THE ASTROPHYSICAL JOURNAL, **301**:629–633, 1986 February 15

A NEW ESTIMATE OF THE ^{19}Ne(p, γ)^{20}Na AND ^{15}O(α, γ)^{19}Ne REACTION RATES AT STELLAR ENERGIES

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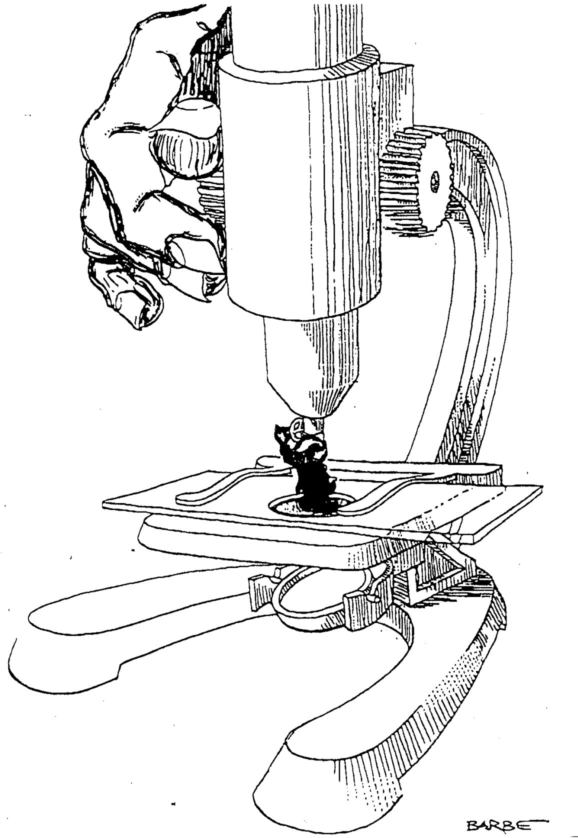
Received 1985 May 24; accepted 1985 August 19

ABSTRACT

We have improved the Wallace and Woosley estimates of the ^{19}Ne(p, γ)^{20}Na and ^{15}O(α, γ)^{19}Ne reaction rates at stellar energies by using the most recent experimental and theoretical data and a firmer theoretical background. We find a considerable increase in the ^{19}Ne(p, γ)^{20}Na reaction rate at temperatures $T_9 \leq 0.3$, which may lead to a greater production of intermediate mass elements in the rp-process in stellar evolution.

Subject headings: nuclear reactions — nucleosynthesis

Nuclear Astrophysics Deep Underground



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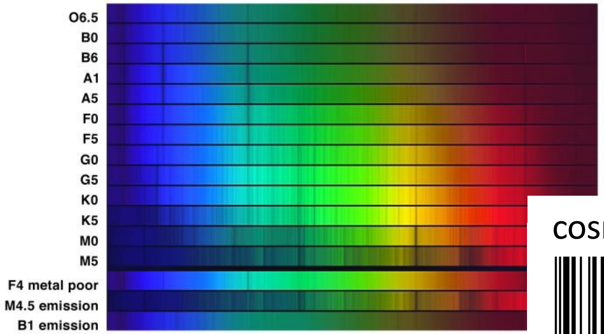
GSI-FAIR Special Colloquium for Michael Wiescher's 75^{th} Birthday

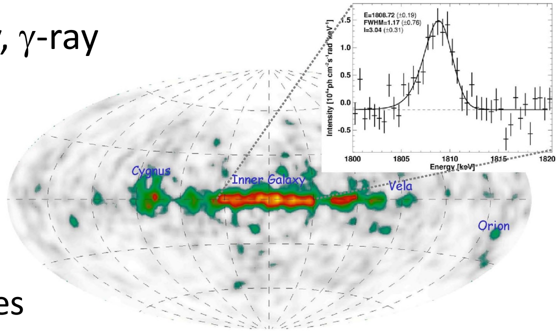
The Messengers of the Universe

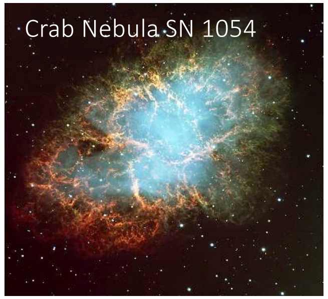
electromagnetic emissions

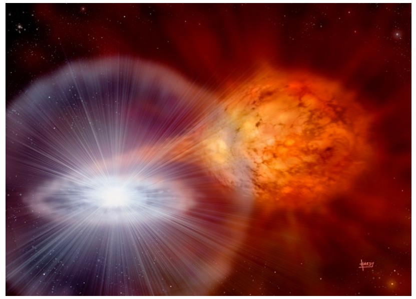
radio, microwave, infrared, optical, X-ray, γ-ray



cosmic bar codes

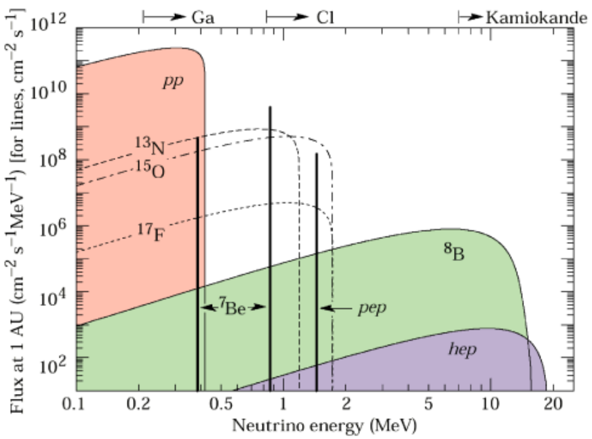


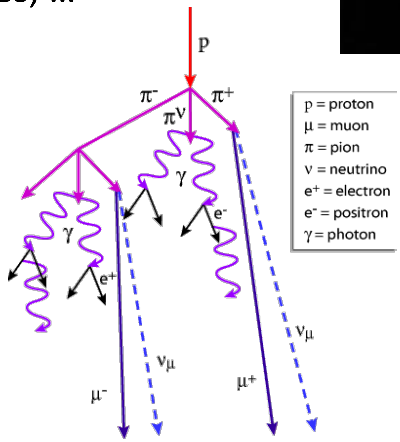




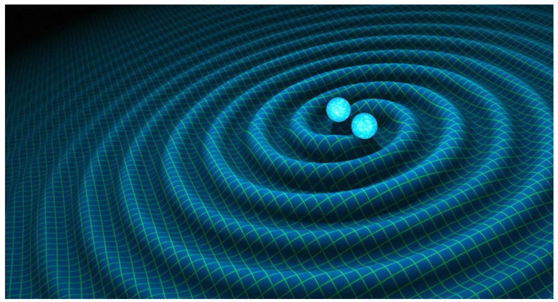
direct messengers

neutrinos, cosmic rays, meteorites, lunar samples, …

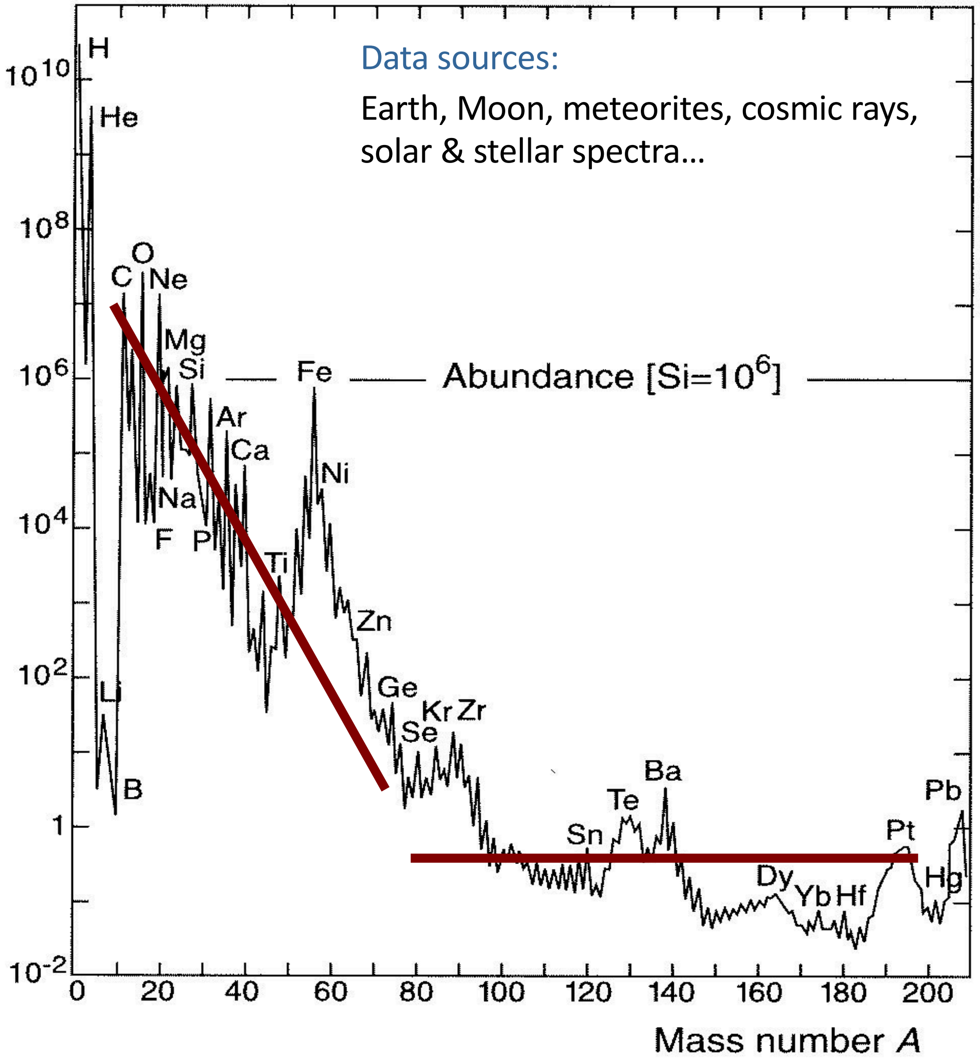




gravitational waves



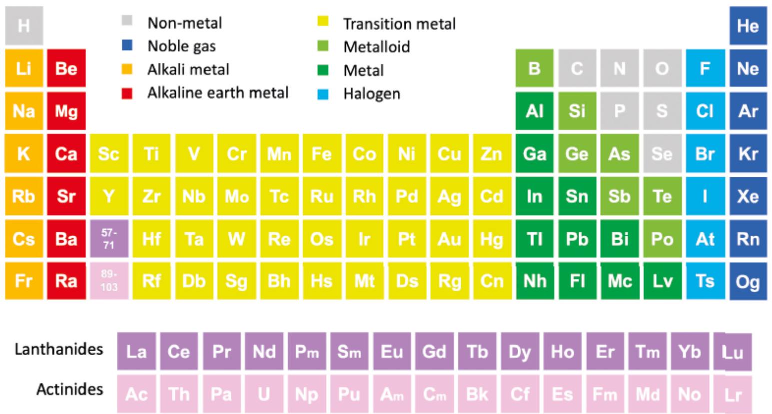
Solar Abundance Distribution



Features:

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

Why these features? Where do all elements come from?



REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

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

Rev. Mod. Phys. 29 (1957) 547 (B^2FH, 1957)

PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

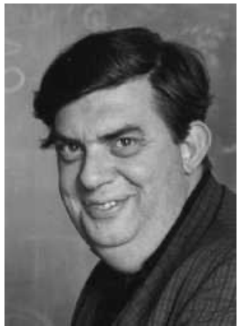
Vol. 69 June 1957 No. 408

NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

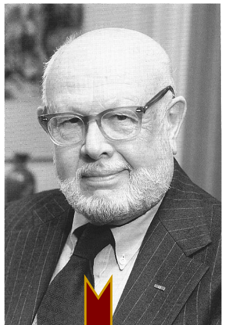
A. G. W. CAMERON
Atomic Energy of Canada Limited
Chalk River, Ontario

Burbidge

Burbidge



Fowler



Hoyle

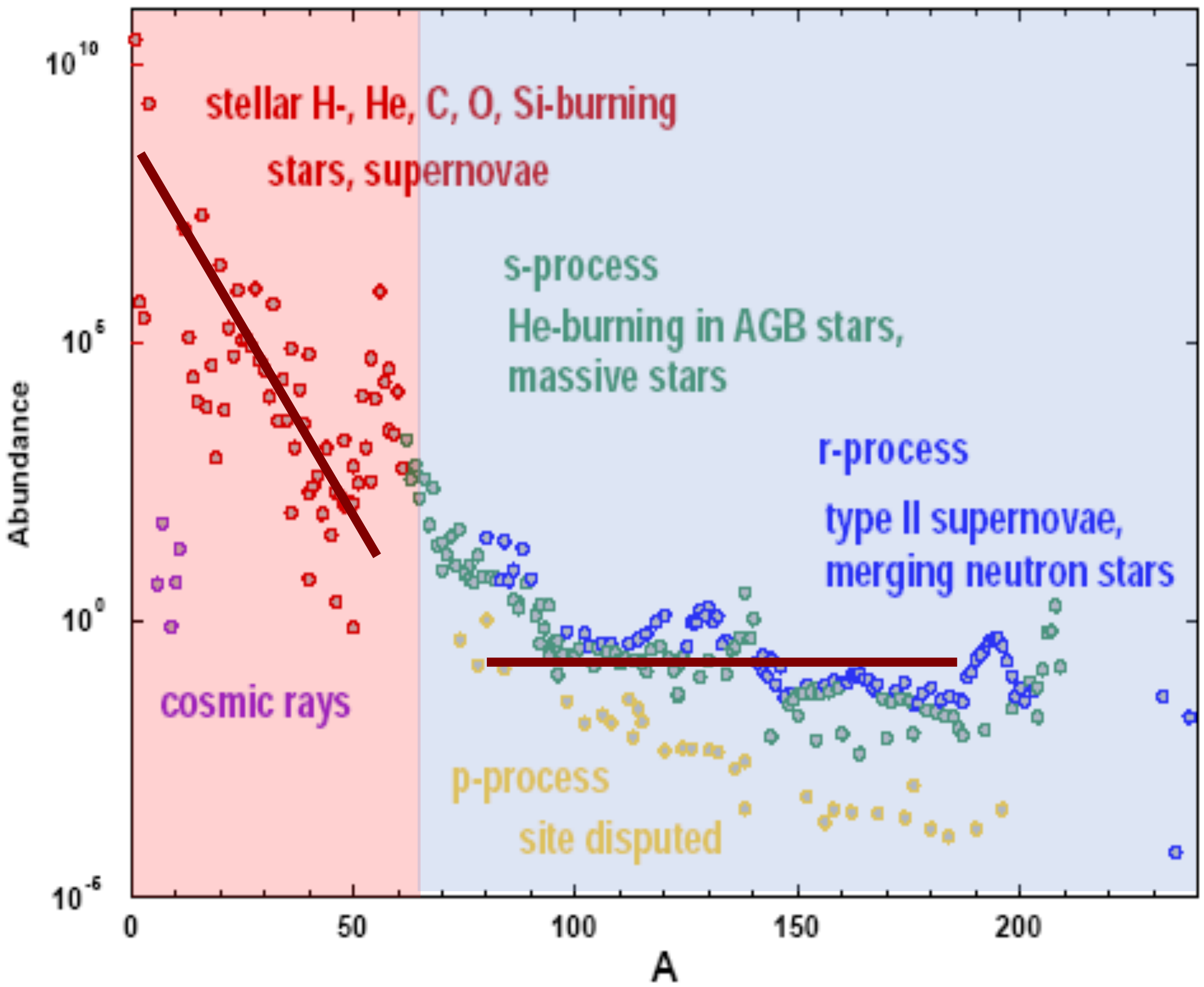
1983
Nobel Prize

"for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"

