper limits based on simulation, natural argon, material assay limits, and radon daughter deposition of 1 alpha/m^2/ hour (goal is 1 alpha /m^2/ day)



DEAP-3600 Detector



DEAP-3600 Detector

3600 kg argon target
(1000 kg fiducial)
in sealed ultraclean
Acrylic Vessel

Vessel is "resurfaced"
in-situ to remove
deposited Rn daughters
after construction

255 Hamamatsu
R5912 HQE PMTs 8-inch
(32% QE, 75% coverage)

50 cm light guides +
PE shielding provide
neutron moderation

Steel Shell immersed in 8 m
water shield at SNOLAB

DEAP-3600 Background limits

SNOLAB

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	150	<0.2
^{39}Ar β's (natural argon)	1.6×10^{9}	<0.2
^{39}Ar β's (depleted argon)	8.0×10^{7}	<0.01

Neutrons: Acr+H_2O shield

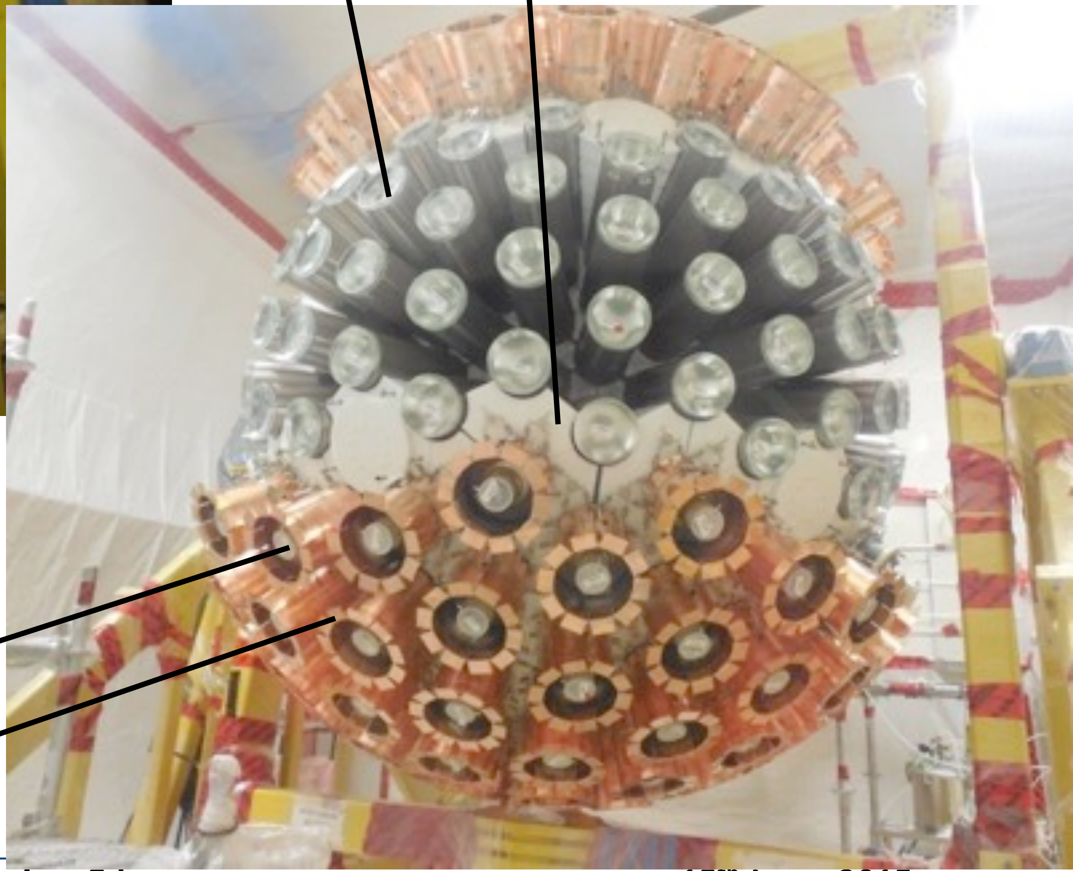
Surface α's: Resurfacer

^{39}Ar β's: PSD

→ Need to resurface inner vessel and ensure purity of acrylic.

