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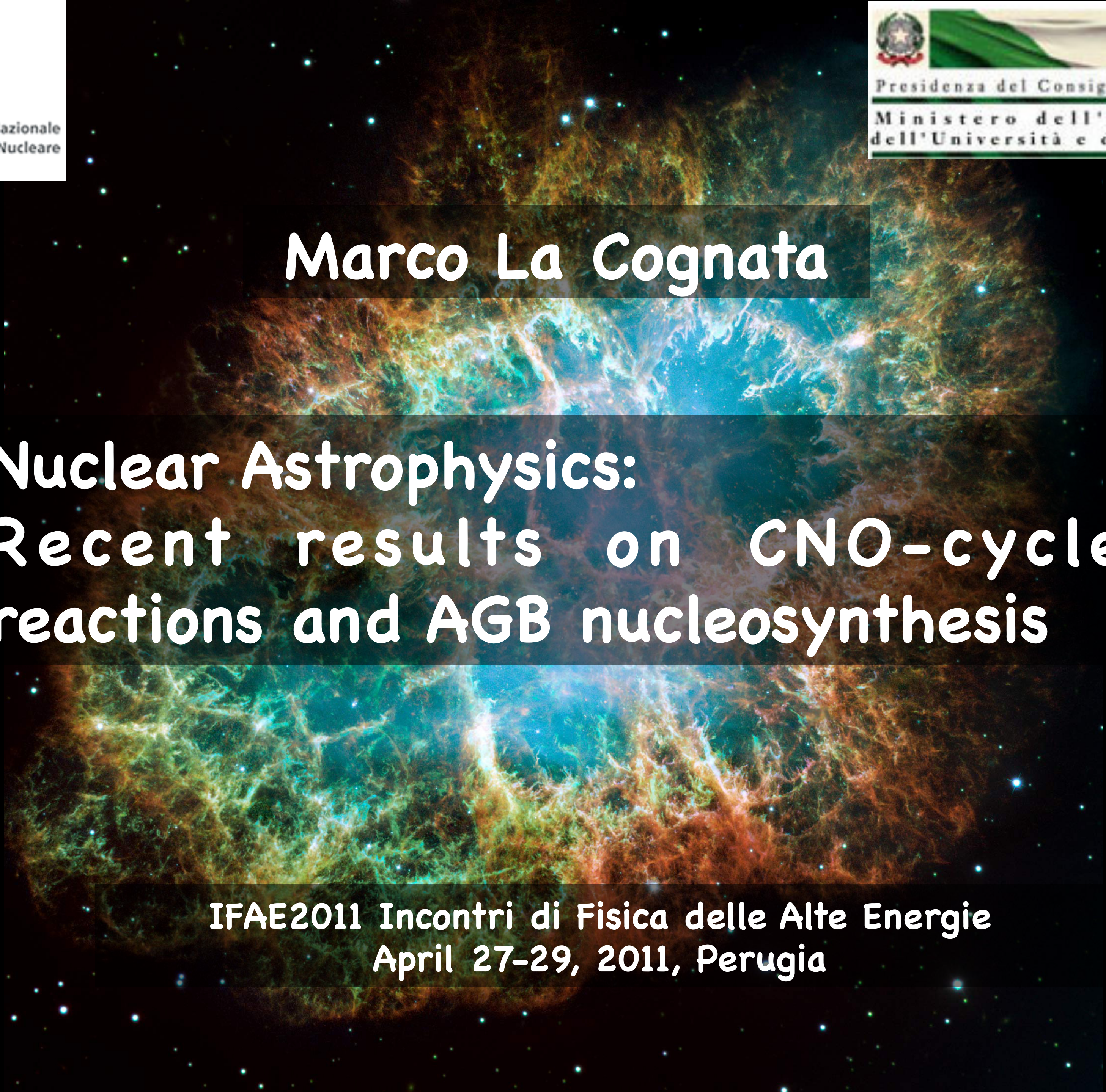
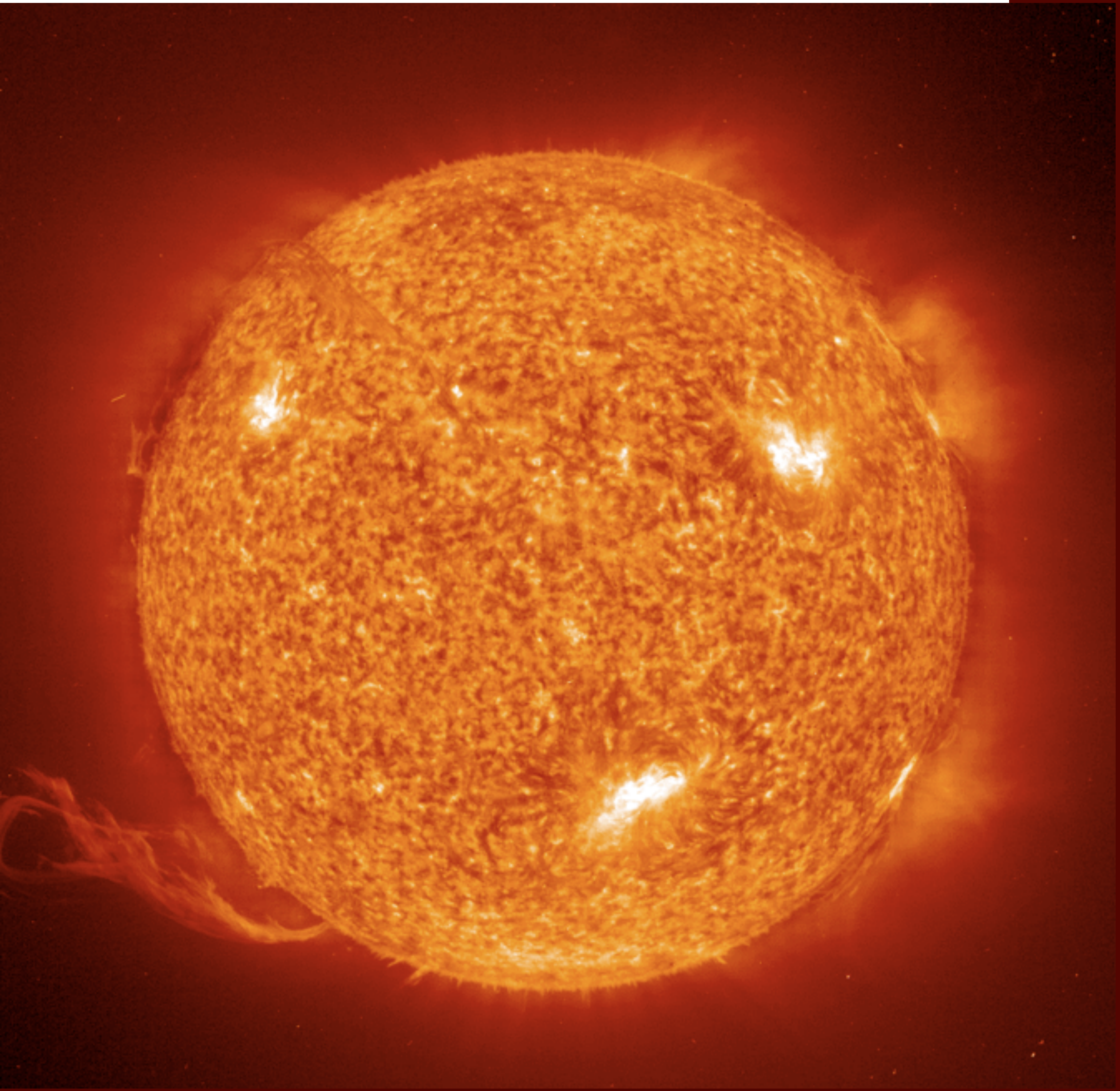


Marco La Cognata

Nuclear Astrophysics: Recent results on CNO-cycle reactions and AGB nucleosynthesis

IFAE2011 Incontri di Fisica delle Alte Energie
April 27-29, 2011, Perugia

1. Introduction



SOlar and Heliospheric Observatory (SOHO)

Life on Earth depends on nuclear processes deep inside the Sun

How do other stars produce energy? How do they evolve?

