Direct Studies of Stellar Reactions: Progress and Prospects from LUNA

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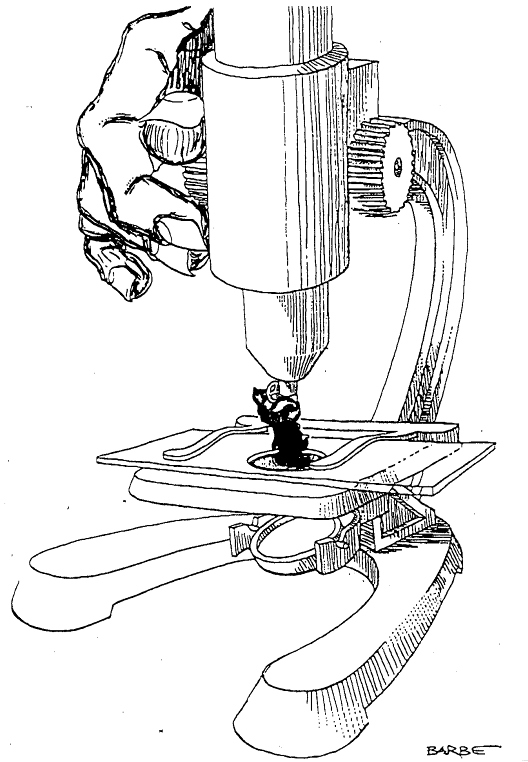
Laboratori Nazionali di Frascati, 04 June 2025

Nuclear Astrophysics in a Nutshell

investigating the MICRO COSMOS (nuclear physics)

to understand the MACRO COSMOS (astrophysics)



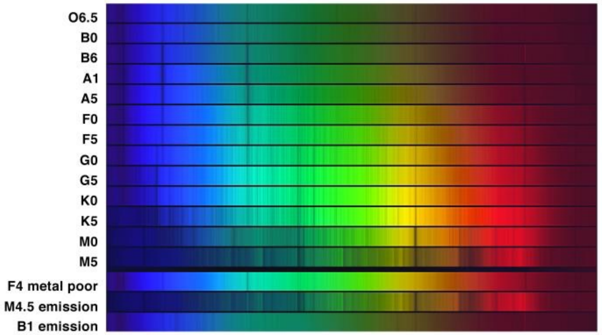
Courtesy: M. Arnould

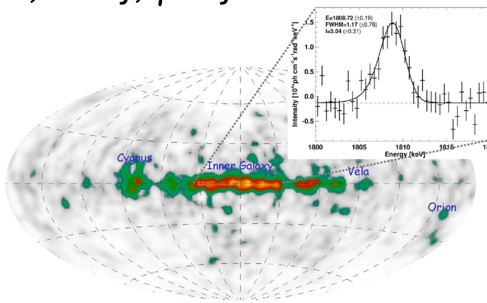
Seminar Layout

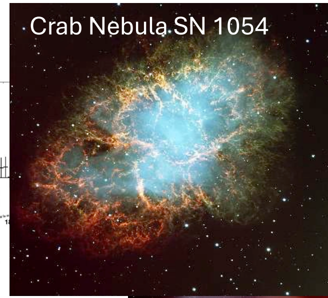
- key features of Nuclear Astrophysics
- stellar reaction studies in the laboratory
- why going underground?
- the LUNA experiment
- past, present, and future activities (a biassed view!)

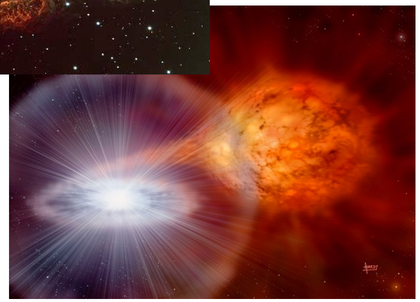
electromagnetic emissions

radio, microwave, infrared, optical, X-ray, γ-ray



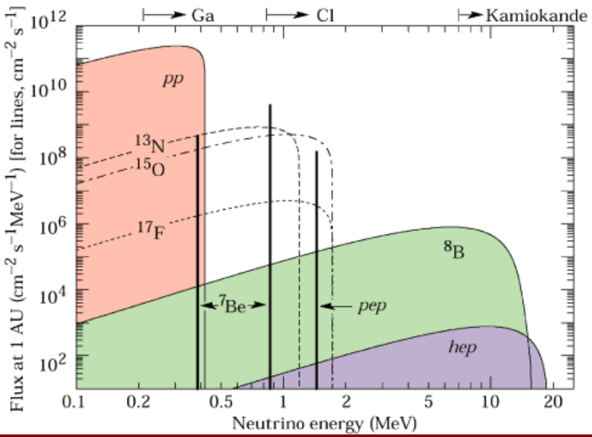


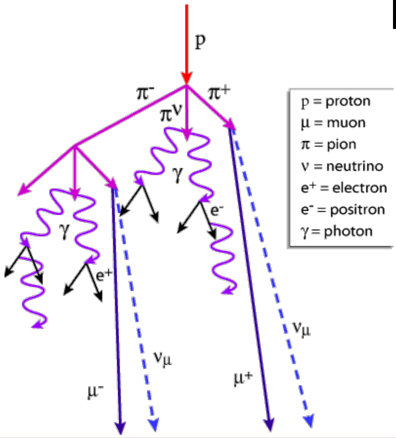




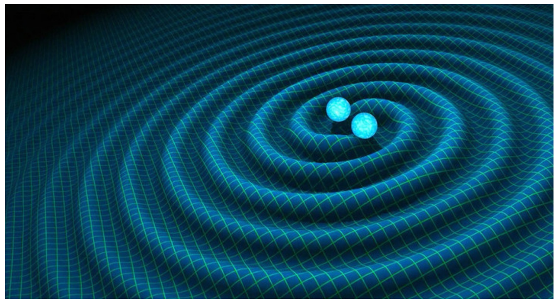
direct messengers

neutrinos, cosmic rays, meteorites, lunar samples, ...





gravitational waves



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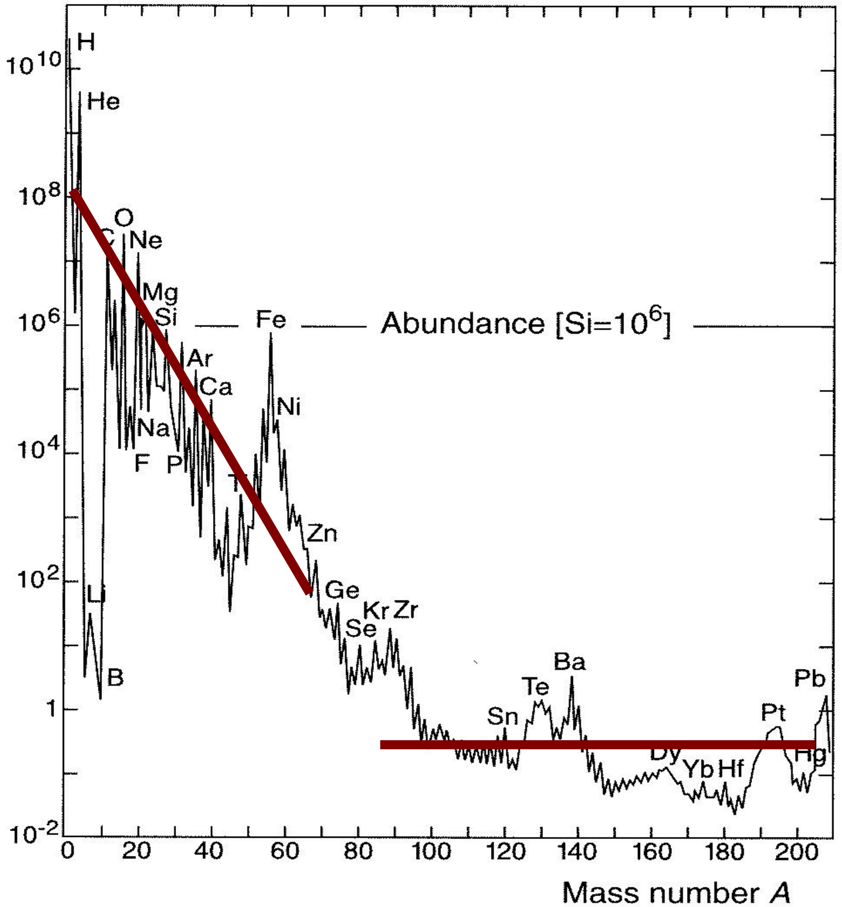
(Solar) Abundance Distribution



Data sources:

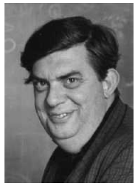
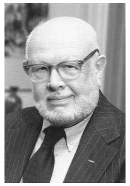
Earth, Moon, meteorites, cosmic rays, solar & stellar spectra…

Features:

- 12 orders-of-magnitude span
- H ~ 75%, He ~ 23%
- C → U ~ 2% ("metals")
- D, Li, Be, B under-abundant
- exponential decrease up to Fe
- nearly flat distribution beyond Fe

Stellar Nucleosynthesis: A Major Breakthrough

Burbidge, Burbidge, Fowler & Hoyle (B^2FH): Rev. Mod. Phys. 29 (1957) 547


Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 69 June 1957 No. 408

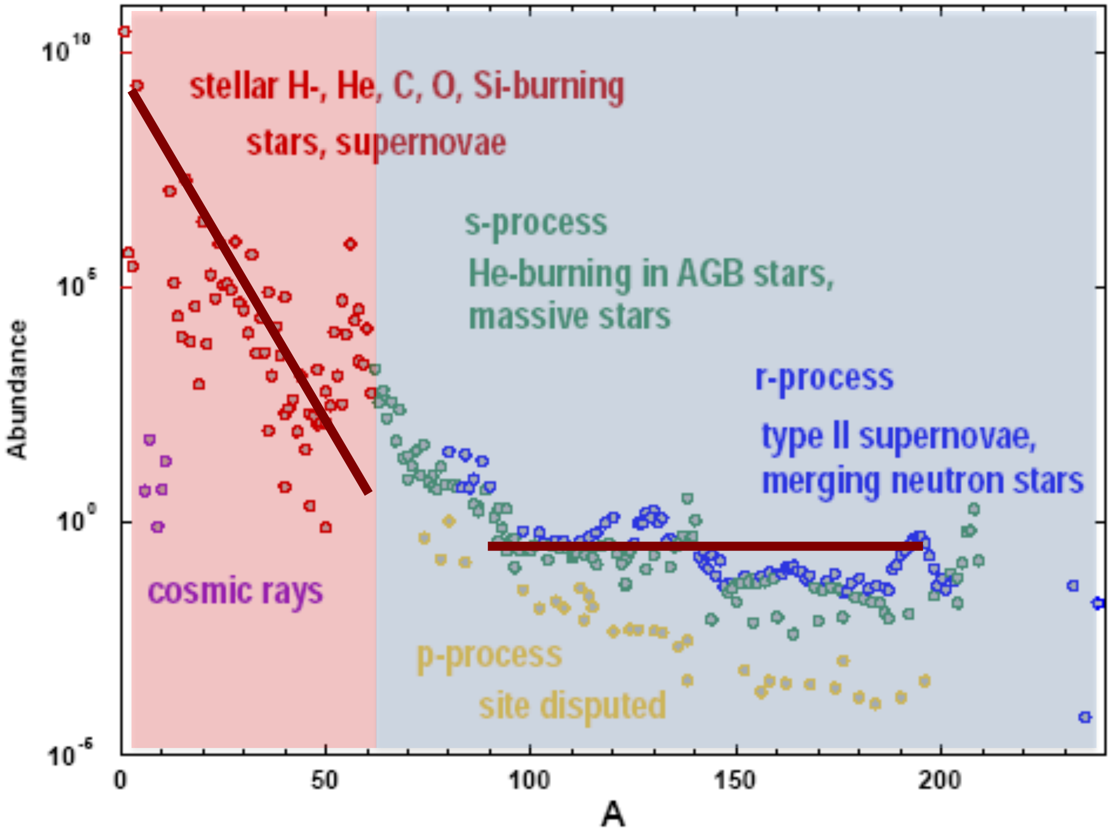
NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

A. G. W. CAMERON

Atomic Energy of Canada Limited
Chalk River, Ontario

fusion of charged particles

mainly **stable nuclei**



M. Wiescher, JINA lectures on Nuclear Astrophysics

neutron-capture reactions

mainly **unstable nuclei**

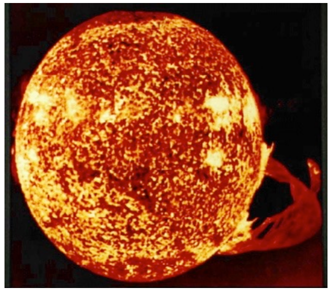
Inter-stellar medium

BIRTH

gravitational contraction

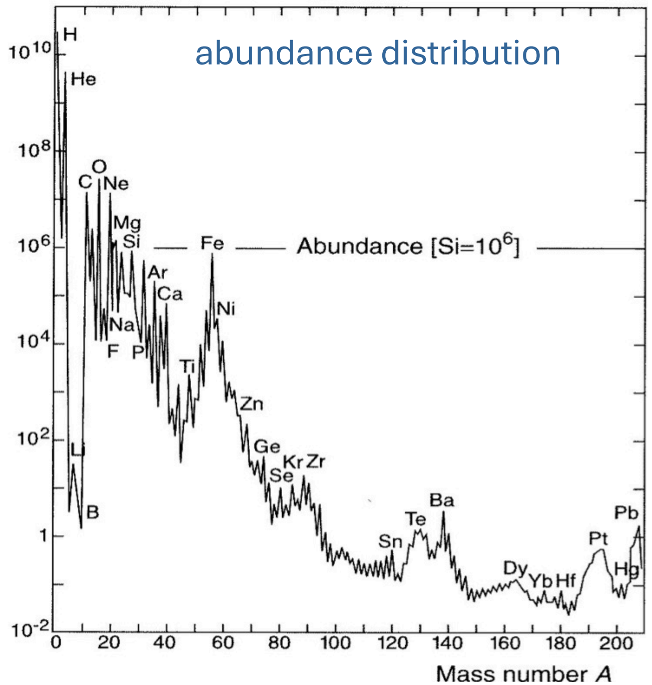
explosion ejection

DEATH



Stars

- energy production
- stability against collapse
- synthesis of "metals"



Stellar Evolutionary Paths

birth

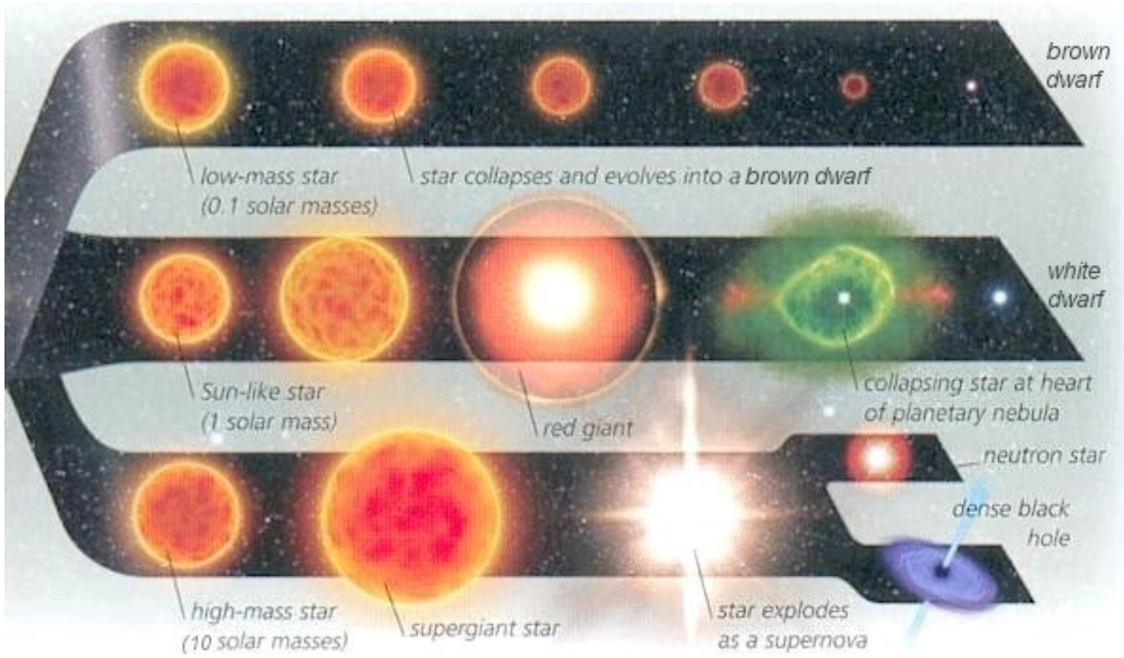
evolution

death

low-mass star
0.1 solar masses

sun-like stars
1 solar mass

high-mass stars
10 solar mass



brown dwarf

white dwarf

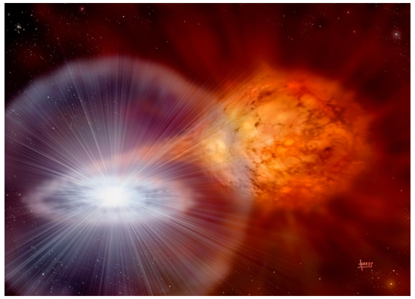
neutron star

black hole

massive stars contribute to **chemical evolution** of the Universe

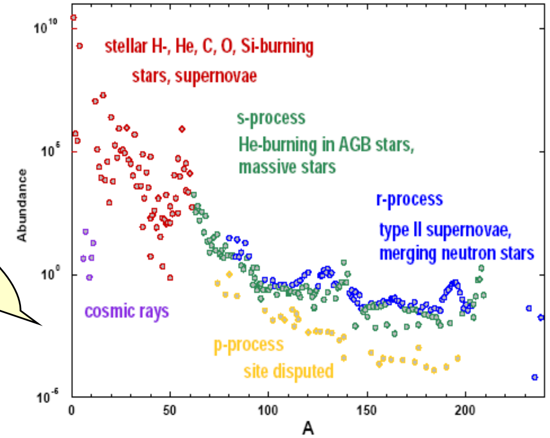
low-mass stars critical for existence and evolution of **life**

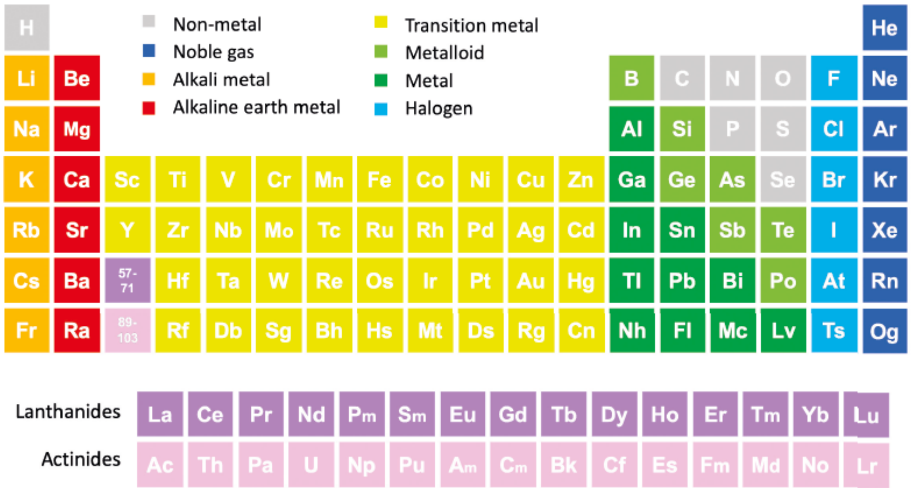
Nuclear Astrophysics: A truly interdisciplinary field



Astrophysics

stellar evolutionary codes
nucleosynthesis calculations
astronomical observations



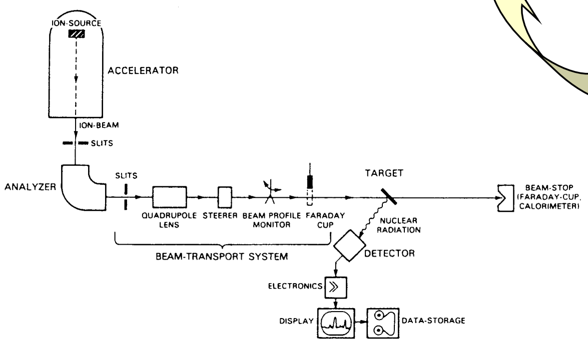


Nuclear Physics

experimental and
theoretical inputs
stable and exotic nuclei

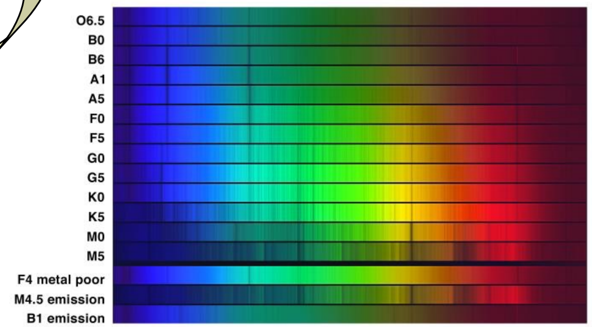
Plasma Physics

degenerate matter
electron screening
equation of state



Atomic Physics

radiation-matter interaction
energy losses, stopping powers, spectral lines
materials and detectors

