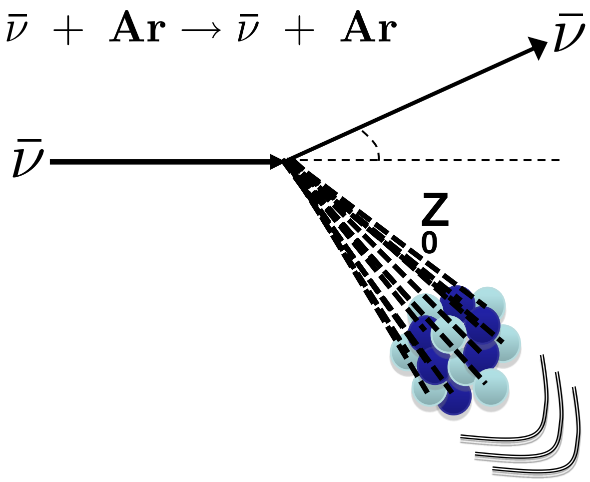


$$\bar{\nu} + \mathbf{Ar} \rightarrow \bar{\nu} + \mathbf{Ar}$$

Coherent Neutrino-Nucleus Scattering

Adam Bernstein
Advanced Detectors Group Leader
Physics Division

Lawrence Livermore
National Laboratory

6th International Workshop on Low Energy Neutrino Physics
Nov 2011

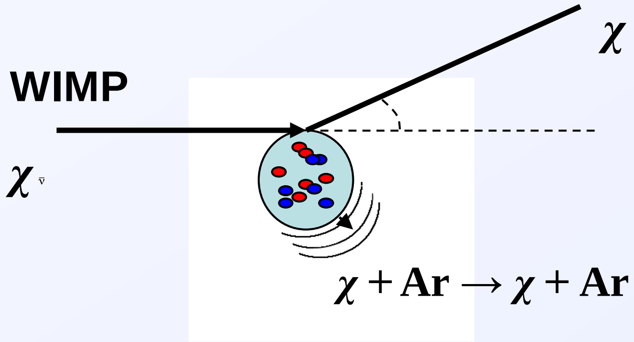
This work was performed under the auspices of the U.S. Department of Energy by
Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Talk Outline

1. Coherent scatter and dark matter detection
2. Dual-phase ionization detectors
3. The dual phase test-bed at LLNL
4. Neutron and gamma beam measurements of ionization ‘quenching’

Coherent Scatter Processes

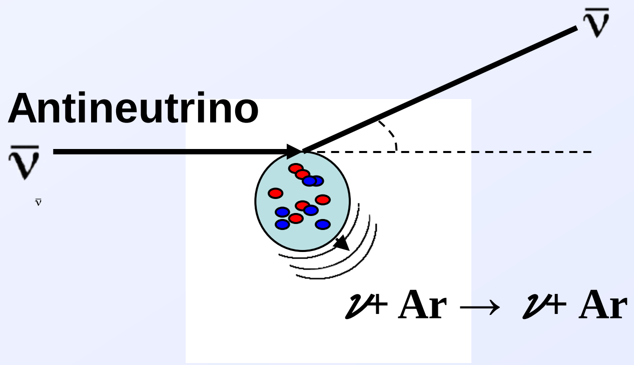
Weakly Interacting Massive Particles



$$\lambda_{\text{300 Gev WIMP}} = \frac{h}{m \times v} = 5\,fm$$

$$R_{\text{Xe nucleus}} = 6\,fm$$

Neutrino-nucleus scattering



$$\lambda_{\text{reactor antineutrino}} = 300\,fm$$

$$R_{\text{Ar nucleus}} \sim 3\,fm$$

Both processes satisfy the coherence condition:

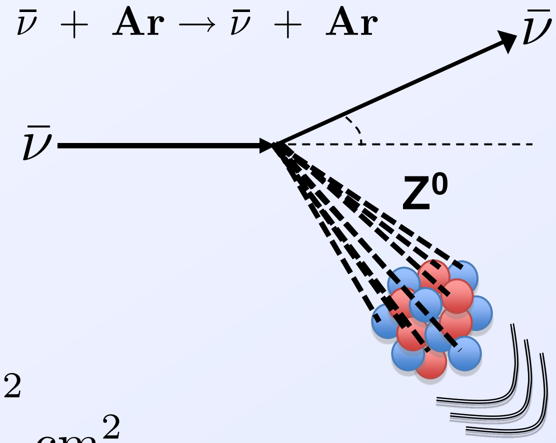
$$\lambda \geq R_{nucleus}$$

Coherent Neutrino Scattering (CNS)

A neutrino elastically scatters on a nucleus via Z0 exchange with all nucleons

- flavor blind, no threshold
- predicted by the SM, long-sought
- **high cross-section:**

$\bar{\nu} + \mathbf{Ar} \rightarrow \bar{\nu} + \mathbf{Ar}$



$$\sigma_{\rm cs} \simeq \frac{G^2 \boxed{N^2}}{4\pi} E_\nu^2 \simeq 0.42 \times 10^{-44} N^2 \left(\frac{E_\nu}{\rm MeV}\right)^2 {\rm cm}^2$$

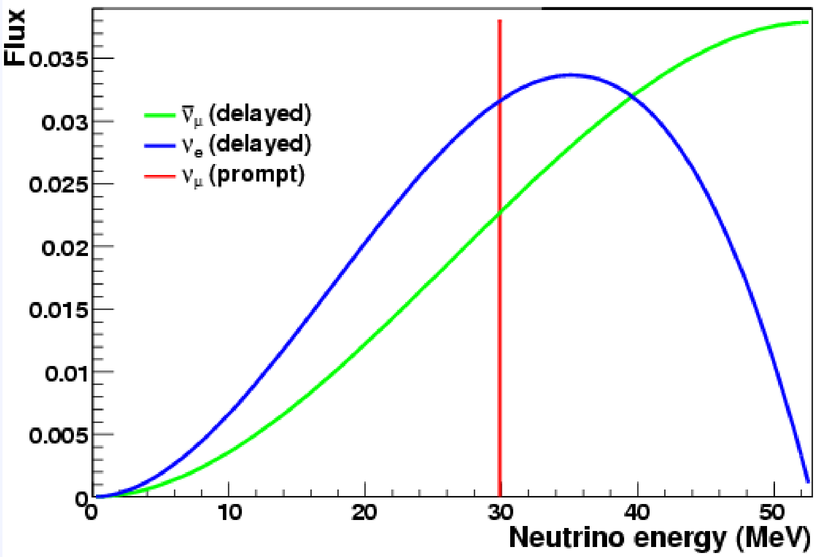
- **But low recoil energy:**

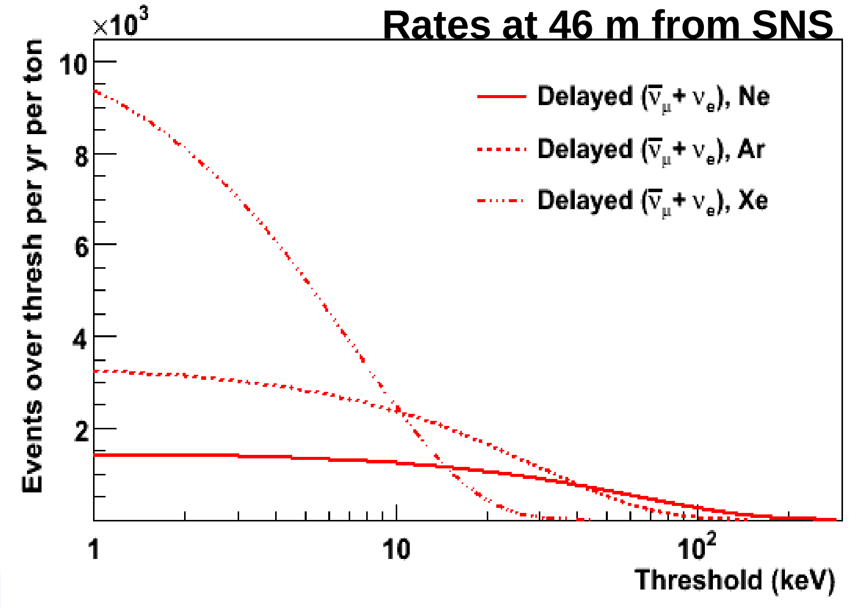
$$\langle E_r \rangle = 716\,{\rm eV}\ \frac{(E_\nu/{\rm MeV})^2}{\boxed{A}}$$

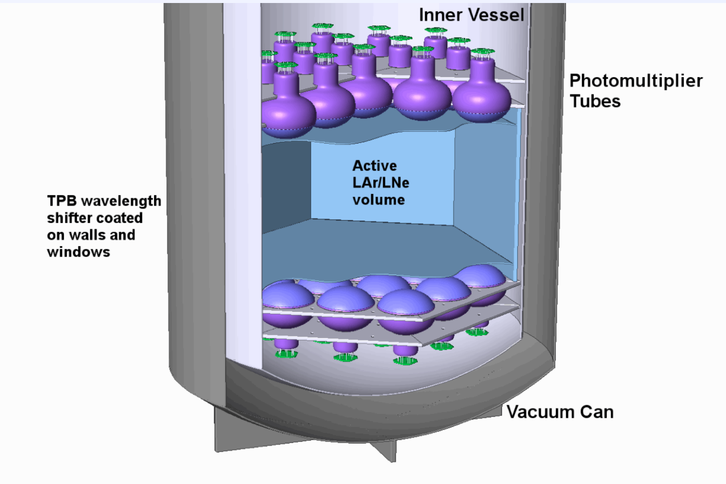
Sources of < 50 MeV neutrinos

- **Reactors**
- **spallation sources**
- **supernovae**
- **the Sun**

stopped pion sources are a useful source of neutrinos for coherent scatter




Rates at 46 m from SNS



Recoil energies and cross-sections are higher than for reactors; good timing structure for bg rejection also may be possible

