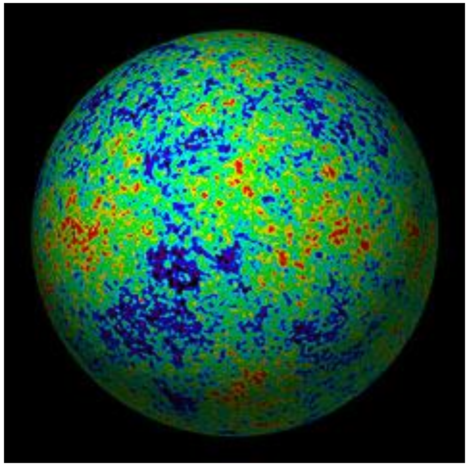
Physics cases of LUNA MV

D. Trezzi (for the LUNA collaboration)

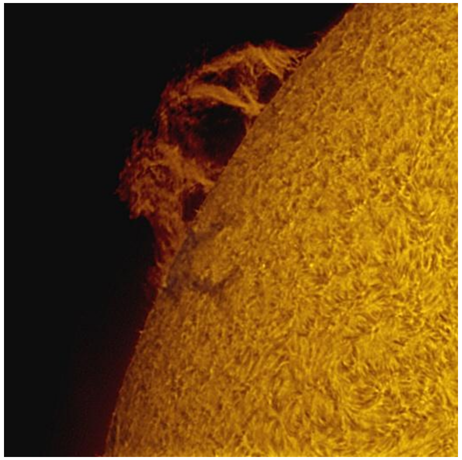
Laboratori Nazionali del Gran Sasso, Assergi (AQ) – March 19th, 2013

NUCLEAR ASTROPHYSICS: Understanding the Universe

Astronomy: measurement of the chemical abundances in astrophysical environments like stellar atmospheres, dusts, nebulae, CMB, novae and supernova explosions.



Cosmology: understand the processes involved in the first stages of the Universe, particularly during the Big Bang Nucleosynthesis era.

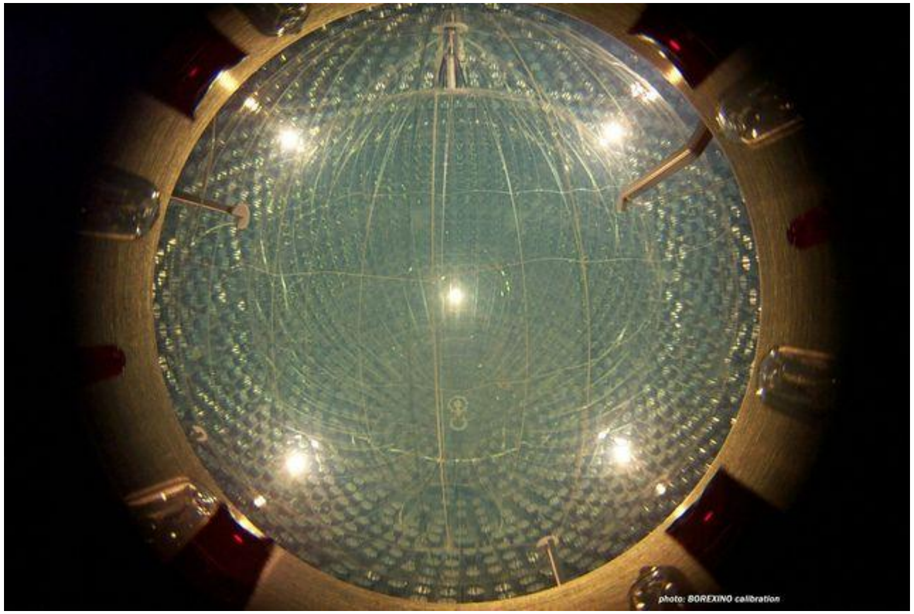


Astrophysics: modeling the stellar evolution especially for what concern our star, the Sun.

ASTRONOMY AND ASTROPHYSICS

NUCLEAR ASTROPHYSICS: Understanding the Universe

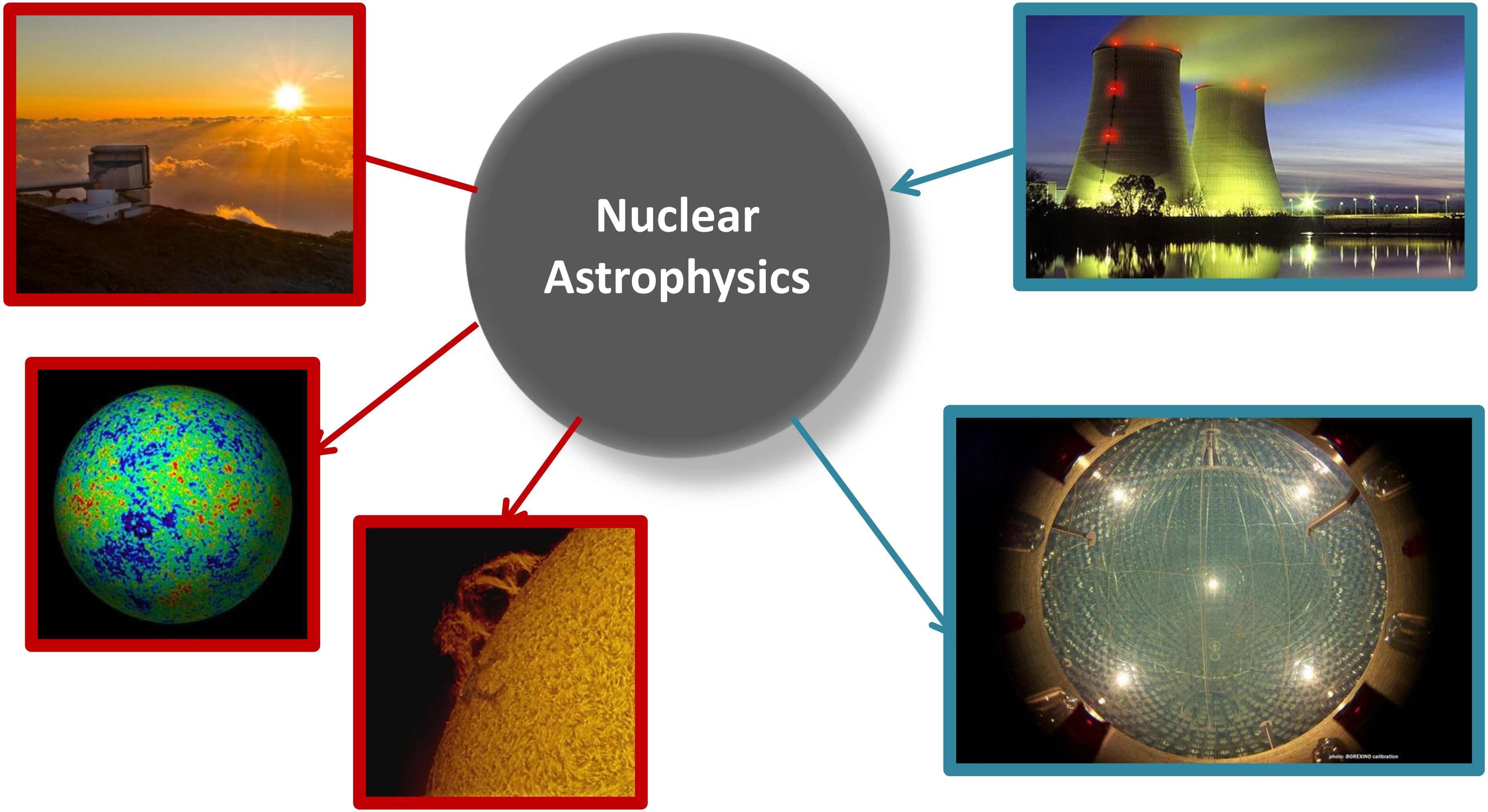
Nuclear Physics: is the field of physics that studies the constituents and interactions of atomic nuclei.



Neutrino Physics: use the neutrino particle in order to investigate the inaccessible solar core