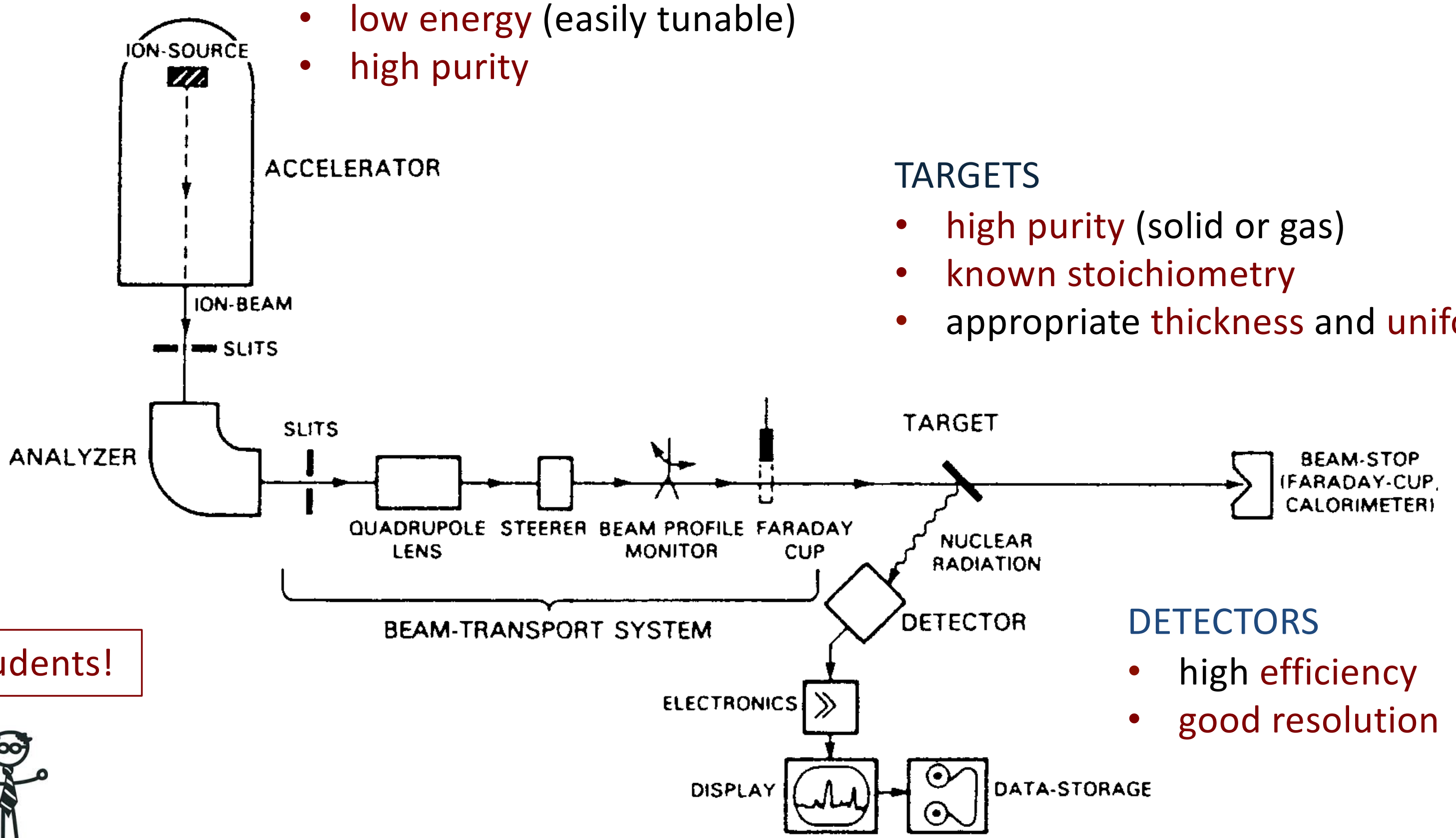


Astrophysical Reaction Studies in the Laboratory: Experimental Challenges

Schematic Layout for Nuclear (Astro-)Physics Experiments

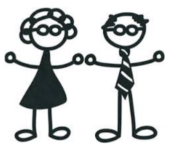
BEAMS
- high beam currents
- low energy (easily tunable)
- high purity

TARGETS
- high purity (solid or gas)
- known stoichiometry
- appropriate thickness and uniformity



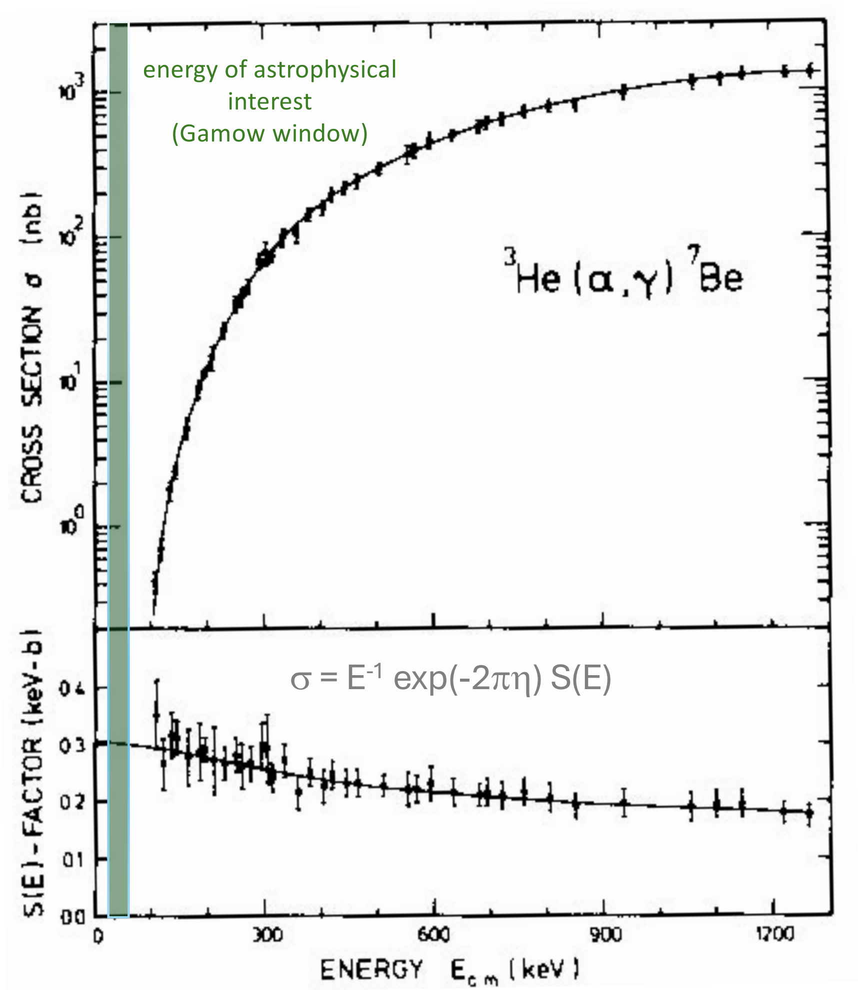
DETECTORS
- high efficiency
- good resolution

Excellent Students!



Experimental Challenges

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



Yield = N_p x N_t x cross section x detection efficiency

10^{14} pps (~100 μA q=1+) typical stable beam intensities

10^{19} atoms/cm^2 typical solid-state targets

10^{-15} barn (often even smaller)

100% for charged particles

~1-10% for gamma rays (HPGe detectors)

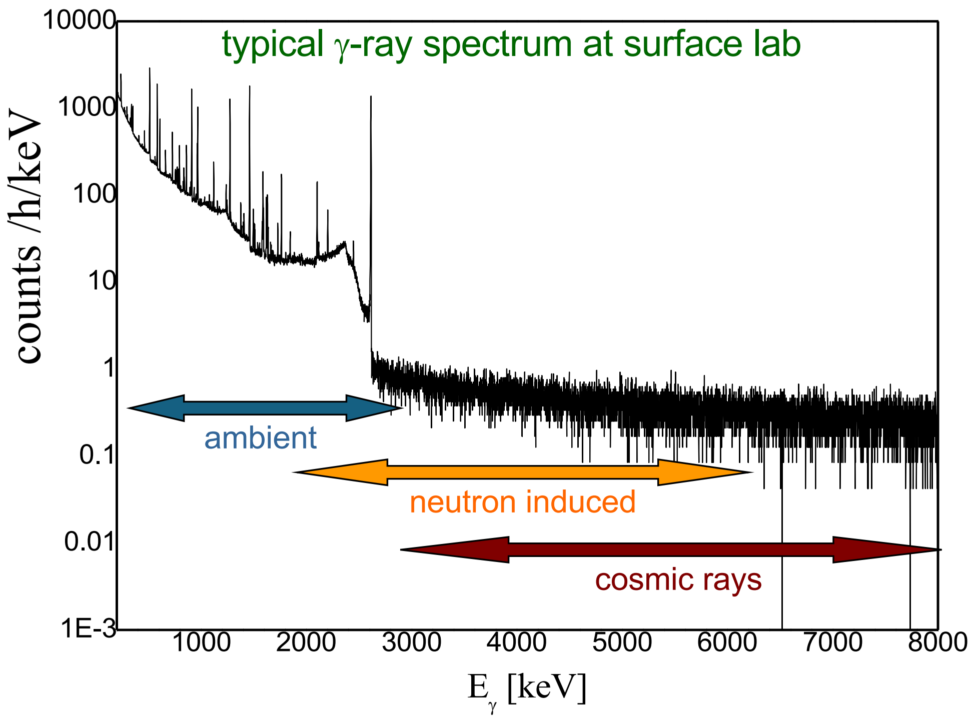
Y = 0.3-30 counts/year

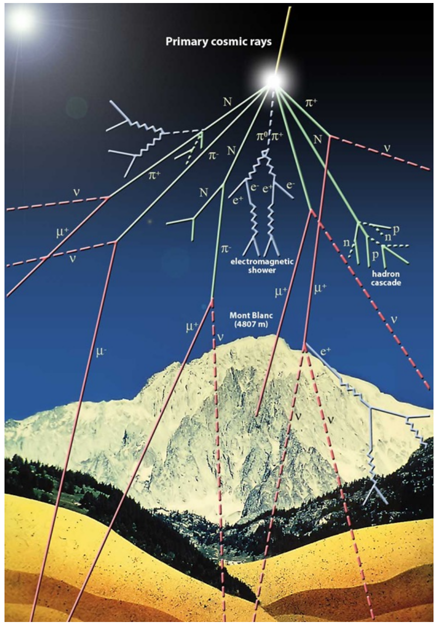
~ 1.2-120 counts/PhD

How to increase the signal-to-noise ratio?

Main Sources of Background

- natural radioactivity (mainly from U and Th chains and from Rn)
- cosmic rays (muons, $^{1,3}H$, ^{7}Be, ^{14}C, ...)
- neutrons from (α,n) reactions and fission

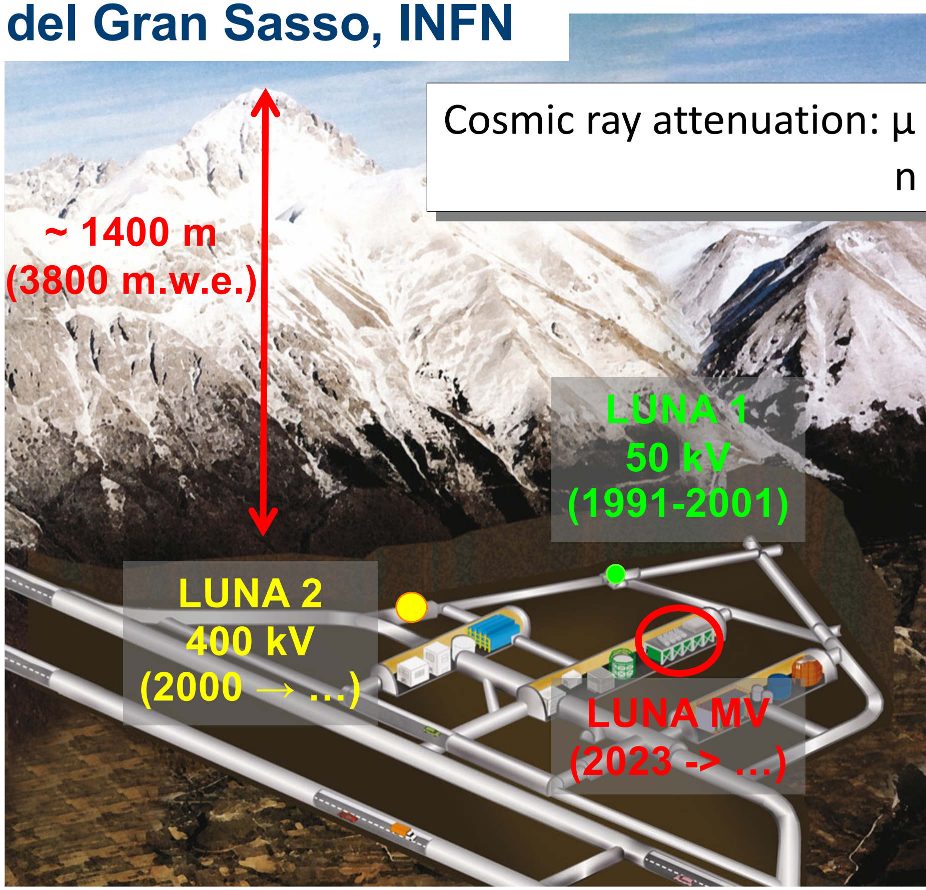




ideal location: underground + low concentration of U and Th

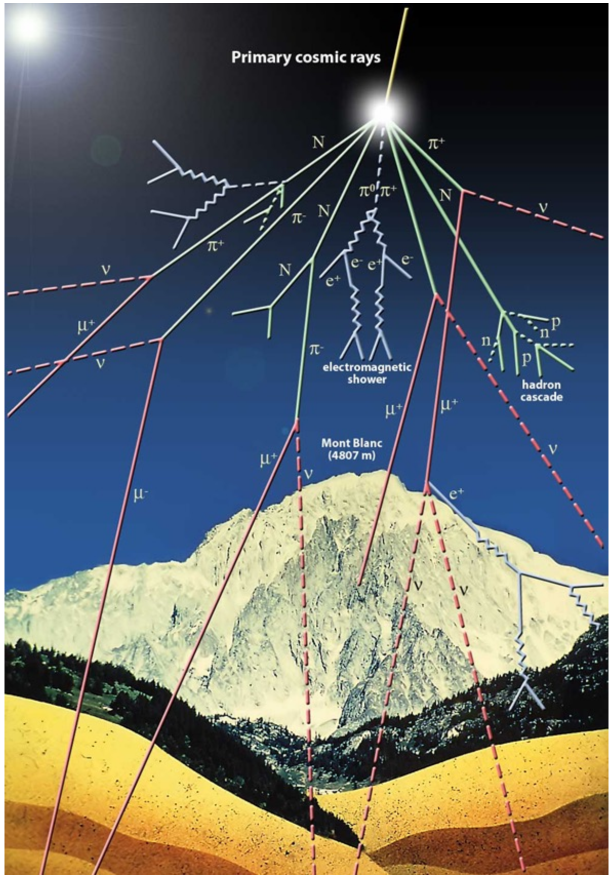
LUNA: **L**aboratory for **U**nderground **N**uclear **A**strophysics (established early 1990s)

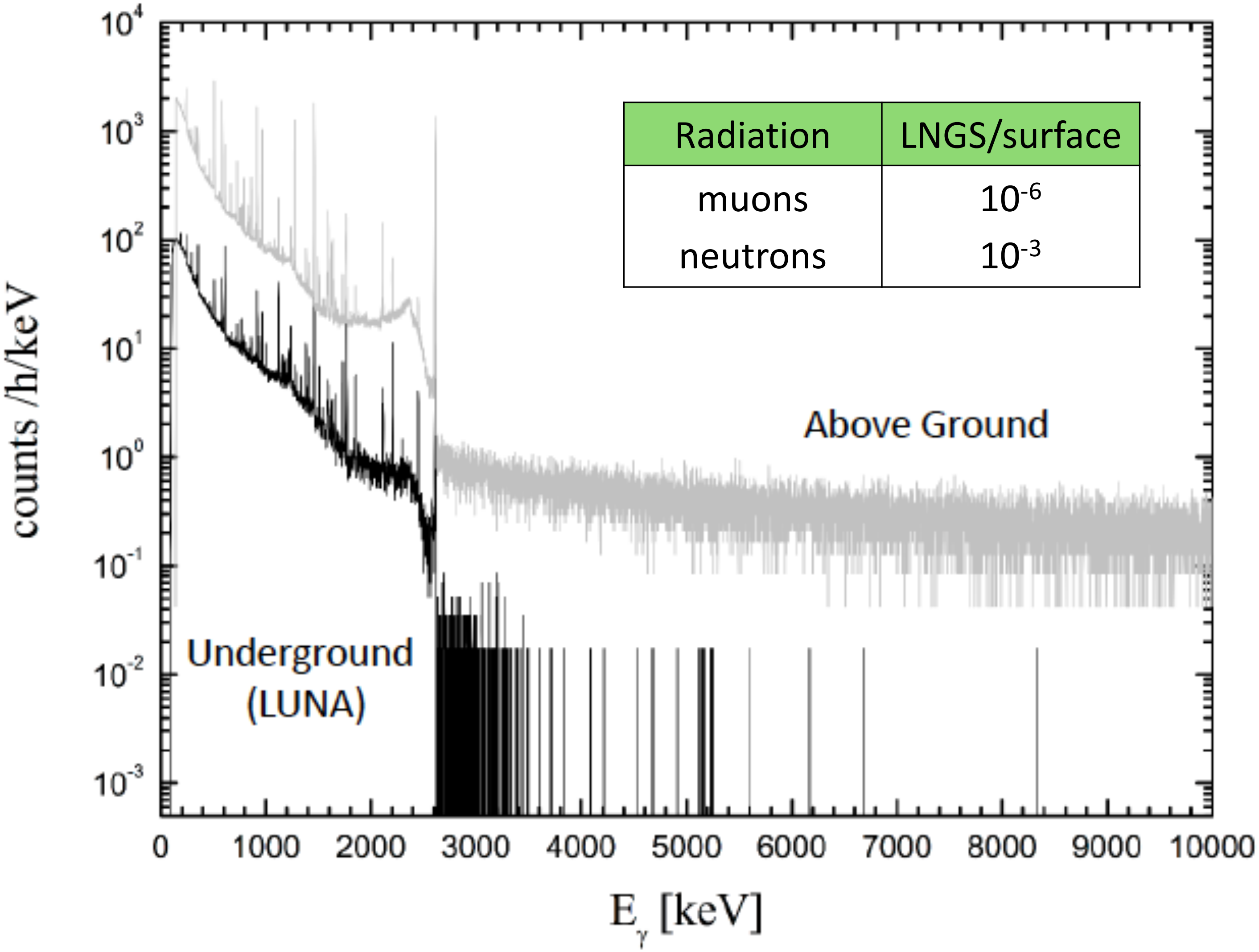
Laboratori Nazionali del Gran Sasso, INFN



Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$

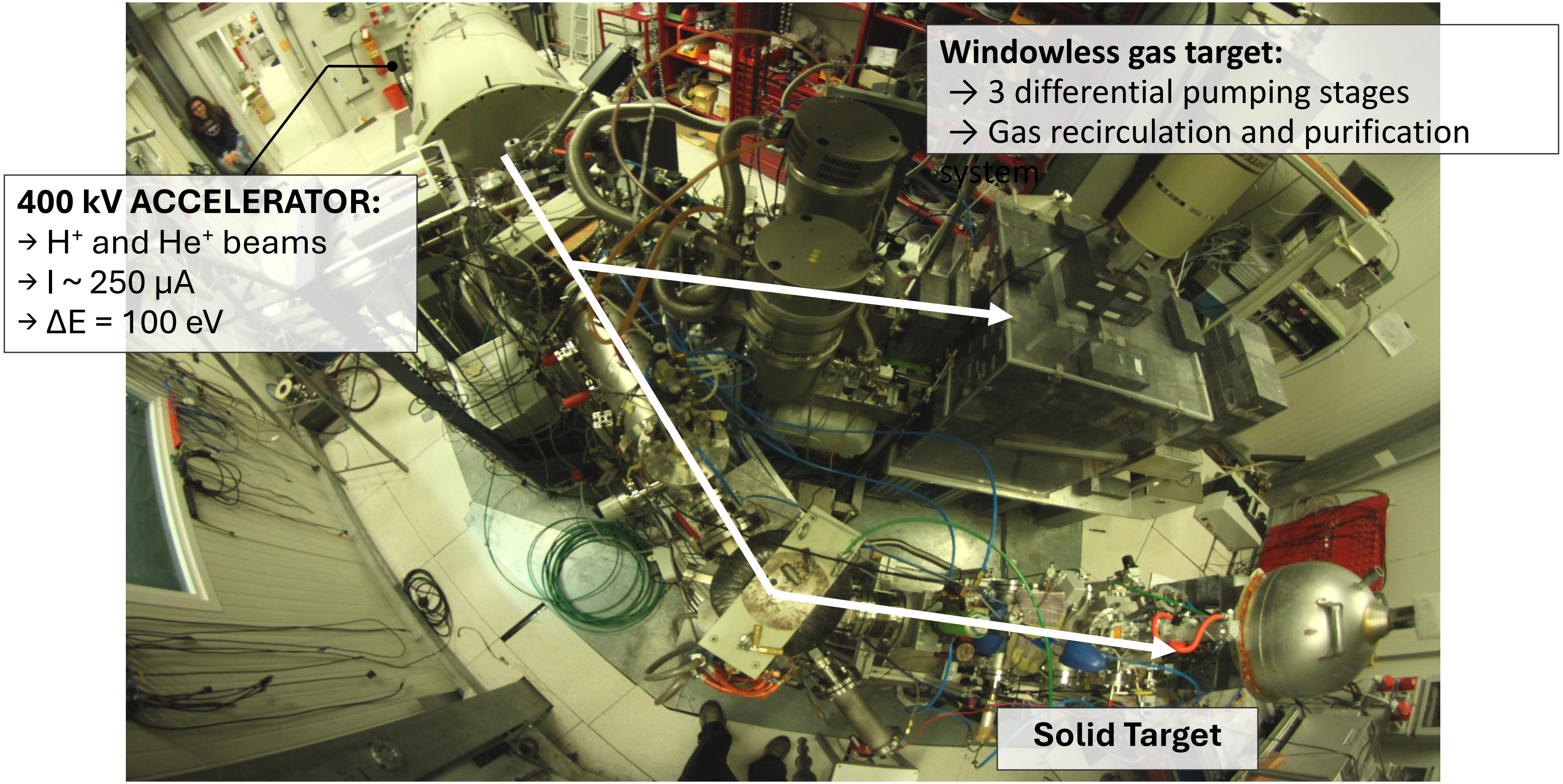
Gamma-ray background: underground vs overground comparison





Costantini et al. Rep. Prog. Phys. 72 (2009) 086301

The LUNA 400 kV facility



LUNA: The First Underground Laboratory for Nuclear Astrophysics

30 years of Nuclear Astrophysics at LUNA (LNGS, INFN)

- **solar fusion reactions**
  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$
- **electron screening and stopping power**
  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$
- **CNO, Ne-Na and Mg-Al cycles**
  $^{12,13}C(p,\gamma)^{13,14}N$ $^{14,15}N(p,\gamma)^{15,16}O$ $^{16}O(p,\gamma)^{17}F$ $^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$
- **(explosive) hydrogen burning in novae and AGB stars**
  $^{17}O(p,\gamma)^{18}F$ $^{17}O(p,\alpha)^{14}N$ $^{18}O(p,\gamma)^{19}F$ $^{18}O(p,\alpha)^{15}N$
- **Big Bang nucleosynthesis**
  $^{2}H(\alpha,\gamma)^{6}Li$ $^{2}H(p,\gamma)^{3}He$ $^{6}Li(p,\gamma)^{7}Be$
- **neutron capture nucleosynthesis**
  $^{13}C(\alpha,n)^{16}O$

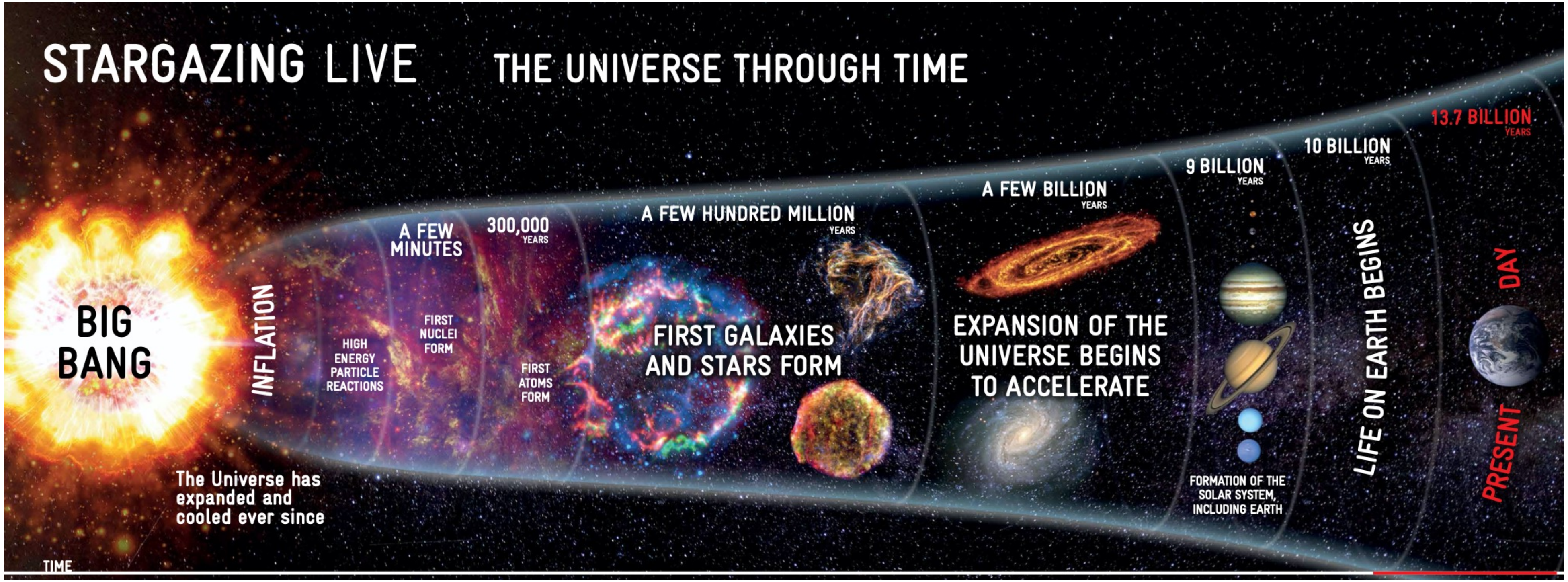
some of the lowest cross sections ever measured (few counts/month)

ca. 24 reactions in 30 years: ~15 months data taking per reaction!

