Spin dependent limits on WIMP-proton scattering cross-section from PICASSO

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for
the PICASSO collaboration

Université de Montréal

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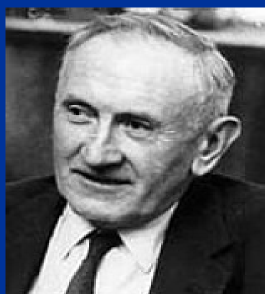
Outline

- Dark Matter, a brief history
- PICASSO
  - Introduction
  - Neutron Beam Calibration
  - Data Analysis
  - Results
  - Present & Future

Dark Matter, a brief history

Coma cluster Anomalies

In the beginning… well… in 1933…



Fritz Zwicky, 1937

•Measured kinetic energies of 8 galaxies of the Coma Cluster
•Used virial theorem (2<KE> = <PE> to calculate the average mass of galaxies of the Coma cluster
•Discrepancy between this value and the value obtained from luminosity of galaxies.
•Mass/luminosity > 100
•Nearby galaxies had mass/luminosity ~3

Fritz Zwicky postulates

Dark Matter

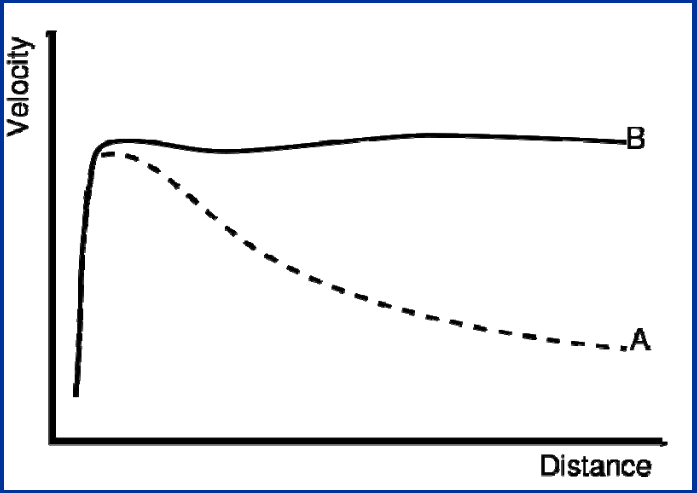
meaning something not luminous.

Galactic Rotational Curve Anomalies

Vera Rubin, 1950

in the 1960-70's –

- Observed bodies far away from the galactic center had same speeds as those near the center (curve B)
- Against Newton's laws; We'd expect $v^2 \alpha \ 1/r$ (curve A)



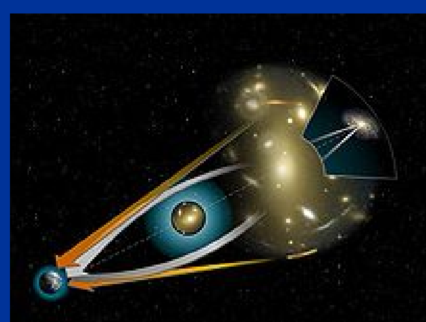
Dark Matter

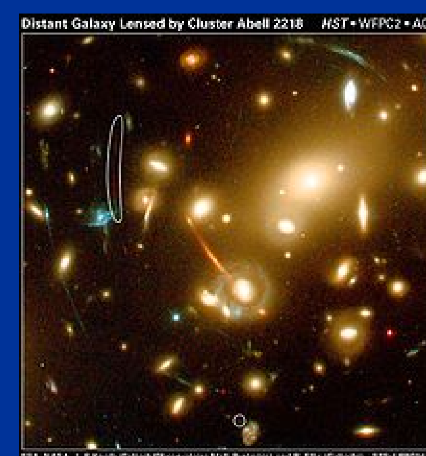
in the

outskirts of galaxies?

Gravitational Lensing

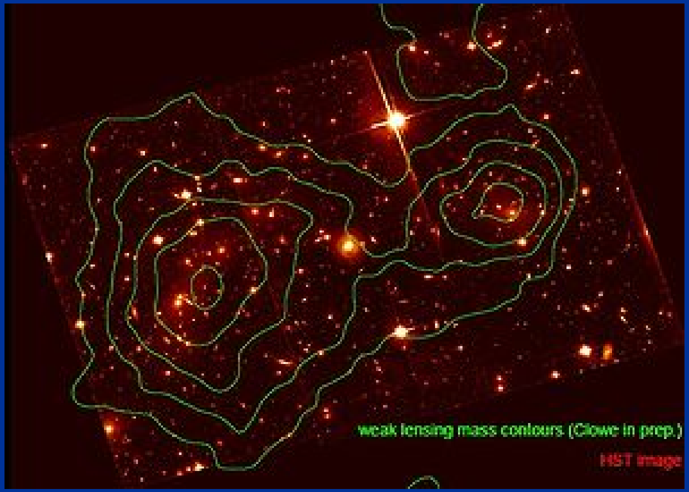
- First postulated by Orest Chwolson (1924), made famous by Albert Einstein (1936) in his general theory of relativity.
- Light from far away bright objects is bent by large masses.
- First observed in Twin QSO in 1979.





Bullet Cluster

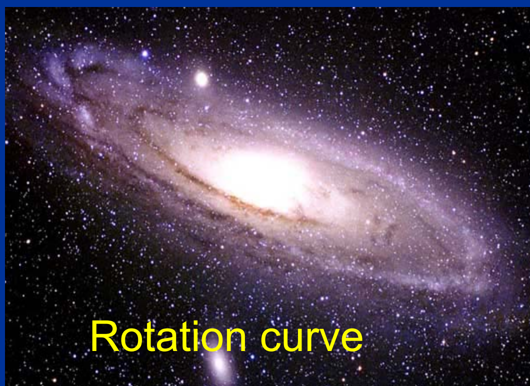
2006
best evidence
for
Dark Matter

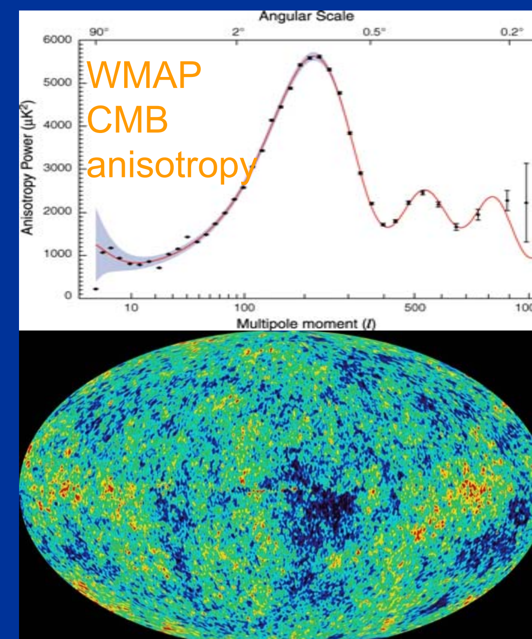


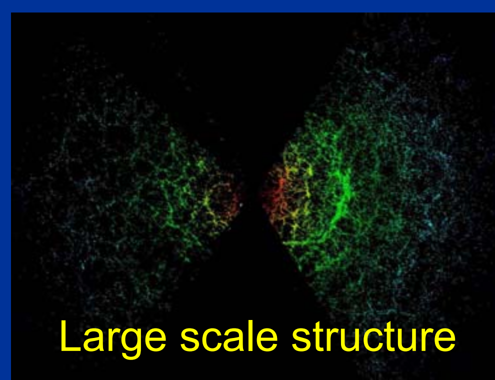
- Two clusters of galaxies collided 150 million years ago; the galactic bodies traveled with their velocities unaltered; the gas slowed down and remained near the collision center.
- The gas accounted for most of the visible mass, so one would expect today, to see larger gravitational lensing effects from around the collision center.
- But when Chandra mapped the gravitational lensing contours, the largest effect was in fact offset from this collision center by 8σ.

Other Evidence for the existence of Dark Matter

(lots more, but you don't want to stay here all day)







What causes all these Anomalies?

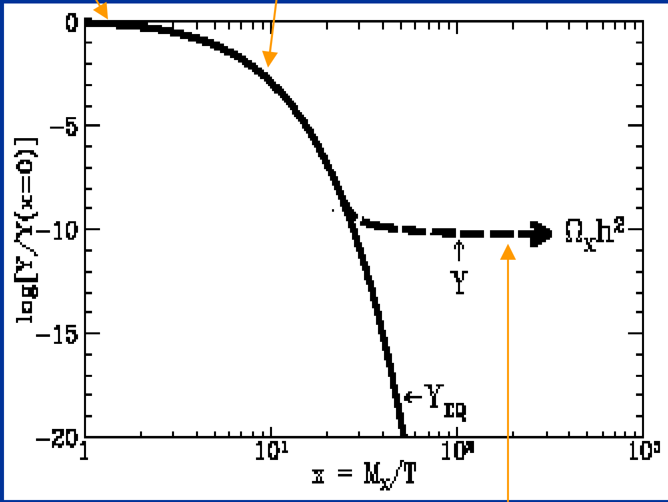
- Modified Newtonian Dynamics (MOND)? No; Bullet cluster disproves this and also F=ma has been tested at 10^{-15} $ms^{-2.}$
- Neutrinos? The maximum space density from the CMB neutrinos that have a Fermi-Dirac distribution is much less that the missing density. So maybe they make some of the missing matter, but not the majority
- Primordial black holes? No, we do not see them
- Gravitons? Maybe maybe not. Theoretical explanations available
- Bose-Einstein Condensate? Solitons? Maybe maybe not. Again theoretical explanations available.
- Virtual particles? Probably not, as whatever it is that's causing these anomalies seem to have been made at the early stages of the universe, and they still stay around. Virtual particles decay rapidly
- Other baryonic matter? Baryon-and-photon-only models predict primodial fluctuations that exceed those observed in CBR.
- **Non-baryonic dark matter particles? Most probably.**

WIMPs

- WIMP (Weakly Interacting Massive Particles), denoted by χ, are non-baryonic particles.
- Produced in the early universe from $e^+e^- \rightarrow X\overline{X}$
- They annihilate with the reverse reaction. $X\overline{X} \rightarrow e^+e^-$
- As long as temperature, $T > M_X$, then, WIMP number density, Y, is constant.
- Annihilation stops when WIMPS are too sparse; mean free time of annihilation is smaller than the Hubble age of the universe; $n_X\langle\sigma_A v\rangle < H$
- WIMP number density constant after that: feeze-out

X's produced & annihilated; $T>>>M_X$

X's production stopped, annihilation continues; $T<M_X$



Freeze out; $T<<<M_X$

$$WIMP\ relic\ abundance\ today = \Omega_X h^2 \approx \frac{10^{-37}\,cm^2}{\sigma_a}$$

Determining m_X *and* σ_A *from electroweak theory, we expect* $\boldsymbol{\Omega_X = 0.3}$

Standard Model for Astro-Particle Physics

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- Dark Energy – vacuum energy state; in fact the universe today is dominated by this state
- Cold Dark Matter
  - WIMPs (Weakly Interacting Massive Particles), Axions
- Baryonic matter – stars, gas, MACHOs, etc

- χ_1 can be lightest stable super symmetric particle – LSP
- Majorana particle
- interaction with matter electro-weak
- can provide closure density
- relic population from early BB

$$\chi_1 = N_{11}\tilde{\gamma} + N_{12}\tilde{Z} + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

"photino" "zino" higgsino"

WMAP RESULTS (2009):

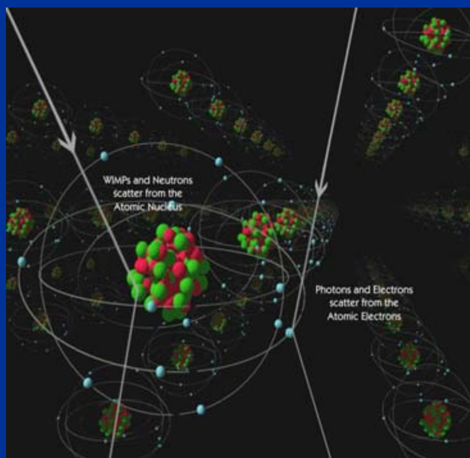
Ω_{tot} = 1.02±.02

Ω_b = 0.04 ±0.004

Ω_X = 0.27 ±0.04 ← **Same as expected!!!!**

Ω_Λ = 0.73 ±0.04

How to Detect Dark Matter

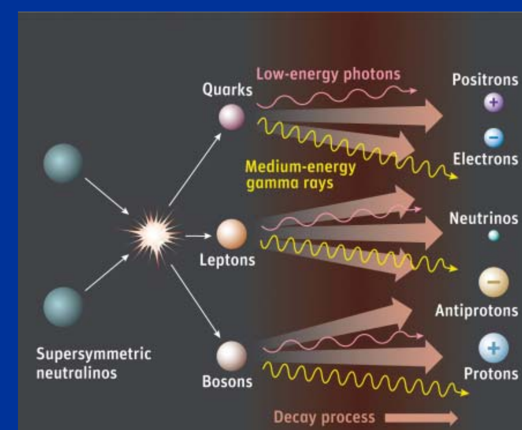


DIRECT SEARCHES

INDIRECT SEARCHES

χ - CDM ?

