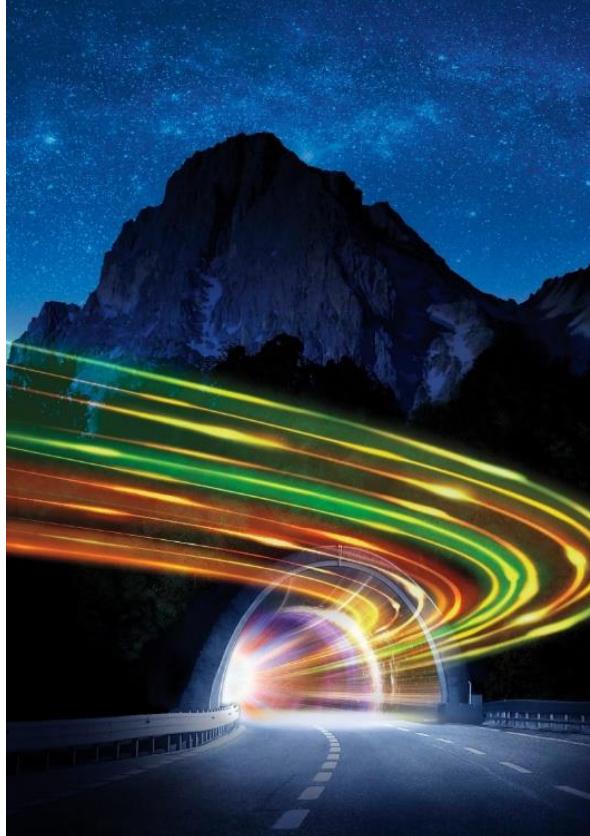


# Nuclear Astrophysics at the Low-Energy Frontiers: updates from underground laboratories

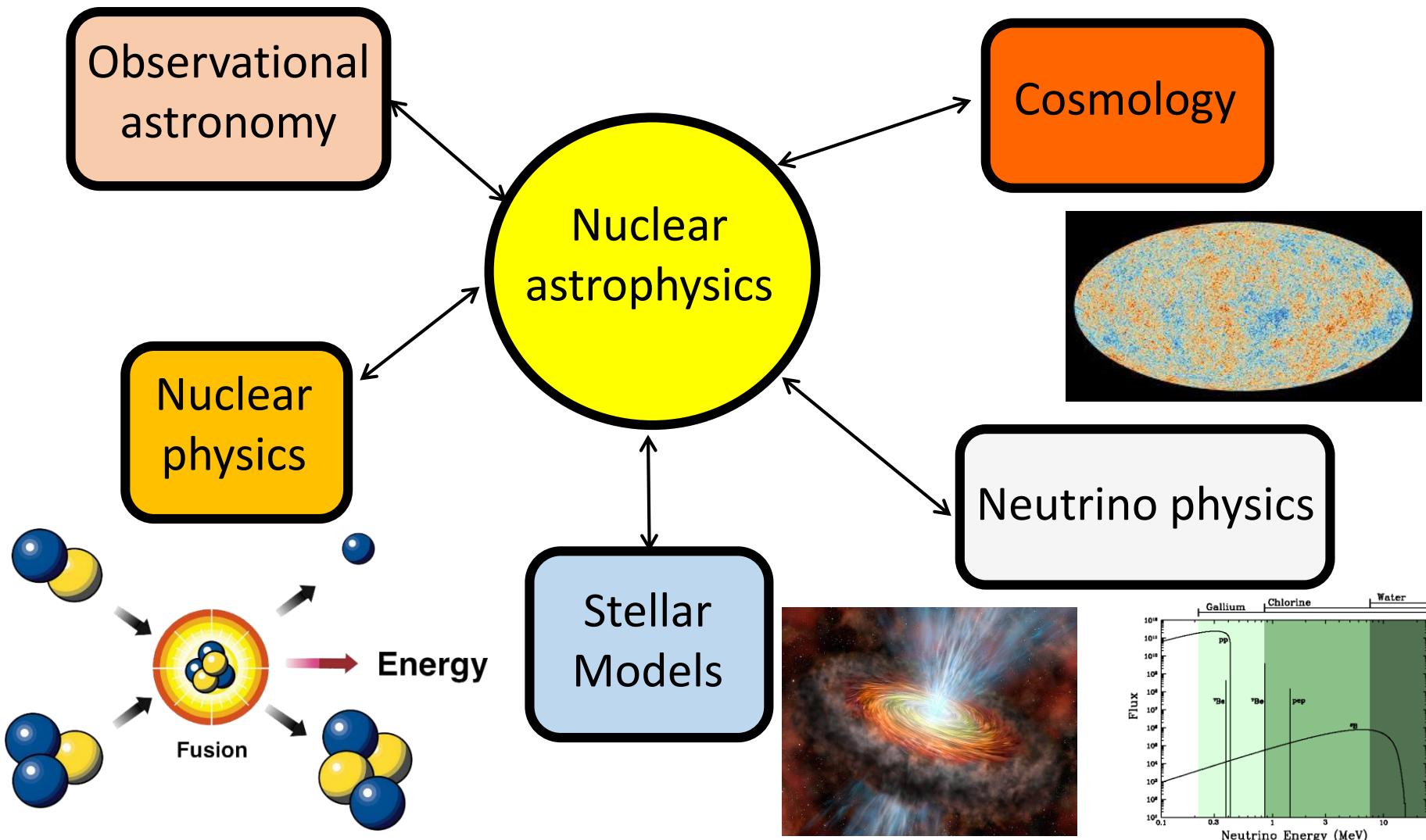


Francesca Cavanna  
for the LUNA collaboration

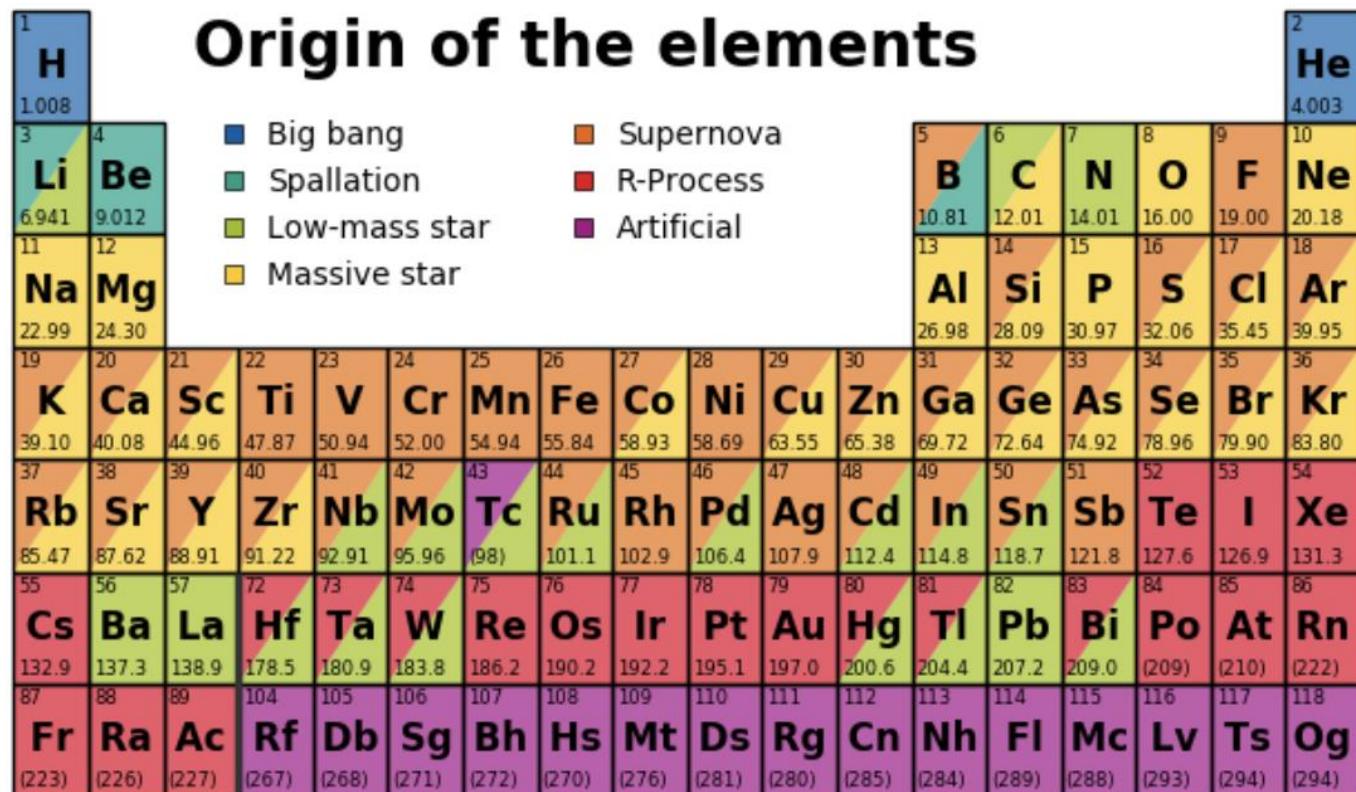
European Nuclear Physics Conference 2022



