Reaction rates for nucleosynthesys of light and intermediate-mass isotopes

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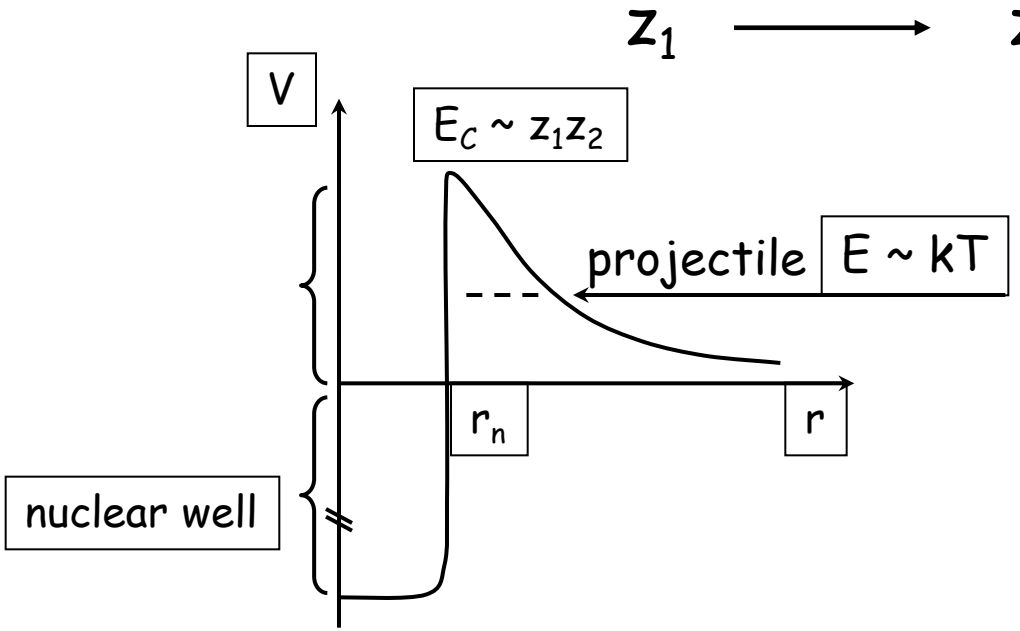
…but before I would like to remind..

Charged particle reaction in stars



Example

z_1=p and z_2=p (e.g. in the Sun)

$T \sim 15 \times 10^6$ K $\Rightarrow$ $E = kT \sim 1$ keV

$E_C = 550$ keV

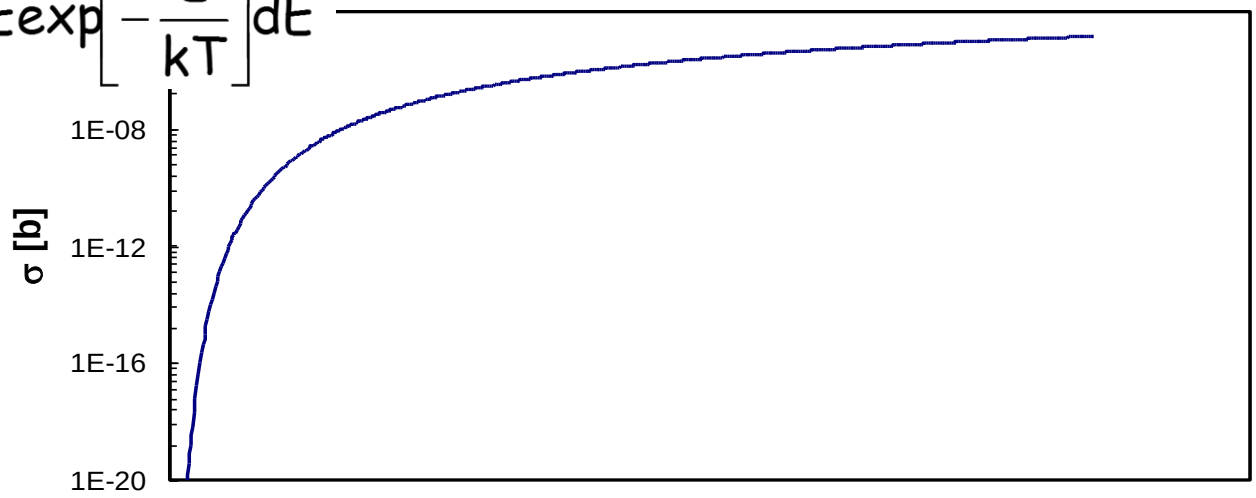
during quiescent burnings:

$kT \ll E_c$

reactions occur through

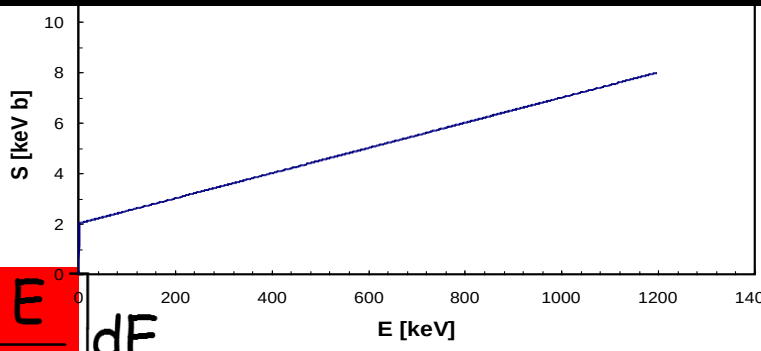
TUNNEL EFFECT

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left[-\frac{E}{kT}\right] dE$$



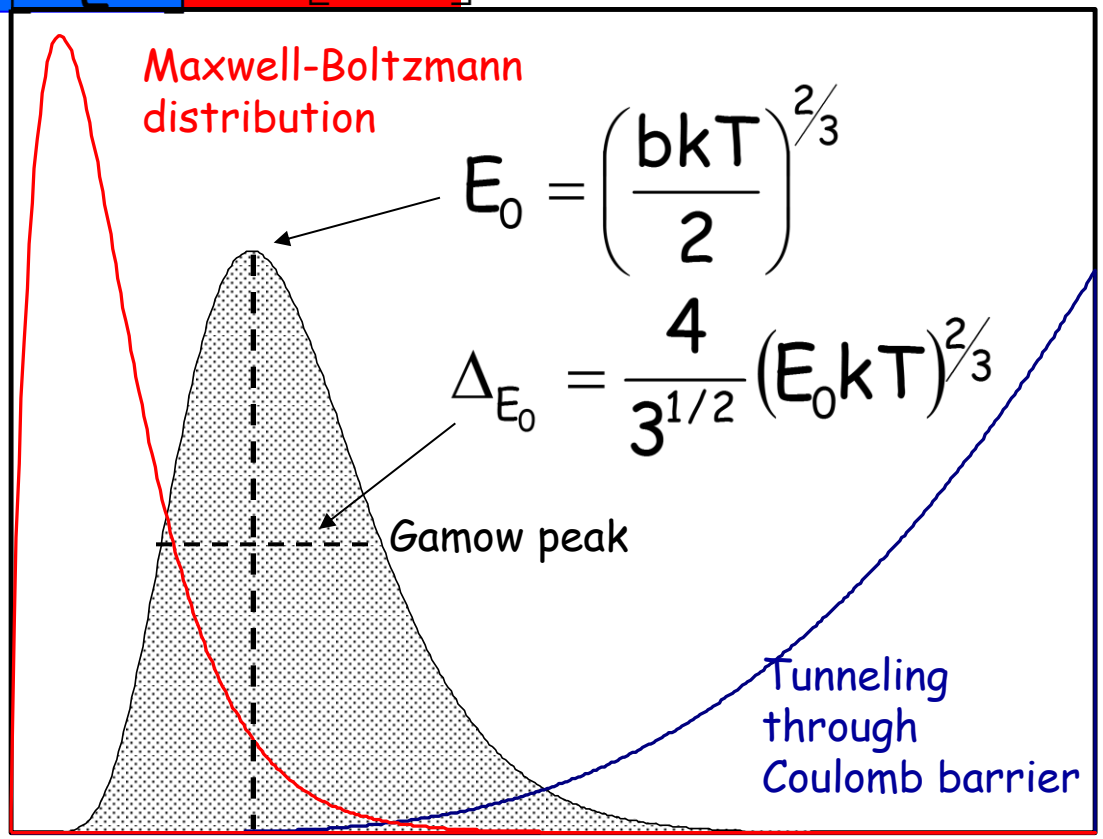
Astrophysical factor and Gamow peak

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta) \qquad \eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

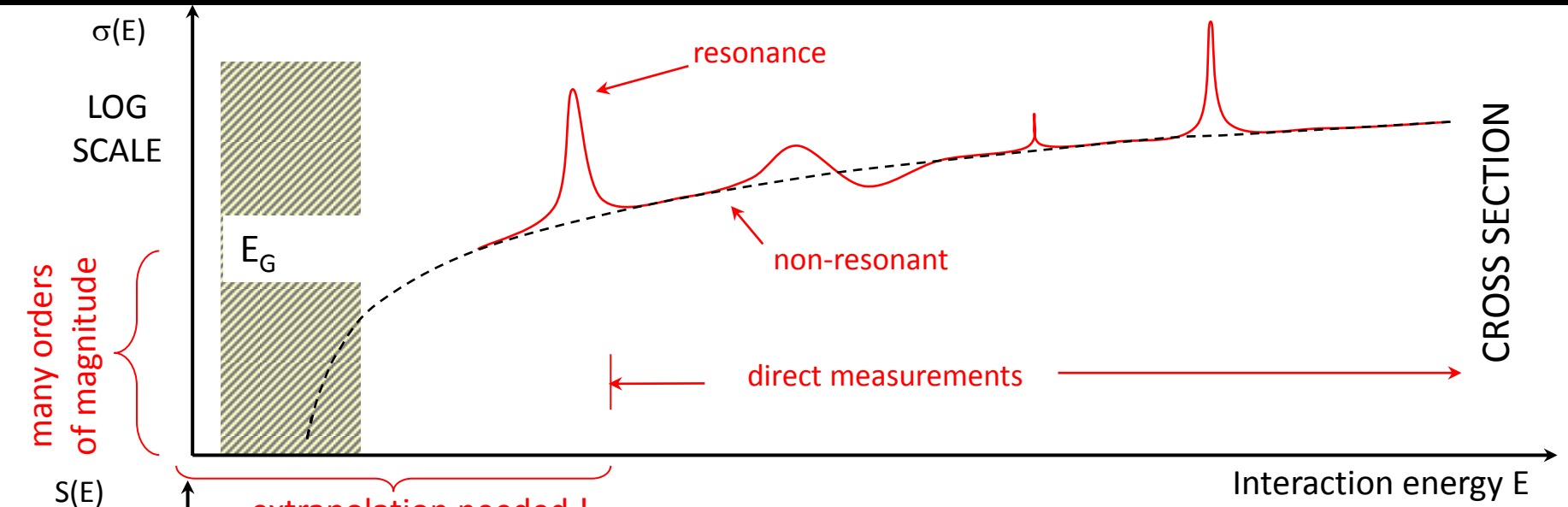


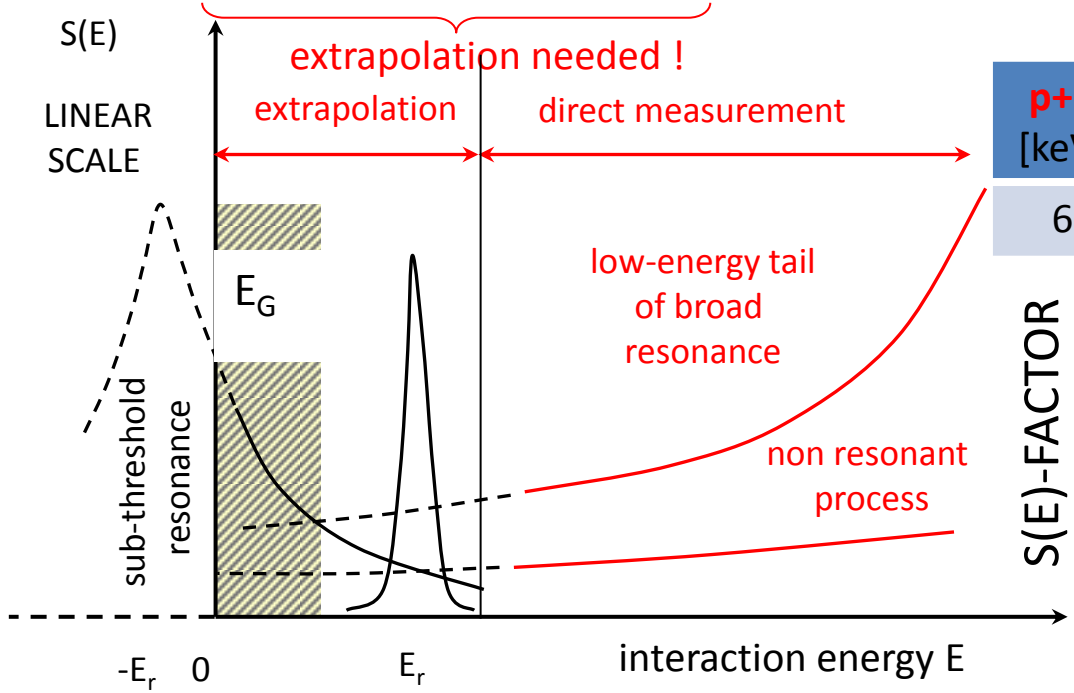
$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \frac{S(E)}{E} \exp\left[-\frac{b}{E^{1/2}}\right] E \exp\left[-\frac{E}{kT}\right] dE$$

reaction	Coulomb barrier (keV)	E_0 (keV)
p + p	550	5.9
$\alpha + {}^{12}C$	3430	56
${}^{16}O + {}^{16}O$	14070	237



