Nuclear Astrophysics: An Introduction

Marialuisa Aliotta
School of Physics and Astronomy - University of Edinburgh, UK
Scottish Universities Physics Alliance

Russbach School, 3-8 March 2024

Lecture 1

- brief overview of Nuclear Astrophysics
- thermonuclear reactions in stars
- reaction mechanisms:
    - non-resonant and resonant reactions
    - reaction rates, cross sections and yields

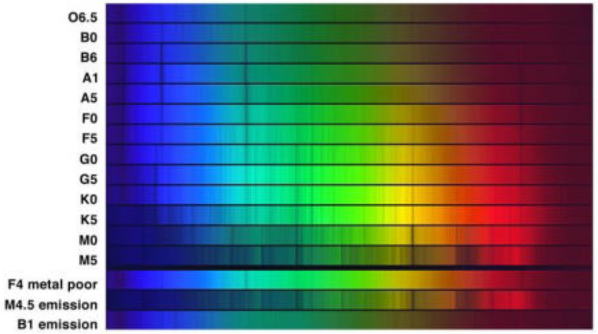
Lecture 2

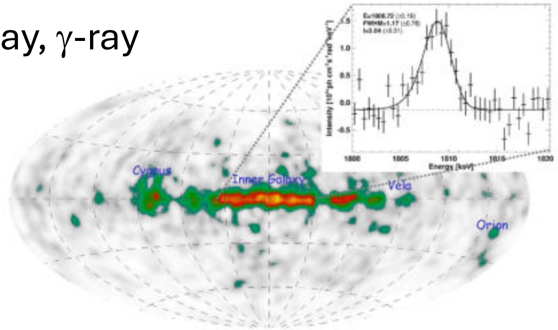
- stellar reactions in the lab: challenges and requirements
- underground Nuclear Astrophysics
    - the LUNA experiment: selected studies
    - gamma-ray, charged-particle, and neutron- detection
- future opportunities

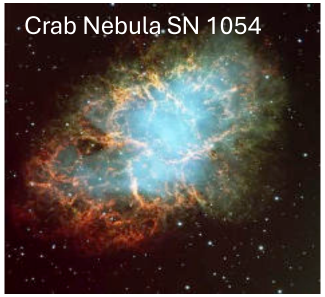
The Messengers of the Universe

electromagnetic emissions

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

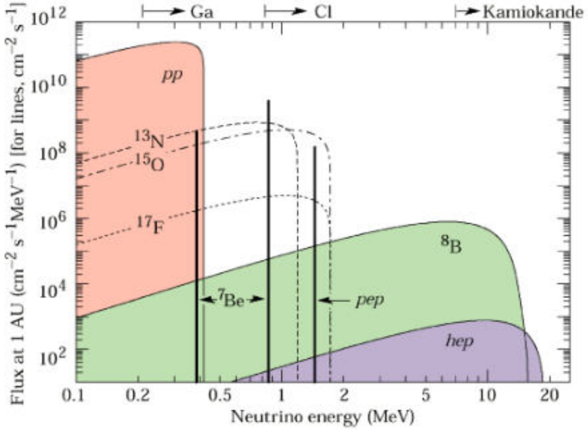


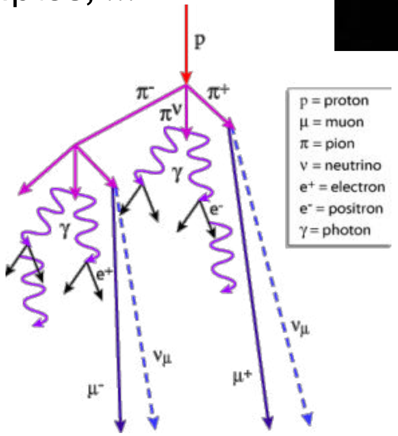




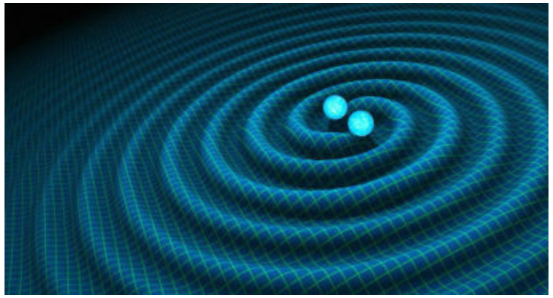
direct messengers

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



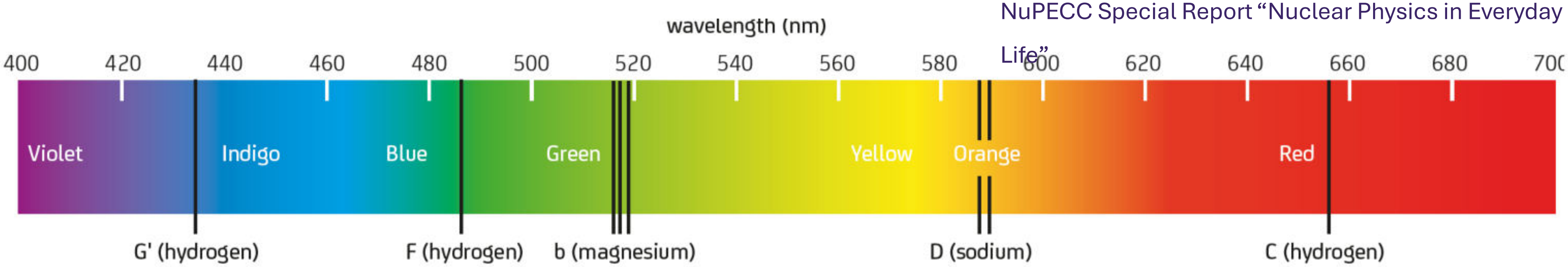


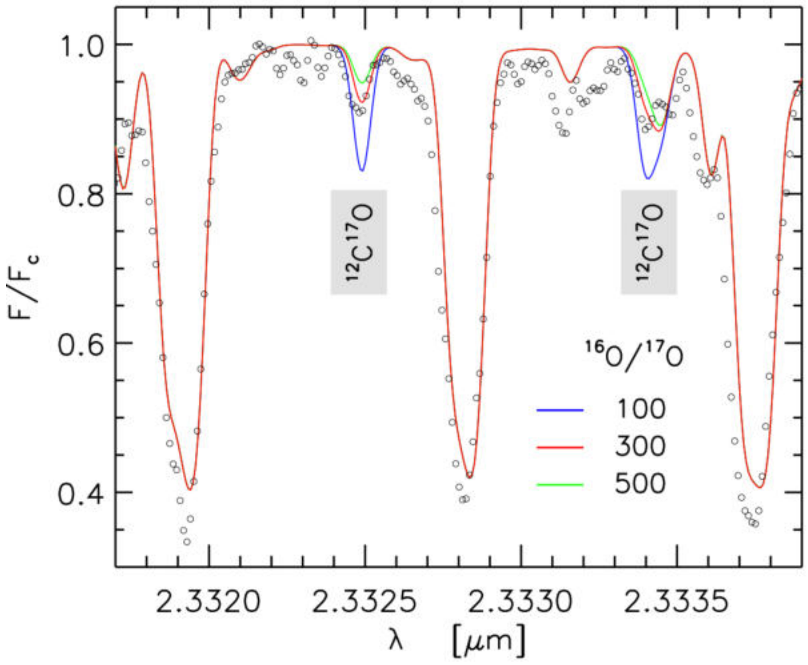
gravitational waves



Electromagnetic Radiation: The Messenger of the Universe

NuPECC Special Report "Nuclear Physics in Everyday Life"



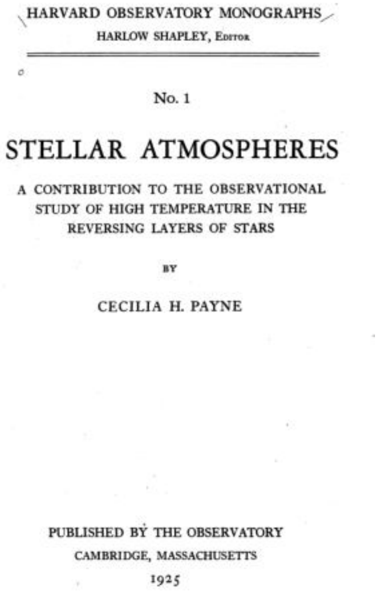


Lebzelter et al A&A 578 (2015) A33

shape of spectral lines give info on **chemical abundances** and on physical conditions of stellar atmospheres

Cosmic Barcodes

Cecilia Payne PhD Thesis (1925): A Revolution in



HARVARD OBSERVATORY MONOGRAPHS
HARLOW SHAPLEY, Editor

No. 1

STELLAR ATMOSPHERES

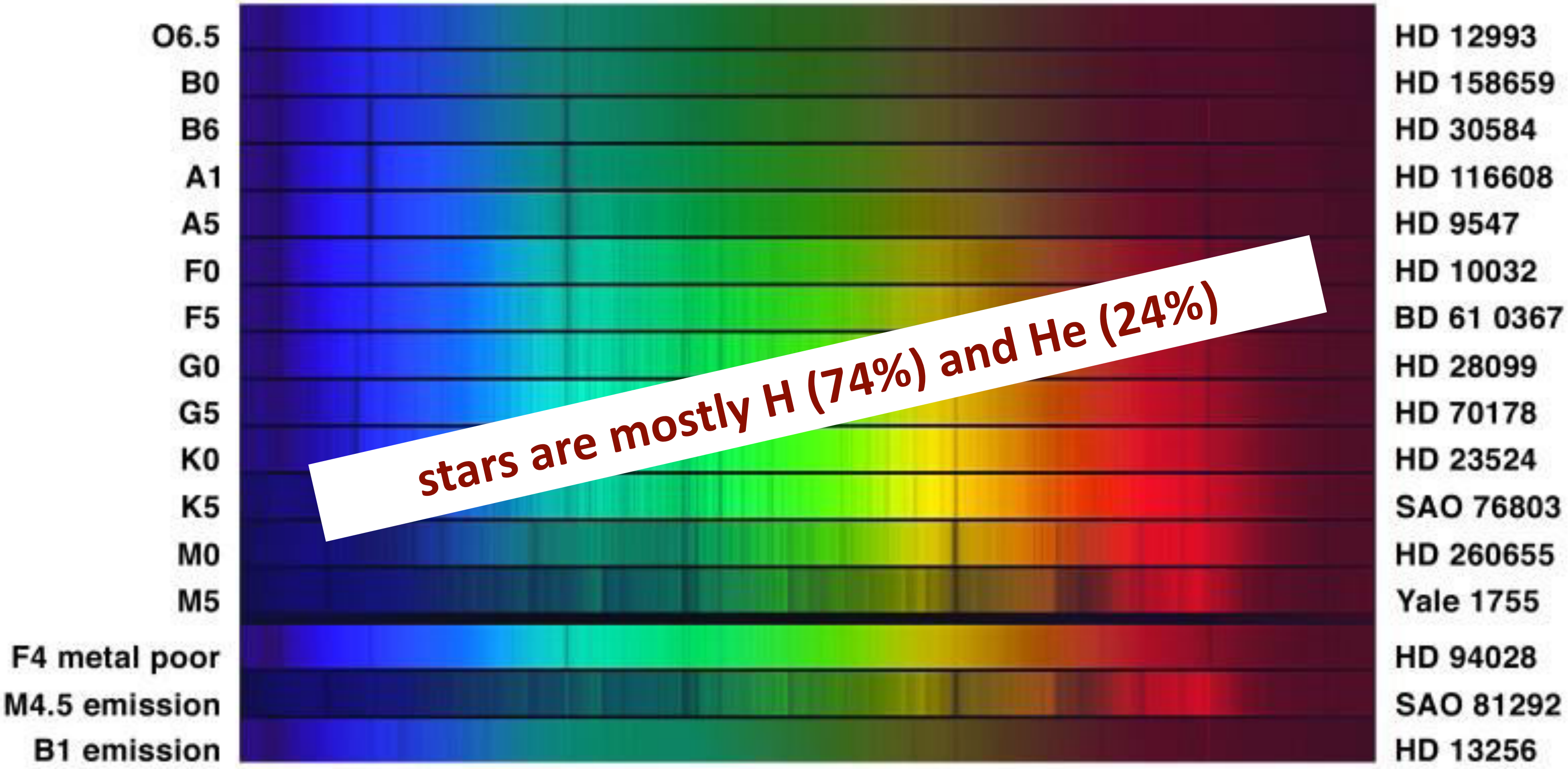
A CONTRIBUTION TO THE OBSERVATIONAL
STUDY OF HIGH TEMPERATURE IN THE
REVERSING LAYERS OF STARS

BY

CECILIA H. PAYNE

PUBLISHED BY THE OBSERVATORY
CAMBRIDGE, MASSACHUSETTS
1925

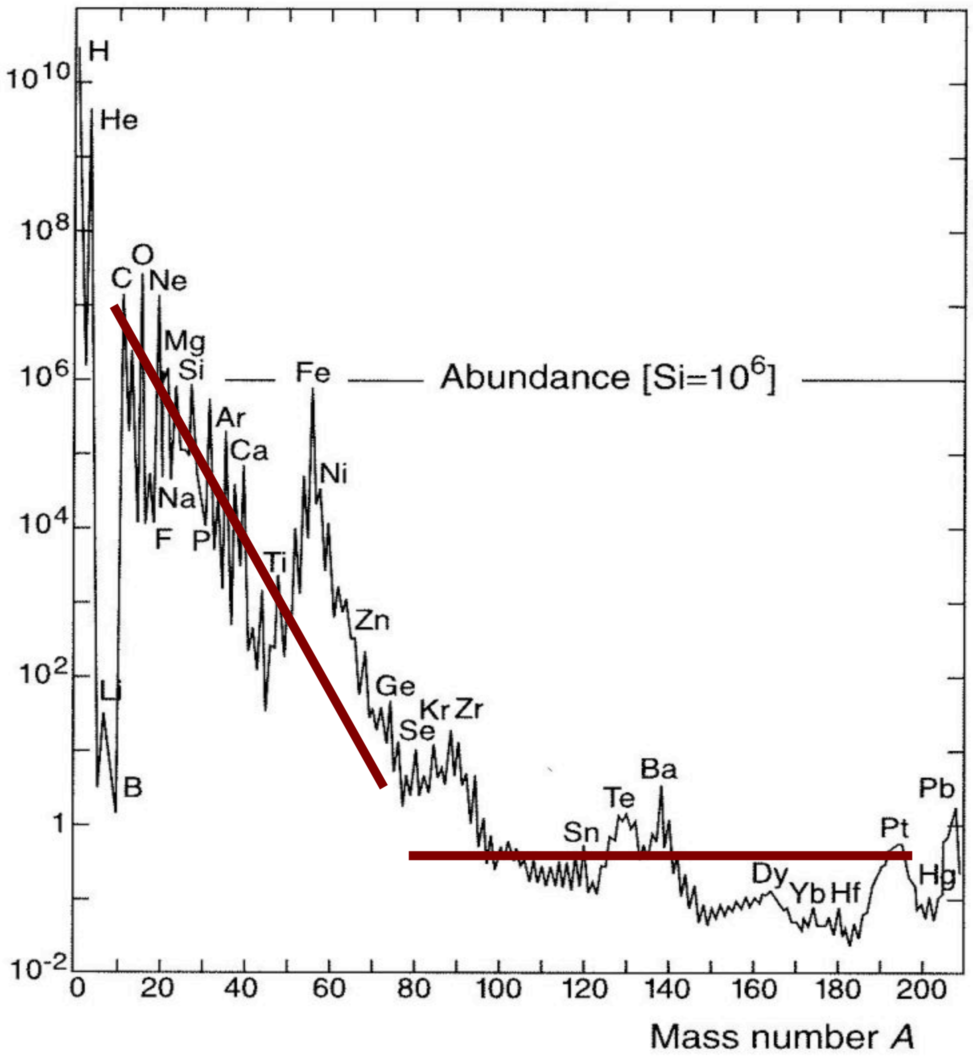
Otto Struve: “the most brilliant PhD thesis ever written in astronomy”



stars are mostly H (74%) and He (24%)

Henry Norris Russell strongly opposed this conclusion and convinced her to omit it from her thesis...

Solar Abundance Distribution



Data sources:

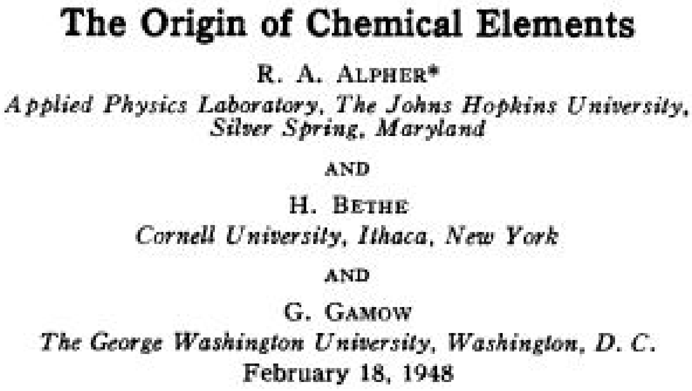
Earth, Moon, meteorites, cosmic rays, solar & stellar spectra...

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
- almost flat distribution beyond Fe

Why these features?

On the Origin of the Chemical Elements



The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University,
Silver Spring, Maryland

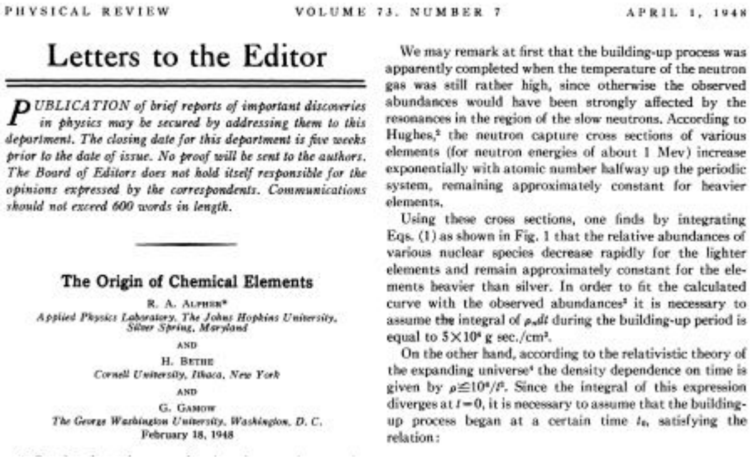
AND

H. Bethe
Cornell University, Ithaca, New York

AND

G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

Phys. Rev. 73 (1948) 803



PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. Alpher*
Applied Physics Laboratory, The Johns Hopkins University,
Silver Spring, Maryland

AND

H. Bethe
Cornell University, Ithaca, New York

AND

G. Gamow
The George Washington University, Washington, D. C.
February 18, 1948

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

Alpher

Bethe

Gamow

the "aβγ" paper

1st April

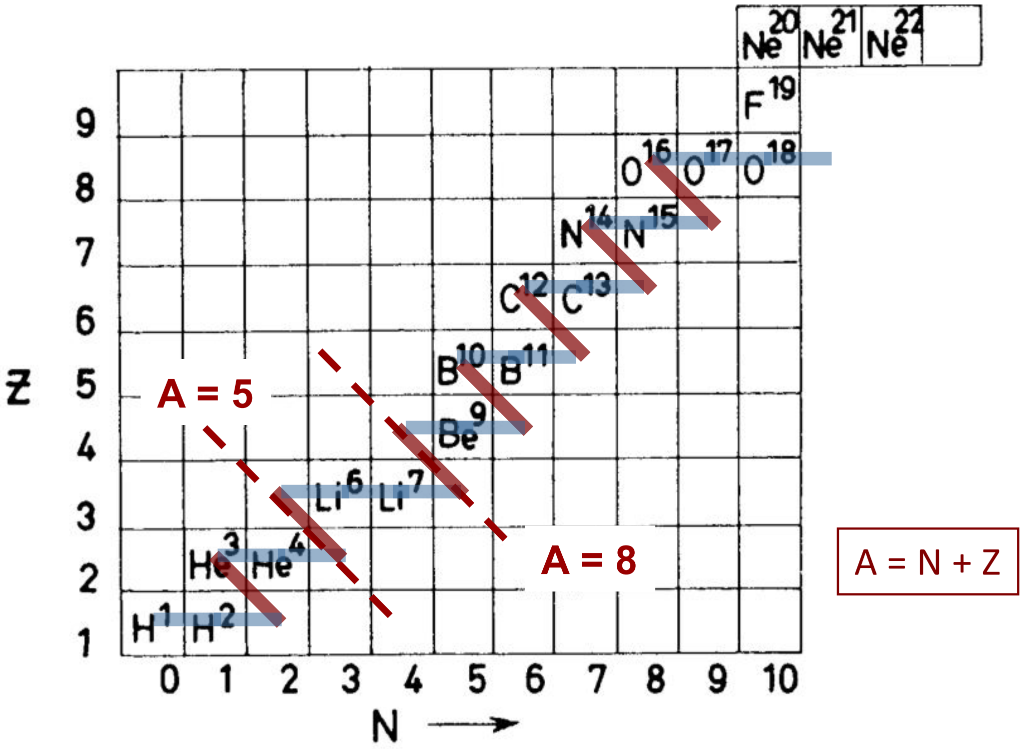
Gamow’s Idea

all elements formed from primordial **protons** and **neutrons**

through sequence of **n-captures** and **β decays** soon after the Big Bang

β decay =
n → p
p → n

an electron (positron) and and anti-neutrino (neutrino) produced in the decay



A = N + Z

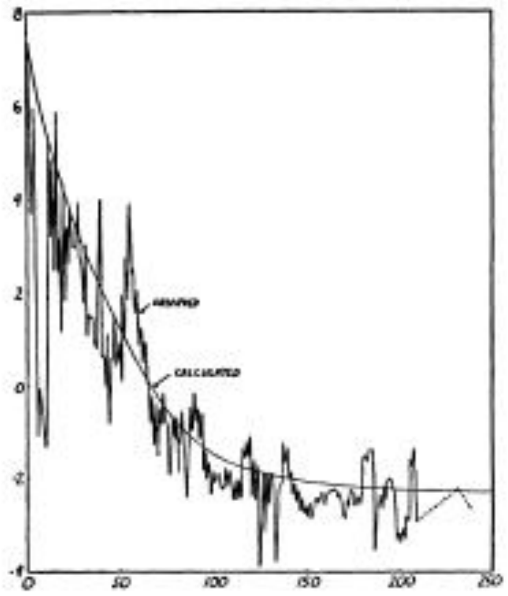


FIG. 1.
Log of relative abundance
Atomic weight

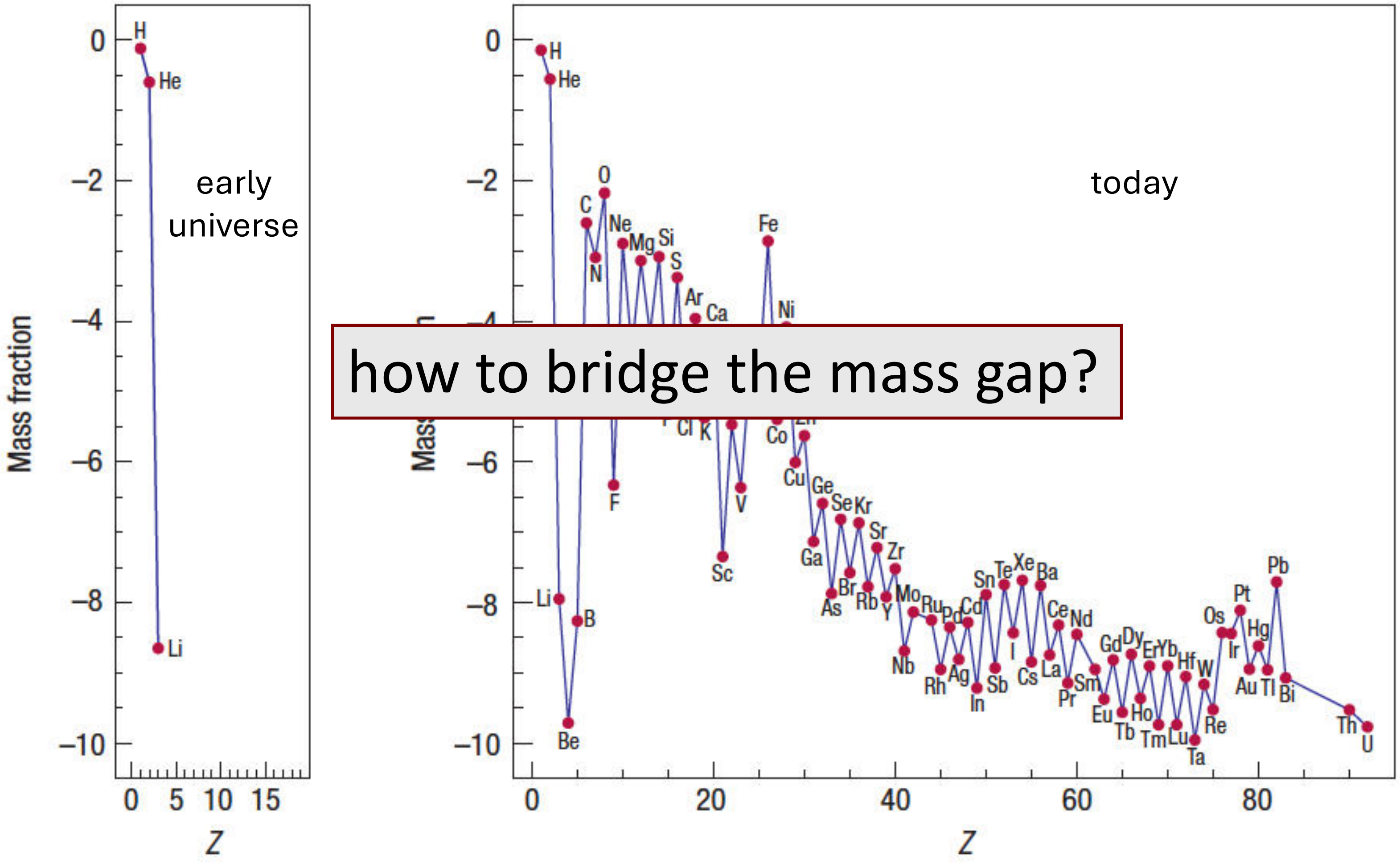
αβγ paper

NO STABLE nuclei with A=5 or A=8

M Aliotta

Chemical Composition of the Universe

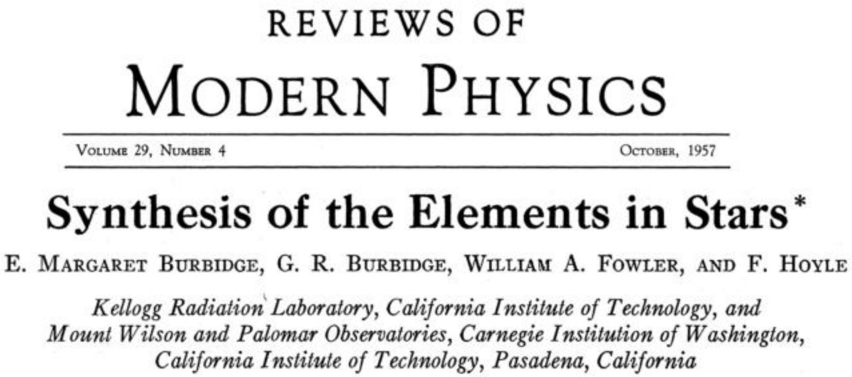
composition of Universe soon after Big Bang: ^{1}H, ^{2}H, ^{3,4}He, traces of Li, e^{-} & γ



how to bridge the mass gap?

