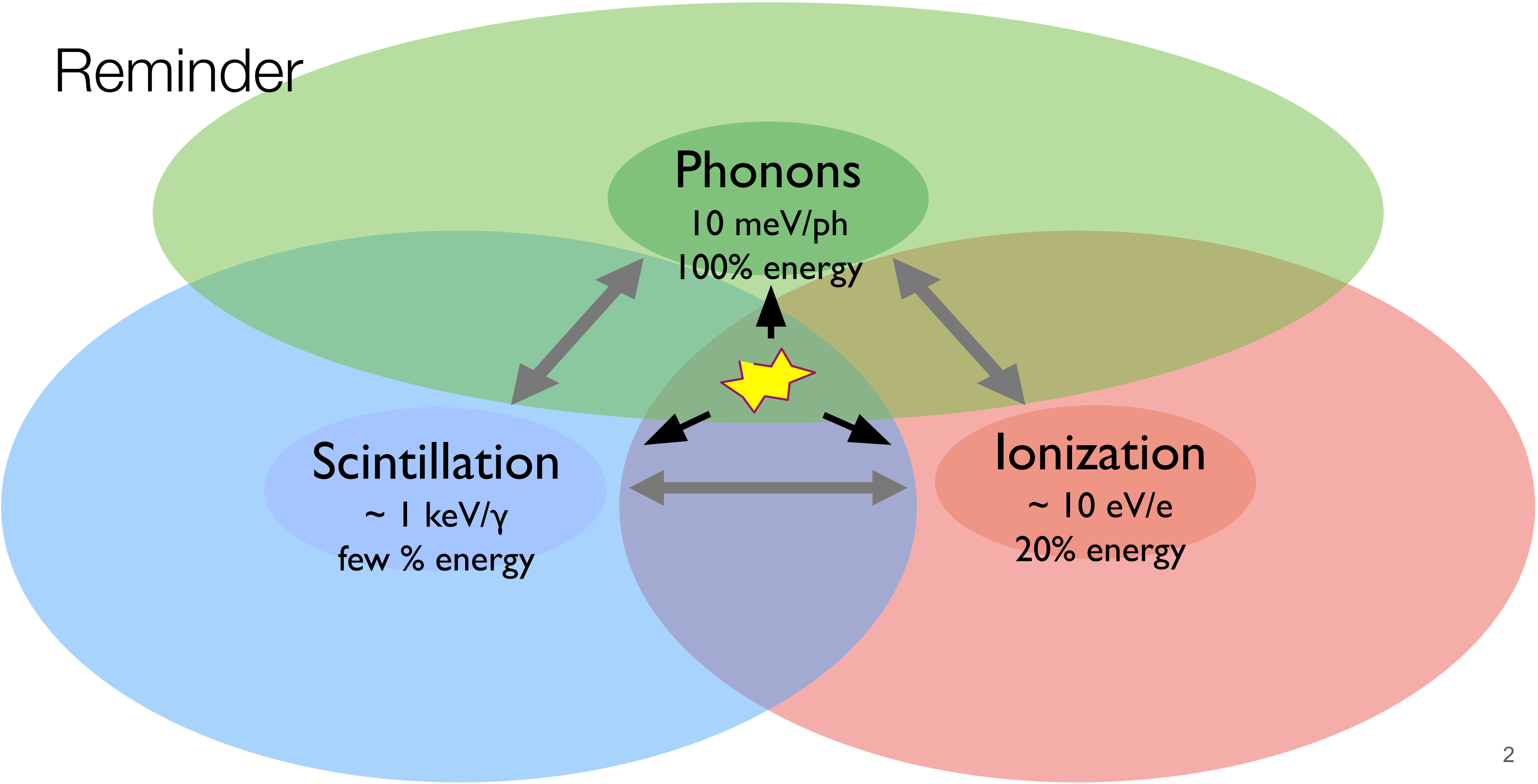
Other Rare Event Detectors

-- Other than SuperCDMS…

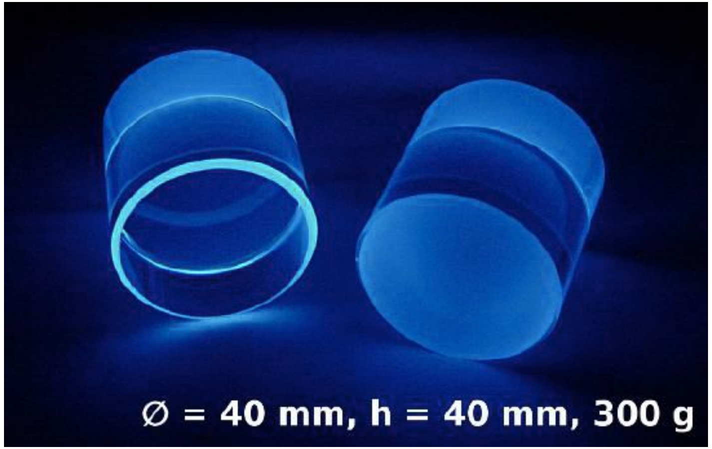
Reminder

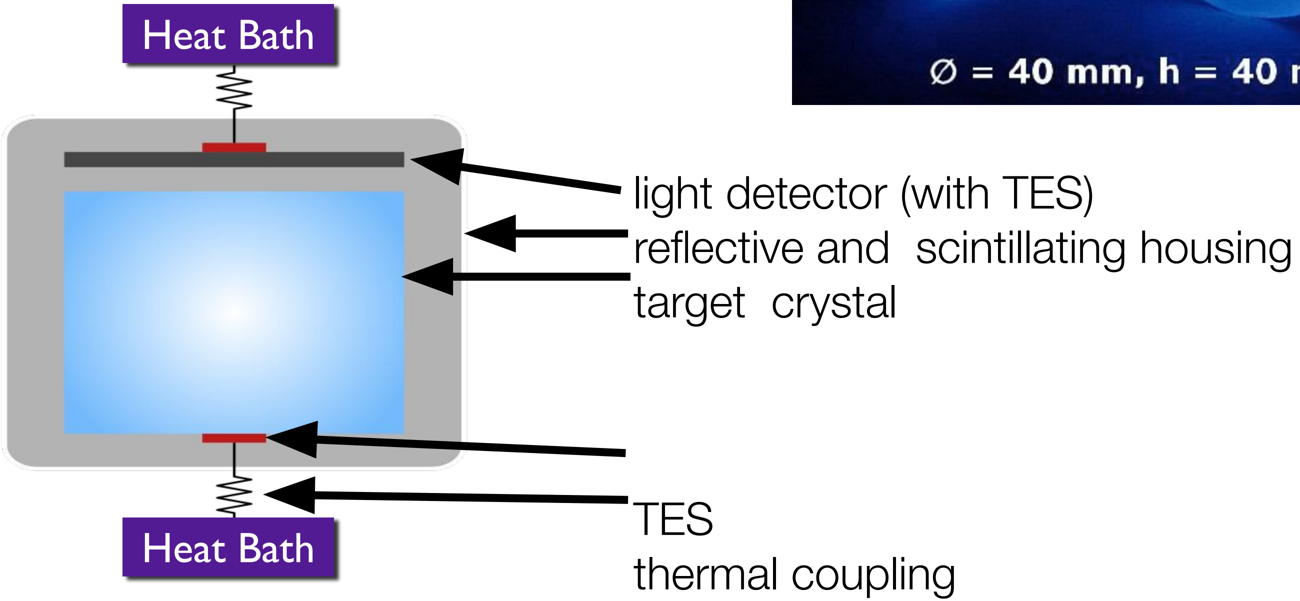


Phonons
10 meV/ph
100% energy
Scintillation
~ 1 keV/γ
few % energy
Ionization
~ 10 eV/e
20% energy

CRESST

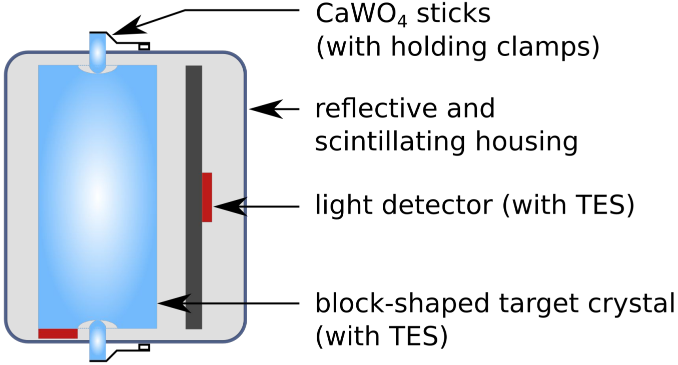
- CRESST: phonon + light
- Thermal TES sensors

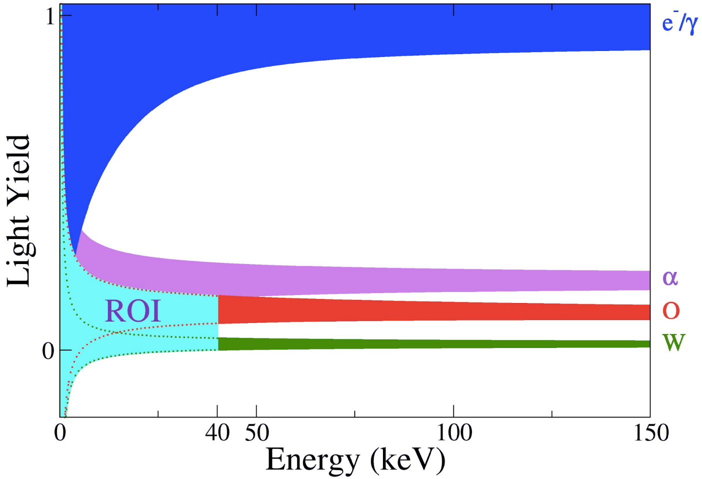




CRESST

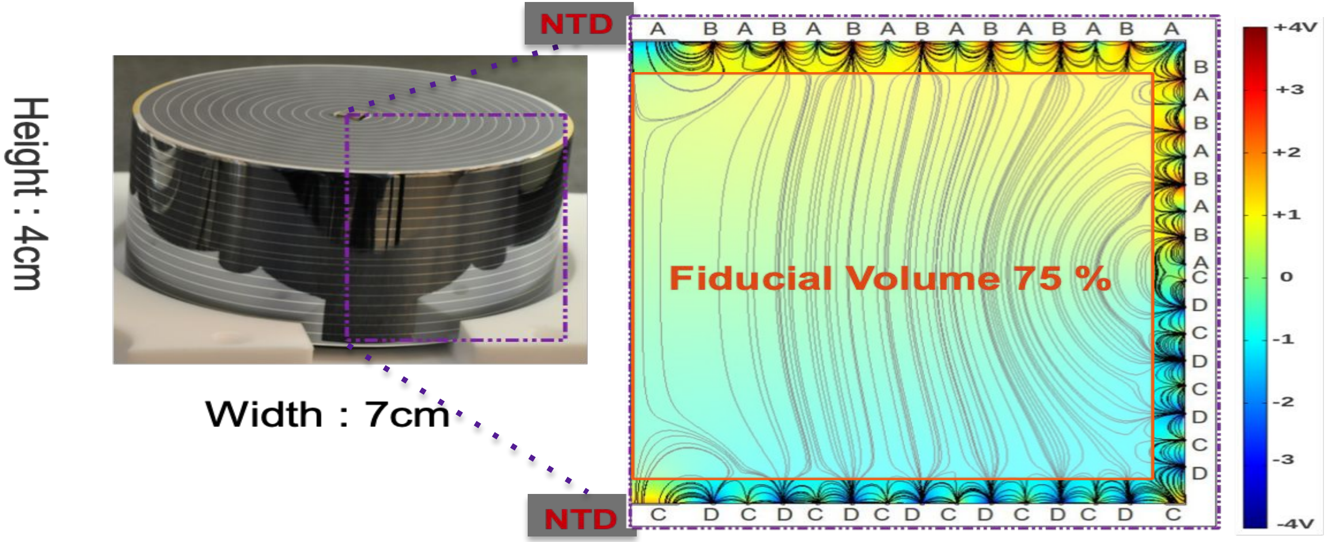
- CRESST III detectors focused on low-mass WIMPs
- Design Goal: Threshold of 100 eV. How? Smaller Crystals!
- Going from 250g in CRESST II to 24g in CRESST III





