An underground nuclear astrophysics laboratory at LS Canfranc

L.M. Fraile

Universidad Complutense de Madrid

for the Canfranc Underground Nuclear Astrophysics collaboration

LSC – Basic facts

- ✓ Under the Pyrenees, (unused) railway tunnel
  - → Canfranc, close to Jaca (Huesca)
  - → Created in the 1980s by A. Morales, Univ. Zaragoza
- ✓ New lab built when the parallel road tunnel excavated
  - → Structures completed 2005
  - → Construction faults solved end 2009
  - → Horizontal access (road tunnel, safety tunnel)
- ✓ Managed by a consortium
  - → Spanish Ministry for Science and Innovation, the Regional Government of Aragon and the University of Saragossa.
  - 850 m of rock ~2400 mwe
  - $\phi_\mu = 3 \times 10^{-3}\ m^{-2}s^{-1}$
  - $\phi_n = 2 \times 10^{-2}\ m^{-2}s^{-1}$
  - Rn (in air) ~ 50 to 80 Bq/m^3

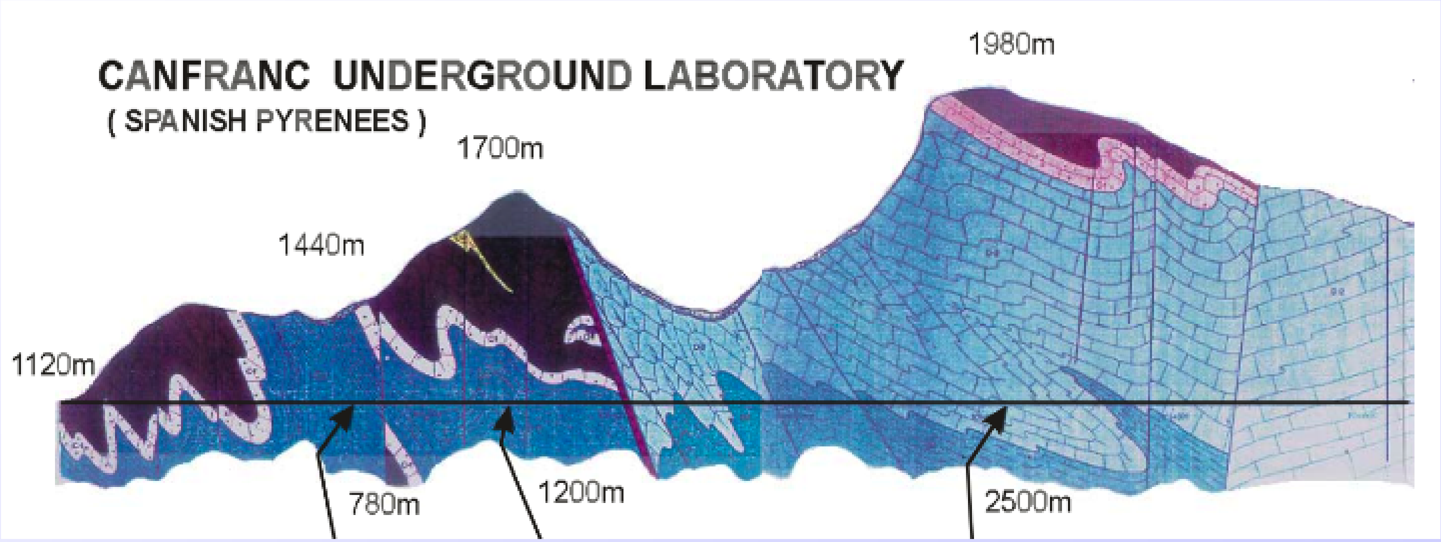
Canfranc


Santander
Castro-Urdiales
Medio Cudeyo
Getxo
Bilbao
Amurrio
Eibar
Mondragón
San Sebastián
Irun
Bayonne
Oloron-Sainte-Marie
Pau
Tarbes
Lourdes
Saint-Gaudens
Toulouse
Tournefeuille
Castres
Mazamet
Castelnaudary
Carcassonne
Béziers
Agde
Sète
Montpellier
Narbonne
Perpignan
Andorra
Figueres
Olot
Girona
Palafrugell
Vic
Palamós
Lloret de Mar
Manresa
Terrassa
Mataró
Barcelona
Viladecans
Vilanova i la Geltrú
Tarragona
Cambrils
Tortosa
Amposta
Pamplona
Medina de Pomar
Miranda de Ebro
Vitoria-Gasteiz
Logroño
Calahorra
Arnedo
Corella
Tudela
Ejea de los Caballeros
Tarazona
Jaca
Sabiñánigo
Huesca
Barbastro
Monzón
Lleida
Fraga
Caspe
Alcañiz
Utebo
Zaragoza
Calatayud
Calamocha
Teruel
Burgos
Lerma
Aranda de Duero
Soria
Cuéllar
Segovia
Sigüenza
Alcobendas
Algete
Madrid
Alcalá de Henares
Vaciamadrid
Fuenlabrada
Valdemoro
Aranjuez
Toledo
Alcázar de San Juan
Cuenca
Utiel
Requena
Castellón de la Plana
Onda
Burriana
Sagunto
Valencia
Ciutadella
Alaior
Maó
Pollença
Alcúdia
Sóller
Inca
Capdepera
Calvià
Palma
Manacor
Campos
E-5
E-80
E-804
E-7
E-90
E-9
E-15
E15
E80
E-901
100 km
50 mi


N134
E07
Peyrénère
Candanchú
Canfranc-Esta
E-7
N-330
Canfranc
Aísa
Cabrica de Marbles
Esposa
Borau
Aratorés
Castiello de Jaca
N-330
E-7
Canias
Novés
Guasillo
Banaguás
N-330a
Abay
Jaca
N-330