ACCELERATOR SEARCHES



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Neutralino Nucleon Interaction Cross-sections

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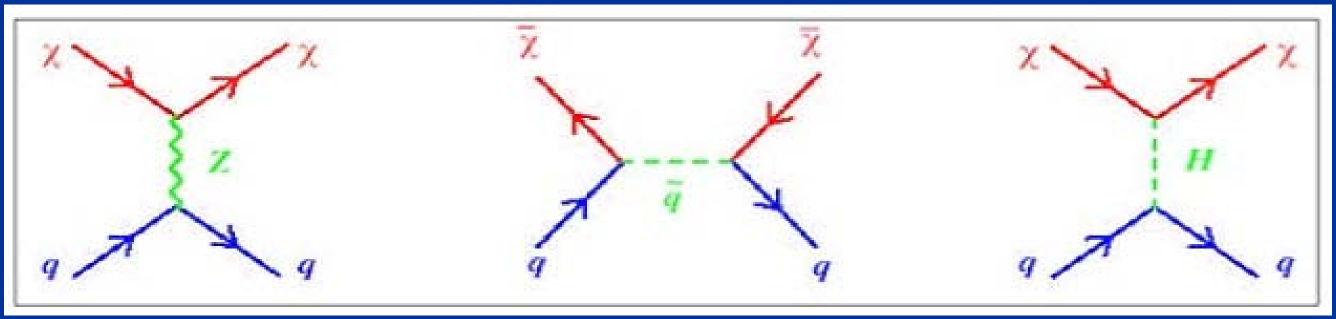


Spin-dependent **Spin-independent**

General form of cross sections:

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^{SI} : Spin independent – coherent interaction □ A^2

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

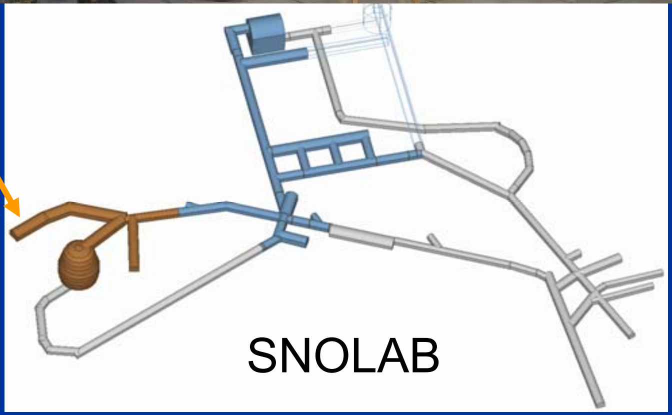
$F(q^2)$: nucl. form facor □ important for large q^2 and large A

PICASSO

A Spin Dependent Direct Dark Matter Search

Projet d'**I**dentification de **CA**ndidats **S**upersymétriques **SO**mbres

Project **I**n **CA**nada to **S**earch for **S**upersymmetric **O**bjects



Université de Montréal - Queen's University, Kingston - Laurentian University, Sudbury - University of Alberta - Saha Institute Kolkata, India – SNOLAB - University of Indiana, South Bend - Czech Technical University in Prague – Bubble Technology Industry, Chalk River.

How does PICASSO Detect WIMPs?

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How to Detect Neutralinos

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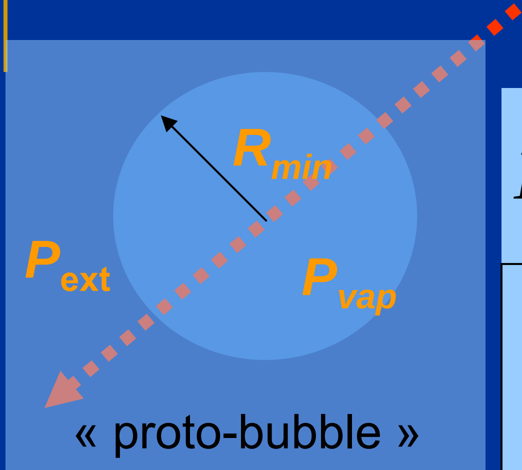
- Weakly Interacting particles
  - Use bubble chamber principal
- Minimize background
  - Go underground: shield from Cosmic Rays (SNOLAB)
  - Use water boxes to shield radioactivity
  - Carefully purify ingredients to remove radioactive U/Th

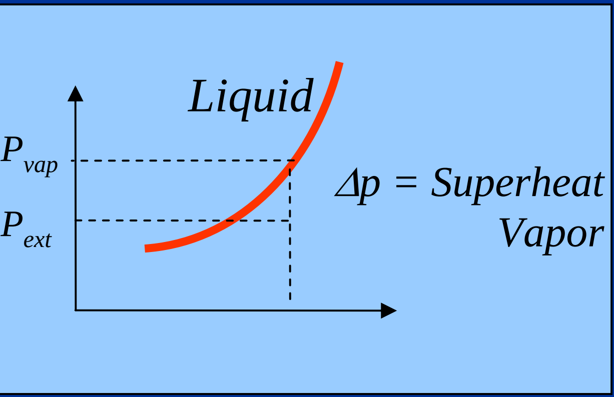
The Seitz Theory of Bubble Chambers



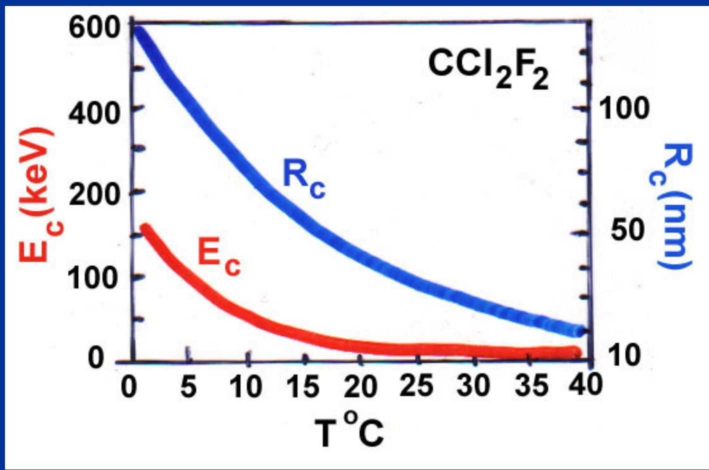
$$E_{dep} = \frac{dE}{dx} \cdot R_{\min} \geq E_{\min}$$

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

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



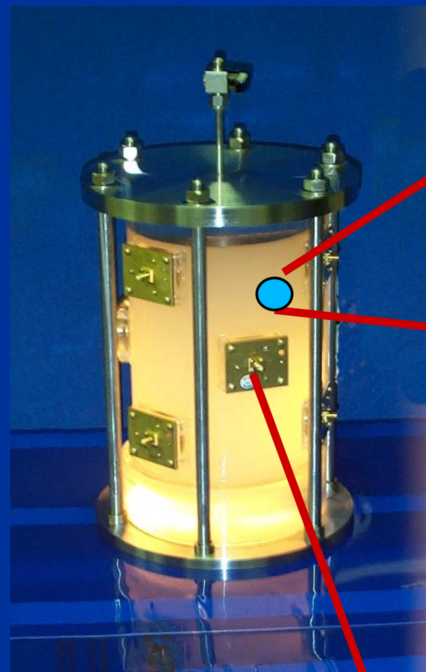
A bubble forms if a particle deposits enough energy, E_{min}, within a radius R_{min}

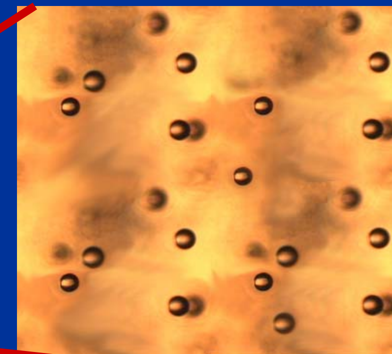


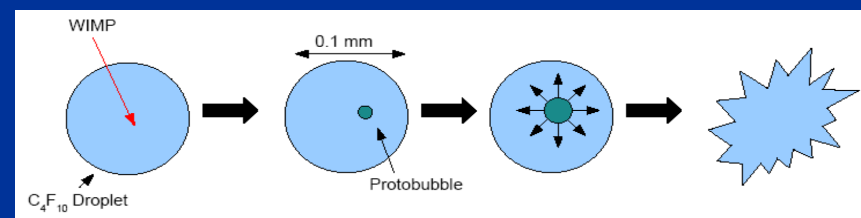
F. Seitz, Phys. Fluids I (1) (1958) 2

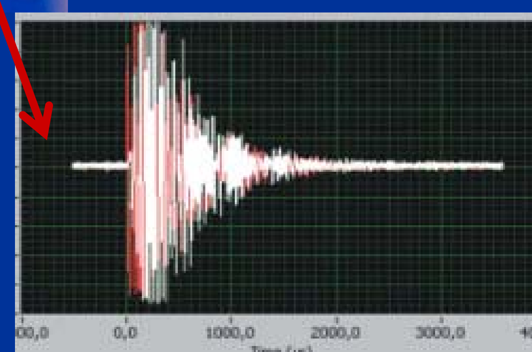
PICASSO Detectors

- **Super heated C_4F_{10} droplets**
  - 200um,
  - held in matrix in polymerized gel
  - act as individual bubble chambers
- **When ionizing particle deposits energy**
  - F^{19} recoils
  - Creates nucleation centre in superheated liquid.
  - Bubbles grow, turning entire C_4F_{10} droplet to vapor
  - resulting acoustic signal registered by piezo electric sensors





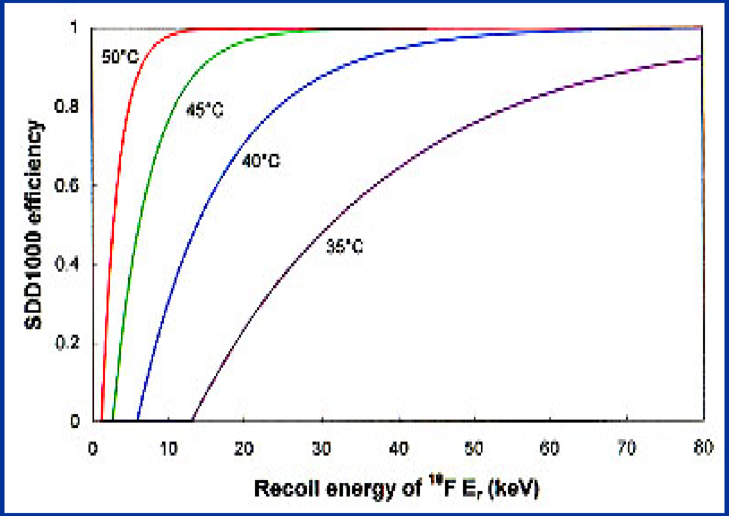




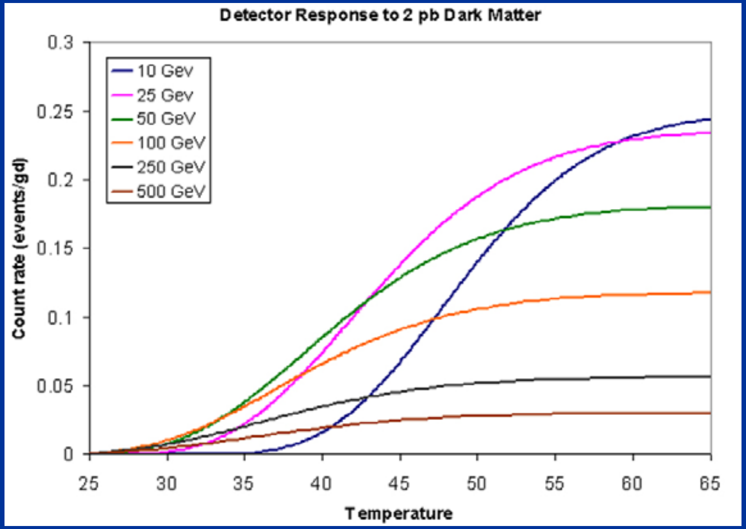
Neutron Beam Calibration

Test Beam Calibration

- PICASSO is a threshold detector.
- Threshold depends on T, P
- Calibration with mono-energetic neutrons
- neutron induced nuclear recoils similar to WIMPS
- n-p reactions on ^{7}Li and ^{51}V targets at 6 MV UdeM-Tandem

