

Title: The PICASSO Dark Matter Search Experiment

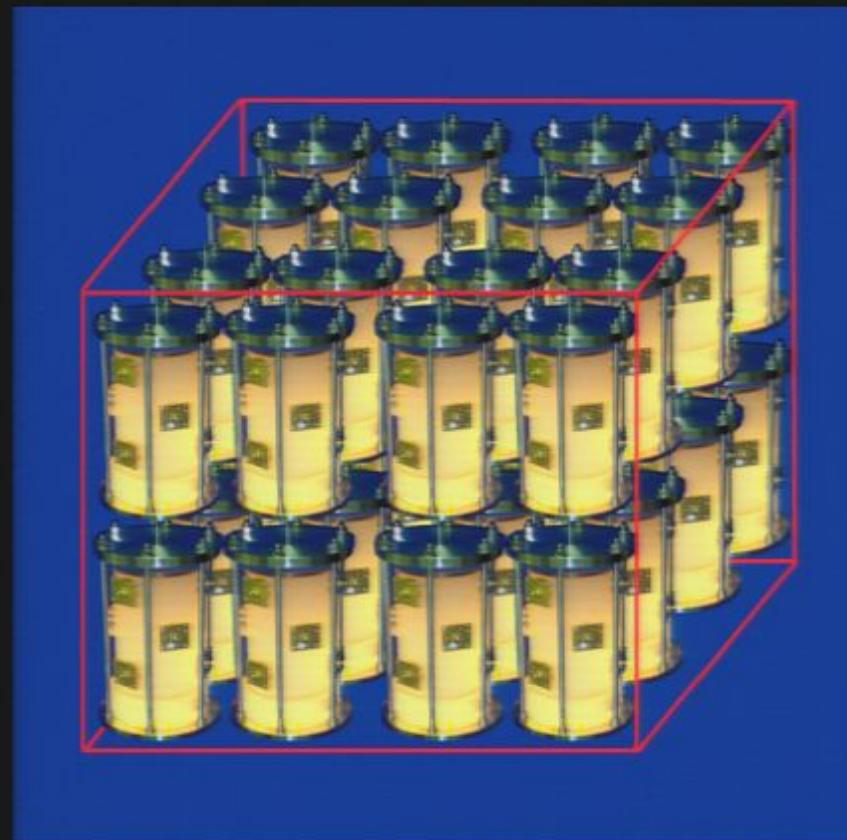
Date: Jun 12, 2009 09:00 AM

URL: <http://pirsa.org/09060058>

Abstract: The PICASSO experiment searches for cold dark matter through the direct detection of weakly interacting massive particles (WIMPs) via their spin-dependent interactions with fluorine at SNOLAB, Sudbury - ON, Canada. The detection principle is based on the superheated droplet technique; the detectors consist of a gel matrix with millions of droplets of superheated fluorocarbon (C_4F_{10}) dispersed in it.

The previous phase of the experiment, which employed 1-litre detector modules (for a total of about 20g of active mass), ended in 2005. The present phase of the PICASSO experiment consists of 32 4.5-litre detector modules for a total of approximately 1,795 g of active mass. In this talk, I will give an overview of the experiment, discuss the progress in background mitigation, which includes improved purification and fabrication techniques, as well as a background discrimination technique that we have recently discovered.

The PICASSO Dark Matter Search Experiment



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Laurentian University

Project in Canada to Search for Supersymmetric Objects

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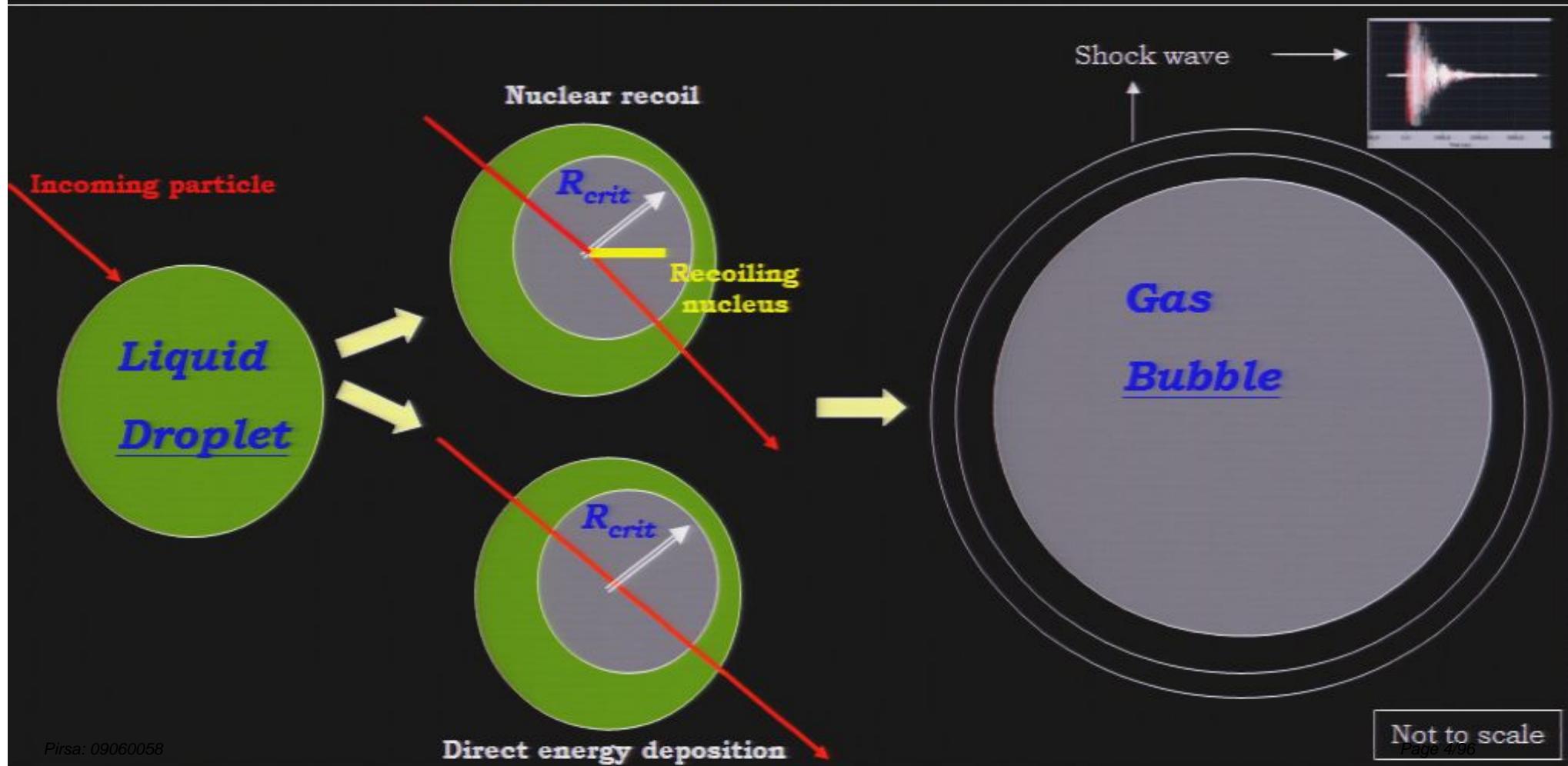


Superheated droplet technique

Seitz theory of phase transition of superheated liquids

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

Liquid-to-vapour phase transition



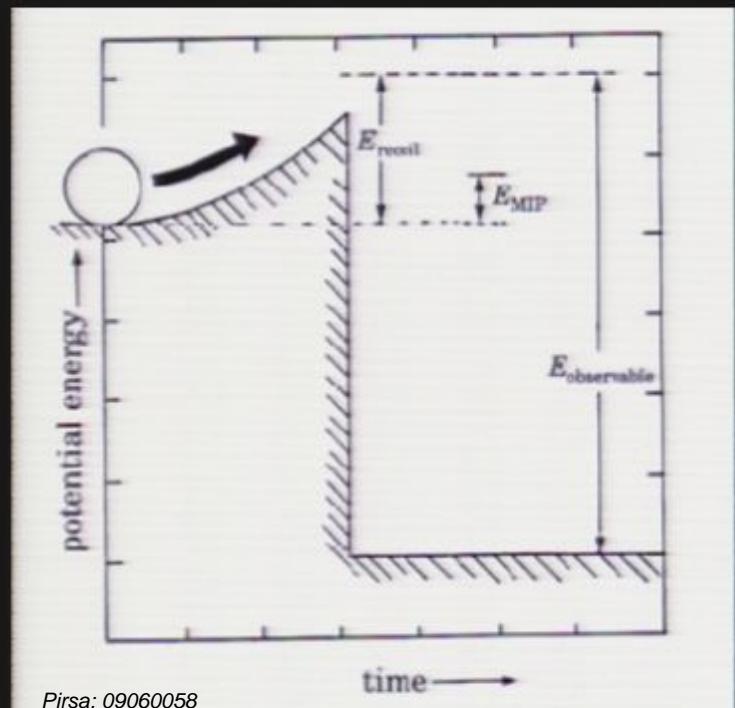
A bubble forms if a particle creates a heat spike

- with enough energy E_{\min}
- deposited within R_{\min}

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

$$R_{\min} \equiv \frac{2\gamma(T)\varepsilon}{\Delta P(T)}$$

$$E_{\min} \equiv \frac{16\pi}{3 \times \eta} \frac{\gamma^3(T)}{(\Delta P(T))^2}$$



$\Delta P(T)$ = superheat
 $\gamma(T)$ = Surface tension
 ε = critical length factor
 η = energy convrs. efficiency

Main Advantages

- Room Temperature operation
- Insensitive to mips – better than up to 10^{10} at operating temperatures (pressures)

Experiments: SIMPLE, COUPP, PICASSO

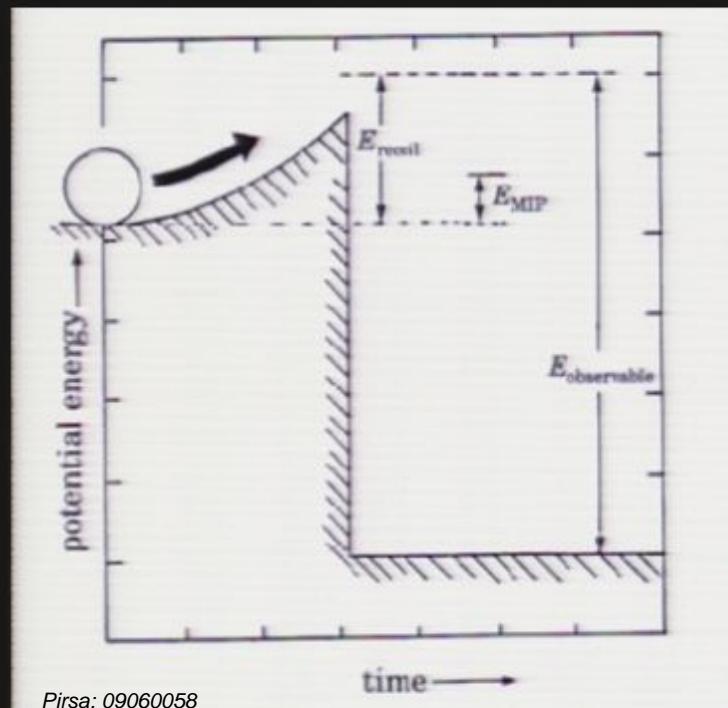
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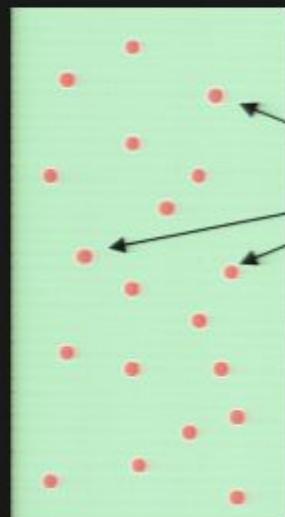
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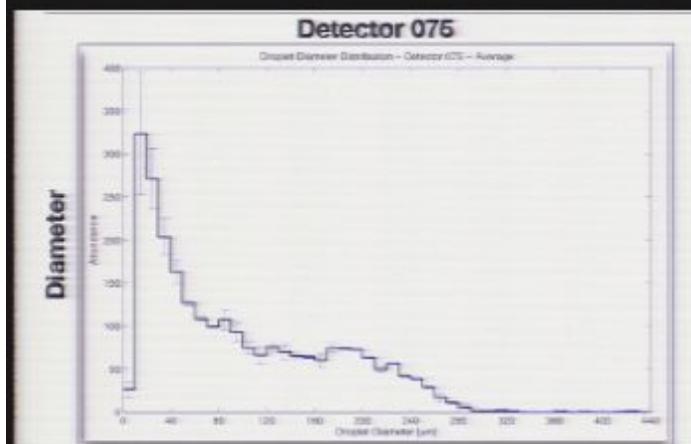
Experiments: SIMPLE, COUPP, PICASSO

Special Bubble Detectors

1) Polymerized Aqueous Gel Matrix
Inert Component



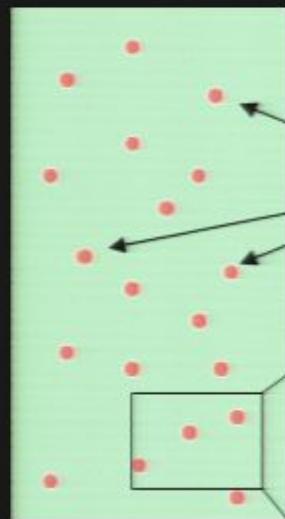
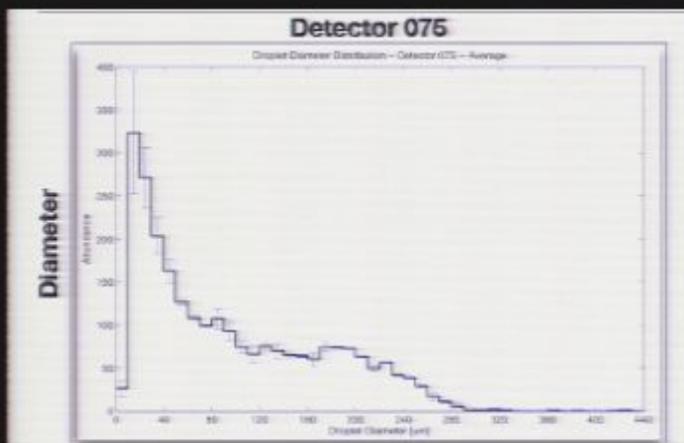
2) Freon C₄F₁₀ Droplets
Active Component



- Fabrication technique based on the Bubble Detectors produced by **Bubble Technology Industries**
- Modified to customize the detectors for the Dark Matter Search (Larger, Cleaner)
- Gel ingredients: water, acrylamide, bis-acrylamide... **Cesium Chloride** (to equalize densities)
- Gel ingredients – saltless: water, glycol, glycerine (viscosity principle)

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Bubble detectors for dark matter detection

Picasso

“Search for Dark Matter with Moderately Superheated Liquids”
(V.Z., Il Nuovo Cimento, 107, 2, 1994)



1st generation* : 10ml

Main Features

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- continuous operation 40h
- recompression recycles burst droplets
- low cost, with potential for a large DM experiment in house fabrication



2nd generation : 1L

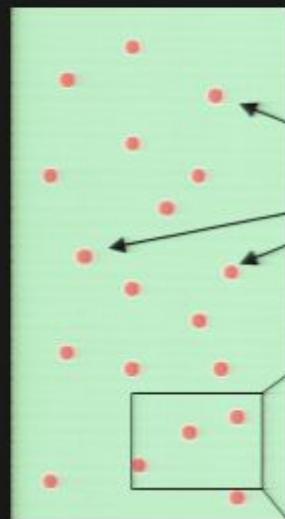
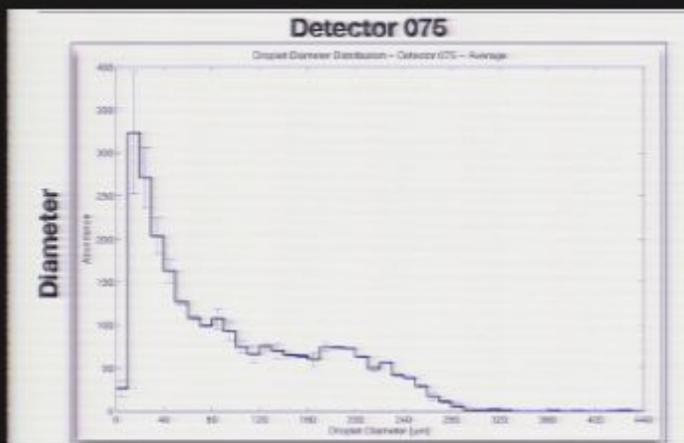


3rd generation : 4.5L

* Picasso inspired by personal neutron dosimeters @ Bubble Technology Industries, ON

Special Bubble Detectors

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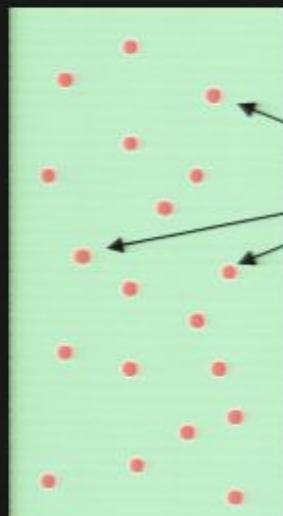
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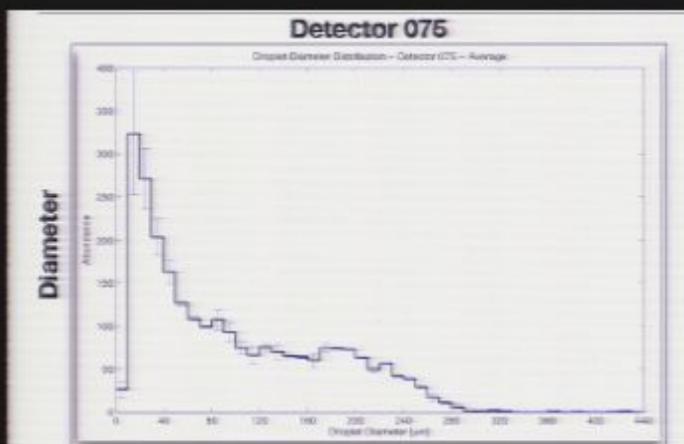
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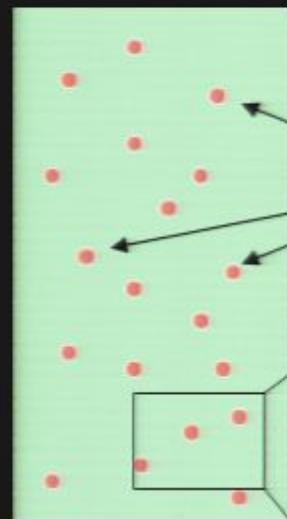
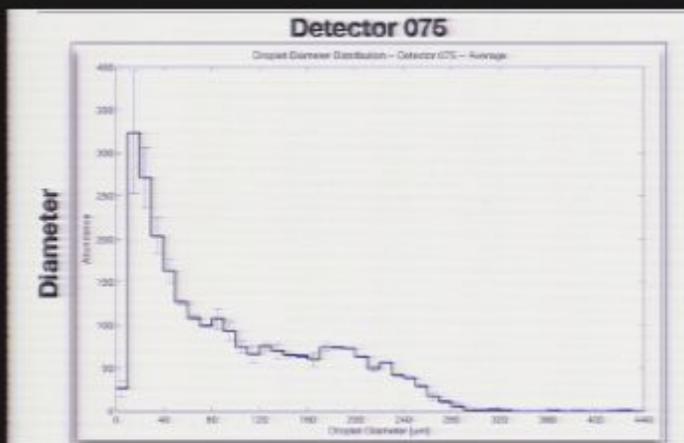
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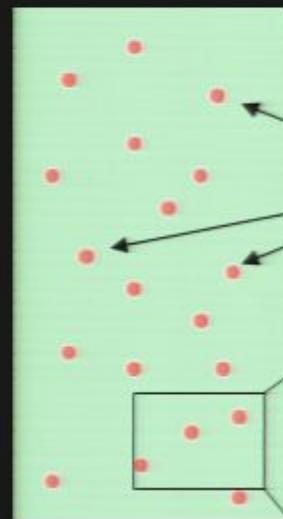
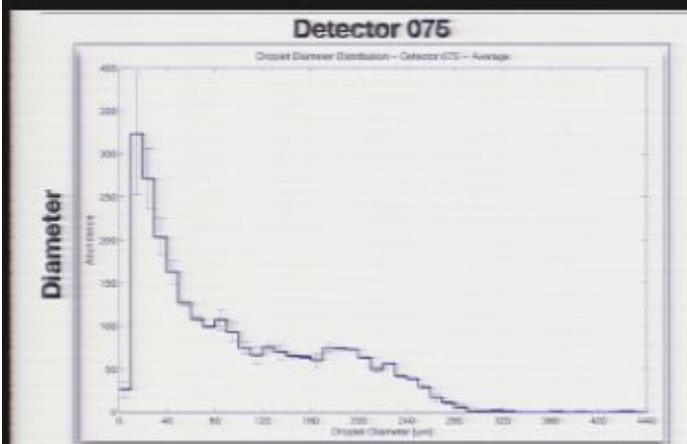


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Operation cycle

Data taking: (> 30h)

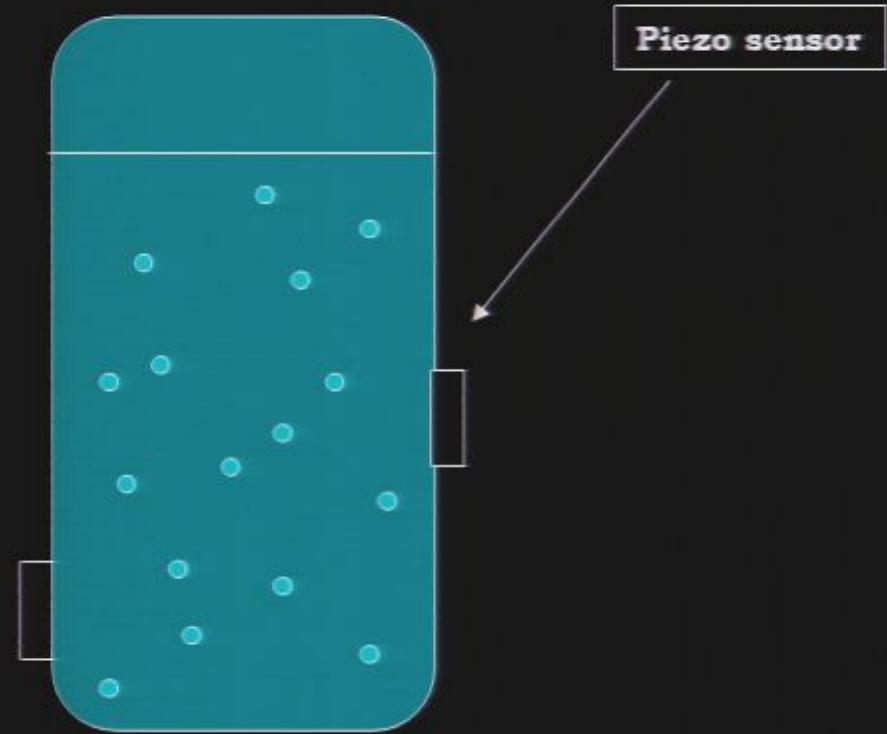
Temperature range: ~15 C
to ~50 C

Relative pressure: 0 psi

Recompression: (~10h)

