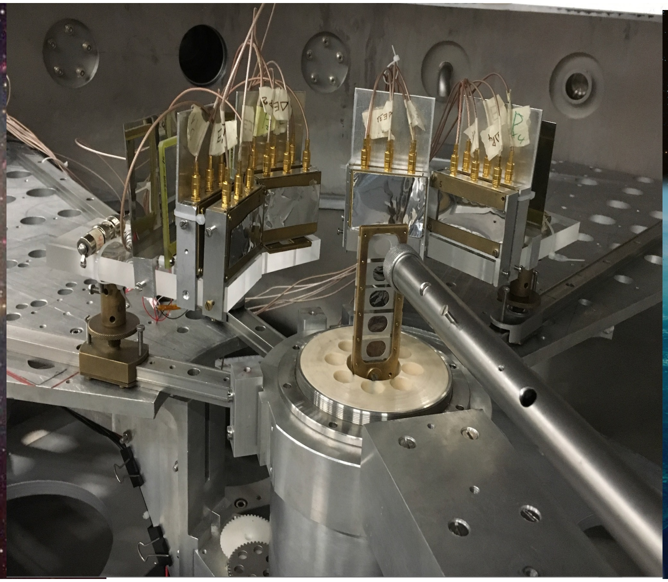
32ND NATIONAL NUCLEAR PHYSICS SUMMER SCHOOL
(NNPSS 2021)

Nuclear Astrophysics: a nuclear introduction



Aurora Tumino

Istituto Nazionale di Fisica Nucleare

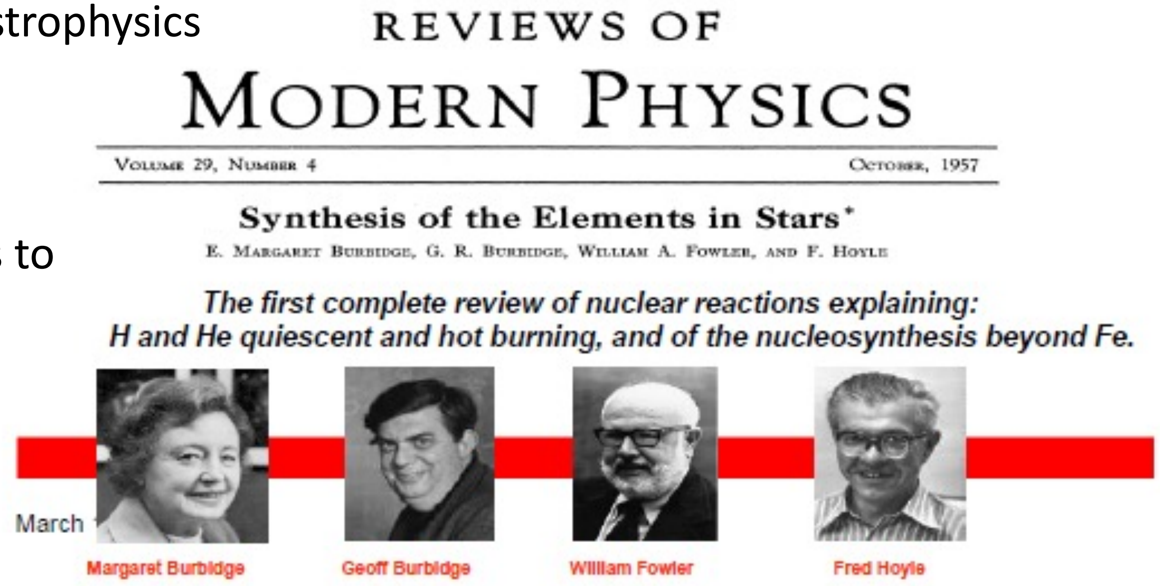
Outline of my talk

- Nuclear physics in the abundance curve
- Features of thermonuclear reactions
- Experimental approaches
- Physics cases

Nuclear Astrophysics → Rich & Diverse Interdisciplinary Field bringing together

- Modelers
- Observers
- Nuclear physicists: Experimentalists as well as Theorists

... from the seminal **B²FH** review paper of 1957,
the basis of the modern nuclear astrophysics



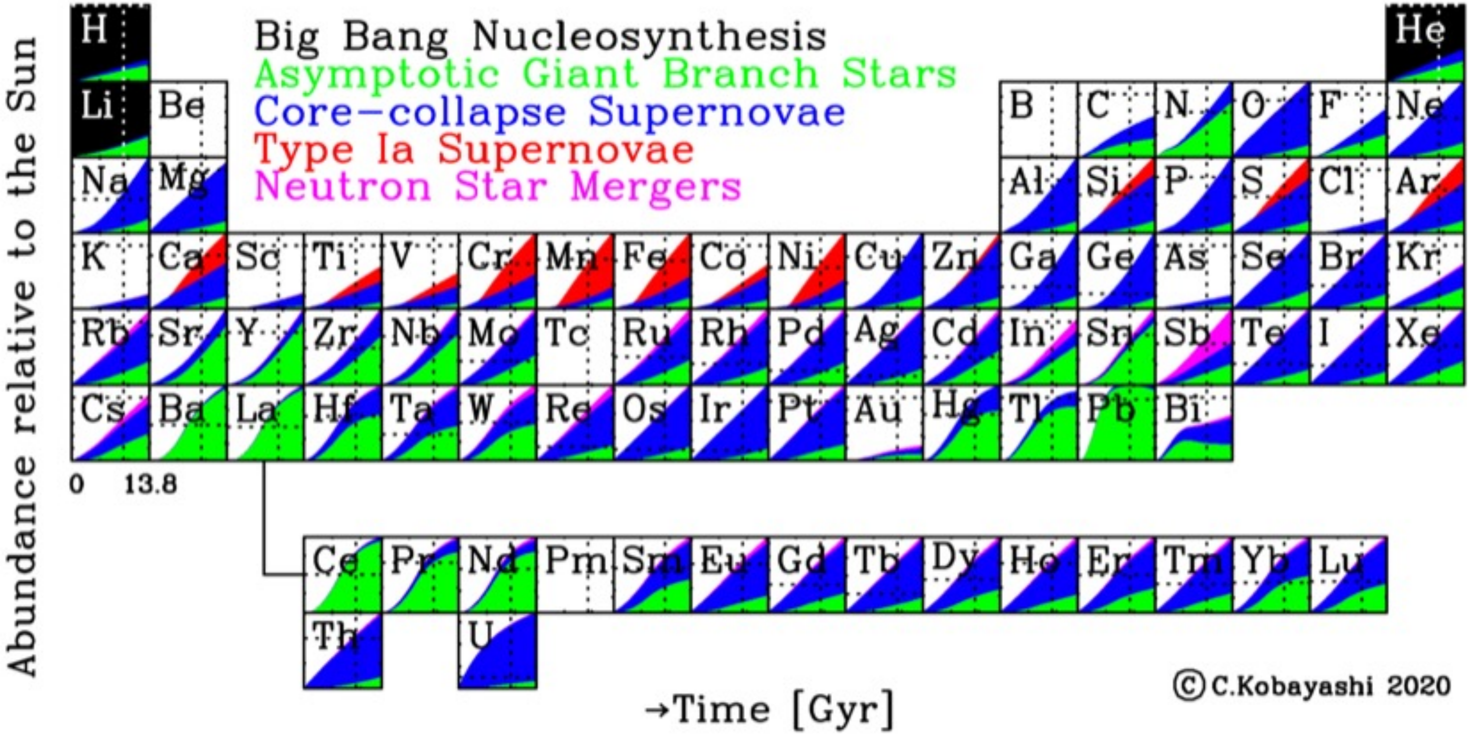
this work has been considered as the greatest gift of astrophysics to modern civilization

Nuclear reactions responsible for both ENERGY PRODUCTION and CREATION OF ELEMENTS in 4 ways/environments:

- Cosmological nucleosynthesis: creation in the Big Bang
- Stellar nucleosynthesis: synthesis of elements by fusion in stars
- Explosive nucleosynthesis: synthesis of elements by neutron and proton capture reactions in supernovae
- Galactic nucleosynthesis: synthesis of elements by cosmic ray spallation reactions

Where the elements are made...we WISH we knew that!
Here is the "current belief" in terms of nucleosynthetic source of elements in the Solar System

Each element in this periodic table is color-coded by the relative contribution of nucleosynthesis sources



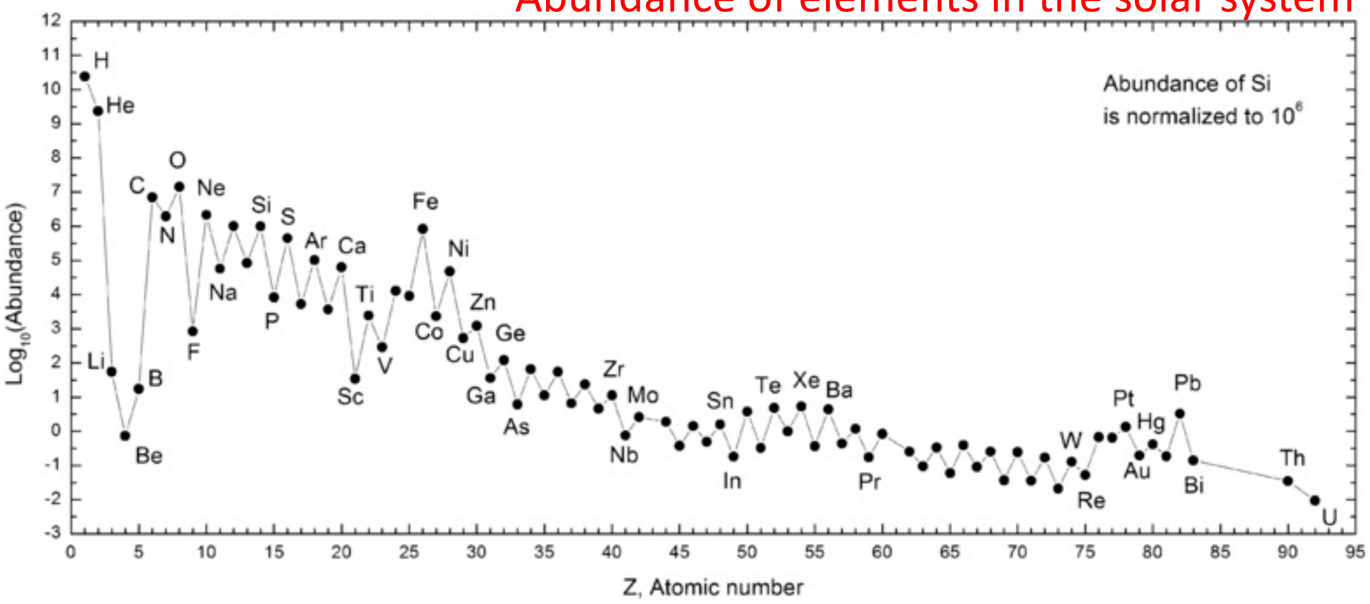
In astronomy, a "metal" is any element other than hydrogen or helium, the only elements that were produced in significant quantities in the Big Bang. Thus, the metallicity of a galaxy or other object is an indication of stellar activity after the Big Bang.

Where's the Nuclear Physics?

