# 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

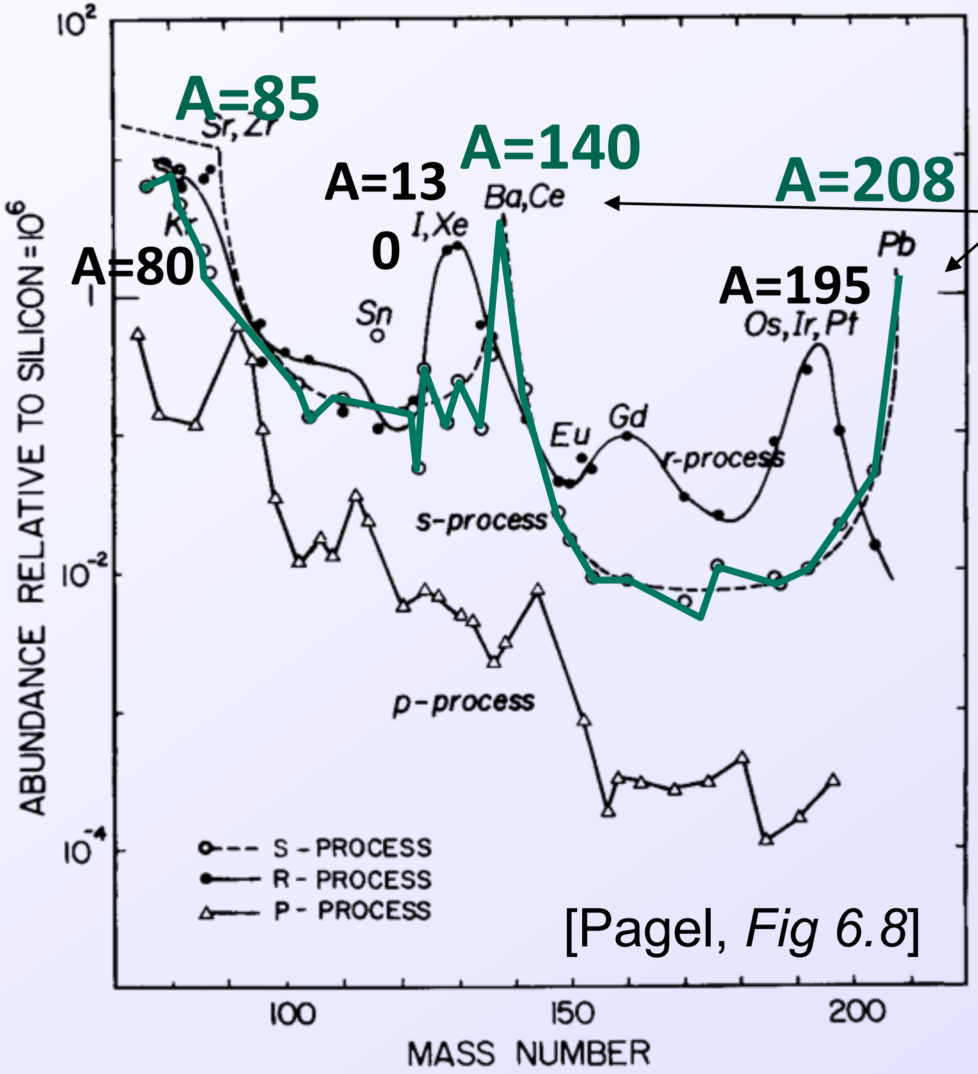

C. Abia, A. Algora, J. Benlliure, R. Caballero, F. Calviño, D. Cano-Ott, I. Domínguez, L.M. Fraile, M.B Gómez-Hornillos, M. Hernanz, I. Irastorza, M.D. Jordán, J. José, R. Longland, G. Luzón, T. Martínez, B. Olaizola, A. Parikh, J.L. Taín, J.M. Udías