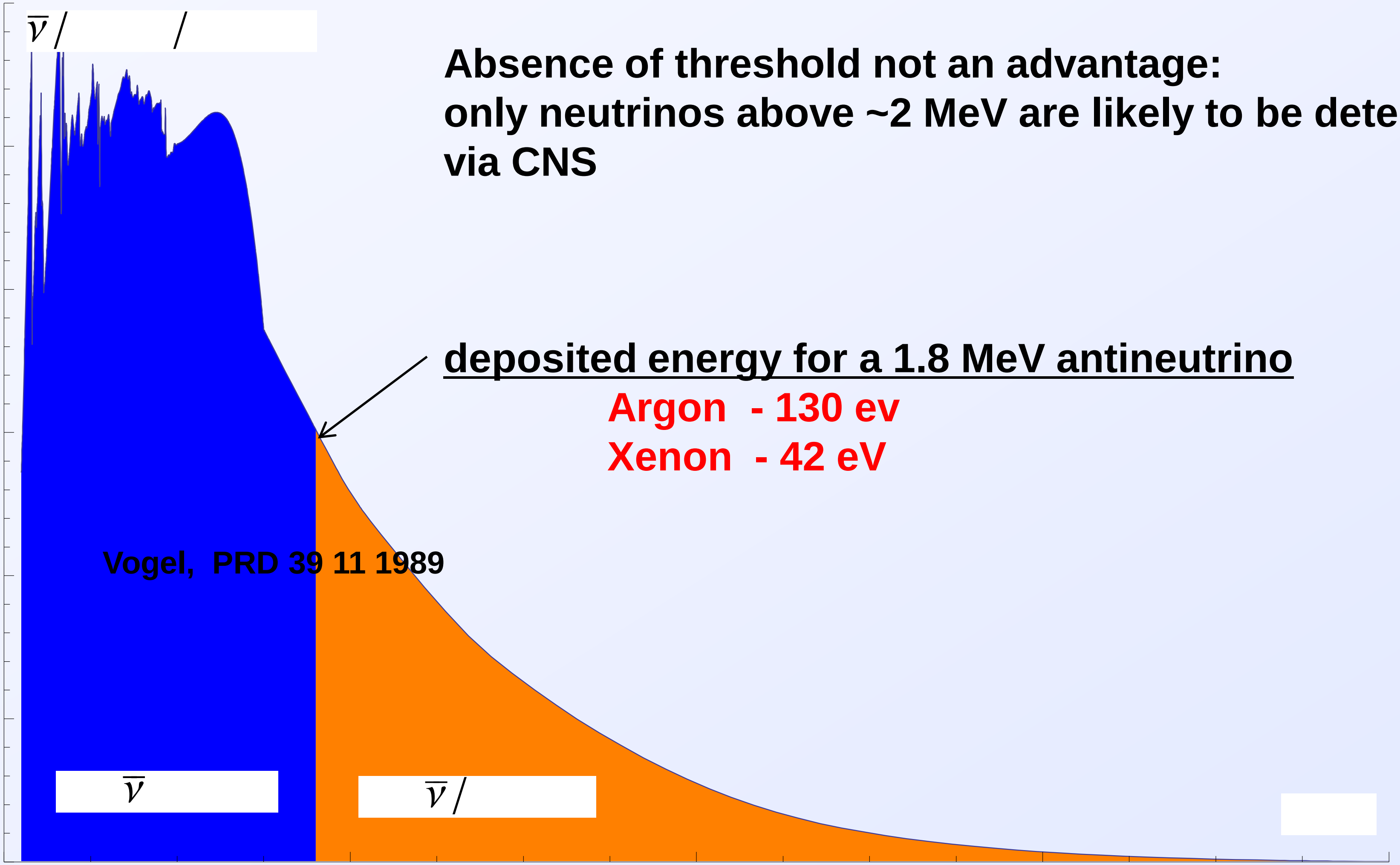
Some possibilities:

- Spallation Neutron Source,
- European Spallation Source,
- DAEδALUS

Slide courtesy Kate Scholberg

Refs: hep-ex/0511042, arXiv:0910.1989, arXiv:1103.4894

1-10 MeV reactor antineutrinos also satisfy the coherence condition



Vogel, PRD 39 11 1989

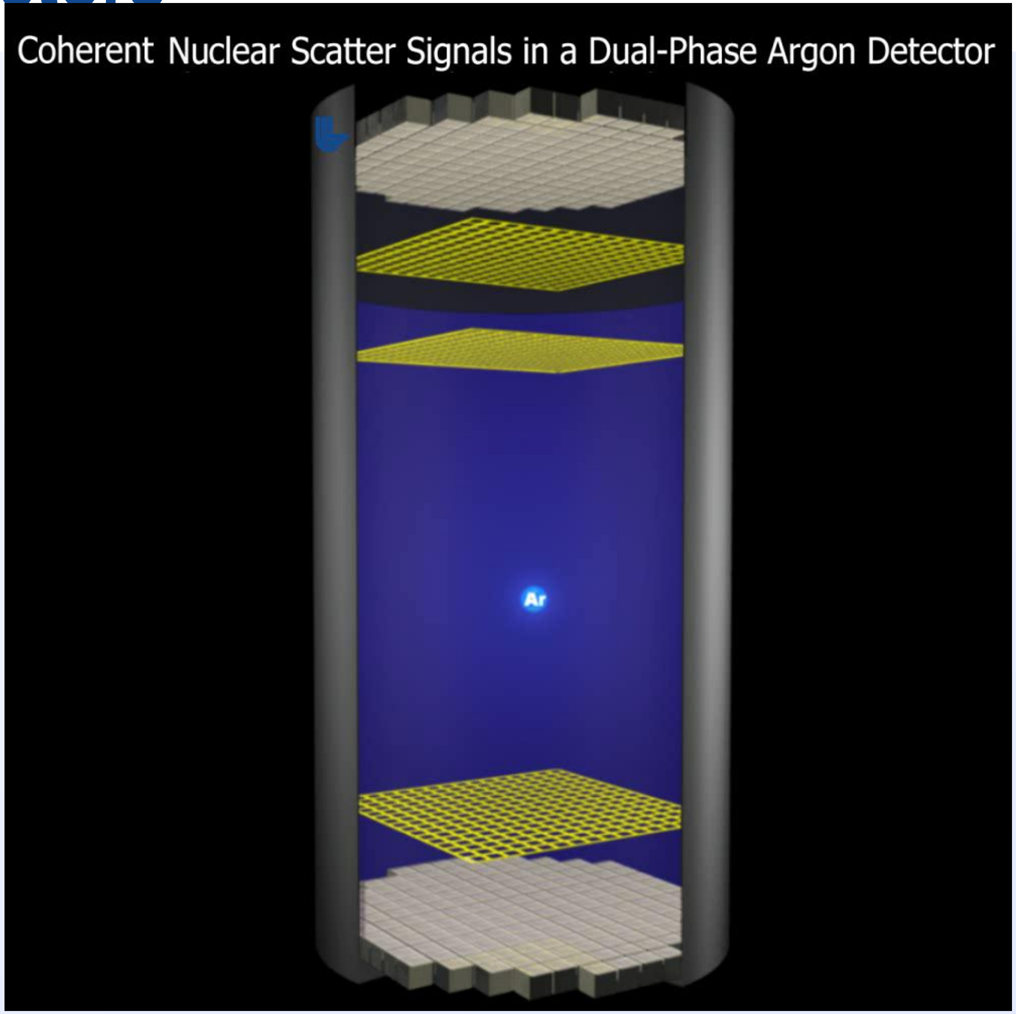
Absence of threshold not an advantage:
only neutrinos above ~2 MeV are likely to be detectable via CNS

deposited energy for a 1.8 MeV antineutrino

Argon - 130 ev
Xenon - 42 eV

One approach to CNS discovery/detection: dual phase noble liquid detectors

- Well known technology, proven in Dark Matter experiments
- Measures primary scintillation (S1) and secondary scintillation (S2, charge)
- Good electron drift properties
- Large mass
- mm 3-D signal localization *
- Discrimination between nuclear and eletromagnetic recoils *

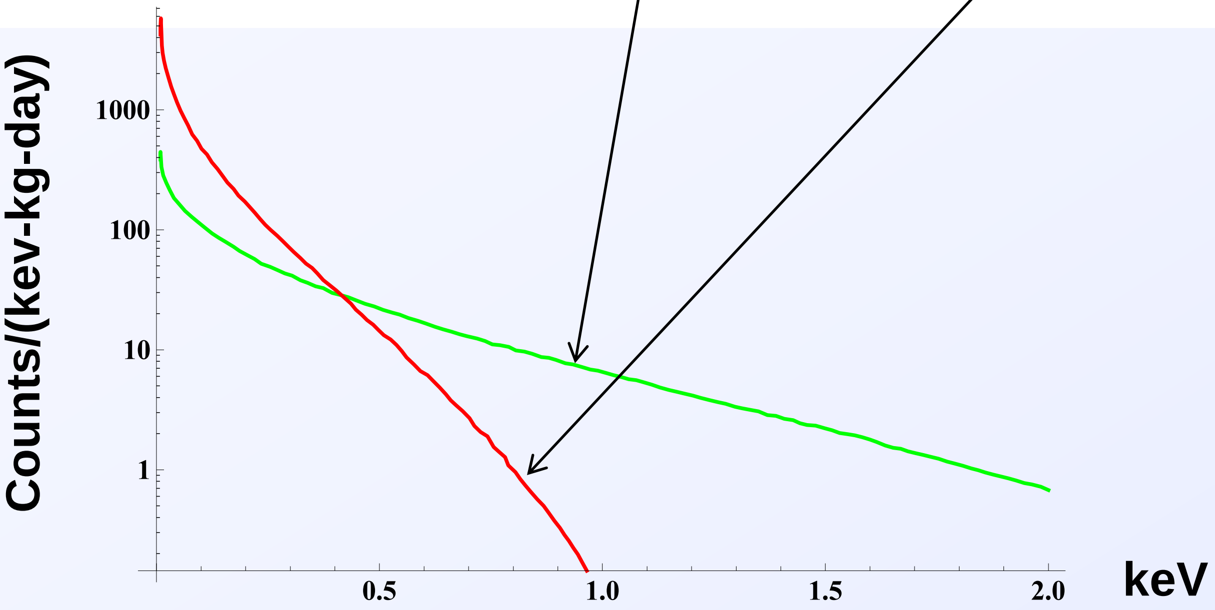


*** Not easy to achieve for the CNS process**

Dark Matter and Coherent Scatter: The Devil and the Deep Blue Sea

Detector feature	**Coherent scatter**	**Dark Matter**
Nuclear recoil energy threshold	~1-2 keV	~5-10 keV nuclear recoil
Primary (S1) and secondary (S2, ionization induced) scintillation	Little or no primary scintillation light	Charge and light together provide discrimination *and* fiducialization
Overburden	10 meters	~1000 mwe overburden
Events per kg and day	~1-10	~1/100th (or ZERO)
Mass	10-20 kg	100 kg minimum price of admission
Purity	Medium 0.2-0.5 meter drift length	High purity: 1-2 meter drift length
Source characteristics	Reactor (and beam) neutrino sources can be turned off	Source is either nonexistent or can't be switched off..

The recoil energy spectrum of reactor antineutrinos in argon and xenon



$$\frac{d\sigma}{d(\cos\theta)} \approx \frac{G^2}{8\pi} N^2 E^2 (1+\cos\theta)$$

$$\langle E_r \rangle = 716eV \frac{(E_\nu / MeV)^2}{A}$$

1/A and N compete

Our assertion based on modeling:
for reactor antineutrinos
Argon (Z-20) gives the best
balance between high cross
section and detectable energy

The induced signal in a dual-phase detectors

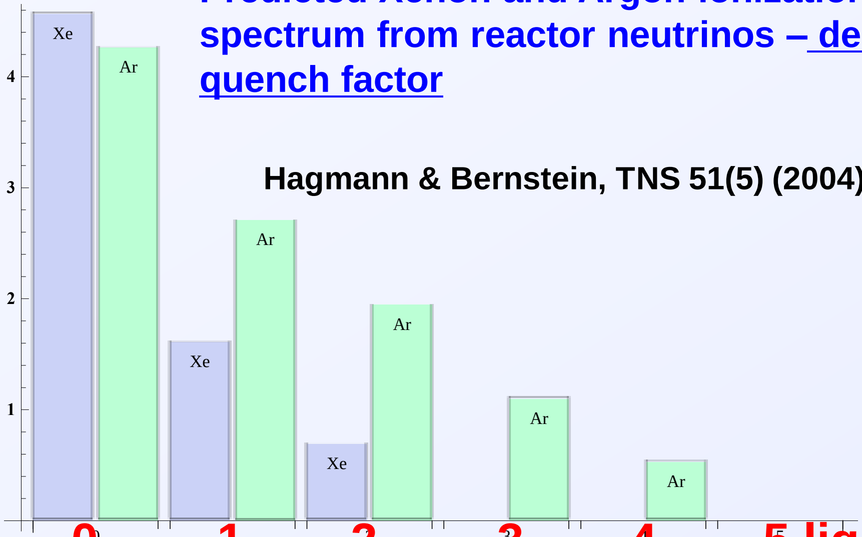
- In general nuclear recoils yield **less ionization** than electromagnatic recoils →

nuclear ionization quench factor

$$q(E_r) = \frac{N_{ion}(E_r, \text{nucleus})}{N_{ion}(E_r, \text{electron})}$$

Predicted Xenon and Argon ionization spectrum from reactor neutrinos – depends on quench factor