Problem of extrapolation

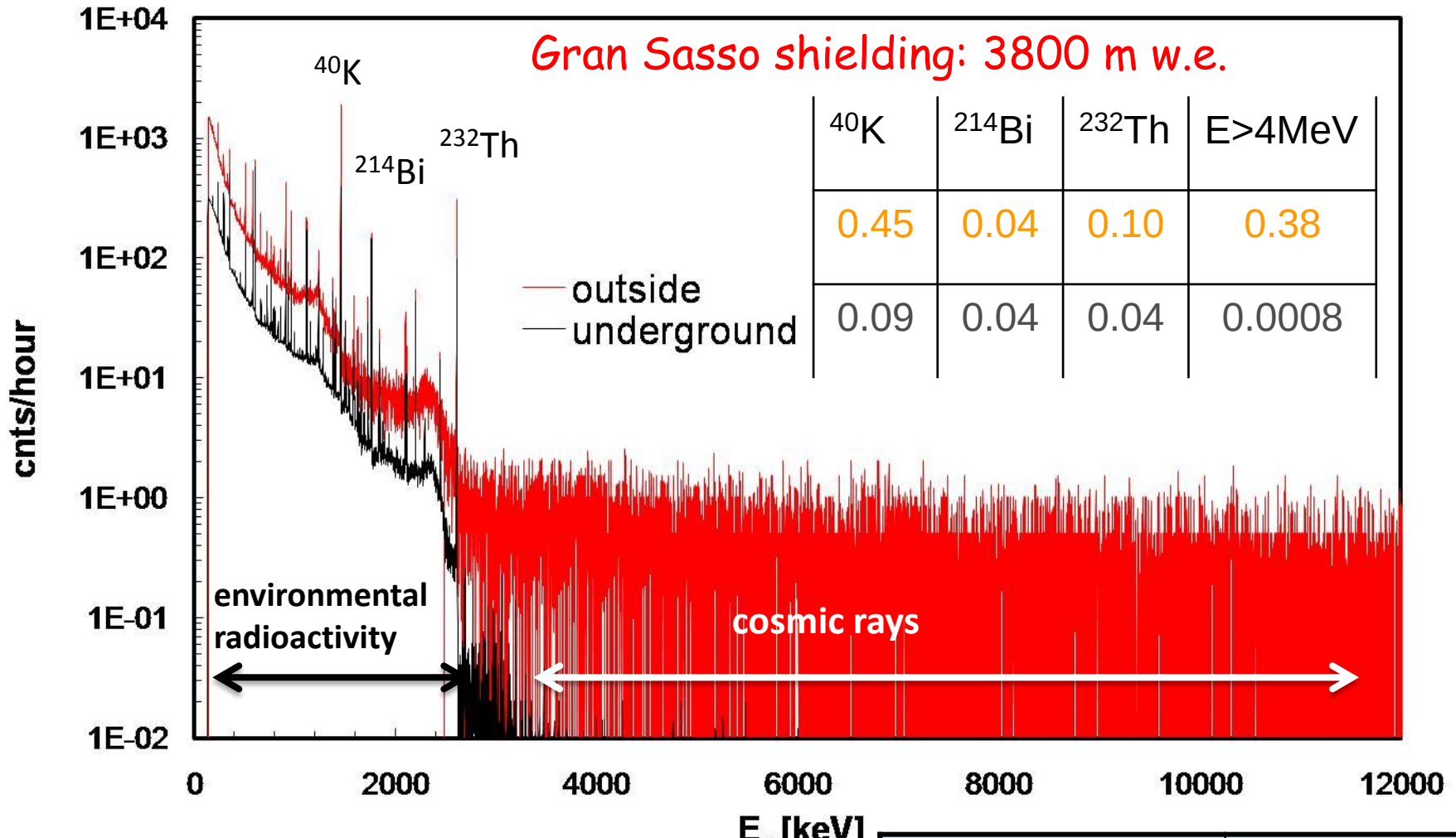




p+p [keV]	^{3}He+^{3}He [keV]	^{3}He+^{4}He [keV]	^{7}Be+p [keV]	^{14}N+p [keV]
6	22	23	18	27

Most of the reactions of astrophysical interest happen via radiative capture.
^{3}He(α,γ)^{7}Be, ^{14}N(p,γ)^{15}O , ^{12}C(α,γ)^{16}C...

Why going underground 1st

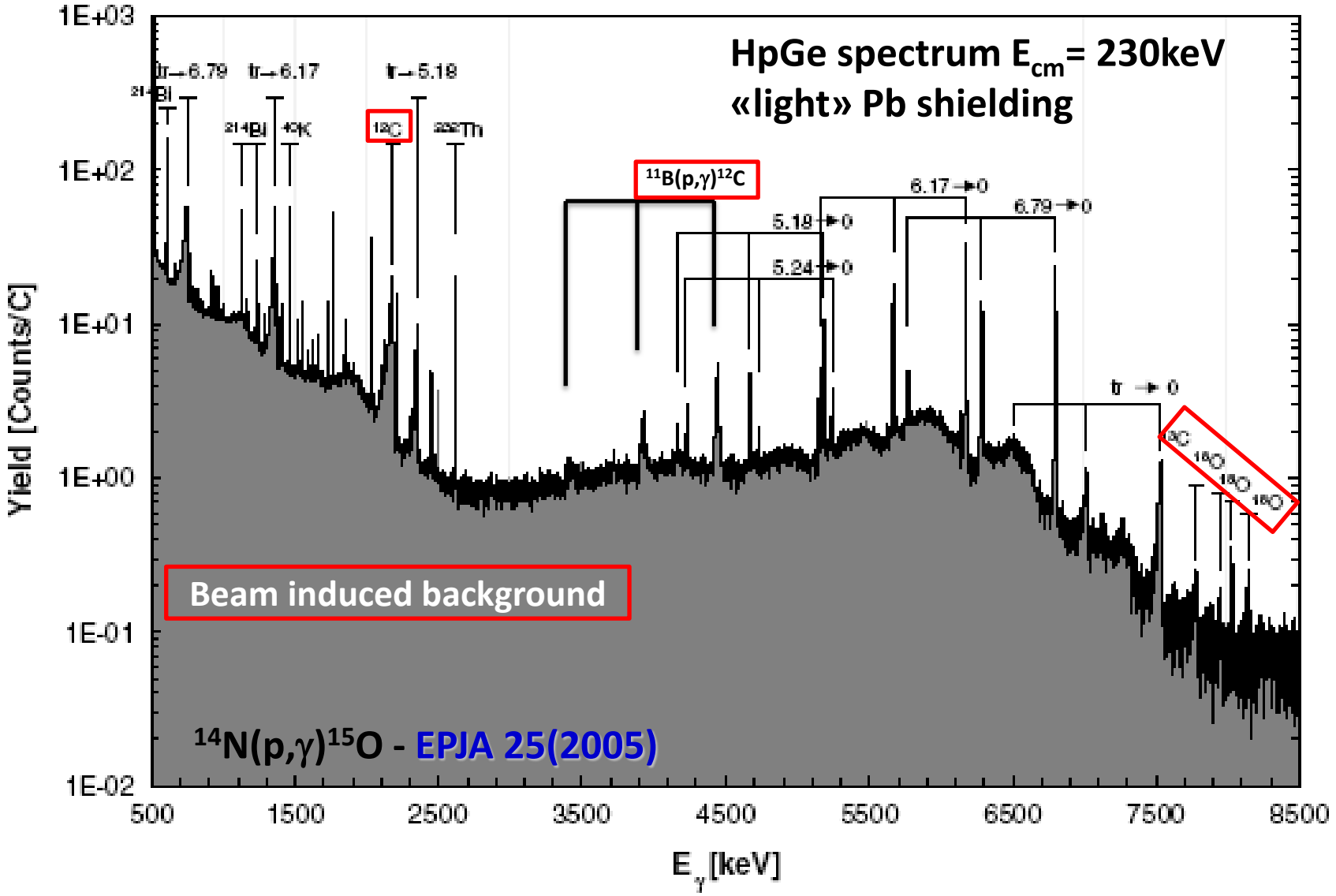


40K	214Bi	232Th	E>4MeV
0.45	0.04	0.10	0.38
0.09	0.04	0.04	0.0008

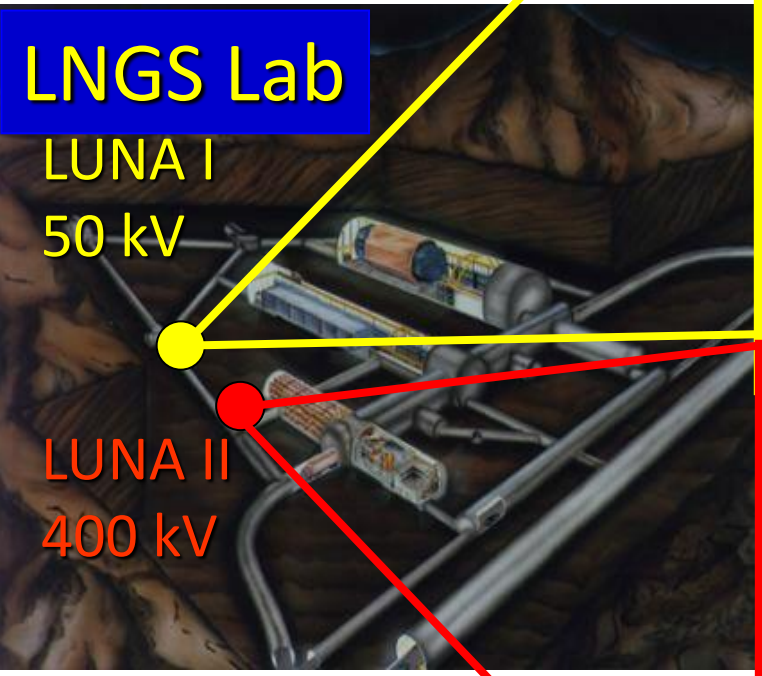
Therefore, the advantage of an underground environment is evident for high Q-value reactions such as **^{14}N(p,γ)^{15}O, ^{15}N(p,γ)^{16}O, ^{17}O(p,γ)^{18}F, ^{25}Mg(p,γ)^{26}Al**.....

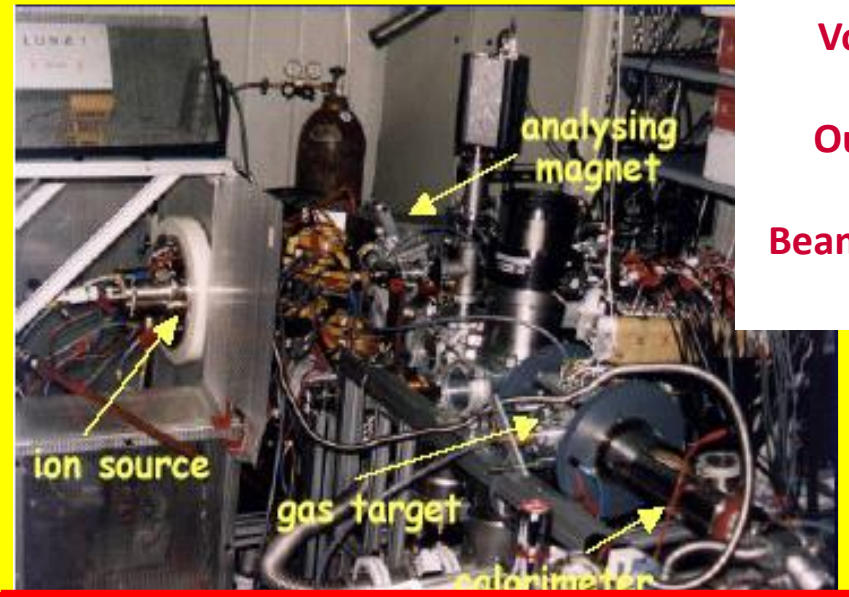
Radiation	LNGS/out
muons	10^{-6}
neutrons	10^{-3}

Why going underground 2nd

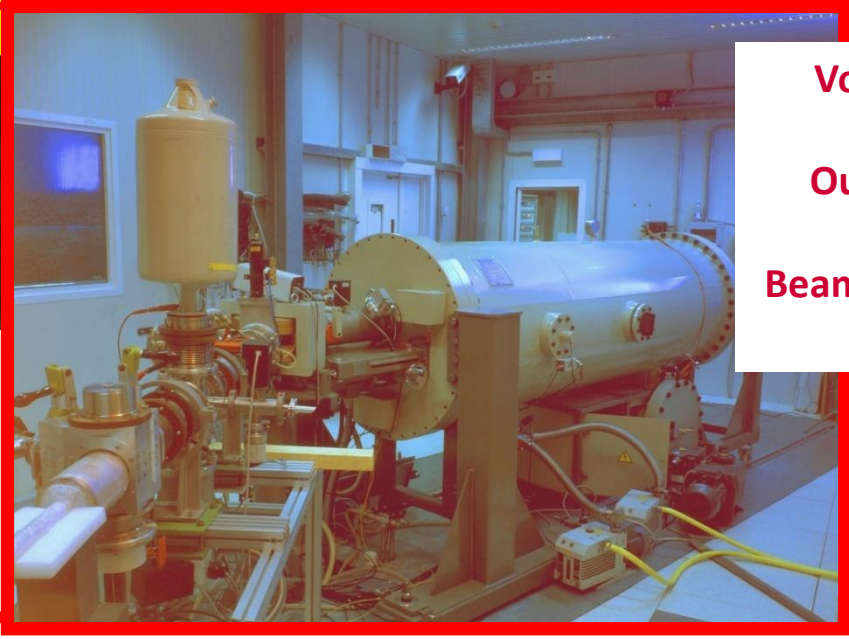


LUNA 1997-2012 - experimental set-ups





Voltage Range :
1 - 50 kV
Output Current:
1 mA
Beam energy spread:
20 eV



Voltage Range :
50 - 400 kV
Output Current:
500 μA
Beam energy spread:
70 eV

LUNA program: astrophysical motivation

- **Solar neutrinos**:

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

- **Big Bang nucleosynthesis**:

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

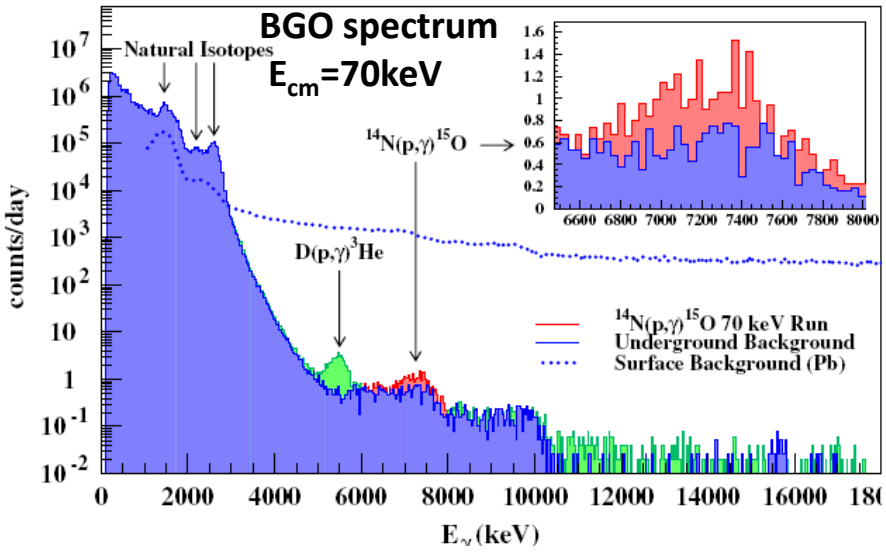
- **Age of Globular Clusters and C production in AGB:**

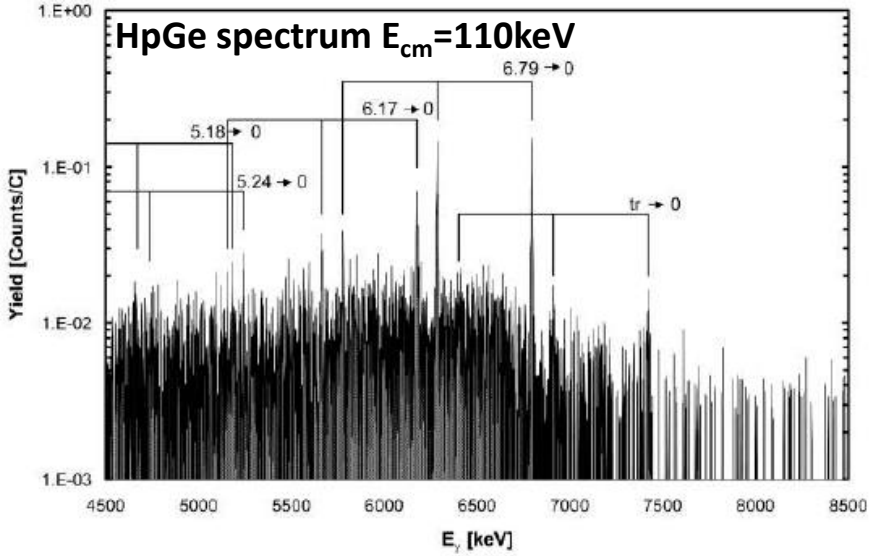
  $^{14}N(p,\gamma)^{15}O$

- **Light nuclei nucleosynthesis - $^{17}O/^{18}O$ abundaces, F origin, ^{26}Al γ-ray in the Galaxy, ^{26}Mg excess....:**

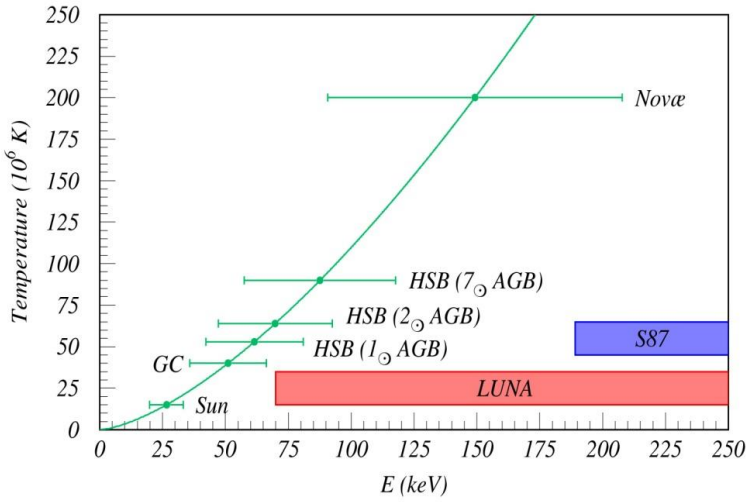
  $^{15}N(p,\gamma)^{16}O$, $^{17}O(p,\gamma)^{18}F(\beta^{+})^{18}O$, $^{25}Mg(p,\gamma)^{26}Al(\beta^{+})^{26}Mg$

$^{14}N(p,\gamma)^{15}O$: LUNA results

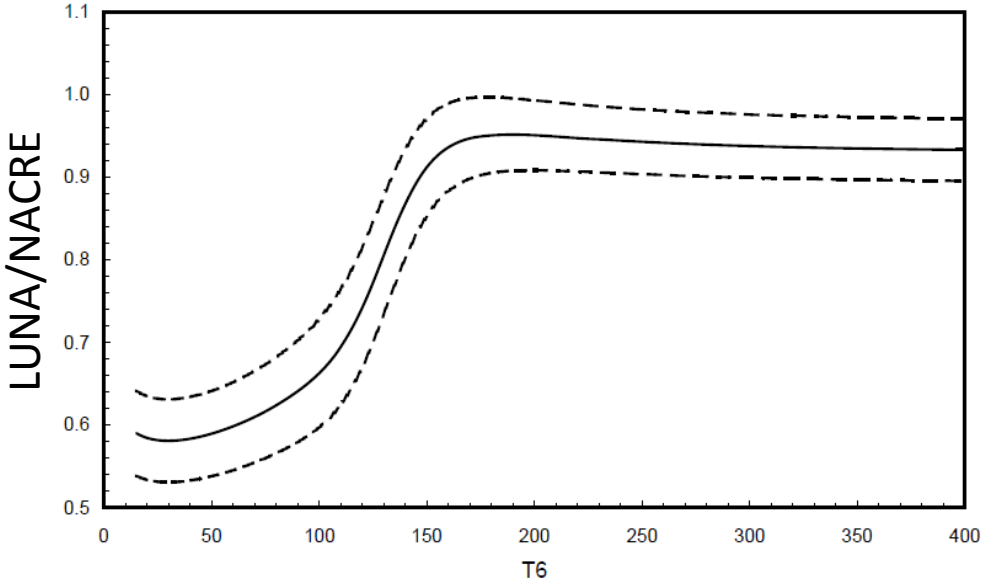




D. Bemmer, et al. NuPhyA 779(2006)

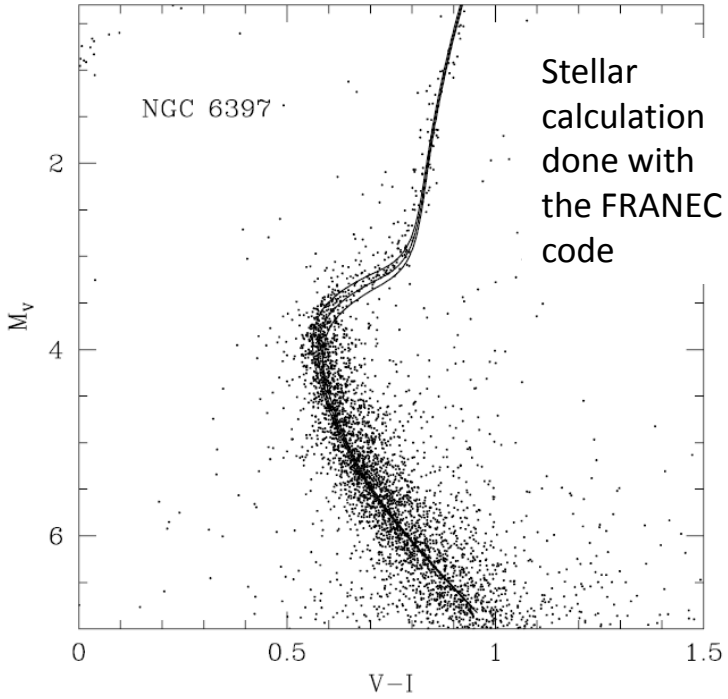


G. Imbriani, et al., EPJA 25(2005)



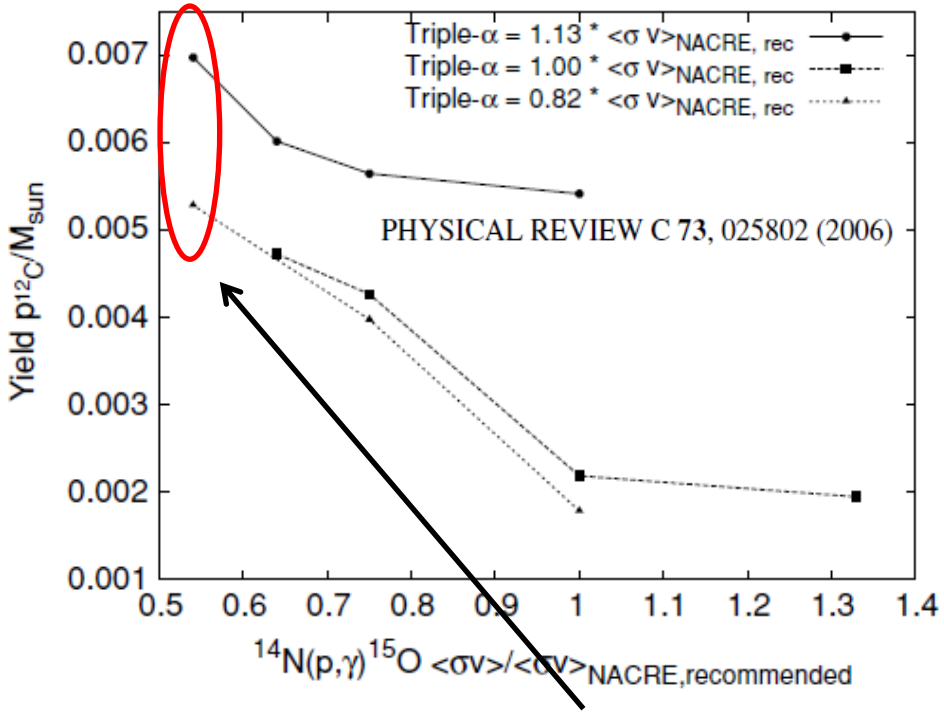
$^{14}N(p,\gamma)^{15}O$: astrophysical consequences

G. Imbriani, et al., A&A 420(2004)



The age of the oldest Globular Clusters should be increased by about 0.7-1 Gyr. The lower limit to the Age of the Universe is 14 ± 1 Gyr.
In good agreement with the precise detrmination of WMAP.

FALK HERWIG, SAM M. AUSTIN, AND JOHN C. LATTANZIO



With **$^{14}N(p,\gamma)^{15}O$** rate = ½ of NACRE better agreement between observation and calculation.

H-shell burning @LUNA

- **Solar neutrinos**:

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

- **Big Bang nucleosynthesis**:

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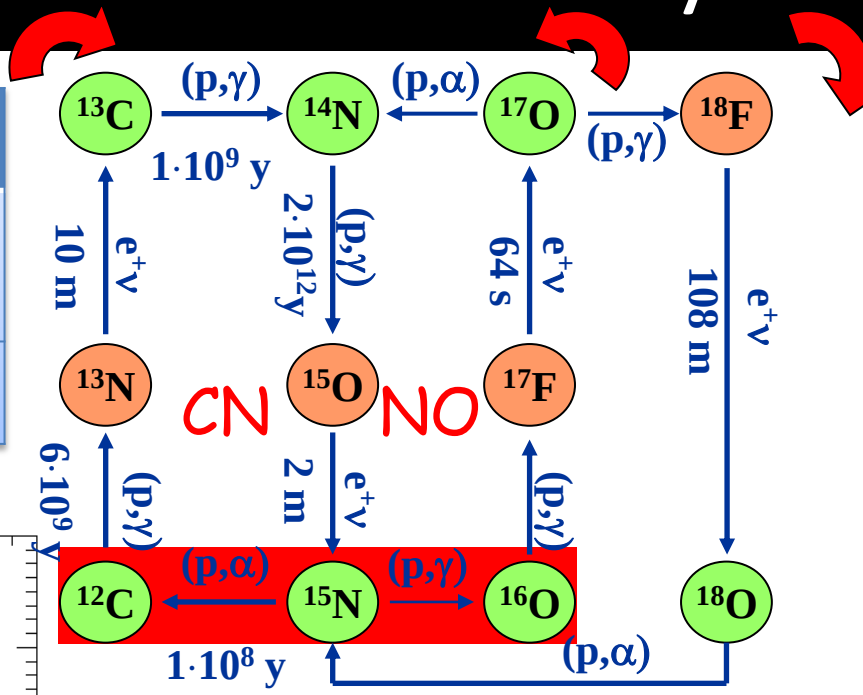
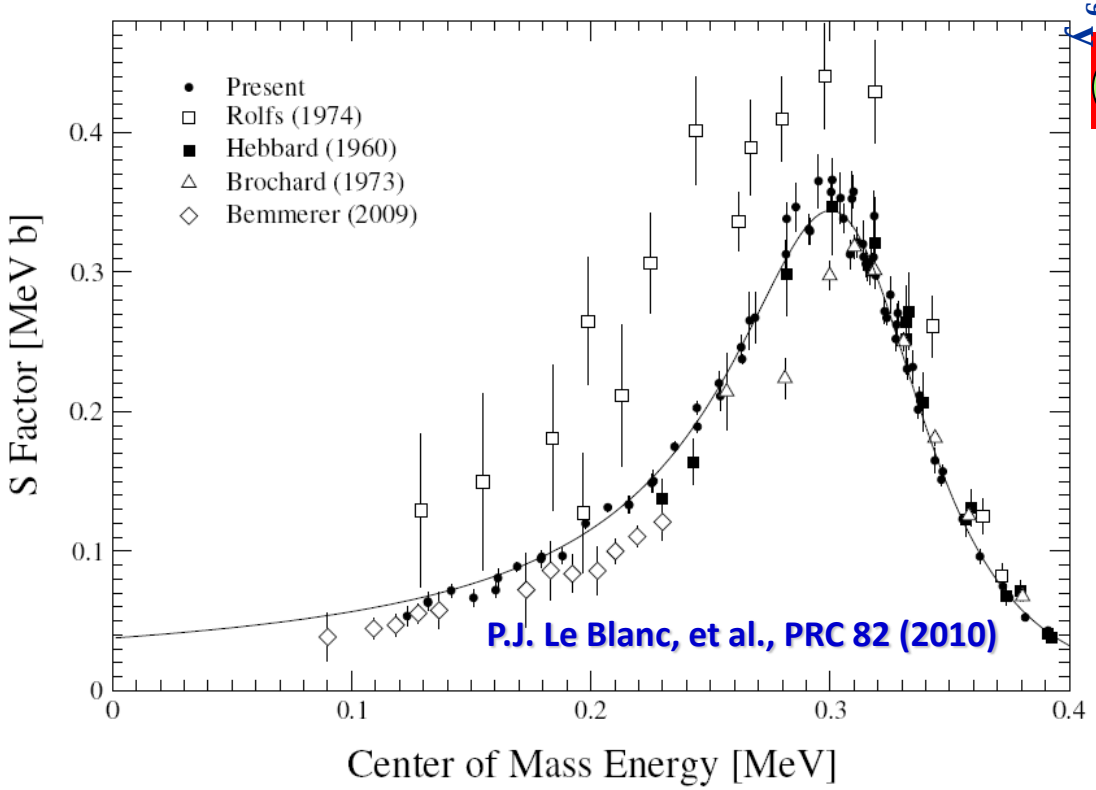
- **Light nuclei nucleosynthesis - $^{17}O/^{18}O$ abundaces, F origin, ^{26}Al γ-ray in the Galaxy, ^{26}Mg excess....:**