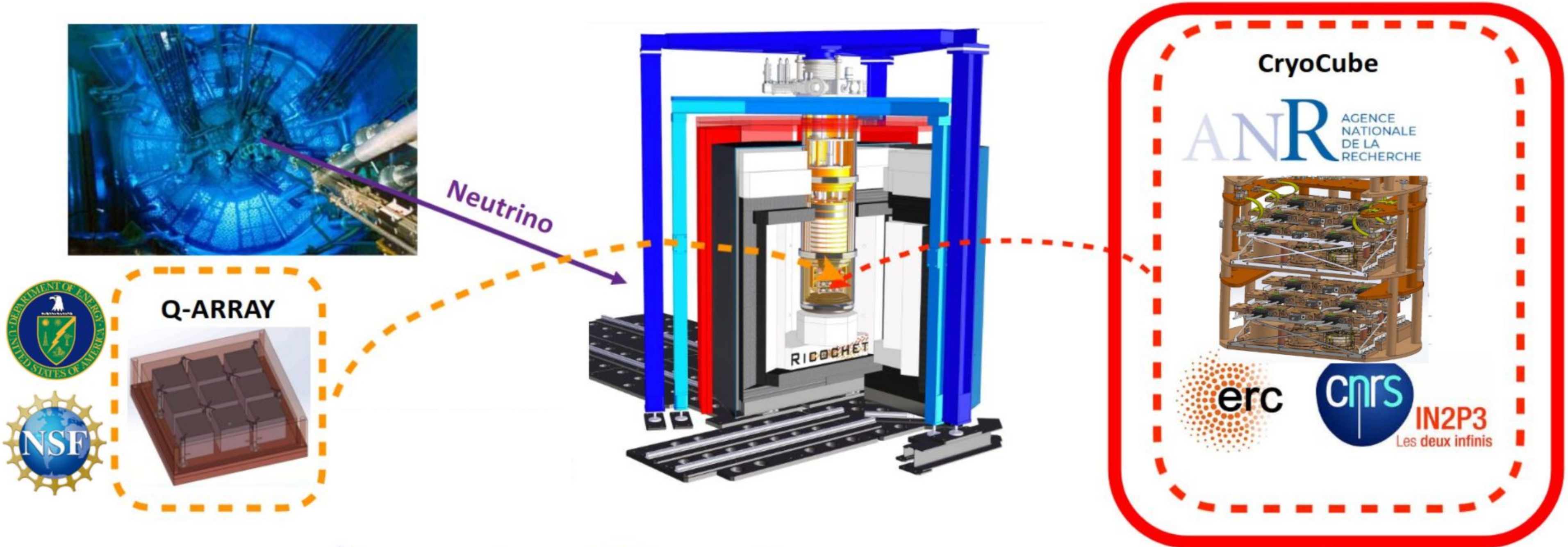
EDELWEISS

- EDELWEISS: phonon + charge
- 36 x 800 g detectors
- “Fully Inter-Digitized” charge sensors -- instrumented on the sidewalls
- NTD as heat sensor -- thermal detector



Slide from Nicolas MARTINI, Magnificent CEvNS, 2024

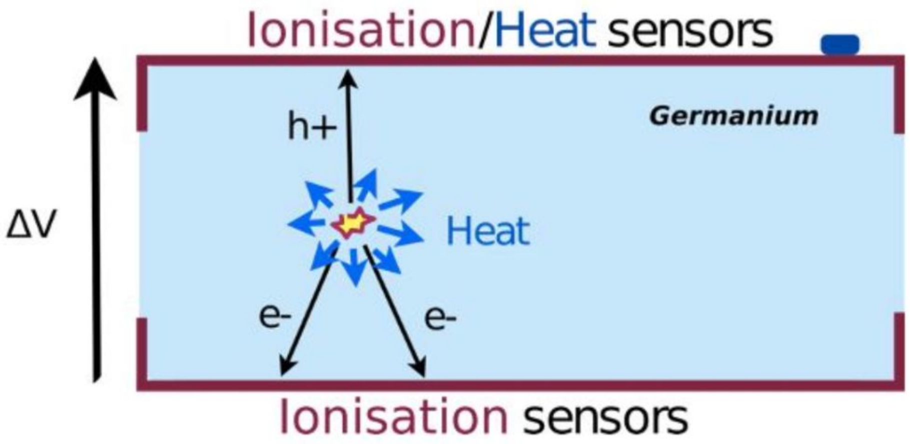
RICOCHET: a reactor neutrino observatory



MIT UMASS AMHERST UNIVERSITY OF TORONTO C2N Northwestern University ILL IJCLab Irène Joliot-Curie NÉEL iP2i LPSC Grenoble

Slide from Nicolas MARTINI, Magnificent CEvNS, 2024

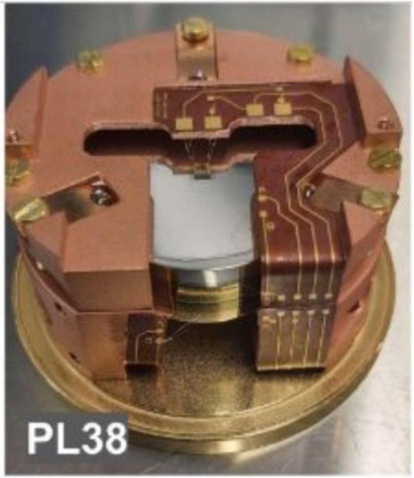
CryoCube detectors



Particle ID based on **Ionization/Heat** ratio

$Q = E_{ion}/E_{recoil}$

- Electronic recoils : Q = 1
- Nuclear recoils : Q ~ 0.3 (Lindhard)



Planar :
Fiducial volume = 98.6%

No surface events rejection

FID :
Fiducial volume = 62%

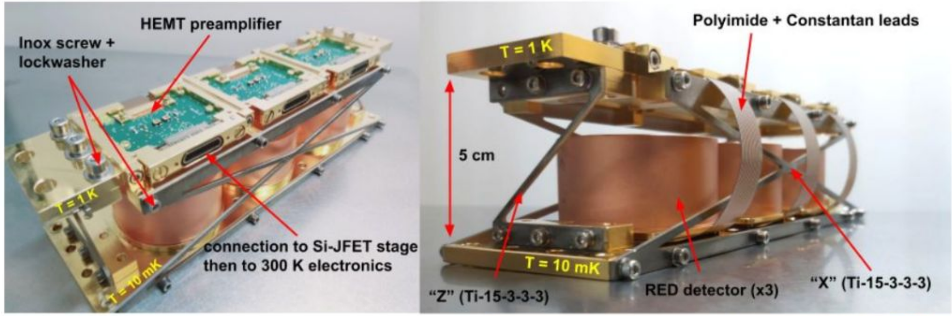
Surface events rejection

Final detector design will be based on on-site data-driven CEvNS sensitivity

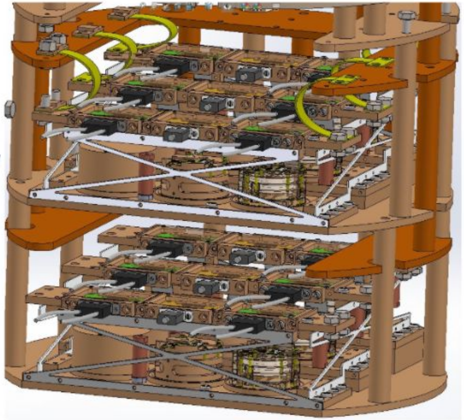
Slide from Nicolas MARTINI,
Magnificent CEvNS, 2024

CryoCube specifications

MiniCryoCube:
3 Ge bolometers with their cold electronics (1 K)



CryoCube (Spring 2025):
3 MiniCryoCubes per level,
2 levels
→ **Array of 18 x 38 g**
@ ~10 mK



- Heat resolution:
  20 eV (RMS)
- Ionization resolution:
  20 eVee (RMS)
- Timing resolution:
  ~100 us @ 100 eV
- Detector payload:
  680 g
- Two detector technologies:
  planar and FID electrodes

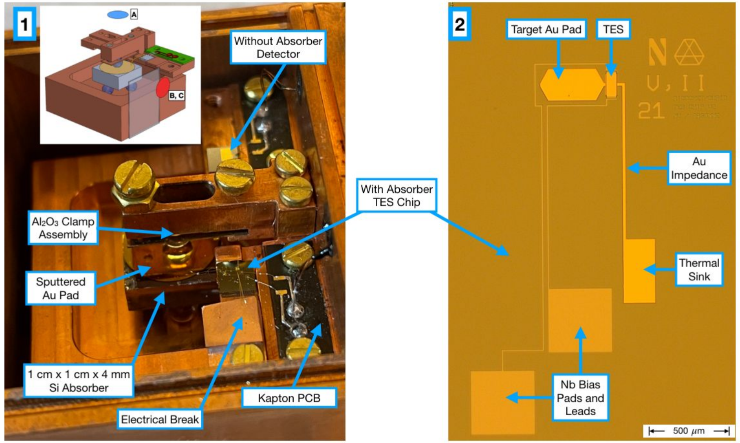
→ **Achieve Particle ID down to O(10) eV with a rejection > 10^3**

Paper on Ionization performances of the MiniCryoCube:
RICOCHET Coll. EPJC **84** (2024), 186

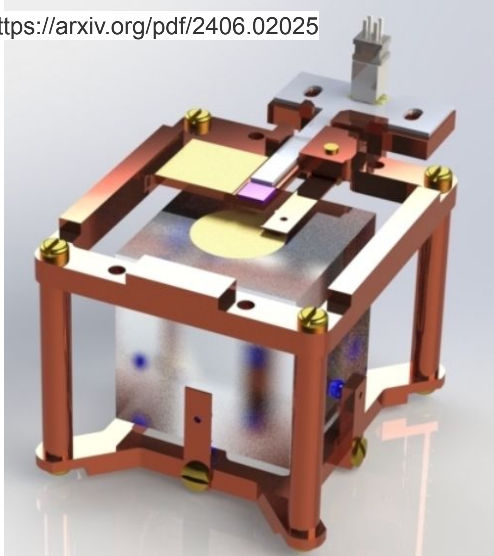
NIM A 1057 (2023) 168765

Modular TES detector

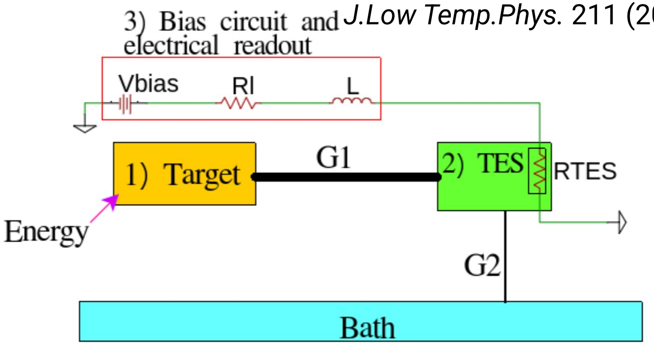
- Thermally couple a TES thermometer onto an arbitrary target
- Target can be almost any solid: semiconductor, metal, superconductor, etc
  - **12 eV** resolution achieved on 1 gram silicon
  - **0.85 keV** resolution on 21 gram Li_2**Mo**O_4
    - **Excellent detector also for neutrinoless double beta decay!**
- Further improvements to come



