A nuclear astrophysics facility for the LSC.

The **sources of neutrons** in the stars and other reactions of astrophysical interest

L.M. Fraile, GFN-UCM

Letter of Intent

Canfranc Underground Nuclear Astrophysics

EoI-12-2009-CUNA

October 2012

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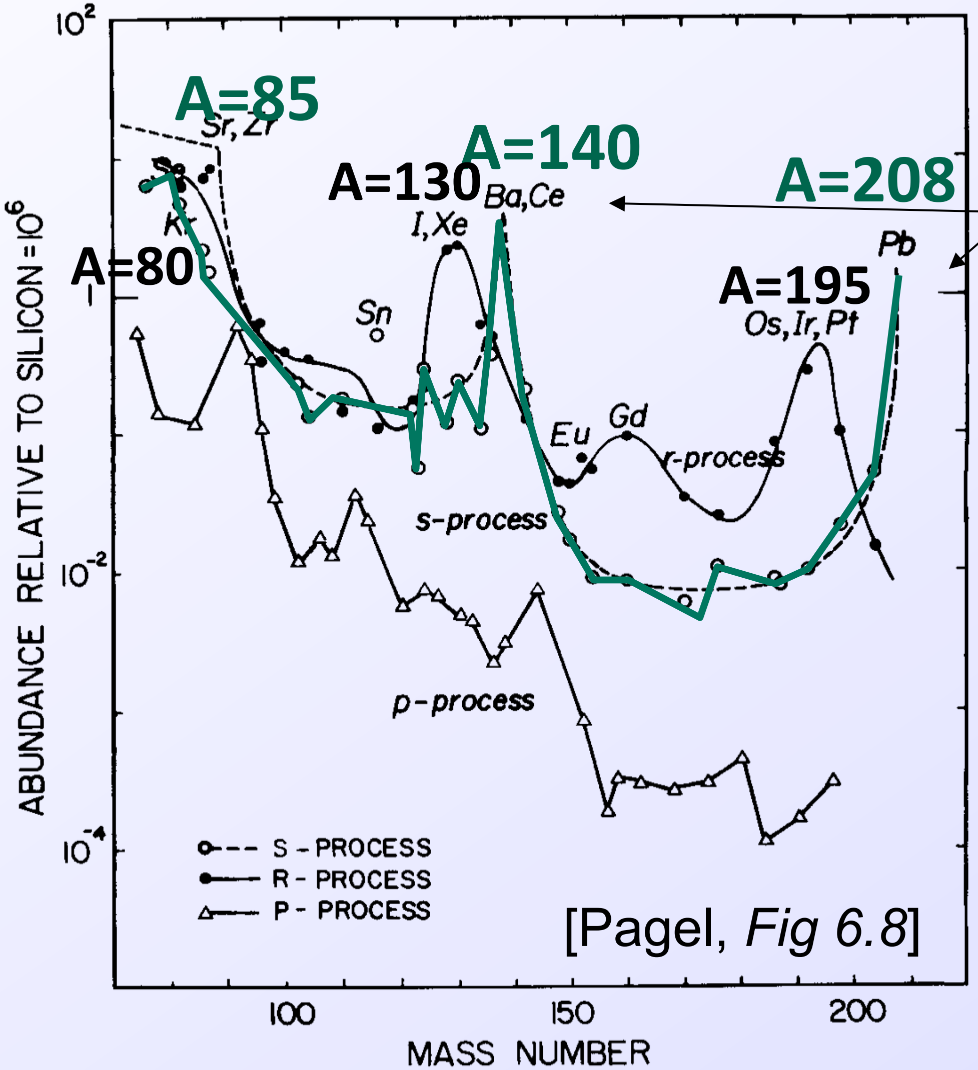
Summary

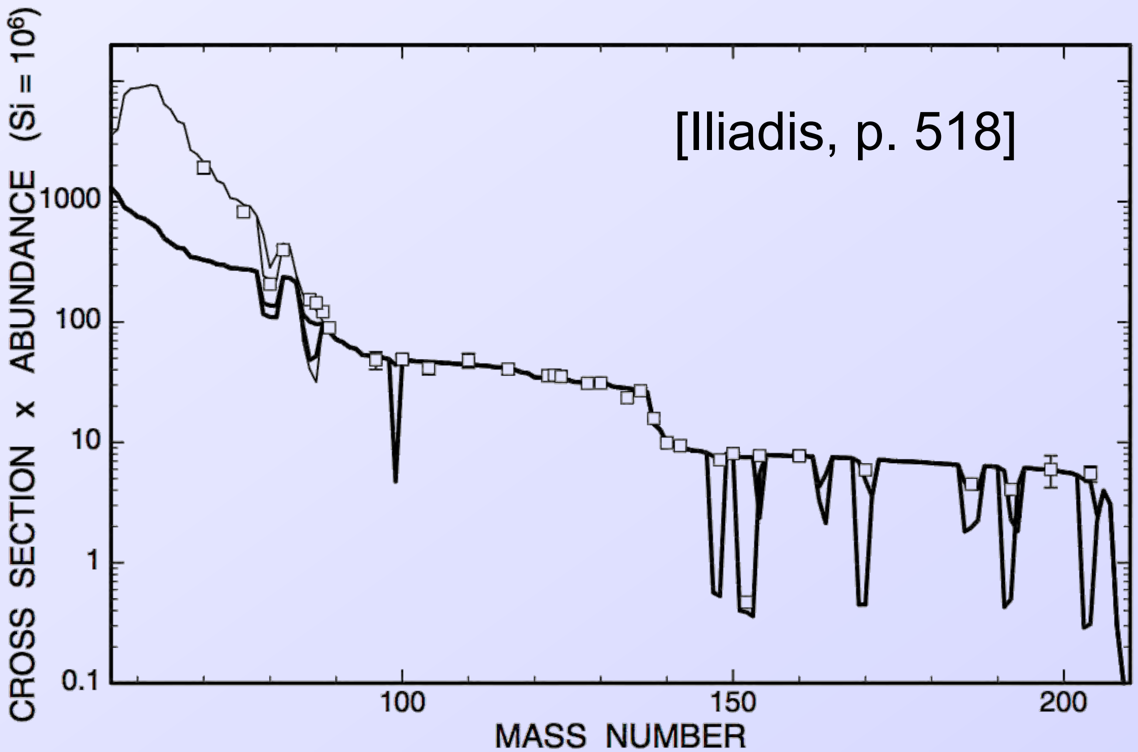
The s-process

The origin of heavy elements in the solar system

Abundance peaks: n capture along valley of stability → **s-process**

- slow neutron captures
- 50% of the isotopes above Fe





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Stellar evolution: s-process

Main component

Thermally pulsing, low mass ($M = 1.5 – 3\ M_{\odot}$) AGB stars

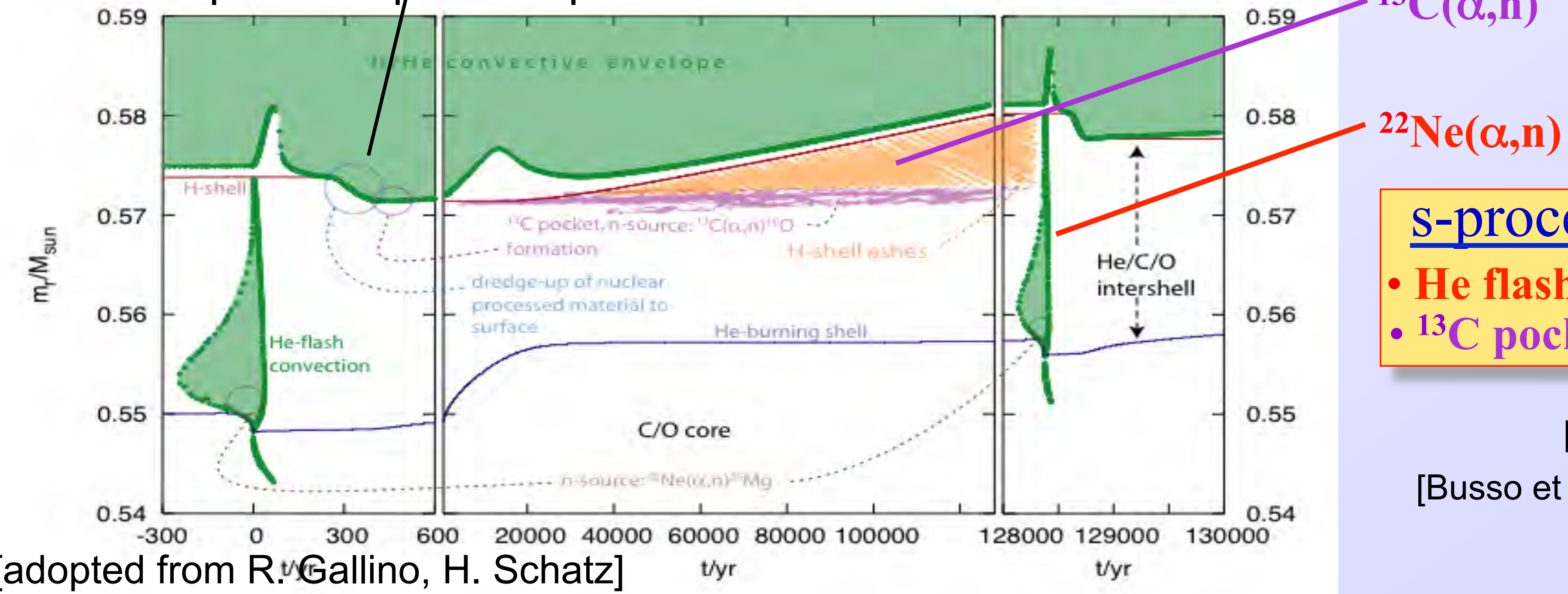
- Originate from main sequence stars, ejection of the outermost layers of the star
- AGB stage: Combination of H- & He-burning shells produces s-process elements A = 90-209

Weak component

Massive stars ($M > 13\ M_{\odot}$) during He- and C-burning Red Giant phase

- produces species with A = 60 – 90
- ^{14}N quickly converted to ^{22}Ne
- ^{22}Ne(α,n)^{25}Mg provides the neutron source

Transport of s-process products to the surface



[adopted from R. Gallino, H. Schatz]

s-process

- **He flash via ^{22}Ne(α,n)**
- **^{13}C pocket via ^{13}C(α,n)**

[Straniero et al. 1997]

[Busso et al., ARA&A 37, 1999]

Impact of reaction rates for $^{22}Ne(\alpha,n)^{25}Mg$

✓ $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction also has impact on n flux

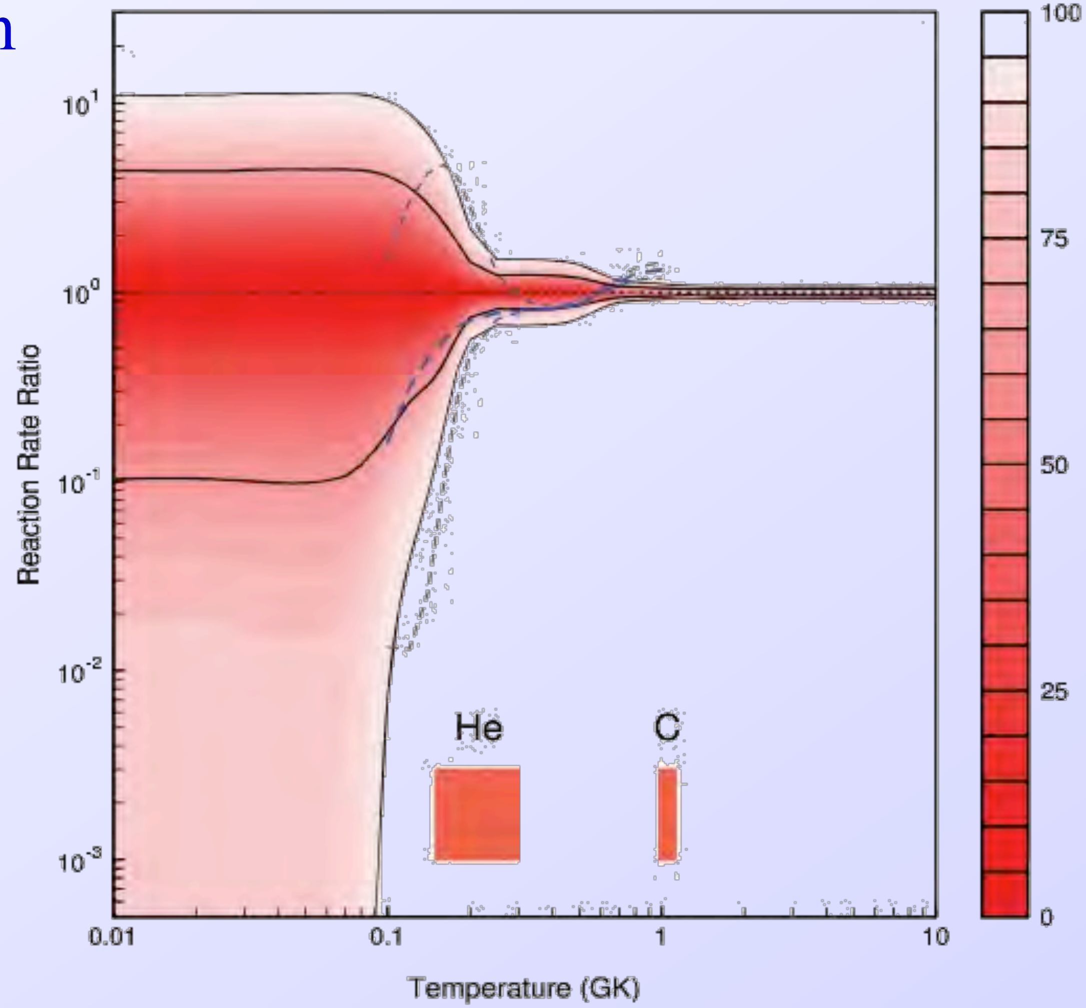
✓ Improved $^{22}Ne + \alpha$ reaction rates based on new experimental information since NACRE and Jäger et al.

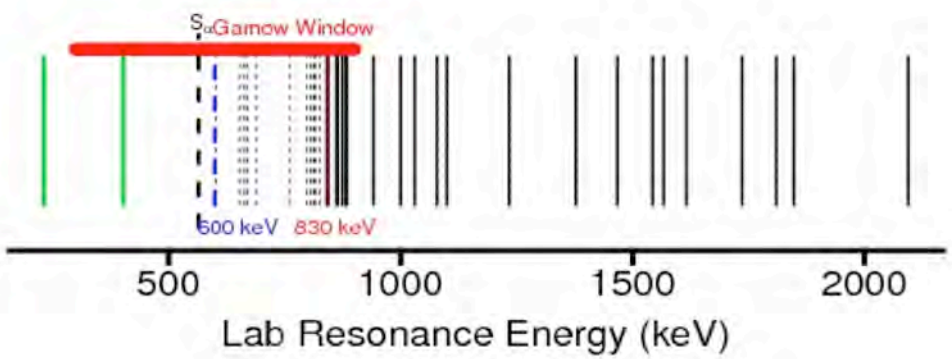
✓Computational method [22]

- Much improved uncertainties
- Changes for AGB starts: increase of production by up to a factor of 2 for higher masses.