elements created by **nuclear reactions** in stars

fusion of
charged
particles

mainly
stable
nuclei



neutron-
capture
reactions

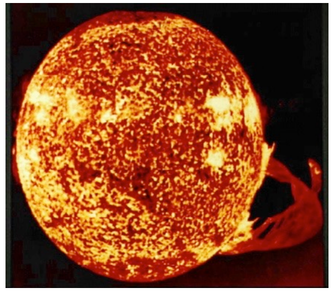
mainly
unstable
nuclei

M Aliotta

Inter-stellar medium

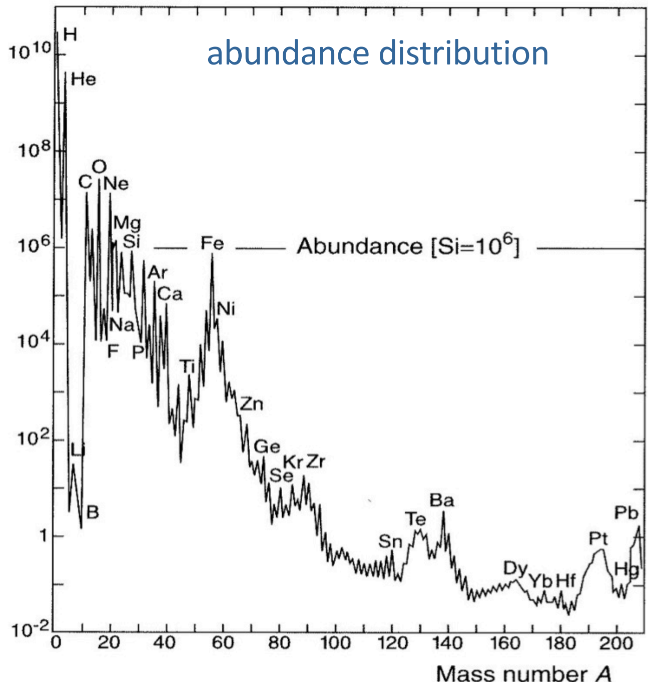
BIRTH
gravitational contraction

explosion
ejection
DEATH

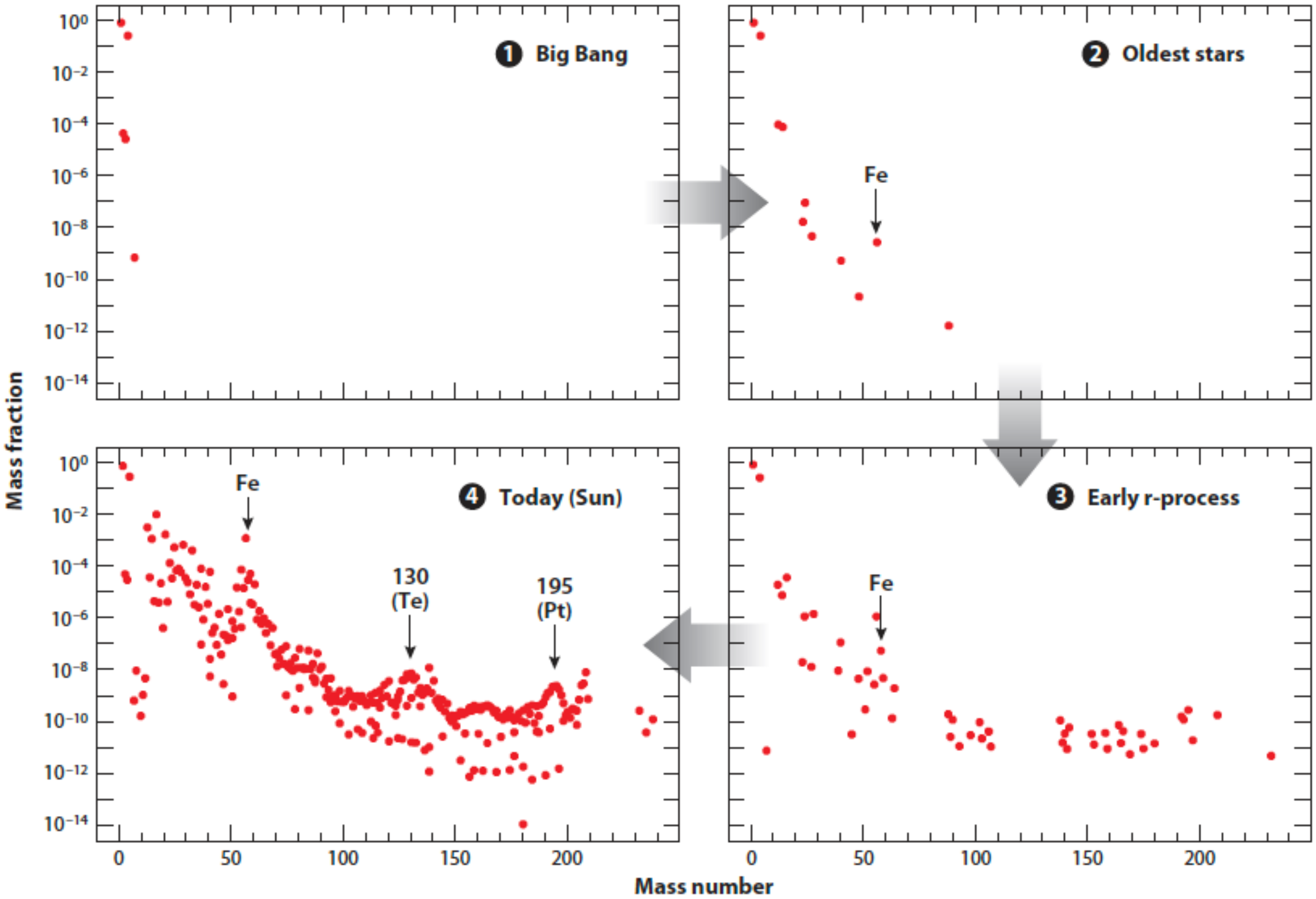


Stars

- energy production
- stability against collapse
- synthesis of “metals”



Galactic Chemical Evolution



Wiescher, Kaeppeler and Langanke, Annu. Rev. Astron. Astrophys. 50 (2012) 165-210

Stellar Reactions in the Laboratory: Experimental Challenges of Direct Measurements

Astrophysical energies (Gamow window) << Coulomb repulsion between interacting charges

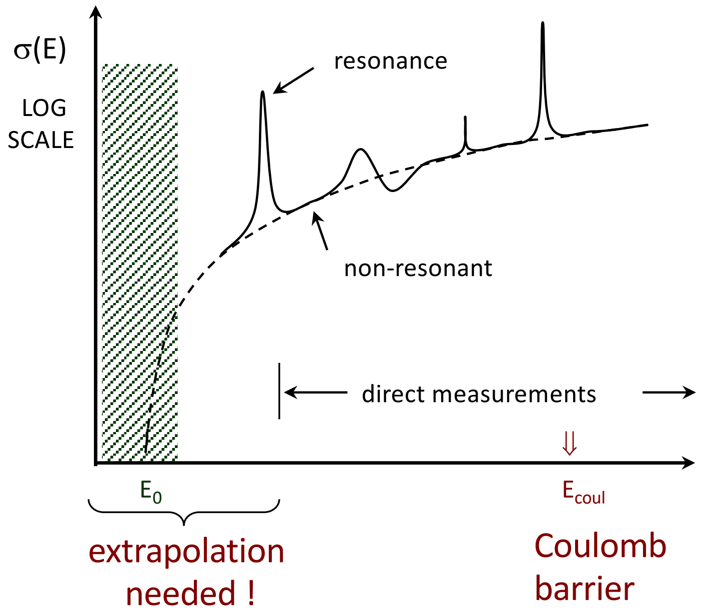
Experimental approach: measure $\sigma(E)$ over wide energy, then extrapolate down to E_0!

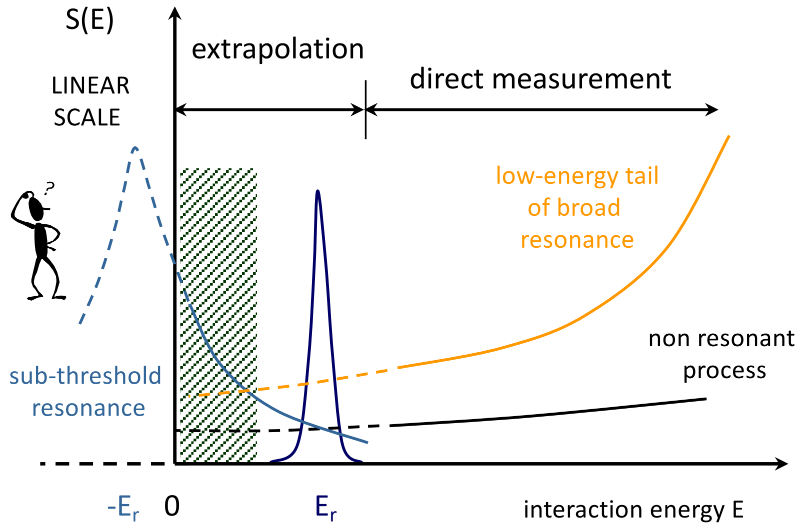
CROSS SECTION

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)\, S(E)$$

S-FACTOR

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$





DANGER OF EXTRAPOLATION !

low cross sections → low yields → poor signal-to-noise ratio

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?

A Pivotal Encounter

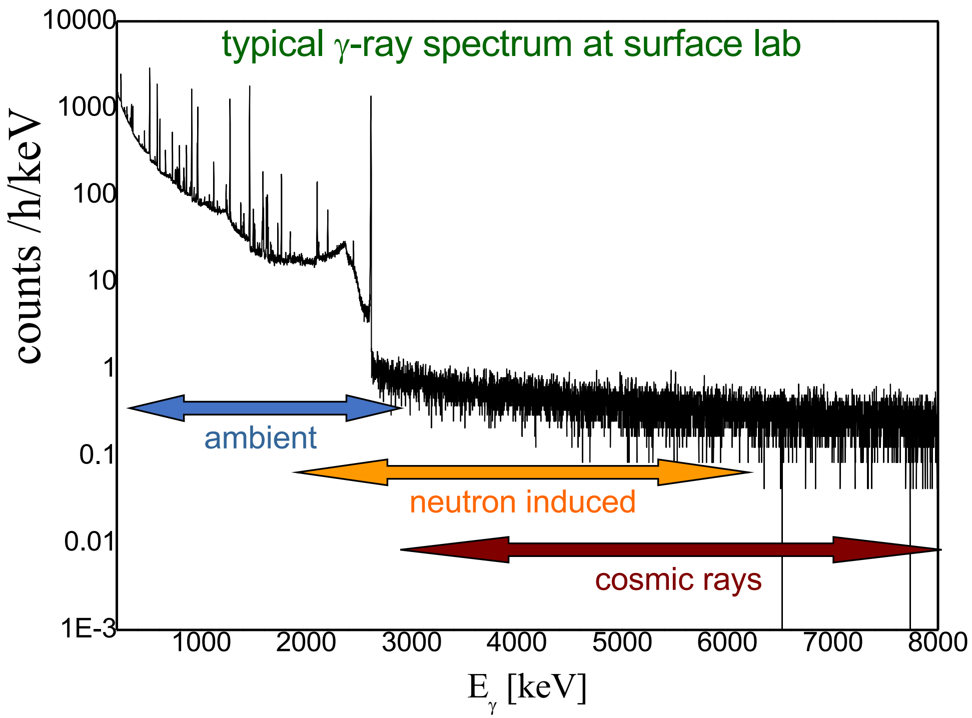
Nuclei in the Cosmos I, 1990 – Baden/Vienna, Austria

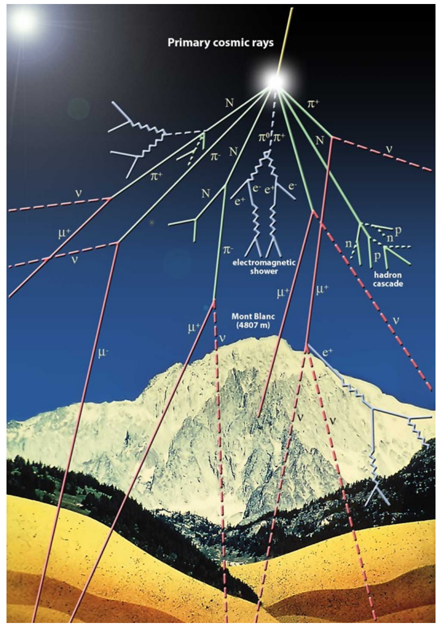
Why don’t you do your measurements underground?

This is such a great idea, it could have been mine!