https://arxiv.org/pdf/2406.02025



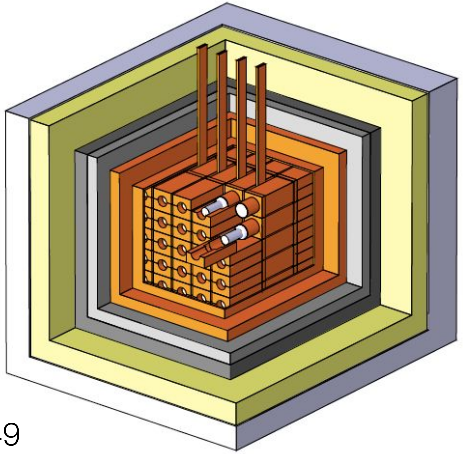
J.Low Temp.Phys. 211 (2023) 5



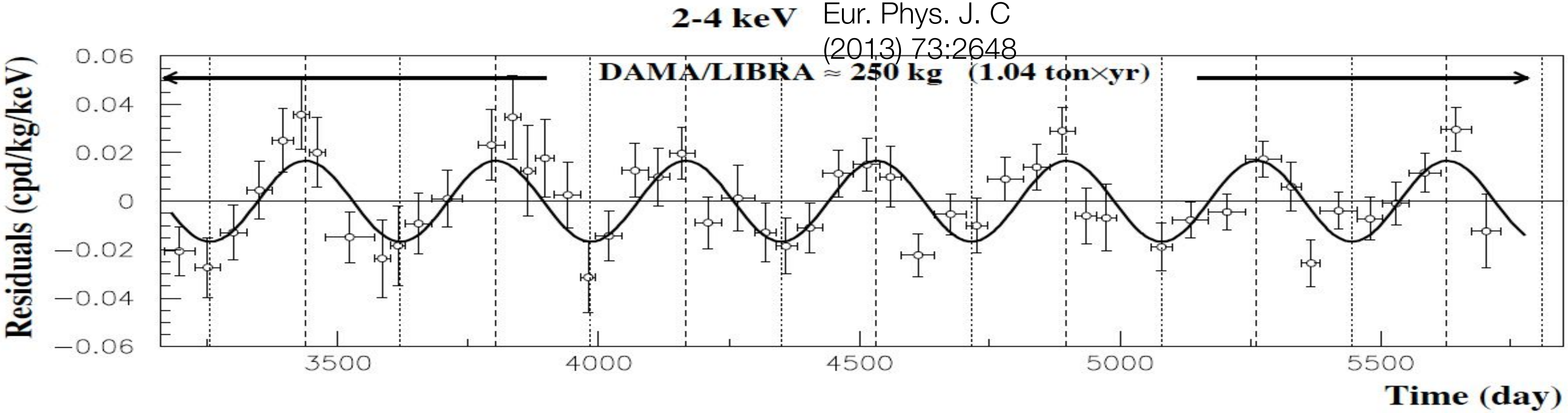
DAMA/LIBRA Experiment

Have we already detected dark matter?

- Using an array of 25 radiopure NaI(Tl) crystals, DAMA/NaI reported an annual modulation in event rate consistent with dark matter, observed over 7 annual cycles.



Eur. Phys. J. C (2010) 67: 39–49
Eur. Phys. J. C (2013) 73:2648



Checking DAMA with NaI Detectors

Northern Hemisphere	Gran Sasso **DAMA/LIBRA** 250 kg running	Boulby **DM-Ice North** 37 kg R&D 250 kg planned	Canfranc **ANAIS** 37 kg R&D 250 kg planned	Y2L **KIMS** 45 kg R&D 200 kg planned	Gran Sasso **SABRE** R&D	Kamioka **PICO-LON** **KamLAND-PICO** R&D
Southern Hemisphere		South Pole **DM-Ice** 17 kg running 250 kg planned			Stawell **SABRE** Lab completion 2017	rock ice

Ultra-pure crystal development underway by DM-Ice, KIMS, ANAIS, SABRE, and PICO-LON collaborations

South Pole offers:

- Ultra-clean and ultra-stable environment
- Seasonal variation unambiguously different from dark matter modulation
- IceCube offers muon monitoring and veto as well as experience
- NSF-run South Pole Station for logistical support

Note: Annual Modulation is also being looked for with other detector technologies!

DM-ICE 17

Location: South Pole, Antarctica

Depth: 2457 m (2200 m.w.e)

Deployment: Dec. 2010

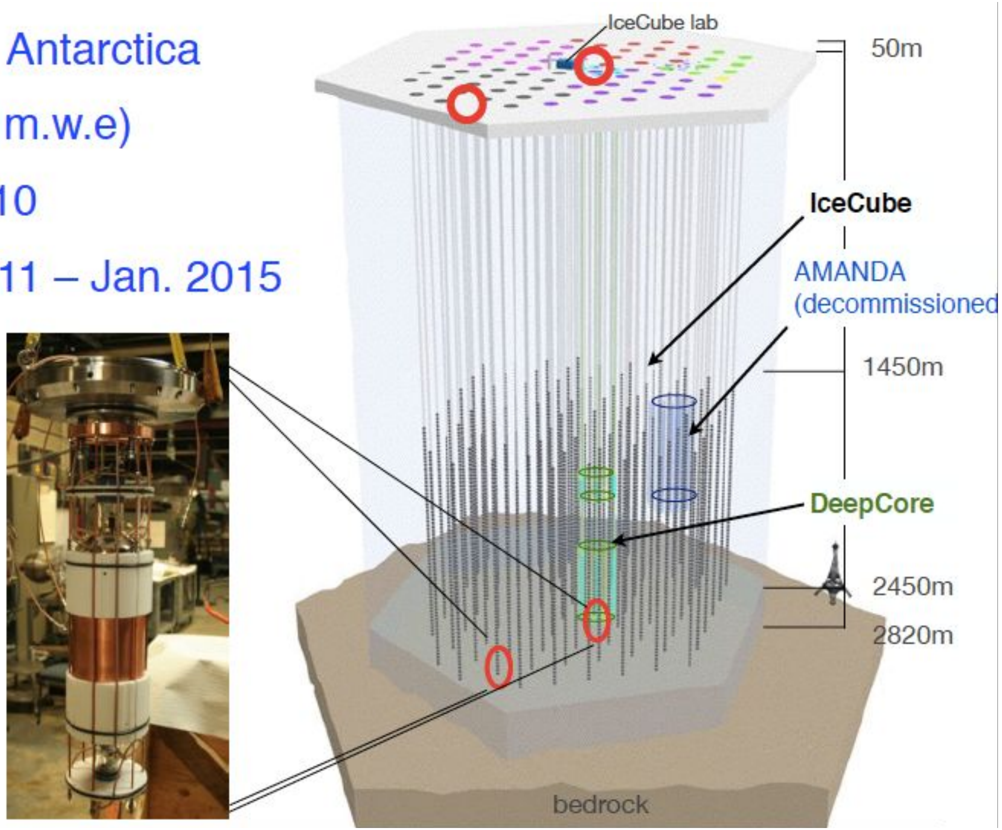
Science Run: Jun. 2011 – Jan. 2015

Uptime: > 99%

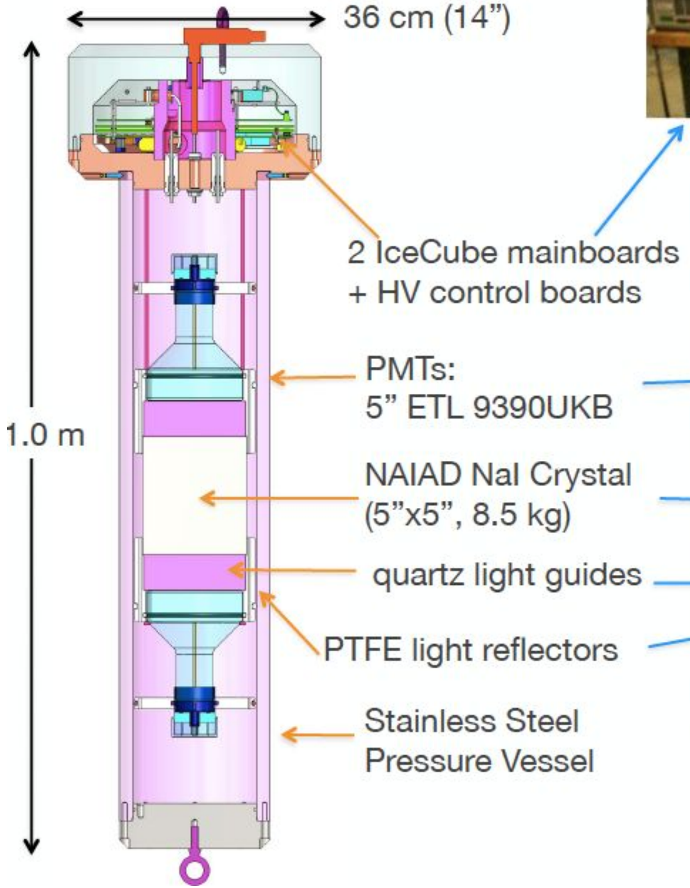
Exposure: 60.8 kg-yr

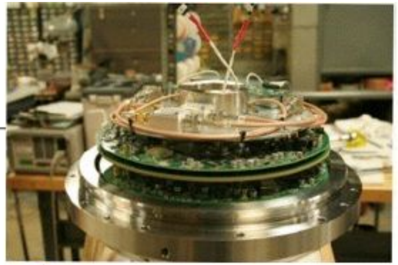
Target: NaI(Tl)

