Nucleosynthesis in First Stars ~~(and Other Puzzles)~~
Experimental Prospects at LUNA

European Research Council
Established by the European Commission

nuclear
nuclear clustering effects in astrophysical reactions

UK Research and Innovation

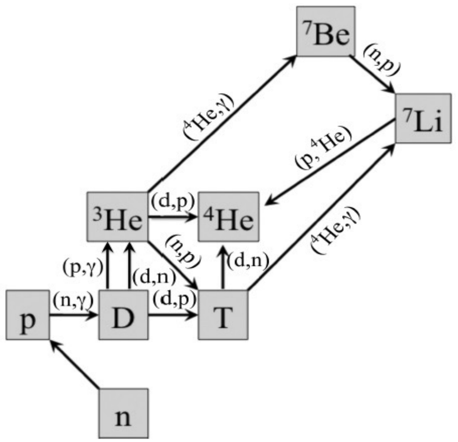
LUNA

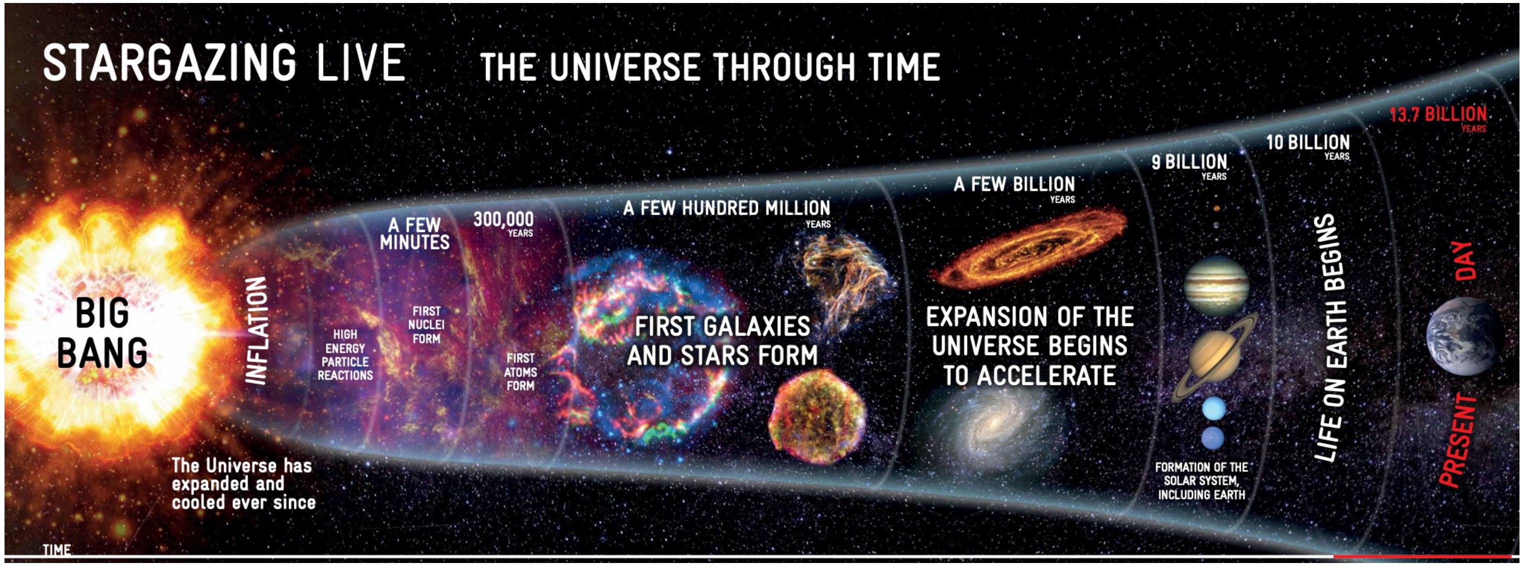
Marialuisa Aliotta – University of Edinburgh, UK

European Nuclear Physics Conference, 21-26 September 2025, Caen France

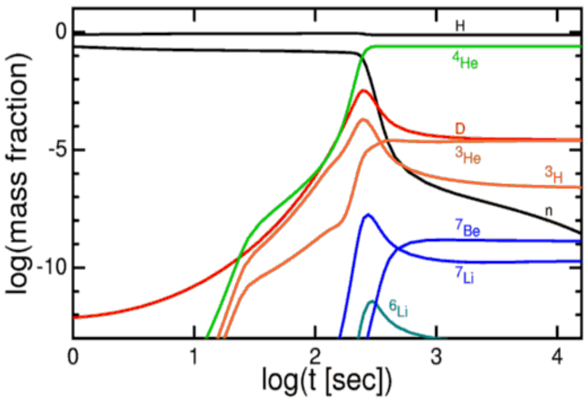
The Chemical Evolution of the Universe (in a Nutshell)

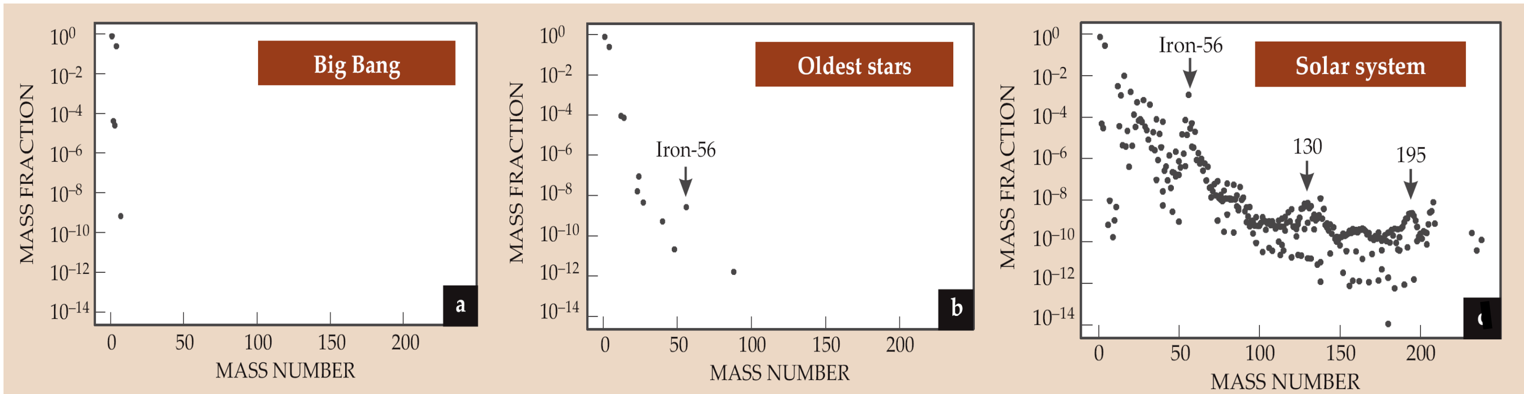
Big Bang Nucleosynthesis





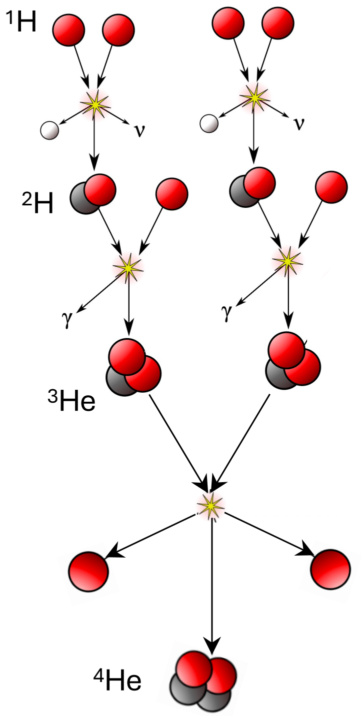
3-20 min after BB





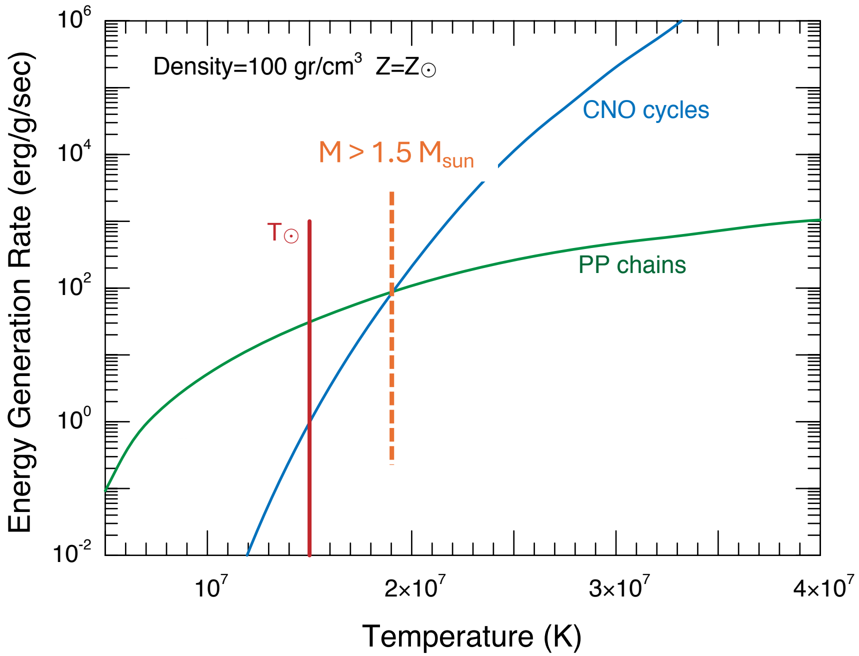
Stellar Nucleosynthesis: Hydrogen Burning in Stars

