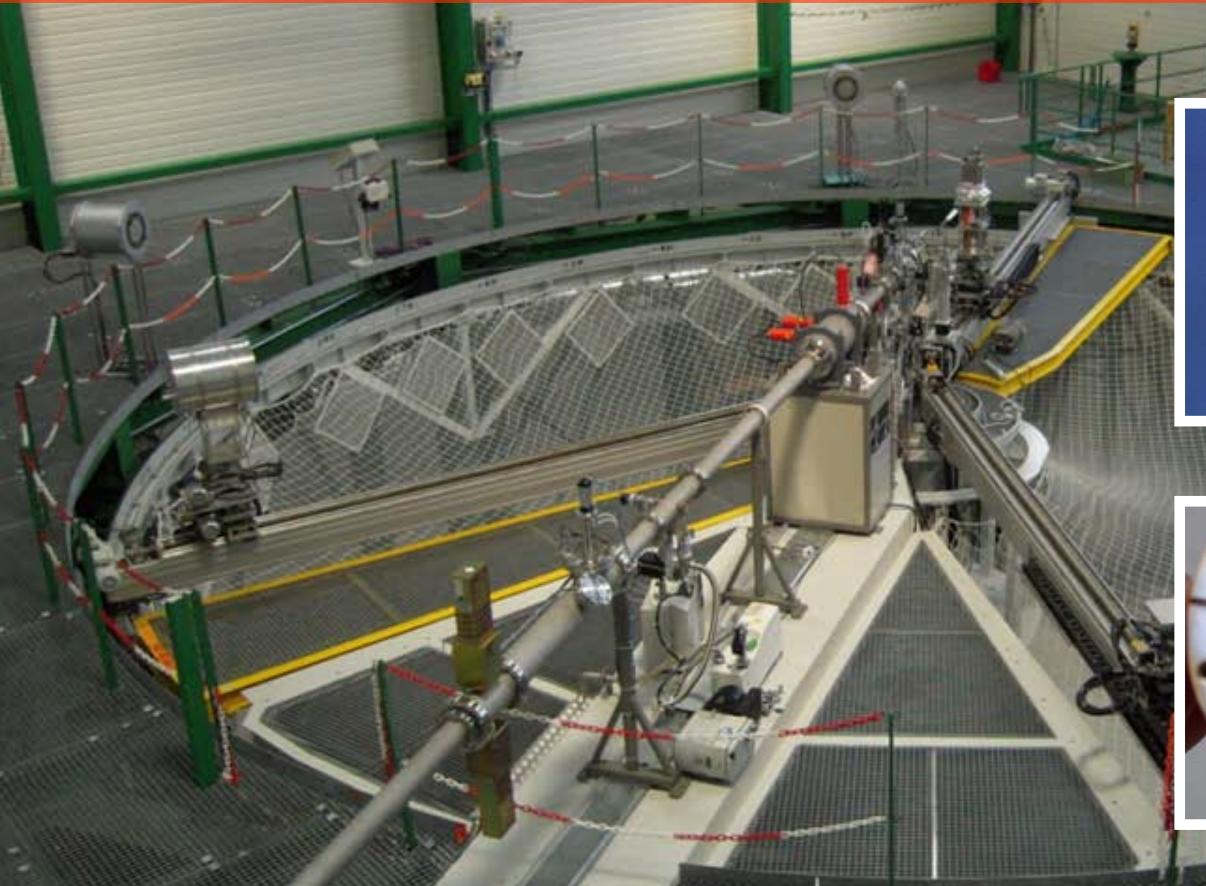
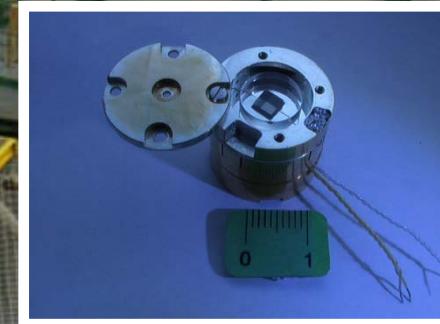


Fast neutron spectrometry with ${}^6\text{Li}$ -bolometers: from single heat detectors to dual scintillating ones

FNDA2011

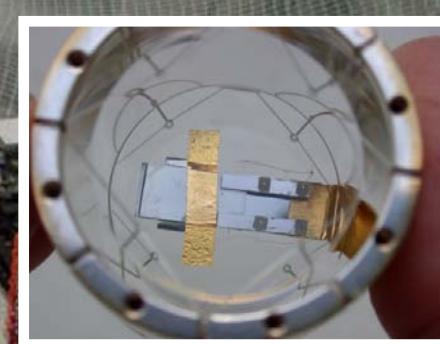


CNRS & IRSN, France



IRSN

INSTITUT
DE RADIOPROTECTION
ET DE SÉCURITÉ NUCLÉAIRE



Neutron detection with scintillating bolometers

❑ Motivations

- ❑ monitoring of fast neutron backgrounds in Dark Matter detection

❑ Basic principles

- ❑ (${}^6\text{LiF}$) bolometers and neutron capture
- ❑ Conventional fast neutron detectors

❑ Spectrometric performances of a 0.5g ${}^6\text{LiF}$ bolometer

- ❑ Calibration at IRSN, Cadarache (AMANDE facility)
- ❑ Discussion

❑ Massive LiF scintillating bolometers

- ❑ A 16g natural LiF detector
- ❑ A 32g natural LiF detector
- ❑ A 32g enriched ${}^6\text{LiF}$ detector



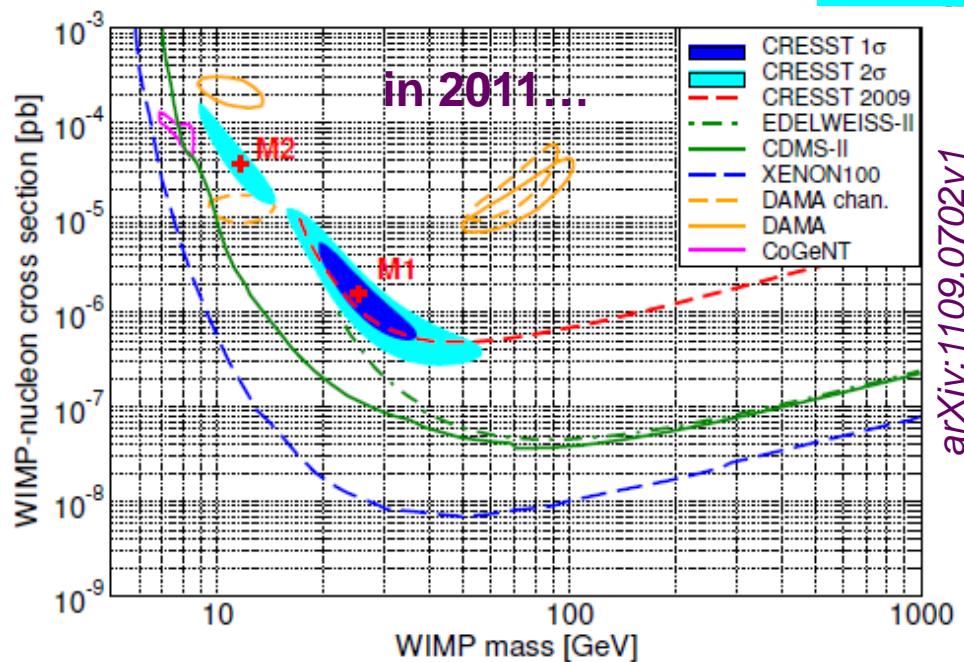
above and underground

❑ Alternative Li-targets

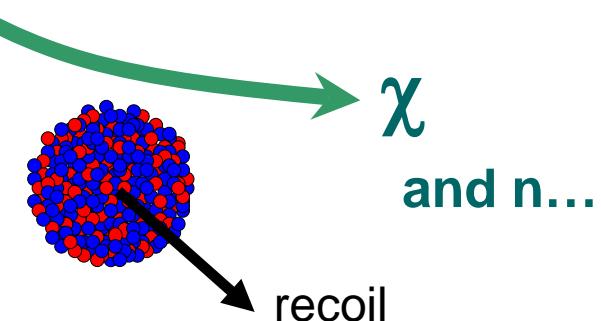
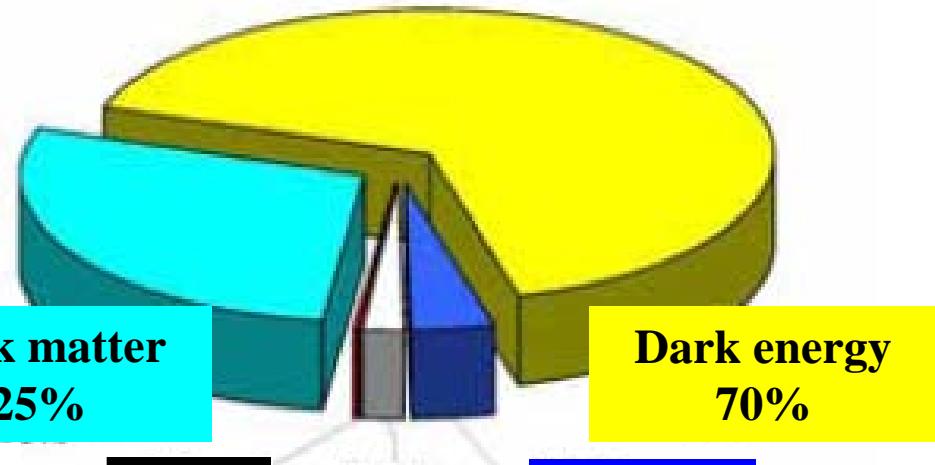
❑ Future steps ?

Neutron Background in « Dark Matter » experiments

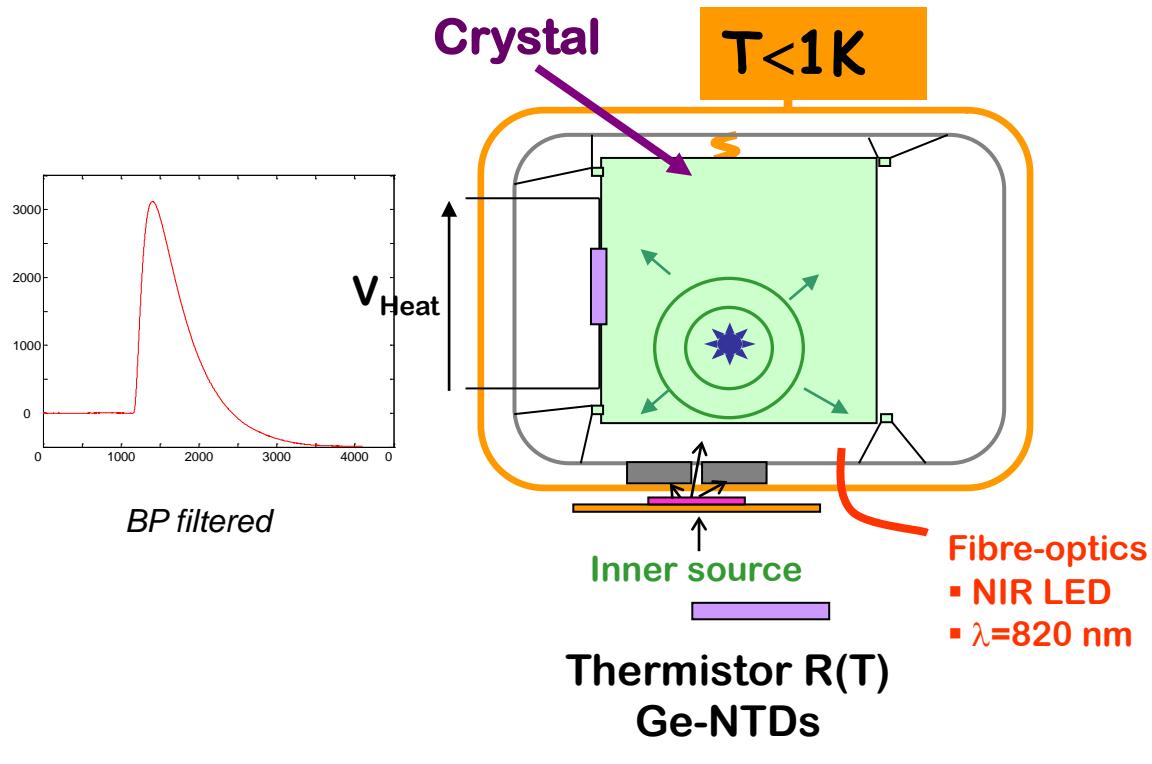
- Evidence for Dark Matter at all scales
- Nature ?
→ Supersymmetric particles (χ) ?
- Detectable through scattering
(measuring **the nucleus recoil**)
 $\sigma\chi\text{-n} < 10^{-8} \text{ pb}$
- Fast neutrons are the ultimate background !



The Universe content



(⁶Li) Bolometers and neutron capture



- Pros**
- **solid target = detector**
 - no straggling
 - high efficiency
- **high resolution** achieved.
Ex.: for insulators,
Energy quantum=phonon
 $\sim kT < 10^{-4} \text{ eV}$ at $T < 1\text{K}$
- a wide **choice of targets**
- **record of all particles**

- Contras**
- **cryogenics** are needed
- time constants $> \text{ms}$

$$\Delta E_{FWHM} \text{ ultimate} = \xi \sqrt{kT^2 C(T)}$$

$\propto (MT^5)^{1/2}$ for insulators

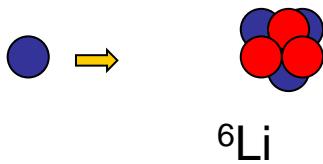
- High flux → low M → $T \leq 1\text{ K}$ is sufficient
- Rare events → high M → $T \leq 100\text{ mK}$ is needed

Fast neutron spectroscopy in ${}^6\text{LiF}$ bolometers

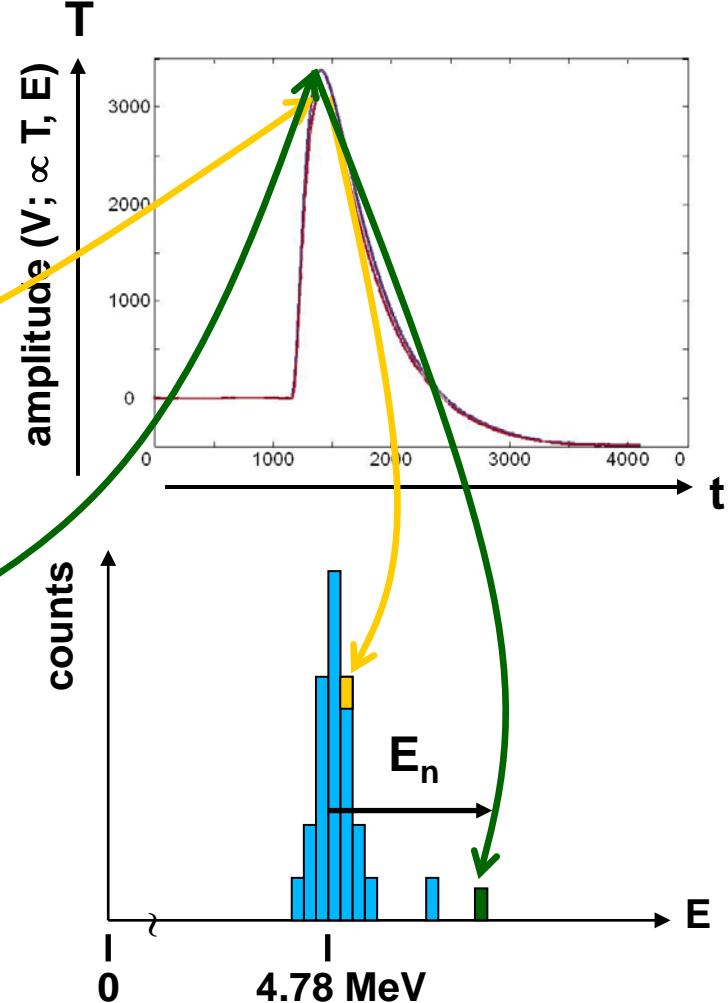
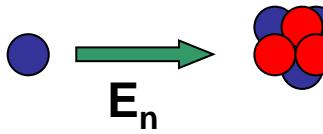


→ En easily recovered, in principle
→ background from alphas only

Thermal neutron (25 meV)

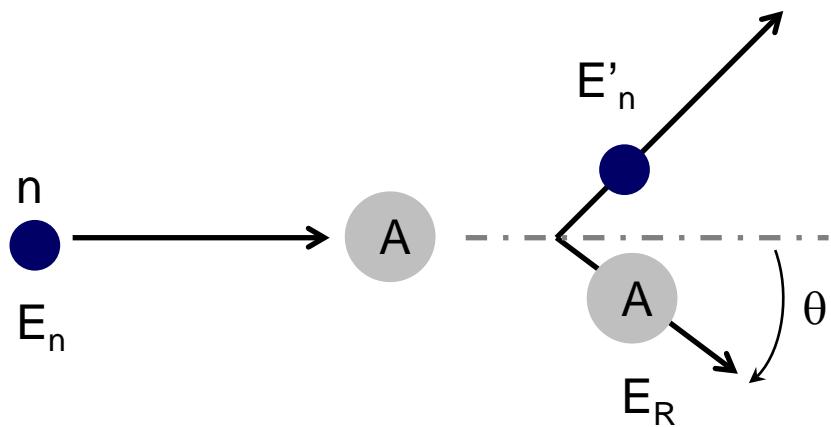


Fast neutron (1keV-20MeV....)

