CAP Annual Congress
Ottawa, June 2026

Detecting Dark Matter at the Particle Level

Viktor Zacek
Groupe de physique des particules
Université de Montréal

…a Big Thank You to…

PICASSO

PICO

PX17

Université de Montréal

GPP

SNOLAB

TRIUMF

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

INNOVATION
Canada Foundation for Innovation
Fondation canadienne pour l'innovation

BTI BUBBLE Technology Industries

NSERC CRSNG

If it is not **Dark** it does'nt **Matter !**

(unknown author)

Intro DM etc…

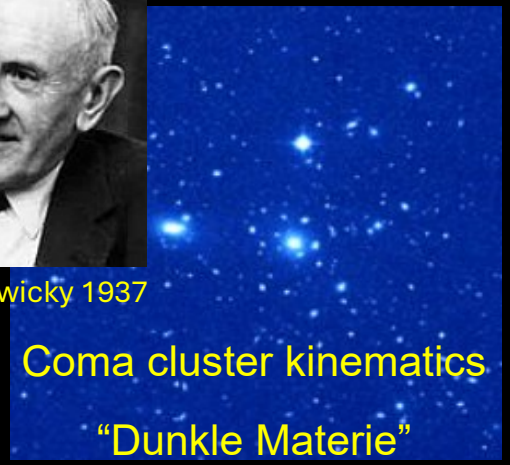
Superheated liquids & how to listen to Dark Matter

The PICASSO, PICO programs at SNOLAB

Exploring the Dark Sector in nuclear transitions with Project X17

Convincing Evidence for Dark Matter !

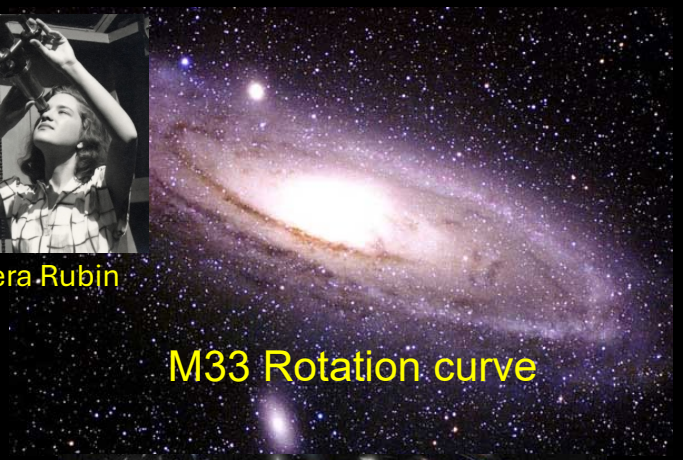
Fritz Zwicky 1937



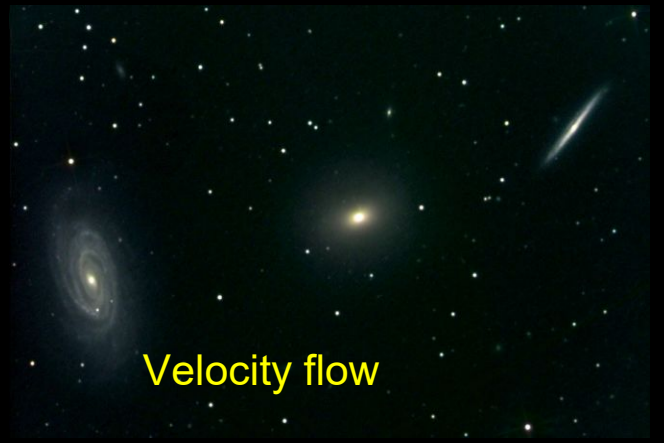
Coma cluster kinematics

"Dunkle Materie"

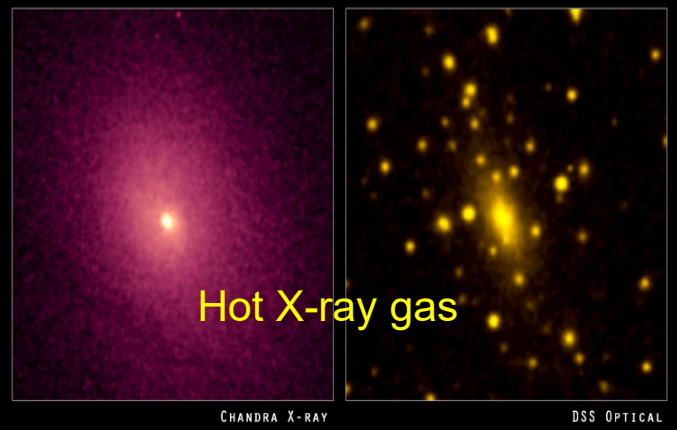
1974 Vera Rubin



M33 Rotation curve



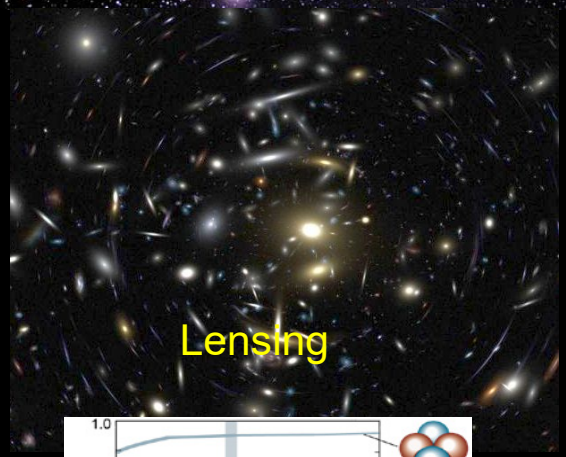
Velocity flow



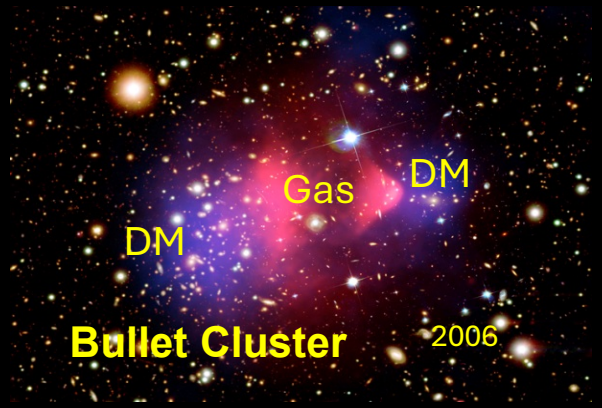
Hot X-ray gas

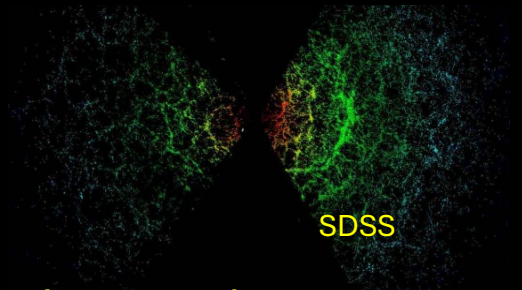
CHANDRA X-RAY

DSS OPTICAL



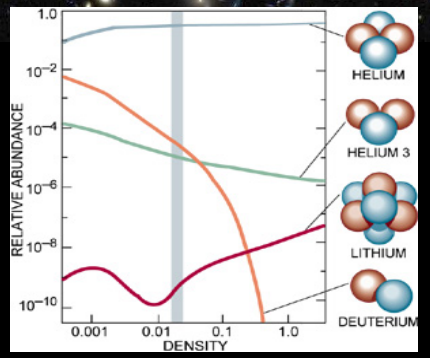
Lensing



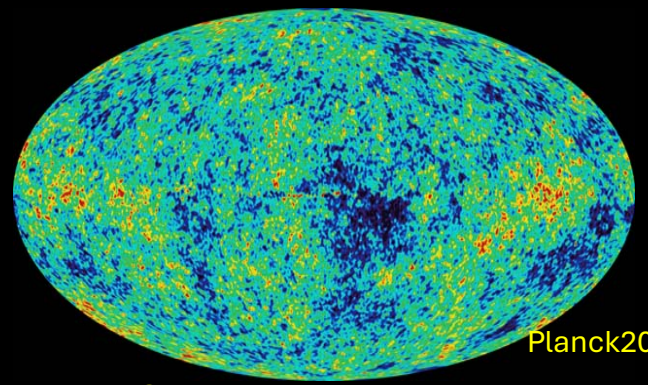


SDSS

Large scale structure

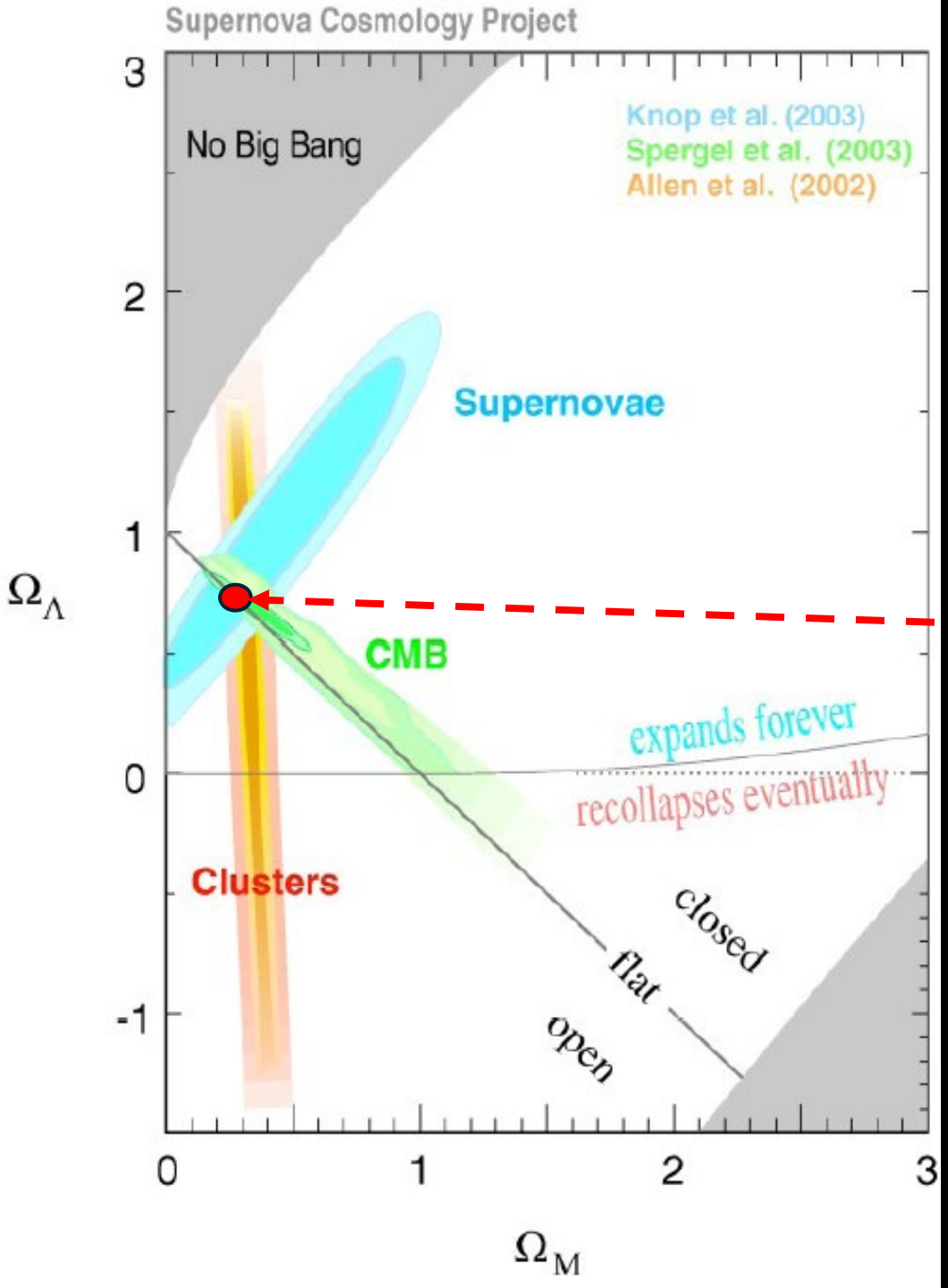


BB nucleosynthesis

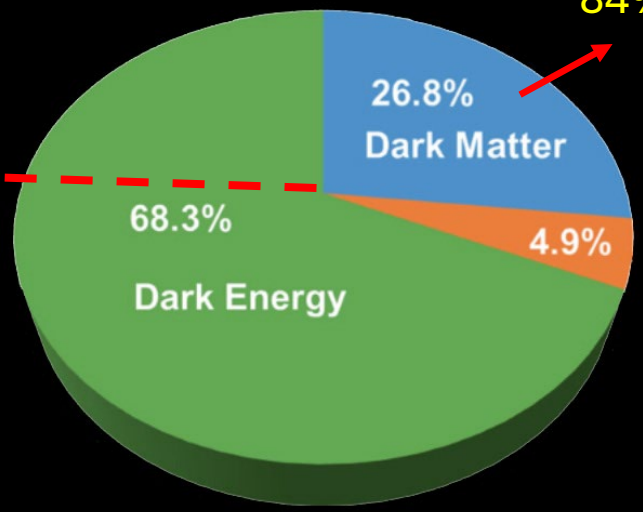


Planck2010

CMB anisotropy



The Concordance Model (ΛCDM)



84% of all matter is dark !

DESI (2025) : ...is Dark Enery weakening ?!!

$$\Omega_{M,\Lambda} = \frac{\rho_{M,\Lambda}}{\varrho_{crit}}$$

What Can Dark Matter Be?

Cannot be baryons
(CMB, LSS, BBNS)

Cannot be charged
(CMB different)

Primordial black holes
→ maybe ?