Main Sources of Background

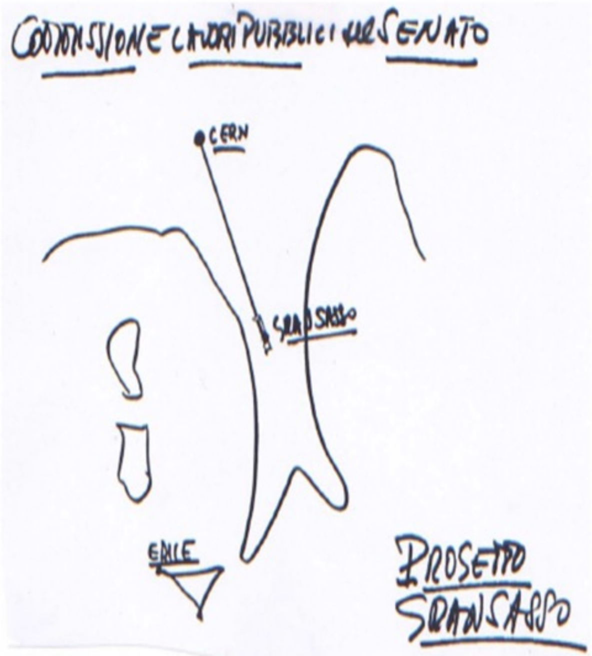
- natural radioactivity (mainly from U and Th chains and from Rn)
- cosmic rays (muons, $^{1,3}H$, ^{7}Be, ^{14}C, …)
- neutrons from (α,n) reactions and fission



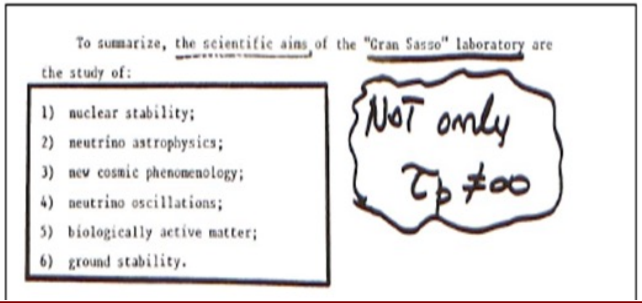


ideal location: underground + low concentration of U and Th

The Ideal Location: Laboratori Nazionali del Gran Sasso



Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).



To summarize, the scientific aims of the "Gran Sasso" laboratory are the study of:

1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

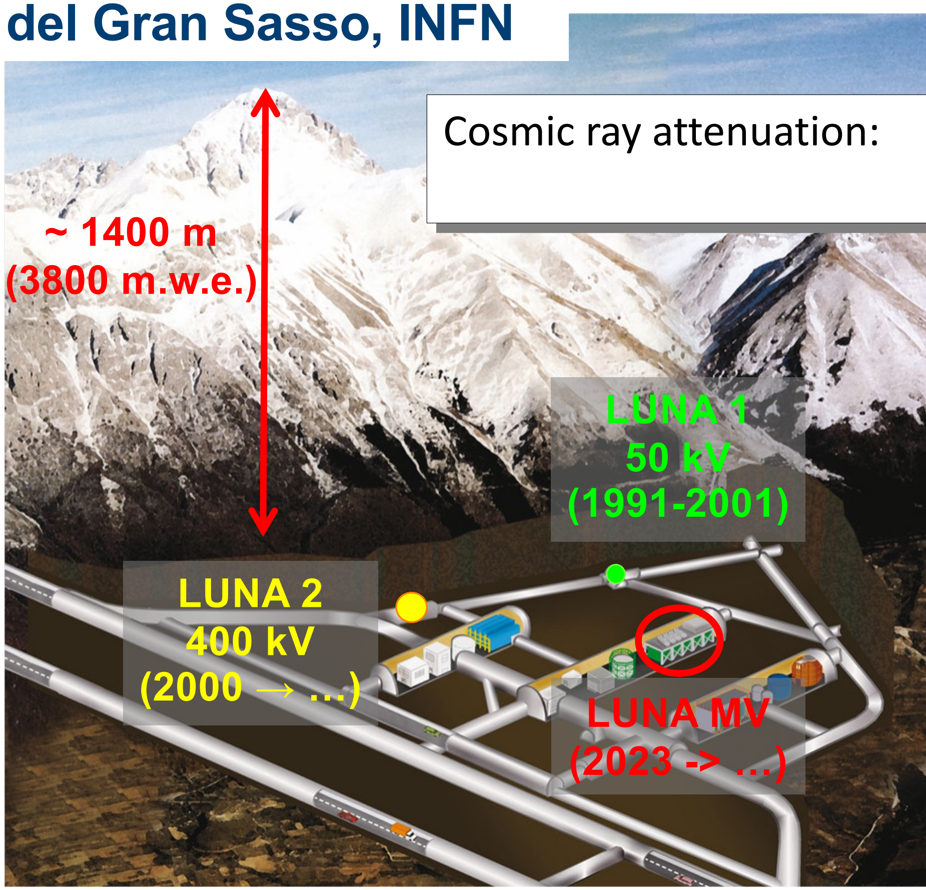
Not only $\tau_p \neq \infty$

Antonino Zichichi

courtesy: C Broggini

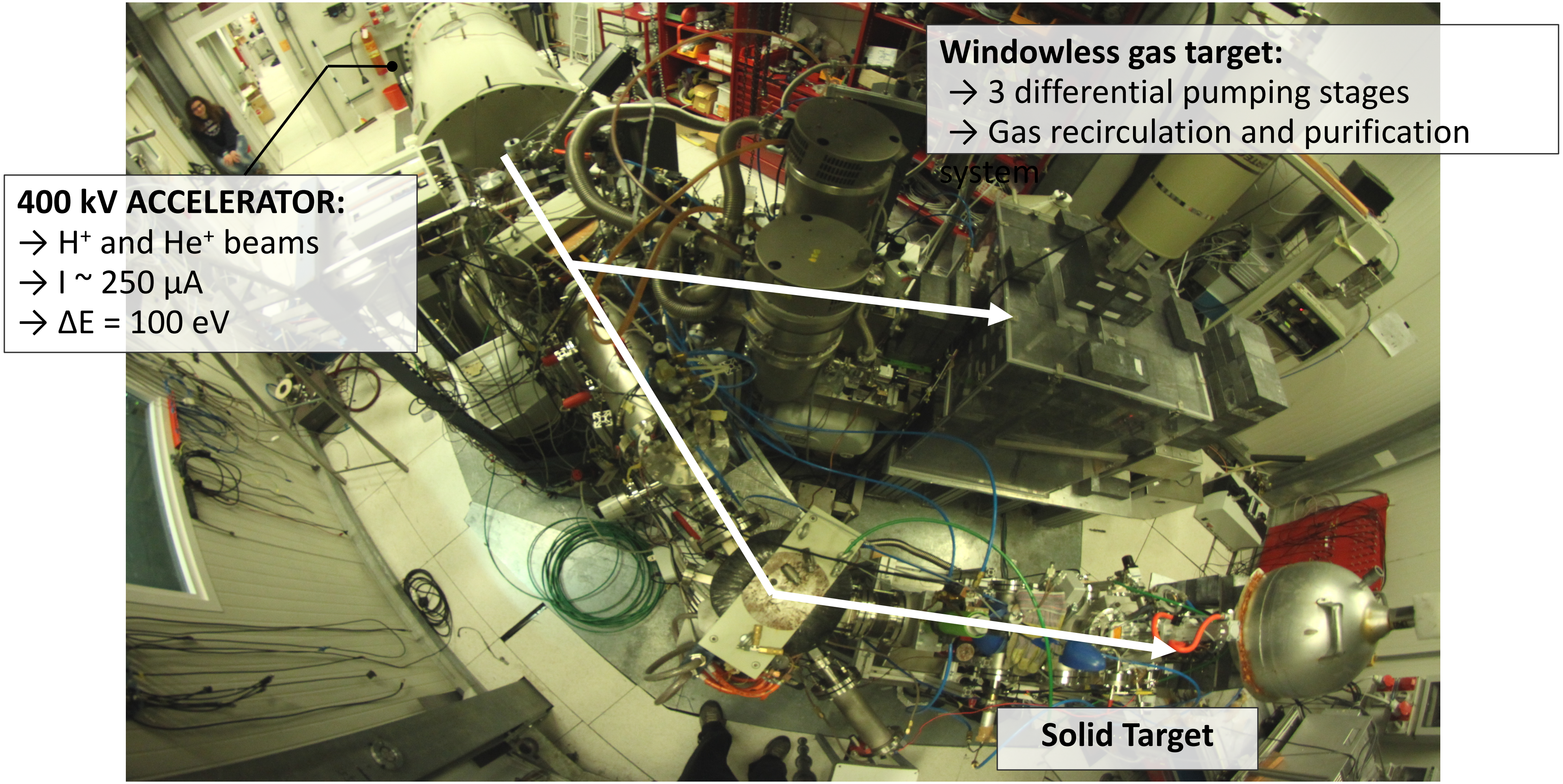
LUNA: **L**aboratory for **U**nderground **N**uclear **A**strophysics (established early 1990s)