Courtesy: Alex Hager

On the Origin of the Chemical Elements



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)

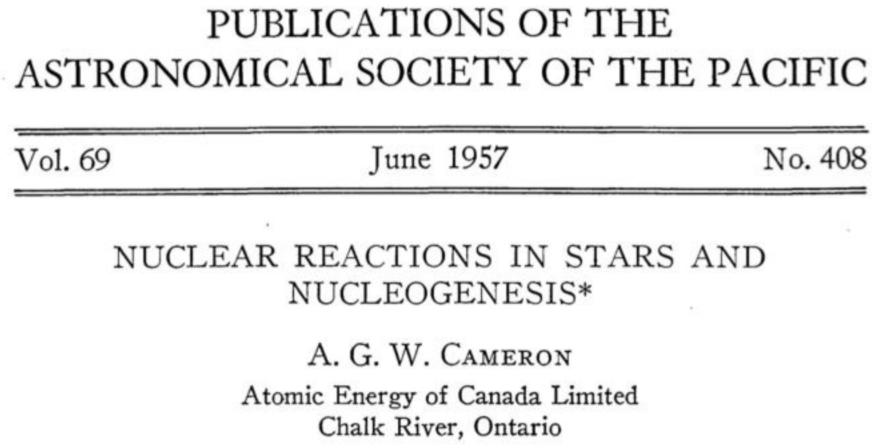
Burbidge

Burbidge

Fowler

Hoyle

1983
Nobel Prize



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

A.G.W. Cameron

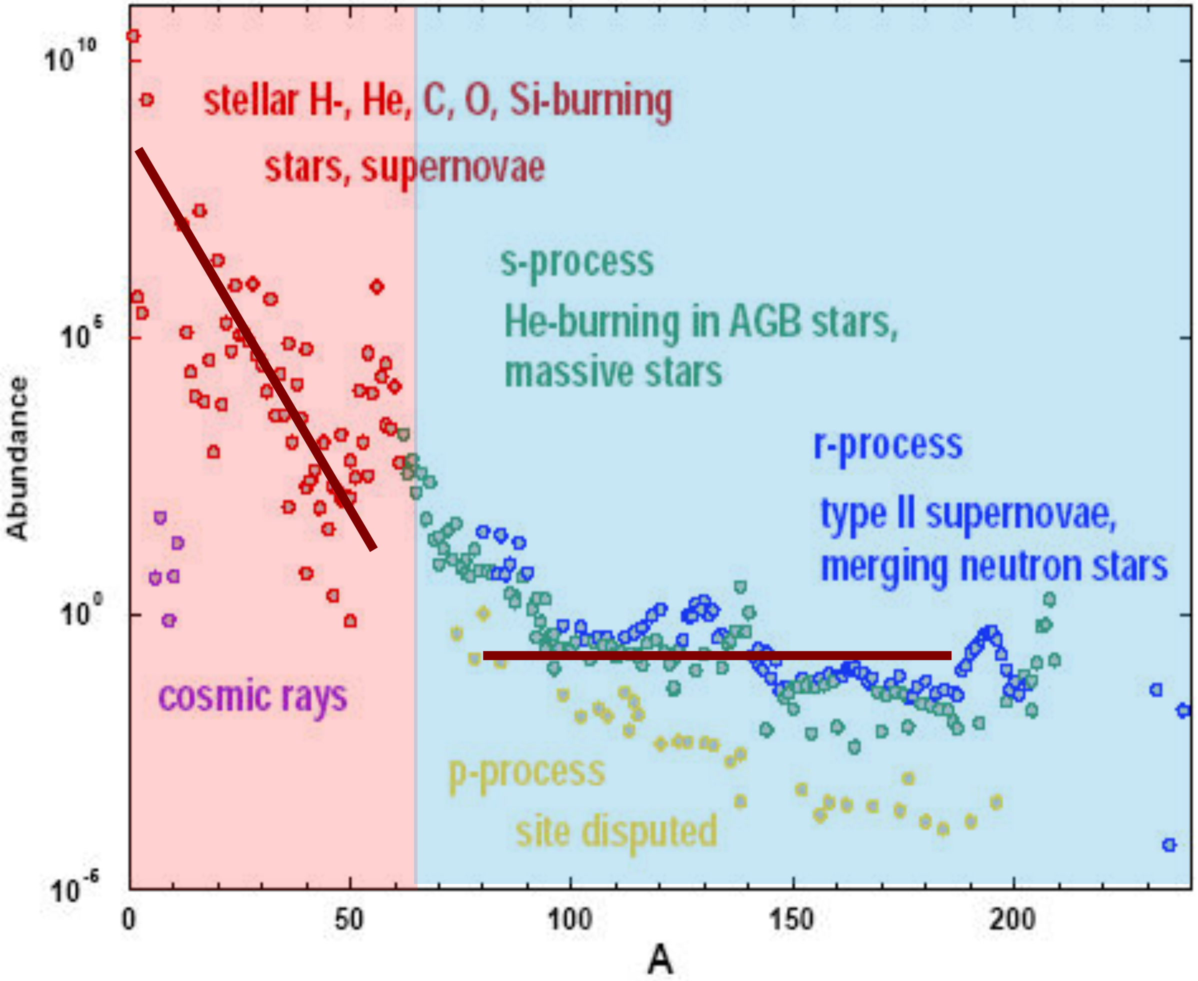
"for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"

Stellar Nucleosynthesis: A Major Breakthrough

elements created by **nuclear reactions** in stars

fusion of
charged
particles

mainly
stable
nuclei

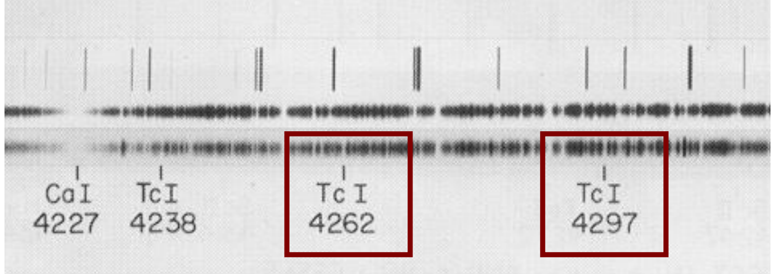


neutron-
capture
reactions

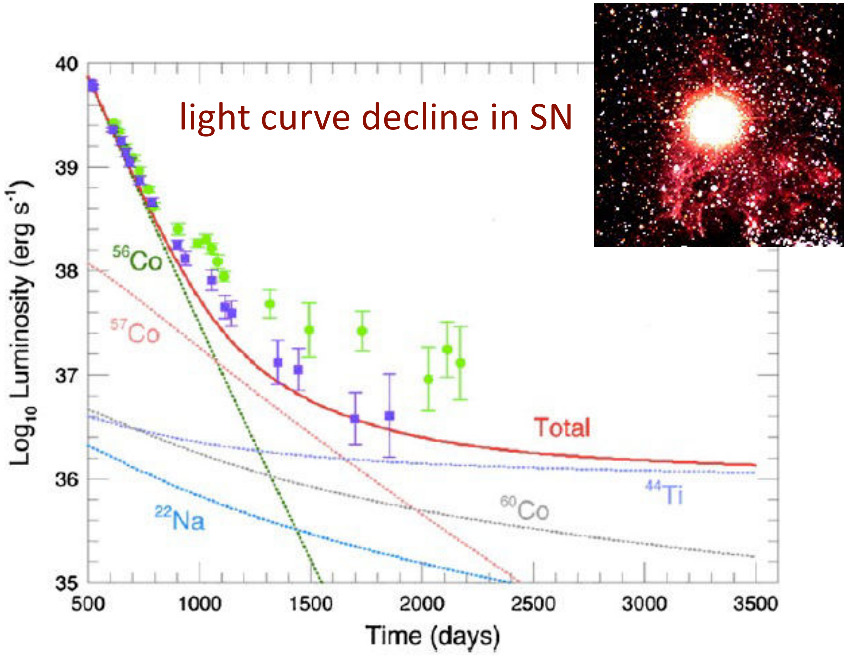
mainly
unstable
nuclei

Direct Evidence for Nuclear Reactions in Stars

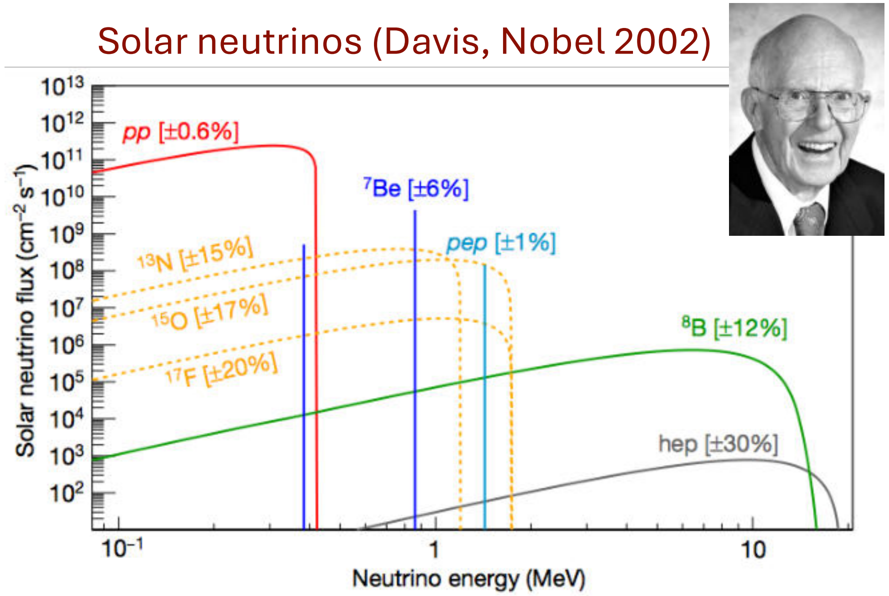
Technetium in stellar spectra (Merrill, 1952)



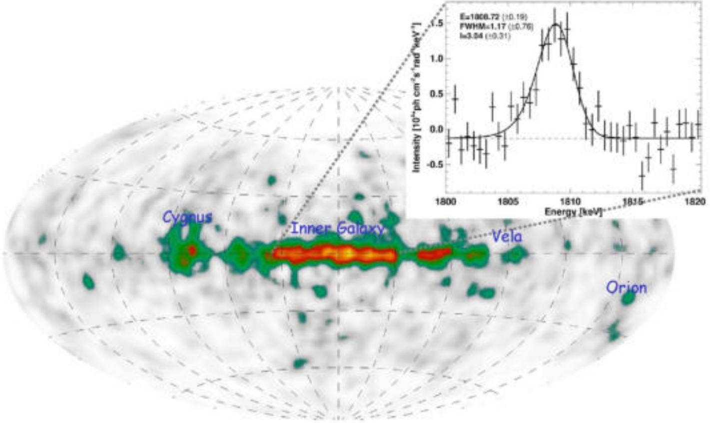
light curve decline in SN



Solar neutrinos (Davis, Nobel 2002)

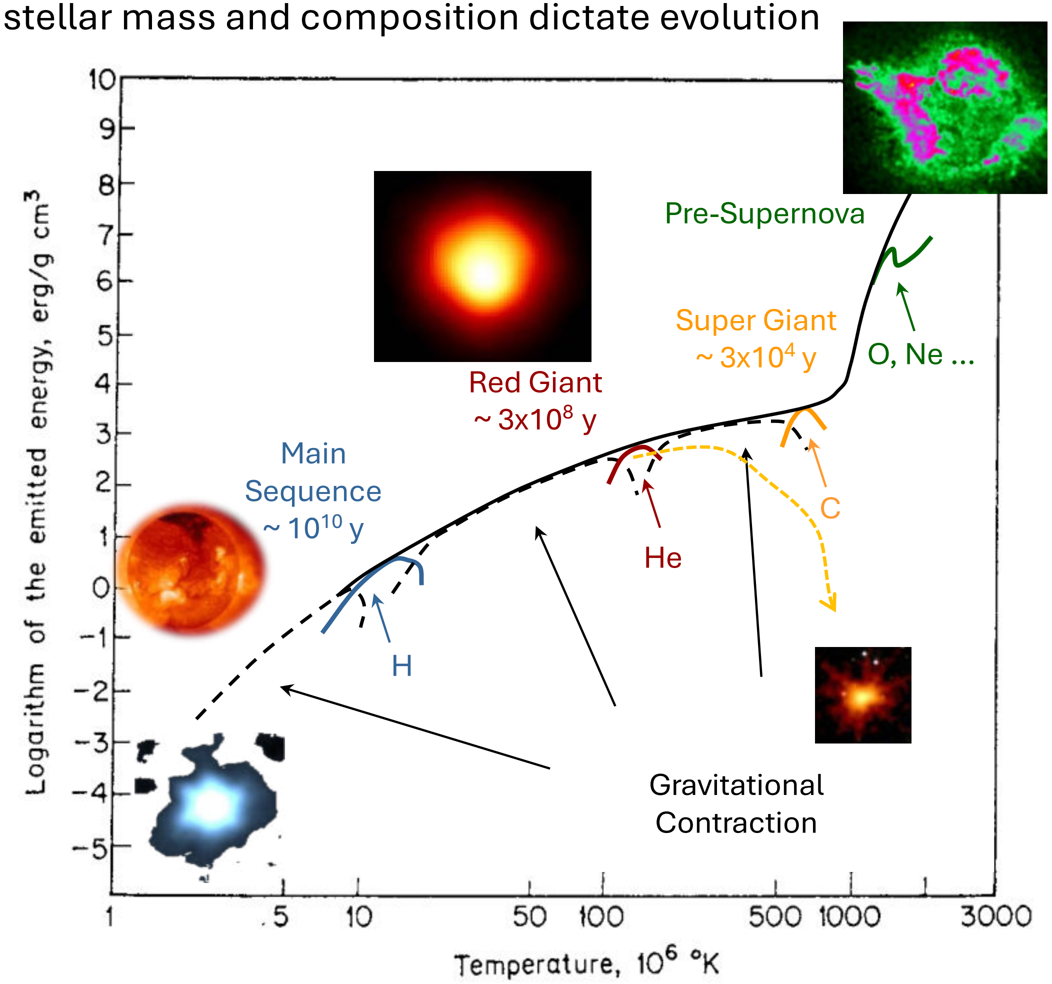


γ-ray emissions from ^{26}Al

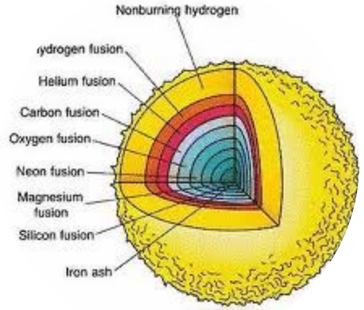


Stellar Evolution and Nucleosynthesis in a Nutshell

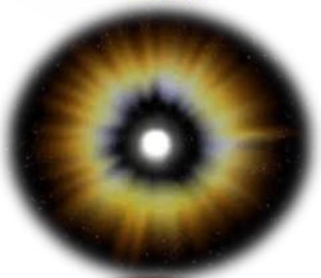
stellar mass and composition dictate evolution



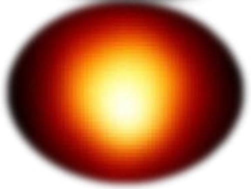
Ne-, O-, Si-burning: ^{56}Fe, A~60



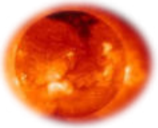
C-burning: ^{16}O, ^{20}Ne, ^{24}Mg,



He-burning: ^{12}C, ^{16}O

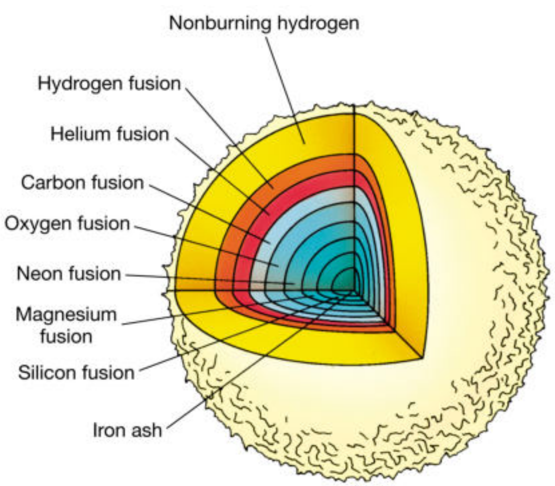


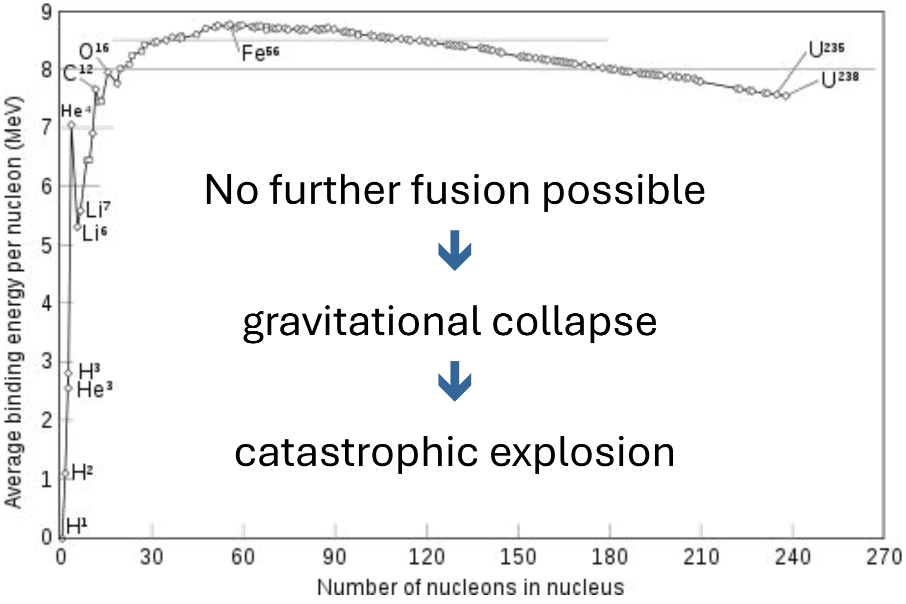
H-burning: ^{4}He, ^{14}N



tunnelling probability → exponential decrease in abundance

Nuclear Burning in Stars





No further fusion possible

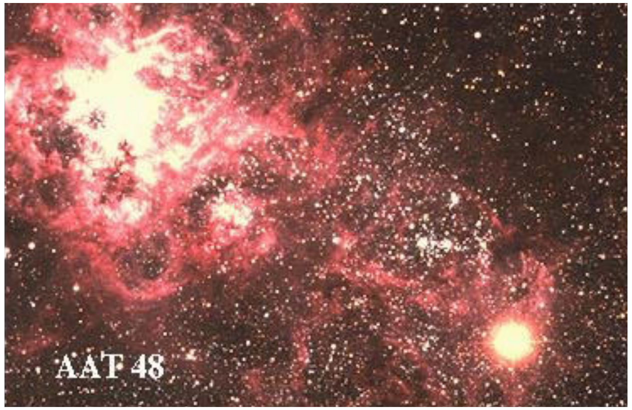
↓

gravitational collapse

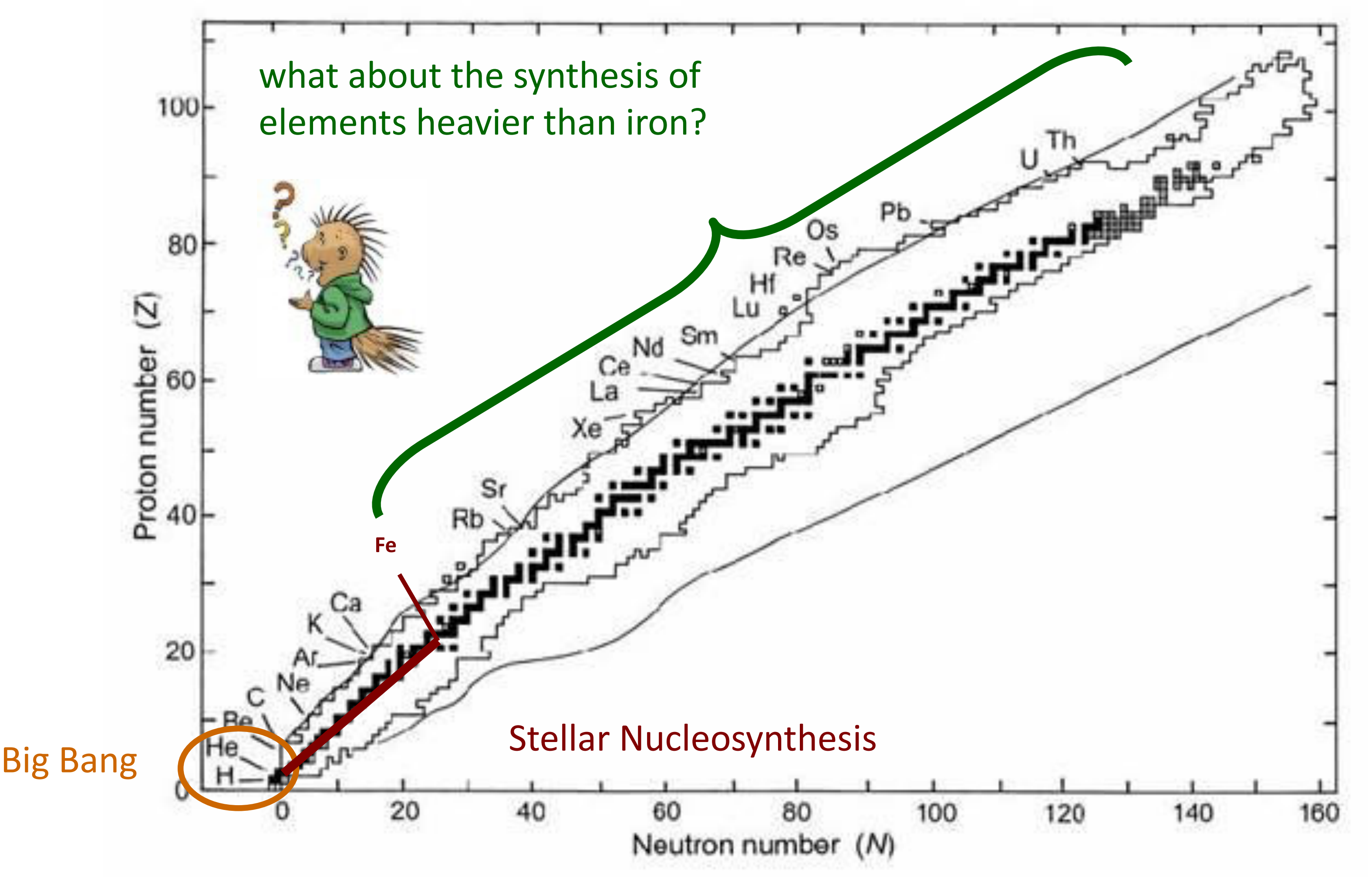
↓

catastrophic explosion

23 February 1987 - Large Magellanic Cloud



The Creation of Heavy Elements



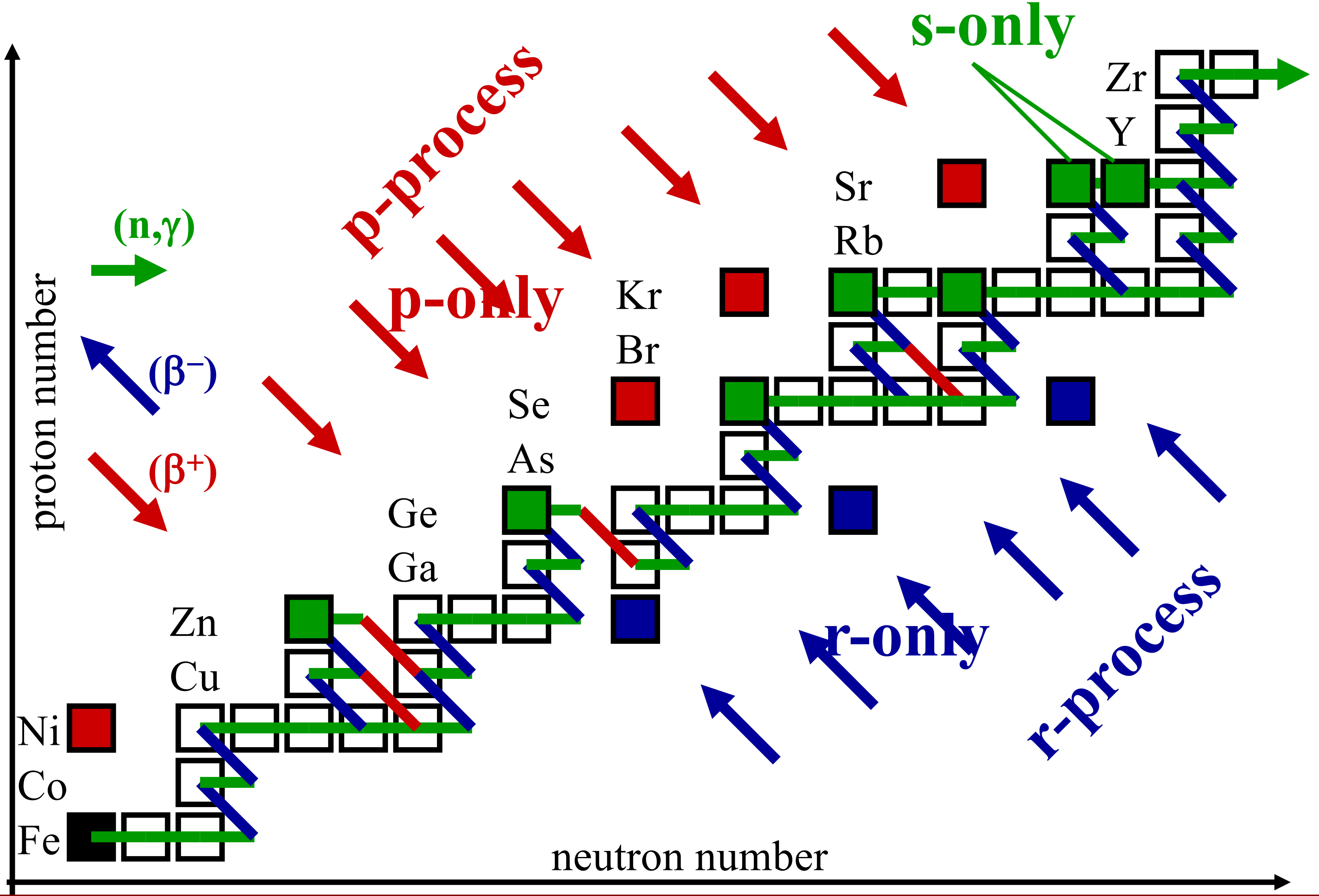
what about the synthesis of elements heavier than iron?

Big Bang

Stellar Nucleosynthesis

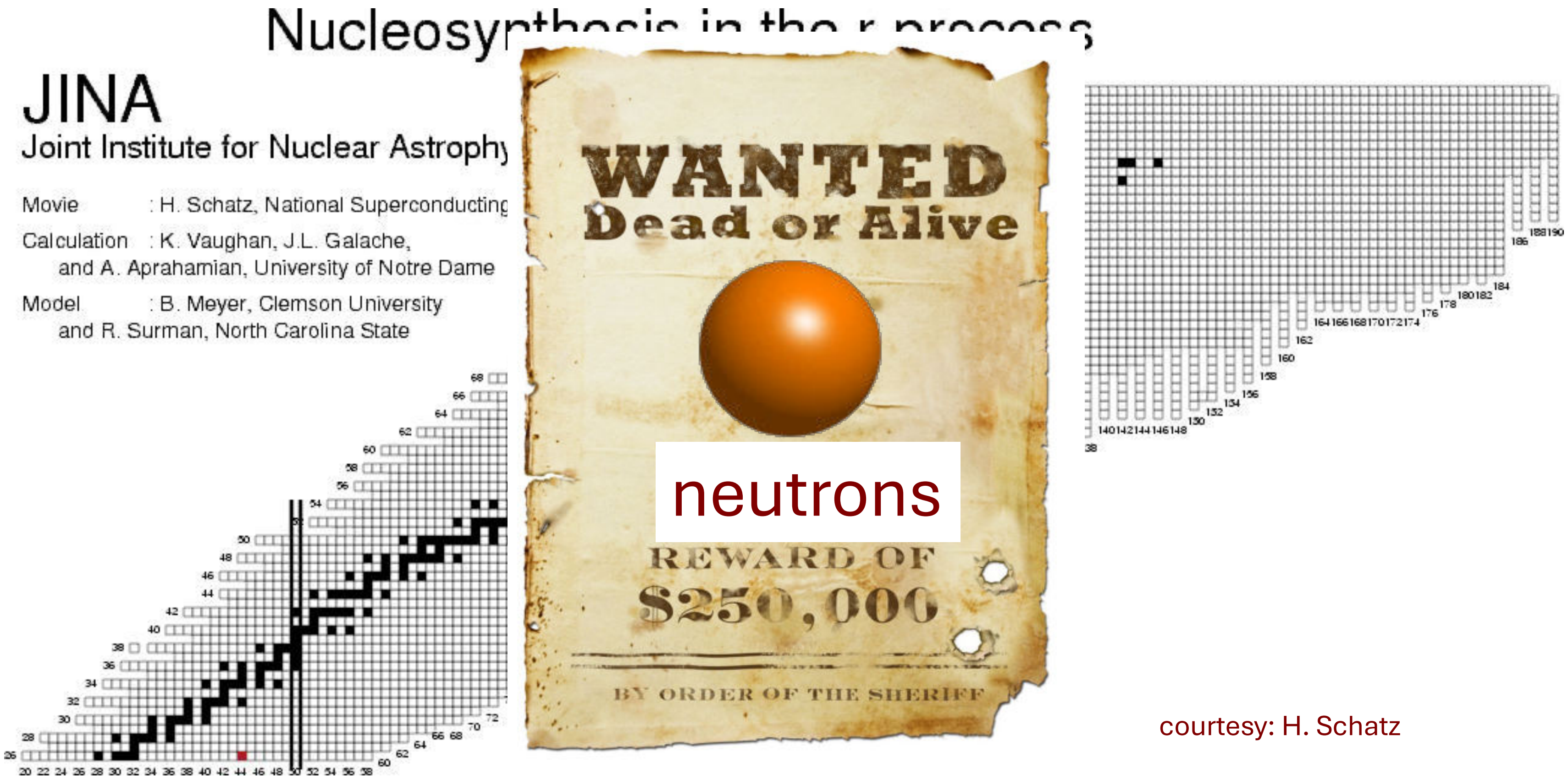
Neutron capture reactions: the s(low) and the r(apid) processes

Neutron Capture Processes: the s- and the r-Processes



courtesy:
René Reifarth

Nucleosynthesis in the r-process



JINA

Joint Institute for Nuclear Astrophy

Movie : H. Schatz, National Superconducting

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

courtesy: H. Schatz

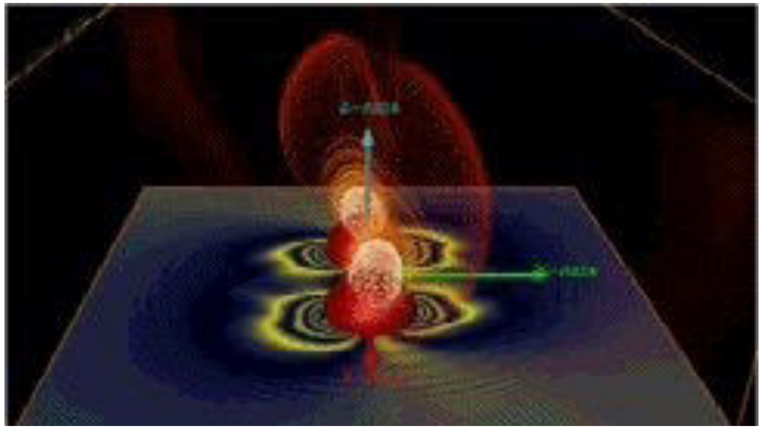
- time scale ~ some seconds!
- thousands of unstable nuclei involved
- large neutron fluxes required! (~10^{26} n/cm^3)

Neutron Sources for the r-Process?

core collapse supernovae

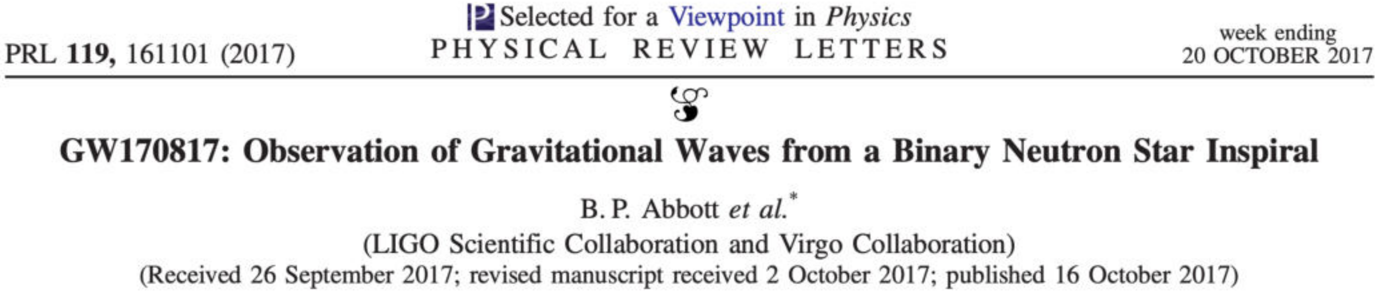
large enough neutron flux?

neutron star mergers



do they exist?
how often/early can they occur?