# NUCLEAR ASTROPHYSICS: AN INTERDISCIPLINARY FIELD

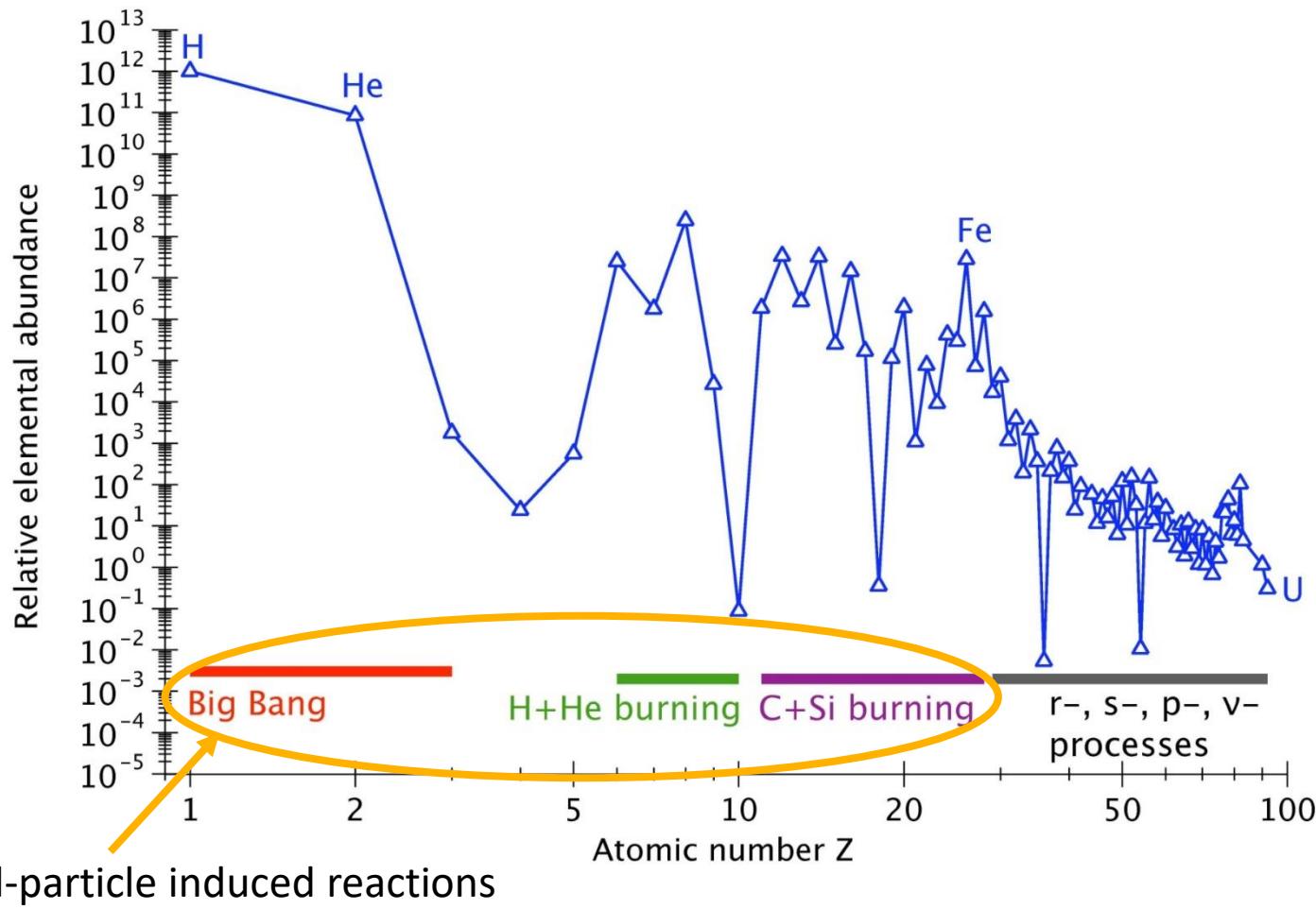


# THE ORIGIN OF THE CHEMICAL ELEMENTS



58 <b>Ce</b> 140.1	59 <b>Pr</b> 140.9	60 <b>Nd</b> 144.2	61 <b>Pm</b> (145)	62 <b>Sm</b> 150.4	63 <b>Eu</b> 152.0	64 <b>Gd</b> 157.2	65 <b>Tb</b> 158.9	66 <b>Dy</b> 162.5	67 <b>Ho</b> 164.9	68 <b>Er</b> 167.3	69 <b>Tm</b> 168.9	70 <b>Yb</b> 173.1	71 <b>Lu</b> 175.0
90 <b>Th</b> 232.0	91 <b>Pa</b> 231.0	92 <b>U</b> 238.0	93 <b>Np</b> (237)	94 <b>Pu</b> (244)	95 <b>Am</b> (243)	96 <b>Cm</b> (247)	97 <b>Bk</b> (247)	98 <b>Cf</b> (251)	99 <b>Es</b> (252)	100 <b>Fm</b> (257)	101 <b>Md</b> (258)	102 <b>No</b> (259)	103 <b>Lr</b> (262)

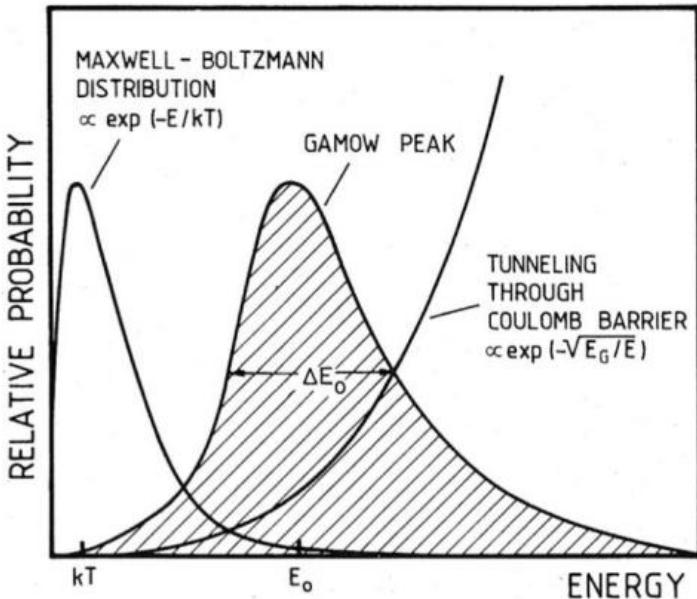
# THE ORIGIN OF THE CHEMICAL ELEMENTS



# Challenges of nuclear astrophysics experiments

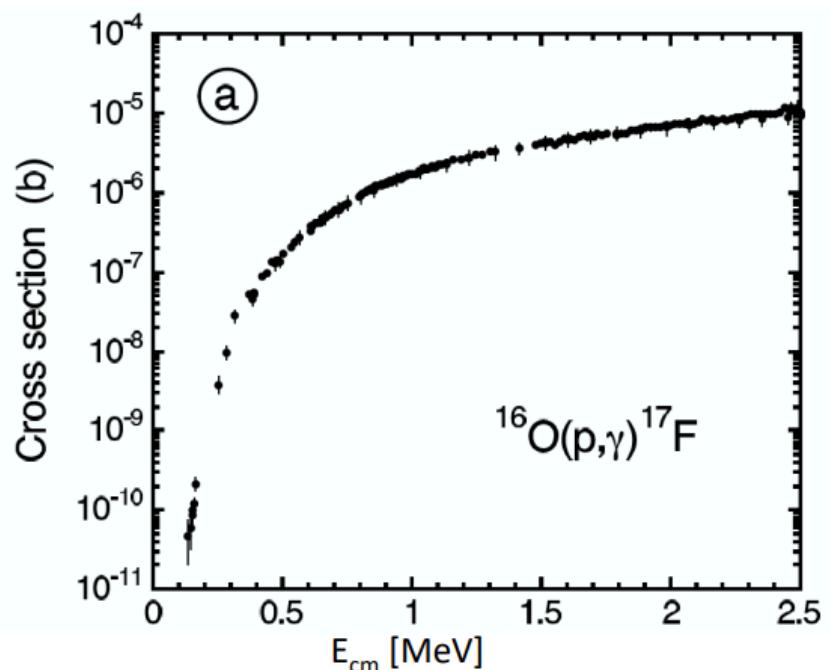
## CHARGED-PARTICLES-INDUCED REACTION RATES

Rolfs, Rodney, Cauldrons in the Cosmos (1988)



- In the Gamow peak, the cross section can be extremely small

- Nuclear reactions occur at energies far below the Coulomb barrier (quantum-mechanical tunnel)
- Cross sections are strongly energy-dependent



Iliadis, Nuclear physics of stars (2007)

## EXPERIMENTAL CHALLENGES OF DIRECT MEASUREMENTS

Counting Rate =  $N_p \times N_t \times$  cross section  $\times$  detection efficiency

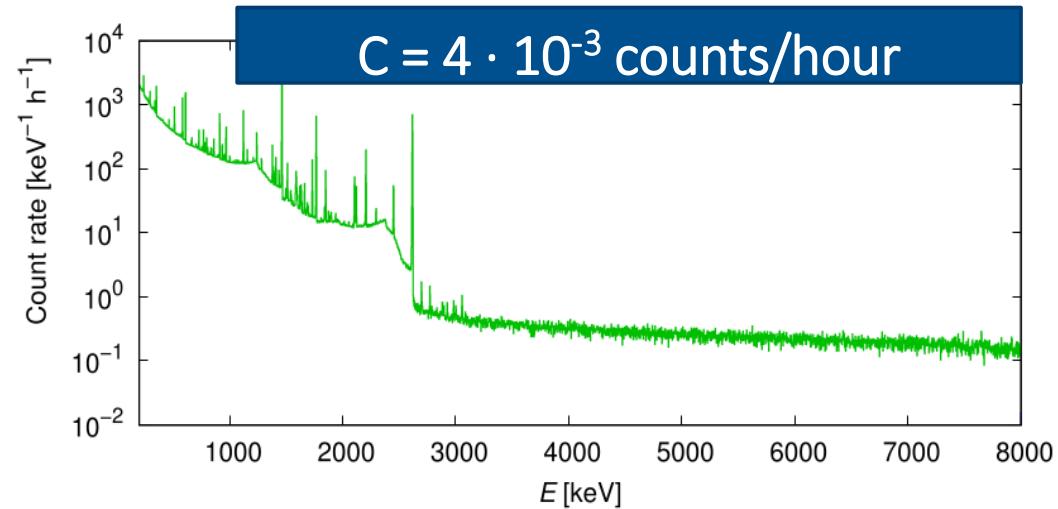
↓  
 $10^{14}$  pps ( $\sim 100 \mu\text{A}$  q=1+) typical stable beam intensities

↓  
 $10^{18}$  atoms/cm<sup>2</sup> typical solid state targets

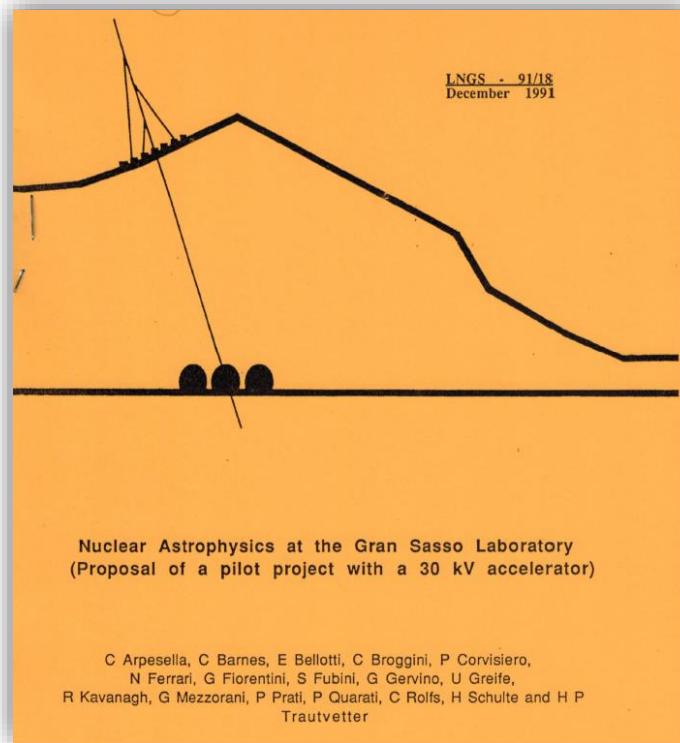
↓  
 $10^{-36}$  cm<sup>2</sup> (often even smaller)

$$C = 4 \cdot 10^{-3} \text{ counts/hour}$$

↓  
 $\sim 1\text{-}5\%$  for gamma rays (HPGe detectors)



