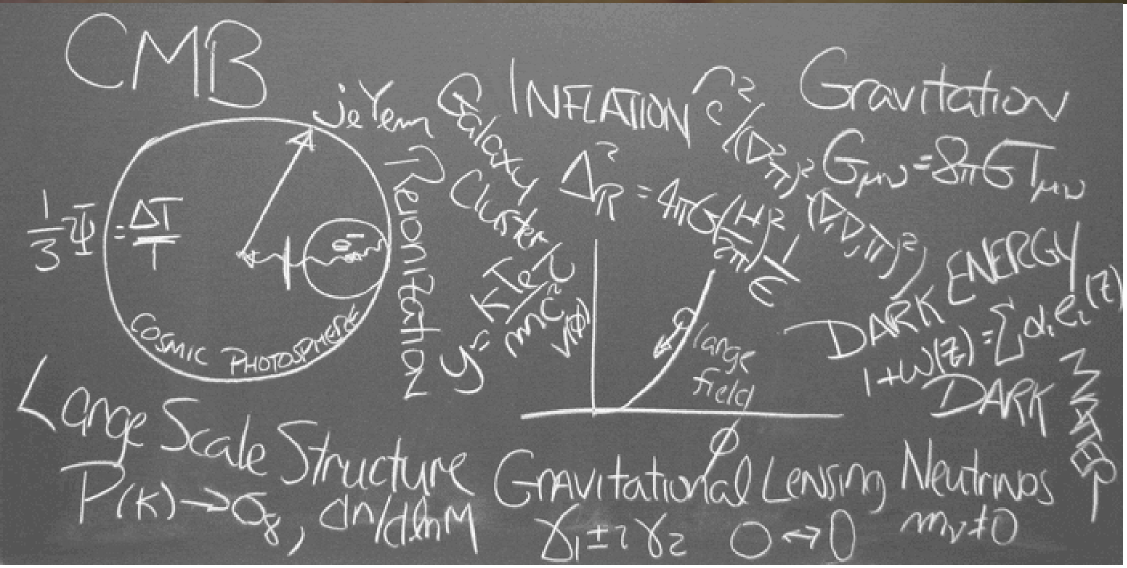
NUCLEAR REACTIONS OF ASTROPHYSICAL INTEREST AT LUNA

D. Trezzi (for the LUNA collaboration)

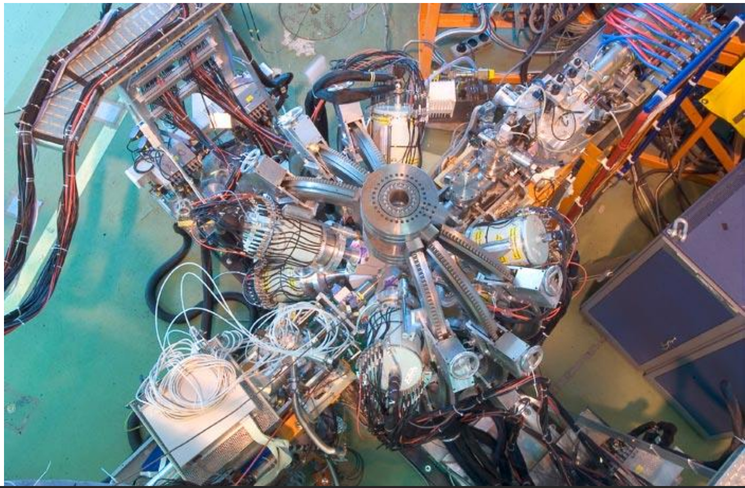


ASTROPHYSICS & PLASMA PHYSICS

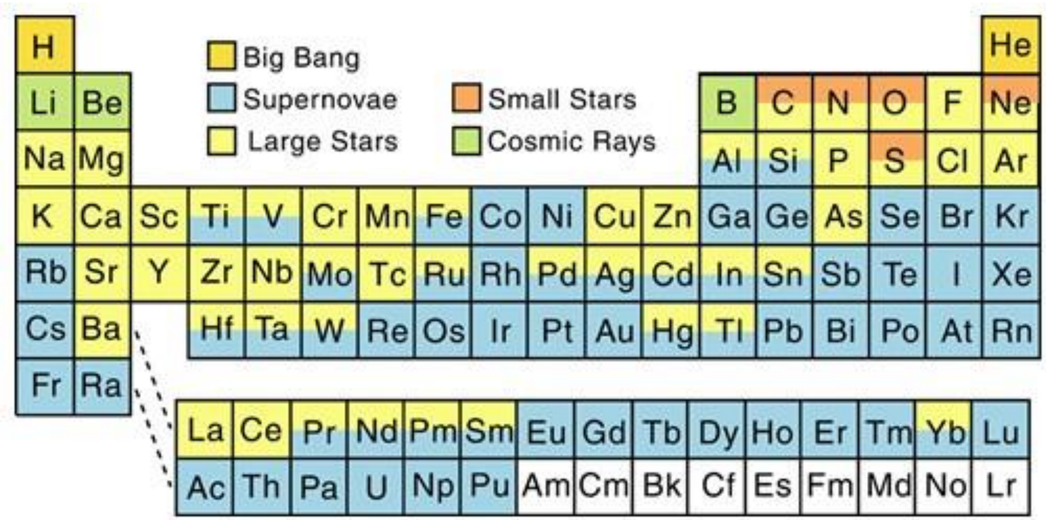
PARTICLE PHYSICS

NUCLEAR PHYSICS

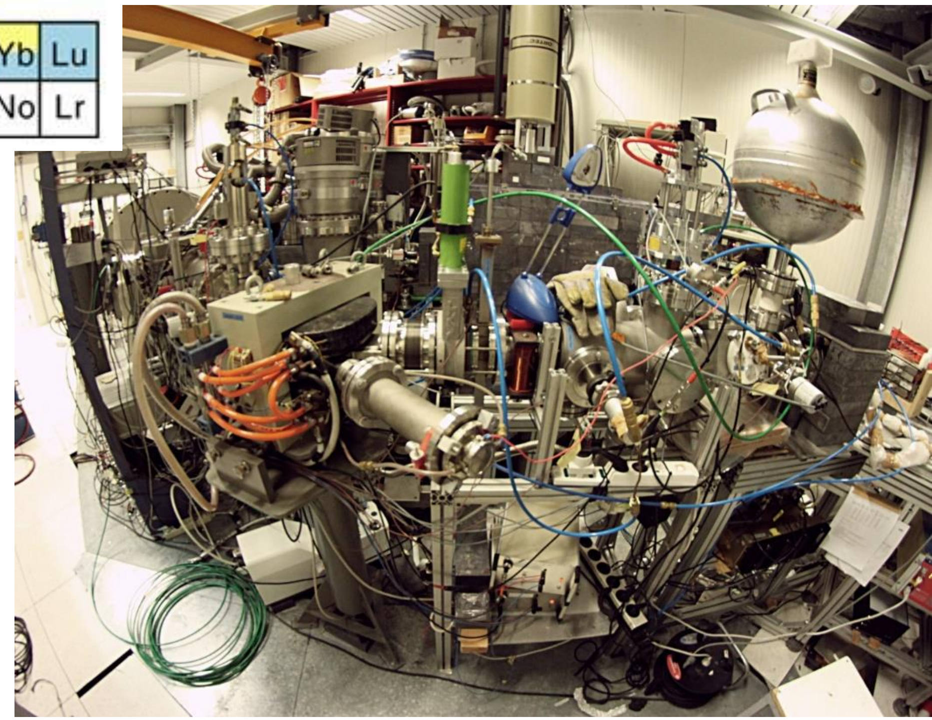
ASTRONOMY & COSMOLOGY



NUCLEAR ASTROPHYSICS: the origin of the elements



- Elements that make up everything that we see around us were made by **nuclear reactions** and decays in stars.
- These processes also produce the energy that makes stars shine.



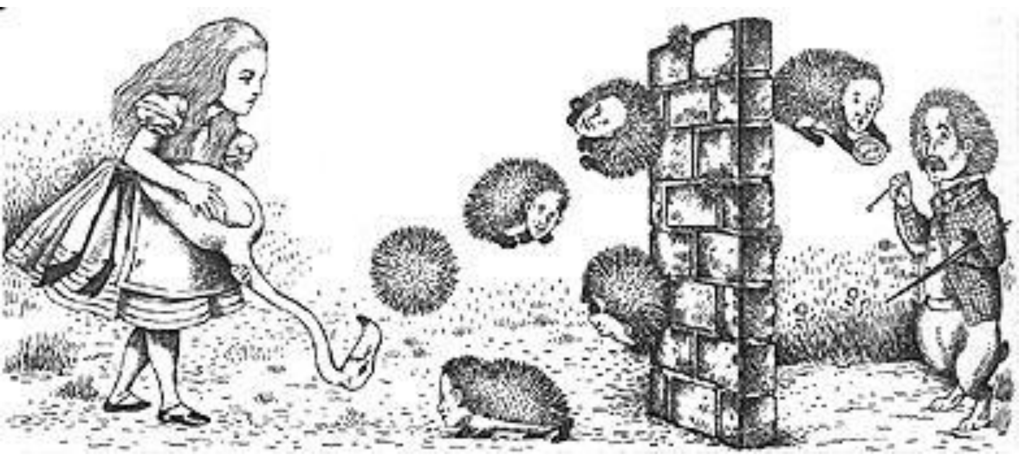
- The abundances of the elements and isotopes provide important information about the astrophysical environments where they were created.
- This field of research is called **Nuclear Astrophysics**.