The Past:
Recent Selected Highlights

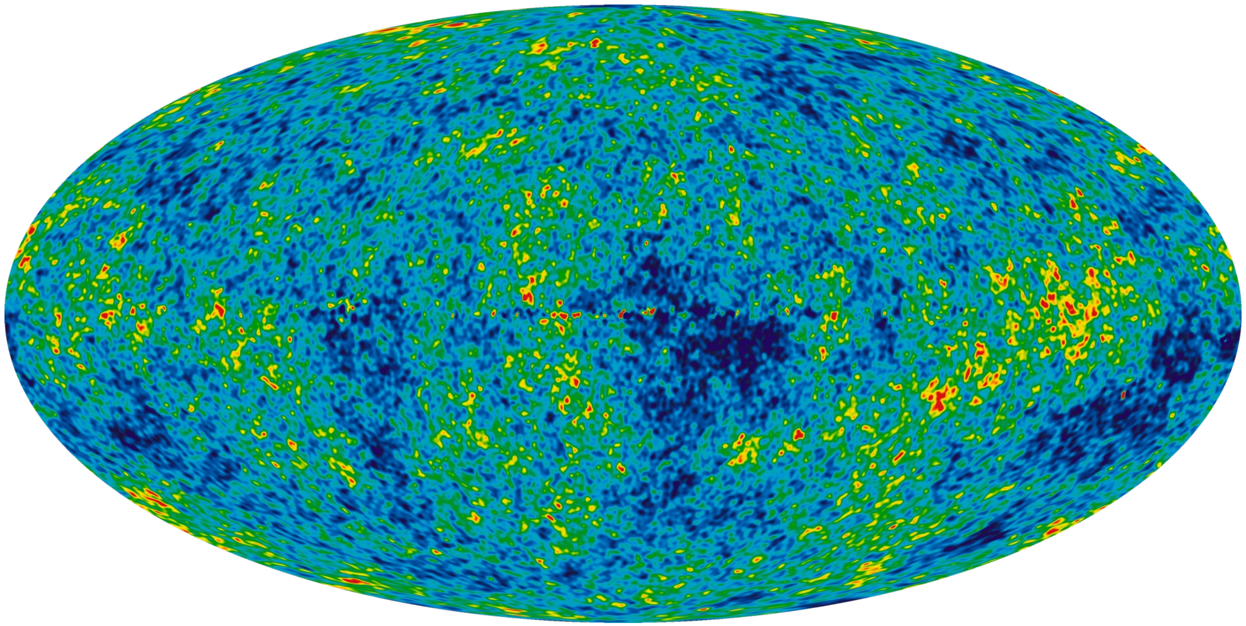
- Big Bang Nucleosynthesis: $^{2}H(p,\gamma)^{3}He$ (gamma rays)
- O-rich Pre-Solar Grains: $^{17}O(p,\alpha)^{14}N$ (charged particles)
- Neutron source for heavy elements: $^{13}C(\alpha,n)^{16}O$ (neutrons)

Big Bang Nucleosynthesis



Cosmic Microwave Background (CMB) radiation

oldest electromagnetic radiation in the Universe (~ 380,000 y after Big Bang)

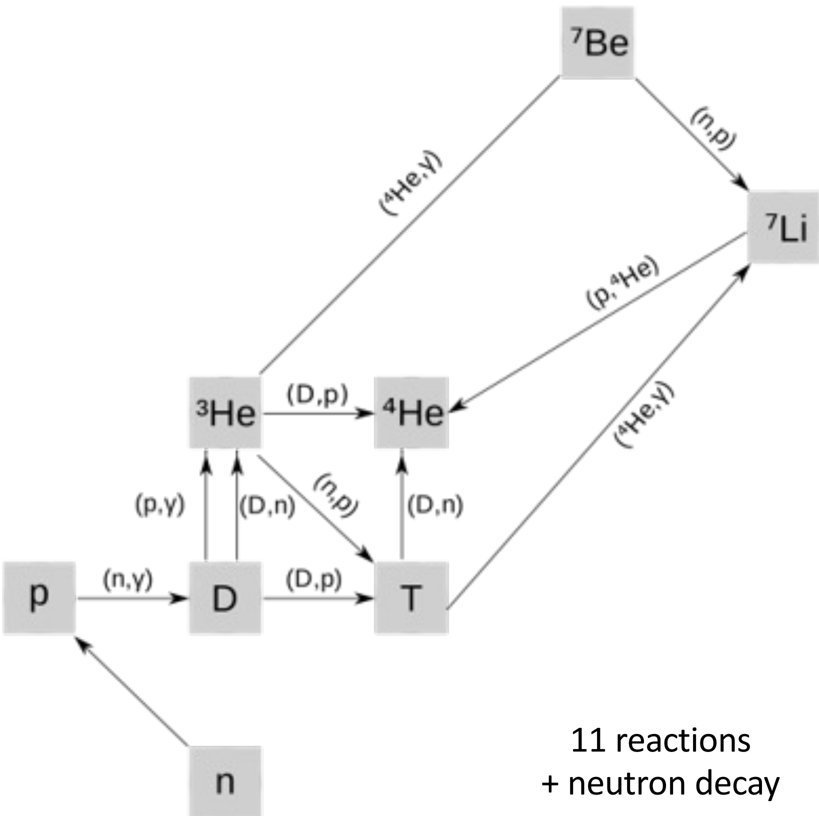


NASA - http://wmap.gsfc.nasa.gov/media/101080

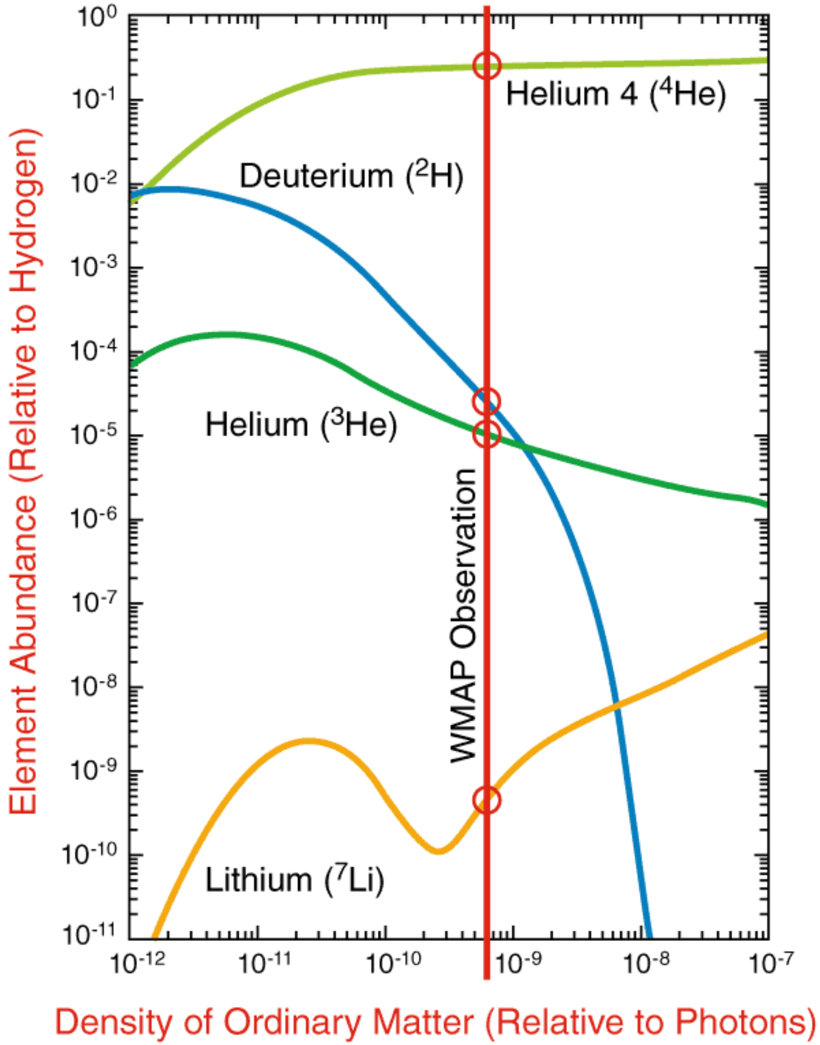
accidentally discovery by Penzias and Wilson in 1965 (Nobel Prize in 1978)

Big Bang Nucleosynthesis (BBN): 3 minutes after Big Bang

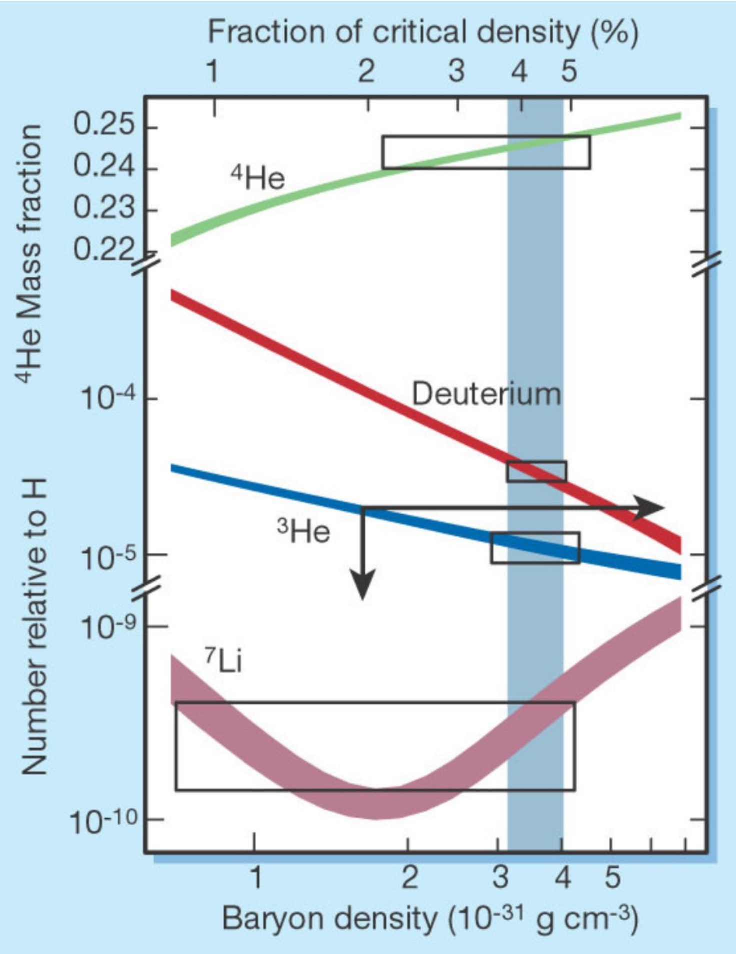
BBN is only tool to probe state of early universe



11 reactions
+ neutron decay



determine baryon density from comparison between BBN predictions and observations



Deuterium is an excellent baryometer

- D is only produced during Big Bang Nucleosynthesis
- D is destroyed easily in stars
- D abundance is the most sensitive to the baryon density $\Omega_b h^2$

- baryon density inferred from BBN → early epoch
- baryon density inferred from CMB → recombination epoch

(380000 years after Big Bang)

according to Standard Cosmological Model (ΛCDM)

baryon density can only vary as a result of Universe expansion, which can be calculated

if present-day value of Ω_b (BBN) = Ω_b (CMB) → validity of ΛCDM

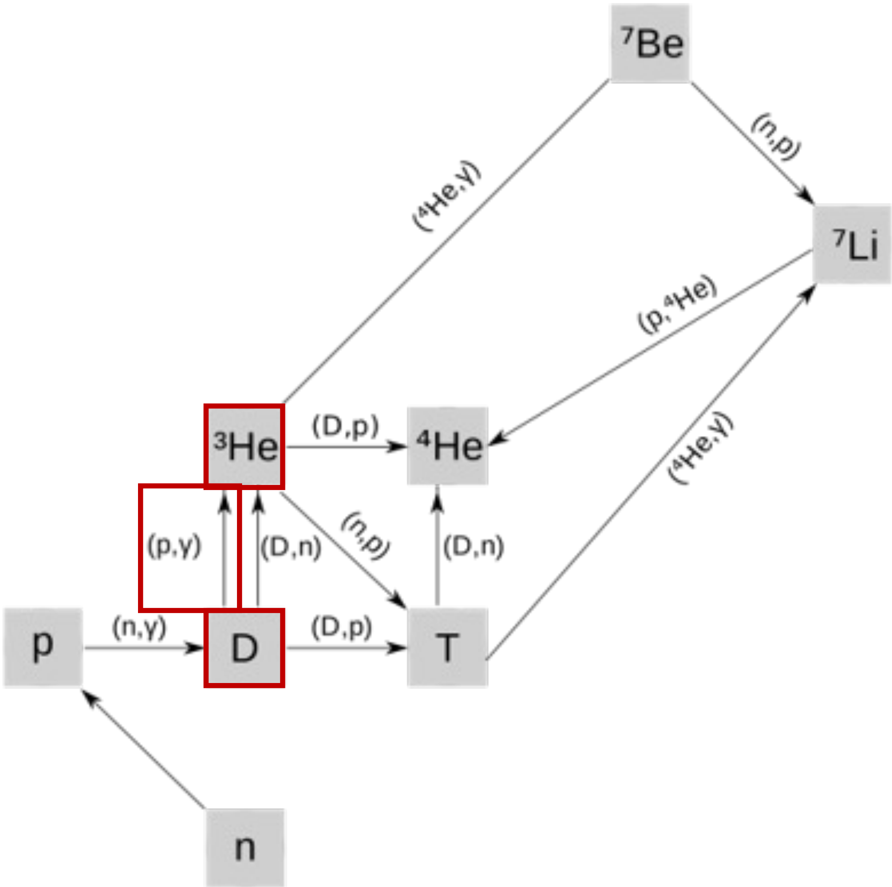
if present-day value of Ω_b (BBN) ≠ Ω_b (CMB) → new physics beyond ΛCDM

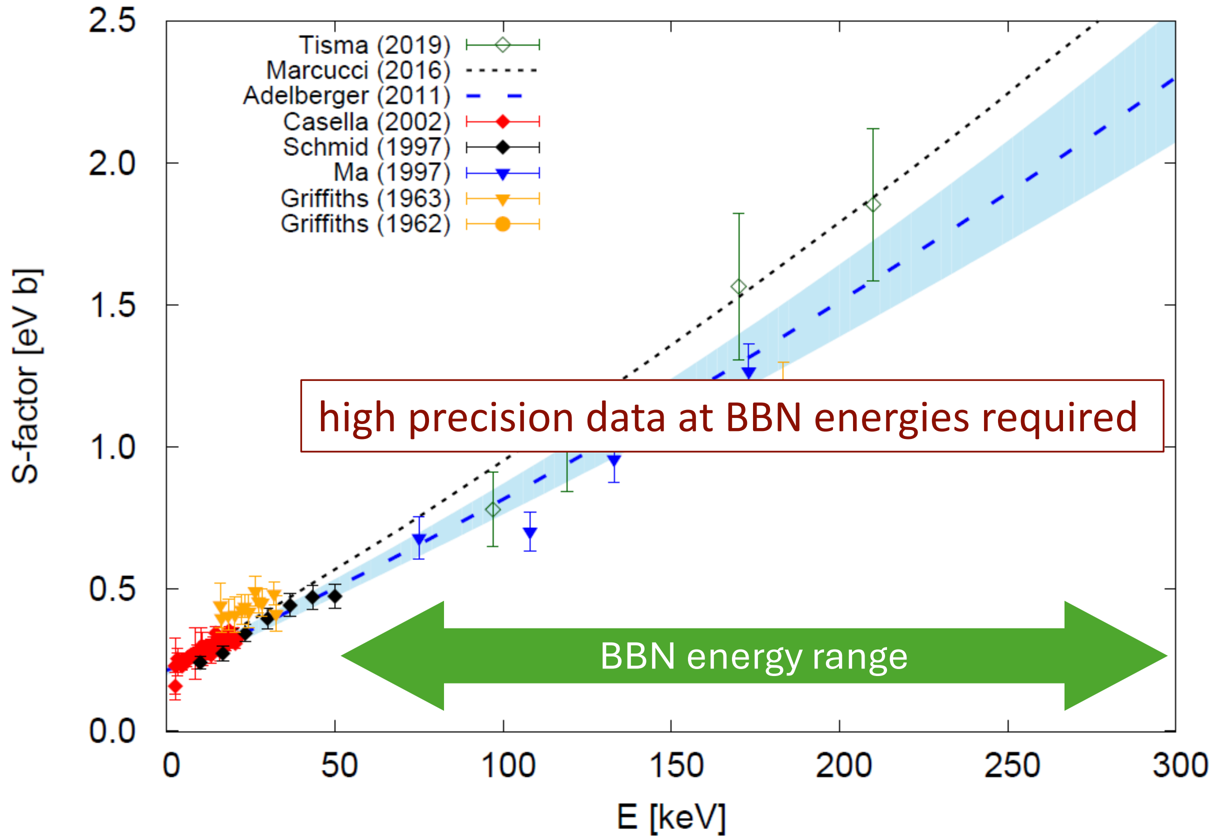
independent determinations of Ω_b can provide useful tests

M. Aliotta

The d(p,γ)^{3}He reaction: state of the art before study at LUNA

- Astronomical observations of deuterium abundance have reached % accuracy [Cooke et al, APJ 781 (2014) 31]
- BBN predictions of deuterium abundance affected by large uncertainties [Di Valentino et al, PRD 90 (2014) 023543]

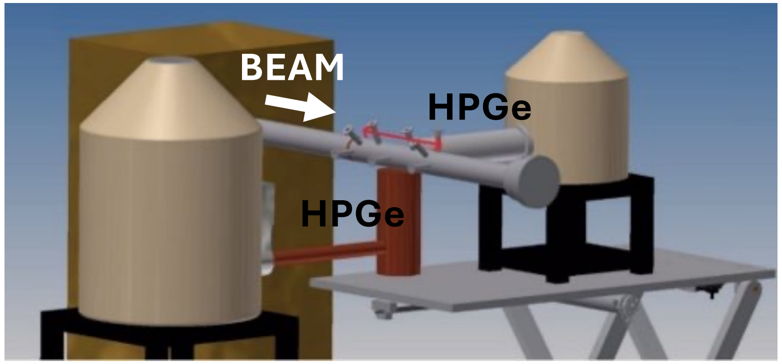


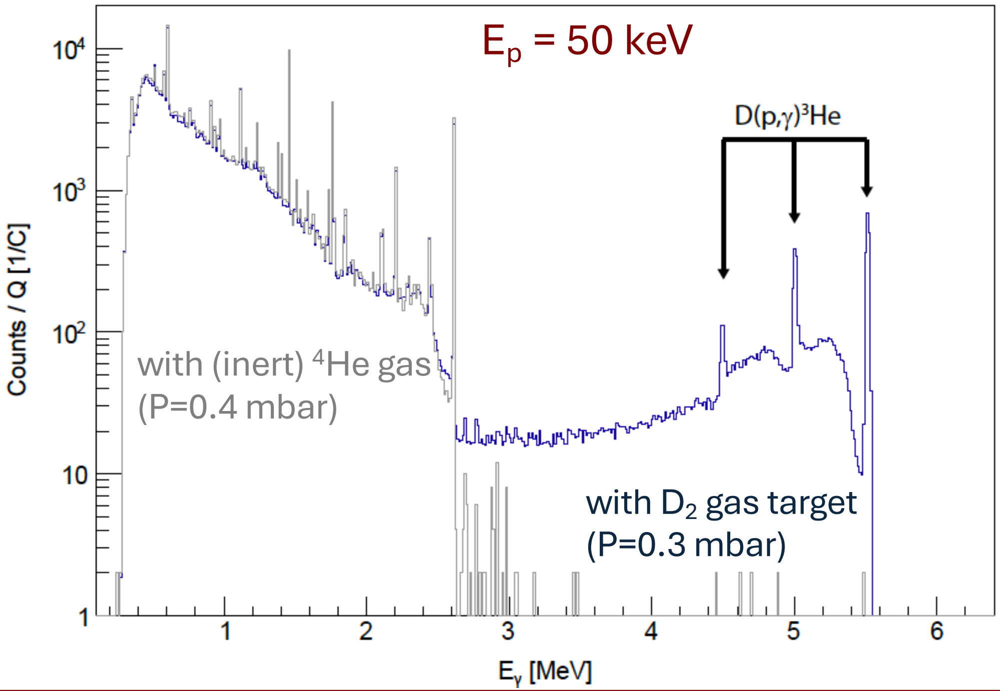


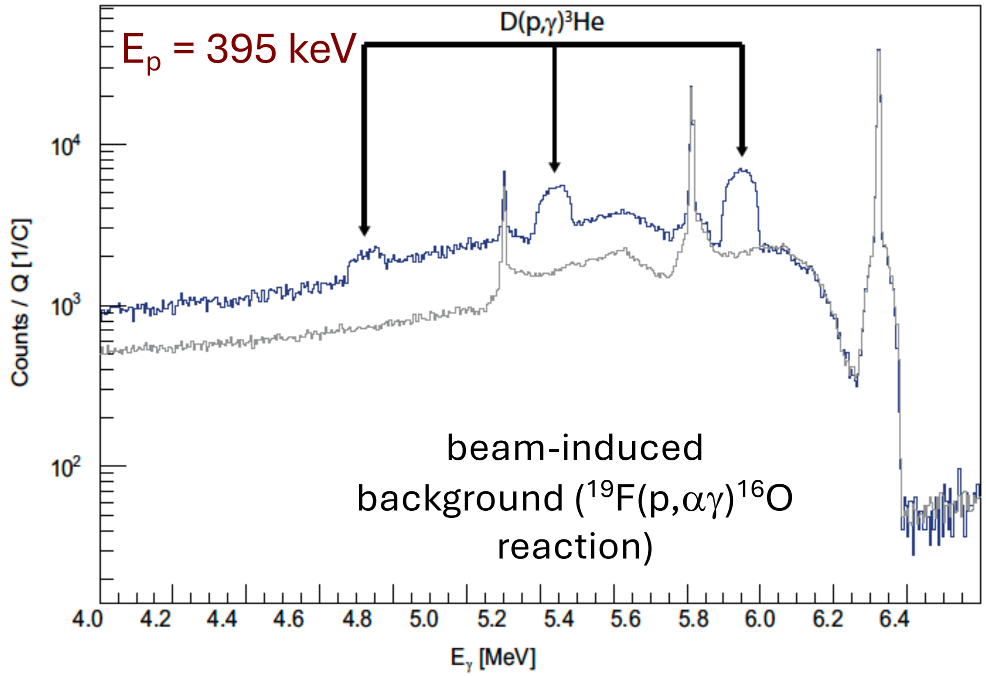
Primordial Deuterium Abundance:
The $d(p,\gamma)^3He$ Reaction