Proton-Proton Chain

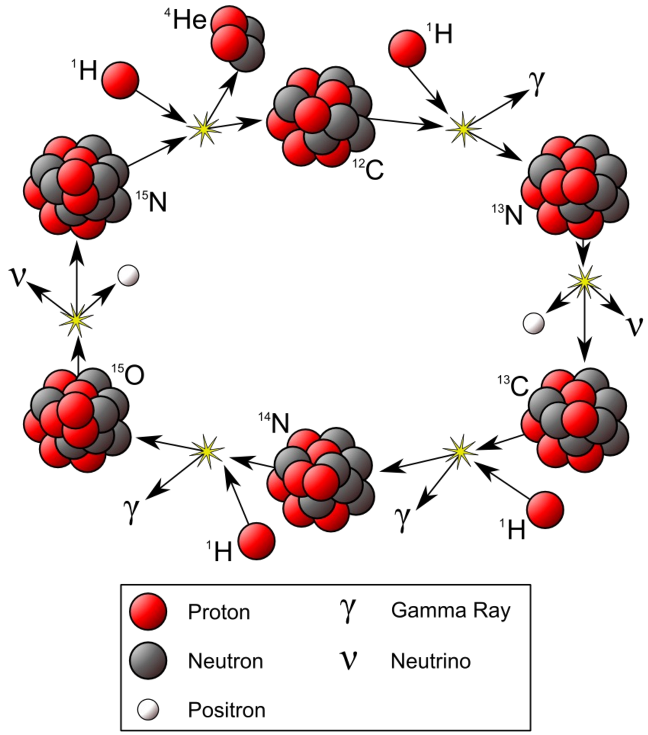


low-mass stars: $M < 1.5\ M_{sun}$

$4H \rightarrow {}^4He + 2e^+ + 2\nu$

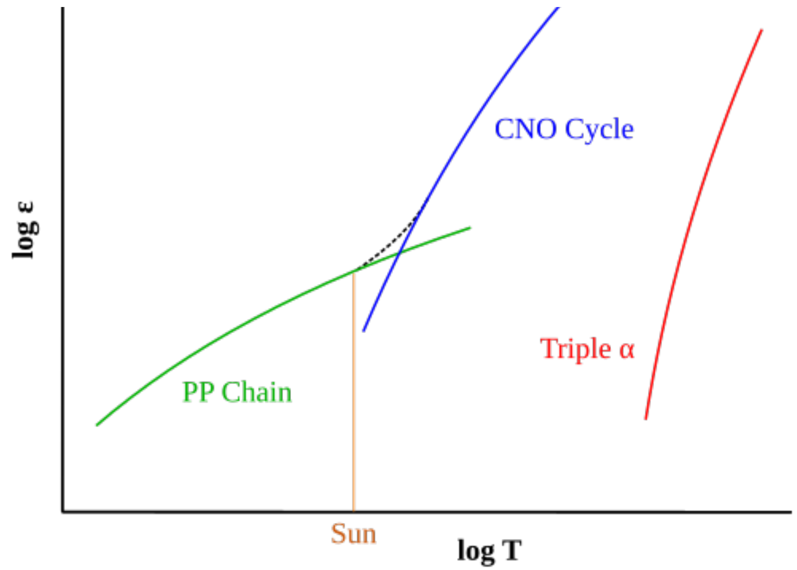


CNO cycle



high-mass stars: $M > 1.5\ M_{sun}$
+ pre-existing CNO material

Evolution of First Stars (Population III)



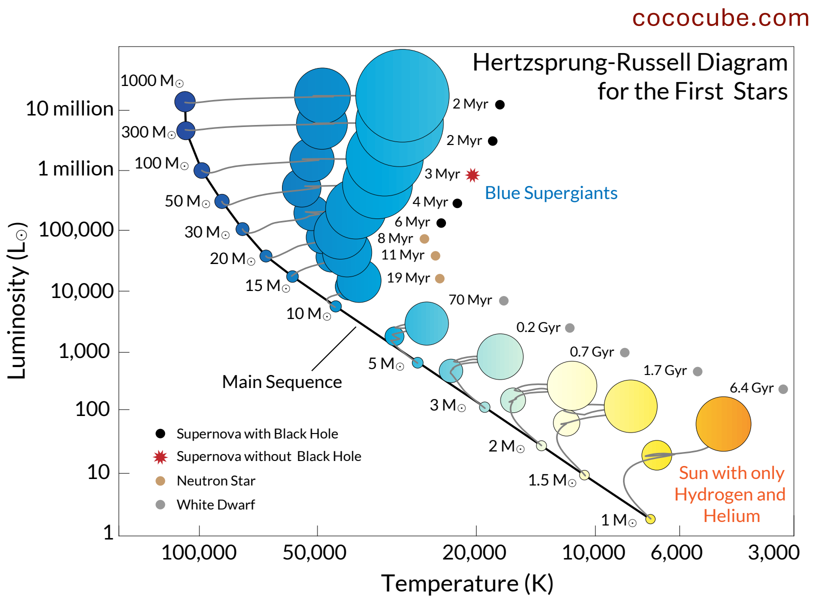
- formed 200-400 million years after Big Bang
- very massive (up to 100-1000 $M_\odot$)
- made of primordial H and He
- no CNO to sustain star against gravity

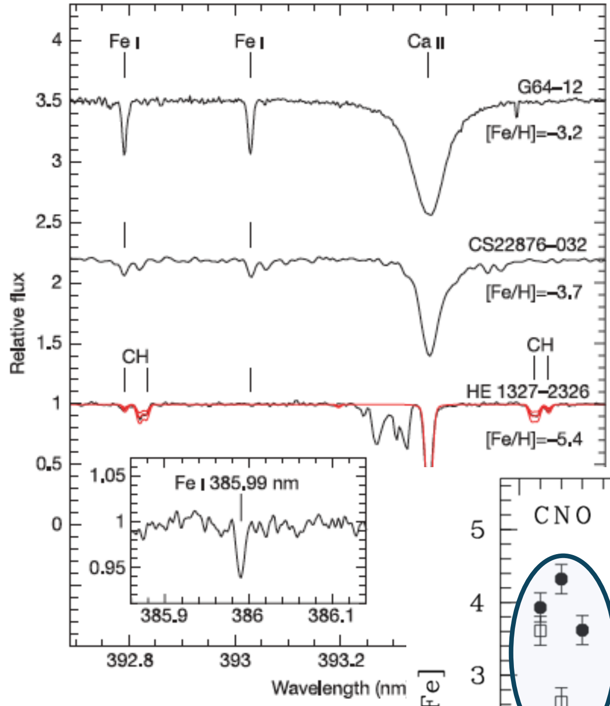
how did first stars evolve?

currently accepted wisdom:

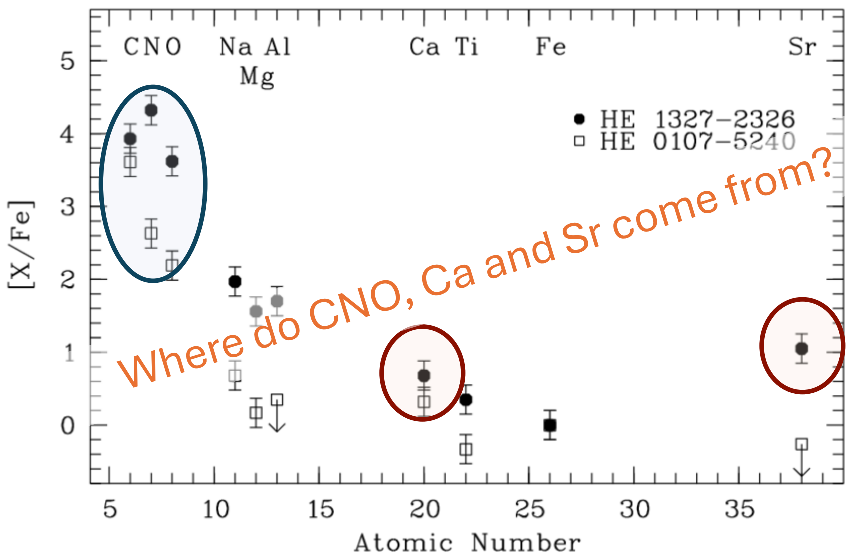
- effectively 'skip' H burning
- burn He via $3\alpha \rightarrow {}^{12}C \rightarrow$ onset of CNO cycle

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)

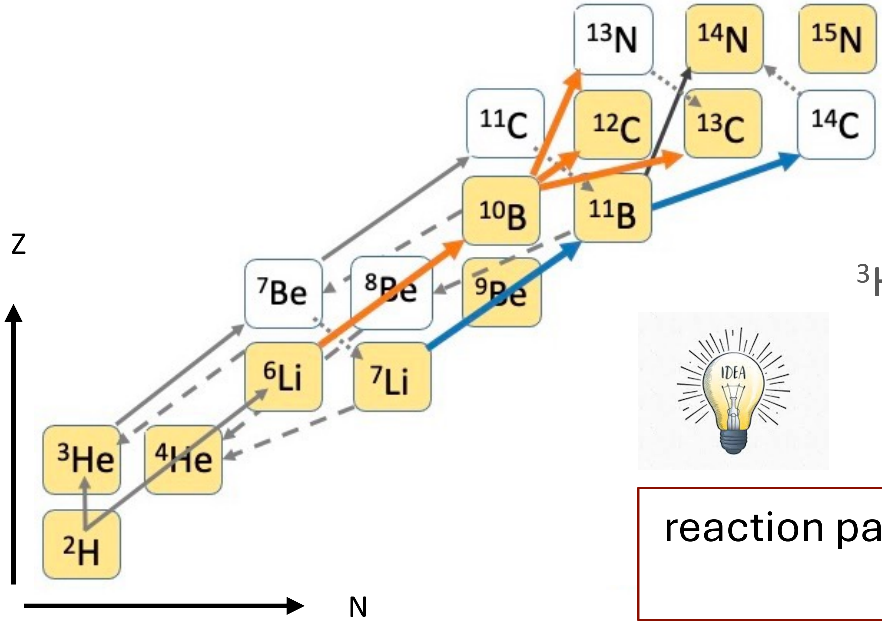
... but their imprints remain visible
in the composition of second-generation stars

Alternative Pathways to the CNO Production in First Stars

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

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

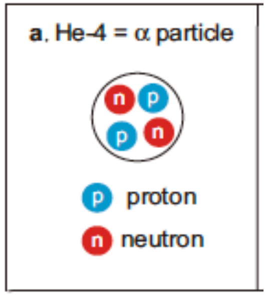
$^{10}B(\alpha,n)^{13}N$ possible neutron source

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

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

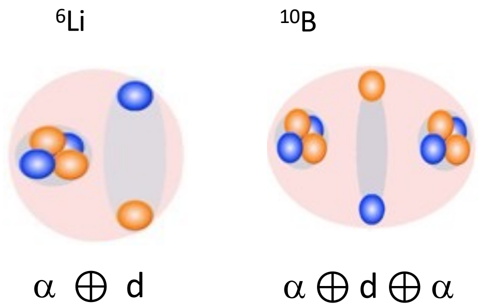
reaction paths viable only if α-induced reactions are strongly enhanced e.g. by nuclear clustering