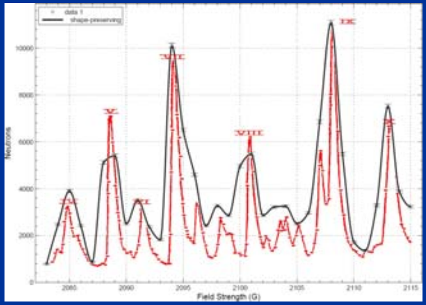


Detection efficiency (T)



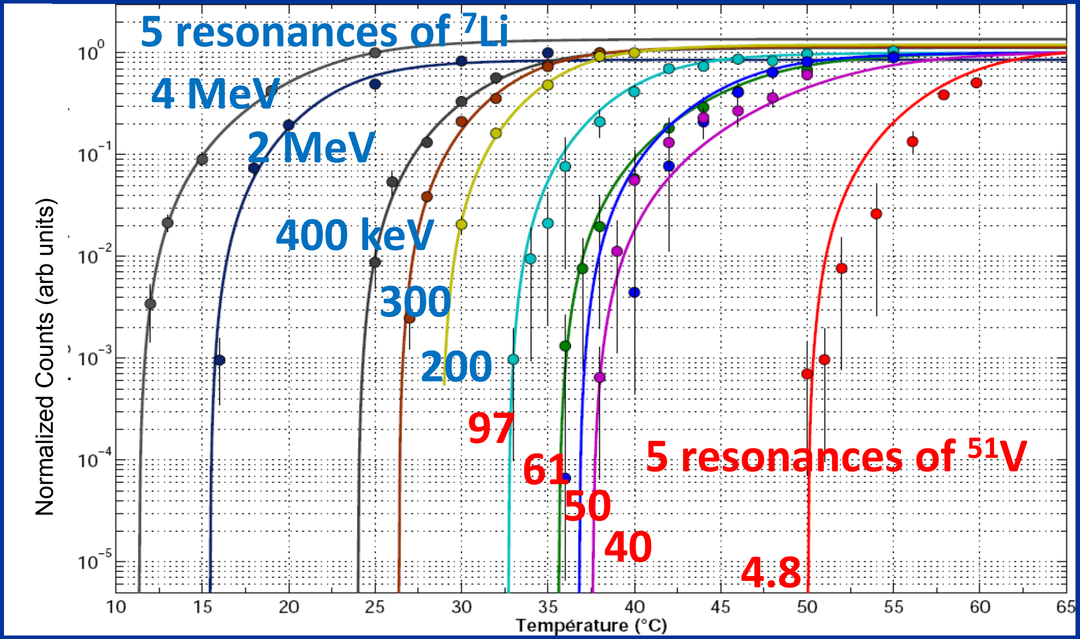
Neutralino response (T)

Temperature Thresholds for Different Neutron Energies



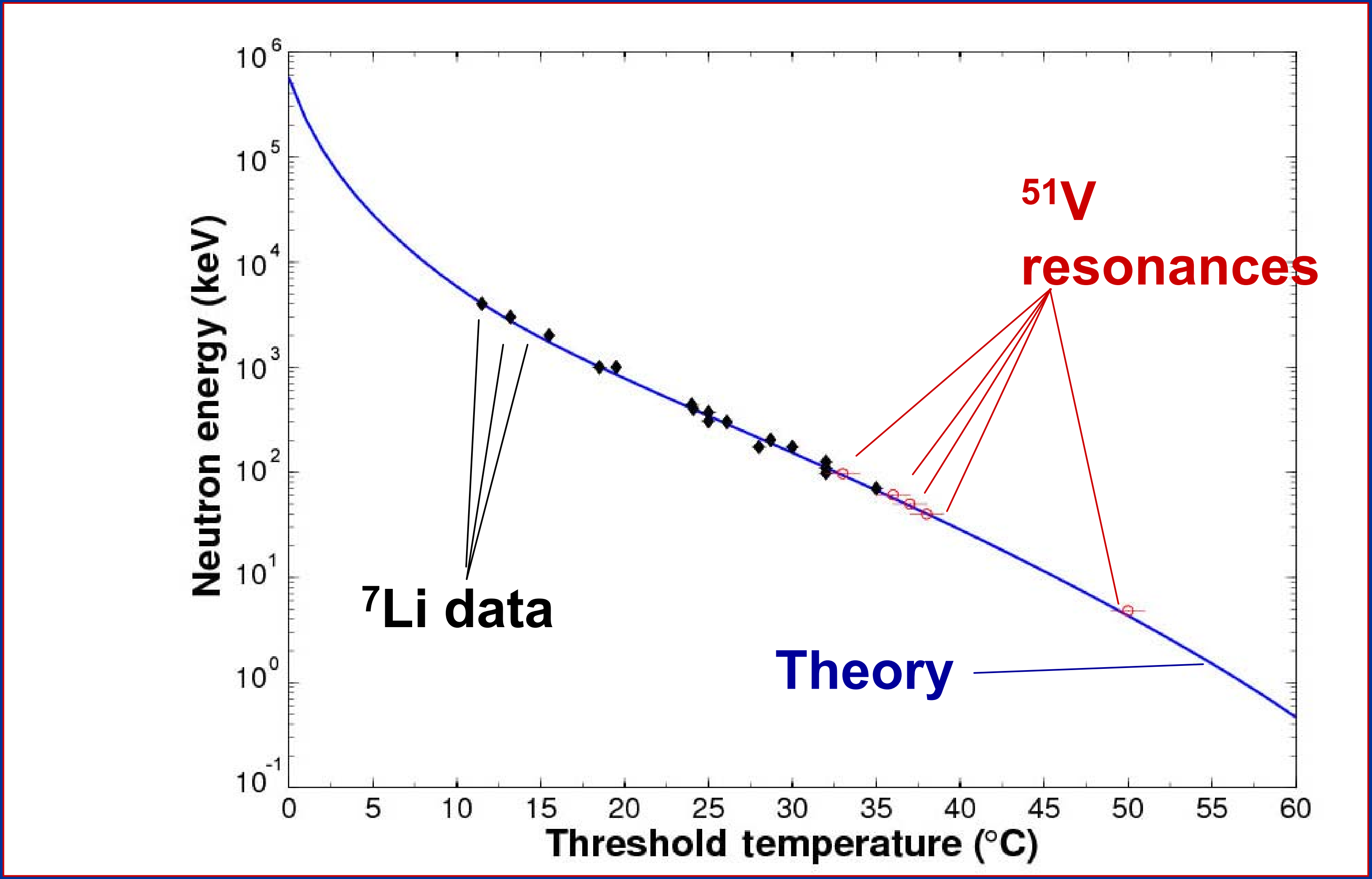
Five ^{51}V resonances:

97, 61, 50, 40 and 4.8 keV



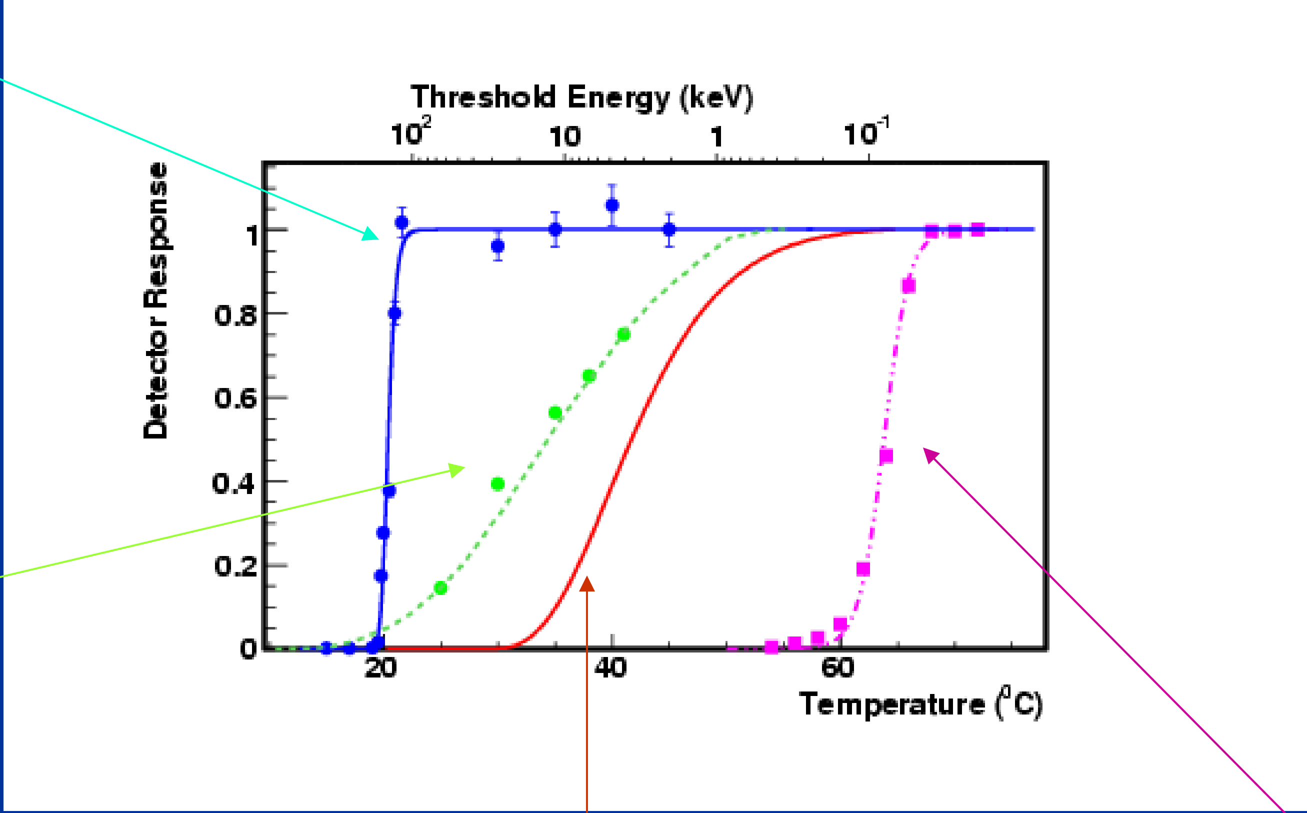
Lowest threshold measurement for similar experiments : 4.8 keV

Improved Calibration of the Detector Response



PICASSO Detector Responses

α - particles from ^{226}Ra spike



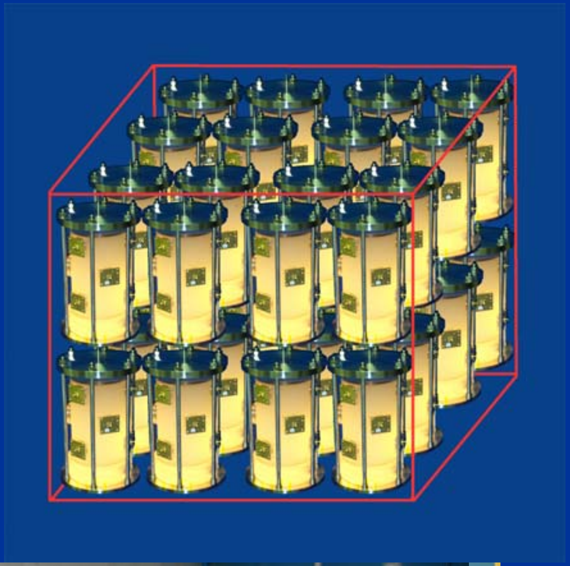
Neutrons from AcBe source (data +MC)

Recoil nuclei from 50 GeV /c^2 WIMP

γ's from ^{22}Na & MIP's

PICASSO Detector Status

- Now Complete
  - 32 detectors, 9 piezos each
  - total active mass of 2248.6g
  - 1795.1g of Freon mass
  - Temperature & Pressure control system
- 40 hr data taking
- 15hr recompression