R. Longland et al.

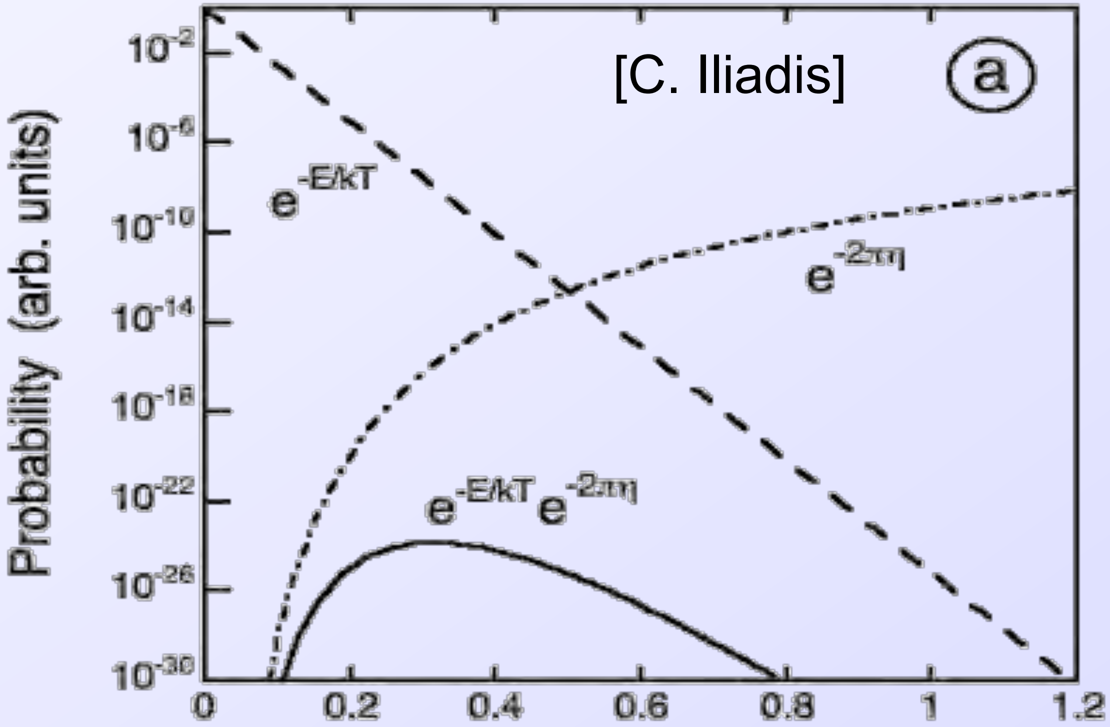
PHYSICAL REVIEW C **85**, 065809 (2012)





Measurements

- ✓ Cross-sections
  - → parameterized models
  - → Typical stellar T (10^7-10^{10} K) and Coulomb barrier translates into very low LAB energies (0.001-1 MeV): Gamow peak
  - → Cross-sections are extremely small (10^{-12} –10^{-20} barn)
  - → Low energies resonances may appear
- ✓ Measure at (close) the relevant E
  - → Requires high luminosity (beam current)
  - → Requires large signal/noise ratio
  - → Extrapolations



$$\text{Rate} \propto \langle \sigma v \rangle \propto \int \Phi(E)\sigma(E)dE$$

$$\Phi(E) \propto \mathrm{E}\, \mathrm{e}^{-\mathrm{E}/\mathrm{kT}}$$

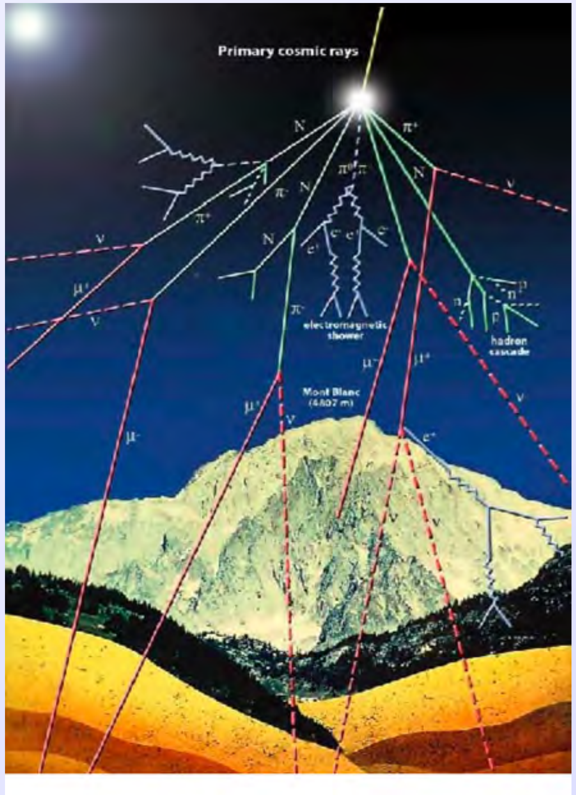
$$\sigma(E) = 1/E \; \mathrm{e}^{-2\pi\eta}\, \mathrm{S}(E)$$

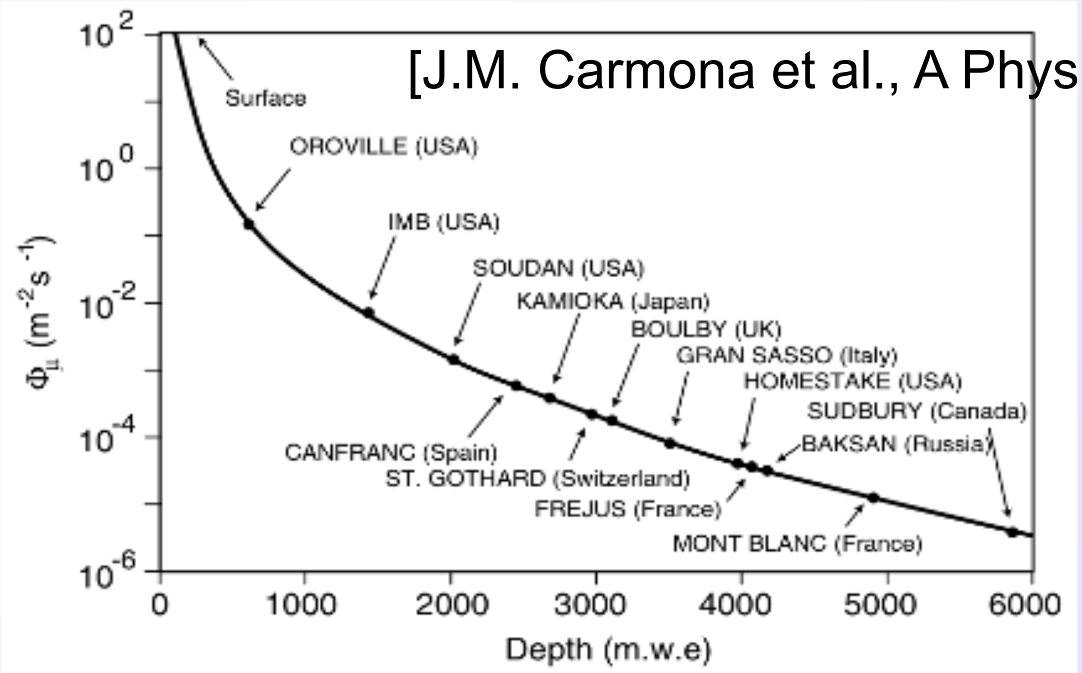
Possibilities at ground level exhausted

Solution: going underground

✓ Background sources

- → Cosmic ray muons
- → Muon-induced neutrons & radioactivity
- → Rn and A=210 Pb-Bi-Po daughters
- → Gamma and n emission from materials
- → Rn emanation from materials
- → Beam induced reactions





[J.M. Carmona et al., A Phys, 2004]

UNDERGROUND

- → Cosmic rate reduction
- → Significant below 1000 mwe
- → Additional background reduction

S-process in AGBs and massive stars

	$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$	$^{22}Ne(\alpha,n)^{25}Mg$
Location	AGB - Pocket	AGB - He flash (short, intense burst)	$M > 13\ M_\odot$ Red Giant He- & C-burning
Importance	Primary source (weaker but longer)	Secondary source (slight change of abundances)	Weak component
Requirements	Needs ^{13}C	^{22}Ne is abundant	^{14}N converted to ^{22}Ne
Temperature	0.9 – 1.0 x 10^8 K	2.7 x 10^8 K	2.2 - 3.5 x 10^8 K
Neutron density	7 x 10^7 cm^{-3}	10^{10} cm^{-3} (peak)	2 x 10^7 cm^{-3} max
Duration	20,000 yr	few years	Red giant phase
Neutron exposure $\tau = \int j_n(t)dt$	0.1 / mb (90% exposure)	0.01 / mb	0.2 / mb

What is the source of the required stellar neutron flux?

The rates of these reactions must be accurately known

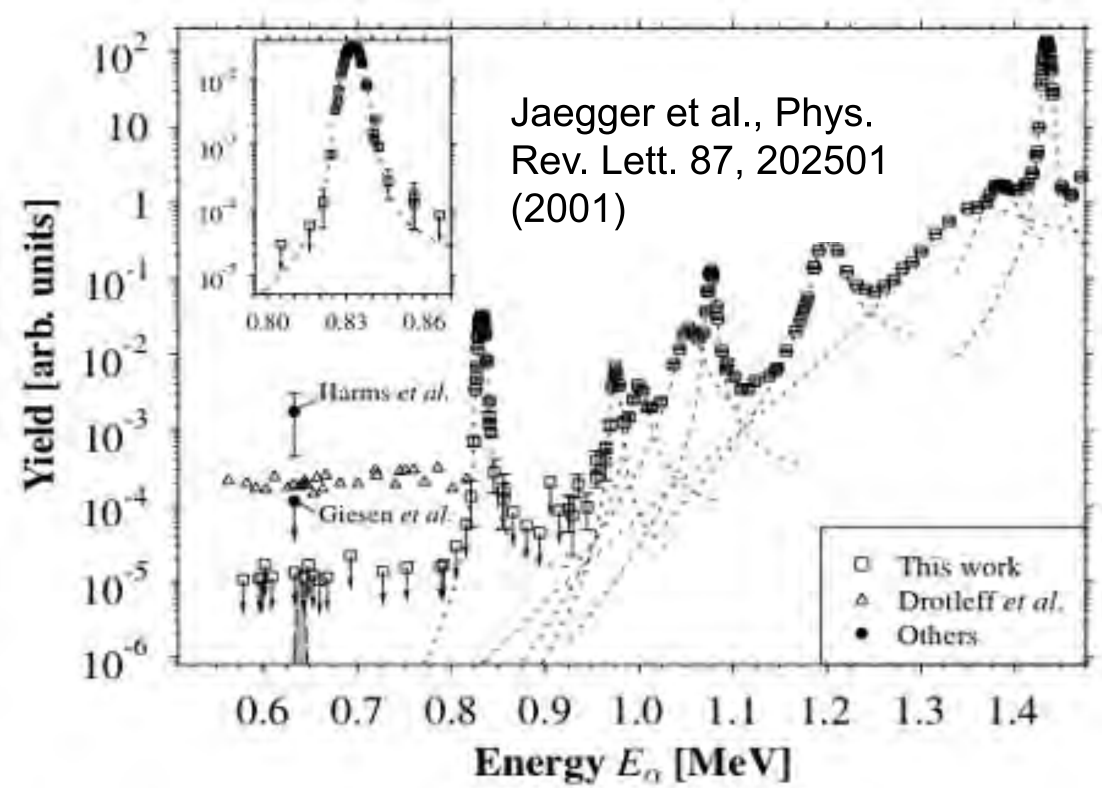
Countrate estimates $^{22}Ne(\alpha,n)^{25}Mg$

Astrophysically relevant range E_x = 10.9 – 11.5 MeV

- High density, resonances not resolved, widths not known

✓ The α-particle separation energy in ^{26}Mg is at S_α=10.6 MeV

- Assume hypothetical resonance at E^R_{CM} = 537 keV (E_a = 635 keV)
- $\omega\gamma$ < 60 neV [Jaeger et al.]
- Thick, ^{22}Ne:Ni = 2:1 target, **(active region ≈30 keV thick)** e.g., produced using 80 keV ^{22}Ne implanted in ≈ 0.5 mm Ni backing



Assumptions:

I (^{4}He) ≈ **500 μA** and

detection efficiency of **η ≈ 50%**

10 counts / hour

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

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

✓ Astrophysically relevant region E_r^{CM} = 150 keV to E_r^{CM} = 230 keV

- Free from narrow resonances
- Assume slowly vayring S-factor down to E^R_{CM} = 200 keV (E_a = 260 keV) [Drotleff et al.]
- S-factor is approximately S = 10^6 MeV·barn
- $\sigma \approx 10^{-13}$ b
- Thick, ^{13}C + Cu target (evaporated/implanted, **active region ≈ 30 keV** thick)

