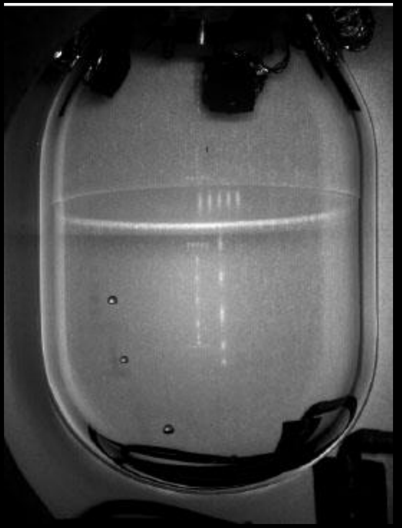
PICO & New Directions in Dark Matter Searches



Intro (DM, etc…)

The Superheated Liquid Technique

The PICO Program at SNOLAB

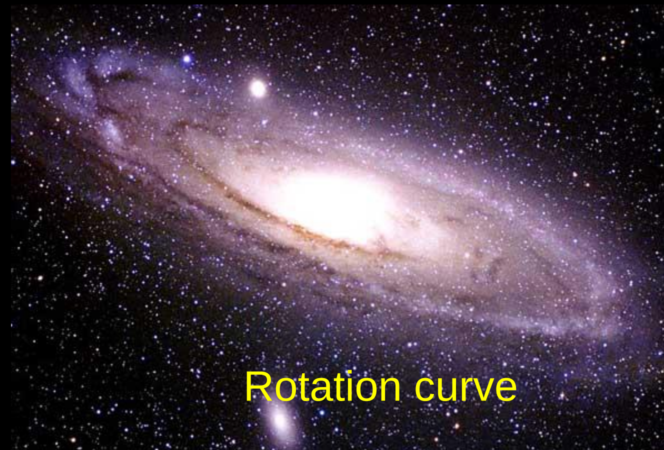
Ongoing R&D with Superheated Liquids

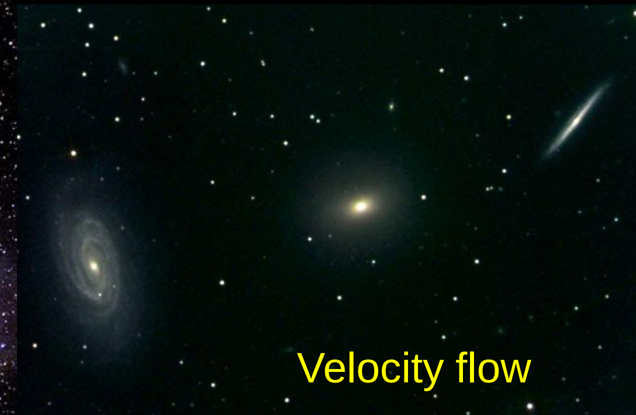
Exploring the Dark Sector in Nuclear Transitions

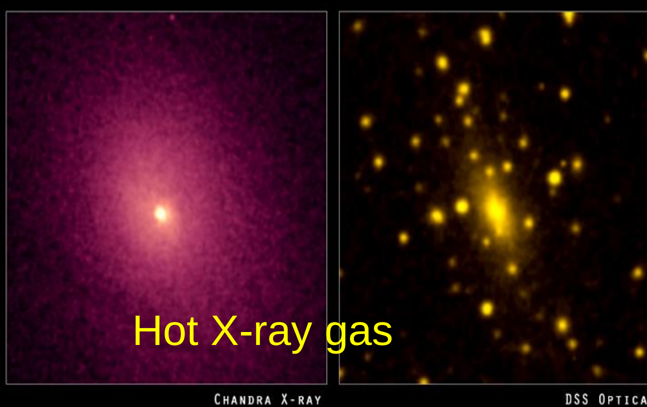
Viktor Zacek, Université de Montréal

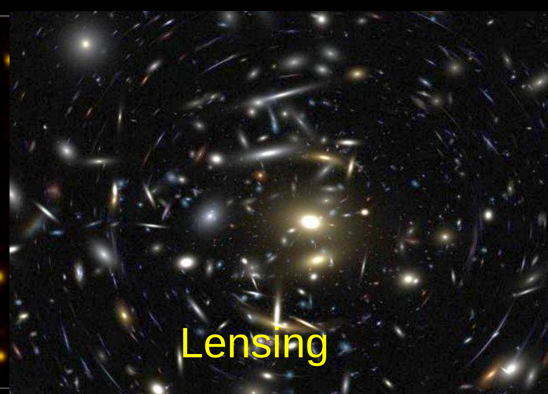
Harvard University, November 14, 2018

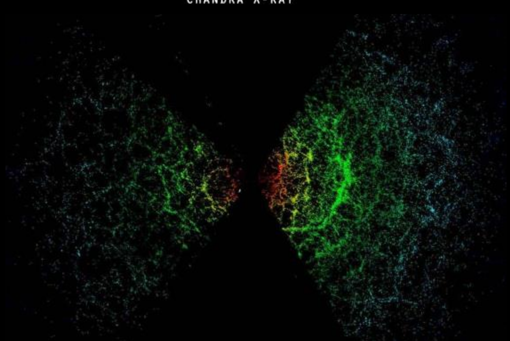
Convincing Evidence for Dark Matter !



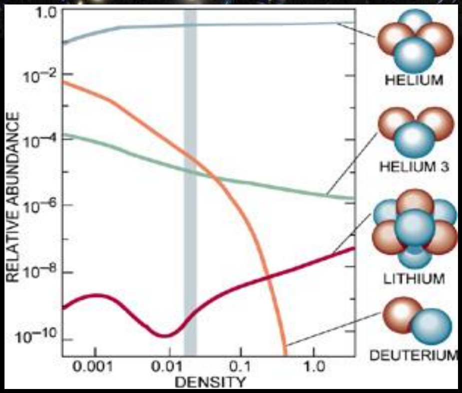




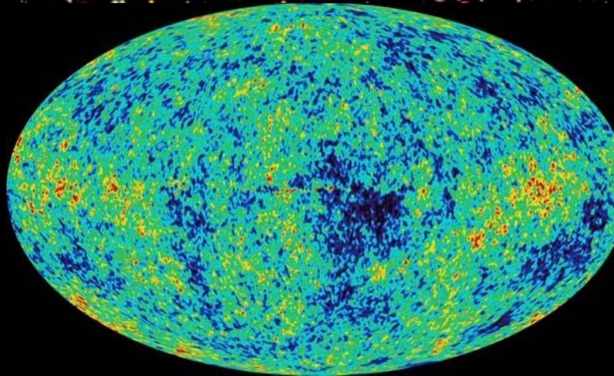




Large scale structure

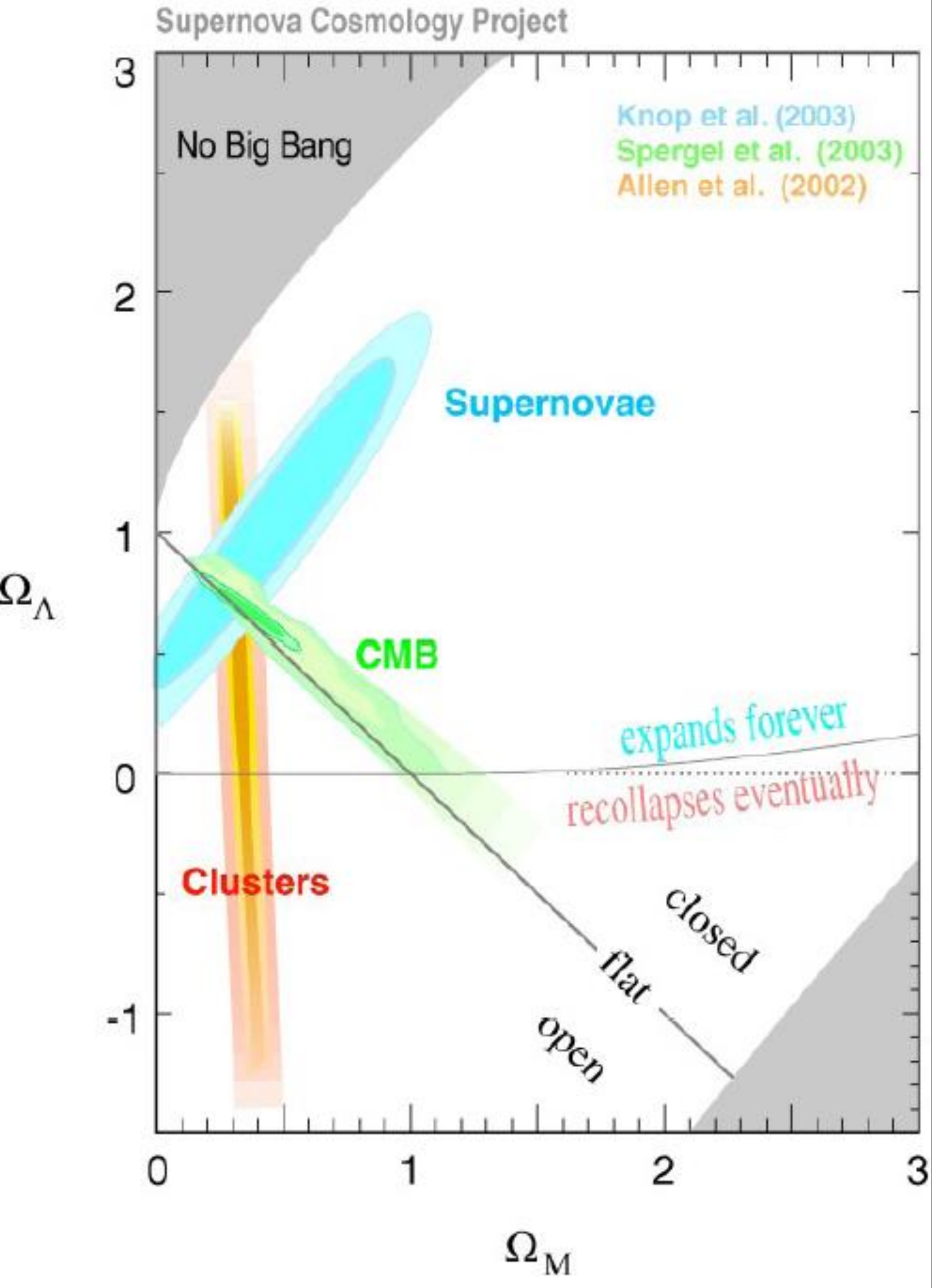


BB nucleosynthesis



CMB anisotropy

The Concordance Model



What Can Dark Matter Be?

Primordial black holes recently less probable → SN lensing

Cannot be baryons (CMB, LSS, BBNS)

Cannot be charged (CMB different)

No MACHOS (they are not there)

MOND unlikely (Bullet Cluster)

Must clump on small scale (dwarf galaxies M/L ~ 1000)

Stable or at least metastable (τ > 10 Gyr)

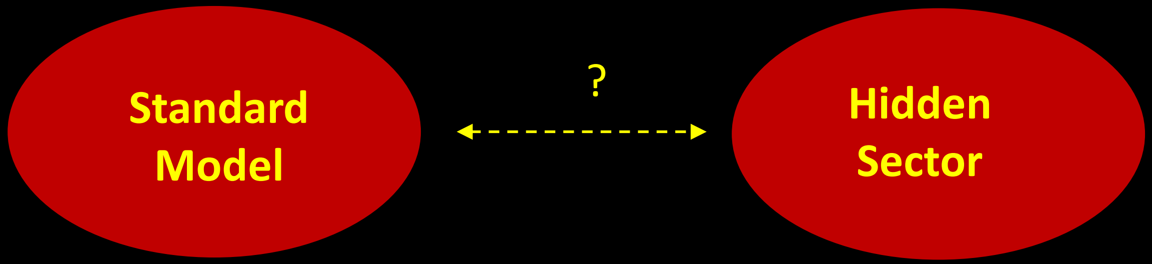
Must be cold or warm to explain structure

Self-interaction constrained ($\sigma/m < 1\ cm^2g^{-1}$ from galaxy clusters)

Must have right relic abundance

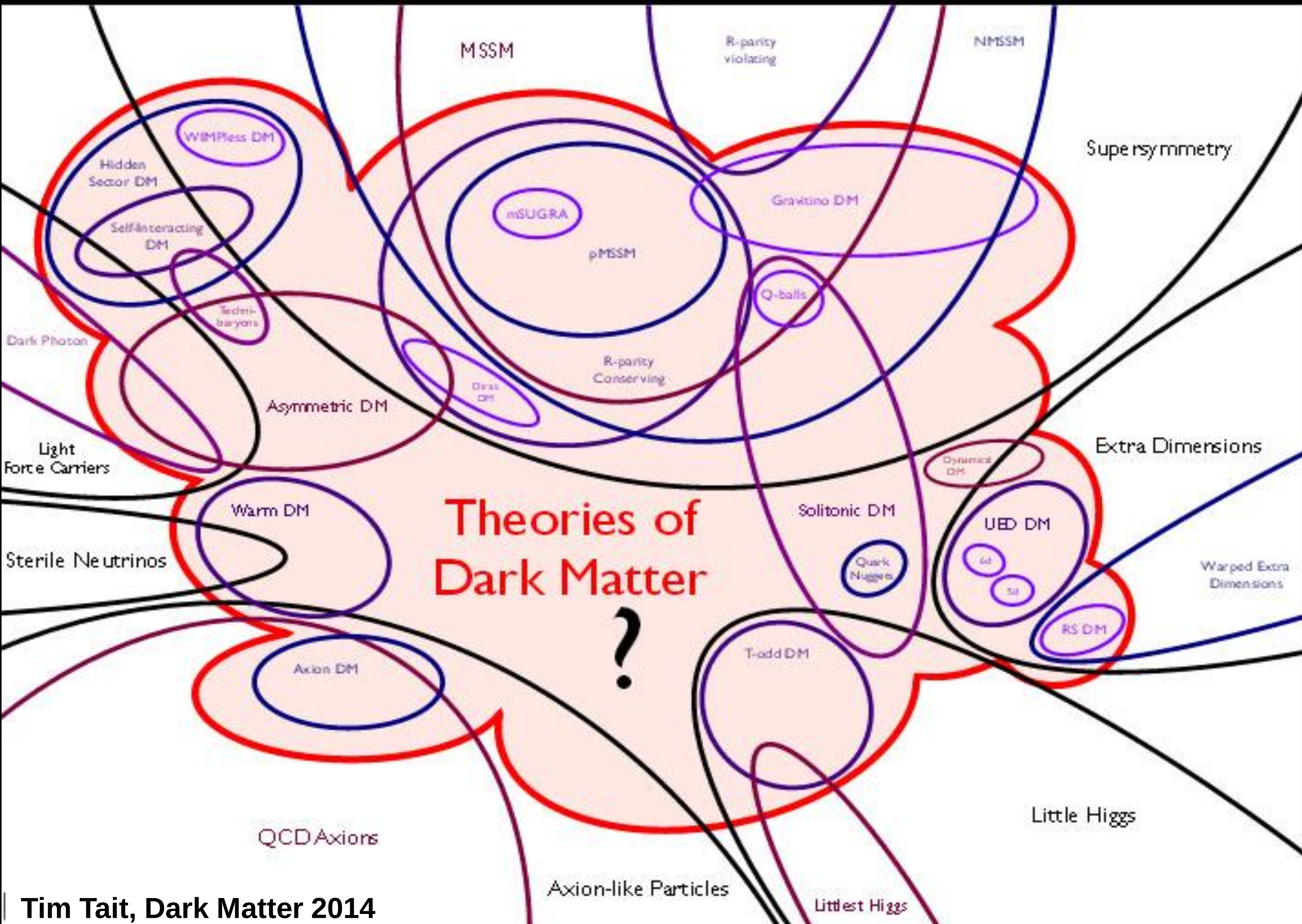
But maybe….

…since all evidence for DM is only gravitational so far, DM might also live in a hidden sector, composed of particles with no SM gauge interactions (electroweak, strong)



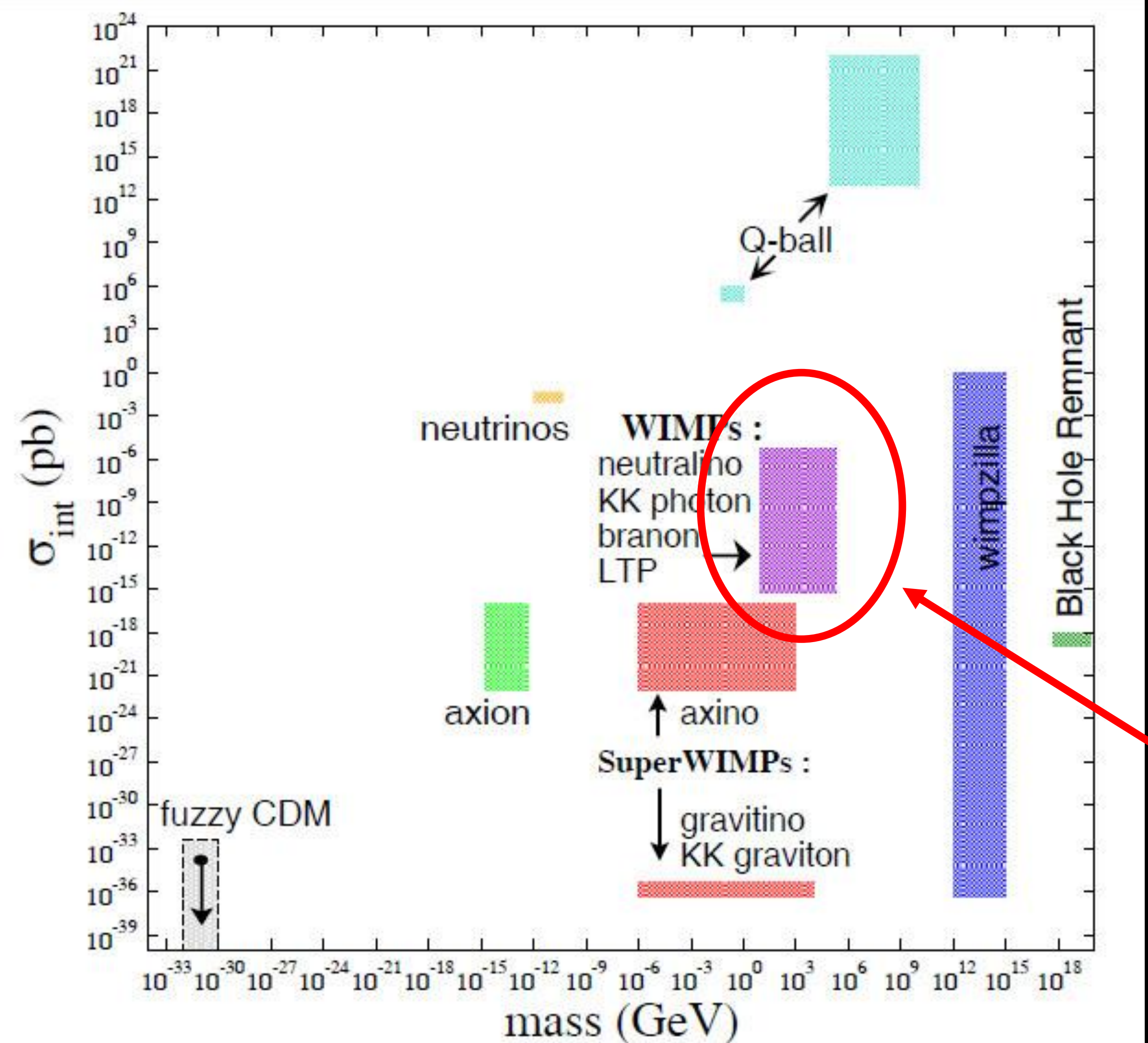
This hidden sector can have a rich structure with matter and forces by its own !

Today no Lack of Options...



Tim Tait, Dark Matter 2014

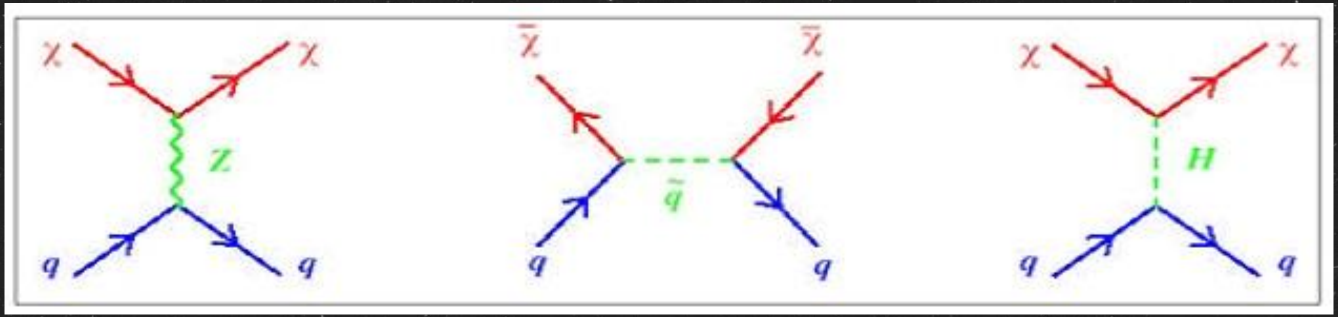
Dark Matter Candidates



- +
- Hidden sector particles
- Dark photons
- Sterile neutrinos
- Asymmetric dark matter
-
-
-

In this talk…

How do WIMPS Interact with SM Particles ?



Spin-dependent Spin-independent

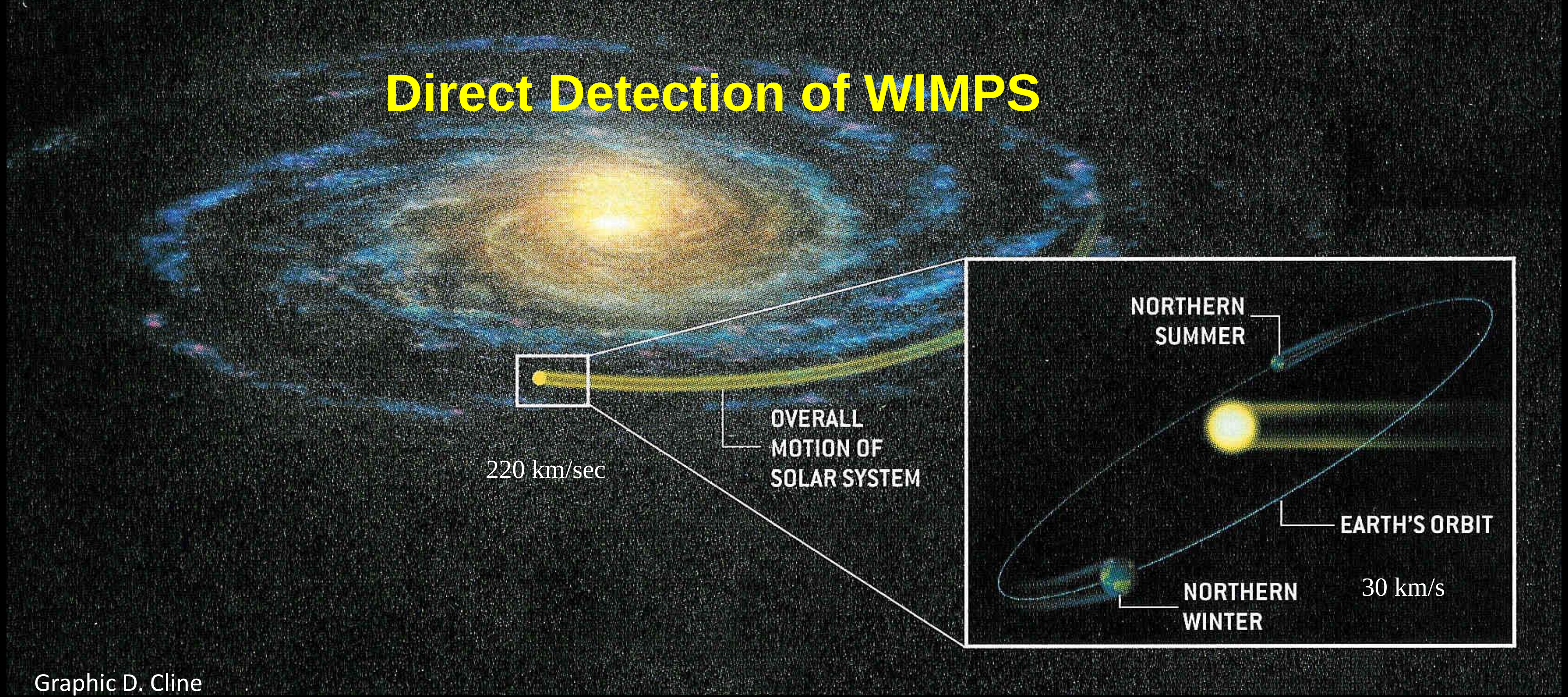
Enhancement factor

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

C_A^{SD} **: Spin dependent interaction** $\propto \langle S_{p,n}\rangle^2$

C_A^{SI} **: Spin independent – coherent interaction** $\propto A^2$

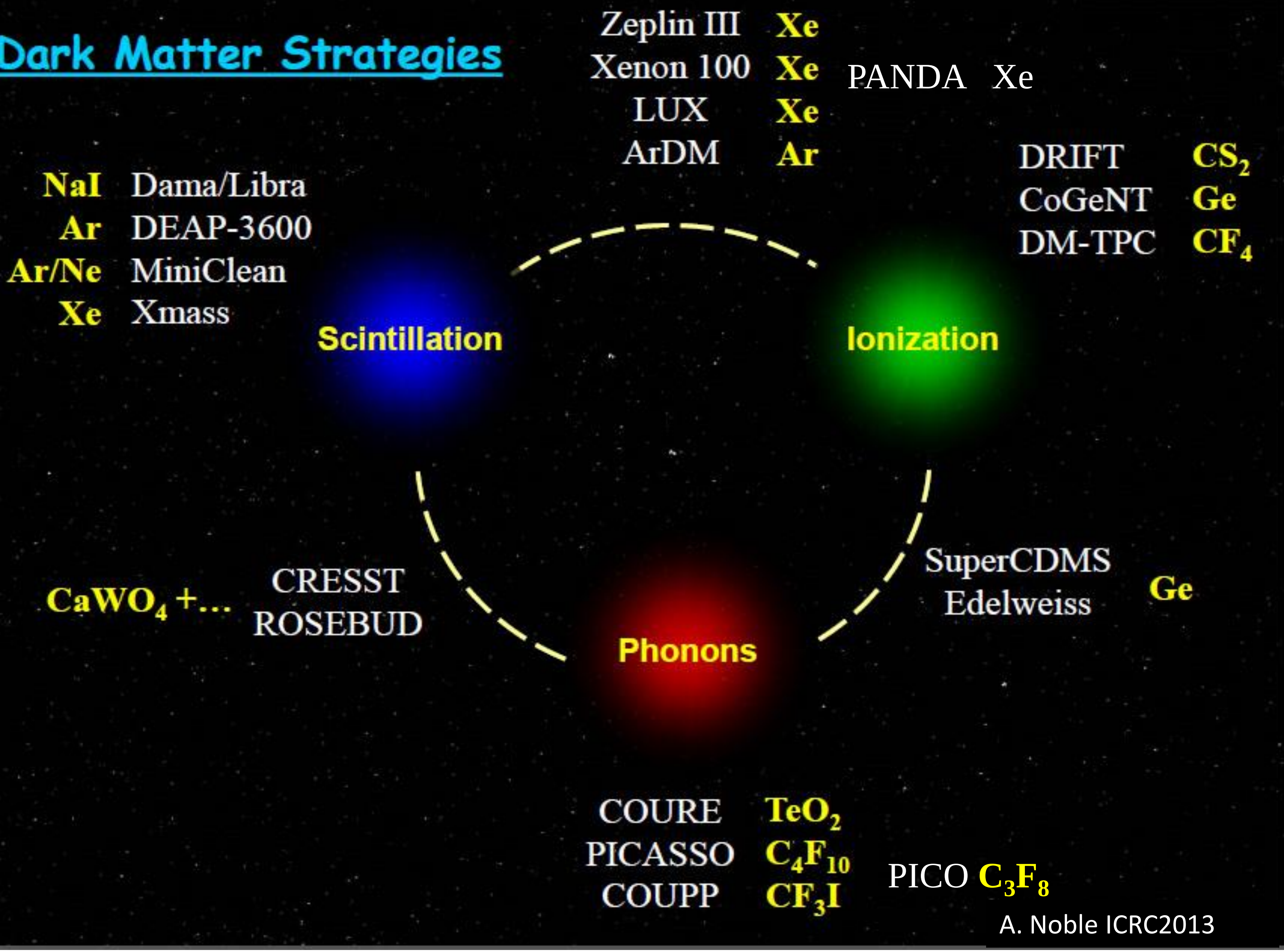
Direct Detection of WIMPS



- …only 5-10% of matter visible in MW!
- $\rho_{DM} \sim 0.3\ m_p/cm^3$ @ solar system
- Recoil energies: < 100 keV ….for ~ GeV masses
- Rates: << 0.1 count /kgd

A. Drukier, K. Freese, Spergel PRD 33(86)3495

Dark Matter Strategies



Detecting WIMPS means fighting Backgrounds !

Neutrons look like WIMPs !

- μ spallation in det. material,
- in shielding, in surr. rock

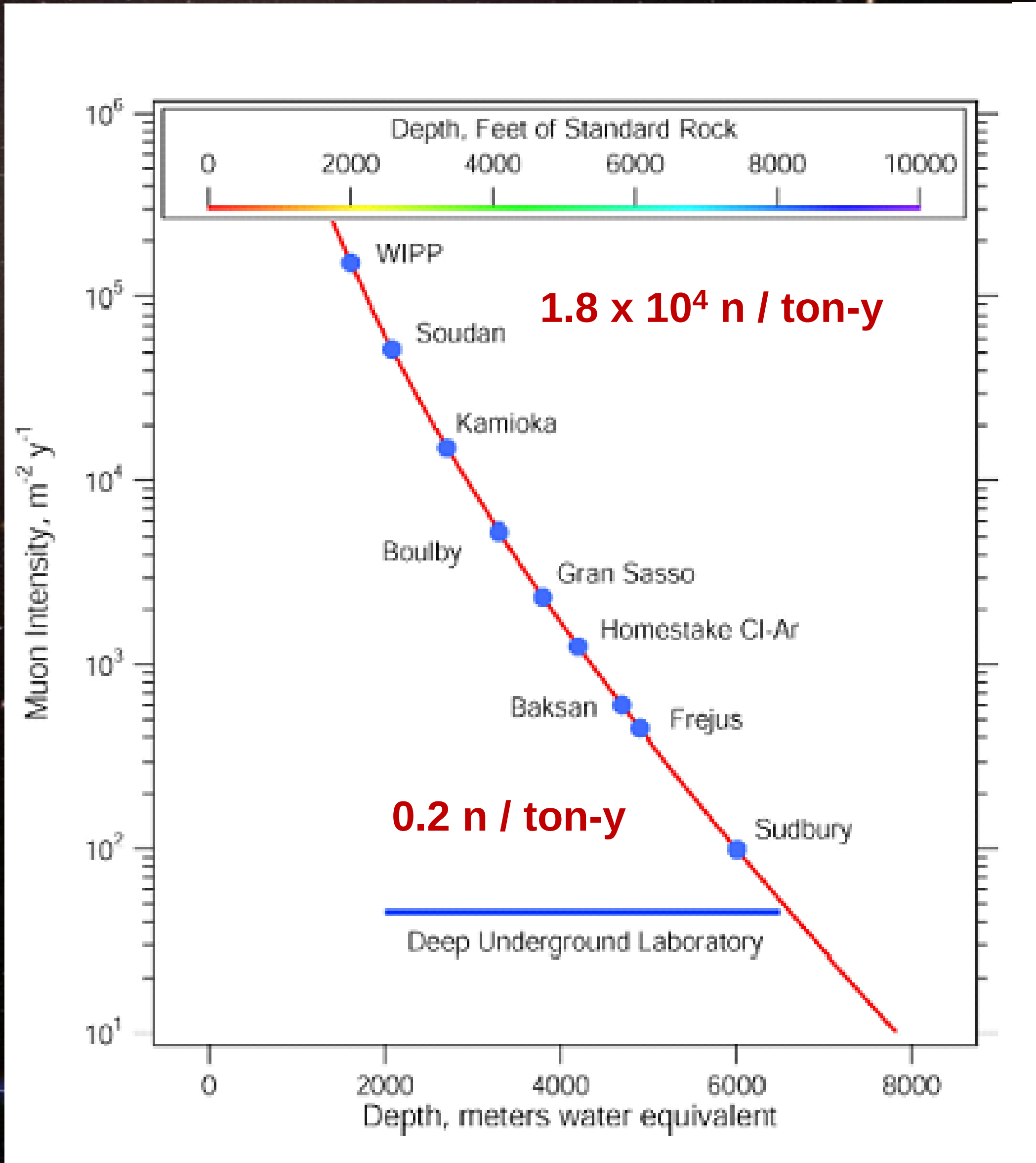
Mitigated by going u/g

U/Th (α,n) reactions in rock

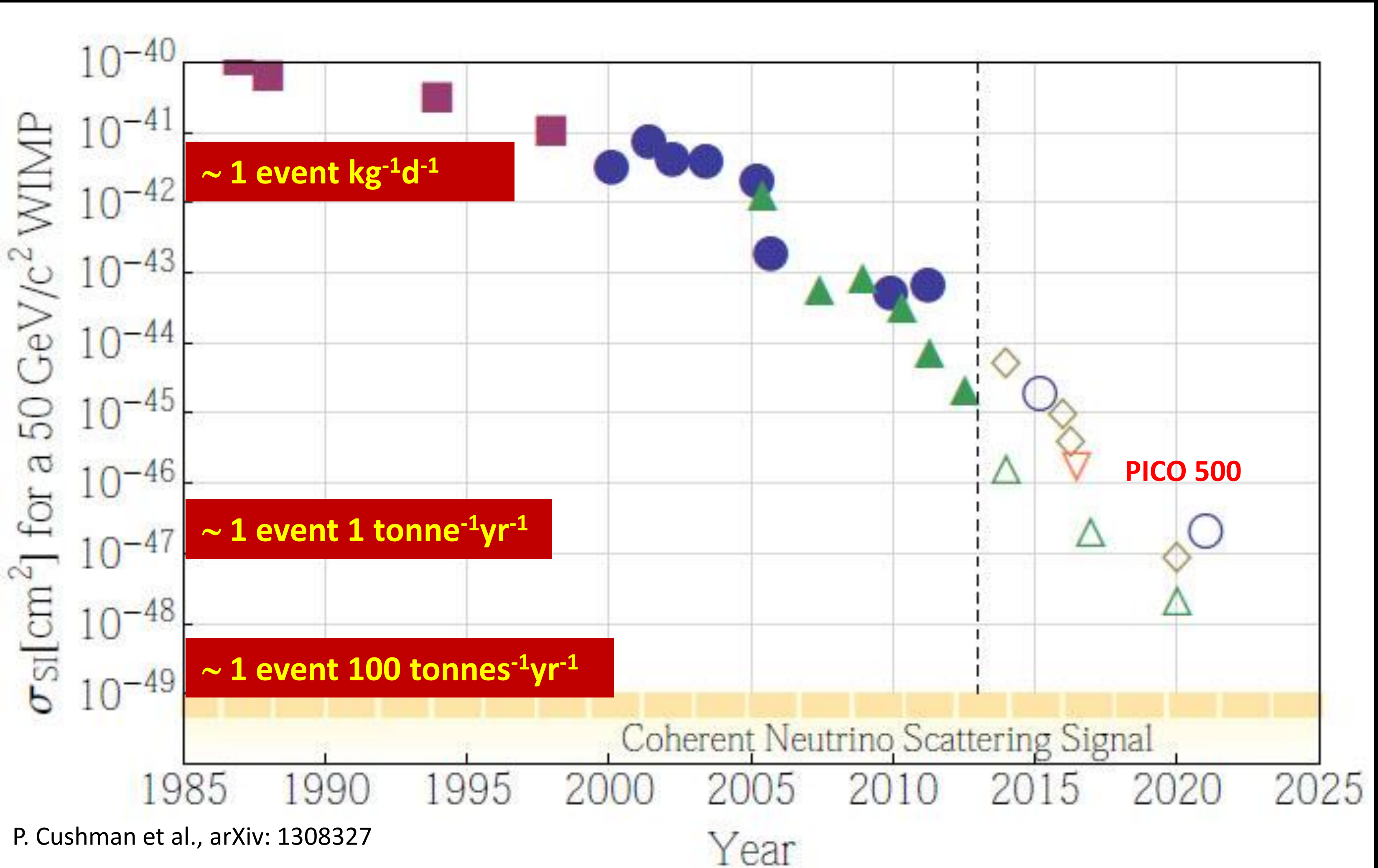
Mitigated by shielding

Other backg. α, β,γ !
Mitigated by…

- Radiopurity of det. material
- << 1ppb U/Th required
- Shielding
- Active backg. discrimination

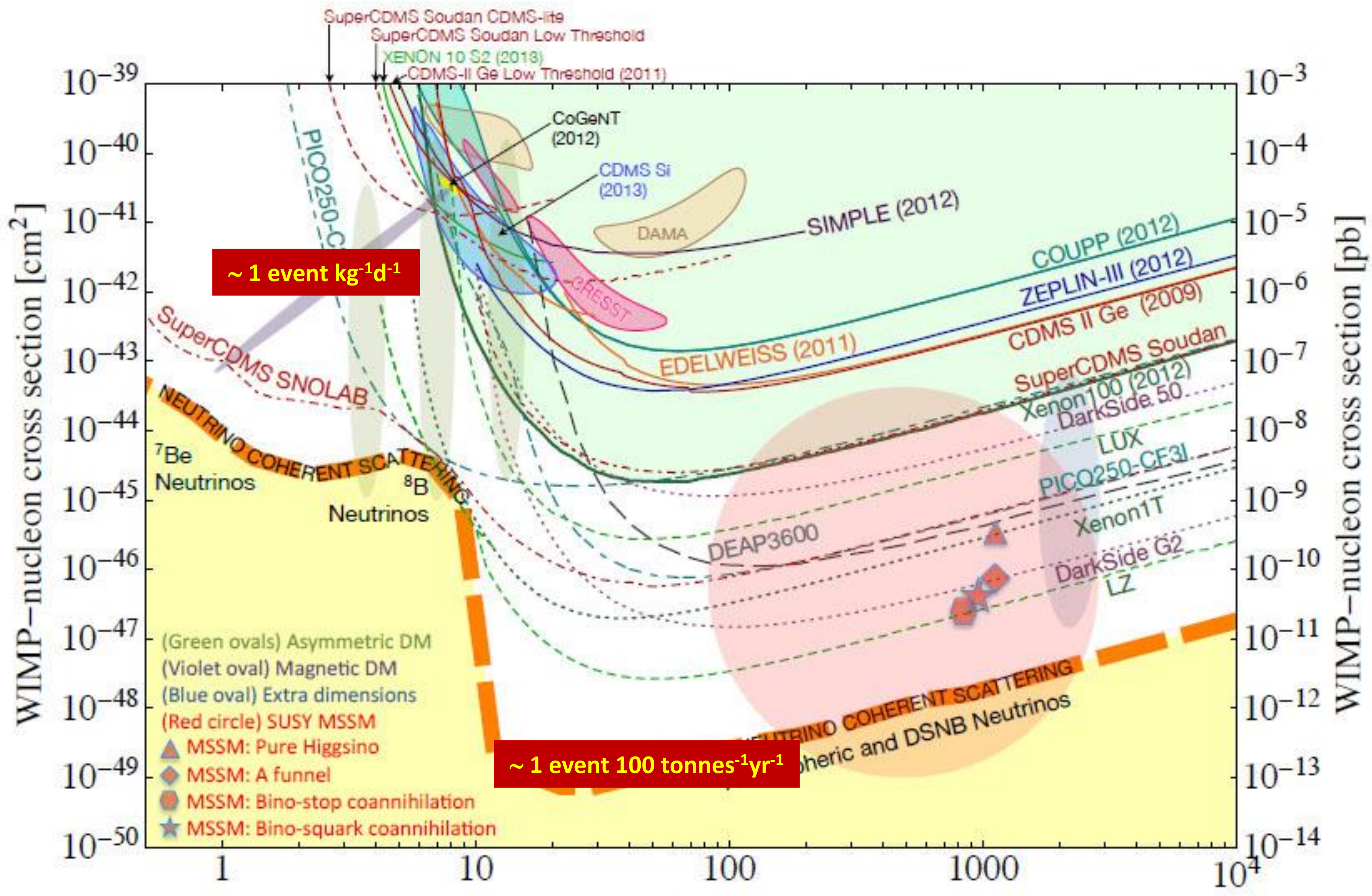


Tremendeous Progress over the Years !