# How to improve the signal-to-noise ratio?



# LABORATORY FOR UNDERGROUND NUCLEAR ASTROPHYSICS



Radiation

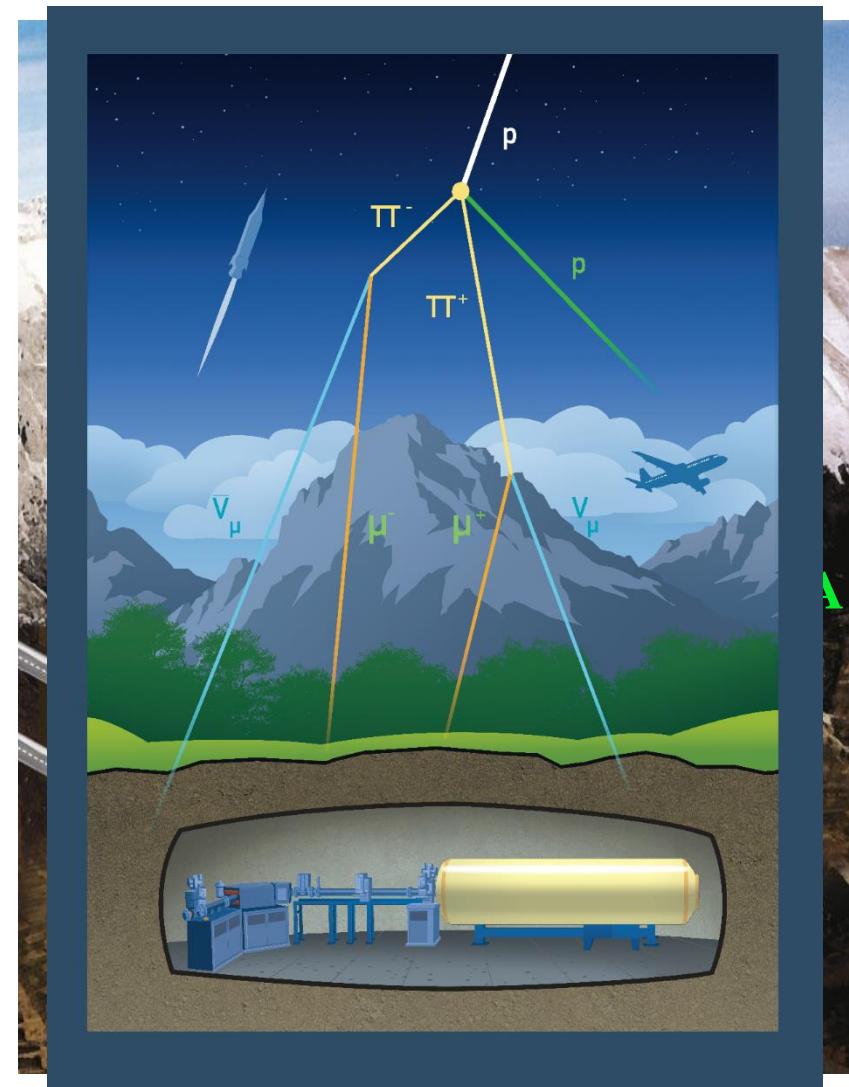
LNGS/surface

Muons

$10^{-6}$

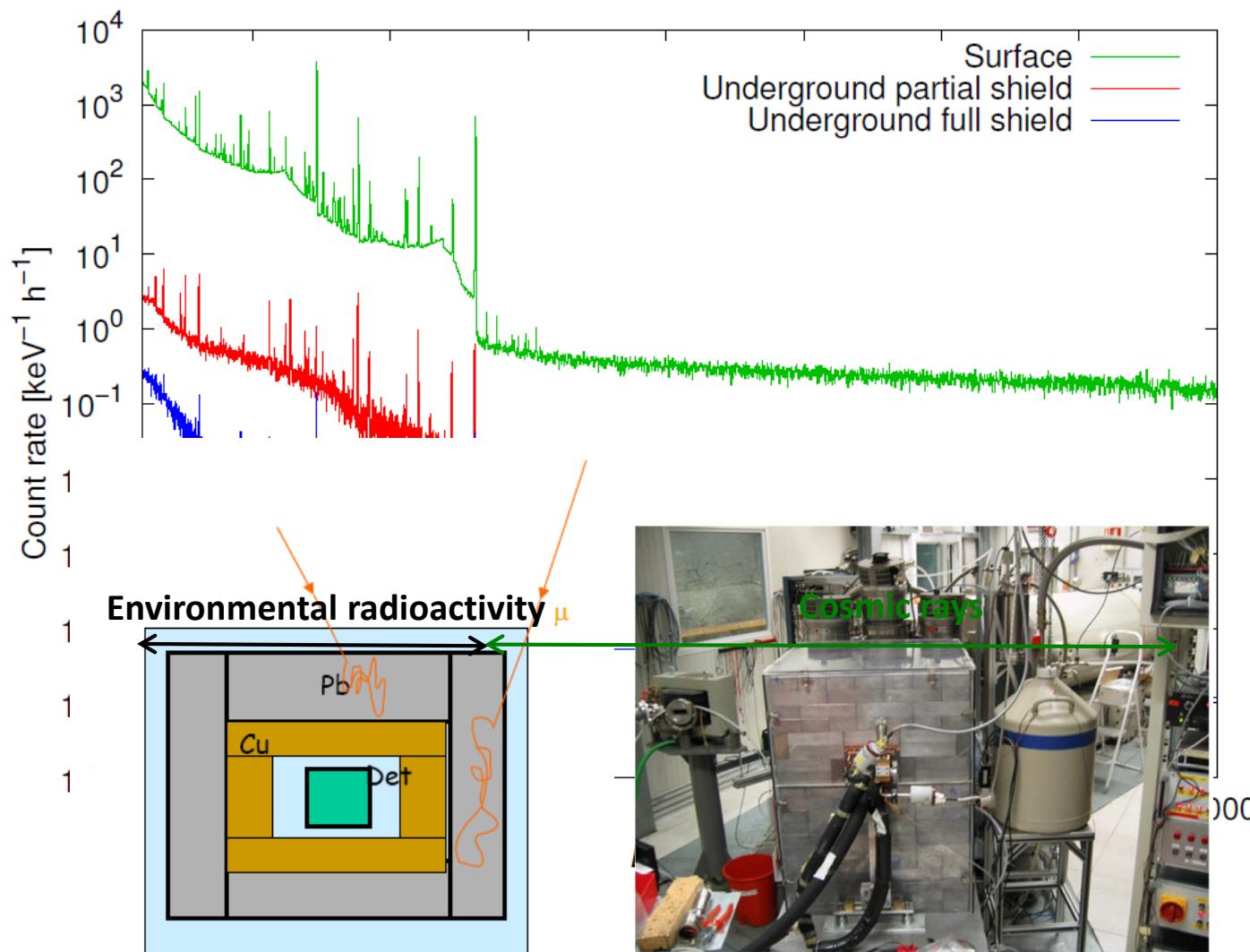
Neutrons

$10^{-3}$



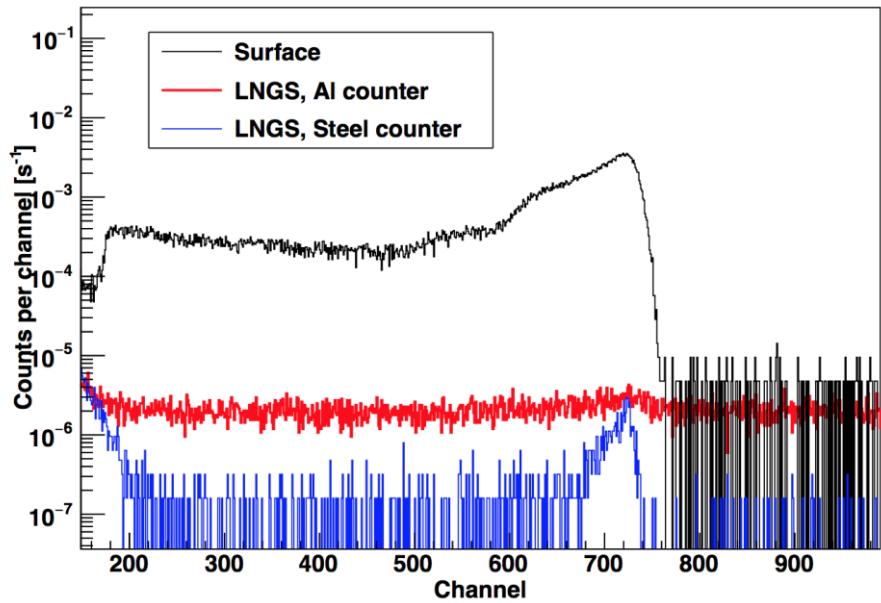
LNGS (1400 m rock shielding  $\equiv$  4000 m w.e.)

