Trojan Horse Method: a powerful tool to study nuclear reactions at astrophysical energies

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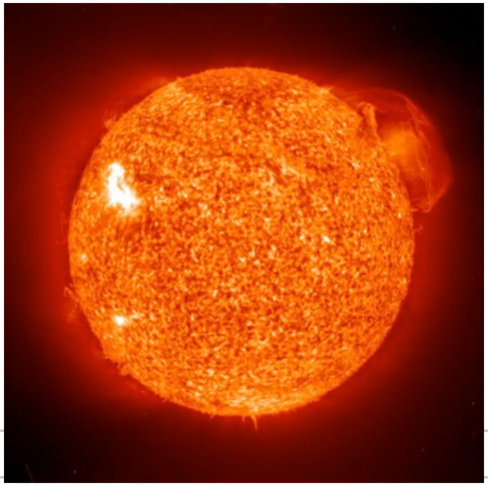
Or… Experimental challenges in nuclear astrophysics

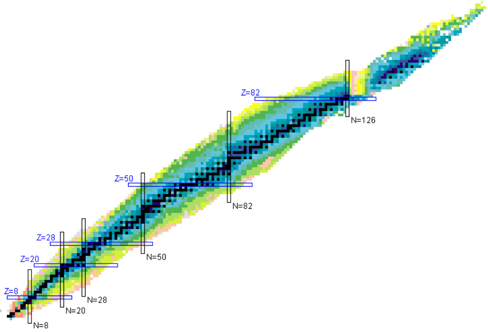
Exploring the connection between micro- and macro-cosmos

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

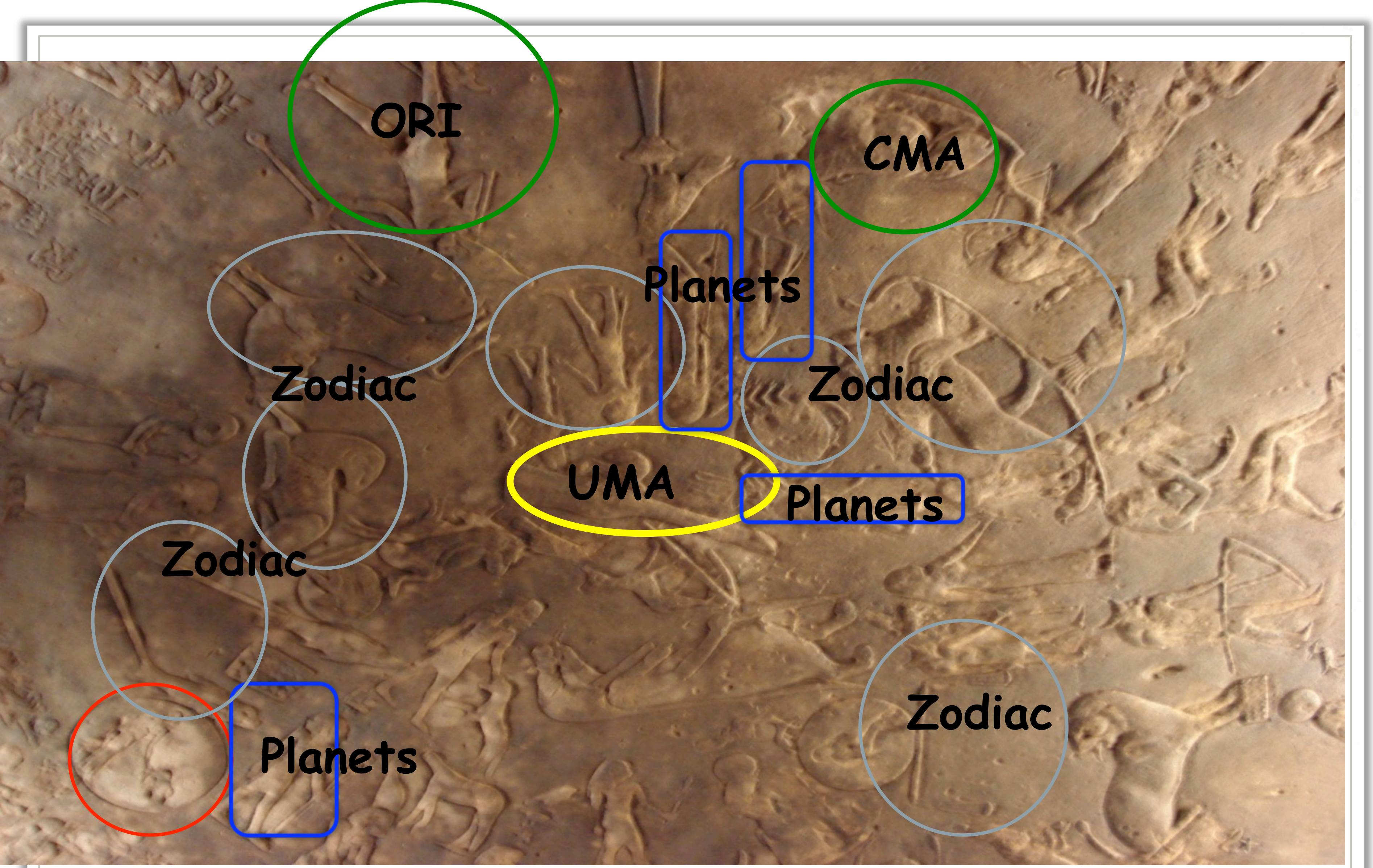
Part 1 : Introduction





OUTLINE

- Main questions and issues for nuclear astrophysics
- Some necessary definitions
- Direct methods: the LUNA project @ Gran Sasso Lab
- Indirect Methods
- Trojan Horse Method
- Some results by THM
- Astrophysical contexts where THM has played a role



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

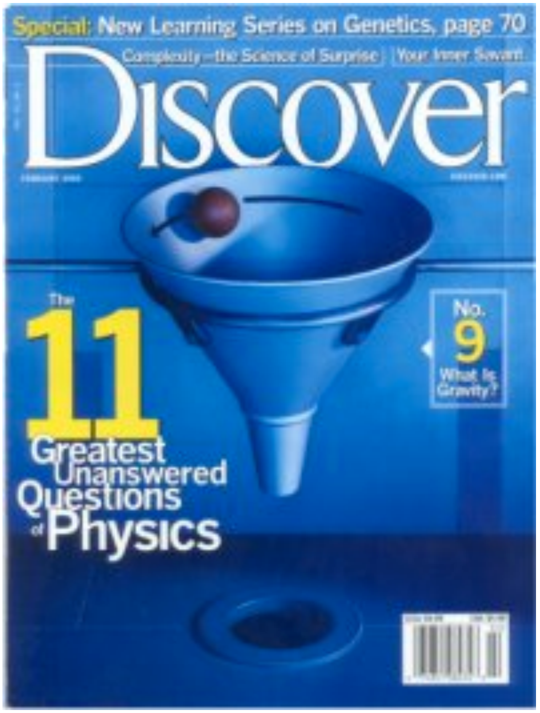
Nuclear Astrophysics: study of nuclear processes which take place in the Universe

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??



The February 2002 issue of Discover magazine based its cover story on the recent 105-page public draft of the National Research Council Committee on Physics of the Universe report, Connecting Quarks with the Cosmos: 11 Science Questions for the New Century

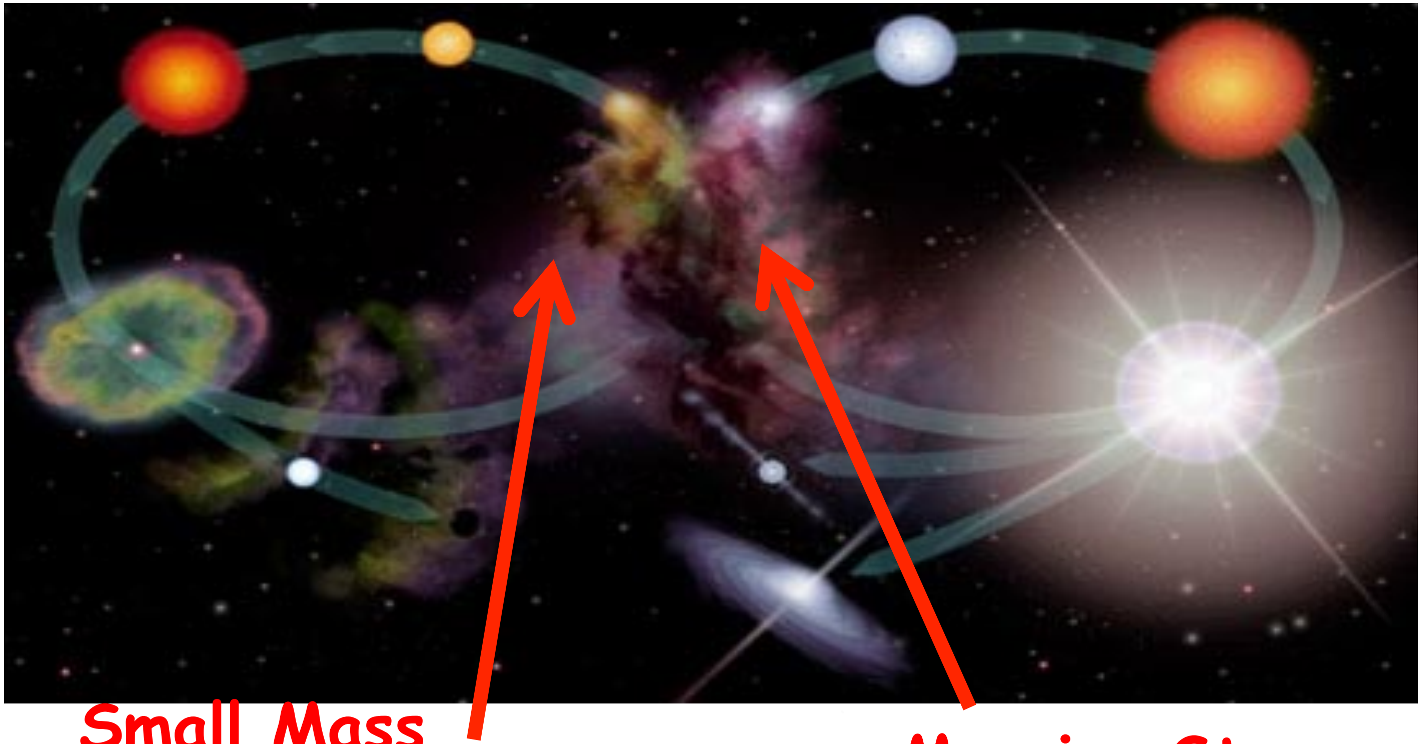
#3 Scientist's understanding of the production of elements up to iron in stars and supernovae is fairly complete, but the precise origin of the heavier elements from iron to uranium remains a mystery.

#11 How did the Universe Begin?
WMAP & Planck connection to primordial Nucleosynthesis!!!

Another issue: how stars evolve?

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

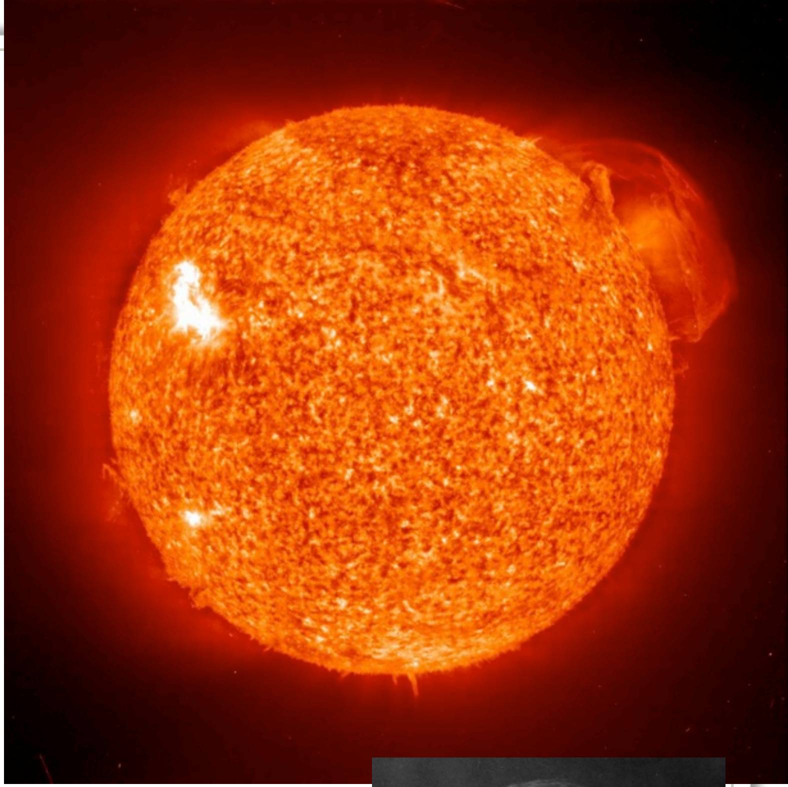
The birth of a start: Galactic gas and powder



Small Mass
Star (Sun)

Massive Star

We know from geology Earth is 4.65 x10^9 years old. What source can guarantee solar luminosity for such a long time?



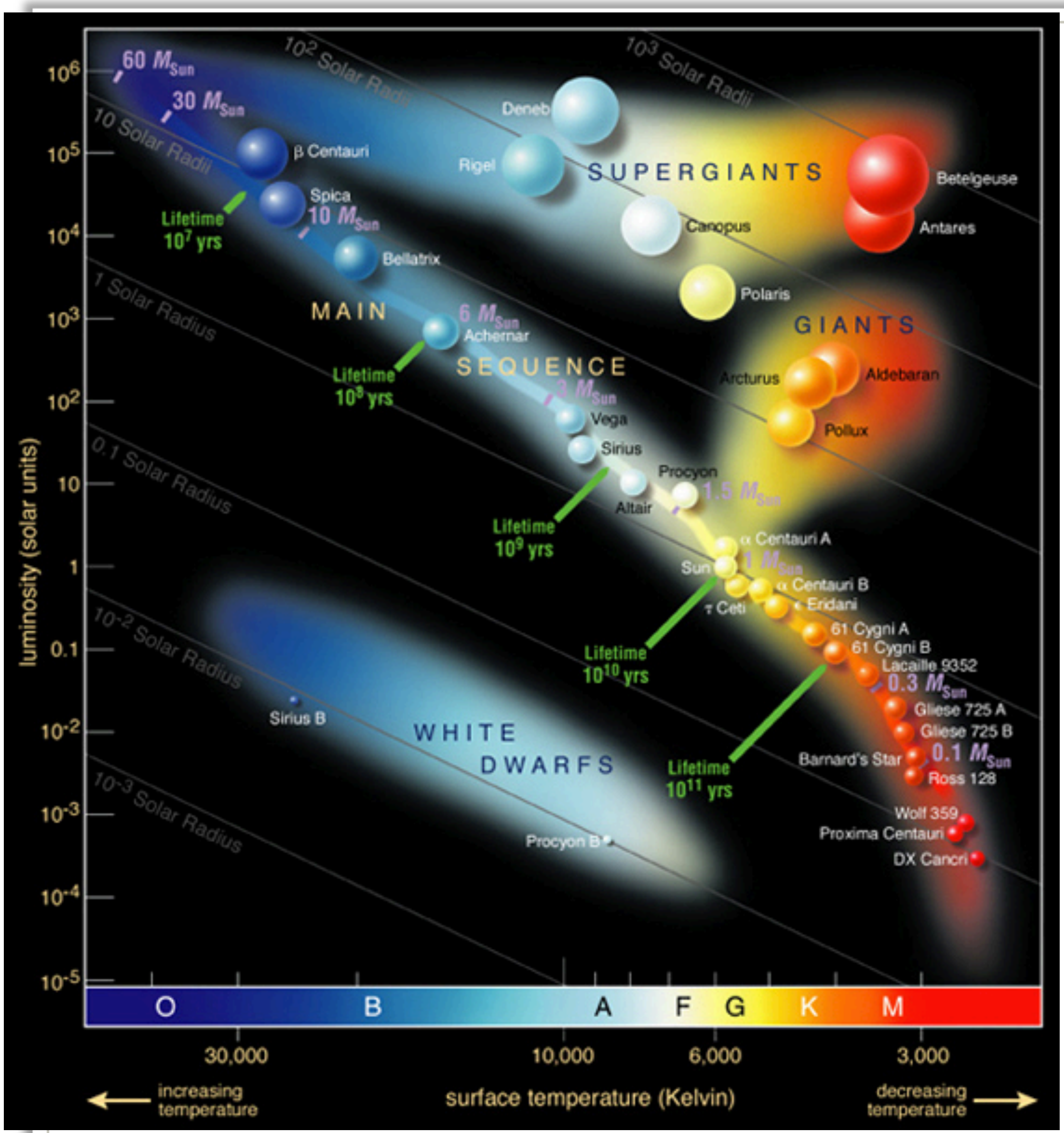
Gravitational contraction?

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?

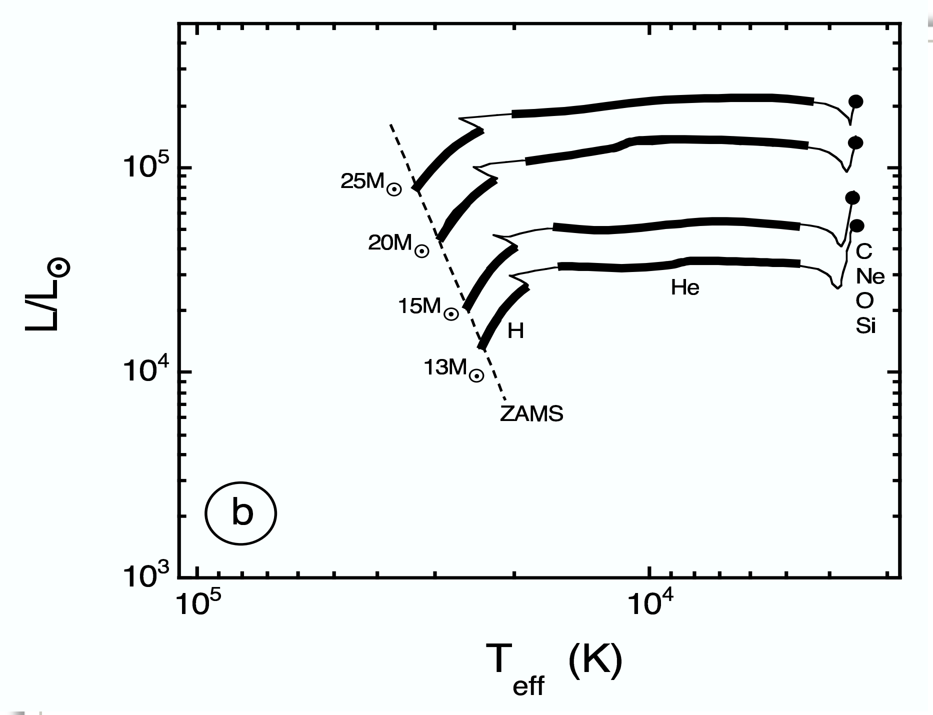
First ideas suggested 4 H nuclei can merge into a He
Producing energy from mass defect (Eddington)



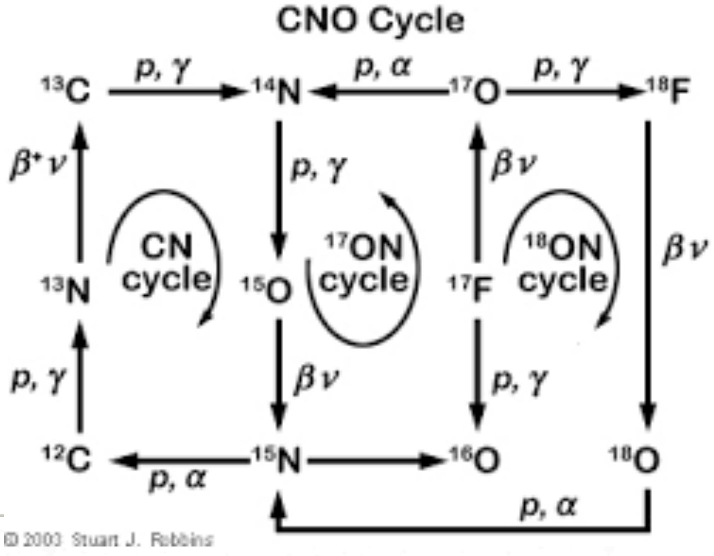
Each phase of a star's Life depends on nuclear Reactions and some nuclear properties

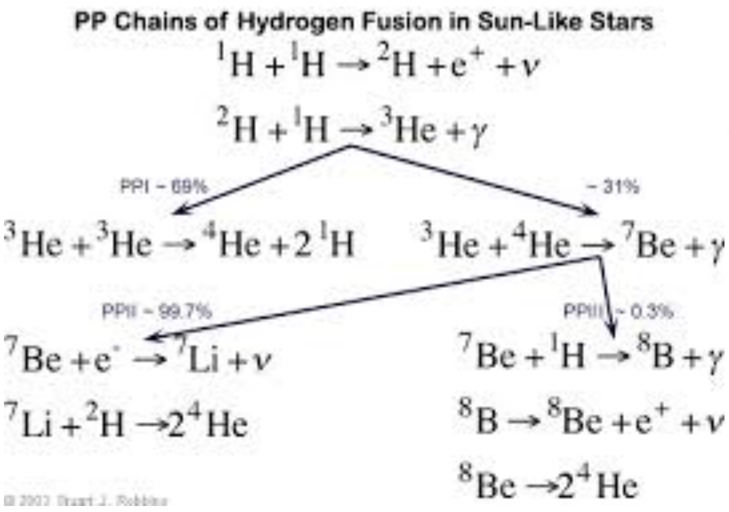
e.g. light elements burning (PMS),
H-burning (MS)
He burning (AGB)
C-O burning massive stars

Energy generation in stars is due to nuclear astrophysics processes



Massive stars





PP Chains of Hydrogen Fusion in Sun-Like Stars

$^1H + ^1H \rightarrow ^2H + e^+ + \nu$

$^2H + ^1H \rightarrow ^3He + \gamma$

PPI ~ 69% | ~ 31%

$^3He + ^3He \rightarrow ^4He + 2\,^1H$ | $^3He + ^4He \rightarrow ^7Be + \gamma$

PPII ~ 99.7% | PPIII ~ 0.3%

$^7Be + e^- \rightarrow ^7Li + \nu$

$^7Li + ^2H \rightarrow 2\,^4He$

$^7Be + ^1H \rightarrow ^8B + \gamma$

$^8B \rightarrow ^8Be + e^+ + \nu$

$^8Be \rightarrow 2\,^4He$

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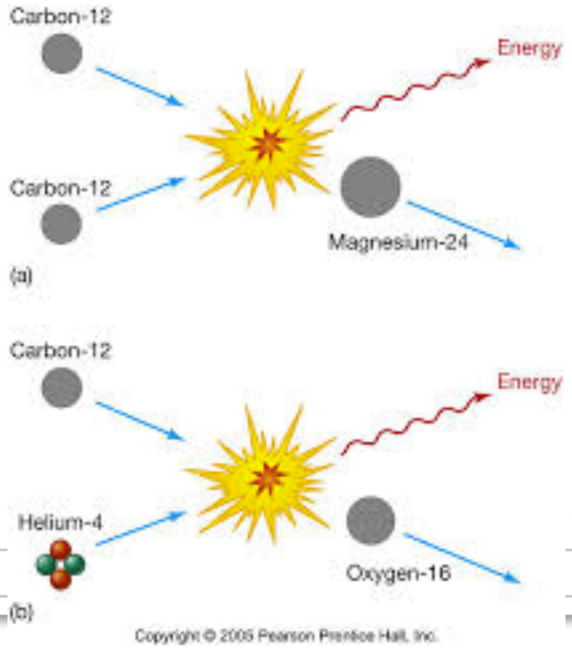
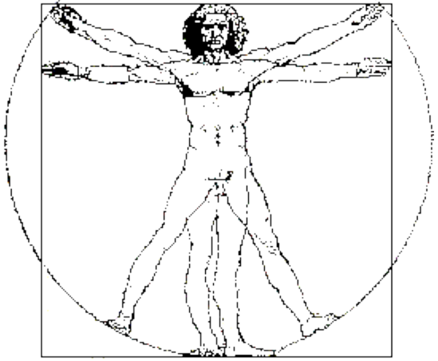
P-p chain Solar like stars



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

Man: H,C,N,O



Sun: H, He

Earth: Fe, Si, O, Mg

U

Au

Li

A "cosmic abundance"?

Meteorites: Fe, Ni

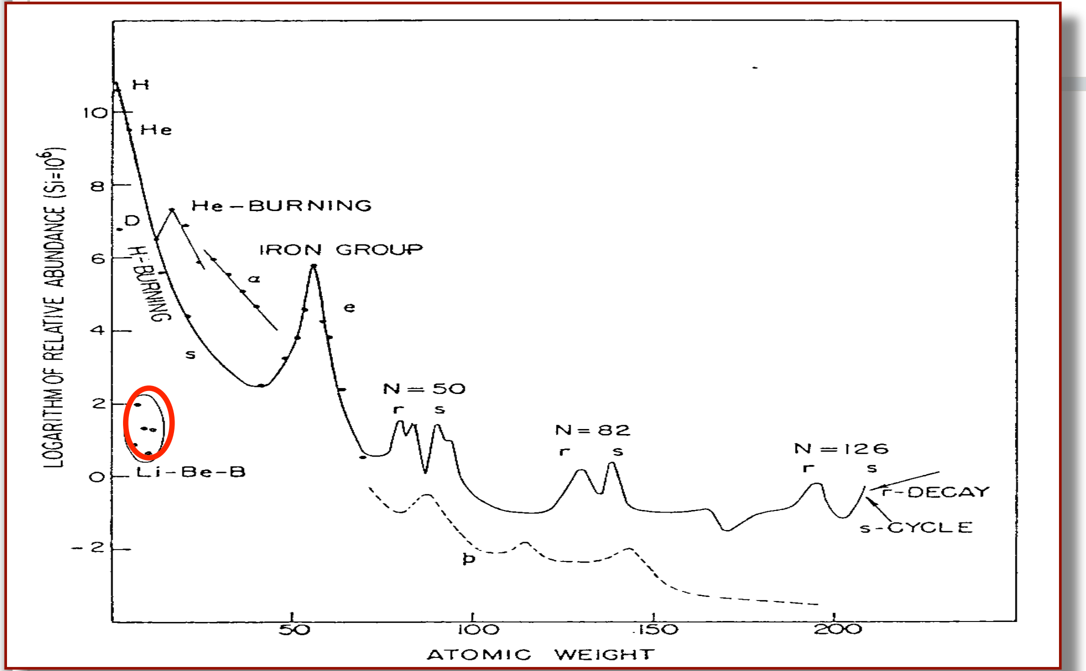
The elemental abundance in the universe is determined in the Solar neighborhood and is assumed to be Universal.

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

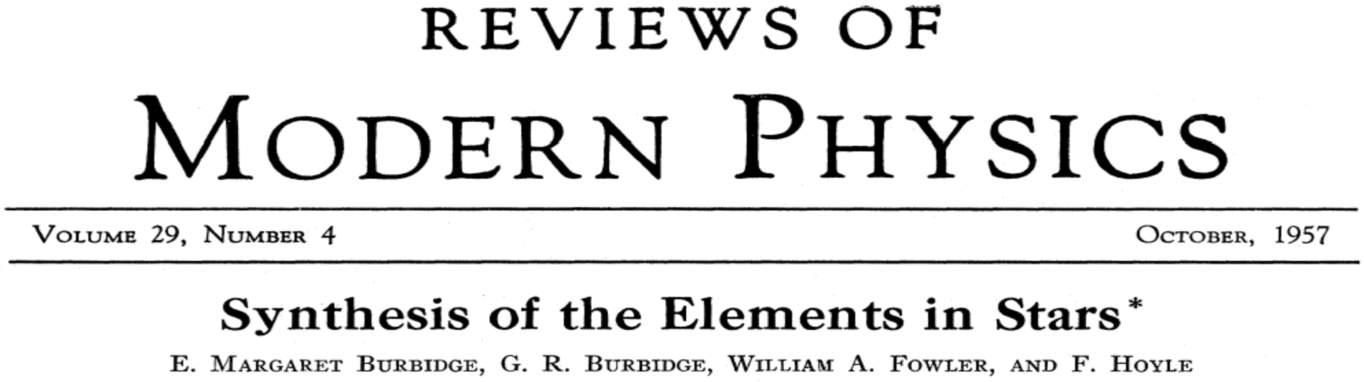
The answer to such question is given by…
Nuclear astrophysics

- **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

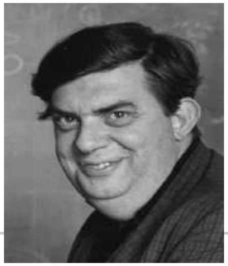
VOLUME 29, NUMBER 4 OCTOBER, 1957

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.