P. Cushman et al., arXiv: 1308327

Example of Activity in the Field (SI)



P. Cushman et al., arXiv: 1308327

DM Searches at SNOLAB

Located 2 km underground in a mine in Sudbury

Dark Matter at SNOLAB

PICASSO 2.5kg	Superheated Droplet	C_4F_{10}	Completed
DEAP I 7kg	Scintillation	LAr	ProtoType Completed
COUPP/PICO2L	Superheated Bubble Ch.	CF_3I/C_3F_8	Completed
PICO 60	Superheated Bubble Ch.	C_3F_8	Completed
DAMIC	CCD	Si	Operational
DEAP 3600kg	Scintillation	LAr	Operational
NEWS	Spherical drift chamber	Ar/ He	Operational
PICO 40L	Superheated Bubble Ch.	C_3F_8	Under Construction
PICO 500	Superheated Bubble Ch.	C_3F_8	In Preparation
SuperCDMS	CryogenicéSolidState	Ge Si	In Preparation

PICO

Merger of PICASSO and COUPP Collaborations

Queen's, PNNL, Northwestern, Saha, FNAL, Toronto, Chicago, Montreal, Laurentian, SNOLAB, Alberta, Mexico, Drexel

- Develop the BC technology with the ultimate goal of building a **tonne scale detector** at SNOLAB
- Fully explore the **Spin-Dependent** sector with F-loaded targets and particular sensitivity to **low mass WIMPs**
- Exploit the **multi target** capacity of this approach (C_3F_8, CF_3I…)

PICO 2L → PICO 60 L → PICO 500 L

PICO

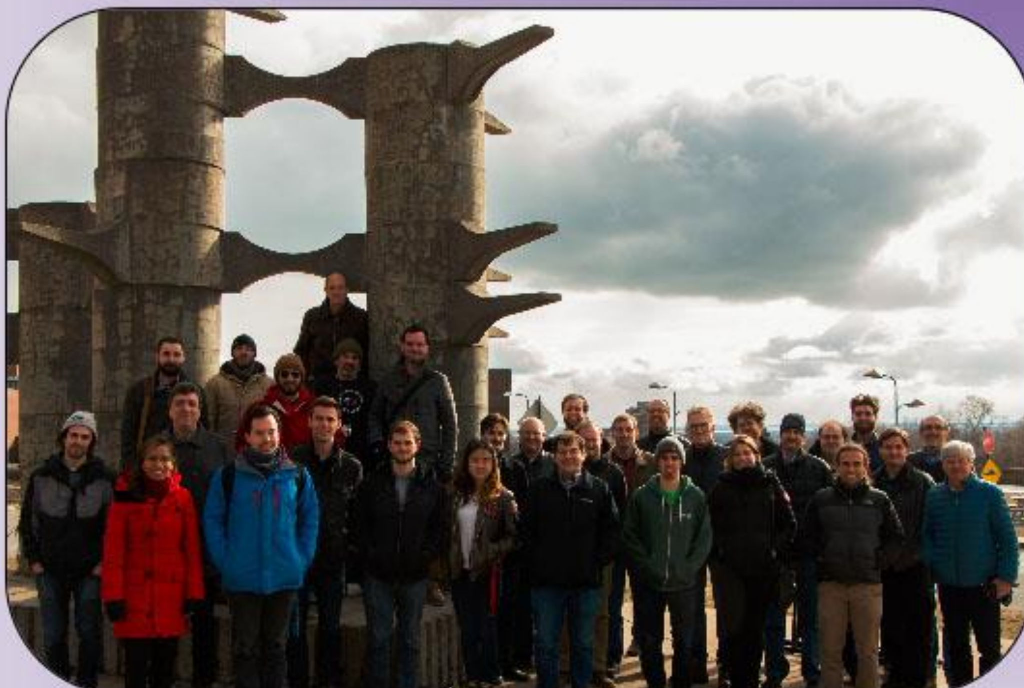
Northeastern Illinois University
O. Harris

České Vysoké Učení Technické v Praze
R. Filgas, I. Stekl

KICP Kavli Institute for Cosmological Physics at The University of Chicago
J.I. Collar, A. Ortega

Université de Montréal
S. Chen, M. Laurin, J.-P. Martin, A. Plante, A.E. Robinson, N. Starinski, F. Tardif, D. Tiwari, V. Zacek, C. Wen Chao,

SNOLAB
I. Lawson



Indiana University South Bend
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Universitat Politècnica de València
M. Ardid, M. Bou-Cabo, I. Felis

M. Das, S. Sahoo, S. Seth

Drexel University
M. Bressler, R. Neilson

PennState
D. Maurya, S. Priya, Y. Yan

Fermilab
P.S. Cooper, M. Crisler, W.H. Lippincott, A. Sonnenschein

University of Alberta
C. Coutu, S. Fallows, C. Krauss, M.-C. Piro

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

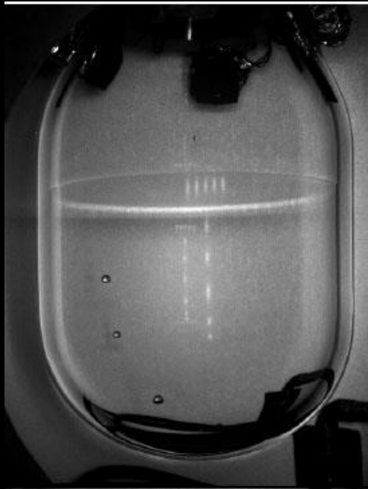
E. Vázquez-Jáuregui

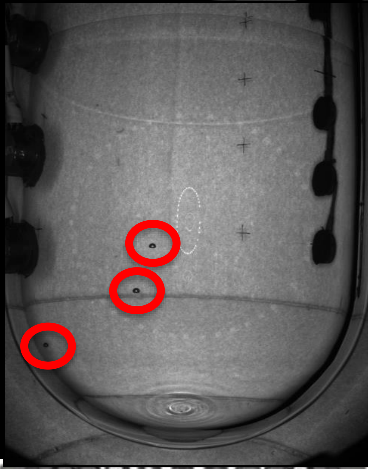
Queen's University
B. Broerman, G. Cao, K. Clark, G. Giroux, C. Hardy, C. Moore, A. Noble

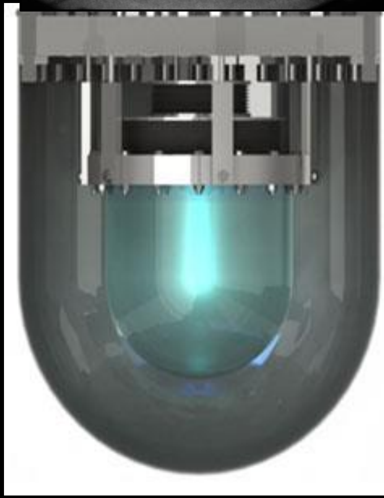
Pacific Northwest National Laboratory
I. Arnquist , C. Cowles, C.M. Jackson, B. Loer, K. Wierman

Laurentian University Université Laurentienne
J. Farine, A. Le Blanc, C. Licciardi, O. Scallon, U. Wichoski

Particle Detection with Superheated Liquids

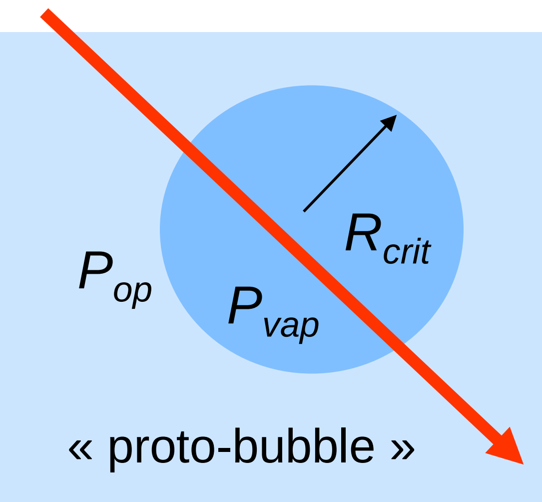






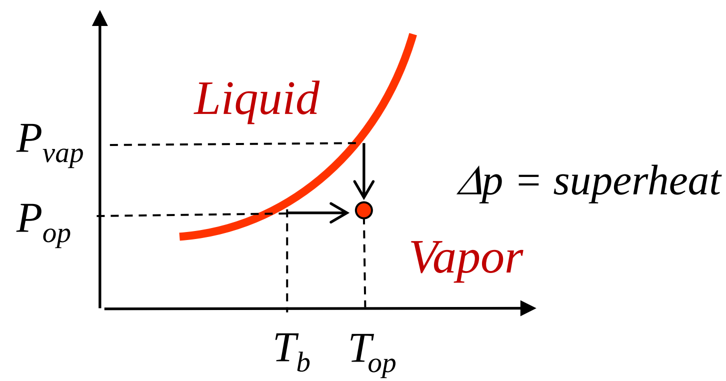
Superheated Liquids as Threshold Detectors

Much simpler for DM search!



Idea:

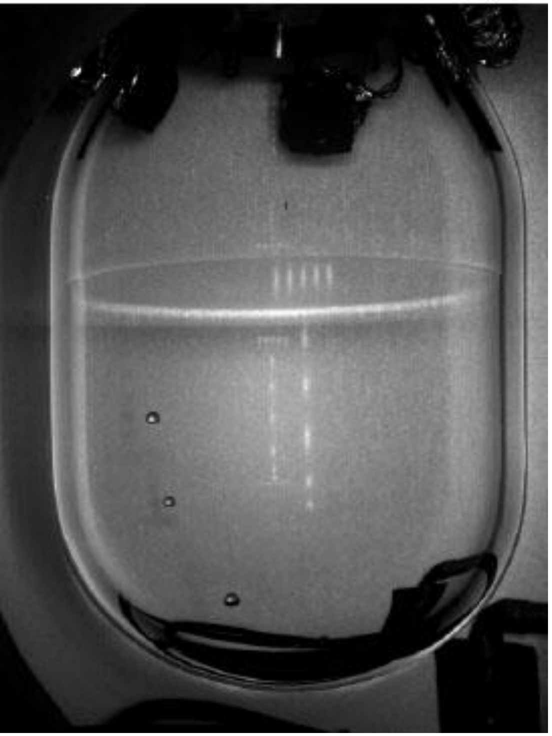
- SHL is a fluid in a metastable state
- which can be quenched by energy depositions of particles
- Tiny energy deposition → Macroscopic phase transition



Bubble chamber principle: (D. Glaser, 1952)

- $E_{dep} < E_{thr}$ within R_{crit} → proto-bubble collapses
- $E_{dep} > E_{thr}$ within R_{crit} → irreversible bubble expansion!

Superheated Liquids as Threshold Detectors



Fluids of choice: Fluorinated halocarbons → SD, SI

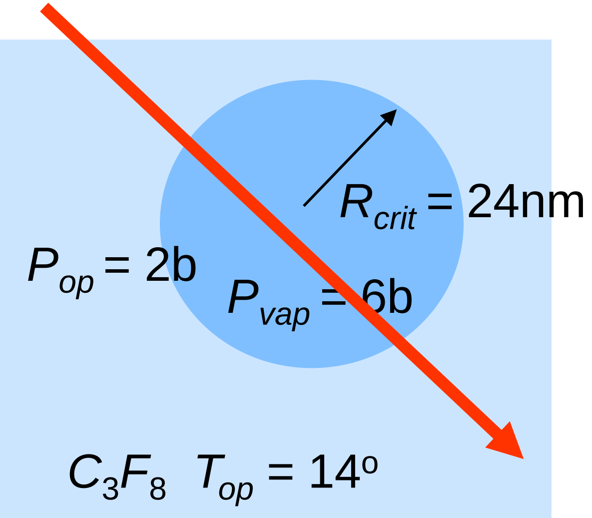
- C_4F_{10}, C_5F_{12}, C_3F_8, CF_3I,… (right surface tension)
- But in principle any liquid

What does it take to create a bubble ?

Surface tension

$$R_c = \frac{2\sigma}{\Delta p} \qquad E_{thr} = 4\pi R_c^2\left(\sigma - T\frac{\partial\sigma}{\partial T}\right) + \frac{4}{3}R_c^3\rho_v h$$

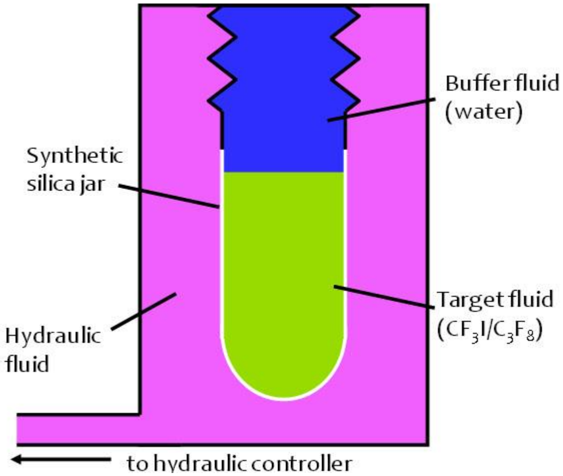
Crit. Radius (24 nm) | Surface energy (1.53 keV) | Latent heat (1.81 Kev)



$$E_{dep} = \frac{dE}{dx}\cdot R_{crit} \geq E_{thr}$$

Threshold energy E_{thr} is set by varying (T_{op}, P_{op})

Technical Realizations

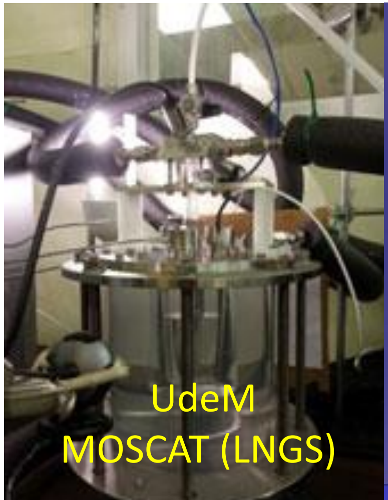


Bubble chambers

Acoustic & optical read out

Droplet detectors

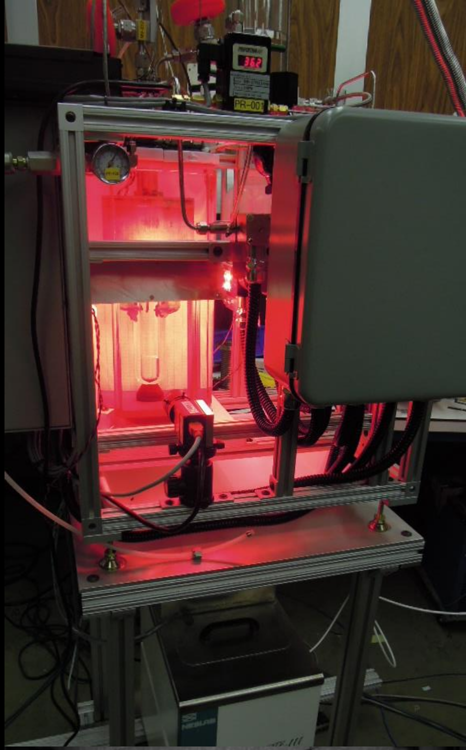
Acoustic read out

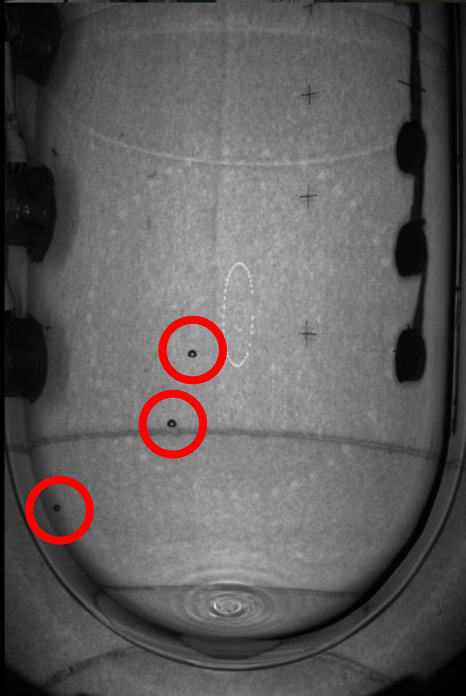


Condensation chambers "Geyser"

Acoustic & optical read out

Background Mitigation Strategies



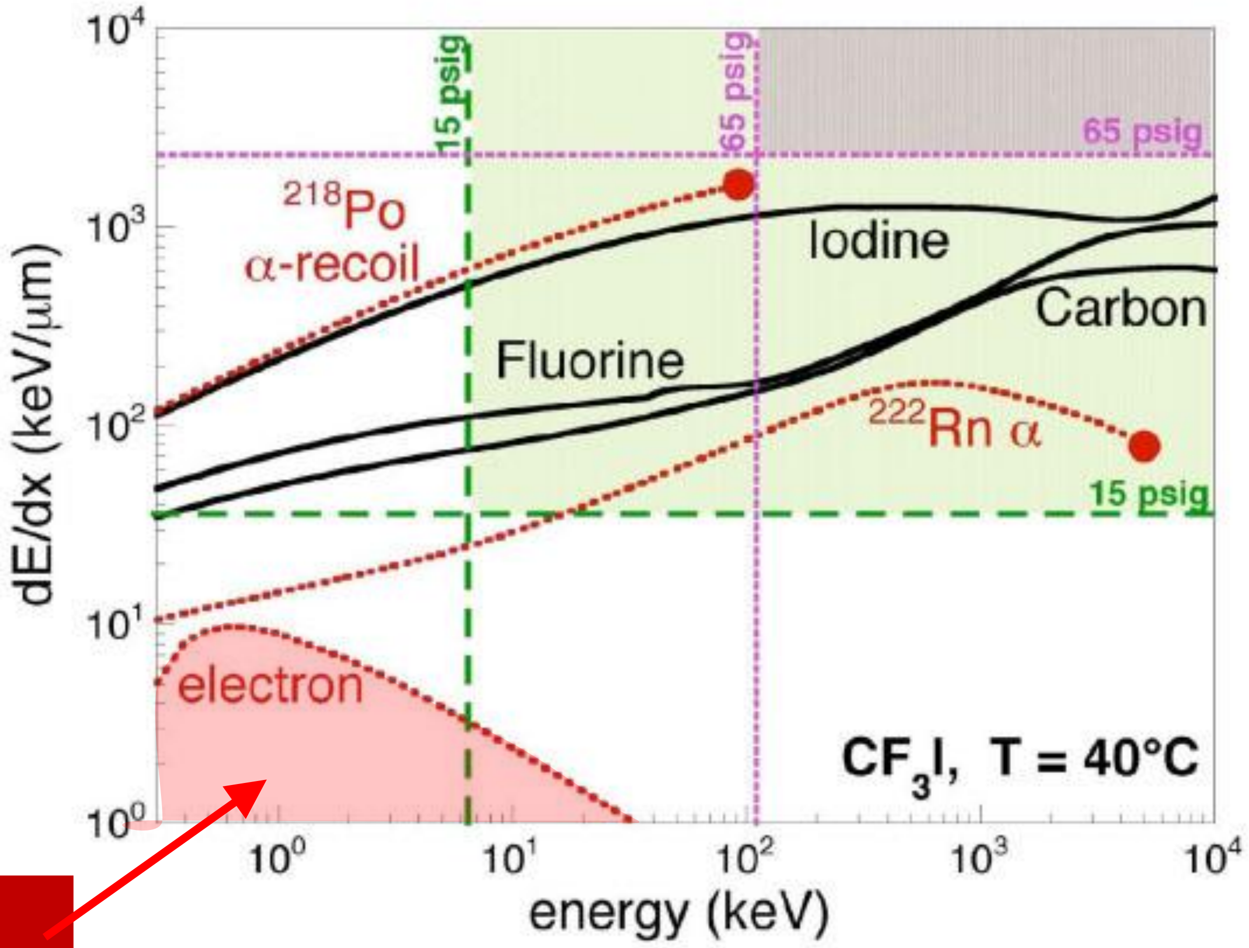


Particle Discrimination in S. H. Liquids

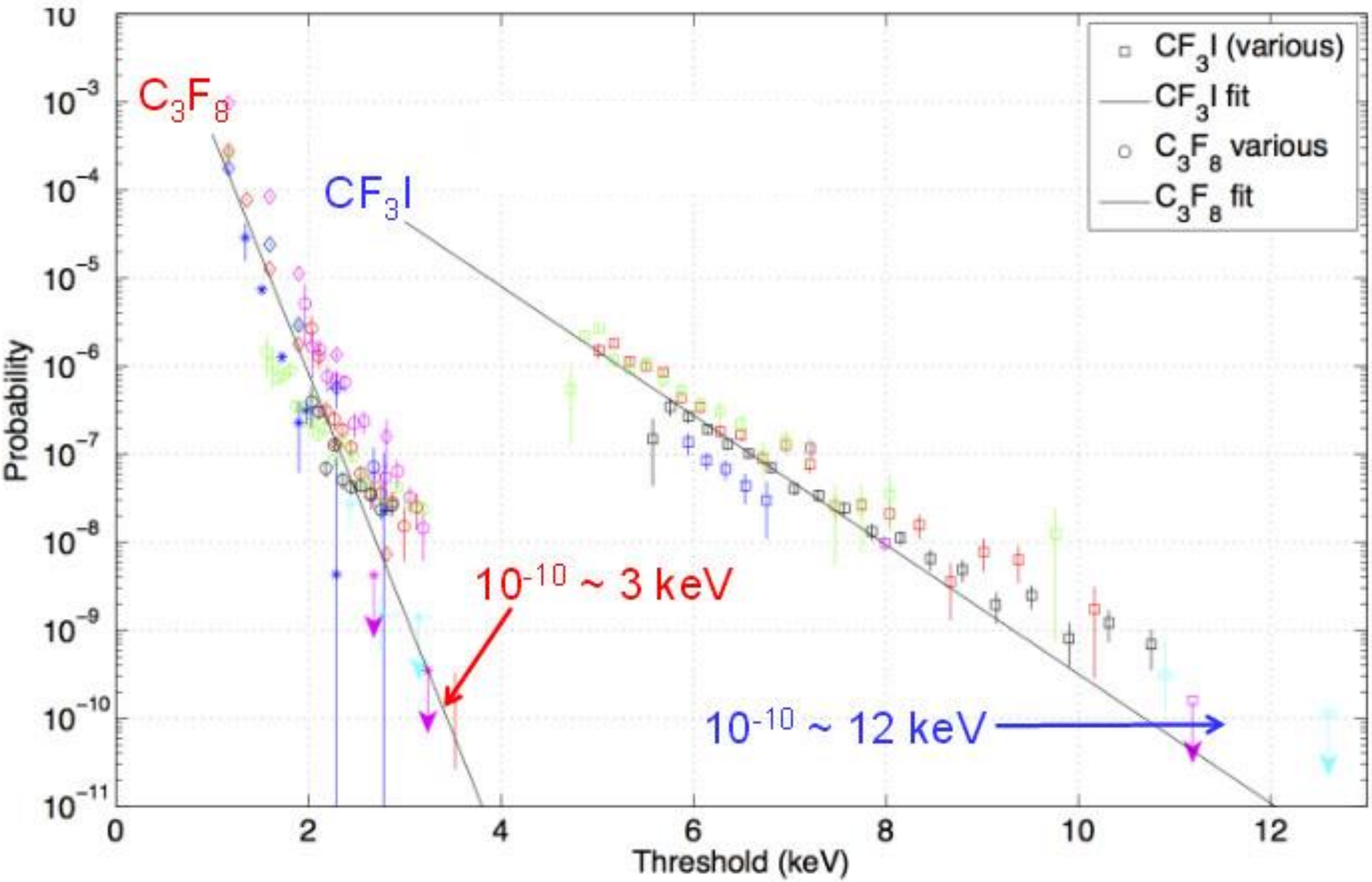
$$E_{dep} = \frac{dE}{dx} \cdot R_{crit} \geq E_{thr}$$

Threshold in dE/dx

Can tune detector to become insensitive to γ's!



Gamma Rejection in Superheated Liquids



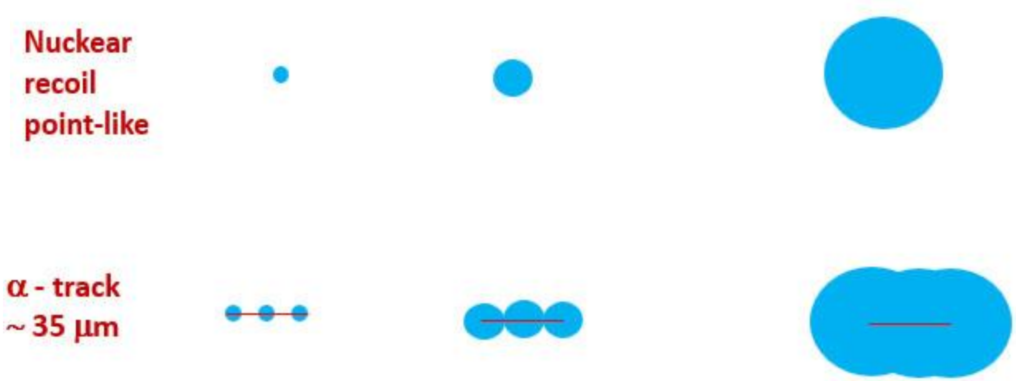
Can set superheat parameters (T,P) such that γ - rejection 10^{-10} or better!

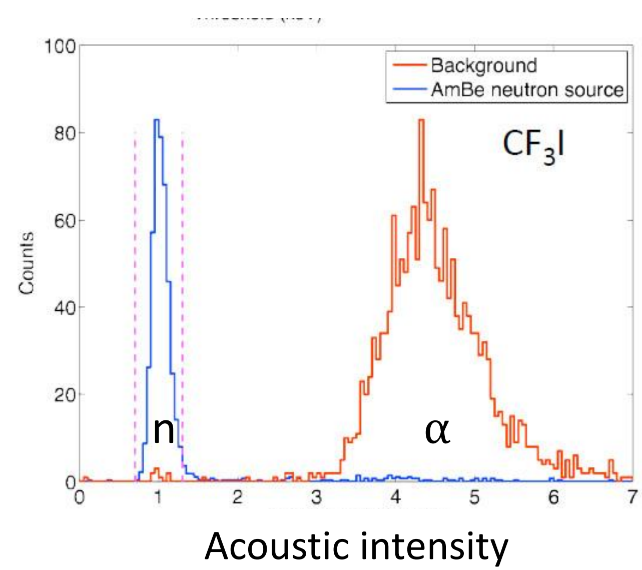
Acoustic Alpha Rejection

Bubble dynamics allows for alpha-nuclear recoil discrimination Picasso

10^{-14}	10^{-13}	10^{-10}	10^{-9}	10^{-3}	Time (s)
Interaction with electrons	Local heating	Phase transition at nucleation site (10 nm)		Rapid expansion of proto bubble with strong acoustic emission	

Intensity of acoustic signal: $$I = \frac{\rho \ddot{V}^2}{4\pi c}$$ **depends on volume acceleration**

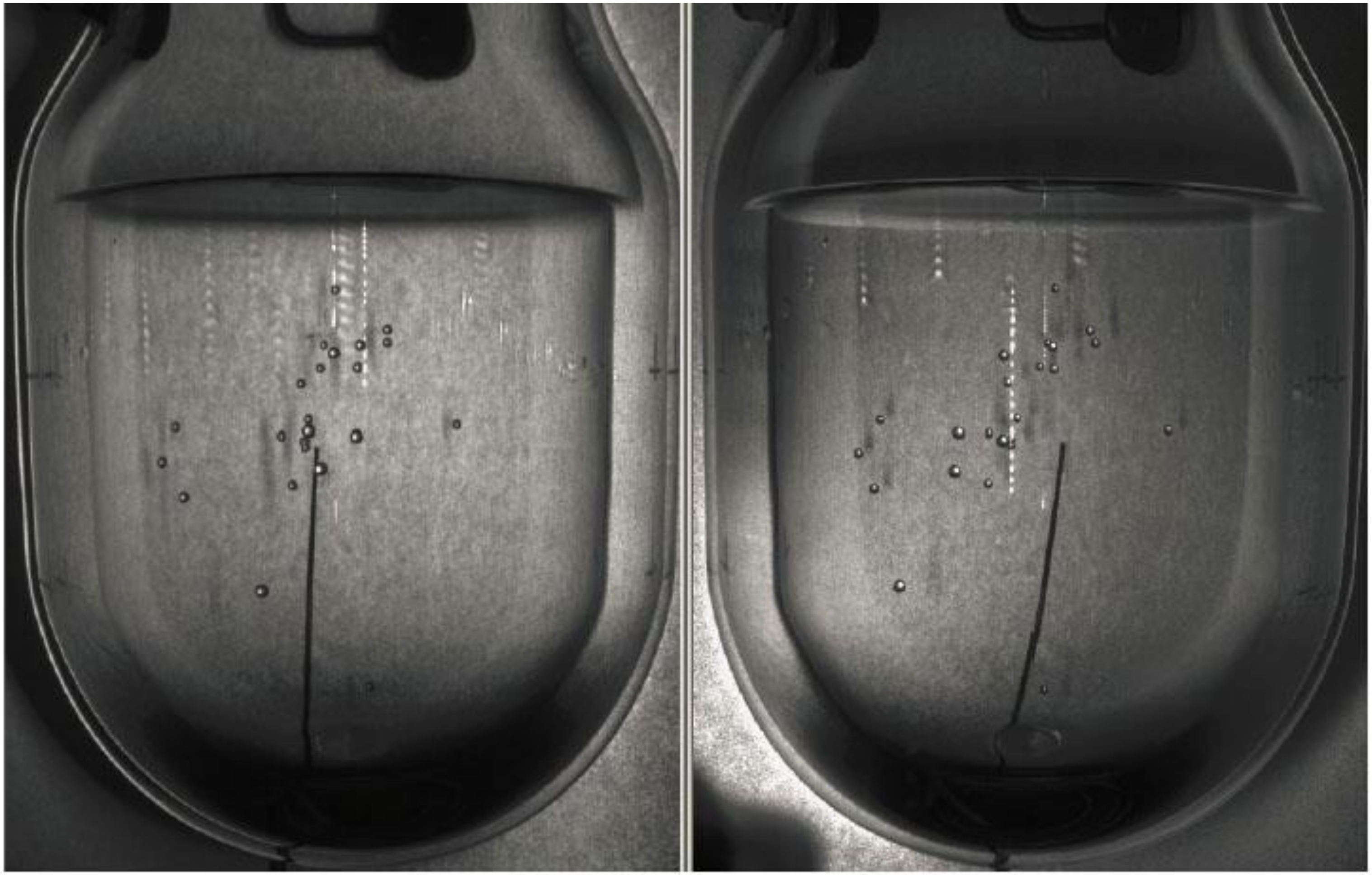




$$\ddot{V}_\alpha >> \ddot{V}_{\mathrm{Recoil}}$$

99.3% α- rejection demonstrated

A 23 - Bubble AmBe Neutron Event!

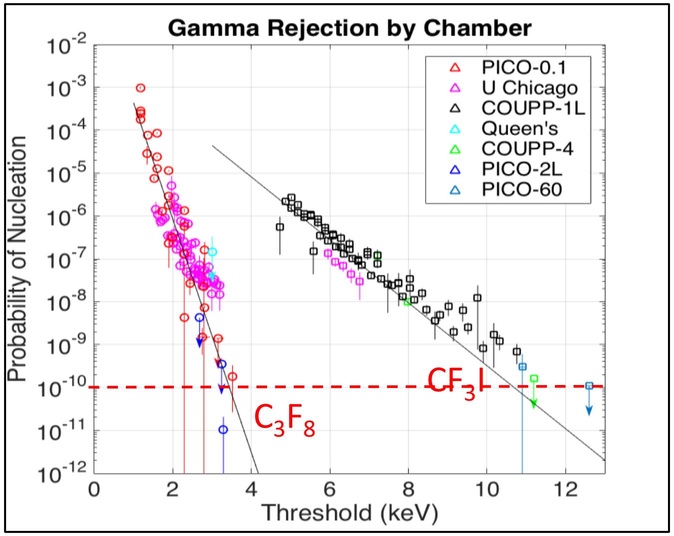


High multiplicity is a result of high bubble nucleation efficiency; 60% of neutron calibration events in C_3F_8 are multiples.

