Dark matter searches with the PICO bubble chambers

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TeVPA 2017 – August 8 – Ohio State University

PICO

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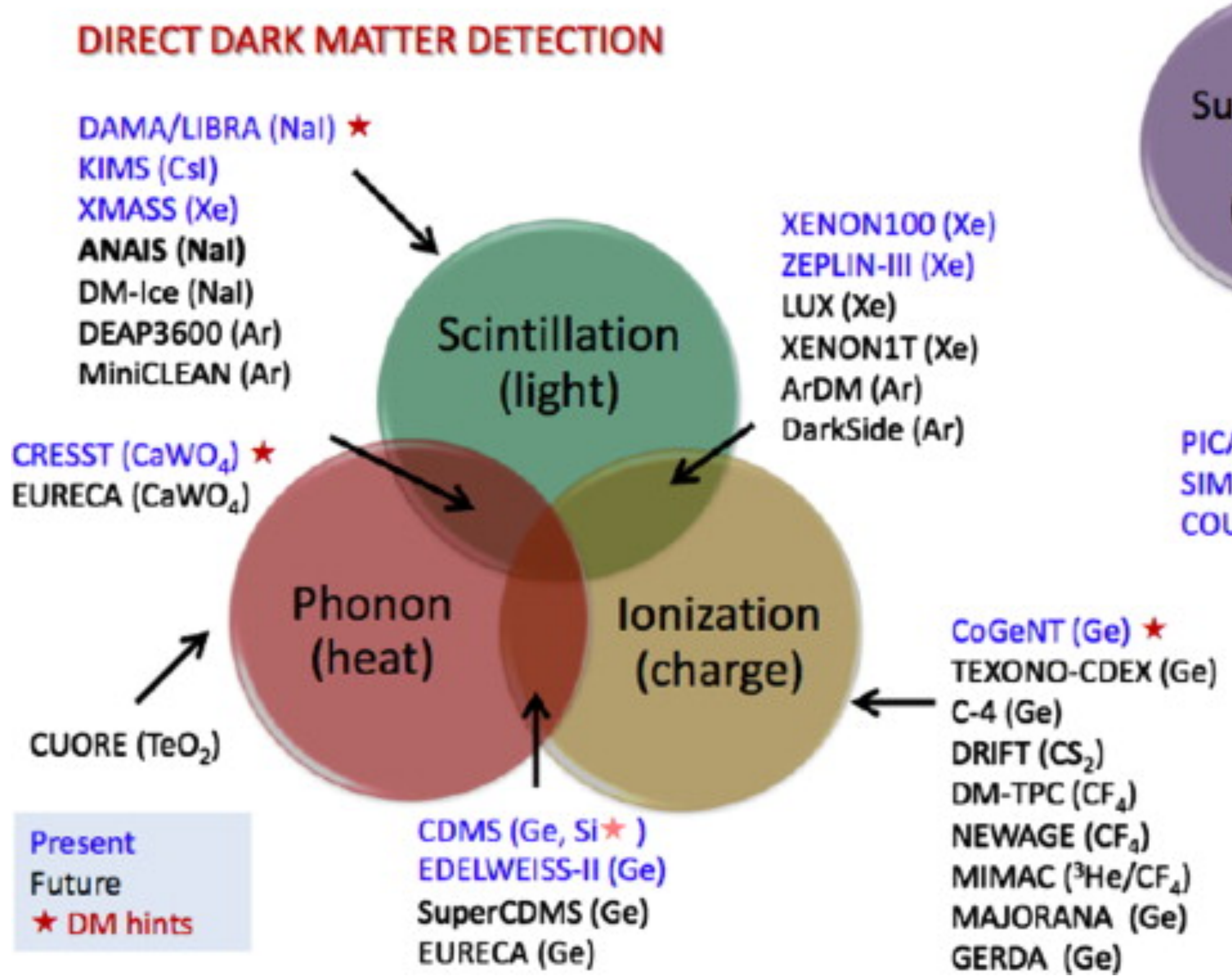
Overview

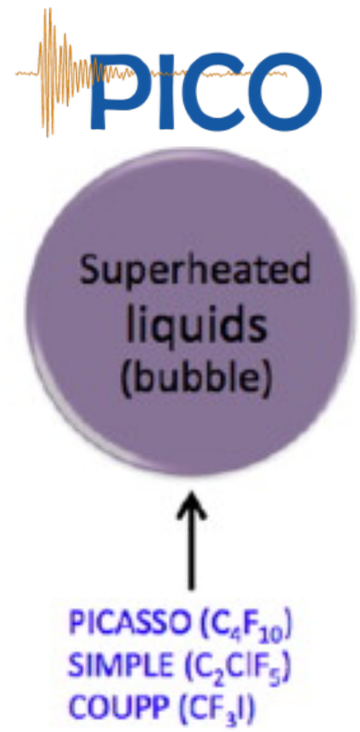
- Dark matter direct detection: spin-independent **(SI)** vs. spin-dependent **(SD)** WIMP-nucleon couplings
- Bubble chambers for direct detection: the PICO program
- The **PICO-60** C_3F_8 detector; Run-1 WIMP-search results
- Next chamber: **PICO-40L**

  Design/background goals, timeline, physics reach
- Future ton-scale chamber: **PICO-500**

Direct detection: channels



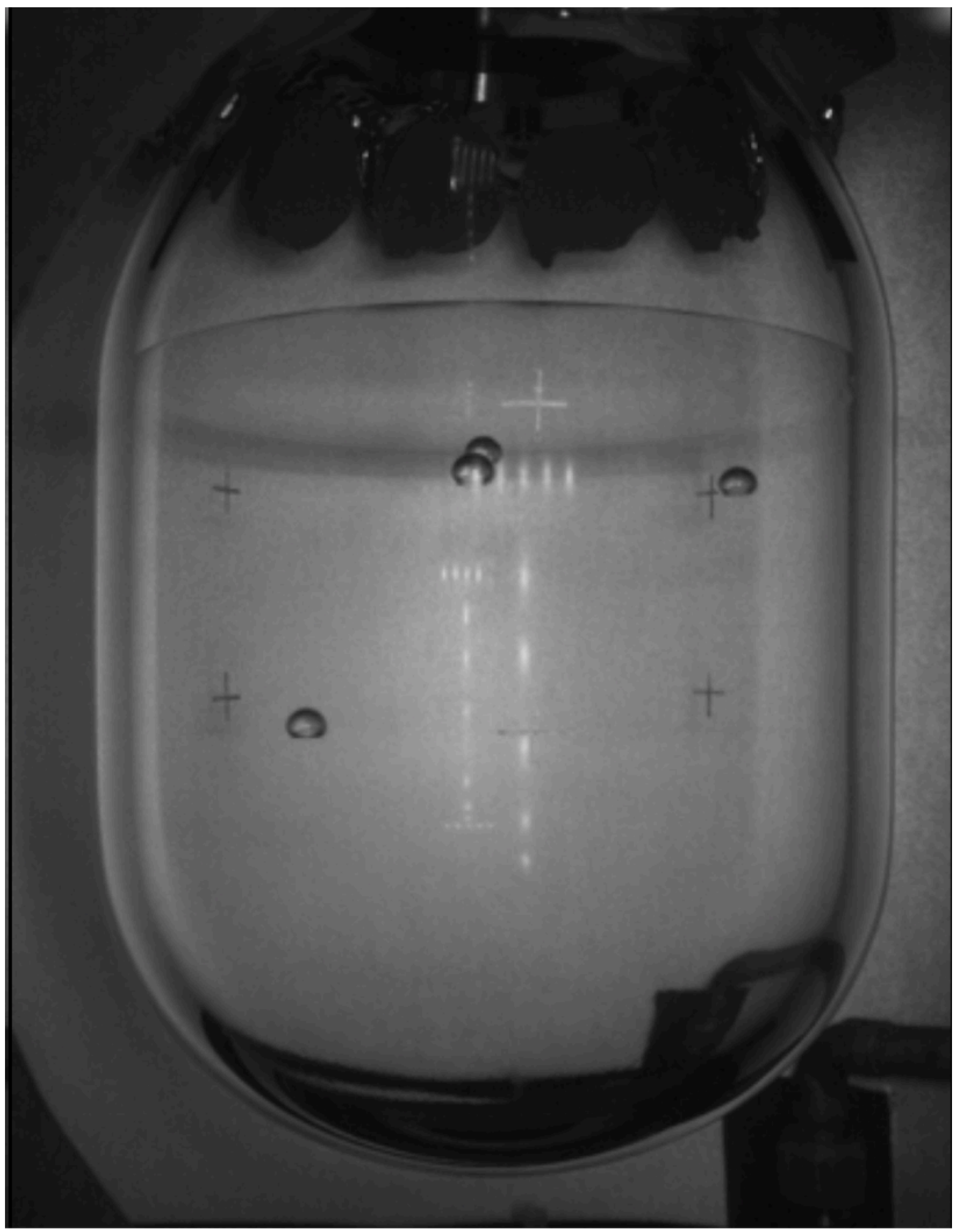
Zornoza, NIM. A 742 130-138 (2014)

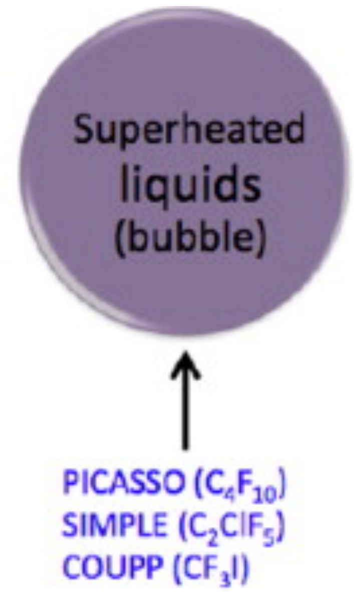


- Bubble chambers **don't** use the typical direct detection channels

(exception: scintillating LXe BC – see slides from J. Zhang's talk, TeVPA 2017, Mon 7 Aug, 5:15pm)

Direct detection: channels





- Bubble chambers **don't** use the typical direct detection channels
- They're **threshold** detectors
- No direct measurement of recoil energy, however…
- **Acoustic** signals do enable both spectroscopy and discrimination (arguably fits in the "heat" category)

Direct detection: SI vs SD

Two primary interactions considered by experimentalists:

- **Spin-independent (SI):** couples to all nucleons
  - A^2 enhancement for large nuclei (coherent scattering)
- **Spin-dependent (SD):** couples to the spin of the nucleus, i.e. unpaired spin of one nucleon

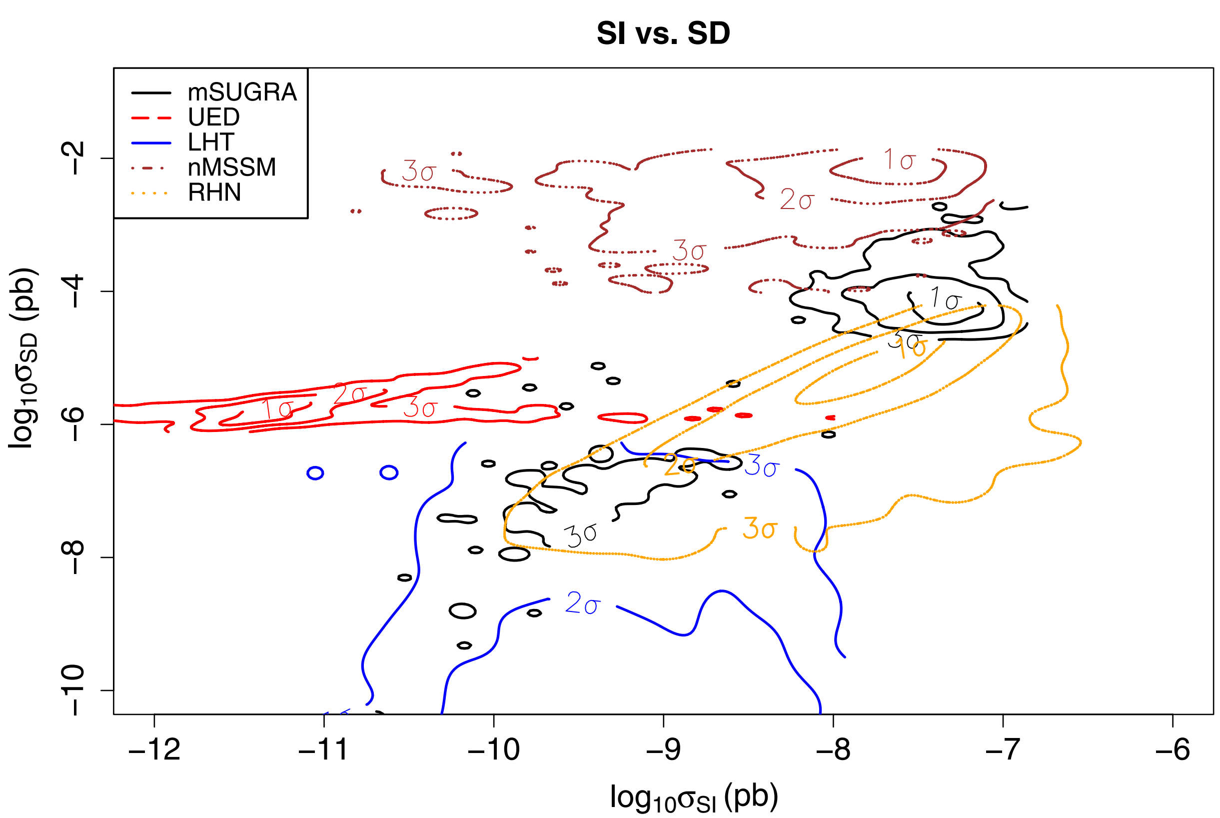
(^{19}F, ^{73}Ge, $^{129/131}Xe$, …)

  - "SDp" and "SDn" are similar but not directly comparable

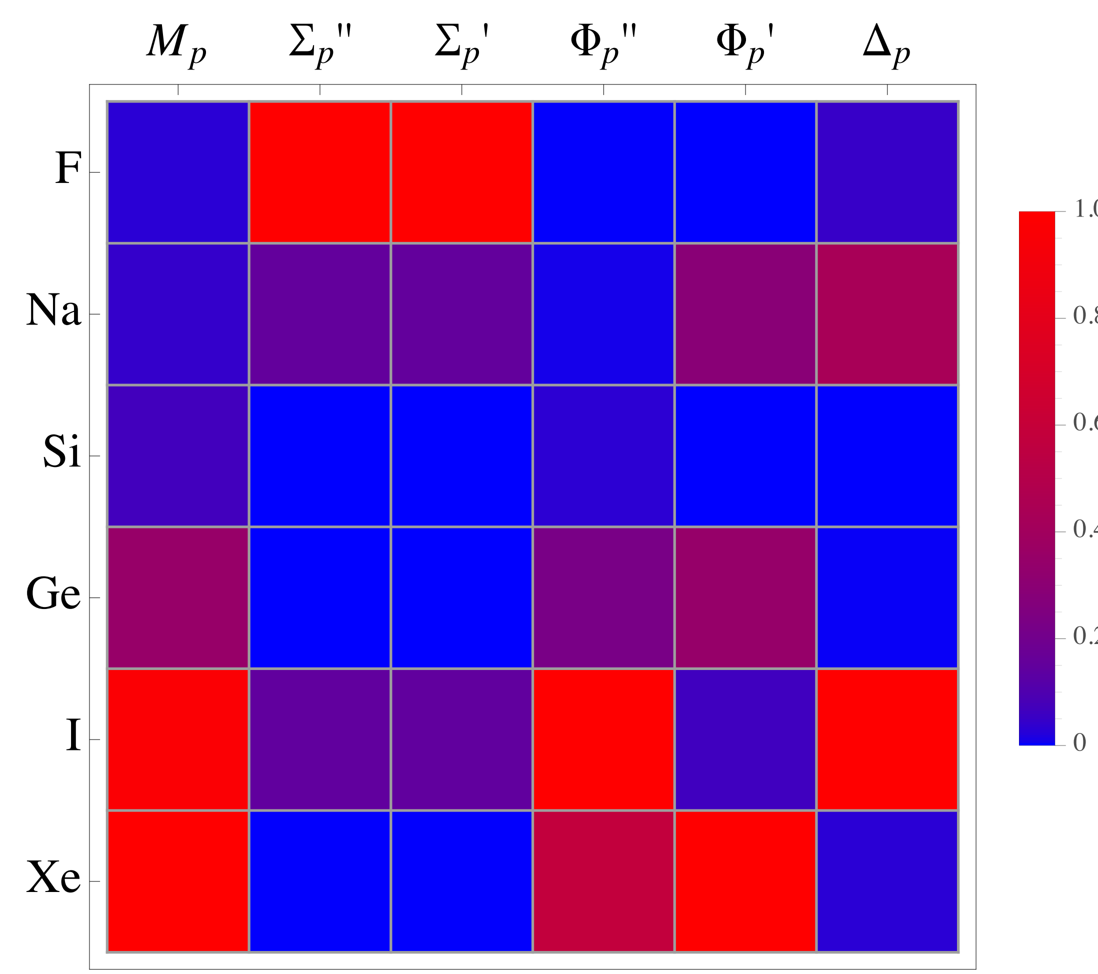
SI vs. SD (vs. nuclear physics/EFT)

- Spin-independent searches have received the most attention due to the A^2 rate enhancement (>15,000 for xenon)

- But the actual mechanism is unknown, and may be more complicated



SD vs. SI cross section predictions for different models (Barger, PRD, 78 056007)



Sensitivity of different p-coupling operators to various nuclear targets (L. Fitzpatrick, INT Workshop, 2014)

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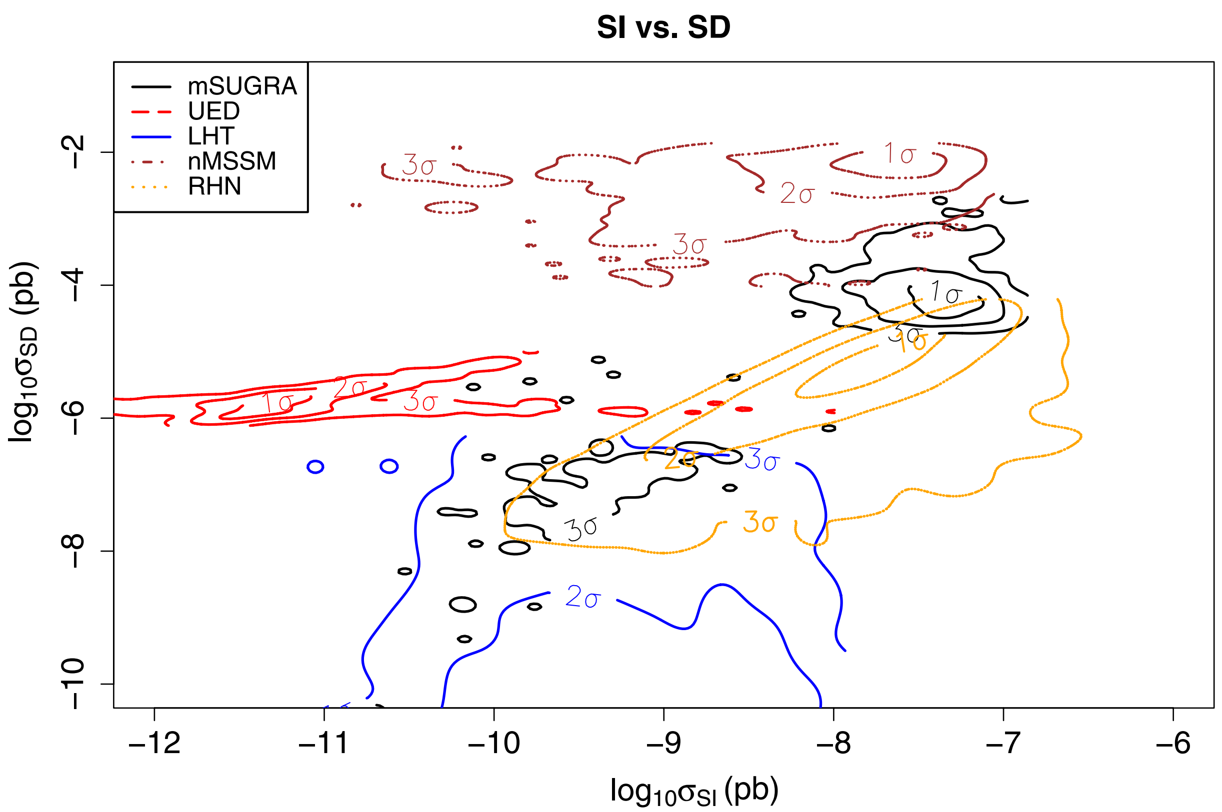