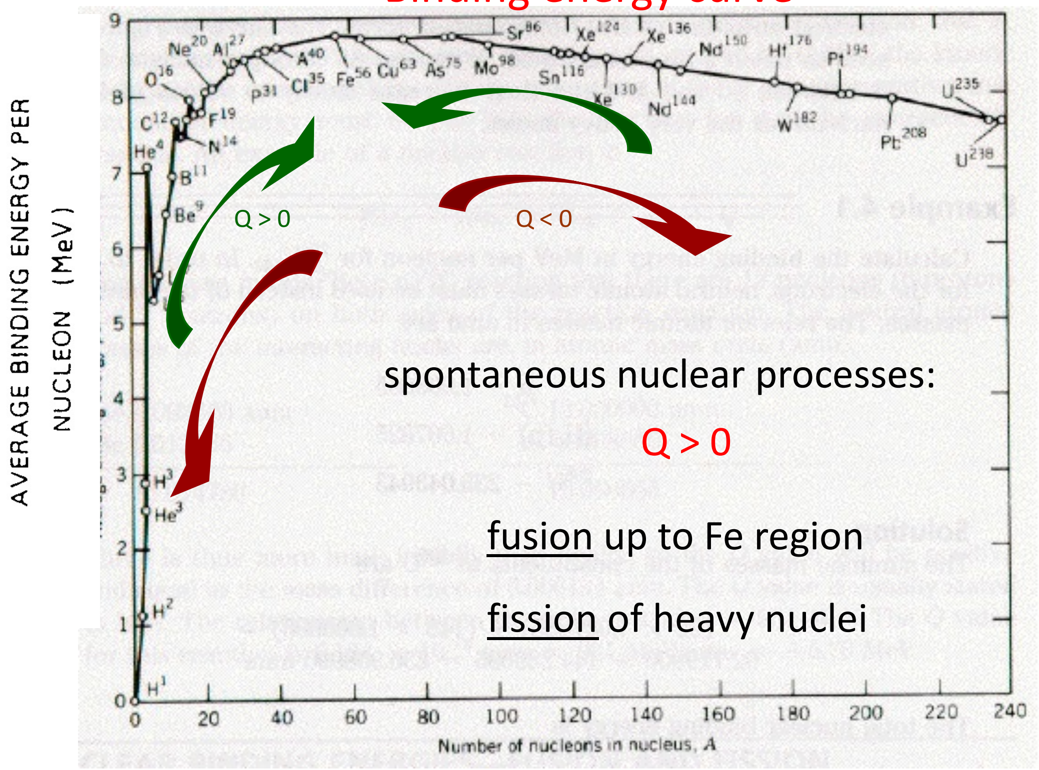
H burning → conversion of H to He
He burning → conversion of He to C, O …
C, O and Ne burning → production of A: 16 to 28
Si burning → production of A: 28 to 60
s-, r- and p-processes → production of A>60
Li,Be, and B from cosmic rays

- Big Bang Nucleosynthesis does not go beyond Li due to missing stable nuclei of mass number 5 or 8
- Odd-even staggering of abundances (Oddo-Harkins rule)
- Larger alpha-nuclei abundance, particularly those connected to particular values of Z and N (so called magic numbers,2,8,20,28,50 …) which are significant with regard to the structure of nuclei … at least up to Fe
- Broad peak around Fe

Abundance of elements in the solar system



Binding energy curve



for a nuclear reaction $\boxed{1+2 \rightarrow 3+4}$

Total reaction rate: $R_{12} = (1+\delta_{12})^{-1} N_1 N_2 \langle\sigma v\rangle_{12}$ reactions $cm^{-3}\, s^{-1}$, N_i number density

Energy production rate: $\varepsilon_{12} = R_{12}\, Q_{12}$ reaction Q-value: $Q_{12}=[(m_1+m_2)-(m_3+m_4)]c^2$

Nuclear physics information

energy production as star evolves ⇐ $\boxed{\langle\sigma v\rangle = \text{KEY quantity}}$ ⇒ change in abundance of nuclei

to be determined from experiments and/or theoretical considerations

stars = cooking pots of the Universe

a) velocity distribution

interacting nuclei in plasma are in thermal equilibrium at temperature T

also assume non-degenerate and non-relativistic plasma

⇒ Maxwell-Boltzmann velocity distribution

b) cross section

no nuclear theory available to determine reaction cross section a priori

cross section depends sensitively on:

- the properties of the nuclei involved
- the reaction mechanism

in practice, need **experiments** AND **theory** to determine stellar reaction rates

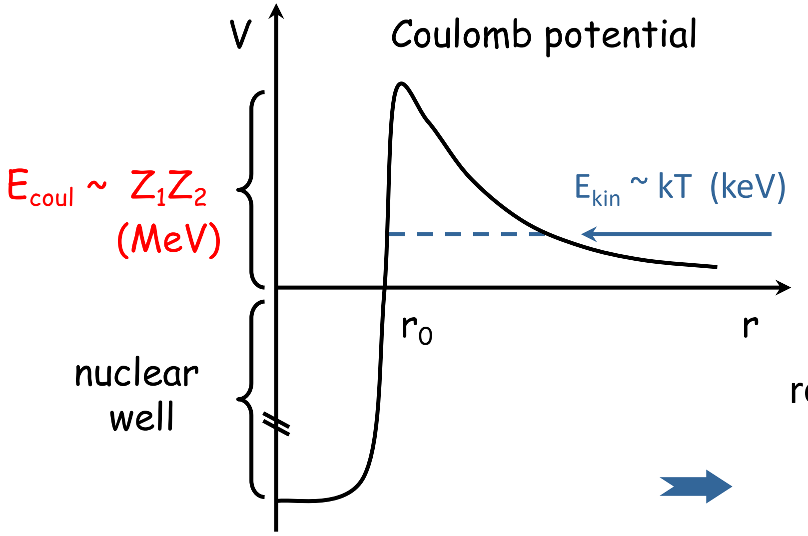
Nuclear reactions between charged particles

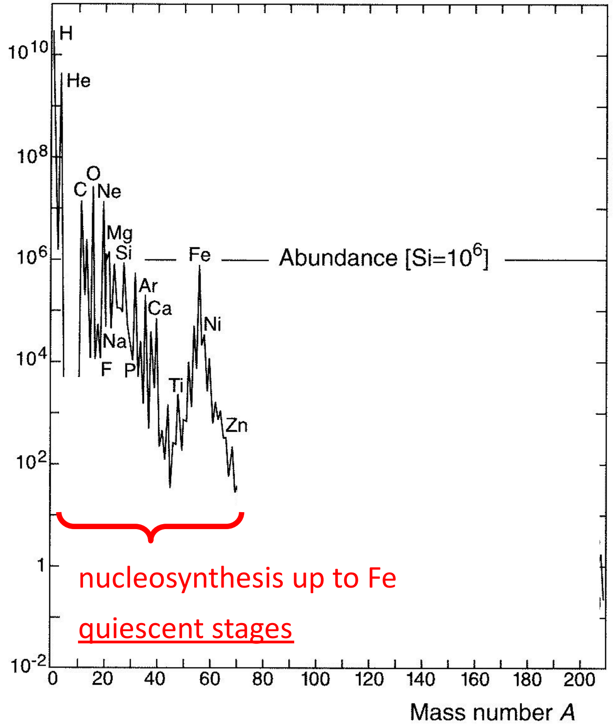
charged particles ➡ Coulomb barrier

energy available: from thermal motion

during static burning: $kT \ll E_{Coul}$

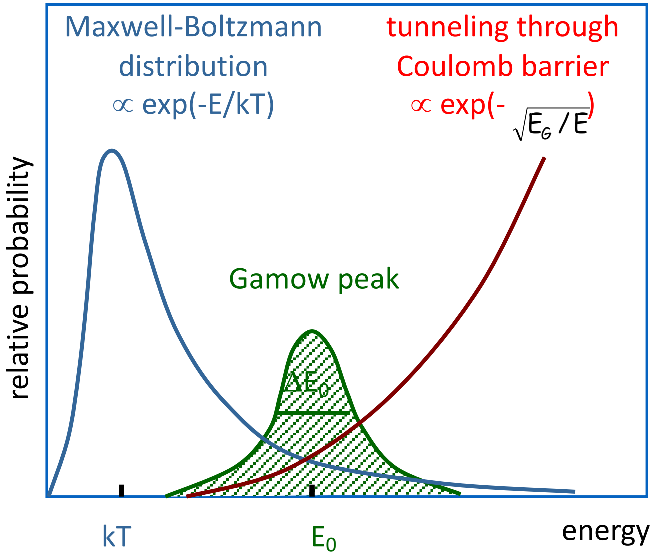
$T \sim 15 \times 10^6$ K (e.g. our Sun) $\Rightarrow kT \sim 1$ keV





reactions occur through TUNNEL EFFECT

➡ tunneling probability $\boxed{P \propto \exp(-2\pi\eta)}$



Gamow peak: most effective energy region for thermonuclear reactions

It is where measurements should be carried out

Gamow energy:

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

⇓

varies depending on reaction and/or temperature

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

reaction	Coulomb barrier (MeV)	E_0 (keV)	area under Gamow peak ~ $\langle\sigma v\rangle$
p + p	0.182	5.9	7.0×10^{-6}
$\alpha + {}^{12}C$	2.242	56	5.9×10^{-56}
${}^{16}O + {}^{16}O$	10.349	237	2.5×10^{-237}

$kT \ll E_0 \ll E_{coul}$

10^{-18} barn $< \sigma < 10^{-9}$ barn major experimental challenges

⇓

STRONG sensitivity to Coulomb barrier ⇒ separate stages: H-burning

He-burning

C/O-burning …

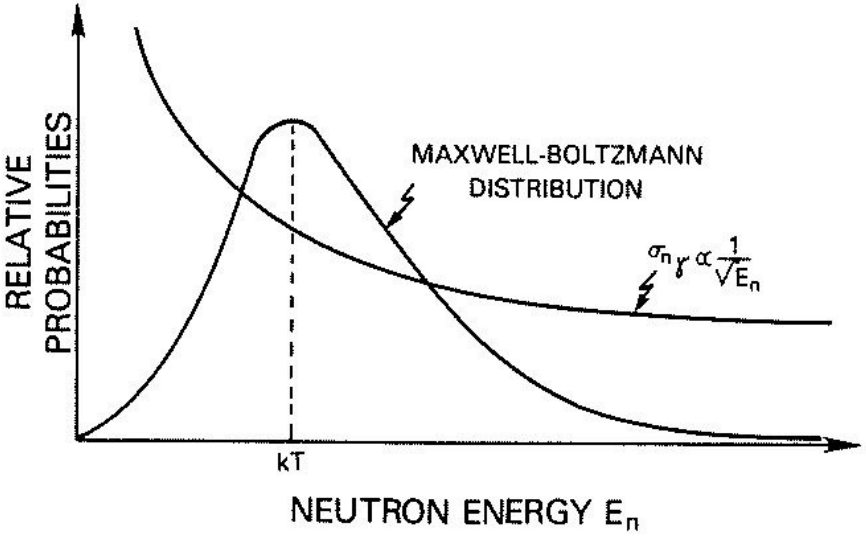
neutron captures

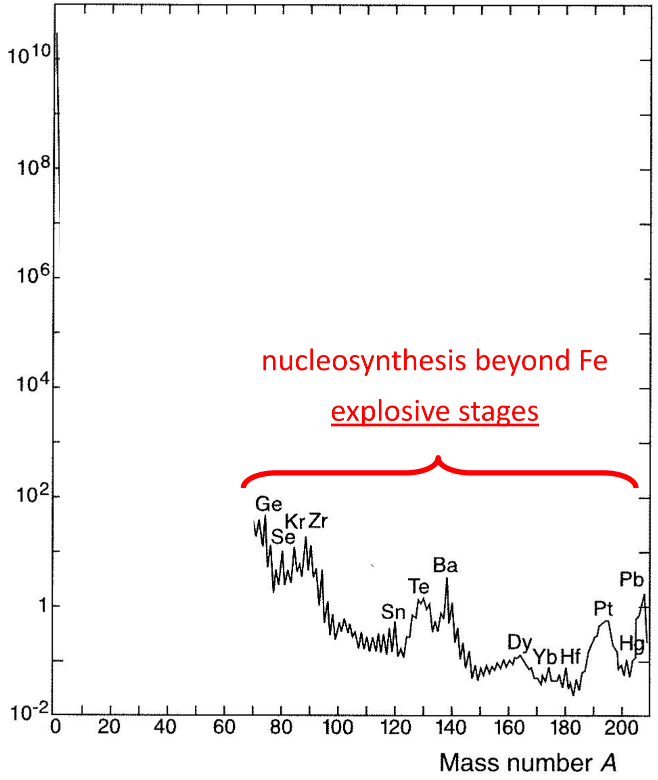
NO Coulomb barrier

neutrons produced in stars are quickly thermalised

$E_0 \sim kT$ = relevant energy (e.g. $T \sim 1\text{-}6\times10^8$ K $\Rightarrow$ $E_0 \sim 30$ keV)

