Measurement of very low (α,n) cross-sections of astrophysical interest

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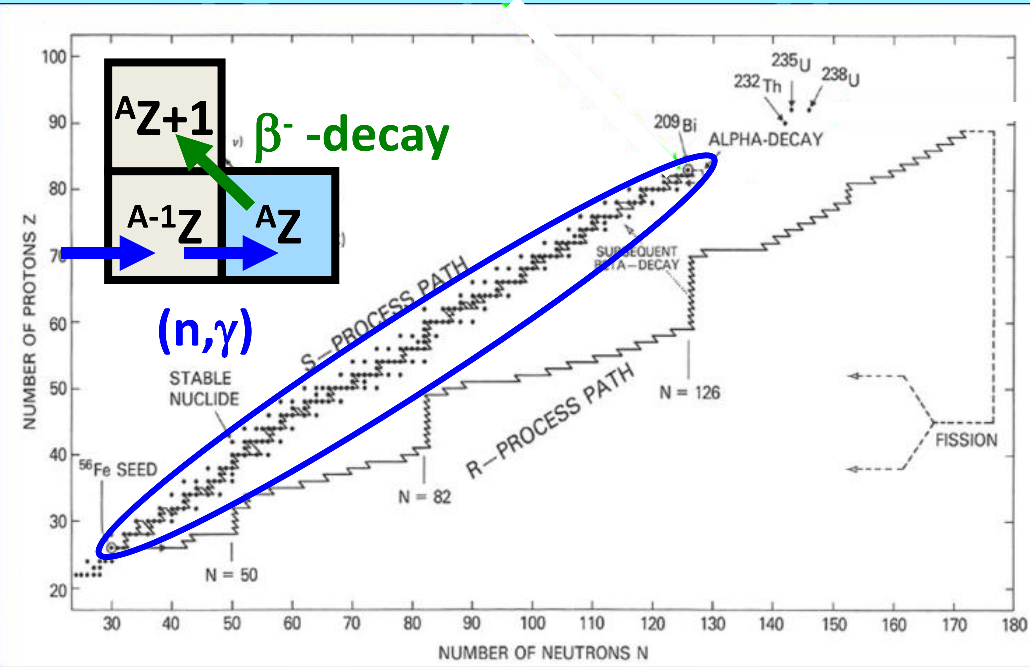
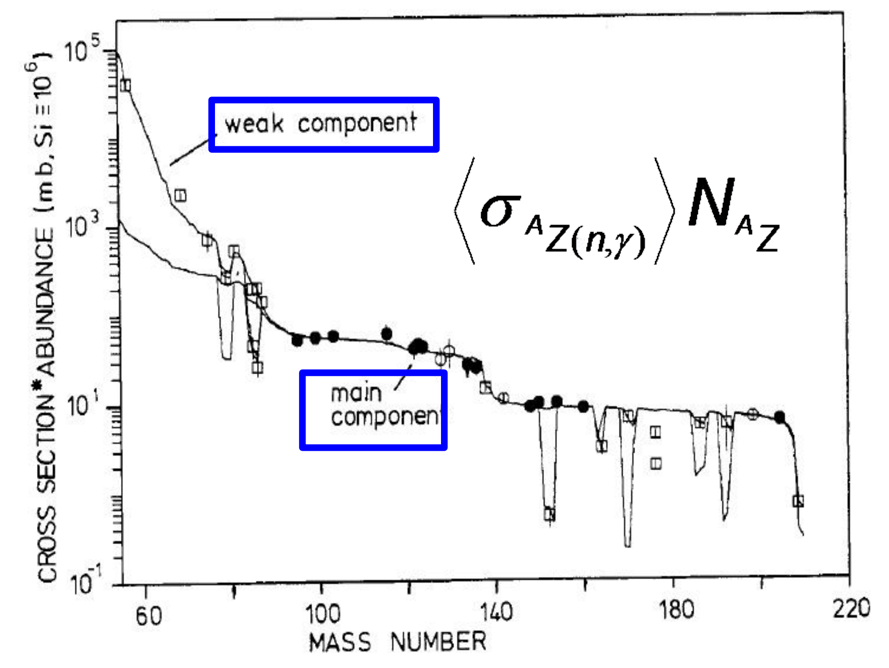
UCM-Madrid: P.Calvo, L.M. Fraile
LSC-Canfranc: I. Bandac

- **The source of neutrons for the slow neutron capture process**
- **The experimental challenge of the ^{13}C,^{22}Ne(α,n) measurements**
- **Neutron background at Canfranc Underground Laboratory (LSC)**
- **Sensitivity limit of the BELEN 4π neutron counter**
- **Conclusions and outlook**

CUNA Workshop II, Canfranc, Feb 29-Mar 1, 2016

Synthesis of the heavy elements: the astrophysical s-process

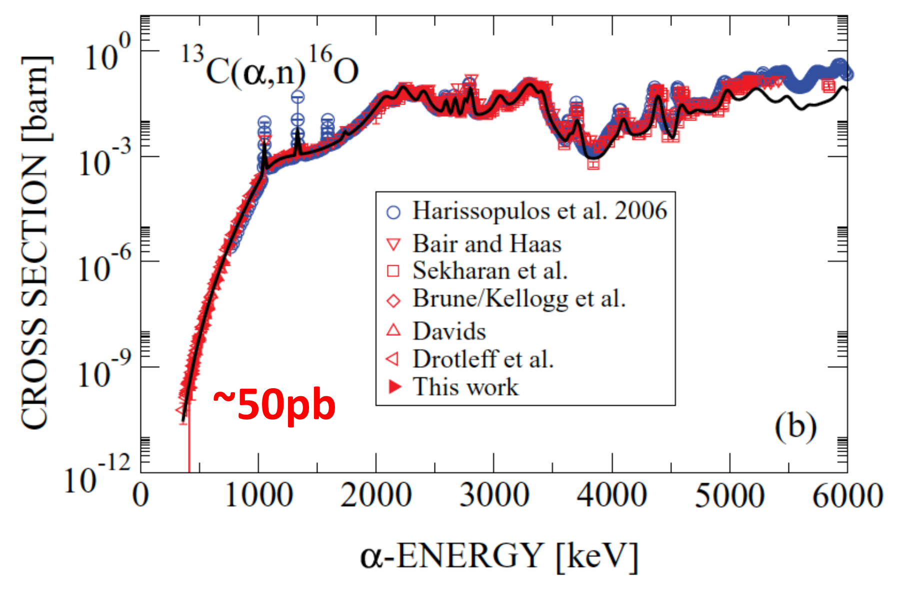


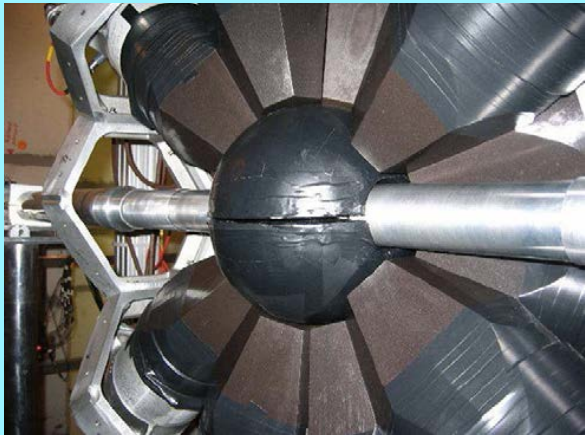


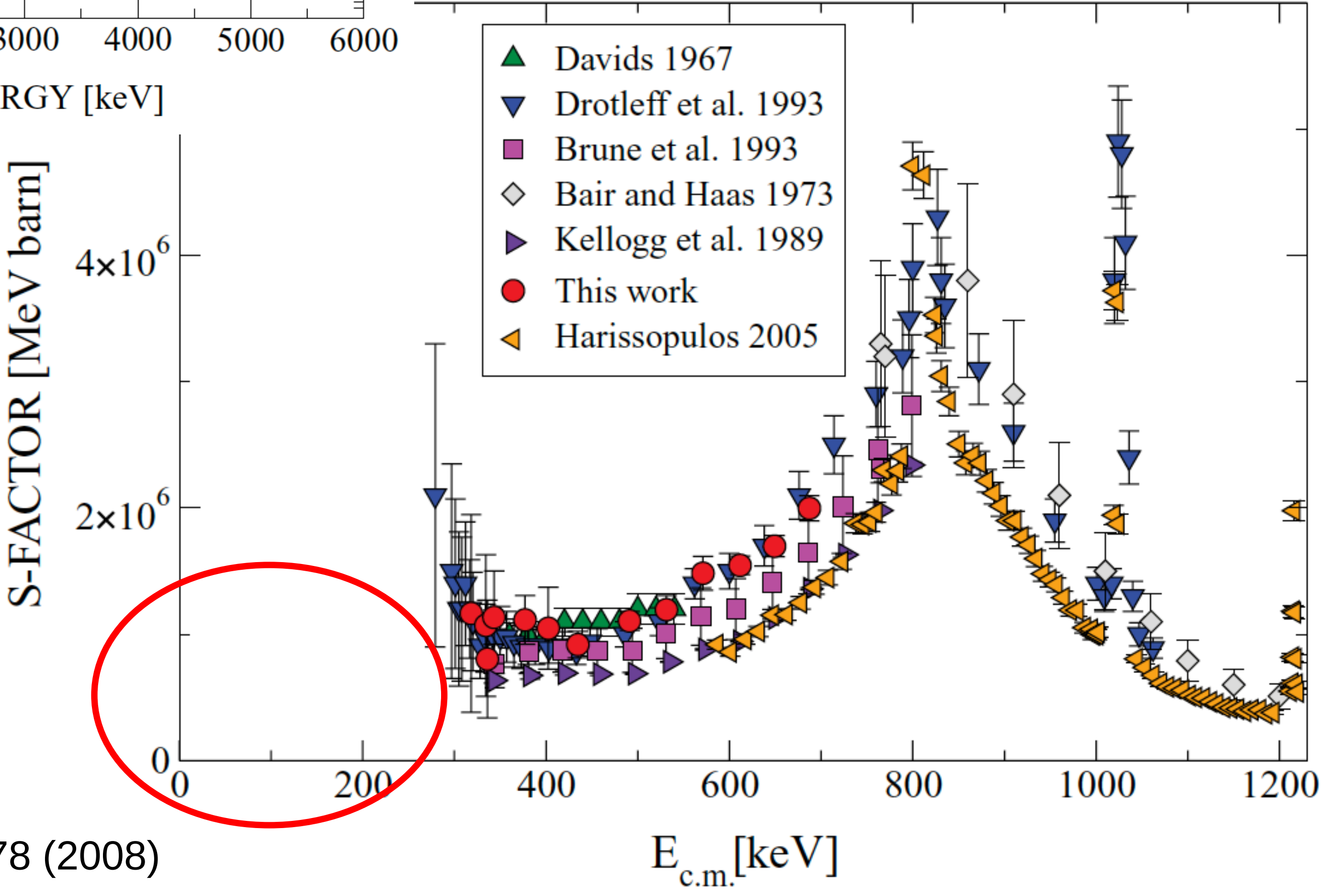
process	T (K)	N_n (cm^{-3})	site	reaction
weak	~3×10^8	~7×10^5	He-core/C-shell burning massive RG stars (>$10M_\odot$)	^{22}Ne(α,n)
main	~10^8 ~3×10^8	~10^8 ~10^{10}	He/C/O-intershell pulses He-flash AGB stars (1-$8M_\odot$)	13C(α,n) 22Ne(α,n)

