LUNA-MV and LUNA
status and next steps

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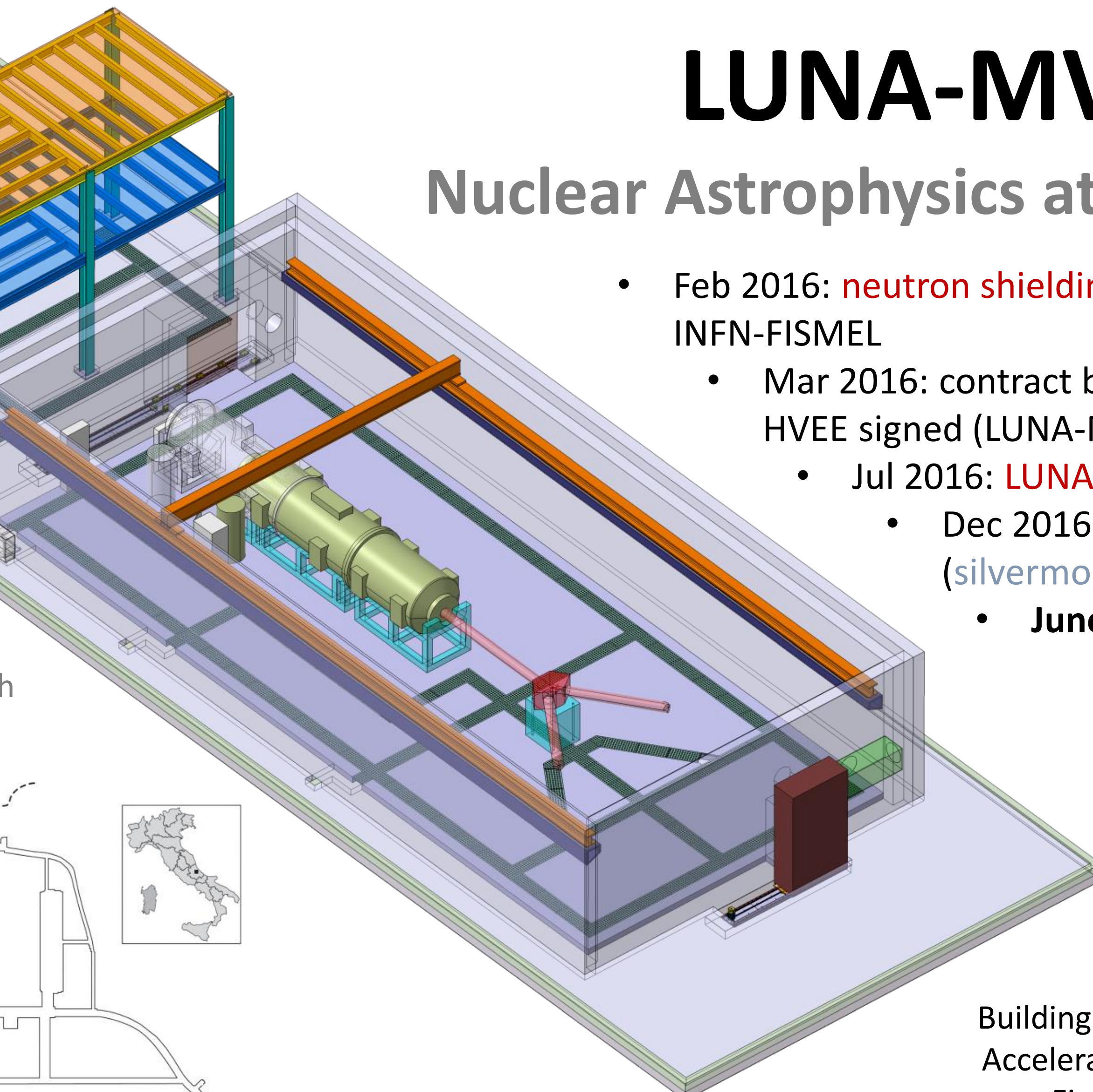
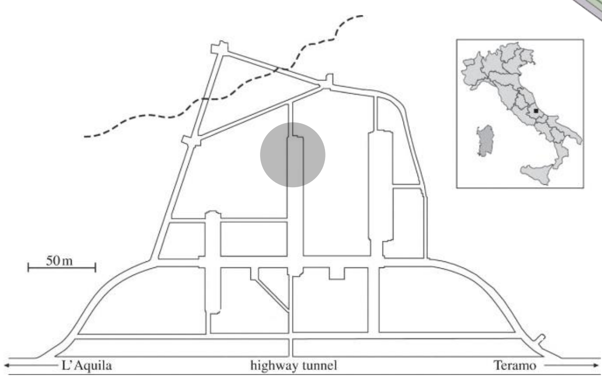
LUNA-MV