GW170817: A Major Discovery



Selected for a Viewpoint in *Physics*

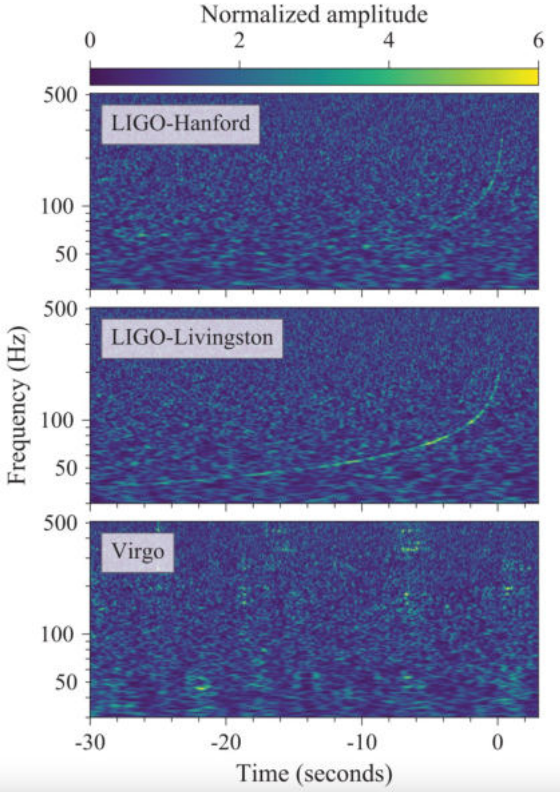
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]

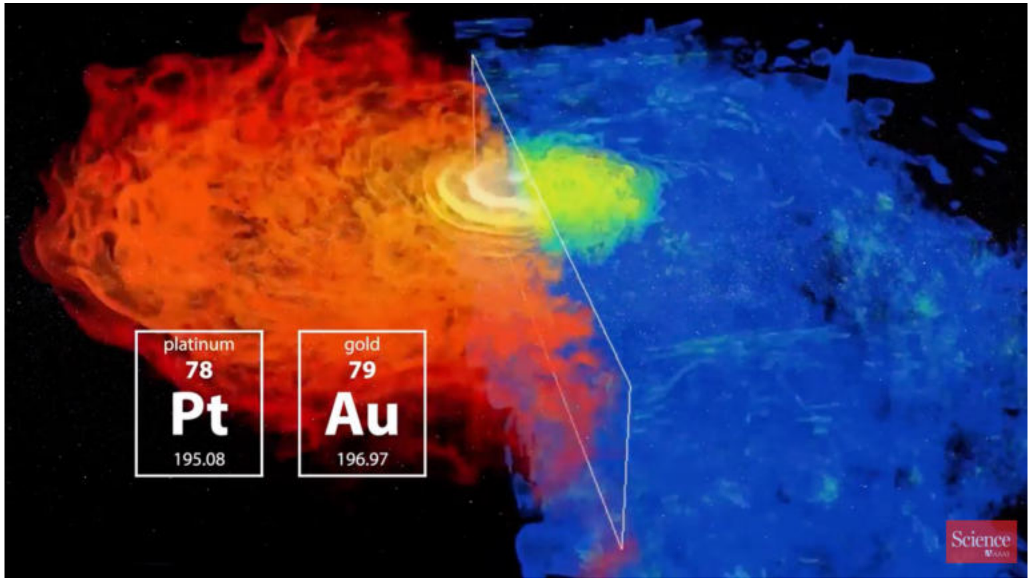
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)



event observed by 70 ground- and space-based observatories including in visible light 11h after GW detection

130 million
light years
from Earth



r-process Abundances in Metal Poor Stars

THE ASTROPHYSICAL JOURNAL, 662:39–52, 2007 June 10
© 2007. The American Astronomical Society. All rights reserved. Printed in U.S.A.

EXPLORATIONS OF THE *r*-PROCESSES: COMPARISONS BETWEEN CALCULATIONS AND OBSERVATIONS OF LOW-METALLICITY STARS

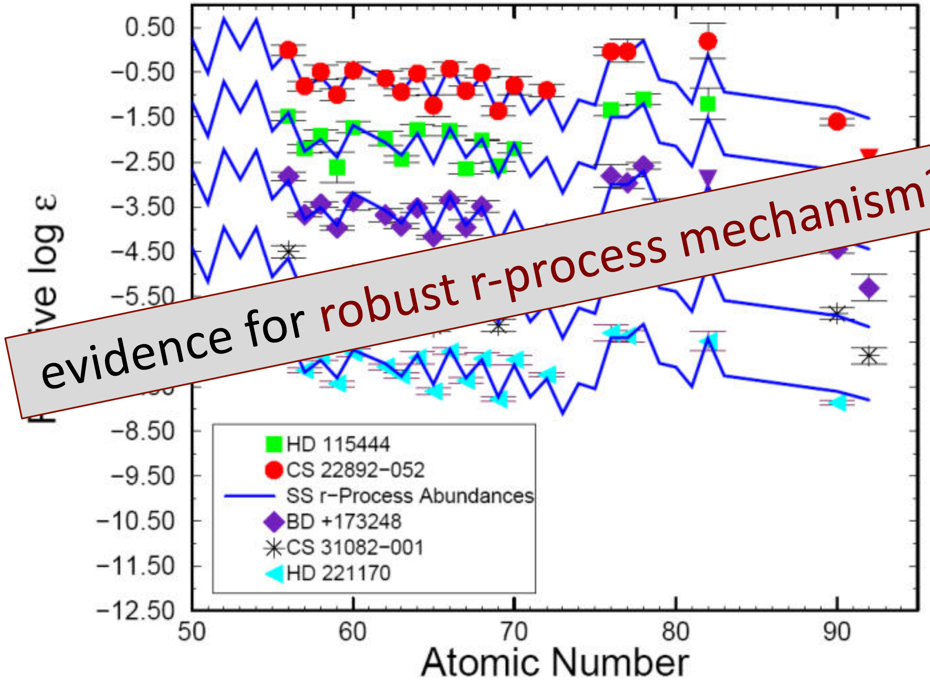
KARL-LUDWIG KRATZ,[1,2] KHALIL FAROUQI,[2] BERND PFEIFFER,[2] JAMES W. TRURAN,[3]
CHRISTOPHER SNEDEN,[4] AND JOHN J. COWAN[5]
Received 2006 August 24; accepted 2007 March 1

r-process abundances in metal poor stars

show remarkable similarities

and excellent agreement with solar values

(not a metal poor star!)



evidence for robust r-process mechanism?

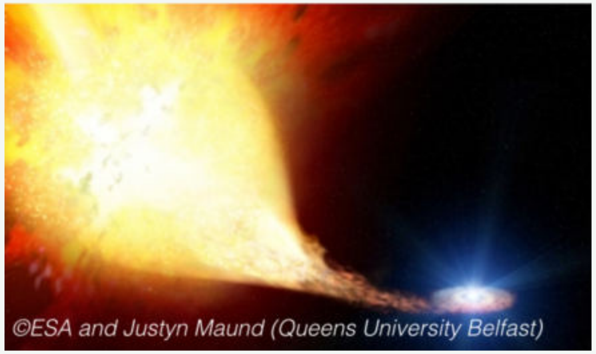
Nucleosynthesis in Binary Systems

Compact binary mergers
r-process

svs.gsfc.nasa.gov

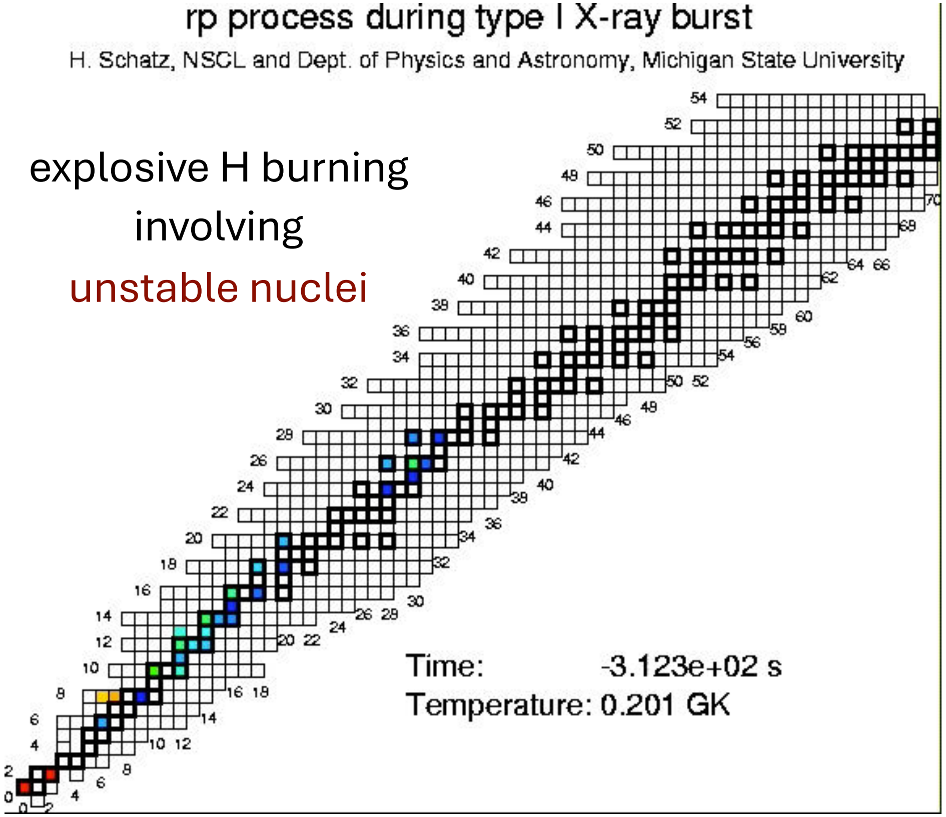
Type Ia supernovae
Fe, Mn

Tycho SN



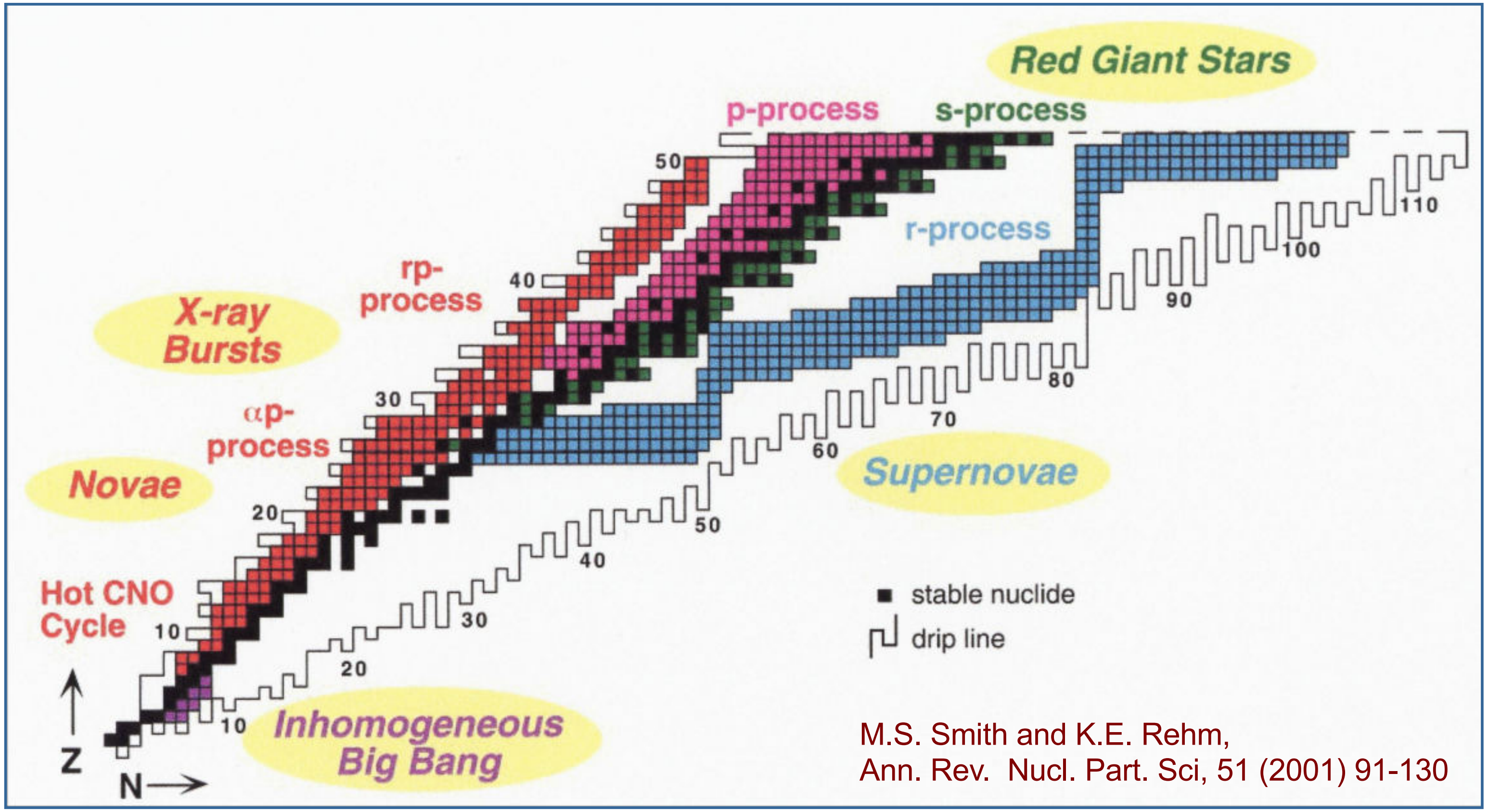
©ESA and Justyn Maund (Queens University Belfast)

Artist's representation of an X-Ray Burst



explosive H burning
involving
unstable nuclei

Overview of main nuclear processes in astrophysical sites



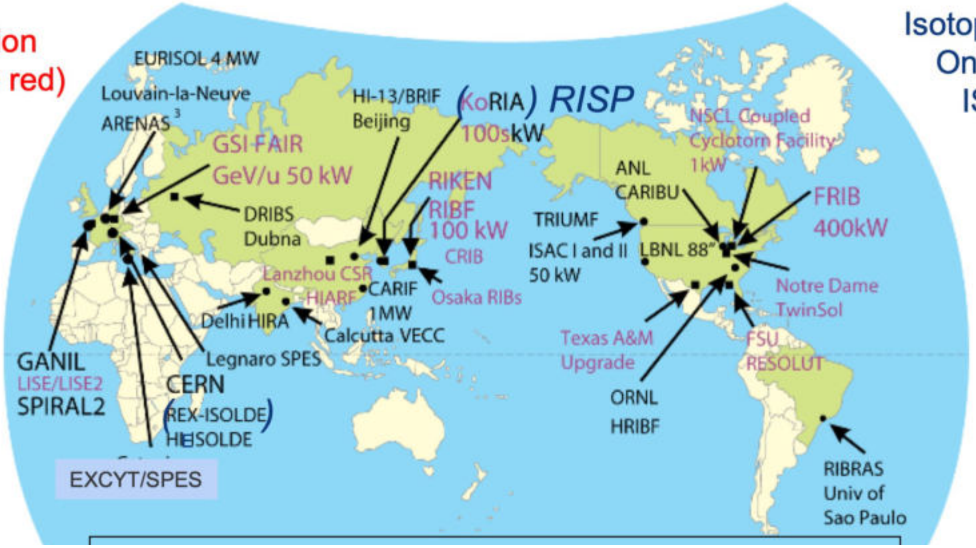
M.S. Smith and K.E. Rehm,
Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

the vast majority of reactions encountered in these processes involve UNSTABLE species hence the need for **Radioactive Ion Beams**

Radioactive Ion Beam Facilities

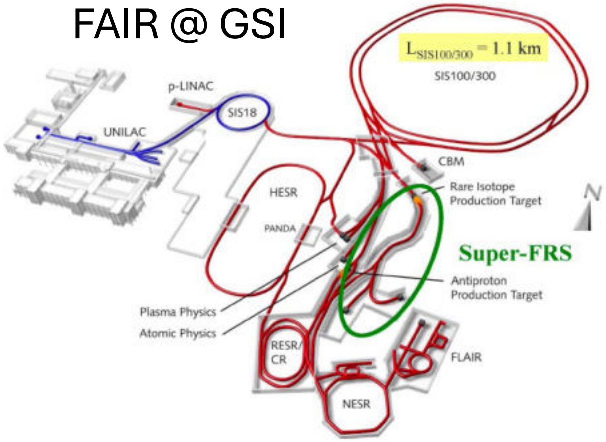
In-flight Fragmentation Facilities (in red)

Isotope Separation OnLine Facilities ISOL (in black)



courtesy: T. Stora

FAIR @ GSI

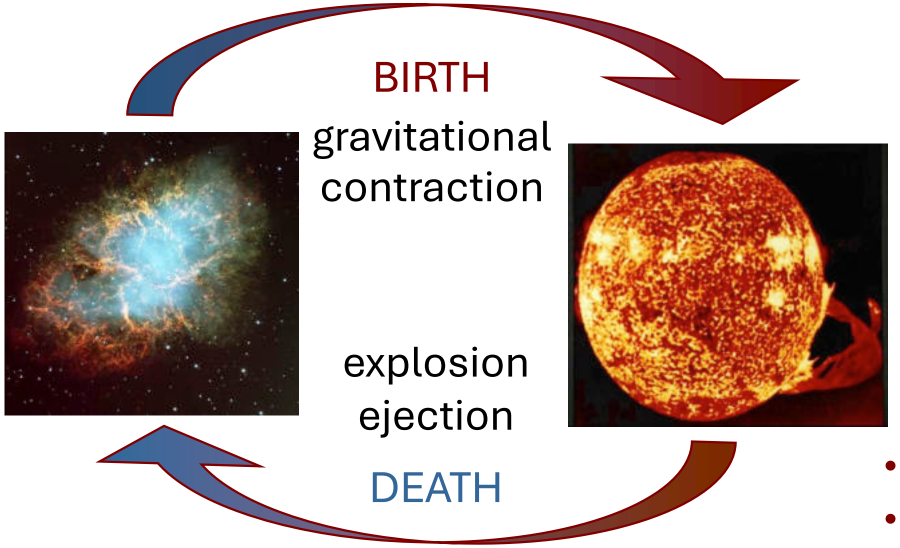


ARIEL @ TRIUMF

FRIB @ MSU

Life Cycles of Stars

Inter-stellar medium



BIRTH

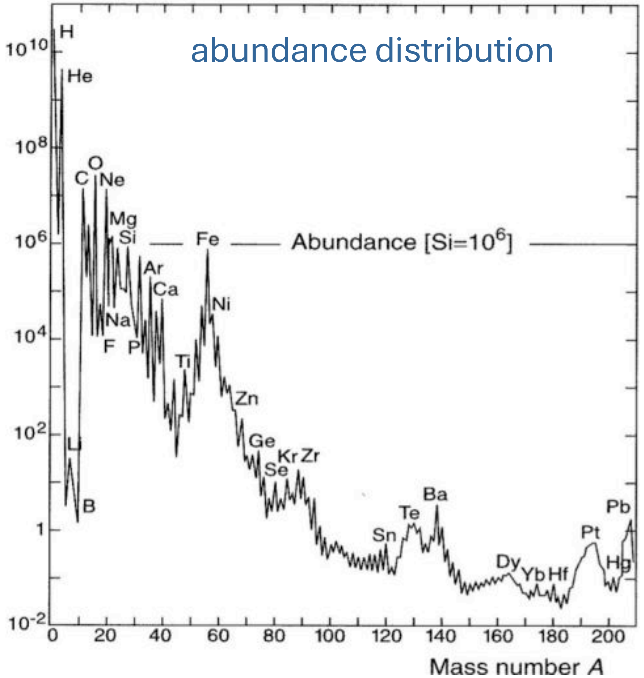
gravitational contraction

explosion ejection

DEATH

Stars

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



abundance distribution

Stellar Evolutionary Paths

birth

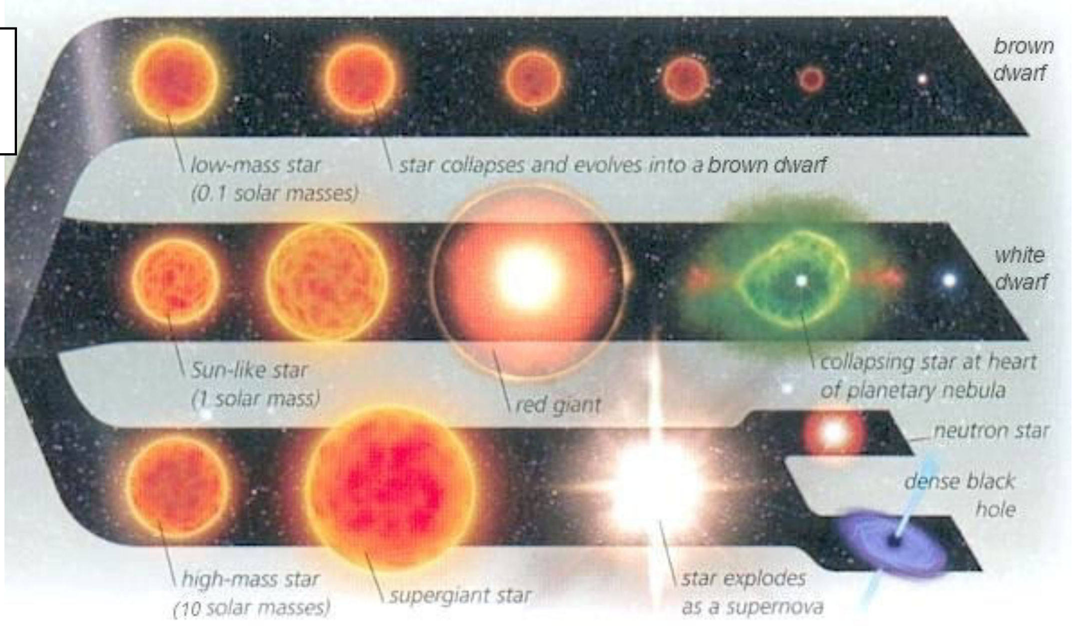
evolution

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 live longer → important for **evolution of life**

Thermonuclear Reactions in Stars

Nuclear reactions: Key concepts

Consider reaction: $1 + 2 \rightarrow 3 + 4$ $Q_{12} > 0$ ($\Leftarrow$ known from atomic mass tables)

probability for a reaction to occur $\Rightarrow$ reaction cross section σ

Dimension: area Unit: barn (b) = 10^{-24} cm^2

In general: not possible to determine reaction cross section from first principles

However:

- cross sections depend on nature of force involved

Reaction	Force	σ (barn)	E_{proj} (MeV)
$^{15}N(p,\alpha)^{12}C$	strong	0.5	2.0
$^{3}He(\alpha,\gamma)^{7}Be$	electromagnetic	10^{-6}	2.0
$p(p,e^{+}\nu)d$	weak	10^{-20}	2.0

- cross sections are energy (i.e. velocity) dependent

Reaction rate: $r = N_1 N_2 v\sigma(v)$

Nuclear reactions in stars

In stellar plasma: velocity of particles varies over wide range

Reaction rate per particle pair: $<\sigma v>_{12} = \int_0^\infty v\sigma(v)\phi(v)dv$ $\phi(v)$ velocity distribution

Quiescent stellar burning:

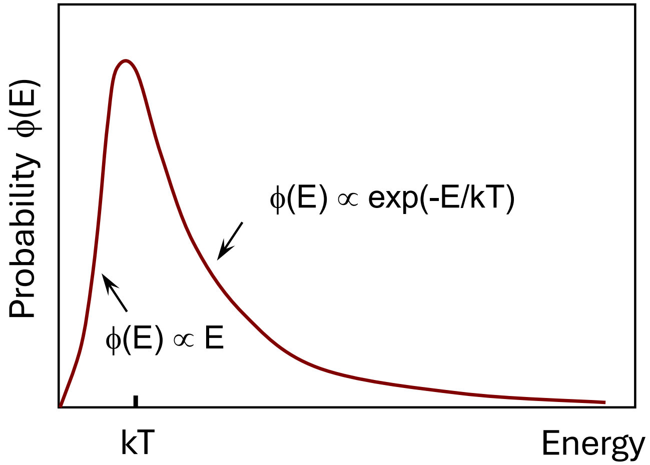
non-relativistic, non-degenerate gas in thermodynamic equilibrium at temperature T

Maxwell-Boltzmann distribution

$$\phi(v) \propto \exp\left(-\frac{\mu v^2}{2kT}\right) = \exp\left(-\frac{E}{kT}\right)$$

μ = reduced mass

v = relative velocity



$$<\sigma v>_{12} = \left(\frac{8}{\pi\mu_{12}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) \exp\left(-\frac{E}{kT}\right) E\, dE$$

Reaction rates

Total reaction rate: $R_{12} = (1+\delta_{12})^{-1} N_1 N_2 <\sigma v>_{12}$

reactions cm^{-3} s^{-1}

N_i = number density

Energy production rate: $\varepsilon_{12} = R_{12} Q_{12}$

Mean lifetime of nuclei X

against destruction by nuclei a

$$\tau_a(X) = \frac{1}{N_a < \sigma v >}$$

energy production as star evolves ⇐ $<\sigma v>$ = KEY quantity ⇒ change in abundance of nuclei X

to be determined from experiments and/or theoretical considerations

as star evolves, T changes ⇒ evaluate $<\sigma v>$ for each temperature

NEED ANAYLITICAL EXPRESSION FOR σ!

Reaction Mechanisms

I. direct (non-resonant) reactions

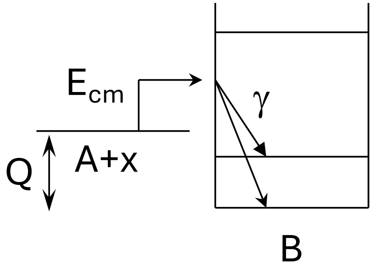
II. resonant reactions

direct (non-resonant) reaction process

one-step process

direct transition into a bound state

example: radiative capture A(x,γ)B



$$\sigma_\gamma \propto \left| \langle B | H_\gamma | A + x \rangle \right|^2$$

H_γ = electromagnetic operator describing transition

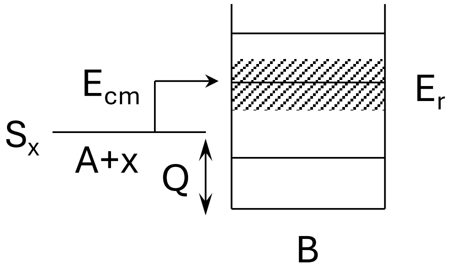
- reaction cross section proportional to single matrix element
- can occur at all projectile energies
- smooth energy dependence of cross section

examples of direct processes: scattering, stripping, pickup, charge exchange, Coulomb excitation

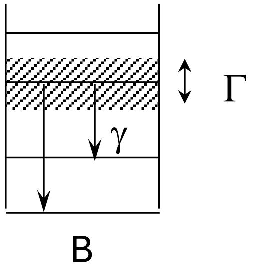
Resonant reaction mechanism

two-step process example: **resonant radiative capture A(x,γ)B**

1. Compound nucleus formation
(into unbound state)



2. Compound nucleus decay
(to lower excited states)



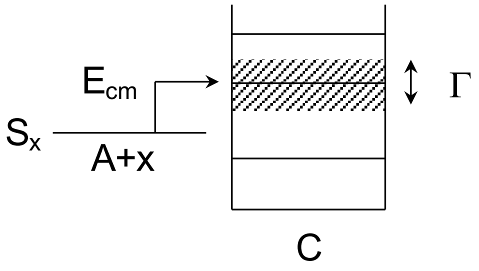
$$\sigma_\gamma \propto \underbrace{\left|\langle E_f|H_\gamma|E_r\rangle\right|^2}_{\substack{\text{compound decay}\\ \text{probability} \propto \Gamma_\gamma}} \underbrace{\left|\langle E_r|H_B|A+x\rangle\right|^2}_{\substack{\text{compound formation}\\ \text{probability} \propto \Gamma_x}}$$

- reaction cross section proportional to two matrix elements
- only occurs at energies $E_{cm} \sim E_r - Q$
- strong energy dependence of cross section

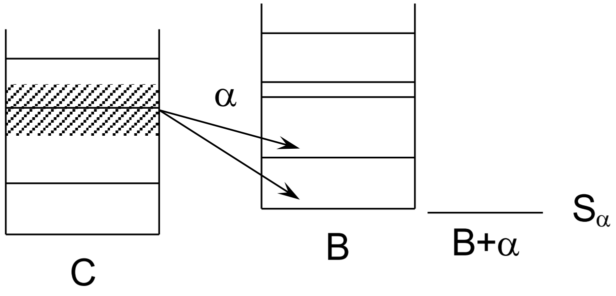
Resonant Reactions

example: **resonant reaction A(x,α)B**

1. Compound nucleus formation
   (into unbound state)



2. Compound nucleus decay
   (by particle emission)



$$\sigma_\gamma \propto \underbrace{\left|\langle B+\alpha|H_\alpha|E_r\rangle\right|^2}_{\text{compound decay probability } \propto \Gamma_\alpha} \underbrace{\left|\langle E_r|H_x|A+x\rangle\right|^2}_{\text{compound formation probability } \propto \Gamma_x}$$

N. B. energy in entrance channel (S_x+E_{cm}) has to match excitation energy E_r of resonant state, however all excited states have a width ⇒ there is always some cross section through tails