Boulay

DEAP-3600 Construction



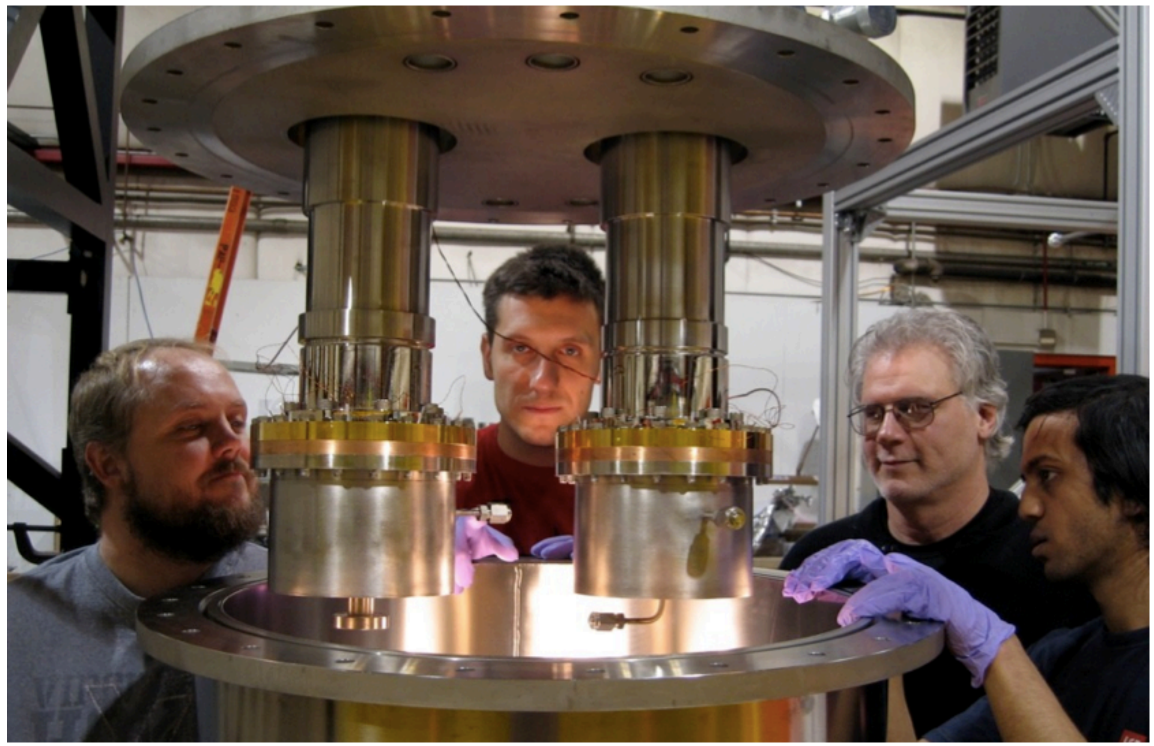
DEAP-3600

External containment vessel

Neutron water shield

Depleted Argon

- Cosmic ray production of ^{39}Ar in the atmosphere
  - Beta decay (565 keV; $T_{1/2}$ = 269 years)
  - Atmospheric argon has 8 x 10^{-16} $^{39}Ar/Ar$
  - Creates activity of 1 Bq/kg: limits size and sensitivity of detectors
- ^{39}Ar depleted Ar is available from deep reservoirs underground where cosmic ray production suppressed
  - Depletion of >100 observed
- 75 kg (of 110kg) collected
  - 0.5kg/day
  - Expansion to >10kg/day underway



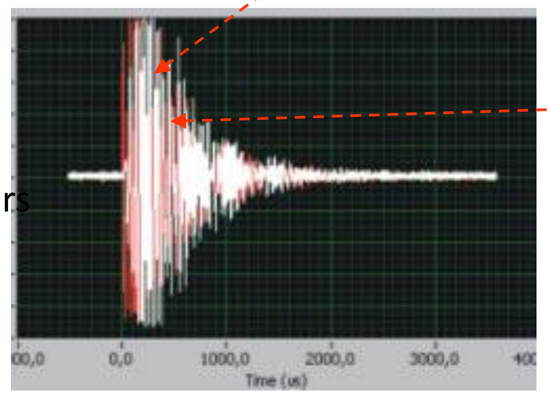
Cryogenic Extraction Column

PICASSO Technique

- 150 μm droplets of C_4F_{10} dispersed in polymerised gel *
- Droplets superheated at ambient T & P (T_b= - 1.7 ºC)
- Radiation triggers phase transition
- Events recorded by piezo-electric transducers
- Operating temperature determines energy threshold

Main attractive features:

- **low threshold 45ºC → E_{th} = 2 keV**
- **inexpensive! 0.19 k$/kg ($C_4F_{10}$)**
- **insensitive to γ - background**

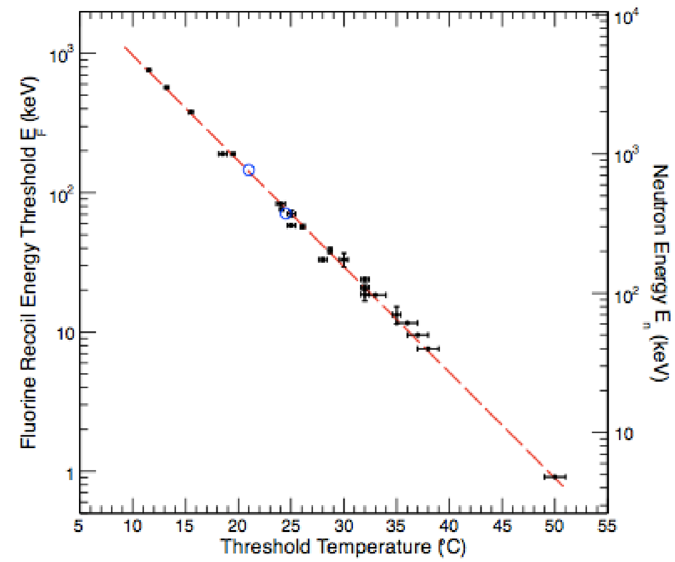


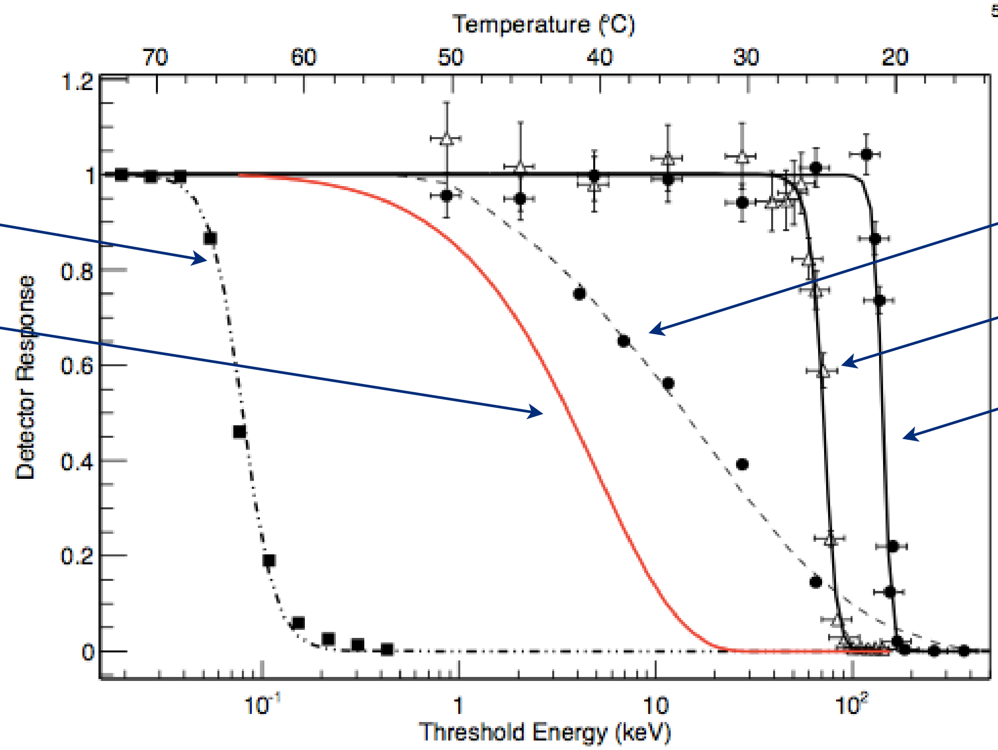
* Inspired by personal neutron dosimeters @ Bubble Technology Industries, ON