No MACHOS
(they are not
there)

MOND unlikely
(Bullet Cluster)

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

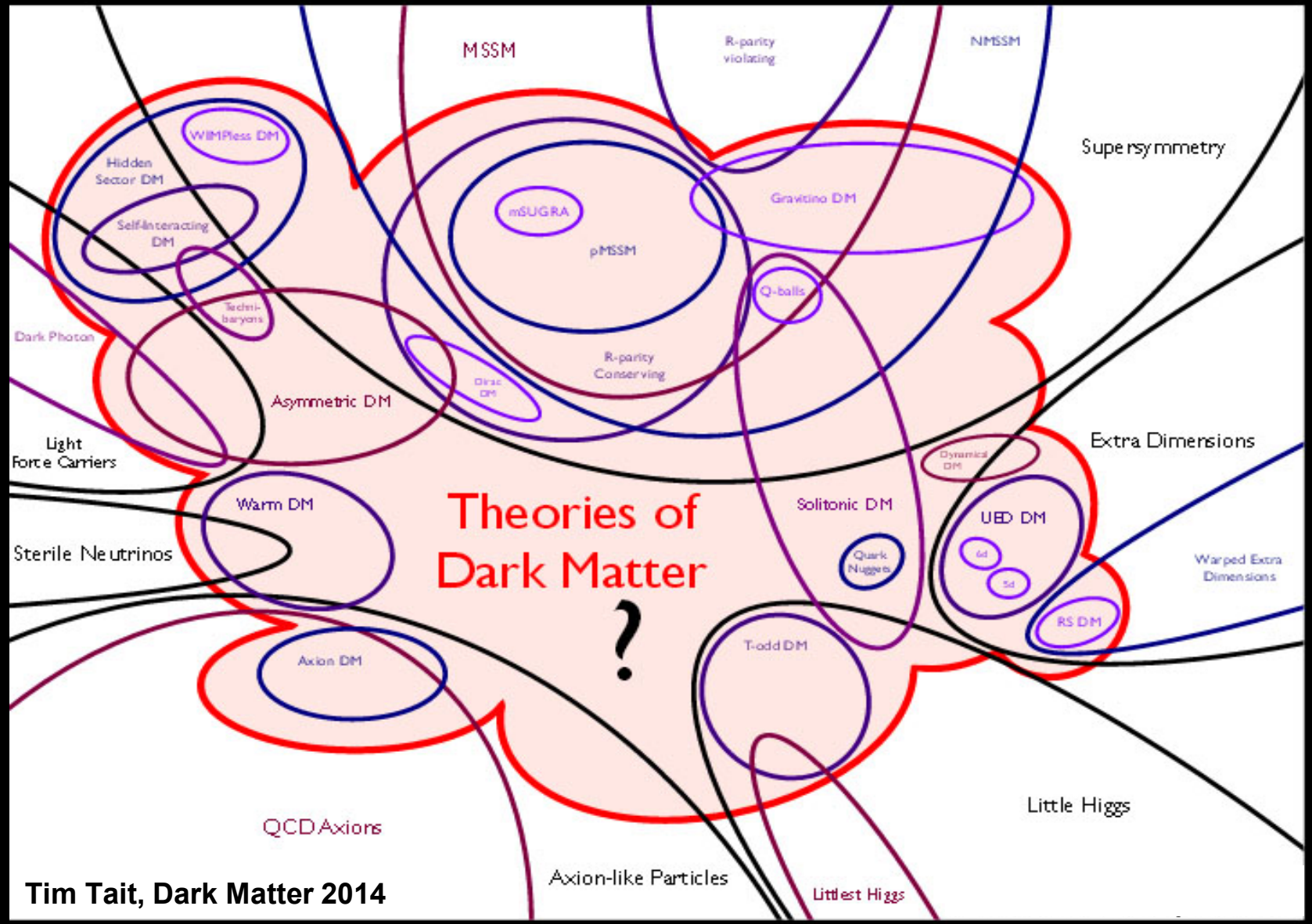
Stable or at least metastable
(τ > 10 Gyr)

Must be cold or warm to explain structure

Must have right relic abundance

…we know what DM does, but not what it is !

No Lack of Options...



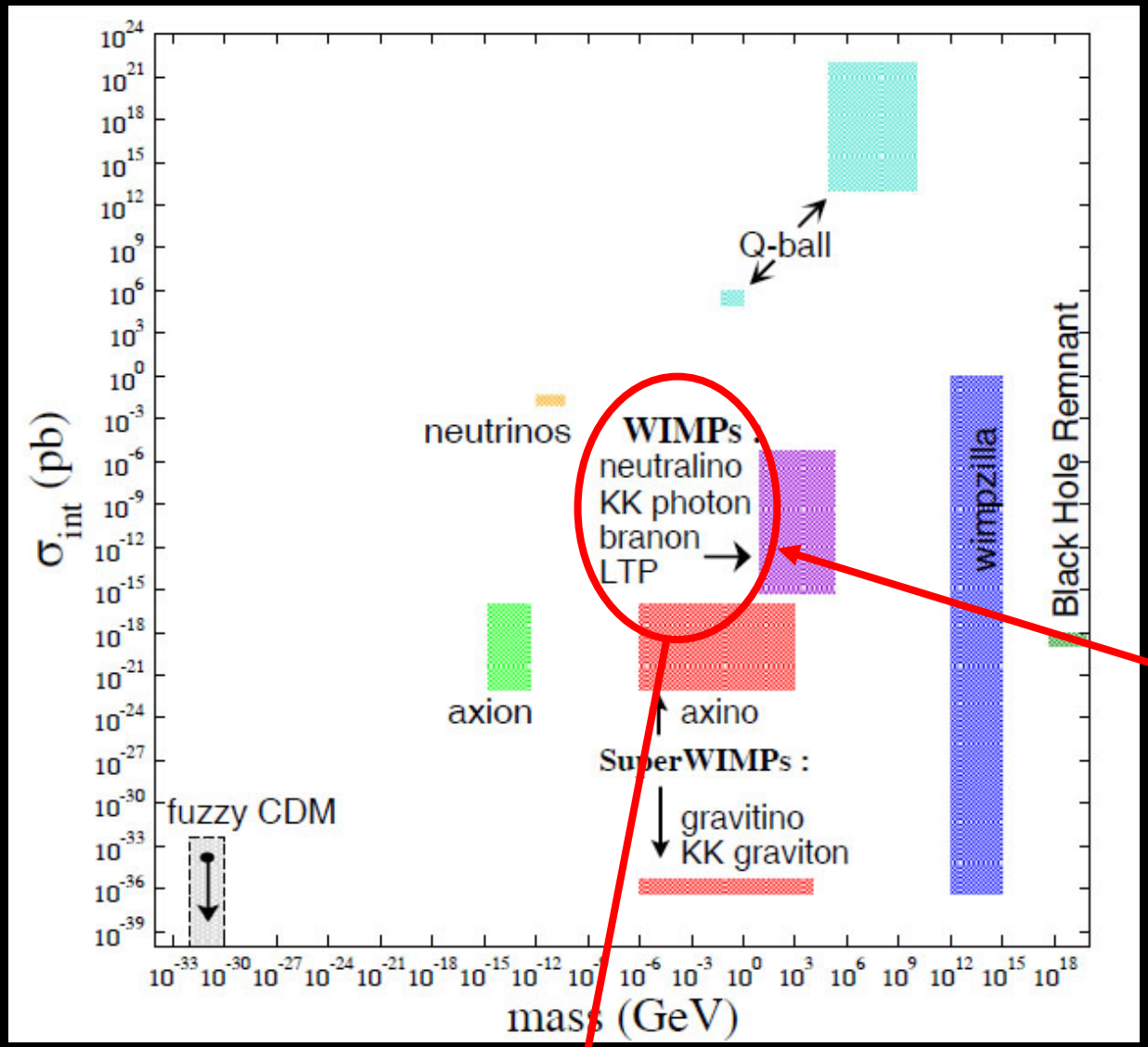
Tim Tait, Dark Matter 2014

Today:

29 000 papers on the arXive mentioning DM !

(1.8 % of total data base!)

Dark Matter Candidates



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

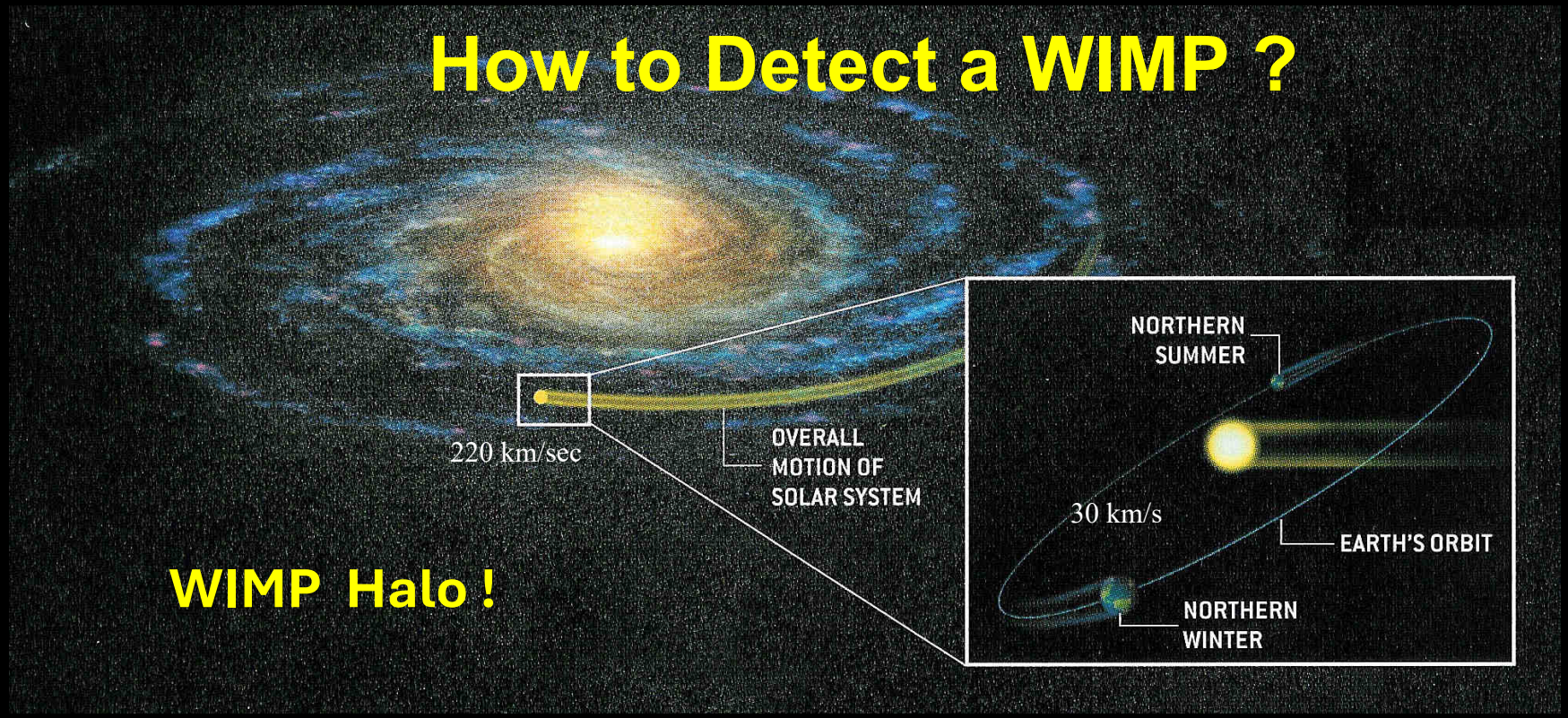
In this talk…

…and much more @

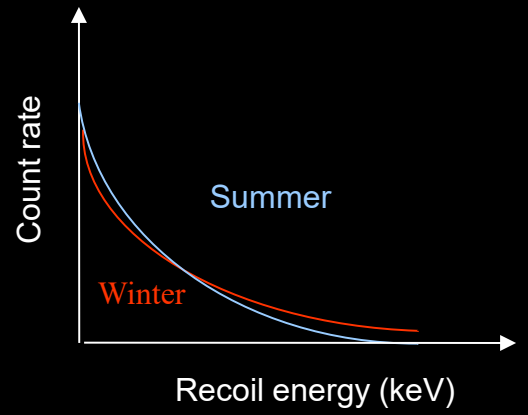
- CAP sessions on DM !!!
- Light Dark World 2026
  Carleton U. (28/7 – 31/7)

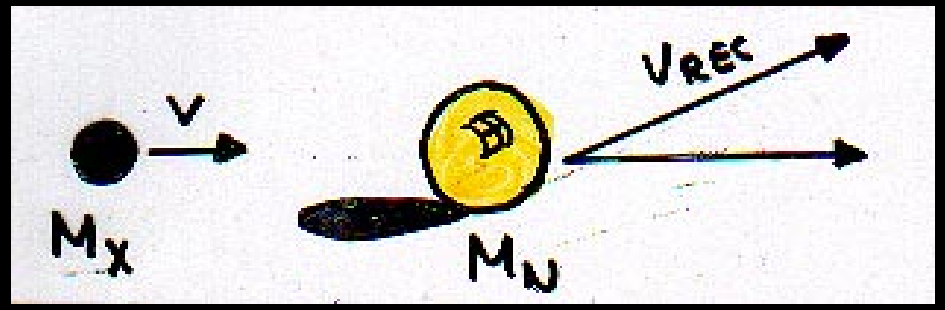
Weakly Interacting Massive Particles

How to Detect a WIMP ?



Graphic D. Cline





…only 5-10% of matter visible in MW!

….and there is a WIMP WIND !

scattering off detector nuclei & recoil detection

Small signals: < 100 keV recoils….maybe even meV?

Small rates: << 0.1 count /kgd (rare !!!!)

…and there are Backgrounds !