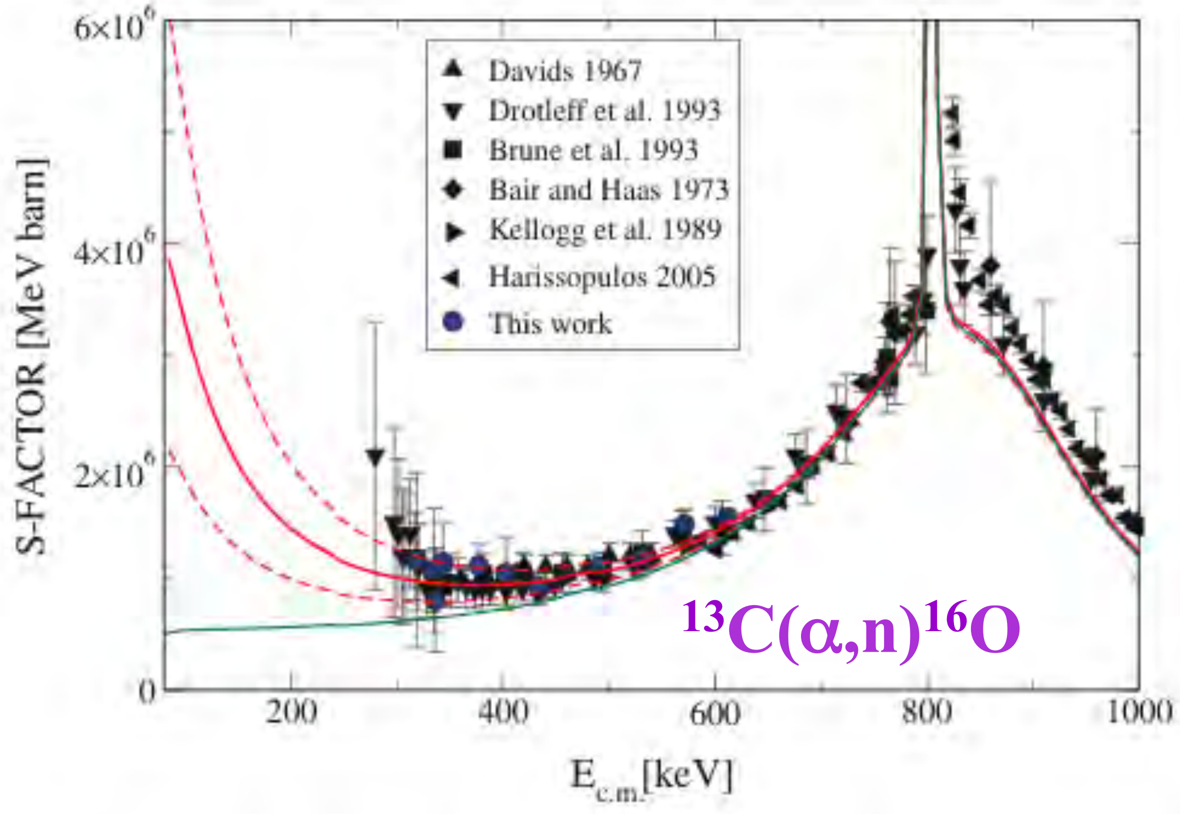
Assumptions:

I (^4He) ≈ **500 µA** and detection efficiency of **η ≈ 50%**

2.5 counts/hour

Minimum measured E: 270 keV [Drotleff]

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



International framework

Existing and proposed facilities

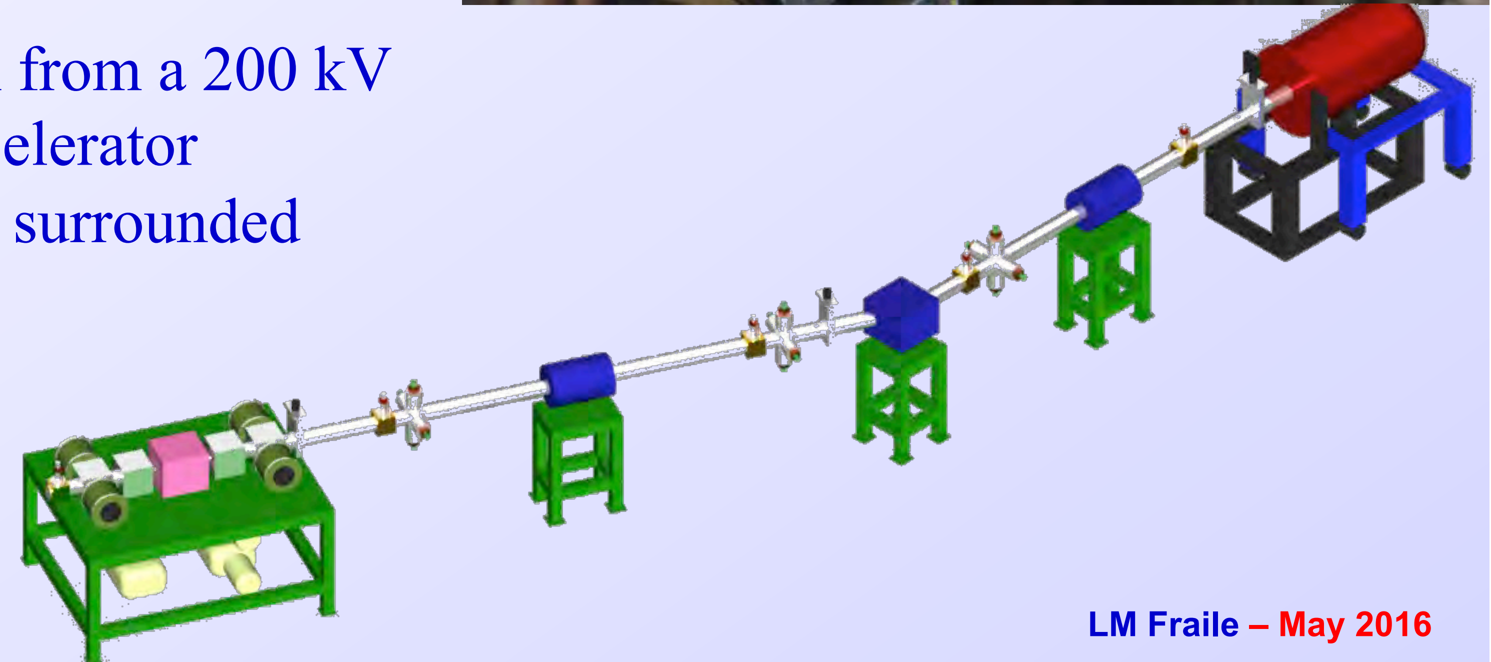
LUNA 400kV - LNGS

LUNA-MV - LNGS

Funded "premium project"
Italian Ministry - 5 M€
2018/2019

CASPER – Sandford - USA

Proton and Helium beam from a 200 kV to 1 MV electrostatic accelerator
Extended ^{22}Ne gas target surrounded by ^{3}He neutron detector



Project in China

LSC Proposal – LOI-12-2012

✓ European expert committee (of ESF) statement in Long Range Plan for Nuclear physics:

> *„The effort to put into operation a machine of several MV in a European deep underground laboratory should be considered with the highest priority. This could be achieved in the next three to five years with the opportunity to measure one or two key reactions within the next decade. Considering the high scientific interest in measuring several more nuclear reactions, the case could be made to complete the programme with a second facility designed for a complementary set of measurements."*

✓ Second underground facility

→ one is not enough to measure all the important reactions in a reasonable time frame

→ independent confirmation of the results is always important, so even if LUNA could measure everything, more facilities are needed

Proposal – LOI-12-2012

✓ Underground accelerator-based facility at LSC

→ Ideal location: significant cosmic rate reduction below 1000 mwe

→ Competitive at the world scale

→ Impact on visibility of LSC as a whole

✓ Questions towards construction and implementation:

→ Ideal energy

- measurements at low energy
- matching high energy /surface reactions
- resonances/tails can be relevant

→ Detection techniques

- Can we achieve the sensitivity with "standard" detectors?

→ Background level

- Limiting factor (beam induced, rock, concrete …)

Letter of intent

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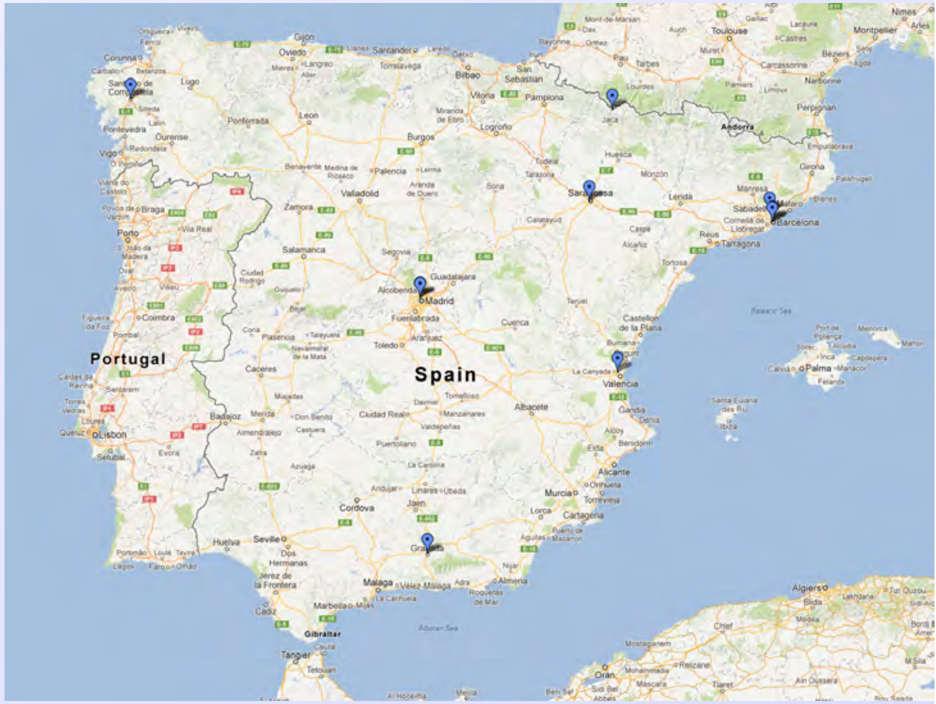

Global support from community

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→ T. Motobayashi (RIKEN, Japan)
→ J. Aysto (U Jyväskylä, Finland)
→ …

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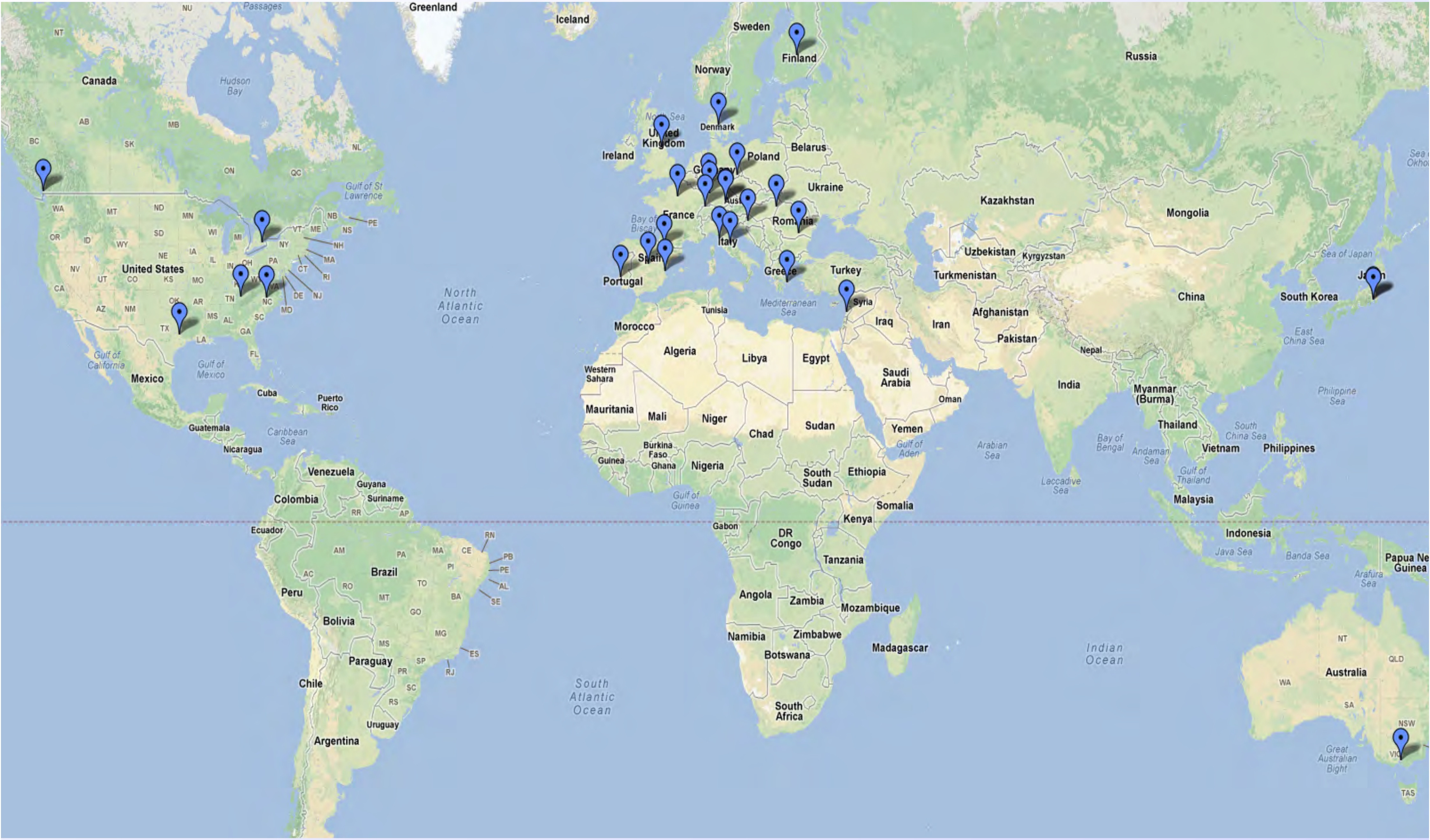


Infrastructure

Accelerator

3.5 MV HVee Singletron (2.0 MV HVee)

Terminal V: 0.2-3.5 MV

Terminal V ripple: 200 Vpp

V stability (at 2250 kV): ±150 V

X-ray radiation level (at 1 m from the tank): less than 2 μSv/h

H+ beam current (after the magnet): 100 μA

RF ion source (H+, He+)

Other options considered for future upgrades

D.J.W. Mous et al., NIM B130 (1997) 31-36

✓ AIFIRA (CENBG Bordeaux)

→ measured Ripple: V_{pp} = 28 V at 2250 keV

→ Beam current @ 3.5 MeV > 80 μA (He^+), good beam brightness

Possibility of beam induced background measurements at their lab

Other options… recycle!

NEC 5SDH-2 Pelletron

"Recycled" from Aarhus laboratory

In working condition

Similar to Jyväskylä VTT (materials)

Tandem 1.7 MV terminal voltage

H and He source, maximum $^{4}He^{++}$ energy 5.1 MeV

Currents ~1 μA

Still available

A similar NEC pelletron under exploration

Needs to be refurbished

Lower energy

???