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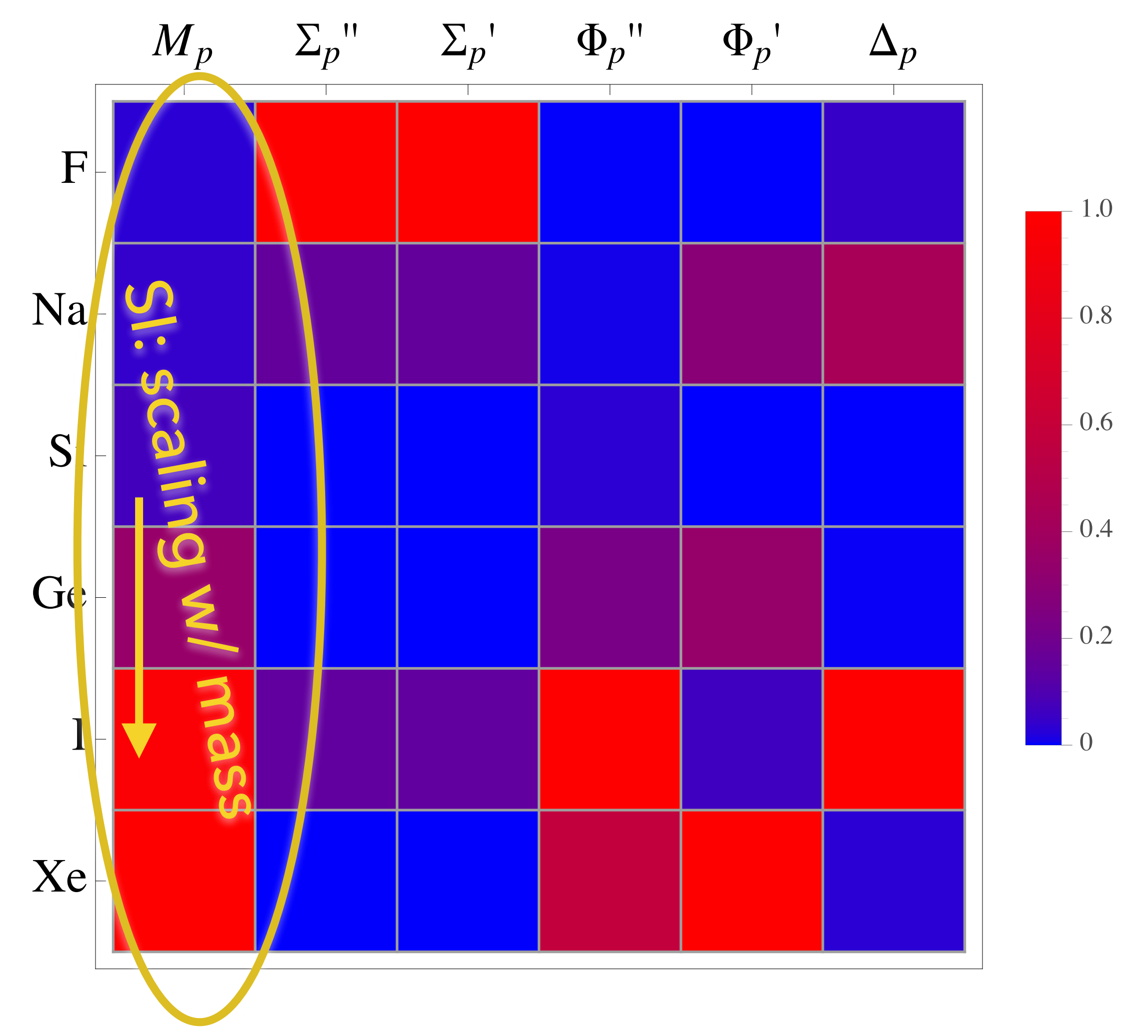

Sensitivity of different p-coupling operators to various nuclear targets (L. Fitzpatrick, INT Workshop, 2014)

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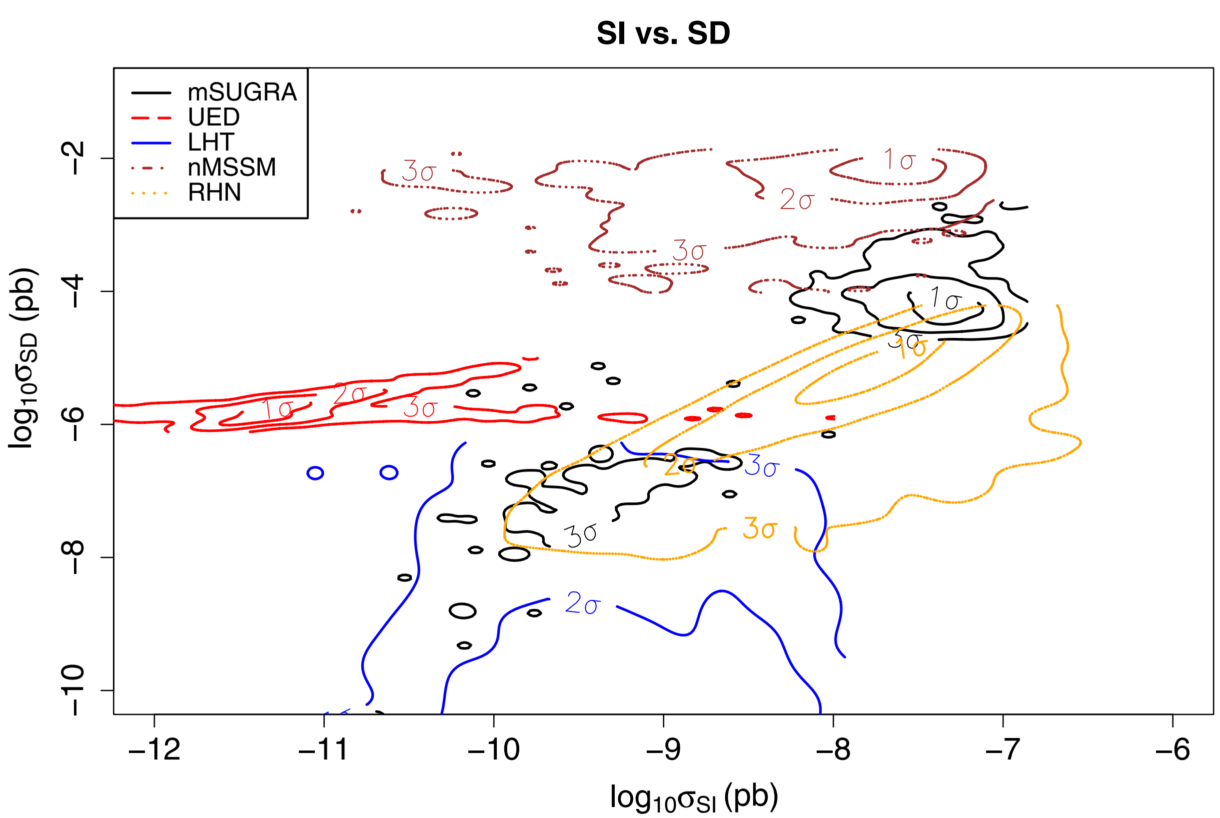

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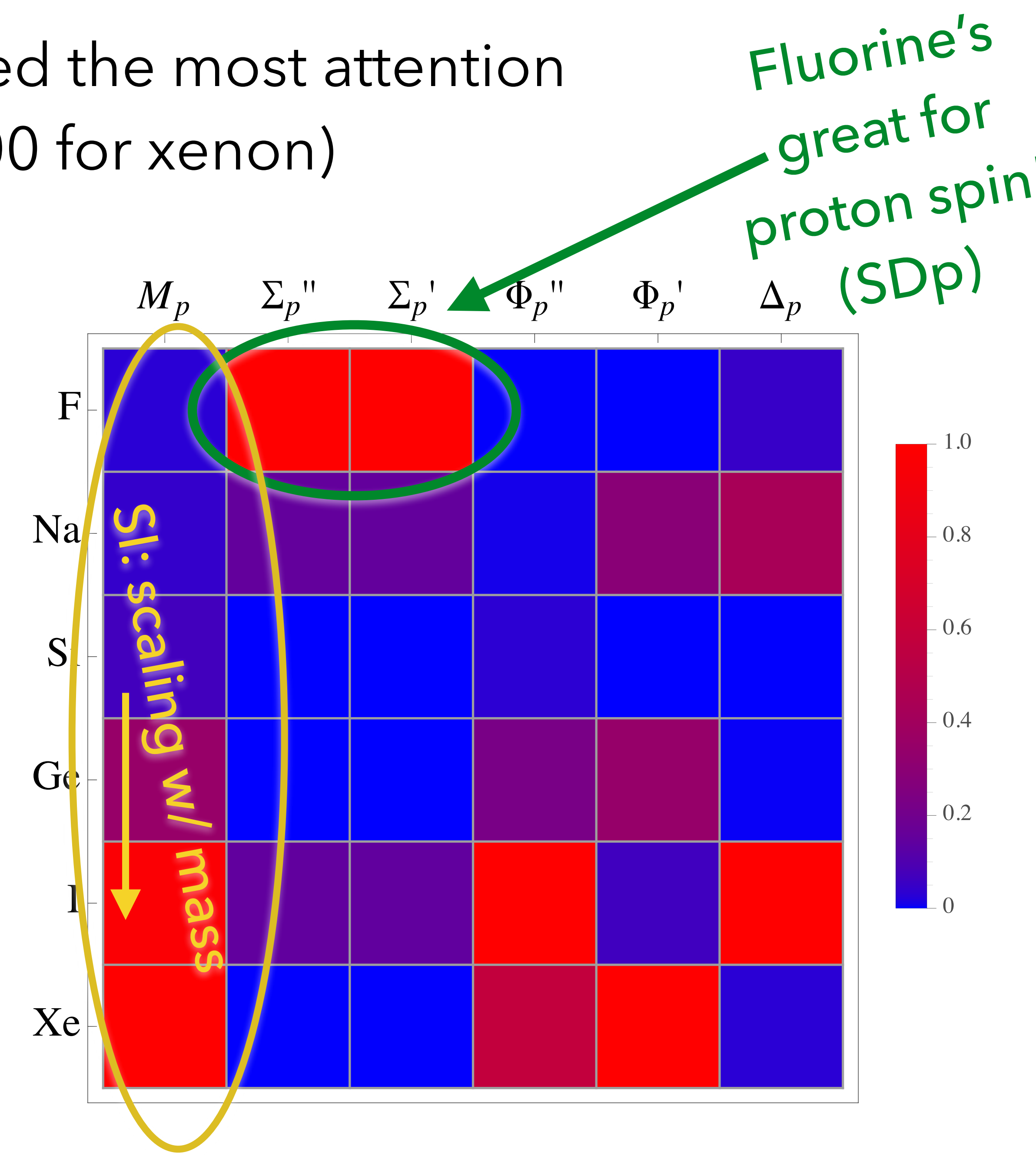

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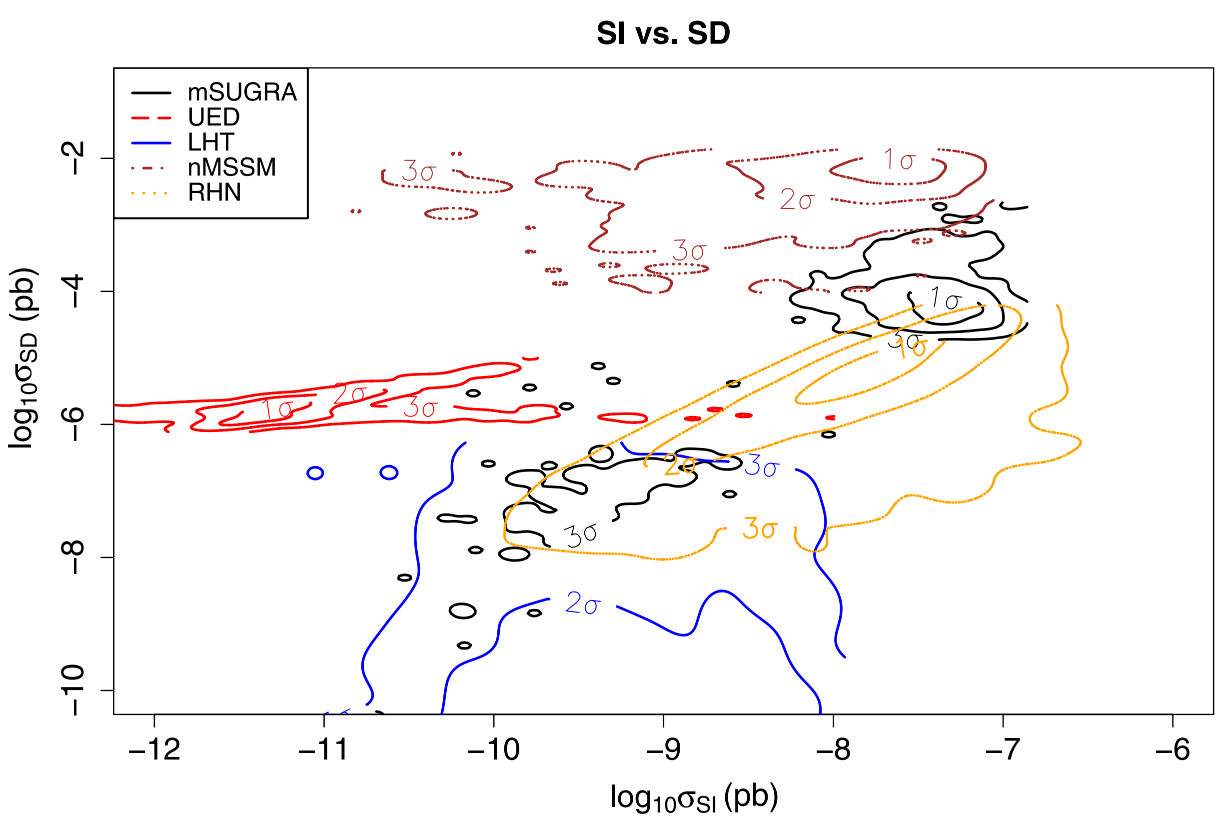

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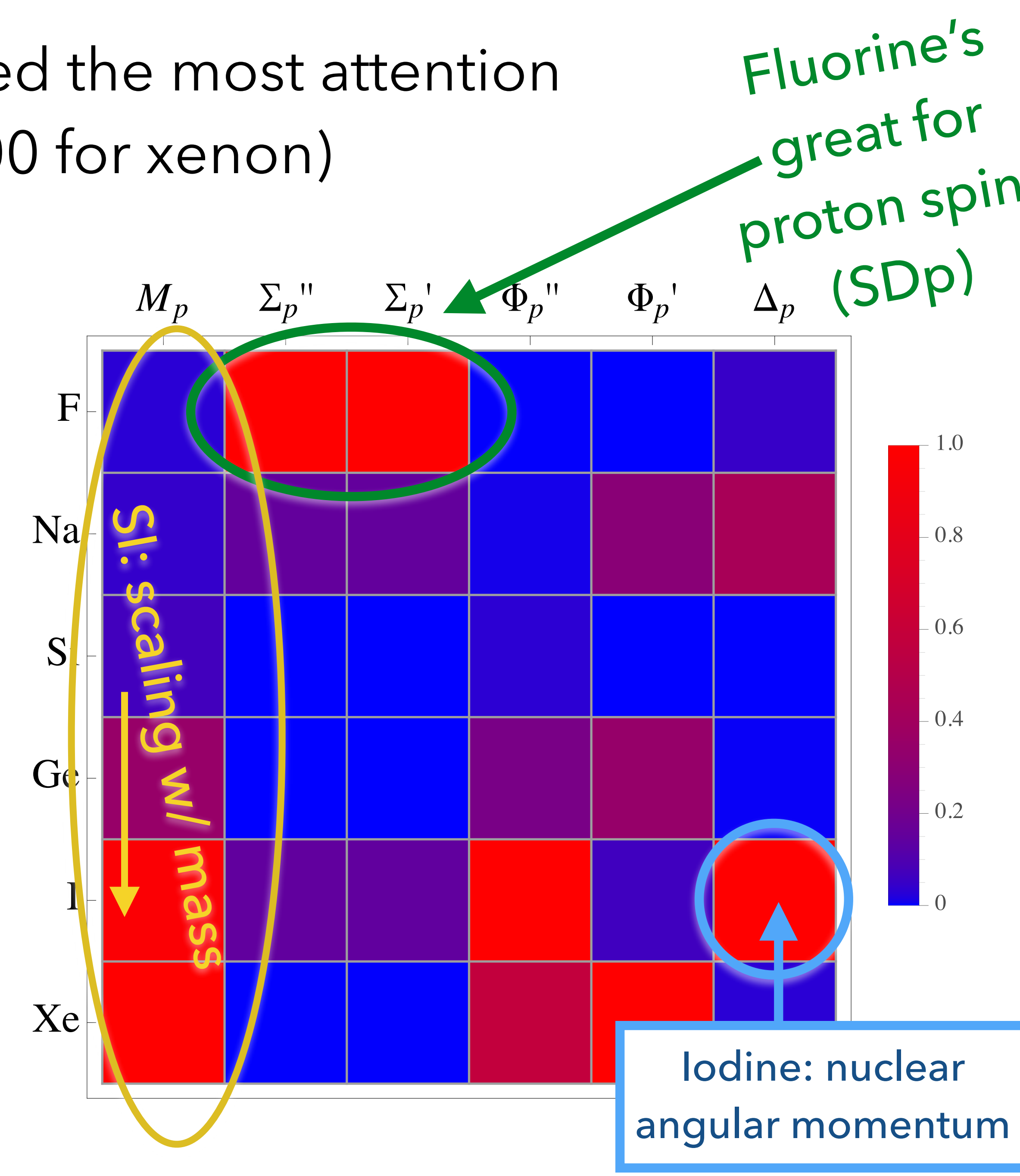
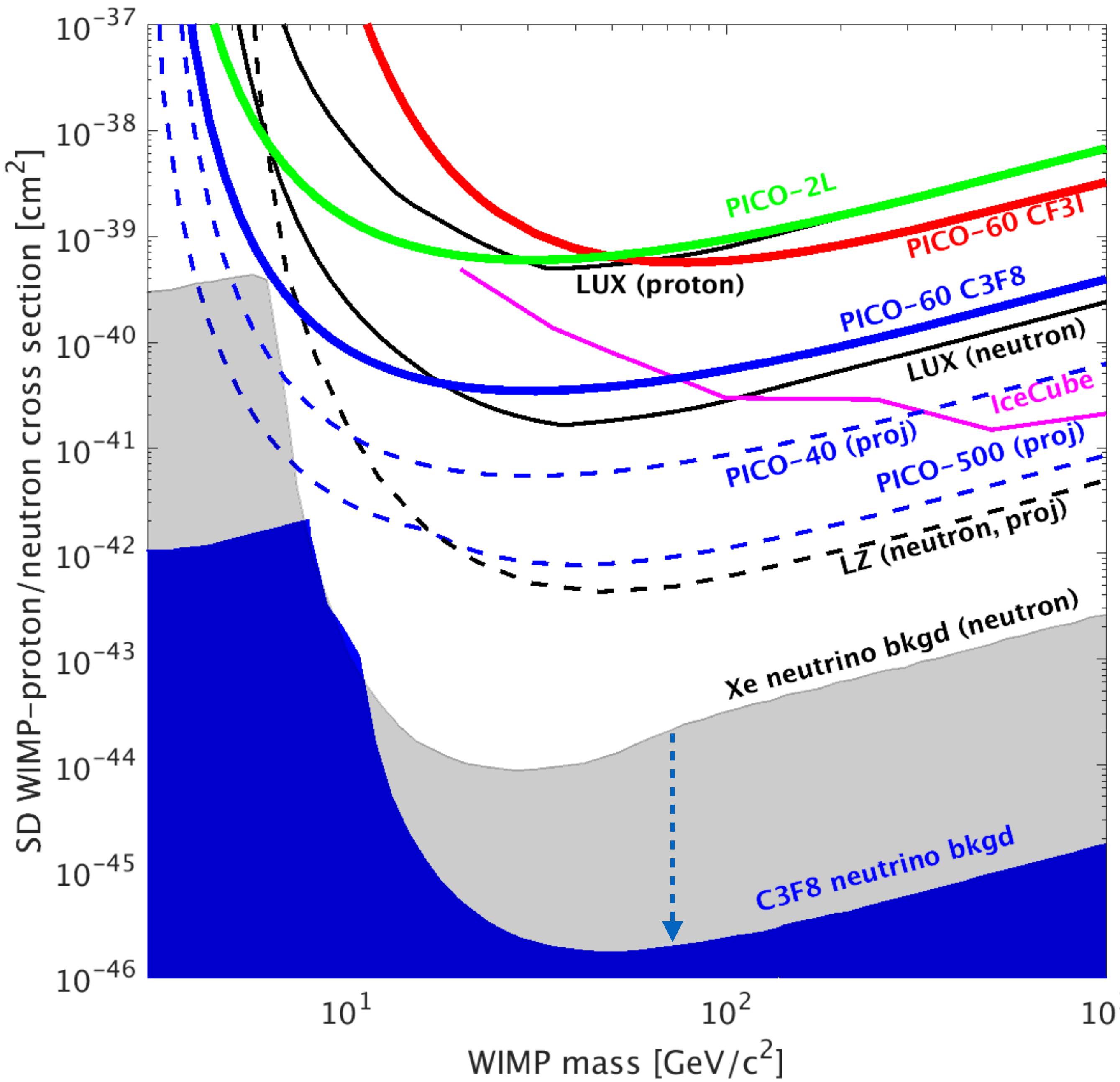