Cosmic rays

Nat. radioactivity

Neutrons

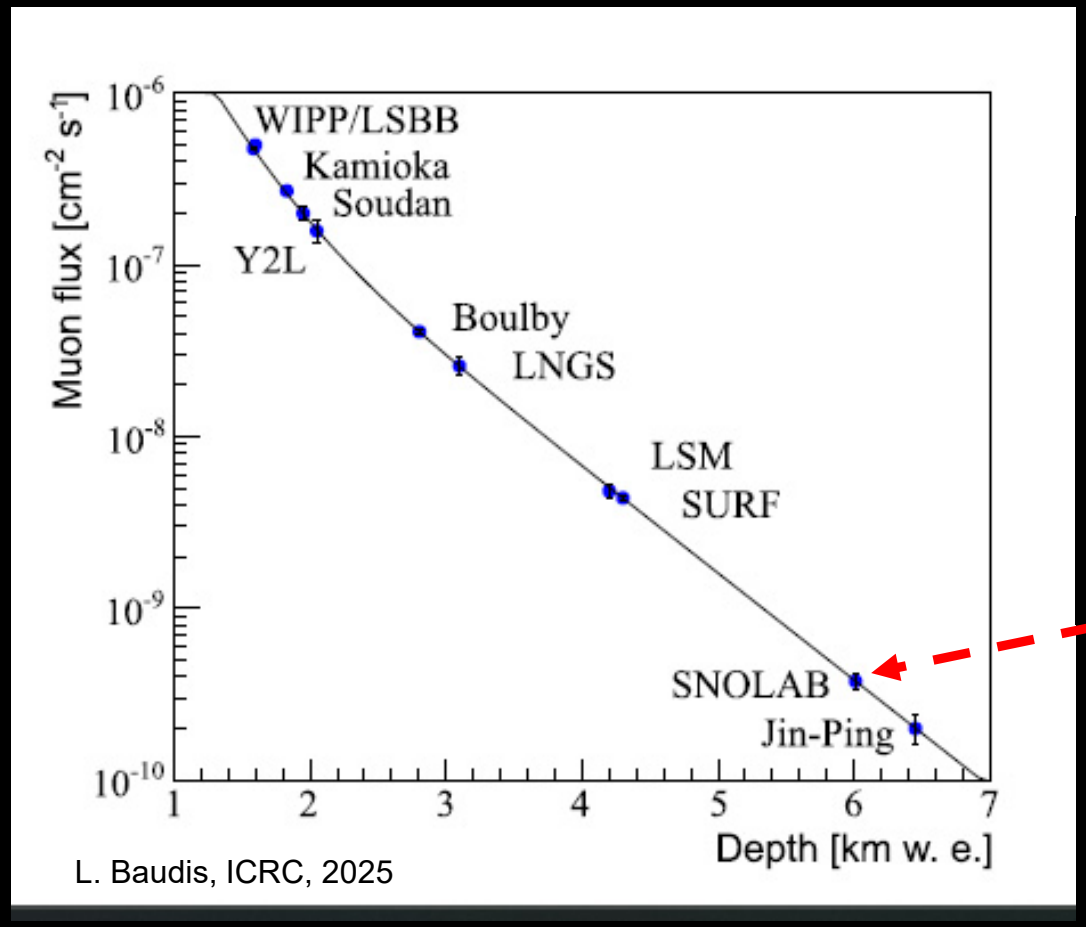
Deep underground !

Purification!

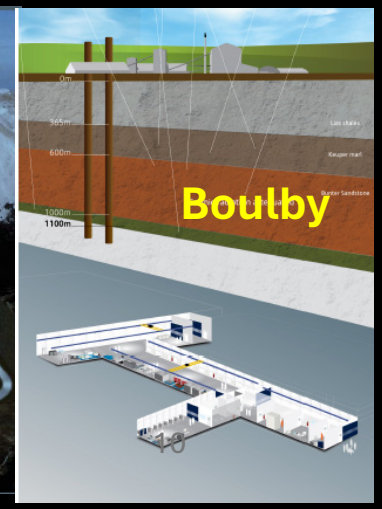
Clean Rooms !

Shielding !

Ultimate: ☀ neutrinos !

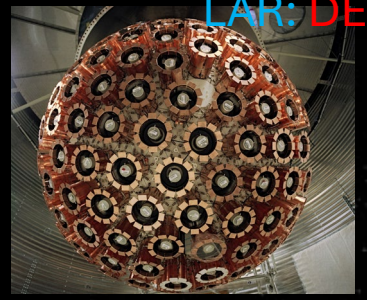


L. Baudis, ICRC, 2025

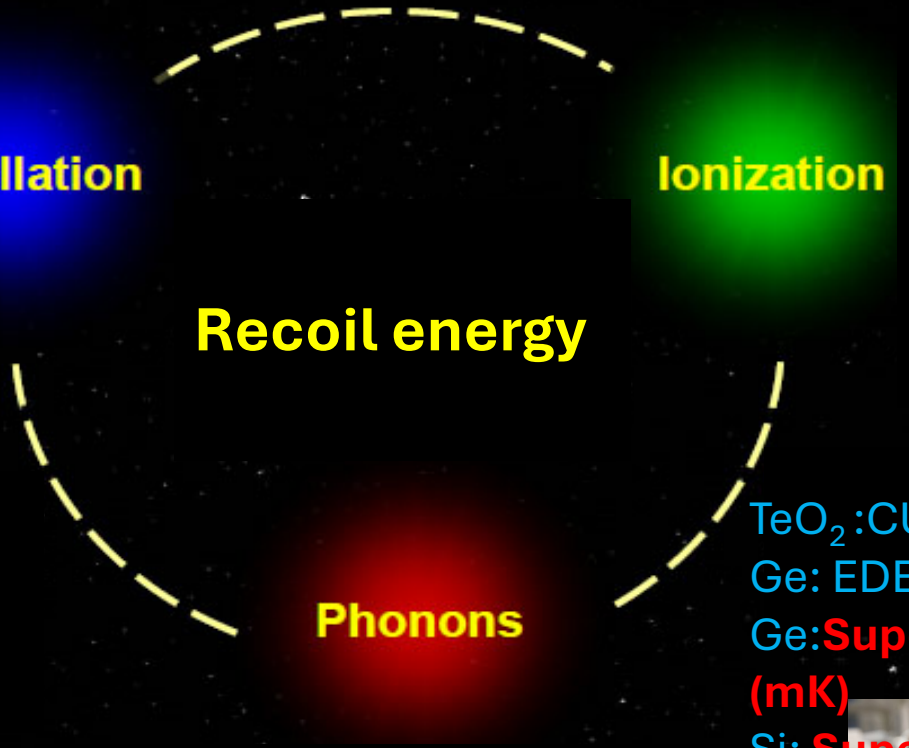


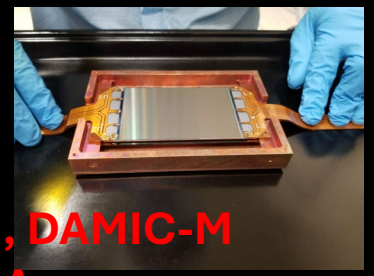
More than 30 Ongoing Searches !

NaI: ANAIS
NaI: DAMA/LIBRA,
NaI: COSINE,
NaI: SABRE
LAR: DEAP



LXe: LZ, PandaX-4T, XENONnT,
LAr: DarkSide-20k



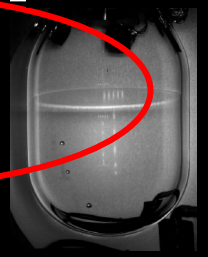


Ge: CDEX
Si: **SENSEI, DAMIC-M**
Si: **OSCURA**
Ne: TREXDM;
He:SF6: CYGNUS,
Ag, Br, C: NEWSdm,
H, He, Ne: **NEWS-G**

$CaWO_4$: CRESST
NaI: COSINUS
LAr: SBC

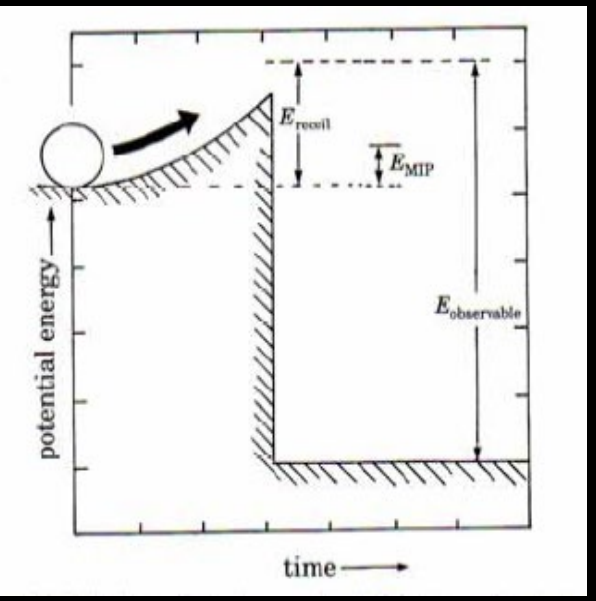
TeO_2 :CUORE
Ge: EDELWEISS
Ge:**SuperCDMS (mK)**
Si: **SuperCDMS**

C_3F_8: **PICO**



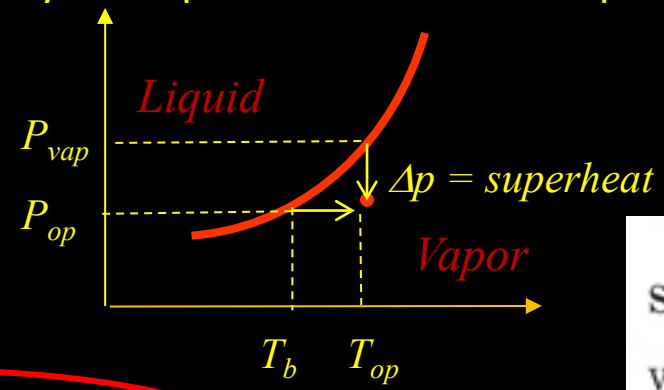
In red: @ SNOLAB !

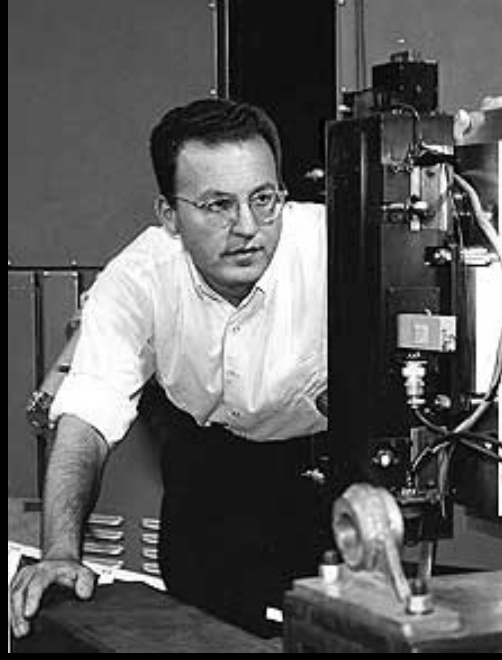
Superheated Liquids for WIMP Detection



Idea (D. Glaser, 1952):

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





At moderate superheat low sensitivity to γ's and e^- !

Urban myths:

Glaser invented BC over a glass of beer ...wrong!

Glaser filled a prototype with beer.....true!

Search For Dark Matter with Moderately Superheated Liquids (*).

(Il Nuovo Cimento, 107, 2, 1994)

V. ZACEK (**)

Dipartimento di Fisica, II Università di Roma - Roma
INFN, Sezione di Roma II - Roma

(ricevuto il 19 Luglio 1993; approvato il 26 Ottobre 1993)

Summary. — A «background blind» bubble chamber, which is exclusively sensitive to nuclear recoils and which is operated in a quasi-continuous mode is described for an improved search of dark-matter candidates. The detection principle is based on the metastability of superheated liquids, which can be tuned such that the detector becomes insensitive to ordinary α, β, γ-radiation.

PACS 96.40 – Cosmic rays.

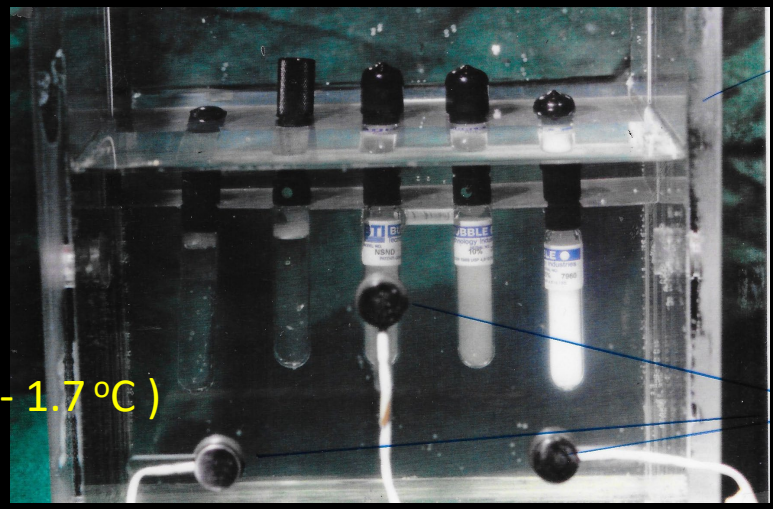
Listening to Dark Matter!

R&D coll. UdeM - BTI , Deep River

Clean room UdeM

1.5 L Detector

- 150 μm droplets of C_4F_{10} dispersed in polymerised gel
- Each droplet is a tiny bubble chamber !
- Droplets moderately superheated at ambient T & P (T_b= - 1.7 °C)
- Optical/acoustic detection and 3D localization



1st Dark Matter Exp. @ SNOLAB !

UdeM, Queen's U. Indiana U., BTI, SNOLAB

Listening to Dark Matter!

R&D coll. UdeM - BTI , Deep River

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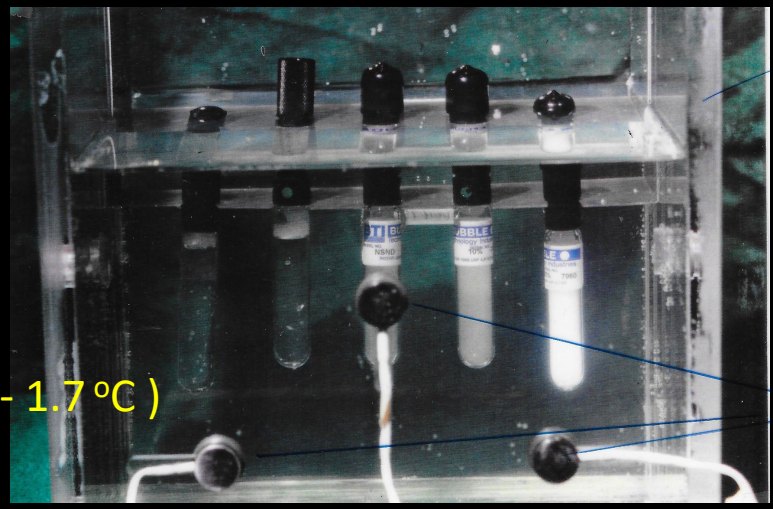
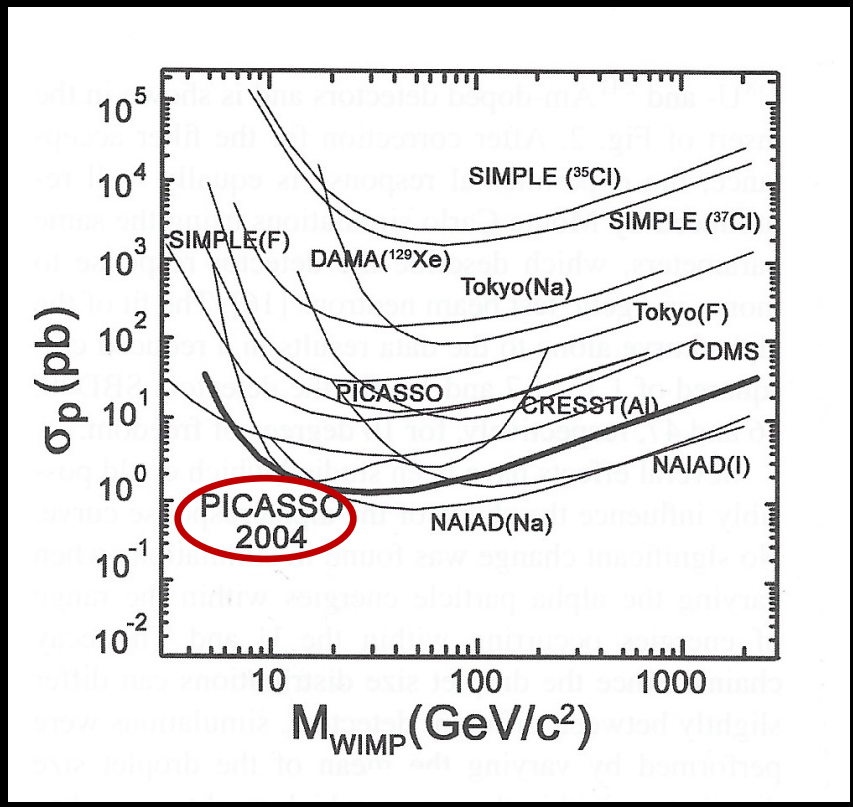


Clean room UdeM

1.5 L Detector

1st Dark Matter Exp. @ SNOLAB !