Nuclear Astrophysics at the LNGS



- Feb 2016: neutron shielding validated by INFN-FISMEL
- Mar 2016: contract between INFN and HVEE signed (LUNA-MV accelerator).
- Jul 2016: LUNA-MV proposal
- Dec 2016: Silver Moon (silvermoon.lngs.infn.it)
- **June 2018: NIC @ LNGS**

Installed in the north side of Hall B



Building construction: Sep 2017
Accelerator delivering: Jul 2018
First experiment: Jan 2019

The LUNA-MV accelerator

$^{1}H^{+}$ (TV: 0.3 – 0.5 MV): 500 μA
$^{1}H^{+}$ (TV: 0.5 – 3.5 MV): 1000 μA

$^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 μA
$^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 μA

$^{12}C^{+}$ (TV: 0.3 – 0.5 MV): 100 μA
$^{12}C^{+}$ (TV: 0.5 – 3.5 MV): 150 μA
$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

inline Cockcroft Walton accelerator

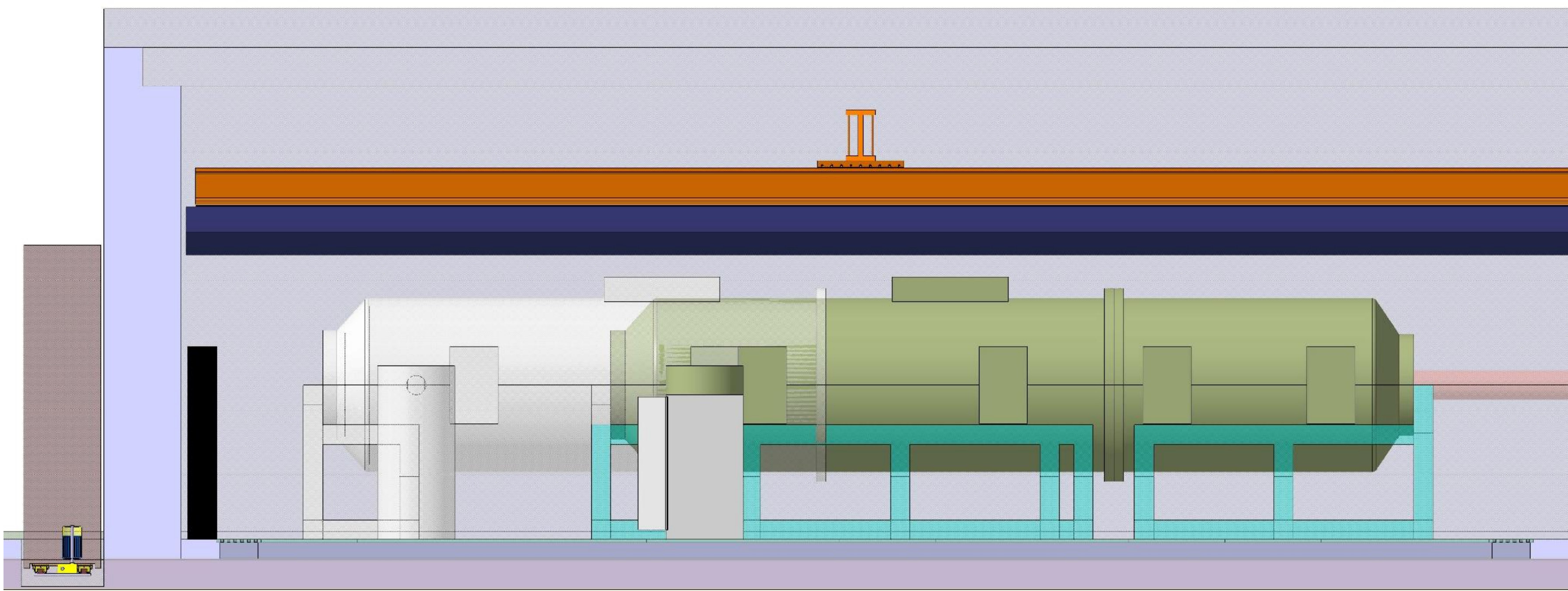
TERMINAL VOLTAGE: 0.2 – 3.5 MV

Precision of terminal voltage reading: 350 V

Beam energy reproducibility: 0.01% TV

Beam energy stability: 0.001% TV / hrs

Beam current stability: < 5% / hrs



The LUNA-MV scientific program

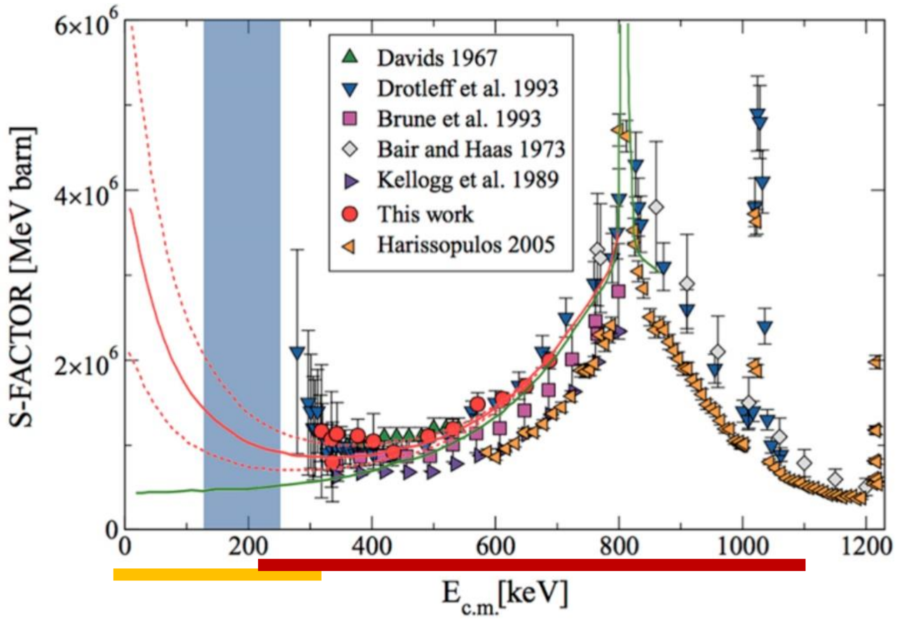

LUNA MV

LUNA MV Proposal
2018 - 2022