Cross Section for Non-Resonant Reactions

I. reactions with neutrons

II. reactions with charged particles

Reactions with neutrons

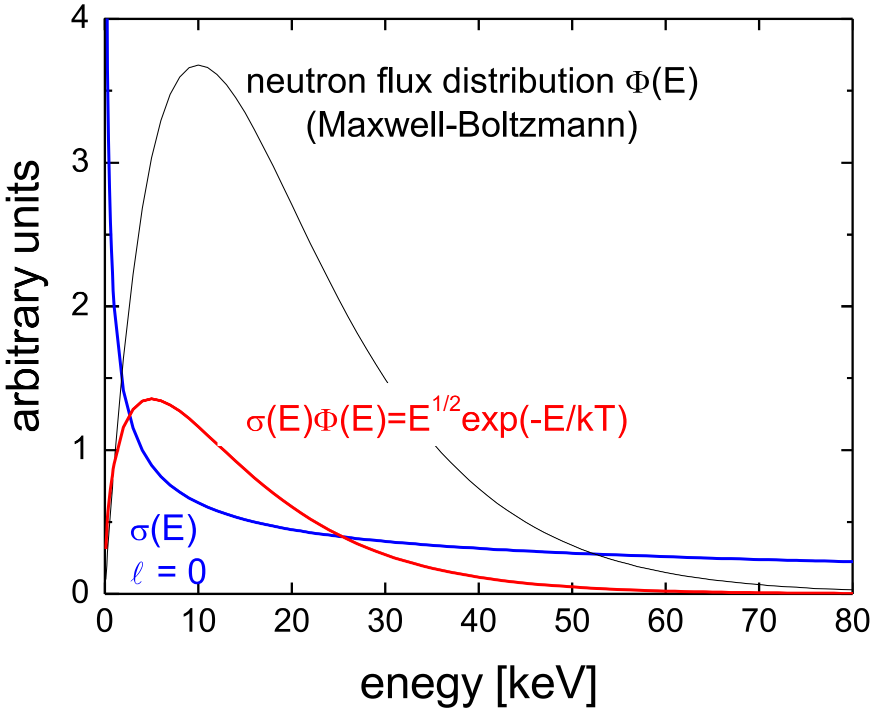
no Coulomb barrier to worry about

energy range of interest E ~ kT

$$\sigma \propto \frac{1}{v}$$

stellar reaction rate

$$\langle \sigma v \rangle = v_T \sigma_{th}$$



σ_{th} = measured cross section for thermal neutrons

neutron-capture cross sections can be measured DIRECTLY at relevant energies

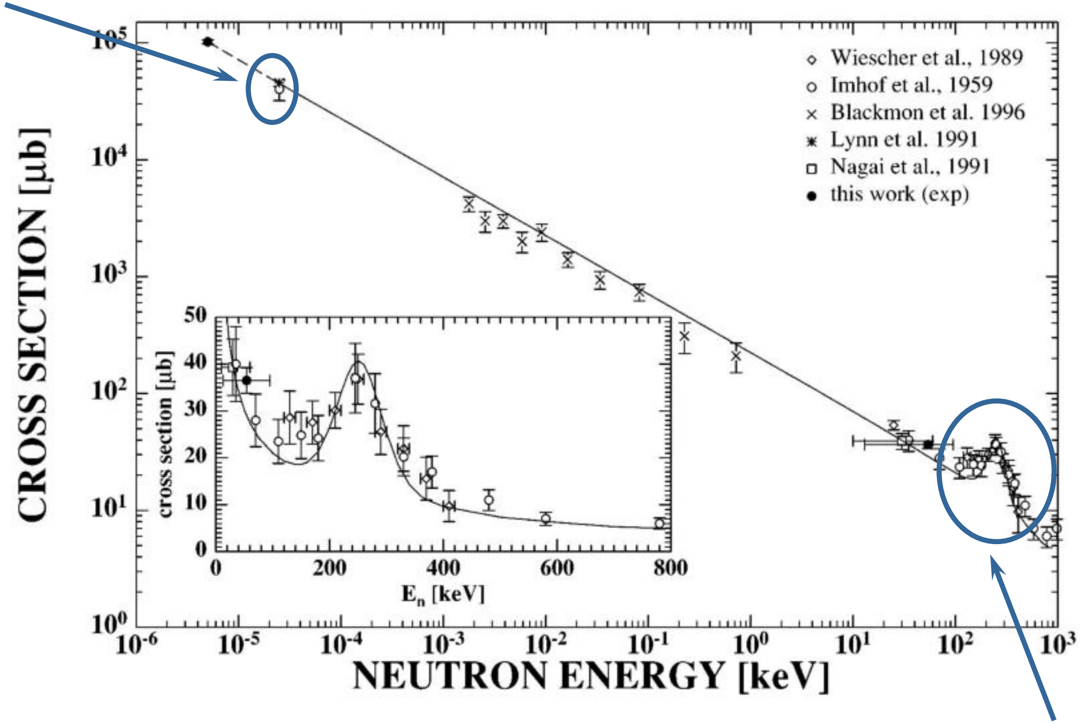
Reactions with neutrons

s-wave neutron capture

$$\sigma \propto \frac{1}{\sqrt{E}} = \frac{1}{v}$$

example: $^{7}Li(n,\gamma)^{8}Li$

thermal cross section
<σ> = 45.4 mb



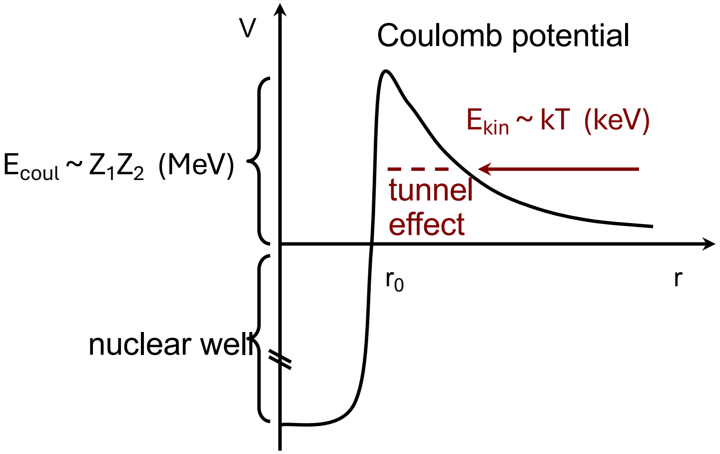
deviation from 1/v trend due
to resonant contribution (see later)

Cross Section for Non-Resonant Reactions

I. reactions with neutrons
II. reactions with charged particles

Reactions with charged particles

charged particles ➡ Coulomb barrier



energy available to initiate reaction comes from thermal motion

$$\boxed{kT \sim 8.6 \times 10^{-8}\ T[K]\ \text{keV}}$$

$T \sim 15 \times 10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

$T \sim 10^{10}$ K (Big Bang) $\Rightarrow$ $kT \sim 2$ MeV

during <u>quiescent burnings</u>: $kT \ll E_c$ ➡ reactions occur through TUNNEL EFFECT

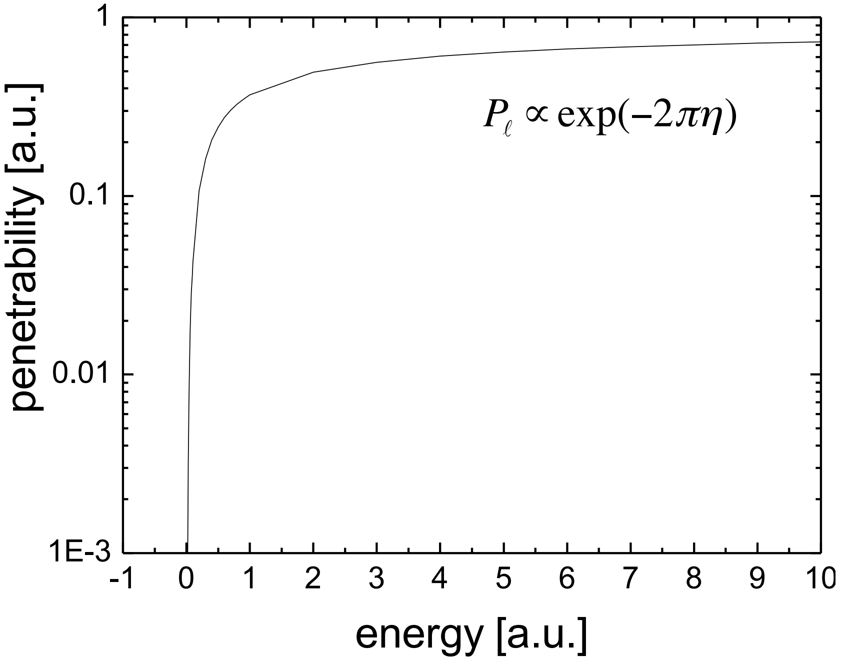
Tunnelling Probability

probability of tunnelling through Coulomb barrier for charged particle reactions at energies $E << V_{coul}$ assuming full ion charges and zero orbital angular momentum:

$$\boxed{P_\ell \propto \exp(-2\pi\eta) = \exp\left(-\frac{b}{\sqrt{E}}\right)}$$

$$\eta = \sqrt{\frac{\mu}{2E}}\frac{Z_1 Z_2 e^2}{\hbar}$$ Sommerfeld parameter

determines exponential drop in abundance curve!



GAMOW factor $\boxed{2\pi\eta = 31.29\, Z_1 Z_2 (\mu/E)^{1/2}}$ μ in amu and E_{cm} in keV

Non-Resonant Reactions

Non-resonant reactions

$$\sigma \propto \pi\lambda^2 \cdot P_\ell(E) \cdot \left|\langle b+Y|H|a+X\rangle\right|^2$$

geometrical factor
(particle's de Broglie wavelength)

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}$$

penetrability probability depends on projectile's angular momentum ℓ and energy E

interaction matrix element

$$\boxed{\sigma(E) = \underbrace{\frac{1}{E}\exp(-2\pi\eta)}_{\text{non-nuclear origin}}\ \underbrace{S(E)}_{\text{nuclear origin}}}$$

(for s-waves only!)

non-nuclear origin
STRONG energy dependence

nuclear origin
WEAK energy dependence

Above relation defines ASTROPHYSICAL S(E)-FACTOR (units: keV barn, MeV barn, …)

N.B.
If angular momentum is non zero

$\Rightarrow$ centrifugal barrier $V_\ell = \frac{\ell(\ell+1)\hbar^2}{2\mu r^2}$ must also be taken into account

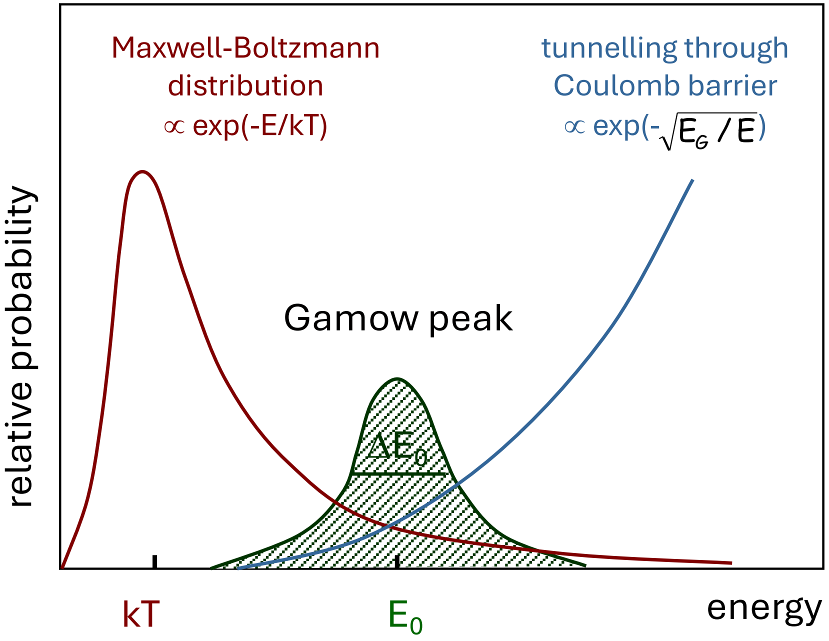
M Aliotta

The Gamow Peak

$$\langle\sigma v\rangle = \int \sigma(v)\phi(v)v\,dv = \int \sigma(E)\exp(-E/kT)E\,dE$$

and substituting for σ: $$\langle\sigma v\rangle \propto \int S(E)\exp\left(-\frac{E}{kT}-\frac{b}{\sqrt{E}}\right)dE$$

maximum reaction rate at E_0: $$\frac{d}{dE}\left[\exp\left(-\frac{E}{kT}-\frac{b}{\sqrt{E}}\right)\right]=0$$



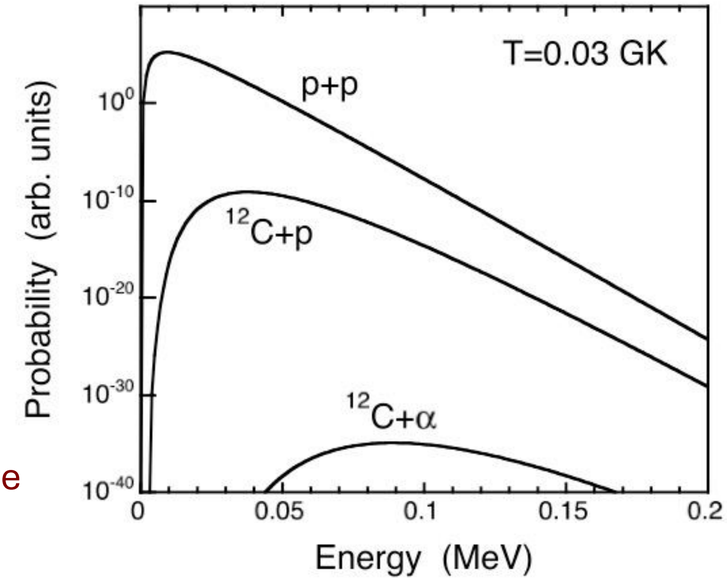
Gamow Peaks and Reaction Rates

Gamow peak: $E_0 \pm \Delta E_0/2$

energy window of astrophysical interest

$E_0 = f(Z_1, Z_2, T)$

varies depending on reaction and/or temperature



Iliadis, Nuclear Physics of Stars, 2007

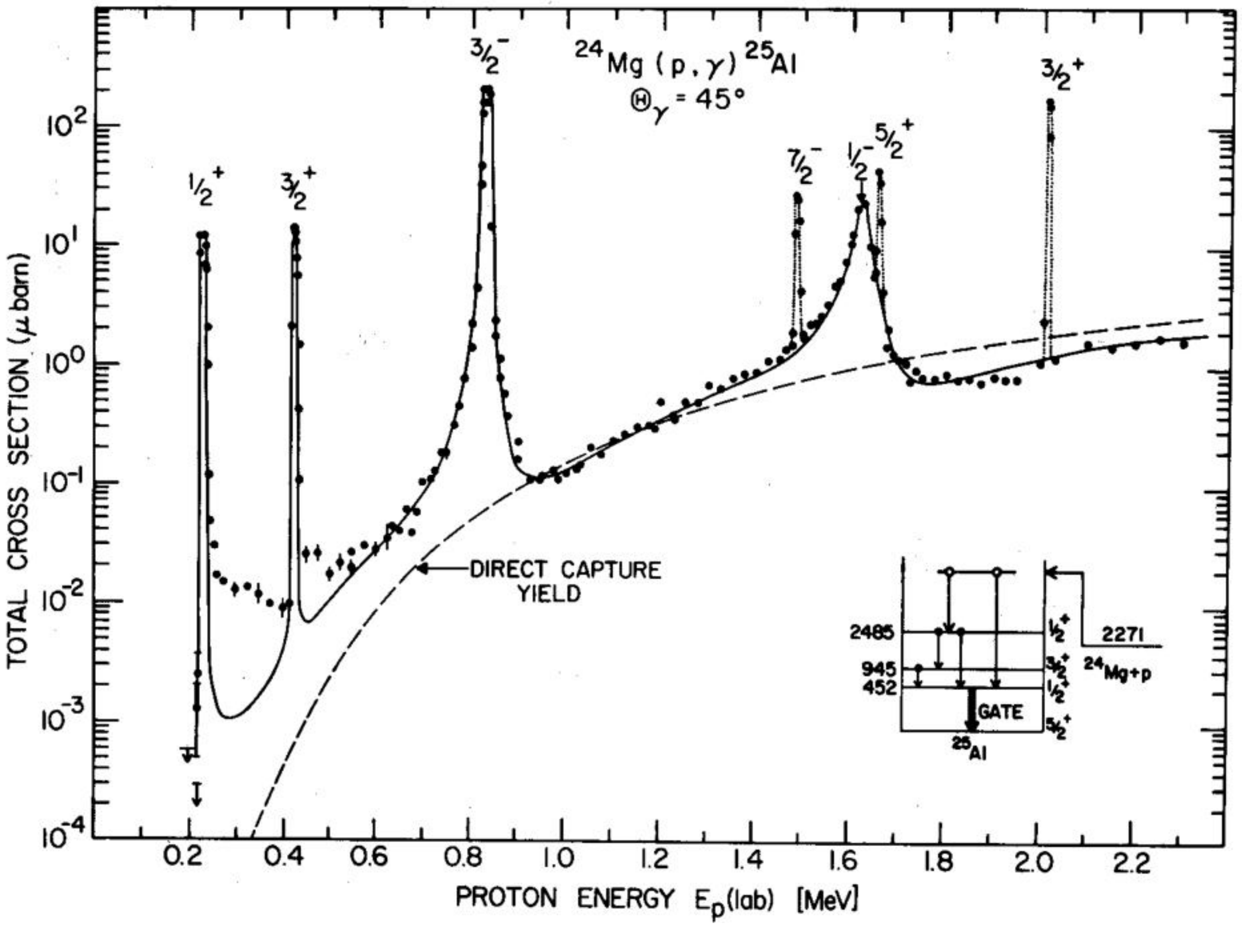
Examples: $T \sim 15 \times 10^6$ K ($T_6 = 15$)

reaction	Coulomb barrier (MeV)	E_0 (keV)	area under Gamow peak ~ $<\sigma v>$
p + p	0.55	5.9	7.0×10^{-6}
α + ^{12}C	3.43	56	5.9×10^{-56}
^{16}O + ^{16}O	14.07	237	2.5×10^{-237}

STRONG sensitivity
to Coulomb barrier

separate stages: H-burning
He-burning
C/O-burning
...

example: $^{24}Mg(p,\gamma)^{25}Al$



Cross Section for Resonant Reactions

reactions with either neutrons or charged particles

Resonant Reaction Cross Sections

for a **single isolated resonance**:

resonant cross section given by **Breit-Wigner expression**

$$\sigma(E) = \pi\lambdabar^2 \frac{2J+1}{(2J_1+1)(2J_T+1)} \frac{\Gamma_1\Gamma_2}{(E-E_R)^2+(\Gamma/2)^2}$$

for reaction: 1 + T → C → F + 2

geometrical factor

$\propto$ 1/E

spin factor ω

J = spin of CN's state

J_1 = spin of projectile

J_T = spin of target

strongly energy-dependent term

Γ_1 = partial width for decay via emission of particle 1

= probability of compound formation via entrance channel

Γ_2 = partial width for decay via emission of particle 2

= probability of compound decay via exit channel

Γ = total width of compound's excited state

$= \Gamma_1 + \Gamma_2 + \Gamma_\gamma + \ldots$

E_r = resonance energy

what about penetrability considerations? $\Rightarrow$ look for energy dependence in partial widths!

partial widths are NOT constant but energy dependent!

Partial Widths and Tunnelling Probabilities

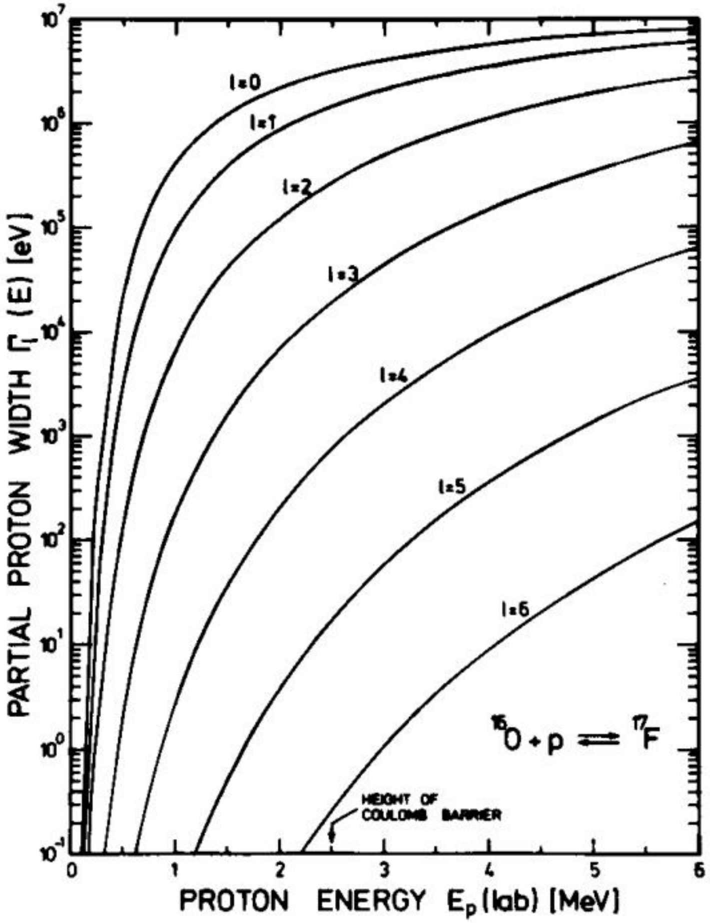
particle widths

$$\boxed{\Gamma_1 = \frac{2\hbar}{R} P_\ell(E_1)\theta_\ell^2}$$

θ_l = “reduced width” (contains nuclear physics info)
P_ℓ gives strong energy dependence

example: **$^{16}O(p,\gamma)^{17}F$**

energy dependence of proton partial width Γ_p as function of ℓ



particle partial widths have approximately same energy dependence as penetrability function seen in direct reaction processes

Reaction Rate

reaction rate: $\langle\sigma v\rangle = \int \sigma(v)\phi(v)v\,dv = \int \sigma(E)\exp(-E/kT)E\,dE$

↓

here Breit-Wigner cross section

$$\sigma(E) = \pi\bar{\lambda}^2 \frac{2J+1}{(2J_1+1)(2J_T+1)} \frac{\Gamma_1\Gamma_2}{(E-E_r)^2+(\Gamma/2)^2}$$

integrate over appropriate energy region

if compound nucleus has an exited state (or its wing) in this energy range

⇒ RESONANT contribution dominates reaction rate (if allowed by selection rules)

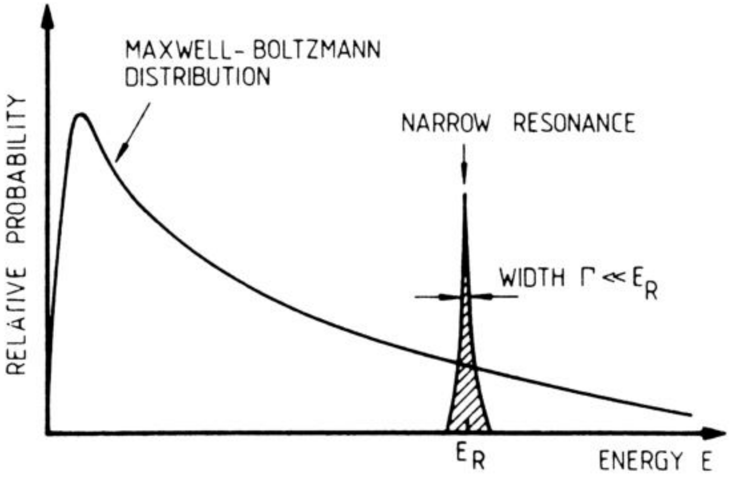
Reaction Rates

I. Narrow Resonances
II. Broad Resonances
III. Sub-threshold resonances

Resonant Reactions through Narrow Resonances

Narrow resonances

$\boxed{\Gamma << E_R}$



- resonance must be **near** energy of astrophysical interest to contribute to stellar rate
- MB distribution assumed **constant** over resonance region
- partial widths also **constant**, i.e. $\Gamma_i(E) \cong \Gamma_i(E_R)$

reaction rate for a single narrow resonance

$$\boxed{\langle \sigma v \rangle_{12} = \left(\frac{2\pi}{\mu_{12} kT} \right)^{3/2} \hbar^2 (\omega\gamma)_R \exp\left(-\frac{E_R}{kT} \right)}$$

NOTE - exponential dependence on energy means:

- rate strongly dominated by low-energy resonances (**$E_R \rightarrow kT$**) if any
- small uncertainties in E_R (even a few keV) imply large uncertainties in reaction rate

Resonance Strengths

rate entirely determined by “**resonance strength**” $\omega\gamma$ and **energy of the resonance E_R**

resonance strength

(integrated cross section over resonant region)

$$\boxed{\omega\gamma = \frac{2J+1}{(2J_1+1)(2J_T+1)}\frac{\Gamma_1\Gamma_2}{\Gamma}}$$

(Γ_i values at resonant energies)

often

$$\Gamma = \Gamma_1 + \Gamma_2$$

$$\Gamma_1 << \Gamma_2 \longrightarrow \Gamma \approx \Gamma_2 \longrightarrow \frac{\Gamma_1\Gamma_2}{\Gamma} \approx \Gamma_1$$

$$\Gamma_2 << \Gamma_1 \longrightarrow \Gamma \approx \Gamma_1 \longrightarrow \frac{\Gamma_1\Gamma_2}{\Gamma} \approx \Gamma_2$$

reaction rate is determined by the **smaller** width !

experimental info needed:

- partial widths Γ_i
- spin **J**
- energy E_R

note: for many unstable nuclei

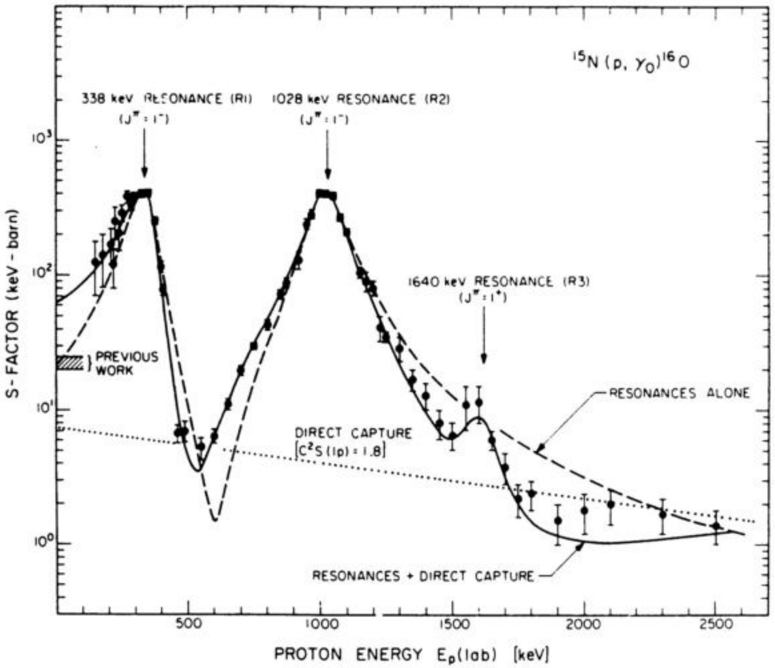
most of these parameters are

UNKNOWN!

Resonant Reactions through Broad Resonances

II. Broad resonances

$\boxed{\Gamma \sim E_R}$



resonances can also contribute through their tails

→ cannot assume constant widths and constant MB distribution over resonance

need energy dependence of partial and total widths to calculate contribution far from E_R

$$\langle\sigma v\rangle = \langle\sigma v\rangle_{tail} + \langle\sigma v\rangle_{res}$$

$\langle\sigma v\rangle_{tail}$…. non-resonant formalism can be applied (i.e. S-factor, Gamow energy etc.)

Note:

- overlapping broad resonances of same $J^\pi \rightarrow$ **interference effects in cross section**
- also interference effects between same ℓ for direct and resonant reactions

Resonant Reactions through Sub-Threshold States

III. Sub-threshold ~~resonances~~ states

any exited state has a finite width

$\Gamma \sim h/\tau$

high energy wing can extend

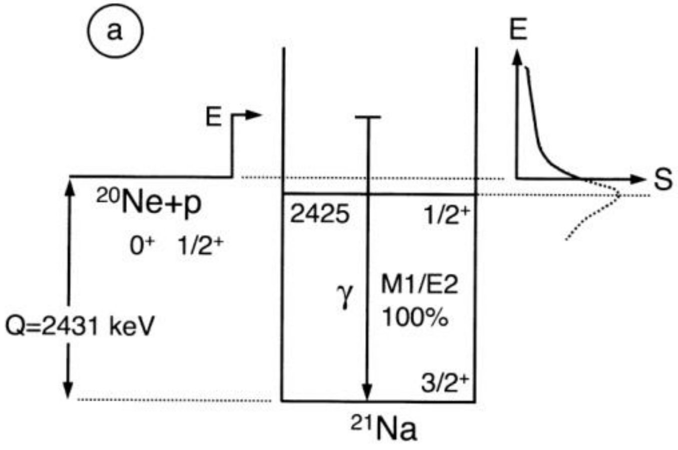
above particle threshold

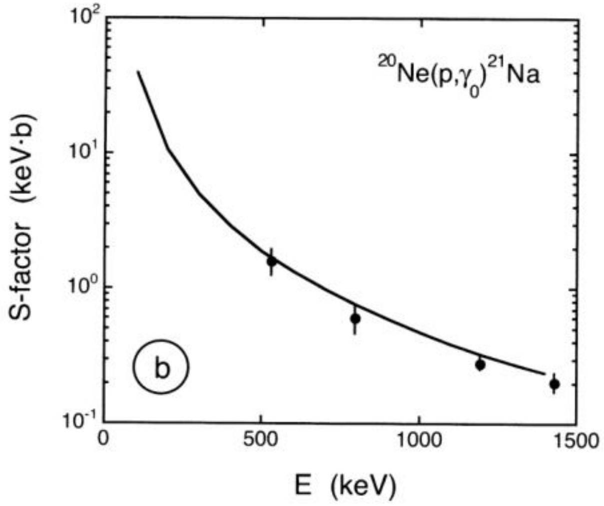
↓

cross section can be entirely dominated

by contribution of sub-threshold state(s)

Examples: $^{20}Ne(p,\gamma)^{21}Na$, $^{12}C(\alpha,\gamma)^{16}O$





Iliadis, 2007

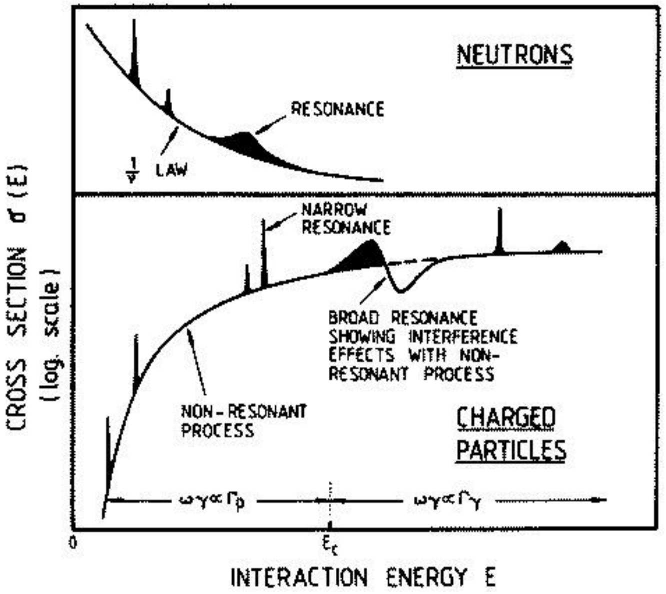
Stellar Reaction Rates

stellar reaction rates include contributions from

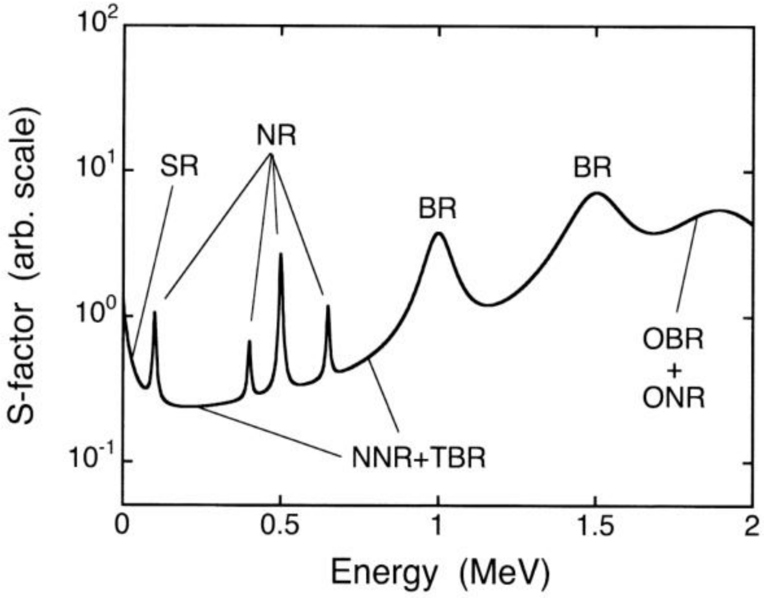
- direct transitions to the various bound states
- all narrow resonances in the relevant energy window
- broad resonances (tails) e.g. from higher lying resonances
- any interference term

total rate

$$\boxed{\langle \sigma v \rangle = \sum_i \langle \sigma v \rangle_{\mathrm{DCi}} + \sum_i \langle \sigma v \rangle_{\mathrm{Ri}} + \langle \sigma v \rangle_{\mathrm{tails}} + \langle \sigma v \rangle_{\mathrm{int}}}$$