1st results published 2004

Picasso

- 32 detectors : 2.6 kg of C_4F_{10}
- 288 acoustic R/O channels
- 3D event localization

4.5 L modules @ 85 g C_4F_{10}

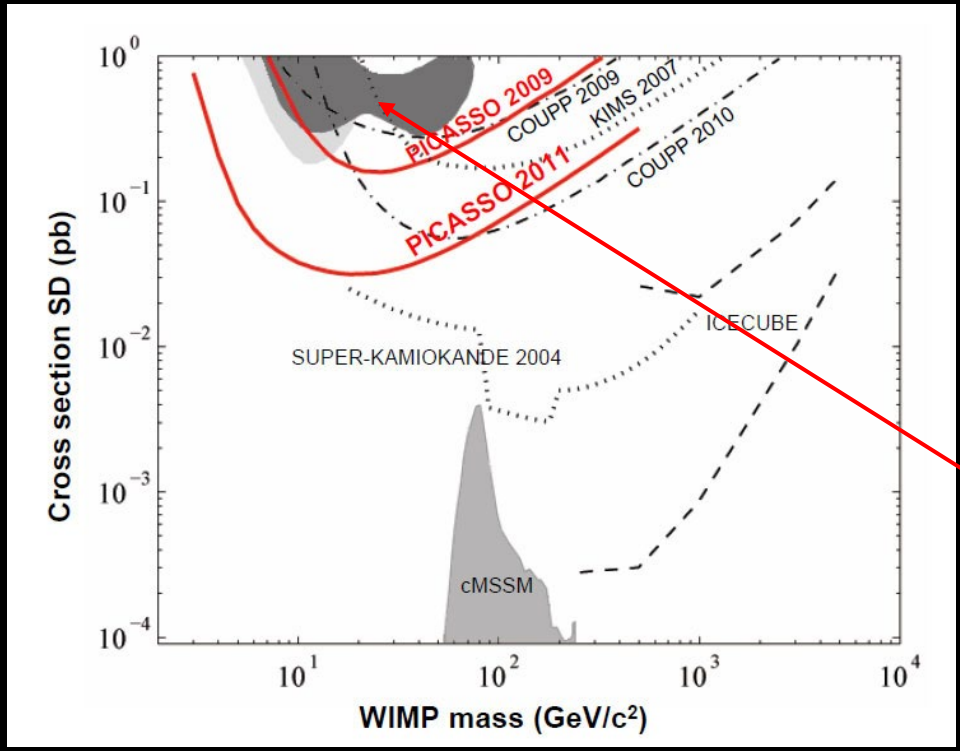
University of Montreal
Queen's University
University of Alberta
Laurentian University
SNOLab,
Bubble Technology I.

Indiana University
South Bend

Czech Technical
University In Prague

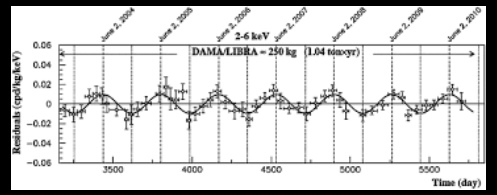
CAPP at Saha
Institute for
Nuclear
Physics

Montréal, June 2011



World leading limits in spin-dependent sector ^{19}F

DAMA effect excluded !

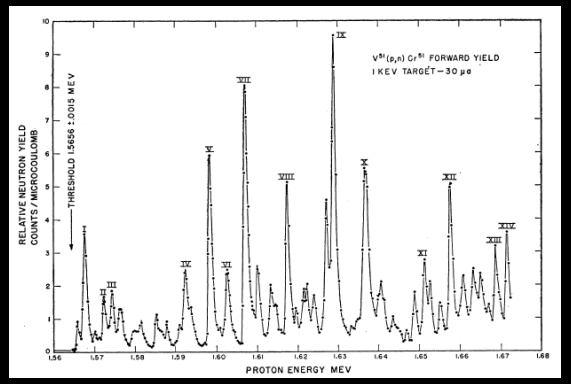



Picasso
15 Septembre 2012

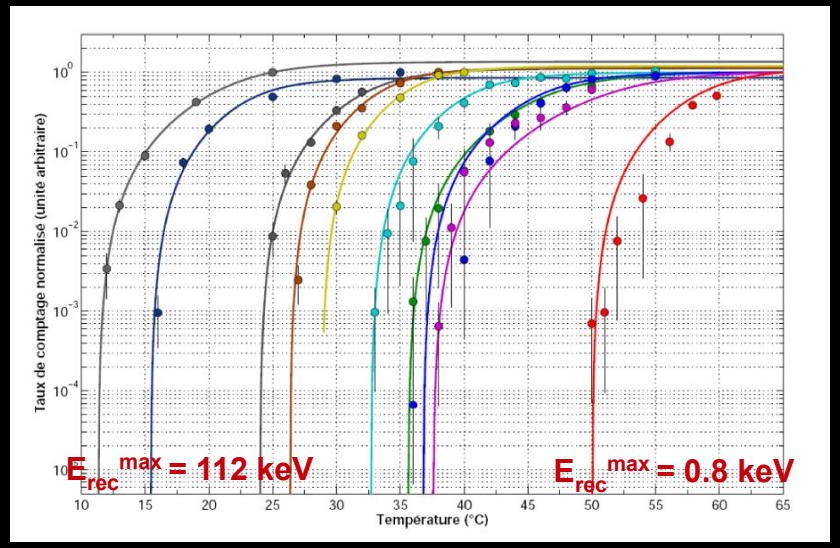
Calibrations & a Surprise!

Picasso

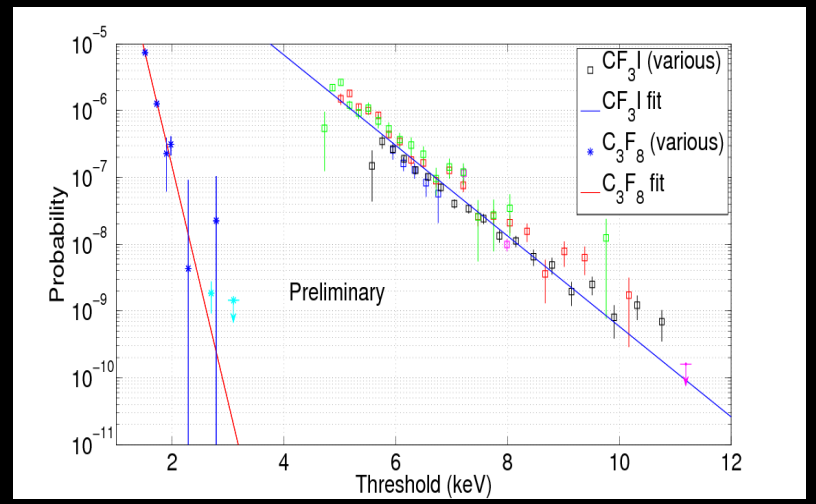
UdeM VdG accelerator



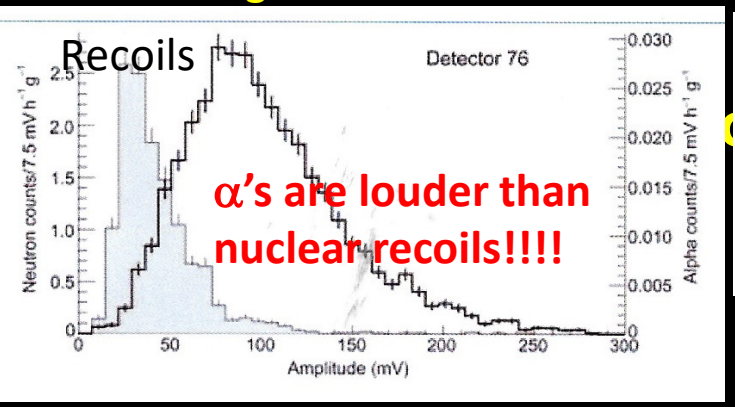
Mono-energetic neutrons



Calibrations down to 1 keV



Excellent γ - discrimination ~10^{-10}



Acoustic α - recoil discrimination !

Best of 2008

New Journal of Physics
The open-access journal for physics

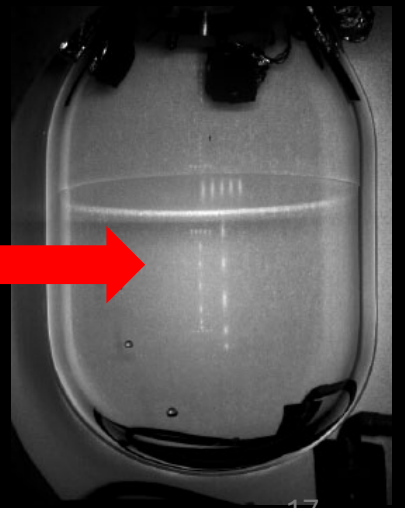
Discrimination of nuclear recoils from alpha particles with superheated liquids

F Aubin[1,7], M Auger[1,8], M-H Genest[1,9], G Giroux[1], R Gornea[1,8], R Faust[1], C Leroy[1], L Lessard[1], J-P Martin[1], T Morlat[1,10], M-C Piro[1], N Starinski[1], V Zacek[1,12], B Beltran[2], C B Krauss[2], E Behnke[3], I Levine[3], T Shepherd[3], P Nadeau[4], U Wichoski[4], S Pospisil[5], I Stekl[5], J Sodomka[5], K Clark[6,11], X Dai[6], A Davour[6], C Levy[6], A J Noble[6] and C Storey[6]

New. J. Phys.10 (2008) 103017

α -Discri in bulk BC better !

More active mass in BC !



PICO = PICASSO + COUPP

SNOLAB
Mining for knowledge
Creuser pour trouver... l'excellence

I. Lawson

Universitat Politècnica de València

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

Northwestern University

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

Saha Institute of Nuclear Physics, Calcutta

P. Bhattacharjee. M. Das, S. Seth

Czech Technical University in Prague

R. Filgas, I. Stekl

D. Maurya, S. Priya

KICP Kavli Institute for Cosmological Physics at the University of Chicago

J.I. Collar, A.E. Robinson

Indiana University South Bend

E. Behnke, H. Borsodi, O. Harris, A. LeClair, I. Levine, E. Mann, J. Wells

Université de Montréal

F. Debris, M. Fines-Neuschild, C.M. Jackson, M. Lafrenière, M. Laurin, J.-P. Martin, A. Plante, N. Starinski, V. Zacek

Fermilab

S.J. Brice, D. Broemmelsiek, P.S. Cooper, M. Crisler, W.H. Lippincott, E. Ramberg, M.K. Ruschman, A. Sonnenschein

Drexel University

R. Neilson

Instituto de Física

E. Vázquez-Jáuregui

Queen's University

C. Amole, M. Besnier, G. Caria, G. Giroux, A. Kamaha, A. Noble

Pacific Northwest National Laboratory

D.M. Asner, J. Hall

University of Alberta

S. Fallows, C. Krauss, P. Mitra

University of Toronto

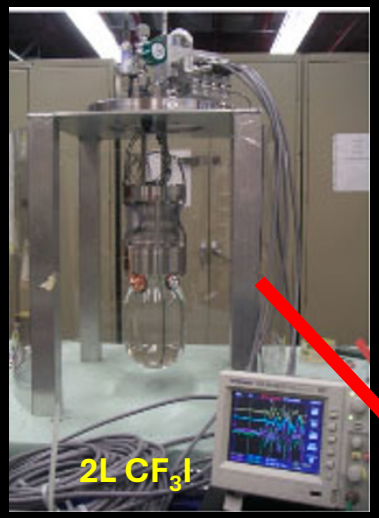
K. Clark

Laurentian University / Université Laurentienne

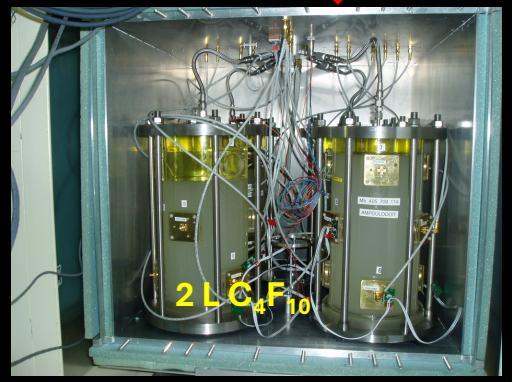
J. Farine, F. Girard, A. Le Blanc, R. Podviyanuk, O. Scallon, U. Wichoski

PICO Program Overview

- 2012
COUPP



PICASSO



PICO

+ CFI

2013-16
PICO2L

2016-17
PICO60

2019 –
PICO40L

...results soon
on arXive..