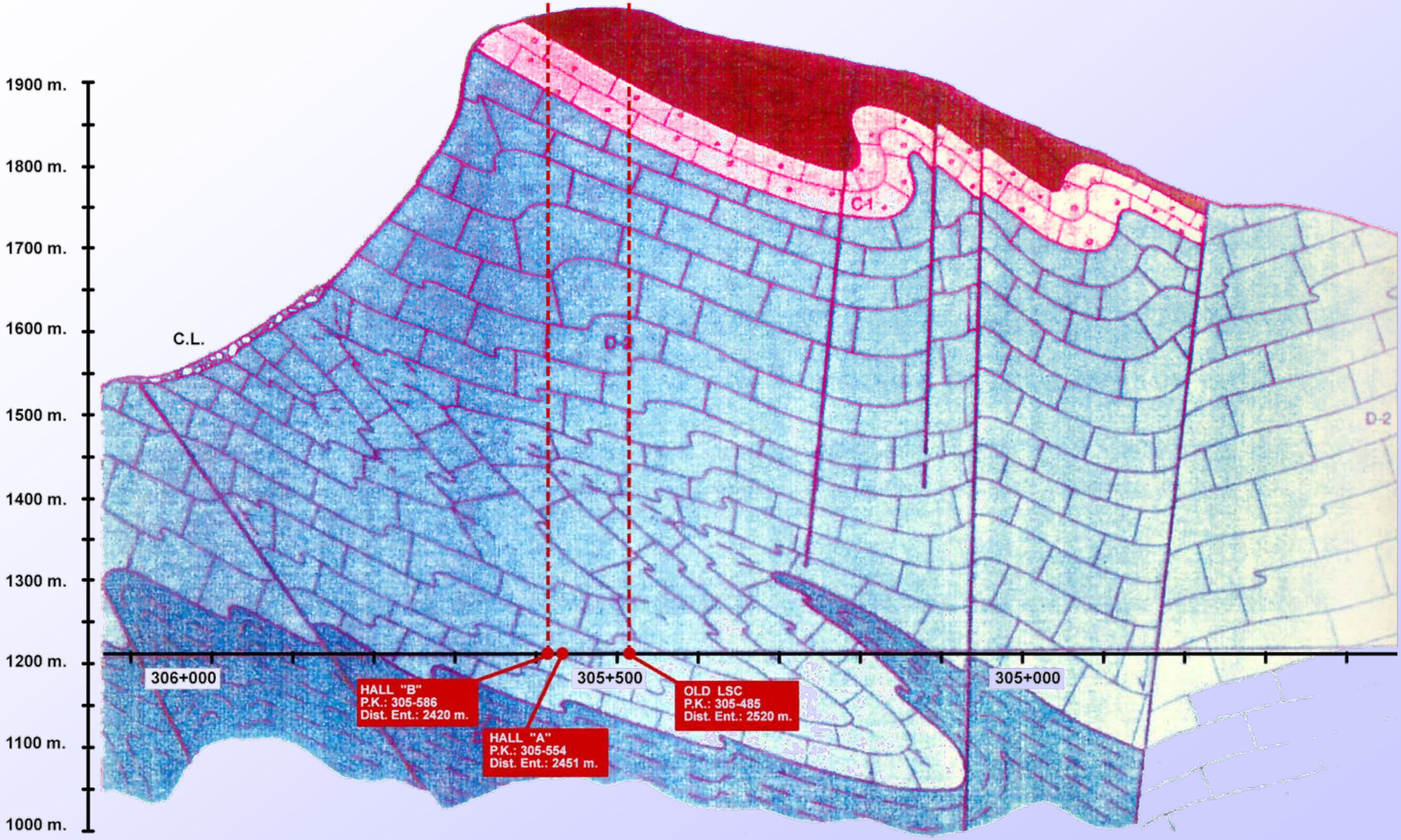
Somport Tunnel

Laboratorio Subterráneo de Canfranc

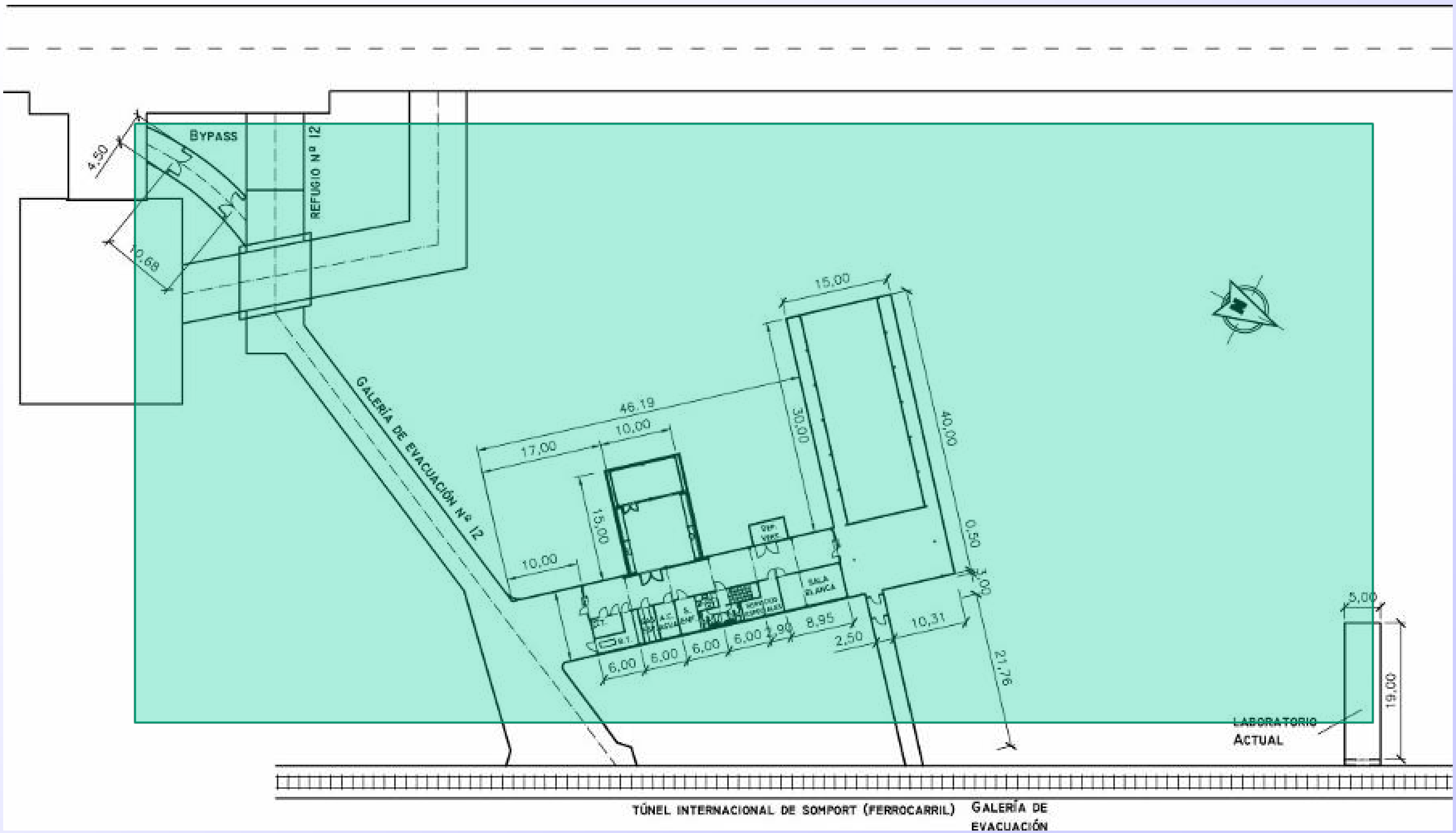


LSC

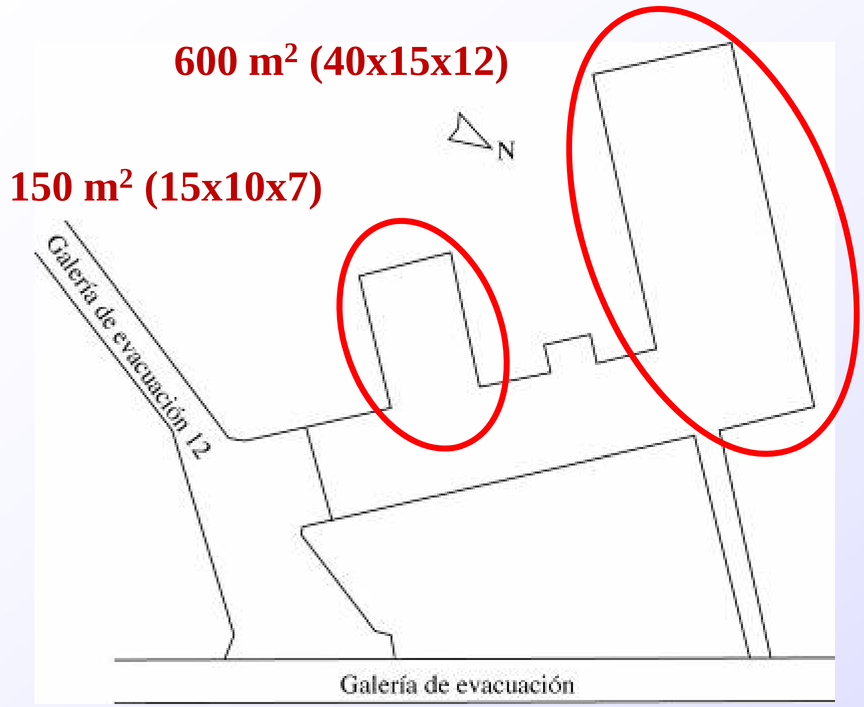
Lab cross section

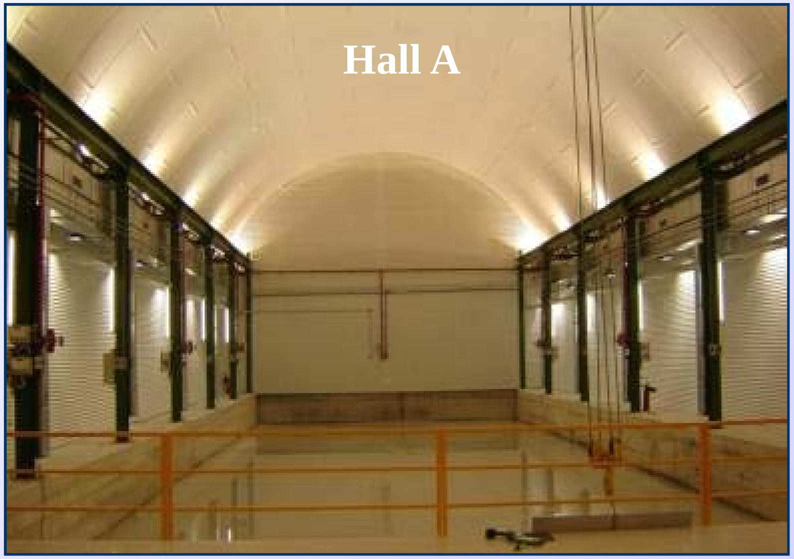


Map of the LSC



Experimental halls A, B and C





Depth: ~850 m

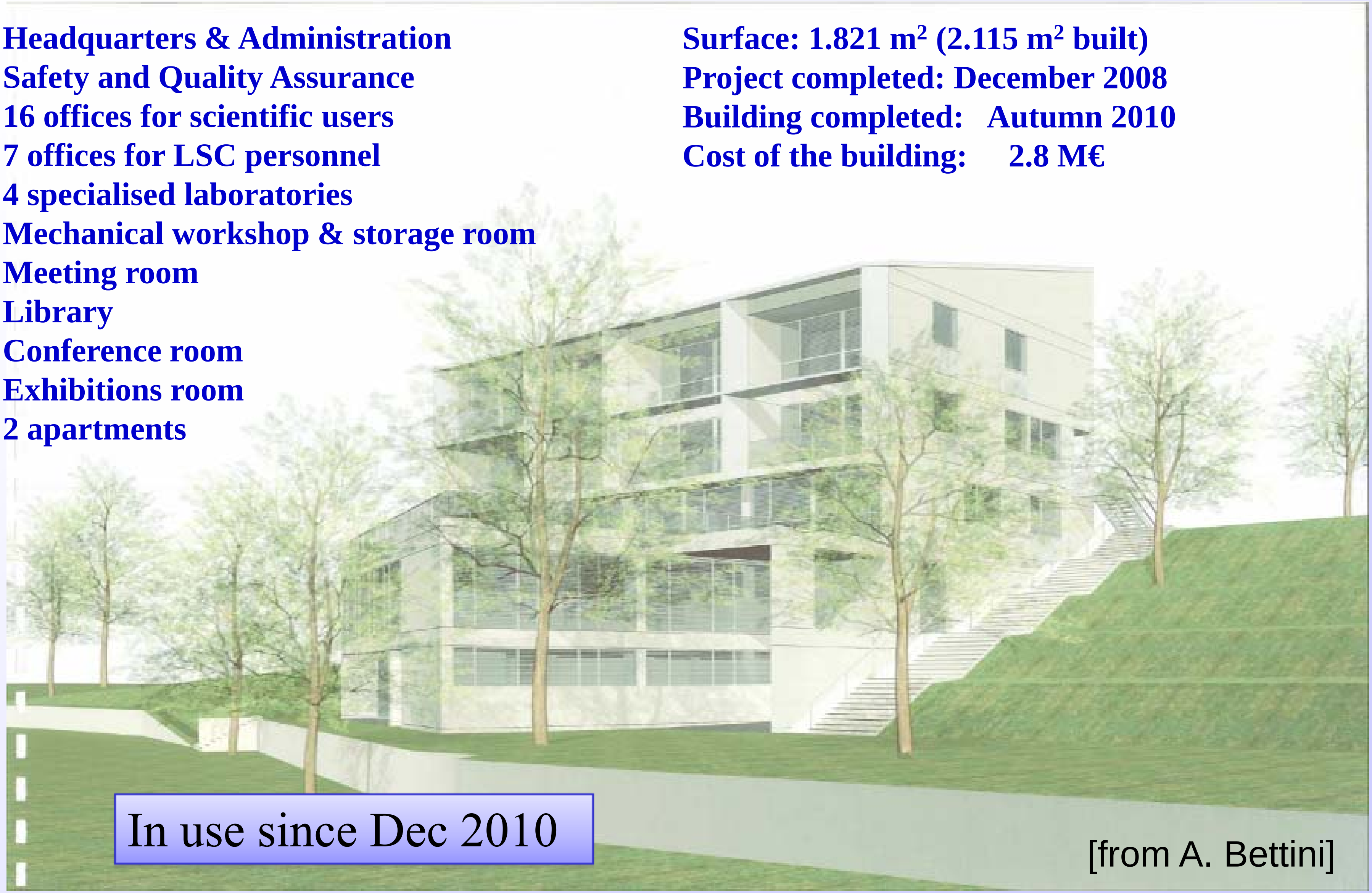
Muons: 0.2 to 0.4 x 10^{-2} m^{-2} s^{-1}