Nuclear Clustering



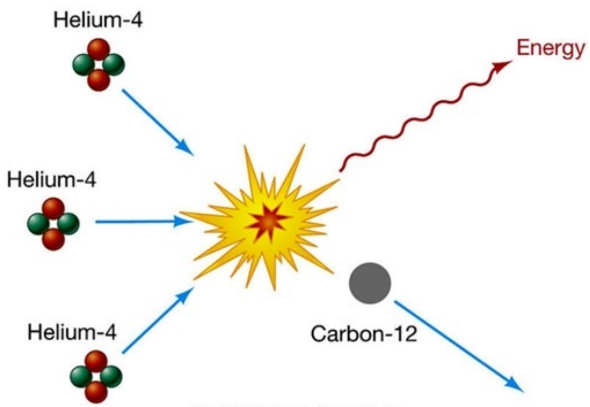
very stable configurations

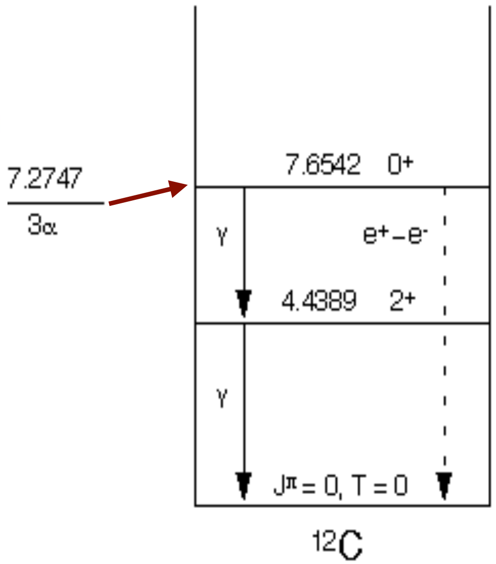
→ building blocks for other nuclei



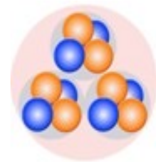
nuclear clustering may greatly enhance fusion probabilities at low (i.e. astrophysical) energies

triple alpha process





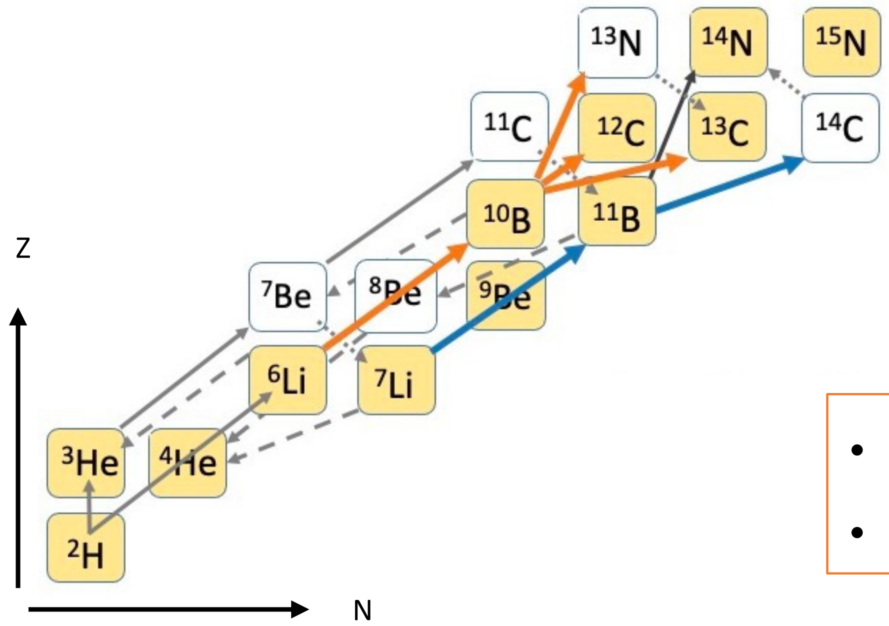
Hoyle state

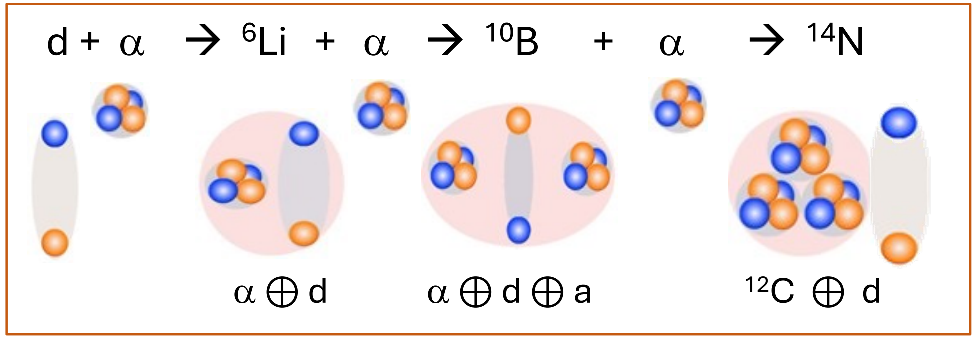


~10^{7} times faster

Nucleosynthesis in First Stars

sequences proposed to produce CNO in first stars involve nuclei with strong cluster configurations





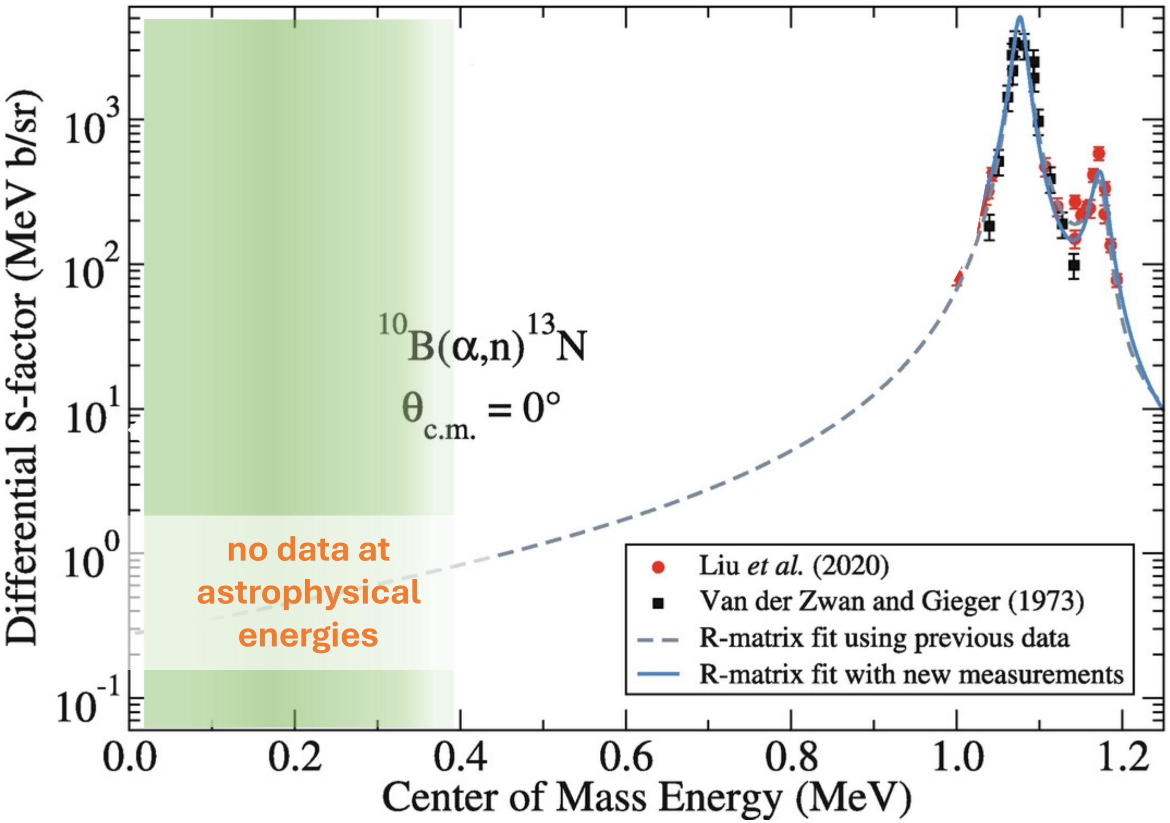
- do cluster states exist near threshold in these reactions?
- can they enhance fusion probabilities?

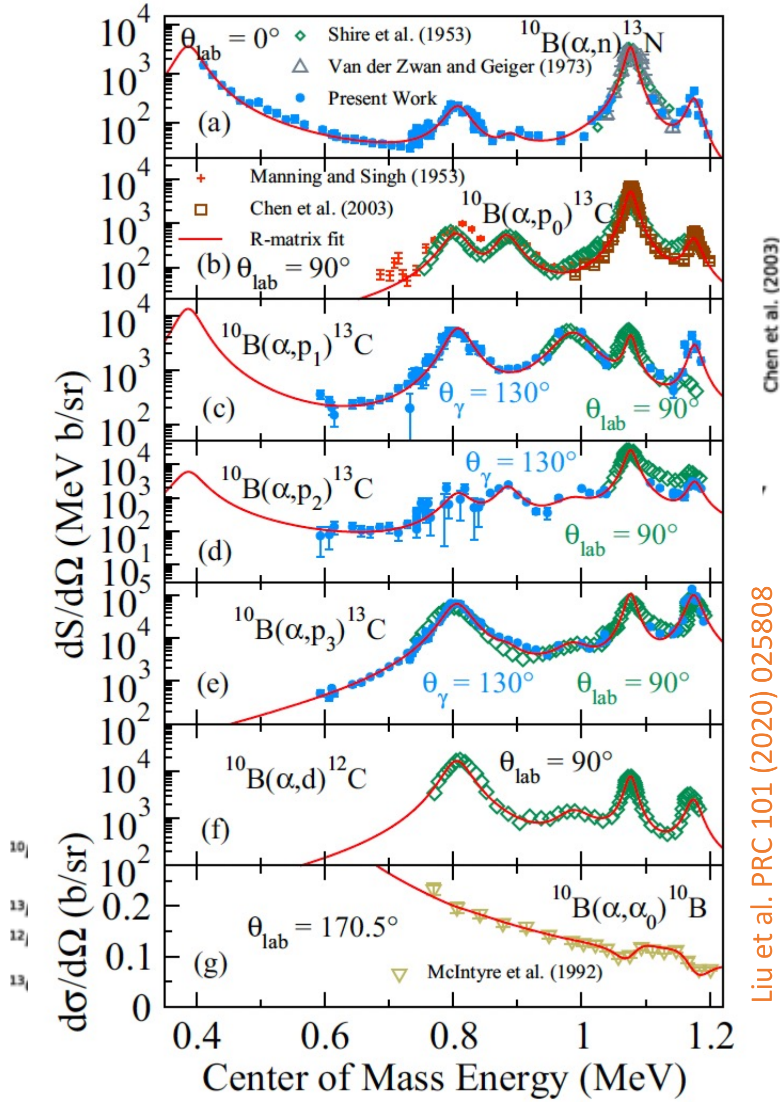
hypothesis untested both experimentally and theoretically until recently…