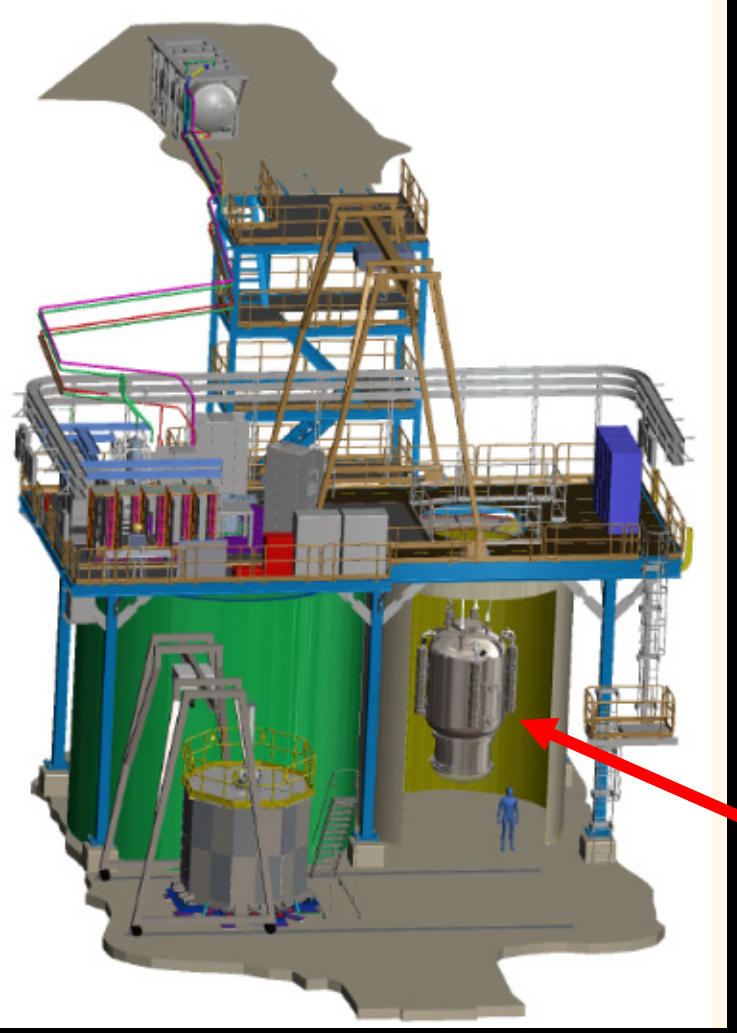
2026 –
PICO500

World leading results at each stage* !

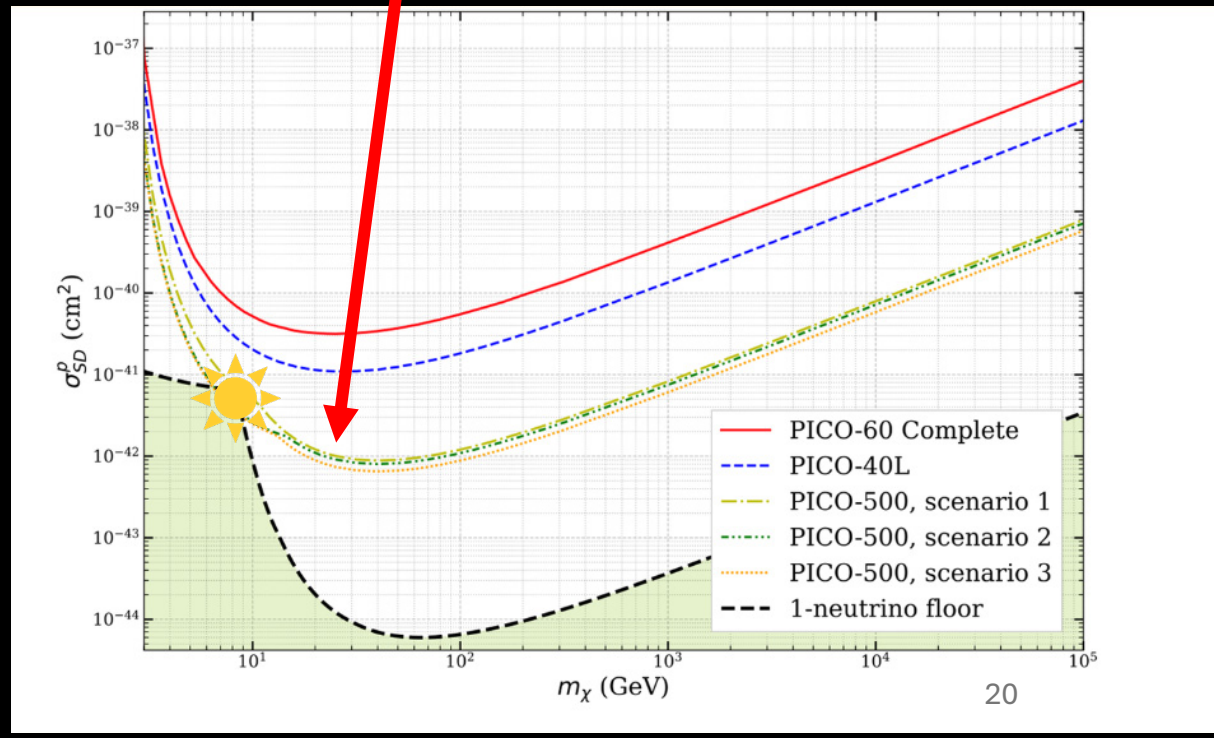
* in the spin-dependent sector

Coming Up: PICO 500

- **250 L of Freon C_3F_8** (≅ 5 Mio BTI dosimeters :)
- **Largest synth. quartz jar ever made**
- **Assembly under way**
- **Fluid Fill Fall 2026**
- **Leading results expected**

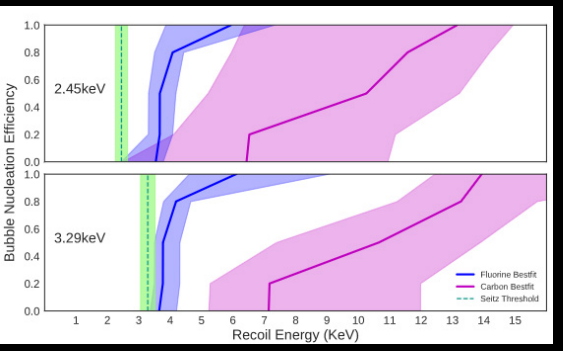


Cube Hall
SNOLAB

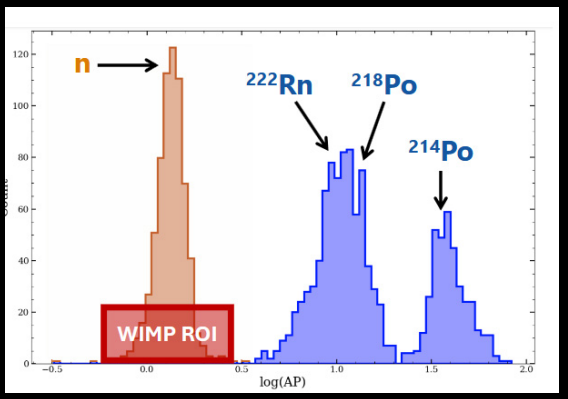


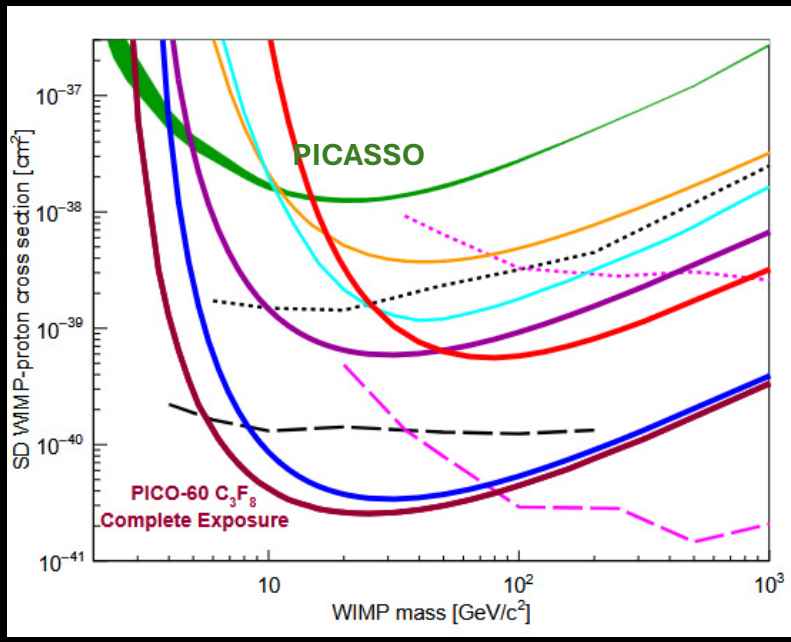
3 Talks @ CAP ’26: Q. Malin, H. Nozart, J. Savoie

Some DM - Bubble Chamber Highlights

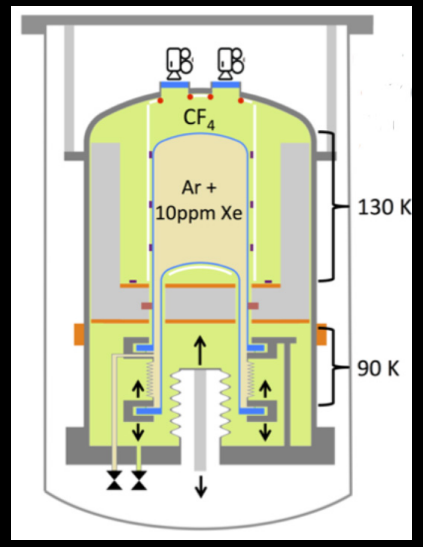


- PICO: the leader in SD – interaction searches
- Largely improved understanding of thresholds & bubble nucleation efficiency
- Molecular dynamics response simulations !
- Acoustic alpha spectroscopy !





PICO 60 2019

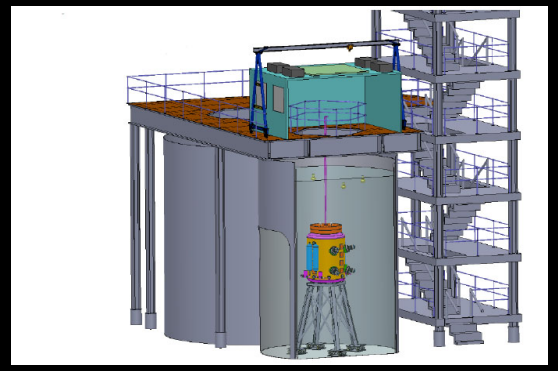


Scintillating BC (Queen's U, FNAL + 12 Inst.)

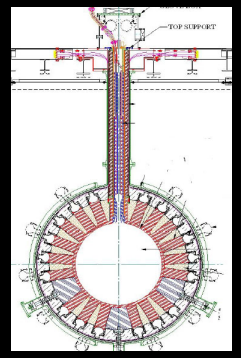
- 10kg LAr
- Push for low thresholds → 100 eV !
- Low WIMP mass region < 1 GeV

The Future of Direct DM - Searches

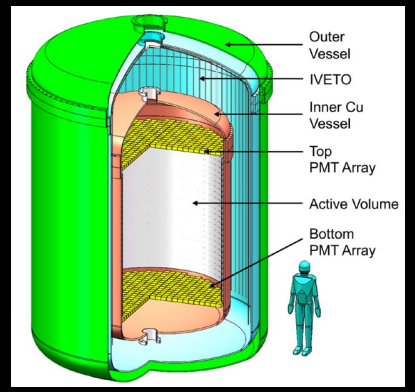
Trend towards a few very large experiments....



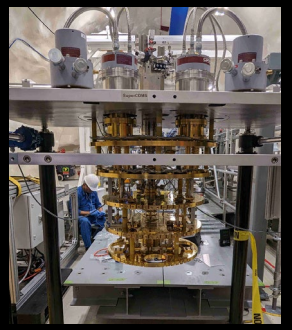
PICO - 500
250 L Freon
SNOLAB



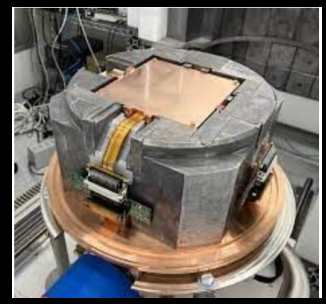
DEAP 3.6 t LAr
SNOLAB



Panda X
43 t LXe
JingPing

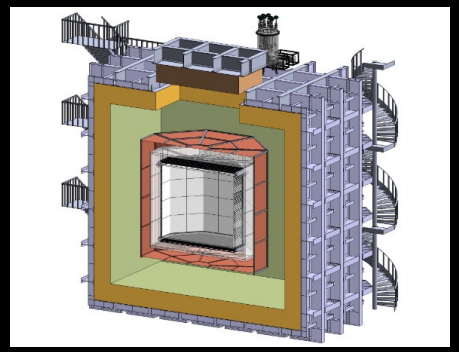


Super CDMS 0.2 t Ge
→ GEODM 1.5t Ge
SNOLAB

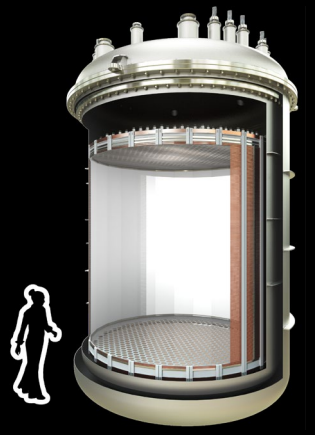


CCDs: DAMIC, SENSEI,
OSCURA : 10kg
SNOLAB

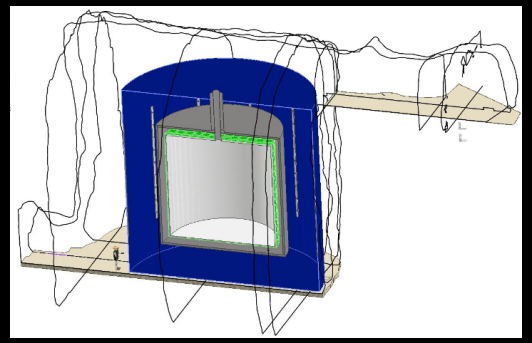
….and experiments with sub - keV sensitivity



DARKSIDE 20K
50 t LAr
LNGS

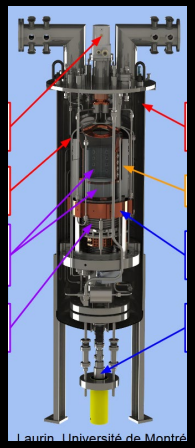


XLZD
(Xenon-LZ-DARWIN)
60 t LXe
SNOLAB ?



