Nuclear Astrophysics and Underground Accelerators

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Laboratory
Underground
Nuclear
Astrophysics

Outline:

-Nuclear Fusion reactions in stars: why measuring their cross section?

-Why going underground to perform these experiments?

-The LUNA Experiment at LNGS: recent results

- On-going measurements and future perspective: the LUNA-MV project

Nuclear Astrophysics

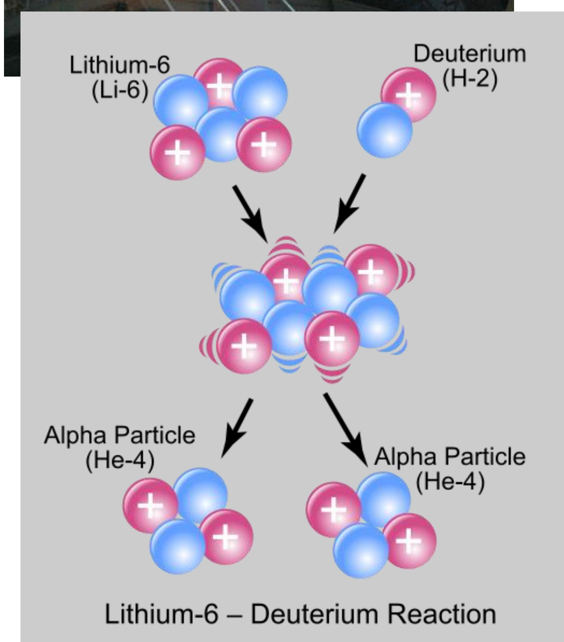
Nuclear astrophysics

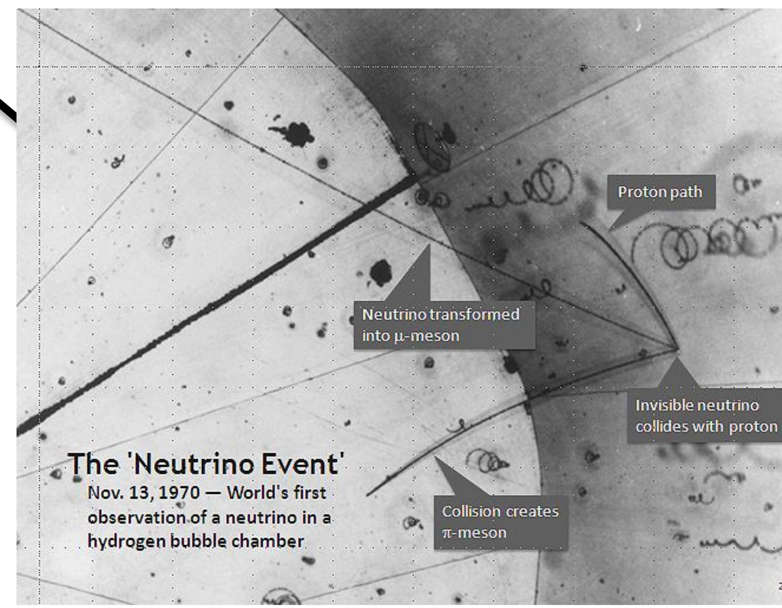
$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$

$$\frac{dT}{dM_r} = \nabla \frac{GM_r T}{4\pi r^2 P}$$

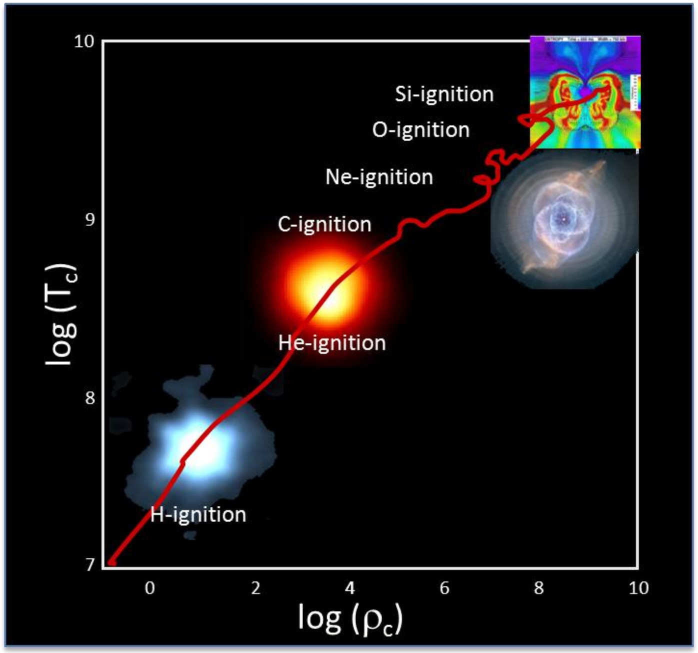
$$\frac{dr}{dM_r} = -\frac{1}{4\pi r^2 \rho}$$

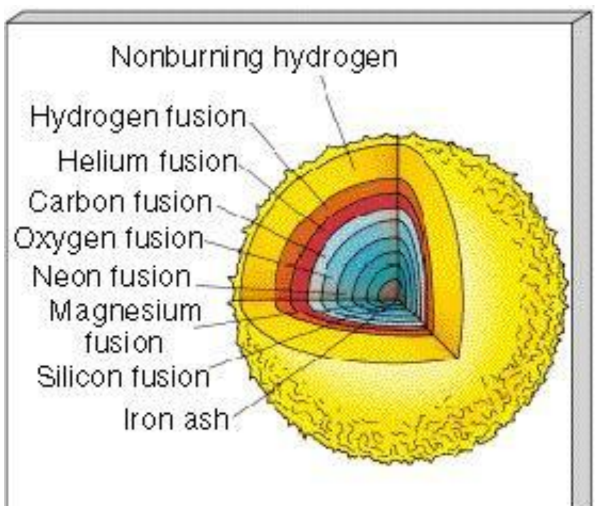
$$\frac{dL_r}{dM_r} = \varepsilon_g + \varepsilon_\nu + \varepsilon_n$$





Why studying nuclear fusion reaction cross sections?





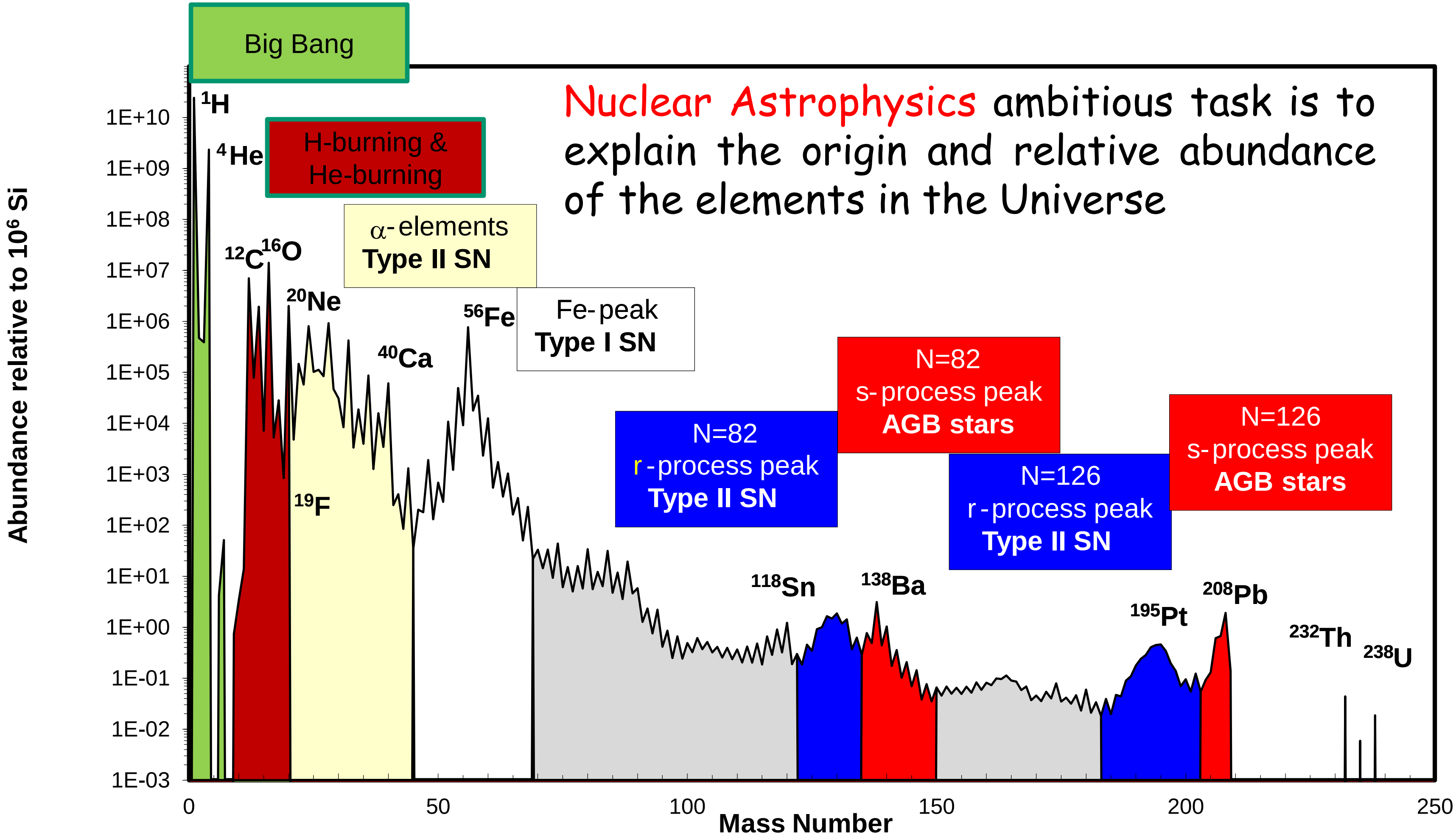
-Stars are powered by nuclear reactions

-Among the key parameters (chemical composition, opacity, etc.) to model stars, reactions cross sections play an important role

- They determine the origin of elements in the cosmos, stellar evolution and dynamic

- Many reactions ask for high precision data.