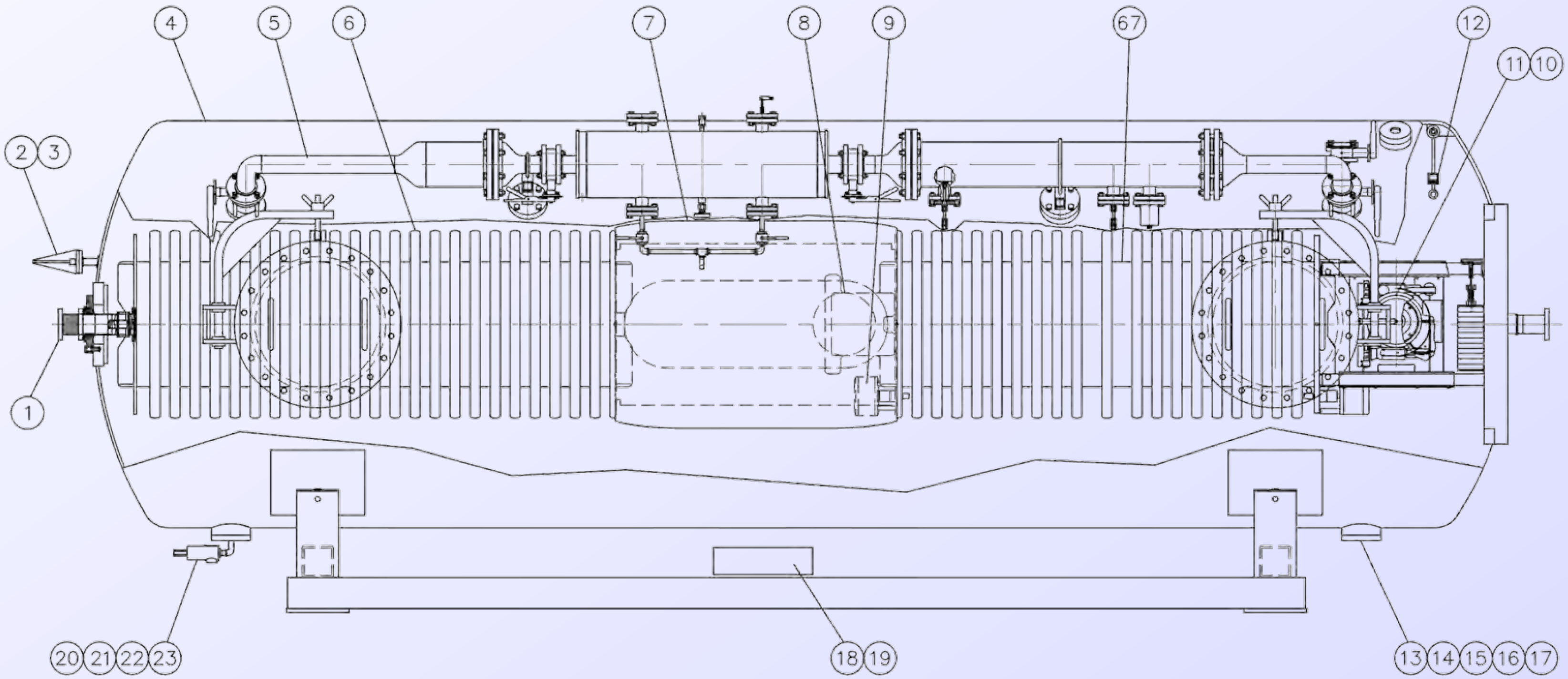
NEC single-ended / tandem **Pelletron**

10.5SDH-4 Pelletron

3.5 MV and 600 μA nominal

Terminal V ripple via corona probe and the generating voltmeter

7 m long tank, SF_6



In principle this solution will perfectly fit

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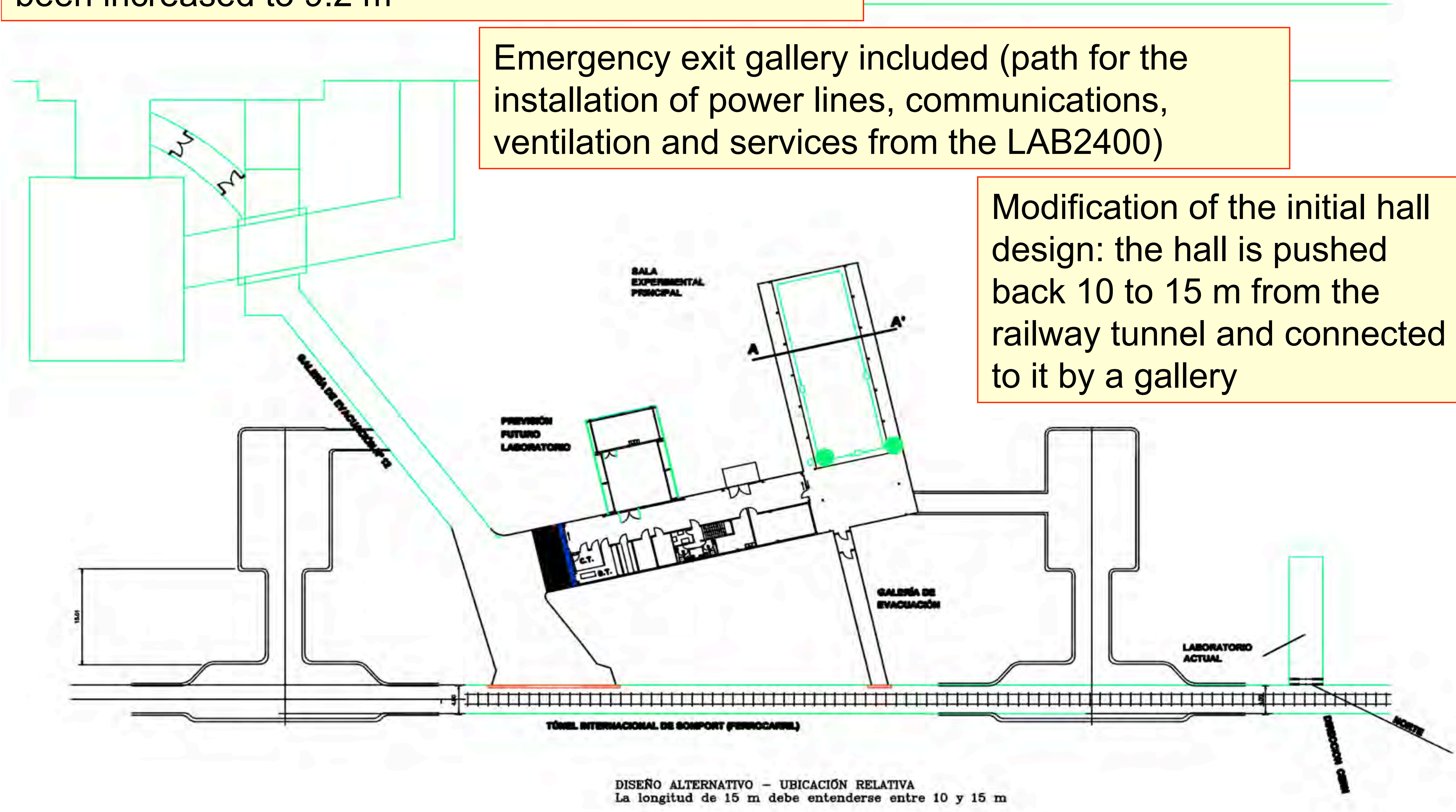
Cave design study - 2012

Modifications to dimensions: height at the arch has been increased to 9.2 m

Emergency exit gallery included (path for the installation of power lines, communications, ventilation and services from the LAB2400)

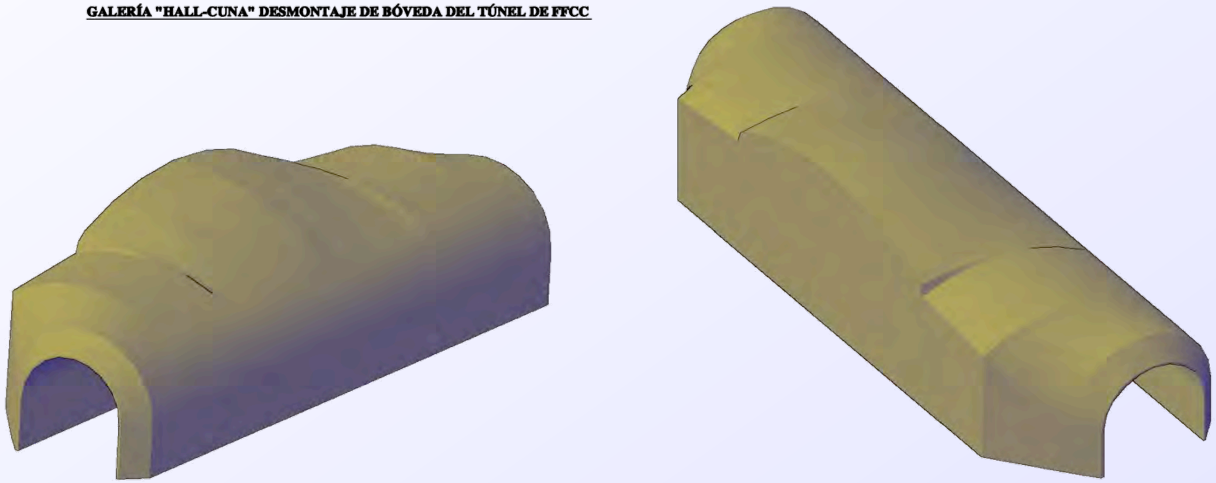
Modification of the initial hall design: the hall is pushed back 10 to 15 m from the railway tunnel and connected to it by a gallery

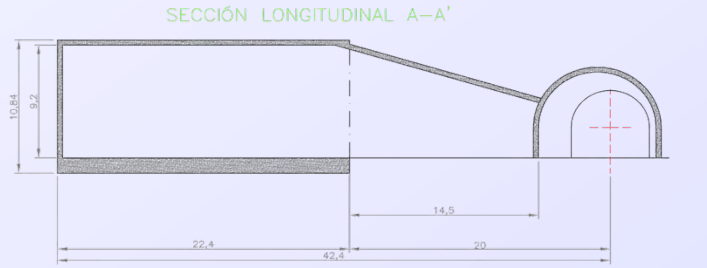


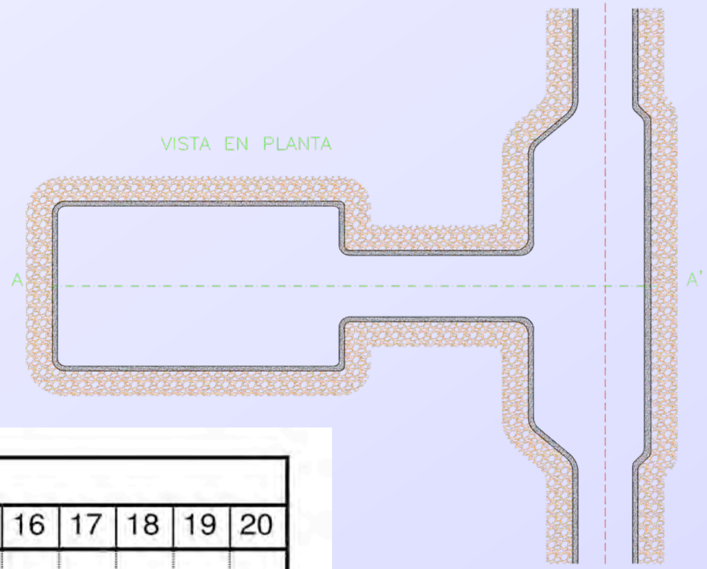
Pre-project for the cave

Option B considered in simulations

GALERÍA "HALL-CUNA" DESMONTAJE DE BÓVEDA DEL TÚNEL DE FFCC







PLANNING DE EJECUCIÓN																					
MESES		01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
ESTUDIOS PREVIOS - GEOTECNIA - PROYECTO																					
	Consultas y pedidos																				
	Elaboración																				
CÁMARA - ENTRONQUE - ENSANCHE TÚNEL																					
	Consultas y pedidos																				
	Ejecución																				
EDIFICACIÓN, INSTALACIONES Y DIVERSOS																					
	Consultas y pedidos																				
	Fabricación y montaje																				