Slide from V.Zacek

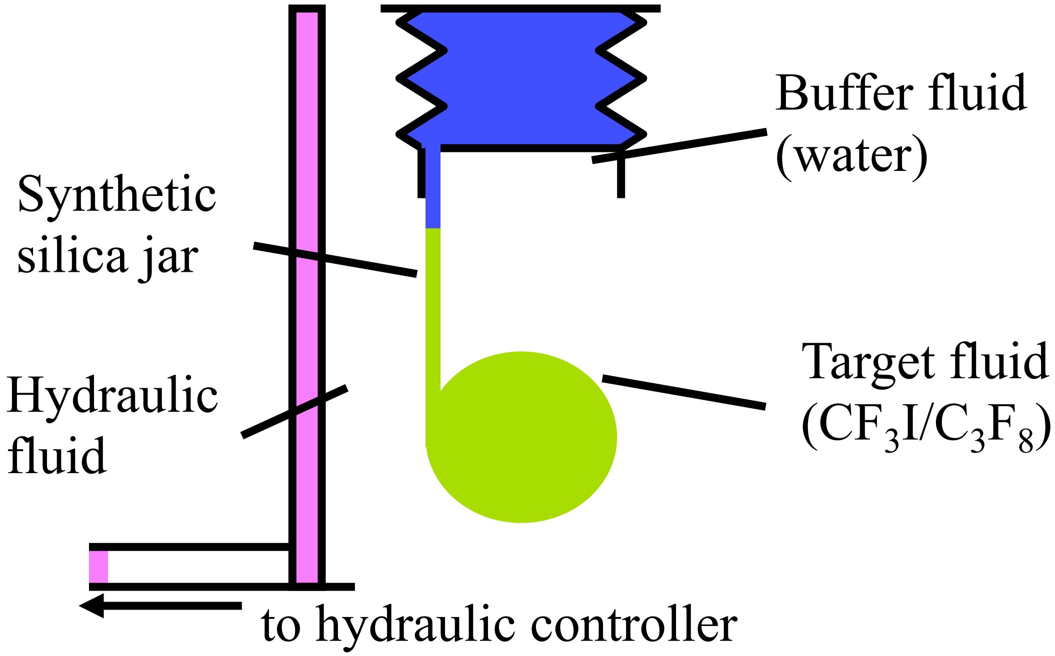
Detector response

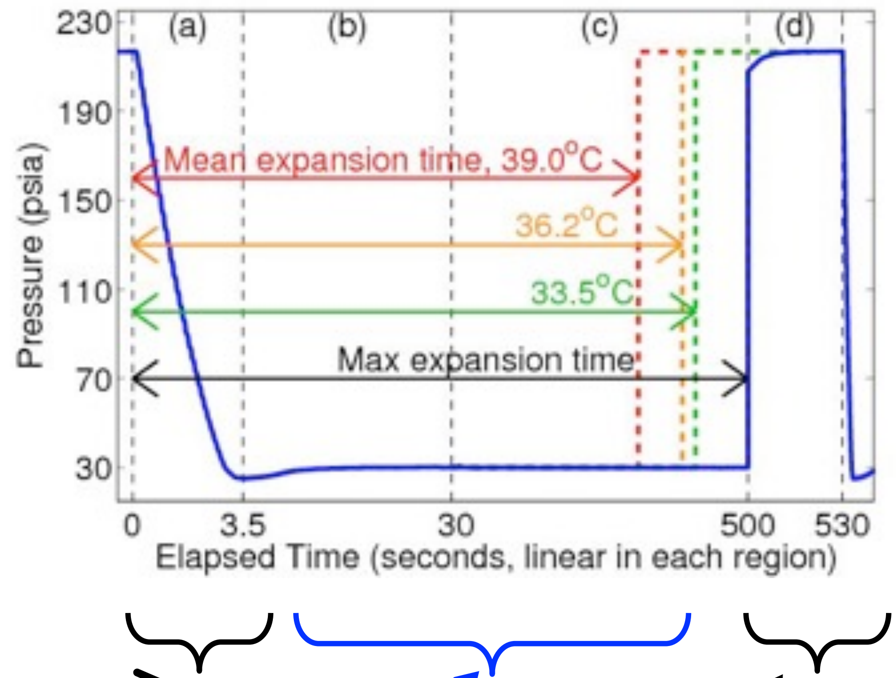
- Threshold detectors, depend on temperature
- Calibrate detector response for various incident species
  - mono-energetic neutron beams
  - poly-energetic neutron sources
  - alpha/nuclear recoils





Principle of Operation: Bubble Chamber





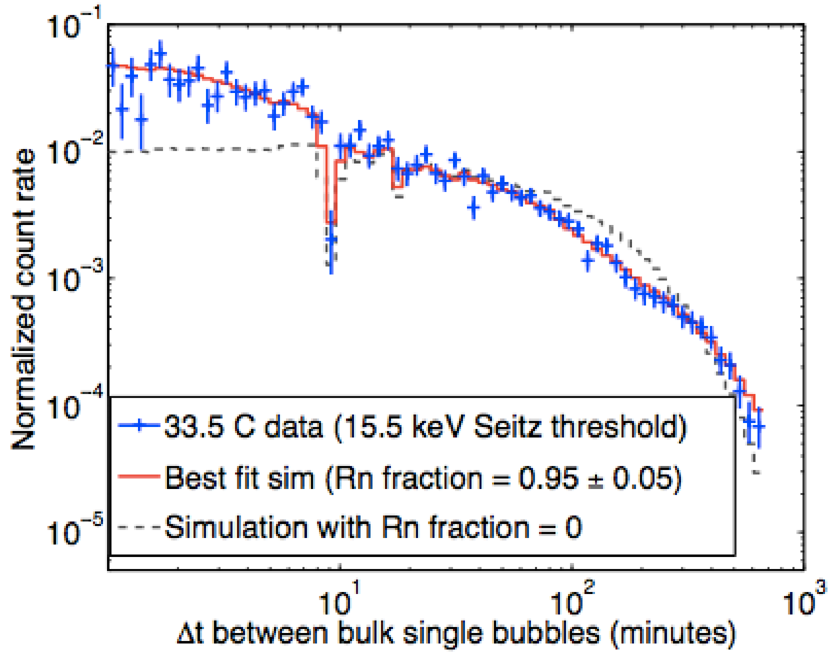
1. Lower the pressure to a superheated state.

