The PICO Dark Matter Search Experiment

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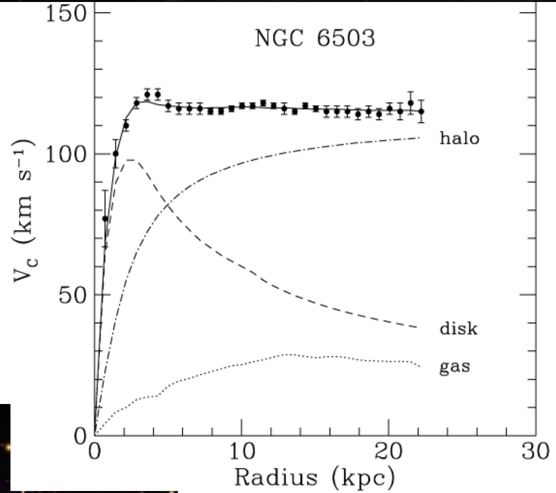
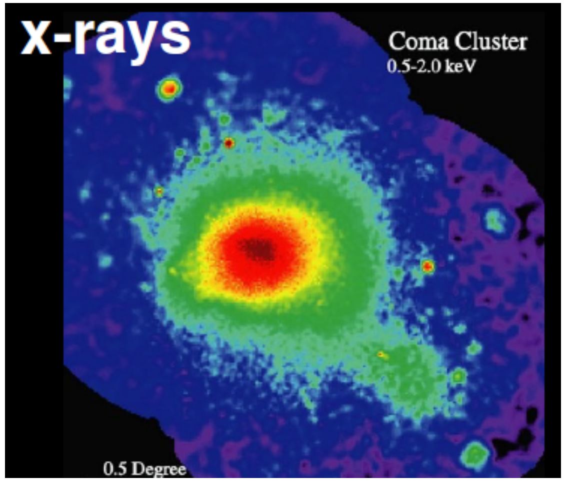
Evidence for DM

Since the 1930s, observations of galaxies, clusters of galaxies and larger scale structures show that they contain far more mass than can be accounted for by the atoms in these systems.

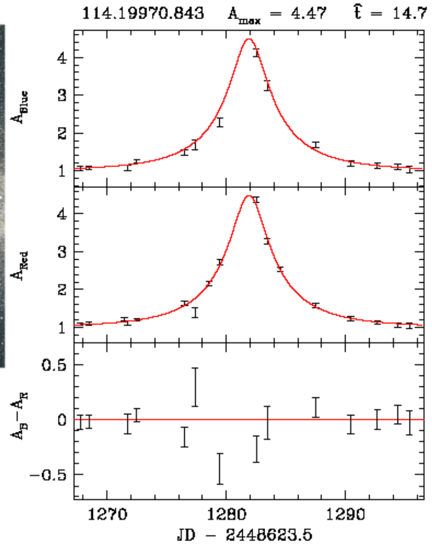
What is responsible? We don't know.

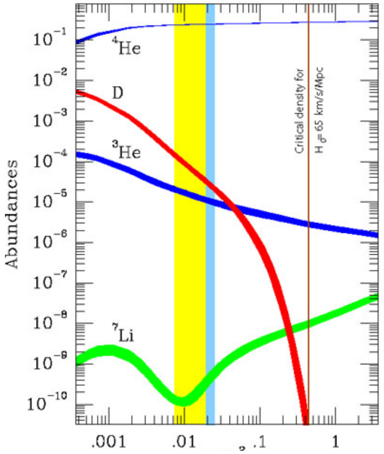




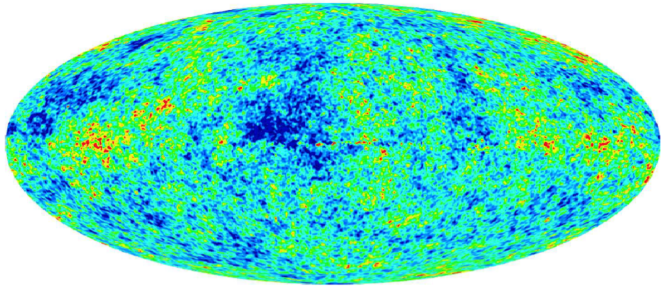
We haven’t missed SM particles

a) Effects from diffuse or concentrated baryonic matter aren’t enough.
b) MACHO search (microlensing of stars in LMC and MW bulge)
c) BBN strongly constrains the baryonic budget for the universe.
d) Large scale structure needs far more than this source of gravity to have formed by this time.
e) Can’t interfere with BBN
f) Can’t interact with the CMB.





A Weakly Interacting Massive Particle matches these criteria.



There Are Lots of Plausible Candidates

Excellent Candidates From… **SUSY**

UED?

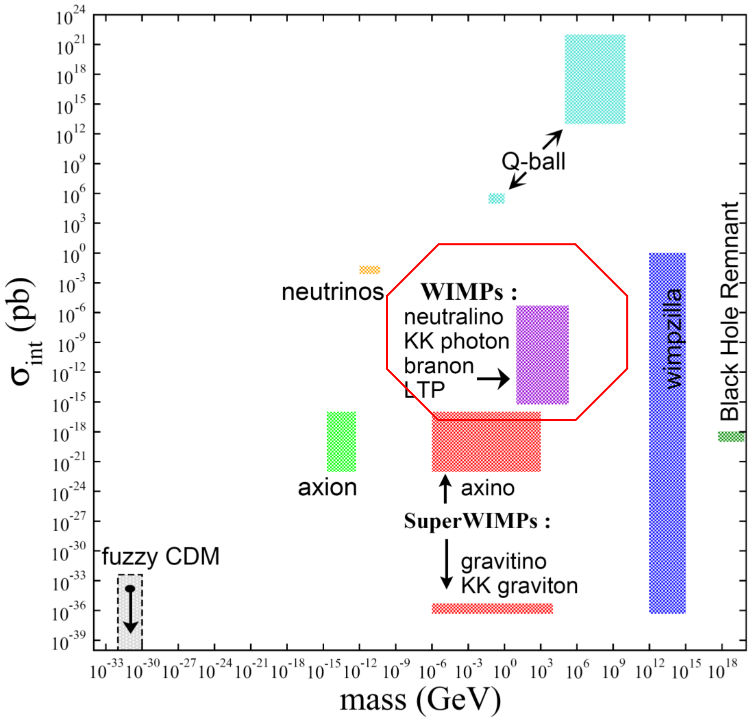
…Or, **Axions?**

…Or,

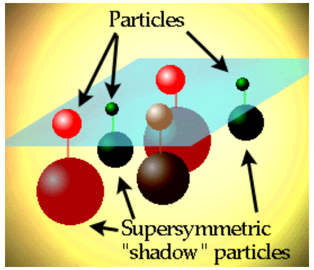
…Or, techni-baryons, gravitinos, axinos, WIMPZILLAS, Sterile neutrinos, Little Higgs, Q-balls CHArged massive particles (CHAMPS), Self-interacting,D-matter, Cryptons, Superweakly interacting dark matter (SWIMPS), Brane-world dark matter, Heavy 4th generation neutrinos,Mirror particles,

…etc.

Patient compilation by C. Hailey (Columbia)

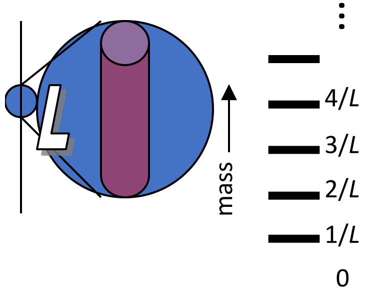


HEPAP/AAAC DMSAG Subpanel (2007)



LSP stable assuming R-parity conservation.

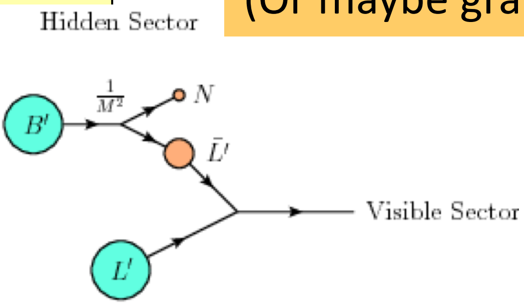
Particle Data Group



A particle moving in an extra dimension of size *L* appears to us as a set of particles with masses *0, 1/L, 2/L, 3/L, 4/L, …*

- Each known particle has a heavy partner at each mass level.

(Or maybe gravity is very different than we think on large scales?)



WIMPs are a plausible and testable hypothesis

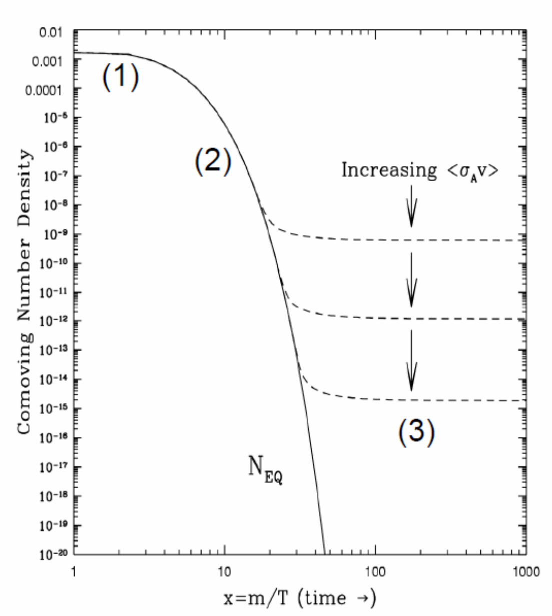
Suppose Stable LSP Weakly Interacting Massive Particles Are the Dark Matter

"WIMP Miracle"

Assume dark matter is stable relic from early universe.

Freeze out of a ~100GeV particle with EW scale interactions gives measured relic density.

SUSY inspired WIMPs fit this bill.

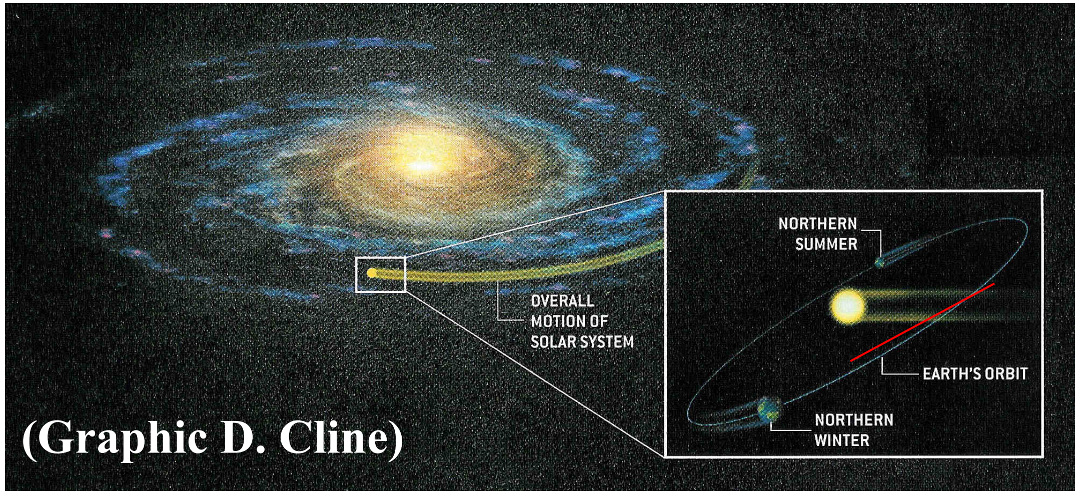


In self gravitating halo

Maxwellian velocity distribution

(< v > ~230km/s) Local density: ρ_{Sun} ~ 0.3 GeV / cm^3.
J.D. Lewin and P. Smith, Astrop. Phys.6 (1996) 87

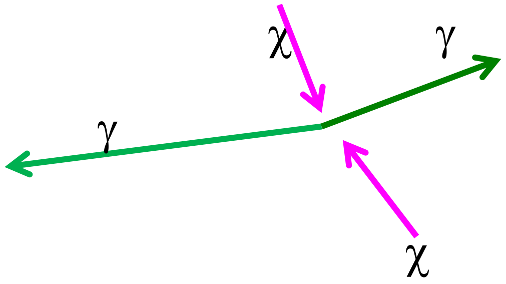
annual variation

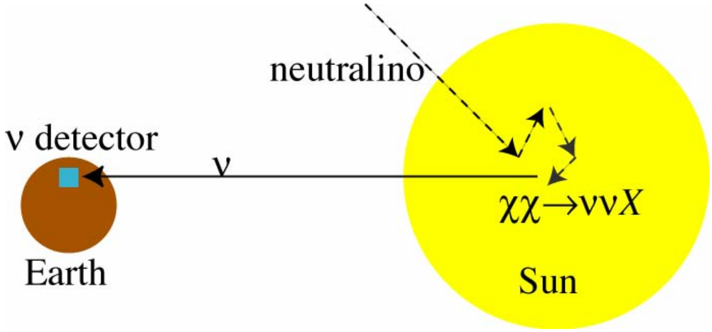


(Graphic D. Cline)

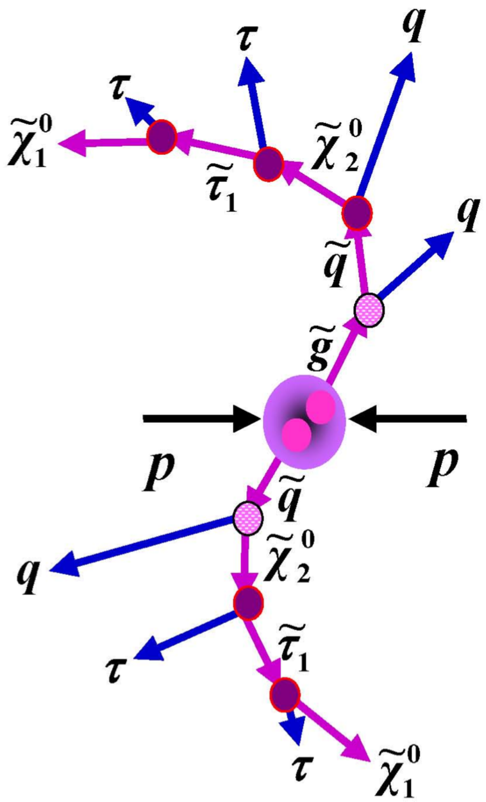
How to Detect WIMPs?

Indirect detection: Annihilation to SM particles (eg Fermi or Icecube)

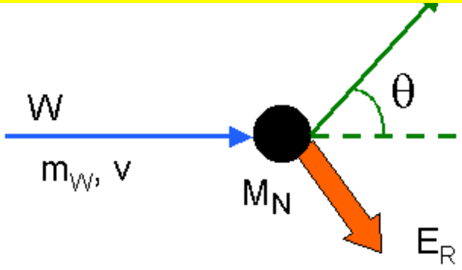




Manufacture: (CMS, ATLAS, LHCb, BaBar & CODEX talks)



Direct detection: Observe scatter of ordinary atoms by invisible projectile



Heat, ionization, etc.
Rare event, low energy experiments, so need to go underground.

Which atoms to use as target?

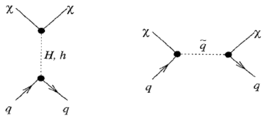
Selection of nuclear target

Neutralino Interaction with matter:

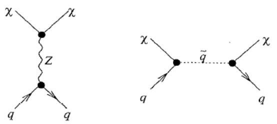
$$(\tilde{B}, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$$

$$\sigma_A = 4G_F^2 \left(\frac{M_\chi M_A}{M_\chi + M_A} \right)^2 C_A$$

More Higgsino



More Bino



Spin independent interaction ($C_A \propto A^2$) (but small or vanishing cross sections possible)

$$C^{SI}_A = (1/4\pi)(Zf_p + (A-Z)f_n)^2$$

Spin dependent interaction

(small, but stable and can dominate for some candidates)

$$C^{SD}_A = (8/\pi)(\underbrace{a_p\langle S_p\rangle + a_n\langle S_n\rangle}_{\lambda})^2(J+1)/J$$

(Spin of nucleus ~ spin of unpaired proton or neutron)

Cf: JD. Lewin and P Smith Astrop. Phys. 6 (1996) 87 and J. Engel et al., Int J. Mod Phys. E1 (1991) 1

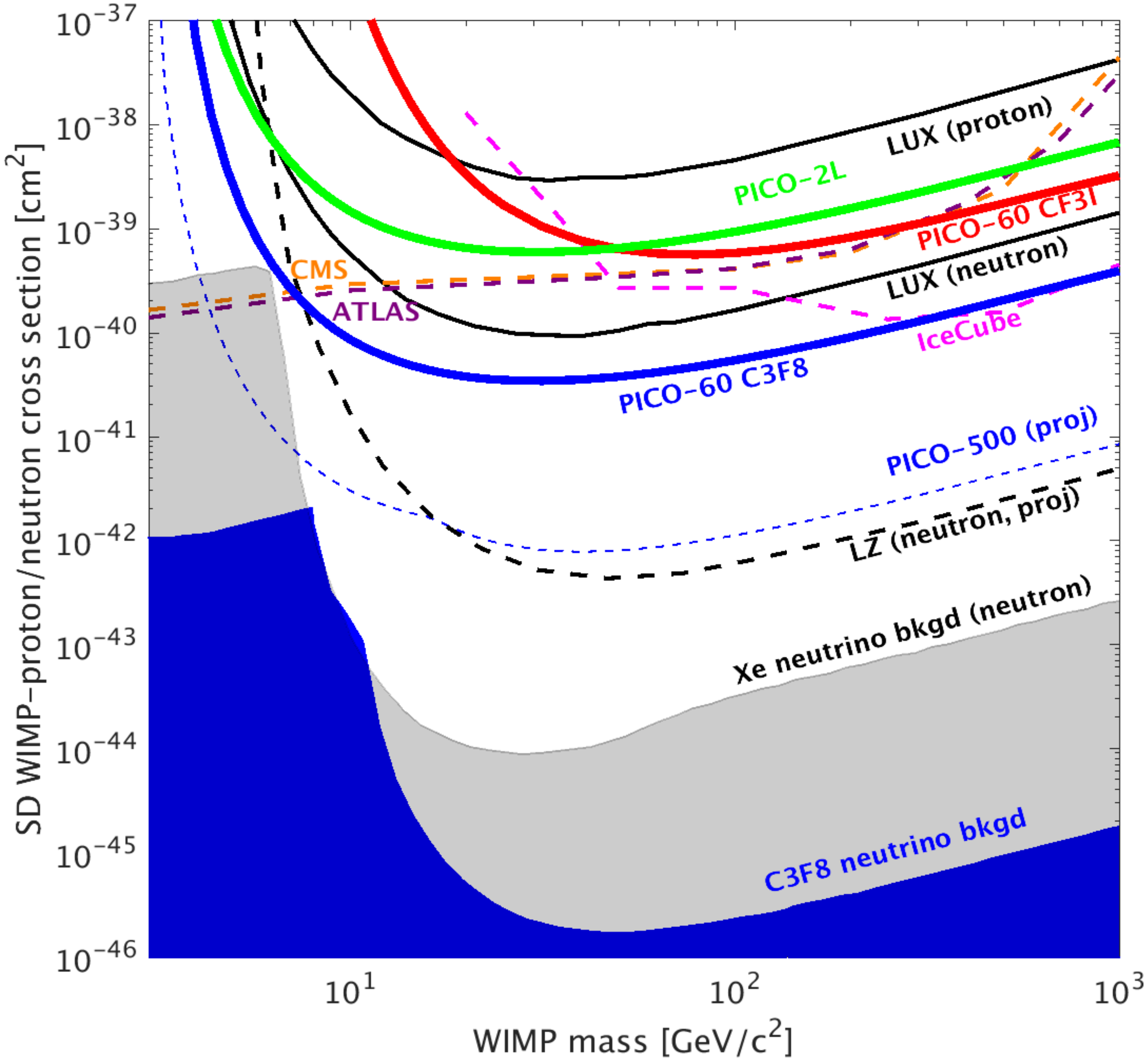
Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	**1/2**	**p**	**0.863**
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

^{19}F ideal for SD(p)
^{127}I excellent for SI

Best of both worlds: CF_3I

J. Ellis and R. Flores, PLB **263**, no. 2, pg 259, 1991

The Physics Case for ^{19}F



A gen-3 ^{19}F search experiment cost is comparable to gen-2 xenon experiment

The "neutrino floor" for Xe is not a barrier for ^{19}F!