Rolfs, 1988



Iliadis, 2007

Electron Screening

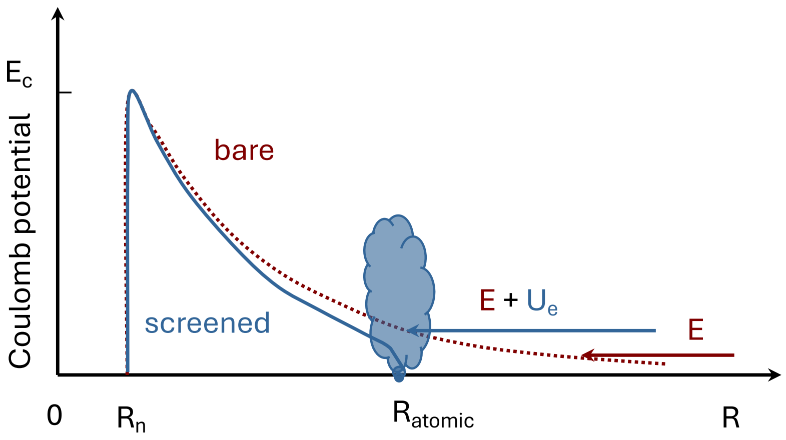
Electron Screening

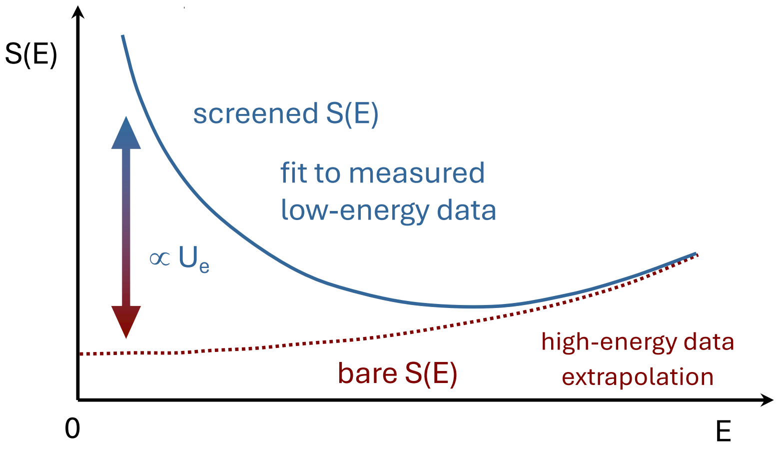
$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)\, S(E)$

assumption: $2\pi\eta \sim Z_1 Z_2(\mu/E)^{½}$

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)

⇒ corrections typically negligible

⇒ except for ultra-low energies

typically, experimental investigations

⬇

U_e in excess of theoretical limit !

electron screening puzzle

Part II

Astrophysical Reaction Studies in the Laboratory: Experimental Challenges of Direct Measurements

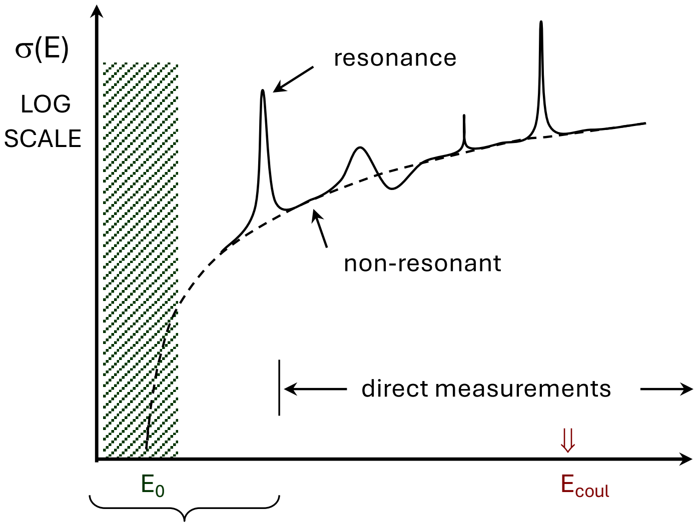
Thermonuclear Reactions in Stars

Gamow peak: energy window where information on nuclear processes is needed

BUT: $kT \ll E_0 \ll E_{coul}$ ➡ 10^{-18} barn < $\boldsymbol{\sigma}$ < 10^{-9} barn ➡ Major experimental difficulties

Procedure: measure σ(E) over wide energy, then extrapolate down to E_0!

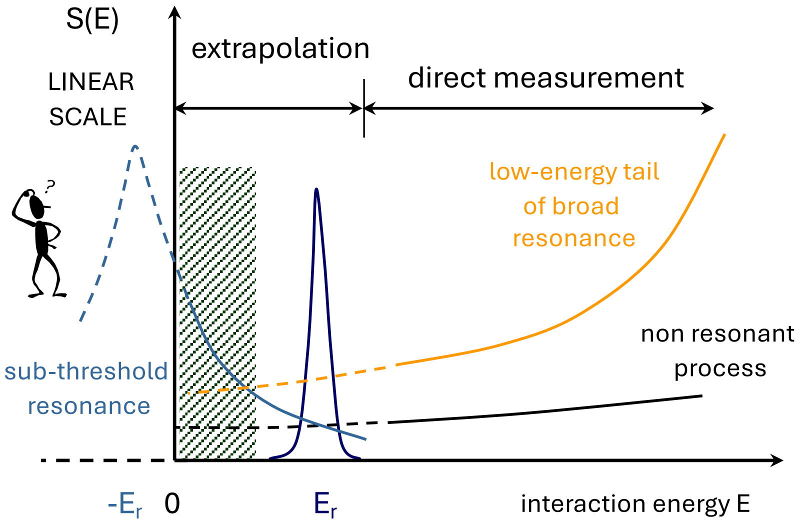
CROSS SECTION



extrapolation needed !

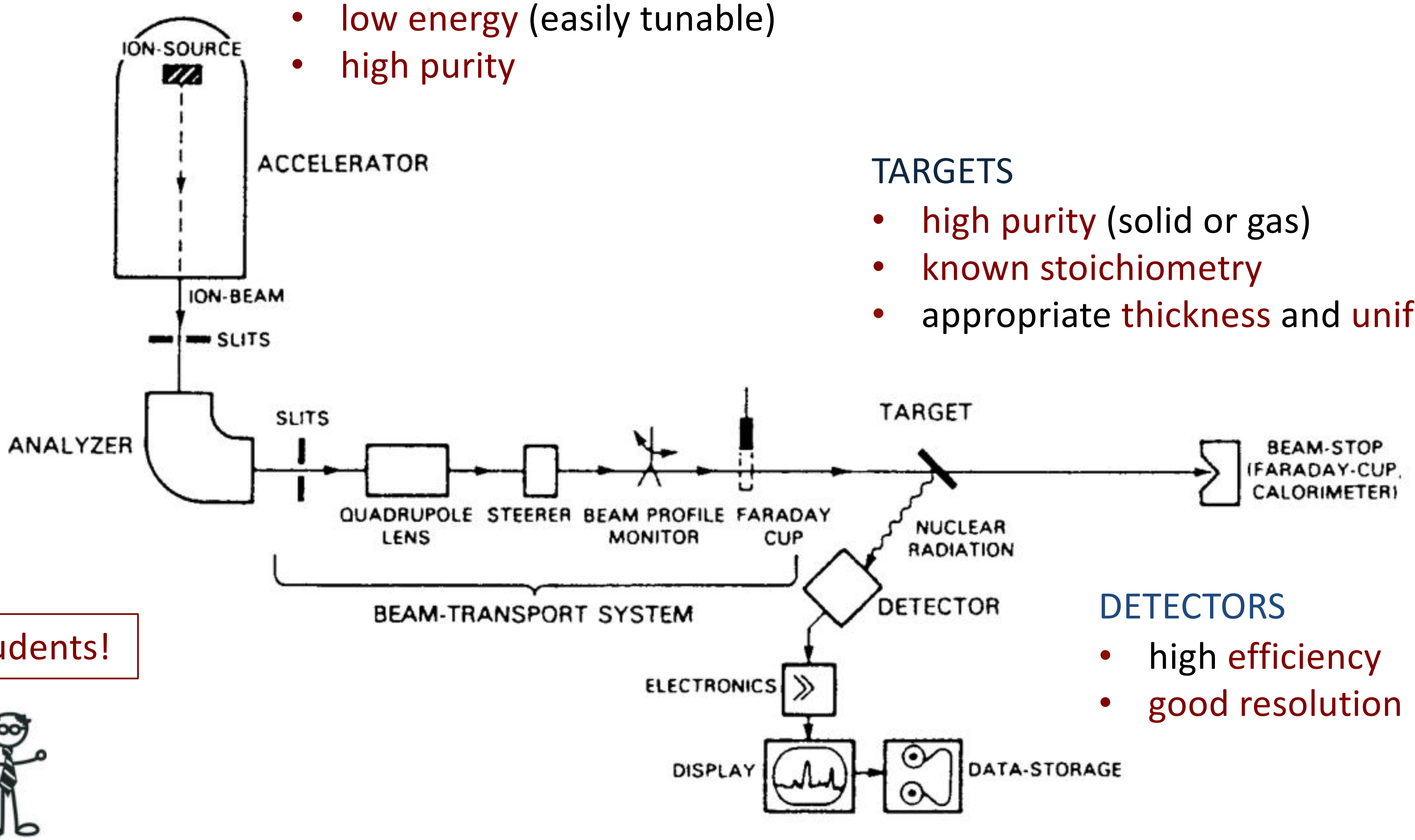
Coulomb barrier

S-FACTOR



DANGER OF EXTRAPOLATION !

Schematic Layout for Nuclear (Astro-)Physics Experiments

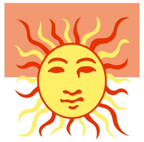


BEAMS
- high beam currents
- low energy (easily tunable)
- high purity

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

DETECTORS
- high efficiency
- good resolution

Excellent Students!



Quiescent stages of stellar evolution

FEATURES

$T \sim 10^6 - 10^8$ K ⇒ $E_0 \sim 100$ keV << E_{coul} ⇒ tunnel effect

⇒ 10^{-18} barn < σ < 10^{-9} barn

⇒ average interaction time $\tau \sim \langle\sigma v\rangle^{-1} \sim 10^9$ y

unstable species DO NOT play significant role

CHALLENGES

10^{-18} b < σ < 10^{-9} b

- ⇒ poor signal-to-noise ratio
- ⇒ major experimental challenge
- ⇒ extrapolation procedure required

REQUIREMENTS

poor signal-to-noise ratio

- ⇒ long measurements
- ⇒ ultra-pure targets
- ⇒ high beam intensities
- ⇒ high detection efficiency

Explosive stages of stellar evolution

FEATURES $T > 10^8$ K

$\Rightarrow$ $E_0 \sim 1$ MeV $\sim$ E_{coul}

$\Rightarrow$ 10^{-6} barn $< \sigma < 10^{-3}$ barn

$\Rightarrow$ cross sections “easy” to measure

CHALLENGES unstable nuclei

$\Rightarrow$ short half-lives ($10^{-6} – 10^1$ s)

$\Rightarrow$ unknown nuclear properties

REQUIREMENTS

$\Rightarrow$ **R**adioactive **I**on **B**eam facilities

$\Rightarrow$ produce and accelerate ions of interest

$\Rightarrow$ dedicated detection systems 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)

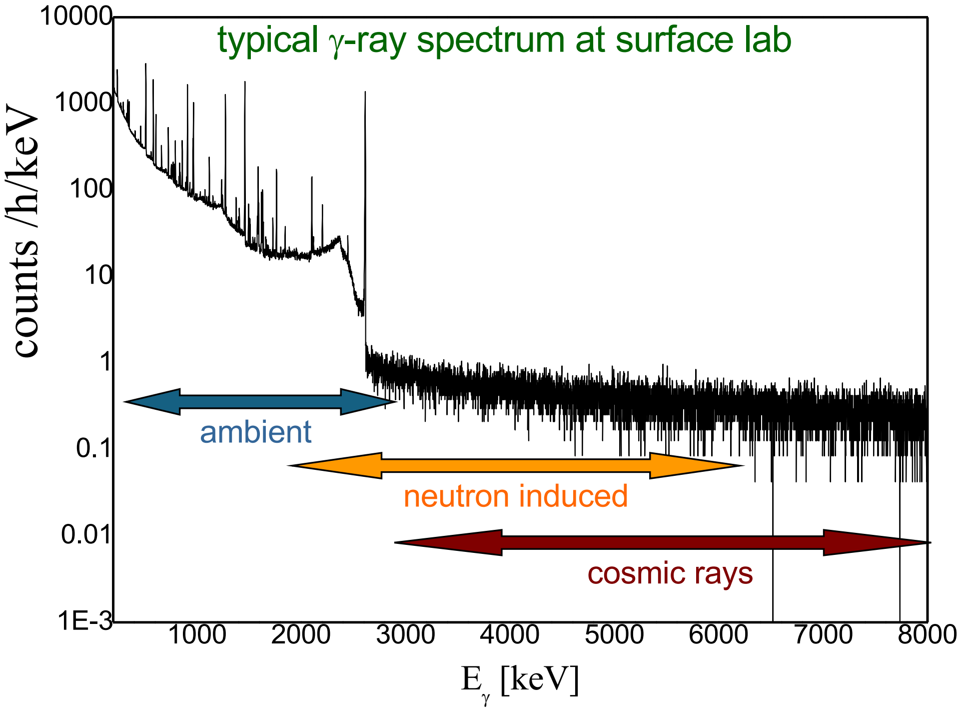
Y = 0.3-30 counts/year

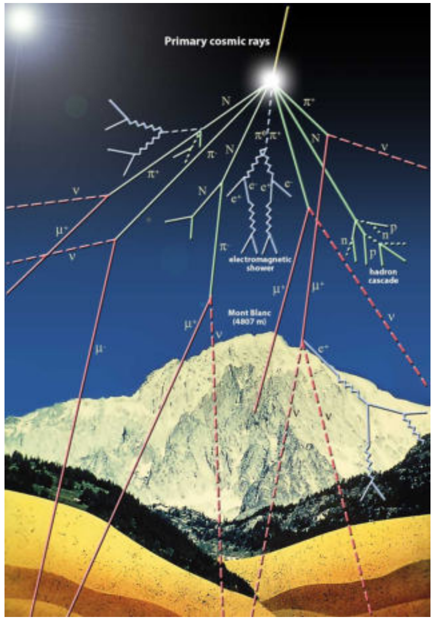
~ 1.2-120 counts/PhD

How to increase the signal-to-noise ratio?

Main Sources of Background

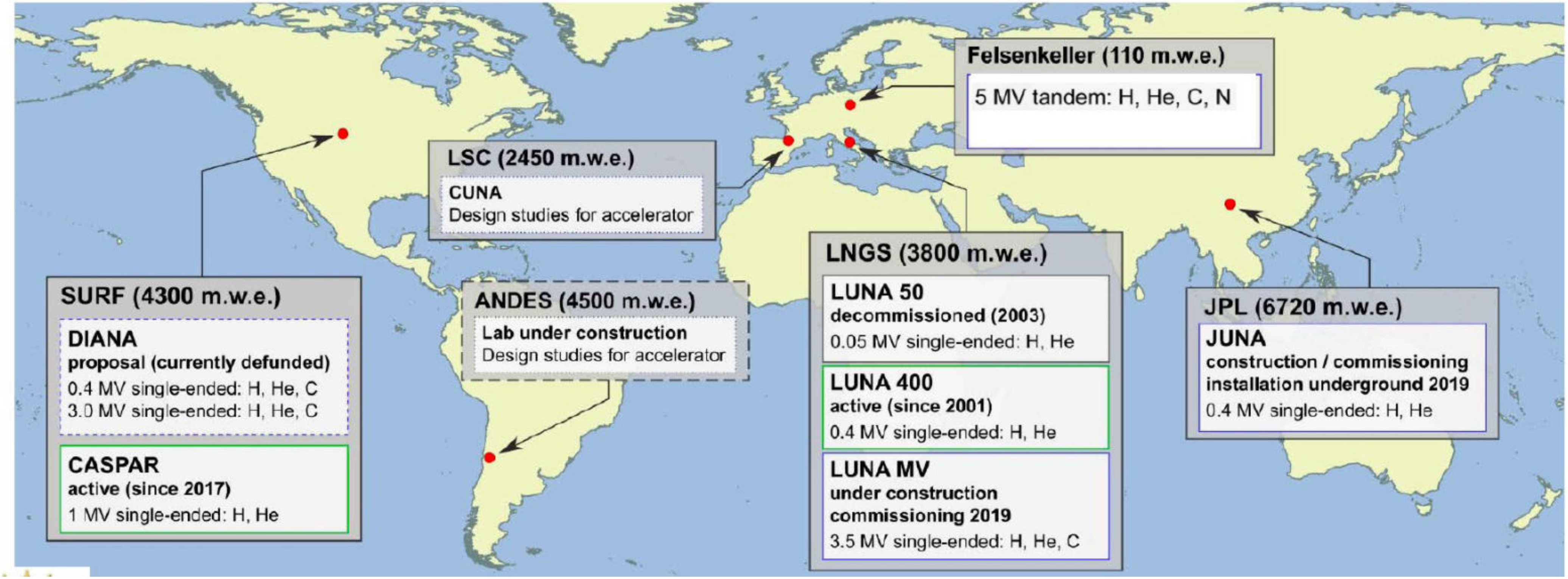
- natural radioactivity (mainly from U and Th chains and from Rn)
- cosmic rays (muons, $^{1,3}H$, ^{7}Be, ^{14}C, ...)
- neutrons from (α,n) reactions and fission





ideal location: underground + low concentration of U and Th

Underground Laboratories for Nuclear Astrophysics



SURF (4300 m.w.e.)

DIANA
proposal (currently defunded)
0.4 MV single-ended: H, He, C
3.0 MV single-ended: H, He, C

CASPAR
active (since 2017)
1 MV single-ended: H, He

LSC (2450 m.w.e.)

CUNA
Design studies for accelerator

ANDES (4500 m.w.e.)

Lab under construction
Design studies for accelerator

Felsenkeller (110 m.w.e.)

5 MV tandem: H, He, C, N

LNGS (3800 m.w.e.)

LUNA 50
decommissioned (2003)
0.05 MV single-ended: H, He

LUNA 400
active (since 2001)
0.4 MV single-ended: H, He

LUNA MV
under construction
commissioning 2019
3.5 MV single-ended: H, He, C

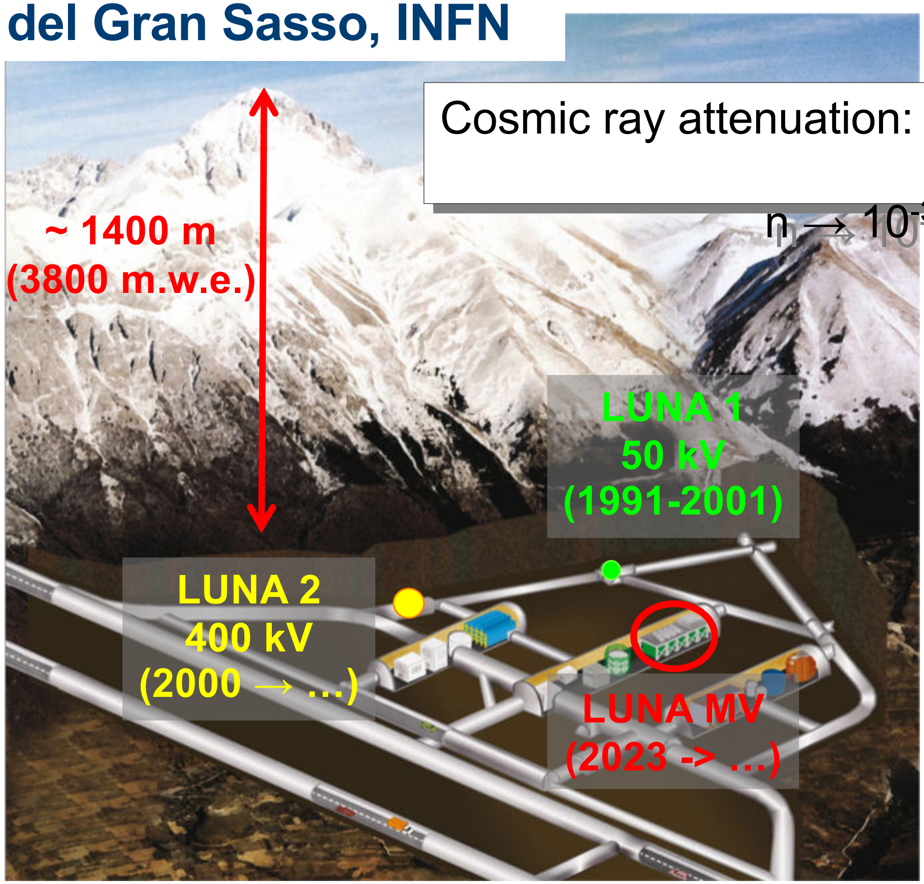
JPL (6720 m.w.e.)

JUNA
construction / commissioning
installation underground 2019
0.4 MV single-ended: H, He

courtesy: A. Boeltzig

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

Laboratori Nazionali del Gran Sasso, INFN



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

$n \rightarrow 10^{-3}$

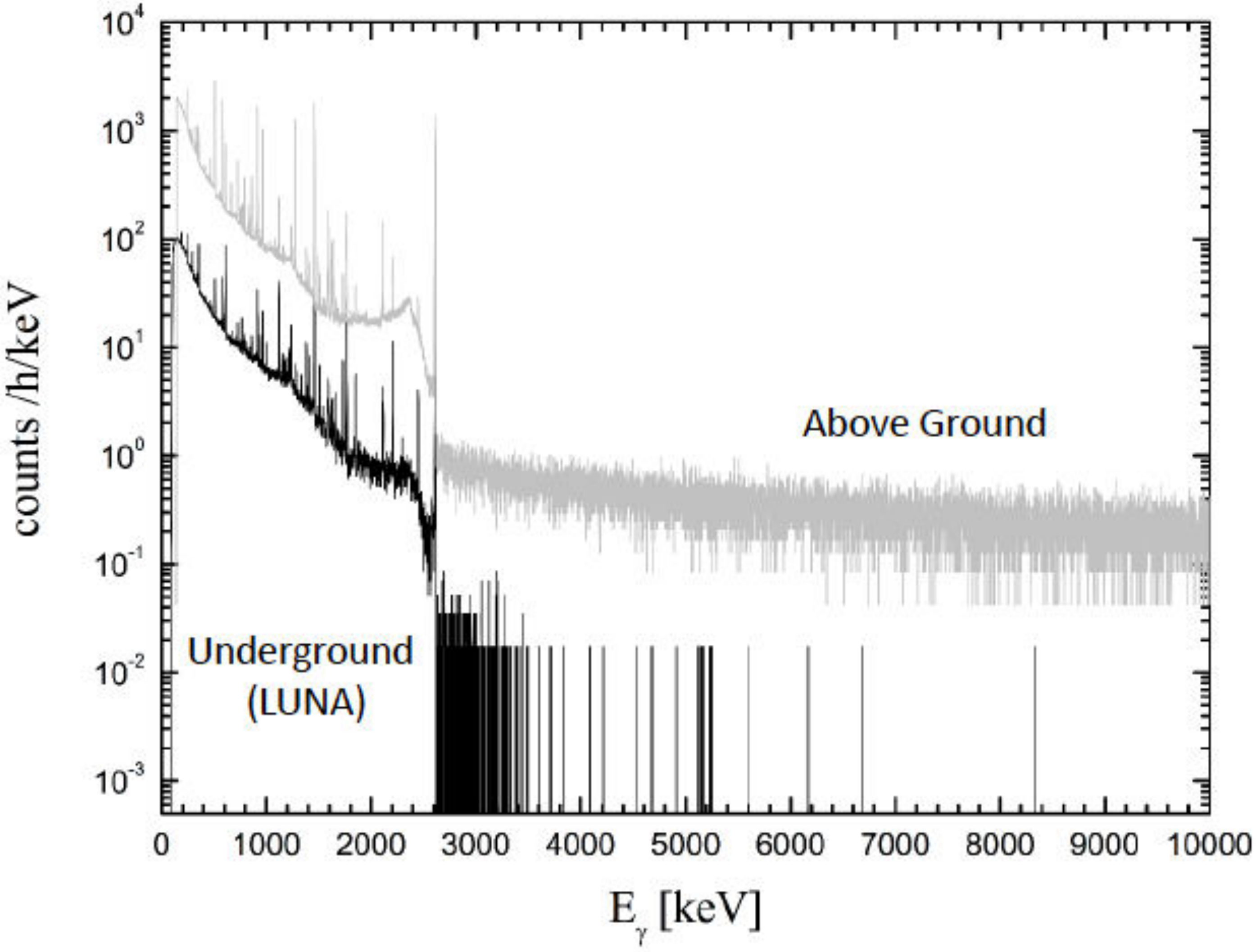
~ 1400 m
(3800 m.w.e.)

LUNA 1
50 kV
(1991-2001)

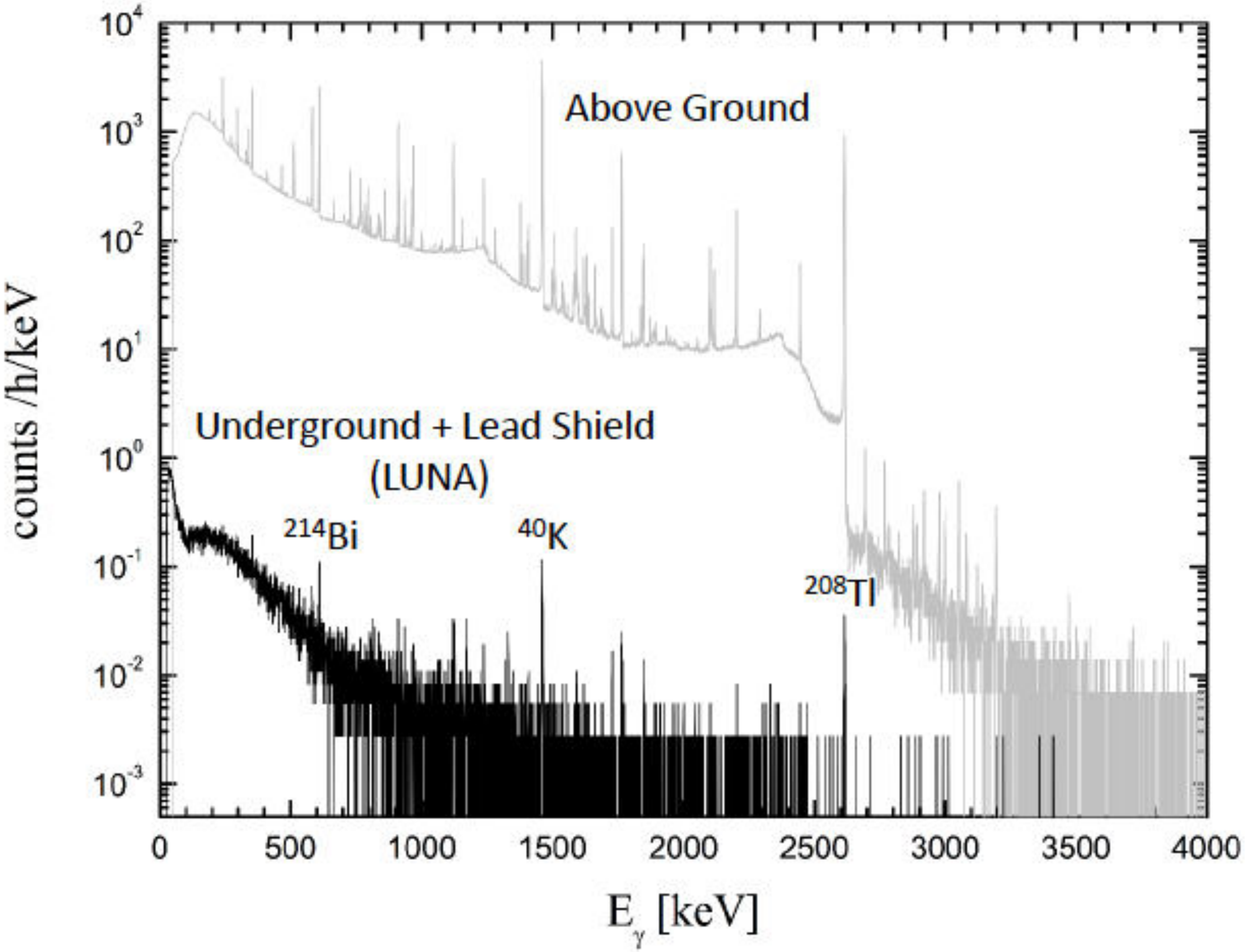
LUNA 2
400 kV
(2000 → …)

LUNA MV
(2023 -> …)