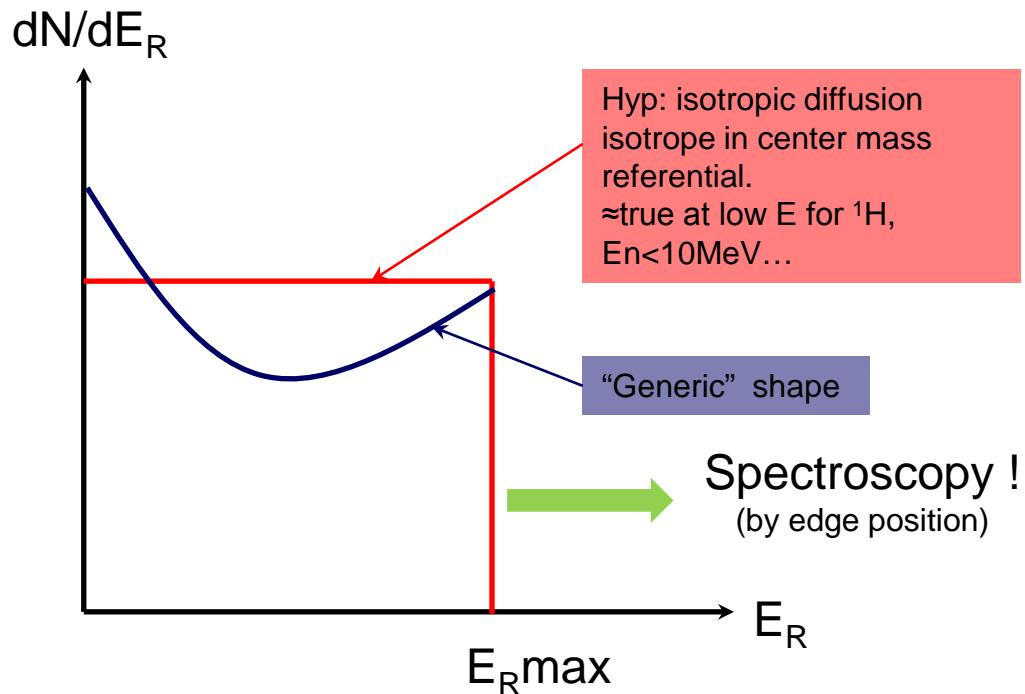


Elastic scattering(n,n)

1. Principles



Theoretical responsivity



kinematics

$$\begin{cases} E_R = \frac{4A}{(A+1)^2} \cos^2 \theta \times E_n \\ E'_n = E_n - E_R \end{cases}$$

then

$$E_{R\max} = \frac{4A}{(A+1)^2} E_n \quad (\approx \frac{4}{A} E_n \text{ si } A \gg 1)$$

Target	A	$E_{R\max}/E_n$
H	1	1
He	4	0.64
Li	6	0.49
C	12	0.28
O	16	0.22
F	19	0.19
Ge	74	0.053

$\sigma_{el} \sim \text{barn}, \forall A, E_n$

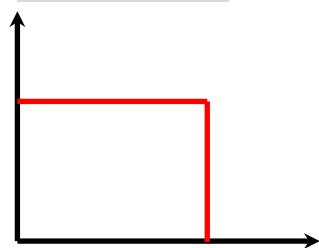
Elastic scattering (n,n)

2. Real recoils spectra

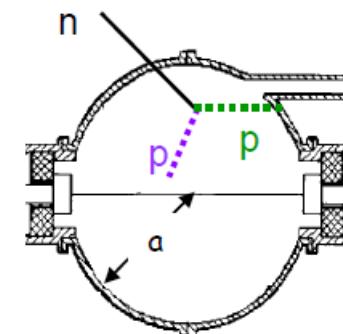
ROSPEC (kit of 6 proportional counters)



Theory



Mesure

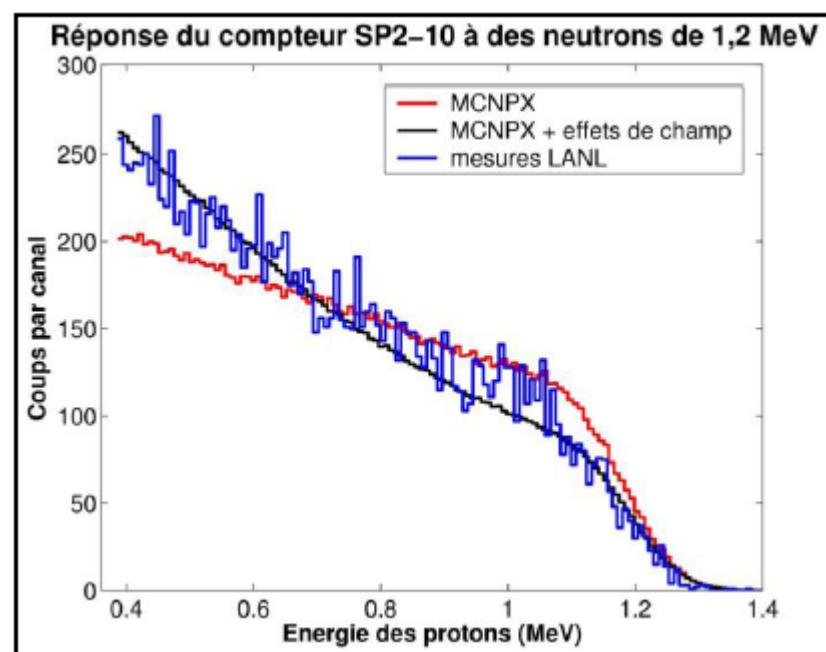


Sphere filled with H₂, 10 atm

→ degradation of the theoretical “rectangular responsivity” by instrumental effects: edge effects, resolutions,...

Recoils protons

- Good for mono-En, but important dilution of the signal
- strong degeneracy in neutron field measurements : for a given signal, one knows only the minimal neutron energy detected.

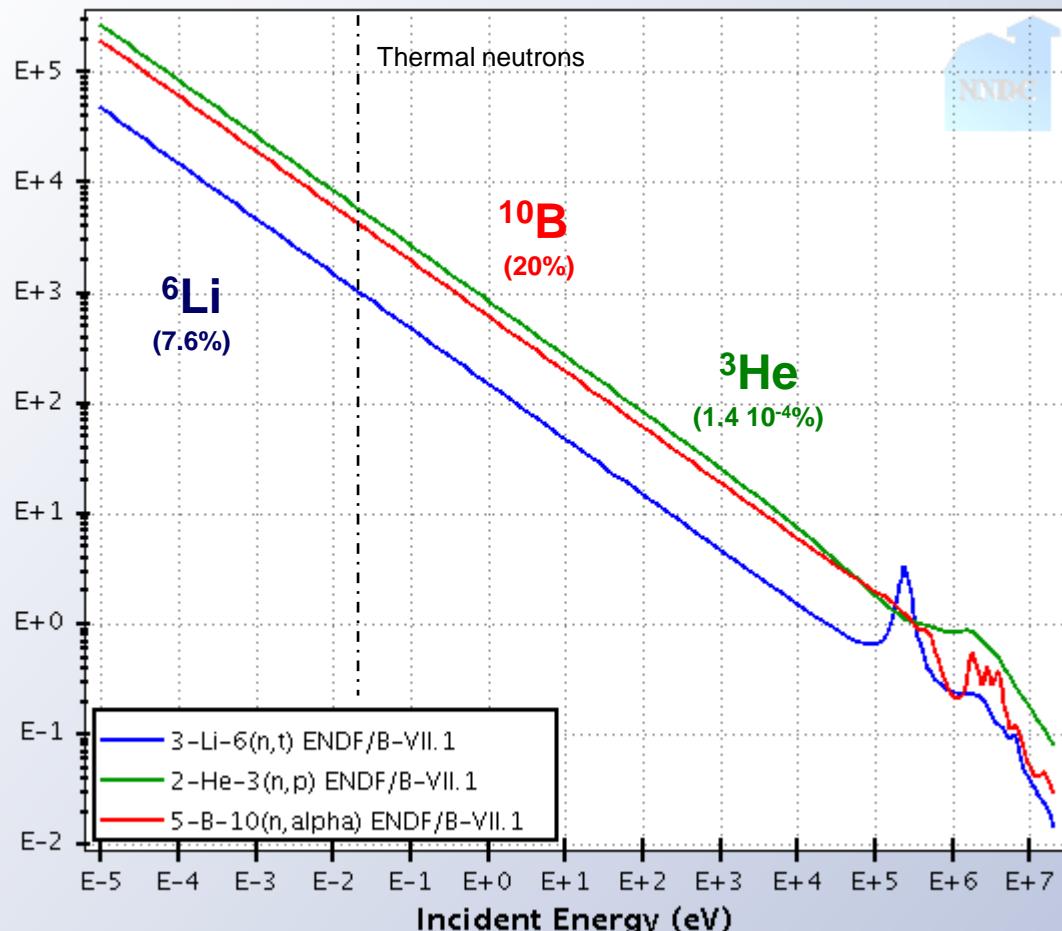


Nuclear capture reactions (n,p), (n,t), (n,α)

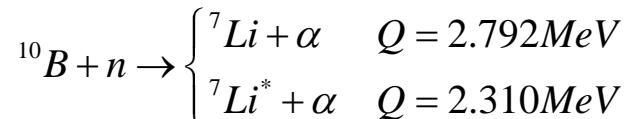
1H

3H

4He



Trio of reactions



- ✓ The products are high energetic particles, strongly ionizing, **easily detectables**
 - incorporation in ~all types of traditional detectors
 - gaz : $^3He, ^{10}B$ (BF_3)
 - solids, liquids: ^{10}B & 6Li
- ✓ High cross section for thermal neutrons n_{th}
 - Neutron counters after moderation
 - n_{th} capture in screens
- ✓ **cross section strongly decreasing with energy ($\sim 1/v_n$)**

A direct and straightforward measurement of the captured neutron energy !

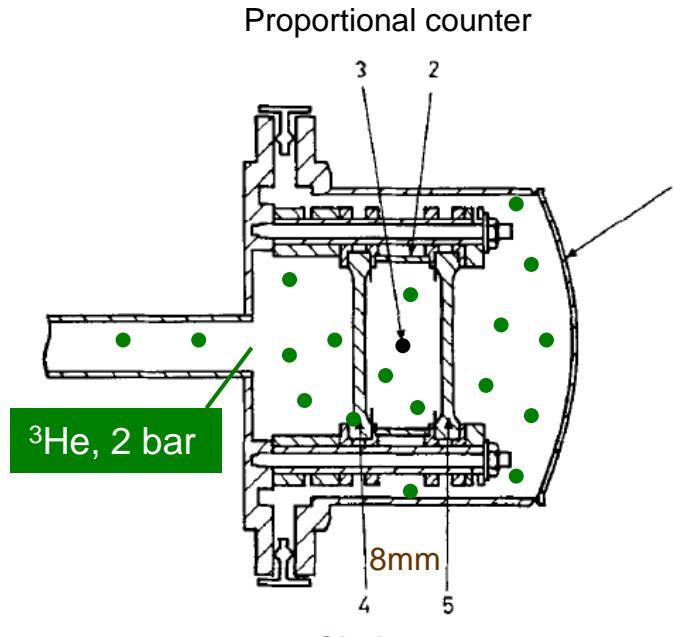
$$A_{rest} + n \rightarrow B + C \quad E_n + Q = E_B + E_C \quad \rightarrow E_n$$

known measured deduced

- ✓ accuracy ?
- ✓ efficiency ?

“Conventional” detectors using n-capture reactions

With Hélium-3



- 1 Stainless steel window
- 2 Cathode box
- 3 Anode wire
- 4 Back surface barrier detector
- 5 Front surface barrier detector

for E_n : 100keV-15MeV

Resolution FWHM ~50 keV & efficiency (0.1%)

With Lithium-6

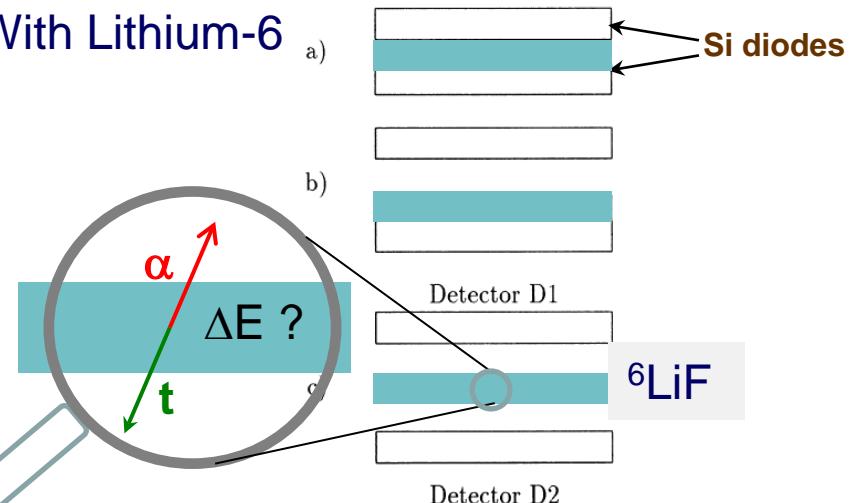


Fig. 1. The spectrometer designs. (a) the Sandwiched Target Spectrometer (STS), (b) the Deposited Target Spectrometer (DTS) and (c) the Symmetric Neutron Spectrometer (SNS).

Spectrometer design	Target thickness ($\mu\text{g cm}^{-2}$)	Spectrometer resolution (keV) @ n_{th} (4.78 MeV)
STS	30	300
	142	300
DTS	150	126
SNS	20	50
	57	70
	65	78
	97	120
	157	235

0.08 μm

0.6 μm

Conventional fast neutrons detectors

Table 1
Neutron spectrometer characteristics

Spectrometer				Typical characteristics for		
No.	Type	Ref.	Energy range (MeV)	Energy (MeV)	Resolution (FWHM)	Detection efficiency
1	Recoil proportional counter	[27]	0.05–5	1	10% ^a	3%
2	Organic scintillator	[31]	2–150	8	4% ^a	20%
3	Recoil proton telescope	[45]	1–250	60	4% ^a	<0.05%
4	Capture-gated	[49]	1–20	5	50% ^a	1%
5	³ He gridded ionization chamber	[61]	0.05–10	1	2% ^a	0.3%
6	³ He-semiconductor sandwich	[64]	0.1–20	1	50 keV ^a	0.1%
7	Diamond semiconductor	[68]	8–20	14	1% ^b	1%
8	Time-of-flight	[74]	1–15	2.5	5% ^c	0.05 cm ⁻²
9	Foil radioactivation	[79]	0.2–20	—	—	—
10	Superheated drop (bubble)	[82]	0.1–20	—	—	—
11	Multisphere	[91]	10 ⁻⁸ –200	—	—	—

^aPulse height resolution.

^bEnergy resolution.

^cTime-of-flight resolution.

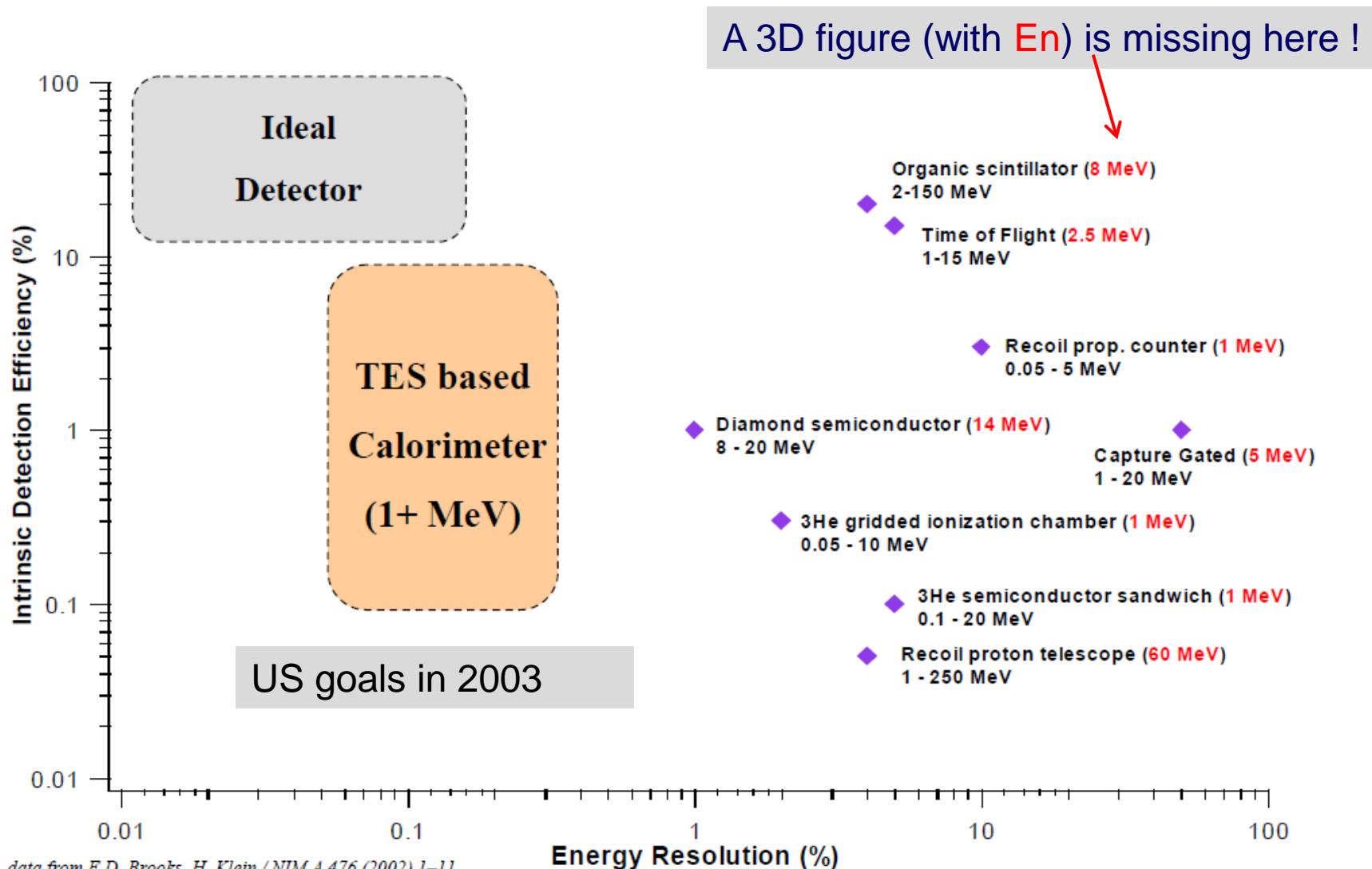
All techniques ...

...excepts cryodetectors !

Neutron spectrometry—historical review and present status,
F.D. Brooks , H. Klein, NIMA 476 (2002) 1-11

found ~ everywhere (ISS, satellites, poles, mountains,
undergrounds...)