Element abundances in the solar system



Nuclear Astrophysics ambitious task is to explain the origin and relative abundance of the elements in the Universe

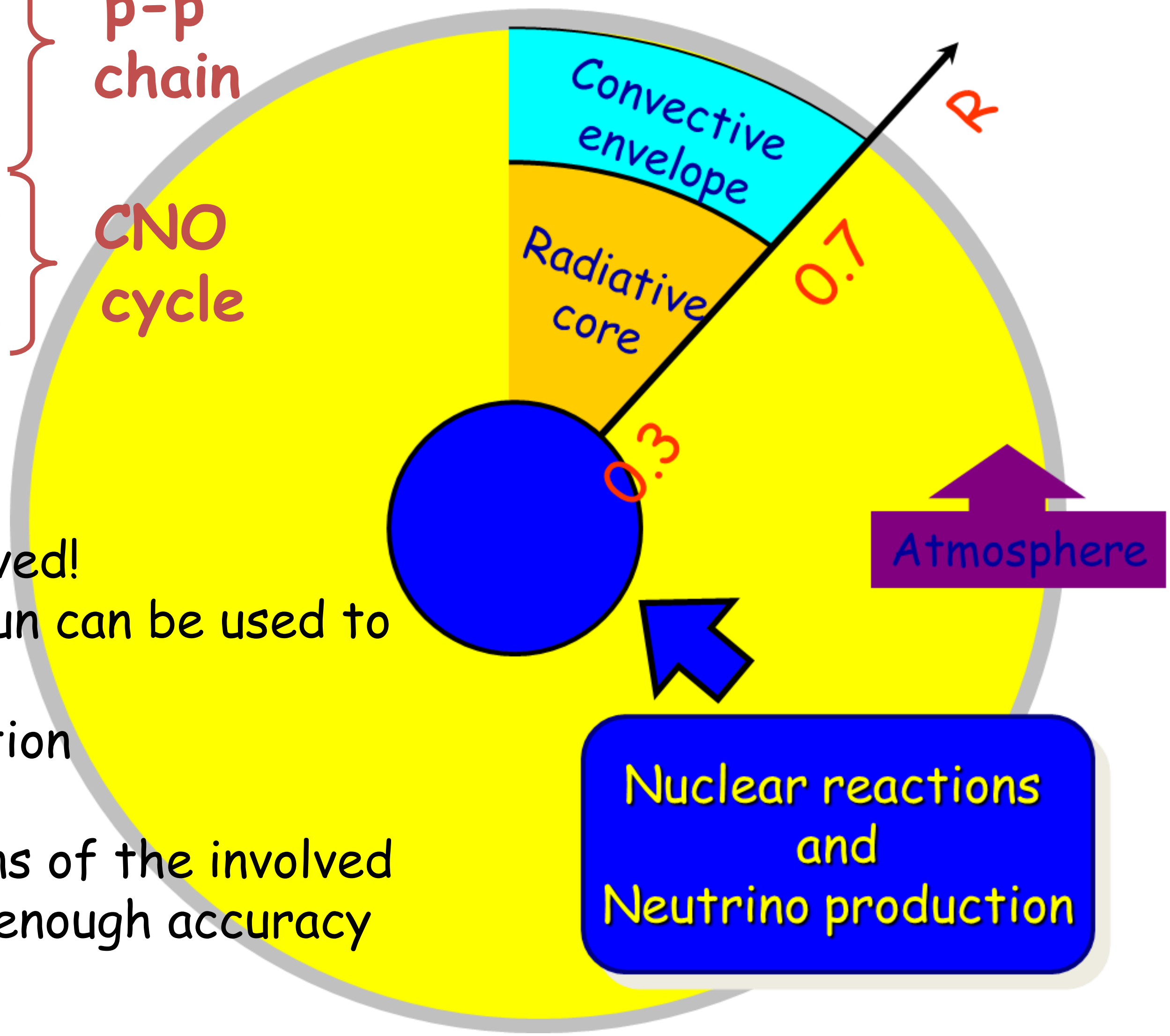
Neutrino production in stars

$p + p \rightarrow {}^2H + e^+ + \nu$
$p + e^- + p \rightarrow {}^2H + e^+ + \nu$
${}^3He + p \rightarrow {}^4He + e^+ + \nu$
${}^7Be + e^- \rightarrow {}^7Li + \nu$
${}^8B \rightarrow {}^8Be + e^+ + \nu$

} p-p chain

${}^{13}N \rightarrow {}^{13}C + e^+ + \nu$
${}^{15}O \rightarrow {}^{15}N + e^+ + \nu$
${}^{17}F \rightarrow {}^{17}O + e^+ + \nu$

} CNO cycle



Solar neutrino puzzle: solved!
Neutrino flux from the Sun can be used to study:

- Solar interior composition
- Neutrino properties

ONLY if the cross sections of the involved reactions are known with enough accuracy

Big Bang nucleosynthesis

Production of the lightest elements (D, ^{3}He, ^{4}He, ^{7}Li, ^{6}Li) in the first minutes after the Big Bang

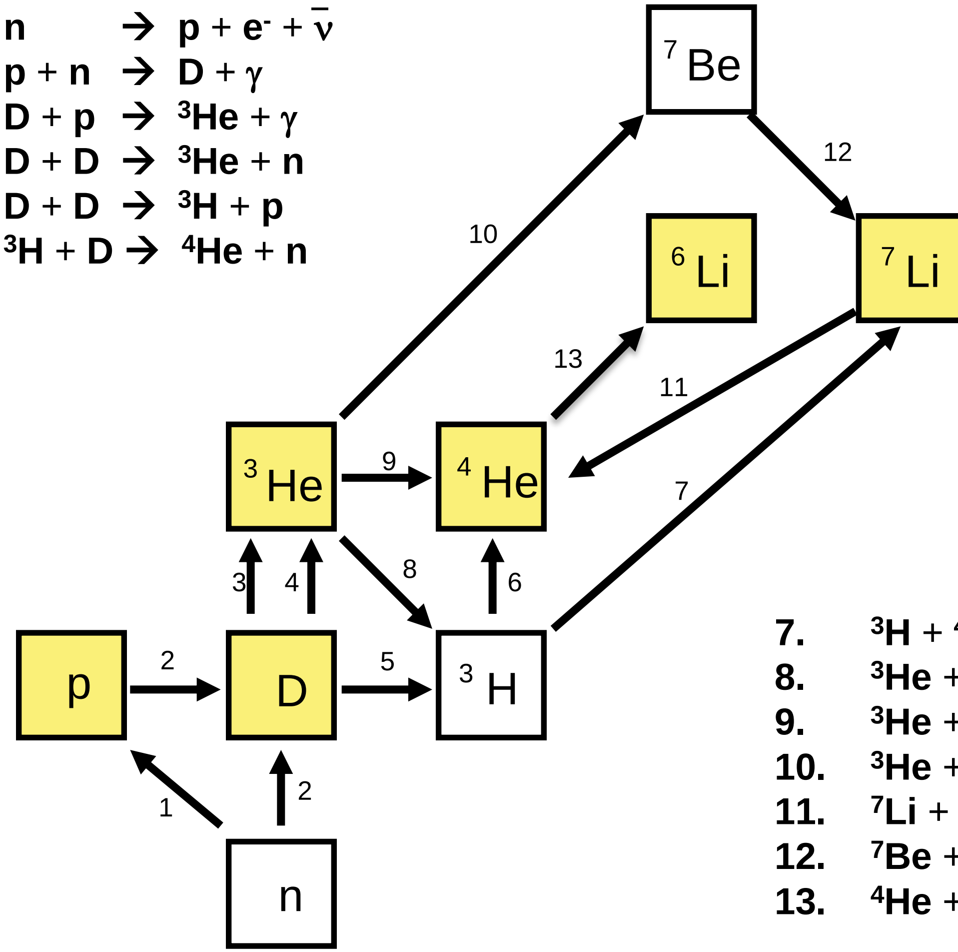
The general concordance between predicted and observed abundances (spanning more than 9 orders of magnitude) gives a direct probe of the Universal baryon density

CMB anysotropy measurements (WMAP/Plank satellites) gives an independent measurement of the Universal baryon density

The concordance of the two measurements has to be understood in terms of uncertainties in the BBN predictions

BBN reaction network

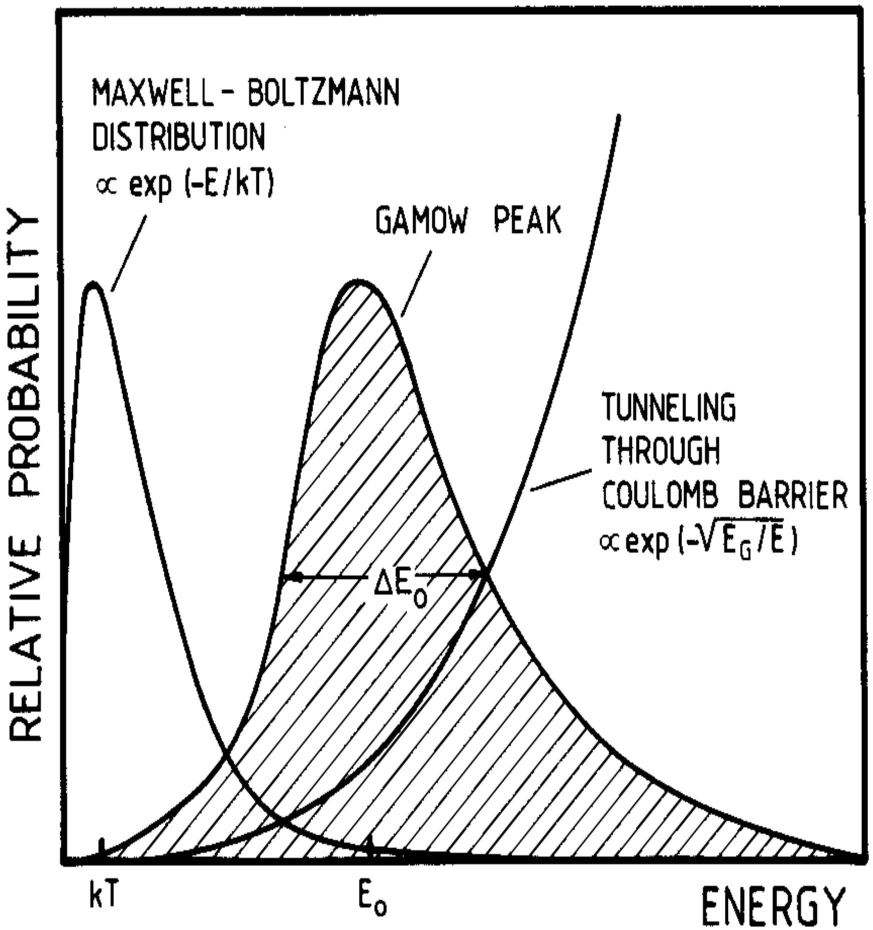
1. n → $p + e^- + \bar{\nu}$
2. p + n → $D + \gamma$
3. D + p → $^3He + \gamma$
4. D + D → $^3He + n$
5. D + D → $^3H + p$
6. $^3H + D$ → $^4He + n$



7. $^3H + {}^4H$ → $^7Li + \gamma$
8. $^3He + n$ → $^3H + p$
9. $^3He + D$ → $^4He + p$
10. $^3He + {}^4He$ → $^7Be + \gamma$
11. $^7Li + p$ → $^4He + {}^4He$
12. $^7Be + n$ → $^7Li + p$
13. $^4He + D$ → $^6Li + \gamma$

Apart from ^4He, uncertainties are dominated by systematic errors in the nuclear cross sections

Nuclear reactions in stars



Sun:

T= 1.5 10^7 K

kT = 1 keV<< E_C (0.5-2 MeV)

Reaction	E_0
$^3He(^3He,2p)^4He$	21 keV
$d(p,\gamma)^3He$	6 keV
$^{14}N(p,\gamma)^{15}O$	27 keV
$^3He(^4He,\gamma)^7Be$	22 keV