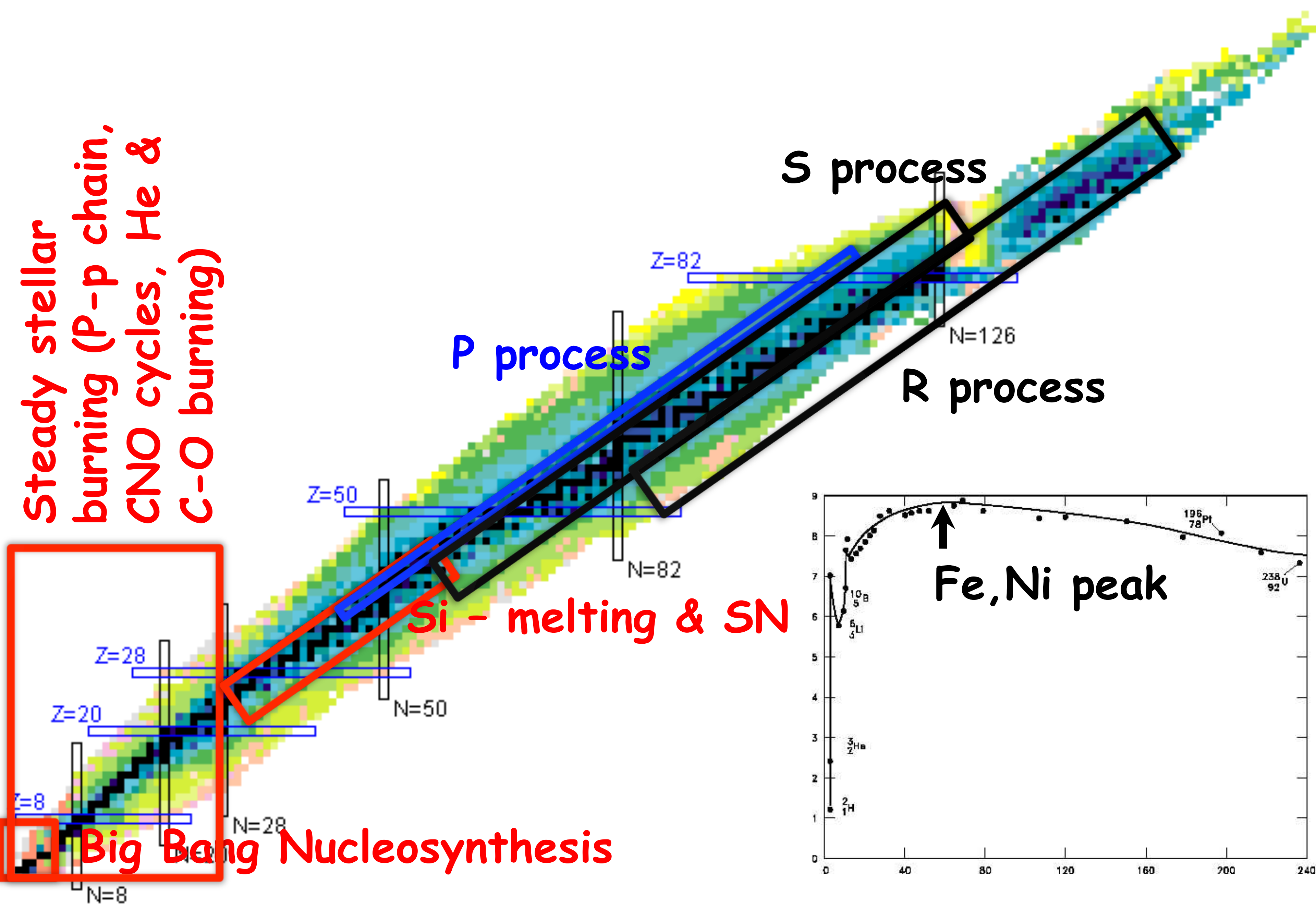
Margaret Burbidge



Geoff Burbidge

William Fowler

Fred Hoyle



Steady stellar burning (P-p chain, CNO cycles, He & C-O burning)

S process

P process

R process

Fe,Ni peak

Si - melting & SN

Big Bang Nucleosynthesis

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

- In the Sun $T=1.5\times10^7$ K then $E=kT\sim$ keV
- In large masses stars or Big Bang nucleosynthesis $T\sim 10^9$ $E\sim 0.5$-1 MeV

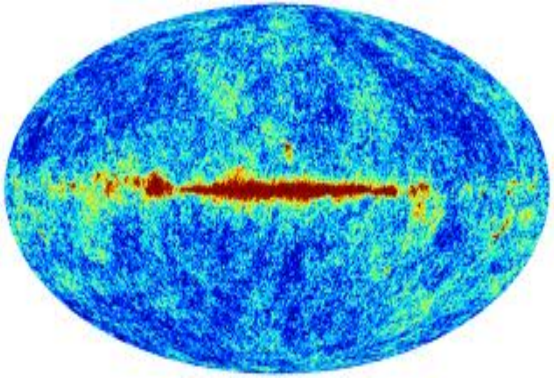
Nuclear astrophysics as a key to cosmology

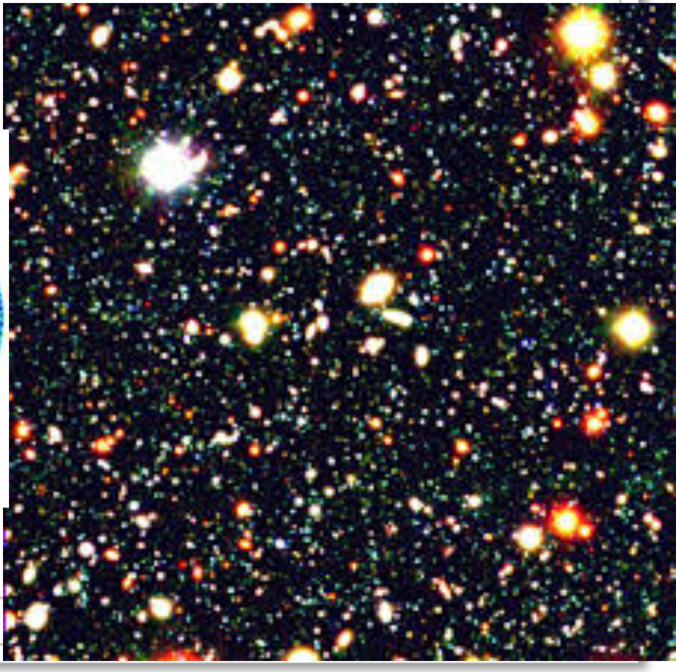
Primordial nucleosynthesis is one of the pillars of the current Cosmological models.

Main evidences of Standard Big Bang scenario:

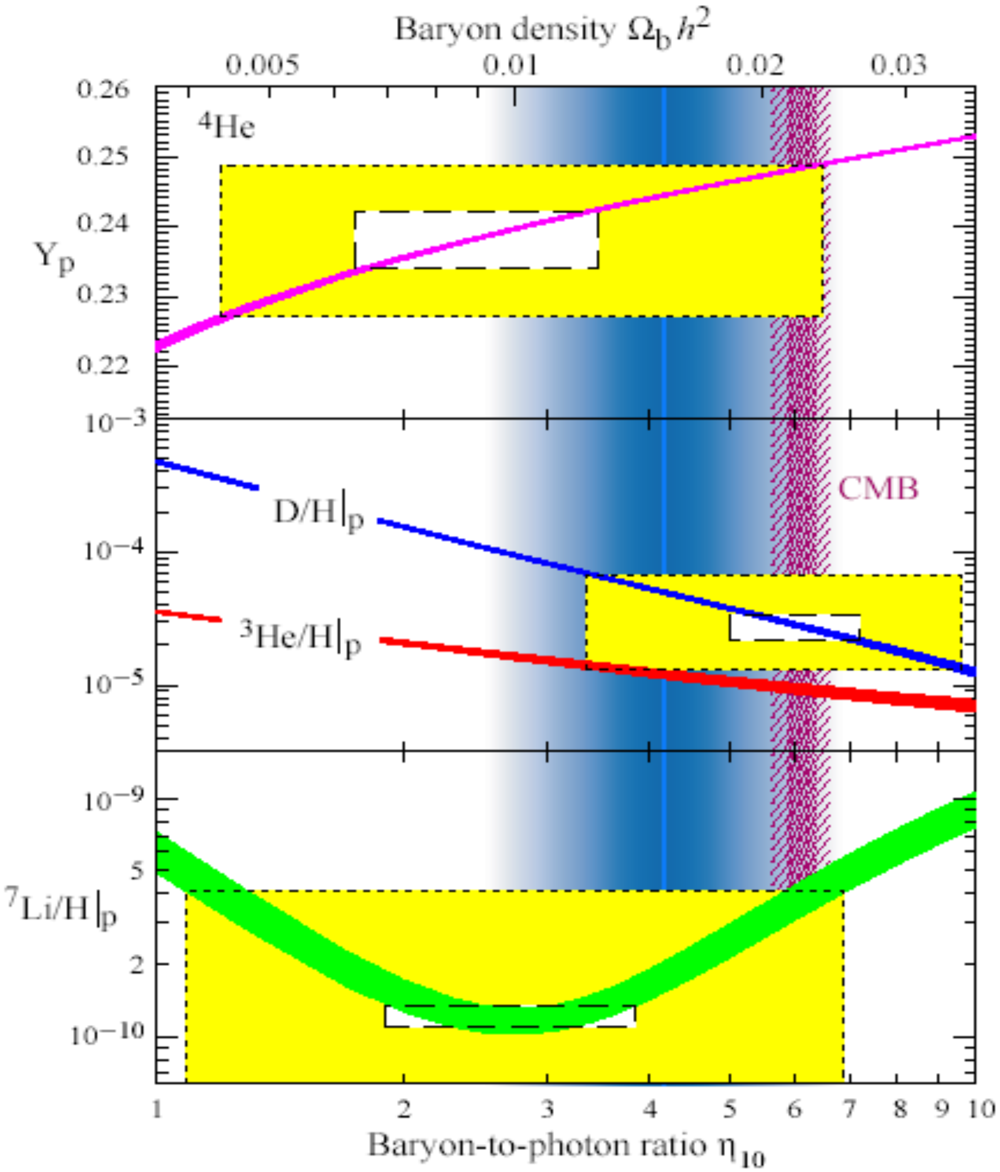
- Galactic expansion (Hubble Law) from SN measurements,
- Cosmic Microwave Background radiation probes the universe at time around 3×10^5 years after BB
- Primordial nucleosynthesis probes the universe at around 1-20 minutes after Big Bang!!

The only in the radiation dominated era



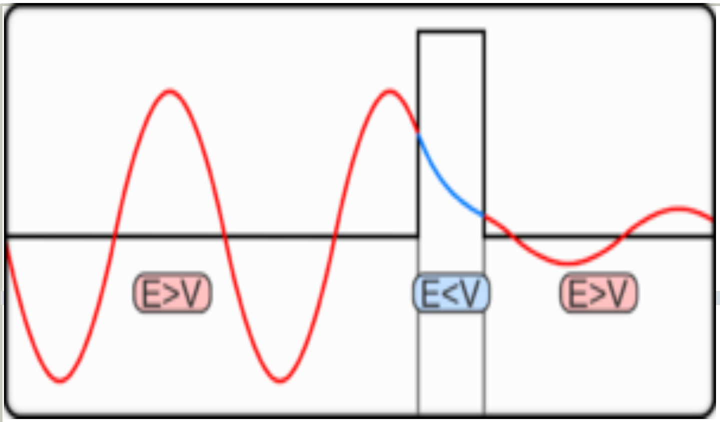


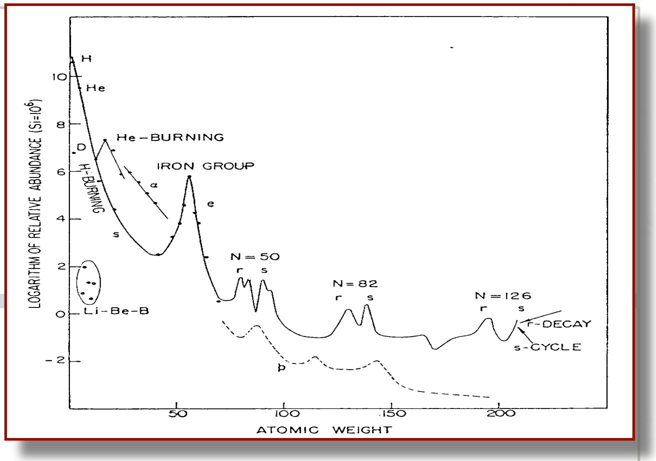
Nuclear Astrophysics **Role**



Comparison of observed primordial abundances with calculated ones as a function of the baryon-to-photon ratio

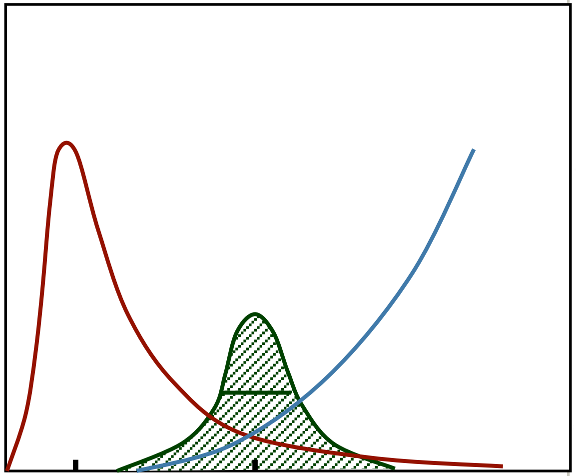
From abundances to cosmological parameters and viceversa





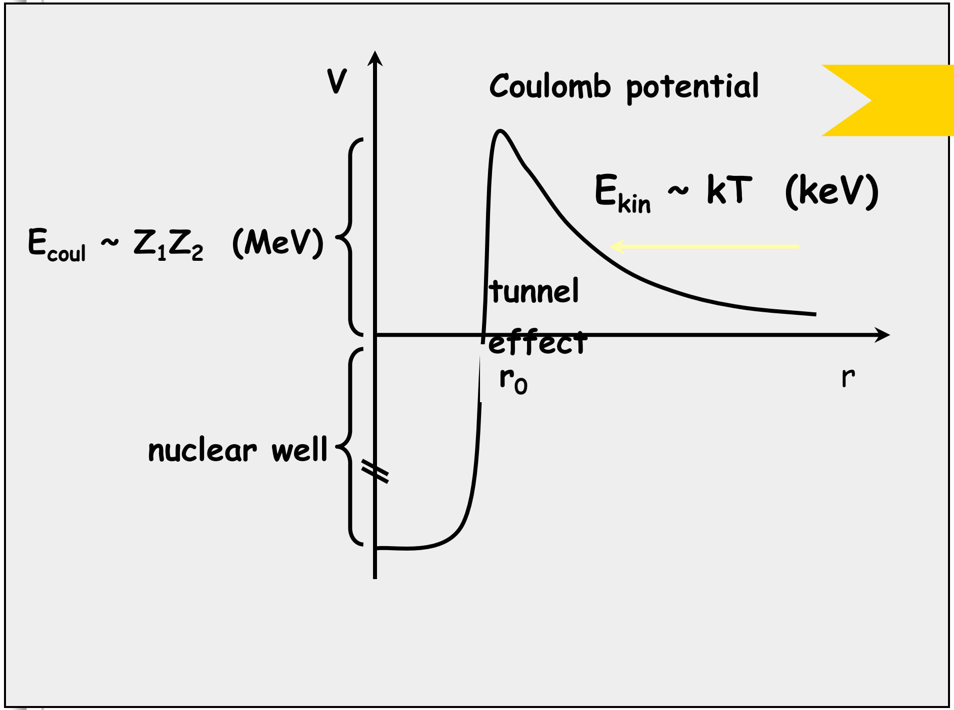
Part 2:

Useful definitions



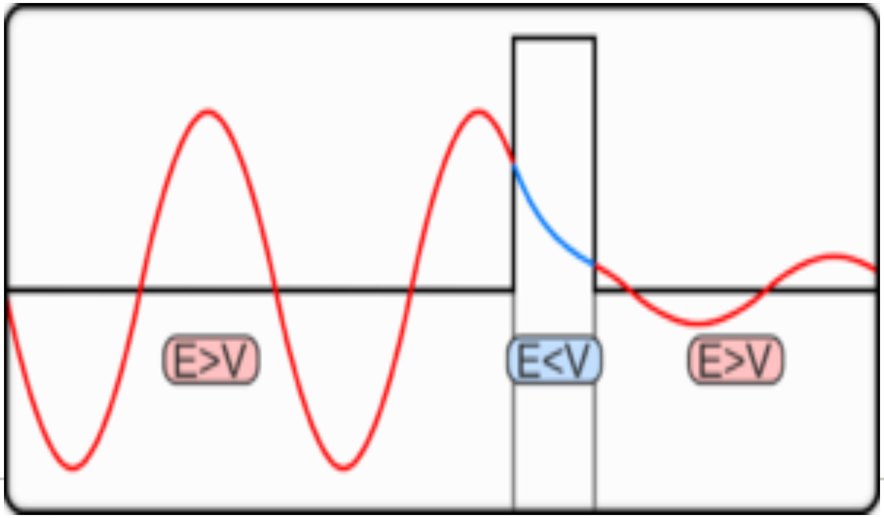
cross sections measurements: Reactions between charged particles

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

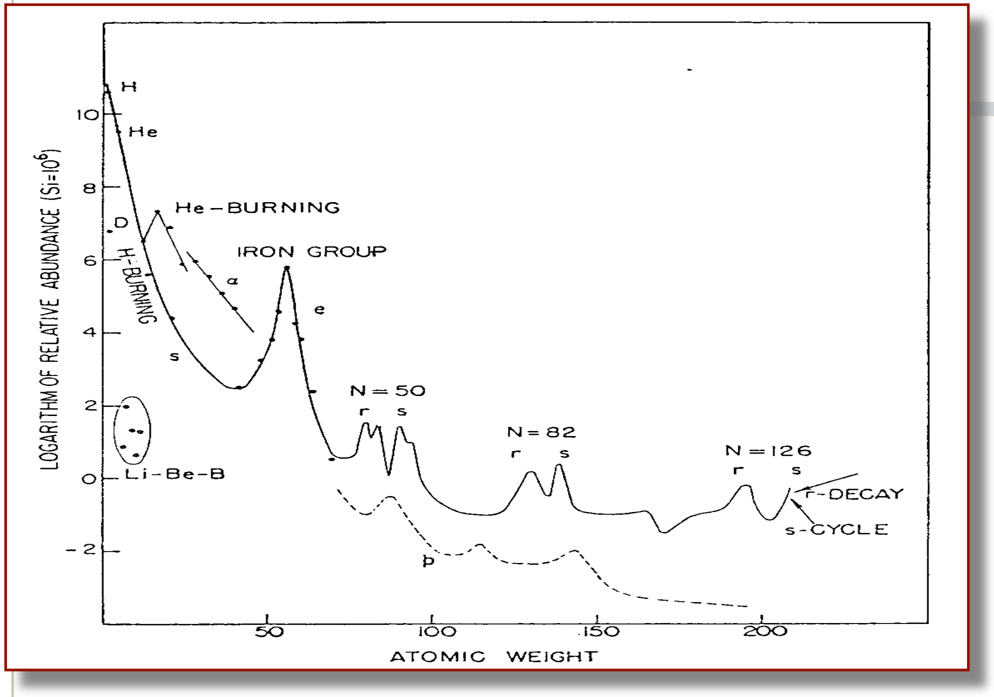


reactions occur through

TUNNEL EFFECT



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

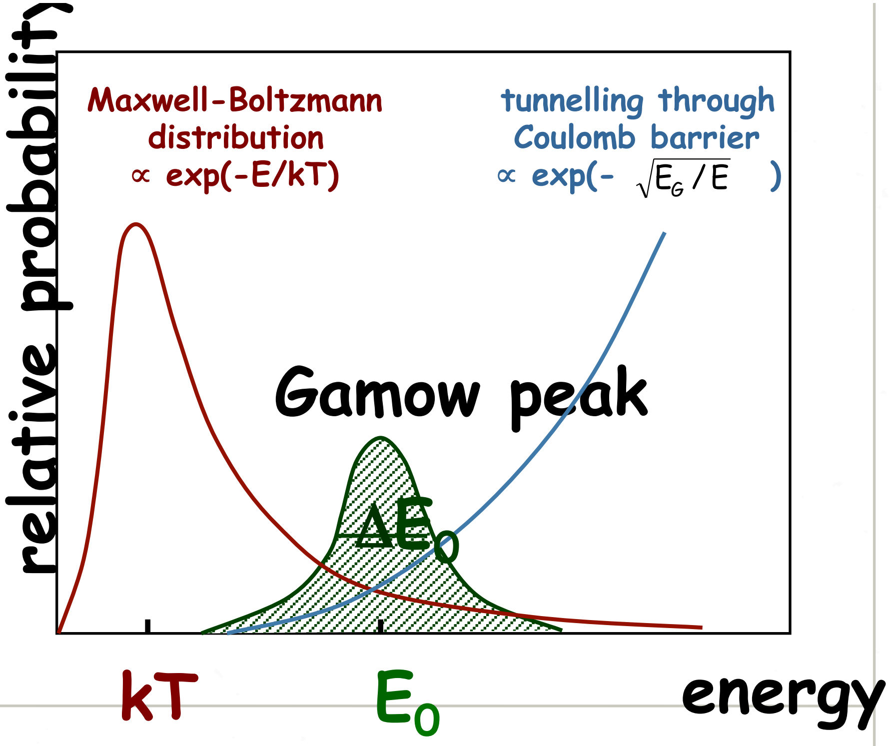
$\langle\sigma v\rangle$ = KEY quantity to be determined from experiments

⇒ 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

➤ **<u>Well-defined</u> stages:**

He-burning

C/O-burning …

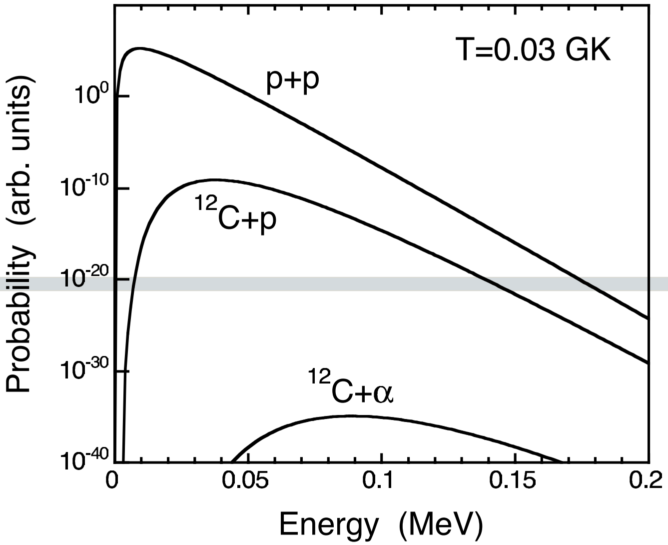
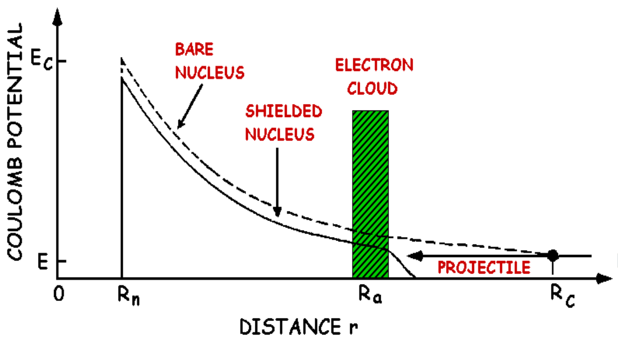
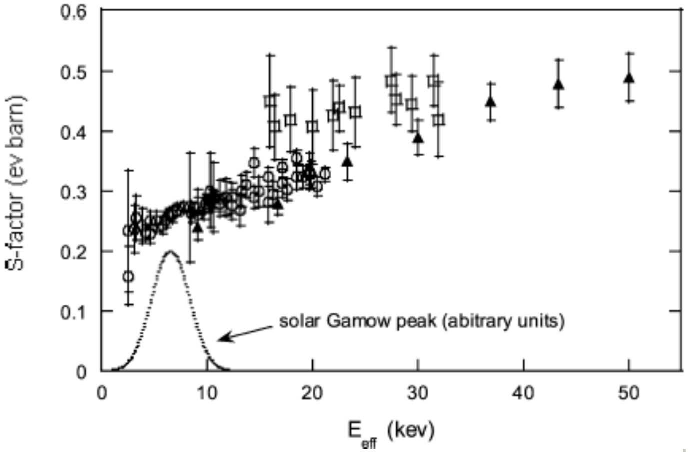


Fig. 3.14 The Gamow peaks for the p + p, ^{12}C + p, and ^{12}C + α reactions at a temperature of T = 0.03 GK.

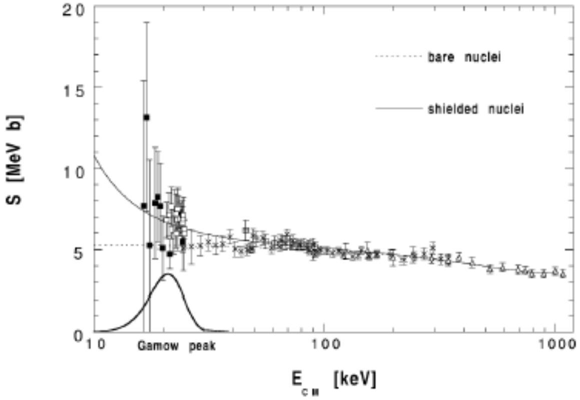
Dramatic dependence with Z!!