Laboratori Nazionali del Gran Sasso, INFN



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

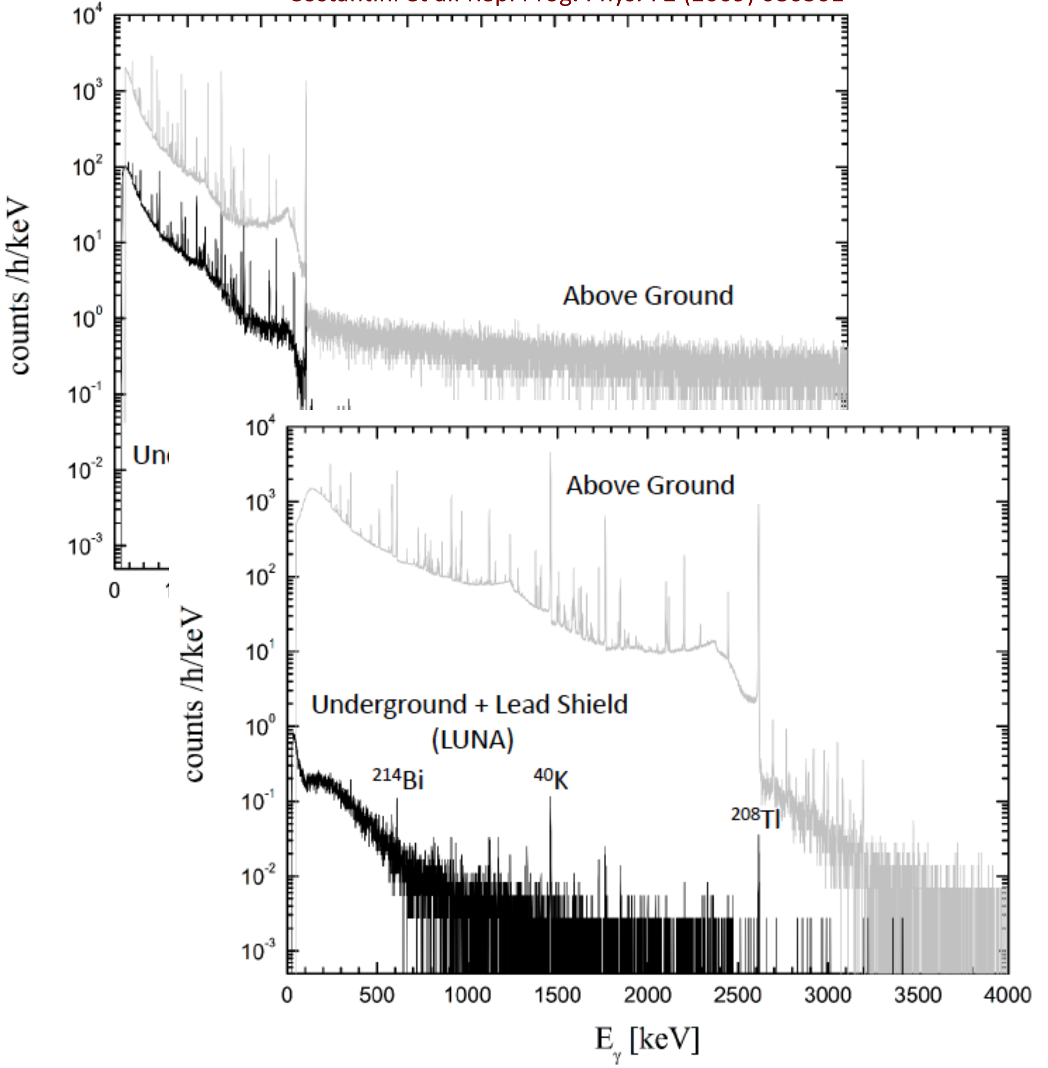
The LUNA 400 kV facility



M. Aliotta

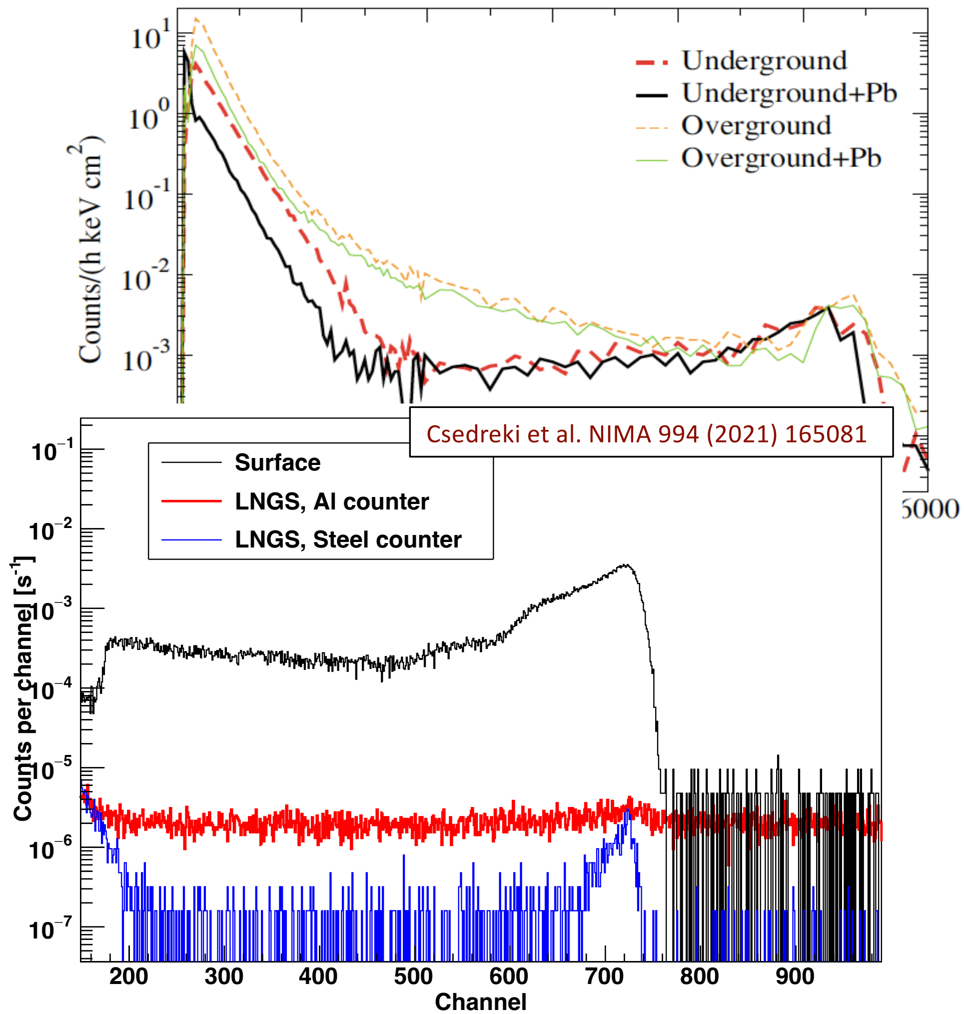
Gamma-ray Background Suppression

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



Bruno et al EJPA 51 (2015) 94

Csedreki et al. NIMA 994 (2021) 165081



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

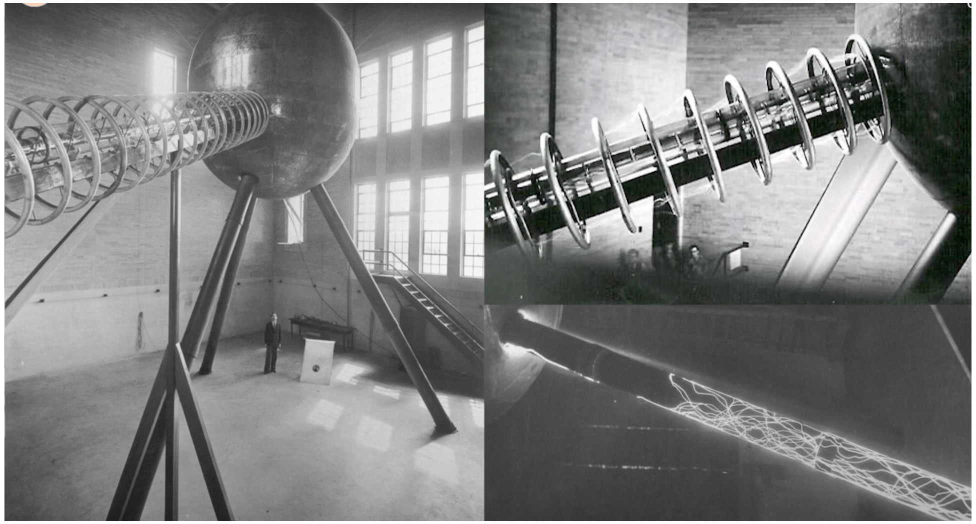
- **solar fusion reactions**
  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$
- **electron screening and stopping power**
  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$
- **CNO, Ne-Na and Mg-Al cycles**
  $^{12,13}C(p,\gamma)^{13,14}N$ $^{14,15}N(p,\gamma)^{15,16}O$ $^{16}O(p,\gamma)^{17}F$ $^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$
- **(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**
  $^{13}C(\alpha,n)^{16}O$

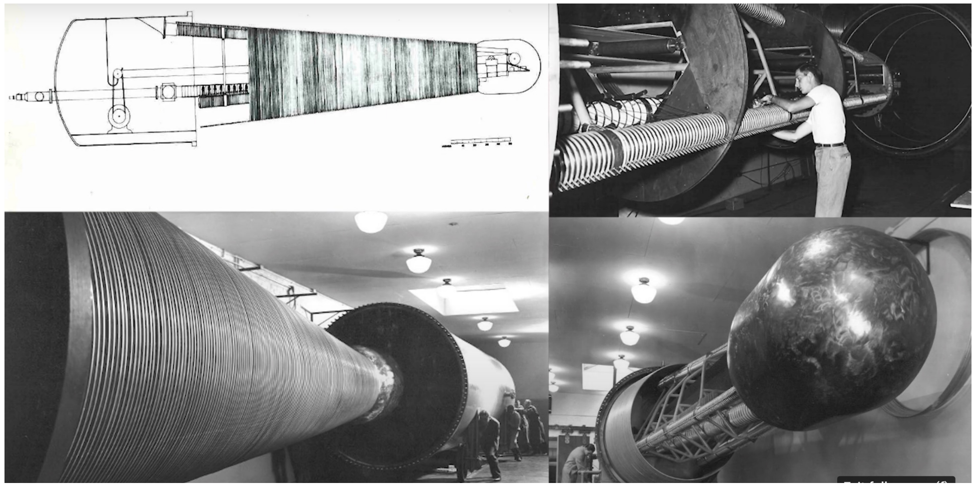
some of the lowest cross sections ever measured (few counts/month)

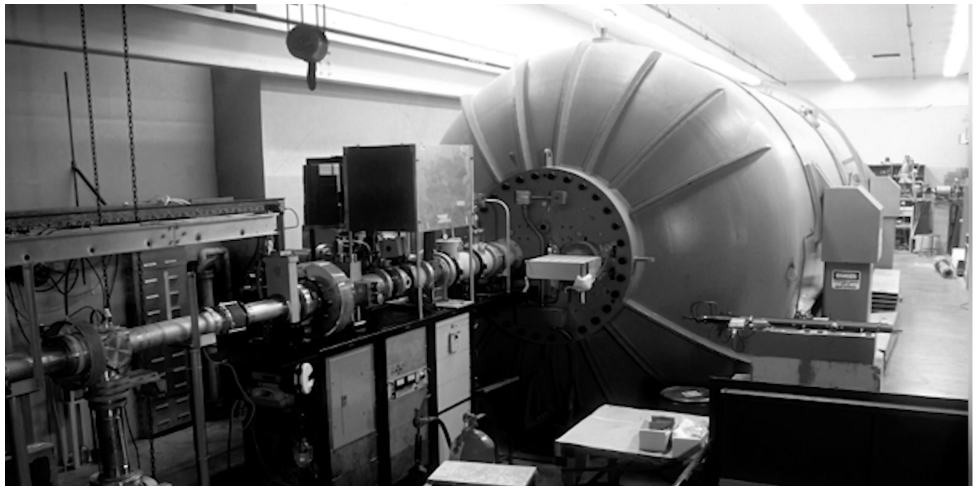
24 reactions in 30 years: ~15 months data taking per reaction!

M Aliotta

Notre Dame University

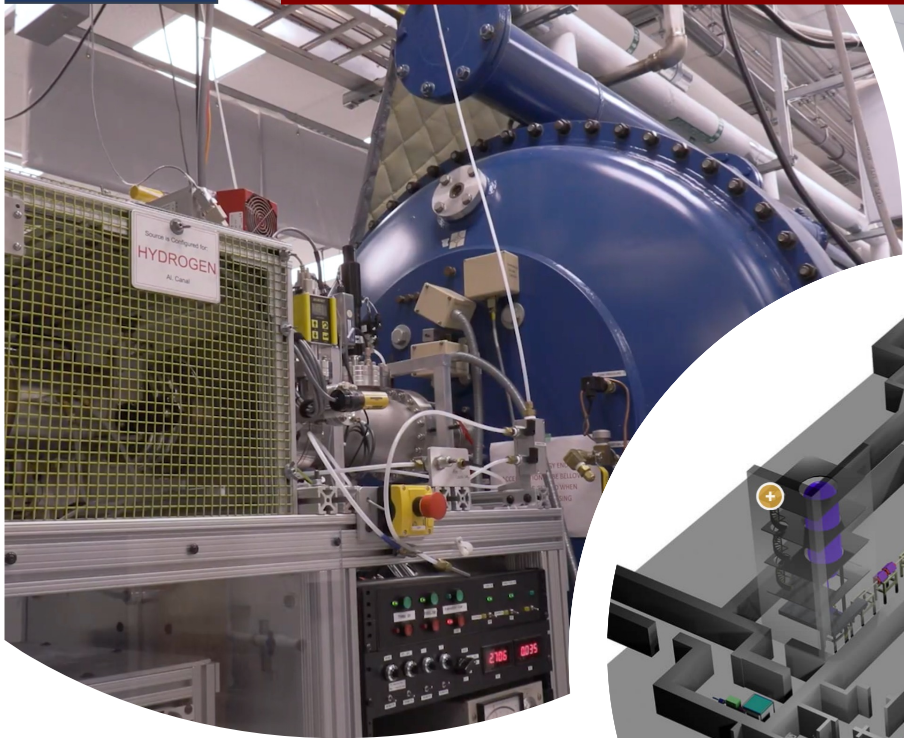






M Aliotta

Notre Dame University



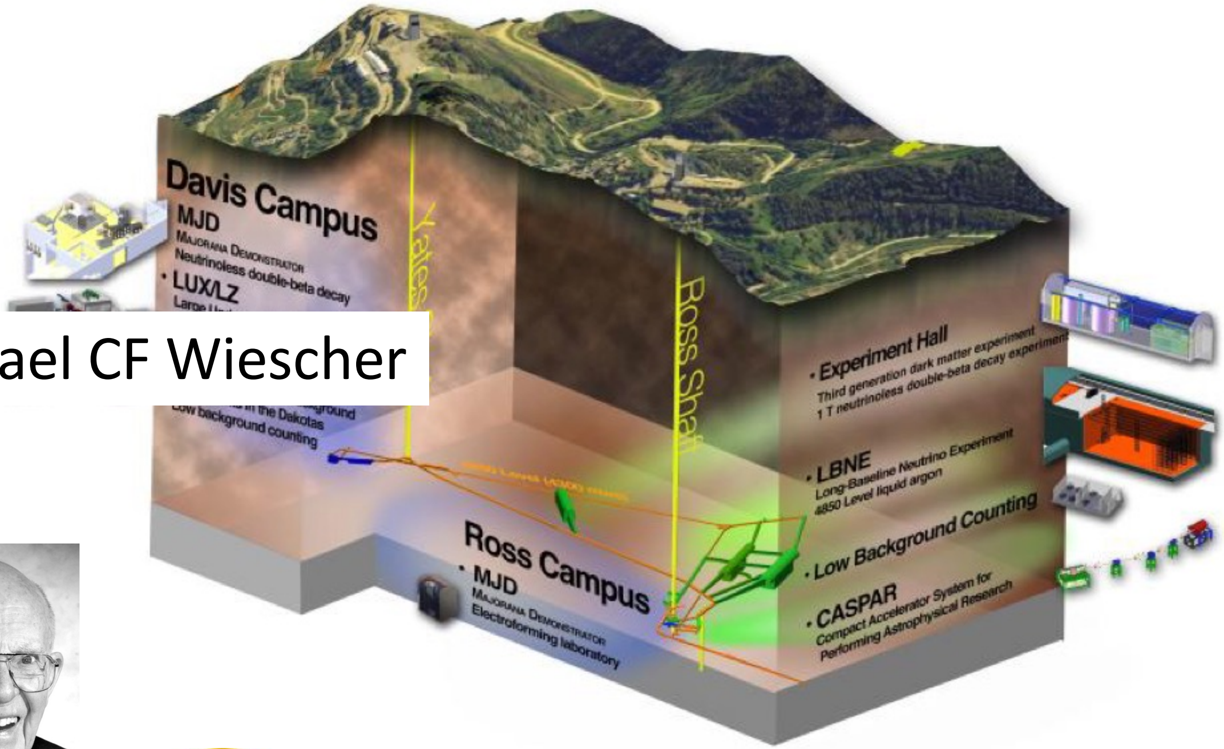
UNIVERSITY *of* NOTRE DAME

I S N A P

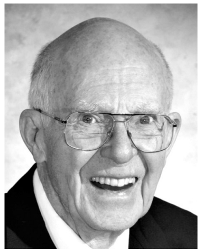
INSTITUTE FOR STRUCTURE AND NUCLEAR ASTROPHYSICS

SURF: Sandford Underground Laboratory at Homestake (South Dakota)