Conventional fast neutrons detectors and cryo-ones

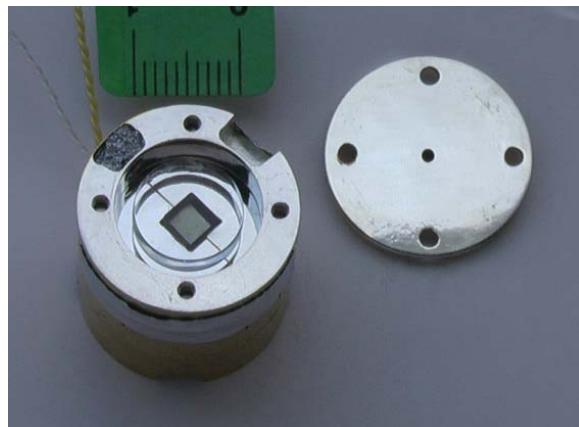


data from F.D. Brooks, H. Klein / NIM A 476 (2002) 1-11

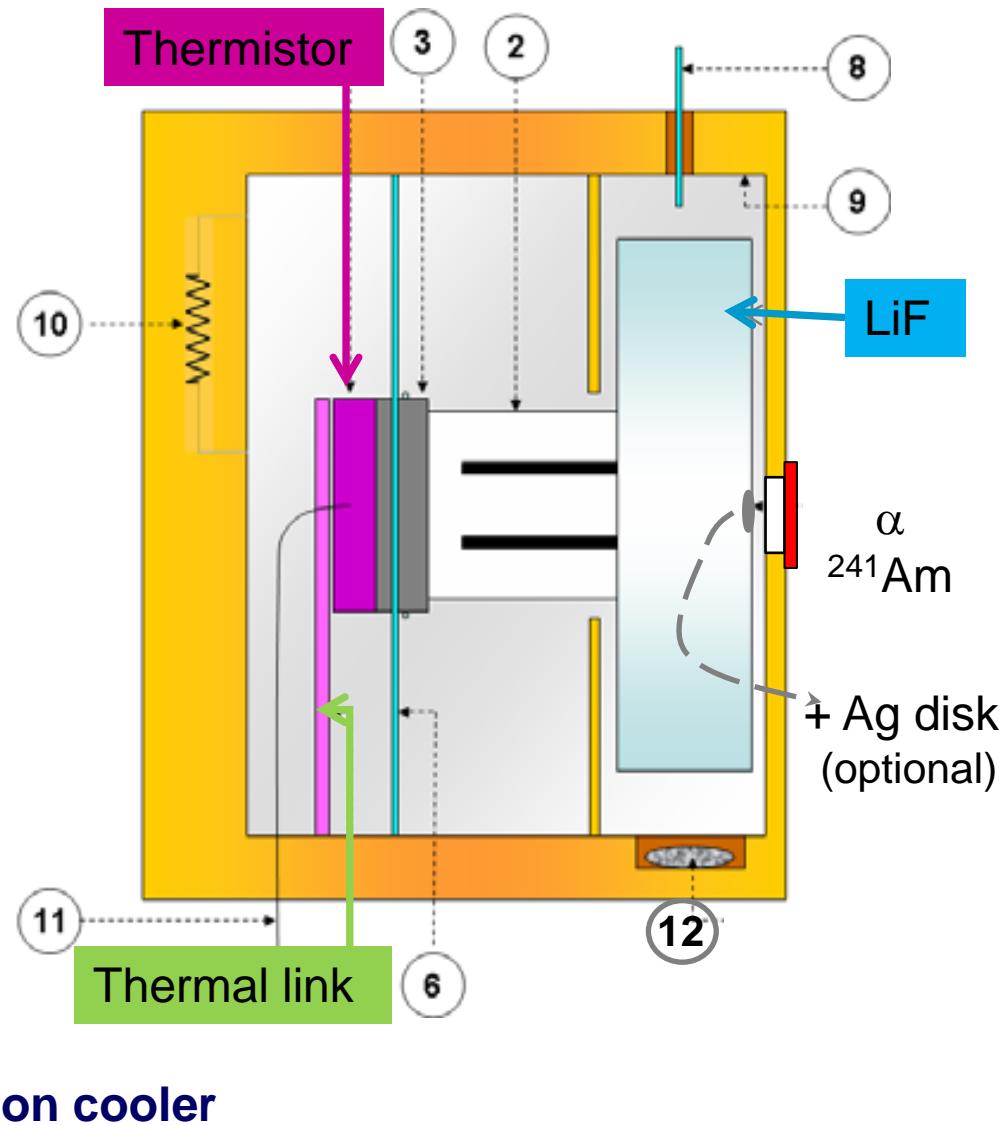
A transportable neutron spectrometer

(Ph.D thesis, J. Gironnet, 2010)

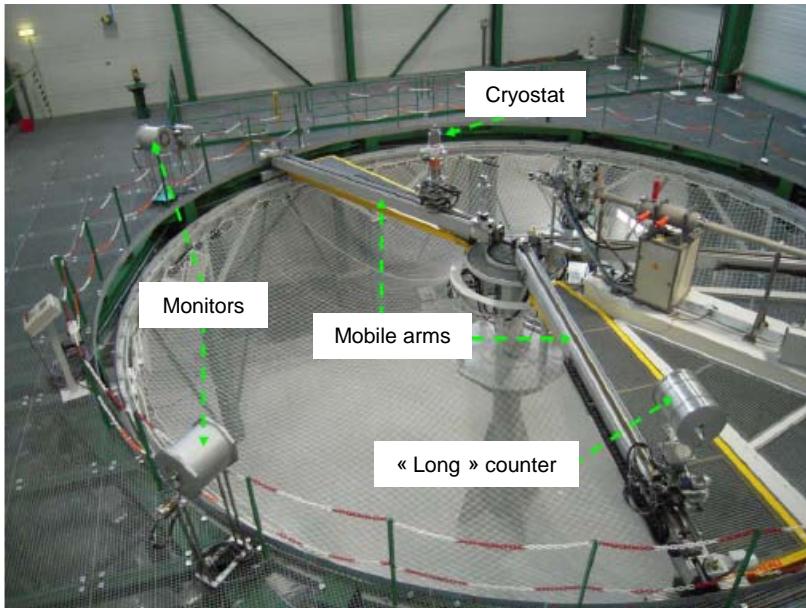
A **0.5g** ${}^6\text{LiF}$ (${}^6\text{Li} \approx 95\%$) bolometer...



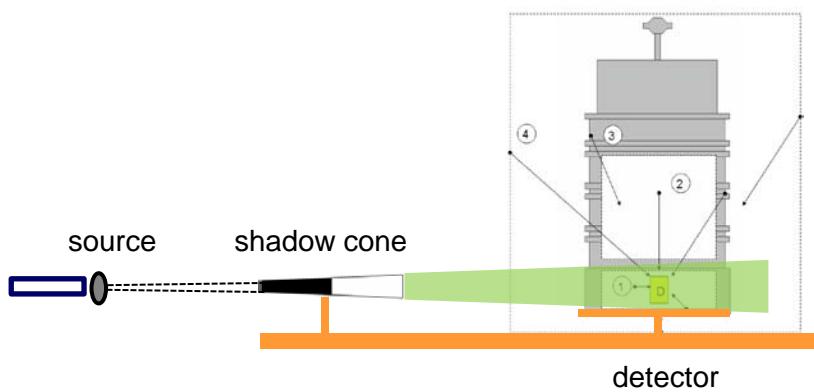
...in a 300mK cryostat...



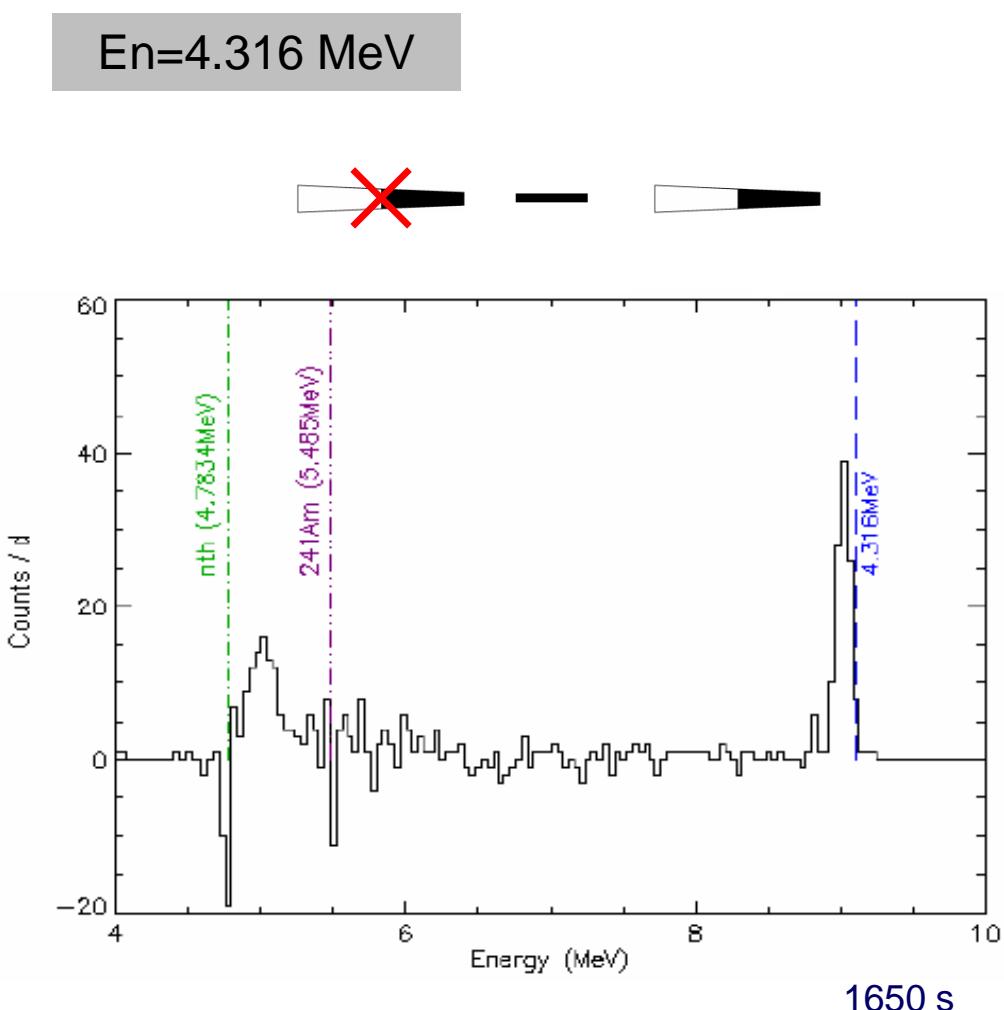
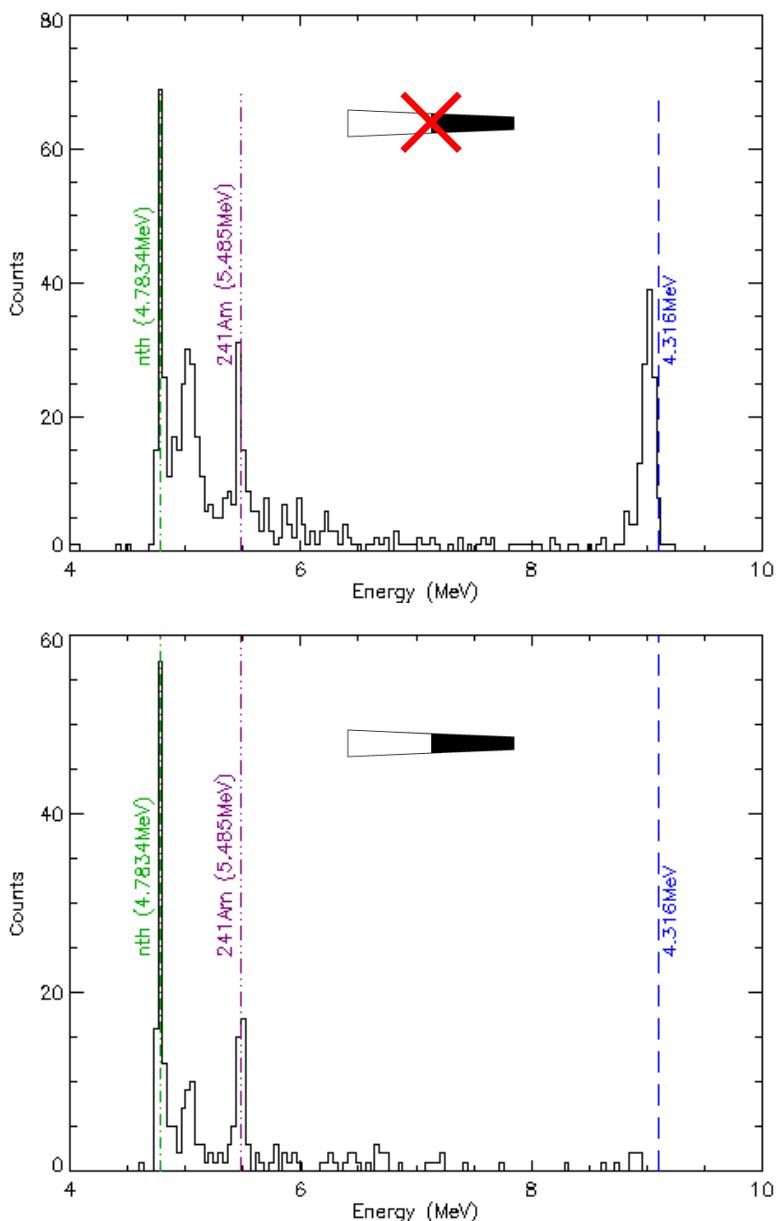
Calibration @ AMANDE facility (IRSN, Cadarache)



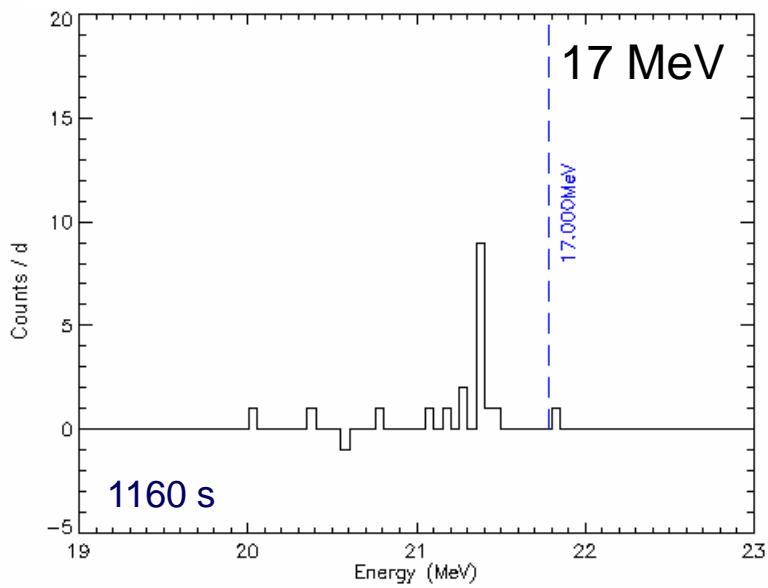
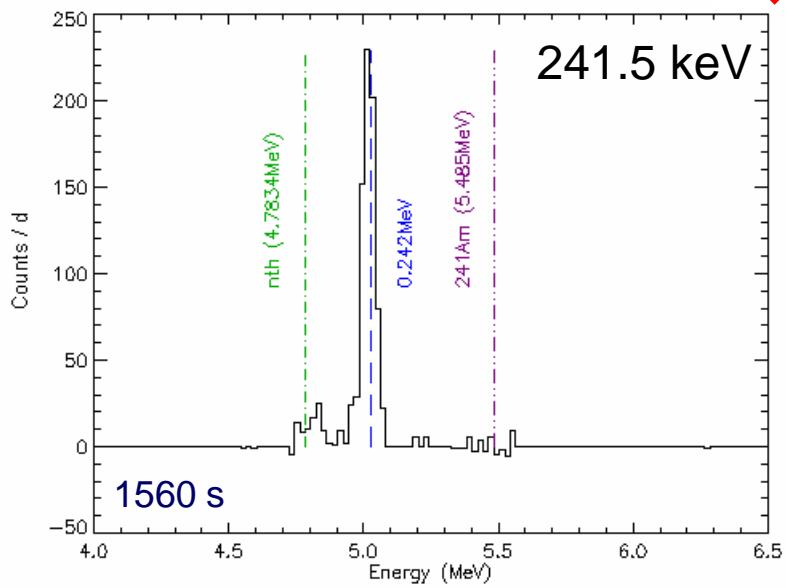
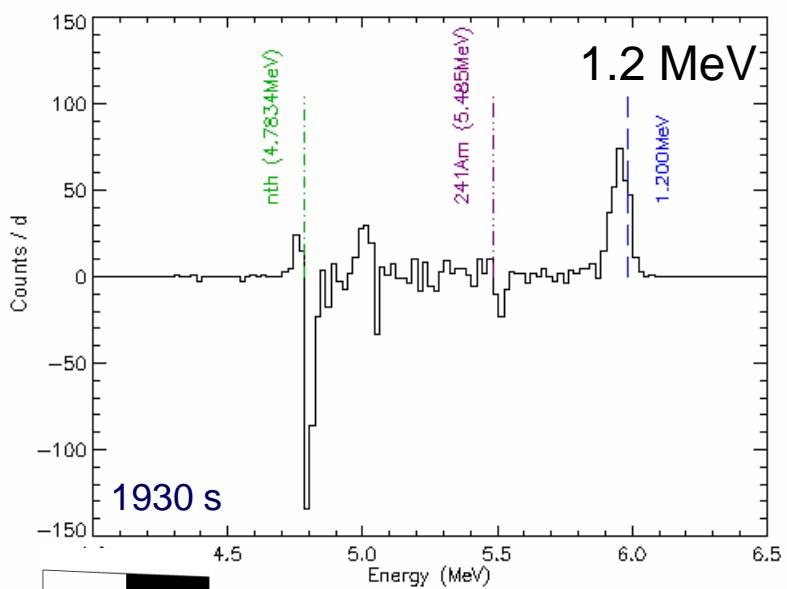
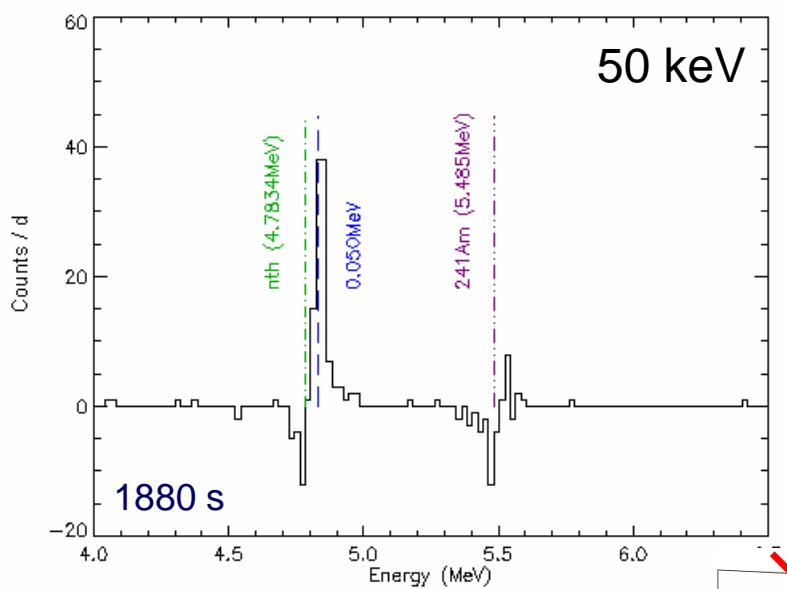
Neutron spectrometer
0.5g ${}^6\text{LiF}$ @ 430mK