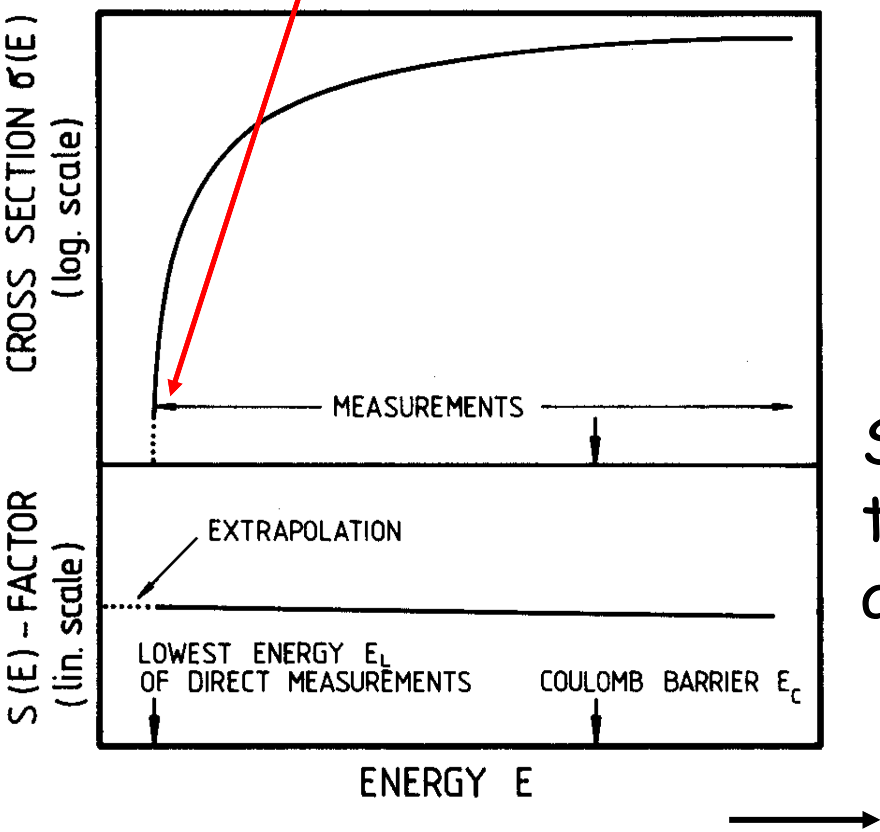
Cross section and astrophysical S factor

$$\sigma(E) = \frac{1}{E} \exp(-31.29 Z_1 Z_2 \sqrt{\mu/E})\, S(E)$$

Astrophysical factor

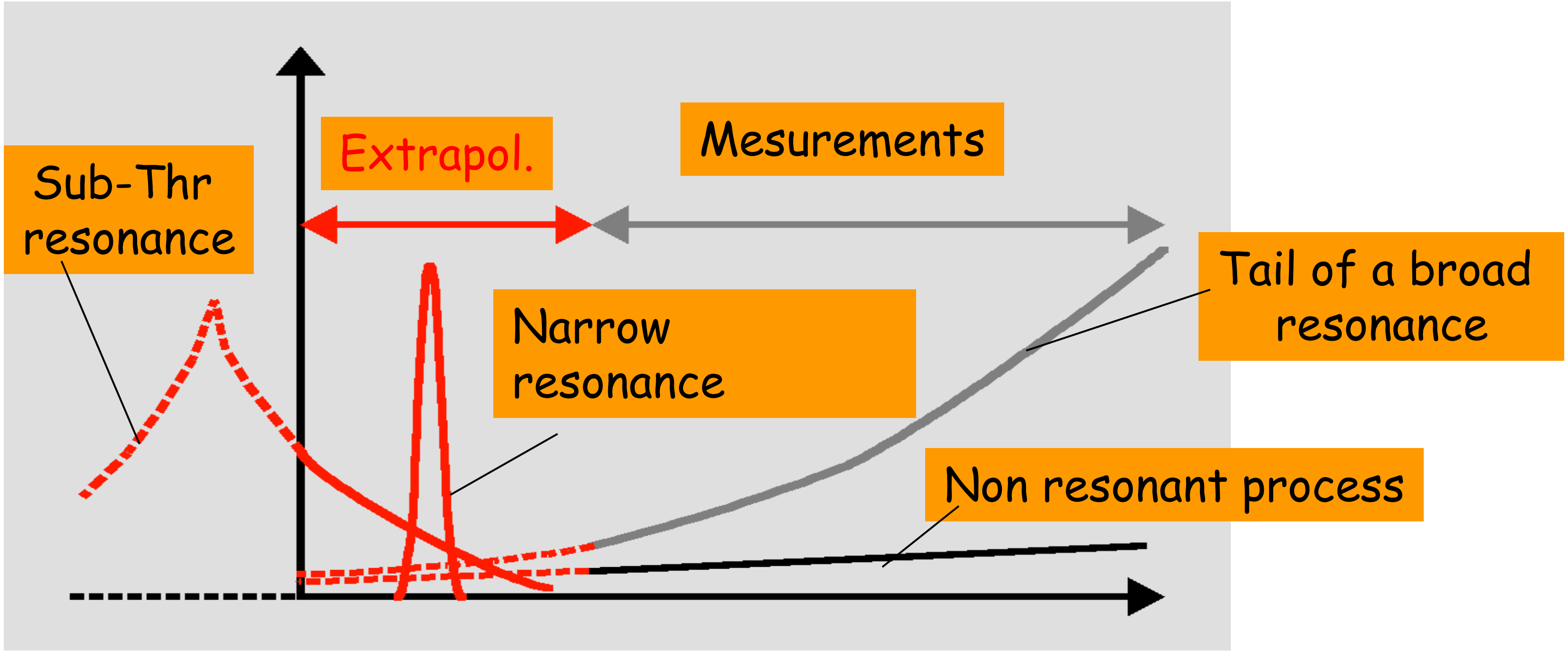
Gamow factor E_G

Gamow energy region



Cross section of the order of pb!

S factor can be extrapolated to zero energy but if resonances are present?



Danger in extrapolations!

Sun

Luminosity = $2 \cdot 10^{39}$ MeV/s

Q-value (H burning) = 26.73 MeV

Reaction rate = 10^{38} s^{-1}

Laboratory

$R_{lab} = N_p N_t \sigma \varepsilon$

N_p = number of projectile ions ≈ 10^{14} pps (100 μA $q=1^+$)

N_t = number of target atoms ≈ 10^{19} at/cm^2

σ = cross section = 10^{-15} barn

ε= efficiency ≈ 100% for charged particles
1% for gamma rays

R_{lab} ≈ 0.3-30 counts/year

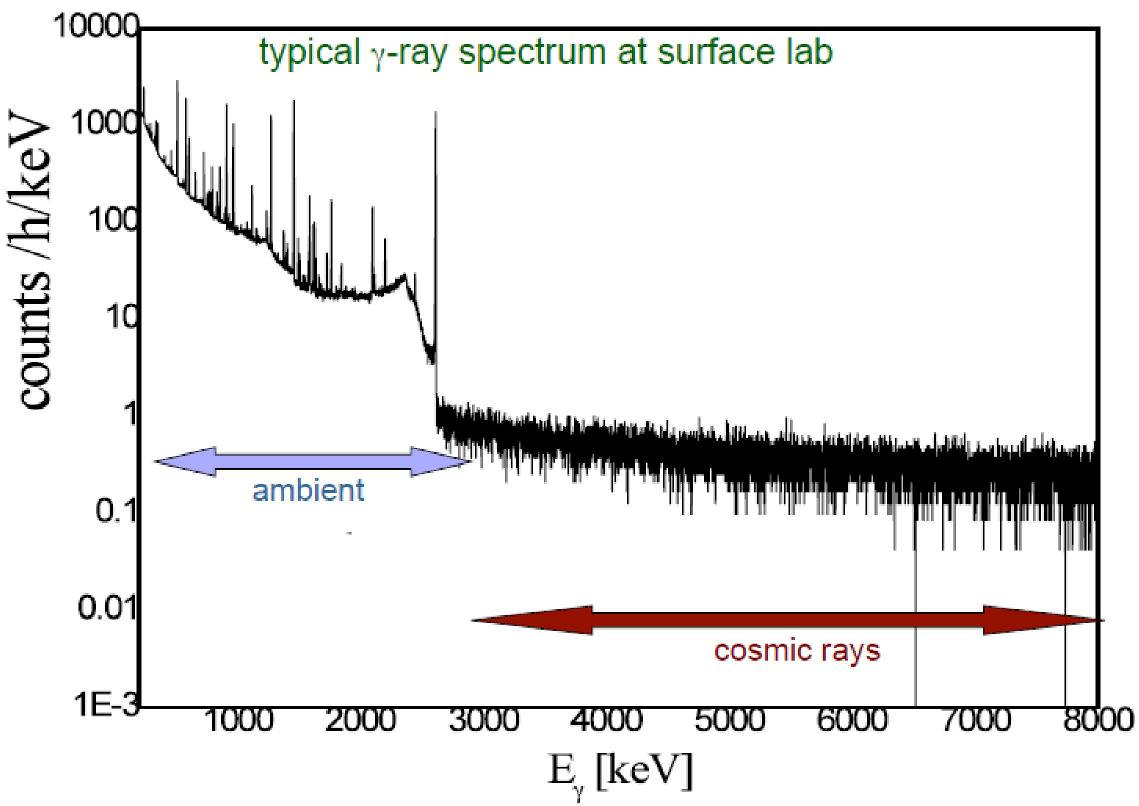
$R_{lab} > B_{beam\ induced} + B_{env} + B_{cosmic}$

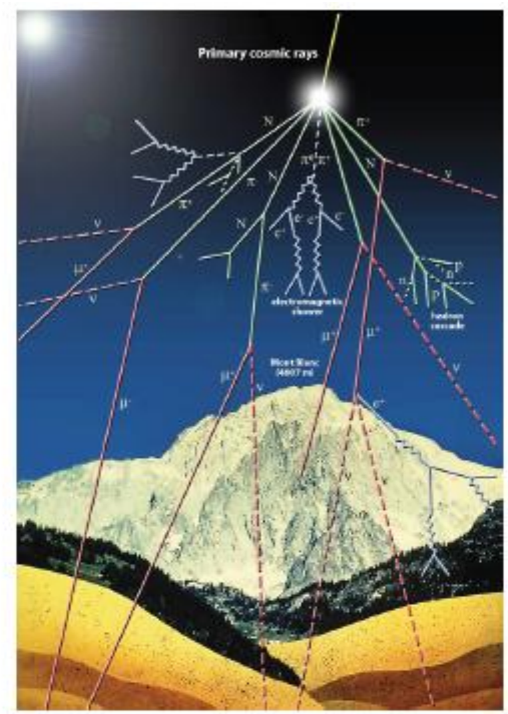
$B_{beam\ induced}$: reactions with impurities in the target

reactions on beam collimators/apertures

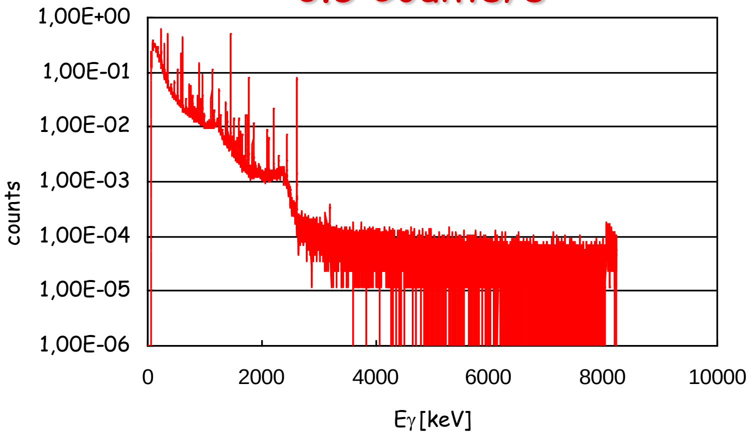
B_{env} : natural radioactivity mainly from U and Th chains