Experimental Setup

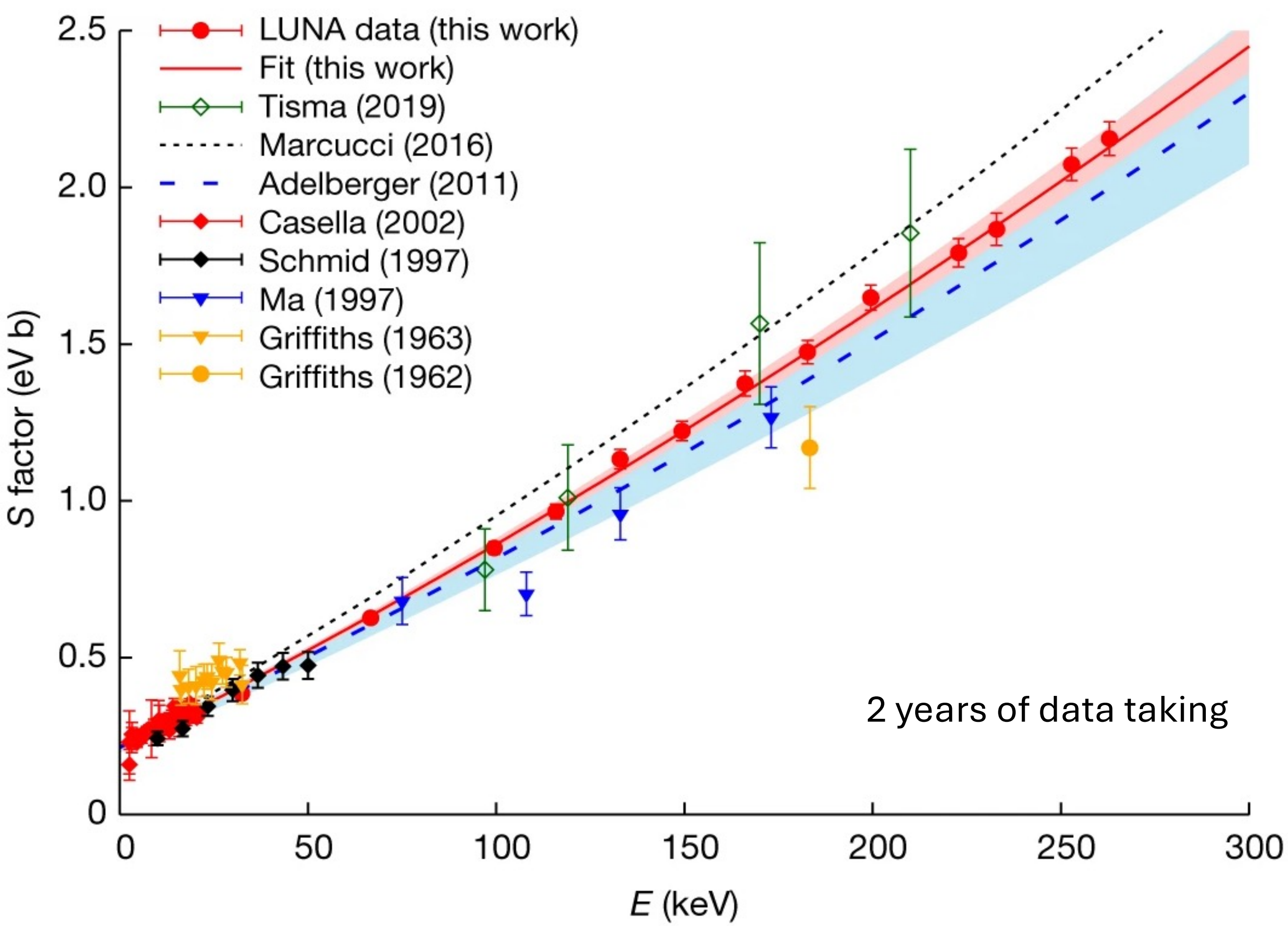
- proton beam (100 uA)
- E_{beam} = 50 - 400 keV (full BBN range)
- extended D_2 gas target (99.99% isotopic purity)
- Beam stop = calorimeter -> current measurement







The d(p,γ)^{3}He reaction at LUNA



Mossa et al. Nature, 587 (2020) 210

faster destruction of deuterium

better agreement with observations

Mossa et al. EPJA, 56 (2020) 144

Source	Method	$\Delta S/S$ (%)
Beam energy	Direct measurement	0.2
Energy loss	Low gas pressure	0.04
T and P profiles	Direct measurement	1.0
Beam heating	Direct measurement	0.5
Gas purity	Data sheet	0.1
Beam current	Calorimeter calibration	1.0
Efficiency	Direct measurement	2.0
Instrumental effects	Pulser method	0.2
Angular distribution	Simulations	0.5
Total		2.6

Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, C Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarell

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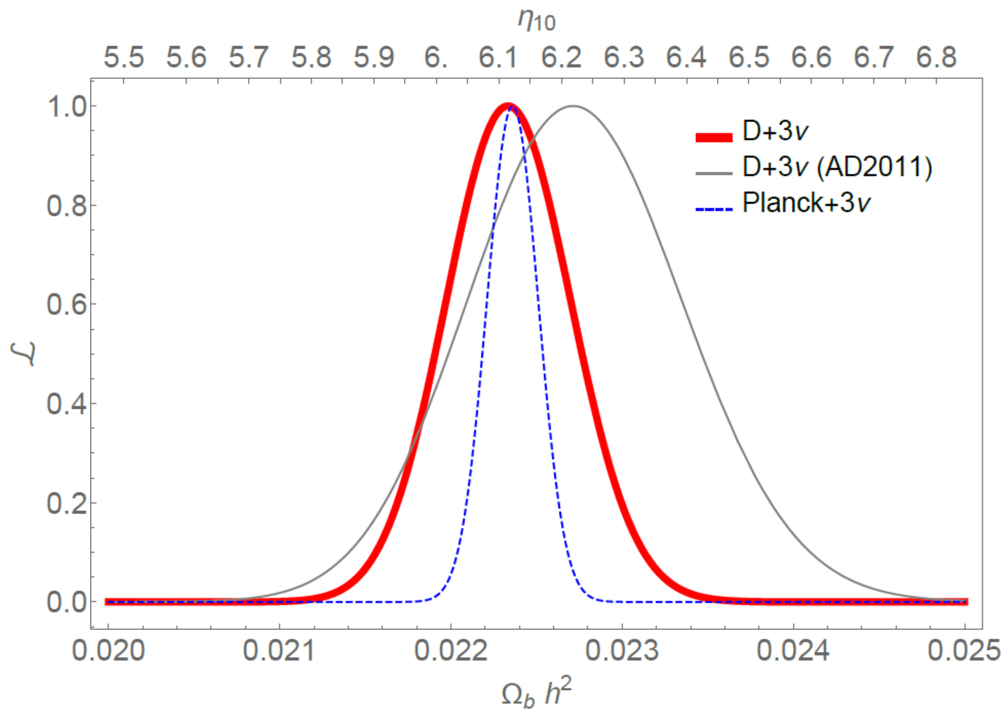
Nature **587**, 210–213(2020) | Cite this article

standard cosmological model seems safe for now...

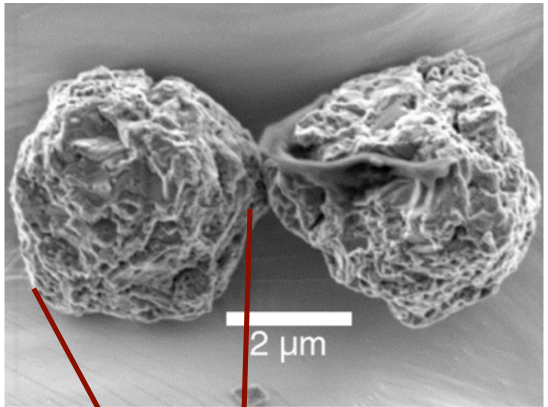


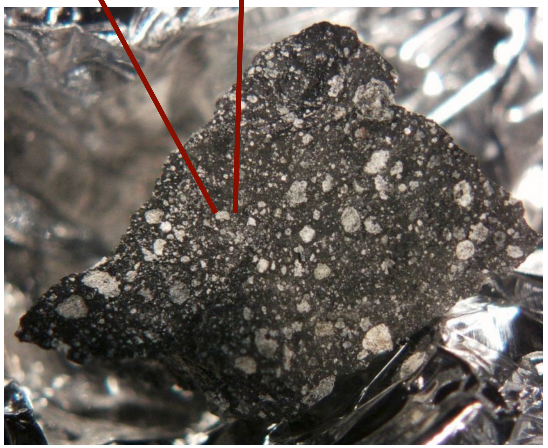
baryon density ($\Omega_b h^2$) now in excellent agreement with Planck and with comparable uncertainty

analysis by
Gianpiero Mangano and Ofelia Pisanti (Uni Naples)

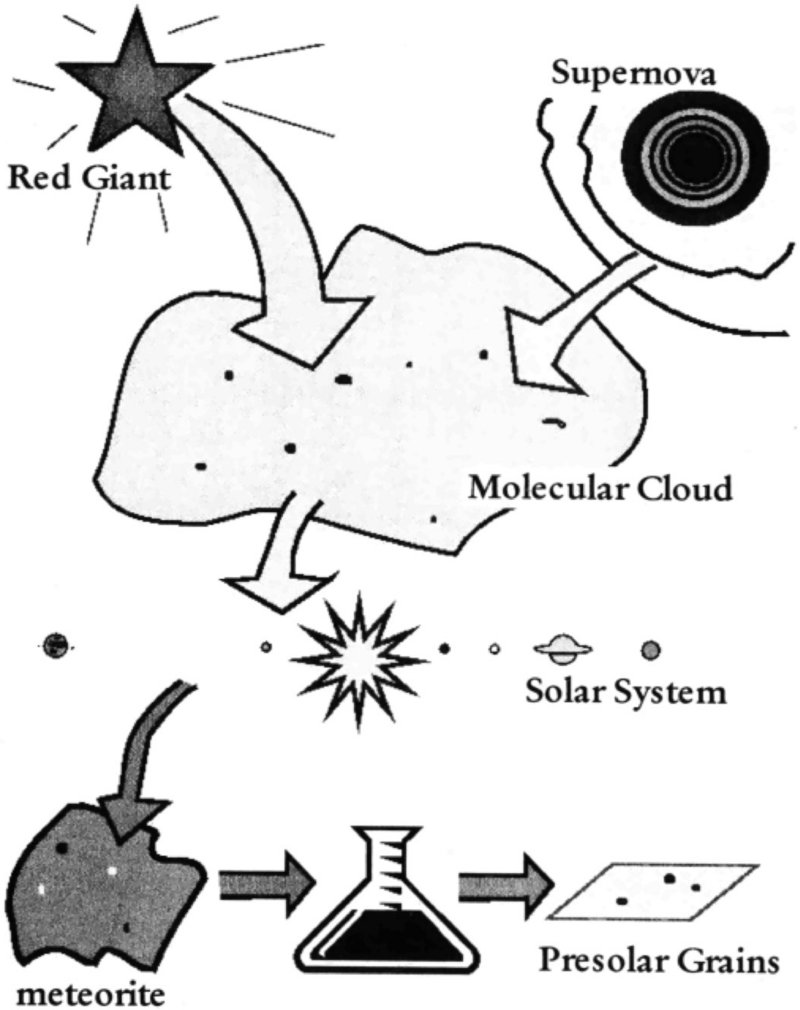
Pre-Solar Grains Composition:
the $^{17}O(p,\alpha)^{14}N$ reaction

Pre-solar grains:
stellar dust trapped in meteorites





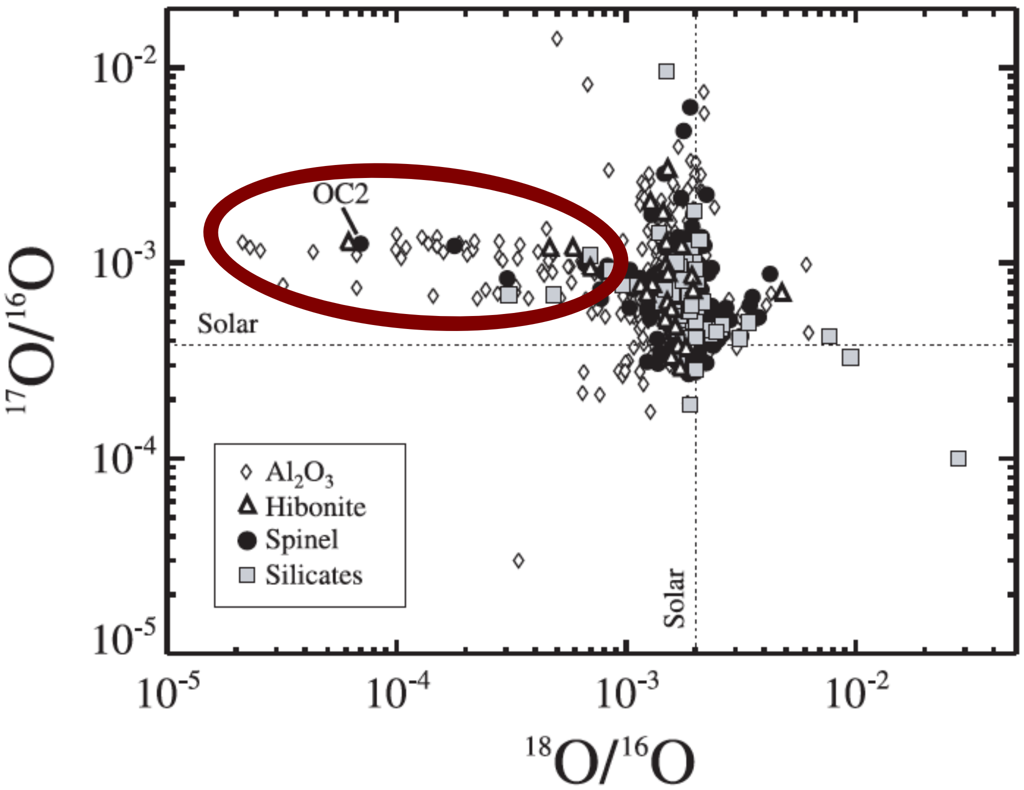
Murchison meteorite
geosci.uchicago.edu

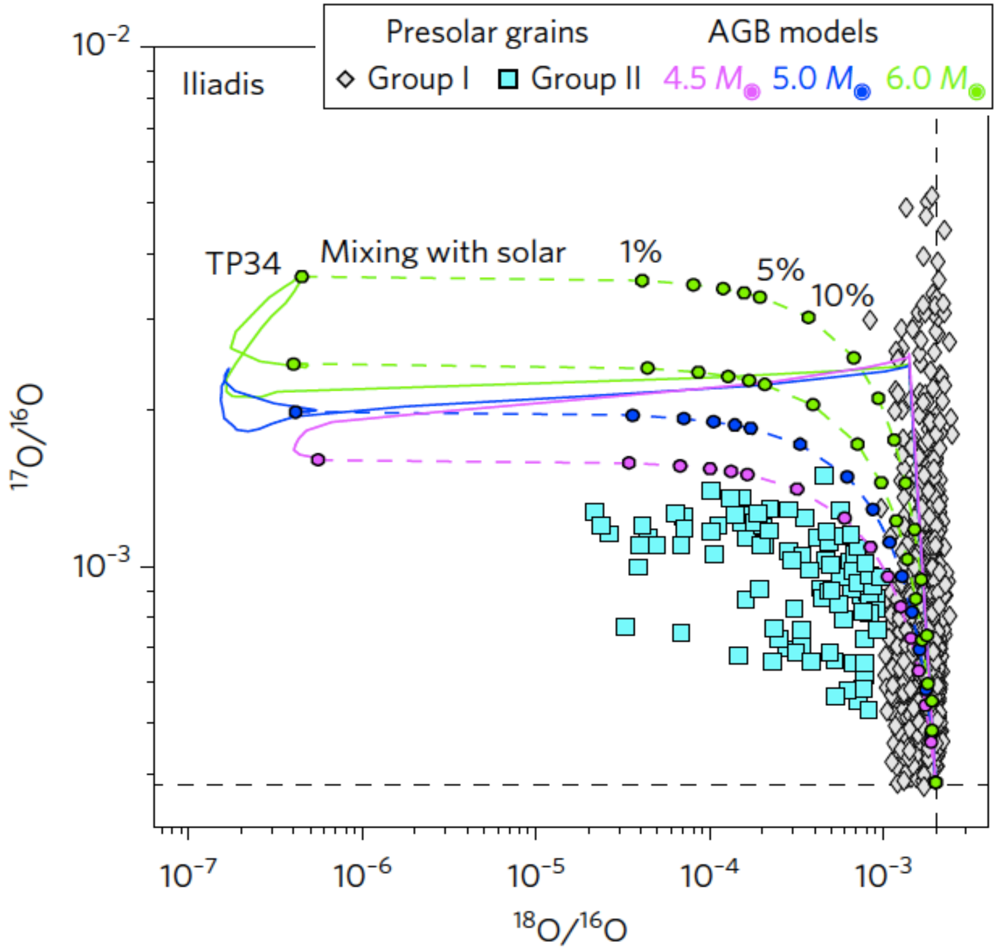


Hoppe & Zinner, Journ. Geophys. Res. 105 (2000) 10371

Pre-solar grains in meteorites

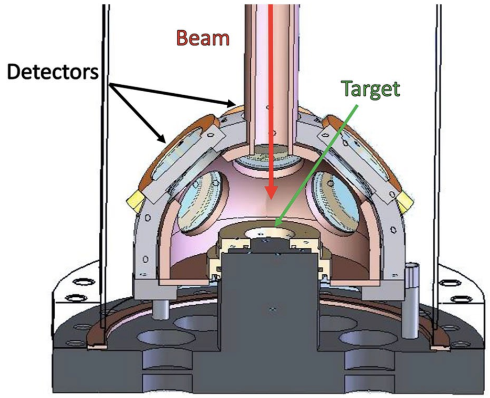
puzzling origin of Oxygen-rich grains

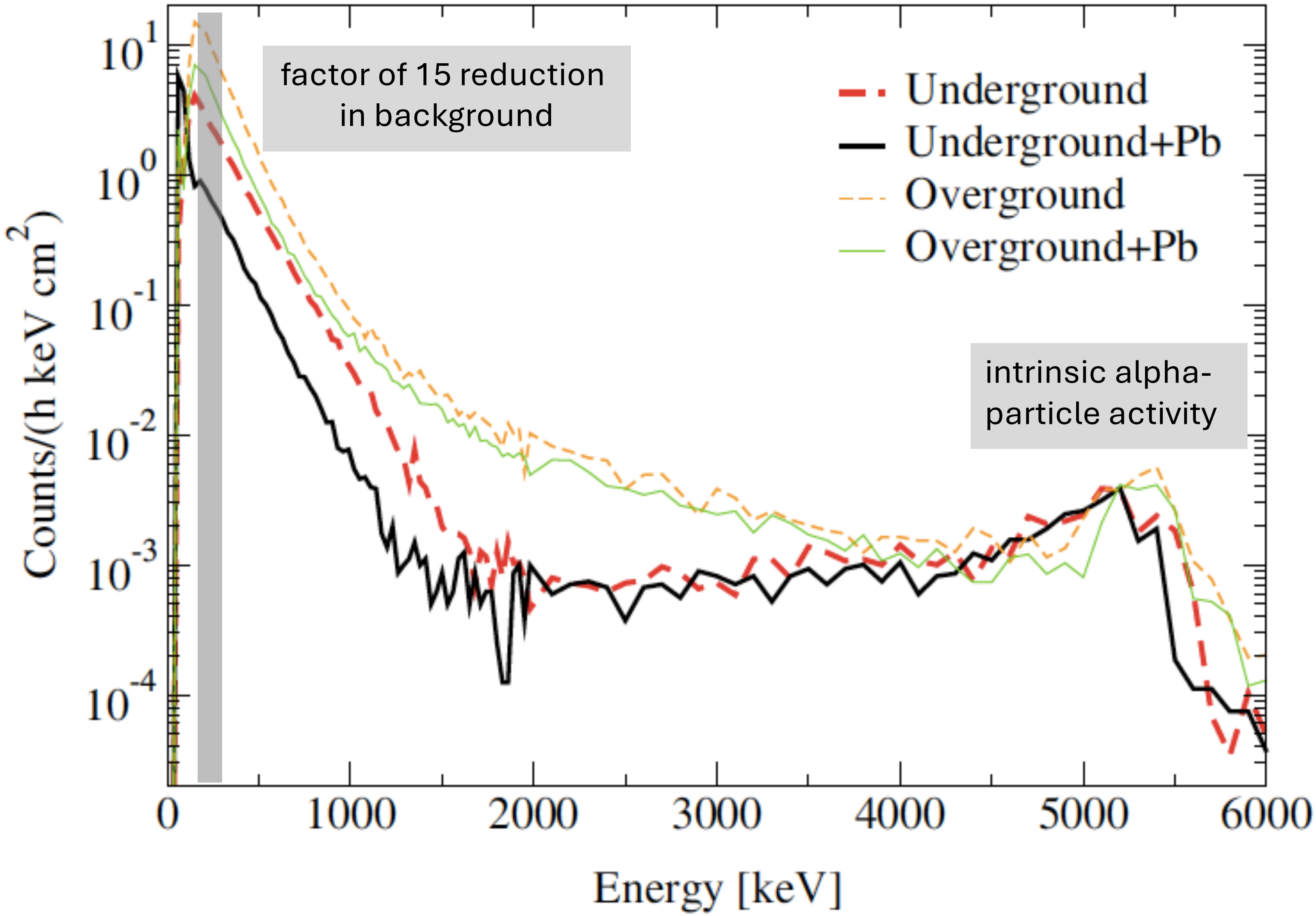




an improved study of $^{17}O(p,\alpha)^{14}N$ was needed

Background Suppression





Bruno et al EJPA 51 (2015) 94

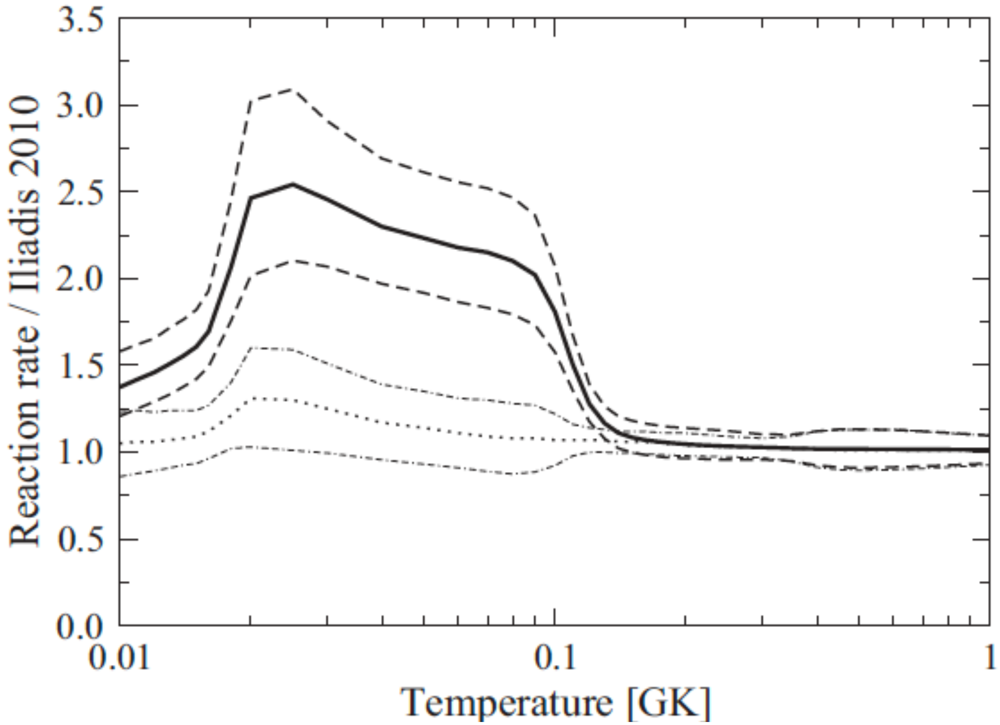
$^{17}O(p,\alpha)^{14}N$ Results

PRL 117, 142502 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

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

C. G. Bruno,[1,*] D. A. Scott,[1] M. Aliotta,[1,†] A. Formicola,[2] A. Best,[3] A. Boeltzig,[4] D. Bemmerer,[5] C. Broggini,[6] A. Caciolli,[7] F. Cavanna,[8] G. F. Ciani,[4] P. Corvisiero,[8] T. Davinson,[1] R. Depalo,[7] A. Di Leva,[3] Z. Elekes,[9] F. Ferraro,[8] Zs. Fülöp,[9] G. Gervino,[10] A. Guglielmetti,[11] C. Gustavino,[12] Gy. Gyürky,[9] G. Imbriani,[3] M. Junker,[2] R. Menegazzo,[6] V. Mossa,[13] F. R. Pantaleo,[13] D. Piatti,[7] P. Prati,[8] E. Somorjai,[9] O. Straniero,[14] F. Strieder,[15] T. Szücs,[5] M. P. Takács,[5] and D. Trezzi[11]