90%
10%

$^{13}C(\alpha,n)^{16}O$



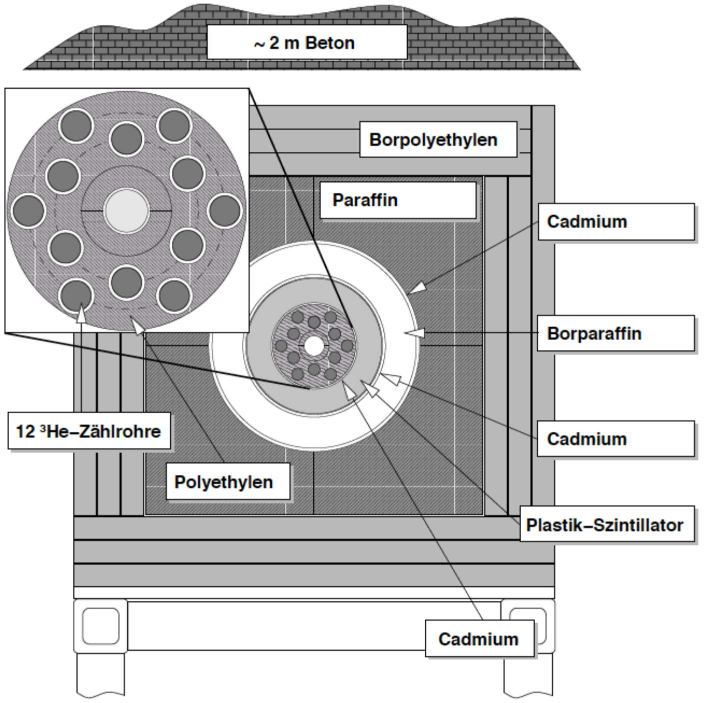




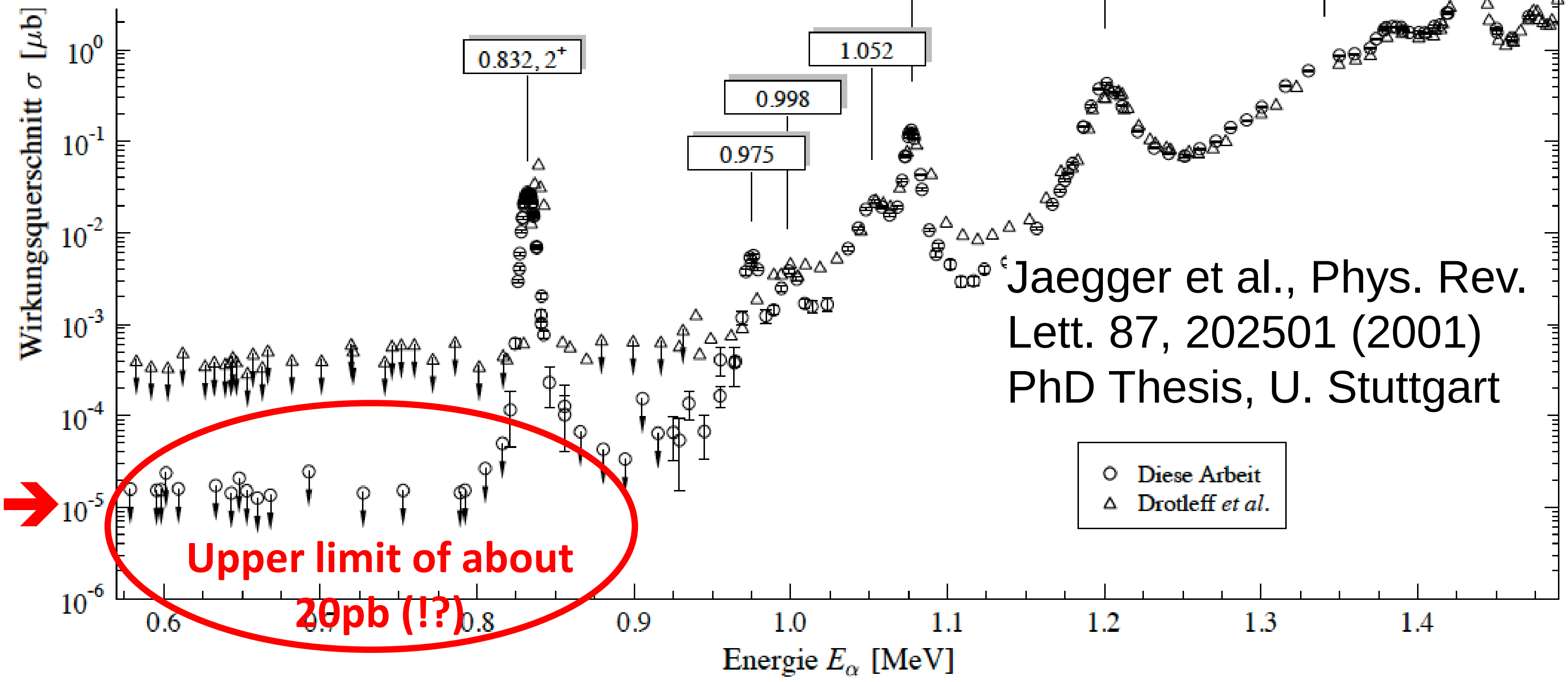
Heil et al., Phys. Rev. C 78 (2008) 025803

The “best” setup until now

With an active veto they were able to reduce neutron background to 0.028 n/s



$^{22}Ne(\alpha,n)^{25}Mg$



Jaegger et al., Phys. Rev. Lett. 87, 202501 (2001)
PhD Thesis, U. Stuttgart

2.8×10^{-2} s^{-1} →

Upper limit of about 20pb (!?)

Expected rates

$$N_n\left[s^{-1}\right]=\sigma\left[barn\right]\cdot n\left[barn^{-1}\right]\cdot i\left[s^{-1}\right]$$

σ = **10^{-12} barn**
n = 10^{-6} barn^{-1} : **22 µg/cm^2 (^{13}C)** or **$\Delta E \approx$ 50 keV (^{22}Ne)**
i = 10^{15} s^{-1} : **160 particle-µA** α-beam

N_n (1pb) = 10^{-3} s^{-1} = 3.6 hour^{-1}

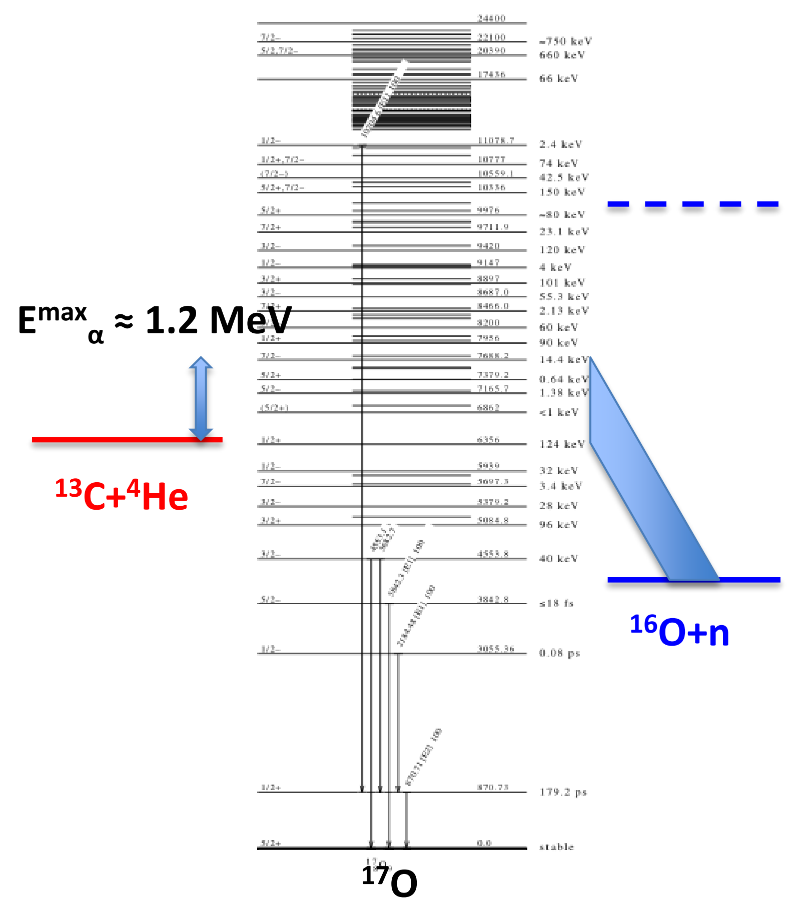
Detection efficiency must be added. For ε_n=50%:

N_n (1pb) = 5×10^{-4} s^{-1} = 1.8 hour^{-1}

Expected neutron energies

$^{13}C(\alpha,n)^{16}O$

Q= 2.216 MeV



$E^{max}_{\alpha} \approx 1.2$ MeV

$^{13}C+^{4}He$

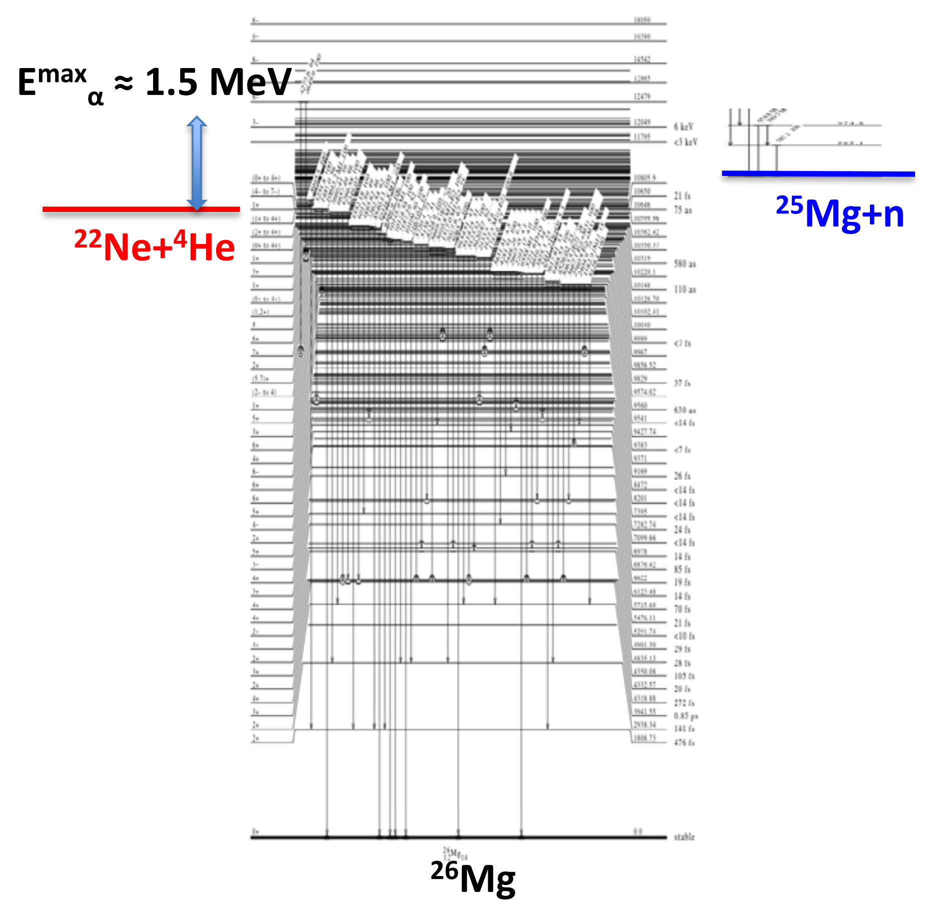
$^{16}O+n$

^{17}O

$E_n = 2.2 – 3.5$ MeV

$^{22}Ne(\alpha,n)^{25}Mg$

Q= -0.478 MeV



$E^{max}_{\alpha} \approx 1.5$ MeV

$^{22}Ne+^{4}He$

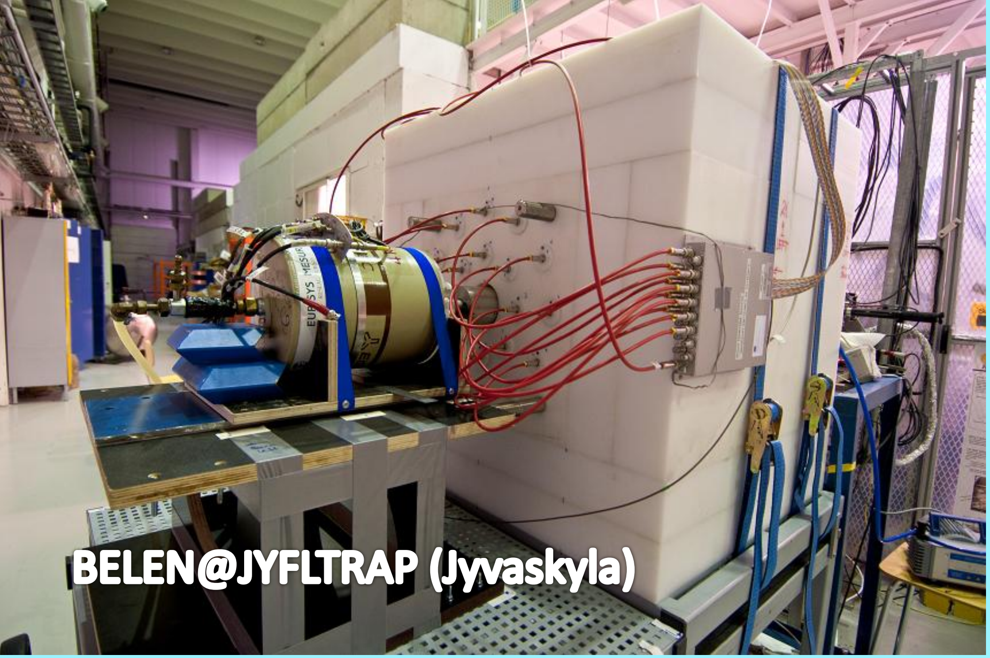
$^{25}Mg+n$

^{26}Mg

$E_n < 1$ MeV

Detection devices in the past:

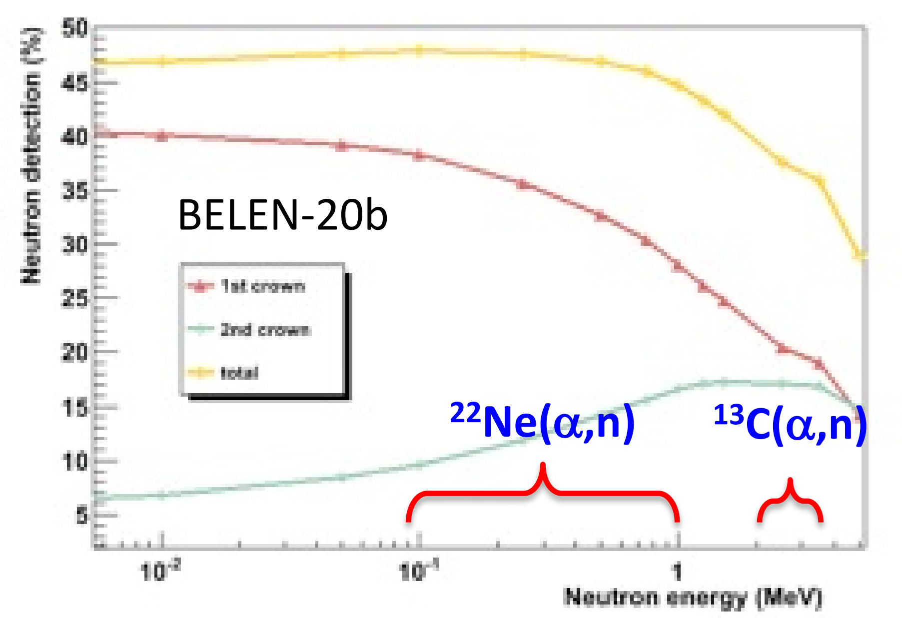
- **Organic scintillator (stilbene)**: Davids-1968
- **Time-of-flight detector (plastic) + γ-ray detector (NaI)**: Ashery-1969
- **Graphite moderator sphere + BF_3 tubes**: Bair-1973, Haas-1973
- **γ-ray detector (Ge) + ^{3}He spectrometer**: Wolke-1989
- **^{3}He spectrometer**: Harms-1991
- **Polyethylene moderator matrix + ^{3}He tubes**: Drotleff-1991, Drotleff-93, Brune-1993, Giessen-93, Jaegger-2001, Harrisopulos-2005
- **Cd-loaded neutron converter + 4π γ-ray calorimeter (BaF_2)**: Heil-2008