Sensitivity of different p-coupling operators to various nuclear targets (L. Fitzpatrick, INT Workshop, 2014)

Why is SD interesting?

- **PICO-500's SD-proton** sensitivity is very similar to **LZ's SD-neutron** sensitivity
- So: given typical SD/SI cross-section ratios, a first discovery by PICO-500 is plausible
- The CEνNS floor is much lower for F than for Xe: we actually want to **minimize SI** sensitivity in order to **maximize SD reach**

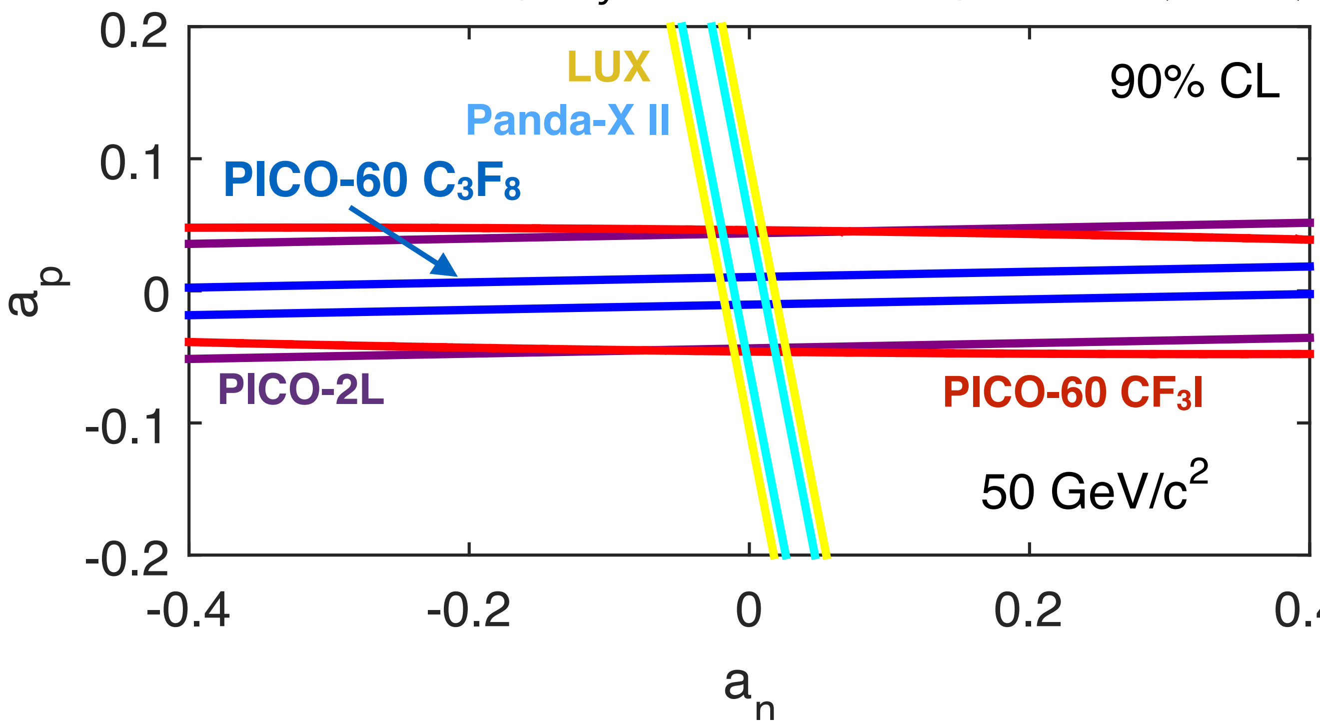
SD WIMP-proton/-neutron **combined** plot



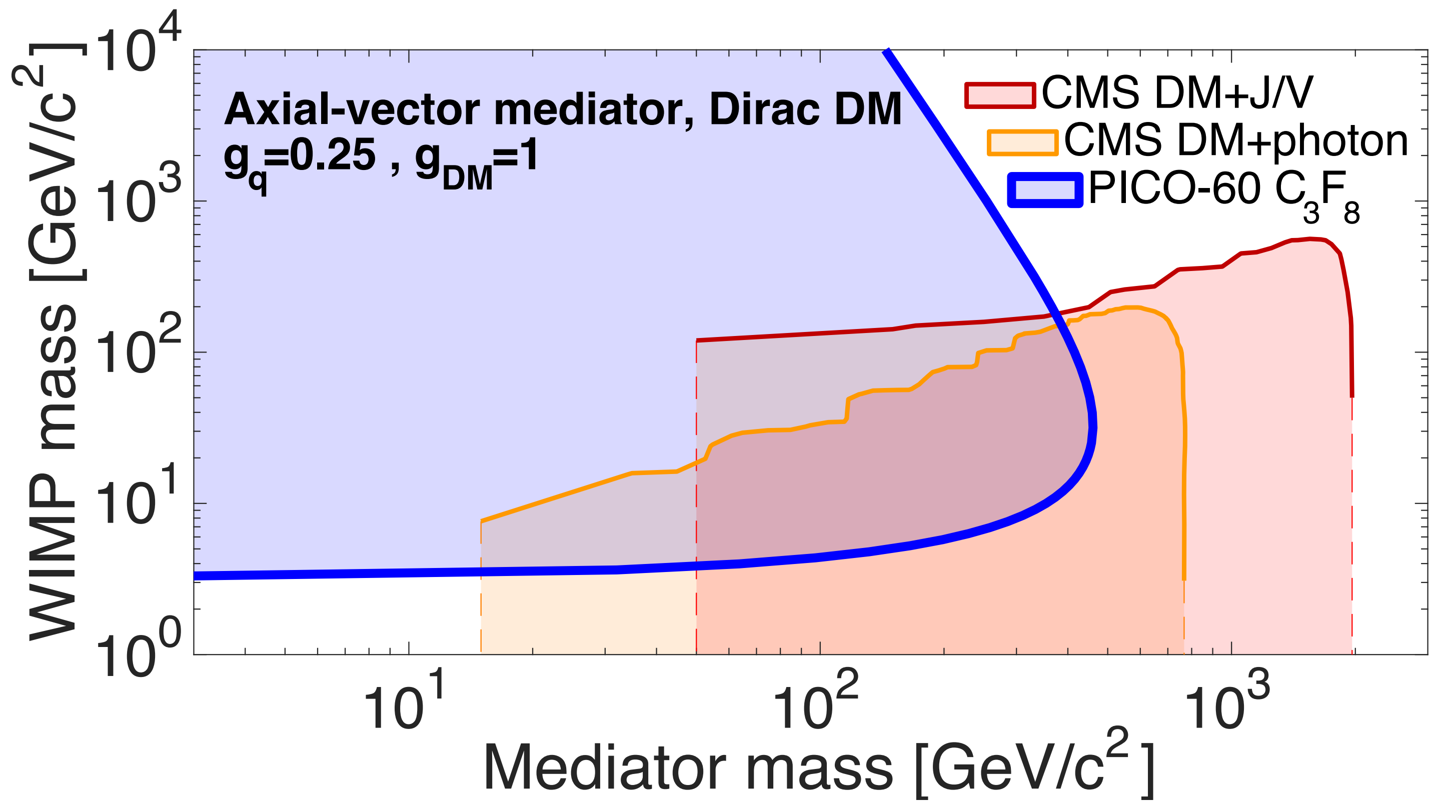
Complementarity w/ xenon, colliders

- A more model-independent comparison: bubble chamber (fluorine) results constrain effective proton coupling in a complementary way to xenon TPC constraints on effective neutron coupling

*C. Amole *et al.*, Phys. Rev. Lett. **118**, 251301 **(2017)**



- Complementarity with LHC: limit from simplified collider production model for CMS, following recommendations of LHC Dark Matter Working Group



Why bubble chambers?

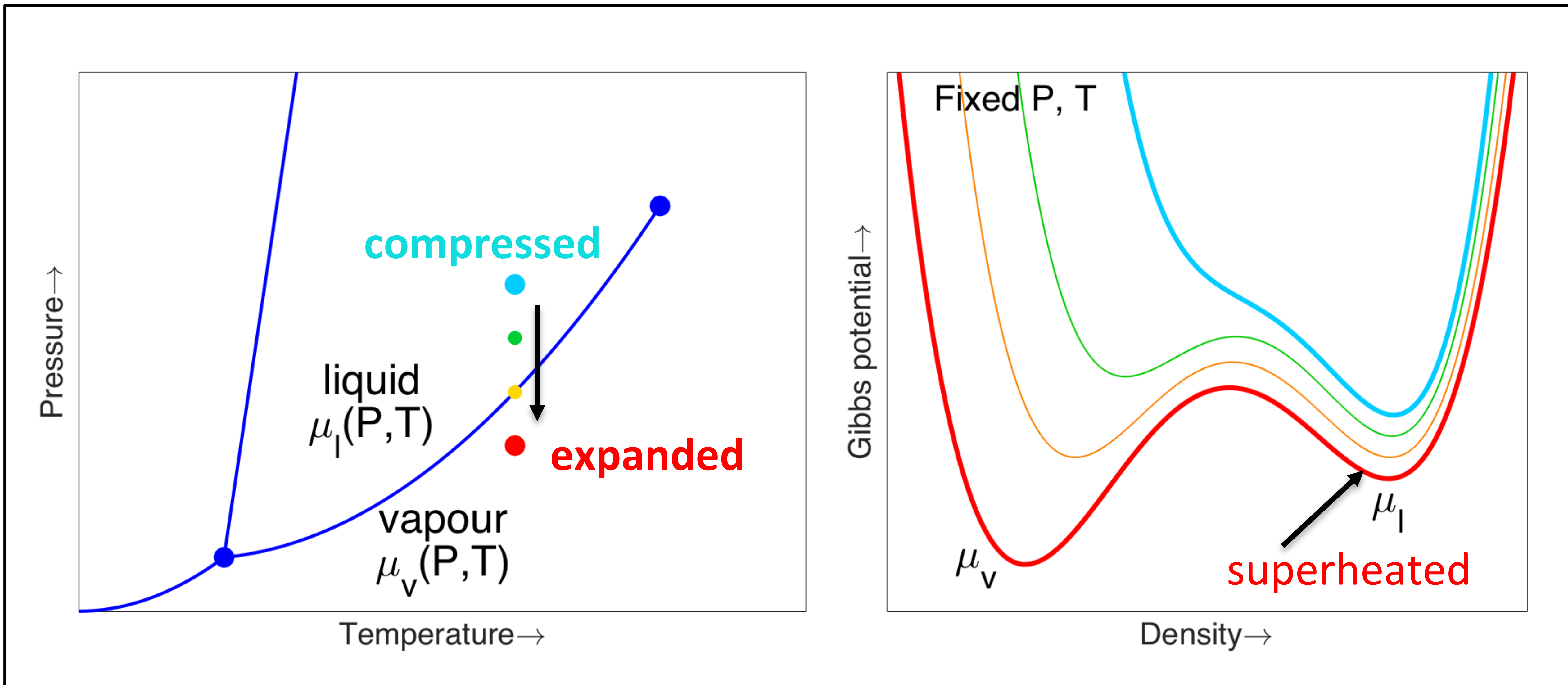
- High density of ^{19}F means great SDp sensitivity
- Intrinsic rejection of electron recoil backgrounds
- Low energy recoil sensitivity (< 5.5 keV)
- Large, monolithic (self-shielding) target mass – ton-scale next generation
- **Multiple target nuclei:** ability to test scattering rate dependence on atomic number, nuclear spin, etc.
- Disadvantages: no measurement of recoil energy; threshold calibrations may be difficult; recompression dead-time requires very low overall event rate

Target: superheated fluid

Lower pressure in target liquid until it is in **metastable superheated** state

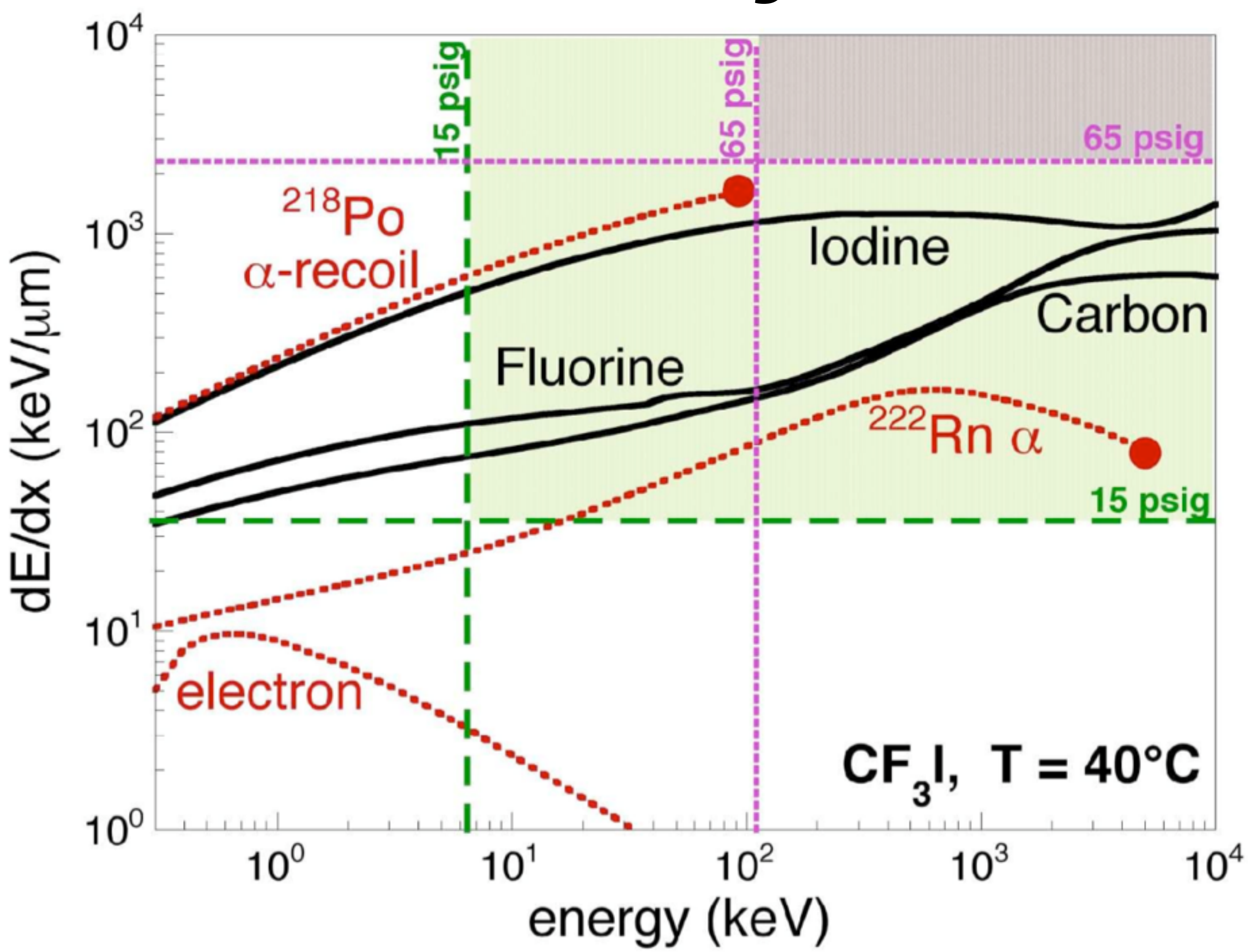
Energy deposition **nucleates** small bubble that grows to visible size