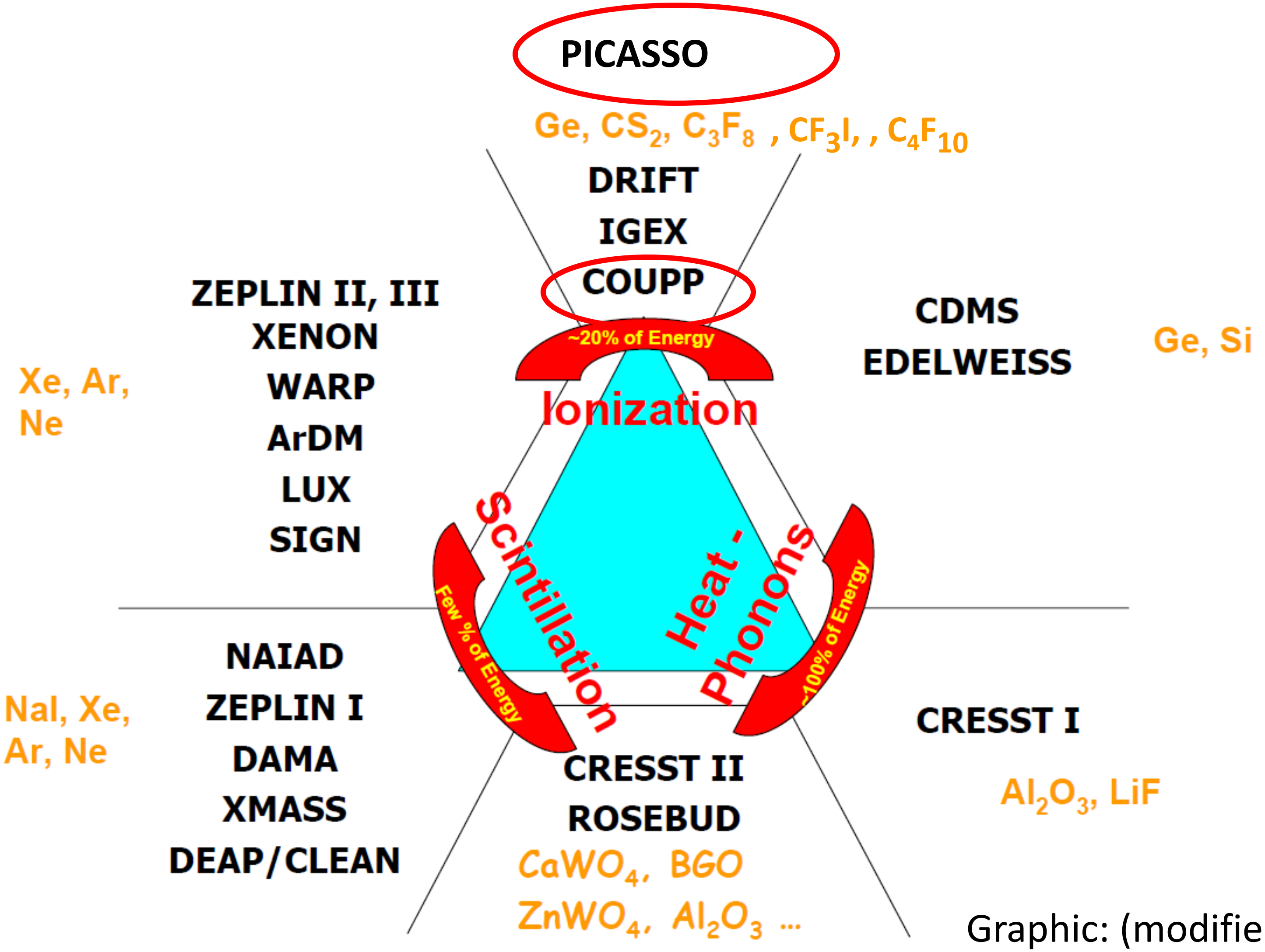
LZ projections: LUX Collaboration, Phys. Rev. Lett. 116, 161302 (2016)

Neutrino floors: F. Ruppin *et al.*, Phys. Rev. D 90, 083510 (2014)

How to amplify ~1-100 keV?

Direct Detection Strategies

Superheated Liquids! PICASSO+COUPP=PICO



PICASSO

Ge, CS_2, C_3F_8 , CF_3I, , C_4F_{10}

DRIFT
IGEX
COUPP

ZEPLIN II, III
XENON
WARP
ArDM
LUX
SIGN

Xe, Ar, Ne

CDMS
EDELWEISS

Ge, Si

NAIAD
ZEPLIN I
DAMA
XMASS
DEAP/CLEAN

NaI, Xe, Ar, Ne

CRESST I

Al_2O_3, LiF

CRESST II
ROSEBUD

$CaWO_4$, BGO
$ZnWO_4$, Al_2O_3 …

Graphic: (modified)
Hank Sobel

PICO

SNOLAB

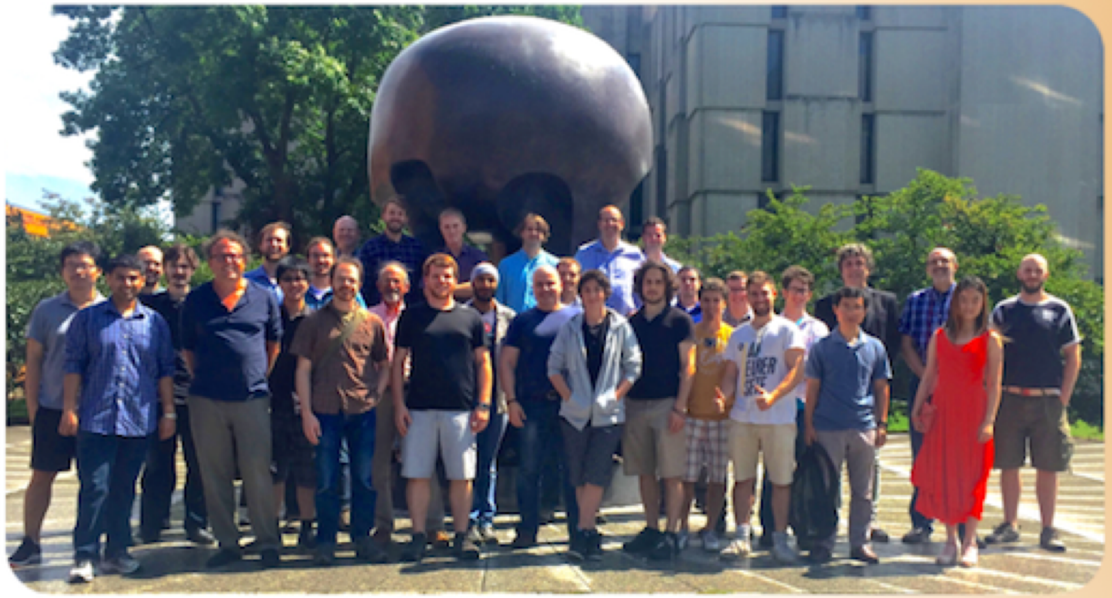
K. Clark, I. Lawson

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

M. Ardid, M. Bou-Cabo, I. Felis

NORTHWESTERN UNIVERSITY

D. Baxter, C.E. Dahl, M. Jin, J. Zhang



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KICP Kavli Institute for Cosmological Physics

J.I. Collar, A. Ortega

Université de Montréal

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VirginiaTech

D. Maurya, S. Priya

Laurentian University Université Laurentienne

J. Farine, F. Girard, A. Le Blanc, R. Podviyanuk, O. Scallon, U. Wichoski

IU South Bend Astroparticle Group 2017

Major	# students	# in/went grad school	# planning grad school	# STEM (non-academic)	
Physics/astro	29	11	6	14	
Other science/Eng	12	4	2	3	
non-science	4	1		2	
Education	3				
total*	45				

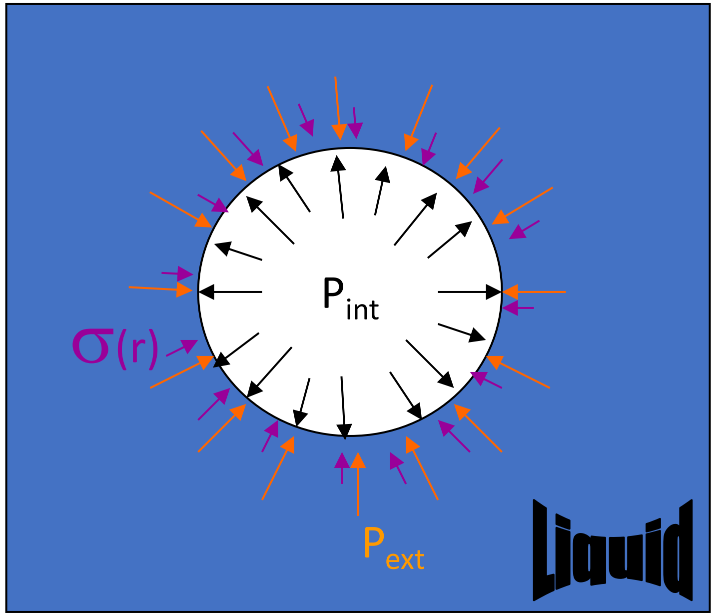
IUSB Team Historical

45 Undergraduate Students
7 High School Students
6 High School Science teachers

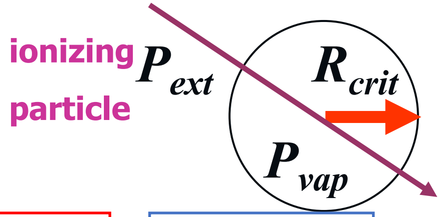
Postdoctoral Research Fellow: Orin Harris, 2013-2016. Current position: Assistant Professor of Physics, Northeastern Illinois University Department of Physics & Astronomy

Help from IUSB Chemistry Department Faculty

Superheated Liquid Detection Technique



$$\frac{dE}{dx} > \frac{E_c}{a r_c}$$



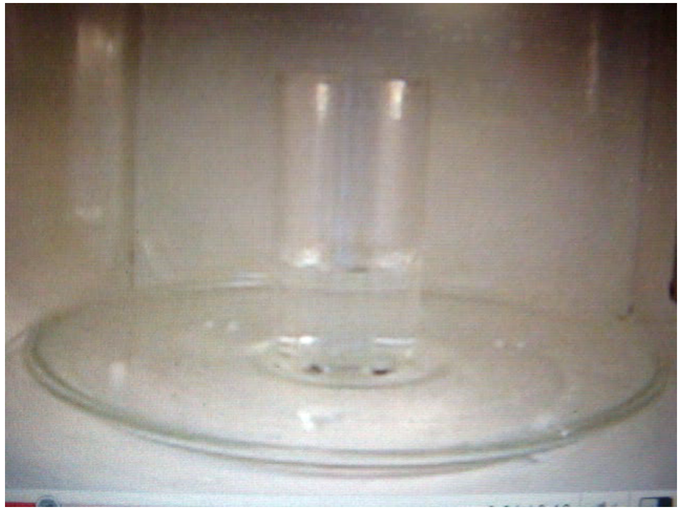
$$E > E_c = \underbrace{\boxed{4\pi r_c^2\left(\gamma - t\frac{\partial\gamma}{\partial T}\right)}}_{\text{Surface energy}} + \underbrace{\boxed{\frac{4}{3}\pi r_c^3 \rho_v \frac{h_{fg}}{M}}}_{\text{Latent heat}}, \quad r_c = \frac{2\gamma}{\Delta P}$$

A Double Threshold (Energy and dE/dx)

Can adjust operating parameters to be fully sensitive to recoiling nuclei while insensitive to the most pernicious backgrounds.

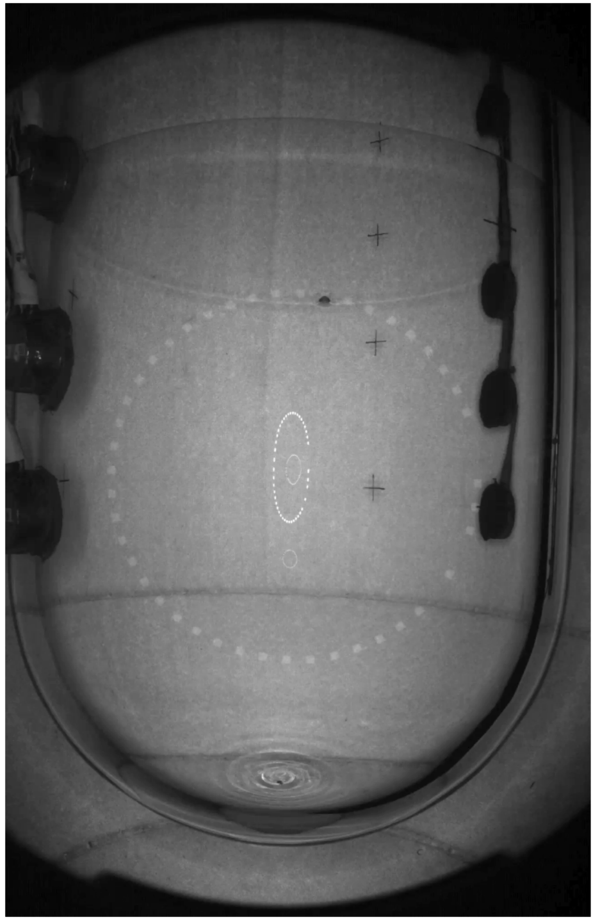
Superheated Liquid Detectors

(Water & CF_3I, respectively)



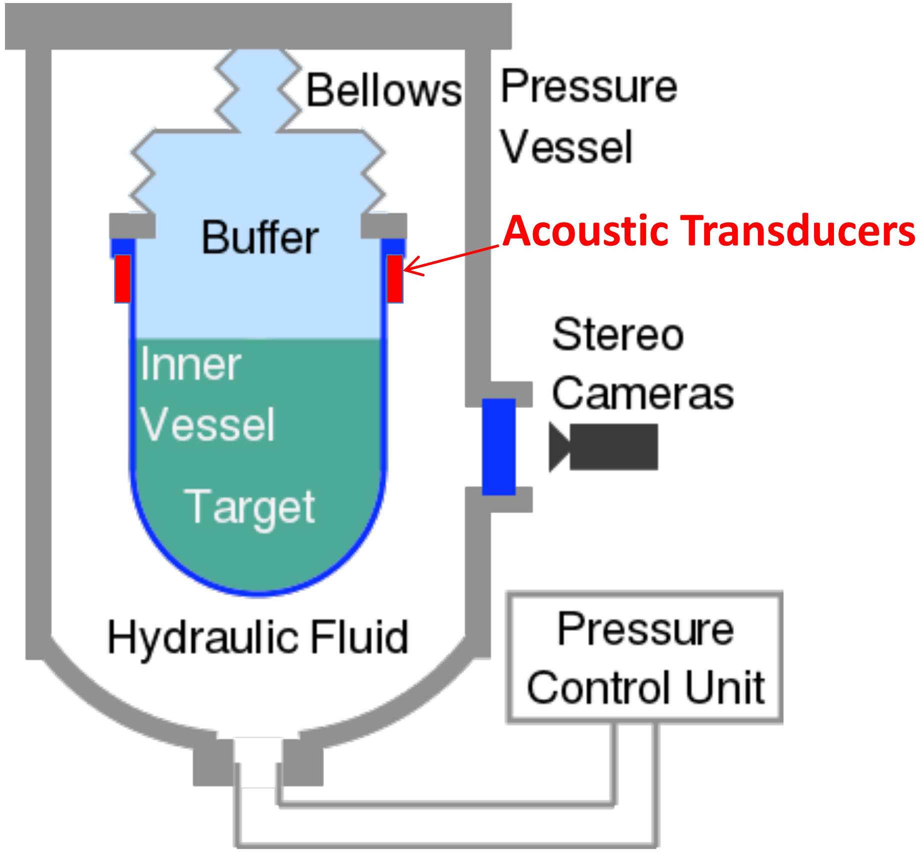
A penny detector

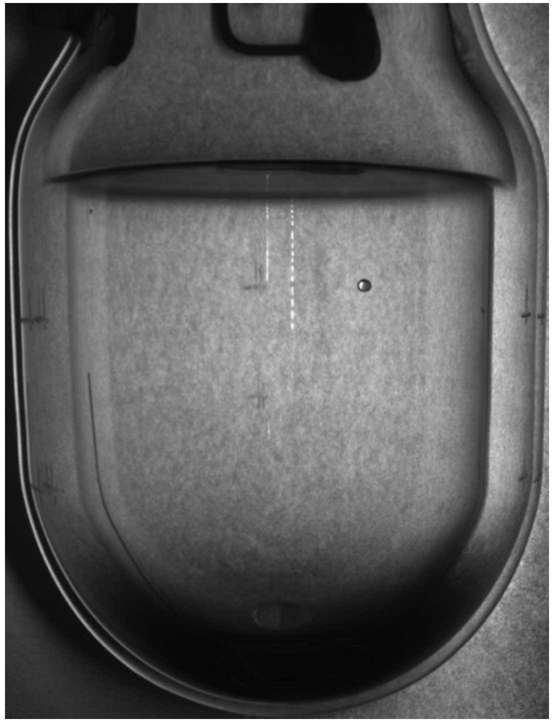
Self-magnifying signal!



A WIMP detector

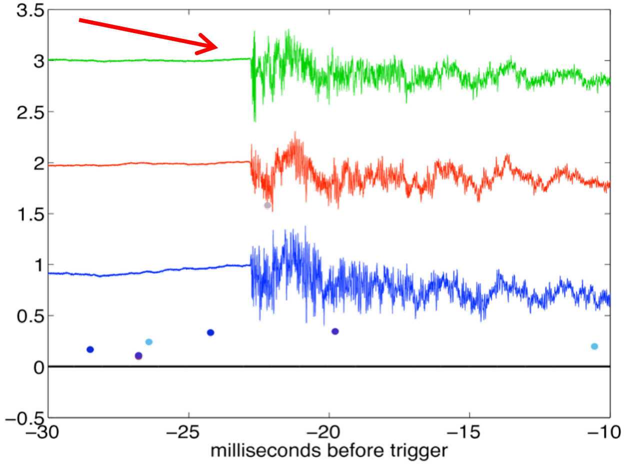
Traditional PICO Bubble Chamber Overview





Single bubble event in a 2 Liter Chamber.