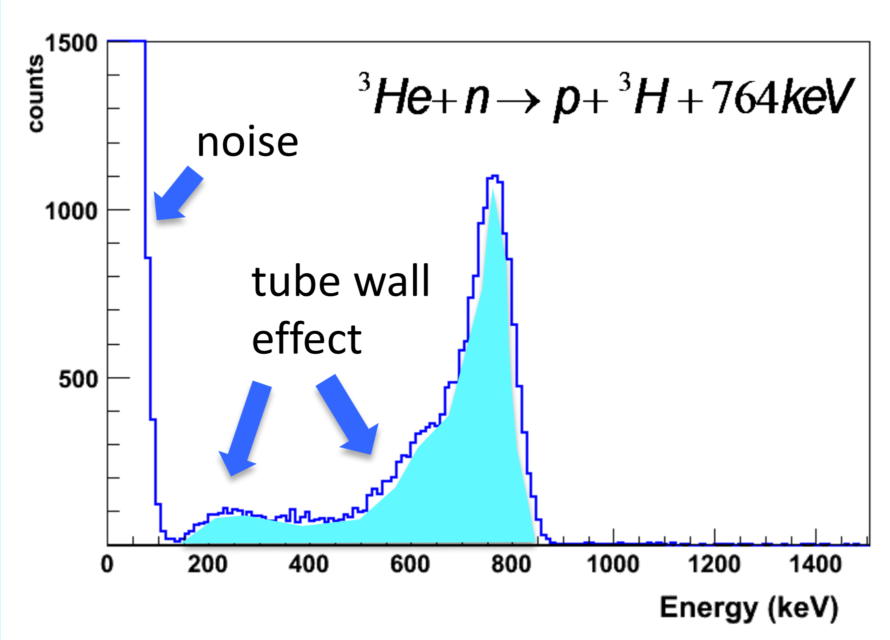
BELEN detector used for β-delayed neutron measurements at JYFLTRAP and GSI-FRS (updated version is BELEN-48 see talk F. Calviño)

BELEN-20 (UPC-IFIC):
PE: 90cm×90cm×80cm, R_{hole}= 5.5 cm
^{3}He-tube: 20 atm, ⃠2.54cm×60cm
8 counters (R_{1st} = 9.5 cm)
12 counters (R_{2nd} = 14.5 cm)

MCNPX calculated efficiency

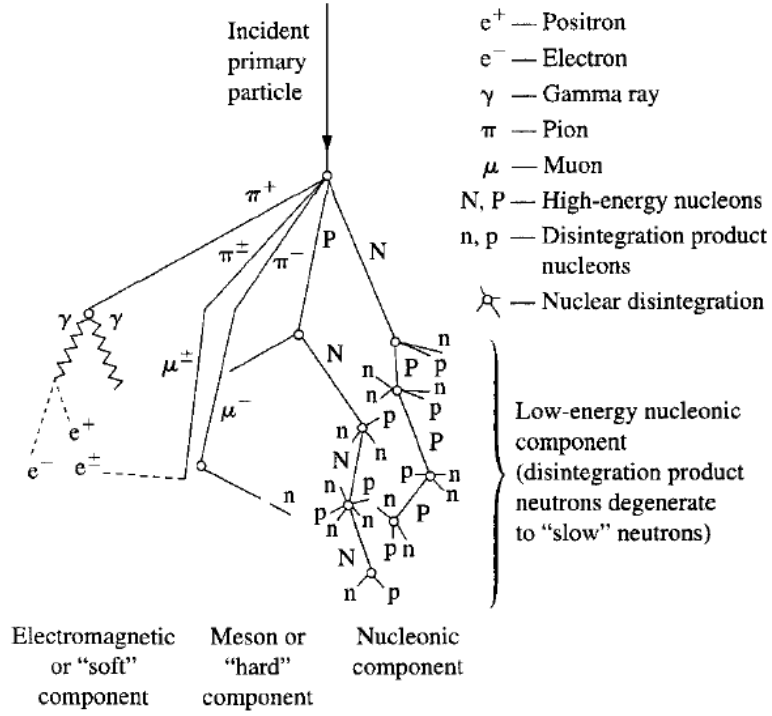


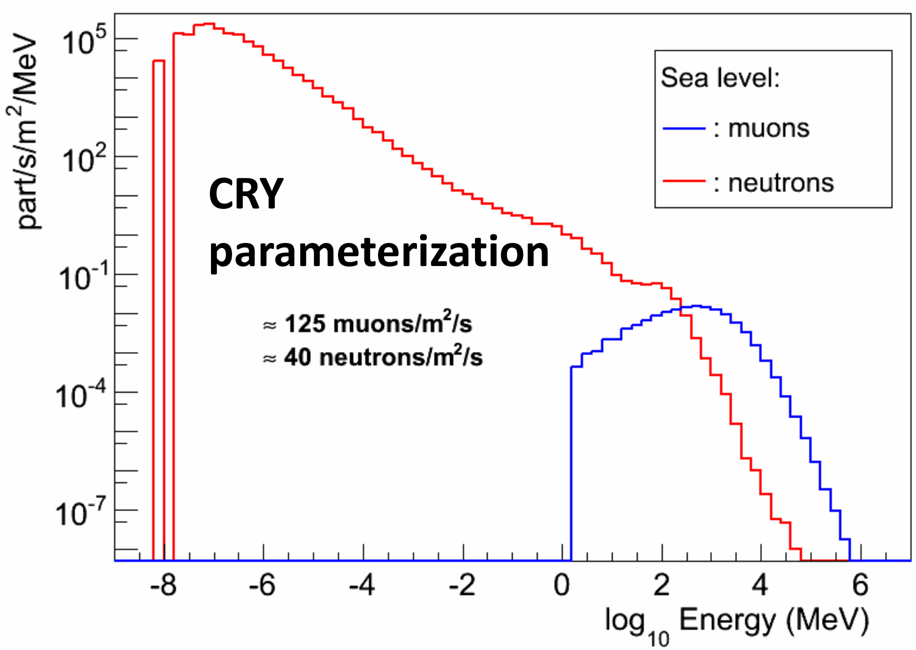
^{3}He-tube response to thermalized neutrons



J. Agramunt et al., NIMA807 (2016) p69

Neutron background above ground



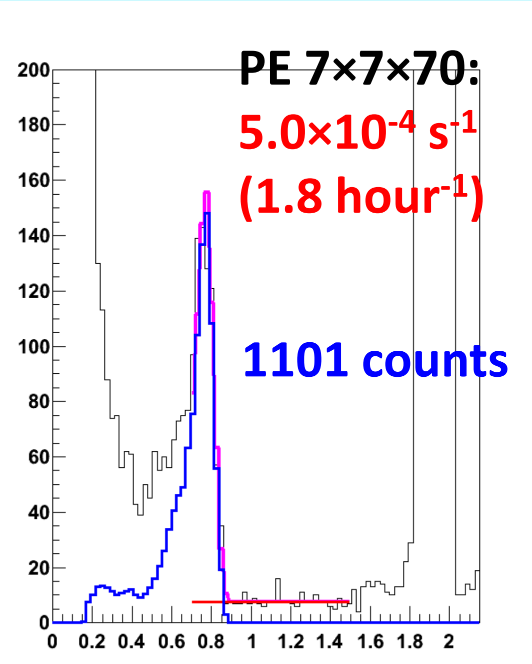


- The magnitude, composition and energy distribution of the cosmic ray field depends on altitude, geo-coordinates and datum
- Neutrons above ground are mainly coming from muon spallation and muon capture
- The neutron field at sea level is severely altered by the interaction with the environment

≈4×10^{-3} n/cm^2/s

Measurement of LSC neutron background

M.D. Jordan et al., Astrop. Phys. 42 (2013) 1

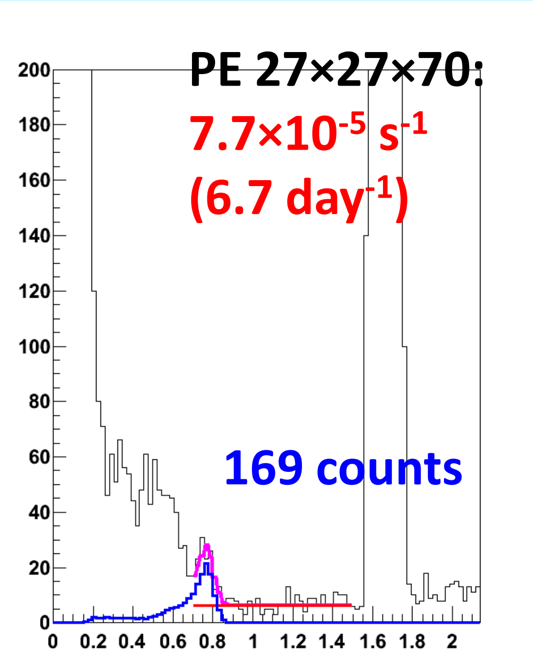


PE 7×7×70:

$5.0\times10^{-4}\ \mathrm{s}^{-1}$

$(1.8\ \mathrm{hour}^{-1})$

1101 counts



PE 27×27×70:

$7.7\times10^{-5}\ \mathrm{s}^{-1}$

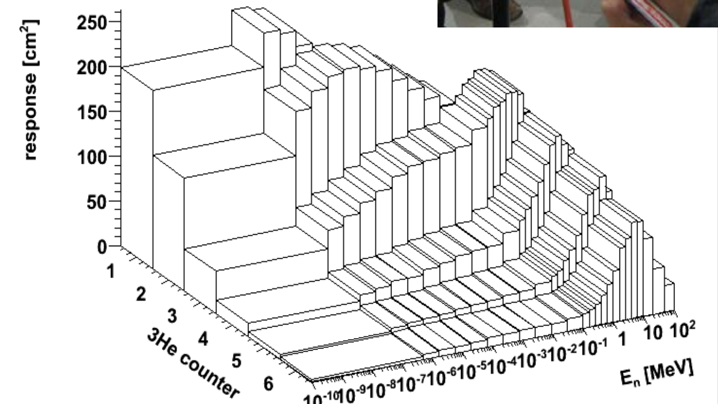
$(6.7\ \mathrm{day}^{-1})$

169 counts

t_{meas} = 25.3 days

Six BELEN ^{3}He tubes with different size PE moderator

Same principle as Bonner Sphere Spectrometer

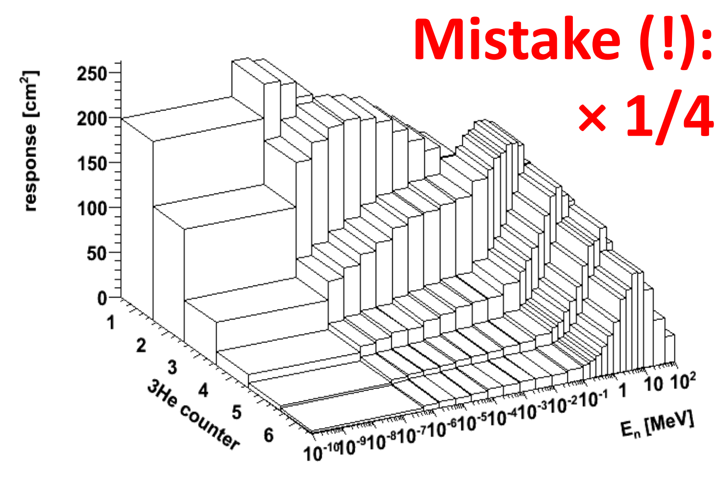


Efficiency vs. neutron energy

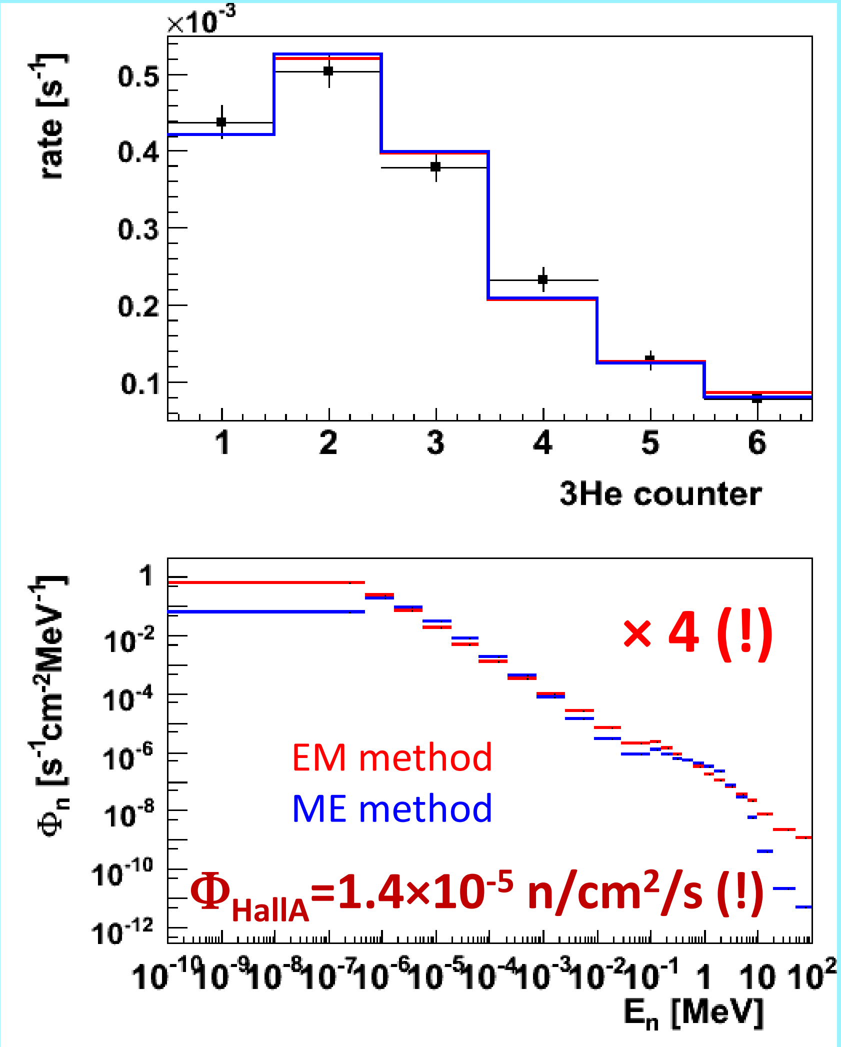
Relation between rate in one detector and the flux at a given energy:

$$n_i = \sum_i \varepsilon_{ij} \Phi_j$$

i: detector #
j: energy bin



Mistake (!):
× 1/4



× 4 (!)