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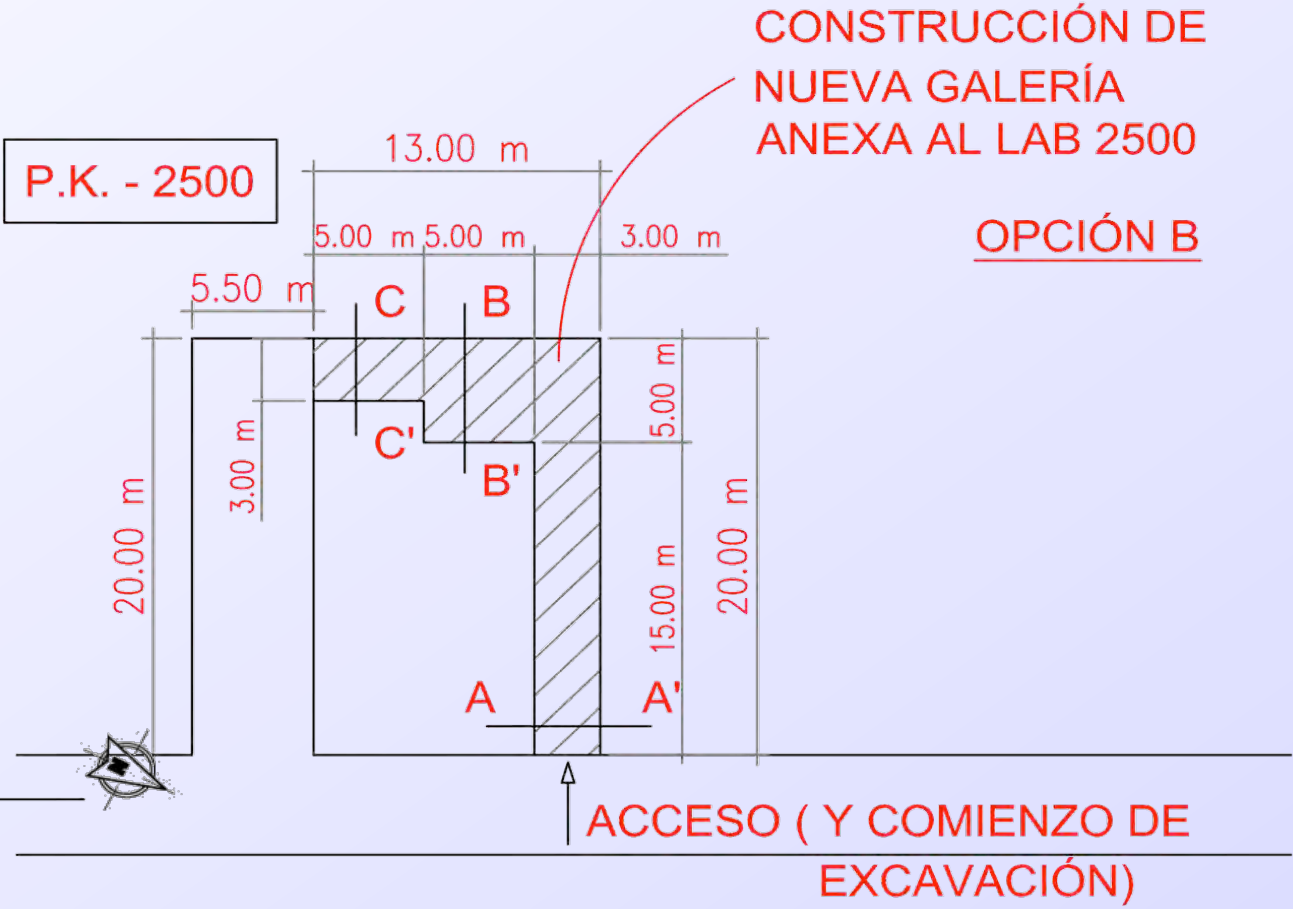
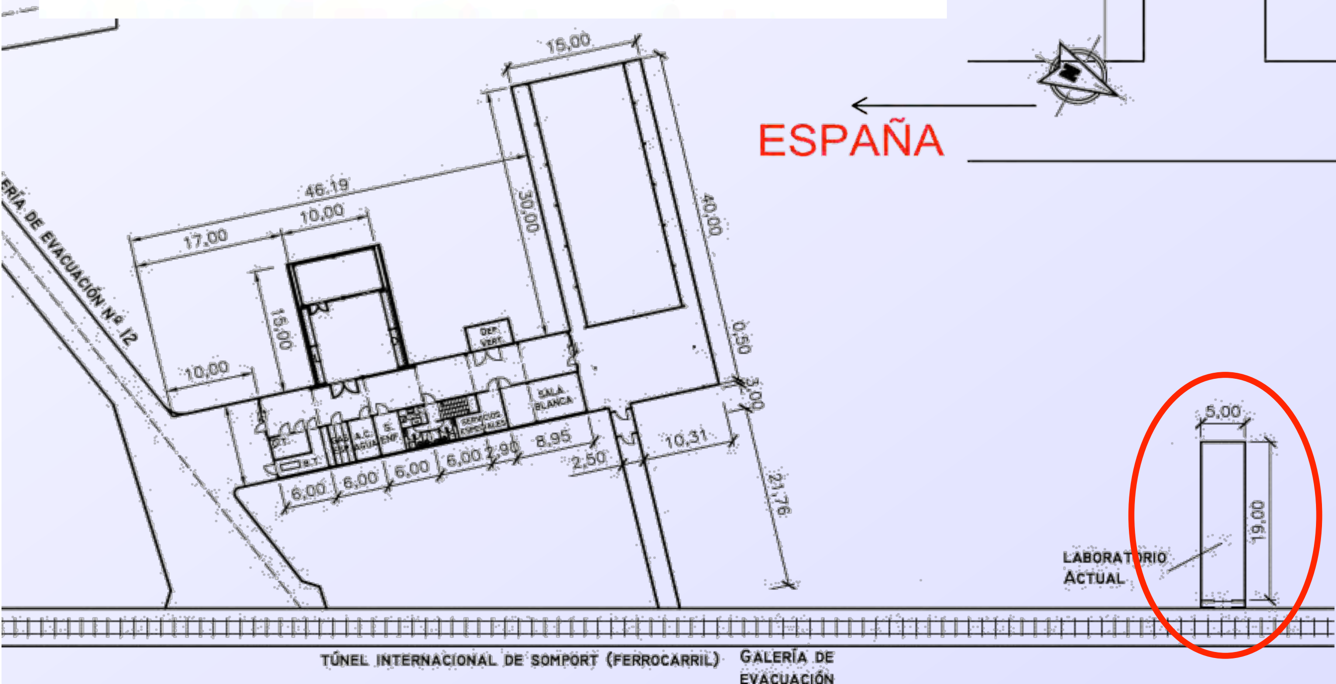
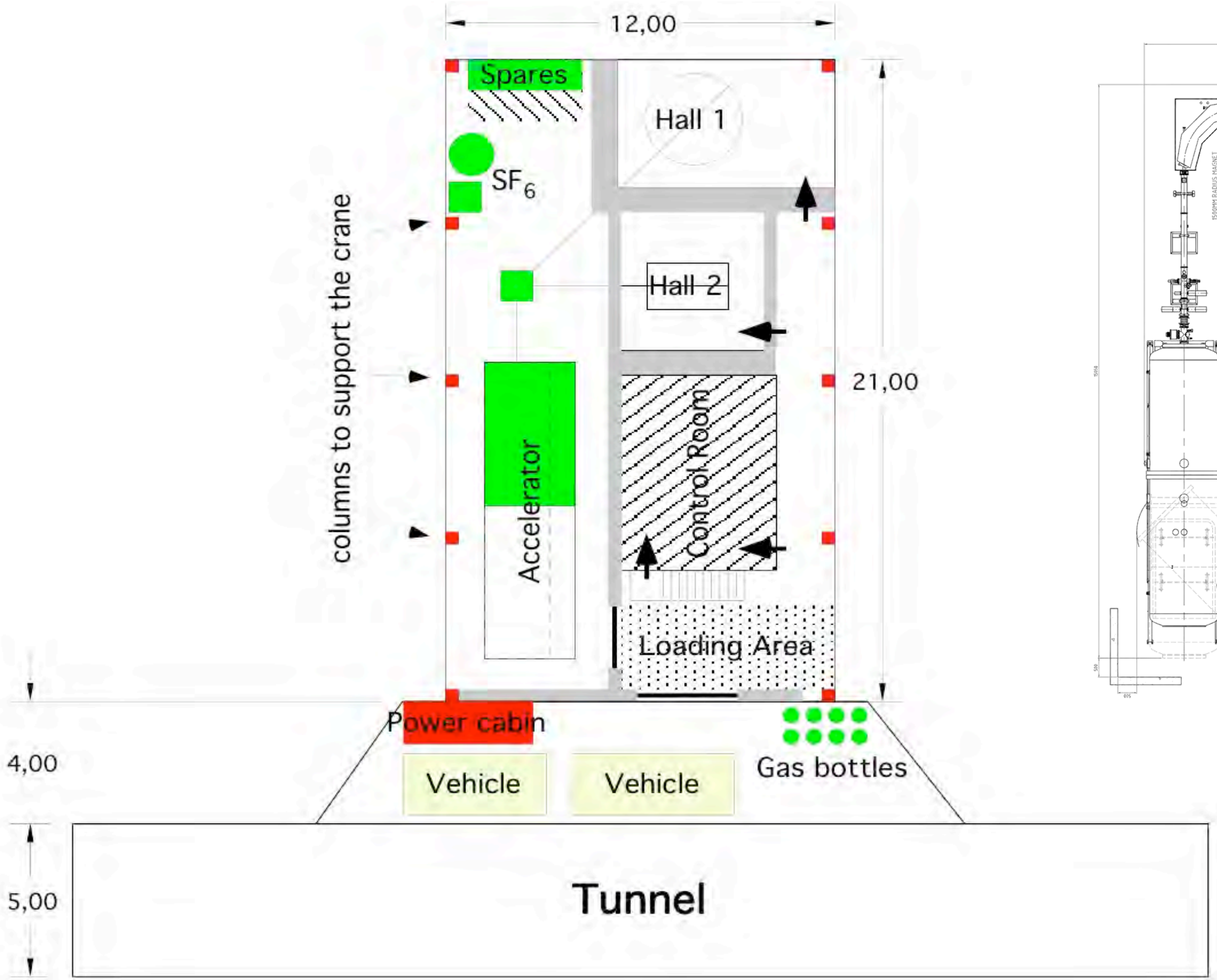
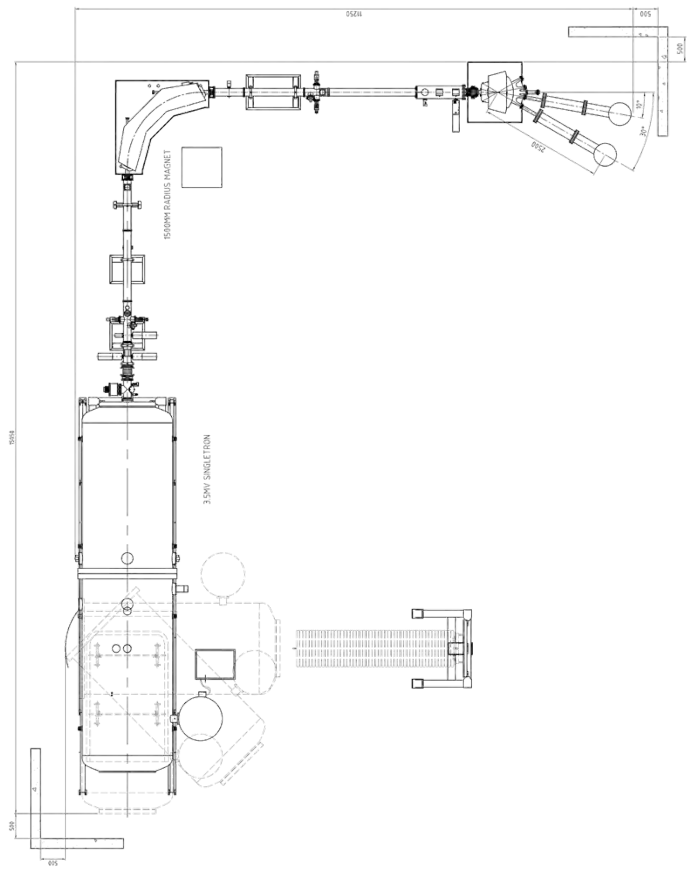
Exploratory LAB2500 option





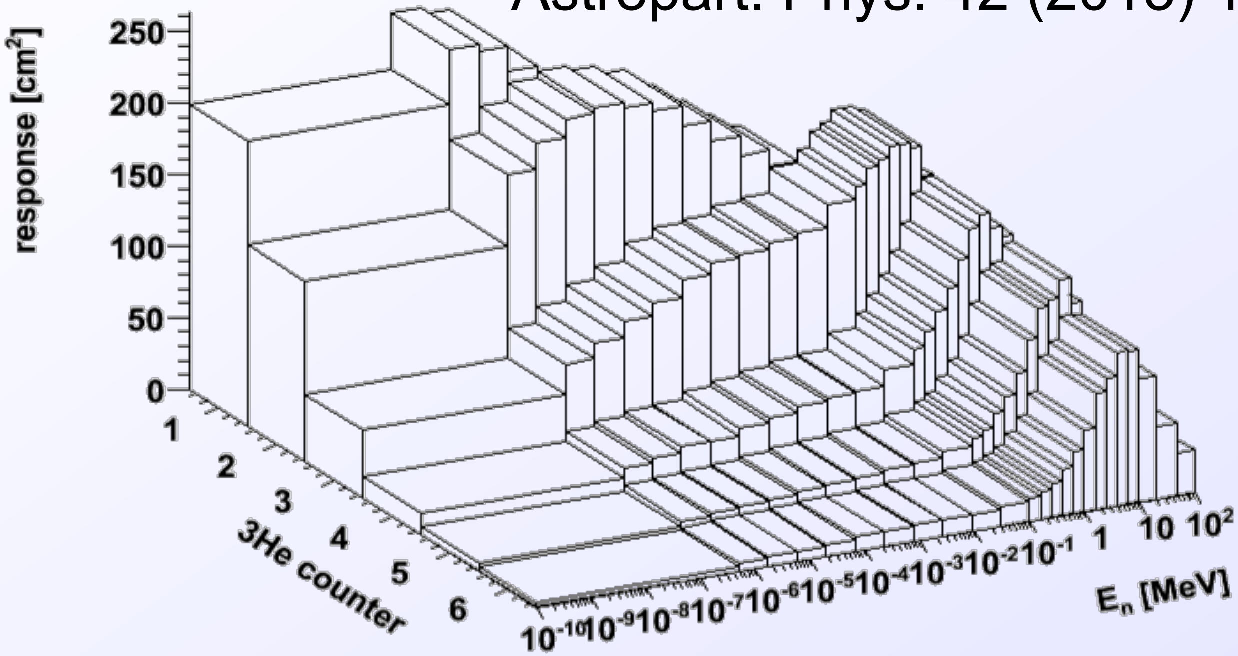

12,00
Spares
Hall 1
SF6
Hall 2
columns to support the crane
21,00
Accelerator
Control Room
Loading Area
Power cabin
Gas bottles
4,00
Vehicle
Vehicle
5,00
Tunnel



Neutron detection
Background and simulations

Neutron flux

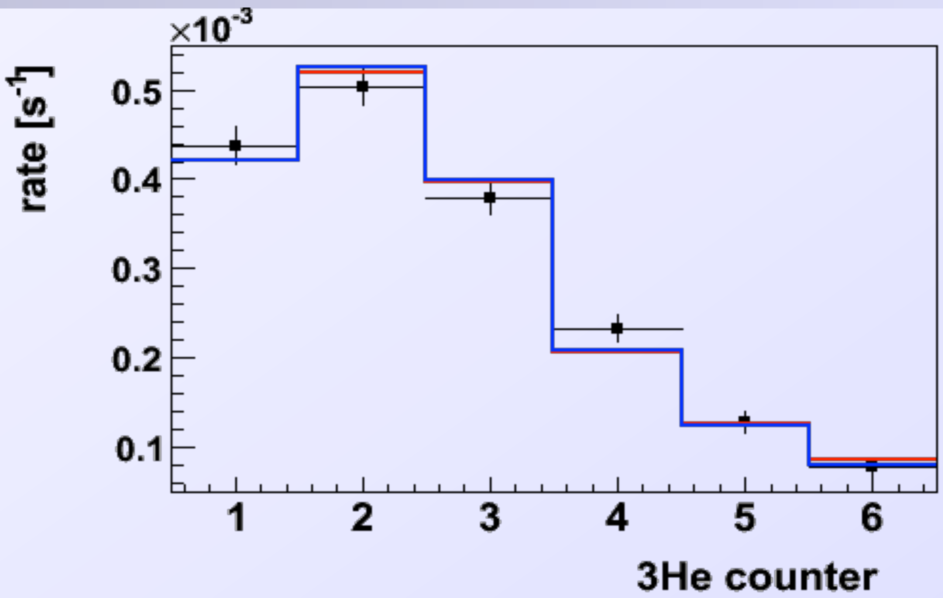
[M.D. Jordán, J.L. Taín et al. Astropart. Phys. 42 (2013) 1]