ARGO
Global Argon Dar Matter Coll.
400 t LAr
SNOLAB?

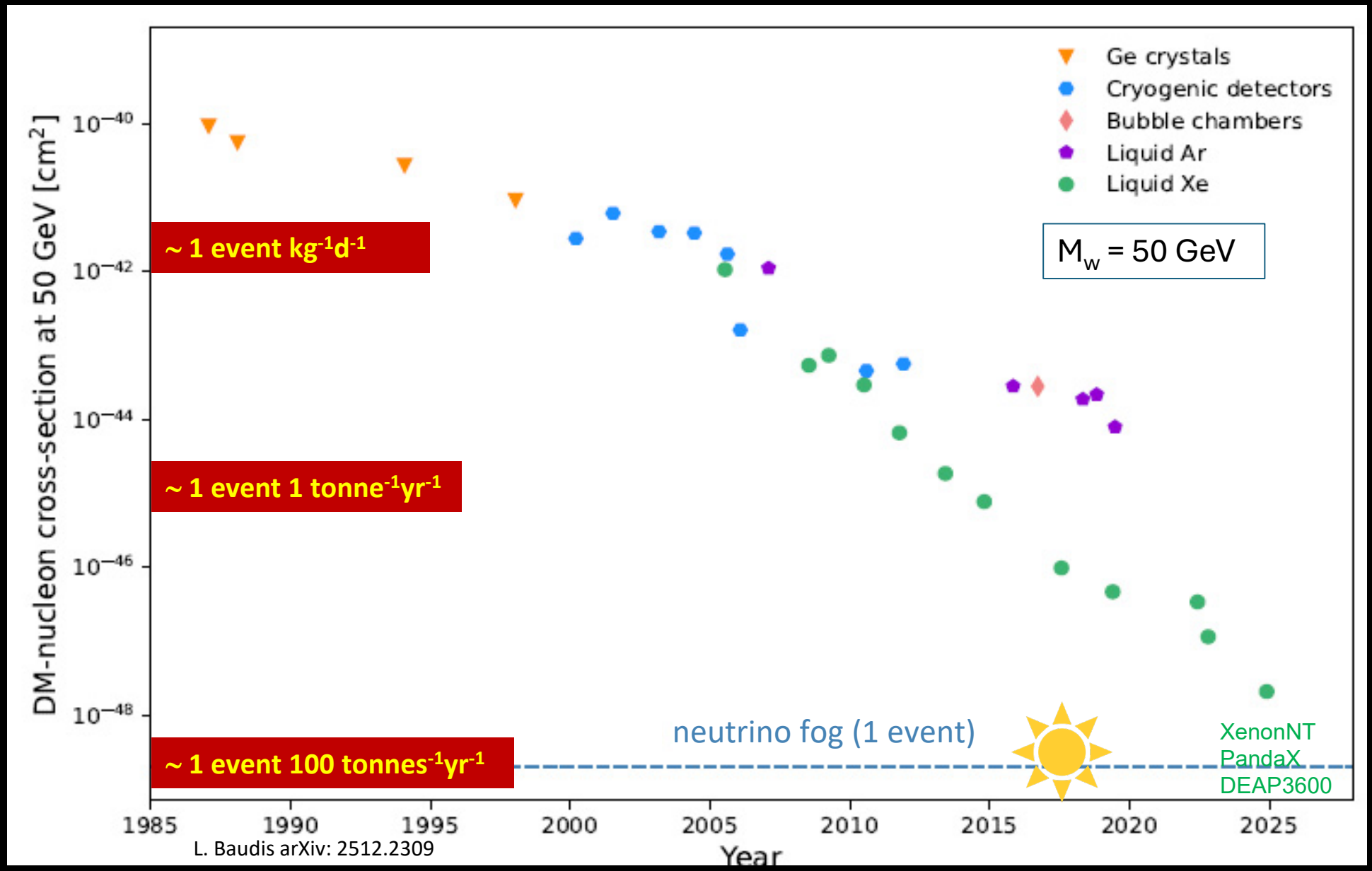
NEWS-G
H,He,Ne
SNOLAB



SBC
10 kg LAr
SNOLAB

….and directionality ?

Tremendeous Progress Over the Years!



L. Baudis arXiv: 2512.2309

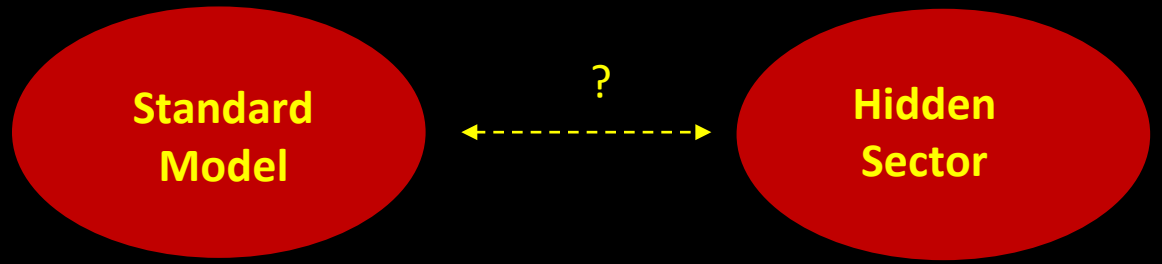
Sensitivity increased by 10^8 !

Solar ν's seen !

...but no DM !

But maybe….

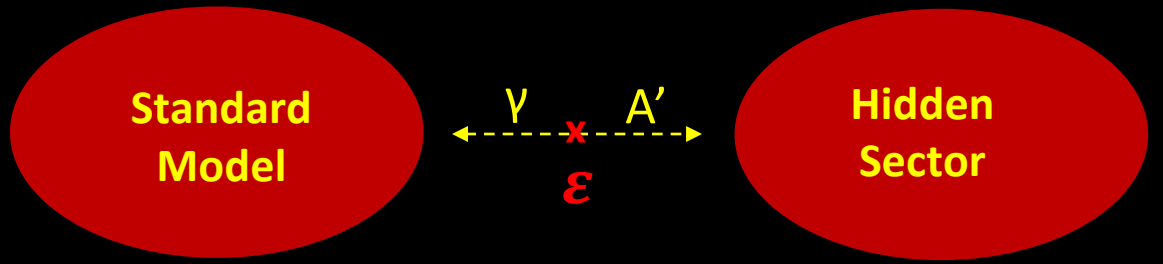
…since all evidence for DM is only gravitational so far, DM might also live in a hidden sector, composed of particles with no SM gauge interactions (electroweak, strong)



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

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)



Maybe an A' mediates interaction with ord. matter $\sim\varepsilon$

A' mixes kinetically with γ

A > 5σ Evidence for a New 17 MeV Mediator 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

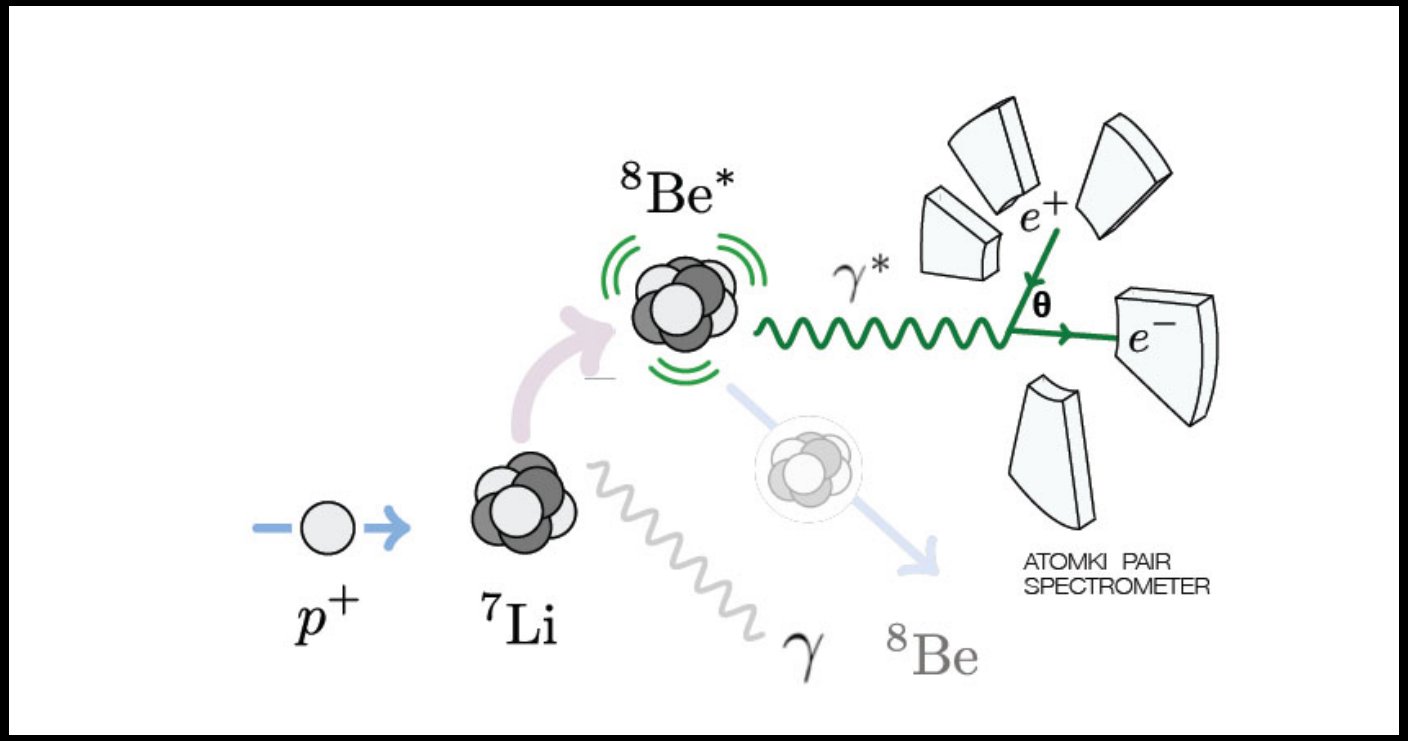
Nikhef National Institute for Subatomic

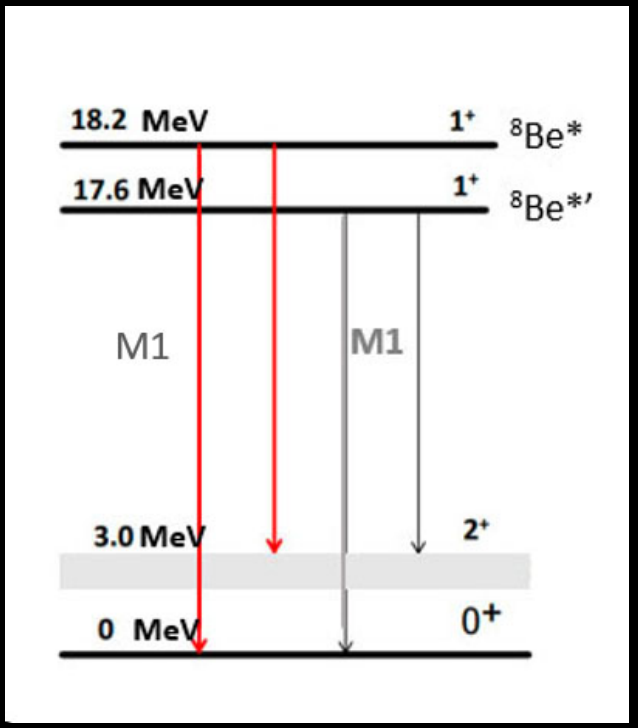
CERN, CH-1211 Geneva 23, Switzerland and Insti
P.O. Box
(Received 7 A

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.

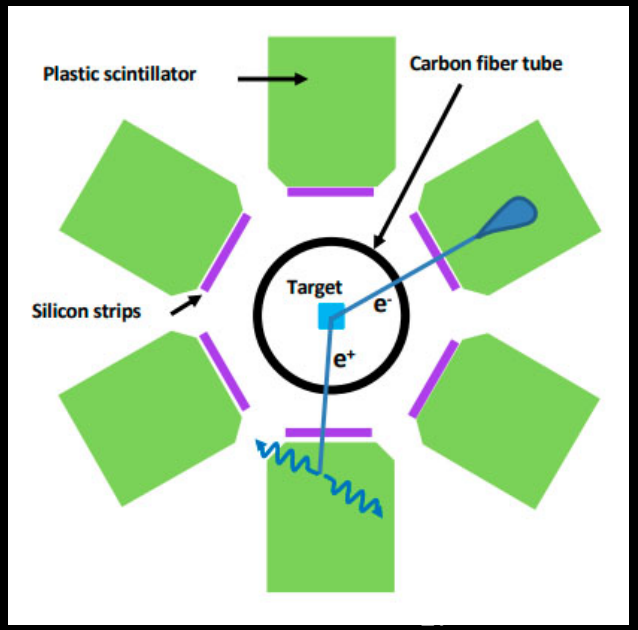
The ATOMKI Experiment! (2016)





- Fraction of γ's converted into e^+e^- by Internal Pair Conversion (IPC)
- Measure angular distribution of e^+e^- pairs

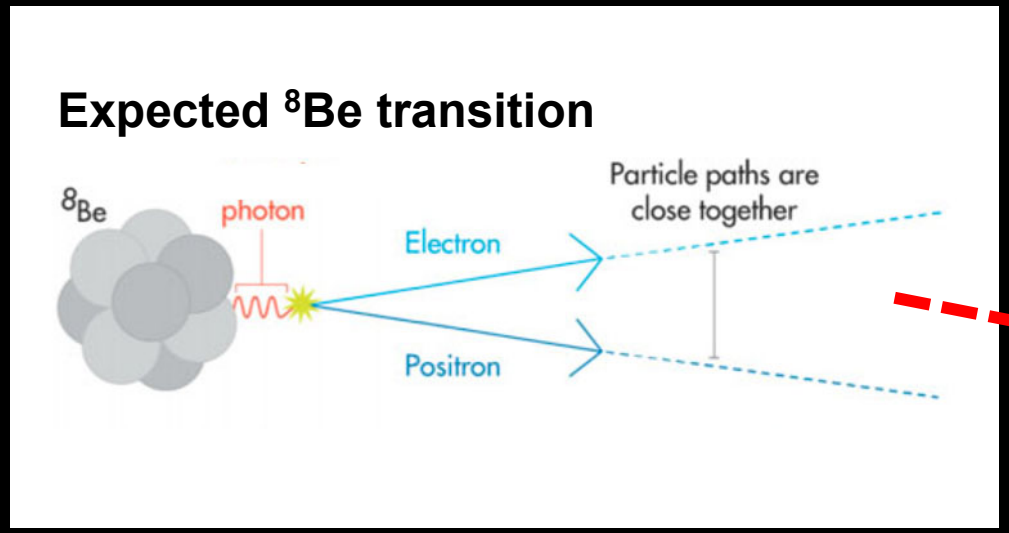
Text book physics !