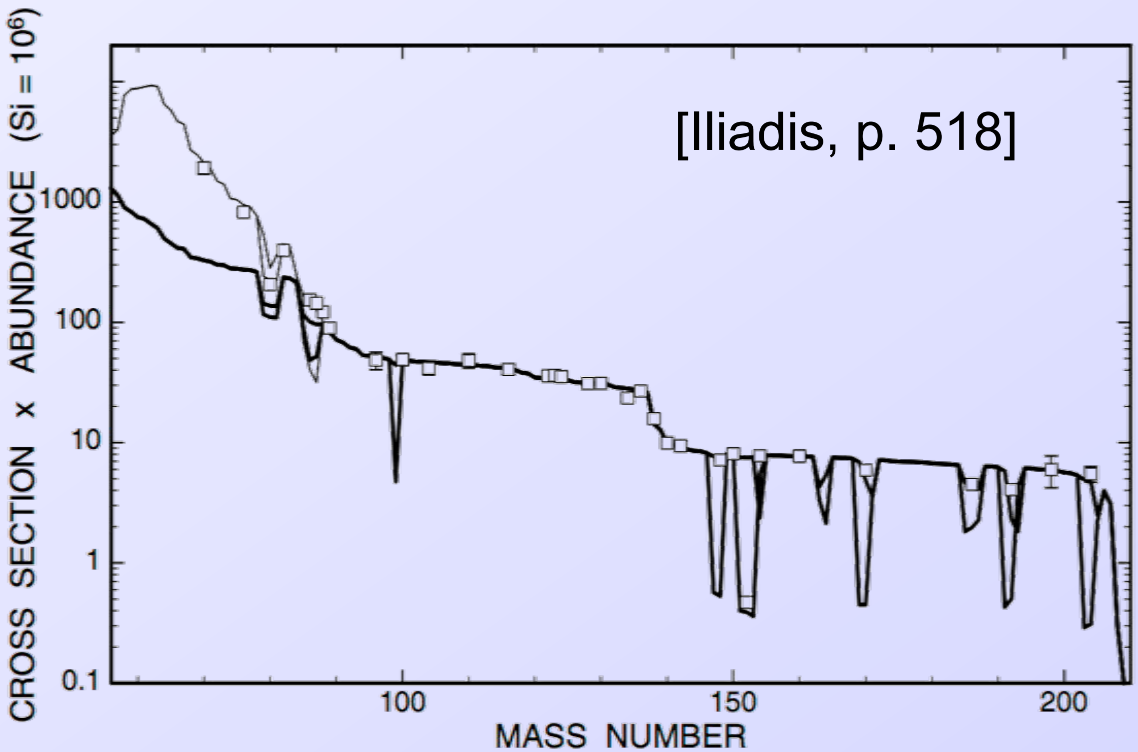
# The s-process

## 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



# Stellar evolution: s-process

## Main component

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

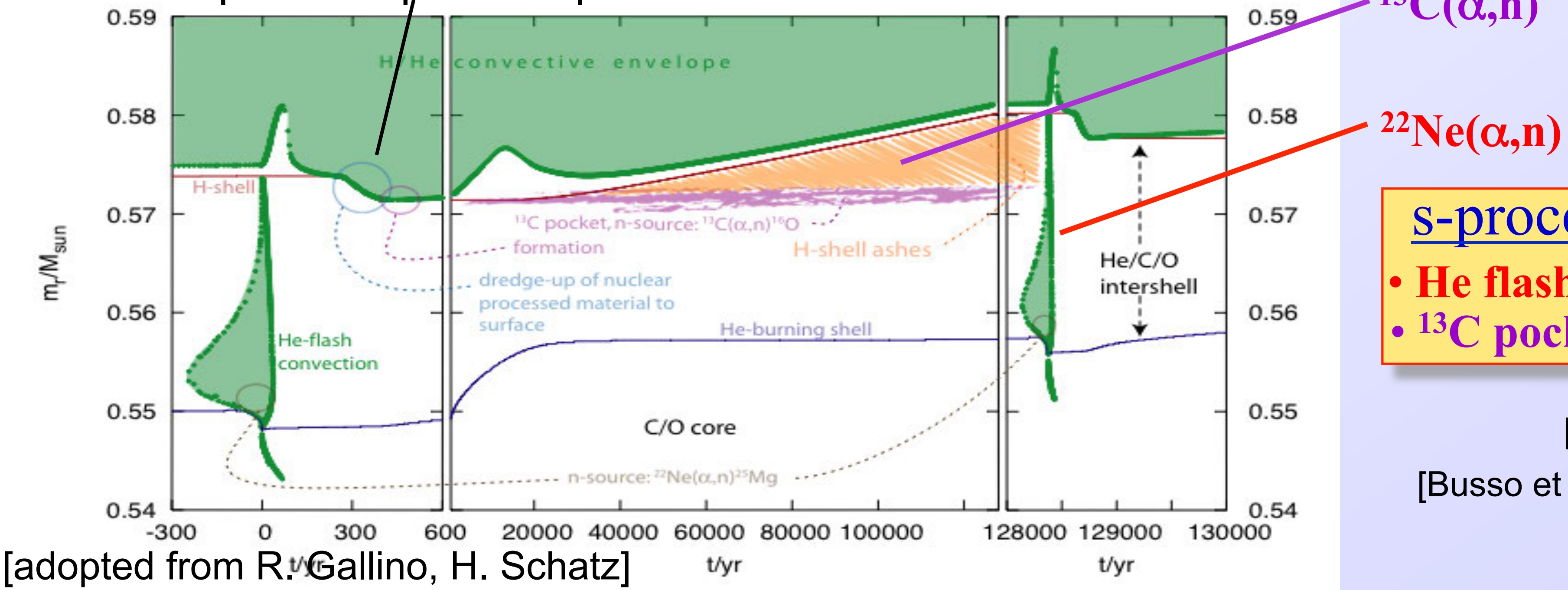
- Originate from main sequence stars, ejection of the outermost layers of the star
- AGB stage: Combination of H- & He-burning shells produces s-process elements A = 90-209

## 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

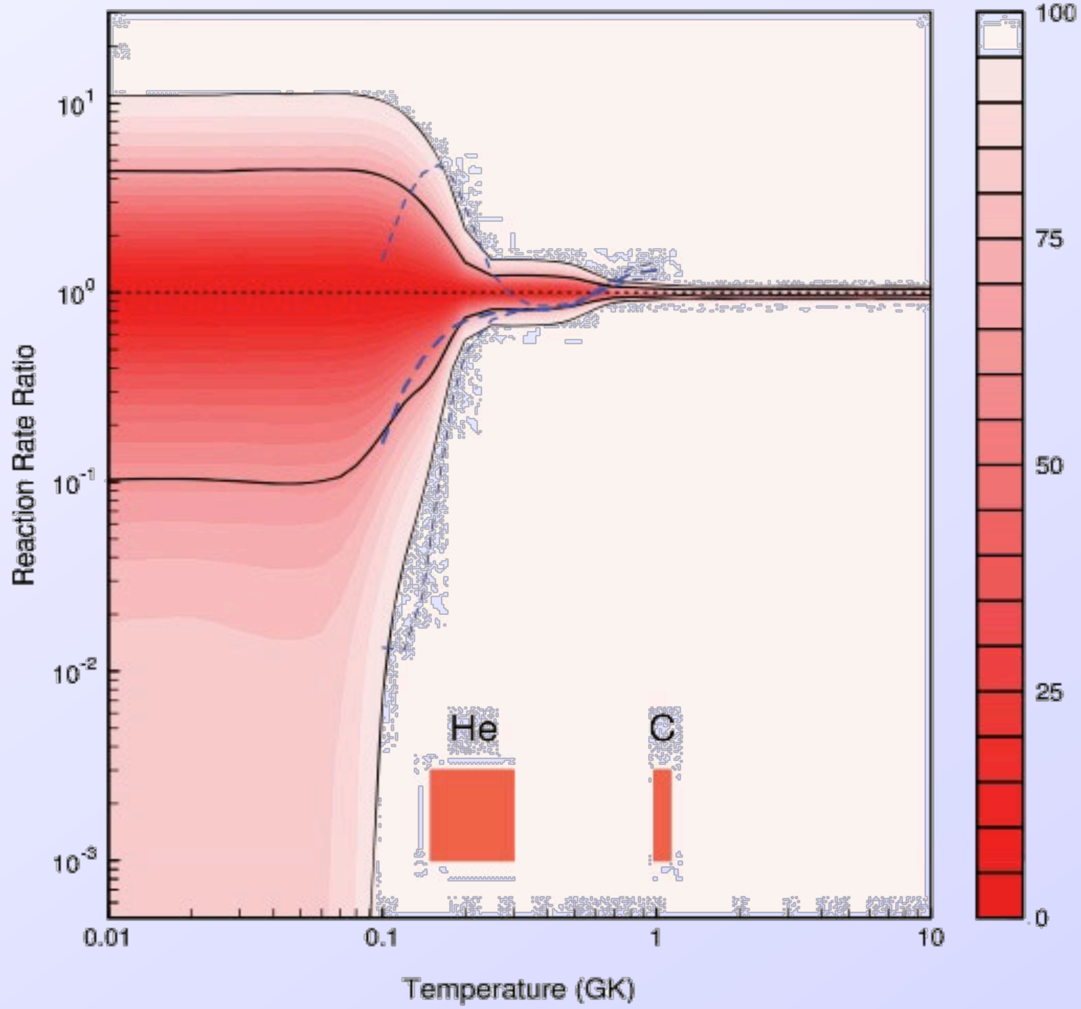
✓ Improved $^{22}Ne + \alpha$ reaction rates based on new experimental information since NACRE and Jäger et al.