Fusion of H to He:

Bethe & Critchfield (1938)
[pp chains]
Bethe 1939; von Weizsaecker 1938
[CNO cycle]

Nobel prize to Hans Bethe (1967)

Accurate nuclear physics information is crucial for understanding of stars

Sun did not produce elements found on Earth…

Supernova 1994D in galaxy NGC 4526

Credit: NASA/ESA

Remnant of Tycho’s supernova

Credit: NASA/CXC

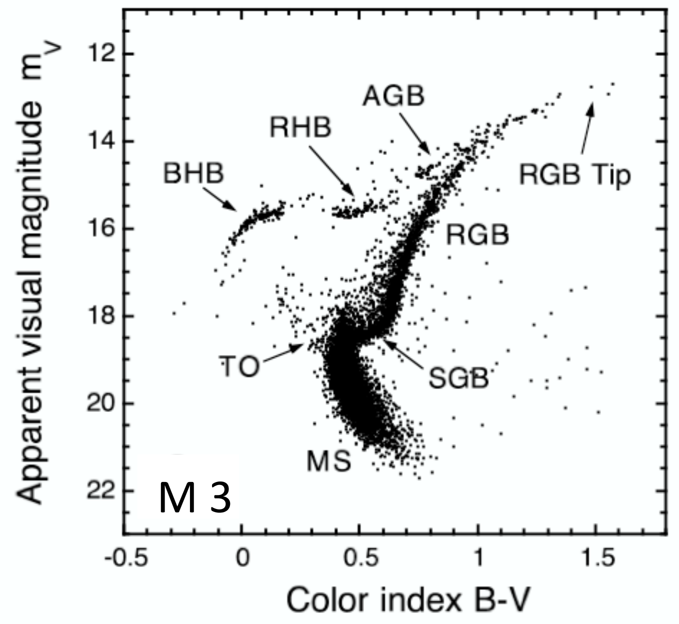
- smaller fraction (approximately 15%) of supernovae are type Ia supernovae
- believed to occur in binary stars: CO white dwarf + other star
- high mass accretion onto white dwarf surface (to avoid classical nova!)
- white mass grows to near Chandrasekhar limit ($1.4M_{sol}$)
- carbon ignites under degenerate conditions (thermonuclear runaway)
- nuclear energy release disrupts white dwarf, no remnant left behind
- nucleosynthesis in hottest zone: produces mainly ^{56}Ni via NSE at low neutron excess
- outer regions attain smaller temperatures: explosive Si and O burning

Globular cluster M 10

Red giant stars:
H→He via CNO cycles in
H shell surrounding He core
S-process → synthesis of nuclei
beyond the Fe-peak

Horizontal branch stars:
He→C, O in core
H→He in shell

Main sequence stars:
H→He via pp chains in core



Direct and indirect measurements I

Direct measurements:

Straightforward but complicated

✓ Coulomb barrier exponentially suppresses the cross section (E<100 keV)

- → low count rate and low statistics
- → high background and poor signal-to-noise ratio
- → no access to the low energy region

✓ Straggling

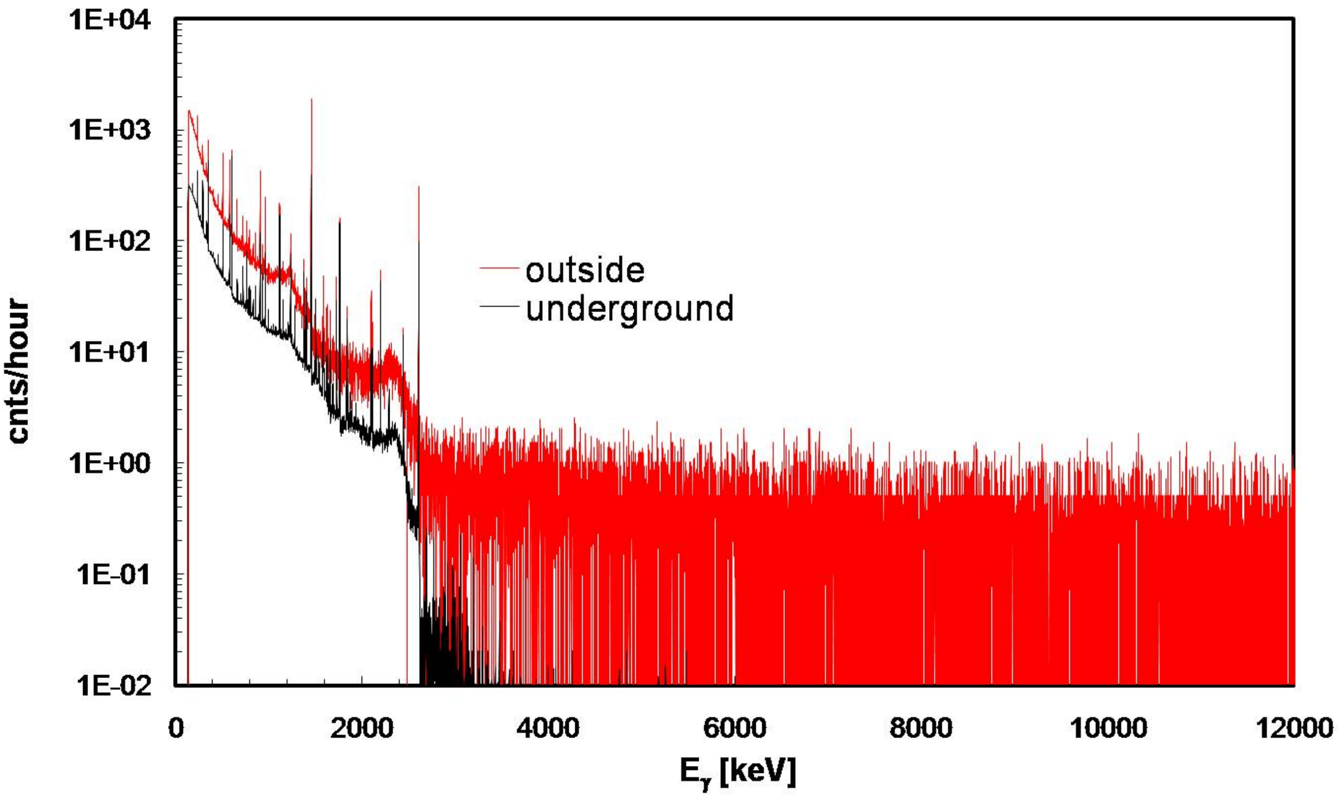
- → possible errors in energy calibration
- → poor energy and angular resolution

✓ Electron screening

- → trend of the bare-nucleus S-factor altered
- → systematic error due to poor knowledge of the process

... even in the few cases when the low-energy S-factor has been measured the bare-nucleus S-factor has not being determined accurately

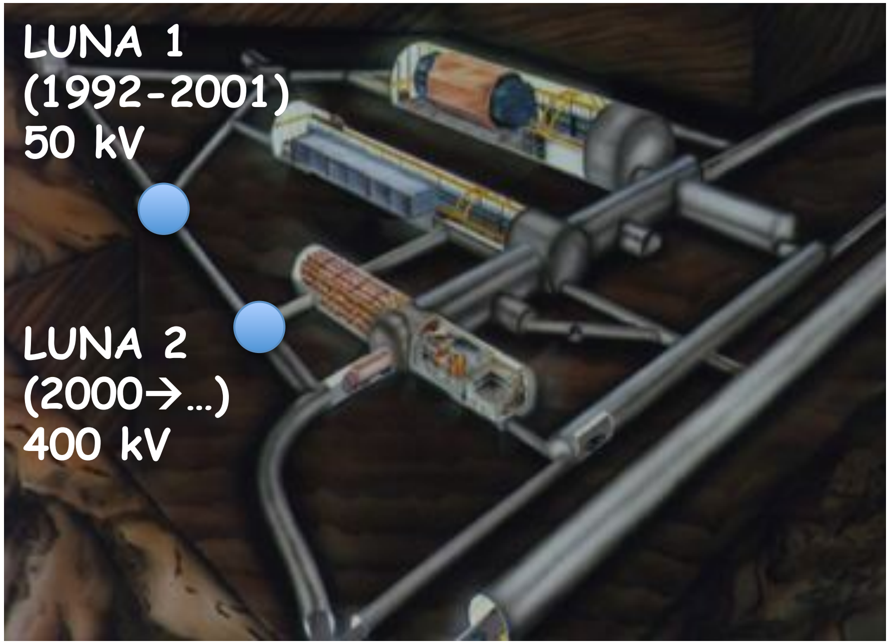
Why underground laboratories



Therefore, the advantage of an underground environment is evident for high Q-value reactions such as $d(p,\gamma)^3He$, $^{14}N(p,\gamma)^{15}O$, $^{15}N(p,\gamma)^{16}O$, $^{25}Mg(p,\gamma)^{26}Al$...