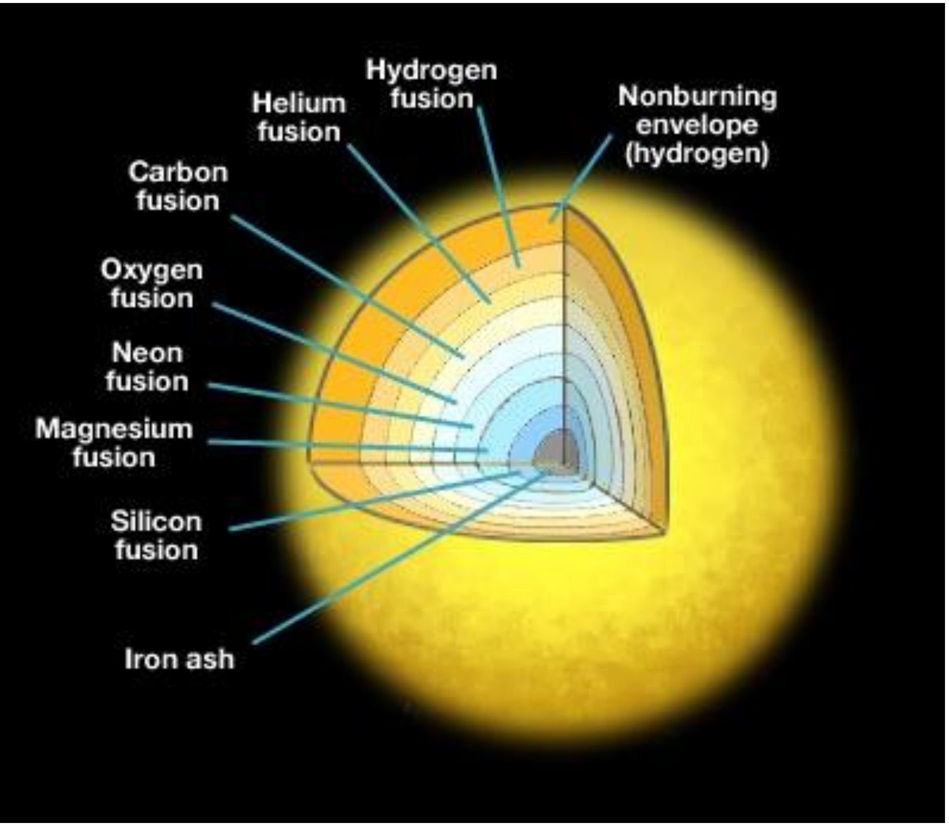
NUCLEAR AND PARTICLE PHYSICS

NUCLEAR ASTROPHYSICS: Understanding the Universe

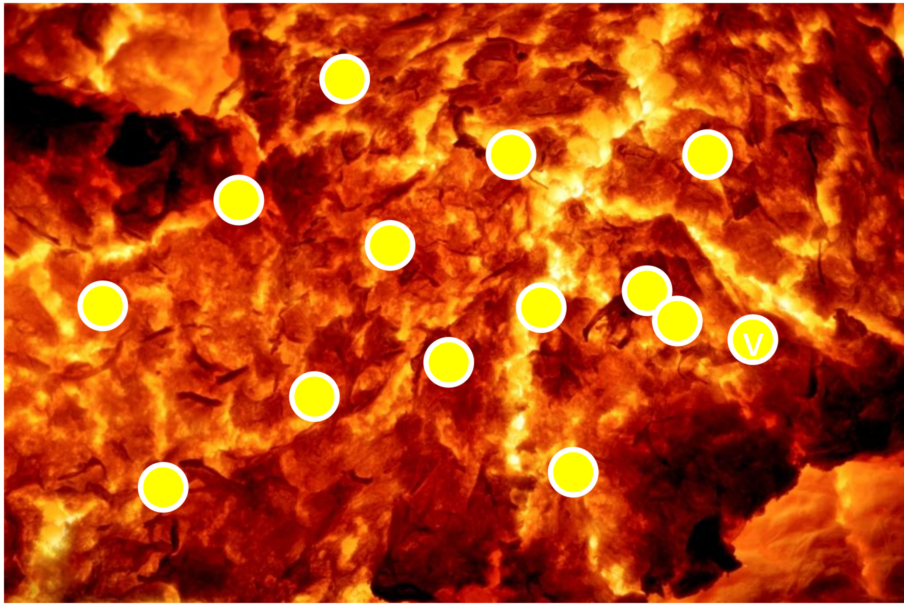


Nuclear Astrophysics

NUCLEAR ASTROPHYSICS: Understanding the Universe



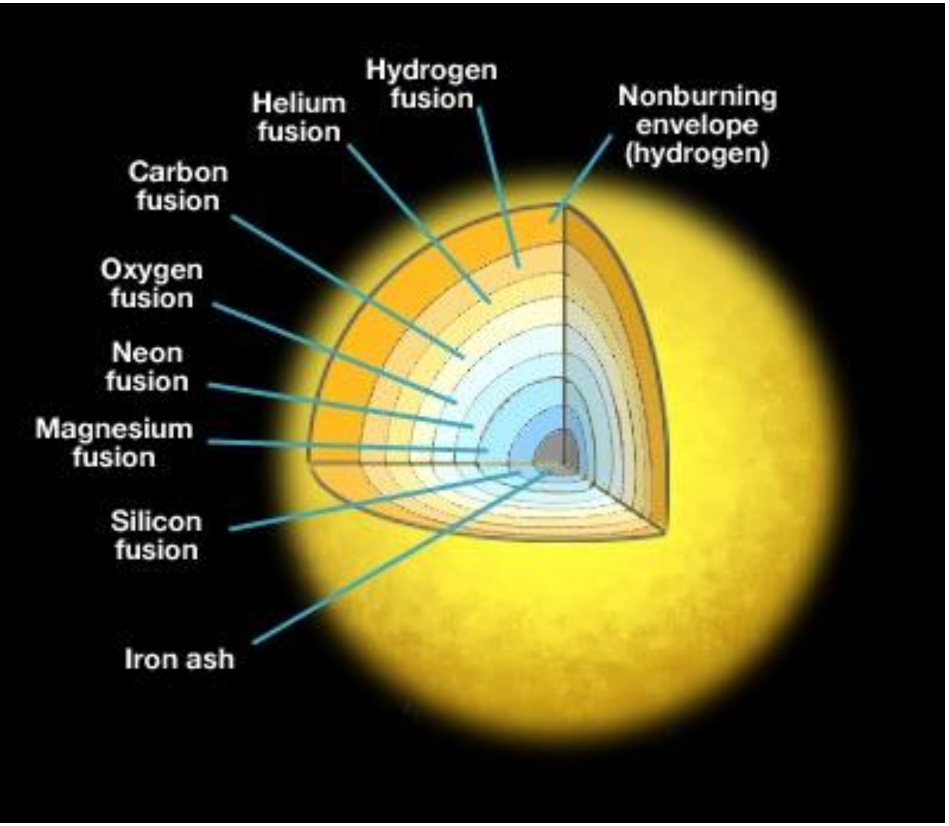
Stars can survive billion of years thanks to thermonuclear fusion reactions that take place into the stellar core.



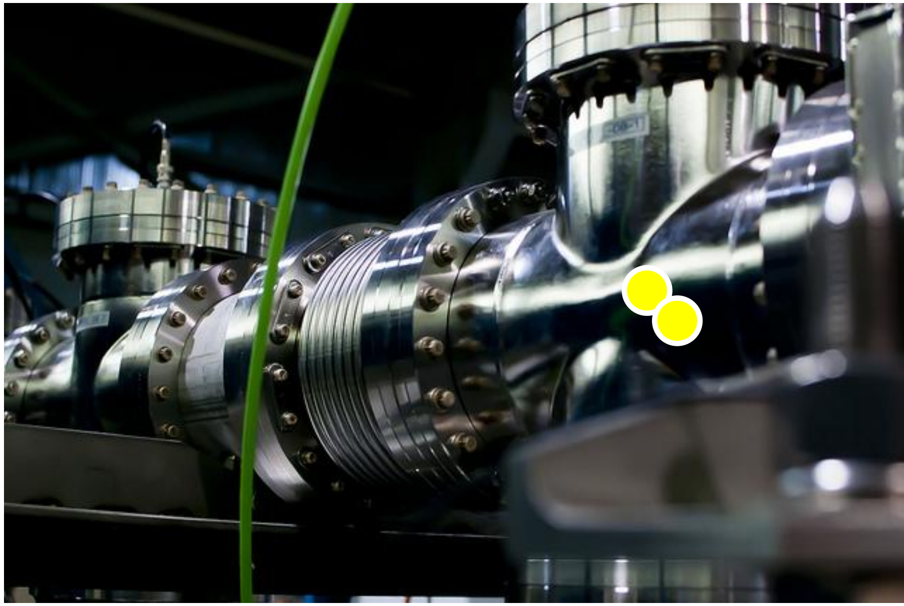
Sun core temperature: about 15.7 MK

NUCLEAR REACTION IN THE STARS

NUCLEAR ASTROPHYSICS: Understanding the Universe



Stars can survive billion of years thanks to thermonuclear fusion reactions that take place into the star.



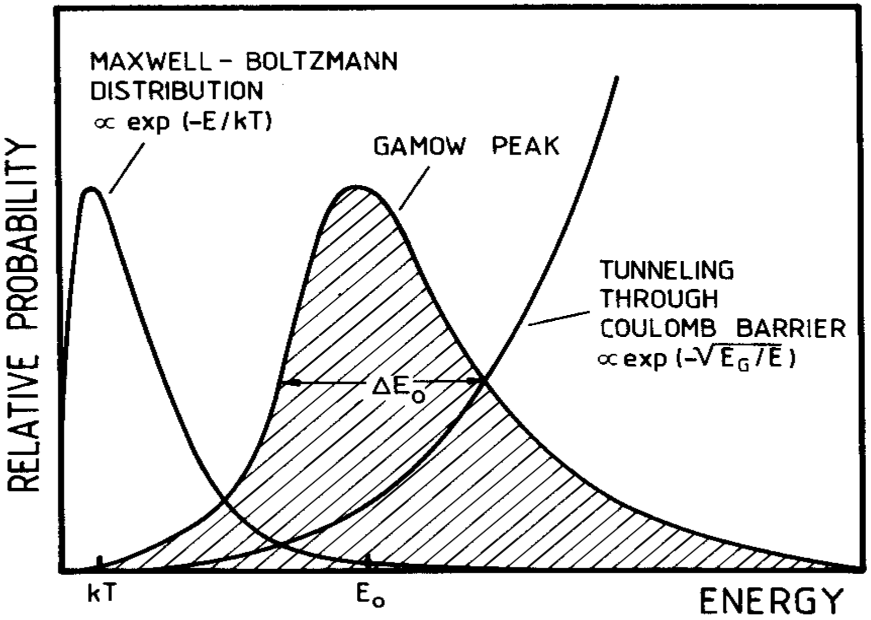
Particle Energy (Sun): about 20 keV

NUCLEAR REACTION IN THE LAB

Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

NUCLEAR FUSION: The nuclear cross section



X (projectile)+Y (at rest)

The rate of a nuclear reaction *r* is given by:

$$r = \frac{1}{1+\delta_{xy}} N_x N_y < v\sigma(v)>$$

Nuclear cross section

Number of X nuclei per unit volume

Number of Y nuclei per unit volume

Velocity of nuclei X

In a star

$$< v\sigma(v) > = \int_0^{+\infty} \phi(v) v\sigma(v)$$

Maxwell Boltzmann distribution

The nuclear cross section can be written as:

$$\sigma(E) = \frac{1}{E} S(E) e^{-31.29\, Z_x Z_y \sqrt{\frac{\mu}{E}}}$$

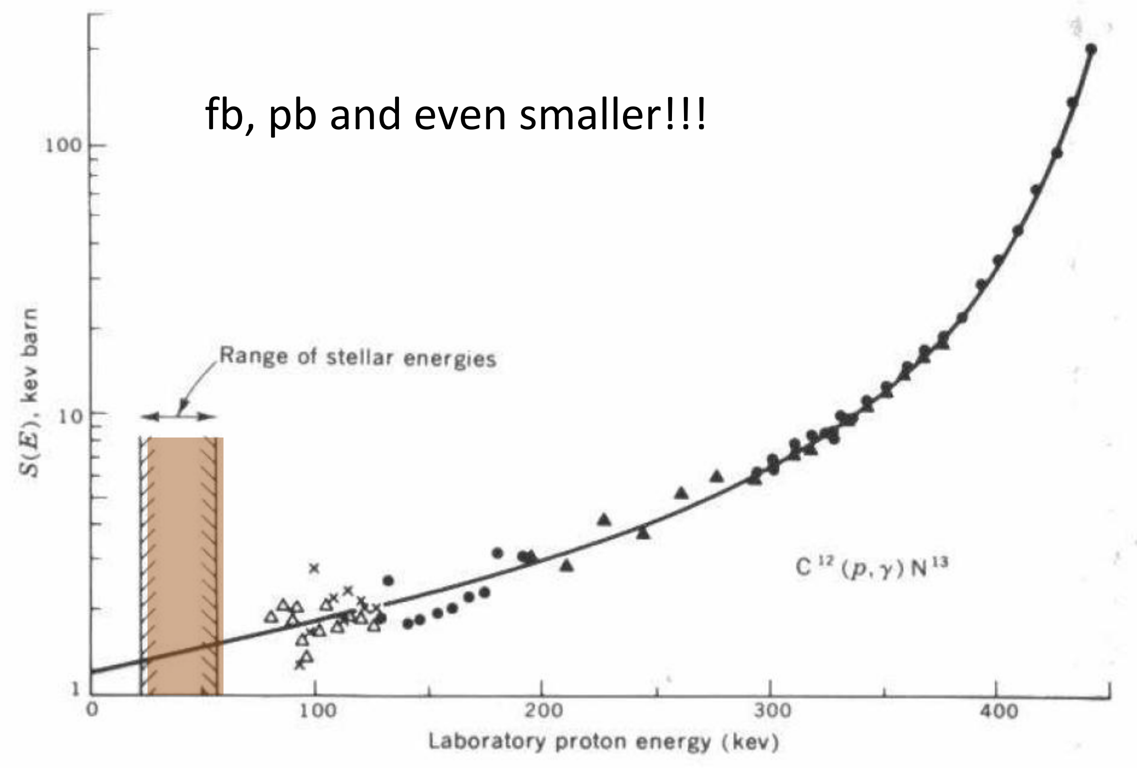
Quantum nature of the interaction

Nuclear effects

Tunneling effect

THE GAMOW PEAK

NUCLEAR FUSION: The nuclear cross section



fb, pb and even smaller!!!

Gamow peak for a typical thermonuclear reaction in a star is at low energy : 10-100 keV

LOW ENERGY MEANS LOW CROSS SECTION VALUE

CROSS SECTION VALUE

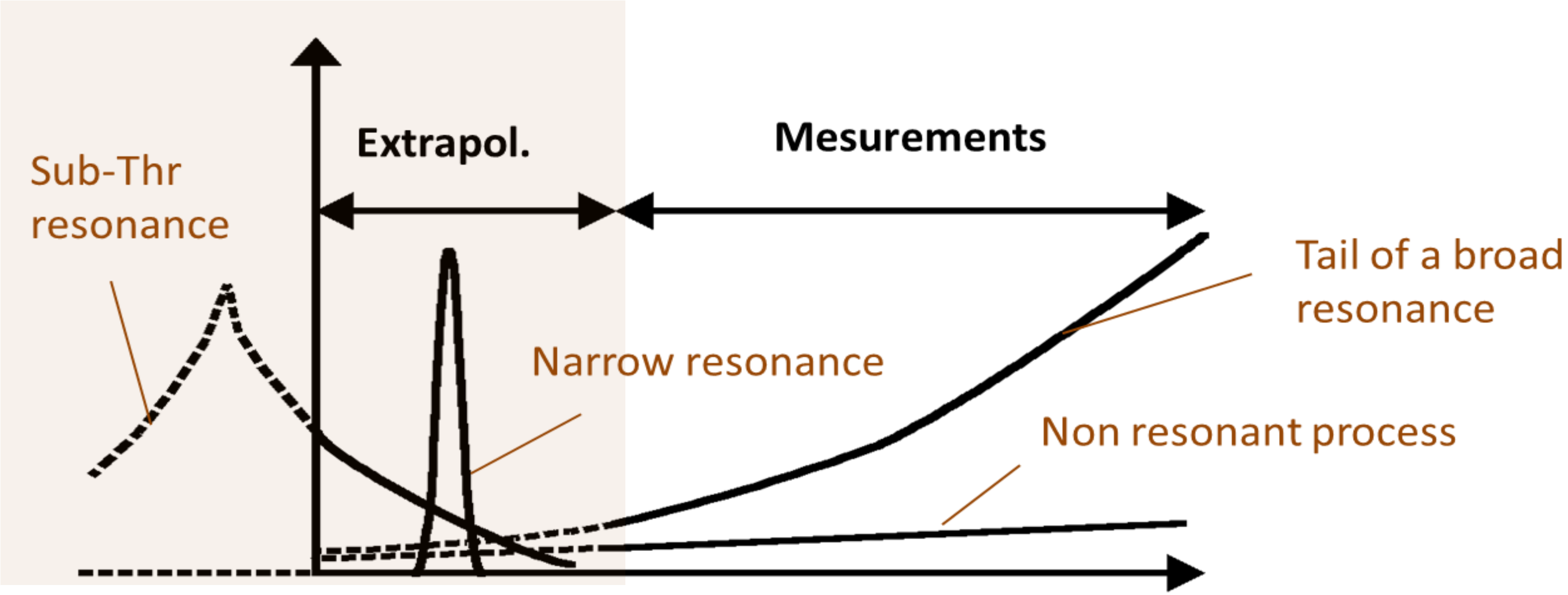
At the Earth surface: the very few fusion reaction events are completely covered by the background.