Acoustic traces



Bubble chambers

- Target fluid C_3F_8, CF_3I in low activity pure quartz vessel
- Fast re-pressurization after bubble formation
- Events recorded optically & acoustically
- Operating pressure determines energy threshold

Why Superheated Liquids?

MIPs are not a background

Easy to identify Neutron backgrounds

Target is easy to change

Easily purify arbitrary target mass

No cryogenics system

Simple DAQ: Cameras and Piezos

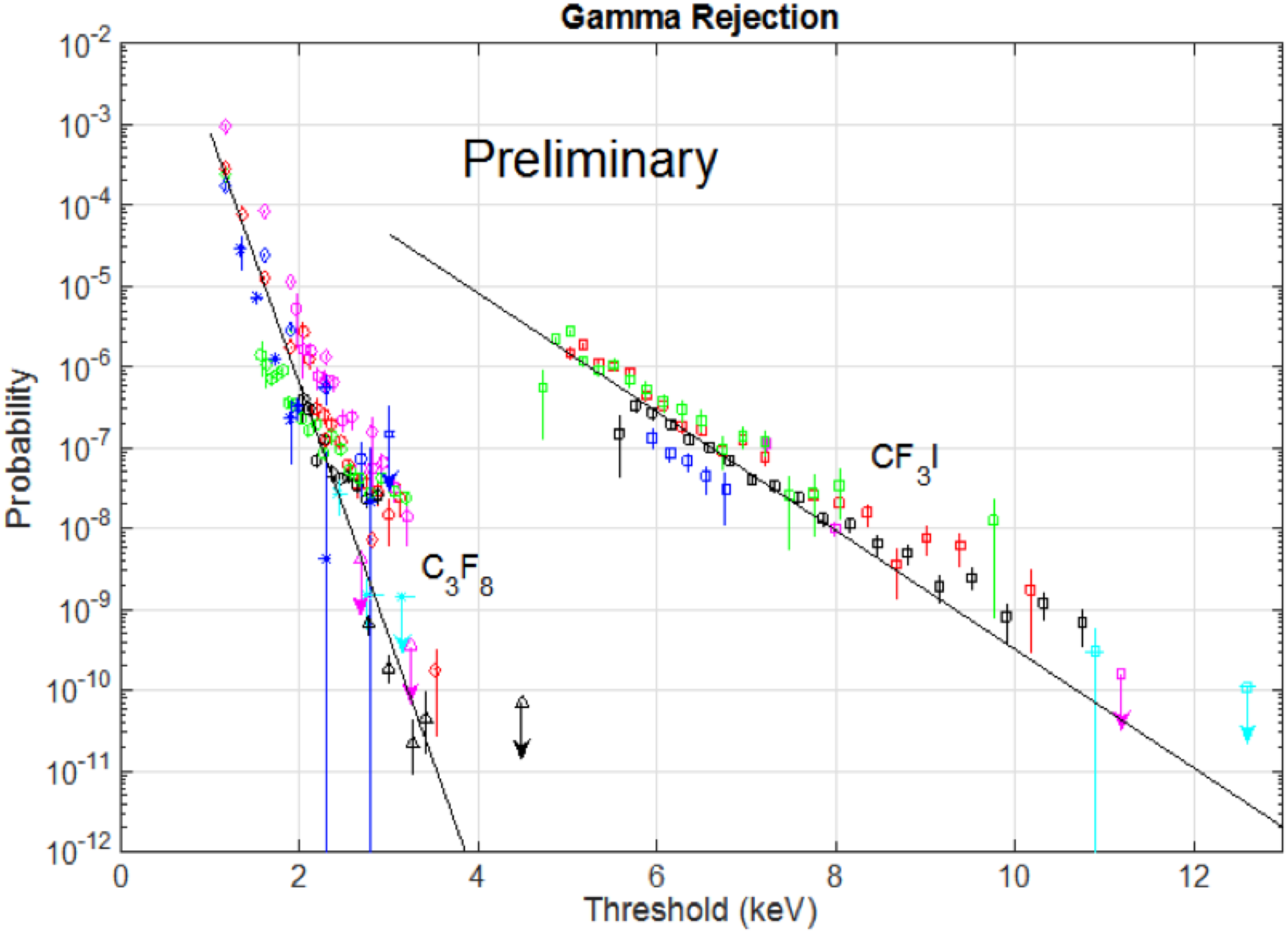
No signal loss with target size.

No isotopic purification.

Low cost

Gamma rejection in CF_3I: ~10^{-10} @12 keV

Gamma rejection in C_3F_8: ~10^{-10} @3 keV



No cuts: Electrons/photons don't make bubbles!

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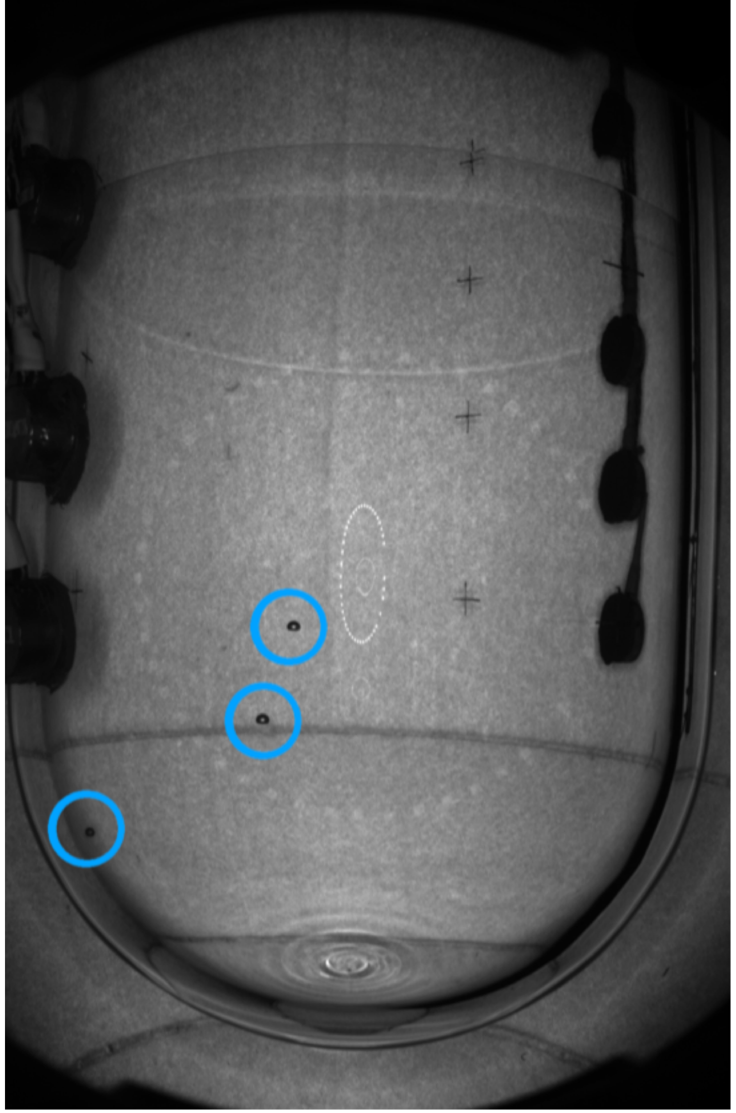

Multi-bubble/Single Bubble ratio,
Spatial distributions

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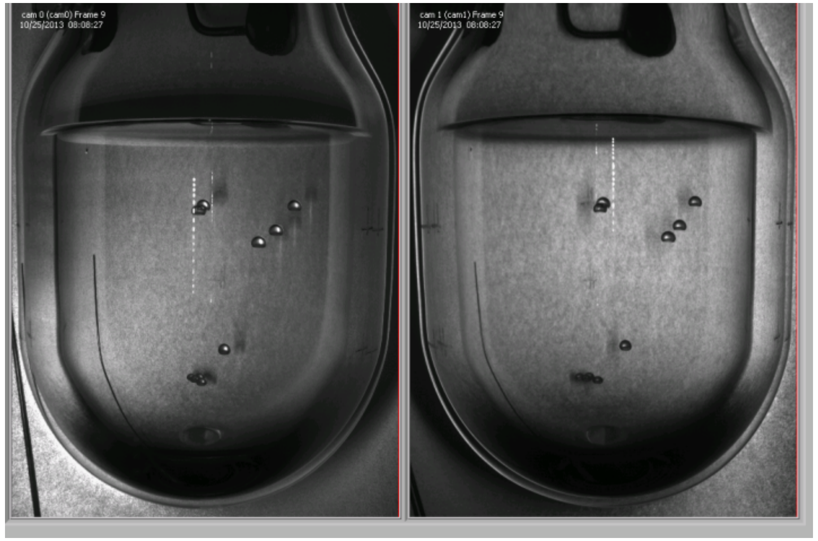


PICO has operated various chambers with C_3F_8, CF_3I, CF_3Br, C_4F_{10} with essentially the same hardware

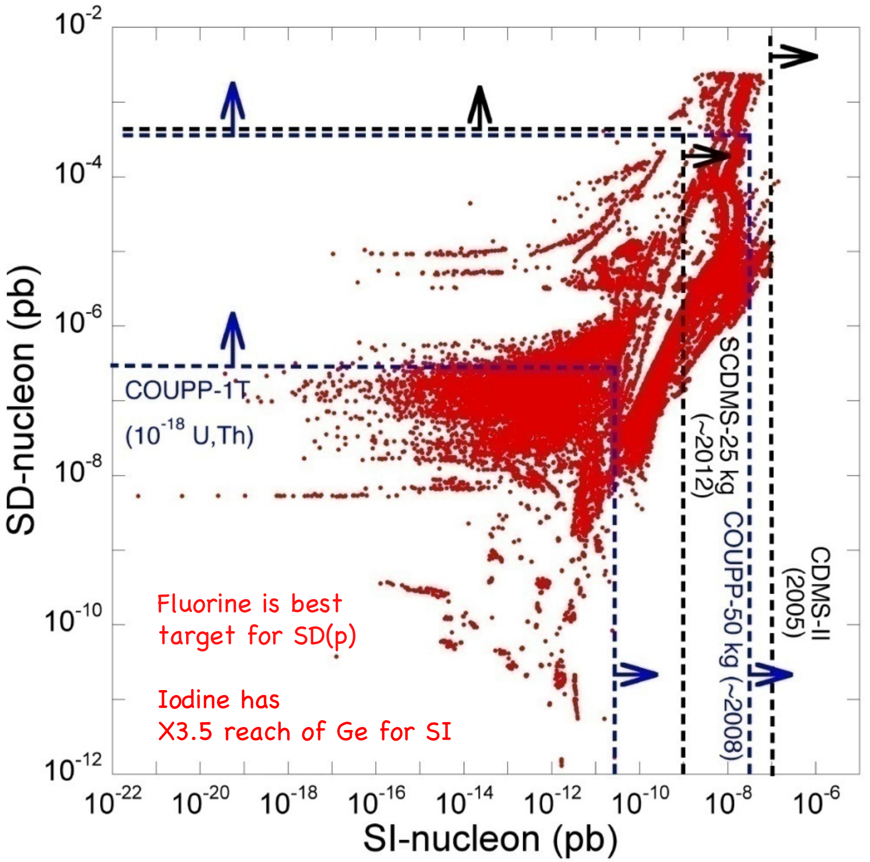
More target mass just means more time operating the fluid handling system.

No complicated cryogenics needed for a wide range of fluids which are superheated at ~room temperature.

Target Is Relatively Easy to Change in PICO

- SD and SI couplings

Search on both fronts



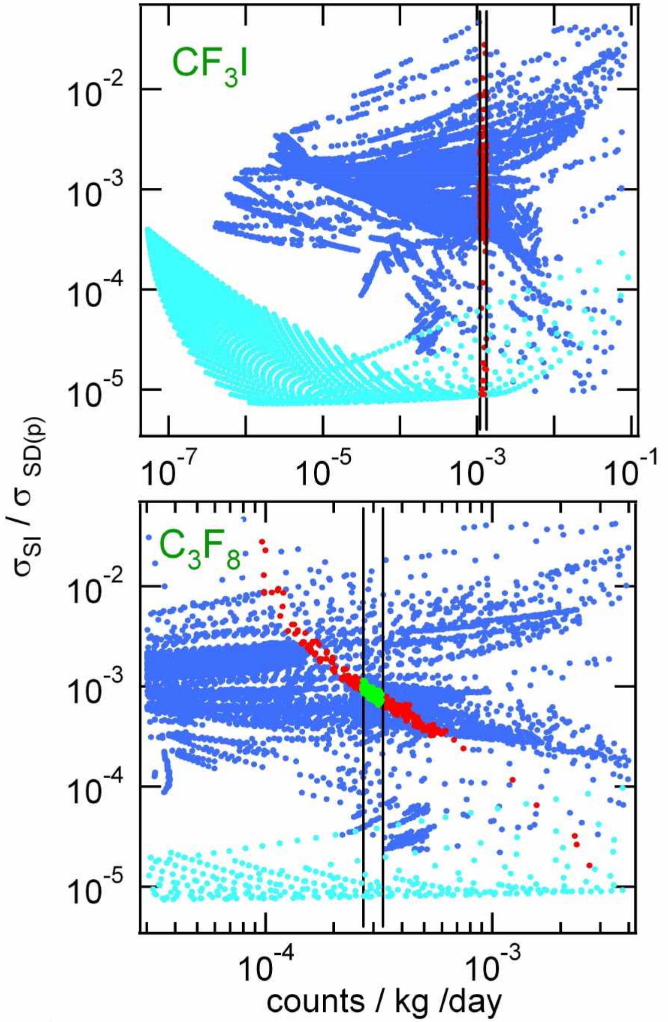
Fluorine is best target for SD(p)

Iodine has X3.5 reach of Ge for SI

Baltz & Gondolo, JHEP 0410:052,2004. (WMAP-II update)

SD SUSY space harder to get to, but predictions are more robust and phase-space more compact. Worth the effort. (astro-ph/0001511, 0509269, and refs. therein)

- Target fluid can be replaced (e.g., C_3F_8, C_4F_{10}, CF_3Br). Useful for separation between n- and WIMP-recoils and pinpointing WIMP in SUSY parameter space.



Bertone, Cerdeno, Collar and Odom (Phys. Rev. Lett. 99(2007)151301)

Rate measured in CF_3I and C_3F_8 (vertical bands) tightly constrains responsible SUSY parameter space and type of WIMP (LSP vs LKKP)

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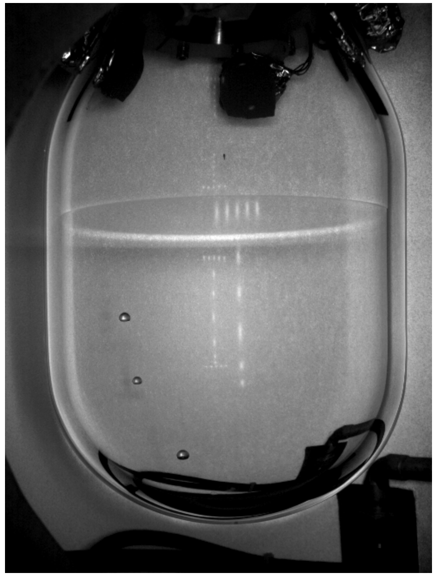
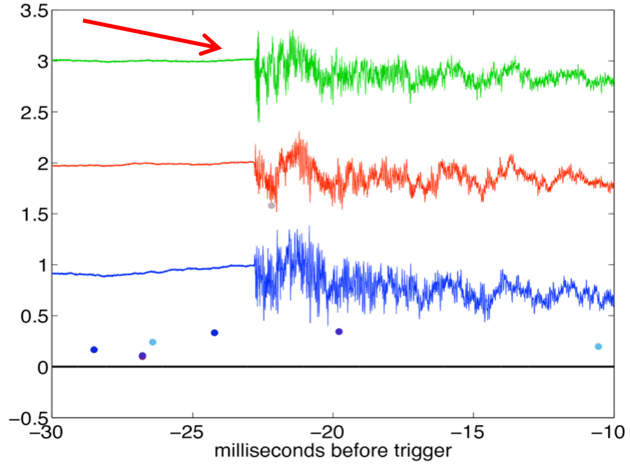
Trigger frame



Acoustic traces



Once the critical radius bubble is created, it grows without bound until the trigger system pressurizes the chamber.

Cost per unit mass of ~$200/kg for C_3F_8 and $5000/kg for CF_3I is tiny in comparison with targets for other detectors.

Drawback

Threshold detectors
-> Less information per event
-> *Alphas do* cause bubbles

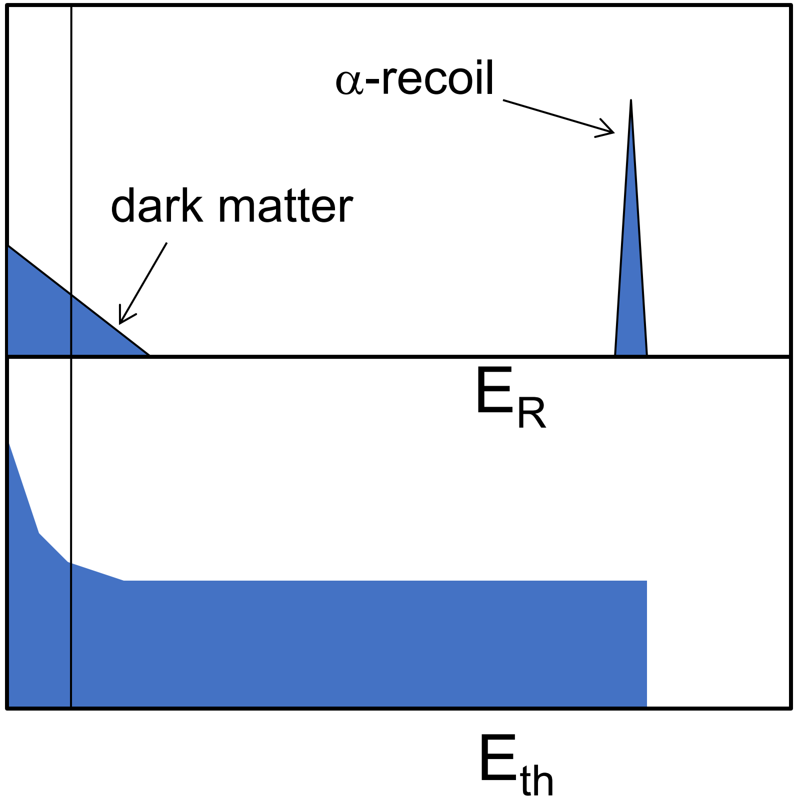
Energy Threshold calibrations are difficult and necessary

Slow Devices (30s deadtime/event
-> Overall rate must be low

We do not measure E_R…

We measure:

$$\int_{E_{th}}^{\infty} \frac{dN}{dE_R}\, dE_R$$



…so bubbles initiated by recoiling α-decay daughters are counted along with dark matter candidate events. And we don't have event-by-event energy information….