Homestake Gold Mine 4850 ft (1.5km) below sea level



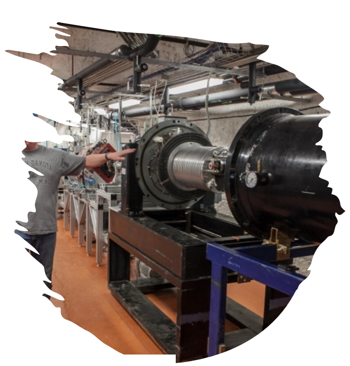
Michael CF Wiescher

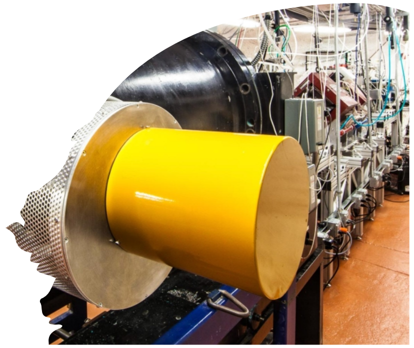


Ray Davis Jr.
2002 Nobel Prize

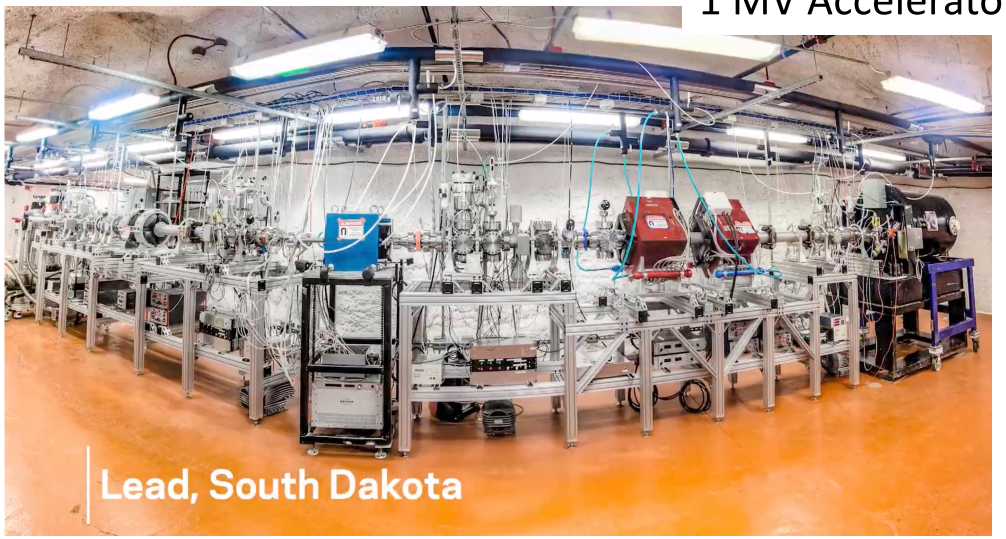
https://sanfordlab.org/facility

CASPAR
Compact Accelerator Systems for Performing Astrophysical Research





1 MV Accelerator Inaugurated July 2017

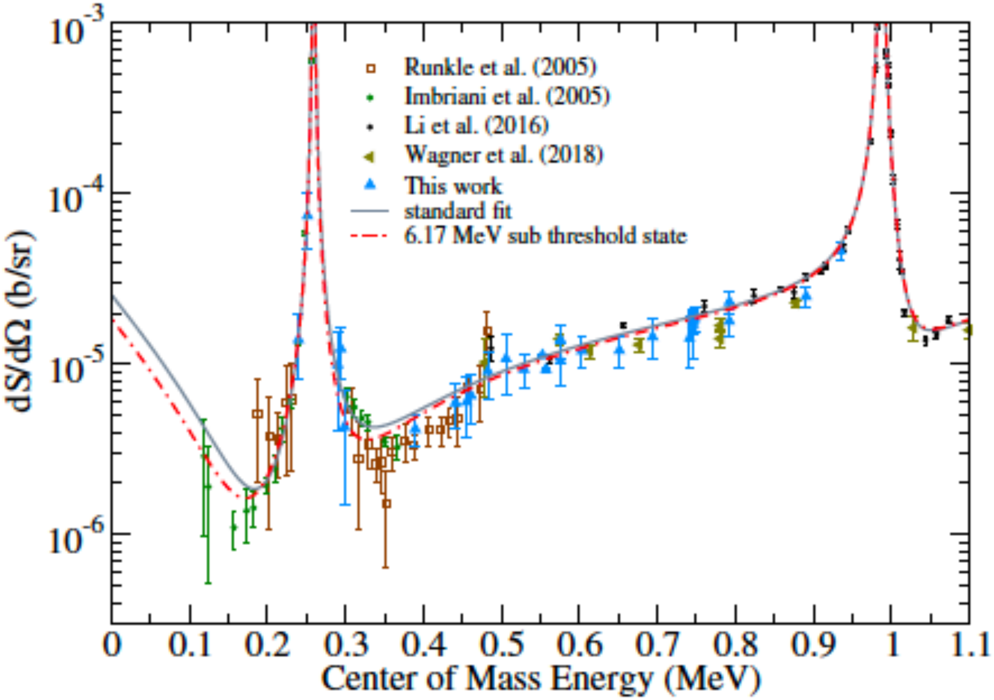


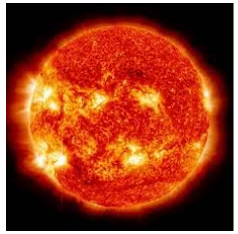
SURF: Sandford Underground Laboratory at Homestake (South Dakota)

PHYSICAL REVIEW C **106**, 065803 (2022)

Investigation of the $^{14}N(p,\gamma)^{15}O$ reaction and its impact on the CNO cycle

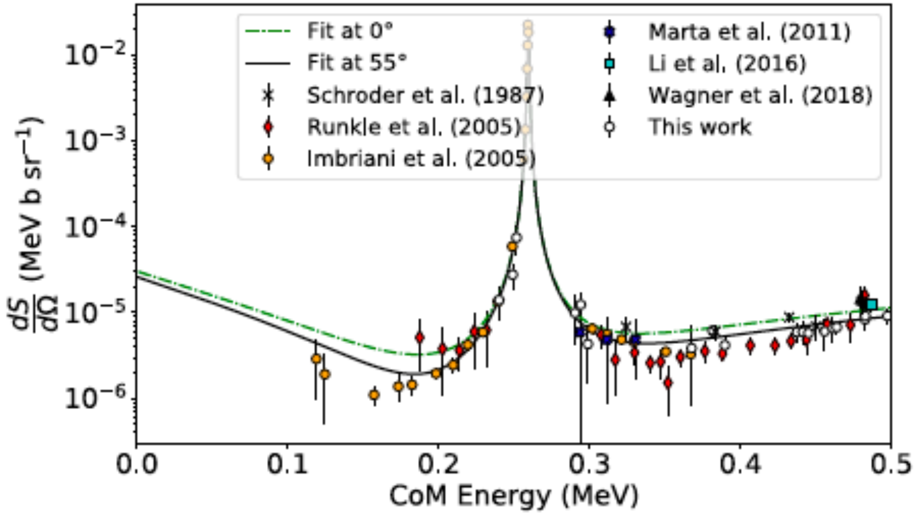
B. Frentz,[1] A. Aprahamian,[1] A. Boeltzig,[1,*] T. Borgwardt,[2,†] A. M. Clark,[1] R. J. deBoer,[1] G. Gilardy,[1] J. Görres,[1] M. Hanhardt,[2,3] S. L. Henderson,[1] K. B. Howard,[1] T. Kadlecek,[2] Q. Liu,[1] K. T. Macon,[1,‡] S. Moylan,[1] C. S. Reingold,[1] D. Robertson,[1] C. Seymour,[1] S. Y. Strauss,[1] F. Strieder,[2] B. Vande Kolk,[1] and M. Wiescher[1]
[1]*Department of Physics and Astronomy and the Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2]*Department of Physics, South Dakota School of Mines & Technology, Rapid City, South Dakota 57701, USA*
[3]*Sanford Underground Research Facility, Lead, South Dakota 57754, USA*





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

CNO cycle, solar neutrinos, solar metallicity, age of Globular Clusters, …



discrepancies still remain…

SURF: Sandford Underground Laboratory at Homestake (South Dakota)

PHYSICAL REVIEW C **106**, 025805 (2022)

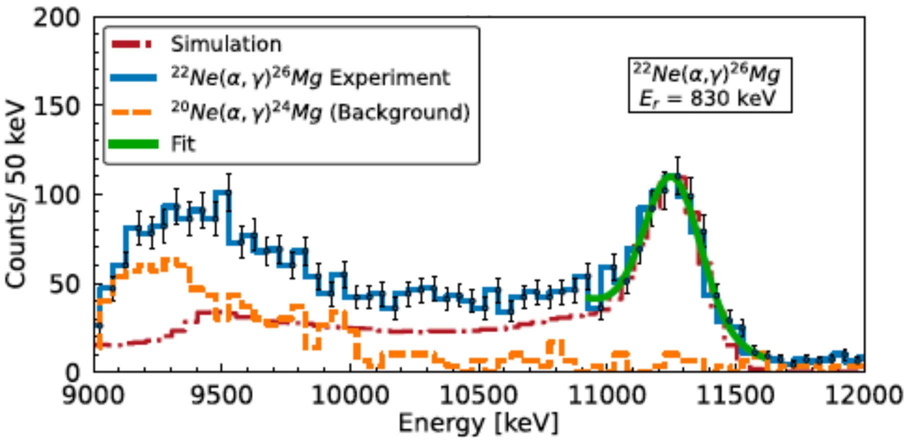
Direct measurement of the low-energy resonances in ^{22}Ne(α, γ)^{26}Mg reaction

Shahina,[1,2] J. Görres,[1,2] D. Robertson,[1,2] M. Couder,[1,2] O. Gomez,[1,2] A. Gula,[1,2] M. Hanhardt,[3,4] T. Kadlecek,[3] R. Kelmar,[1,2] P. Scholz,[1,2] A. Simon,[1,2] E. Stech,[1,2] F. Strieder,[3] and M. Wiescher[1,2]
[1]*Department of Physics and Astronomy, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[2]*The Joint Institution of Nuclear Astrophysics-Center for the Evolution of the Elements, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[3]*Department of Physics, South Dakota School of Mines and Technology, Rapid City, South Dakota 57701, USA*
[4]*South Dakota Science and Technology Authority, Sanford Underground Research Facility, Lead, South Dakota 57754, USA*

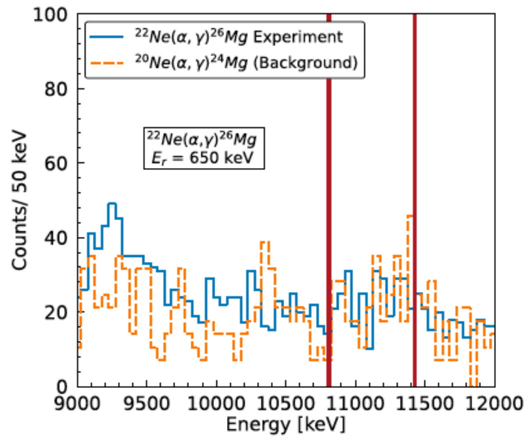
^{22}Ne(α,γ)^{26}Mg reaction:

competitor to ^{22}Ne(α,n)^{25}Mg

(n-source for synthesis of elements with 60 < A < 90)



$\omega\gamma$ = 35 ± 4 μeV
(in good agreement with literature)



$\omega\gamma$ < 0.15 μeV
(a factor of 4 smaller than literature)

γ-ray summing detector HECTOR

→ lower depletion of ^{22}Ne → enhanced production of s-process elements

SURF: Sandford Underground Laboratory at Homestake (South Dakota)

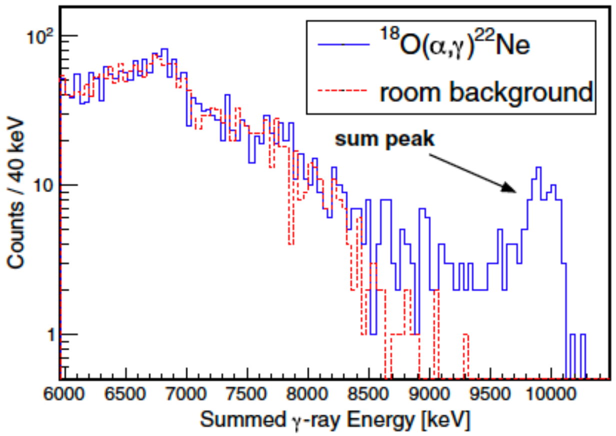
PHYSICAL REVIEW LETTERS **128,** 162701 (2022)

Measurement of Low-Energy Resonance Strengths in the $^{18}O(\alpha,\gamma)^{22}Ne$ Reaction

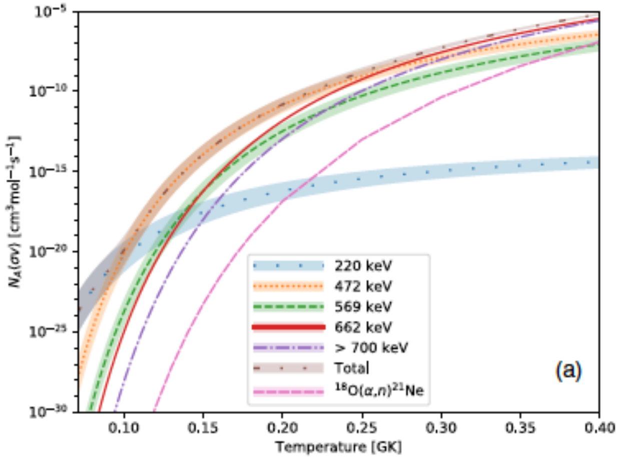
A. C. Dombos,[1,*] D. Robertson,[1,†] A. Simon,[1] T. Kadlecek,[2] M. Hanhardt,[2,3] J. Görres,[1] M. Couder,[1] R. Kelmar,[1] O. Olivas-Gomez,[1] E. Stech,[1] F. Strieder,[2] and M. Wiescher[1]
[1]*Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556-5670, USA*
[2]*Department of Physics, South Dakota School of Mines and Technology, Rapid City, South Dakota 57701, USA*
[3]*South Dakota Science and Technology Authority, Sanford Underground Research Facility, Lead, South Dakota 57754, USA*

$^{18}O(\alpha,\gamma)^{22}Ne$ reaction:

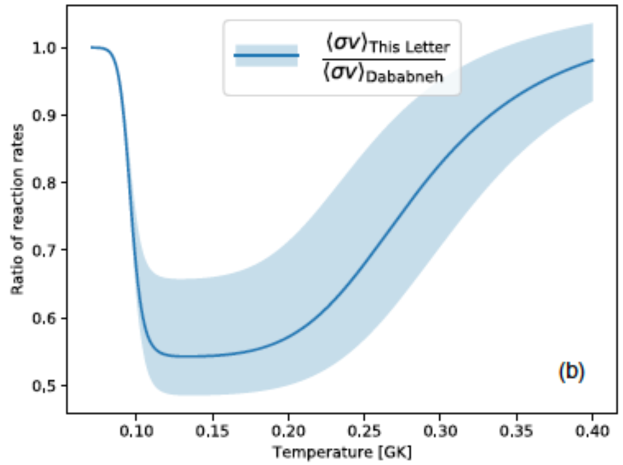
feeds $^{22}Ne + \alpha$ reaction channels



strong background suppression



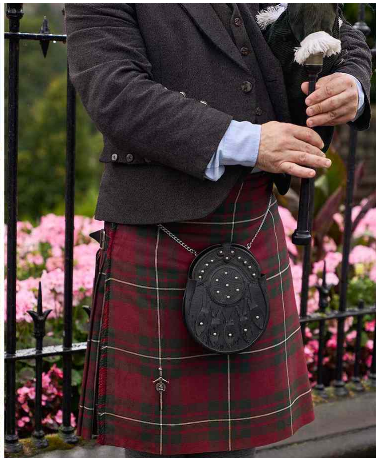
various resonances studies



nearly 50% reduction in reaction rate

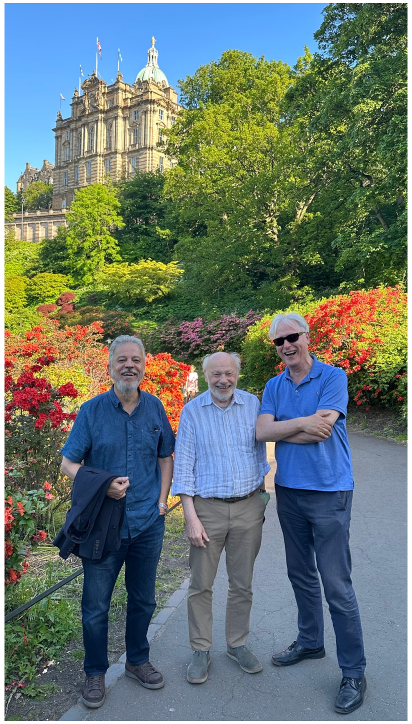
M Aliotta

Edinburgh's Attractions



M Aliotta

Enjoying the Scottish Lifestyle

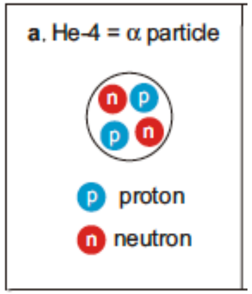


The Full Scottish Attire

Nuclear Clustering and Open Questions in Astrophysics

- Cosmological Lithium Problem(s)
- Nucleosynthesis in First Stars
- Electron Screening Puzzle