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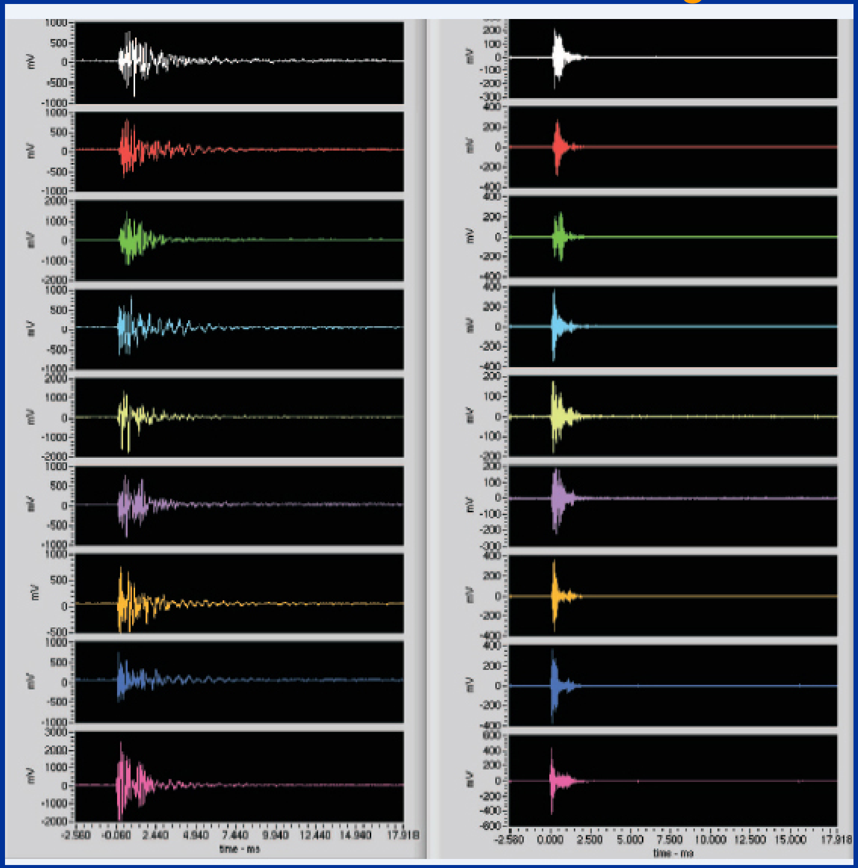
Data Analysis

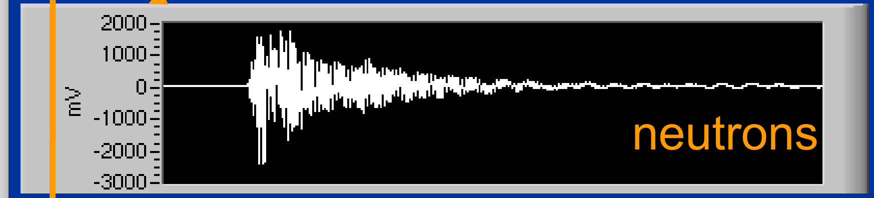
PICASSO events

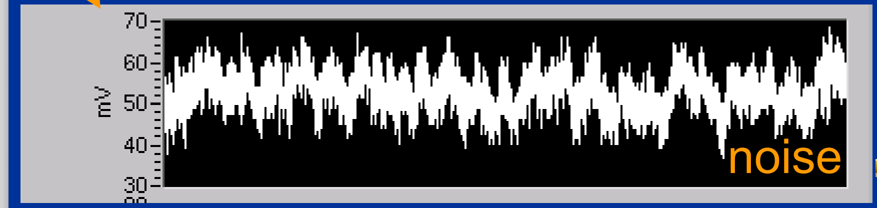
raw signal

high pass
filtered signal



different amplitude scales

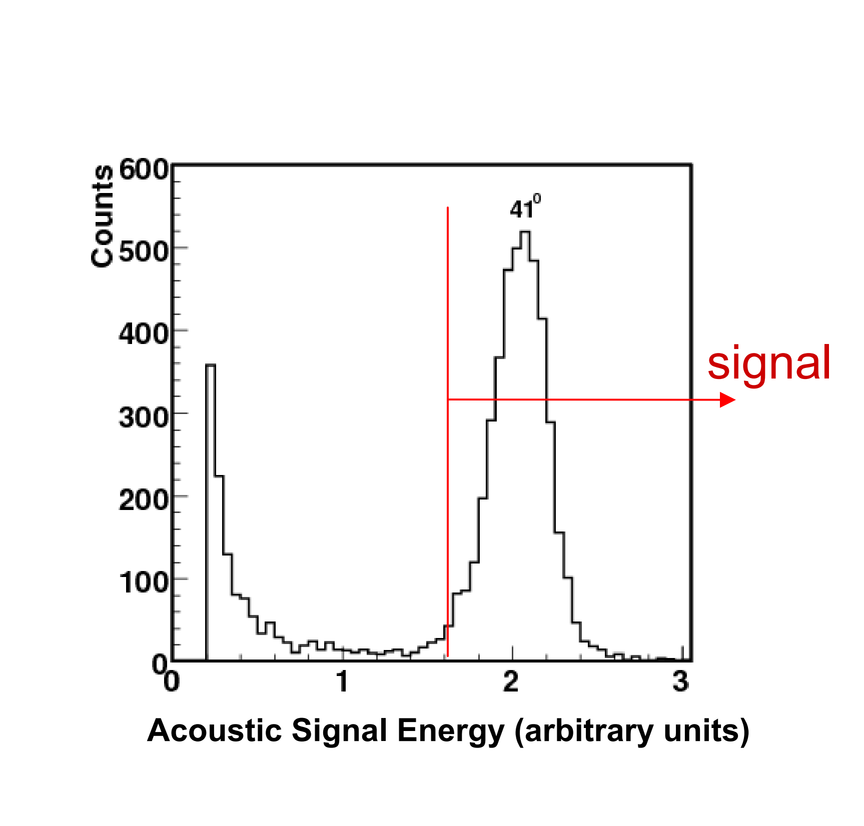


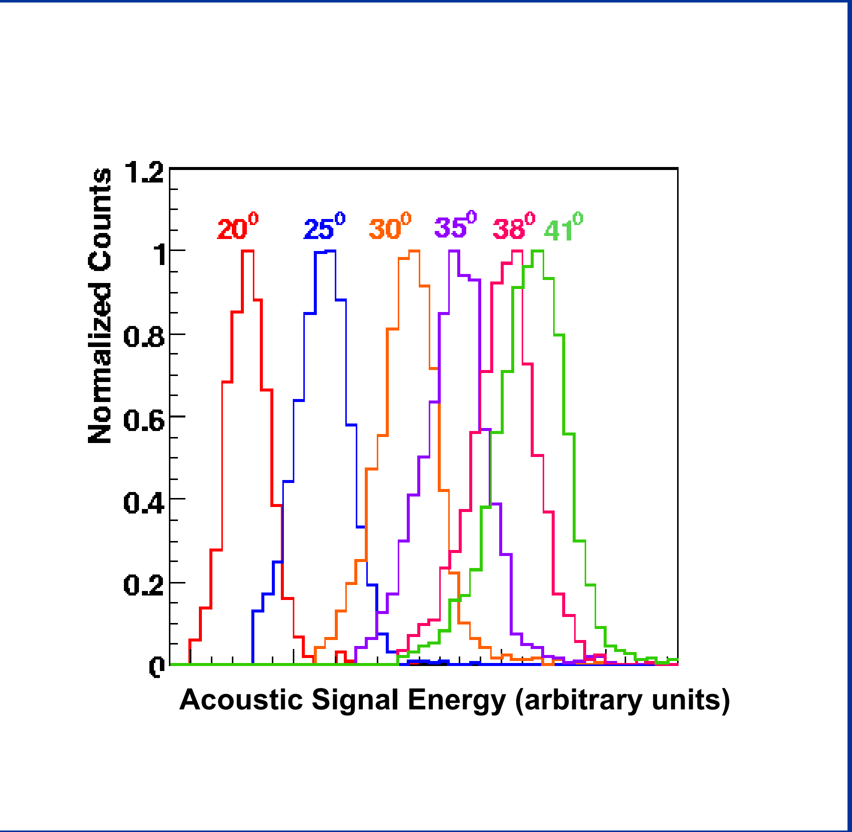


Two Discrimination Variables:

1. **Energy Variable (PVar)**
2. **Frequency Variable (FVar)**

Energy Distributions for Neutron

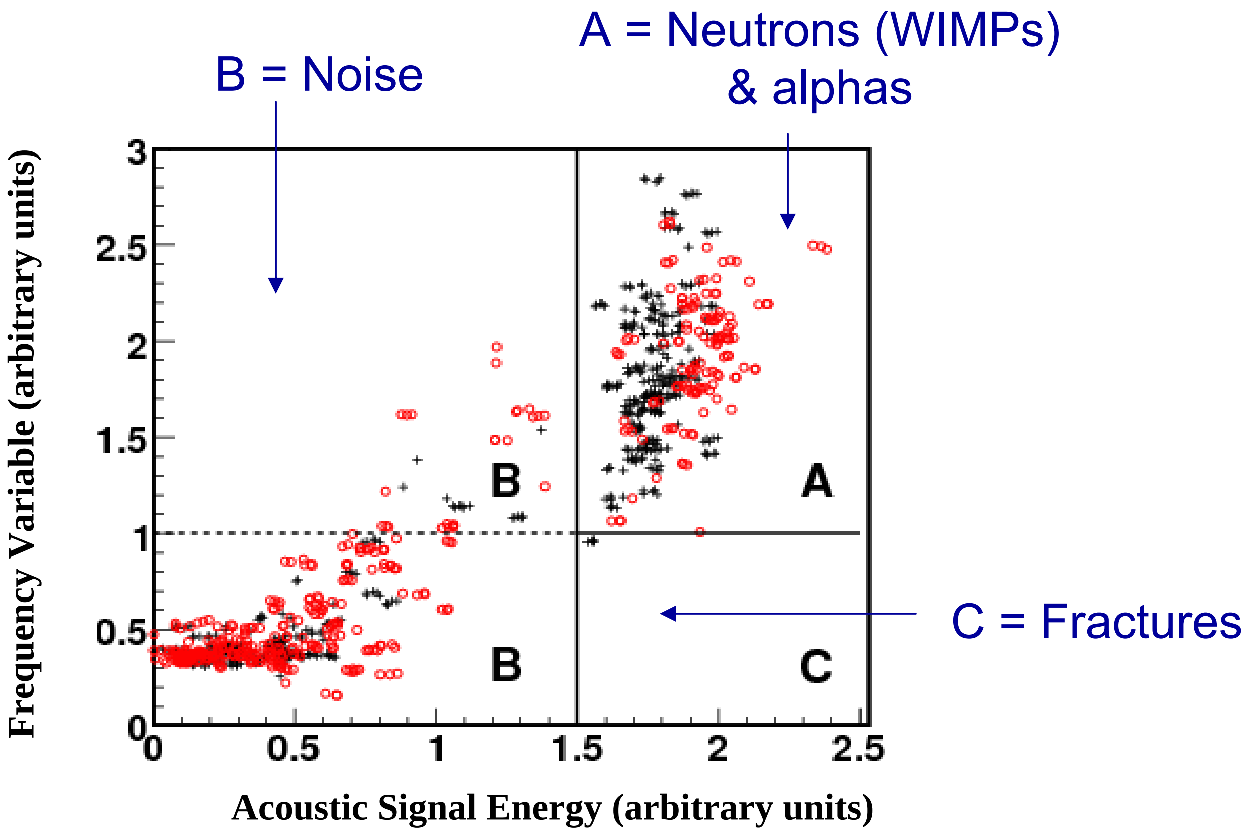




Signal and noise well separated

Temperature dependent energy distribution

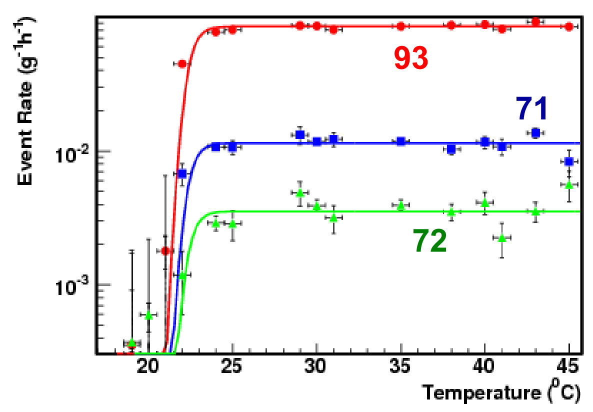
Frequency Variable Distributions for Neutron and Background



