Experimental challenges in nuclear astrophysics

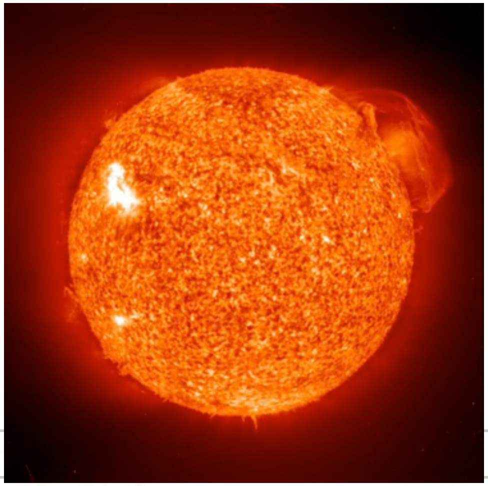
Answering to ancient questions

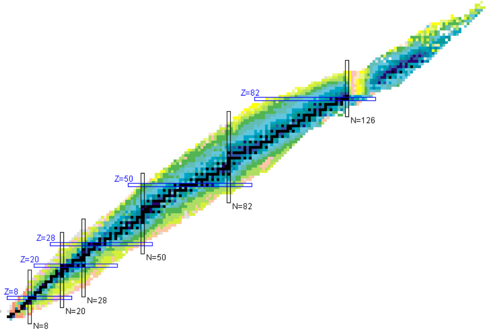
Rosario Gianluca Pizzone

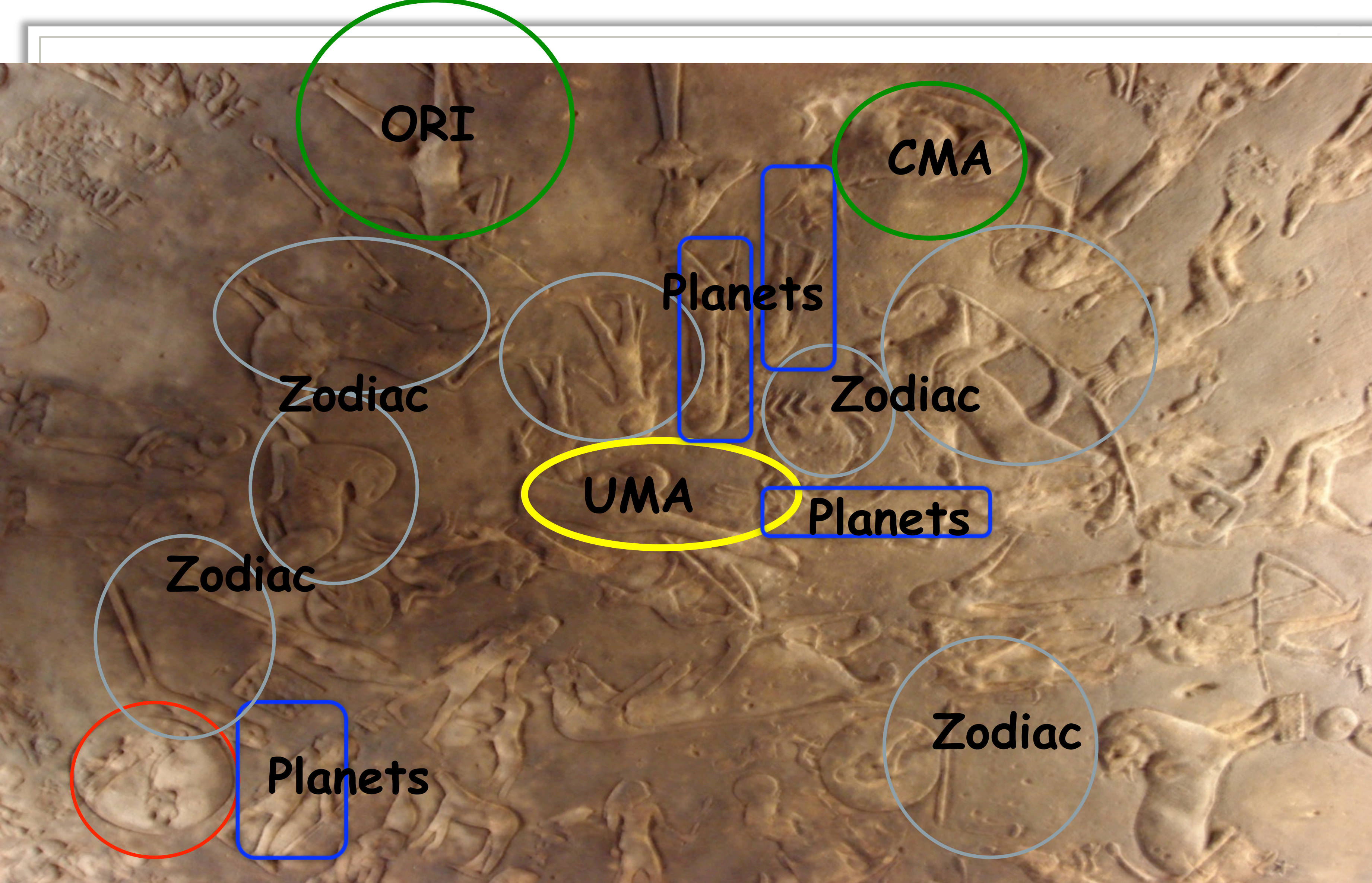
Nature triggers men's admirations; and we look at everything and wonder, but seldom we investigate the causes; thus we ignore the Movements of the Sun and stars As well as the explanations of many other phenomena

Cicero, I century BC

Part 1 : Introduction







Observation and understanding of the stars started together with mankind (Denderah Zodiac)

And much progress was made in the last centuries through astronomical studies

But… it was realized that it was not enough.

In order to understand astrophysical processes, we need to know what's going on there

Astrophysics: studying the Universe through the laws of physics

Nuclear Astrophysics: study of nuclear processes which take place in the Universe

Understanding MACROCOSMOS through MICROCOSMOS

WHY?

- to understand how stars produce the energy they emit;
- to understand how chemical elements were produced
- to understand the first seconds of the Universe and help to track how it will end

Why gold costs much more than iron??

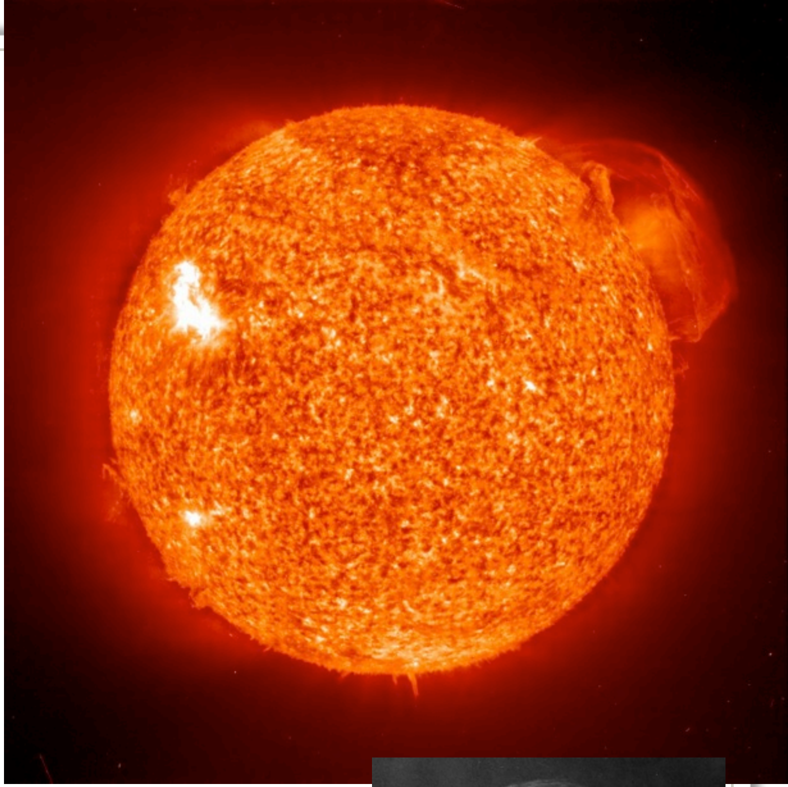
Stars emit energy thoughout their lives
and stars also change (evolve) during their lives.
are these aspects connected?How?

The birth of a start: Galactic gas and powder

Small Mass Star (Sun)

Massive Star

We know from geology Earth is 4.65 $\times 10^9$ years old. What source can guarantee solar luminosity for such a long time?



Gravitational contraction?

It can be shown Sun can hold From GC for 10^7 year (Kelvin Helmoltz timescale)

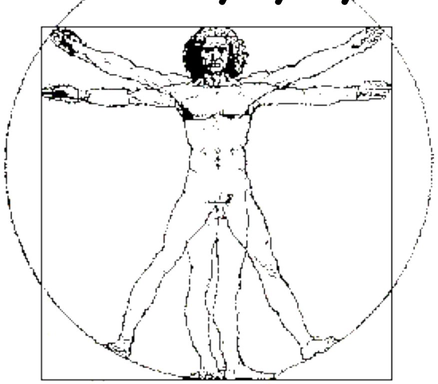
Nuclear fusion?

Simple estimates show it's the right answer.

But HOW?

First ideas suggested 4 H nuclei can merge into a He Producing energy from mass defect (Eddington)

Man: H,C,N,O



Where are the 92 natural elements coming from? How were they produced?

Sun: H, He

Earth: Fe, Si, O, Mg

U

Au

Li

A “cosmic abundance”?

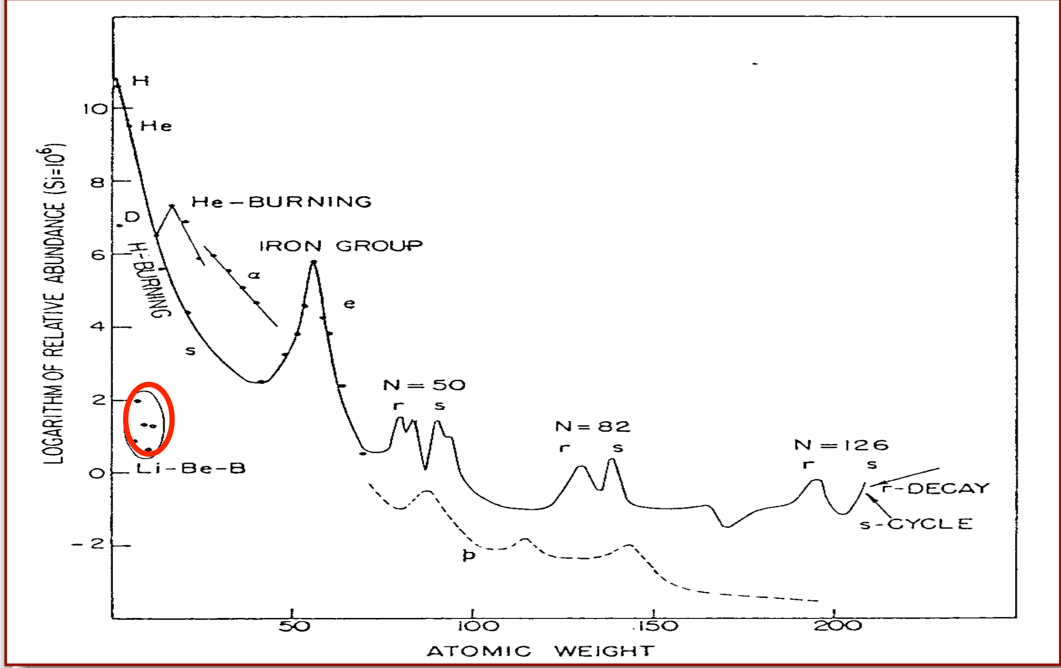
The elemental abundance in the universe is determined in the Solar neighborhood and is assumed to be Universal.

It is measured in Earth,Sun, Meteorites,Stars … by different methods.

Several features are visible in the curve of abundance.

Elemental Abundance in the Universe

Elemental abundance in the Universe



Features:

- Li, Be, B under-abundant
- peak around A=56 (Fe)
- almost flat distribution beyond Fe
- exponential decrease up to iron peak

- **Eddington** 1920, **Bethe** 1938, **von Weiszäcker** 1938, **Gamow** 1948, **Cameron** 1957 …

In **1957**, B^{2}FH presented the basis of the modern nuclear astrophysics in their review paper explaining *by* ***nuclear reactions occurring in the interior of the stars*** :

→ The production of energy

→ The creation of elements

REVIEWS OF

MODERN PHYSICS

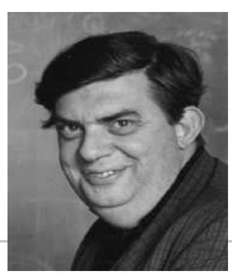
VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

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

The first complete review of nuclear reactions explaining:
H and He quiescent and hot burning, and of the nucleosynthesis beyond Fe.