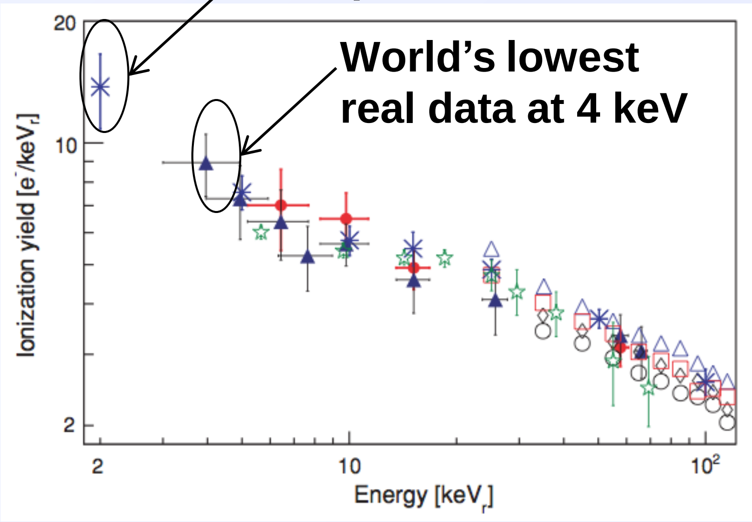
Hagmann & Bernstein, TNS 51(5) (2004)



0 1 2 3 4 5 liquid electrons

Manzur et al, Phys. Rev. C 81 (2010)

Extrapolation



World's lowest real data at 4 keV

Argon (and Xenon) low energy electron yield must both be measured

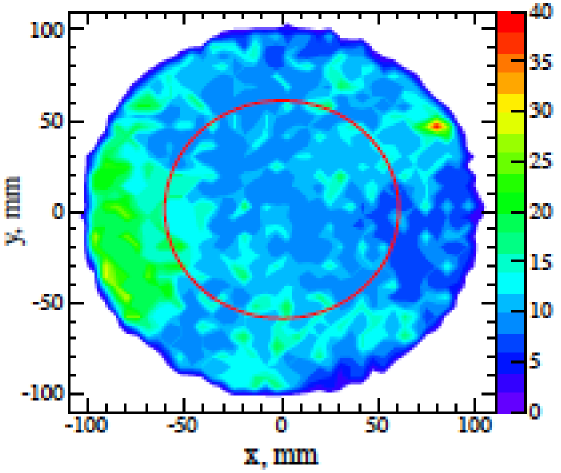
- our experimental program

Data in xenon still allow for a wide range of ionization yields at 1 keV

Akimov, arxiv 0903.4821

Single liquid electrons - sensitivity and background

Signal:
Isolated single liquid electrons must be countable in order to detect CNS
ZEPLIN-III (and Xenon-10) have both demonstrated this



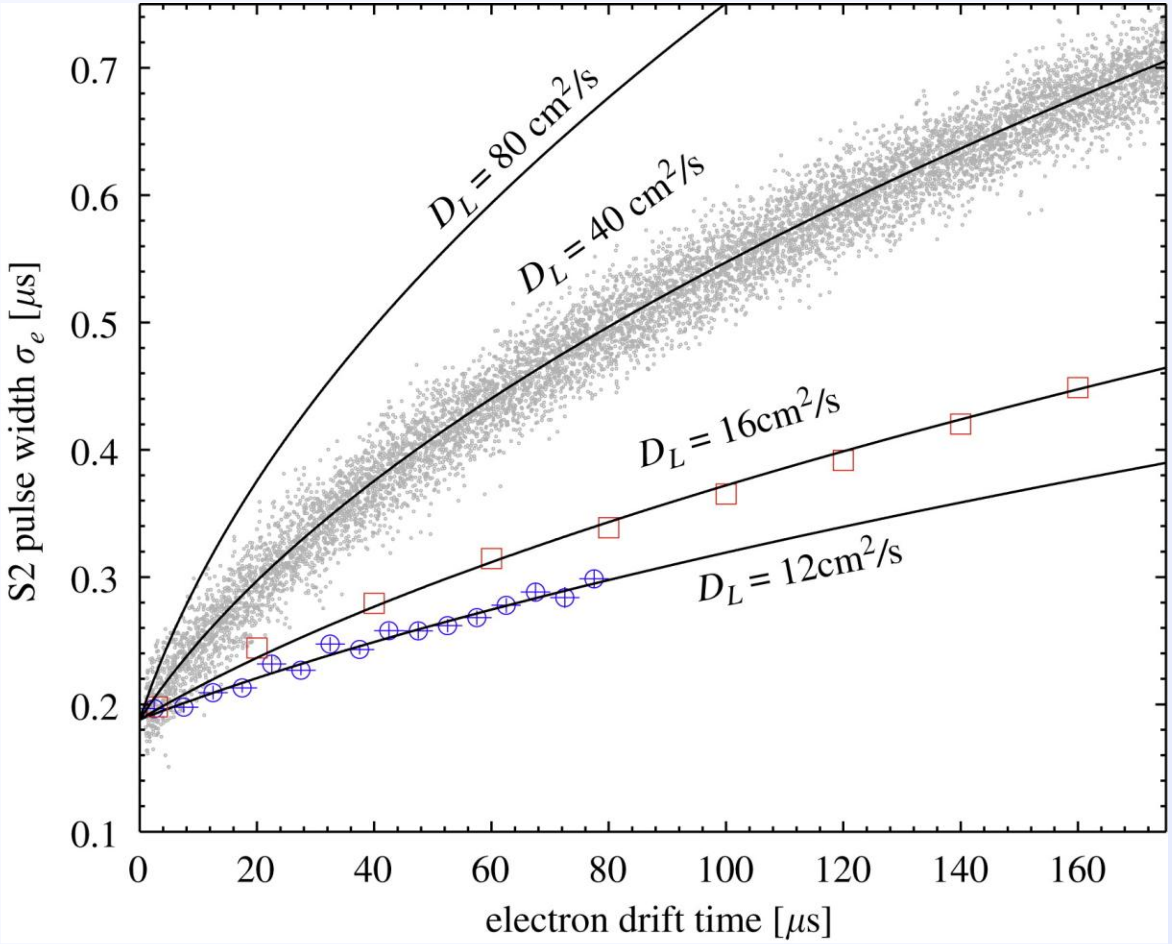
ZEPLIN-III data showing the x-y reconstructed positions of single electron events in a 12 kg dual phase xenon detector

Background:

- **5 Hz spontaneous rates from single electron emission in 10 kg detectors**
- **Possible sources: grid emission, accumulation of surface charge..**
- **Single electron events will likely have to be removed from the data sample to suppress this background**

Santos – arxiv 1110.3056v1

Time Projection breaks down at low energy: recover z position by diffusion



Without a starting flash of light, we need a way to reconstruct vertical position

Answer: measure the transverse width of the electron cloud

(but it won’t work for one electron…)

P.Sorensen -arXiv:1102.2865

Summary of signal and backgrounds near a reactor

- All process that produce a small number (1-5) of primary electrons in the active region:

10 kg Ar, 25 m standoff, 3.4 GWt Signal:

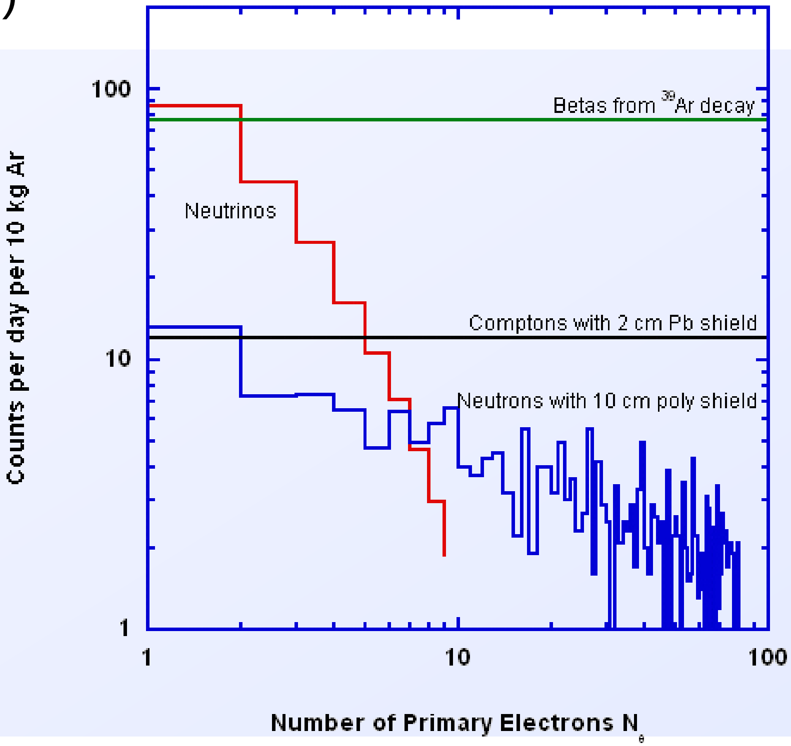
→ after quenching: 1-10 free e-
→ ~170 per day (1 or more liquid e-)

→ ~80 per day (2 or more liquid e-)

Breakdown of backgrounds

Background type	counts/ dy/10 kg
Dominant: ^{39}Ar (sim.; depleted Ar reduces 20x)	1000
External U/Th/K : (sim., after2 cm Pb shield)	~ 100
External neutrons: (sim. @ 20 mwe, after 10 cm borated poly shield):	~ 32
Internal gammas or spontaneous emission single e-: (measured, XENON10):	~ 50 per day @ 3 keVee; but ~1 Hz of single liquid electrons

Monte Carlo Simulation



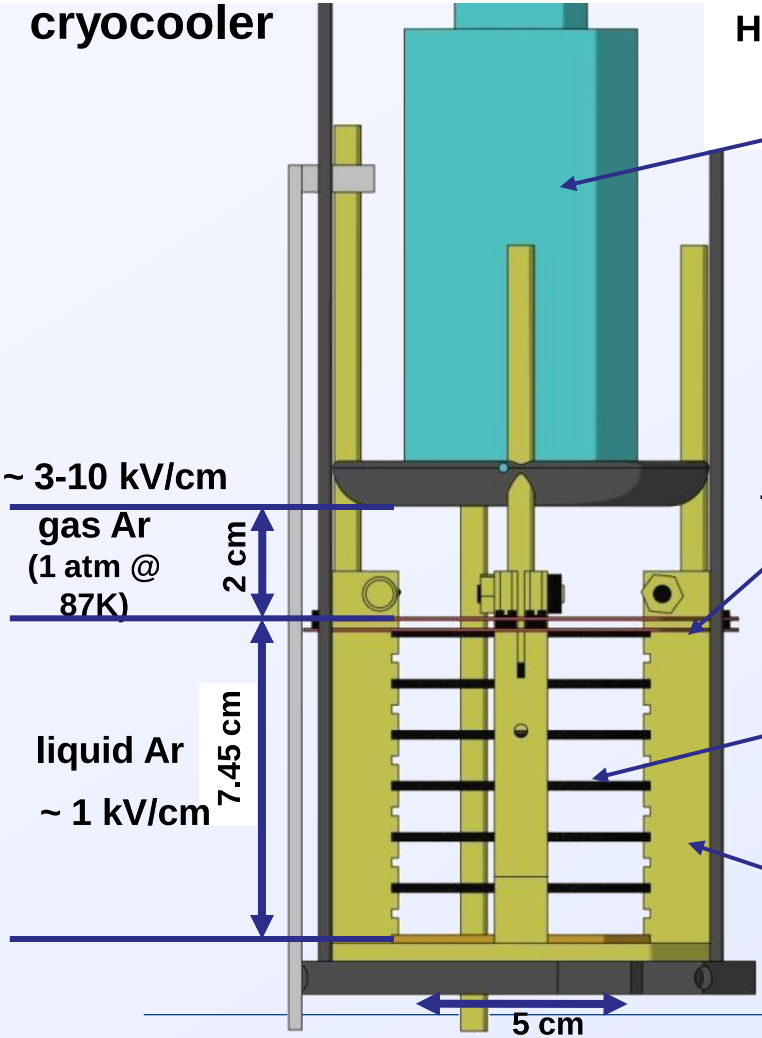
Shield: Inner: 2cm Lead
Outer: 10cm borated polyethylene