B_{cosmic} : mainly muons





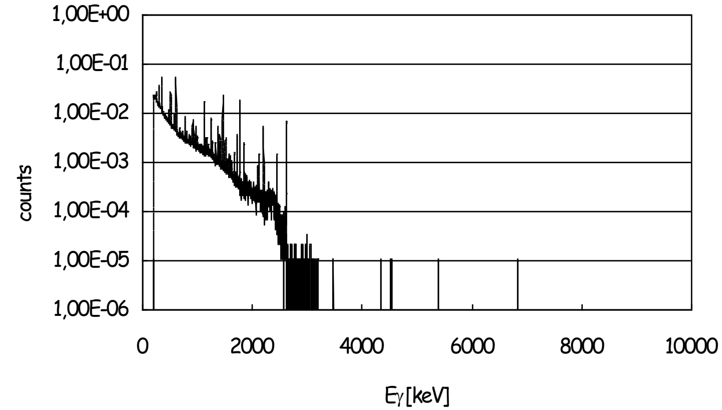
3MeV < Eγ < 8MeV:
0.5 Counts/s



HpGe

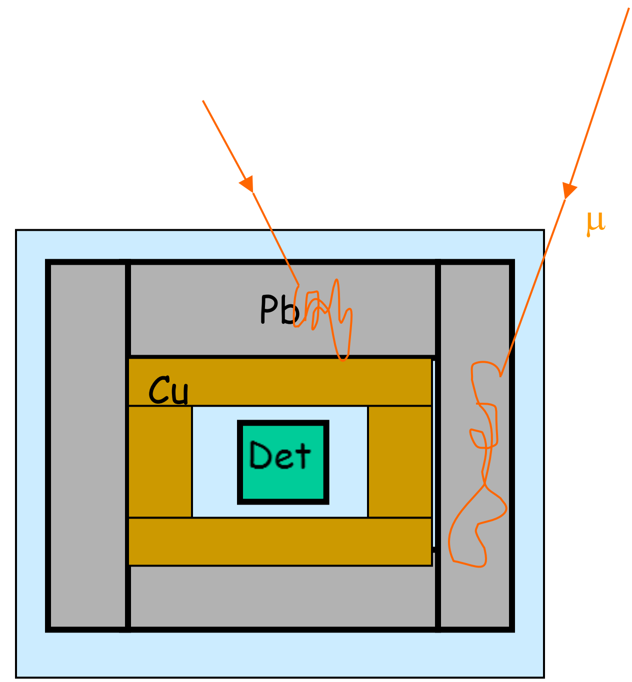
GOING UNDERGROUND →

3MeV < Eγ < 8MeV
0.0002 Counts/s

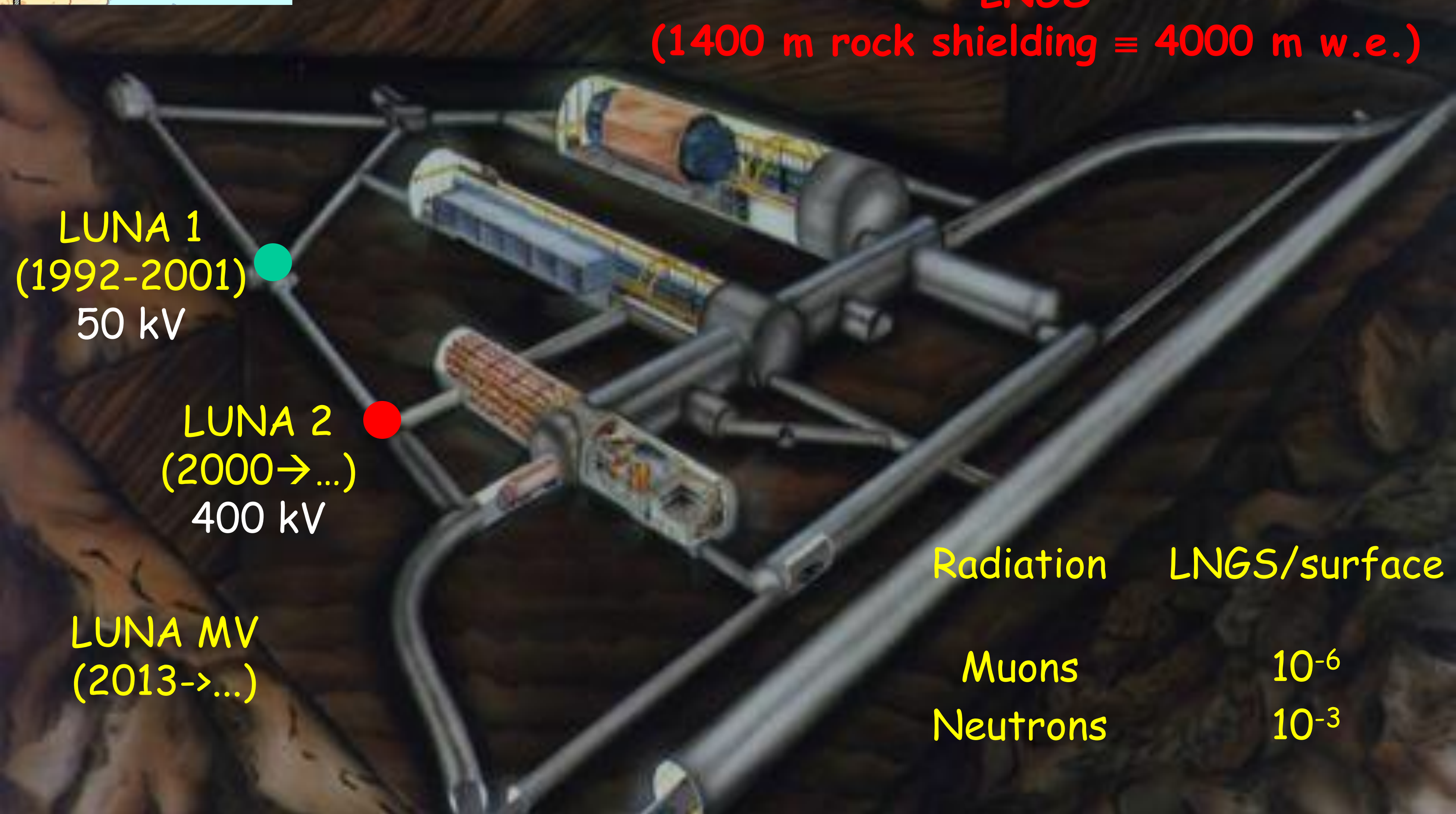


E_γ<3MeV→passive shielding for environmental background radiation

underground passive shielding is more effective since μ flux,that create secondary γ's in the shield, is suppressed



Laboratory for Underground Nuclear Astrophysics



Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}

LUNA program: astrophysical motivation

Solar neutrinos: $^{3}He(^{3}He,2p)^{4}He$, $^{3}He(^{4}He,\gamma)^{7}Be$, $^{14}N(p,\gamma)^{15}O$

Age of globular cluster: $^{14}N(p,\gamma)^{15}O$

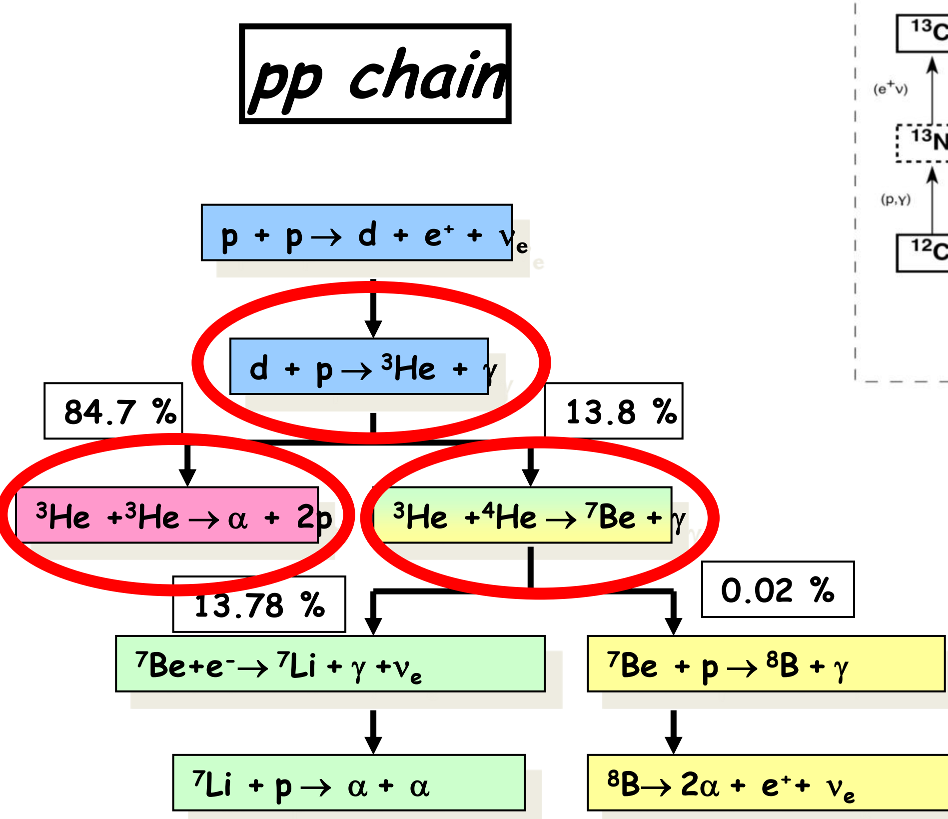
Light nuclei nucleosynthesis ($^{17}/^{18}O$ abundances, ^{19}F production, ^{26}Mg excess,...): $^{15}N(p,\gamma)^{16}O$, $^{17}N(p,\gamma)^{18}O$, $^{25}Mg(p,\gamma)^{26}Al$