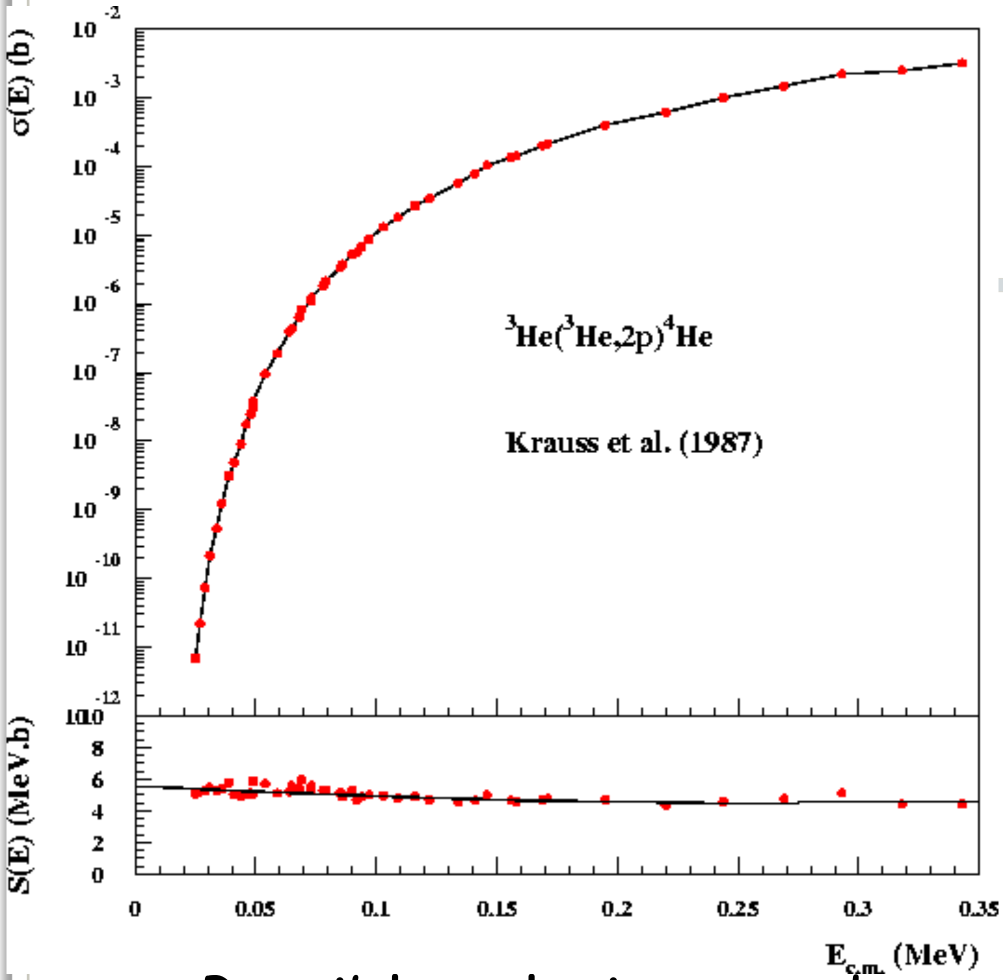




Part 3:

Direct & Indirect Methods





@ Gamow energies

σ in the range nano-picobarn

in general, their direct evaluation is

-severely hindered (1 ev/month)

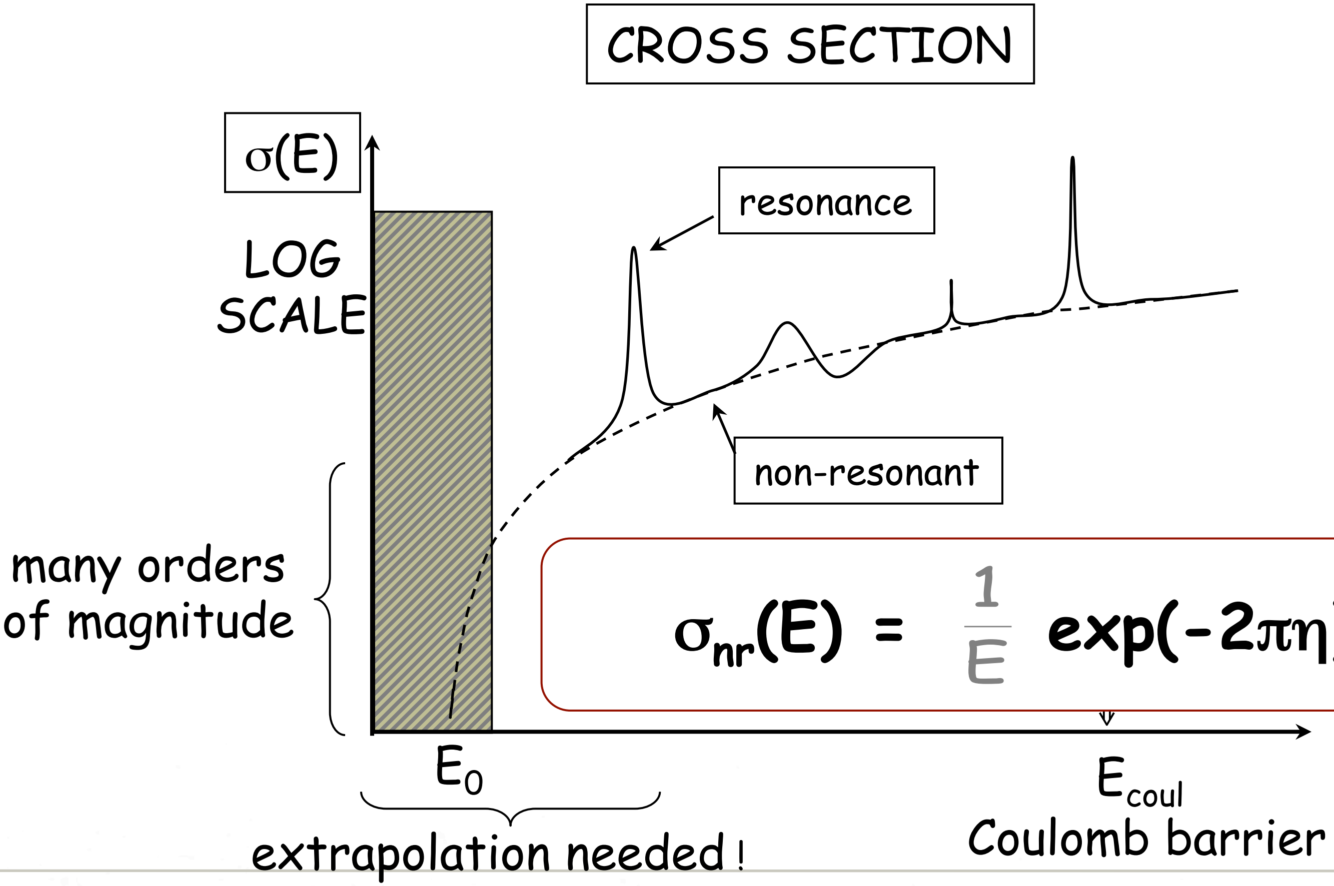
-and in some cases even beyond present technical possibilities.

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

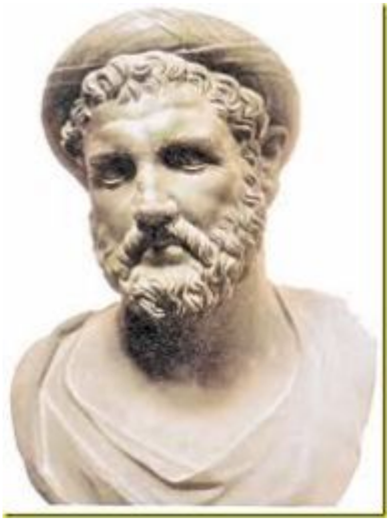
- IMPROVEMENTS TO REDUCE THE BACKGROUND

Use of laboratory with natural shield - (underground physics)

Use of magnetic apparatus (Recoil Mass Separator)

"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.



C. PLINII SECUNDI
NATURALIS
HISTORIÆ,
TOMUS PRIMUS.

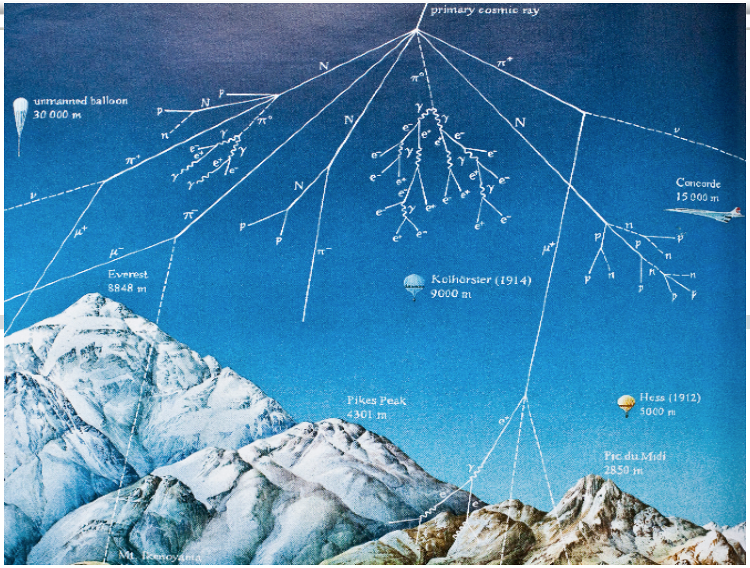
Cum Commentariis & adnotationibus HERMOLAI
BARBARI, PINTIANI, RHENANI, GELENII,
DALECHAMPII, SCALIGERI, SALMASII,
IS. VOSSII, & Variorum.

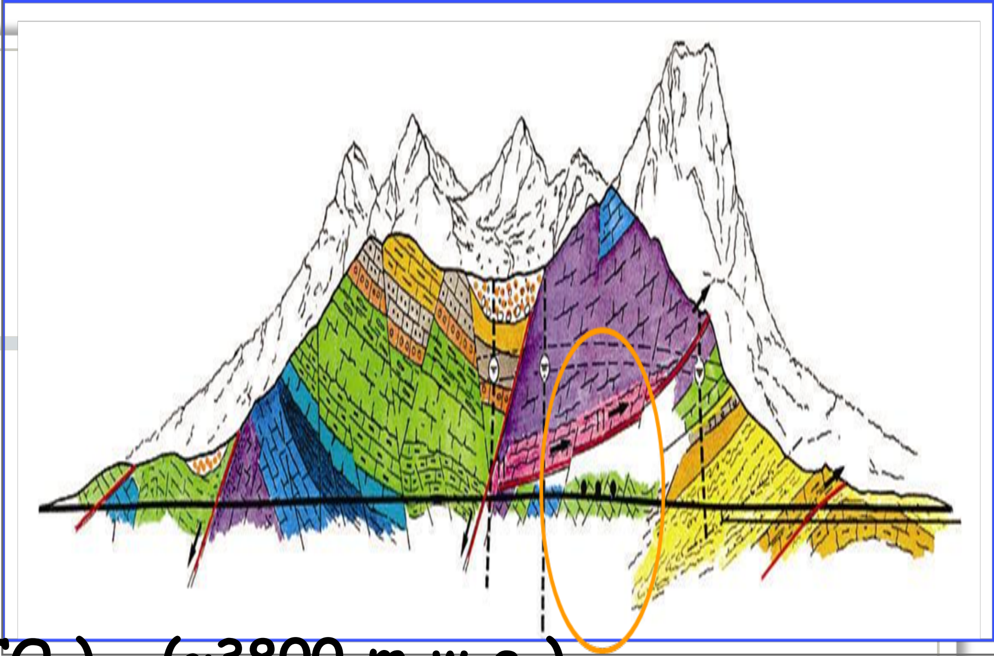
Accedunt praeterea variae Lectiones ex MSS. compluribus ad oram Paginarum accurate indicatae.

Item JOH. FR. GRONOVII Notarum Liber Singularis
ad Illustrem Virum *Johannem Capellanum.*

LUGD. BATAV.
ROTERODAMI. } Apud HACKIOS, A°. 1669.

Fleet commander in Tyrrenum sea during Pompei Eruption,
Great latin scientist, died on the attempt of rescuing people and perform scientific observations during the Vesuvius eruption of 79 DC



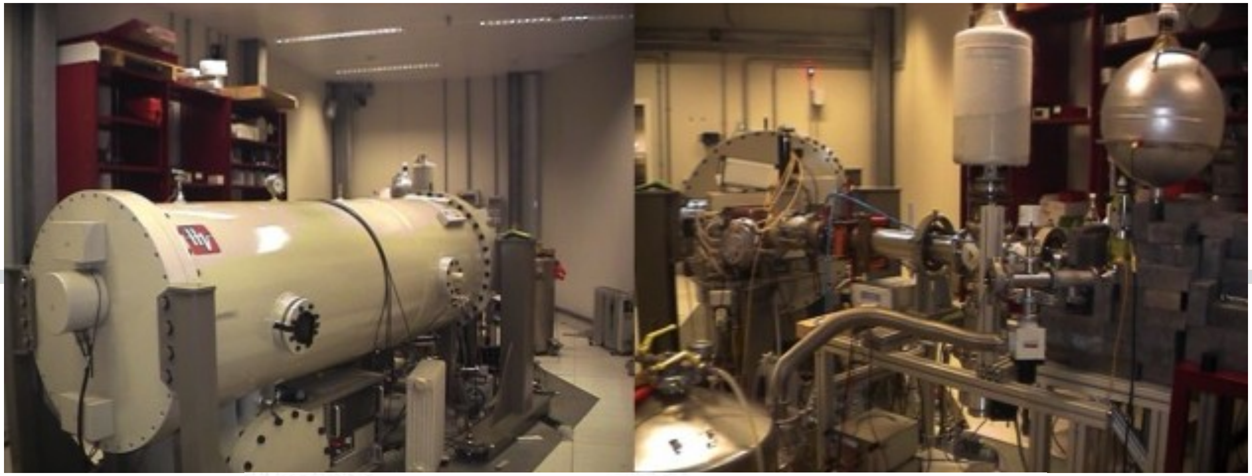


1400 m of dolomite rock, $CaMg(CO_3)_2$, (~3800 m w.e.)

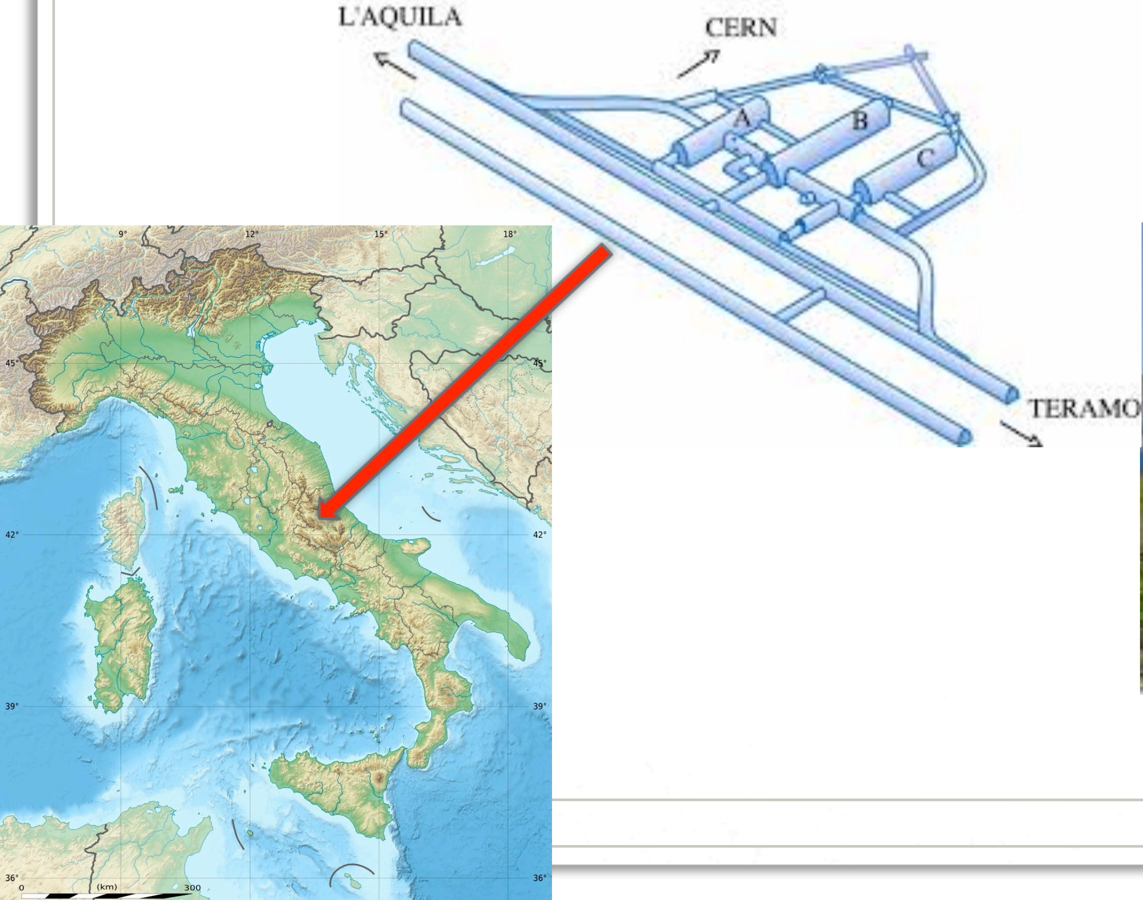
Muon flux: 1.1 $m^{-2}h^{-1}$, 6 orders of magnitude reduction

Neutron flux, mainly from (α,n) : 2.92 10^{-6} $cm^{-2}s^{-1}$ (0-1 keV), 0.86 10^{-6} $cm^{-2}s^{-1}$ (> 1 keV), 3 orders of magnitude reduction

Gamma rays: only 1 order of magnitude reduction, but with thick shield (no muon activation) about 5 orders of magnitude in the region of natural radioactivity and 4-5 orders above 3.2 MeV without any shield (gamma rays due to n-interaction)



Luna underground facility INFN LNGS



Hard Work is necessary

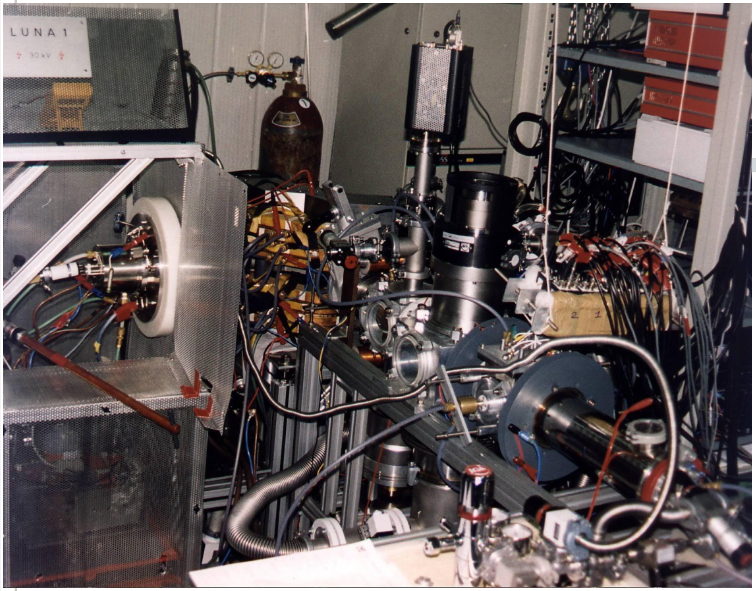
To understand what we see

…

To try to go inside
the problem

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

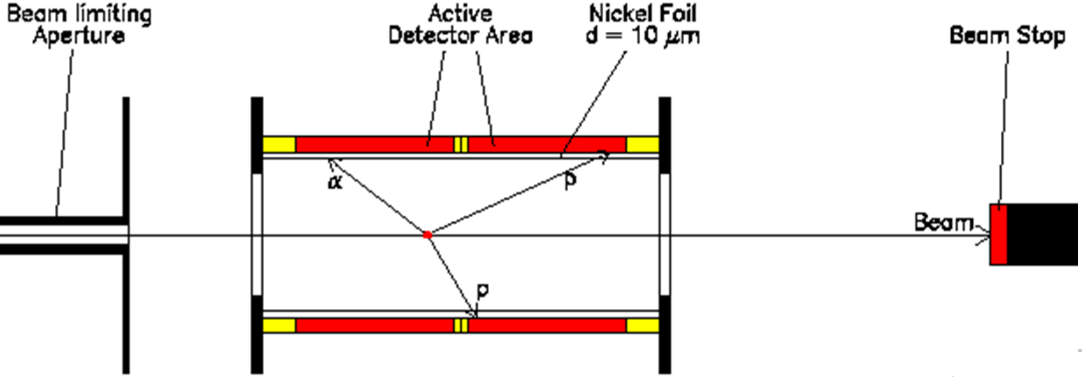
$Q = 12.86$ MeV $E_p^{max} = 10.7$ Me

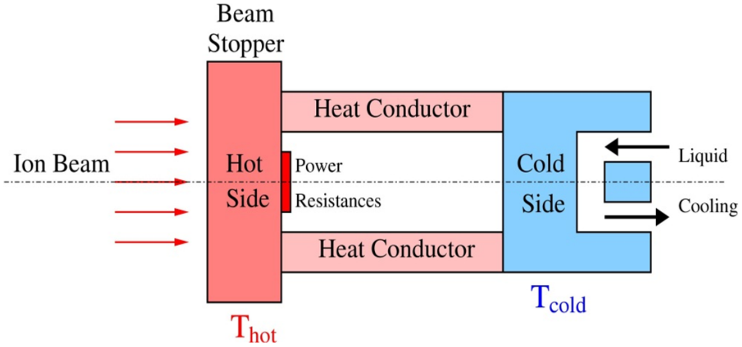


Suppression of ^7Be and ^8B ν_e in pp chain due to a resonance in $^3He(^3He,2p)^4He$ which modifies the neutrino spectrum?

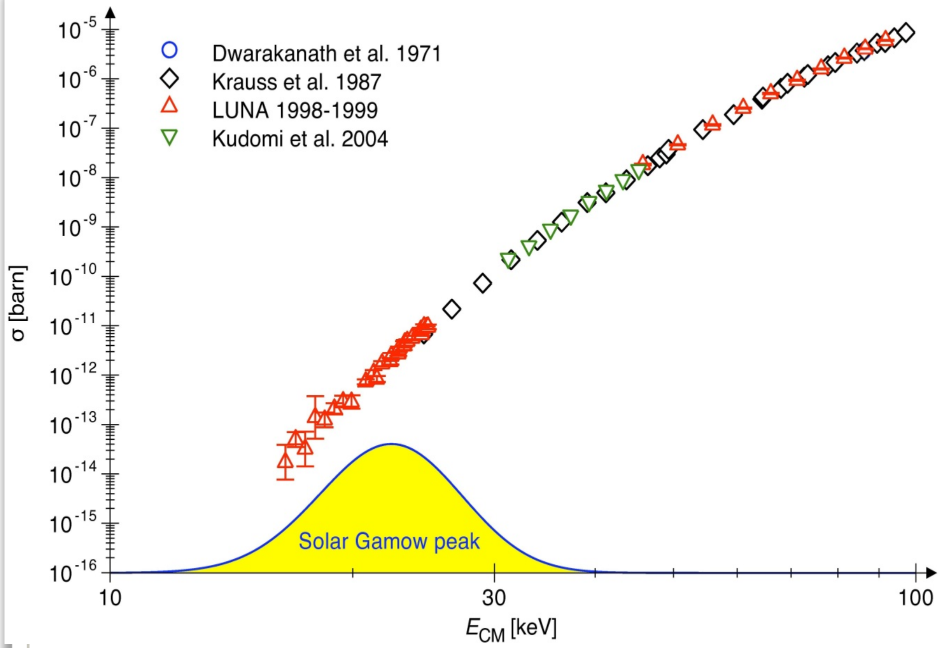
H^+, $^3He^+$ beam
Voltage Range: 1 - 50 kV
Output Current: 1 mA
Beam energy spread: 20 eV
Long term stability (8 h): 10^{-4}
Terminal Voltage ripple: $5\ 10^{-5}$

Windowless gas target (3He @ 0.5 mbar) + 8 silicon detectors (5cmx5cm, 1mmthick)





Courtesy C. Broggini



S$_{min}$=20 fb (2 events/month) (same value of Superheavy nuclei formation - frontier physics)

No resonance at the Gamow peak

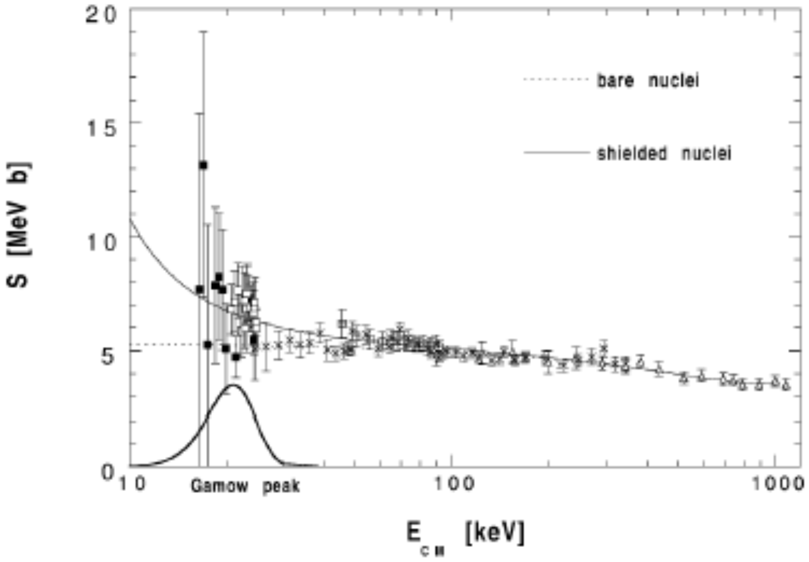
Nuclear astrophysics is not the reason for the suppression of ν_e from the Sun

LUNA (Laboratory Underground for Nuclear Astrophysics)

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

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

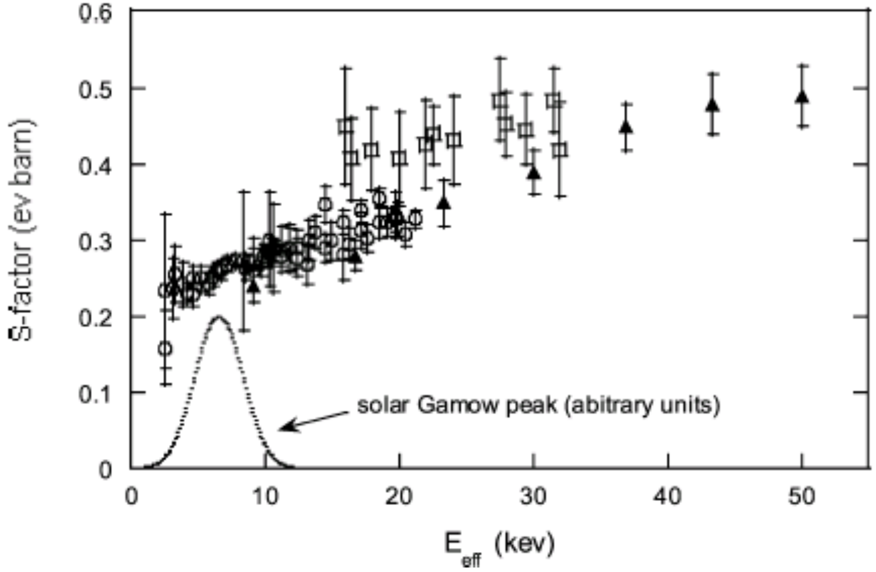
R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



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

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

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

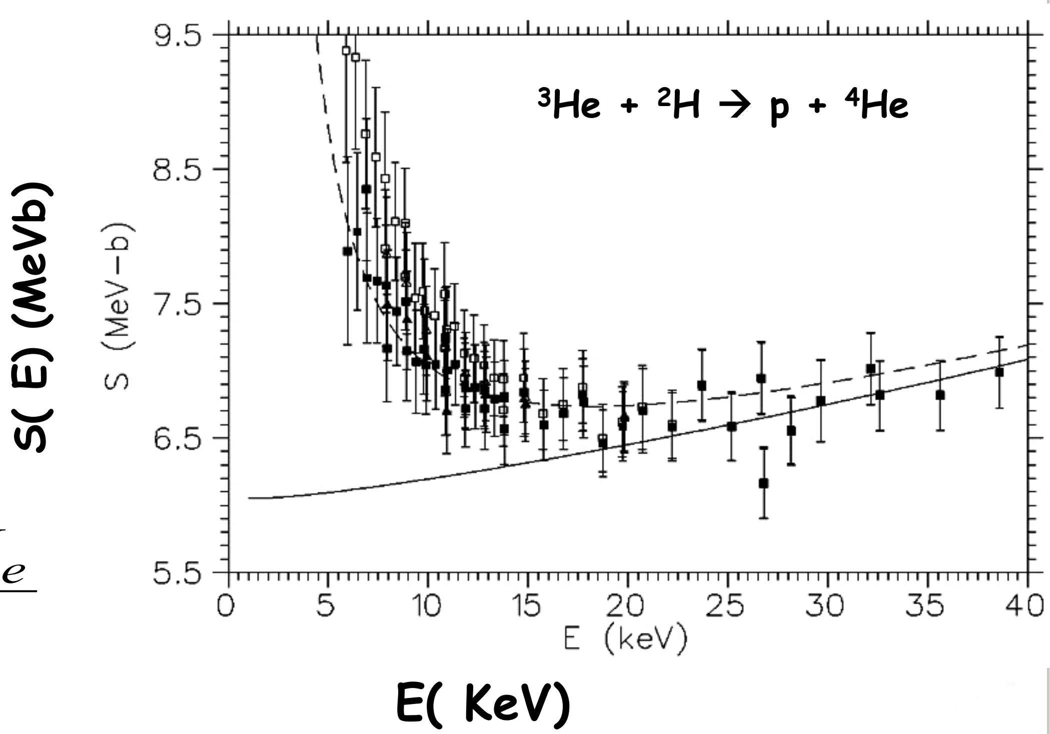


At lowest energy: σ ~ 9 pb → 50 counts/day

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

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

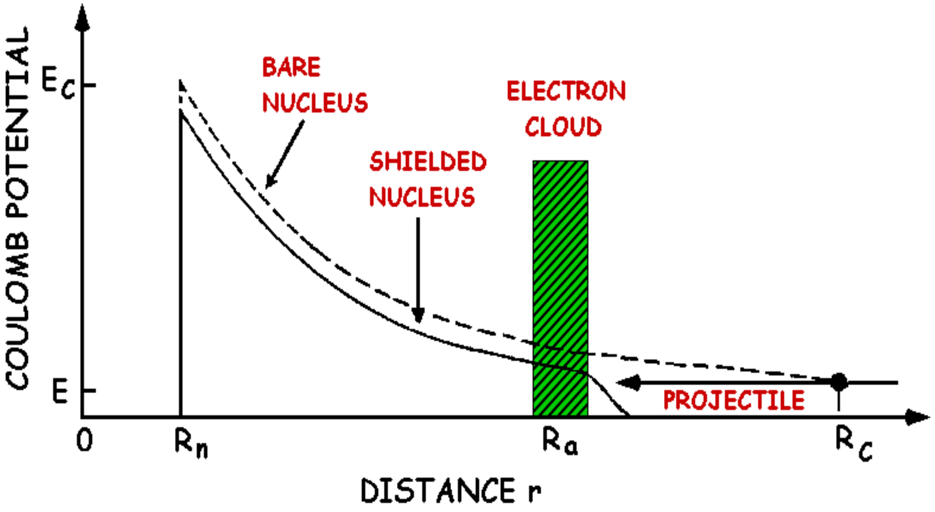
In the accurate measurements for the determination of nuclear cross-sections at the Gamow energy, in laboratory, enhancement $f_{lab}(E)$ –factor in the astrophysical $S_b(E)$-factor has been found



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

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

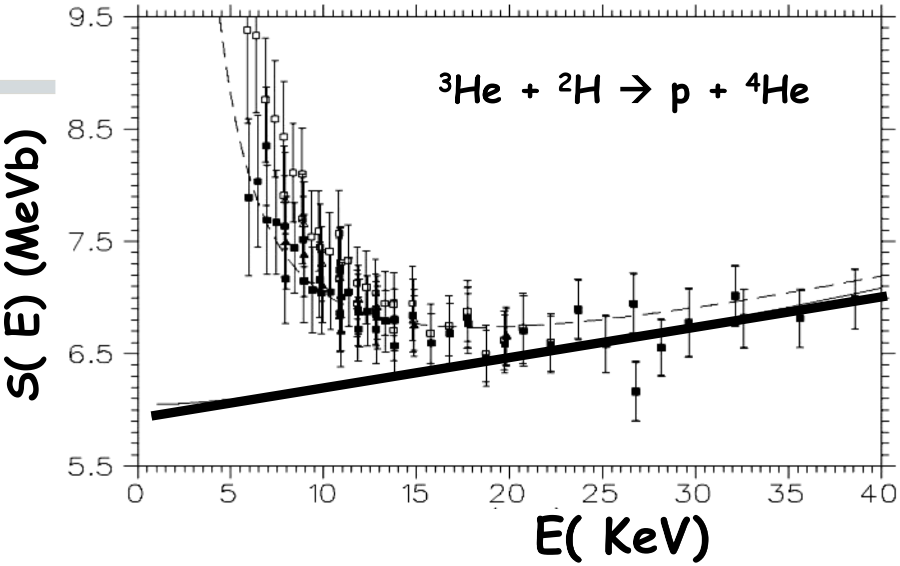
- Phenomenological approach

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

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

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) General Features:

-2-body reaction of astrophysical interest is replaced by a proper reaction which is less difficult to study;

-Nuclear theory is used for connecting the measured cross section and the one of astrophysical interest

Methods:

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

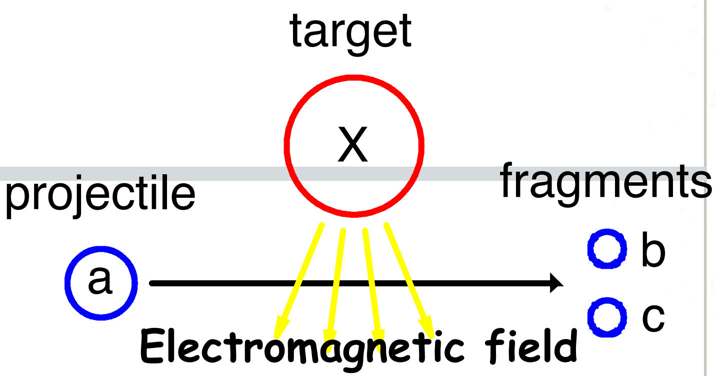
Coulomb Dissociation

Coulomb dissociation

- study inverse of radiative capture reaction
  $b(c,\gamma)a \;\Leftrightarrow\; a(\gamma,c)b$
- use Coulomb field of target nucleus X as source of photons
  $a(\gamma,c)b \Leftrightarrow X(a,bc)X$

$\Downarrow$

absolute S factors as a function of E



radiative capture	$c(b,\gamma)a$
detailed balance	$\Updownarrow$
photo dissociation	$a(\gamma,b)c$
equivalent photons in Coulomb field of target X	$\Updownarrow$
Coulomb dissociation	$X(a,bc)X$

Idea: Baur Bertulani & Rebel 1986
Experimental applications: Motobayashi, Iwasa, Hammache, Heil et al.

