Nuclear Cross Sections for Physics in the Sun

Matthias Junker

INFN-LNGS

Solar Neutrinos: Status and Prospects

W. C. Haxton, R. G. Hamish Robertson, Aldo M. Serenelli

ArXive: 208.5725v1 [astro-ph] 28 Aug 2012

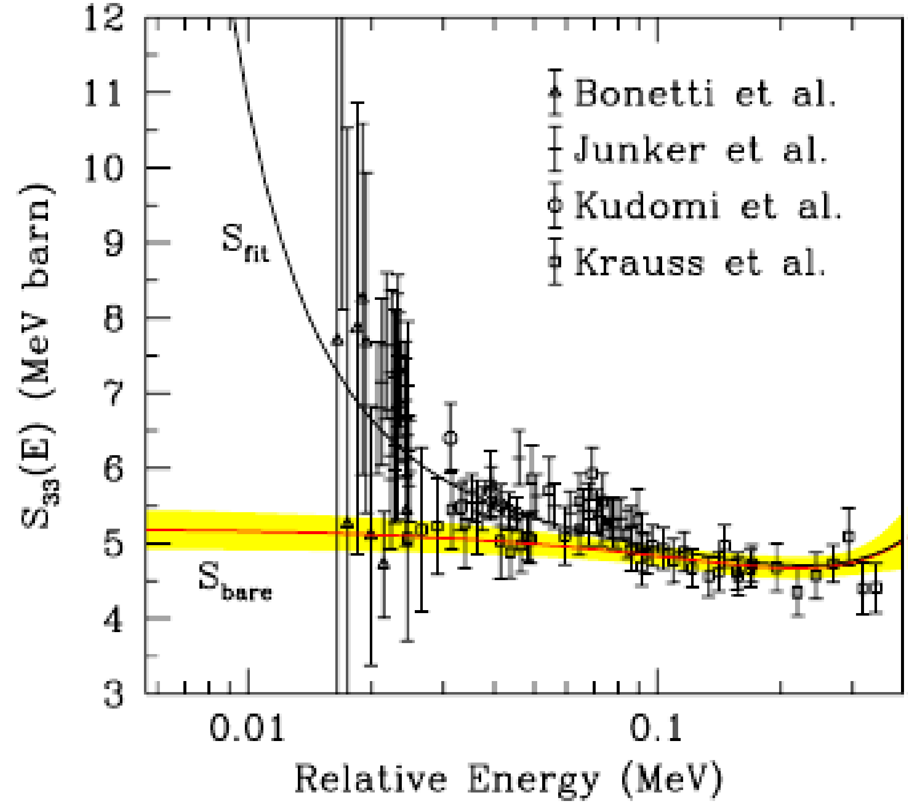
- **Neutrinos as a Direct Probe of Solar Composition: SNO+**
  - "(…) there are **nuclear physics uncertainties**. These **dominate** the overall **error budget**, with the combined (in quadrature) error reflecting a **7.2% uncertainty from the ^{14}N(p,γ)** reaction and a **5.5% uncertainty from ^{7}Be(p,γ)**" (p. 48).
- **The Solar Abundance Problem and its SSM Implications**
  - "In the case of the **^{8}B flux**, the **important uncertainties include** those for the atomic opacities (6.9%), the diffusion coefficient (4%), the nuclear S-factors for **^{3}He+^{4}He (5.4%) and ^{7}Be+p (7.5%)**, and the Fe abundance (5.8%). (p. 52)"

Approaches

- **Measurements in relevant energy range**
  - no extrapolation needed
    - no model dependence (?)
  - low cross sections
    - Background issues;
    - large statistical errors
  - systematic uncertainties (e.g., stopping power, effective energy, electron screening)
- **Extrapolation from higher energies**
  - experimental data taken at "high" energies with "high" cross sections
    - good signal to background ratio
    - low statistical and systematic errors in data
  - requires good understanding of reaction
    - needs additional input (levels, angular distributions, potentials)
    - Requires high quality data over a wide energy range from high to low energies
  - data must have excellent statistics and low systematic errors
  - data must cover a wide energy range
- **Indirect methods (transfer reactions, trojan horse, etc.)**
  - provides data at (almost) any energy of interest
  - always model dependent

$^3He(^3He,2p)^4He$

- Lowest cross section measured: 0.02 pb at 16.5 keV
- Lowest reaction rate: 2cts/month
- Excluded low energy resonance
- Confirmed increase of S(E) at low energies as effect of Electron Screening $S_{bare}(E_0=21.94keV)=5.11+-0:22$ MeV b



"(...) existing **data cannot strongly constrain all of the fitting parameters separately**, and, in particular, **do not sharply constrain Ue**. To improve constraints on the screening potential one will **need more precise data from near the Gamow peak**, as well as **new measurements up to the MeV range** (with well-documented systematics) to better determine the higher-order terms in the quadratic fit. **New theory efforts** in determining the shape of this S factor would also be beneficial, as new low-energy 3He-3He elastic scattering data could be used as an additional constraint." (Adelberger 2011)

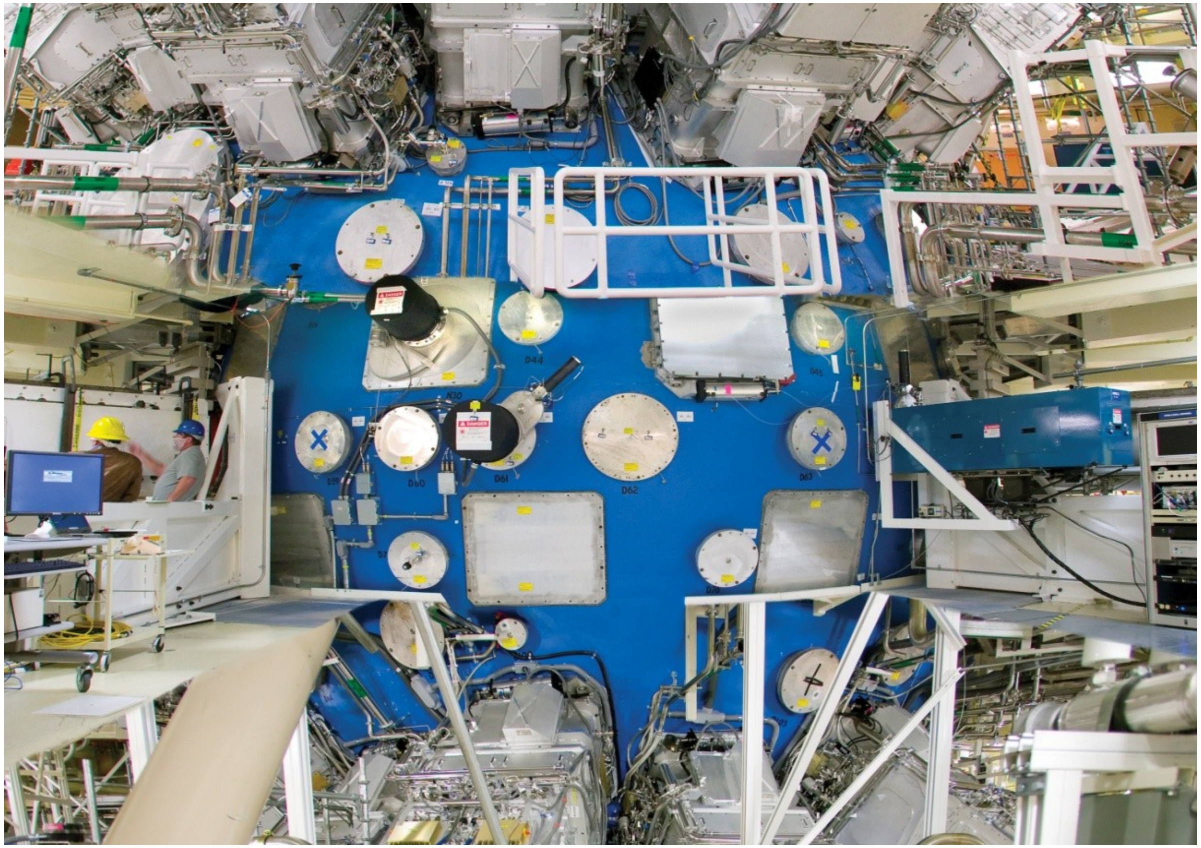
Nuclear astrophysics in hot, dense, and dynamic laboratory plasmas

Cairns, Australia

6 August 2012

Dennis P. McNabb

Lawrence Livermore National Laboratory



LLNL-PRES-562760

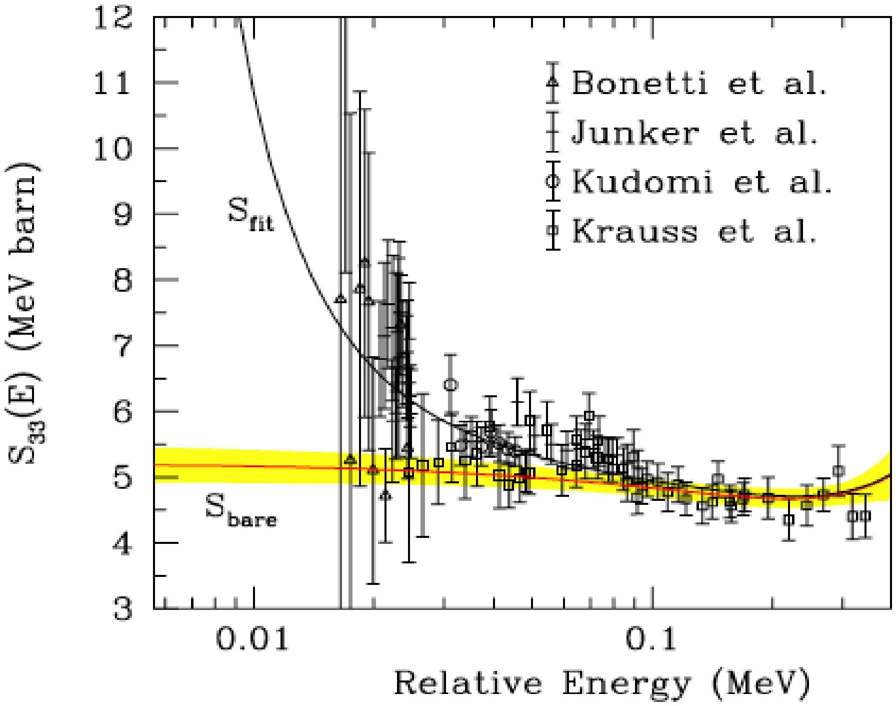
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC


National Ignition Facility
NIF is a three football stadium-sized laser, which delivers ~1.8 MJ to a cm-scaled hohlraum
Capsule diameter ~1 mm
Hohlraum
Matter Temperature >10^8 K
Radiation Temperature >3.5 x >10^6 K
Densities >10^3 g/cm^3
Pressures >10^{11} atm
NIF-0706-12555 L2

HED plasmas are a very different environment from accelerators

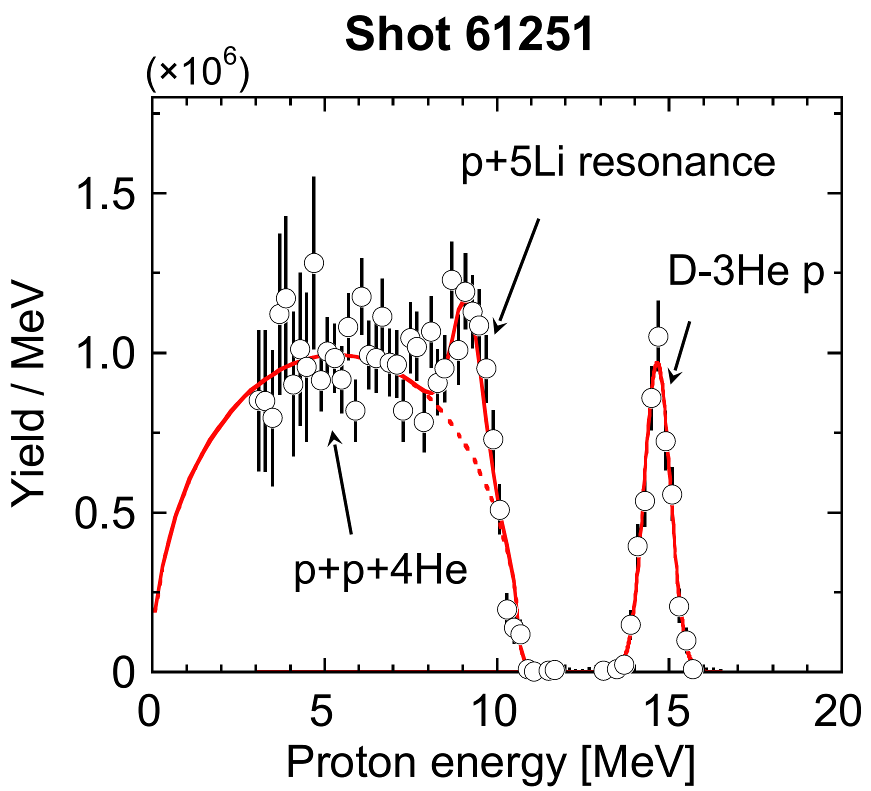
Advantages

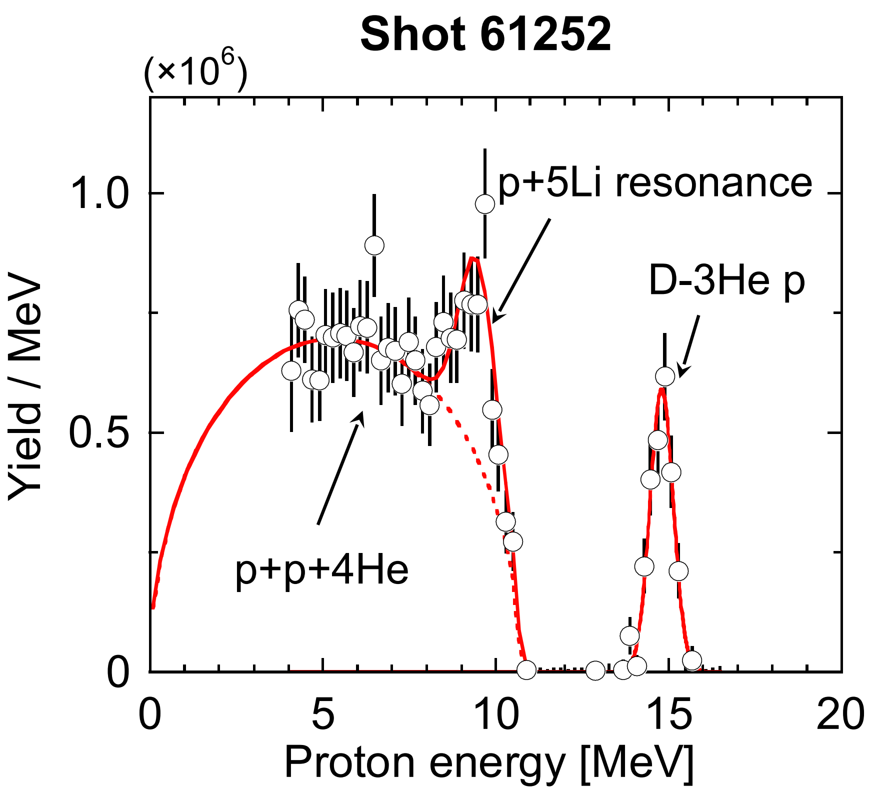
- Plasma environment like a star
  - No electron screening corrections
  - New phenomena
  - NIF implosions could be a place to test electron screening corrections:
  - Weak screening in plasma
  - Accelerator measurements extrapolated with a quadratic
  - For 3He+3He, terms are ~70% uncertain



Complementary techniques allow us to understand how reactions in a plasma environment differ from precision accelerator measurements

We measured proton spectrum from 3He(3He,2p)4He at OMEGA with a ~12 keV plasma

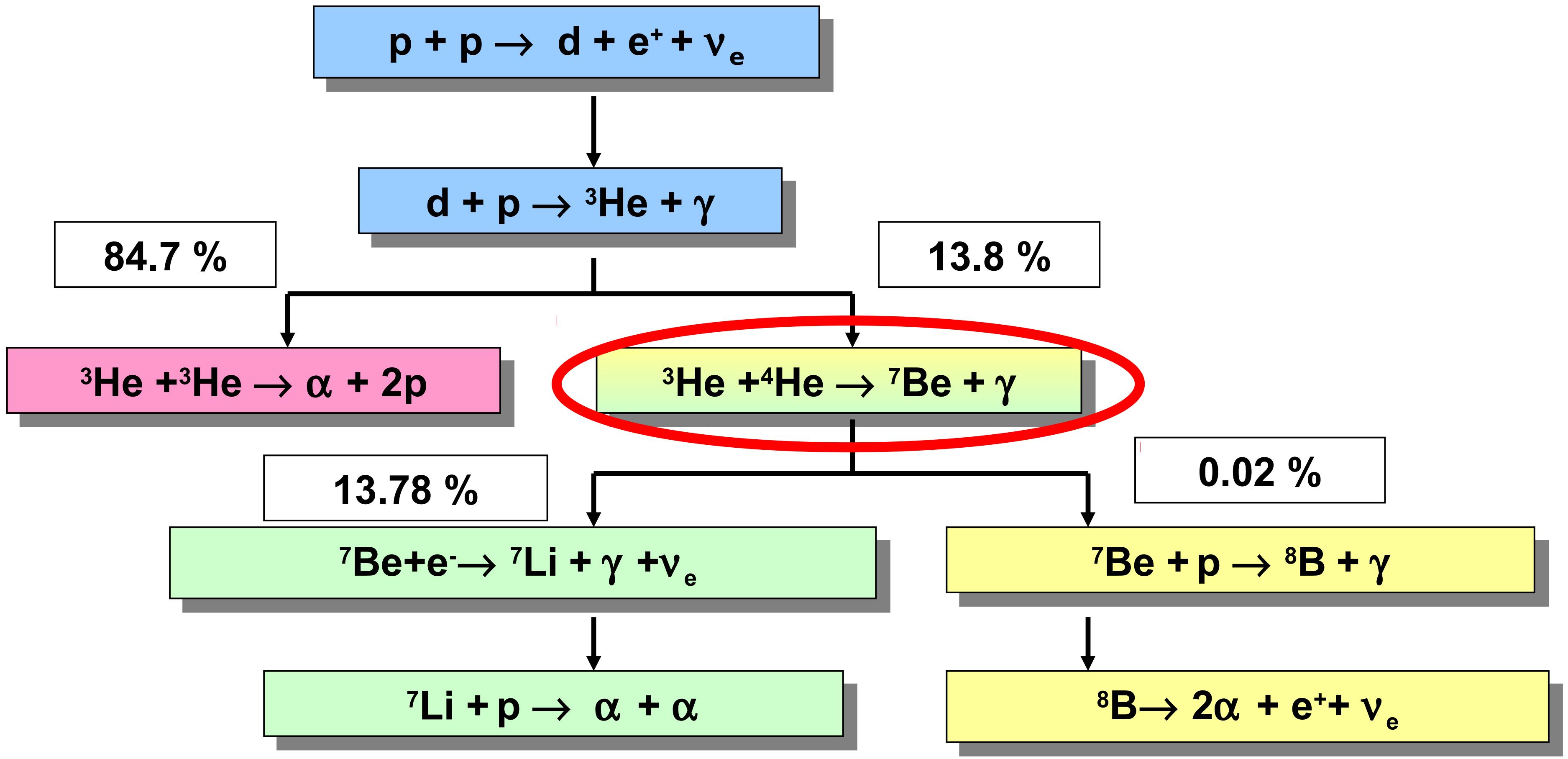




Yields near solar temperatures will be very low (better at NIF)

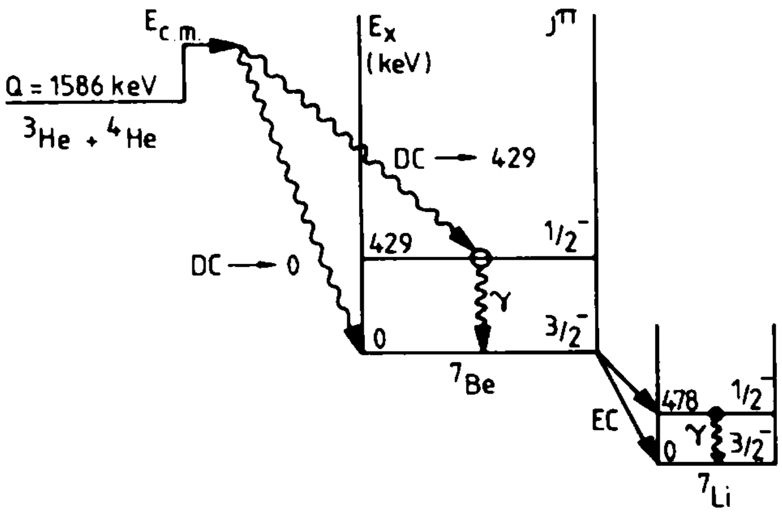
Need to develop techniques to measure protons <4 MeV