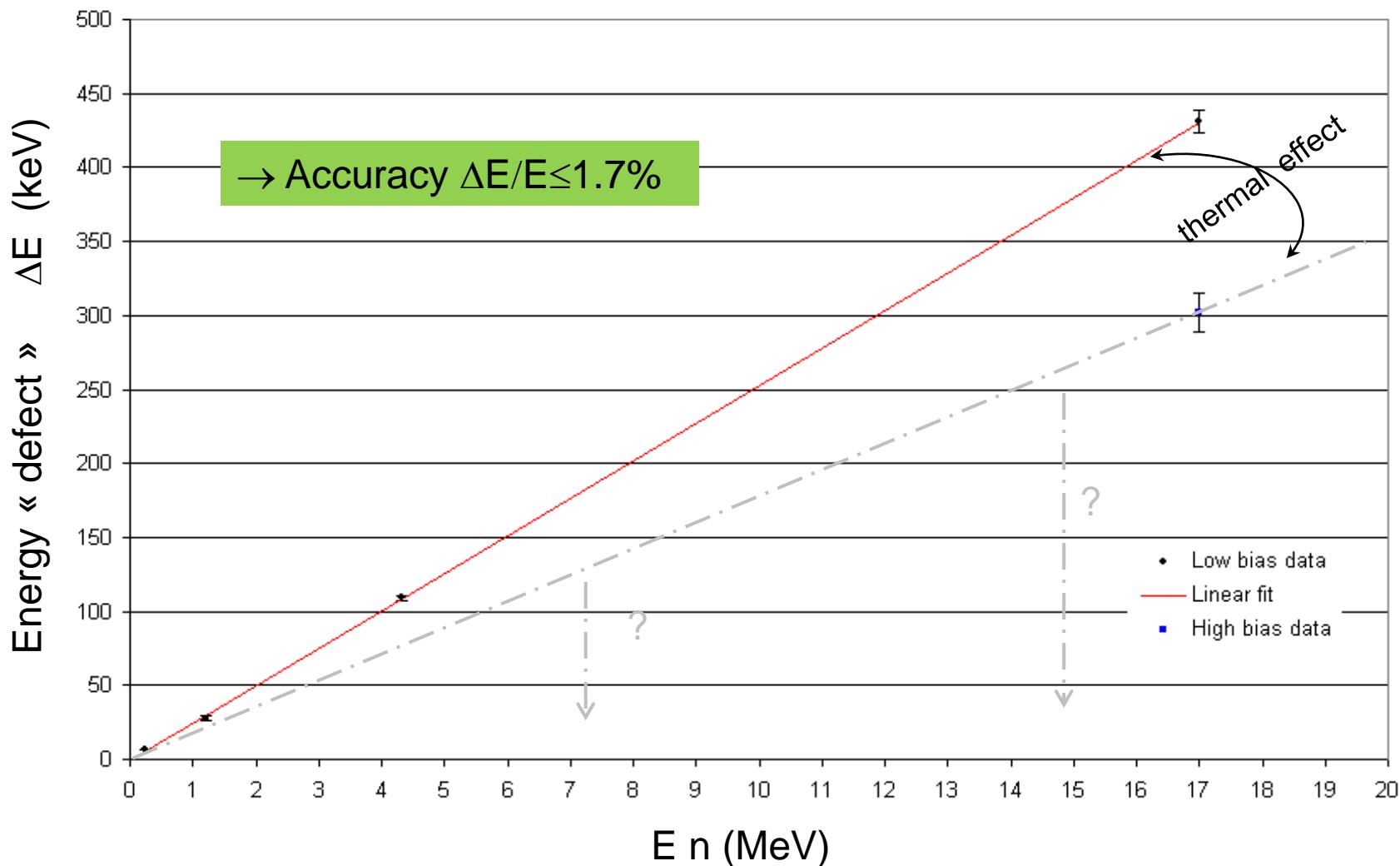
Neutron peaks are observed



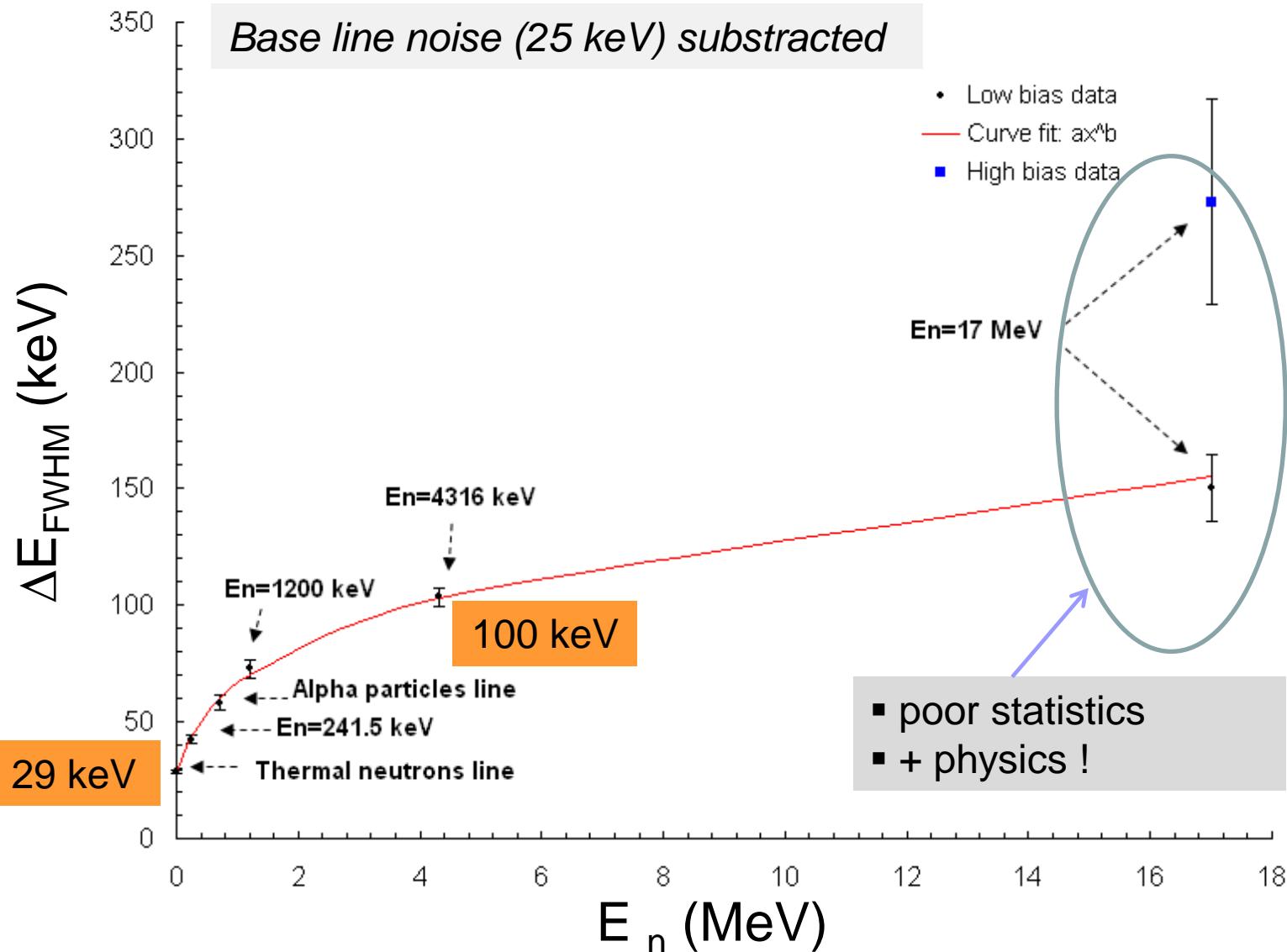
General trend (calibration from thermal peak)



Recovering the neutron energy with accuracy...

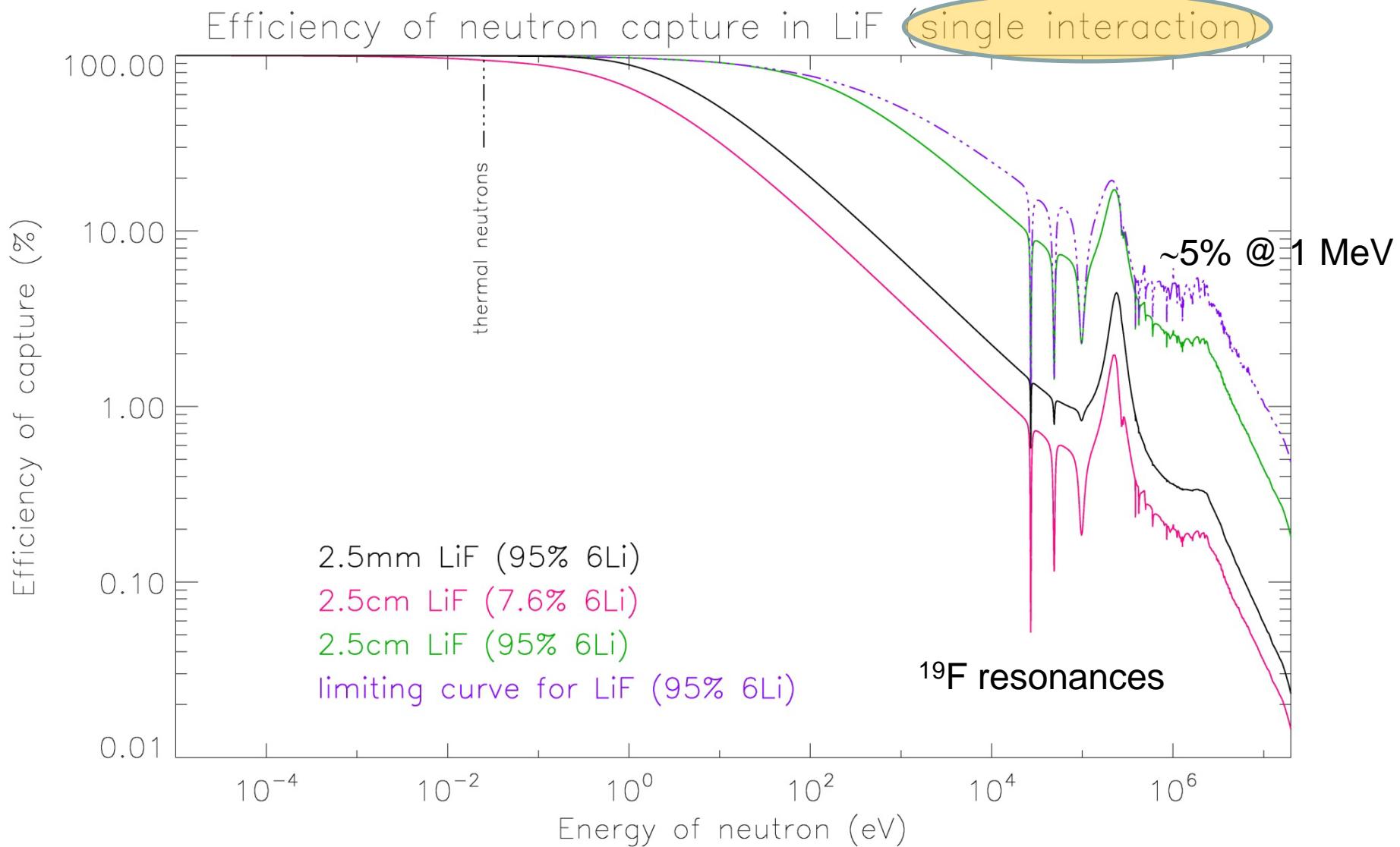


Resolution ΔE_{FWHM}



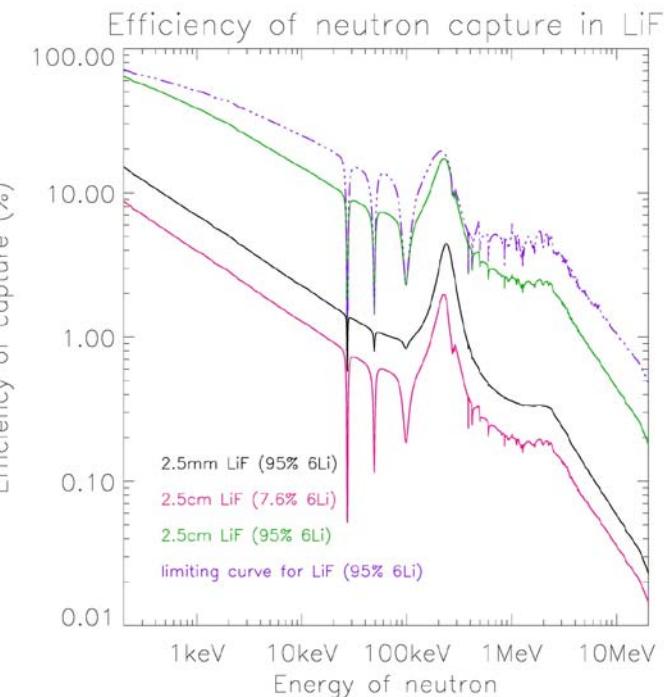
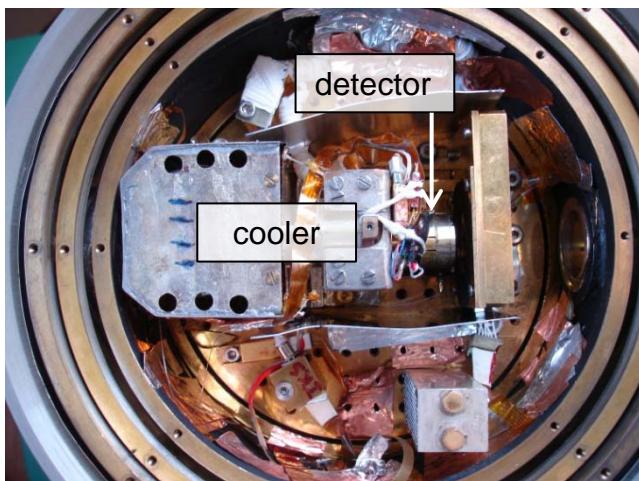
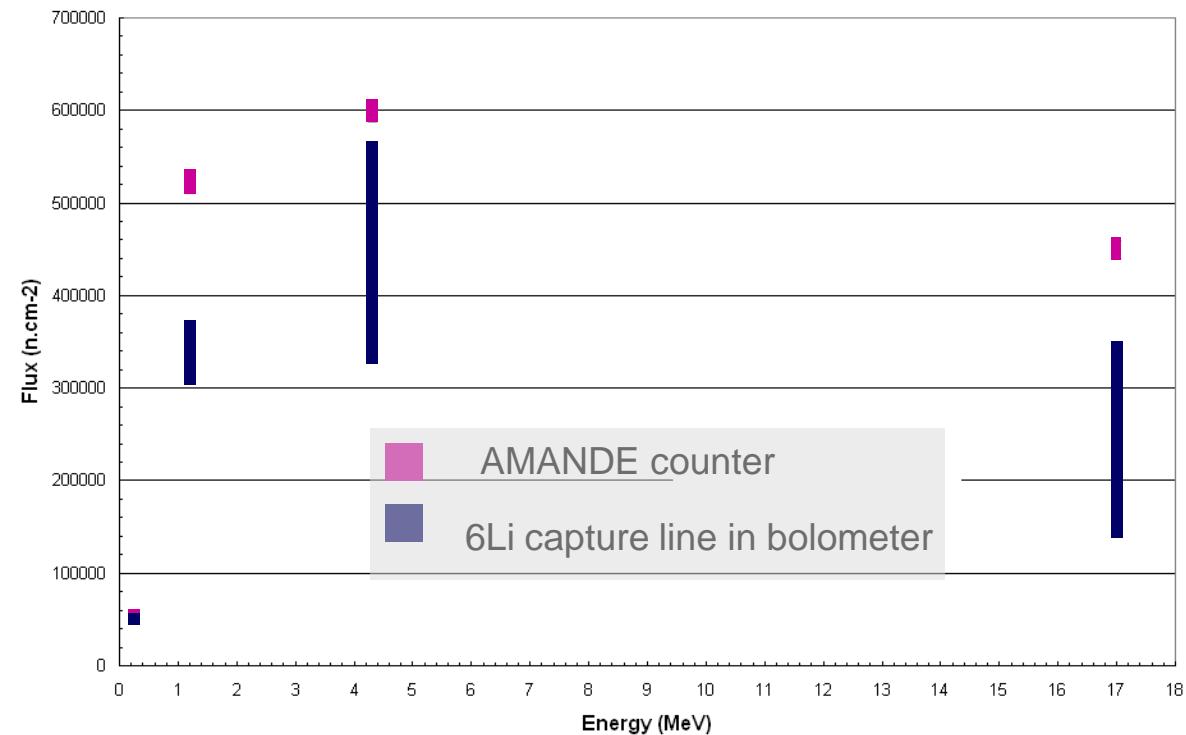
Detection efficiency in LiF

1. Tabulated (ENDF/B-VII)



Detection efficiency in LiF

2. Fluences



- a lot of « useless » matter
- neutrons lost in line with the beam
- detailed simulations missing
→ cold finger needed

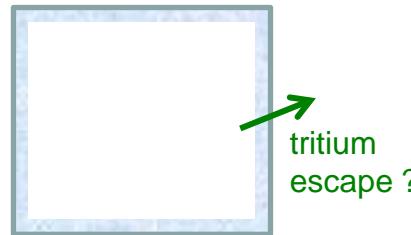
Discussion / Resolution
sources of $\Delta E_{FWHM} \uparrow ?$

Discussion

1. Size & enrichment effects

- to compare with the ranges of alpha & tritium:

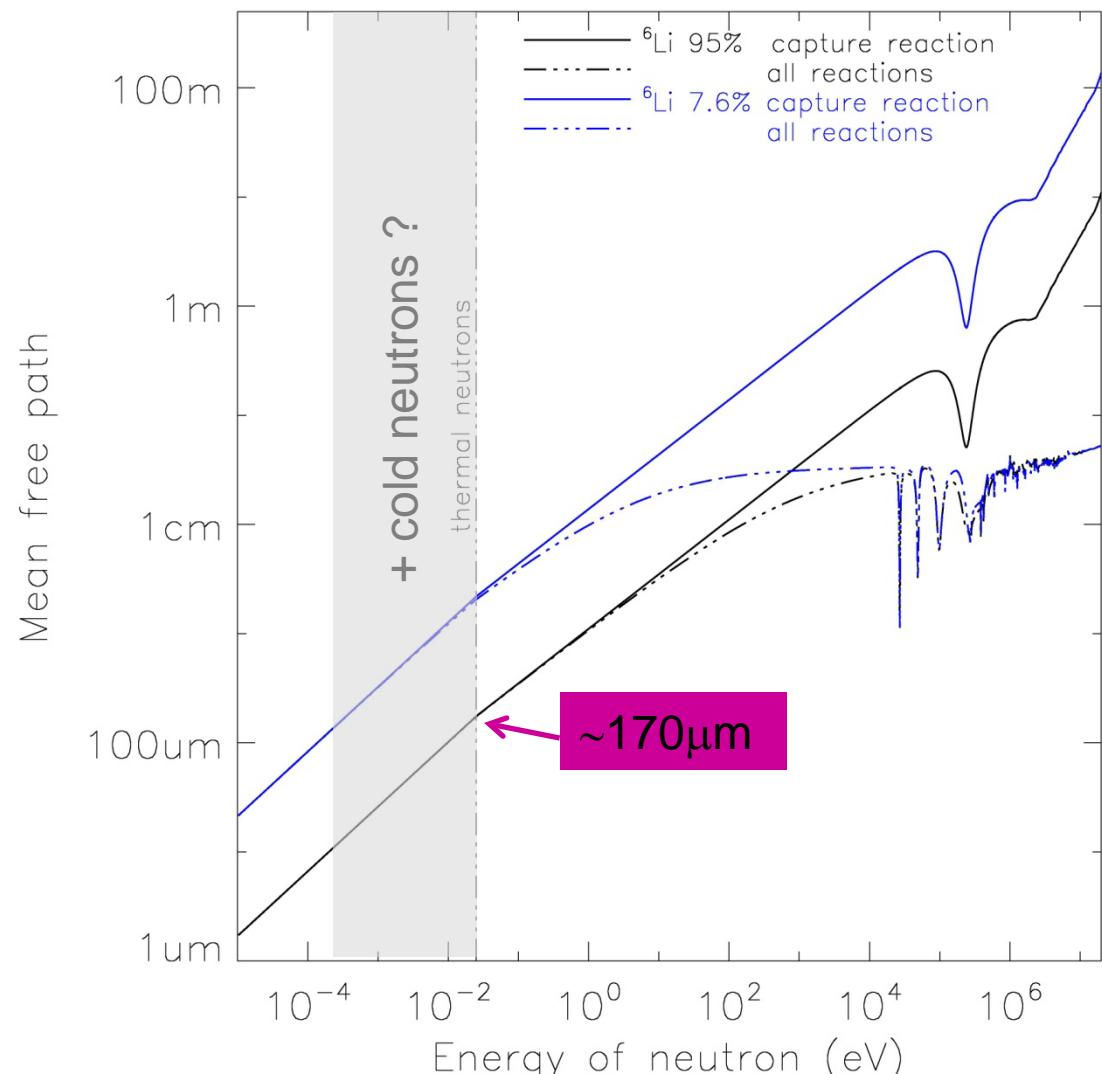
Range (max)	Thermal neutrons	$E_n=20$ MeV
Alphas	6 μm	160 μm
Tritium	34 μm	1 mm



Slow neutrons interactions



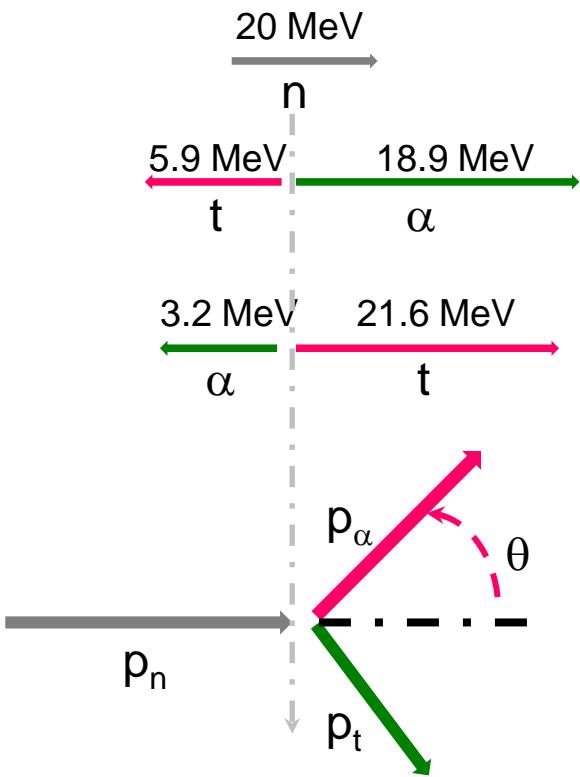
Fast neutrons interactions



Above 100eV, mean free paths ≥ 1 cm

Discussion

2. kinetic energy partition

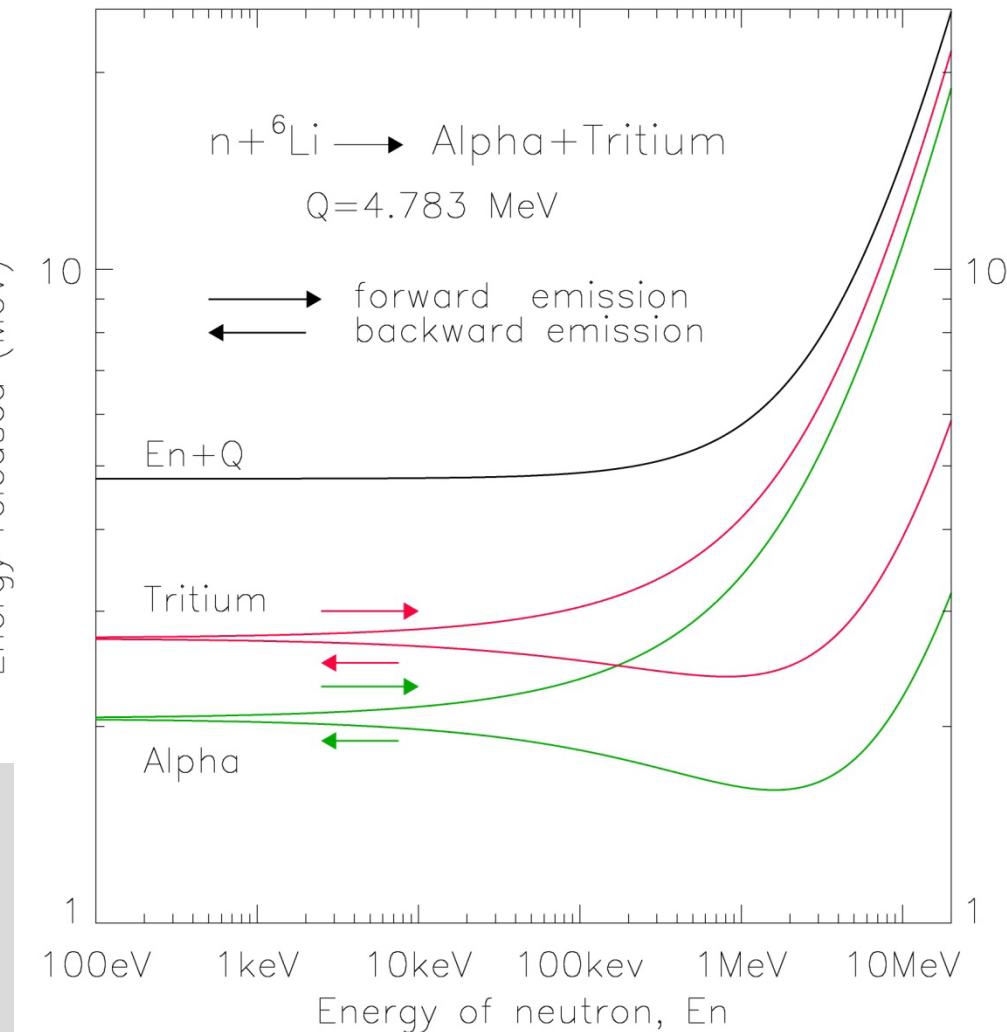


(E, p) conservation laws

→ one free parameter (θ, \dots)

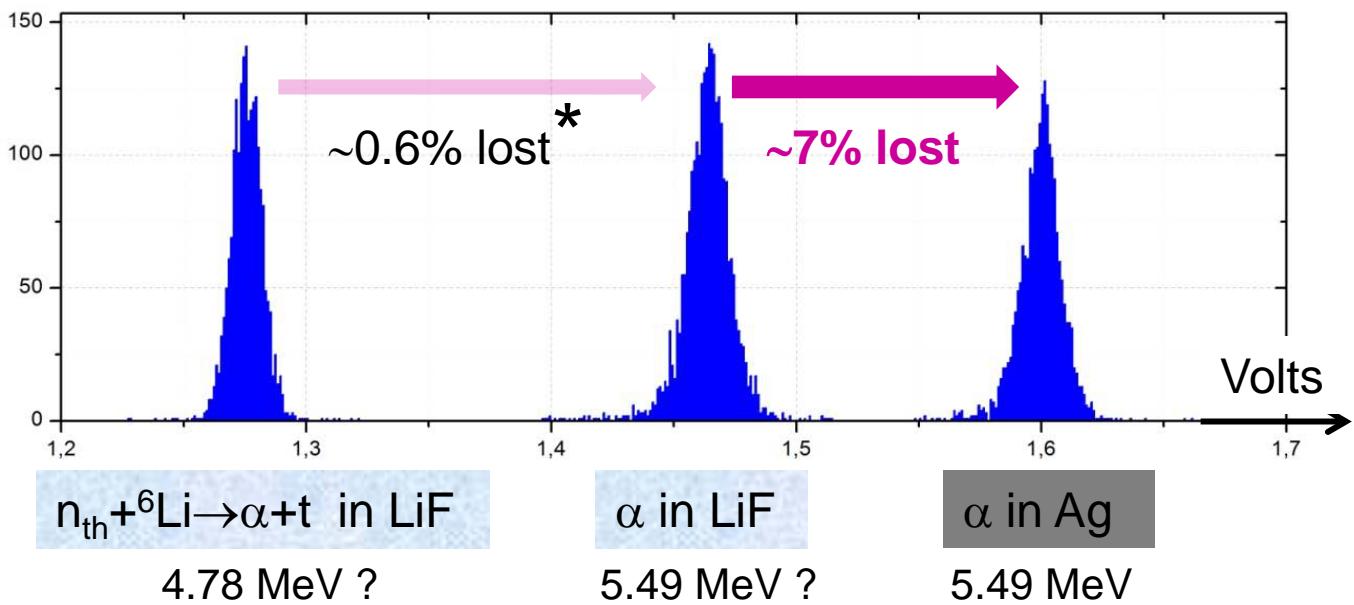
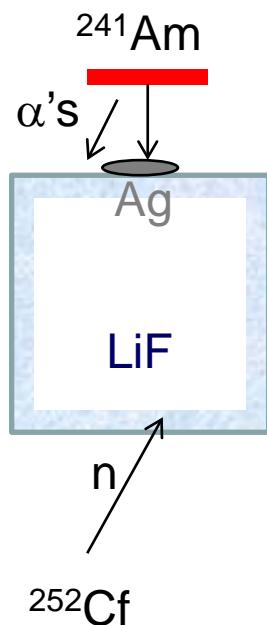
- probably the main cause of energy dispersion, if alphas & tritium are not equally thermalised in the crystal

$\rightarrow \Delta E_{FWHM} \uparrow$ with $E_n \uparrow$



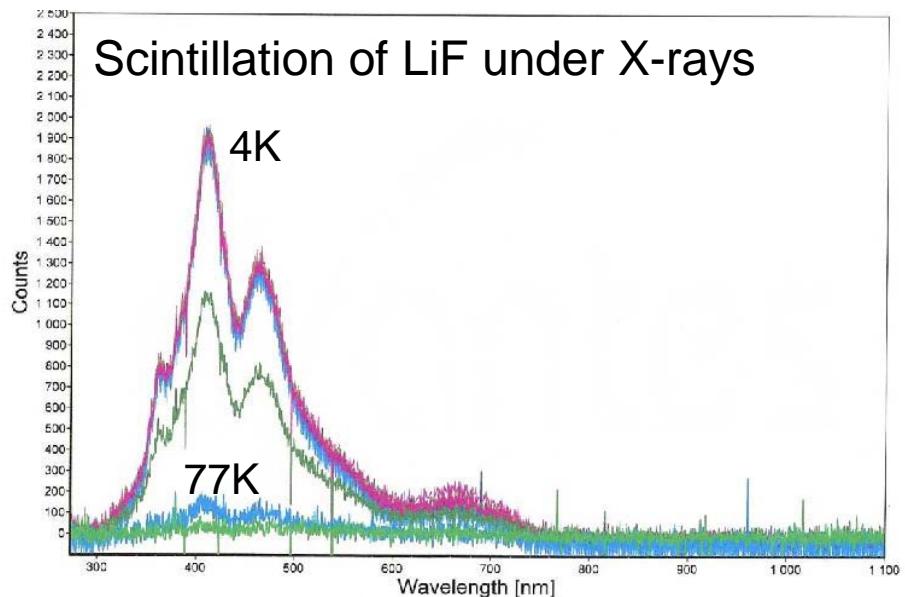
Discussion

3. Thermal conversion at 100% ?



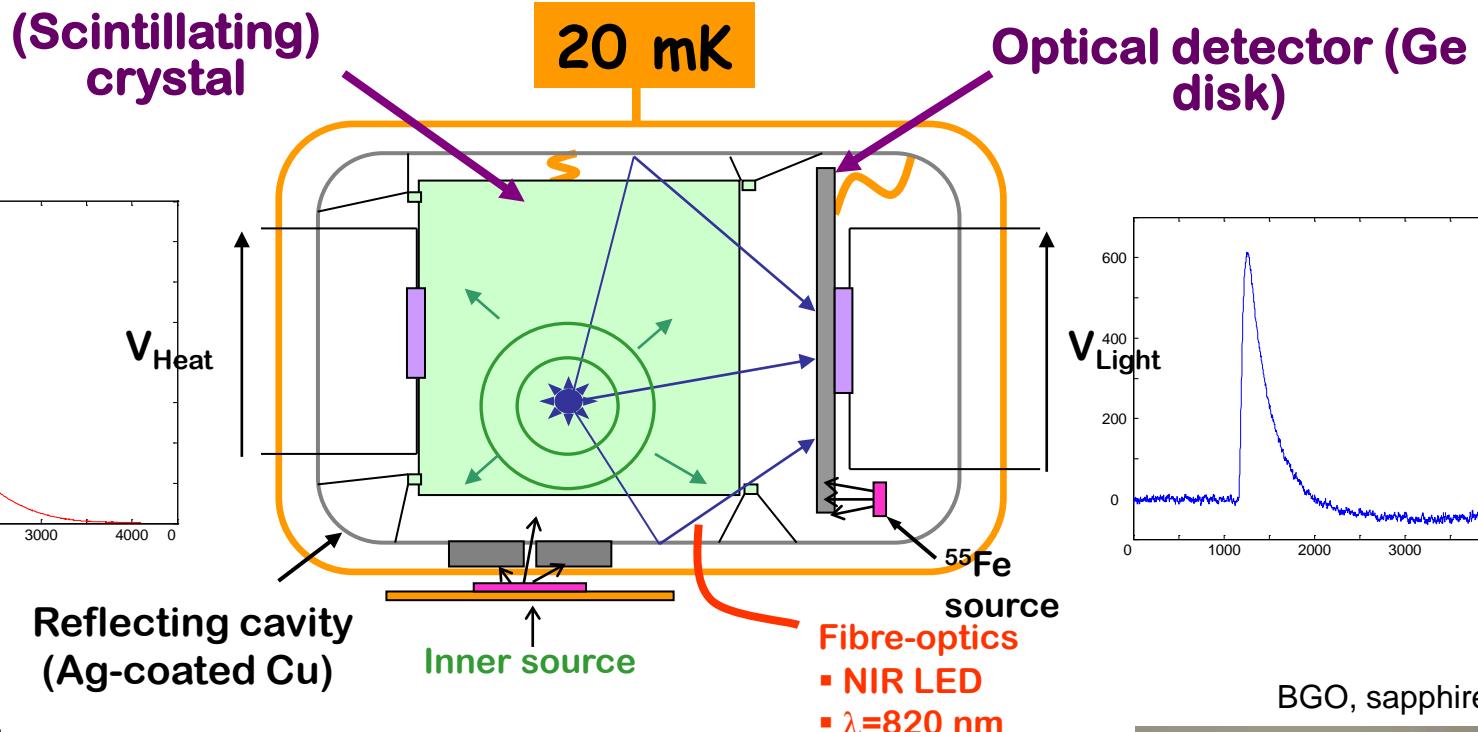
« thermalized »

- an energy loss was expected !
LiF is thermoluminescent @ 300K
(dosimeters...)...
& **trapping** is worse at low T !
- + light emission ? YES, at low T !

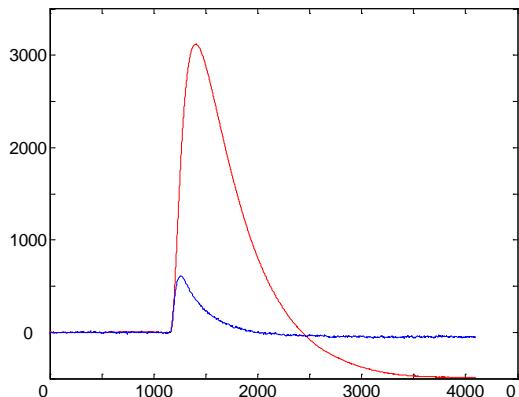


*our paper in NIM A 337 (1993) 95-100

Scintillating bolometers



Ge-NTDs
thermistor

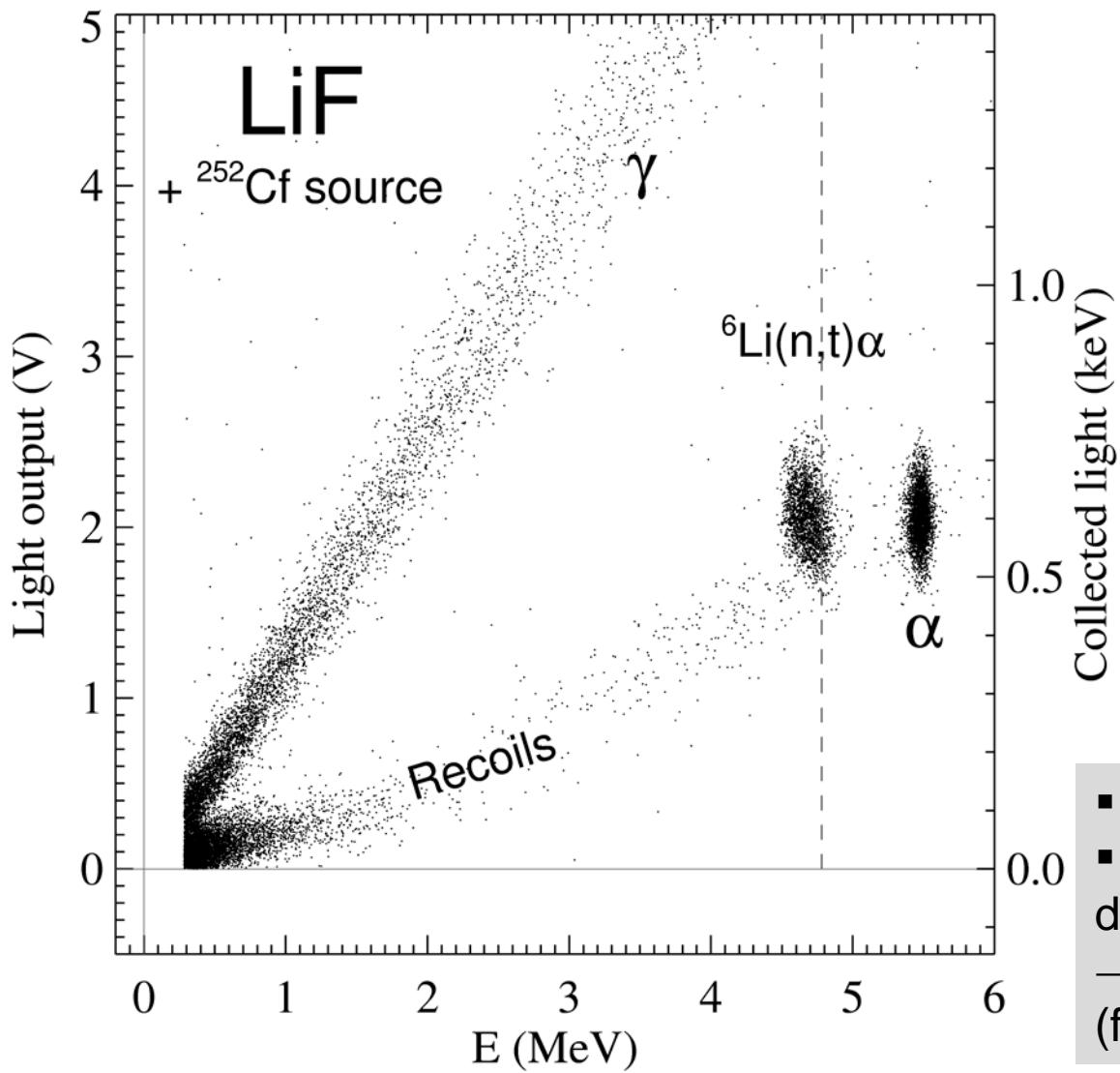


BGO, sapphire, LiF...