EM method
ME method

Φ_{HallA}=1.4×10^{-5} n/cm²/s (!)

Solution of the inverse problem:

Expectation-maximization method (EM):

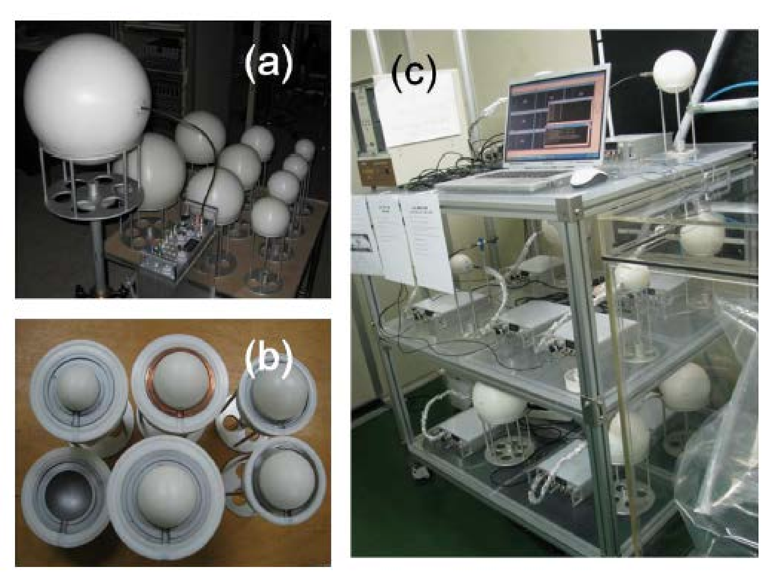
$$\Phi_j^{(s+1)} = \frac{1}{\sum_i \varepsilon_{ij}} \sum_i \frac{\varepsilon_{ij} \Phi_j^{(s)} n_i}{\sum_k \varepsilon_{ik} \Phi_k^{(s)}}$$

Maximum-Entropy method (ME)

$$\Phi_j^{(s+1)} = \Phi_j^{(s)} \exp\left(\frac{2}{\lambda} \sum_i \varepsilon_{ij} \left(n_i - \sum_k \varepsilon_{ik} \Phi_k^{(s)} \right) \Big/ \sigma_i^2 \right)$$

Neutron background measurement at YangYang underground laboratory in Korea

H. Park et al., Appl. Rad. & Isot. 81 (2014) 302

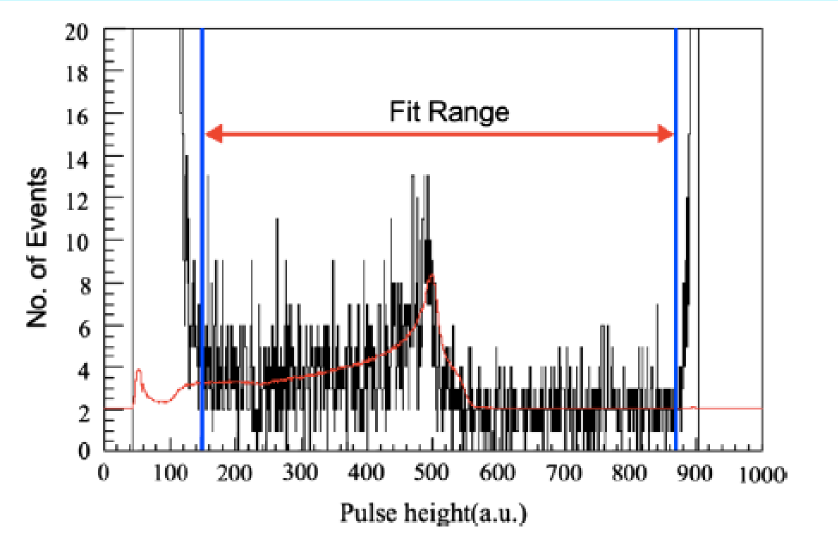


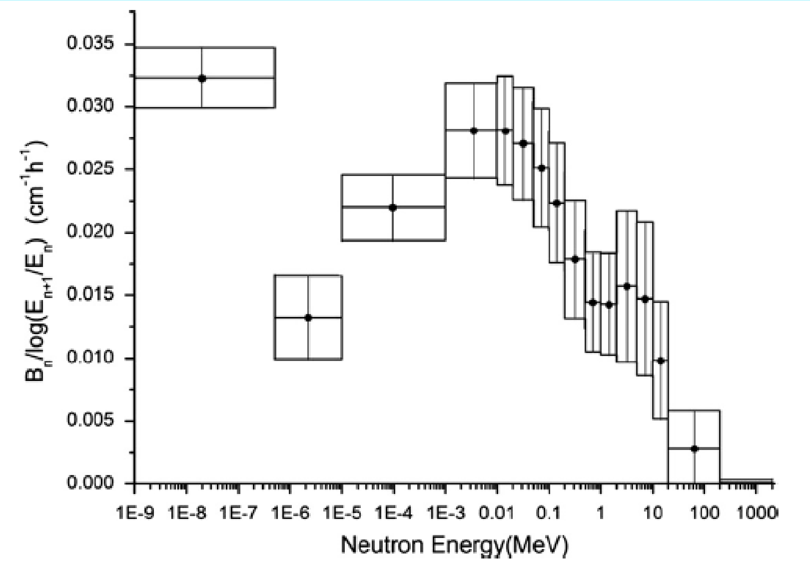
- 700m earth overburden
- Extended Bonner Sphere System
- 100 days measurement

Φ= 6.7(2)×10^{-5} n/cm2/s

5× larger than LSC (!?)

(They also say that their Φ is 5× larger than obtained by KIMS collab. using liq. scint.)

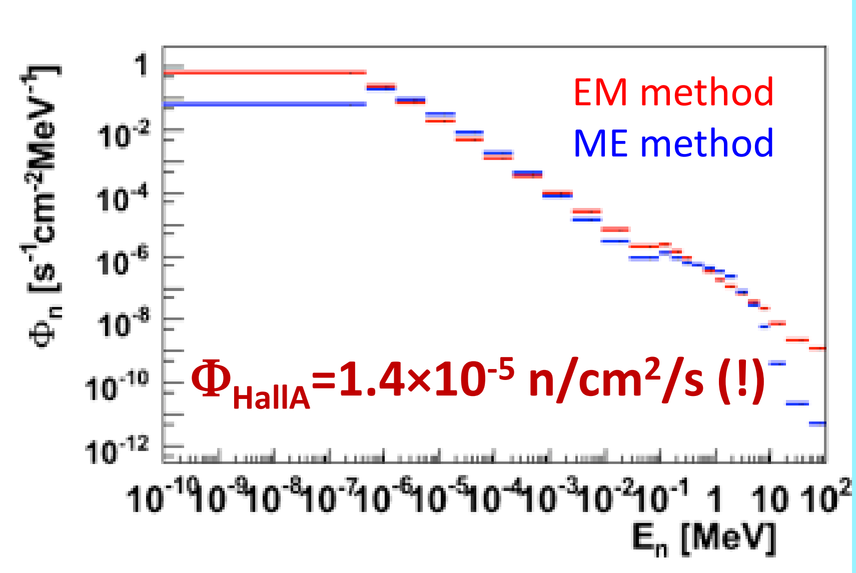




Monte Carlo simulation of background in a neutron counter at LSC:

J.L. Tain et al., NPA6, Lisbon, 2013, J.Phys: Conf. Ser. 665 (2016) 012031

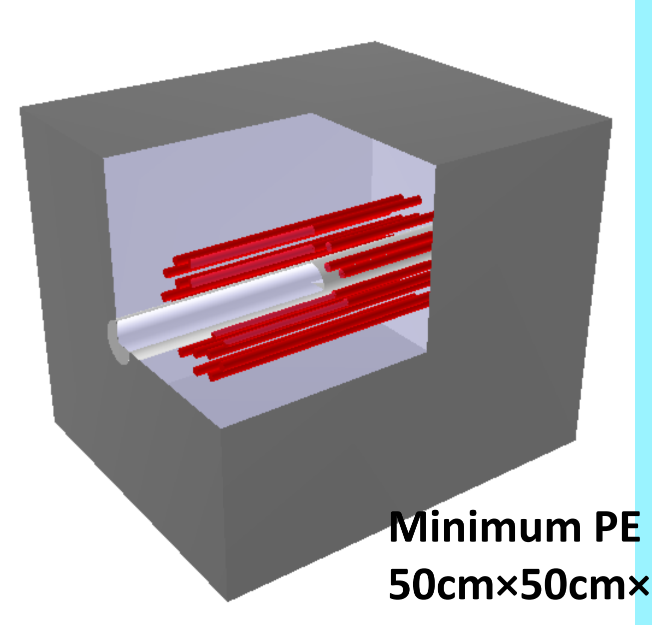
Measured background



$\Phi_{HallA}=1.4\times10^{-5}$ n/cm²/s (!)

+

BELEN-20b



Minimum PE block size:
50cm×50cm×80cm

Sensitive to solution used:

PE shielding (cm)	Rate per counter 1st crown (s^{-1})	Rate per counter 2nd crown (s^{-1})	Total rate (s^{-1})
0	3.9×10^{-5}	4.9×10^{-5}	9.0×10^{-4}
20	7.5×10^{-6}	5.7×10^{-6}	1.3×10^{-4}
40	3.2×10^{-6}	2.5×10^{-6}	5.6×10^{-5}

MCNPX simulations

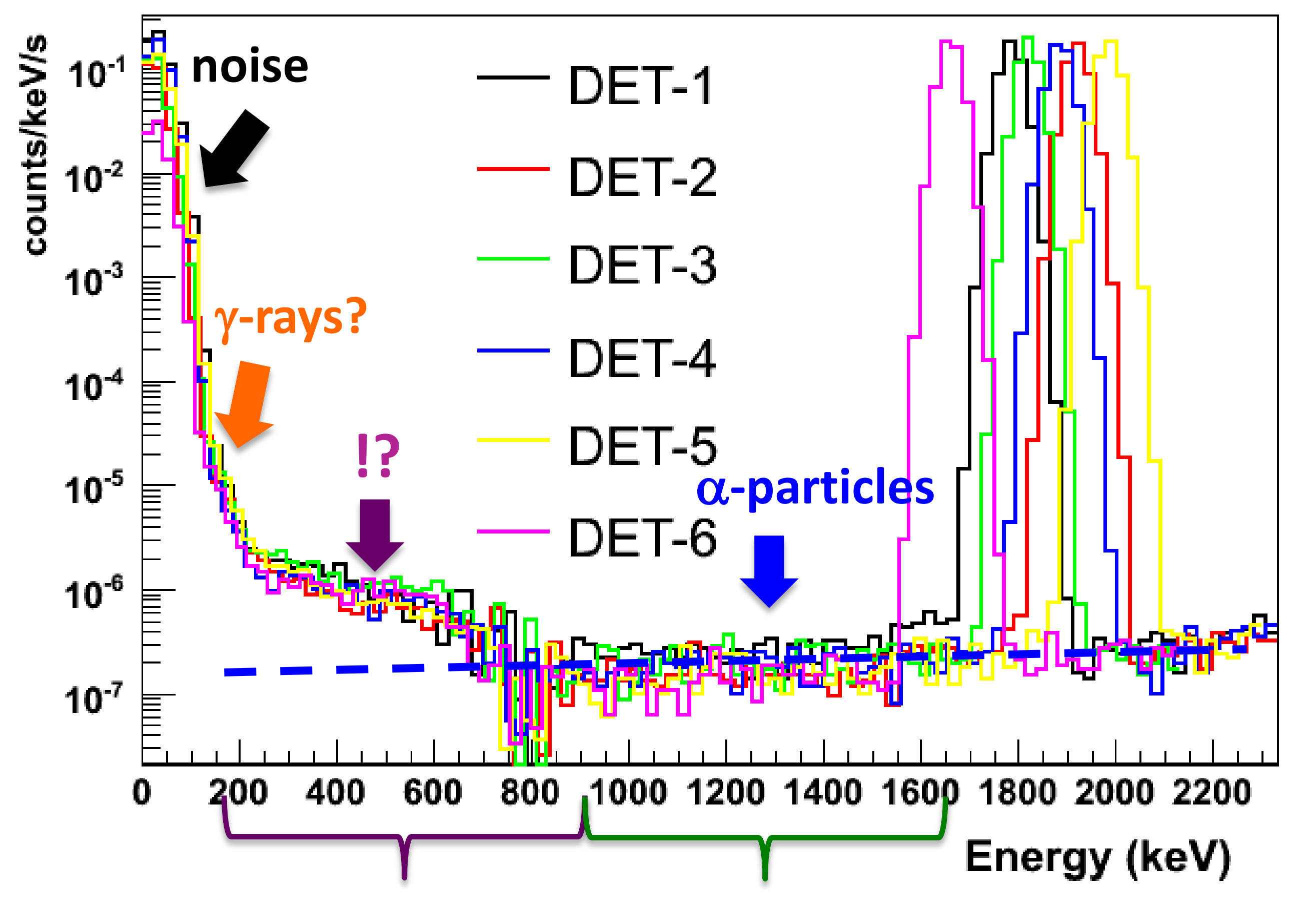
→ equivalent to $\sigma \approx 0.1$ pb!