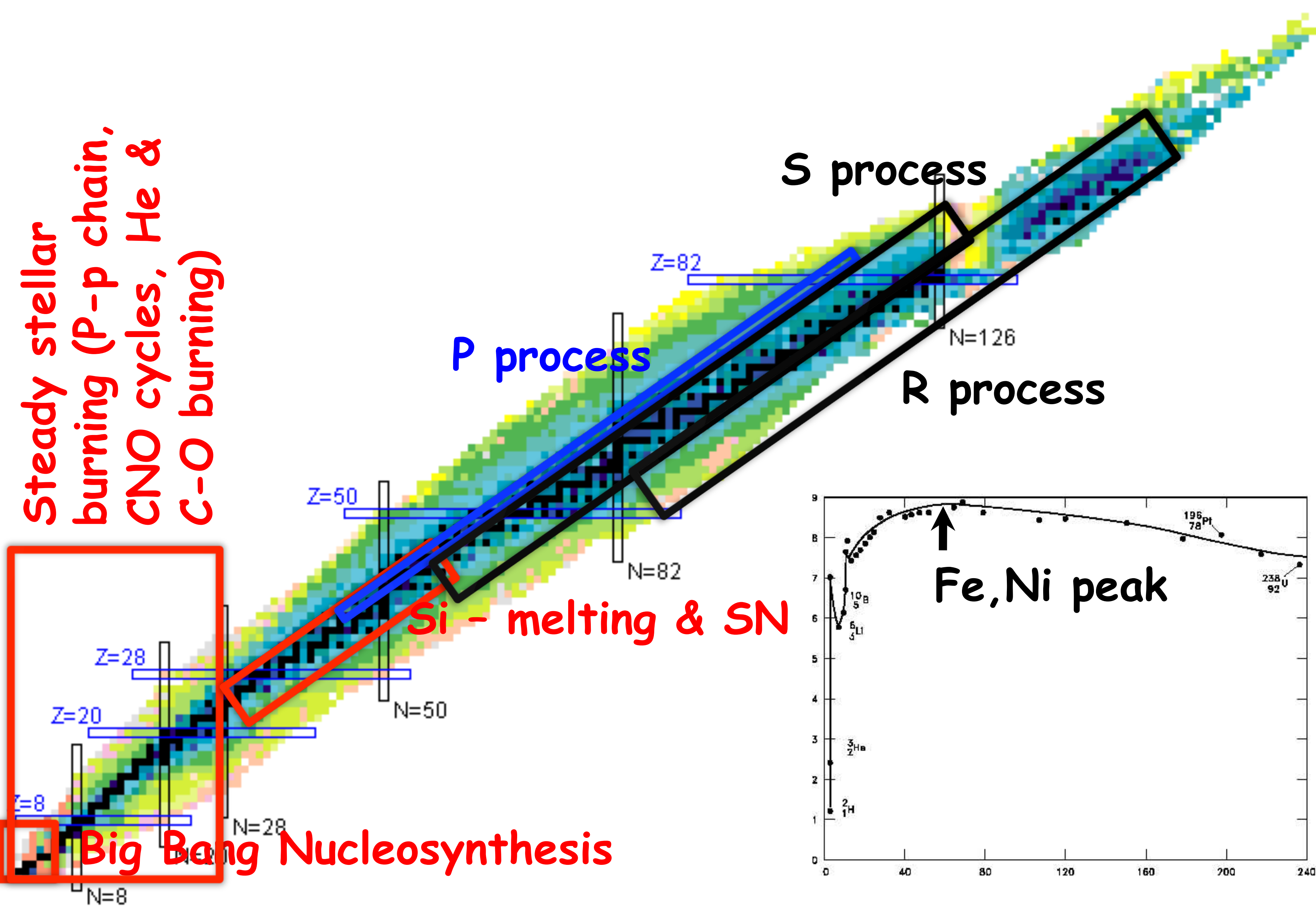
Margaret Burbidge



Geoff Burbidge

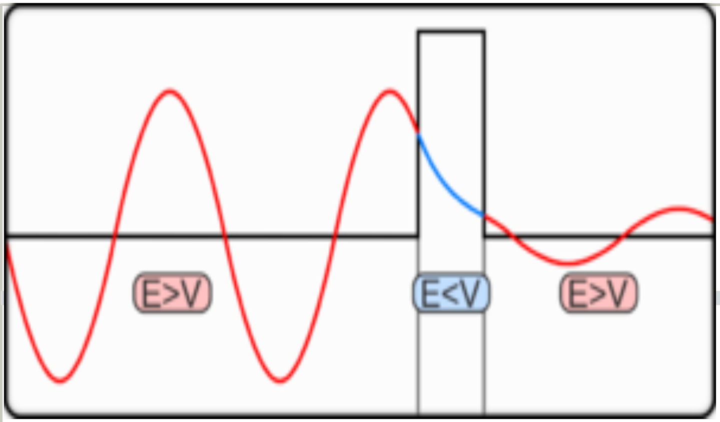
William Fowler

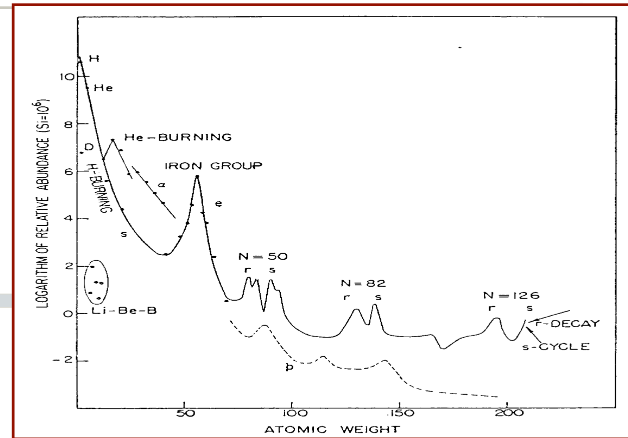
Fred Hoyle


Steady stellar burning (P-p chain, CNO cycles, He & C-O burning)
S process
P process
R process
Z=82
N=126
Z=50
N=82
Z=28
Z=20
N=50
Z=8
N=28
N=8
Si - melting & SN
Big Bang Nucleosynthesis
Fe,Ni peak

- In the astrophysical environments the energy required for particle interactions is taken from Thermal Energy

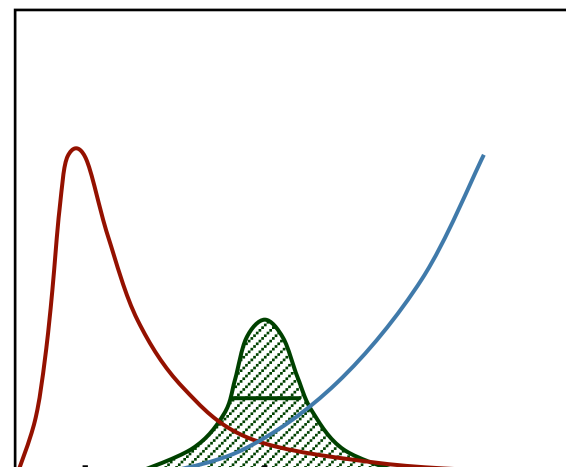
- In the Sun $T=1.5x10^7$ K then $E=kT\sim$ keV
- In large masses stars $T\sim 10^9$ $E\sim 0.5$-1 MeV





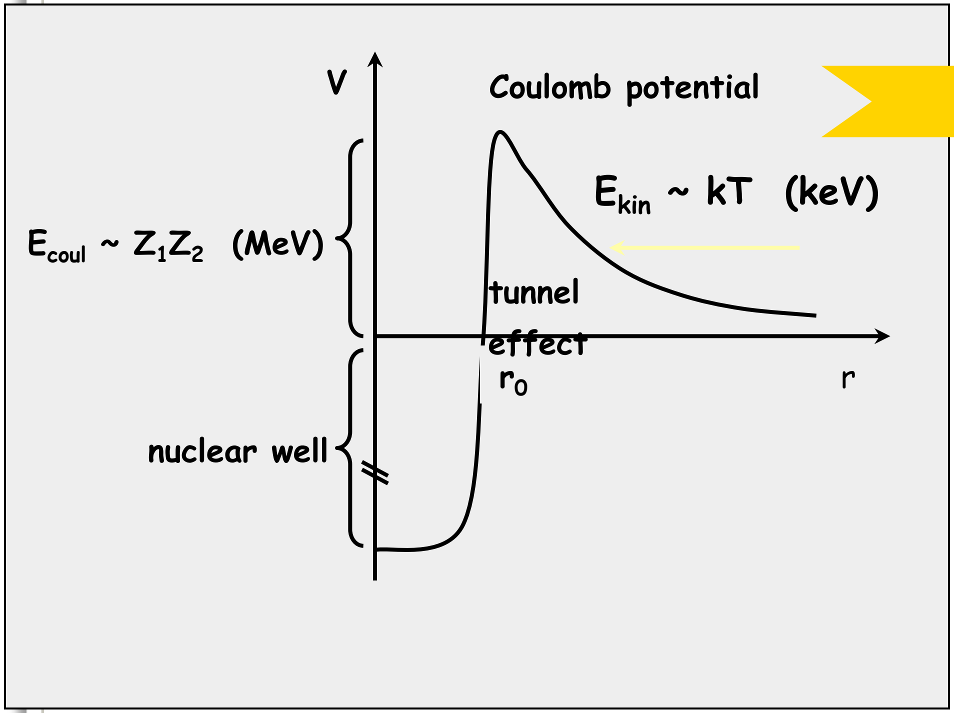
Part 2:

Useful definitions



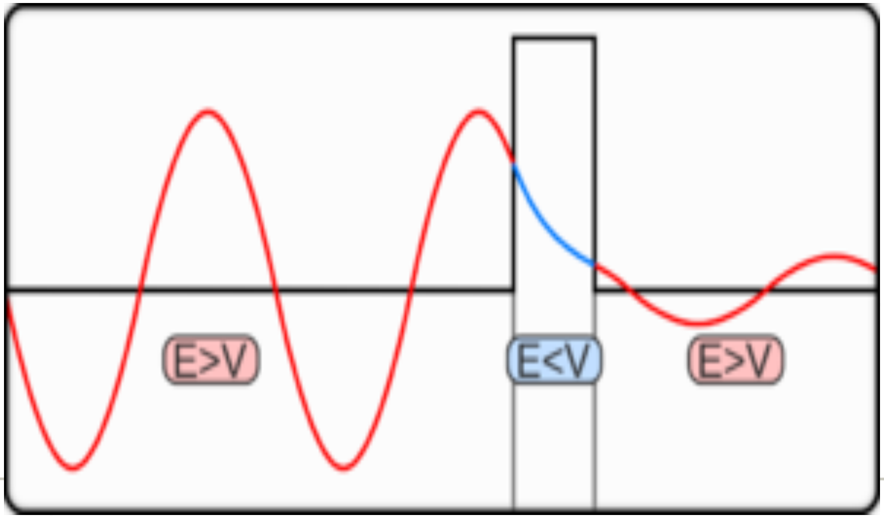
cross sections measurements: Reactions between charged particles

The main problem in the charged particle cross section measurements at astrophysical energies is the presence of the Coulomb barrier between the interacting nuclei

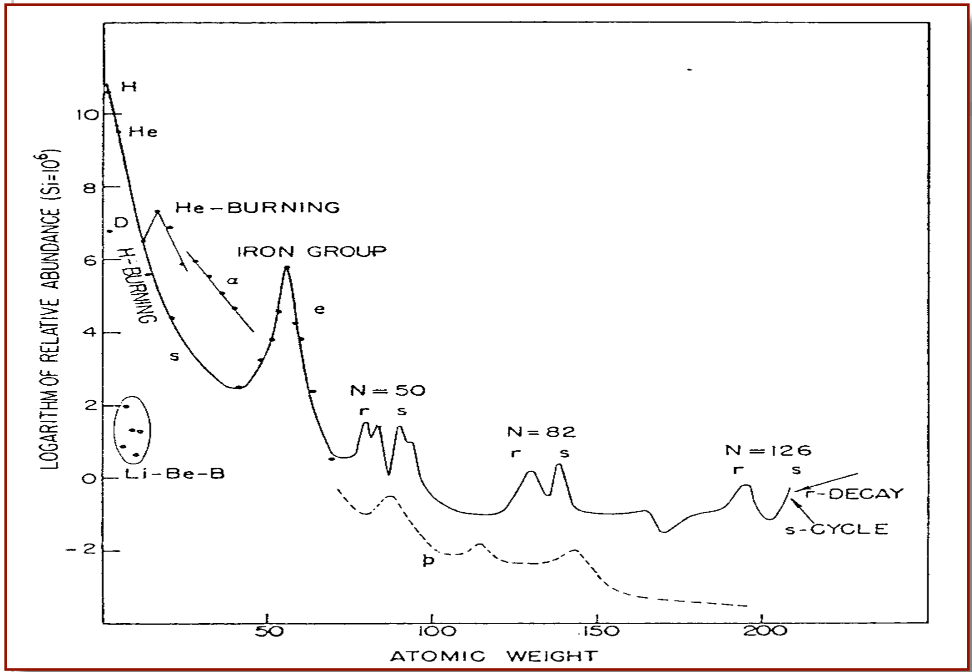


reactions occur through

<u>TUNNEL EFFECT</u>



It determines exponential drop in abundance curve !



tunneling probability

$$P \propto \exp(-2\pi\eta)$$

$2\pi\eta$ = GAMOW factor

in numerical units:

$$2\pi\eta = 31.29\, Z_1 Z_2 (\mu/E)^{\frac{1}{2}}$$

μ in amu and E_{cm} in keV

Consider reaction $1 + 2 \rightarrow 3 + 4 \quad Q_{12} > 0$

Reaction per unit time per unit volume: $v\sigma(v)N_1N_2$

In stellar plasma: $\varphi(v) \propto \exp\left(-\frac{\mu v^2}{2kT}\right) = \exp\left(-\frac{E}{kT}\right)$