Cameras watch for visible bubble and issue the **primary trigger**



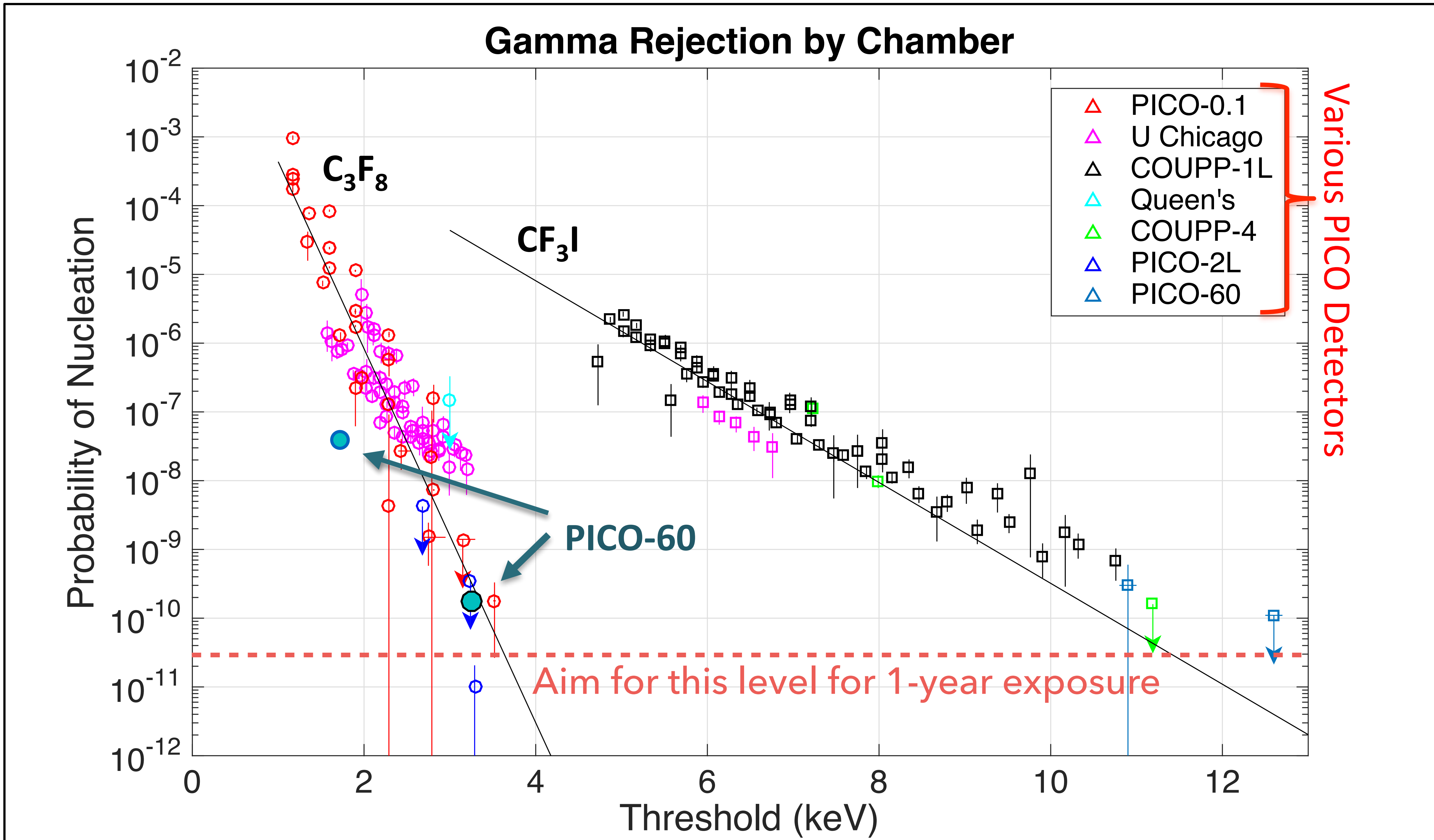
(plots by Eric Dahl)

Gamma rejection



Set temp. & pressure for sensitivity to nuclear recoils (α, n, nuclei, WIMPs), and **insensitivity to electron recoils** (γ/β) [protobubble immediately collapses]

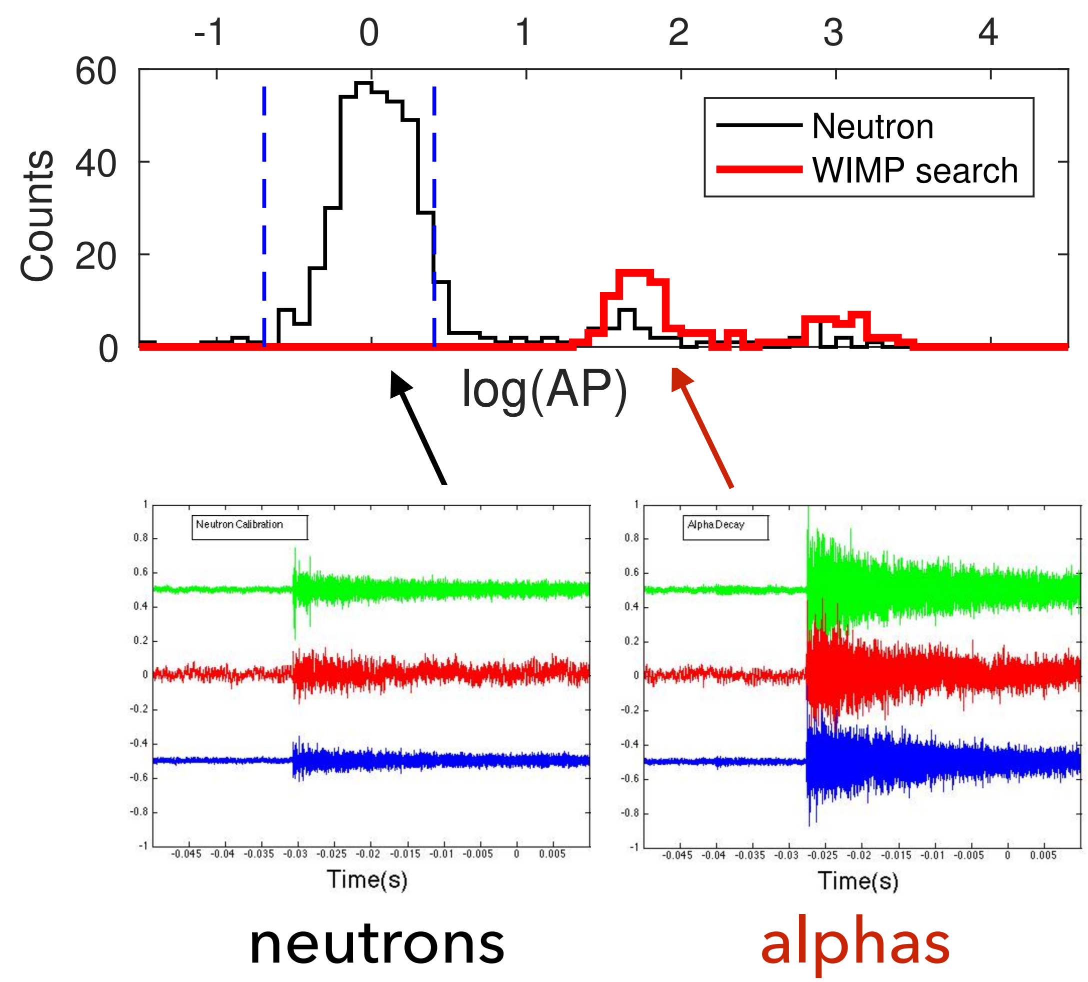
Gamma rejection

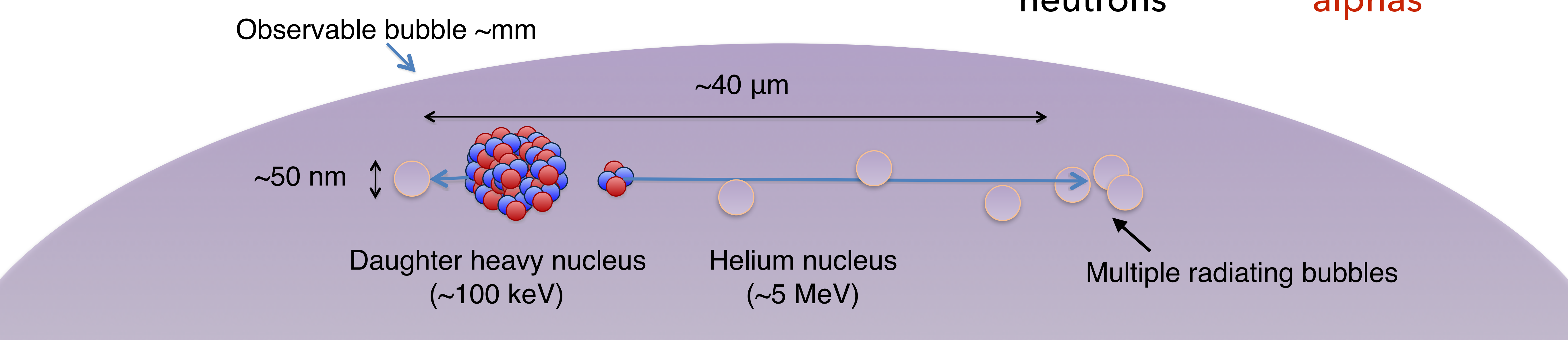


(Dan Baxter, Conference on Science at SURF, May 14, 2017)

Acoustic discrimination

- Acoustic discrimination against alphas discovered by PICASSO
  (Aubin *et al.*, New J. Phys.10:103017, **2008**)
  - Alphas deposit their energy over **tens of μm**
  - Nuclear recoils deposit energy over **tens of nm**
- In PICO, **alphas** are several times **louder** than recoils
- For a WIMP-search run, the acoustic signals are blinded in order to set an unbiased cut on this “acoustic parameter” (“AP”)



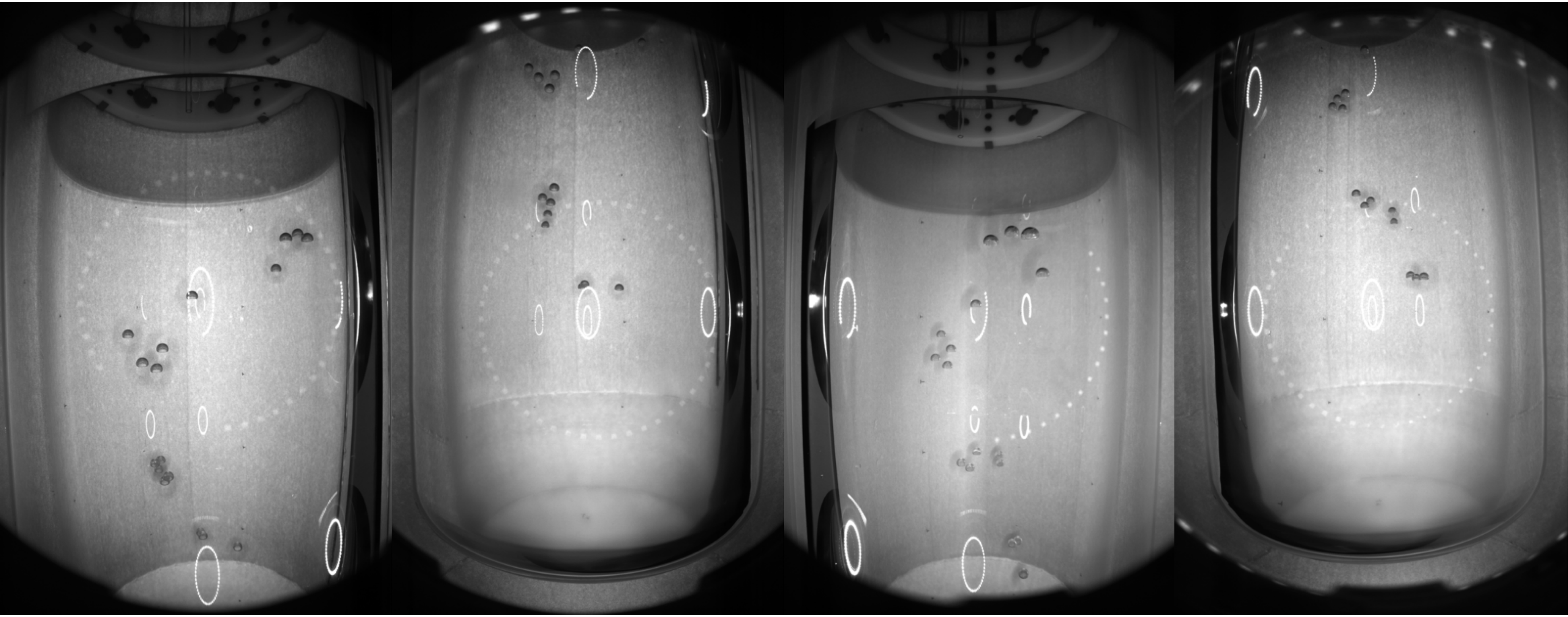


Neutron background

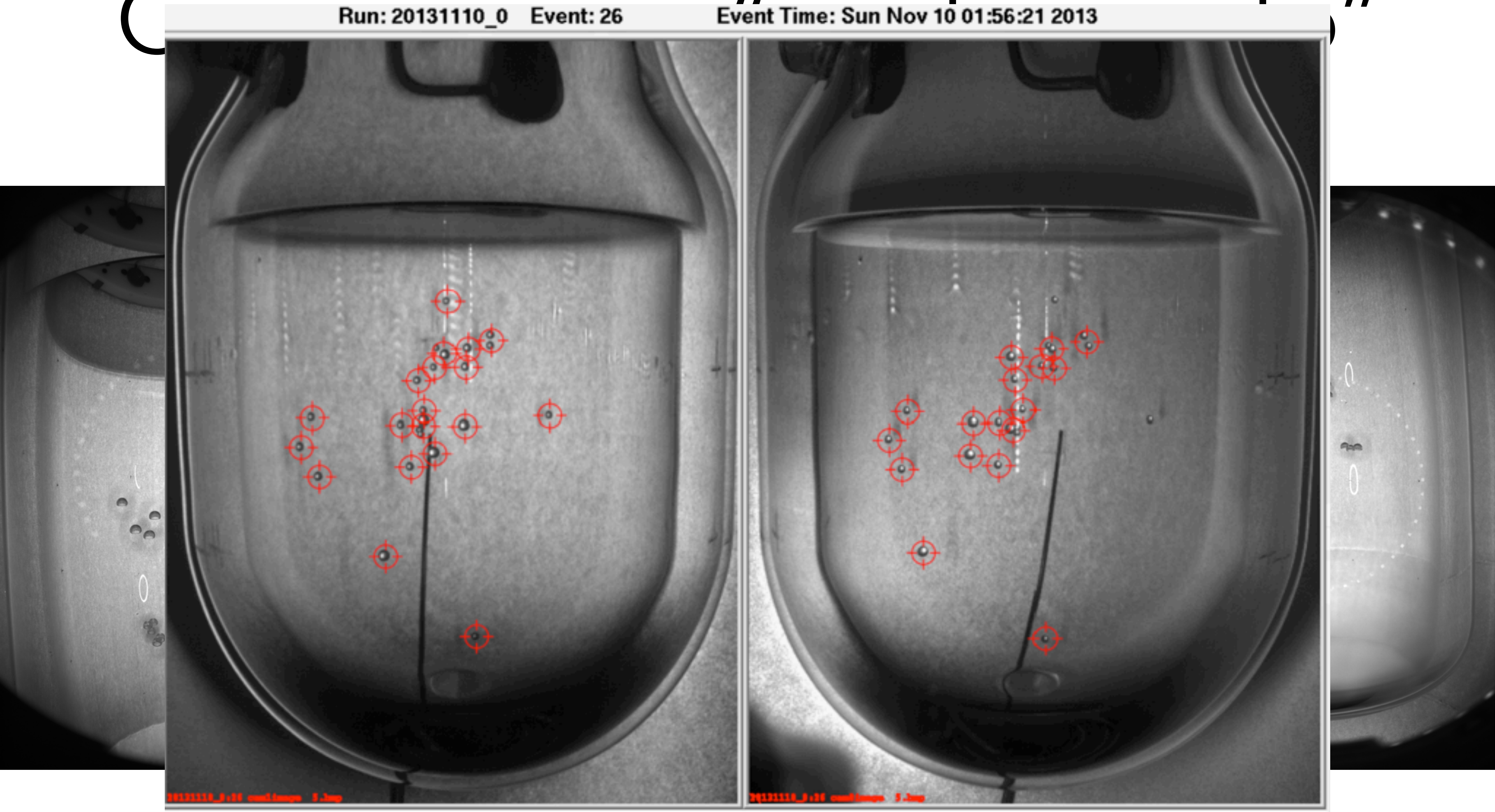
- Single-scatter neutrons are indistinguishable from WIMPs in these detectors
- Can't discriminate against them, so minimize them
- Two neutron sources for PICO-60:
    - **Cosmogenic:** spallation in rock near detector by high energy cosmic ray muons (veto present for C_3F_8 Run-1, saw no muons)
    - **Radiogenic:** natural radioactivity in rock and detector apparatus (alpha-n and spontaneous fission)
- Total neutron background estimate for PICO-60 C_3F_8 Run-1:
0.25 ± 0.09 (0.96 ± 0.34) **single-** (multiple)-bubble events

Cameras as a "neutron veto"

Multiply-scattering neutrons won't be mistaken for WIMPs (3:1)



Four views of a neutron event from an AmBe source



26 bubbles in the small 2L chamber!

Backgrounds checklist

- **Gammas/betas:**
  - *dE/dx* **threshold** in superheated detectors affords "intrinsic" rejection ~10^{-11} for typical PICO energy thresholds in C_3F_8
- **Alpha decays:**
  - large **acoustic signals** allow discrimination at >99.4% (stats. limited)
- **Neutrons:**
  - reject **multiple scatters** visually, **veto** detector-adjacent cosmogenics, **minimize** other sources (extensive material **screening, shielding**)

The PICO program

- **PICO** – 2012 merger of the **PICASSO** and **COUPP** collaborations

- Small surface test chambers at Université de Montréal, Queen's University, Northwestern, Drexel, NEIU (for threshold calibration, etc.)