LiF scintillating bolometers

A 16g natural LiF (2003)

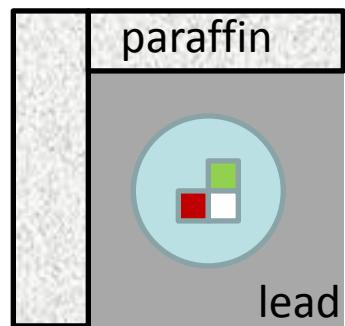


- low light yield for LiF
- but a very good discrimination of particles
→ hope to measure the rarest (fast) neutrons underground

LiF scintillating bolometers

A 32g natural LiF (2007)

20mK



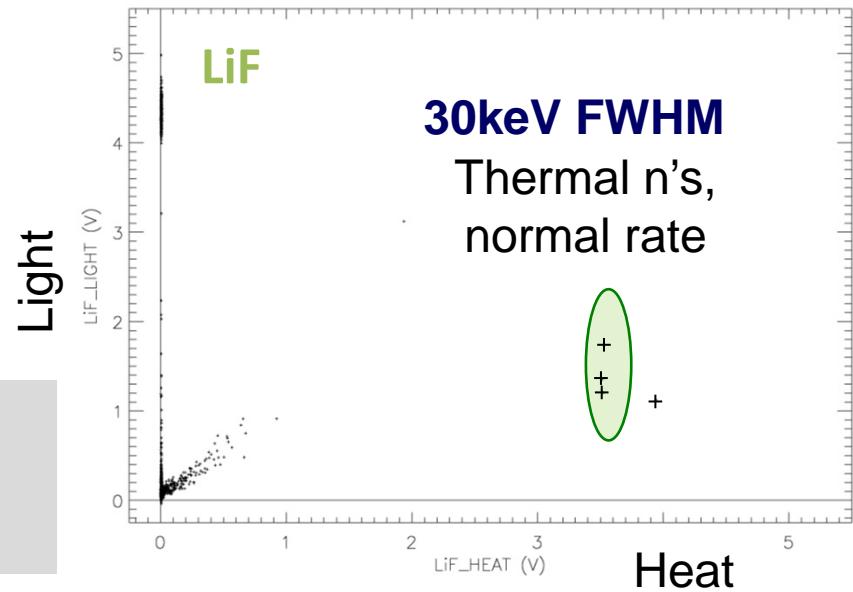
LiF
33g

Backgrounds at Canfranc
underground lab
 \approx 1 night

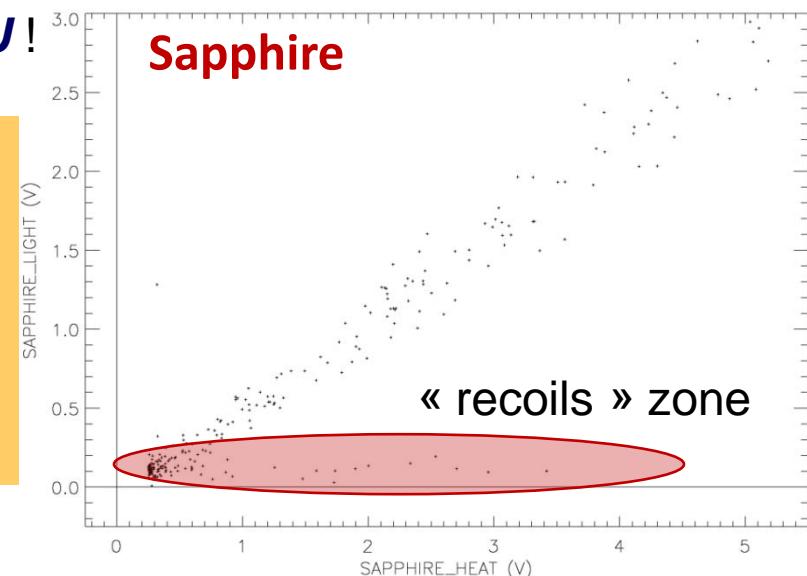
Measuring Neutrons ***IN SITU***!

Sapphire
50g

^{252}Cf calibrations showed that ^6Li enrichment in LiF was needed to conclude about a neutron origin to the background in sapphire...



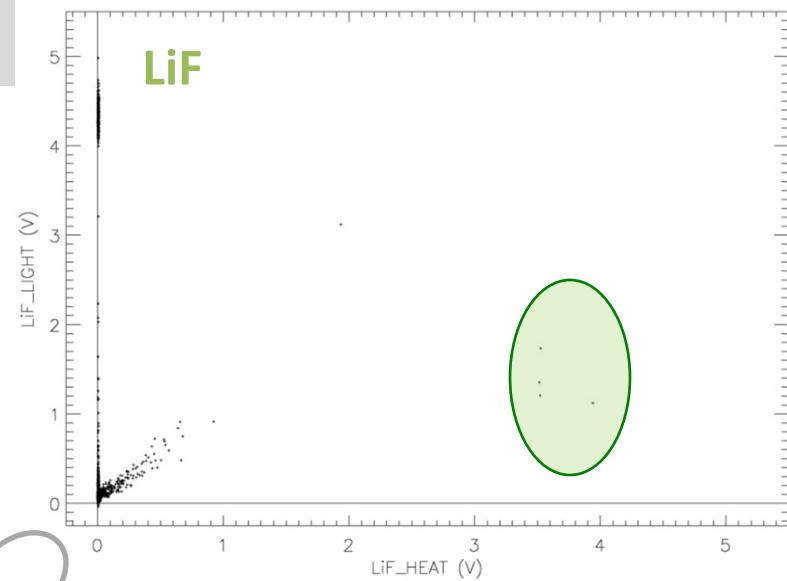
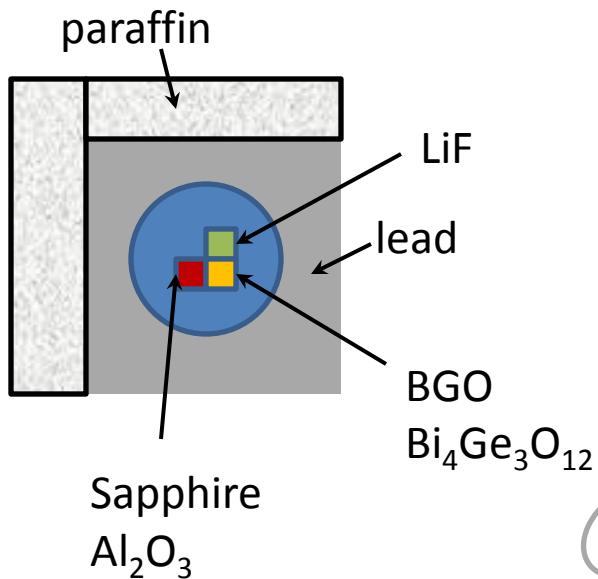
30keV FWHM
Thermal n's,
normal rate



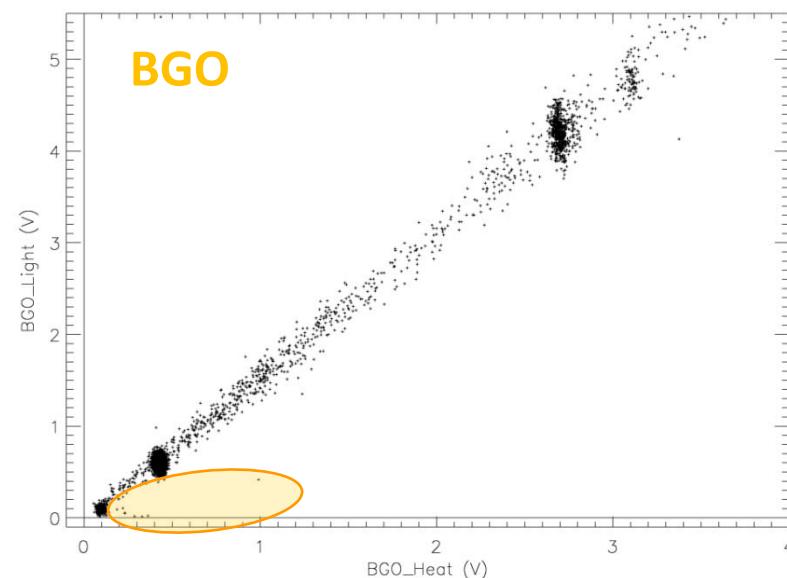
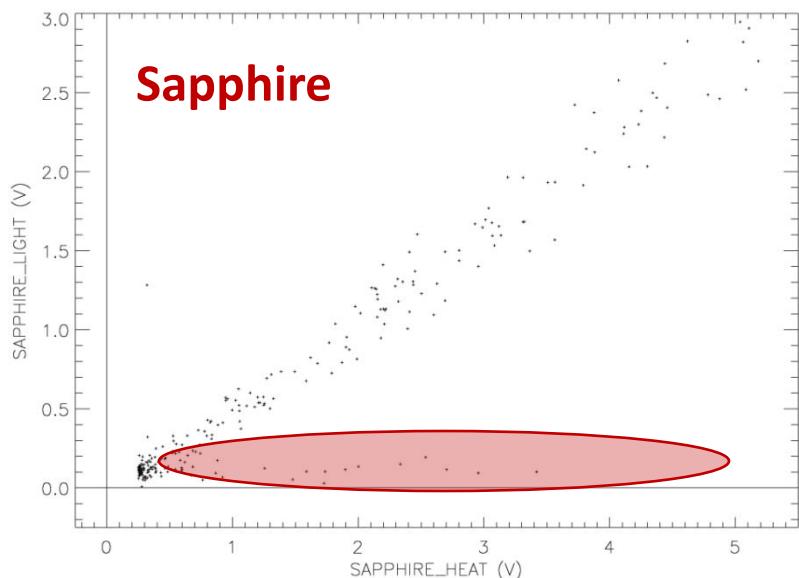
« recoils » zone

Typical backgrounds

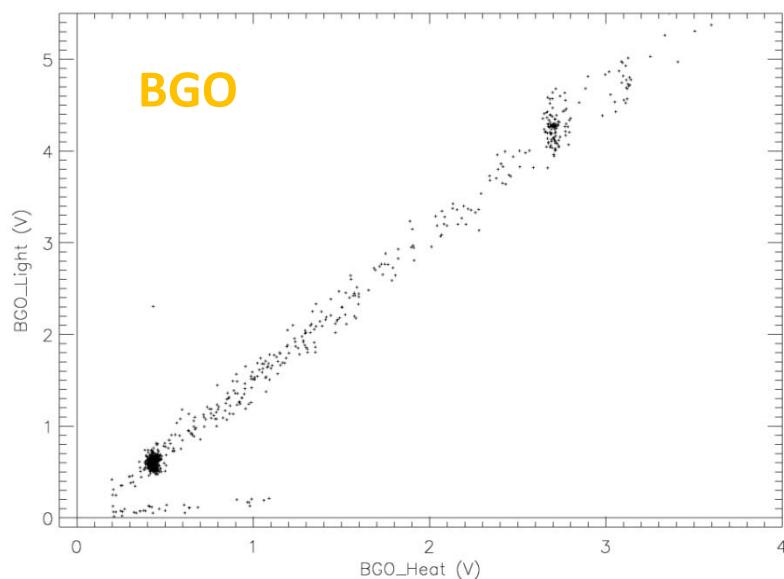
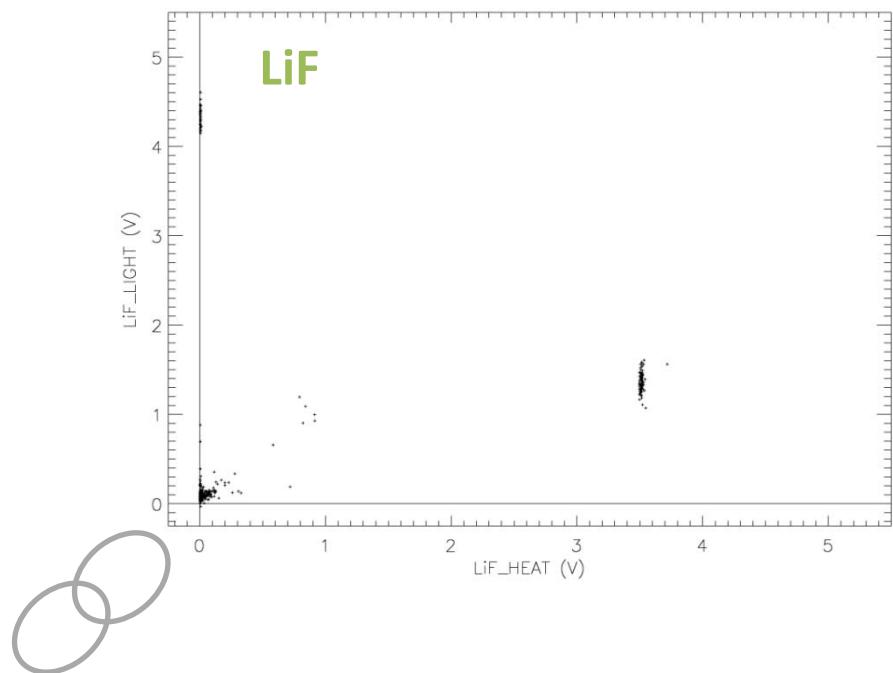
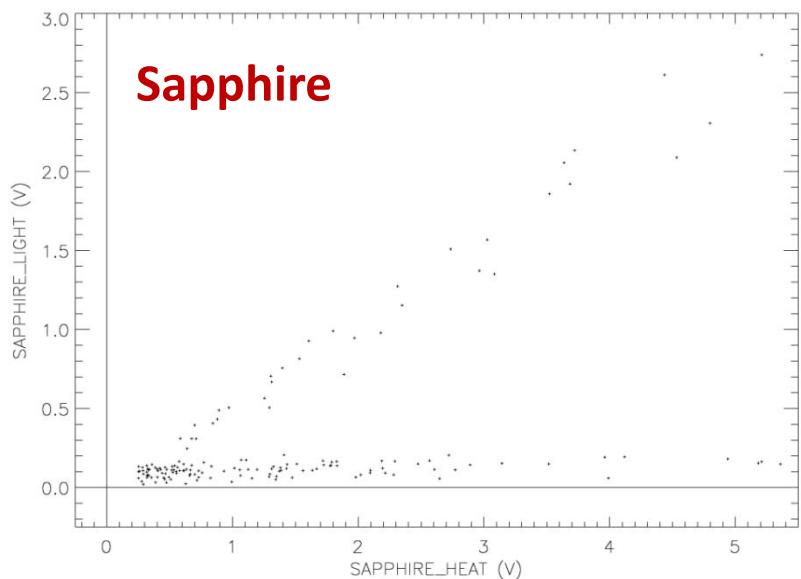
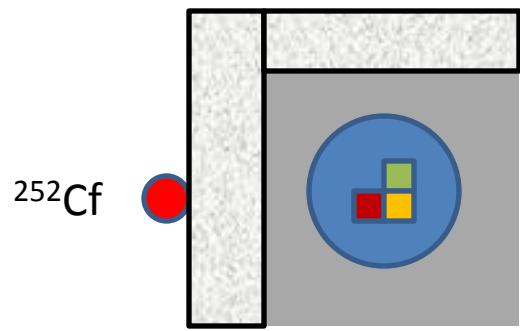
Nov. 2007
≈ 1 night