**** Neutron calibration run

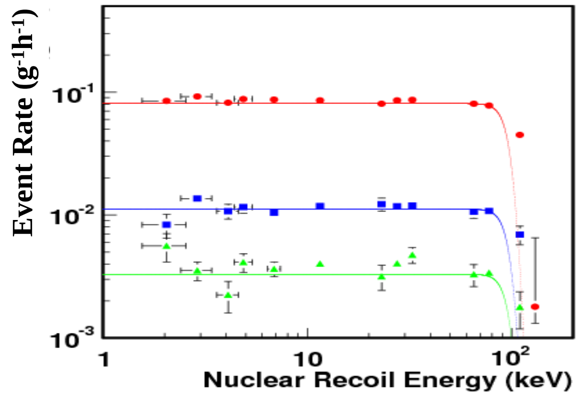
ooooo Background run

Null Hypothesis
Alpha Rate Fitted: Detectors 71,72



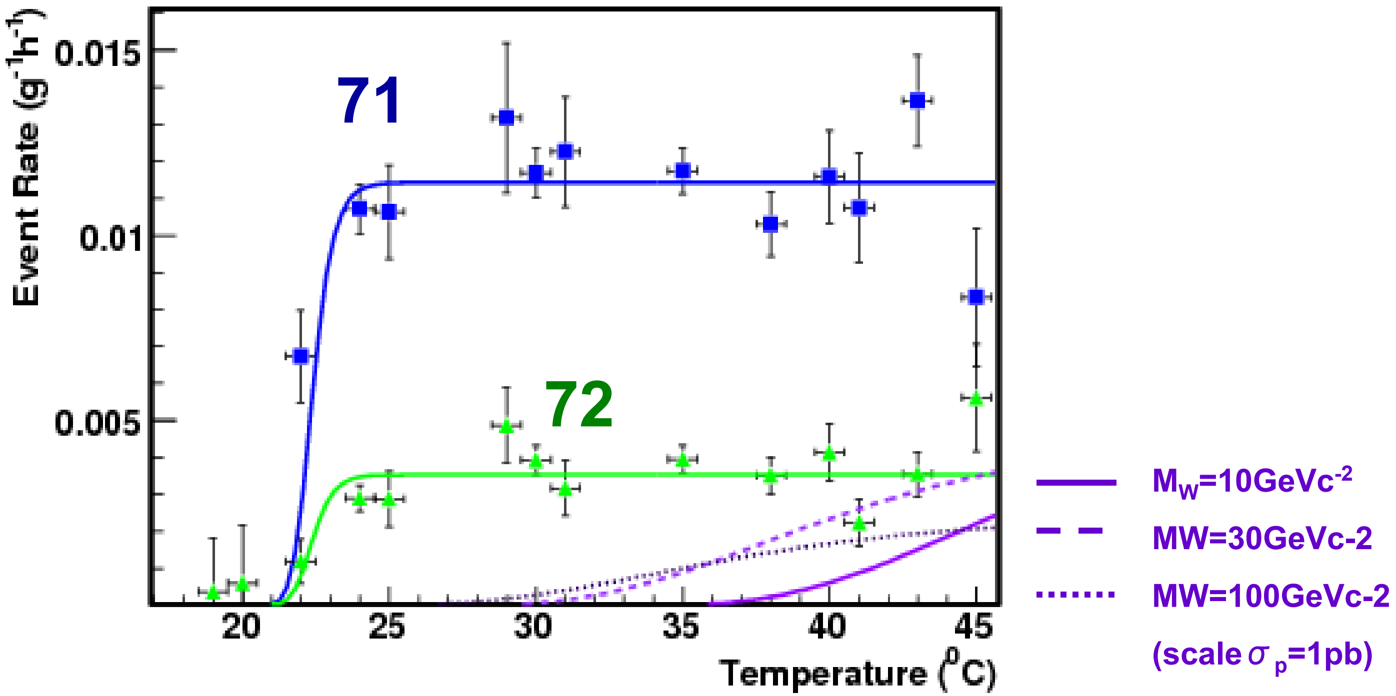
$$\left.\frac{\chi^2}{ndf}\right|_{71} = 1.15$$

$$\left.\frac{\chi^2}{ndf}\right|_{72} = 1.25$$



- Rates have been normalized to ^{19}F
- Radioactivity = 3.3 mBq/kg (2.7 x 10^{-10} gUg^{-1}, 8.1 x 10^{-11} gThg^{-1})

Null Hypothesis
Alpha Rate Fitted: Detectors 71,72



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2009 Results

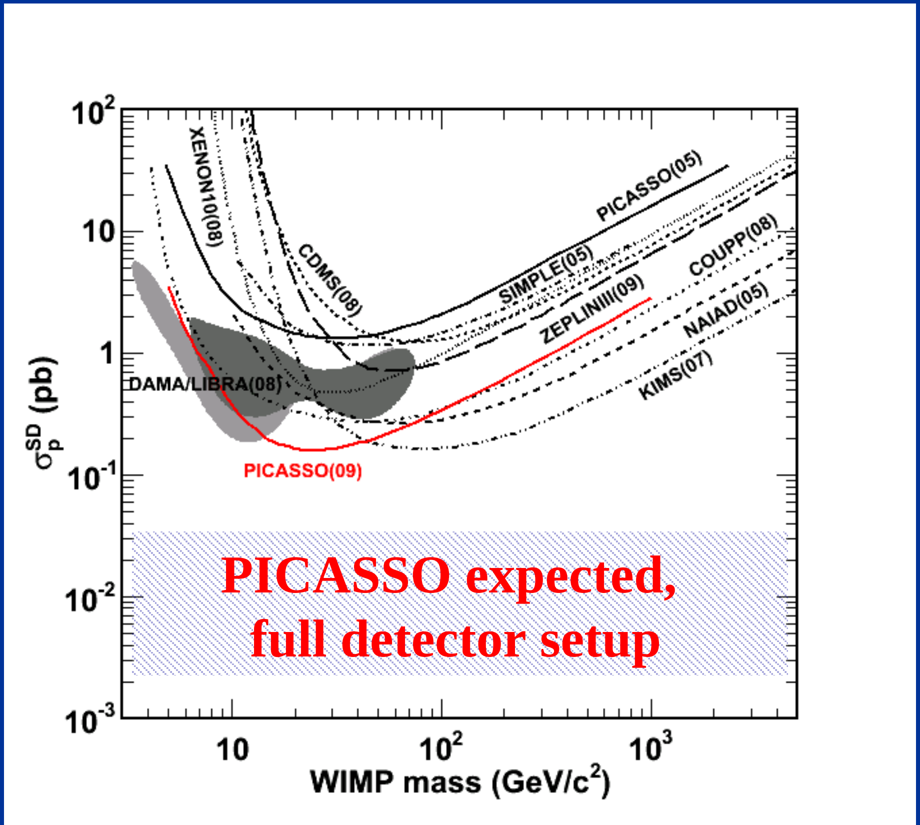
PICASSO New Results

2009

σ_p = - 0.0051pb ± 0.124pb ± 0.007pb (1 σ)

13.75±0.48 kg.days

(134g ^{19}F)



in progress

full analysis
32 detectors
2.6 kg ^{19}F, 144 kgd

limit of σ_p = 0.16 pb (90%C.L.) for a WIMP mass of 24 GeV/c2

* S. Archambault et al.; Phys. Lett B. 682 (2009) 185 (arXiv: 0907.0307)

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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

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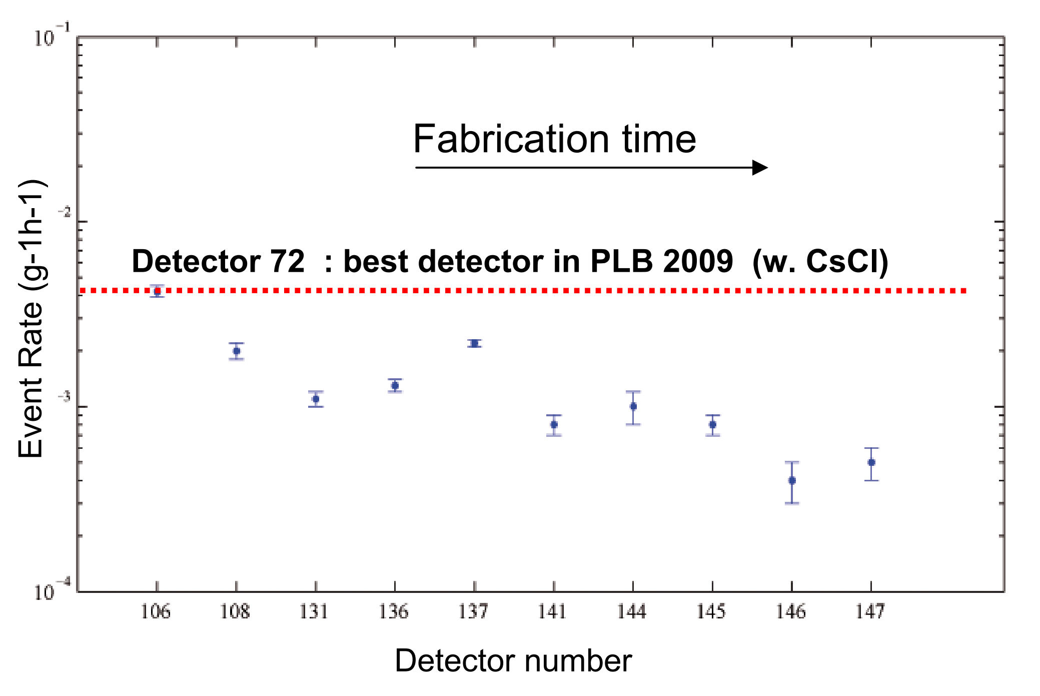
Present

PICASSO Present

- Using saltless detectors - 10 to 5 times background reduction
- Already 13 of the 31 active detectors are saltless



Event Localisation

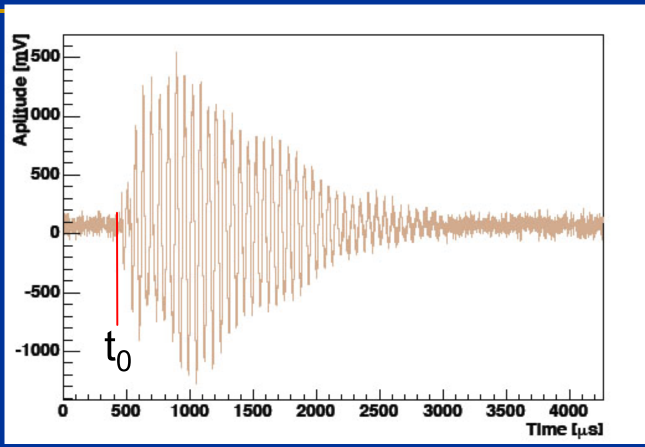
Reconstruction of event position very promising

Allows suppression of hot spots or surface events

Determine t_0 from wave form

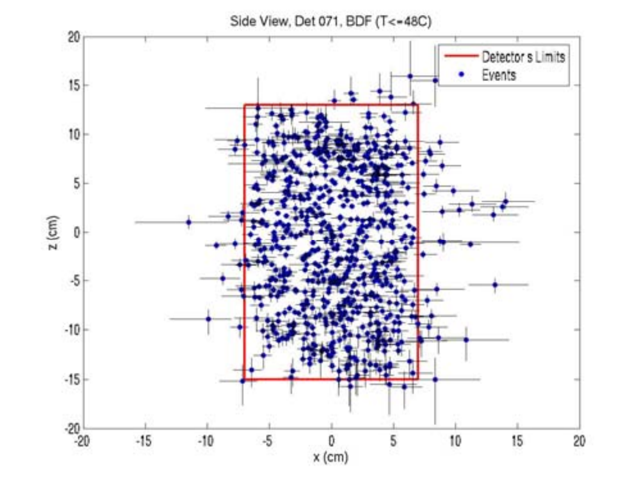
Would allow better gain calibration

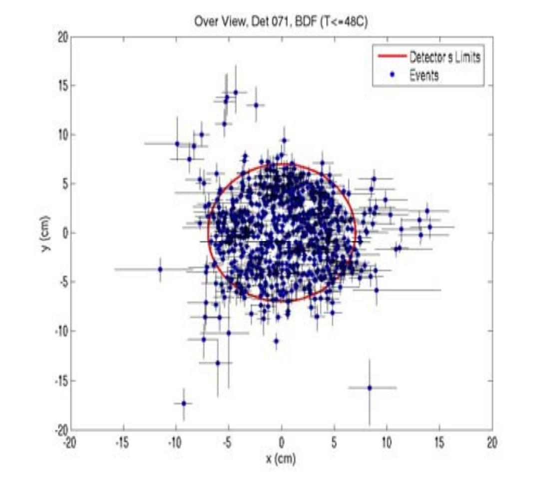
$$\chi^2 = \sum_{i=0}^{8} \left(\frac{(th_i - th_0) - (t_i - t_0)}{\sigma_i} \right)^2$$



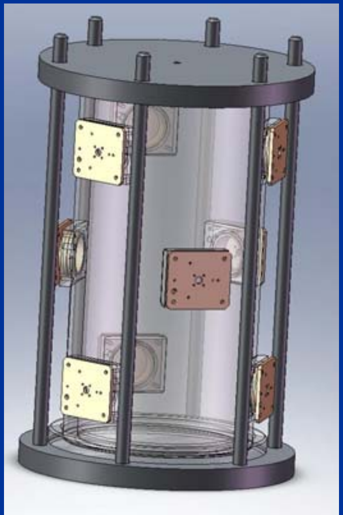
th_i : Calculated time from the fitted point to the i^{th} piezo.

t_i : Measured time of the beginning of the event on the i^{th} channel.