The pp Chain



$p + p \rightarrow d + e^+ + \nu_e$
$d + p \rightarrow {}^3He + \gamma$
84.7 %
13.8 %
${}^3He + {}^3He \rightarrow \alpha + 2p$
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
13.78 %
0.02 %
${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$
${}^7Be + p \rightarrow {}^8B + \gamma$
${}^7Li + p \rightarrow \alpha + \alpha$
${}^8B \rightarrow 2\alpha + e^+ + \nu_e$

$^{3}He(^{4}He,\gamma)^{7}Be$

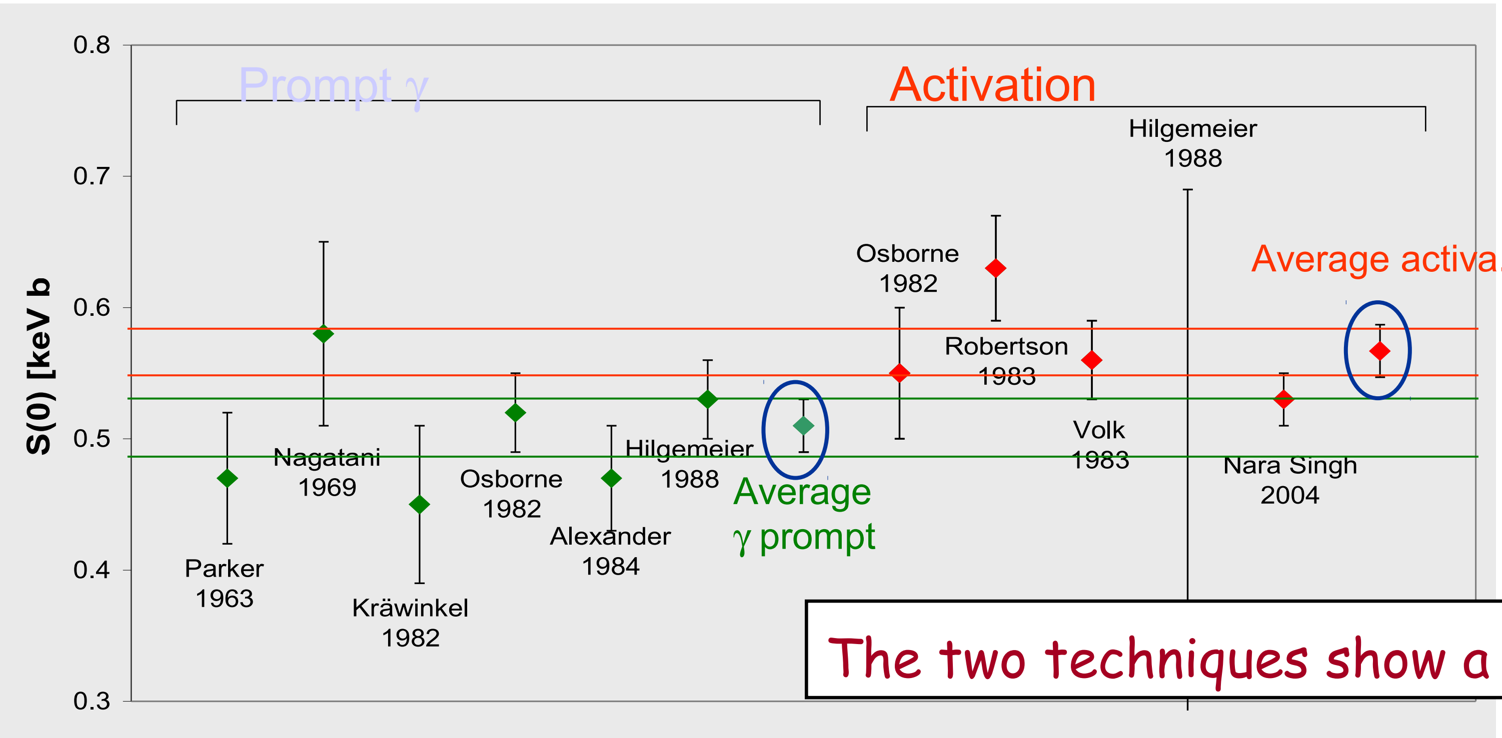


$E\gamma$ = 478 keV

$E\gamma$ =1586 keV + E_{cm} (DC → 0);

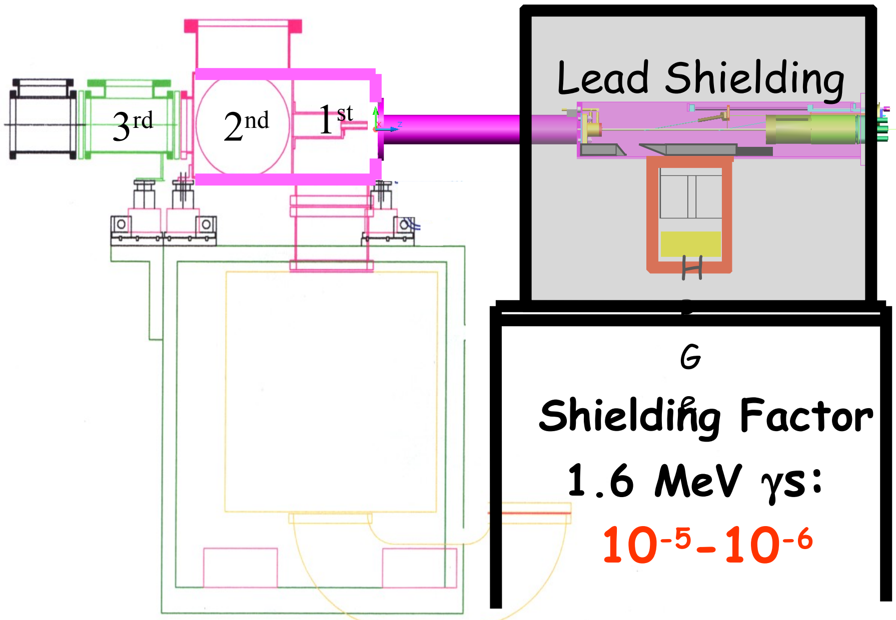
$E\gamma$ = 1157 keV + E_{cm} (DC → 429)