≈1/500 of Jaegger et al. (!?)

✔ Can be reduced enough

($n = 10^{-6}$ barn^{-1}, $i = 10^{15}$ s^{-1}, ε_n=0.48

Background remaining after subtraction of neutron signals



Variation between tubes: a factor of 2

Rate per counter:

[200,900] keV: $4.8\text{-}8.9\times10^{-4}$ s^{-1} (1.7-3.2 $hour^{-1}$)

[900,1600] keV: $1.0\text{-}2.0\times10^{-4}$ s^{-1} (0.4-0.7 $hour^{-1}$)

20 counters:

➔ equivalent 20-40pb

➔ equivalent 4-8pb

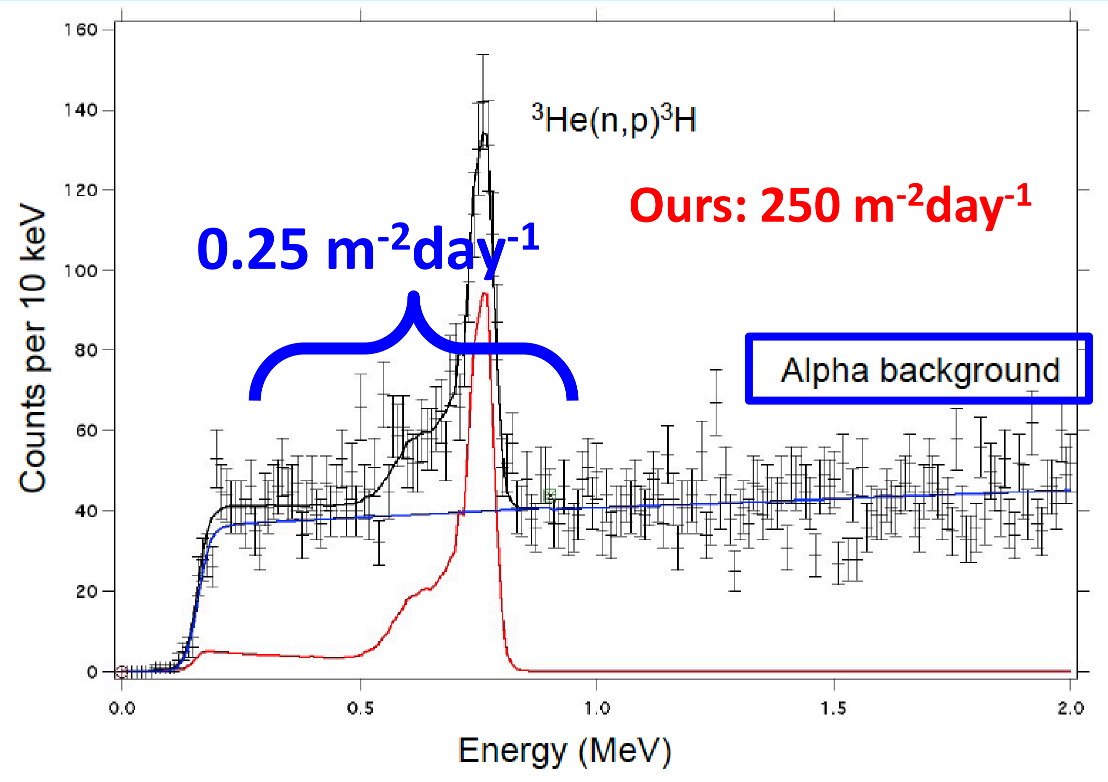
➔ ^{3}He tube background must be studied and reduced

Is it then hopeless the measurement?: no!

Sudbury Neutrino Observatory (SNO)

NCD detector (very low background ^{3}He tubes):

- **200-300cm × ⦸5.08cm, 2.5atm**
- **Special fabrication (low activity materials)**



0.25 m^{-2}day^{-1}

Ours: 250 m^{-2}day^{-1}

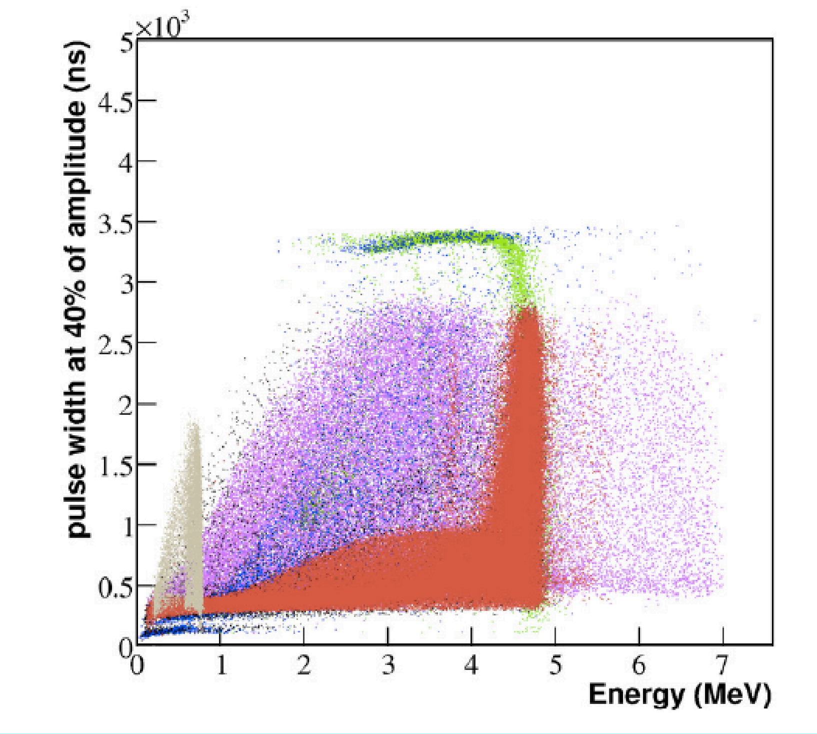
Alpha background

McDonald, JPhysConfSer173(2009)012002

No extra background, α background reduced by 500!

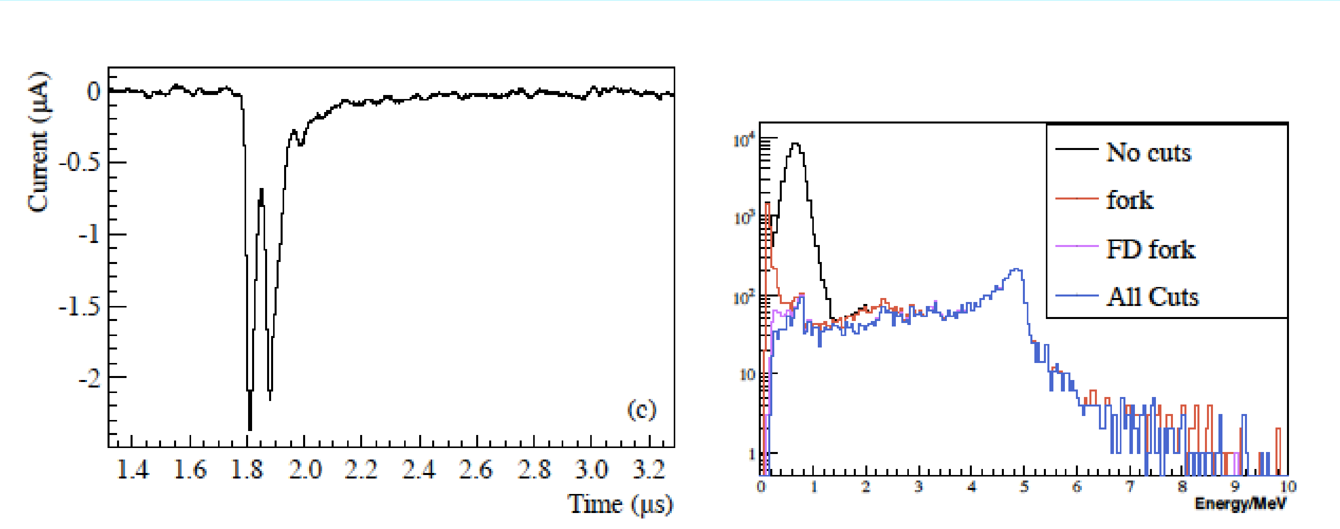
An easier/cheaper solution for α background:

- **Carbon coated tubes (inner wall) to stop α-particles**
- **Prototype ordered and being tested**



In addition they perform a pulse shape analysis to discriminate α-particles from p+t (neutron) tracks

B. Beltran et al.,
NewJPhys 13 (2011) 73006



(a) Discharge event

(b) Shaper/ADC spectrum

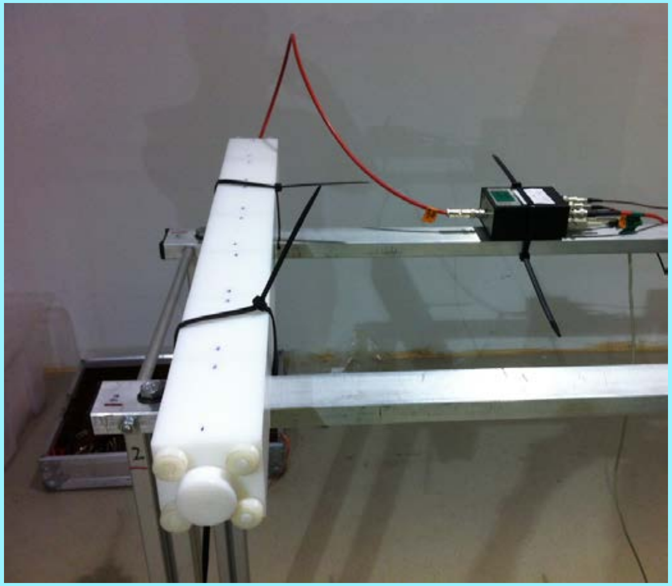
They see also some discharge events producing signals in the range of our strange background

R. Martin , PhD Thesis, 2009, Queens Univ. Ontario

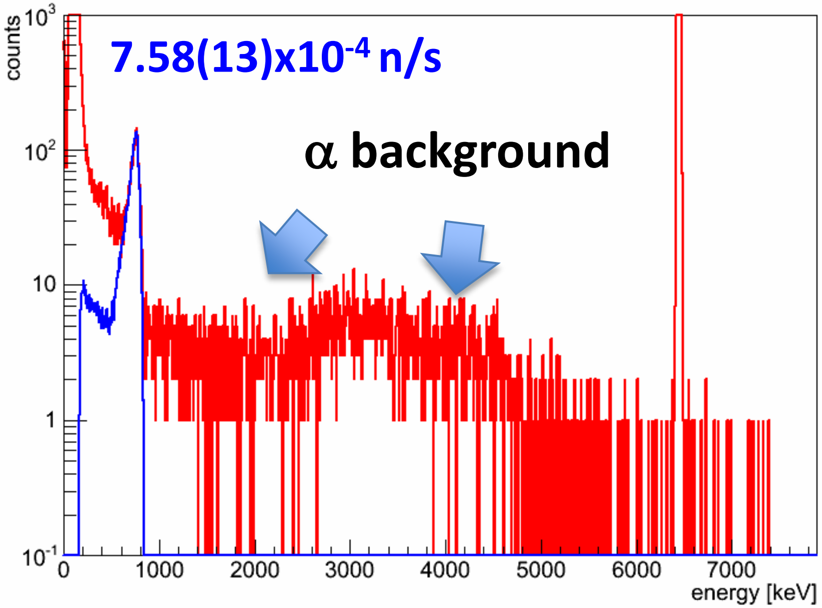
New neutron background measurements at LSC in 2015

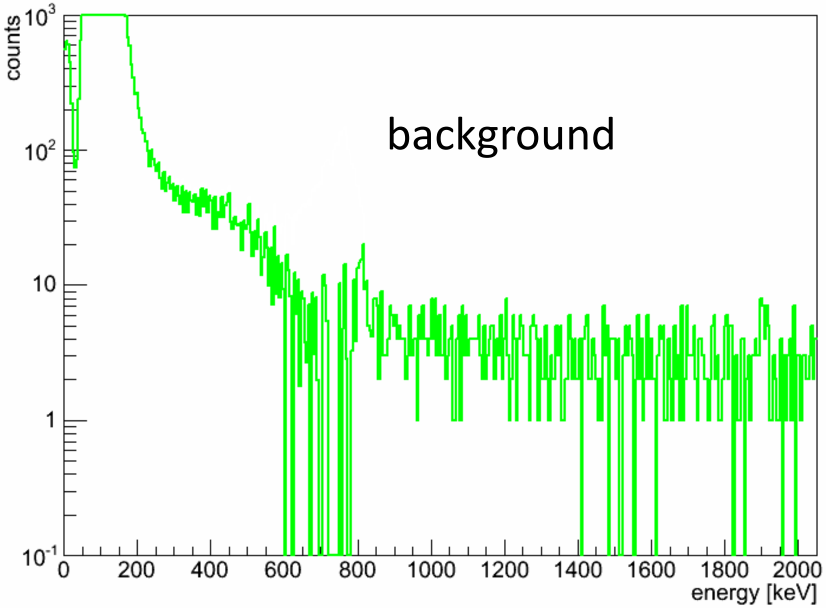
- Investigate the origin of the excess background in the 200-900 keV region
- Test the alpha background reduction of C coated tubes
- Measure the thermal neutron flux
- Check for flux variations with position in the Hall