- **$^{13}C(\alpha,n)^{16}O$**: AGB STARS AND SUPERNOVAE EXPLOSION investigate the energy range of interest were no data / a few data are presents.
- **$^{14}N(p,\gamma)^{15}O$:** SUN provide valuable data to reduce the error in the low energy extrapolation of the cross section.
- **$^{12}C+^{12}C$**: MASSIVE STARS AND UNIVERSE investigate the energy range of interest and solve disagreement in existing data.
- **$^{22}Ne(\alpha,n)^{25}Mg$**: AGB STARS AND SUPERNOVAE EXPLOSION investigate the 0.47 – 1.20 MeV energy range
- **$^{12}C(\alpha,\gamma)^{16}O$** : MASSIVE STARS the holy grail of Nuclear Astrophysics. Investigate the low energy range where no data / a few data are presents.
  (not before 2023)

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

heavy elements nucleosynthesis



M. Heil et al., PRC 78 (2008) 025803

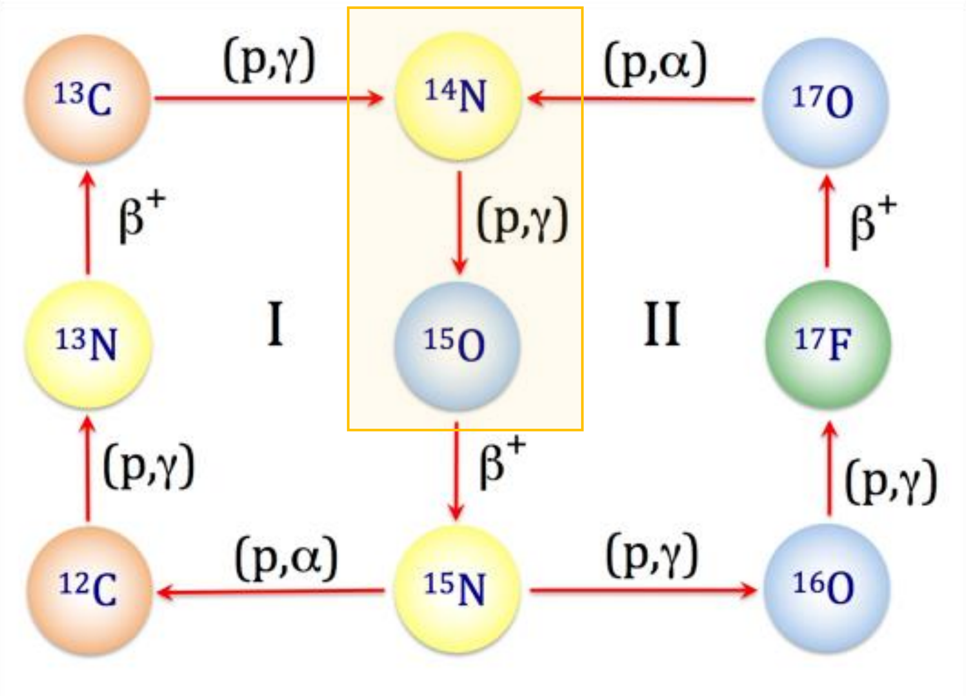
Measured at LUNA 400 kV
in November 2017 (early?)

The $^{13}C(\alpha,n)^{16}O$ reaction takes place in thermally pulsing, low-mass, asymptotic giant branch (ABG) stars.
This reaction is the "neutron source" for the s-process and the nucleosynthesis of heavy elements.