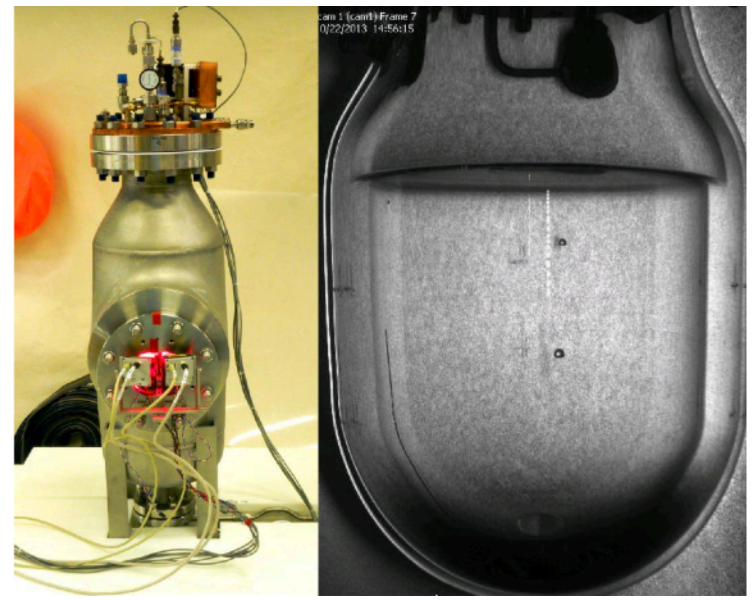
- PICO-2L C_3F_8 (2014-17)
  C. Amole *et al.*, PRL **114**, 231302 **(2015)**
  C. Amole *et al.*, PRD **93**, 061101 **(2016)**

- PICO-60 CF_3I (2013)
  C. Amole *et al.*, PRD **93**, 061101 **(2016)**

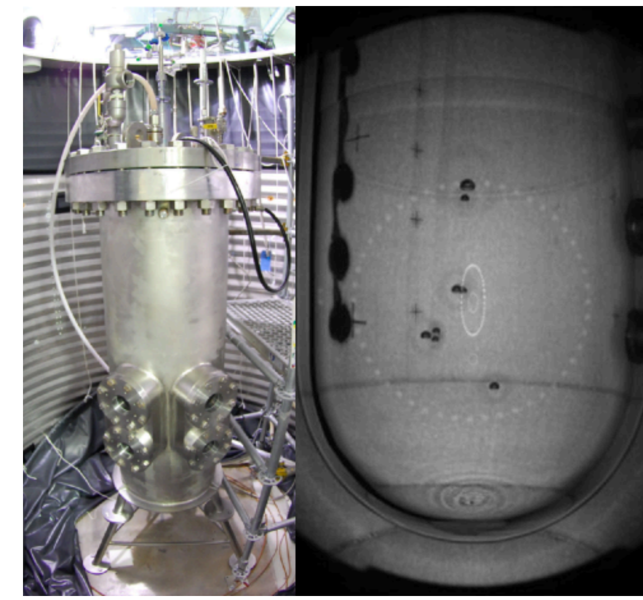
  PICO-60 C_3F_8 (2016-17)
  C. Amole *et al.*, PRL **118**, 251301 **(2017)**

- **PICO-40L (2017-19)**

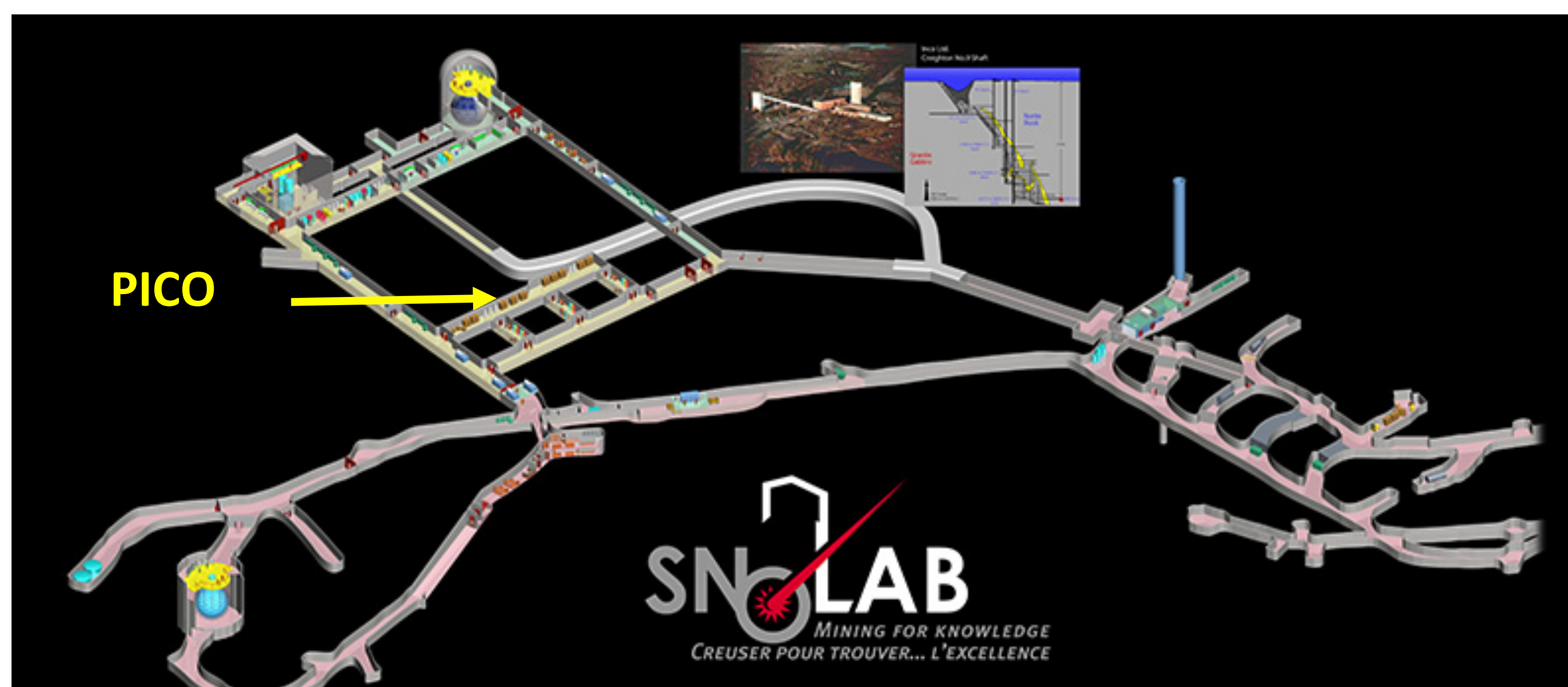
- PICO-500 (~2018+)



PICO-2L
C_3F_8

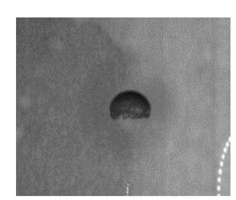


COUPP-60 → **PICO-60**
CF_3I, C_3F_8

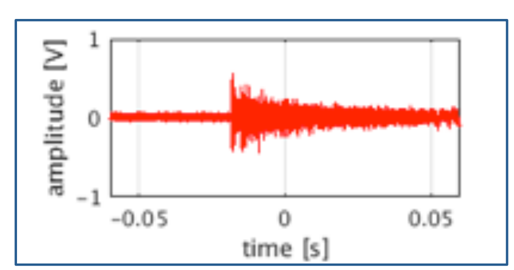


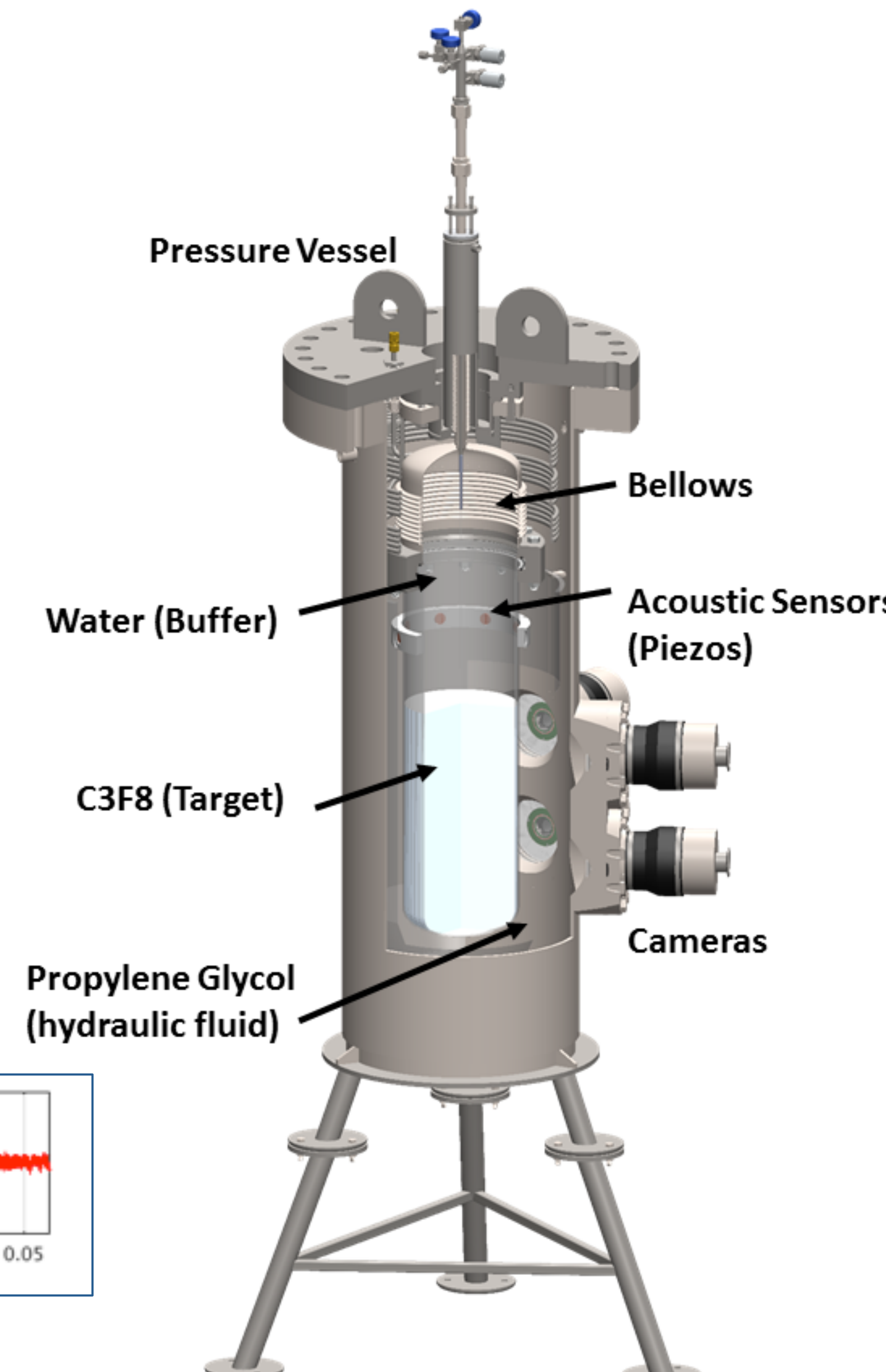
The PICO-60 detector

- Deployed 2 km underground at SNOLAB
- C_3F_8 target: 52 kg total
  (45.7 ± 0.5 kg fiducial, 87.7%)
- Synthetic fused silica inner vessel, stainless steel pressure vessel, water tank, muon veto
- Bellows allow expansion to superheated state with typical per-event cycle of 800s, >80% live-fraction
- Four cameras monitor for bubble nucleation using LED illumination

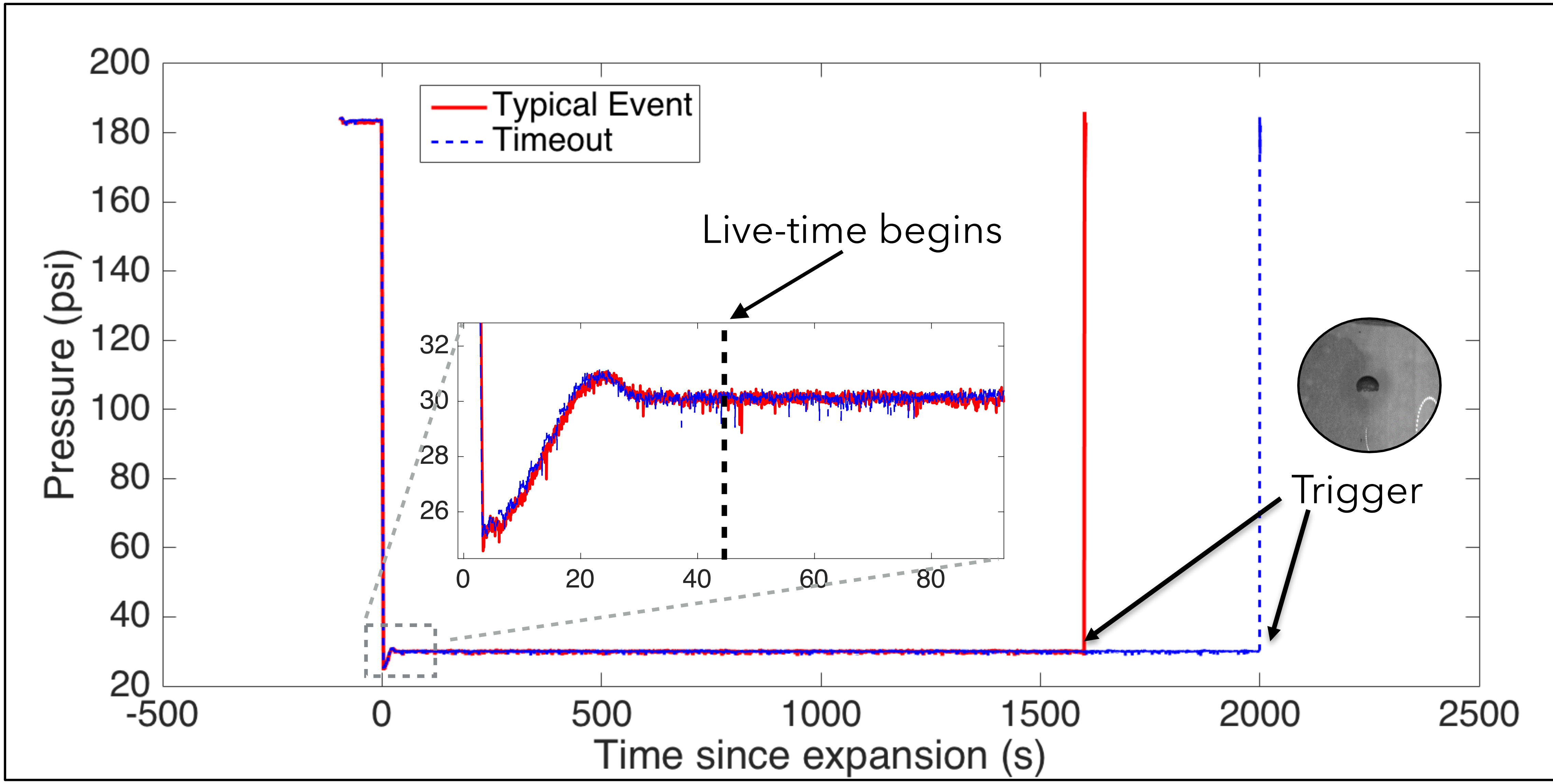


- Eight piezoelectric acoustic sensors monitor sound of bubble nucleation





Event cycle



(plot by Dan Baxter)

Expand to target pressure; begin counting live-time after 25s stability

Primary trigger: changes in image information content (bubble appearance)

Time-out trigger set to 2000s – regular cycling improves detector stability

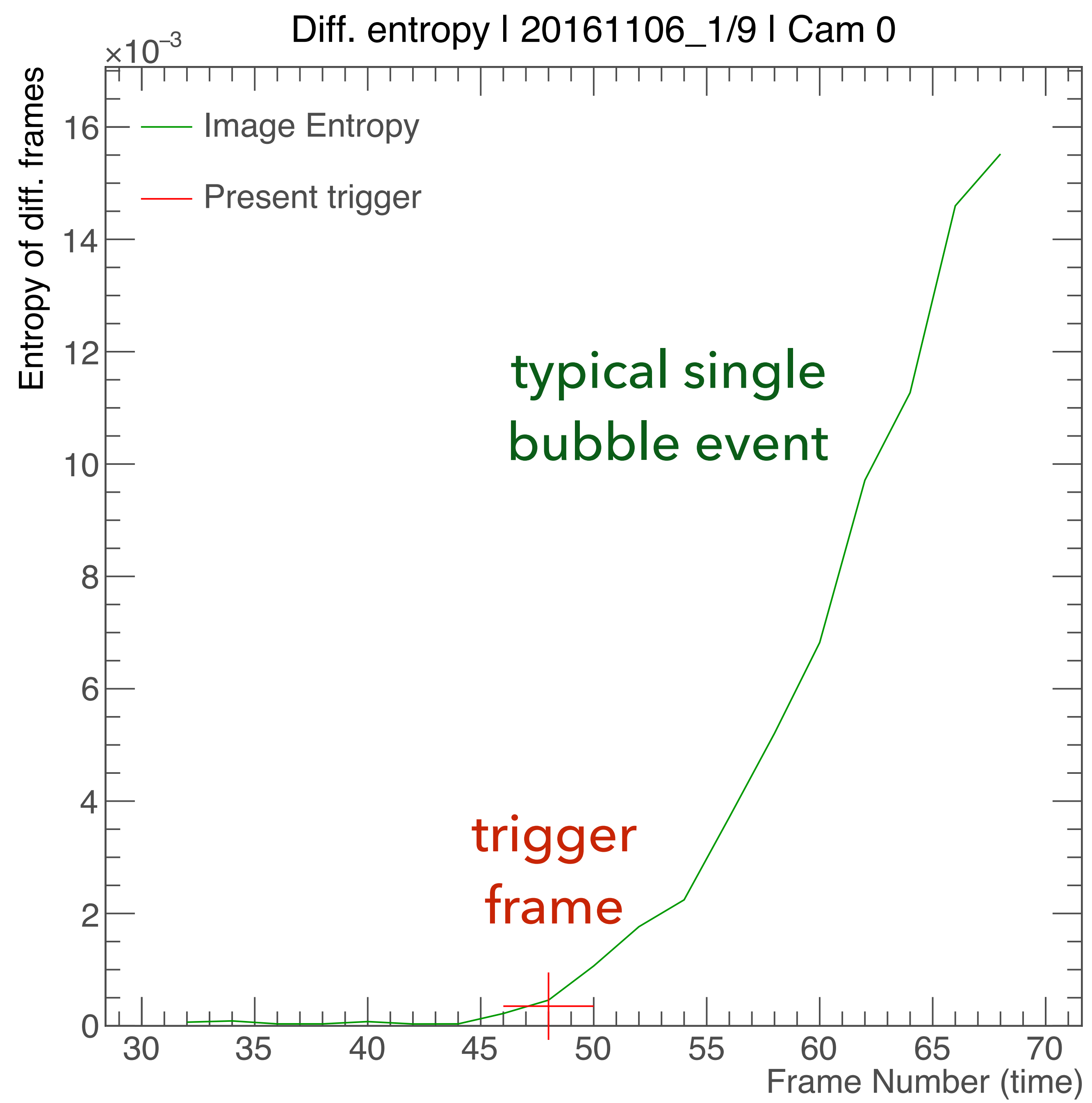
Fast camera trigger

- Primary trigger: "image entropy"

$$S_I = -\sum_i P_i \log_2 P_i$$

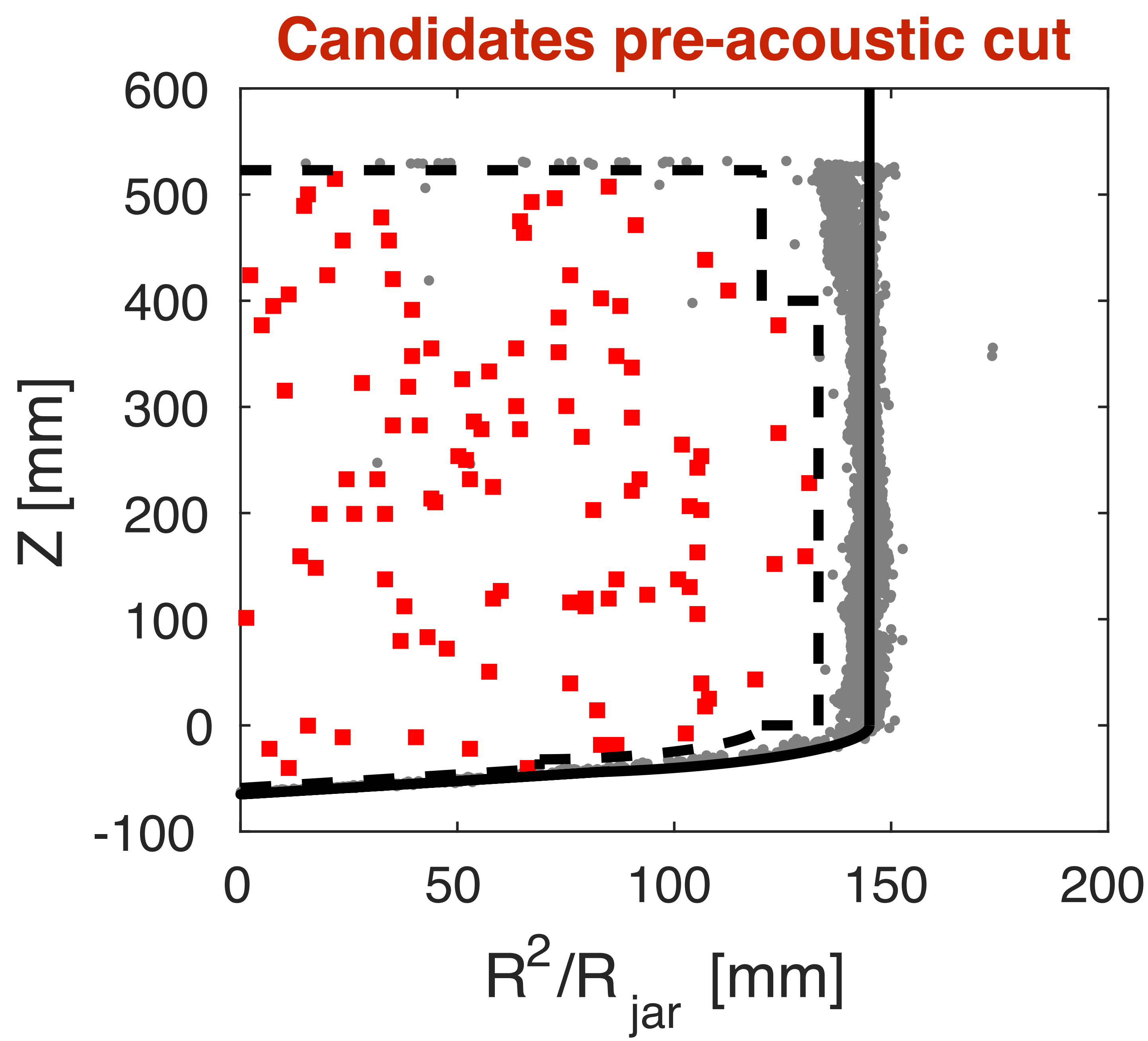
- Calculate absolute difference of successive frames, searching for changes in information content