Results

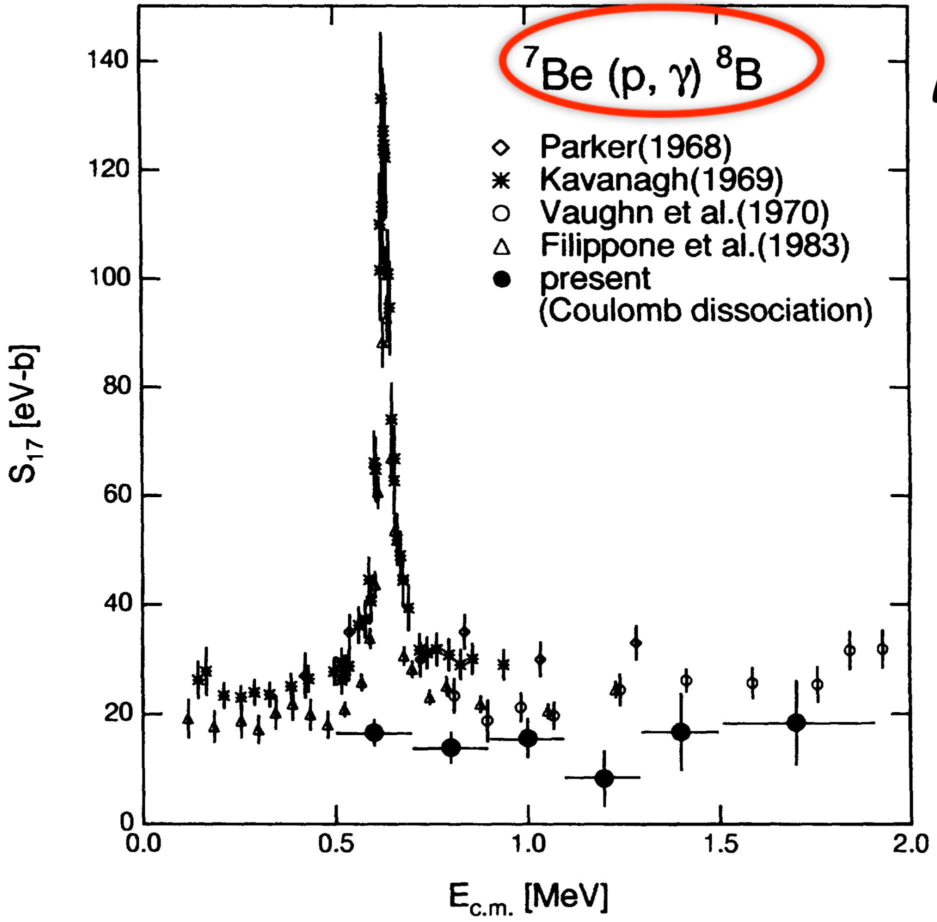
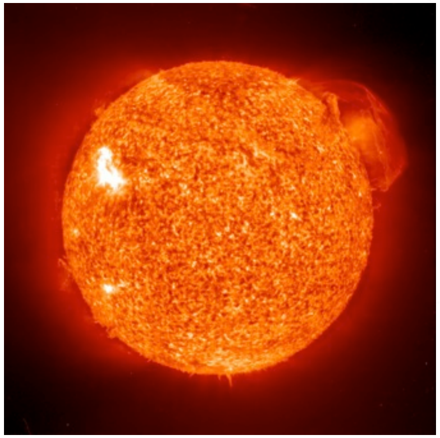


FIG. 3. Comparison of S_{17} extracted from the Coulomb dissociation of ^{8}B and the previous highest precision results.

Motobayashi et al 1994



ANC METHOD

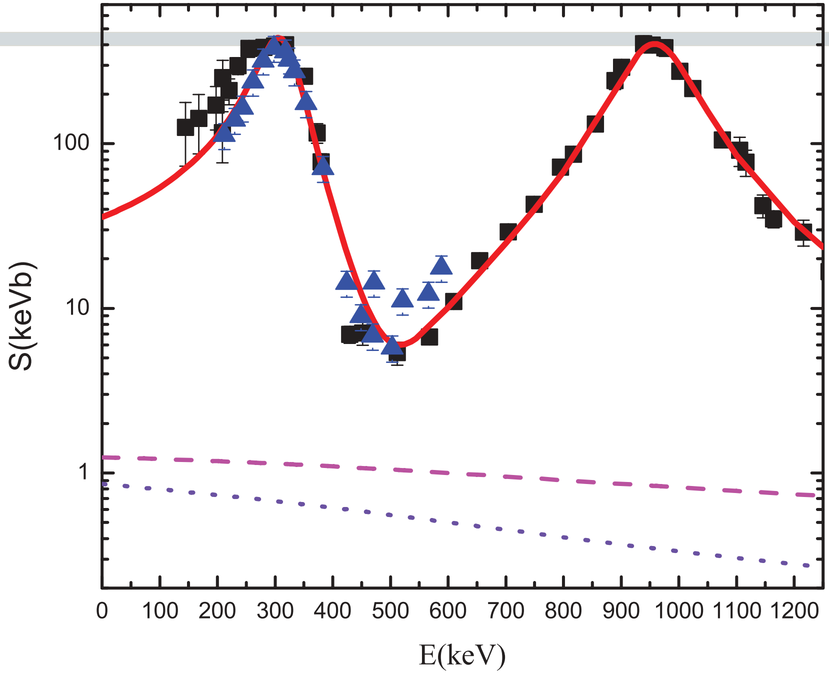
- extract asymptotic normalization coefficient of ground state wave function of nucleus c from transfer reactions
- calculate matrix elements for radiative capture reaction $b(c, \gamma)a$

$$\Downarrow$$

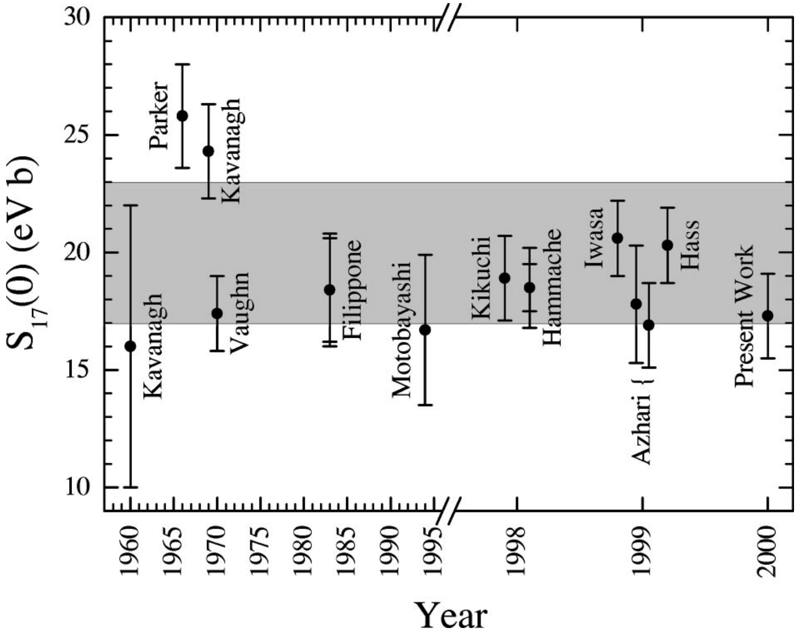
S factor at zero energy

IDEA MUKHAMEZHANOV A.

New astrophysical S factor for the $^{15}\mathrm{N}(p,\gamma)^{16}\mathrm{O}$ reaction via the asymptotic normalization coefficient (ANC) method



MUKHAMEZHANOV ET AL. 2008



Asymptotic normalization coefficients and the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ astrophysical S factor

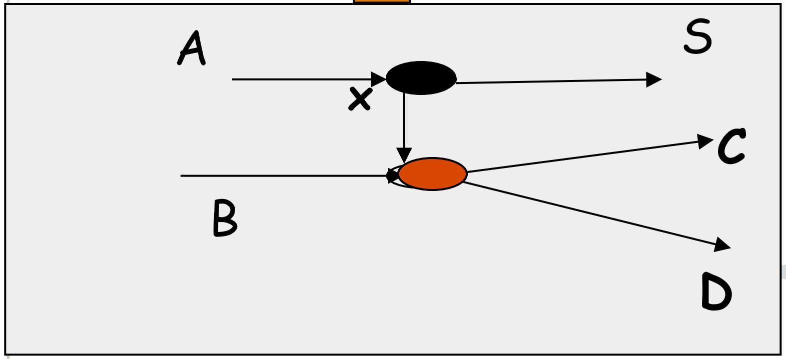
Azhari et al. 2001

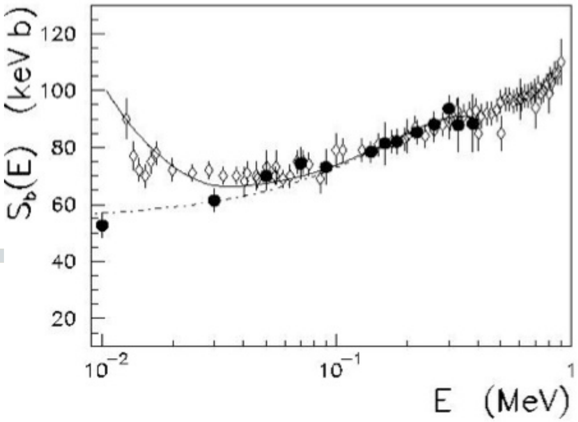
OUTLINE

- Main questions and issues for nuclear astrophysics
- Some necessary definitions
- Direct methods: the LUNA project @ Gran Sasso Lab
- Indirect Methods

… next lecture

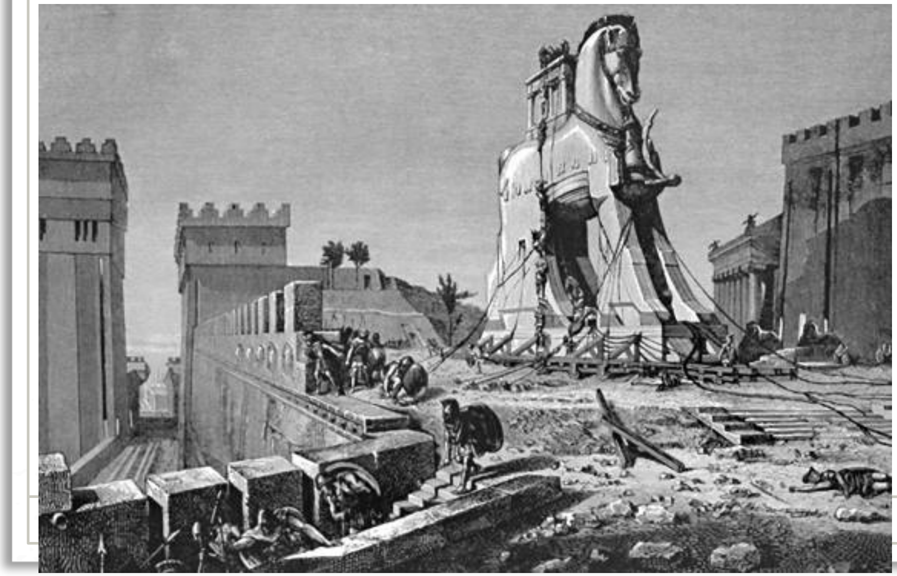
- Trojan Horse Method
- Some results by THM
- Astrophysical contexts where THM has played a role

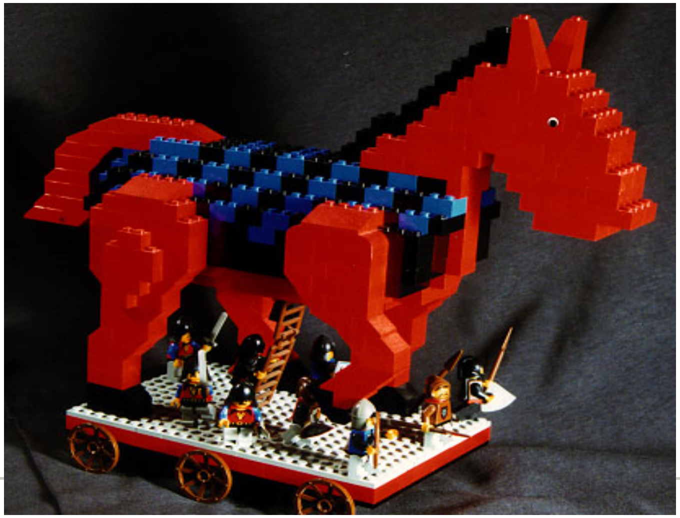




Part 4:

Trojan Horse Method from basics





OUTLINE

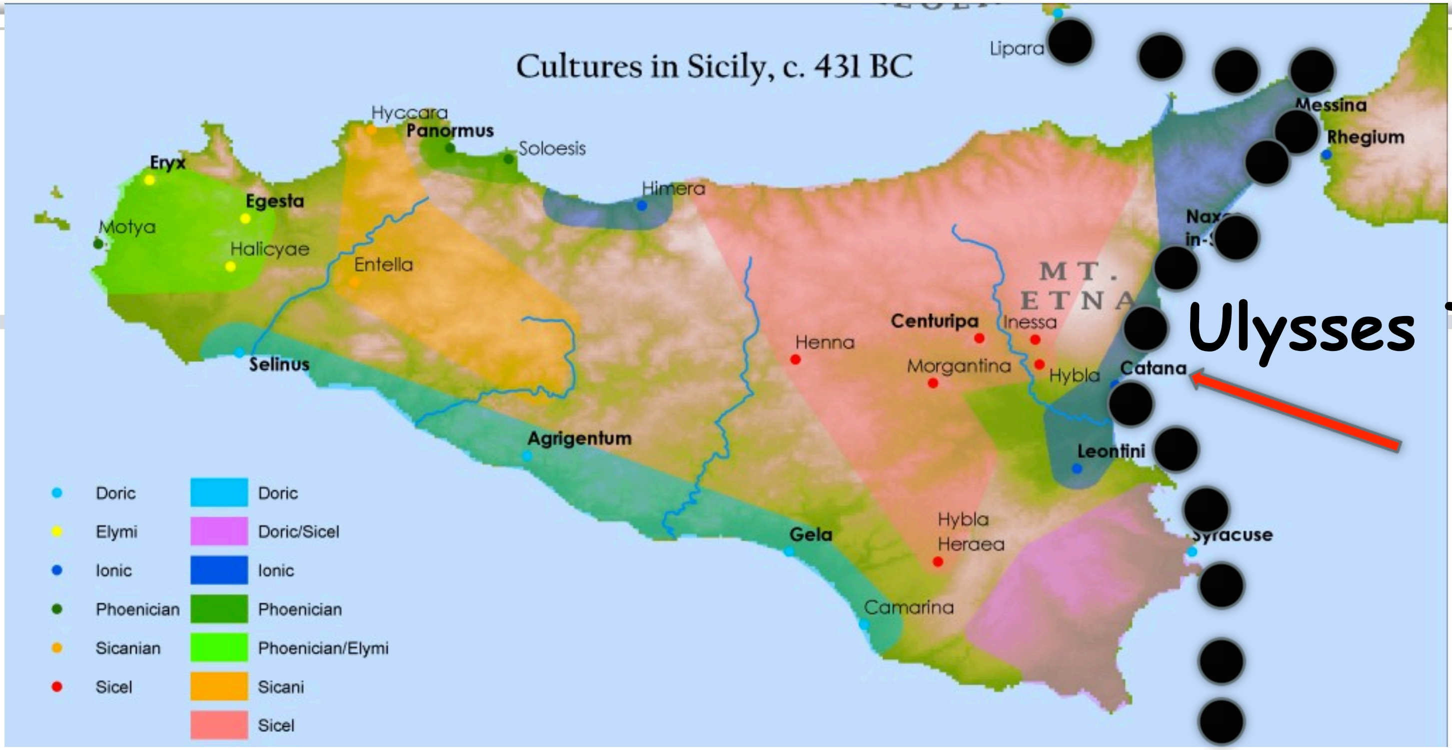
- Main questions and issues for nuclear astrophysics
- Some necessary definitions
- Direct methods: the LUNA project @ Gran Sasso Lab
- Indirect Methods

… today's lecture

- Trojan Horse Method
- Some results by THM
- Astrophysical contexts where THM has played a role

It all began in Sicily 12 centuries ago...

It is the period of the Troy war
And after conquesting the city
The Greeks battleships wander in the
Mediterranean sea carrying the secret
Of the Greek ultimate weapon…



Ulysses TRIP

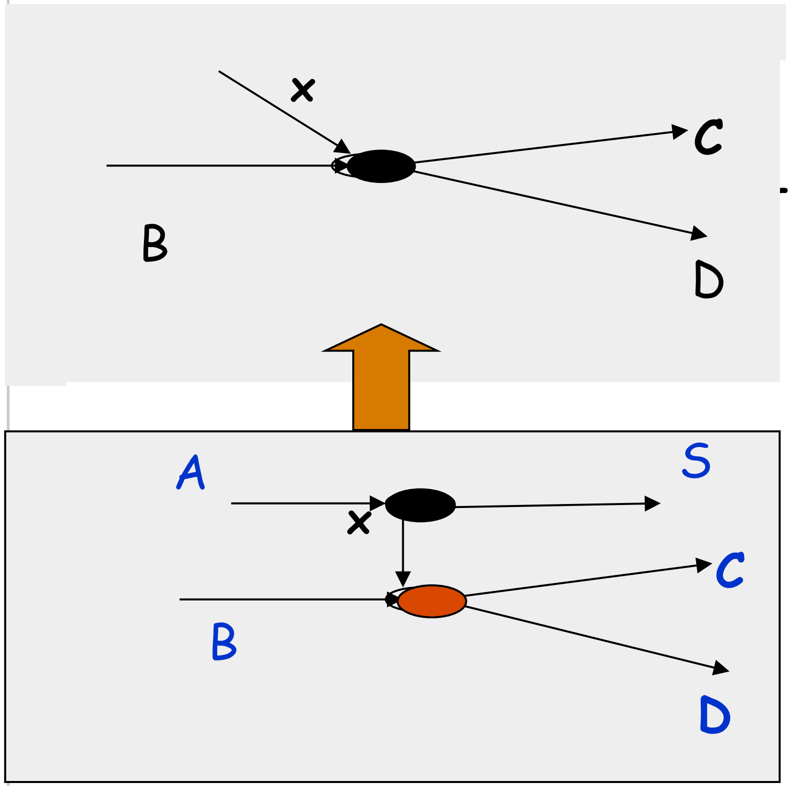
Builders of this method:

G. Baur 1986

C. Spitaleri 1990

Trojan Horse Method

Quasi-Free mechanism



-The A nucleus present a strong cluster structure: A = x ⊕ S clusters

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

B + x → 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

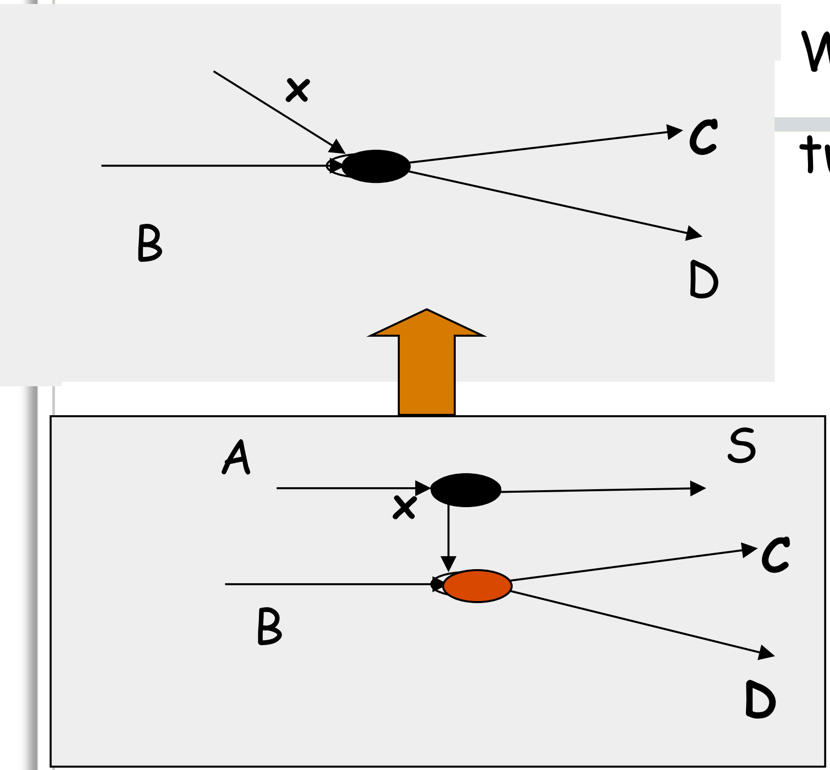
Basic idea:

It is possible to extract astrophysically the 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



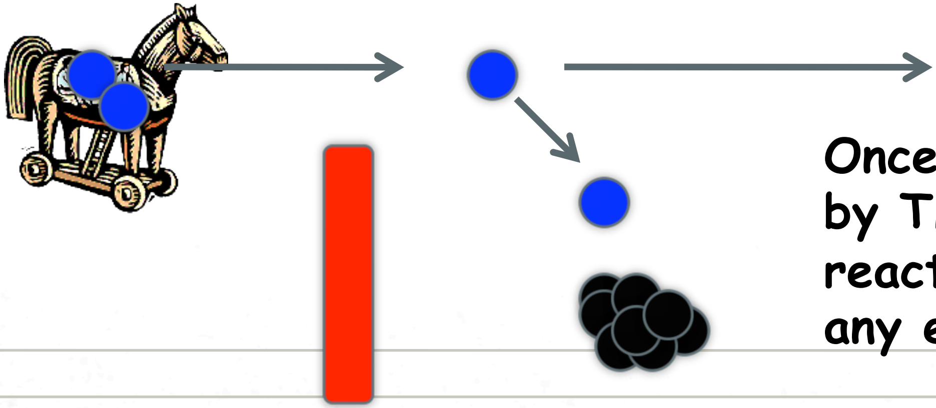
We can extract astrophysically relevant two-body cross section σ

B + x → C + D

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

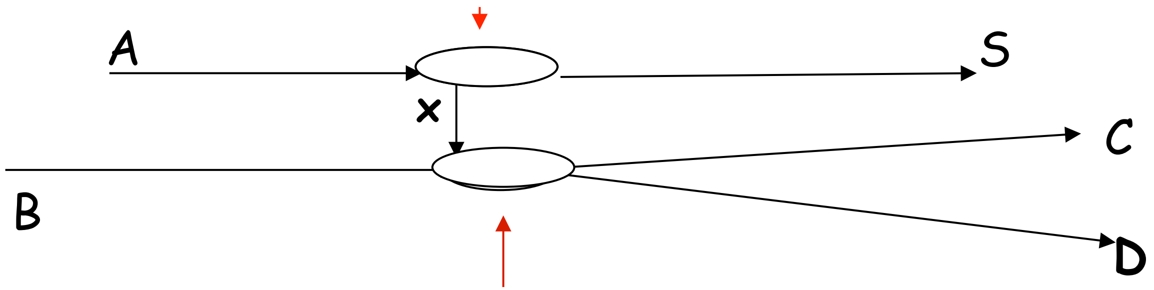
A + B → C + D + S

Coulomb Barrier Suppression



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

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

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

x + B→ C + D

Second vertex

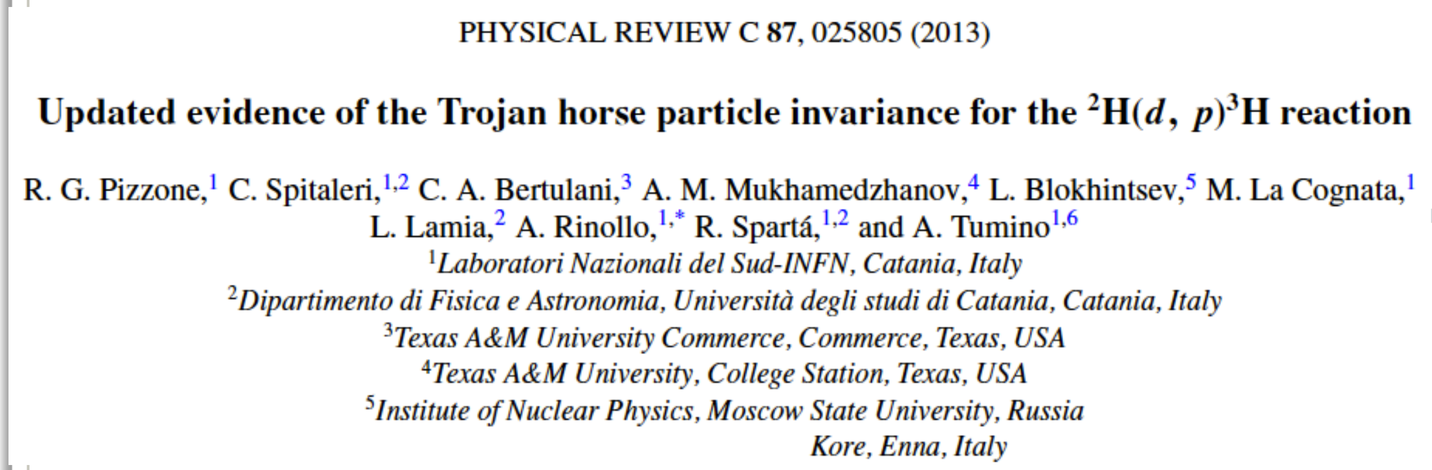
First vertex

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**

pole-invariance effects



PHYSICAL REVIEW C **87**, 025805 (2013)