Typically
s-wave neutrons: $\sigma \sim \frac{1}{v}$ → $\langle\sigma v\rangle \sim \text{const} = \langle\sigma_T v_T\rangle$ → accounts for almost flat abundance distribution beyond iron peak





neutron-capture cross sections can be measured directly at the relevant energies

Features - General Overview

Quiescent burning stages

$T \sim 10^6 - 10^8$ K $\Rightarrow$ $E_0 \sim 10$ keV – 1 MeV $\ll$ E_{coul}

$\Rightarrow$ 10^{-18} barn $< \sigma < 10^{-9}$ barn

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

unstable species DO NOT play significant role

Explosive burning stages

$T > 10^8$ K $\Rightarrow$ $E_0 \sim$ MeVs $\leq$ E_{coul}

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

$\Rightarrow$ Extrapolation may not be needed

$\Rightarrow$ average interaction time $\tau \sim \langle\sigma v\rangle^{-1} \sim$ seconds

$\Rightarrow$ unstable species DO play significant role

Main Issues

Quiescent:
- poor signal-to-noise ratio

Explosive:
- unknown nuclear properties
- low beam intensities (several o.d.m. lower than for stable beams)

Requirements

Quiescent:

Extrapolation procedure (?)
long measurements
ultra pure targets
high beam intensities
high detection efficiency
…

Explosive:

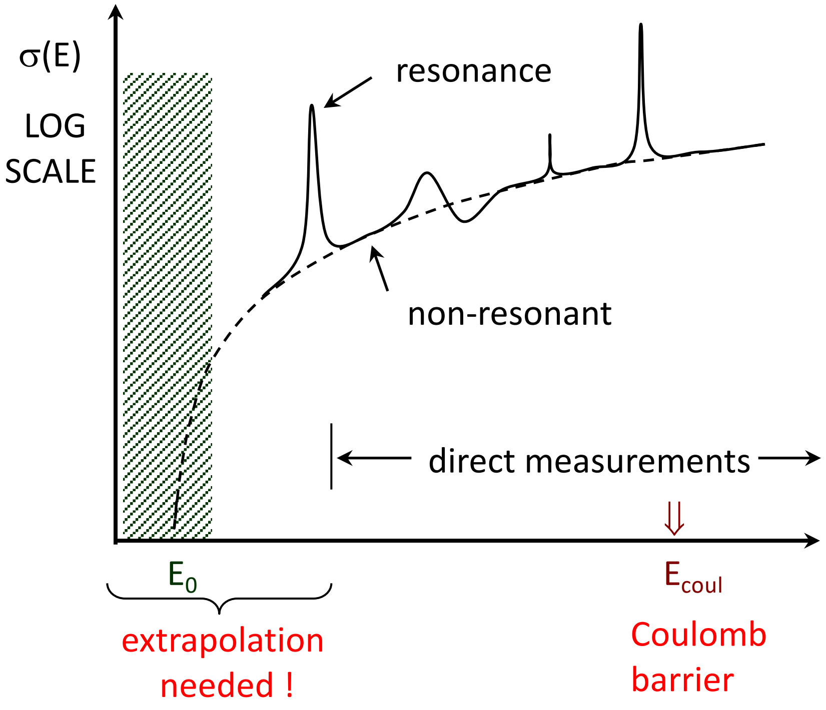
RIBs production and acceleration
large area detectors
high detection efficiency
Storage rings
…

Experimental approach: extrapolation

measure $\sigma(E)$ over as wide a range as possible, then extrapolate down to E_0!

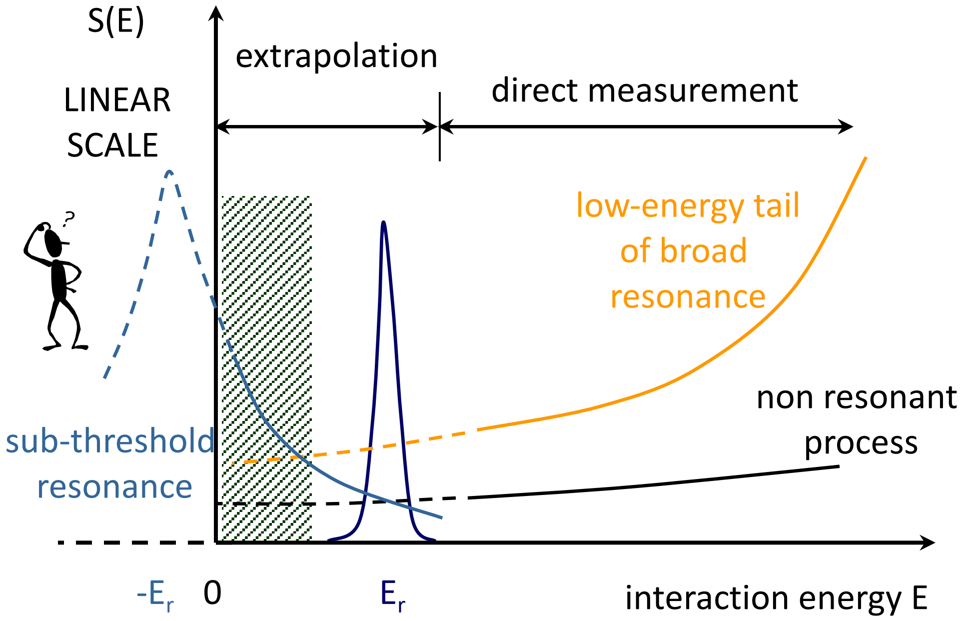
CROSS SECTION

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



S-FACTOR

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



DANGER OF EXTRAPOLATION !

Experimental approach: alternative solutions

- Underground experiments to reduce (cosmic) background: LUNA (LNGS Italy), Felsenkeller (Germany), CASPAR (USA), JUNA (China), particularly suited to perform gamma spectroscopy

- Surface experiments:

inverse kinematics;

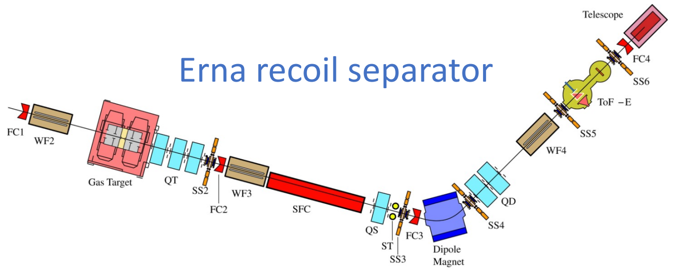
coincidence experiments (g-g, g-particle, …) ;

recoil separators, separate reaction products from unreacted beam and disperse them according to their mass-to-charge-state ratio;

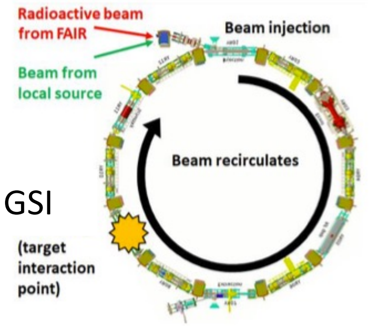
storage rings: to overcome beam intensity limitations. The beam is recirculated many times and therefore has repeated chances to interact with the target;