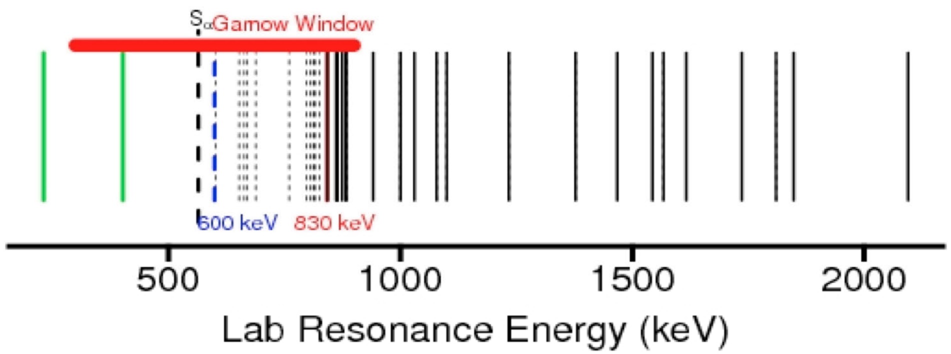
✓Computational method [22]

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

**R. Longland et al.**

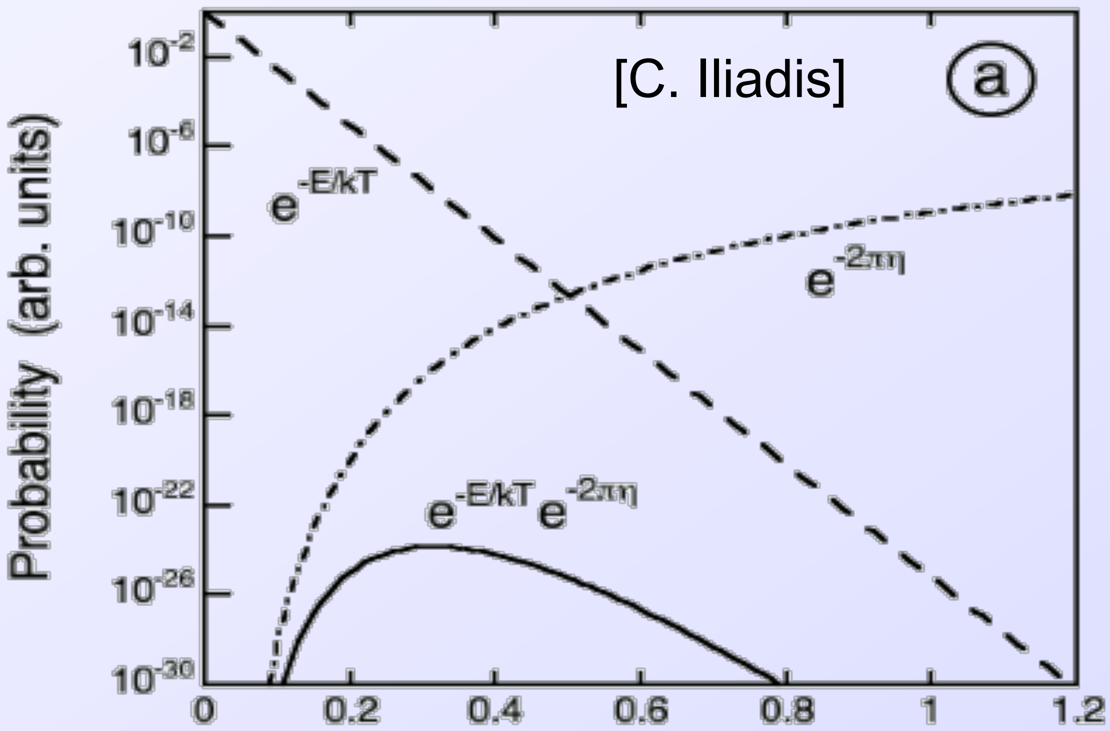
PHYSICAL REVIEW C **85**, 065809 (2012)



# 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




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

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

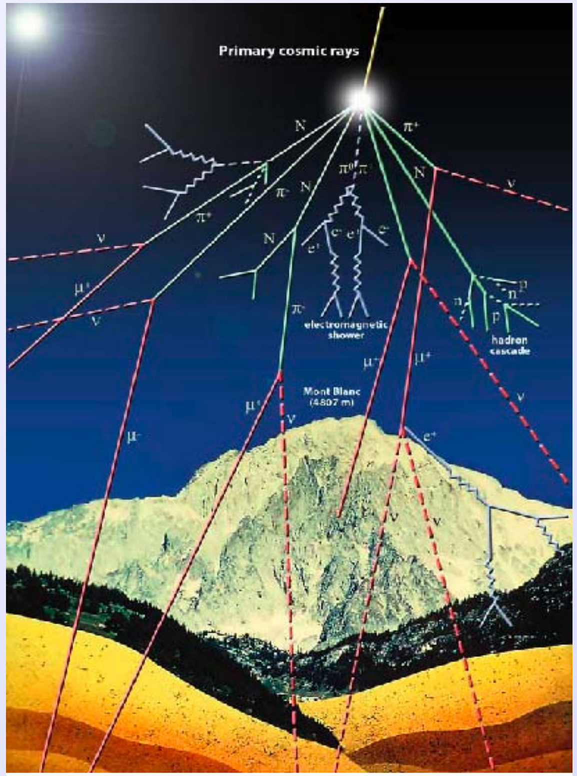
$$\sigma(E) = {}^{1}\!/_{E}\ \mathrm{e}^{-2\pi\eta}\ \mathrm{S}(E)$$

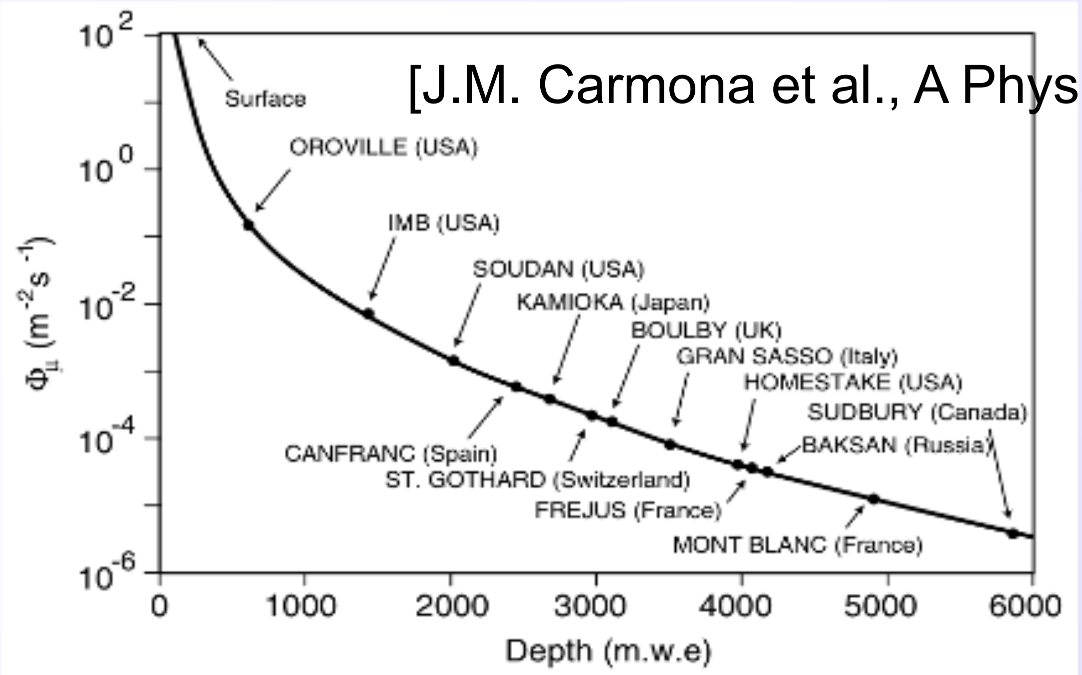
Possibilities at ground level exhausted

# 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

# LUNA 400kV - LNGS

# LSC Proposal – LOI-12-2012

- ✓ 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
- ✓ 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."*