Ventilation: 11.000 m^3/h

LSC – external building

Headquarters & Administration
Safety and Quality Assurance
16 offices for scientific users
7 offices for LSC personnel
4 specialised laboratories
Mechanical workshop & storage room
Meeting room
Library
Conference room
Exhibitions room
2 apartments

Surface: 1.821 m^2 (2.115 m^2 built)
Project completed: December 2008
Building completed: Autumn 2010
Cost of the building: 2.8 M€



In use since Dec 2010

[from A. Bettini]

Expression of Interest
Underground NA @ LSC

✓ Expression of interest to Scientific Committee – 2009

Expression of Interest to the Canfranc Underground Laboratory

CUNA

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

Participants

F. Calviño, E. Garcia-Berro, B. Gomez, J. Jose
Universitat Politecnica de Catalunya, Barcelona

J. Isern, M. Hernanz
Institut de Ciencies de l'Espai-CSIC, Bellaterra

C. Abia, I. Dominguez
Universidad de Granada

D. Cano, T. Martinez
Centro de Investigaciones Energeticas y Medioambientales, Madrid

J. Benlliure, M. Caamaño
Universidad de Santiago de Compostela

A. Algora, J. L. Tain
Instituto de Fisica Corpuscular, CSIC-Universidad de Valencia

A. Pedro de Jesus, D. Galaviz, J. P. Ribeiro, J. Cruz, L. R. Gasques
Centro de Fisica Nuclear da Universidade de Lisboa

S. Harissopoulos
Institute of Nuclear Physics "Demokritos", Atenas

C. Broggini, A. Caciolli, R. Menegazzo, C. Rossi Alvarez
INFN, Sezione di Padova

P. Corvisiero
Università di Genova ed INFN, Sezione di Genova

P. Bezzon
INFN, Laboratori Nazionali di Legnaro

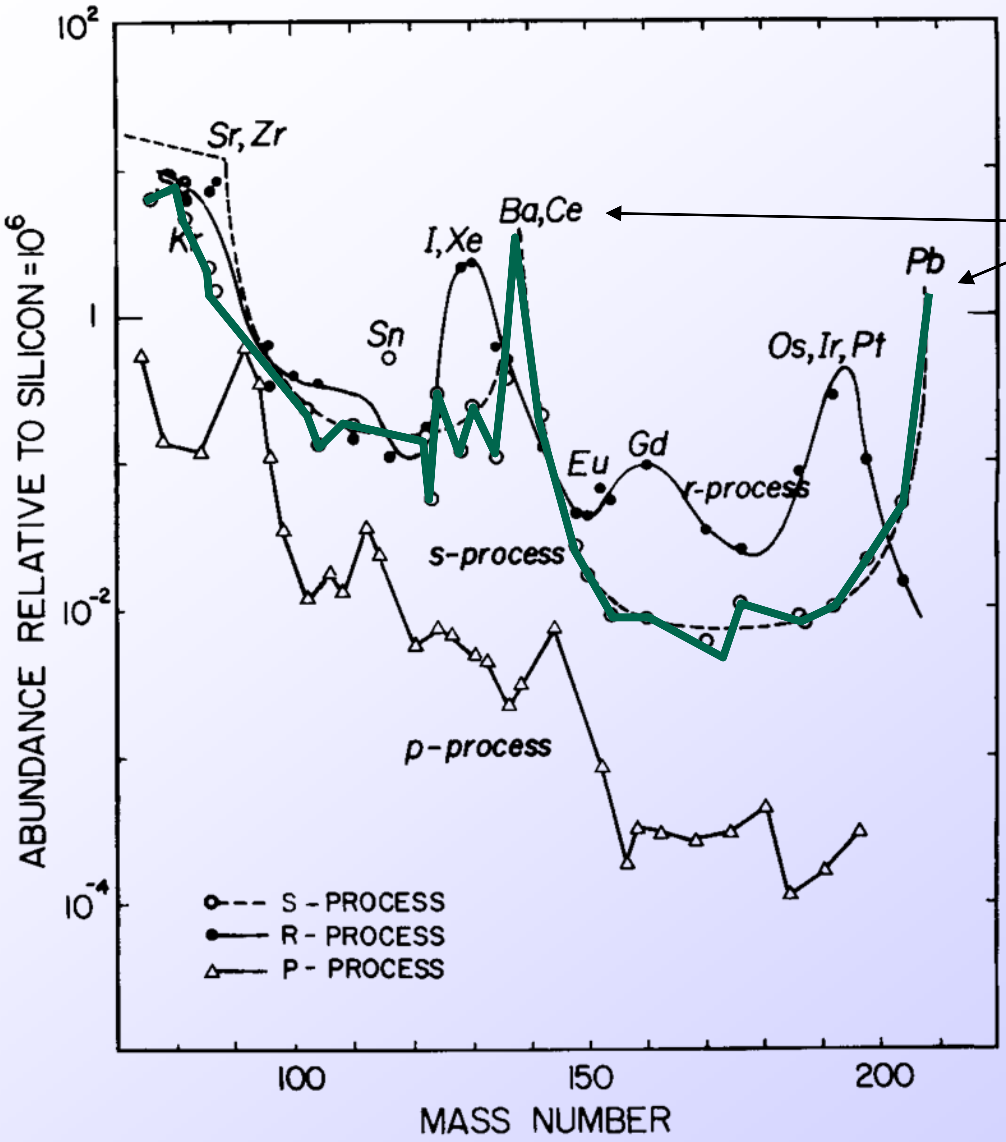
A. Guglielmetti, C. Mazzocchi
Dipartimento di Fisica, Università di Milano ed INFN, Sezione di Milano

D. Bemmerer, M. Marta
Forschungszentrum Dresden-Rossendorf, Dresden

Zs. Fülöp, Gy. Gyürky
ATOMKI, Debrecen

^{13}C(α,n)^{16}O **^{22}Ne(α,n)^{25}Mg** Other reactions

The s-process



The origin of heavy elements in the solar system

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

s-only isotopes are above p-process level

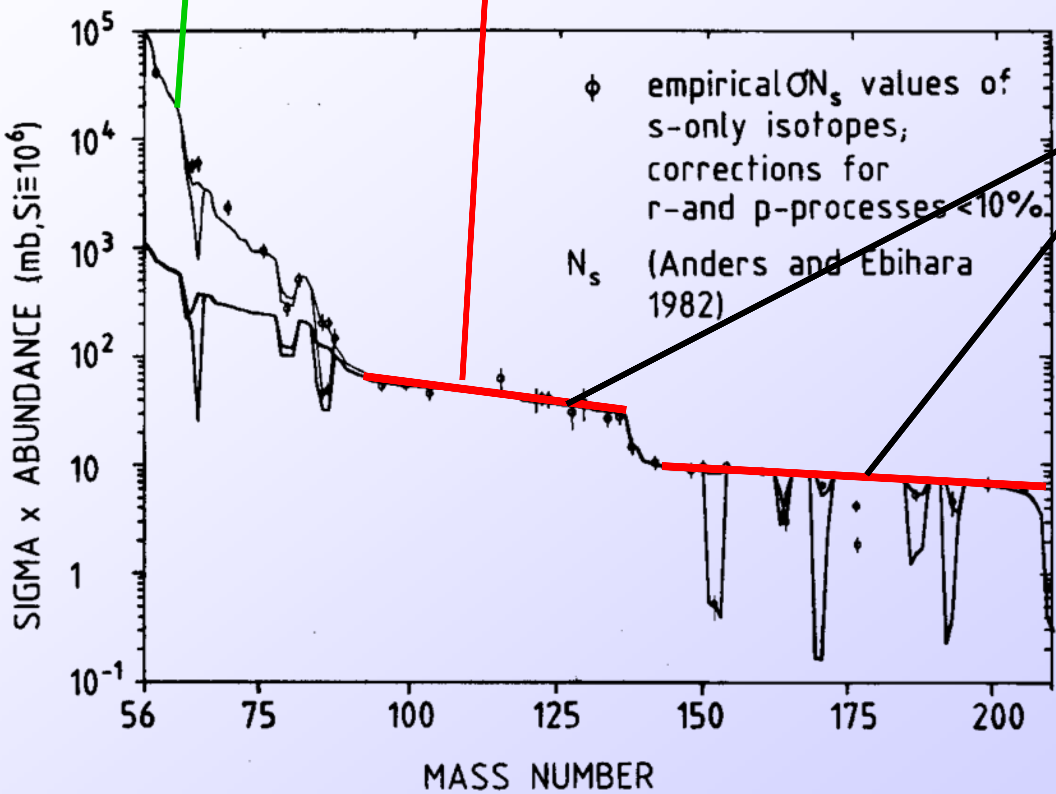
[Pagel, *Fig 6.8*]

s-process components

weak s-process

[Clayton and Rassbach, 1974]
[Käppeler et al., 1982]

main s-process



approx. steady flow
$$Y\lambda \propto Y\sigma_{(n,\gamma)} \approx \text{const}$$