Different Ranges of Nuclei Necessitate E^{th} calibration

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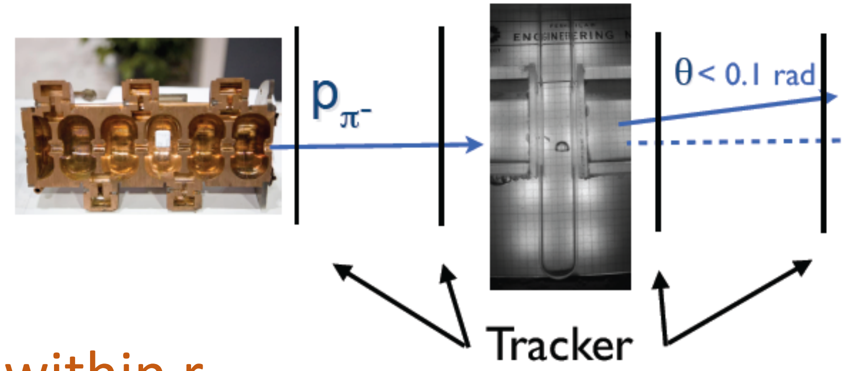
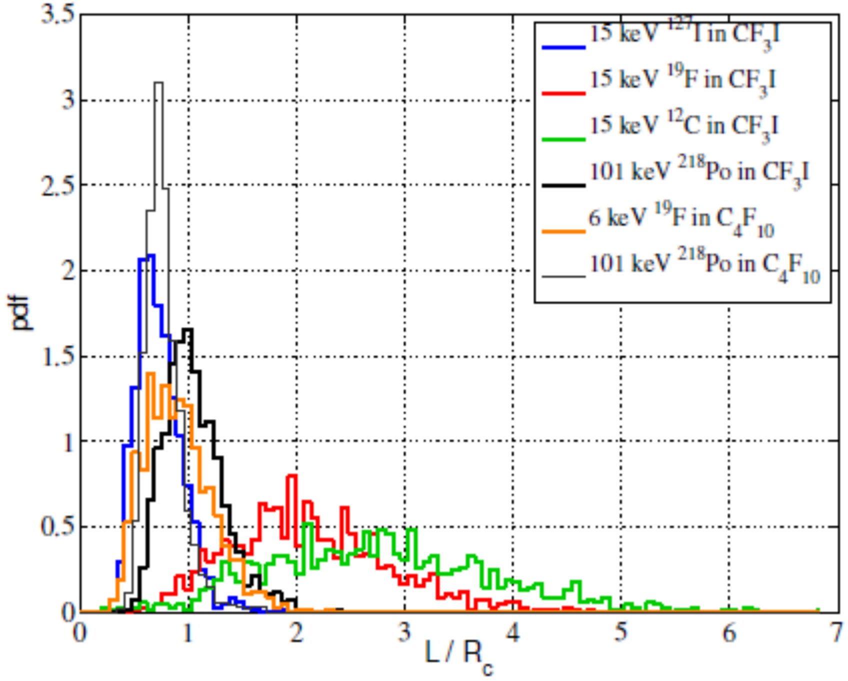
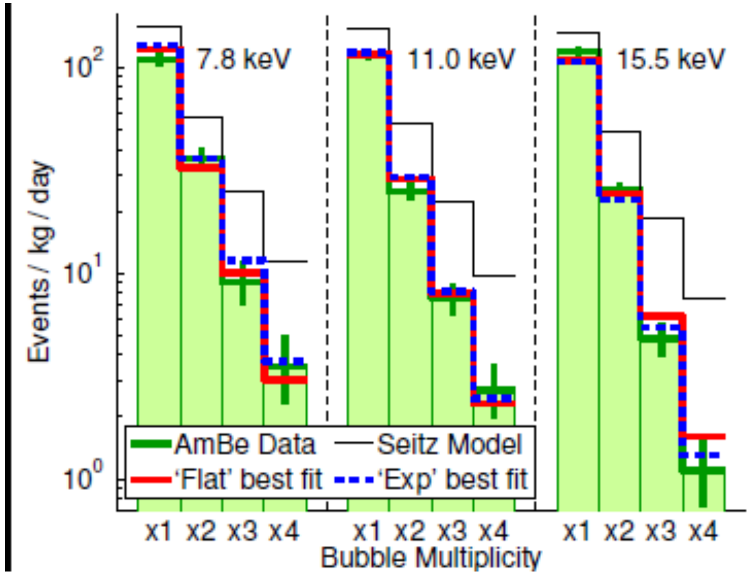
Neutrons mostly probe C and F, not I. Is I efficiency described by Seitz and useable for SI searches?

dE/dx needs to be large to get E_c within r_c .





Caused apparent discrepancy with Seitz (`Hot Spike') model.



This Drawback is Not As Limiting As It Would First Appear

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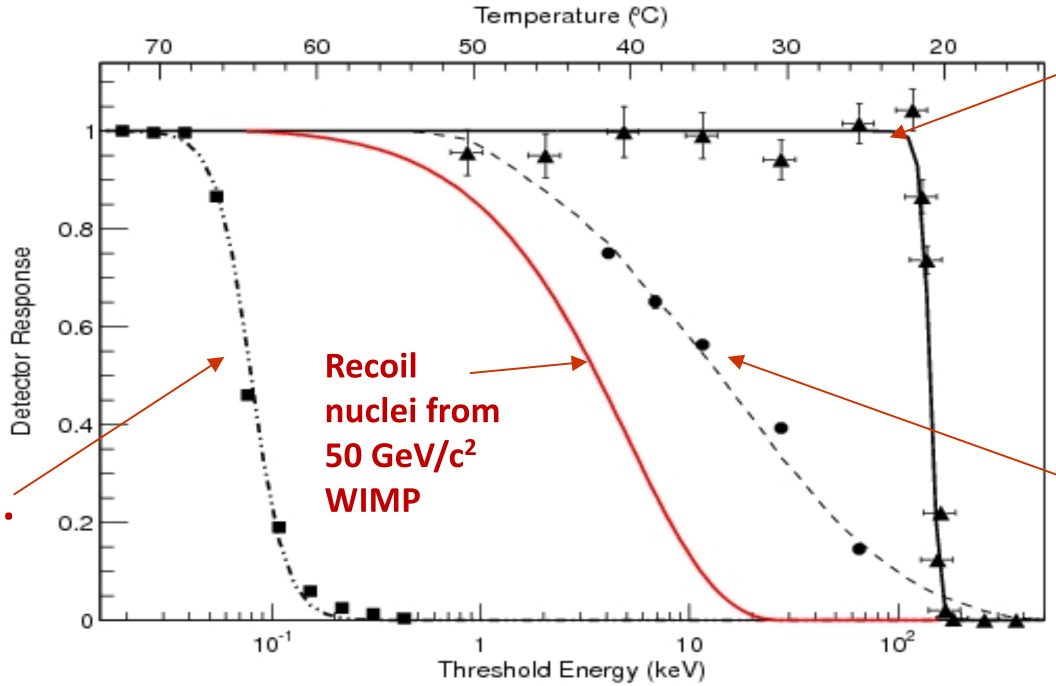
Slow Devices (30s deadtime/event -> Overall rate must be low



α-response

γ's from ^{22}Na, ^{60}Co..

Recoil nuclei from 50 GeV/c^2 WIMP

Neutrons from AcBe source (data + MC)

By running at different thresholds, background separation and WIMP spectrum can be mapped.

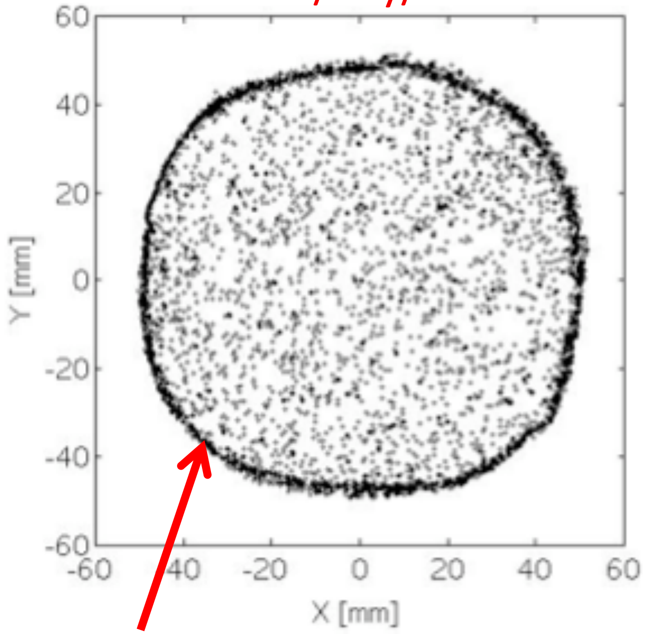
Drawback: Relatively Slow Devices

Threshold detectors
-> Less information per event
-> *Alphas* do cause bubbles

Energy Threshold calibrations are difficult and necessary

Slow Devices -> Overall rate must be low

0.8/day/cm^2



Surface run data using natural glass vessel at Fermilab (2007.) Had radon and surface activity on the glass.

Wall events: A deadtime issue

Glass activity was not a source of background, but same level of activity would have resulted in ~80% deadtime for 60 kg vessel.

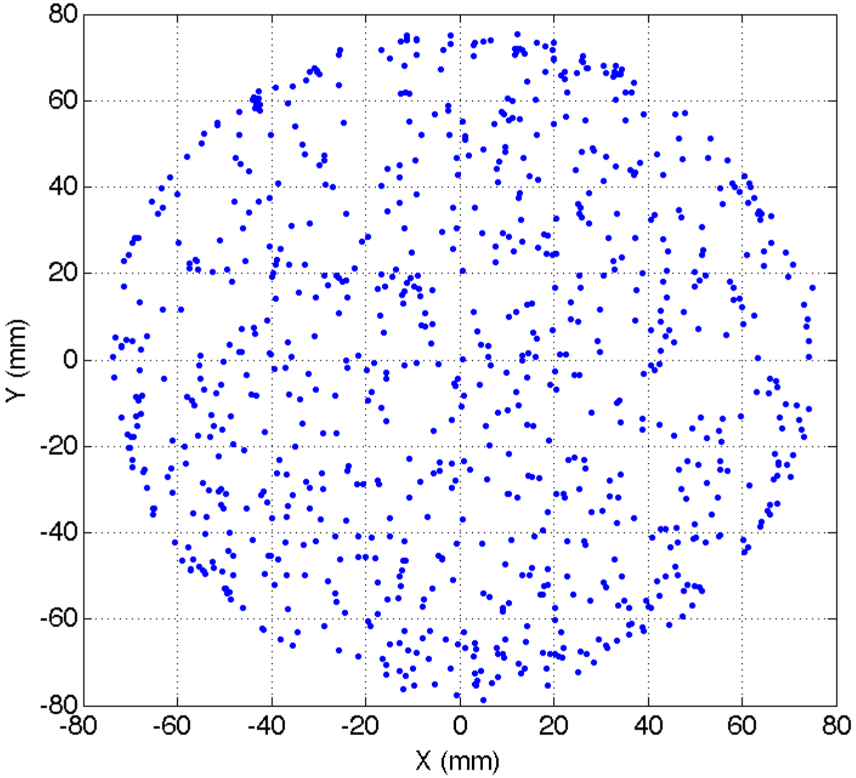
Purified Silica: No deadtime issue

Threshold detectors
-> Less information per event
-> *Alphas* do cause bubbles

Energy Threshold calibrations are difficult and necessary

Slow Devices -> Overall rate must be low

Synthetic Silica: <1e-2/day/cm^2



Surface run data using synthetic fused silica vessel at Fermilab (2009.) Wall activity is gone!

Even ton-scale detector will have no significant deadtime from wall events!

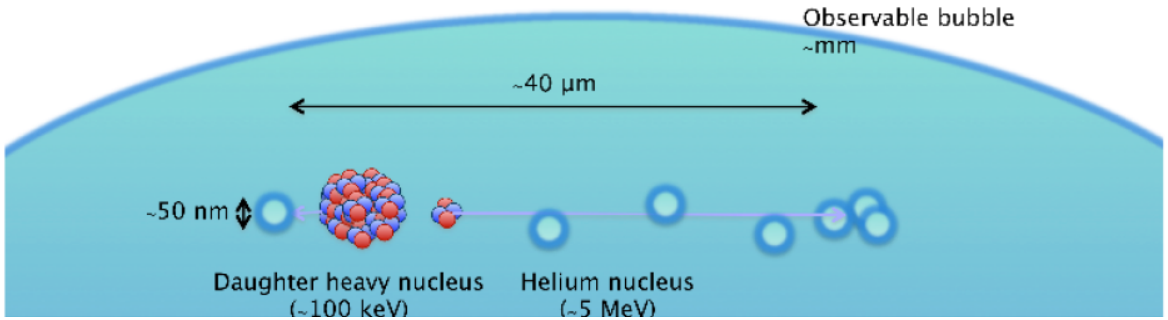
Extraordinary Advantage: **Event-by-Event Background Discrimination**

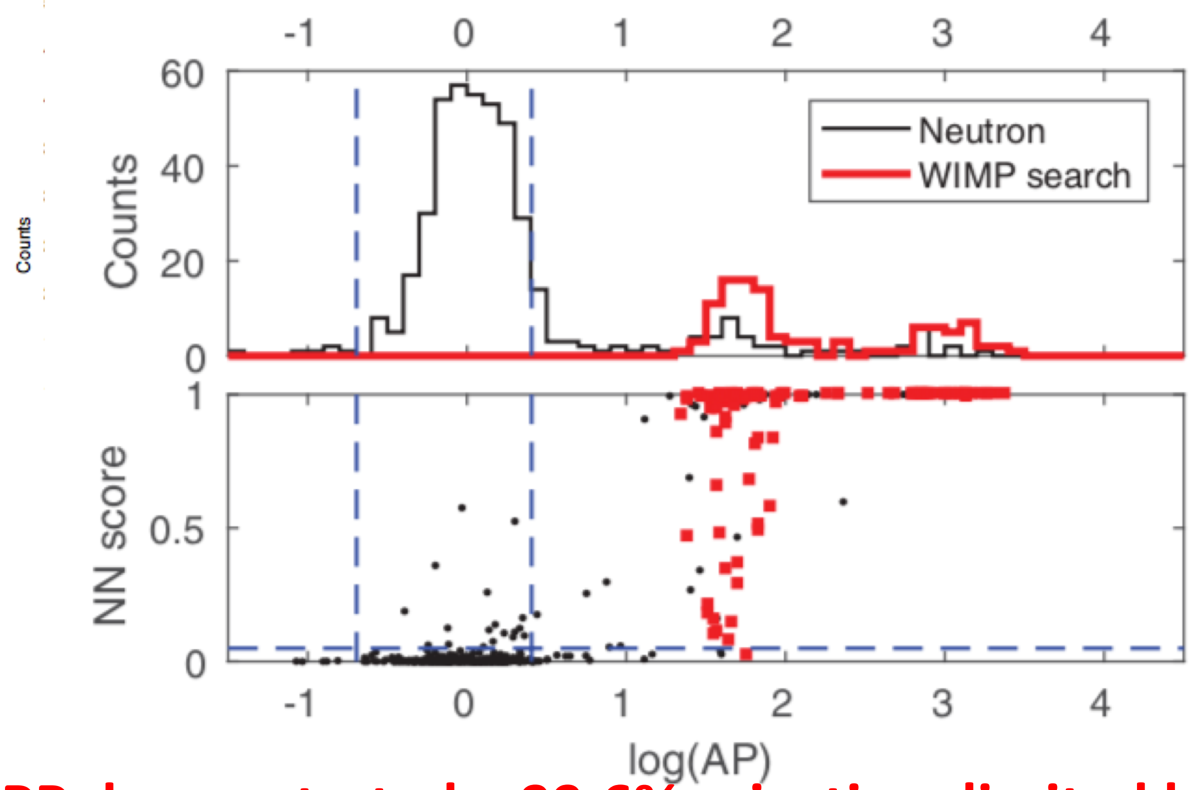
Effect discovered by PICASSO:
F. Aubin *et al.*, New J. Phys 10 (2008) 103017

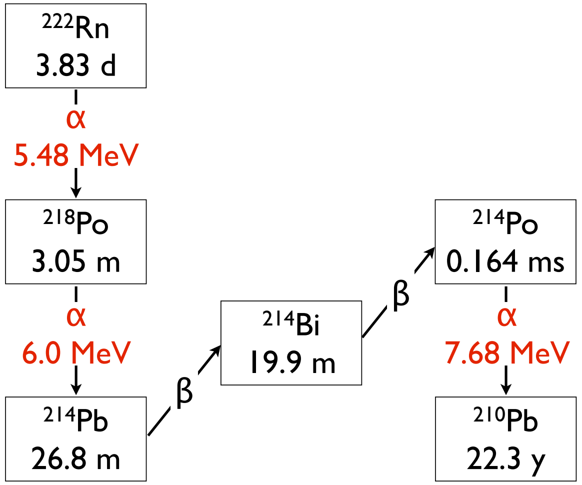
Threshold detectors
-> Less information per event
-> *Alphas do* cause bubbles

Energy Threshold calibrations are difficult and necessary

Slow Devices (30s deadtime/event -> Overall rate must be low





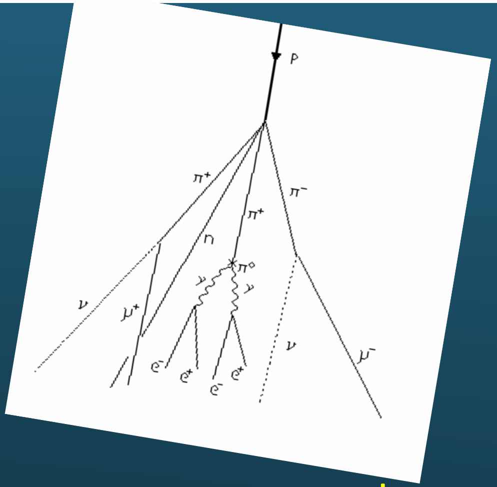


^{222}Rn
3.83 d
α
5.48 MeV
^{218}Po
3.05 m
α
6.0 MeV
^{214}Pb
26.8 m
β
^{214}Bi
19.9 m
β
^{214}Po
0.164 ms
α
7.68 MeV
^{210}Pb
22.3 y