Background Comparison

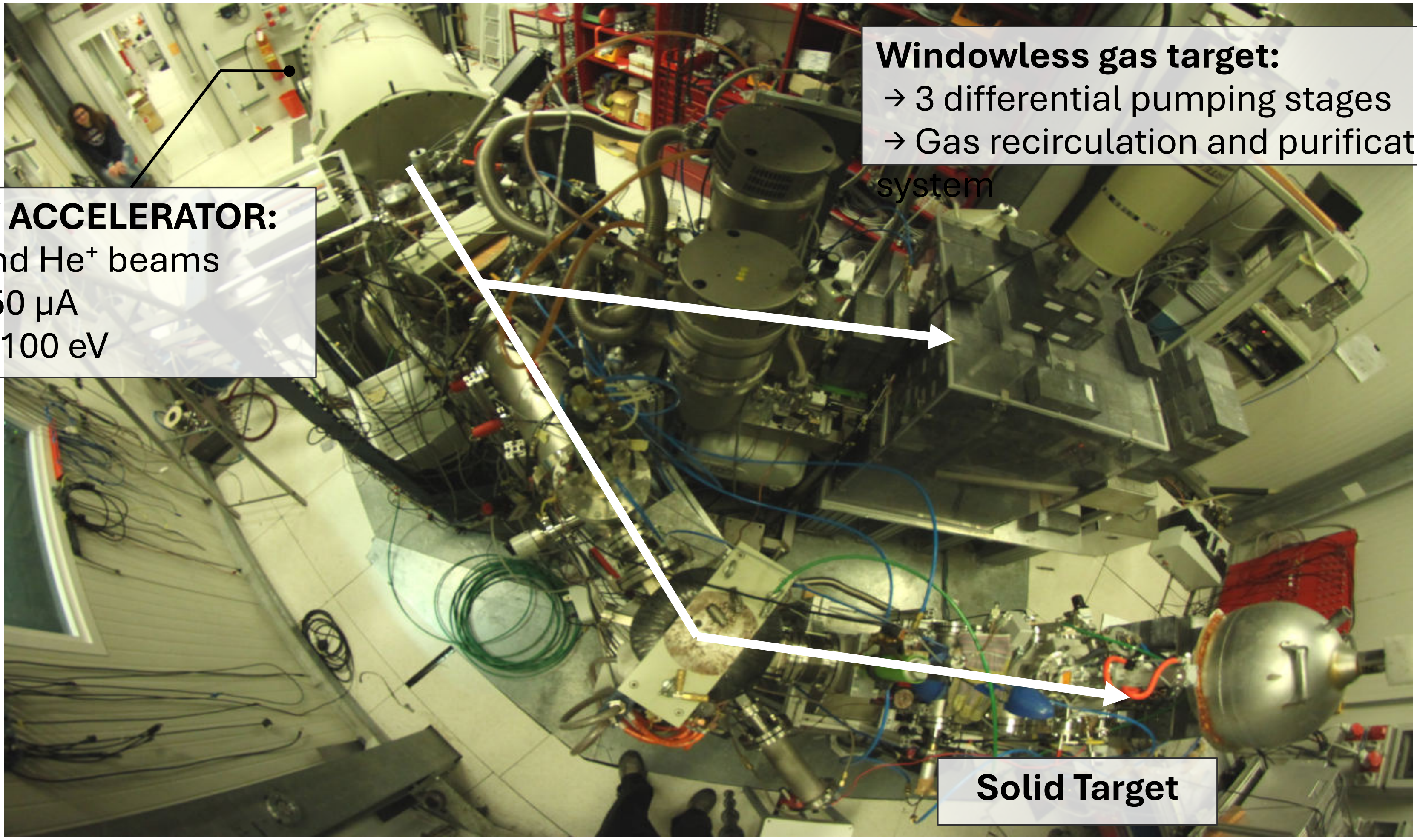


Background Comparison



NB shielding becomes even more efficient underground

The LUNA 400 kV facility



Windowless gas target:
- → 3 differential pumping stages
- → Gas recirculation and purification system

400 kV ACCELERATOR:
- → H^+ and He^+ beams
- → I ~ 250 μA
- → ΔE = 100 eV

Solid Target

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**

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

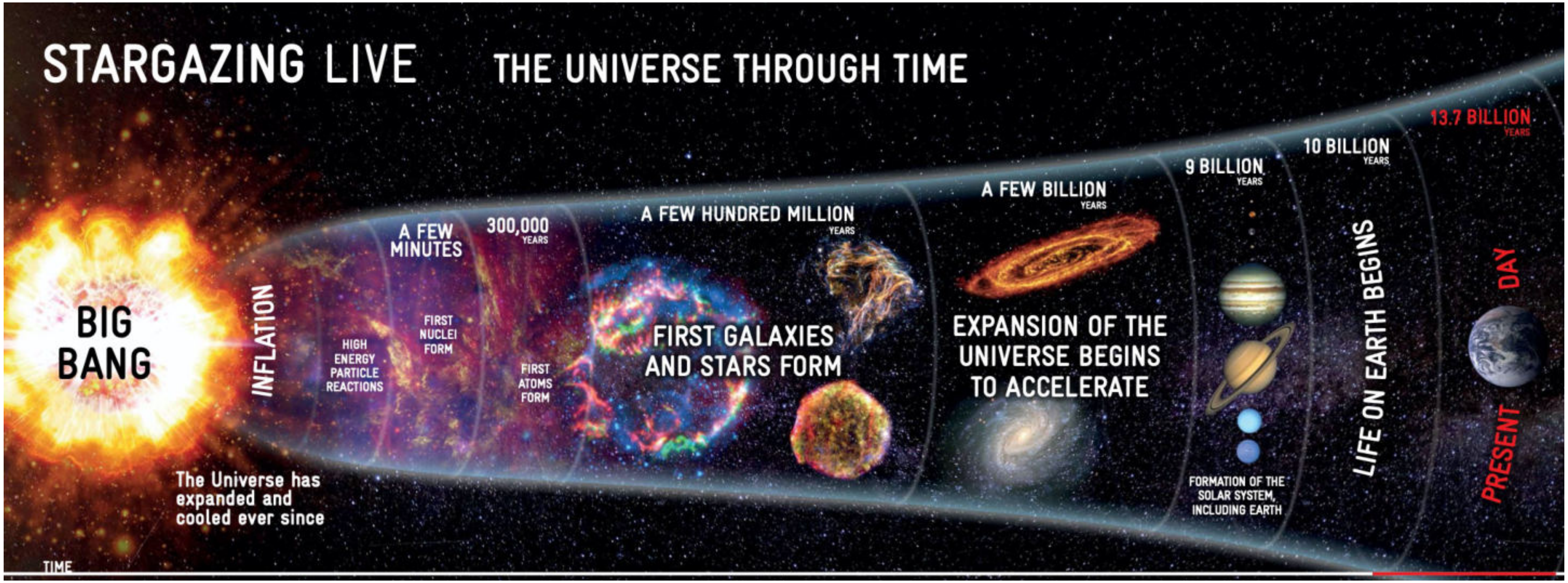
some of the lowest cross sections ever measured (few counts/month)

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

Recent Selected Highlights

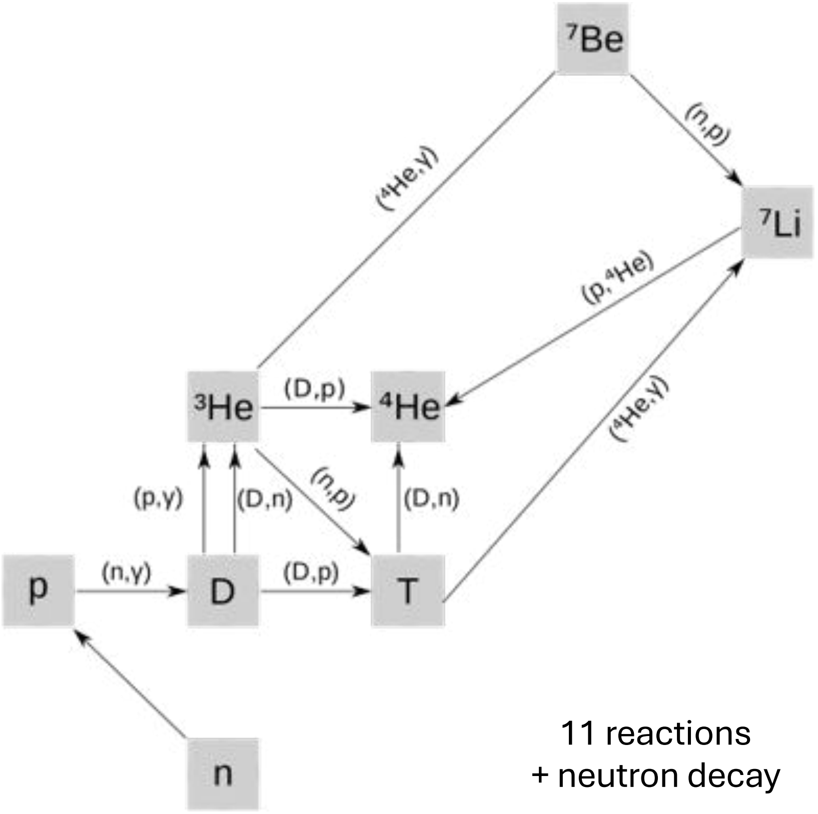
• Big Bang Nucleosynthesis:	$^{2}H(p,\gamma)^{3}He$	(gamma rays)
• O-rich Pre-Solar Grains:	$^{17}O(p,\alpha)^{14}N$	(charged particles)
• Neutron source for heavy elements:	$^{13}C(\alpha,n)^{16}O$	(neutrons)

Big Bang Nucleosynthesis

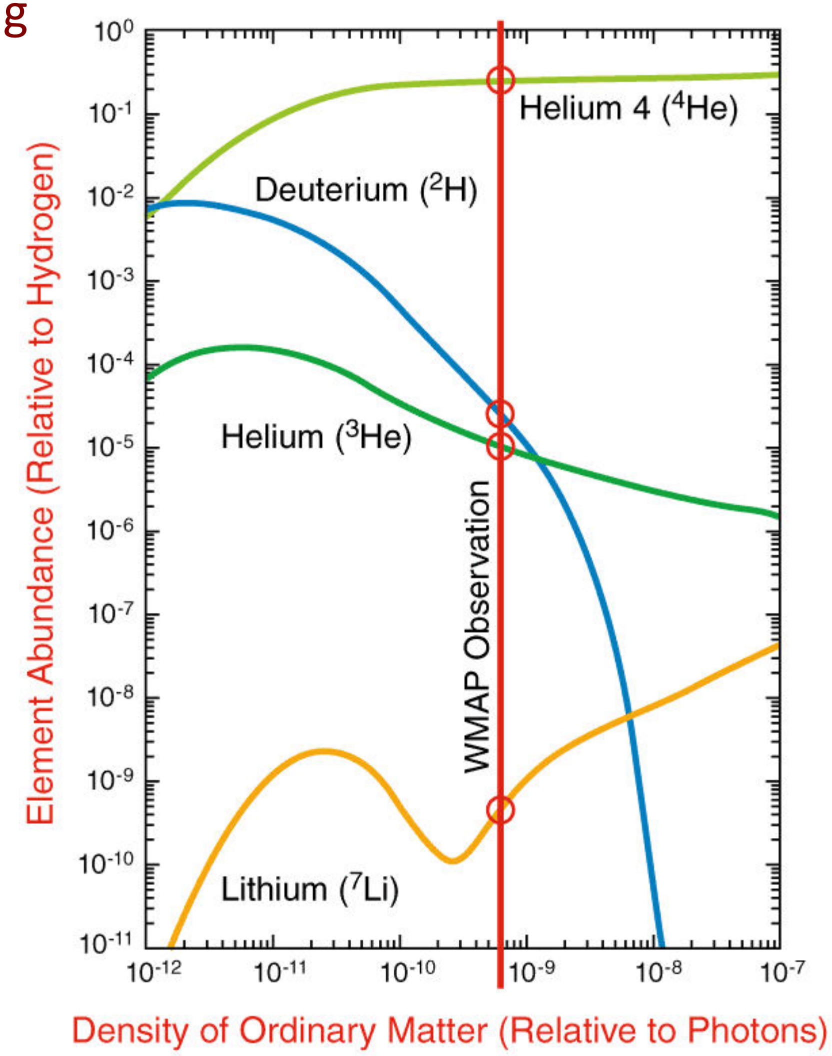


Primordial Nucleosynthesis (BBN): 3 minutes after Big Bang

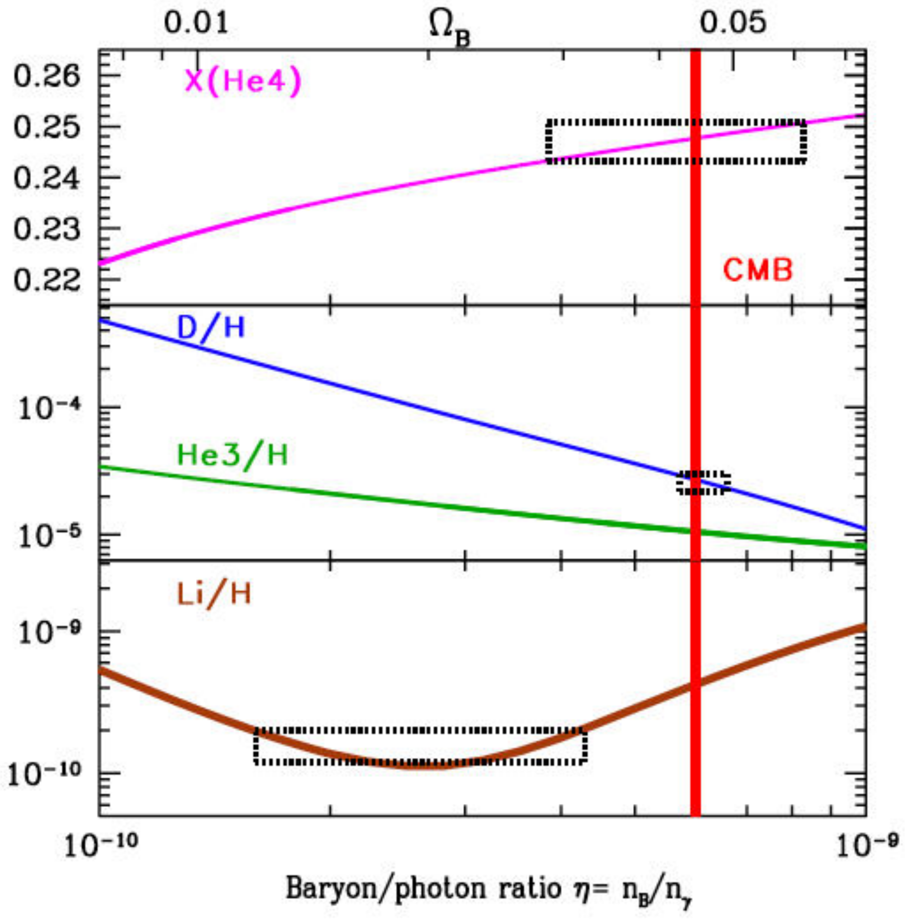
BBN is only tool to probe state of early universe



11 reactions
+ neutron decay



determine baryon density from comparison between BBN predictions and observations



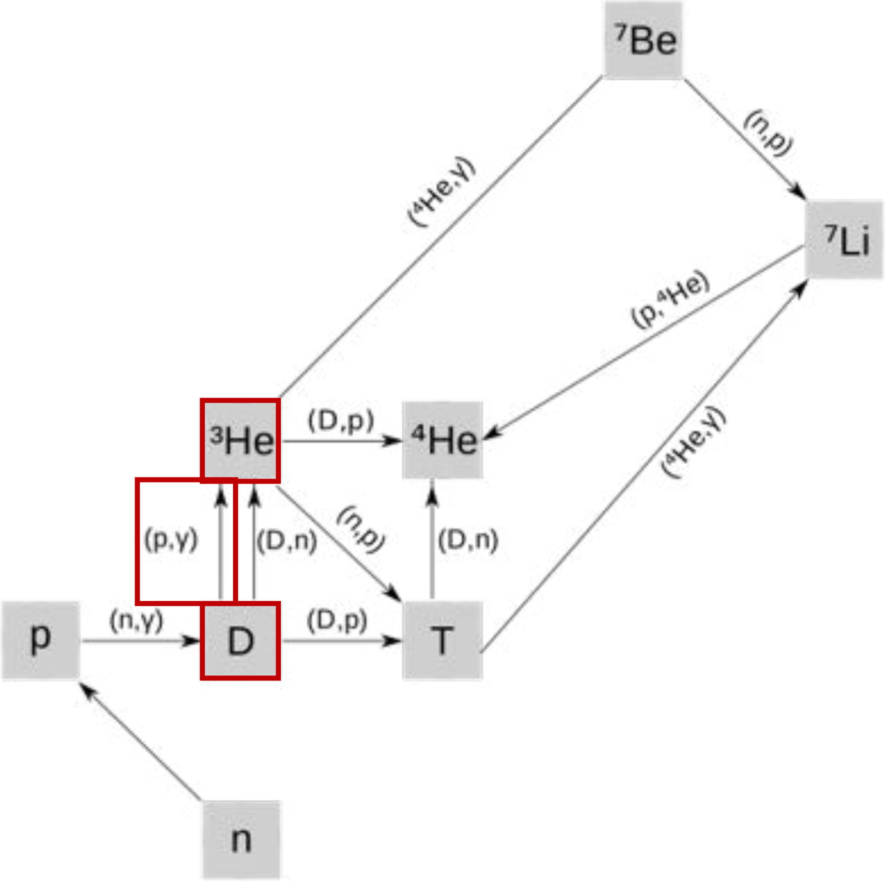
Deuterium is an excellent baryometer

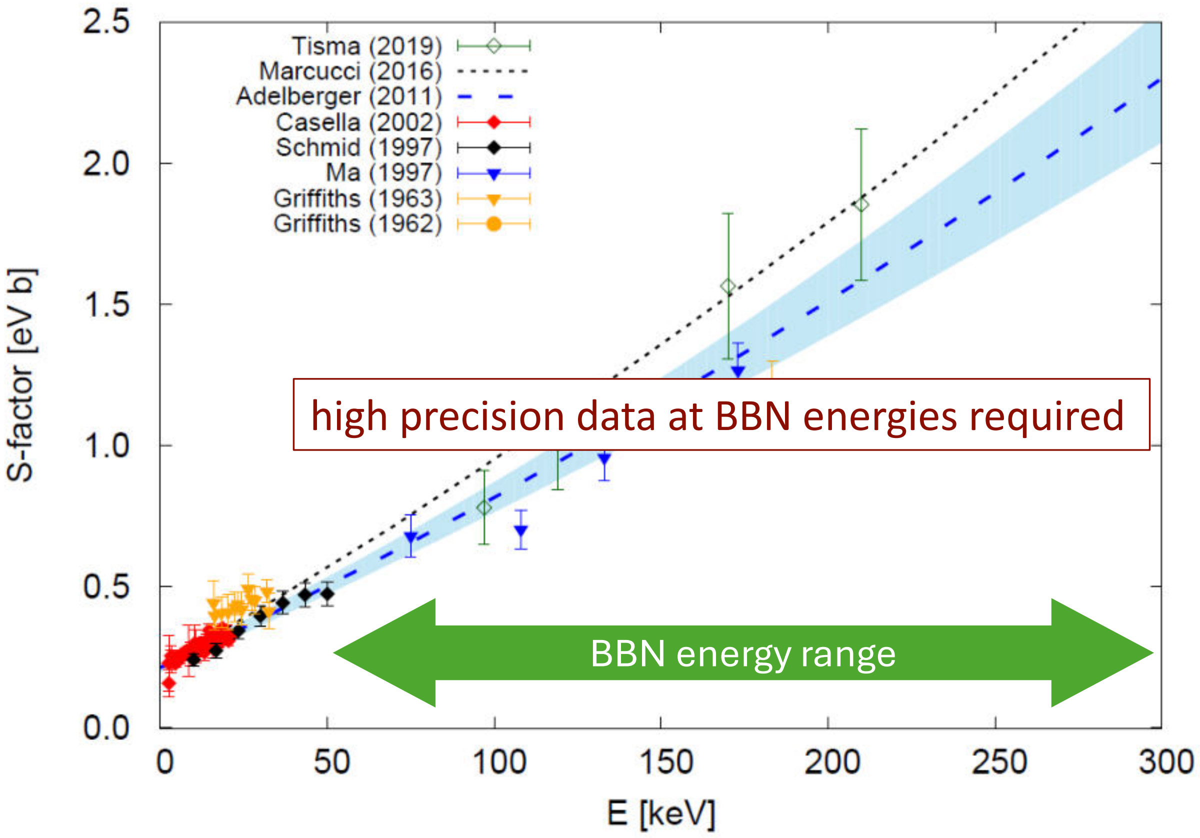
- D is only produced during Big Bang Nucleosynthesis
- D is destroyed easily in stars
- D abundance is the most sensitive to the baryon density Ω_b
- D abundance also depends on the effective number N_{eff} of neutrino species

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]





high precision data at BBN energies required

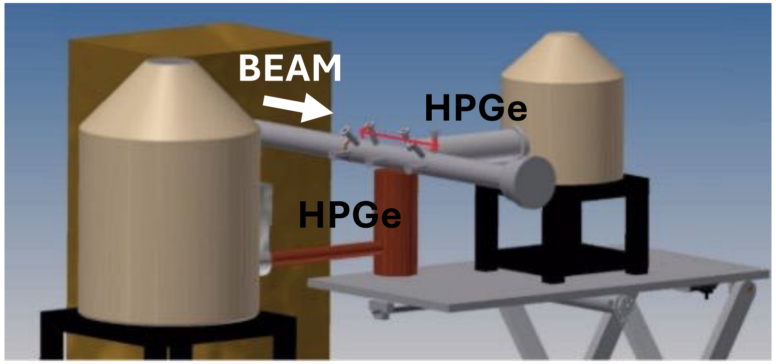
BBN energy range

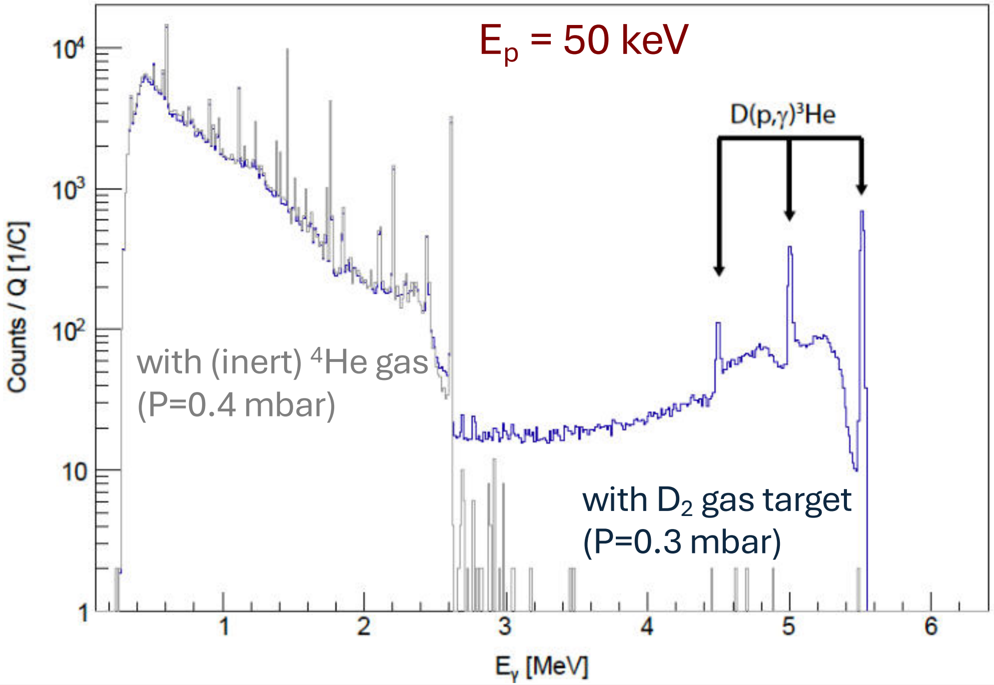
Primordial Deuterium Abundance: The d(p,γ)^{3}He Reaction

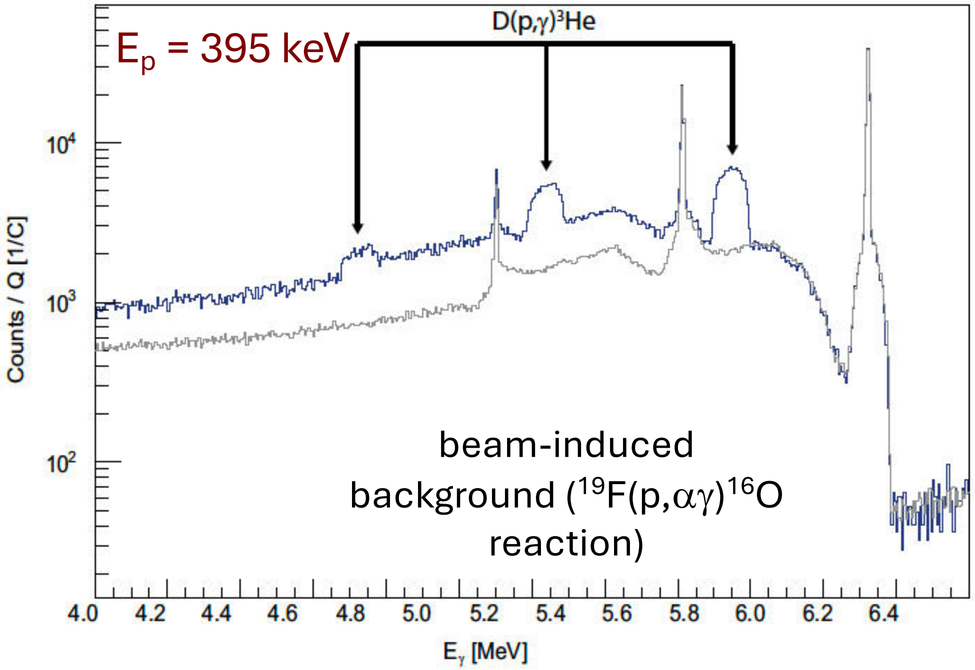
The d(p,γ)^{3}He reaction at LUNA

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

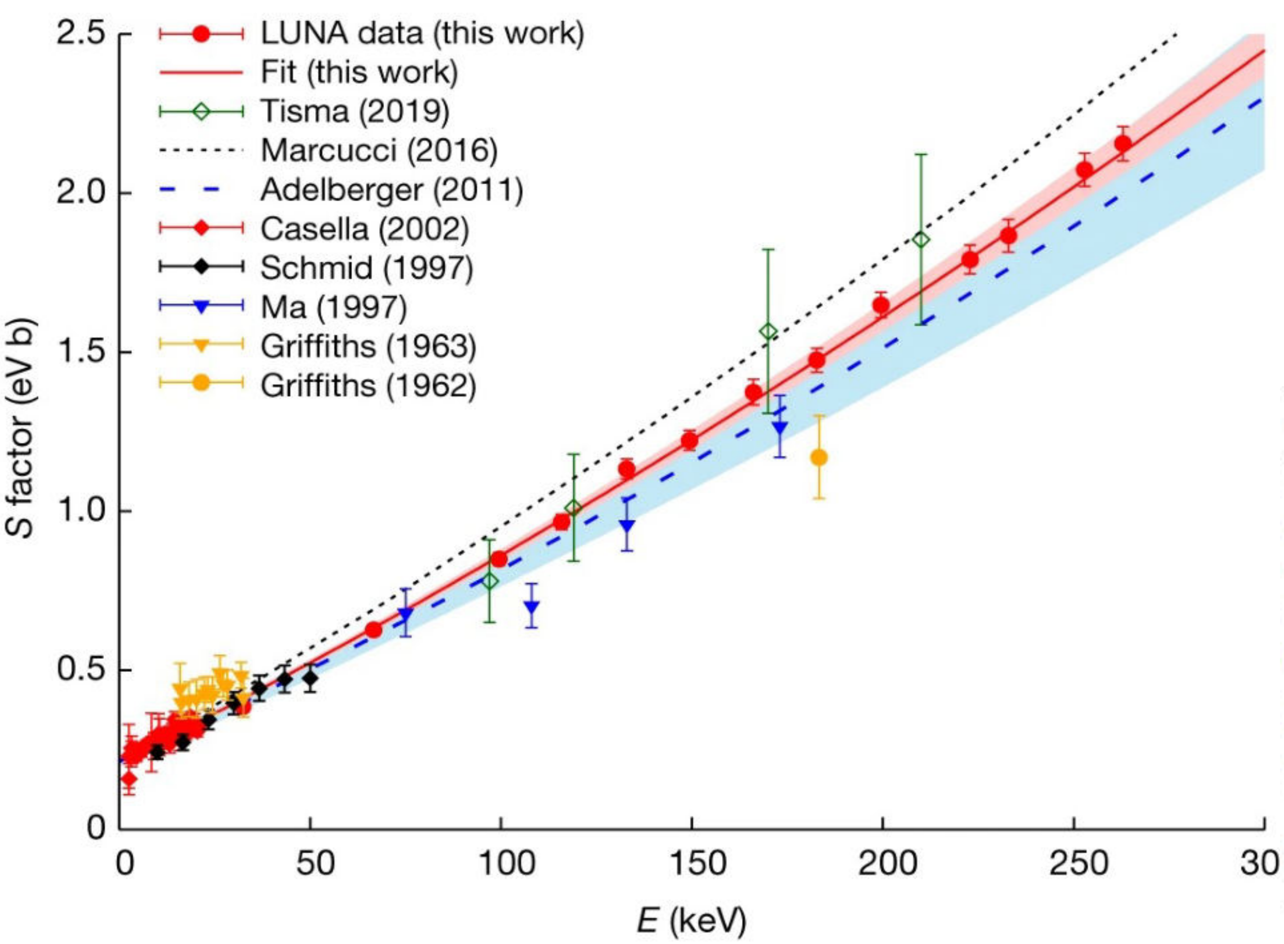






M. Aliotta

The d(p,γ)^{3}He reaction at LUNA

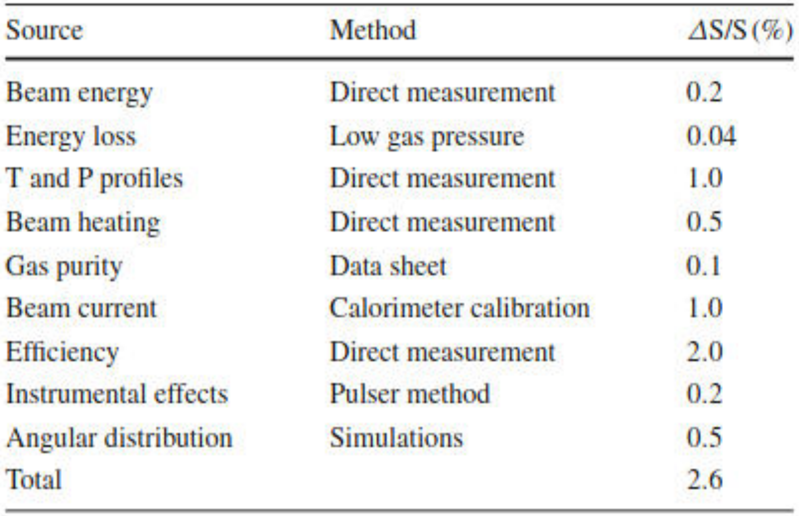


Mossa et al. Nature, 587 (2020) 210

faster destruction of deuterium

better agreement with observations

Mossa et al. EPJA, 56 (2020) 144



Source	Method	ΔS/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

The d(p,γ)^{3}He reaction at LUNA

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

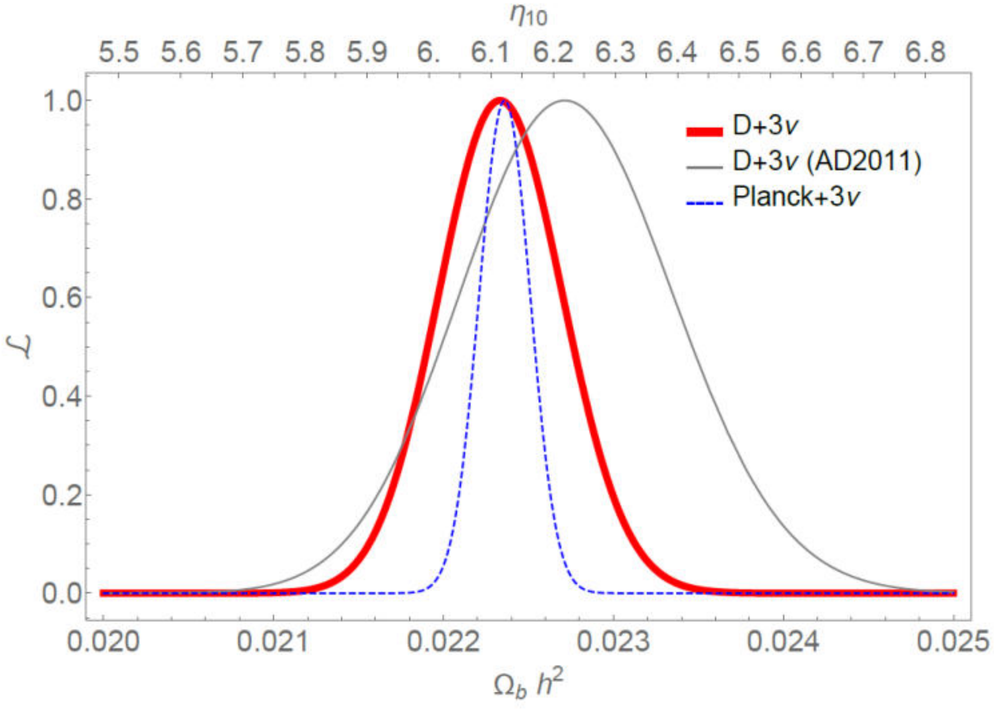
✉ -Show fewer authors

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

standard cosmological model seems safe for now...