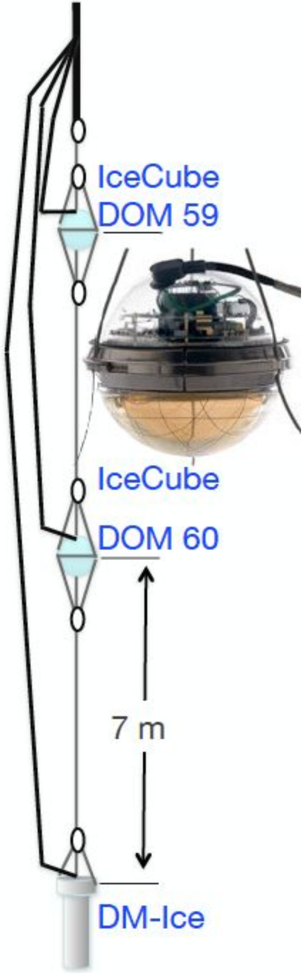
Mass: 2 x 8.5 kg



DM-Ice-17 Detector

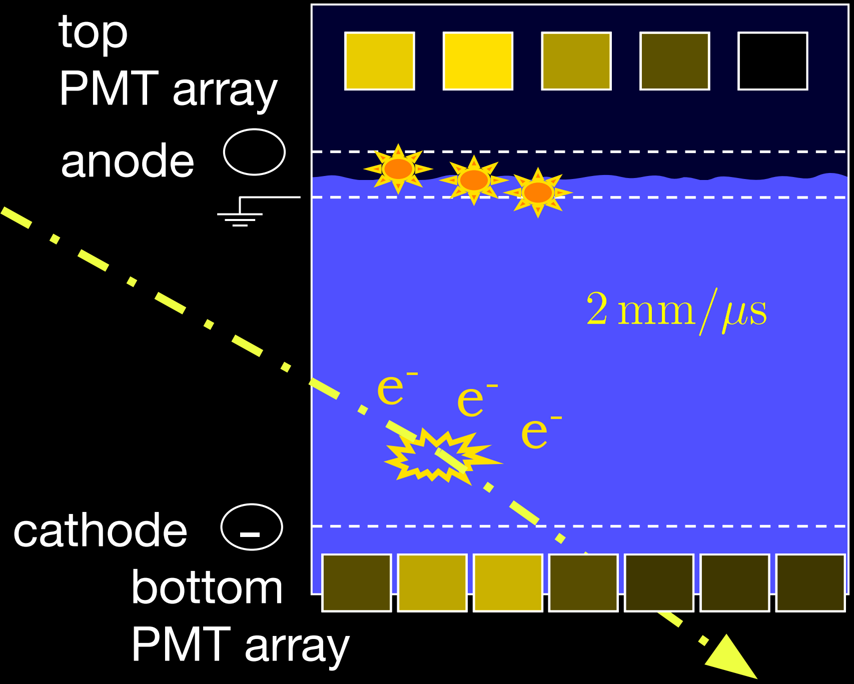




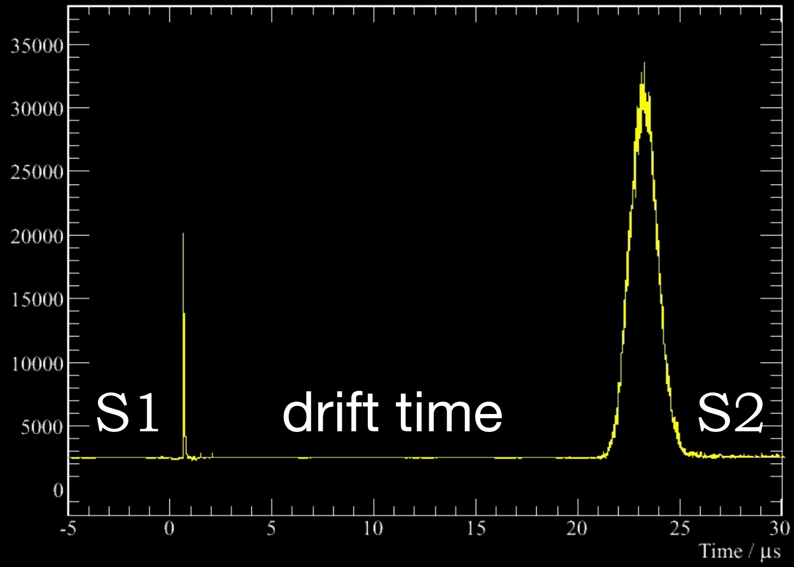


Noble Liquid Time Projection Chambers

https://xenonexperiment.org/time-projection-chamber/

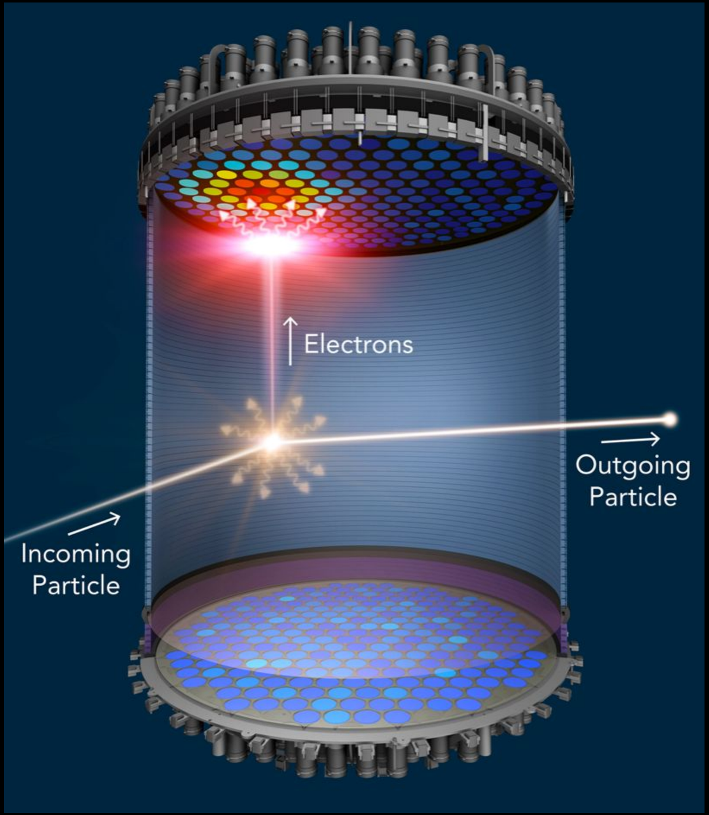


- Obtain vertex position from S2 hit pattern and drift time
- Ratio of S2/S1 provides nuclear/electron recoil discrimination



Slide courtesy of Rafael Lang

Noble Liquid Time Projection Chambers



- Obtain vertex position from S2 hit pattern and drift time
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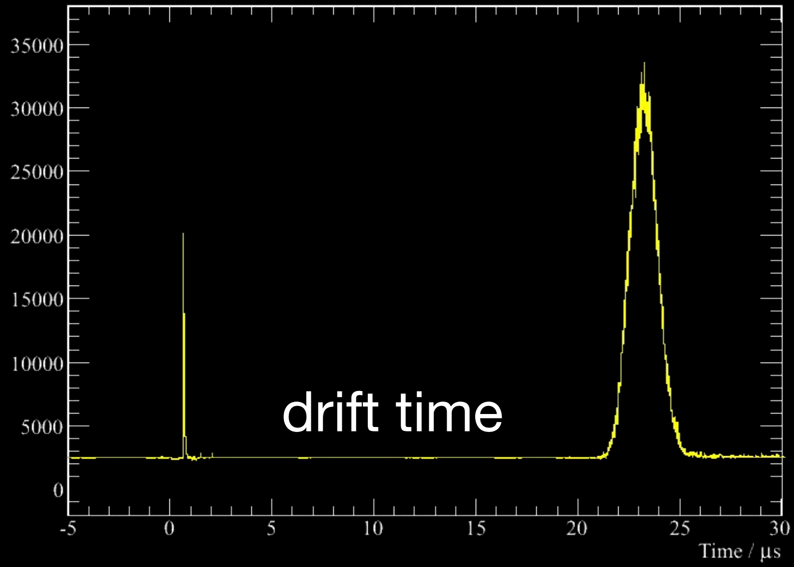