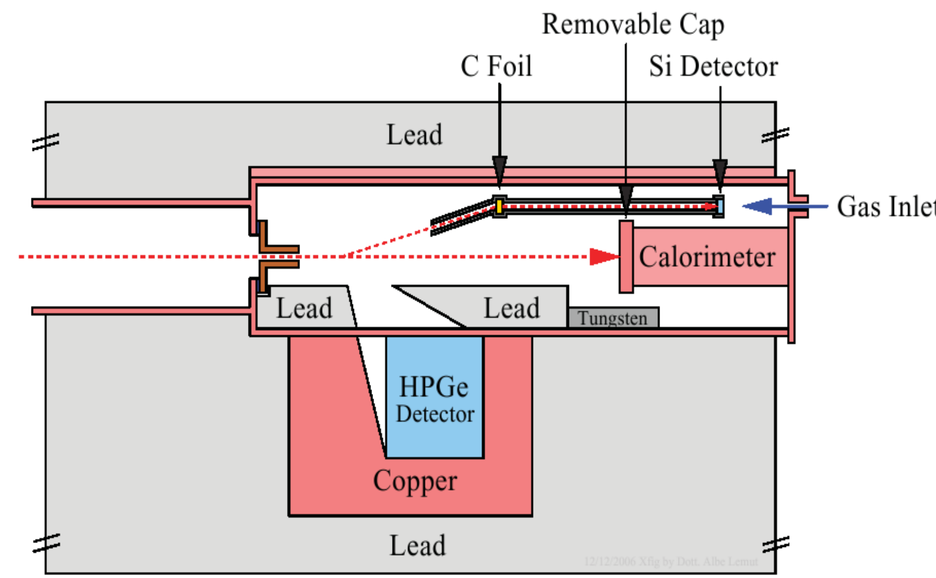
$E\gamma$ = 429 keV

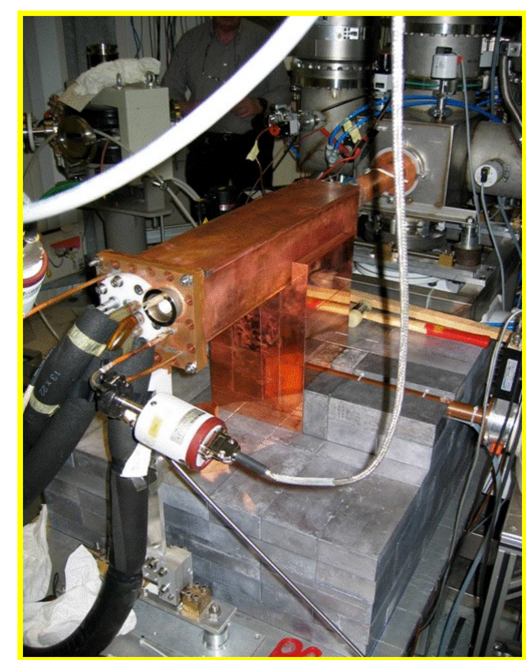


The two techniques show a 9% discrepancy

$^{3}He(\alpha,\gamma)^{7}Be$ – LUNA-Setup





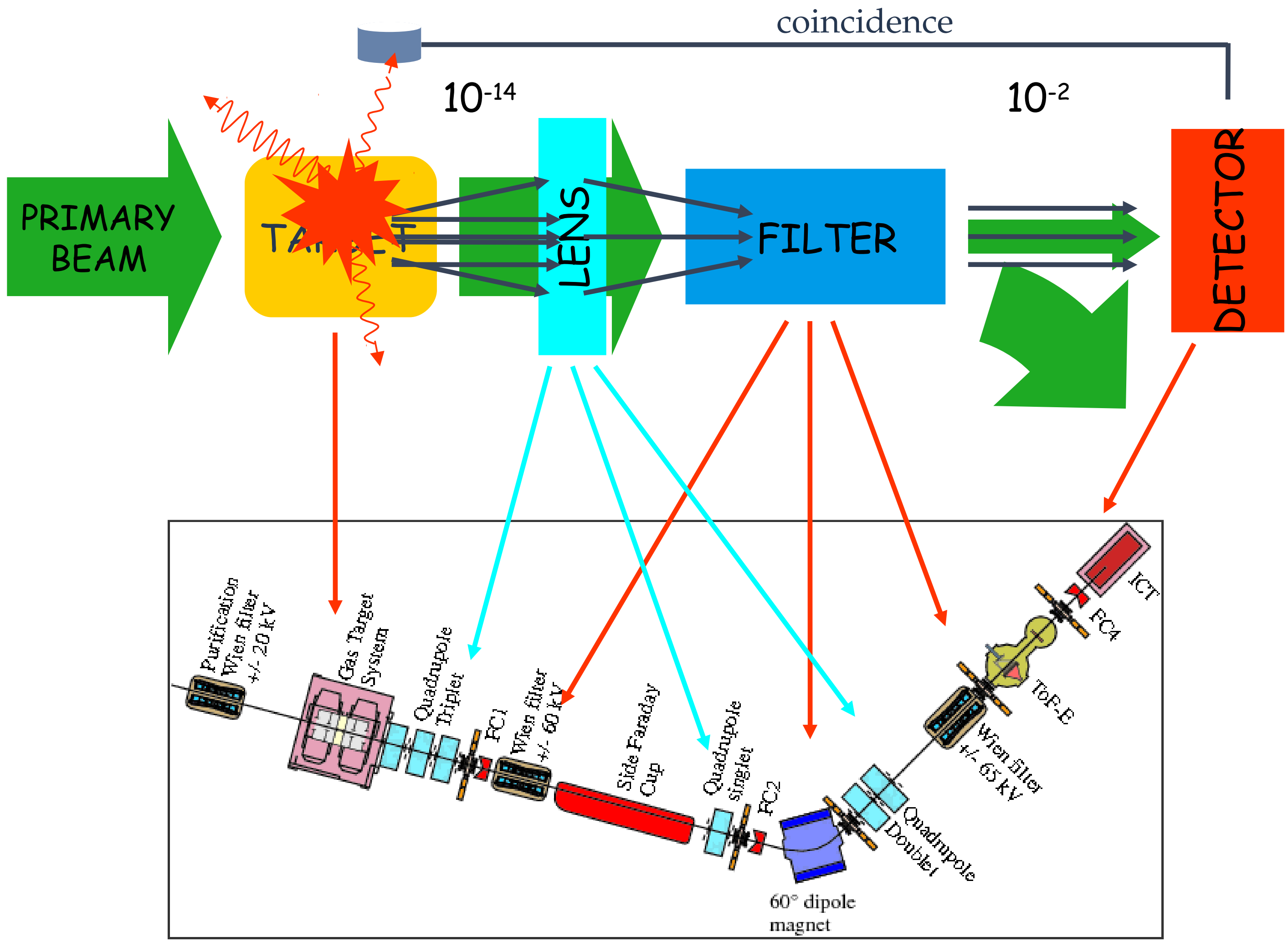


Luna measurement: both techniques and accuracy of 4-5%

- ^{3}He recirculating gas target p=0.7mbar
- Si-monitor for target density measurement (beam heating effect)
- Collimated HPGe detector to collect ㄹㅅ ray at 55 ㅊ
- 0.3 m^3 Pb-Cu shield suppression five orders of magnitude below 2MeV
- Removable calorimeter cap for offline ^{7}Be counting

Erna - Recoils measurement

$^{3}He(\alpha,\gamma)^{7}Be$



Recoil mass separator ERNA

Courtesy
A. Di Leva, INFN Napoli

Extrapolation to solar energies

Potential models (global scaling parameter):

Tombrello & Parker, Descouvemont (R-matrix based), Mohr

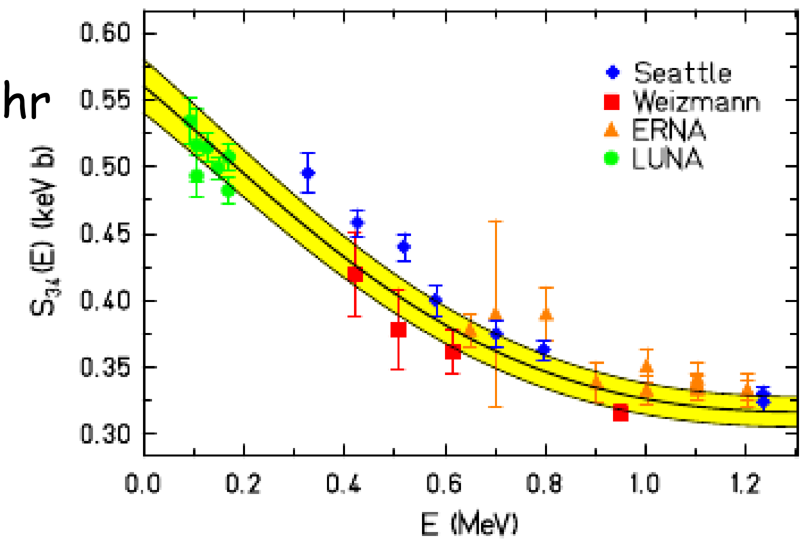
Microscopic models (no global scaling parameter):

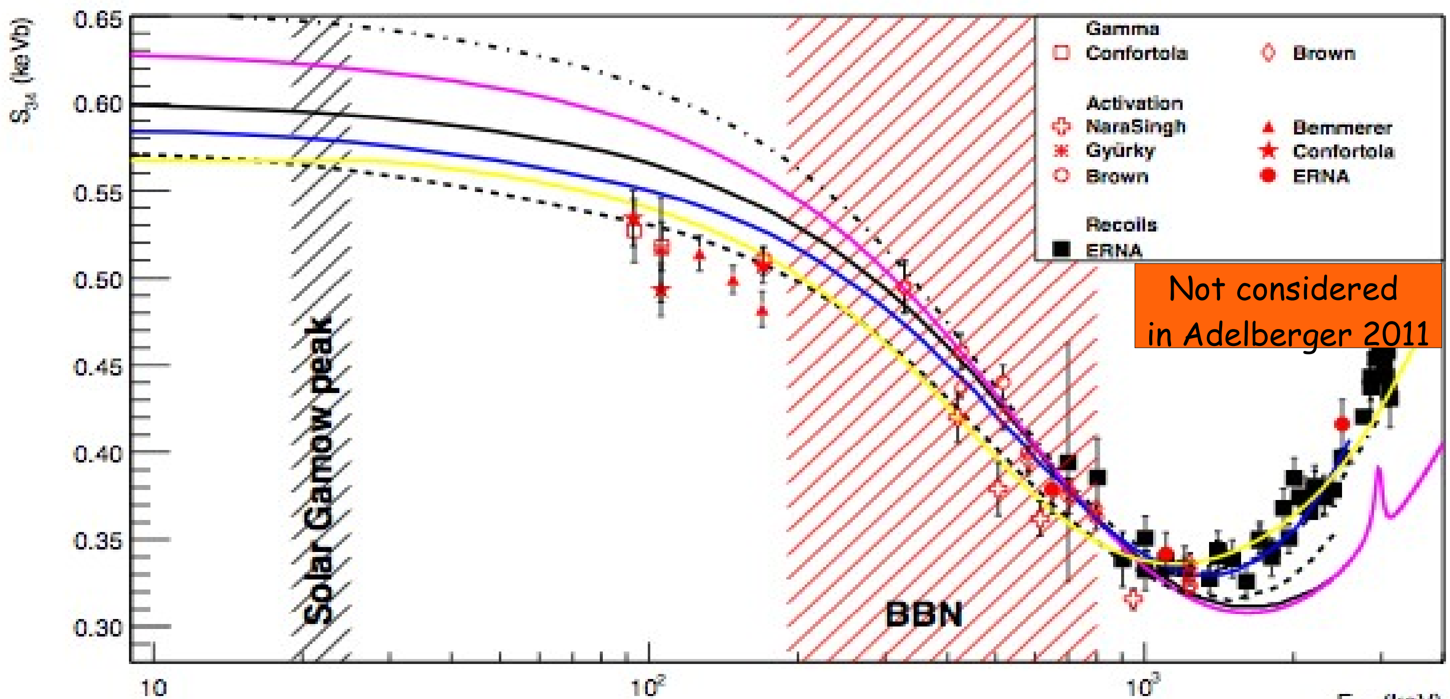
Csótó & Langanke, Kajino et al., Nollett, etc...

Usually claimed to be valid up to E_{cm}~2.0MeV

Fermionic Molecular Dynamics (FMD)

T. Neff, PRL106, 042502 (2011) (not incl. in Adelberger 2011)





Adelberger 2011 S_{34}=0.56 +- 0.02(exp) +- 0.02(theory) keV b

Courtesy
A. Di Leva, INFN Napoli

Hc

European Research Council

ERC Synergy Grant
Research proposal (Pa

Nuclear cross sections and neut
understanding of the :
NUNESUN

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Proposal summary (h

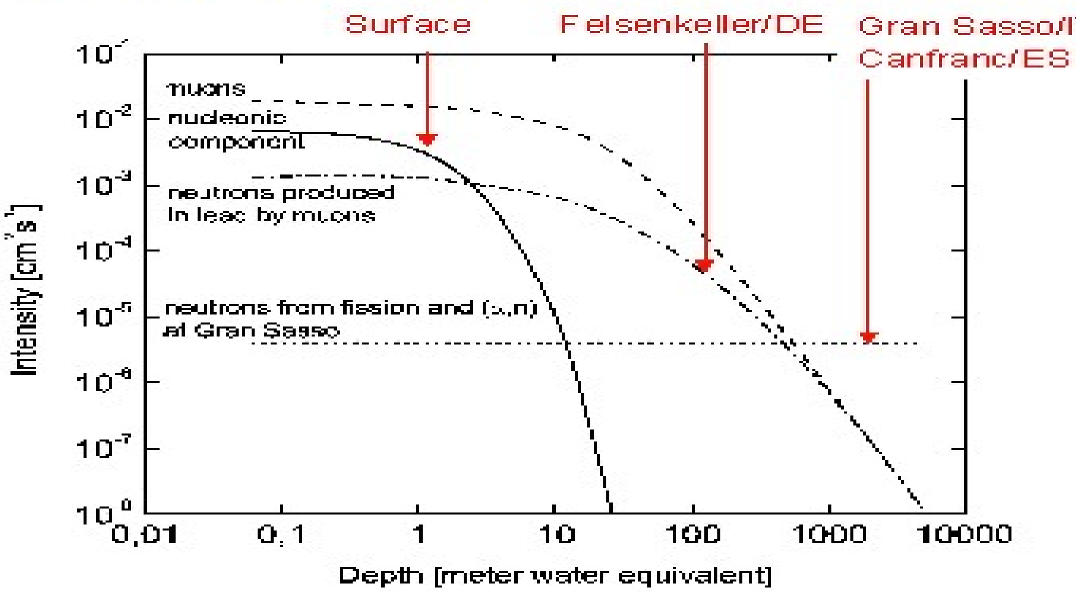
The general objectiv experimental and the neutrino fluxes and r The unique synergy a activity both in the th gained at the Gran Sa astrophysics (LUNA) about the Sun, one r stellar astrophysics.