# GAMMA BACKGROUND REDUCTION AT LNGS

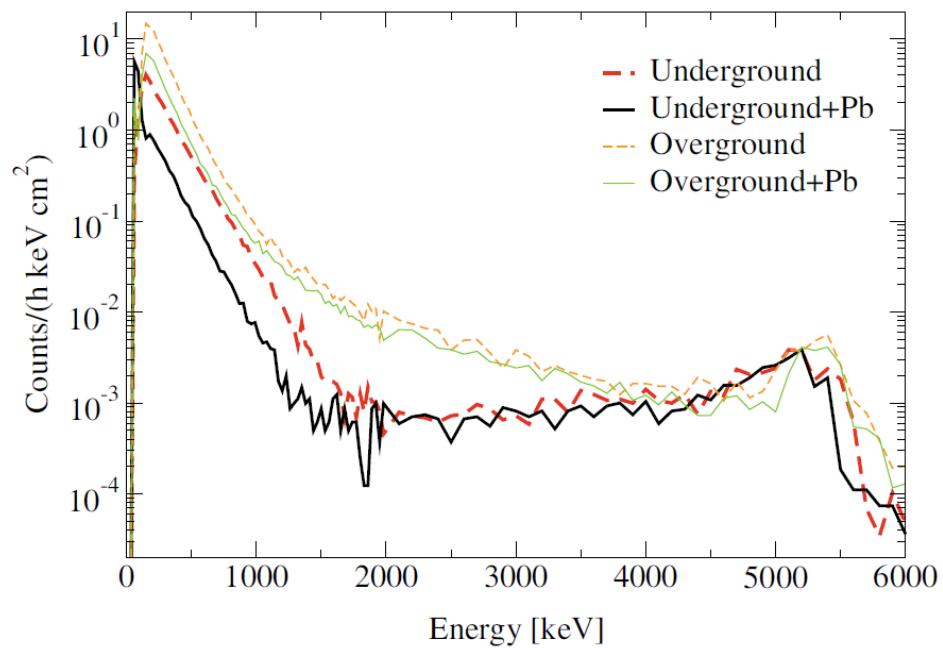


# PARTICLE BACKGROUND REDUCTION AT LNGS

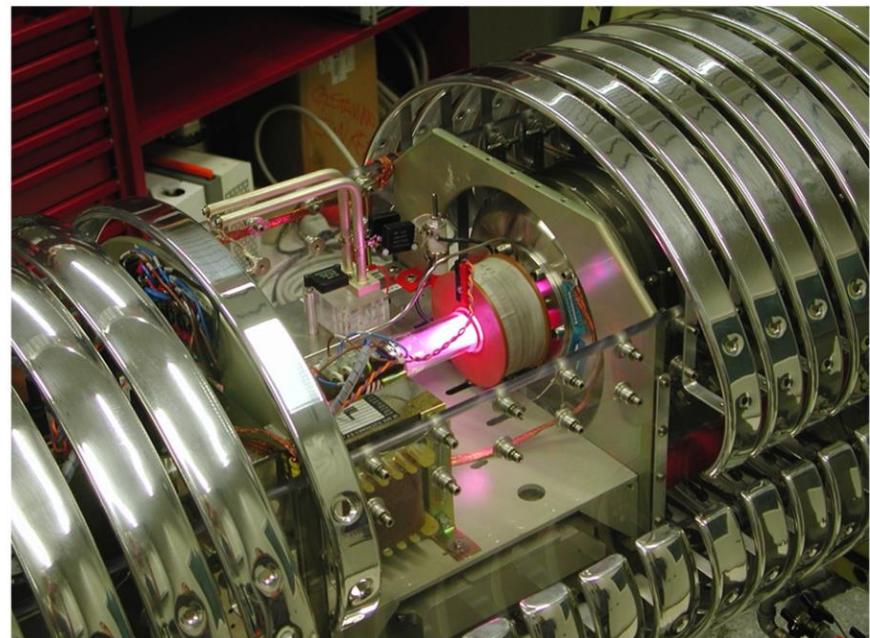
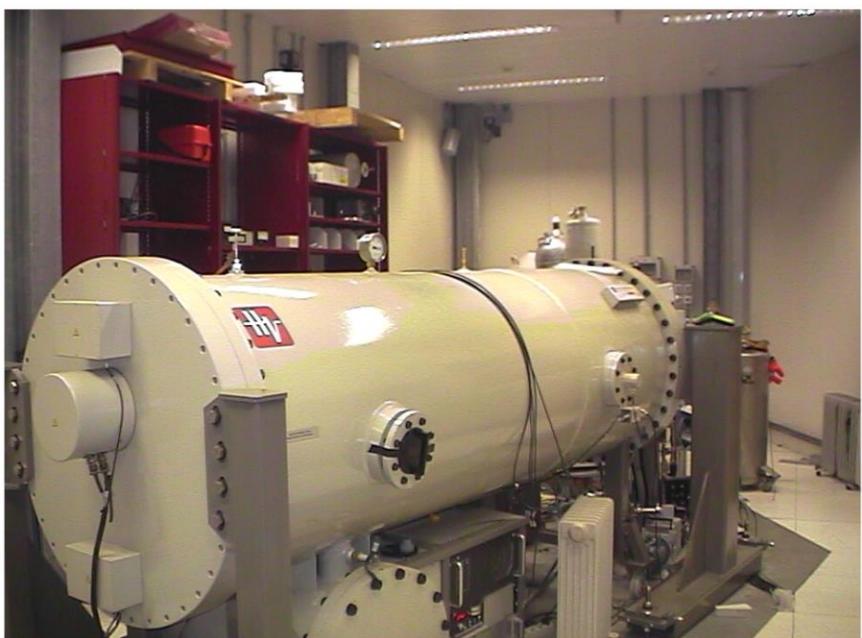
## NEUTRON DETECTION



## PARTICLE DETECTION

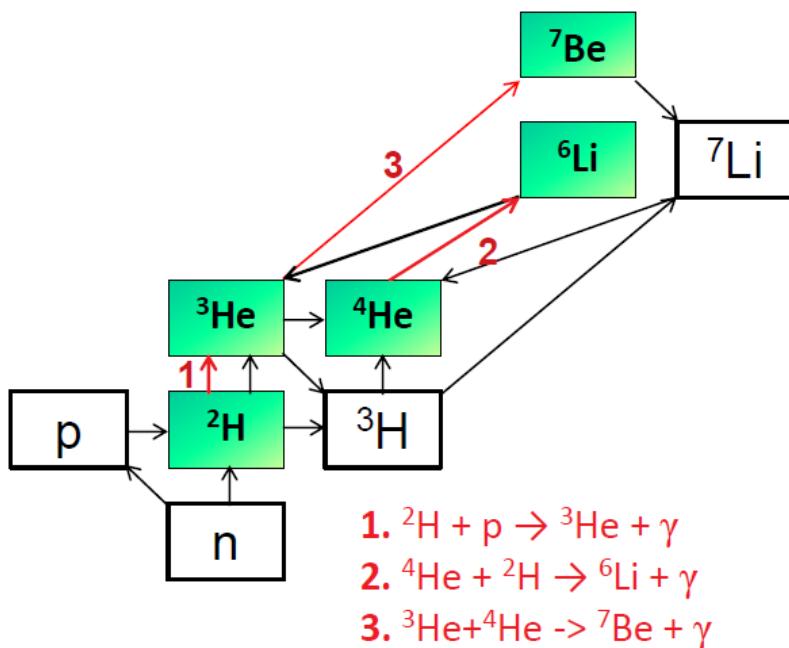


## LUNA EXPERIMENTAL SETUP

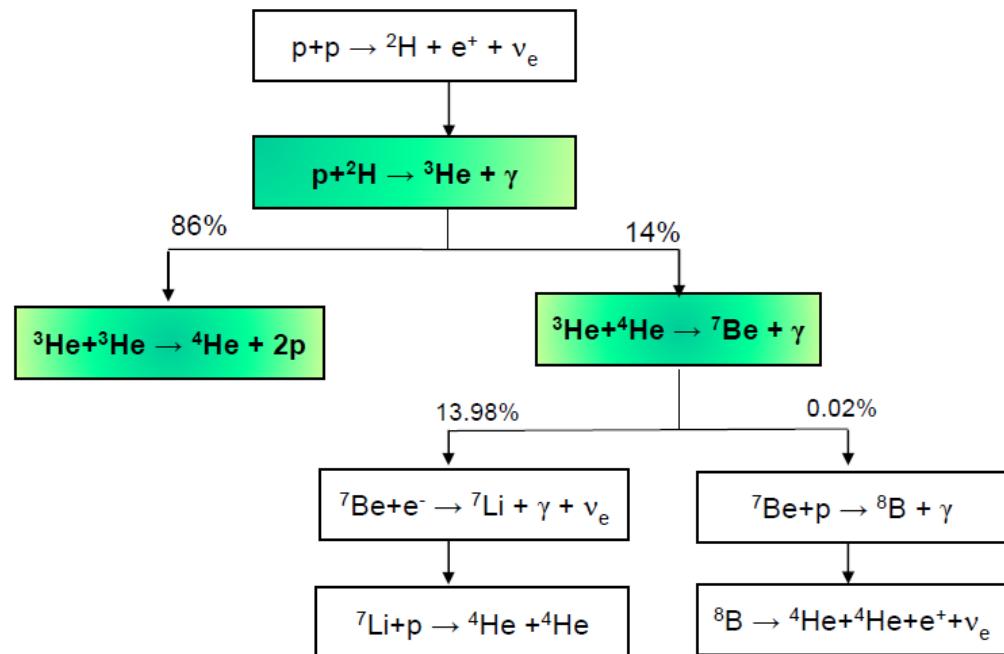


# REACTIONS STUDIED SINCE 1991

## Big Bang Nucleosynthesis

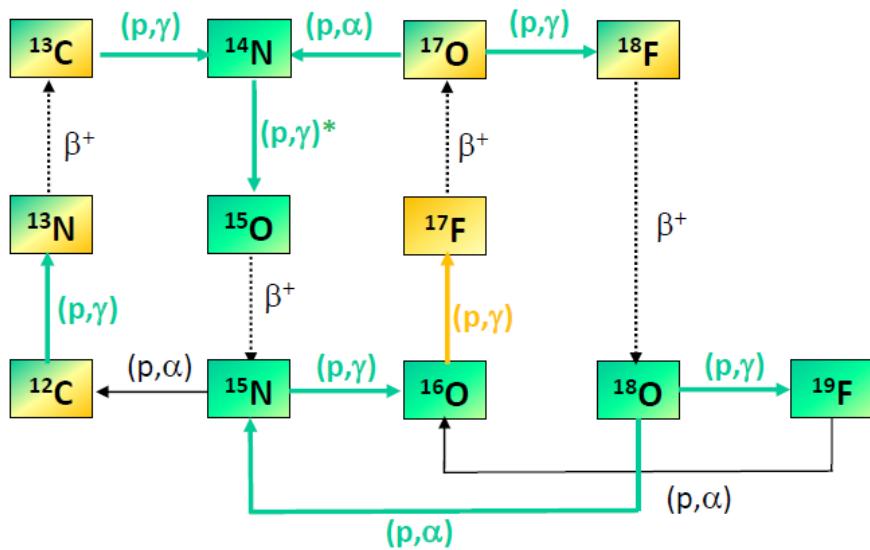


## pp chain

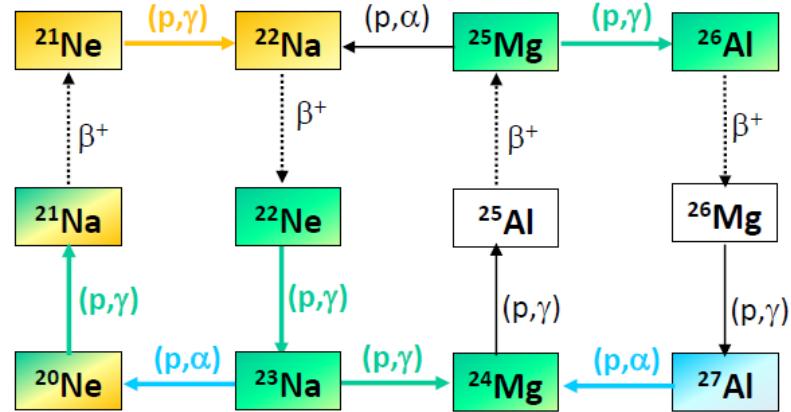


# REACTIONS STUDIED SINCE 1991

CNO CYCLE



NeNa and MgAl CYCLES



- Done
- In progress
- Planned

PRE-MAIN SEQUENCE:  $^6\text{Li}(\text{p},\gamma)^7\text{Be}$

S-PROCESS NUCLEOSYNTHESIS:  $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$ ,  $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}$

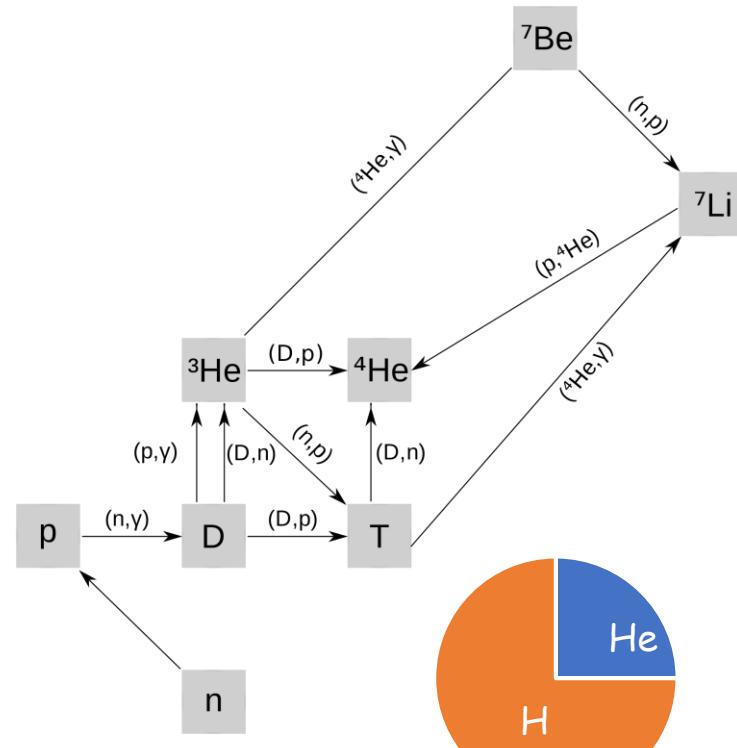
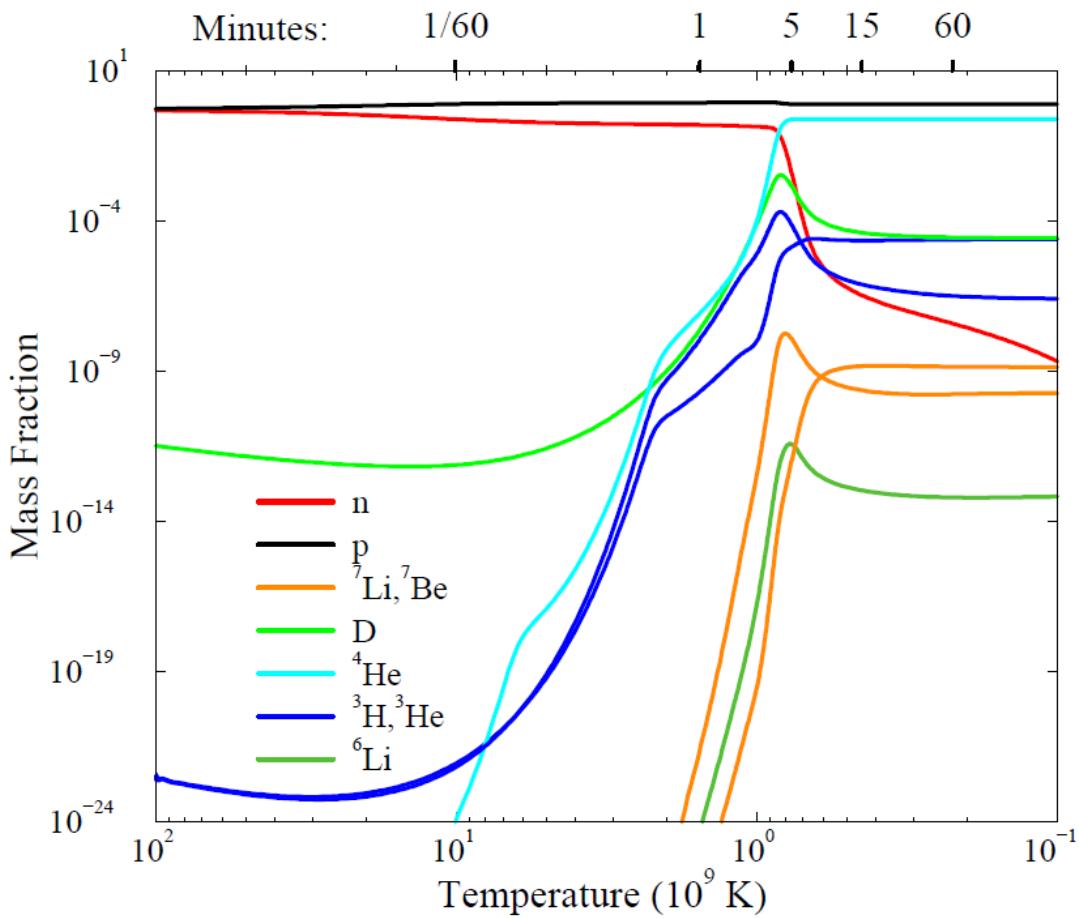
Talk of David Rapagnani (P3 this afternoon)