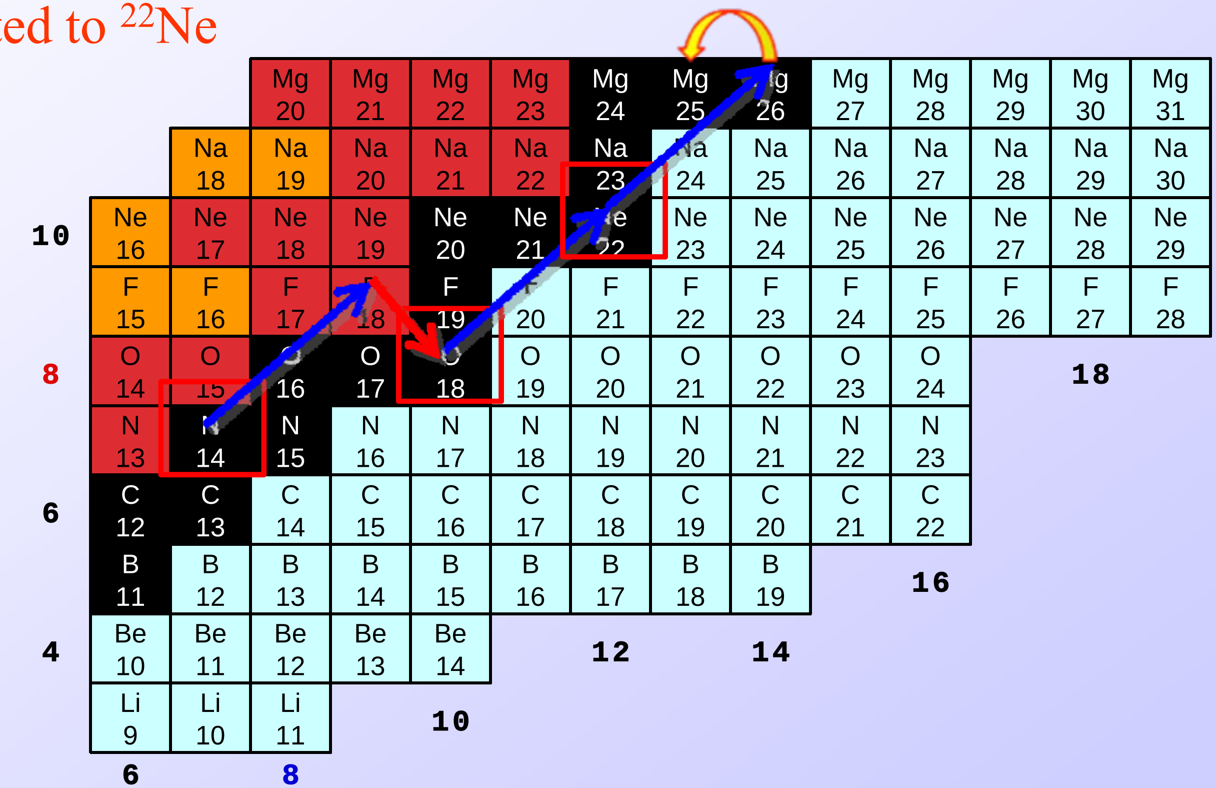
↓

Possible to extract the s-contribution for s+r-nuclei provided <u>n-capture cross sections</u> are known.

The weak s-process

- ✓ Core He burning (and shell C-burning) in massive stars
  - → (e.g. 20 solar masses)
  - → ^{14}N quickly converted to ^{22}Ne

He burning core contains initially ^{14}N



At the end of the He burning (T~3E8 K) **^{22}Ne(α,n)^{25}Mg** provides the neutron source

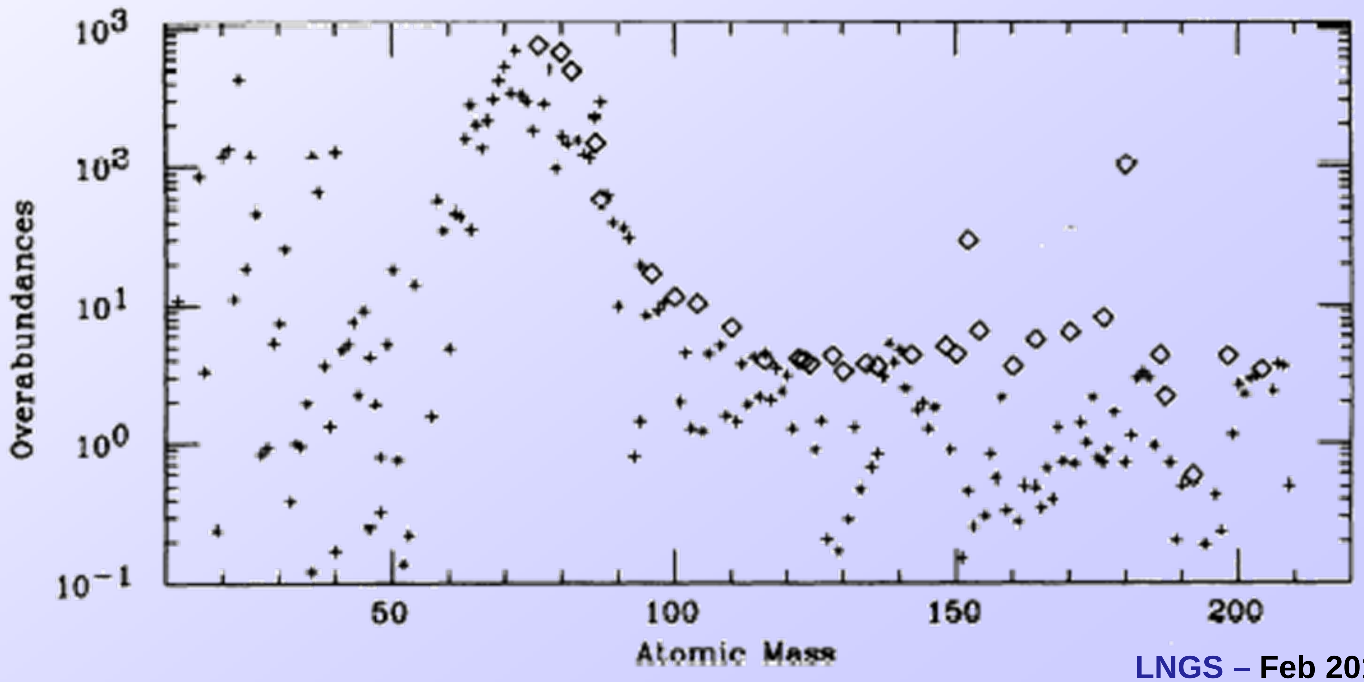
The existing Fe (and other nuclei) are seeds for a (secondary) s-process

The weak s-process

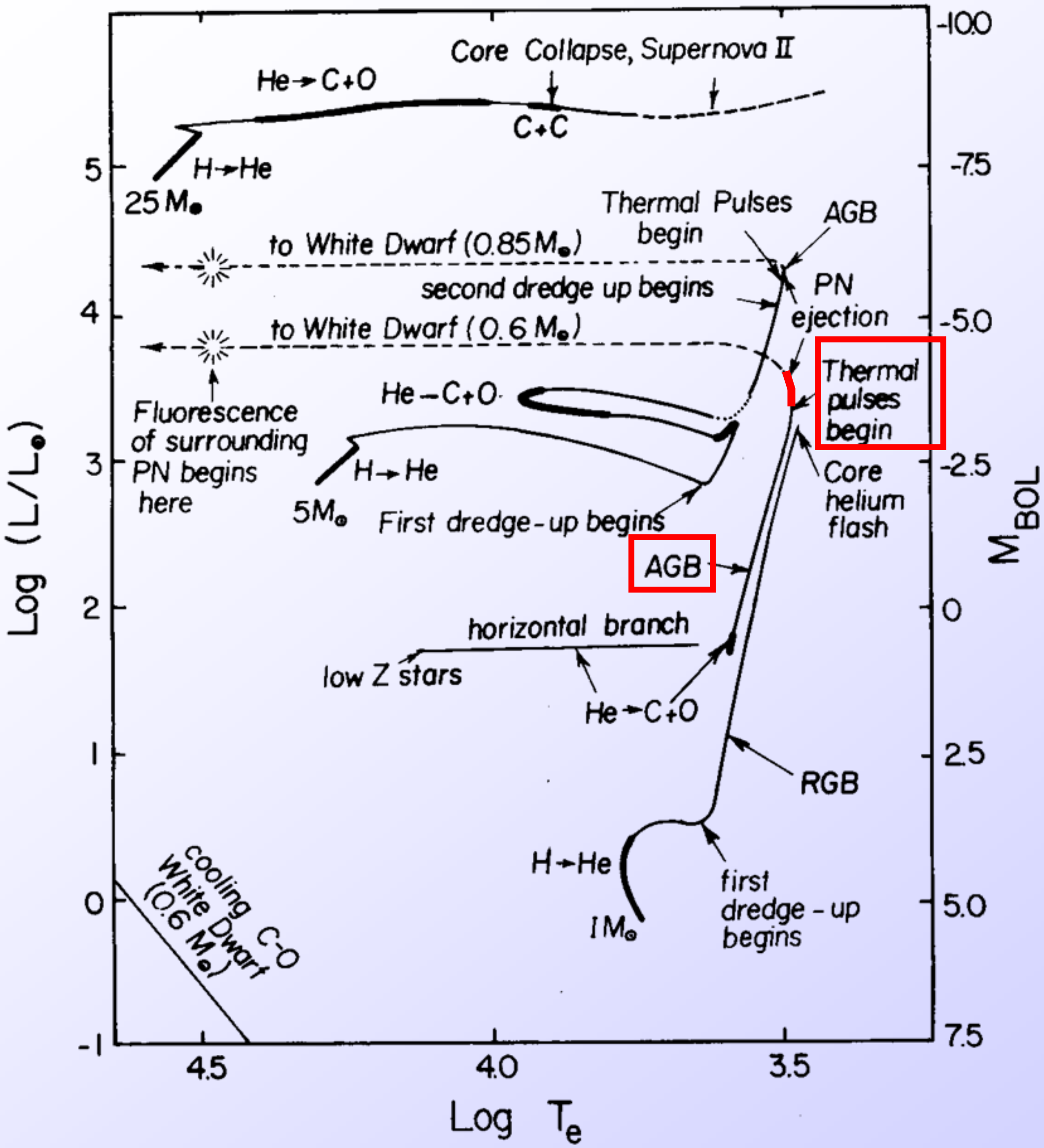
Temperature	2.2 - 3.5 E8 K
Density	1 – 3E3 g/cm^3
Average neutron density	7 E5 cm^{-3}
Peak neutron density	2 E7 cm^{-3}
Neutron exposure $\tau = \int j_n(t)dt$	0.206 / mb

[adopted from H. Schatz, C. Iliadis]

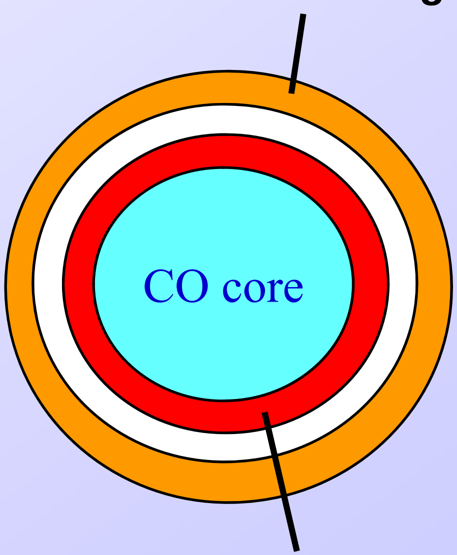
produced abundance/solar



The main s-process



- ✓ Low mass (1.5 – 3 solar masses) thermally pulsing stars on the asymptotic giant branch in the HR diagram