# 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


**L.M. Fraile** (spokesperson), B. Olaizola, J.M. Udías
*Grupo de Física Nuclear, **Universidad Complutense de Madrid**, Madrid, Spain*

J. José, R. Longland, A. Parikh
*GAA, Universitat Politecnica de Catalunya, Barcelona, Spain*

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

C. Abia, I. Domínguez
*Universidad de Granada, Granada, Spain*

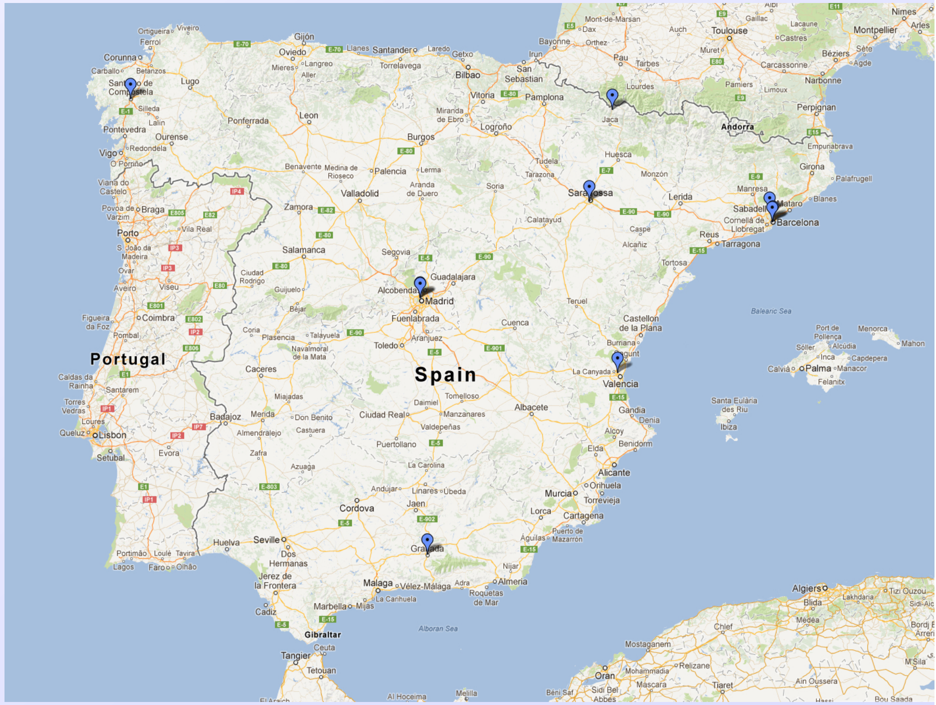
F. Calviño, B. Gómez-Hornillos,
*GREENER, Universitat Politecnica de Catalunya, Barcelona, Spain*