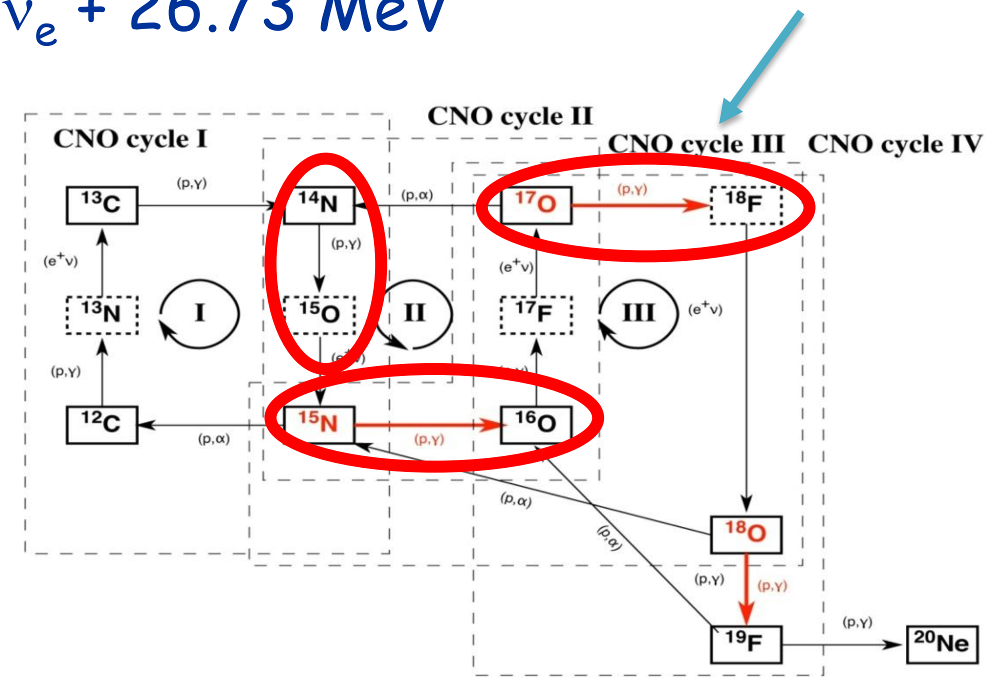
Big Bang Nucleosynthesis: $^{2}H(\alpha,\gamma)^{6}Li$, $^{3}He(^{4}He,\gamma)^{7}Be$, $^{2}H(p,\gamma)^{3}He$

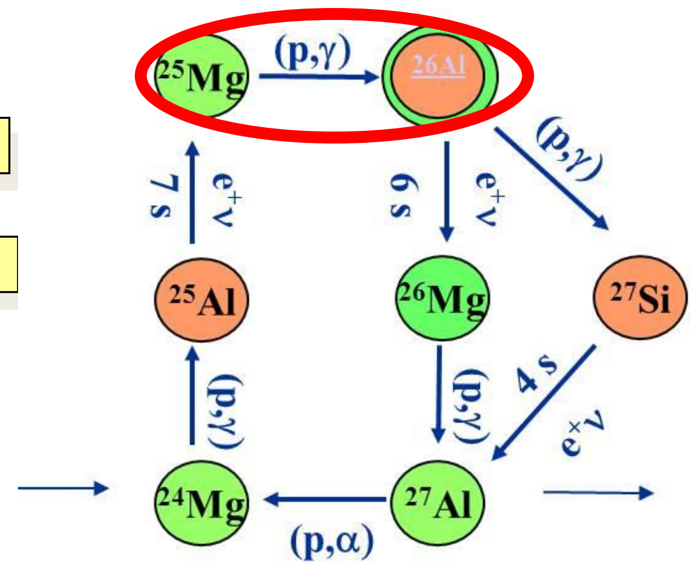
Next:
Light nuclei nucleosynthesis: $^{17}O(p,\alpha)^{14}N$, $^{22}Ne(p,\gamma)^{23}Na$, $^{23}Na(p,\gamma)^{24}Mg$, $^{18}O(p,\gamma)^{19}F$, $^{18}O(p,\alpha)^{15}N$
He burning and stellar evolution: $^{12}C(\alpha,\gamma)^{16}O$
s process nucleosynthesis: $^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$

Hydrogen burning

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$



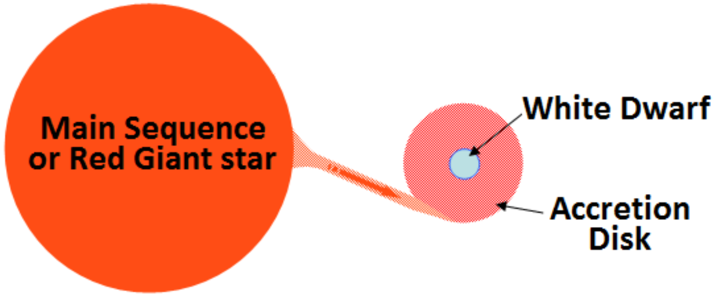




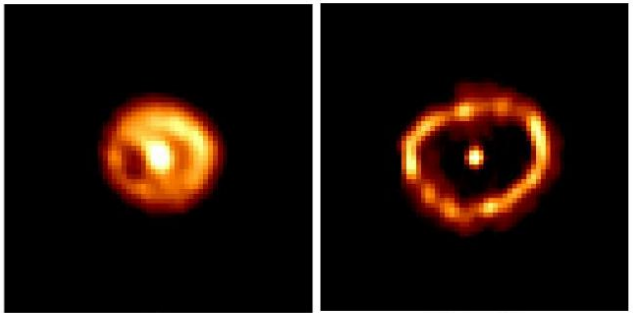
$^{17}O(p,\gamma)^{18}F$ measurement

17O+p is very important for hydrogen burning in different stellar environments:

- Red giants
- Massive stars
- AGB
- Novae



1. production of light nuclei ($^{17}O/^{18}O$ abundances....);
2. observation of ^{18}F γ-ray signal (annihilation 511 keV).

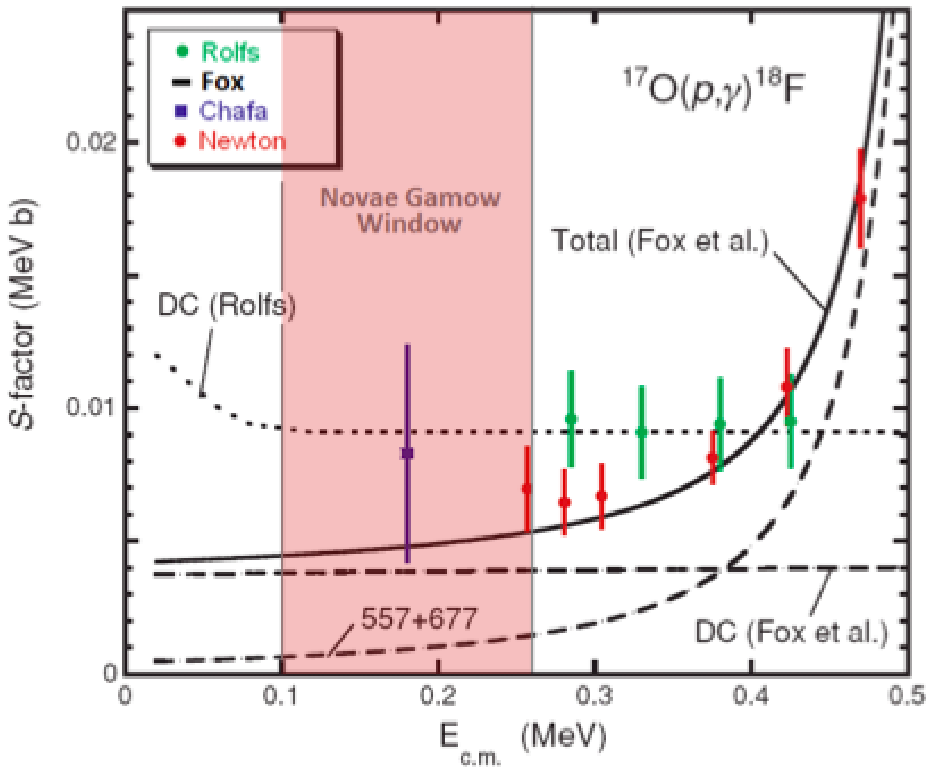


(Cygni 1992)

Classical novae **T=0.1-0.4 GK => E_{Gamow} = 100 - 260 keV**
Resonant Contribution: $^{17}O(p,\gamma)^{18}F$ resonance at **E_p = 183 keV and non resonant contribution**

$^{17}O(p,\gamma)^{18}F$ measurement

State of the art before the LUNA measurement (1):



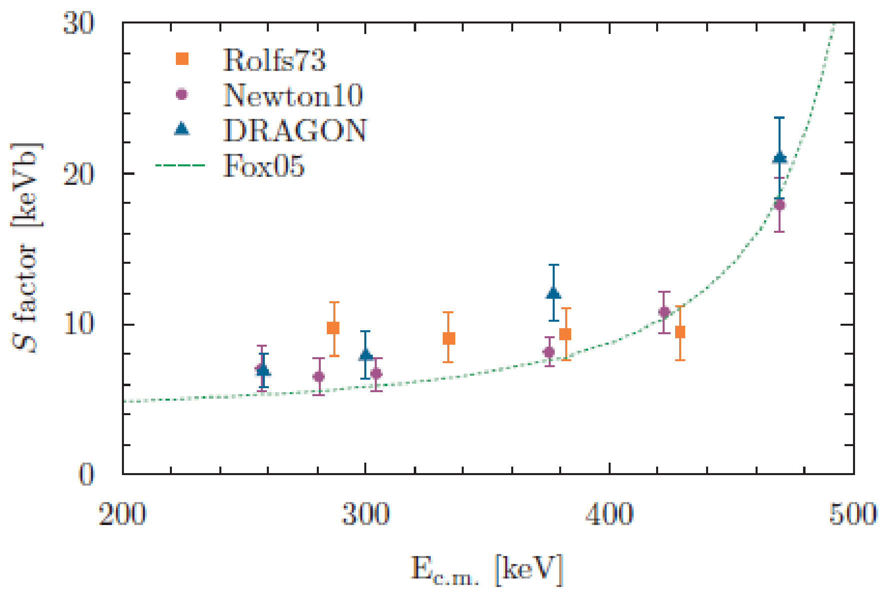
Rolfs et al., 1973, prompt γ
S_{DC} measured at 4 energies in the range E_{cm} = 290-430 keV
$S_{DC} \approx$ 9 keV b for E_{cm}= 100-500 keV

Fox et al., 2005, prompt γ
discovered 183 keV resonance
$\omega\gamma = (1.2 \pm 0.2)\ 10^{-6}$ eV
calculation of DC
$S_{DC} = 3.74 + 0.676E - 0.249E^2$
determination of high energy resonance influence on S total

Chafa et al., 2007, activation
$\omega\gamma = (2.2 \pm 0.4)\ 10^{-6}$ eV
measured $S_{DC} = (8.3 \pm 4.0)$ keV b
$S_{DC} = 6.2 + 1.61E - 0.169E^2$
larger than Fox by more than 50%

$^{17}O(p,\gamma)^{18}F$ measurement

Status of the art before the LUNA measurement (2):