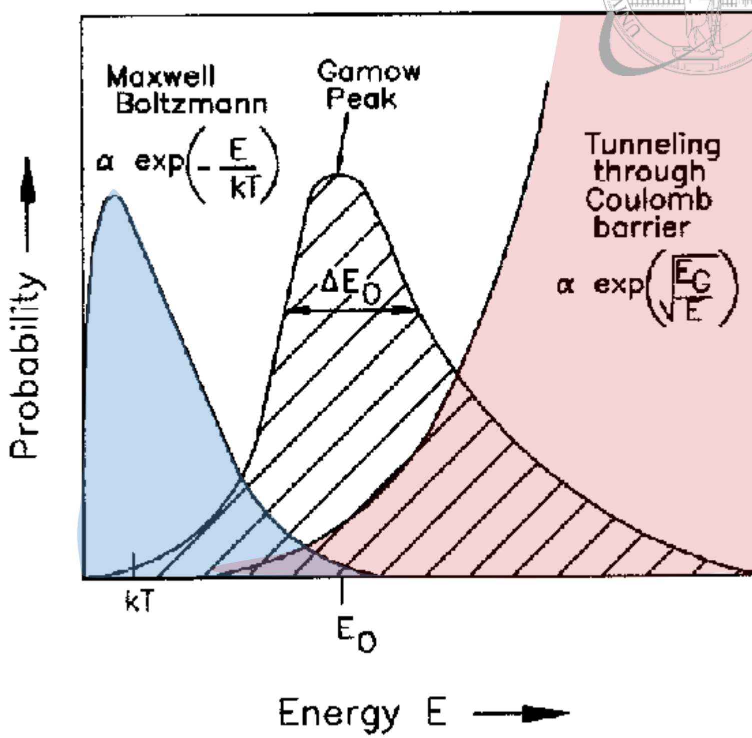
LUNA: **L**aboratory for **U**nderground **N**uclear **A**strophysics

THERMONUCLEAR FUSION

Gamow Peak and Astrophysical S-factor

[charge particles]





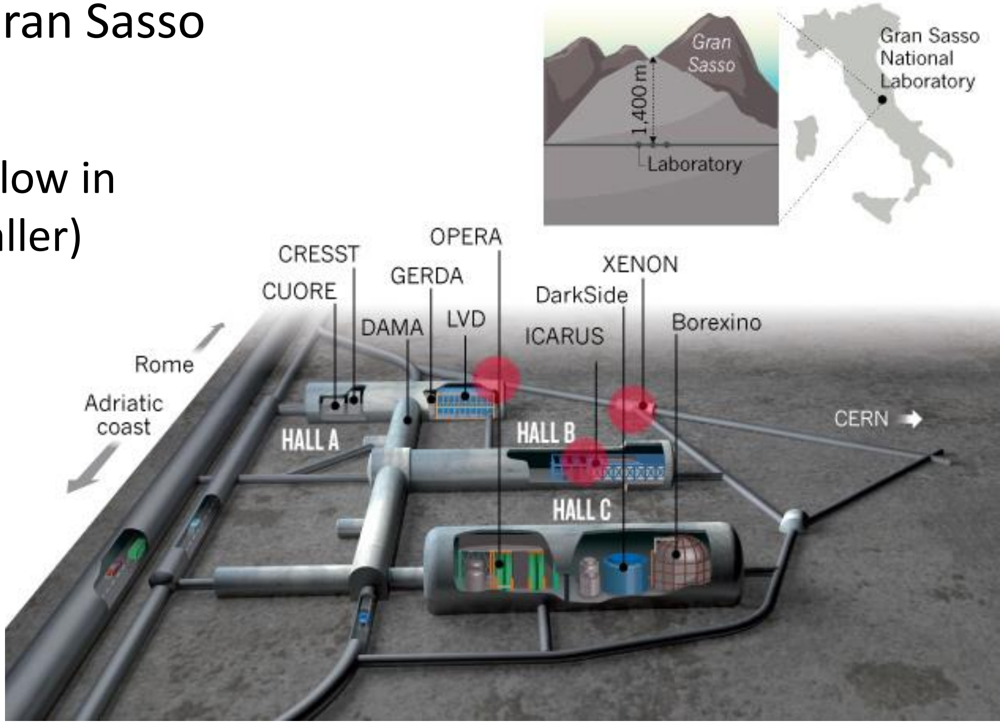
$$r_{a,x} = \frac{1}{1+\delta_{ax}} N_a N_x \left(\frac{8}{\mu\pi}\right)^{\frac{1}{2}} (k_B T)^{3/2} \int_0^\infty S(E)\, e^{-E/kT} e^{-31.29 Z_1 Z_2 \sqrt{\frac{\mu}{E}}} dE$$

where the **Astrophysical S-factor** S(E) is related to the cross section through:

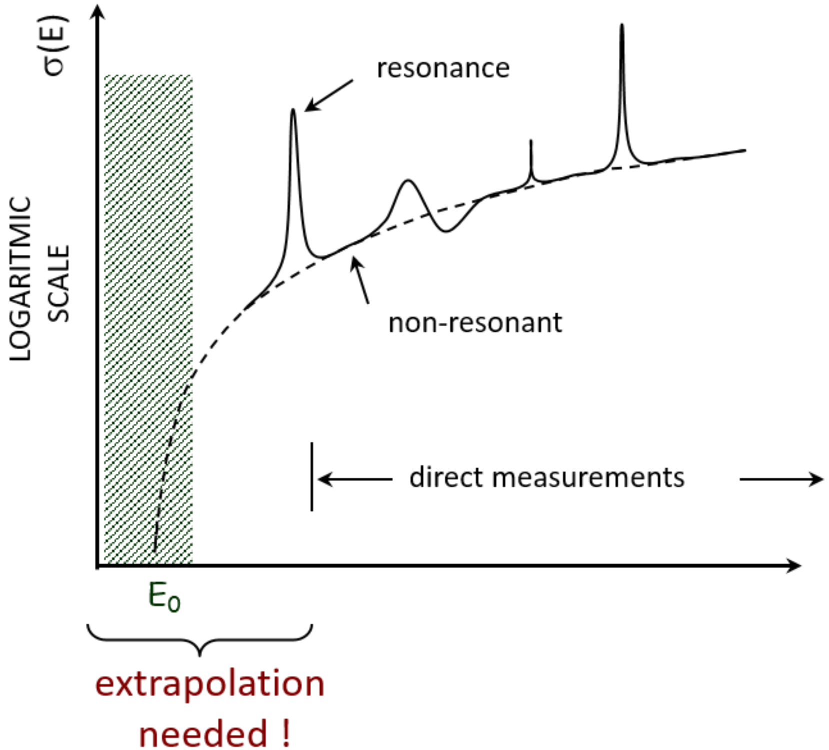
$$\sigma(E) = \frac{1}{E} \boldsymbol{S(E)} e^{-31.29 Z_1 Z_2 \sqrt{\frac{\mu}{E}}}$$

GOING DEEP UNDERGROUND

LUNA and the Laboratori Nazionali del Gran Sasso



Nuclear Fusion cross sections are usual very low in the Gamow window (μb to pb and even smaller)



The reaction particles are hidden by natural (cosmic ray) background

Deep Underground Laboratories are necessary: Gran Sasso, Felsenkeller and Canfranc in **Europe**