15x lower background underground



reaction rate ~ 2x higher than previously assumed

reaction becomes effective at lower temperatures, i.e. those attained in IM AGB stars

On the origin of Group II grains

nature astronomy
LETTERS
PUBLISHED: 30 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0027

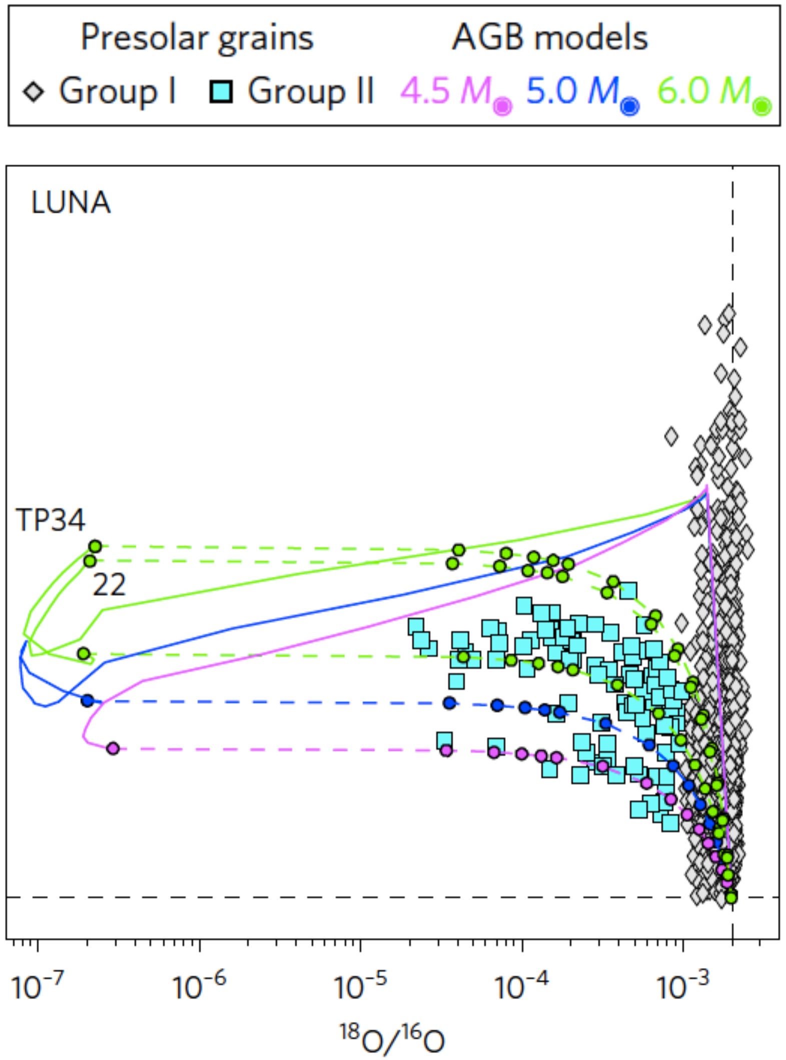
Origin of meteoritic stardust unveiled by a revised proton-capture rate of ^{17}O

M. Lugaro[1,2*], A. I. Karakas[2-4], C. G. Bruno[5], M. Aliotta[5], L. R. Nittler[6], D. Bemmerer[7], A. Best[8], A. Boeltzig[9], C. Broggini[10], A. Caciolli[11], F. Cavanna[12], G. F. Ciani[9], P. Corvisiero[12], T. Davinson[5], R. Depalo[11], A. Di Leva[8], Z. Elekes[13], F. Ferraro[12], A. Formicola[14], Zs. Fülöp[13], G. Gervino[15], A. Guglielmetti[16], C. Gustavino[17], Gy. Gyürky[13], G. Imbriani[8], M. Junker[14], R. Menegazzo[10], V. Mossa[18], F. R. Pantaleo[18], D. Piatti[11], P. Prati[12], D. A. Scott[5,†], O. Straniero[14,19], F. Strieder[20], T. Szücs[13], M. P. Takács[7] and D. Trezzi[16]

new LUNA rate allows to reproduce correct abundances

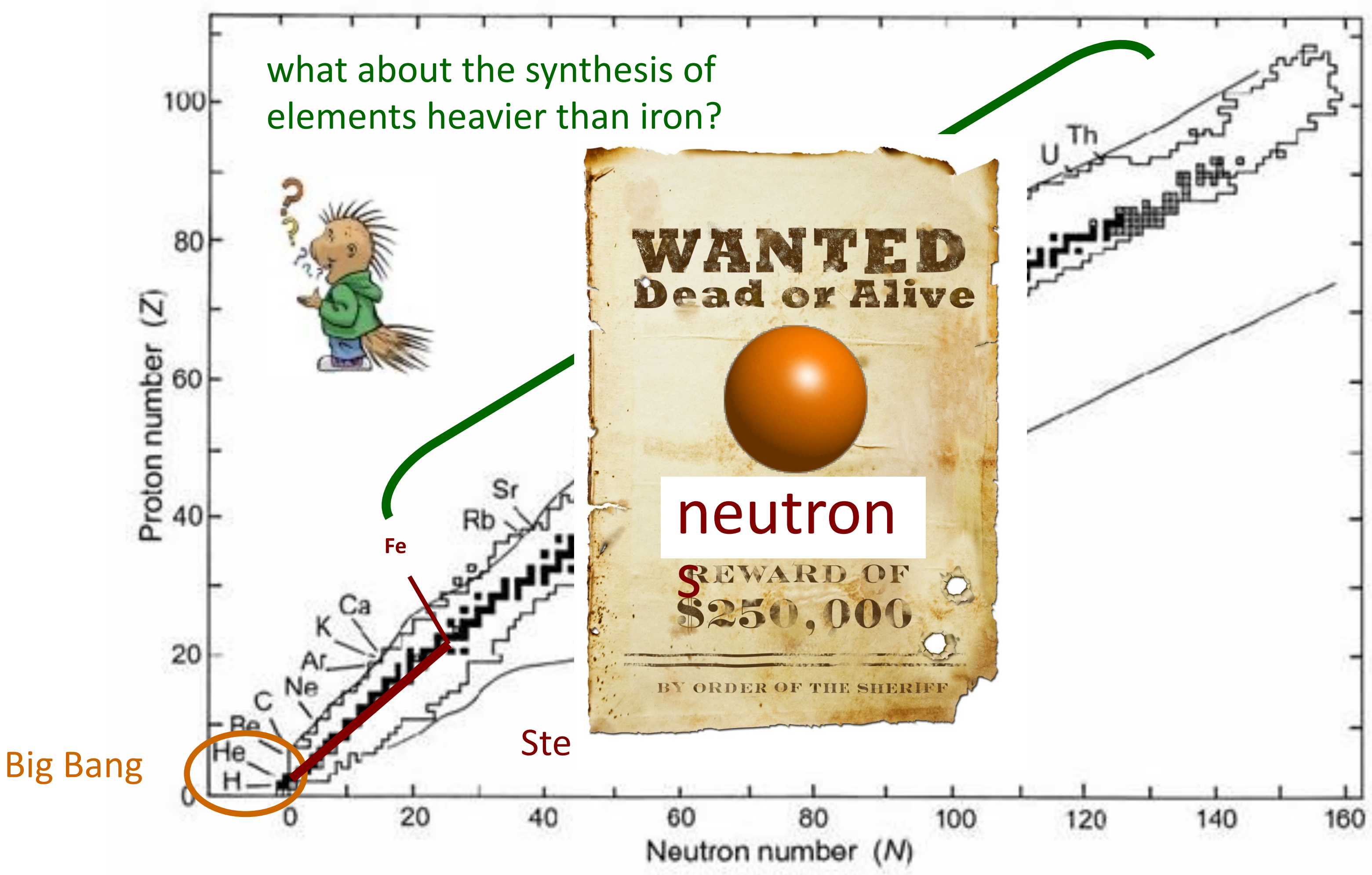
confirms intermediate mass AGB as likely site of production

for oxygen-rich pre-solar grains



The Creation of Heavy Elements: the $^{13}C(\alpha,n)^{16}O$ reaction

M Aliotta



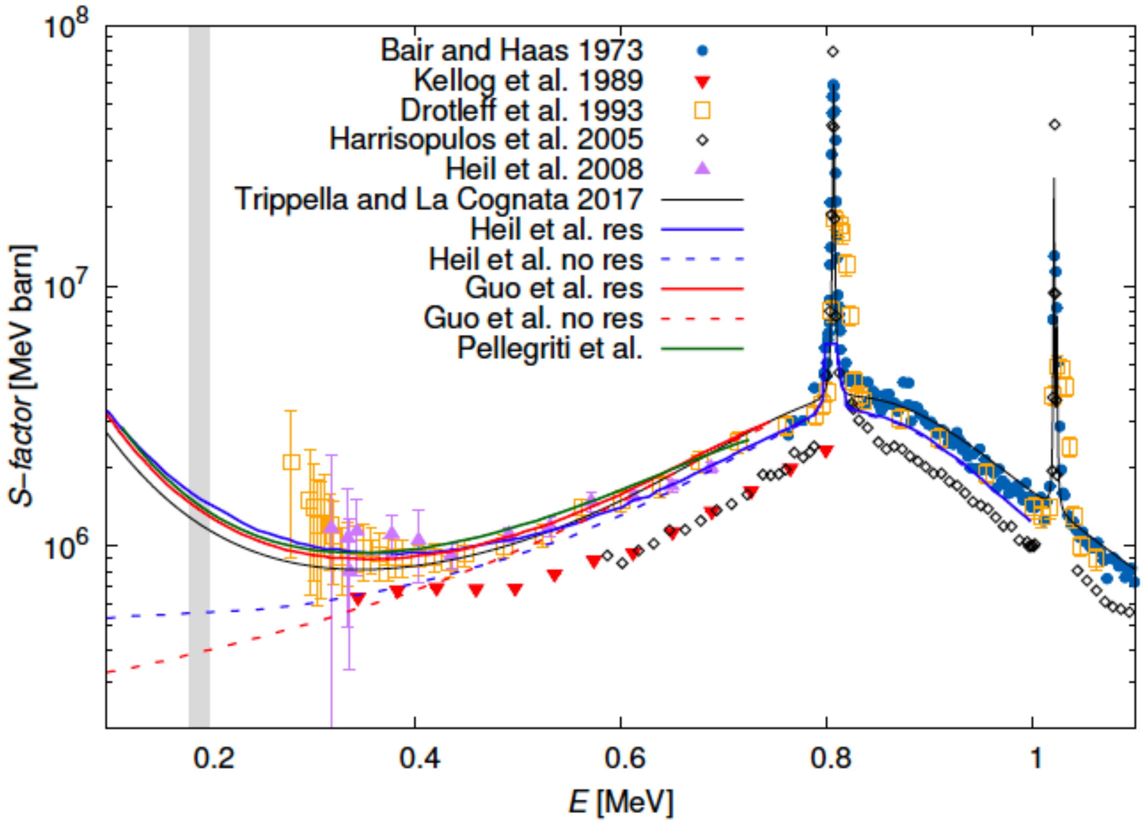
Neutron capture reactions: the s(low) and the r(apid) processes

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

importance: s-process in AGB stars

Gamow region: 130 - 250 keV

min. meas. E_{cm}: 280 keV

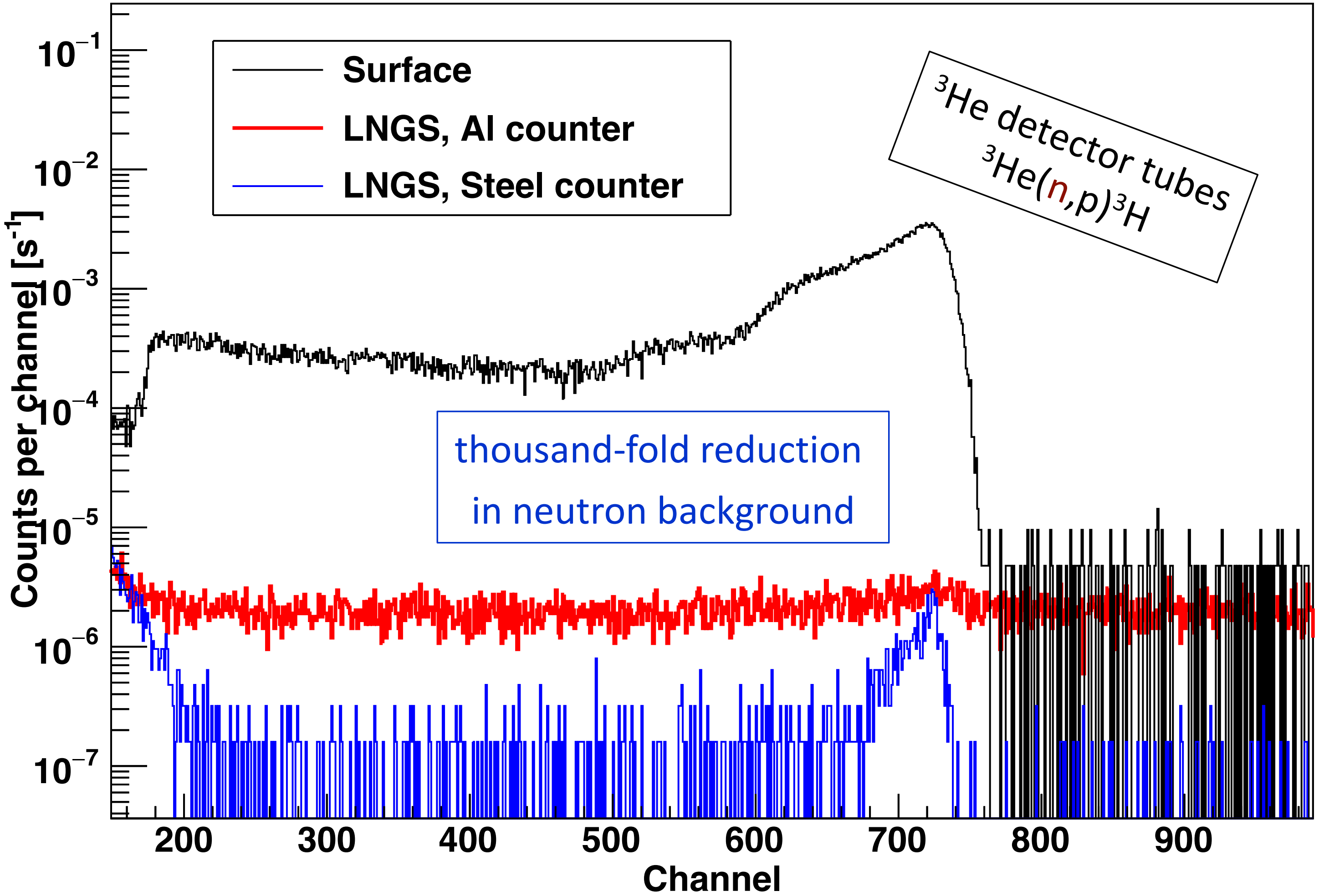


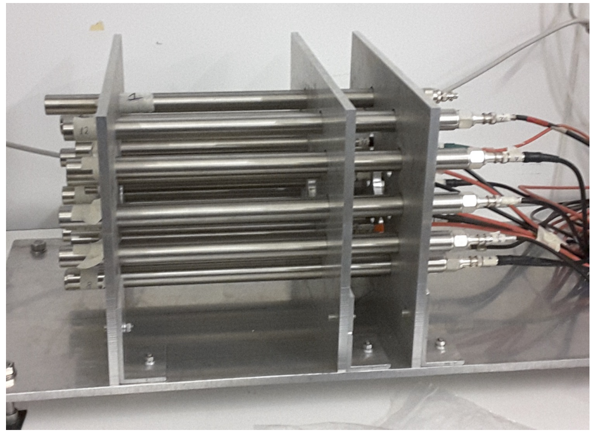
Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55

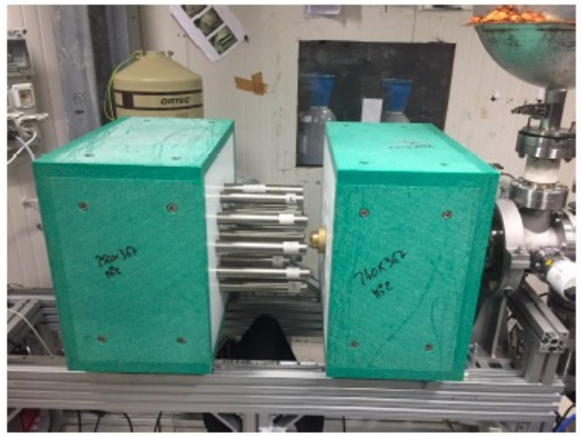
mainly hampered by cosmic background → excellent case for underground study

Neutron Background Reduction at LNGS

Csedreki et al. NIMA 994 (2021) 165081







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

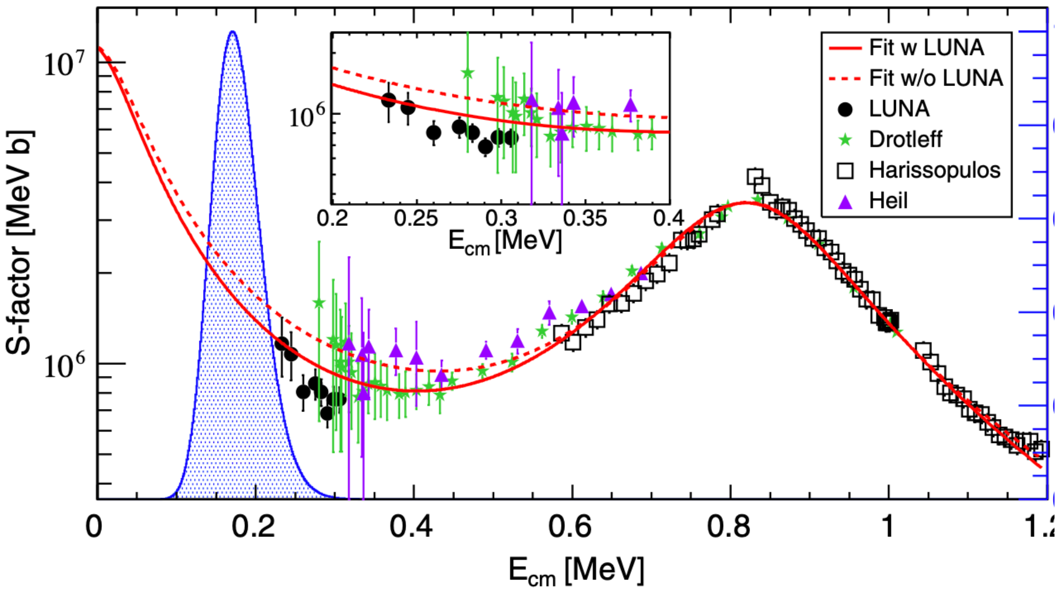
$^{13}C(\alpha,n)^{16}O$

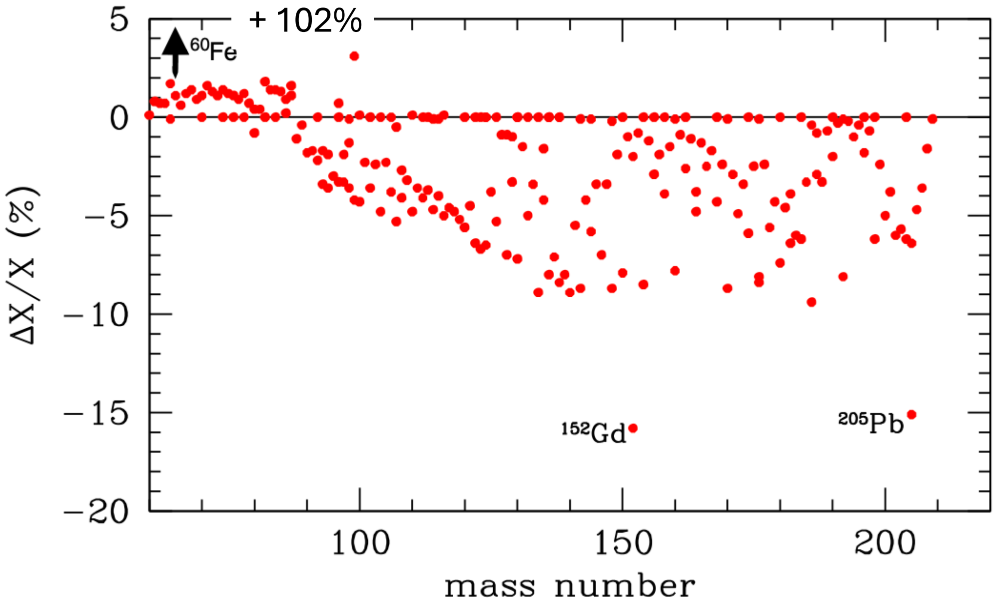
PHYSICAL REVIEW LETTERS **127,** 152701 (2021)