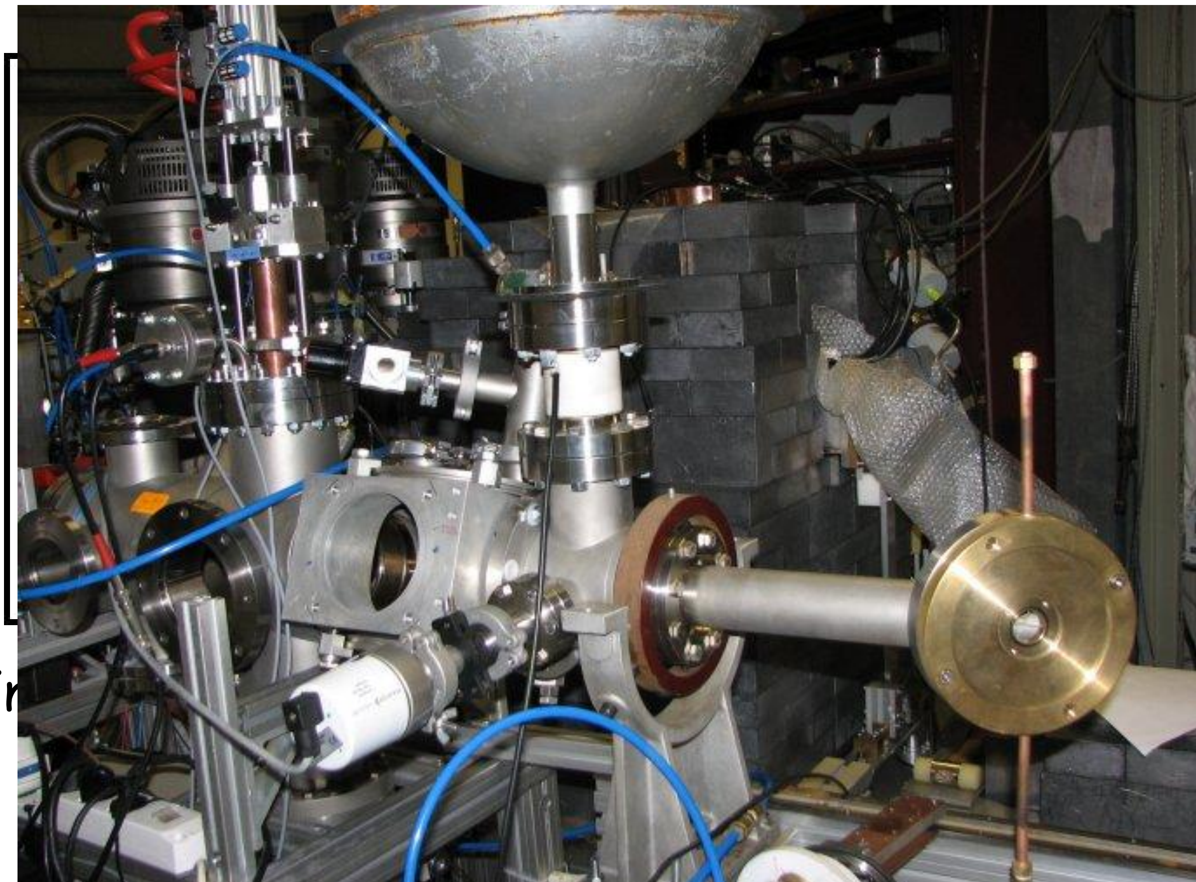


Newton et al., 2010, prompt γ
S_{DC} measured at 6 energies in the range E_{cm} = 260-470 keV
Calculated $S_{DC}(E)$ = 4.6 keV b (±23%)

Hager et al.(DRAGON), 2012, recoil separator
E_{cm} = 250-500 keV
S_{DC} higher than Newton and Fox. No flat dependence. Re-evaluate resonant contributions

$^{17}O(p,\gamma)^{18}F$ measurement

183 keV resonance and direct capture component for E=200-370 keV measured with prompt gammas and activation →Gamow window for Novae region explored with the highest precision to-date

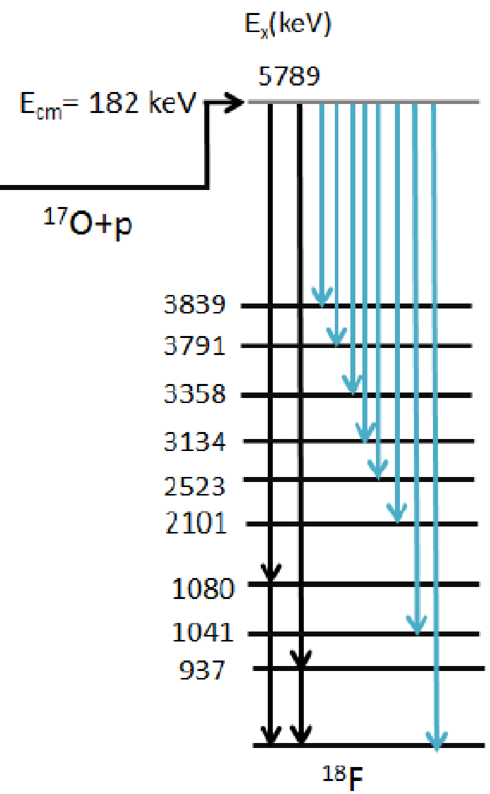


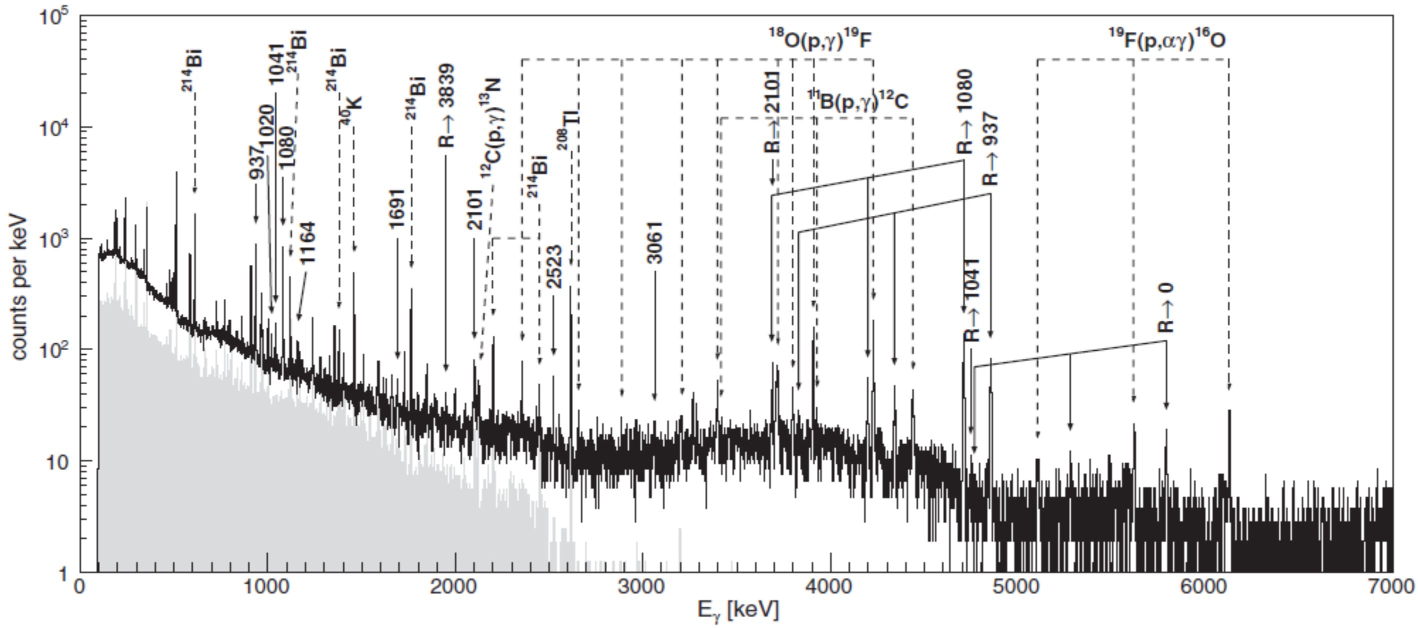
Er (anodization process)

$^{17}O(p,\gamma)^{18}F$ measurement

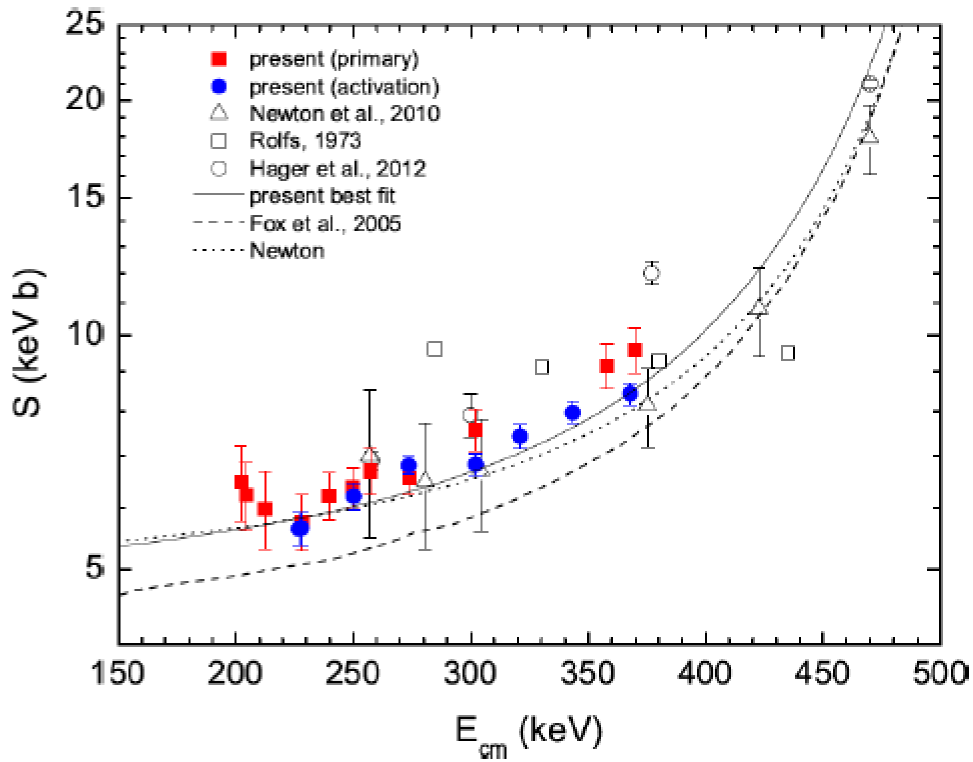
183 keV resonance: $\omega\gamma$=1.67±0.12 μeV (weighted average of prompt and activation)

Several new transitions identified and branching ratios determined





$^{17}O(p,\gamma)^{18}F$ results



The best fit includes the contribution from the E=557 and E=667 broad resonances from literature and a constant direct capture component

Improvement of a factor of 4 in the reaction rate uncertainty!