# Recent results: Big Bang Nucleosynthesis

The  $D(p,\gamma)^3He$  reaction

# BIG BANG NUCLEOSYNTHESIS

Burles, Nollett and Turner 1999



- BBN occurs 3 minutes after Big Bang
- After BBN we have mainly H and  $^4\text{He}$  plus small amounts of D,  $^3\text{He}$ ,  $^6\text{Li}$  and  $^7\text{Li}$

# THE PRIMORDIAL DEUTERIUM ABUNDANCE

- Observed abundance:  
Direct astronomical observation

$$[D/H]_{\text{OBS}} = (2.527 \pm 0.030) \times 10^{-5}$$

Cooke et al, APJ 855 (2018) 102

1% accuracy

- Predicted abundance:  
From BBN theory, knowing the cosmological parameters  
and the cross sections of the processes responsible for D  
creation and destruction  $[D/H]_{\text{BBN}}$

Depending on the adopted  
cross sections



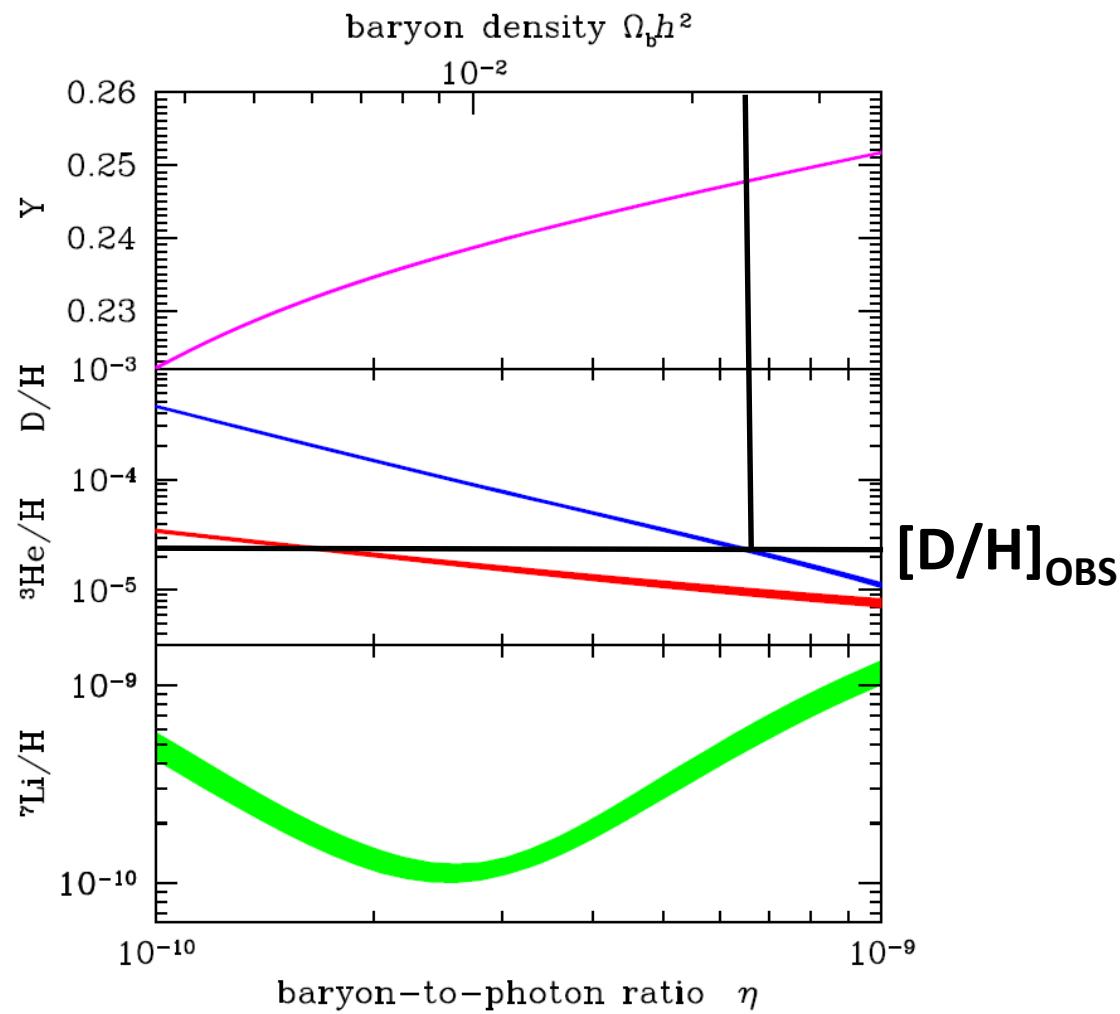
$$[D/H]_{\text{BBN}} = (2.587 \pm 0.055) \times 10^{-5}$$

$$[D/H]_{\text{BBN}} = (2.439 \pm 0.052) \times 10^{-5}$$

Planck, A&A 641 (2018) A6

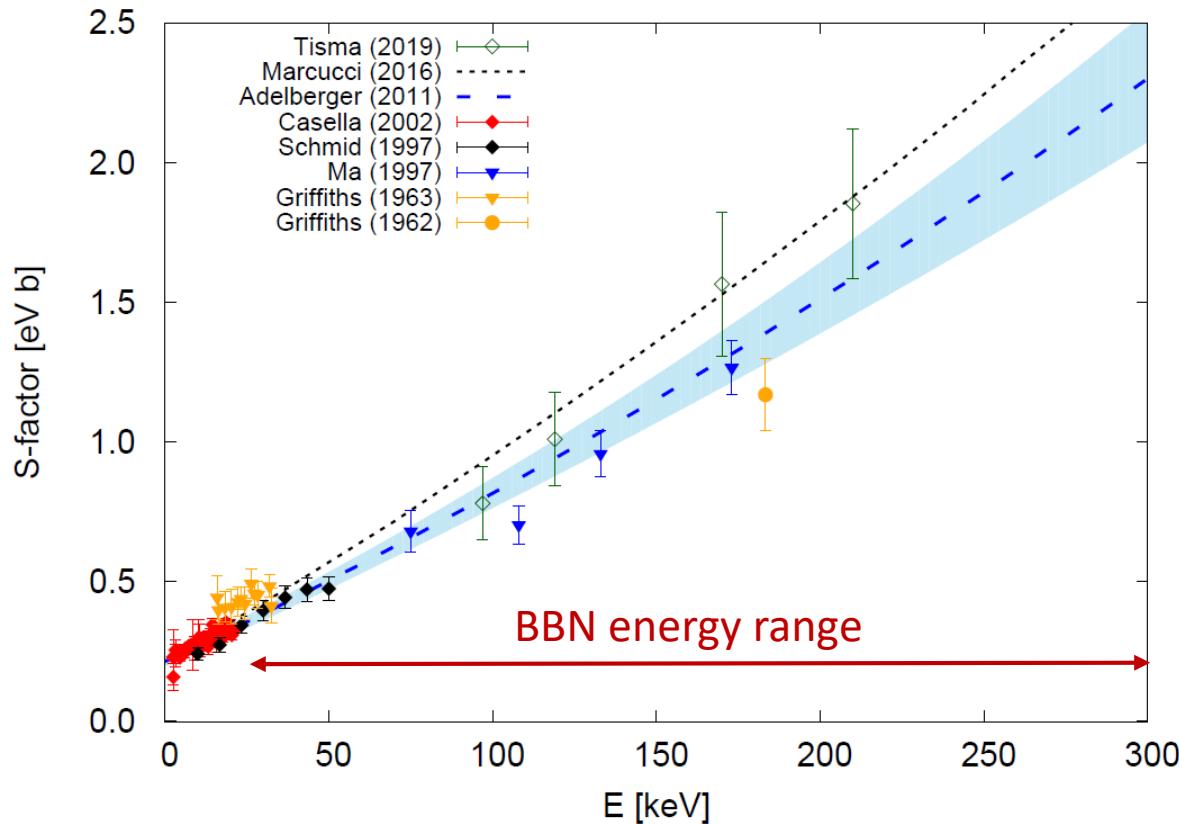
By comparing  $[D/H]_{\text{OBS}}$  and  $[D/H]_{\text{BBN}}$  → the Universal Barion density  $\Omega_B$   
and/or  $N_{\text{eff}}$  can be derived

# THE PRIMORDIAL DEUTERIUM ABUNDANCE



## STATE OF THE ART

- The cross section of the  $D(p,\gamma)^3\text{He}$  is the main source of uncertainty on the primordial D abundance



- Experimental data: two datasets currently available in the BBN energy range with a systematic error of 9-15%
- Ab initio calculations disagree with experimental data