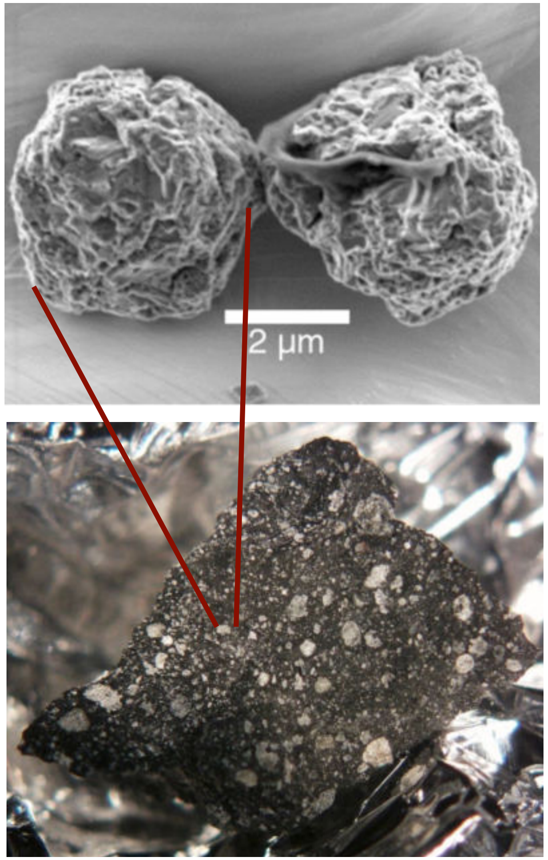
baryon density ($\Omega_b h^2$) now in excellent agreement with Planck and with comparable uncertainty

analysis by
Gianpiero Mangano and Ofelia Pisanti (Uni Naples)

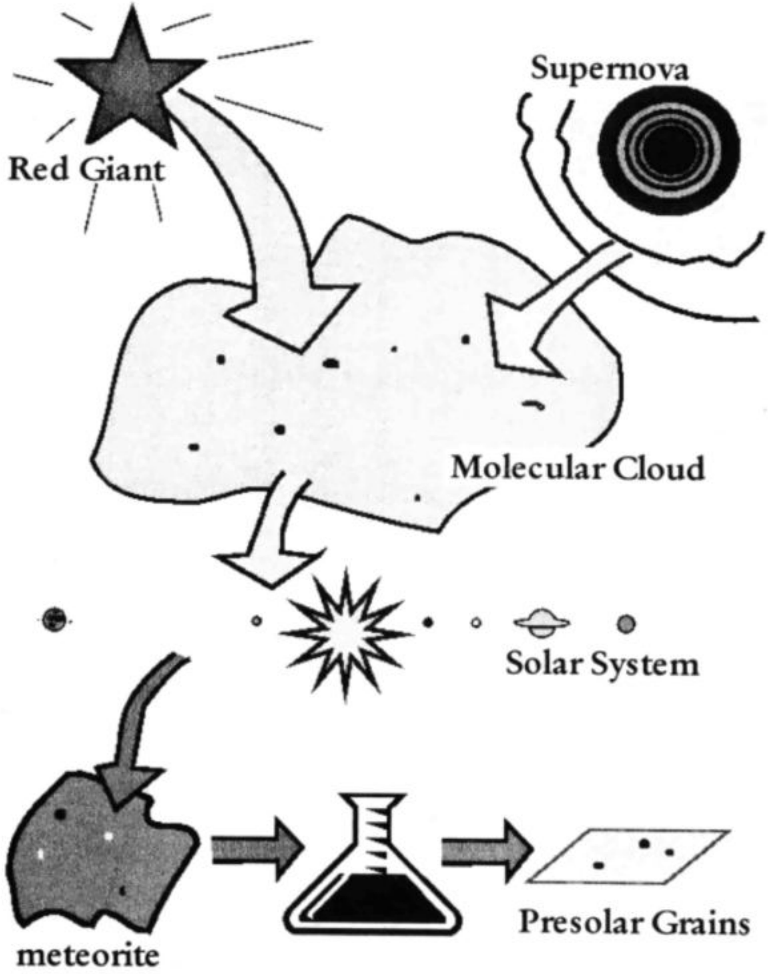


Pre-Solar Grains Composition:
the $^{17}O(p,\alpha)^{14}N$ reaction

Pre-solar grains:
stellar dust trapped in meteorites



Murchison meteorite
geosci.uchicago.edu



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

the puzzling origin of Oxygen-rich pre-solar grains

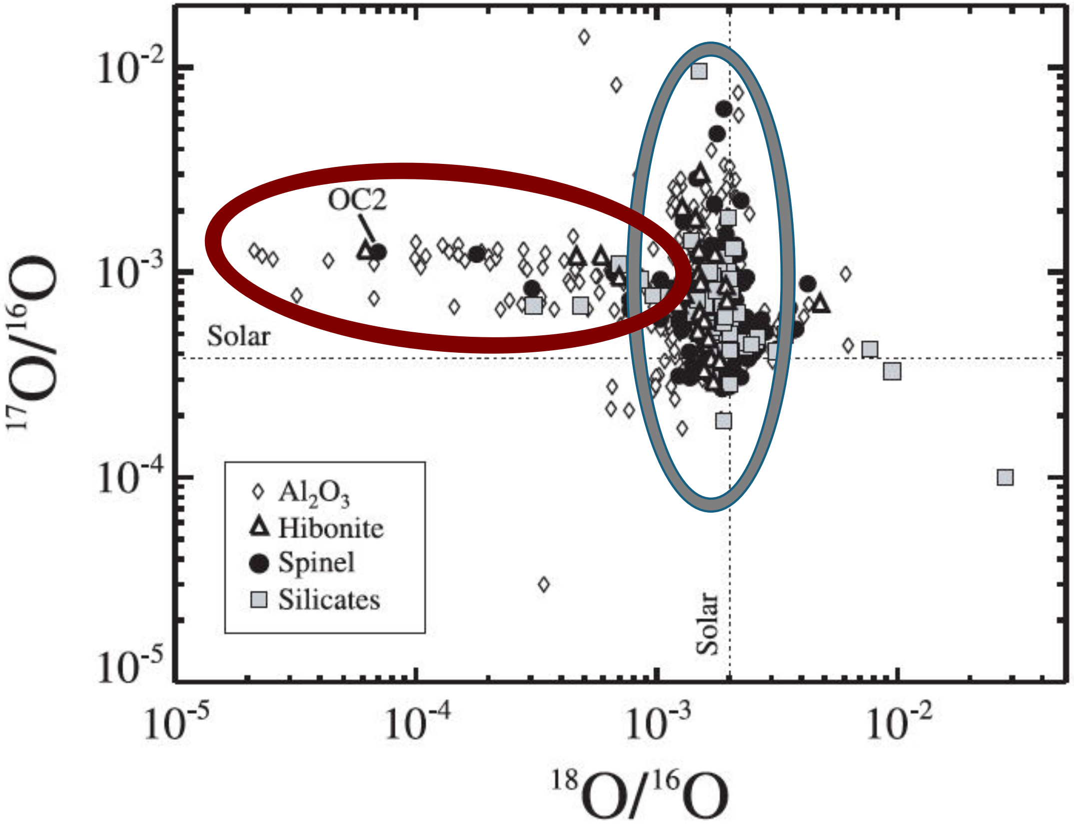
- **Group I** (about 75%): show excess in ^{17}O compared to solar values;

  origin well-understood:

  red giant stars (1-3 $M_\odot$)

- **Group II** (about 10%): excess in ^{17}O, but strongly depleted in ^{18}O

  origin highly debated!



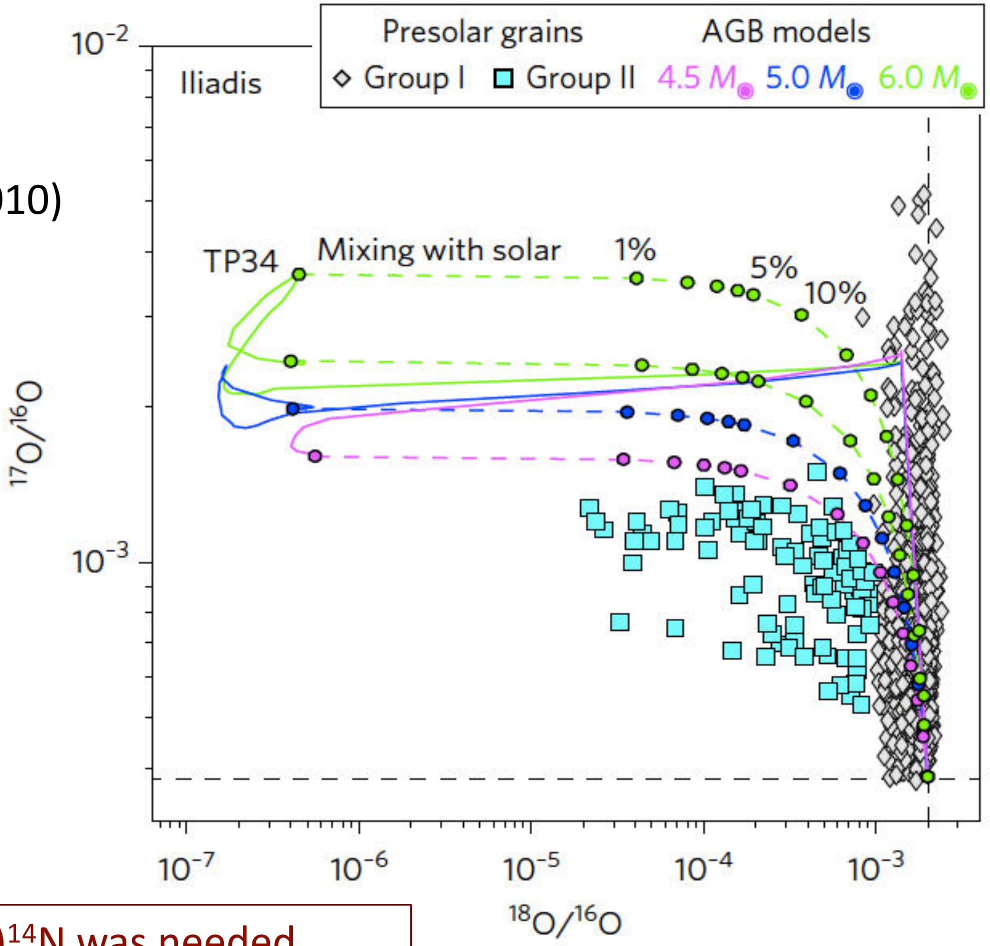
Pre-solar grains in meteorites

intermediate-mass (4-8 $M_\odot$) AGB stars

expected to produce large amounts of dust but…

H-burning temperatures too low to explain $^{17}O/^{16}O$ ratios

with available models and $^{17}O(p,\alpha)^{14}N$ reaction rate (Iliadis, 2010)

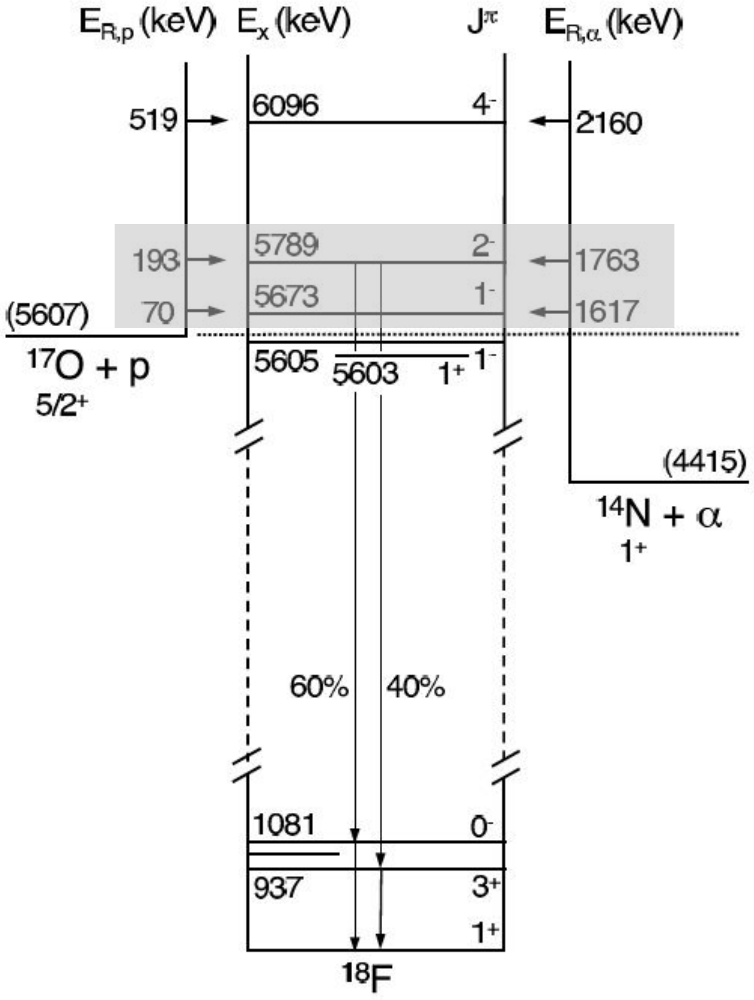


an improved study of $^{17}O(p,\alpha)^{14}N$ was needed

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

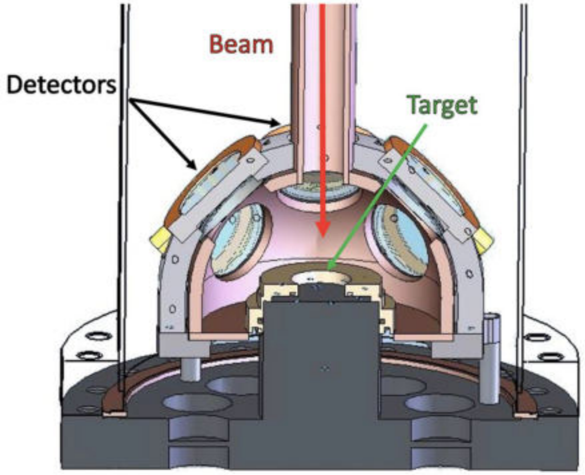
M Aliotta

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



- resonance strength of 193keV state well known
- resonance strength of 70keV state largely uncertain

MAIN GOAL: measure the strength of the E_p= 70 keV resonance



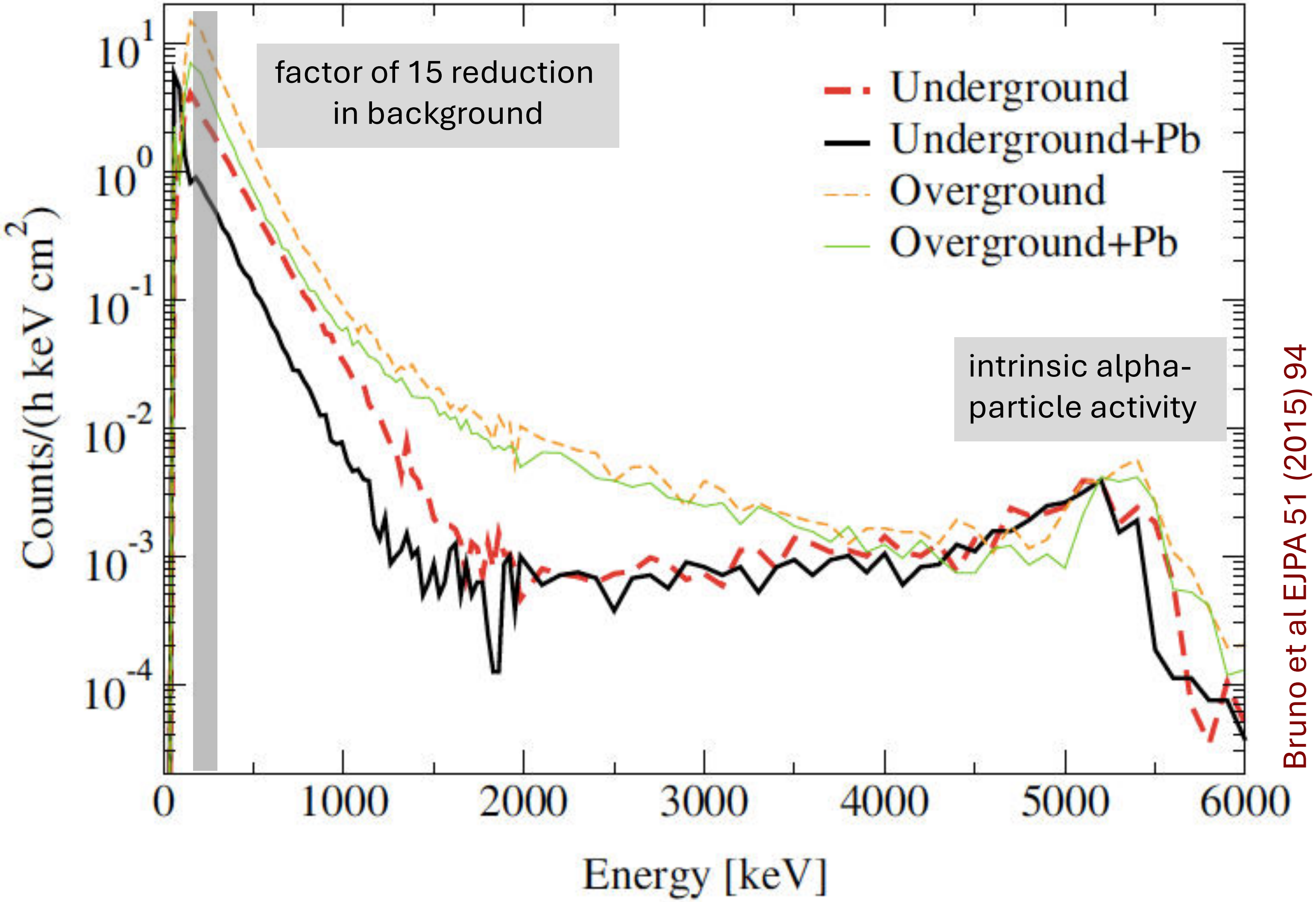
Bruno et al EJPA 51 (2015) 94

- protective aluminized Mylar foils (2.4 mm) before each detector
- expected alpha particle energy E_a ~ 200 keV (from 70 keV resonance)

Background Suppression

Edinburgh

Gran Sasso

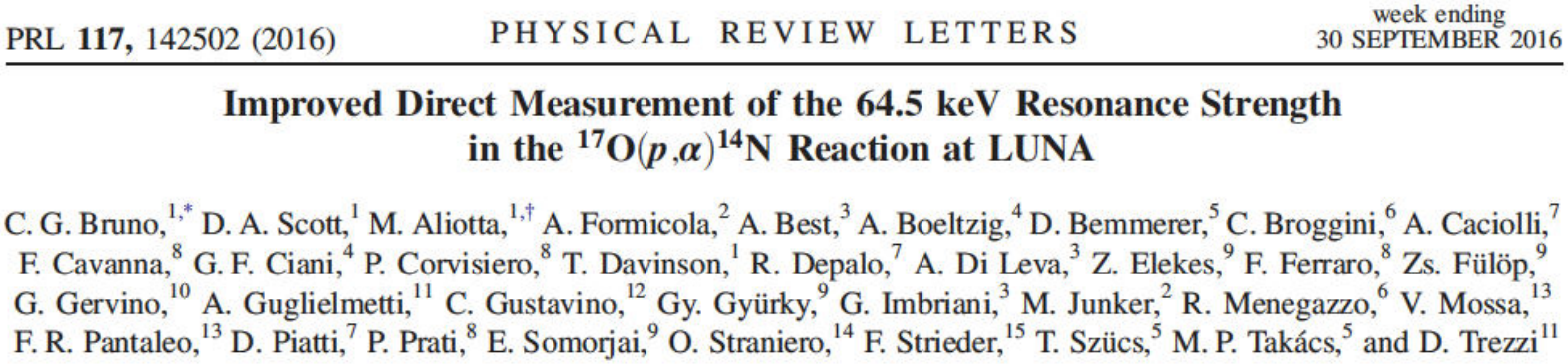


factor of 15 reduction in background

intrinsic alpha-particle activity

Bruno et al EJPA 51 (2015) 94

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

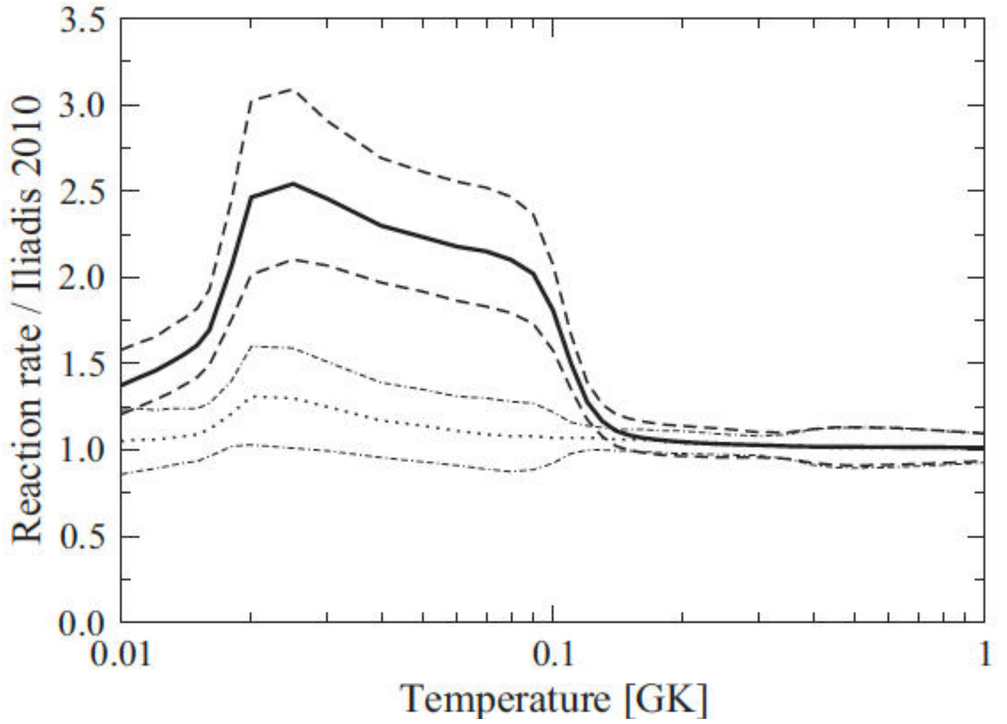


PRL **117,** 142502 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

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

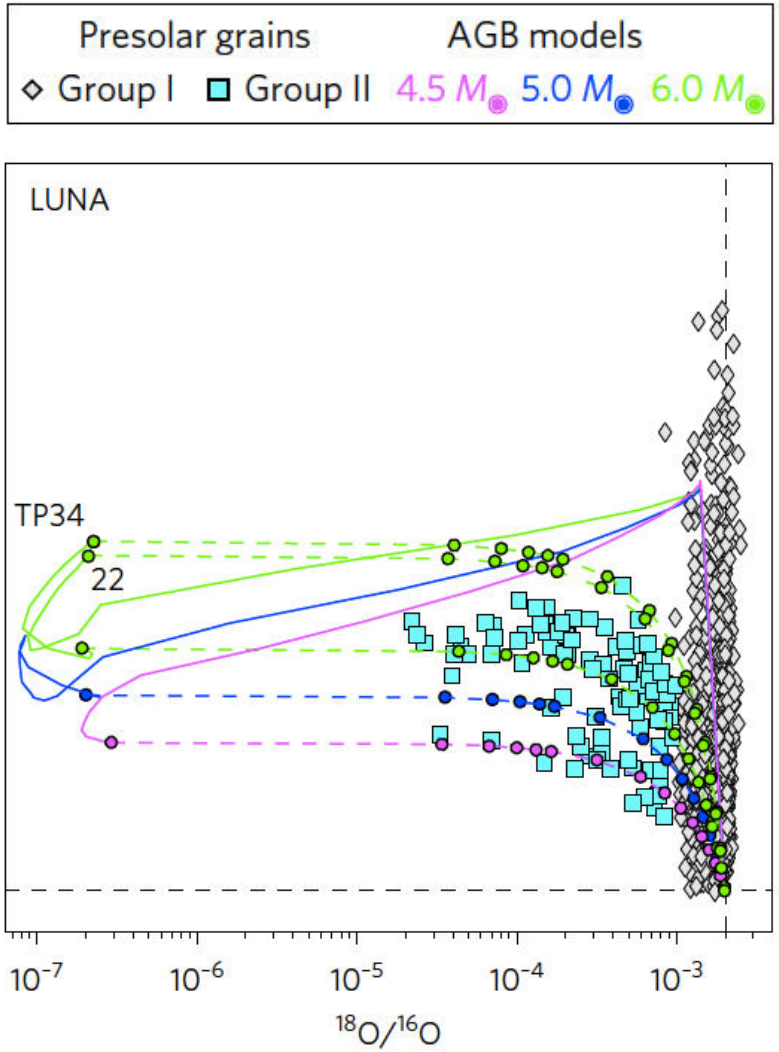
M. Lugaro[1,2*], A. I. Karakas[2–4], C. G. Bruno[5], M. Aliotta[5], L. R. Nittler[6], D. Bemmerer[7], A. Best[8],
A. Boeltzig[9], C. Broggini[10], A. Caciolli[11], F. Cavanna[12], G. F. Ciani[9], P. Corvisiero[12], T. Davinson[5], R. Depalo[11],
A. Di Leva[8], Z. Elekes[13], F. Ferraro[12], A. Formicola[14], 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