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

The LUNA experiment: an example



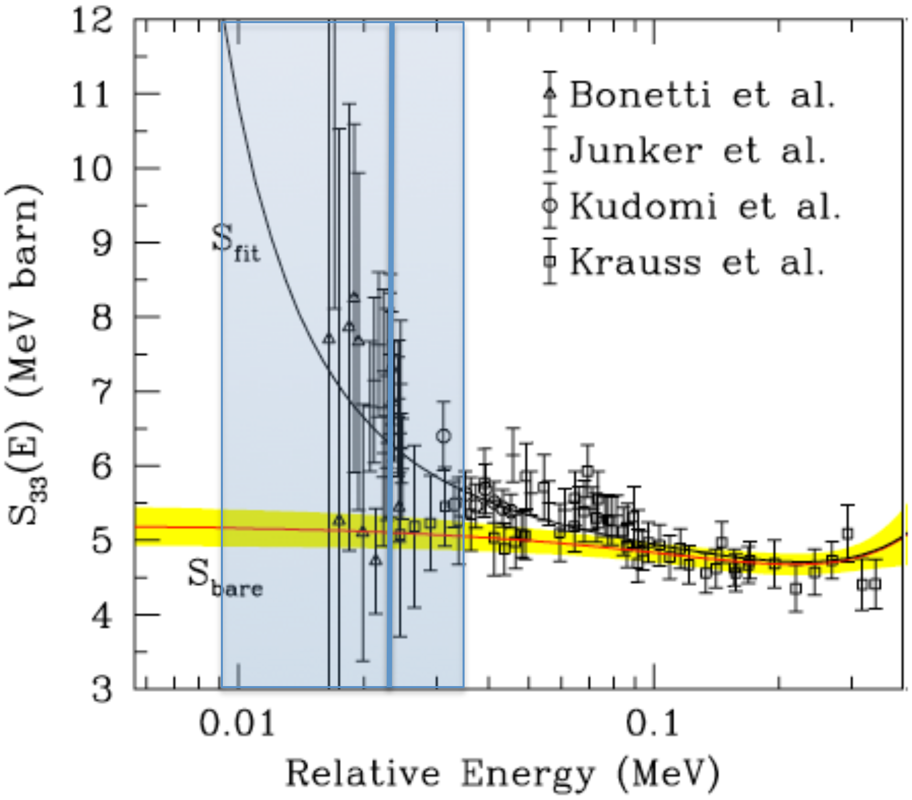
$^3He+^3He \rightarrow 2p+^4He$

First measurement spanning the astrophysical energy range, namely the **Gamow peak**

E_G=9-34 keV

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

Astrophysical factor: useful for more accurate extrapolation

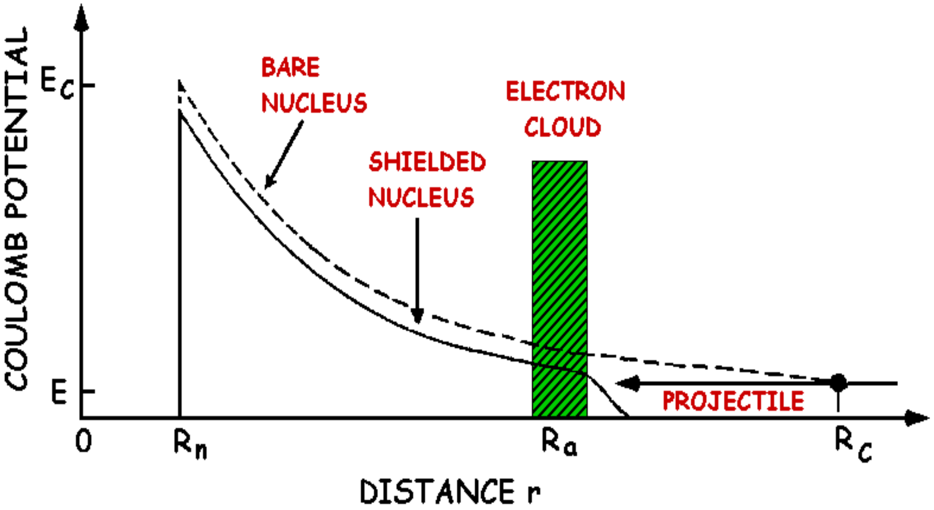


The electron screening effect.

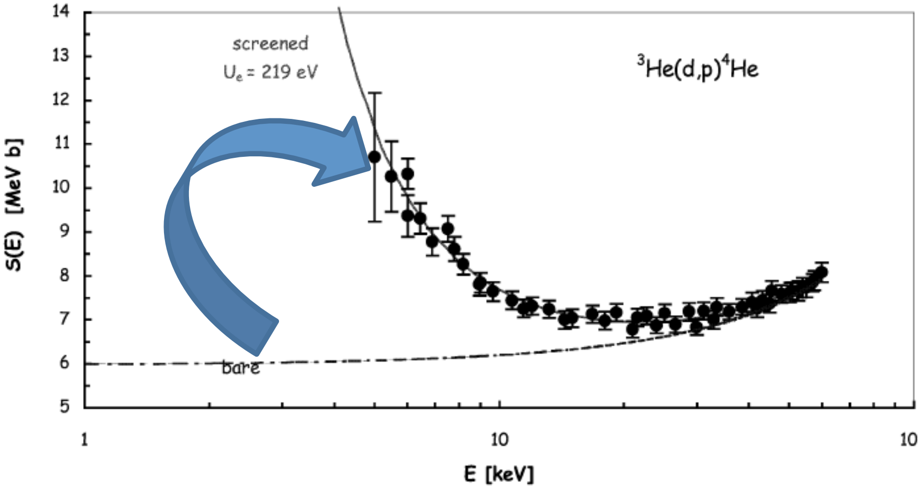
Thanks to recent experimental developments, measurements have been extended to the energies of interest for several reactions.

This lead to the discovery of electron screening: a such low energies atomic degrees of freedom cannot be neglected.

Pictorial view:



Experimentally:



The electron cloud shields the nuclear charge thus the projectile meets a reduced Coulomb barrier → enhancement of the reaction probability as tunneling is more likely.

Exponential enhancement!

$$\sigma_s(E)/\sigma_b(E) \propto \exp(\pi\eta U_e/E),$$

Direct and indirect measurements II

Indirect measurements:

Complicated but rewarding

✓ High energy experiments: up to several hundreds MeV

→ no Coulomb barrier suppression

→ negligible straggling

→ no electron screening

Indirect measurements are the only ones allowing you to measure down to astrophysical energies with the present day facilities

Nuclear reaction theory required

→ cross checks of the methods needed

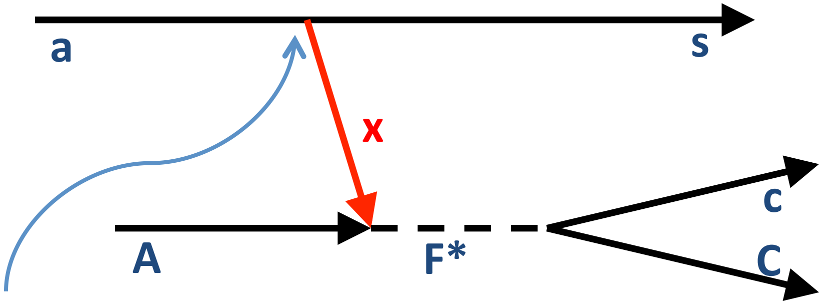
→ possible spurious contribution

→ additional systematic errors (is the result model independent?)

... Indirect techniques are complementary to direct measurements
Examples: Coulomb dissociation, ANC and Trojan horse method

The Trojan horse method for resonant reactions

In the "Trojan Horse Method" (THM) the astrophysically relevant reaction, in particular A(x,c)C, is studied through the 2→3 direct process → A(a,cC)s:



Upper vertex: direct *a* breakup

The process is a transfer to the continuum where x is the transferred particle, e.g. a proton or an alpha particle

Standard R-Matrix approach cannot be applied to extract the resonance parameters of the A(x,c)C reaction because x is virtual → Modified R-Matrix is introduced instead