Signal Production in Noble Liquids

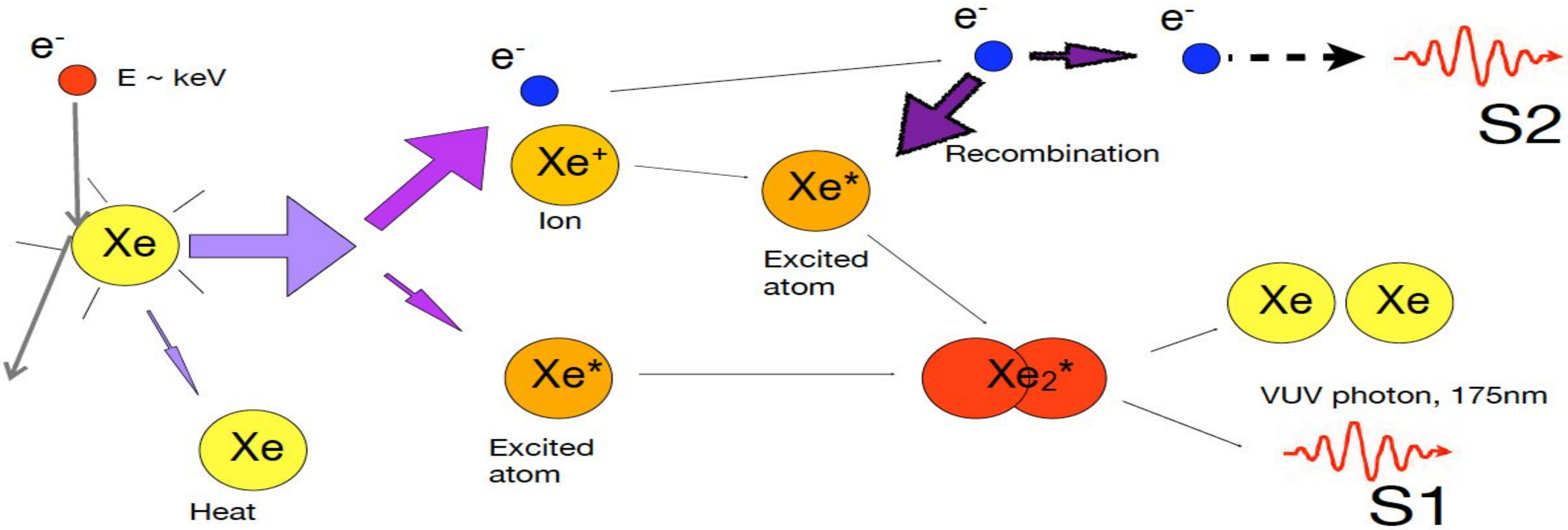


Figure: Gibson/Shutt

Electron Recoils
Low field, low energy

Signal Production in Noble Liquids

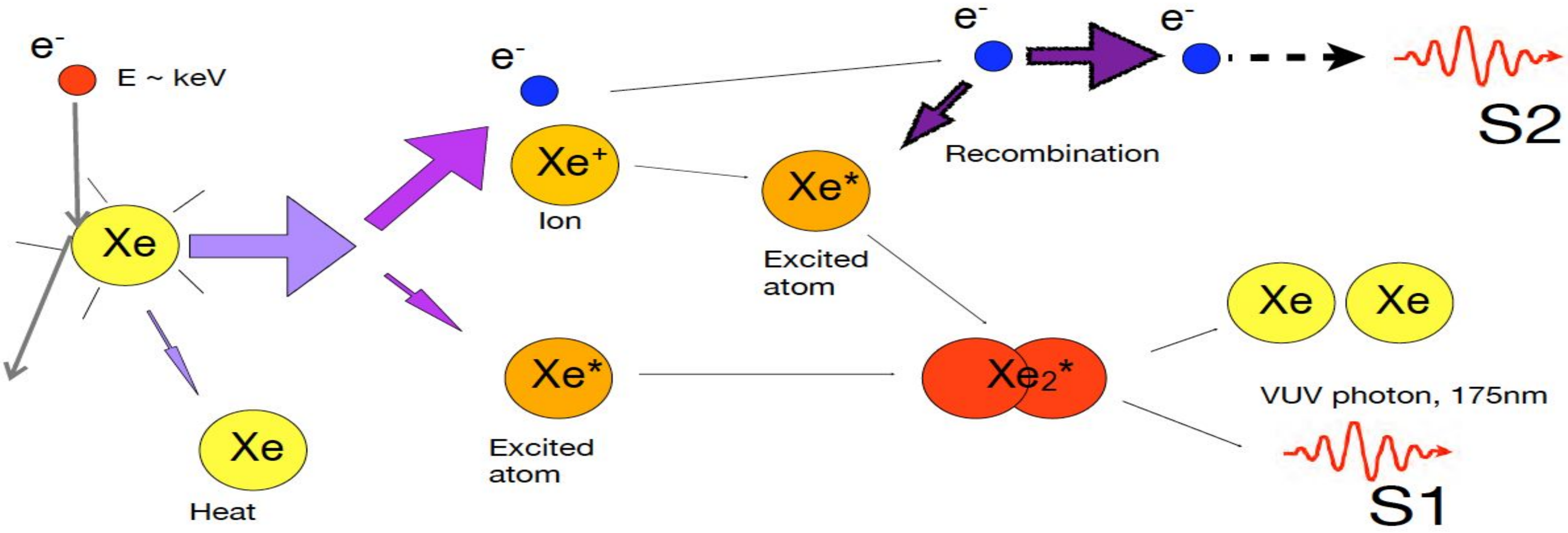


Figure: Gibson/Shutt

Electron Recoils
High field, high energy

Signal Production in Noble Liquids

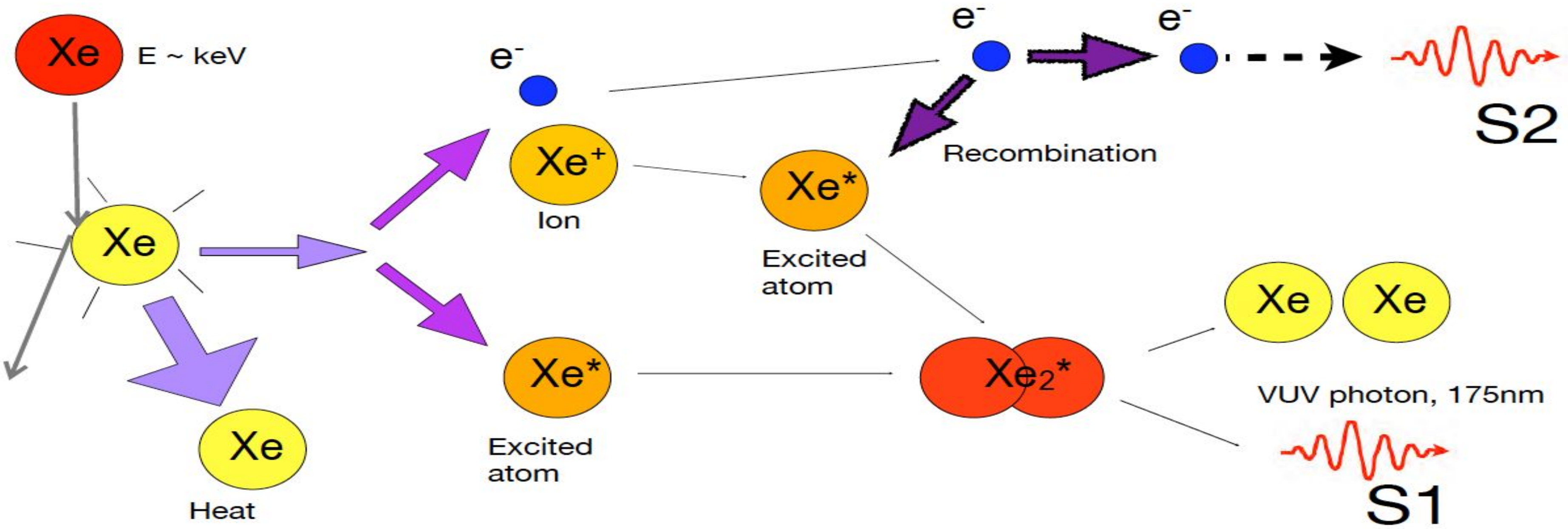
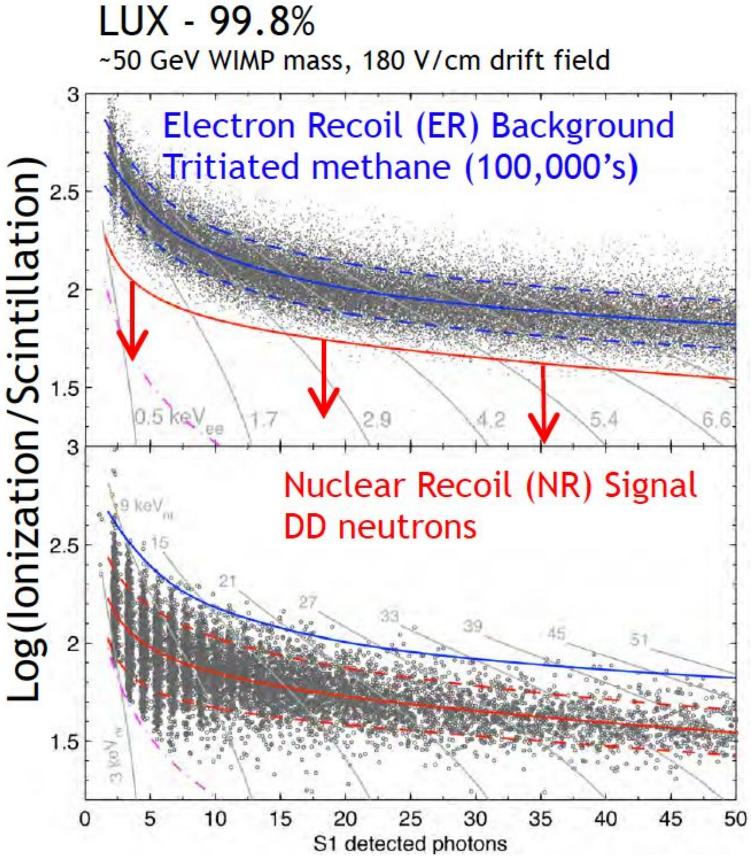


Figure: Gibson/Shutt

Nuclear Recoils

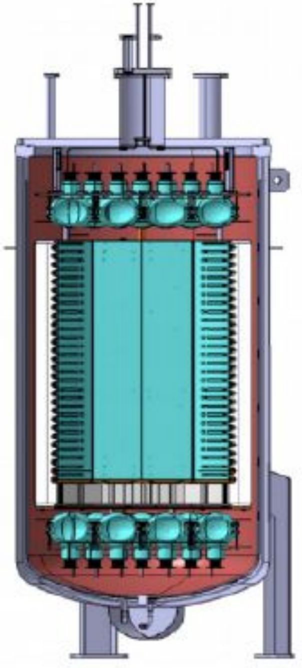
Signal Production in Noble Liquids

- Electron Recoils and Nuclear Recoils are Separated in Log(S2/S1) vs S1 plane
- Look for WIMPs below the mean of the nuclear recoil distribution (the red line in the plot)

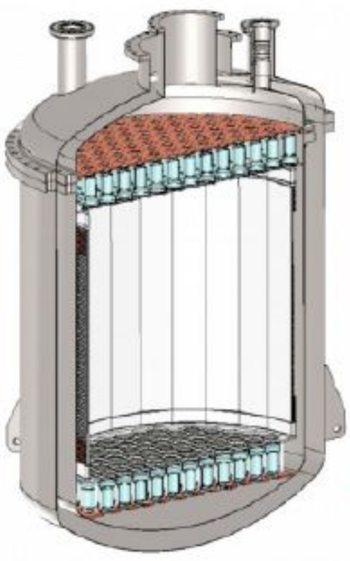


Noble Liquid Time Projection Chambers

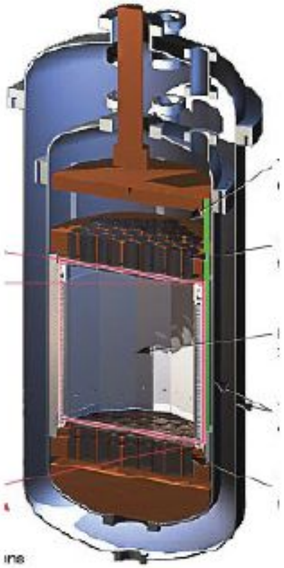
ArDM



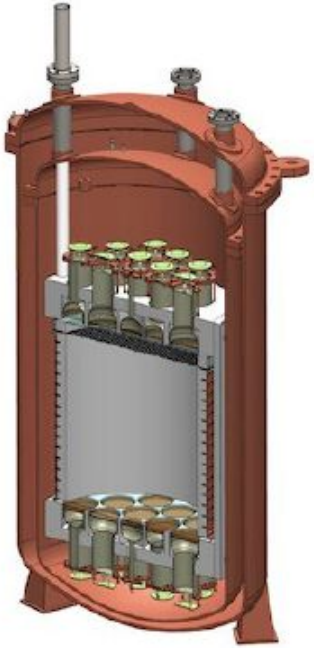
XENON1T



LUX



DarkSide-50



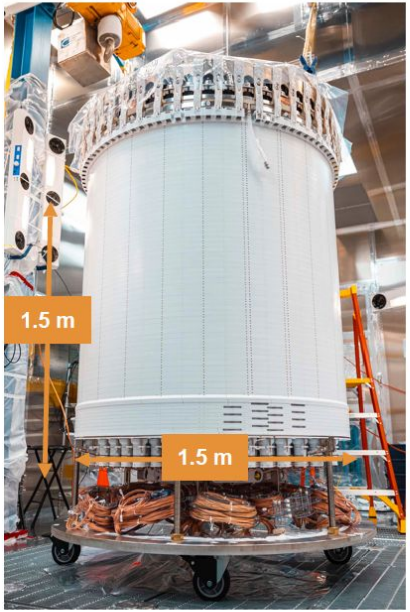
NOT TO SCALE!

Current Two-Phase XeTPCs for WIMP Search

https://indico.cern.ch/event/1188759/contributions/5044010/

XENONnT@LNGS

LZ@SURF

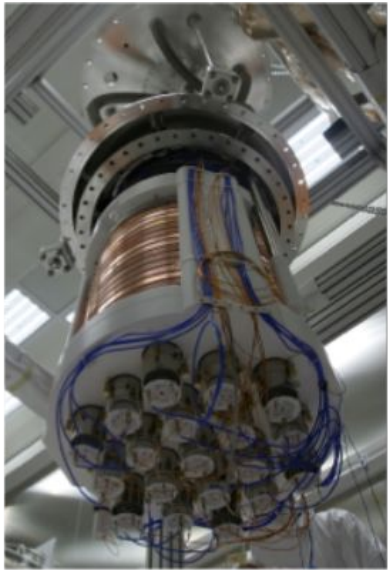


PandaX-4T@JinPing

	XENONnT	LZ	PandaX-4T
Total (sensitive) mass	8.5 (5.9) tonnes	10 (7) tonnes	5.6 (3.7) tonnes
3-inch PMTs	494	494	368
Drift Field	23 V/cm	193 V/cm	93 V/cm

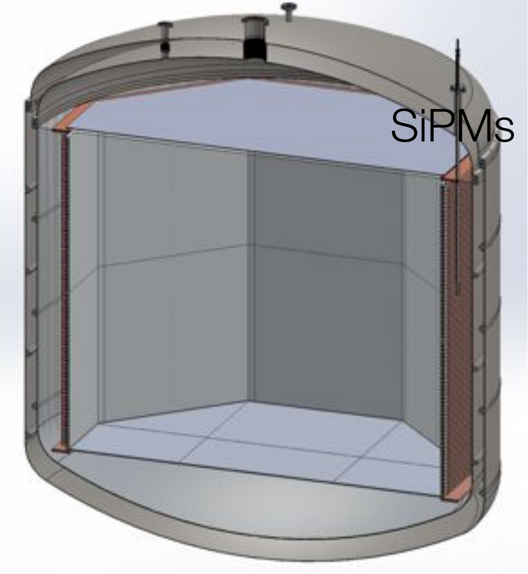
The DarkSide Program: Liquid Argon TPC

DarkSide-50



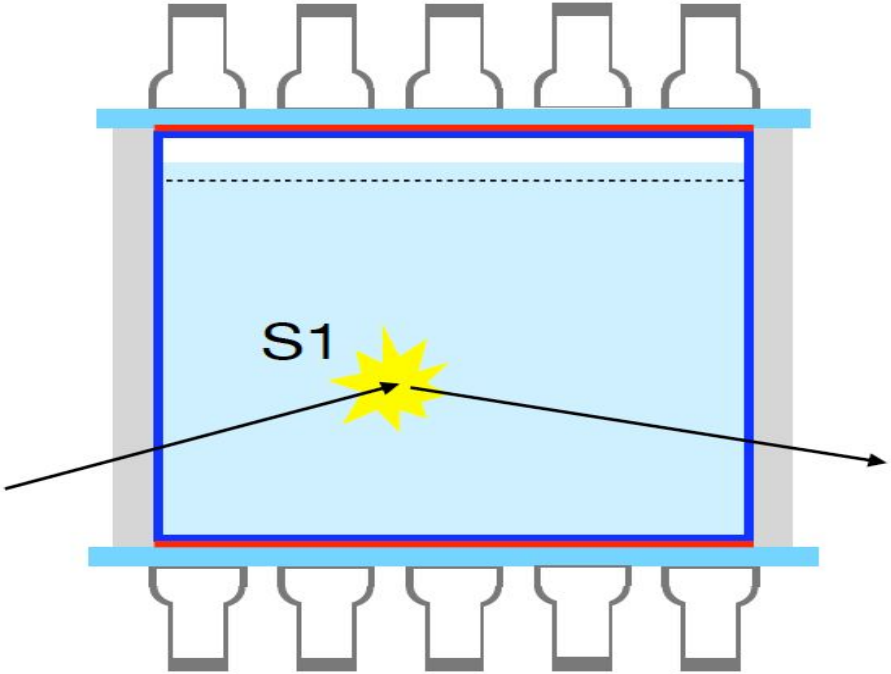
- 46 kg active Ar, 36.9 kg Fiducial
- Active neutron veto (borated liquid scintillator)
- Using underground Ar obtained 1400x less ^{39}Ar events that atmospheric Ar