D. Scott et al., Phys Rev Lett 109 (2012) 202501

LUNA 400 kV program

	reaction	Q-value (MeV)
completed	$^{17}O(p,\gamma)^{18}F$	5.6
just started	$^{17}O(p,\alpha)^{14}N$	1.2
→	$^{18}O(p,\gamma)^{19}F$	8.0
→	$^{18}O(p,\alpha)^{15}N$	4.0
→	$^{23}Na(p,\gamma)^{24}Mg$	11.7
just started	$^{22}Ne(p,\gamma)^{23}Na$	8.8
completed	$D(\alpha,\gamma)^{6}Li$	1.47

Still three reactions to be measured→ to be completed by 2015

LUNA MV Project

April 2007: a Letter of Intent (LoI) was presented to the LNGS Scientific Committee (SC) containing key reactions of the He burning and neutron sources for the s-process:

$^{12}C(\alpha,\gamma)^{16}O$

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

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

(α,γ) reactions on $^{14,15}N$ and ^{18}O

$^{3}He(\alpha,\gamma)^{7}Be$ on a wide energy range to reduce uncertainty

These reactions are relevant at higher temperatures (larger energies) than reactions belonging to the hydrogen-burning studied so far at LUNA

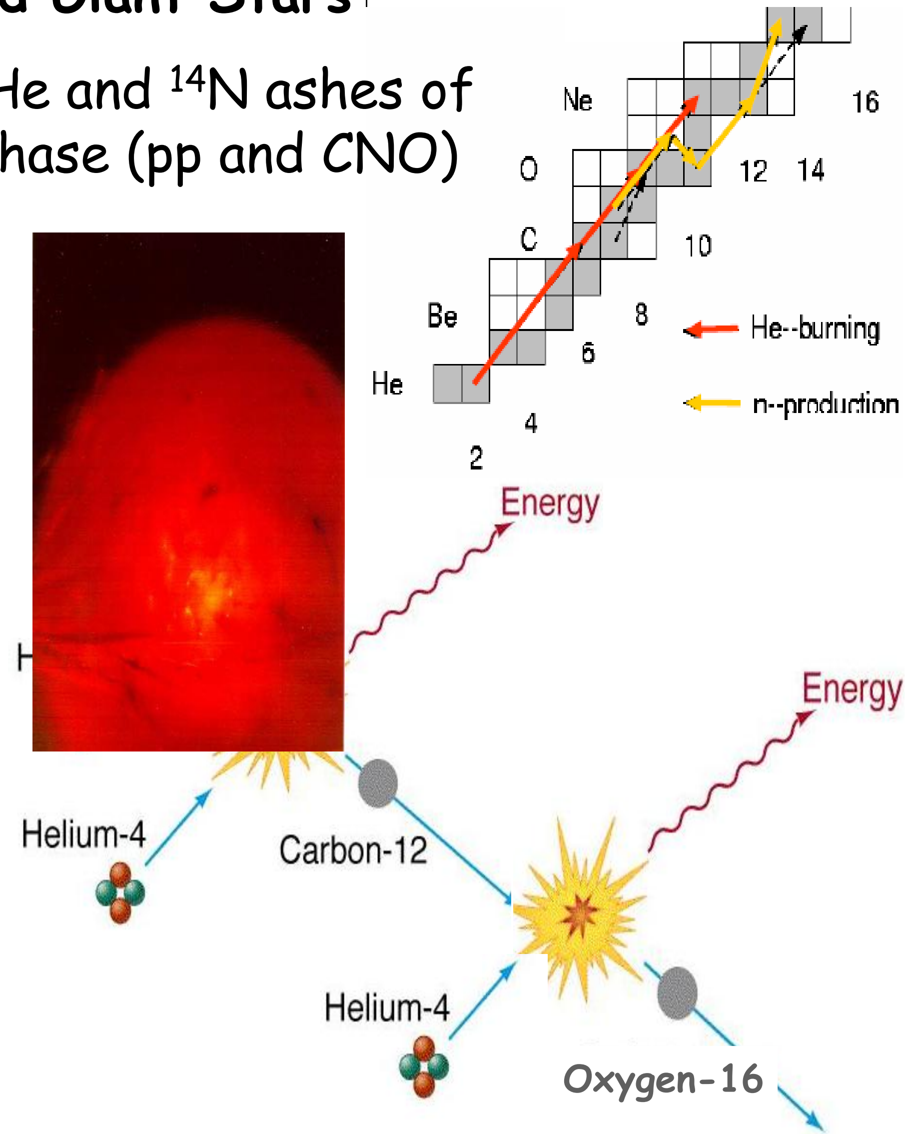
↓

Higher energy machine → 3.5 MV single ended positive ion accelerator

$^{12}C(\alpha,\gamma)^{16}O$ – Holy Grail of Nuclear Astrophysics

Stellar Helium burning in Red Giant Stars

the He burning is ignited on the ^{4}He and ^{14}N ashes of the preceding hydrogen burning phase (pp and CNO)



relevant questions:

Energy production and time scale of Helium burning:

- late stellar evolution
- composition of C/O White dwarfs
- Supernova type I explosion
- Supernova type II nucleosynthesis

Consequences

$^{4}He(2\alpha,\gamma)^{12}C(\alpha,\gamma)^{16}O(\alpha,\gamma)^{20}Ne$

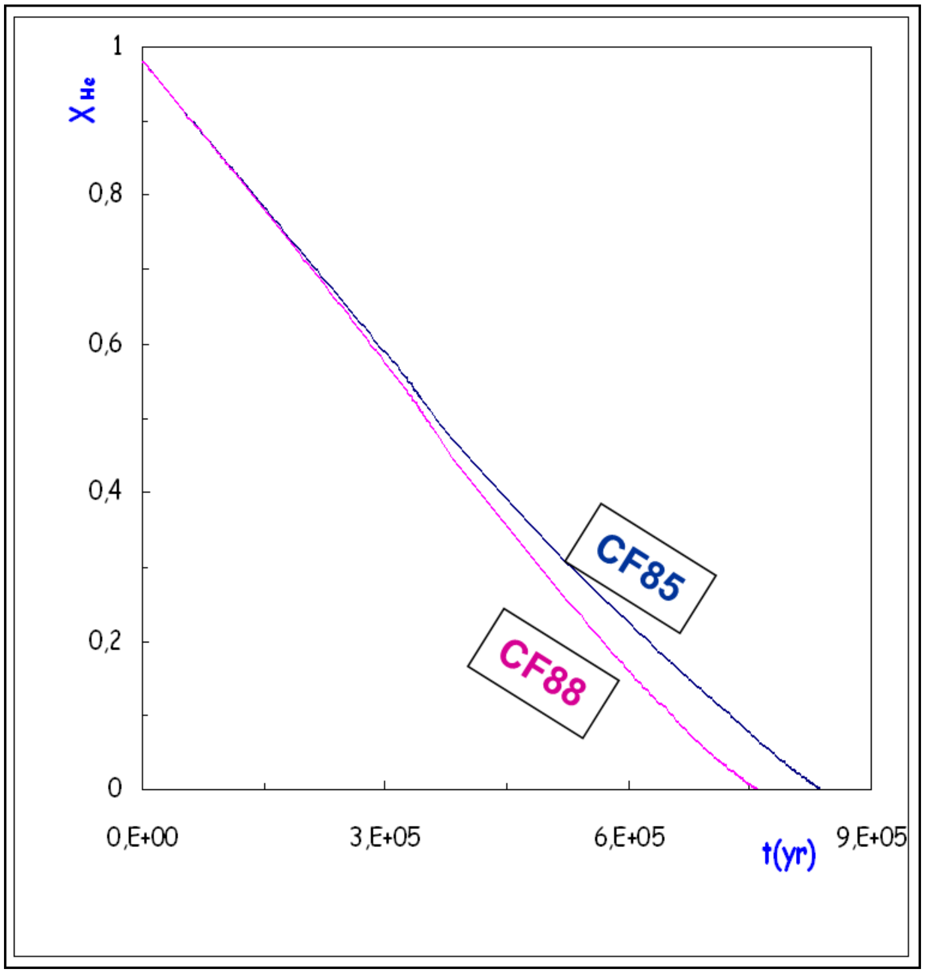
Neutron sources for s process:

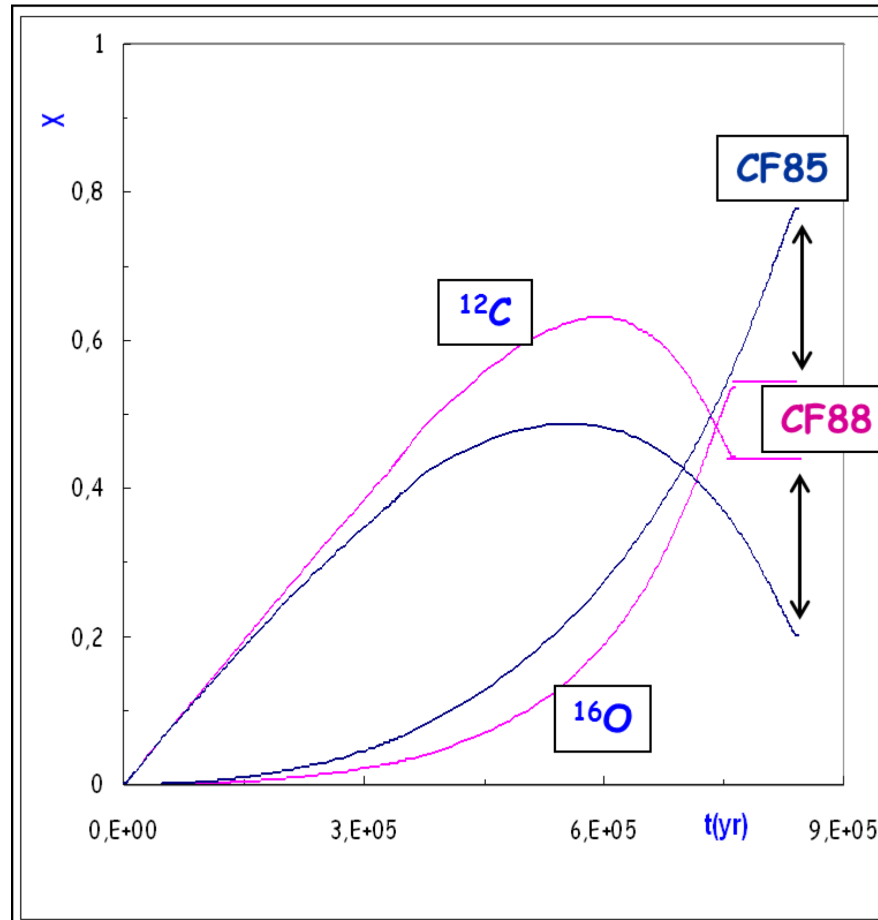
$^{14}N(\alpha,\gamma)^{18}F(\beta+\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)$