Background Rejection Summary

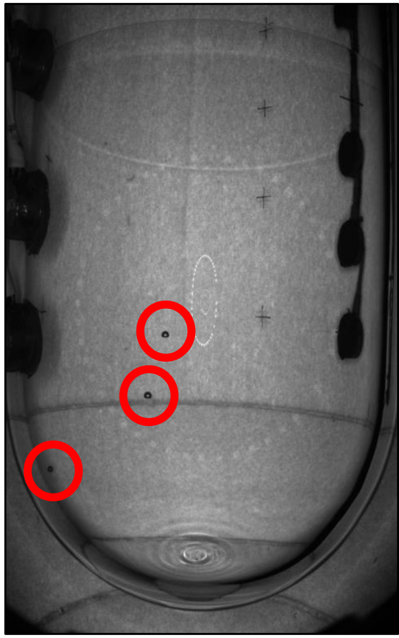
Gamma/Beta:

- Select material
- Operate above gamma threshold



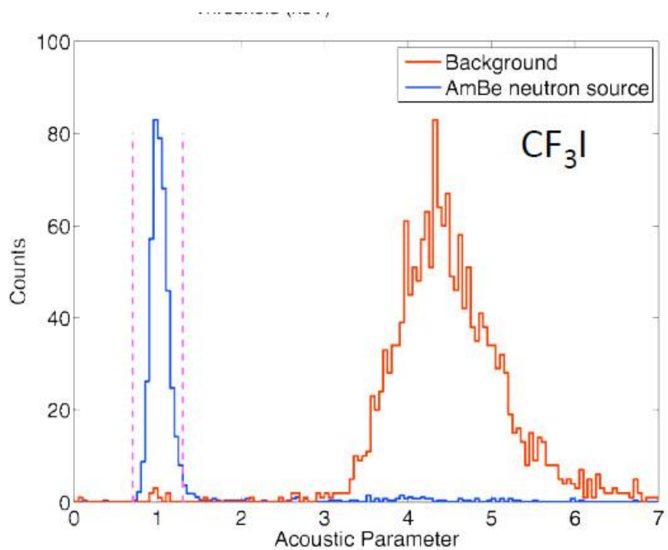
Neutrons:

- Operate underground
- Add local shielding
- Select material
- Use multiplicity

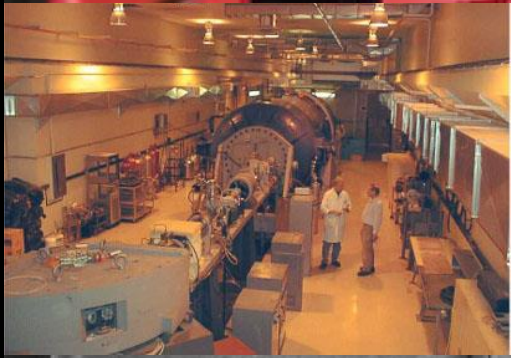


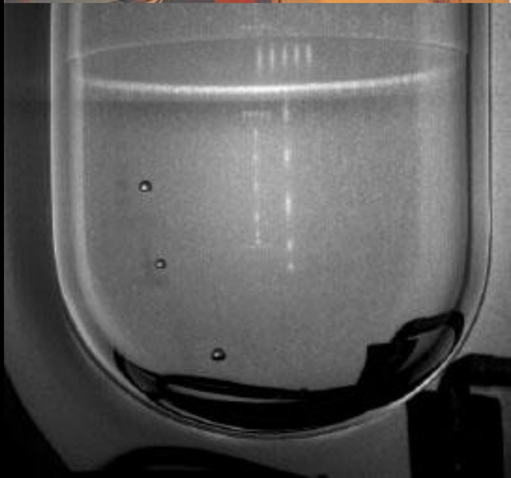
Alpha particles:

- Purify materials
- Optimize piezo analysis
- > 99.3% acoustic rejection

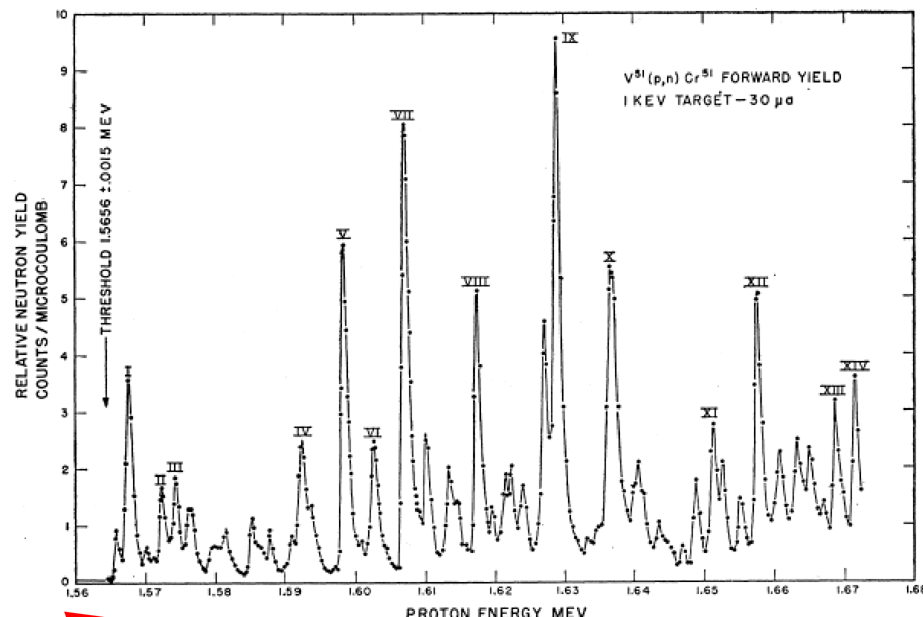


How to Calibrate a PICO Bubble Chamber



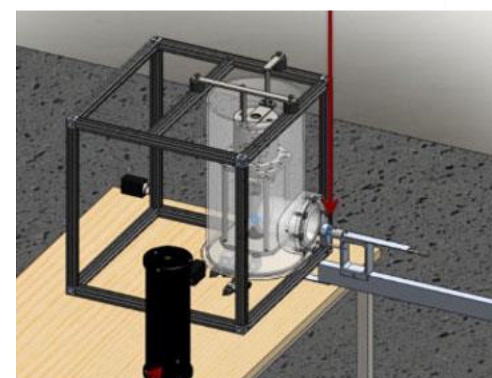


Low-Energy Neutron Calibration



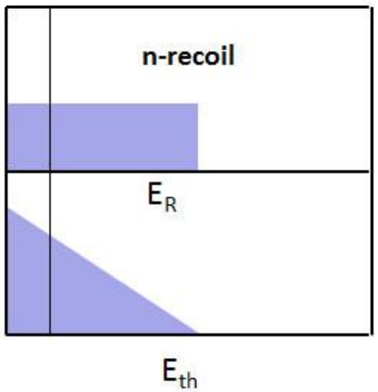
Tandem Van de Graaff at
Université de Montréal
Resonances in $^{51}V(p,n)^{51}Cr$

^{124}SbBe photo-neutron source
1691 keV γ gives 34 keV neutrons



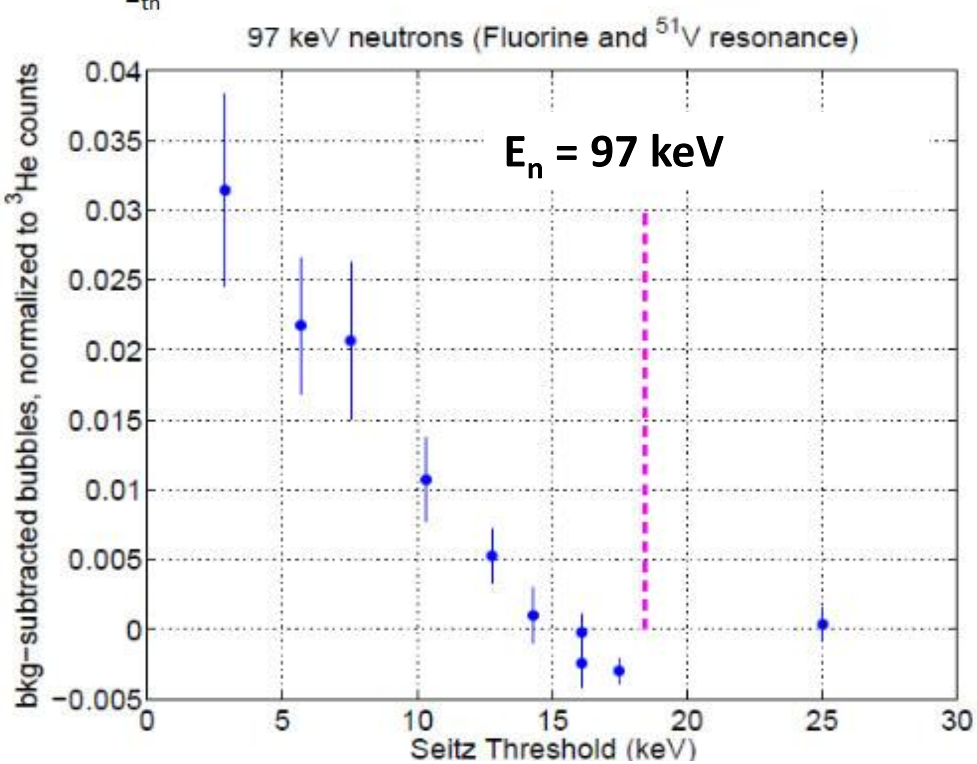
Low-Energy Neutron Calibration

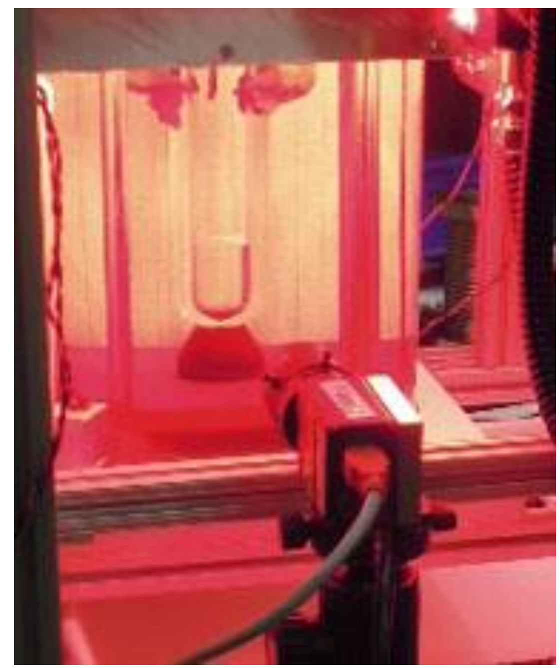
Mono-energetic n-test beam @ Montréal



Recoil spectrum for mono-energetic neutrons

$E^{F}_{max} = 0.18 \times E_n$

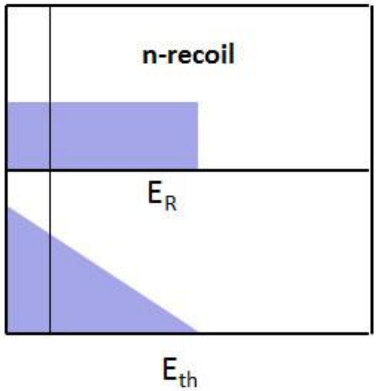




C_3F_8 PICO 0.3L Bubble ch.

Low-Energy Neutron Calibration

Mono-energetic n-test beam @ Montréal



Recoil spectrum for mono-energetic neutrons

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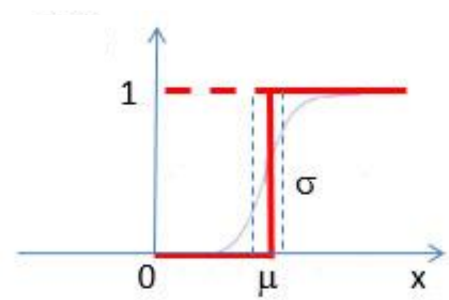
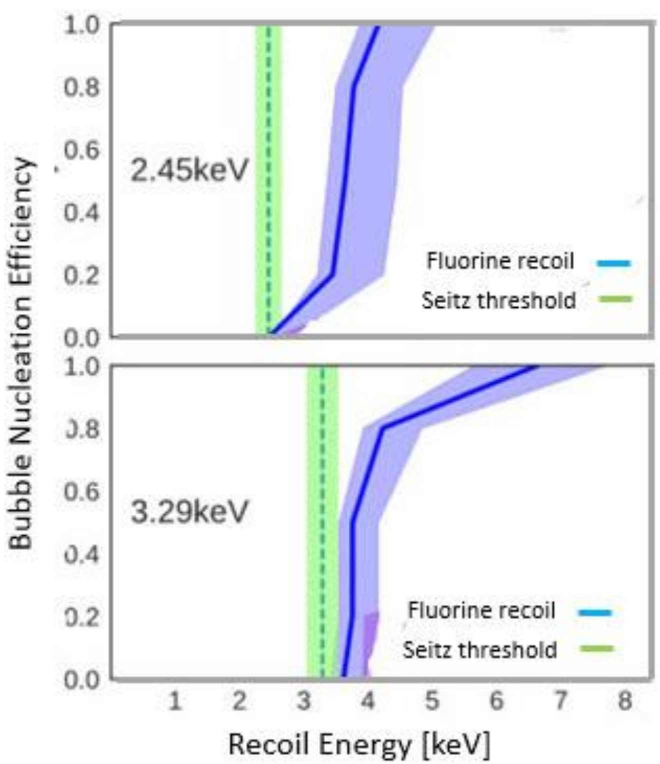
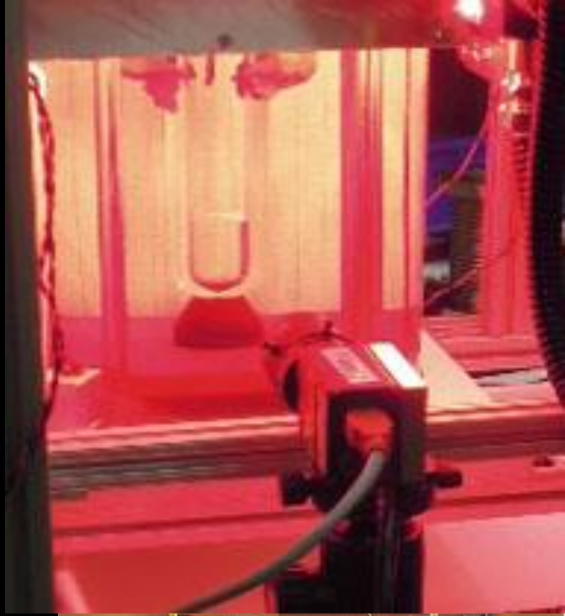


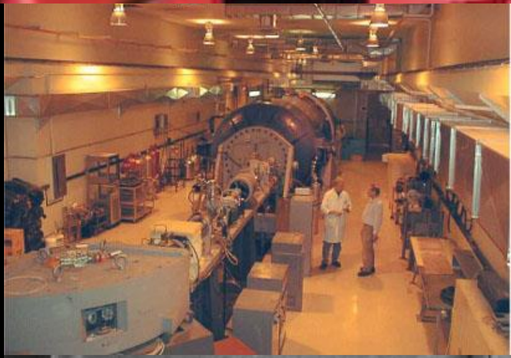
Nucleation Efficiency Best Fit for ^{19}F

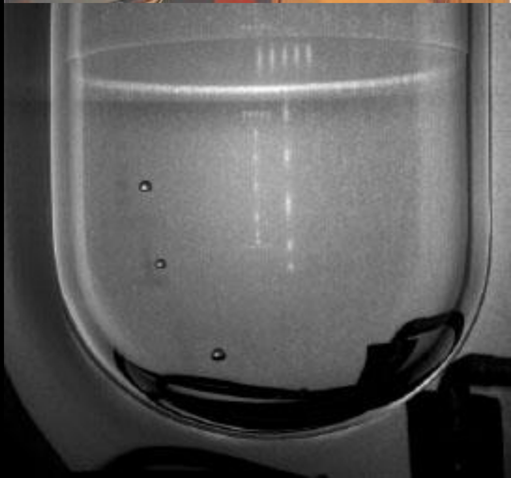


Fit all neutron data with systematic uncertainties for each data set to piecewise efficiency curves with Markov Chain Monte Carlo

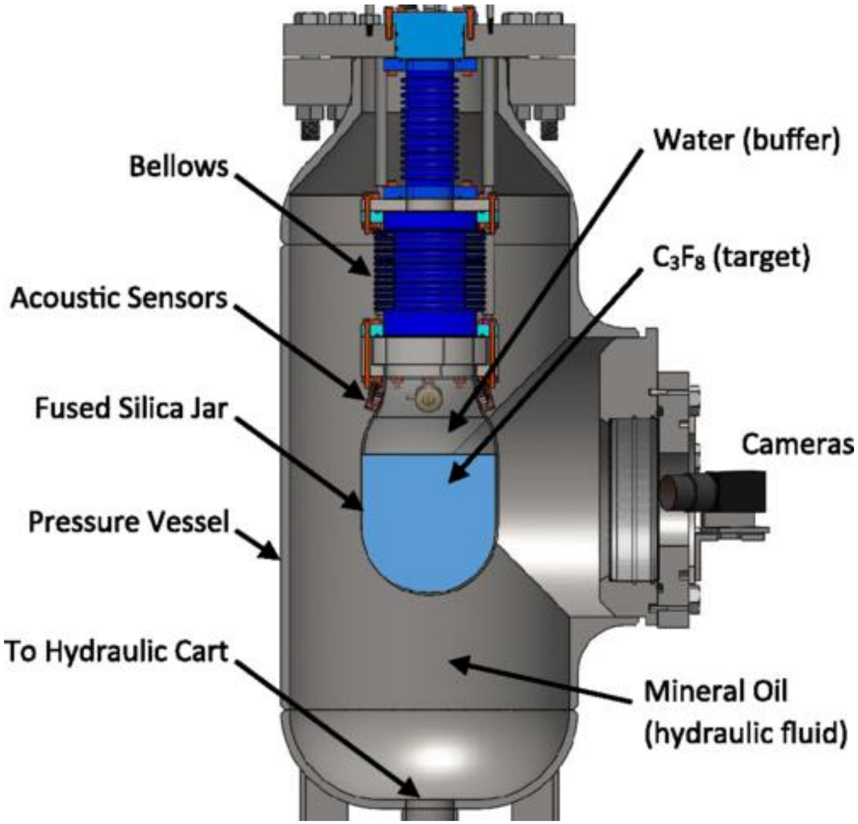
How to operate a PICO Bubble Chamber



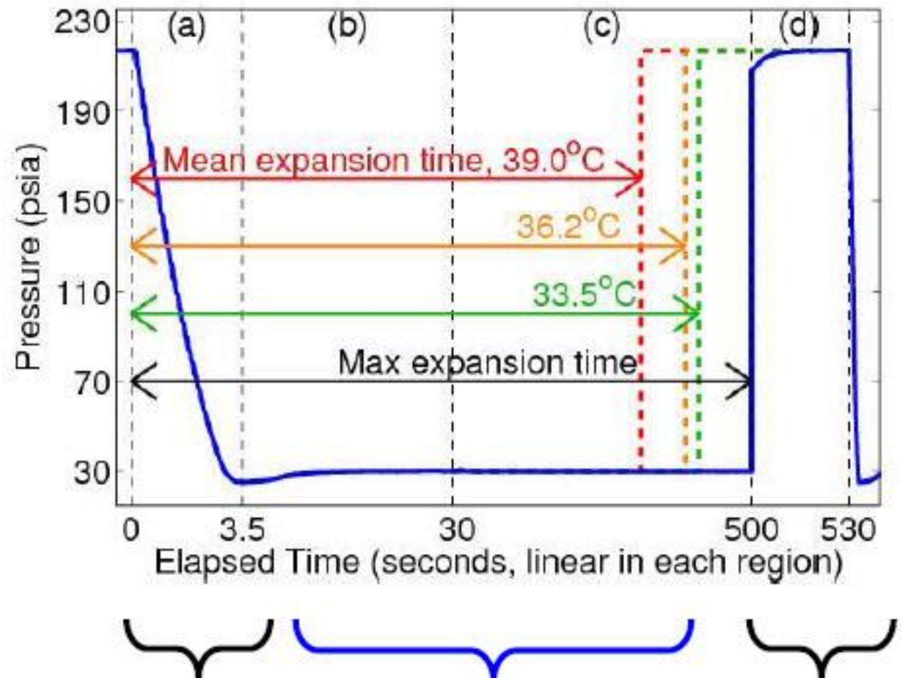




Operating a PICO Bubble Chamber



(PICO 2L with C_3F_8)

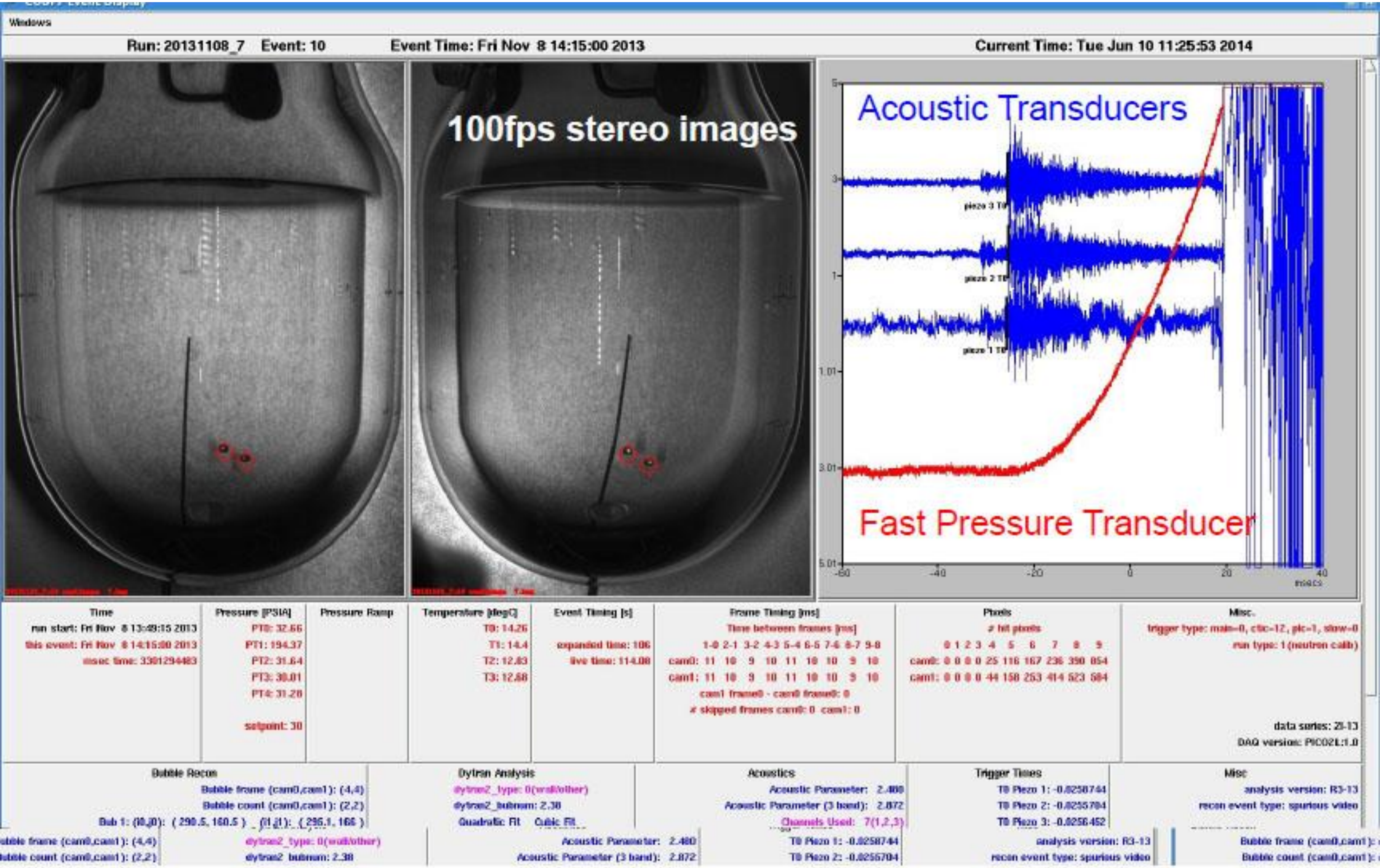


Pressure drop to superheat state

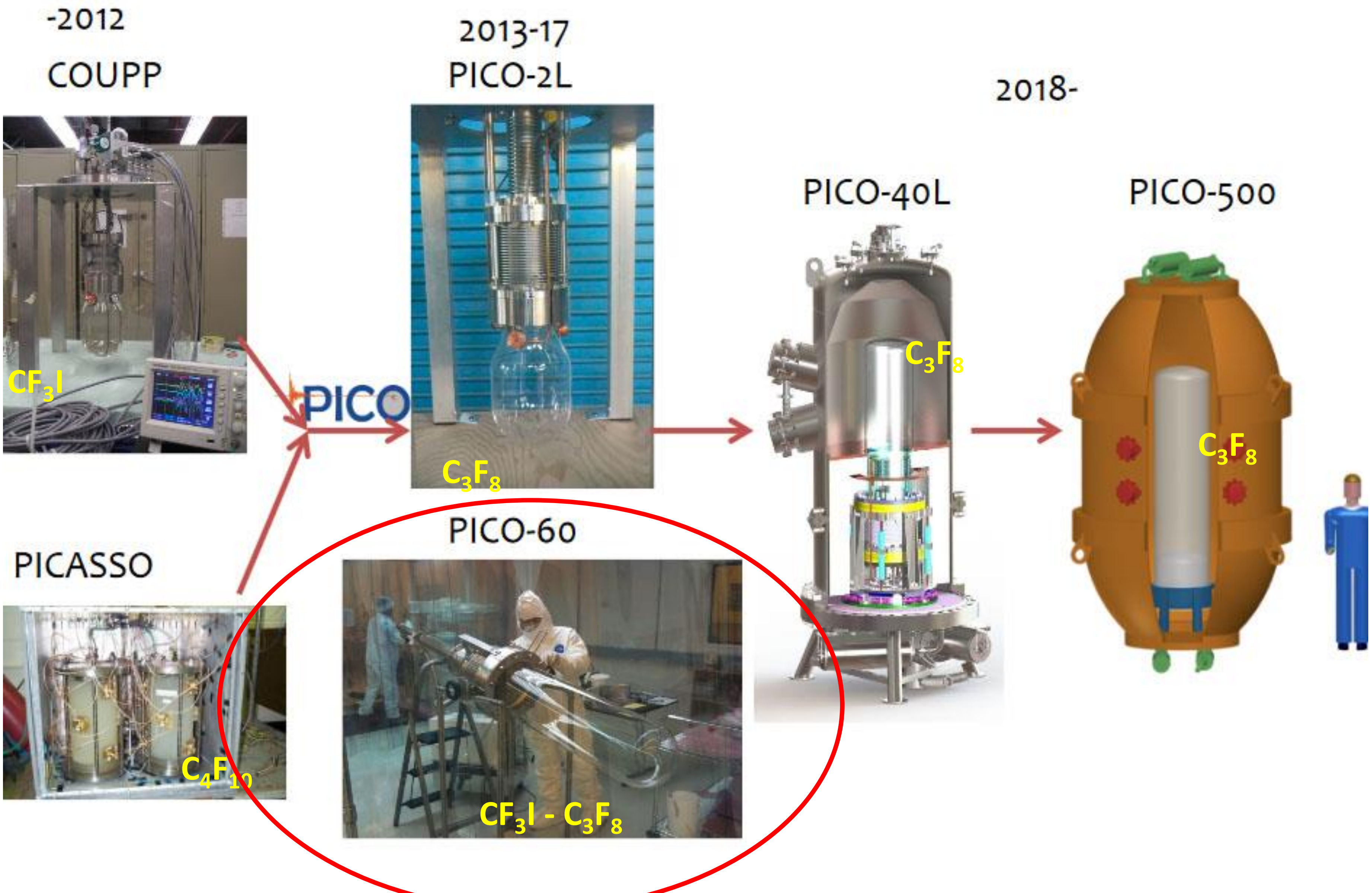
Bubble event: Cameras trigger, record position, Microphones record acoustic traces

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

Screen Display during operations



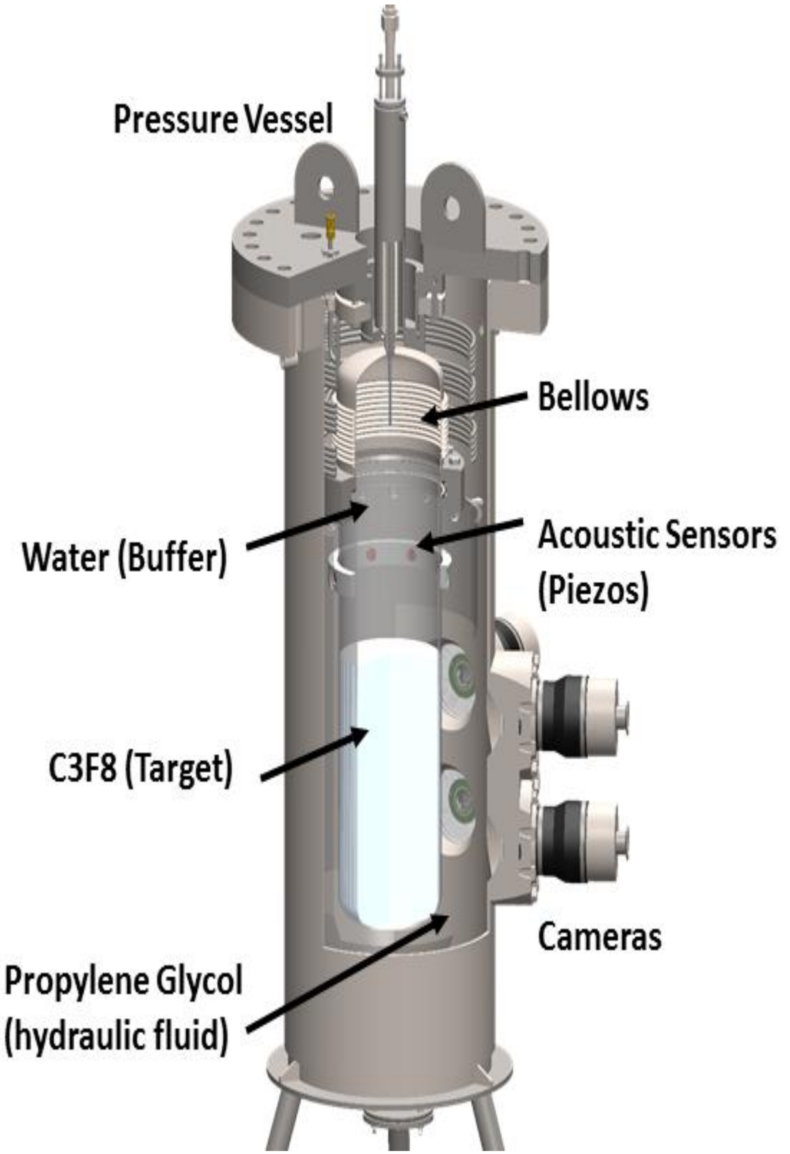
PICO Program Overview



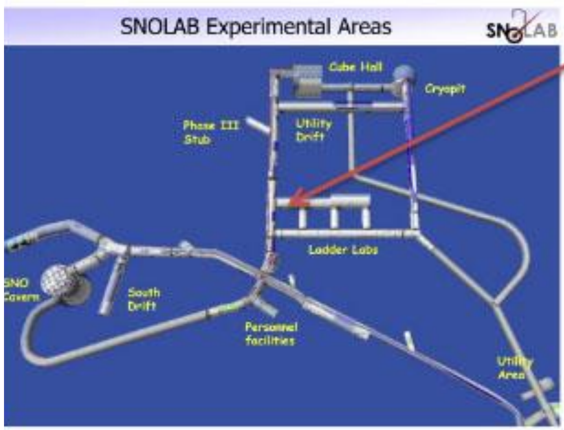
PICO 60 with C_3F_8

….largest BC built by PICO

- Fill with 52 kg of C_3F_8 (summer 2016)
- 4 cameras at 300 fps (monitor 45L volume)
- Active fluid recirculation with filtering
- Muon veto



PICO 60



Filled with 40L C_3F_8 on June 30, 2016

PICO 60 Run with C_3F_8

Physics run: Nov 28, 2016 – Jan 13, 2017

- Threshold: 3.29 $\pm$ 0.09 keV (30.2 $\pm$ 0.3 psi, 13.9 $\pm$ 0.1 ^{0}C)
- *Blinded* acoustic analysis
- Fiducial mass: 45.7 kg
- Total live-time: 30.0 days
- WIMP selection efficiency: 85.1% (Dominated by acoustic cuts)

Final exposure: 1.3 ton-days

X 9 improvement over PICO-2L**!**

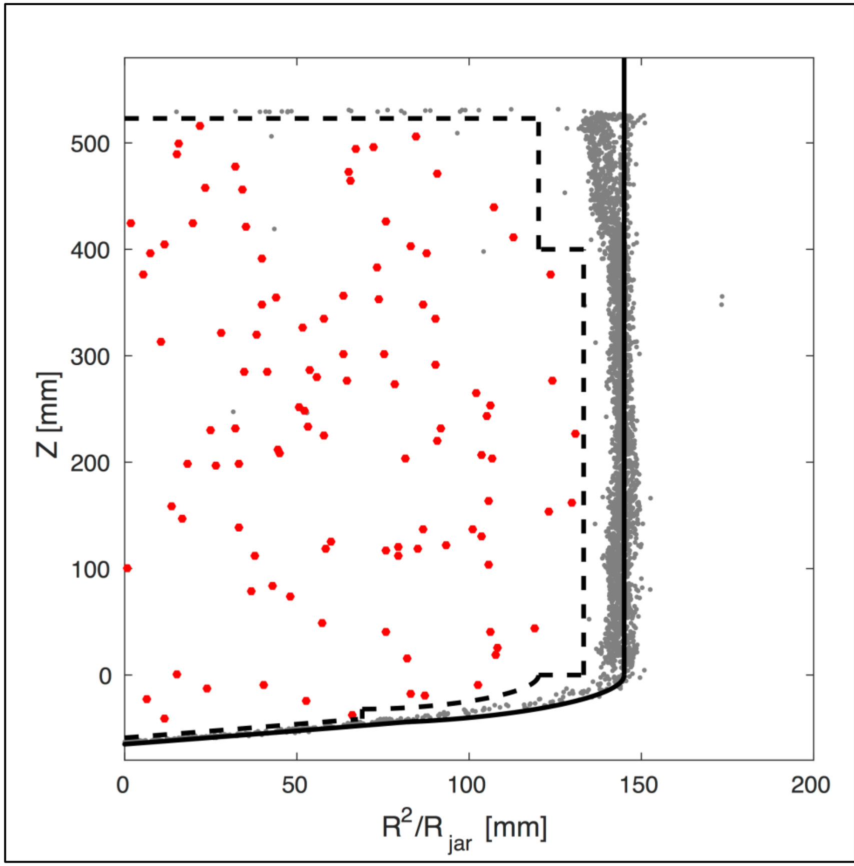
Before Opening The Box

106 bulk singles in WIMP search dataset

- *Acoustics Still Blind*
- Consistent with Rn decay rate

Neutron Background

- Not blinded to multiplicity
- 3 multiple bubbles in the physics data
- Multiples to singles ratio is approximately 3:1

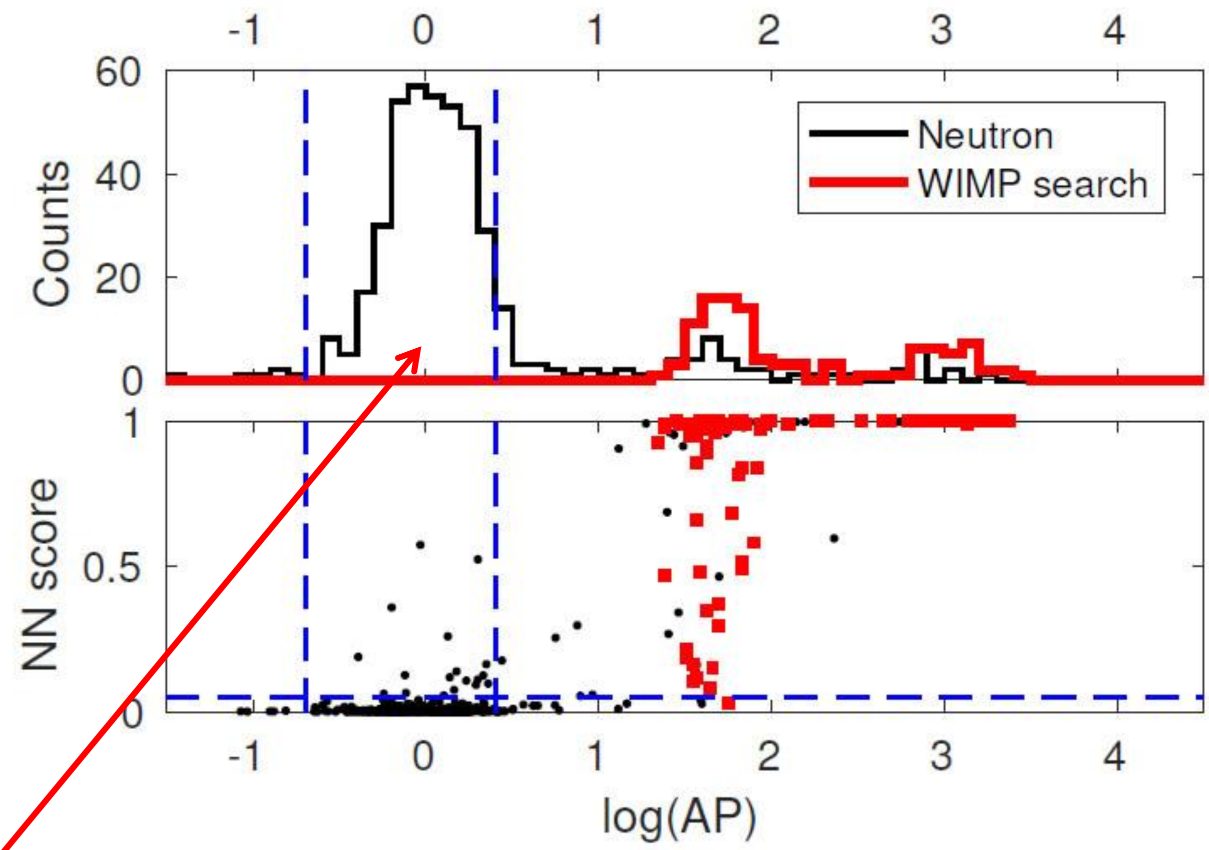


Multiples monitor (α,n) backg.

After Opening The Box !