Relative pressure: ~ 90 psi

Duty Cycle: ~75%



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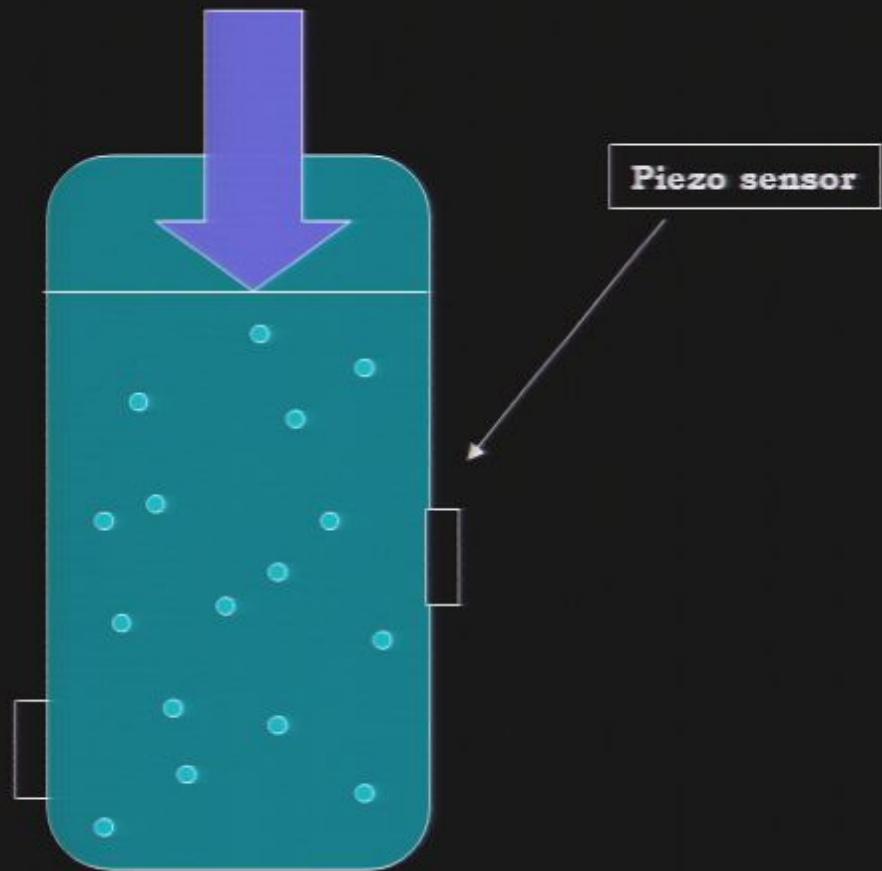
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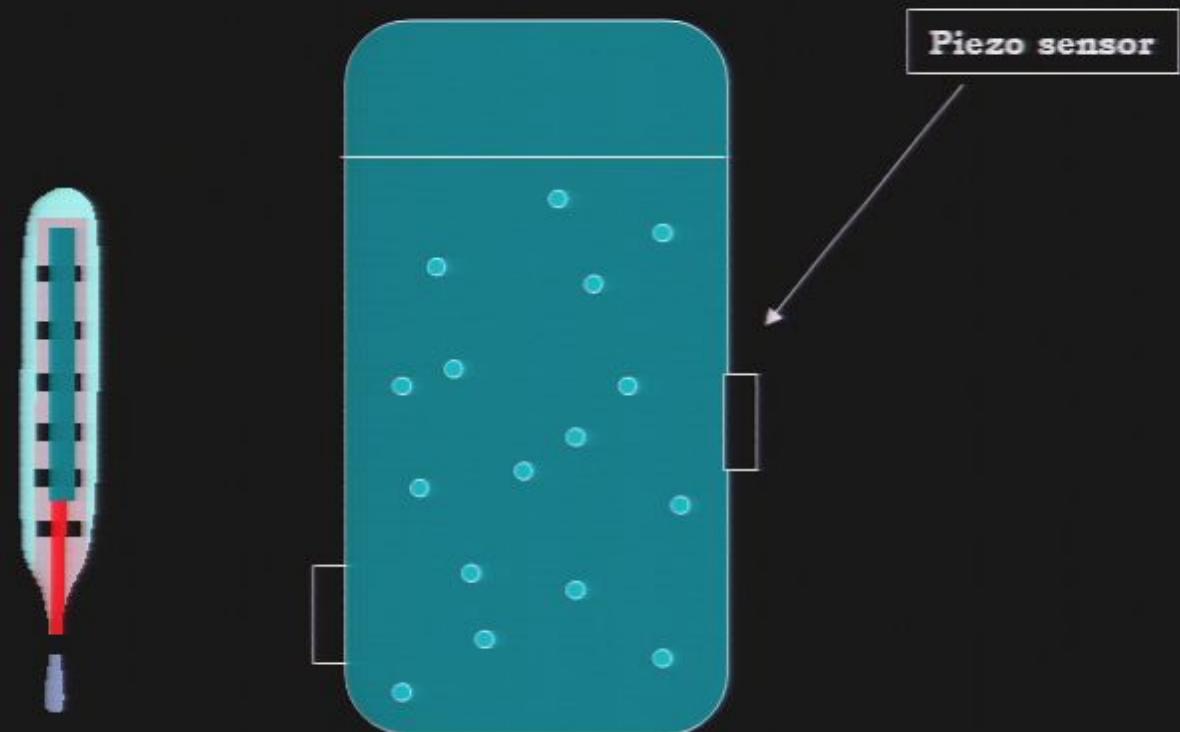
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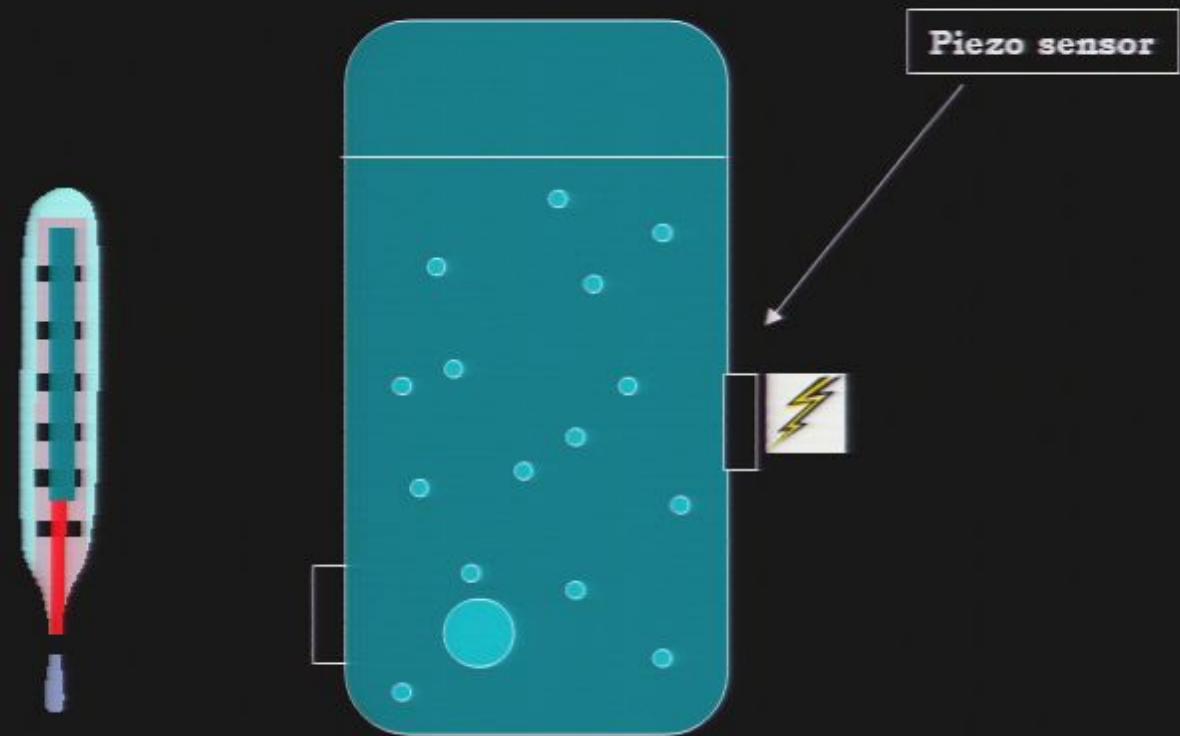
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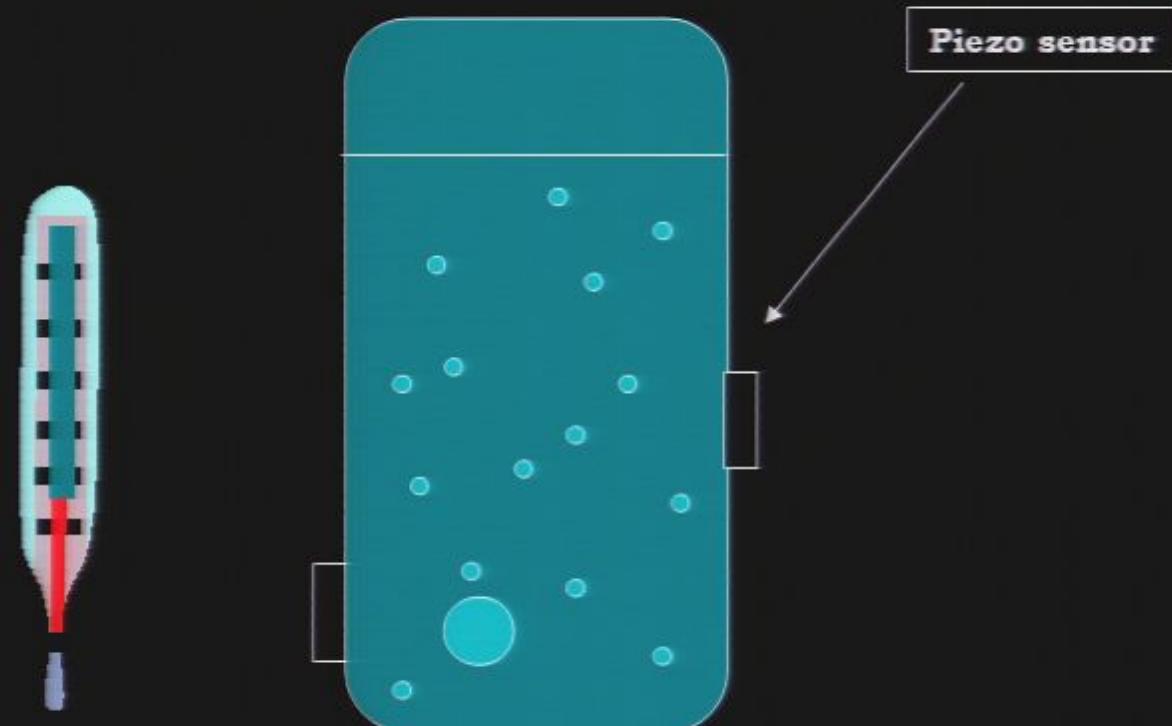
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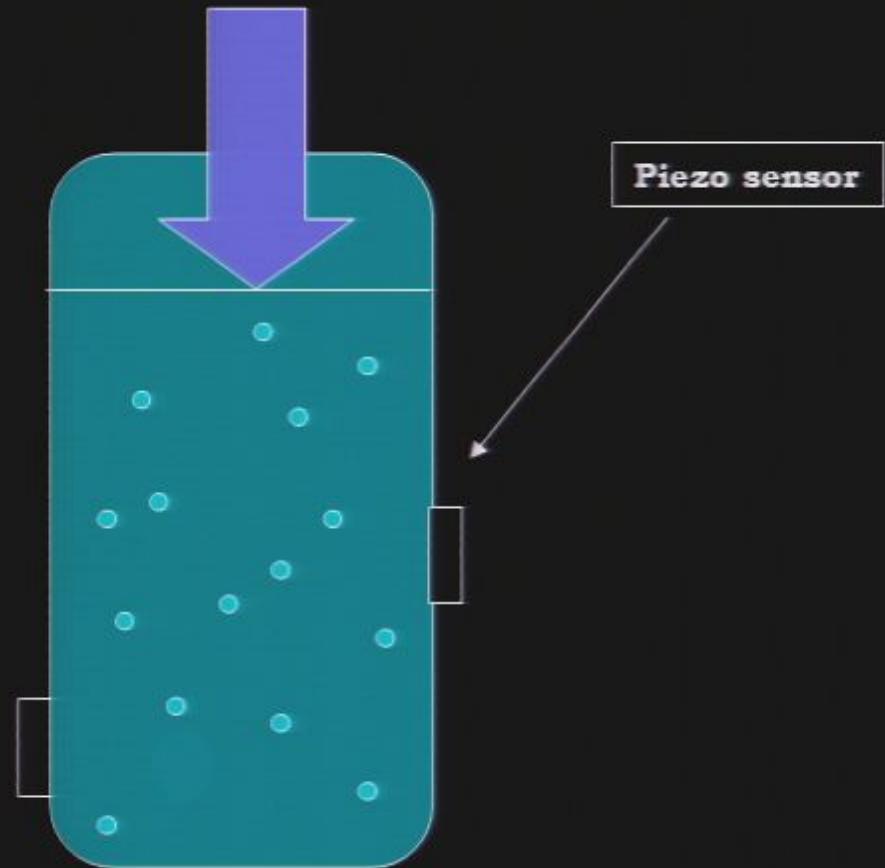
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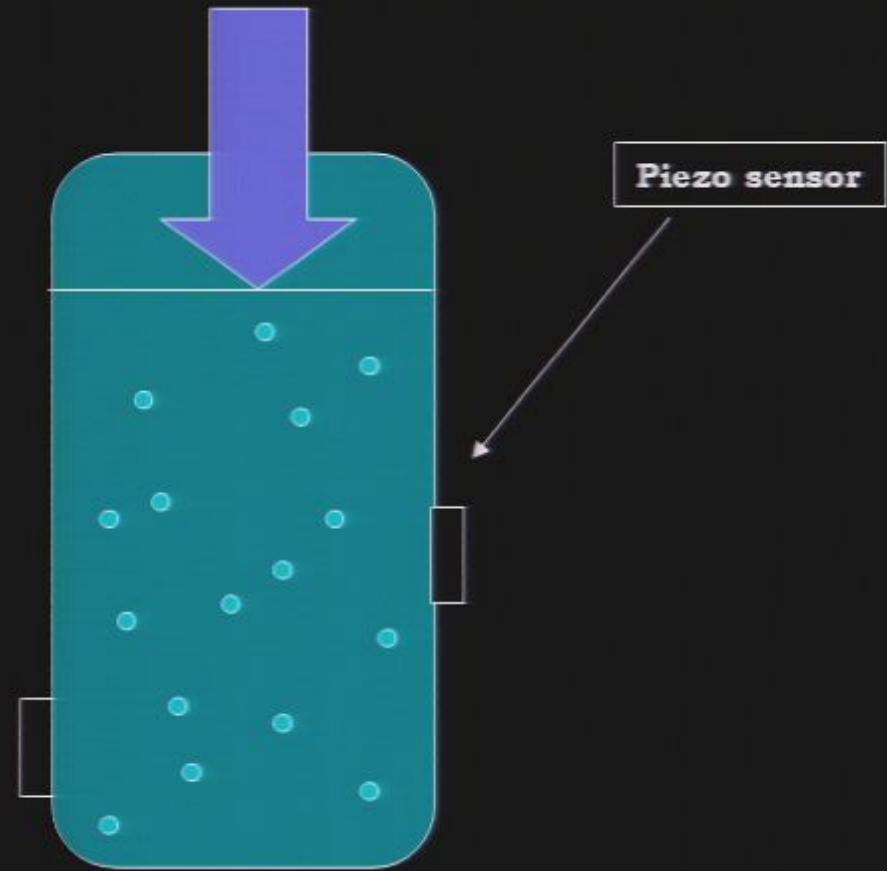
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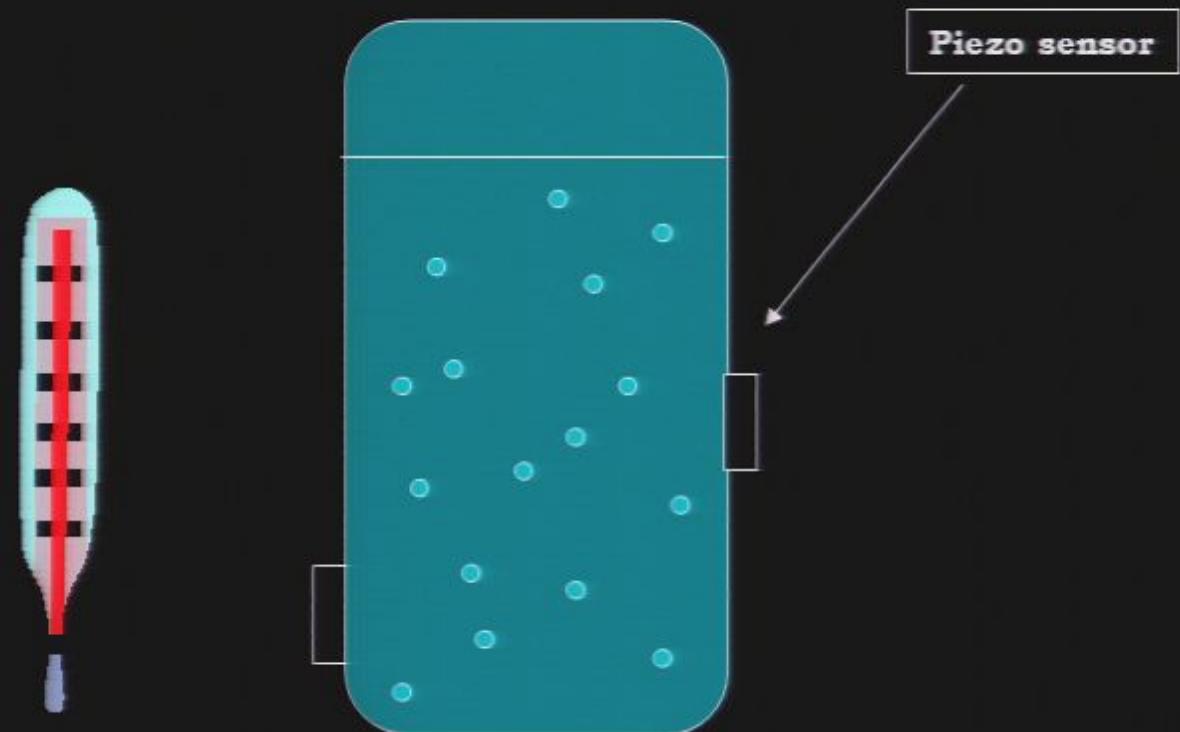
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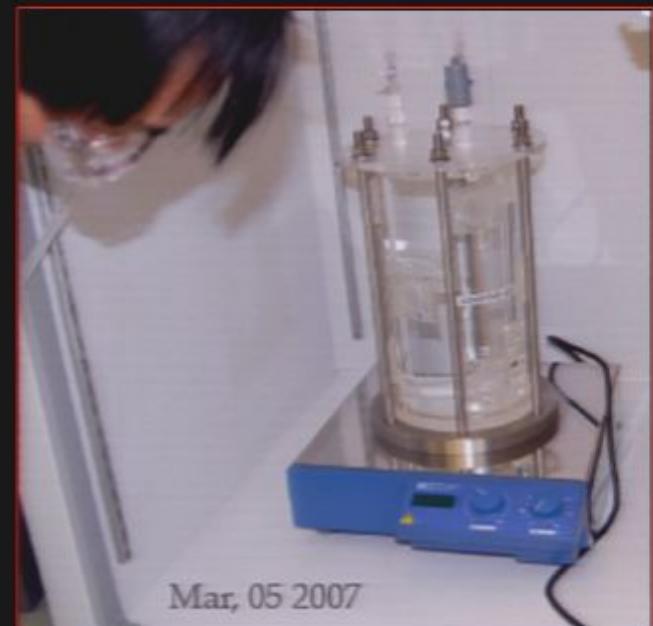
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How to make *Picasso* Detectors



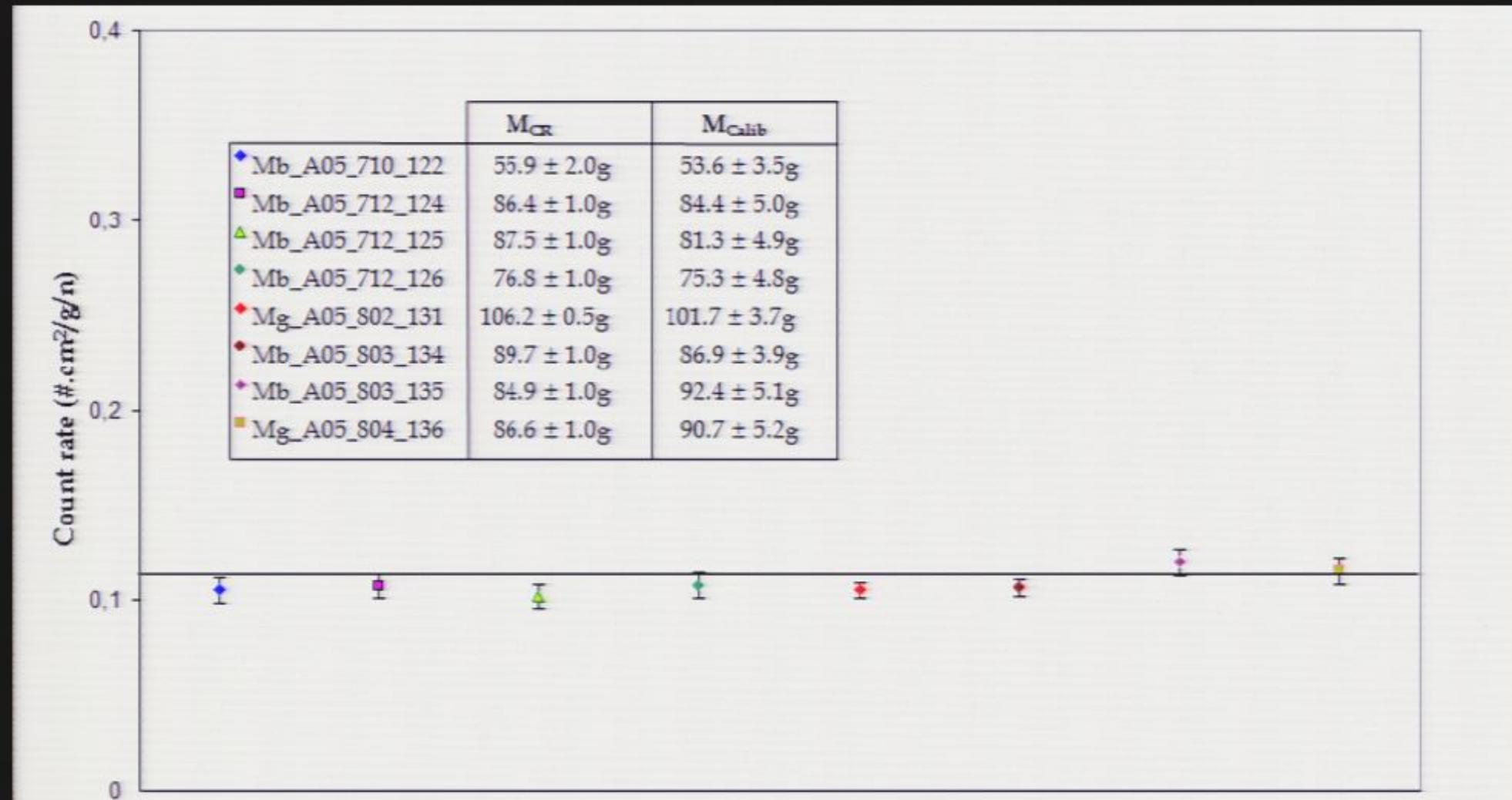
- R&D in collaboration with BTI, Chalk River
- start with monomer matrix solution
- add heavy CsCl solution to match density of active gas ($\rho = 1.6 \text{ g/cm}^3$)
- add active gas in liquid form
- magnetic stirring to disperse droplets
- polymerize matrix
- all done in clean room to avoid U/Th, Rn



Determination of the active mass

Weighing of C_4F_{10} during detector fabrication

Control of active mass by calibration in known AcBe neutron flux



Why C_4F_{10} ? Spin Dependent

Neutralino interaction with matter:

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



Enhancement factor

Depending on the type of target nucleus
and neutralino composition

$\left\{ \begin{array}{l} \text{Spin independent interaction } (C_A \propto A^2) \\ \text{Spin dependent interaction} \end{array} \right.$



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

**Spin of the nucleus is approximately the spin
of the unpaired proton or neutron**

Isotope	Spin	Unpaired	λ^2
^7Li	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

Detection of Nuclear Recoils

- Calibration with mono-energetic neutrons
- neutron induced nuclear recoils similar to WIMPS
- at low energies only s-wave scattering is important
- Reaction: ${}^7\text{Li}(\text{p},\text{n})$ reaction at 6 MV UdeM-Tandem

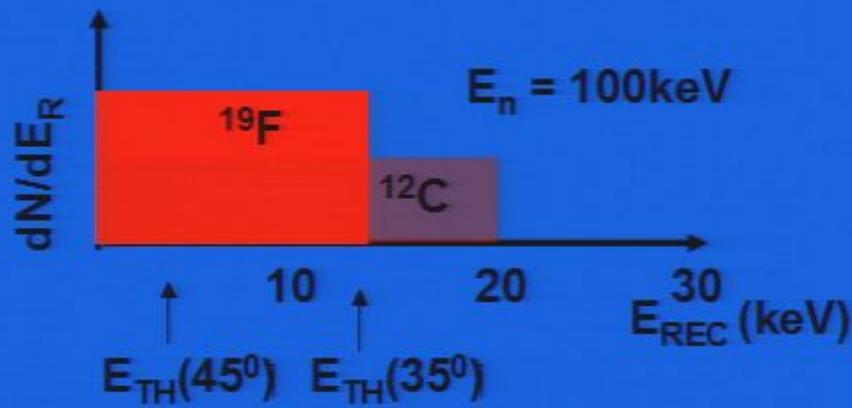


- recoil detection efficiency
- control of active mass in detectors
- comparison of different liquids

Ideal tool for calibrating
droplet detectors!

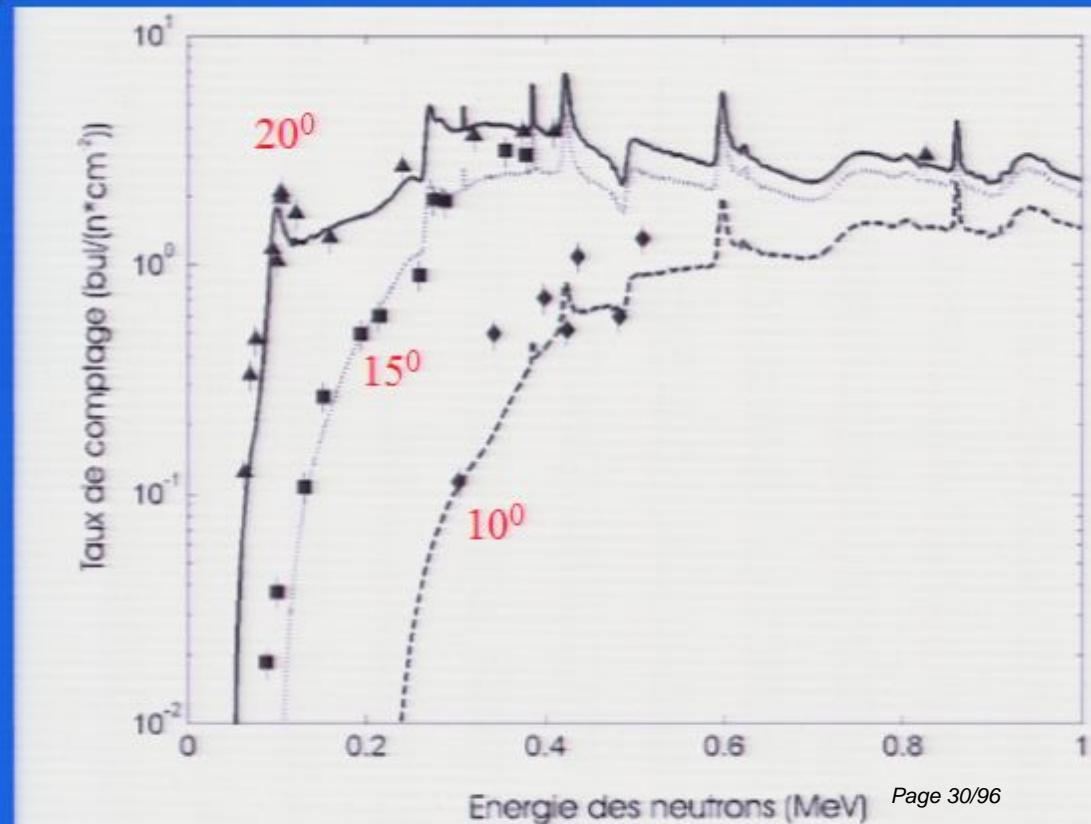
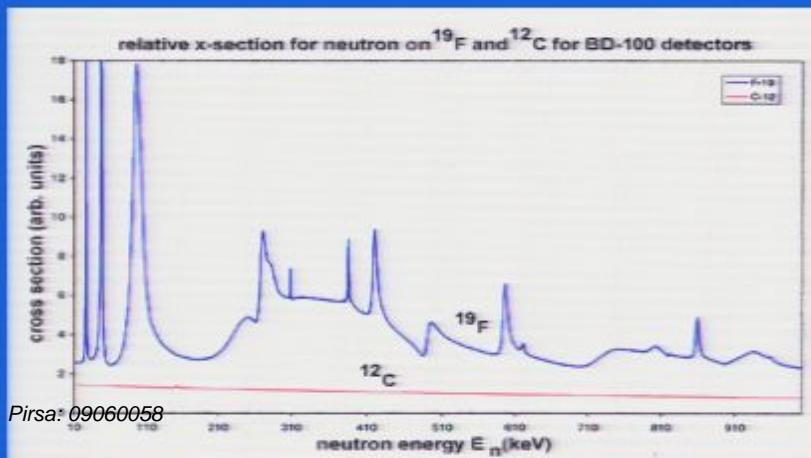
Droplet Detectors are Threshold Detectors...

Determine energy response as a function of T & P → superheat!

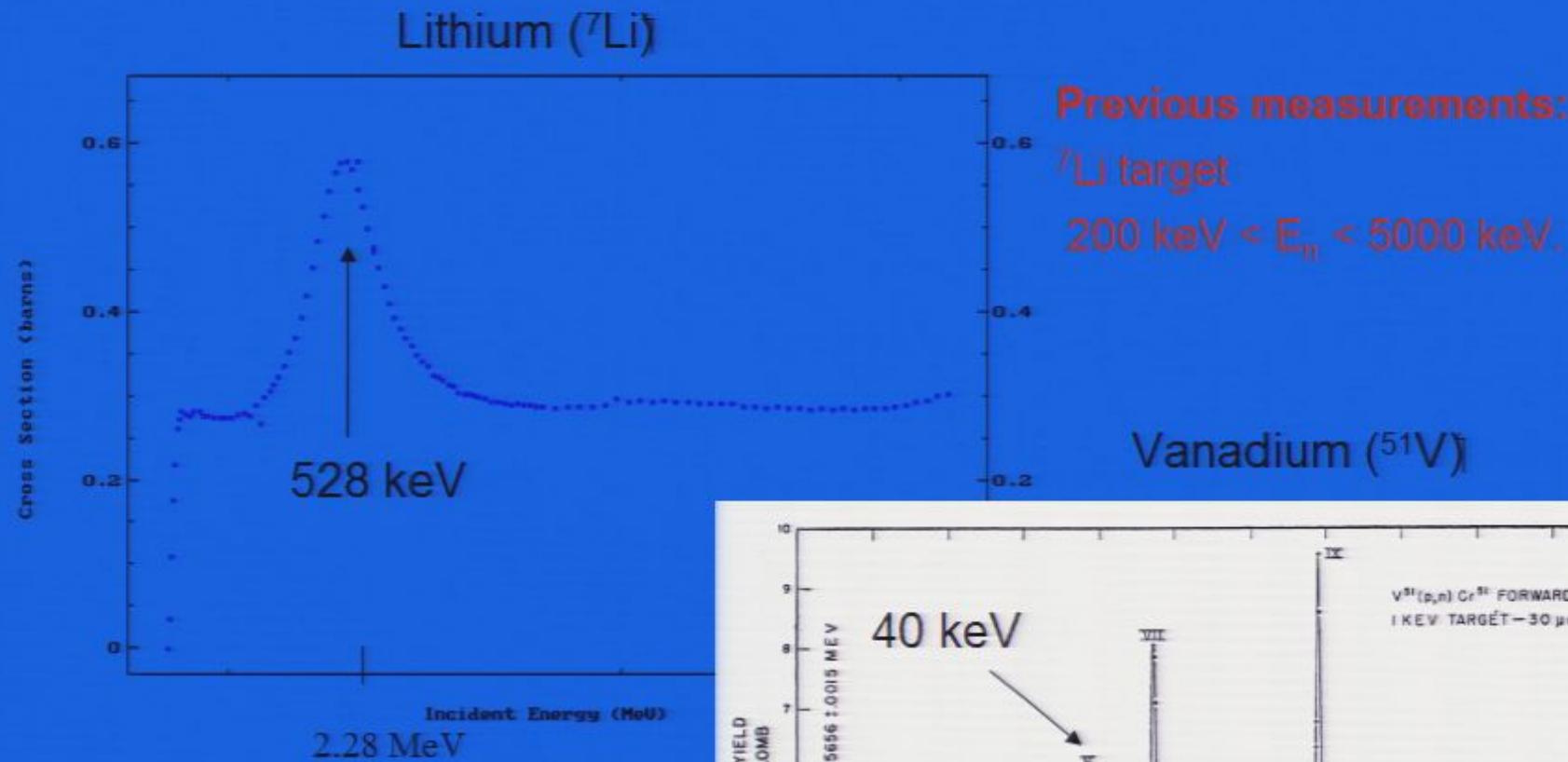


$$E_{\text{Rec}} = E_n \frac{2A}{(A+1)^2} (1 - \cos \theta)$$

Cross sections well known:

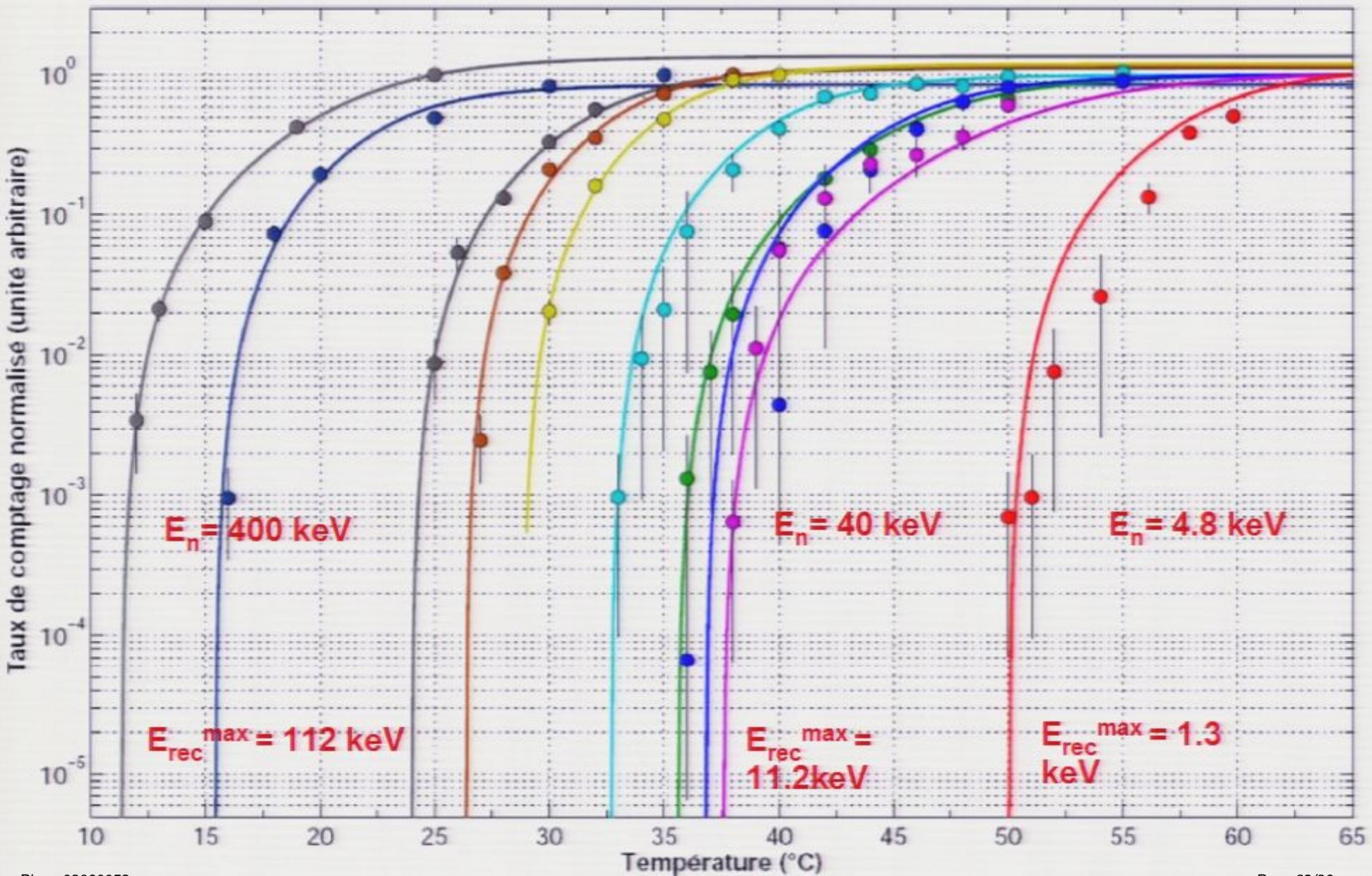


Target selection

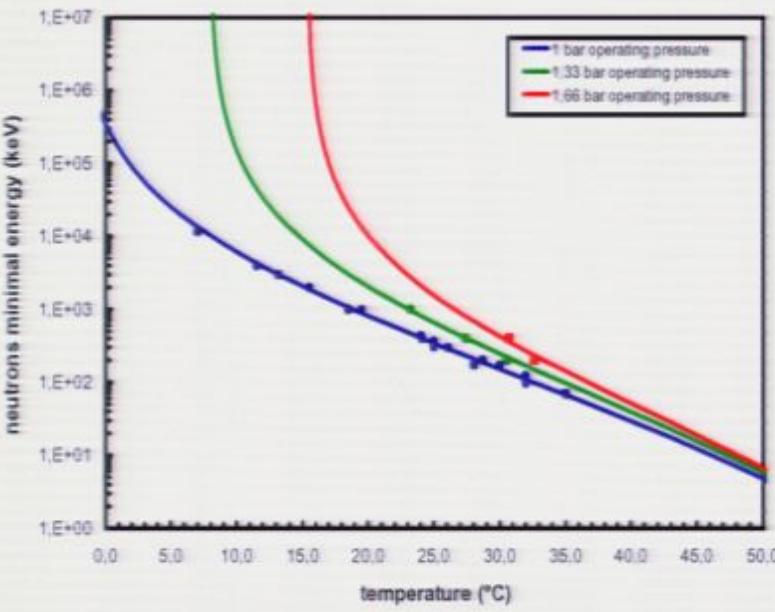


New measurements:
 ^{51}V target
 $5 \text{ keV} < E_n < 90 \text{ KeV}$

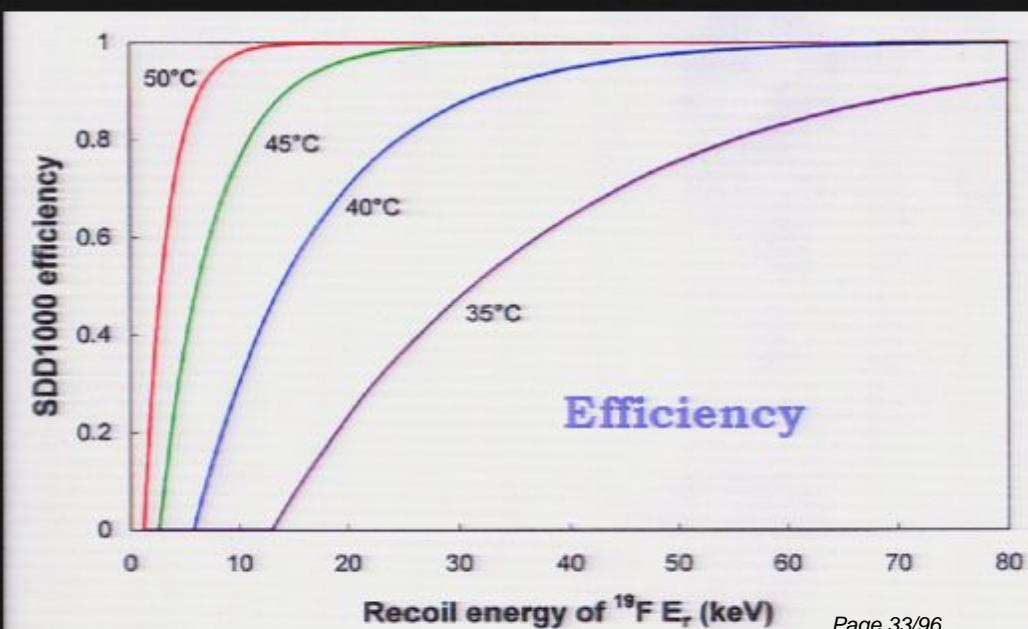
Neutron Beam Calibration



Thresholds & Efficiency

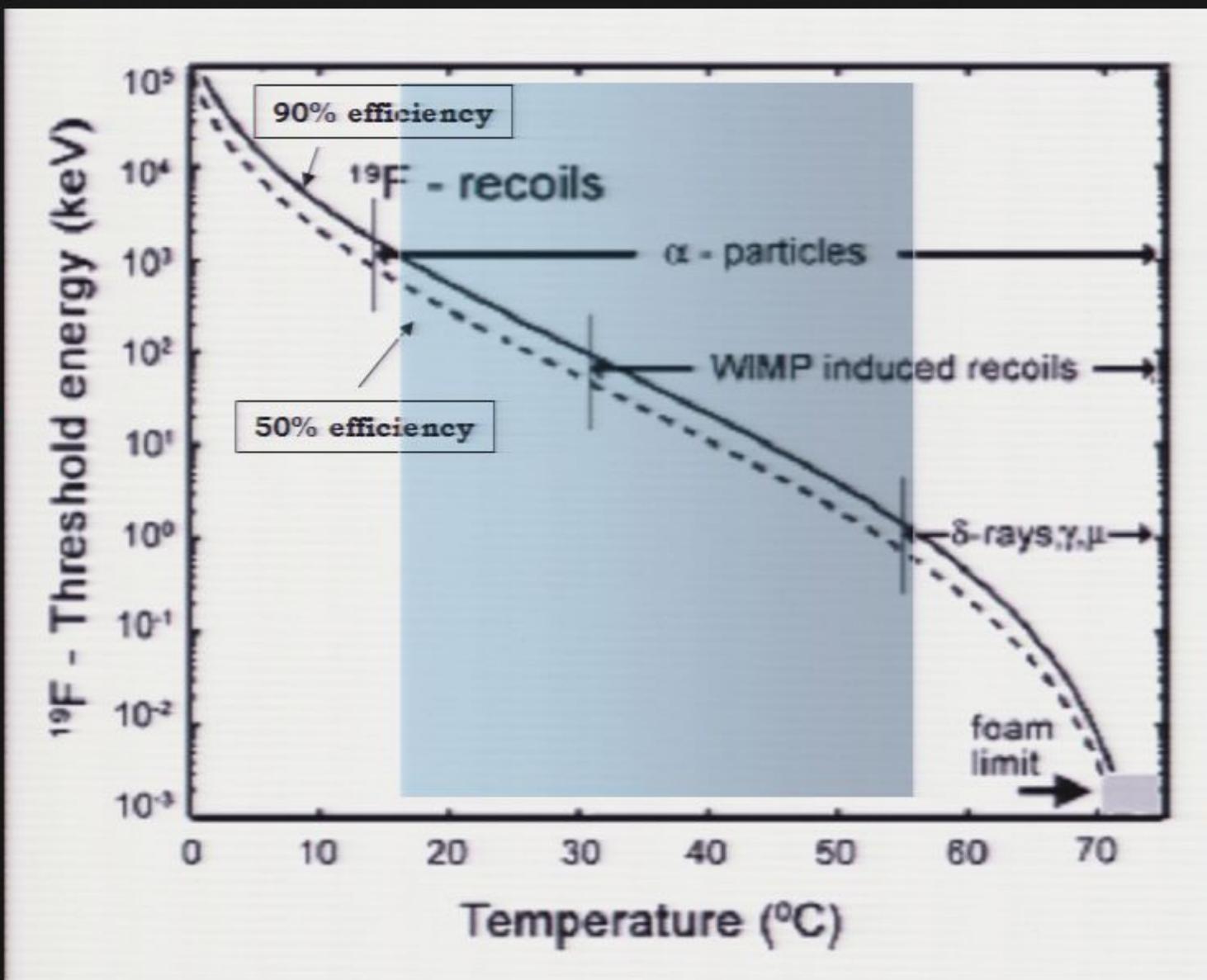


Energy Thresholds



^{19}F Recoils in the PICASSO Detectors

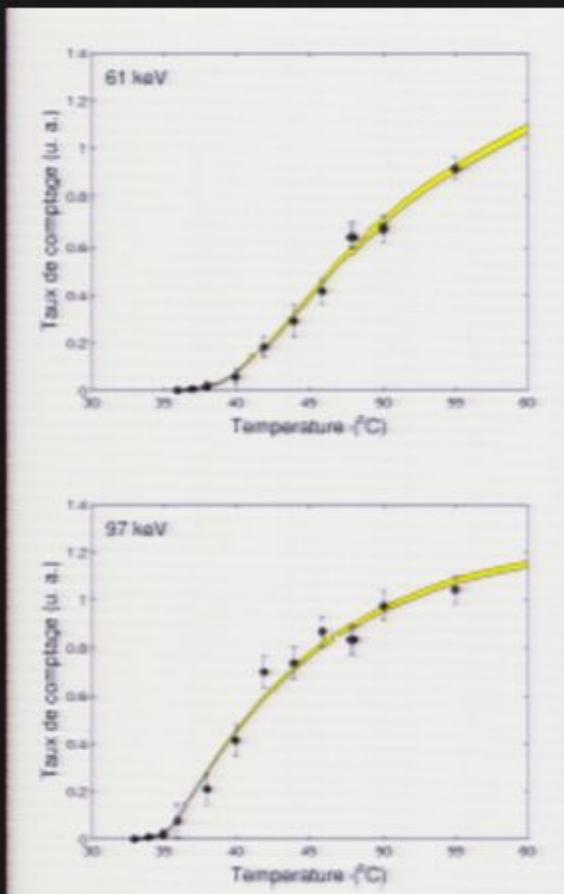
Sensitivity
to keV
recoils



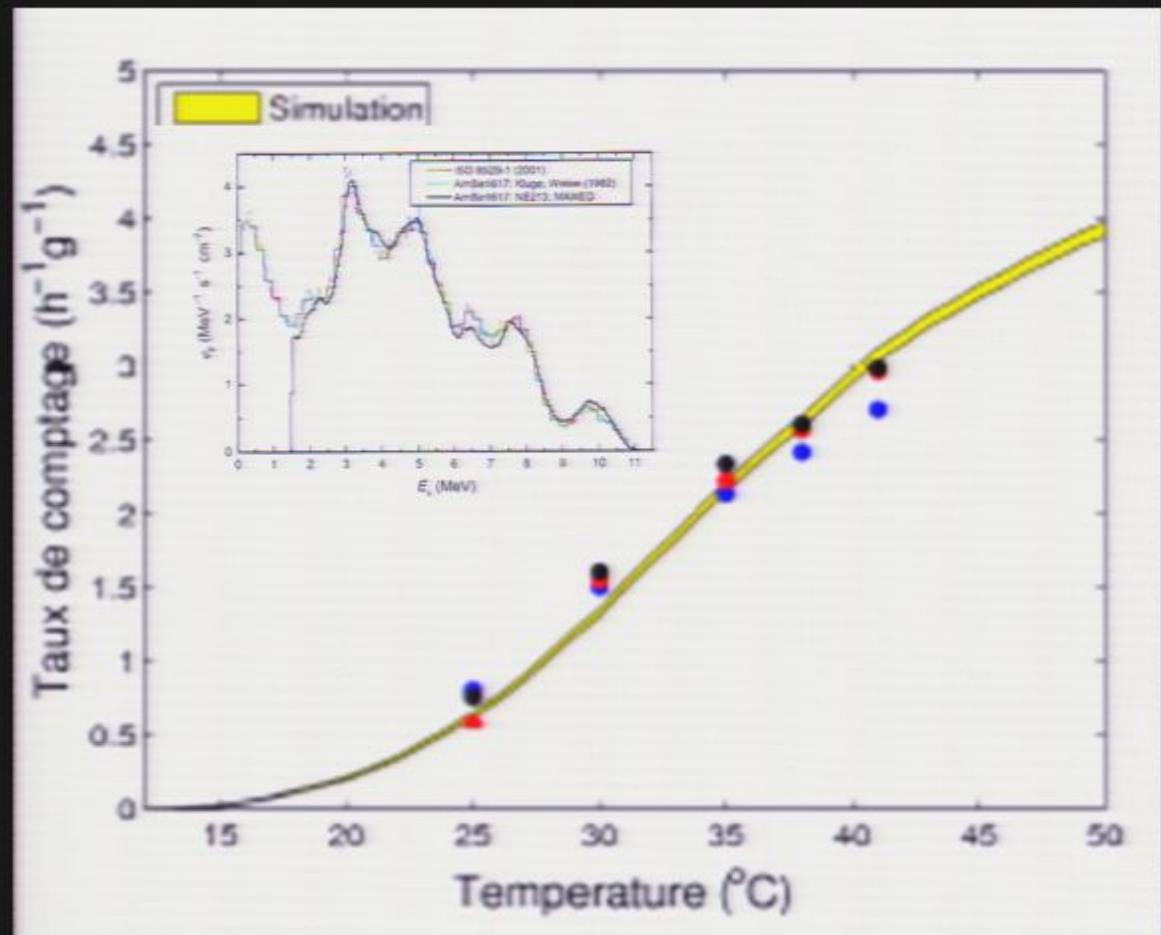
Evolution of the energy threshold for ^{19}F recoils (1.23 bar)

Monte Carlo Simulations

Test beam



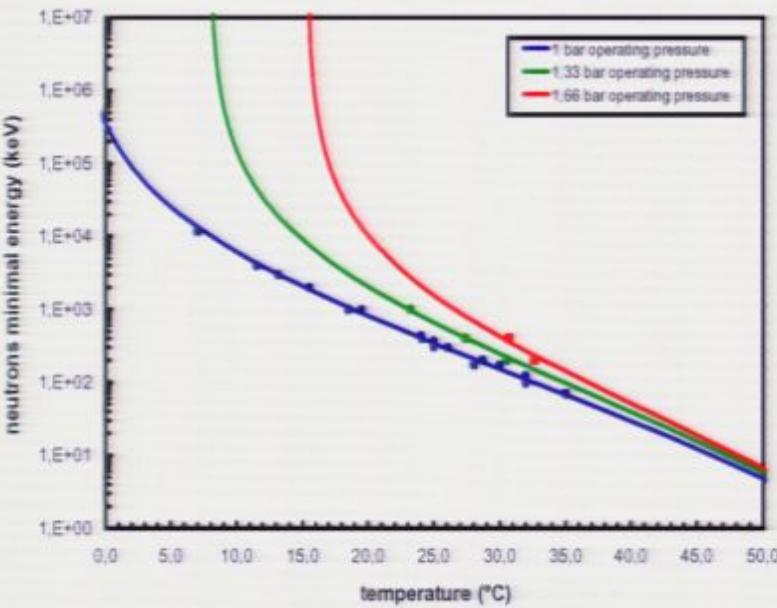
AmBe source (u/g calib.)



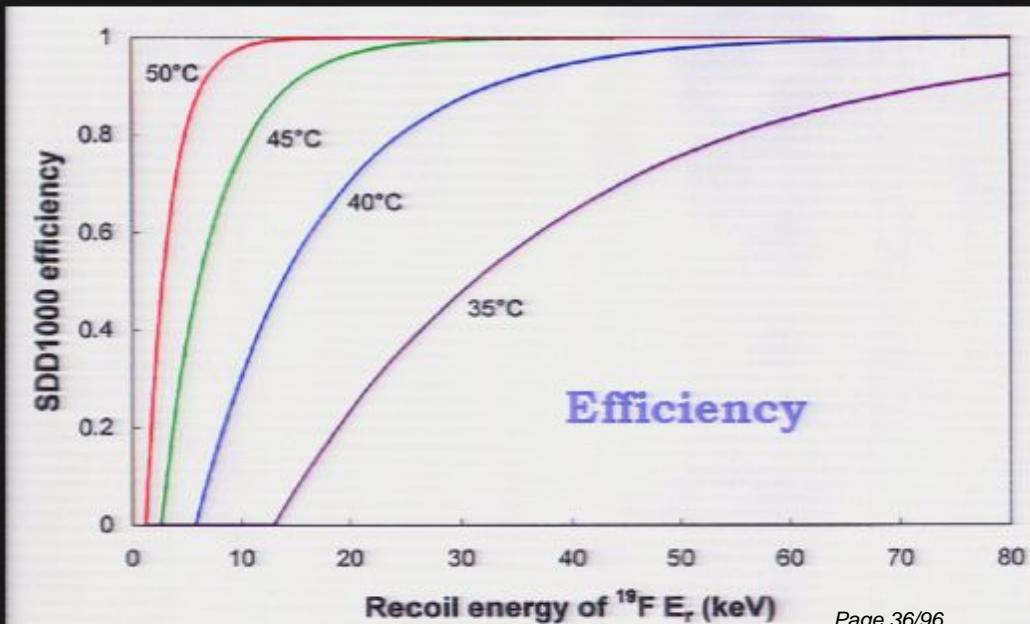
Response at threshold not a step function!

$$P(E, E_{th}) = 1 - \exp a(1 - \frac{E}{E_{th}})$$

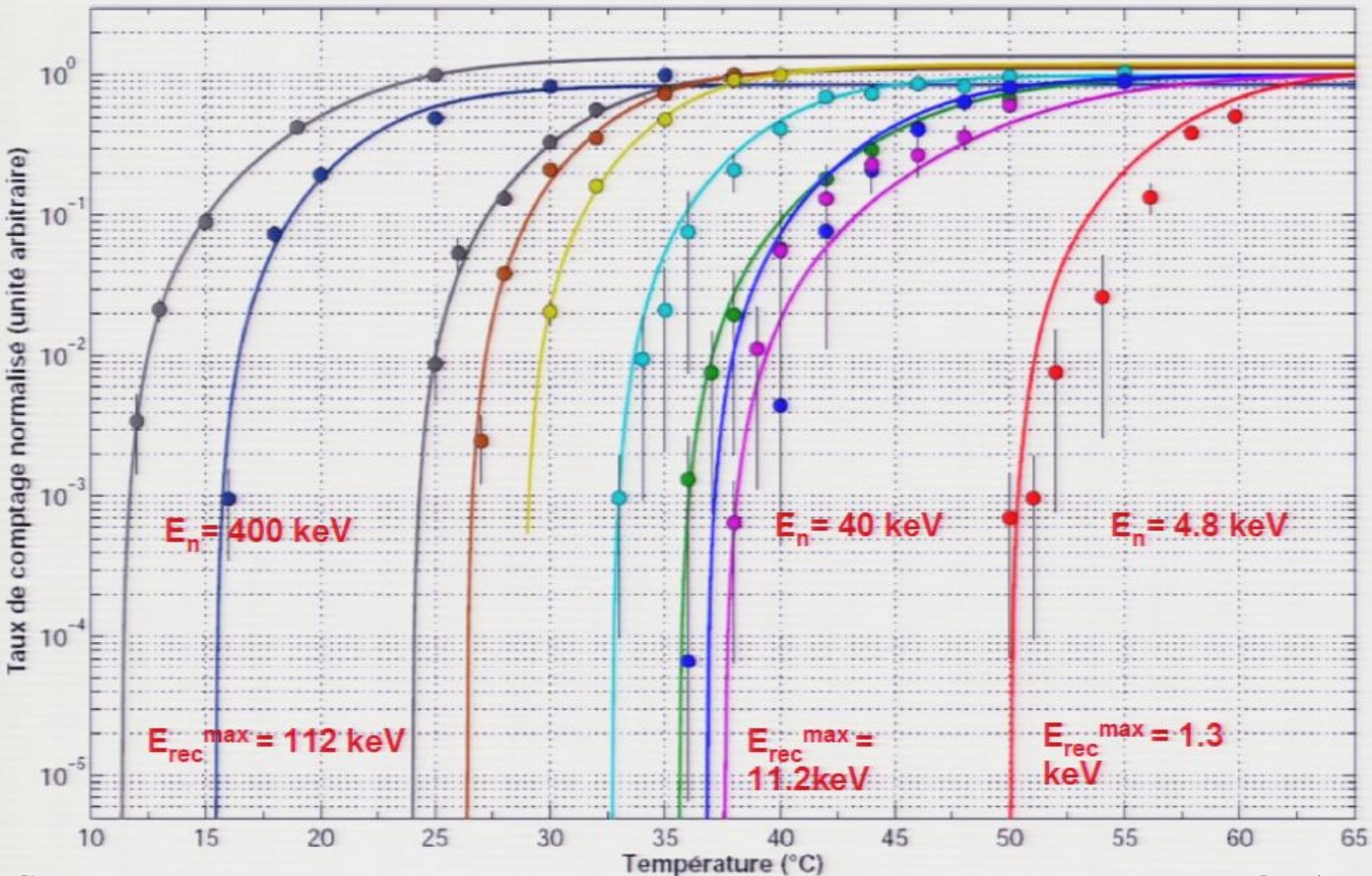
Thresholds & Efficiency



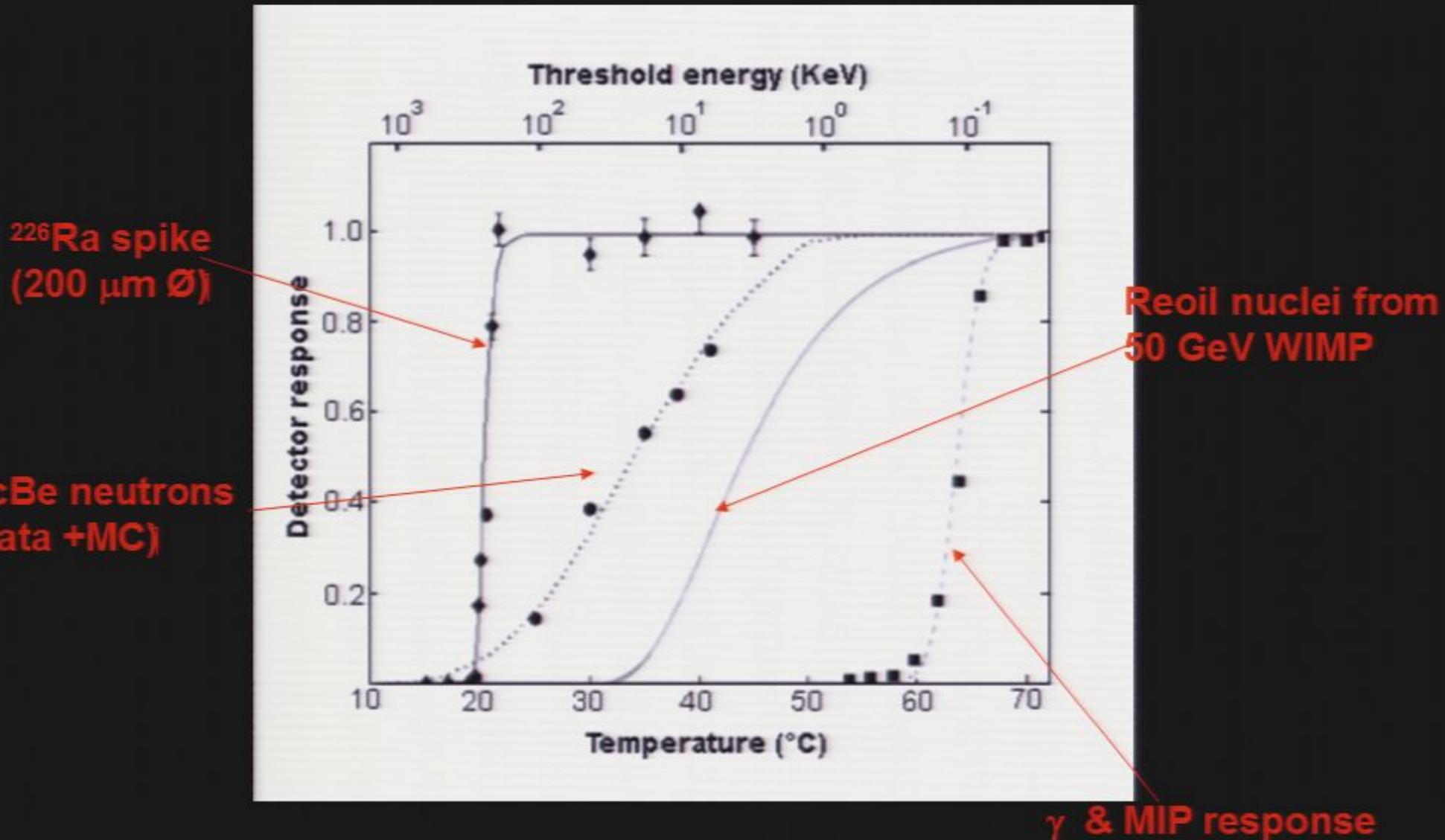
Energy Thresholds



Neutron Beam Calibration

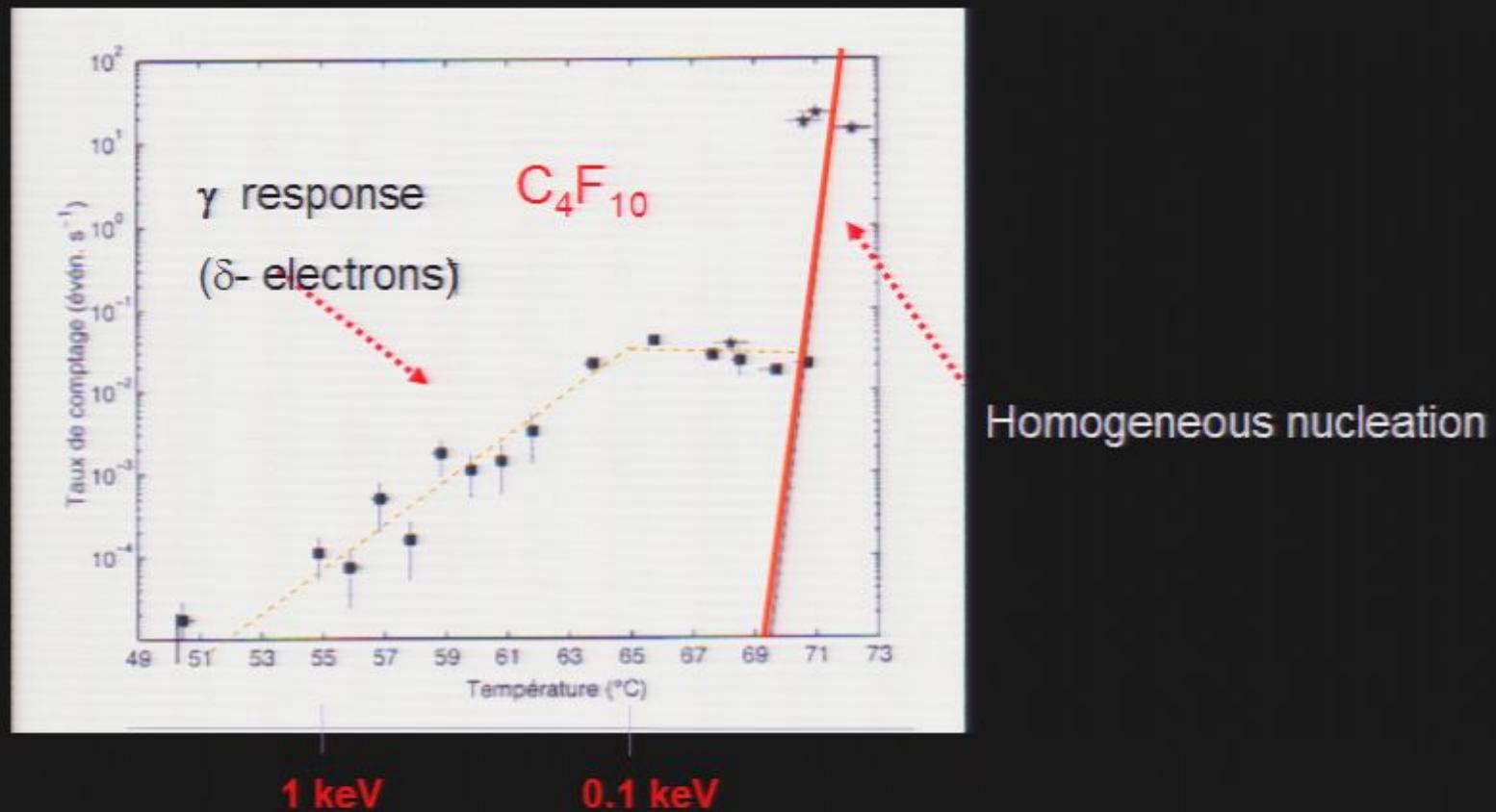


Detector Response

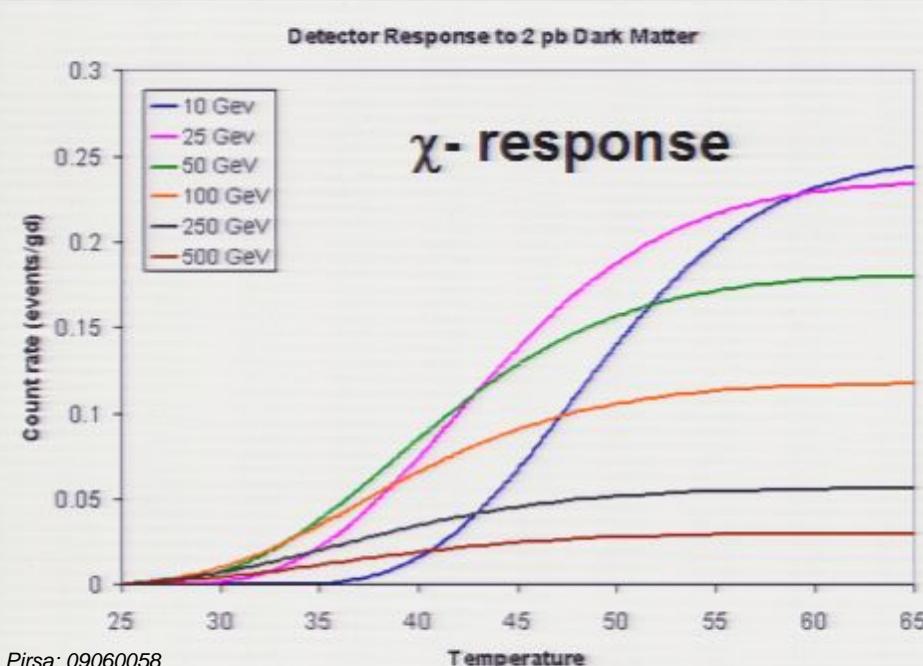
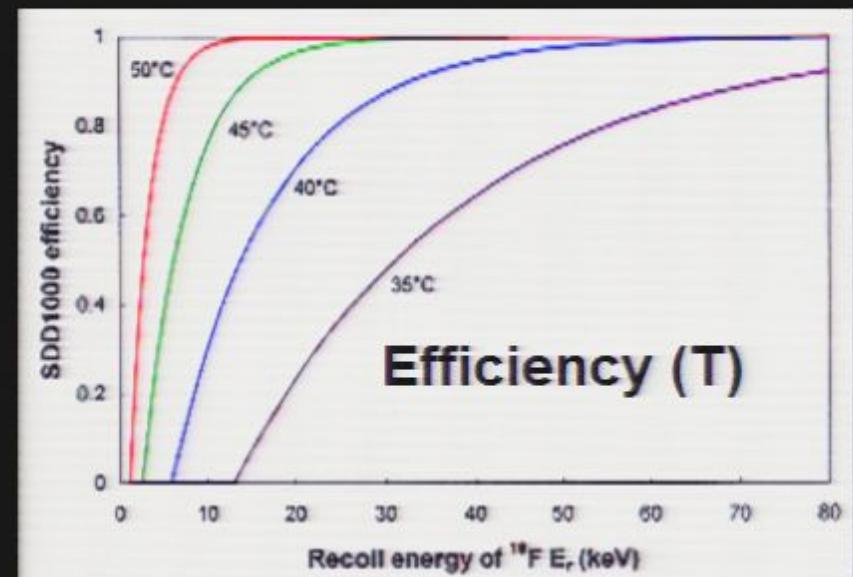
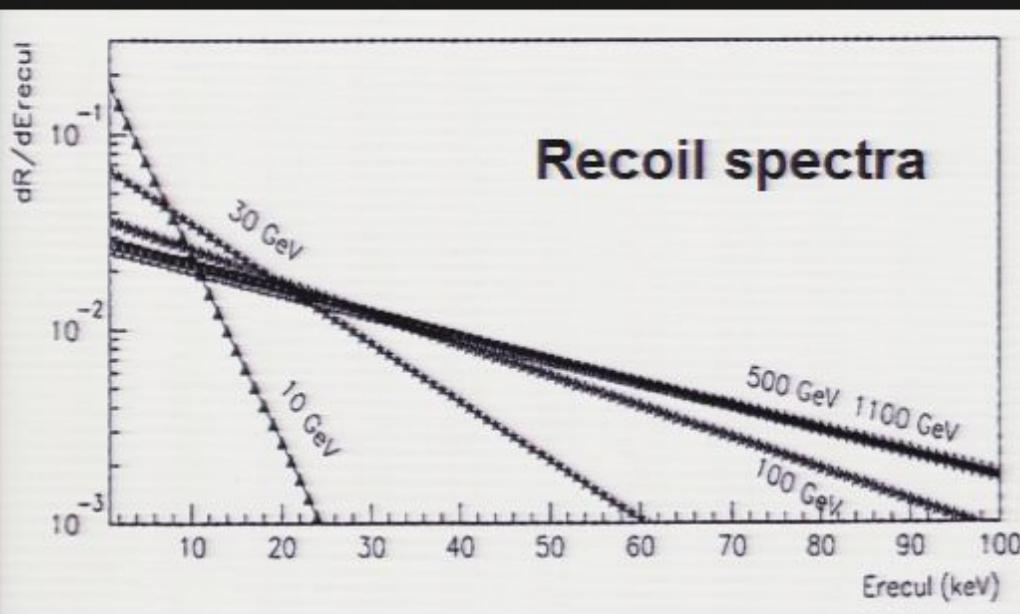