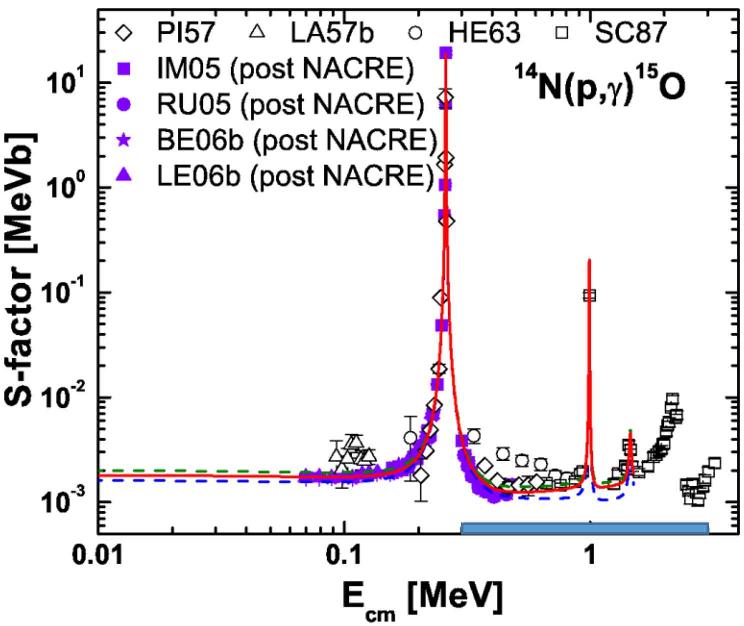
NO DATA AVAILABLE BELOW 300 keV
EXTRAPOLATION ERROR (factor 4)

Analyzed in direct ($E_{\alpha} = 0.3 - 1.4\ MeV$) and inverse kinematics at LUNA-MV ($E_{13C} = 0.9 - 4.5\ MeV$)

The $^{14}N(p,\gamma)^{15}O$ reaction



Control the CNO cycle during the hydrogen burning → CNO neutrino flux.



A good reaction to be used for testing the new LUNA-MV machine
DAY ZERO EXPERIMENT

The $^{12}C+^{12}C$ reaction

Carbon burning

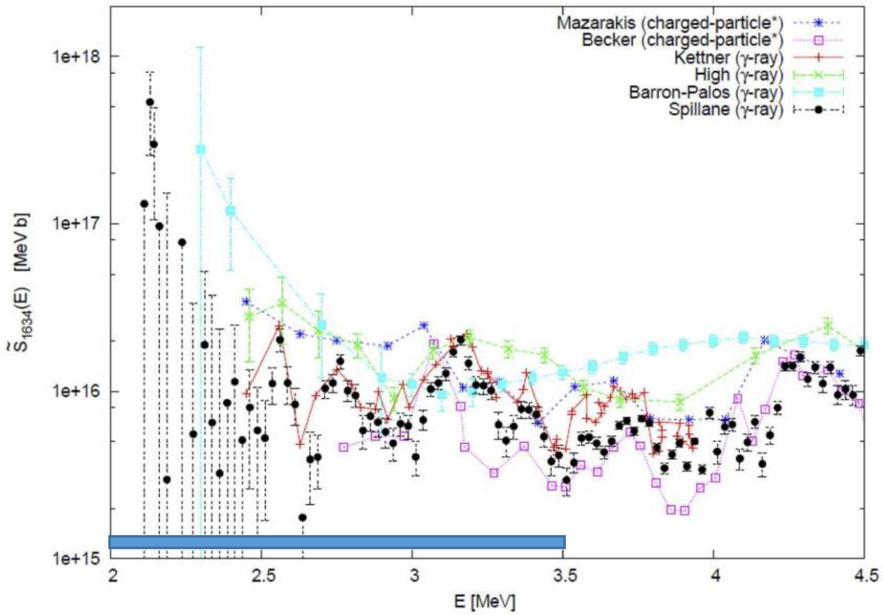


Figure 6: Modified astrophysical S factor relative to the 1634 keV transition (i.e., the de-excitation of the first excited state of ^{20}Ne populated by the $^{12}C(^{12}C,\alpha)^{20}Ne$ reaction).

The fusion reaction $^{12}C+^{12}C$ is critically important in nuclear astrophysics: it regulates the energy production and nucleosynthesis of the carbon burning phase and ultimately influences the global chemical evolution of the Universe.