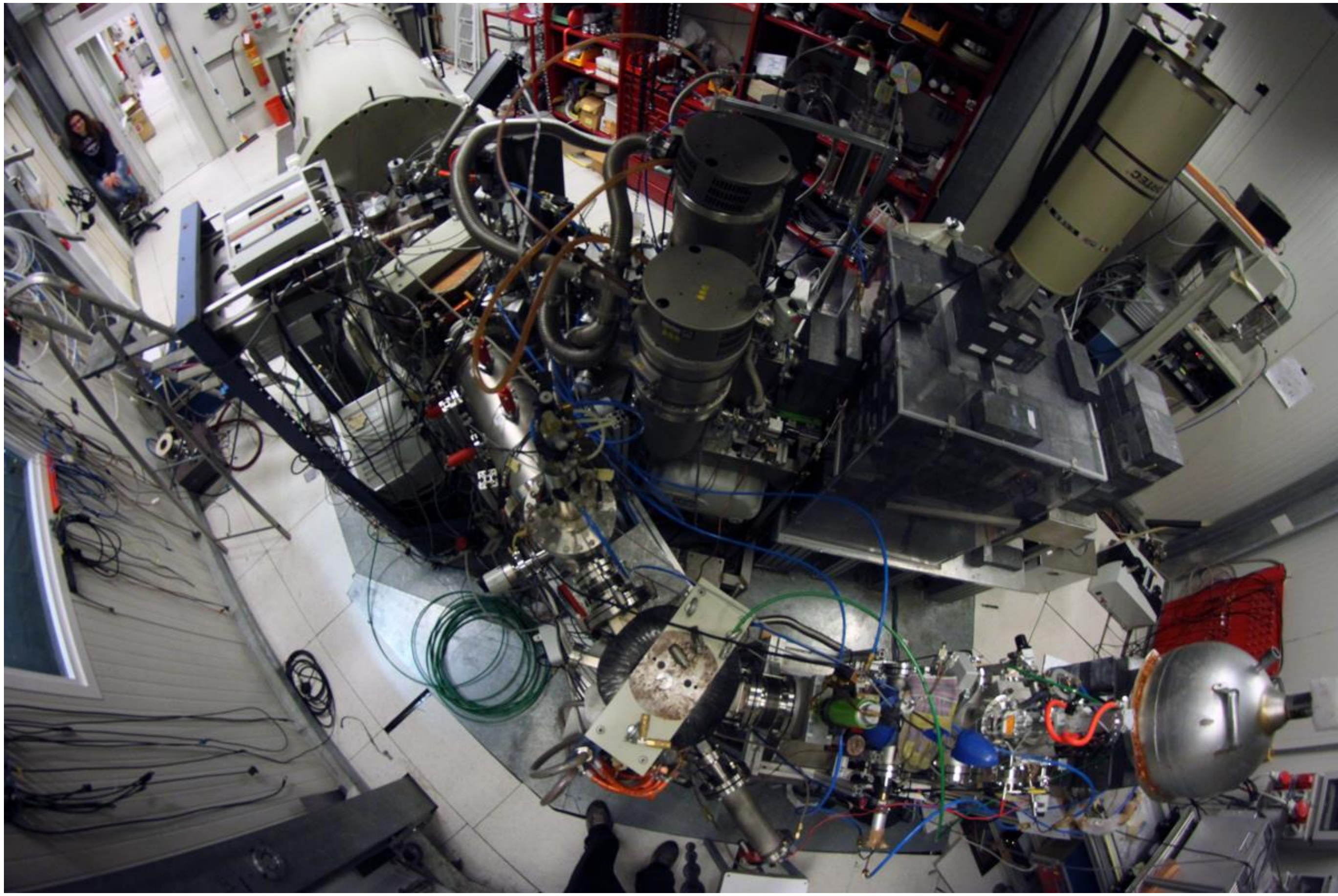
THE LUNA EXPERIMENT

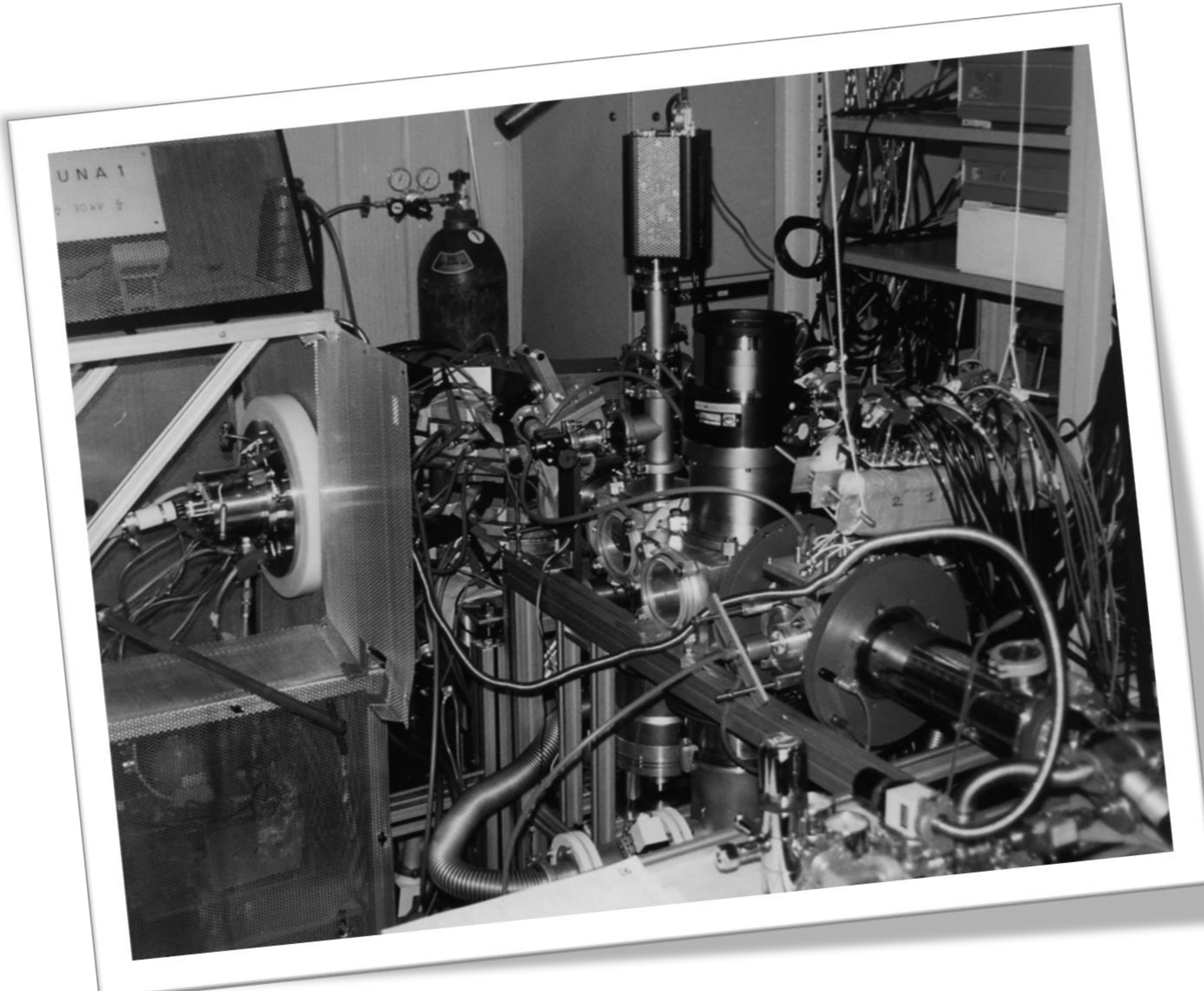
LUNA 50 kV (1992-2001) – Solar Phase
LUNA 400 kV (2000-2018) – CNO, Mg-Al and Ne-Na cycles, BBN
LUNA-MV (since 2018) – Helium burning

LUNA ACCELERATOR
- High current
- Long term stability
- High energy accuracy

TARGETS
- Windowless gas target
- Solid target

DETECTORS
- 137% HPGe
- BGO
- Silicon
- NaI



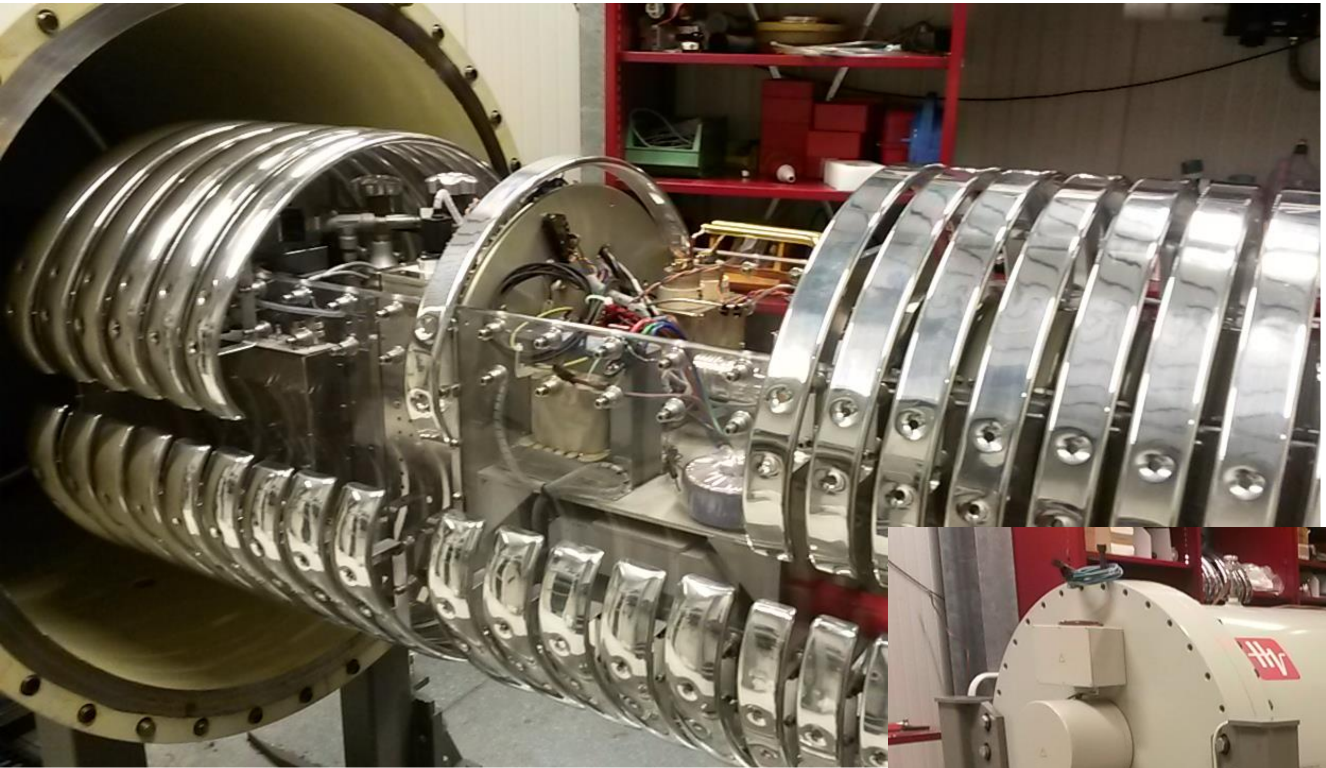


LUNA 50 kV

Energy range: 10-50 kV
Current: 1 mA
Beam spread: 20 eV

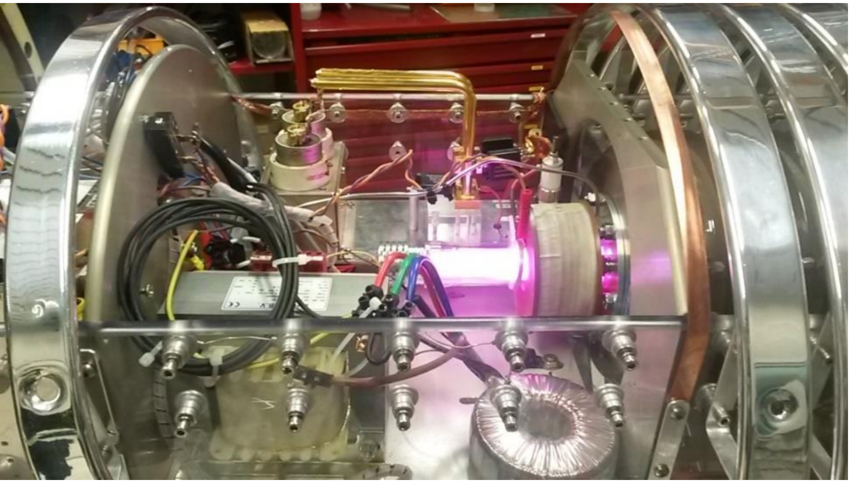
years and years ago…

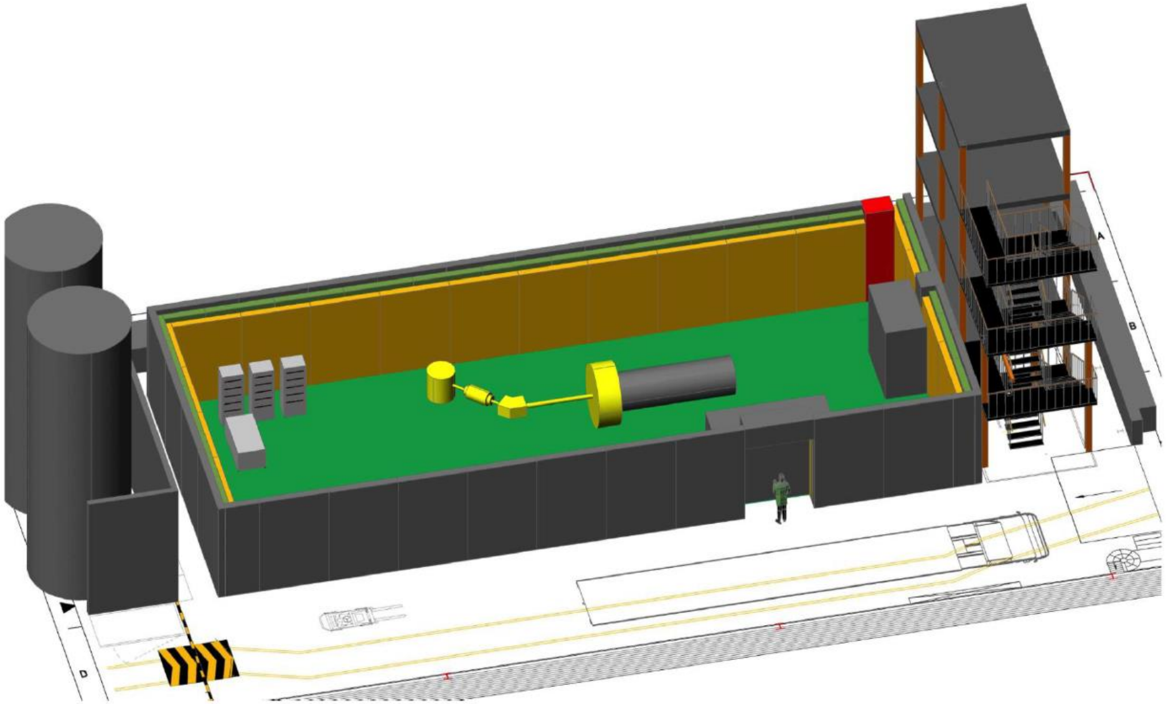
TAKE NOTE!
Silver Moon workshop at LNGS



LUNA 400 kV

Energy range: 50-400 kV
Current: 1 mA
Beam spread: < 100 eV
Stability: 5 eV/h



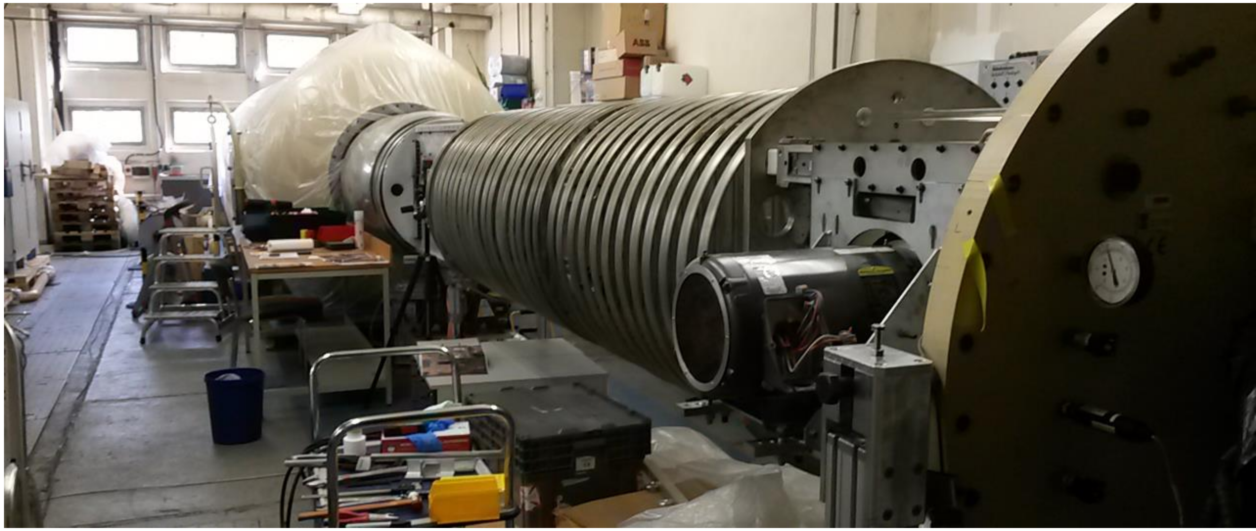


This machine will provide not only proton and helium (3/4) but also $^{12}C^{+}$ and $^{12}C^{++}$