Limit of Stability: Homogeneous Nucleation

Limit of stability when thermal fluctuations deposit E_{min} within R_{min}
Theory predicts instability of liquid phase at app. 90% T_c



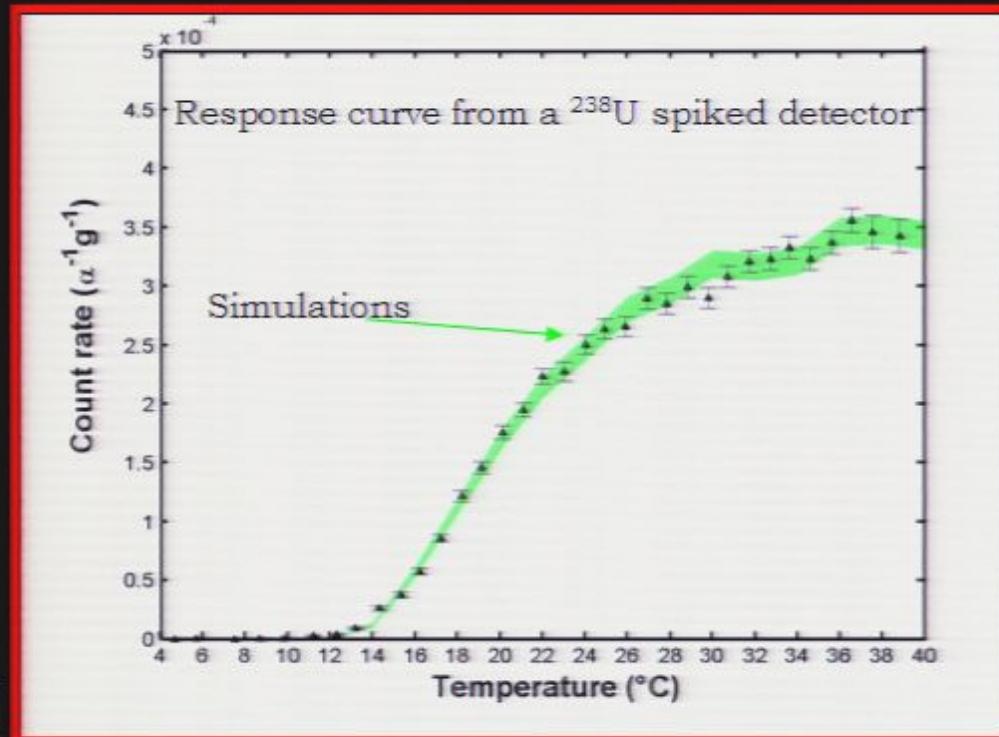
Expected Neutralino Response



$$R(g^{-1}d^{-1}) = \text{const.} \frac{\varepsilon(M_\chi, T)}{M_\chi} \sigma_F v_\chi \rho_\chi$$

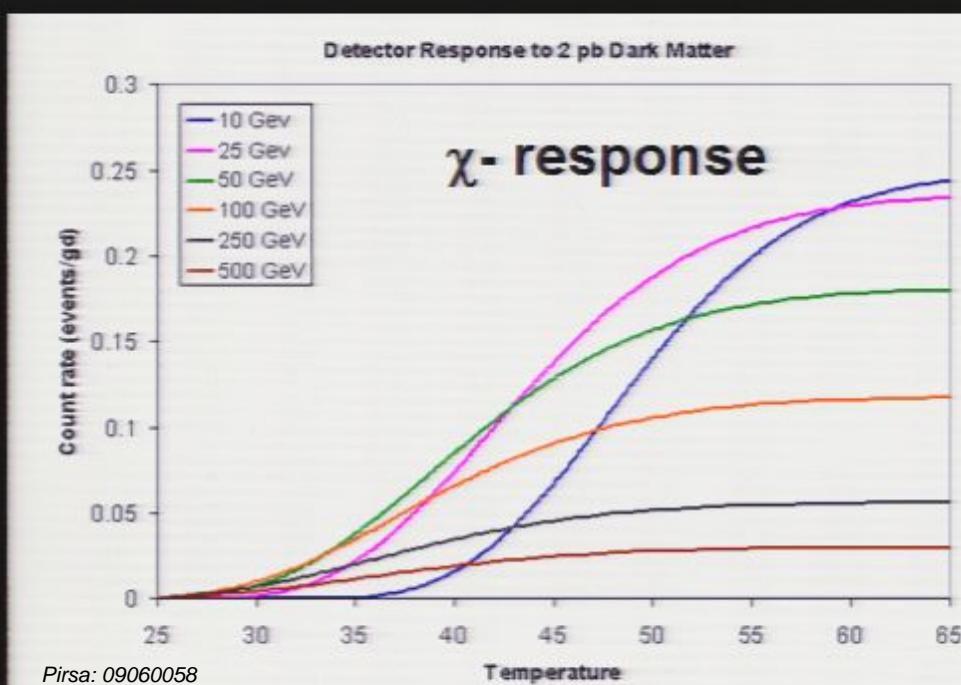
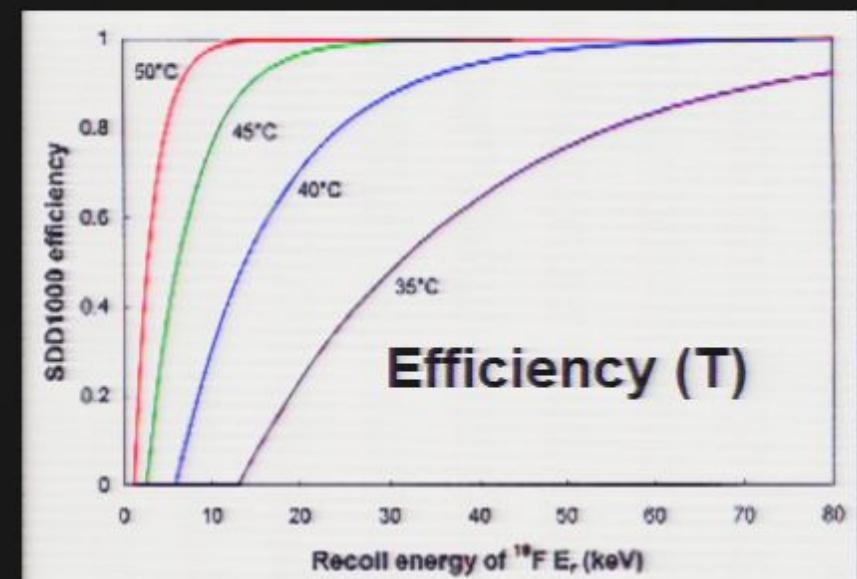
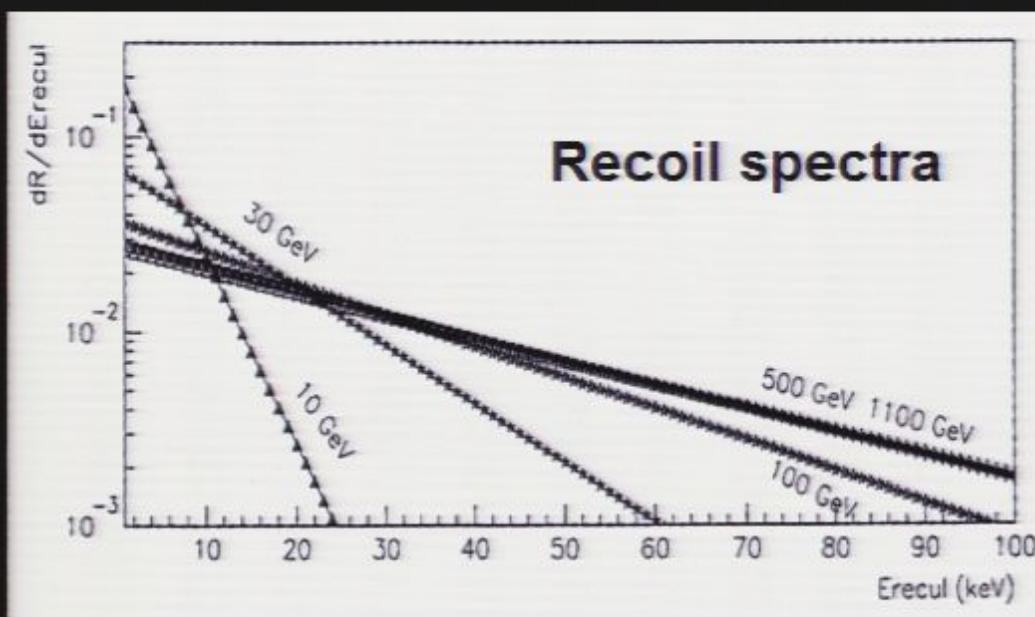
Backgrounds

- **Cosmic ray muons** → induce high energy neutrons ($E > 10\text{MeV}$)
- Radioactivity from the environment neutrons → ($E < 10 \text{ MeV}$)
- MIPS → Mostly suppressed at the operating temperature range
(better than up to 10^{10})
- **α -particles are the dominant background (for WIMP runs, mainly from CsCl)**



(Bckg. values:
integrated from
6 keV – 1 MeV)

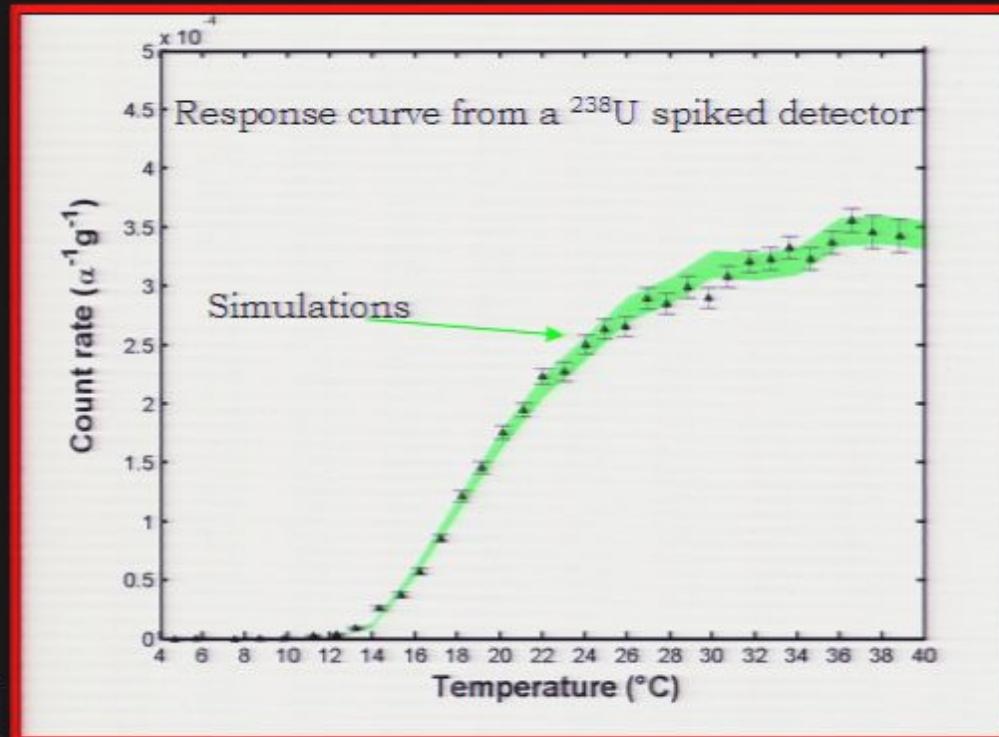
Expected Neutralino Response



$$R(g^{-1}d^{-1}) = \text{const.} \frac{\varepsilon(M_\chi, T)}{M_\chi} \sigma_F v_\chi \rho_\chi$$

Backgrounds

- **Cosmic ray muons** → induce high energy neutrons ($E > 10\text{MeV}$)
- Radioactivity from the environment neutrons → ($E < 10 \text{ MeV}$)
- MIPS → Mostly suppressed at the operating temperature range
(better than up to 10^{10})
- **α -particles are the dominant background (for WIMP runs, mainly from CsCl)**



(Bckg. values:
integrated from
6 keV – 1 MeV)

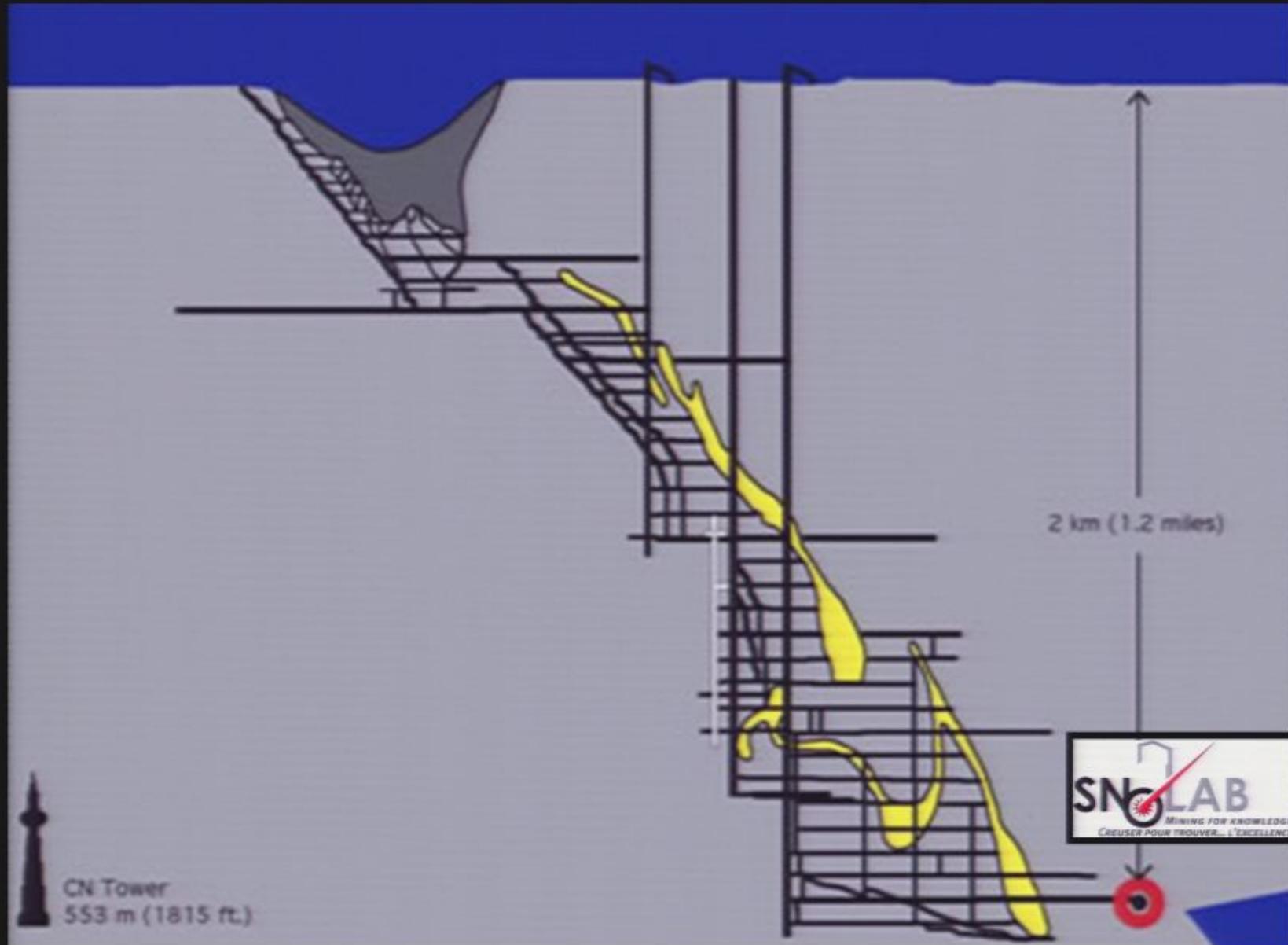
PHASE Ia – 20g: PICASSO @ SNO

- Installation at SNO underground facility at a depth of 6,800 feet
- Data taking and data analysis during 2004/05
- Important step for PICASSO as a long term data taking experiment
- Fabrication of the 1-liter detectors in house
- ~20g of active mass