- Images initially acquired at 200 Hz – increased to hardware maximum 340 Hz for low threshold run – fast trigger ensures stable operations at very low pressures



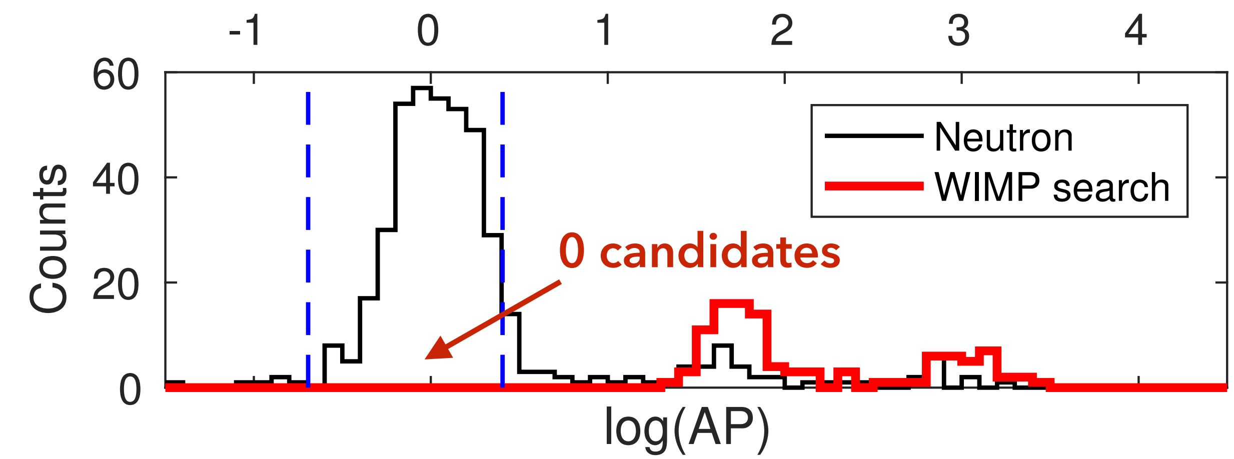
PICO-60 Run-1: blinded

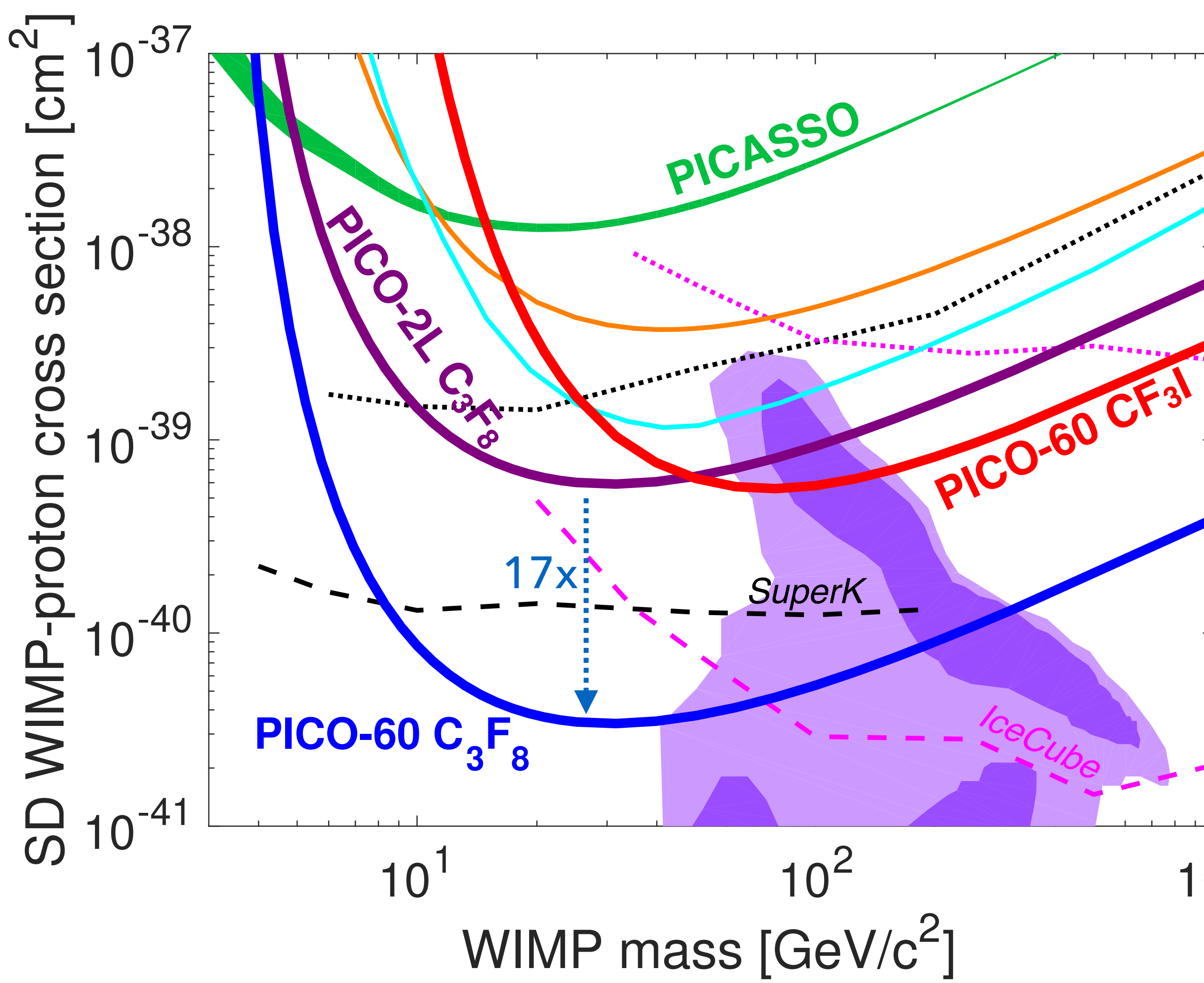
- Following "pre-physics" background and calibration data, detector performance was assessed good enough to allow a blind analysis
- Acquired acoustically blinded background data from **28 Nov 2016 to 13 Jan 2017** (no power outages, remarkably stable running)
- Saw **106 bulk singles** in WIMP-search dataset: consistent with Rn decay rate seen in unblinded pre-physics data
- Saw **3 multiples**, so given 3:1 multiples to-singles ratio from *n* calibration and simulation, expected 0-3 bulk *n* singles



PICO-60 Run-1: unblinding

- **30 live-day run at 3.3 keV** threshold, published in PRL*: a *background-free* **1167 kg-day** WIMP-search exposure
- **Factor of 17** improvement in upper limit on spin-dependent WIMP-proton cross-section
- Additional blinded exposure acquired at lower thresholds
- Now decommissioning, as any additional exposure would be expected to be **background limited**

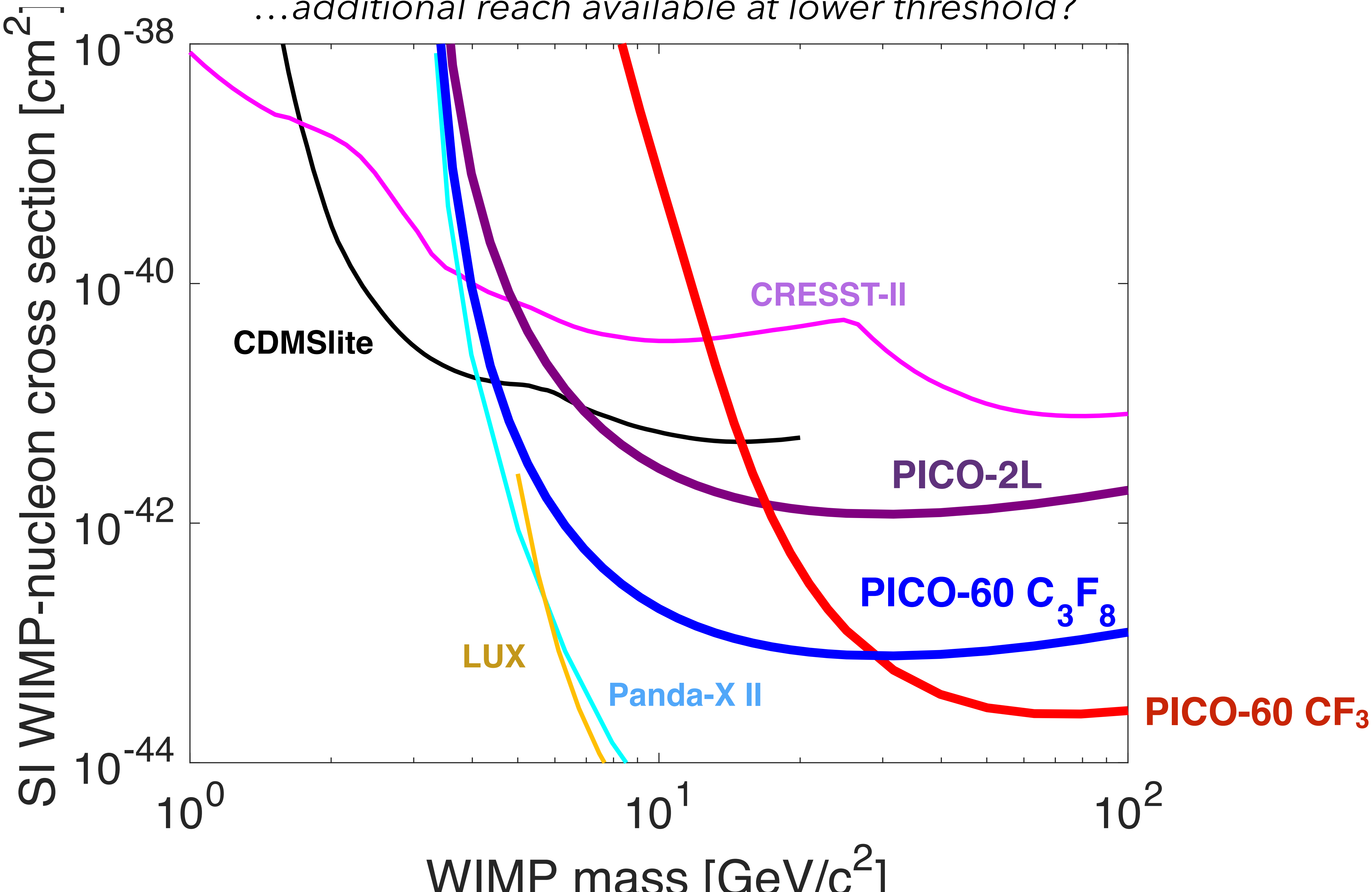




*C. Amole *et al.*, Phys. Rev. Lett. **118**, 251301 **(2017)**

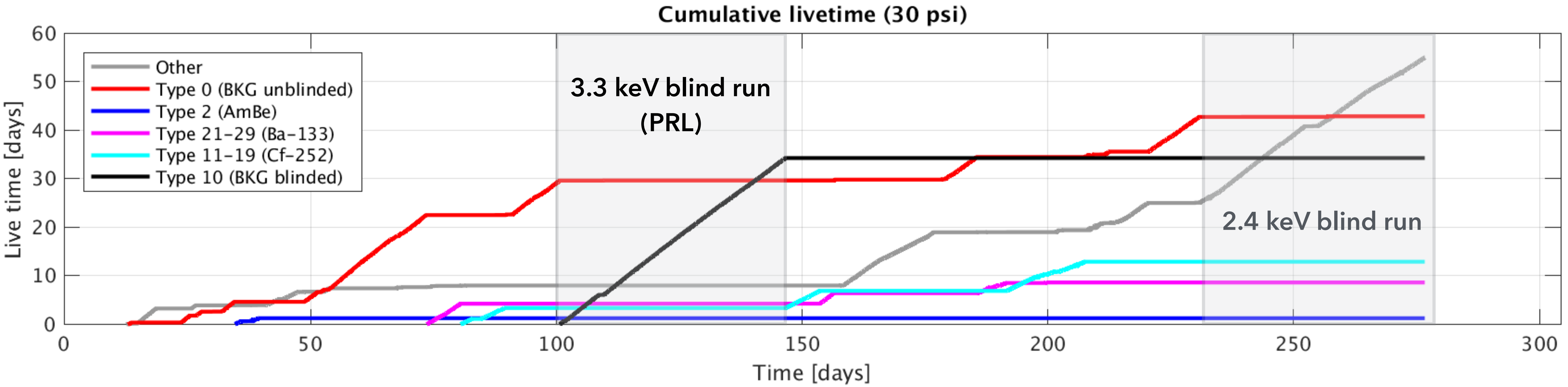
Nearly competitive in SI at low mass

...additional reach available at lower threshold?



PICO-60 low threshold run

- Second physics run prompted by observation of far fewer recoil events than expected at lower thresholds
- Decided on a threshold of **2.4 keV**, where backgrounds were projected to produce <5 events over a 30 live-day exposure, now acquired
- Analysis is wrapping up, results soon…



Why end PICO-60?

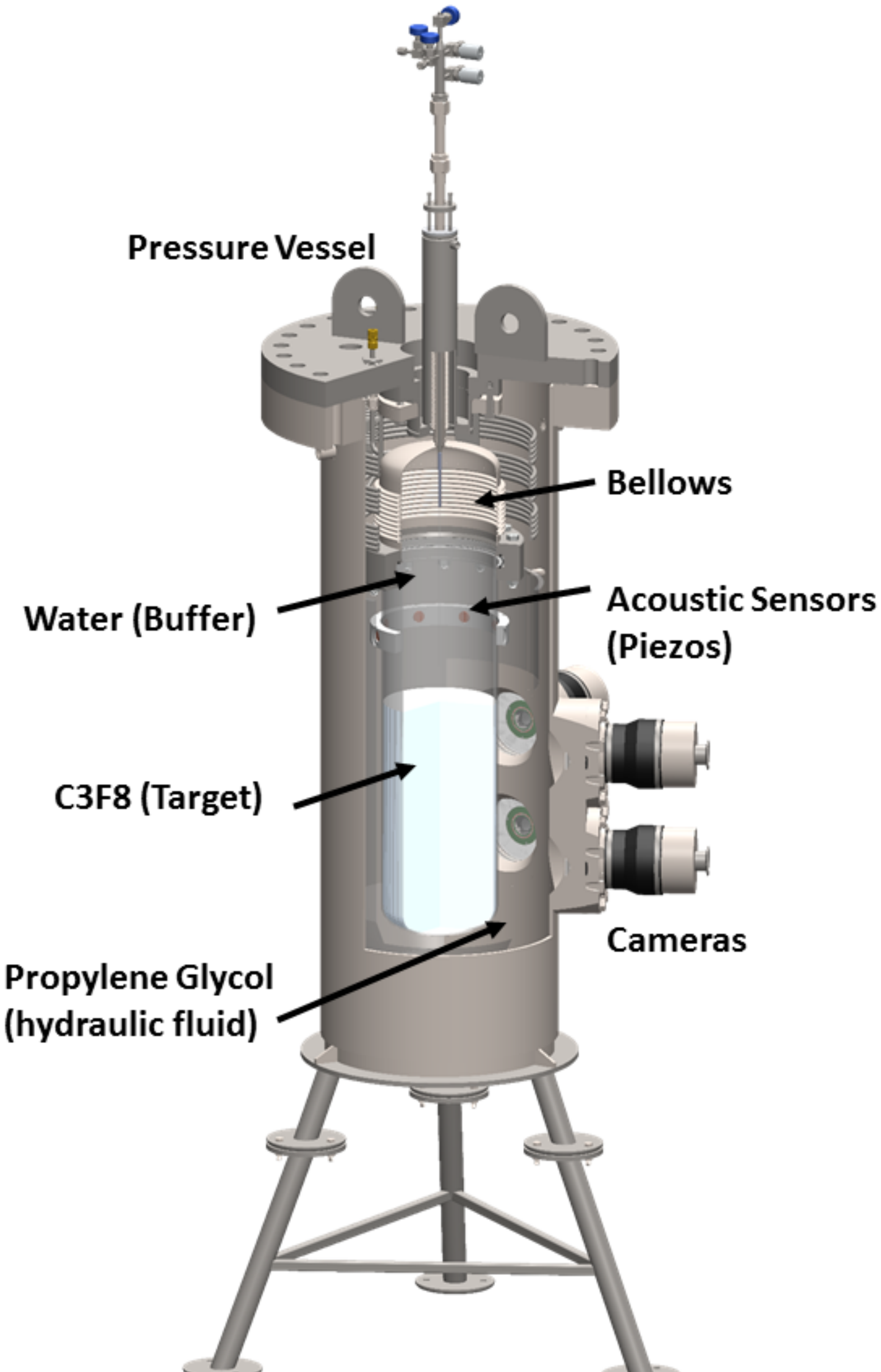
- Only published 30 live days, with ~30 more on the way…
- After over a year commissioning, why acquire so little data?
- Short answer: 3 multiple-scatter neutron events in Run-1 meant expectation of 1 single-scatter neutron (which we didn't see)
- That rate now appears to have been a slight upward fluctuation, but the full (3.3, 2.4) keV dataset (~60 days) will almost certainly be **background limited: very slow gains** if we'd continued
- More pressing need: build the next chamber!