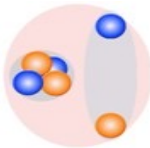
Nuclear Clustering



very stable configurations

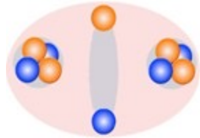
→ building blocks for other nuclei

^{6}Li



α ⊕ d

^{10}B

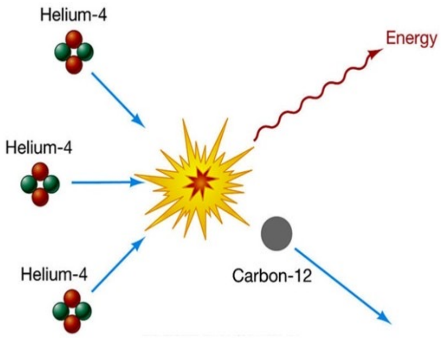


α ⊕ d ⊕ α

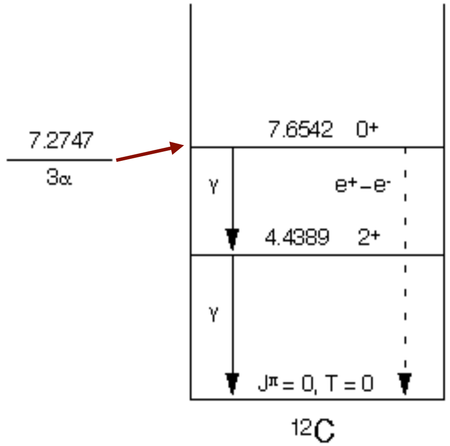
nuclear clustering may greatly

enhance fusion probabilities

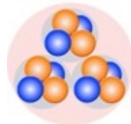
at low (i.e. astrophysical) energies



triple alpha process



Hoyle state



~10^{7} times faster

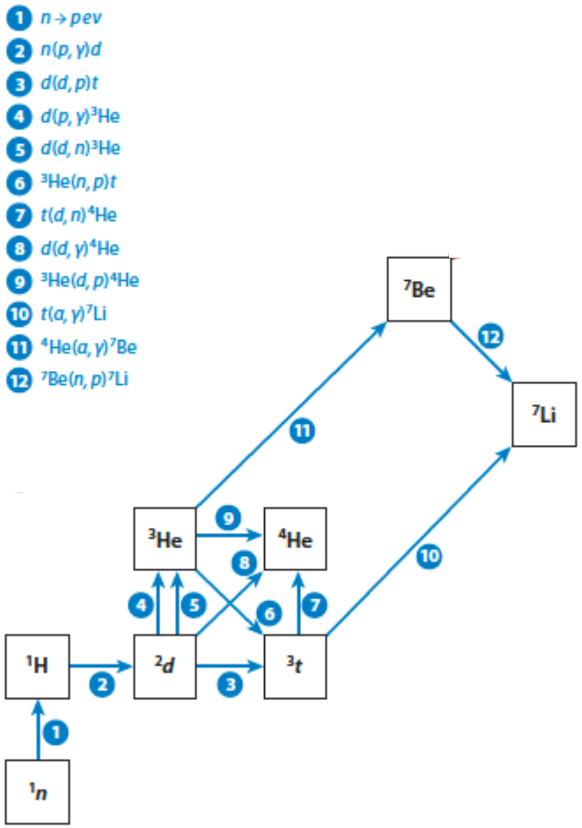
do similar cluster resonances exist in other key nuclear reactions?

can they solve all three open questions?

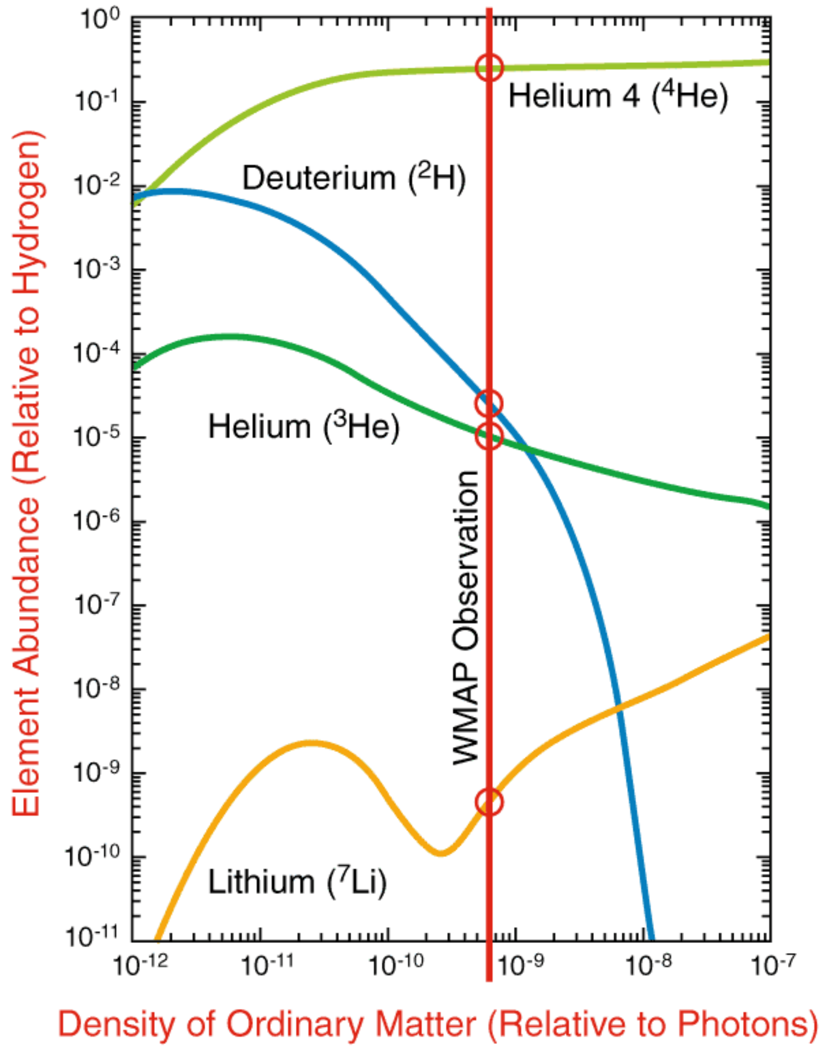
The Cosmological Lithium Problem(s)

Primordial Nucleosynthesis (BBN) and Primordial Abundances

3 minutes after Big Bang



adapted from Fields (2011) ARNPS©



Primordial Lithium Abundances

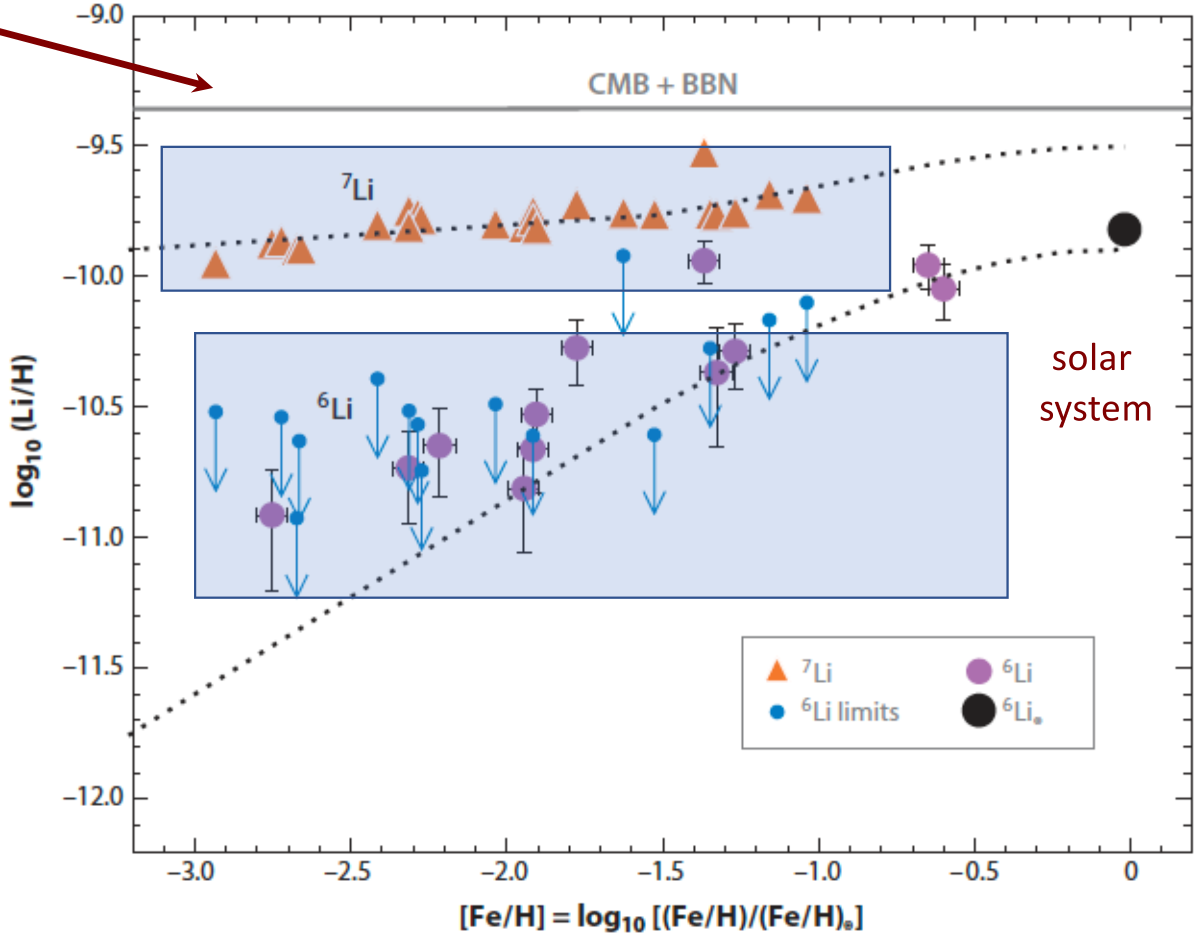
CBM + BBN predictions
^{7}Li abundance (^{6}Li/^{7}Li ~ 10^{-5})

observed ^{7}Li ~ 3x lower
than predicted

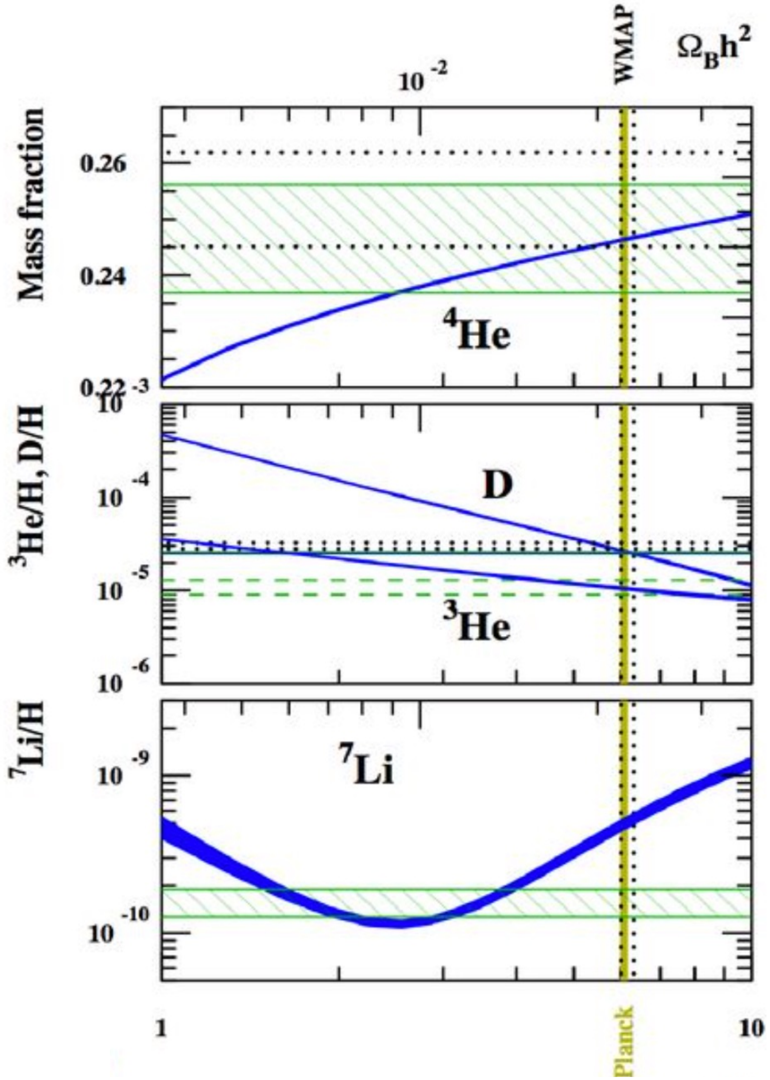
first Lithium Problem

observed ^{6}Li ~ $10^2 – 10^3$ higher
than predicted

second Lithium Problem



solar
system



D, ^{3}He and ^{4}He: good agreement

Li: overestimated by factor 3-4!

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?