EXTRAPOLATION FROM HIGH ENERGIES

Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

NUCLEAR FUSION: Direct measurements



Extrapolation is not straightforward since possible resonances or unexpected behaviors of the cross section in the extrapolated energy region could be neglected.

GOING UNDERGROUND

UNDERGROUND LABORATORY: Background

Low background laboratory: music for our detectors…

$$R_{lab} \geq \overbrace{B_{cosmic} + B_{environment}}^{\text{Minimize}} + \overbrace{B_{BIB}}^{\text{\& Understand}}$$

Fusion reaction events

Cosmic ray induced events

GOING UNDERGROUND

Environmental radioactivity events

SHIELDING

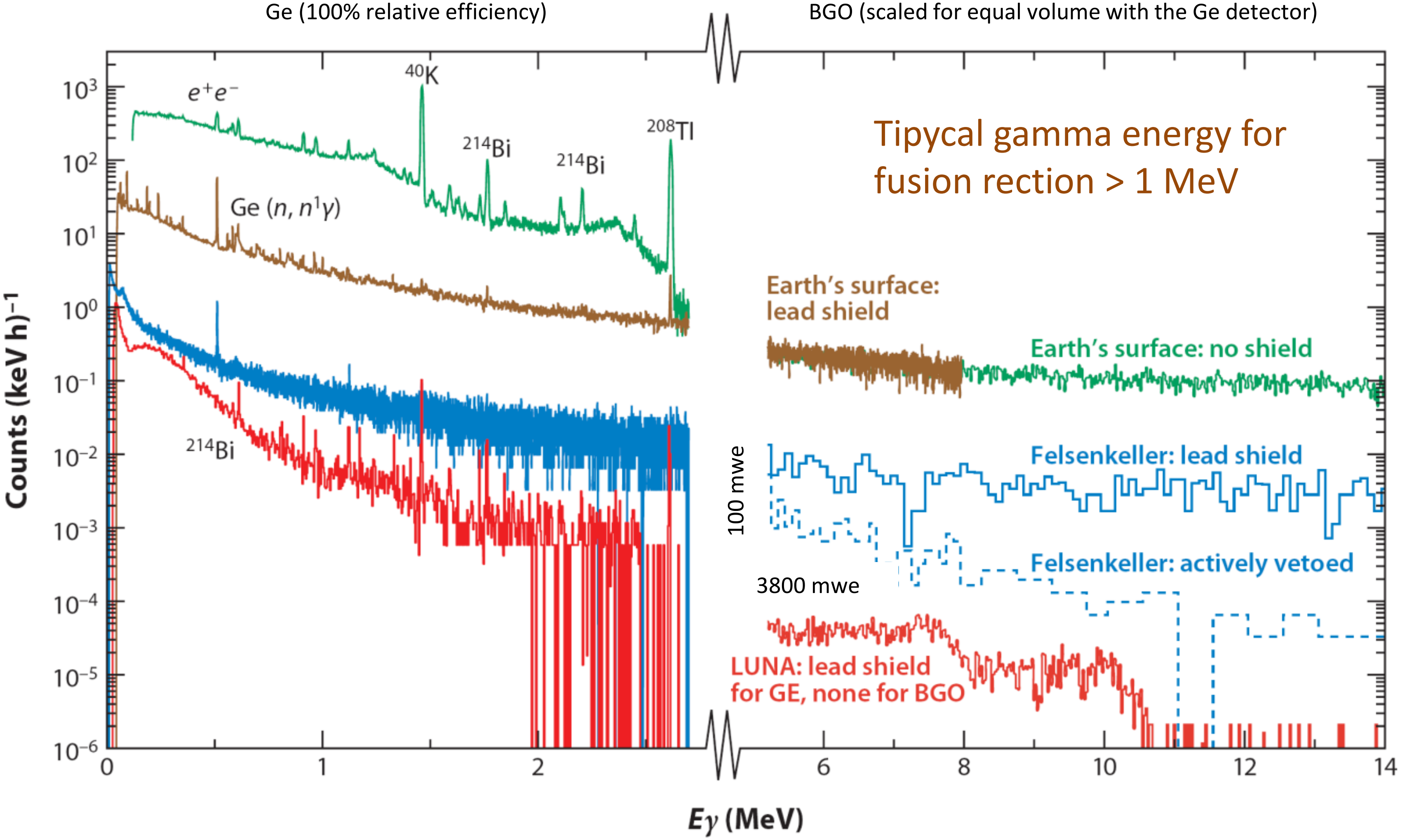
Beam induced background events from impurities in beam and target

HIGH PURITY TARGETS & MC SIMULATIONS

LABORATORI NAZIONALI DEL GRAN SASSO (LNGS)

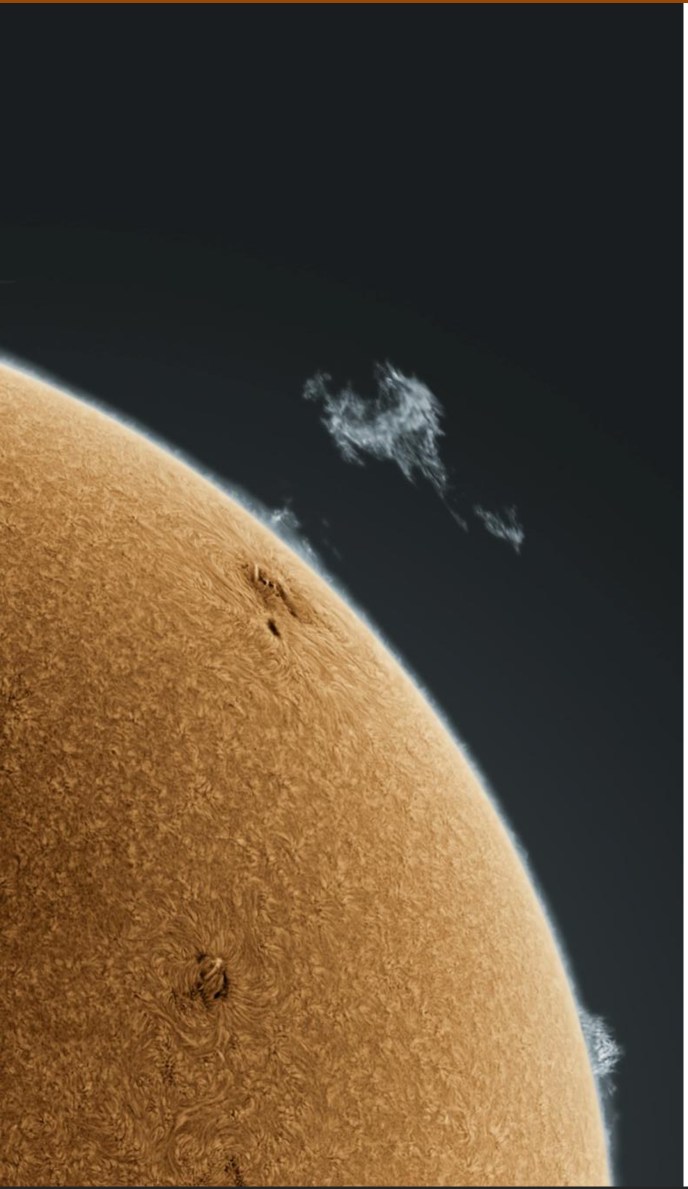
Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013



Physics cases of LUNA MV

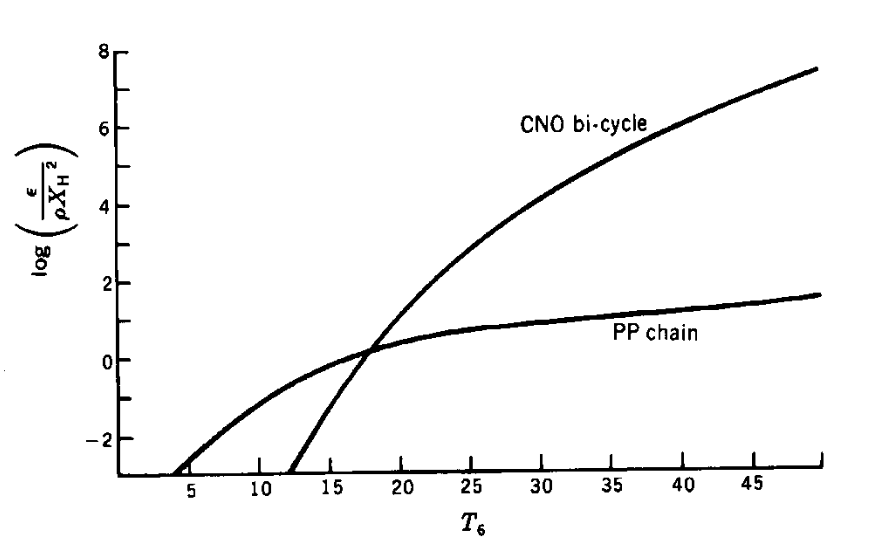
Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013



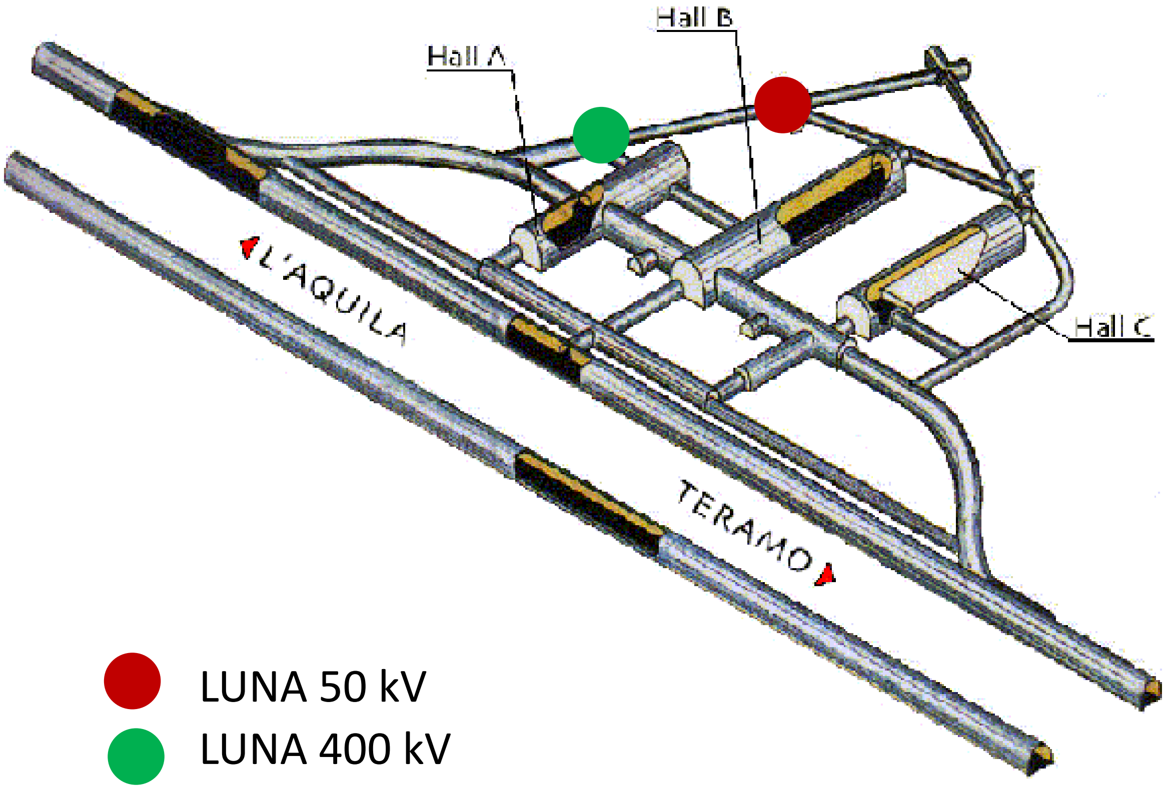
HYDROGEN BURNING: an overview

Hydrogen burning is the fusion of 4 hydrogen nuclei into a single helium nucleus. The fusion takes place via a series of reactions (depends on the mass, core **temperature** and density of the star).

- Proton - proton chain reactions [SUN],
- CNO cycles, NeNa cycle, MgAl cycle.