Updated evidence of the Trojan horse particle invariance for the ^{2}H(d, p)^{3}H reaction

R. G. Pizzone,[1] C. Spitaleri,[1,2] C. A. Bertulani,[3] A. M. Mukhamedzhanov,[4] L. Blokhintsev,[5] M. La Cognata,[1]
L. Lamia,[2] A. Rinollo,[1,*] R. Spartá,[1,2] and A. Tumino[1,6]
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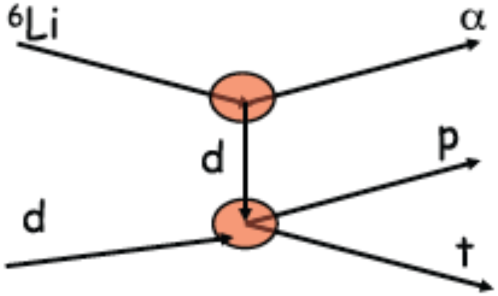
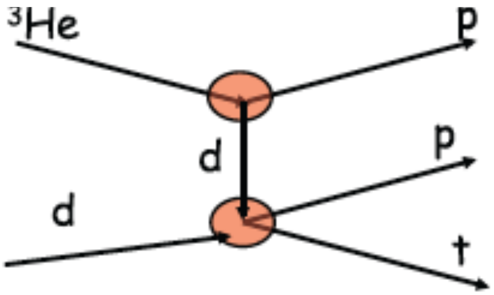
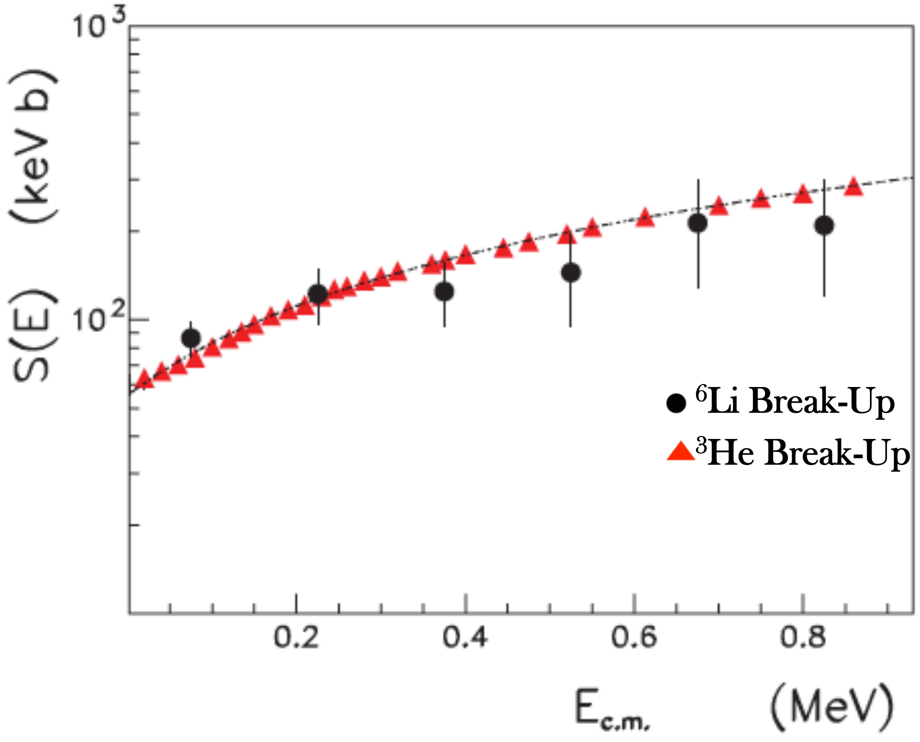
Kore, Enna, Italy



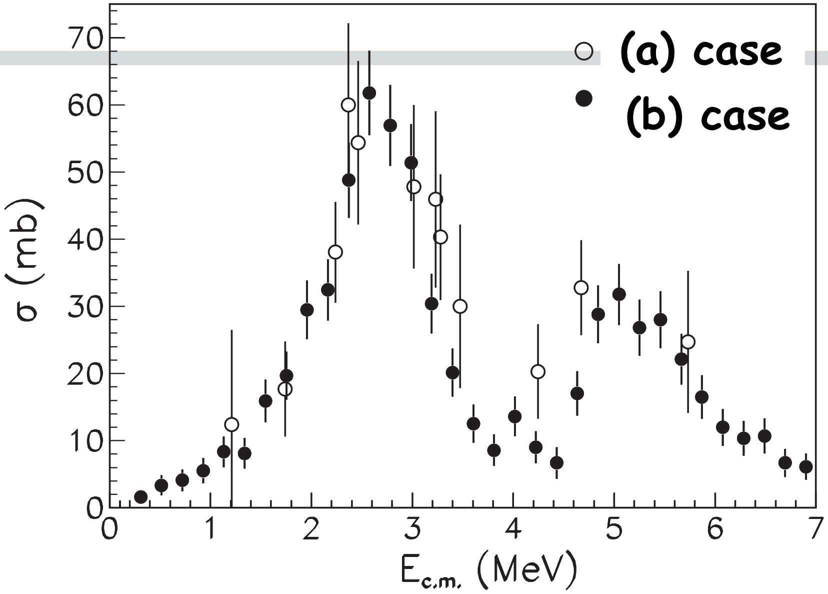
(a)



(b)



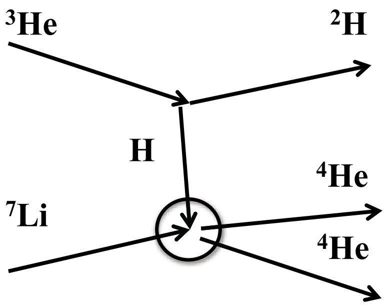
Pole invariance II



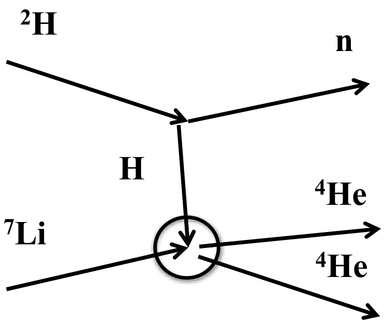
(a) ^{3}He break-up
(b) D break-up

R.G. Pizzone et al. PRC 2011

(a)



(b)

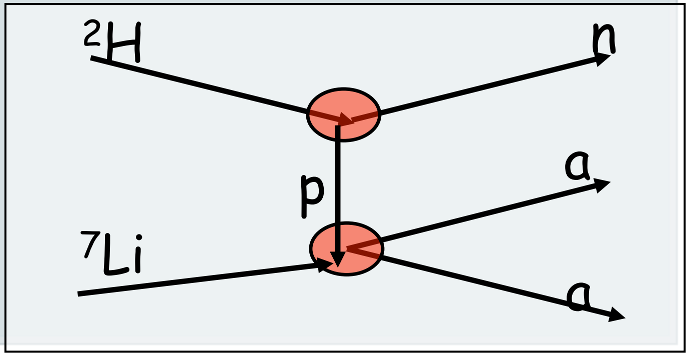


Advantages: Simple & cheap
Experimental setup

THM: study of the ^{7}Li(p,α)^{4}He reaction from the 3-body one:

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

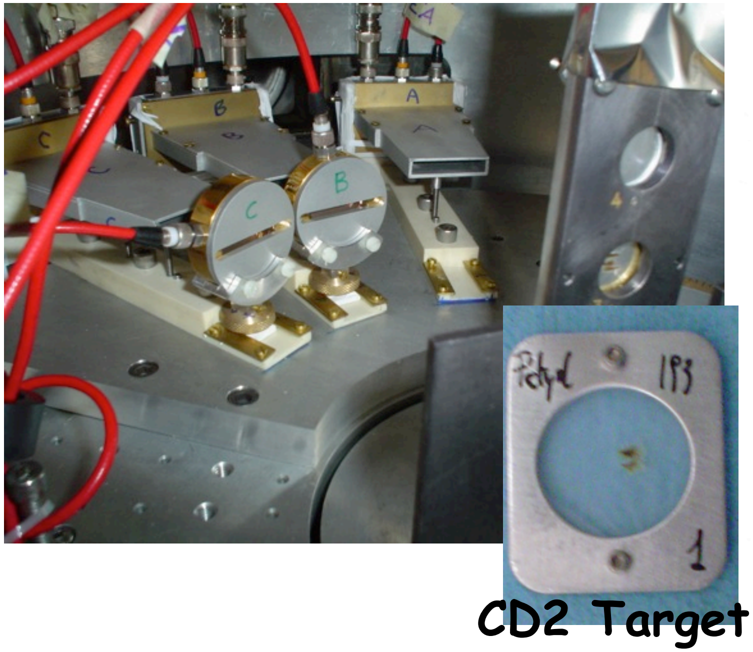
TH nucleus deuteron, E_{beam}= 19,5 MeV @ LNS Catania



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 simple



CD2 Target

Good ideas make research possible in tough times!!

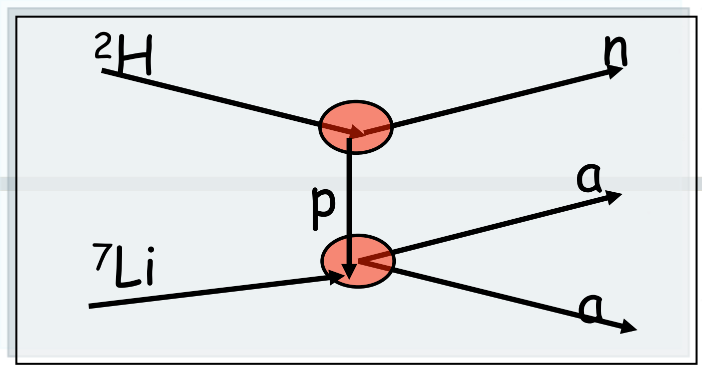
Data Analysis Phases:

- 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.

1 *Find the 3-body reaction of interest among the ones occurring in the target.*

- The case of ^{7}Li(p,α)^{4}He studied via the ^{7}Li(d,$\alpha\alpha$)n with THM applied to the deuterium.

D was chosen since its simple clusterization and low binding energy. ^{7}Li was chosen as beam with energy 19.5 MeV (why??)



E_{qf}. = E_{Lip} – B

Where

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

B is the binding energy of the two clusters inside the Trojan Horse nucleus and plays a key role in compensating for the beam energy

In our case: E_{qf} nearly 0 **(ASTROPHYSICAL CASE)**

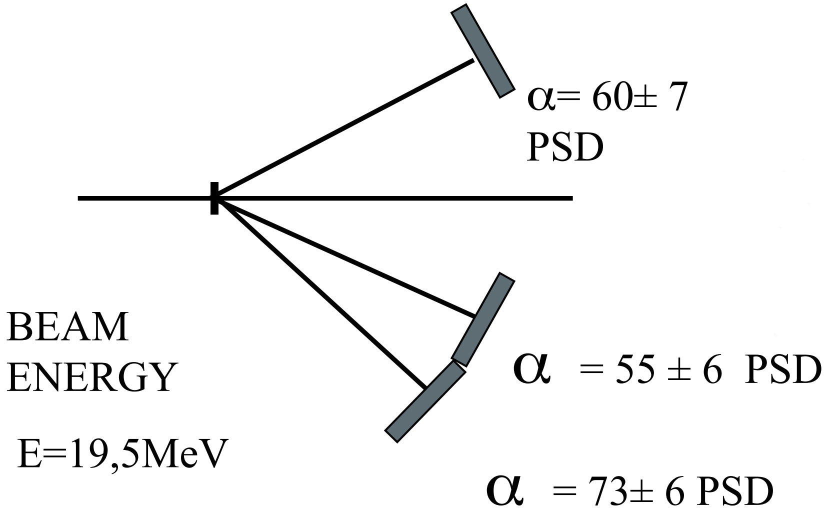
E_{qf} is the energy between the interacting ^{7}Li and transferred particle p. Thus part of the beam energy is necessary to break deuteron up.

Once the beam energy is chosen we should choose kinematic conditions.

Experimental setup

Tandem,INFN-LNS,
^{7}Li 19,5 MeV
3 Position Sensitive Detectors

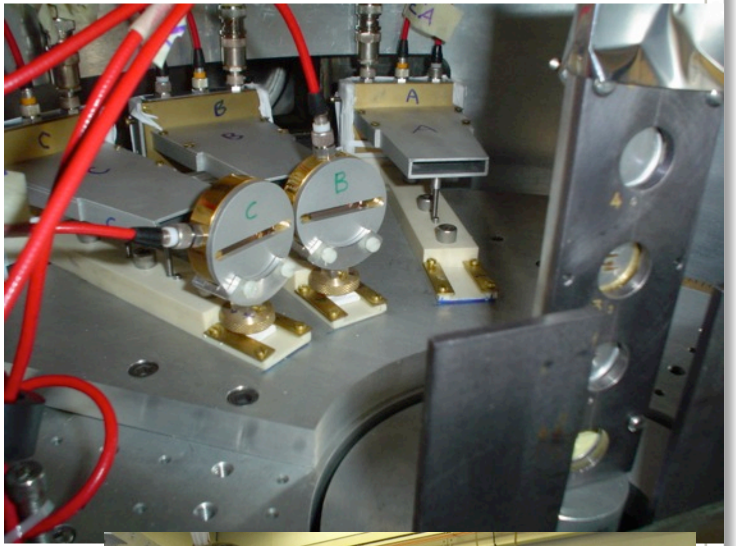
Target: deuterated polyethylene

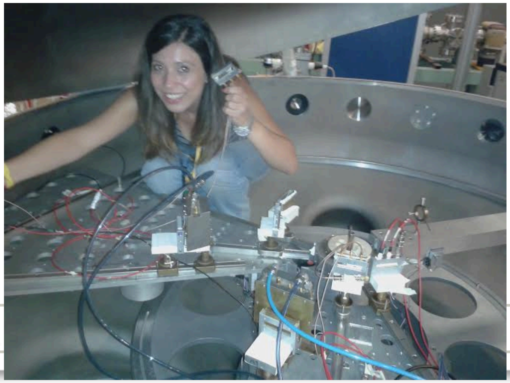


Angles were selected in such a way that the yeld from (the probable) quasi-free mechanism is maximum
(2 particles detected, one not – full kinematics)

Sometimes preparing experiment is a hard task

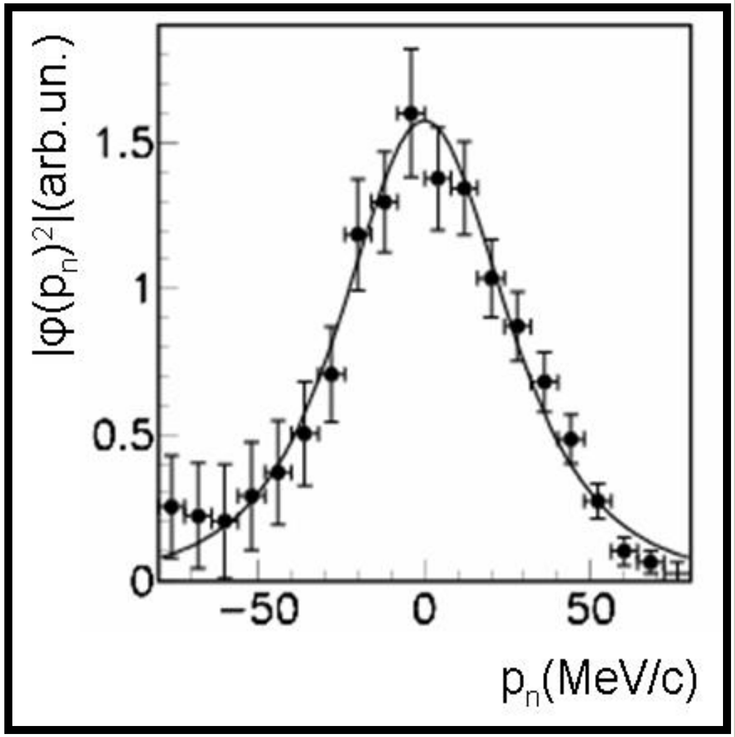
… but problems are usually fixed





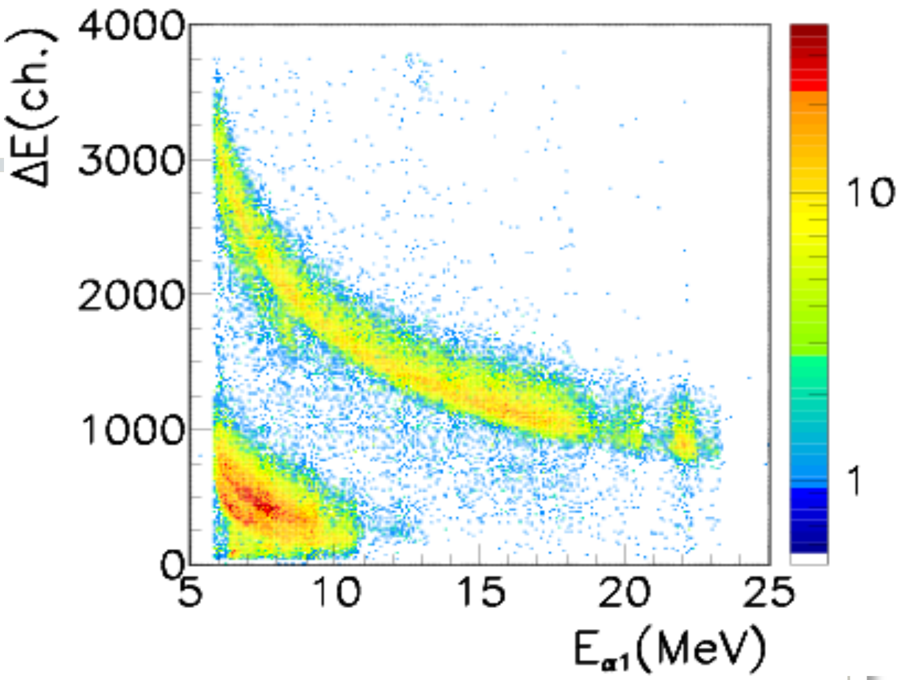
- Experimental angles are chosen to maximize the quasi-free contribution. Once beam energy is selected only for some angular pairs we will have quasi free conditions, i.e. for deuteron case $p_s=0$.

  One can calculate these conditions imposing this and finding the corresponding angular pairs.



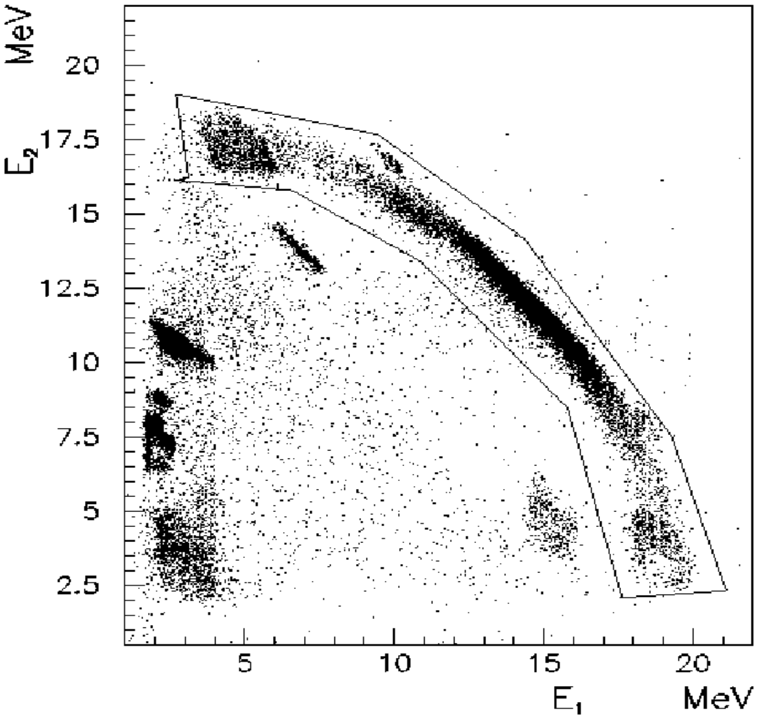
- Once detectors are calibrated particles should be identified

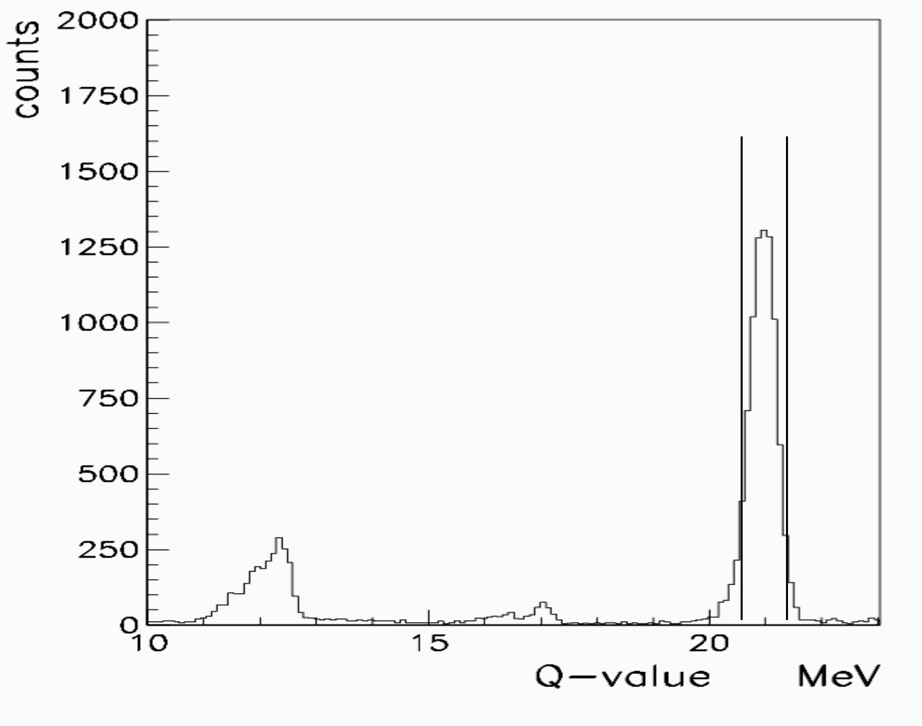
  (by means of usual DE/E techniques).



•After doing this, the expected channel ^{7}Li(d,aa)n should be discriminated from other reactions

Then cuts are made in the kinematic locus as well as in the Q-value spetrum to ensure only events due to the correct reaction are analysed.





Show the presence of quasi free-mechanism

Rejection of sequential mechanism and after…

- Clear evidences of quasi free mechanism should be found:

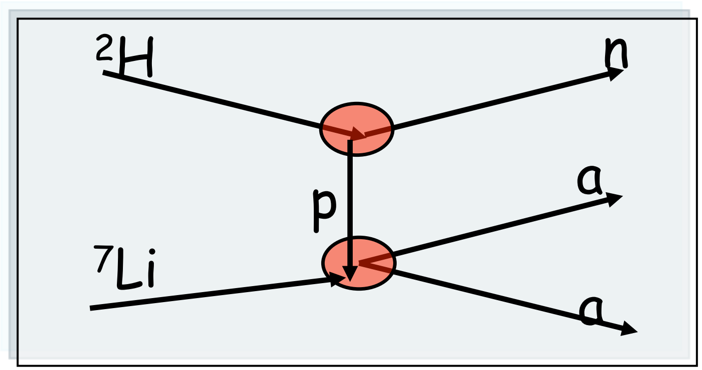
  -angular correlation;

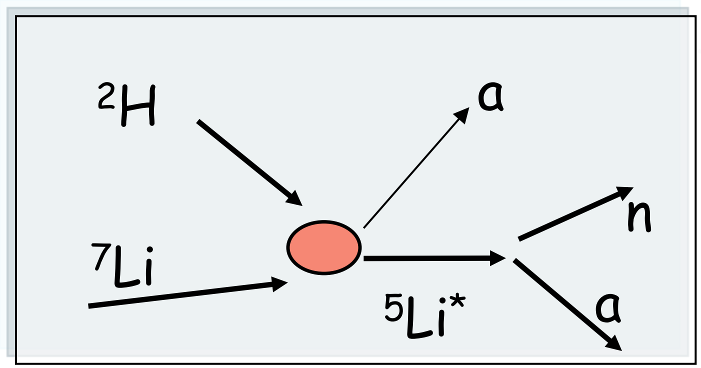
  -momentum distribution;

i.e. events should be correlated properly with momentum distribution of the spectator.