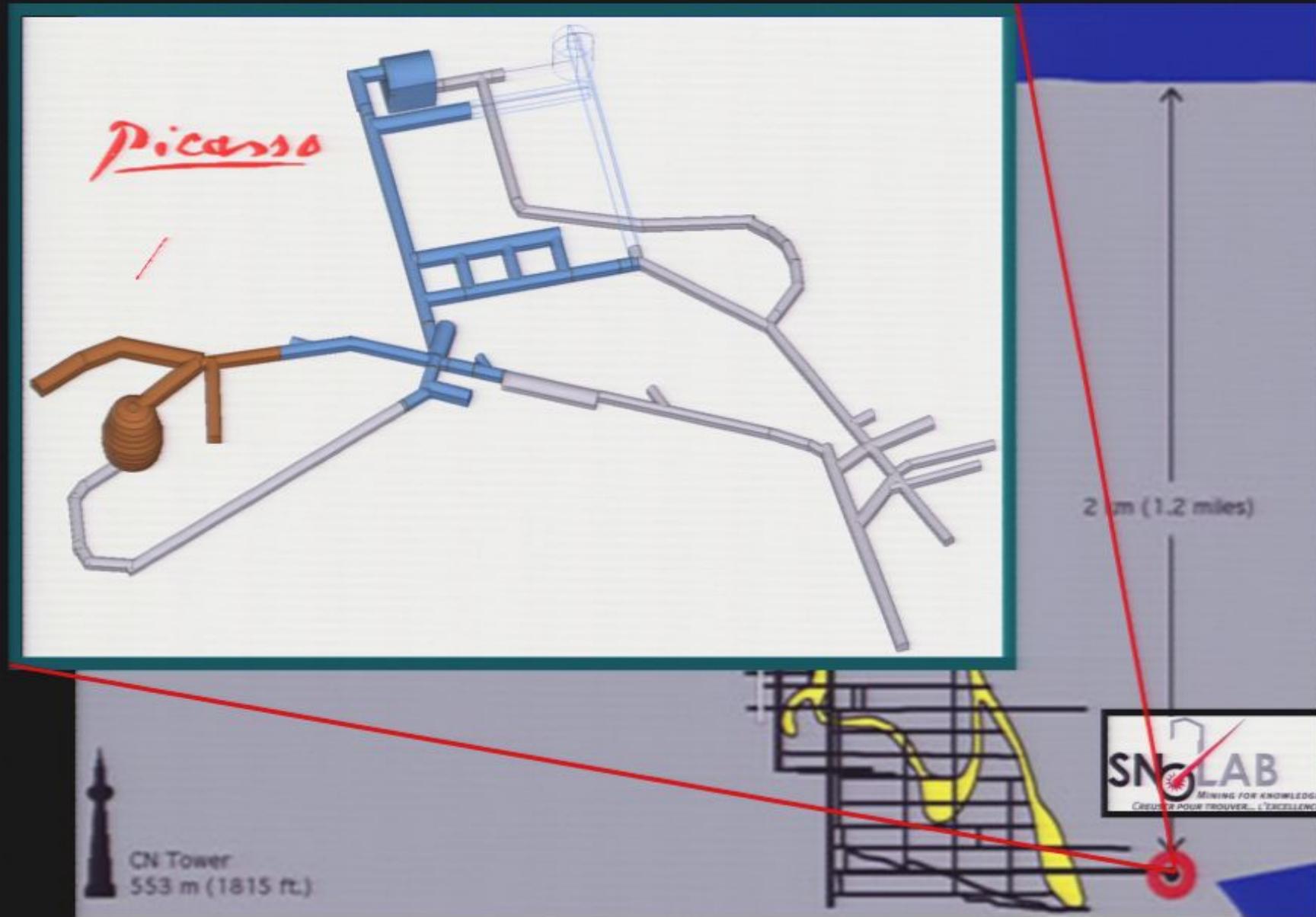


Creighton mine shaft head #9

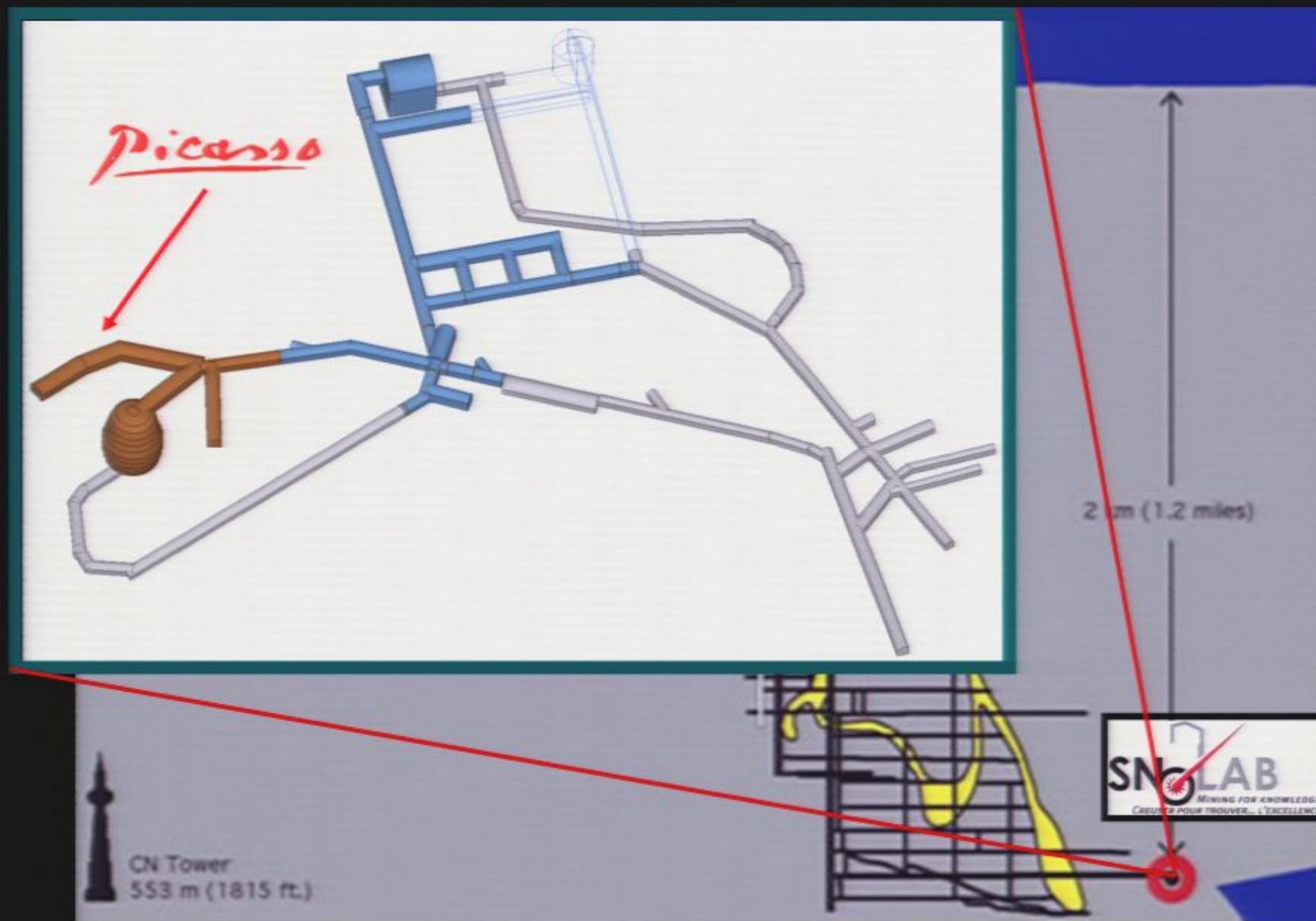
PICASSO at SNOLAB



PICASSO at SNOLAB



PICASSO at SNOLAB



PHASE Ia – 20g: PICASSO @ SNO

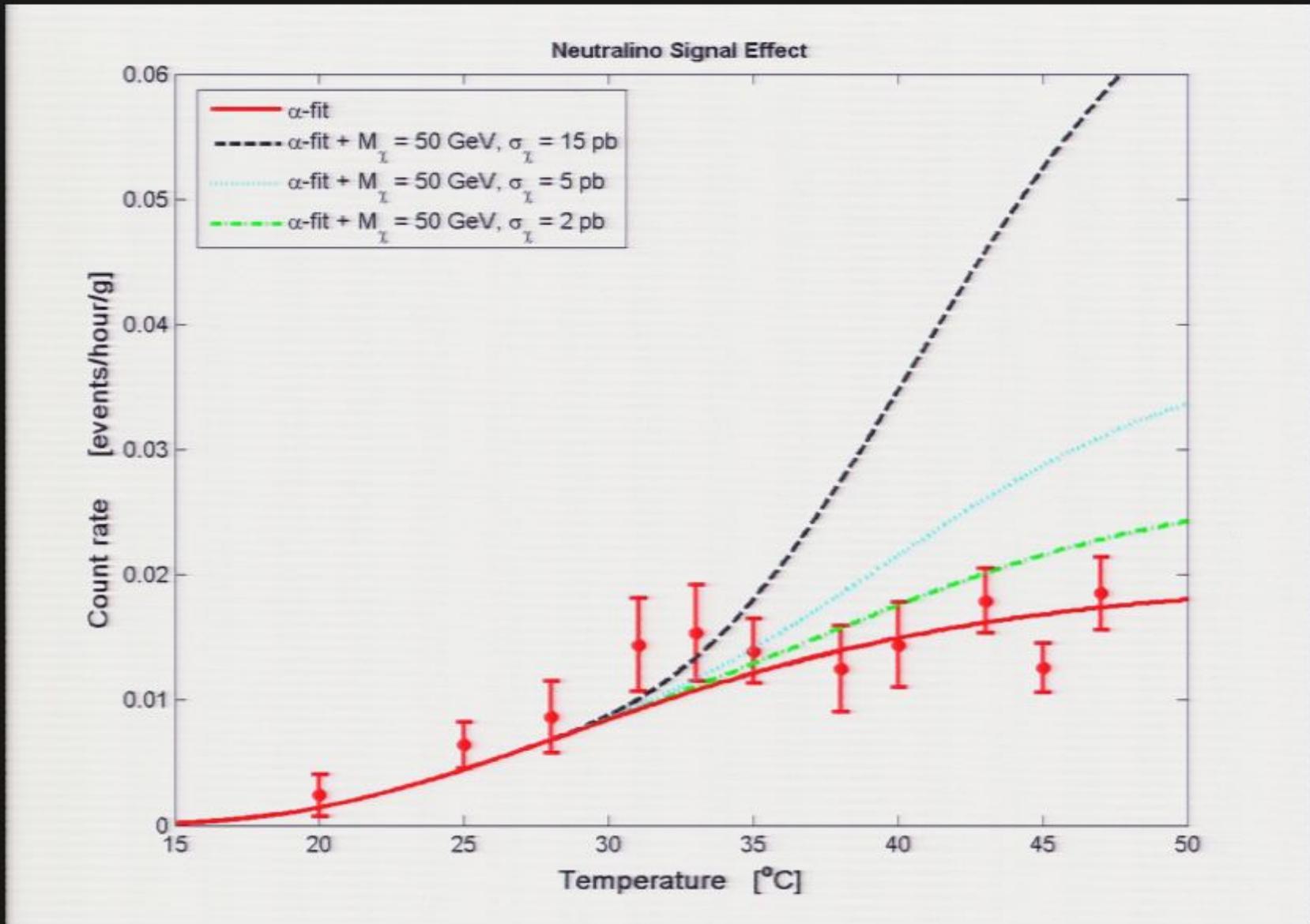
Operation in the (active) mine at SNO

- 2 piezo sensors per module
- N2 compression system

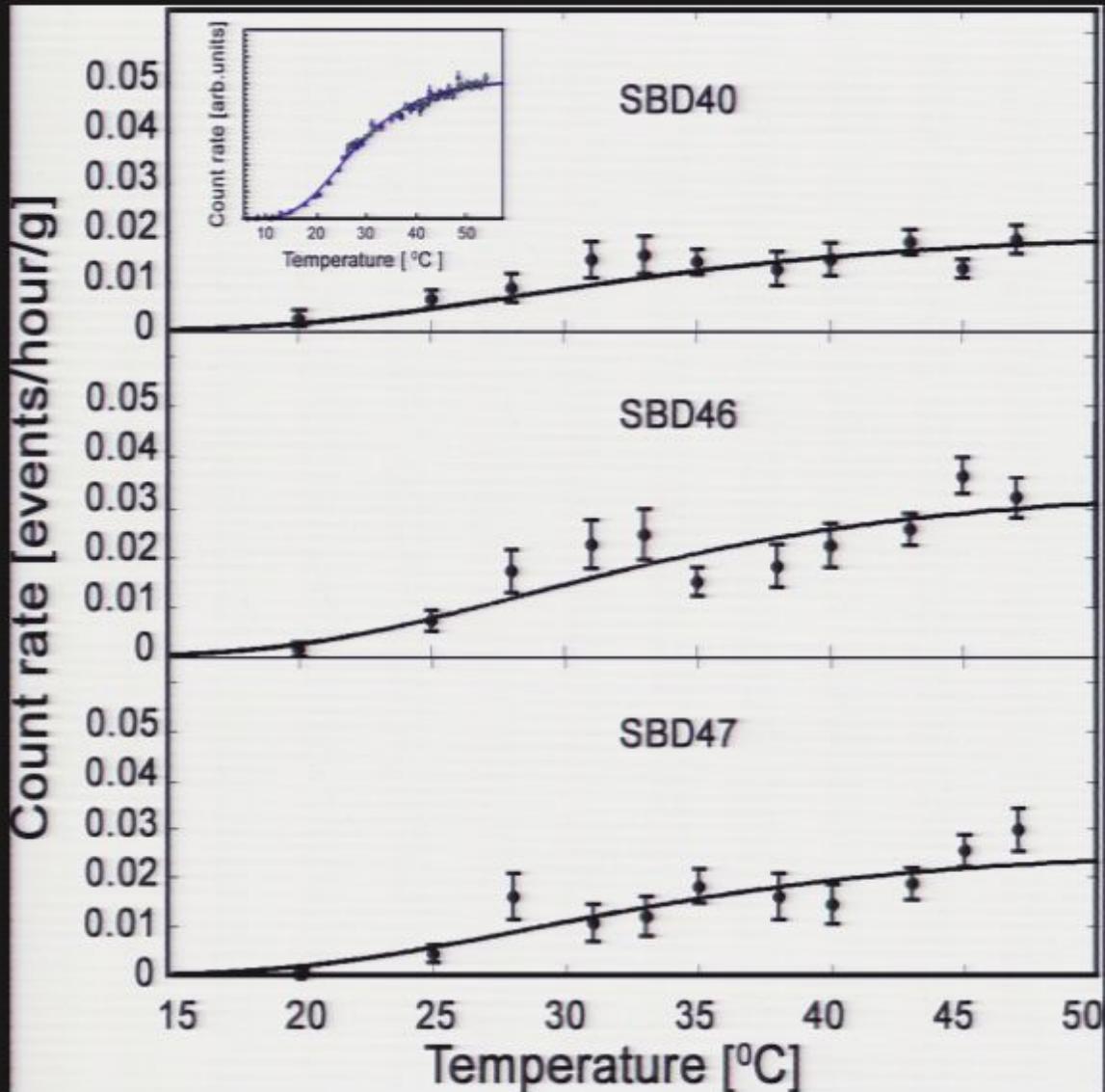


TCS

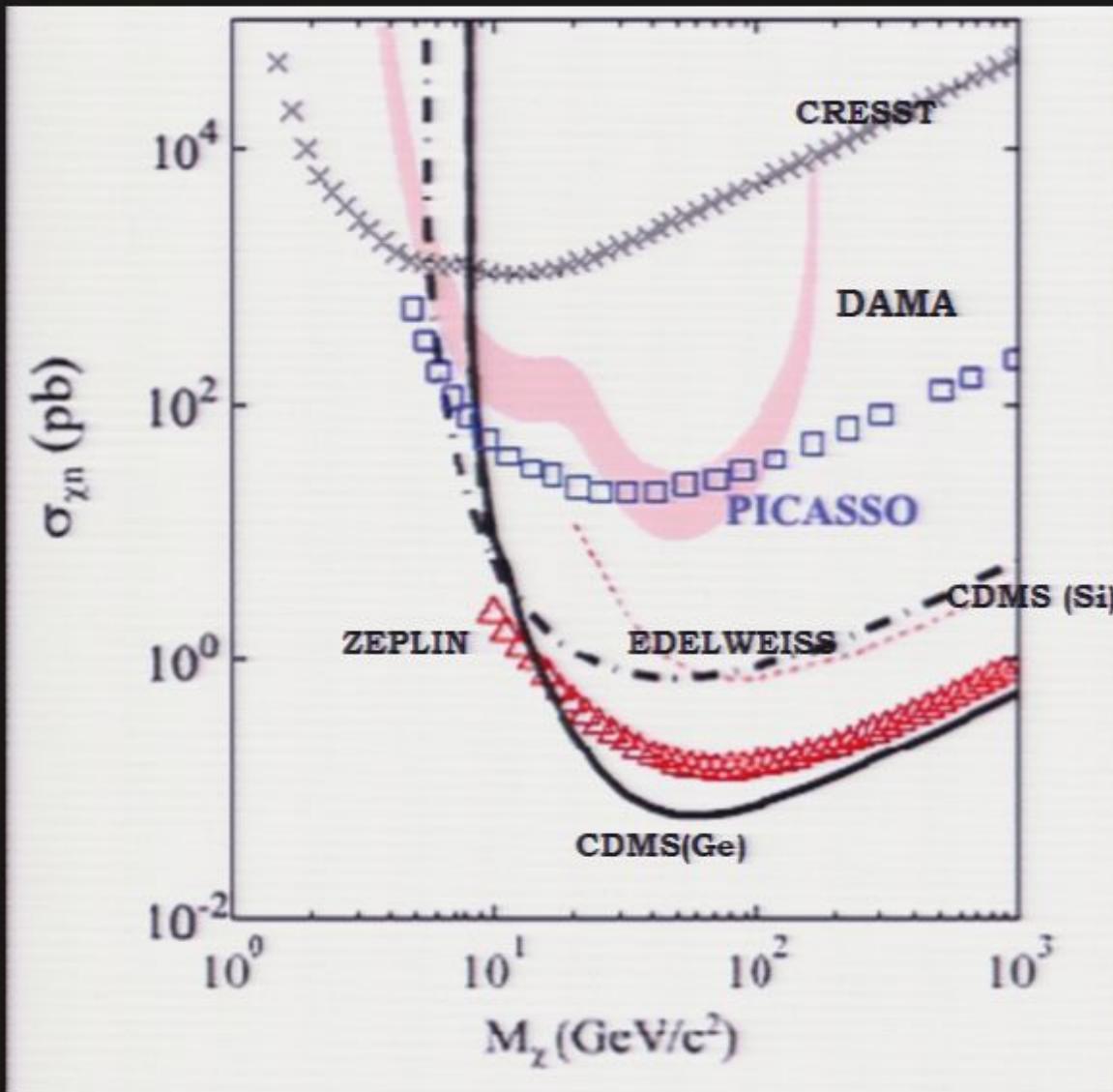
Signal \times Background shape



(Bckg. values: integrated from 6 keV – 1 MeV)



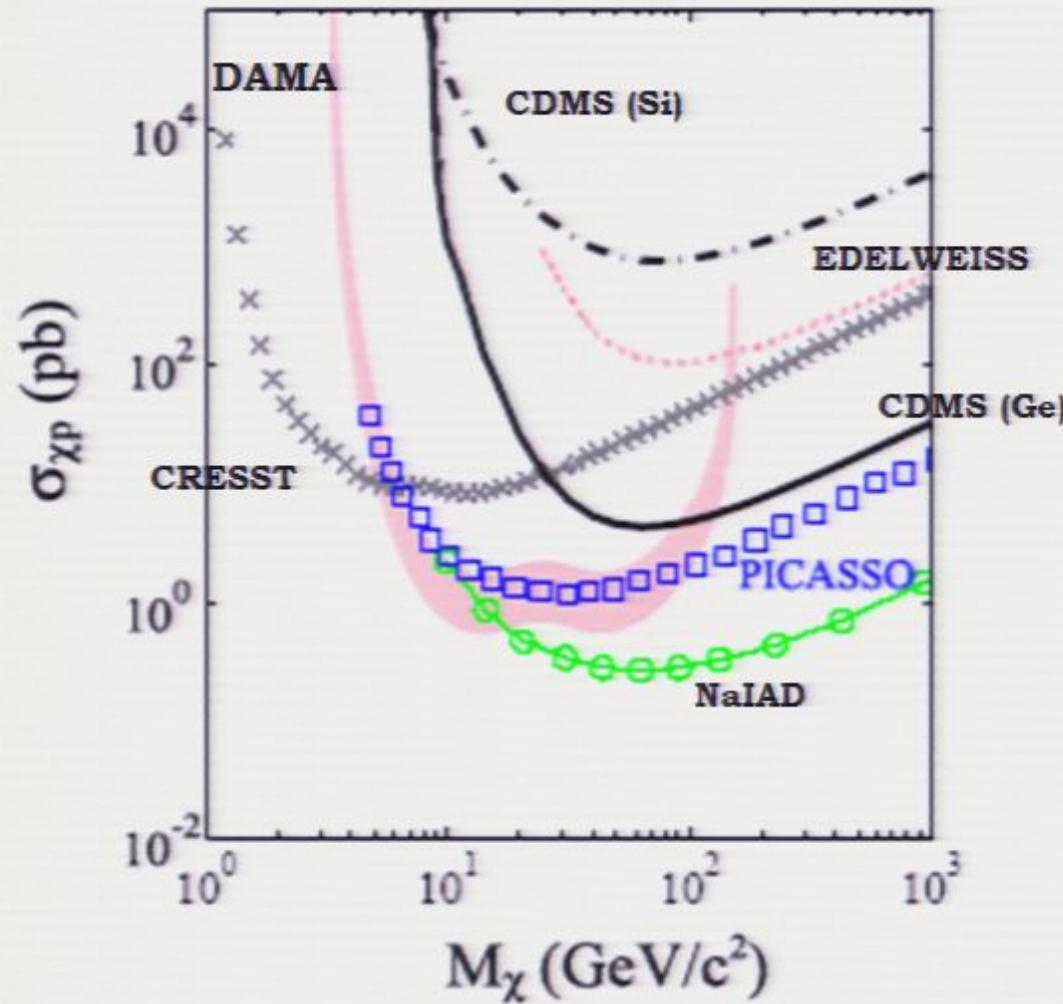
- 3 one-litre detectors
- ~20g of active mass
- $1.98 \pm 0.19 \text{ kgd}$



SPIN DEPENDENT Neutron-Neutralino

Upper limit of $\sigma_{\chi n} = 21.5$ pb
for $M_\chi = 29\text{GeV}/c^2$

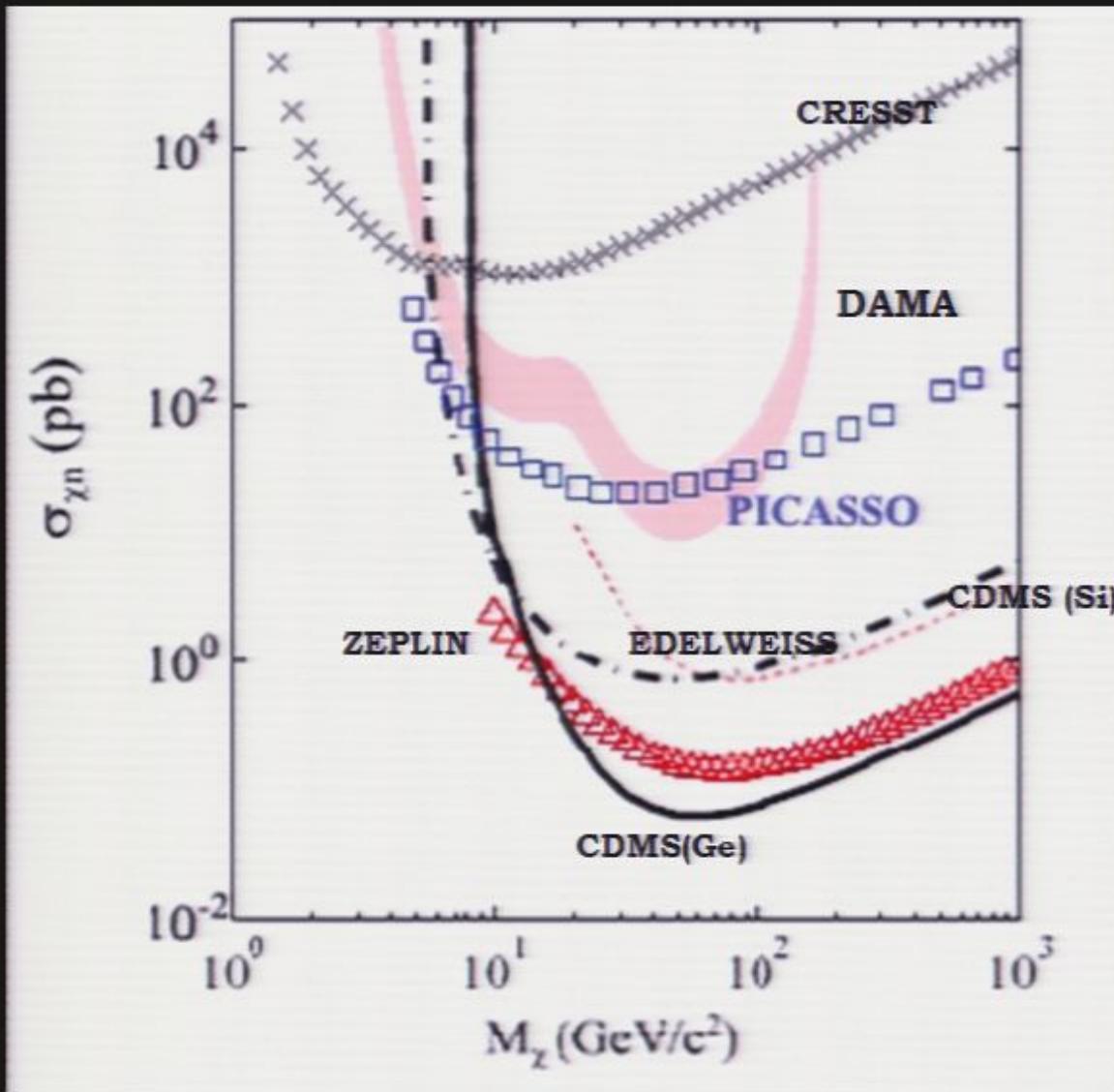
Courtesy <http://dmtools.brown.edu/>
Gaitskell&Mandic



SPIN DEPENDENT Proton-Neutralino

Upper limit of $\sigma_{\chi p} = 1.3 \text{ pb}$
for $M_\chi = 29 \text{ GeV}/c^2$

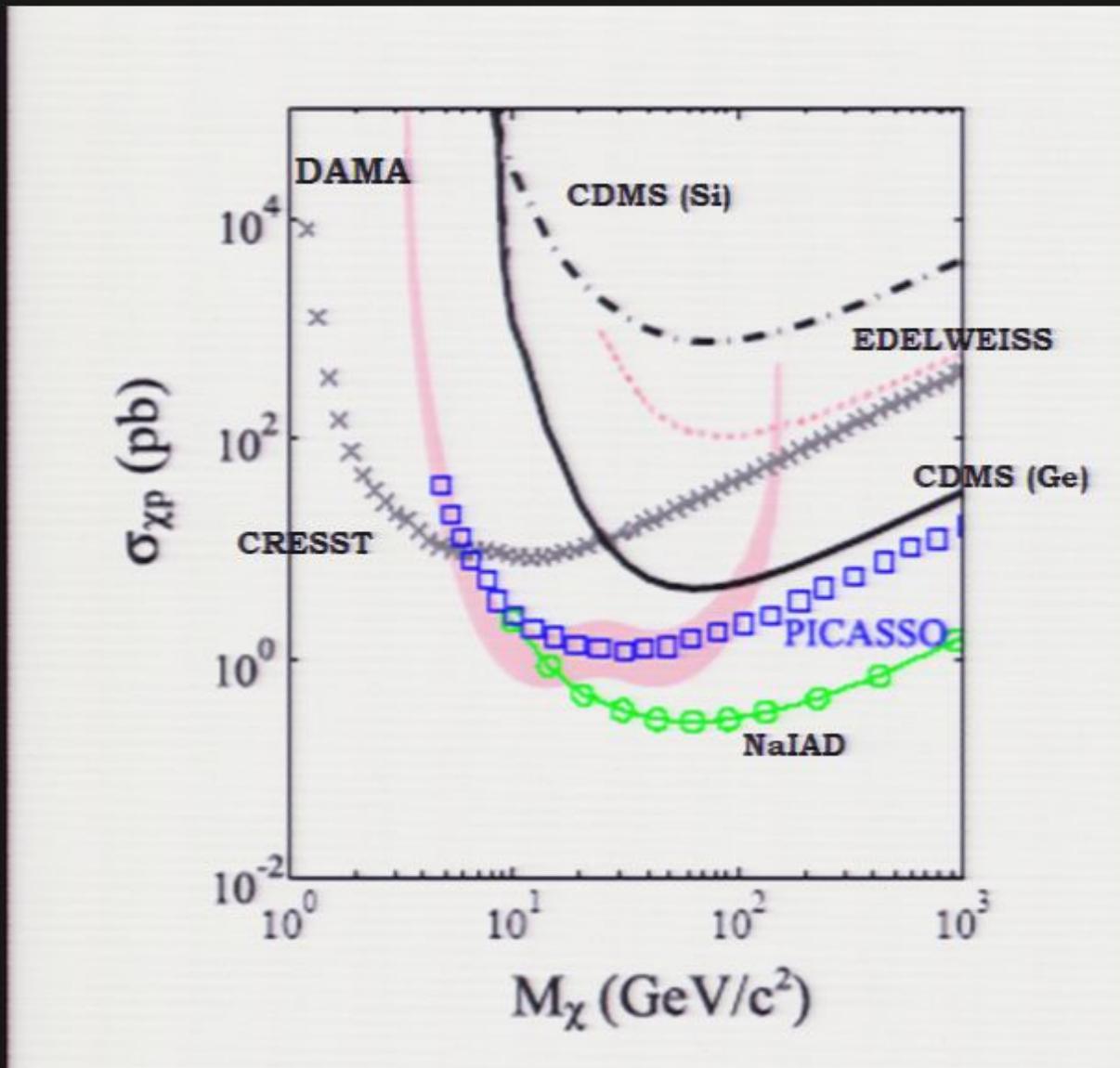
Courtesy <http://dmtools.brown.edu/>
Gaitskell&Mandic



SPIN DEPENDENT Neutron-Neutralino

Upper limit of $\sigma_{\chi n} = 21.5 \text{ pb}$
for $M_\chi = 29 \text{ GeV}/c^2$

Courtesy <http://dmtools.brown.edu/>
Gaitskell&Mandic

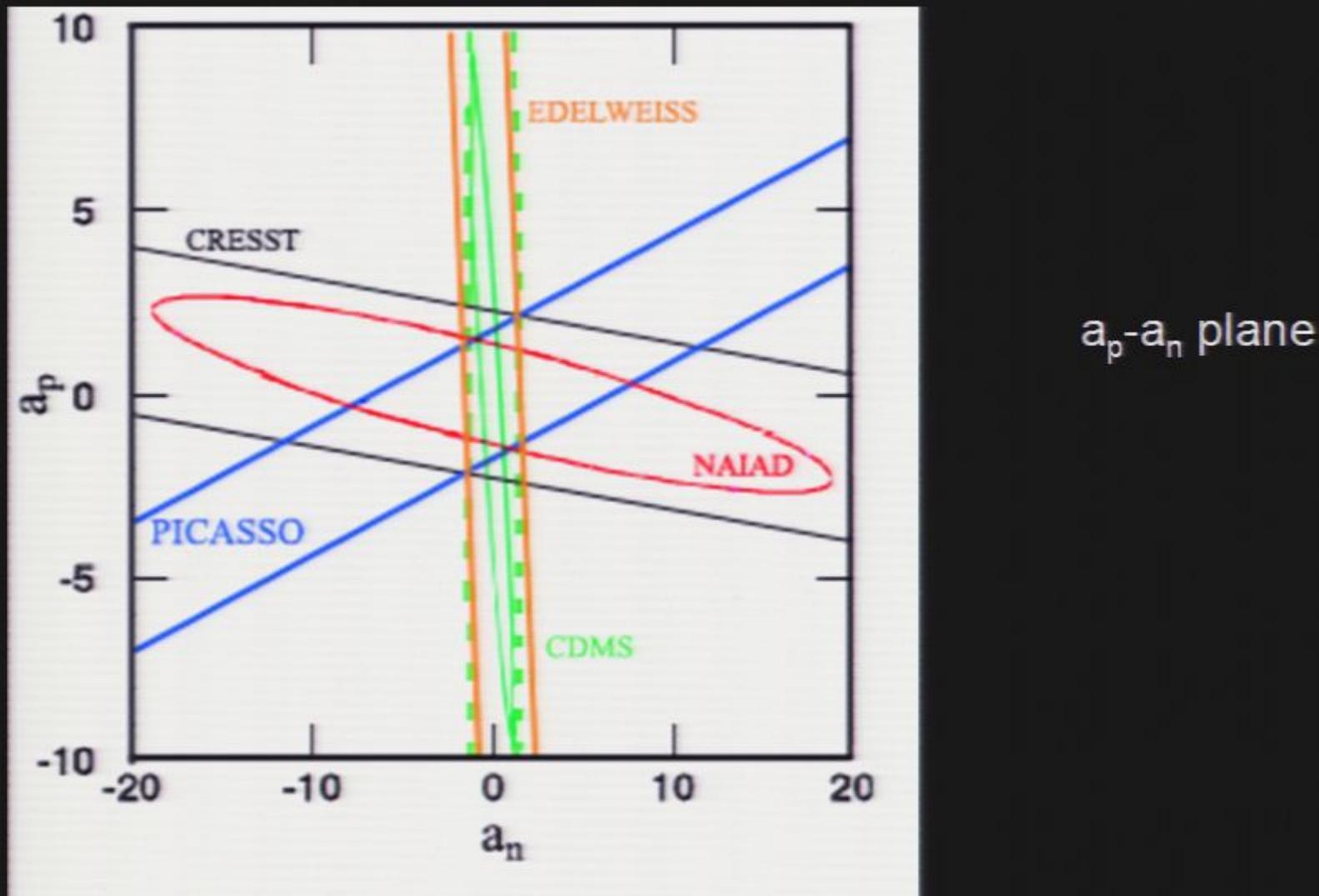


SPIN DEPENDENT Proton-Neutralino

Upper limit of $\sigma_{\text{cp}} = 1.3 \text{ pb}$
for $M_\chi = 29 \text{ GeV}/c^2$

Courtesy <http://dmtools.brown.edu/>
Gaitskell&Mandic

Neutralino couplings to protons and neutrons



PHASE Ib



- First experiment at **SNOLAB**
- **4.5 L Detector Modules: 32**
- **Total net detector volume: ~ 150 L**
- **Total active mass (C_4F_{10}): ~ 2.2 kg**
- **Acoustic channels: 288 (9 channels per detector)**
- **Mineral oil compression system**



Production of the 4.5L detectors

Improved fabrication Method: The 4.5L detector

1. Reduction of the internal background: Cleaner materials
2. Improved fabrication procedure – Defect-free gel & Homogeneous distribution of droplets
3. Reduction of the internal background - Purification of the ingredients
(PICASSO Collaboration technology)

Exp-ID	PZS50A	PZS50B	PZS50D	PZS60B&C
CsCl concentration	50%	50%	60%	60%
HZrO concentration	2 g Zr/L	0.28 g Zr/L	0.05 g Zr/L	0.13 g Zr/L
Extraction efficiency				
^{228}Th	>99.7%	>98.8%	$99.8 \pm 0.4\%$	$99.1 \pm 1.5\%$
^{224}Ra	>99.6%	$99.2 \pm 0.8\%$	-	$97.0 \pm 1.2\%$
^{226}Ra	>99.5%	$97.3 \pm 1.1\%$	$64.9 \pm 3.8\%$	$97.1 \pm 0.6\%$
^{212}Pb	-	-	-	$96.1 \pm 0.8\%$
^{212}Bi	-	-	-	$92.8 \pm 1.6\%$

→ New method: co-precipitation of Th, Ra and Pb with (HZrO) Hydrous Zirconium Oxide

Production of the 4.5L detectors

Improved fabrication Method: The 4.5L detector – Saltless

1. Saltless detectors: Glycol + Glycerine
2. Same Improved fabrication procedure – Defect-free gel & Homogeneous distribution of droplets
3. Reduction of the internal background - Purification of the ingredients
(PICASSO Collaboration technology)

Production of the 4.5L detectors

Improved fabrication Method: The 4.5L detector

1. Reduction of the internal background: Cleaner materials
2. Improved fabrication procedure – Defect-free gel & Homogeneous distribution of droplets
3. Reduction of the internal background - Purification of the ingredients
(PICASSO Collaboration technology)

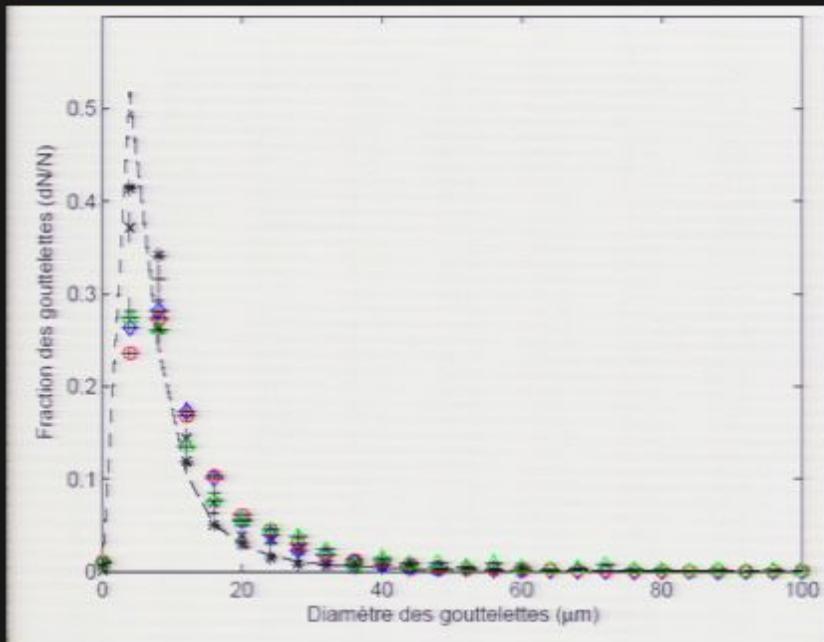
Exp-ID	PZS50A	PZS50B	PZS50D	PZS60B&C
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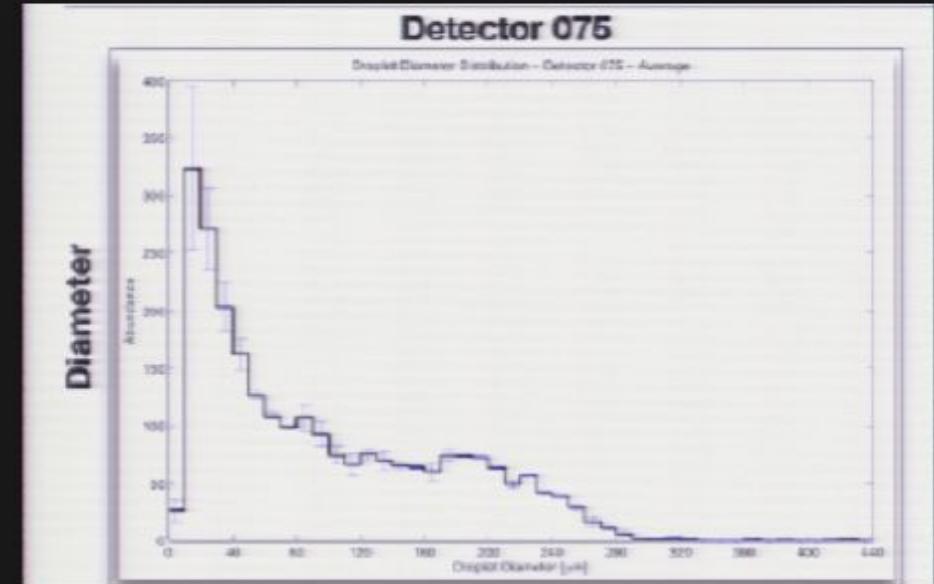
Production of the 4.5L detectors

Expected performance of the 4.5L PICASSO detector's production

→ Droplet Distribution



1-Litre



4.5-Litre

→ Higher loading

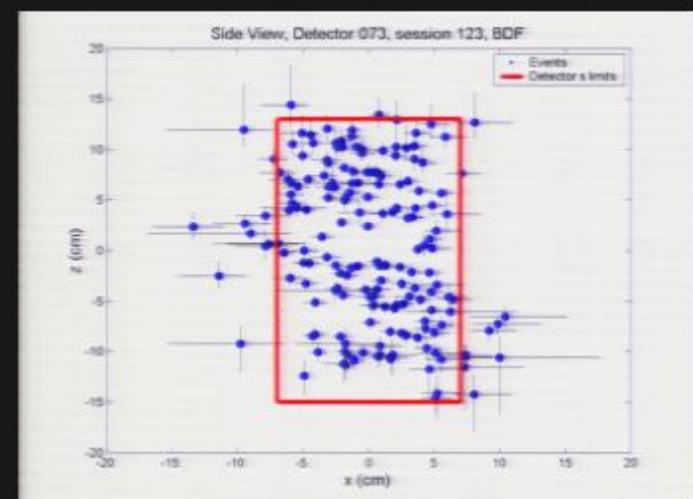
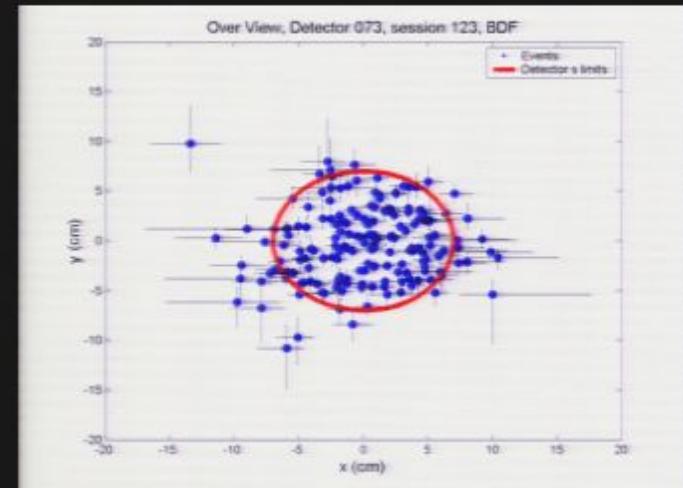
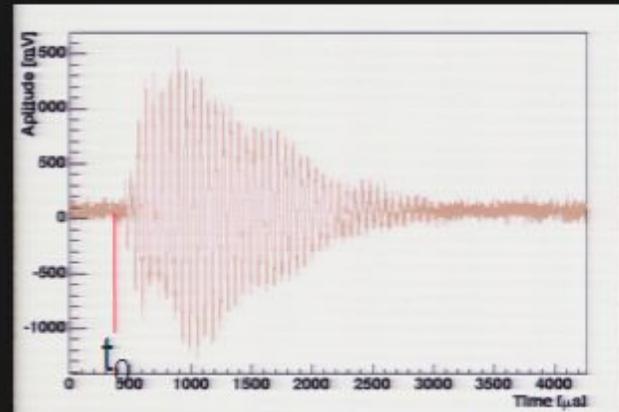
Active Mass: ~ 7g/L
Loading = 0.5%