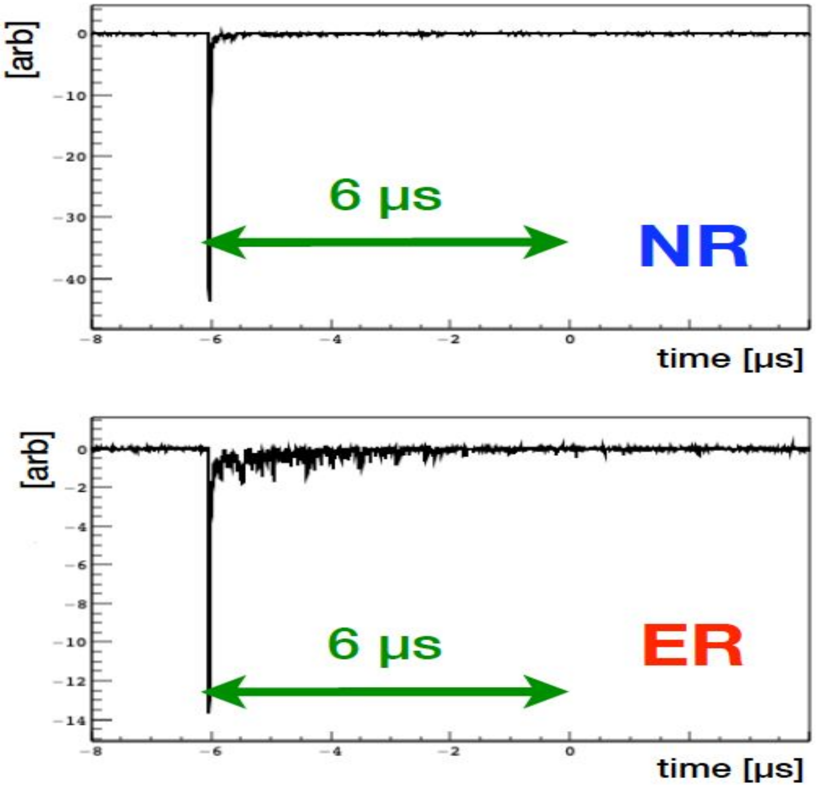
DarkSide-20k



- 23 Ton Ar, 20 Ton fiducial
- 100 Ton-yr background-free exposure
- Gd-loaded Water Cherenkov active veto
- Timeline: TBD

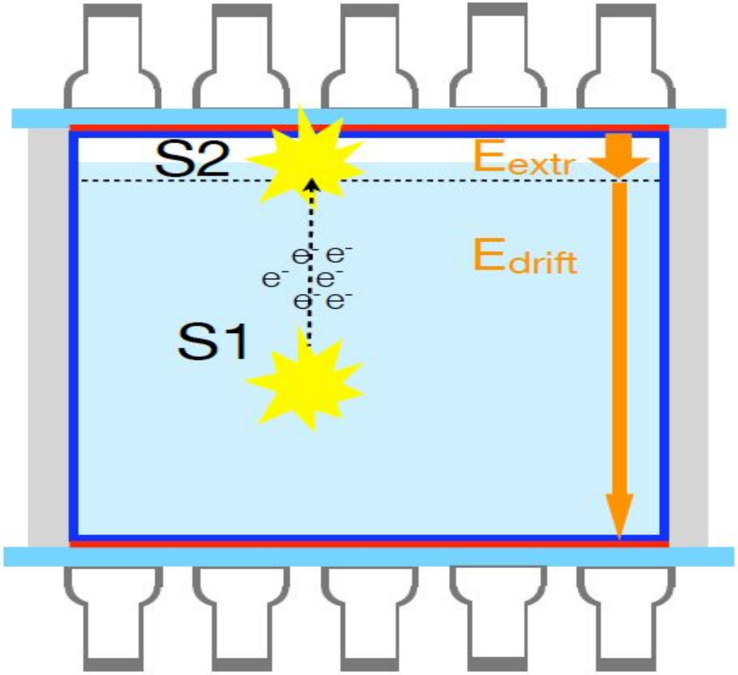
Dual Phase Liquid Argon TPC

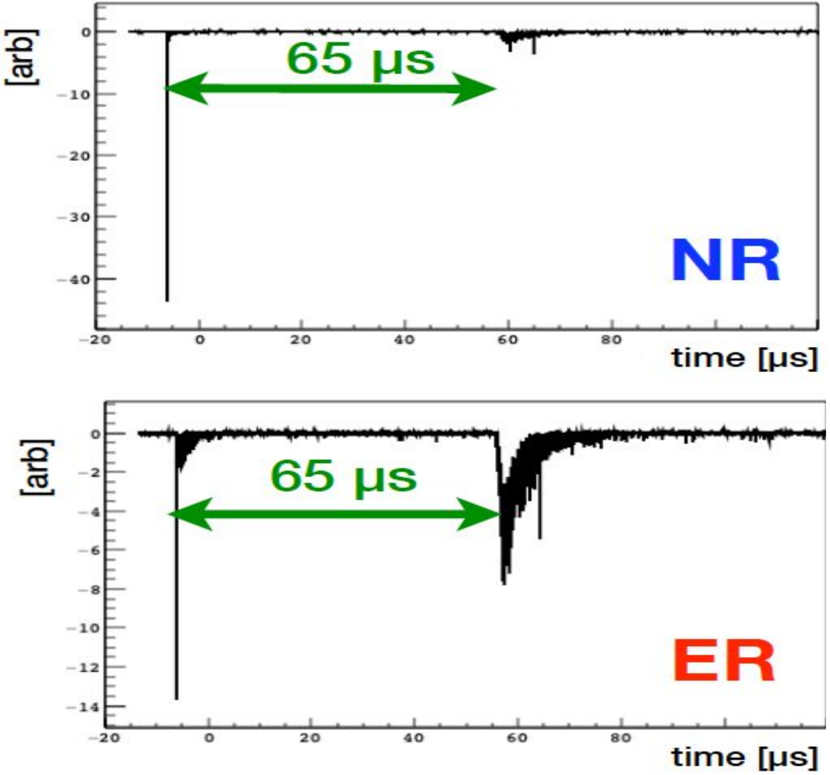




PSD parameter: **F90** = fraction of light in first 90 ns

Dual Phase Liquid Argon TPC

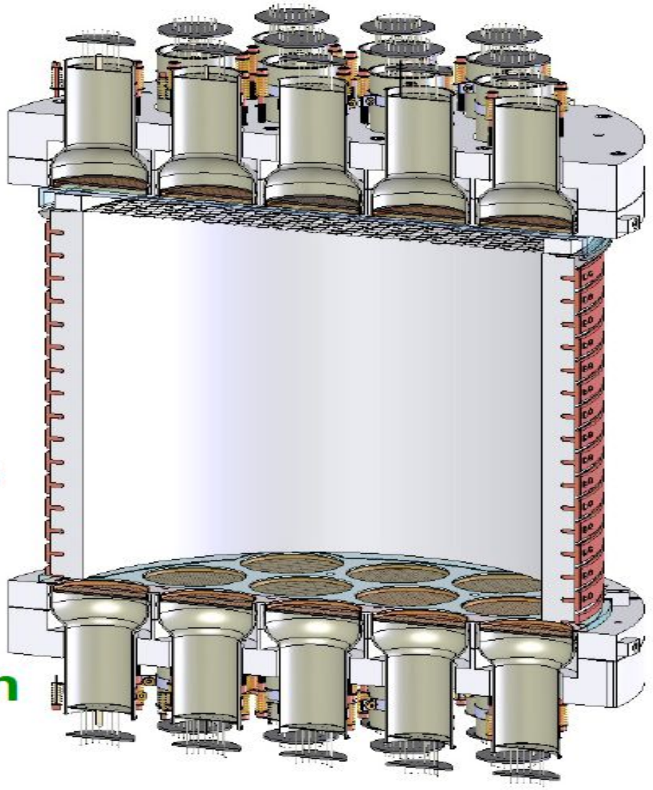




S2 allows for **3D position reconstruction** and additional discrimination power

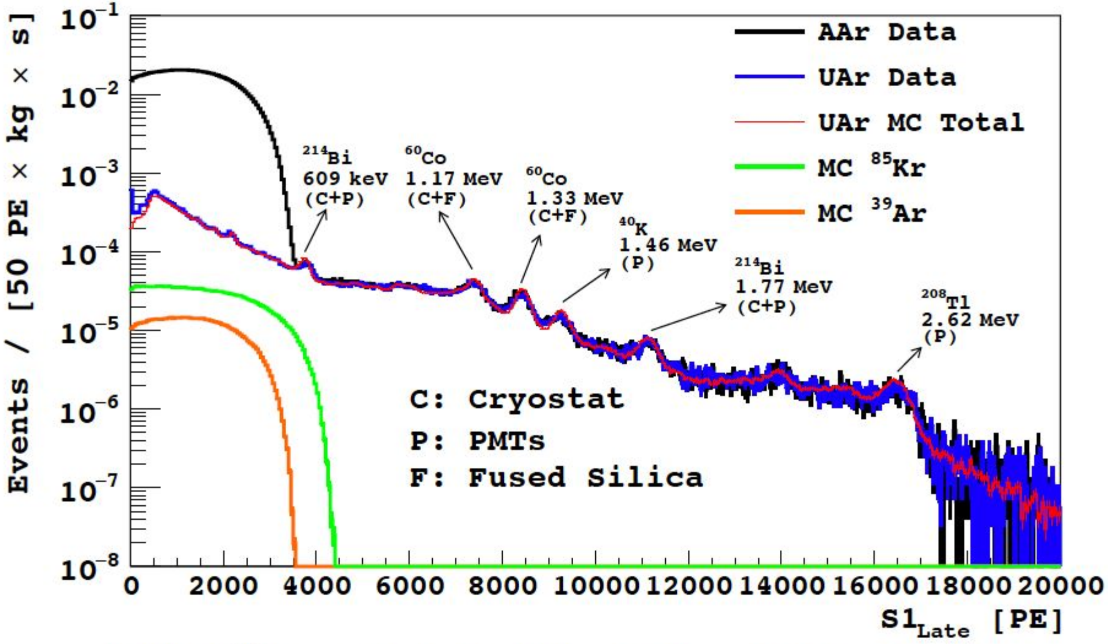
Dual Phase Liquid Argon TPC

- **46 kg active** volume
- 36 cm diameter, 36 cm height
- 38 3" PMTs
- **Cold pre-amps**
- High **reflectivity** Teflon walls
- Fused silica anode and cathode windows
  - Coated with **transparent conductor** (Indium Tin Oxide)
- All inner surfaces coated with **wavelength shifter** (Tetraphenyl Butadiene)
- 0.2 kV/cm drift, 2.8 kV/cm extraction