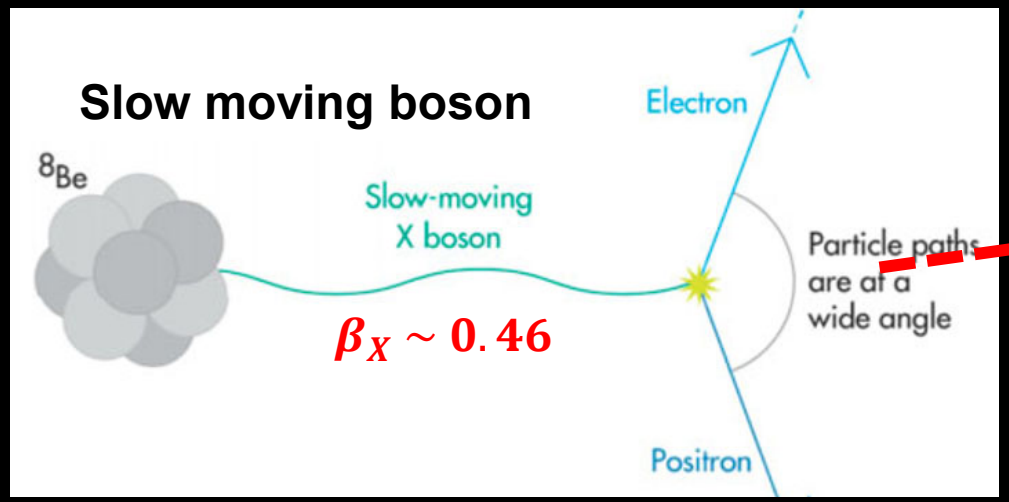


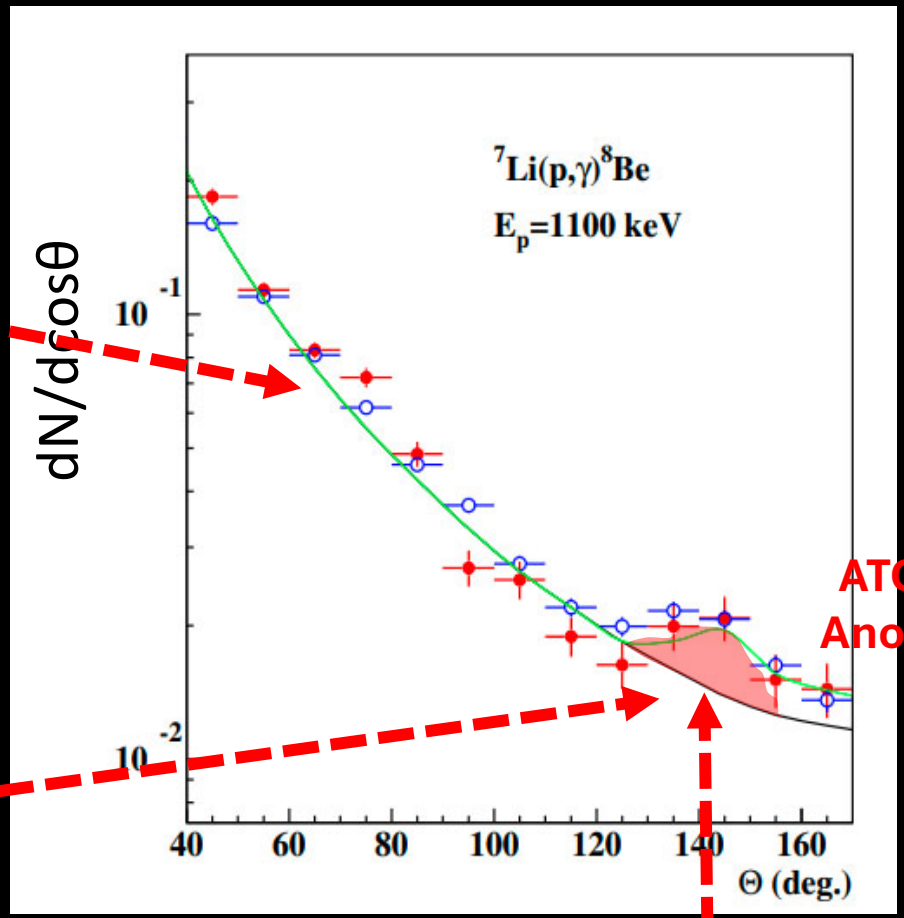
(Graphics J. Feng et al; arxiv:1707.09749)

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

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



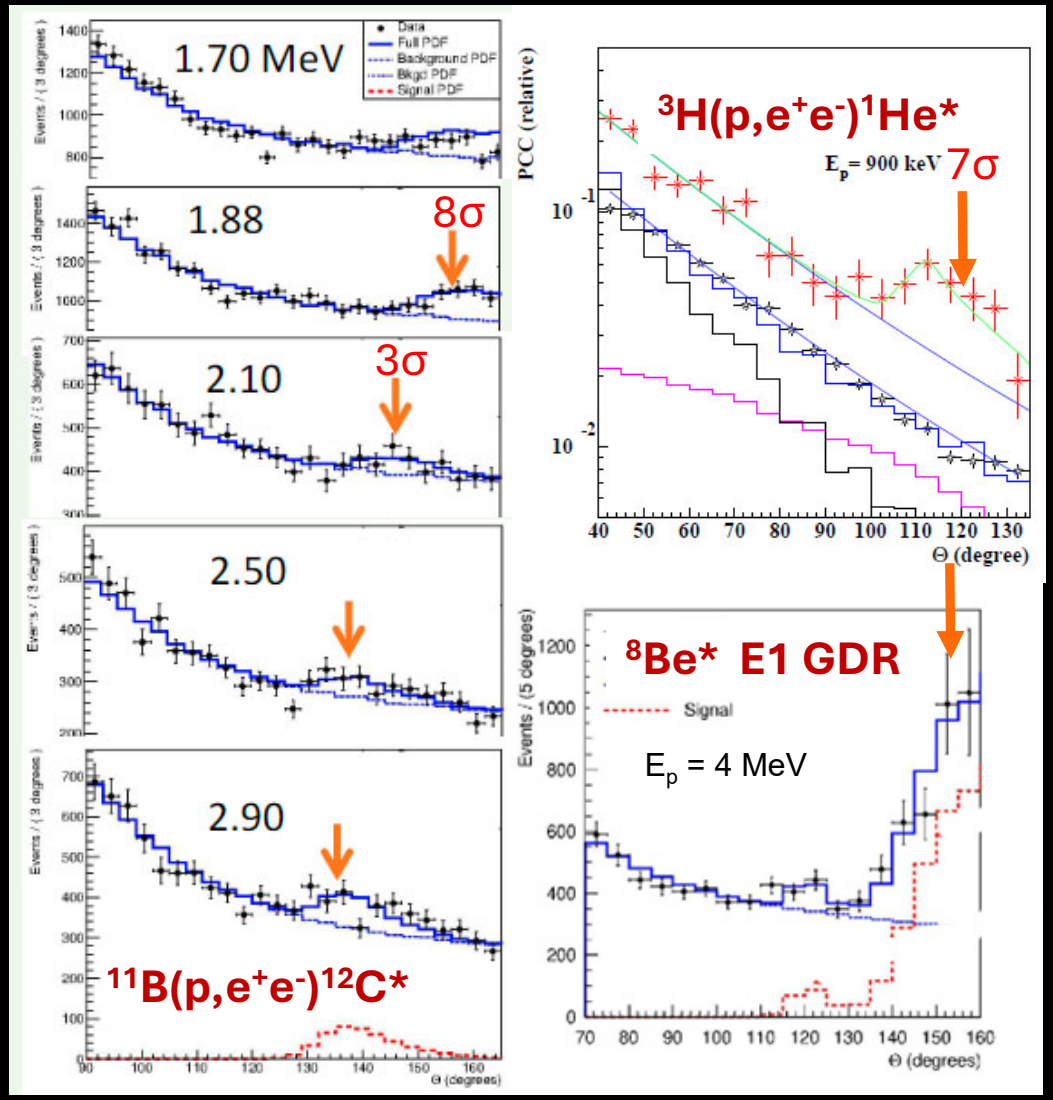




$M_X = 16.7 \pm 0.6$ MeV

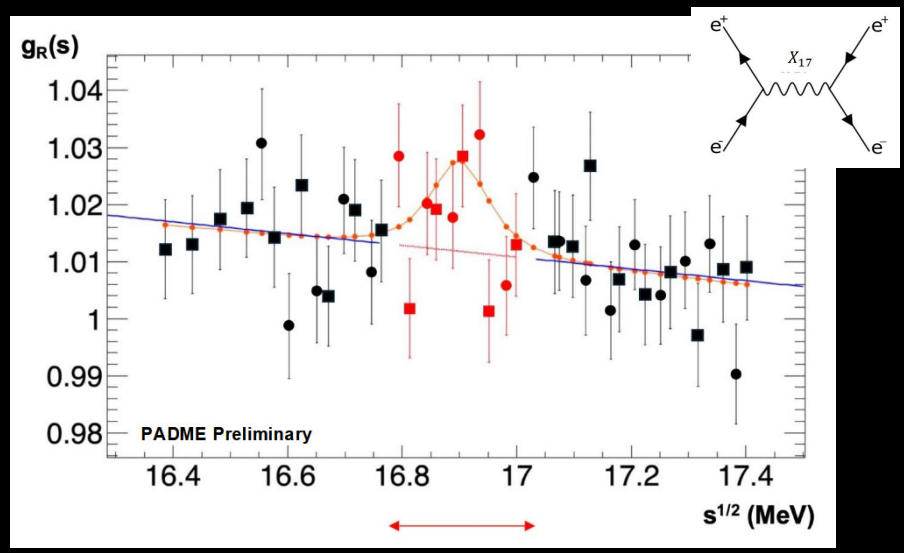
Where Else ?

ATOMKI: other nuclei / energies



Consistent with M_x ~ 17 MeV !

PADME (Frascati) : $e^+ e^- \rightarrow X17 \rightarrow e^+ e^-$



M_x ~ 17 MeV ? (only 2σ… need statistics!)

Situation inconclusive

Presently 15 experiments ongoing !

Canada: DARKLIGHT (TRIUMF) & PX17 UdeM

The Montreal X-17 Project

G. Azuelos[1], D. Bryman[2], W.C. Chen[1], L. Doria[3], L.-A. Hamel[1], M. Laurin[1], L. Lessard[1], M. Lauzon[1], S. Lussier[1], H. de Luz[4], J.P. Martin[1], H. Nozart[1], A. Robinson[1], N. Starinski[1], R. Sykora[4], V. Zacek[1], S. Zhang[1]

[1]U. Montreal, [2]UBC, [3]U. Mainz, [4]CTU Prague,

Main goals:

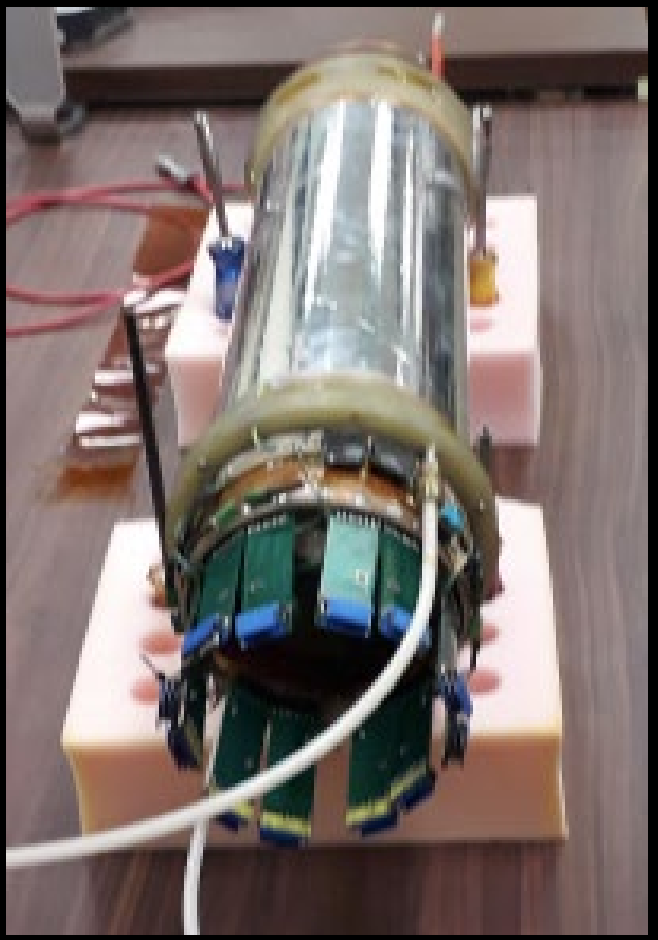
- Verification of ATOMKI results
- Increase acceptance → 0.95 x 4π
- Extend to other nuclei: ^{10}B , ^{12} C, ^{4}He, GDR…

The Montreal Facility

Tandem Van de Graaff (6 MV) :

- Up to 20 μA proton beam on target
- Energy res.: 2 keV for E_p = 0.4 -1 MeV
- Dedicated beam line for PX17