In the case of a resonant THM reaction the cross section takes the form

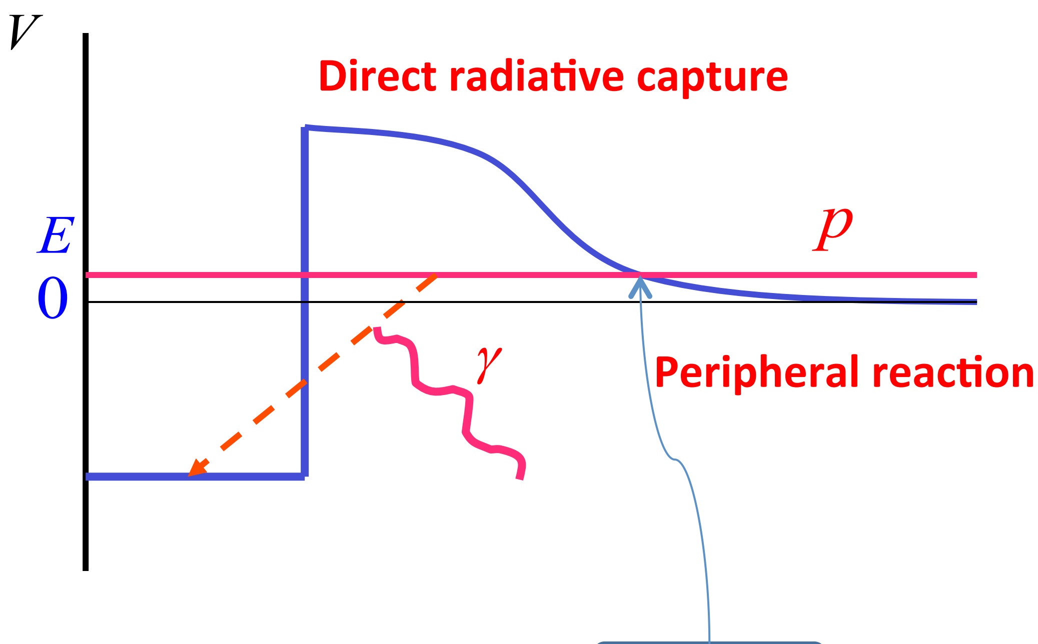
$$\frac{d^2\sigma}{dE_{Cc}\,d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E)\,|M_i(E)|^2}{(E-E_{R_i})^2+\Gamma_i^2(E)/4}$$

$M_i(E)$ is the amplitude of the transfer reaction (upper vertex) e.g. from FRESCO
→ The resonance parameters can be extracted and in particular the strength

Asymptotic Normalization Coefficient (ANC)

Radiative *p* (α) capture at stellar energies

- Classical **barrier penetration** problem



Direct radiative capture

Peripheral reaction

- **low energies** ⇒ **capture at large radii**
- **very small cross sections**

The cross section is determined by ANCs

$$\sigma \propto |M|^2$$

$$M = \left\langle I^{A}_{Bp}(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

$$I^{A}_{Bp}(r_{Bp}) \overset{r_B > R_N}{\approx} C^{A}_{Bp} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

ANC ⇒ amplitude for tail of overlap function

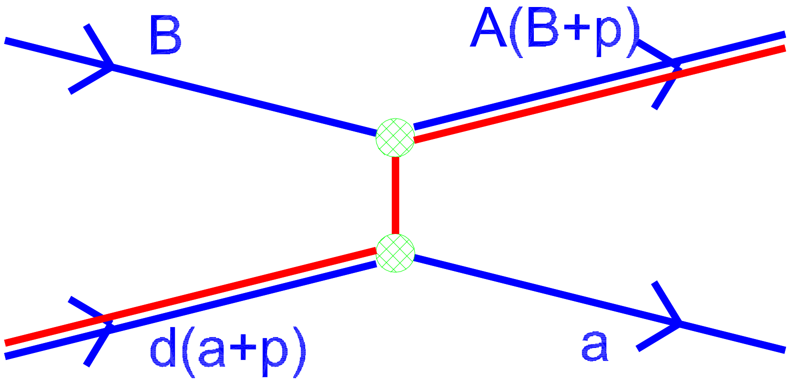
$$\sigma_{capture} \propto (C^{A}_{Bp})^2$$

ANCs determine the capture cross section at low energies.

How can we measure them?

Where do we get the ANCs from?

Transfer reactions

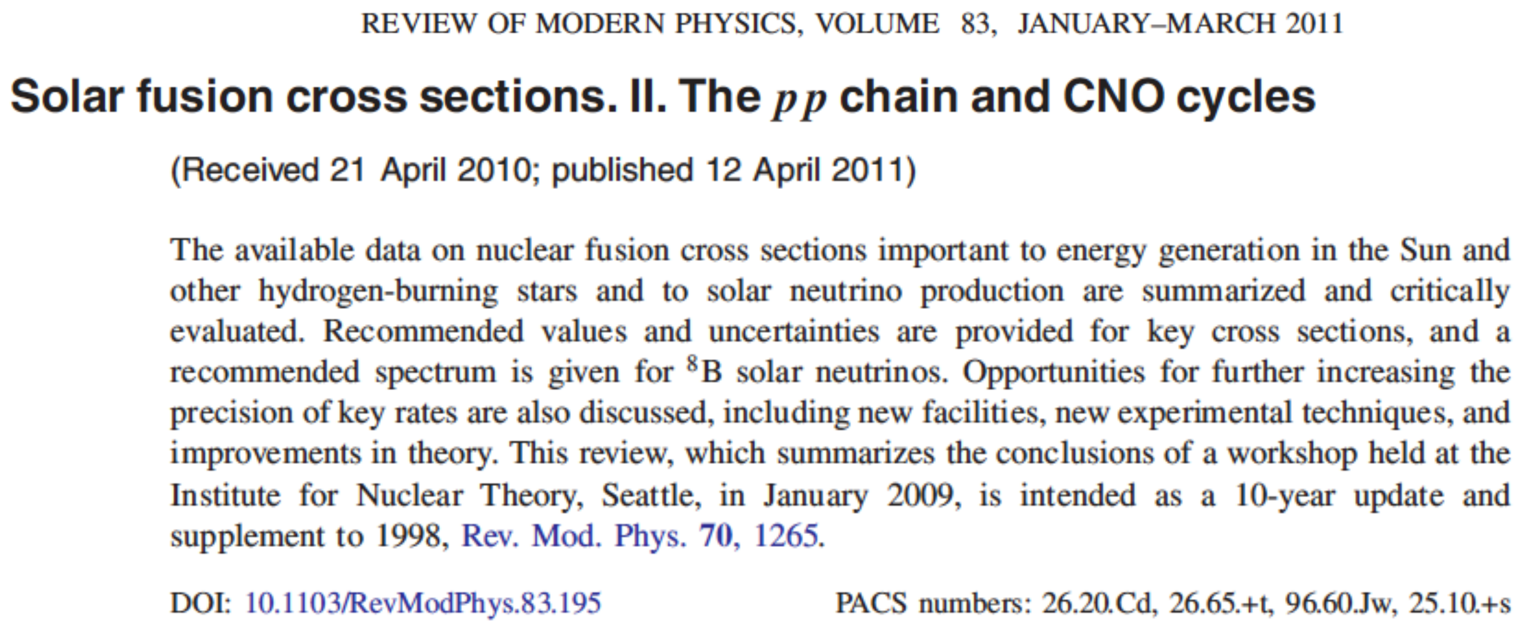


Transition amplitude: $$M = \sum \left\langle \chi_f^{(-)} I_{Bp}^{A} \middle| \Delta V \middle| I_{ap}^{d} \chi_i^{(+)} \right\rangle$$

Peripheral transfer: $$I_{Bp}^{A} \overset{r_{Bp} > R_N}{\approx} C_{Bp}^{A} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

$$\frac{d\sigma}{d\Omega} = (C^{A}_{Bpl_A j_A})^2 (C^{d}_{apl_d j_d})^2 \frac{\sigma^{DW}_{l_A j_A l_d j_d}}{b^2_{Bpl_A j_A} \, b^2_{apl_d j_d}}$$

The transfer cross section is proportional to the needed ANCs
→ From a measurement @ several tens of MeV one can get the zero energy S-factor for a radiative capture reaction



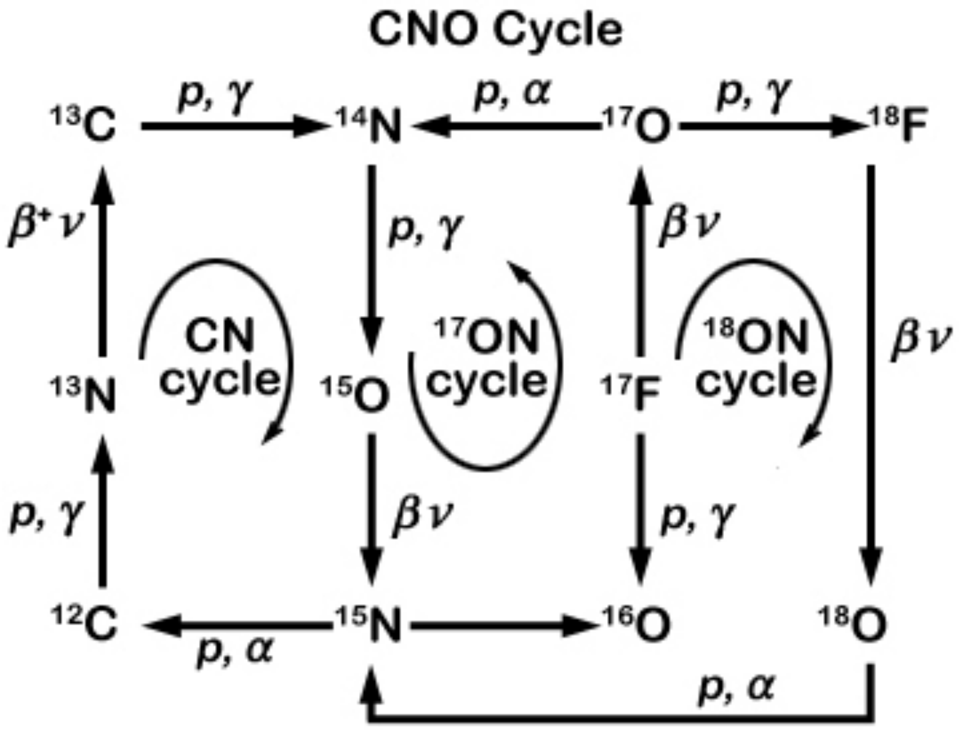
REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