Lowering ^{39}Ar background using Underground Ar

^{39}Ar reduction factor: 1400



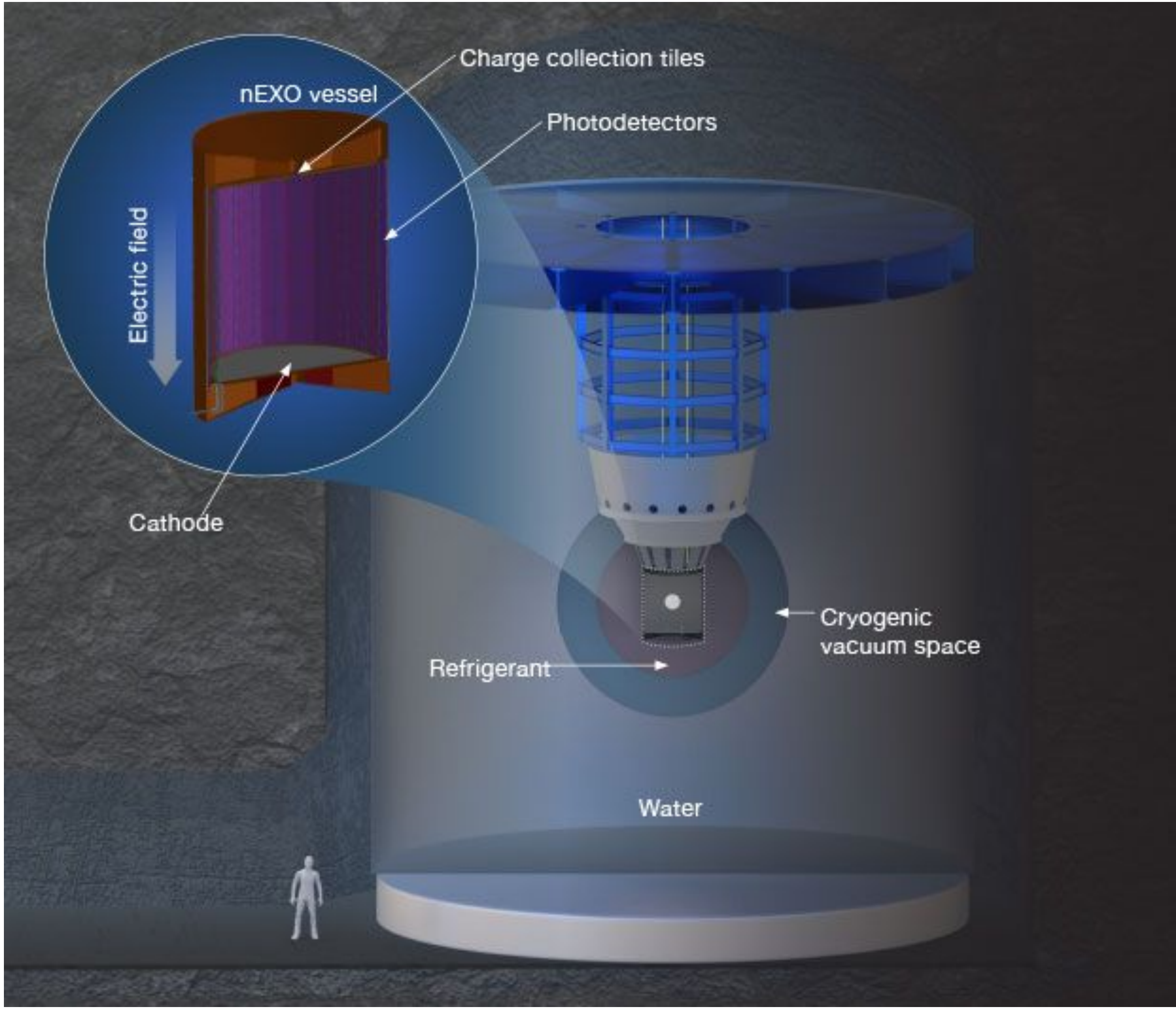
Fitted ^{85}Kr activity in UAr: 2.05 ± 0.13 mBq/kg

Fitted ^{39}Ar activity in UAr: 0.73 ± 0.11 mBq/kg

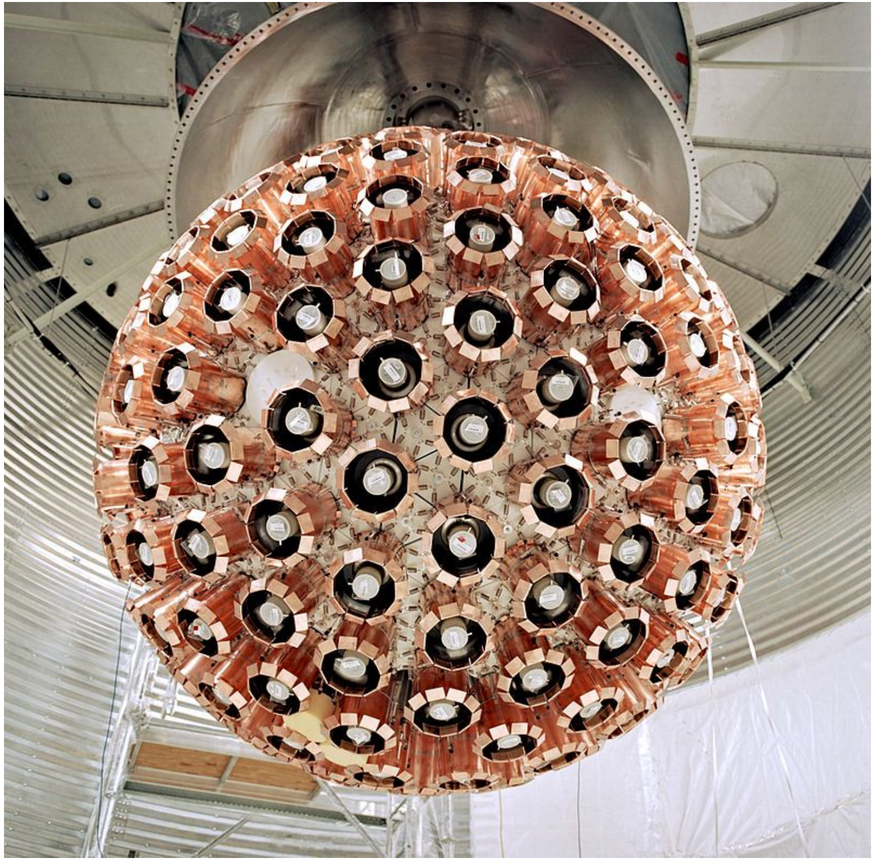
^{39}Ar activity in AAr: 1000 mBq/kg

Single phase TPC

- nEXO
- LXe
- Single phase TPC easier to build
- Measure charge directly on electrode
  - No amplification like S2
- Maybe will go to SNOLAB soon?



Single-phase Noble Liquid Detectors



DEAP3600

- 3600 kg Ar, 1000 kg Fiducial
- 3 Ton-yr exposure
- Scintillator detector

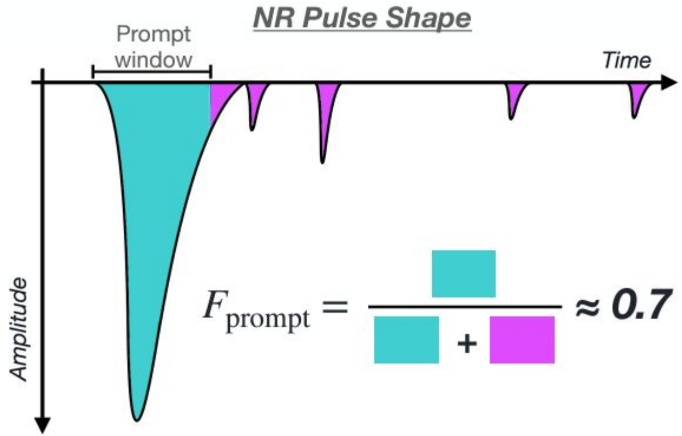
Pulse Shape Discrimination

http://deap3600.ca/wp-content/uploads/2022/08/ICHEP2022_JMcLaughlin_DEAP_final.pdf

Nuclear Recoils

Scattering directly with argon nuclei; excimers mostly populate the ***singlet state***, relax quickly. Induced by:

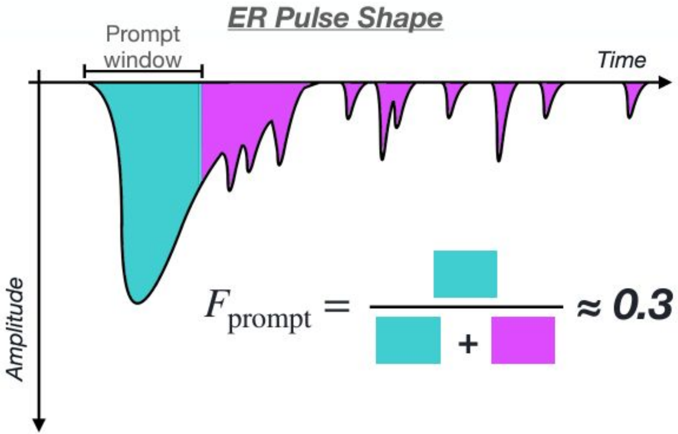
- Neutrons
- Alphas
- WIMPs



Electronic Recoils

Scattering with argon atomic electrons, ionizing argon; excimers tend to populate ***triplet state***, relax slowly. Induced by:

- Betas (especially ^{39}Ar at ~3 kHz)
- Gammas

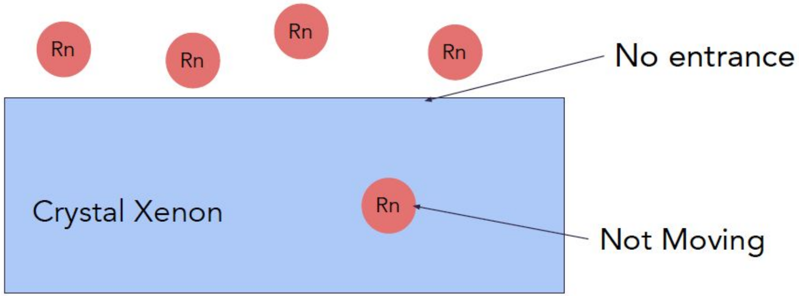


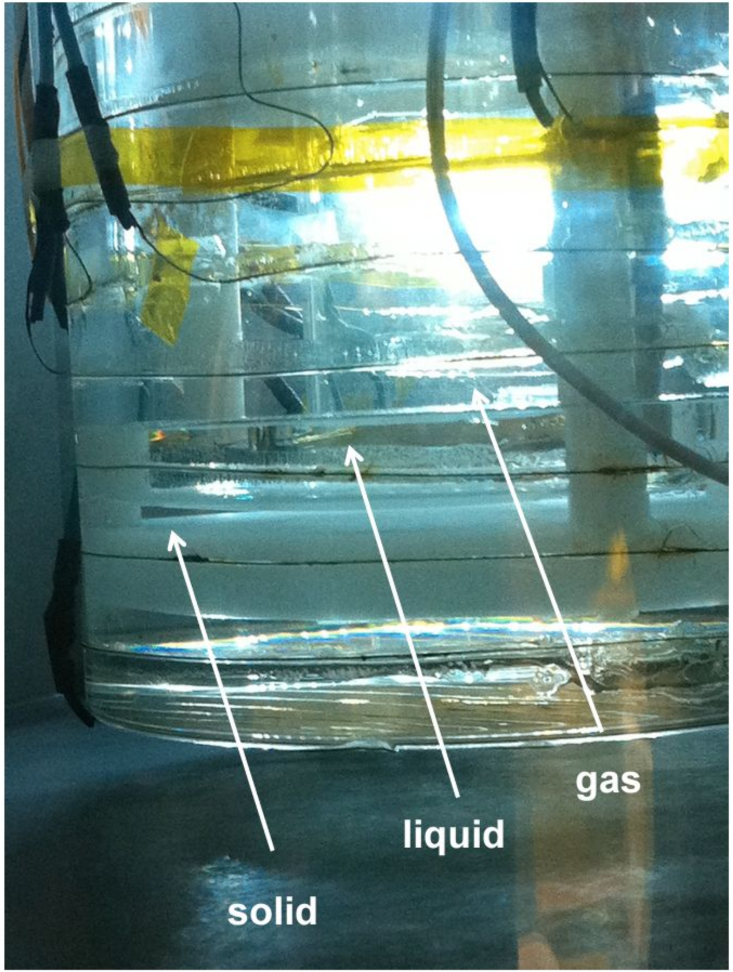
joseph.mclaughlin.2018@live.rhul.ac.uk

https://indico.fnal.gov/event/6424/contributions/96002/attachments/62734/75184/pahlka_lidine_sxenon_052913_1.pdf

Freeze it up?