new tantalizing evidence for broad cluster resonances is emerging

$^{10}B+\alpha$ Reactions: Current Status

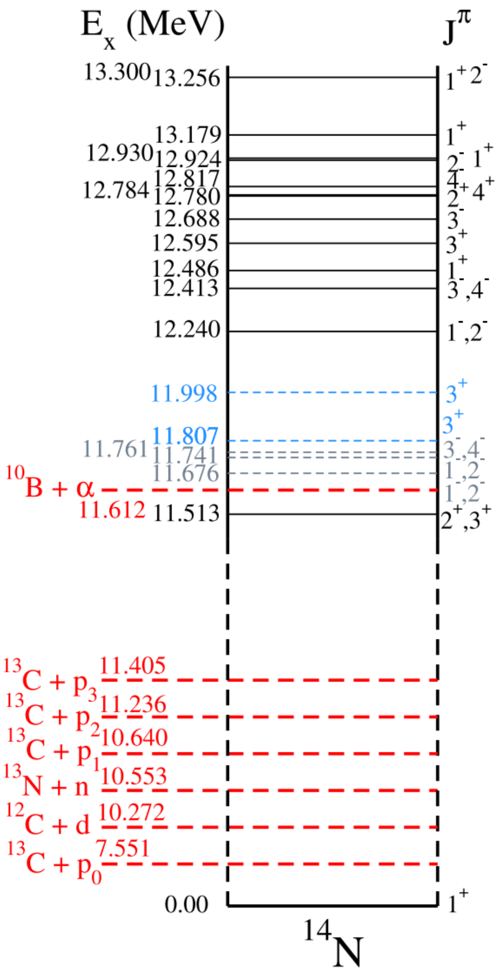
$^{10}B(\alpha,n)^{13}N$

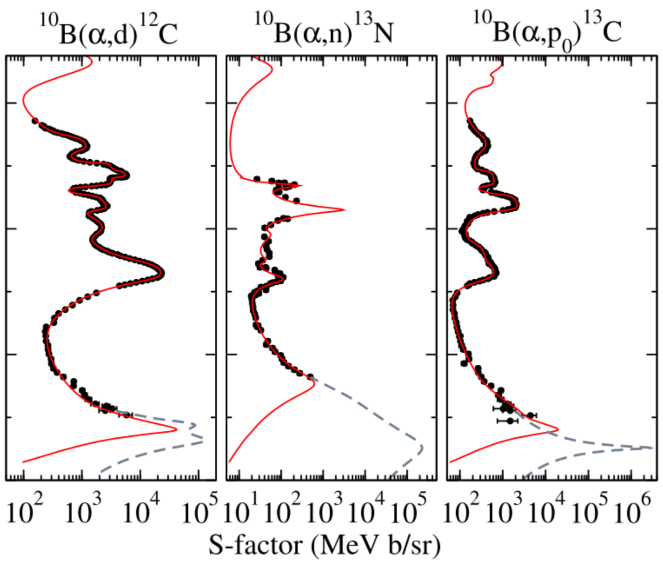




Liu et al. PRC 101 (2020) 025808

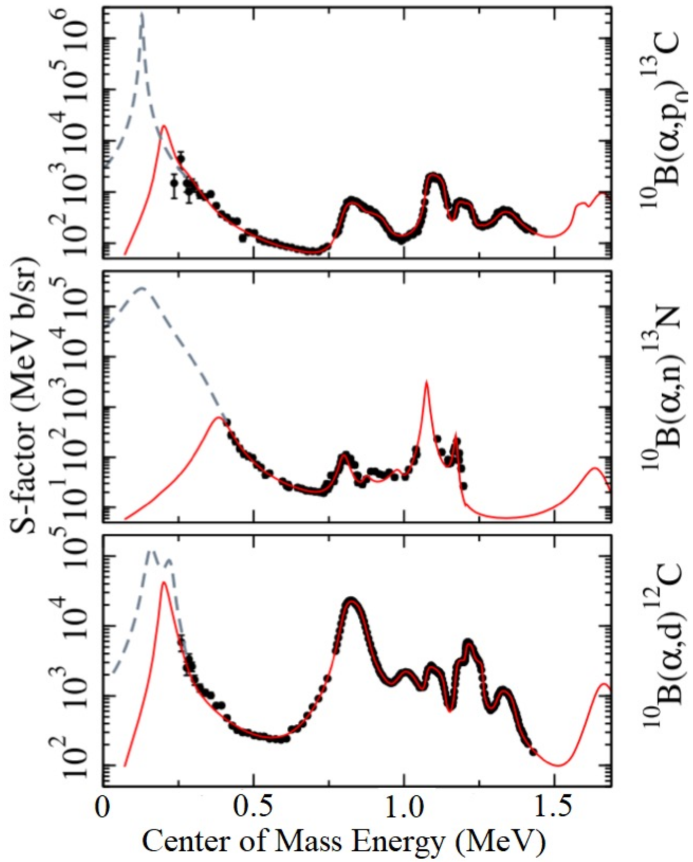
How Strong an Enhancement?





Global R-matrix Analysis

S-factors



Low-Energy Data Needed!

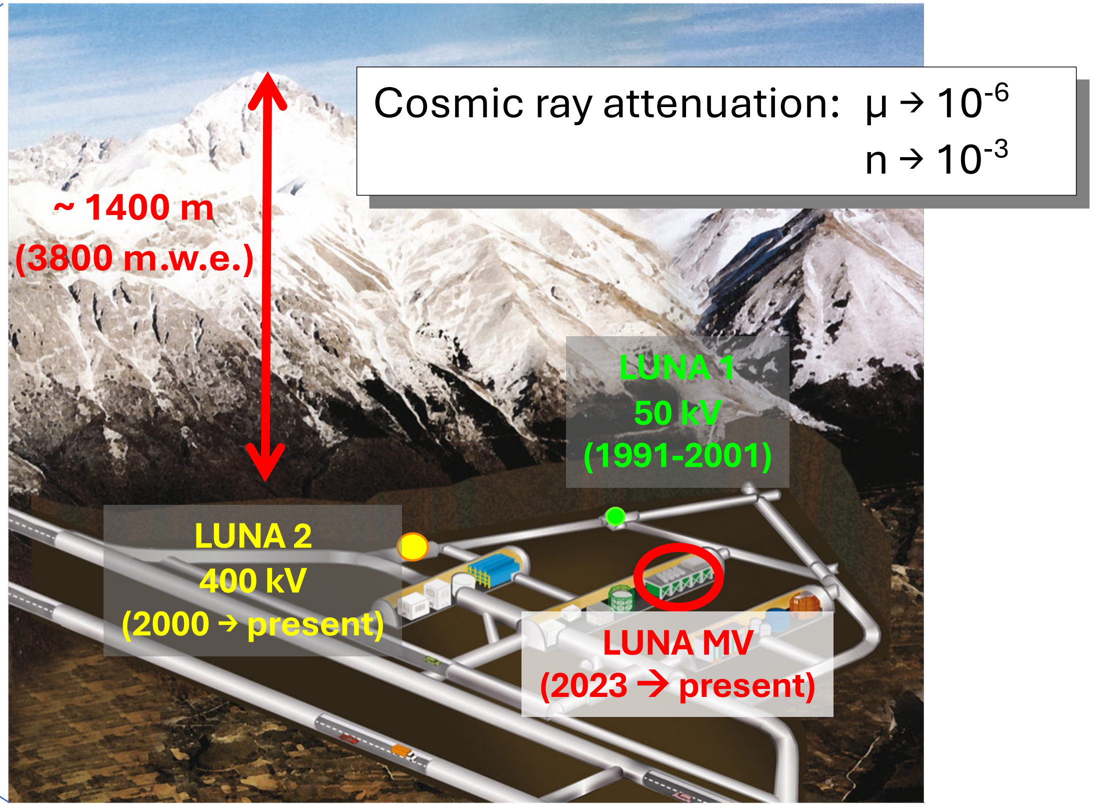
Wiescher et al. Rev. Mod. Phys. 97 (2025) 025003

ERC Work: Experimental Programme

LUNA

- α+B and α+Li reactions at lowest energies feasible
- ultra-low background @LUNA

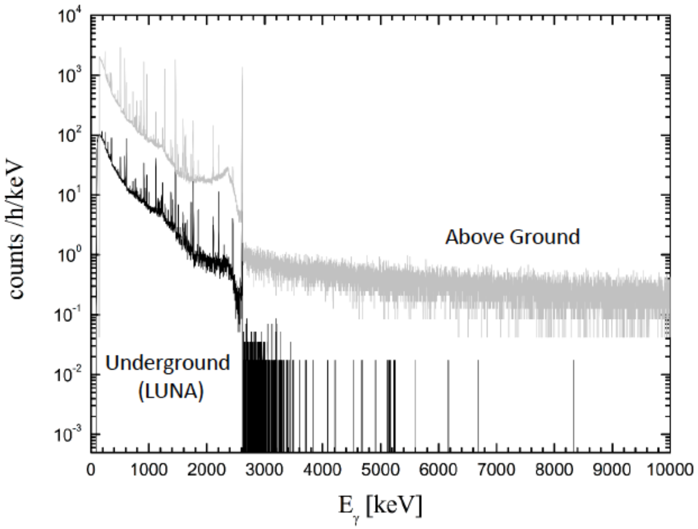
LUNA: Laboratory for **U**nderground **N**uclear **A**strophysics
at Laboratori Nazionali del Gran Sasso