Solar fusion cross sections. II. The *pp* chain and CNO cycles

(Received 21 April 2010; published 12 April 2011)

The available data on nuclear fusion cross sections important to energy generation in the Sun and other hydrogen-burning stars and to solar neutrino production are summarized and critically evaluated. Recommended values and uncertainties are provided for key cross sections, and a recommended spectrum is given for ^{8}B solar neutrinos. Opportunities for further increasing the precision of key rates are also discussed, including new facilities, new experimental techniques, and improvements in theory. This review, which summarizes the conclusions of a workshop held at the Institute for Nuclear Theory, Seattle, in January 2009, is intended as a 10-year update and supplement to 1998, Rev. Mod. Phys. 70, 1265.

DOI: 10.1103/RevModPhys.83.195 PACS numbers: 26.20.Cd, 26.65.+t, 96.60.Jw, 25.10.+s



CNO Cycle

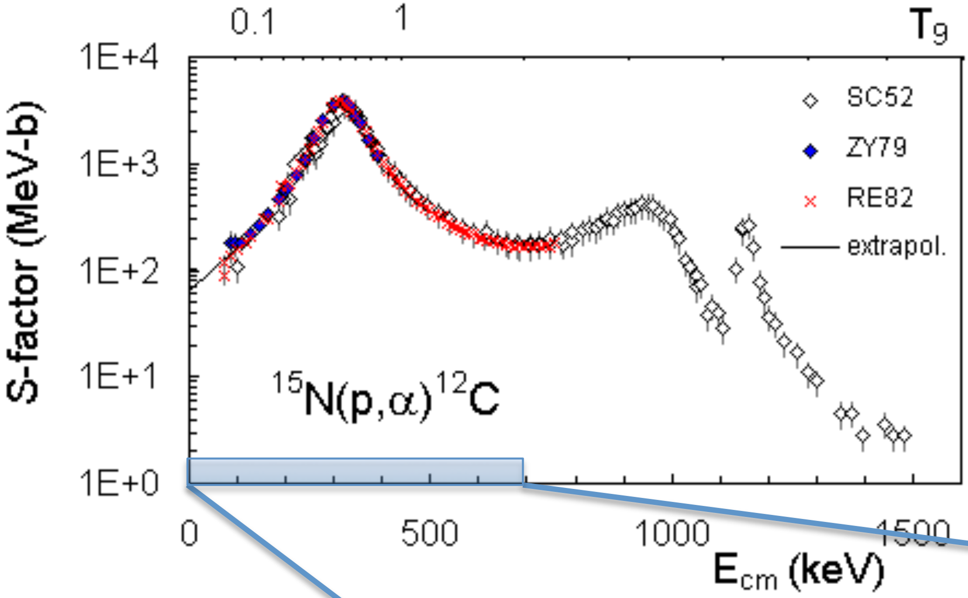
In the following, we will focus on recents results on nuclear reactions forming the CNO cycle

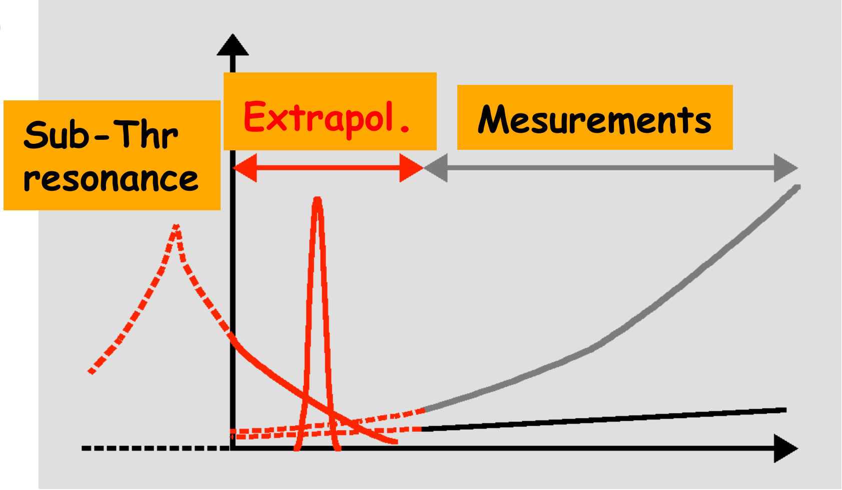
- → H-burning in the core of main-sequence massive stars
- → Nucleosynthesis at the bottom of the convection envelope (cool bottom process)

The $^{15}N(p,\alpha)^{12}C$ reaction

Gamow window: 13-40 keV
Direct data stop at 70 keV

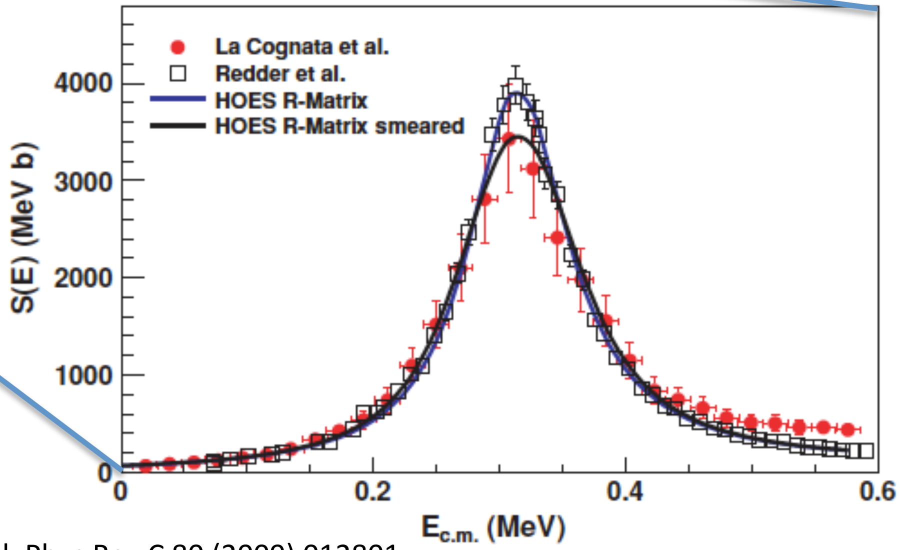
Angulo et al, Nucl Phys A656 (1999) 3





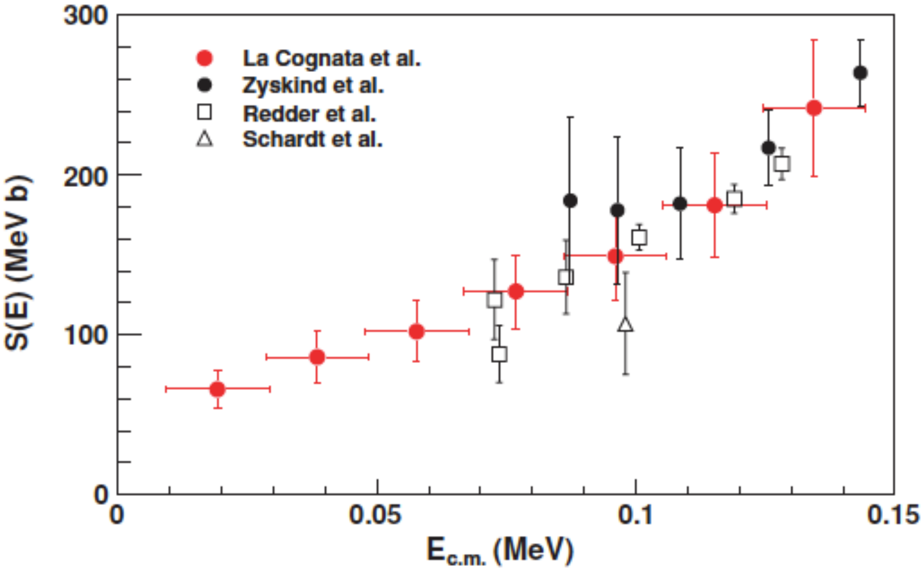
Two effects have to be taken into account:

1. **Energy resolution broadening experimental resonances**
2. **Non quasi-free effects at higher energies introducing spurious contributions not present in direct data**