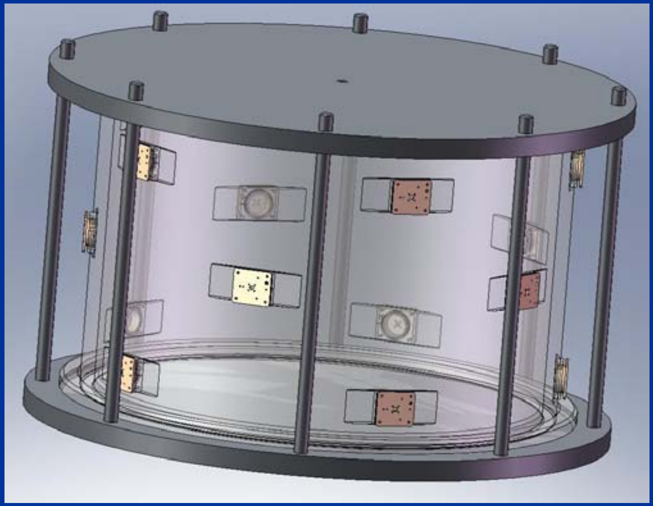


How to Increase the Active Mass?



Large drops

Larger modules
+larger droplets



Single Droplet Modules

Industrial dispersion technique – capillary arrays

Single Droplet Modules

	Current detector	New detector (x2)
Active mass	80 g	80 g
Droplet volume	4.2×10^{-6} cm^3	50 cm^3
Number of droplets	12 000 000	2
Total surface	15 000 cm^2	100 cm^2

150 times less surface

Single droplet module (SDM)

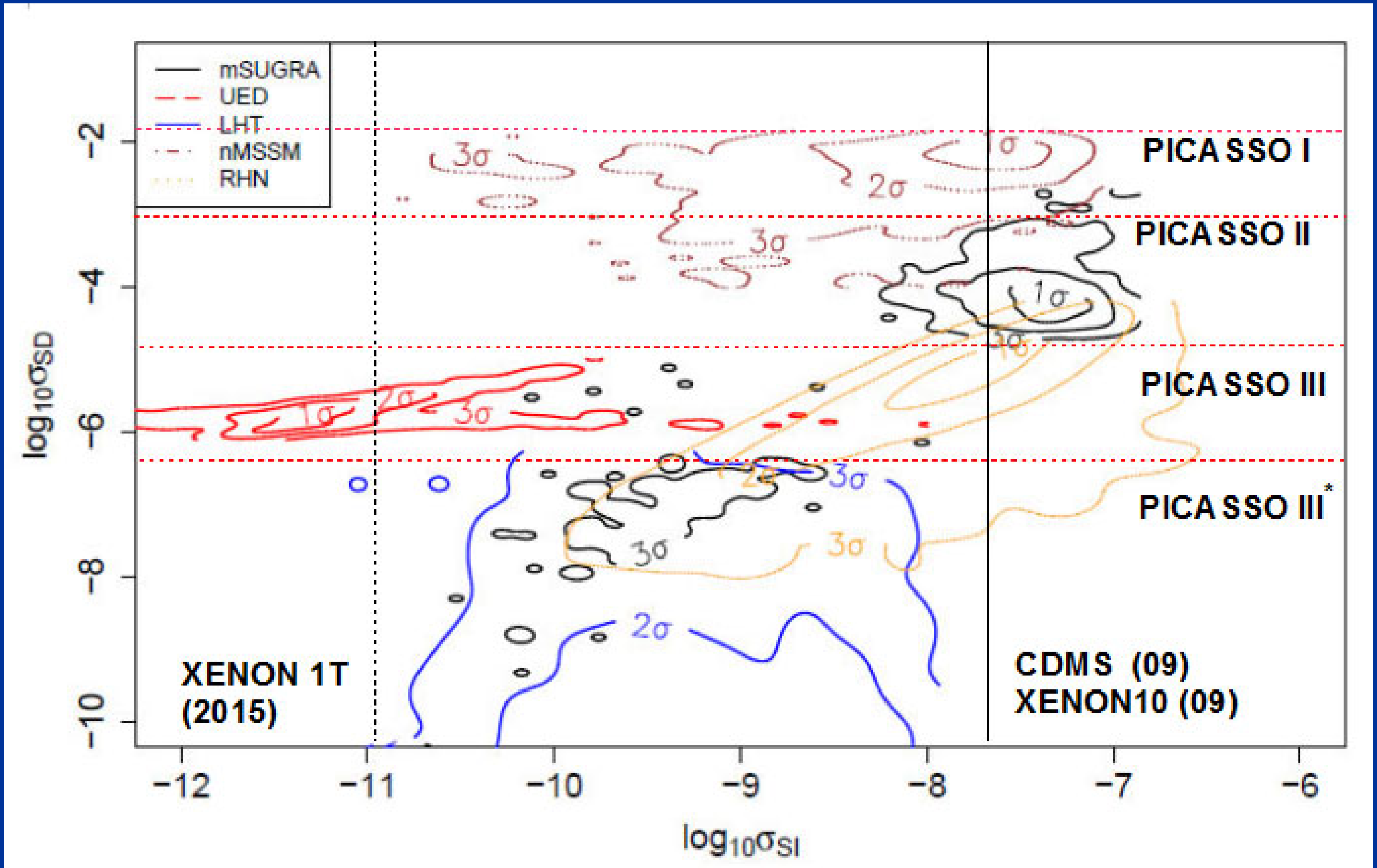
Less alpha events

- Present surface - alpha activity: 8×10^{-7} cm^{-2} d^{-1}
- At least 2 orders of magnitude less surface alpha's
- Controlled smooth polymer surface

PICASSO Future

- PICASSO set up now complete
- Analysis of the other detectors underway
- New detector fabrication methods allow significant alpha background reduction
- Work on improved α-n discrimination
- Exploring other event discrimination techniques to separate signal from noise and background
- Moving to new location at SNOLab now
- R&D for 25kg ongoing

Spin Dependent and Spin Independent Comparison



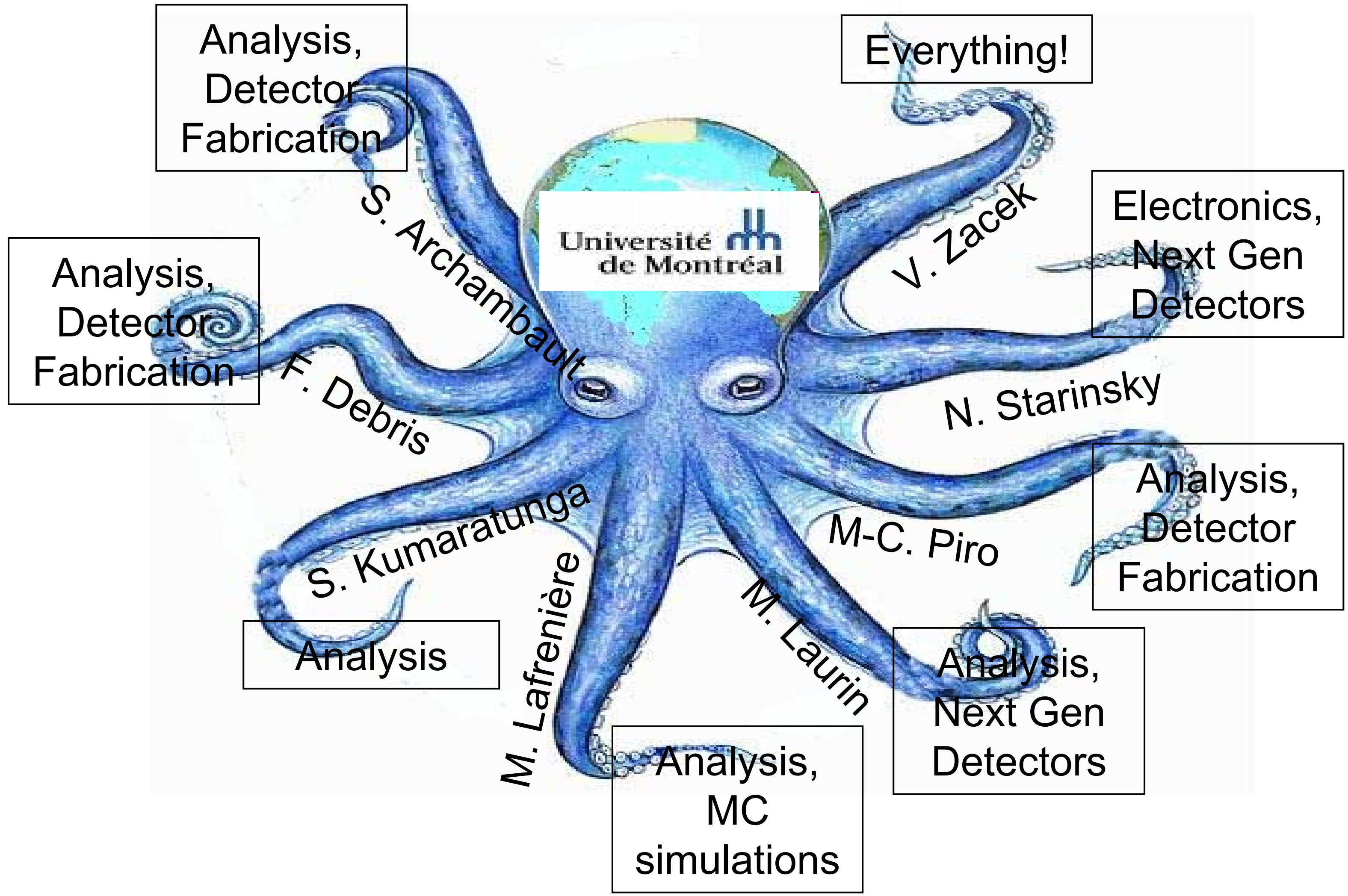
Spin – dependent

Spin – independent

- On-going 2.5 kg
- Upgrade to 25 kg 1/10 backg
- 500 kg 1/100 backg
- 500 kg with full α -n discrim.

V. Barger et al.; hep-ph: 0806.1962

UdeM Contributions



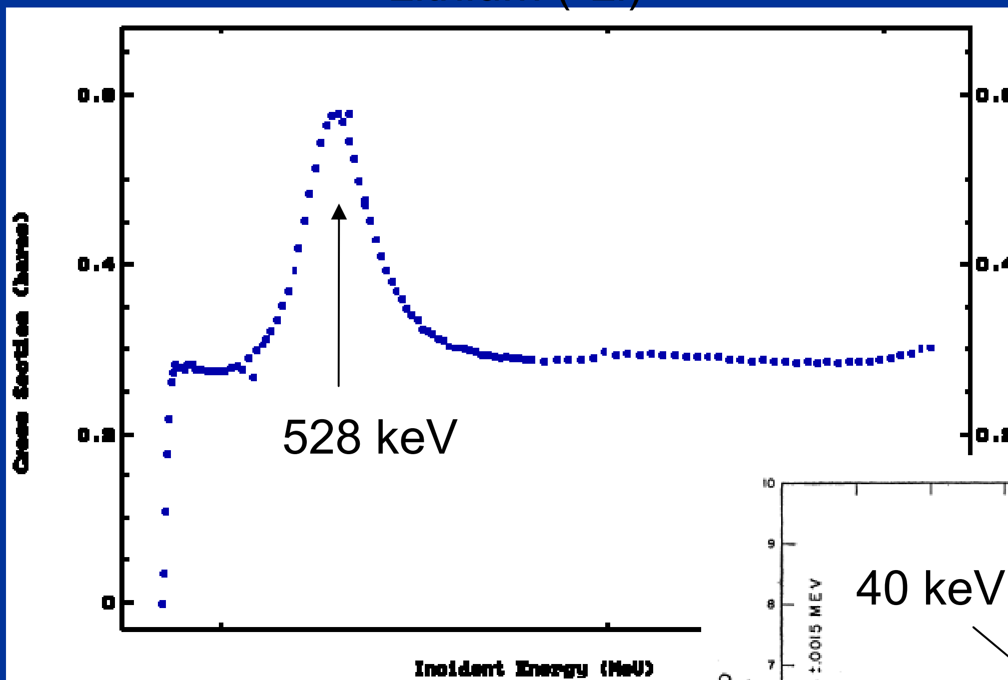
Thank you!