$^{22}Ne(\alpha,\gamma)$

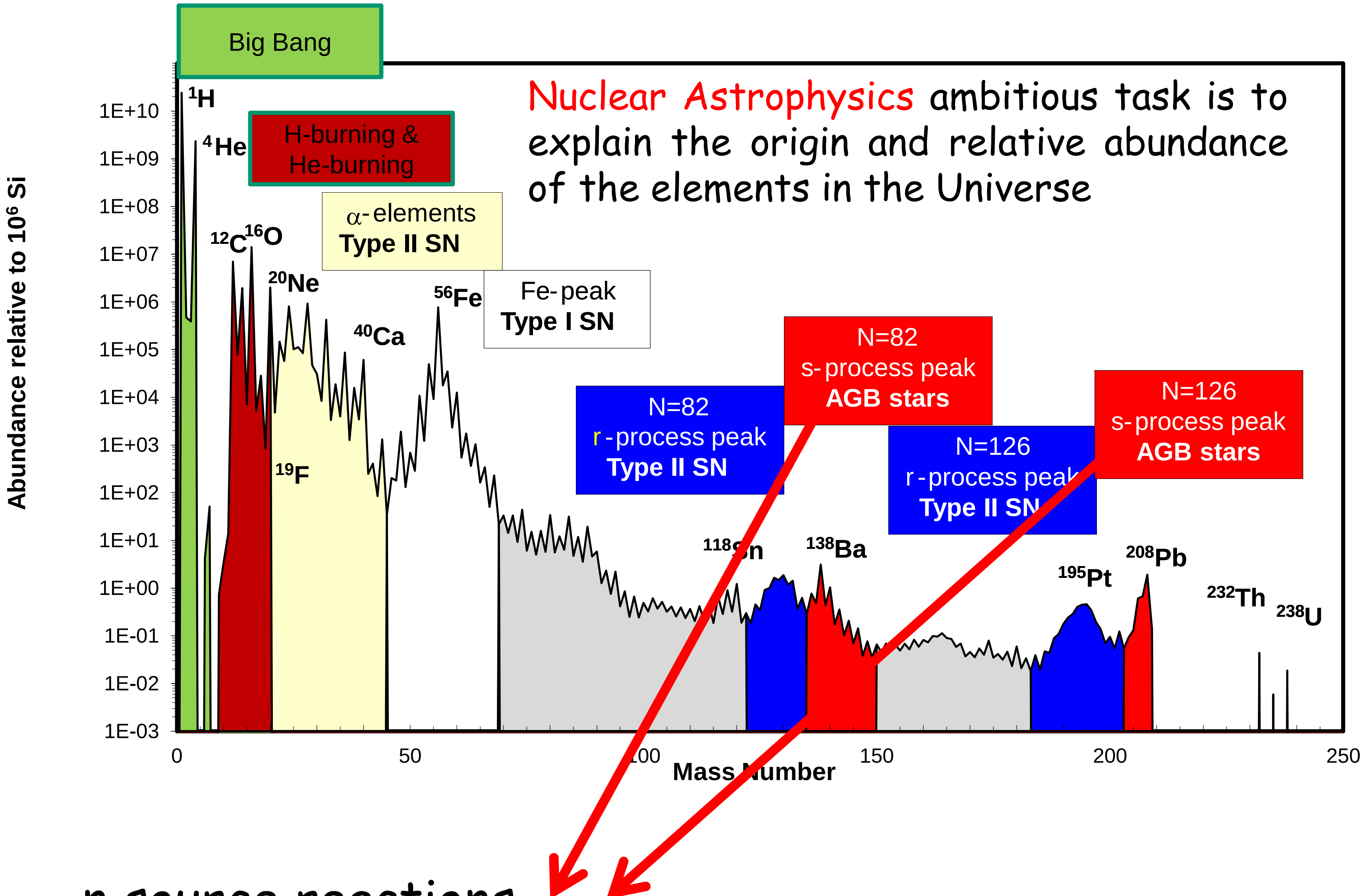
$^{12}C/^{16}O$ ratio at the end of Helium burning

example: Stellar model for a 20 M_{solar} Star
S factor(CF85) = 2 × S factor(CF88)





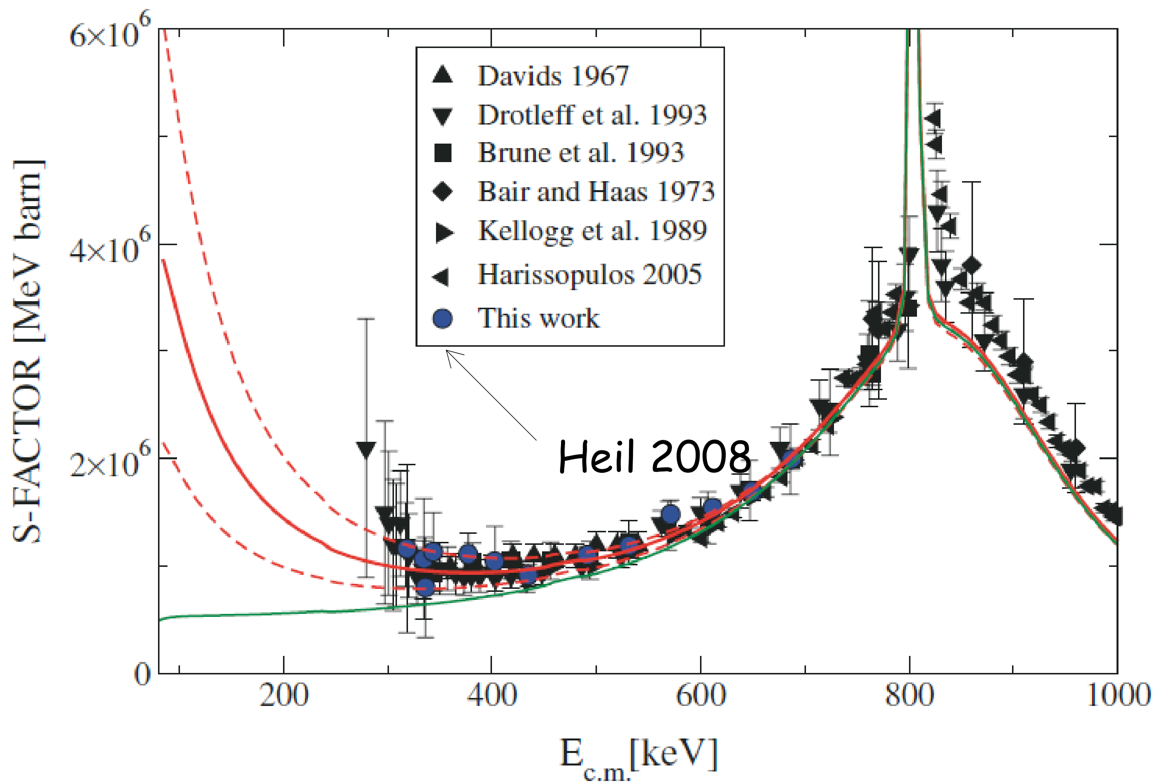
Element abundances in the solar system



Nuclear Astrophysics ambitious task is to explain the origin and relative abundance of the elements in the Universe

n source reactions

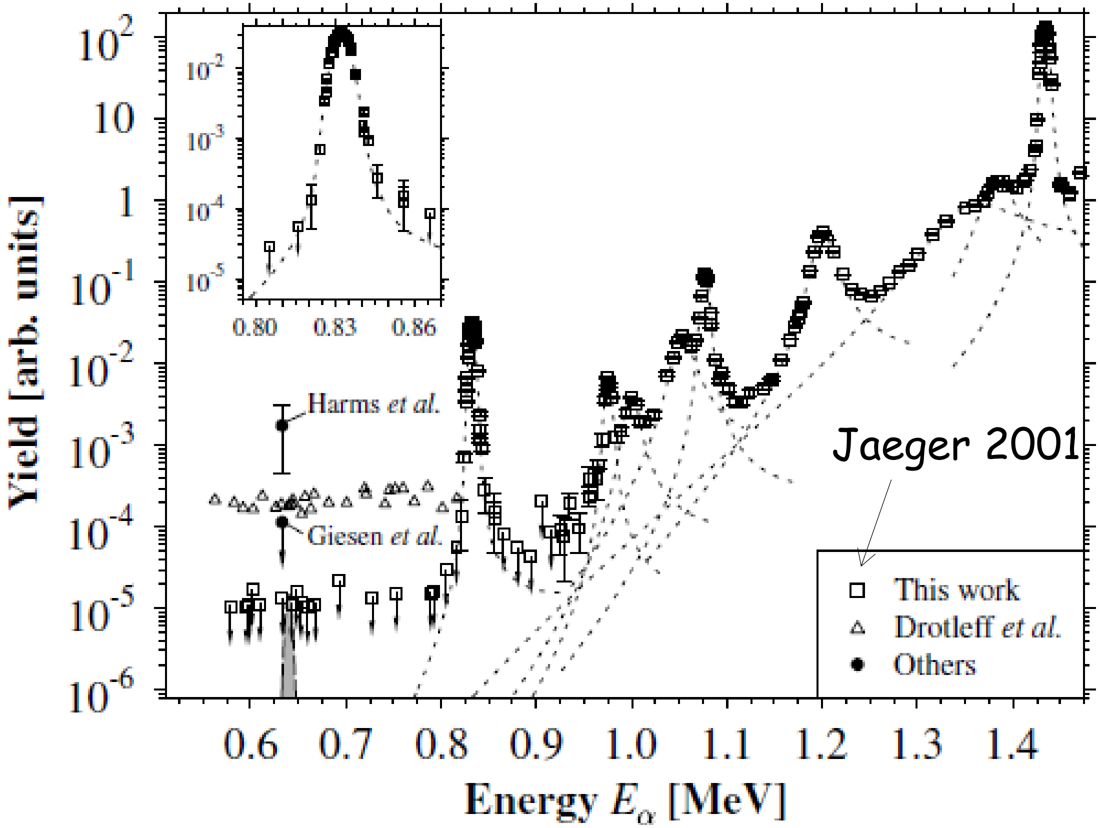
$^{13}C(\alpha,n)^{16}O$ experimental status of the art



Big uncertainties in the R-matrix extrapolations. Presence of subthreshold resonances.

A low background environment is mandatory for any new study

$^{22}Ne(\alpha,n)^{16}O$ experimental status of the art



Precise measurement of the known resonances down to the one at E_α = 831 keV to be performed at first, followed by a detailed search for unknown resonances down to E_α ~ 600 keV.

"Progetto Premiale LUNA -MV"

Special Project financed from the Italian Research Ministry with 2.805 Millions of Euros in 2012

Schedule:
2013-2014 Hall preparation- Tender for the accelerator-Shielding
2015 Beam lines R&D- Infrastructures
2016 Accelerator installation - Beam lines construction-Detectors installation
2017 Calibration of the apparatus and first tests of beam on target

New collaborations are highly welcome!

DIANA Project

Scope

- Deliver a next generation underground accelerator as NSF user facility

- Facility consists of two accelerators covering an energy range from 50keV to 3MeV with 100 keV overlap between the two accelerators
- Accelerators are coupled to two target stations
  A high density gas jet target and a solid target station
- Detectors system with optimum design
  A set of Germanium detectors and a high efficiency neutron counter
- Target stations are flexible to enable various detector and measurements set-ups.

see D. Robertson talk

THE LUNA COLLABORATION

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