μ = reduced mass
v = relative velocity
T = plasma temperature

non-relativistic, non-degenerate gas
in thermodynamic equilibrium

Maxwell-Boltzmann distribution

THEN averaging over v distribution

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

Total reaction rate $\quad R_{12} = (1+\delta_{12})^{-1} n_1 n_2 \langle\sigma v\rangle_{12}$

reactions $cm^{-3}\ s^{-1}$
n_i = number density

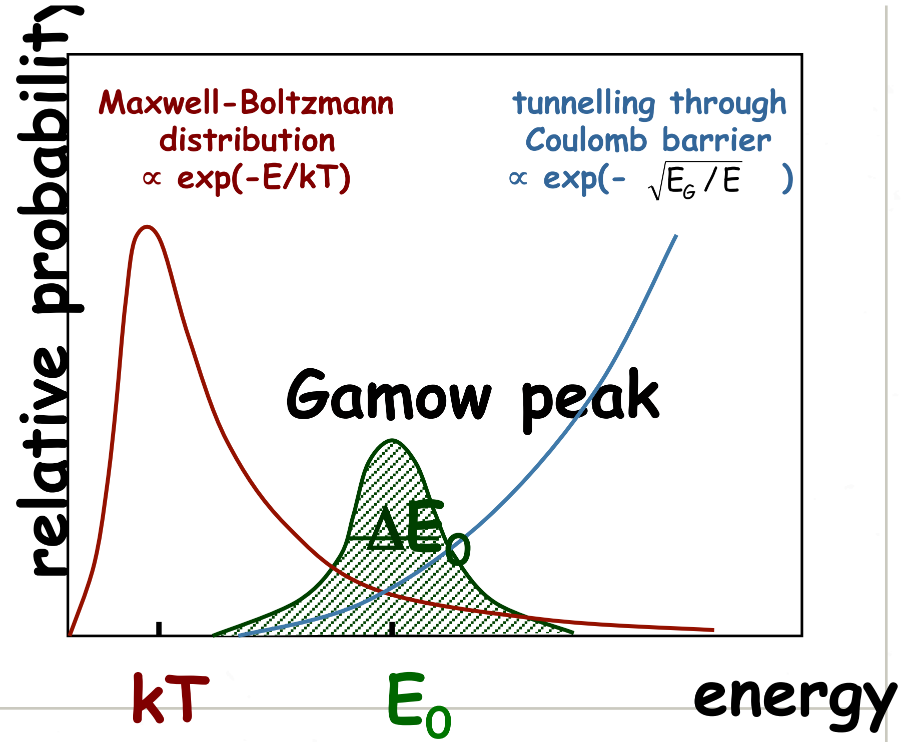
$\langle\sigma v\rangle$ = KEY quantity to be determined from experiments

$\Rightarrow$ NEED ANAYLITICAL EXPRESSION FOR σ!

The probablility for penetrating the Coulomb barrier goes down rapidly with decreasing energy, but at a given temperature the possibility of having a particle of high energy (and therefore high velocity) decreases rapidly with increasing energy (the red curve).

The sum of these opposing effects produces an energy window for the nuclear reaction: only if the particles have energies approximately in this window can the reaction take place.

E_{pp}~ 20 keV
E_{SN}~ 300-800 keV
E_{BBN}~100-600 keV



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

Most favourable energy region varies with reaction and/or temperature

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

reaction	Coulomb Barrier (MeV)	E_0 (keV)	$\Delta E_0 \exp(-3E_0/kT)$
p + p	0.55	5.9	7.0×10^{-6}
$\alpha + {}^{12}C$	3.43	56	5.9×10^{-56}
${}^{16}O + {}^{16}O$	14.07	237	2.5×10^{-237}

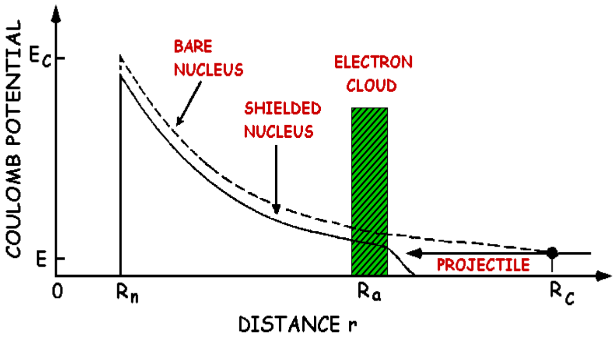
area of Gamow peak ~ $\langle \sigma v \rangle$ (height x width)

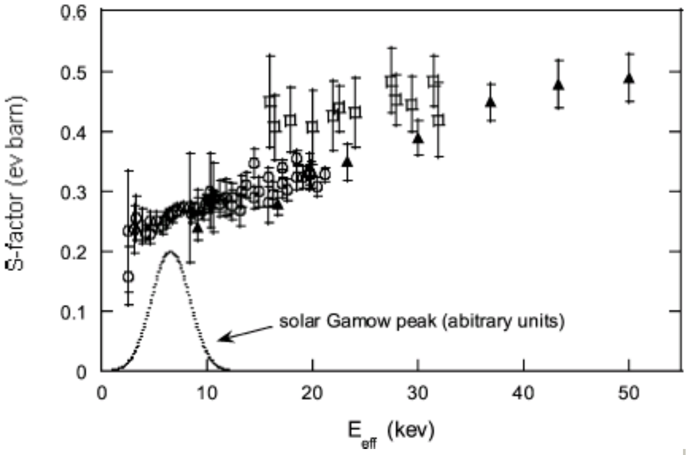
Strong sensitivity to Coulomb barrier

➤ Well-defined stages:

He-burning

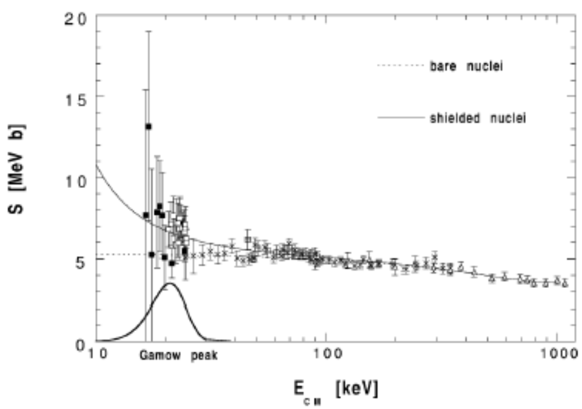
C/O-burning ...

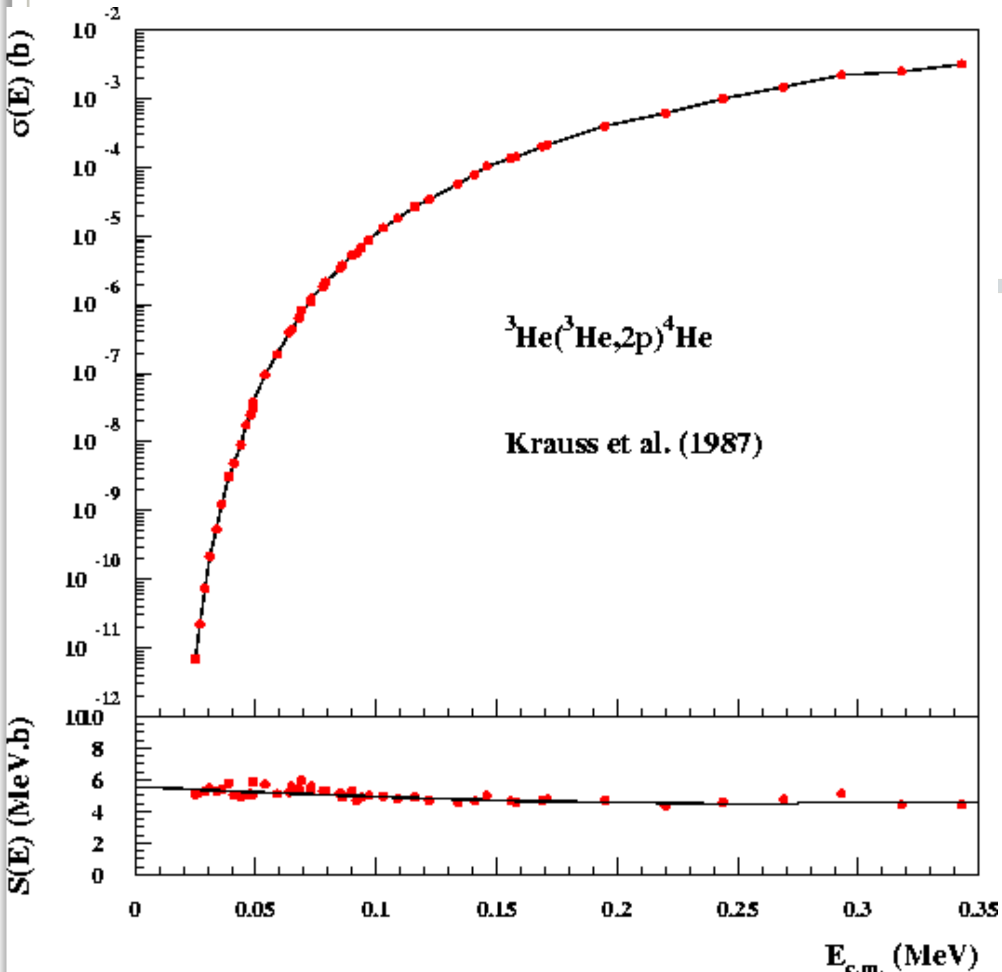




Part 3:

Direct Methods





@ Gamow energies

σ in the range nano-picobarn

in general, their direct evaluation is

-severely hindered (1 ev/month)

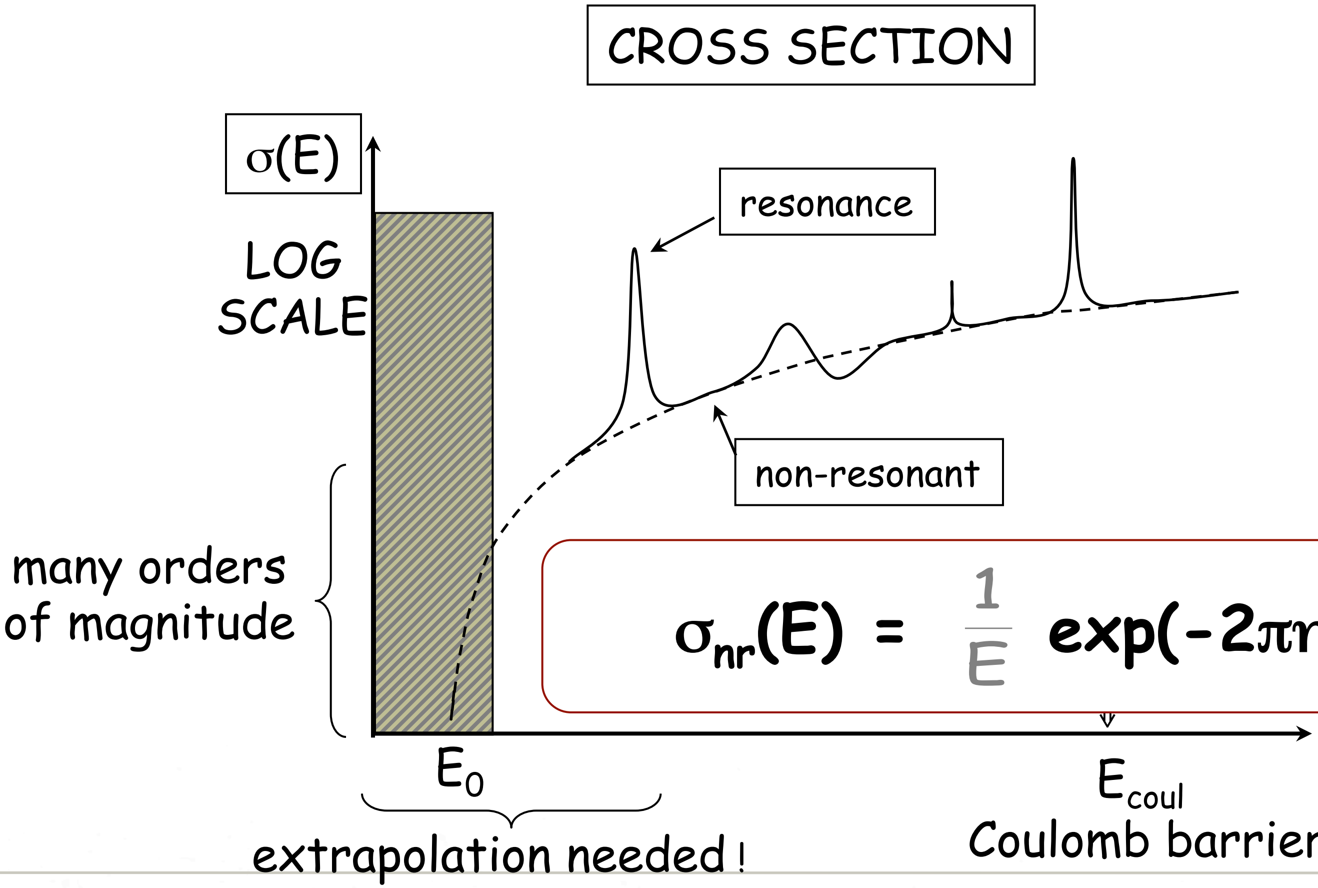
-and in some cases even beyond present technical possibilities.