La Cognata et al, Phys Rev C 80 (2009) 012801

The $^{15}N(p,\alpha)^{12}C$ reaction



Gamow window: 13-40 keV
Direct data stop at 70 keV

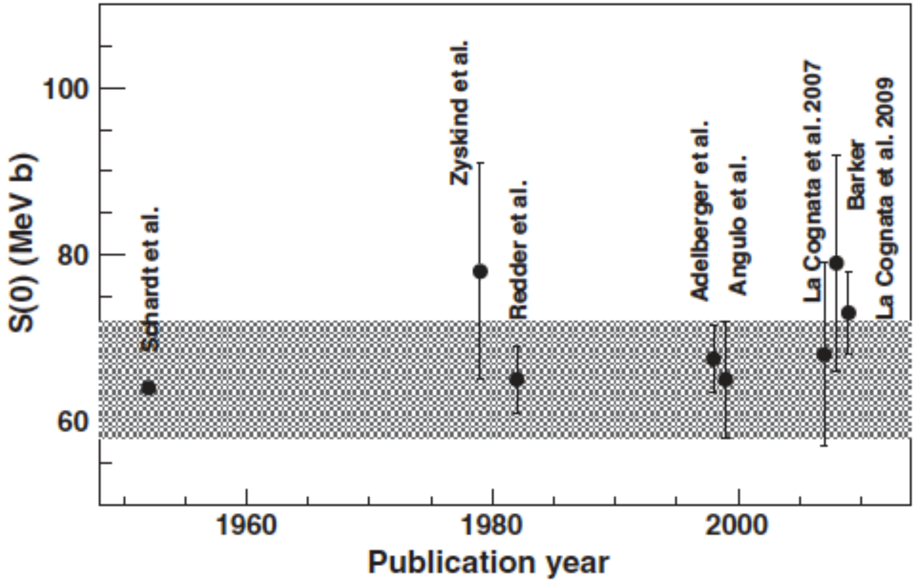
→ The cross section at 20 keV is about 10^{-10} times smaller than at 70 keV so there is no way to measure the cross section inside the Gamow window

La Cognata et al, Phys Rev C 80 (2009) 012801

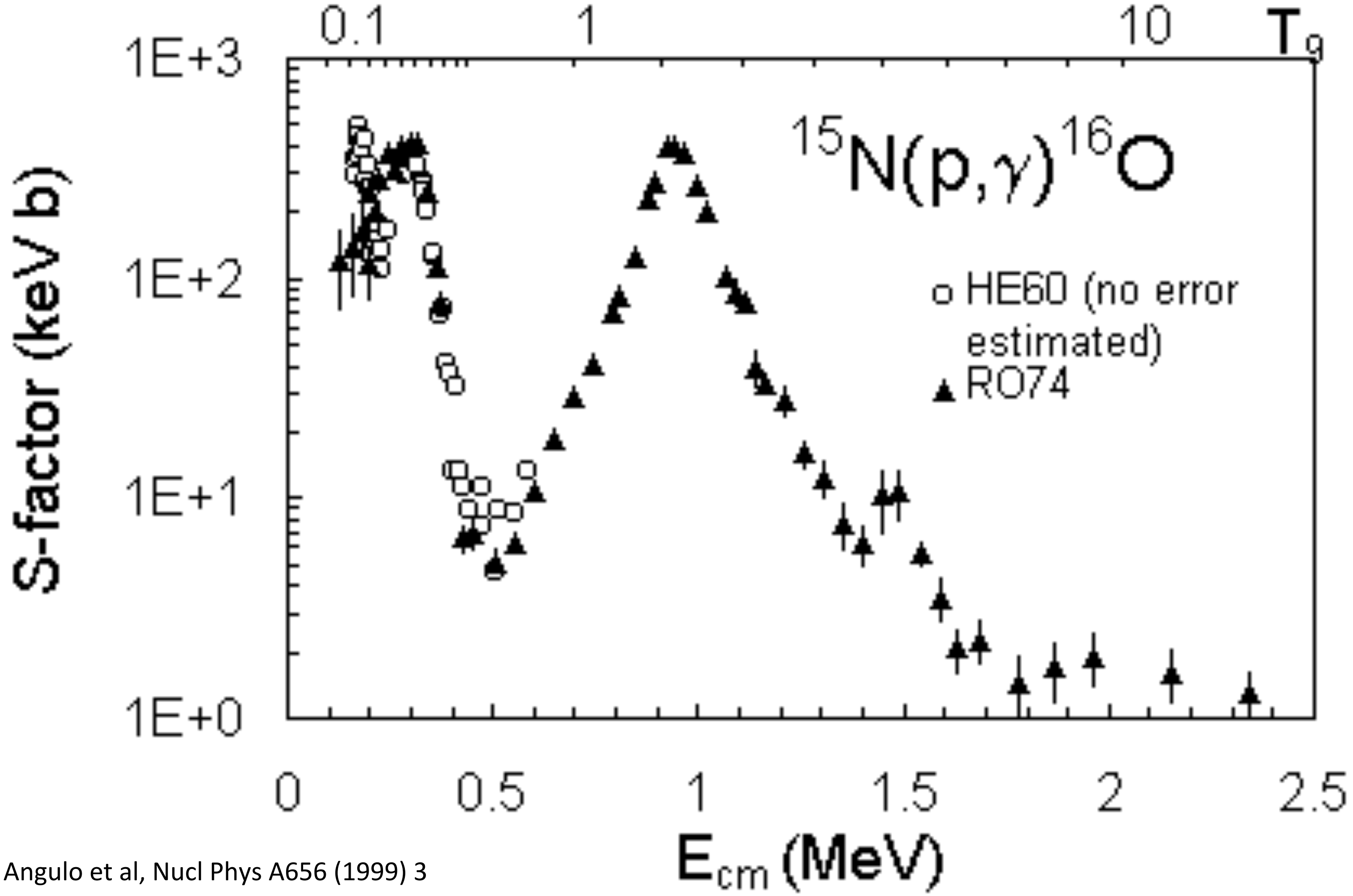
Summary of the available measurements of S(0) showing values as originally reported on the dates indicated.

The shaded band corresponds to the NACRE compilation (Angulo et al., 1999).

The result from indirect measurements is slightly larger than given in compilations