Acoustic intensity

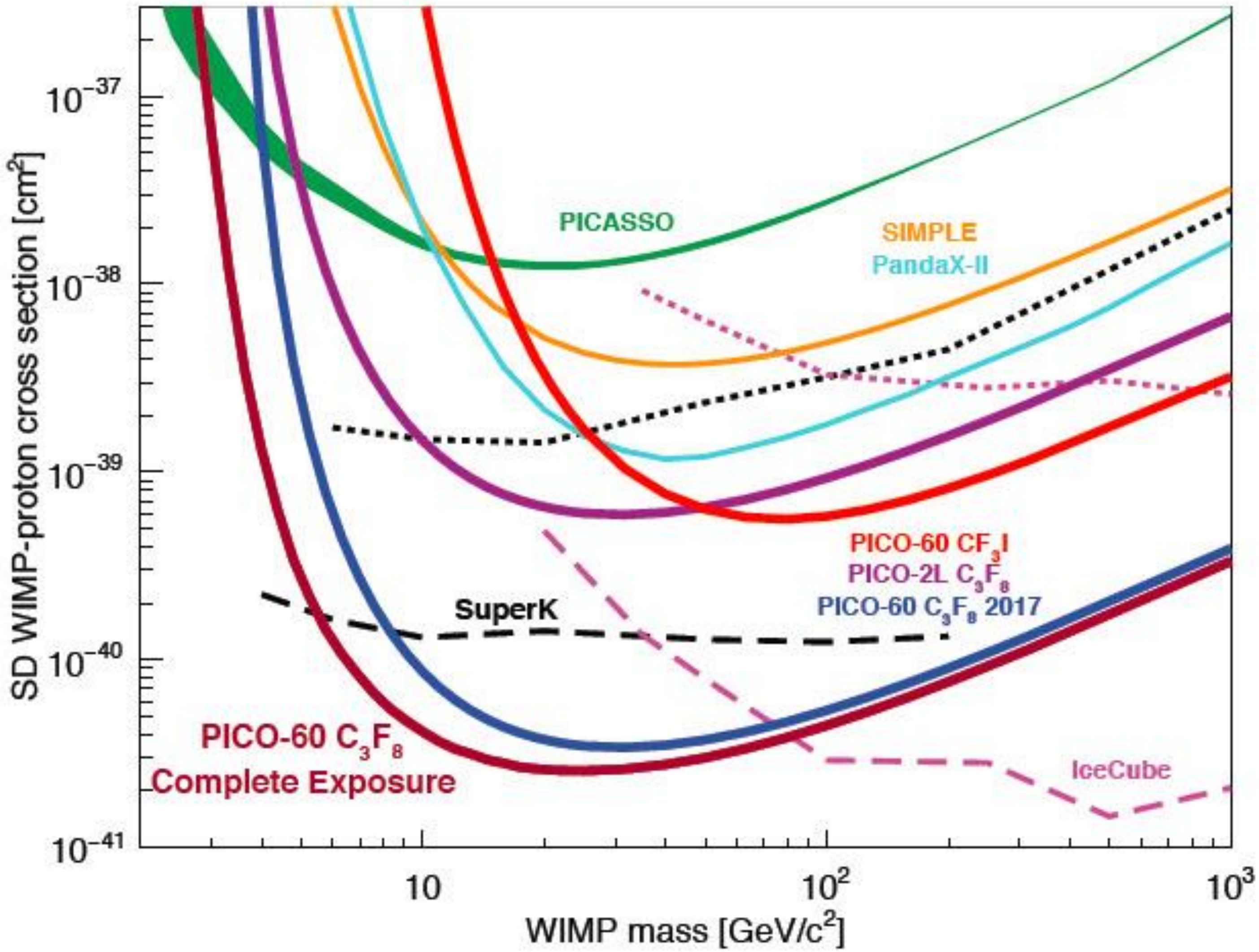
Neural net



Zero events in nuclear recoil region!

Total exposure 1167 ± 28 kgd

Spin-dependent WIMP-Proton Coupling



C. Amole *et al.*, Phys. Rev. Lett. 118, 251301 - new paper on archive soon

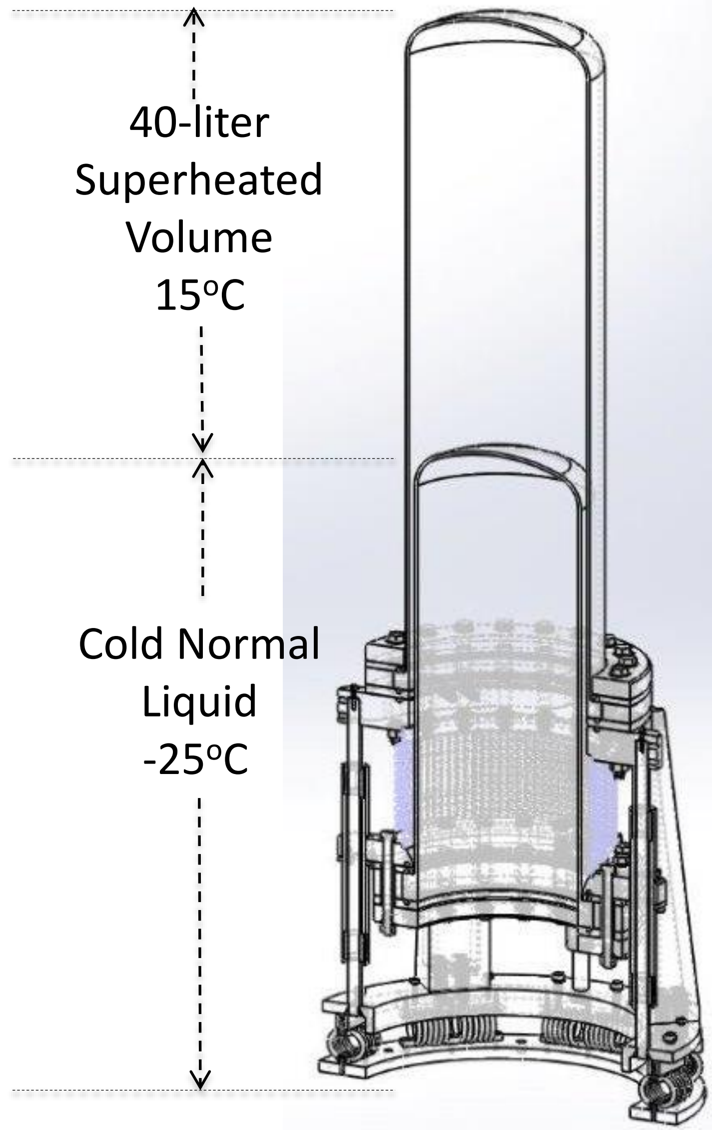
- World leading results in SD-sector
- Threshold lowered to 2.45 keV for additional 1.4 ton-days

NEXT: PICO- 40L

PICO-60

Purpose of buffer liquid is to isolate the active liquid from the stainless parts

Thermal gradient can ensure that target fluid near stainless parts is not active



NEXT: PICO- 40L

Various improvements based on the PICO 60 operational experience

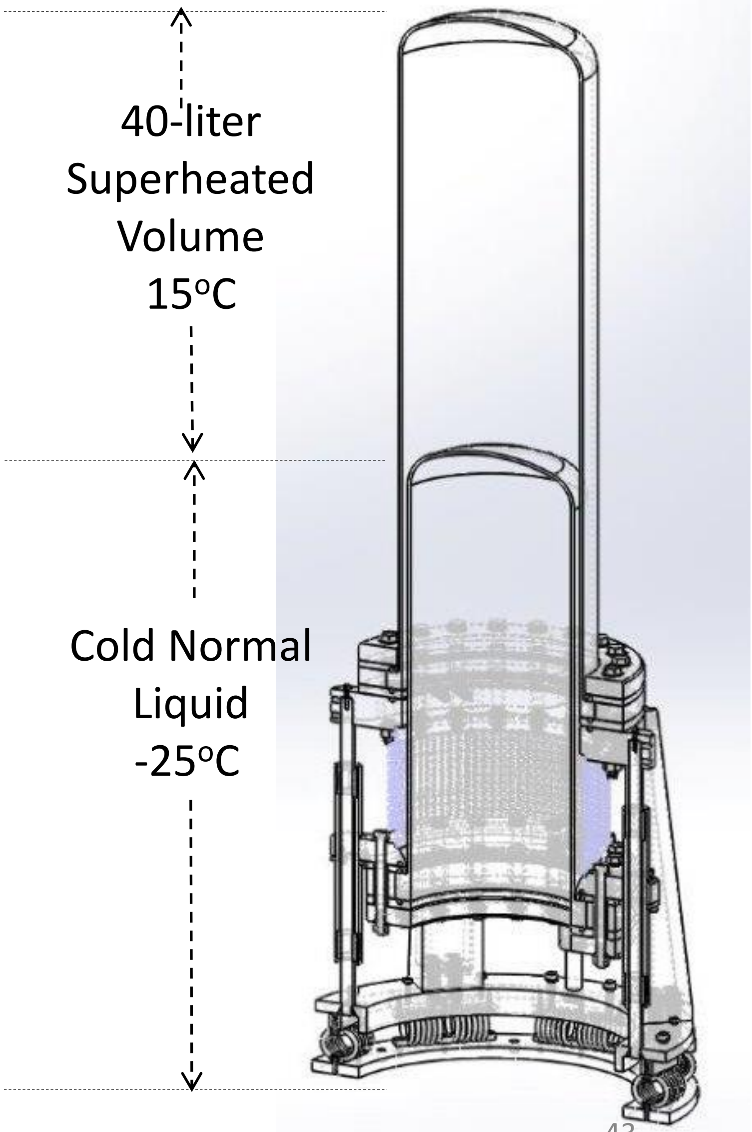
Elimination of any "anomalous" backgrounds

….Background caused by

- Water plus
- Particulates plus
- Surface tension effects

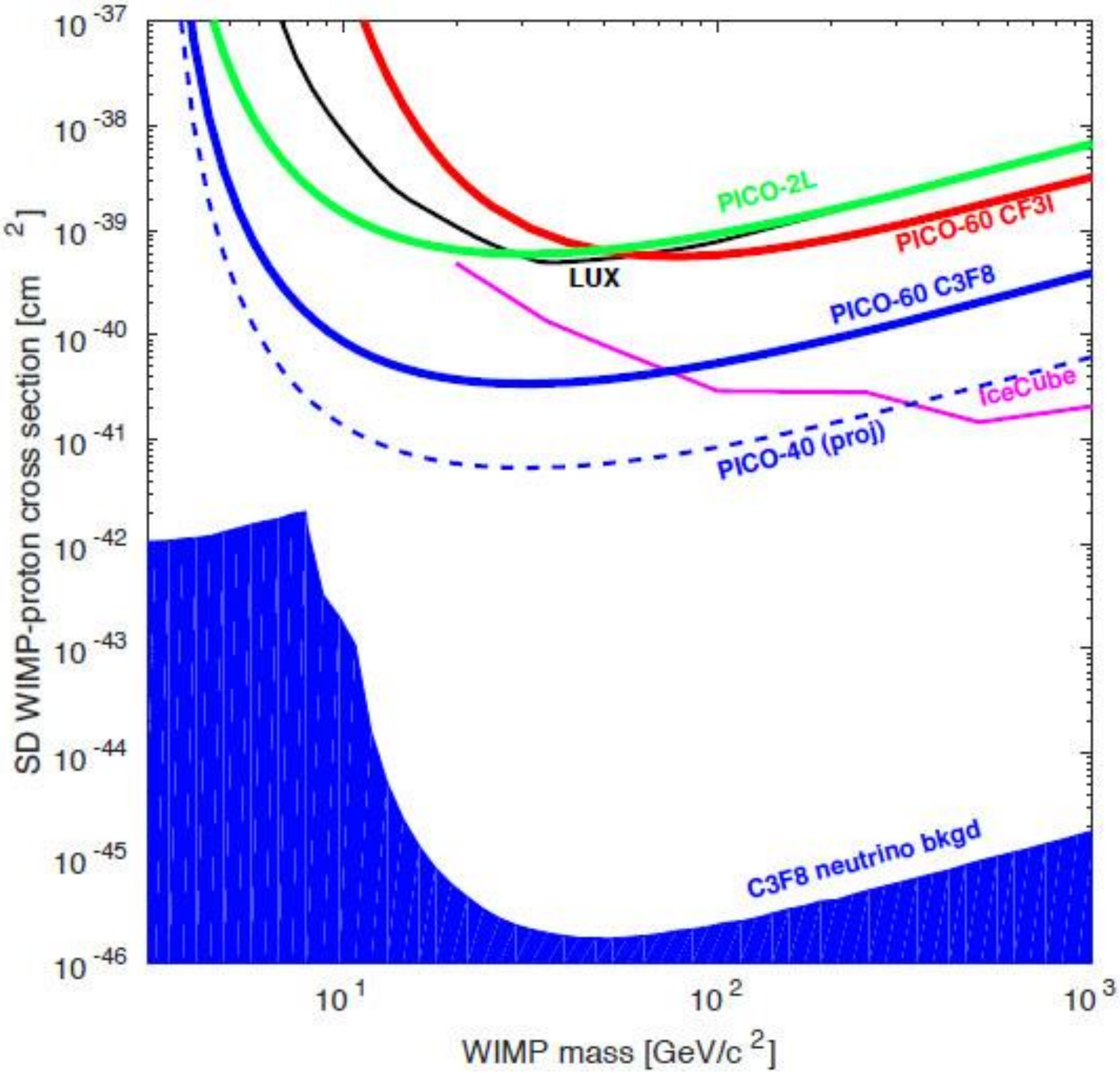
Additional technical benefits

- Full recirculation & in-place purification
- Can operate below 0 °C



NEXT: PICO- 40L

NEXT: PICO - 40L



Assumed 1 year of running with threshold @ 3.2 keV

Prototyping for PICO 500!

...and then PICO 500

PICO

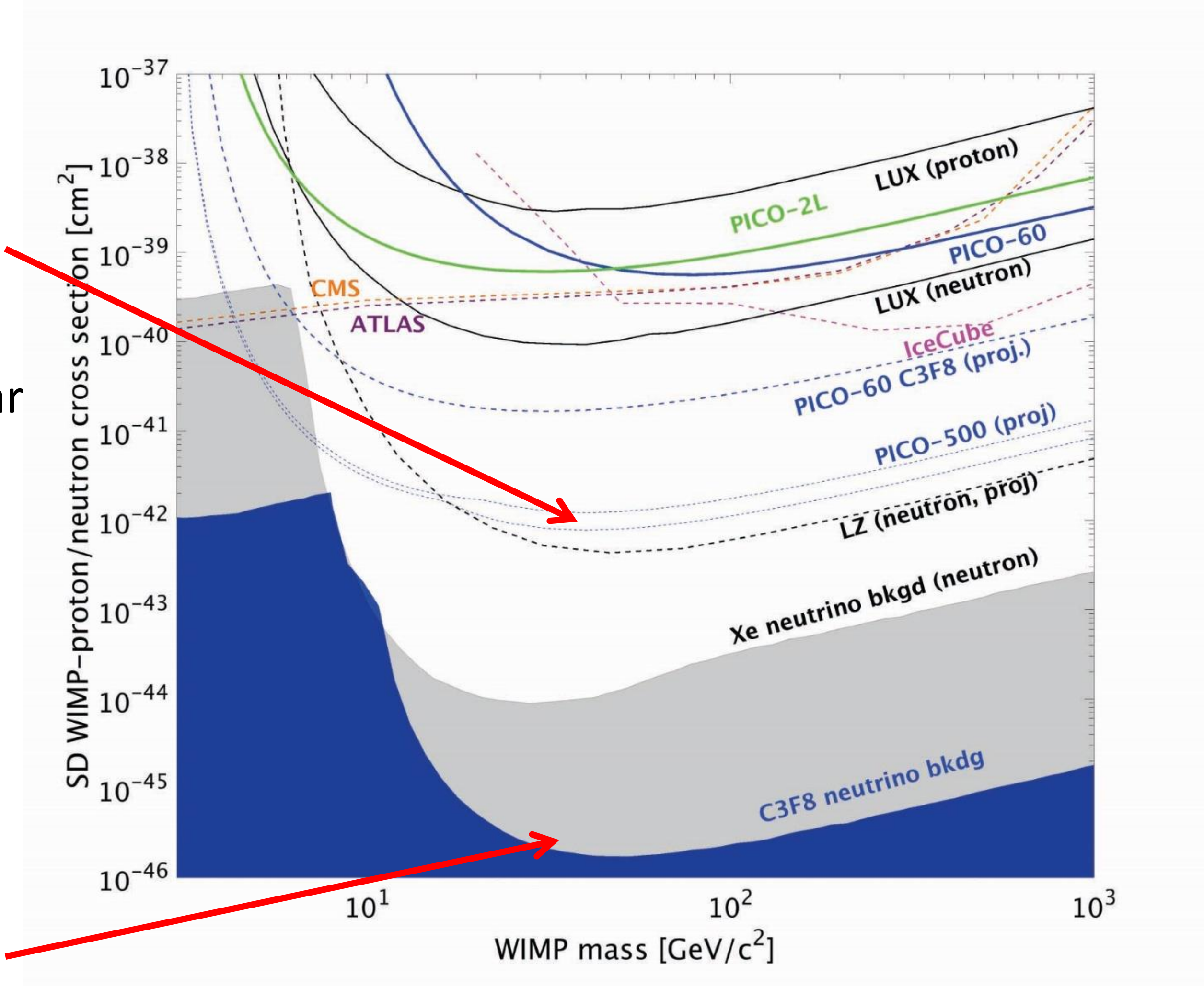
- Active volume 500L C3F8 in synthetic silica vessel
- Design based on PICO 40L concept & engineering
- Location: SNOLAB cube hall
- Funding secured (CFI, provinces, NSF, India Czech Republic)
- Timeline: procurement and first installation 2019

Push SD limit to solar neutrino background!

…and then PICO 500

- Assuming 500 litres C3F8
  1/4 year @ 3keV thresh.
  1/2 year @ 10keV thresh.

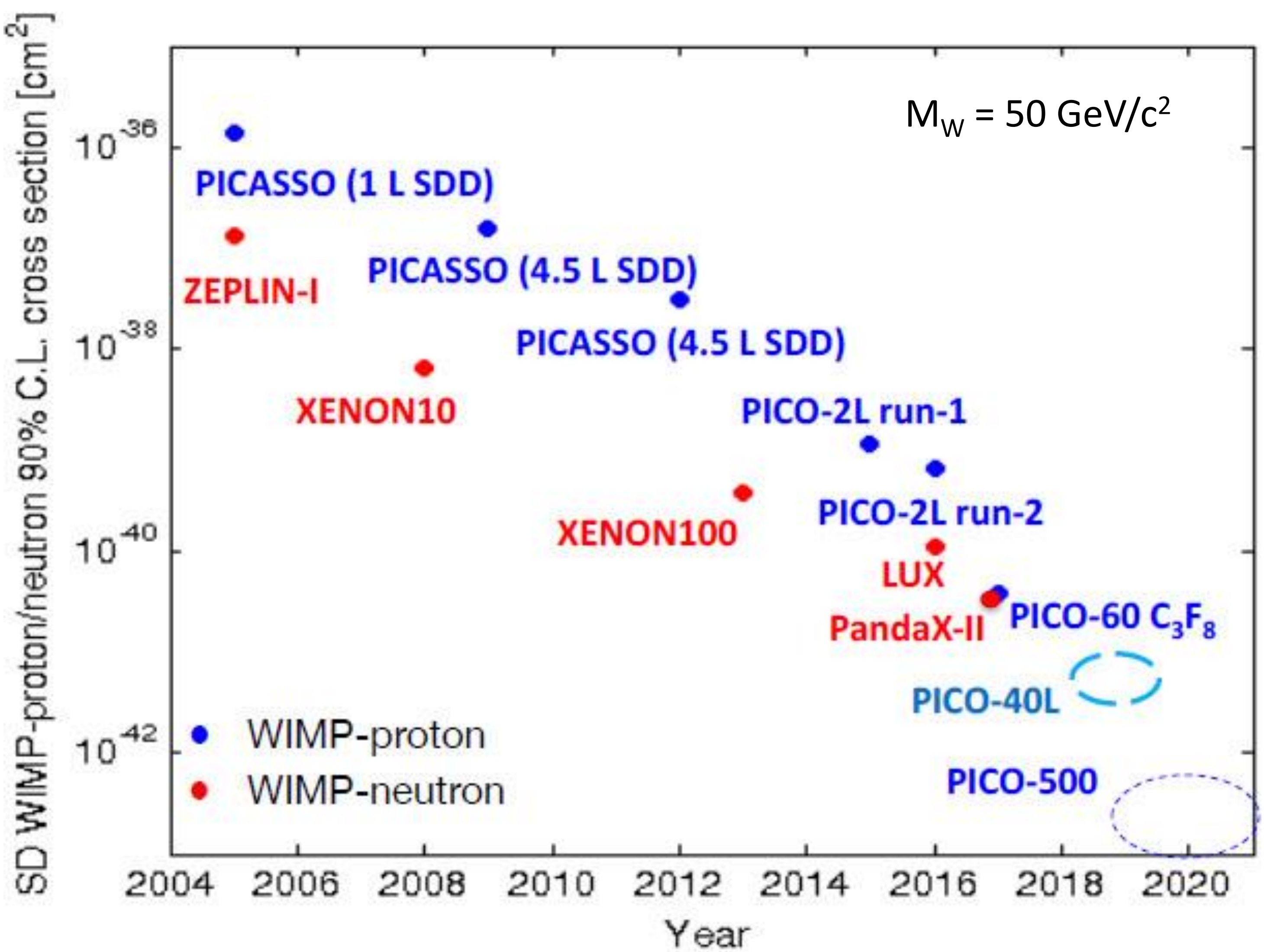
- Expecting <1 neutron/year in the active volume



Lower neutrino floor due to low mass target!

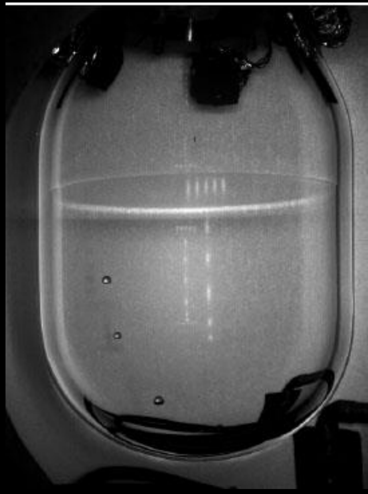
Progress of SHL- Technique

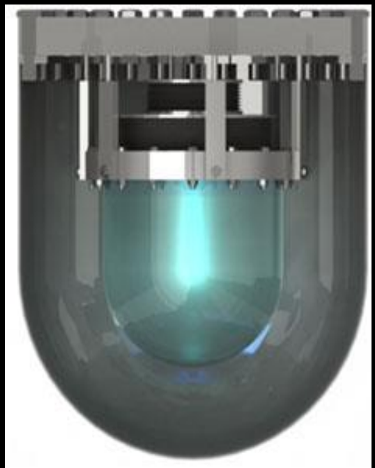
….parallels progress of complementary techniques in SD-sector !

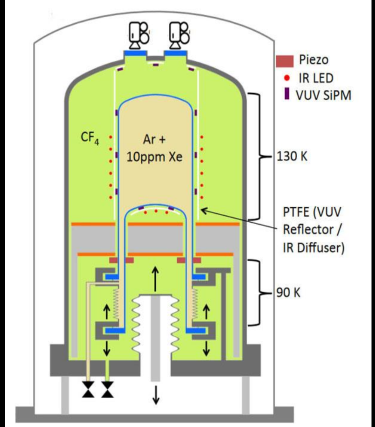


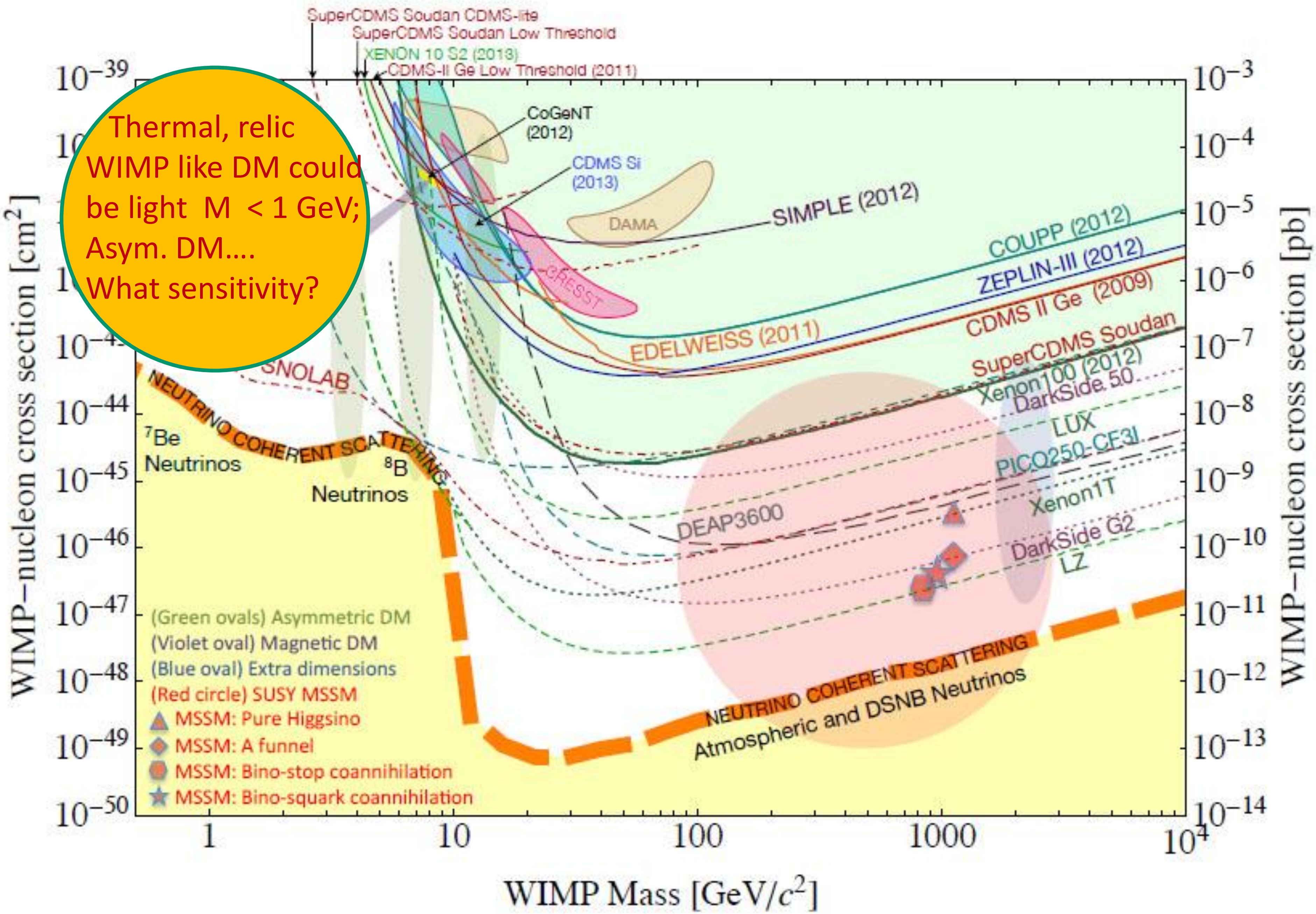
Ongoing R & D with S.H. Liquids

- Extending the low mass frontier
- Towards lower thresholds
- Scintillating bubble chambers
- CEvNS with supernova & reactor ν's



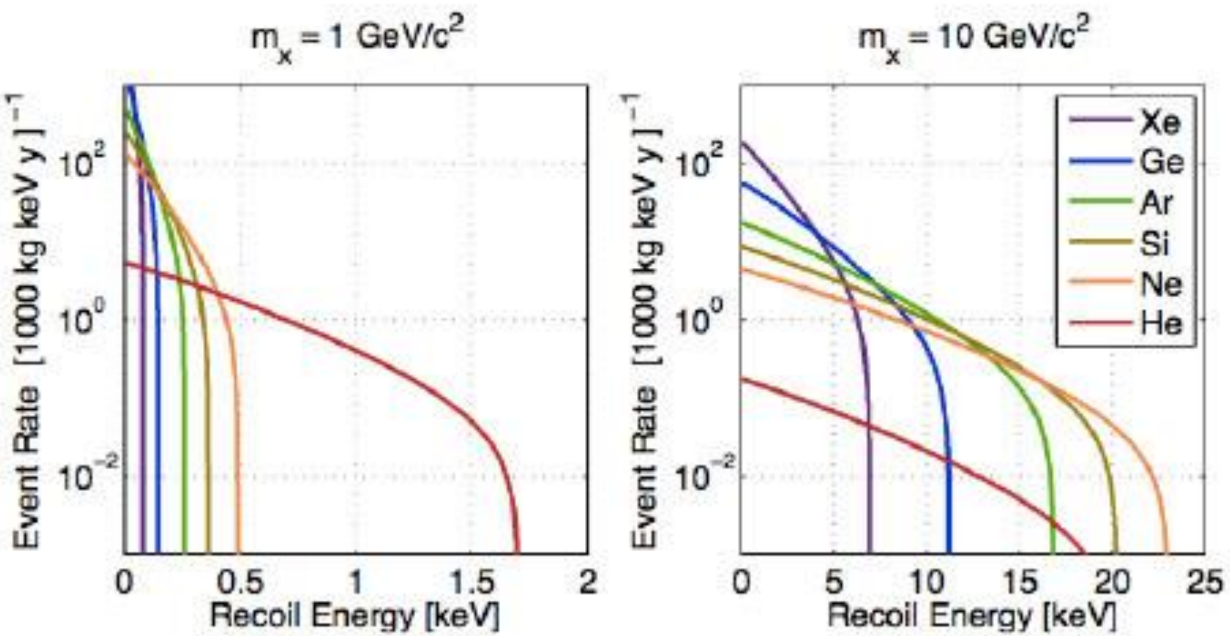






Thermal, relic WIMP like DM could be light M < 1 GeV; Asym. DM…. What sensitivity?
SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
Xenon1T
DEAP3600
DarkSide G2
LZ
SNOLAB
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
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 [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]

The Low Mass WIMP Direct Detection Challenge!



$M_X < 1$ GeV

$v_X \approx 10^{-3}$ c

Need very low mass target → H ?

Need very low threshold → 1 keV ?

Can we do it with PICO ?

H – loaded Fluids in PICO ?

20 $ / kg !

	T_b (^{0}C)	Molec. Weight	Density (g/cm^3)	Remark
$C_2H_2F_4$	**-26.6**	**102**	**1.2**	**@Walmart!**
C2HF5	-48.5	120	1.5	
CH_3CF_3	-47.6	84	1.2	Flammable
NH_3	-33.0	21	0.7	Flammable

P_{op} = 25 PSI
P_V = 159 PSI
T_{op} = 43^0

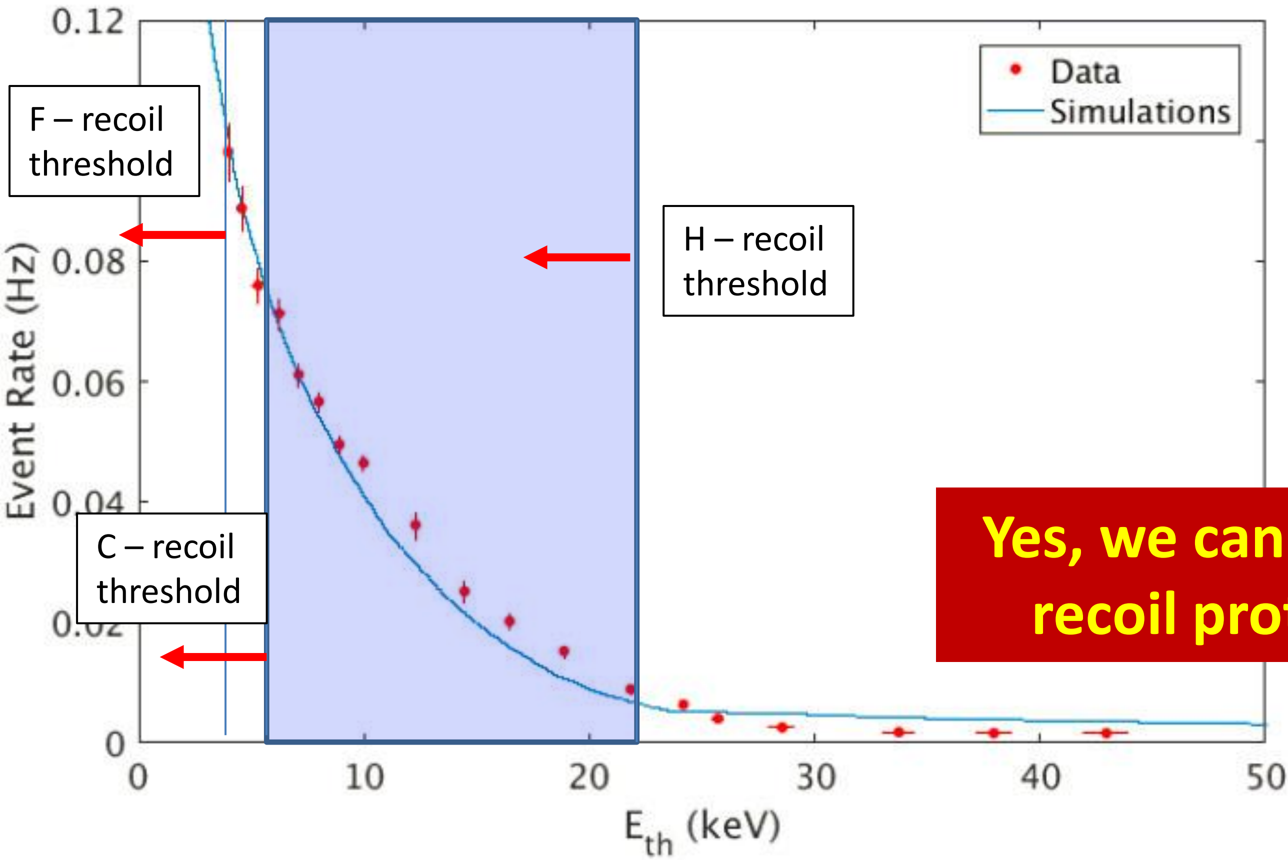
PICO 40L (RSU): 48 kg $C_2H_2F_4$ $\rightarrow$ 1 kg H

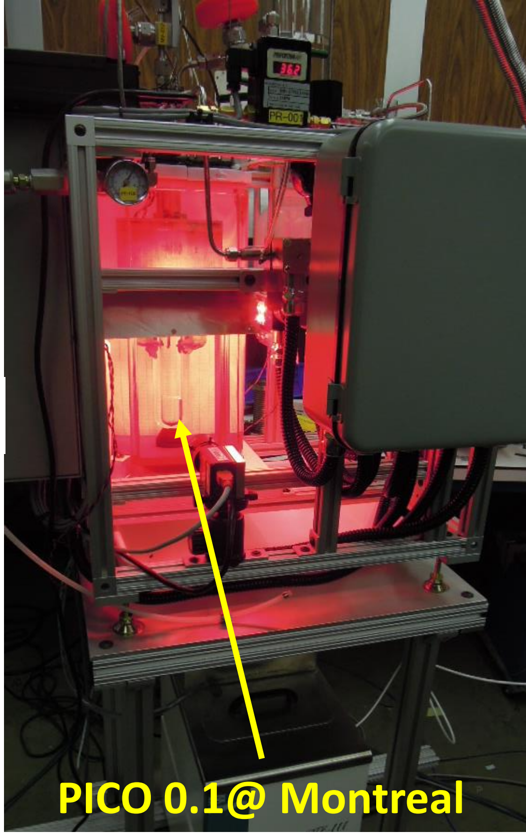
…but can we detect protons?

PICO 0.1 & test beam !

PICO 0.1 Response to ^{124}Sb-Be Neutrons

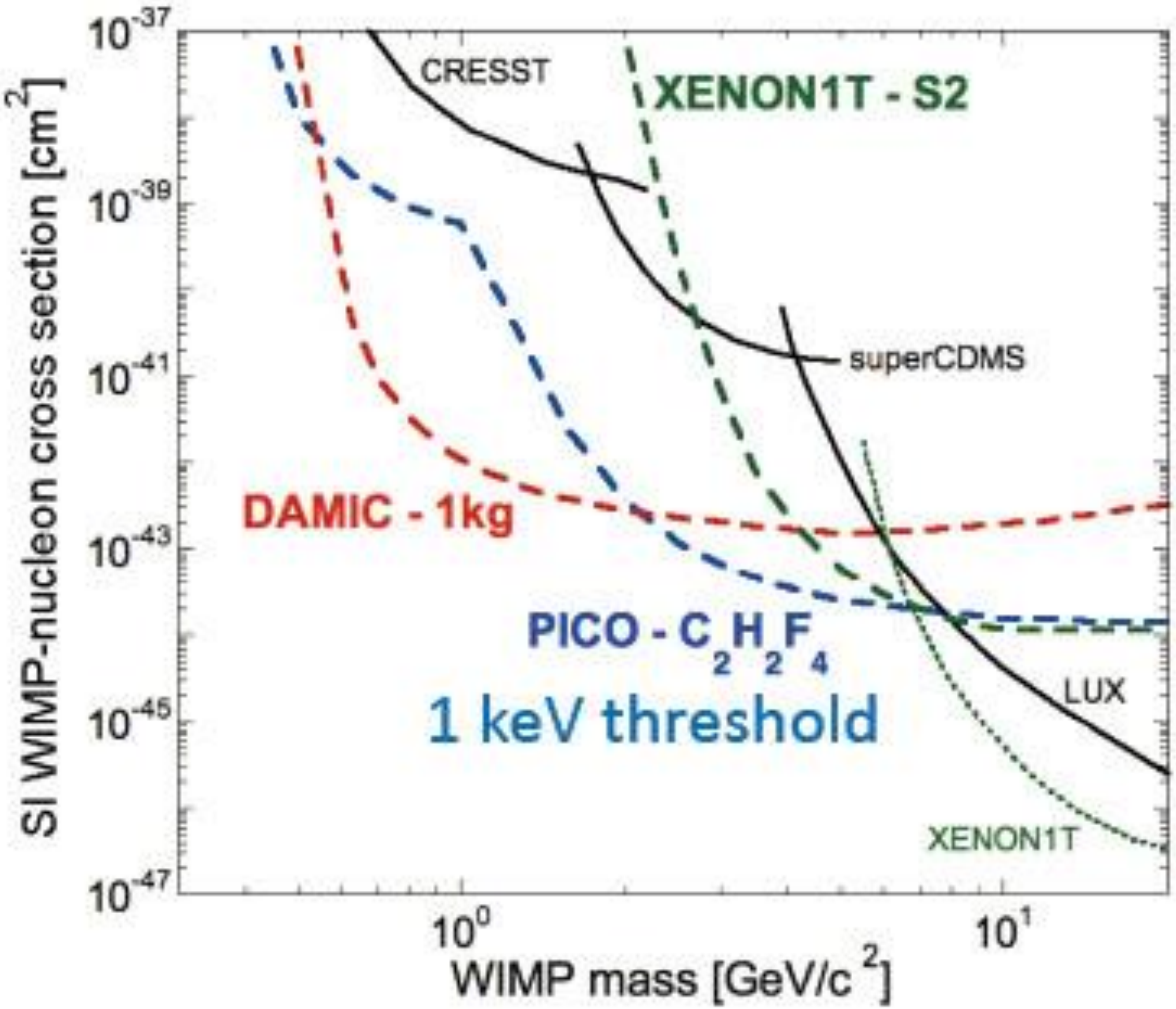
- Use ^{124}SbBe photo n-source: E_n = 23 keV
- ^{124}Sb (~ 700 μC) Polytech Montreal @ Slow Poke reactor





Yes, we can detect recoil protons!