  $^{15}N(p,\gamma)^{16}O$, $^{17}O(p,\gamma)^{18}F(\beta^{+})^{18}O$, $^{25}Mg(p,\gamma)^{26}Al(\beta^{+})^{26}Mg$,

$^{15}N(p,\alpha)/(p,\gamma)$: first branch of the CNO cycle

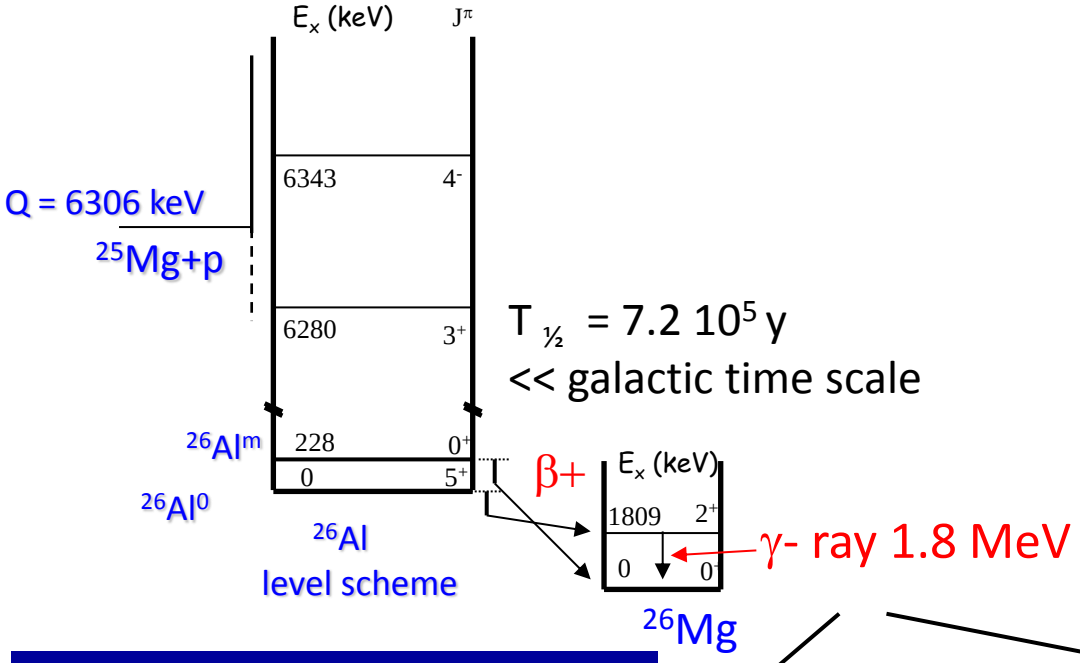
	DIRECT MEASUREMENTS			INDIRECT MEASUREMENTS
	Hebbard'60 NuPhy 15(1960)	Rolfs'74 NuPhy A 235(1974)	LUNA-ND PRC 82(2010)	Mukhamedzhanov et al. PRC 78(2008)
S(0) keVb	32 ± 6	64 ± 6	39.6 ± 2.6	36 ± 6



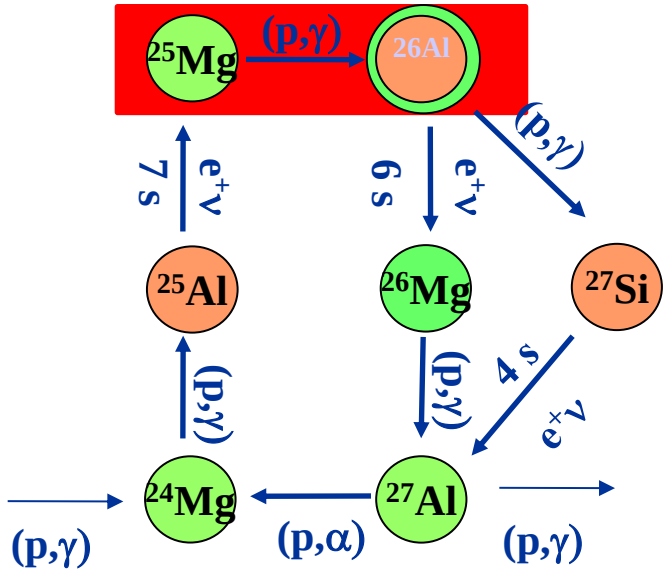


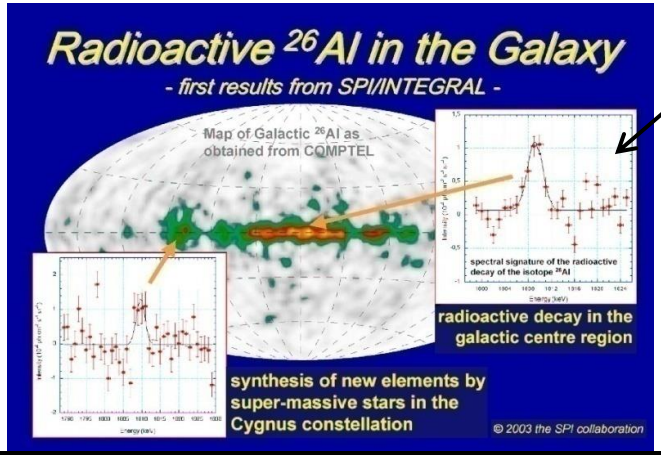
The leakage from CN to NO reduces of a factor 2:
every about 2000 cycles of the main CN cycle, one goes to NO cycle.
Before every 1000 cycles was the value recommended by the NACRE compilations (Angulo et al., 1999)

$^{25}Mg(p,\gamma)^{26}Al$ – Astrophysical motivations



$T_{1/2}$ = 7.2 10^5 y
<< galactic time scale



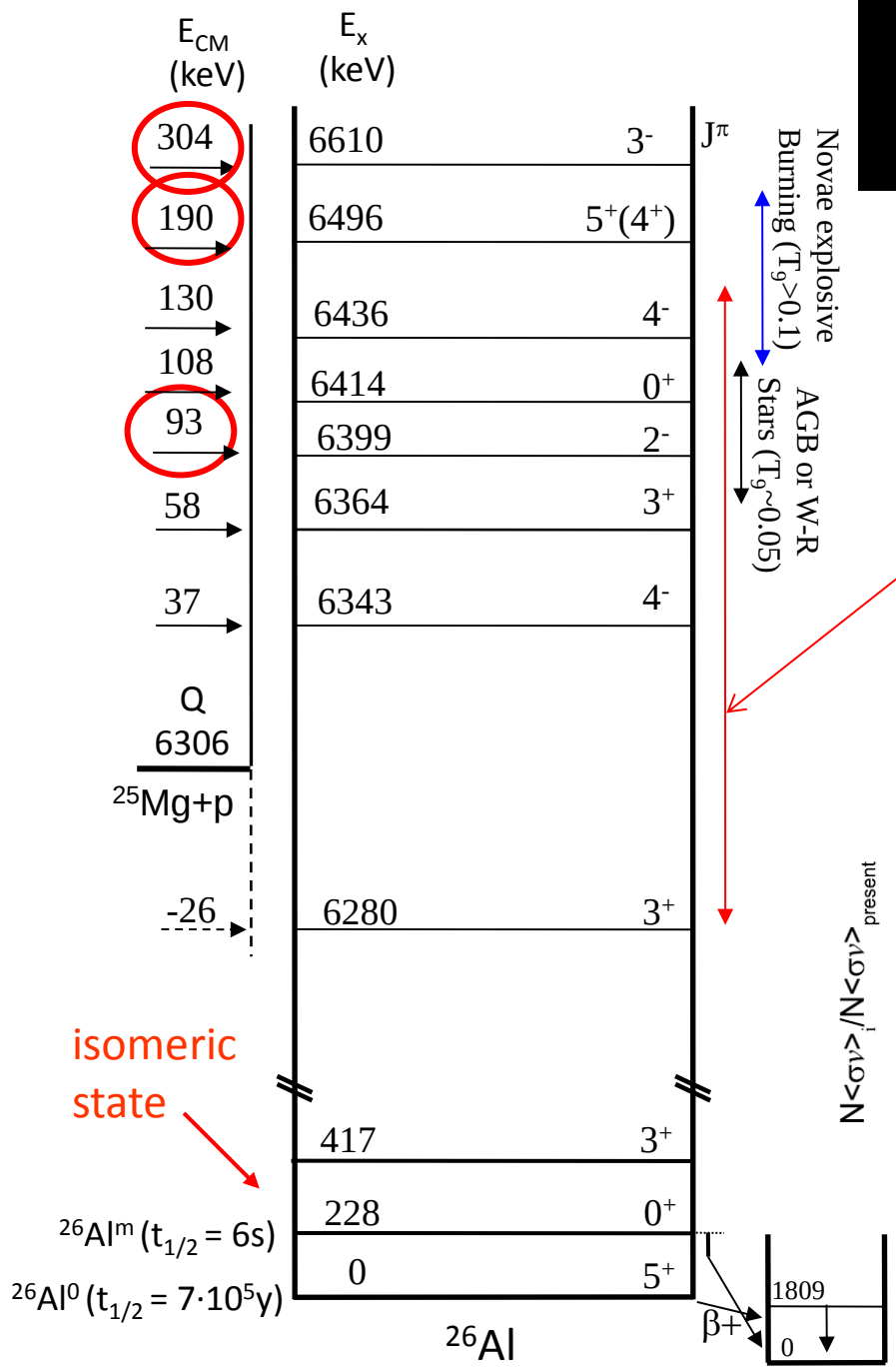


^{26}Mg excess in meteorites

Evidence that ^{26}Al nucleosynthesis is still active (WR stars, SN and NOVAE)

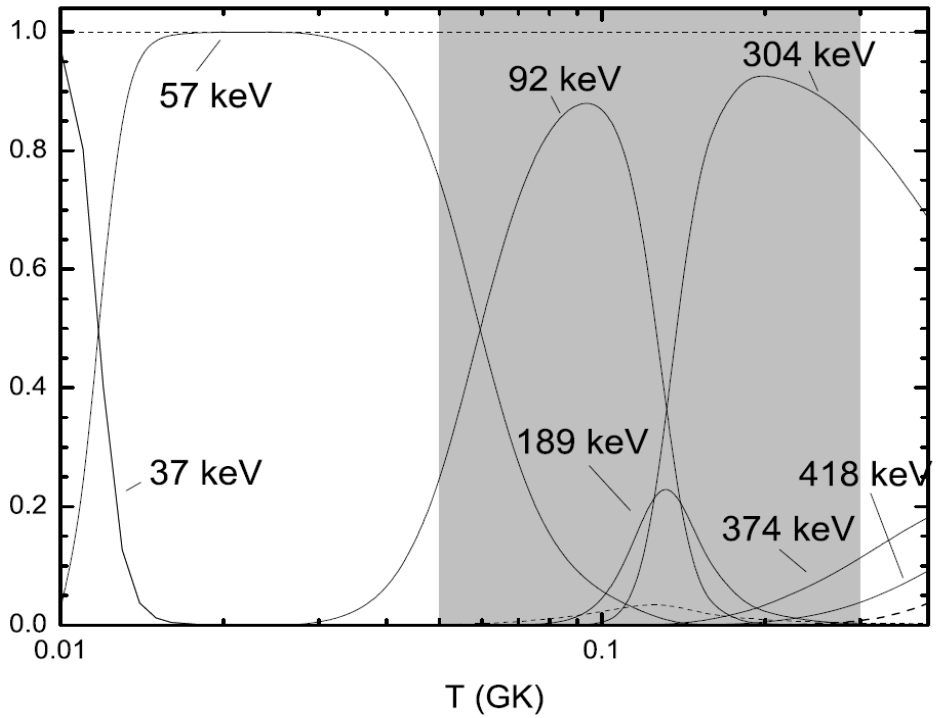
Signature of ^{26}Mg production during the Hydrogen burning (RGB, AGB)