Active Mass: ~ 19g/L detector
Loading ~ 1.2%

Event Localization

- Performance
 - All piezos sensors see individual events
 - No dead regions
 - Localization of events



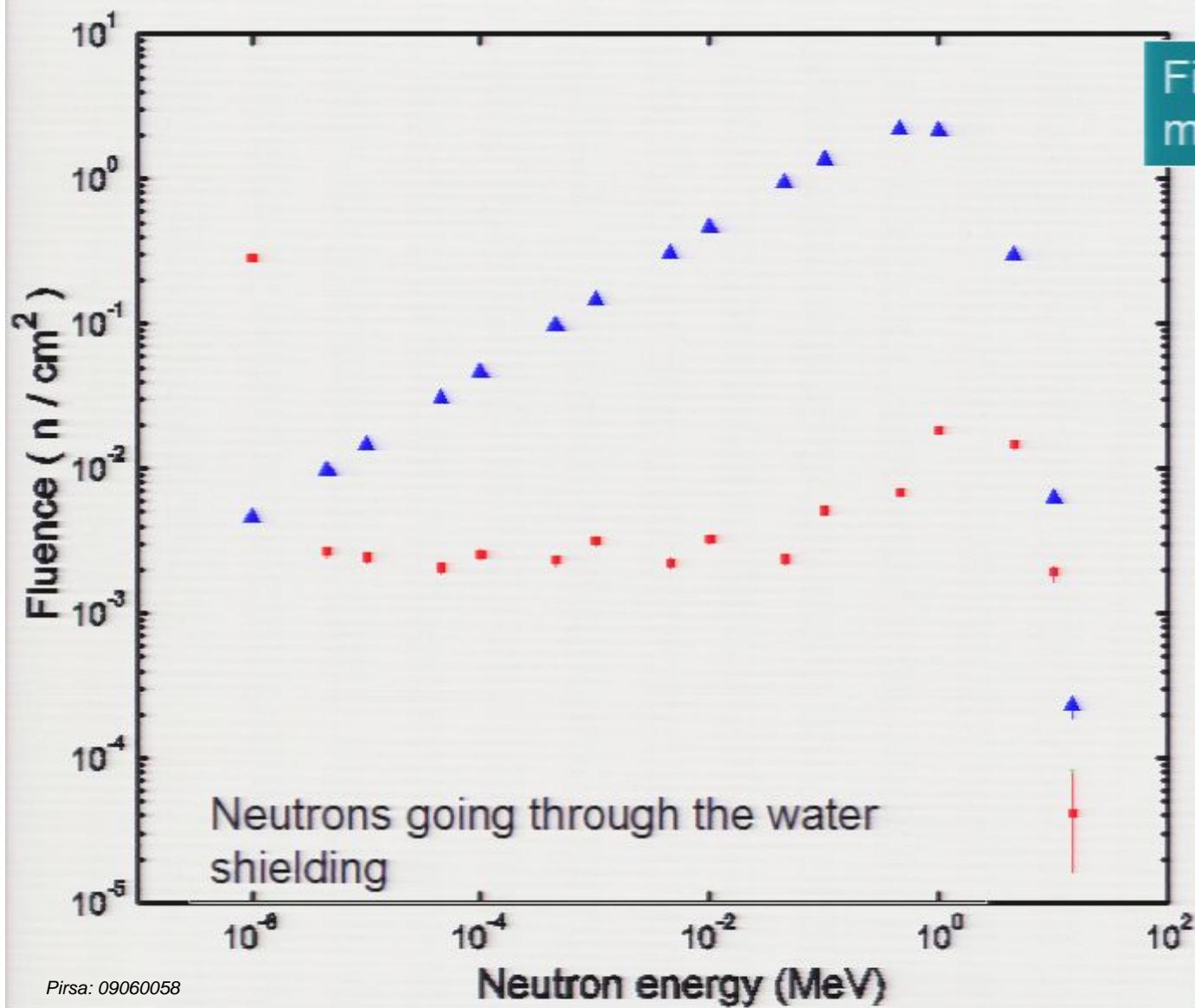
Reconstruction of event position very promising

Allows suppression of hot spots or surface events

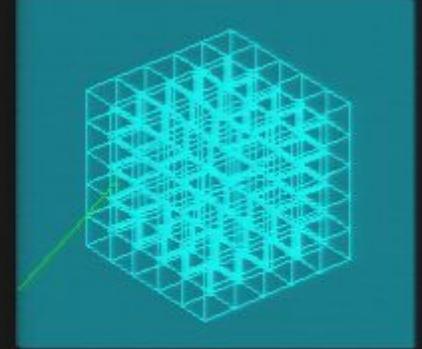
Determine t_0 from wave form

Reconstruction efficiency > 80%

Neutron shielding

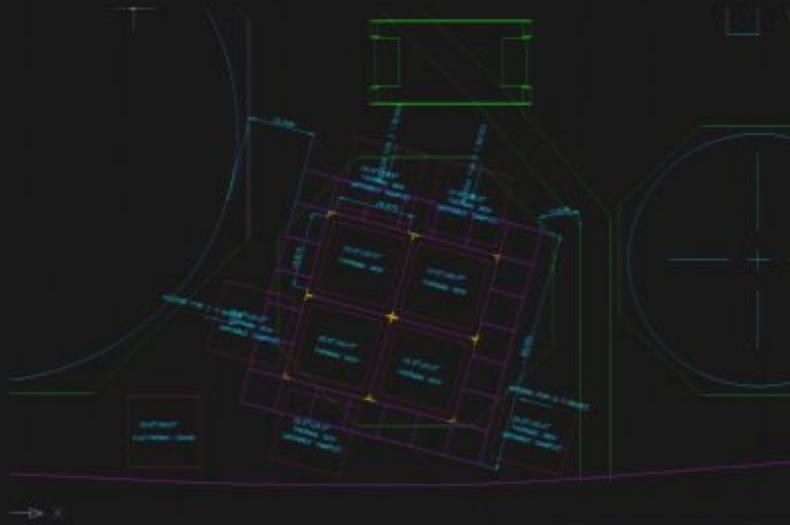


Fission neutrons in the mine



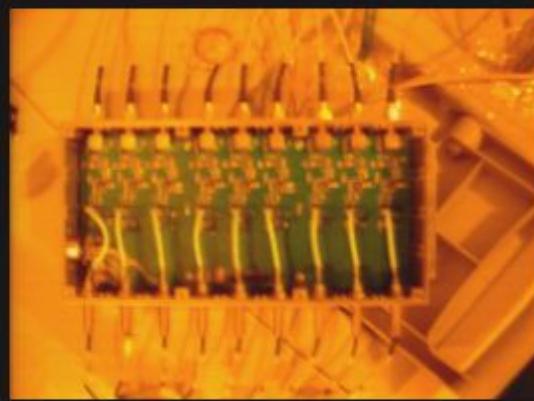
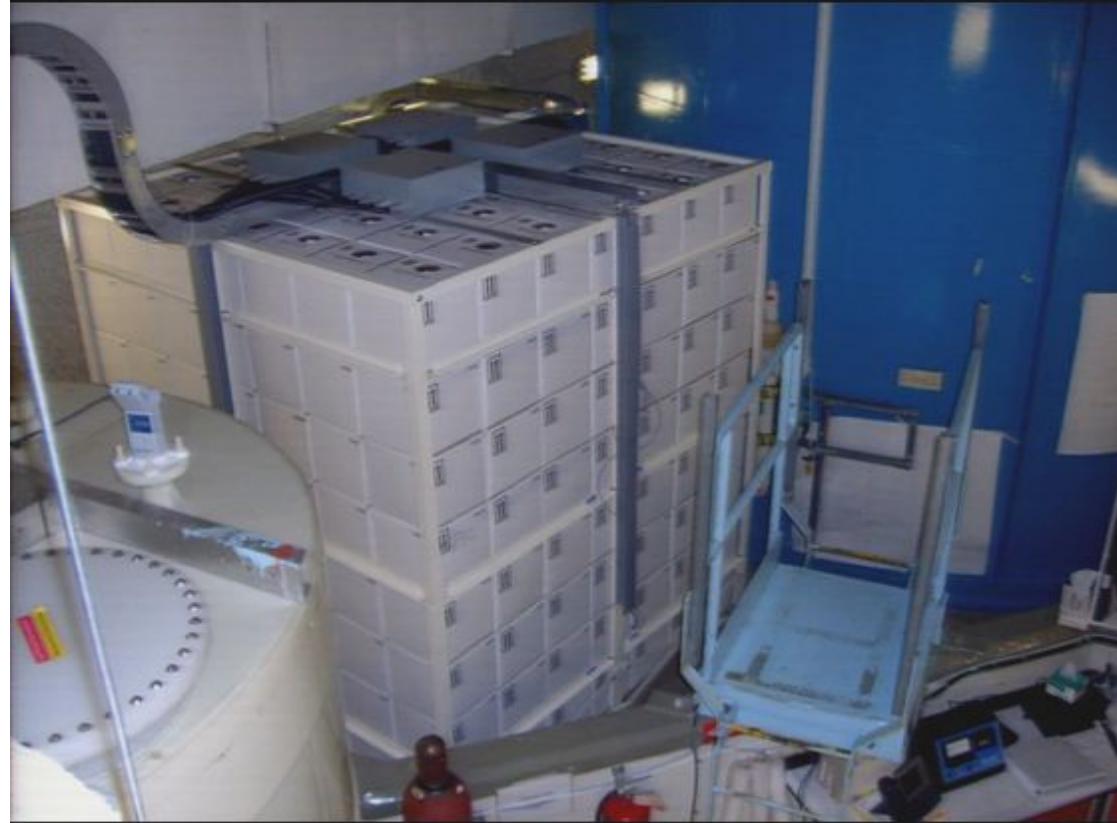
Shielding: 30 cm water cubes placed around the experimental set-up

Installation @ SNOLAB

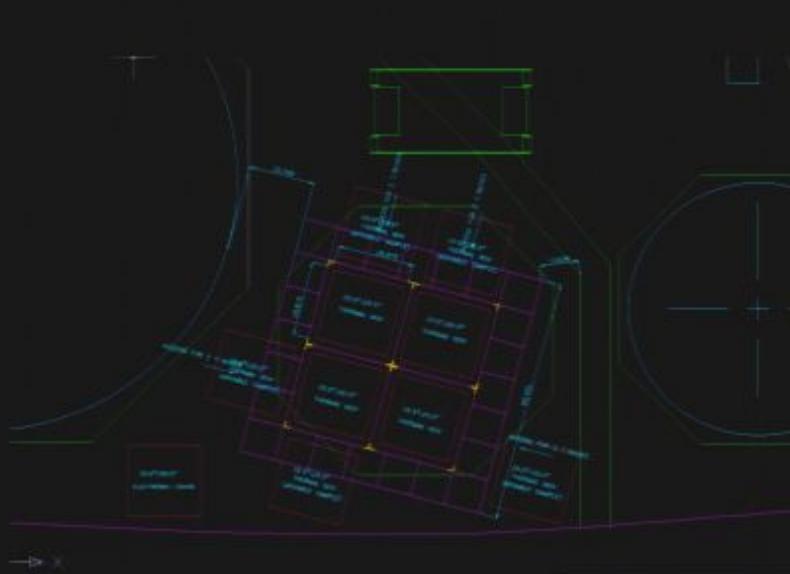


January 2006

Installation @ SNOLab

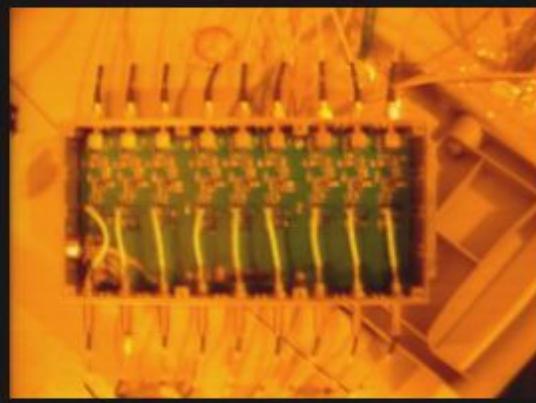


Installation @ SNOLAB



January 2006

Installation @ SNOLab

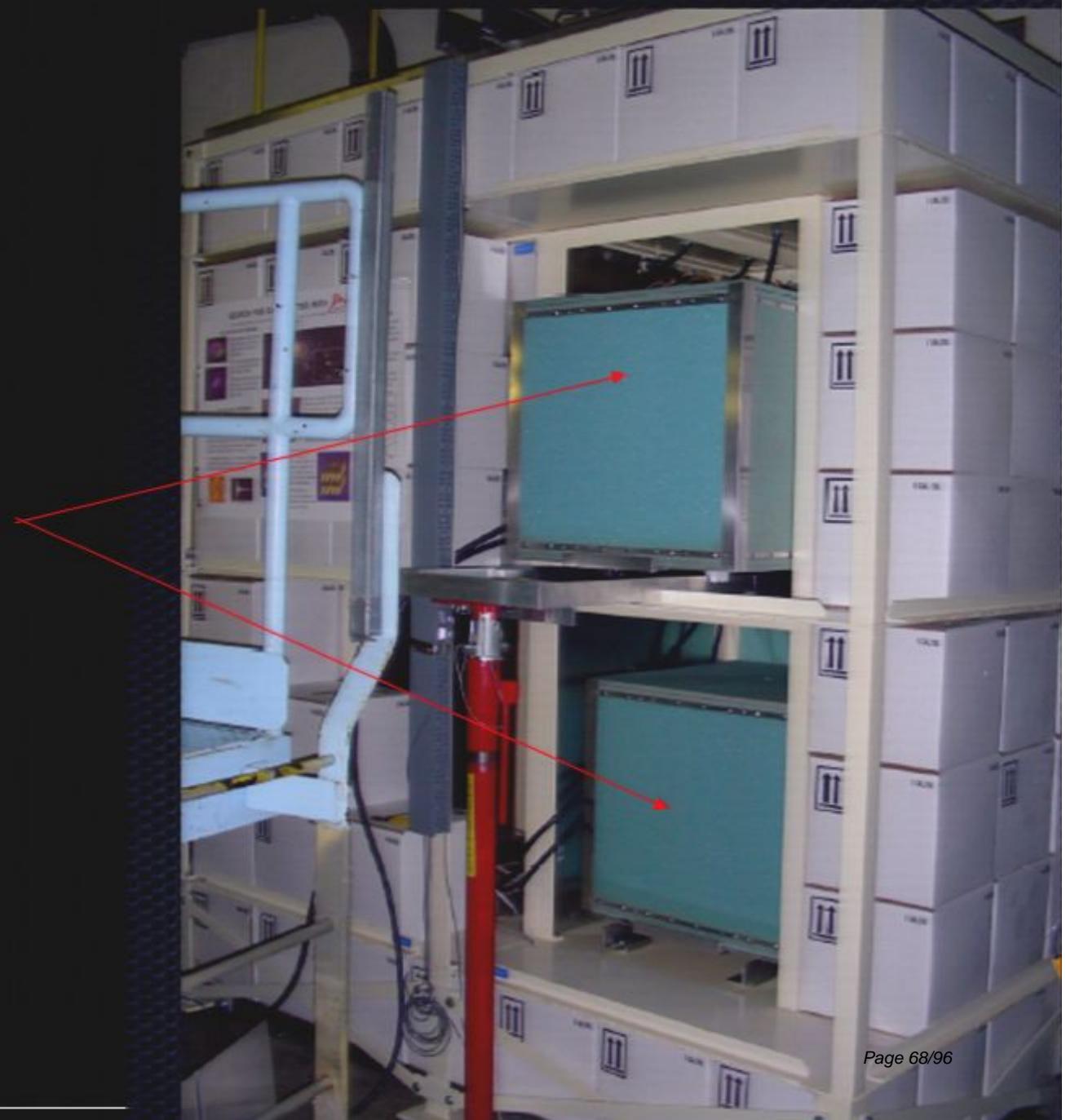




Picasso

Temperature & Pressure Control System (TPCS)

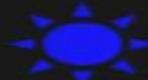
- TPCS units
- temp. precision: $\pm 0.1^{\circ}\text{C}$
- 4 detectors /TPCS
- 40 h data taking
- 15 h recompression



LOWER LEVEL OF THE TPCS

(The red arrow means the direction of opening, i.e. the front part of the TPCS.)

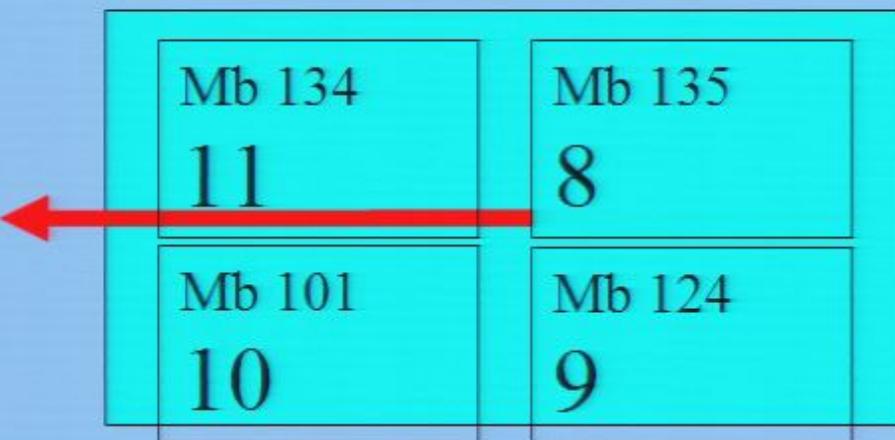
source =



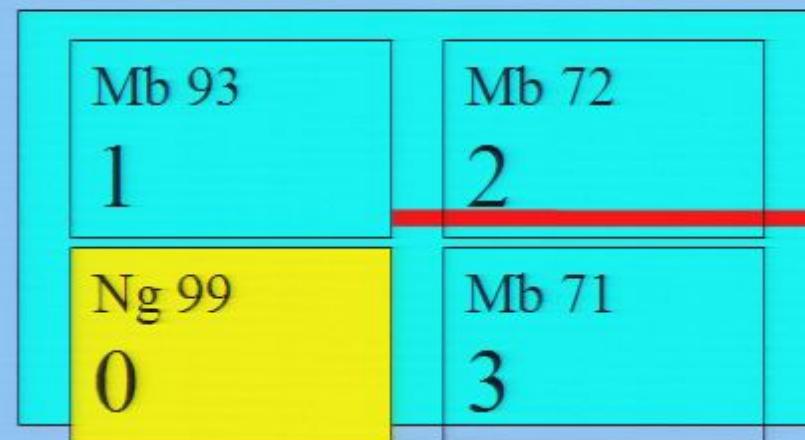
g = Saltless

M = C4F10, N = C4F8,

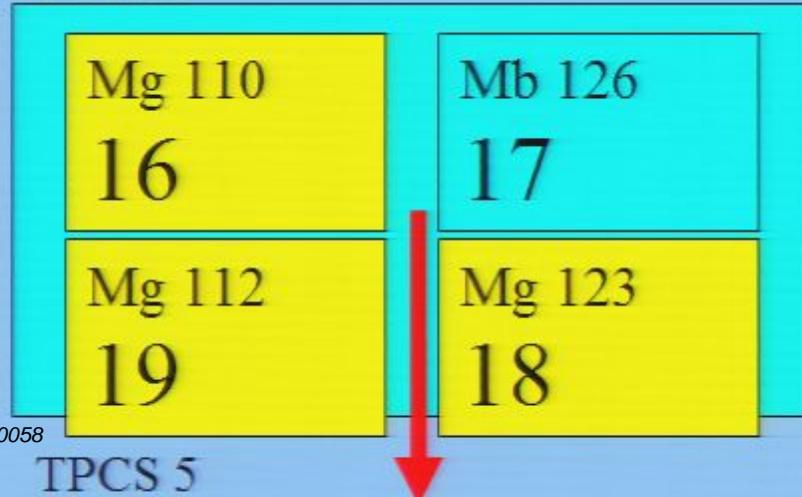
S = Detector without C4F10. Same solution of CsCl and monomer that the detector
139.



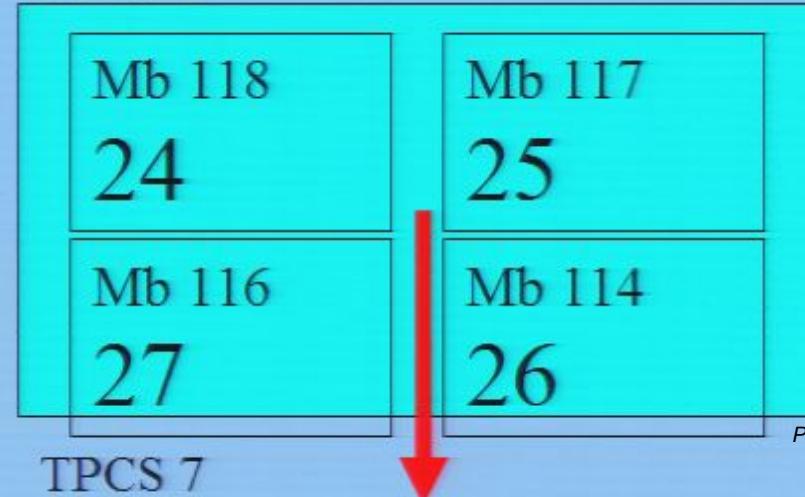
TPCS 3



TPCS 1



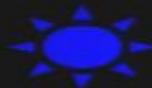
TPCS 5



UPPER LEVEL OF THE TPCS

(The red arrow means the direction of opening, i.e. the front part of the TPCS.)

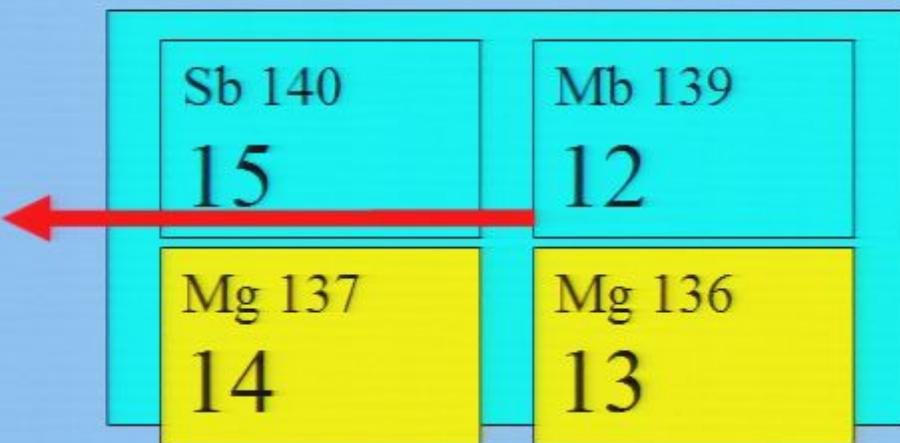
source =



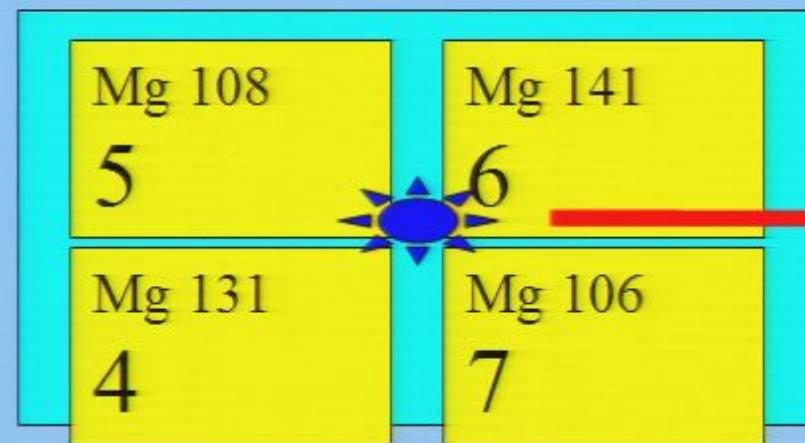
g = Saltless

M = C4F10, N = C4F8,

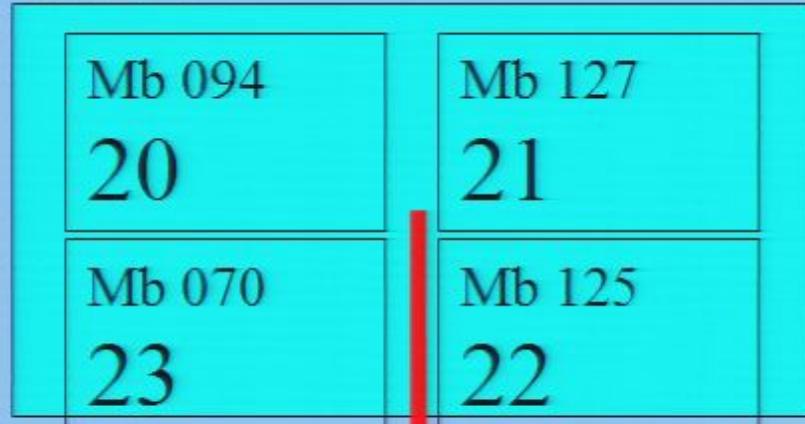
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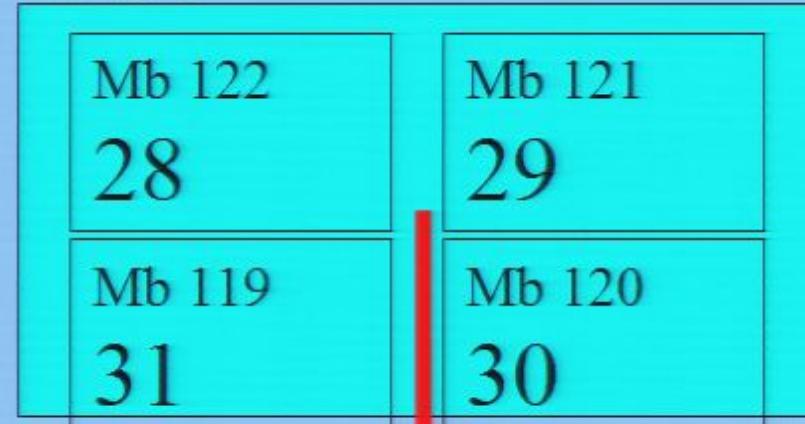
TPCS 4