- At a corner of Hall A
- Original 20 atm large tube
- New 8 atm large tube
- Two identical small tubes with and without C coating
- New Mesytec preamp
- Canberra 2006 preamps
- With/without shaper
- Updated DACQ
- Check digital processing (traces stored)



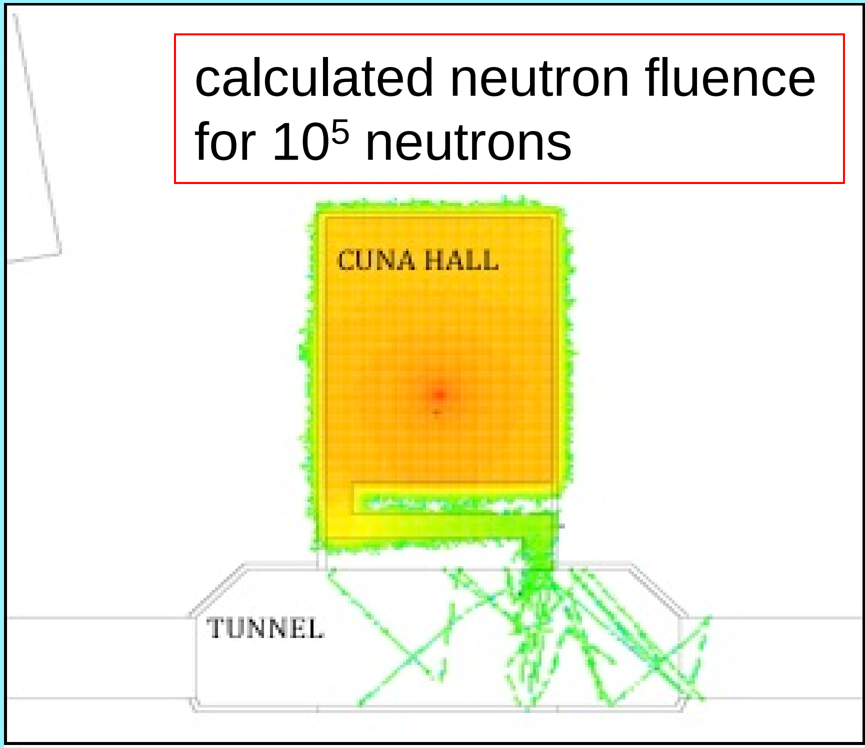
- 52 days
- PE block: $7x7x70cm^2$
- Canberra preamp, no shaper
- Neutron rate 60% larger than in 2011 probably because we are close to the walls
- Similar background to 2011: we can exclude some causes

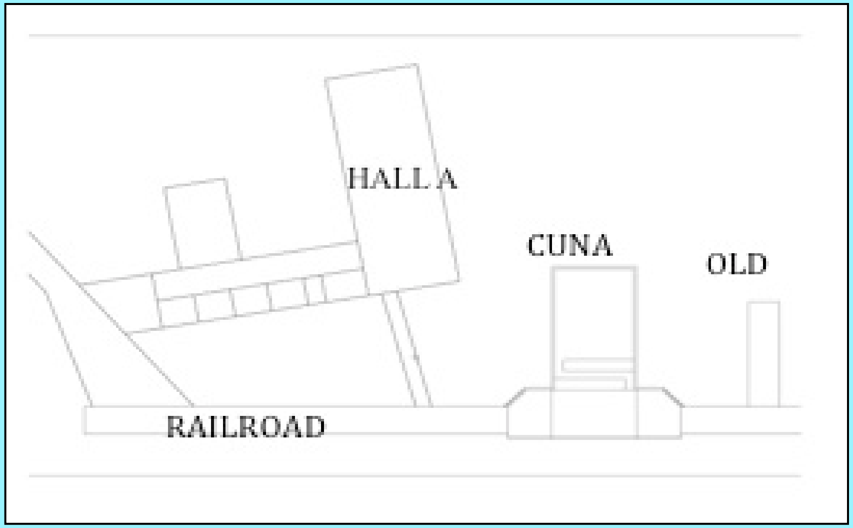




Beam induced neutron background estimates for others

- Entrance to the hall with a two-wall maze
- Walls made of concrete are 2 m thick and are placed leaving a passage 1.5 m wide.
- Standard concrete composition in MCNPX
- Walls of the hall and of the tunnels are covered with 40 cm of the same concrete
- Simplified geometry
- Isotropic neutron 3.6 MeV in the centre of the CUNA hall

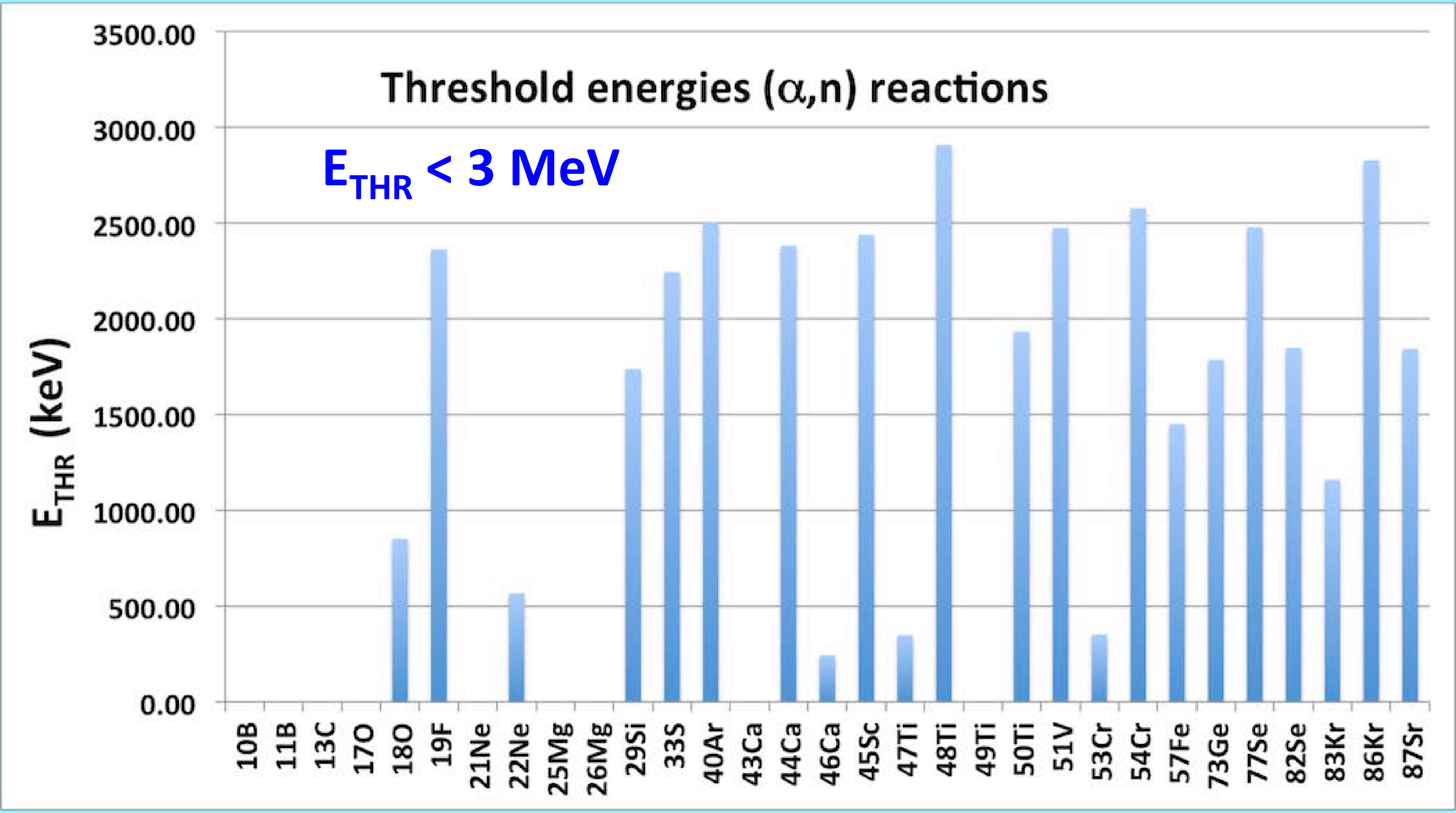

calculated neutron fluence for 10^5 neutrons



Result:

- An unshielded source of 10^5 n/s is required to reach the level of the LSC n background.
- With the experimental rates plus shielding it is very unlikely that neutrons escaping from the CUNA hall will represent a challenge to other measurements.

In addition investigate accelerator induced neutron background

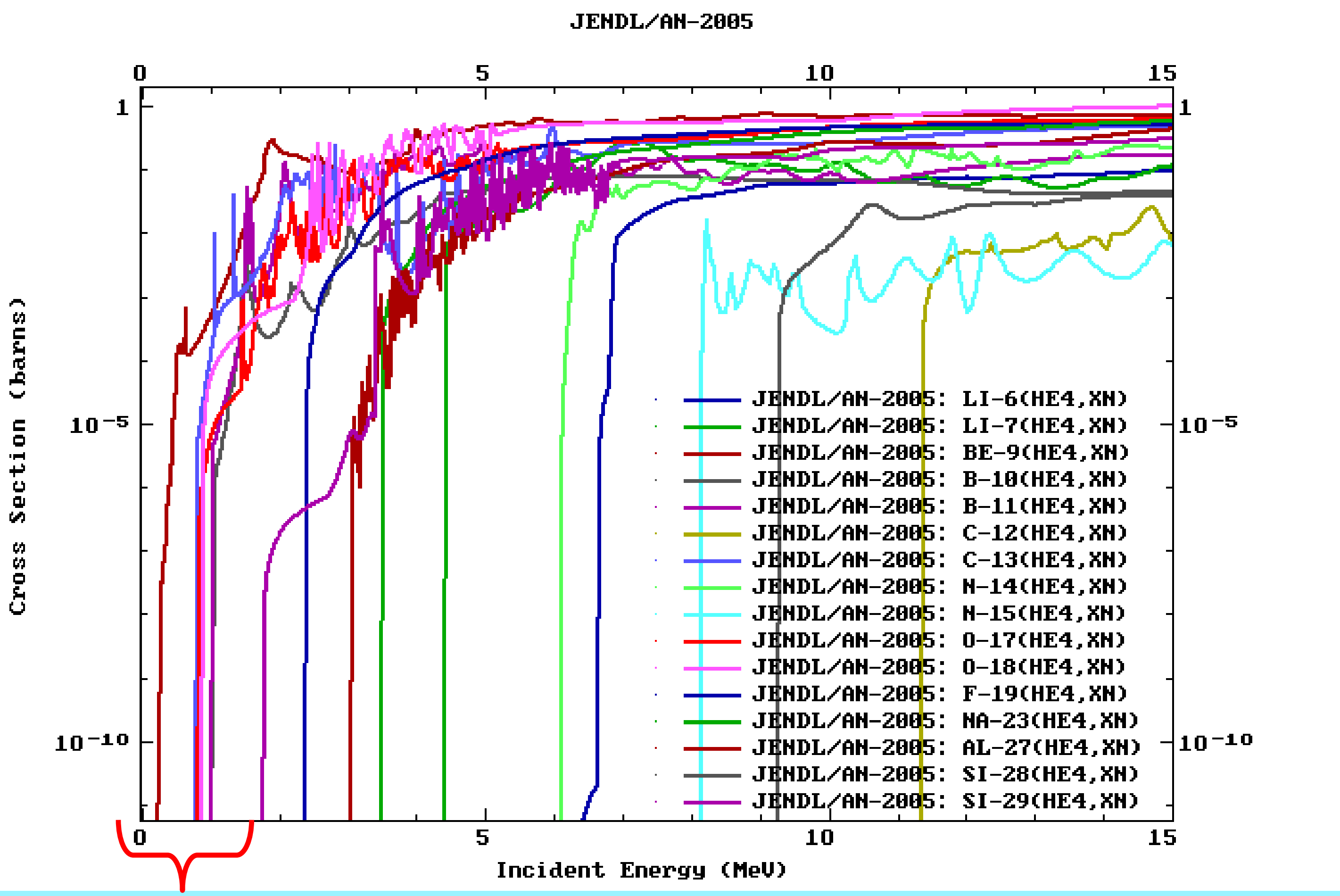


$E_{THR} < 3$ MeV

Avoid dangerous materials in contact with the beam!