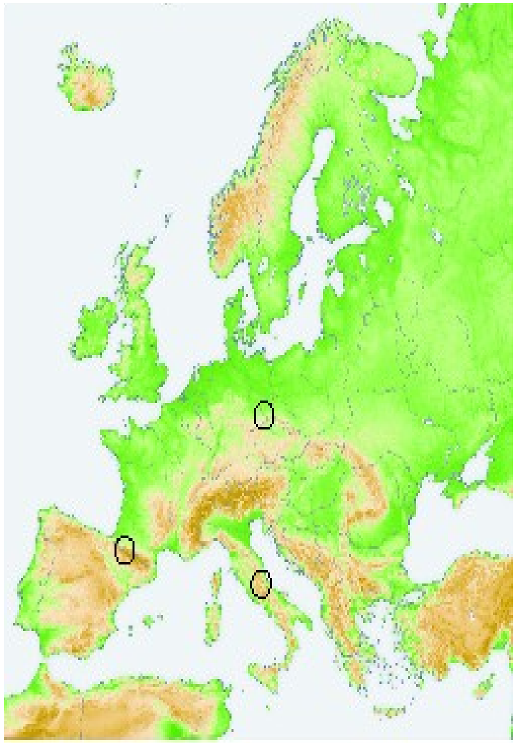
In the framework of t cross section of ^{3}He(level of 3%, and an c solar interior. The p astrophysics and in o for both stellar atmos

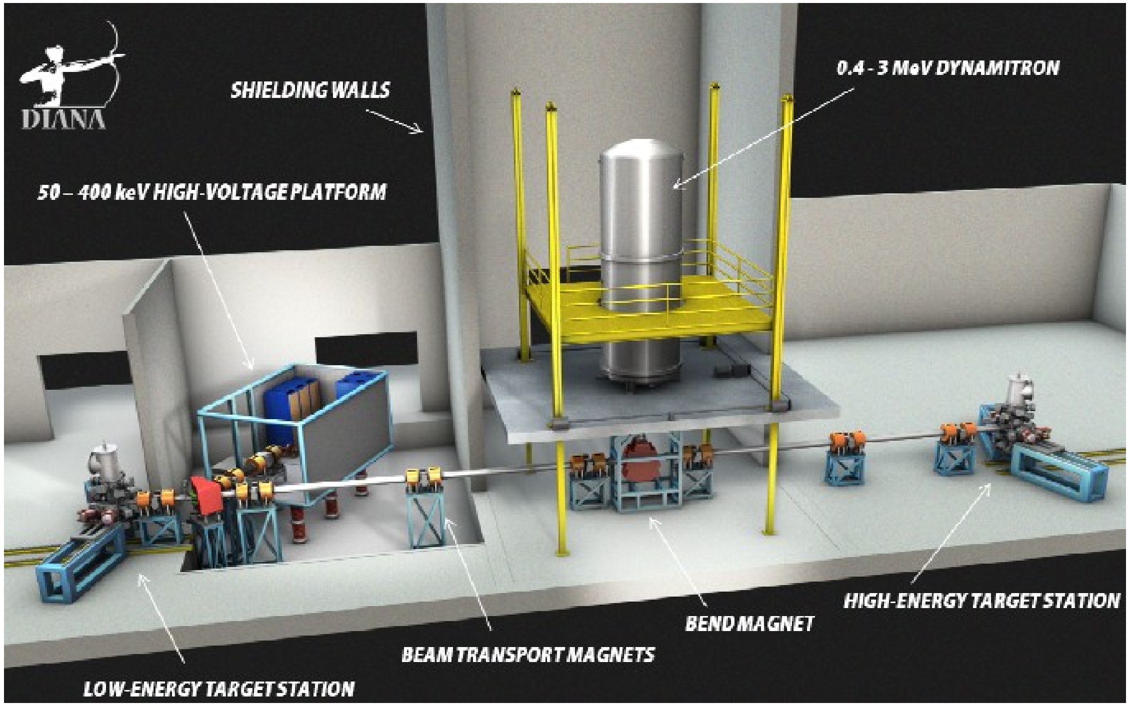
	PROGETTO PREMIALE INFN
TITOLO	**LUNA-MV:** Laboratory for Underground Nuclear Astrophysics and Applications-MegaVolts
COORDINATORE	ALESSANDRA GUGLIELMETTI (UNI-INFN Milano)
HORIZON 2020	EXCELLENT SCIENCE – BETTER SOCIETY

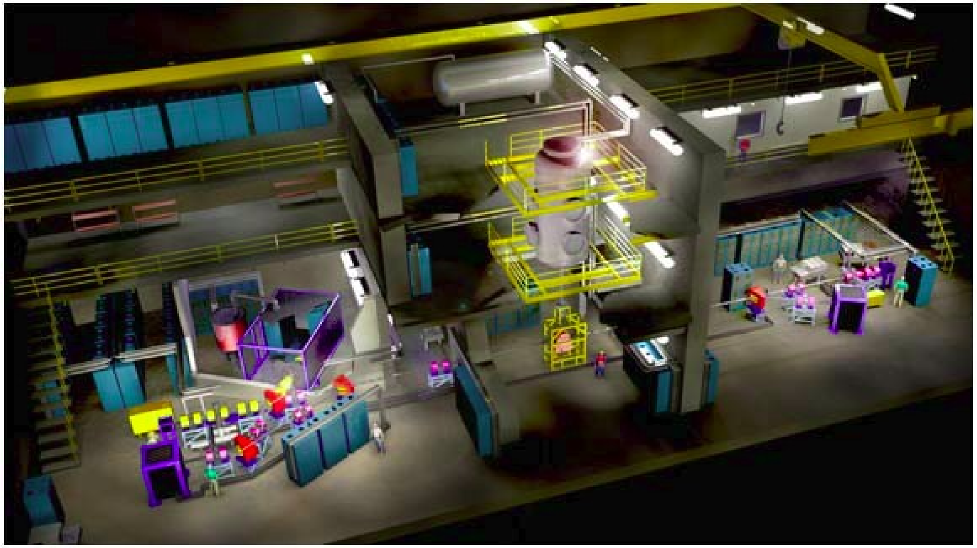
Anno 1	Anno 2	Anno 3	Anno 4	Anno 5
Preparazione del sito all'interno dei LNGS (strutture edilizie, impianti, schermature, sicurezze). *Definizione delle specifiche dell'acceleratore di particelle, avvio della gara di acquisto ed emissione dell'ordine di fornitura* Approved	*Progettazione delle linee di fascio per i bersagli di tipo solido e gassoso. Acquisto e costruzione delle apparecchiature e delle strutture necessarie* *Progettazione dei sistemi di rivelazione e di acquisizione dati. Acquisto e costruzione dell'hardware e del software necessari.*	*Installazione acceleratore.* *Costruzione delle linee di fascio.* *Costruzione dei sistemi di rivelazione ed acquisizione dati*	*Messa a punto e calibrazione di acceleratore, linee di fascio, rivelatori.* *Esecuzione di esperimenti di prova*	*Esecuzione del primo esperimento sulla linea di fascio con bersaglio gassoso (misura della sezione d'urto della $^{3}He(\alpha,\gamma)^{7}Be$ su un ampio intervallo energetico).* *Esecuzione del primo esperimento sulla linea di fascio con bersaglio solido (determinazione della contaminazione di nano polveri a base di titanio)*

The future of underground nuclear physics









Projects for Underground Nuclear Astrophysics

CUNA, Spain (Canfranc Underground Nuclear Astrophysics)

- Accelerator-based nuclear astrophysics project proposed 2009 at the Laboratorio Subterráneo de Canfranc (LSC)
- Multi MV accelerator with RF source for proton and alpha beams
- Scientific Program: $^{12}C(a,g)^{16}O$, $^{13}C(a,n)^{16}O$, $^{22}Ne(a,n)^{25}Mg$
- Engineering design has recently been completed for independent experimental hall, distant from the rest of the caves at the LSC.
- Viable alternative presently under consideration: Refurbishing and extension of one of the existing caves.
- Neutron background measurements and simulations have recently been completed and submitted for publication (D. Jordán et al., Astro. Part. Phys. (2012)
- Funds for the accelerator are being sought at present.
- A Letter of Intent, extending the case presented in the Expression of Interest from 2009, will be presented to the LSC Scientific Committee by the collaboration in the next few months..

Projects for Underground Nuclear Astrophysics

Felsenkeller, Germany (Helmholtz Zentrum Dresden Rossendorf (HZDR) and the University of Dresden)

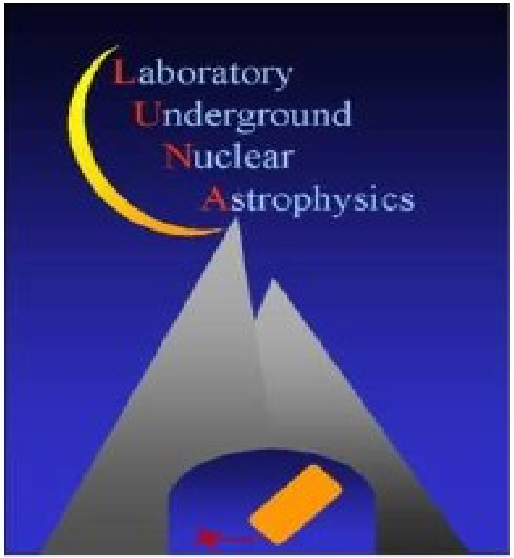
- Installation of used MV scale accelerator in a site shielded by 112 m.w.e., Used 5MV NEC Pelletron tandem accelerator system delivered to HZDR in July 2012, now undergoing a refurbishing at HZDR
- User facility, detailed scientific program has not been published.
- Facility shared with other research groups, available for Nuclear Astrophysics only for limited times.