↓ credits: HZDR, Dresden

LUNA MV

Energy range: 200-3500 kV
Current: < 1 mA
Beam spread: 350 eV
Stability: < 35 eV/h



THE LUNA EXPERIMENT

LUNA 50 kV (1992-2001) – Solar Phase
LUNA 400 kV (2000-2018) – CNO, Mg-Al and Ne-Na cycles, BBN
LUNA-MV (since 2018) – Helium burning

LUNA ACCELERATOR

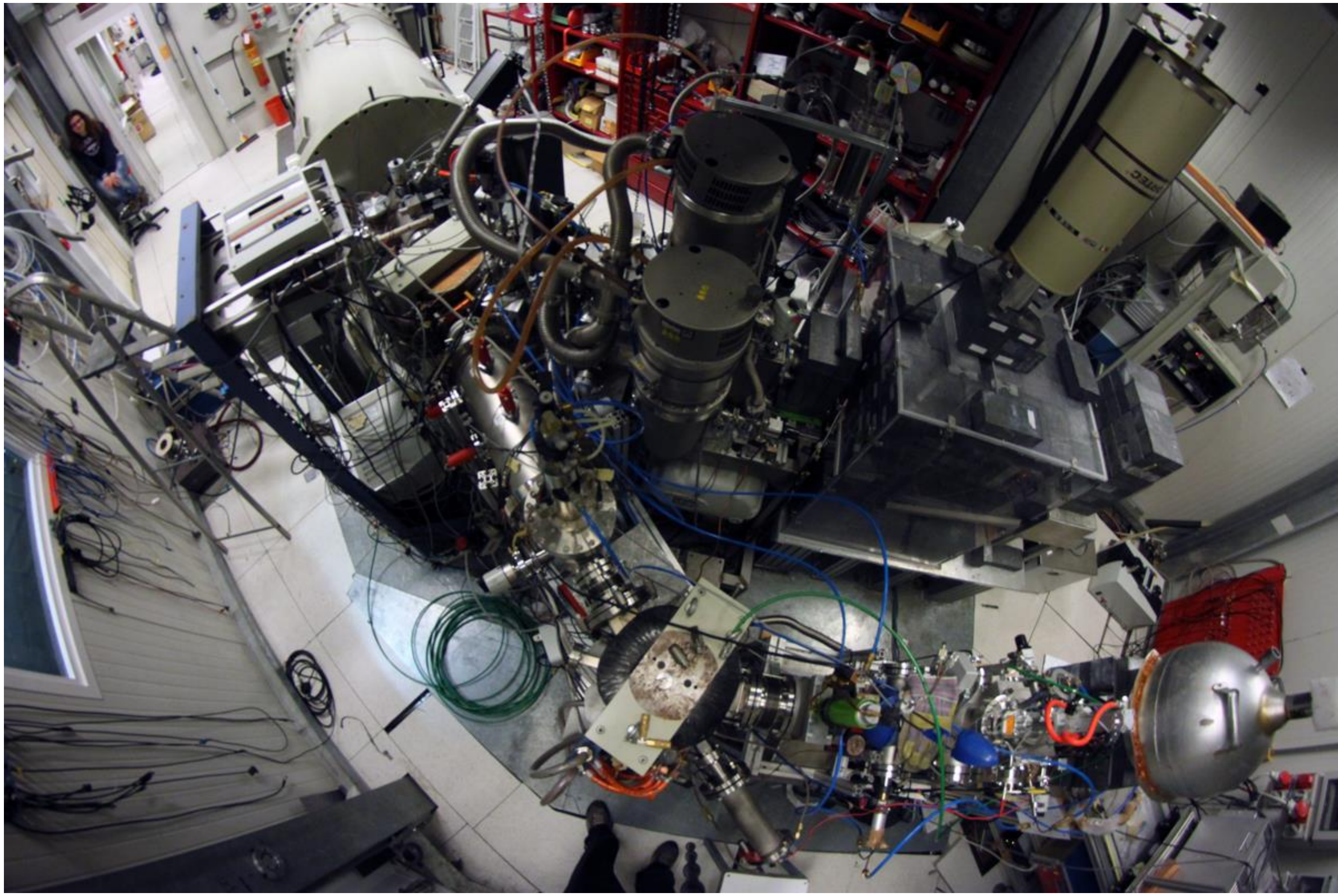
- High current
- Long term stability
- High energy accuracy

TARGETS

- Windowless gas target
- Solid target

DETECTORS

- 137% HPGe
- BGO
- Silicon
- NaI



THE LUNA EXPERIMENT

LUNA 50 kV (1992-2001) – Solar Phase
LUNA 400 kV (2000-2018) – CNO, Mg-Al and Ne-Na cycles, BBN
LUNA-MV (since 2018) – Helium burning

LUNA ACCELERATOR

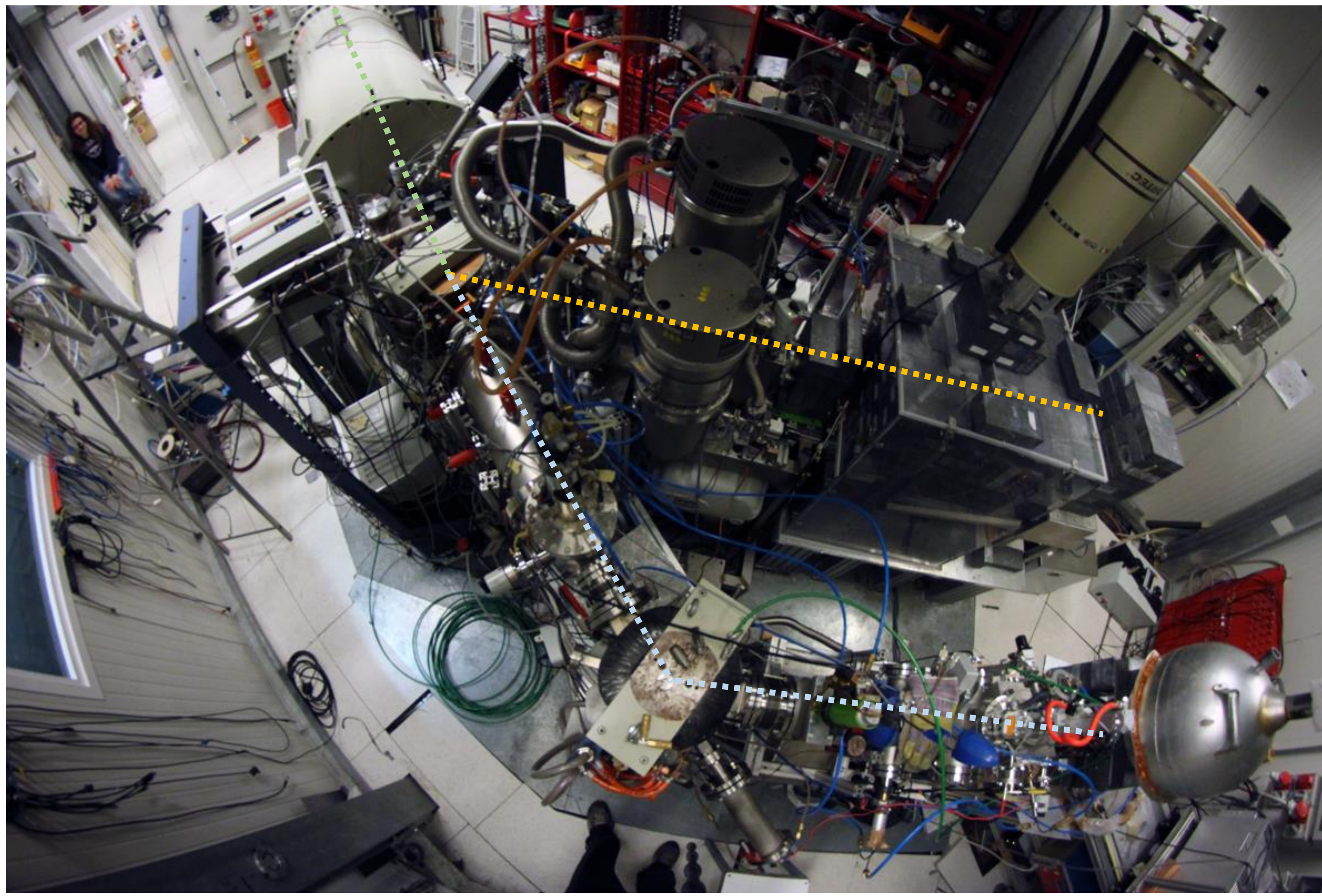
- High current
- Long term stability
- High energy accuracy