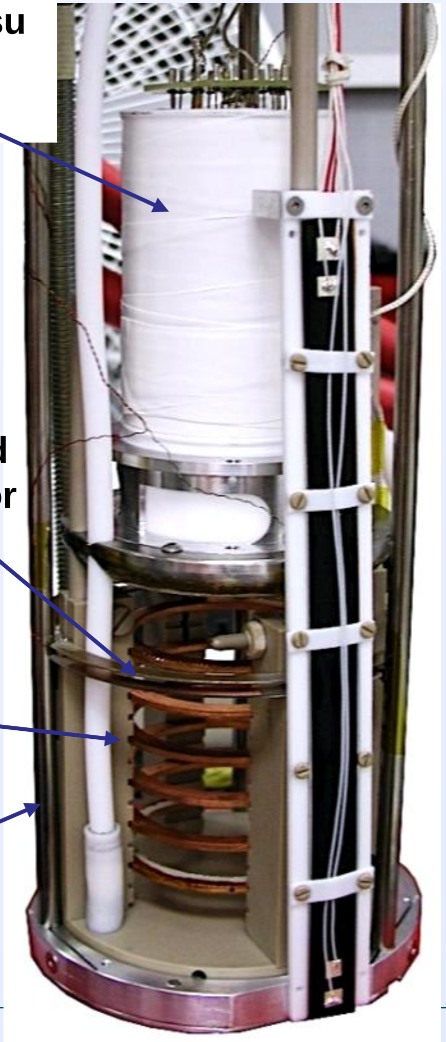
Rates in plot simulated@ 20 mwe

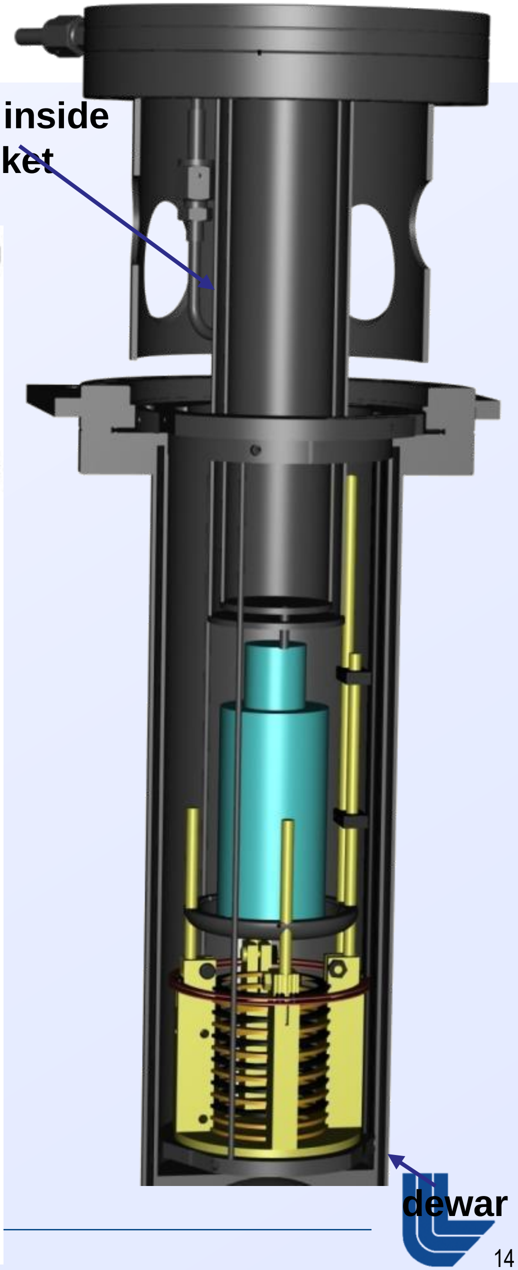
fiducialization of active volume and good discrimination between events with 1 and 2 primary electrons

Small Dual-phase Ar Detector

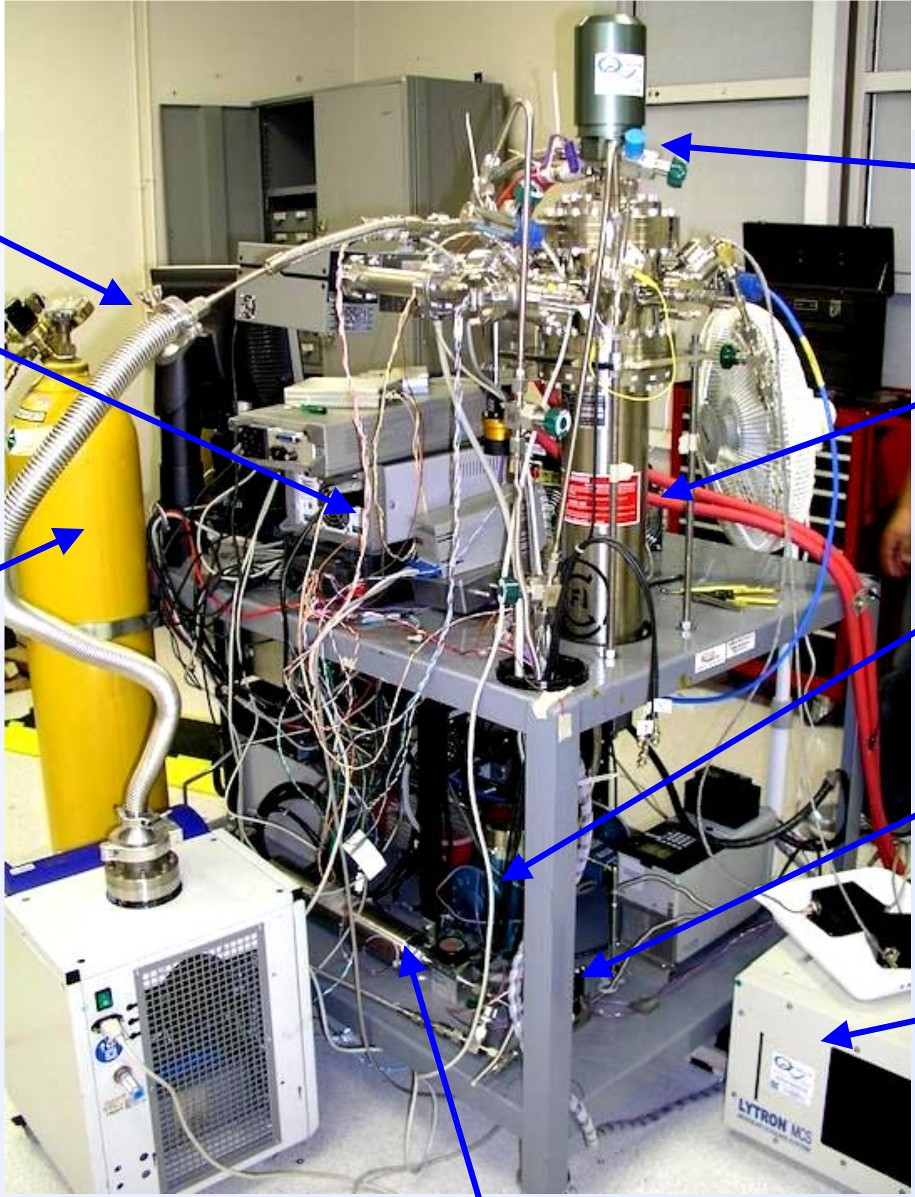
- Primary region volume: ~ 200 g LAr
- In-situ Liquid Ar production with cryocooler







Experiment Setup



DAQ

Slow control

Argon gas

cryocooler head

cryogenic dewar

circulation pump

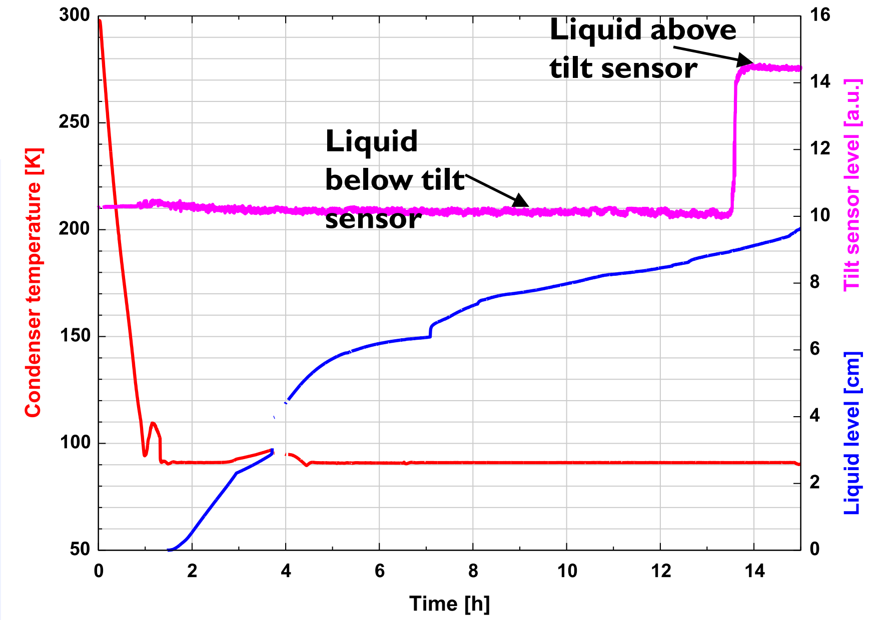
flow control

cryocooler cooling system

gas purifier

Cryogenic Performance

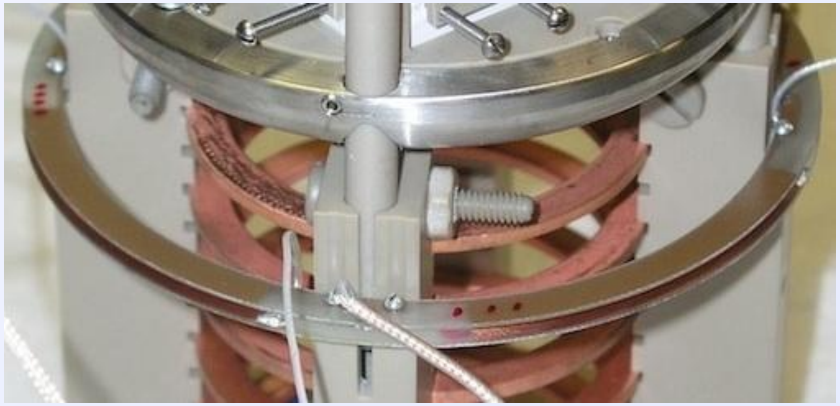
- Overnight cool-down and liquefaction
- Temperature stability ± 0.05 K
- Pressure stability ± 1 torr
- Continuous purification of Ar 2-3 times per day