D. Cano, T. Martínez
*Centro de Investigaciones Energéticas y Medioambientales, Madrid, Spain*

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

A. Algora, D. Jordán, J.L. Taín
*Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain*

I. Irastorza, G. Luzón
*Lab. de Física Nuclear y Astropartículas, Universidad de Zaragoza, Zaragoza, Spain*

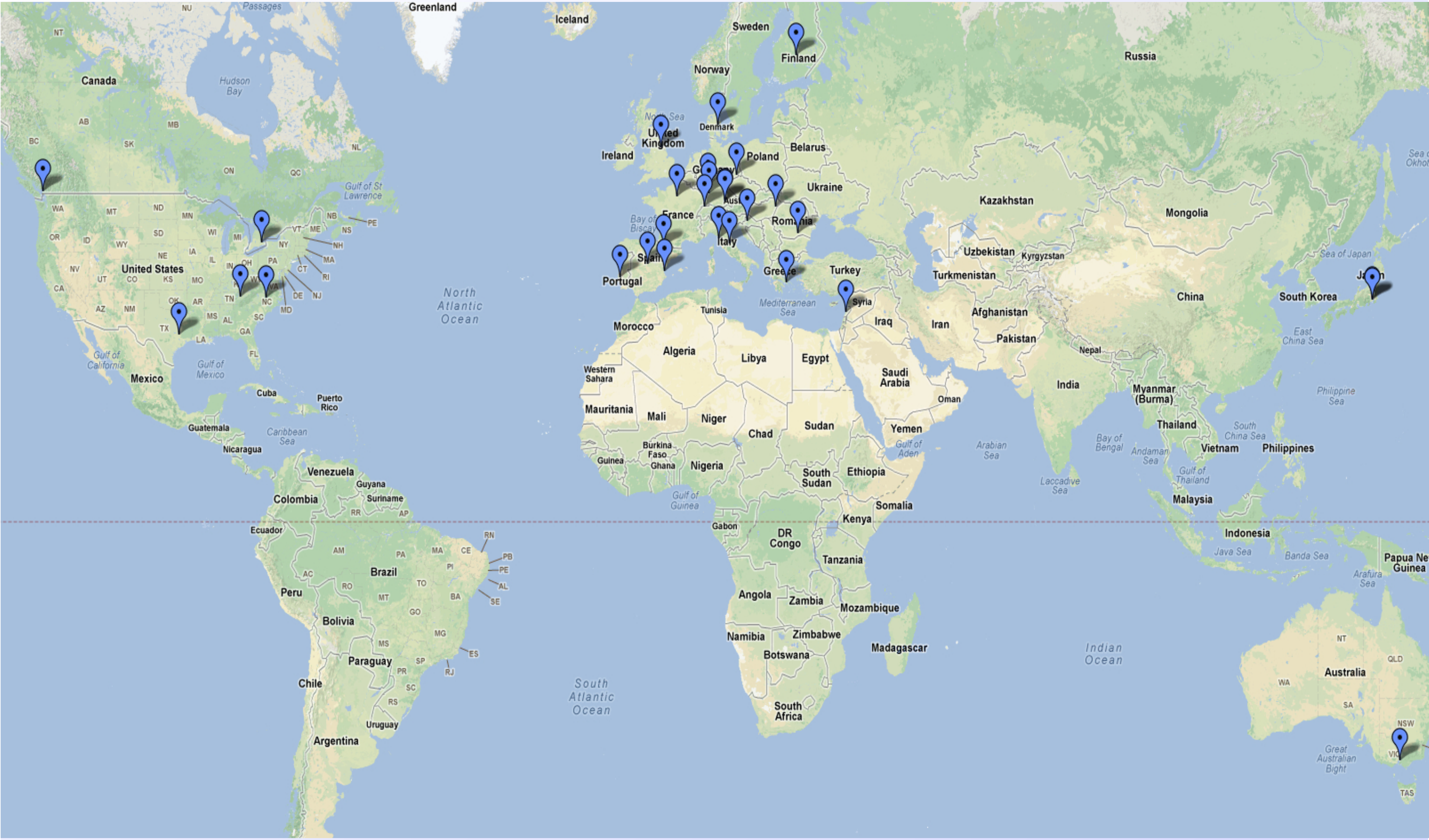



# Global support from community

- → C. Iliadis (UNC CHapel Hill, USA)
- → F.-K. Thieleman (U Basel, Switzerland)
- → H. Leeb (TU Wien, Austria)
- → J. Lattanzio, M. Lugaro (Monash, Australia)
- → T. Kajino (U Tokyo, Japan)
- → B. Fulton, A. Laird (U York, UK)
- → S. Harissopoulos (INP Athens, Greece)
- → N. Soic (Zagreb, Croatia)
- → B. Davids (TRIUMF Vancouver, Canada)
- → S. Bishop (TUM Munich, DE)
- → L. Trache (NIPNE Bucharest, RO)
- → K.-L. Kratz (MPI Mainz, DE)
- → D. Bemmerer (HZDR Dresden, DE)
- → Z. Fülöp, G. Gyurky (ATOMKI Debrecen, HU)
- → R. Tribble, C. Bertulani (Texas A&M, USA)
- → M. Smith, D. Bardayan (Oak Ridge, USA)
- → A.P de Jesús, D. Galaviz (CFNUL, Lisbon, PT)
- → F. Hammache (IPN Orsay, FR)
- → A. Coc (CNSMN Orsay, FR)
- → M. Busso (U Perugia, IT)
- → H. Fynbo (Aarhus, Denmark)
- → F. Kaeppeler (Karlsruhe, DE)
- → R. Diehl (MPI Garching, DE)
- → M. El Eid (AUB Beirut, Lebanon)
- → B. Rubio (IFIC, Valencia, ES)
- → E. Moya (UCMadrid, ES)
- → S. Shore (U Pisa, IT)
- → A. Chen (U McMaster, Canada)
- → T. Motobayashi (RIKEN, Japan)
- → J. Aysto (U Jyväskylä, Finland)
- → …

L.M. Fraile

# Letter of intent



L.M. Fraile

# 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** $\tau = \int j_n(t)dt$ | 0.1 / mb | 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

L.M. Fraile

# 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 $S_\alpha$=10.6 MeV

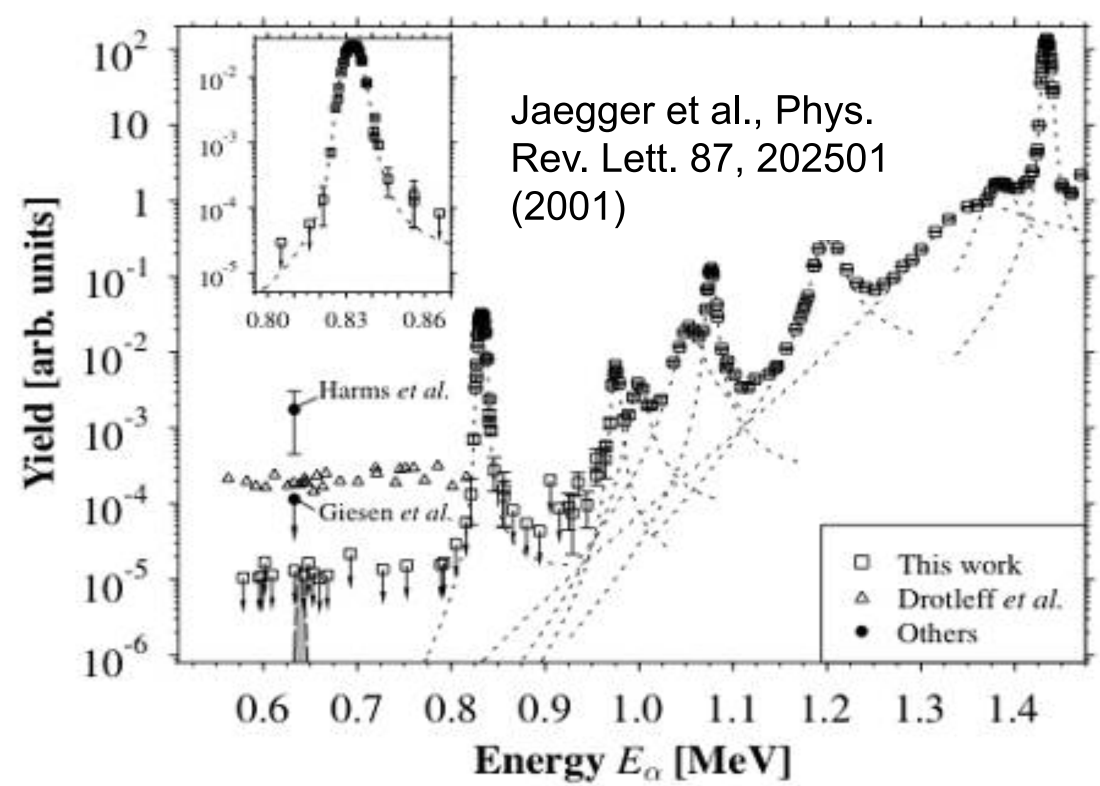
- Assume hypothetical resonance at $E^R_{CM}$ = 537 keV ($E_a$ = 635 keV)
- $\omega\gamma < 60$ neV [Jaeger et al.]
- Thick, $^{22}Ne:Ni$ = 2:1 target, **(active region ≈30 keV thick**) (e.g., produced using 80 keV $^{22}Ne$ implanted in ≈ 0.5 mm Ni backing)

Assumptions:

I ($^4He$) ≈ **500 μA** and

detection efficiency of **η ≈ 50%**

**10 counts / hour**




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

# 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)

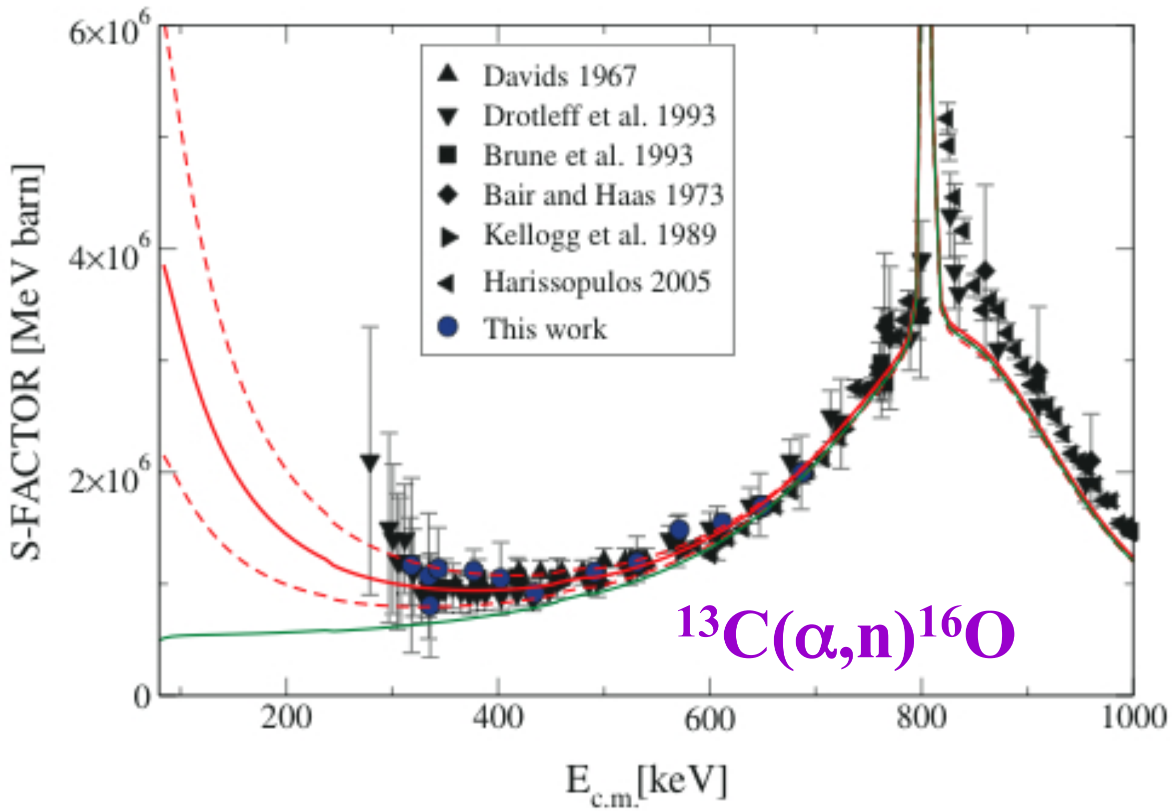
Assumptions:

I ($^4$He) ≈ **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)



# Plans - Implementation

- ✓ LSC strategic plan
  - → CUNA for the period 2015-2020 [cf. talk by A. Ianni]
  - → Expending profile, resources
- ✓ Decisions on infrastructure
  - → accelerator, hall, shielding
- ✓ Collaboration/complementarity to other facilities (LUNA-MV)
  - → Several talks on the Physics!
- ✓ Neutron background study
  - → Jordán, Taín et al., Astropart. Phys. 42 (2013) 1
  - → Several measurements ongoing - See talk by J.L. Taín
- ✓ Development of a detector for (α,n) reactions
  - → Detector prototype, low background - See talks by J.L. Taín and P. Calviño
- ✓ Test beam for radiative capture - gamma detection
  - → Total absorption measurements, simulations - See talks by A. Algora

# Infrastructure

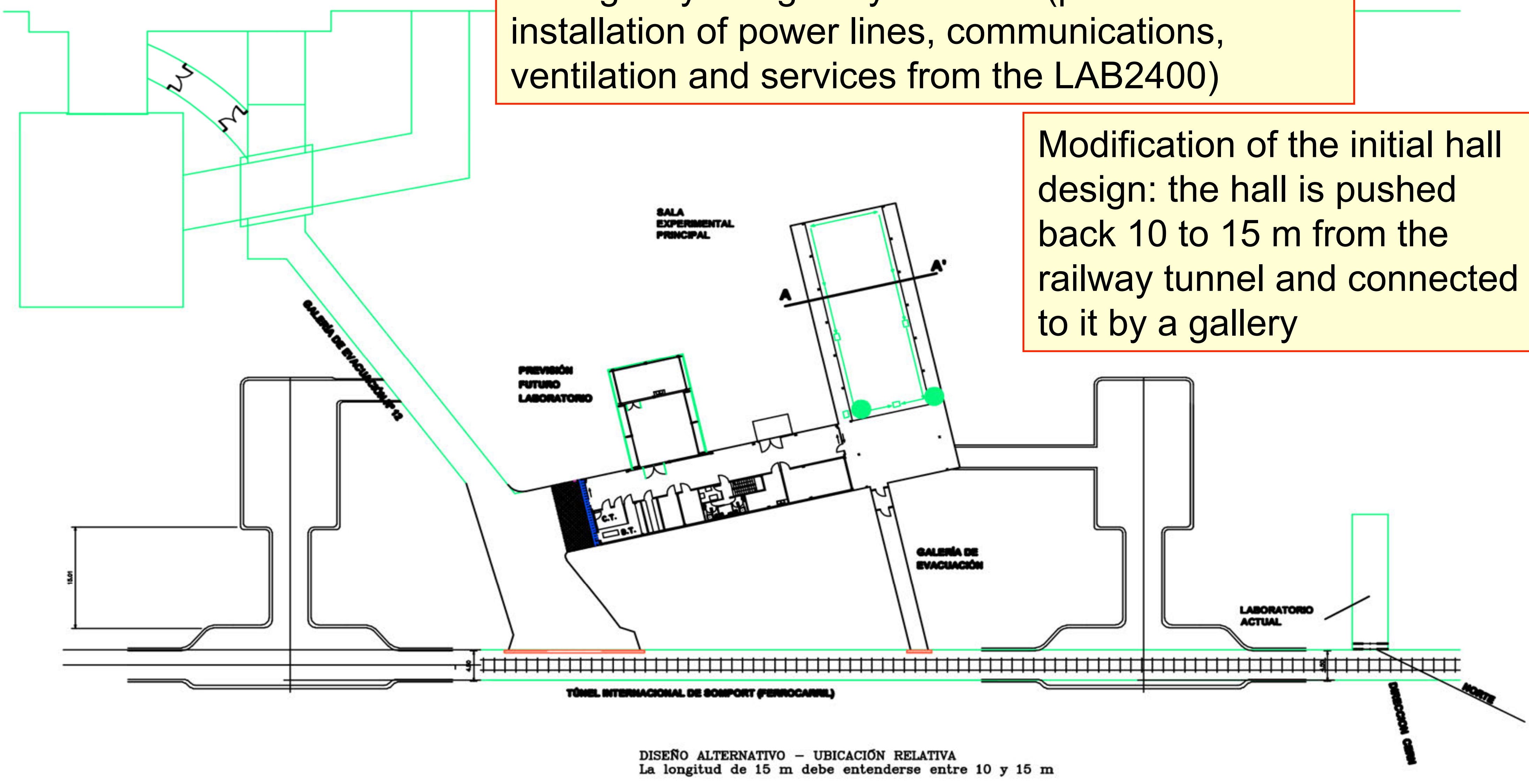
L.M. Fraile

# Cave design study

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)