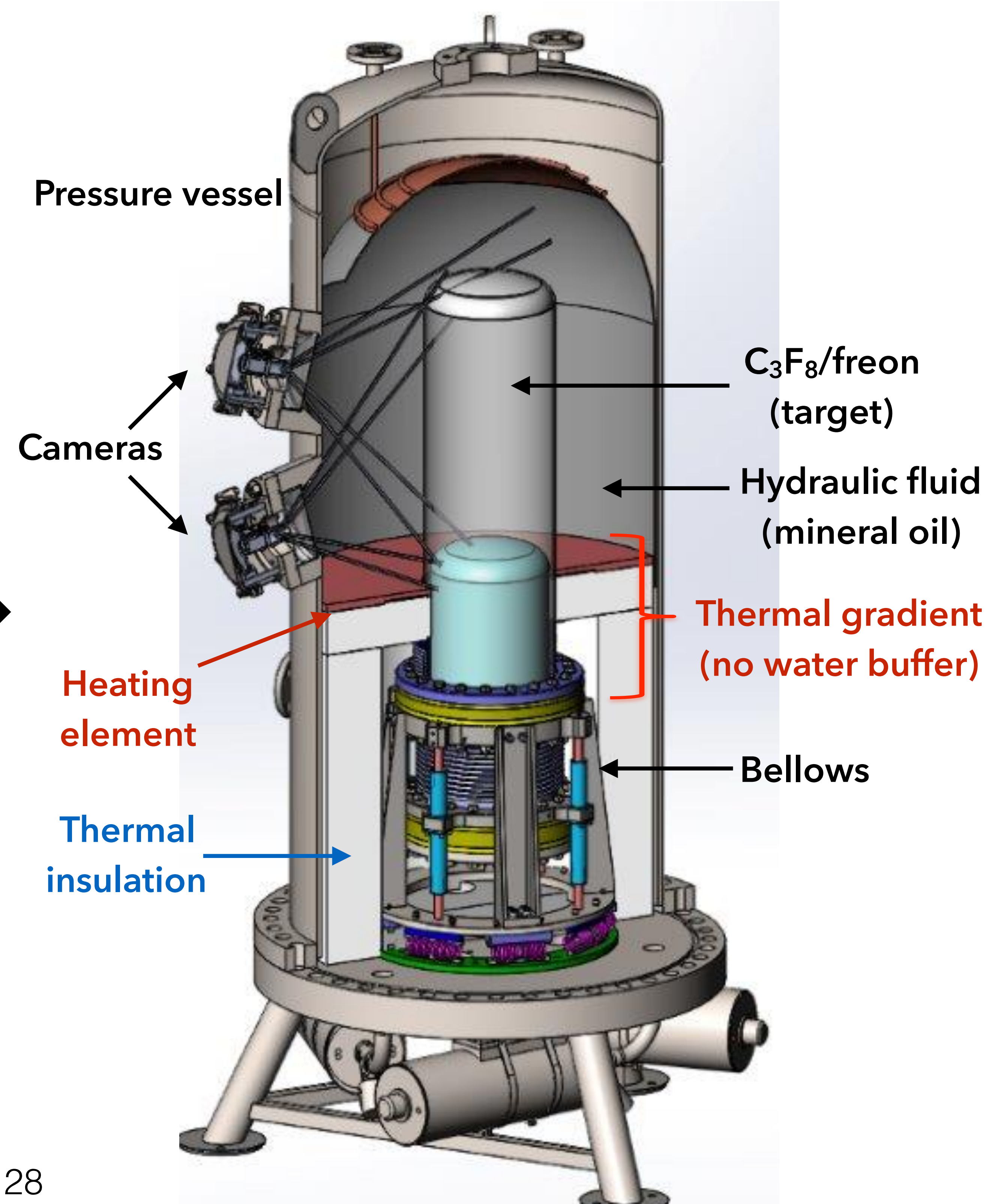
PICO-40L Goals

where the "L" again indicates, approximately, "demonstrator for next, bigger chamber"

- **Science:** acquire one-year background-free exposure
  - Order of magnitude improvement on PICO-60 limits
- **Engineering:** demonstrate background reduction and technology improvements for PICO-500
  - Focus on (neutron) background reduction
  - Confirm "RSU" design used in prototype chambers

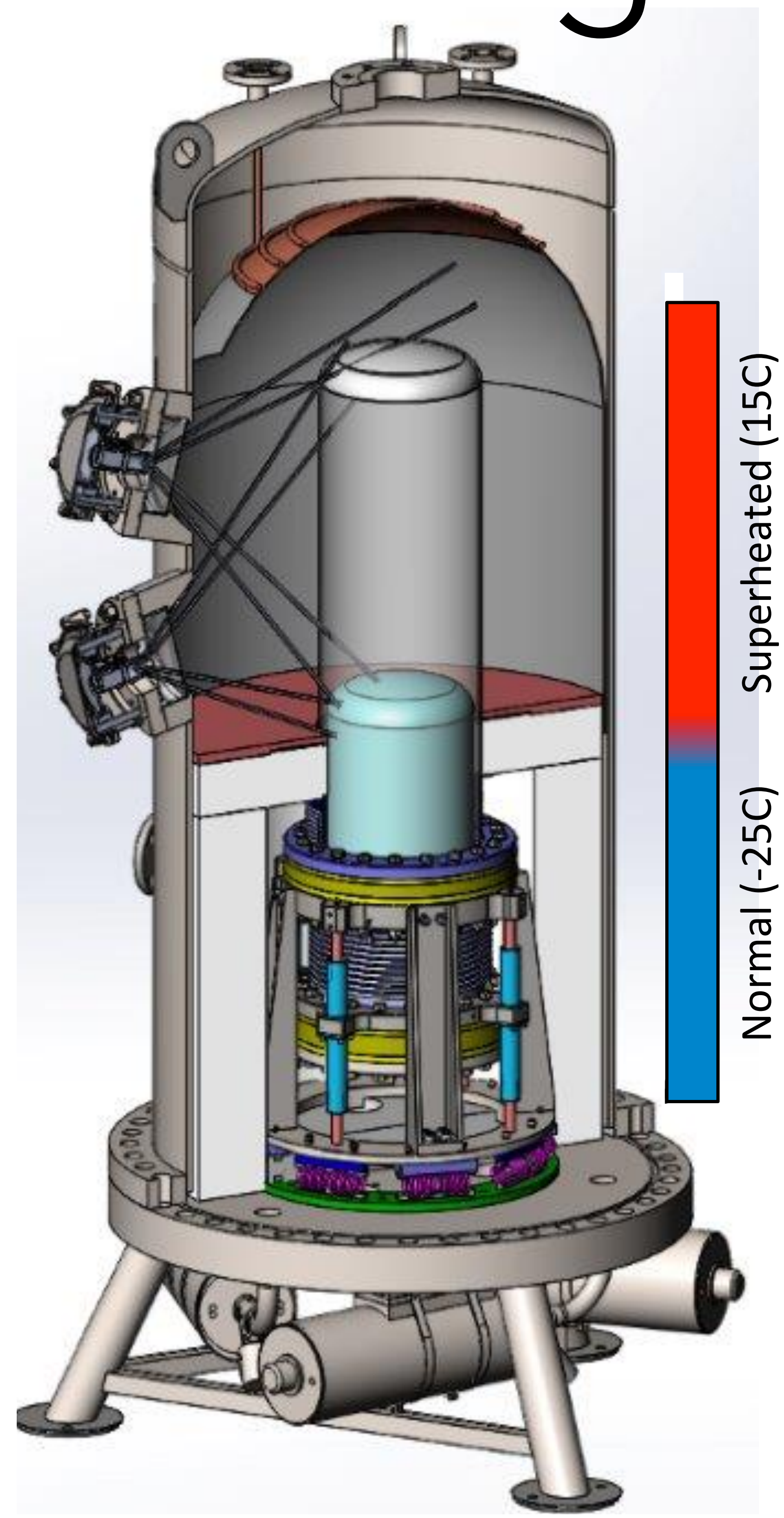
PICO-60 → PICO-40L





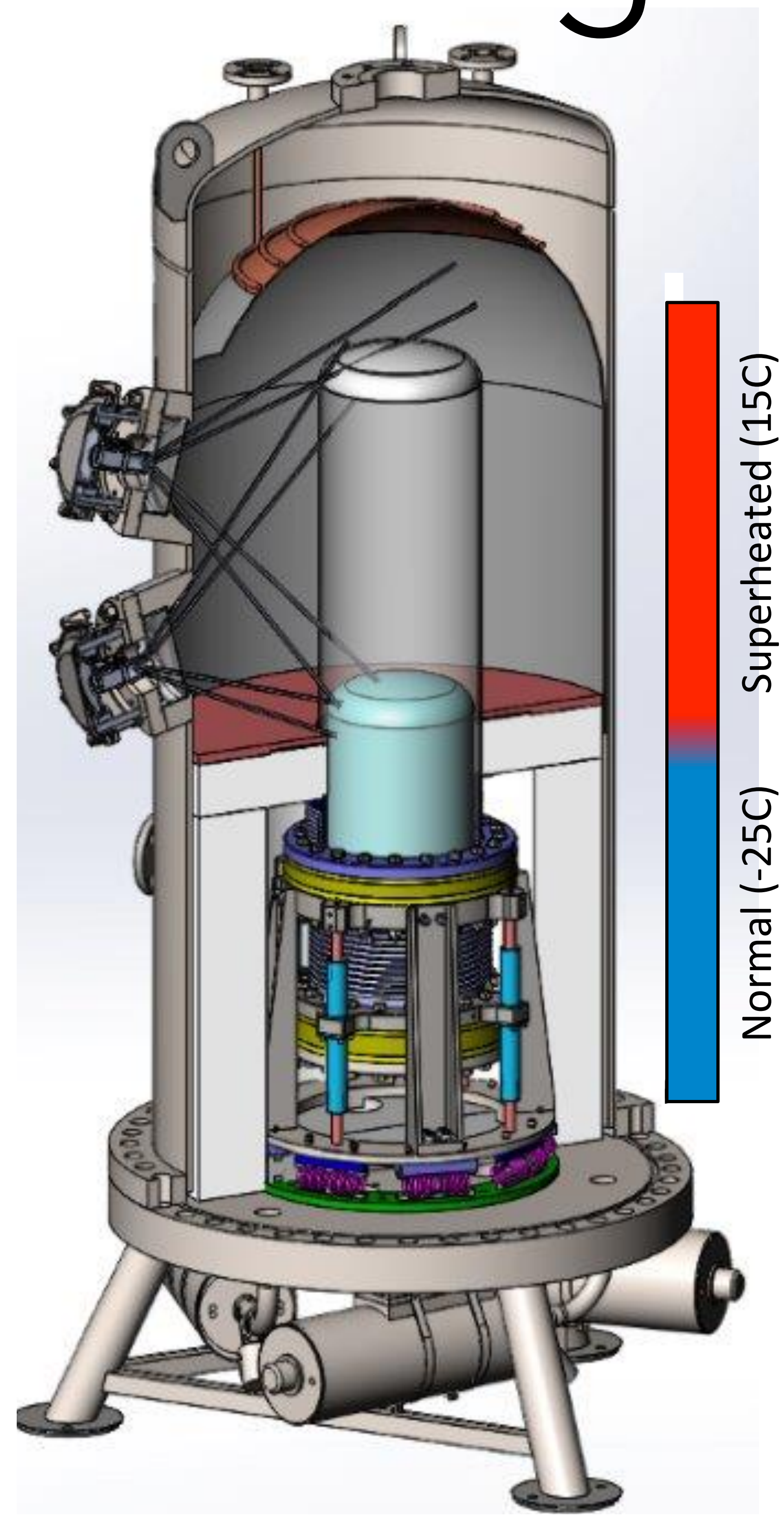
PICO-40L detector design

- To be deployed 2 km underground at SNOLAB ("ladder labs" area)
- Target: ~40L C_3F_8, (proj. >90% fiducial)
- Synthetic fused silica inner vessel and piston (no more "water piston")
- **Larger** stainless steel pressure vessel, 20t water tank, muon veto – all minimize neutron backgrounds



PICO-40L detector design

- Inversion eliminates potential sources of background:
  - water droplets
  - surface tension effects
  - particulates – would now fall out of active region into cold annulus
- No buffer: allows wider choice of target fluid, wider range of operating temperatures; directly enables full target recirculation and purification



Many upgraded systems

- Optics/DAQ: much better Basler cameras using new Sony IMX174 CMOS sensor
  - running on newer USB3 Vision interface for more programming flexibility
  - better lenses (higher resolution, reduced barrel distortion, etc.)
  - better stereoscopic viewing angles and camera mounts
  - better retroreflector and improved LED lighting rings

Basler CMOS camera with new IMX714 sensor

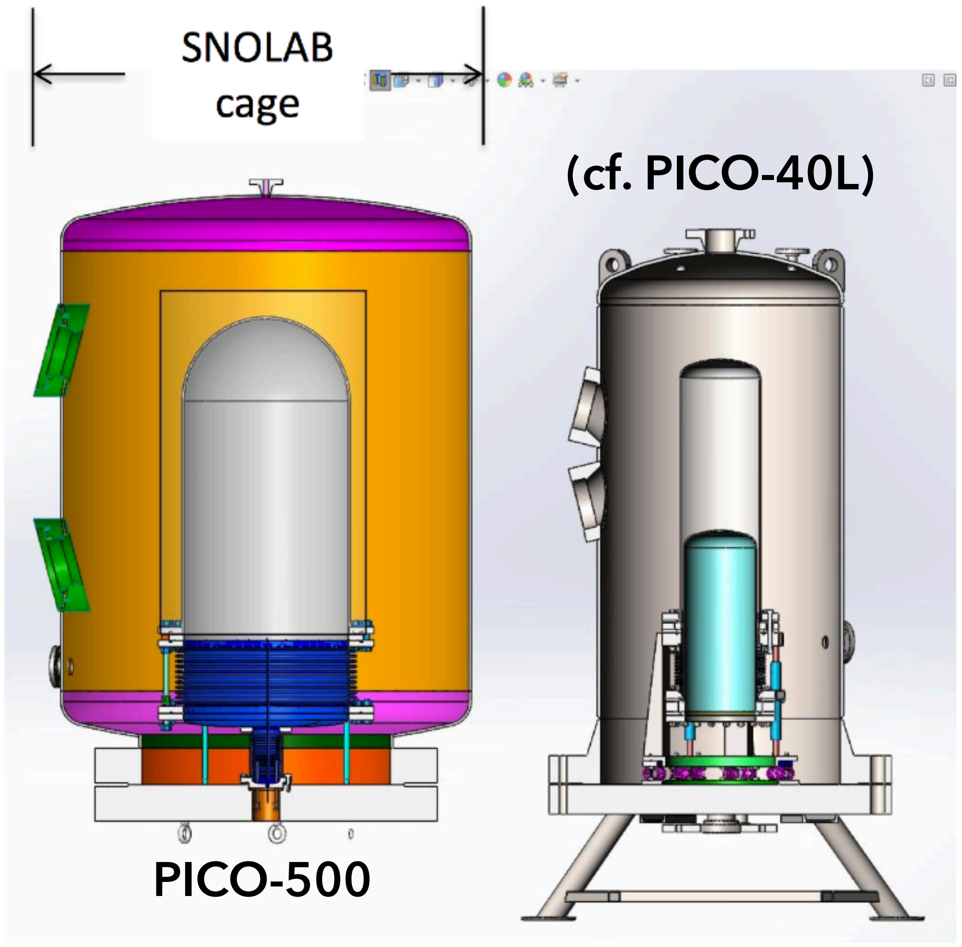
- Hydraulic system control: brought into alignment with new designs used on several test chambers; will enable continuous active recirculation/filtration
- Piezo acoustic sensors: better physical coupling, and improved longevity in different hydraulic fluid (mineral oil rather than propylene glycol)

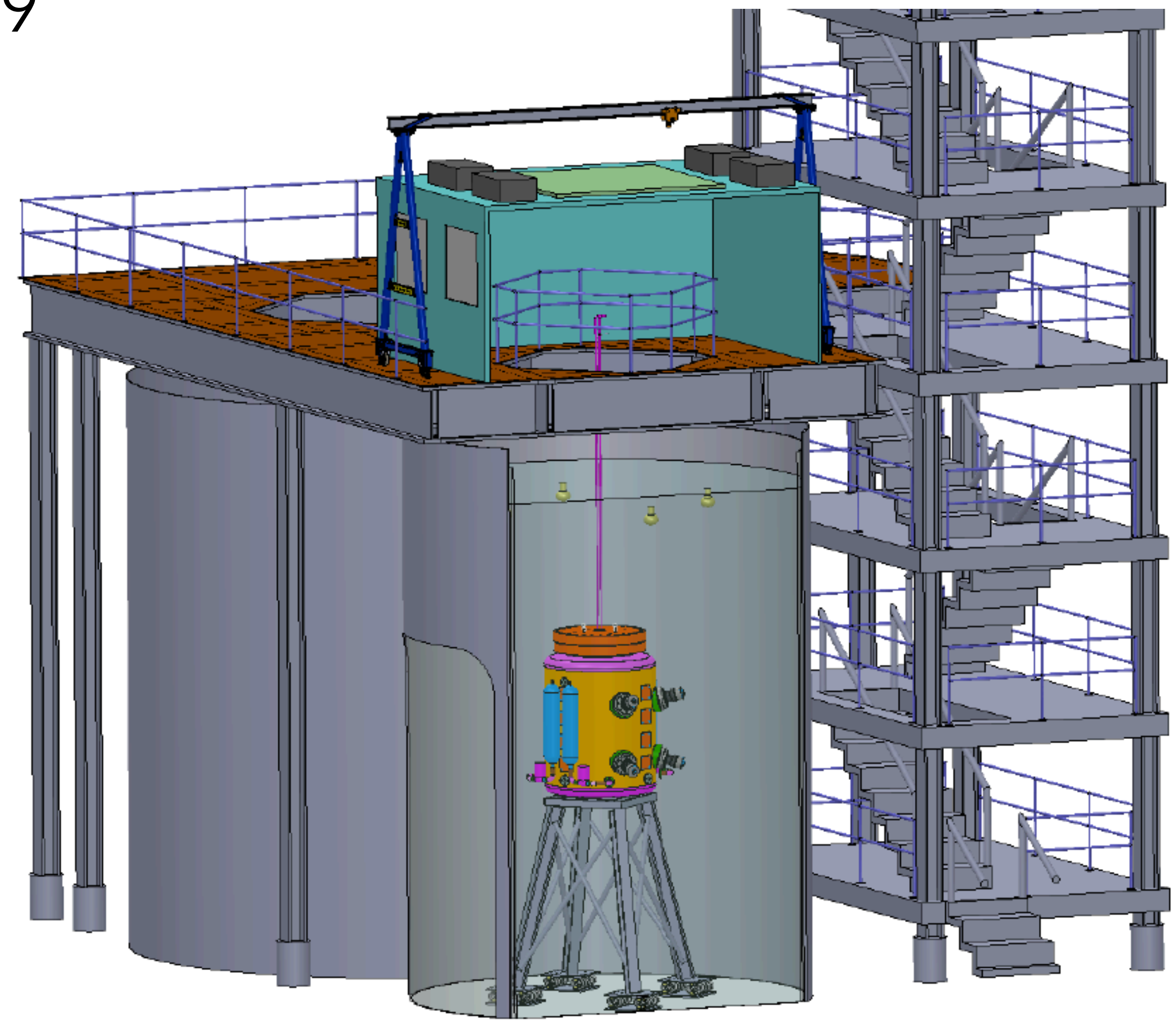
PICO-40L timeline

- Pressure vessel arrived to SNOLAB surface 18 May 2017
- Clean surface commissioning ongoing presently
- Full detector assembly to be shipped underground to SNOLAB Dec 2017
- First data January 2018
- End of physics data in 2019