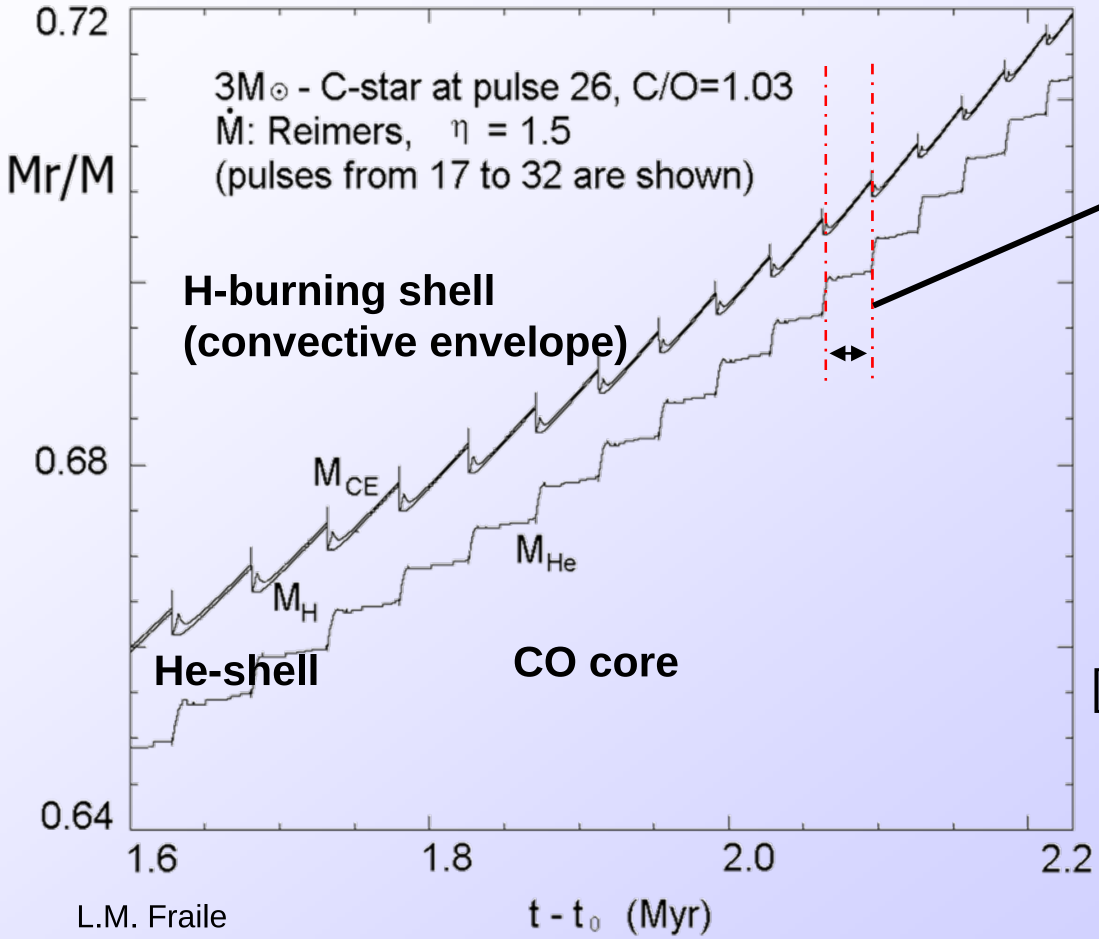


He-burning shell
unstable - burns in flashes
(thin shell instability)

The main s-processs - AGBs

✓ Outcome of many generations of AGB stars populating the interstellar medium before the solar system formed

→ Model for thermally pulsing stars (TPs)



→ number of He flashes in stars life: few to 100

→ period of flashes: 1000 – 100,000 years

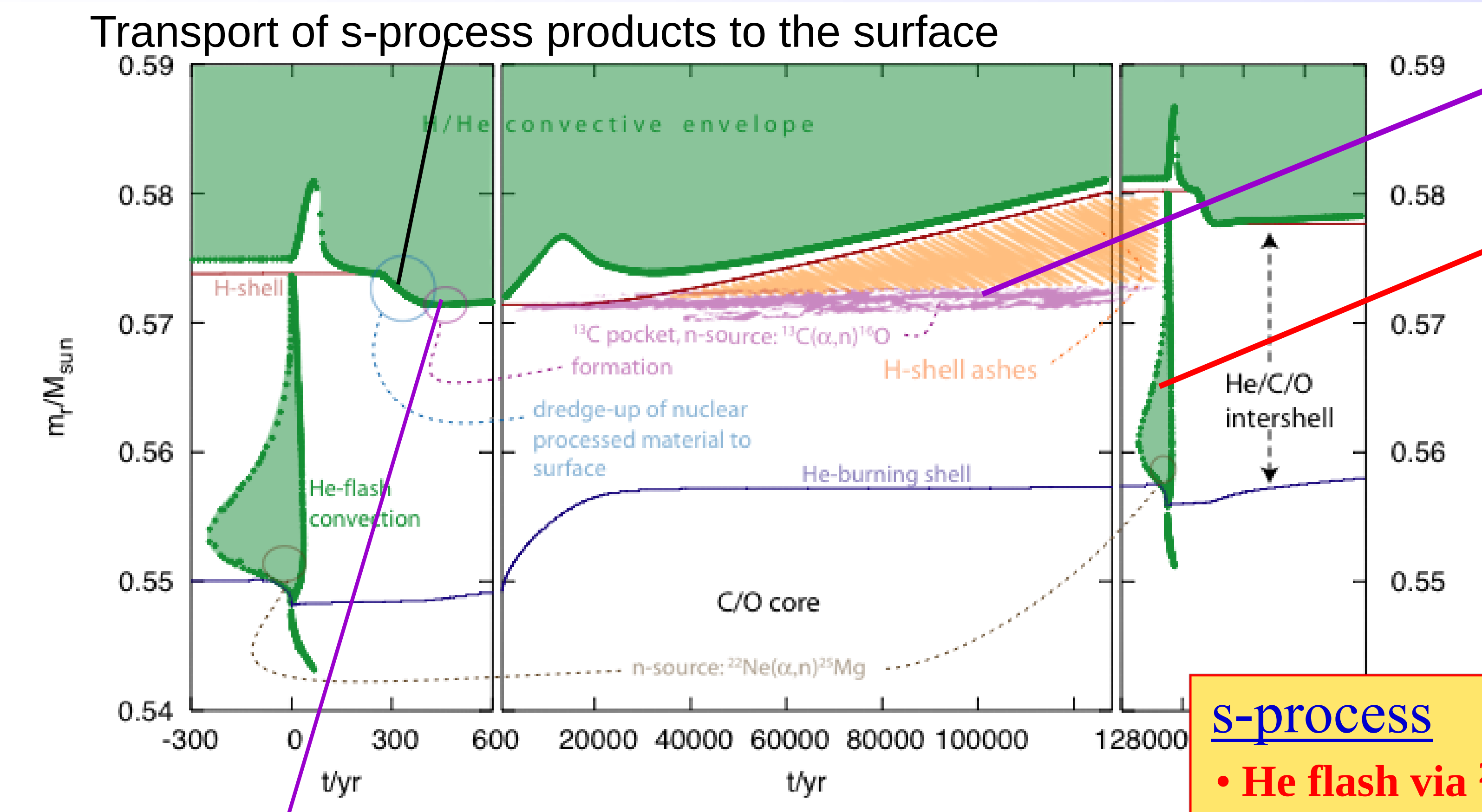
[Straniero et al. 1997]

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

[adopted from R. Gallino, H. Schatz]

AGB stars

The main s-component is not a unique process, depending on the efficiency of the so-called ^{13}C pocket, on the initial mass, and on the metallicity.



^{13}C(α,n)

^{22}Ne(α,n)

[H. Schatz]

^{13}C pocket formation by mixing He burning products with H via $^{12}C + p \rightarrow {}^{13}N \rightarrow {}^{13}C$

s-process

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

Main s-process in AGBS

	$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$
Location	Pocket	He flash (short, intense burst)
Importance	Primary source (weaker but longer)	Secondary source (slight change of abundances)
Requirements	Needs ^{13}C	^{22}Ne is abundant
Regime	Radiative	Convective
Temperature	0.9 – 1.0 x 10^8 K	2.7 x 10^8 K
Neutron density	7 x 10^7 cm^{-3}	10^{10} cm^{-3} (peak)
Duration	20,000 yr	few years
Neutron exposure τ	0.1 / mb (90% exposure)	0.01 / mb

Measuring stellar burning rates

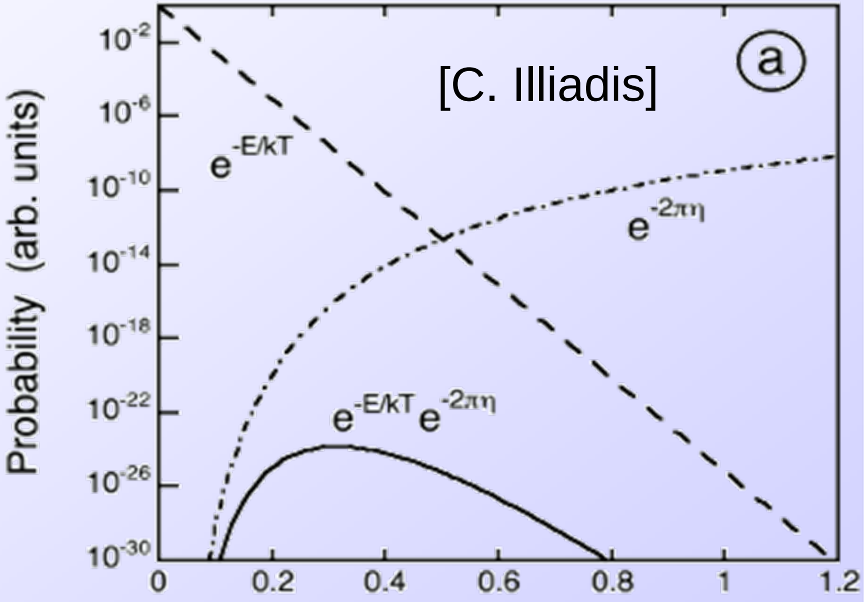
- ✓ Cross-sections
  - → parametrized models
  - → Typical stellar temperatures (10^7-10^{10} K) and Coulomb barrier translates into low LAB energies (0.001-1 MeV): Gamow peak
  - → Low energies resonances may appear
- ✓ Measure at (close to) the relevant energies → Extrapolations