…

Erna recoil separator



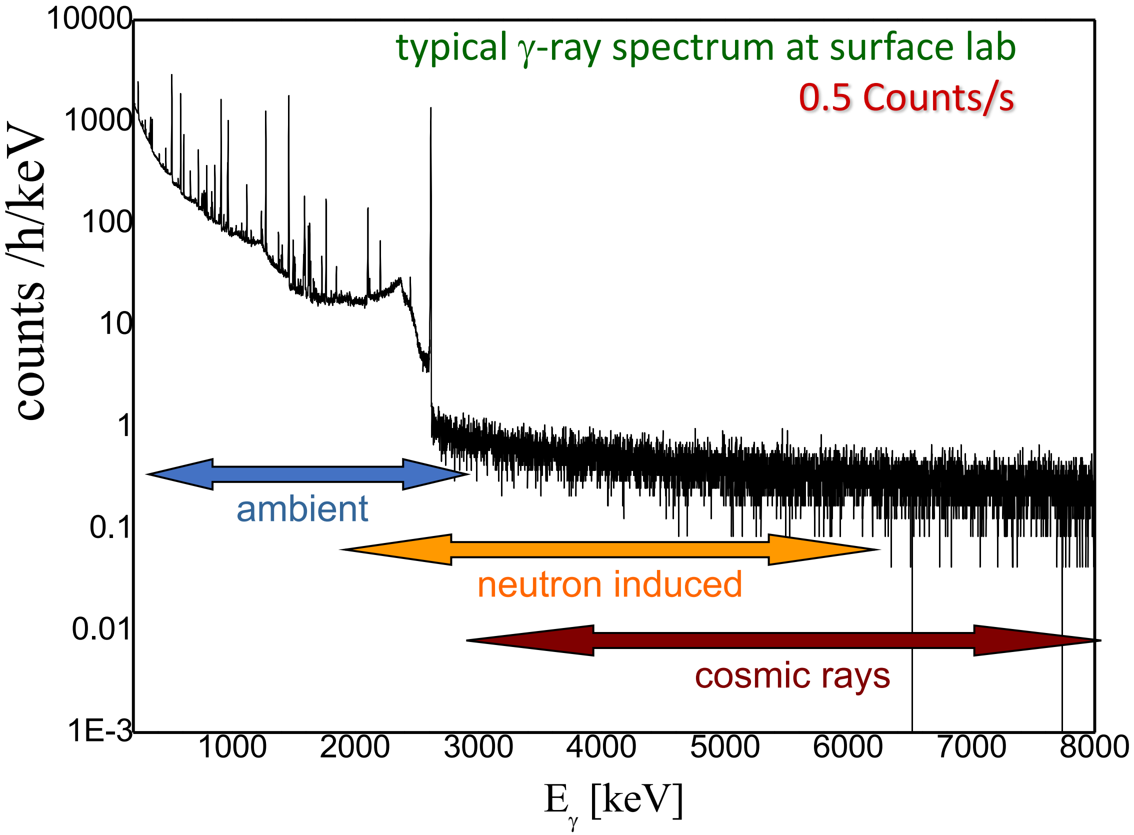
Cryring GSI

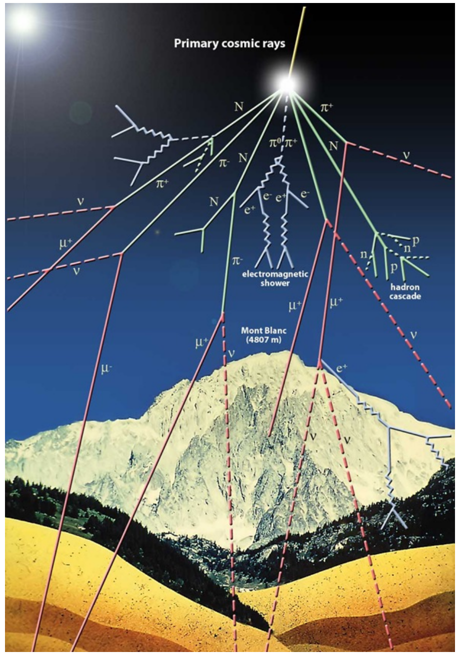


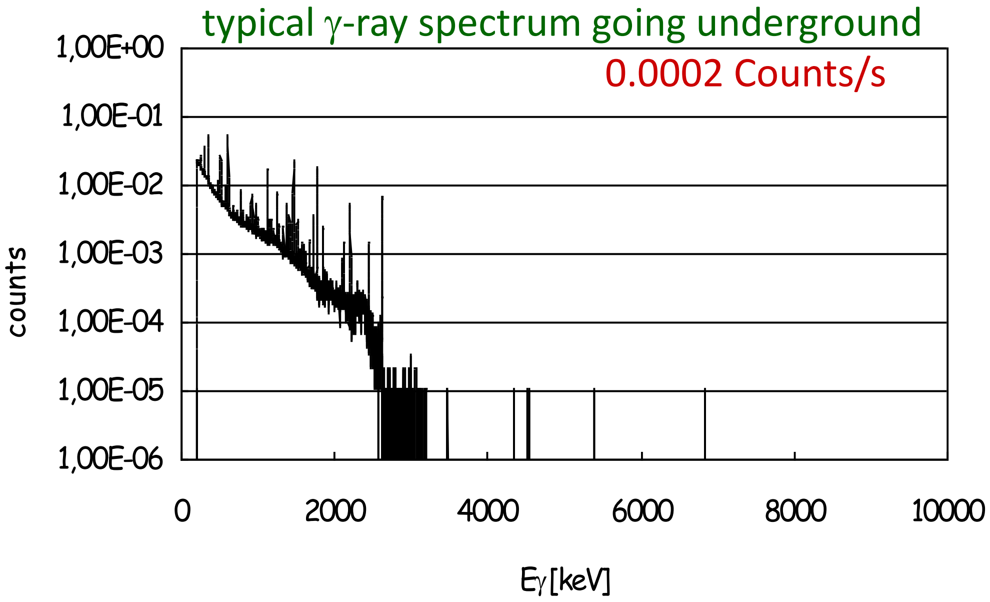
- Use indirect methods: Coulomb Dissociation (CD), Asymptotic Normalization Coefficients (ANC), Trojan Horse Method (THM)

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 (a,n) reactions and fission







ideal location: underground + low concentration of U and Th

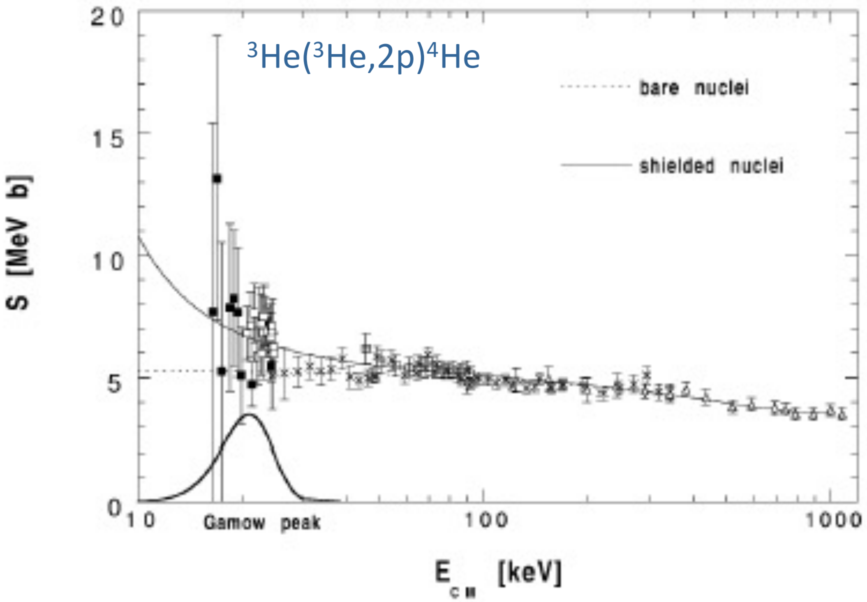
the advantage is evident for high Q-value capture reactions, less evident for low Q-value reactions

LUNA= Laboratory for Underground Nuclear Astrophysics

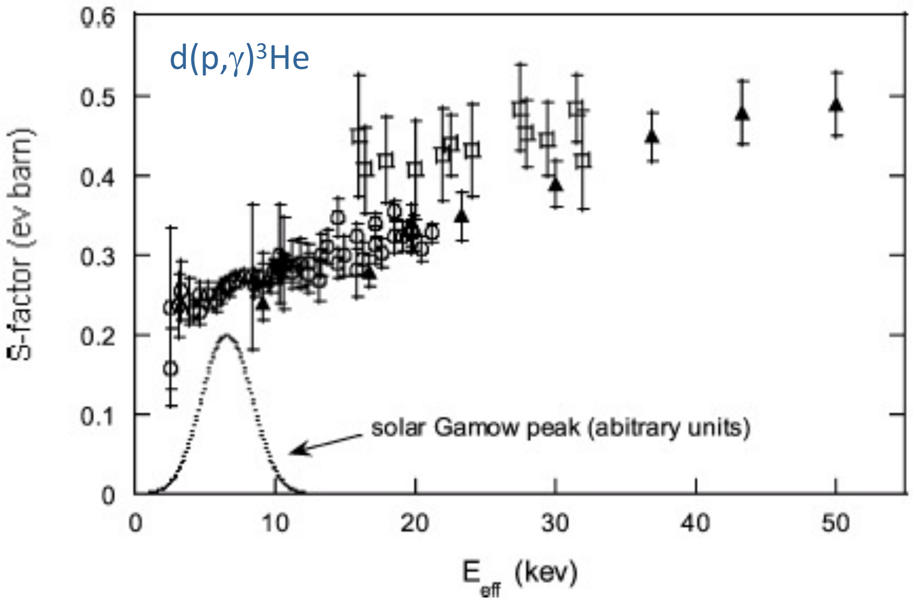
LUNA – Phase I: 50 kV accelerator (1992-2001)

investigate reactions in solar pp chain

R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



C. Casella et al.: Nucl. Phys. A706 (2002) 203-216



@ lowest energy:

σ ~ 20 fb → 1 count/month

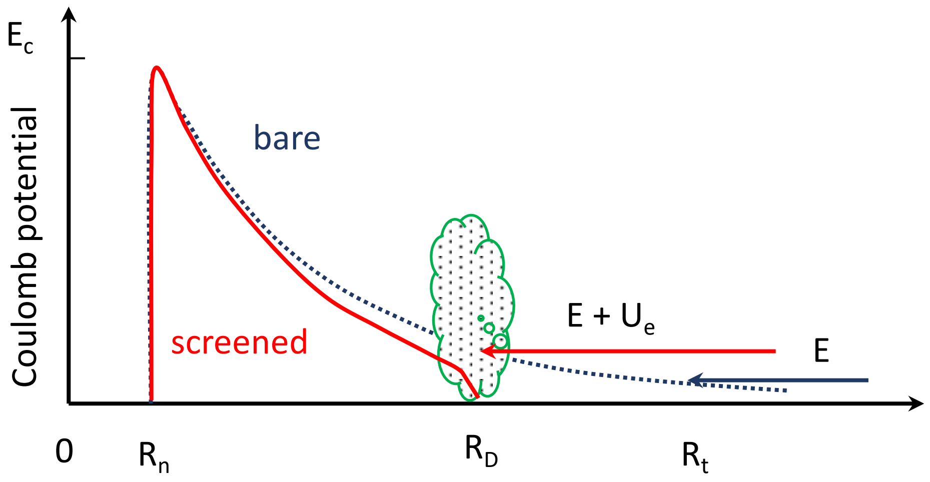
@ lowest energy:

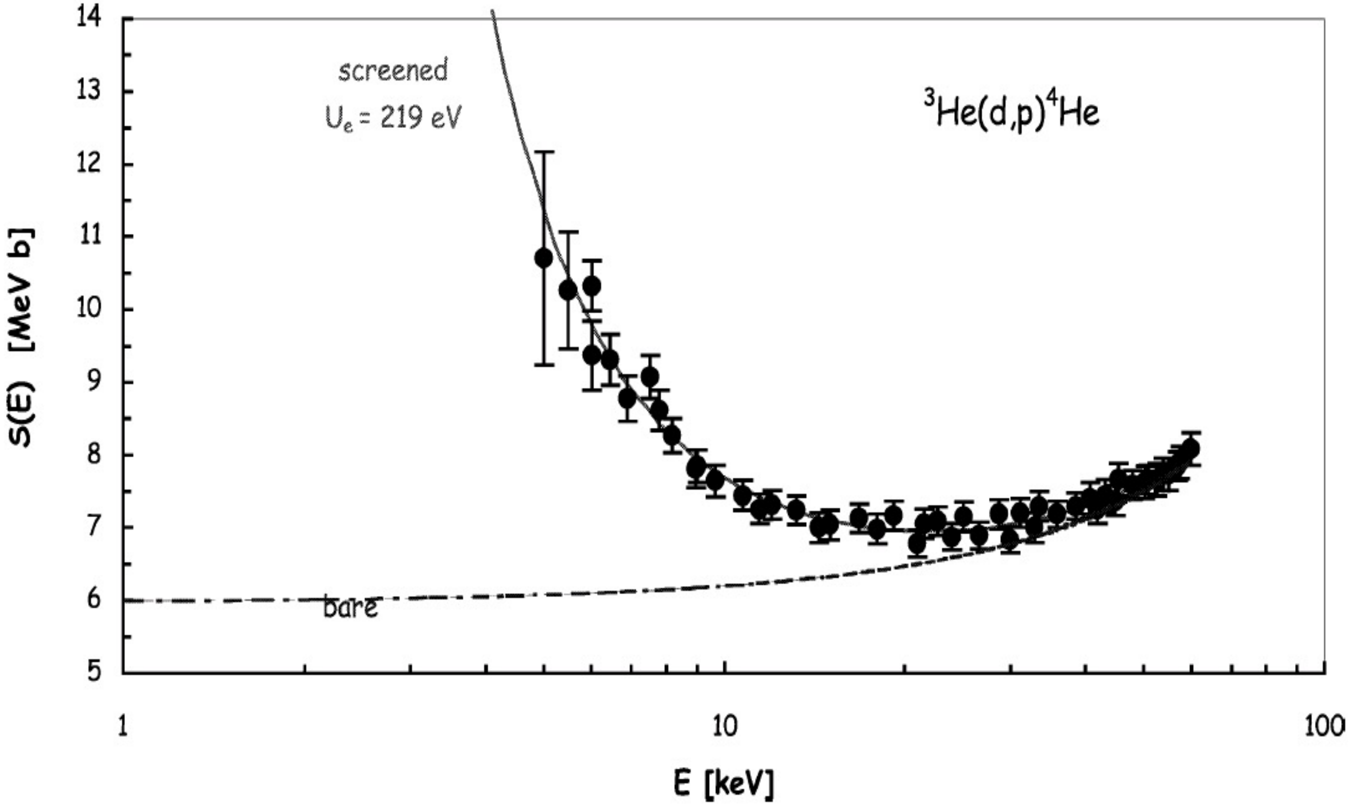
σ ~ 9 pb → 50 counts/day

only two reactions studied directly at the Gamow peak

…but… intrinsic limitation at astrophysical energies → → → → Electron Screening

S(E) experimental enhancement due to the electron screening $S(E)_s = S(E)_b \exp(\pi\eta Ue/E)$