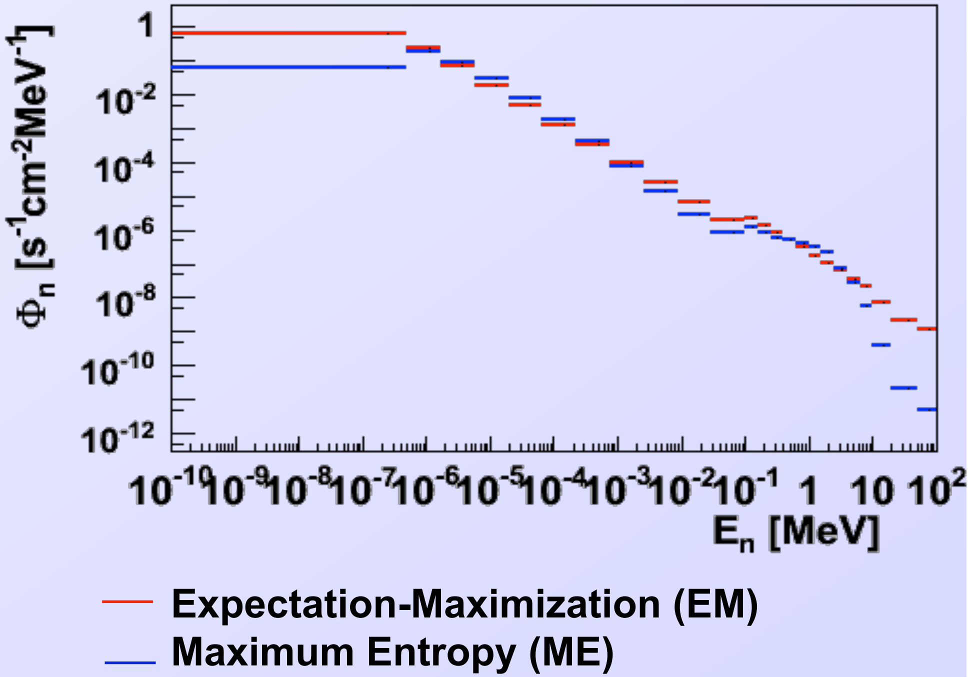


Response used for deconvolution

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

- ✓ Deconvolution for rates and **fluxes**
- ✓ Good agreement (some exceptions)
- ✓ $\Phi_{\text{hall A}} = (1.4 \pm 0.2) \times 10^{-5}$ n / cm^2 s





Feasibility for measurement (α,n) cross sections

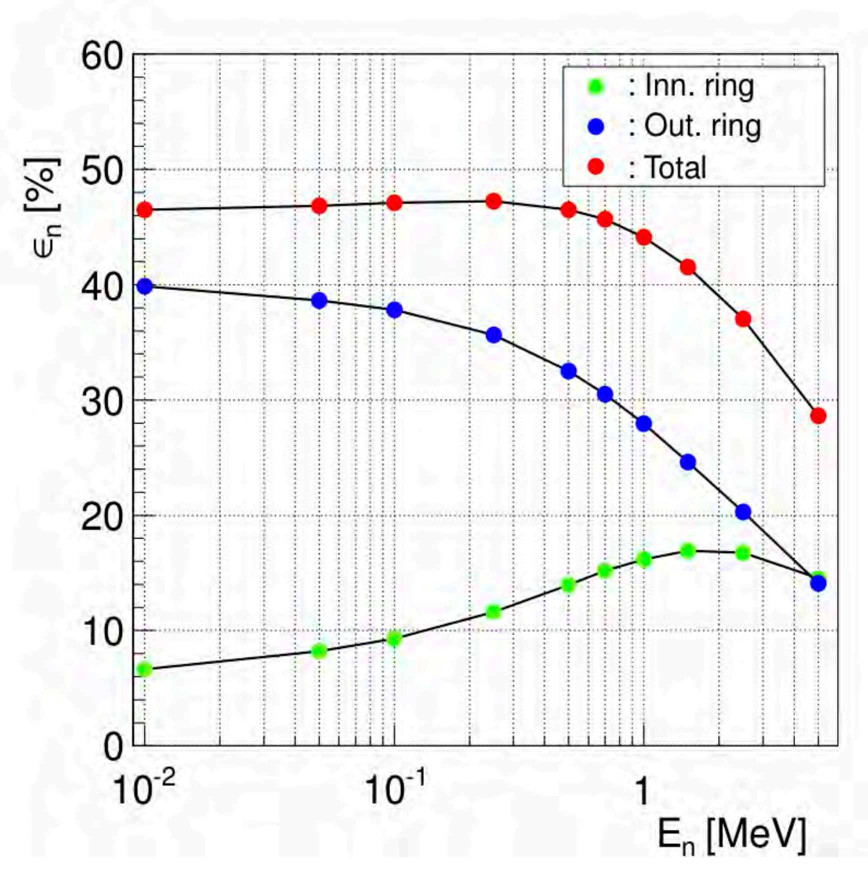
- ✓ **^{3}He proportional chambers embedded in a PE matrix**
  - → large detection efficiencies ~50%
  - → clean signal (…see below)
- ✓ Simulations of background event rate
  - → EFFICIENCY: MCNPX Monte Carlo
    - **20 ^{3}He tubes** in two rings
    - Central hole 11 cm diameter
    - PE neutron moderator of **50 × 50 × 80 cm^3** and above
  - → Background rate from measured distribution

6×10^{-4} to 9×10^{-4} s^{-1}

8×10^{-6} to 6×10^{-5} s^{-1} for increased PE

Increased sensitivity for a fraction of picobarn is possible

J.L. Taín et al., J. Phys. Conf. Series 665 (2016) 012031



efficiency for detecting neutrons emitted randomly from the center of the detector as function of energy

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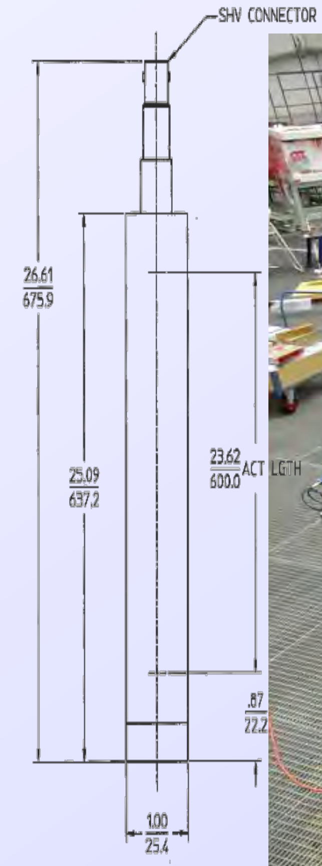
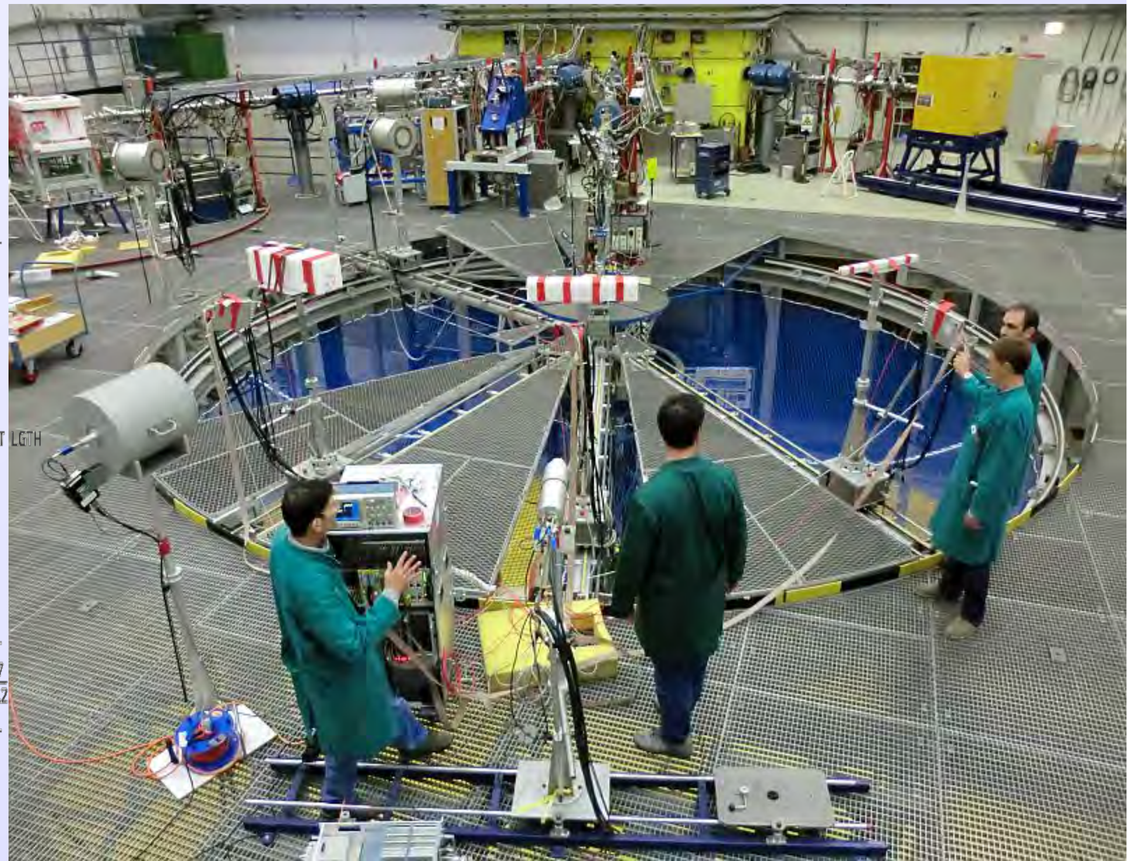
Neutron detector for astrophysical (α,n) reactions

✓ Characterization of ^{3}He counters at PTB

→ Response of the full BELEN-48 detector, suited for (α,n) reactions:

- calibrated with several reactions, **n** energies in the relevant range
- 48 ^{3}He tubes, about 60% efficiency
- needs reduction of n background rate





Neutron detector for astrophysical (α,n) reactions

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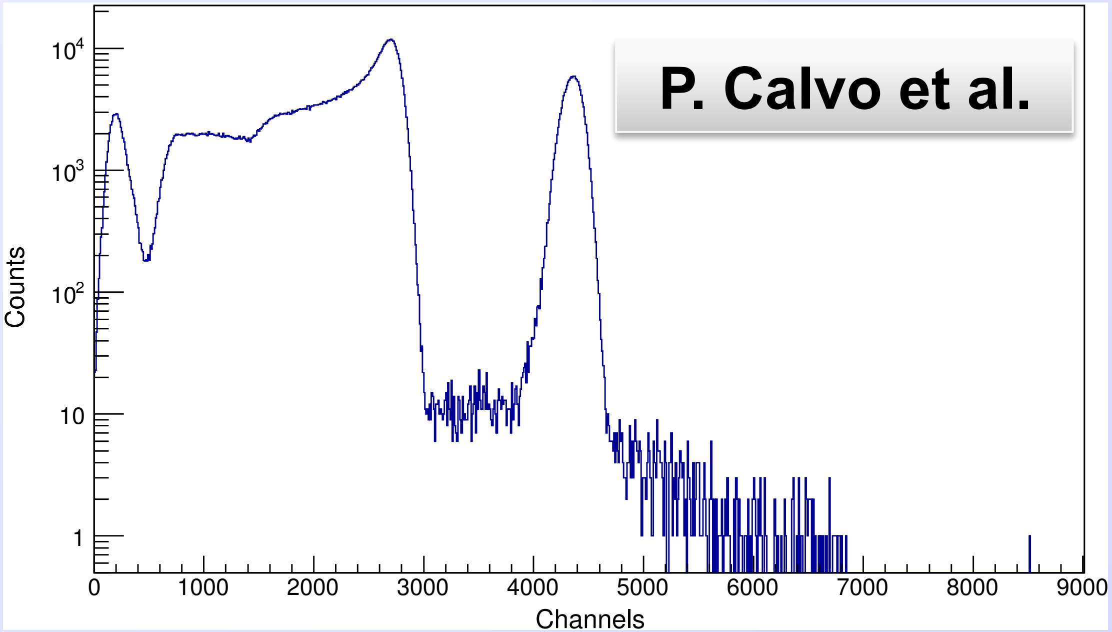
→ Individual ^{3}He tubes embedded in PE blocks

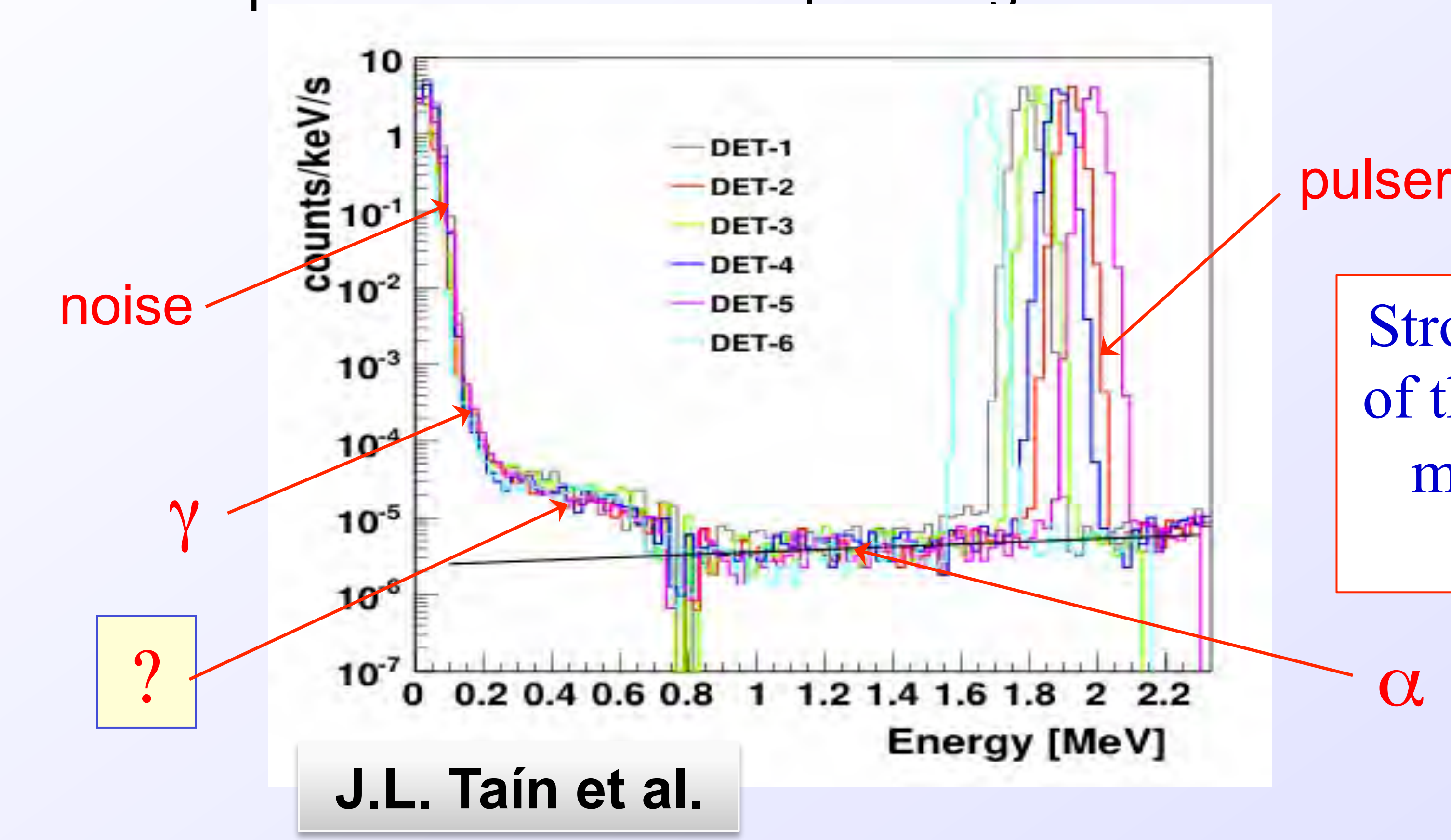
- Irradiated with 5 well-characterized neutron beams at $110 < E_n < 2240$ keV
- Complementary to the measurements of the LSC **n background** measurement
- Verification of the detector response & reduce systematic uncertainty on the measured neutron fluence at Hall A.