Direct Measurement of the $^{13}C(\alpha,n)^{16}O$ Cross Section into the *s*-Process Gamow Peak

G. F. Ciani,[1,2,3] L. Csedreki,[1,2,3] D. Rapagnani,[4,5] M. Aliotta,[6] J. Balibrea-Correa,[4,5] F. Barile,[7,8] D. Bemmerer,[9] A. Best,[4,5,*] A. Boeltzig,[4,5] C. Broggini,[10] C. G. Bruno,[6] A. Caciolli,[10,11] F. Cavanna,[12] T. Chillery,[6] P. Colombetti,[12] P. Corvisiero,[13,14] S. Cristallo,[15,16] T. Davinson,[6] R. Depalo,[11,10] A. Di Leva,[4,5] Z. Elekes,[3] F. Ferraro,[13,14] E. Fiore,[7,8] A. Formicola,[2,†] Zs. Fülöp,[3] G. Gervino,[17,18] A. Guglielmetti,[19,20] C. Gustavino,[21] Gy. Gyürky,[3] G. Imbriani,[4,5] M. Junker,[2] M. Lugaro,[22,23] P. Marigo,[10,11] E. Masha,[19,20] R. Menegazzo,[10] V. Mossa,[8] F. R. Pantaleo,[7,8] V. Paticchio,[8] R. Perrino,[8,‡] D. Piatti,[10,11] P. Prati,[13,14] L. Schiavulli,[7,8] K. Stöckel,[9,24] O. Straniero,[15,2] T. Szücs,[3] M. P. Takács,[9,24] F. Terrasi,[25,5] D. Vescovi,[16,26] and S. Zavatarelli[14]

(12 months data taking)





The Present:
Currently Ongoing

Just Completed and Ongoing Reaction Studies at LUNA (with strong Edinburgh involvement)

$^{16}O(p,\gamma)^{17}F$ — $^{16}O/^{17}O$ ratio in red giants and AGB spectra; pre-solar grain compositions

Duncan Robb's
PhD project

$^{21}Ne(p,\gamma)^{22}Na$ — first and slowest reaction in NeNa cycle; ^{22}Na production in novae

Ragan Sidhu
(now Fellow @Surrey)

$^{23}Na(p,\alpha)^{20}Ne$ — O-Na anti-correlation in spectra of globular clusters

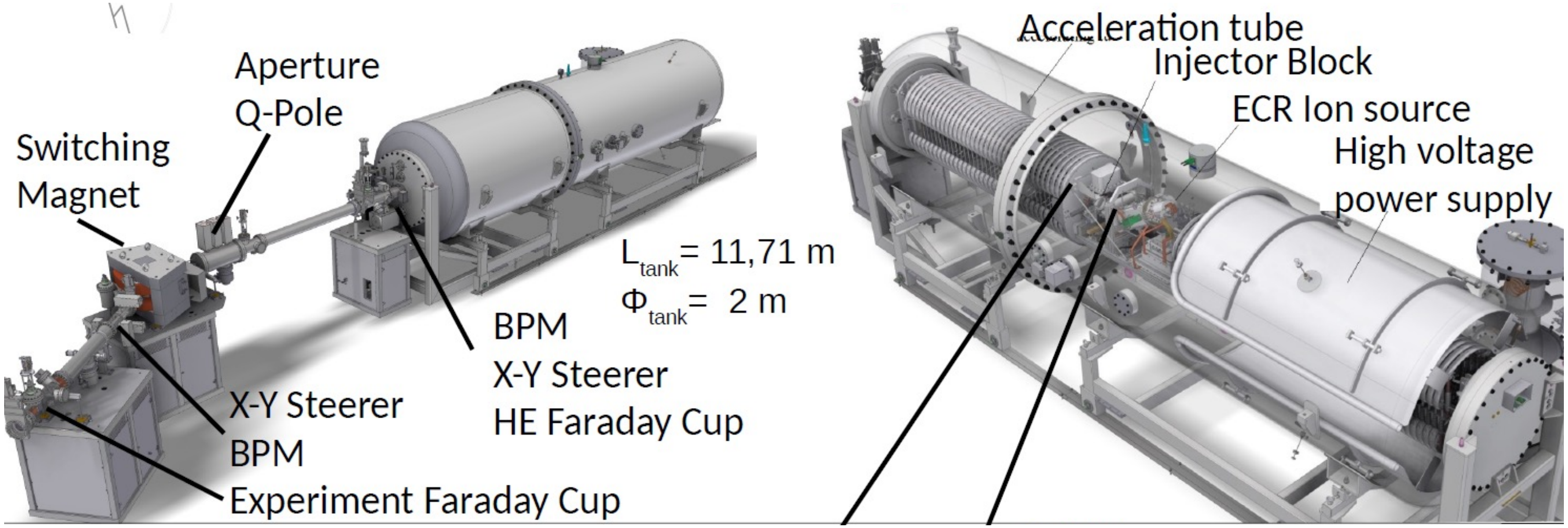
$^{27}Al(p,\alpha)^{24}Mg$ — Mg and Al abundances; MgAl cycle; ^{26}Al abundance

Lucia Barbieri's
PhD project

M. Aliotta

A new 3.5 MV Accelerator with ECR Ion Source: Bellotti Ion Beam Facility

LUNA



Sen et al. NIM B450 (2019) 390

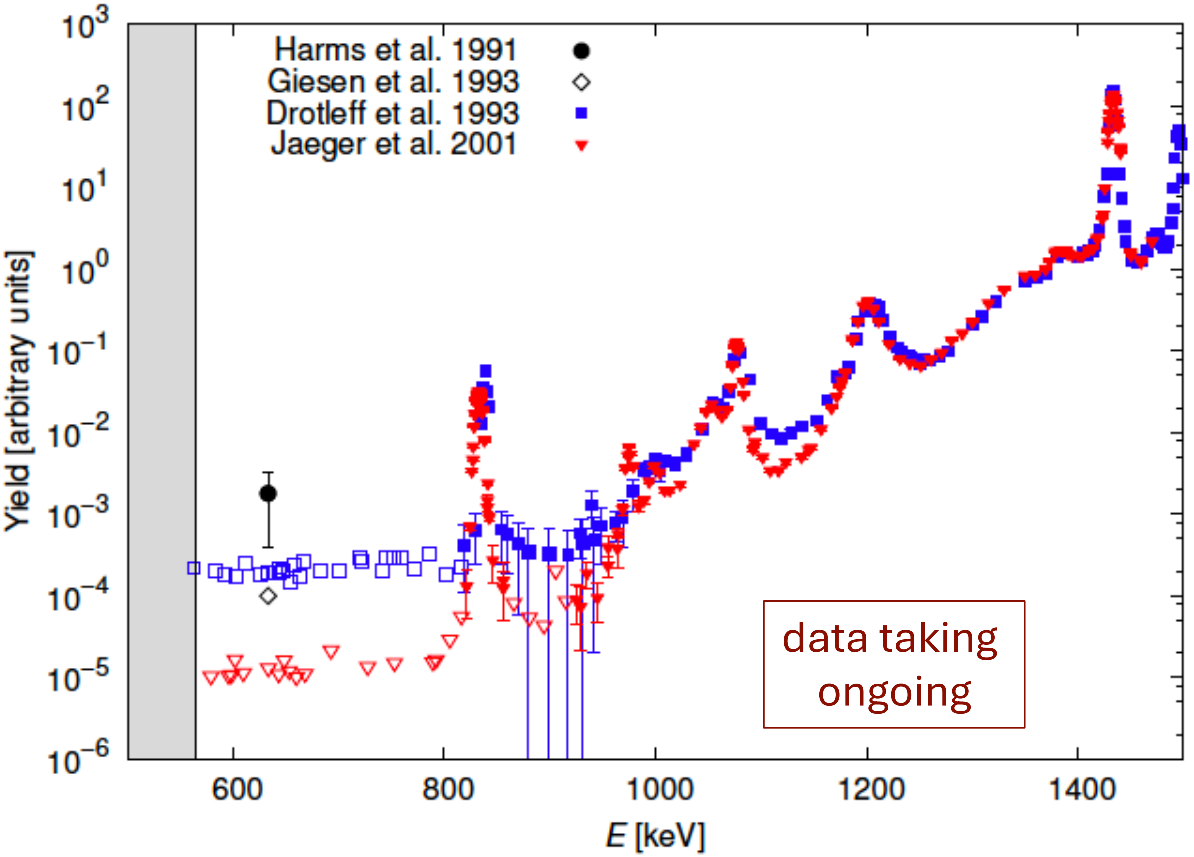
Intense H, He, and C beams

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

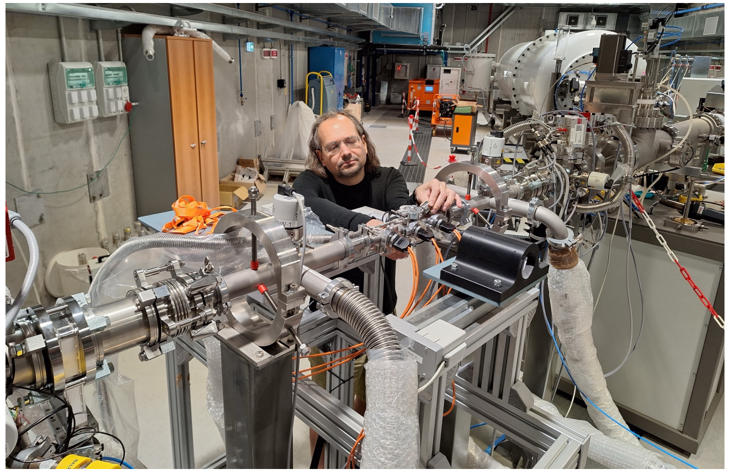
importance: weak s-process component

energy of interest: 360-690 keV

min. measured E: 700 keV



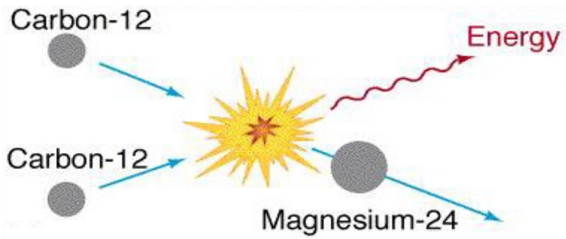
Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55



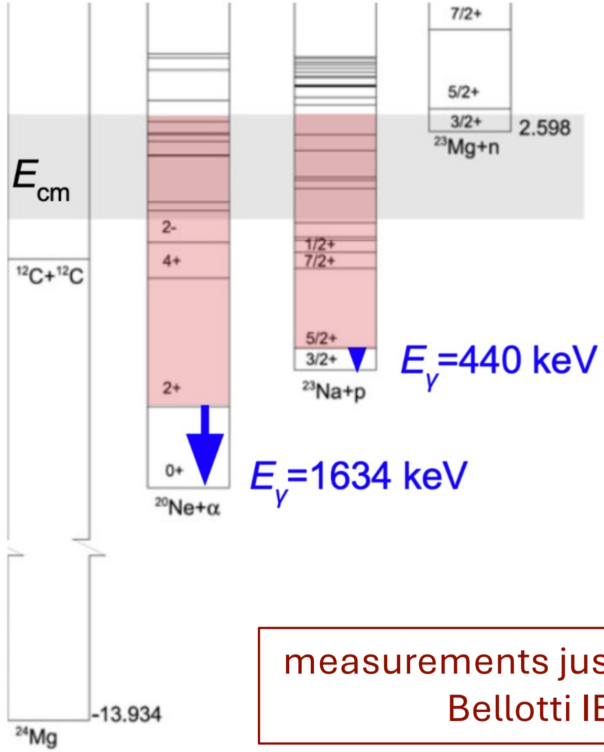
European Research Council
Established by the European Commission

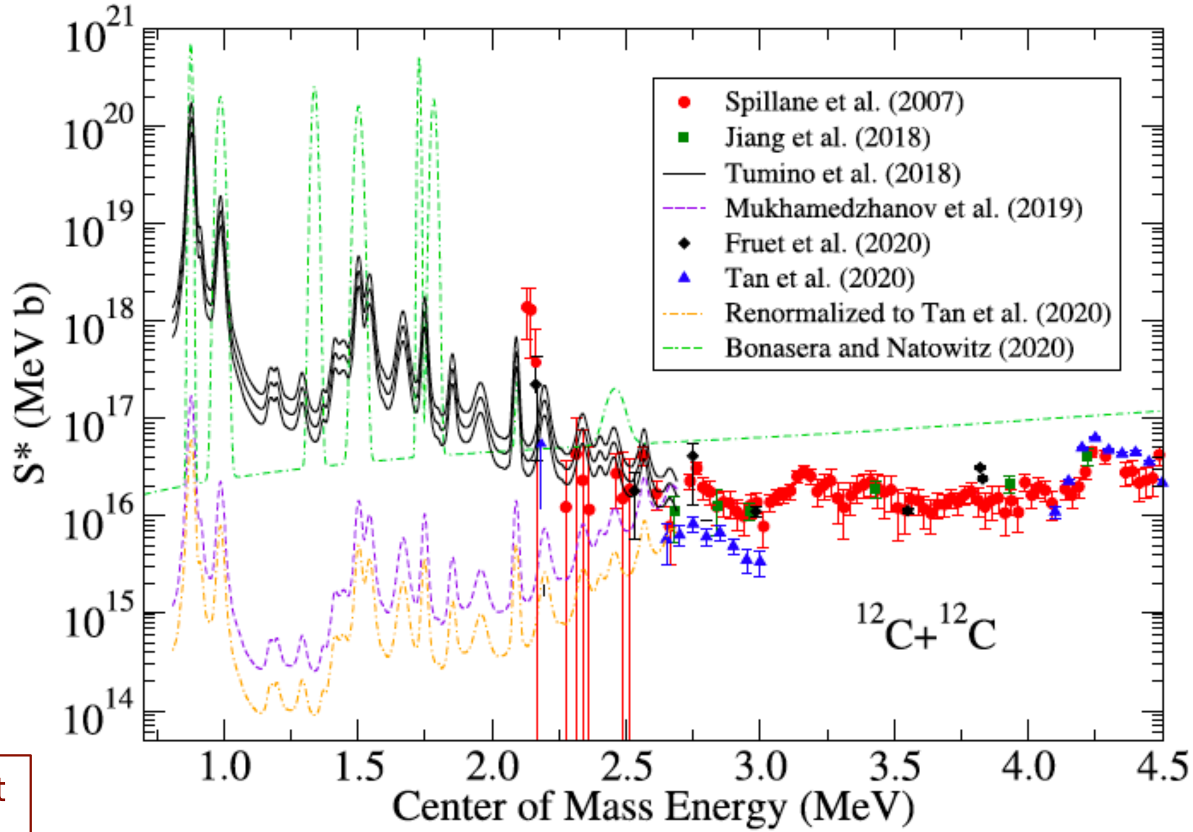
SHADES
Andreas Best (Naples)

$^{12}C + ^{12}C$



<u>$^{12}C/^{16}O$ BURNING</u> ^{12}C ashes = Ne, Na, Mg
^{16}O ashes = Al, … Si





measurements just started at Bellotti IBF

Aliotta et al. J. Phys. G: Nucl. Part. Phys. 49 (2022) 010501

Plans for the Future…

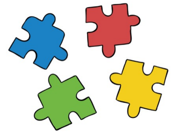
NUclear CLustering Effects in Astrophysical Reactions

NUCLEAR

European Research Council
Established by the European Commission

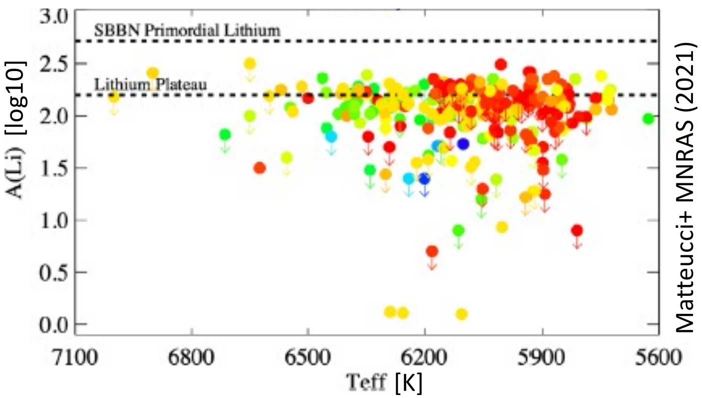
UK Research
and Innovation

Nucleosynthesis in First Stars and Other Puzzles



Long-Standing Questions in Nuclear Astrophysics

Q1. Cosmological Lithium Problem



Matteucci+ MNRAS (2021)

factor of 3 discrepancy between observed and predicted Li abundance

↓

Standard Model of Particle Physics + Cosmology

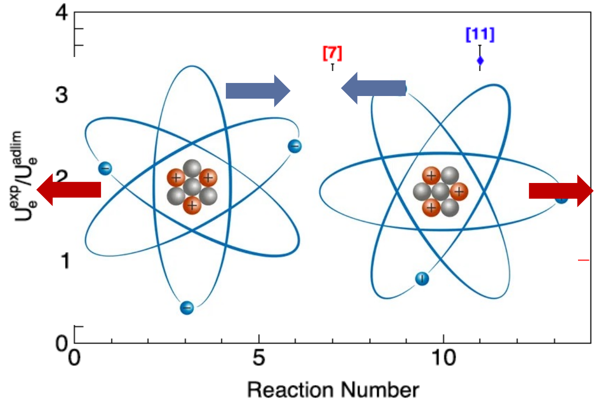
Q2. Nucleosynthesis in First Stars

made of pristine H and He
very massive → need CNO nuclei

↓

Chemical Evolution of Early Universe + Astronomical Observations (JWST)

Q3. Electron Screening Puzzle



Spitaleri+ PLB (2016)

discrepancy between experiment and theory remains unexplained

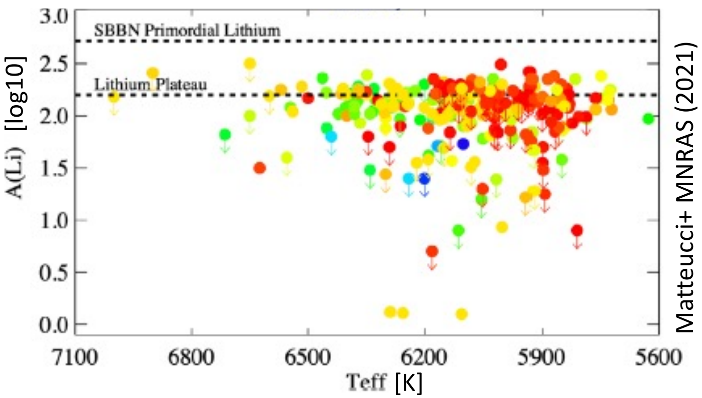
↓

Reactions in Plasmas
Fusion-driven Energy Generation

Long-Standing Questions in Nuclear Astrophysics

THE UNIVERSITY of EDINBURGH

Q1. Cosmological Lithium Problem



Matteucci+ MNRAS (2021)

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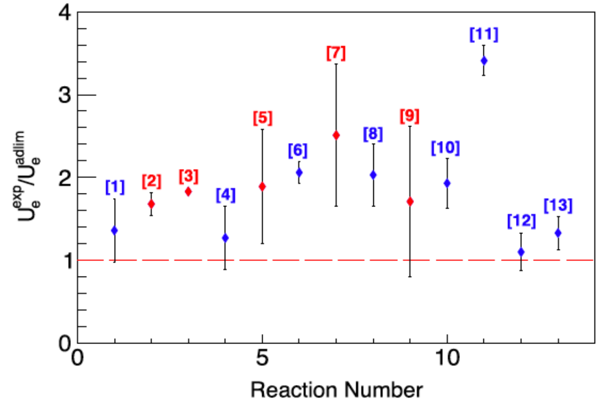


Spitaleri+ PLB (2016)

discrepancy between experiment and theory remains unexplained

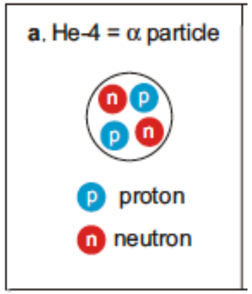
key idea:

Nuclear Clustering

⬇

key to unlock all three puzzles

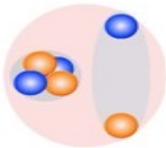
Nuclear Clustering



very stable configurations

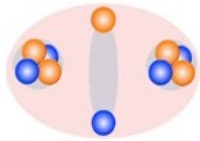
→ building blocks for other nuclei

^{6}Li



$\alpha \oplus d$

^{10}B



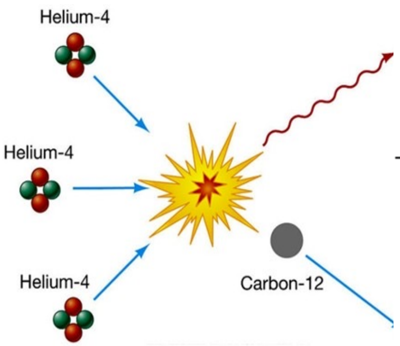
$\alpha \oplus d \oplus \alpha$

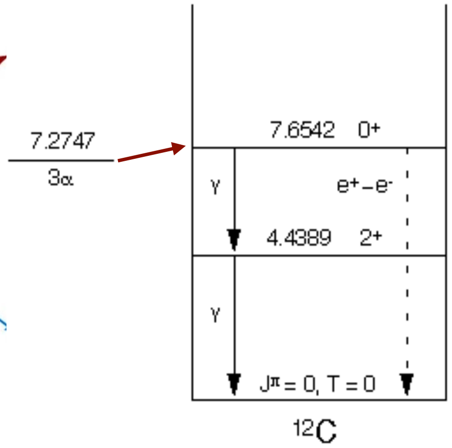
nuclear clustering may greatly

enhance fusion probabilities

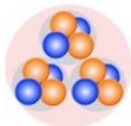
at low (i.e. astrophysical) energies

triple alpha process



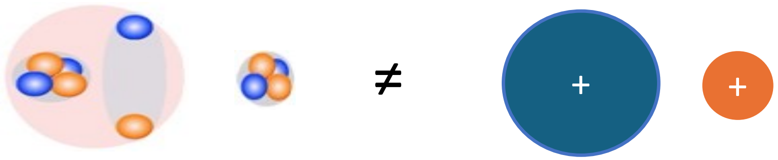


Hoyle state



~10^{7} times faster

electron screening puzzle

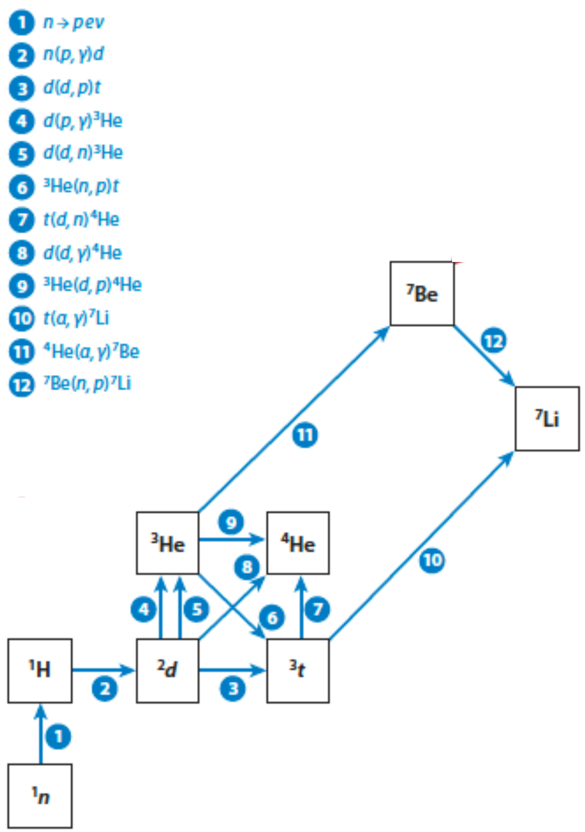


lower Coulomb barrier → enhanced fusion

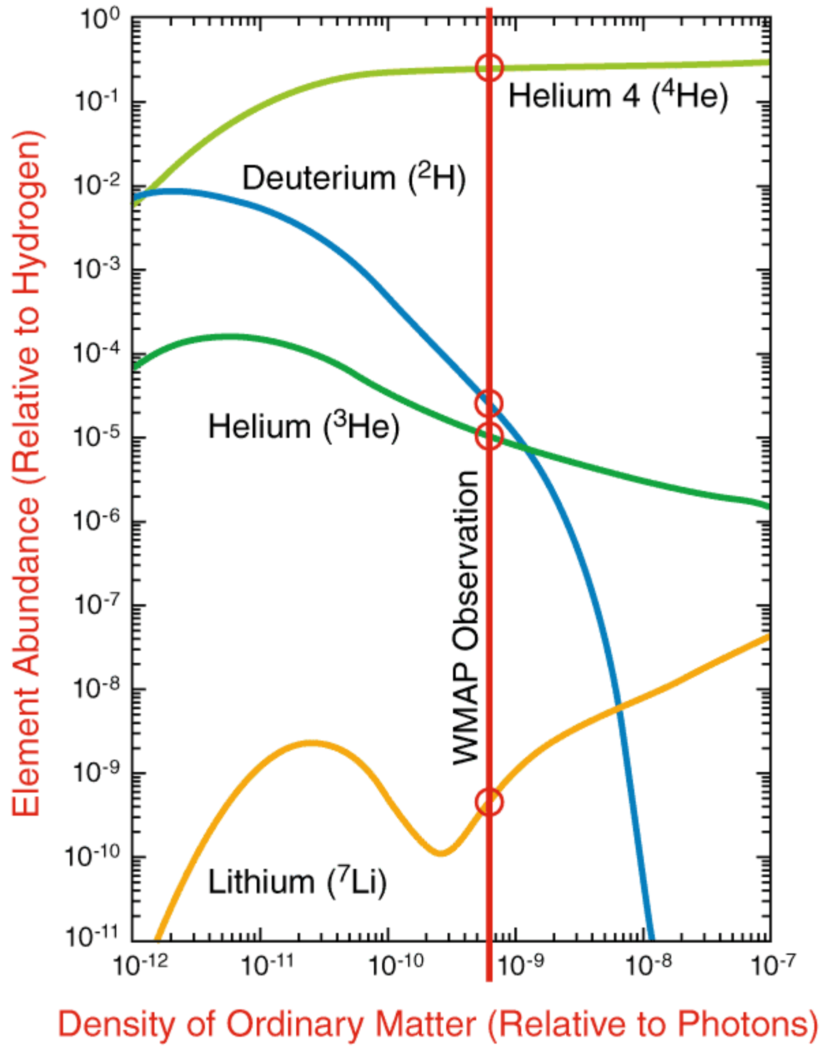
The Cosmological Lithium Problem(s)

Primordial Nucleosynthesis (BBN) and Primordial Abundances

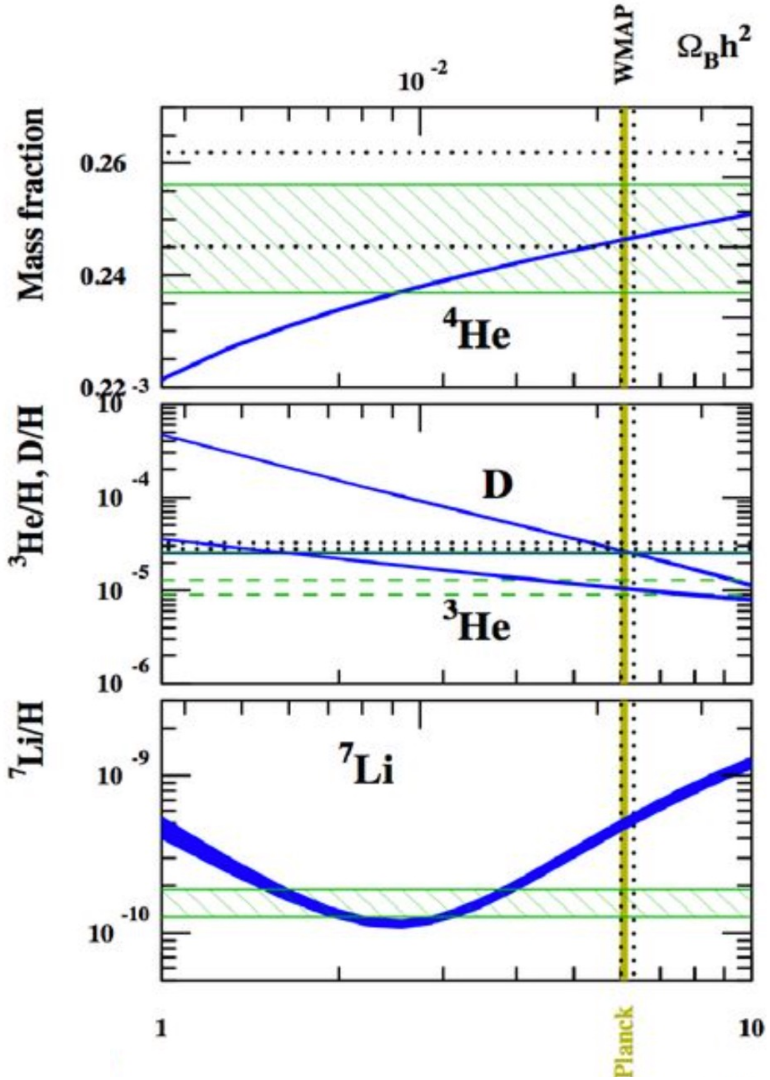
3 minutes after Big Bang



adapted from Fields (2011) ARNPS©



The Cosmic Lithium Problem: Possible Solutions



D, ^{3}He and ^{4}He:	good agreement
Li:	overestimated by factor 3!

Astrophysics:
incorrect interpretation of astronomical observation?
depletion mechanisms in stars?

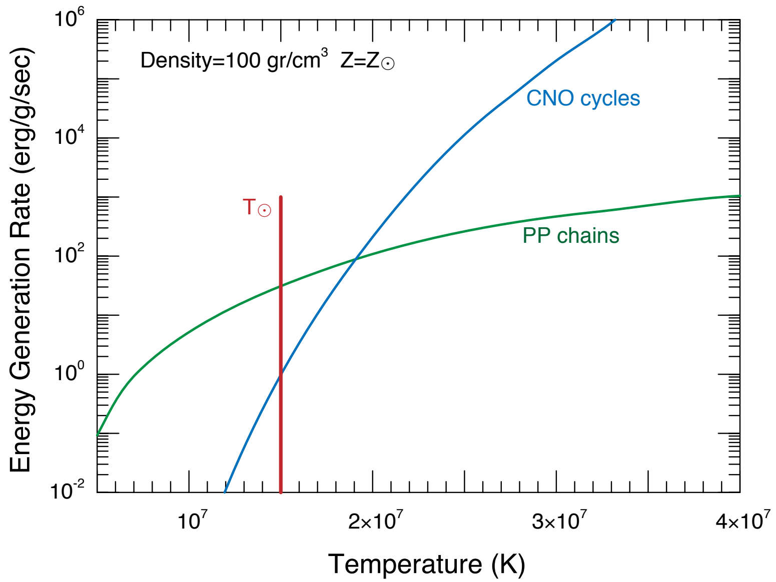
Nuclear physics:
wrong or incomplete nuclear reaction rates?
other key reactions controlling ^{7}Li yield?

Non-standard model:
current theories incorrect or incomplete?

Nucleosynthesis in First Stars

Identikit of First Stars

- formed 200-400 million years after Big Bang
- very massive (up to 100-1000 $M_{\odot}$)

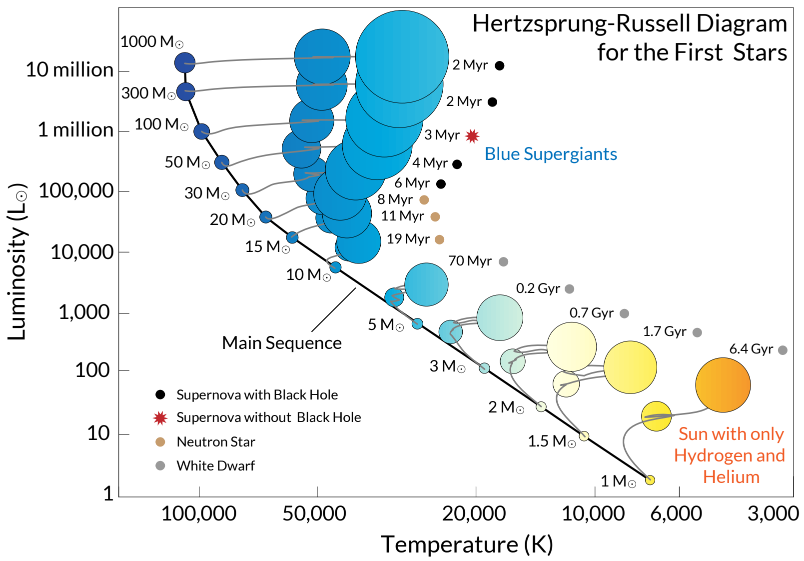


- made of primordial H and He
- no CNO to sustain star against gravity

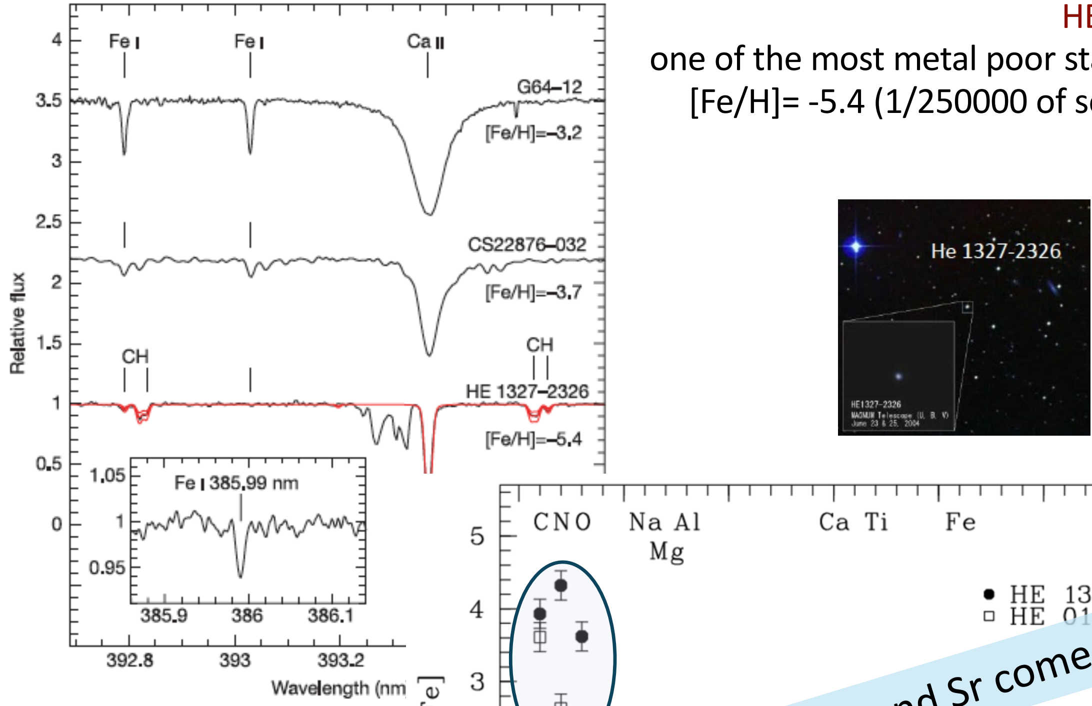
How did first stars evolve?

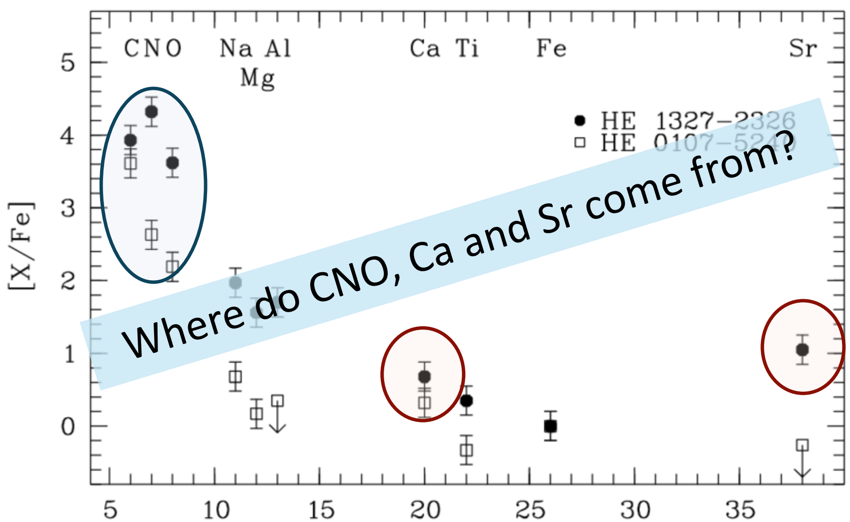
- burn He via 3α?
- form CNO nuclei?
- die as CCSN, pair production SN, or BHs?

First stars are difficult to observe today…



HE 1327-2326:
one of the most metal poor stars observed
[Fe/H]= -5.4 (1/250000 of solar Fe value)





Frebel *et al.* *Nature* **434**, 871–873 (2005)

… but their imprints remain visible
in the composition of second-generation stars

M Aliotta

Nuclear Clustering: A Possible Solution?

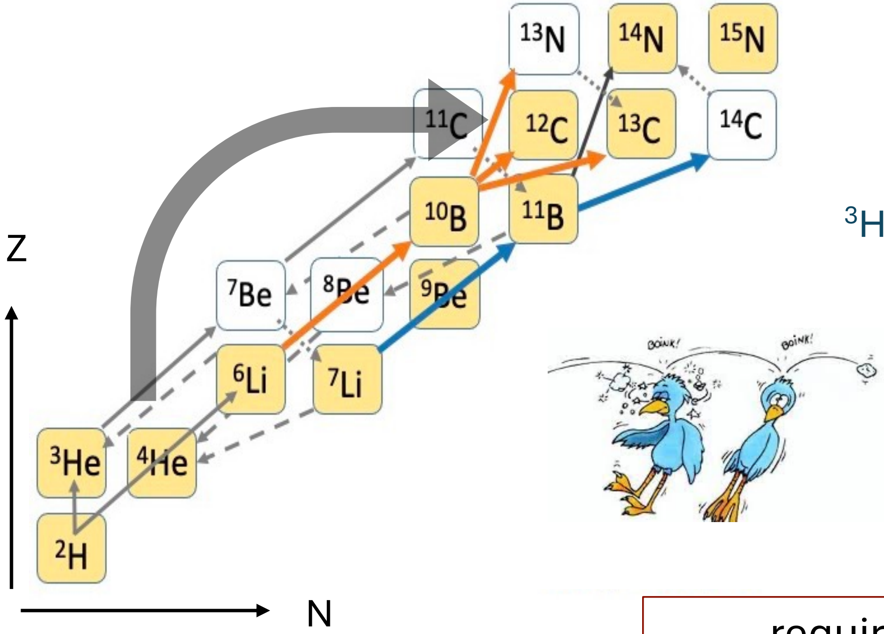
Eur. Phys. J. A (2021) 57:24
https://doi.org/10.1140/epja/s10050-020-00339-x

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Theoretical Physics

Nuclear clusters as the first stepping stones for the chemical evolution of the universe

Michael Wiescher[1,a], Ondrea Clarkson[2], Richard J. deBoer[1], Pavel Denisenkov[2]
[1] Department of Physics, The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA
[2] Department of Physics & Astronomy, University of Victoria, Victoria, BC V8W 2Y2, Canada



$^{4}He(d,\gamma)^{6}Li(\alpha,\gamma)^{10}B(\alpha,d)^{12}C$ deuterons as catalyst isotope

$^{10}B(\alpha,p)^{13}C$

$^{10}B(\alpha,n)^{13}N$ possible neutron source

$^{3}He(\alpha,\gamma)^{7}Be(e,\gamma)^{7}Li(\alpha,\gamma)^{11}B(a,p)^{14}C$

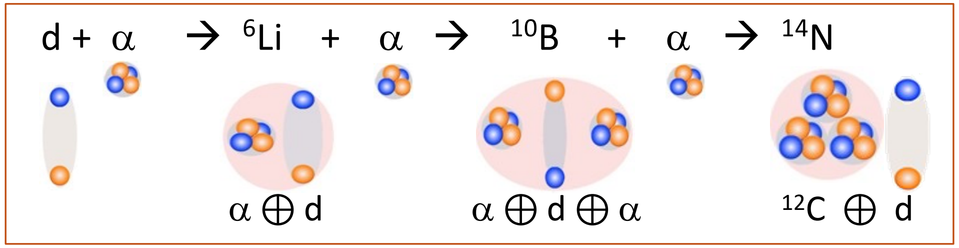
$^{11}B(\alpha,n)^{14}N$ possible neutron source

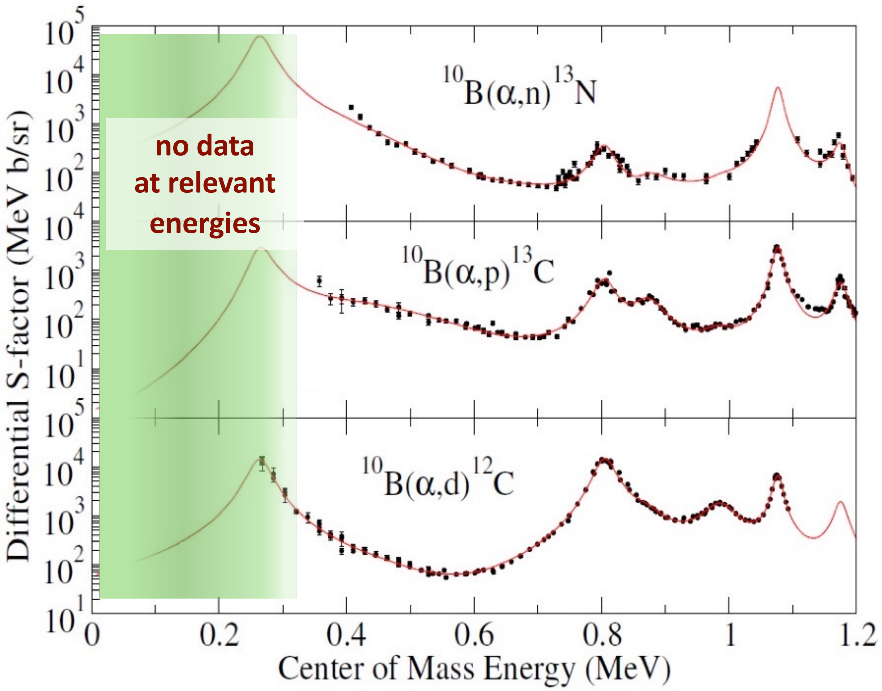
NOTE: 3α process forms C but completely by-passes Li; instead, proposed reaction sequences would also alter Li abundances → solution to CLiP?

requirement: strong enhancement of (α,γ) reaction rates

Current Status

proposed reactions involve strong cluster configurations





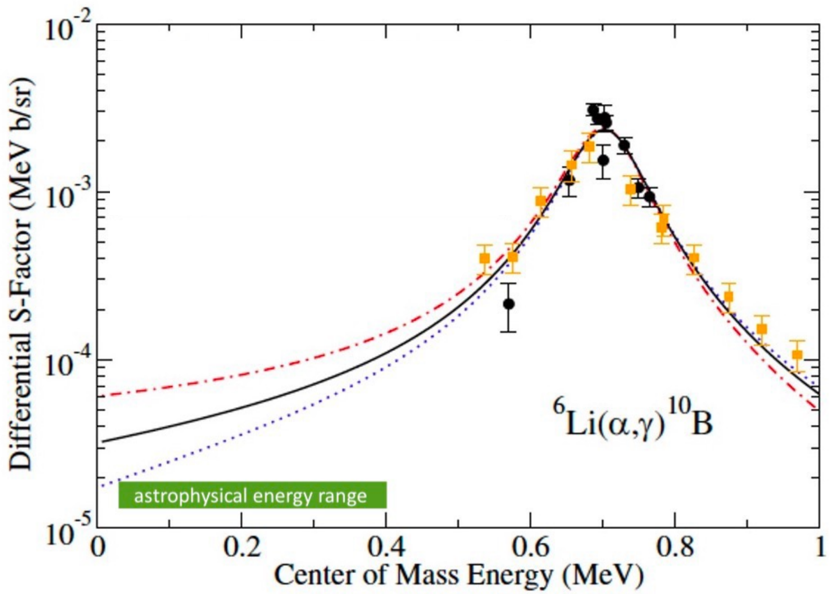
tantalizing new evidence for broad cluster resonances

PHYSICAL REVIEW C **106**, 065801 (2022)

Excitation function for the ^{6}Li + α reaction between 0.5 and 1.4 MeV

A. Gula, R. J. deBoer, R. Kelmar, J. Görres, K. V. Manukyan, E. Stech, W. Tan, and M. Wiescher

Department of Physics and the Joint Institute for Nuclear Astrophysics, Notre Dame, Indiana 46556, USA



new measurements UNDERGROUND needed

Strategic Approach: Synergic Exploitation of Critical Expertise

Experimental Program:
α-induced reactions on Li and B isotopes

optimize information transfer across boundaries

for **accelerated progress** with **widest impact**

Theoretical Program

Computational Program

Work Programme and Outcomes

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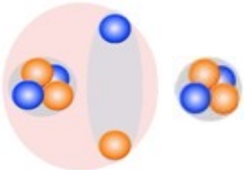
Theoretical Programme