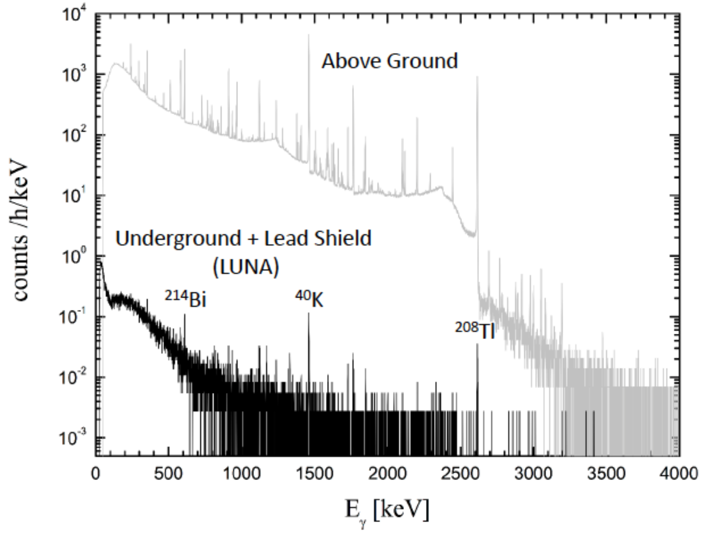


Background Suppression @LUNA

Ideal location
for low-energy studies

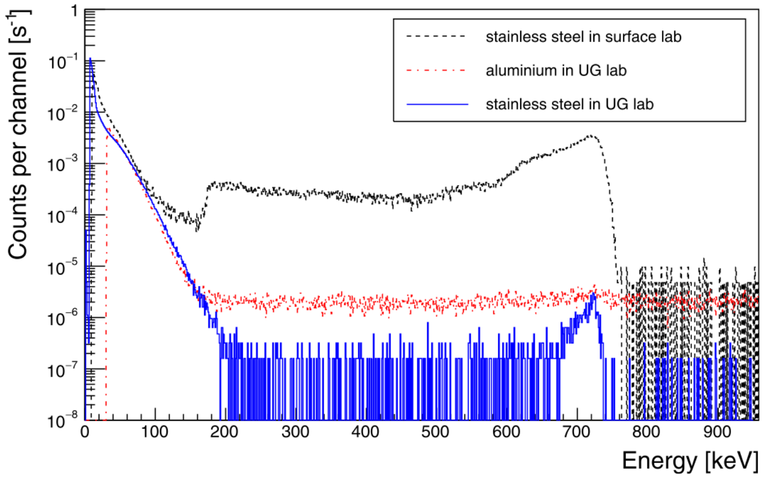
gamma-ray detection





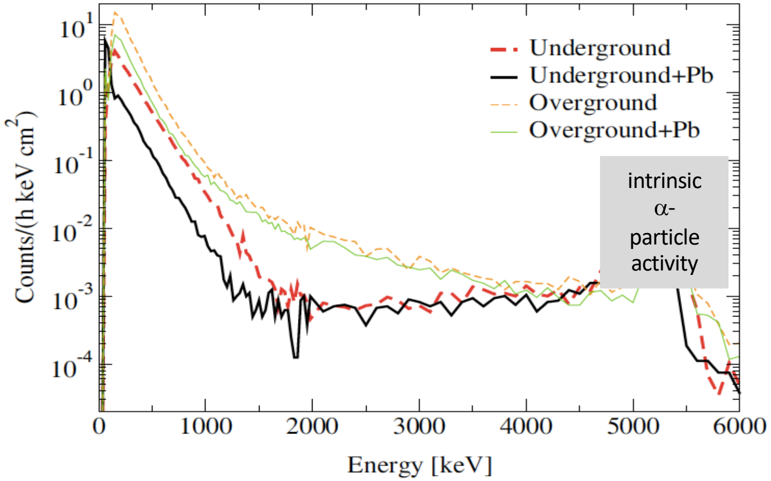
Costantini et al. Rep. Prog. Phys. 72 (2009) 086301

neutron detection



Csedreki et al. NIMA 994 (2021) 165081

charged-particle detection



Bruno et al EJPA 51 (2015) 94

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

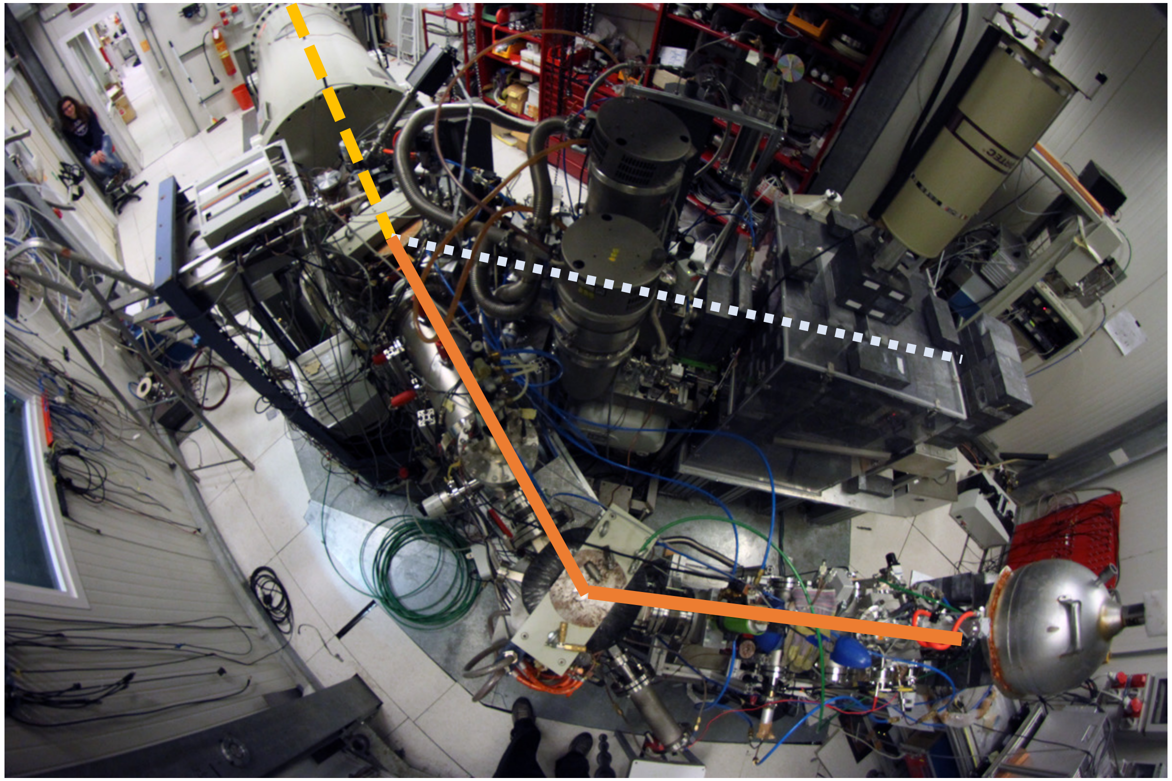
LUNA-Notre Dame Collaboration

LUNA Facility:

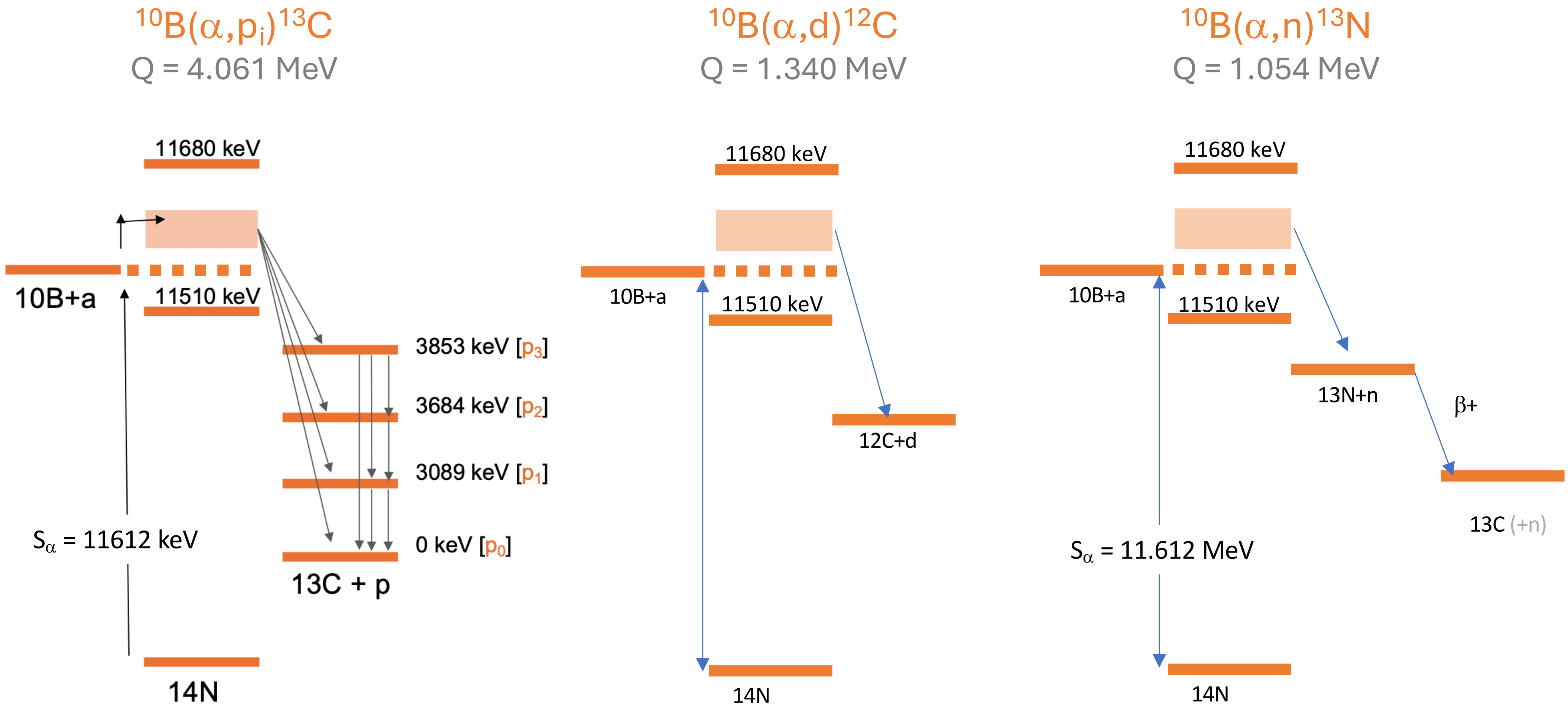
- 400keV accelerator
- H^+ and He^+ beams
- I = 200 – 300 uA
- ΔE = 100 eV

Goal:

Measure $\alpha+^{10}B$ reactions down to lowest accessible energies



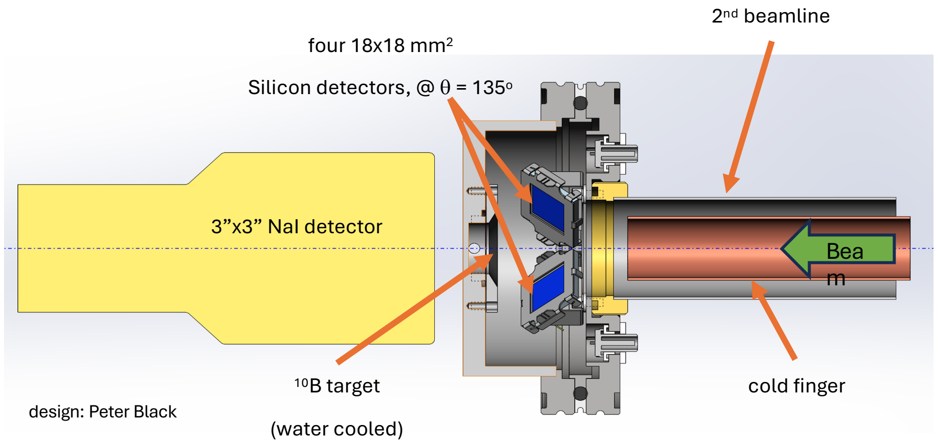
$^{10}B+\alpha$ Reaction Channels

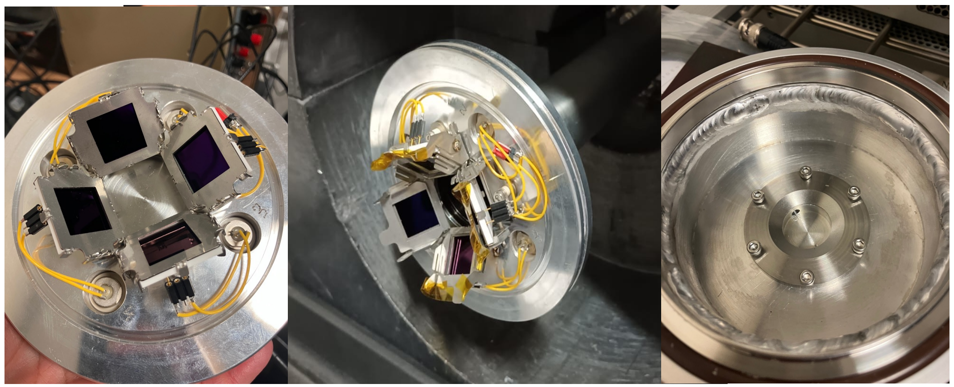


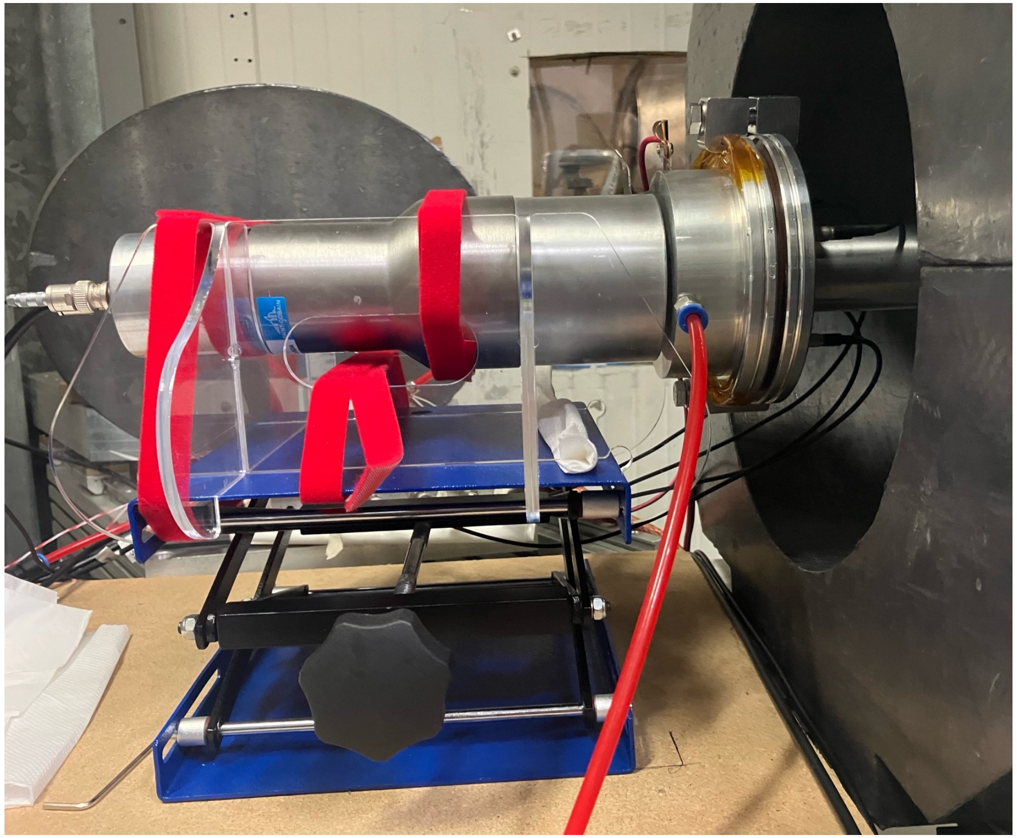
Experimental Campaigns @LUNA

- target thickness measurements (using well-known resonance in $^{11}B(p,\gamma)^{12}C$ reaction)
- target durability measurements (with low-energy $^{4}He^{+}$ beam)
- data taking for cross section measurements
  - charged-particle channels $^{10}B(\alpha,p)^{13}C$ and $^{10}B(\alpha,d)^{12}C$
  - neutron channel $^{10}B(\alpha,n)^{13}N$

Charged-particle Channels: $^{10}B(\alpha,p)^{13}C$ and $^{10}B(\alpha,d)^{12}C$



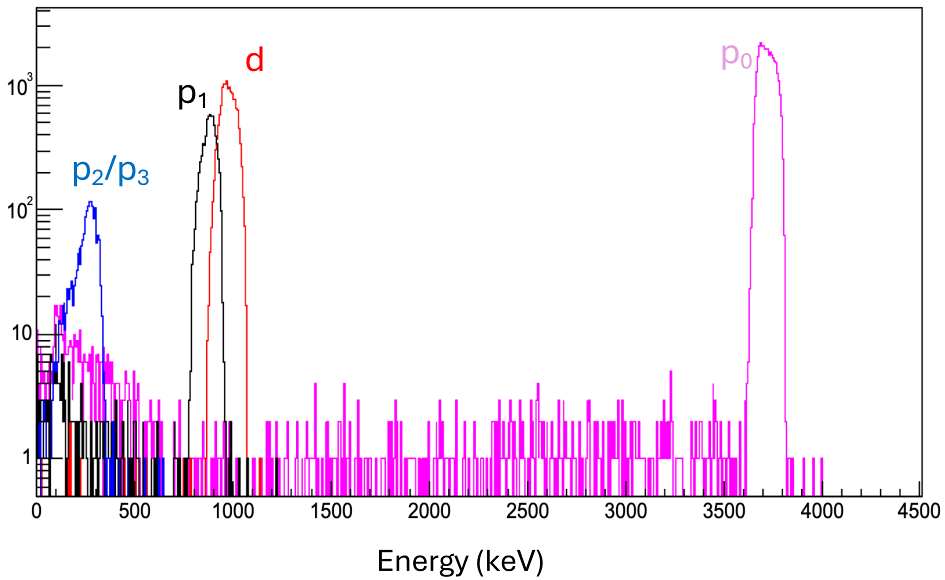


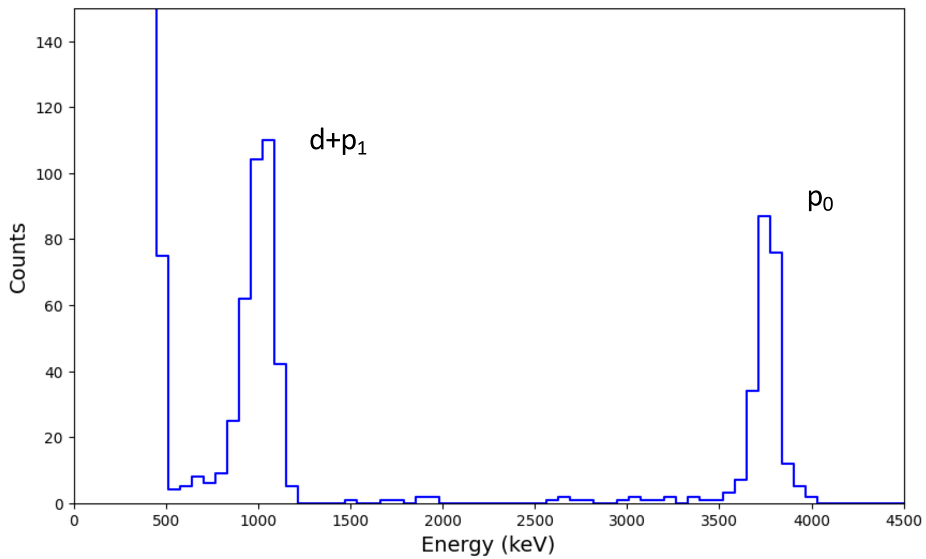


Cross-Section Measurements: the $^{10}B(\alpha,p_0)^{13}C$ Channel

$^{10}B+\alpha$: Simulated vs Experimental Spectra

E_{beam} = 400 keV, 3.5 um mylar foils





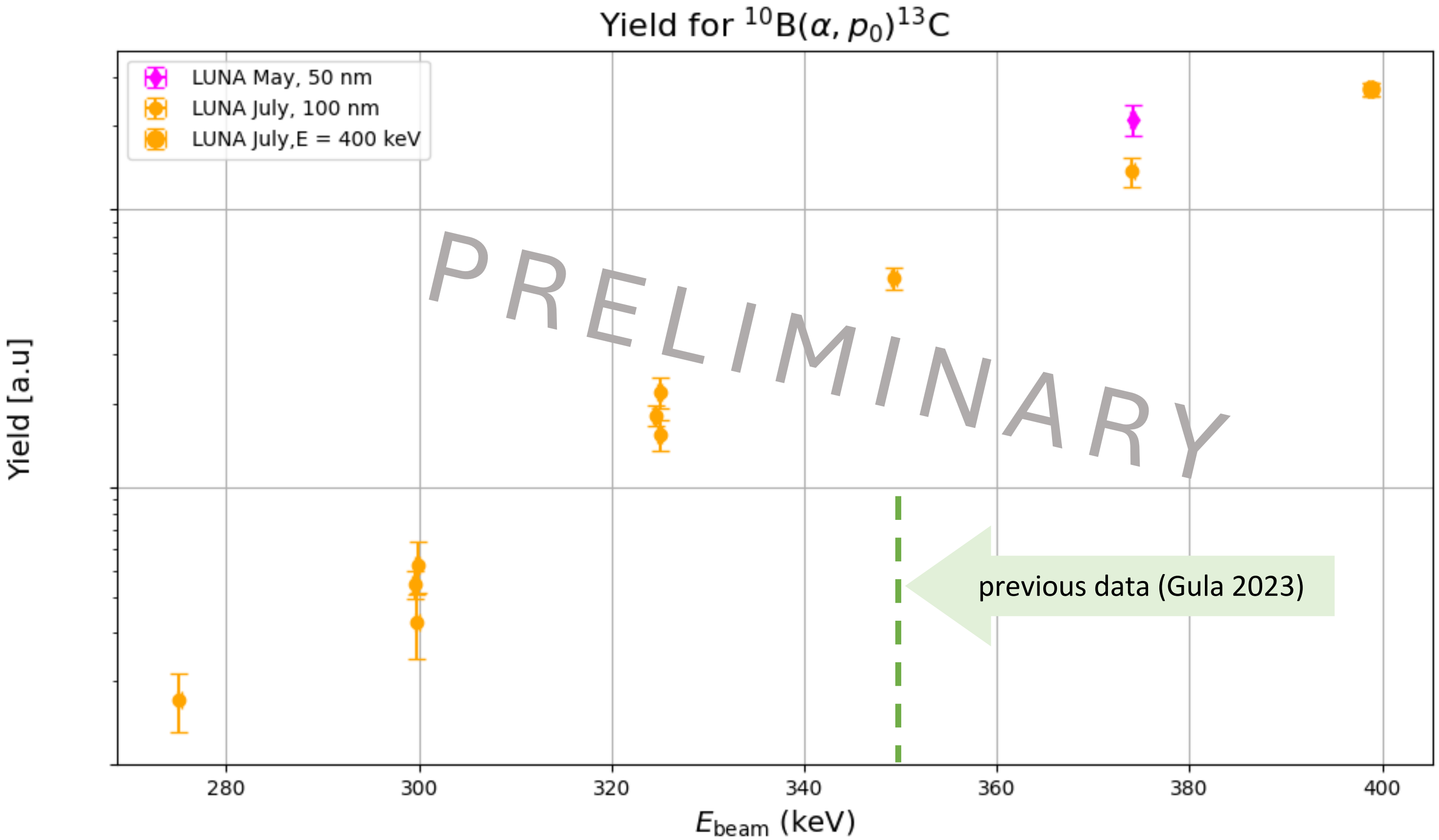
contributions scaled by respective cross sections (R-matrix estimates)

good overall agreement, but:

- p_1 and d peaks cannot be resolved
- p_2/p_3 lost in low-energy background

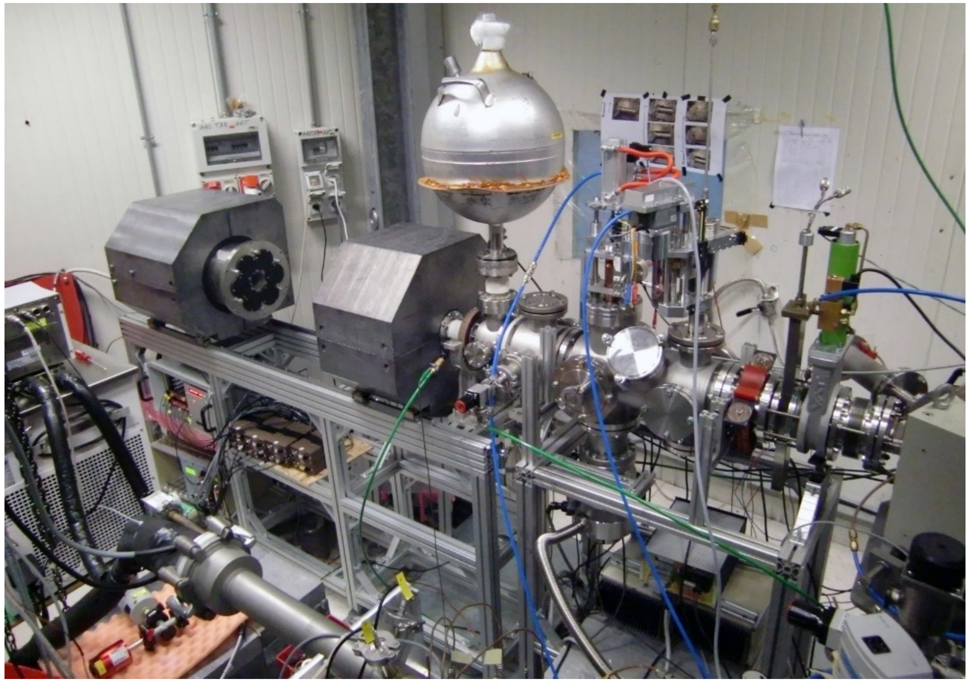
Preliminary Results: $^{10}B(\alpha,p_0)^{13}C$

- measured yield at beam energies E_α=250-400 keV
- data analysis in progress…
- target degradation corrections included
- target thickness effects still to be included

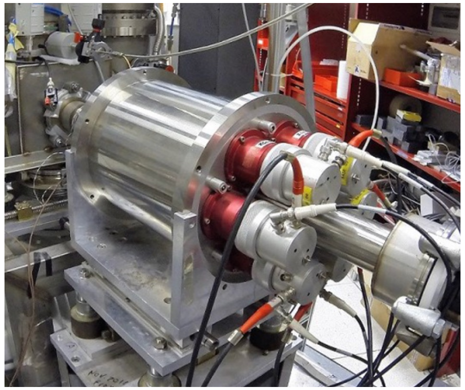


Cross-Section Measurements: the $^{10}B(\alpha,n)^{13}N$ Channel

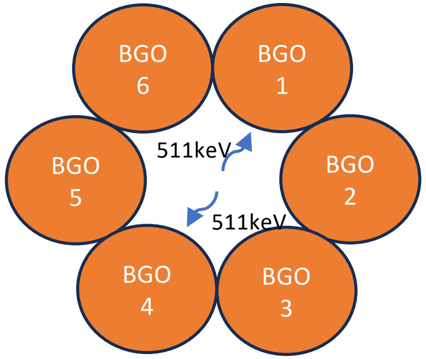
Neutron-channel $^{10}B(\alpha,n)^{13}N$: Activation Technique



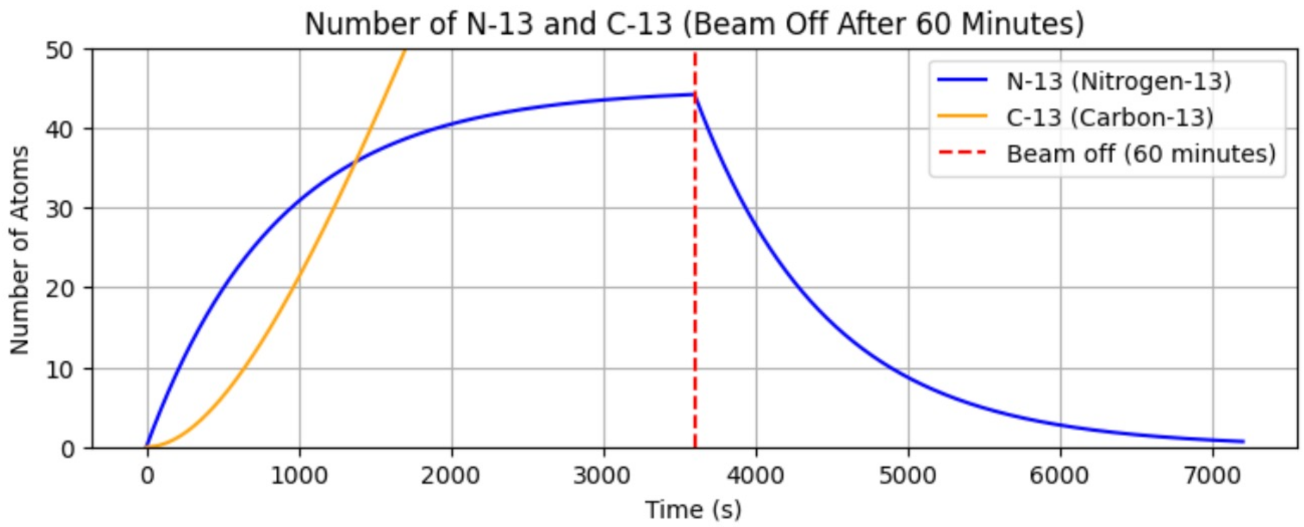
- activation technique (^{13}N lifetime ~ 10 min)
- coincident measurement of 511 keV annihilation γ rays following β^+ decay of ^{13}N
- 6-segments BGO detector
- coincidence in opposite crystals → reduce intrinsic and environmental background



LUNA BGO Detector



Activation Cycles: Beam On – Beam Off



$$(\text{Activation phase: beam ON}) \quad t \leq t_{\text{off}}$$

$$y(t) = N_0\left(1 - e^{-\lambda_{13_\text{N}} t}\right)$$

$$(\text{Decay phase: beam OFF}) \quad t > t_{\text{off}}$$

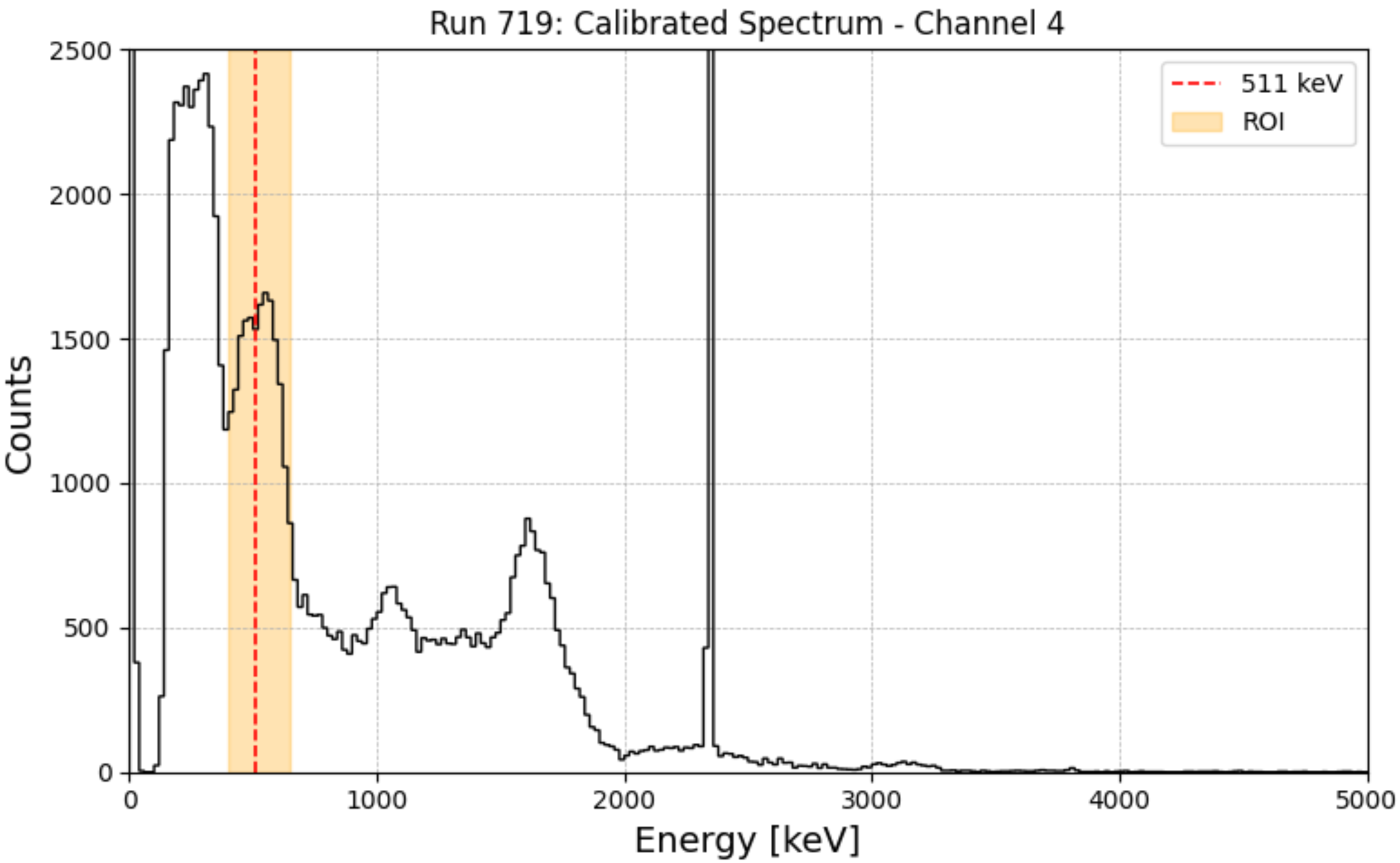
$$y(t) = N_0\left(1 - e^{-\lambda_{13_\text{N}} t_{\text{off}}}\right) e^{-\lambda_{13_\text{N}}(t - t_{\text{off}})}$$