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{16}_{8}O + 2\,^{4}_{2}He$$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{20}_{10}Ne + ^{4}_{2}He$$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{23}_{11}Na + ^{1}_{1}H$$

$$^{12}_{6}C + ^{12}_{6}C \rightarrow ^{24}_{12}Mg + \gamma$$

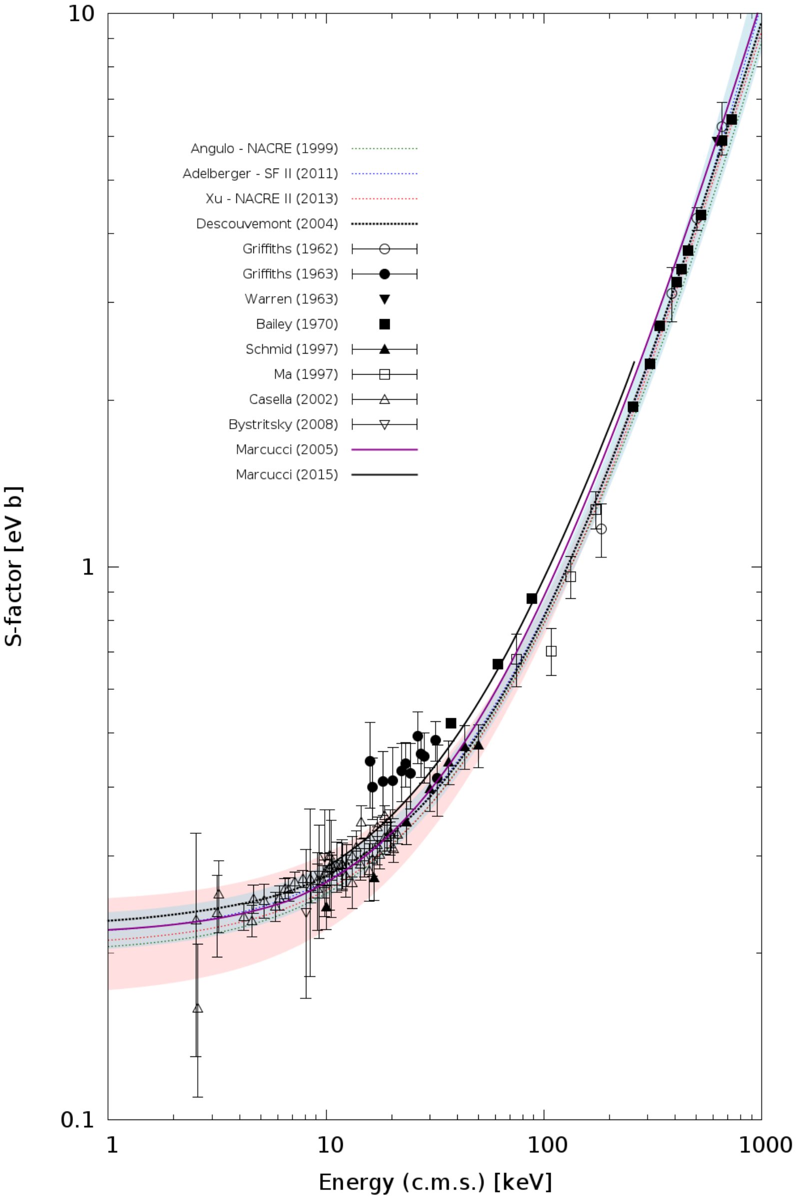
$^{12}C^{++}$ beam must be used in order to reach the MeV energy range

LUNA 400 kV activities

past, present and future

REACTION	TARGET	DETECTOR	DATA TAKING	DATA ANALYSIS	PI
$^{18}O(p,\gamma)^{19}F$	Solid	BGO	Completed	In progress	A. Best
$^{22}Ne(p,\gamma)^{23}Na$	Gas	BGO	Completed	In progress	D. Bemmerer A. Caciolli
$^{18}O(p,\gamma)^{19}F$	Solid	HPGe	Completed	In progress	A. Best
$^{22}Ne(\alpha,\gamma)^{26}Mg$	Gas	BGO	Completed	In progress	D. Bemmerer A. Caciolli
$^{2}H(p,\gamma)^{3}He$	Gas	BGO	Completed	In progress	D. Trezzi
$^{2}H(p,\gamma)^{3}He$	Gas	HPGe	In progress	No	D. Trezzi
$^{6}Li(p,\gamma)^{7}Be$	Solid	HPGe	December 2016	No	R. Depalo

Details presents on the new LUNA website
presented during the Silver Moon event



$^{2}H(p,\gamma)^{3}He$ reaction at LUNA

Big Bang Nucleosynthesis

Total amount of deuterium produced in the early Universe depends on the **cosmological parameters** and on the **nuclear cross sections** of the reactions involved (main source of uncertainty $^{2}H(p,\gamma)^{3}He$).