TPCS 2



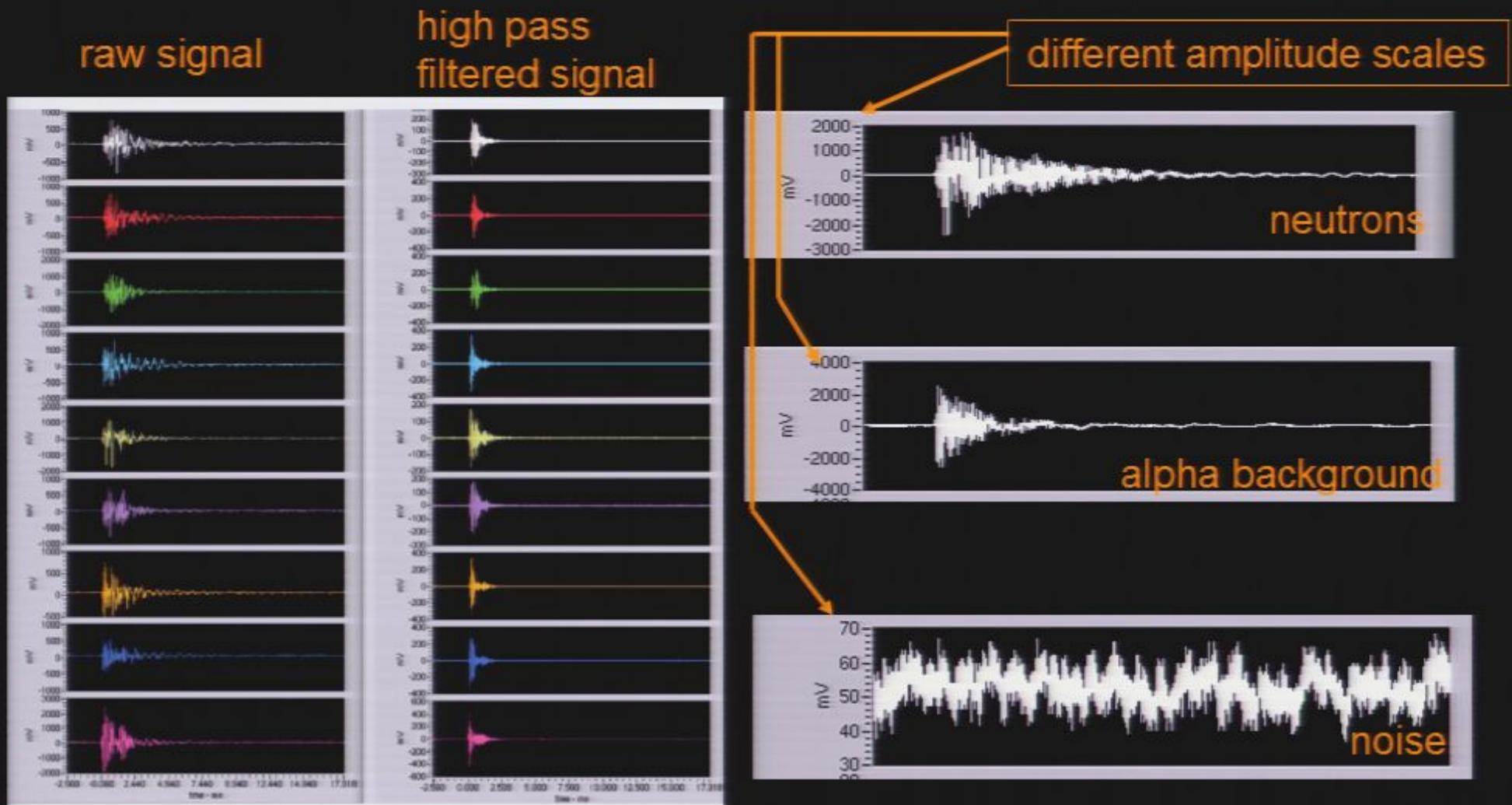
TPCS 6



TPCS 8

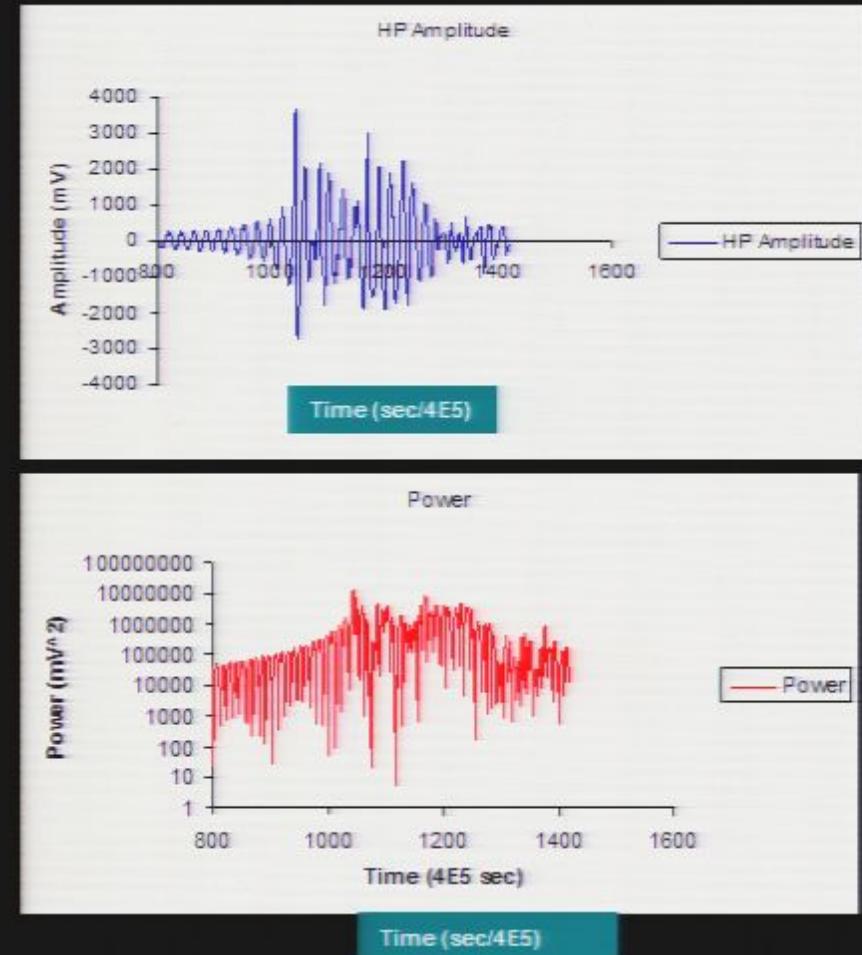


PICASSO events



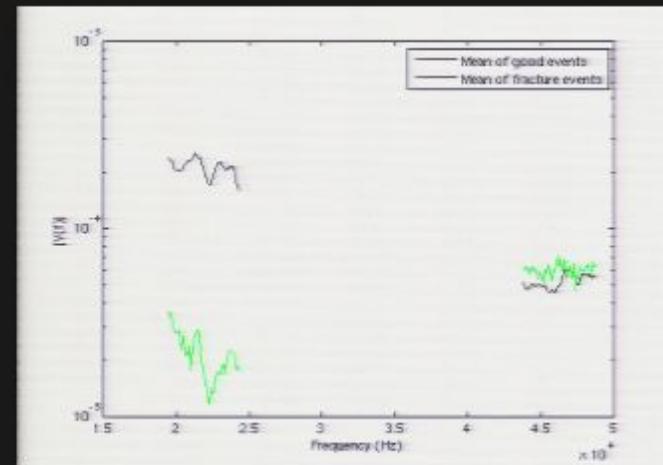
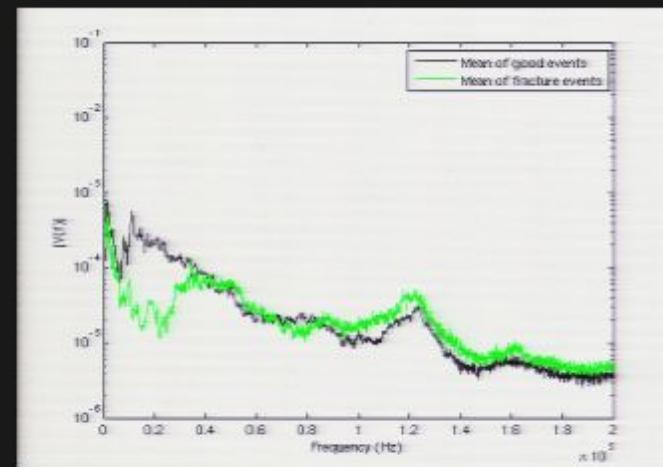
Data Analysis

- PVar
 - High pass filter events
 - Integrate Power to get energy



Data Analysis

- FVar
 - Fourier Transform
 - Ratio between low and high frequency windows



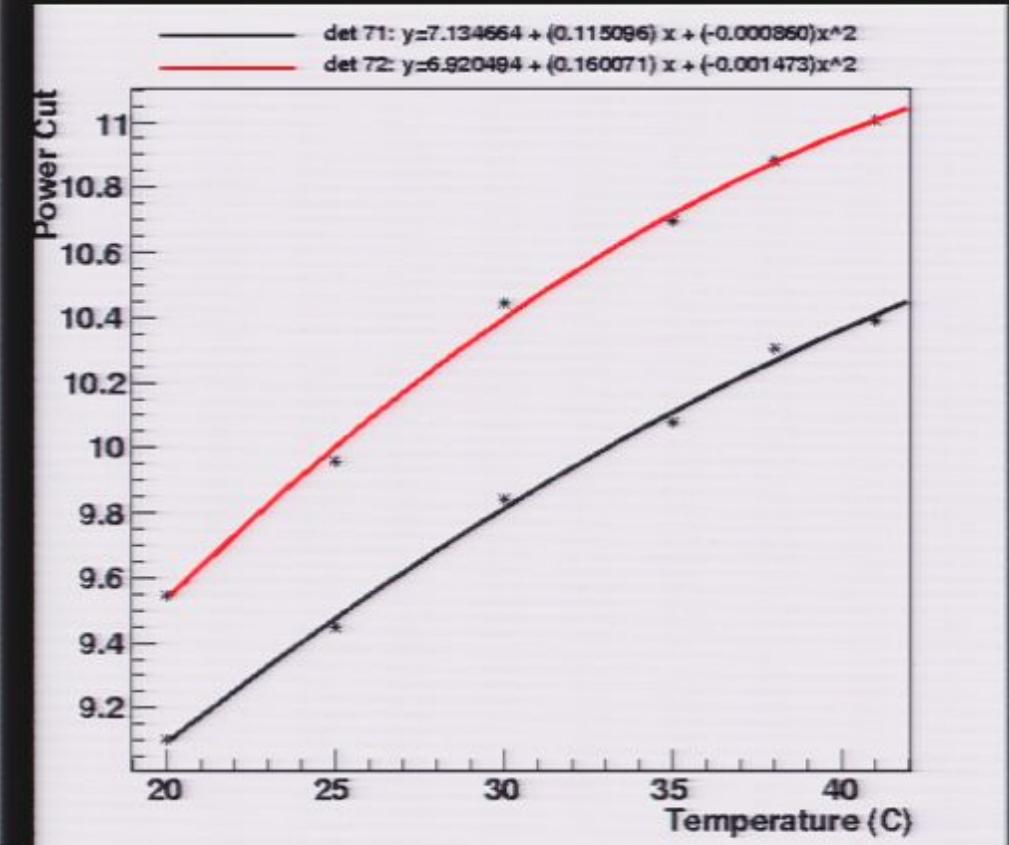
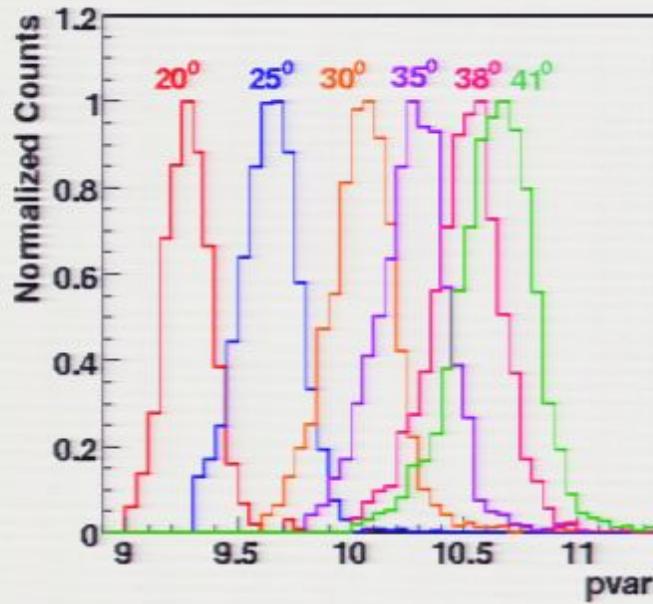
What next with PVar?

- Use neutron calibration runs to get PVar distributions for neutrons.
- Fit a Gaussian and select 95% : this will be our signal
- If $PVar > PCut \Rightarrow$ we got particle induced event!!

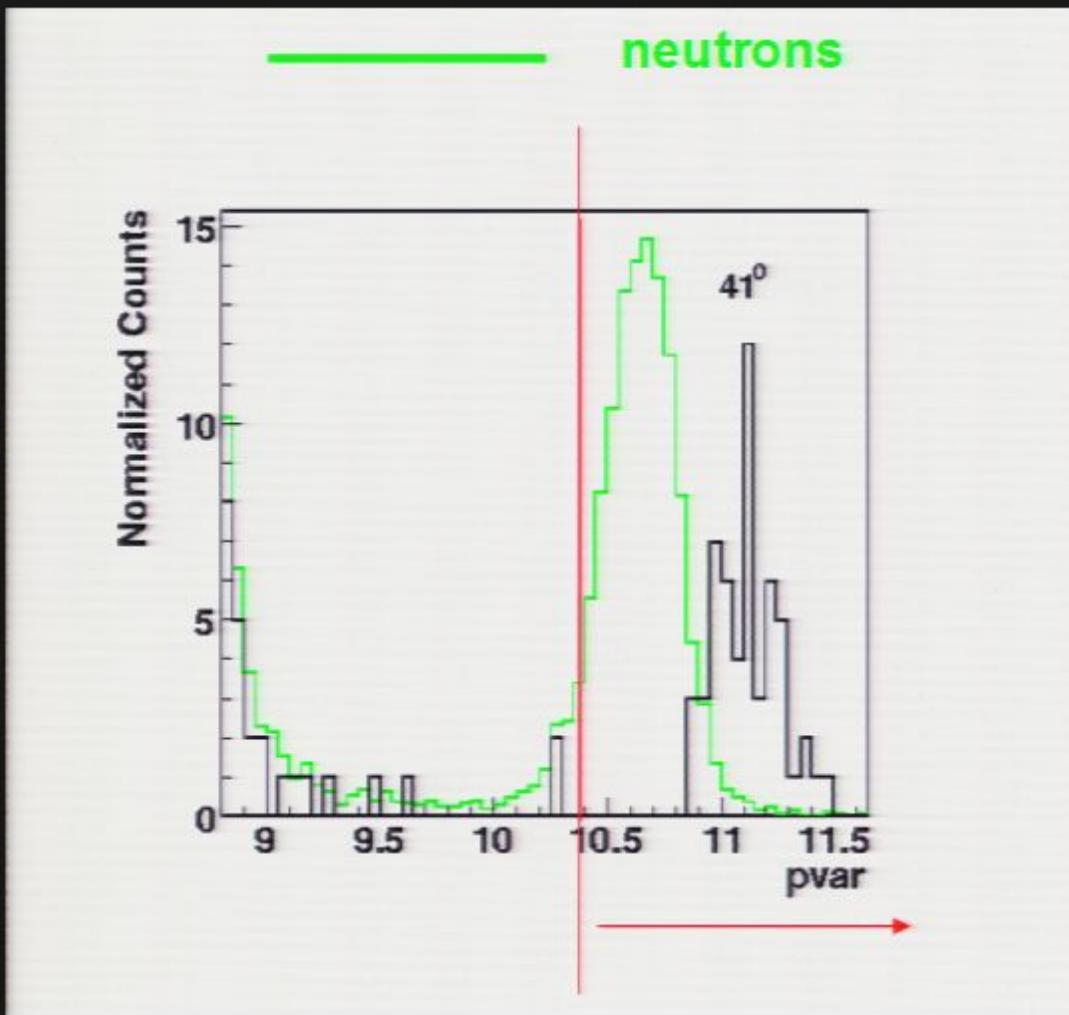
$PCut = \mu - 1.64\sigma$ of Gaussian

PVar Distributions for Calibration Runs

Distributions are temperature dependant



PVar Distributions for neutron and alpha background



Neutrons and alphas
well separated

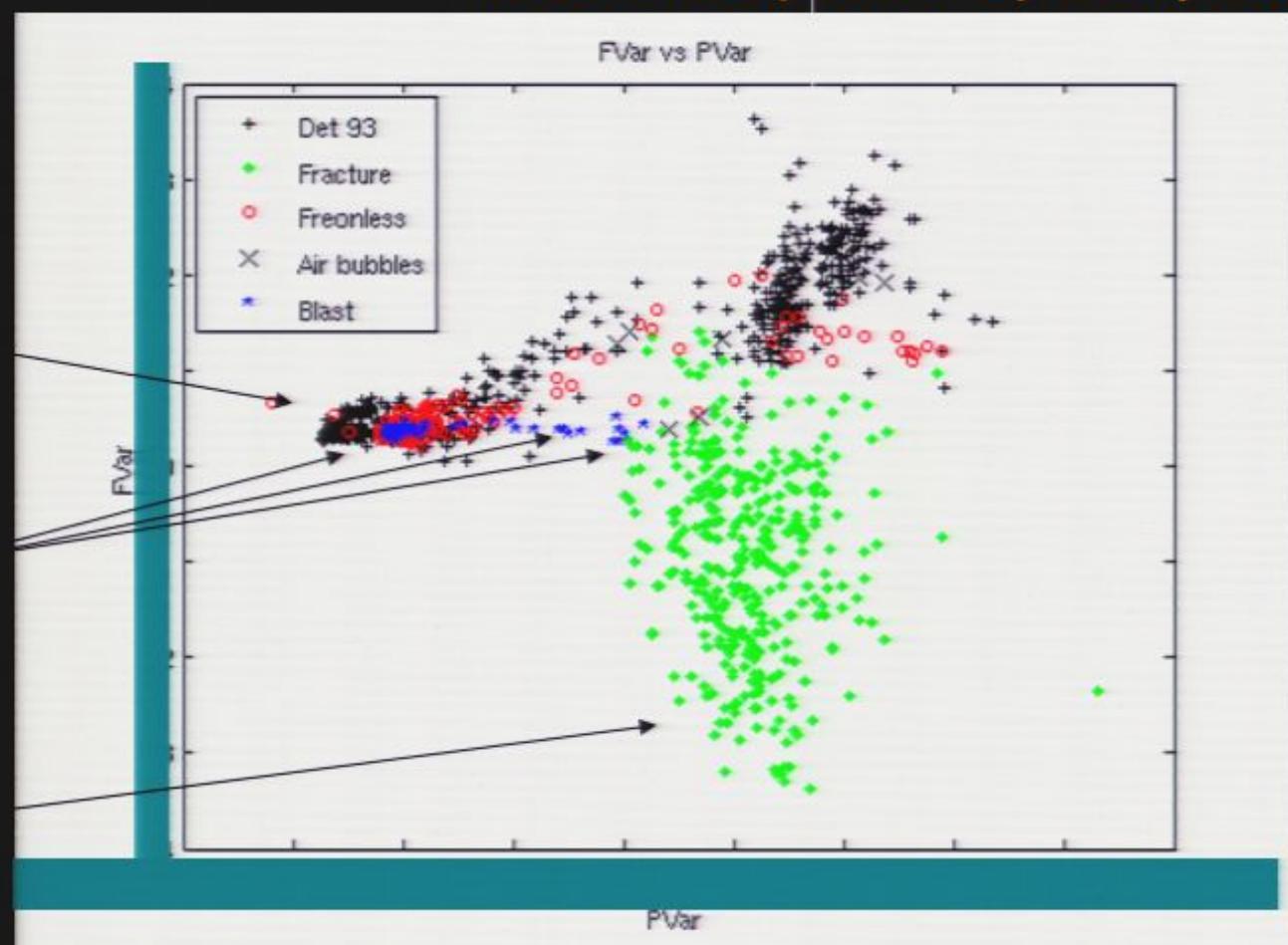
FVar Distributions for neutron and background

Neutrons (WIMPs) & alphas

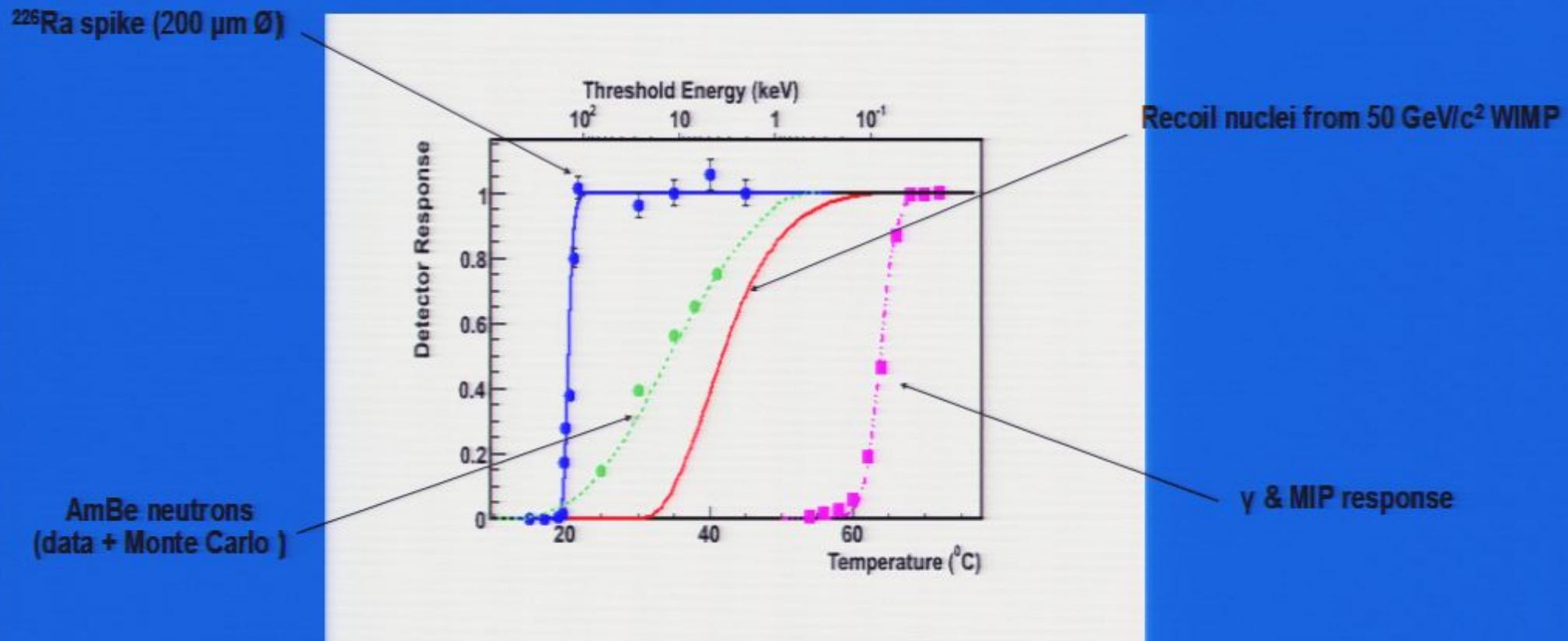
Noise

Blast

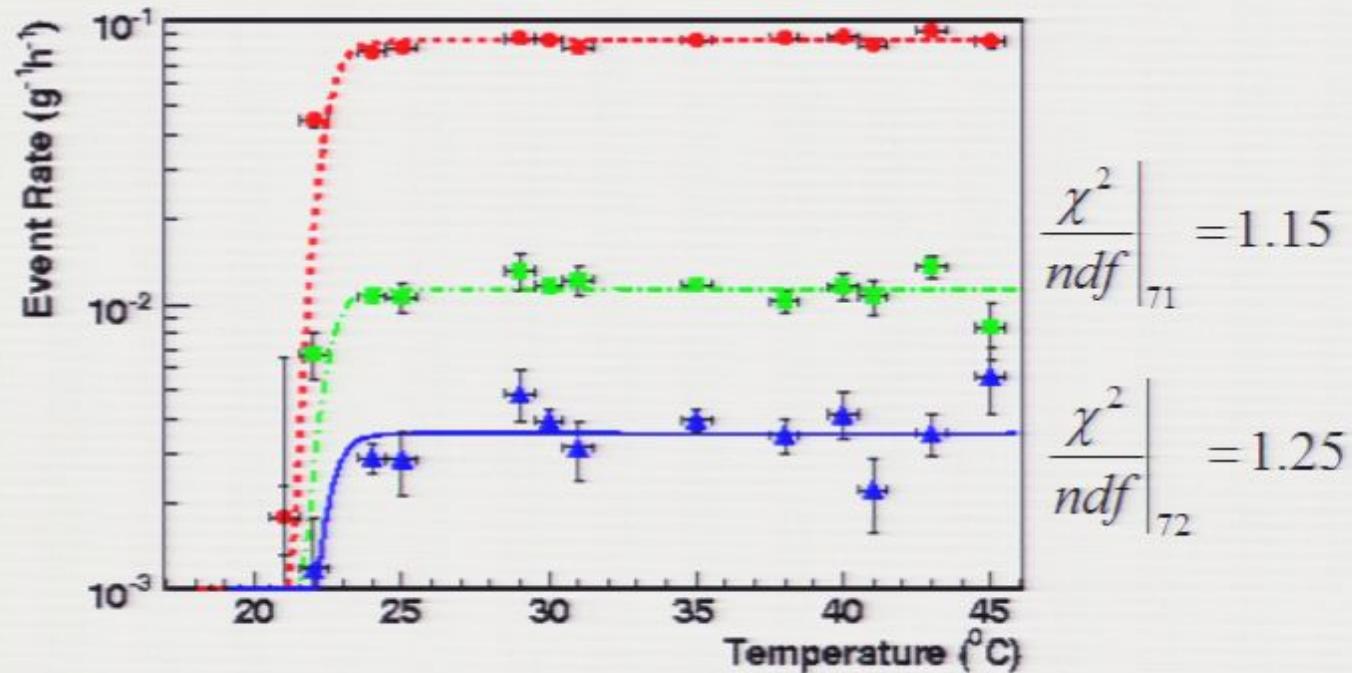
Fracture



PICASSO detector responses



Null Hypothesis Alpha Rate Fitted: Detectors 71,72



- Rates have been normalized to F^{19}

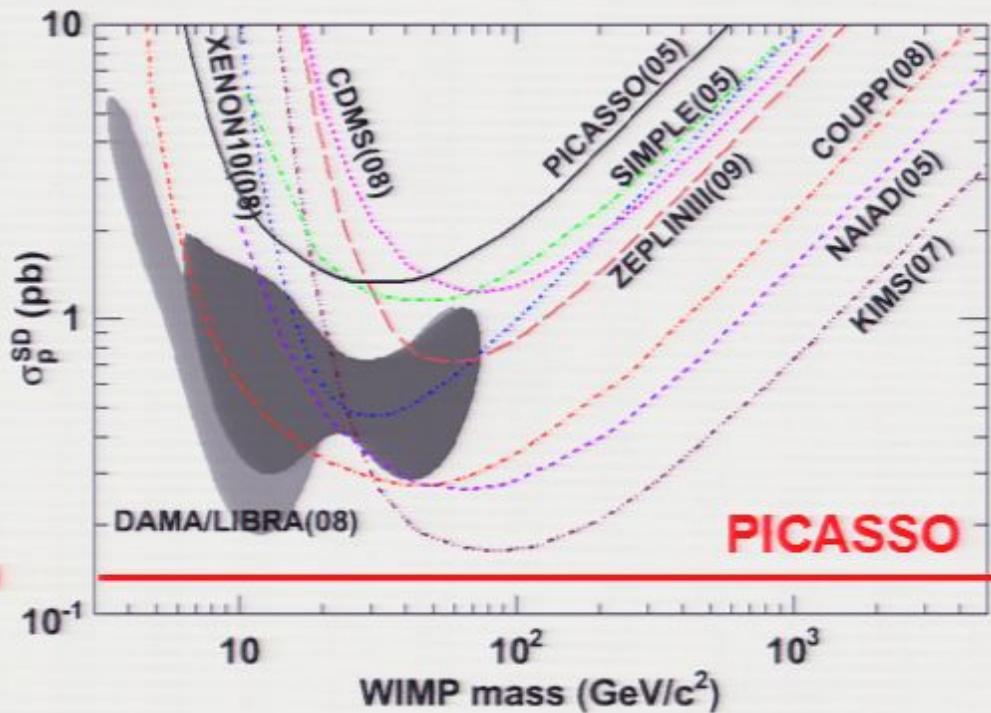
Systematics

Systematic	Uncertainty
Active mass (C_4F_{10})	5%
Neutron Threshold Energy	3%
Pressure variation	3%
Hydrostatic pressure gradient inside detector	2%
Energy resolution	20%
Temperature	0.1C

PICASSO

New Results

PICASSO New Results



Exposure
 13.75 ± 0.48
kg.days

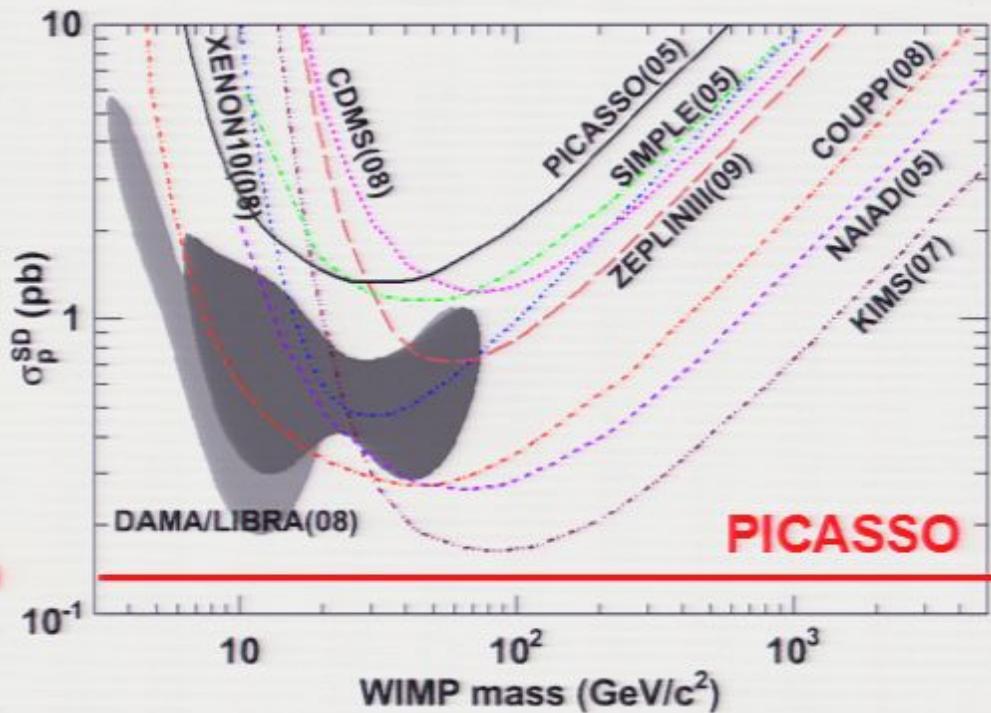
(Previous
exposure
1.98 kg
days)

32 det
expected
sensitivity
0.05 pb

PICASSO

New Results

PICASSO New Results



Exposure
 13.75 ± 0.48
kg.days

(Previous
exposure
1.98 kg
days)

32 det
expected
sensitivity
0.05 pb

Discrimination of Nuclear Recoils from Alpha Particles

PICASSO discovered a significant difference between amplitudes of neutron and α - particle induced events !