LUNA: Laboratory for Underground Nuclear Astrophysics



● LUNA 50 kV

● LUNA 400 kV

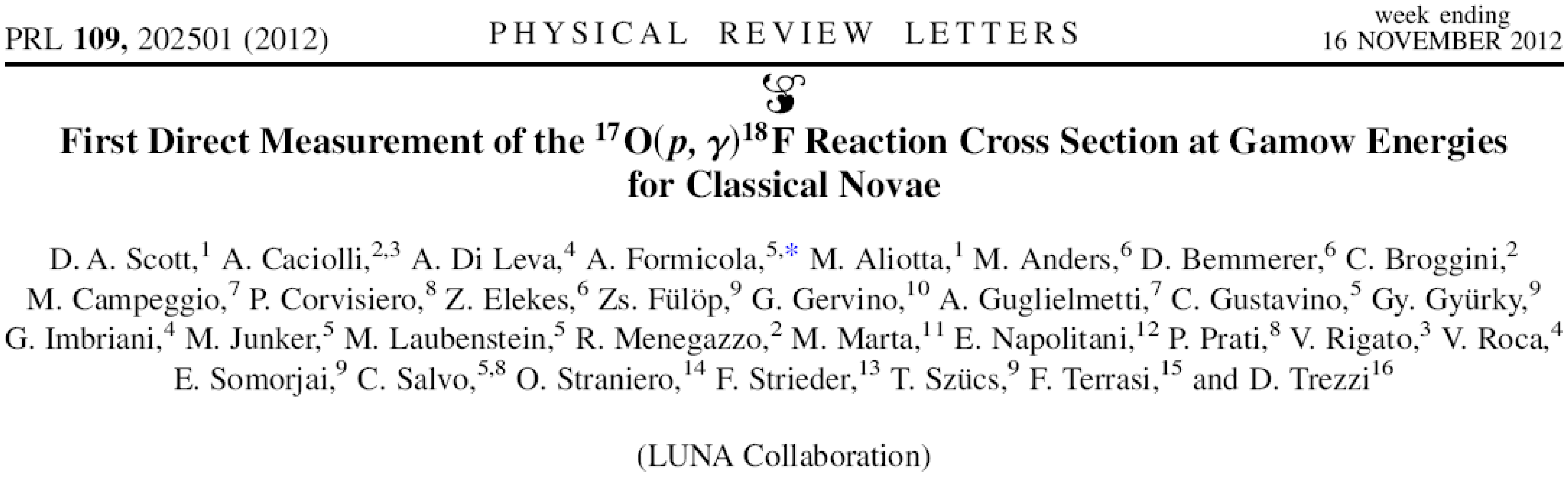
LUNA 50 kV (1992-2001) demonstrated that it is possible to measure nuclear cross sections down to the energy of the nucleosynthesis inside stars.

LUNA 400 kV (2000- still working) measured the nuclear cross sections for key reactions of the CNO, NeNa and MgAl cycles.

LUNA EXPERIMENT

Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

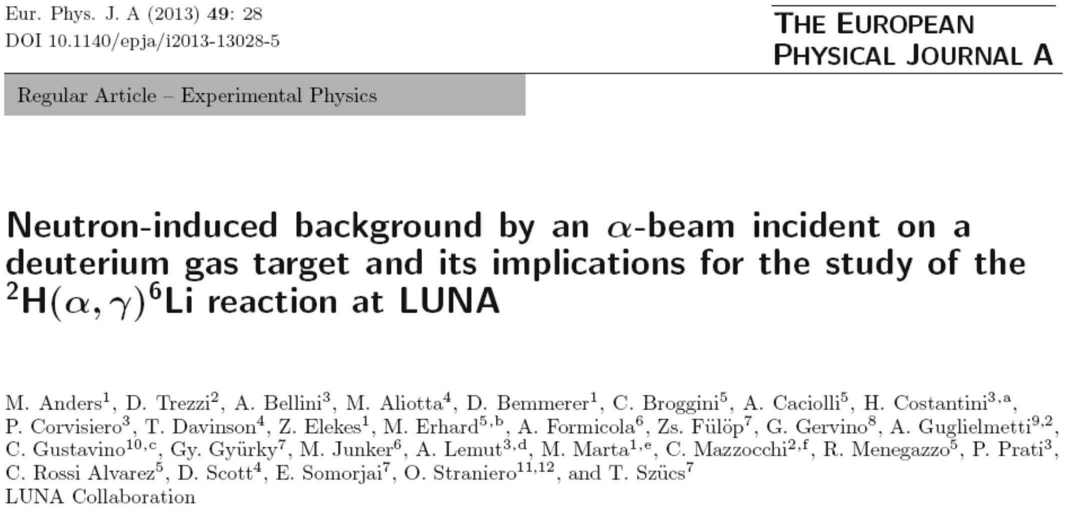


PRL **109,** 202501 (2012) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2012

First Direct Measurement of the $^{17}O(p,\gamma)^{18}F$ Reaction Cross Section at Gamow Energies for Classical Novae

D. A. Scott,[1] A. Caciolli,[2,3] A. Di Leva,[4] A. Formicola,[5,*] M. Aliotta,[1] M. Anders,[6] D. Bemmerer,[6] C. Broggini,[2]
M. Campeggio,[7] P. Corvisiero,[8] Z. Elekes,[6] Zs. Fülöp,[9] G. Gervino,[10] A. Guglielmetti,[7] C. Gustavino,[5] Gy. Gyürky,[9]
G. Imbriani,[4] M. Junker,[5] M. Laubenstein,[5] R. Menegazzo,[2] M. Marta,[11] E. Napolitani,[12] P. Prati,[8] V. Rigato,[3] V. Roca,[4]
E. Somorjai,[9] C. Salvo,[5,8] O. Straniero,[14] F. Strieder,[13] T. Szücs,[9] F. Terrasi,[15] and D. Trezzi[16]

(LUNA Collaboration)



Eur. Phys. J. A (2013) **49**: 28
DOI 10.1140/epja/i2013-13028-5

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Neutron-induced background by an α-beam incident on a deuterium gas target and its implications for the study of the $^{2}H(\alpha,\gamma)^{6}Li$ reaction at LUNA

M. Anders[1], D. Trezzi[2], A. Bellini[3], M. Aliotta[4], D. Bemmerer[1], C. Broggini[5], A. Caciolli[5], H. Costantini[3,a],
P. Corvisiero[3], T. Davinson[4], Z. Elekes[1], M. Erhard[5,b], A. Formicola[6], Zs. Fülöp[7], G. Gervino[8], A. Guglielmetti[9,2],
C. Gustavino[10,c], Gy. Gyürky[7], M. Junker[6], A. Lemut[3,d], M. Marta[1,e], C. Mazzocchi[2,f], R. Menegazzo[5], P. Prati[3],
C. Rossi Alvarez[5], D. Scott[4], E. Somorjai[7], O. Straniero[11,12], and T. Szücs[7]
LUNA Collaboration

More information on
http://luna.lngs.infn.it

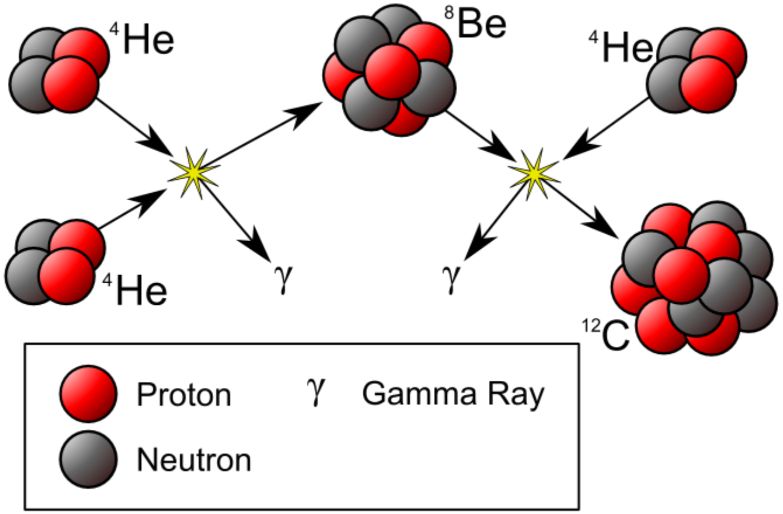
AND IN PROGRESS…

$^{22}Ne(p,\gamma)^{23}Na$

$^{17}O(p,\alpha)^{14}N$

HELIUM BURNING: an overview

When the temperature in the core of a star reaches about 100 million degrees, three colliding helium nuclei can fuse to form a **CARBON** nucleus. This set of reactions is called the triple alpha process



As a side effect of the process, some carbon nuclei can fuse with additional helium to produce **OXYGEN**:

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

$^{12}C(\alpha,\gamma)^{16}O$: The Holy Grail of Nuclear Astrophysics

This reaction determines the amount of Carbon (Oxygen) left in the stellar core after the helium burning:

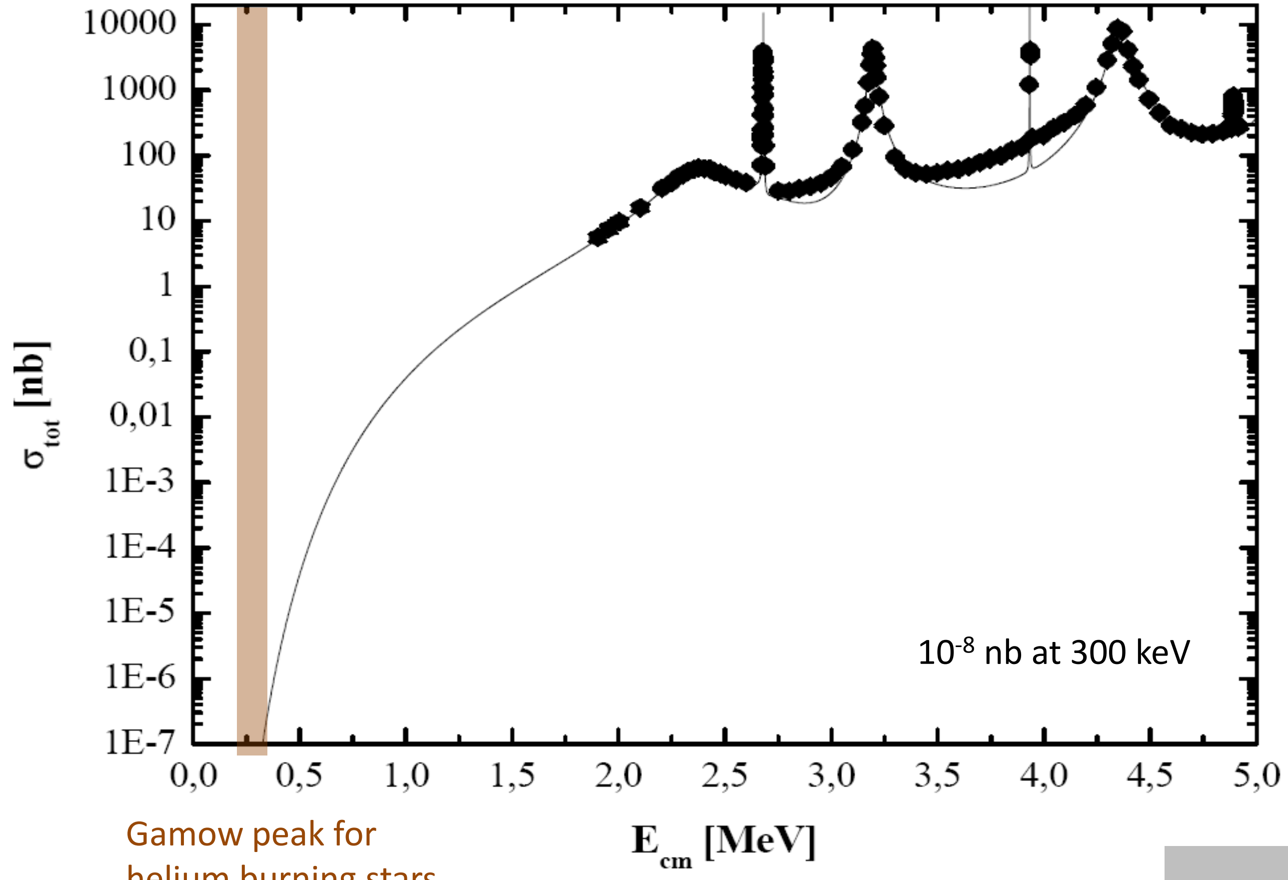
- The late evolution of massive stars is strongly dependent on the amount of Carbon left in the core after helium burning.
- The Carbon left in the core after helium burning also affects the proprieties of the CO white dwarfs like the cooling timescale (useful like a clock for dating old stellar system like Globular Clusters).
- The light curves of supernova explosions (type Ia) depend indirectly by the Carbon present in the core after the Helium burning.
- Oxygen and Carbon are fundamental for life (61% O, 23% C in human body).