…with Help from DAPHNE & TRIUMF

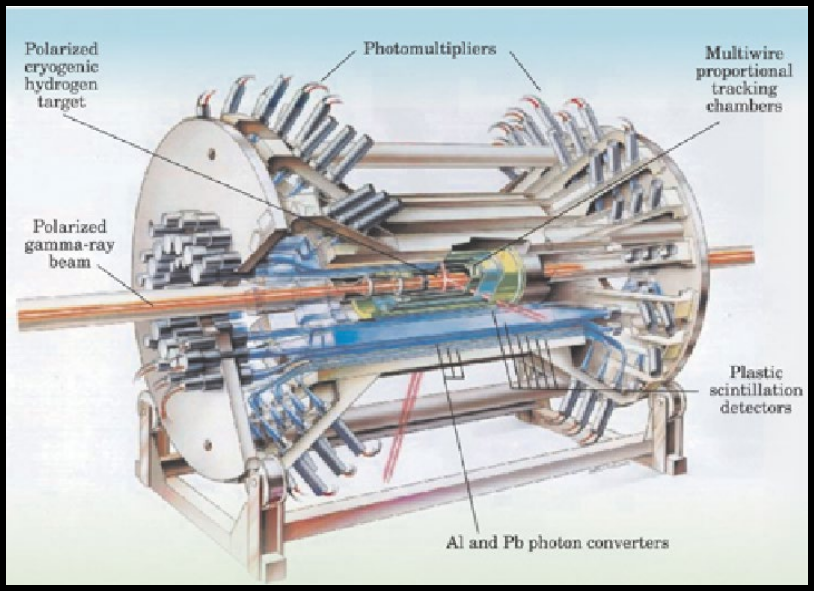


Tracking Chamber & 16 Scintillator bars

Shipped from Mainz to Montreal*

PMT's & Digitizers provided by TRIUMF*

Refurbished + New Electronics @ U. Montreal

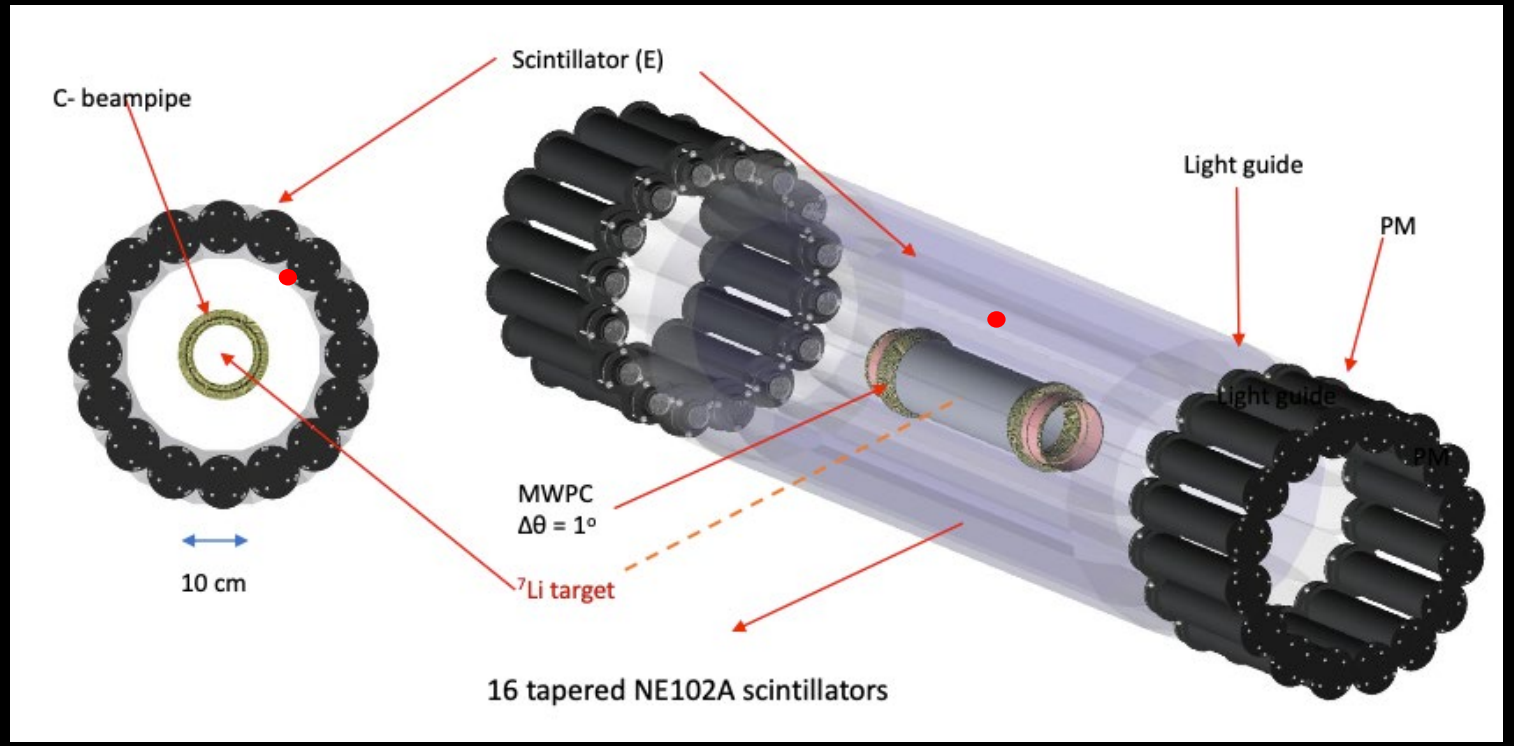


G.Audit et al., Nucl. Instr. Meth. A301, 473 (1991)

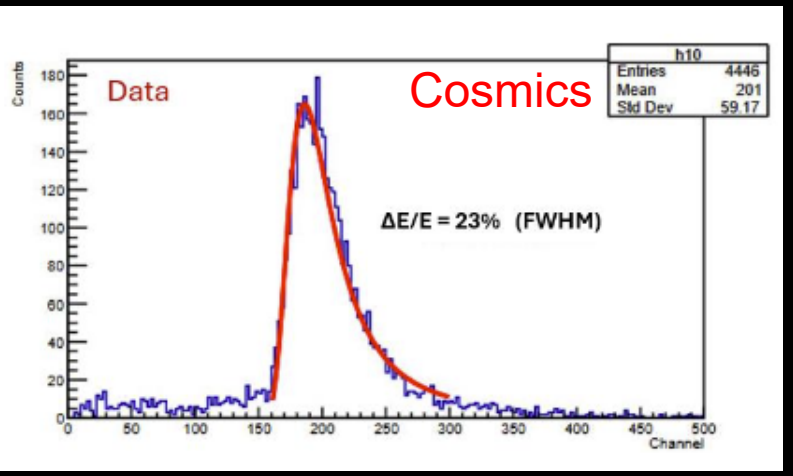
* Special thanks to Doug Bryman, Luca Doria

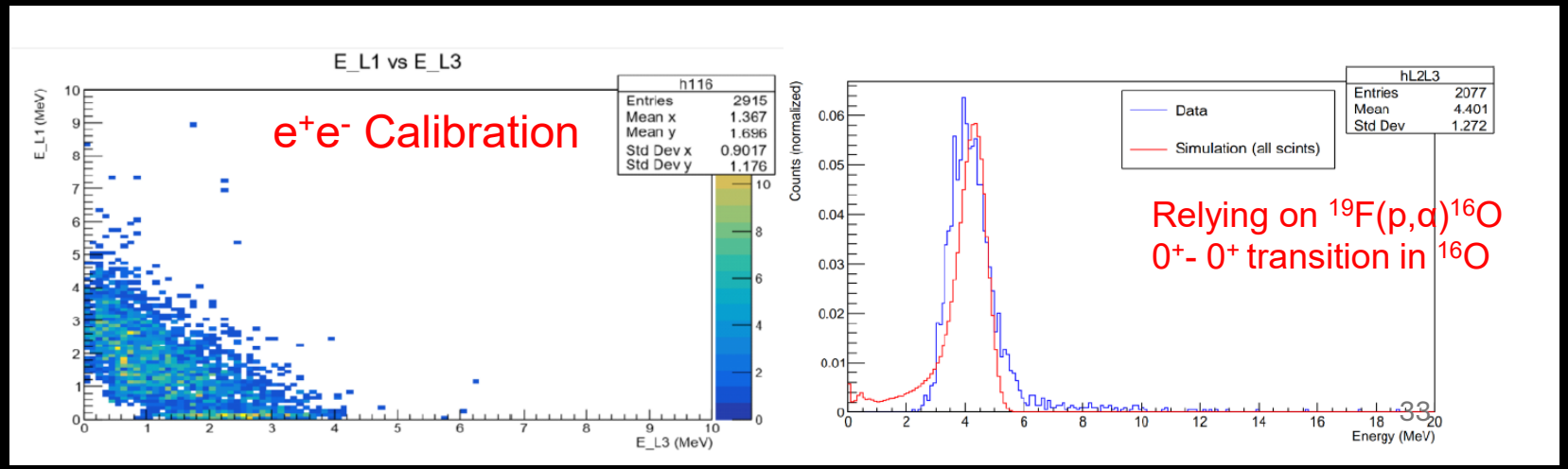
PX17 Detector System

- 16 Scintillators (NE102A)
- MWPC Chamber (2^{o} ang. res)
- Solid angle: 89%
- Carbon-fiber beam-pipe



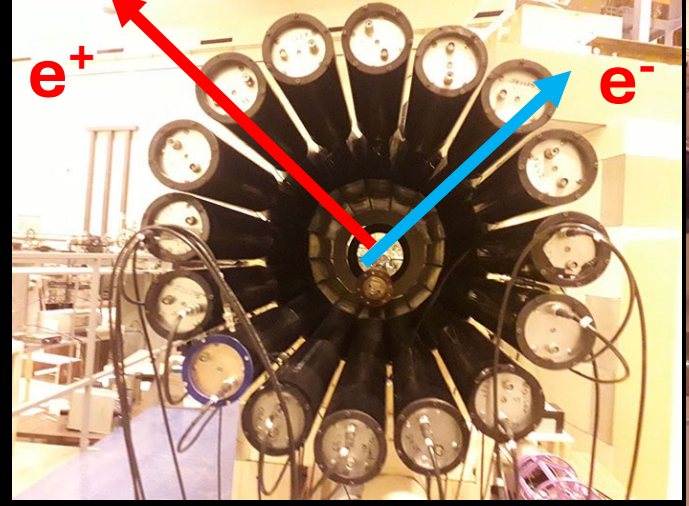
MWPC Readout: VF48 50MHz FADC, 192 (wires) + 120 (strips) channels

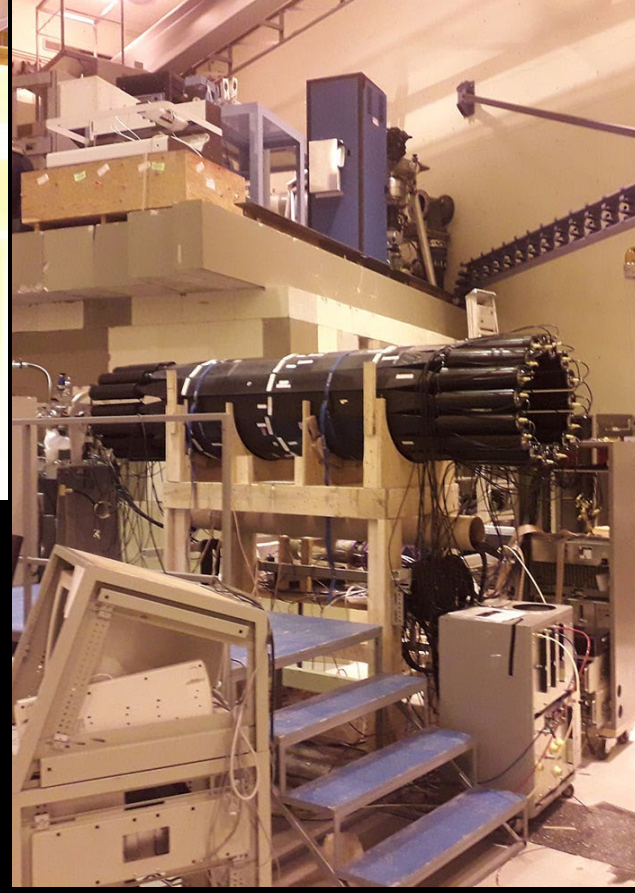


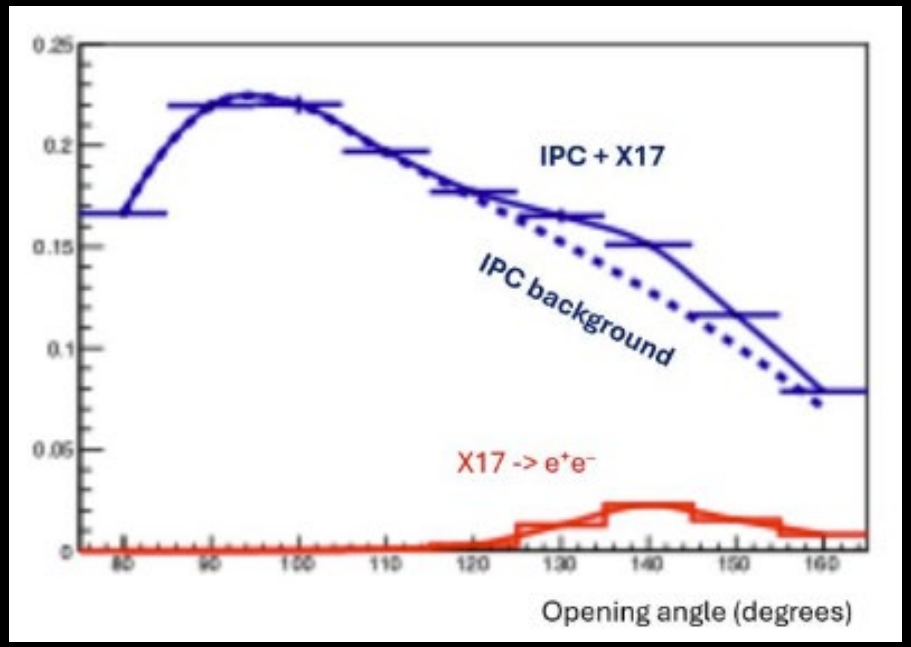


PX17 Status Set-Up

- 10 μA on LiF target demonstrated (cooling!)
- 16 scints calibrated, DAQ & trigger working
- MWPC r/o complete
- 1st level trigger w.1 mm scintillator shell & SiPM – r/o (to be finalized)







GEANT 4 simul for I_p = 2 μA:

- R_{IPC} = 15 cts/h
- R_{X17} = 9 cts/h

Several week of running !

Physics Runs → Fall 2026 ?

Summary and Outlook

- Direct DM searches: no signal detected so far !
- Many different technologies, covering a large range in DM masses & cross sections, starting to hit the ν - floor
- World leading searches at SNOLAB !
- X17 – a Dark Mediator? Intriguing results by ATOMKI in Be*, C* and He*
- PX17 @ UdeM → for independent verification

Be prepared for the unexpected !