E_n (MeV)	Response (cm^2)		
	Matrix #1	Matrix #3	Matrix #5
0.139(7)	7.6(4)	40.7(10)	7.2(2)
0.565(4)	4.2(10)	52.1(8)	17.9(6)
1.20(5)	1.91(14)	40.0(10)	21.6(4)
2.50(6)	2.0(9)	51.5(6)	46(4)



Low background detectors

Neutron spectra with neutron capture signals removed



M.D. Jordán *et al.*, AP Physics 42 (2013) 1

Strong intrinsic background of the ^{3}He tubes observed in measurement of neutron field at Hall A

✓ Component in the region 200 to 800 keV

→ not clear origin and overlaps with neutron signals

→ rate from $5\times10^{-4}\,s^{-1}$ to $9\times10^{-4}\,s^{-1}$ (20% from α-component)

→ needs reduction for measurements

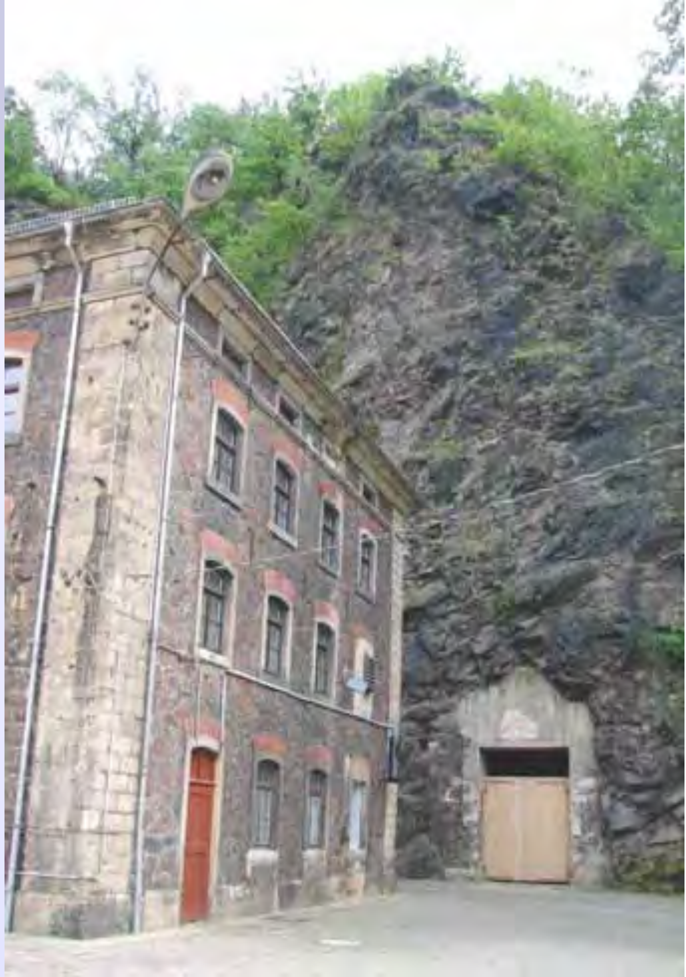
Measurement of intrinsic background in ^{3}He tubes

- ✓ It may limit the lowest measurable (α,n) cross-section
- ✓ Investigate its origin and how to reduce it
  - → Two small identical tubes, one with internal C coating for α-particle stopping
  - → Modified DAQ to record pulse shapes and investigate signal origin from PSA
  - → Different preamplifiers to investigate electronics influence
  - → Normalization to previous measurements with 1 of the original BELEN ^{3}He tubes

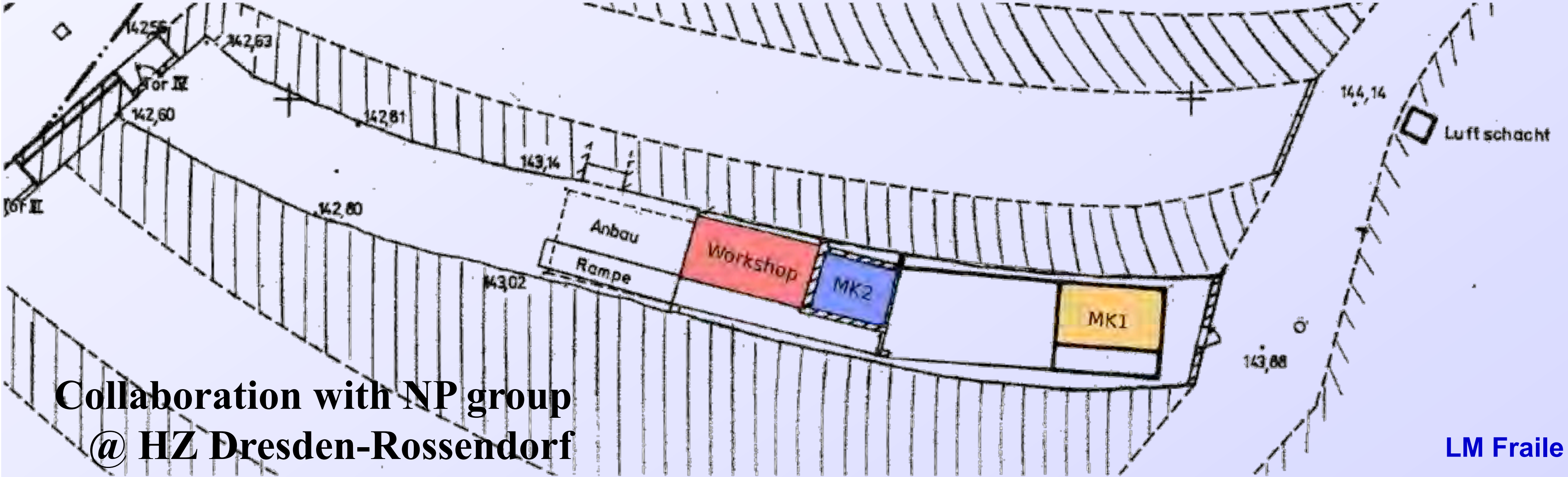
Under analysis

J.L. Taín *et al.*

Measurements at Felsenkeller



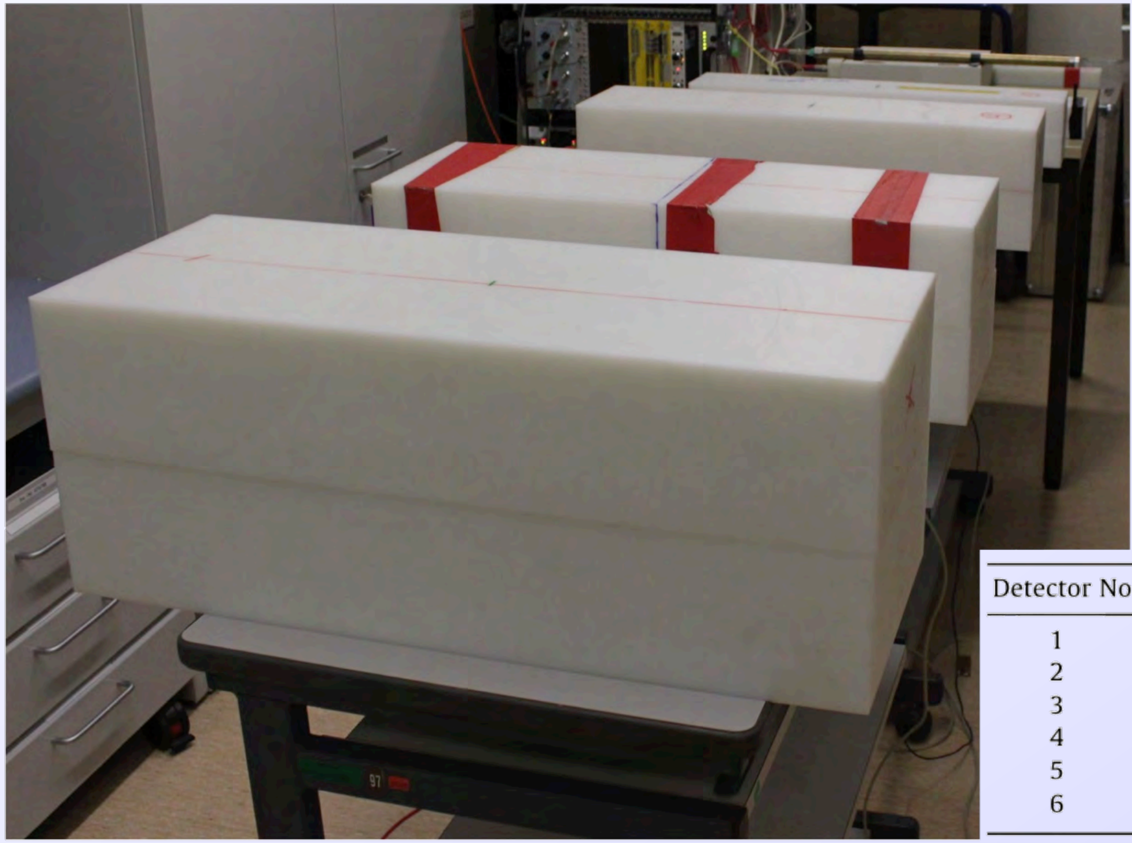
- ✓ "Shallow" underground facility in Dresden
  - → Seven HDPE n-moderated ^{3}He counters from the BELEN collaboration
    - 6 already employed at the LSC
    - Read out by the gasIFIC-TL *digital* DAQ
  - → MNCPX simulations
  - → Measurements **15 Dec 2014 – 12 Feb 2015**

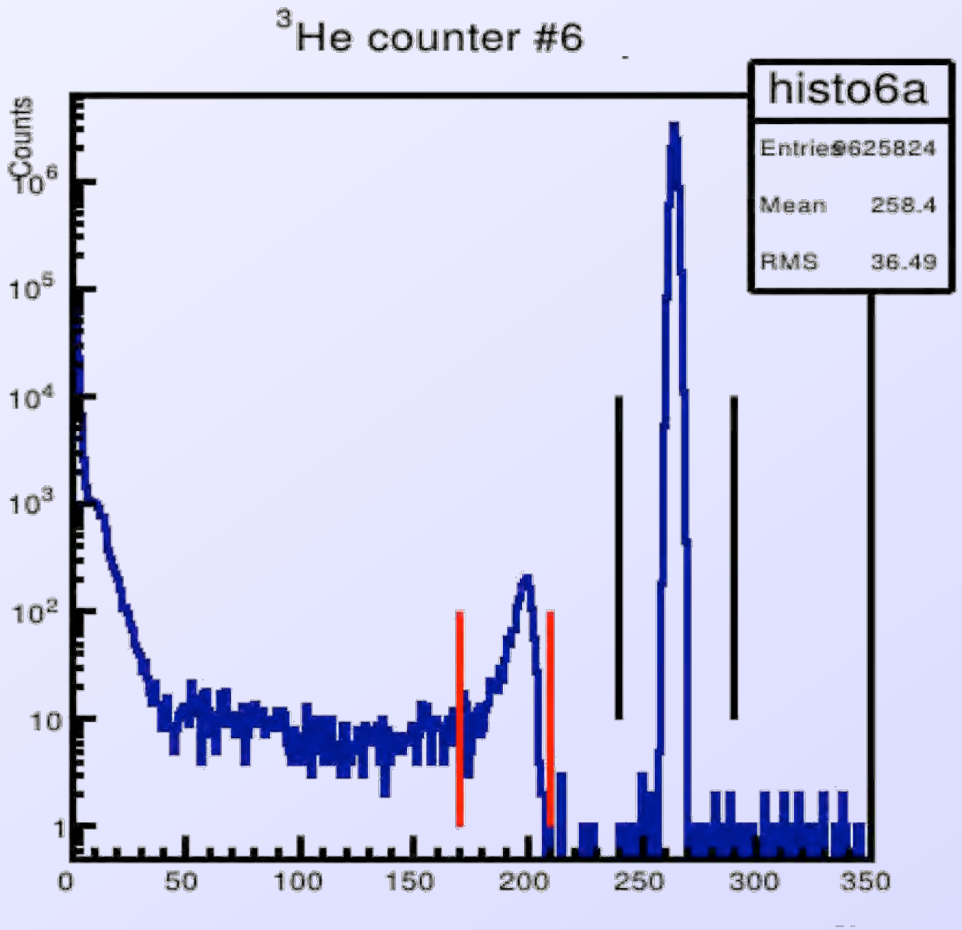


Collaboration with NP group @ HZ Dresden-Rossendorf

Felsenkeller

- ✓ Depth: 110 m.w.e. (similar for all)
- ✓ Shielding:
  - → Workshop: none
  - → MK1: Serpentinite (radiopure rock)
  - → MK2: Steel, lead