Possible solutions: underground measurements, extrapolations

Direct Measurement: Perform the experiment with beam-target interacting at astrophysical energies

Experimental procedure Often cross sections are too low to be measured

Bare Nucleus Astrophysical S(E)-factor is introduced for a easier extrapolation.
measurements performed at higher energies



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

The DANGER OF EXTRAPOLATION …

large uncertainties in the extrapolation!

Necessary is Maximize the signal-to-noise ratio

SOLUTIONS

- IMPROVEMENTS TO INCREASE NUMBER OF DETECTED PARTICLES

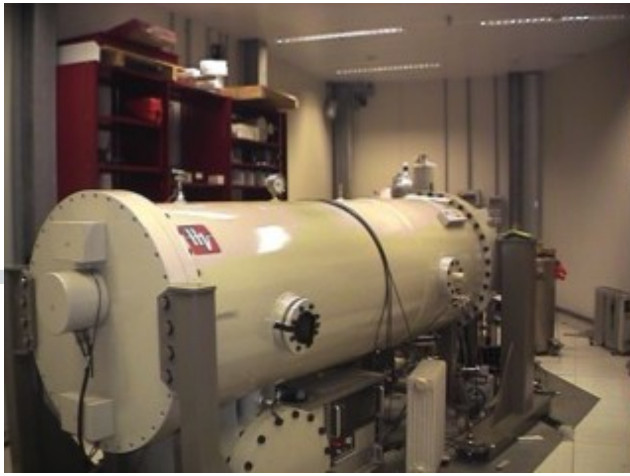
4 π detectors

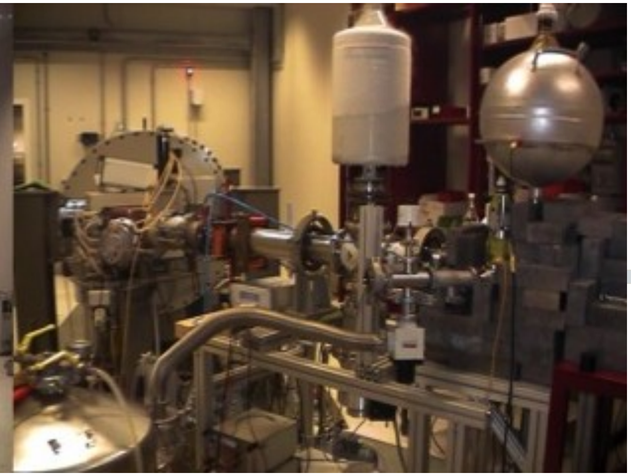
New accelerator at high beam intensity

- IMPROVEMENTS TO REDUCE THE BACKGROUND

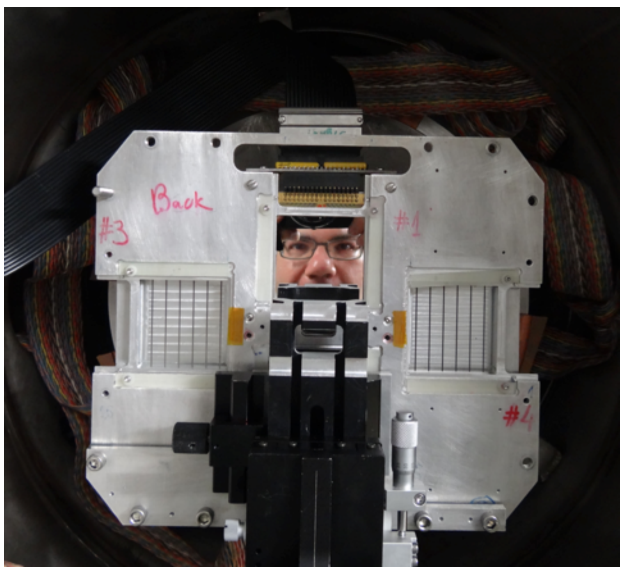
Use of laboratory with natural shield - (underground physics)

Use of magnetic apparatus (Recoil Mass Separator)



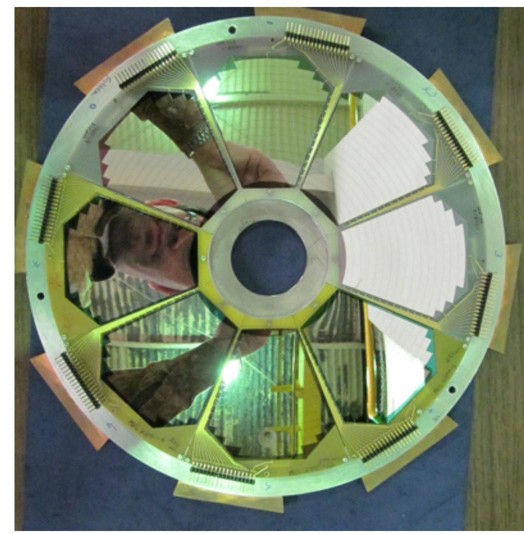


Luna underground facility INFN LNGS



TECSA array

TAMU C.S. & INFN LNS



Hard Work is necessary

To understand what we see

...

To try to go inside the problem

"Some people are so crazy that they actually venture into deep mines to observe the stars in the sky"

Naturalis Historia – Plinius, 44 A.D.

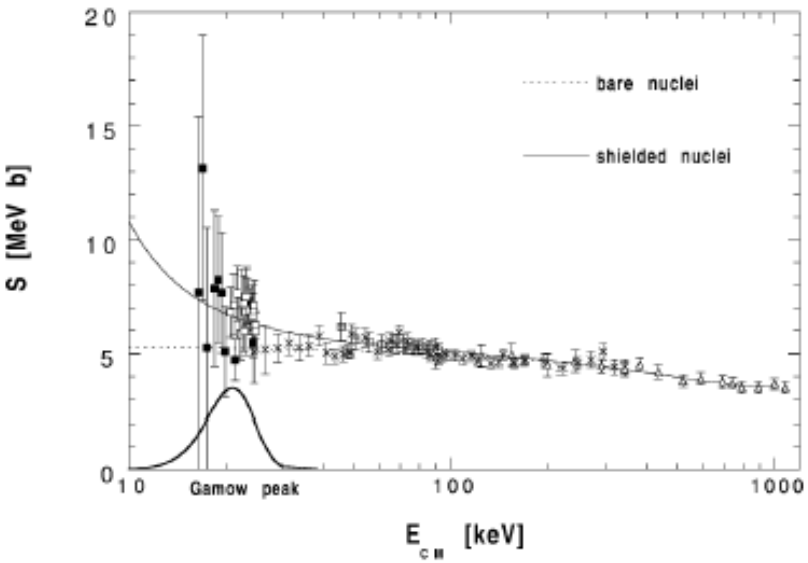
LUNA (Laboratory Underground for Nuclear Astrophysics)

50 kV accelerator @ Gran Sasso – Italy (1400 m rock -> 10^6 shielding factor)

Two reactions (solar pp chain) already studied at Gamow peak:

$^3He(^3He,2p)^4He$

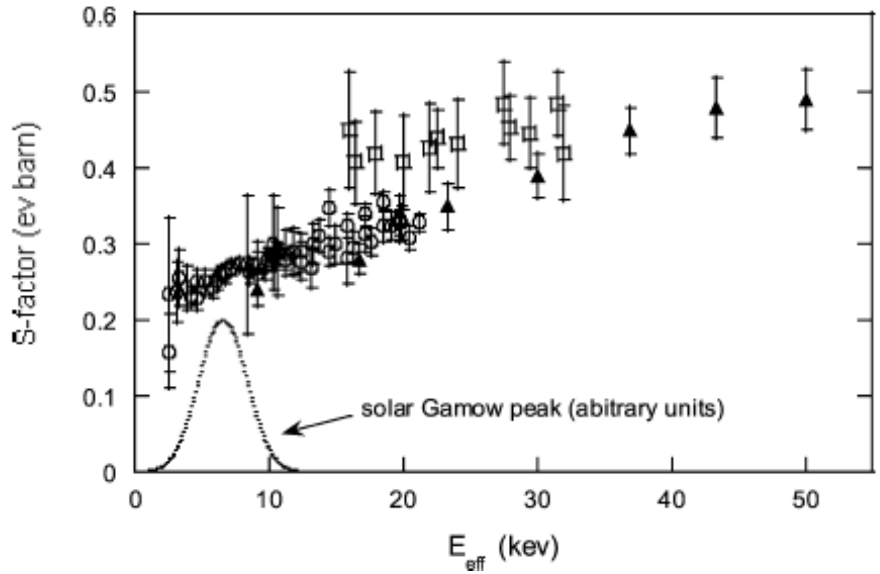
R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



At lowest energy: σ ~ 20 fb → 1 event/month

$d(p,\gamma)^3He$

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



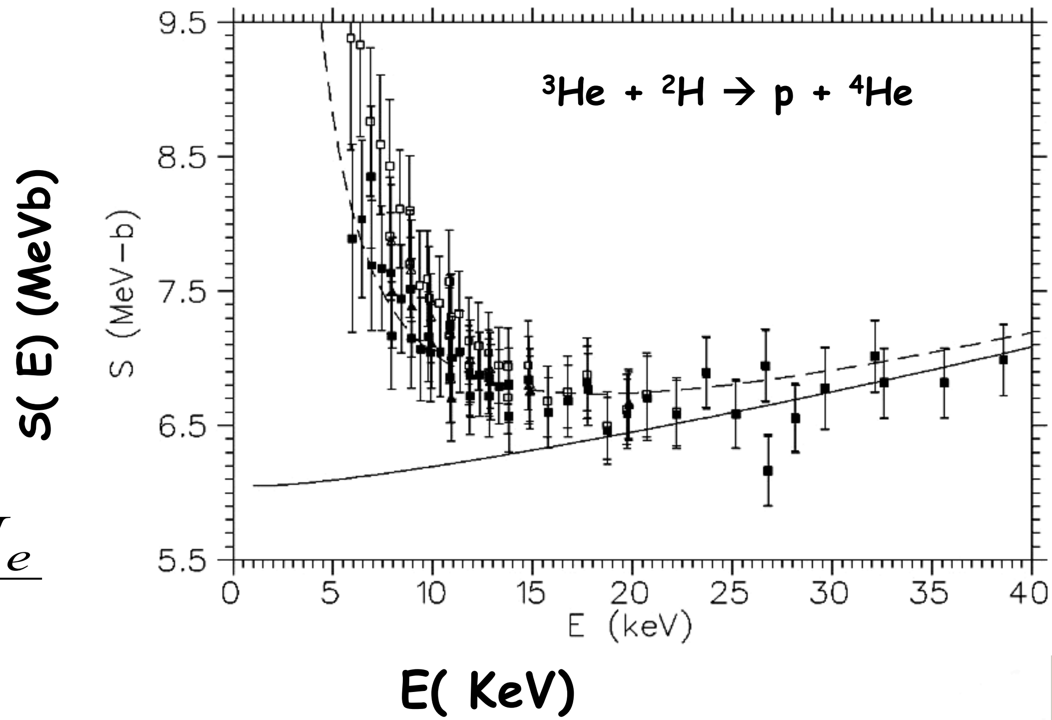
At lowest energy: σ ~ 9 pb → 50 counts/day

However The electron screening effect must be taken into account at such low energies

(Assenbaum,Langanke,Rolfs: Z.Phys.327(1987)461)

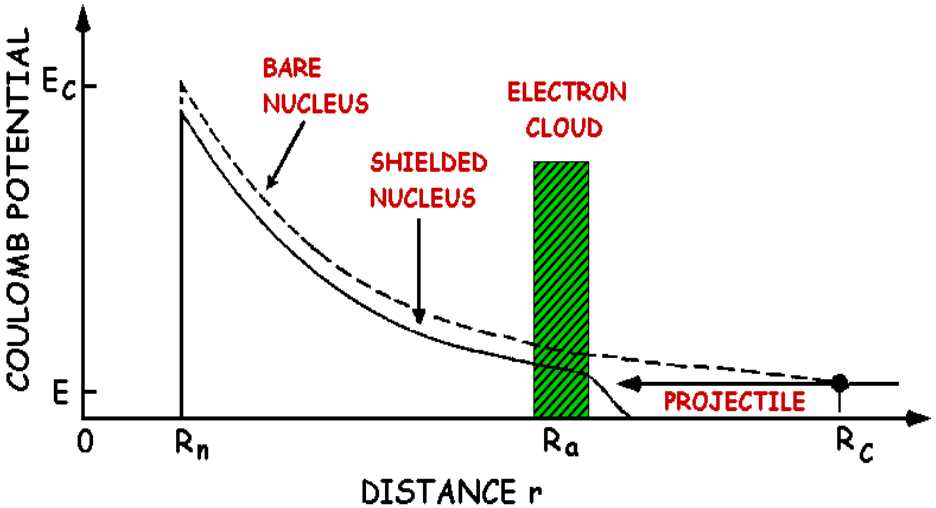
In the accurate measurements for the determination of nuclear cross-sections at the Gamow energy, in laboratory, enhancement $f_{lab}(E)$ –factor in the astrophysical $S_b(E)$-factor has been found

$$S_{Sh} \propto S_b \cdot e^{\frac{\pi\eta U_e}{E}}$$



Electron Screening

At astrophysical energies the presence of electron clouds must be taken into account in laboratory experiments.