PICO-500

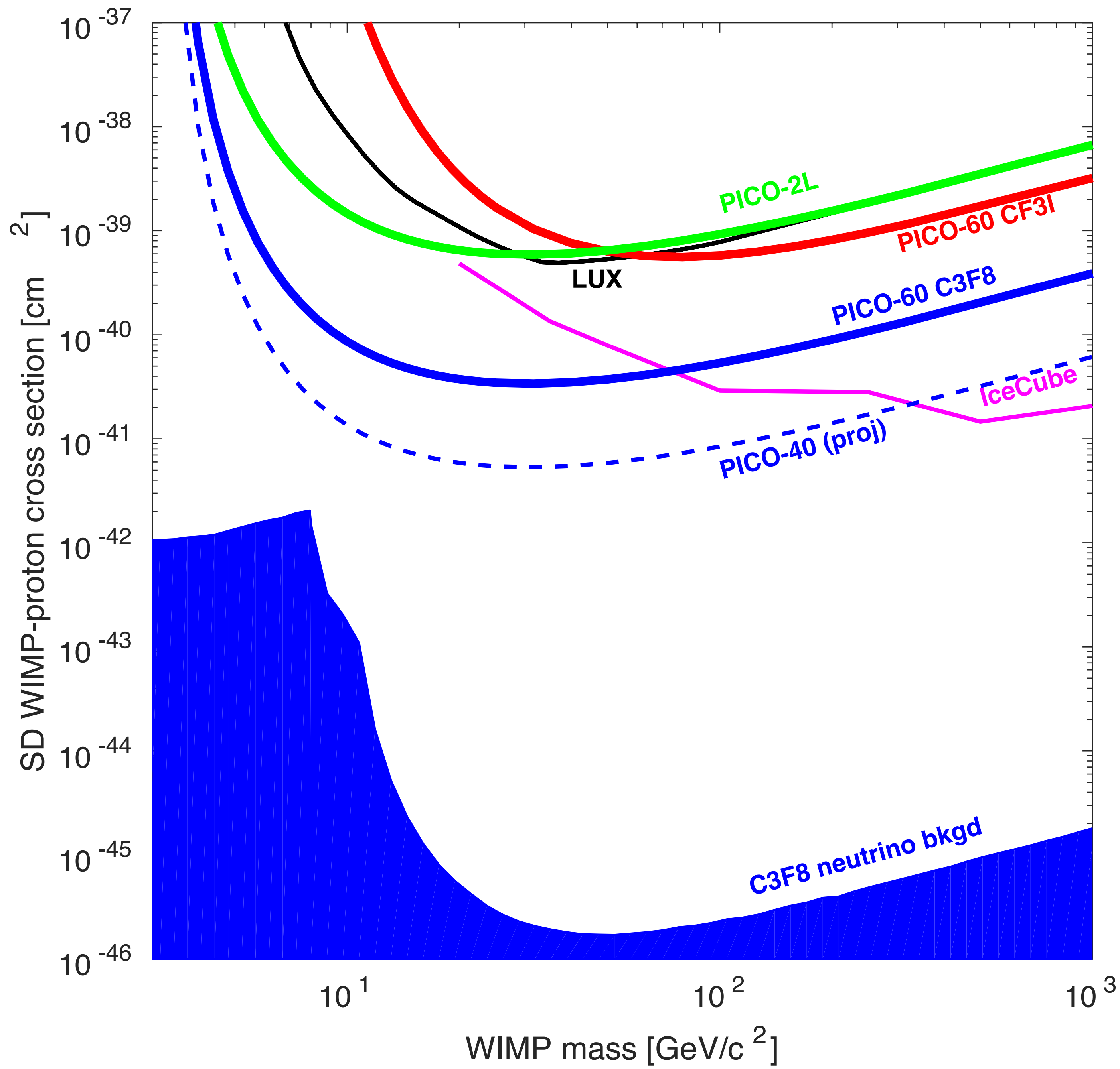
- Planned ton-scale detector
- Intended to begin surface commissioning as soon as late 2018
- Goal is to begin data-taking in 2019





PICO-500

- Designed to have an additional order of magnitude sensitivity beyond PICO-40L
- Could run C_3F_8 and/or several other targets (i.e. CF_3I or hydrocarbons: $C_2H_2F_4$, etc.) to probe higher/lower mass or reduce a WIMP signal in a predictable way



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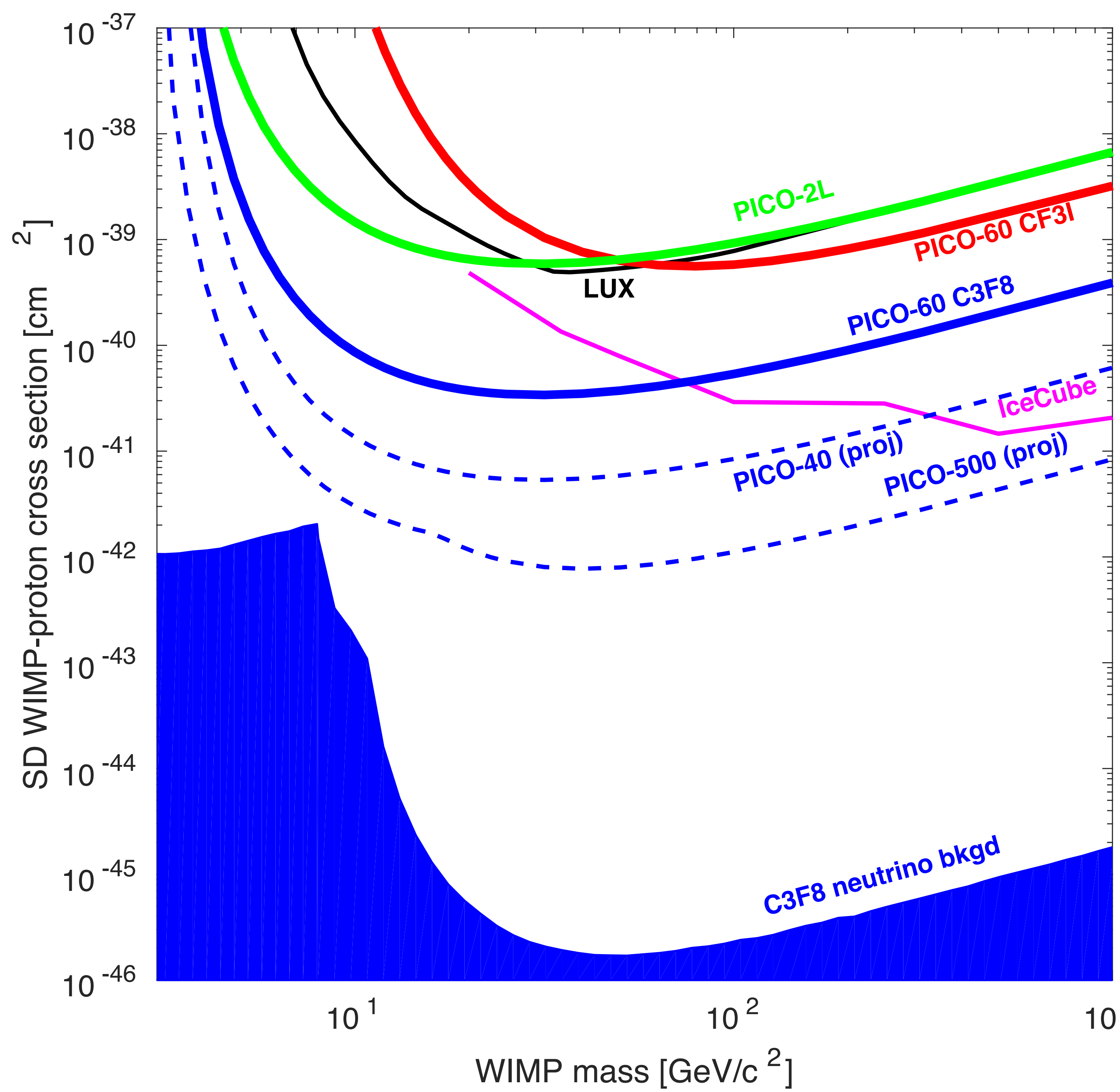

Summary and outlook

- **PICO-40L** commissioning now, data in **early 2018**
  - One year background-free run – order of magnitude improvement on PICO-60 result
  - Demonstrate background reduction advances enabling ton-scale PICO-500
- **PICO-500** could begin data taking as early as **2019**
  - Sensitivity to additional order of magnitude in SDp beyond PICO-40L, covering significant new well motivated parameter space
  - Could check itself/signals from other detectors with a **target change**
- PICO detectors are relatively cheap and flexible, with very quick turnaround time
- SD WIMP interactions are arguably just as promising as SI! Imagine a first signal in 2019?

Extra slides

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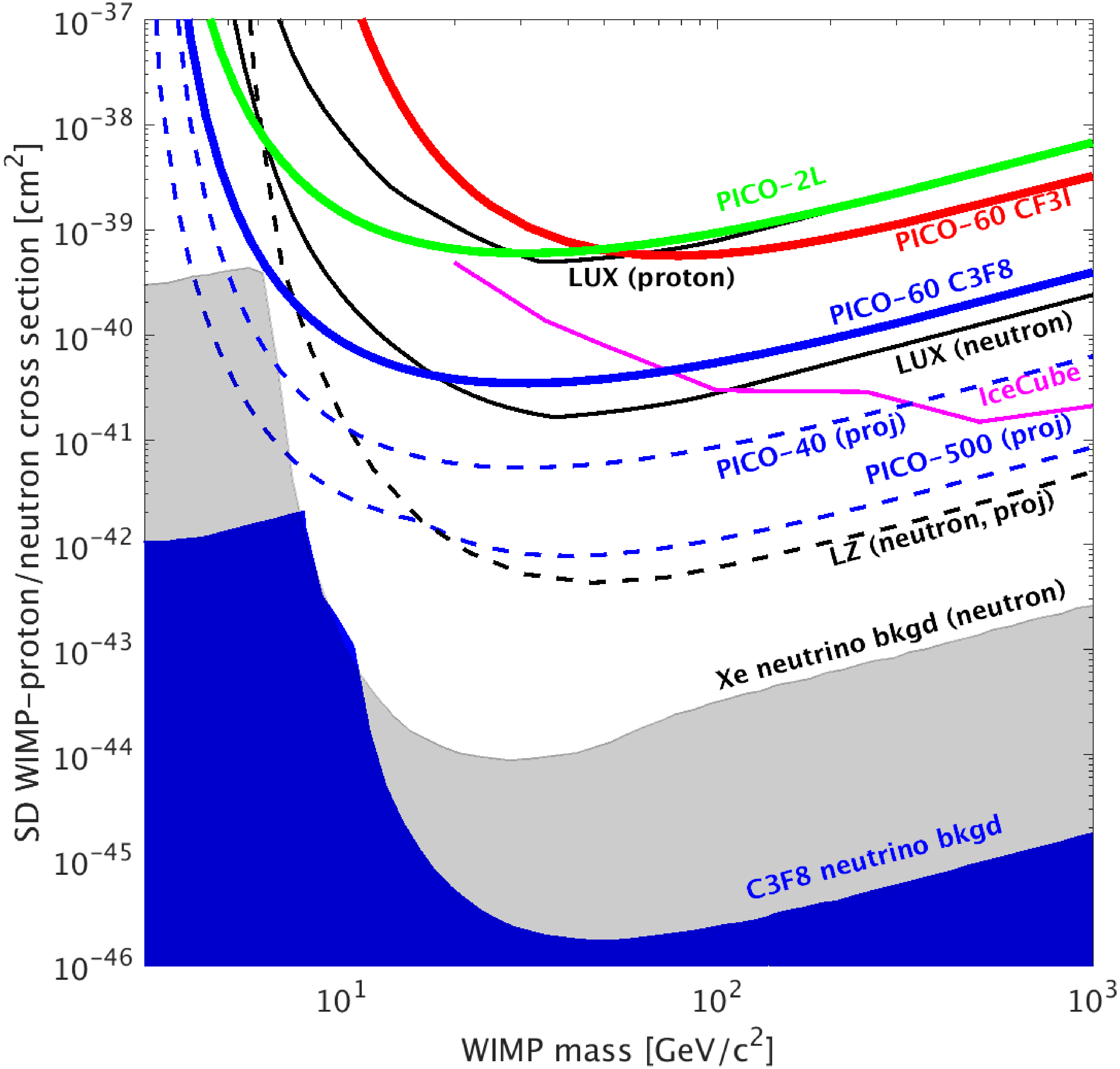
SD WIMP-proton/-neutron combined sensitivity plot



Direct Detection Rates

$$\frac{dR}{dQ} = \frac{\rho_0}{m_\chi} \times \frac{\sigma_0 A^2}{2\mu_p^2} \times F^2(Q) \times \int_{v_m} \frac{f(v)}{v} dv$$

- DM density component
- Unknown cross section – *what we set upper limits on*
- Nuclear form factor: $F^2 \propto \exp(-Q/Q_0)$ where $Q_0 \sim (80\ \mathrm{MeV})/A^{5/3}$
- Velocity distribution of dark matter in the galactic halo

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Comparing SD limits

SD WIMP-nucleus cross-section at ***q***=0

$$\sigma_A = \frac{32}{\pi} G_F^2 \mu_A^2 \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2 \frac{J+1}{J}$$

WIMP-nucleon cross-sections (in limiting cases $a_{n,p}$=0)

from experiment → σ_A

$$\sigma_{p,n}^{\lim(A)} = \frac{3}{4} \frac{J}{J+1} \frac{\mu_{p,n}^2}{\mu_A^2} \frac{\sigma_A}{\langle S_{p,n} \rangle^2}$$

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LHC comparison method

4.1.2 SD case: Axial-vector mediator

For the axial-vector mediator, the scattering is SD and the corresponding cross section can be written as

$$\sigma_{\rm SD} = \frac{3\, f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4} \,. \tag{4.7}$$

In general $f^{p,n}(g_q)$ differs for protons and neutrons and is given by

$$f^{p,n}(g_q) = \Delta_u^{(p,n)}\, g_u + \Delta_d^{(p,n)}\, g_d + \Delta_s^{(p,n)}\, g_s \,, \tag{4.8}$$

where $\Delta_u^{(p)} = \Delta_d^{(n)} = 0.84$, $\Delta_d^{(p)} = \Delta_u^{(n)} = -0.43$ and $\Delta_s = -0.09$ are the values recommended by the Particle Data Group [50]. Other values are also used in the literature (see e.g. [51]) and differ by up to $\mathcal{O}(5\%)$.

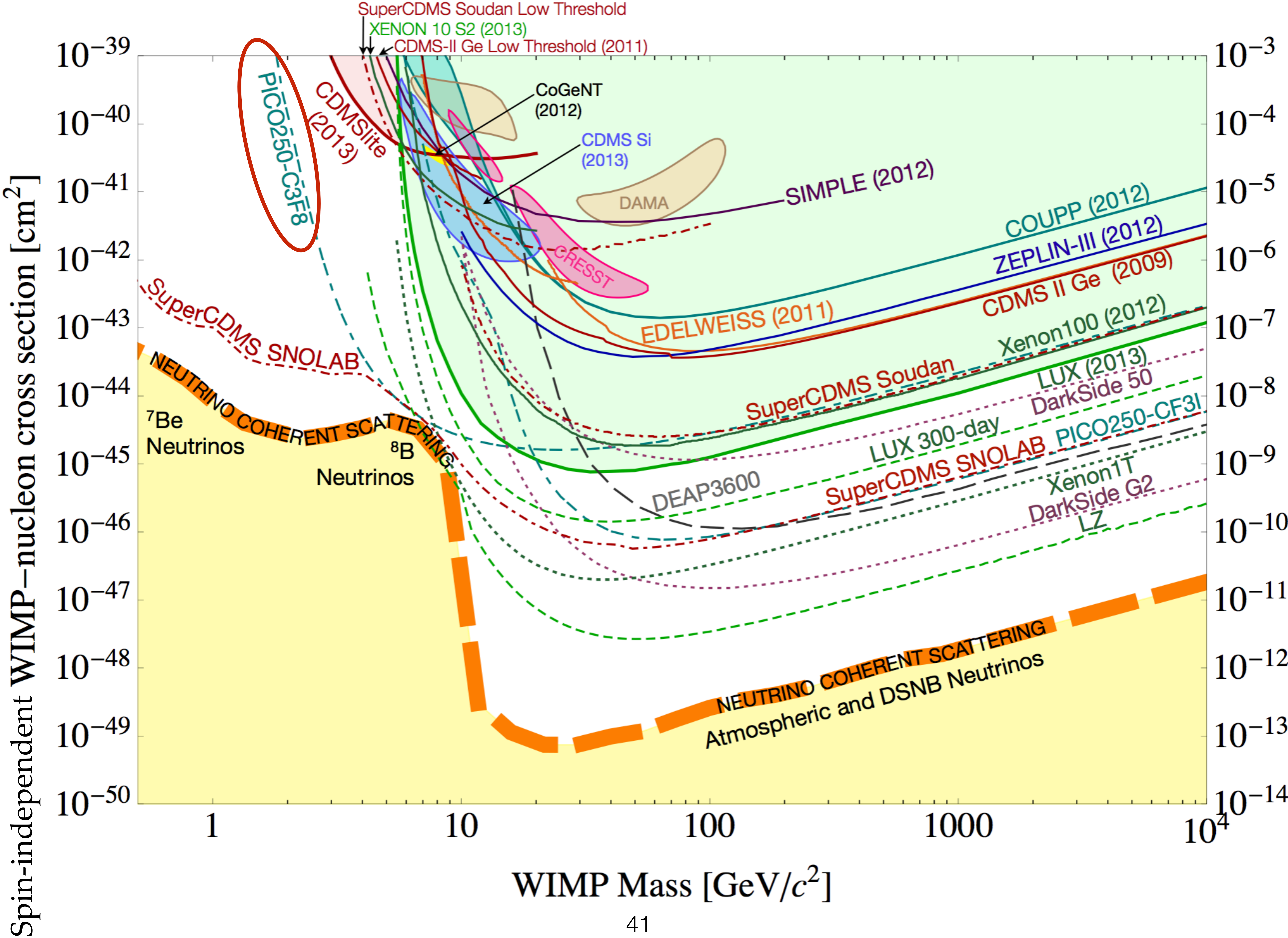
Under the assumption that the coupling g_q is equal for all quarks, one finds

$$f(g_q) = 0.32\, g_q \,, \tag{4.9}$$

and thus

$$\sigma^{\rm SD} \simeq 2.4 \times 10^{-42}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{0.25}\right)^2 \left(\frac{1\,{\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2 . \tag{4.10}$$

(arXiv:1603.04156)



SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
PICO250-C3F8
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
Spin-independent WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
1
10
100
1000
10^4
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
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