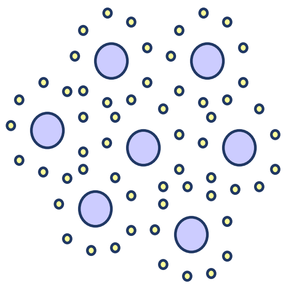




Electron Screening

In astrophysical plasma:

- the screening, due to free electrons in plasma, can be different
  → we need $S(E)_b$ to evaluate reaction rates



Debye-Hückel radius

$R_D \sim (kT/\rho)^{½}$

A theoretical approach to extract the electron screening potential U_e in the laboratory is needed

… however, experimental studies of reactions involving light nuclides have shown that the observed exponential enhancement of the cross section at low energies were in all cases significantly larger

(about a factor of 2)

than it could be accounted for from available atomic-physics model, i.e. the adiabatic limit $(U_e)_{ad}$ … screening yet to be fully understood

→ No way to measure $S(E)_b$ from direct experiments at energies where screening is important

$S_b(E)$-factor extracted from extrapolation of higher energy data

Indirect Methods for Nuclear Astrophysics

- to measure cross sections at never reached energies (no Coulomb suppression), where the signal is below current detection sensitivity
- to get independent information on U_e
- to overcome difficulties in producing the beam or the target (Radioactive ions, neutrons..)

Quite straightforward experiment, no Coulomb suppression, no electron screening but …

Entrance channel
A+a → Several reaction mechanisms link the two channels → Reaction products
C+c+…

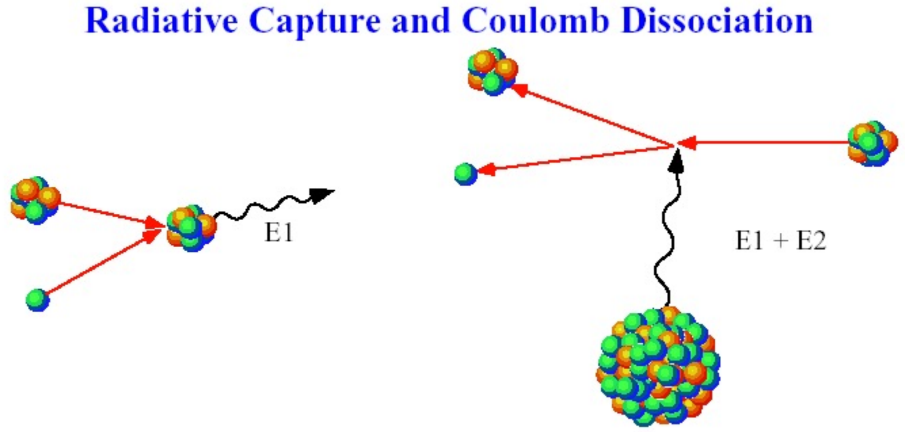
The reaction theory is needed to select only one reaction mechanism. However, nowadays powerful techniques and observables for careful data analysis and theoretical investigation.

Coulomb Dissociation in short

to determine the absolute S(E) factor of a radiative capture reaction **A+x → B+γ** studying the reversing photodisintegration process **B+γ → A+x**

- Breakup of fast projectile by Coulomb field of a high-Z nucleus.
- Detailed balance ⇒ S-factor for radiative capture. Inverse cross section is larger.
- Advantages: possibility to use thick targets, large σ ⇒ high rates.
- Issues: Nuclear breakup if E_γ is large, contributions of other multipoles.

$$\frac{d^2\sigma}{d\Omega dE_\gamma} = \frac{1}{E_\gamma}\frac{dn_{\pi,\lambda}}{d\Omega}\sigma_{\pi,\lambda}^{photo}$$



Early and forthcoming Experiments

^{13}N(p,γ)^{14}O, ^{7}Be(p,γ)^{8}B, breakup of ^{8}B, ^{14}O

GSI, NSCL: ^{7}Be(p,γ)^{8}B, ^{8}Li(n,γ)^{9}Li, ^{12}C(α,γ)^{16}O

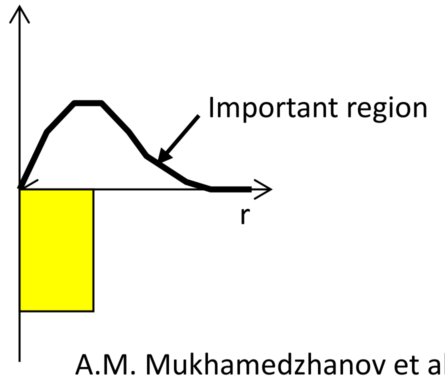
G. Baur, C. Bertulani, H. Rebel, Nucl. Phys. A (1986)
G. Baur et al. Annu. Rev. Nucl. Part. Sci. (1996)
T. Motobayashi et al.:NPA (2003)

ANCs in short

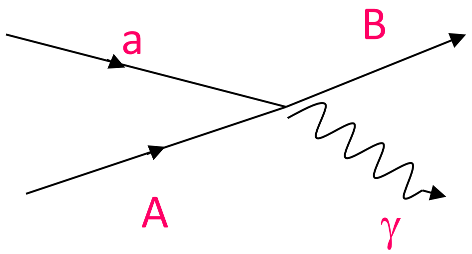
… to determine the S(0) factor of the radiative capture reaction, **A+x → B+γ** studying a peripheral transfer reaction into a bound state of the B nucleus

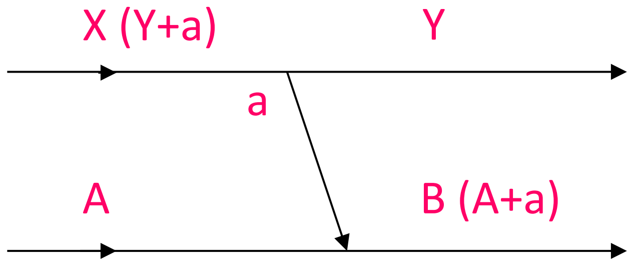
S(E =0) for (p, γ), (α, γ) reactions from measuring ANC

- Low-energy (x,γ) reactions occur far from the nuclear surface
- $\sigma \propto |\psi(\text{large r})|^2 \propto \text{ANC}^2$, ANC from a suitable peripheral transfer reaction into a bound state of B
- Issues: Require accurate OM Potentials



A.M. Mukhamedzhanov et al. (1997)





Early and recent Experiments

^{7}Be(p, γ)^{8}B via ^{10}B (^{7}Be,^{8}B)^{9}Be and ^{14}N(^{7}Be ,^{8}B)^{13}C
^{13}C(α, n)^{16}O via the ^{13}C(^{6}Li,d)^{17}O
^{15}N(p, γ)^{16}O via the ^{15}N(^{3}He,d)^{16}O transfer reaction
^{26}Si(p, γ)^{27}P via the ^{26}Mg(d,p)^{27}Mg transfer reaction

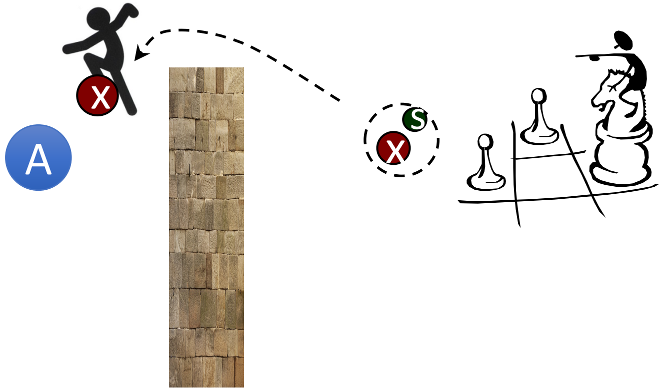
A.Azhari et al, (2001)
S. Kubono et. al, (2003),
N. Keeley et al., Nucl. Phys. A (2003)
A.M. Mukhamedzhanov et al.,J.Phys.:Conf.Ser. (2010)
G. D'Agata et al. (2020)

THM in short

Basic principle: relevant low-energy two-body σ from quasi-free contribution of an appropriate three-body reaction in quasi free kinematics

$$A + a \rightarrow b + B + s \quad \rightarrow\rightarrow\rightarrow \quad A + x \rightarrow b + B$$

a: $x \oplus s$ clusters



Repulsion wall

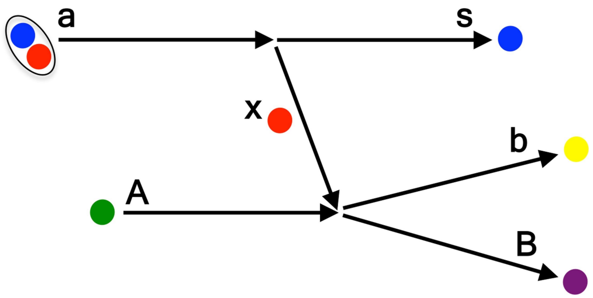
Quasi free mechanism

- ✓ only x - A interaction
- ✓ s = spectator (p_s~0)

$E_A > E_{Coul} \Rightarrow$

<u>NO Coulomb suppression</u>

<u>NO electron screening</u>



$$\frac{d^3\sigma}{d\Omega_c d\Omega_C dE_c} \propto KF \cdot |\Phi(p_s)|^2 \frac{d\sigma^{off}}{d\Omega}$$

Issue: need to normalize the two-body σ to direct data

THM applied so far to more than 30 reactions, such as $^{6}Li(p,\alpha)^{3}He$, $^{7}Li(p,\alpha)\alpha$, $^{2}H(d,p)^{3}H$, $^{2}H(d, n)^{3}He$, $^{10}B(p,\alpha)^{7}Be$, $^{11}B(p,\alpha)^{8}Be$, $^{17,18}O(p,\alpha)^{14,15}N$, $^{13}C(\alpha, n)^{16}O$, $^{7}Be(n,\alpha)^{4}He$, $^{18}F(p,\alpha)^{15}O$, $^{19}F(p,\alpha)^{16}O$, $^{10}B(p,\alpha)^{7}Be$, $^{11}B(p,\alpha)^{8}Be$, $^{12}C(^{12}C,\alpha)^{20}Ne$, $^{12}C(^{12}C,p)^{23}Na$ …

See for review:
R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901
C. Spitaleri et al. EpJA , 55, (2019), 161
R.G. Pizzone et al EpJA, (2020)

Next:

a few cases of study:

- the cosmological Lithium problem;
- focus on helium and carbon burning;
- the neutron sources in the s process;
- r-process nucleosynthesis: challenges of study (n,γ).