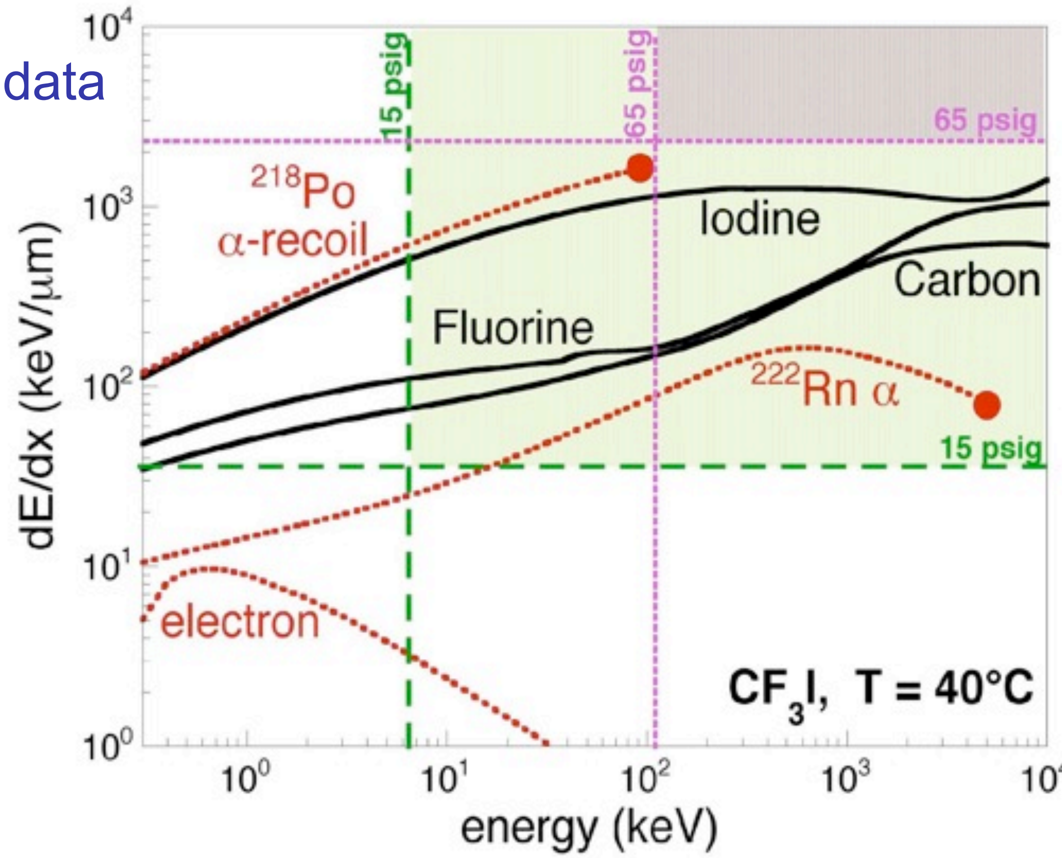
2. See the bubble:
   - Cameras trigger. record position, multiplicity
   - Microphones record acoustic trace
   - Fast pressure transducer recording.

3. Raise pressure to stop bubble growth (100ms), reset chamber (30sec)

COUPP: bubble nucleation

- Target material CF_3I
  - provides spin dependent (F) and spin independent (I) sensitivity
- Energy threshold determined from Seitz 'hot-spike' model of bubble nucleation
  - benchmarked against calibration data
  - alphas used as a cross check