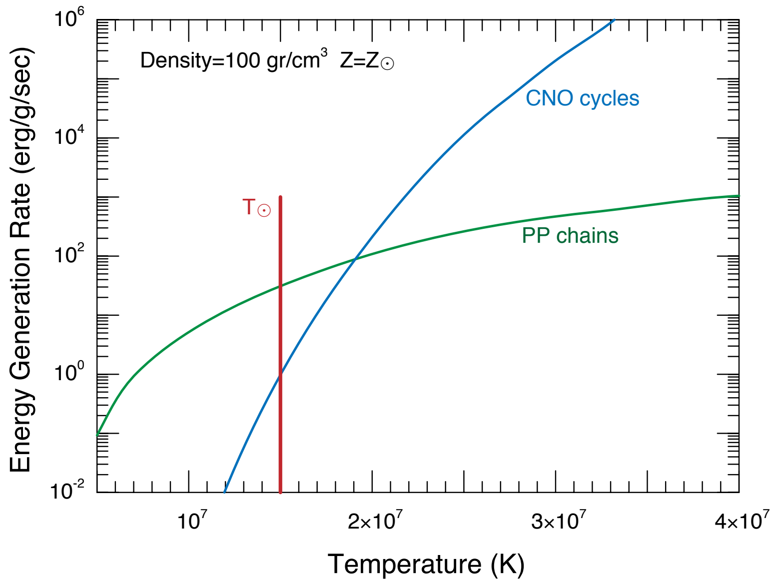
Non-standard model:

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 $M_\odot$)



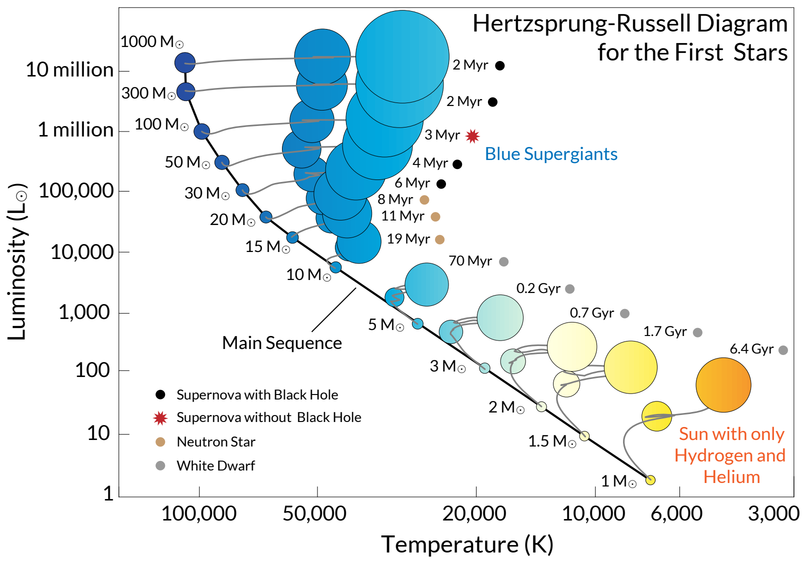
- made of primordial H and He
- no CNO to sustain star against gravity

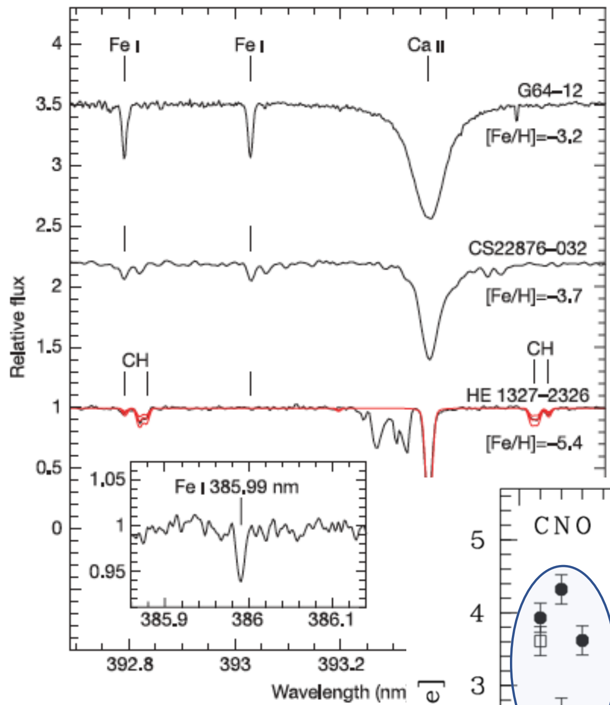
How did first stars evolve?

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

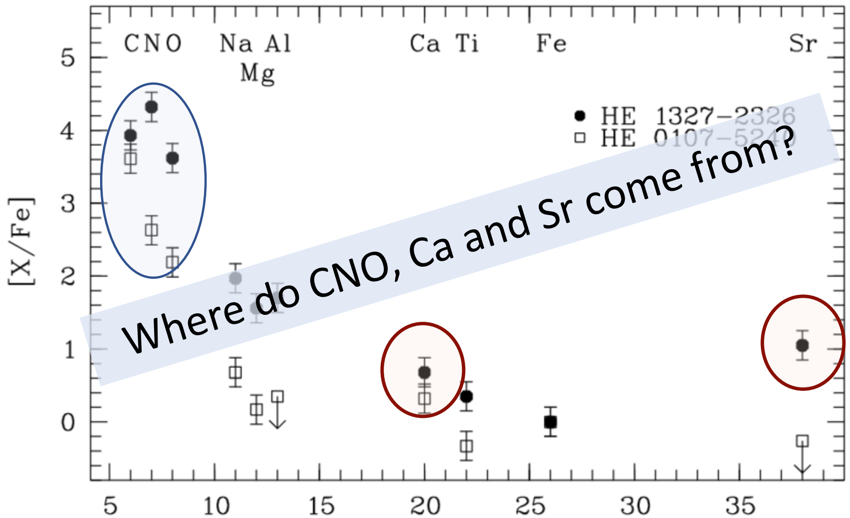
First stars are difficult to observe today…

cococube.com





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

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

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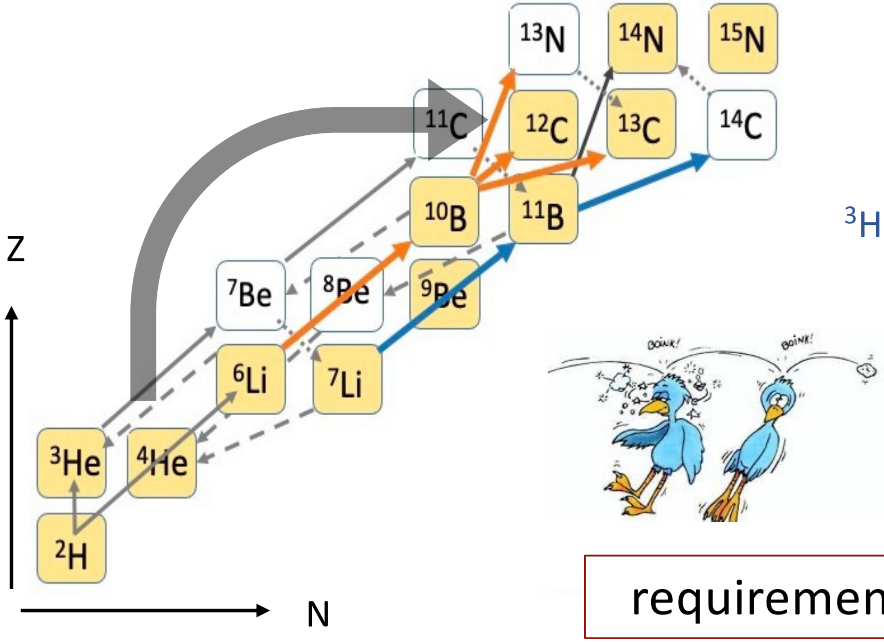


$^{4}He(d,\gamma)^{6}Li(\alpha,\gamma)^{10}B(\alpha,d)^{12}C$ — deuterons as catalyst isotope

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

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

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

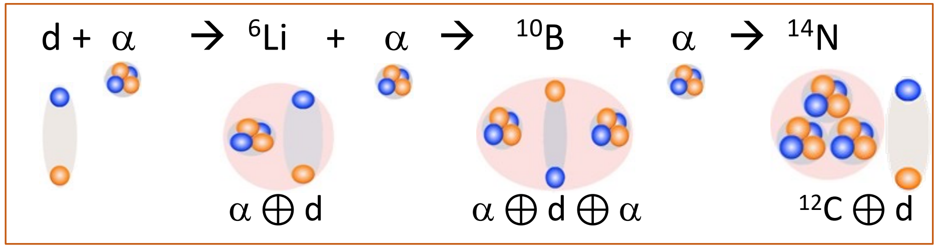
$^{11}B(\alpha,n)^{14}N$ — possible neutron source

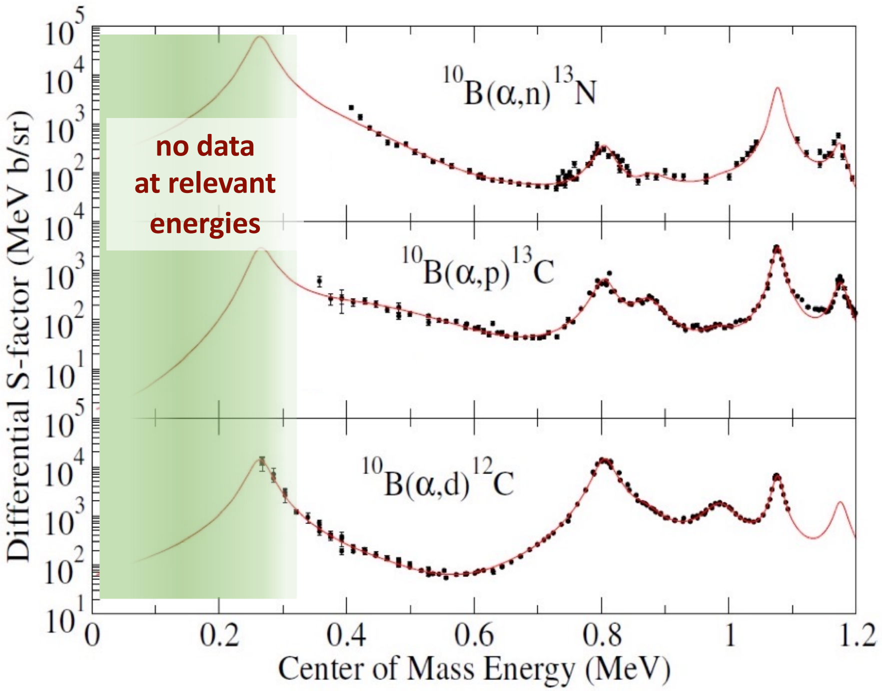
NOTE: 3α process forms C but completely by-passes Li; instead, proposed reaction sequences would also alter Li abundances → solution to CLiP?

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

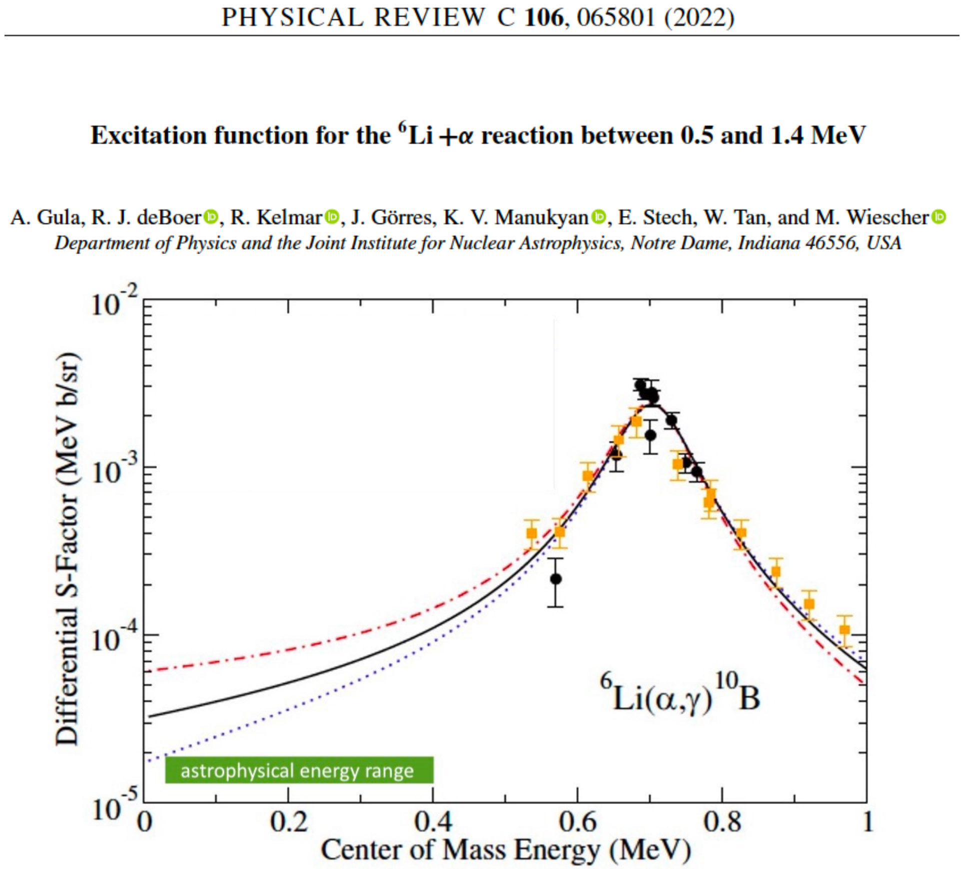
Current Status

proposed reactions involve strong cluster configurations





tantalizing new evidence for broad cluster resonances



“run out of steam” … further breakthrough will require new measurements UNDERGROUND

The Electron Screening Puzzle

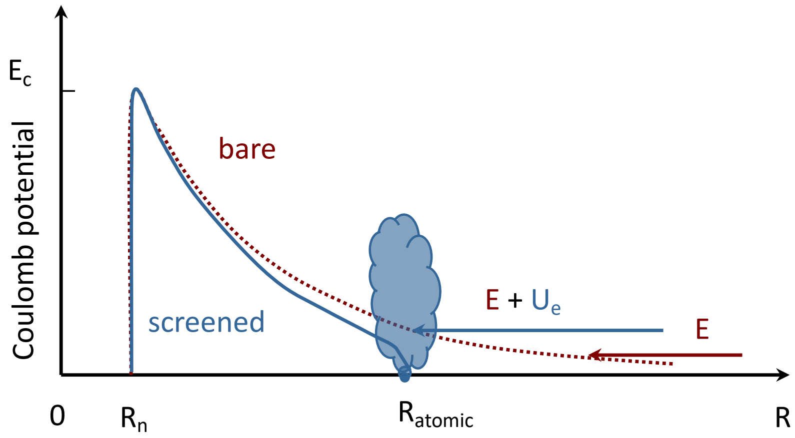
Electron Screening Effect

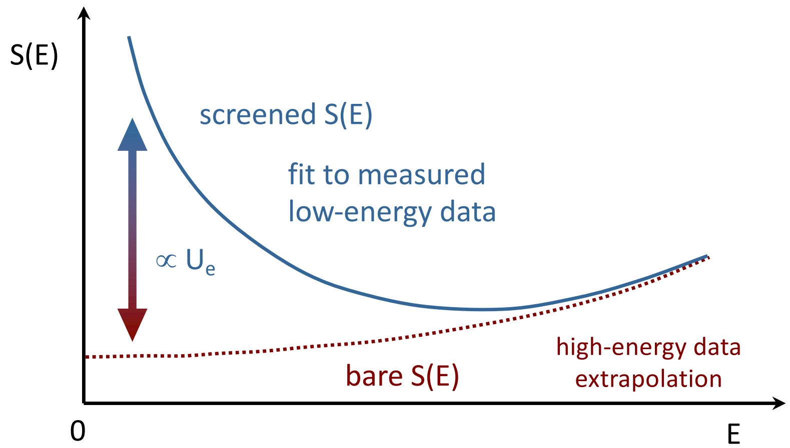
$$\sigma(E) = \frac{1}{E} \exp(-2\pi\eta)\, S(E)$$

assumption: $2\pi\eta \sim Z_1 Z_2 (\mu/E)^{1/2}$

bare nuclei

$$f_{lab}(E) = \frac{S_{screen}(E)}{S_{bare}(E)} \sim \exp(\pi\eta U_e/E)$$





in the lab and in stellar plasmas

interaction affected by electrons

SCREENING POTENTIAL U_e

typically tiny amount (~ 10-100 eV)