BBN and the cosmological Lithium problem

First proposed by Alpher, Bethe and Gamow in 1948, responsible for the nucleosynthesis of lighter elements.
BBN does not go beyond Li due to missing stable nuclei of mass number 5 or 8

1. p(n,γ)d
2. $^{2}H(p,\gamma)^{3}He$
3. $^{2}H(d,n)^{3}He$
4. $^{2}H(d,p)^{3}H$
5. $^{3}He(n,p)^{3}H$
6. $^{3}H(d,n)^{4}He$
7. $^{3}He(d,p)^{4}He$
8. $^{3}He(\alpha,\gamma)^{7}Be$
9. $^{3}H(\alpha,\gamma)7Li$
10. $^{7}Li(p,\alpha)^{4}He$
11. $^{4}He(d,\gamma)^{6}Li$
12. $^{6}Li(p,\alpha)^{3}He$

Using as inputs:
-12 key nuclear cross section
-the baryon-to-photon ratio $(6.19 \pm 0.15) \times 10^{-10}$ from WMAP)
-the neutron lifetime, (which is a puzzle itself)
we can predict the abundances of d, He, Li relative to H

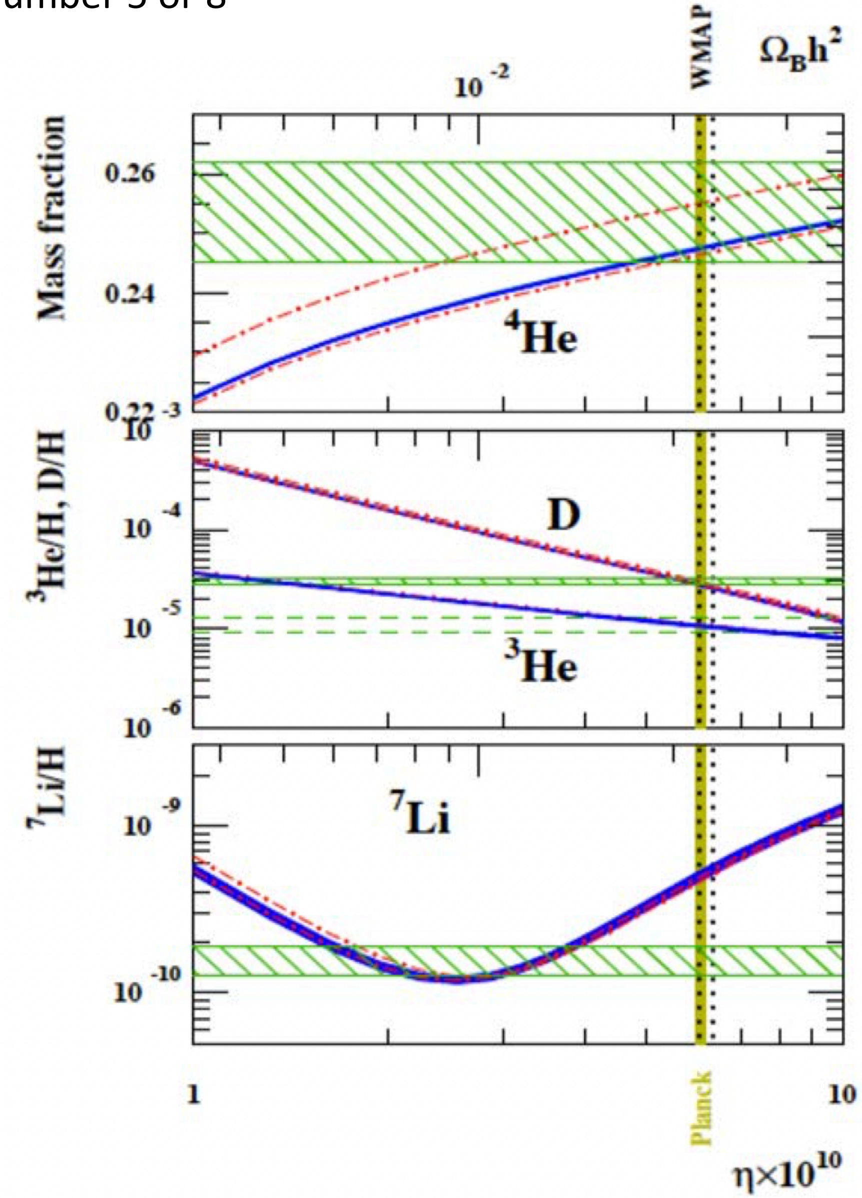
To check if these numbers from BBN hold we compare with abundance measurements in old parts of the Universe (metal poor halo stars, globular clusters)

What do we get? → → →

Green areas from observations
Blue and red lines from calculations
^{3}He is hard to measure since most stars burn it

Remaining abundances agree within errors except for ^{7}Li …

cosmological Lithium problem!



cosmological Lithium problem … what else could be wrong or missing?

- Improve cross sections of the network reactions
- Improve observations with unexplored areas

or/and introduce new Physics

- ^7Li also from primordial ^7Be, but in this case need to measure processes that would get rid of ^7Be

13. $^7Be(n,p)^7Li$
14. $^7Be(n,\alpha)^4He$
15. $^7Be(d,p)2^4He$

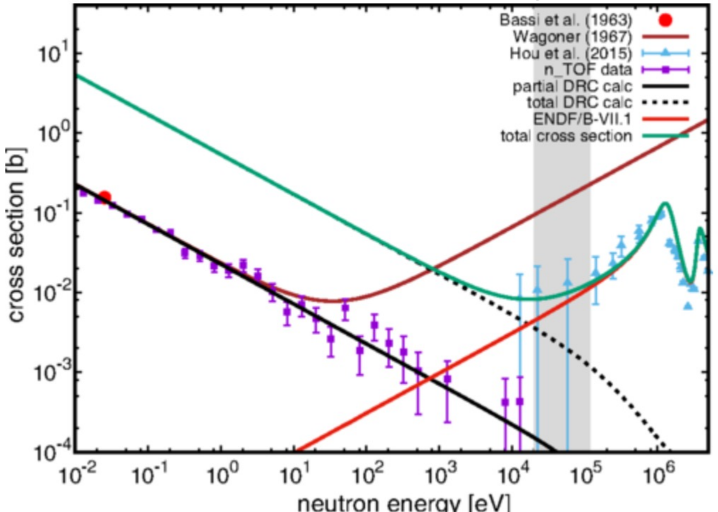
-Wimps decay as early speculation, but insufficient

For review see:
B. D. Fields, Ann. Rev. Nucl. Part. Sci. **61**, 47 (2011)
R. H. Cyburt *et al.*, Rev. Mod. Phys. **88**, 015004 (2016)
S.Q. Hu et al, *The Astrophysical Journal*. **834** (2): 165 (2017).

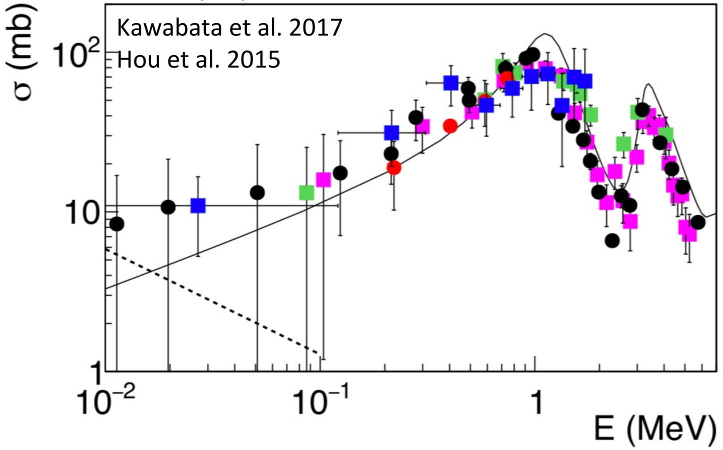
- Decay of GeV scale SUSY particles might bring more neutrons through more complex paths.

-new statistics to describe the velocities of nucleons during the BBN era

$^7Be(n,\alpha)^4He$, Barbagallo et al. 2016

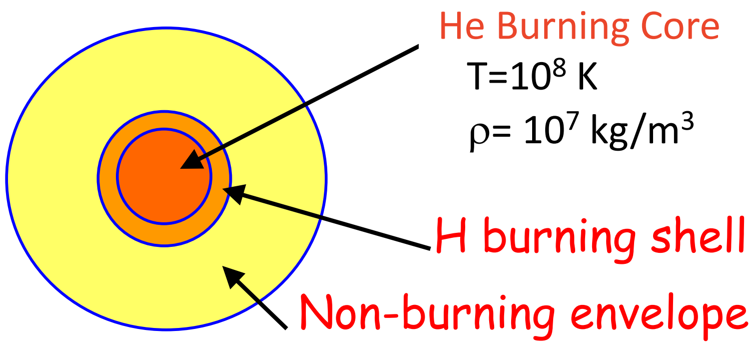


$^7Be(n,\alpha)^4He$, Lamia et al. 2019



Quiescent life of a star: making heavy elements from light ones

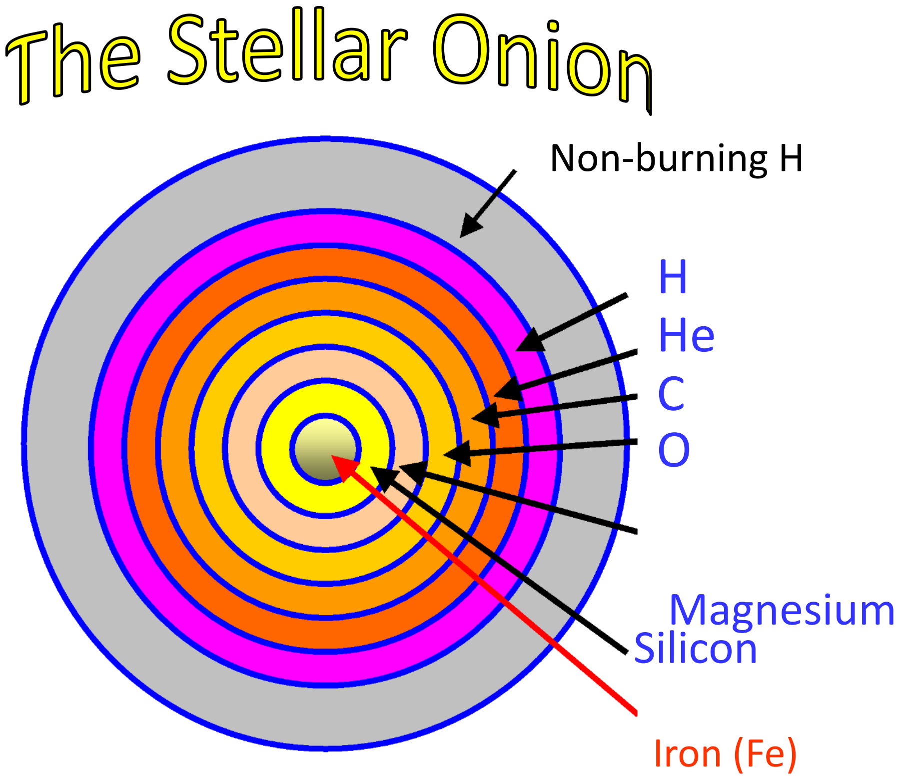
Starts like the sun:



But now, when He is exhausted in the core and the core collapses, it does get hot enough to burn carbon and oxygen.