SI- Limits after 100 Days Running PICO 60



Coming Up: The Scintillating Bubble Chamber!

Bubble Chamber

- 10^{-10} discrimination against ER!
- Cannot measure deposited energy

Two-phase liquid scintillation detector

- $\sim 10^{-4}$ discrim. against ER
- Can measure deposited energy!

Combine the technologies!

LXe: 10^{6} improvement in ER discrimination

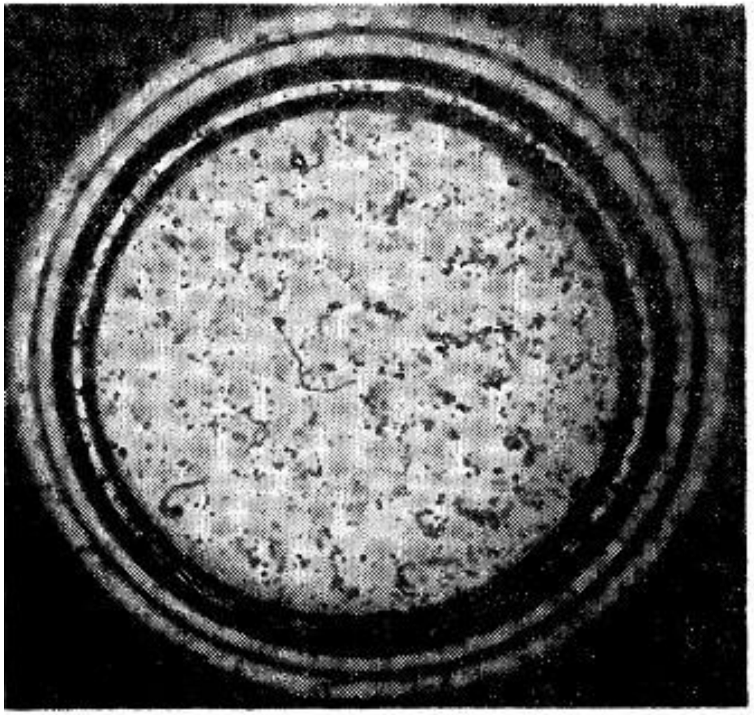
LAr: pulse shape discrimination at higher energies, can achieve low thresholds with coupling to Bubble chamber technology

J. Mock et al, Berkeley Workshop on Dark Matter Detection, June 2015

A quick Step back in History!

Glaser (1956):

- No γ - induced bubbles in pure Xe at E_{th} = 1 keV !
- Bubble formation reappeared by quenching scintillation with 2% ethylene



Phys.Rev. **102**, 586 (1956)

A suspicion:

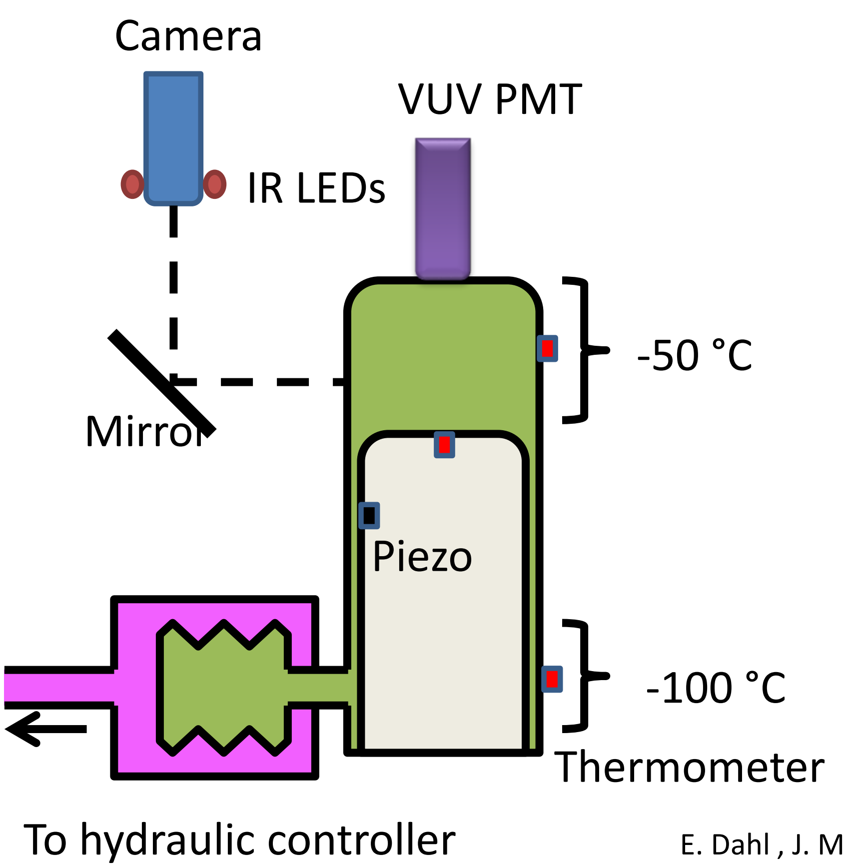
- In mono-atomic liquids ER do not contribute much to heat spike (CM – movement)
- NR however should remain unaffected!

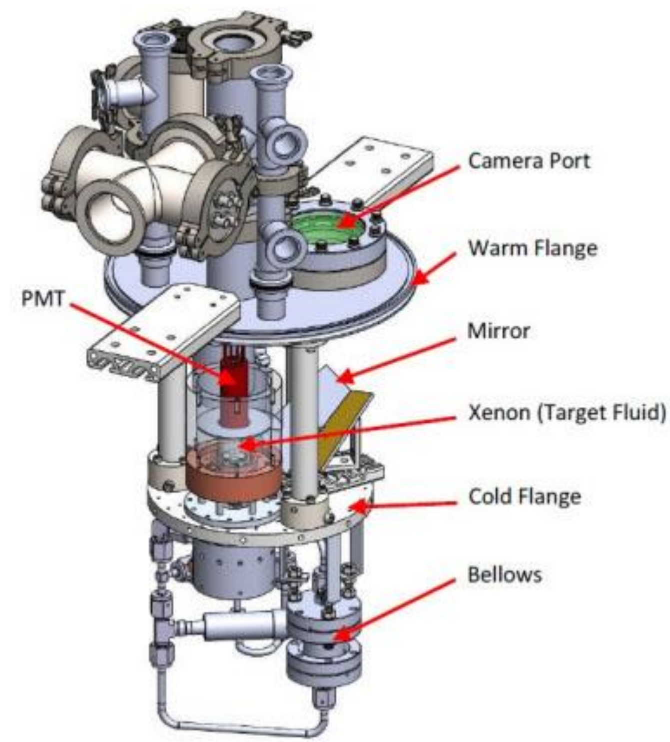
In LAr & LXe sub-kev NR detection possible w/o sensitivity to gammas ??!!

R & D on LXe - Scintillating BC's

NWU PRL 118, 231301

- No buffer fluid - 30 g Xe (RSU)
- VUV PMT collects S1 photons
- Piezo measures acoustic signal





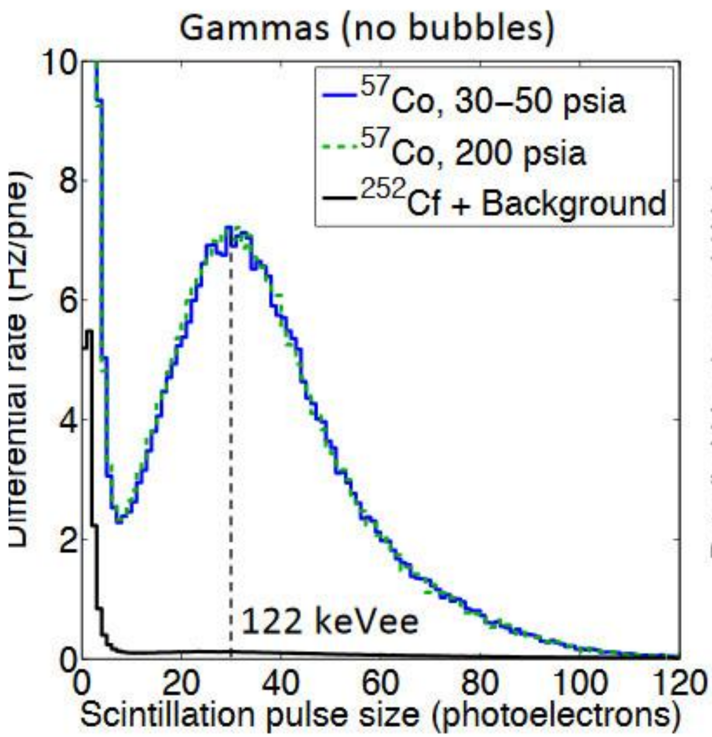
FirstLight January 2017

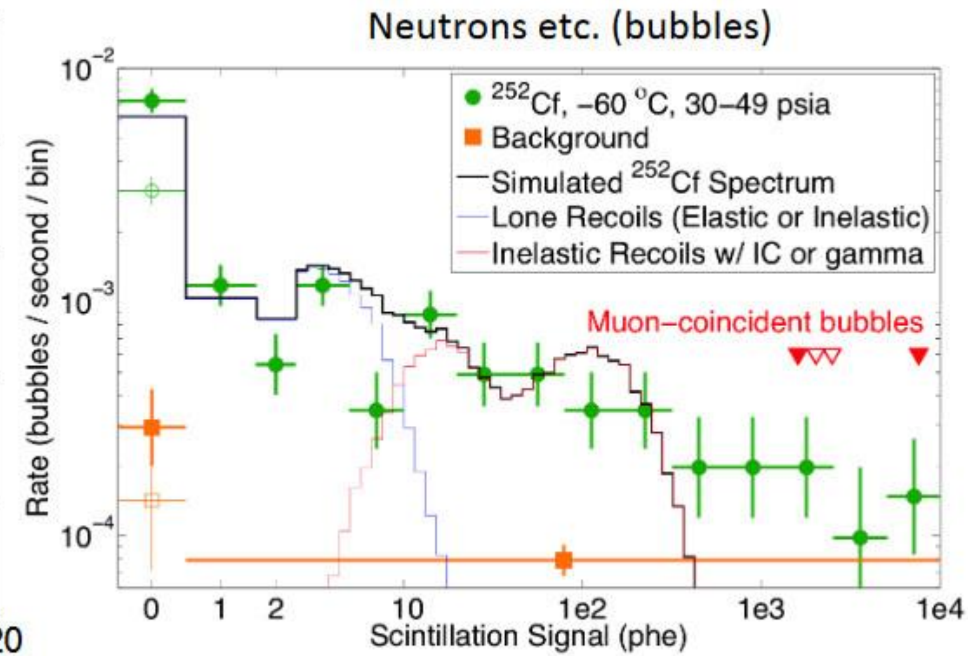
Also U. of Albany arxiv.org/abs/1601.05131v1

E. Dahl , J. Mock, J. Zhang et al, Berkeley Workshop on Dark Matter Detection, June 2015

Scintillation Spectra

NWU. PRL 118, 231301)





- No sign of ER bubble nucleation !!!
- Coincident scintillation and bubble nucleation by nuclear recoils
- 100 eV nuclear recoil thresholds possible?

Glaser was right!

Low threshold operation extremely promising!

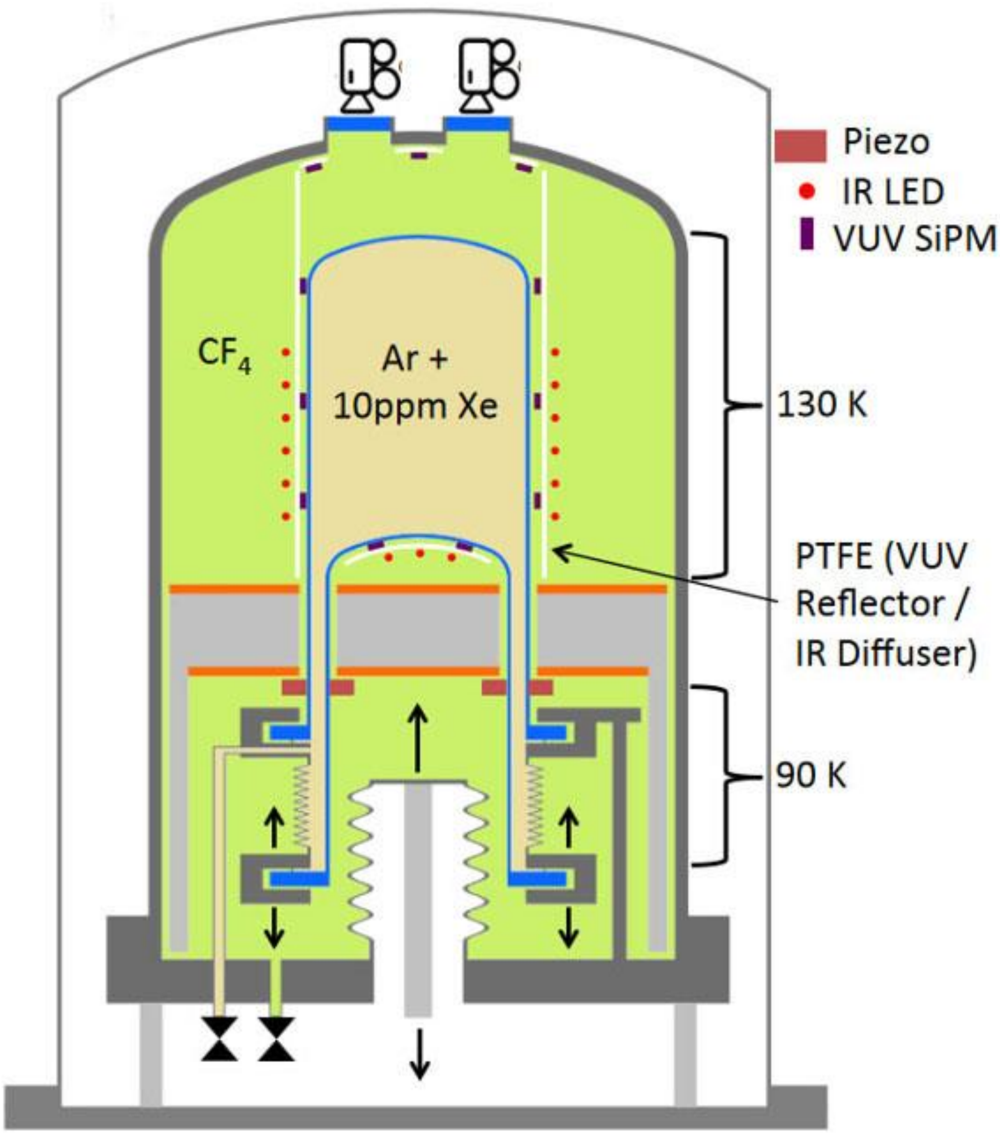
Next: a 10 Kg LAr - SBC (FERMILAB LDRD)

SBC Collaboration:
US: FNAL, Drexel, IUSB, NWU
Canada: Queen's, Alberta (TRIUMF?)
Mexico: UNAM

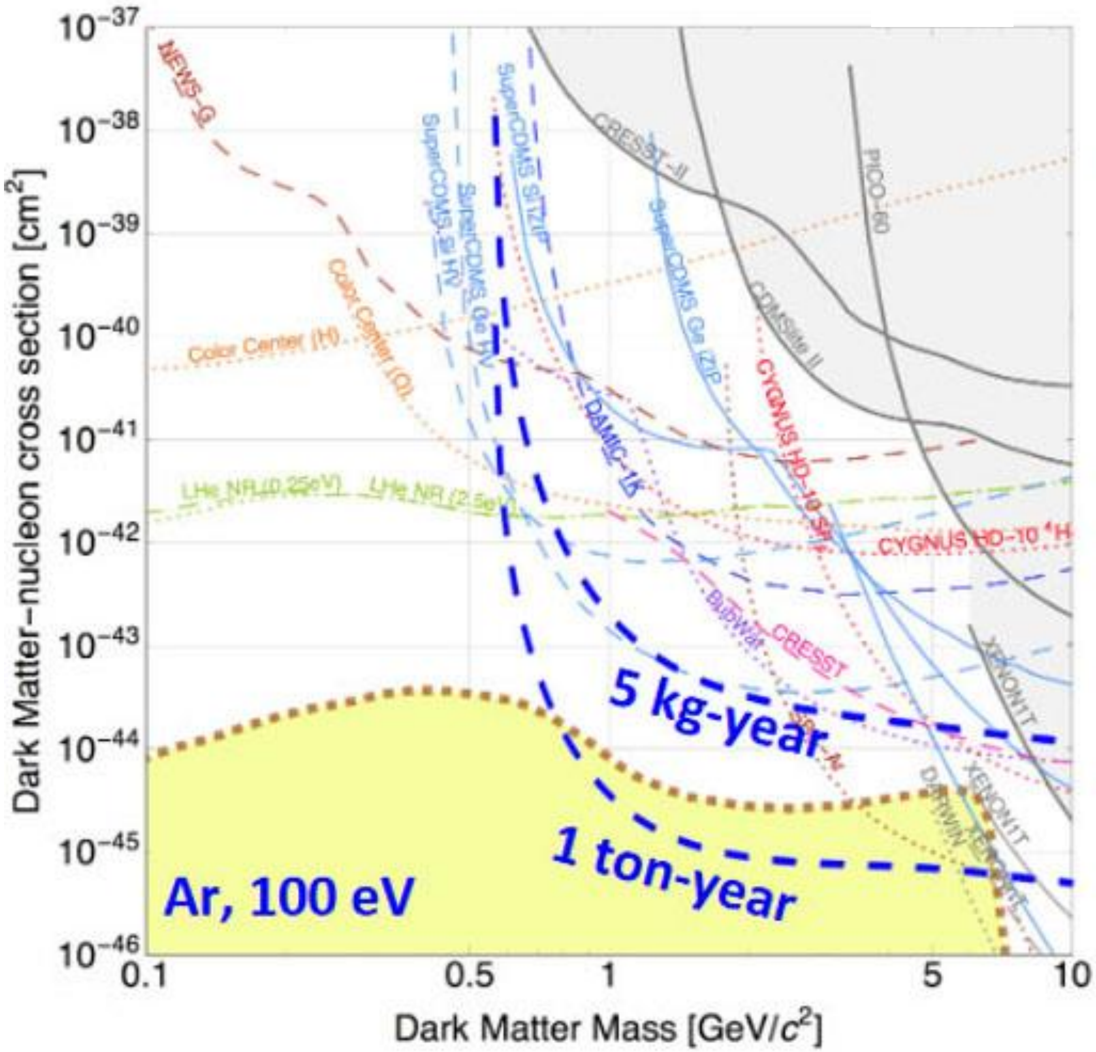
Physics:
GeV WIMPs – reactor CEvNS

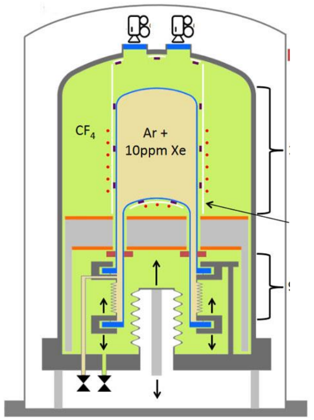
Performance:
100 eV nuclear recoil detection
Background free ton year exposure

Schedule:
FY18 Technical design
FY19/20 Assembly & commissioning at FNAL



Physics Reach with SBC's





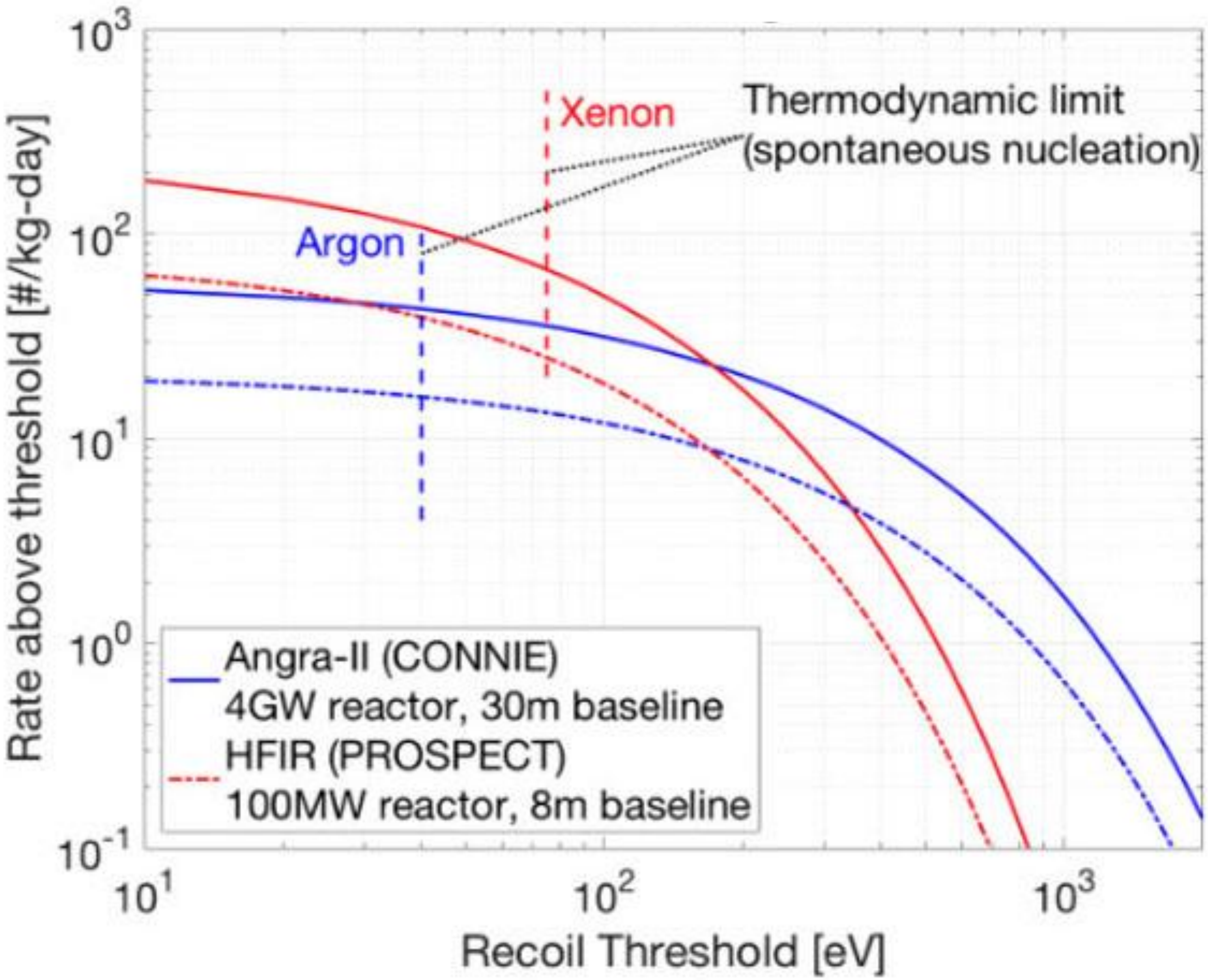
10-kg Lar BC

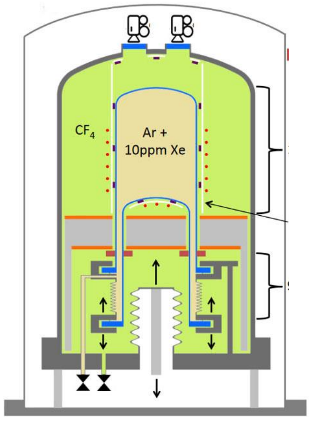
E_{th} = 100 eV

ν – floor (1-7 GeV) in < 1-ton year exposure

R. Neilson, Drexel U.
8/23/2018, DOE-HEP PI

SBC for CEvNS Detection at Reactors





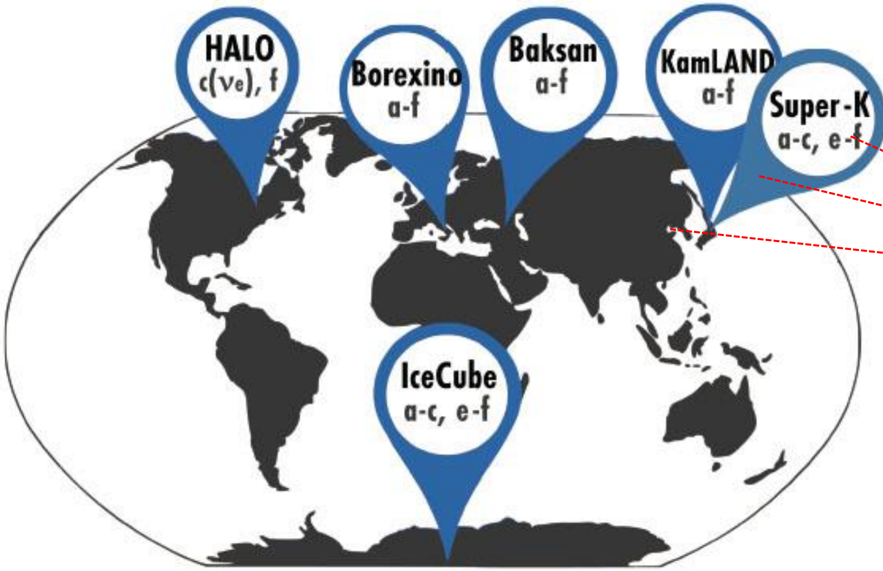
10-kg Lar BC

E_{th} = 100 eV

O(10^6) CEvNS events/ton year @ typical reactor

R. Neilson, Drexel U.
8/23/2018, DOE-HEP PI

Supernova detection via CEvNS with PICO-500 and SBC's



MeV-scale detection thresholds

but…

…a PICO 500 scale detector with E_{th} ~ 1 keV should be sensitive to CEvNS and ν_X

Accessible channels:

a $\bar{\nu}_e + p \rightarrow n + e^+$

b $\nu_e/\bar{\nu}_e + e^- \rightarrow \nu_e/\bar{\nu}_e + e^-$

c $\nu_e/\bar{\nu}_e + A \rightarrow e^{-/+} + B^*$

d $\nu_x + p \rightarrow \nu_x + p$

e $\nu_x + e^- \rightarrow \nu_x + e^-$

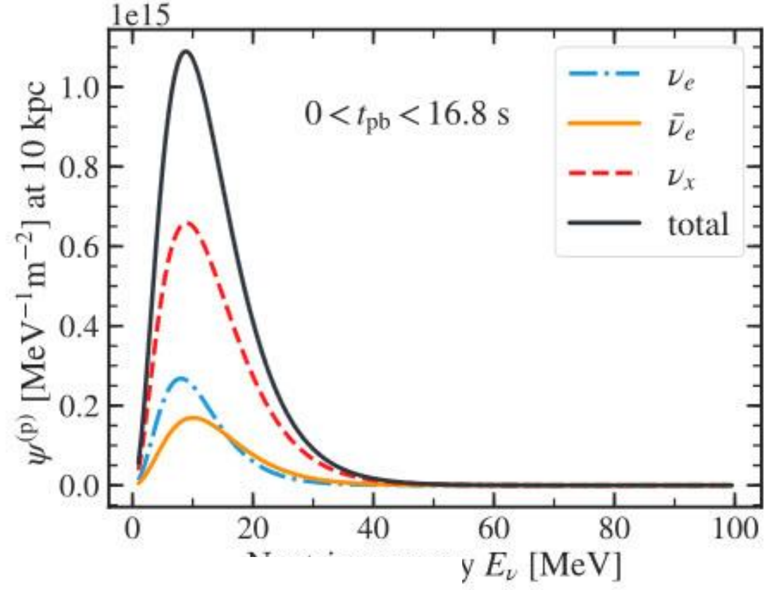
f $\nu_x + A \rightarrow \nu_x + A^*$

…additional info on SN events

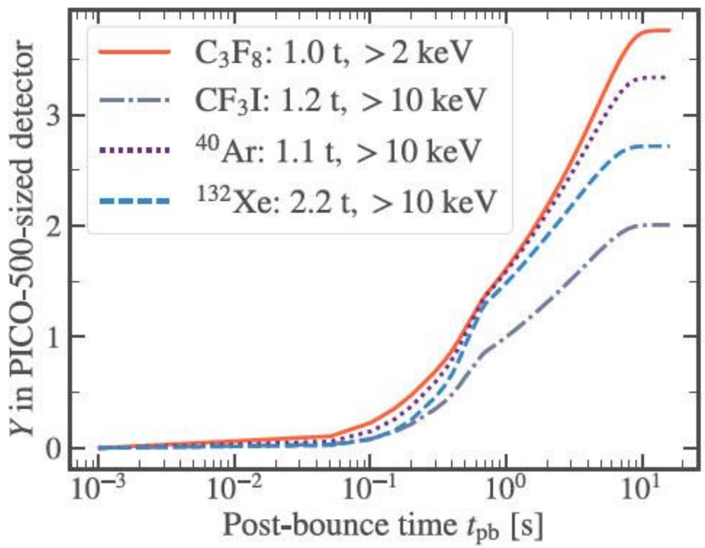
T. Kozynets, S. Fallows, C. Krauss, U. Alberta, PICO Coll. 08-2018

arxiv.org/abs/1806.01417

Supernova detection via CEvNS with PICO-500 and SBC's



- 20 M⊙ progenitor located at 10 kpc distance from the Earth
- ~ 50% of E_{tot} emitted in first 2-3 s



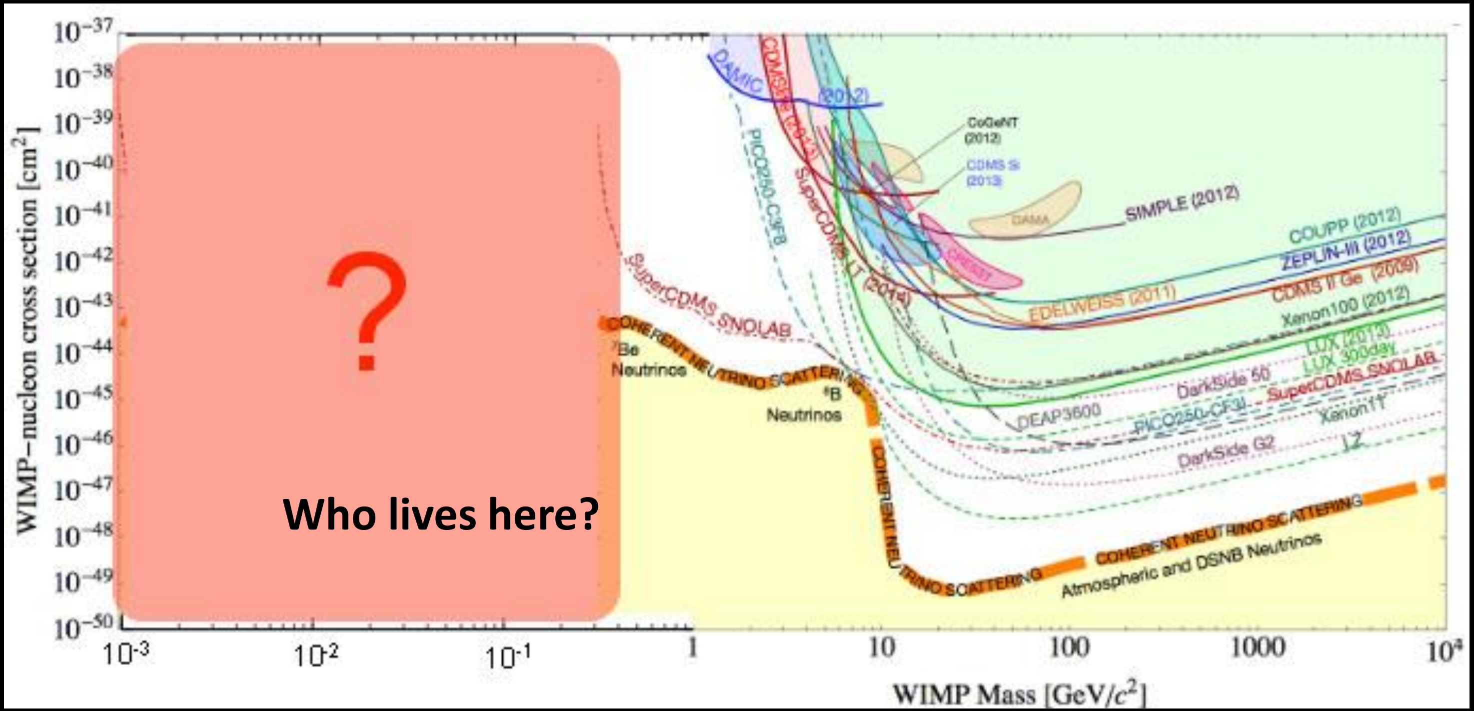
Prove of principle: multi – bubble events observed w/in 2.5 sec window in test chamber (U. Chicago)

T. Kozynets, S. Fallows, C. Krauss, U. Alberta, PICO Coll. 08-2018

arxiv.org/abs/1806.01417

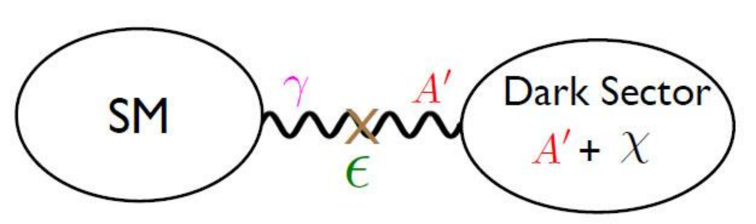
Boehm, Fayet; Pospelov, Ritz, Voloshin; Batell, Pospelov, Ritz; Lin, Yu, Zurek; Izaguirre, Krnjaic, Schuster, Toro; …

Moving Beyond the Standard WIMP …



- Actually sub - GeV Dark Matter well motivated !!!
- Interaction with ord. matter by “dark force” *A‘*
- Gauge boson *A‘* which mixes kinetically with γ
- Light vector mediator decays to low mass WIMPs

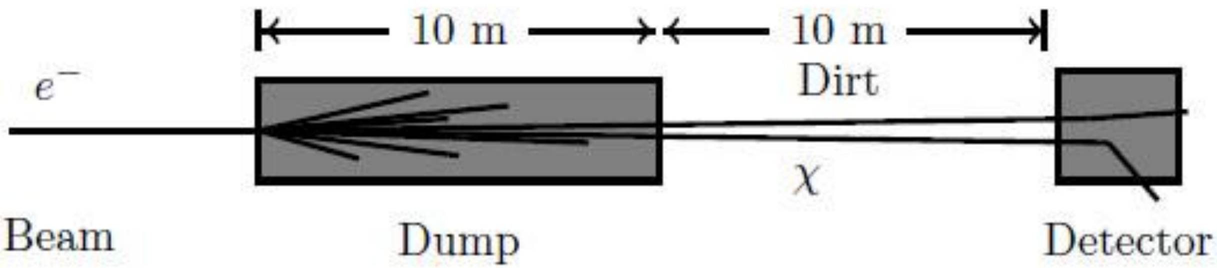
R. Essig, Berkeley WS 2015



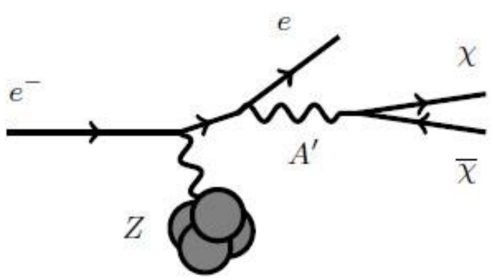
Search For DM in the Dumps!

Example: BDX

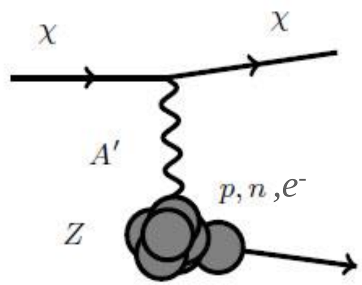
- Production of a DM beam @ CEBAF / Jefferson Lab
- 11 GeV electron beam, 100 μA



Production



Detection:



...complemented by searches for dark mediators/photons

Dark Light, DAEDALUS, SHiP, MESA, LDMX, Earlier LSND, BaBar, MiniBoone, E137, complemented by searches for dark photons

A 6.8σ Evidence for a New 17 MeV Boson?

PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta

Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

Nikhef National Institute for Subatomic

CERN, CH-1211 Geneva 23, Switzerland and Insti

P.O. Bo

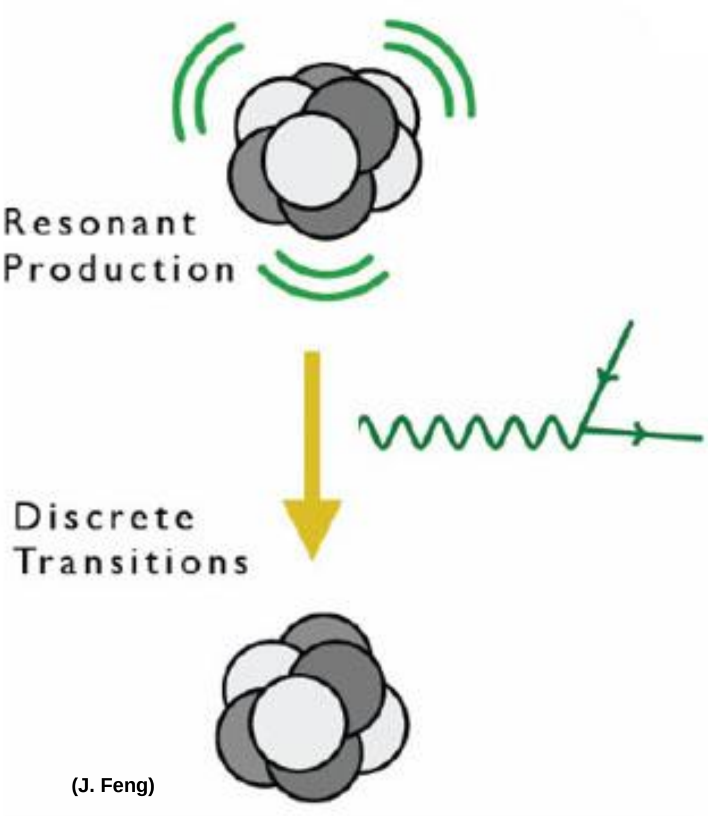
(Received 7 A

not have a nuclear physics related origin.

The deviation observed at the bombarding energy of $E_p = 1.10$ MeV and at $\Theta \approx 140°$ has a significance of 6.8 standard deviations, corresponding to a background fluctuation probability of 5.6×10^{-12}. On resonance, the $M1$ contribution should be even larger, so the background

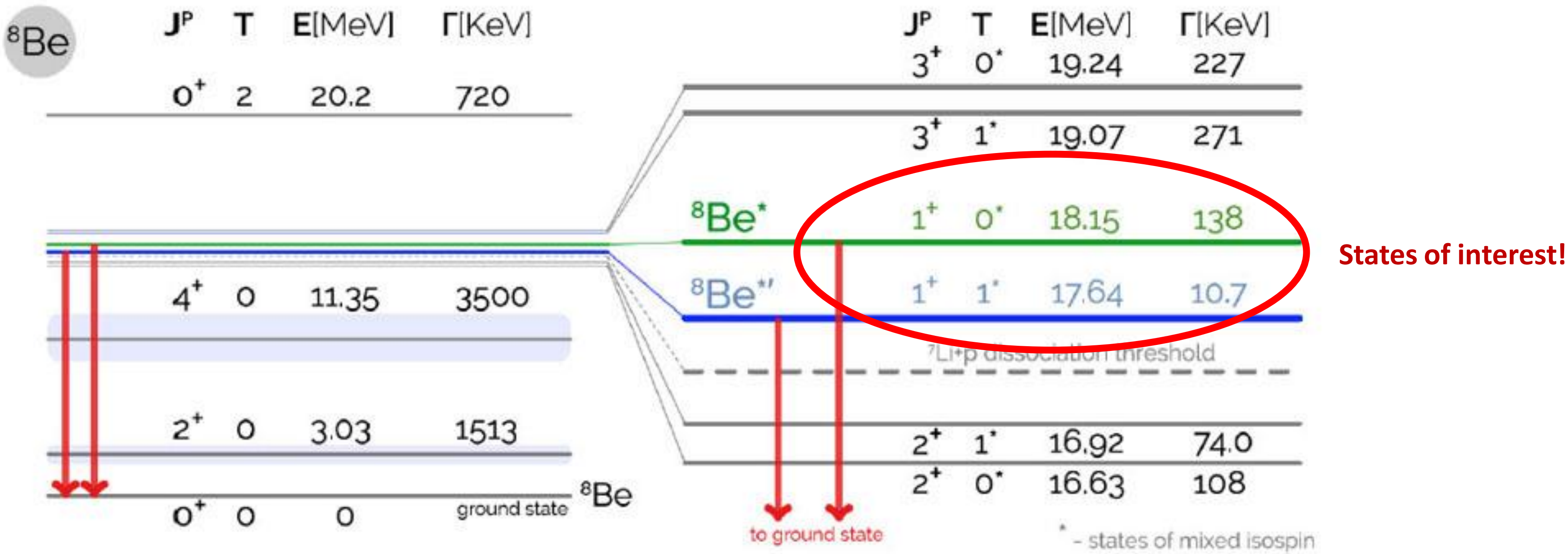
Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV/c^2 and $J^\pi = 1^+$ was created.

^{8}Be* - A New Particle Physics Lab!



- ^{8}Be* composed of 4 neutrons and 4 protons
- Resonant production via p + ^{7}Li → ^{8}Be*
- Large production rate → high statistics
- Excited states decay to ground state with large transition energies (~ 20 MeV)

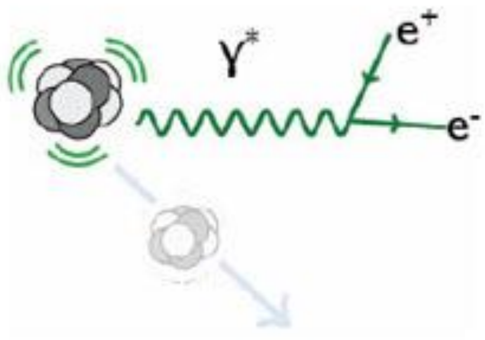
$^8Be^*$ - Decay Scheme



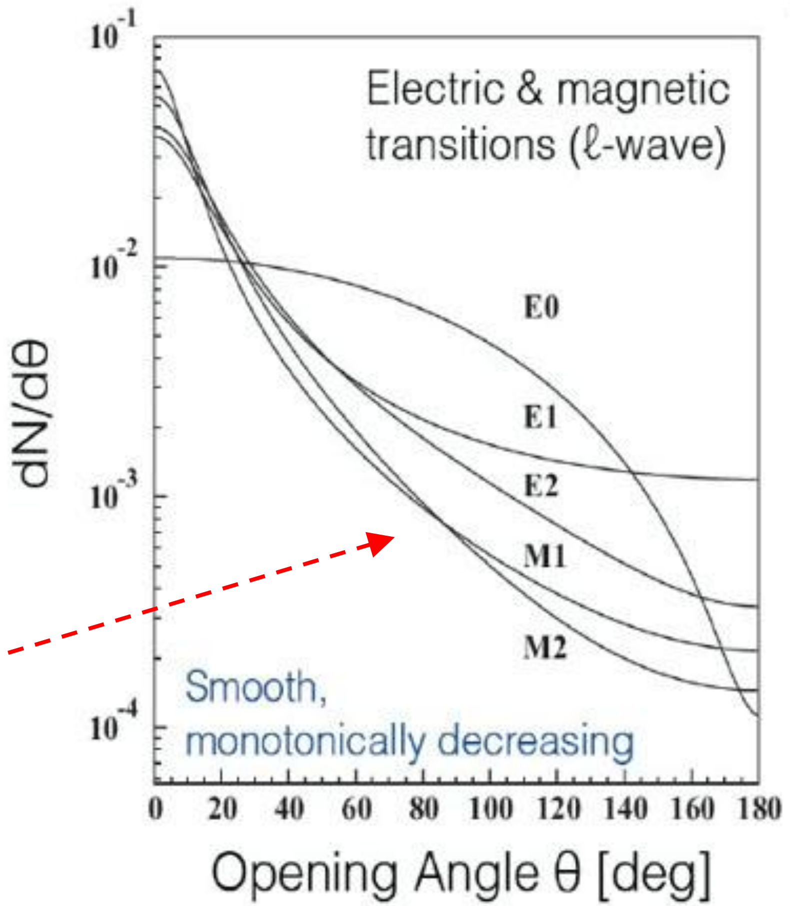
1609.07411; based on Tilley et al. (2004); National Nuclear Data Center, http://www.nndc.bnl.gov/nudat2/

(J. Feng)

^{8}Be* - Decay and Internal Pair Creation (IPC)

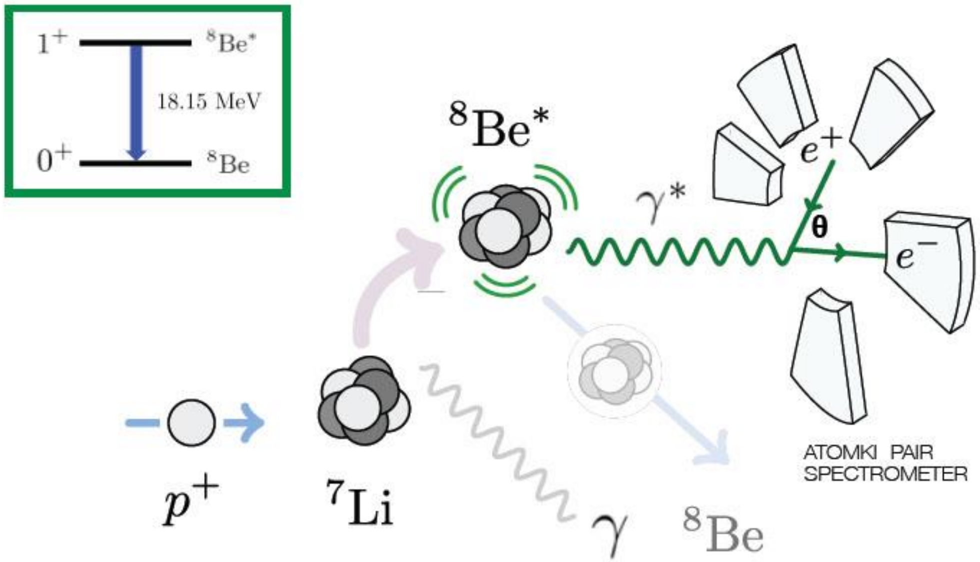


- Branching ratio: B (^{8}Be → e^+e^-) ≈ 5.5 x 10^{-8}
- dN/dθ decreases steadily with increasing θ



Gulyas et al.; http://arxiv.org/abs/1504.00489v1

The ATOMKI ^{8}Be - Experiment



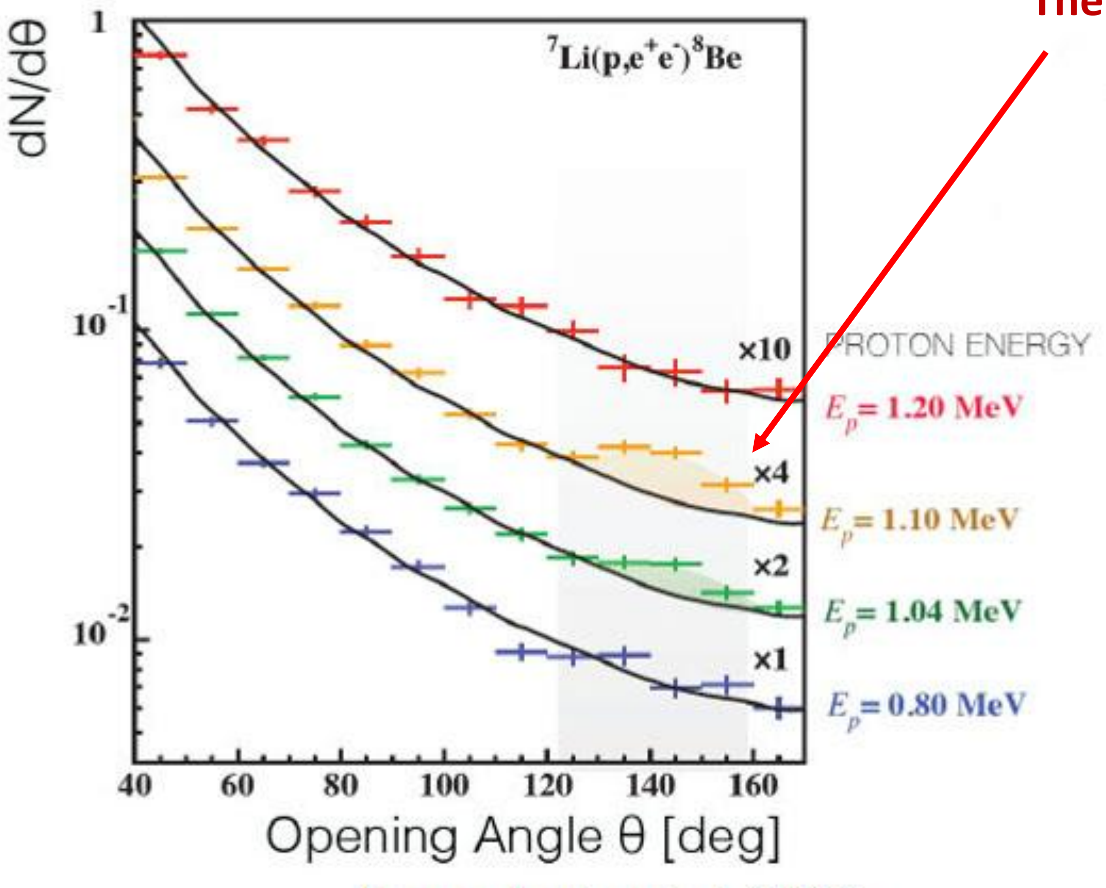
(J. Feng)

- Excited states of ^{8}Be produced through p +^{7}Li - reaction with high statistics
- Beam energy around 1 MeV adjusted to select various resonances
- Measure angular distribution of e^+e^- pairs

Perfect environment to search for new MeV-scale physics!

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501, arXiv:1504.01527 [nucl-ex].

The ATOMKI ^{8}Be - Experiment

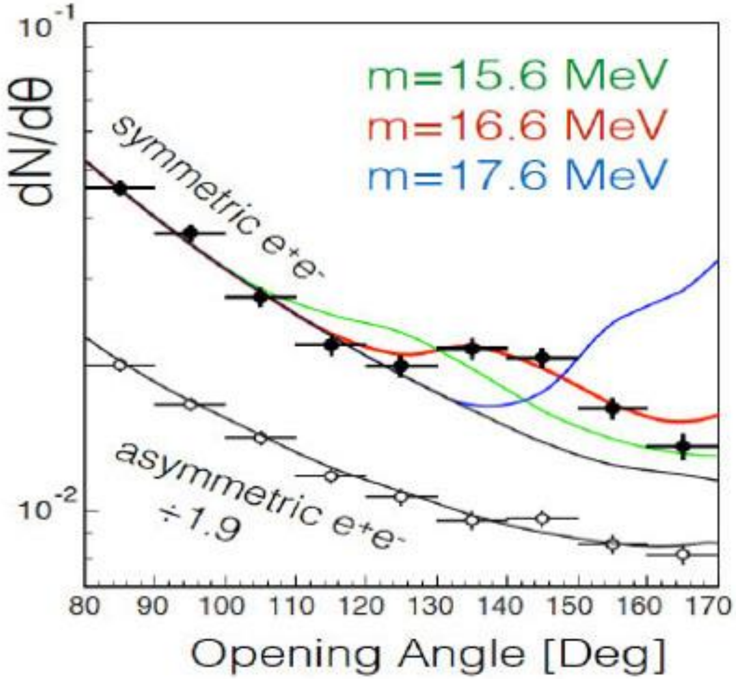


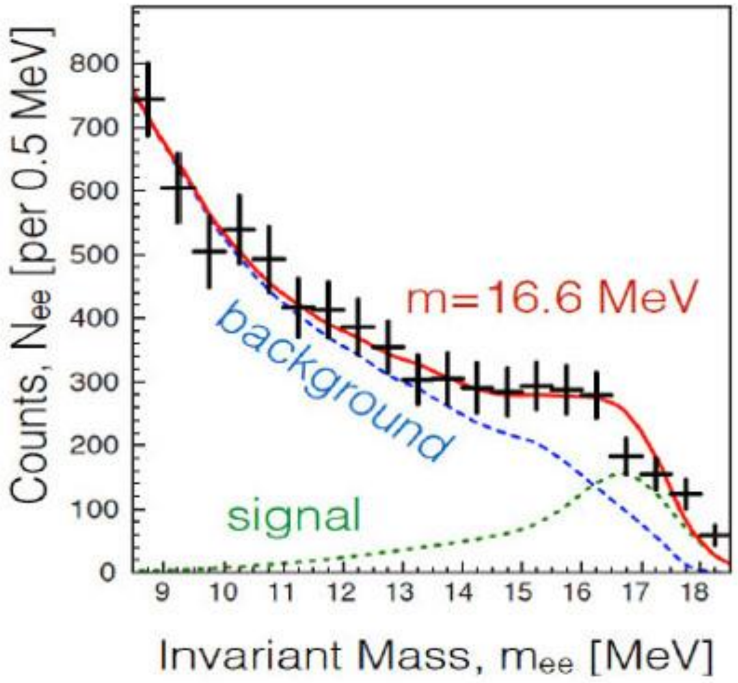
The Anomaly!

- Excess around θ = 140° passing through 18 MeV ^{8}Be*resonance
- Probability for backg. fluctuation: 5.6×10^{-12} (6.8σ)

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501

The ATOMKI ^{8}Be - Experiment



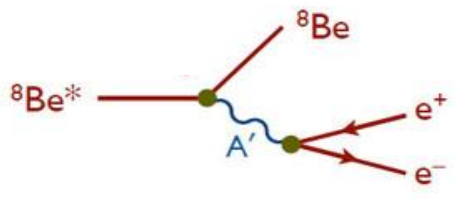


Opening angle and invariant mass consistent with decay of new particle with $J^\pi = 1^+$

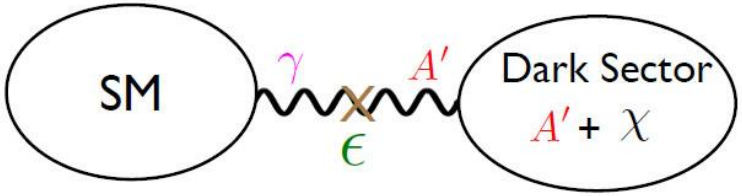
M_X = 16.7 ± 0.35 (stat) ± 0.5 (sys) MeV χ^2/dof = 1.07

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501

Maybe a Dark Photon *A'* ?

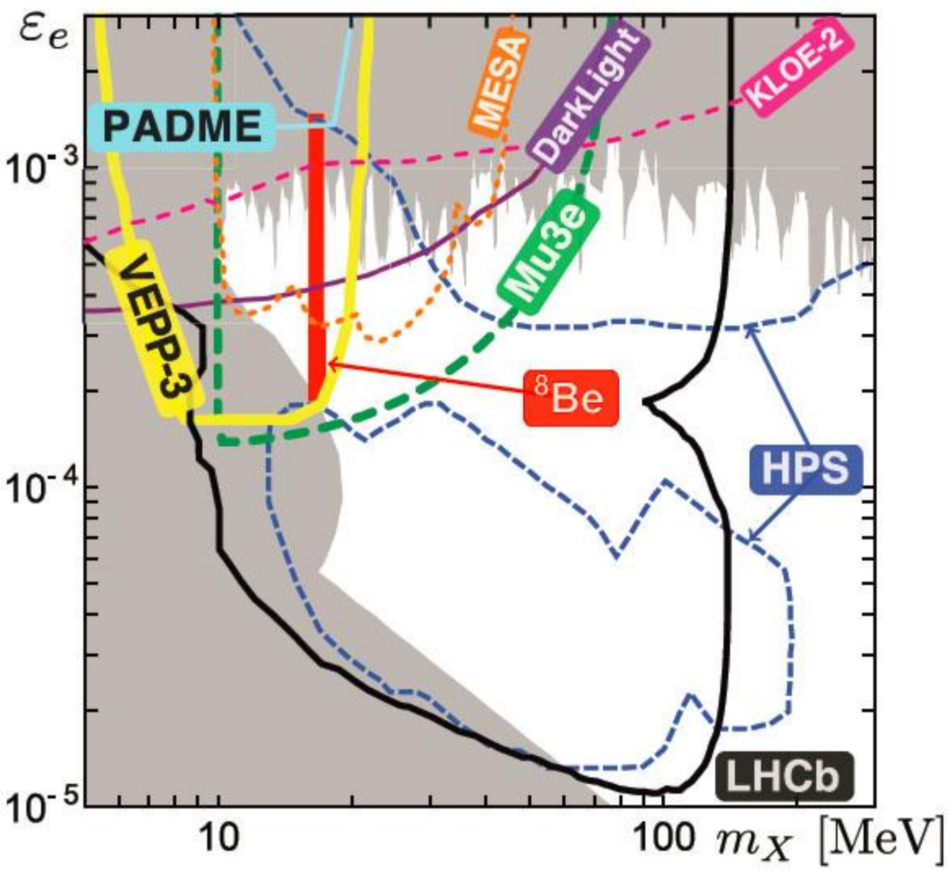


- Interaction with ord. matter mediated by "dark force" *A'*
- Gauge boson *A'* mixes kinetically with γ and **$\varepsilon \sim 10^{-3}$**
- *A'* couples to SM – particles prop. to **ε** and SM charges
- Light vector mediator decays to low mass WIMPs



Prameter Space for Dark Photons limited….but

…bounds, especially $\pi^0 \rightarrow \gamma X$ (NA48/2) can be fine - tuned away!



The ^{8}Be anomaly can be explained by a “proto-phobic” vector gauge boson with:

Range ≈ 200 fm

$$\varepsilon_u \approx \pm 3.7 \times 10^{-3}$$

$$\varepsilon_d \approx \mp 7.4 \times 10^{-3}$$

$$\sqrt{\varepsilon_e \varepsilon_\nu} \leq 7 \times 10^{-5}$$

$$2 \times 10^{-4} \leq |\varepsilon_e| \leq 10^{-3}$$

These lepton couplings could also resolve the (g_μ– 2) anomaly!

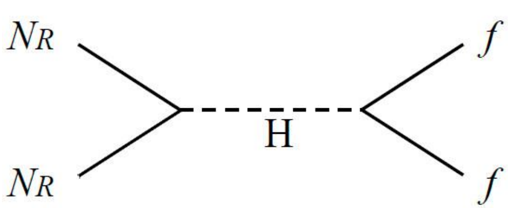
Near future checks: Mu3e, LHCb (2021), Darklight II, VEPP3, Darklight, MESA…

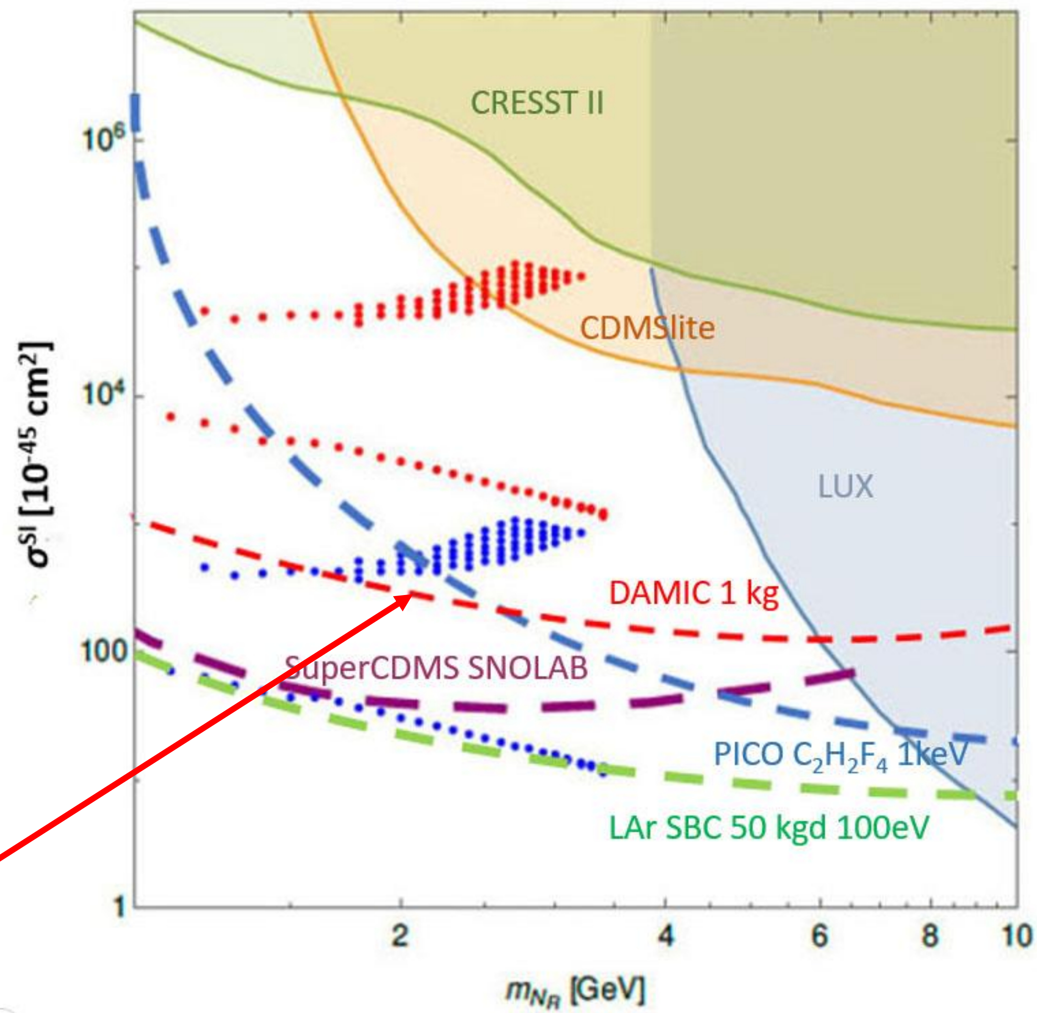
J. L. Feng, *Phys. Rev.* **D95** no. 3, (2017) 035017, arXiv:1608.03591 [hep-ph].

Model Building and Implications for DM Searches

One of many examples…

- Gauged $U(1)_{B-L}$ symm. with Z_2 parity
- Radiative see - saw for RH-M $\nu's$
- RH - ν masses ~ GeV
- 16 MeV X- gauge vector boson ($^8Be^*$)
- RH $\nu's$ are DM w. relic abundance ok





SI - X-sections in reach of PICO, DAMIC et al.

O. Seto, T. Shimonura (arxiv. 1610.08112)

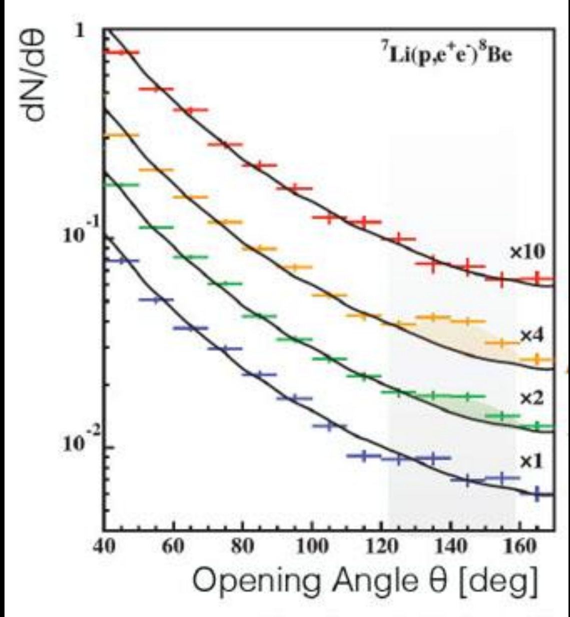
Checking the ^{8}Be Anomaly

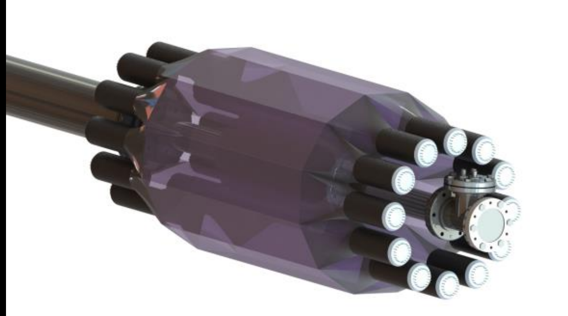
U. Montreal, Laurentian U., UBC, CTU Prague, U. Mainz

- Confirm/refute ATOMKI result
- Improve statistics, angular & energy resolution
- Extend to other nuclei: ^{10}B (19.3), ^{10}Be (17.8)… ?
- Later improved search wit HPGe detectors ?

Other efforts:

- ATOMKI upgrade with double sided Si-strip detectors
- Orsay Tandem: preliminary tests ongoing
- Purdue U., HPGe + Si strip detectors (?)





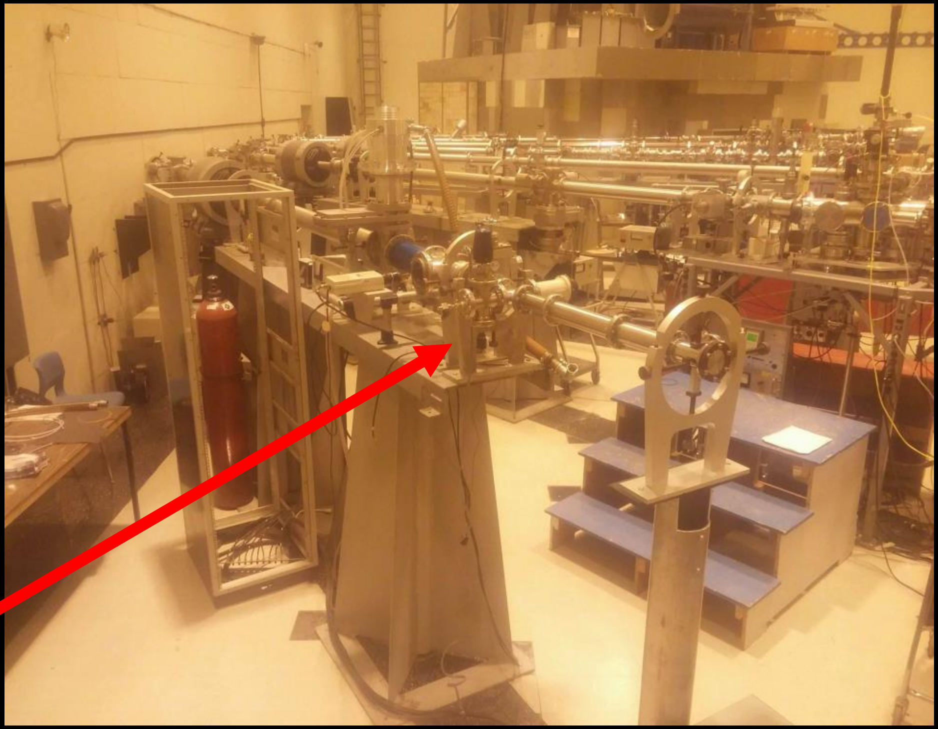
Checking the ^{8}Be Anomaly

U. Montreal – Laurentian U. – UBC - CTU Prague - U. Mainz

Montréal UdeM
6 MeV Tandem
Van de
Graaff Facility

E - resolution ok for
$E_p > 1$ MeV

Dedicated Beam Line
for ^{8}Be –project ready

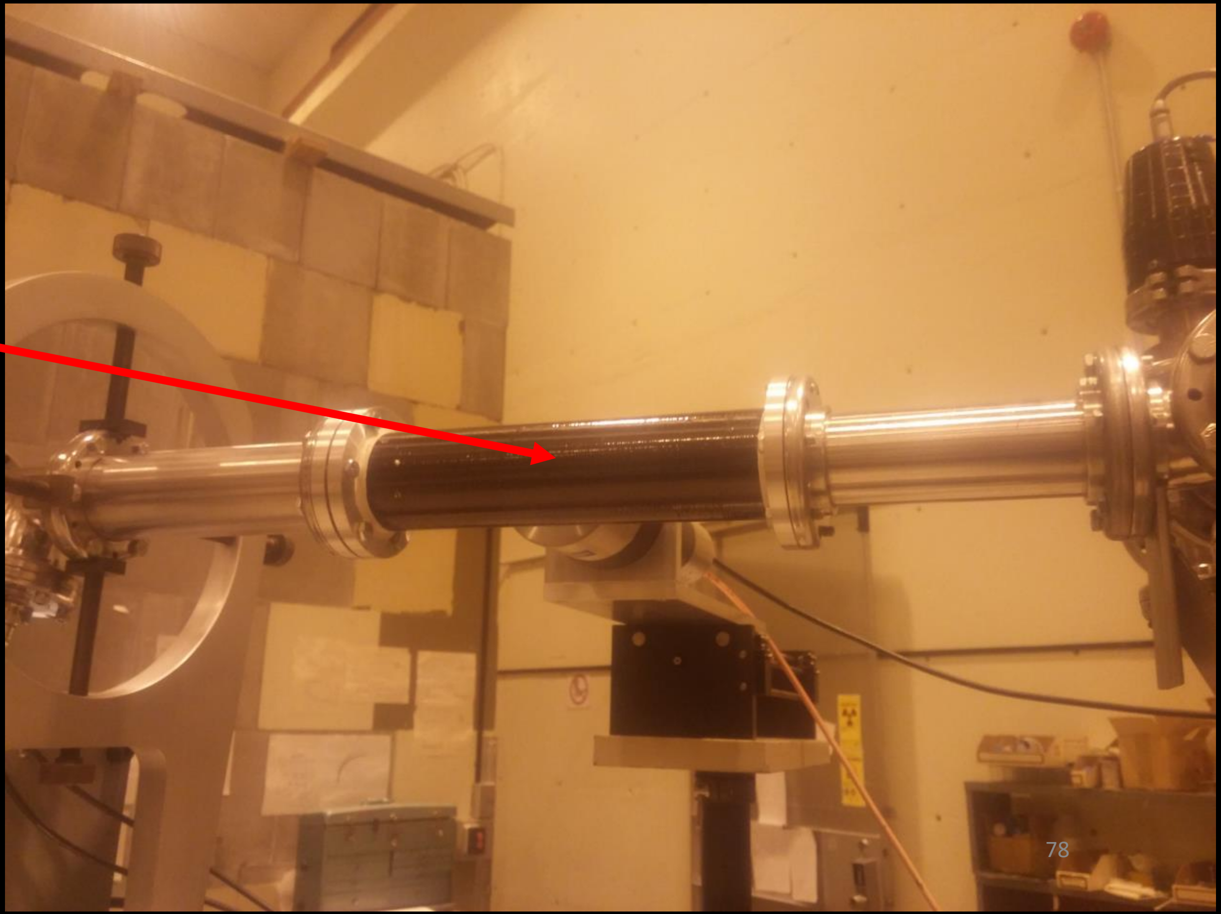


Prague CTU
1 MeV Van de
Graaff Facility

Interesting for lower
proton energies :
$0.4 < E_p < 1$ MeV

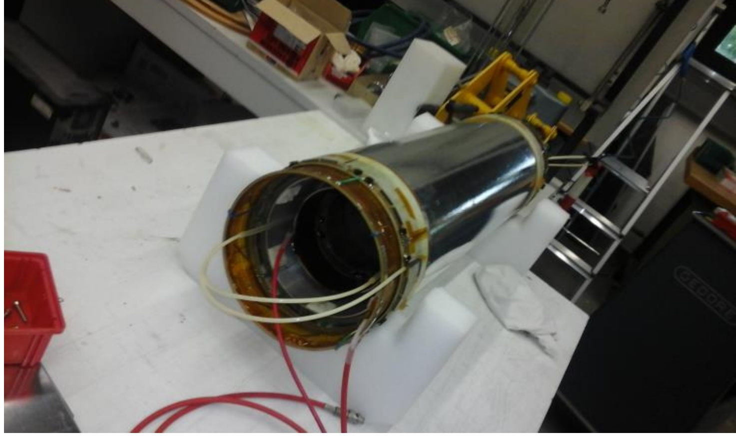
First Beam Tests @ UdeM

- Explore physics environment
- 0.8 mm thick C-beam pipe
- Target: 1.9 µm LiF (0.5 mg/cm^2)
- BGO (5 cm Ø @ 5cm)
- 478 kev γ's from ^{7}Li(p,pγ) ^{7}Li

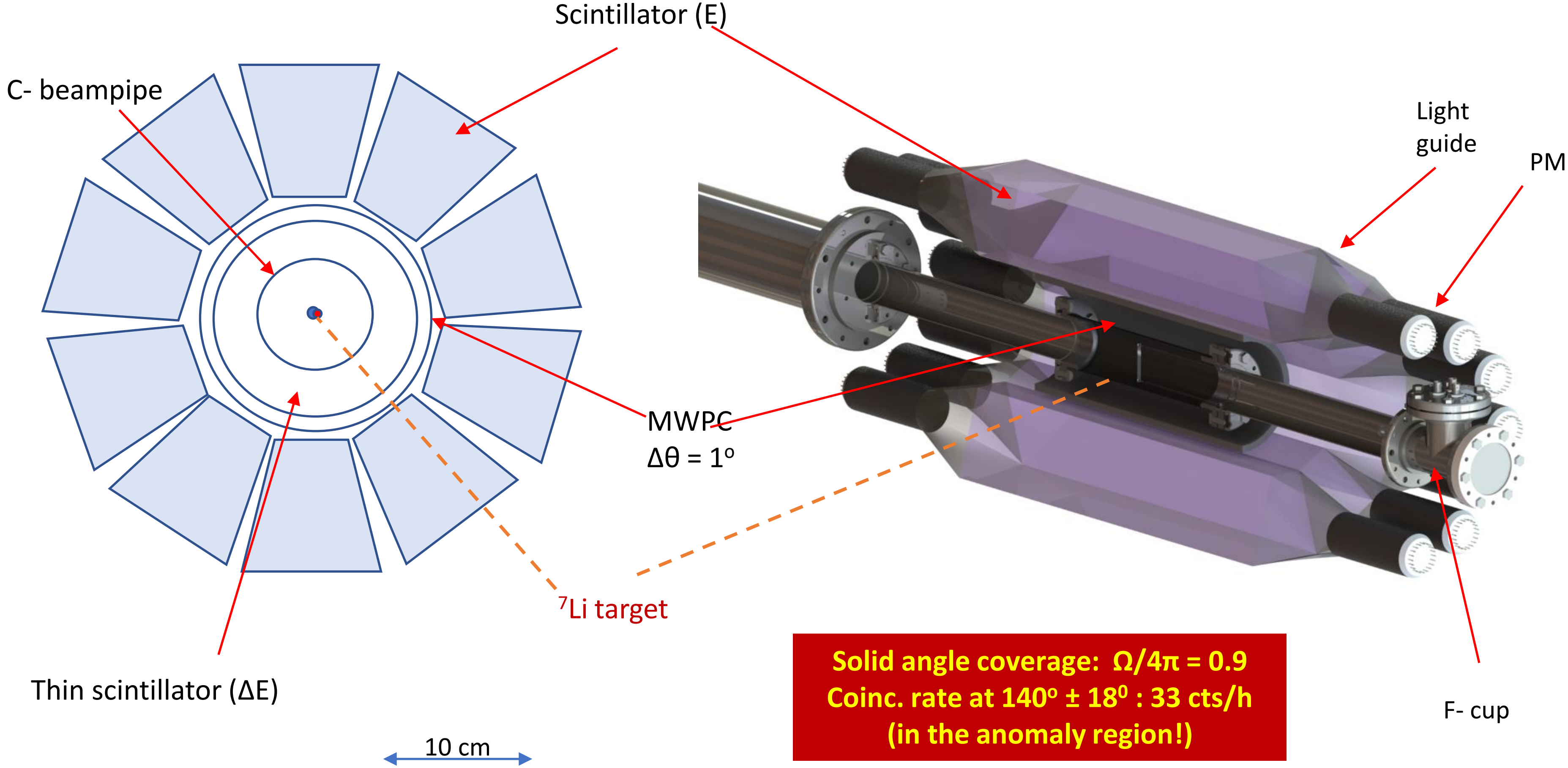


Checking the ^{8}Be Anomaly

- ….using the DAPHNE inner tracking chamber
- Tests ongoing in Mainz
- IR 6 cm / OR 6.8 cm - Length 36 cm
- 10 tapered plastic scintillators (TRIUMF) 5x10x100 cm^3



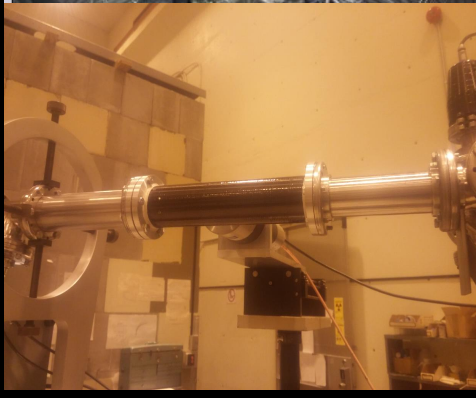
DAHPNE inner chambers at Uni. Mainz



Solid angle coverage: Ω/4π = 0.9
Coinc. rate at 140° ± 18° : 33 cts/h
(in the anomaly region!)