Rejection of sequential mechanism

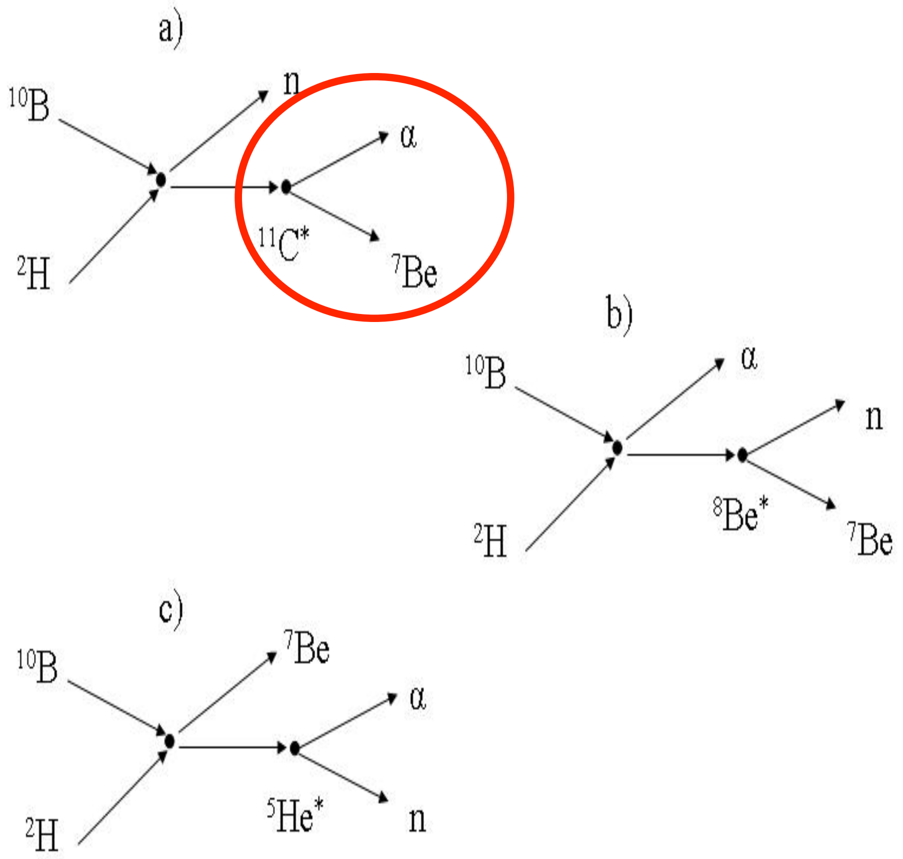
- Mechanisms other than QF must be disciminated and not taken into account in the further analysis. One example: sequential mechanisms

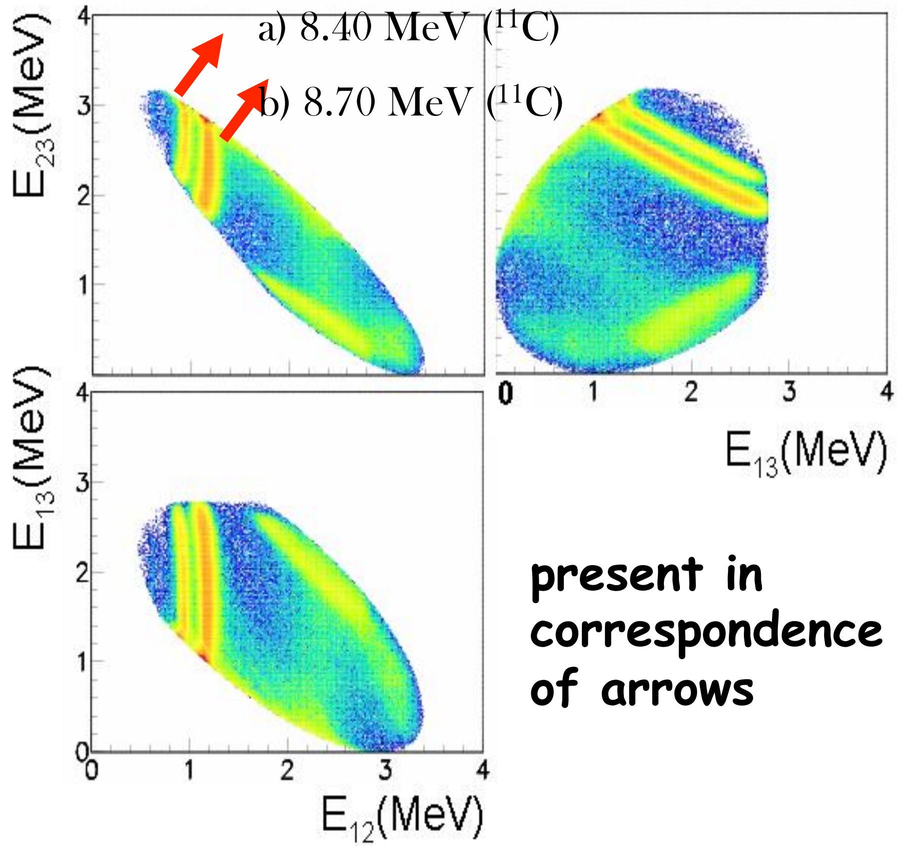




These processes have same ejectiles of QF but proceeds via Some intermediate status.They are clear in relative energy spectra

Not present in our case, another cases where there are evident signatures of sequential decays:





a) 8.40 MeV (^{11}C)

b) 8.70 MeV (^{11}C)

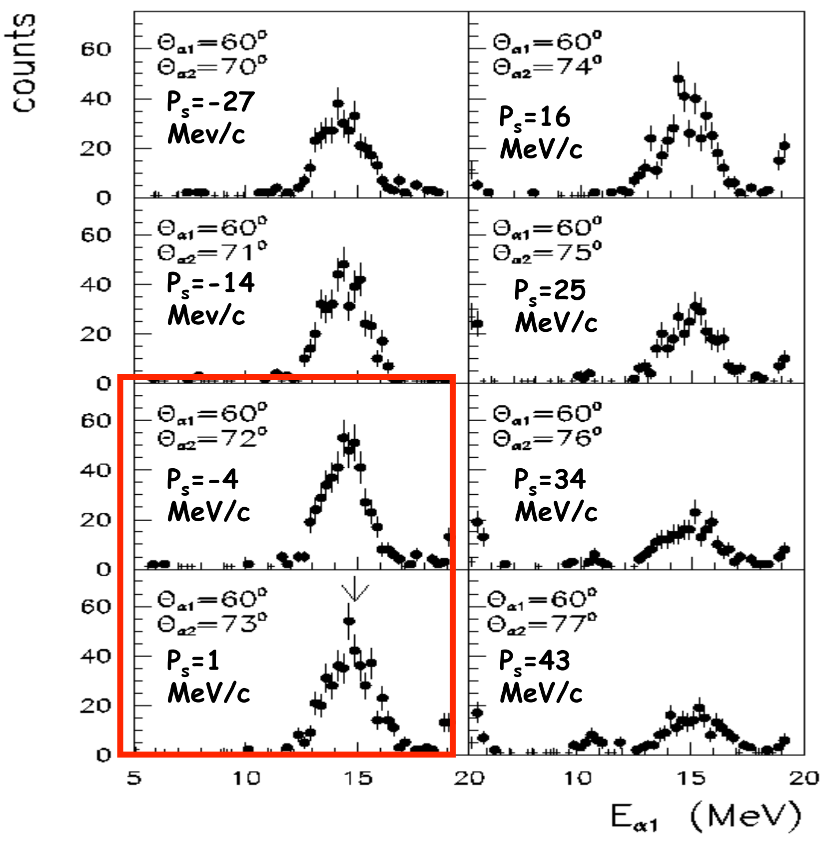
present in correspondence of arrows

Evidences of quasi free mechanism: angular correlation

- We should see an increase in coincidence yeld in correspondance of QF angles (angles where the QF process is more likely).

- This is a necessary condition for the existence of QF mechanism

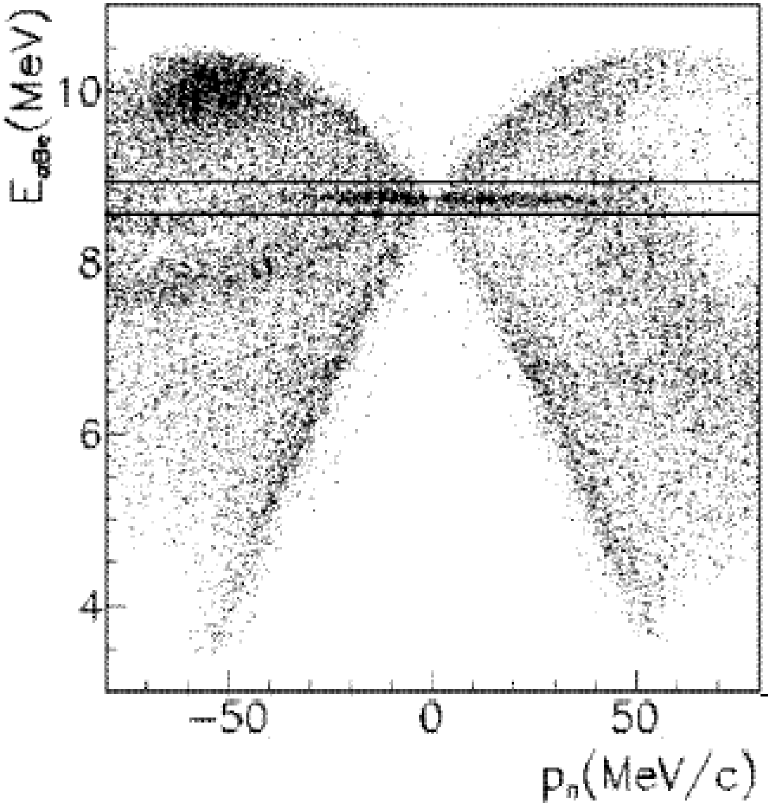
- This behaviour allows to extract a momentum distribution to be compared with theory.



Evidences of quasi free mechanism: momentum distribution

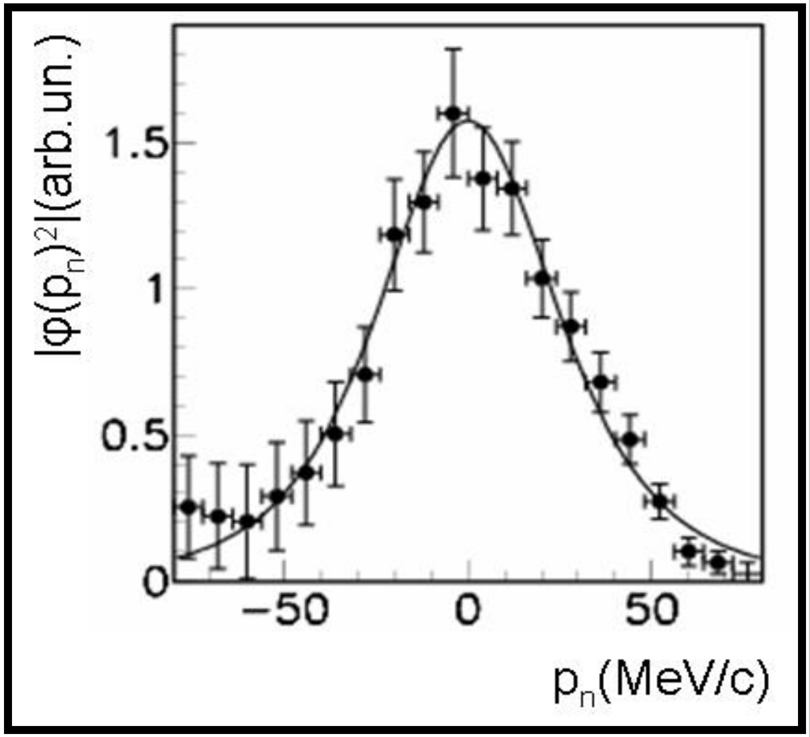
- The momentum distribution of the third (undetected particle) should reflect the theoretical momentum distribution of proton inside deuteron (e.g. Hulthen function)

By measuring the 3-body cross section if a narrow energy range is selected one can measure the momentum distribution



By measuring the 3-body cross section and assuming $d\sigma/d\Omega$ constant (if a narrow energy range is selected), after calculating KF one inverts and get $\Phi(p_s)$ …

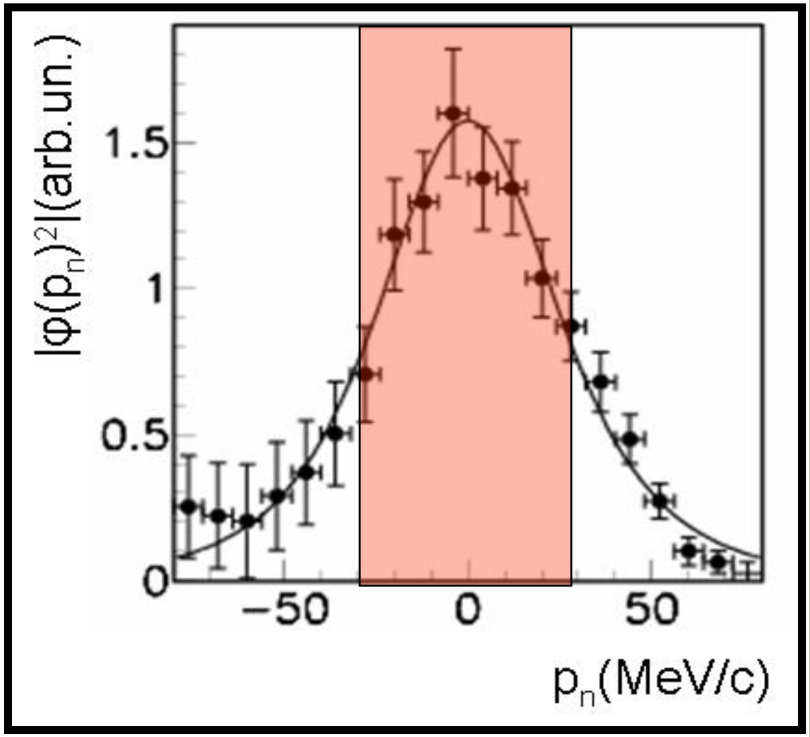
$$\frac{d^3\sigma}{dE_C\, d\Omega_C\, d\Omega_C} \propto KF\left|\Phi(p_S)\right|^2 \left(\frac{d\sigma}{d\Omega}\right)^N$$



Further analysis will be performed after removing sequentail decay (if any) and for low spectator momenta

(e.g. <30, $p_s<k=(2m_{xs}B)^{1/2}$ polar momentum applicability)

- Once it is estabilished the QF contribution only these data (p_s<30 MeV/c) will be considered for further analysis.
- Distortions in the momentum distributions are taken into account (Pizzone et al. 2005&2009)
- Next step is to extract the cross section of astrophysical interest from the measured 3-body one.



$$\left[\frac{d\sigma}{d\Omega}\right]^{\text{Exper.}}_{x+B\to C+D} \propto \frac{\dfrac{d^3\sigma}{dE_C\,d\Omega_C\,d\Omega_D}}{\underbrace{KF\,|\Phi(q_{xs})|^2}_{\text{Calculated}}} \leftarrow \text{Measured} \qquad =$$

Indirect binary cross section

below the Coulomb barrier

$$= \left(\frac{d\sigma}{d\Omega}\right)_{x+B\to C+D} g P_l^{-1}$$

Comparable with direct data

$$P_l(q_{ax}) = \frac{1}{G_l^2(k_{ax}R) + F_l^2(k_{ax}R)}$$

Extraction of the cross section of astrophysical interest

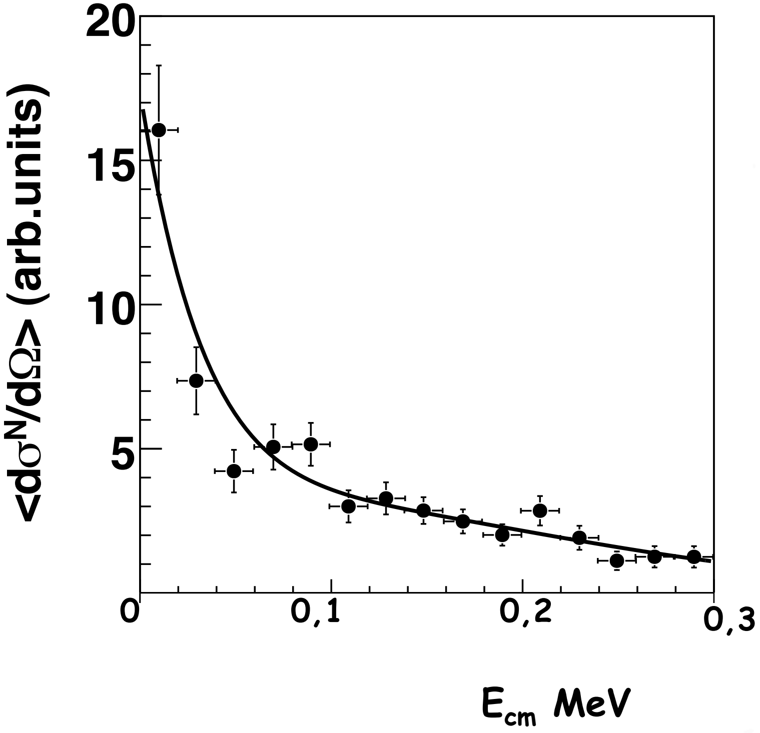
$$\frac{d^3\sigma}{dE_c\, d\Omega_c\, d\Omega_C} \propto KF\left|\Phi(p_S)\right|^2\left(\frac{d\sigma}{d\Omega}\right)^N$$

Dividing the yeld of the 3-body reaction (meas.) by KF $|\Phi(q_{xs})|^2$ (calculated) one gets the nuclear cross section $(d\sigma/d\Omega)^N$

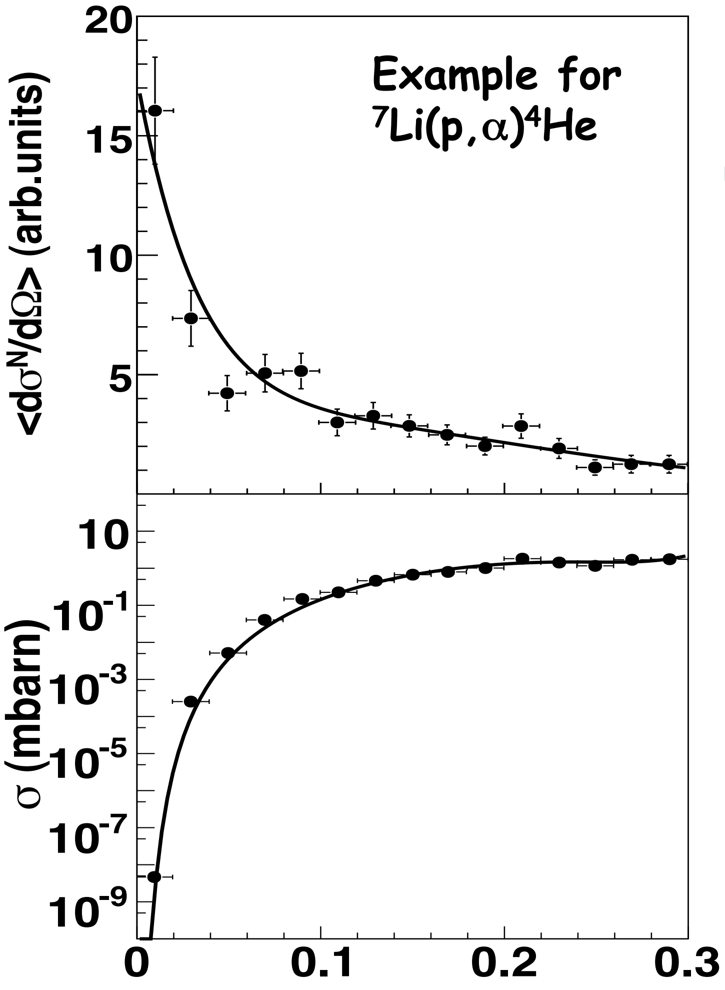
Extraction of the cross section of astrophysical interest

$$\frac{d^3\sigma}{dE_c\, d\Omega_c\, d\Omega_C} \propto KF\left|\Phi(p_S)\right|^2\left(\frac{d\sigma}{d\Omega}\right)^N$$

Dividing the yeld of the 3-body reaction (meas.) by KF $|\Phi(q_{xs})|^2$ (calculated) one gets the nuclear cross section $(d\sigma/d\Omega)^N$



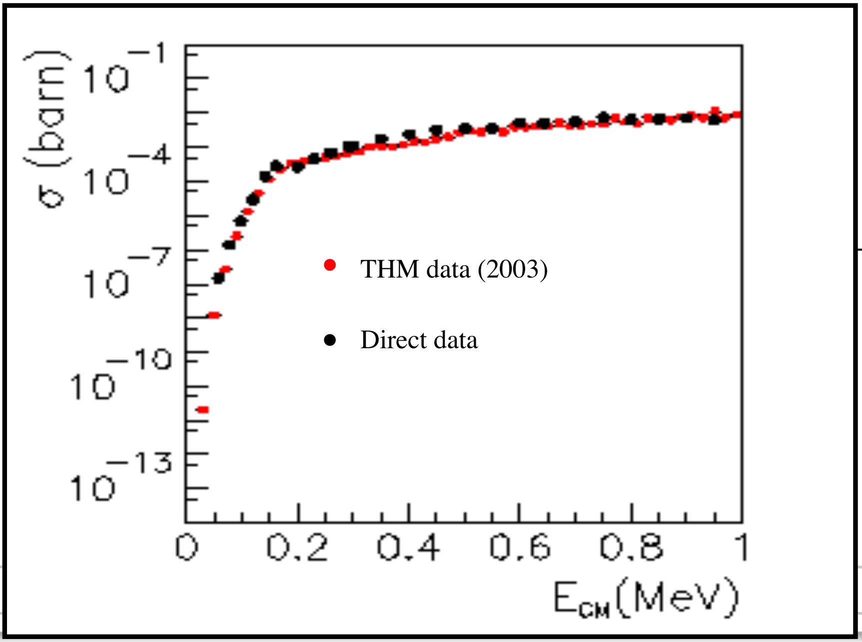
(post collision prescription) $E_{cm}=E_{12}-Q_{2b}$



below the Coulomb barrier

$$\left(\frac{d\sigma}{d\Omega}\right)^{N}_{x+B\rightarrow C+D} g P_l^{-1} = d\sigma/d\Omega^{\text{dir}}$$

Comparable with direct data

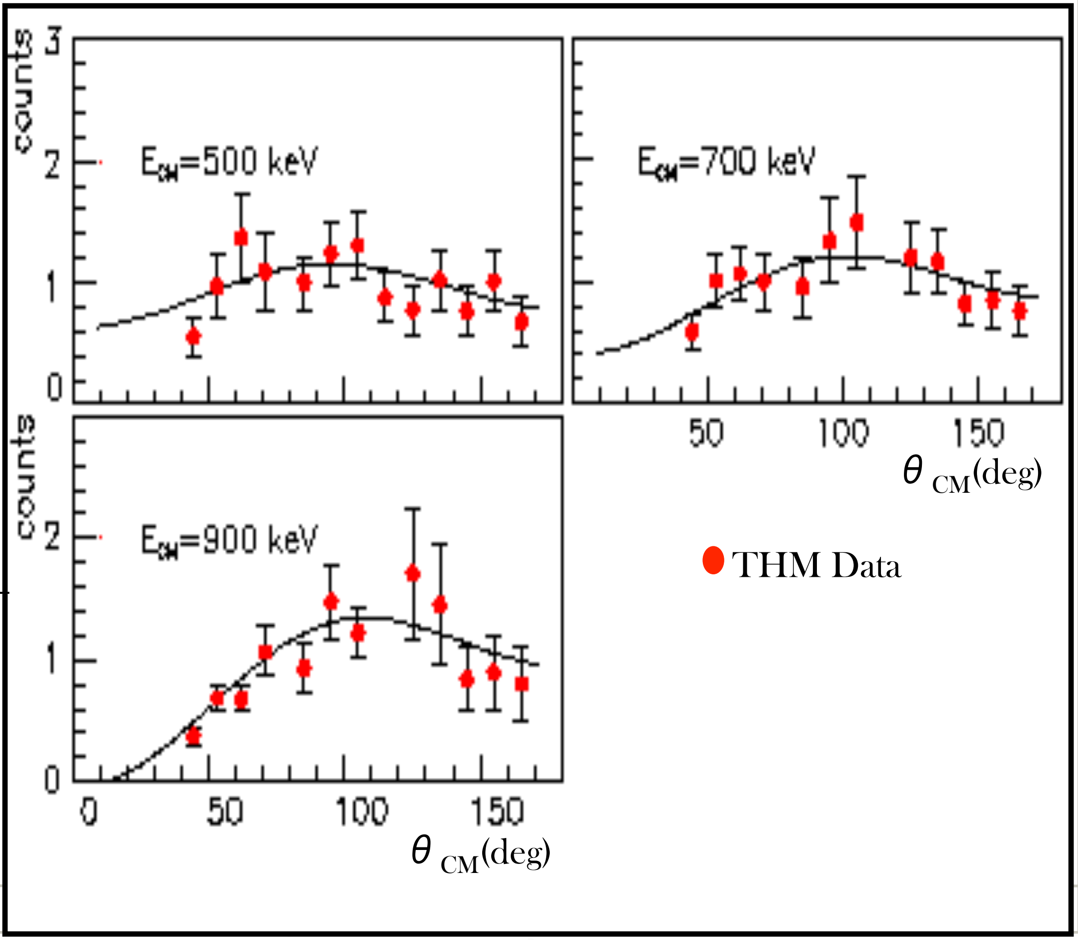


Angular Distribution

- The validity test is performed: the angular distribution in the indirect case should reproduce the direct one

THM data reproduce fairly well the direct data (dashed line)

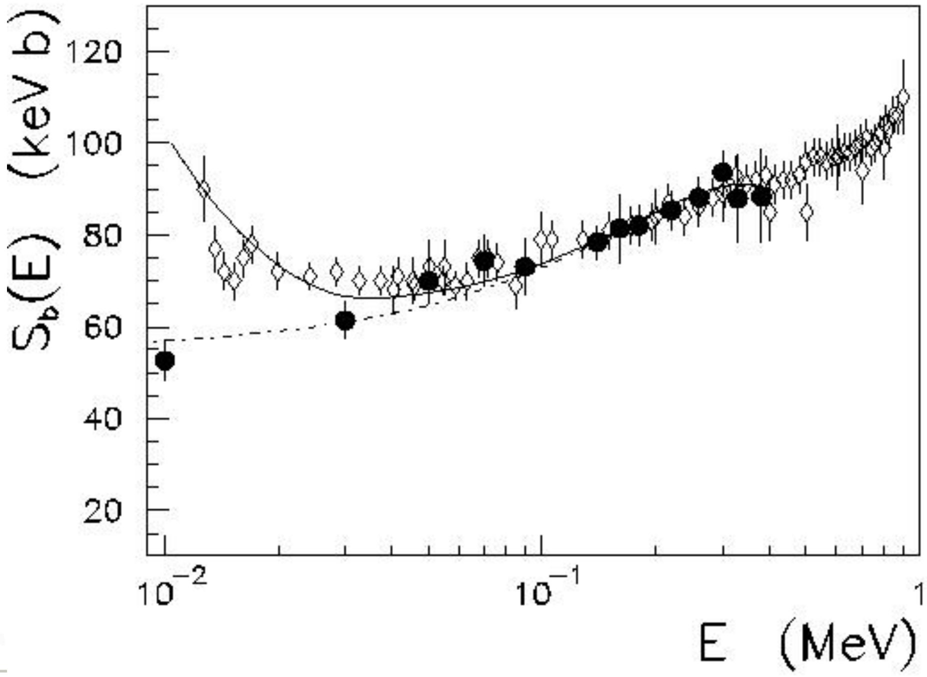
$$\cos\theta_{cm} = \frac{(v_{a1}-v_p)*(v-v_{\alpha 2})}{|v_{a1}-v_p|*|v-v_{\alpha 2}|}$$



Extraction of S(E) factor

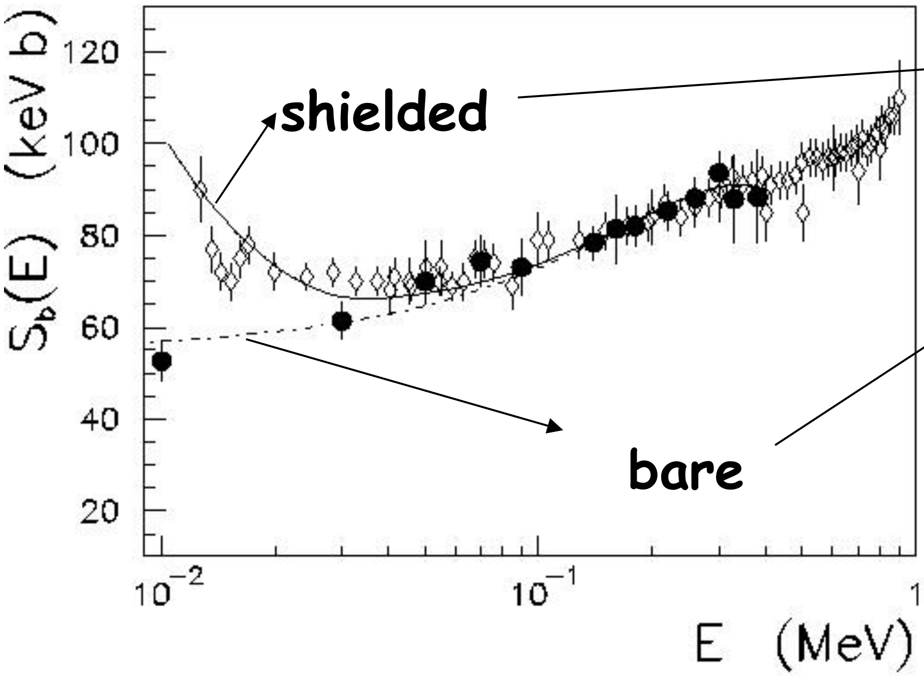
- After measuring the cross section the astrophysical S(E)-factor can be easily deduced.

$$\sigma(E) = 1/E \quad \exp(-2\pi\eta) \quad S(E)$$



THM results should be normalized to direct data at the higher energies and polynomial fits can be deduced

- 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



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

Screening potential

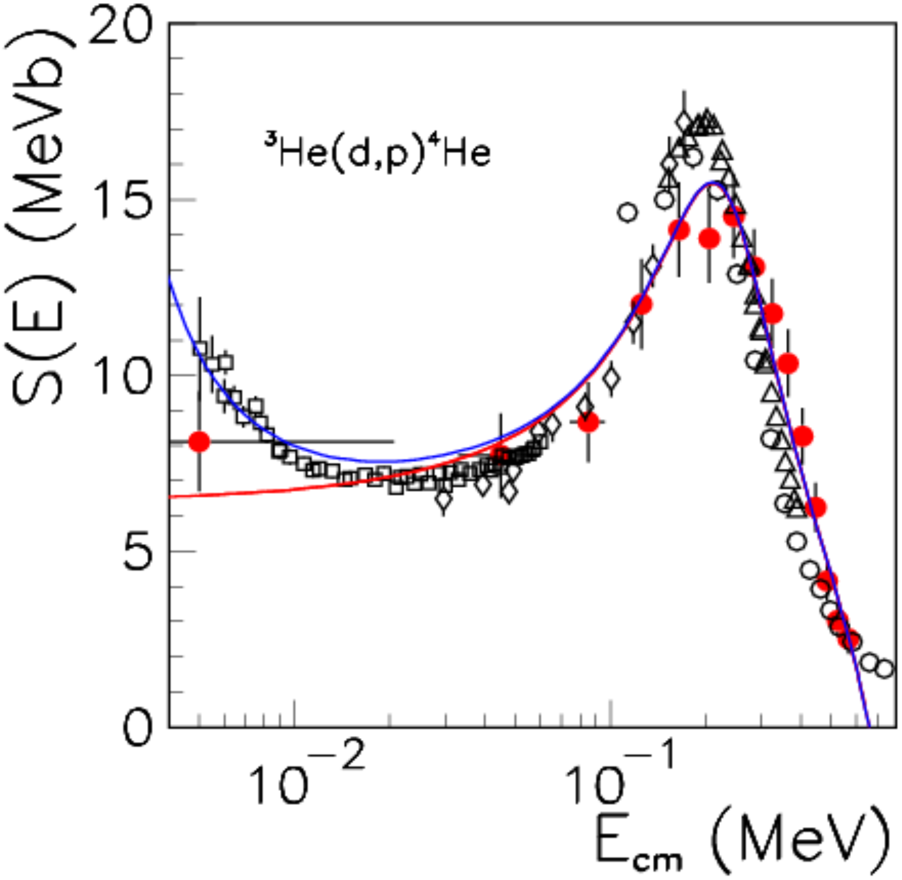
- In case resonances are present a more advanced approach has been applied

(see ref. Tribble et al. Rep. Progr. Phys 77, (2014) 106901)

OTHER RESULTS

- For the ^{3}He(d,p)^{4}He case (La Cognata et al. 2005):

U_e (theo)	$U_e^{(THM)}$ ^{3}He+d	U_e (Dir) ^{3}He+d
115 eV	155 ± 15 eV	175 ± 30 eV



The reaction ^{3}He(d,p)^{4}He is important for primordial nucleosynthesis as well as stellar one.