Where:

- N_0 → Maximum number of nitrogen-13
- λ_{13N} → decay constant of nitrogen -13
- y(t) → total counts (#nitrogen-13) at time t

Sample Spectrum and Coincidence Gating

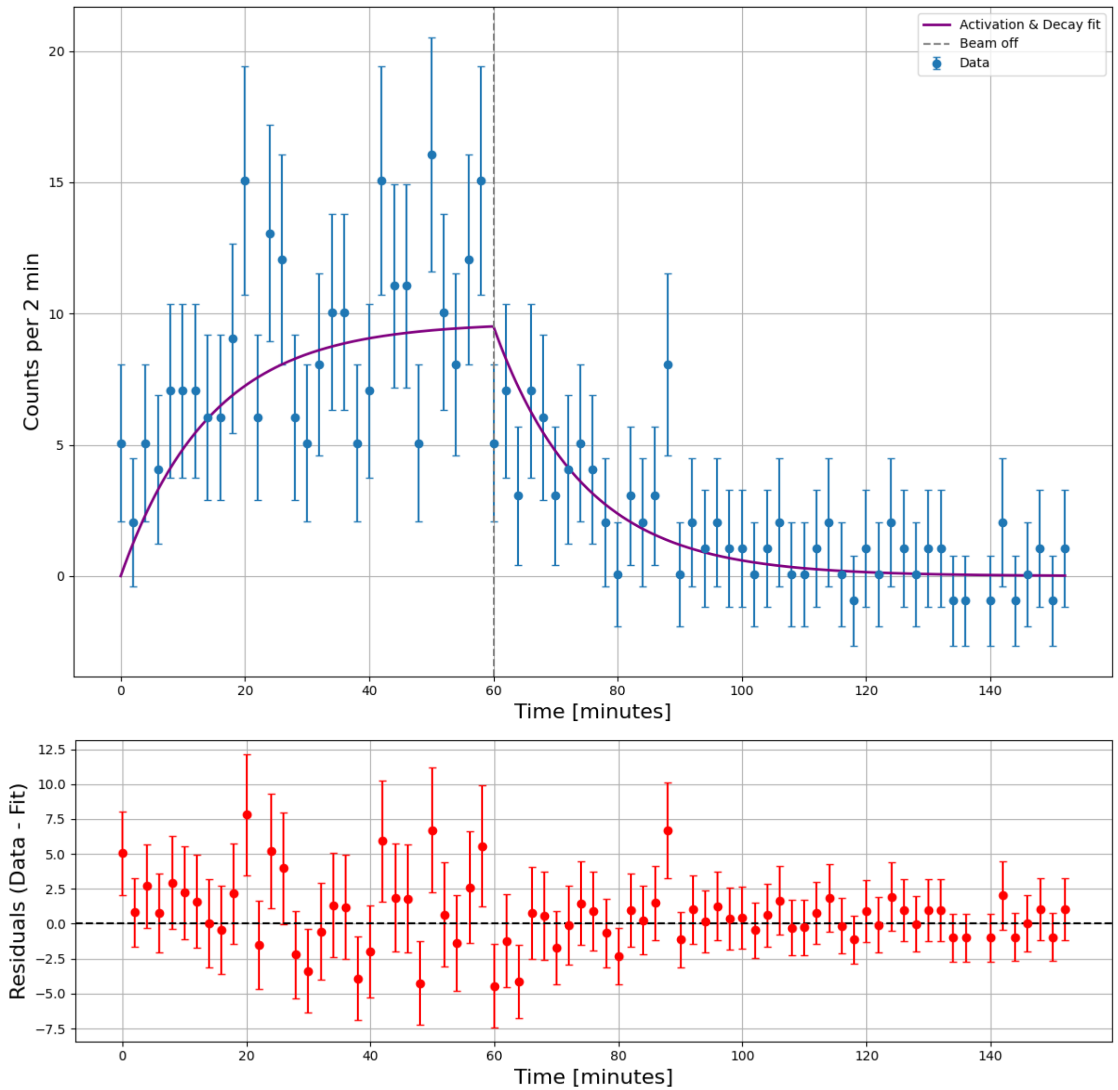
- ROI around 511 keV
- coincidence window: 100 ns
- coincidences in opposite crystals
- coincidence timestamp
- plot coinc. counts vs. time



Activation Data Fitting

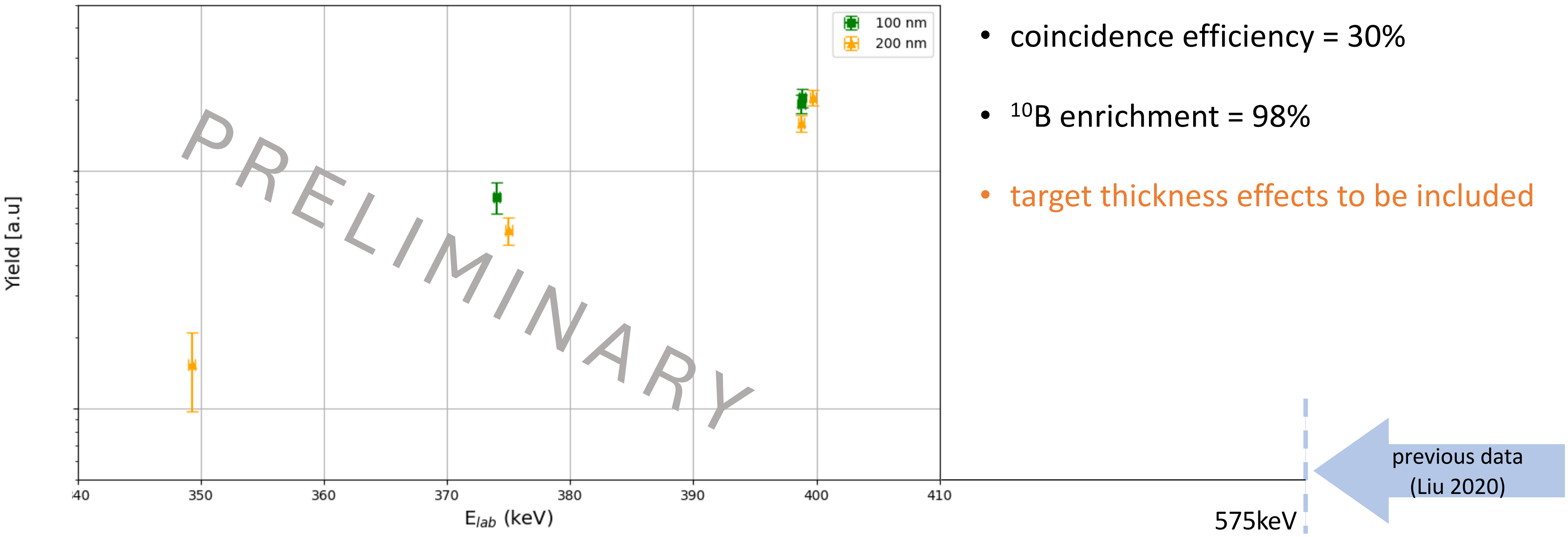
- E_a = 400 keV
- target: 10B4C_100_9
- accumulated charge: 0.49C
- Total Counts (Activation + Decay): 273

- procedure repeated for other beam energies and target thicknesses



Preliminary Results: $^{10}B(\alpha,n)^{13}N$

by Activation Measurement



- coincidence efficiency = 30%
- ^{10}B enrichment = 98%
- target thickness effects to be included

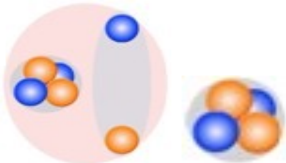
nuclear
nuclear clustering effects
in astrophysical reactions

Work Programme

Theoretical Programme

WP2a: PDRA2

G Hupin



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

RJ deBoer

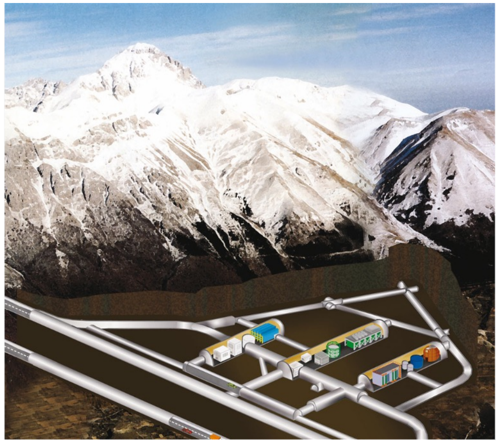
WP2b: **PI**, PDRA2

- improved R-matrix capabilities
- robust reaction rates

Experimental Programme

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

Laboratory for Underground Nuclear Astrophysics

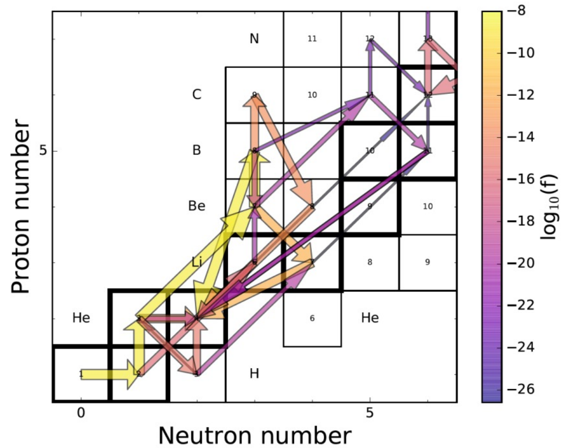


- α+Li and α+B reactions
- ultra-low background @LUNA
- lowest-energy data (world best)

Computational Programme

WP3: **PI**, PDRA3

M Pignatari



- stellar models for first stars (MESA)
- nucleosynthesis networks (NuGRID)
- astrophysical impact

Summary and Outlook

- alpha-induced reactions on B and Li isotopes: alternative pathways to CNO nucleosynthesis in first stars
- nuclear clustering expected to enhance fusion cross sections at low energies
- low-energy data still much needed
- measurements on $^{10}B(\alpha,p)^{12}C$ and $^{10}B(\alpha,n)^{13}N$ cross sections just started at LUNA
- initial results on look very promising
- more beamtime ahead… stay tuned…

PhD Students

Rhys Bonnell

Lavinia Dalla Vedova

Post-Doc

Alessandro Compagnucci

nuclear clustering effects in astrophysical reactions

UK Research and Innovation

https://www.erc-nuclear.uk

LUNA

THE LUNA COLLABORATION

http://luna.lngs.infn.it

UNIVERSITY OF NOTRE DAME

M. Wiescher, J. deBoer, V. Picciotto, K. Manukyan + local staff and students