WP2a: PDRA2

G Hupin



- cluster structures at low energies
- impact on astrophysical reactions & electron screening

RJ deBoer

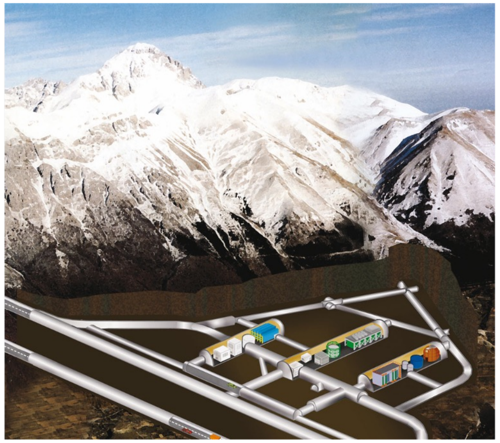
WP2b: **PI**, PDRA2

- improved R-matrix capabilities
- robust reaction rates

Experimental Programme

WP1: **PI**, PDRA1, PhD1,PhD2

Laboratory for Underground Nuclear Astrophysics

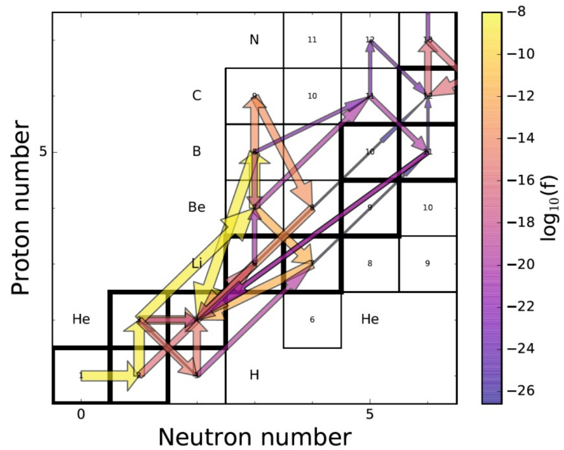


- α+Li and α+B reactions (Q1-Q3)
- ultra-low background @LUNA
- lowest-energy data (world best)

Computational Programme

WP3: **PI**, PDRA3

M Pignatari



- stellar models for first stars (MESA)
- nucleosynthesis networks (NuGRID)
- impact on Q1 and Q2

Grant Start Date: 2 December 2024

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nuclear

nuclear clustering effects in astrophysical reactions

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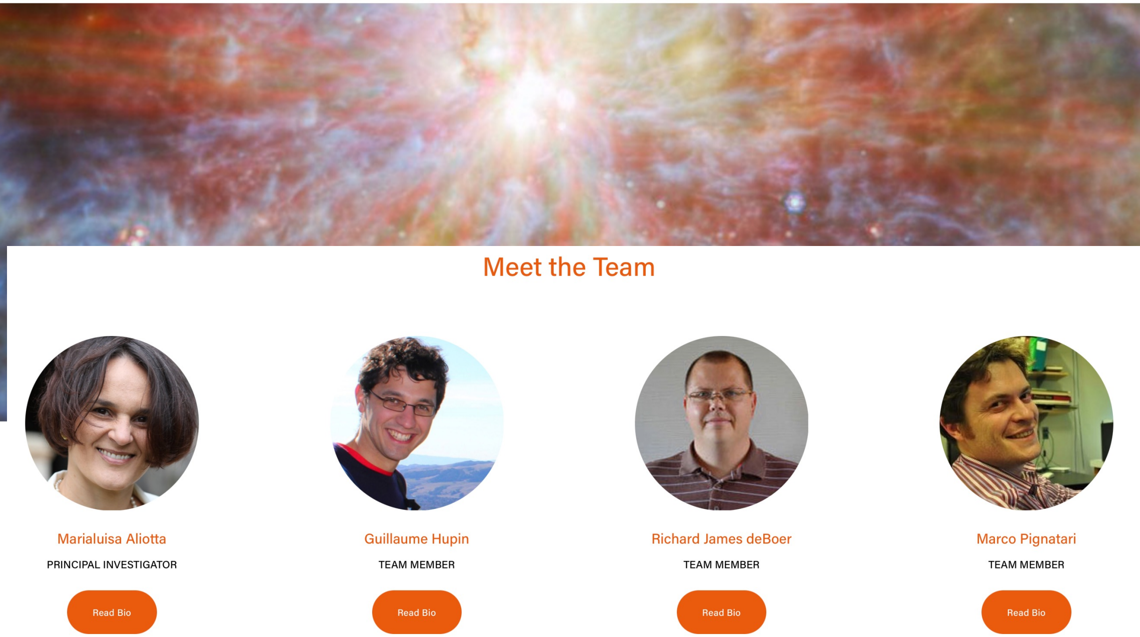
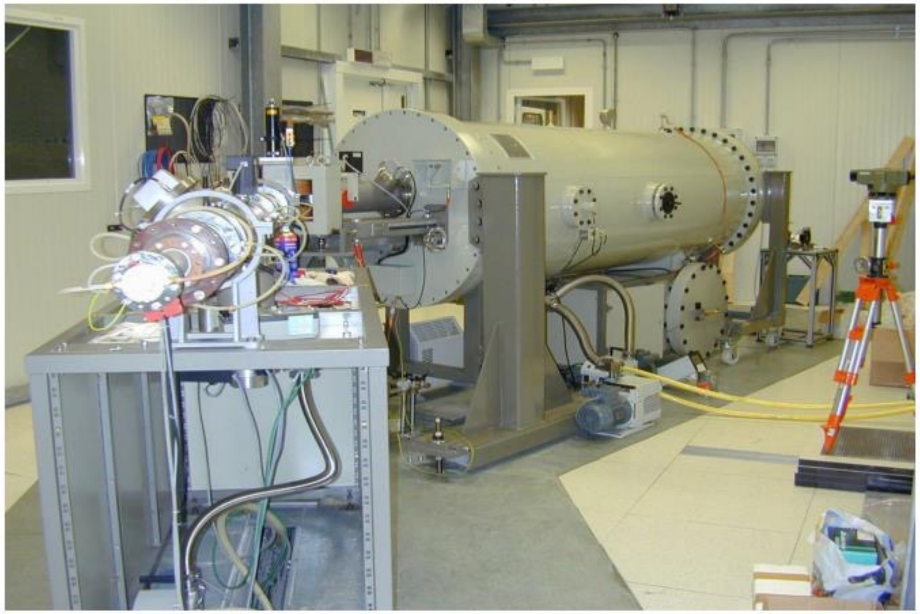
https://www.erc-nuclear.uk



PDRA Experiment
Alessandro Compagnucci
(from February 2025)

PDRA Theory
Kevin Becker
(from July 2025)

$^{10}B + \alpha$ Reaction Studies at LUNA 400kV



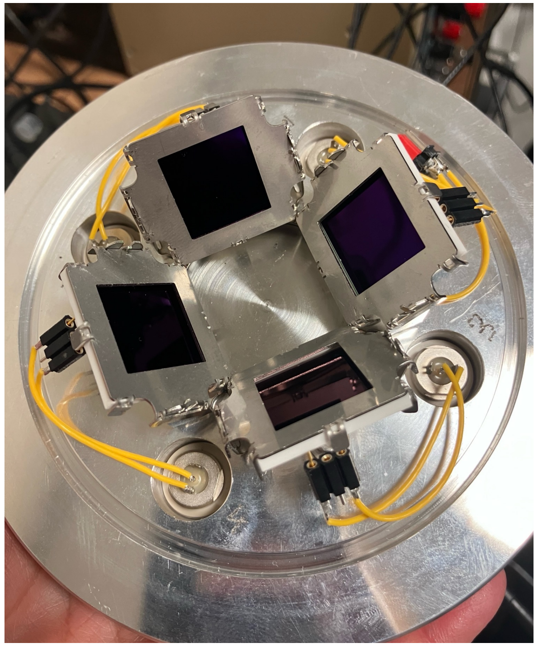
Upcoming measurements at LUNA

$^{10}B(\alpha,d)^{12}C$
$^{10}B(\alpha,p)^{13}C$
charged particle detection

$^{10}B(\alpha,n)^{13}N$ activation measurement:

detect 511 keV annihilation γ rays following β+ decay of ^{13}N ($t_{1/2}$ ~ 10 mins) in opposite crystals

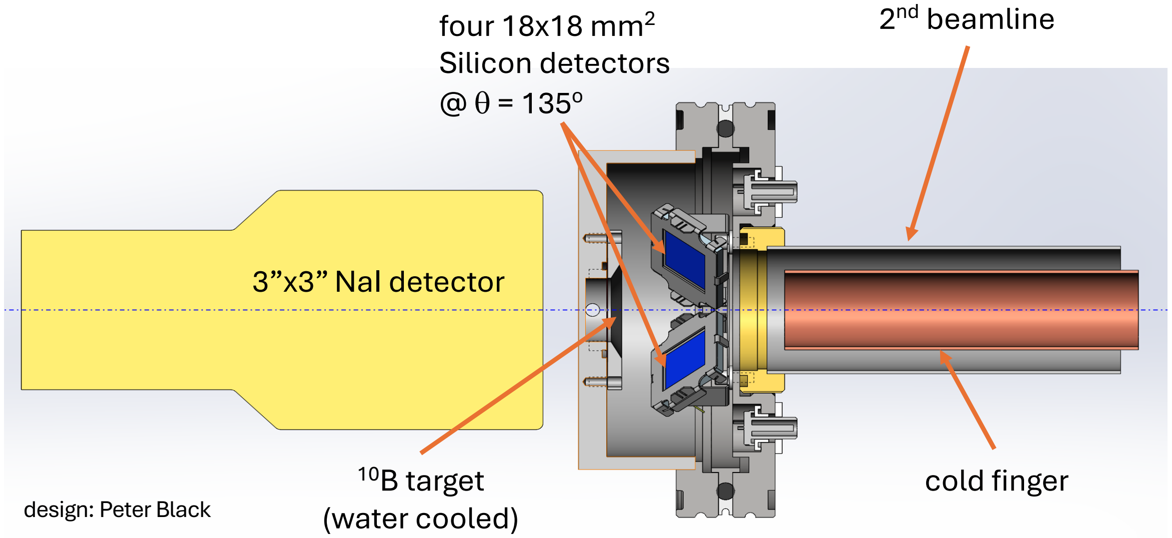
silicon detector array

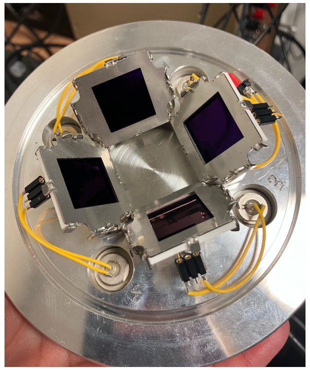


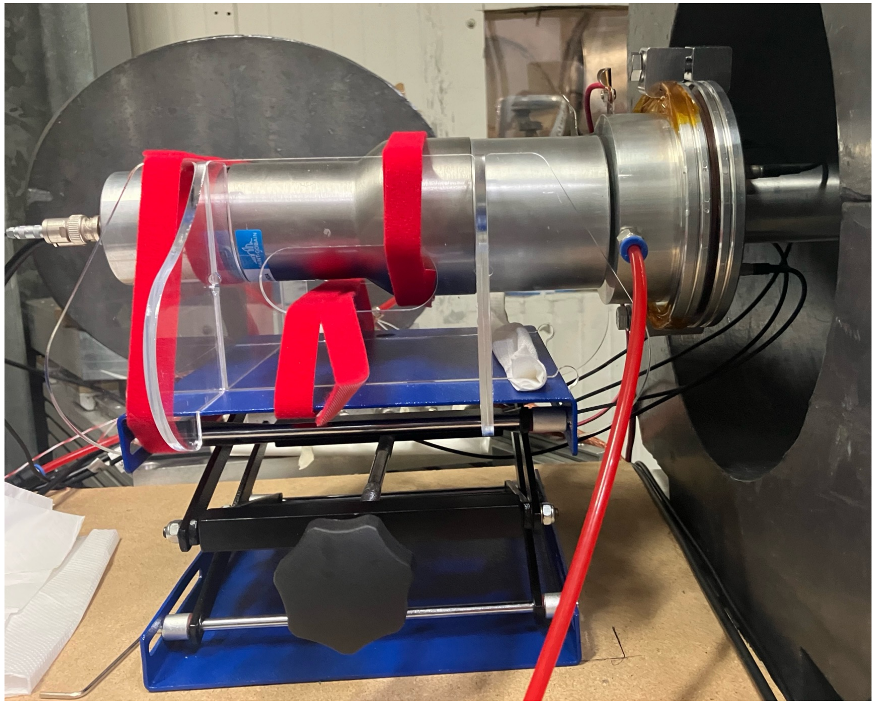
Rhys Bonnell, PhD

segmented BGO detector

Charged-particle + Gamma-ray Detection Setup

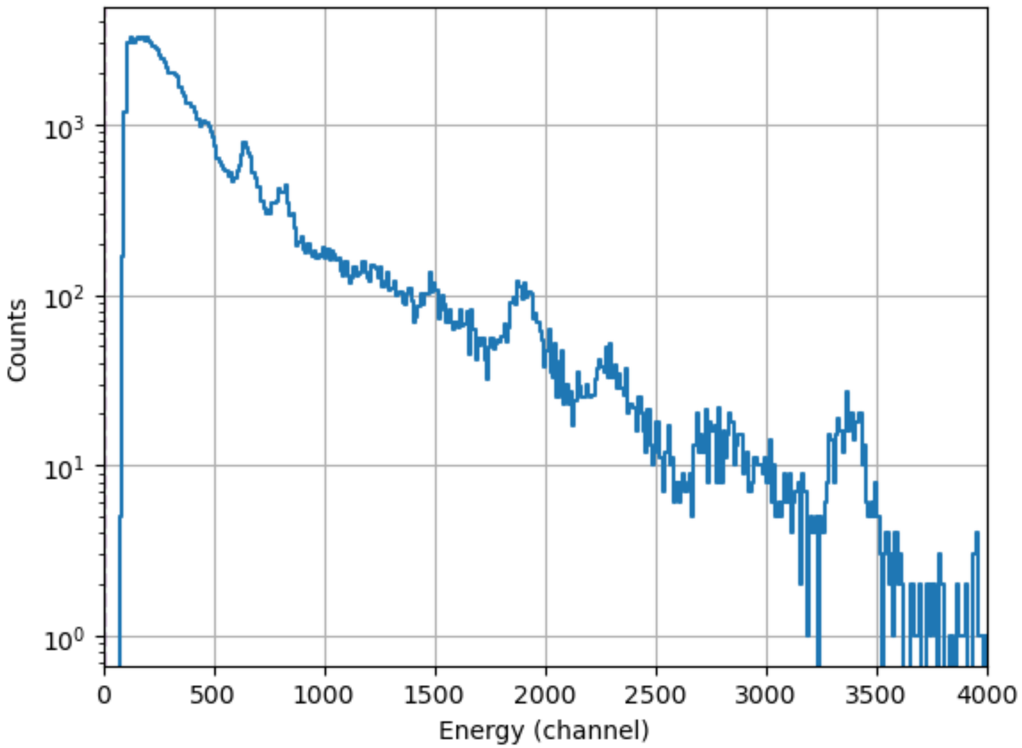




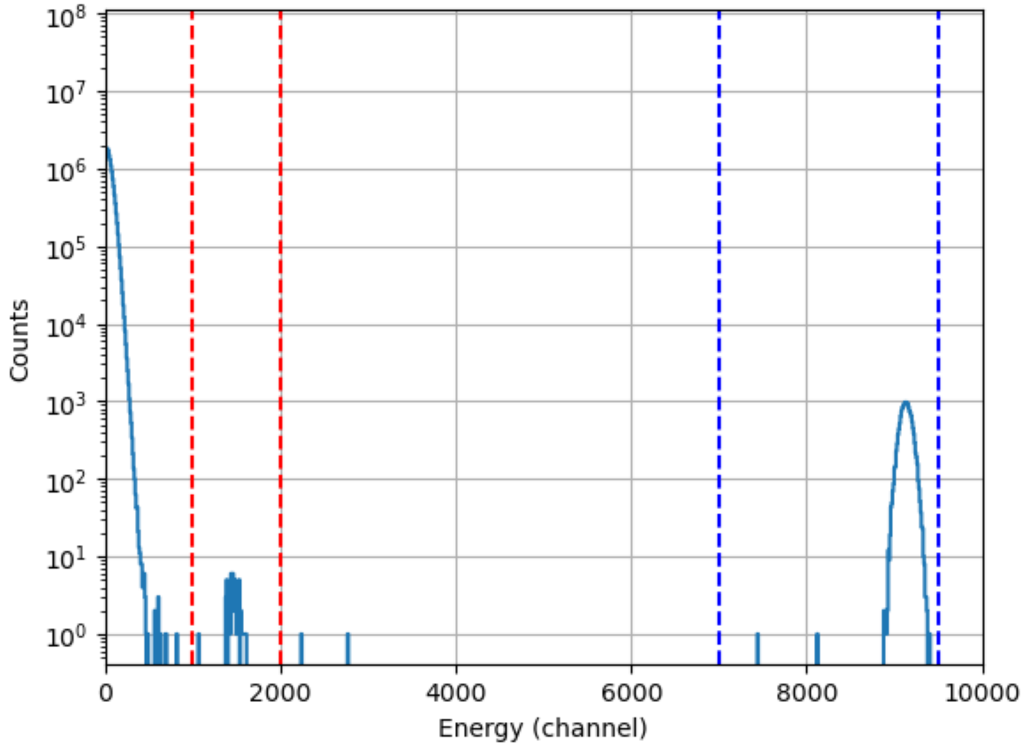


First Spectra (just acquired): $^{10}B(\alpha,p\gamma)^{12}C$

NaI Detector



Si Detector



$^{6,7}Li + \alpha$ Reaction Studies at Bellotti Facility

3.5 MV accelerator

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

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

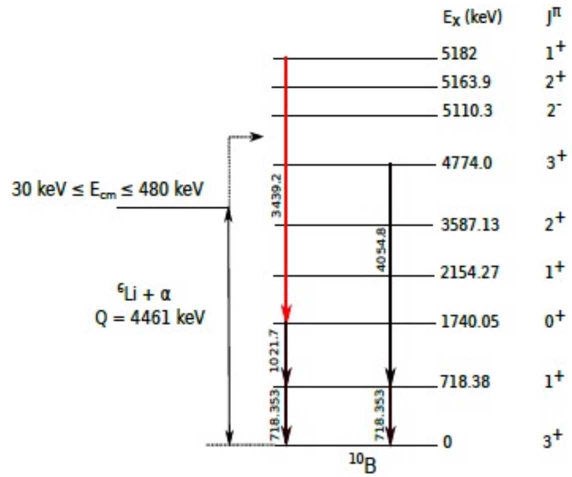
^{6,7}Li(α,γ) reactions: prompt γ-ray measurements

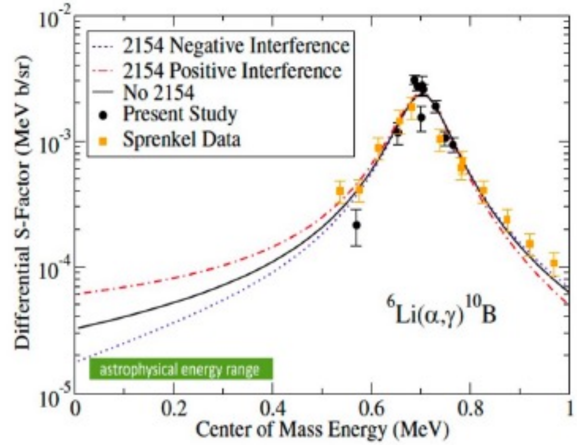
prompt γ-ray detection with either

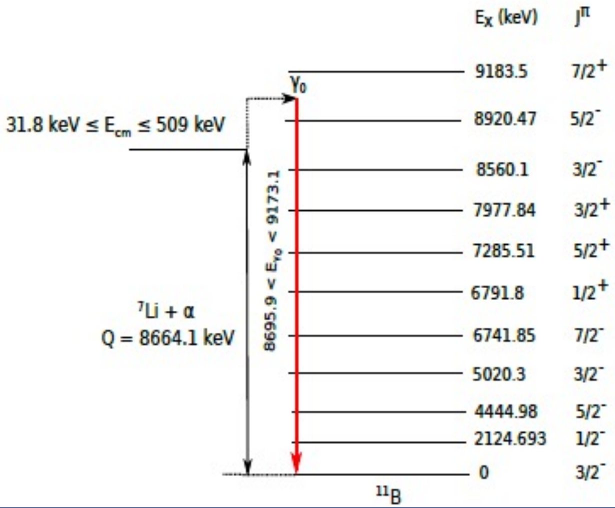
HPGe detectors or the BGO detector

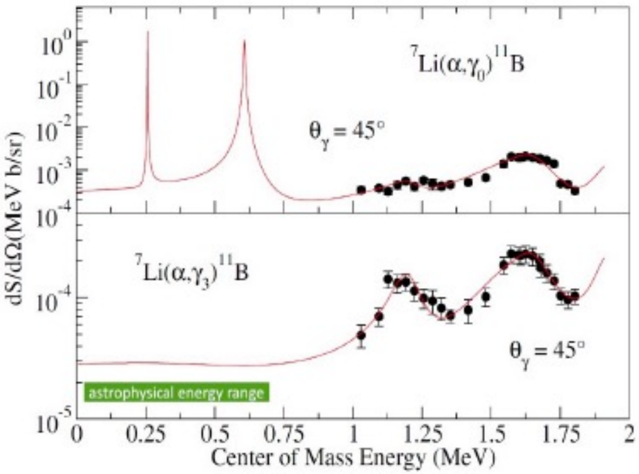
push measurements

to lowest accessible energies









Lavinia Dalla Vedova
(from September 2025)

To Conclude...

- nuclear astrophysics is a very lively & highly interdisciplinary research field
- low-energy, stable-beam experiments pose major experimental challenges
- major advances can come from **underground** measurements

LUNA: A Success Story

LUNA has pioneered underground studies in Nuclear Astrophysics for almost three decades

PHYSICAL REVIEW LETTERS — 28 JUNE 1999

First Measurement of the $^3He(^3He, 2p)^4He$ Cross Section down to the Lower Edge of the Solar Gamow Peak

PRL 115, 252501 (2015) — PHYSICAL REVIEW LETTERS — week ending 18 DECEMBER 2015

Three New Low-Energy Resonances in the $^{22}Ne(p,\gamma)^{23}Na$ Reaction

Physics Letters B 634 (2006) 483–487

First measurement of the $^{14}N(p,\gamma)^{15}O$ cross section down to 70 keV

LUNA Collaboration

nature astronomy — LETTERS — PUBLISHED: 30 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0027

Origin of meteoritic stardust unveiled by a revised proton-capture rate of ^{17}O

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

(LUNA Collaboration)

Astronomy & Astrophysics

The bottleneck of CNO burning and the age of Globular Clusters

Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisani, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli

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Nature **587**, 210–213(2020) | Cite this article

PRL 117, 142502 (2016) — PHYSICAL REVIEW LETTERS — week ending 30 SEPTEMBER 2016

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

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THE LUNA COLLABORATION

http://luna.lngs.infn.it