$^{25}Mg(p,\gamma)^{26}Al$ – Astrophysical motivations

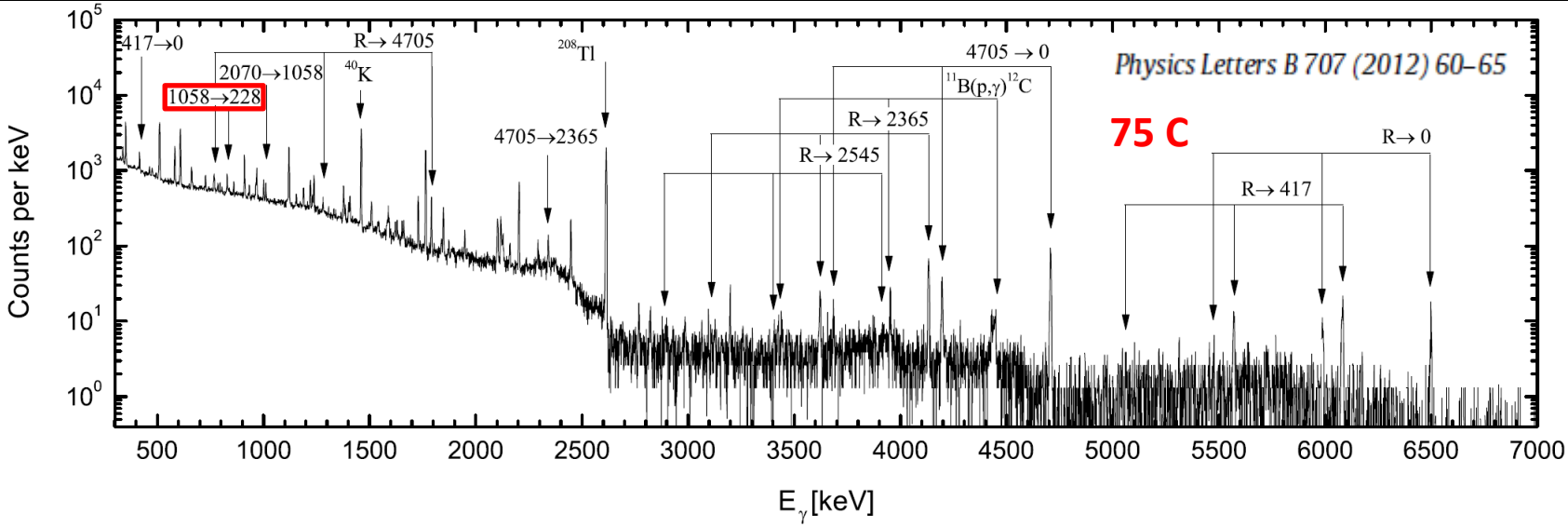


No direct strength resonance data
(level structure derived from the single particle transfer reaction: **$^{25}Mg(^{3}He,d)^{26}Al$**)

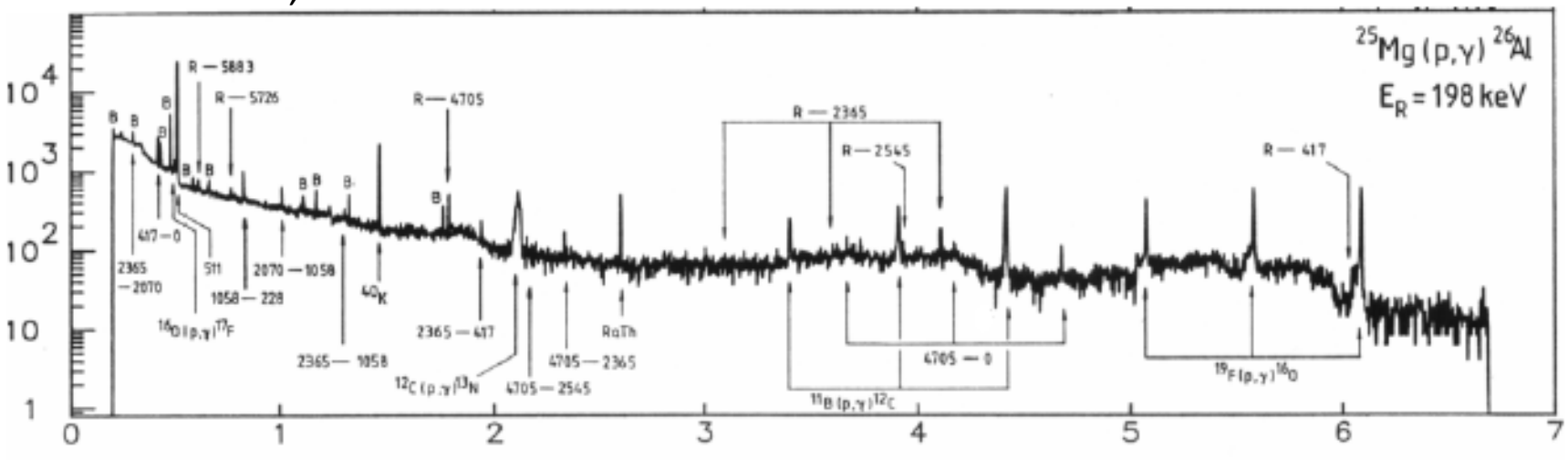
LUNA energy window



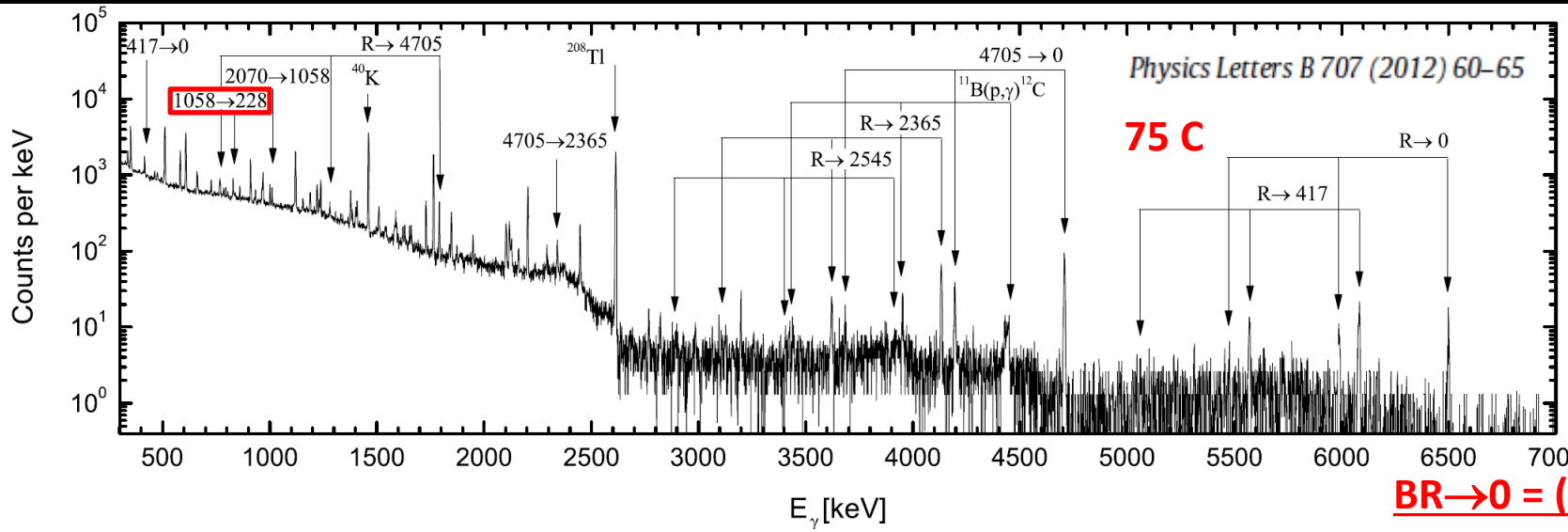
$^{25}Mg(p,\gamma)^{26}Al$ - HPGe spectra E_R = 190 keV



Iliadis et al, 1990



$^{25}Mg(p,\gamma)^{26}Al$ - HPGe spectra E_R = 190 keV



BR→0 = (75 ± 2) %

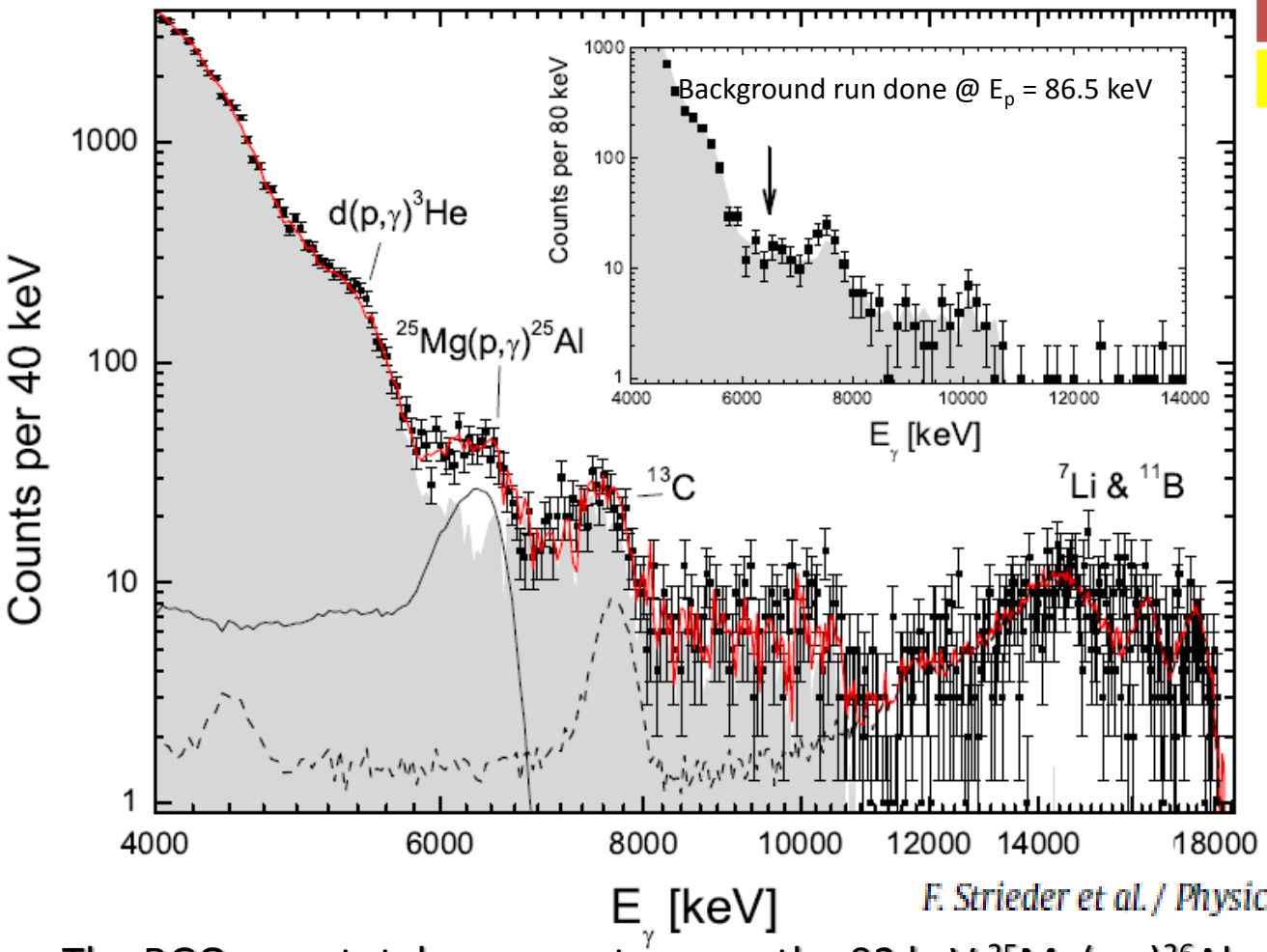
ωγ [eV] **LUNA HPGe**	ωγ [eV] **LUNA BGO**	ωγ [eV] **Iliadis et al. 1990**
(9.0 ± 0.7)×10^{-7}	**(9.0 ± 0.8)×10^{-7}**	(7.4 ± 1.0) ×10^{-7}

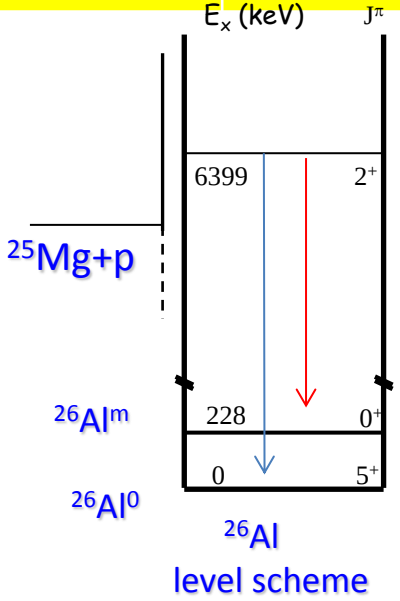
E_x	Present work	[22]	[38]	[39]
5883		8 ± 2		
5726	3.0 ± 1.0	7 ± 2		
4705	48.7 ± 2.0	35 ± 4	50 ± 2	50 ± 8
3403	1.5 ± 0.5	< 3[a]	4.5 ± 0.9	
3074[b]	1.4 ± 0.5	< 4		16 ± 7
2545	7.7 ± 1.0	12 ± 4	5.8 ± 1.2	
2365	21.9 ± 2.0	26 ± 4	19 ± 1	17 ± 7
417	10.2 ± 1.0	12 ± 4	21 ± 3	17 ± 9
0	5.6 ± 1.1			

$^{25}Mg(p,\gamma)^{26}Al$ - BGO spectra E_R = 92 keV

the lowest ever directly measured resonance strength

ωγ [10^{-10} eV] LUNA	ωγ [10^{-10} eV] NACRE ind.
2.9 ± 0.6	$1.16\ ^{+1.16}_{-0.39}$





BR→0 = (60 $^{+20}_{-10}$) %

F. Strieder et al. / Physics Letters B 707 (2012) 60–65

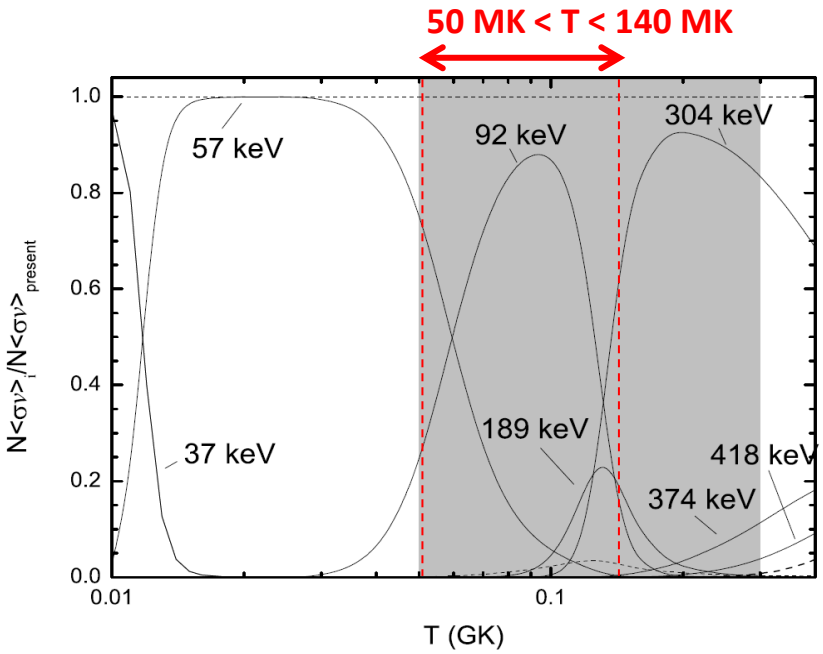
The BGO γ-ray total sum spectrum on the 92 keV $^{25}Mg(p,\gamma)^{26}Al$ resonance (E_p = 100 keV).