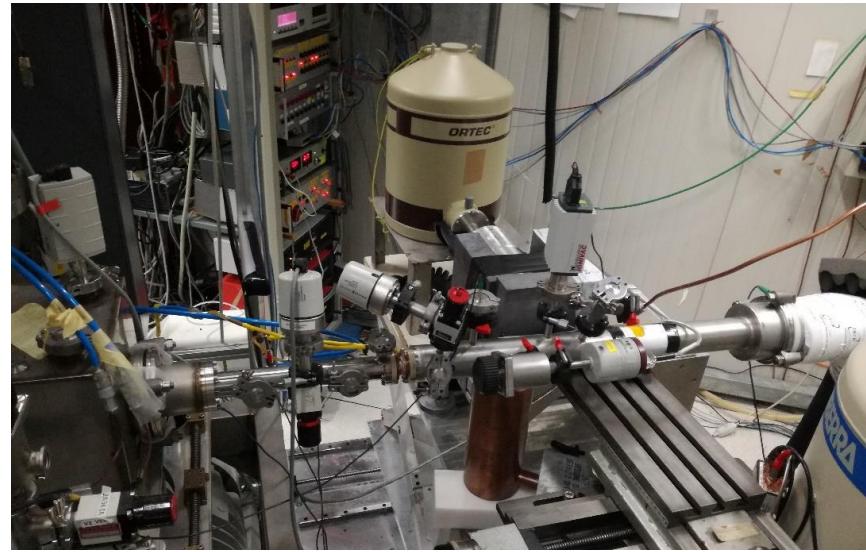
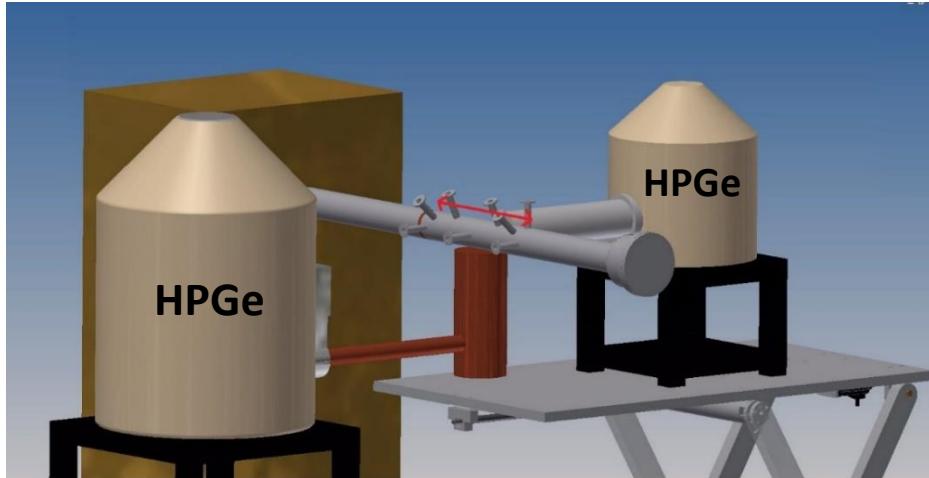
# D(p, $\gamma$ )<sup>3</sup>He MEASUREMENT: EXPERIMENTAL SETUP

## MEASUREMENT GOAL

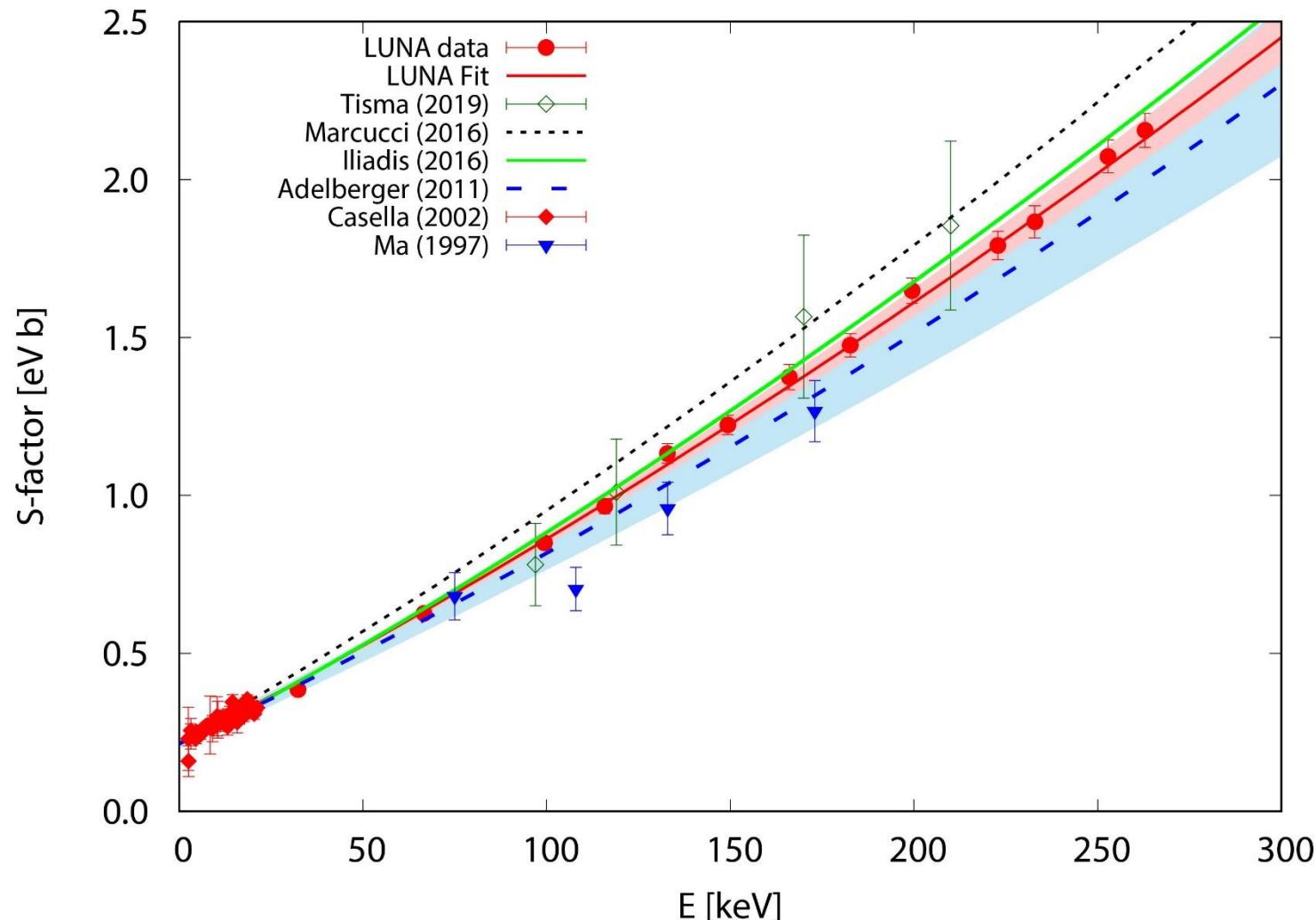
- Cross section measurement with  $\sim 3\%$  accuracy
- $E_{cm} = 30\text{-}300 \text{ keV}$

## EXPERIMENTAL SETUP

- Proton beam
- D<sub>2</sub> windowless gas target
- HPGe detectors for  $\gamma$ -rays ( $E_\gamma \approx 5.8 \text{ MeV}$ )



## D( $p,\gamma$ ) $^3\text{He}$ MEASUREMENT: RESULTS

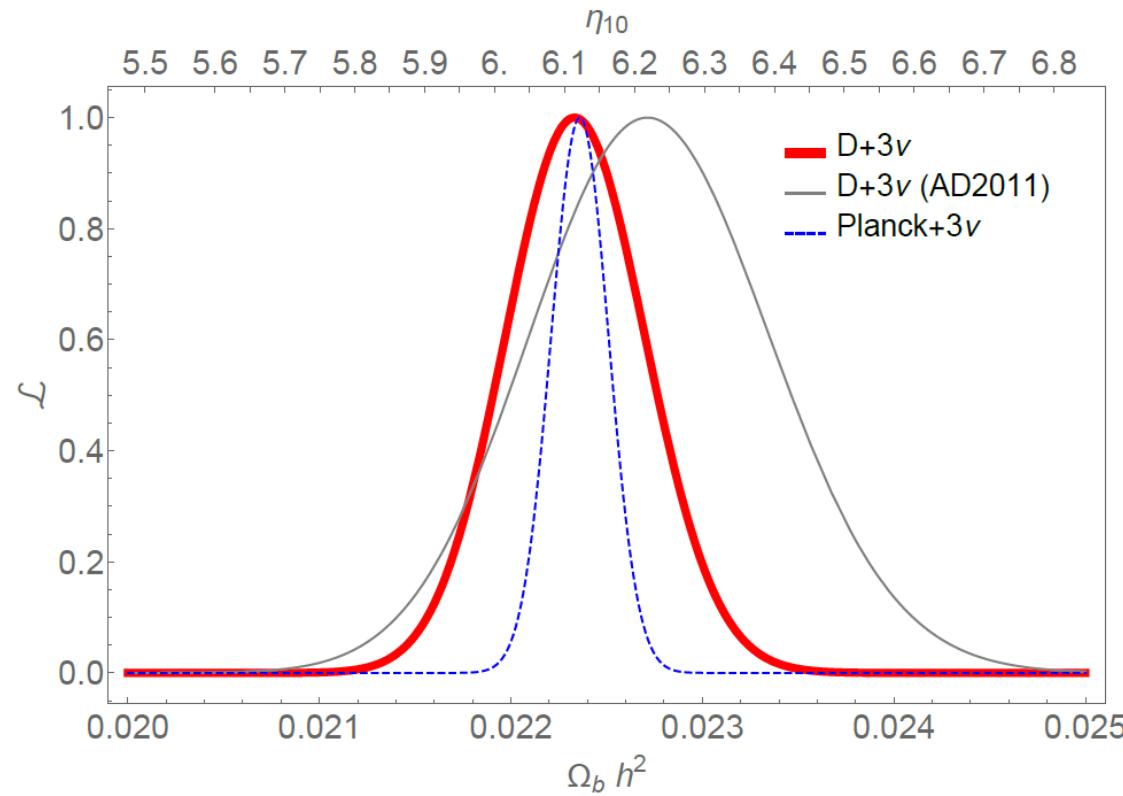


Mossa et al. Nature, 587 (2020)

EuNPC 2022

# D( $p,\gamma$ ) $^3\text{He}$ MEASUREMENT: COSMOLOGICAL IMPLICATIONS

- Baryon density with PARTENOPE code by comparing  $[\text{D}/\text{H}]_{\text{OBS}}$  and  $[\text{D}/\text{H}]_{\text{BBN}}$
- $N_{\text{eff}}$  from Standard Model
- Comparison with Planck results