$\Rightarrow$ corrections typically negligible, except at ultra-low energies

typically, experimental investigations

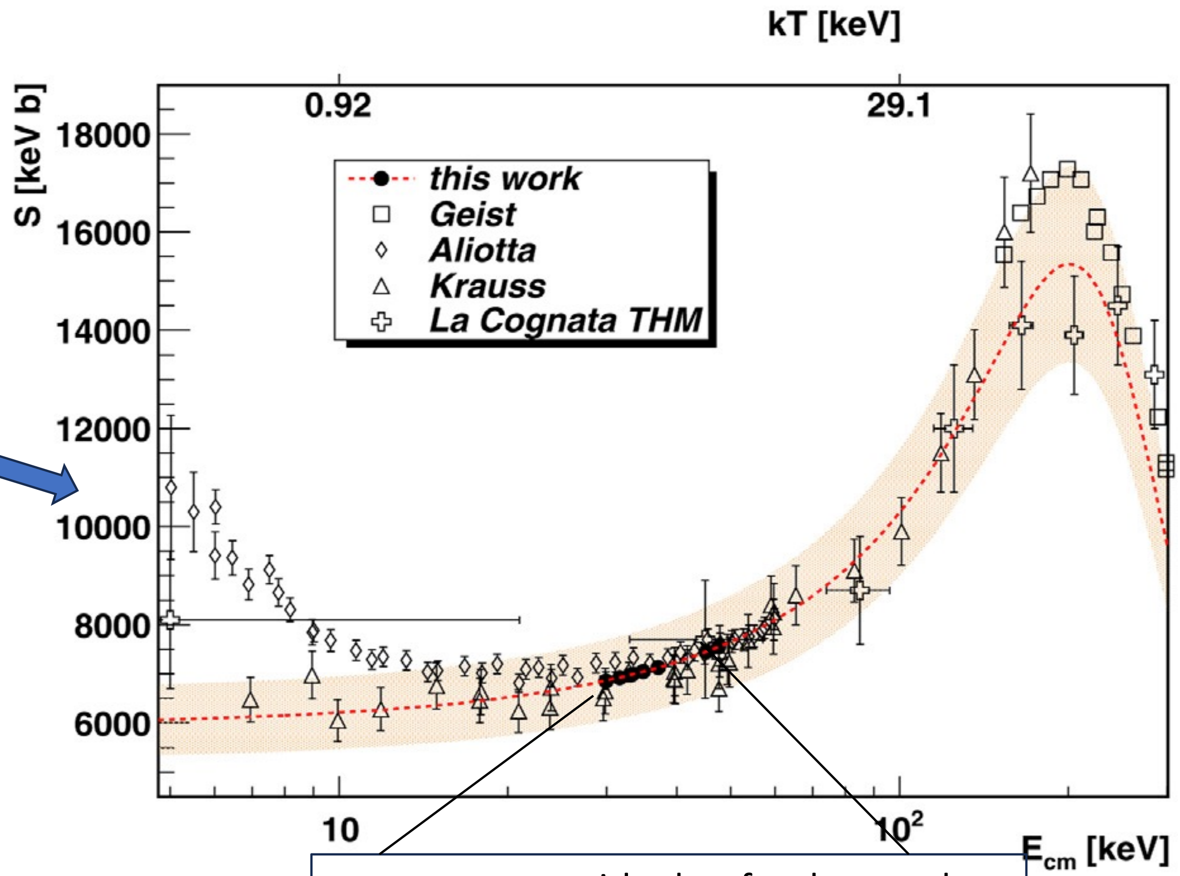
⬇

U_e in excess of theoretical limit !

electron screening puzzle

the ^{3}He(d,p)^{4}He reaction: one of the best studies cases

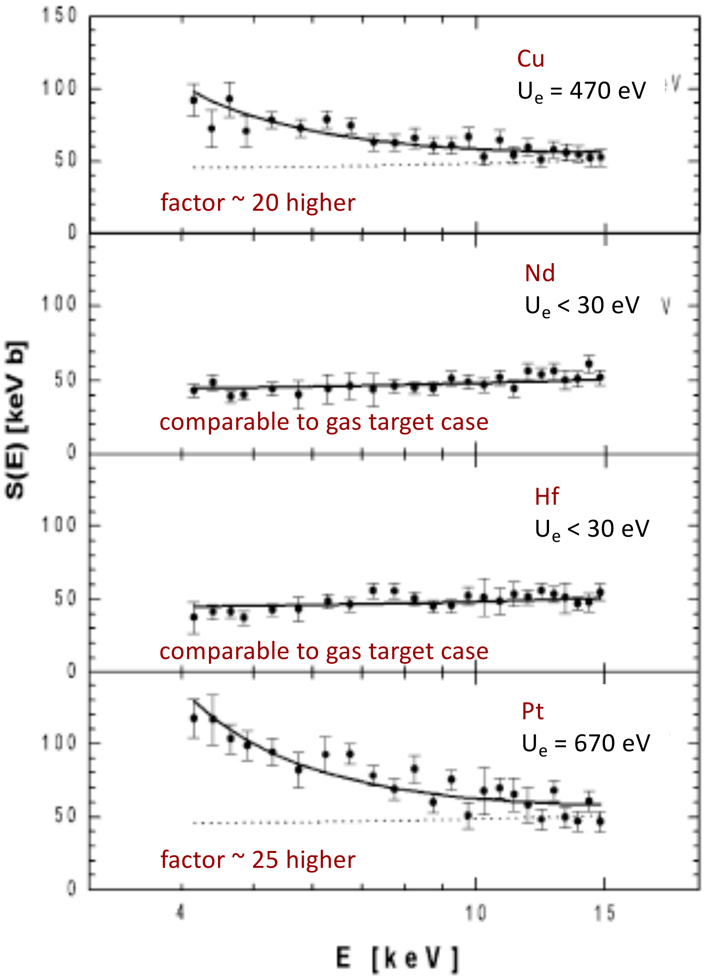
electron screening enhancement

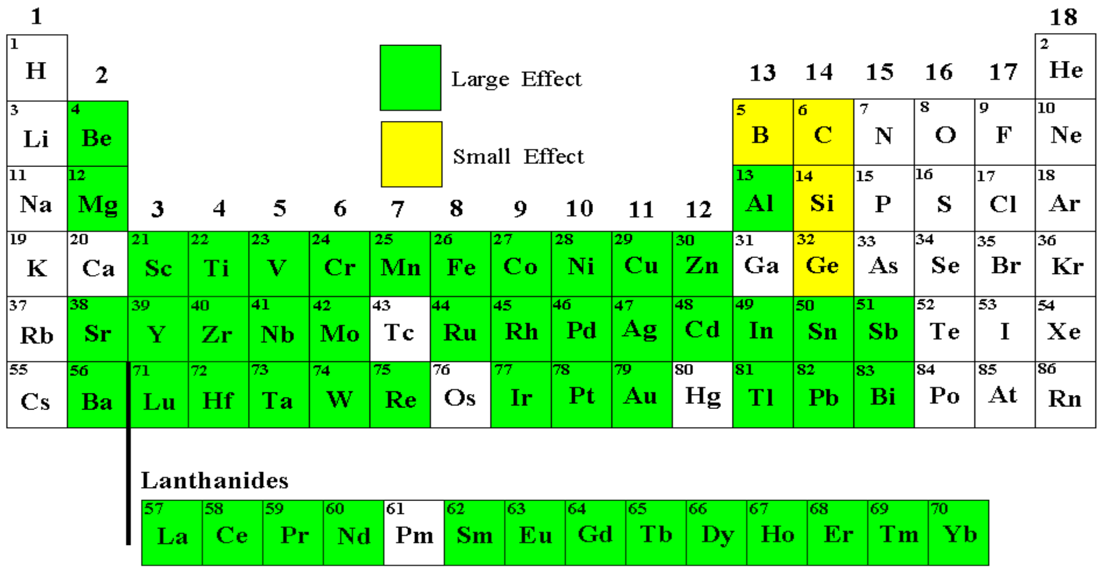


measurement with ultra fast laser pulses

Barbui, PRL 111 (2013) 082502

d(d,p)t reaction in different host materials

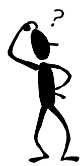




F. Raiola et al.: Phys. Lett. B547 (2002) 193
F. Raiola et al.: Eur. Phys. J A19 (2004) 283

large/small compared to D_2 gas target ($U_e \cong 30$ eV)

anomalous enhancements observed for some materials but not for others



WHY?

Electron Screening: A possible solution from nuclear clustering?

Physics Letters B 755 (2016) 275–278

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The electron screening puzzle and nuclear clustering

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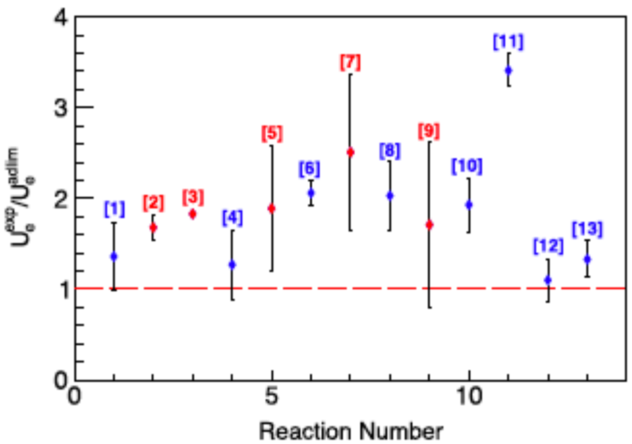
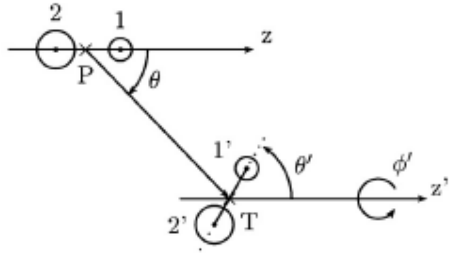
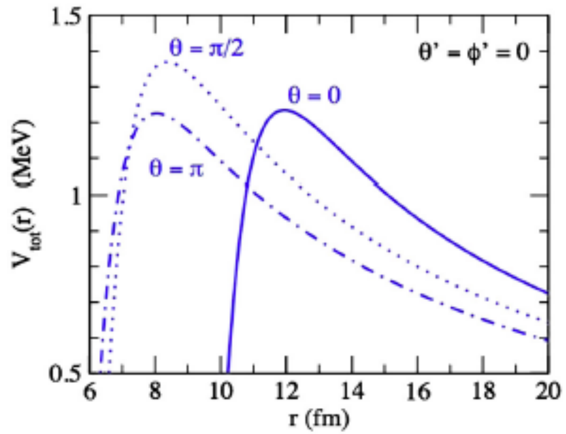
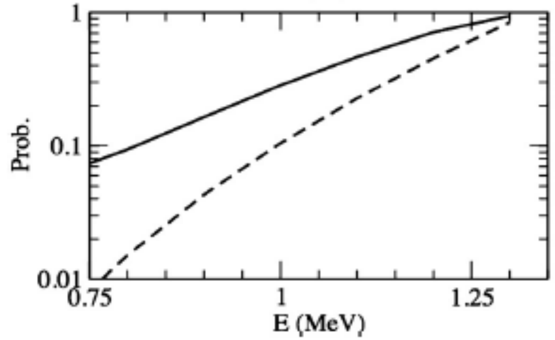
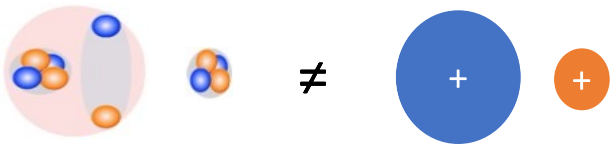


	Reaction	U_e^{adiim} (eV)	U_e^{exp} (eV)	Note	Ref.
[1]	$^2H(d,t)^1H$	14	19.1±3.4		[16,17]
[2]	$^3He(d,p)^4He$	65	109±9	D_2 gas target	[18]
[3]	$^3He(d,p)^4He$	120	219±7		[18]
[4]	$^3He(^3He,2p)^4He$	240	305±90	compilation	[2]
[5]	$^6Li(d,\alpha)^4He$	175	330±120	H gas target	[19]
[6]	$^6Li(d,\alpha)^4He$	175	330±49		[19,20]
[7]	$^6Li(p,\alpha)^3He$	175	440±150	H gas target	[19]
[8]	$^6Li(p,\alpha)^3He$	175	355±67		[19,21,22]
[9]	$^7Li(p,\alpha)^4He$	175	300±160	H gas target	[19]
[10]	$^7Li(p,\alpha)^4He$	175	363±52		[19,21,23]
[11]	$^9Be(p,\alpha_0)^6Li$	240	788±70		[24,25]
[12]	$^{10}B(p,\alpha_0)^7$	340	376±75		[26,27]
[13]	$^{11}B(p,\alpha_0)^8Be$	340	447±67		[26,28]









lower Coulomb barrier → enhanced fusion

To Conclude…

Nuclear Astrophysics Deep Underground: Very Prolific Endeavor

much has been learnt and understood, but many open questions remain:

- cosmological lithium problem
- evolution of first stars
- electron screening

- how do massive stars evolve and die?
- which stars explode as supernovae and which die as white dwarfs?
- what is the core metallicity of the Sun?
- how to explain pre-solar grain anomalies?
- what is the origin of heavy elements?
- and more…

no time to relax…. yet!

Happy Birthday Michael!