BBN predictions (PLANCK+SFII)

$^{2}H/H = (2.65 \pm 0.07) \times 10^{-5}$

ASTRONOMICAL observations

$^{2}H/H = (2.53 \pm 0.04) \times 10^{-5}$

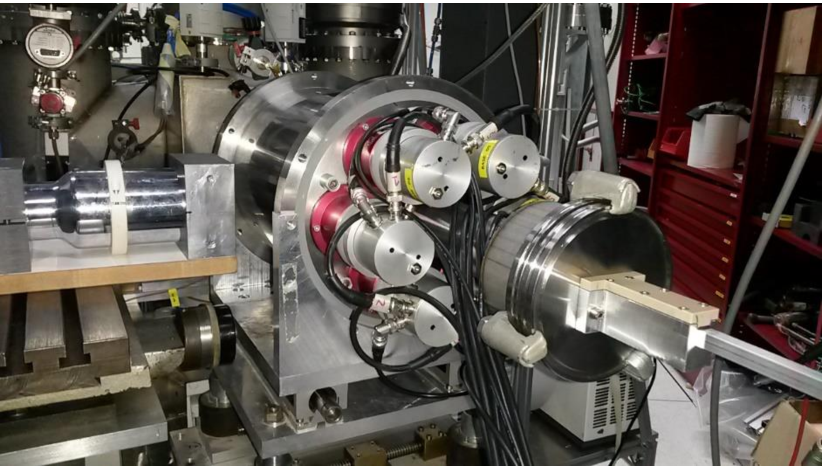
THEORETICAL calculations (MARCUCCI et al.)

$^{2}H/H = (2.49 \pm 0.04) \times 10^{-5}$

L. E. Marcucci et al., PRL 116 (2016) 102501

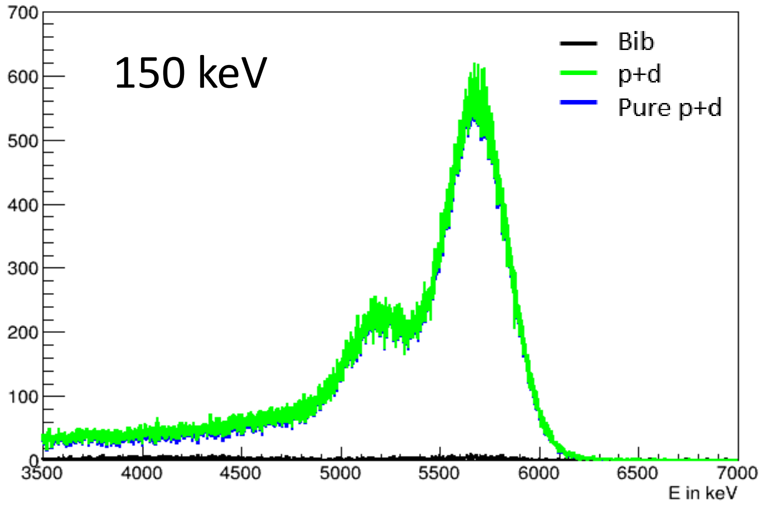
$^{2}H(p,\gamma)^{3}He$ reaction at LUNA