Projects for Underground Nuclear Astrophysics

Diana, USA (Dakota Ion Accelerators for Nuclear Astrophysics)

- University of Notre Dame, University of North Carolina, Western Michigan University, and Lawrence Berkeley National Laboratory
- Designed to achieve large laboratory reaction rates: up to 100 mA to a high density super-sonic jet-gas target as well as to a solid target.

- Two accelerators, 50-400 kV and 0.4-3 MV
- Will address field of solar neutrino sources and the metallicity of the sun, carbon-based nucleosynthesis and neutron sources for the production of trans-Fe elements in stars.
- $1.6 million grant from the National Science Foundation (NSF) for continuing research and development to finalize the design and provide a budget baseline for the final NSF decision on funding and construction of the facility.
- Several underground locations are presently being discussed and the final site decision will be made within this year.



LUNA-MV LETTER OF INTENT

Submitted to LNGS scientific committee
March 2007

COLLABORATION

Germany

BOCHUM, Inst. For Experimental Physics, Ruhr-Universitat:
C. Rolfs, F. Strieder, H.P. Trautvetter

DRESDEN, Inst. For Radiation Physics, Forschungszentrum Dreseden-Rossendorf:
D. Bemmerer, M. Marta

Hungary

DEBRECEN, ATOMKI:
Z. Elekes, Zs Fulop, Gy. Gyurky, E. Somorjai

Italy

GENOVA, Università degli Studi and INFN:
F. Confortola, P. Corvisiero, H. Costantini, A. Lemut, P. Prati

LNGS, Gran Sasso:
A. Formicola, C. Gustavino, M. Junker

MILANO, Università degli Studi, Ist. Di Fisica Generale Applicata and INFN:
R. Bonetti, A. Guglielmetti, C. Mazzocchi

NAPOLI, Università, Dip. Scienze Fisiche and INFN:
N. De Cesare, A. Di Leva, A. D'Onofrio, L. Gialanella, G. Imbriani, B. Limata, V. Roca, M. Romano, O. Straniero

NAPOLI, II Università, Dip. Scienze Ambientali and INFN:
F. Terrasi

PADOVA, Università degli Studi and INFN:
C. Broggini, A. Caciolli, E. Conti, R. Menegazzo, C. Rossi Alvarez

TORINO, Università, Dip. Fisica Sperimentale and INFN:
G. Gervino

LUNA MV Project

April 2007

Letter of Intent (LoI) presented to the LNGS Scientific Committee (SC) containing key reactions of the He burning and neutron sources for the S-process:

$^{12}C(\alpha,\gamma)^{16}O$

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

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

(α,γ) reactions on $^{14,15}N$ and ^{18}O

These reactions are relevant at higher temperatures (larger energies) than reactions belonging to the hydrogen-burning studied so far at LUNA

↓

Higher energy machine

3.5 MV single ended positive ion accelerator

LUNA - MV inside Underground Laboratory

Nupecc Long Range Plan 2010:
Recommendations and Roadmap

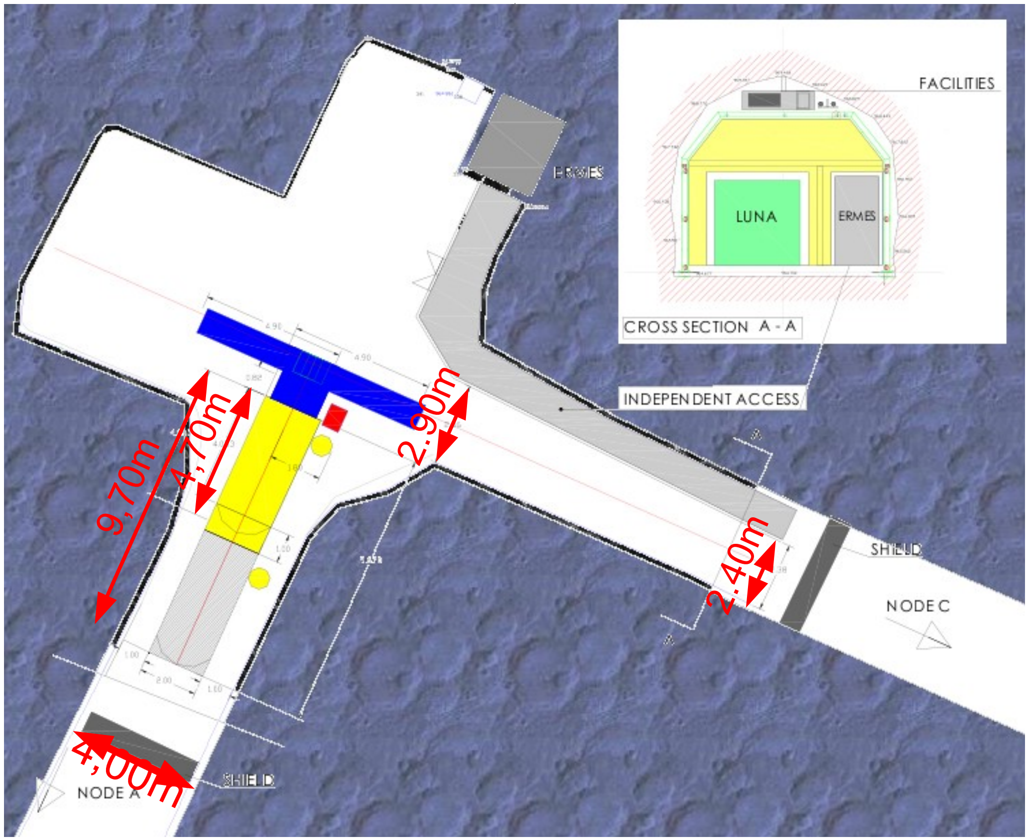
Existing Facilities

Fully exploit the currently existing large-scale research infrastructures (...) and perform limited-size upgrades to ensure the best use of the large investments made in the past:

- The lepton beam facilities (...)
- The heavy ion beam facilities (...)
- **The nuclear astrophysics underground accelerator LUNA at INFN Gran Sasso, and the exploration of advanced new facilities.**
- The ELENA upgrade (...)

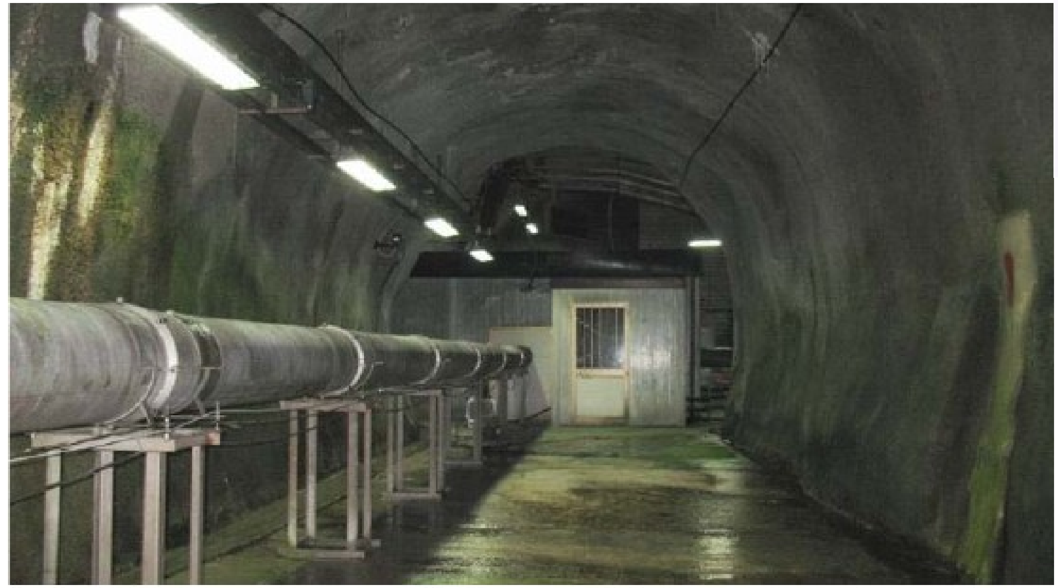
Fully exploit smaller scale national and university Nuclear Physics laboratories across Europe dedicated to nuclear structure and astrophysics experiments, fundamental interactions and nuclear applications.

The proposed accelerator



- **Single ended**
  - RF source for H and He+ beam
- **Robust, commercially available**
  - certain time line, certain cost!
- **2 beam lines accessible independently**
  - One for solid state target station (which can be biased);
  - One for gas target station;
- **Side wide slow control system**
  - full remote control of the experiment
  - automatic shifter alert in case of anomaly.