Radioactive Ion Beams $^{18}F+p\rightarrow{}^{15}O+\alpha$ @ 48 MeV

@CRIB CNS-RIKEN

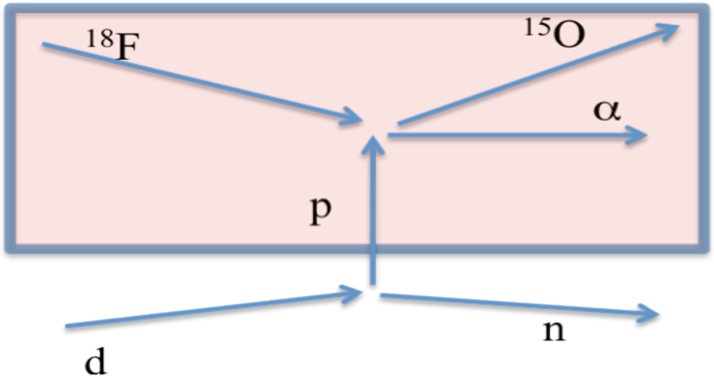
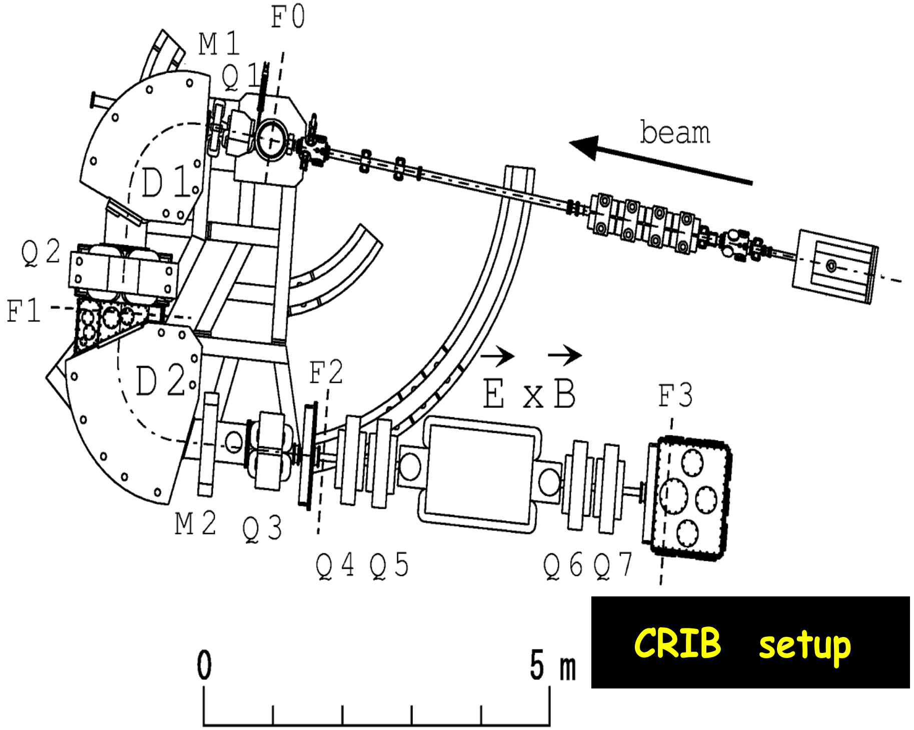


Figure 1: Schematic sketch of the $^{18}F(p,\alpha)^{15}O$ studied by means of the THM

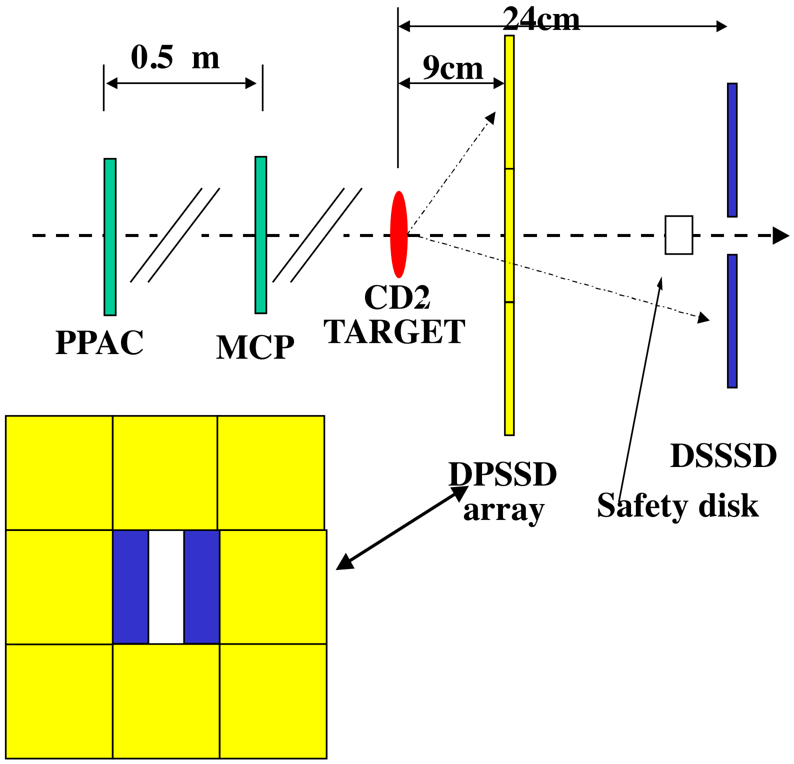
BEAM PRODUCTION AT CRIB

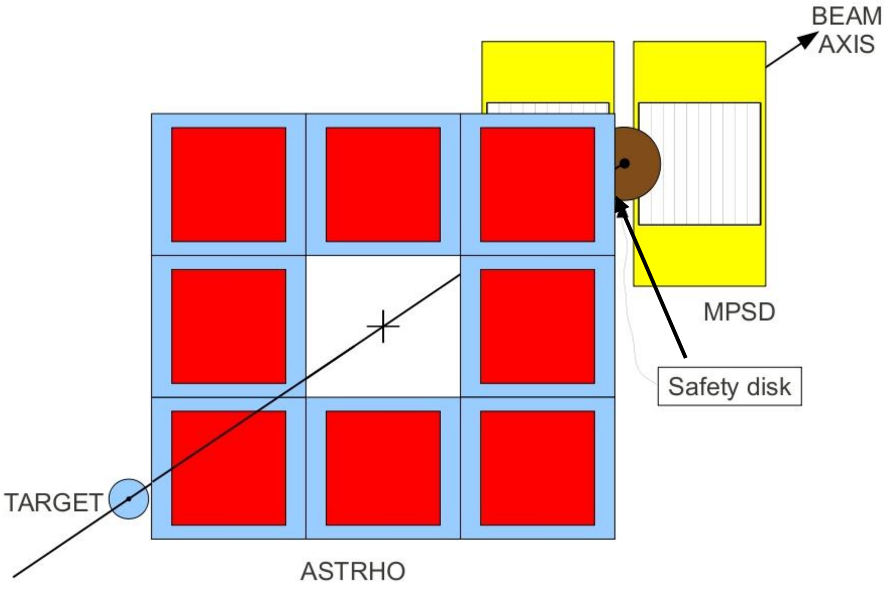


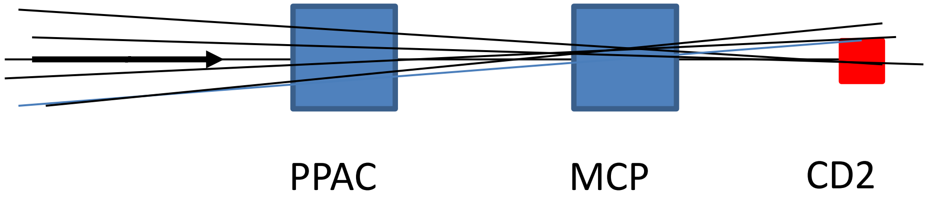
1. Two beam production tests performed (Nov 2005, June 2006)
2. 3*10^5 pps obtained, 10^6 pps within the capabilities of the machine
3. Beam purity > 98%
4. Normalization and deffinitionof the beam particle by particle (PPACs)

EXPERIMENTAL SETUP

(other then CRIB.....)

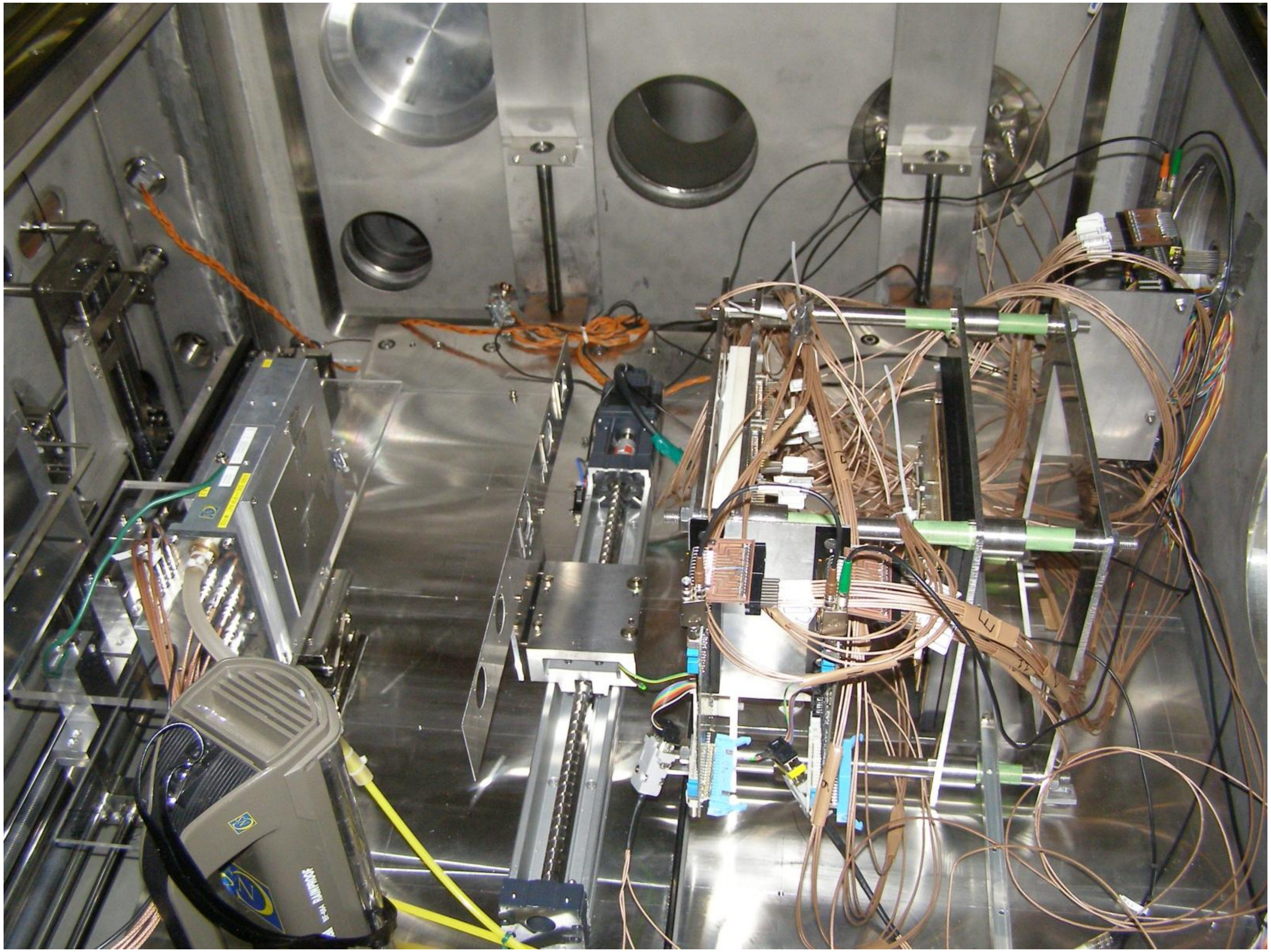






particle by particle beam reconstruction

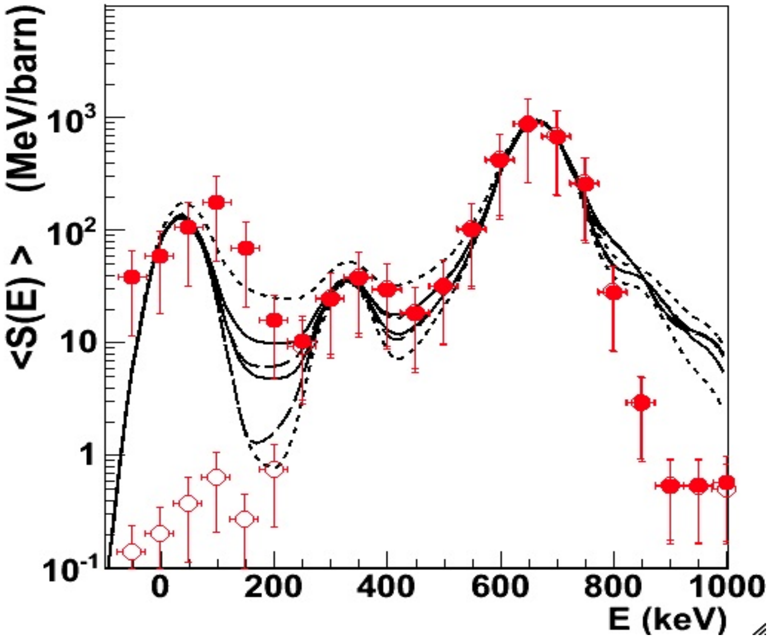
ASTRHO:
Array of Silicons for TRojan HOrse



How ASTRHO looks like in reality

Results:

S. Cherubini et al. PRC 92, 015805 (2015)



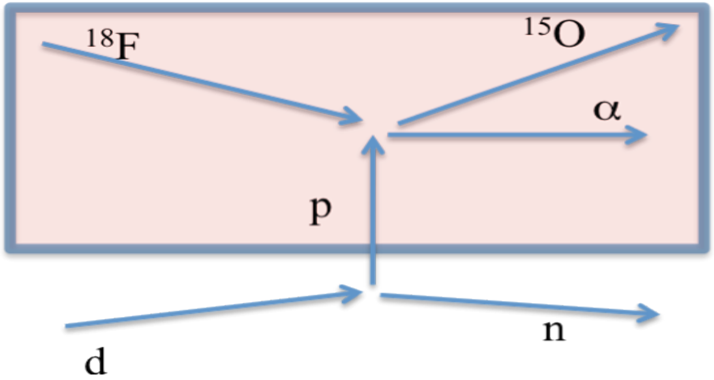
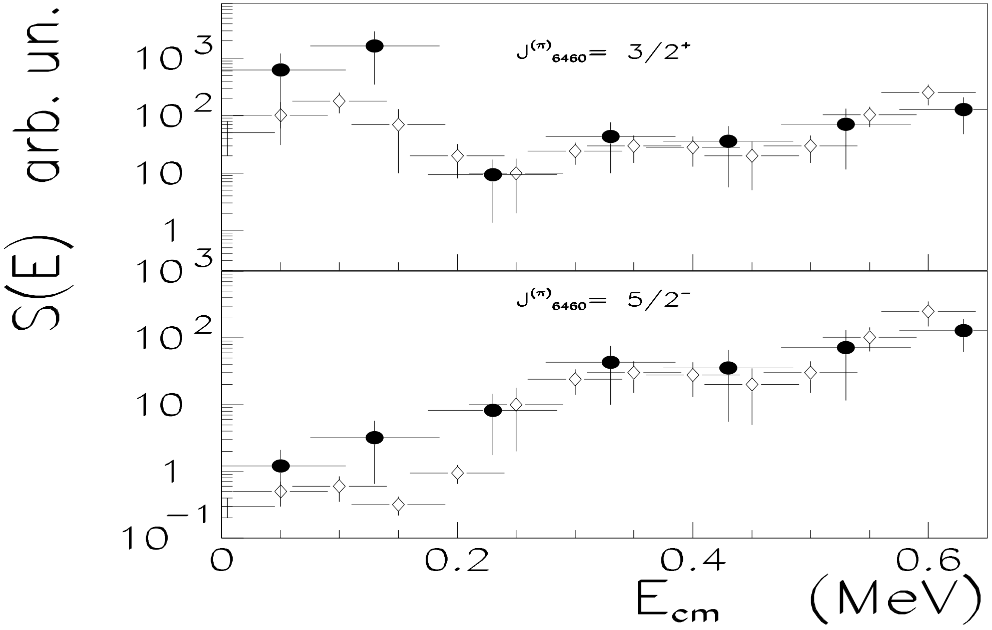


Figure 1: Schematic sketch of the ^{18}F(p,α)^{15}O studied by means of the THM

New Measurement @TAMU Pizzone R.G. et al. EPJ 2016



This reaction rata is crucial for understanding the Novae Nucleosynthesis

Recent TH results: n-producing reactions

The Astrophysical Journal, 777:143 (21pp), 2013 November 10

ON THE MEASUREMENT OF THE ^{13}C(α, n)^{16}O *S*-FACTOR AT NEGATIVE ENERGIES
AND ITS INFLUENCE ON THE *s*-PROCESS

M. La Cognata[1], C. Spitaleri[1,2], O. Trippella[1,3], G. G. Kiss[1,4], G. V. Rogachev[5], A. M. Mukhamedzhanov[6], M. Avila[5], G. L. Guardo[1,2], E. Koshchiy[5], A. Kuchera[5], L. Lamia[2], S. M. R. Puglia[1,2], S. Romano[1,2], D. Santiago[5], and R. Spartà[1,2]
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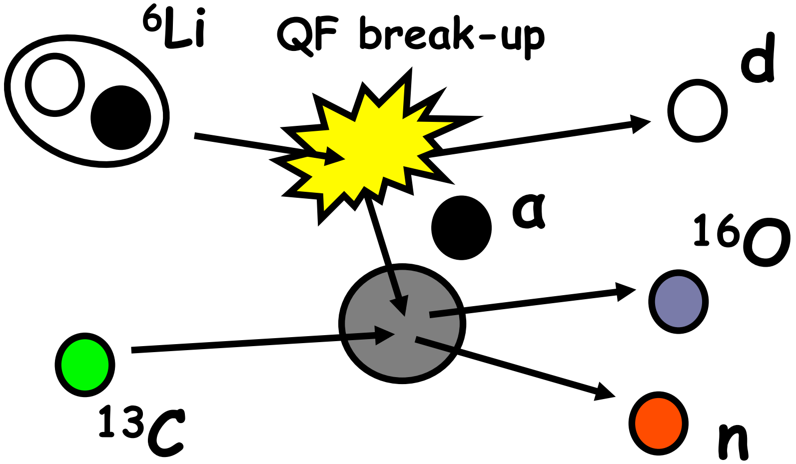
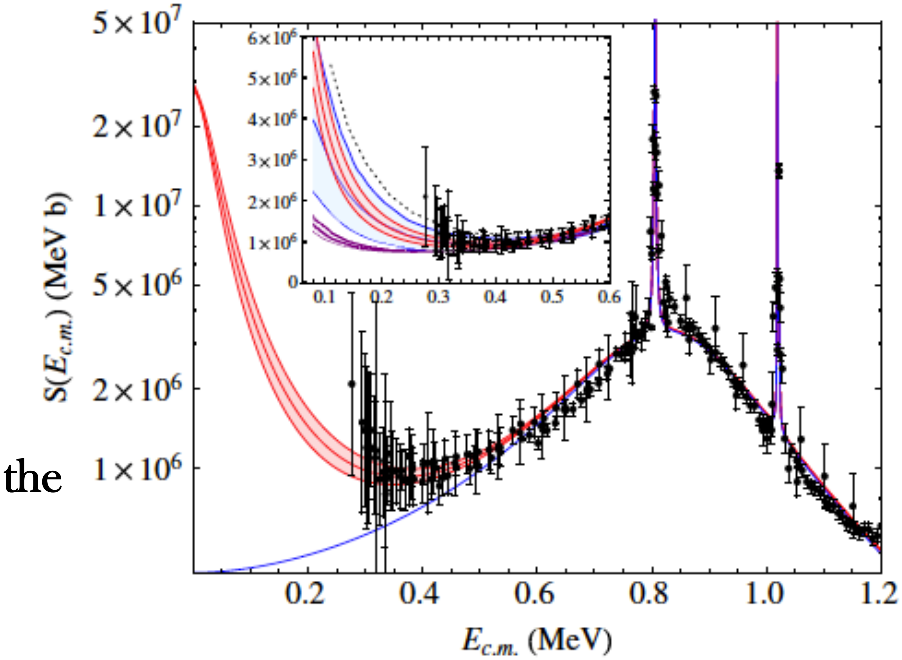
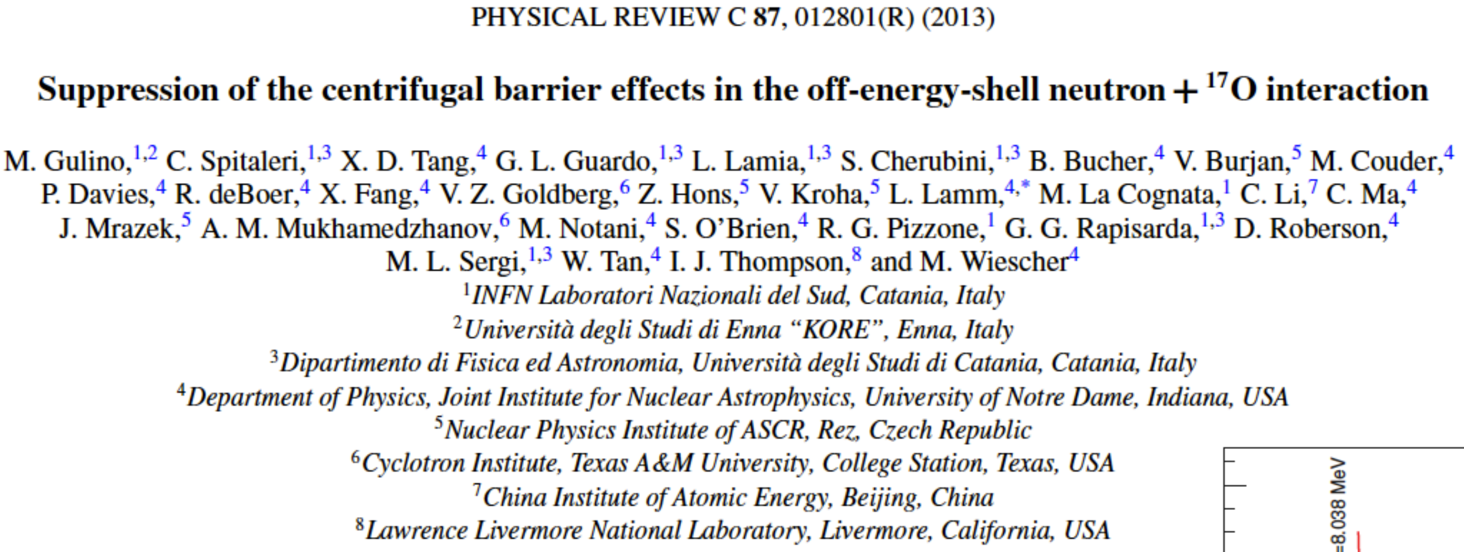
[2] Dipartimento di Fisica e Astronomia, Università di Catania, I-95123 Catania, Italy
[3] Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, & Dipartimento di Fisica, Università di Perugia, I-06123 Perugia, Italy
[4] Institute of Nuclear Research (ATOMKI), Debrecen, Hungary
[5] Department of Physics, Florida State University, Tallahassee, FL, USA
[6] Cyclotron Institute, Texas A&M University, College Station, TX, USA





- 6Li beam→ the TH nucleus is the beam;
- Neutron in the exit channel→ we need to detect the charged spectator (deuteron);
- Measurement of the sub-threshold level -3 keV ANC of importance for astrophysics;
- THM reaction rate higher by a factor 2 with respect the literature.

Recent TH results: n-induced reaction



PHYSICAL REVIEW C **87**, 012801(R) (2013)

Suppression of the centrifugal barrier effects in the off-energy-shell neutron + ^{17}O interaction

M. Gulino,[1,2] C. Spitaleri,[1,3] X. D. Tang,[4] G. L. Guardo,[1,3] L. Lamia,[1,3] S. Cherubini,[1,3] B. Bucher,[4] V. Burjan,[5] M. Couder,[4]
P. Davies,[4] R. deBoer,[4] X. Fang,[4] V. Z. Goldberg,[6] Z. Hons,[5] V. Kroha,[5] L. Lamm,[4,*] M. La Cognata,[1] C. Li,[7] C. Ma,[4]
J. Mrazek,[5] A. M. Mukhamedzhanov,[6] M. Notani,[4] S. O'Brien,[4] R. G. Pizzone,[1] G. G. Rapisarda,[1,3] D. Roberson,[4]
M. L. Sergi,[1,3] W. Tan,[4] I. J. Thompson,[8] and M. Wiescher[4]
[1]*INFN Laboratori Nazionali del Sud, Catania, Italy*
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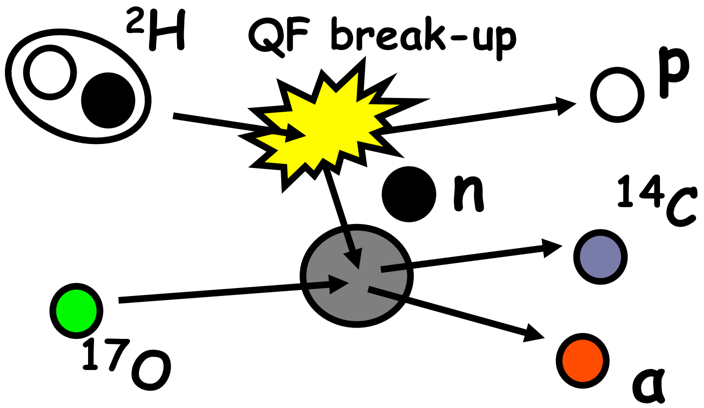
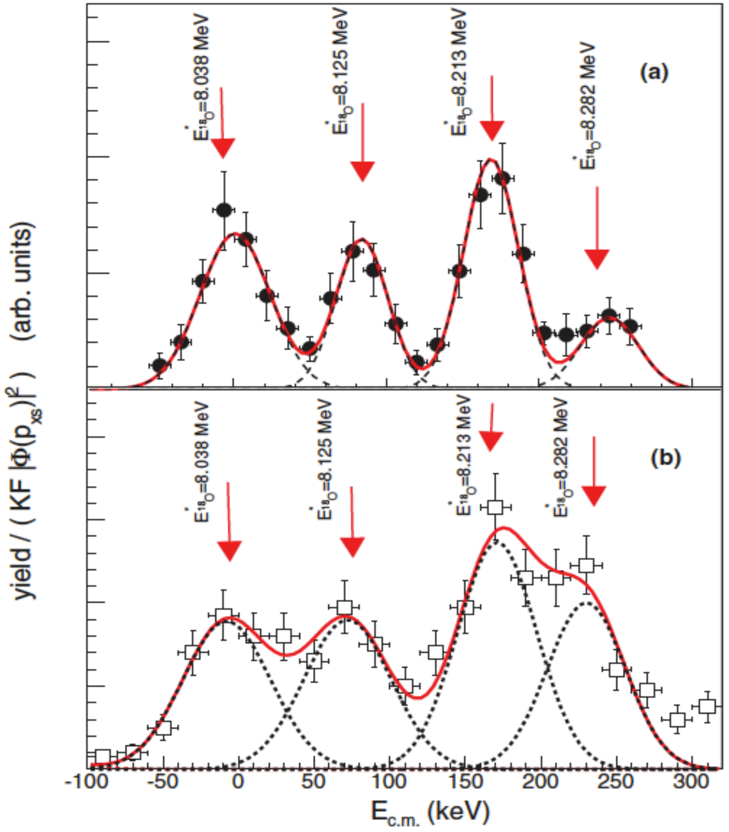
[3]*Dipartimento di Fisica ed Astronomia, Università degli Studi di Catania, Catania, Italy*
[4]*Department of Physics, Joint Institute for Nuclear Astrophysics, University of Notre Dame, Indiana, USA*
[5]*Nuclear Physics Institute of ASCR, Rez, Czech Republic*
[6]*Cyclotron Institute, Texas A&M University, College Station, Texas, USA*
[7]*China Institute of Atomic Energy, Beijing, China*
[8]*Lawrence Livermore National Laboratory, Livermore, California, USA*





- Two experimental runs performed in Catania and South Bend (Notre Dame University);
- First detection of the 8125 keV level as ^{17}O-n (l=3);
- No centrifugal effects in the entry channel;

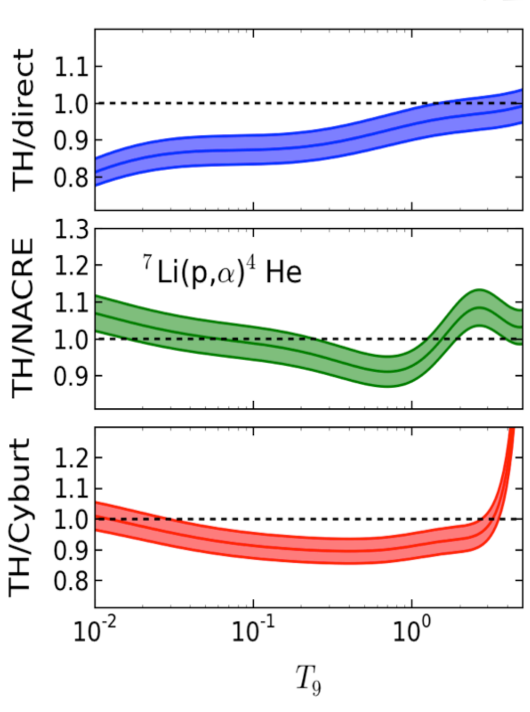
- Once we have the S(E)-factor it is possible to calculate the reaction rate in the astrophysical environment:

$R_{aB} = (1+\delta_{aB})\, N_a \;\; N_B \, \langle\sigma v\rangle_{aB}$

N_a , N_B = number of reacting particles

a, B per cm^3

δ_{aB} = Kronecker symbol



$\langle\sigma v\rangle_{aB} = \int_0 v\, \sigma(v)\, \phi(v)\, dv$ with $\phi(v)$ M

Boltzmann statistic distribution

Pro' s

The advantages of the THM

A - It is possible measure the bare nucleus cross section σ_b (or the bare nucleus Astrophysical Factor $S_b(E)$) at Gamow energy for reactions involving charged particles and neutron.