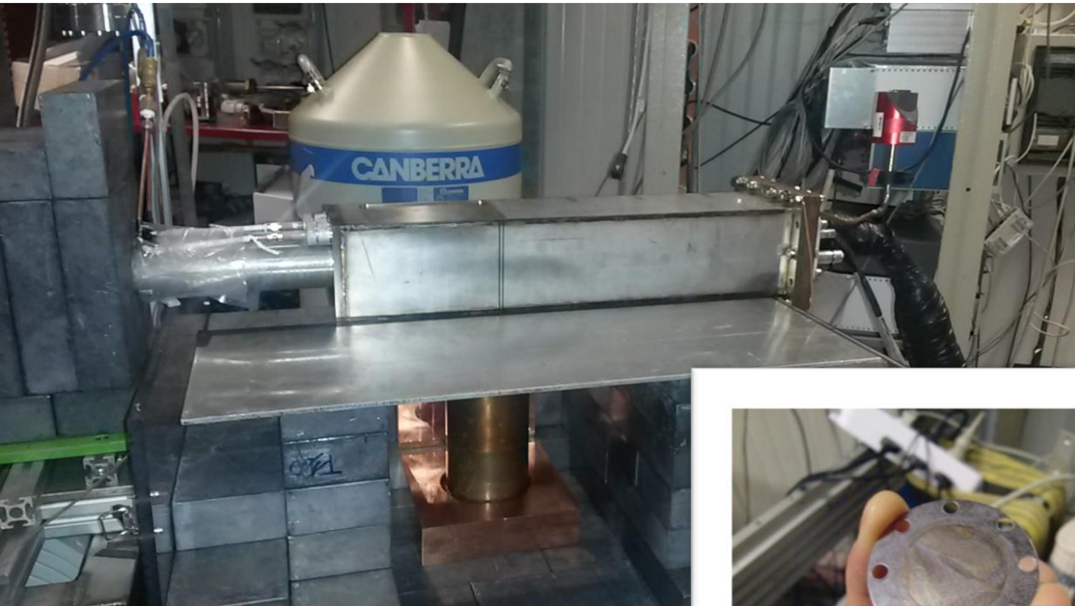
TARGETS

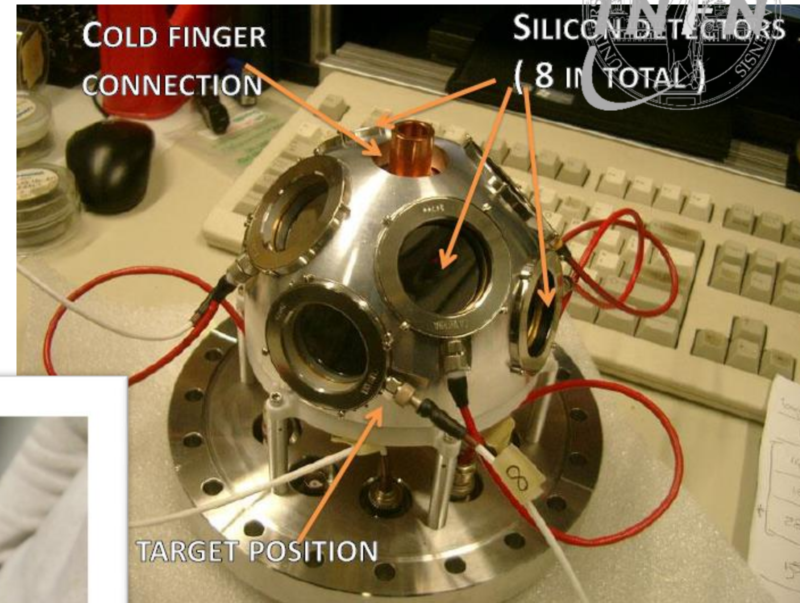
- Windowless gas target
- Solid target

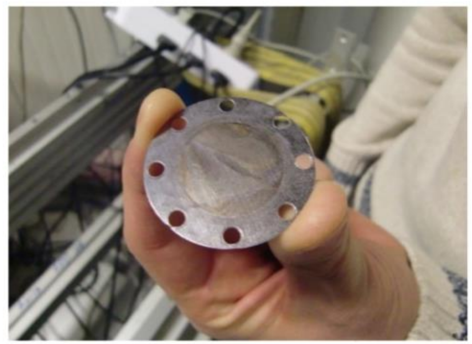
DETECTORS

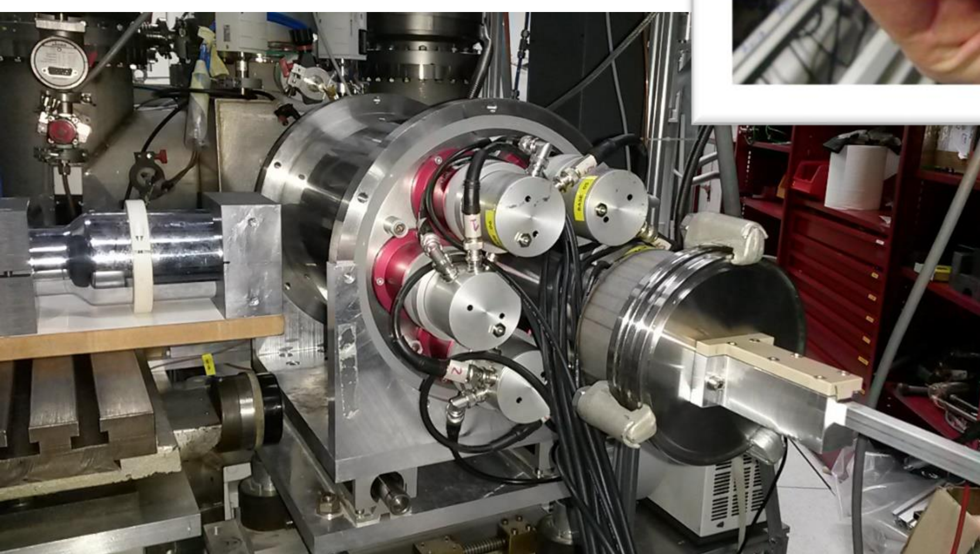
- 137% HPGe
- BGO
- Silicon
- NaI

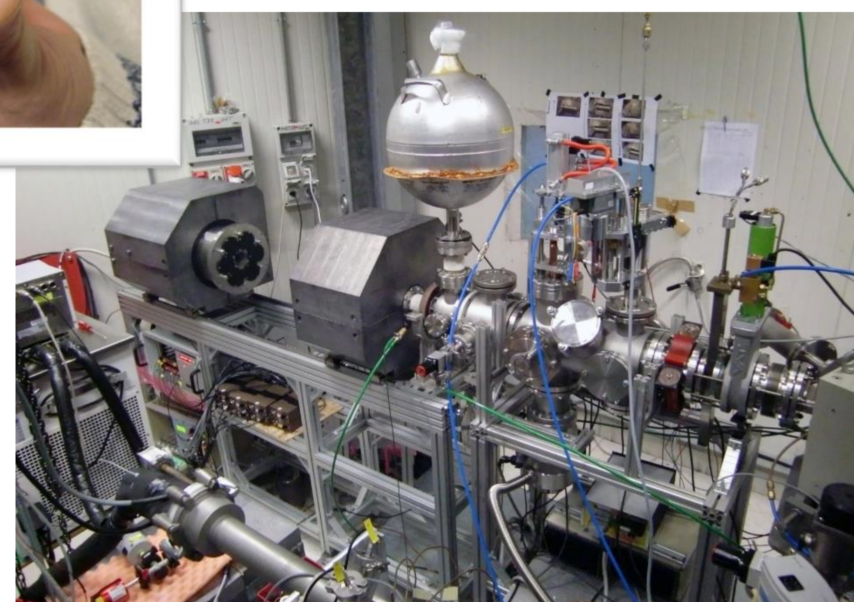





COLD FINGER
CONNECTION
SILICON DETECTORS
(8 IN TOTAL)
TARGET POSITION







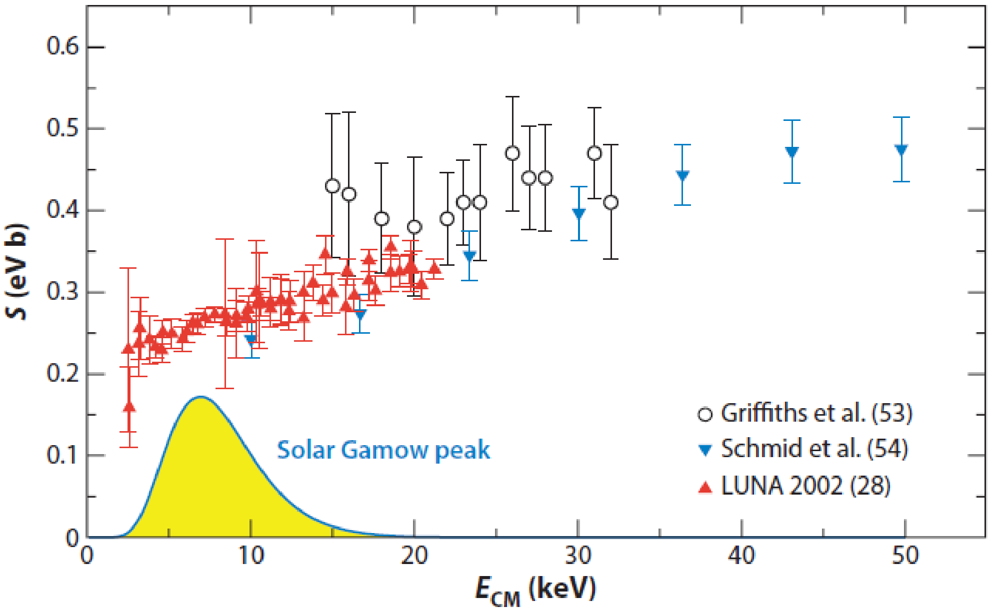
25y of NUCLEAR ASTROPHYSICS AT LUNA

- **ELECTRON SCREENING AND STOPPING POWER**
  $^{2}H(^{3}He,p)^{4}He$ and $^{3}He(^{2}H,p)^{4}He$
- **SOLAR FUSION REACTION**
  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ and $^{3}He(\alpha,\gamma)^{7}Be$
- **CNO, Ne-Na AND Mg-Al CYCLES**
  $^{14}N(p,\gamma)^{15}O$ $^{15}N(p,\gamma)^{16}O$ $^{22}Ne(p,\gamma)^{23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ and $^{25}Mg(p,\gamma)^{26}Al$
- **EXPLOSIVE HYDROGEN BURNING IN NOVAE AND AGB STARS**
  $^{17}O(p,\gamma)^{18}F$ $^{17}O(p,\alpha)^{14}N$ $^{18}O(p,\gamma)^{19}F$ and $^{18}O(p,\alpha)^{15}N$
- **BIG BANG NUCLEOSYNTHESIS**
  $^{2}H(\alpha,\gamma)^{6}Li$ $^{2}H(p,\gamma)^{3}He$ and $^{6}Li(p,\gamma)^{7}Be$
- **NEUTRON CAPTURE NUCLEOSYNTHESIS**
  $^{13}C(\alpha,n)^{16}O$

at LUNA-MV: $^{12}C(\alpha,\gamma)^{16}O$, $^{13}C(\alpha,n)^{16}O$ $^{22}Ne(\alpha,n)^{25}Mg$, $^{12}C+^{12}C$ and much more…

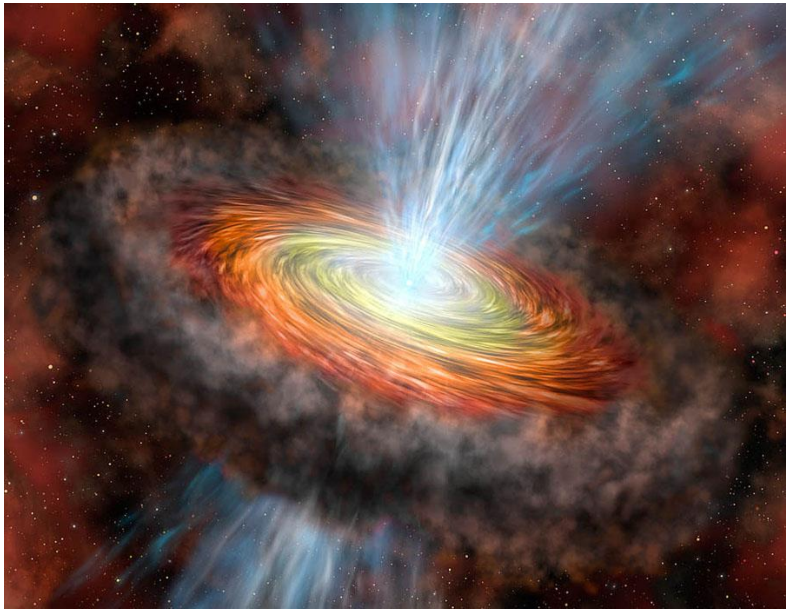
THE $^2H(p,\gamma)^3He$ REACTION

SOLAR FUSION | BIG BANG NUCLEOSYNTESIS



- the $^2H(p,\gamma)^3He$ reaction controls the equilibrium abundance of solar deuterium,
- The $^2H(p,\gamma)^3He$ reaction controls the **life of protostars** before they enter into the main-sequence phase.