The atomic electron cloud surrounding the nucleus acts as a screening potential U_e

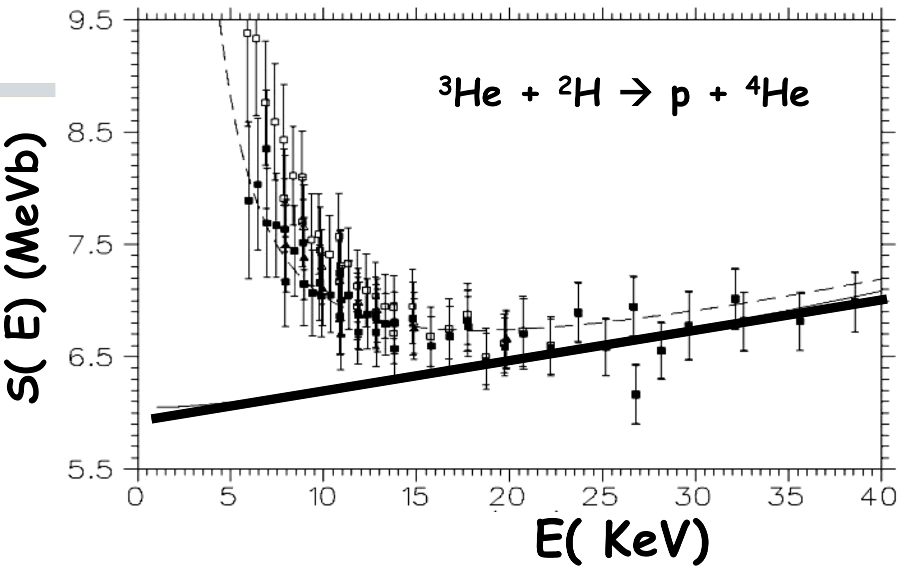
(Assenbaum H.J. et al.: 1987, Z. Phys., A327, 461)

- Phenomenoloaical approach

$$U_e = \frac{Z_1 Z_2 e^2}{R_a}$$

Electron screening in the laboratory

Direct Measurements



Stellar Screening ≠ Laboratory Screening

Experimental Data (Shielded)

Extrapolation of S_b (Bare)
Autofitting procedure

Correction for stellar screening
(Debye-Hückel theory)

An experimental measurement of U_e allows:

- a determination of S_b (applications)
- to study electron screening in laboratory conditions and then in stellar plasma

Since direct measurement are extremely time consuming and difficult (at astrophysical energies) or sometimes beyond present possibilities

Independent measurements of cross sections and electron screening potential U_e are needed !!!

↓

We need to be CLEVER: NEW IDEAS ARE NECESSARY

-to measure cross sections at never reached energies

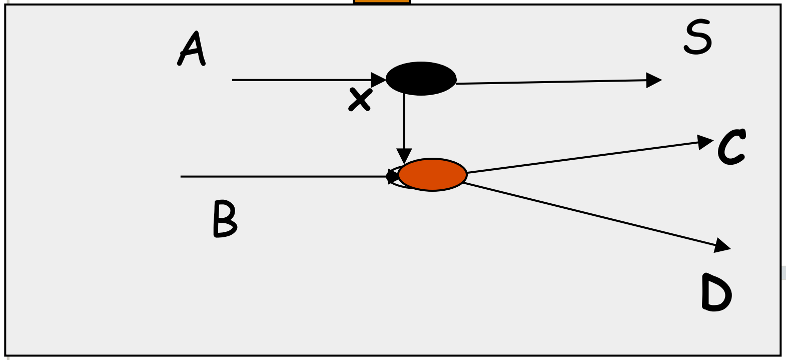
-to retrieve information on electron screening effect when ultra-low energy measurements are available.

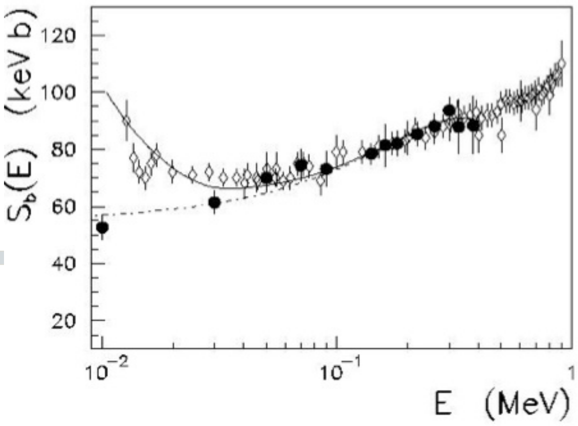
↓

INDIRECT METHODS ARE NEEDED

Indirect Methods in Nuclear Astrophysics (both stable and instable beams)

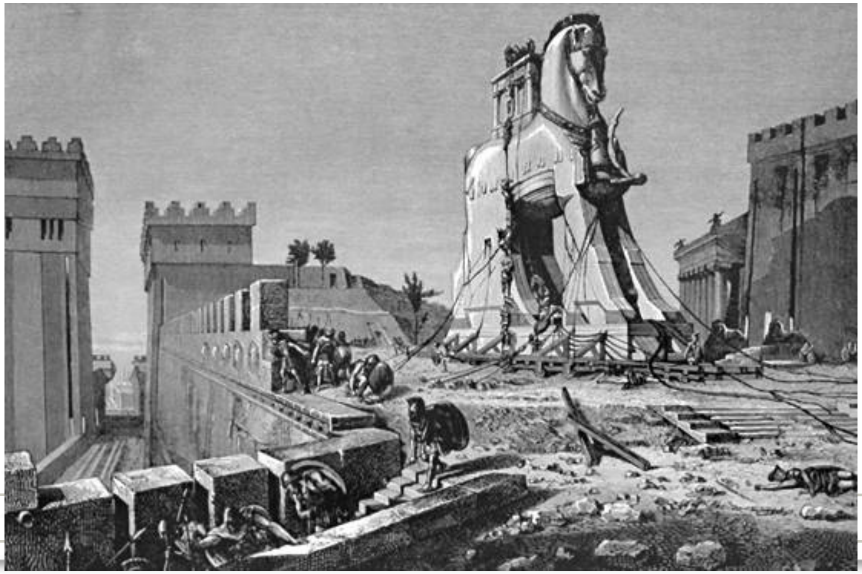
- Coulomb Dissociation
- ANC & transfer reactions
- Trojan Horse Method
- Break-up of loosely bound nuclei
- β-decay, resonant elastic scattering …

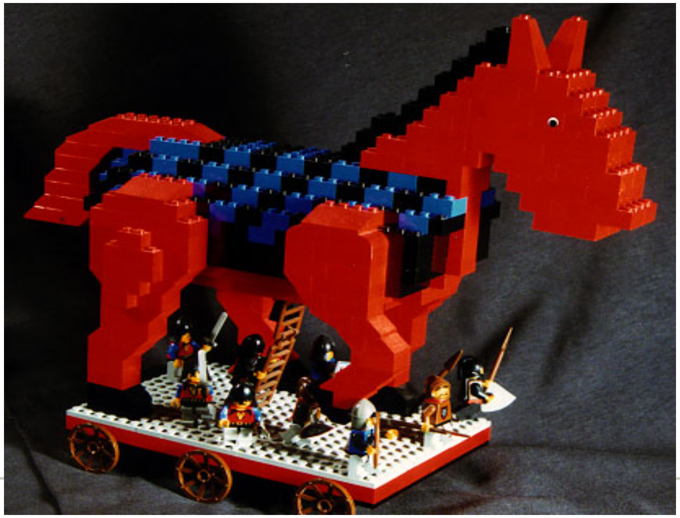




Part 4:

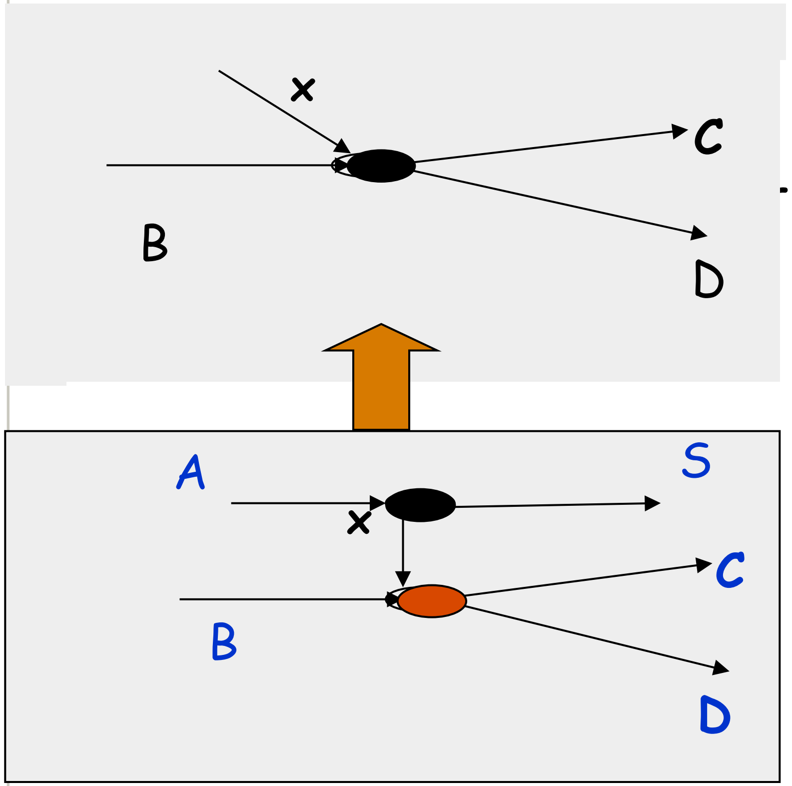
Trojan Horse Method





Trojan Horse Method

Quasi-Free mechanism



Basic idea:

It is possible to extract astrophysically the relevant two-body cross section σ

$B + x \rightarrow C + D$

from quasi- free contribution of an appropriate three-body reaction

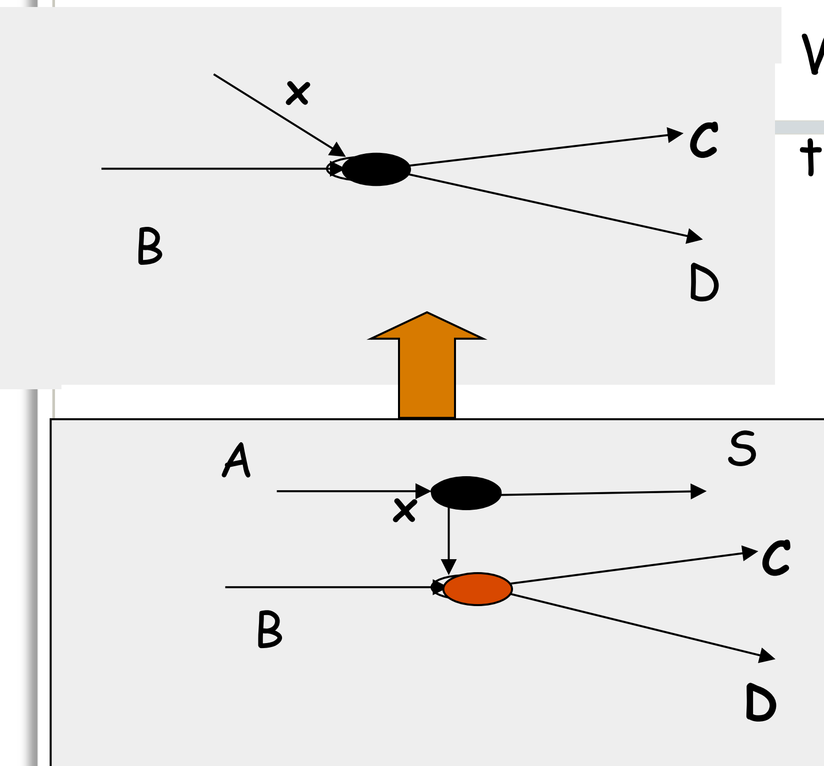
$A + B \rightarrow C + D + S$

-The A nucleus present a strong cluster structure: $A = x \oplus S$ clusters

-The x cluster (participant) interacts with the nucleus B

$B + x \rightarrow C + D$

-The S cluster acts as a spectator (it doesn' t take part to the reaction) and retains the same momentum it had in the entrance channel



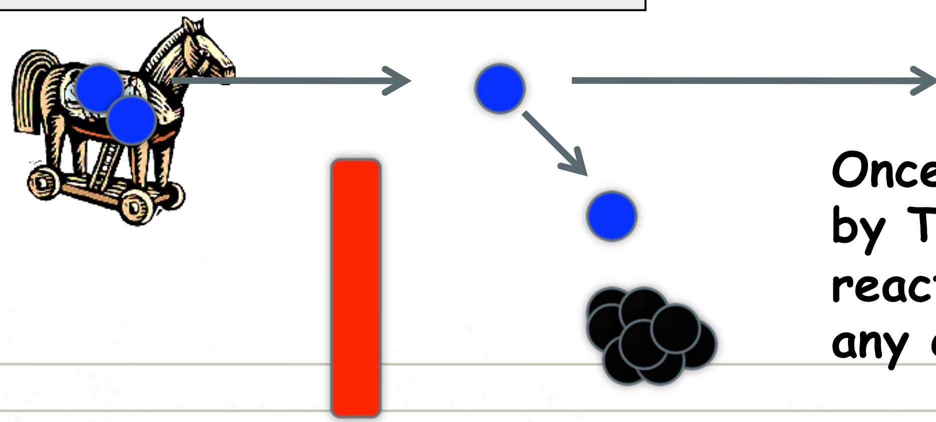
We can extract astrophysically relevant two-body cross section σ