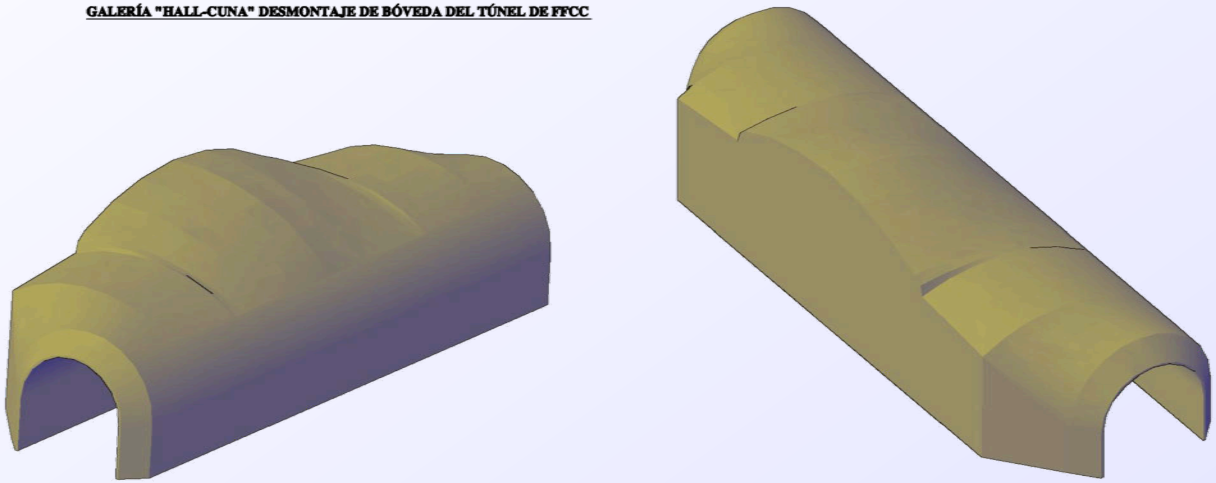
Modification of the initial hall design: the hall is pushed back 10 to 15 m from the railway tunnel and connected to it by a gallery

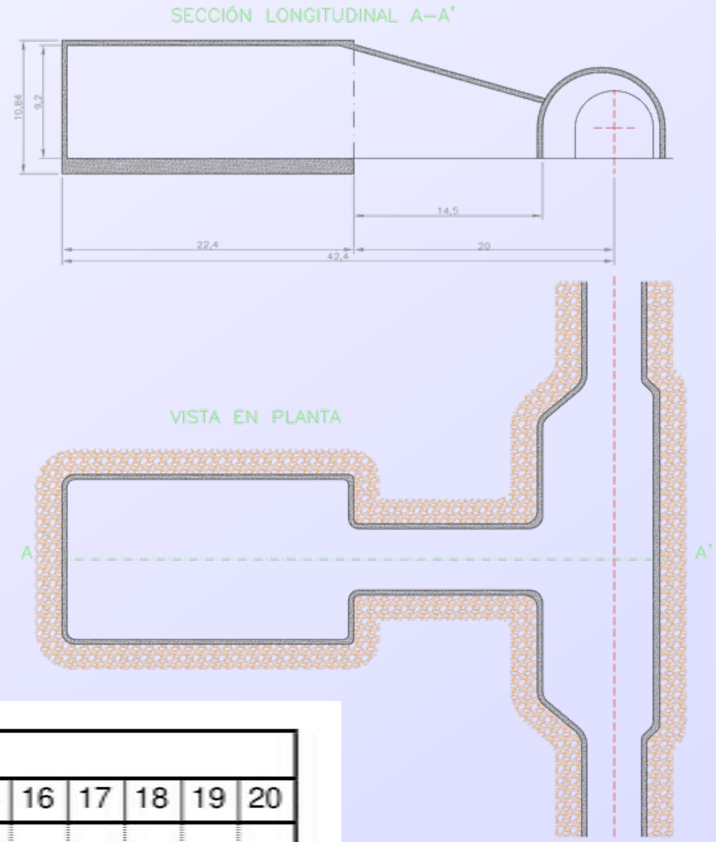


# Pre-project for the cave

## Option B considered in simulations

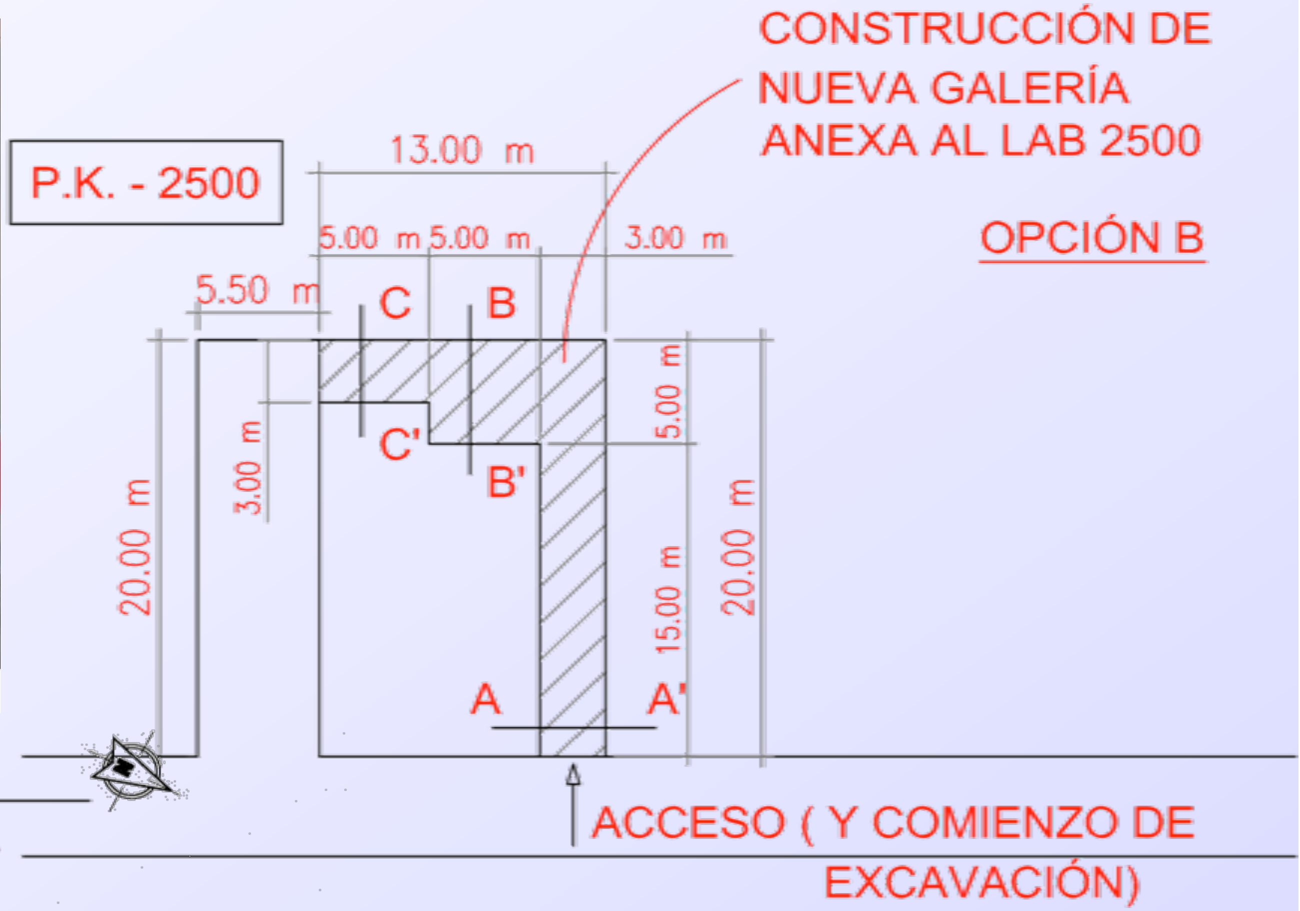
GALERÍA "HALL-CUNA" DESMONTAJE DE BÓVEDA DEL TÚNEL DE FFCC