LUNA demonstrate, for the first time, that it is possible to direct study solar fusion in the Gamow window from underground laboratories.

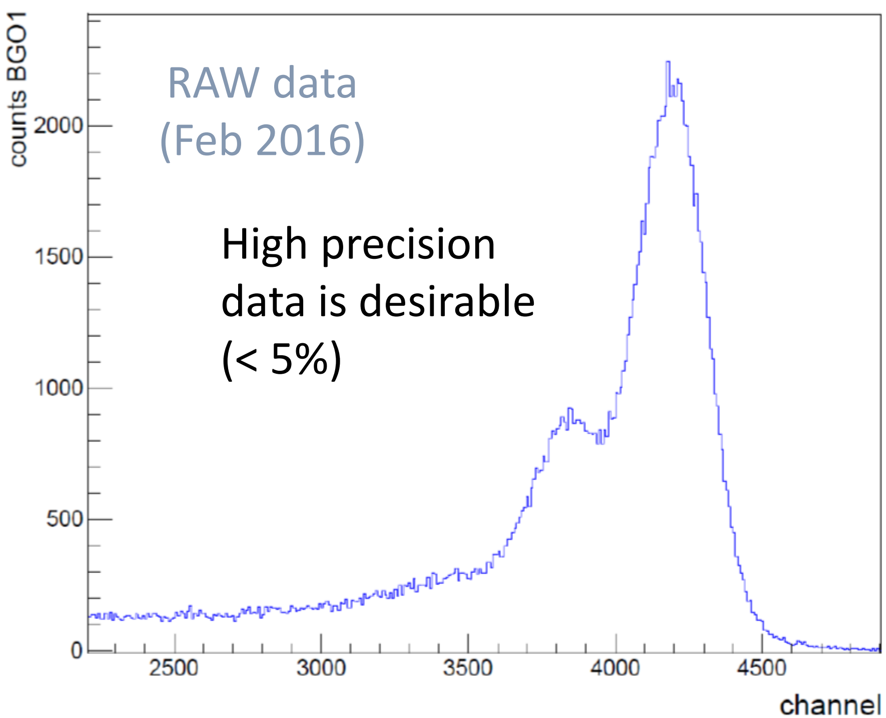


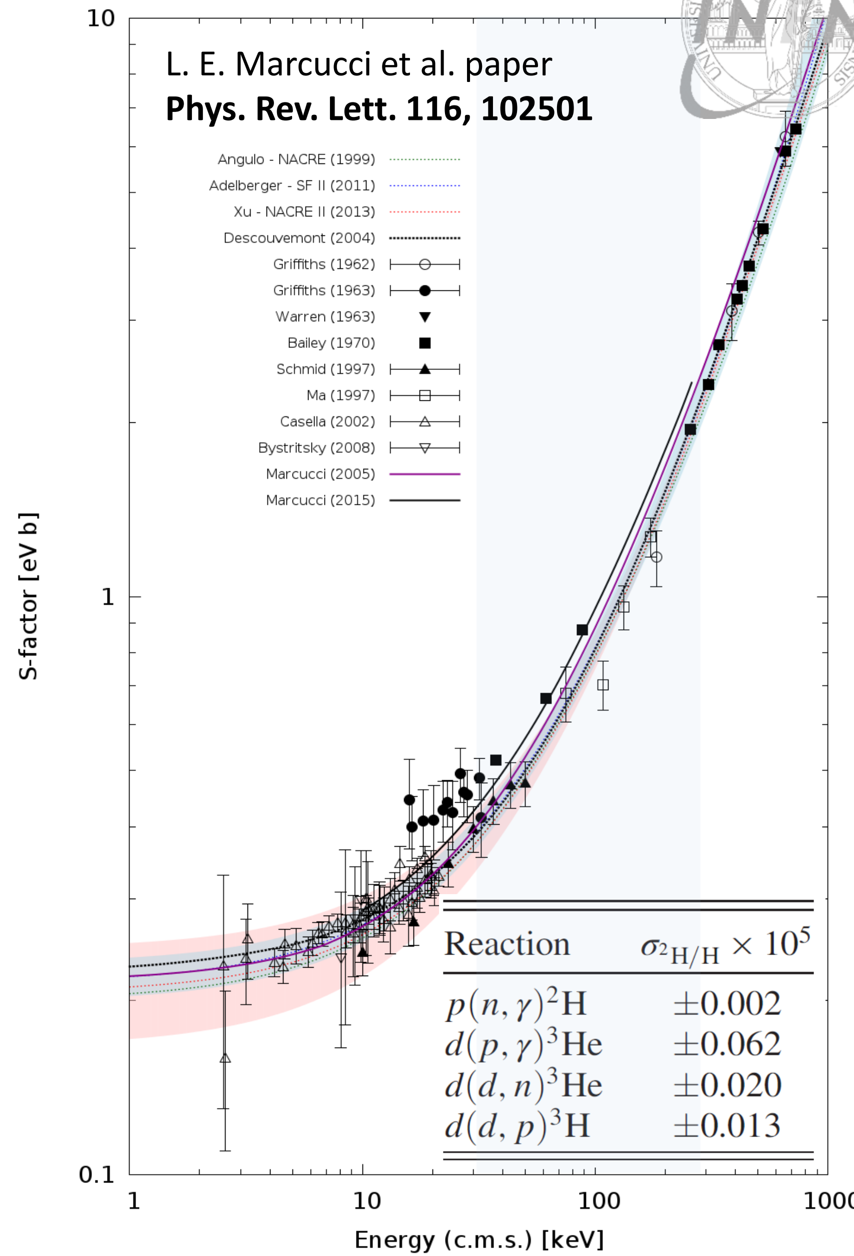
THE $^{2}H(p,\gamma)^{3}He$ REACTION

SOLAR FUSION | BIG BANG NUCLEOSYNTHESIS

Primordial deuterium abundance is quite in agreement with the calculated value:

- HIGH PRECISION COSMOLOGICAL DATA (Planck)
- **LOW** PRECISION (about 9%) NUCLEAR DIRECT DATA IN THE BBN ENERGY RANGE

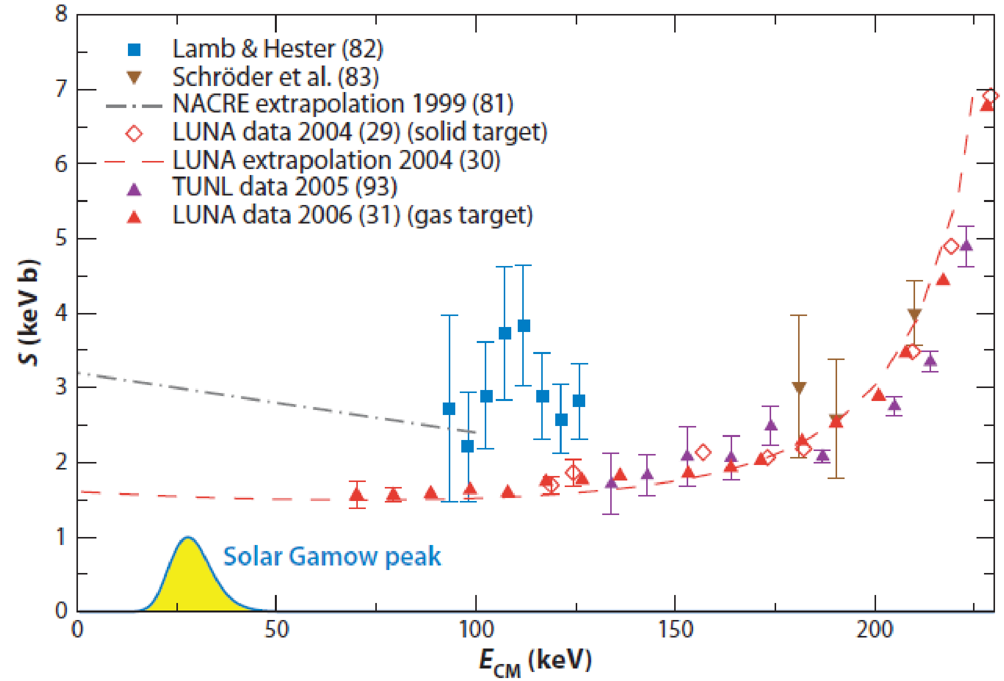


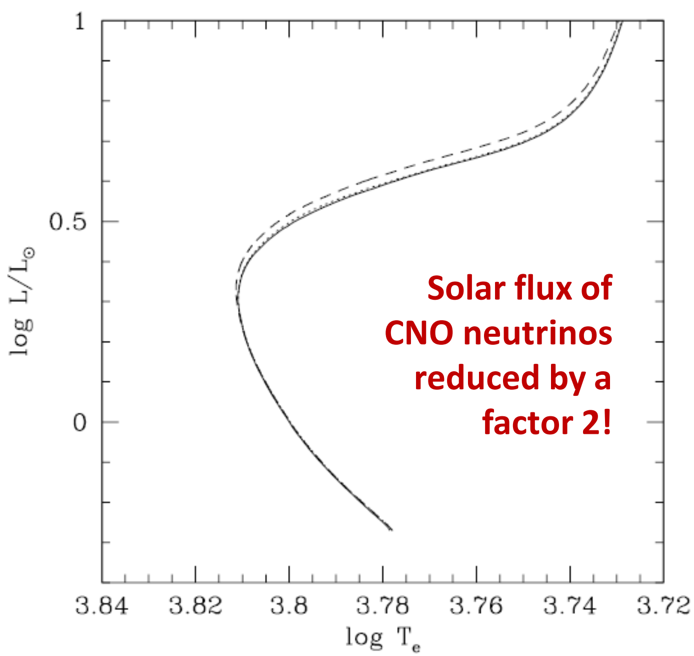


THE $^{14}N(p,\gamma)^{15}O$ REACTION

CNO & GLOBULAR CLUSTER

- The $^{14}N(p,\gamma)^{15}O$ is the slowest reaction of the CNO cycle; it controls the cycle's energy production rate.
- The turnoff luminosity point of a globular cluster is used to determine the age of the cluster → lower limit of the Universe age (TOL-A relation)





Solar flux of CNO neutrinos reduced by a factor 2!