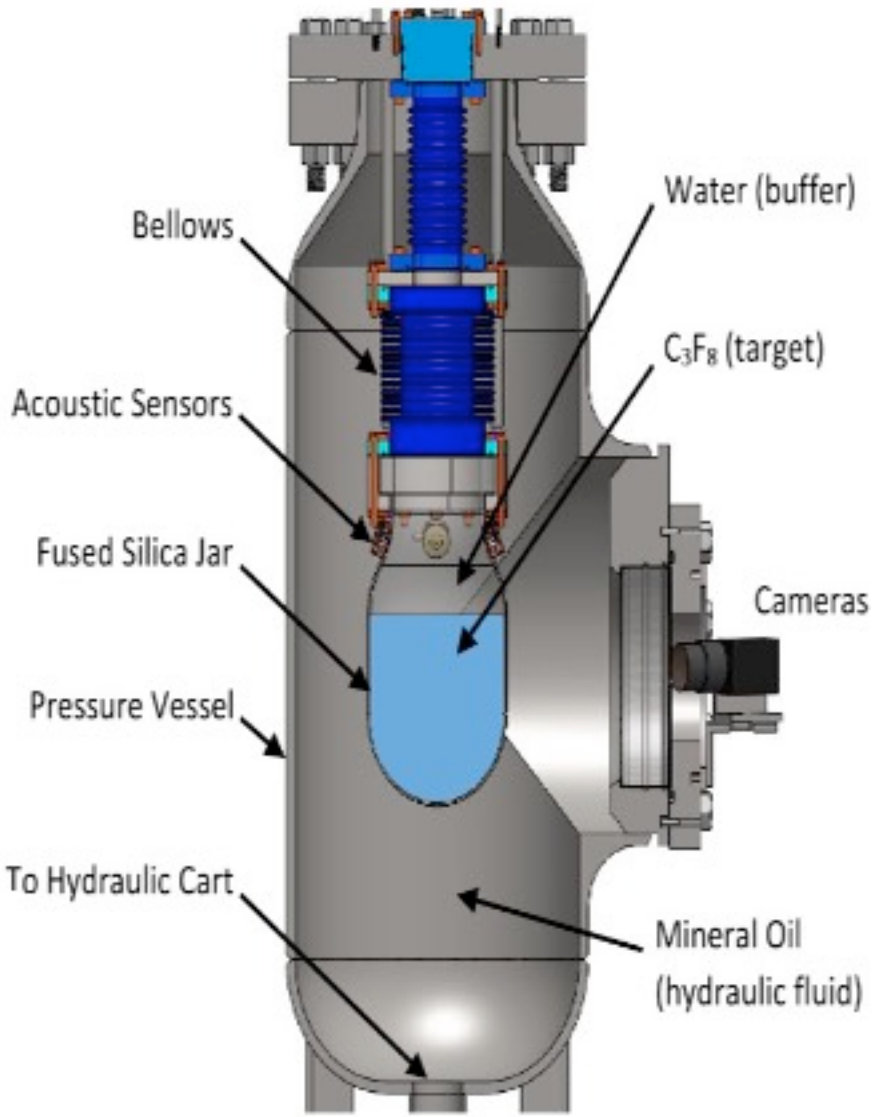




PICO-2L

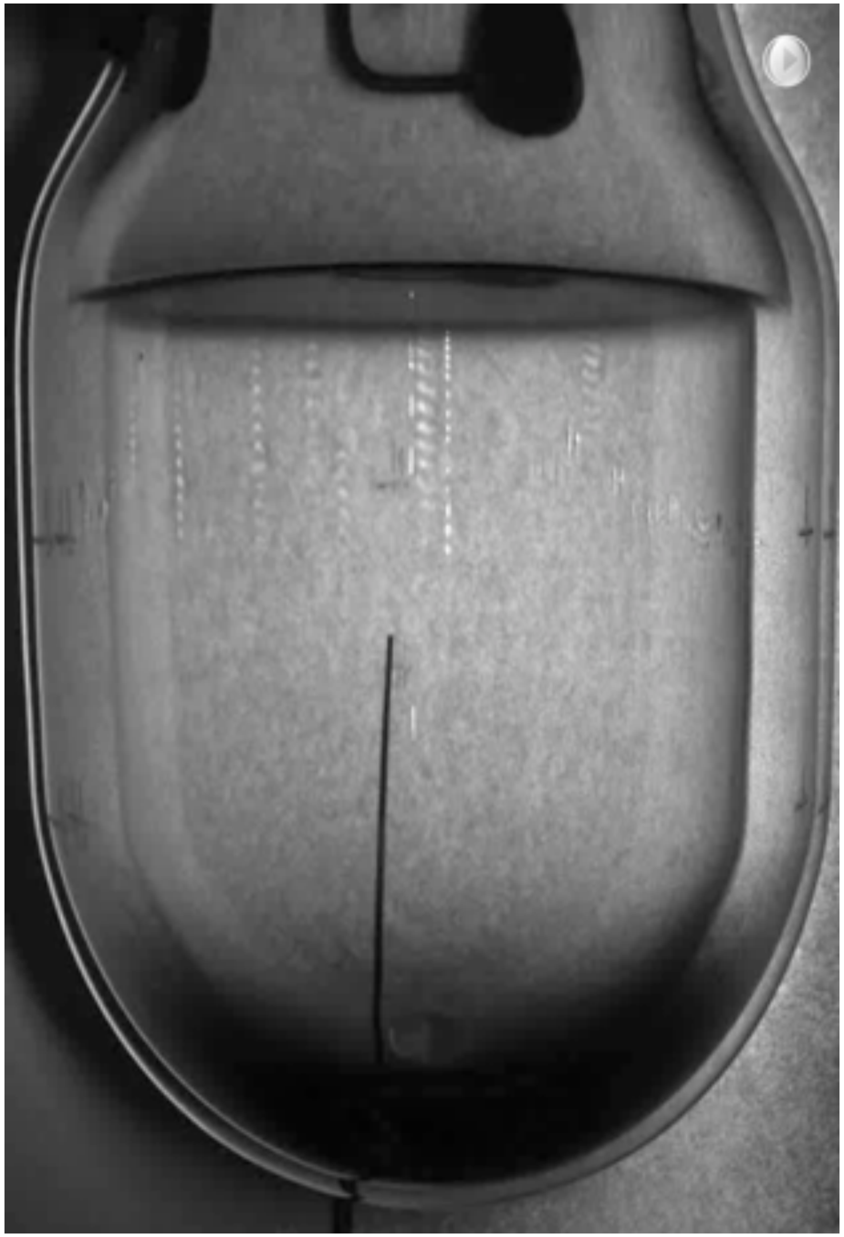
First joint PICO detector: a 2-litre detector filled with C_3F_8

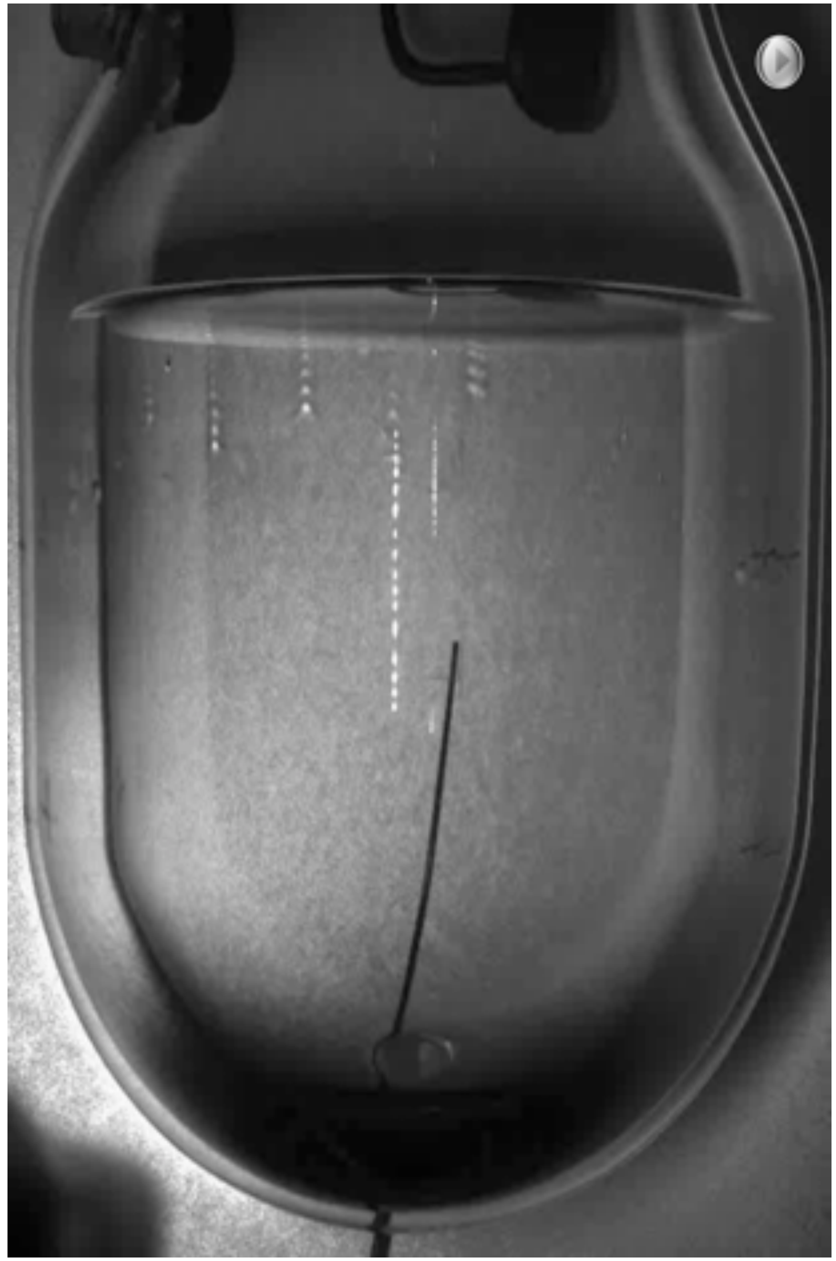
C_3F_8 has better fluorine sensitivity, lower threshold, more stable chemistry