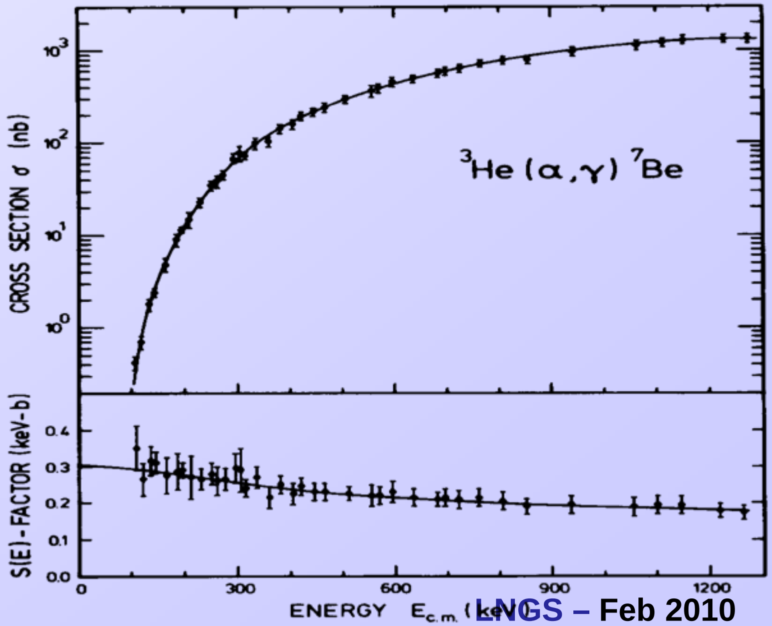
$$\text{Rate} \propto \langle \sigma v \rangle \propto \int \Phi(E)\sigma(E)dE$$

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

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

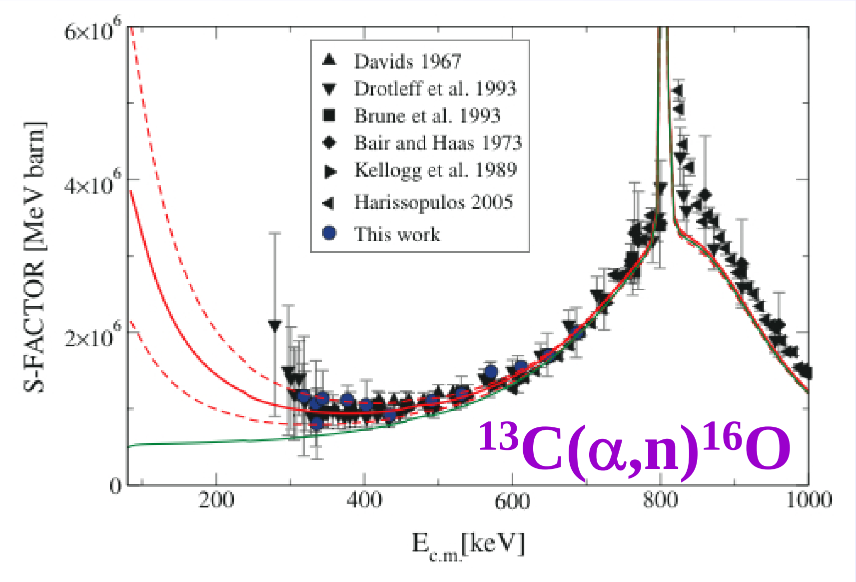
$$2\pi\eta = 31.29\ Z_1 Z_2 (\mu/E)^{0.5}$$





Measurements…

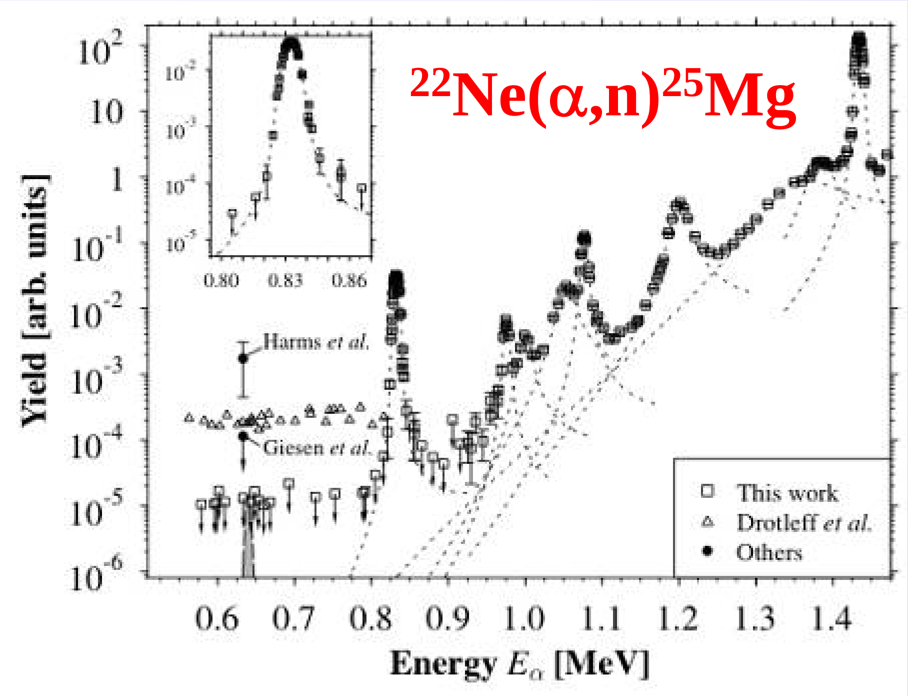
- ✓ Very low energies
  - → Cross-sections are extremely small (10^{-12} –10^{-20} barn)
  - → Requires high luminosity (beam current)
  - → Requires large signal/noise ratio
- ✓ Possibilities at ground level exhausted



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

Astrophysical energies: 130 -250 keV

Minimum measured E: 270 keV

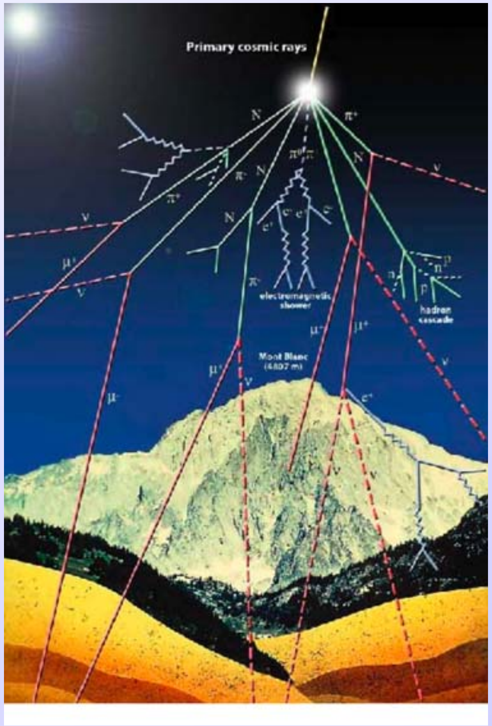


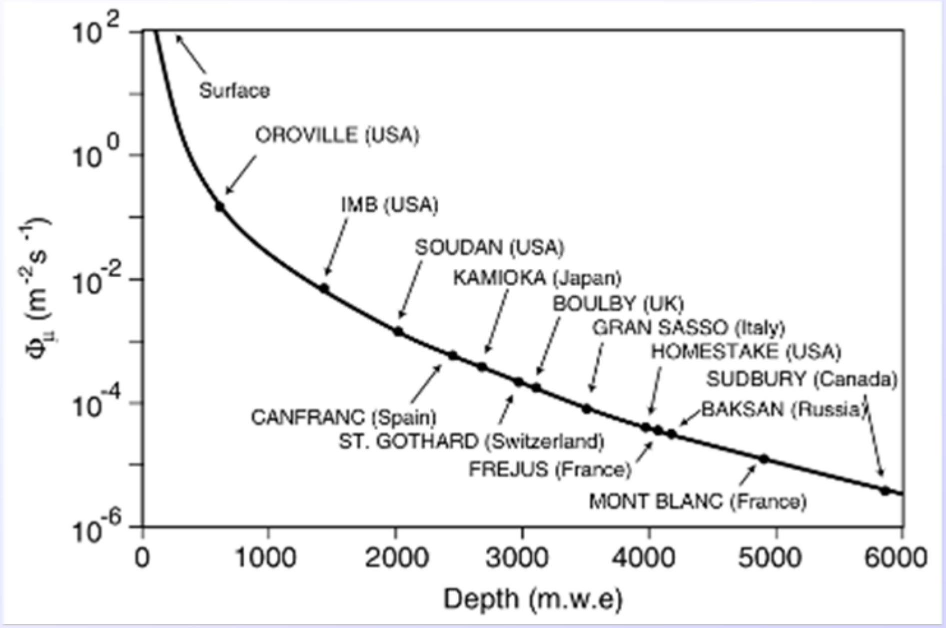
Jaegger et al., Phys. Rev. Lett. 87, 202501 (2001)