Summary

- The bubble chamber technology has excellent sensitivity for nuclear recoil events down to O(keV) thresholds.
- PICO 40L in new configuration is ramping up incorporating all state of the art improvements
- PICO 500 is planned to be operating in 2019+
- On going R&D in PICO pushing for 100 eV thresholds, supernova ν – detection and CNvES
- New MeV scale physics accessible in nucl. transitions competitive with collider and fixed target exp.
- Intriguing observation of 17 MeV boson in Be*
- Independent verification ongoing at UdeM Tandem



PICO

Acknowledgements

- Support:
  - SNOLAB, the National Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation (CFI), the National Science Foundation (NSF) (Grant 1506337, 1242637 and 1205987), U.S. Department of Energy (DOE) Office of Science, Office of High Energy Physics (under award DE-SC-0012161), the Department of Atomic Energy (DAE), DGAPA-UNAM through grant PAPIIT No. IA100316, CONACyT (Mexico) through grant No. 252167, the Government of India, under the Center of AstroParticle Physics II project (CAPP-II) at SAHA Institute of nuclear Physics (SINP), the Czech Ministry of Education, Youth and Sports (Grant LM2015072) and the the Spanish Ministerio de Economía y Competitividad, Consolider MultiDark (Grant CSD2009-00064), Fermi National Accelerator Laboratory (Contract No. De-AC02-07CH11359), and Pacific Northwest National Laboratory, which is operated by Battelle
    for the U.S. Department of Energy under Contract No. DE-AC05-76RL01830.

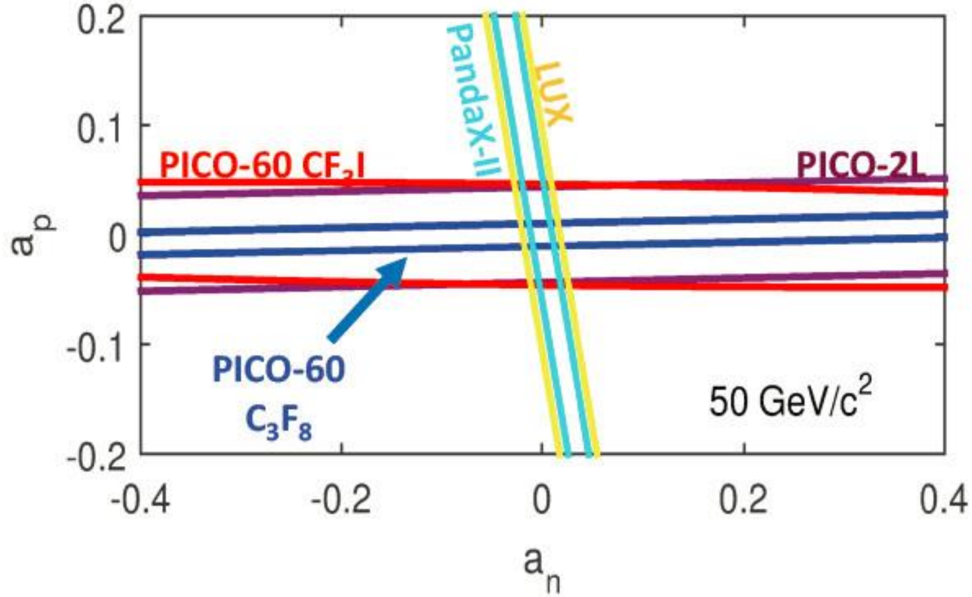
- Papers:

  - C. Amole *et. Al*. (PICO Collaboration), *Dark Matter Search Results from the PICO-60 C3F8 Bubble Chamber*, arXiv:1702.07666, (submitted to PRL)
  - C. Amole *et al*. (PICO Collaboration), *Dark Matter Search Results from the PICO-60 CF_3I Bubble Chamber*, Phys. Rev. D **93**, 052014, Published: 28 March 2016, [arXiv:1510.07754].
  - C. Amole *et al*. (PICO Collaboration), Improved Dark Matter Search Results from PICO-2L Run-2, Phys. Rev. D **93**, 061101(R), Published: 21 March 2016, [arXiv:1601.03729].
  - C. Amole *et al*. (PICO Collaboration), Dark Matter Search Results from the PICO-2L C_3F_8 Bubble Chamber, Phys. Rev. Lett. **114**, 231302, Published: 11 June 2015 [arXiv:1503.00008].

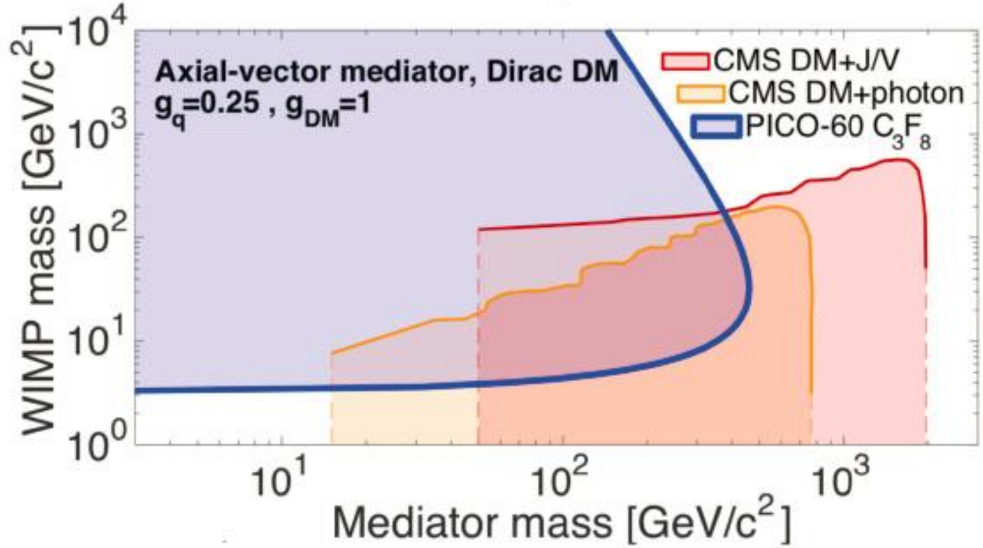
Backup

Complementarity of PICO Results

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



Bubble chamber fluids

- Could make a dark matter bubble chamber with any liquid.

- Fluorocarbon based compounds are ideal:
  - Superheated fluid at room temperature and pressure.
  - Not flammable.
  - Low toxicity.
  - Fluorine is ideal spin-dependent target.
  - Fluorine can be replaced with high-mass halogen (Cl, Br, I) for improved A^2 enhancement.

- COUPP/PICO/PICASSO/MOSCAB used CF_3I, C4F10 and $\mathbf{C_3F_8}$.

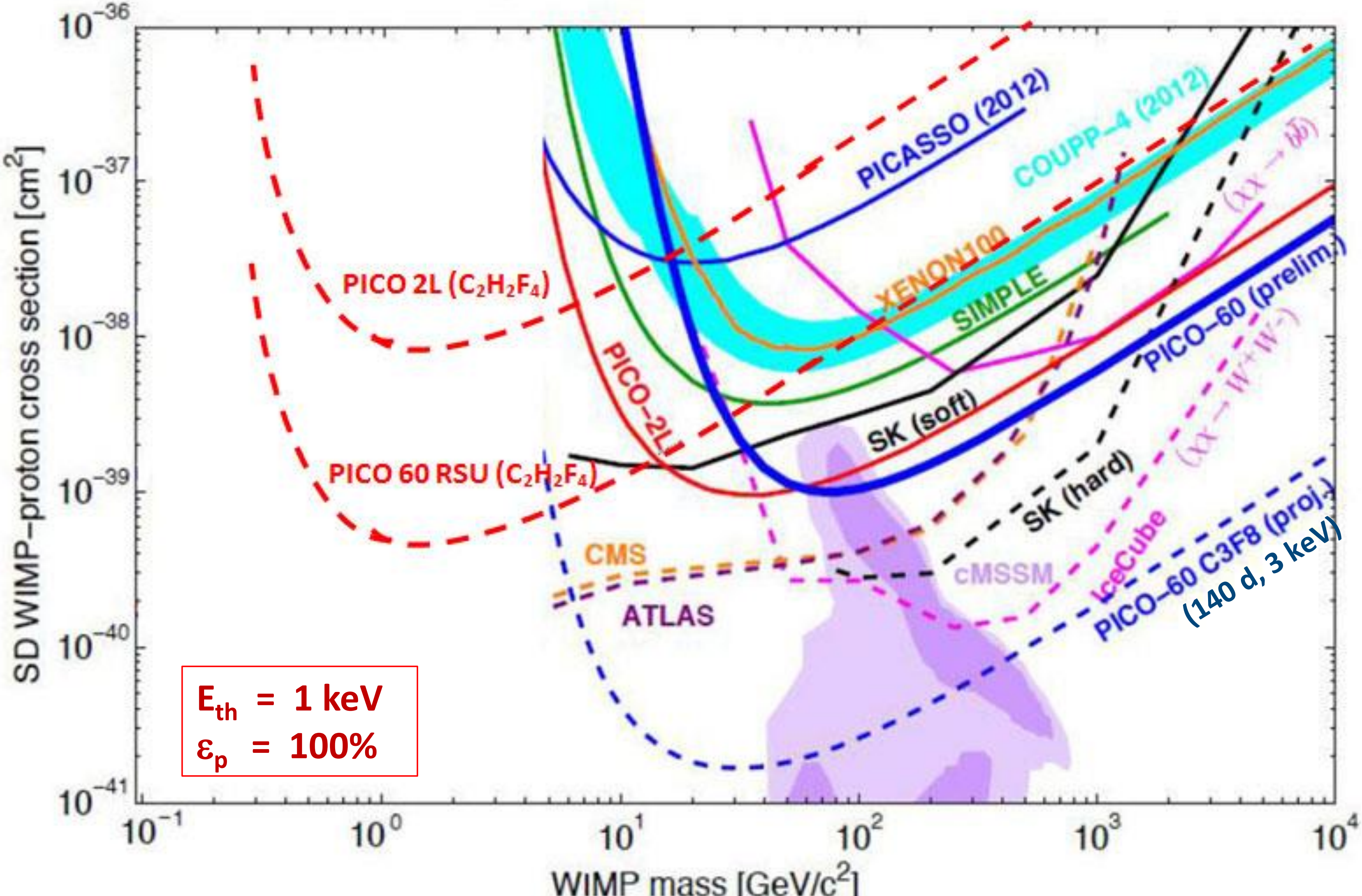
Spin-independent

Spin-dependent

$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \frac{32 G_F^2 \mu^2}{\pi}\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

Nucleus	Z	Odd Nucleon	J	$\langle S_p\rangle$	$\langle S_n\rangle$	C_A^p/C_p	C_A^n/C_n
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}

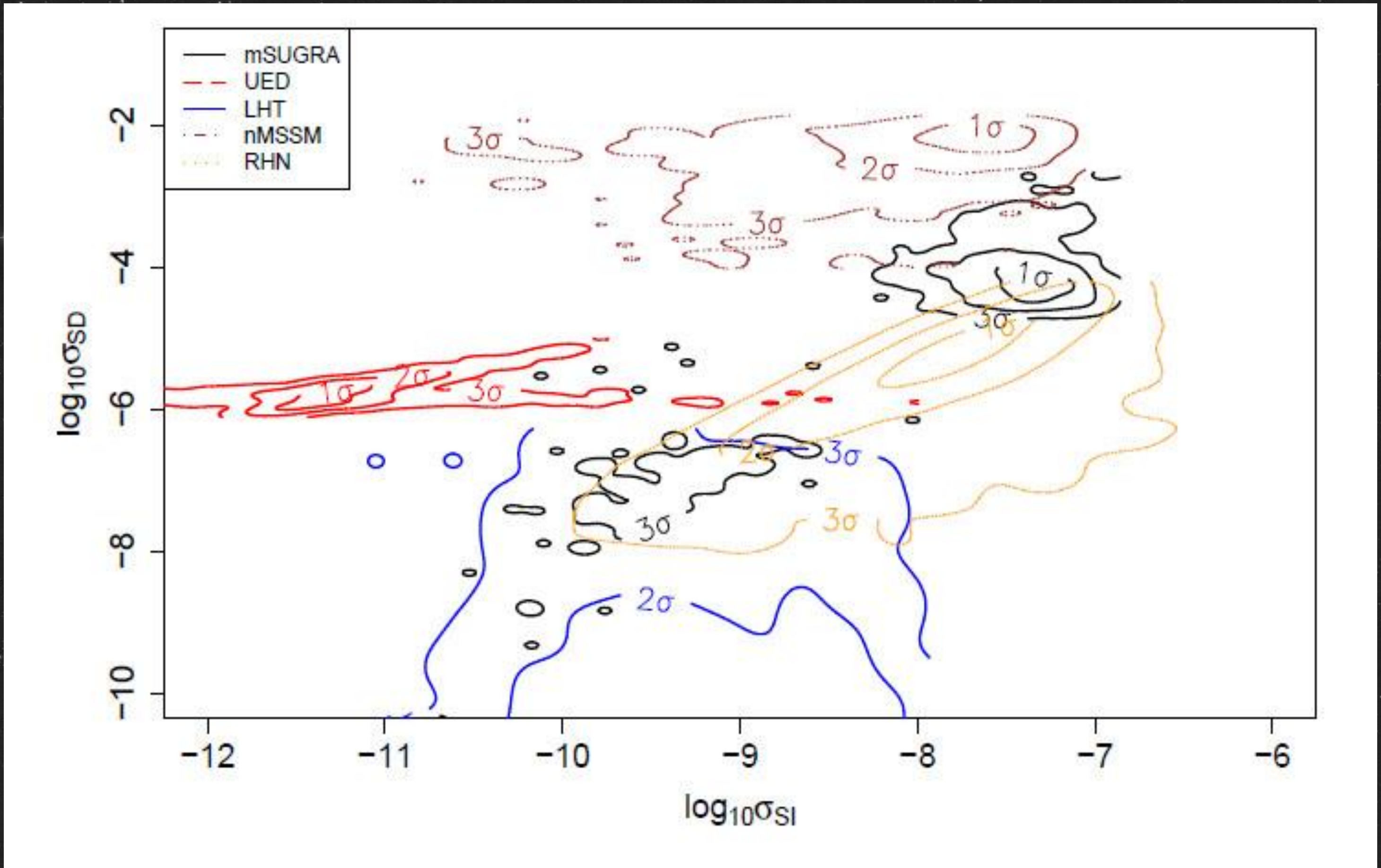
SD- Limits after 100 Days Running PICO 60



E_{th} = 1 keV

ε_p = 100%

Spin Dependent vs Spin Independent

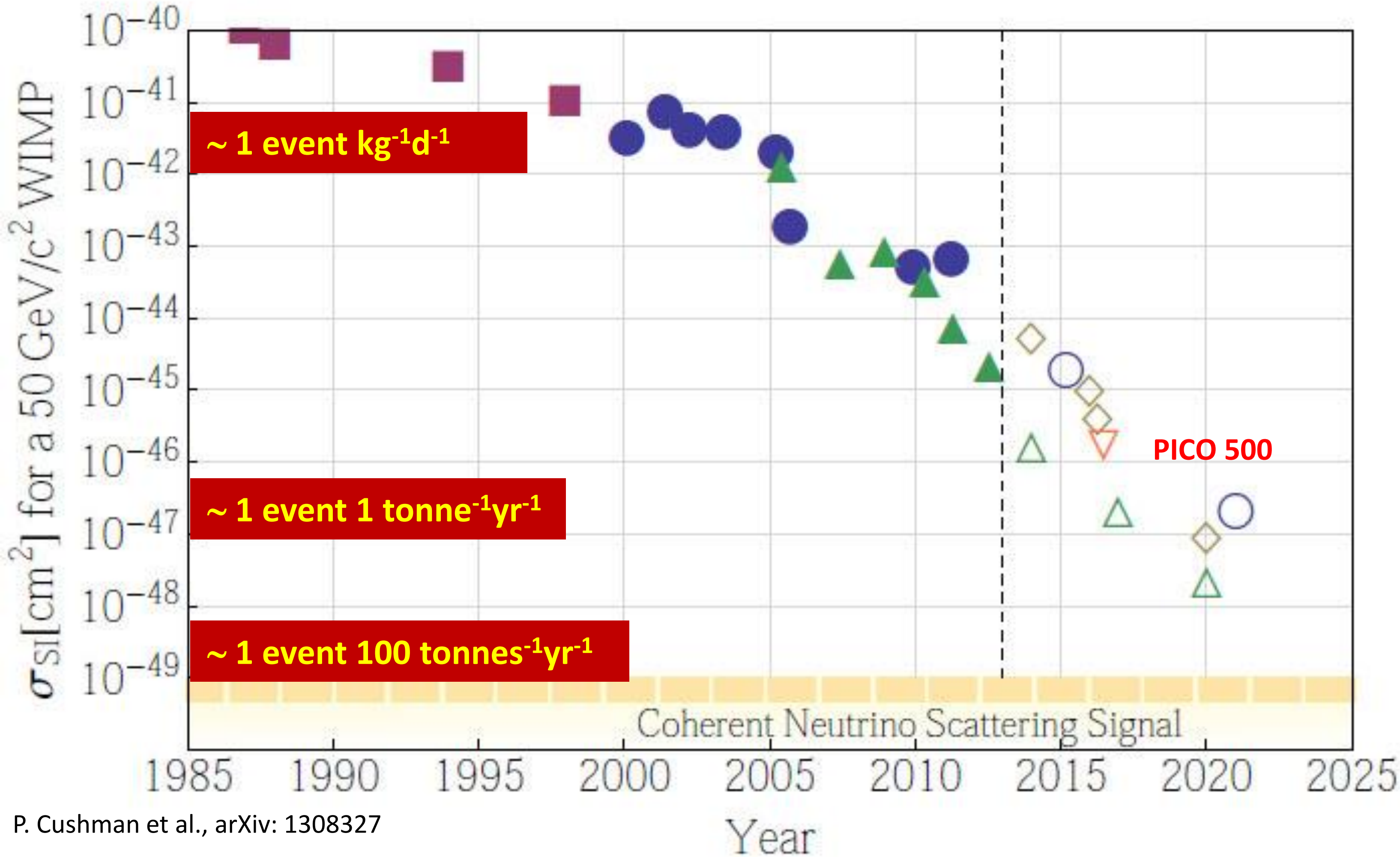


Spin independent (pb)

Spin dependent (pb)

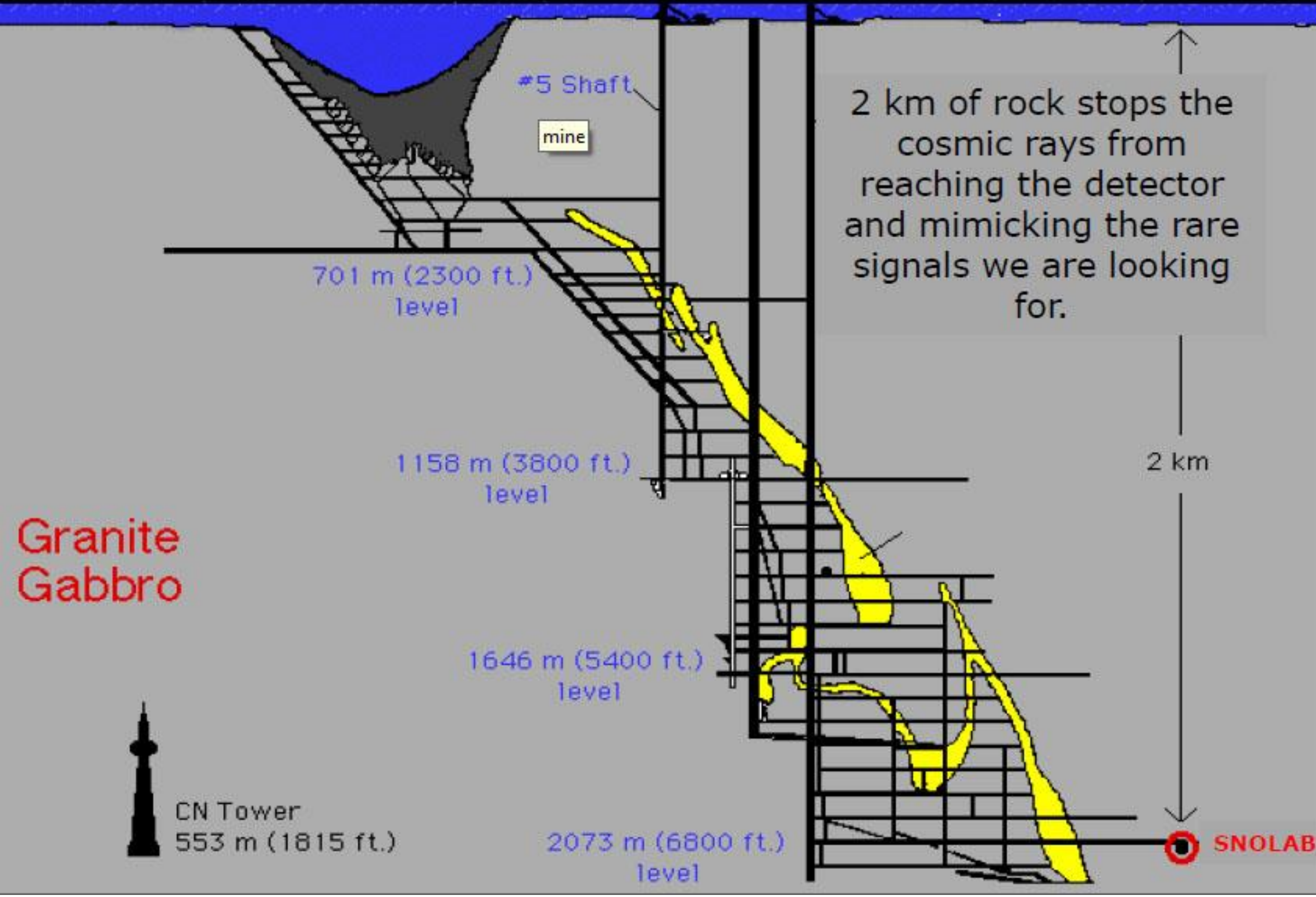
Largely uncorrelated ➡ two classes of searches (SI, SD)

Tremendeous Progress over the Years !



P. Cushman et al., arXiv: 1308327

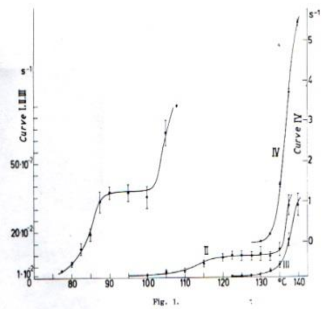
SNOLAB is Situated 2 km underground in a Vale mine in Sudbury.



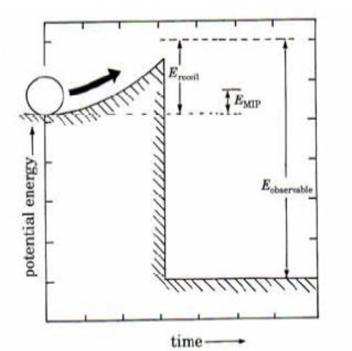
Superheated Liquids For Particle Detection

1952 Donald Glaser: “Some Effects of Ionizing Radiation on the Formation of Bubbles in Liquids” (Phys. Rev. 87, 4, 1952)

1958 G. Brautti, M. Crescia and P. Bassi: “A Bubble Chamber Detector for Weak Radioactivity” (Il Nuovo Cimento, 10, 6, 1958)



1960 B. Hahn and S. Spadavecchia “Application of the Bubble Chamber Technique to detect Fission Fragments” (Il Nuovo Cimento 54B, 101, 1968)

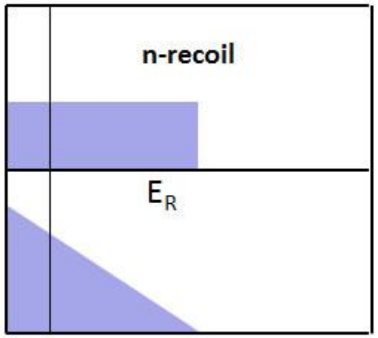


1993 Picasso “Search for Dark Matter with Moderately Superheated Liquids” (Il Nuovo Cimento, 107, 2, 1994)

Superheated Liquids & Dark Matter: PICASSO, COUPP, SIMPLE, PICO, MOSCAB

Low-Energy Neutron Calibration

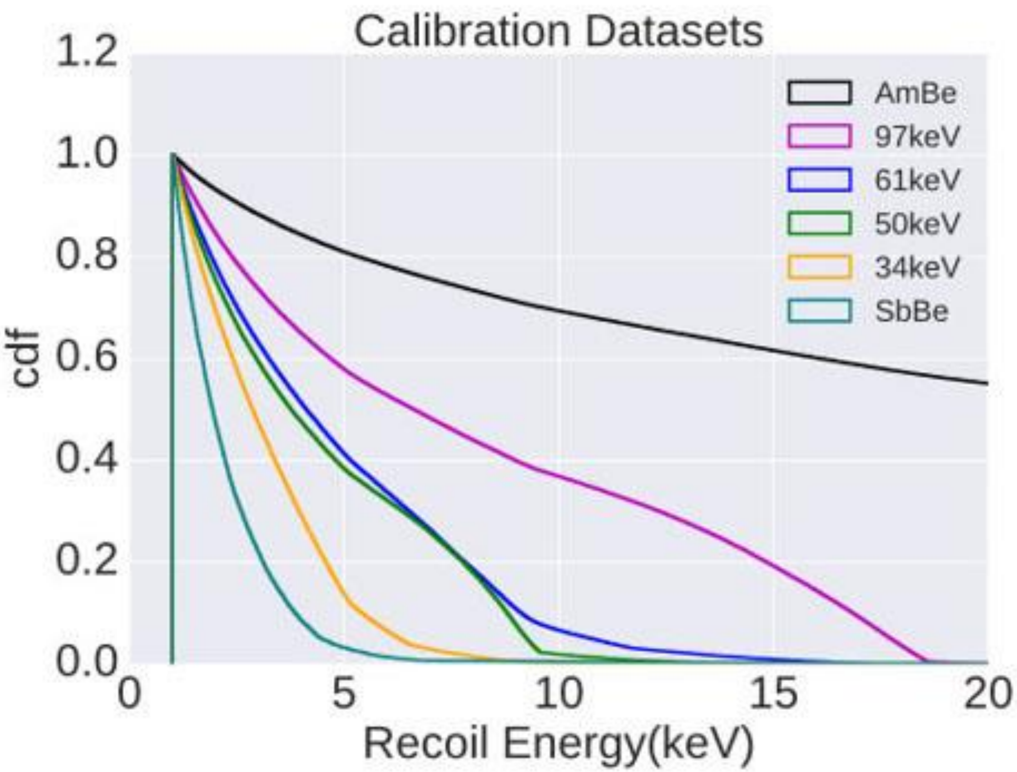
PICO



Mono-energetic n-test beam @ Montréal

Recoil spectrum for mono-energetic neutrons

$E^F_{max} = 0.18 \times E_n$



Fit all neutron data with systematic uncertainties for each data set to piecewise efficiency curves with Markov Chain Monte Carlo

Measurement Strategy

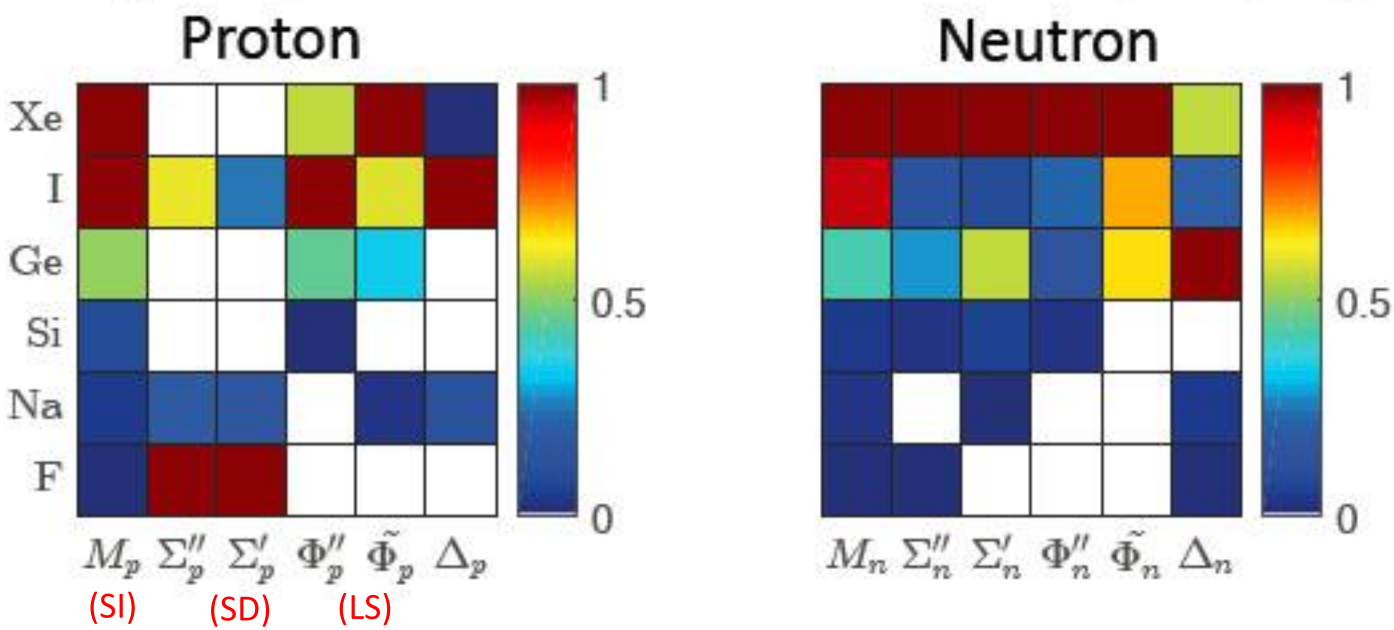
PICO

- Temperature & pressure — Threshold (KeV)
- Primary trigger: camera images
  - Was there a bubble Yes / No
  - How many bubbles ? — Neutron rejection
  - Bubble position — Wall event?
- Secondary trigger: pressure rise — Wall event, neutrons?
- Acoustic signal — Alpha (Rn) rejection

This information should be blinded (as done in PICO 60 run!)

An Important Feature in PICO…

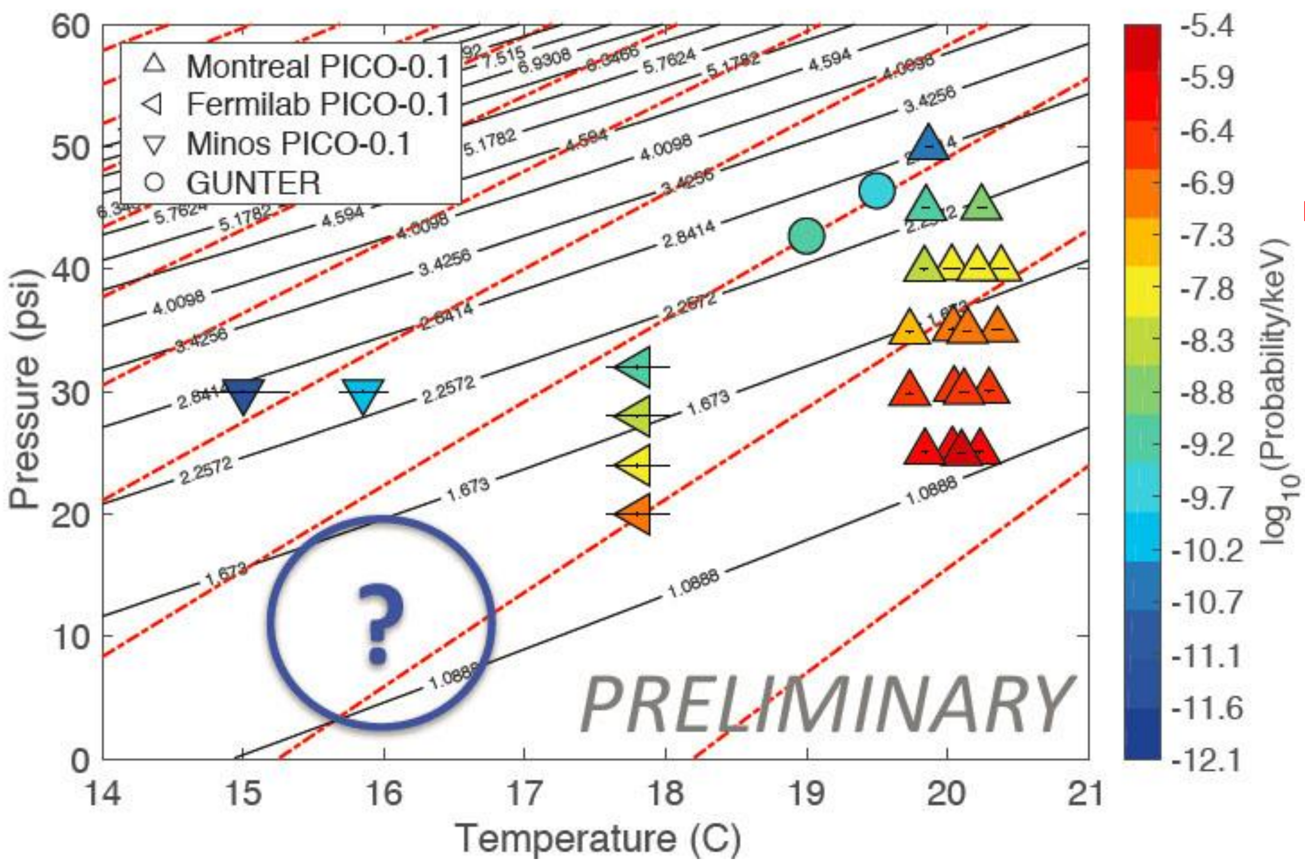
- F gives unique sensitivity to SD proton couplings
- Interachnageable target fluids in same detector can pin down DM characterisrics



Fitzpatrick, Haxton et al. Effective Field theory couplings

Confirm recently discovered γ – sensitivity model!