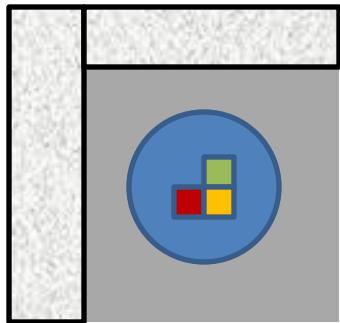
≡ running together



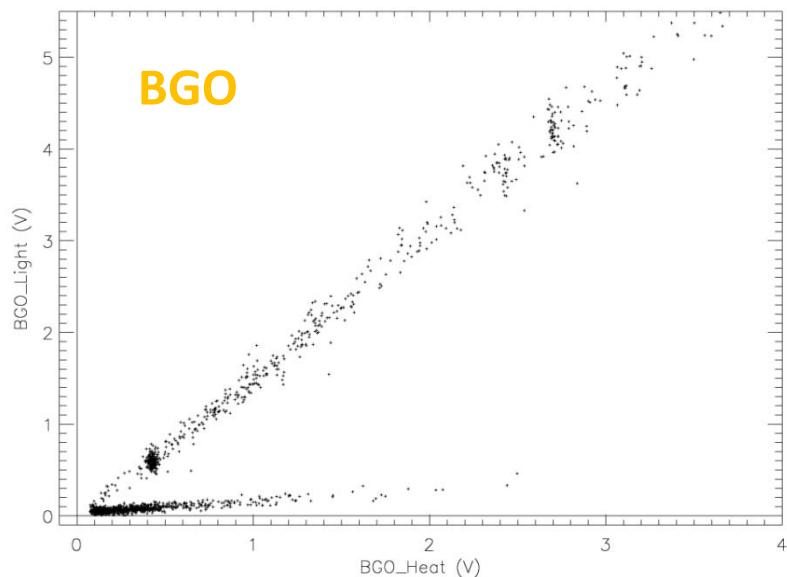
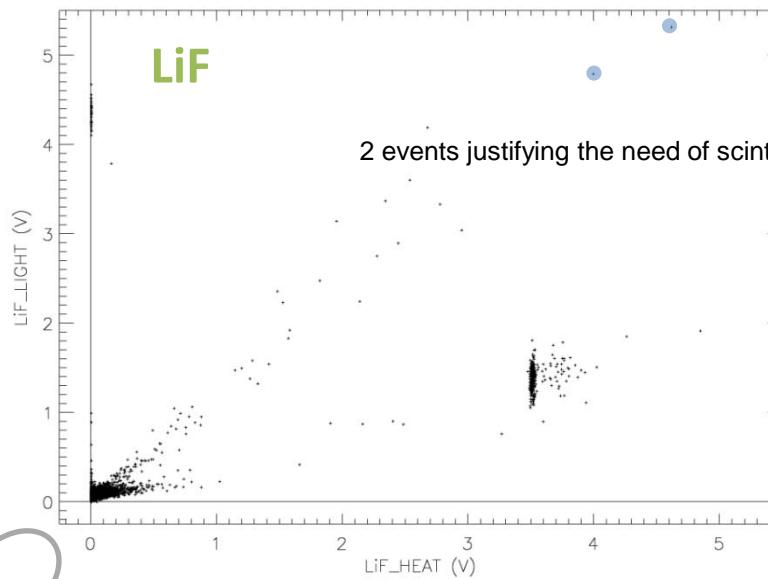
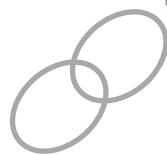
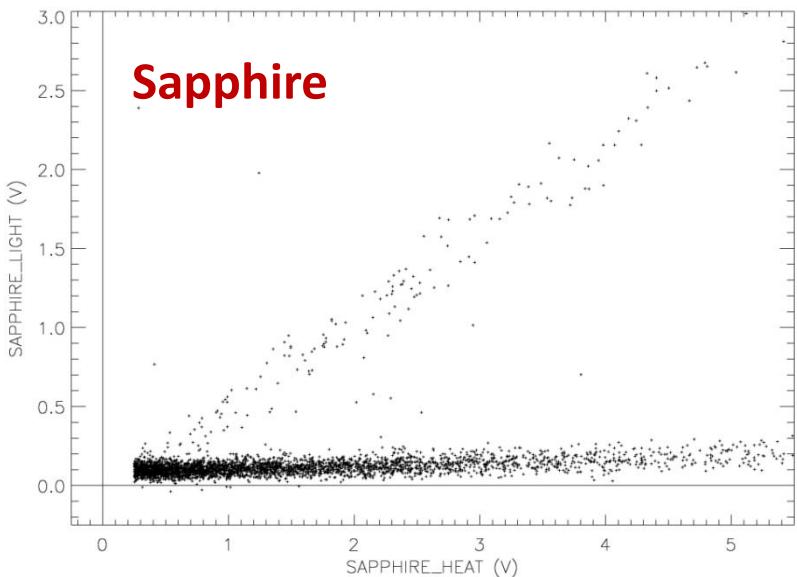
Thermalized neutrons



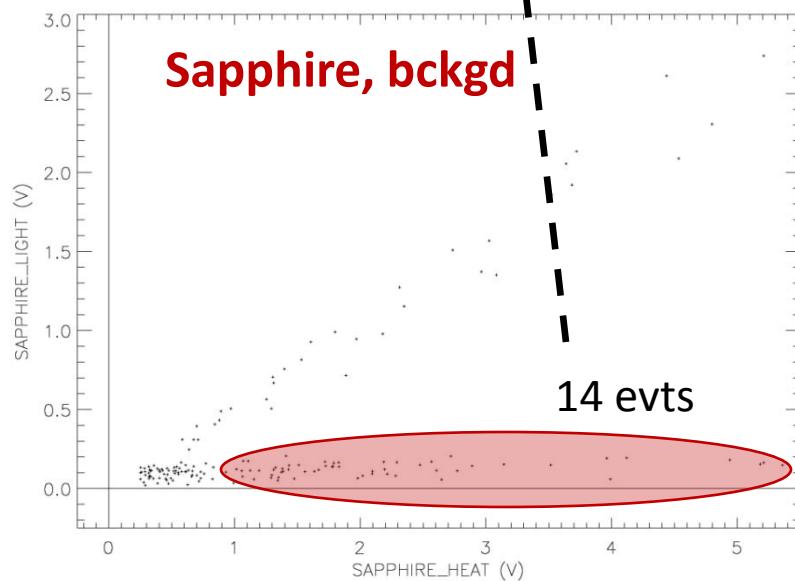
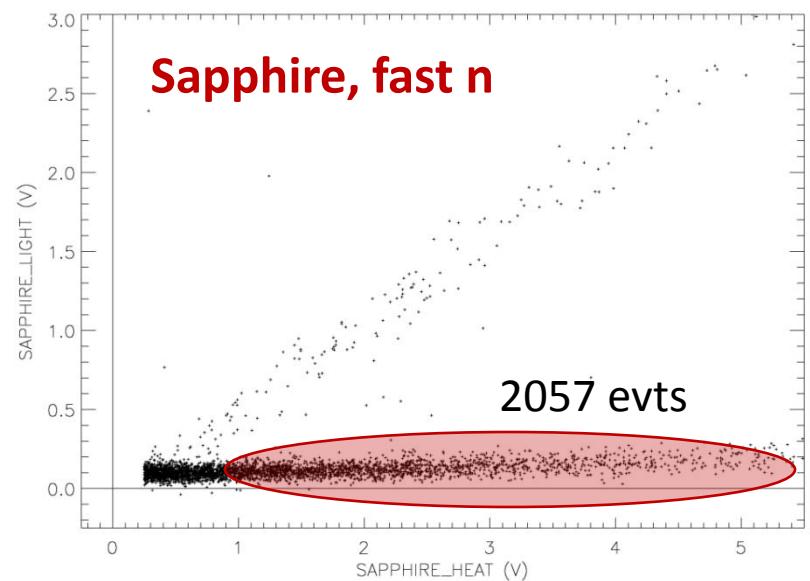
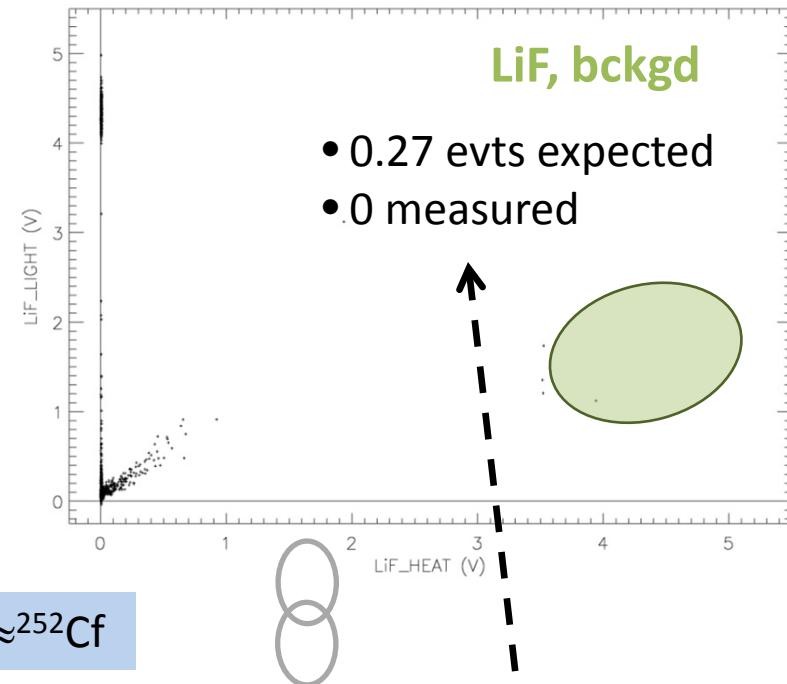
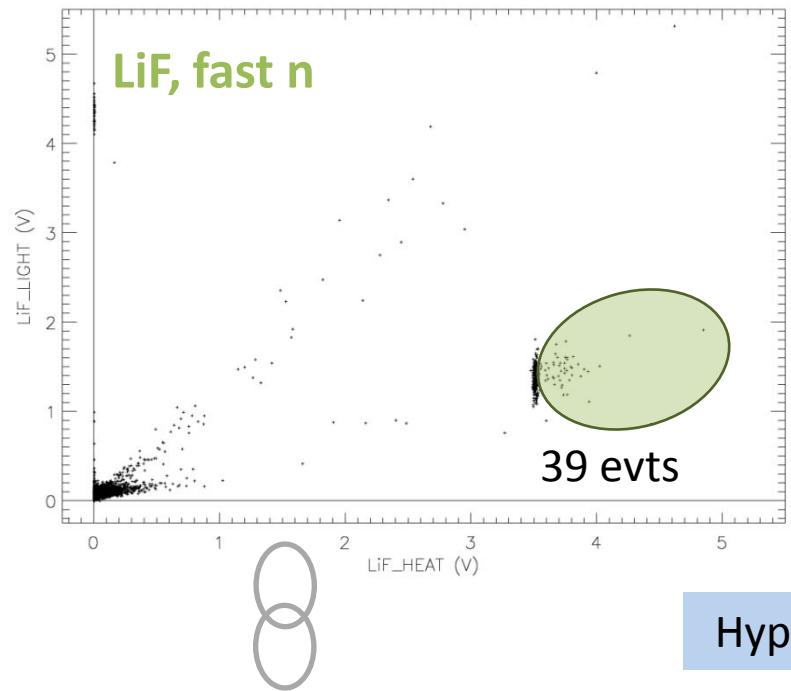
Fast neutrons



^{252}Cf



Learning from LiF & sapphire ?



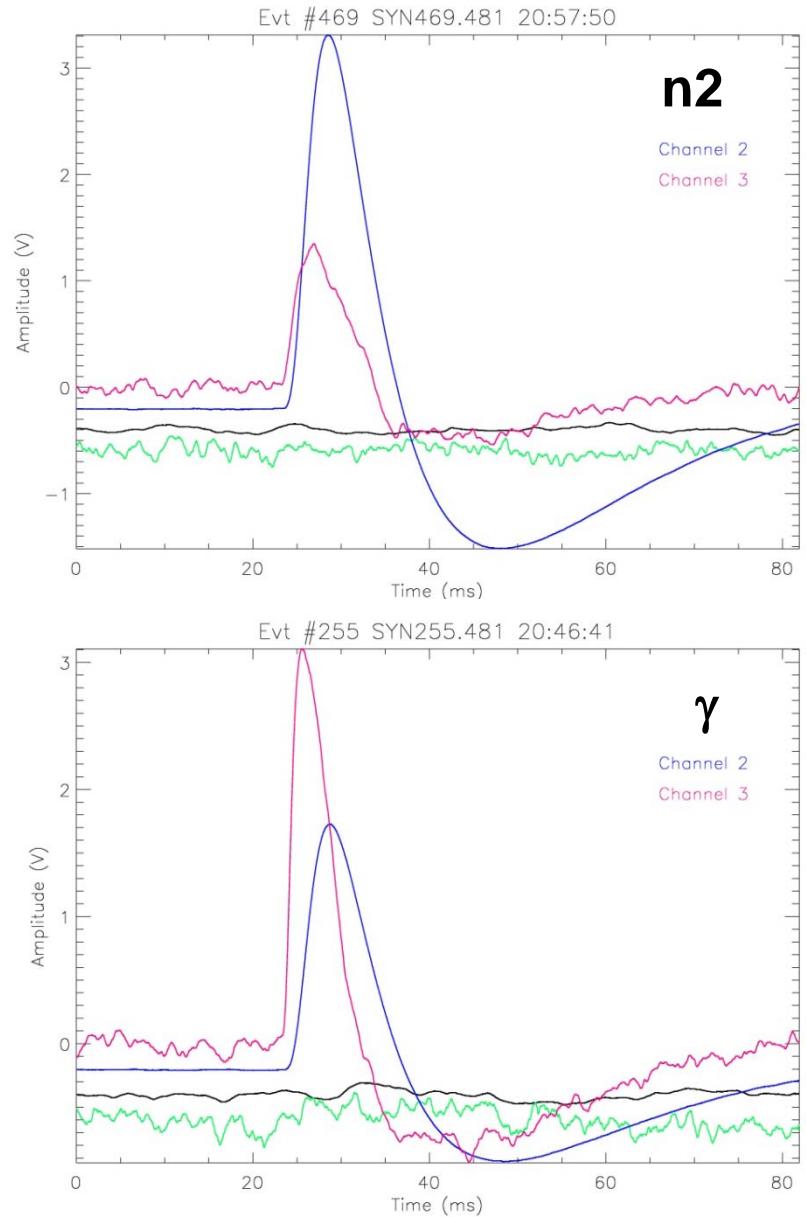
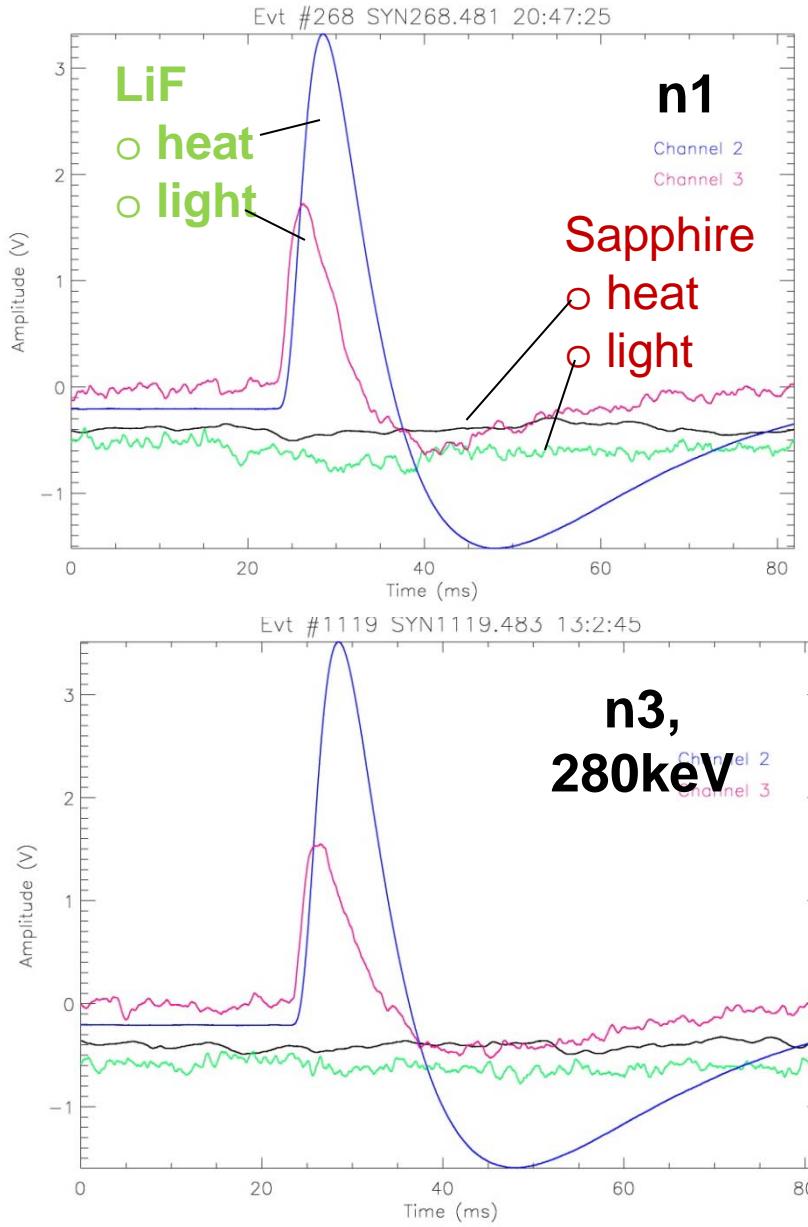
Neutron spectrometry with scintillating bolometers of LiF and sapphire

Noël Coron, Clara Cuesta, Eduardo García, Carlos Ginestra, Johann Gironnet, Pierre de Marcillac, María Martínez, Ysrael Ortigoza, Alfonso Ortiz de Solórzano, Jorge Puimedón, Thierry Redon, Tomás Rolón, María L. Sarsa, Lidia Torres, and José A. Villar

Abstract—Two scintillating bolometers of LiF (33 g) and Al₂O₃ (50 g) at 20 mK, inside a lead shielding at the Canfranc underground laboratory, were irradiated with neutrons from a source of ²⁵²Cf. The analysis of nuclear recoils registered by sapphire and (n,α) captures by ⁶Li shows the feasibility of these cryogenic devices to measure the spectral flux of a neutron field. Data unfolding was done by two models: first one assumes the spectral flux as a function of three parameters and second one as a piecewise constant function defined on energy groups. Latter can be solved by non-negative least squares without additional assumptions on the neutron flux. Both models provide consistent results with the spectra of the observed events in bolometers, giving a fast neutron flux of $\Phi(E > 0.1 \text{ MeV}) = 0.20 \text{ n s}^{-1} \text{ cm}^{-2}$ with a 10% uncertainty after 3 hours of live time. After our analysis, it can be concluded that nuclear recoils in sapphire are more useful than (n,α) captures in LiF for spectrometry of fast neutrons.