COUPP demonstrated > 99.6% rejection, limited by statistics

Cosmic Background: SNOLAB

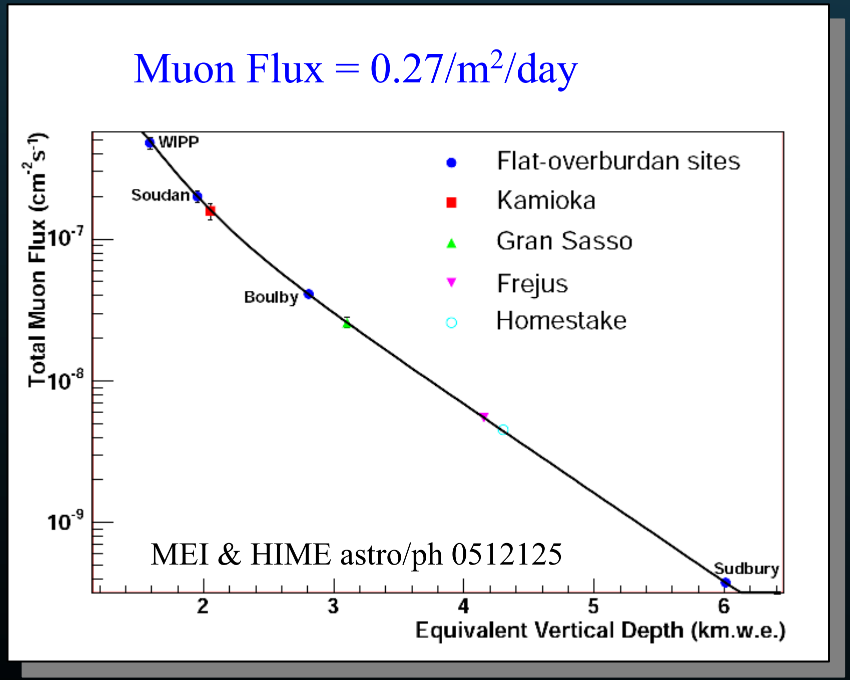
Surface Facility



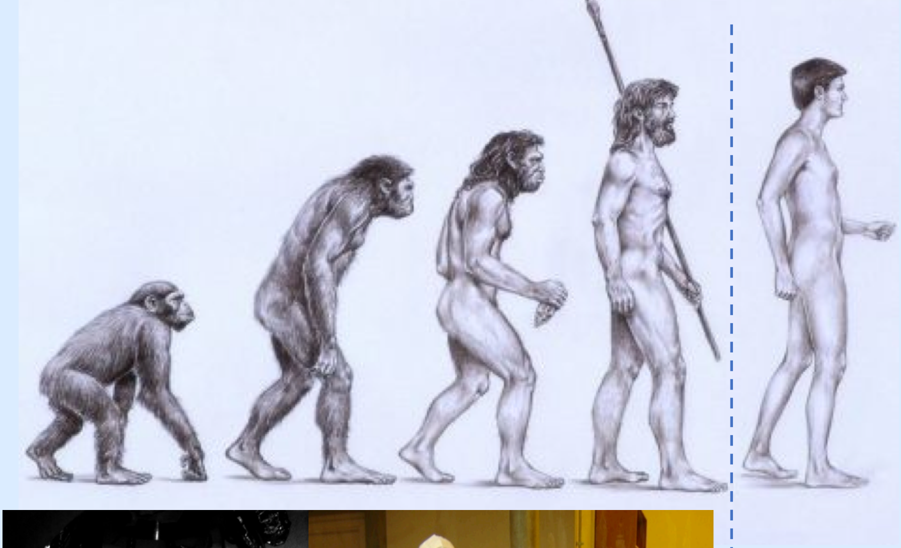
Sea level>100 muons per square meter per second!

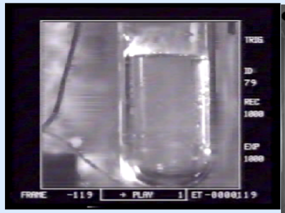
2km overburden (6000mwe)

Underground Laboratory



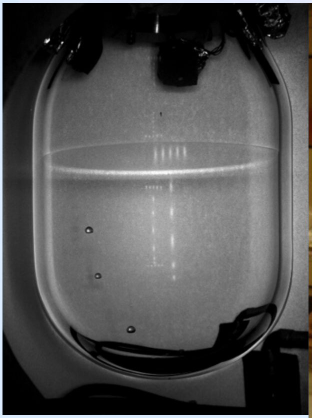
Dark Matter Bubble Chamber Evolution





Test tube

COUPP 2kg

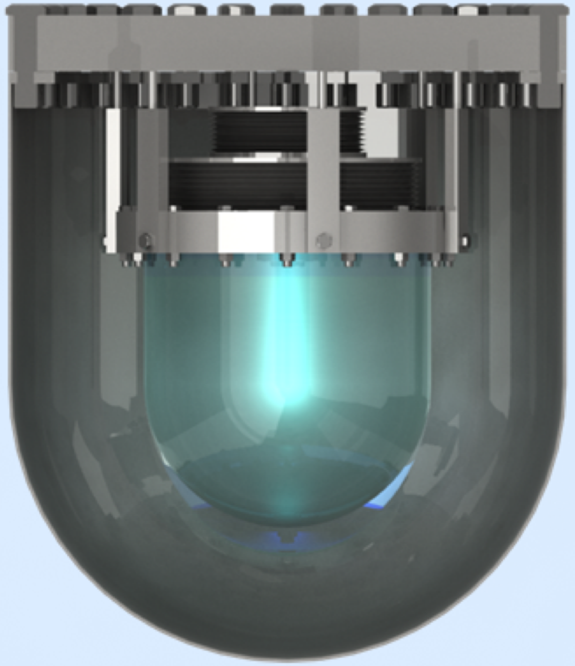


COUPP 4kg

PICO 2liter

COUPP-60kg

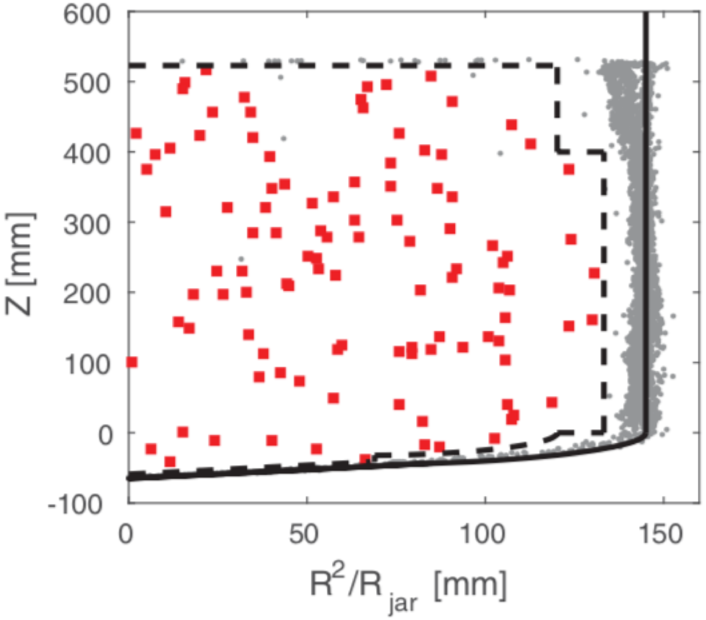
PICO-60 (C_3F_8)



PICO 500

2017 Results: PICO-60 C_3F_8

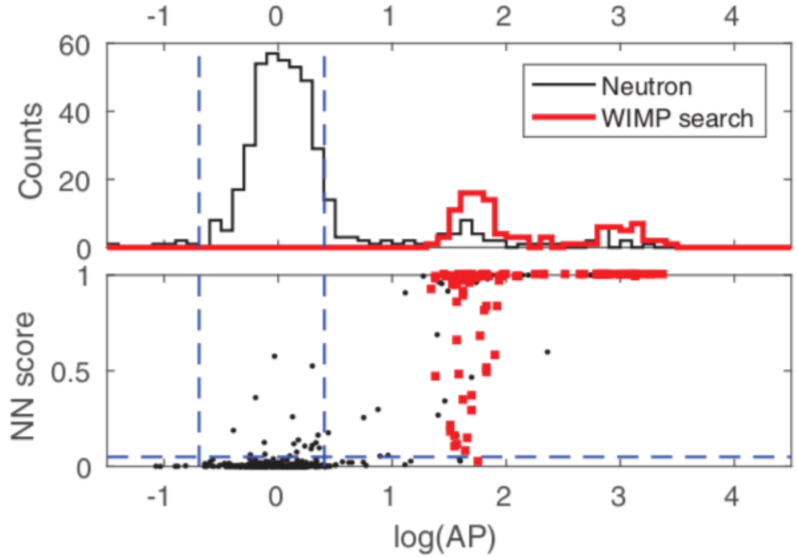
52 kg target liquid, 1167 kg-day WIMP exposure run at 3.3keV threshold
Multiple neutron rate implies .lt. 1 single bubble neutron event expected.



106 candidates in (first ever) blind analysis. No recoil-like events after unblinding the data set (alpha events from their acoustic response)

No Dark Matter Candidates

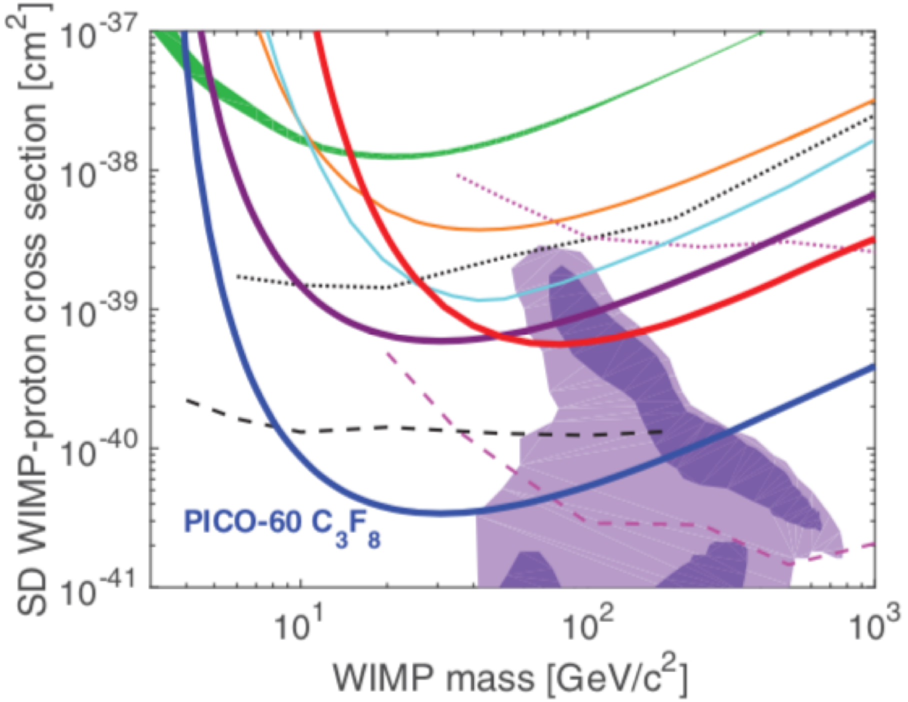
Phys. Rev. Lett. 118, 251301 - Published 2017



2017 Results: PICO-60 C_3F_8

52 kg target liquid, 1167 kg-day WIMP exposure run at 3.3keV threshold
Multiple neutron rate implies .lt. 1 single bubble neutron event expected

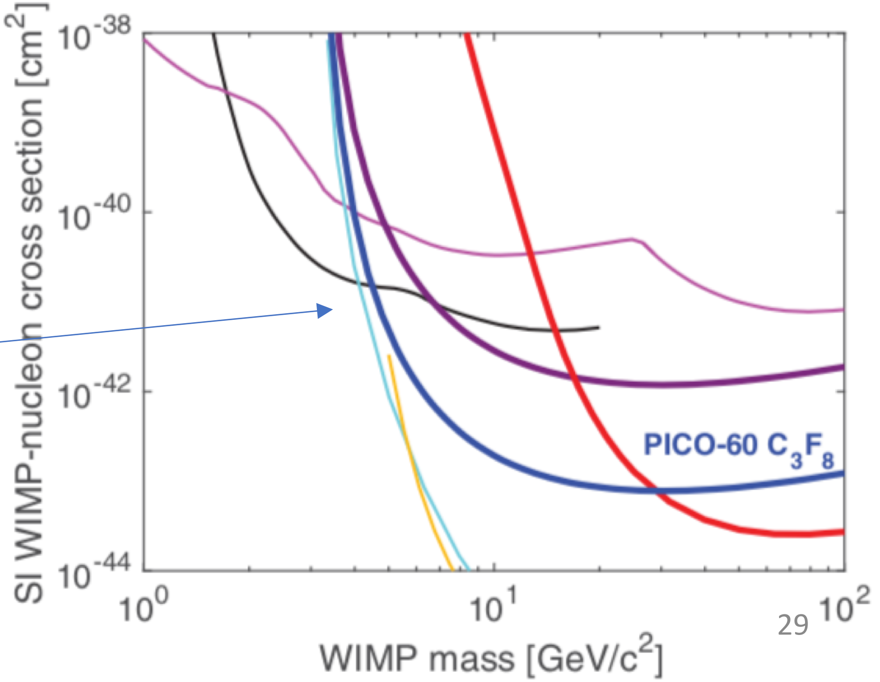
Factor of 17 lowering!



106 candidates before blind analysis
No recoil-like events after unblinding the data set (alpha events from their acoustic response)

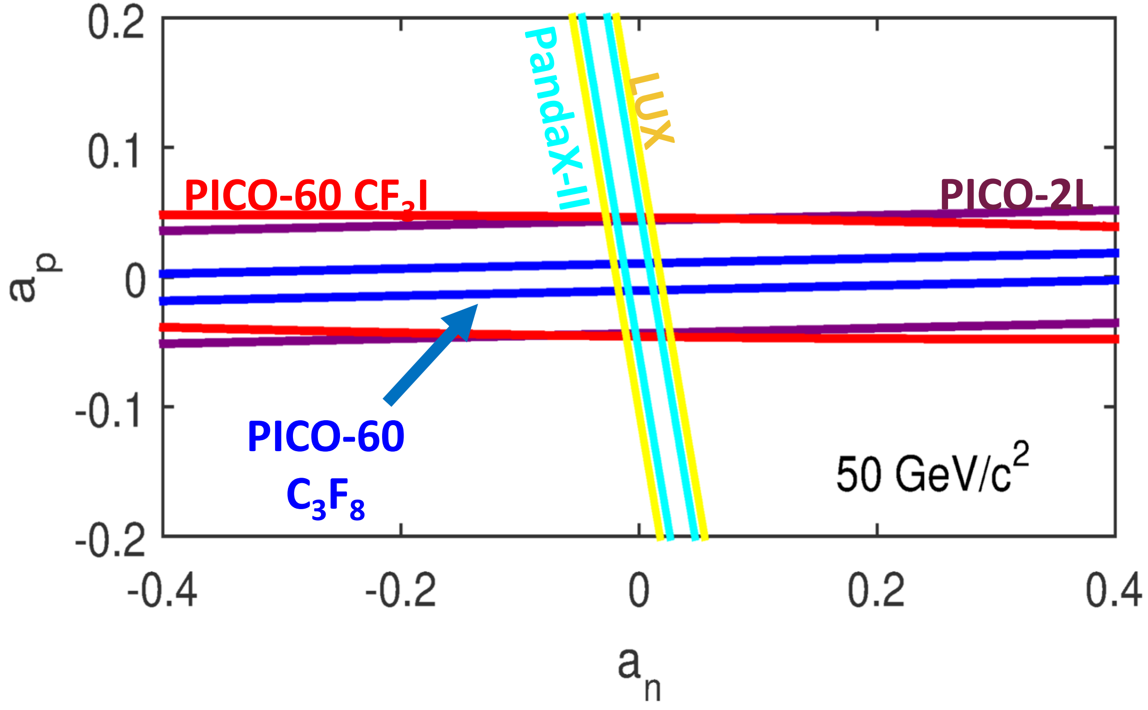
No Dark Matter Candidates

Nearly competitive in SI at low masses

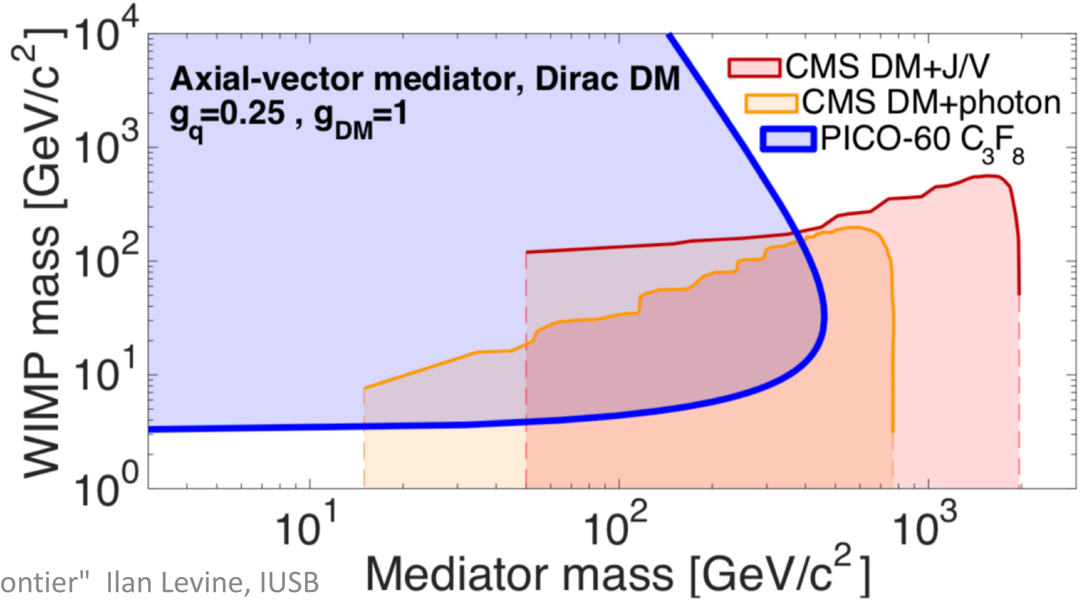


Phys. Rev. Lett. 118, 251301 - Published 2017

PICO Experiment Complementary Sensitivity to SI experiments, SDn experiments and collider limits.



Comparison of sensitivity to effective proton (a_p) and neutron (a_n) spin coupling.



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

PICO-60 C_3F_8 Subsequent Exploration

Prior to decommissioning PICO-60: Explore stability as function of threshold &calibrations.

Scan operating conditions in preparation for future detectors.

Even at 1.2keV, stable operation!