It's a lot of hard work, but lots of fun too…

backup

Target selection

Lithium (^7Li)

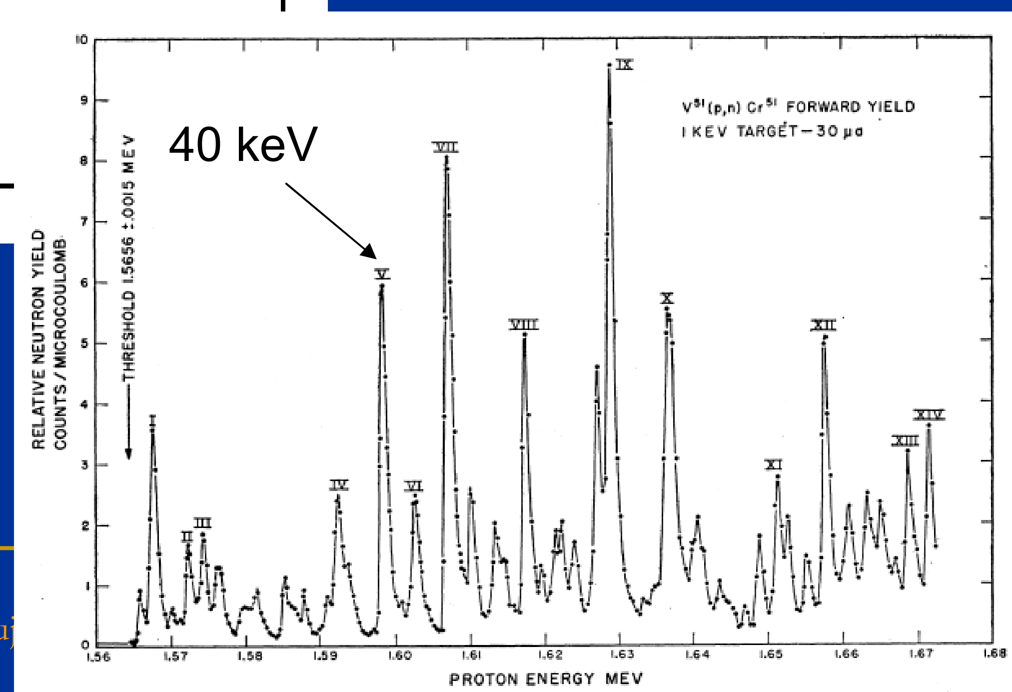


Previous measurements:

^7Li target

200 keV < E_n < 5000 keV.

Vanadium (^{51}V)



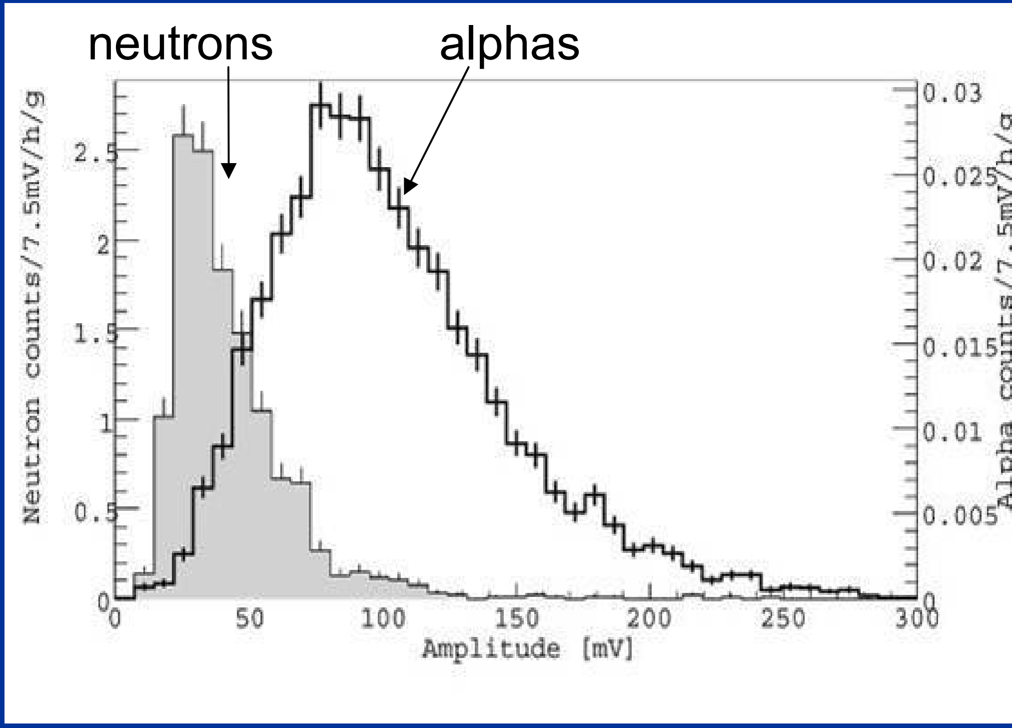
New measurements:

^{51}V target

5 keV < E_n < 90 KeV

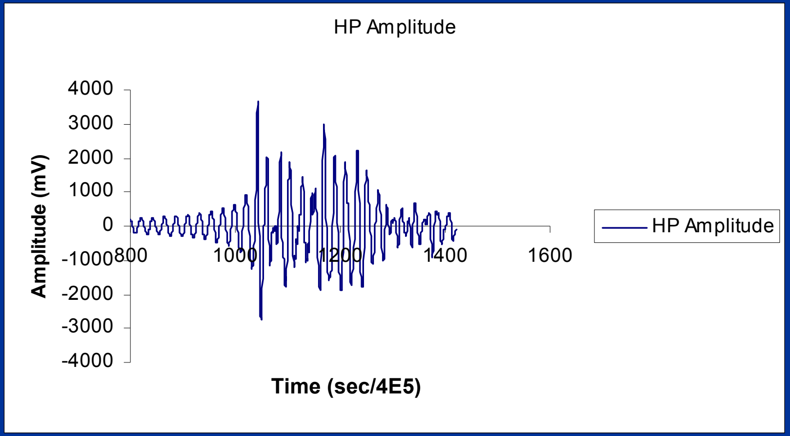
Alpha Neutron Separation

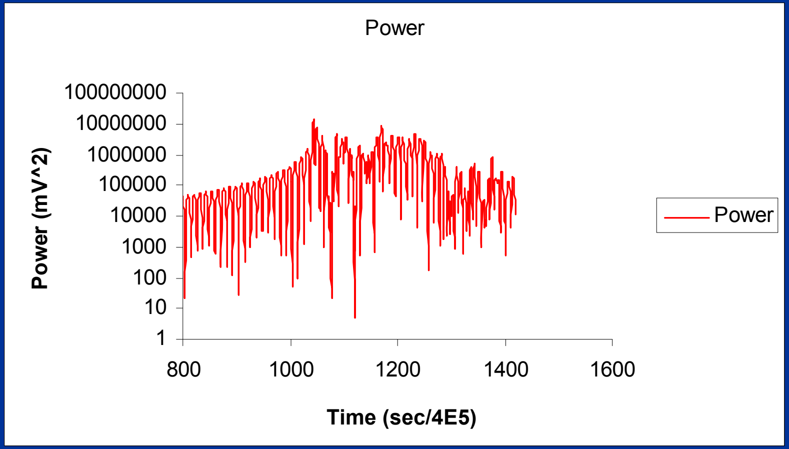
- Average of peak amplitudes of 9 transducers (after HP filter)
- Signals carry information of the first moments of bubble formation
- **Why are neutron and alpha signals different in energy?**
  - Alphas create multiple nucleation sites along tracks from ionization; also 1 nucleation at the beginning from recoiling parent nucleus and 1 at end from Bragg peak
  - Neutron create only 1 nucleation site from the highly localized energy deposition
- **Is this separation a pseudo effect? No!**
  - Neutrons from source are not symmetrical like alphas – does this have an effect? No!
  - Could signal from neutrons attenuate over time due to increased vapor bubble formation? No!



Data Analysis

- PVar
  - High pass filter events
  - Integrate Power to get energy
  - Take average over all piezos

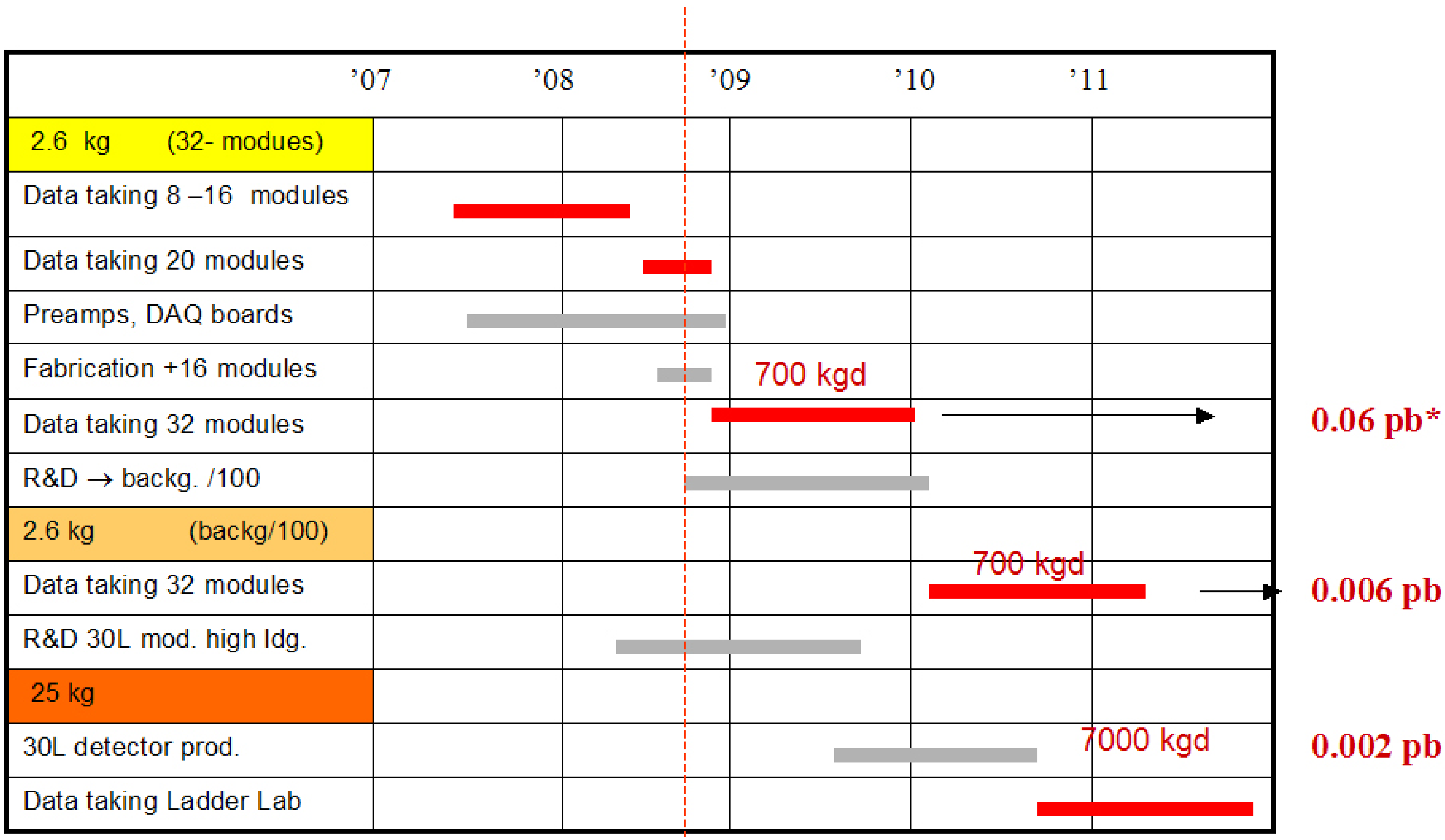




Some numbers…

	Detector 71	Detector 72
Run length (days)	101.5	103.5
Active Mass F^{19} per detetctor (g)	65.06±3.2	68.97 ±3.5
Exposure (kg.d)	6.60	7.14
Total Number of Events selected with Pvar ,Fvar	1721	632

Timeline & Milestones



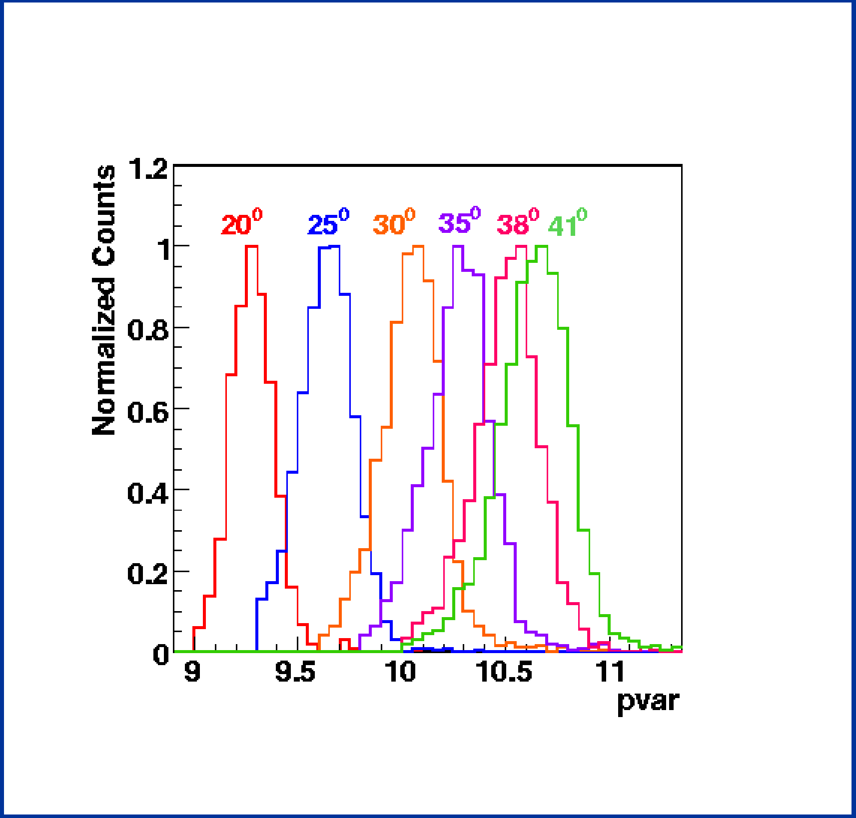
*** Present background of 0.003 cts $g^{-1}h^{-1}$**