- In a very low background environment such as LNGS, it is mandatory not to increase the neutron flux above its average value



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

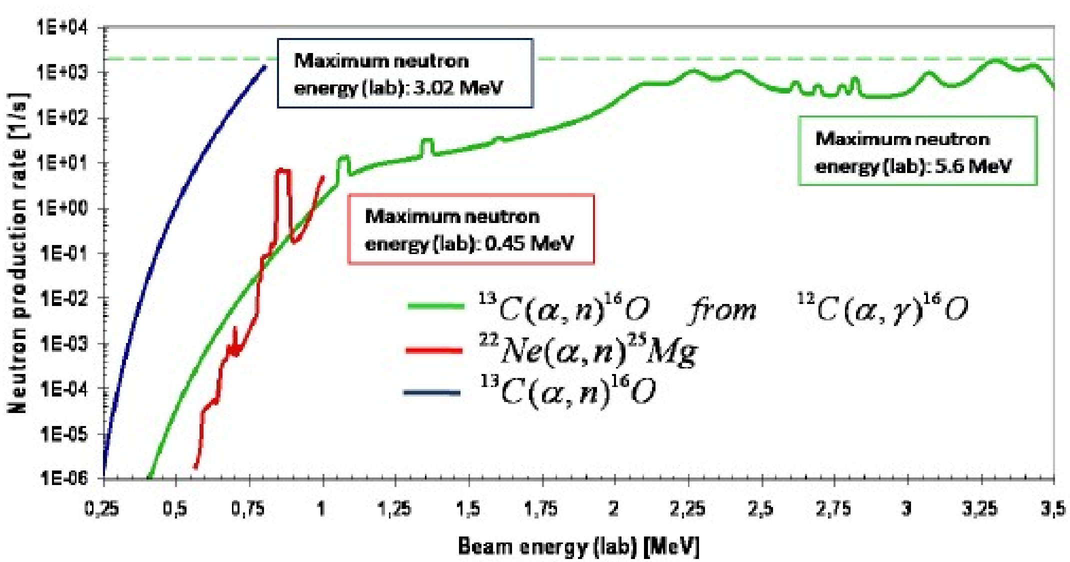
α beam intensity: 200 μA
Target: ^{13}C, 2 10^{17}at/cm^2 (99% ^{13}C enriched)
Beam energy(lab) ≤ 0.8 MeV

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

α beam intensity: 200 μA
Target: ^{22}Ne, 1 10^{18}at/cm^2
Beam energy(lab) ≤ 1.0 MeV

$^{13}C(\alpha,n)^{16}O$ from $^{12}C(\alpha,\gamma)^{16}O$

α beam intensity: 200 μA
Target: ^{13}C, 1 10^{18}at/cm^2 ($^{13}C/^{12}C = 10^{-5}$)
Beam energy(lab) ≤ 3.5 MeV



Natural Neutron flux in LNGS:

appr. 1-2 10^{-6} cm^{-2} s^{-1}

- Maximum neutron production rate : 2000 n/s
- Maximum neutron energy (lab) : 5.6 MeV

November 2009,

LNGS Scientific committee

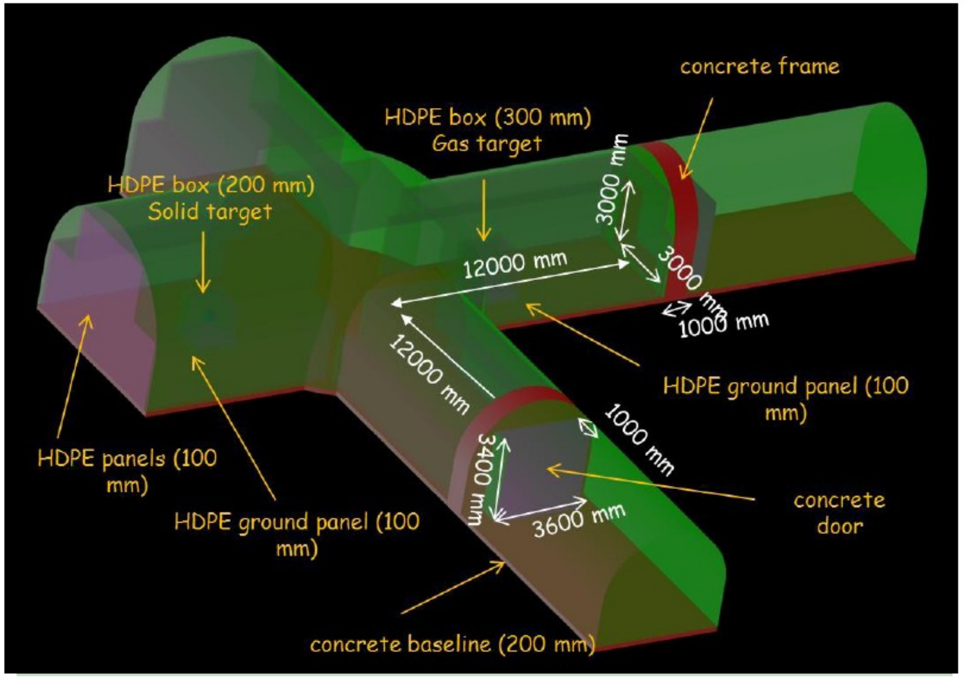
"(...) recommends that the Director set-up a small committee to address the issue of possible neutron generation and the operation of the experiment, in order to ensure that the neutron backgrounds are at a suitable level"

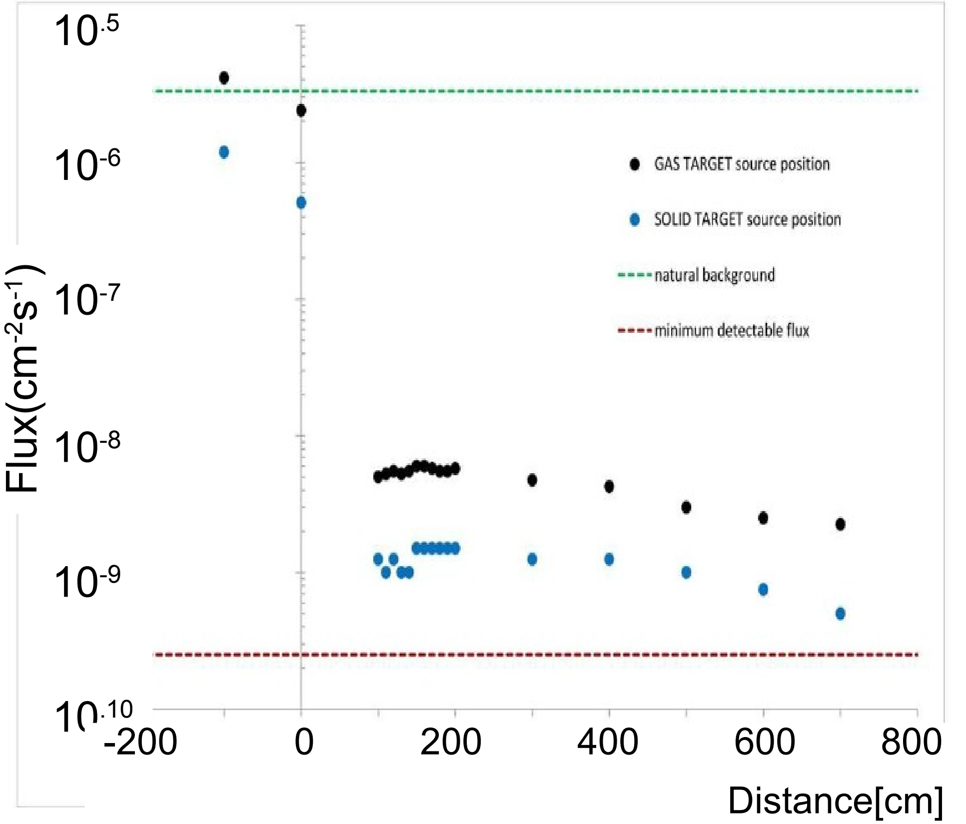
→ Neutron Committee formed (M Hass, A Esposito, W Kutschera, Lembo, M Terrani)

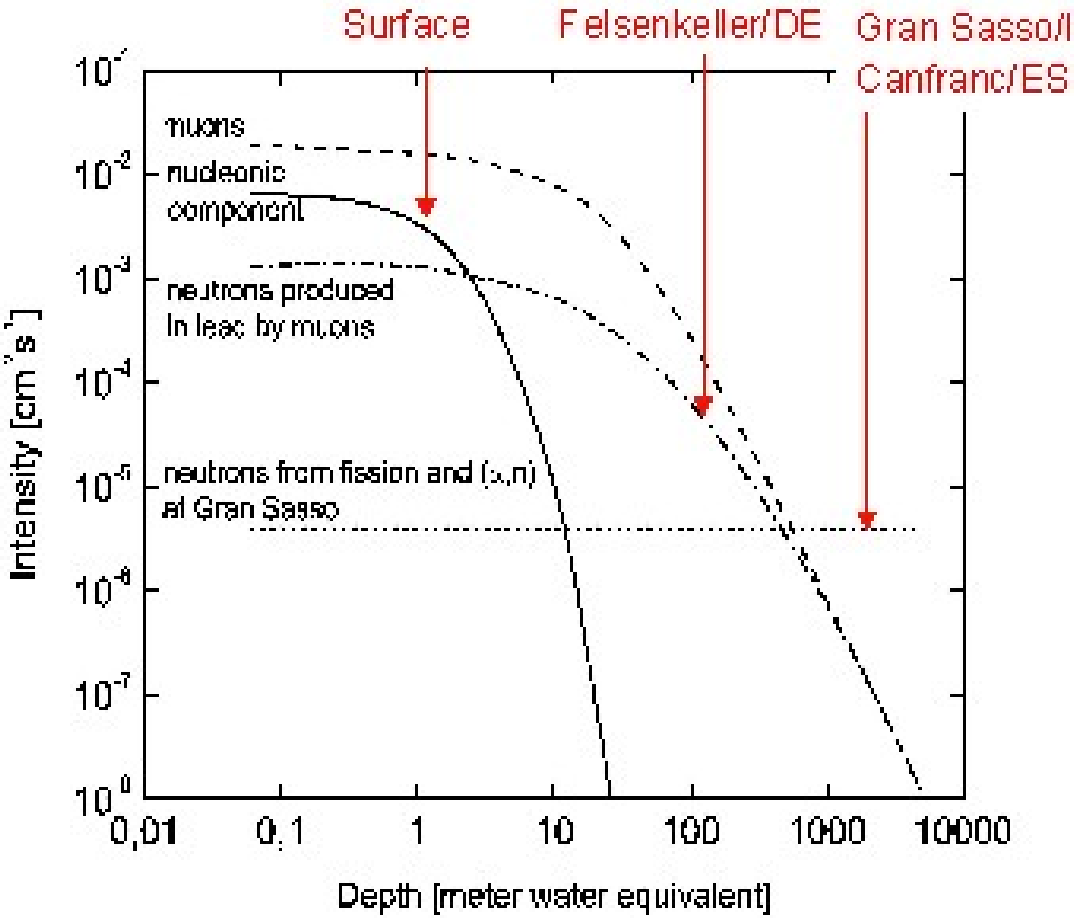
→ LUNA updates the LoI re-evaluating experimental conditions and neutron production rates. Specified further the machine characteristics.