PICO-2L bellows & inner vessel assembly

PICO-2L pressure vessel





PICO-60

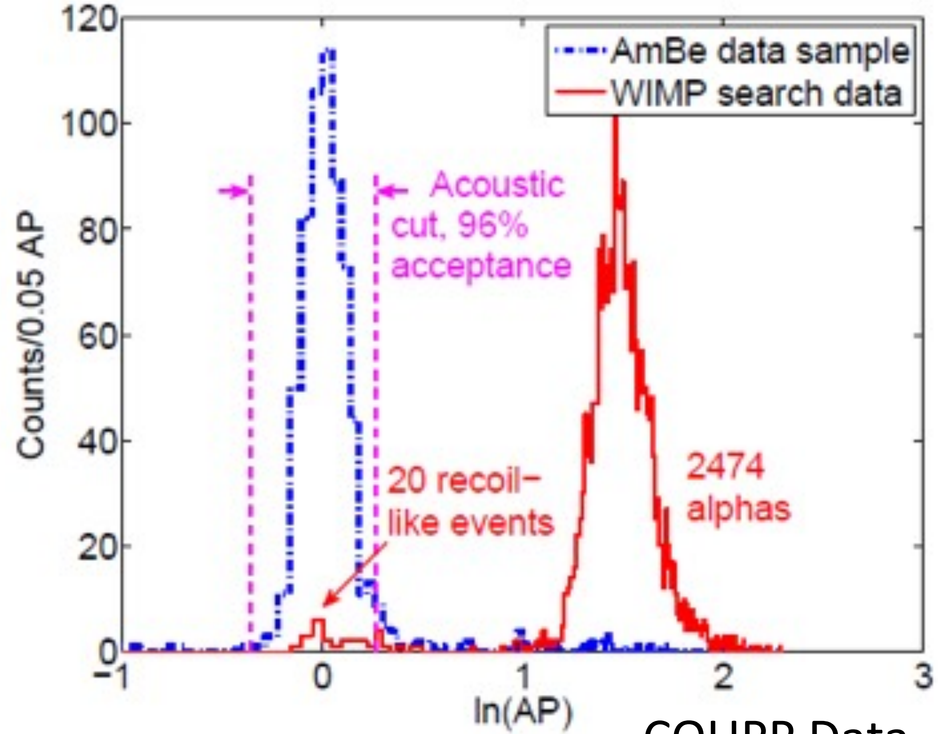
PICO-60 installation in water tank at Snolab

PICO-60 Pressure vessel inside the water tank at Snolab

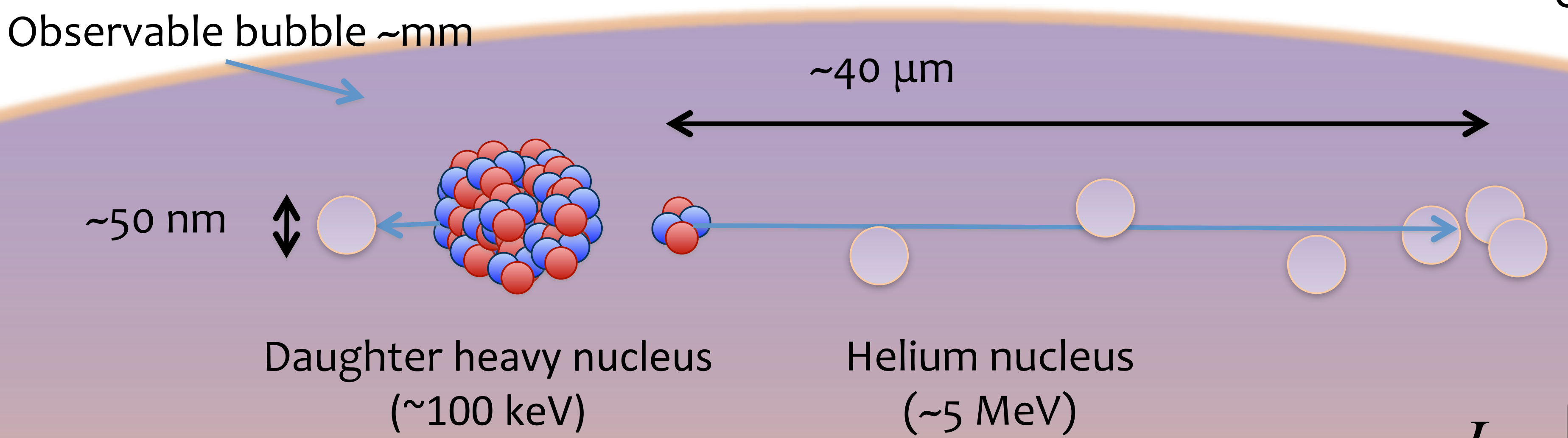
PICO-60 inner vessel preparation

Alpha Acoustic Discrimination

- Discovery of acoustic discrimination between recoils and alphas in PICASSO (Aubin et al., New J. Phys.10:103017, 2008)
  - **Nuclear recoils** deposit their energy over tens of nanometers.
  - **Alphas** deposit their energy over tens of microns.
- In bubble chambers alphas are several times louder due to the expansion rate difference.