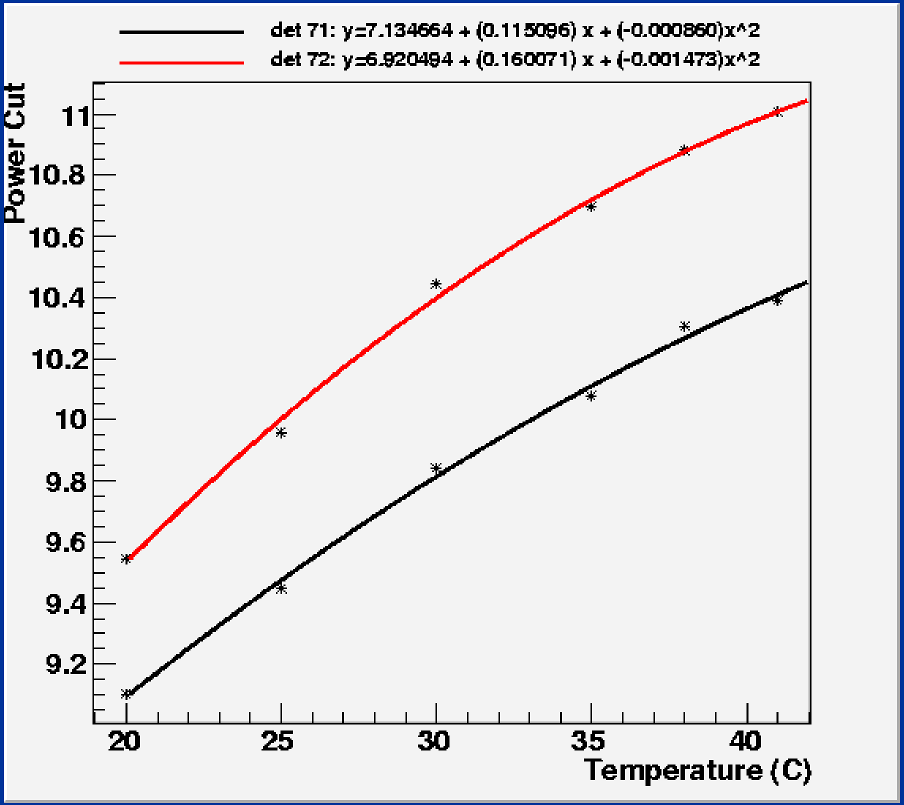
What next with PVar?

- Use neutron calibration runs to get PVar distributions for neutrons.
- Fit a Gaussian and select 95% : this will be our signal (because neutron induced nuclear recoils are like WIMPs)
- If PVar>PCut => we got particle induced event!!

PVar Distributions for Calibration Runs

Distributions are temperature dependant





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Active Target C_4F_{10}

Picasso

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

- Spin independent interaction ($C_A \propto A^2$)
- Spin dependent interaction

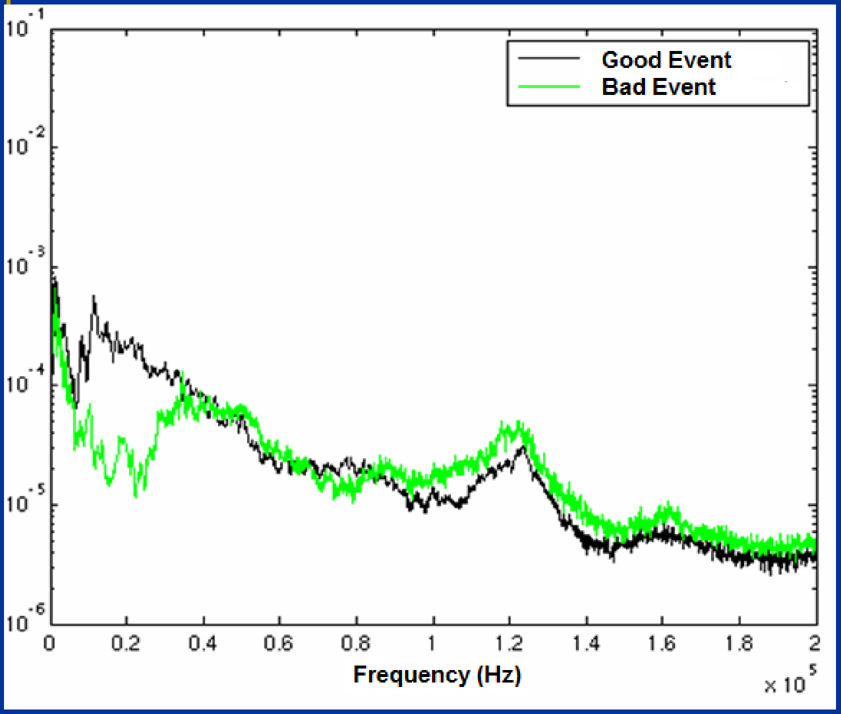
$$C_A = (8/\pi)(a_p\langle S_p\rangle + a_n\langle S_n\rangle)^2(J+1)/J$$

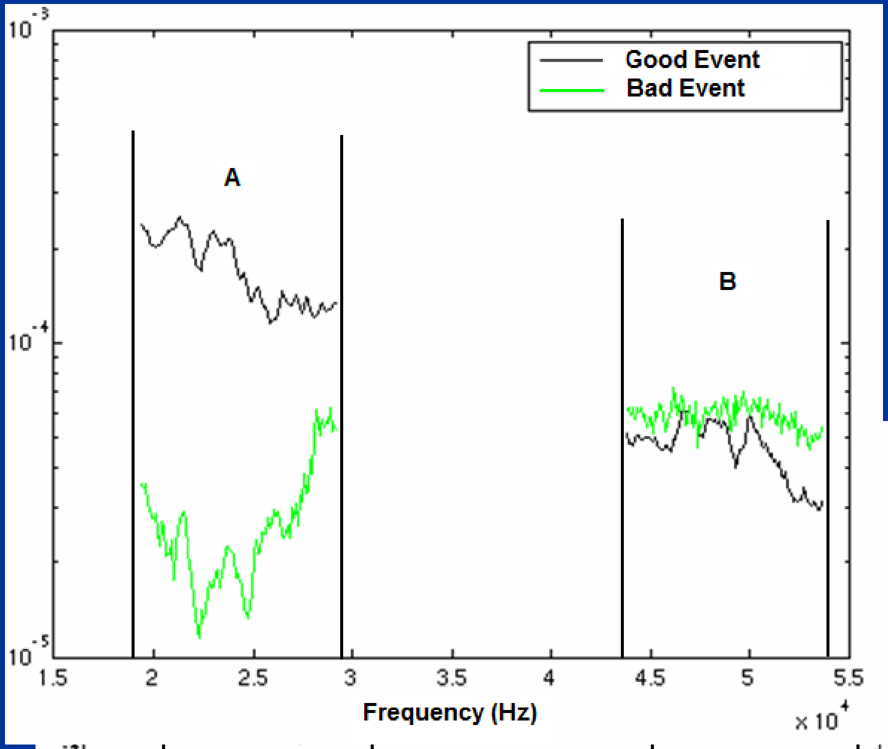
λ = $a_p\langle S_p\rangle + a_n\langle S_n\rangle$

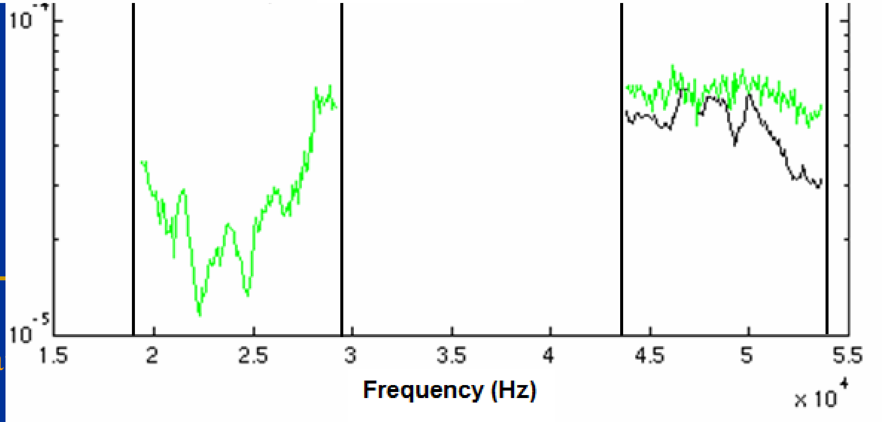
Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

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

The Frequency Variable "Fvar"



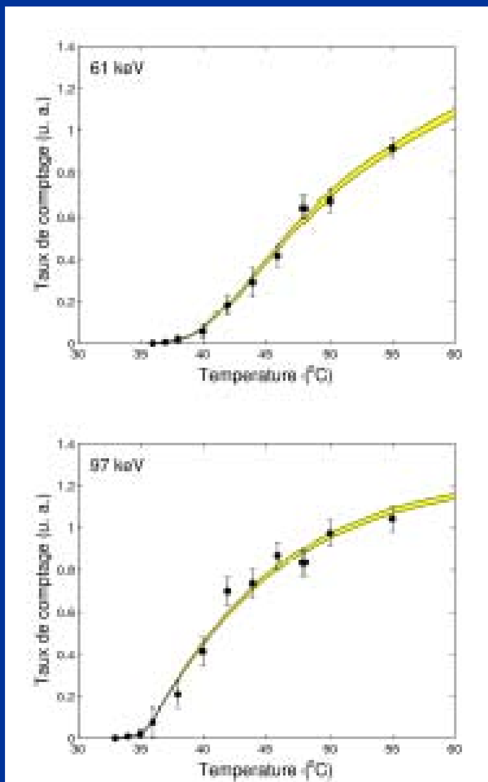




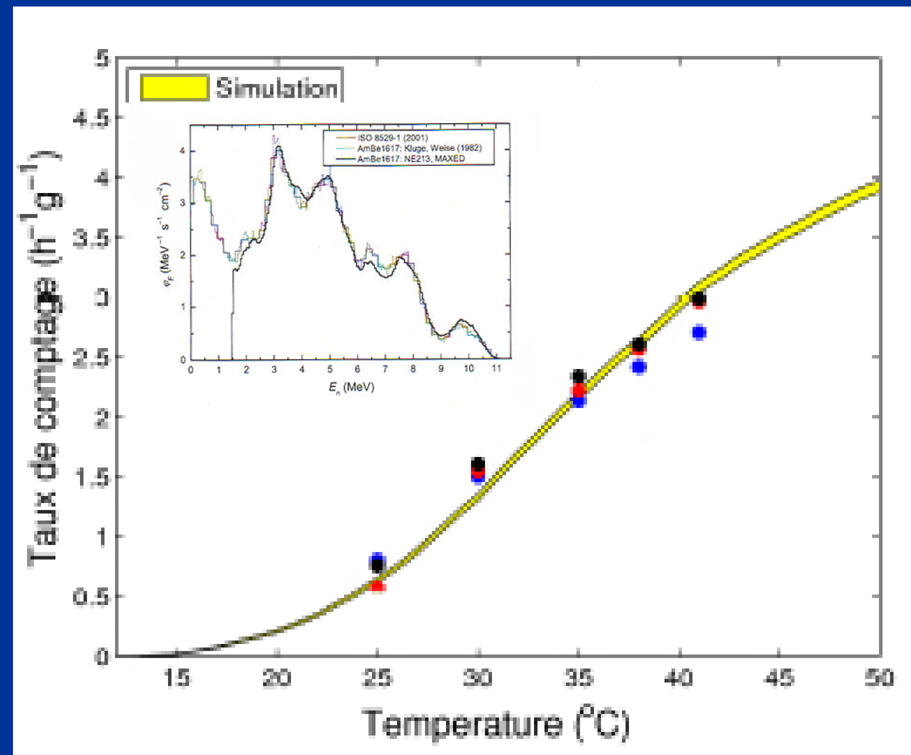
- Construct Fourier Transform
- Ratio of region A / region B → "Fvar"

Monte Carlo Simulations

Test beam



AmBe source (u/g calib.)



- Response at threshold not a step function!
- *a* - increases with neutron energy!

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

New!