A&A 420, 625–629 (2004)
DOI: 10.1051/0004-6361:20040981

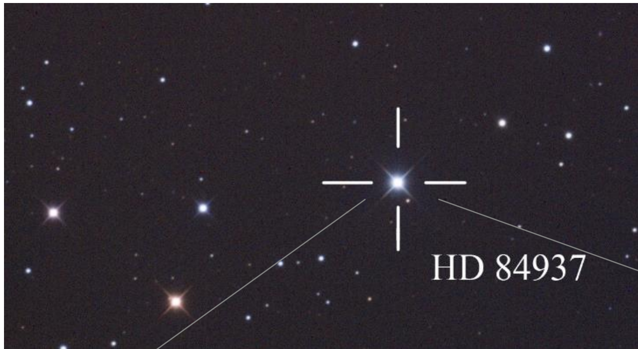
Astronomy & Astrophysics

The bottleneck of CNO burning and the age of Globular Clusters

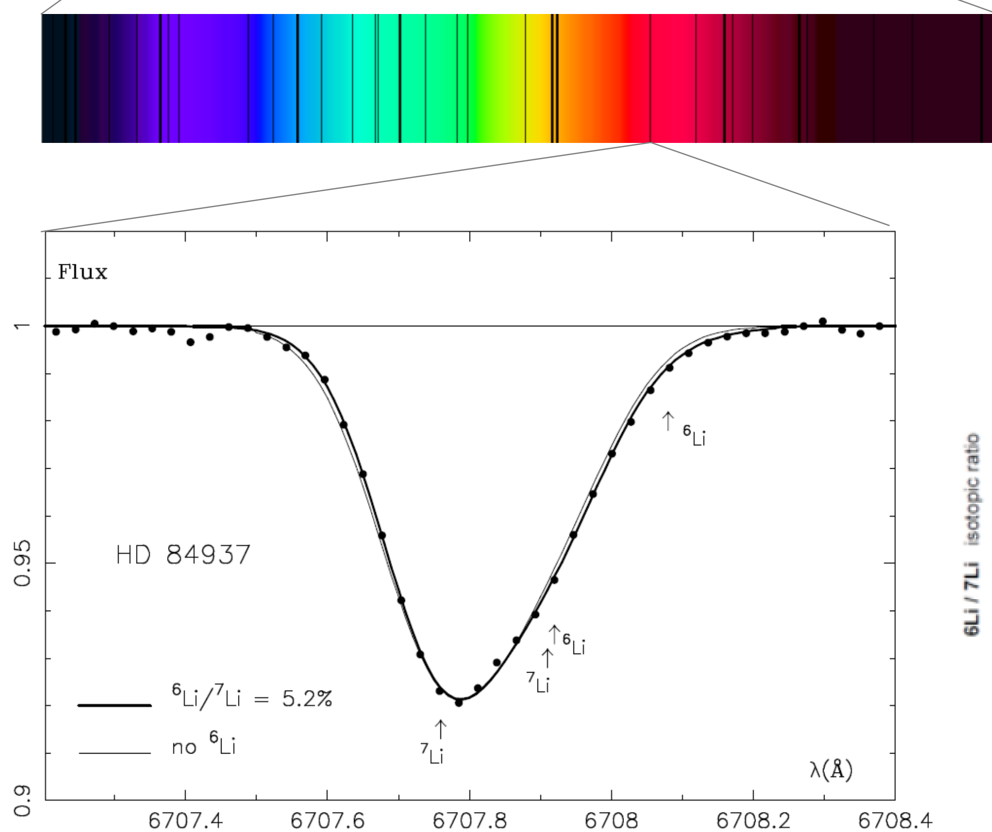
«when a given turnoff luminosity is considered, the revised isochrones imply systematically older ages, namely between 0.7 and 1 Gyr.»

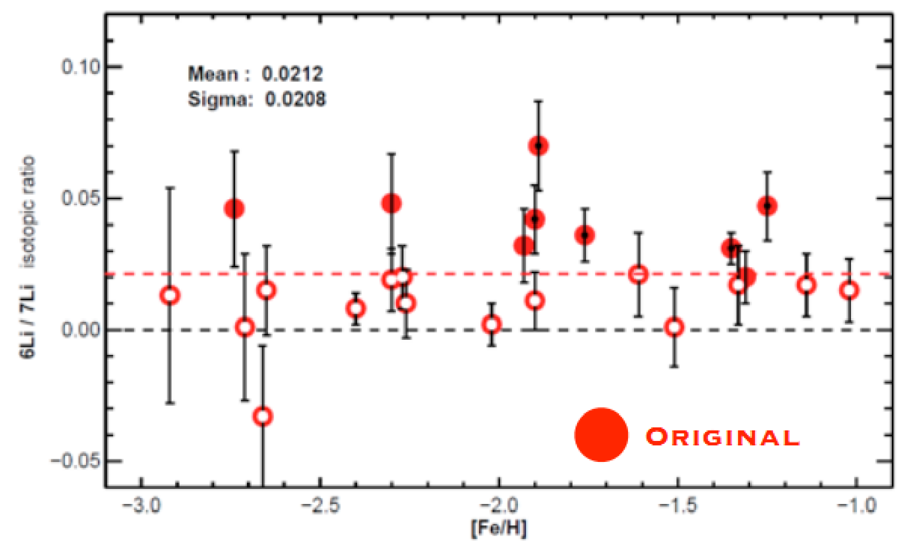
THE $^2H(\alpha,\gamma)^6Li$ REACTION

BIG BANG NUCLEOSYNTHESIS



- Search for metal poor stars*
- Obtain an high resolution absorption spectrum
- Fit the Lithium (^6Li+^7Li) absorption line in order to obtain the ^6Li (stellar atmospheric) abundance
- Use a detailed model of stellar atmospheres and calculate the ^6Li primordial abundance. → $^6Li/H \cong 10^{-11}$





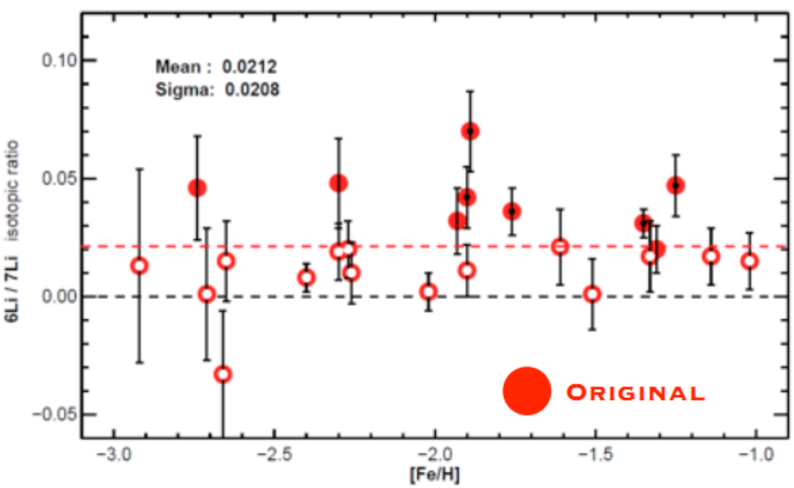
THE $^{2}H(\alpha,\gamma)^{6}Li$ REACTION

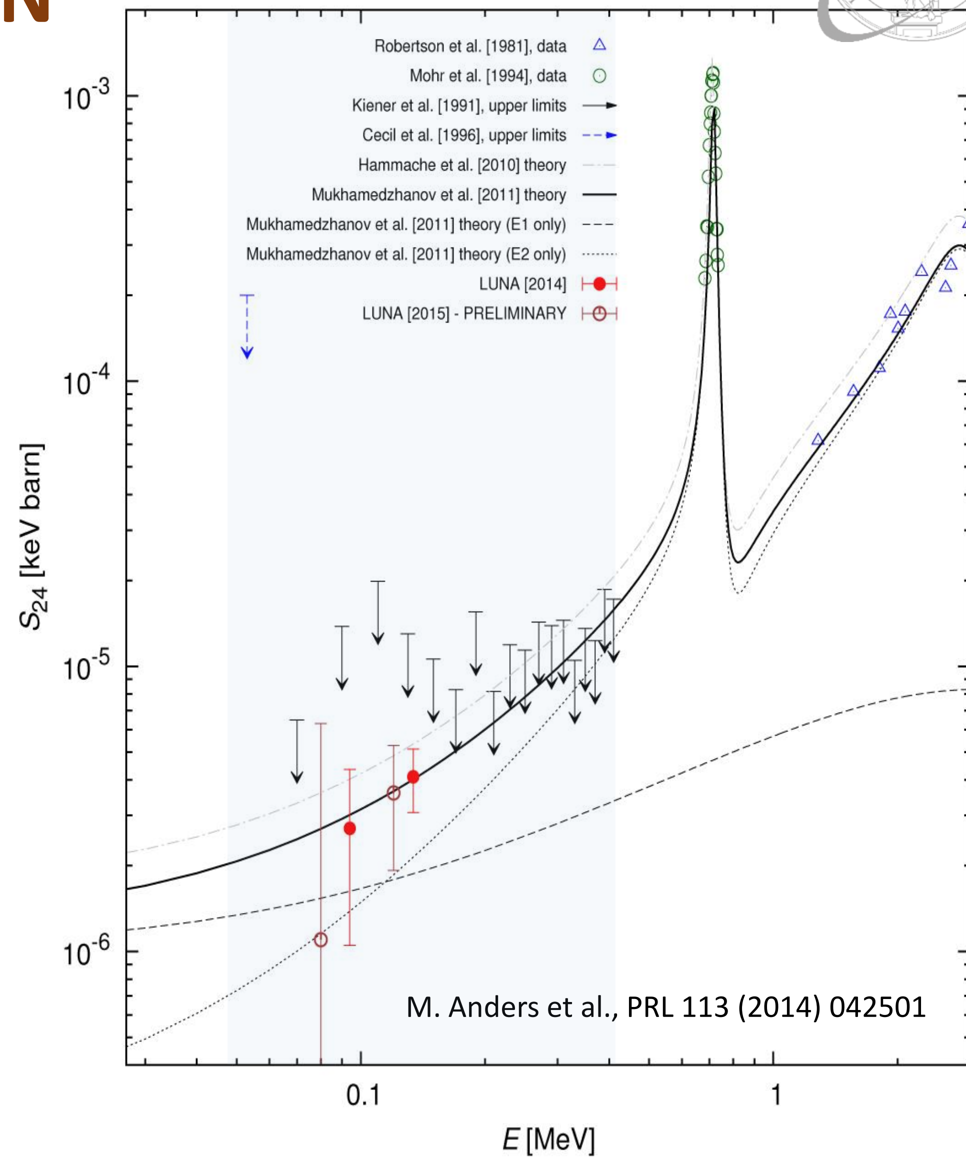
BIG BANG NUCLEOSYNTHESIS

The S-factor of the $^{2}H(\alpha,\gamma)^{6}Li$ nuclear reaction has been measured, providing the firs data points at BBN energies. Using the new $^{2}H(\alpha,\gamma)^{6}Li$ cross section a relative BBN lithium-6 abundance:

$$^{6}Li/H = (0.80 \pm 0.18) \times 10^{-14}$$

is obtained. Three order of magnitude less than the observed one.