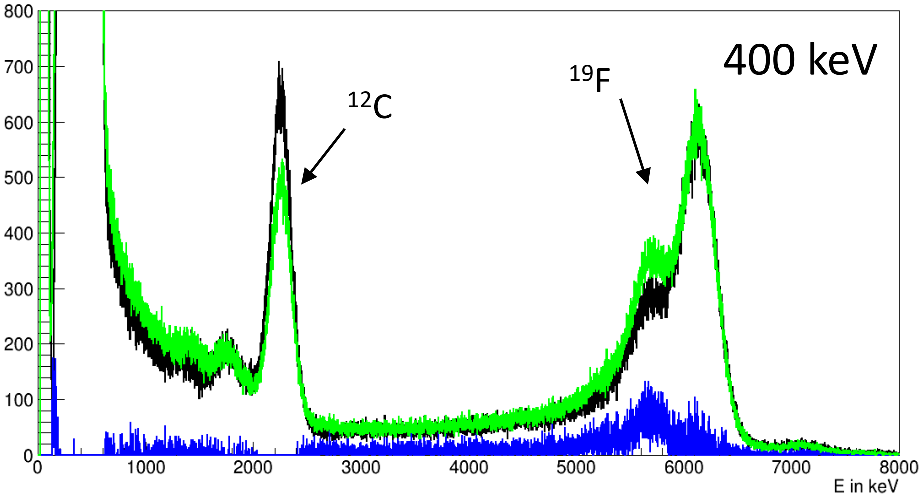
PHASE I – BGO Detector

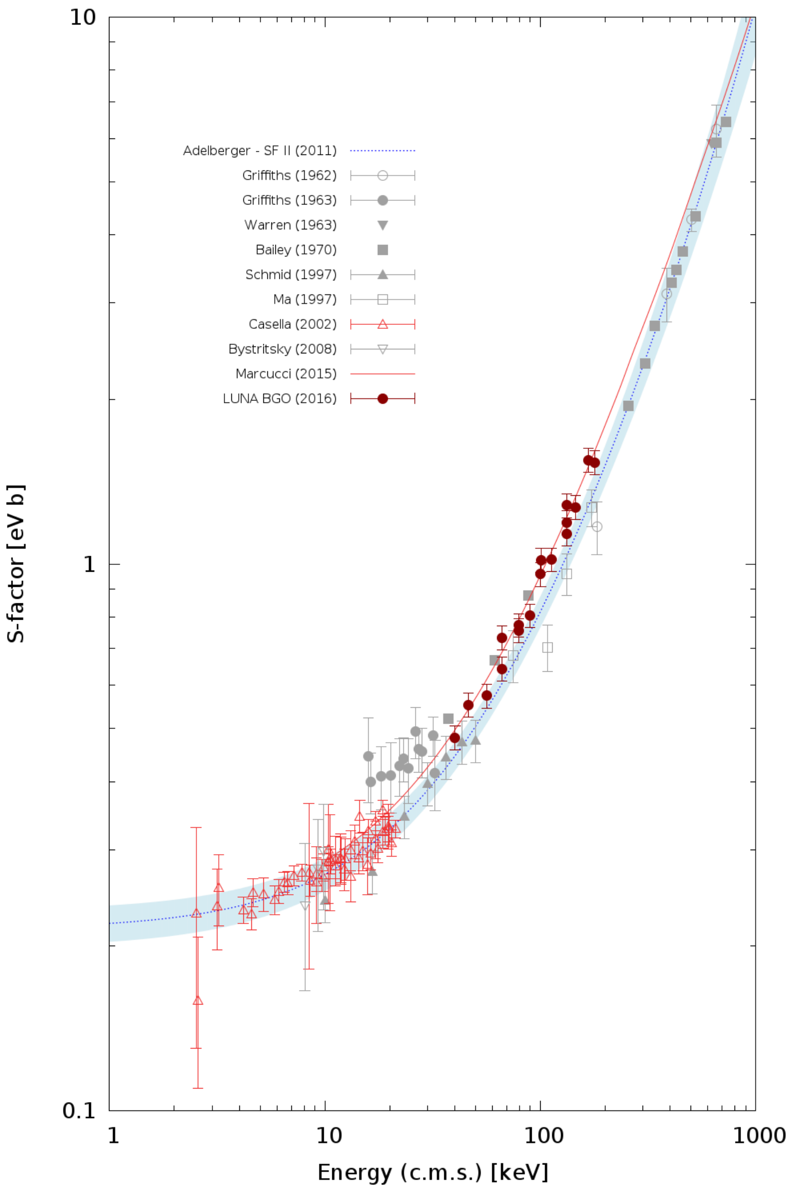


BGO Detector

- Weakly dependence from angular distribution
- High detector efficiency (Montecarlo tuned with ^{60}Co, ^{88}Y, ^{137}Cs and 269 keV $^{14}N(p,\gamma)^{15}O$ resonance)
- High statistics
- Accurate calorimeter calibration
- Accurate density profile
- Beam heating effect estimation
- Expected systematic uncertainty ≤ 3.0 – 3.8%







$^{2}H(p,\gamma)^{3}He$ reaction at LUNA

preliminary data analysis

BGO + NaI Detector

- Weakly dependence from angular distribution (not known → HPGe phase)
- High detector efficiency (Montecarlo tuned with ^{60}Co, ^{88}Y, ^{137}Cs and 269 keV $^{14}N(p,\gamma)^{15}O$ resonance). New measurement accomplished but not analysed.
- High statistics
- Accurate calorimeter calibration
- Accurate density profile (preliminary analysis used approximated values)
- Beam heating effect estimation (not analysed)
- Expected systematic uncertainty ≤ 3.0 – 3.8% (5% in the plot)

CROSS SECTION HIGHER THAN LITERATURE
preliminary agreement with Marcucci et al.

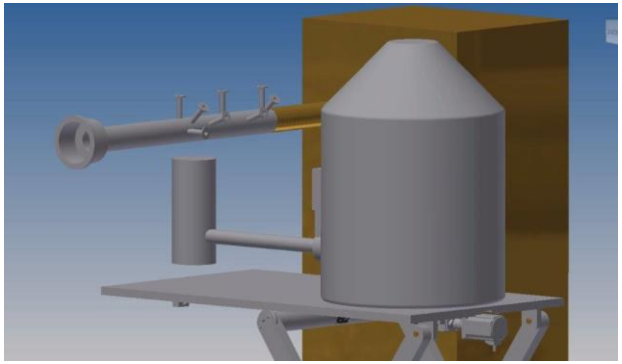
$^{2}H(p,\gamma)^{3}He$ reaction at LUNA