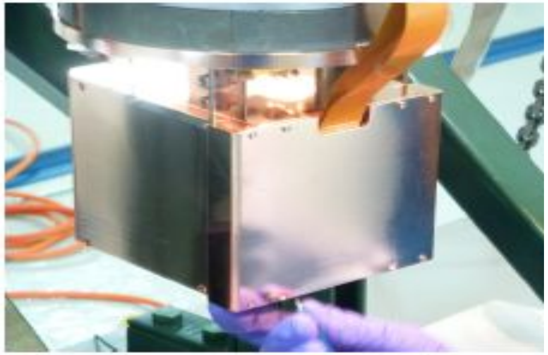
- To reject Radon…
- Can associate multiple decay daughters at the same location

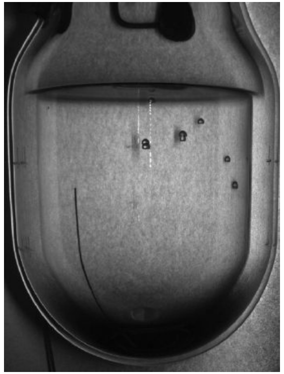


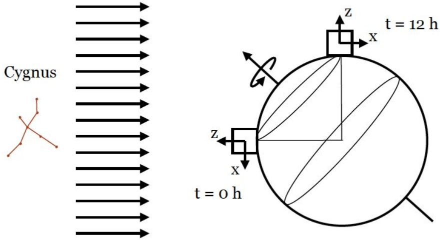


Other Nuclear Detection Technologies

- Silicon CCDs: DAMIC
- Bubble Chamber Experiments
  - PICO
    - Excellent SD Sensitivity
    - (currently running at SNOLAB)
  - Scintillating Bubble Chamber
- Directional Detection Experiments
  - DRIFT, DMTPC, NEWAGE, MIMAC

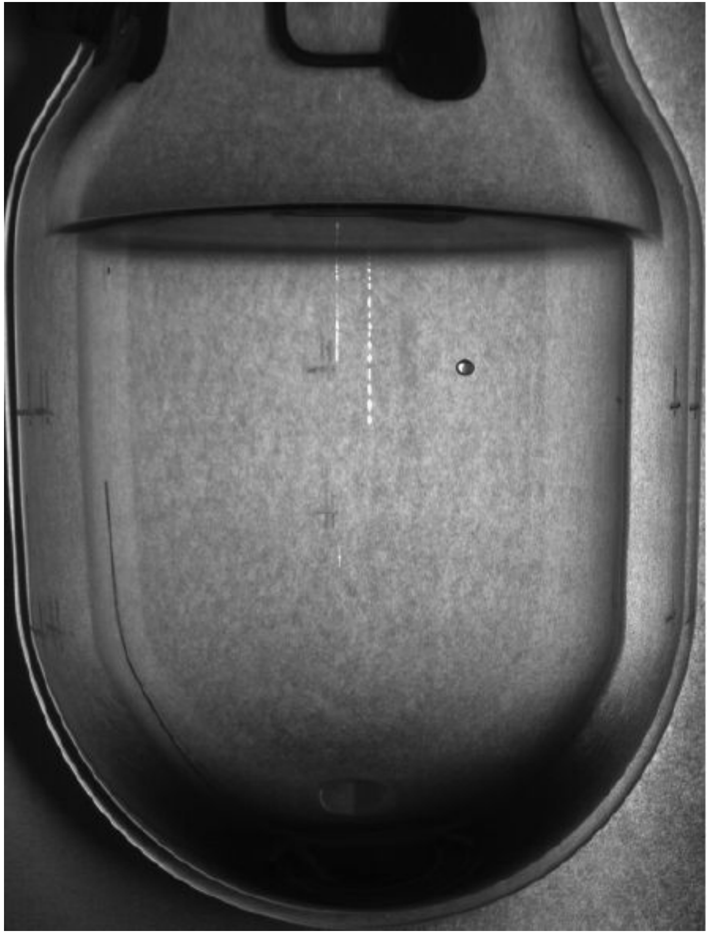




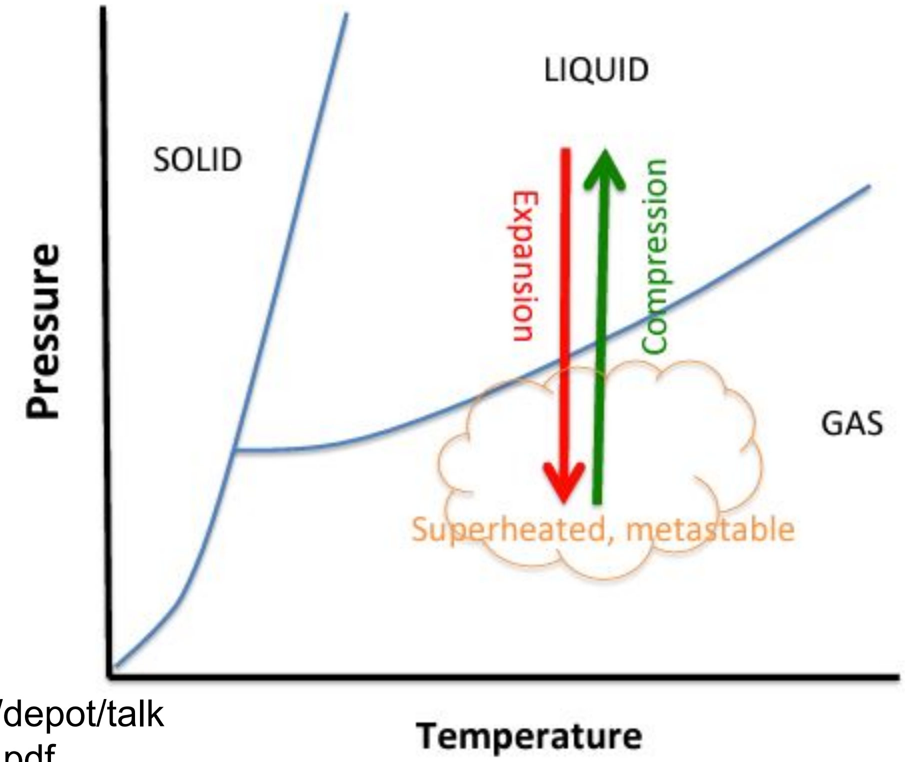


PICO Bubble Chamber

- Insensitive to gamma backgrounds due to dE/dx needed to nucleate a bubble.
- Slow detector, but OK for rare event searches
- Alpha discrimination by acoustic
  - Alpha popping is x4 louder



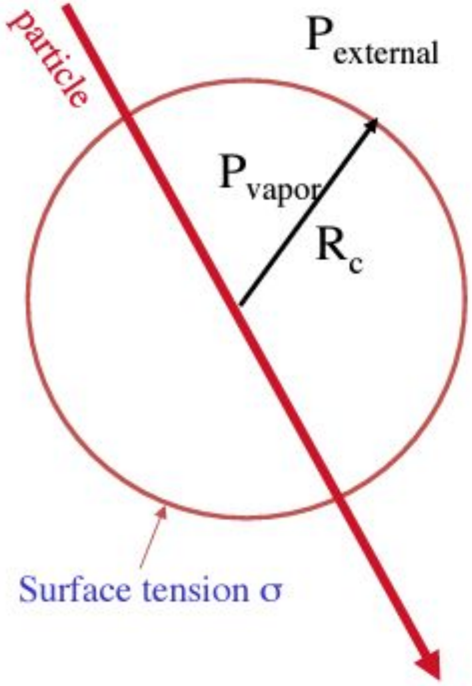
Bubble Chamber Expansion/ Compression Cycle



https://kicp.uchicago.edu/depot/talks/2016-01-19-colloquium.pdf

Bubble Nucleation by Radiation

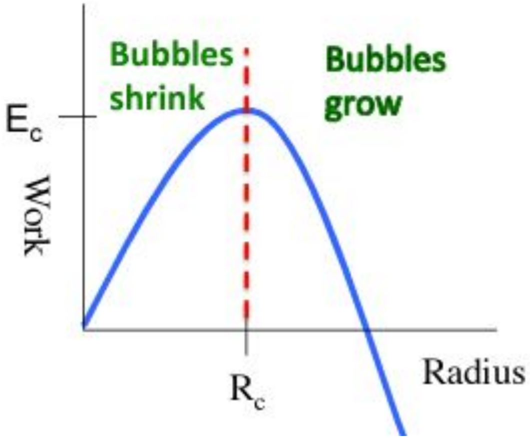
(Seitz, "Thermal Spike Model", 1957)



- Pressure inside bubble is equilibrium vapor pressure.
- At critical radius R_c surface tension balances pressure.

$$R_C = \frac{2\sigma}{P_{vapor} - P_{external}}$$

- Bubbles bigger than the critical radius R_c will grow; smaller bubbles will shrink to zero.



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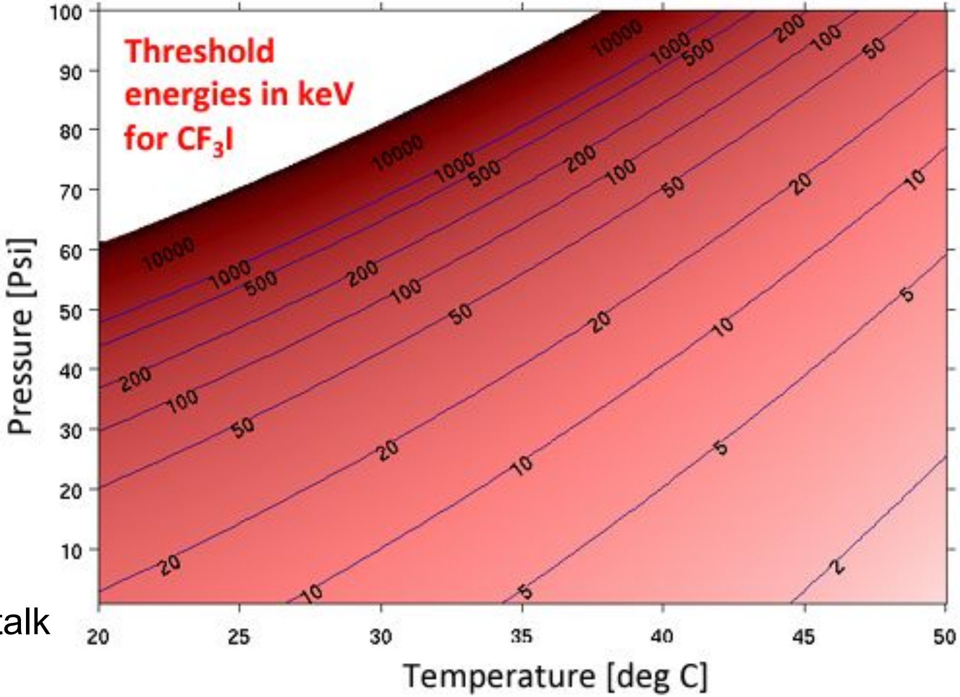
Energy Barrier to Bubble Nucleation

$$E_{th} = 4\pi r_c^2 \left(\sigma - T\frac{\partial \sigma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v h$$

Surface energy   Latent heat



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Robinson, 2015