A KEY REACTION FOR NUCLEAR ASTROPHYSICS

Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

$^{12}C(\alpha,\gamma)^{16}O$: Experimental status of the art



10^{-8} nb at 300 keV

Gamow peak for helium burning stars

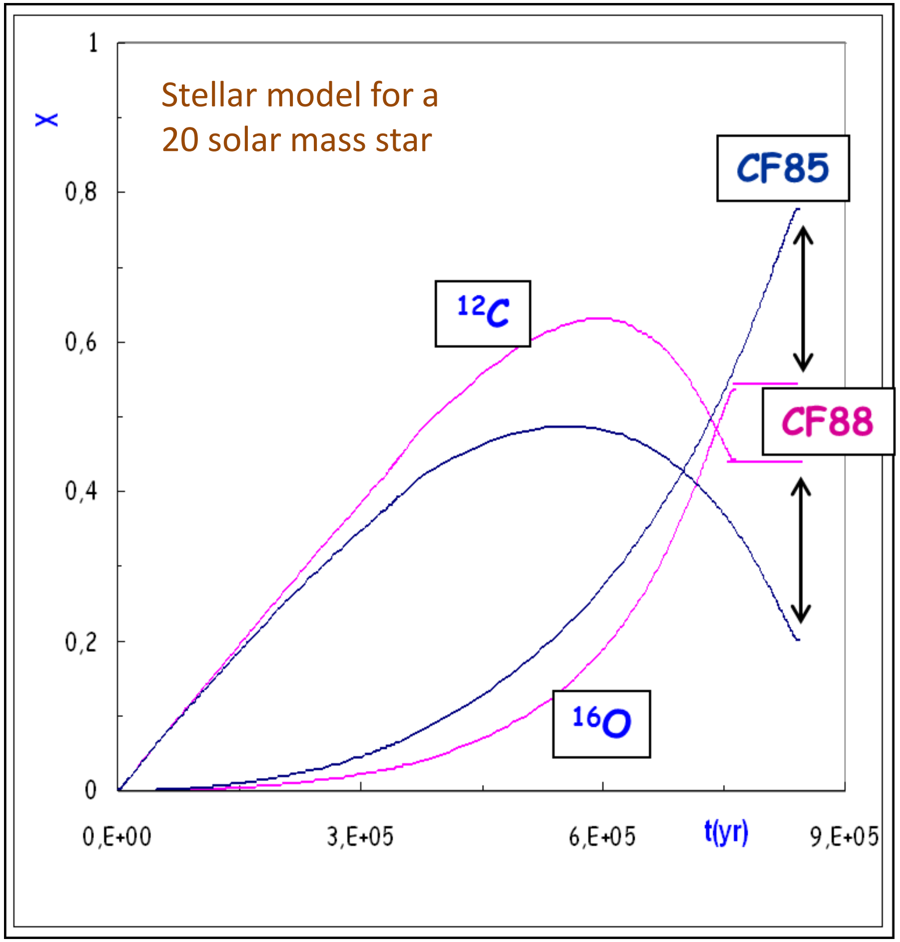
Available data extend down to 1 MeV, **well above the Gamow peak energy** (about 200-300 keV) corresponding to the stellar temperatures experienced within the core of Helium burning stars (100 to 200 MK).

EXPERIMENTAL DATA

Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

$^{12}C(\alpha,\gamma)^{16}O$: Uncertainty effects on the Carbon/Oxygen abundance



At the end of the helium burning phase of a star, the abundance of Carbon and Oxygen is determined by the $^{12}C(\alpha,\gamma)^{16}O$ cross section (i.e. S factor).

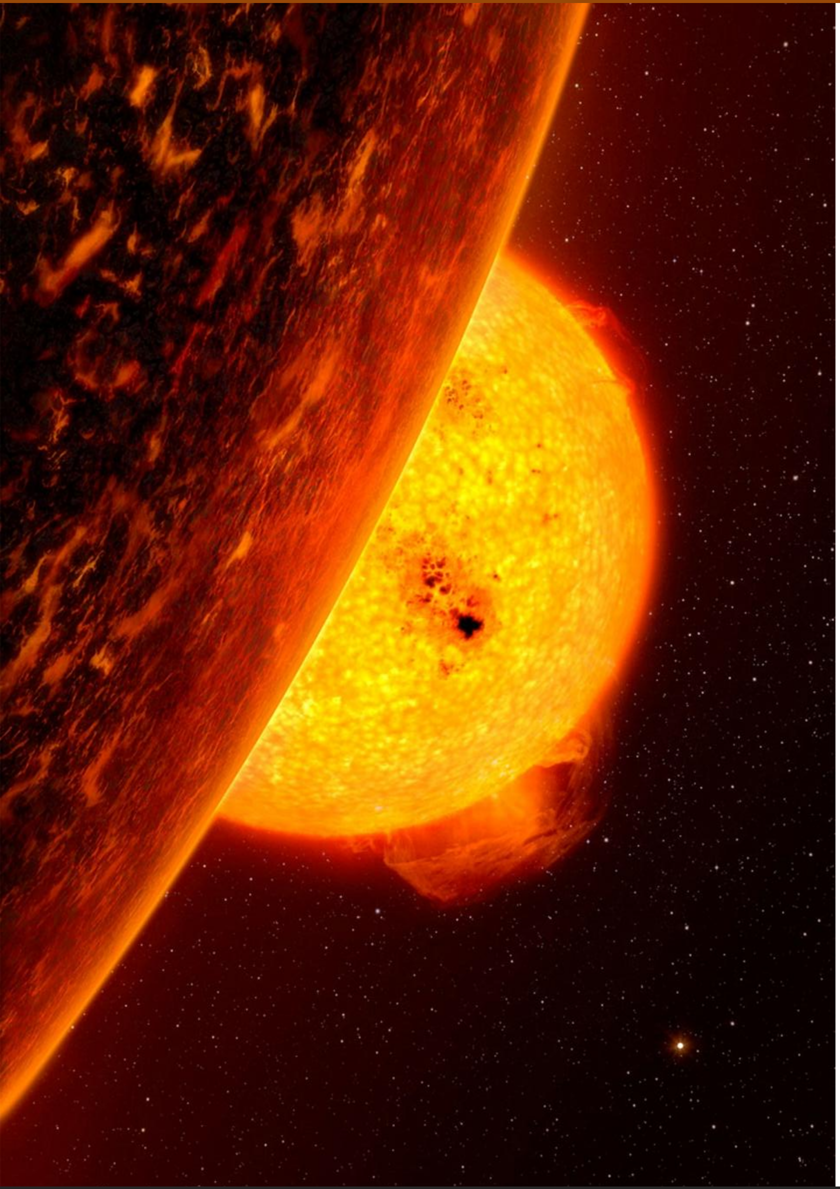
In the CF85 model the S-factor is doubled with respect to the CF88 one.

The cross section at relevant astrophysical energies should be known with a precision of at least 10% for relaiable models of late stellar evolution

EXTRAPOLATION IS NOT ENOUGH

Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013



s Process: an overview

The s-process or **slow-neutron capture process** is a nucleosynthesis process that occurs at relatively low neutron density and intermediate temperature conditions in stars.

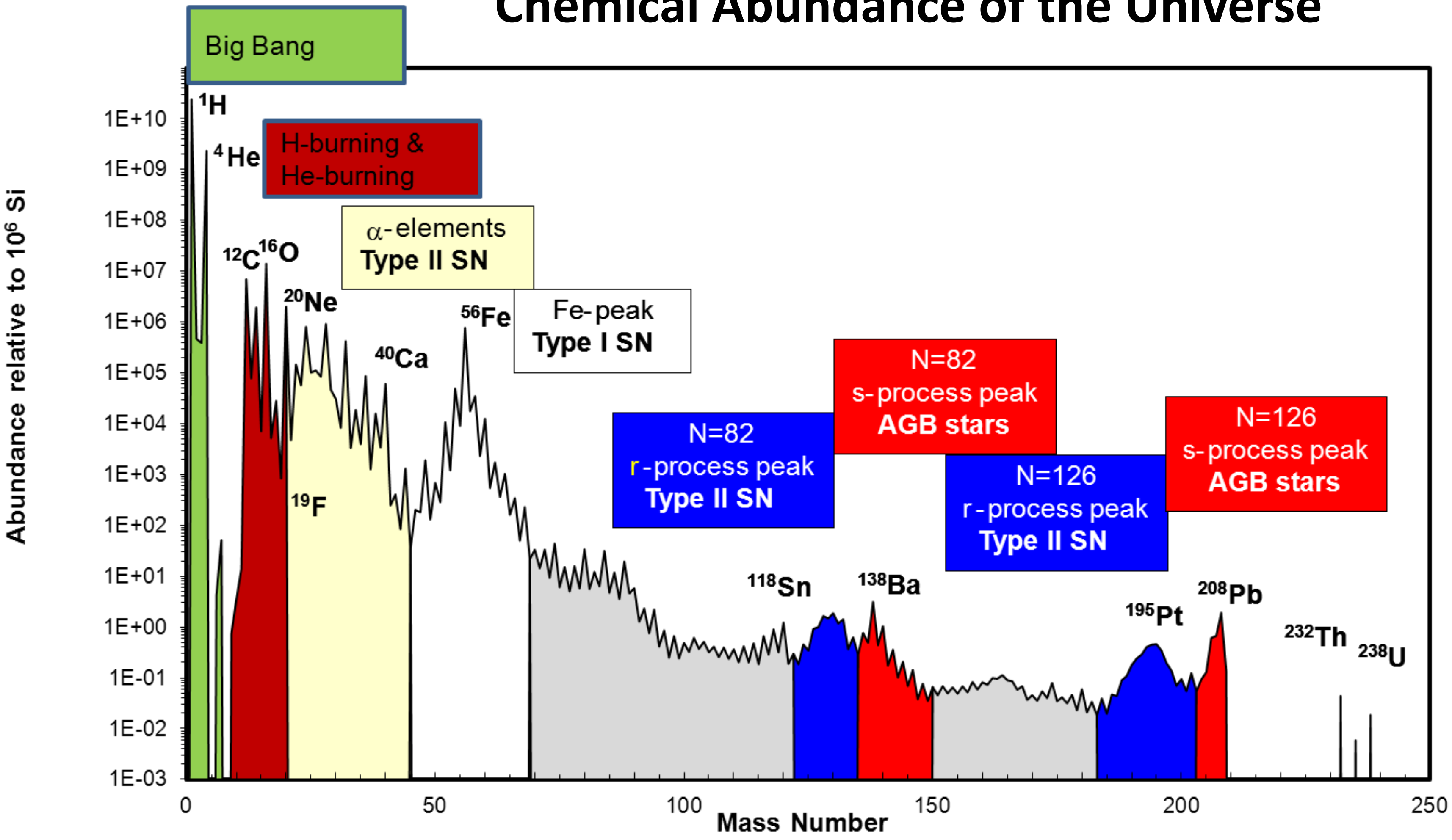
The main neutron source reactions are:

- $^{13}C(\alpha,n)^{16}O$
- $^{22}Ne(\alpha,n)^{25}Mg$

Nuclear Astrophysics ambitious task is to explain the origin and relative abundance of the elements in the Universe. The s-process provide the formation of 50% of the elements beyond iron.