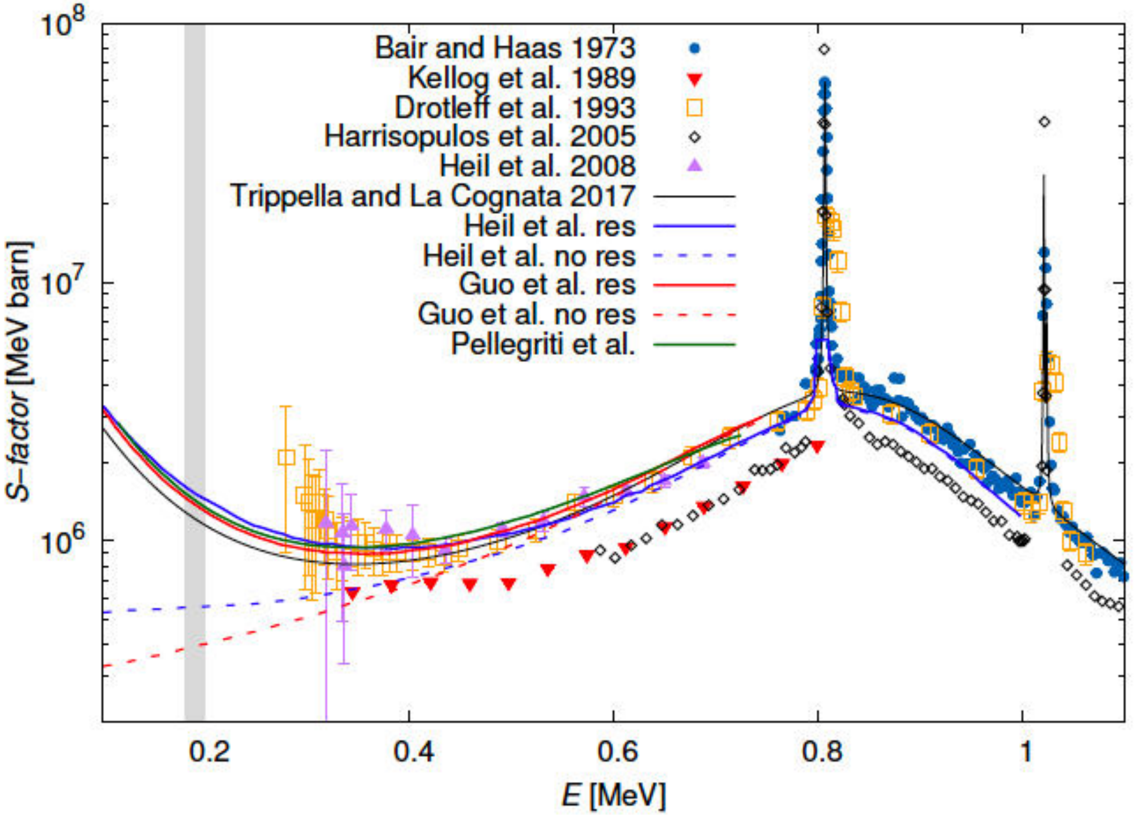
Neutron Sources for the s-process

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

importance: s-process in AGB stars

Gamow region: 130 - 250 keV

min. meas. E_{cm}: 280 keV

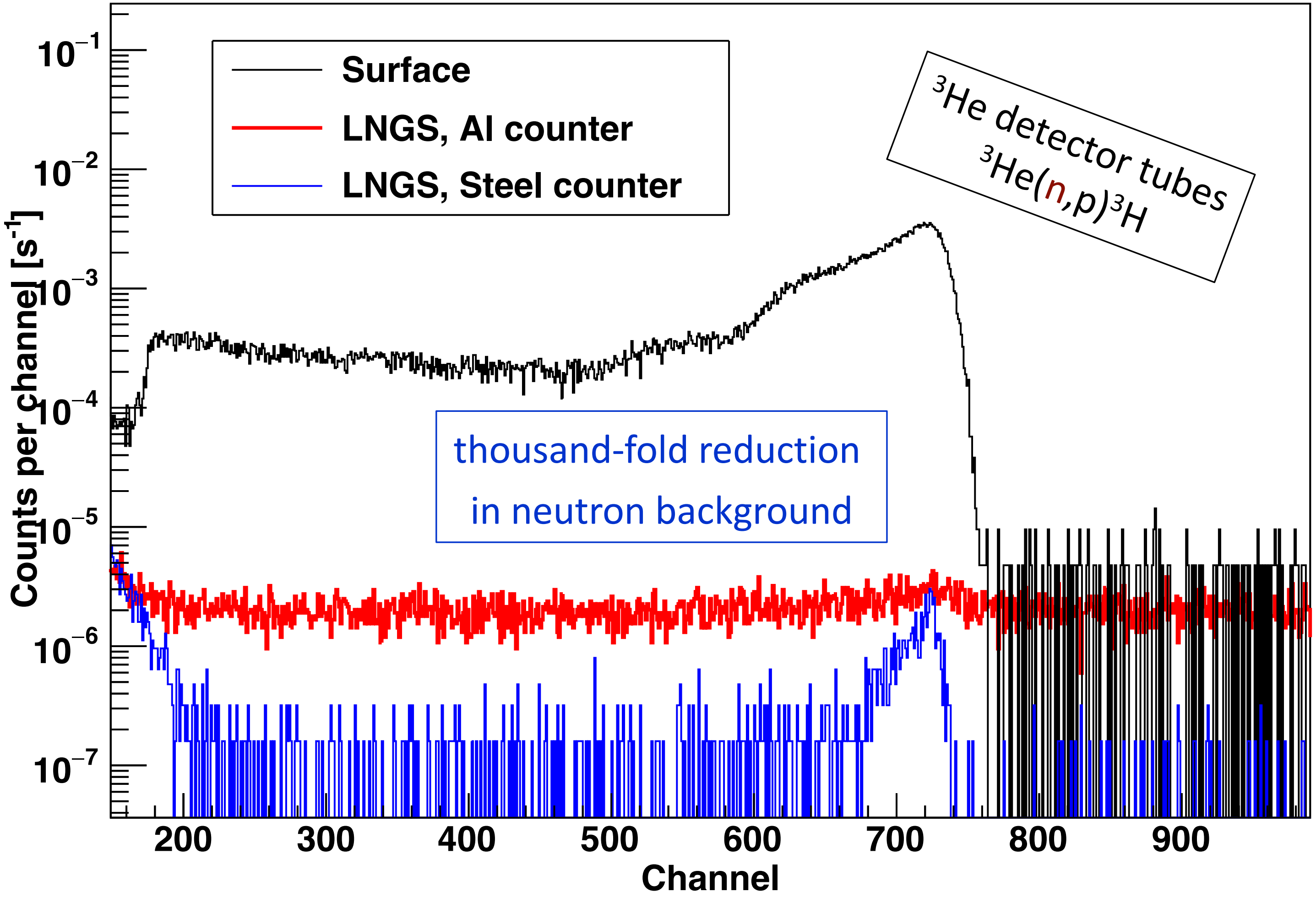


Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55

mainly hampered by cosmic background → excellent case for underground study

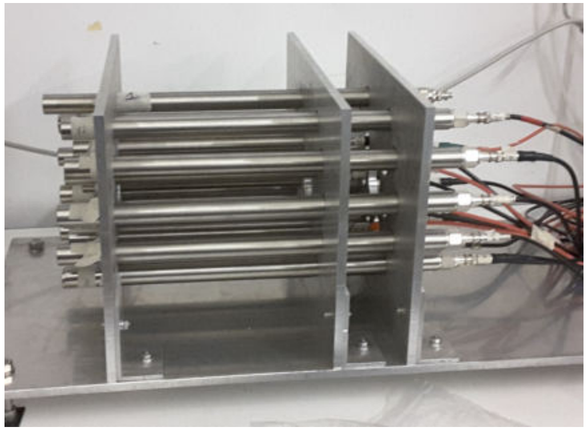
Neutron Background Reduction at LNGS

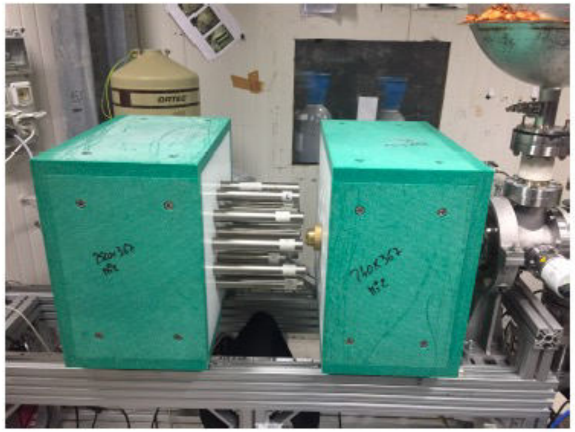
Csedreki et al. NIMA 994 (2021) 165081



^{3}He detector tubes
$^3He(n,p)^3H$

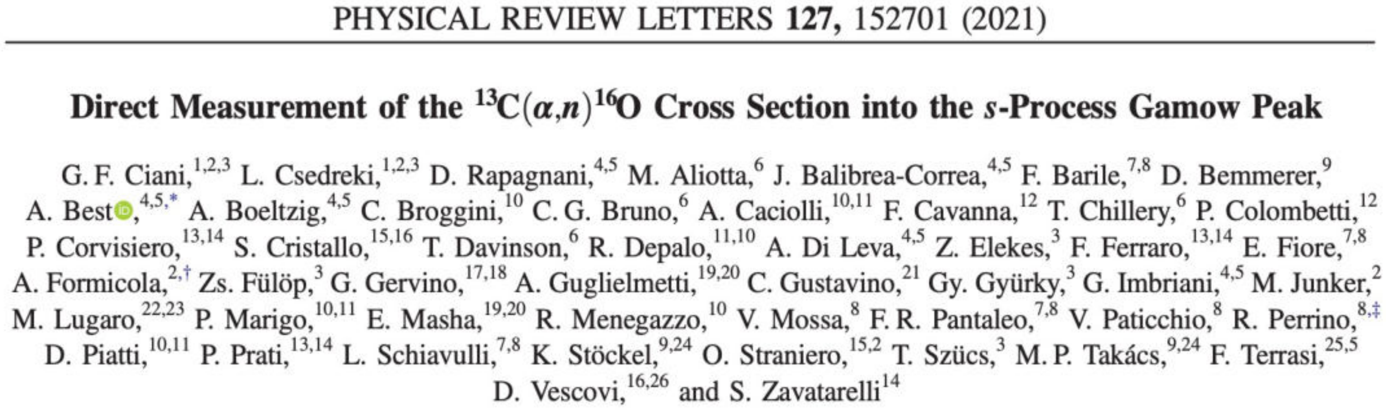
thousand-fold reduction in neutron background





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

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

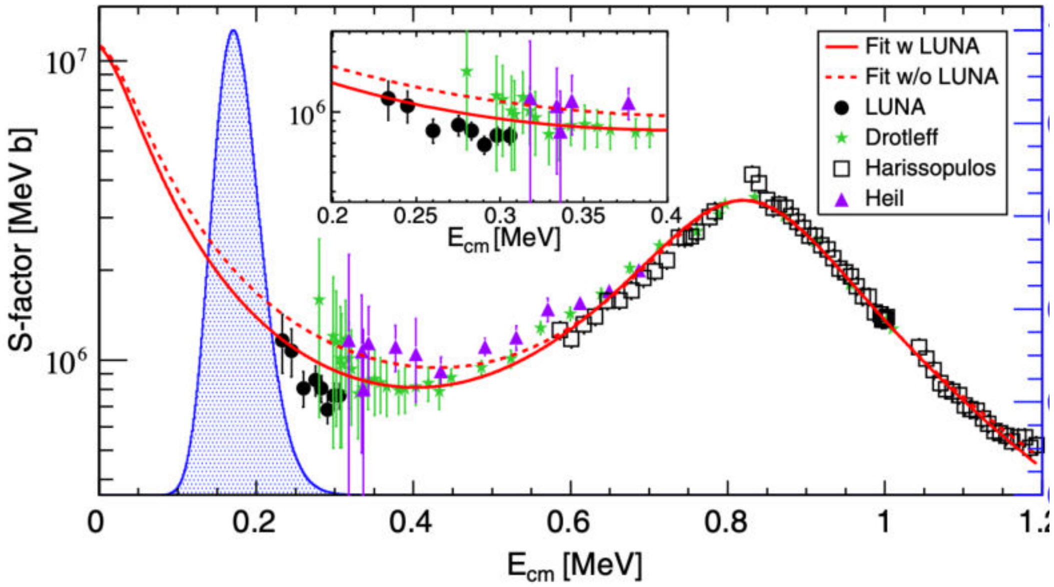


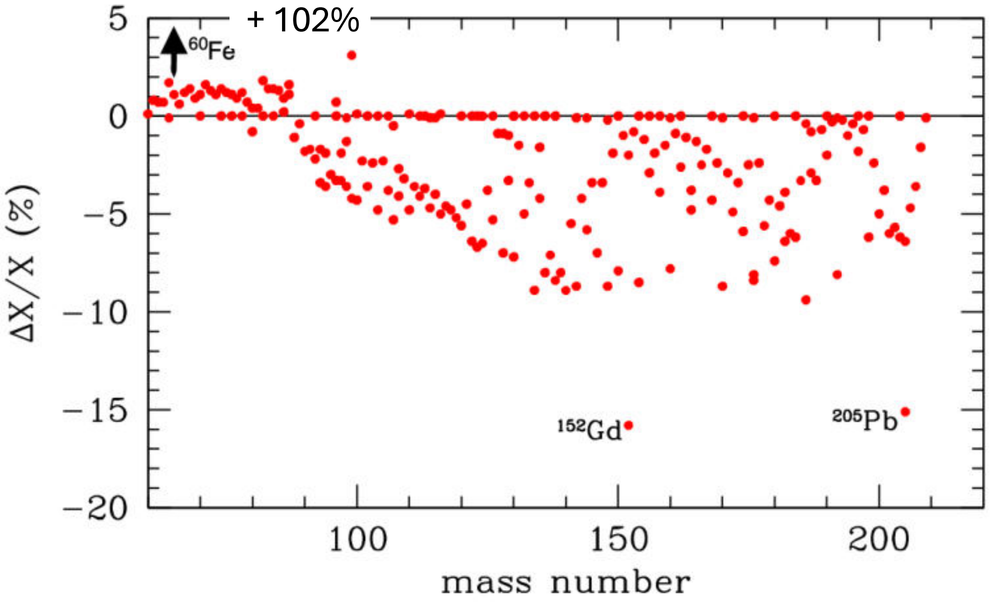
PHYSICAL REVIEW LETTERS **127,** 152701 (2021)

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]

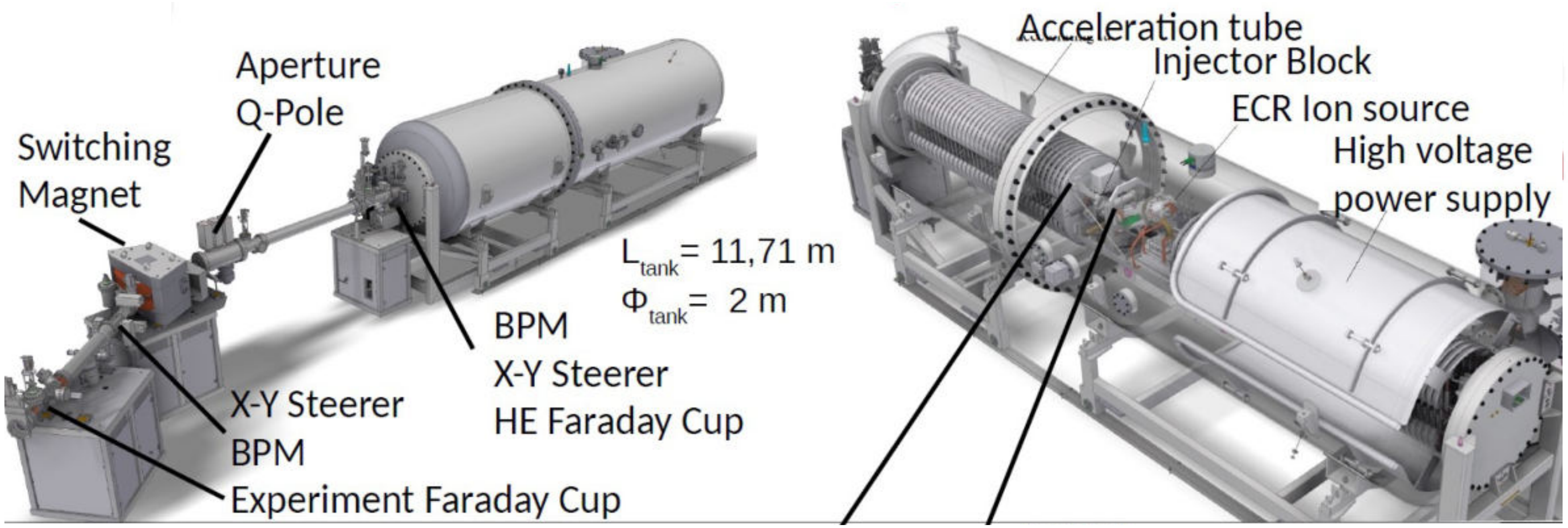
(12 months data taking)





Future Opportunities

A 3.5 MV Accelerator with ECR Ion Source



Sen et al. NIM B450 (2019) 390

H

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

He

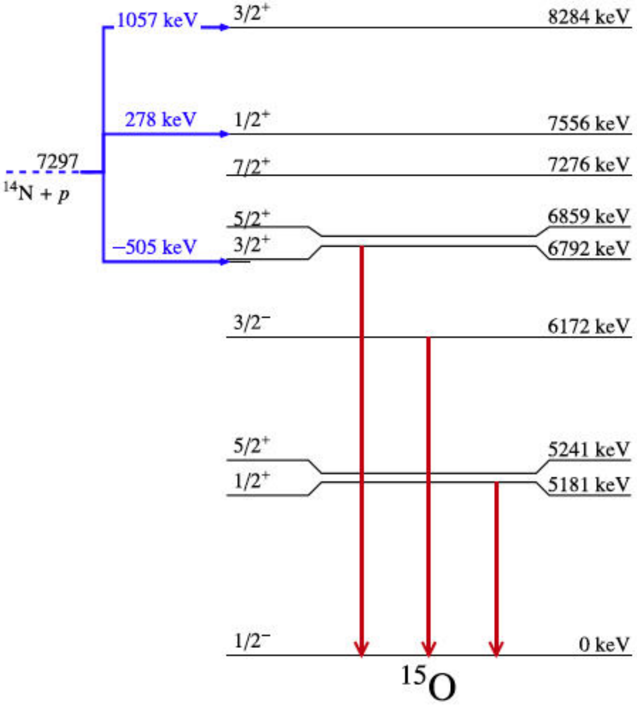
$^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 μA
$^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 μA

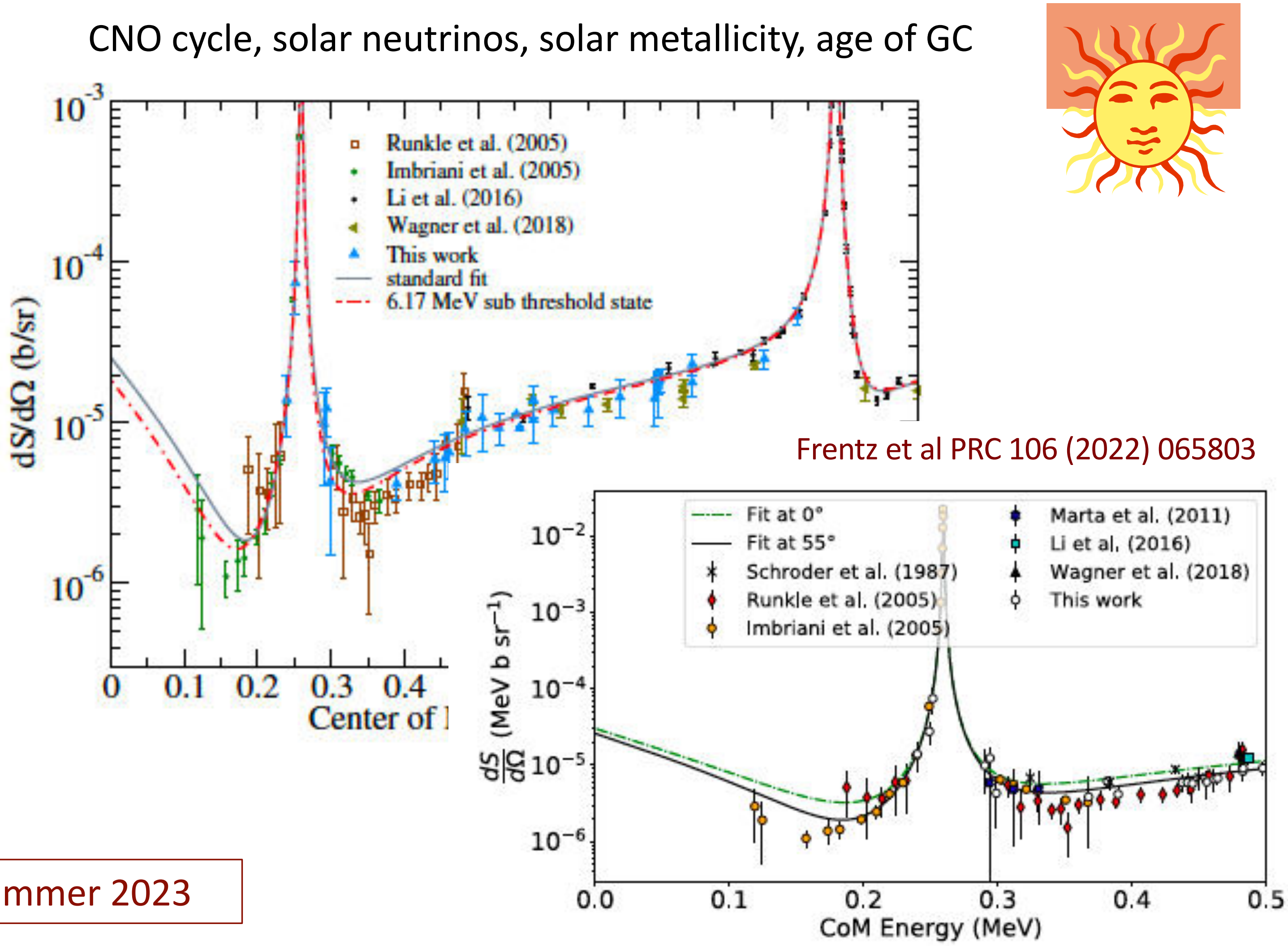
C

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

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

$^{14}N(p,\gamma)^{15}O$ importance: CNO cycle, solar neutrinos, solar metallicity, age of GC





Frentz et al PRC 106 (2022) 065803

data taking started in summer 2023

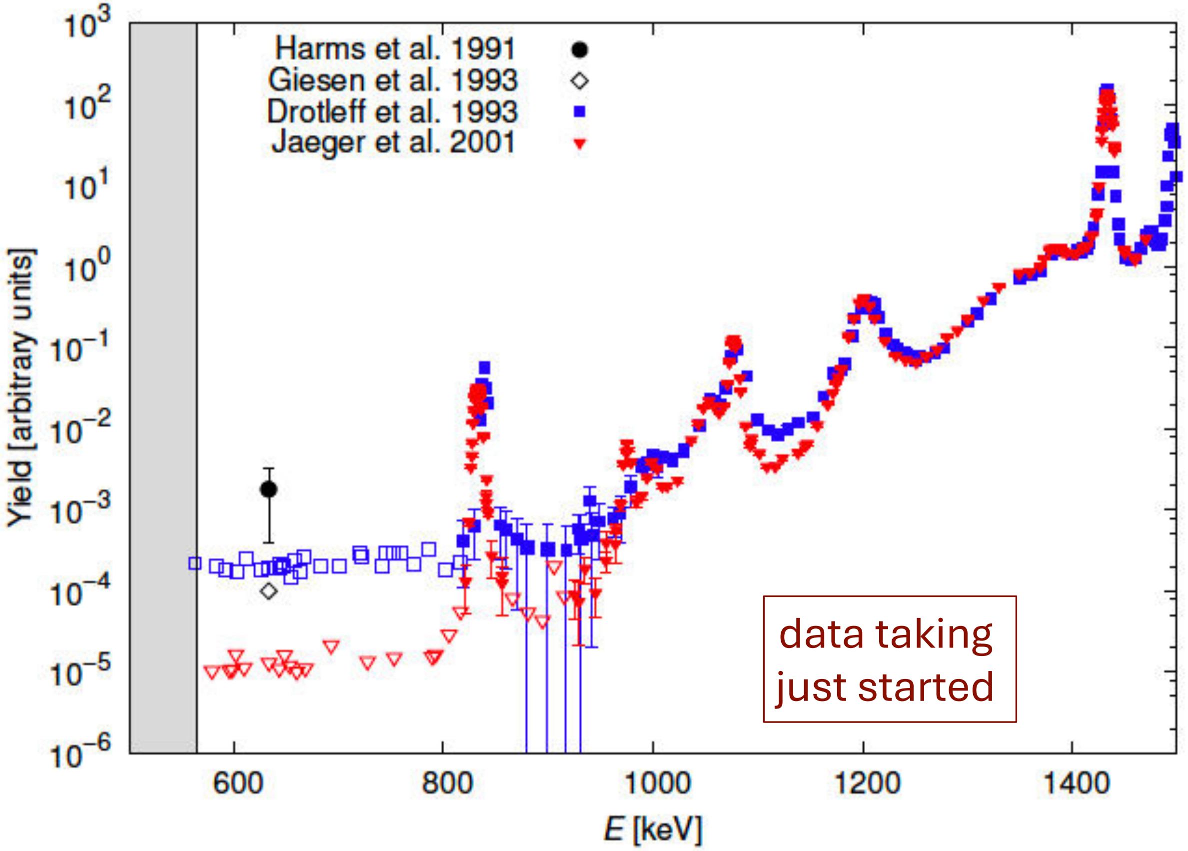
Neutron Sources for the s-process

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

importance: weak s-process component

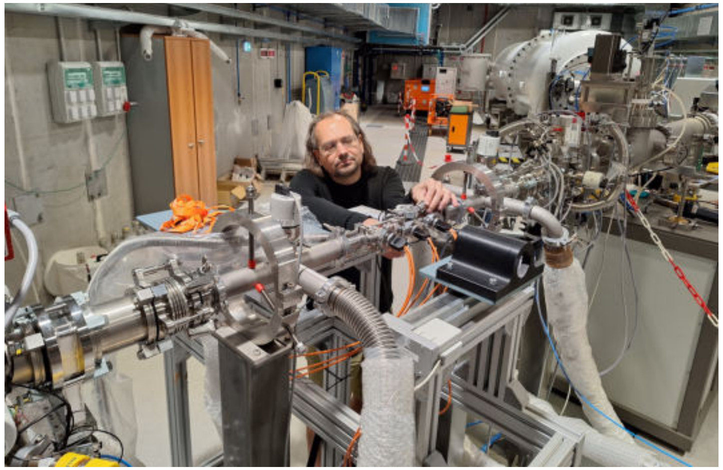
Gamow region: 360-690 keV

min. measured E: 700 keV



data taking just started

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



European Research Council
Established by the European Commission

SHADES
Andreas Best (Naples)

M. Aliotta

The ^{12}C+^{12}C fusion reactions: Current status

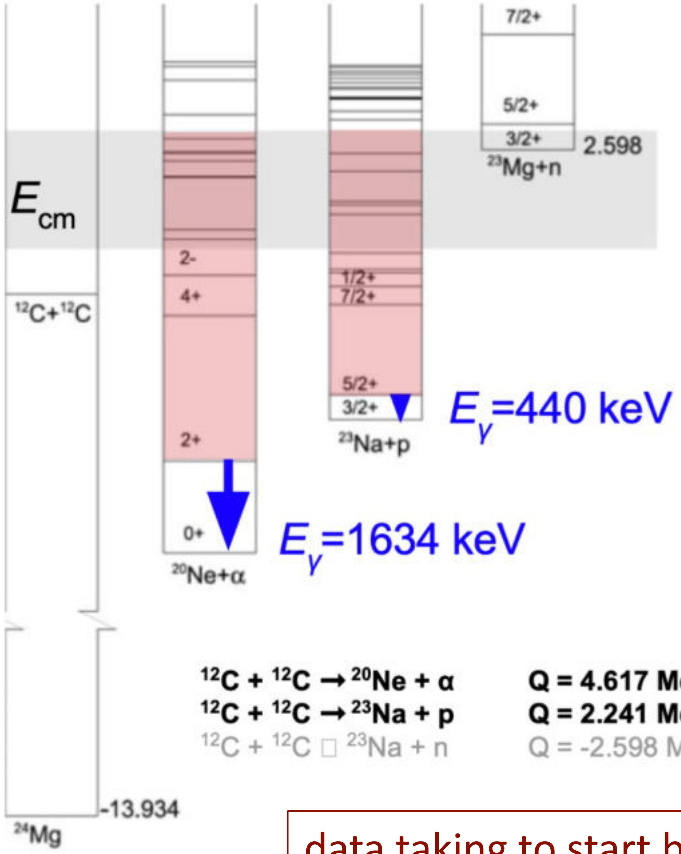
^{12}C+^{12}C

importance: evolution of massive stars

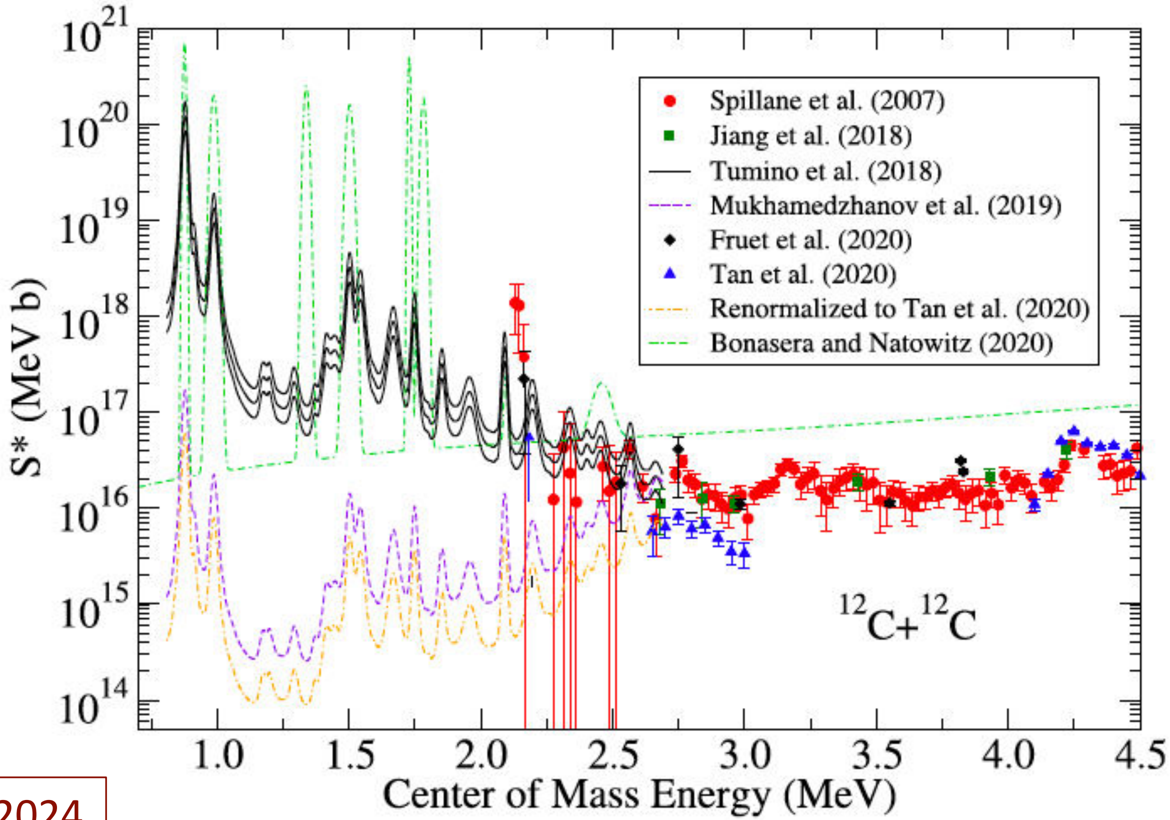
Gamow region: 1 – 3 MeV

min. measured E: 2.1 MeV (by g-ray spectroscopy)


Crab Nebula SN 1054



^{12}C + ^{12}C → ^{20}Ne + α **Q = 4.617 MeV**
^{12}C + ^{12}C → ^{23}Na + p **Q = 2.241 MeV**
^{12}C + ^{12}C □ ^{23}Na + n Q = -2.598 MeV



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

data taking to start by spring 2024

To conclude…

Nuclear Astrophysics: A Truly Interdisciplinary Effort

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

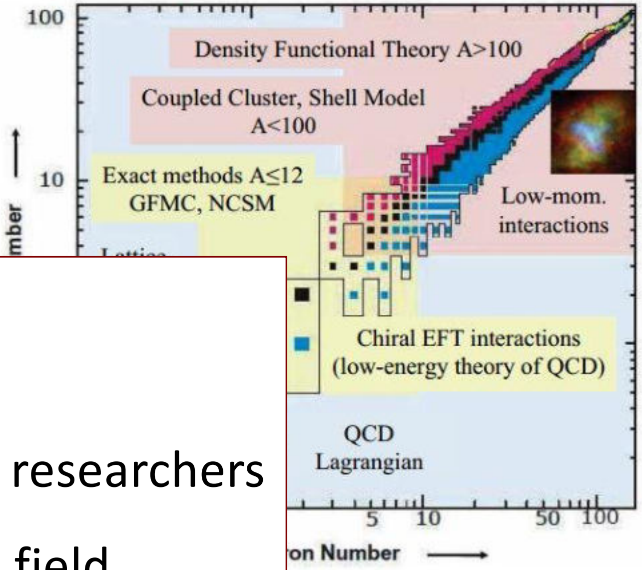
Atomic Physics

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

Ingredients from Future Breakthroughs

experiments

theory



the human factor

training and retention of young researchers

the future leaders in the field

AZURE2 R-Matrix Summer School

23rd - 28th of June 2024
University of Edinburgh
King's Buildings

James deBoer
University of Notre Dame, US

Carl Brune
Ohio University, US

Register here: https://indico.ph.ed.ac.uk/event/274/

Organising Committee:

Marialuisa Aliotta	(University of Edinburgh)
Carl Brune	(Ohio University)
Richard James deBoer	(University of Notre Dame)
Gianluca Imbriani	(University of Naples)
Ragandeep Singh Sidhu	(University of Edinburgh)
Michael Wiescher	(University of Notre Dame)

IReNA
The University of Edinburgh
EMMI
NuPECC
EURO-LABS
ChETEC INFRA
Science & Technology Facilities Council
IOP Institute of Physics


THANK YOU