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





UNDERGROUND

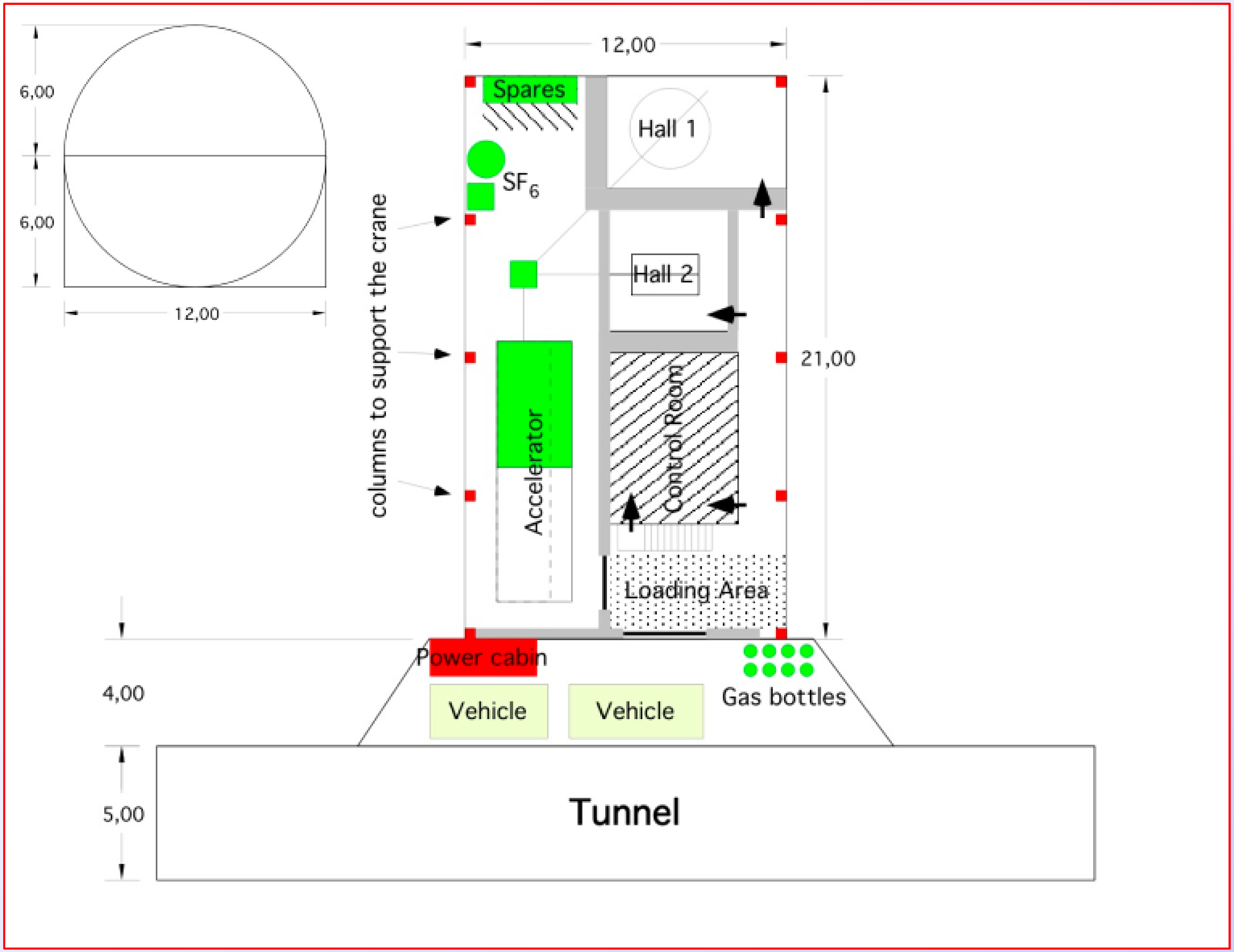
- → Cosmic rate reduction
- → Significant below 1000 mwe
- → Additional background reduction

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

Expression of Interest to LSC - 2009

- ✓ "A Nuclear Astrophysics facility for LSC: The sources of neutrons in stars & other reactions of astrophysical interest"
  - → IFIC-CSIC Valencia, ICE-CSIC Barcelona, U Santiago, CIEMAT, U Granada, UC Madrid, UPC Barcelona, INP Athens, INFN Padova, INFN Genova, INFN Legnaro, INFN Milano, U Lisbon,FZR Dresden, ATOMKI Debrecen
- ✓ Physics case
  - → Europe-wide discussion - collaboration with LUNA
  - → Agreement for multisite complementarity (and with ground based labs)
  - → Neutron sources in stars: **$^{13}C(\alpha,n)^{16}O$**, **$^{22}Ne(\alpha,n)^{25}Mg$**
  - → Other reactions
    - $^{23}Na(p,\gamma)$ and $^{23}Na(p,\alpha)$ – H burning – classical novae
    - $^{12}C+^{12}C$ – Carbon burning – SNII
    - $^{26g}Al(p,\gamma)^{27}Si$ – MgAl chain – AGBs, Wolf-Rayet
    - $^{22}Na(p,\gamma)^{23}Mg$ – 1275 keV – Classical novae
  - → Other possible cases discussed and skipped

EoI: Proposal for new hall



Option for the accelerator

3.5 MV HVEE Singletron

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^+, D^+, He^+)

Other options considered for future upgrades

Matis @ CNR-IMM Catania (IT)

Contact with CENBG Bordeaux

Work packages

→ Science case - Development of the existing Physics case, the background level requirements, energy regime in inverse kinematics, exploration of complementary measurements at other laboratories.

→ Background and shielding - Evaluation of the background with online measurements and support of Monte Carlo simulations, input to the cave design, passive shielding, active shielding, accelerator induced background, limitation of background to other caves.

→ Accelerator and ion sources - Requirements and specifications (energy regime, dispersion, stability, beam current, induced background), input to cave design including dimensions.

→ Targets and experimental detection system - neutron and gamma detection systems (efficiency, range, granularity, background), target (specifications, purity).