B + x → C + D

from quasi- free contribution of an appropriate three-body reaction

A + B → C + D + S

Coulomb Barrier Suppression



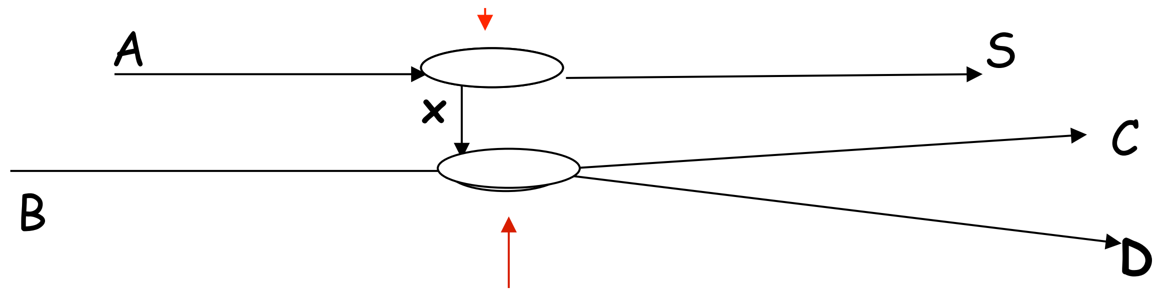
Once Coulomb barrier is overcome by TH nucleus the astrophysical reaction can take place without any evident suppression

Nuclear astrophysics experiments are fun because you never know what you're going to have as a result…

And like gambling
You hardly have money
to cover your expenses

But sometimes you win..
And you get results

virtual decay of nucleus A->x+S First vertex



In Plane
of the

Second vertex

virtual reaction x+B→C + D

corresponding to the two vertices

$$\frac{d^3\sigma}{dE_C\, d\Omega_C\, d\Omega_D} \propto KF\, [\Phi(q)_{xs}]^2 \left[\frac{d\sigma}{d\Omega}\right]$$

x + B→ C + D

Second vertex

First vertex

KF kinematical factor

$|\Phi(q_{xs})|^2$ describes the intercluster (x-S) momentum distribution

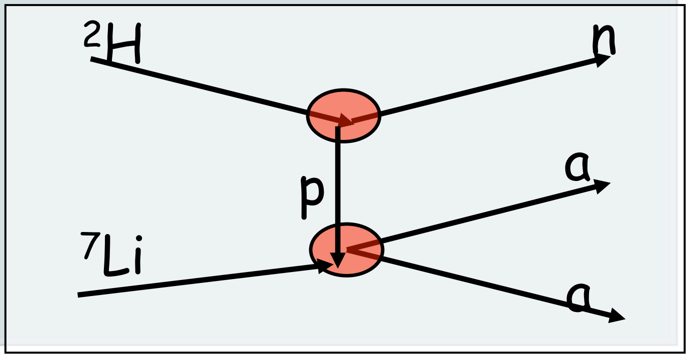
($d\sigma/d\Omega$) two-body cross section of the virtual reaction **x + B→ C + D**

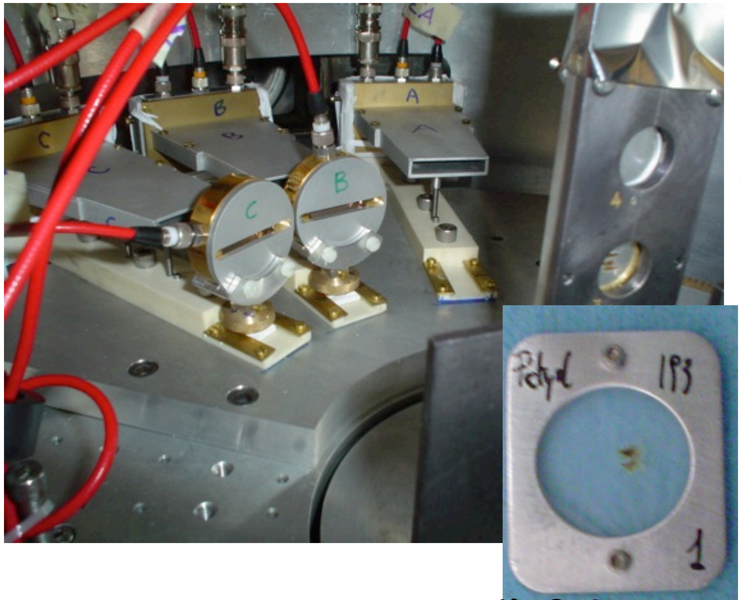
Advantages: Simple & cheap Experimental setup

THM: study of the $^7Li(p,\alpha)^4He$ reaction from the 3-body one:

$^2H(^7Li,\alpha\alpha)n$

TH nucleus deuteron, E_{beam}= 21 MeV @ LNS Catania





CD2 Target

Beam energy much higher than Barrier

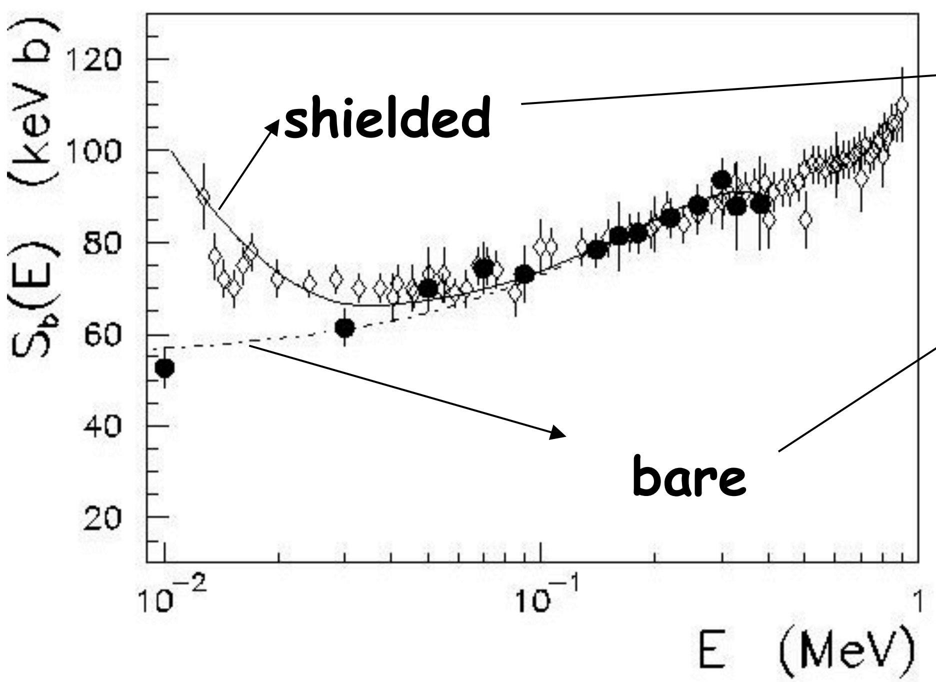
Angles were selected in such a way that the yeld from (the probable) quasi-free mechanism is maximum

Beams and Targets cheap. Detectors set-up trivial

Good ideas make research possible in tough times!!

Results

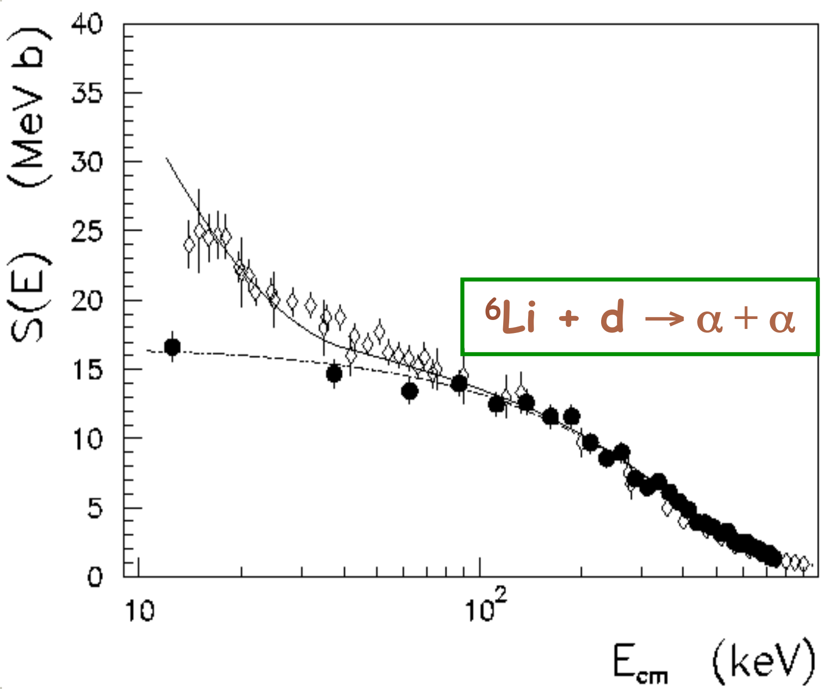
- If one assumes that THM gives the bare nucleus S factor (according to its properties) then by comparing it with direct data one can get the electron screening potential



$$S_{Sh} \propto S_b \cdot e^{\frac{\pi\eta U_e}{E}}$$

Screening potential

RGP et al. A&A 2003



U_e=340±50 eV

U_{ad}=186 eV

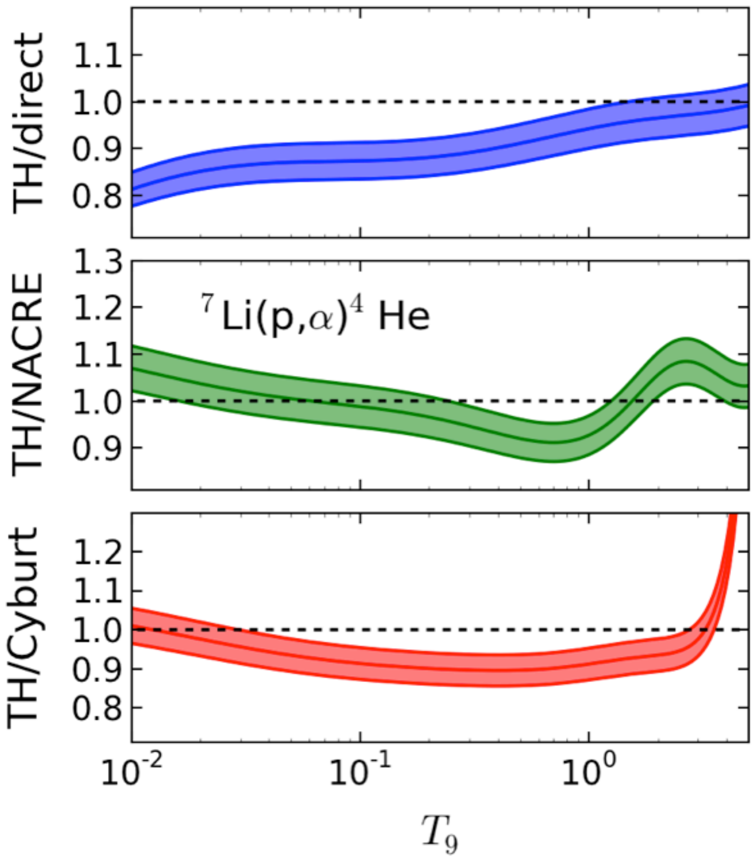
S_0=16.9 MeV b

◊ Engstler S. et al.: 1992, Z. Phys., A342, 471

• C. Spitaleri et al.: 2001, Phys. Rev. C. 63, 055801

- No screening effect at E<100 keV for indirect data;
- Direct and indirect methods are complementary;
- Independent determination of $S_b(E)$ and U_e;
- Previous extrapolations of S_b are confirmed.