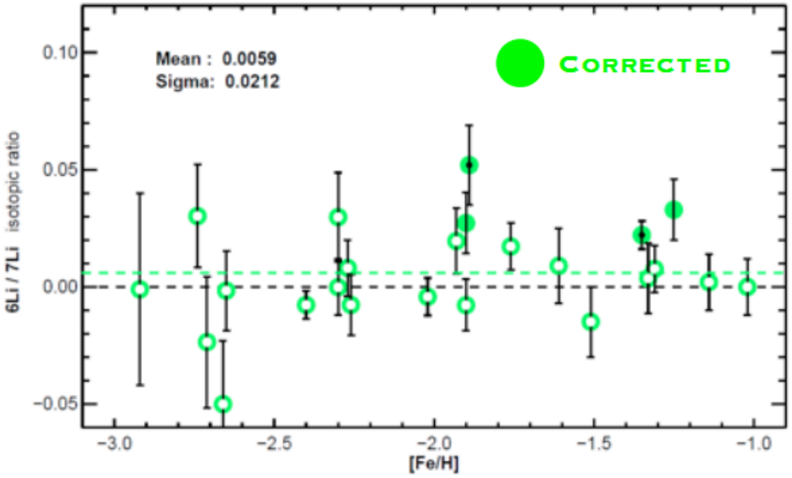
THE $^2H(\alpha,\gamma)^6Li$ REACTION

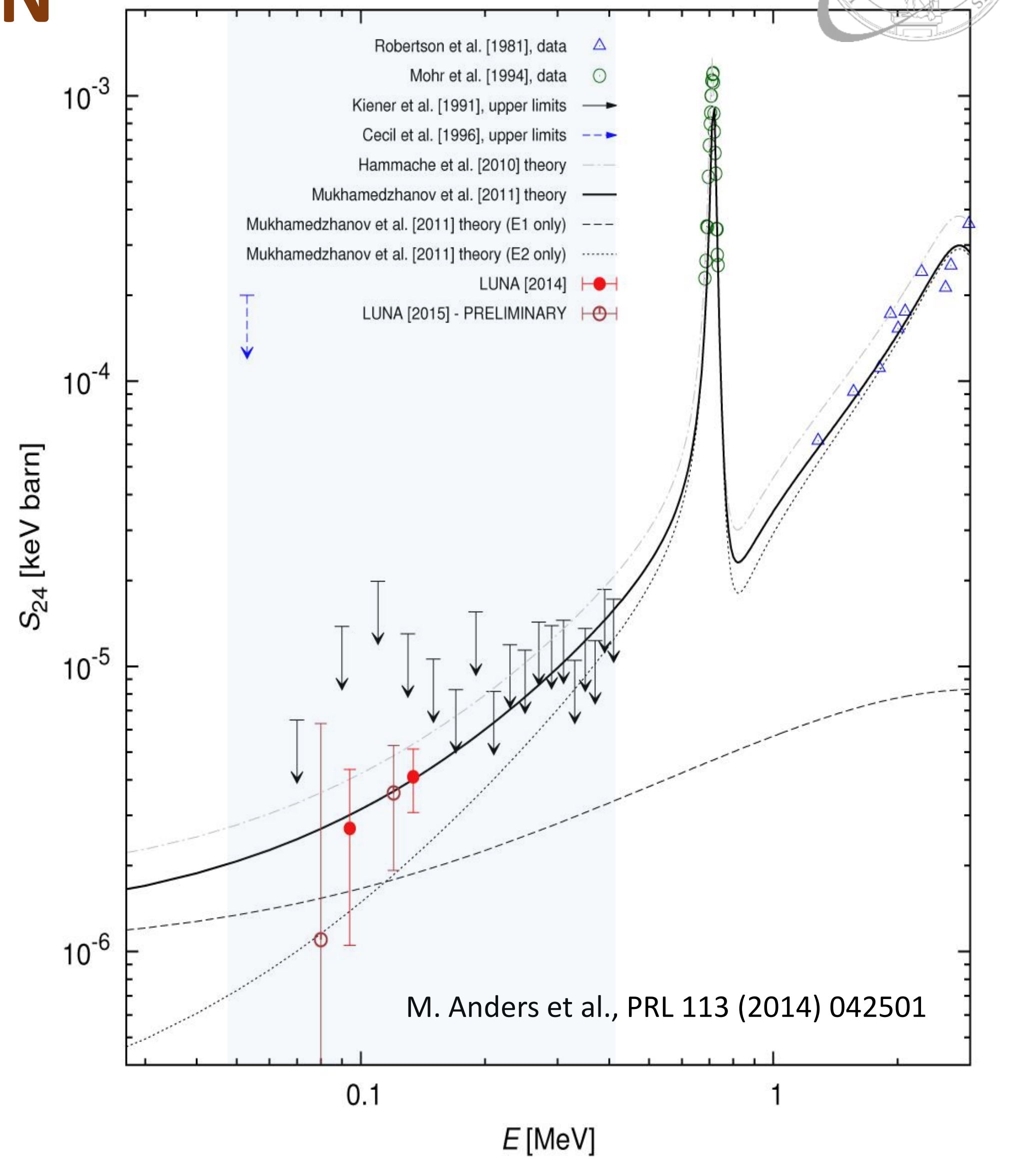
BIG BANG NUCLEOSYNTHESIS

The S-factor of the $^2H(\alpha,\gamma)^6Li$ nuclear reaction has been measured, providing the firs data points at BBN energies. Using the new $^2H(\alpha,\gamma)^6Li$ cross section a relative BBN lithium-6 abundance:

$$^6Li/H = (0.80 \pm 0.18) \times 10^{-14}$$

is obtained. Three order of magnitude less than the observed one.



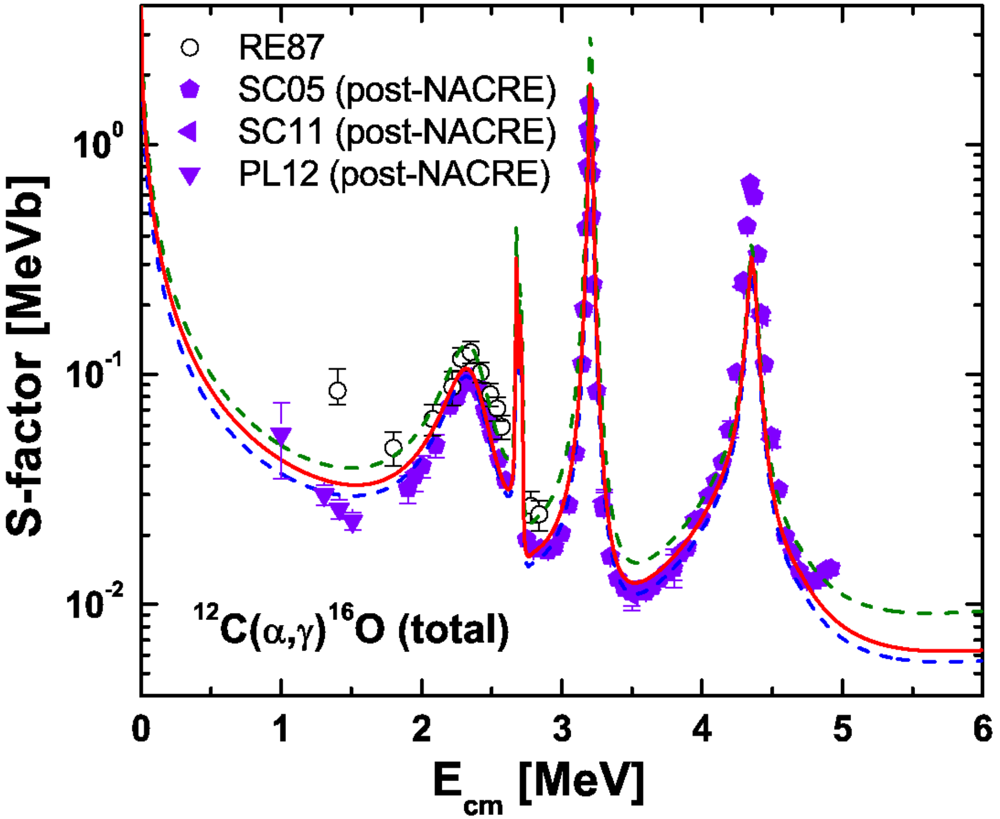


M. Anders et al., PRL 113 (2014) 042501

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

THE HOLY GRAAL OF NUCLEAR ASTROPHYSICS

Gamow peak helium burning 300 keV – 10^{-8} nb



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

- plays a fundamental role in the evolution of **any** star during the helium-burning phase.
- Determines the Carbon to Oxygen ratio abundance.
- Influences the nucleosynthesis of elements up to the iron peak for massive stars.
- Influences the cooling timescale of white dwarfs.
- Influences the proprieties of thermonuclear as well as core collapse supernovae.

> It is little wonder that the determination of the ratio $^{12}C/^{16}O$ produced in helium burning is a problem of paramount importance in Nuclear Astrophysics. This ratio depends in a fairly complicated manner on the density, tempera-

William A. Fowler, Nobel lecture 1983

… waiting for LUNA-MV

CONCLUSIONS: limits and future prospective

- **Nuclear Astrophysics is forever**: reactions never measured, unknown in given energy ranges, high precision required…
- LUNA-MV + LUNA 400 kV "usual" **can not** reach energies lower than 50 keV.
- In some reactions, **electron screening** correction must be applied.
- LUNA-MV can not produce **too much neutrons** (LNGS requirement).

NEW OPPORTUNITIES
for everybody

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

Laboratory for Underground Nuclear Astrophysics

LUNA MV

THE LUNA COLLABORATION

- A. Boeltzig, A. Formicola, M. Junker, I. Kochanek, C. Savarese | Laboratori Nazionali del Gran Sasso/GSSI, Italy
- D. Bemmerer, M. Takacs, T. Szucs | HZDR, Germany
- C. Broggini, A. Caciolli, R. Depalo, R. Menegazzo | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy
- Z. Elekes, Zs. Fülöp, Gy. Gyurky, E. Samorjai | INR MTA-ATOMKI Debrecen, Hungary
- O. Straniero | Collurania Astronomical Observatory Teramo, Italy
- F. Cavanna, P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | Università di Genova and INFN Genova, Italy
- A. Guglielmetti, **D. Trezzi** | Università di Milano and INFN Milano, Italy
- A. Best, G. Imbriani, A. Di Leva | Università di Napoli "Federico II" and INFN Napoli, Italy
- G. Gervino | Università di Torino and INFN Torino, Italy
- M. Aliotta, C. Bruno, T. Davinson | University of Edinburgh
- E. Fiore, V. Mossa, F. Pantaleo, V. Paticchio, R. Perrino, L. Schiavulli, A. Valentini | Università di Bari and INFN Bari, Italy


ANY
QUESTIONS?