No extrapolation

B - It is possible to measure excitation function in a " relatively" short time because typical order of magnitude for a three- body cross- section is mb;

C - One of the few ways to measure the electron screening effect;

comparison with direct data;

D - Possibility (already verified) of application to the radioactive beam measurements;

- It can be used with stable or Radioactive beams (measurements available $^{18}F(p,a)^{15}O$ (Cherubini et al. 2015 @CRIB, Pizzone et al 2016 @TAMU)

- It can be used with neutron induced reactions (n,p) and (n,a) reactions (Gulino et al 2010 & 2013)

- It can be used for interaction of RIB's and neutrons (experiment done in CRIB ($^{18}F(n,a)^{15}N$) & Legnaro LNL ($^{7}Be(n,a)^{4}He$), (see NIC 2016 conference).
  New experimental run in collaboration with CNS (S. Hayakawa, H. Yamaguchi et al.) beam@CRIB in 2016.

Con’s

Main limitations of the method

A- Preliminary study of quasi-free mechanism and tests of validity are necessary.

- Presence of different 3-body reaction mechanisms (Sequential Decay – Quasi-Free)

B- No absolute cross section is measurable:

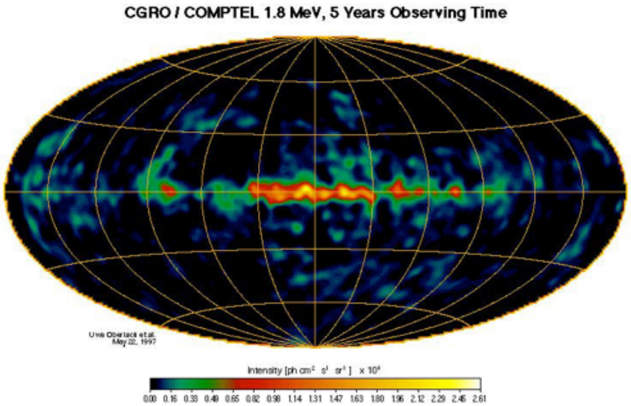
-The excitation functions at energies above/below Coulomb barrier must be known from direct measurements;

C- Measurements with high angular and energy resolutions are needed;

D-**Theoretical analysis is needed**:

- PWIA, MPWBA

TH Method is complementary to direct measurements as well as other indirect methods.

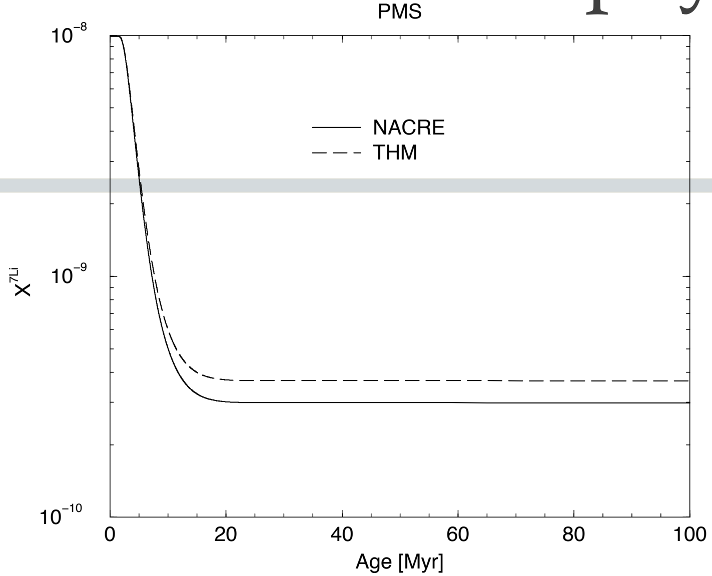


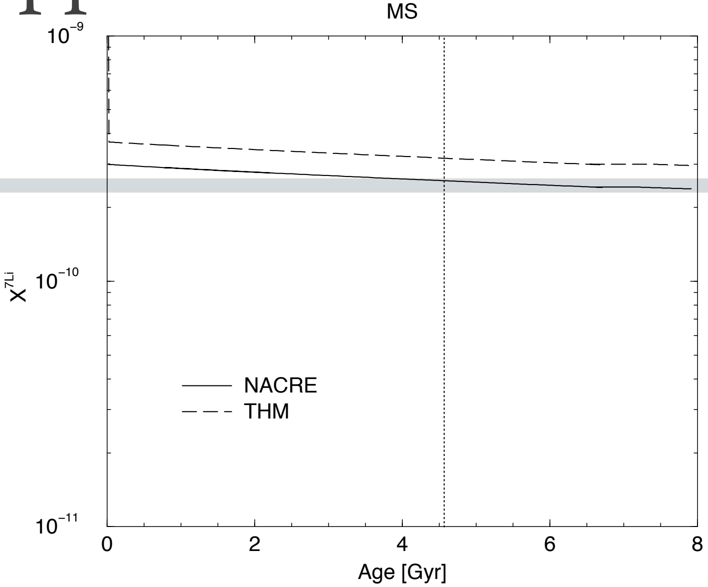
Part 5: astrophysical aplications

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
- Reaction involved: ^{7}Li(p,a)^{4}He & ^{6}Li(p,a)^{3}He

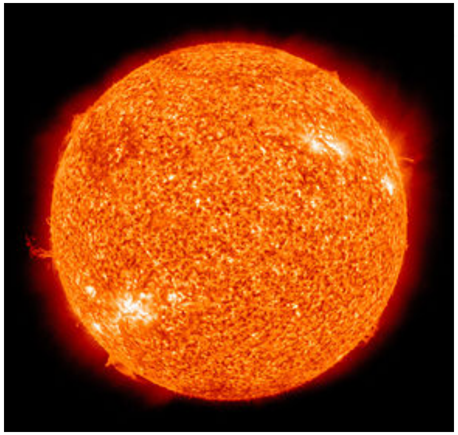
Astrophysical applications



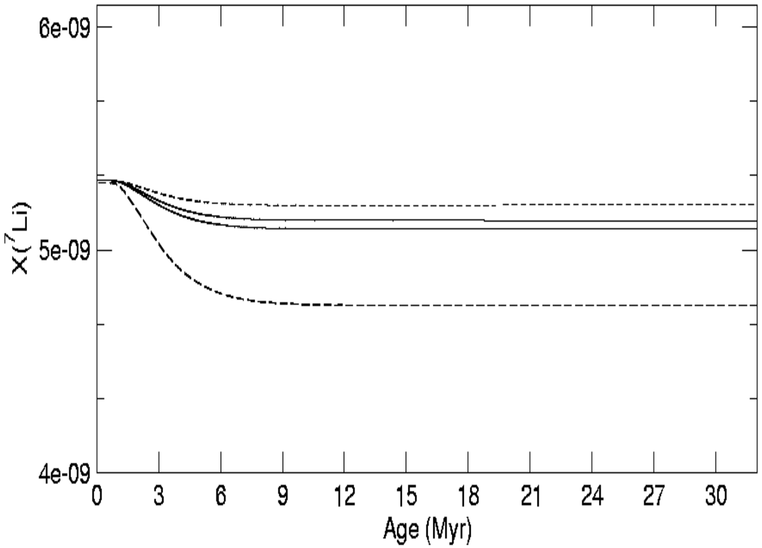


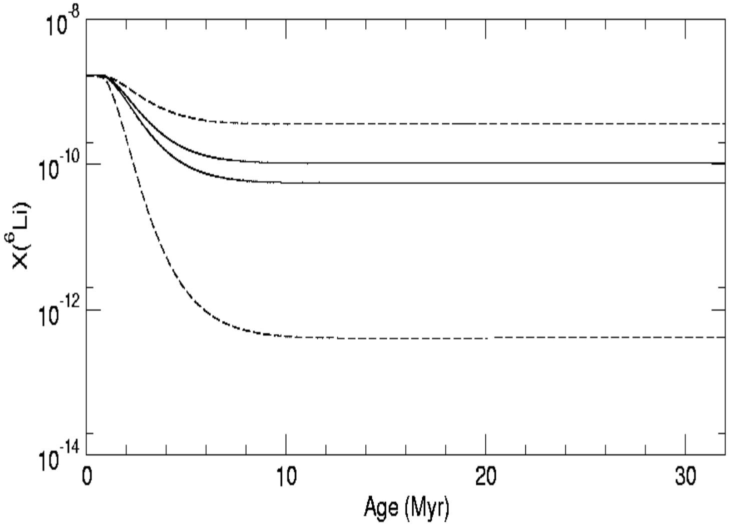
Lithium surface abundance for the Sun,
Good agreement with NACRE results

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)

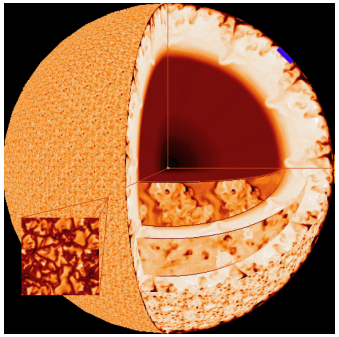
- Lithium problem

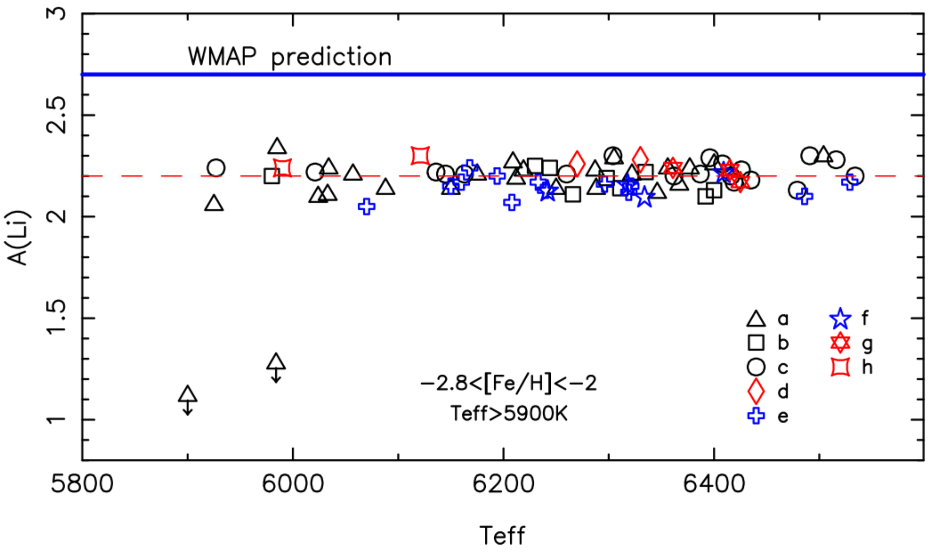
Lattuada M. et al.: 2001 Ap. J. 562, 1076

Spitaleri C. et al.: 1999, Phys. Rev C, 60, 55802

Pizzone R.G. et al.: 2003, A.& A.. 9, 435

Pizzone R.G. et al., A&A 438, 779-784 (2005)
Tumino A. et al.,PRC 67, 065803 (2003)
Lamia et al. Apj 2013 768, 65
Lamia et al A&A 541 158 (2012)





- **Light elements depletion:**

Reaction involved: ^{9}Be(p,a)^{6}Li, ^{10,11}B(p,a)^{7,8}Be

Depletion of LiBeB can give hints to transtort mechanisms in stars…

But their nuclear burning must be well understood

Spitaleri, C. et al. 2004, Phys. Rev. C, 69,055806

Spitaleri, C. et al. 2014, Phys. Rev. C, 89, 032049

Wen et al. 2008 PRC, 78, 035805

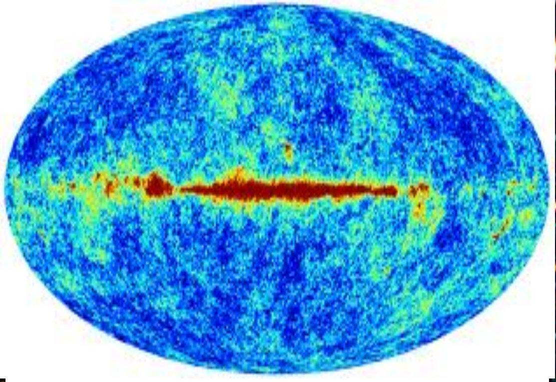
Lamia et al. 2015 APJ

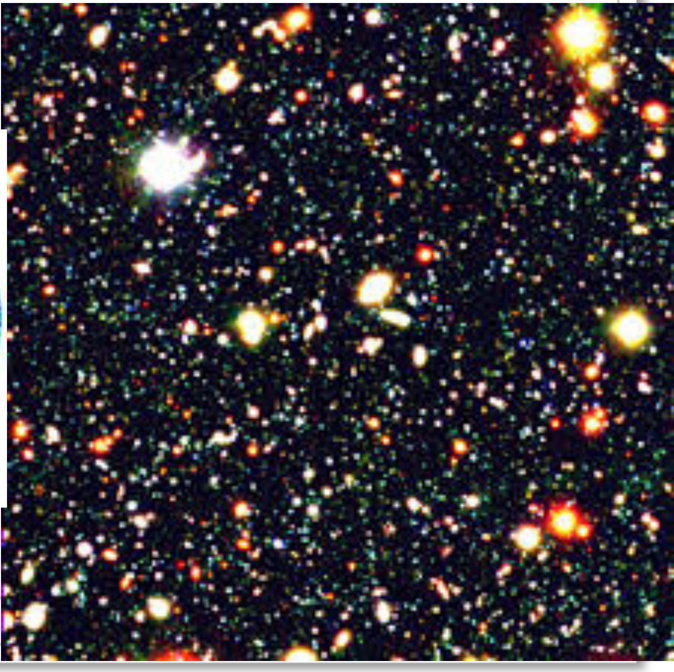
Primordial nucleosynthesis is one of the pillars of the current Cosmological models.

Main evidences of Standard Big Bang scenario:

- Galactic expansion (Hubble Law) from SN measurements,
- Cosmic Microwave Background radiation probes the universe at time around 3×10^5 years after BB
- Primordial nucleosynthesis probes the universe at around 1-20 minutes after Big Bang!!

The only in the radiation dominated era





- Isotopes produced in the first phases of the BBN can give information on the childhood of our universe

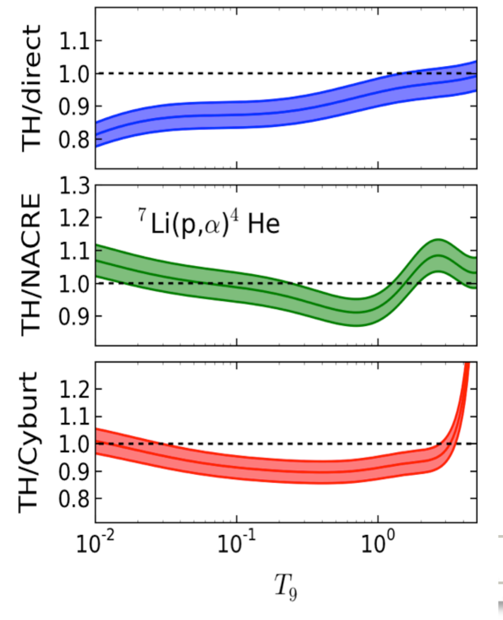
Reactions involved: d(d,pt), d(d,n)^{3}He, ^{3}He(d,p)^{4}He, ^{7}Li(p,a)^{4}He

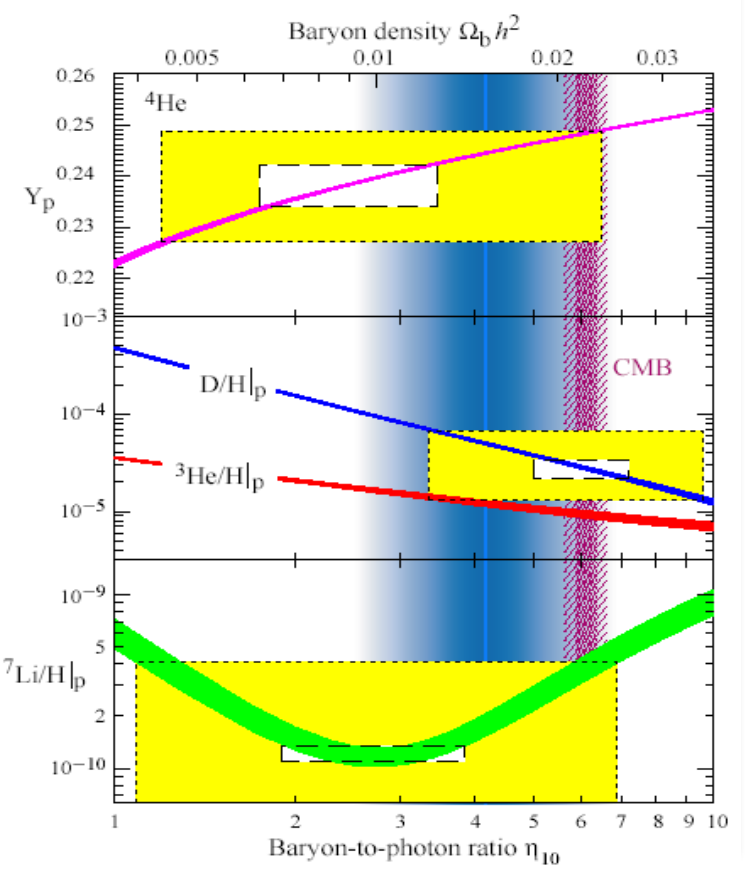
and their impact on astrophysics evaluated

Pizzone R.G. et al.: 2003, A.& A, 9, 435

Pizzone R.G. et al.: 2014, APJ, 786, 14

Tumino A et al. APJ 2014 785, 45





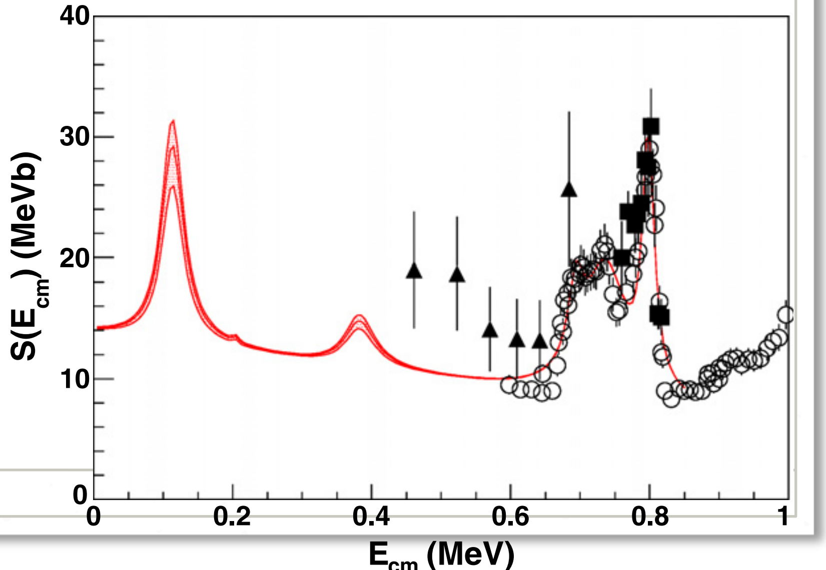
- AGB Nucleosynthesis:
- Reactions of interest for the AGB nucleosynthesis were studied and their impact on astrophysics evaluated

^{15}N(p,a)^{12}C, ^{18}O(p,a)^{15}N, ^{19}F(p,a)^{16} O, ^{19}F(a,p)^{22}N ...

La Cognata M ASTROPHYSICAL JOURNAL 708, 796-811 2010

La Cognata M, PHYSICAL REVIEW LETTERS 101 152501 2008

Palmerini et al. 2011 APJ 741 26

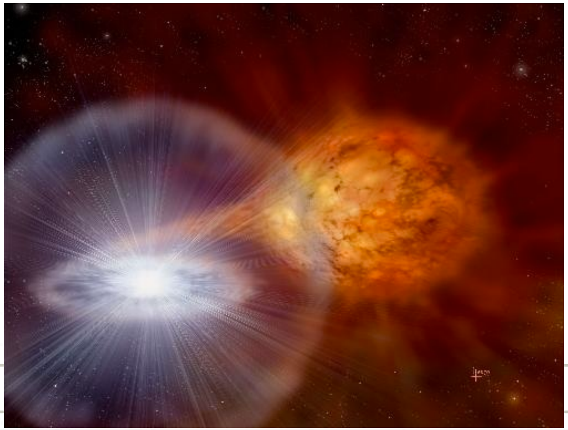


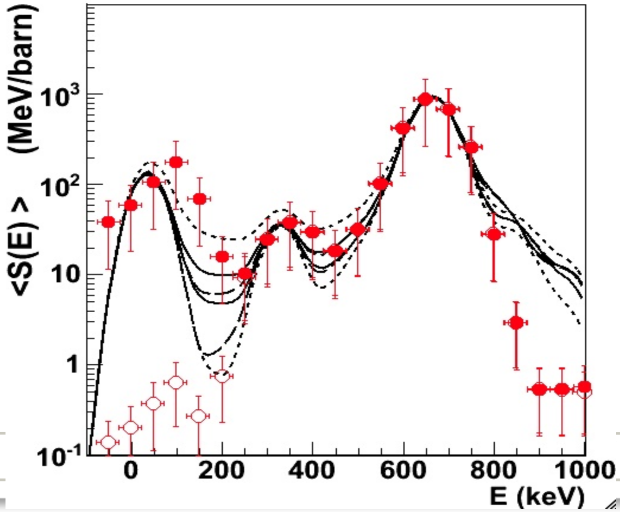
Novae Nucleosynthesis:

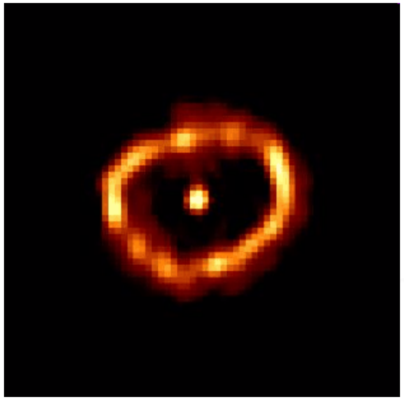
Reactions of interest for the Novae nucleosynthesis were studied and their impact on astrophysics will be evaluated

^{17}O(p,a)^{14}N, ^{18}F(p,a)^{15}O, ^{18}F(n,a)^{15}O

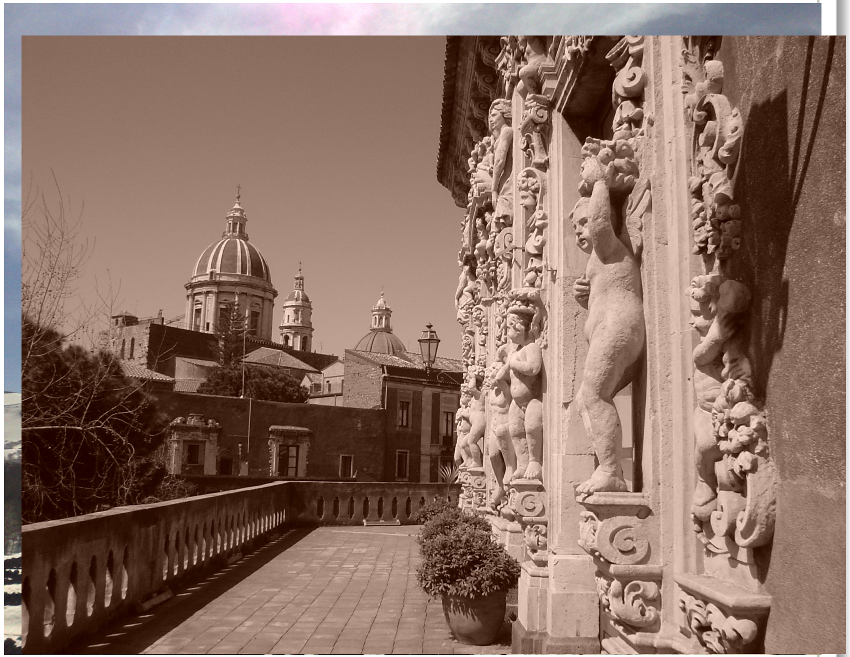
Sergi et al., PRC 2010 79 045801 & 2015 91 065803
Cherubini et al., PRC 2015 92 015805
R.G. Pizzone et al. EPJ 2016







Research mainly carried on in Catania
INFN LNS



The Nuclear Astrophysics Group @ Catania

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M. Gulino, A. Tumino University Kore & INFN LNS Italy

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  - C.N.S. Riken, Wako, Japan: S. Kubono, H. Yamaguchi
  - Riken, Wako, Japan: T. Motobayashi
  - CIAE, Beijing, China: S. Zhou, C. Li, Q. Wen
  - Institute for nuclear research, Rez, Czech rep.: V. Kroha, V. Burjan, J. Mrazek
  - Texas A&M Commerce USA: C. Bertulani
  - INFN LNL: M. Mazzocco
  - Nipne IFIN Bucharest: L. Trache
  - Atomki, Debrecen, Hungary: G. Kiss
  - CSNSM, Orsay, France : A. Coc , F. Hammache, N. De Sereville
  - Florida State University USA: I. Wiedenhofer
  - Notre Dame University USA: M. Wiescher
  - University of Pisa: S. Degl'Innoccenti, P. Prada Moroni
  - RSE INP Alma Aty Kazakhstan: N. Burtibaiev
  - Rudjer Boskovic Institute Zagreb Croatia: N. Soic, M. Milin, D. Miljanic

Further reading

BOOKS

W.D. Arnett & J.W. Truran	*Nucleosynthesis* The University of Chicago Press, 1968
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R. Boyd:	Nucl. Phys. A693 (2001) 249-257	*Big Bang Nucleosynthesis*
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