The successive stages in the core are H $\rightarrow$ He, gravity, He $\rightarrow$ C,O, gravity, $\rightarrow$ C,O $\rightarrow$ Mg, Si, gravity, Si $\rightarrow$Fe.

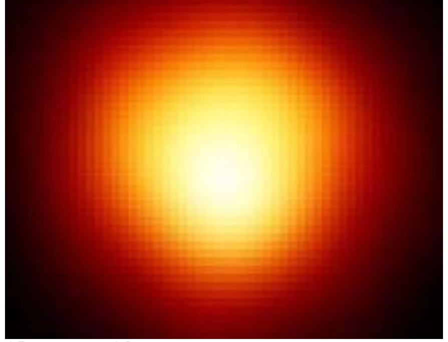
For massive stars



Attention!!!

Massive Stars have complex interiors, where different reactions contribute

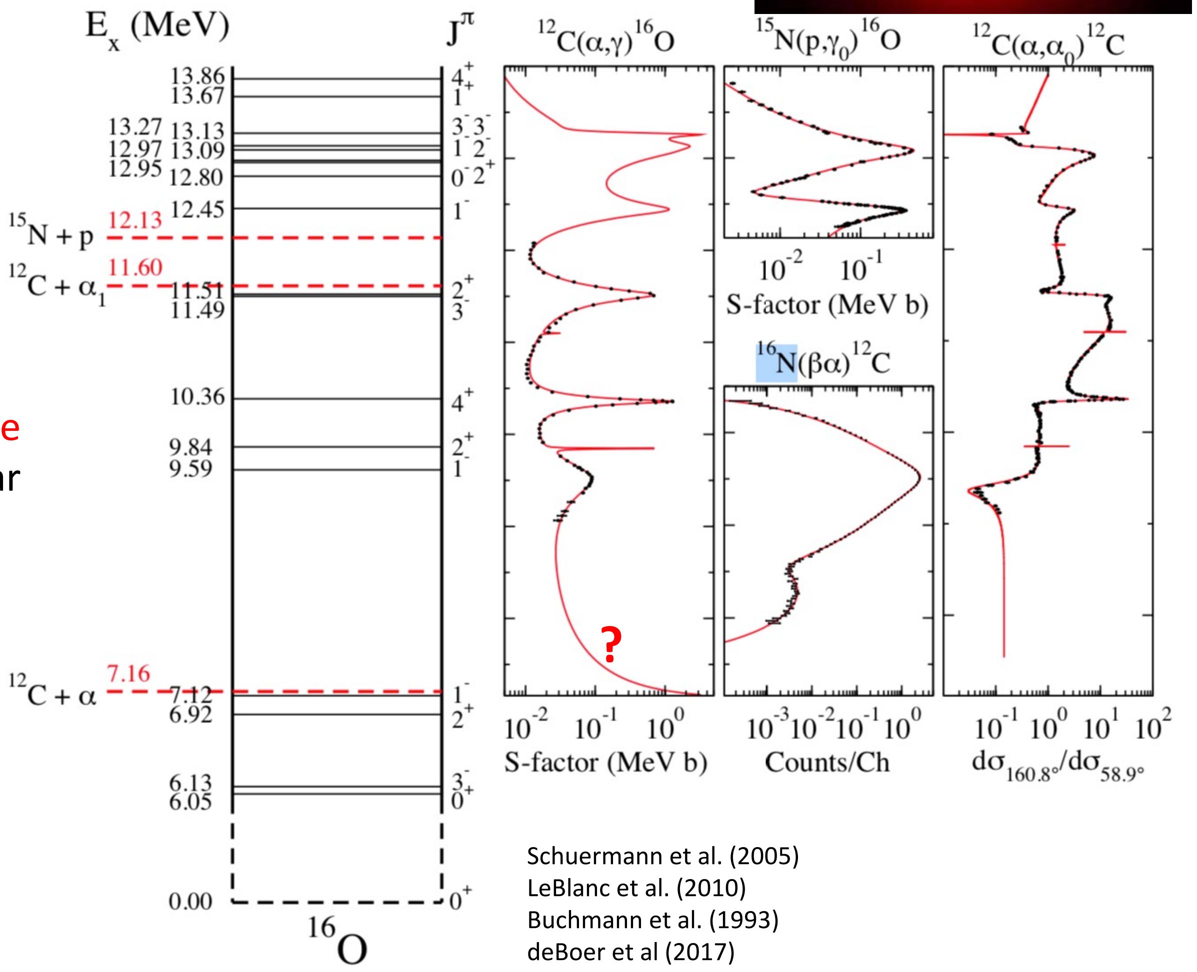
Nucleosynthesis in He burning



- 3α: $\alpha + \alpha \Leftrightarrow {}^{8}Be^{*} + \alpha \rightarrow {}^{12}C^{*} \rightarrow {}^{12}C$ (gs) Rate known to ± 10%
- $^{12}C(\alpha,\gamma)^{16}O$ Poorly known (20-30%)

Gamow peak ~ 300 keV, where cross section enhancement is the result of interferences between resonances and nonresonant components, properties which are much more difficult to determine accurately.

The competition of these two reactions determines the $^{12}C/^{16}O$ ratio in our universe, and thus the late stellar evolution of massive stars and type Ia Supernovae.



Schuermann et al. (2005)
LeBlanc et al. (2010)
Buchmann et al. (1993)
deBoer et al (2017)

Forthcoming attempts:
$^{16}N(\beta\alpha)^{12}C$,
$^{16}O(\gamma_0,\alpha)^{12}C$: inverse photodisintegration
Coulomb dissociation $^{208}P(^{16}O, {}^{16}O^{*})$
Out of nuclear physics: to infer the $^{12}C/^{16}O$ ratio from white dwarf seismology

C-burning

Crucial phase in the nucleosynthesis of massive stars (> 8 $M_{\odot}$), determines M_{up}, ignition trigger for superbursts and Type Ia supernovae

astrophysical energy: 1 – 3 MeV

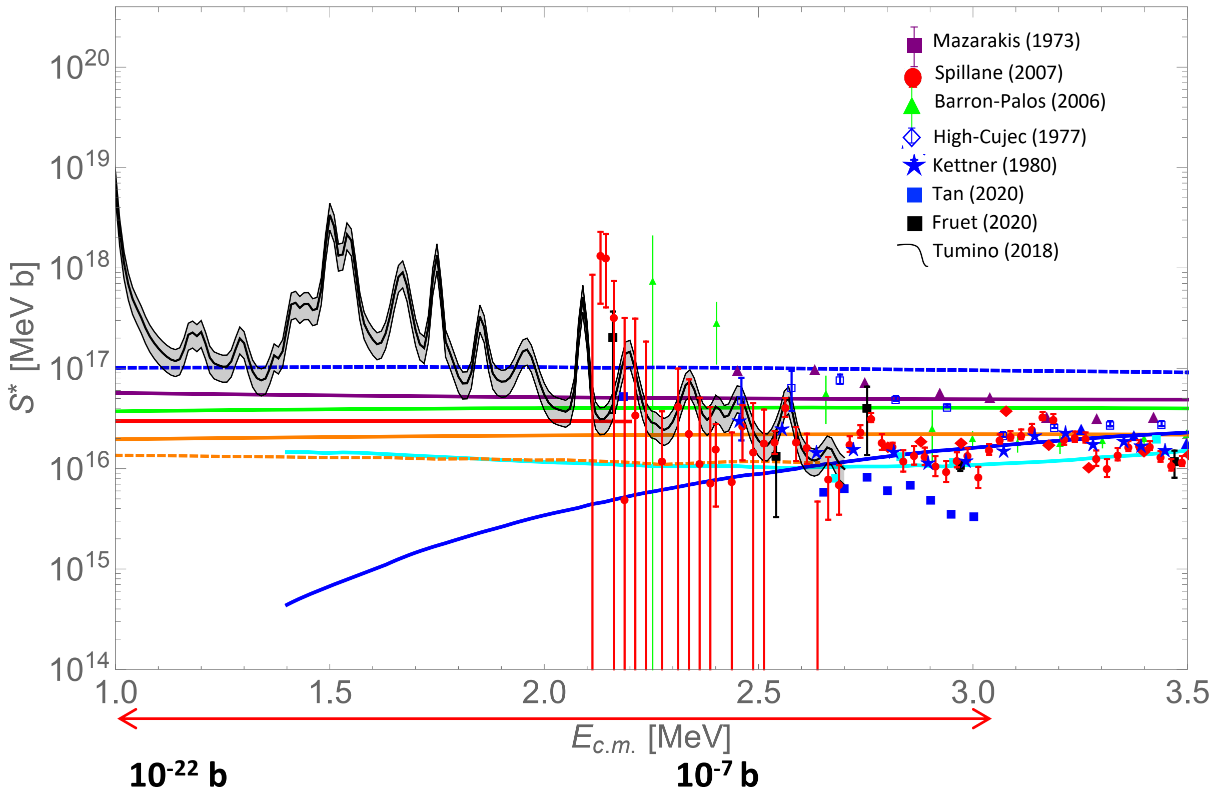
From direct measurement, minimum E: 2.1 MeV

extrapolations differ by 3 orders of magnitude without inclusion of resonances

Indirect measurement with THM down to 1 MeV: resonances dominate the astrophysical energy

$^{12}C + ^{12}C \rightarrow \alpha + ^{20}Ne$

$^{12}C + ^{12}C \rightarrow p + ^{23}Na$



Next step:

-direct data below 2 MeV (STELLA collaboration, LUNA MV)

- improve the normalization of THM data to direct ones with larger overlap

Synthesis of Heavy Elements: s-process neutron sources

Slow or s-process responsible for about 50% of the nuclei heavier than iron

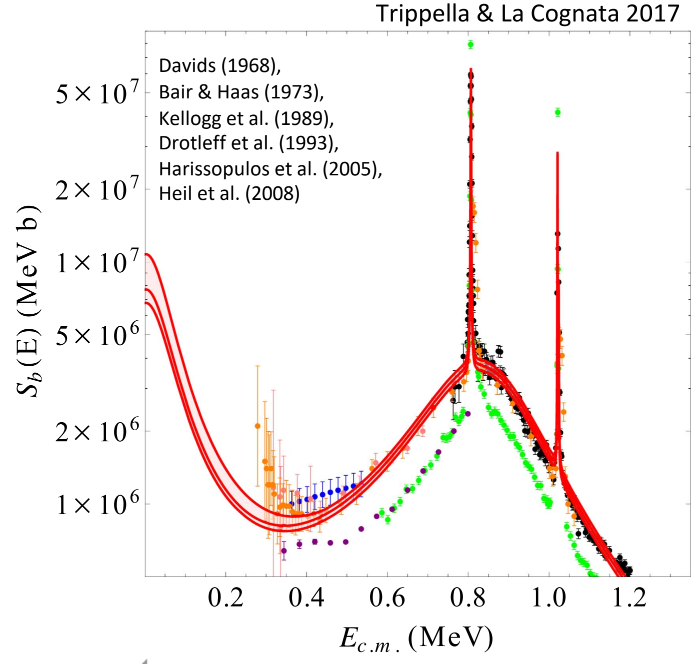
Time scale ~10^3 years

Neutron sources in the s-process:

- $^{13}C(a, n)$, in low-mass AGB stars:

main s-process - production of nuclides with A>90

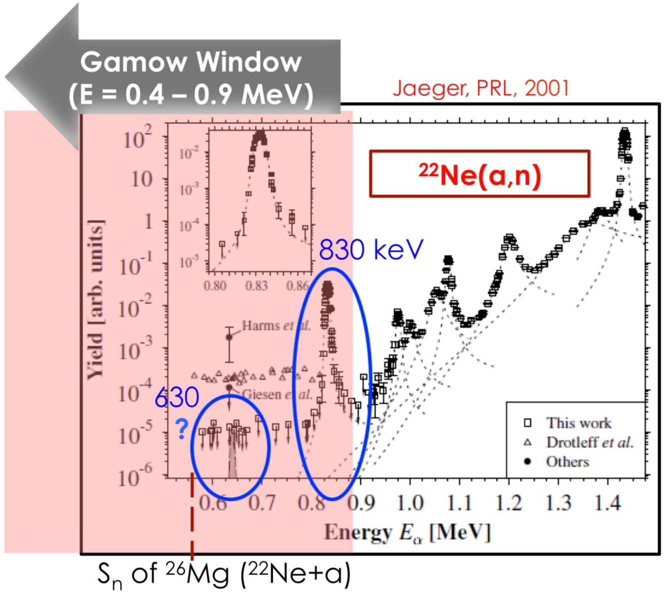
Knowledge of its cross section in the relevant energy window (E ~= 190 keV) is of crucial importance as input for astrophysical models of the s process.
Only indirect measurements at the Gamow window.