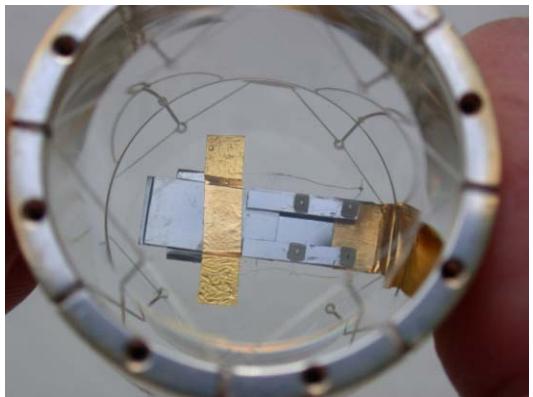
due to low ⁶Li content & confusion with the n-thermal peak

2 thermal n, 1 fast n and 1 γ in the LiF detector

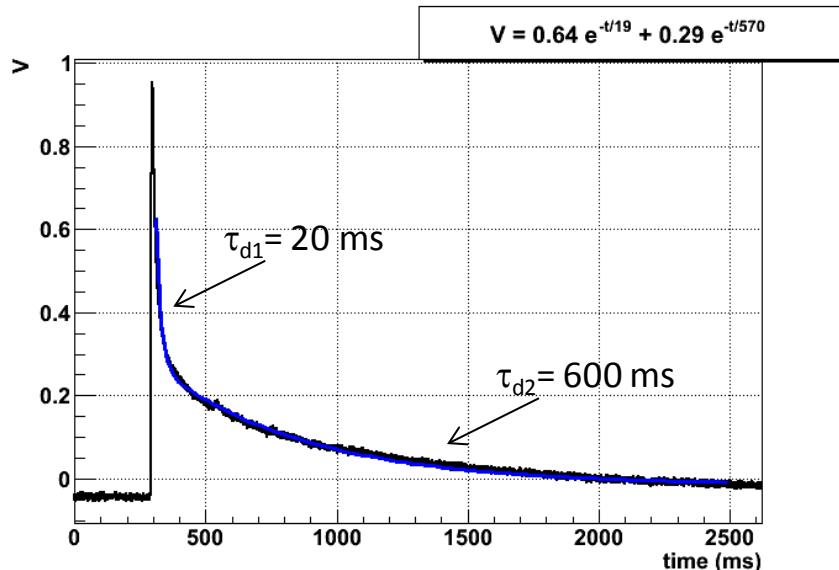
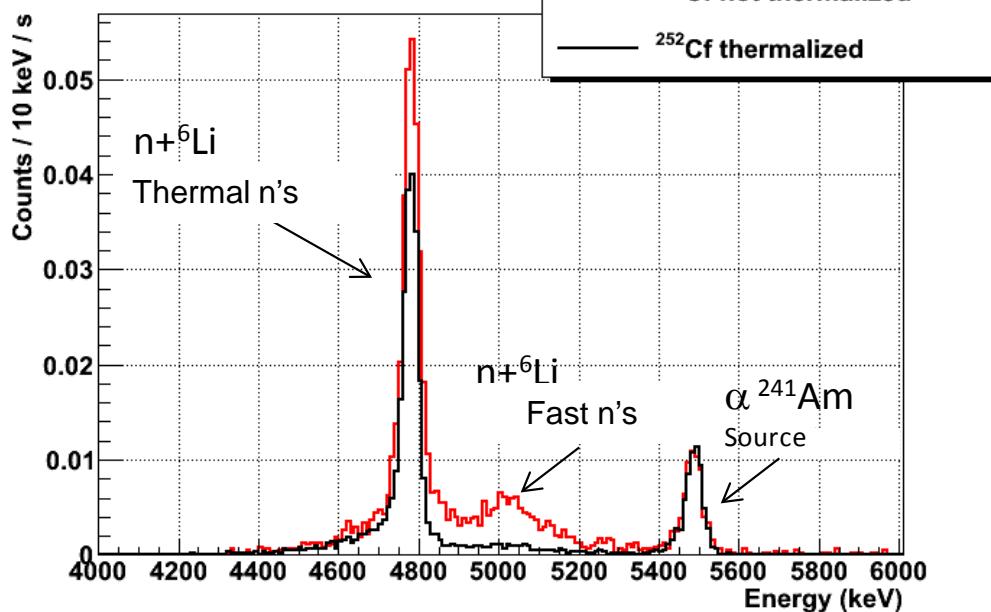


LiF scintillating bolometers

A 32g ${}^6\text{LiF}$ (2011)
aboveground

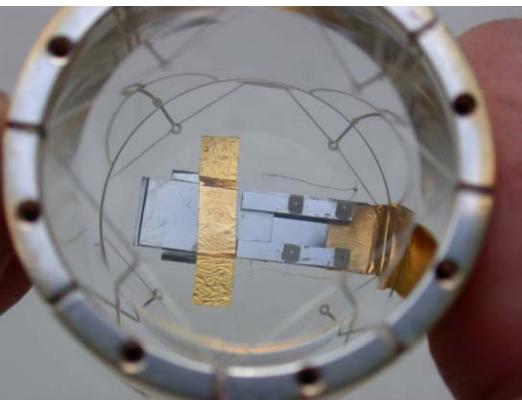


- resolution **50keV FWHM** @ n thermal peak
- target grown at ICMCB (Bordeaux, France)
- escapes from surfaces observed, complicating the analysis !
- anomalous specific heat encountered for a reason not yet known
→ a slow detector, but « fast neutrons sensitive »
- tested underground in 2012



LiF scintillating bolometers

A 32g ${}^6\text{LiF}$ (2012) underground



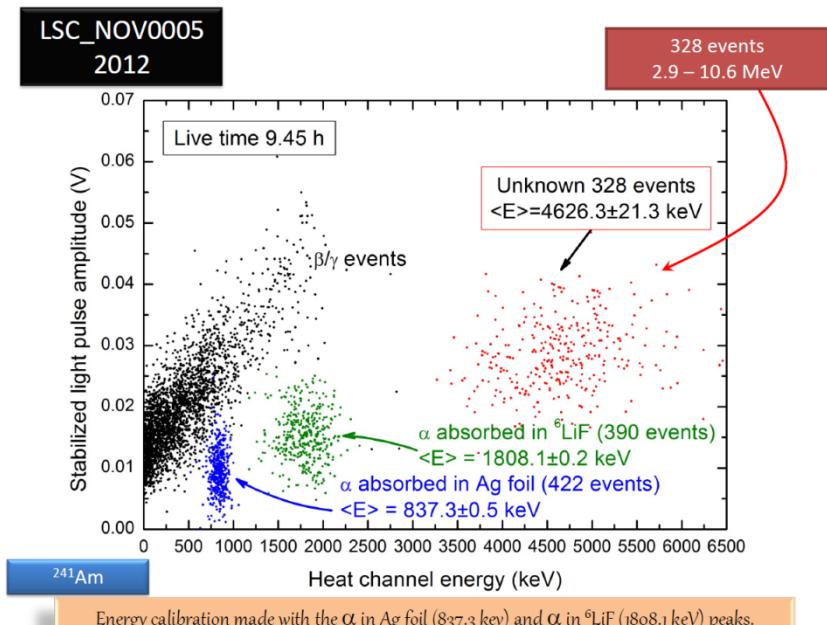
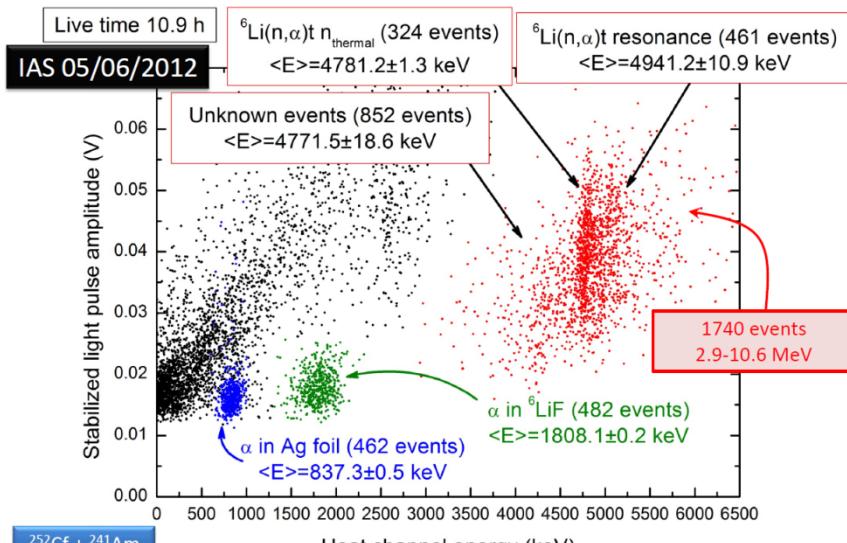
- ✓ ROSEBUD @ LSC 2012 (new lab)
- ✓ Calibration by alphas: ${}^{241}\text{Am} + \text{mylar}$ ($24\mu\text{m}$ foil)
- ✓ irradiating both ${}^6\text{LiF}$ and a Ag spot ($\varnothing \sim 1.6\text{mm}$, $30\mu\text{m}$ thick)

→ An important background is found at the alpha level

Activity~300 mBq/kg

→ could be traced to the original ${}^6\text{LiF}$ powder thanks to LSM gamma measurements: ${}^{238}\text{U} \geq {}^{235}\text{U} \geq {}^{232}\text{Th}$

→ A useless detector for fast neutrons monitoring in DM experiments !



Energy calibration made with the ${}^6\text{Li}(n,\alpha)t$ n_{thermal} (4781.2 keV) and α in ${}^6\text{LiF}$ (1808.1 keV) peaks.

Energy calibration made with the α in Ag foil (837.3 keV) and α in ${}^6\text{LiF}$ (1808.1 keV) peaks.

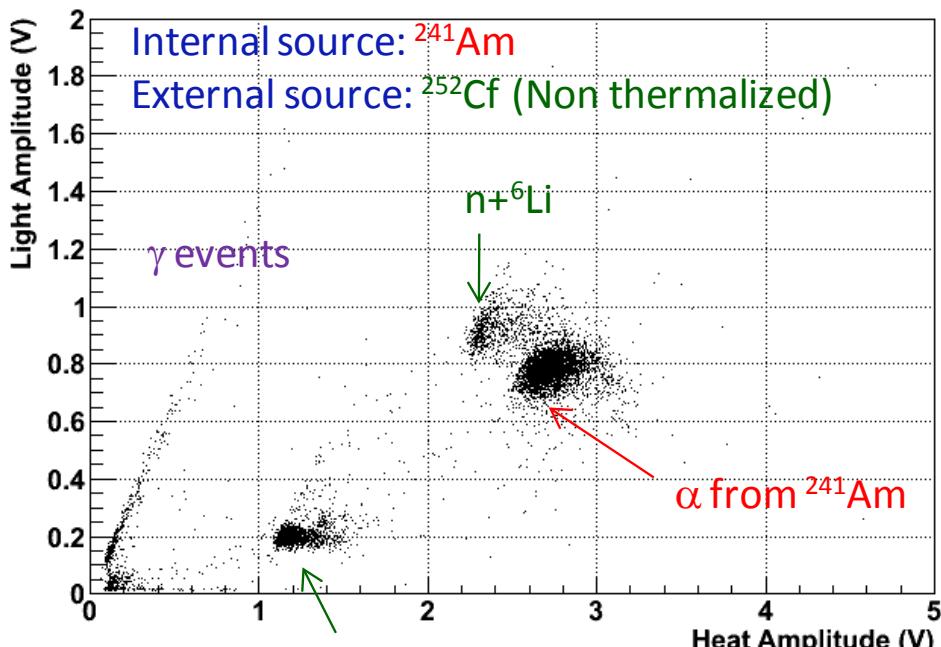
Scintillating bolometers

- poor resolutions observed
- light yield ~ best LiF
- an *a priori* interesting poison effect from ^{157}Gd on thermal n's

LGB

→ another « fresh » sample to be tested

old $^6\text{Li}_6\text{Gd}(^{10}\text{BO}_3)_3$ from ICMCB



$n+^{10}\text{B} \rightarrow \alpha + ^7\text{Li}$ ($Q=2.792$ MeV) (6%)

$n+^{10}\text{B} \rightarrow \alpha + ^7\text{Li} + \gamma$ ($Q=2.31$ MeV) (94%)

Alternative neutron targets

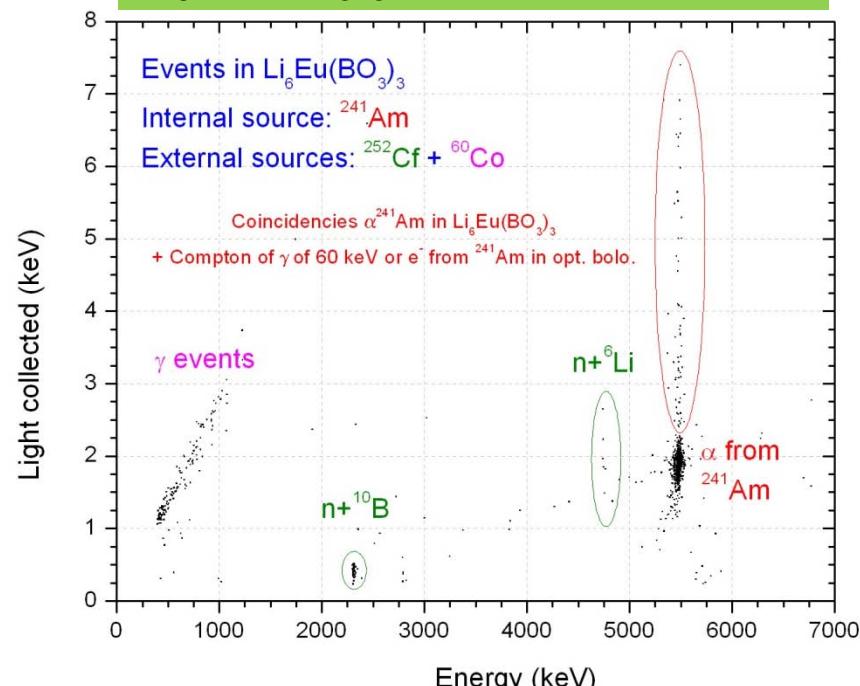


- good resolutions obtained
32 keV FWHM on ^{241}Am
13 keV FWHM at 2.3MeV (^{10}B)
- good light yield

LEB

→ a promising material !

$^6\text{Li}_6\text{Eu}(^{10}\text{BO}_3)_3$ from INR Kiev



→ See also 6.15g LEB detector @ LNGS

Scintillating bolometers

Alternative neutron targets

✓ Li_2MoO_4 crystals

a CSNSM/ICMCB collaboration (CLYMENE project, submitted to ANR):

Czochralski growth of Li_2MoO_4 crYstals for the scintillating boloMeters used in the rare EveNts sEarches



Goals

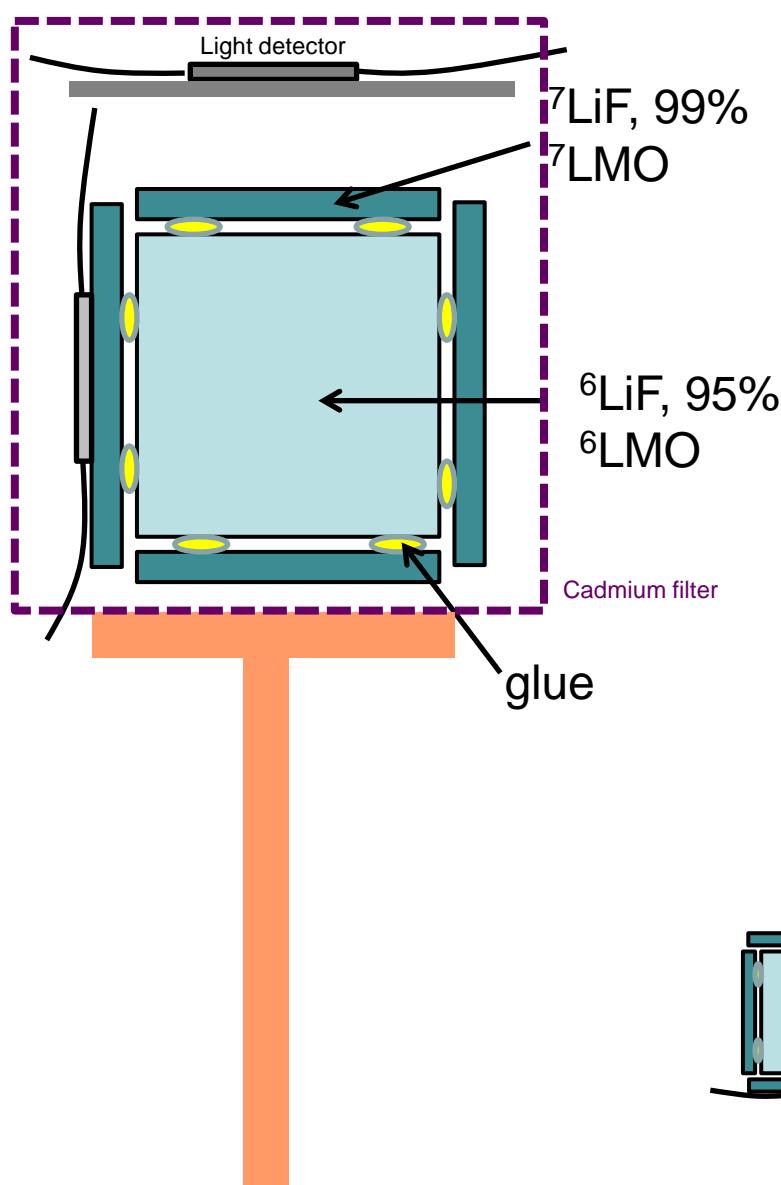
1. $\beta\beta 0\nu$ of ¹⁰⁰Mo...
2. ...with fast neutrons spectroscopy
3. 400g → kg single crystals

1. a ~105 g Li_2MoO_4 crystal grown at ICMCB-Bordeaux.
The most massive LMO grown at birth date (sept 2013),
but cleaved in two parts.
→ M~20g available for detector mounting (2cm cube)
GDMS analysis → ^{40}K content $\leq 3.2 \text{ mBq/kg}$
2. another LMO available (cut → M~57g)
but with a higher ^{40}K content ($42 \pm 10 \text{ mBq/kg}$)

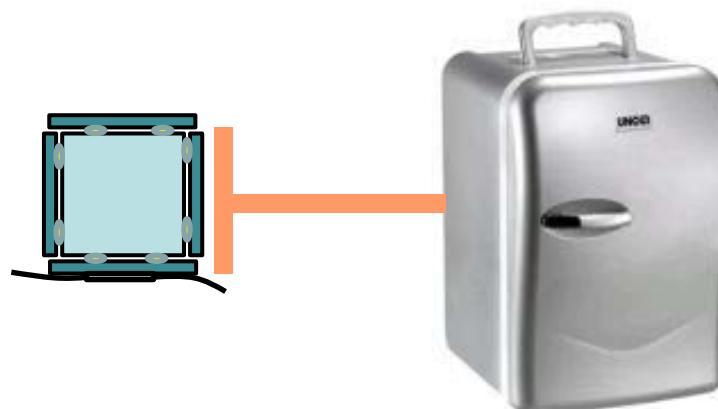
→ other LMO crystals & detectors
see talks by Vladimir Schlegel, Luca Pattavina & Michele Mancuso



Alternative design ?



1. Design a « full containment » detector using a combination of enriched/depleted ^{6}Li material
2. Add a cold finger and reduce all non necessary material in the detector surroundings (for calibration)
3. Conceive a transportable $T < 50\text{mK}$ fast neutron monitor for field measurements



Conclusions...

- ✓ **no hope of substantial fundings for these detectors up to now:** people more prone to invest in the signal (DM, DBD isotope) than in the noise (neutrons) ...
- ✓ but we will have **the fast neutron spectroscopy for free** with $\beta\beta 0\nu$ experiments incorporating Lithium in scintillating bolometers !
- the ability to monitor the neutron background in (future ?) mixed experiments will be appreciated and can be offered as a bonus in the (future ?) discussions
- ✓ **prototypes** still to be built to convince the neutron detectors community
 - simulations needed (MCNPX,...) due to the complexity of neutron interactions
 → choice of the targets, sizes, surroundings
 - necessity of the scintillating part not always obvious
 - simplified and compact cryogenics needed

« UltraSpec » US
ADR + pulsetube 150mK