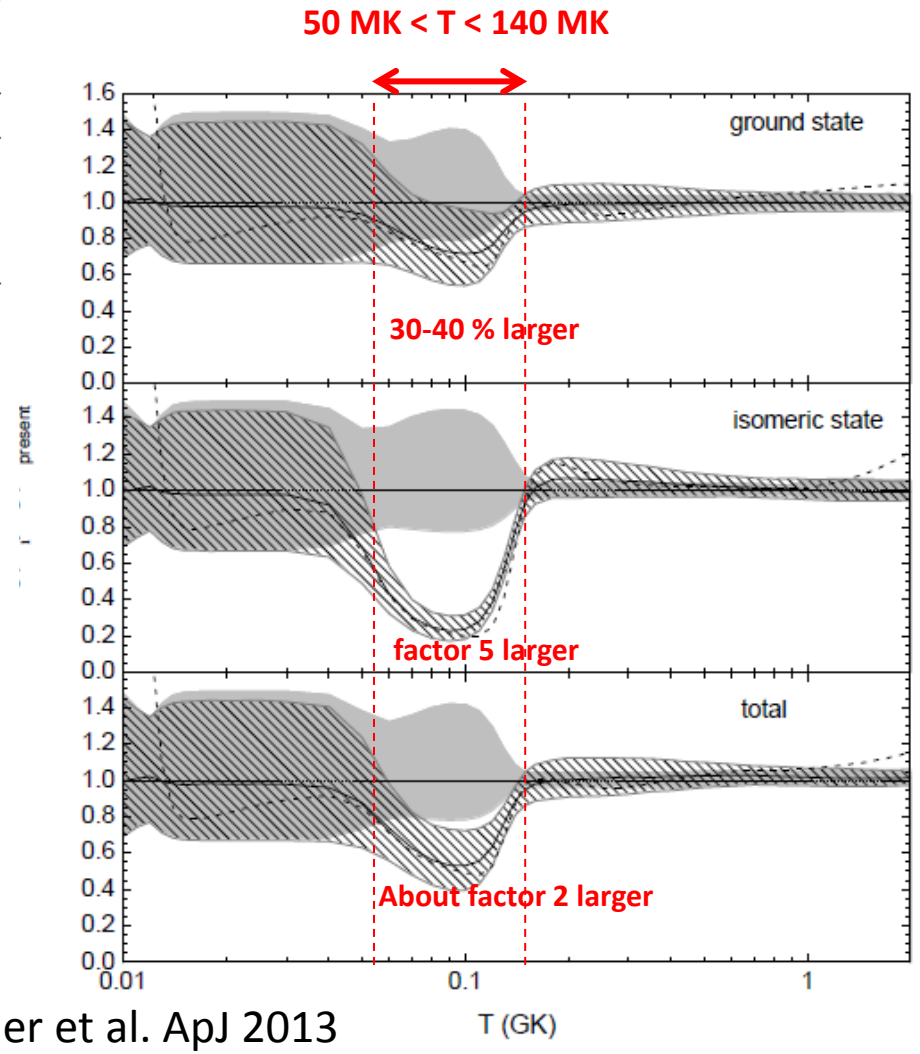
1. The shaded area → envinromental background
2. Thin solid line → $^{25}Mg(p,\gamma)^{26}Al$ simulation varying the primaries branchings .
3. Solid red line → total yield fit including background and simulation.

$^{25}Mg(p,\gamma)^{26}Al$ - Astrophysical consequences

The new recommended $^{25}Mg(p,\gamma)^{26}Al$ resonance strengths (uncorrected for screening) and corresponding ground state fractions f_0. The electron screening enhancement factor f_{es} was calculated according to [46].

E [keV][a]	$\omega\gamma$ [eV]	f_{es}	f_0
304.0	$(3.08 \pm 0.13) \times 10^{-2}$ [b]	1.04	0.878 ± 0.010[b]
189.5	$(9.0 \pm 0.6) \times 10^{-7}$	1.08	0.75 ± 0.02
130.0	$< 2.5 \times 10^{-10}$	1.14	0.73 ± 0.01[c]
92.2	$(2.9 \pm 0.6) \times 10^{-10}$	1.25	$0.6^{+0.2}_{-0.1}$





Straniero, Imbriani, Strieder et al. ApJ 2013

LUNA results fully cover the temperature range of core massive main sequence stars (Wolf-Rayet) as well as the H-burning shell of RGB and AGB stars.

$^{25}Mg(p,\gamma)^{26}Al$ - Astrophysical consequences

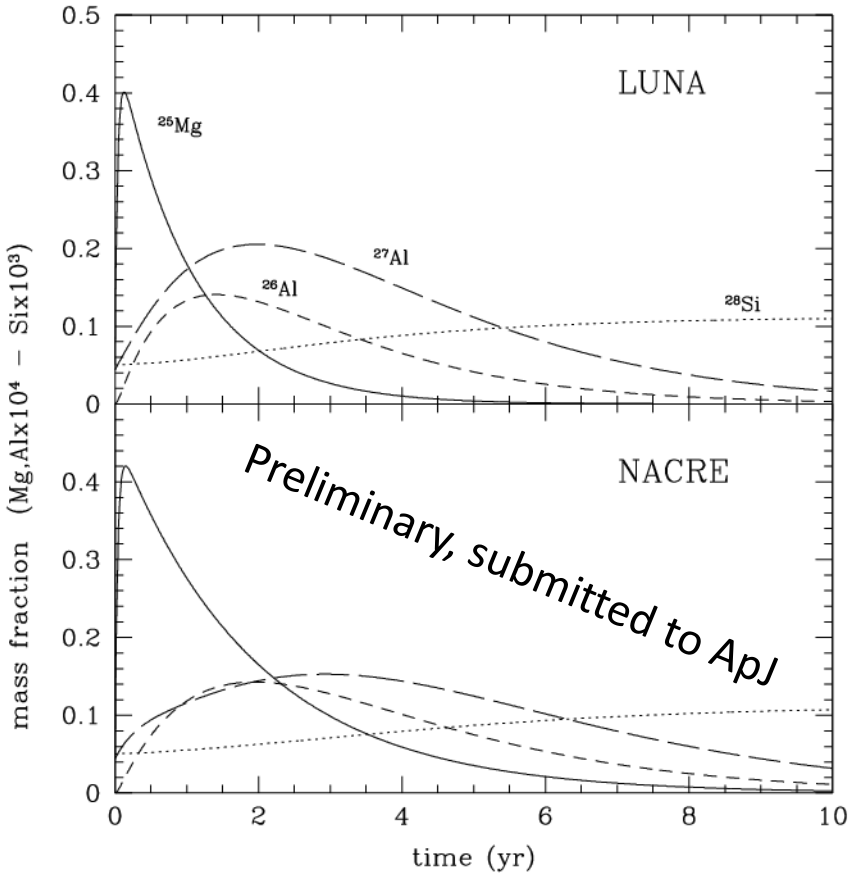


Fig. 6.— Evolution of Mg and Al isotopes. Temperature and density are mantained constant, namely: T=100 MK and ρ = 10 g/cm^3, respectively. At t=0, the composition is scaled solar and Z=0.001. The H mass fraction is X=0.6. The various lines represent the following isotopes: ^{25}Mg (solid), ^{26}Al (dashed), ^{27}Al (long dashed) and ^{28}Si (dotted). The calculation shown in the upper panel has been obtained by using the recommended rates of the $^{25}Mg(p,\gamma)^{26}Al$ reactions. For comparison, the results obtained by means of the NACRE rates are shown in the lower panel.

WR stars:

$N_A\langle\sigma v\rangle_{total}$ factor 2 > NACRE and Iliadis

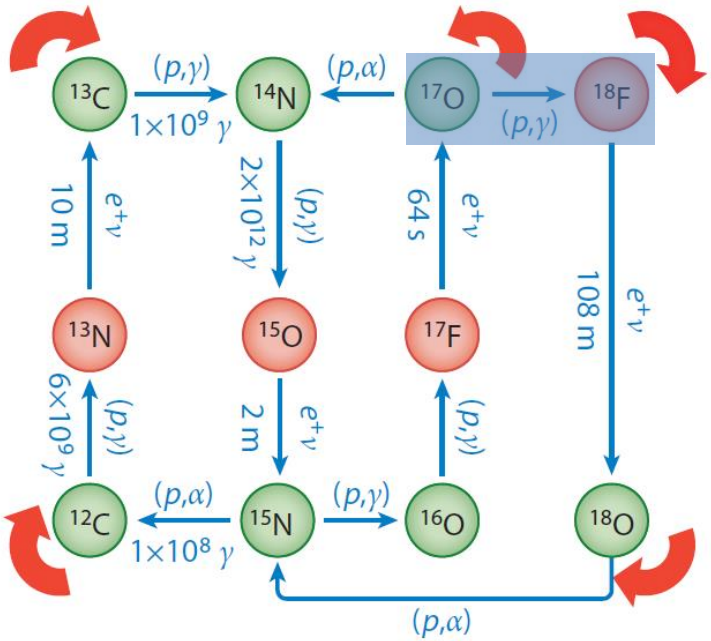
$N_A\langle\sigma v\rangle_{isomeric}$ factor 5 > NACRE and Iliadis

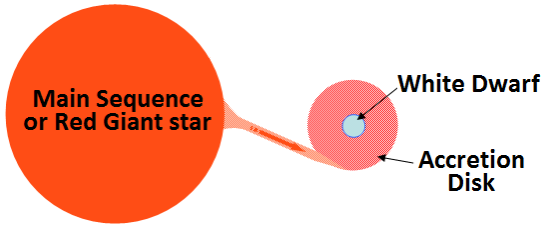
→ the expected production of $^{26}Al_{gs}$ in stellar H-burning zones is **lower** than previously estimated**. This implies a reduction of the estimated contribution of WR stars to the galactic production of ^{26}Al.**

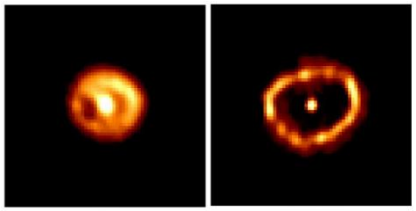
Presolar grains originated in AGB stars: the most important conclusion is that the deep AGB extra-mixing, often invoked to explain the large excess of ^{26}Al in some O-rich grains, does not appear a suitable solution for **$^{26}Al/^{27}Al > 10^{-2}$**.