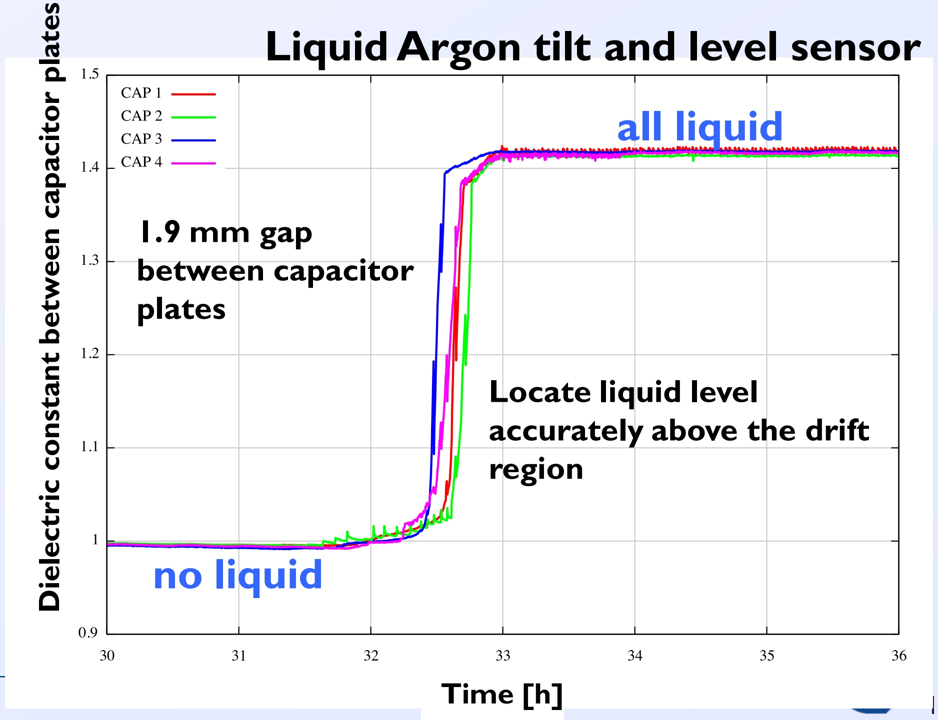


Liquid above tilt sensor

Liquid below tilt sensor

- Sensitive liquid level tilt sensor

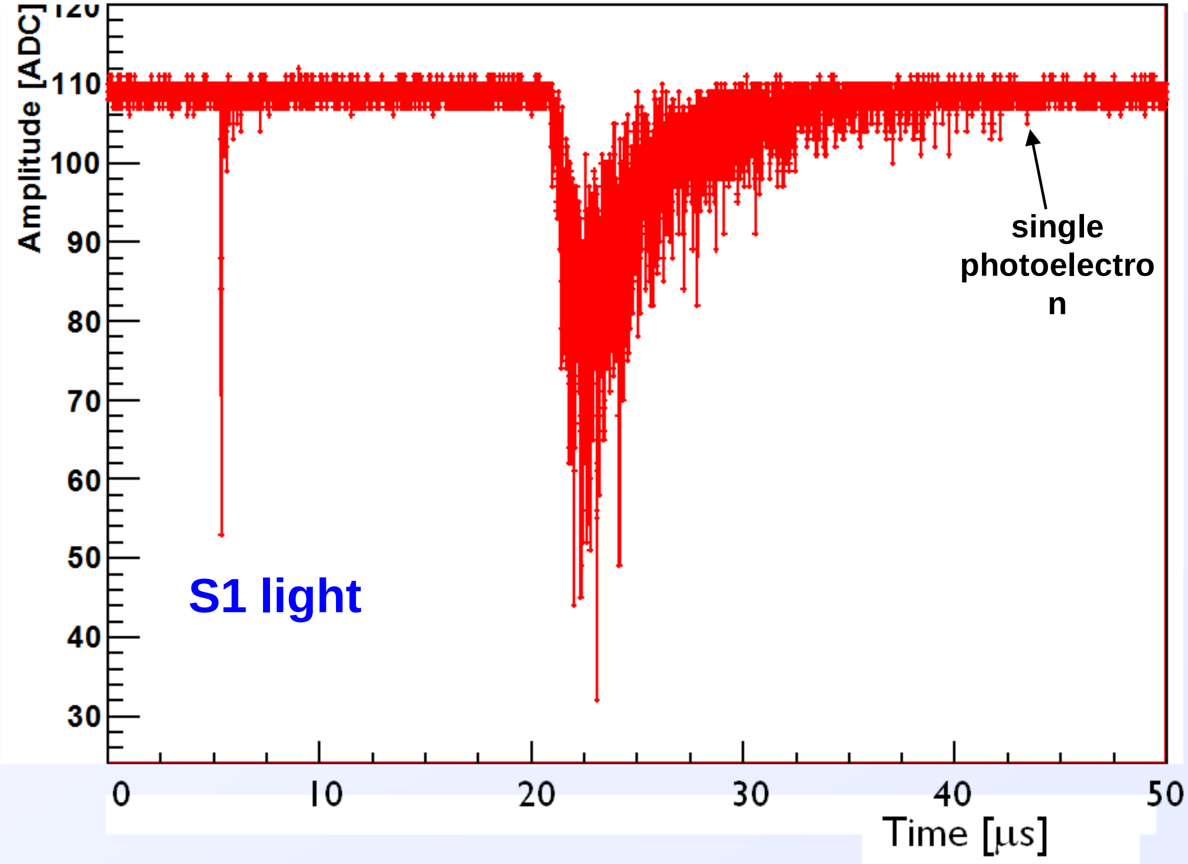


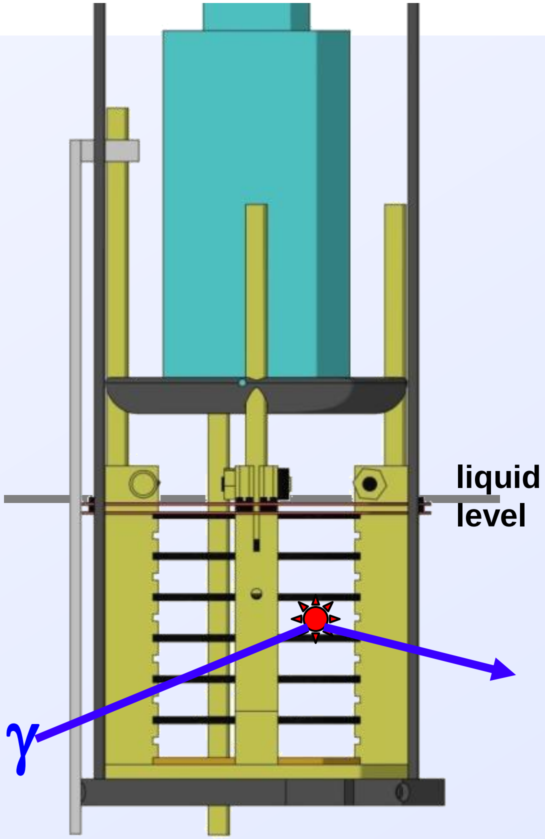


1.9 mm gap between capacitor plates

Locate liquid level accurately above the drift region

Detector Operation with γ Sources

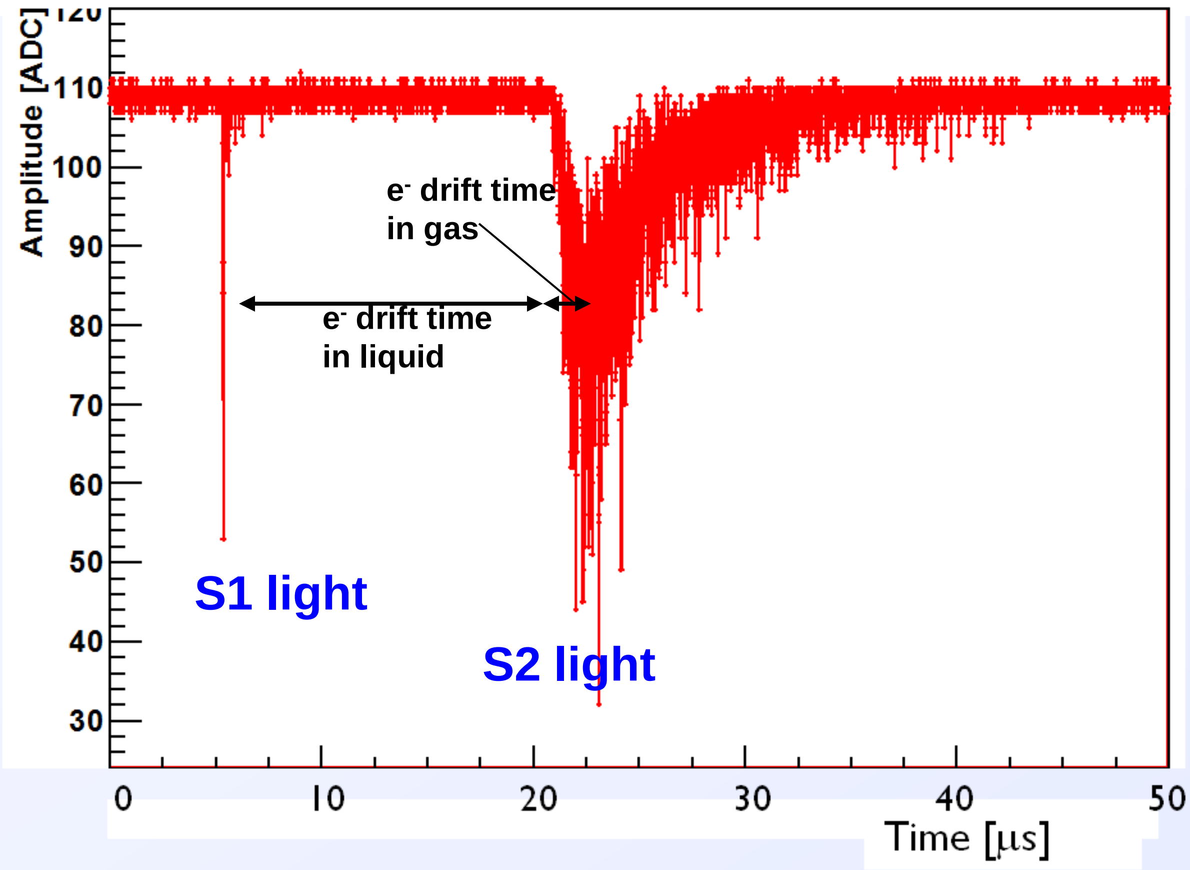


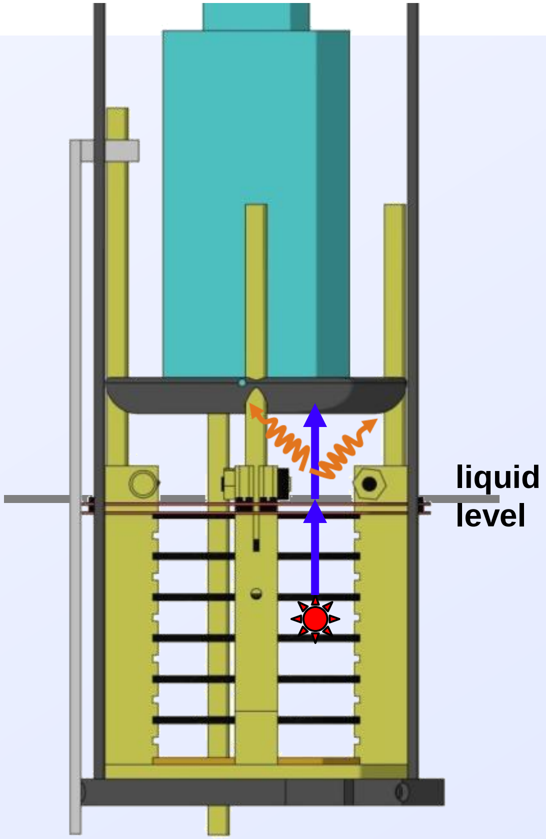


1. A γ interacts in the active region (e.g. Compton scatter)
2. Both excitation and ionization are produced
3. Excitation is detected immediately (S1 light)