CHEMISTRY OF THE UNIVERSE

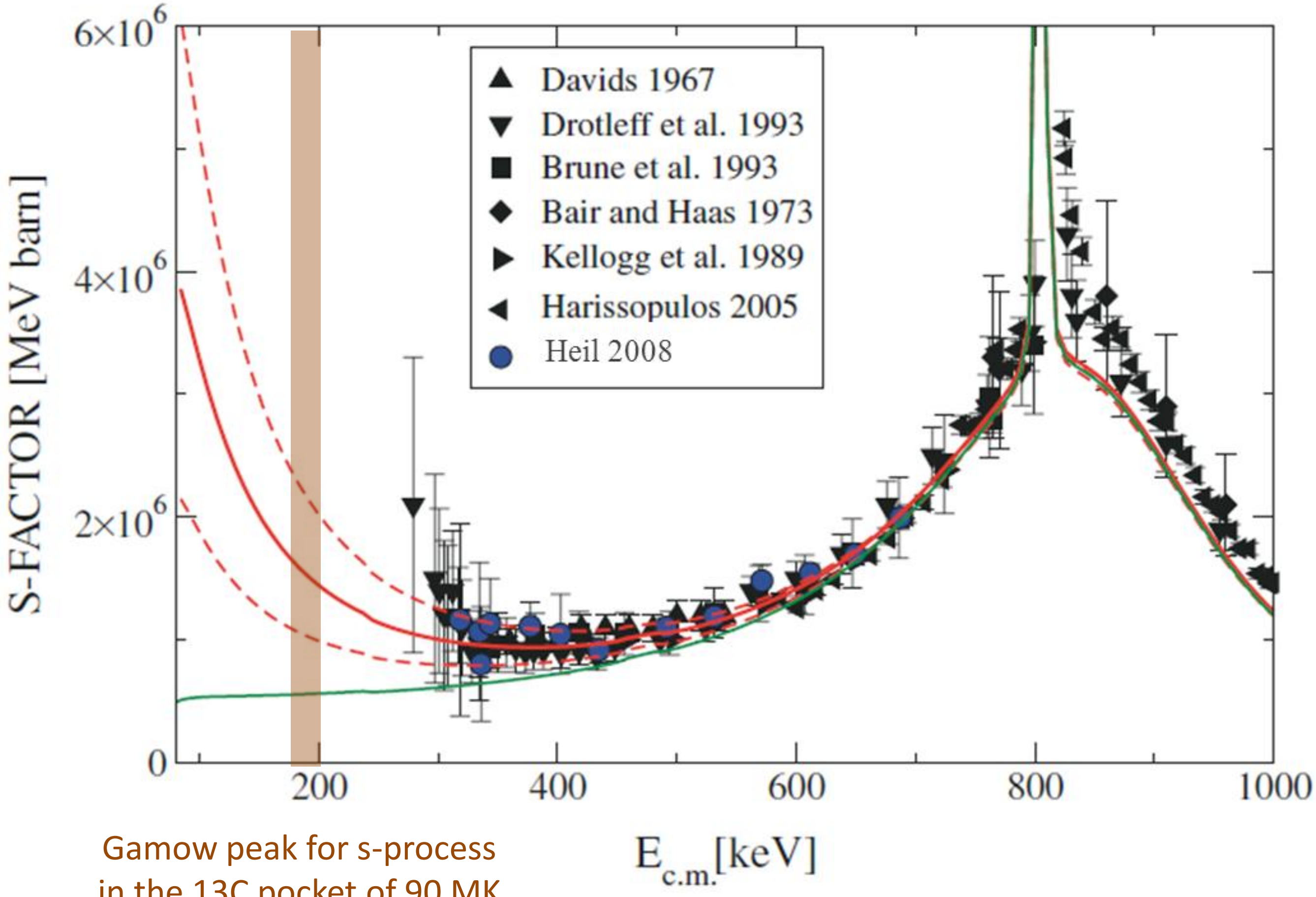
Chemical Abundance of the Universe



Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

$^{13}C(\alpha,n)^{16}O$: Experimental status of the art



Big uncertainties in the R-Matrix extrapolations due to the presence of subthreshold resonances

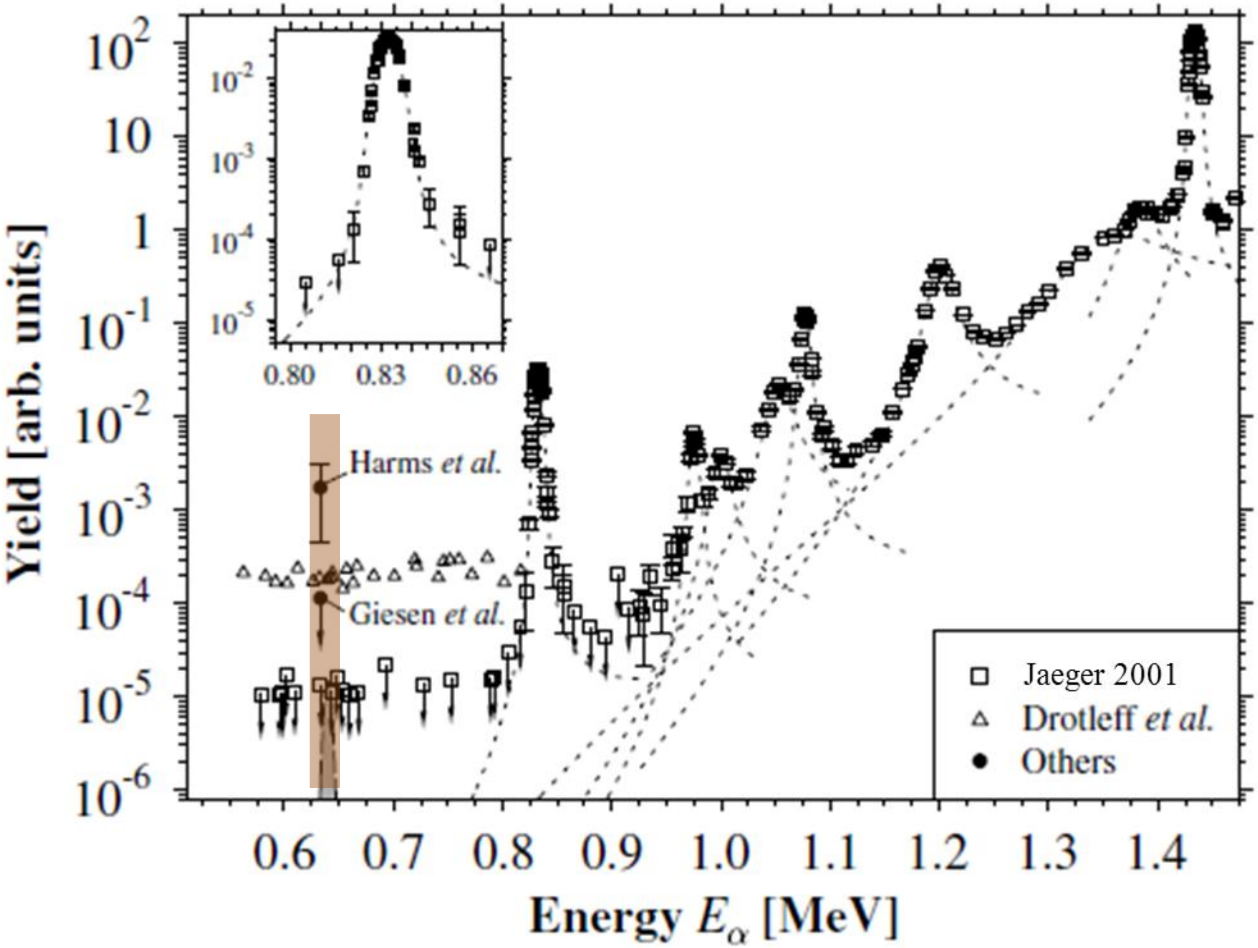
EXPERIMENTAL DATA

Gamow peak for s-process in the 13C pocket of 90 MK (190 keV)

Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

^{22}Ne(α,n)^{25}Mg: Experimental status of the art



Unmeasured resonance at 635 keV. This provides a big uncertainty in the reaction rate.

EXPERIMENTAL DATA

Physics cases of LUNA MV

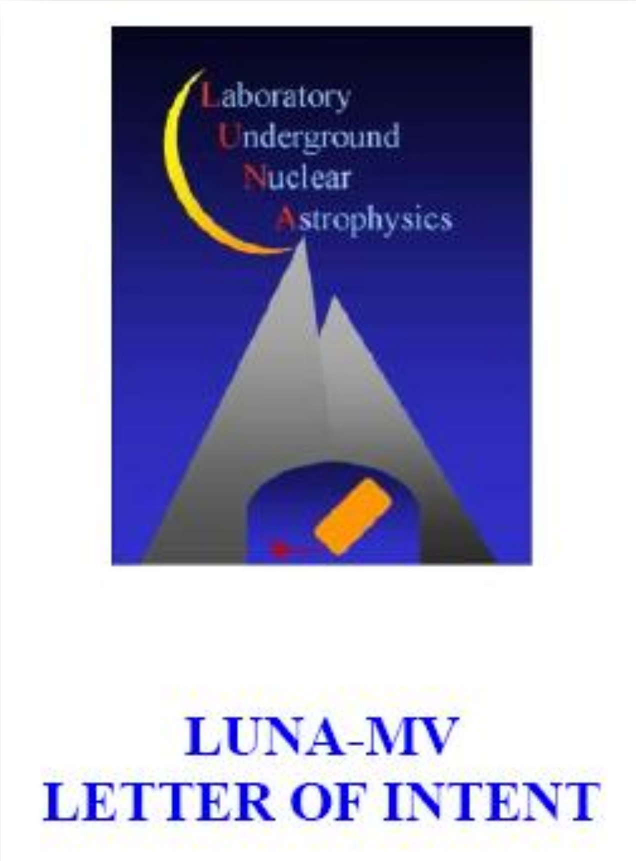
Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

In order to solve the open questions about the helium burning and the s-process a new accelerator is necessary

Due to the low cross sections involved, the beams must be **intense** and **stable** in energy and in time, operating continuously over several weeks without the permanent presence of an operator on site.
Very low beam induced background is also mandatory.

LUNA MV IS COMING…

Physics cases of LUNA MV

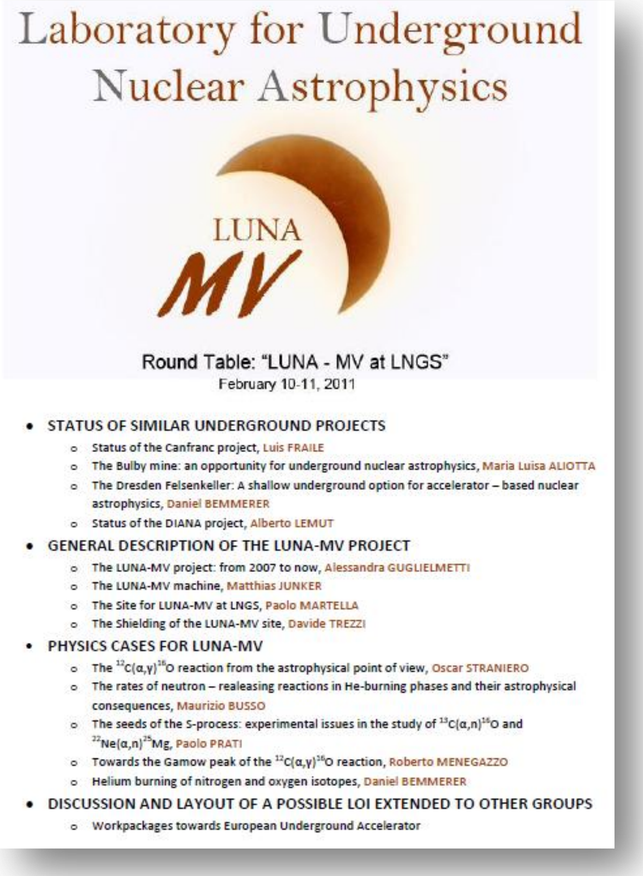


LUNA-MV
LETTER OF INTENT

The LUNA MV project

- April 2007: a **Letter of Intent** (LoI) was presented to the LNGS Scientific Committee (SC),
- October 2007: a LoI addendum with an improved study on the neutron pollution and a better specification of the physics goals was submitted to the SC,
- February 2010: the LUNA collaboration produced an update of the LoI where the neutron production rate was re-evaluated under better specified experimental conditions

AT THE BEGINNING OF THE STORY



Laboratory for Underground Nuclear Astrophysics

LUNA MV

Round Table: "LUNA - MV at LNGS"

February 10-11, 2011

- STATUS OF SIMILAR UNDERGROUND PROJECTS
  - Status of the Canfranc project, Luis FRAILE
  - The Bulby mine: an opportunity for underground nuclear astrophysics, Maria Luisa ALIOTTA
  - The Dresden Felsenkeller: A shallow underground option for accelerator – based nuclear astrophysics, Daniel BEMMERER
  - Status of the DIANA project, Alberto LEMUT
- GENERAL DESCRIPTION OF THE LUNA-MV PROJECT
  - The LUNA-MV project: from 2007 to now, Alessandra GUGLIELMETTI
  - The LUNA-MV machine, Matthias JUNKER
  - The Site for LUNA-MV at LNGS, Paolo MARTELLA
  - The Shielding of the LUNA-MV site, Davide TREZZI
- PHYSICS CASES FOR LUNA-MV
  - The $^{12}C(\alpha,\gamma)^{16}O$ reaction from the astrophysical point of view, Oscar STRANIERO
  - The rates of neutron – realeasing reactions in He-burning phases and their astrophysical consequences, Maurizio BUSSO
  - The seeds of the S-process: experimental issues in the study of $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, Paolo PRATI
  - Towards the Gamow peak of the $^{12}C(\alpha,\gamma)^{16}O$ reaction, Roberto MENEGAZZO
  - Helium burning of nitrogen and oxygen isotopes, Daniel BEMMERER
- DISCUSSION AND LAYOUT OF A POSSIBLE LOI EXTENDED TO OTHER GROUPS
  - Workpackages towards European Underground Accelerator

The LUNA MV project

- February 2011: a **round table** was organized at the LNGS,
- October 2011: a shielding solution was developed, validated by Monte Carlo simulations and approved by the "neutron committee" (chair M. Hass) and the SC of the LNGS,
- The **Premium Project LUNA MV** was submitted to the Italian Research Ministry: the first year of the Premium Project (2011) has been financed with 2.8 M€

WE CAN START

The LUNA MV project

Starting up the
LUNA MV Collaboration

6-8 February 2013
Laboratori Nazionali del Gran Sasso, Italy

Goal of the workshop is to establish the LUNA MV Collaboration, define its structure, and formalize the tasks of its participating institutions.