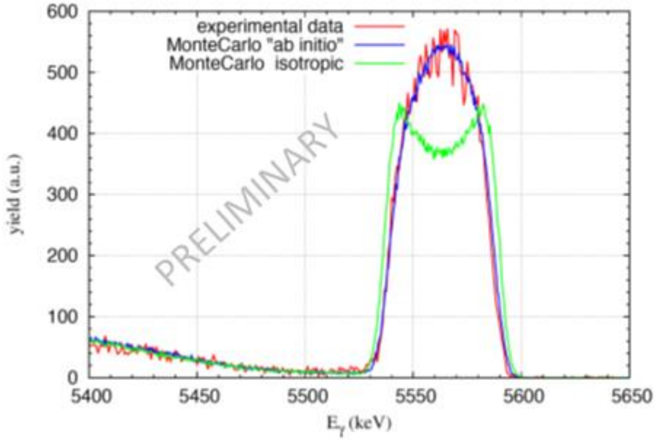
PHASE II – HPGe Detector

HPGe + NaI Detector

- Possibility to measure the angular distribution using the peak shape analysis (Energy → θ angle)
- Accurate detector efficiency determination with different experimental methods
- High energy range (> 100/150 keV)
- Accurate calorimeter calibration
- Accurate density profile, controlled also online
- Expected systematic uncertainty ≤ 4.3%

IN PROGRESS AT LUNA





Improved Direct Measurement of the 64.5 keV Resonance Strength in the $^{17}O(p,\alpha)^{14}N$ Reaction at LUNA

C. G. Bruno et al. (LUNA Collaboration)

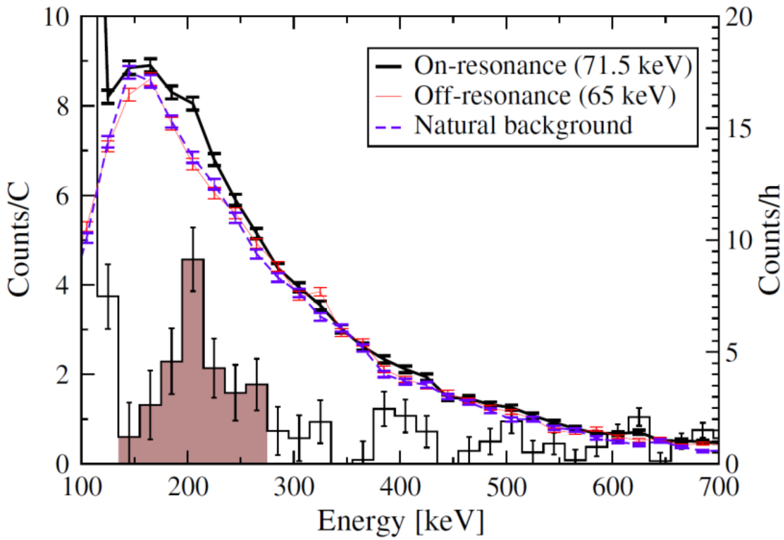


FIG. 3. Overlay of time-normalized on-resonance ($E_p = 71.5$ keV), off-resonance ($E_p = 65$ keV), and natural background spectra in counts/h (lines are to guides to the eye). Also shown is the histogram (in counts/C) obtained after a bin-by-bin subtraction of the time-normalized natural background spectrum from the on-resonance one. The shaded peak corresponds to the region of interest of the alpha particles from the 64.5 keV resonance. Note the different y axes.

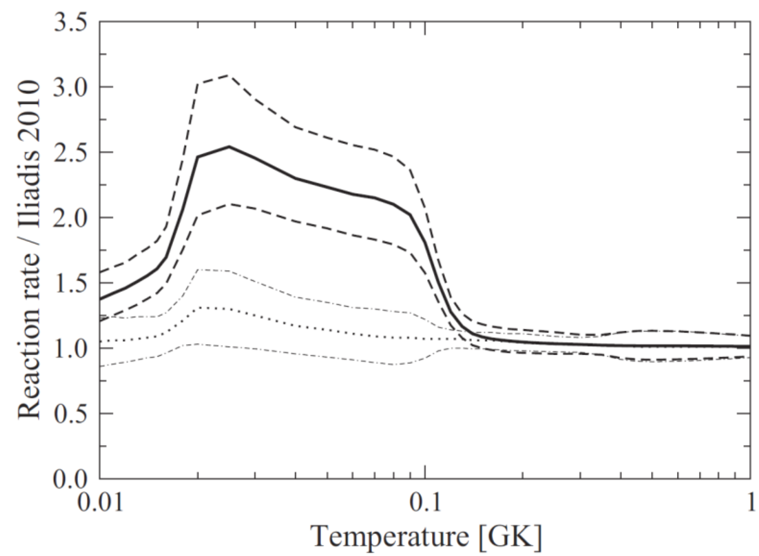


FIG. 4. Ratio of the $^{17}O(p,\alpha)^{14}N$ reaction rate of the present work (solid line) and of Buckner *et al.* [21] (dotted line) to the $^{17}O(p,\alpha)^{14}N$ reaction rate of Iliadis [22]. Dashed and dash-dotted lines correspond to the upper and lower limits as given here and by Buckner *et al.*, respectively.

$$\omega\gamma_{LUNA} = 8.7 \pm 1.2^{stat} \pm 0.6^{syst}\ neV$$

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