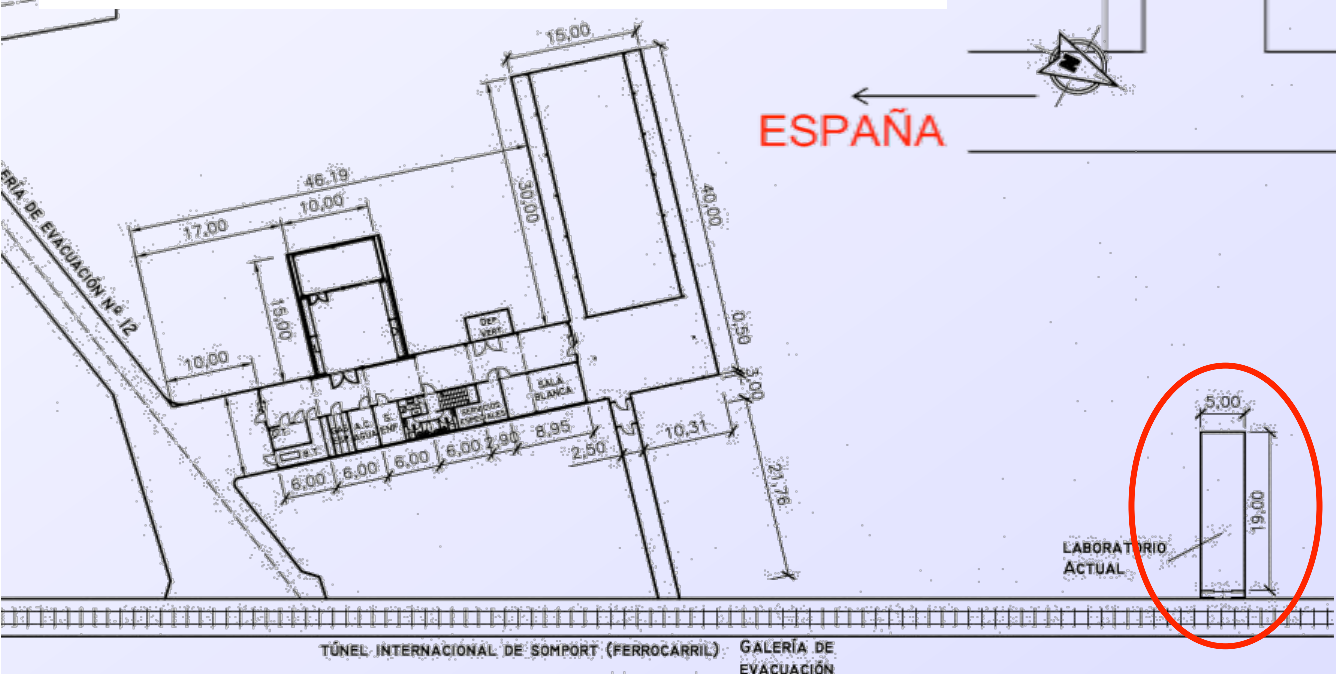





| PLANNING DE EJECUCIÓN | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MESES | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| ESTUDIOS PREVIOS - GEOTECNIA - PROYECTO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

# Another option?

# 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

See talk by T. Kurtukian-Nieto
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


## 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, $SF_6$

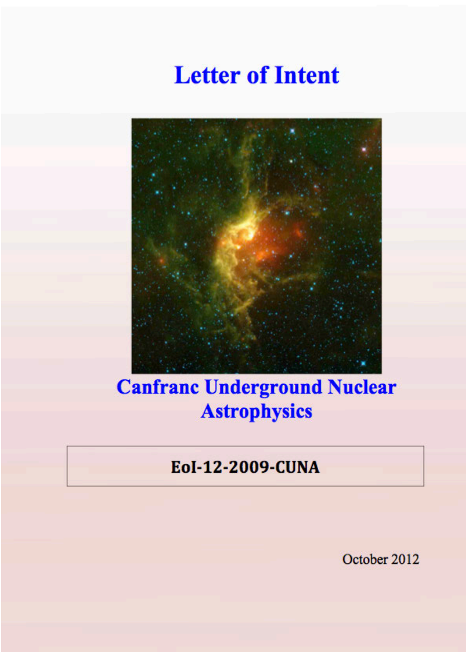
In principle this solution will perfectly fit

# Plans - Implementation

| Material | Cost (k€) |
|---|---|
| Accelerator, beam lines, analyzing magnet | 2000 - 2700 |
| Hall construction, infrastructure and shielding | 1000 - 3500 |
| Neutron detection and DAQ | 500 |
| High resolution gamma detection and DAQ | 200 |
| Scintillator array with DAQ | 350 |
| Experimental mechanics and shielding | 400 |

- ✓ Budget
  - → Hall & infrastructure via FEDER?
  - → Expending profile, resources
  - → Contribution to LSC strategic plan
- ✓ Decisions on infrastructure
  - → **accelerator**, hall, shielding
- ✓ Neutron background study
  - → Jordán, Taín et al., Astropart. Phys. 42 (2013) 1
  - → Several measurements ongoing
- ✓ Development of a detector for (α,n) reactions
  - → Detector prototype, low background
- ✓ Test beam for radiative capture - gamma detection
  - → Total absorption measurements, simulations

See contributions to this workshop


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


**L.M. Fraile (spokesperson)**, B. Olaizola, J.M. Udías
*Grupo de Física Nuclear, **Universidad Complutense de Madrid**, Madrid, Spain*

J. José, R. Longland, A. Parikh
*GAA, Universitat Politecnica de Catalunya, Barcelona, Spain*

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

C. Abia, I. Domínguez
*Universidad de Granada, Granada, Spain*

F. Calviño, B. Gómez-Hornillos,
*GREENER, Universitat Politecnica de Catalunya, Barcelona, Spain*

D. Cano, T. Martínez
*Centro de Investigaciones Energéticas y Medioambientales, Madrid, Spain*

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

A. Algora, D. Jordán, J.L. Taín
*Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain*

I. Irastorza, G. Luzón
*Lab. de Física Nuclear y Astropartículas, Universidad de Zaragoza, Zaragoza, Spain*