- External high-energy γ source.
- Gain ~ 4 kV/cm
- Drift ~ 1 kV/cm

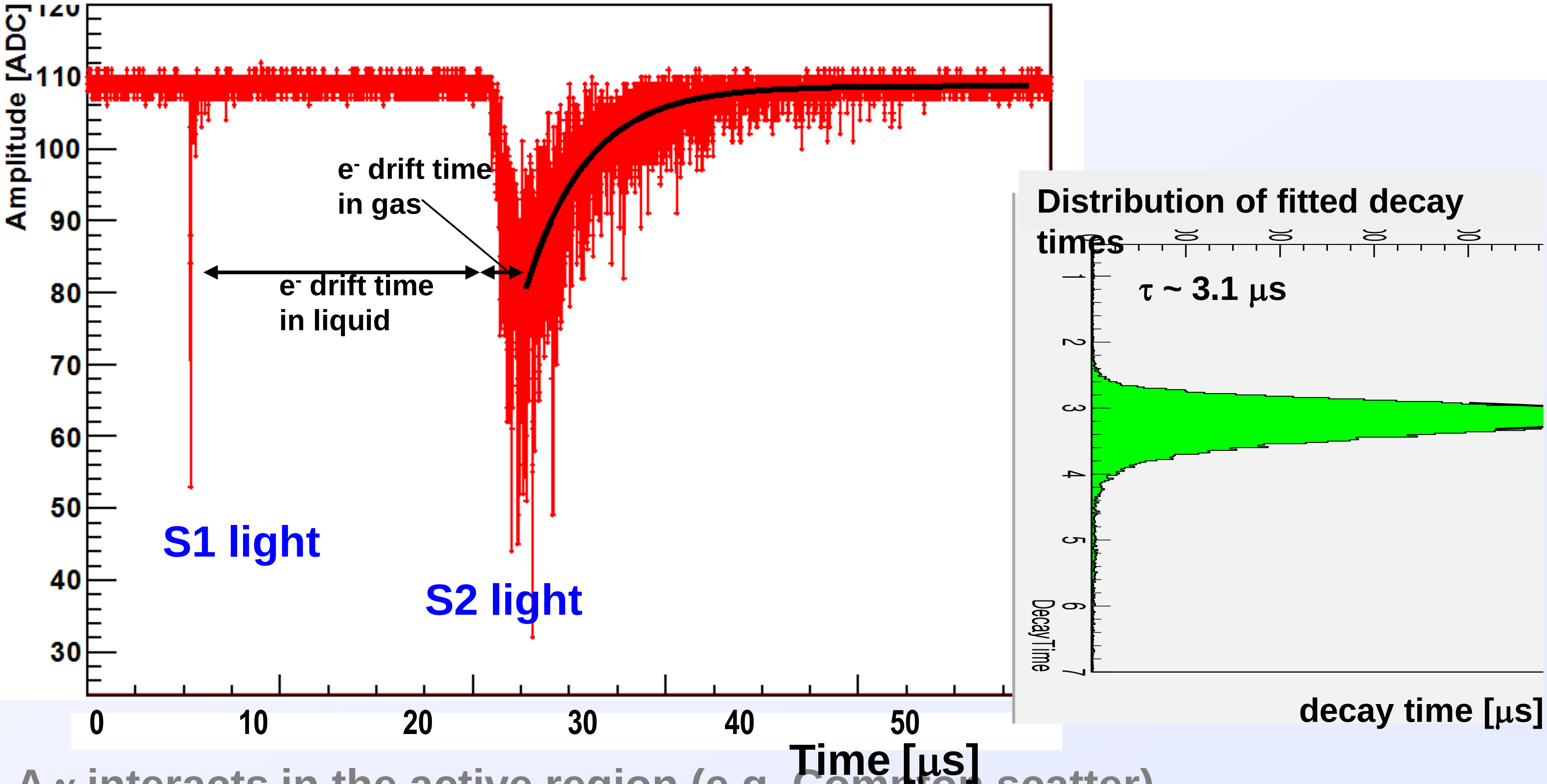
Detector Operation with γ Sources





1. A γ interacts in the active region (e.g. Compton scatter)
2. Both excitation and ionization are produced
3. Excitation is detected immediately (S1 light)
4. **The ionization is drifted in the liquid and transferred in the gas region**
5. **In the gas the electrons induce secondary scintillation (S2 light)**

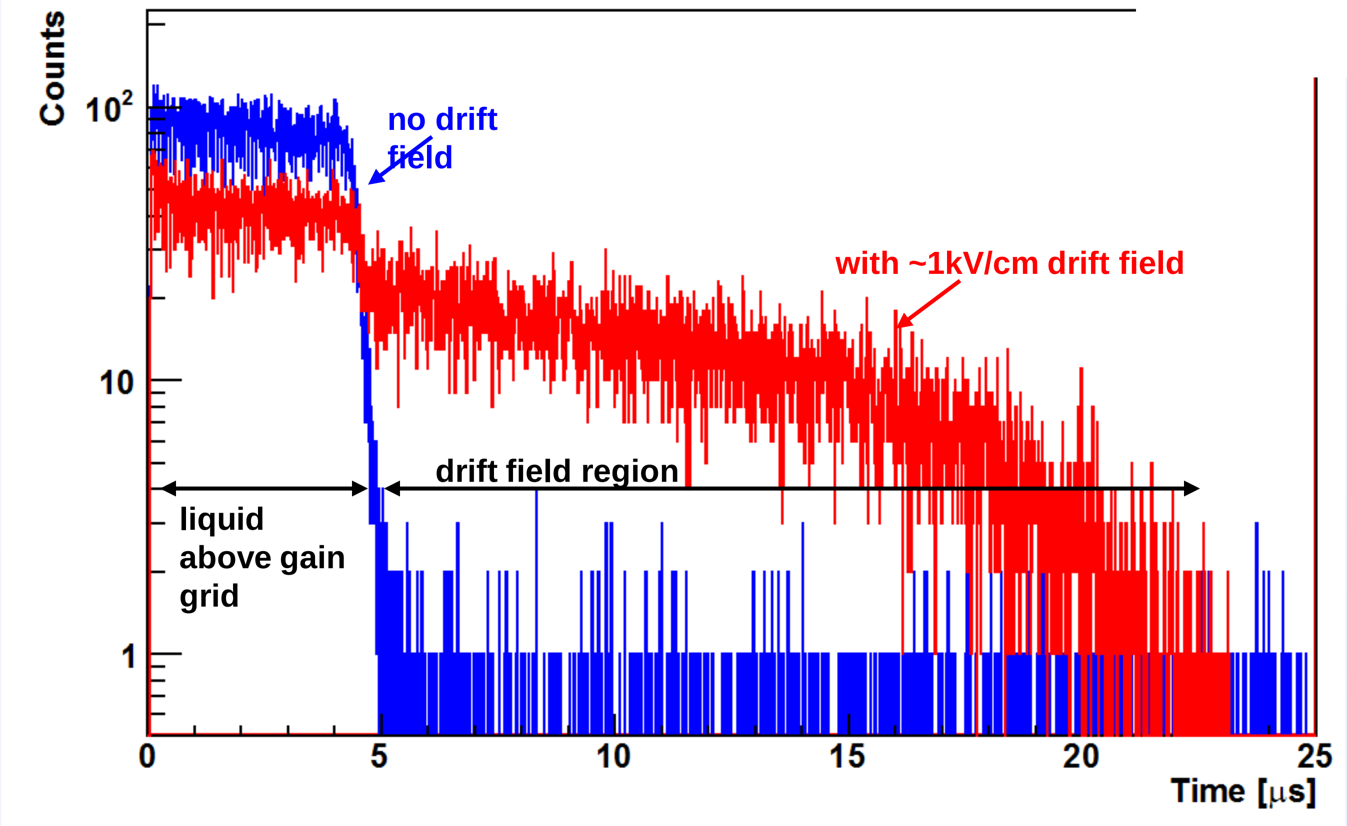
Detector Operation with γ Sources

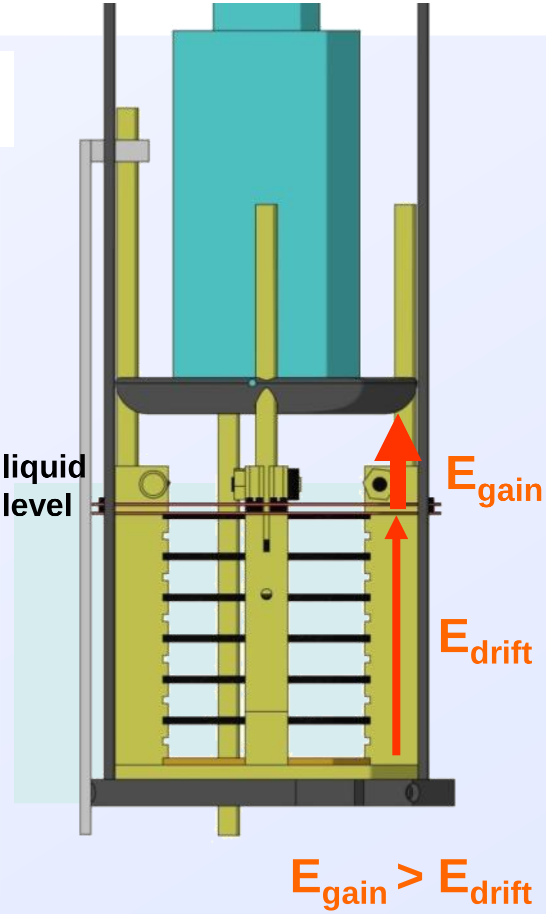


1. A γ interacts in the active region (e.g. Compton scatter)
2. Both excitation and ionization are produced
3. Excitation is detected immediately (S1 light)
4. The ionization is drifted in the liquid and transferred in the gas region
5. In the gas the electrons induce secondary scintillation (S2 light)
6. **The scintillation light decays with its characteristic time constant (expected τ=3.2 µs)**

Electron Drift in Liquid

Distribution of electron drift time in liquid
= time between S1 and S2





Current electron attenuation length of a few centimeters
But with short purification cycle and some outgassing materials

Next steps

- Minor detector modifications (nearly complete)
  - Remove possible contaminating materials, increase recirculation rate
  - Achieve electron drift length of 10 cm

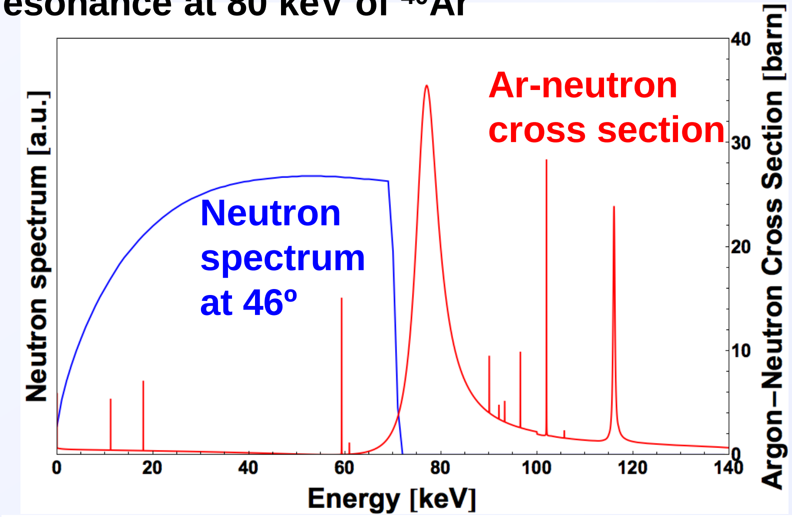
- Commissioning
  - calibration at low-energy electron recoils (^{37}Ar).
  - show sensitivity to single primary electrons