COUPP Data



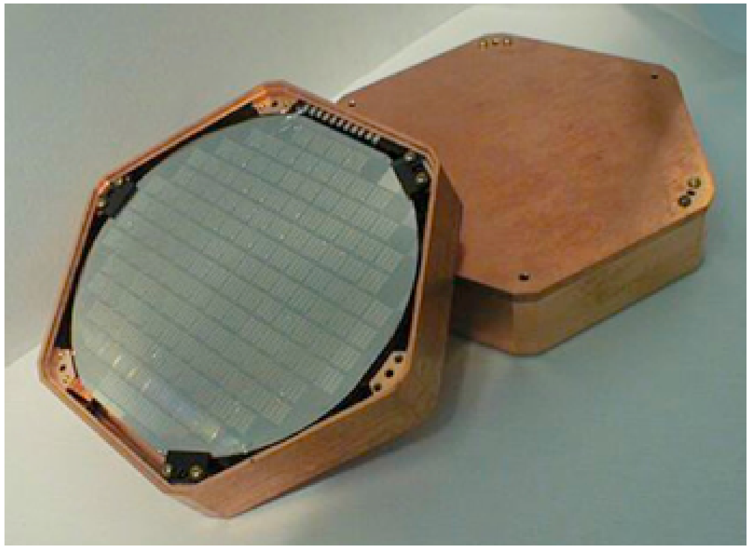
$$I = \frac{\rho \ddot{V}^2}{4\pi c}$$

A.J.Noble (IPP Review)

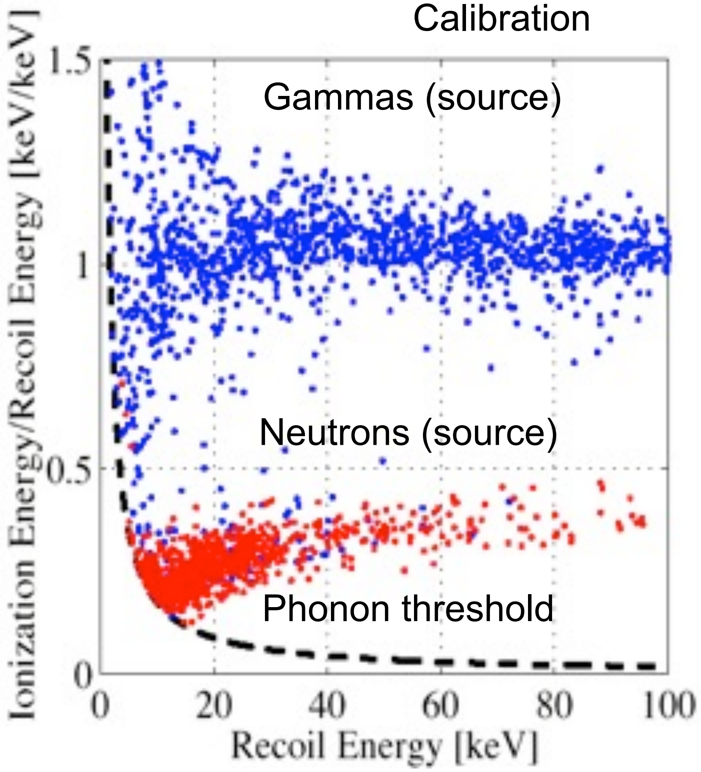
The CDMS-II Detectors

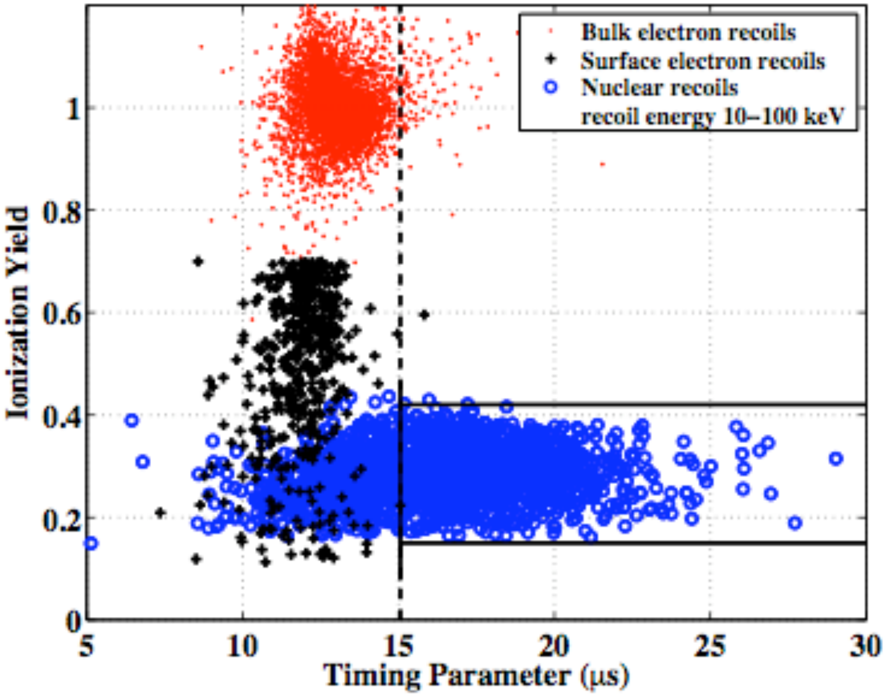
CDMS Collaboration

- Discrimination through
  - recoil E (Heat), ionisation, timing
  - TE tungsten athermal phonon sensors
- Guard ring, x-y sensitive, close packing
- ~ton.d exp.@ Soudan (4.8kg Ge 1.1kg of Si)