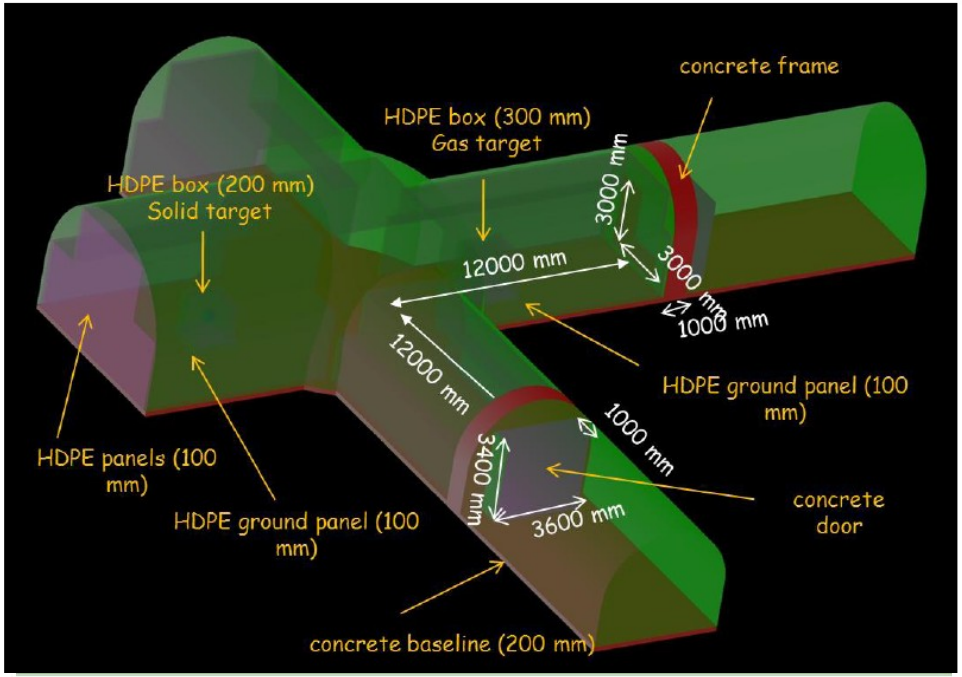
→ LUNA elaborates a document proposing a shielding of 3.5 MeV accelerator based on a GEANT4 simulations (50e6 events for the "gas target" and 50e6 events for the "solid target")

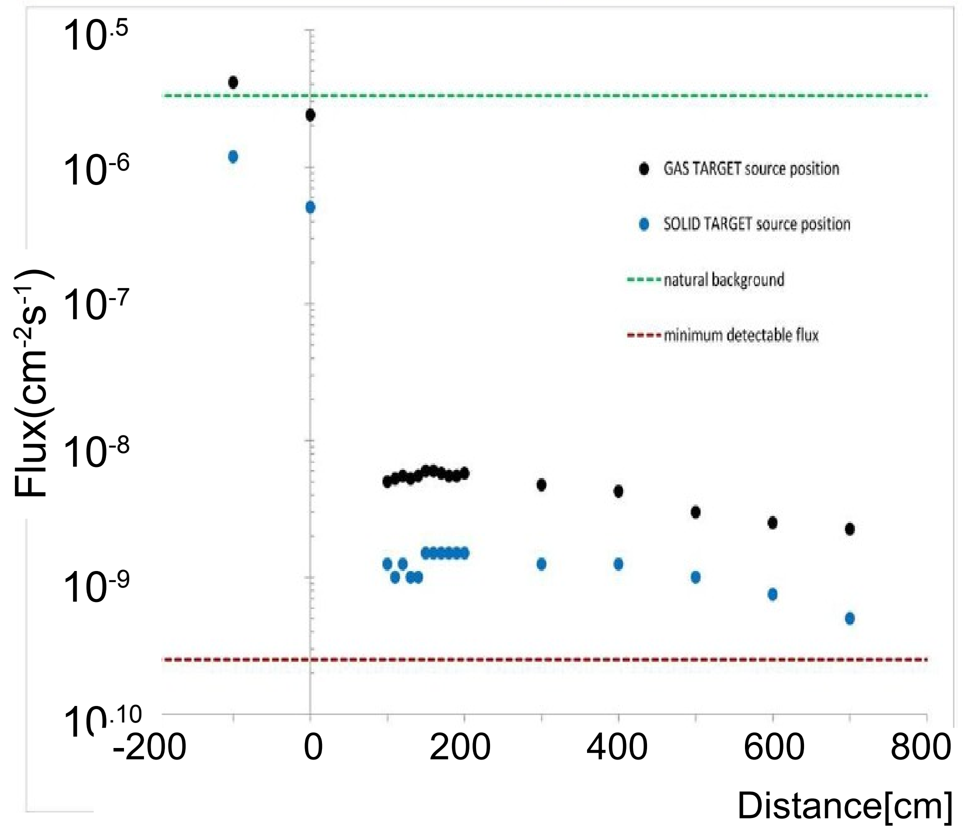
→ Document accepted by Neutron Commission











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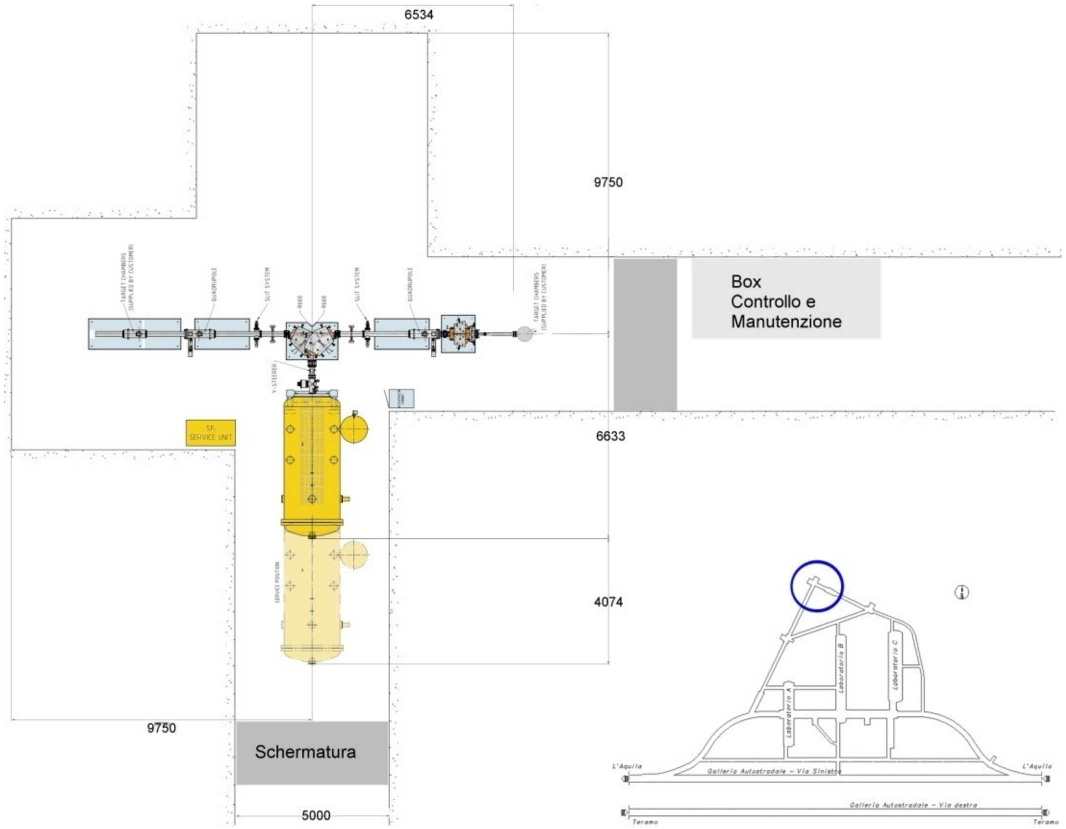
LUNA-MV Funding

Special project "Progetto Premiale"

Physics Case $^{3}He(^{4}He,g)^{7}Be$



Total request:

6.4 M€ in 5 years

(accelerator, site preparation, shielding, beam lines, gas & solid target, detectors)

Request 2012:

2.8 M€ (accelerator, site preparation) **Approved**

Anno 1	Anno 2	Anno 3	Anno 4	Anno 5
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Preparazione sito (500) *Acceleratore (2000)* *Mobilità (120)* *Emolumenti Personale (185)*	*Schermature (400)* *Linee di trasporto del fascio (700)* *Linea di fascio bersaglio gassoso (250)* *Linea di fascio bersaglio solido (200)* *Mobilità (120)* *Ricercatori TD (135)* *Assegni di ricerca (50)*	*Rivelatori gamma (400)* *Rivelatori particelle (50)* *Elettronica e sistemi di acquisizione (150)* *Mobilità (120)* *Ricercatori TD (135)* *Assegni di ricerca (50)* *Borse di dottorato (82,5)*	*Mobilità (120)* *Ricercatori TD (135)* *Assegni di ricerca (50)* *Borse di dottorato (82,5)*	*Mobilità (120)* *Ricercatori TD (135)* *Assegni di ricerca (50)* *Borse di dottorato (82,5)*
Tot = 2805	*Tot = 1855*	*Tot = 987,5*	*Tot = 387,5*	*Tot = 387,5*

Progetto Premiale
LUNA MV

Relation to local bodies

A technical document has been prepared for local authorities.

February 2nd: Meeting with Teramo aqueduct→ very positive
February 28th: Meeting with the Teramo Health Institute (ASL Teramo)→ few issues
Begin of May: Technical specifications of all materials used for the site preparation incl. Technical characteristics of the accelerator and shielding. sent to "Istituto Superiore di Sanità"
June 14th: On site visite of ISS, follow up meeting on October 5th.

Official statement of ISS will be available in about 1 month after official request by LNGS

Tenders for site preparation and refurbishment (to be started by February 2013)

- Task force involving LNGS Technical Division & LUNA Collaboration set up
- Preparation of integrated project (shielding, infrastructure, accelerator)

Tender for the accelerator (to be started by end of 2012)

- Set up committee for tender involving specialists from other INFN Labs.

Technical Design Report under preparation

Enlargement of Collaboration:

- Strengthening of international contacts.
- Workshop at LNGS (February 2013): "Starting-up the LUNA MV collaboration"
  - → Elaboration of Scientific Proposal
  - → Definition of Workpackages :
    - WP1: Accelerator + ion source
    - WP2: Gamma detectors
    - WP3: Neutron detectors
    - WP5: Solid targets
    - WP6: Gas target
    - WP7: Simulations
    - WP8: Stellar model calculations

Laboratory
Underground
Nuclear
Astrophysics

LUNA today.

LUNA MV

LUNA-MV soon
may be with you?

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