Analysis performed by Ofelia Pisanti and Gianpiero Mangano

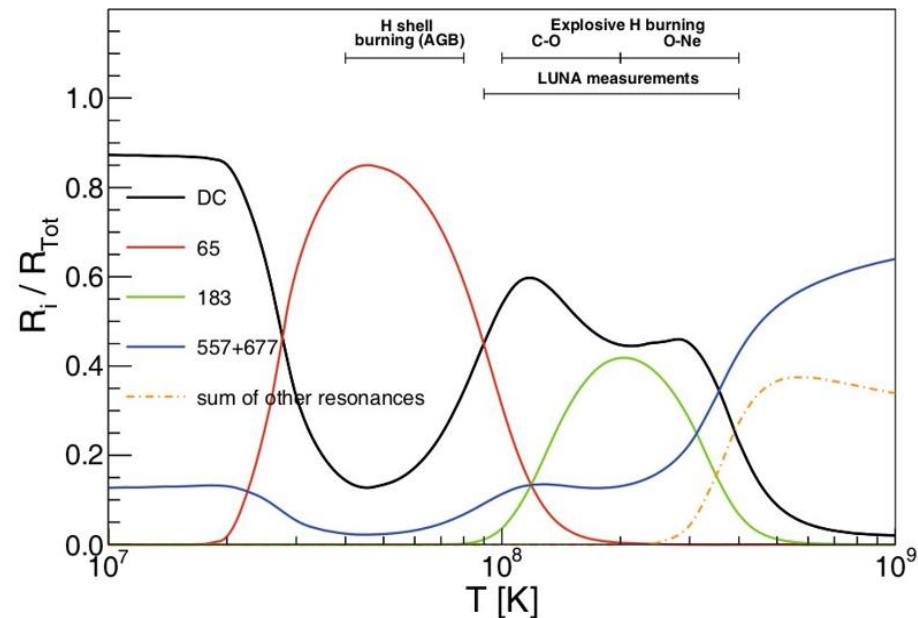
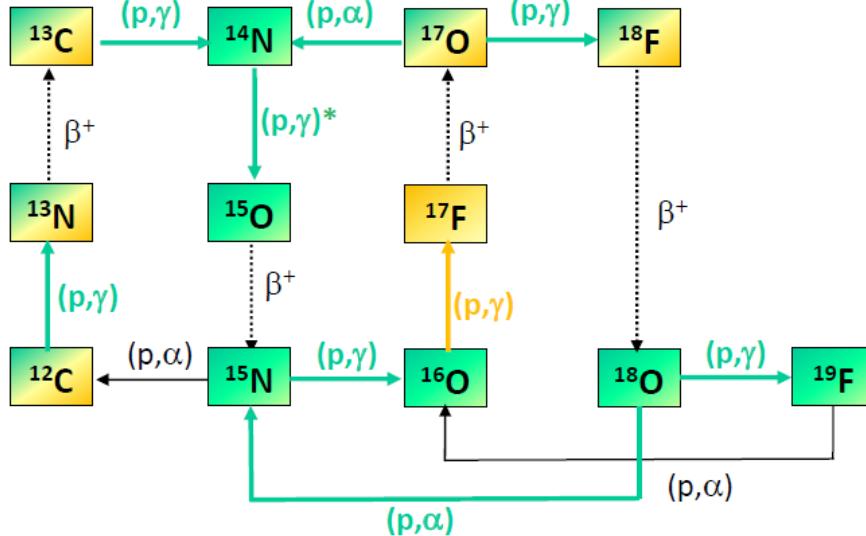
# Recent results: Hydrogen Burning

The  $^{17}\text{O}(\text{p},\gamma)^{18}\text{F}$  reaction

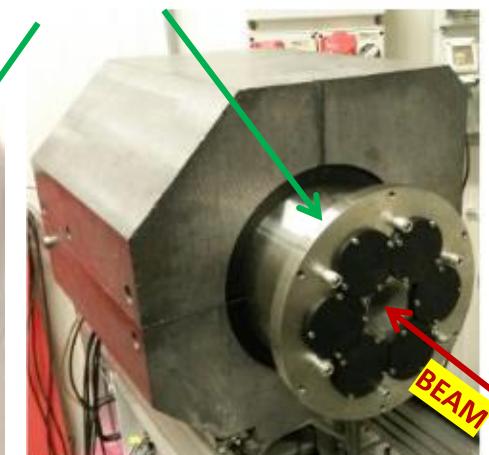
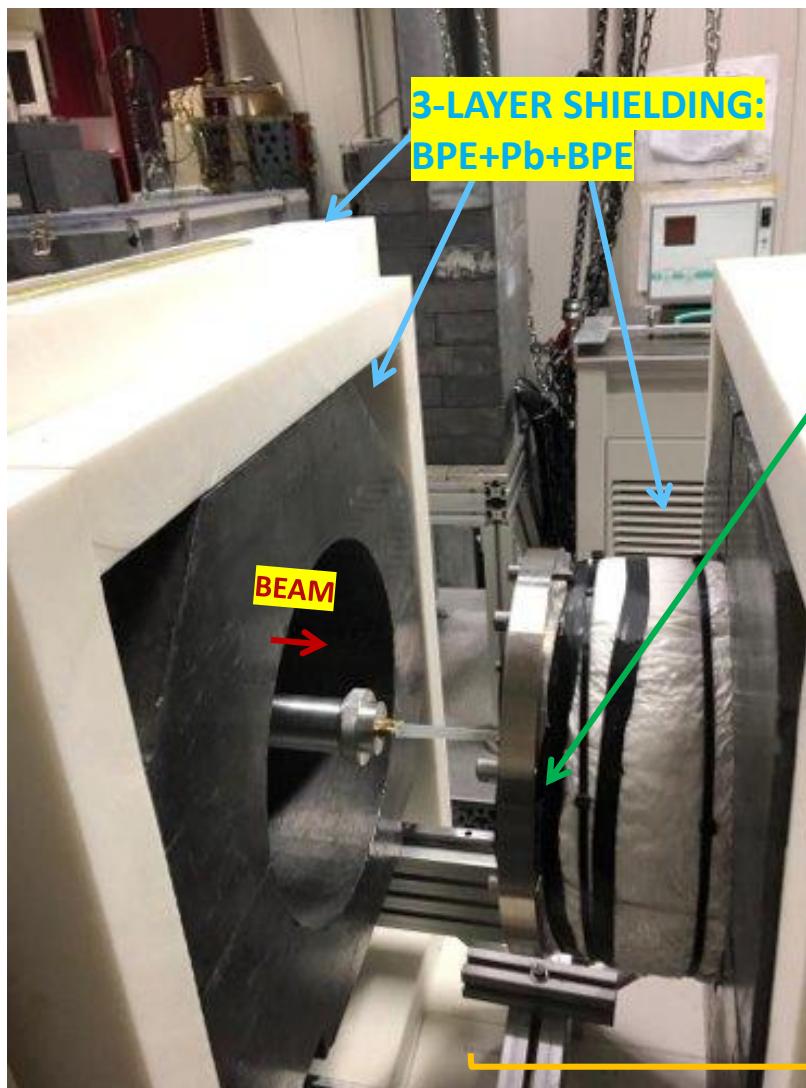
# THE $^{17}\text{O}(\text{p},\gamma)^{18}\text{F}$ REACTION: ASTROPHYSICAL MOTIVATION

- $^{17}\text{O}(\text{p},\gamma)^{18}\text{F}$  reaction ( $Q = 5607 \text{ keV}$ ) takes part to CNO cycle, active during H-shell burning in Asymptotic Giant Branch (AGB) stars
- For  $30 < T < 100 \text{ MK}$  ( $35 < E_{\text{G}} < 140 \text{ keV}$ ) the resonance  $E_{\text{cm}}=65 \text{ keV}$  dominates the reaction rate
- Only indirect measurements reported for the  $E_{\text{cm}}= 65 \text{ keV}$  resonance

## CNO CYCLE



# THE $^{17}\text{O}(\text{p},\gamma)^{18}\text{F}$ REACTION: EXPERIMENTAL SETUP



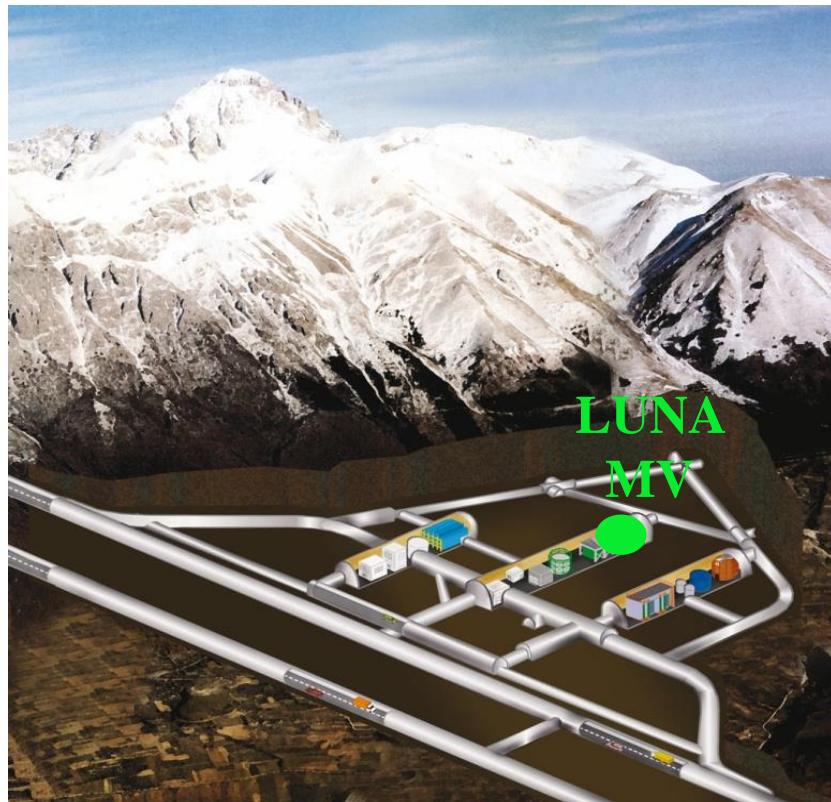
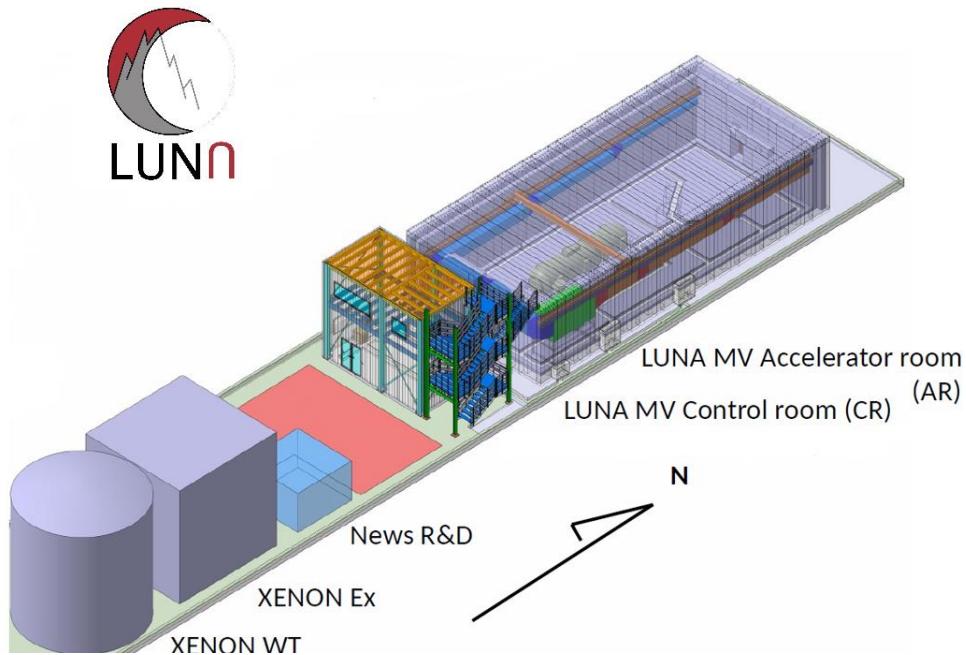
This part can move  
back and forth

# THE $^{17}\text{O}(\text{p},\gamma)^{18}\text{F}$ REACTION: PRELIMINARY RESULTS

- Data analysis is still ongoing
- Preliminary results by two experimental campaigns are in good agreement and suggest a higher  $\omega\gamma$  than reported in literature