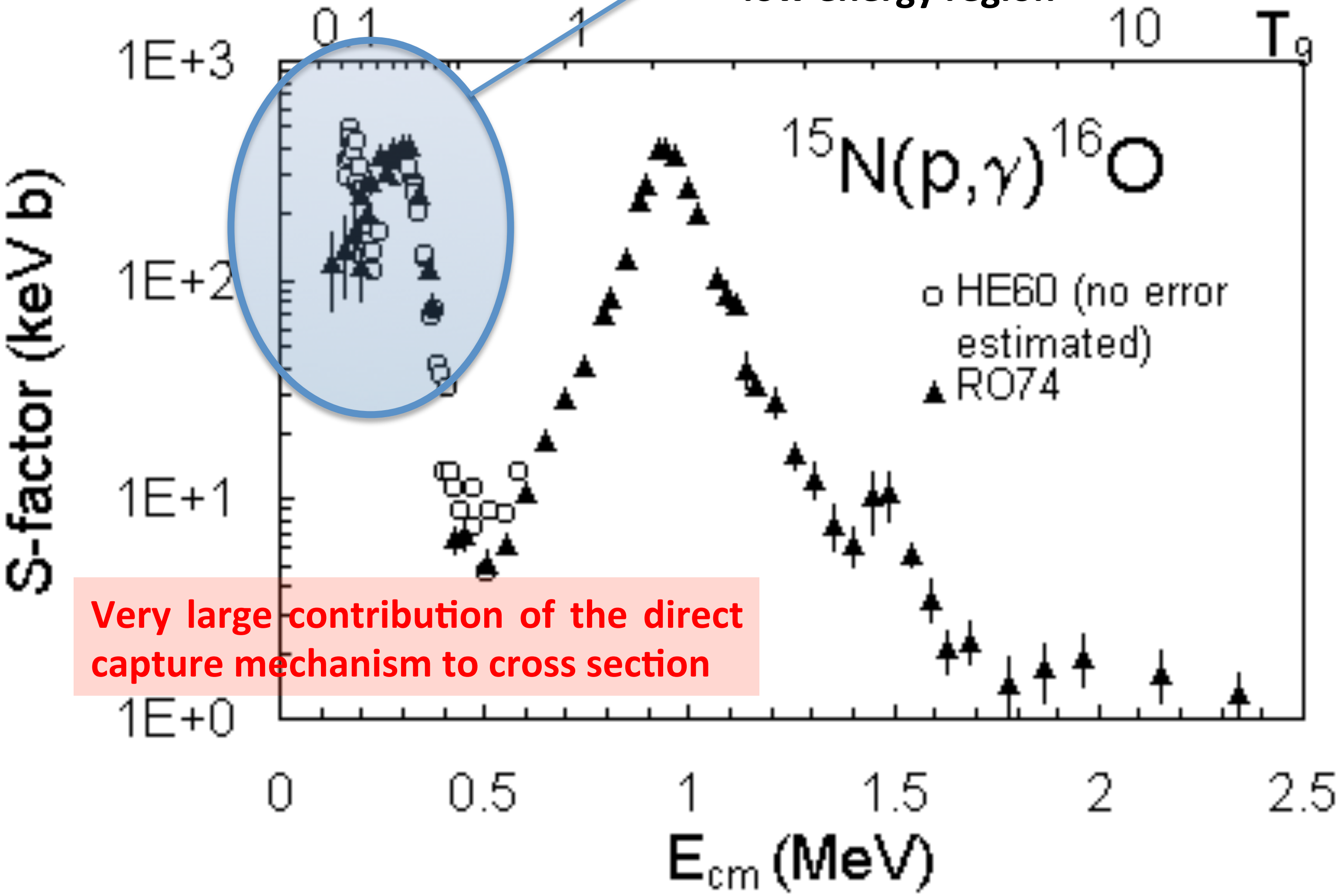


The $^{15}N(p,\gamma)^{16}O$ reaction: Current status



Angulo et al, Nucl Phys A656 (1999) 3

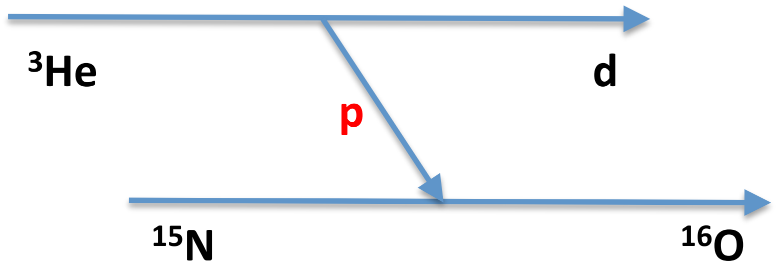
The $^{15}N(p,\gamma)^{16}O$ reaction:
Current status



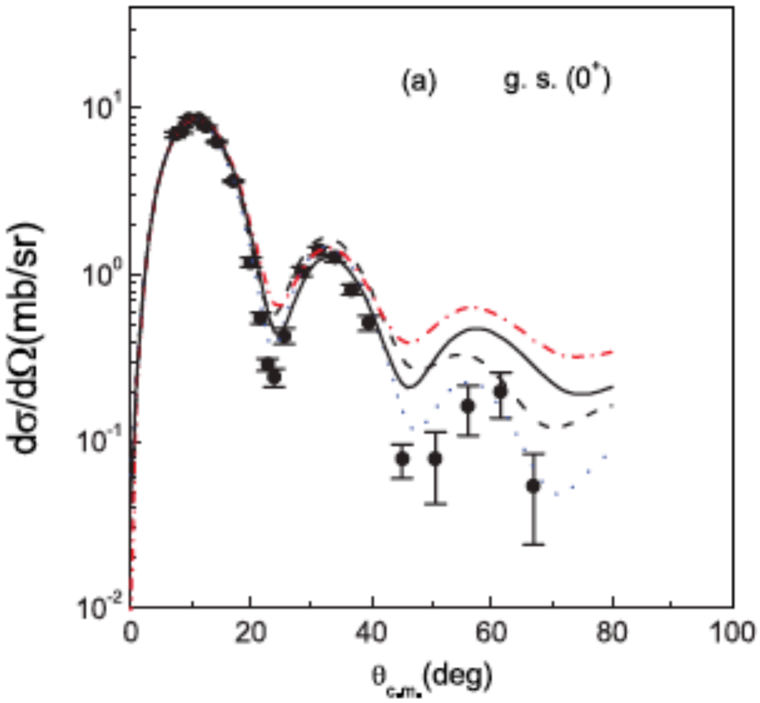
Very poor understanding of the low energy region

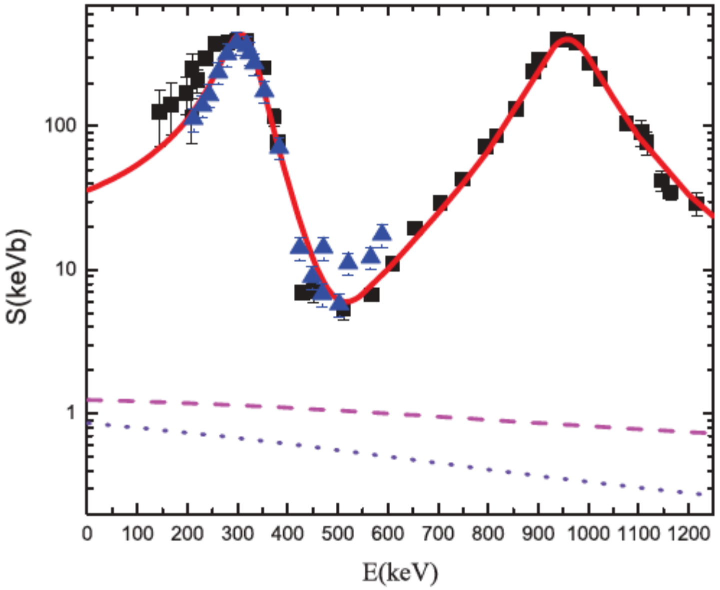
Very large contribution of the direct capture mechanism to cross section

The $^{15}N(p,\gamma)^{16}O$ reaction: Indirect measurement through ANC



From the measurement of the angular distributions for the $^{15}N(^{3}He,d)^{16}O$ reaction the ANC for the the $^{16}O \rightarrow p+^{15}N$ system can be deduced fixing the direct contribution to the total cross section

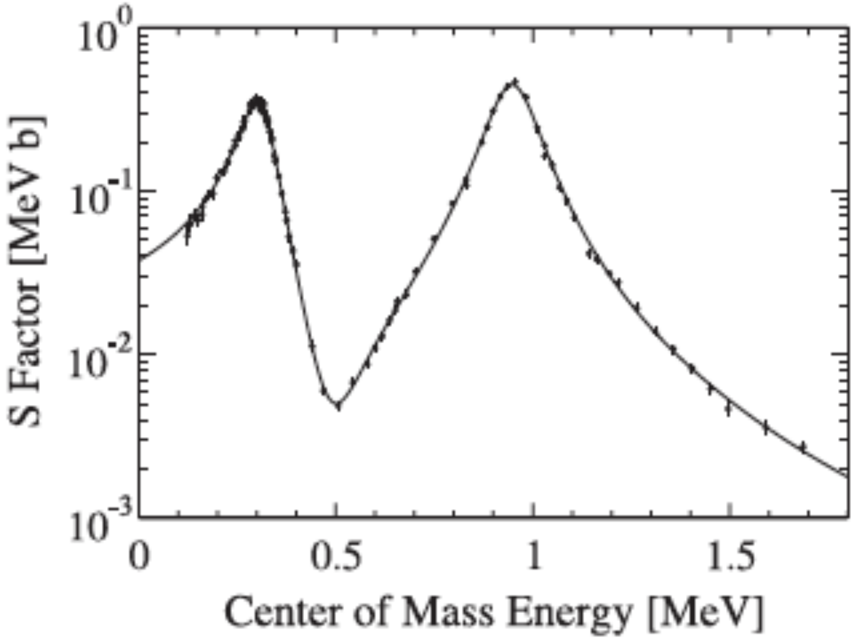


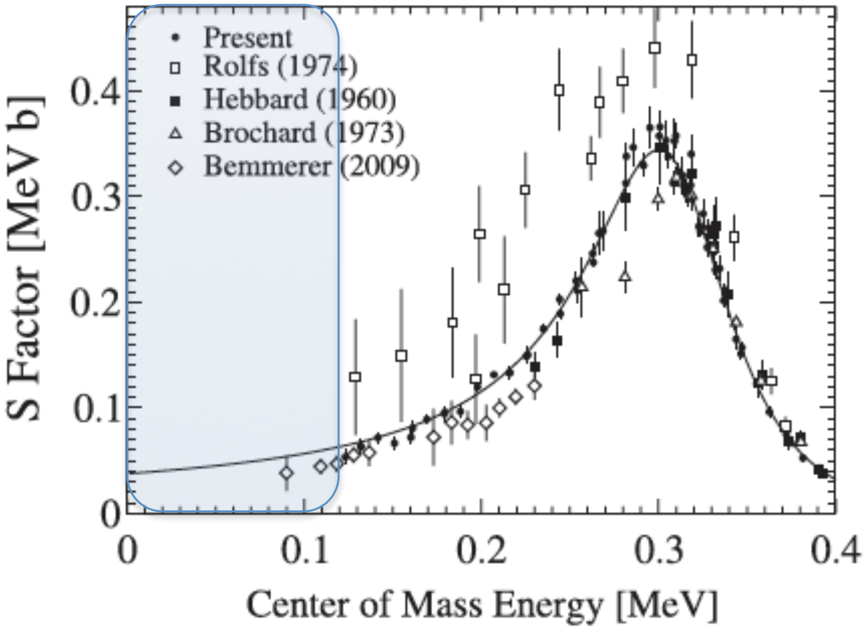


Mukhamedzhanov et al, Phys Rev C 78 (2008) 015804

The $^{15}N(p,\gamma)^{16}O$ reaction: Direct measurement

LeBlanc et al, Phys Rev C 82 (2010) 055804





High accuracy data used to perform R-matrix fitting to extrapolate the astrophysical S(E) factor down to the energies of interest