The LUNA MV project will focus on the measurement of the key astrophysical reactions $^{3}He(\alpha,\gamma)^{7}Be$, $^{12}C(\alpha,\gamma)^{16}O$, $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ using a MV machine located in the Gran Sasso underground laboratory.

International Program Committee

C. Broggini	(INFN, Padova, Italy)
M. Busso	(Perugia University, Italy)
H. Costantini	(Aix-Marseille University, France)
Z. Fülöp	(ATOMKI Debrecen, Hungary)
L. Gialanella	(Seconda Università di Napoli, Italy)
M. Hass	(Weizmann Institute, Israel)
C. Iliadid	(University of North Caroline, US)
A. Lefebvre	(CSNSM CNRS/IN2P3, France)

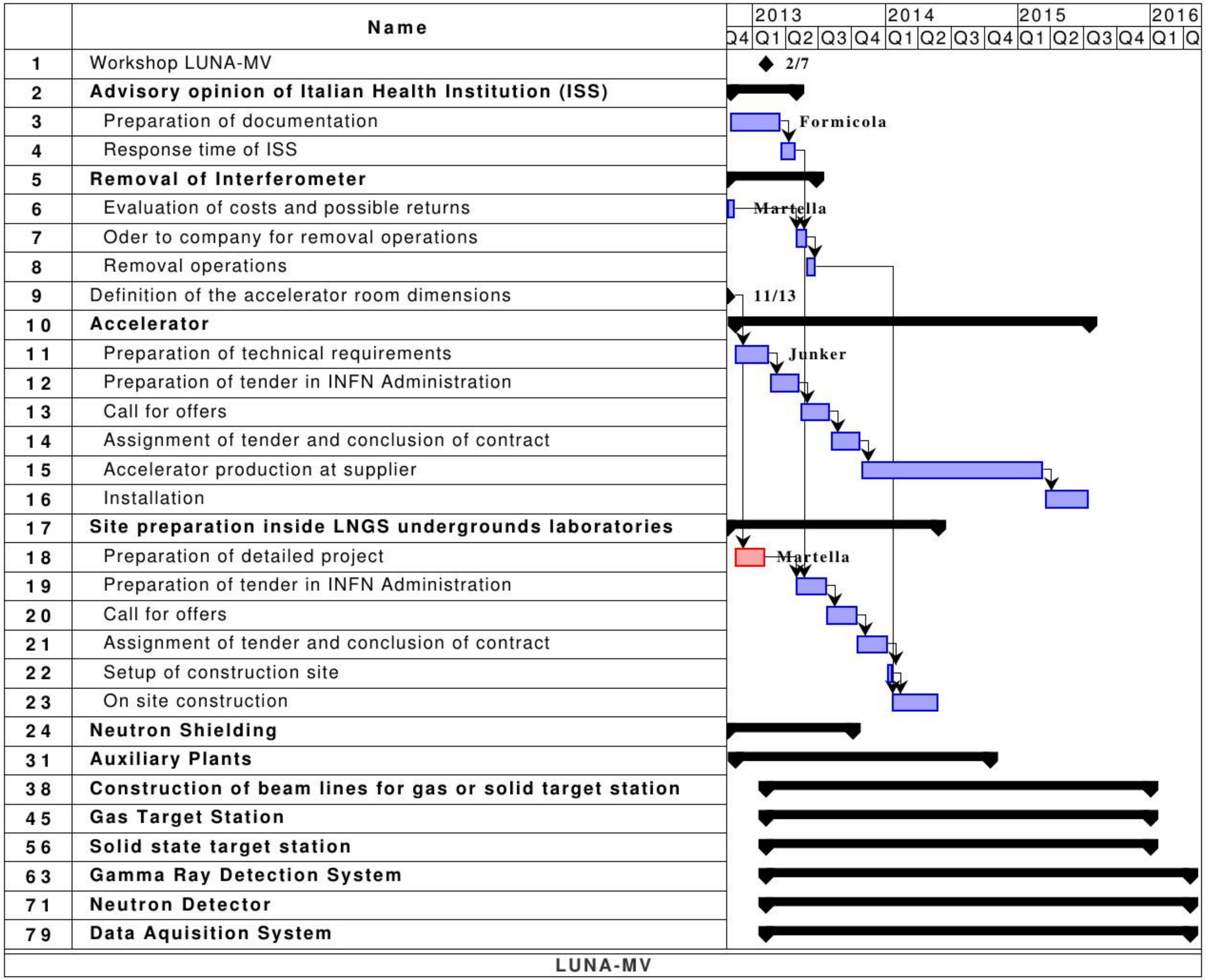
Local Organizing Committee

A. Guglielmetti	(Milano University, Italy - Chair)
A. Formicola	(LNGS, Italy - Scientific Secretary)
M. Junker	(LNGS, Italy)
P. Prati	(Genova University, Italy)
F. Chiarizia	(Conference Secretary)

Registration Deadline: 31 January 2013

http://luna-mv.lngs.infn.it

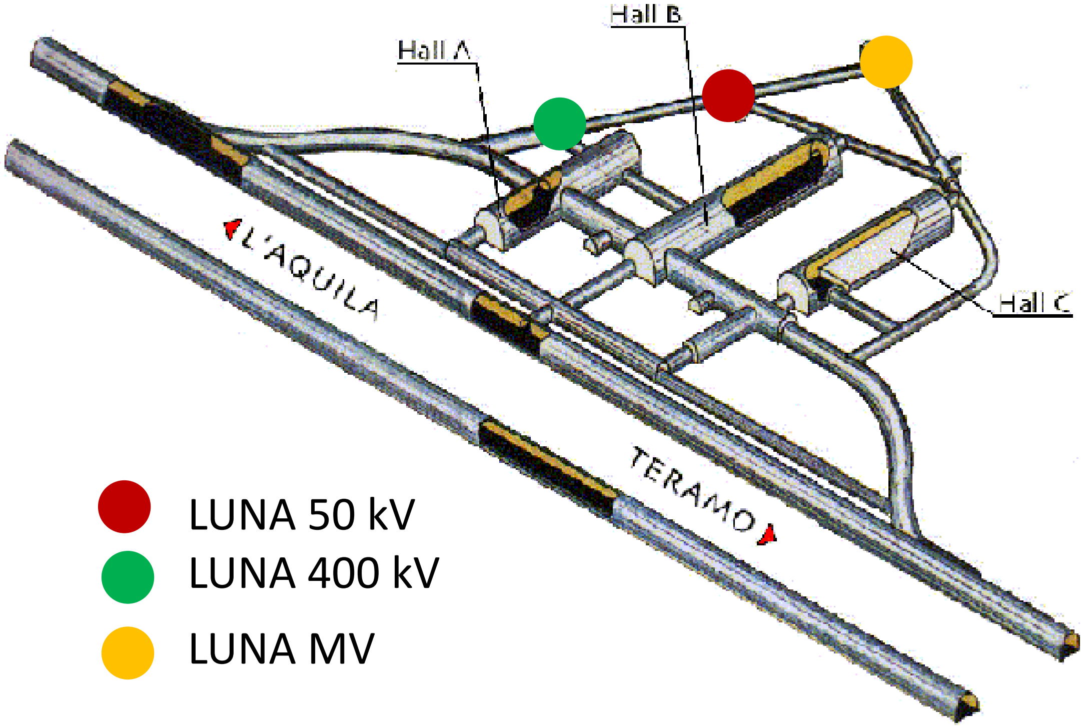
- 6-8 February 2013 the “Starting up the LUNA MV Collaboration” **workshop** was organized at the LNGS
- 11 February 2013: A **document** containing a full description of the LUNA MV installation site, of the accelerator and shielding, of the works necessary for the preparation of the site including technical specifications of all the materials which will be used, and the risk matrices sent **to "Istituto Superiore di Sanità"** for an official answer to the question if the LUNA MV project and site preparation have an impact on the water quality



	Name
1	Workshop LUNA-MV
2	**Advisory opinion of Italian Health Institution (ISS)**
3	Preparation of documentation
4	Response time of ISS
5	**Removal of Interferometer**
6	Evaluation of costs and possible returns
7	Oder to company for removal operations
8	Removal operations
9	Definition of the accelerator room dimensions
10	**Accelerator**
11	Preparation of technical requirements
12	Preparation of tender in INFN Administration
13	Call for offers
14	Assignment of tender and conclusion of contract
15	Accelerator production at supplier
16	Installation
17	**Site preparation inside LNGS undergrounds laboratories**
18	Preparation of detailed project
19	Preparation of tender in INFN Administration
20	Call for offers
21	Assignment of tender and conclusion of contract
22	Setup of construction site
23	On site construction
24	**Neutron Shielding**
31	**Auxiliary Plants**
38	**Construction of beam lines for gas or solid target station**
45	**Gas Target Station**
56	**Solid state target station**
63	**Gamma Ray Detection System**
71	**Neutron Detector**
79	**Data Aquisition System**

LUNA-MV

LUNA MV: Laboratory for Underground Nuclear Astrophysics



🔴 LUNA 50 kV
🟢 LUNA 400 kV
🟡 LUNA MV

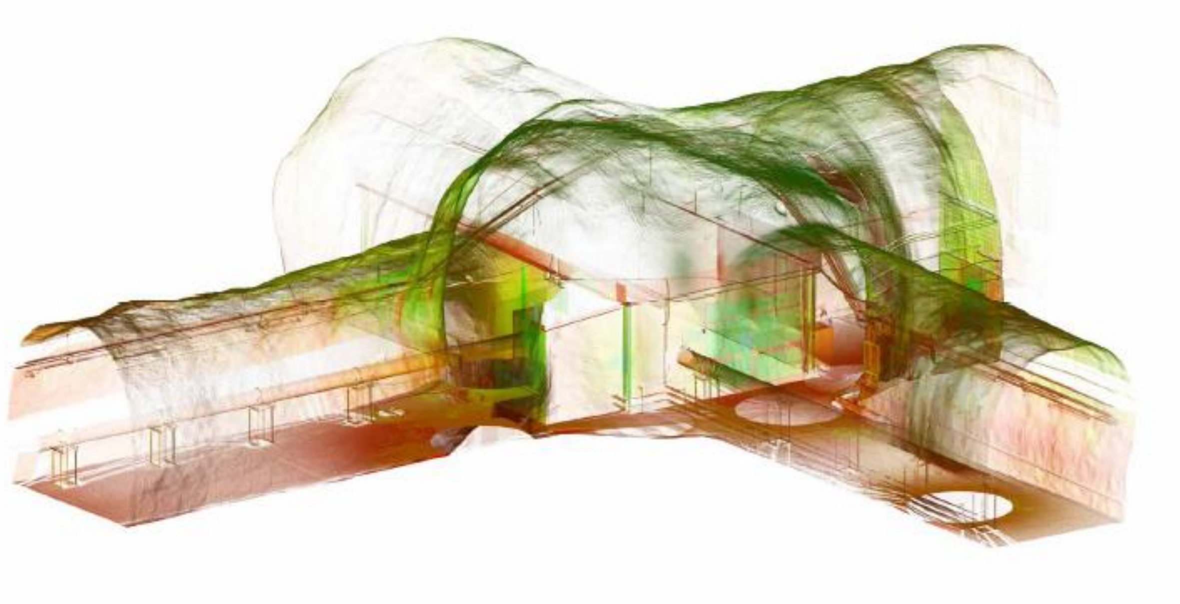
2012-2013: Hall preparation-Tender for the accelerator-Shielding
2014: Beam lines R&D-Infrastructures
2015: Accelerator installation -Beam lines construction-Detectors installation
2016: Calibration of the apparatus and first tests of beam on target

LUNA MV will be located at the LNGS B node

the LNGS B node

LUNA MV SCHEDULE

LUNA MV: The B-node



Situated in the LNGS

Surface of about: 200-230 m^2

The experimental and control rooms will be located here

In **2013**:

- interferometer removal
- Site preparation
- experimental room with shielding construction