We are trying to perform a MC study of accelerator induced background but …

Current status of (α,n) cross-sections in data bases:



Conclusion and outlook:

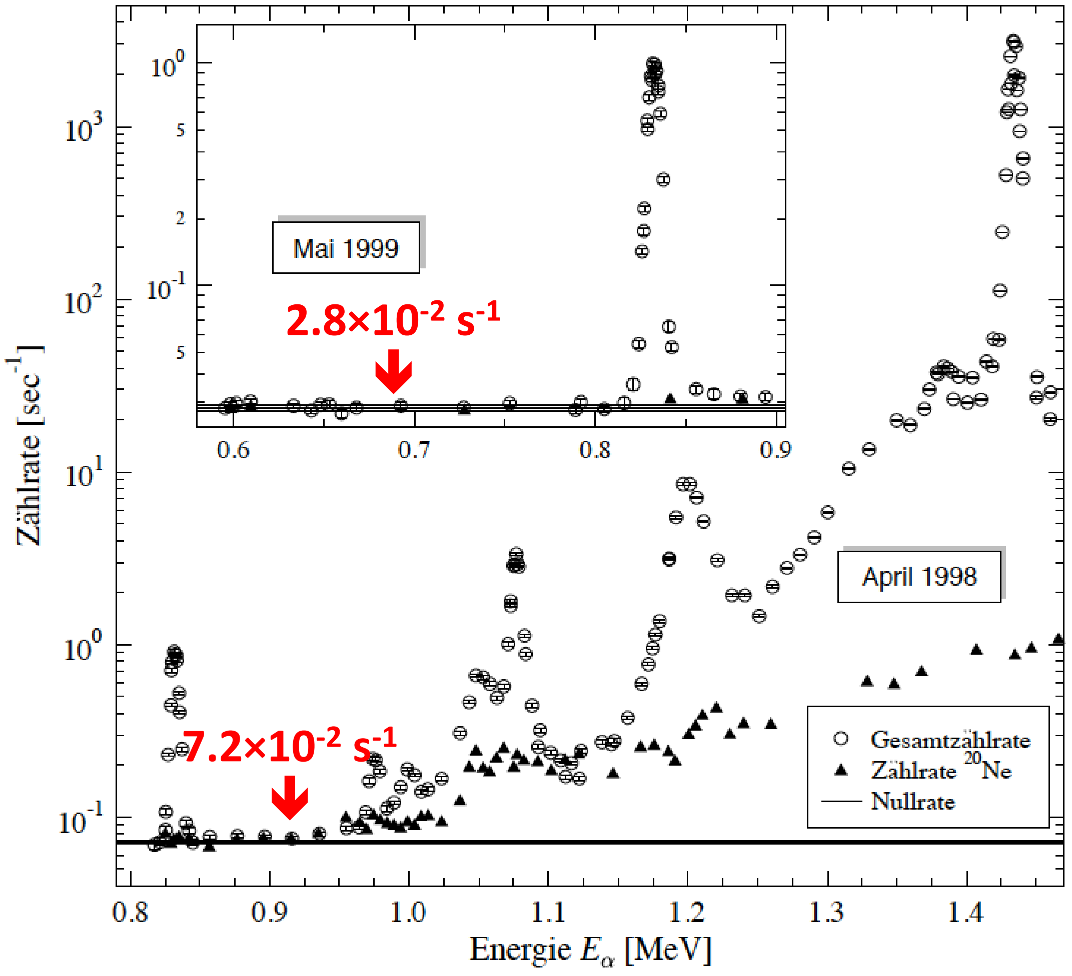
- For the first time we have enough information to discuss quantitatively the sensitivity of underground (α,n) measurements
- The measurement of a fraction of picobarn cross sections seem possible provided a number of issues are solved
- Investigate the origin and reduction of non-neutron background in 3He tubes (prototypes)
- Minimization of accelerator induced backgrounds
- Design of the 4π neutron counter: maximize efficiency, minimize dependence with neutron energy (or very accurate calibration), shielding, …
- Alternative detector types?

THANK YOU!

The "best" setup until now

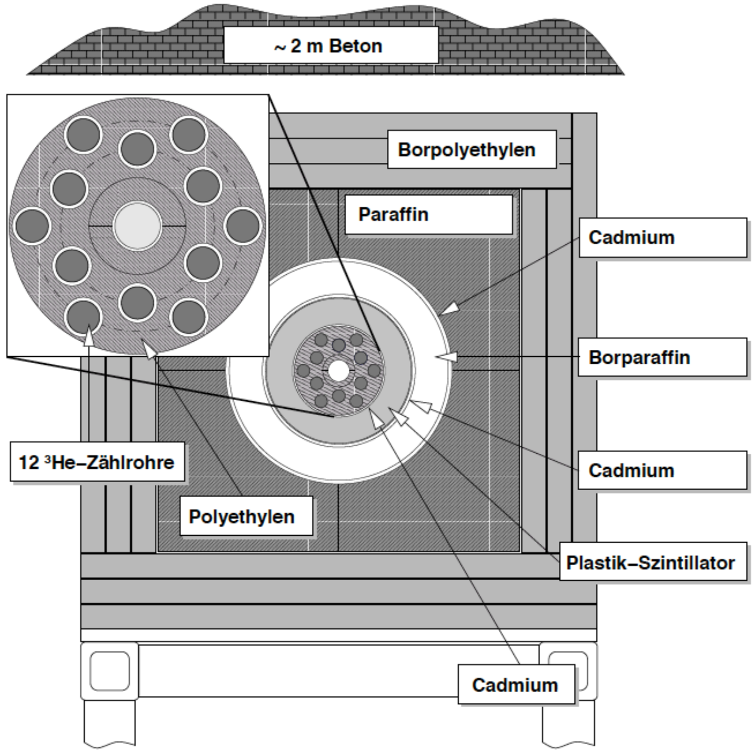
M. Jaegger, PhD Thesis, U. Stuttgart, 2001

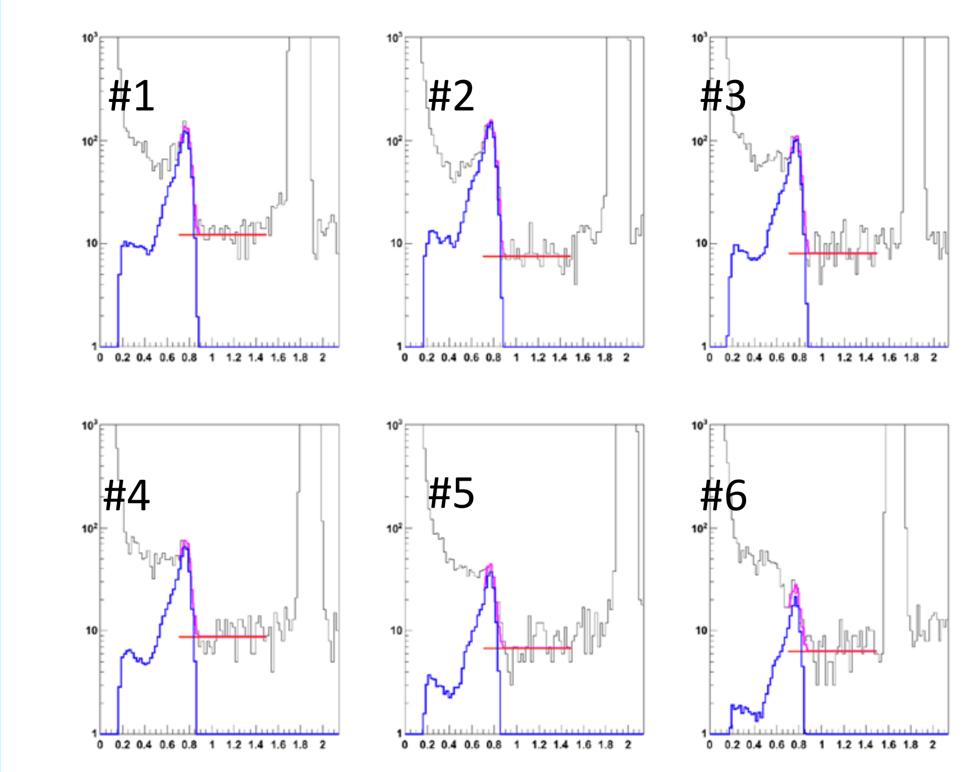
With an active veto they were able to reduce neutron background rate from 0.072 n/s to 0.028 n/s



2.8×10^{-2} s^{-1}

7.2×10^{-2} s^{-1}




#1
#2
#3
#4
#5
#6
10³
10²
10
1
0
0.2
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0.8
1
1.2
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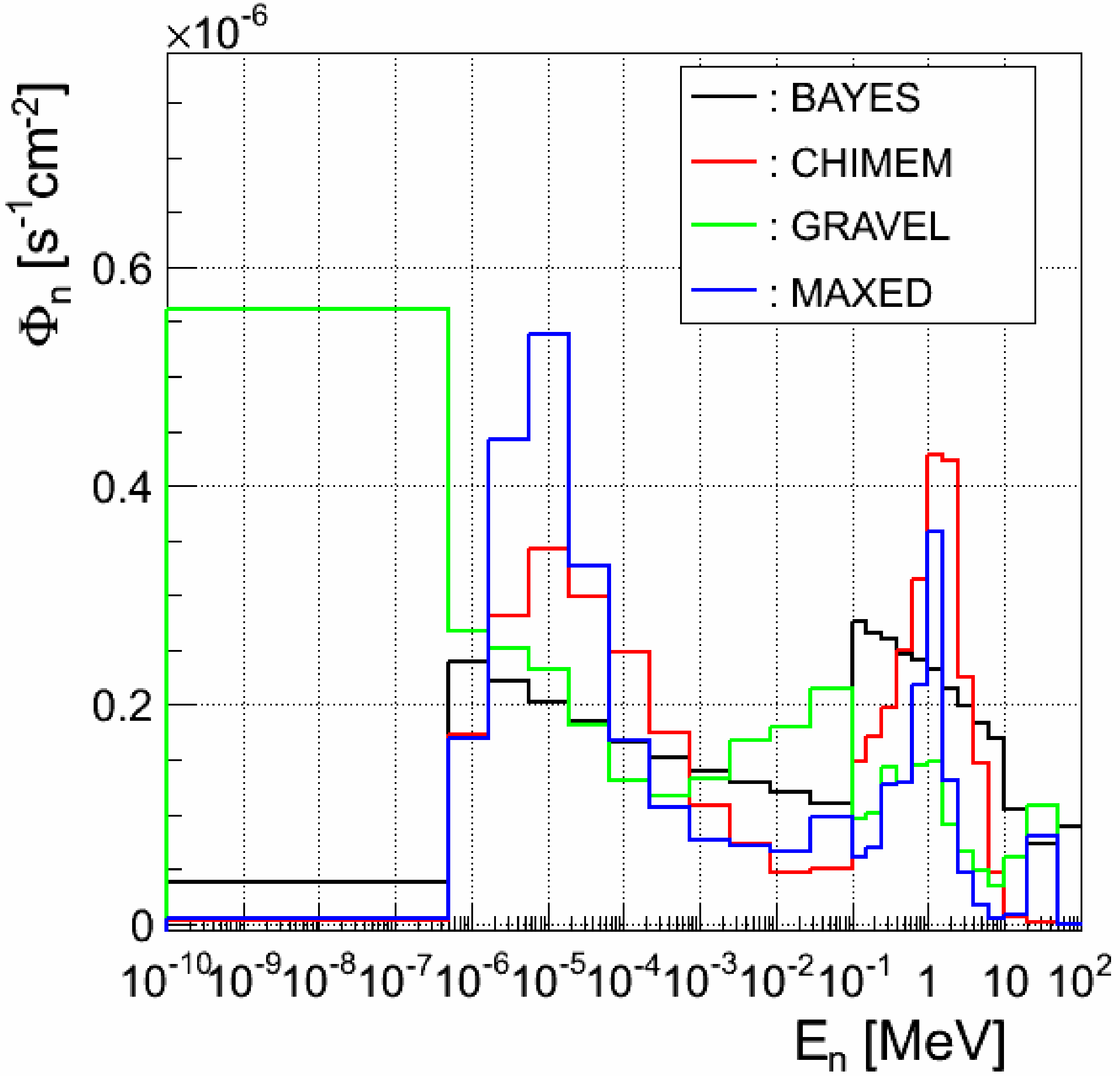
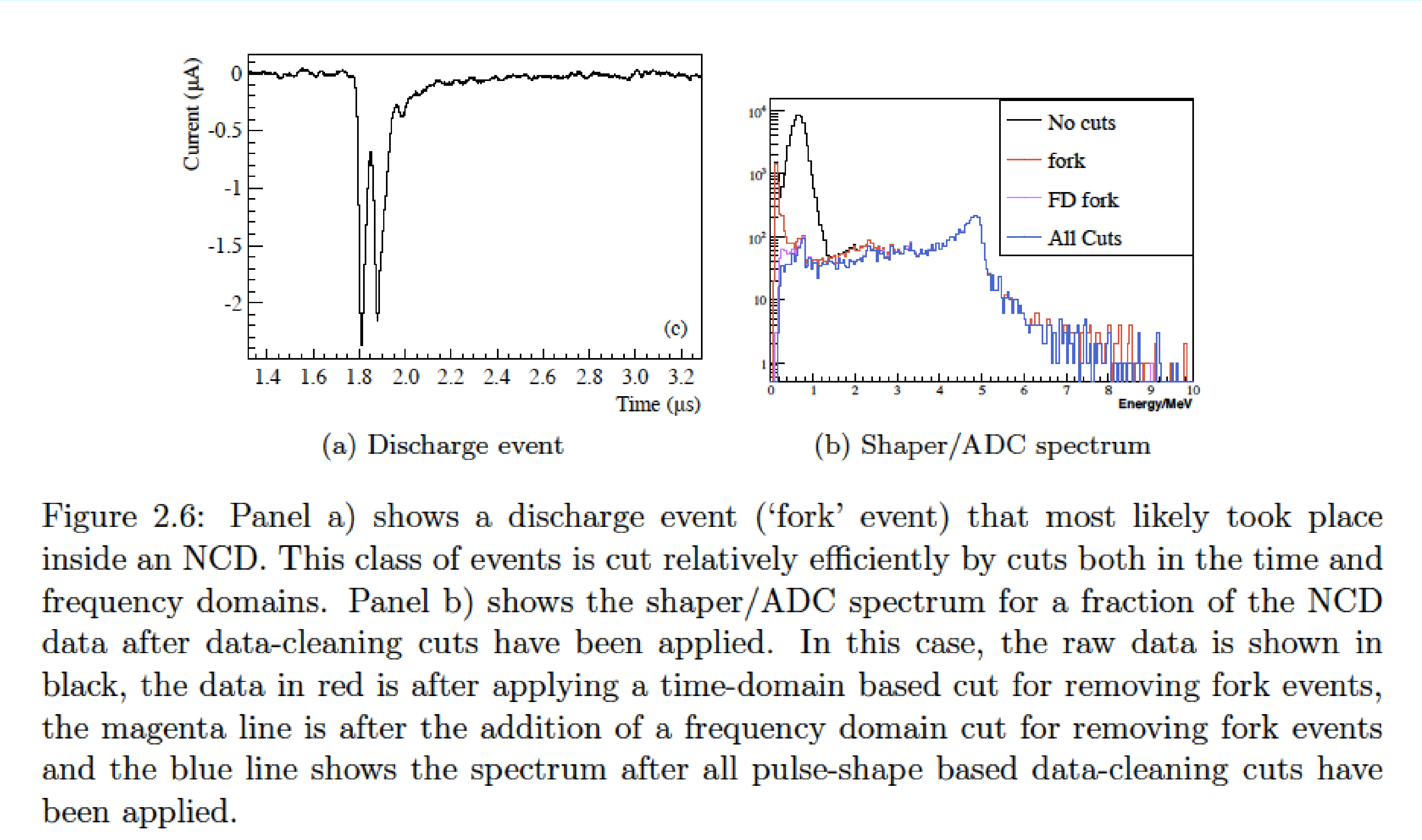
1.6
1.8
2