Mg-Al anti-correlation in Globular Clusters stars: the substantial increase of the total reaction rate **makes** the Globular Cluster self-pollution caused by massive AGB stars a **more reliable scenario for the reproduction of the Mg-Al anti-correlation.**

$^{17}O(p,\gamma)^{18}F$ - Astrophysical motivation

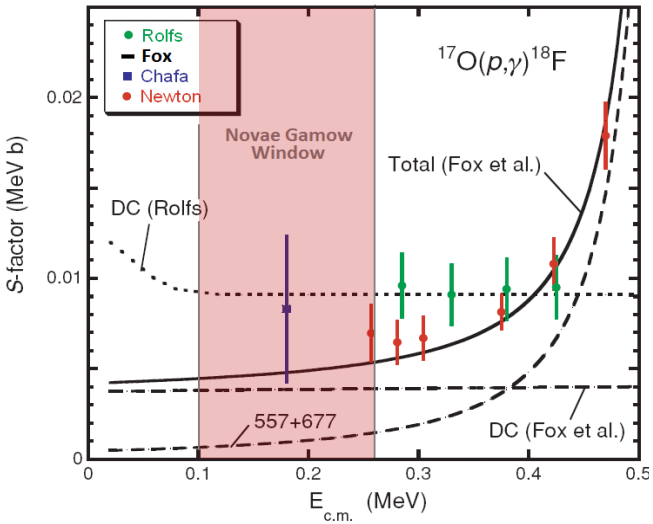




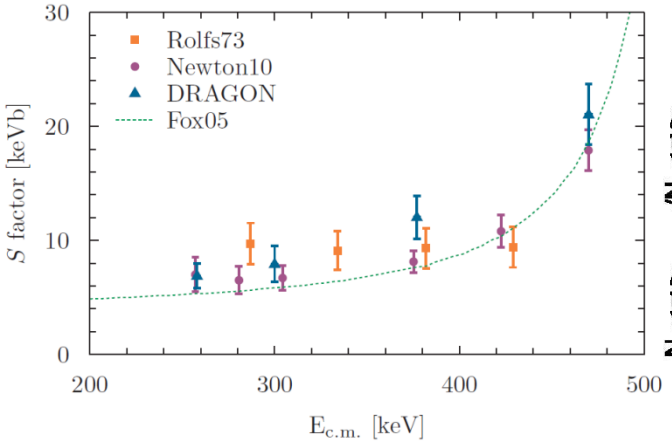


- Classical Novae nucleosythesis (**T=0.1-0.4 GK**):

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



PHYSICAL REVIEW C **81**, 045801 (2010)



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PHYSICAL REVIEW C **85**, 035803 (2012)

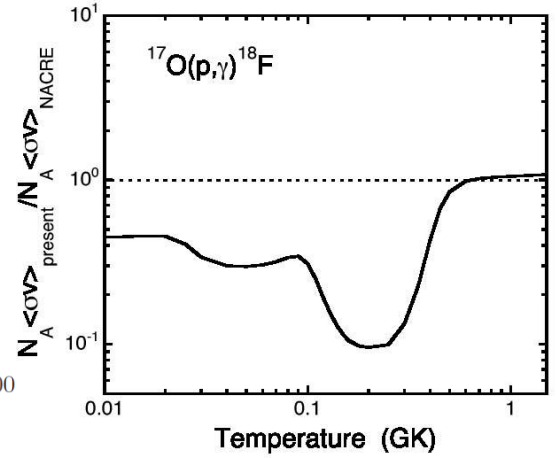
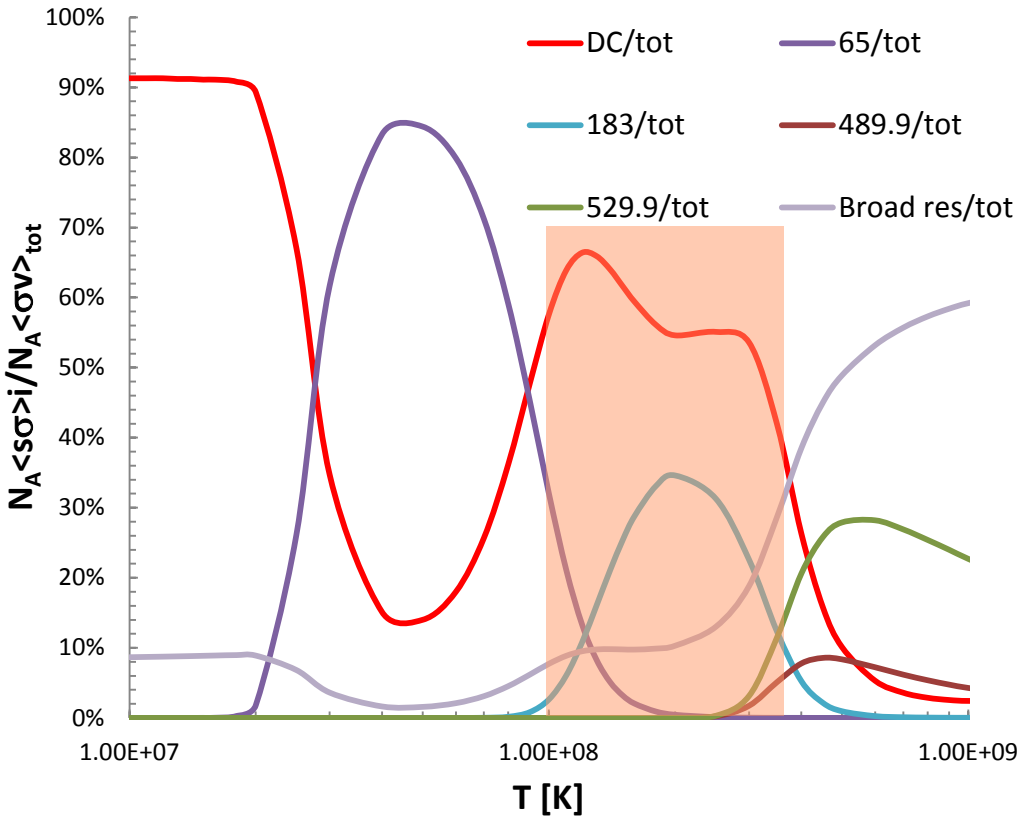
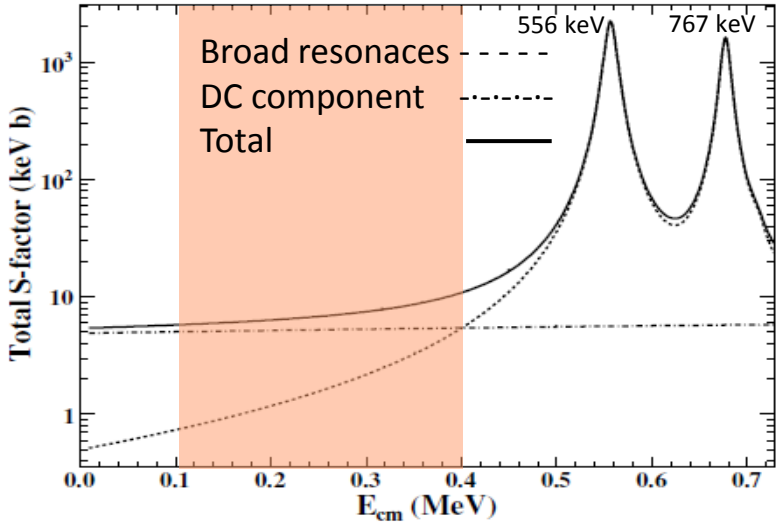
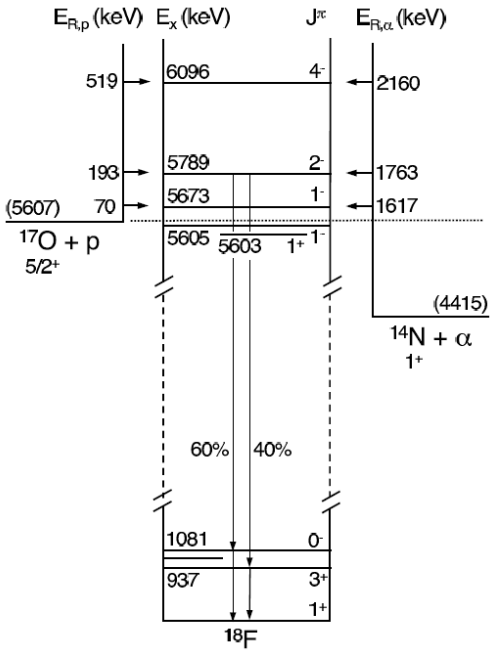


FIG. 10. Ratio of present and previous [1] total recommended tion rates for $^{17}O(p,\gamma)^{18}F$.

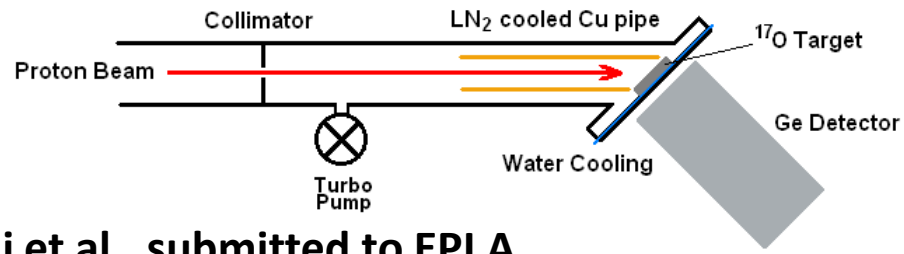
$^{17}O(p,\gamma)^{18}F$ – LUNA experiment





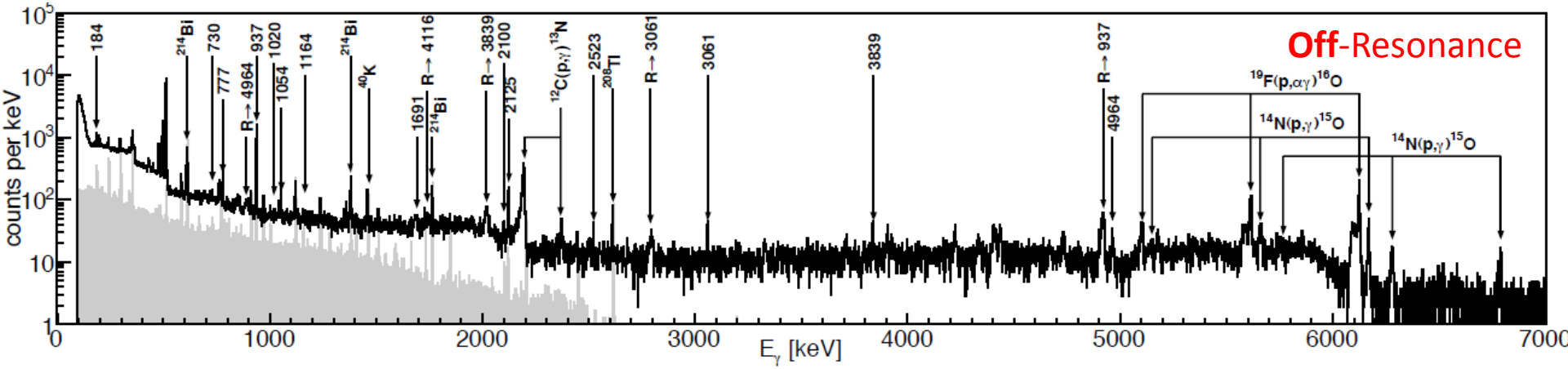


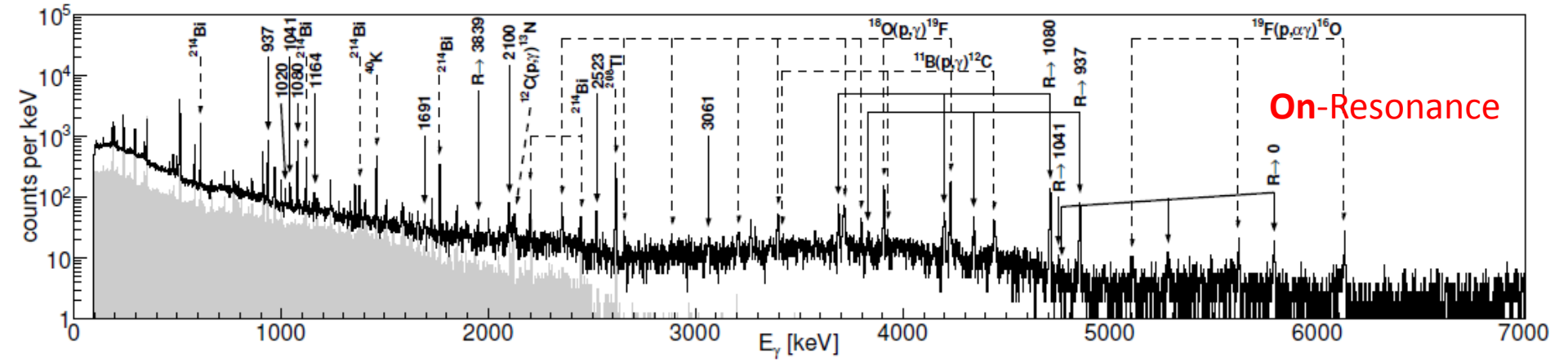
LUNA is directly investigating this energy window