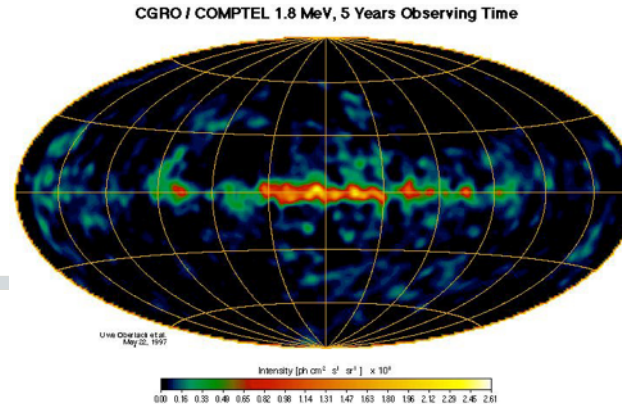
Reaction Rate



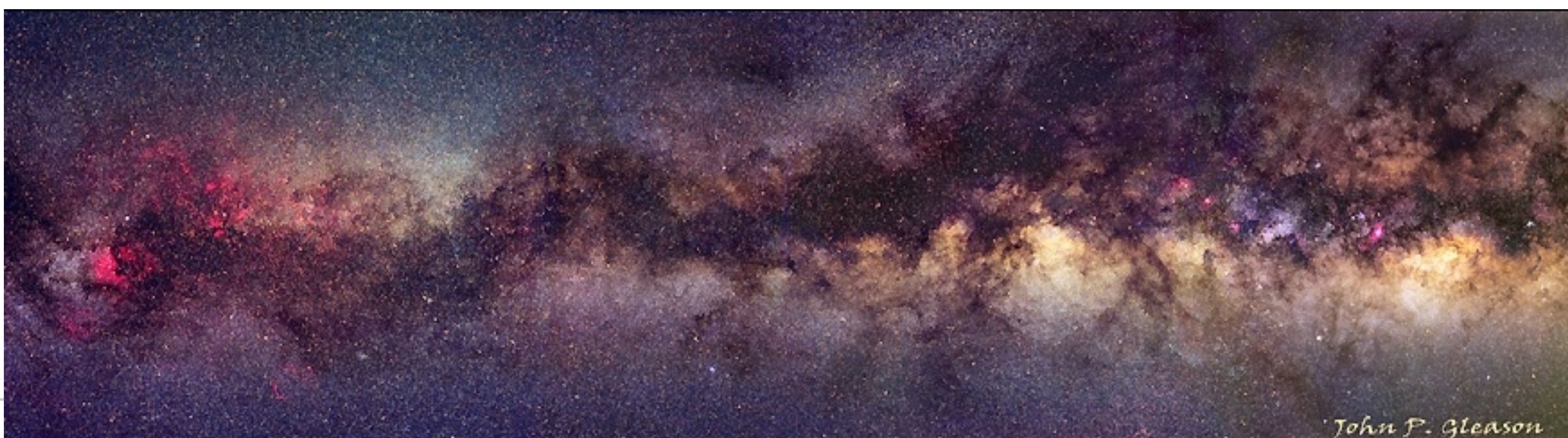
$$\langle\sigma v\rangle_{12} = \left(\frac{8}{\pi\mu_{12}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E)\,\exp\left(-\frac{E}{kT}\right) E\,dE$$

Reaction rate obtained for the 7Li(p,a)4He from THM measure compared with other compilations

Coll. R.G.P, R. Spartà & C.B.



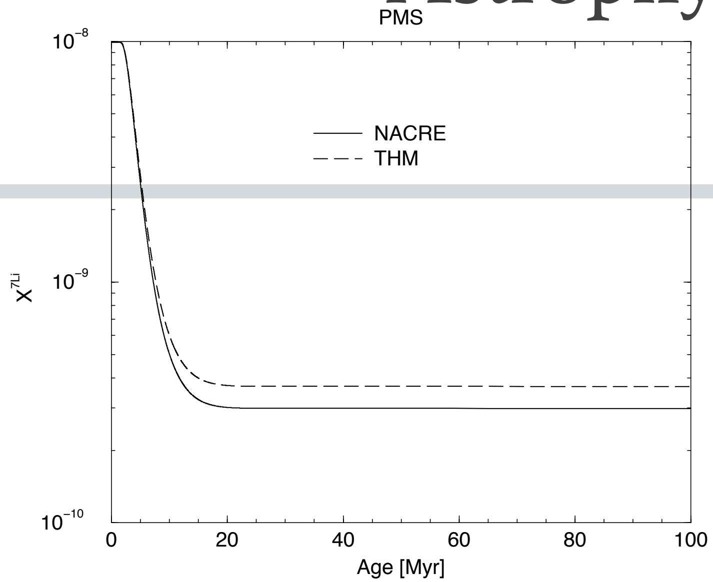
Part 5: ^{6,7}Li and its astrophysical relevance

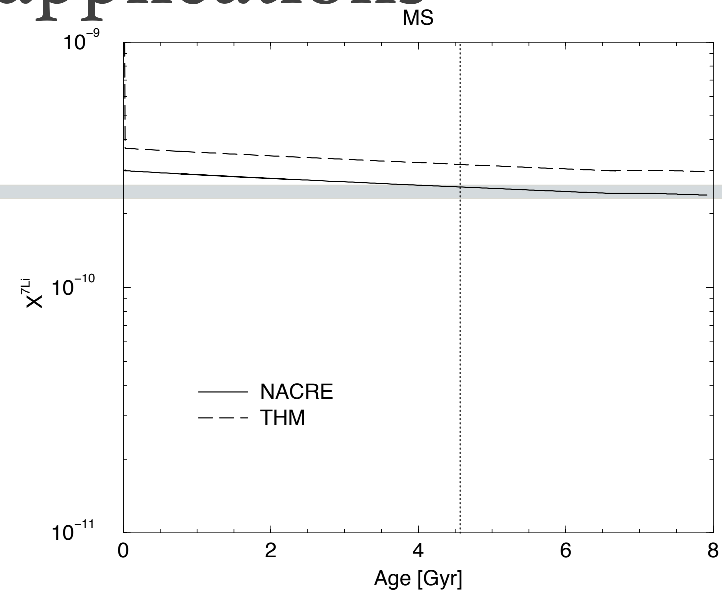


Lithium is important for:

- Probing stellar interiors and structure (need of abundances measurements, stellar modeling, Astro-seismology)
- Probing Primordial nucleosynthesis and early universe
- Fusion reactors and electron screening application

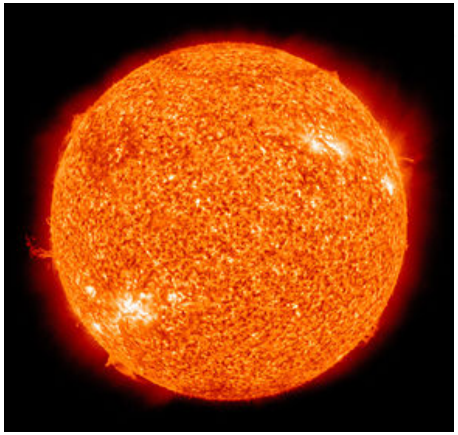
Astrophysical applications



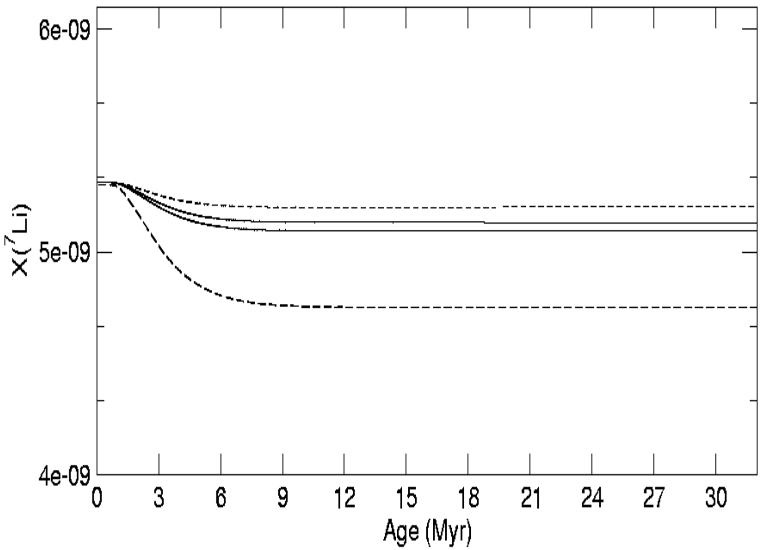


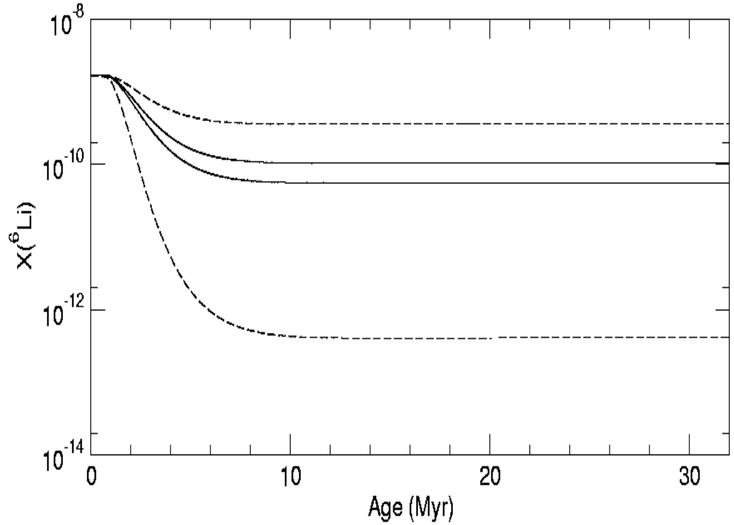
Lithium surface abundance for the Sun,
Good agreement with NACRE results

RPG et al., A&A 2003



Lithium Destruction in disk stars: astrophysical Uncertainties vs. nuclear inputs





Solid lines: THM uncertainties for nuclear rates
Dashed lines: Astrophysical uncertainties (mass=0.9-1 M_O,He abundance =0.24-0.27, convection efficiency)

The Collaboration

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Further reading

BOOKS

W.D. Arnett & J.W. Truran	*Nucleosynthesis* The University of Chicago Press, 1968
E. Böhm-Vitense	*Introduction to Stellar Astrophysics, vol. 3* Cambridge University Press, 1992
D.D. Clayton	*Principles of stellar evolution and nucleosynthesis* The University of Chicago Press, 1983
C. Bertulani	Nuclear Physics in a Nutshell Princeton Univ. Press
C.E. Rolfs and W.S. Rodney	*Cauldrons in the Cosmos* The University of Chicago Press, 1988
C. Iliadis	Nuclear Physics of Stars - Wiley

REVIEW PAPERS

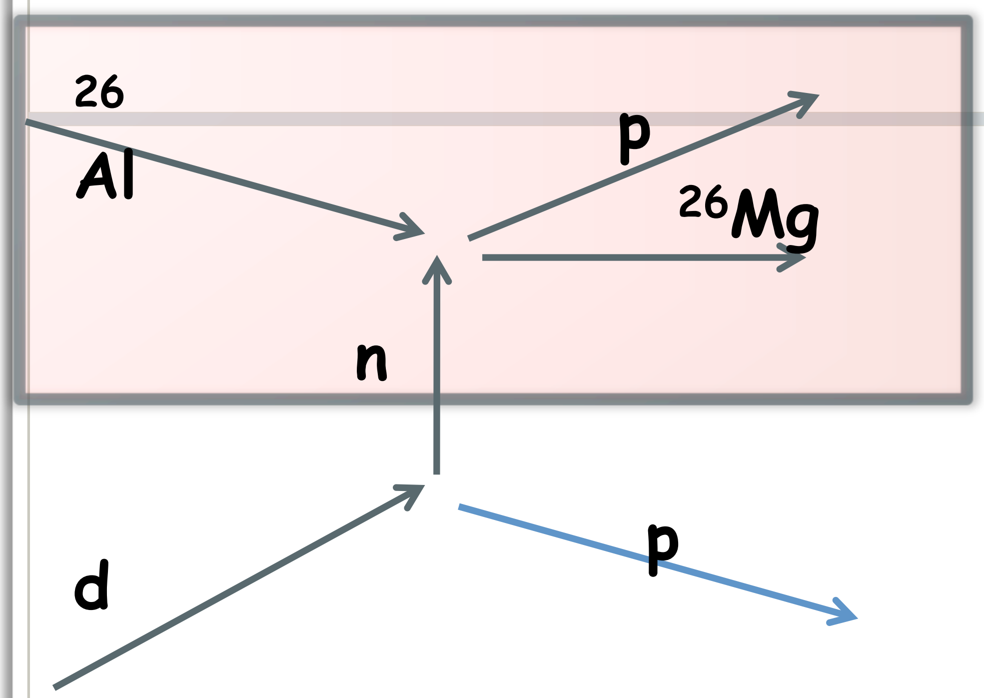
<u>Not an exhaustive list!!</u>

R. Boyd:	Nucl. Phys. A693 (2001) 249-257	*Big Bang Nucleosynthesis*
C. Rolfs:	Progr. Part. Nucl. Phys. 46 (2001) 23	*Nuclear reactions in stars*
Thielemann et al.:	Part. Nucl. Phys. 46 (2001) 5-22	*Element synthesis in stars*
Spitaleri et al:	*Phys. Rev. C (2001) 055801*	*Trojan Horse Method*

The main difficulties for experimental measurement of this cross section derive from:

- ^{26}Al is an unstable isotope. Moreover also cross sections of reactions induced by metastable state should be known with good precision
- Necessity of a n beam at astrophysical energies

Necessity of a THM measurement



Quasi-free break-up of deuteron

Beam Energy around 60 MeV

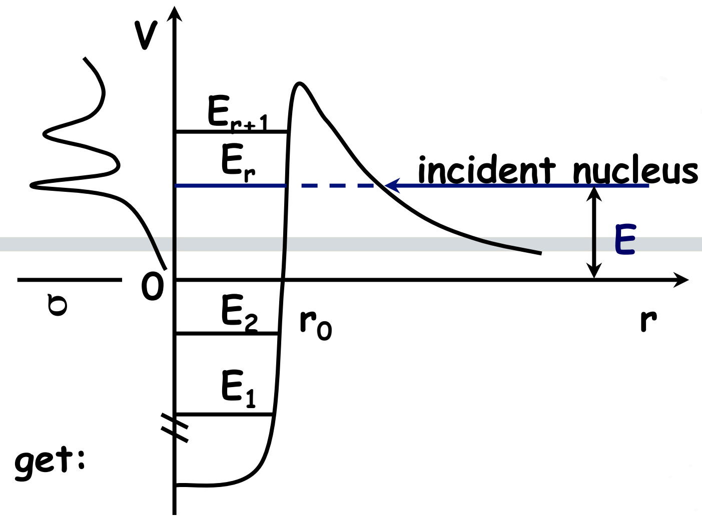
Coincidence detection of p and ^{26}Mg.