- $^{22}Ne(a, n)$, in intermediate mass and massive:

weak s-process - production of nuclides--A= 60-90

still largely unknown. Several evaluations of the reaction rate exist, based on theoretical calculations. No direct measurements at the relevant energies, many spectroscopy studies of the levels involved.



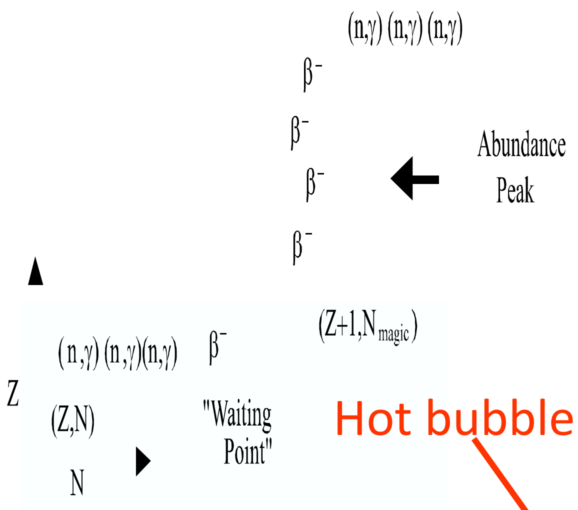
Inputs for s-process nucleosynthesis models

The r-Process

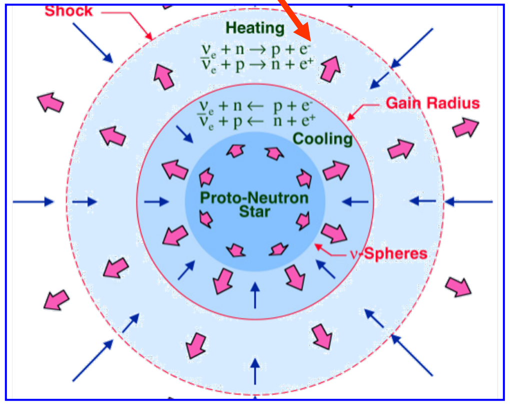
- Heavy elements formed by rapid neutron capture on seed nuclei

- Time scale ~0.1-1.0 seconds
- High T required ($T > 10^9$ K)
- High neutron density ($n_n > 10^{22}$ cm^{-3})

- adds neutrons rapidly, so many neutrons are added before the nucleus has time to decay
- Neutron rich isotopes (waiting points) are unstable to beta decay.
- After beta decay the new nucleus will have a new neutron drip line and in most cases be able to capture more neutrons.



Hot bubble



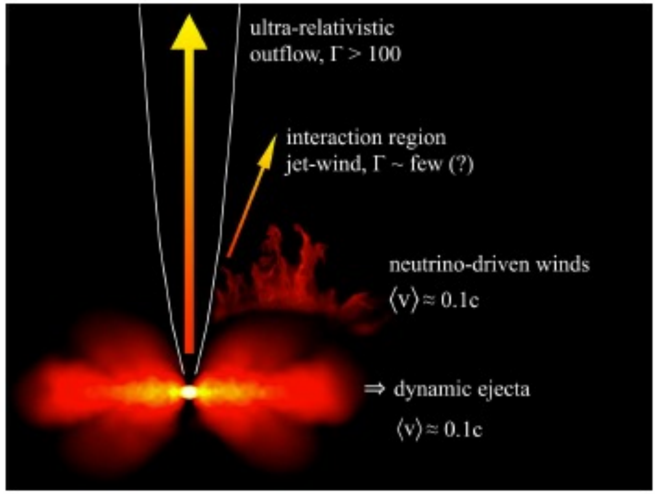
Where does it occur?

- In hot bubble just inside a Supernova shock?

But … very low abundance of r-process nuclei in the interstellar gas

- Or in fusion of two neutron stars?

But … time scale problem and not enough for some elements



Eu abundance: Dwarf galaxies are pointing to two distinct sources of r-processes

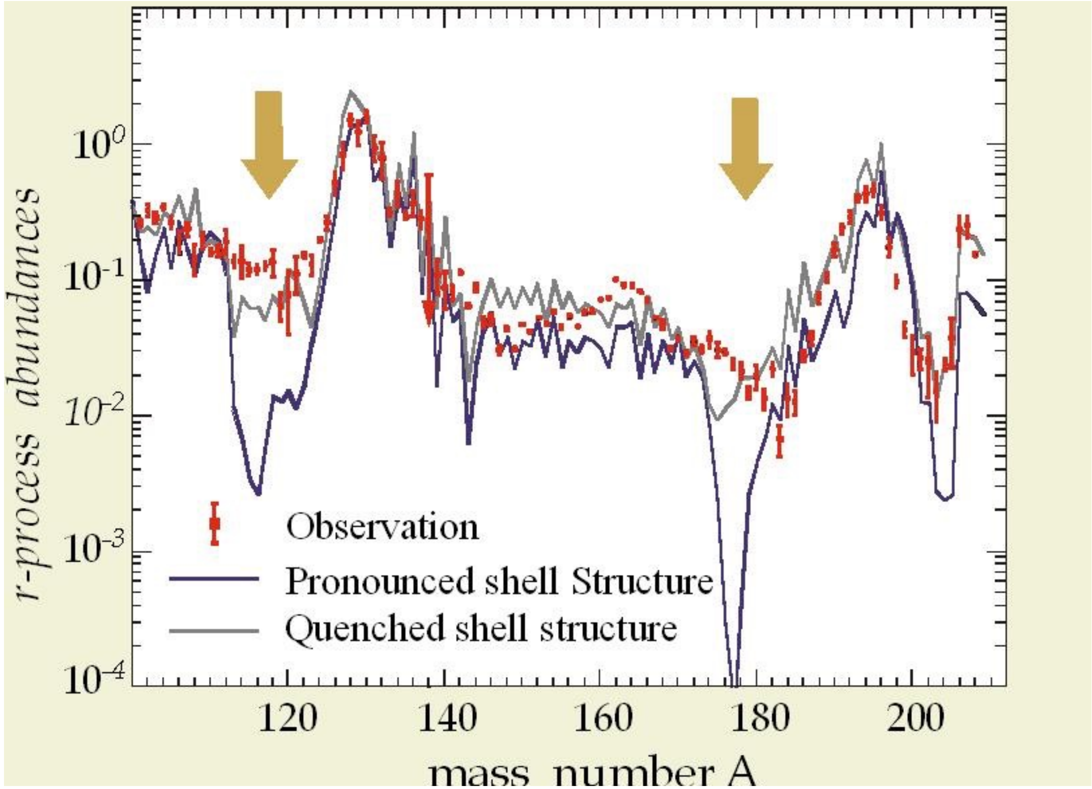
Modeling r-process

To understand the abundance of elements in the universe it is important that we understand r-process

Models are very sensitive to

- neutron capture rates
- β decay properties
- fission barriers
- mass measurements

and do not reproduce the observed abundance of elements in the universe



Challenges of study (n,γ) in the Lab →

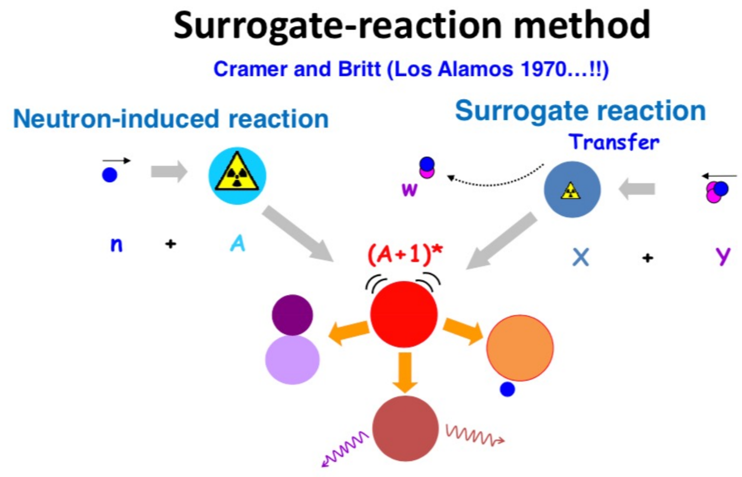
Nuclear physics inputs to r-process

• neutron capture rates, β decay properties, fission barriers, mass measurements

Challenges of study (n,γ) in the Lab

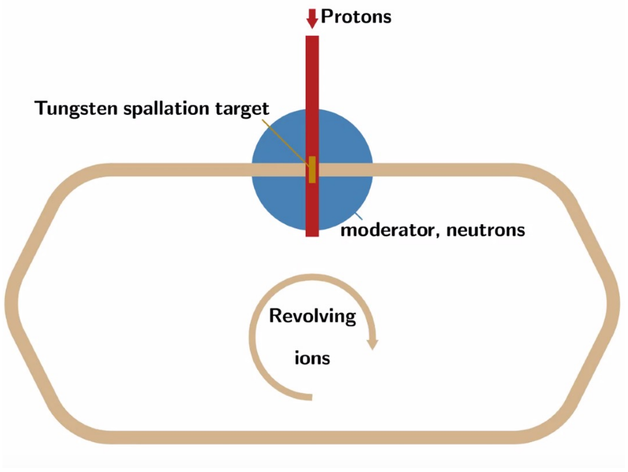
Nuclei involved in r-process are very short-lived, how to proceed:

- To study (n,γ) on short-lived nuclei, we can create radioactive ion beams of these short lived nuclei and deliver them on a deuteron target → surrogate reaction technique, or THM



$$\sigma^{A}_{n,decay}(E^*) = \underbrace{\sigma^{A+1}_{CN}(E^*)}_{\text{Theory, Optical model}} \cdot \underbrace{P^{surro}_{decay}(E^*)}_{\text{Experiment}}$$

- Recent idea to produce a neutron target from a spallation source of protons on tungsten, in a way to destroy nuclei and evaporate neutrons. Neutrons are finally thermalized and can be used as targets. (R. Reifarth 2020)



Very promising technique in conjunction with storage rings

Much remains to say…

this is just an introduction of topics …

Thank you!