Caciolli et al., submitted to EPJ A

$^{17}O(p,\gamma)^{18}F$ – On and off resonance spectra

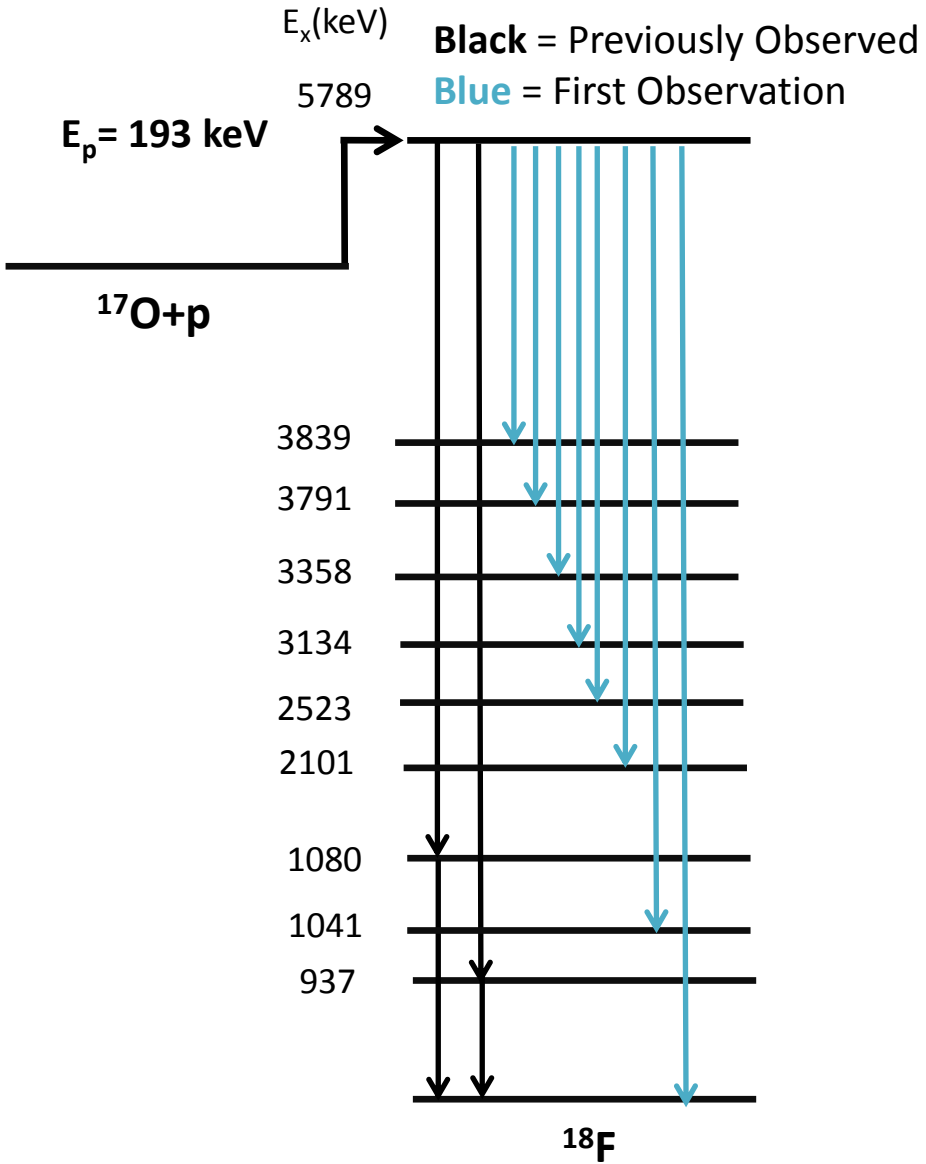




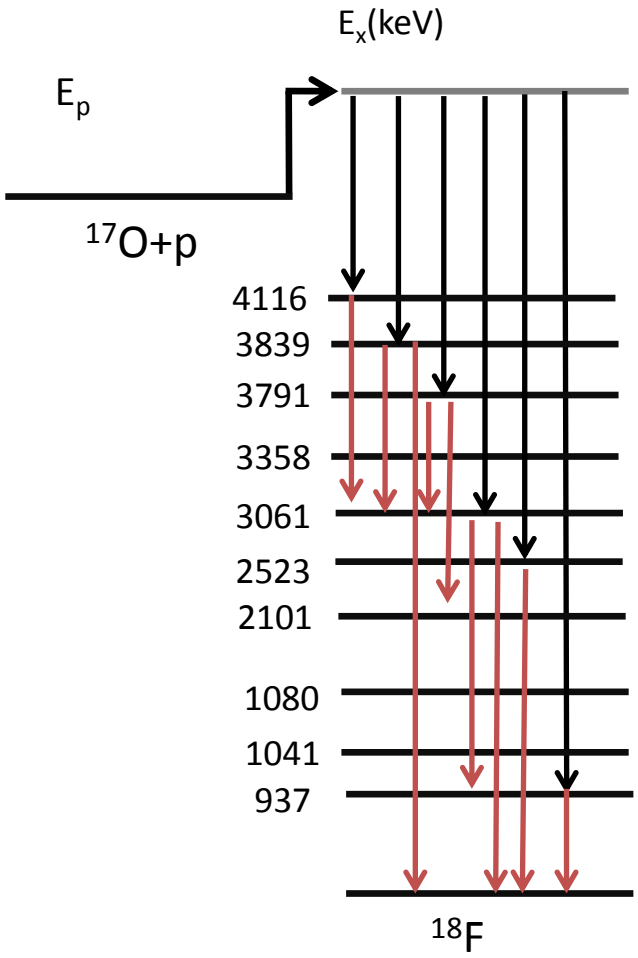
New transitions observed on resonance!

New Transitions Observed

On Resonance



Off Resonance 200<E<370

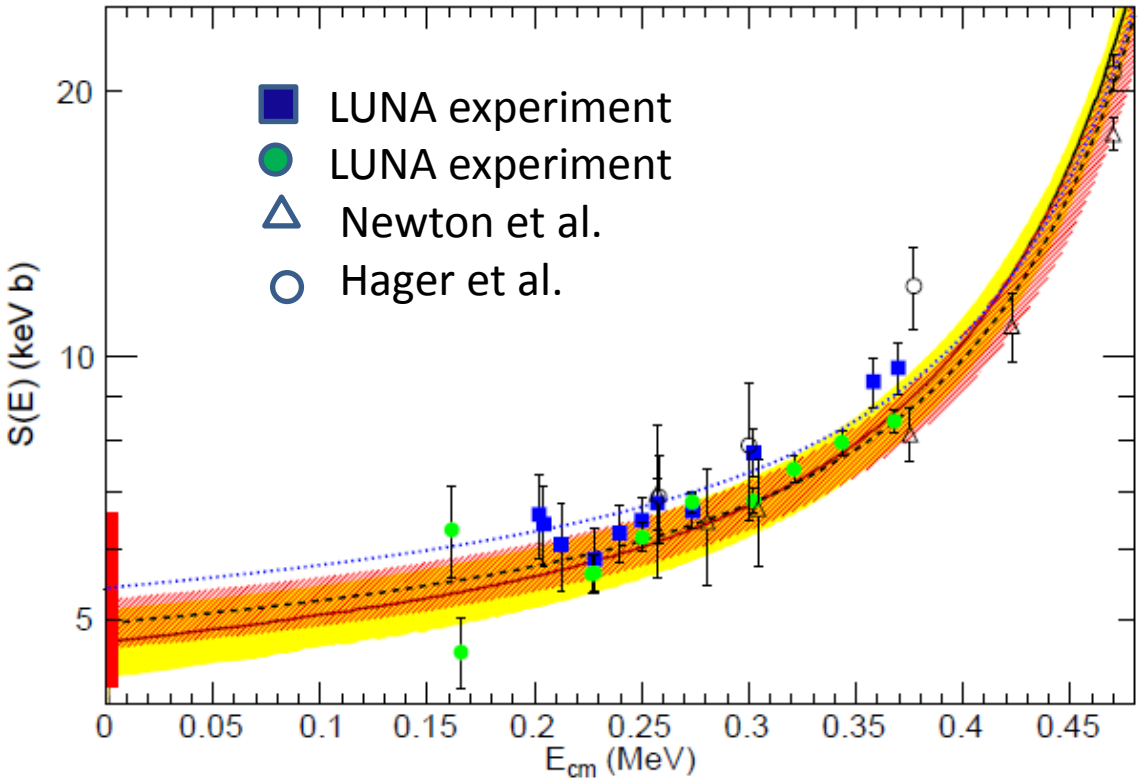


$^{17}O(p,\gamma)^{18}F$ – results

- **Total reaction Cross section** measured between **E_{cm} ≈ 180 – 370 ke**
- Resonance Strength of **E_p=193 keV resonance measured** within an uncertainty of **8%**. (~factor 2 higher accuracy).

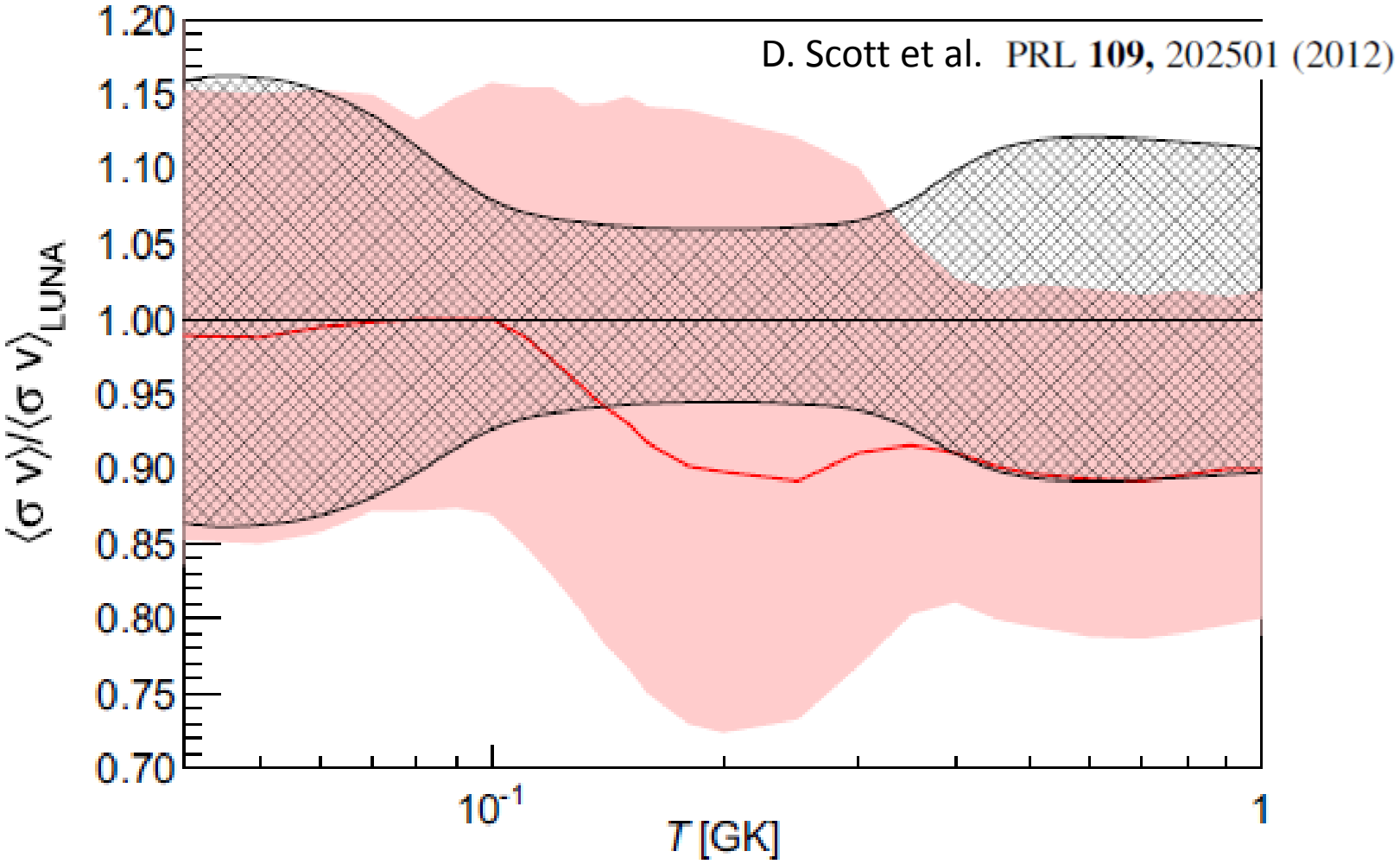
  Activation: **$\omega\gamma_{193}$ = (1.67 ± 0.12) μeV**

$\omega\gamma_{193}$= (1.2±0.2)μeV FOX
$\omega\gamma_{193}$= (2.2±0.4)μeV CHAFA

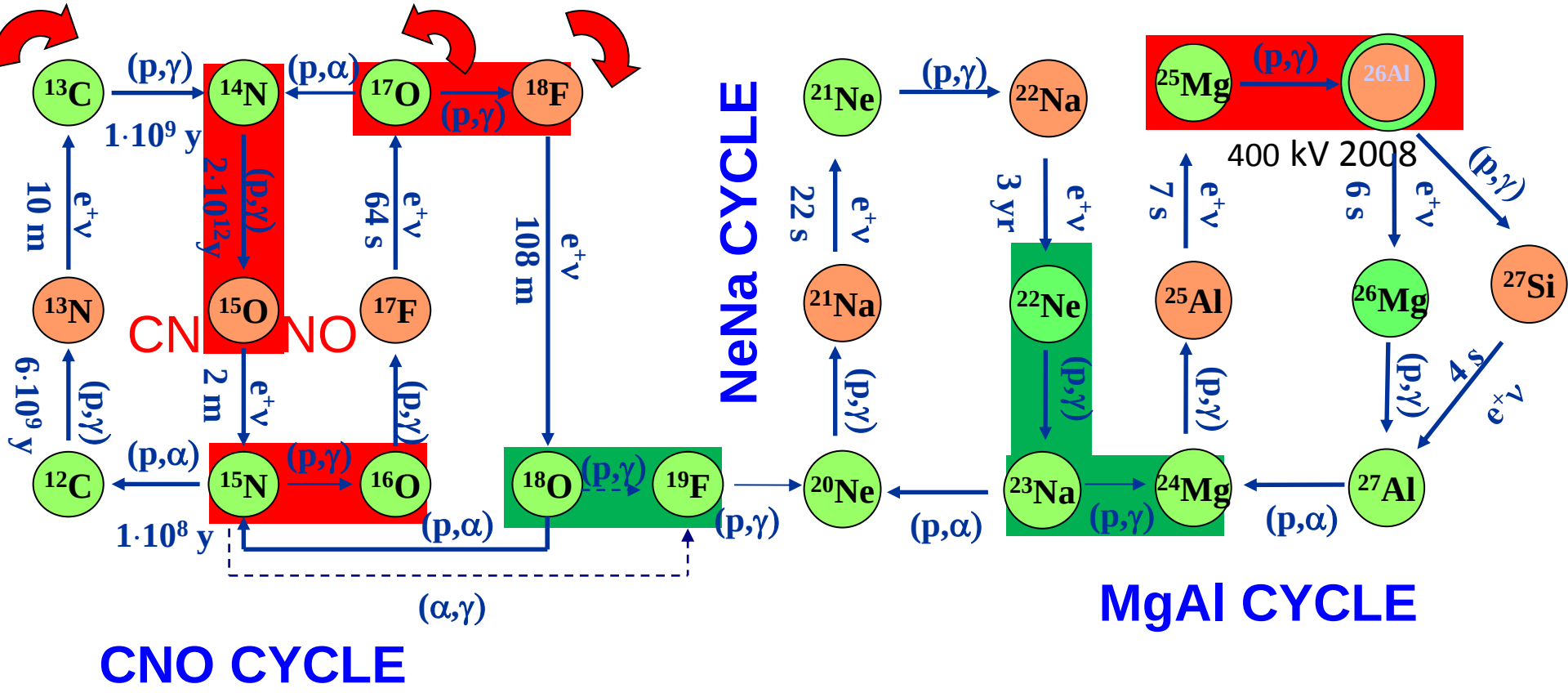


$^{17}O(p,\gamma)^{18}F$ – Reaction rate @ Novae T

five-fold reduction in reaction rate uncertainty.



LUNA 400 kV outlook



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LUNA: Nuclear Astrophysics Deep Underground

Carlo Broggini,[1] Daniel Bemmerer,[2] Alessandra Guglielmetti,[3] and Roberto Menegazzo[1]

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LUNA: a laboratory for underground nuclear astrophysics

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