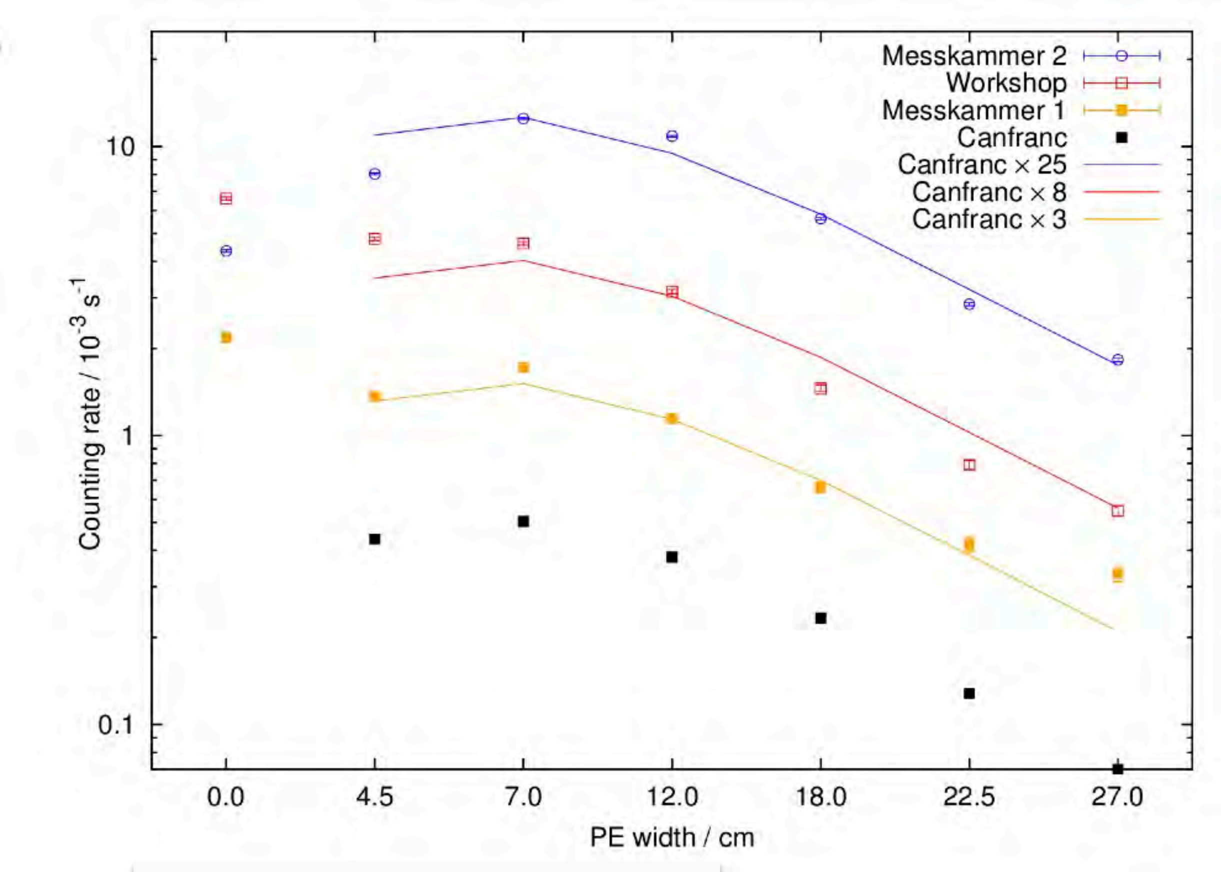




Detector No.	PE block size (cm^3)
1	4.5 × 4.5 × 70.0
2	7.0 × 7.0 × 70.0
3	12.0 × 12.0 × 70.0
4	18.0 × 18.0 × 70.0
5	22.5 × 22.5 × 70.0
6	27.0 × 27.0 × 70.0

M. Grieger, D. Bemmerer et al.

Preliminary results



M. Grieger et al.

- no shielding: thermal neutrons
- 27 cm PE: high E neutrons

Needs *bare counter response* + full deconvolution to obtain fluxes

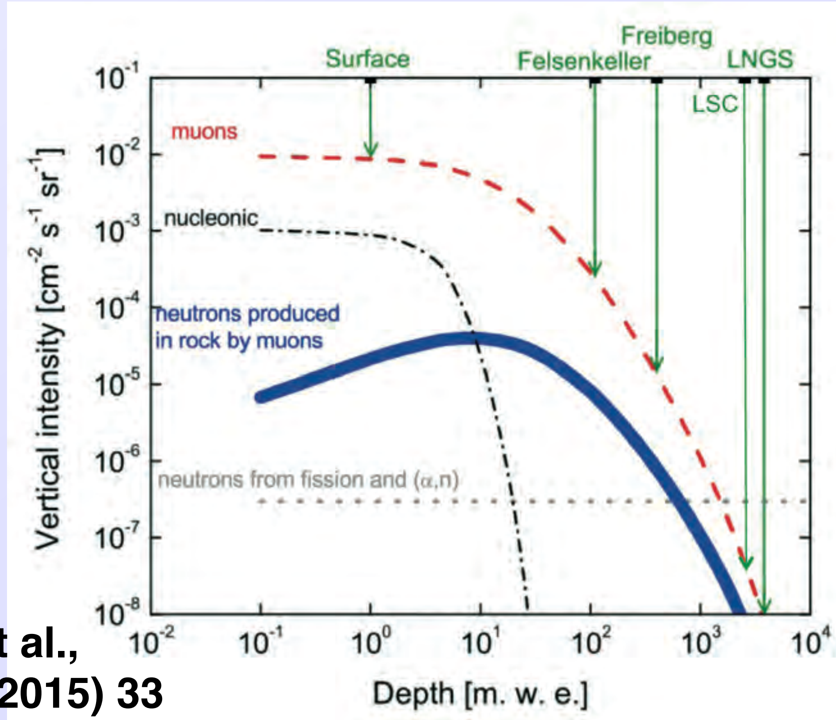
Consistency with previous measurements to be checked:
$\Phi_{PTB}=(5.7 \pm 0.7) \times 10^{-4}$ cm^{-2} s^{-1}

A. Zimbal et al., AIP Conf. Proc. 1549 (2013) 70

→ MK1: less (α,n) from radiopure rock

→ MK2: more neutrons from (μ,n) and (n,xn) in Pb

→ Interference effects?



T. Szücs et al., EPJ A 51 (2015) 33

Measurements at Felsenkeller

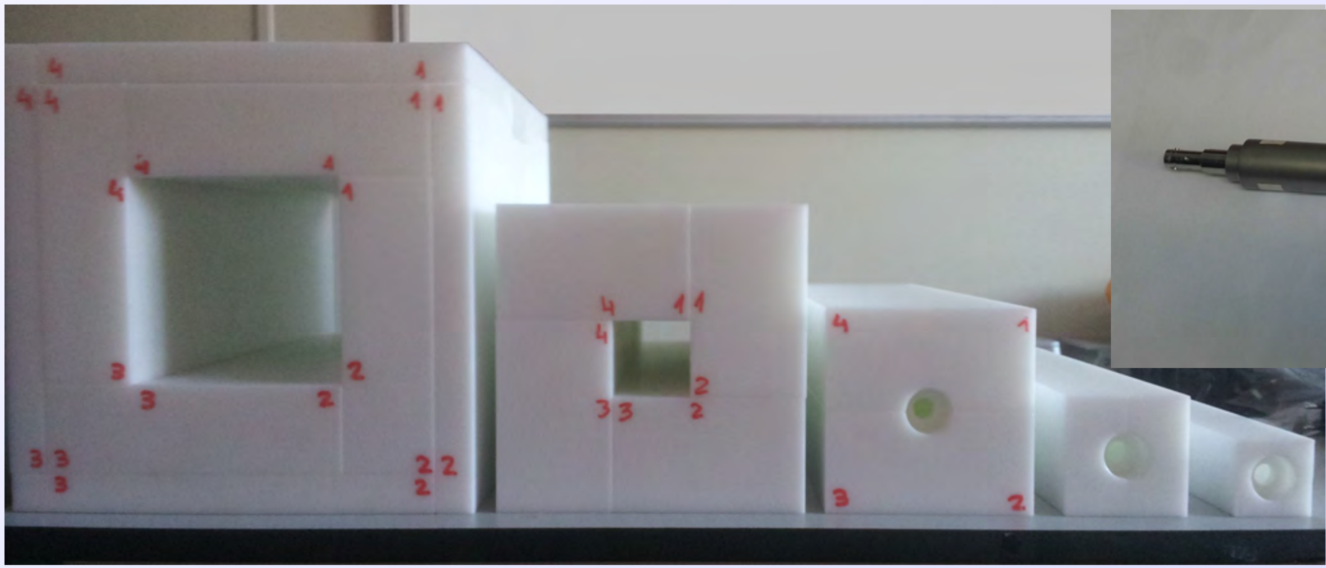
✓ Measurements to be complemented

→ Smaller 3He counters

→ New set of PE

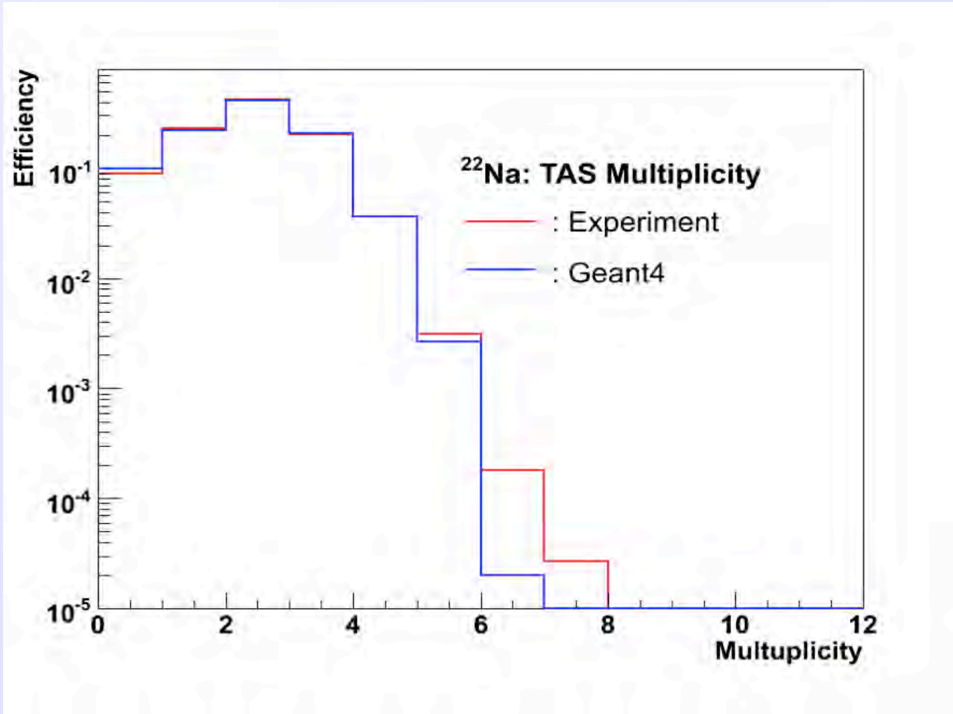
→ PE-Pb-PE matrix with enhanced efficiency at E_n > 10 MeV

June 2016



Detection systems for radiative capture

- ✓ Gamow peak of some α-induced reactions at "high" energy
  - → **$^{22}Ne(\alpha,\gamma)^{25}Mg$**, T_9=0.35 peaks at E_{LAB} ~ 900 keV
  - → **$^{12}C(\alpha,\gamma)^{16}O$** for T_9=0.35, E_{LAB} ~ 600 keV
- ✓ Total absorption γ-ray spectrometer
  - → Valencia segmented BaF_2 VTAS
  - → Cascade energy + multiplicity distributions



Neutron sensitivity of inorganic scintillators

✓ (p,γ) or (α,γ) measurements

→ neutrons are easily produced by accelerators

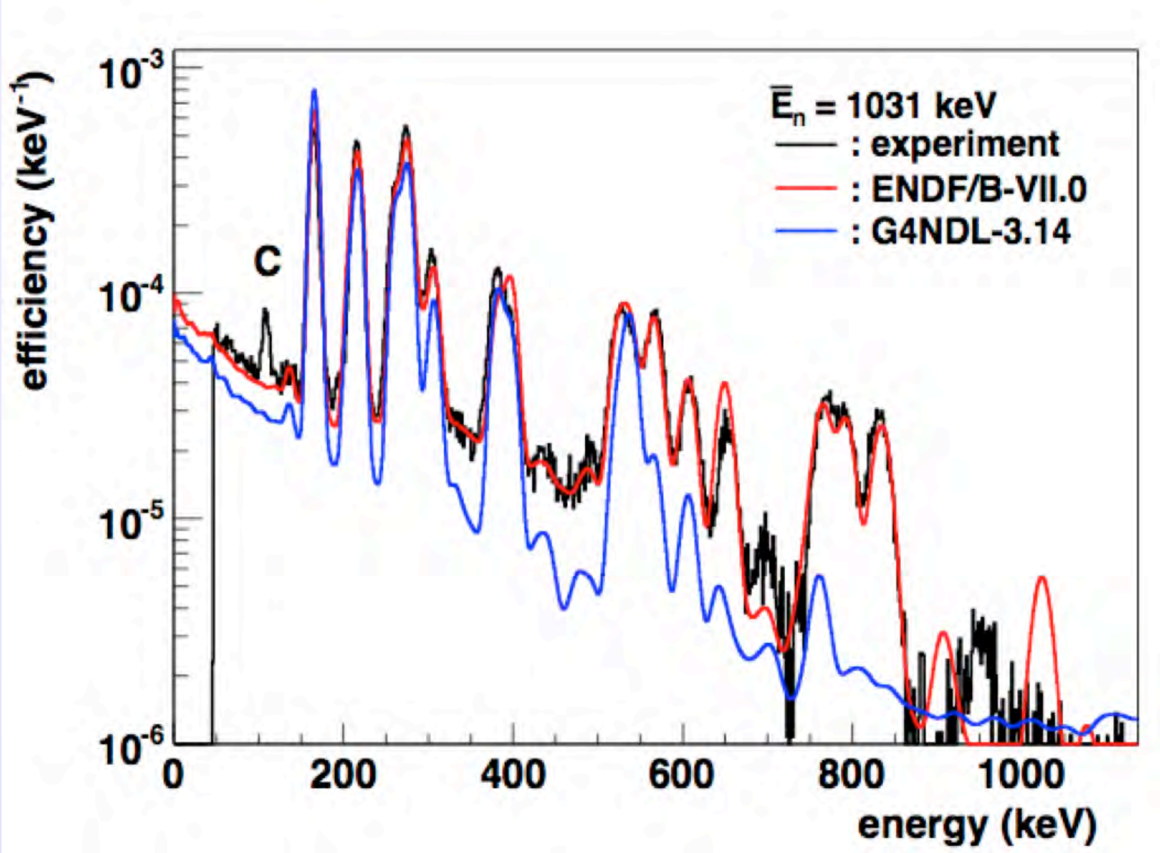
→ induce signals on scintillation detectors through capture or inelastic scattering

✓ $LaBr_3$(Ce)

→ n inelastic scattering reproduced by simulations

→ n energies below the inelastic threshold (42 keV and 128 keV) require new cascade generator

→ Dependence in Geant4 libraries



Approximate cost estimate

Material	Cost (k€)	Comment
Accelerator, beam lines, analysing magnet	450	Based on refurbishing an existing machine. Includes transport.
Hall construction, infrastructure & shielding	1000	Assumes expansion of existing hall. Estimate done 2012.
Neutron detection and DAQ	500	Based on BELEN costs, assuming low background materials and including support and electronics. Partly existing.
High resolution gamma detection and DAQ	200	Assuming 2 HPGe 130% detectors, with low background materials; includes electronics.
Scintillator array with DAQ	350	Based on Total Absorption Spectrometer with standard scintillators, with electronics. Partly funded.
Experimental mechanics and shielding	400	Rough estimate for reaction chambers, vacuum, supporting structures for 2 beam lines.

- ✓ Time line defined by accelerator and infrastructure
- ✓ 2 FTEs (1 Technical + 1 PostDoc) full time + collaboration

Letter of Intent

Canfranc Underground Nuclear Astrophysics

EoI-12-2009-CUNA

October 2012

Letter of Intent

A nuclear astrophysics facility for the LSC.

The sources of neutrons in the stars and other reactions of astrophysical interest

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