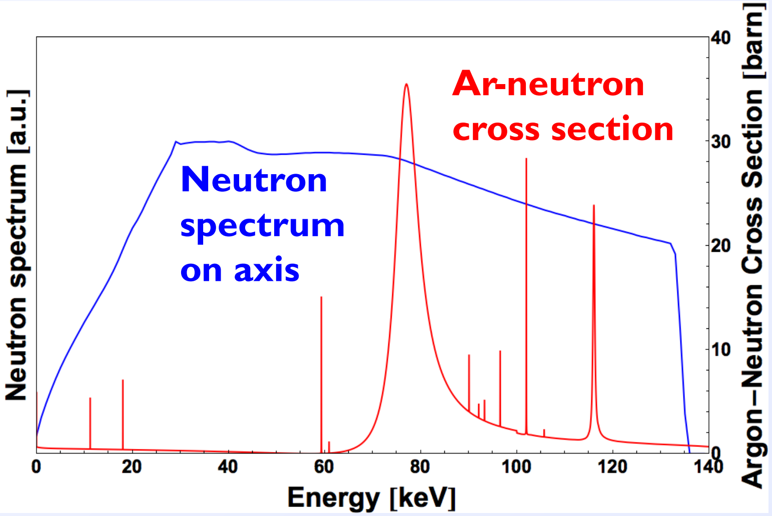
- Measure the Ionization Yield
  - using Neutrons
  - using Nuclear Resonance Fluorescence

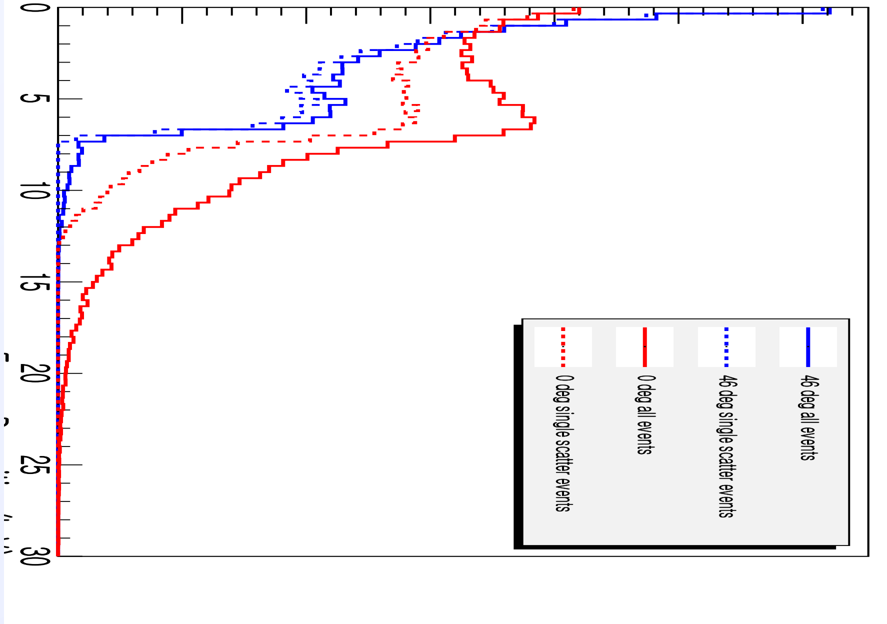
Nuclear-Recoil Ionization Yield using Neutrons

- Neutrons produced from 1.93MeV protons on a Li target at CAMS facility at LLNL
- Neutrons interact primarily within the resonance at 80 keV of ^{40}Ar

Ar recoils with energy up to ~8 keVr.







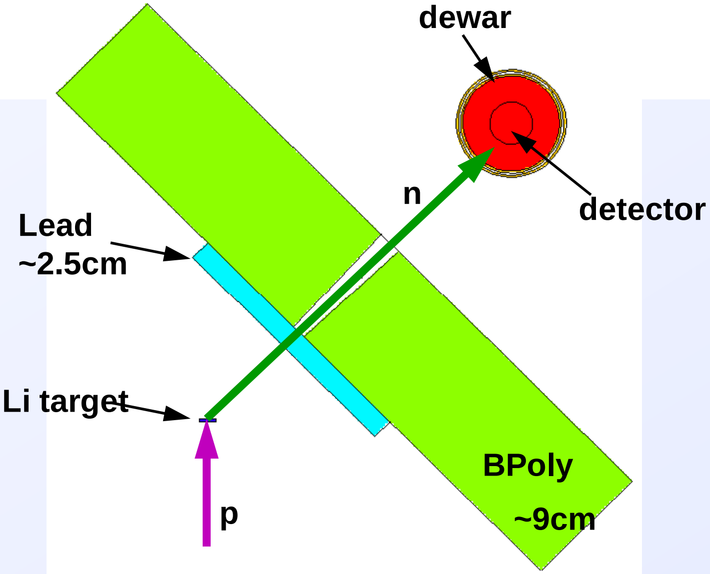
Off-axis:

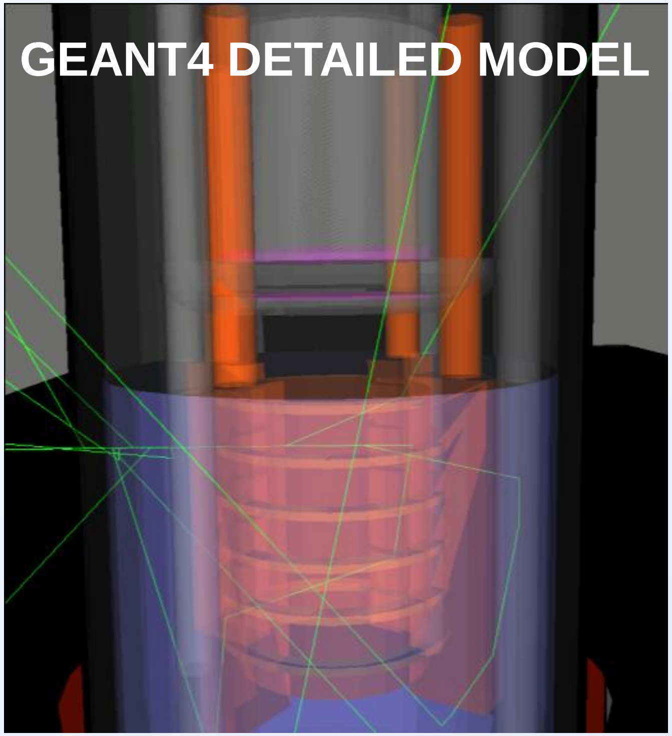
☺ reduced contribution of multiple scatterings

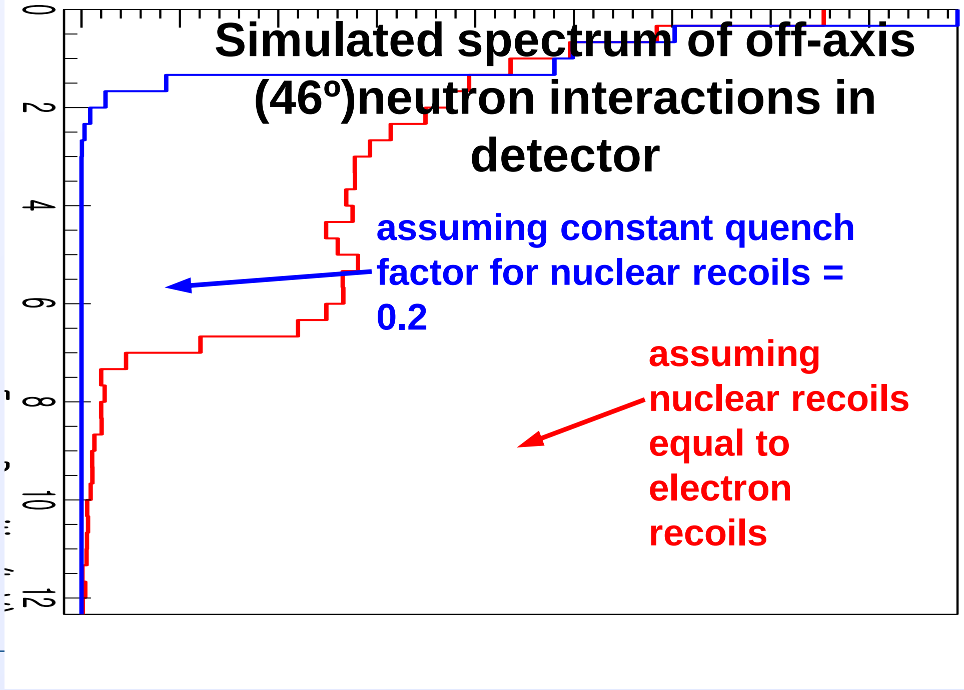
😐 overall lower rates

GEANT4 and MCNPX Simulations

- **Study signal and backgrounds rates**
- **Optimize**
  - **detector position**
  - **proton energy**
  - **collimation and shielding**




GEANT4 DETAILED MODEL

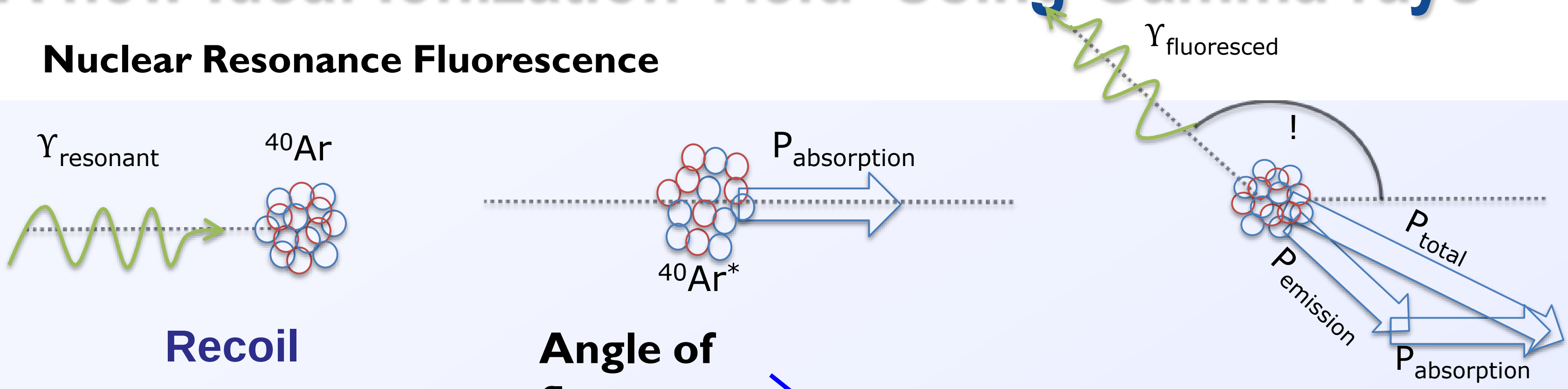

Simulated spectrum of off-axis (46º)neutron interactions in detector

assuming constant quench factor for nuclear recoils = 0.2

assuming nuclear recoils equal to electron recoils

A new Idea: Ionization Yield Using Gamma-rays

- **Nuclear Resonance Fluorescence**



Recoil energy

Angle of fluorescence

$$E_{\mathrm{NR}} = \frac{2(E_r \sin(\theta/2))^2}{Mc^2}$$

Resonance energy
(for Ar: 4.8 MeV & 9.8 MeV)