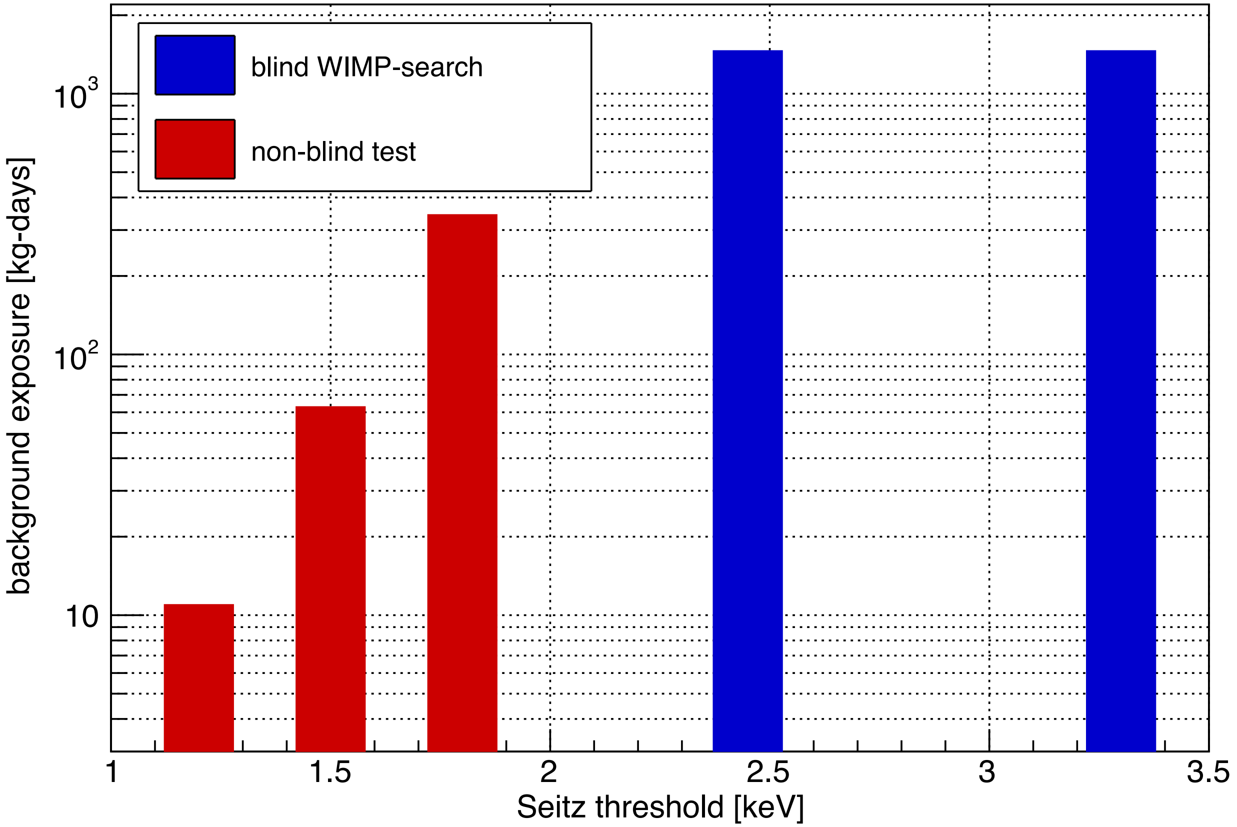
Map out gamma response function and measure environmental gammas.

Improved analysis, increased fiducial volume.

1404 kg-day blind exposure @ 2.45keV
(expect same background rate as 3.3keV run)

New WIMP physics results & γ response forthcoming

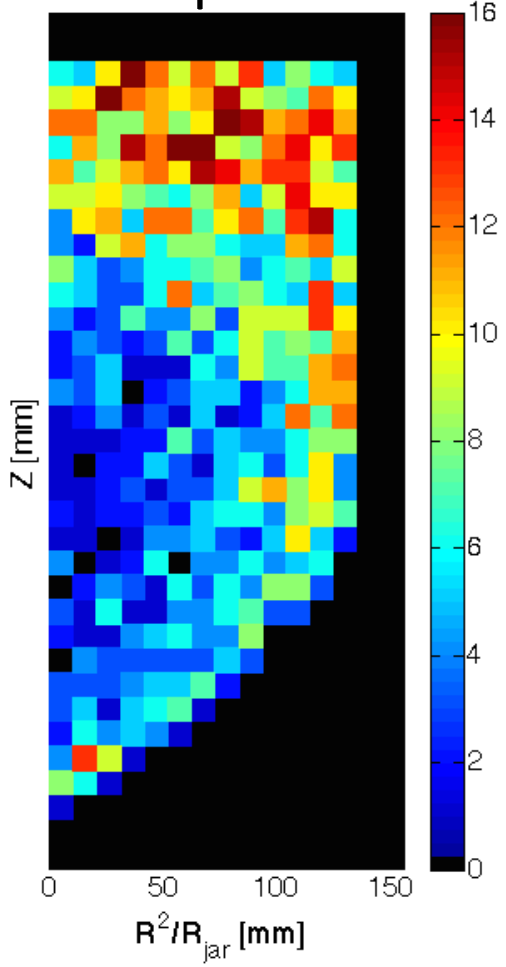
All PICO-60 exposures



Why PICO Is Changing Design of Bubble Chambers

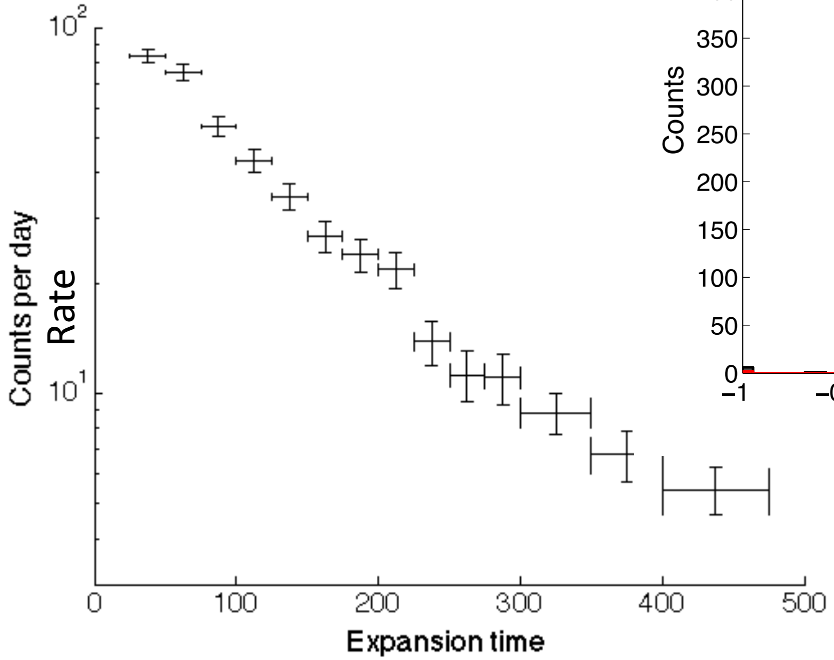
Position dependent

Events cluster near walls & surface, and move upward with time



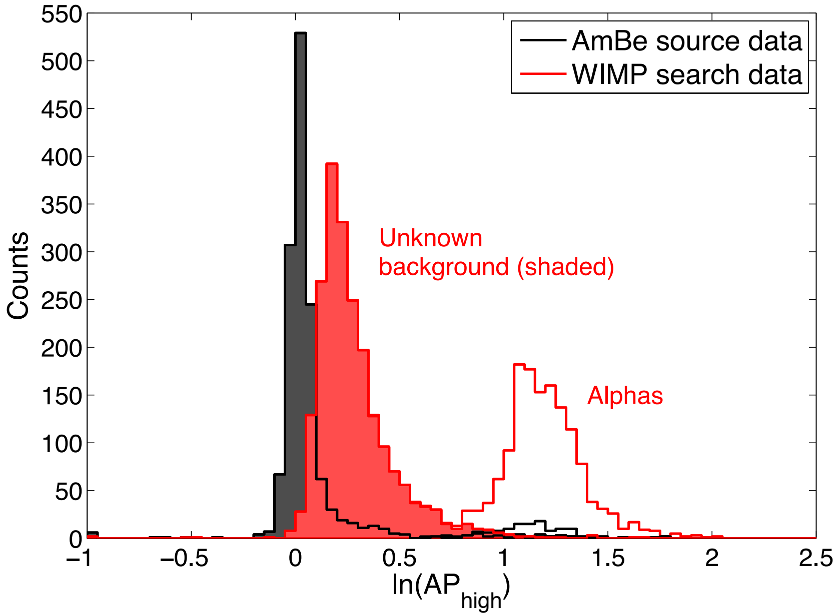
Time dependent

Events occur soon after expansion



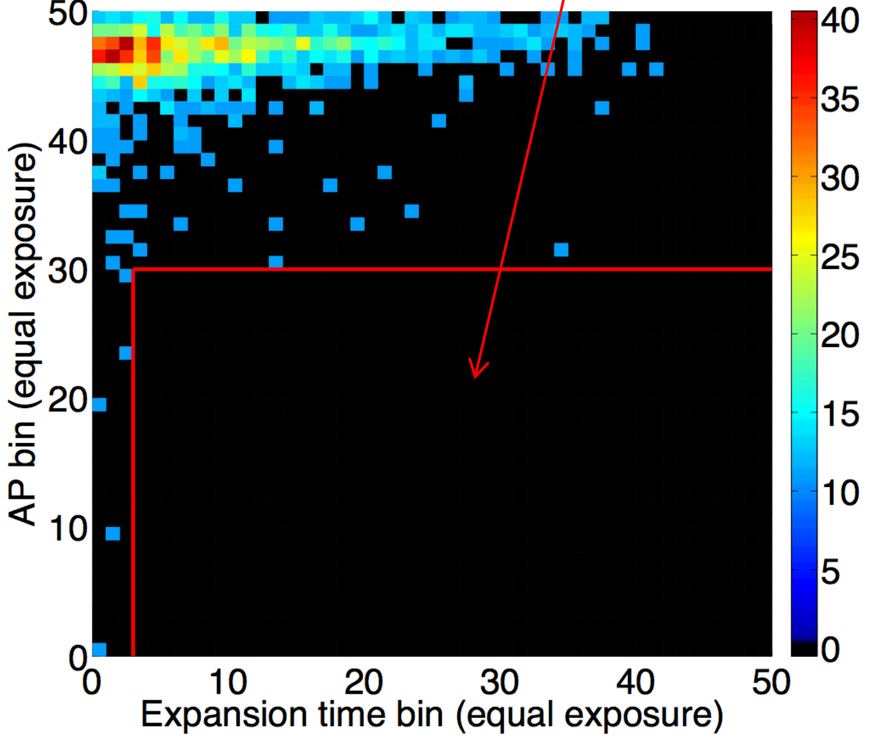
Acoustically anomalous

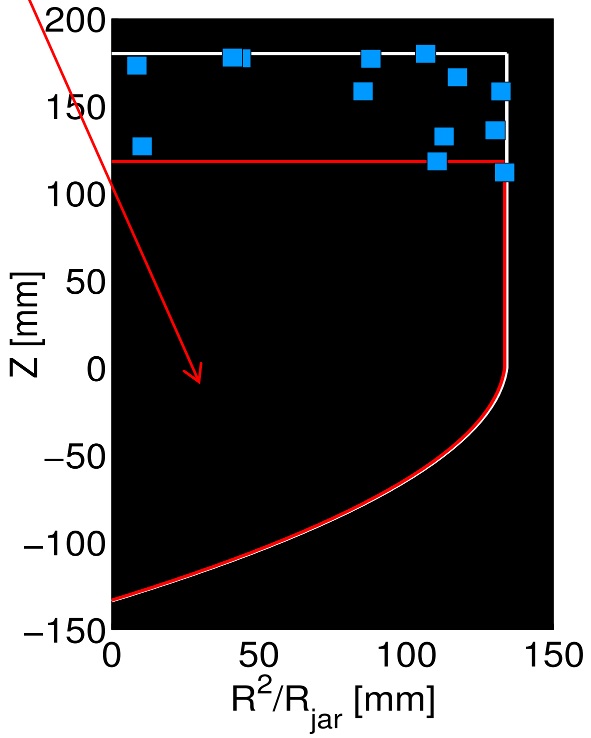
Events are systematically louder than nuclear recoils



PICO-60 (run 1, CF_3I) background

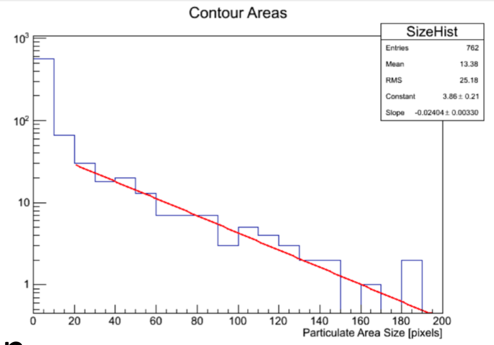
A background free region (~50% of exposure)
by cutting on AP, expansion time, and Z



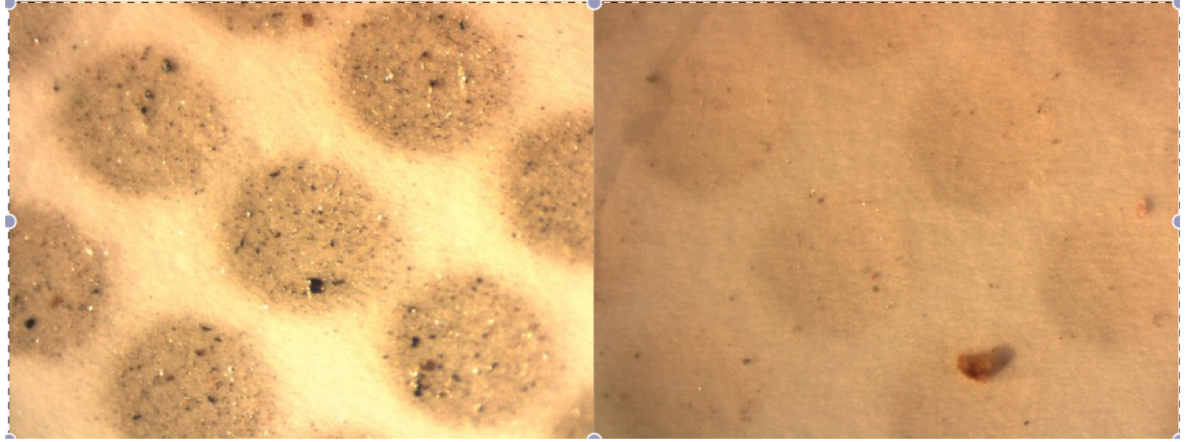


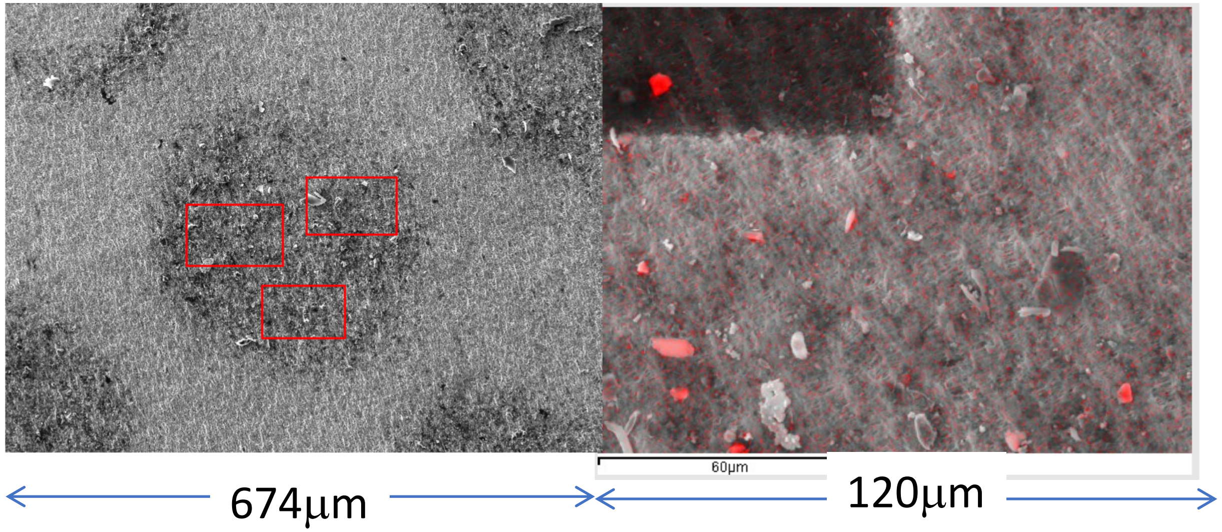
Particulates

Samples of buffer water passed through PTFE filters with 0.2μm pore size.

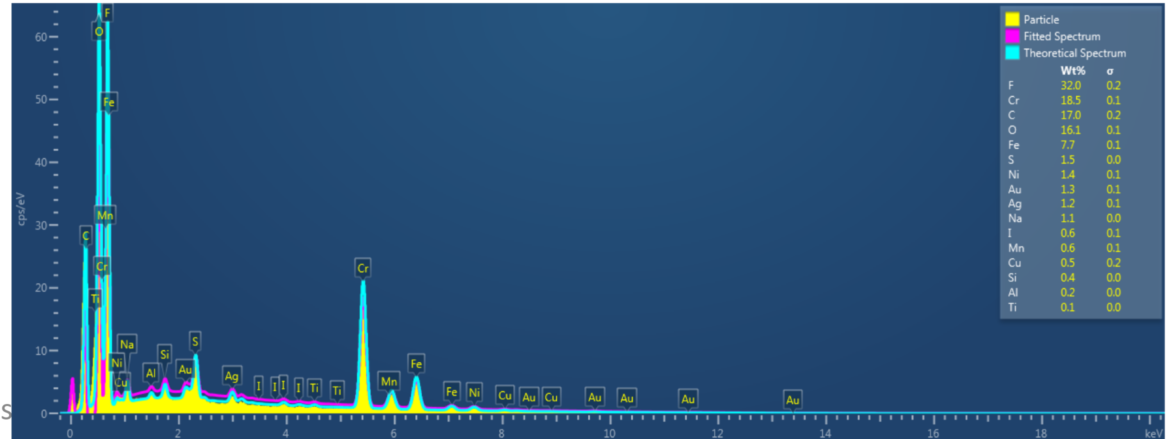


Mild corrosion on surfaces also observed (buffer water made slightly acidic)





Stainless steel
Aluminum
Silver
Gold
Copper



	Wt%	σ
F	32.0	0.2
Cr	18.5	0.1
C	17.0	0.2
O	16.1	0.1
Fe	7.7	0.1
S	1.5	0.0
Ni	1.4	0.1
Au	1.3	0.1
Ag	1.2	0.1
Na	1.1	0.0
I	0.6	0.1
Mn	0.6	0.1
Cu	0.5	0.2
Si	0.4	0.0
Al	0.2	0.0
Ti	0.1	0.0

Tests Demonstrate Particulates/water source of anomalous events

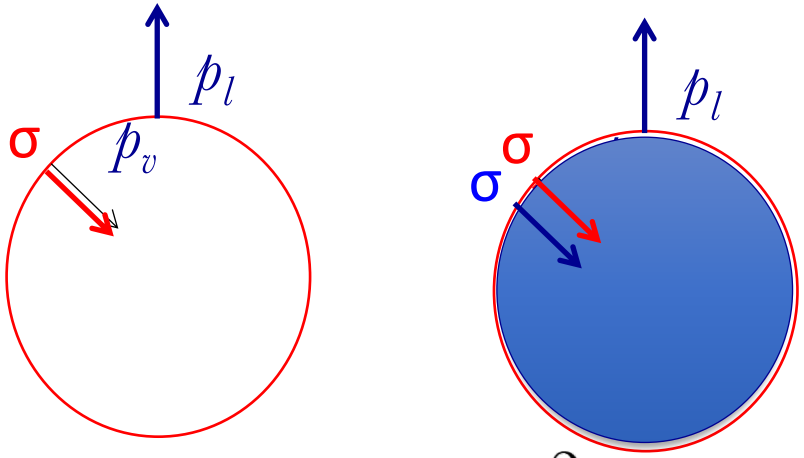
Radioactive particulate injected into a test chamber operated at Queen’s University settles on the walls and liquid interface.