This will allow to measure the excitation
function of the reaction of interest
In the astrophysical energy range
(0-1 MeV)

Once the 3-particle in exit channel reaction cross section is measured, one can
Extract the binary cross section at astrophysical energies according to the prescriptions of th THM

Resonant reactions

1. Narrow resonances $\Gamma_R \ll E_R$



Breit-Wigner formula

$$\sigma(E)_{BW} = \pi\lambda\!\!\!^{-2}(1+\delta_{12})\frac{2J+1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_a\,\Gamma_b}{(E-E_r)^2 + (\Gamma/2)^2}$$

Insert in expression for reaction rate, integrate and get:

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

$$\langle\sigma v\rangle_{12} = \left(\frac{2\pi}{\mu_{12}kT}\right)^{3/2}\hbar^2\sum_i(\omega\gamma)_i \exp\left(-\frac{E_{R_i}}{kT}\right)$$ (for many resonances)

$$(\omega\gamma)_R = (1+\delta_{12})\frac{2J+1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_a\,\Gamma_b}{\Gamma}$$

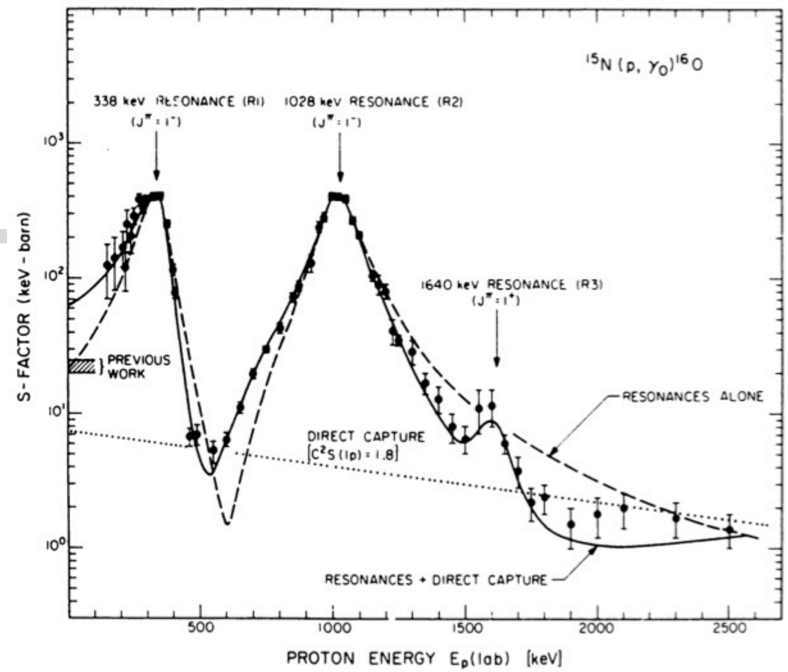
resonance strength
→ integrated cross section over resonant region

Experiment: determine $(\omega\gamma)_R$ and E_R

N.B. $\langle\sigma v\rangle_{12} \propto \exp\left(-\frac{E_R}{kT}\right)$ ➡ Low-energy resonances (E_R → kT) are VERY important

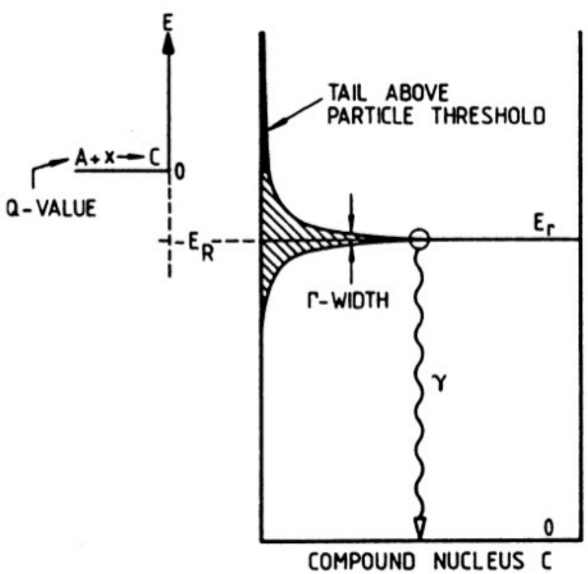
2. Broad resonances $\Gamma_R \sim E_R$

Breit-Wigner formula
+
energy dependence of partial and total widths



N.B. Overlapping broad resonances of same J^π
→ interference effects

3. Sub-threshold resonances



S-factor can be entirely dominated
by contribution of sub-threshold state(s)

if interference effects are negligible,
total reaction rate

$$\langle \sigma v \rangle_{tot} = \langle \sigma v \rangle_r + \langle \sigma v \rangle_{nr}$$

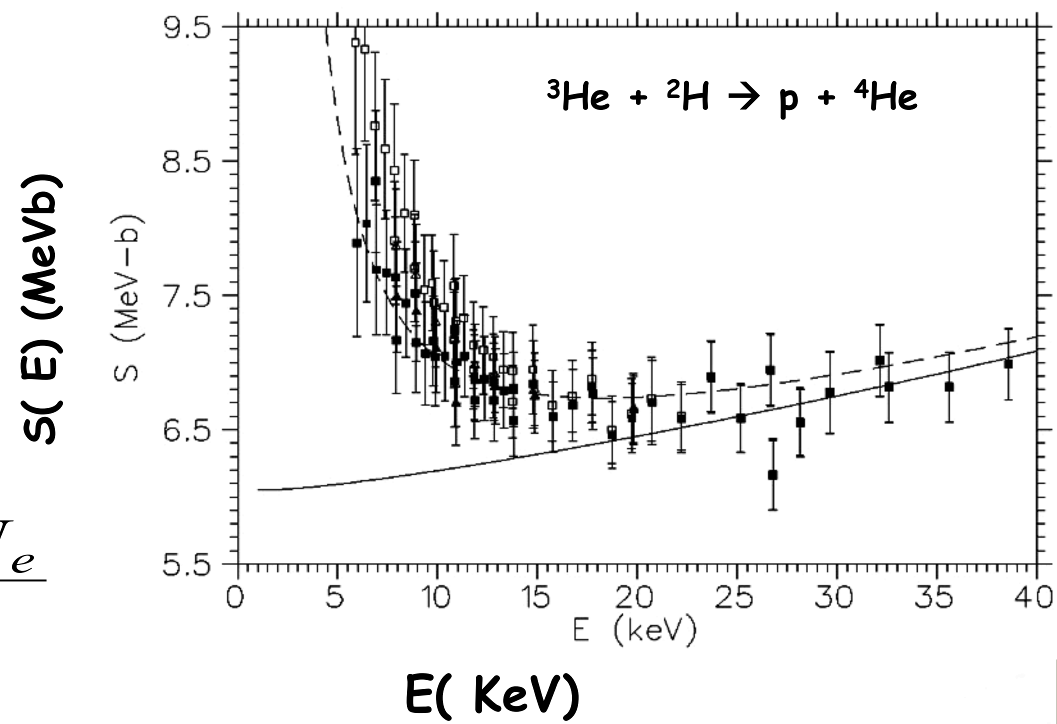
However

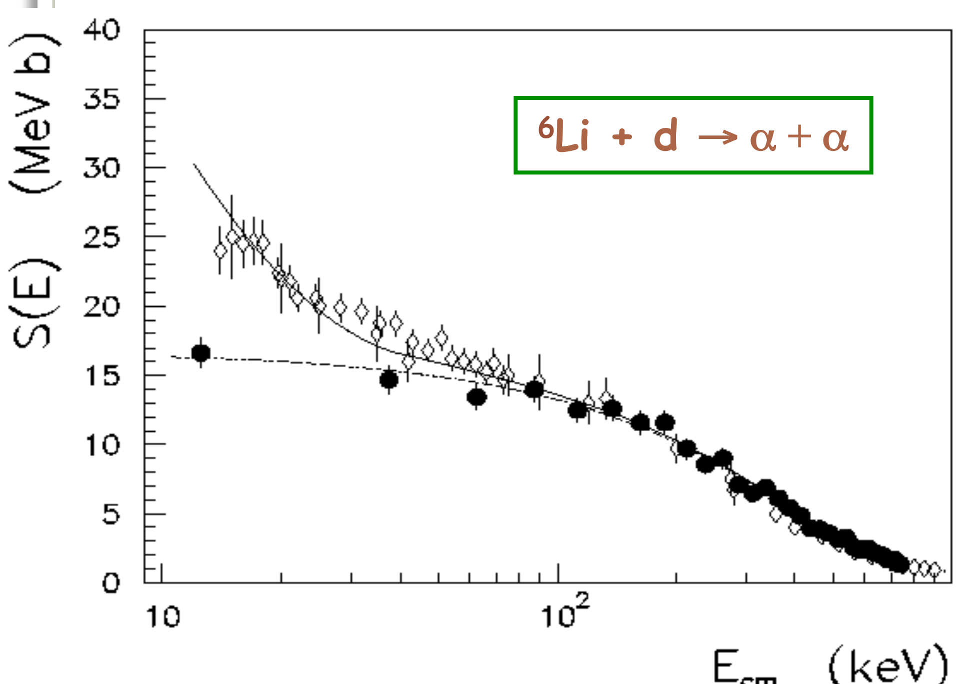
The electron screening effect must be taken into account

(Assenbaum,Langanke,Rolfs: Z.Phys.327(1987)461)

In the accurate measurements for the determination of nuclear cross-sections at the Gamow energy, in laboratory, enhancement $f_{lab}(E)$ –factor in the astrophysical $S_b(E)$-factor has been found

$$S_{Sh} \propto S_b \cdot e^{\frac{\pi \eta U_e}{E}}$$





U_e=340±50 eV

U_{ad}=186 eV

S_0=16.9 MeV b

◊ Engstler S. et al.: 1992, Z. Phys., A342, 471

• C. Spitaleri et al.: 2001, Phys. Rev. C. 63, 055801

S. Cherubini et al.: 1996 Ap. J., 457, 855

- No screening effect at E<100 keV for indirect data;
- Direct and indirect methods are complementary;
- Independent determination of $S_b(E)$ and U_e;
- Previous extrapolations of S_b are confirmed.

Data Analysis Phases:

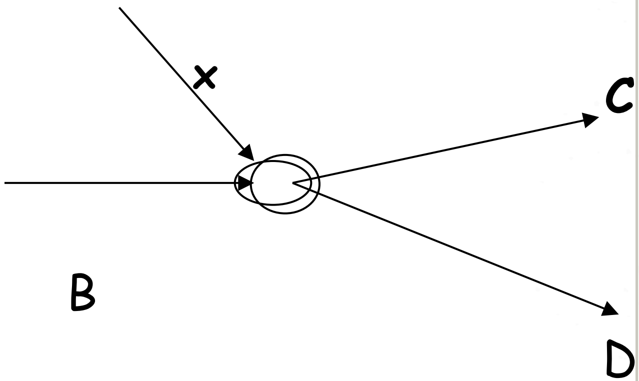
- Find the 3-body reaction of interest among the ones occurring in the target.
- Separate the quasi-free mechanism from all the others
- Measure the binary reaction cross section from the three body one
- Normalization and comparison to direct data: validity test and measurement of astrophysical interest
- Extraction of electron screening potential, reaction rate and so on.

Two body reaction takes place at:

$$E_{qf.} = E_{Bx} - B_{x\text{-}s} \quad = E_{cD} - Q_{2b}$$

Where

E_{Bx} is the beam energy in the center of mass of the two body reaction

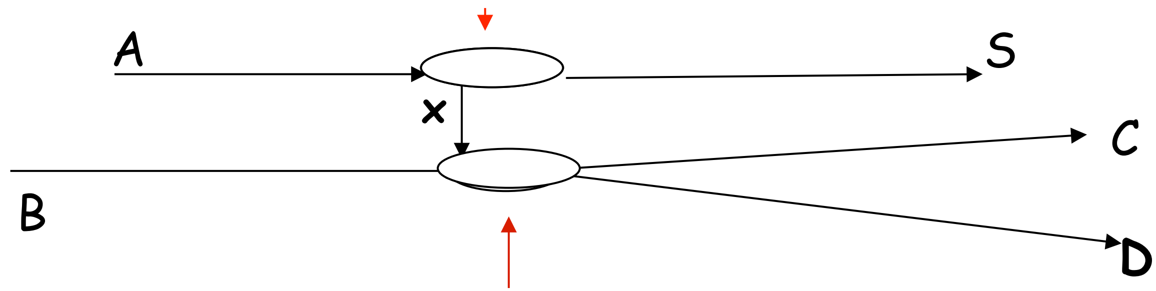


$B_{x\text{-}s}$ binding energy of the two clusters inside the Trojan Horse plays a key role in compensating for the beam energy

(under proper kinematical conditions) $E_{qf} \sim 0$

virtual decay of nucleus A->x+S First vertex

In Plane
of the



virtual reaction x+B→C + D

corresponding to the two vertices

$$\frac{d^3\sigma}{dE_C\, d\Omega_C\, d\Omega_D} \propto KF \; [\Phi(q)_{xs}]^2 \left[\frac{d\sigma}{d\Omega}\right]$$

x + B→ C + D Second vertex

First vertex

KF kinematical factor

$|\Phi(q_{xS})|^2$ describes the intercluster (x-S) momentum distribution

$(d\sigma/d\Omega)$ two-body cross section of the virtual reaction **x + B→ C + D**