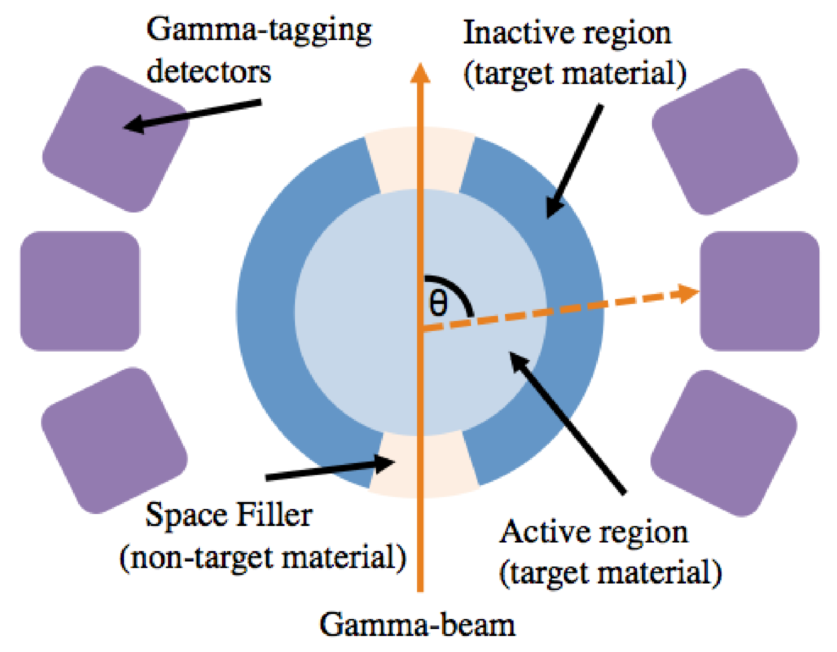
Argon mass

- **Reconstruct energy across full range, not just an end-point**
- 60 hours of beam time awarded by HIγS at Duke Univ.

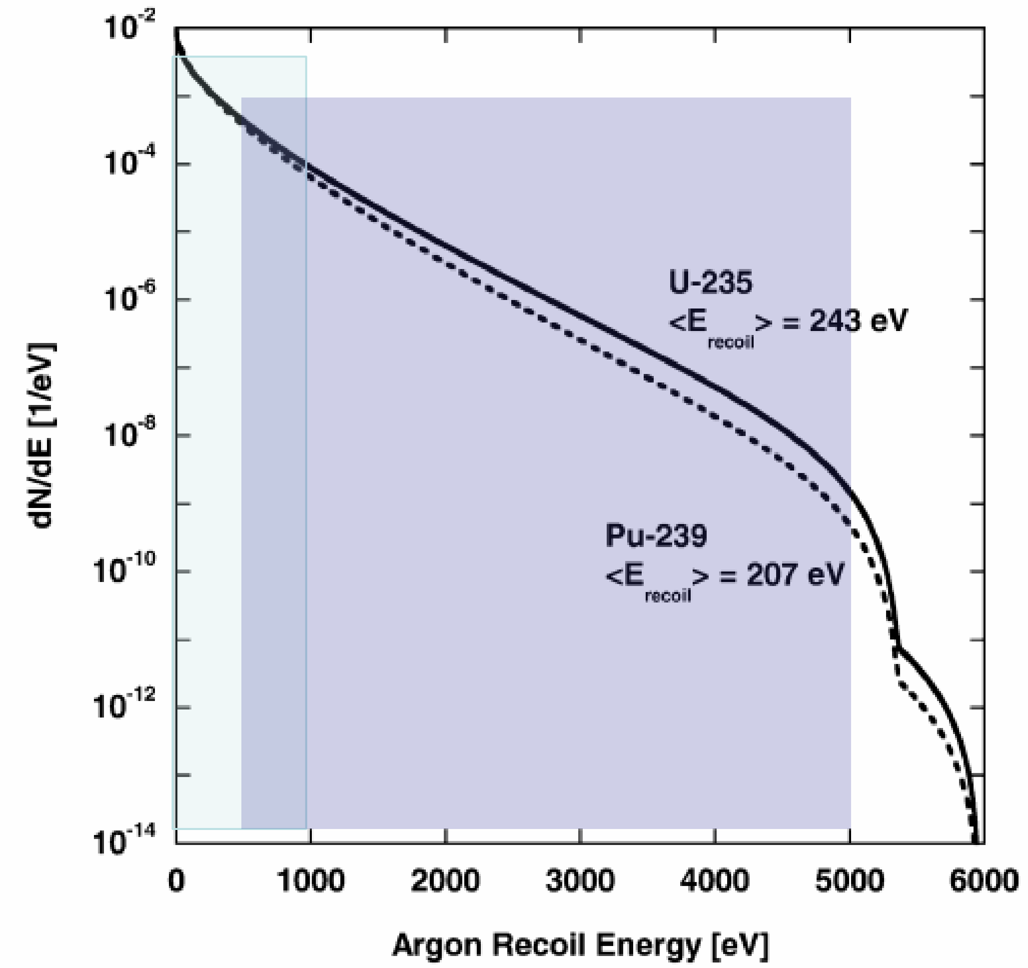
T. Joshi, NIM A 656 (2011)

Probe sub-keV Nuclear Recoil Energies

- **Modify detector**
- **Add gamma tagging detectors**



- **Sub-keV** recoil energies could be accessed depending on the fluorescence angle and resonance energy (4.8/9.8 MeV)



Conclusions

- Coherent Neutrino Scatter is interesting for basic science - and possibly for non-proliferation applications
- Dual-phase noble-element detectors – may be suitable for detecting CNS
- Measurement of the ionization yield for nuclear recoils below ~keVr energies is a key element toward the observation of CNS and its use for reactor monitoring

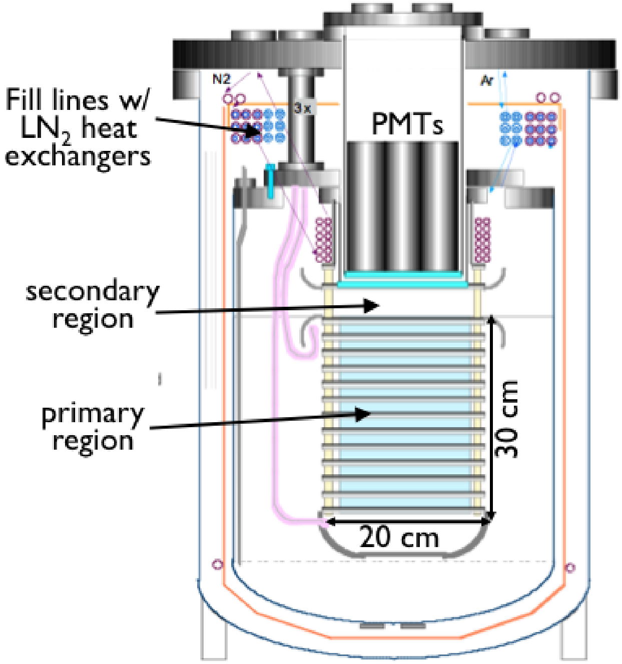
Neutron recoil measurements
Gamma-ray fluorescence measurements

- Upon successful deployment of the small prototype, we will develop a larger detector to measure Coherent Scatter at a nuclear power plant.
- Not discussed here: other detection approaches – phonon based detection may also be possible

Detector for Reactor Monitoring

- Performed preliminary design study for a 10-kg liquid/gas Argon detector
- Stringent technical requirements
  - small footprint
  - movable
  - modular design for installation in hard-to-get locations
  - limited electrical power
  - very limited network access for remote control and operation
  - limited time access for operators
  - no ready access to liquid cryogens
  - shallow depth → shielding
  - safety
  - limited air circulation and no air conditioning
  - harsh environment: dust, humidity, noise, vibrations

A possible schematic design of the 10-kg dual-phase detector



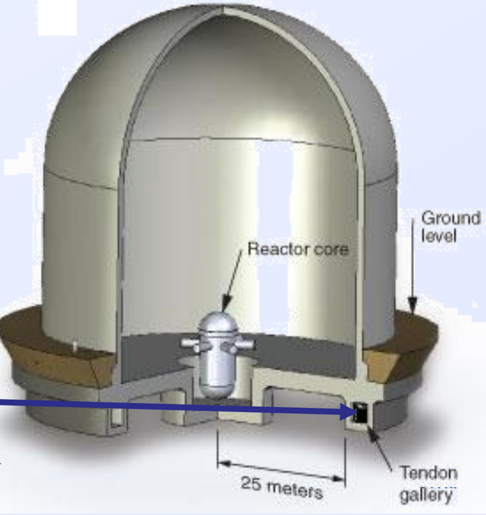


Image from LLNL ST&R Jul/Aug 2008 https://www.llnl.gov/str/JulAug08/bernstein .html

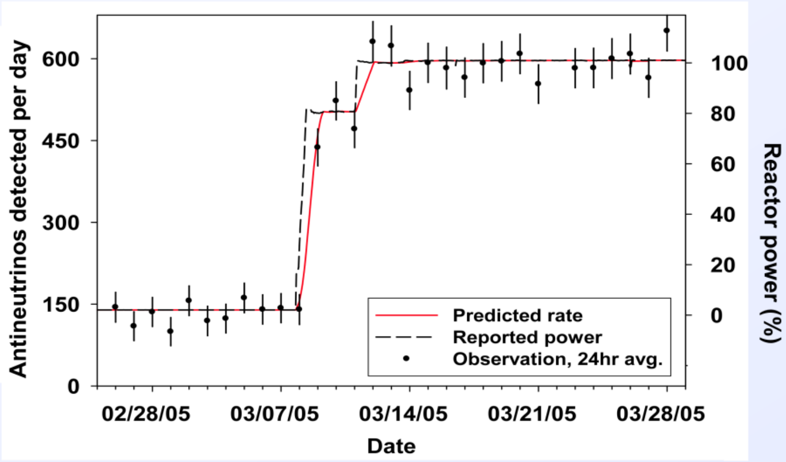
Possible location: Tendon Gallery of a PWR ~ 25 m from core

The eventual deployment site

- To be sited at a nuclear power plant (e.g., the San Onofre Nuclear Generating Station)
- Assuming 100% efficiency in detecting 2 or more primary electrons, we expect ~ 80 events/day (ν flux of 6×10^{12} cm^{-2} s^{-1})

→ first observation ever of CNS !

SONGS antineutrino detector



N. S. Bowden, Journal of Physics: Conference Series, **136** (2008).

from nrc.gov

HIϒS Experiment

High Intensity ϒ-ray Source (HIϒS)

- Located at the Duke Free Electron Laser Laboratory
- γ-Production: Compton backscatter

High Resolution Mode

- Energy resolution ~1%
- ~2 x 10^5 γ/sec at 4.769 MeV [a]
- 2.79 MHz γ production frequency

Experimental plans

- 60 hours of beam-time awarded by HIϒS external Program Advisory Committee
- Instrument dual-phase detector cart with ϒ-tagging detectors and a new DAQ
- Two beam energies
  - 4.769 MeV
  - 9.503 MeV
- Three ϒ-tagging angles per energy
  - 30, 90, 150 degrees