(D. Baxter, NW. U)



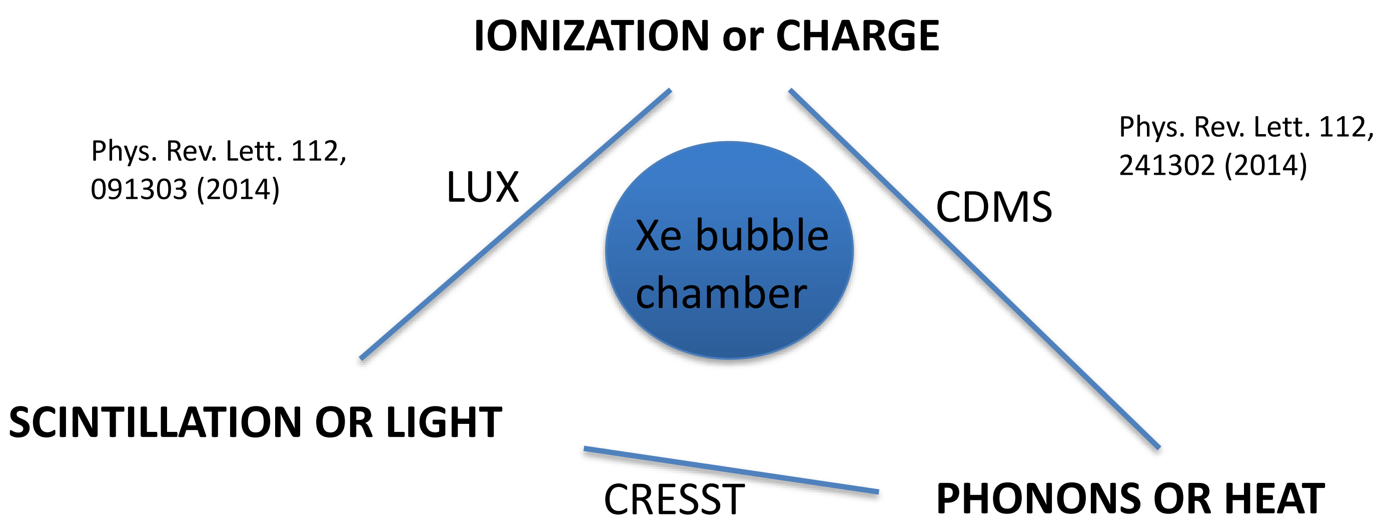
Black: NR(heat) threshold

Red: ER(cavitation) threshold

Different threshold for ER nucleation allows **lower NR thresholds** with same ER rejection!

Coming Up: The Scintillating Bubble Chamber (SBC)!

- LXe BC operated in the past ....with quencher to see gammas
- No quencher needed for DM search ....we do not want to see gammas!
- LXe is a well understood DM target



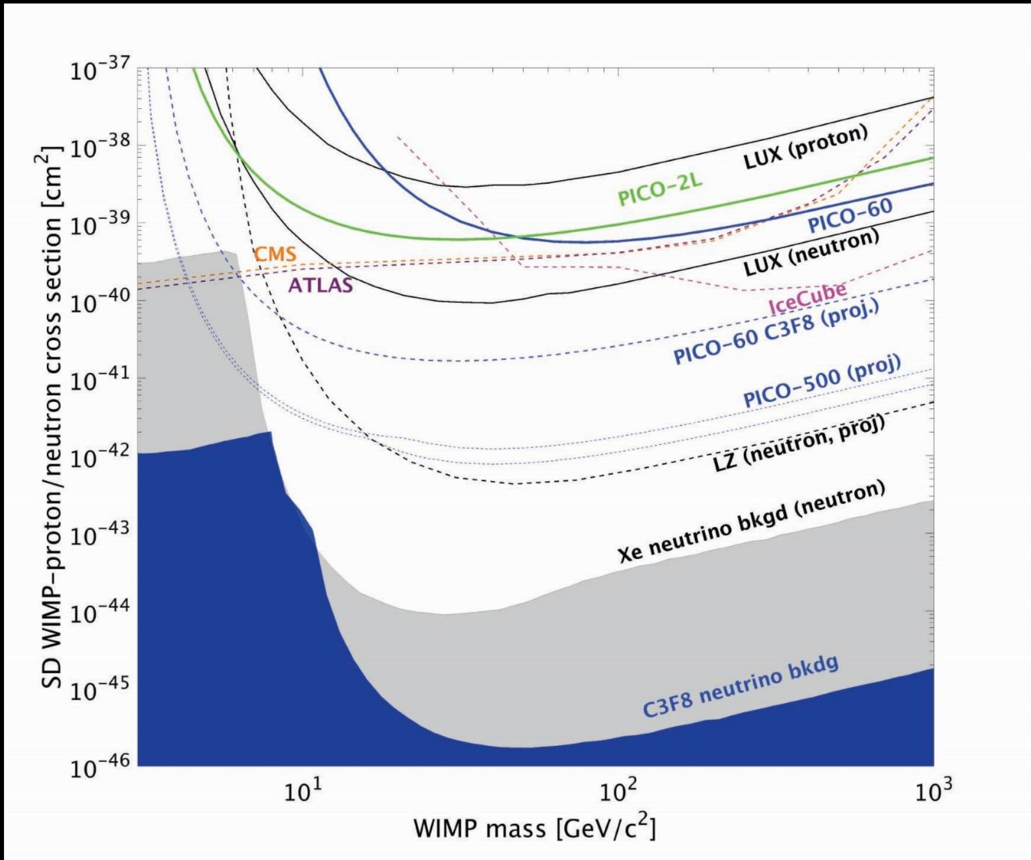
- **Initially scintillation & heat**
- **Later ionization (TPC?)**

→ **All three modes accessible!**

J. Mock et al, Berkeley Workshop on Dark Matter Detection, June 2015

…and if PICO hits the Neutrino Background?

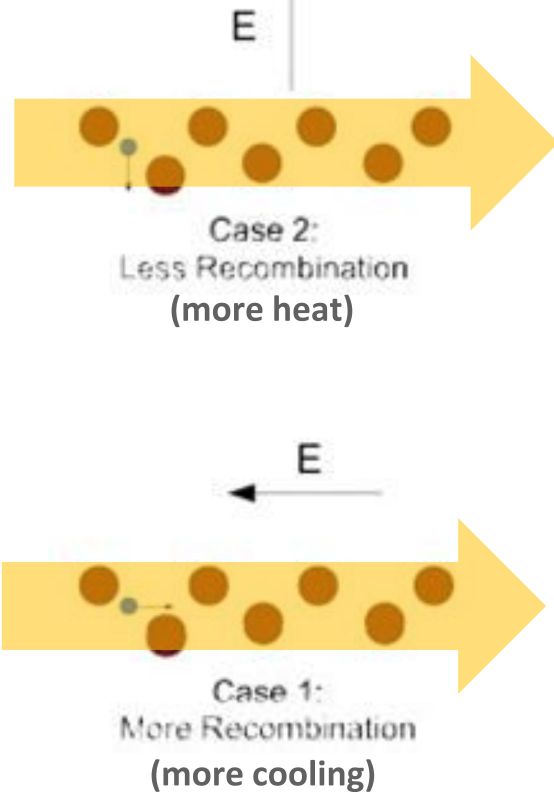
Directionality ?



….a bit of Science Fiction!

Directional Sensitivity in PICO?

Speculation!



LAr TPC (2-phase):

PhysRevD91(2015)092007

- Test with n-beam E_{rec} = 10 - 57 keV
- "Columnar recombination" observed
- More electron – ion recombination on track along E- field
- More scintillation if track along E-field (~ 400 V/cm)
- Anti -correlation btw. ioniz. and scintill. signal

PICO:

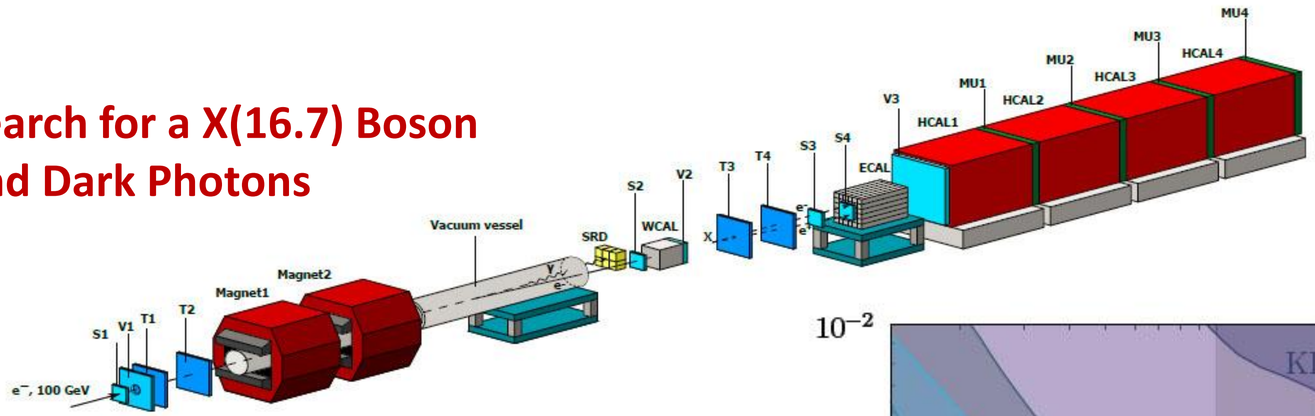
- Track II E-field (~ 400 V/cm?)
- More recombination ? More cooling ?
- Smaller acoustic signal ?
- Higher threshold?
- If yes → modulation of amplitude & rate !

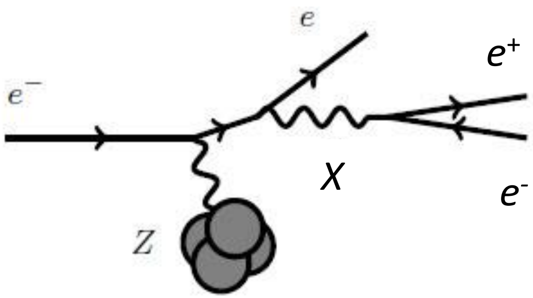
C_3F_8 works in drift chambers
Depends on heat production mechanism
(recoils vs. electrons)

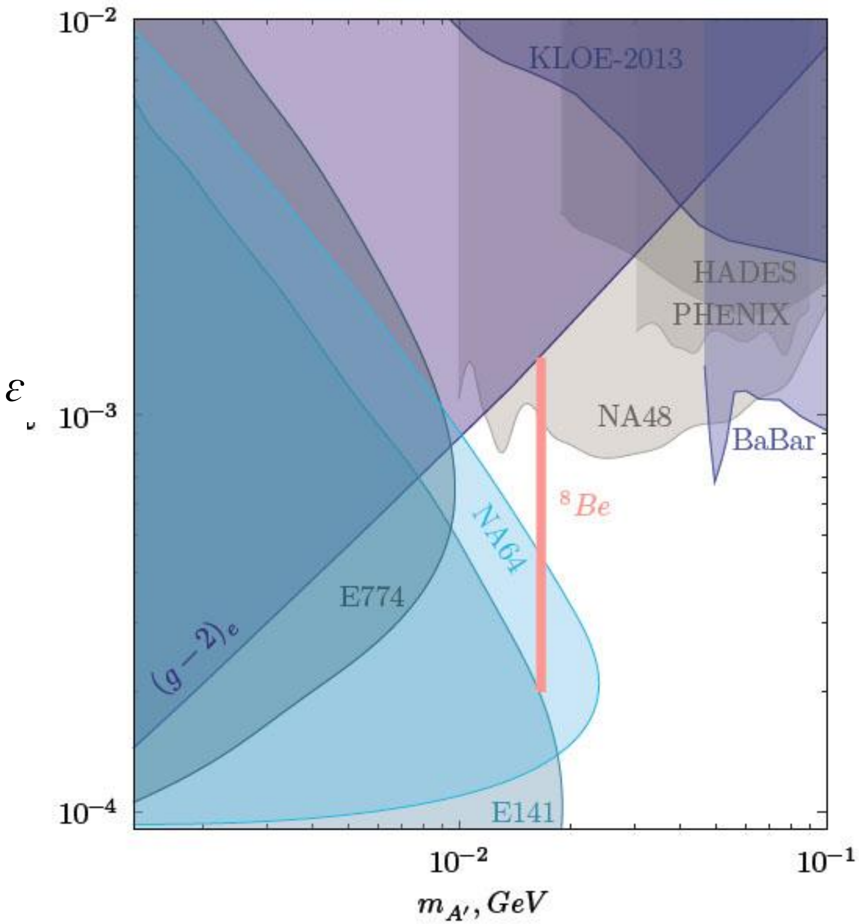
Recently: NA64 @ CERN

arXiv:1803.07748v1

Search for a X(16.7) Boson and Dark Photons

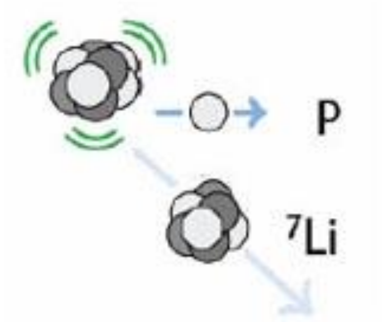






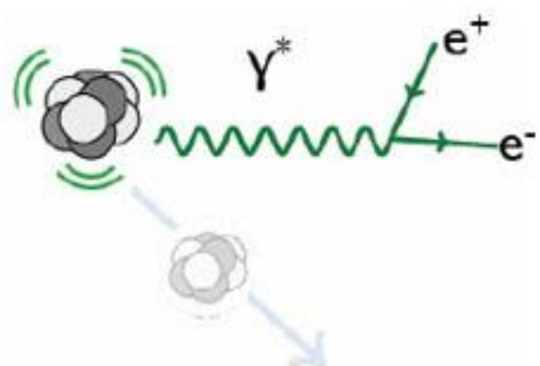
- 100 Gev e^- - beam @ CERN SPS
- 5.4×10^{10} eot – no event obs.
- $1.3 \times 10^{-4} < \varepsilon_e < 4.2 \times 10^{-4}$ excluded for $M_X = 17.6$ MeV

$^{8}Be^{*}$ - Decay



- Hadronic:
  $Br(^{8}Be^{*} \rightarrow p + ^{7}Li\ ) \sim 100\%$

- Electromagnetic:
  $Br(^{8}Be^{*} \rightarrow \gamma + ^{8}Be) \sim 1.5 \times 10^{-5}$

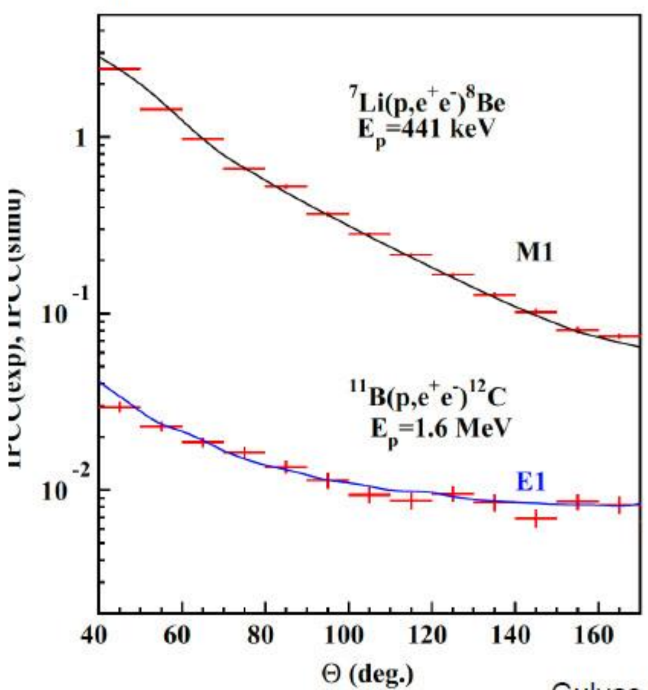


(J. Feng)

- Internal Pair Creation:
  $Br(^{8}Be^{*} \rightarrow e^{+}e^{-} + ^{8}Be) \sim 5.5 \times 10^{-8}$

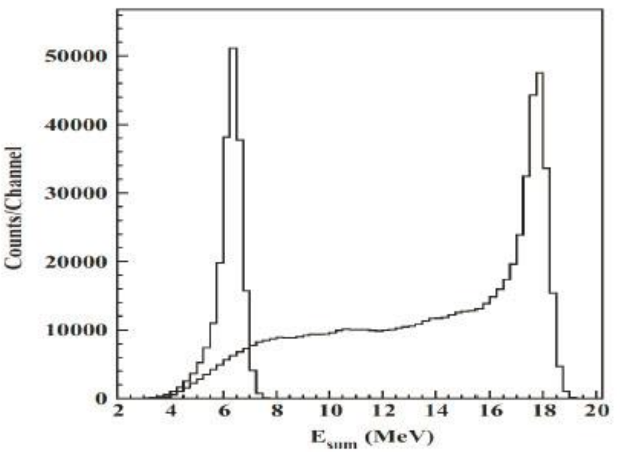
The ATOMKI ^{8}Be - Experiment

Other decays fit theoretical expectation well



Excess confined to events with symmetric energies lyl < 0,5 and large sum-energies E >17MeV

$$E \equiv E_{e^+} + E_{e^-} \qquad y \equiv \frac{E_{e^+} - E_{e^-}}{E_{e^+} + E_{e^-}}$$

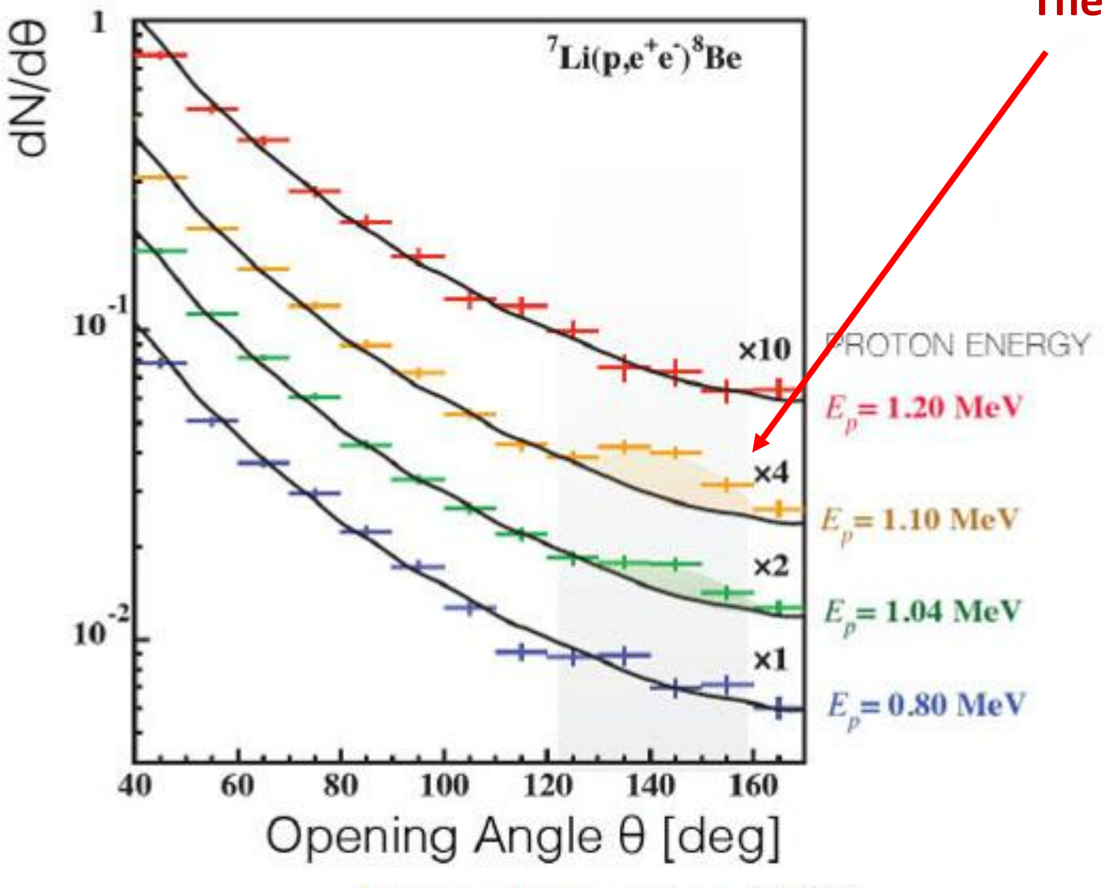


Gulyas et al. NIM (2015)

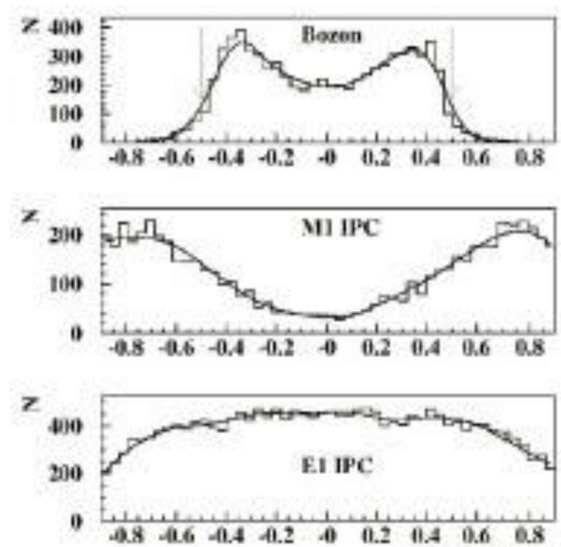
$$\frac{^8Be^* \rightarrow\ ^8Be + X}{^8Be^* \rightarrow\ ^8Be + \gamma} = 5.6 \times 10^{-6}$$

The ATOMKI ^8Be - Experiment

The Anomaly!



- Excess around θ = 140° passing through 18 MeV $^8Be^*$resonance
- Probability for backg. fluctuation: 5.6×10^{-12} (6.8σ)



$Y = (E^+ - E^-)/(E^+ + E^-)$

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501

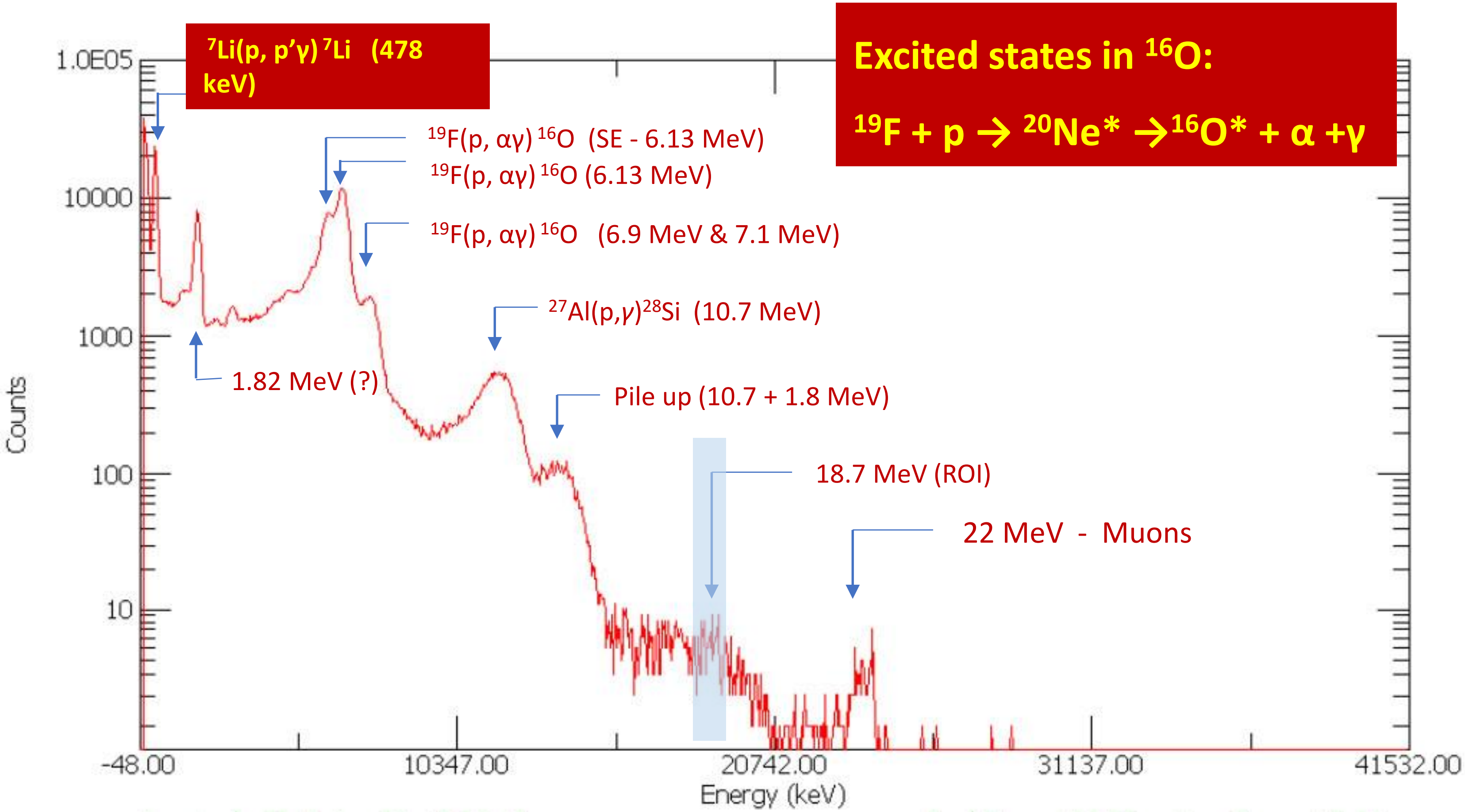
The ATOMKI ^{8}Be - Experiment

Sanity Checks:

- Large number of recorded events → not a statistical fluctuation
- Signal rises and falls when scanning through the resonance
- Excess for symmetric e^+e^- pairs → suggests intermediate massive particle
- Opening angle *and* invariant mass agree (17 MeV)
- Nuclear interference effects? Apparently can weaken effect only somewhat…
- ….or uncontrolled systematic errors?

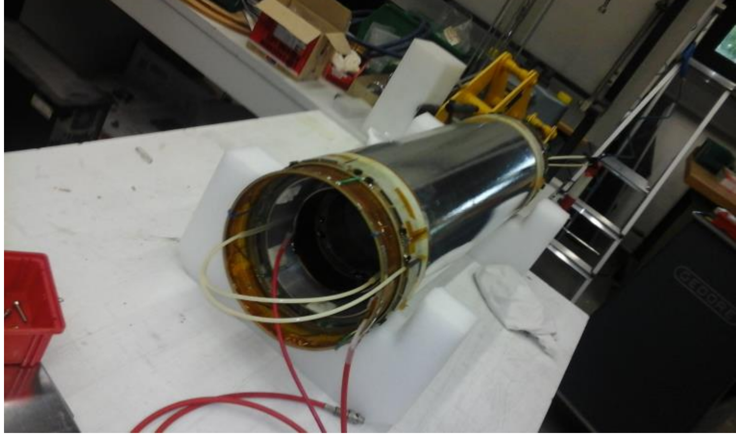
BSM physics requires a new short-lived particle!

BGO γ – Spectrum: E_p = 1.4 MeV

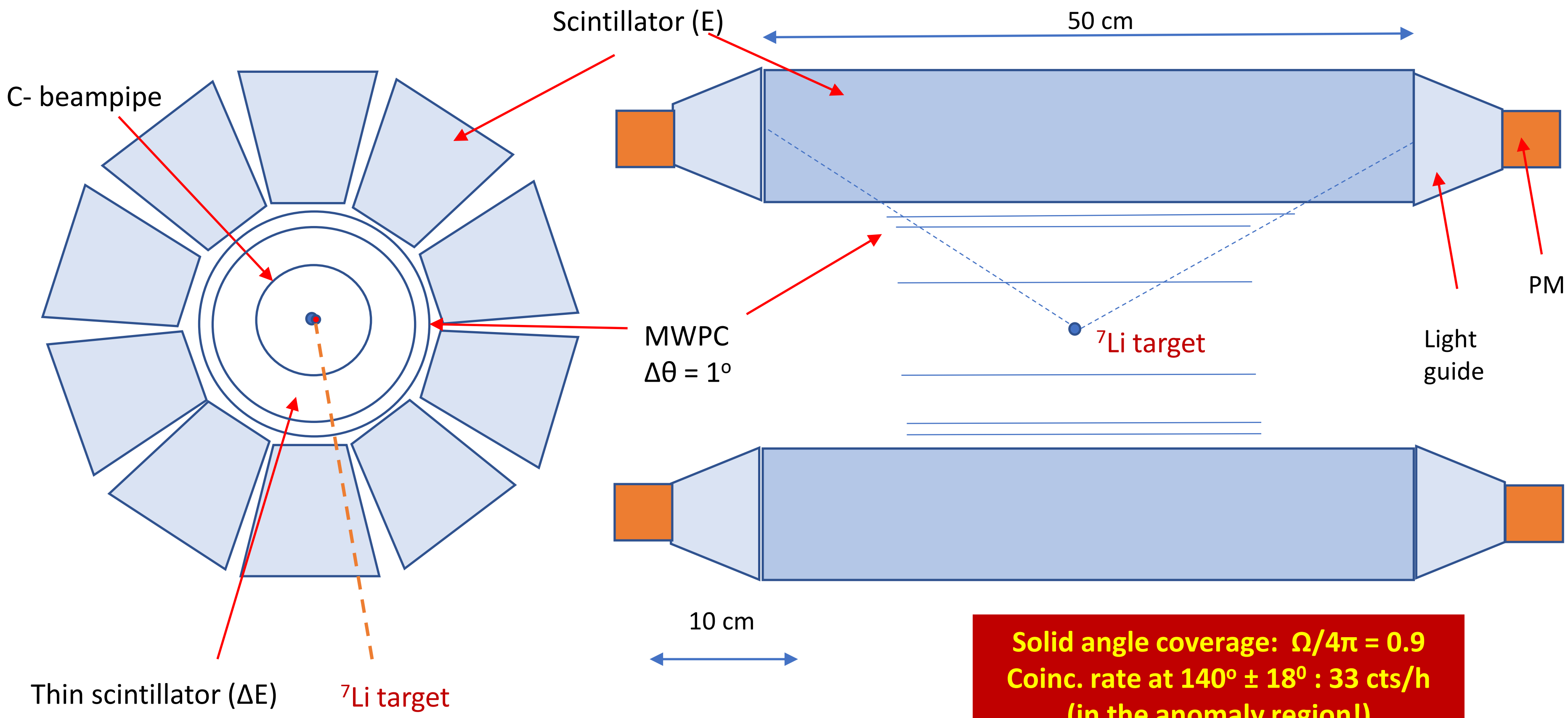


Checking the ^{8}Be Anomaly

- ….using the DAPHNE inner tracking chamber
- Tests ongoing in Mainz
- IR 6 cm / OR 6.8 cm - Length 36 cm
- 10 tapered plastic scintillators (TRIUMF) 5x10x100 cm^3

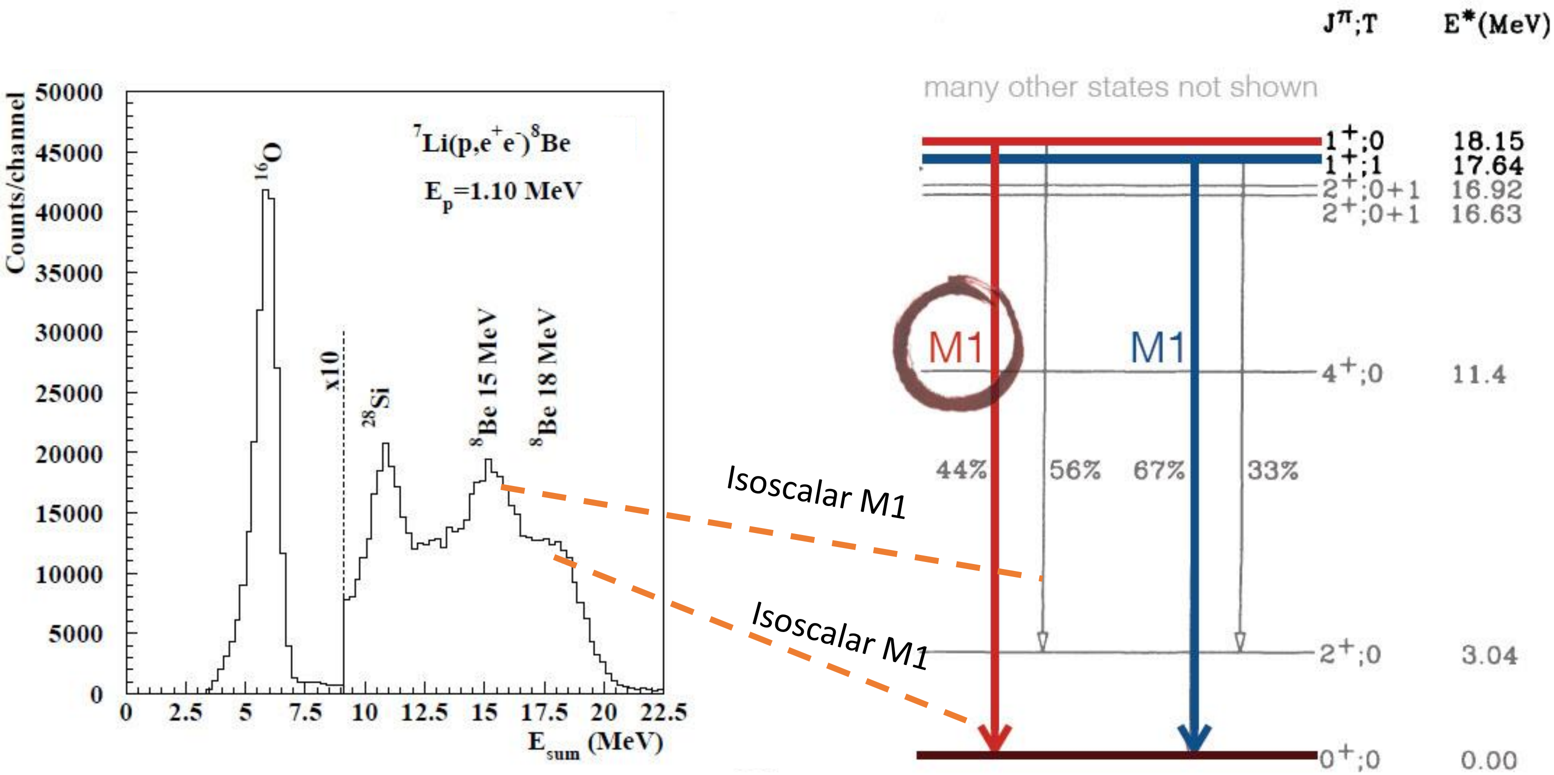


DAHPNE inner chambers at Uni. Mainz



Solid angle coverage: $\Omega/4\pi = 0.9$
Coinc. rate at 140° ± 18° : 33 cts/h
(in the anomaly region!)

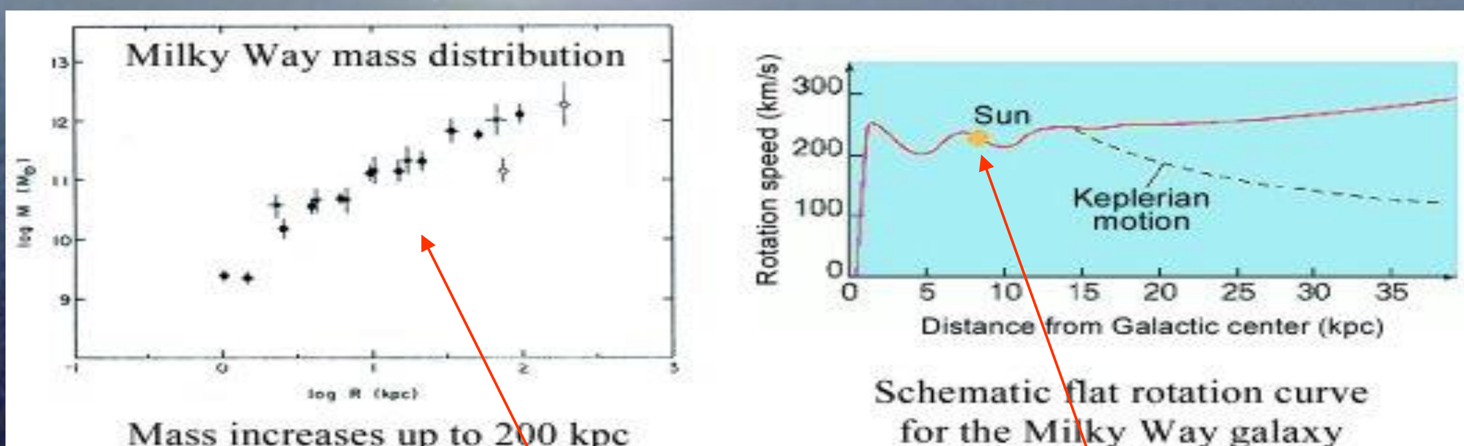
The ATOMKI ^{8}Be - Experiment



Savage et al. Phys. Rev. D37 (1987) 1134

A. J. Krasznahorkay et al.; *Phys. Rev. Lett.* **116** no. 4, (2016) 042501, arXiv:1504.01527 [nucl-ex].

Dark Matter In Our Milky Way



1kpc = 3.259 10^3 Ly

$$M(r) = \frac{v_{rot}^2 r}{G}$$

ρ_{DM} ~ **0.3 m_p/cm^3**

2MASS two Micron All Sky Survey

…only 5-10% of matter visible!