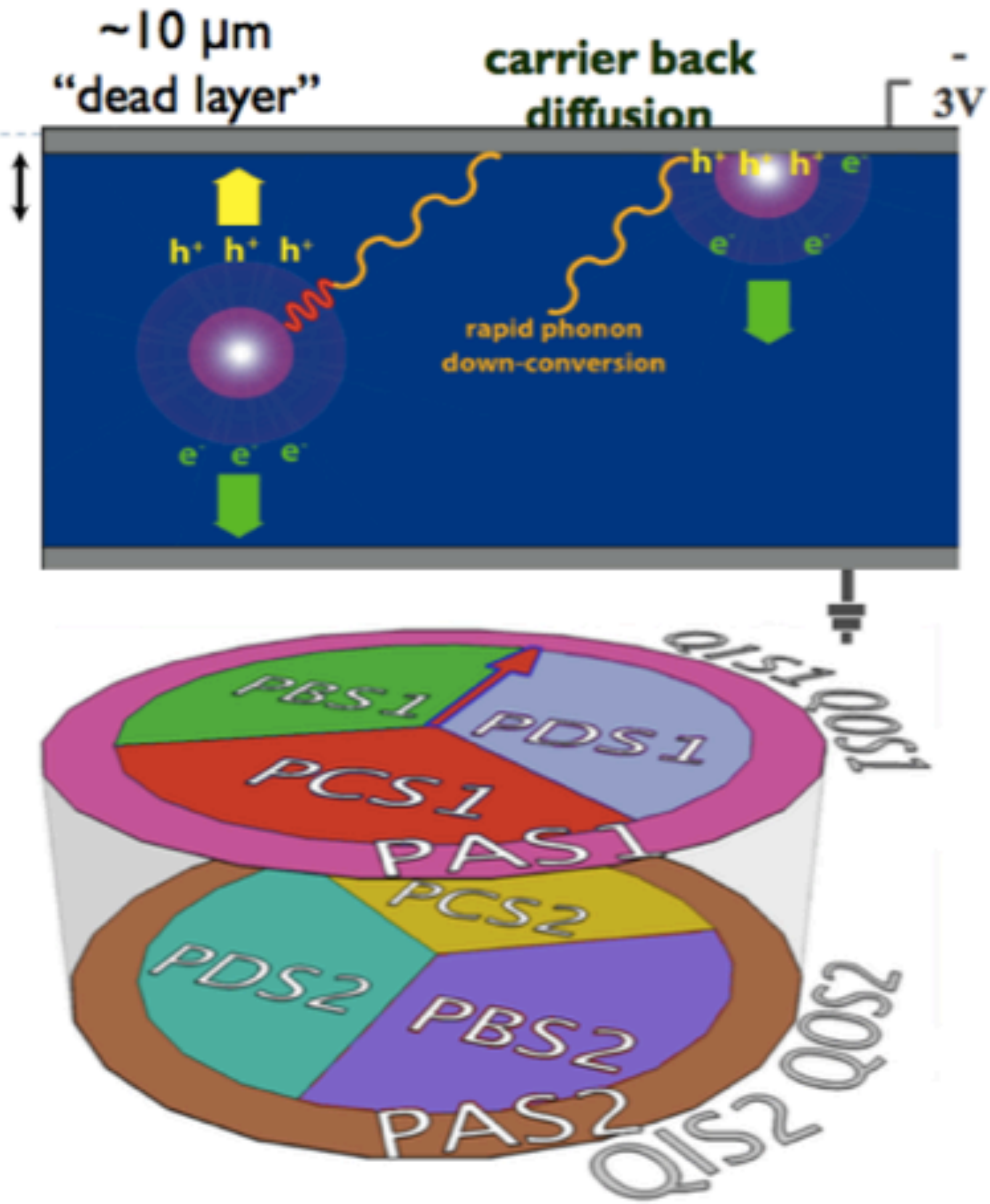
Calibration





SuperCDMS iZIPs

- Ultrapure Ge and Si crystals operated at ~40 mK
- Read out athermal phonon and charge signals
- Phonons give total energy
- Ratio of charge/phonon discriminates bulk gamma and nuclear recoil events
- Outer charge and phonon rings remove outer surface events
- Interleaved 2-sided charge sensors remove face events



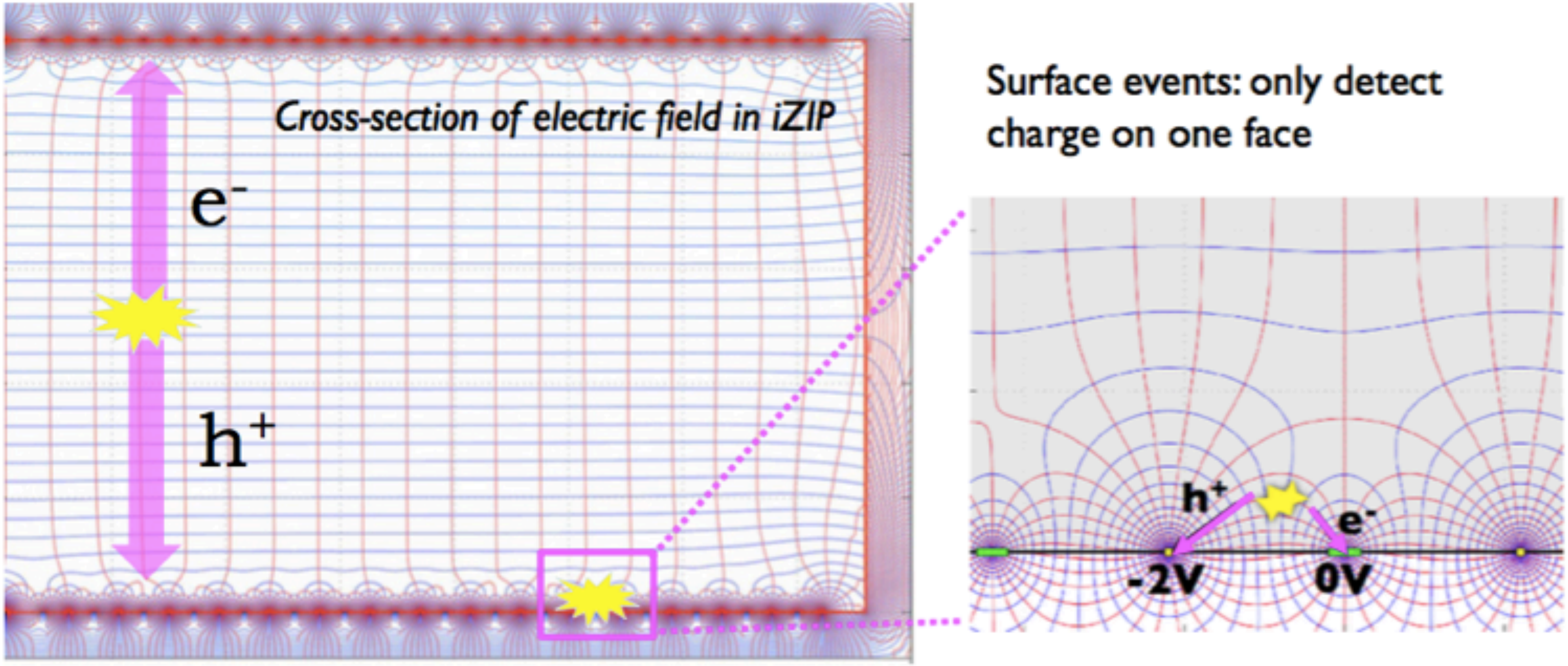
SuperCDMS Soudan: 8 phonon, 4 charge chans
SuperCDMS SNOLAB: 12 phonon, 4 charge

Loer

SuperCDMS iZIP surface rejection

iZIP: *I*nterleaved phonon and charge sensors on both sides

Bulk events: charge collected on both iZIP faces



iZIPs have > 30X better surface event rejection w/ 50% better efficiency to WIMPs compared to CDMS-II ZIPs!

Loer

Advanced Instrumentation

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- Challenges include
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  - High efficiency detection (single photon/phonon)
  - Particle discrimination (esp. neutrons and alphas)
- Techniques developed include
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- Common requirements for the programme include
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  - Low radiological background environments (Chris Jillings)