# Upcoming measurements: LUNA MV

# LUNA MV: A 3.5 MV ACCELERATOR



$^1\text{H}^+$  (TV: 0.3 – 3.5 MV): 500-1000  $\mu\text{A}$



$^4\text{He}^+$  (TV: 0.3 – 3.5 MV): 300-500  $\mu\text{A}$



A Sen. et al, NIM B 450 (2019) 390-395

$^{12}\text{C}^+$  (TV: 0.3 – 3.5 MV): 150  $\mu\text{A}$   
 $^{12}\text{C}^{++}$  (TV: 0.5 – 3.5 MV): 100  $\mu\text{A}$

## LUNA MV SCIENTIFIC PROGRAM

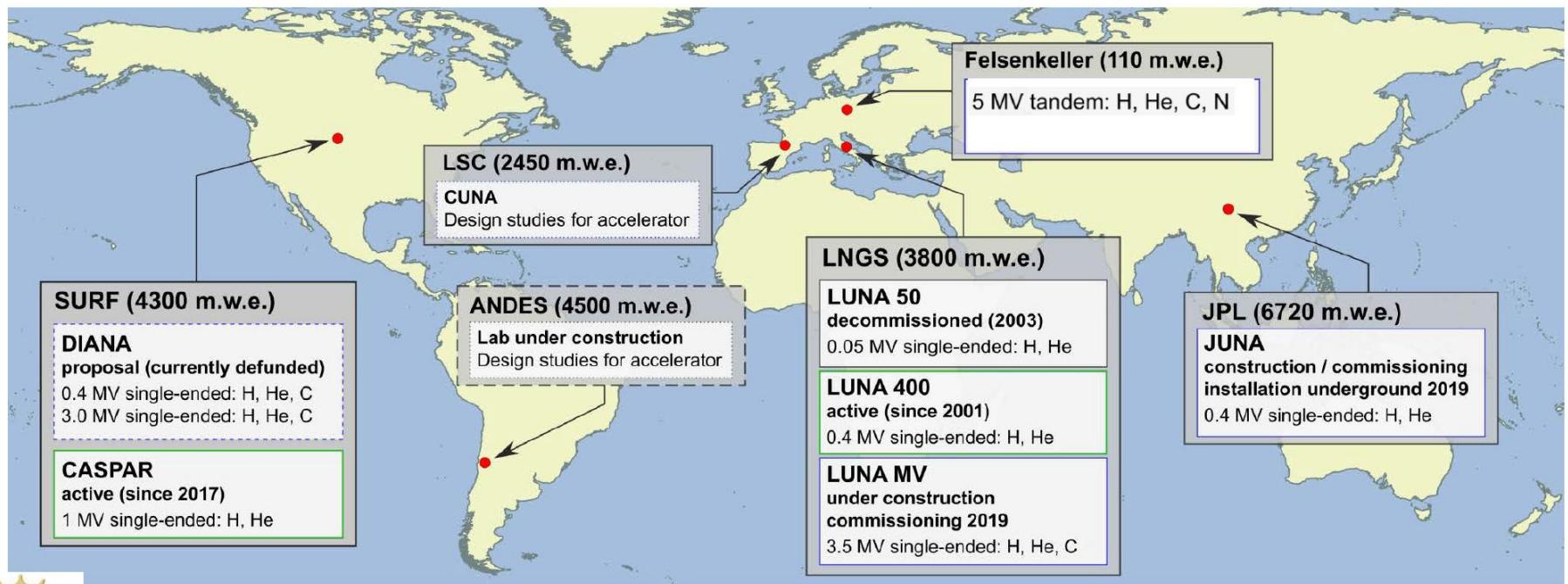
- $^{14}\text{N}(\text{p},\gamma)^{15}\text{O}$ : bottleneck reaction of the CNO cycle. Also commissioning measurement for the LUNA MV facility
- $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$  and  $^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}$ : neutron sources for the s-process (nucleosynthesis beyond Fe)
  - **Talk of David Rapagnani (P3 this afternoon)**
- $^{12}\text{C} + ^{12}\text{C}$ : nucleosynthesis and energy production in carbon burning. Global chemical evolution of the Universe

## LUNA MV STATUS



- Acceptance tests done in September – October 2022
- First experiment in 2023

## Nuclear Astrophysics Underground Laboratories

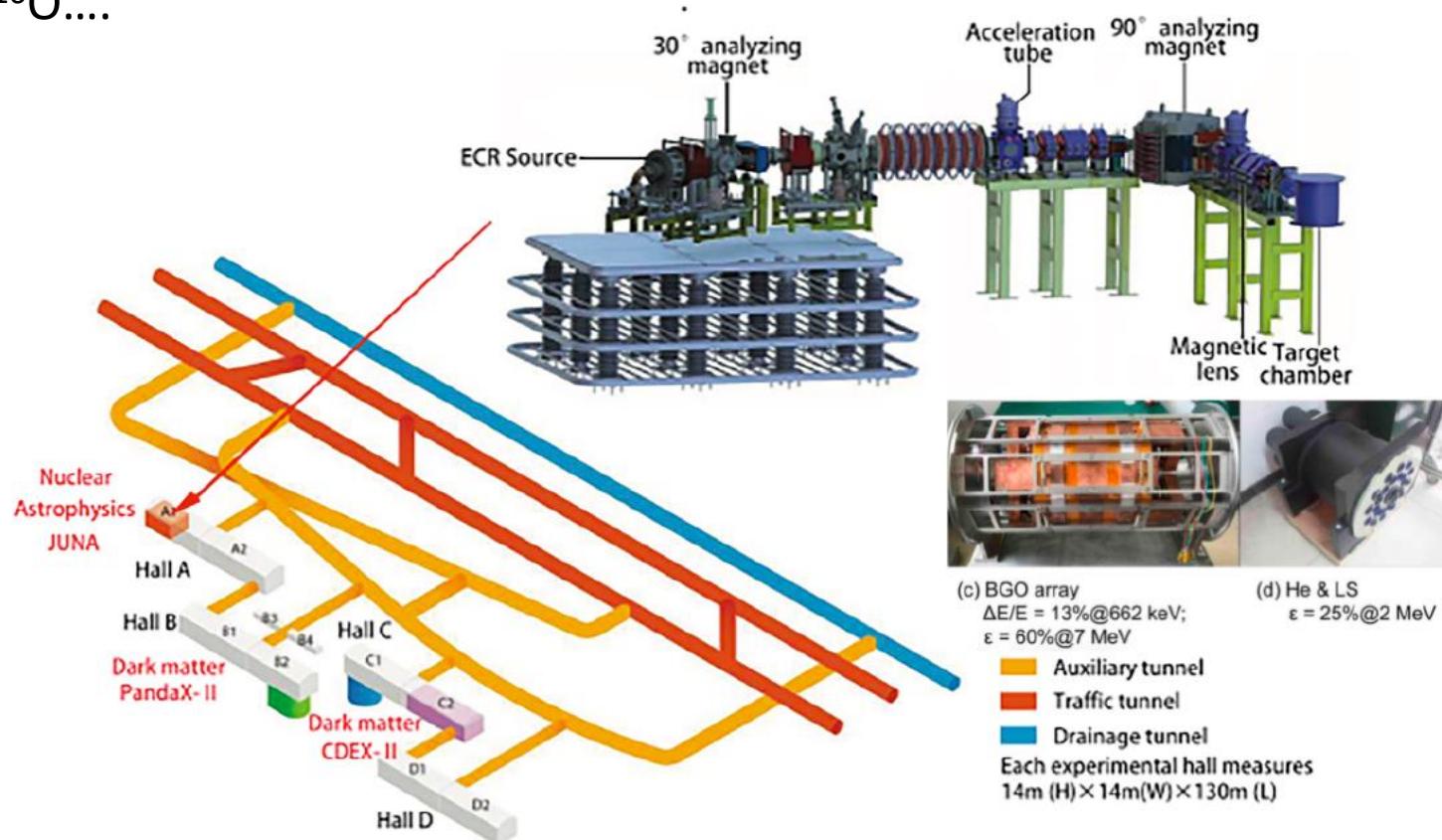


courtesy: A. Boeltzig



# JINPING UNDERGROUND LABORATORY: JUNA

- Under 2400 m of rock
- Proton and alpha beam with a 400 kV accelerator (mA current)
- Reactions already measured:  $^{25}\text{Mg}(\text{p},\gamma)^{26}\text{Al}$ ,  $^{19}\text{F}(\text{p}, \alpha)^{16}\text{O}$ ,  $^{13}\text{C}(\alpha,\text{n})^{16}\text{O}$  and  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ ....



# DRESDEN FELSENKELLER UNDERGROUND LAB

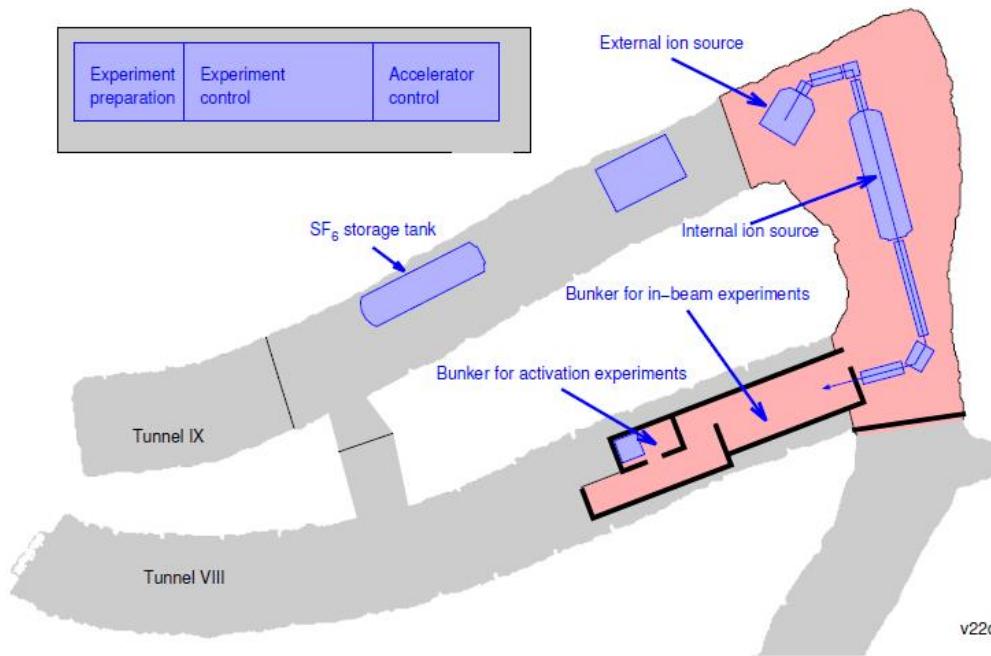
- Under 45 m of rock
- Scientific program: Big Bang Nucleosynthesis and H-burning

Joint effort HZDR – TU Dresden

- Investment by TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
- Day to day operations by HZDR

Two main instruments

- **HZDR:** 5 MV Pelletron, 30  $\mu\text{A}$  beams of  $^1\text{H}^+$ ,  $^4\text{He}^+$ ,  $^{12}\text{C}^+$ , ...
- **TU Dresden:** 163% ultra-low-background HPGe detector for offline radioactivity measurements



## CONCLUSIONS AND OUTLOOK

- LUNA has pioneered underground studies in Nuclear Astrophysics for over three decades
- Direct measurements at lowest possible energies (Hydrogen Burning, Big Bang Nucleosynthesis, s-process)
- LUNA MV: Helium and Carbon burning
- Other laboratories around the world have now started their activity

# THANK YOU FOR YOUR ATTENTION

A. Compagnucci\*, M. Junker | **INFN LNGS/ \*GSSI, L'AQUILA, Italy**



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