$\times 10^{-6}$
Φ_n [s^{-1}cm^{-2}]
0
0.2
0.4
0.6
: BAYES
: CHIMEM
: GRAVEL
: MAXED
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2}
E_n [MeV]



(a) Discharge event

(b) Shaper/ADC spectrum

Figure 2.6: Panel a) shows a discharge event ('fork' event) that most likely took place inside an NCD. This class of events is cut relatively efficiently by cuts both in the time and frequency domains. Panel b) shows the shaper/ADC spectrum for a fraction of the NCD data after data-cleaning cuts have been applied. In this case, the raw data is shown in black, the data in red is after applying a time-domain based cut for removing fork events, the magenta line is after the addition of a frequency domain cut for removing fork events and the blue line shows the spectrum after all pulse-shape based data-cleaning cuts have been applied.

R. Martin, PhD Thesis, 2009

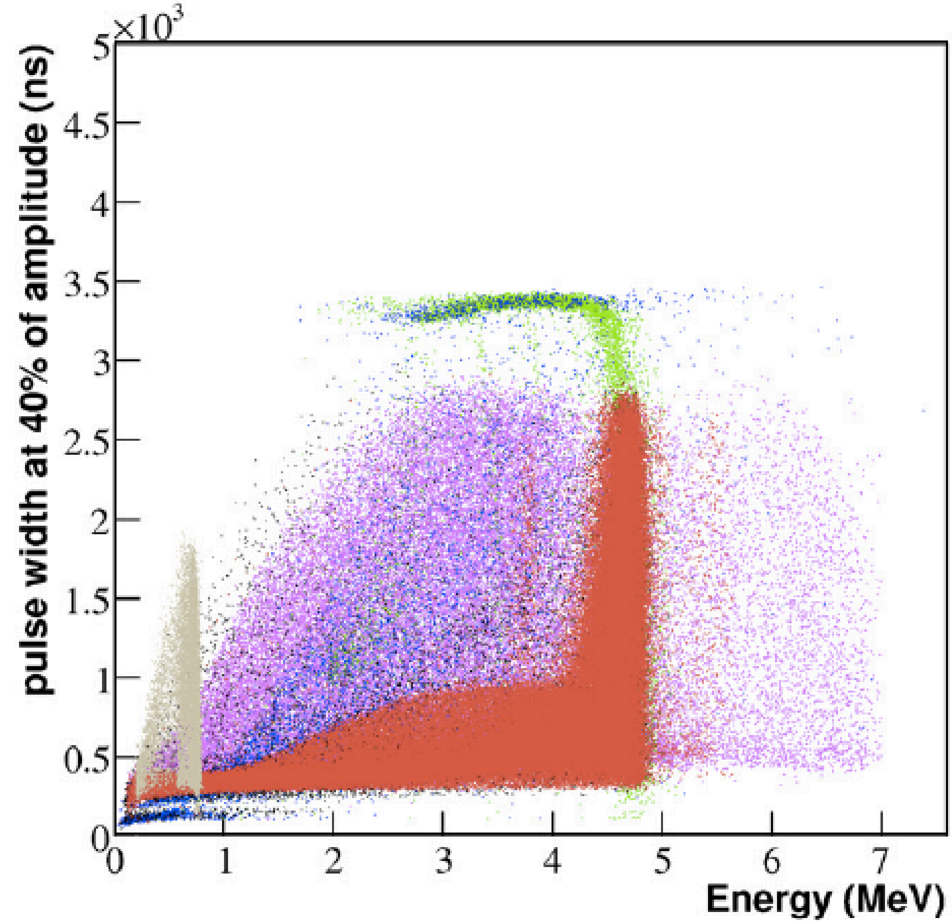
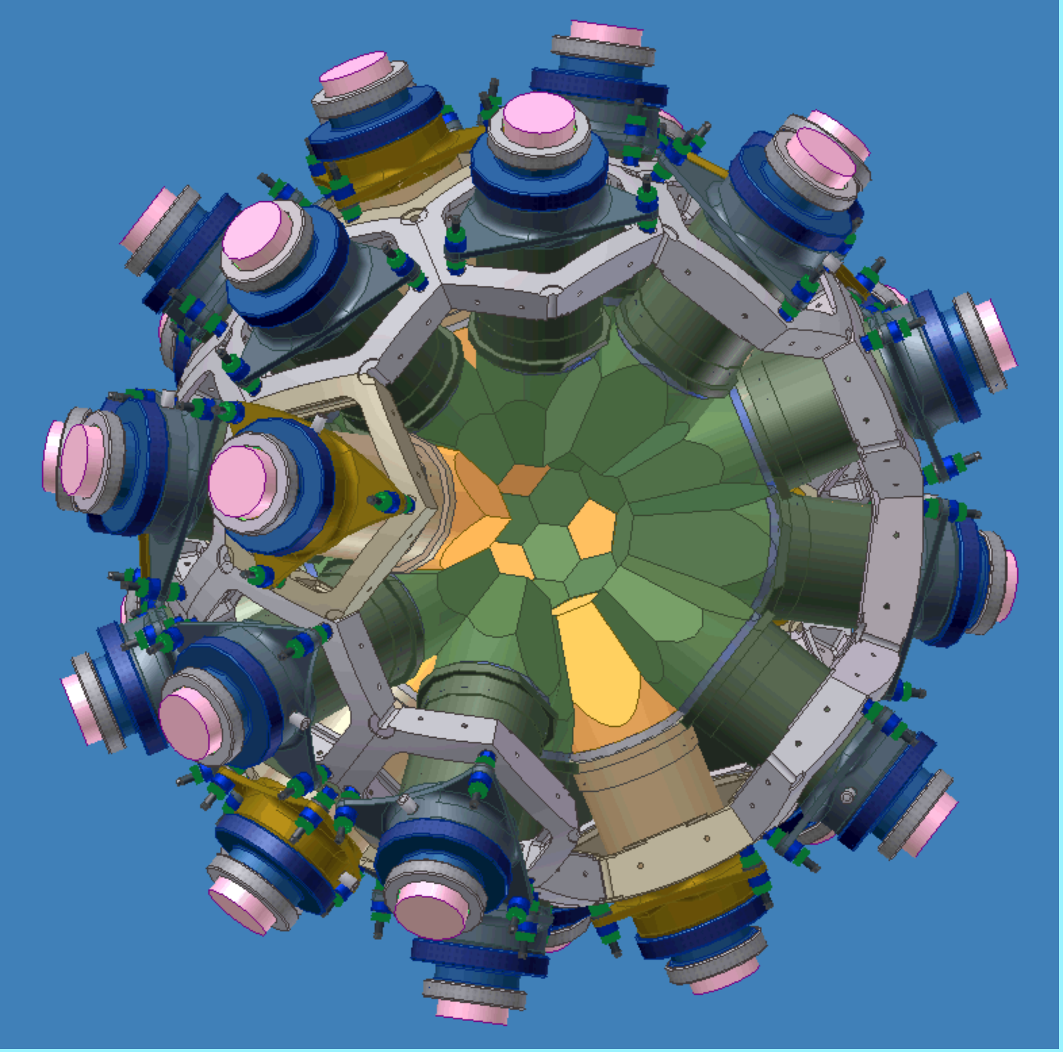


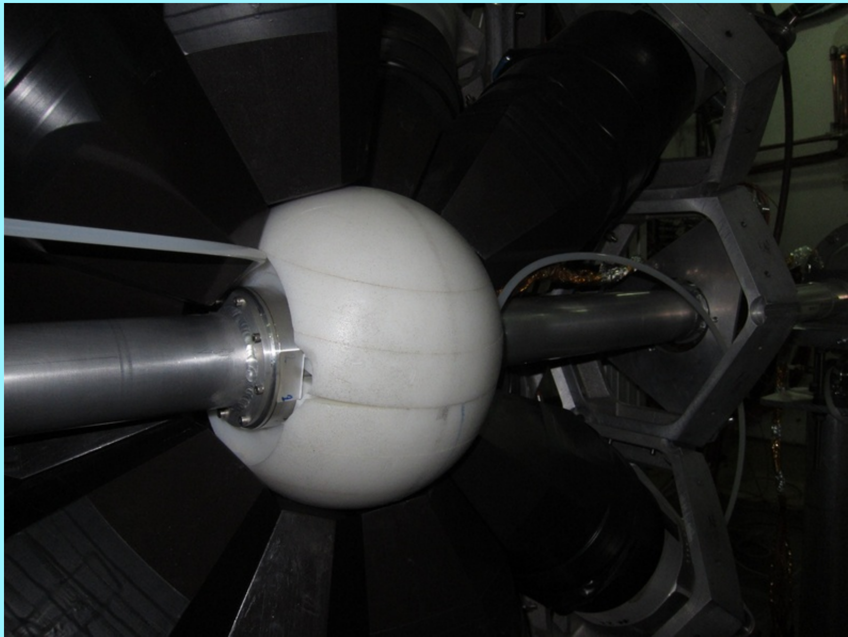
Figure 15. Pulse-width versus energy distributions for simulated neutrons (gray) and alphas. The alpha populations include surface wall ^{210}Po alphas (red), bulk wall ^{238}U alphas (magenta), surface wire ^{210}Po alphas (green), bulk wire ^{238}U alphas (blue) and bulk endcap ^{238}U alphas (black, distributed with the blue points).

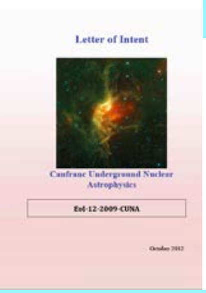


This is not Karlsruhe calorimeter but its twin brother at n_TOF

40 BaF2 crystals

Cd loaded PE absorber





Letter of Intent

Canfranc Underground Nuclear Astrophysics

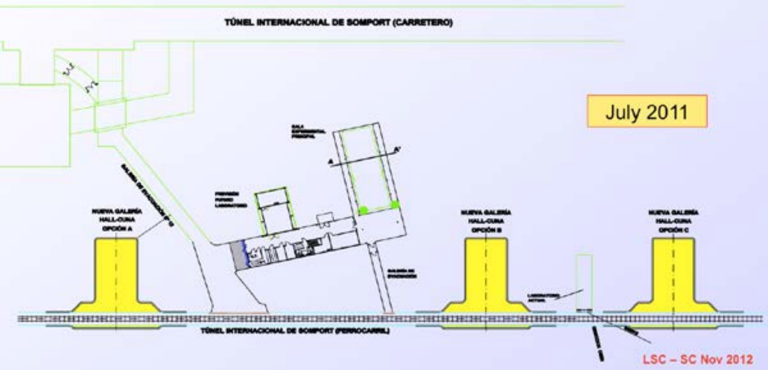
EoI-12-2009-CUNA

October 2012

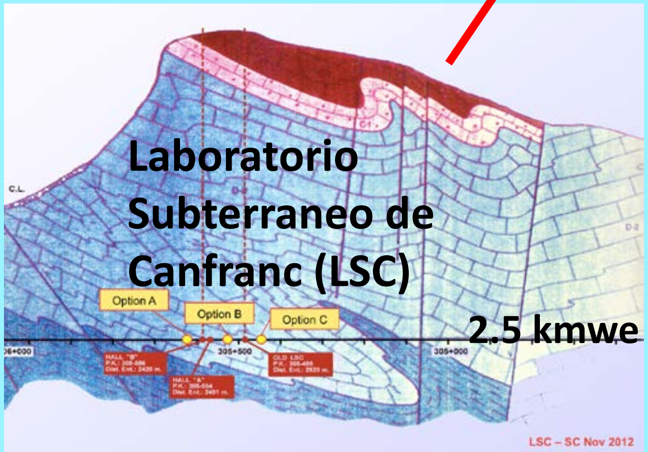
Letter of Intent

A NUCLEAR ASTROPHYSICS FACILITY FOR LSC: THE SOURCES OF NEUTRONS IN THE STARS AND OTHER REACTIONS OF ASTROPHYSICAL INTEREST

EoI-12-2009-CUNA



Possible locations



Laboratorio Subterraneo de Canfranc (LSC)

2.5 kmwe

LAB2500

3.5 MV (HVEE)

A possible accelerator choice