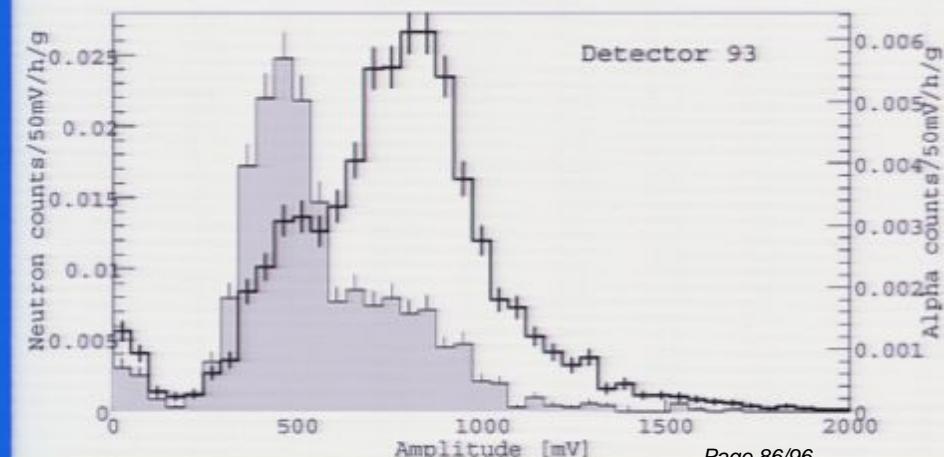
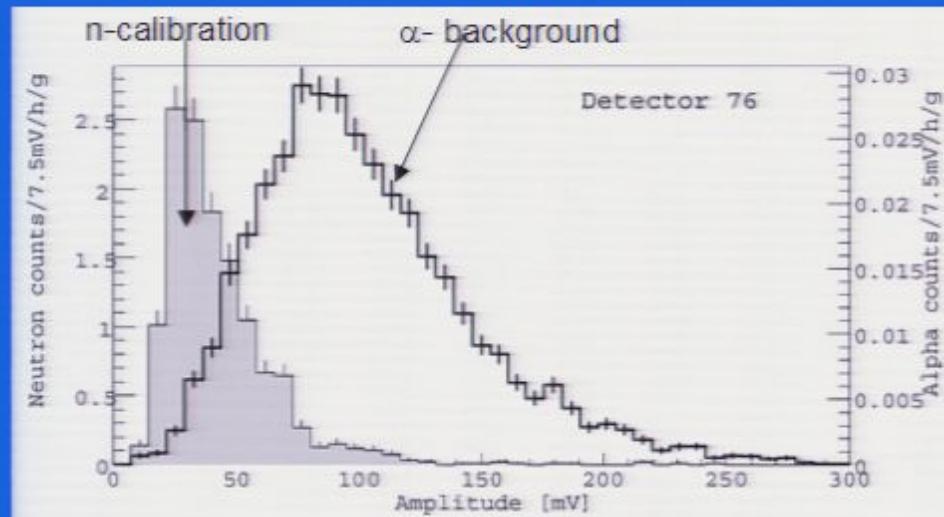
New Journal of Physics 10(2008)103017 arXiv: 0807.1536

Average of peak amplitudes of nine transducers / detector

High pass filter with cut-off at 15 KHz



Signals carry information about first moment of bubble formation

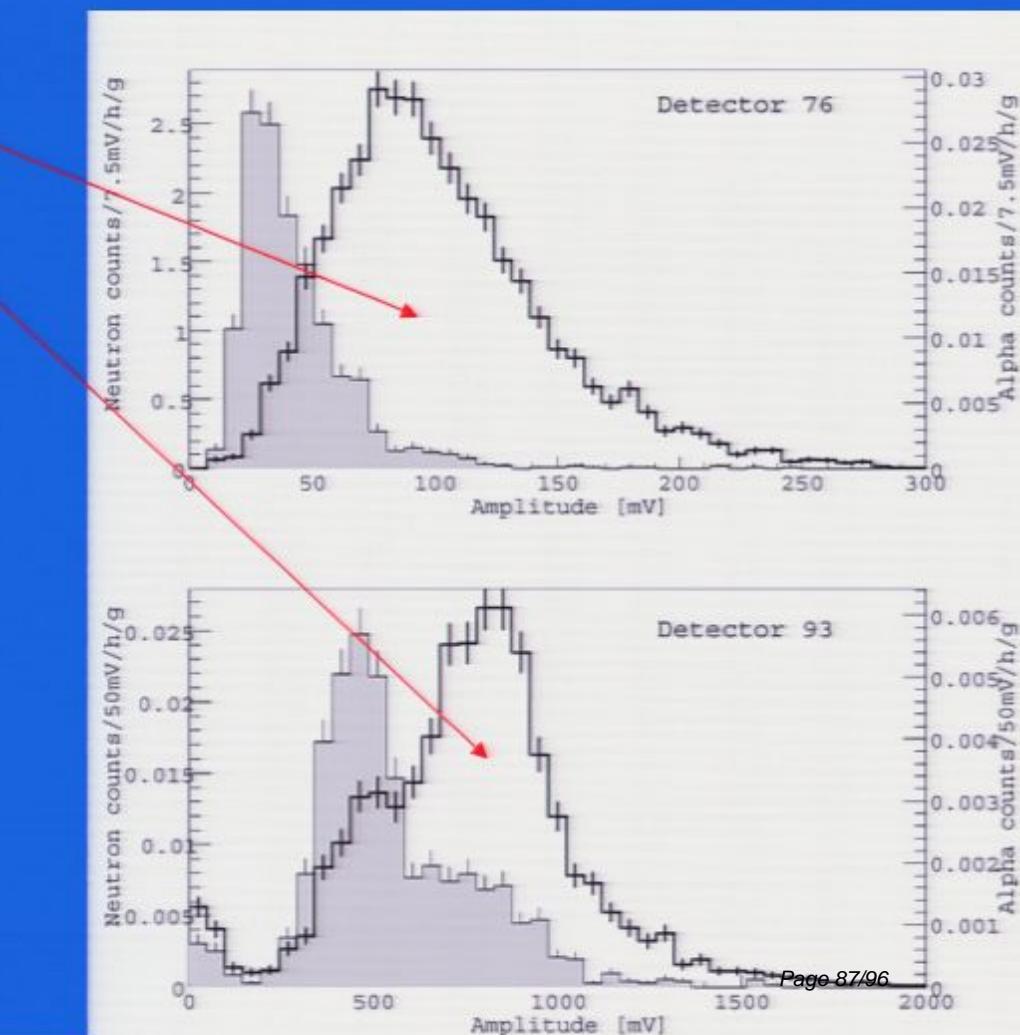
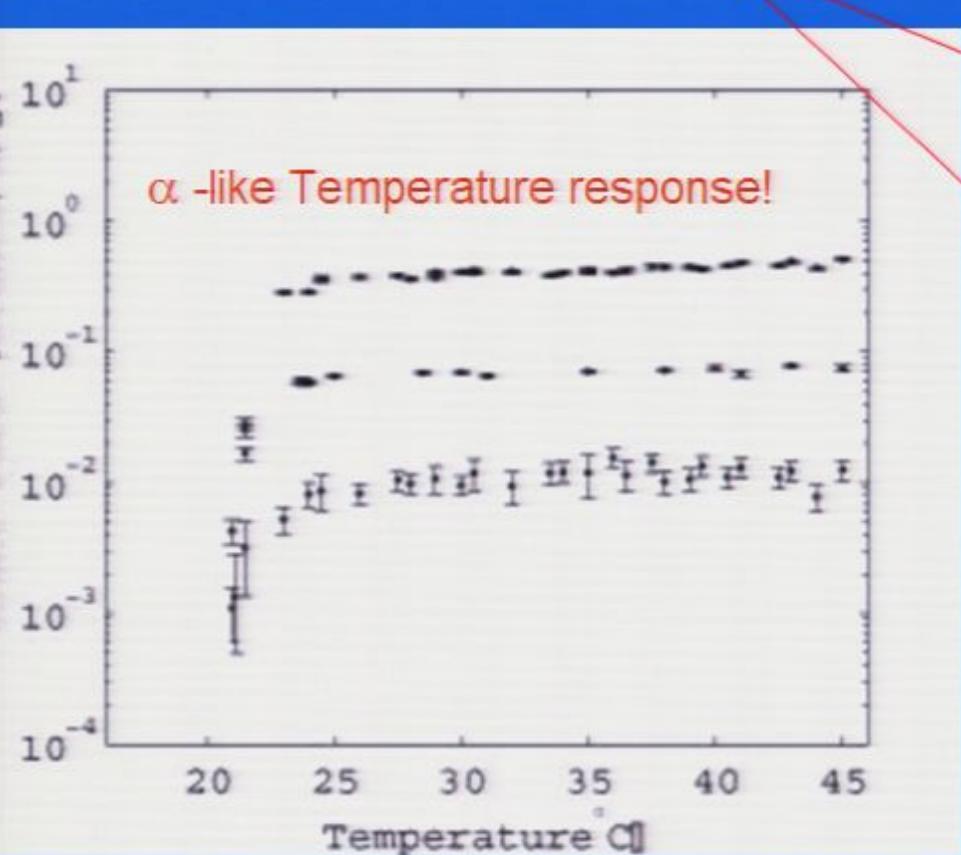


Discrimination of Nuclear Recoils from Alpha Particles

PICASSO discovered a significant difference between amplitudes of neutron and α - particle induced events !

New Journal of Physics 10(2008)103017 arXiv: 0807.1536

Are these really α events?



Discrimination of Nuclear Recoils from Alpha Particles

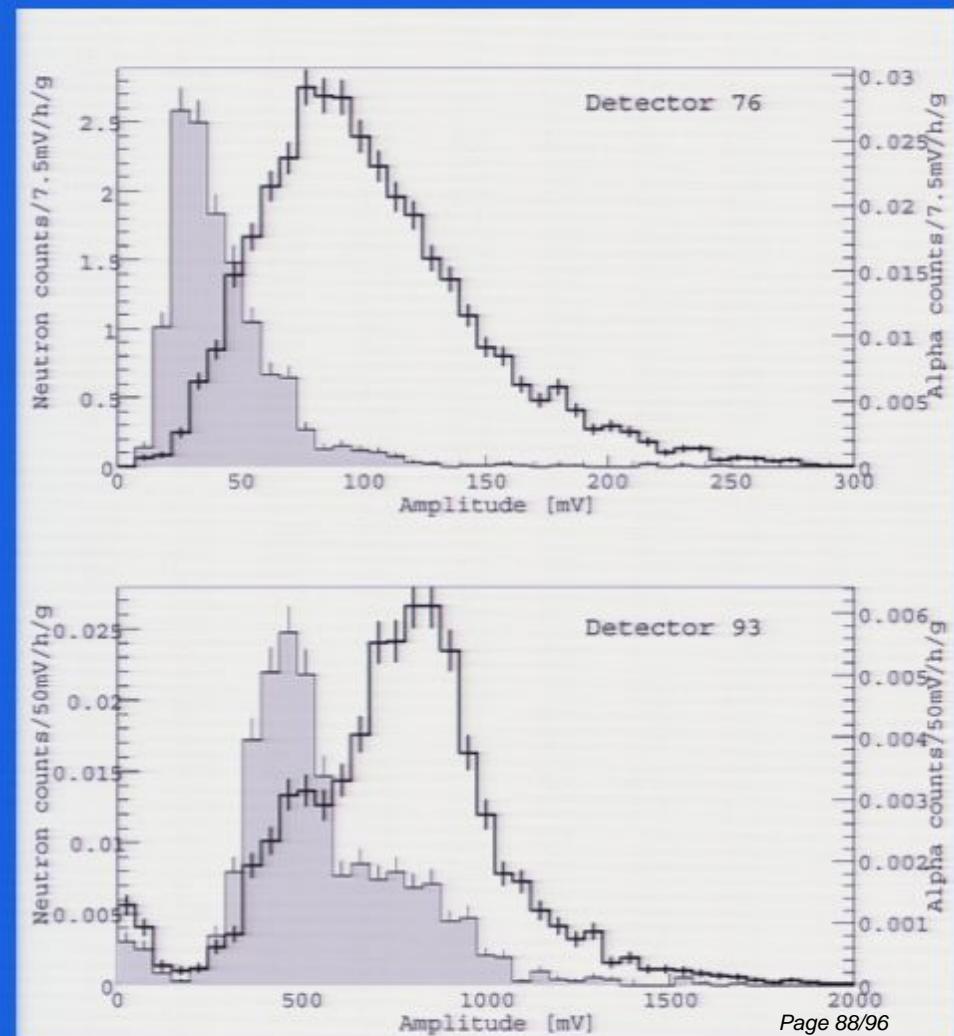
PICASSO discovered a significant difference between amplitudes of neutron and α - particle induced events !

New Journal of Physics 10(2008)103017 arXiv: 0807.1536

Why not observed earlier?

Previous detector had smaller droplets!

- now $200 \mu\text{m}$ compared to $< 10 \mu\text{m}$
- range of nuclear recoils $< L_c$
- but range of alphas $\gg L_c$
- many bubbles can form on α track
(depend on temperature)



α - n Discrimination: a tentative explanation

Nuclear recoil: point like, strong ionisation



α -particles: ionization on $35\mu\text{m}$ track

prim. bubbles *Poisson* distributed !

$T = 30^\circ\text{C}$



$T = 40^\circ\text{C}$



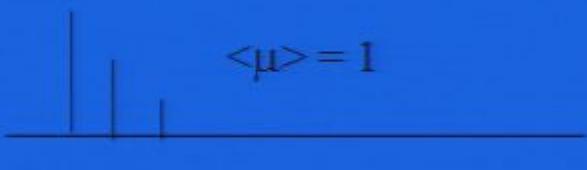
$T = 50^\circ\text{C}$



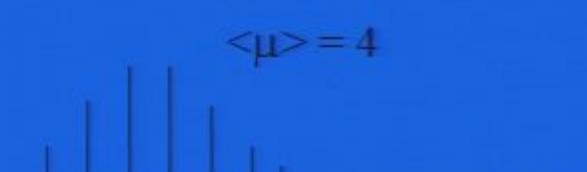
of primary bubbles



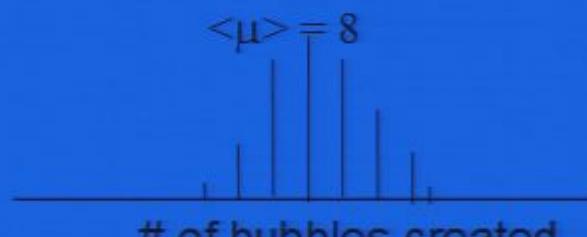
$<\mu> = 1$



$<\mu> = 4$



$<\mu> = 8$



of bubbles created

Discrimination of Nuclear Recoils from Alpha Particles

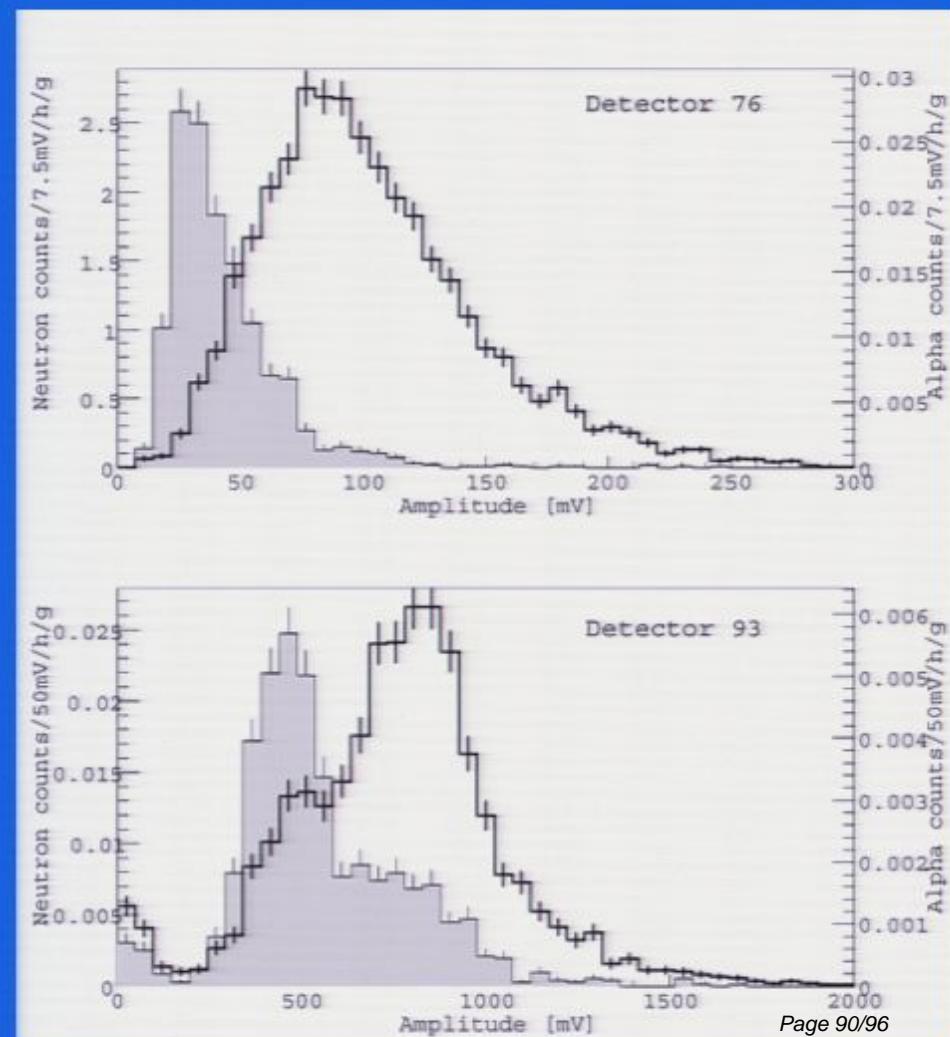
PICASSO discovered a significant difference between amplitudes of neutron and α - particle induced events !

New Journal of Physics 10(2008)103017 arXiv: 0807.1536

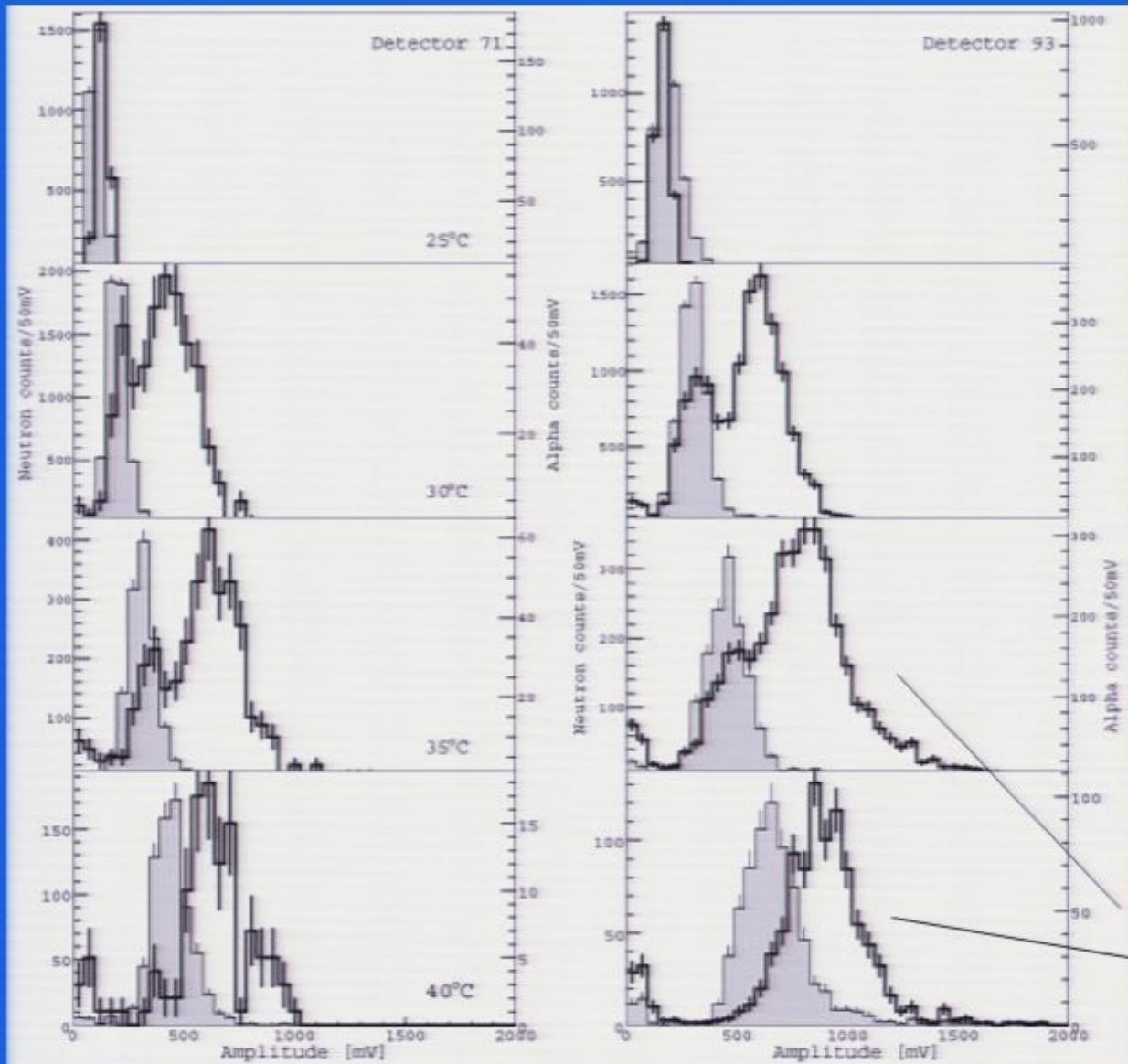
Why not observed earlier?

Previous detector had smaller droplets!

- now $200 \mu\text{m}$ compared to $< 10 \mu\text{m}$
- range of nuclear recoils $< L_c$
- but range of alphas $\gg L_c$
- many bubbles can form on α track
(depend on temperature)



α - n Discrimination: Temperature Dependence



Strong saturation of raw signals above 30°C!

α - n Discrimination: a tentative explanation

Nuclear recoil: point like, strong ionisation



α -particles: ionization on $35\mu\text{m}$ track

prim. bubbles *Poisson* distributed !

$T = 30^\circ\text{C}$



$T = 40^\circ\text{C}$

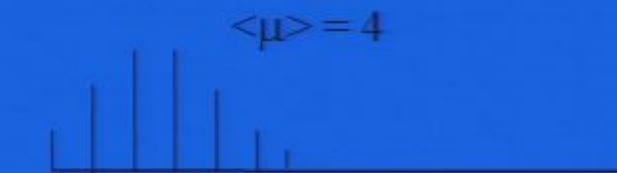


$T = 50^\circ\text{C}$



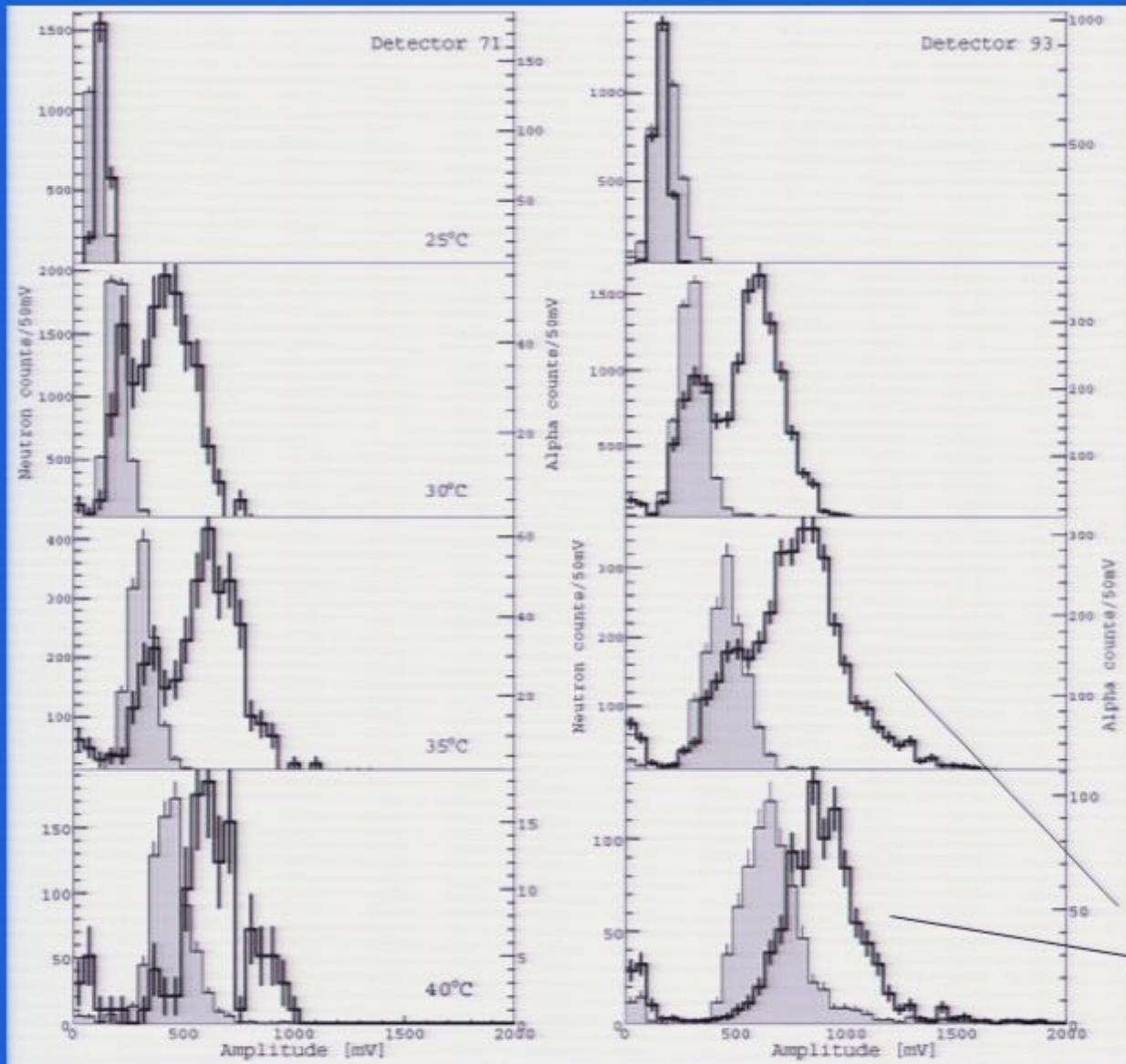
(in MIP sensitive region: $T = 60^\circ\text{ C} \rightarrow > 20$ bubbles)

of primary bubbles



of bubbles created

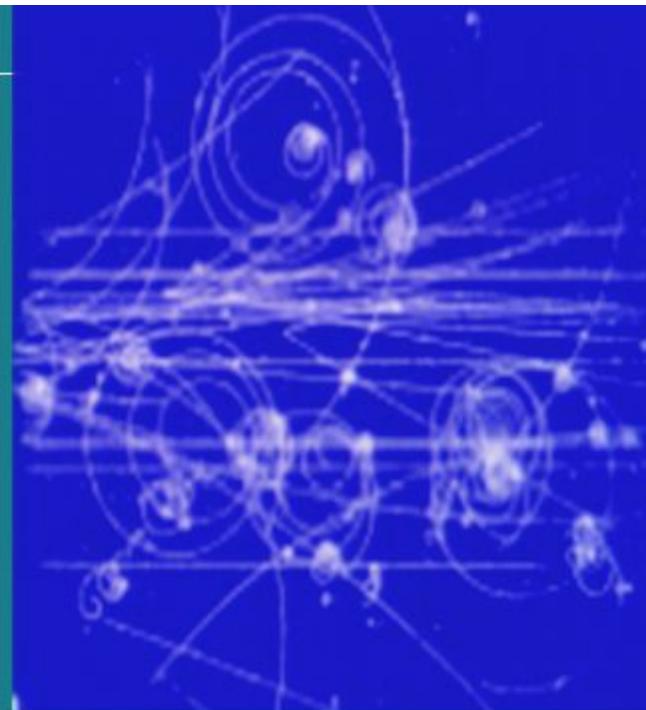
α - n Discrimination: Temperature Dependence



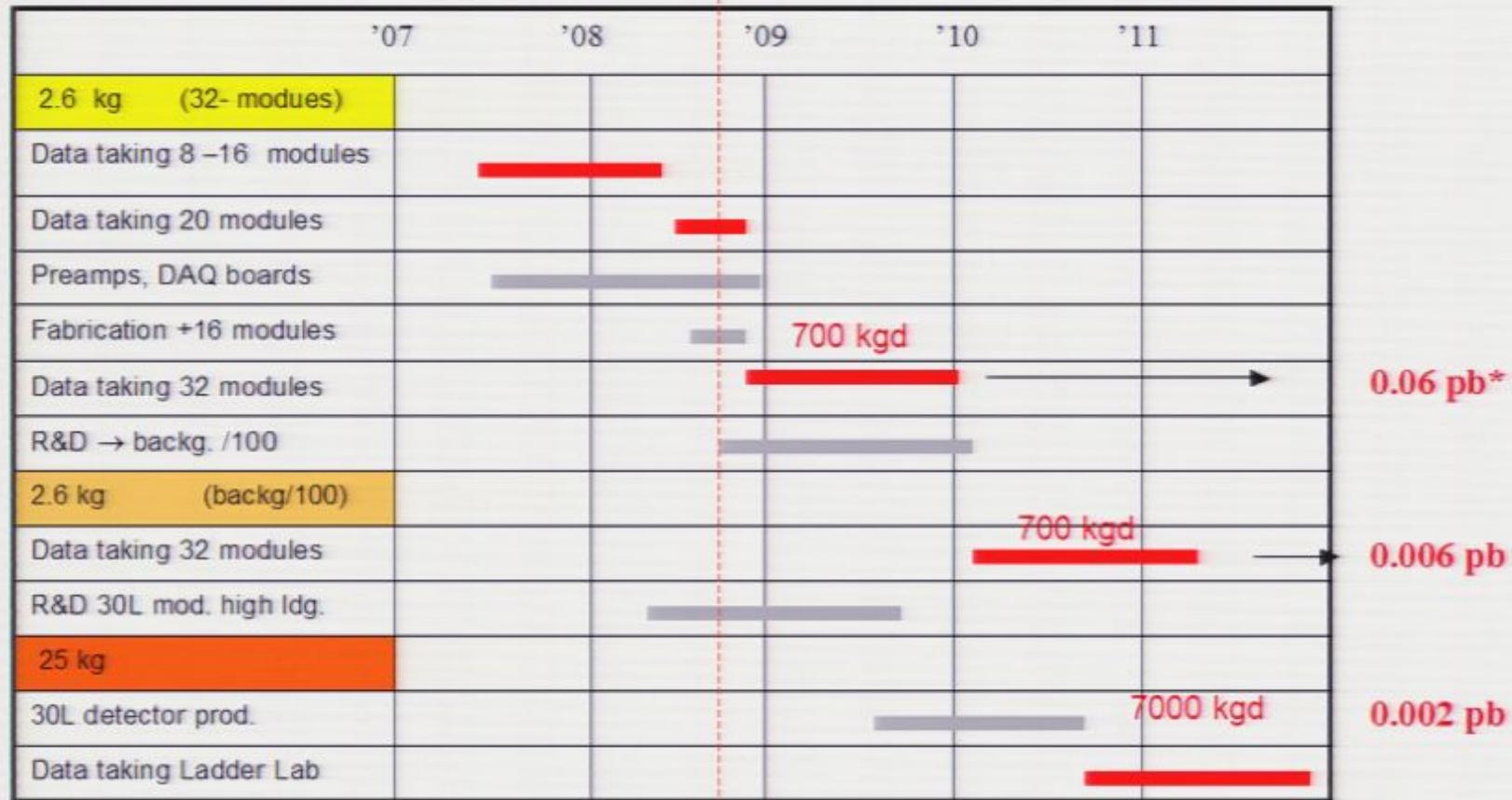
Strong saturation of raw signals above 30°C!

α - n Discrimination: Discussion

- From bubble chamber operation:
 - bubble density $\propto dE/dx$ ✓
 - bubble density strongly increases with T ✓
- Plesset-Zwick theory:
 - bubble growth $\propto \sqrt{t}$
 - pressure amplitude \propto acceleration & temperature ✓
 - first 50 μ s of signal preserve μ m resolution of prim. event



Timeline & Milestones



* Present background of $0.003 \text{ cts g}^{-1}\text{h}^{-1}$

Conclusions

- Phase Ib with 32 detectors is running!
- All detectors installed
- Upgrade gradually with cleaner detectors
→ “saltless” detectors
- New discovery of $n - \alpha$ discrimination
- Physics results in July 2009
- Complete Phase Ib with 700 kgd in 2009
- R&D on purification (1/100) and 30L detectors
- Prepare 25 kg phase → 7000 kgd