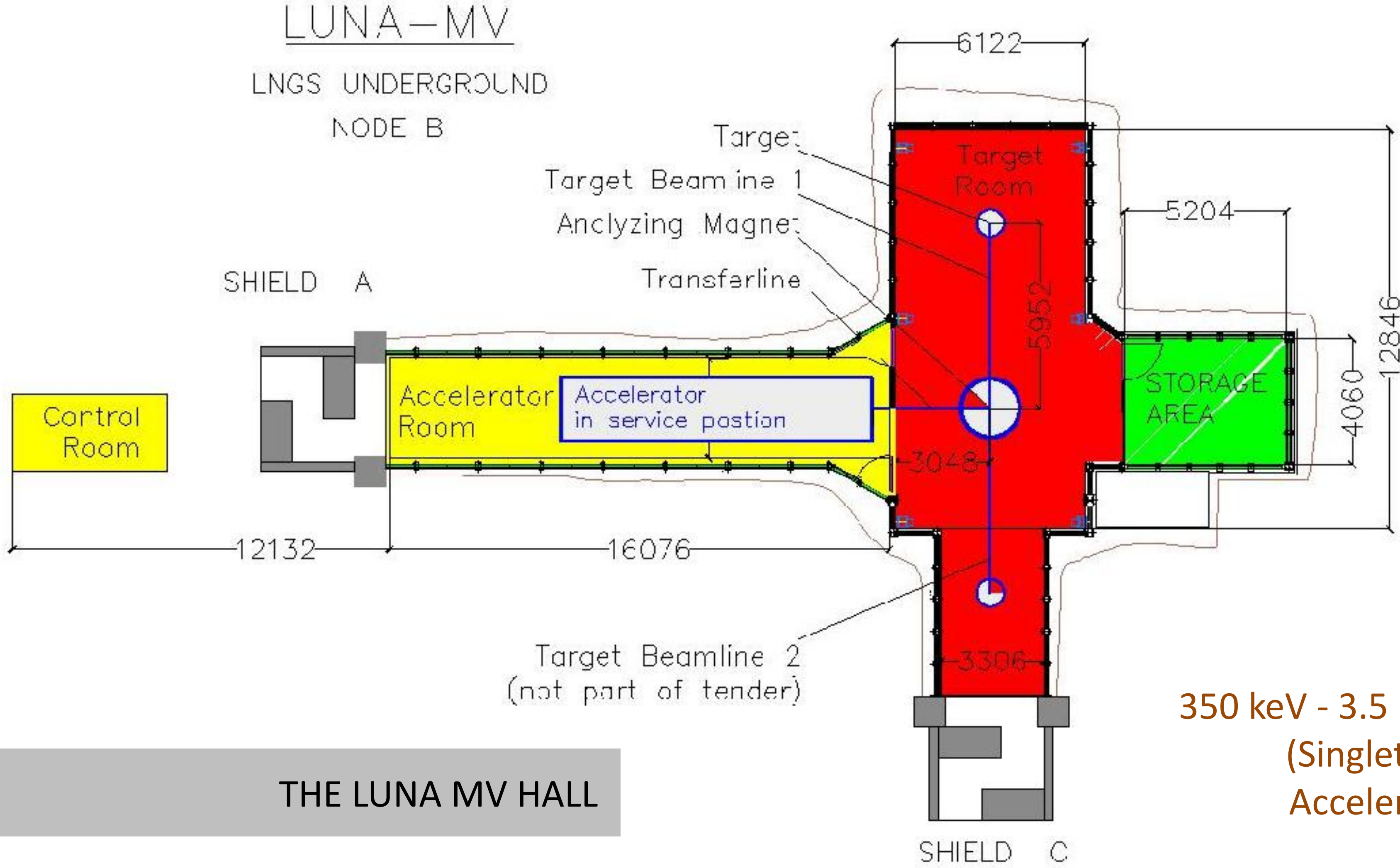
- A 3D LASER scanner profile of the B node
- Technical Design Report has been produced (still on-going)

produced (still on-going)

THE LUNA MV HALL

Physics cases of LUNA MV

Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013



350 keV - 3.5 MeV
(Singletron)
Accelerator

THE LUNA MV HALL

Physics cases of LUNA MV

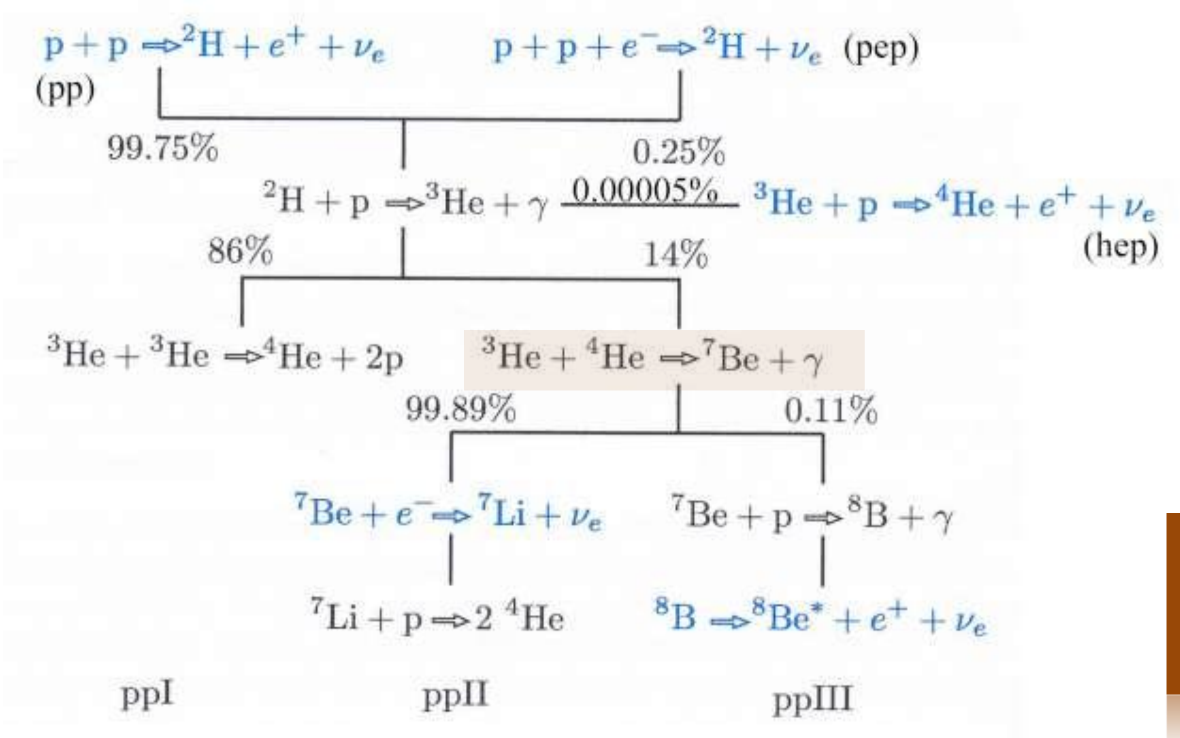
Davide Trezzi (for the LUNA collaboration) @ LNGS, March 19th, 2013

LUNA + LUNA MV: Nuclear Astrophysics at full regime

LUNA 400 keV & LUNA MV

The possibility to have both LUNA 400 kV and LUNA MV machines at LNGS give us the opportunity to investigate nuclear reactions in a wide range of energies.
An example? **The $^3He(\alpha,\gamma)^7Be$ reaction**

^{3}He(α,γ)^{7}Be: An important reaction for the Solar Standard Model



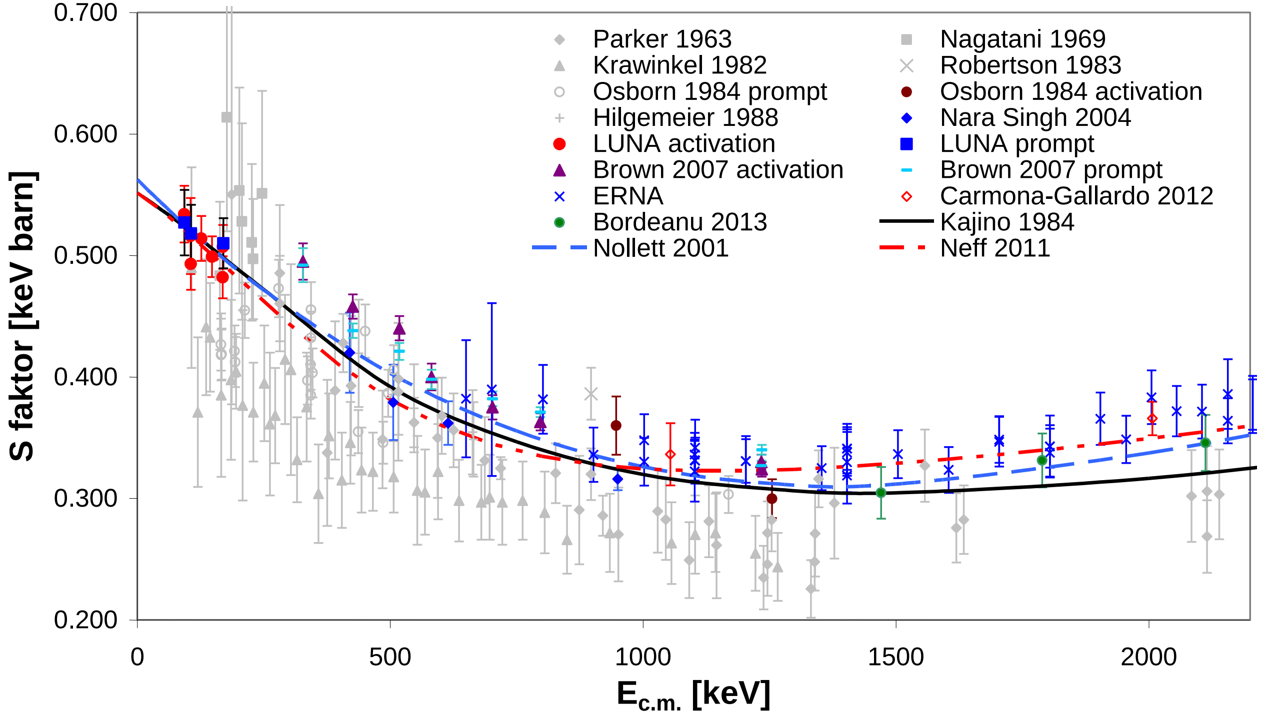
The ^{3}He(α,γ)^{7}Be S-factor at solar energies:
The prompt γ experiment at LUNA
Nuclear Physics A 814 (2008) 144–158

A good measurement (from high to low energy) of the 3He(α,γ)7Be reaction cross section give a reduction of the uncertainly on the parameter of the Solar Standard Model.

LUNA 400 kV already measured this cross section at low energy

COME BACK TO THE SOLAR PHASE

$^{3}He(\alpha,\gamma)^{7}Be$: Experimental status of the art



Even if only the modern datasets are considered there is a significant scatter among the experimental data points. The datasets are statistically consistent taking into account the respective uncertainties, but the resulting final uncertainty is higher than what is needed for the solar models.

A NEW MEASUREMENT IS NECESSARY

Physics cases of LUNA MV

LUNA MV at the LNGS: a new opportunity for Nuclear Astrophysics

- In order to understand the chemical abundance in many astrophysical scenario we need to **measure directly the nuclear cross section** for the reactions involved in the energy range of interest (Gamow peak)
- **LUNA 50 kV** and **LUNA 400 kV** have been pioneering in the direct measurement of nuclear cross section in the astrophysical energy range.
- Other reactions, first of all the $\mathbf{^{12}C(\alpha,\gamma)^{16}O}$, require an experimental investigation with a MV machine.
- **LUNA MV** is the natural consequence of LUNA: just started at the LNGS

JOIN US AND ENJOY NUCLEAR ASTROPHYSICS!

LUNA MV

INFN
Istituto Nazionale
di Fisica Nucleare

Laboratory
Underground
Nuclear
Astrophysics

Grazie per l'attenzione

thank you for your attention

Laboratori Nazionali del Gran Sasso, INFN, ASSERGI
A.Formicola, M.Junker
Forschungszentrum Dresden - Rossendorf, Germany
M. Anders, D. Bemmerer, Z.Elekes, M.-L. Menzel
INFN, Padova, Italy
C. Broggini, A. Caciolli, R. Depalo, R.Menegazzo, C. Rossi Alvarez
Institute of Nuclear Research (ATOMKI), Debrecen, Hungary
Zs.Fülöp, Gy. Gyurky, E.Somorjai, T. Szucs
Osservatorio Astronomico di Collurania, Teramo, and INFN, Napoli, Italy
O. Straniero
Ruhr - Universität Bochum, Bochum, Germany
C.Rolfs, F.Strieder, H.P.Trautvetter
Seconda Università di Napoli, Caserta, and INFN, Napoli, Italy
F.Terrasi
Università di Genova and INFN, Genova, Italy
F. Cavanna, P.Corvisiero, P.Prati
Università di Roma 1
C. Gustavino
Università di Milano and INFN, Milano, Italy
A.Guglielmetti, C. Bruno, M. Campeggio, D. Trezzi
Università di Napoli ''Federico II'', and INFN, Napoli, Italy
A. Di Leva, G.Imbriani, V.Roca
Università di Torino and INFN, Torino, Italy
and G.Gervino
University of Edinburgh
M. Aliotta, T. Davinson and D. Scott