NO measurable increase in low-AP bulk rate.

Particulate can only enter the fluorocarbon in a water droplet

Fine silica powder strongly prefers to stay in the water buffer fluid above the active fluid.

The Seitz Model is modified in the presence of a water droplet



Seitz Model: $p_v - p_l = \frac{2\sigma}{r_c}$

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

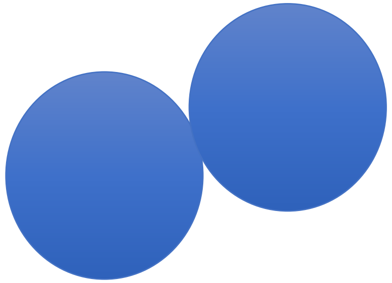
Surface energy
~200 eV

Latent heat
~ 3 keV

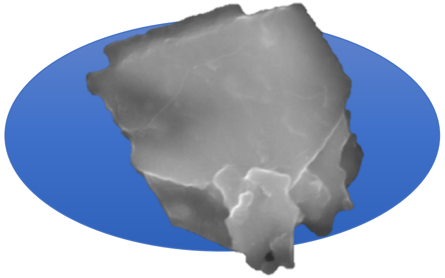
Fine silica powder strongly prefers to stay in the water buffer fluid above the active fluid.

The stored energy in the surface tension of a 50 nm water droplet ~ 3.5 keV

Merging water droplets will nucleate bubbles…



Particulate in a water droplet can nucleate bubbles…

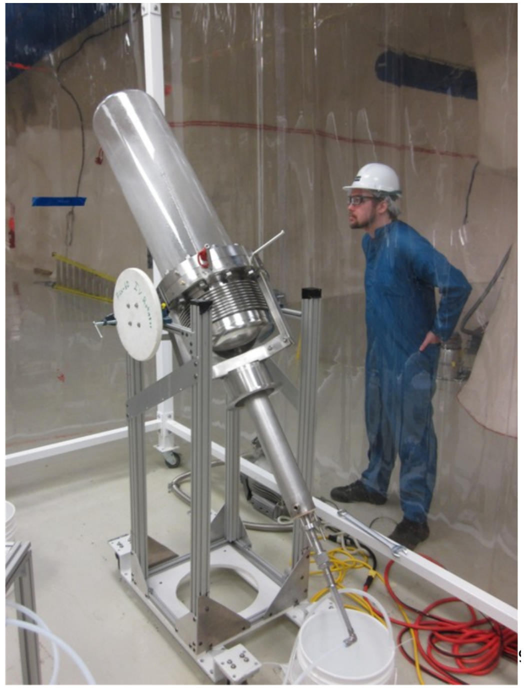


Non-spherical droplet “stretched” over particulate core is meta-stable
If it shifts, it can nucleate a bubble

Mystery Background Present In Every Previous Chamber

- We had an unknown background
  - **COUPP-4 (2010-2011) -- CF_3I with E_{th} down to 8 keV**
    20 time-clustered candidate events in 553 kg-days
    (~5 expected from neutrons)
  - **PICO-2L (2013-2014) -- C_3F_8 with E_{th} down to 4 keV**
    12 time-clustered candidate events in 211 kg-days
    (~1 expected from neutrons)
  - **PICO-60 (2013-2014) -- CF_3I with E_{th} down to 8 keV**
    ~2000 anomalous events in 3415 kg-days
    (~1 expected from neutrons)

Mitigation: PICO-2L/PICO-60 Run 2



- PICO-2L Run 2 - C_3F_8 - SNOLAB (2015)
  - Eliminate quartz flange – replace with fused silica
  - Improved cleaning, baseline particulate measurements
  - Eliminate use of scroll vacuum pump
- PICO-60 Run 2 - C_3F_8 - SNOLAB (2016-2017)
  - Low stress seal
  - Fluid recirculation/filtration
  - Every component cleaned to MIL-STD-1246 Level 50 standard (< 1 50μm particle / ft^2)
  - Physics run fully blind to acoustics

These efforts strongly suppressed particulate/water background below detection in PICO-2L and PICO-60 run 2 data, but still concerning for PICO-500 and WIMP discovery potential.

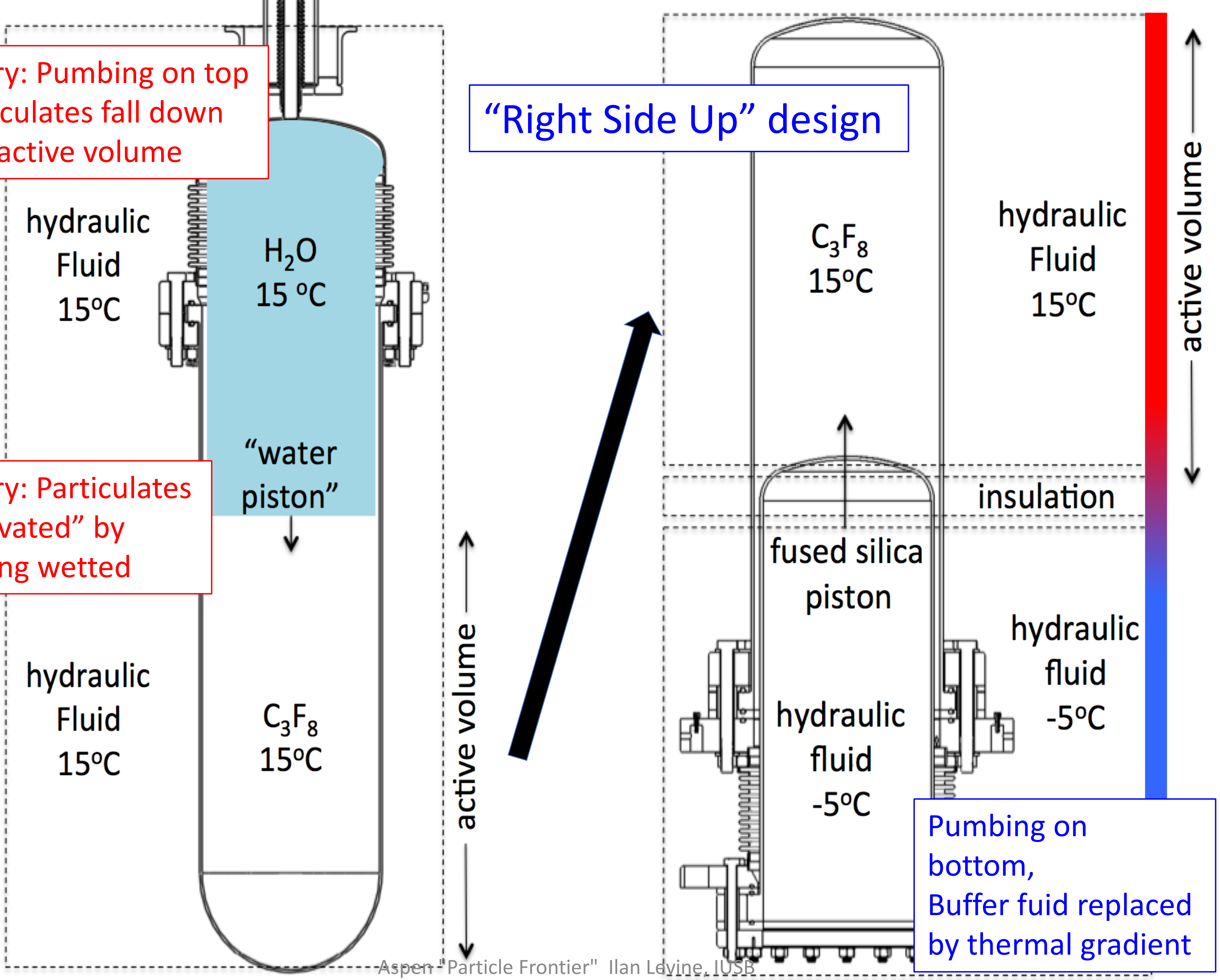
So a new approach is being taken going forward: ``Right Side Up''.

A bubble chamber without water.

“Right Side Up” design

Worry: Pumbing on top particulates fall down into active volume

Worry: Particulates “activated” by getting wetted



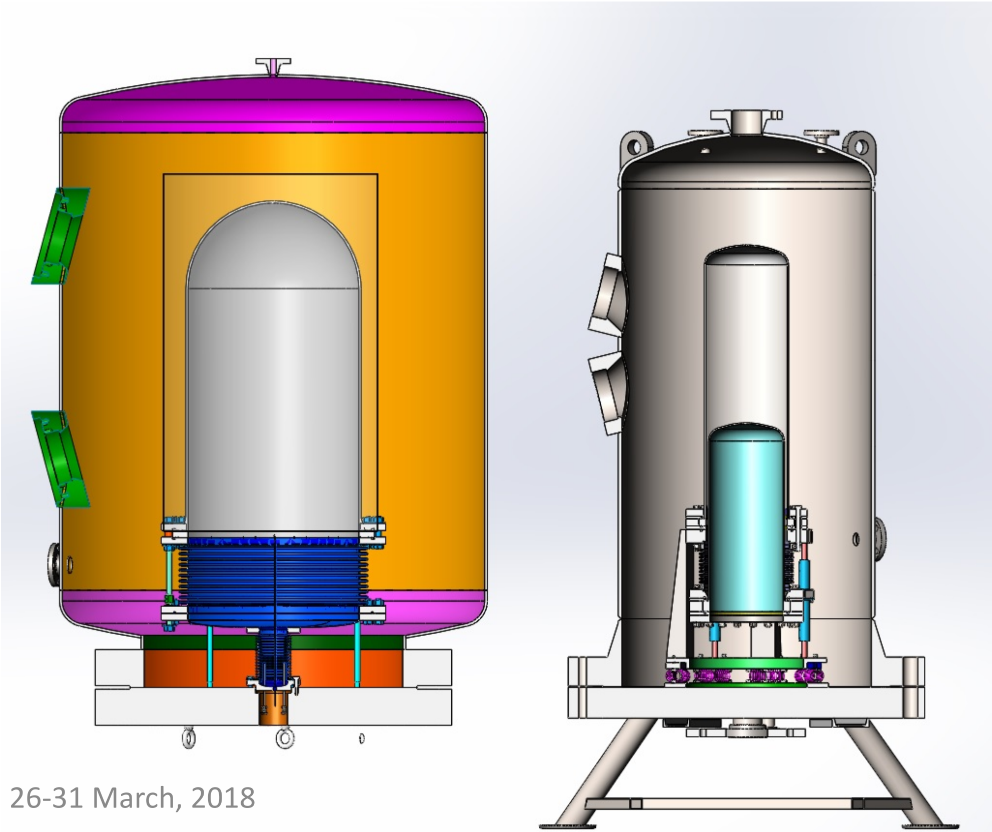
Pumbing on bottom,
Buffer fuid replaced by thermal gradient

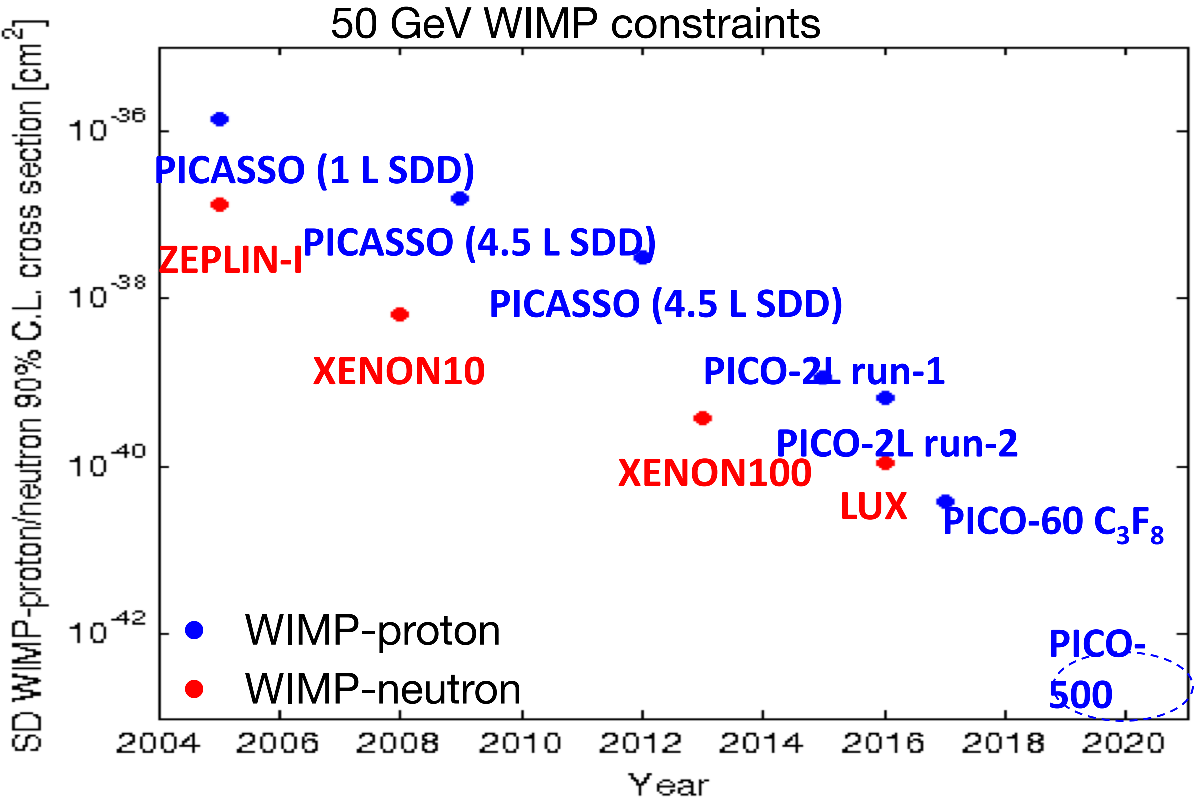
Right Side Up design virtues:

- Superheated/normal transition is maintained by a thermal gradient with no buffer fluid
    - No buffer fluid means *no surface tension effects*
    - No buffer fluid means *no constraint on target fluid*
    - Works with any refrigerant, hydrocarbon, even xenon.
- Thermal gradient is naturally stable
- All metals at the bottom
    - Cold zone, no boiling to liberate particulate
    - No convection to move particulate up
- Geometry naturally lends itself to a recirculation loop

Plan going forward

- PICO-40L (Right Side Up) – 2018 Fabrication/Commissioning
- PICO-500 (ton-scale) -- 2019 Construction Start
    - Canadian groups have won funding for 80% of fabrication costs
    - US University teams have proposals in regular NSF call. IUSB, NEIU & Penn State have also submitted an MRI proposal to NSF





Summary and Plans

PICO has world-leading limits on spin-dependent dark matter (proton) coupling.

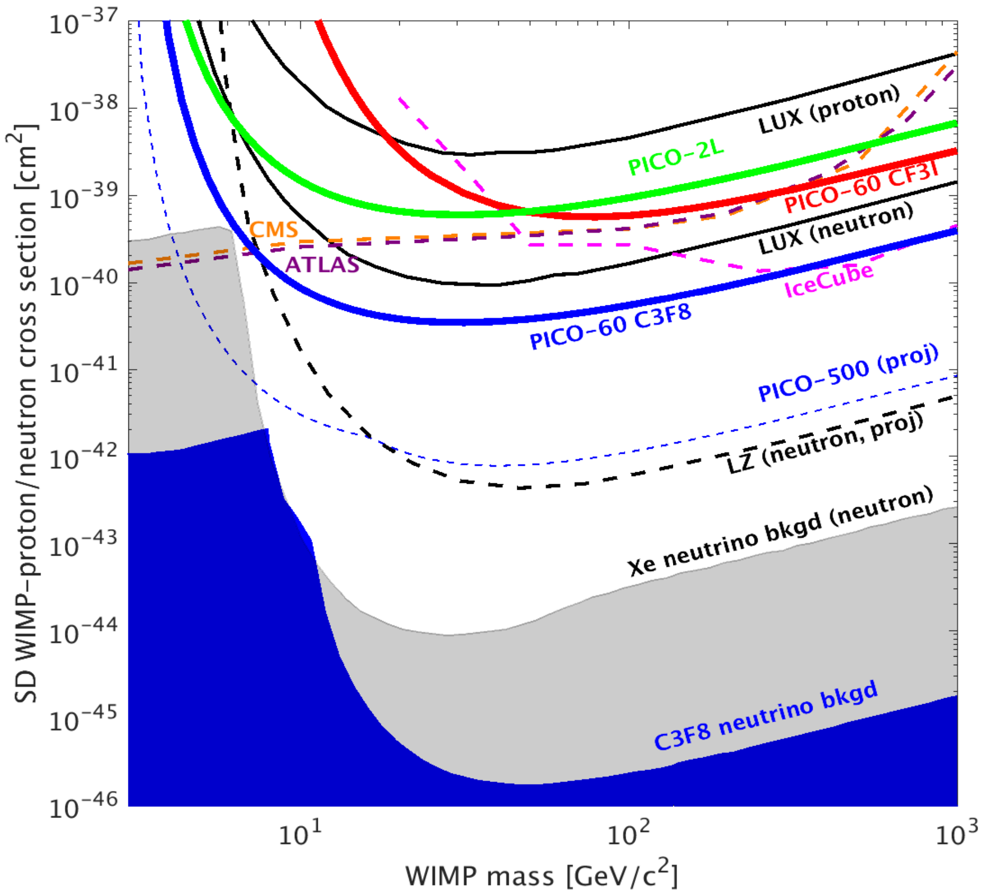
Neutrino floor is 100 times lower for ^{19}F than for Xe.

New technical direction for the experiment `RSU’ design.

Aim for 1 year background-free PICO-40L demonstrator run & slightly improved limits. (start 2018 August)

PICO-500 C3F8 run goal: 1.5 y, 1 neutron background event ~O(30) improved limits from PICO-40 (start 2020 Jan)

Easy to switch targets to many other nuclei with relative ease.
Other target fluids being tested (Hydrocarbons, cryogenic – including scintillating)
-> ability to test scattering rate dependence on atomic number, nuclear spin, etc.