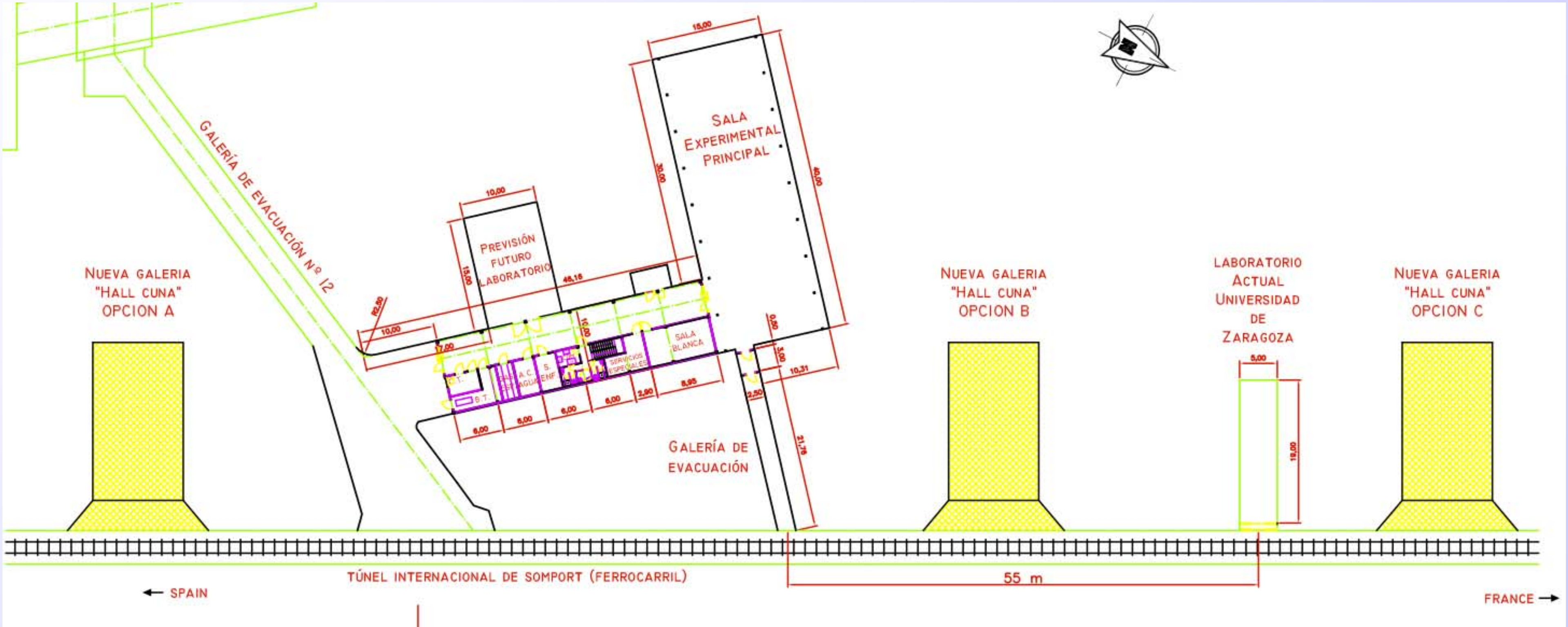
CUNA Hall – call 2010

✓ Feasibility study on CUNA hall by LSC

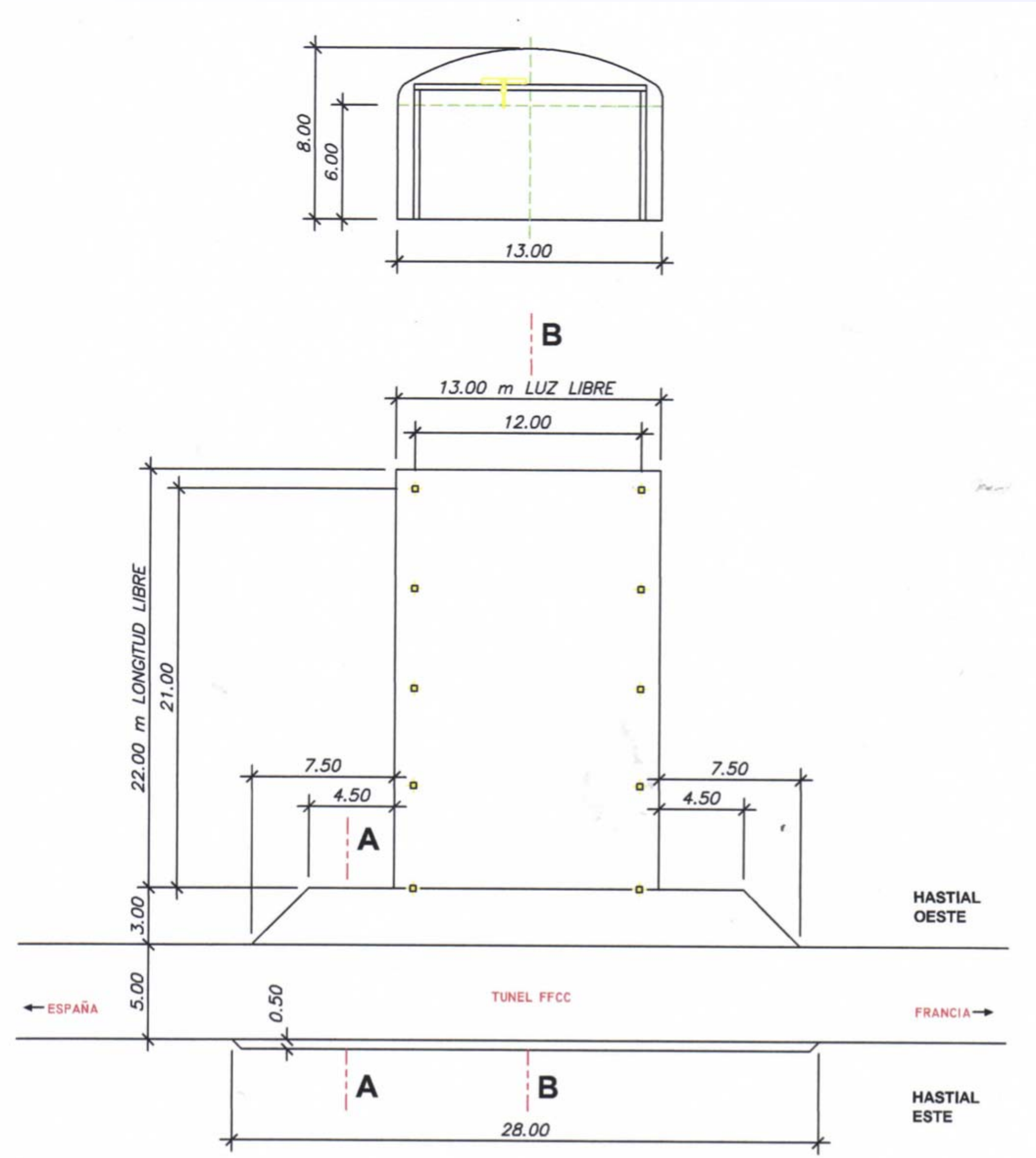
→ Definition of general features – Nov 2010

→ Call for engineering feasibility study report

- Three offers expected, one already received.
- Full engineering study and request to Ministry to follow



CUNA Hall – call 2010

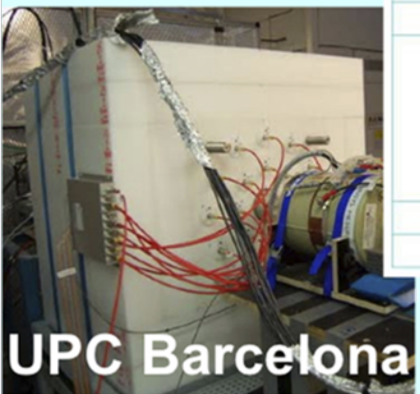


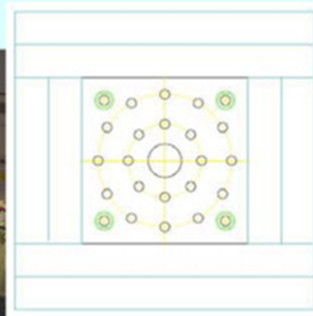
New Hall

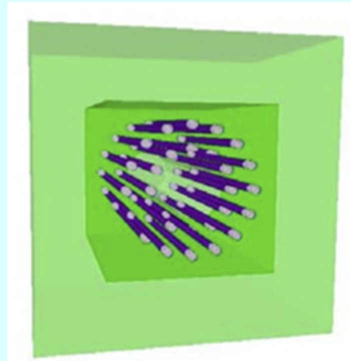
- Separated from the rest – three optional locations
- Area: 22 m □ 13 m
- Height 6 – 8 m
- Crane (arc)
- Accelerator + analyzing magnet + beam lines…
- Two experimental halls
- Services
- Control room
- Instrumentation

Neutron detectors (UPC-Barcelona, CIEMAT-Madrid, IFIC-Valencia)

High efficiency neutron counter



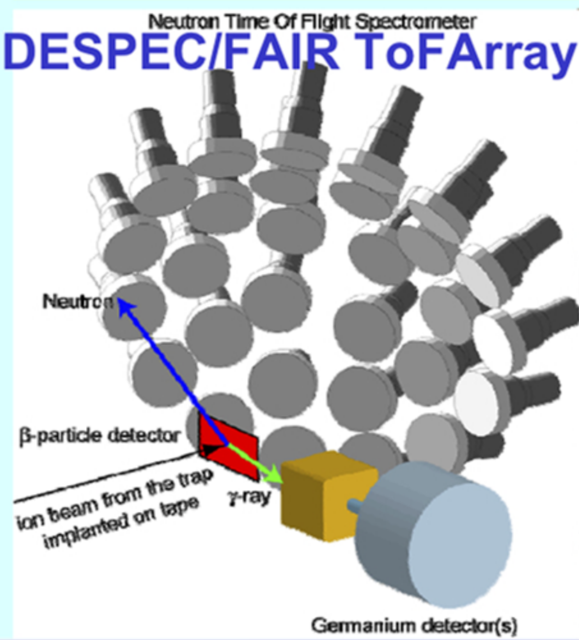


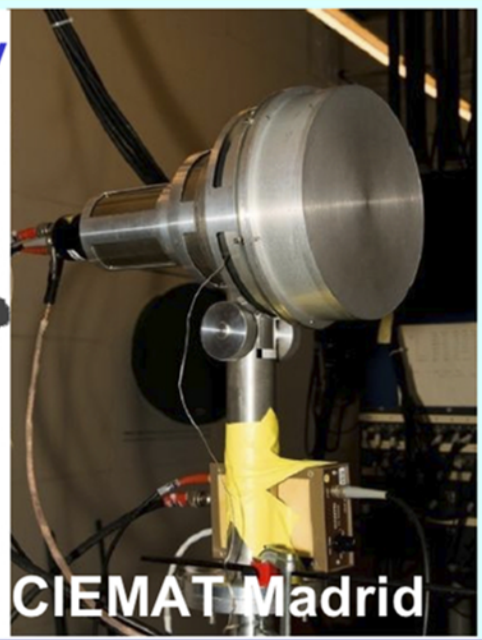


DESPEC/FAIR 4πn

- ^{3}He proportional counters
- PE neutron-moderator matrix
- triggerless DACQ

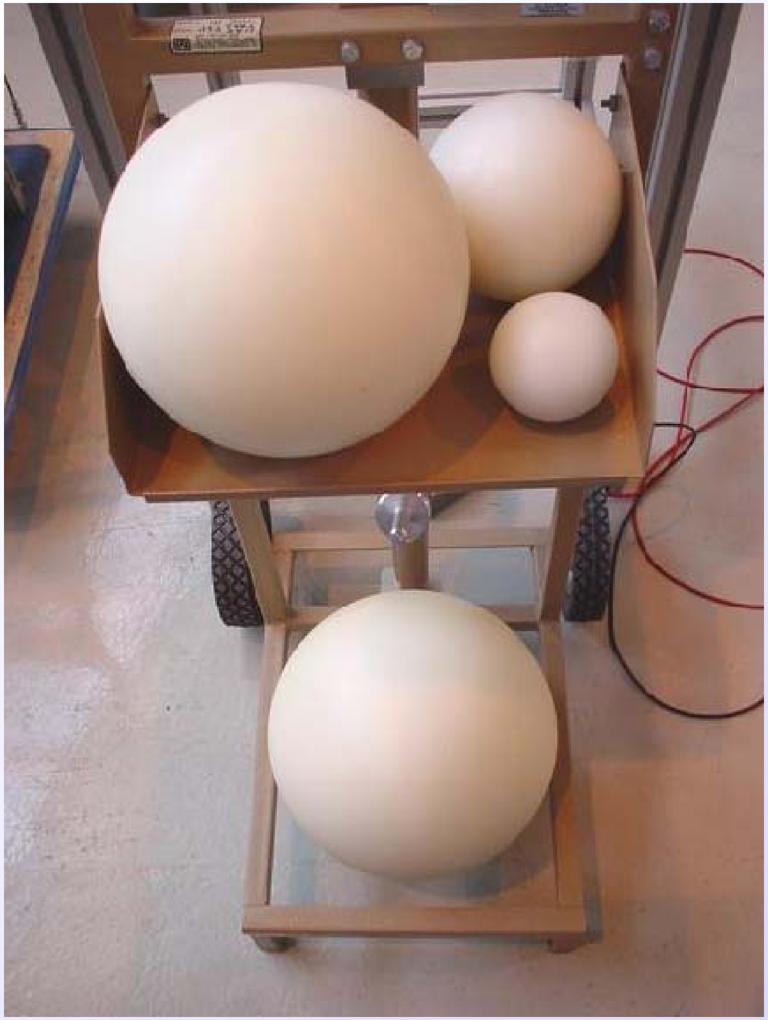
Neutron Time-of-Flight spectrometer





- BC501A liquid scintillation cells
- n/γ discrimination
- fast sampling digitizers

Background and simulations



✓ Assessment of neutron bckg.

→ Bonner spheres

- Collaboration with UAB [C. Domingo et al.], UniZar [I. Irastorza et al.], LSC [I. Bandac]
- Meeting Zaragoza Dec 2010
- Feasibility tests February 2011

→ ^{3}He counters (+ …)

- IFIC, UPC, CIEMAT, UCM
- Planned for March-April 20112011

→ Hall simulations + background

- Collaboration with UniZar (NEXT project)
- PDoc to be hired via CUP @ IFIC

Our aim

✓ Dedicated CUNA hall and associated facilities at LSC

→ Letter of intent to be submitted by end of 2011

- Experimental requirements, Background assessment, Accelerator specifications, Laboratory design and specs, Cost estimates, time scales

→ Eight Spanish groups involved + International collaborators

→ Collaboration with CUP project

→ Support from the LSC laboratory

→ Feasibility study for the hall underway

Excellent opportunity at Canfranc

Complementary to other projects

Outlook

Strong Physics case

→ Based on success by LUNA 400 kV

Continue efforts to establish a EU network on underground NA

→ Develop European programme with several MV complementary sites

→ Dresden meeting April 2010

- EU community strengthened by networking
- Open facilities
- Enhance links to astrophysical themes

→ Endorsed by NuPECC LRP2010

→ CUNA collaboration ready to host next (2012) meeting at Canfranc

Define **common work packages** for site-independent tasks