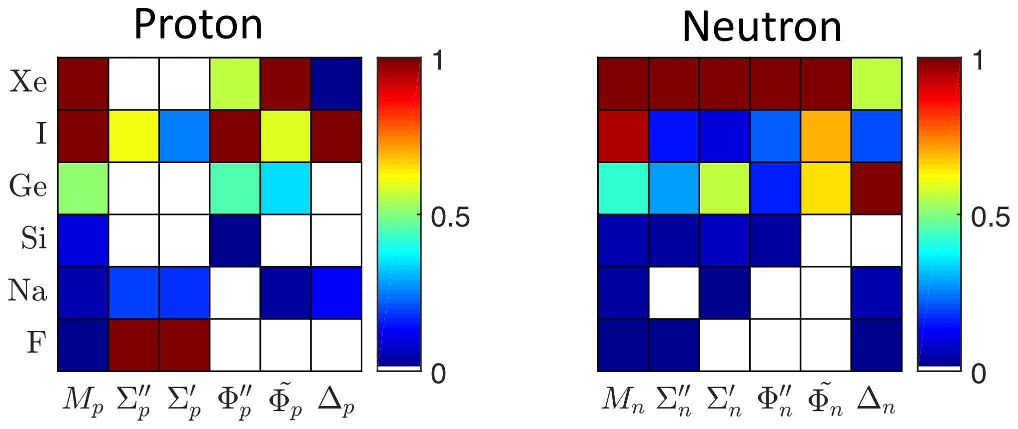
Factor O(30) over PICO-40L

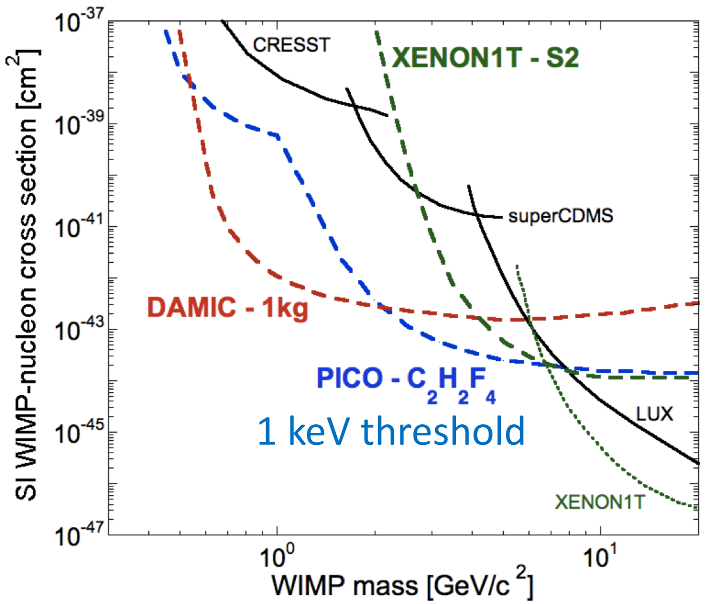
Extras

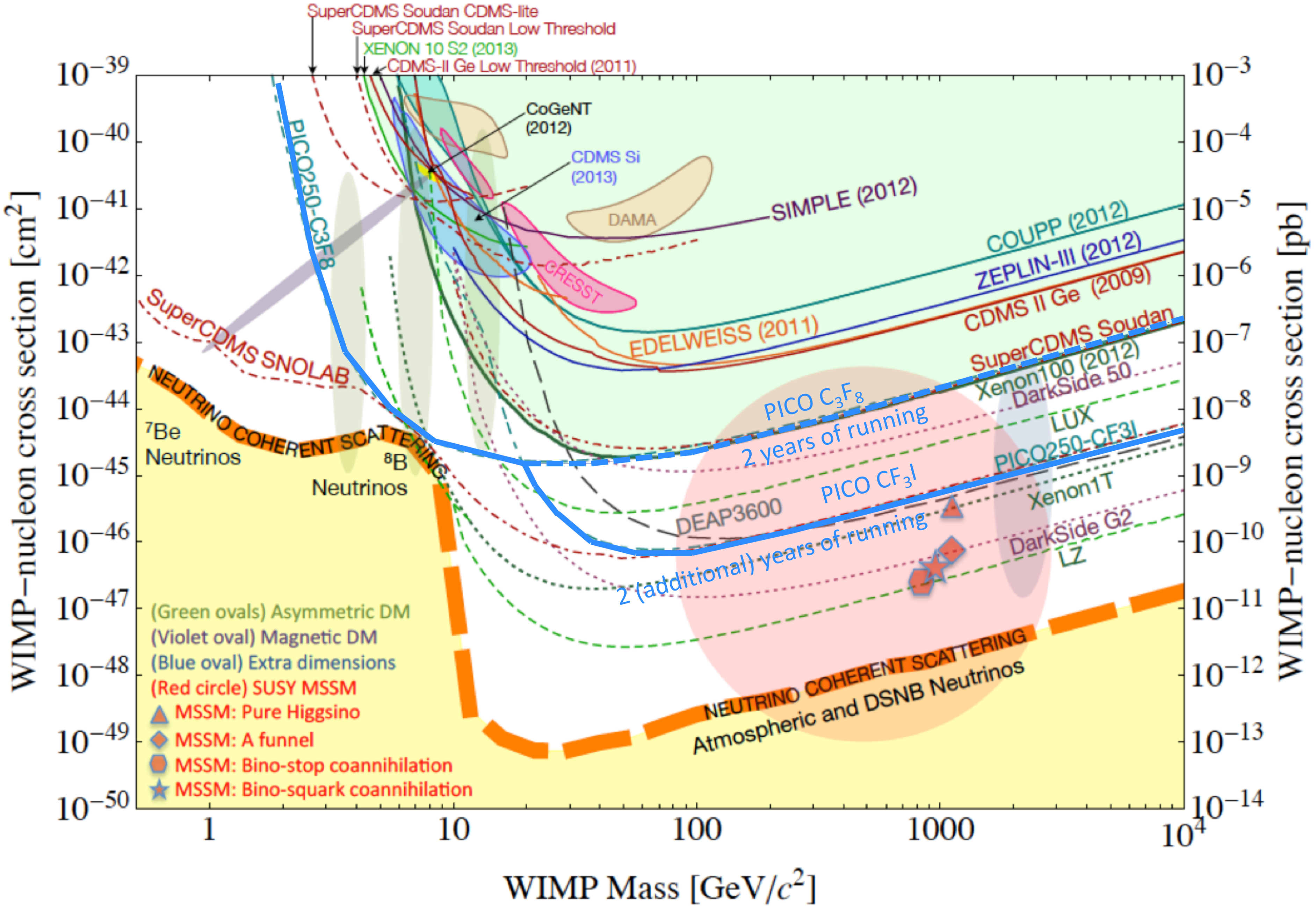
Bubble Chambers Offer A Diversity of Target Nuclei

- Capability to instrument a wide range of target nuclei with sensitivity to diverse WIMP-nucleon couplings. For example,
    - ^{19}**Fluorine:** Best sensitivity to spin-dependent interactions.
    - **Iodine, Bromine, Xenon, Argon:** High-A targets to exploit A^2 dependence of spin-independent cross section.
    - **Hydrogen:** Enhanced sensitivity to low-mass particles.
- Very low backgrounds, due to unique discrimination mechanisms.
- Thresholds below 3 keV nuclear recoil energy.
- Lowest cost per ton of target mass.

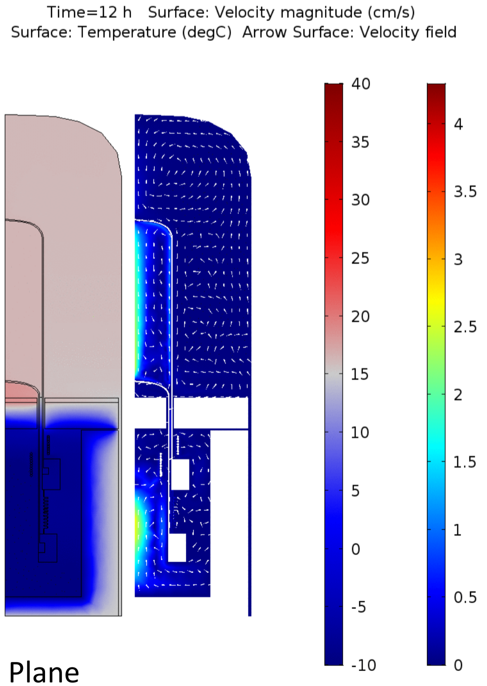
Fitzpatrick, Haxton et al. Effective Field Theory Couplings

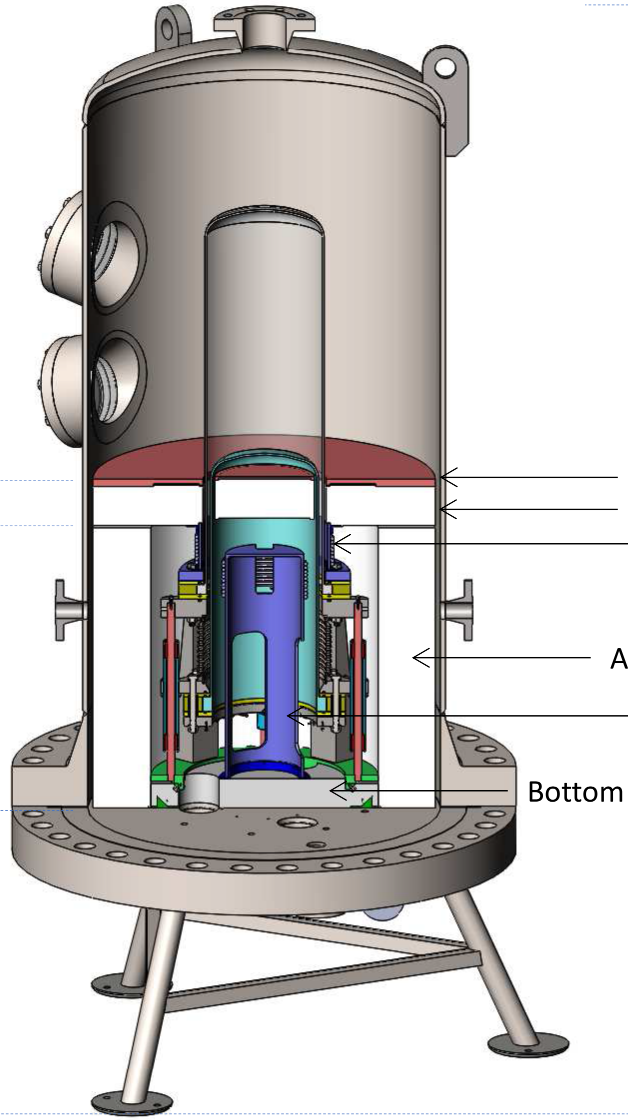





SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
PICO250-C3F8
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
PICO C_3F_8
2 years of running
PICO CF_3I
2 (additional) years of running
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
▲ MSSM: Pure Higgsino
◆ MSSM: A funnel
⬢ MSSM: Bino-stop coannihilation
★ MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
WIMP–nucleon cross section [pb]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4
WIMP Mass [GeV/c^2]

Thermal Control





Warm Zone

Warm Zone

Heating Plane

Insulation Layer

Static Internal Cooling Coil

Annular Insulation Layer

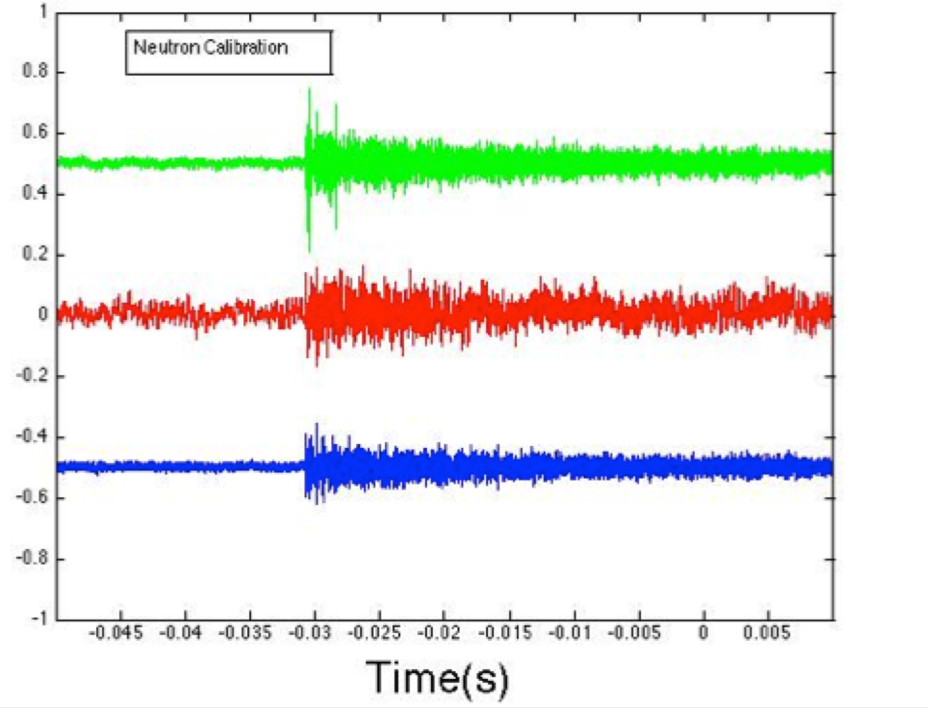
Static Internal Cooling Coil

Bottom Insulation Layer

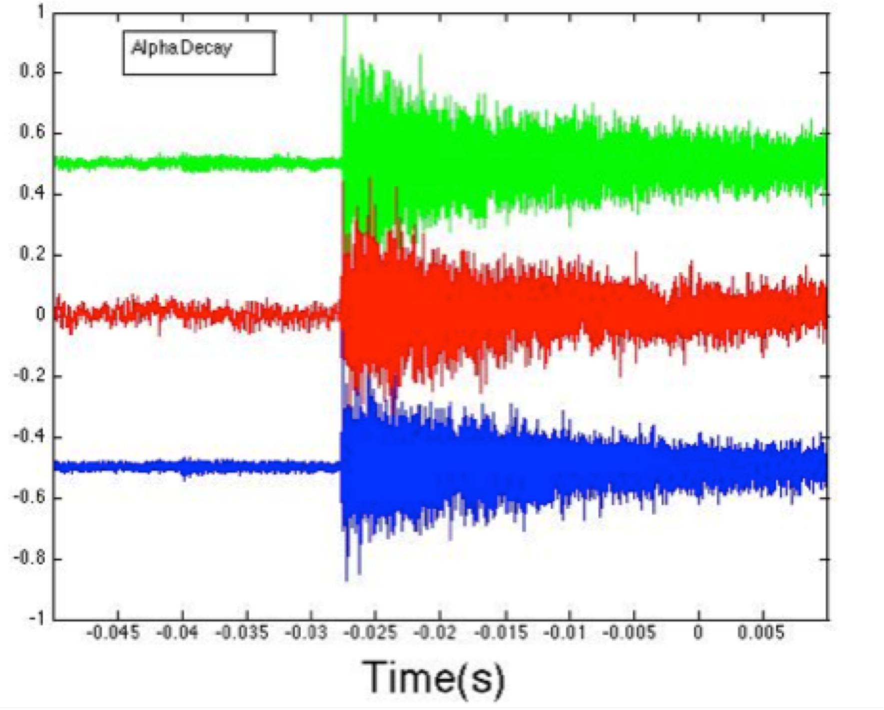
Why bubble chambers

1. Intrinsically insensitive to electron recoils
2. Sensitivity down to 4 keV Fluorine recoils in C_3F_8
3. **Impressive acoustic background rejection**

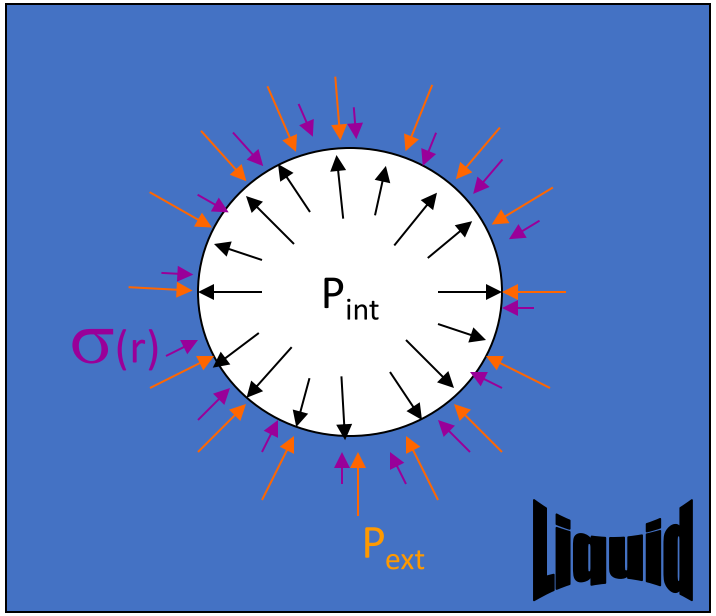
Calibration neutron



Alpha-emitter decay

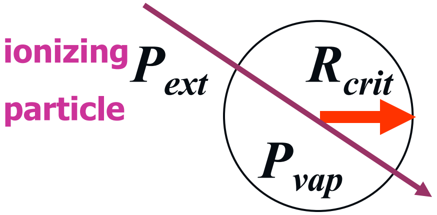


Superheated Liquid Detection Technique

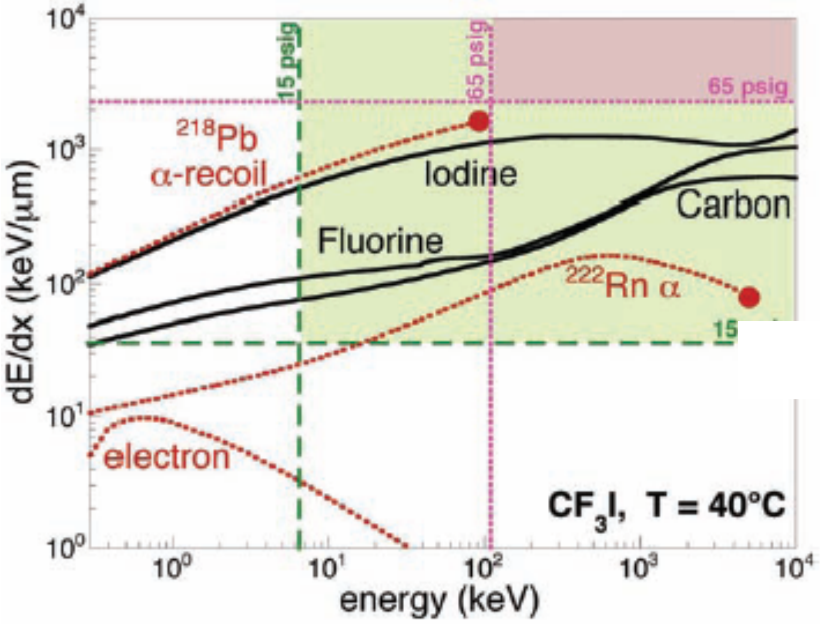


A Double Threshold (Energy and dE/dx)

$$\frac{dE}{dx} > \frac{E_c}{a r_c}$$



$$E > E_c = 4\pi r_c^2\left(\gamma - t\frac{\partial\gamma}{\partial T}\right) + \frac{4}{3}\pi r_c^3 \rho_v \frac{h_{fg}}{M} + \frac{4}{3}\pi r_c^3 P, \quad r_c = \frac{2\gamma}{\Delta P}$$



Can adjust operating parameters to be fully sensitive to recoiling nuclei while insensitive to electromagnetic backgrounds.

Intrinsic electromagnetic rejection ~10^{-11} at threshold of 10 keV