The Gamow window is not covered by the direct data stopping well above 100 keV

THE EXTRAPOLATION OF DIRECT DATA CONFIRMS THE RESULTS OF THE INDIRECT MEASUREMENT

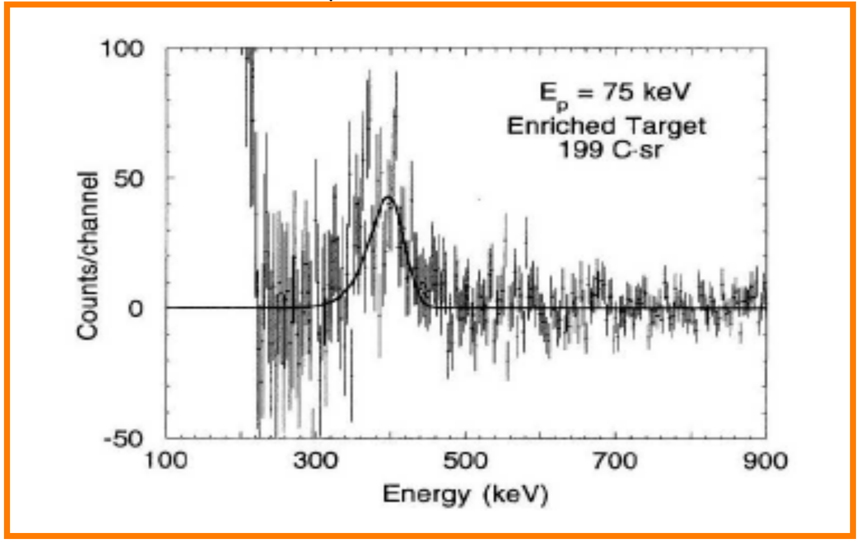
The ^{17}O(p,α)^{14}N reaction

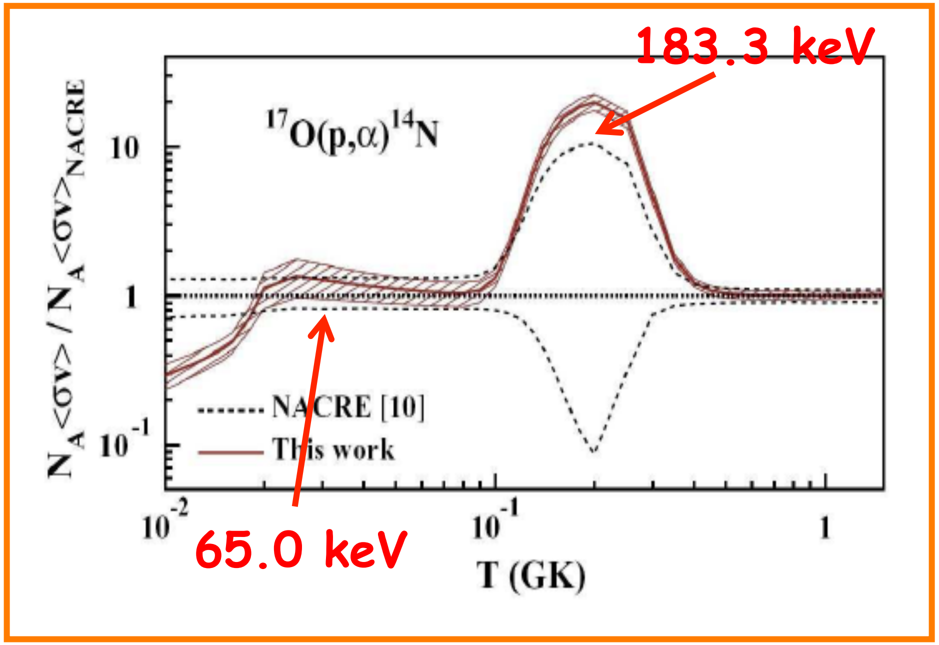
Summary of the current status

The first direct measurement of the ^{17}O(p,α)^{14}N at low energy

LARGE UNCERTAINTIES !!

J.C. Blackmon et al., Phys. Rev. Lett. 74, 2642, (1995)



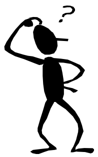


183.3 keV

65.0 keV

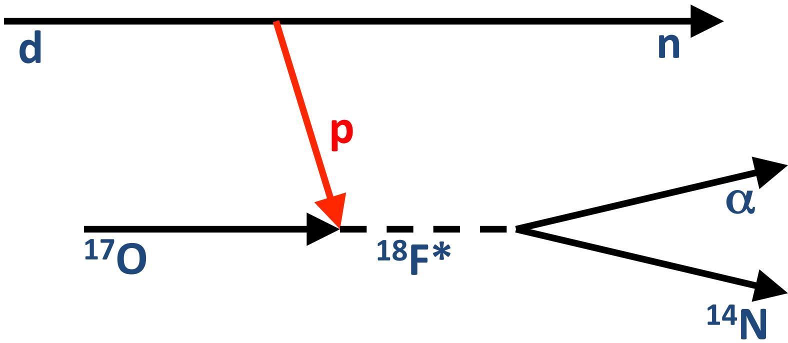
A. Chafa et al., Phys. Rev. C 75, 035810, (2007)

To reduce the uncertainties

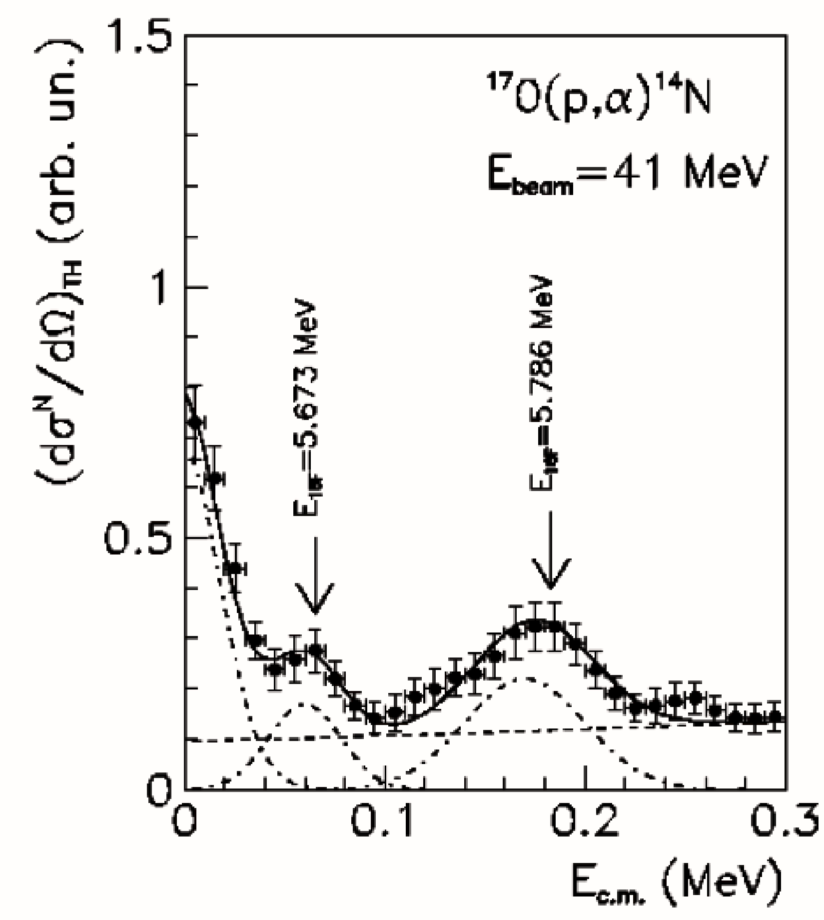


INDIRECT MEASUREMENT

The $^{17}O(p,\alpha)^{14}N$ reaction



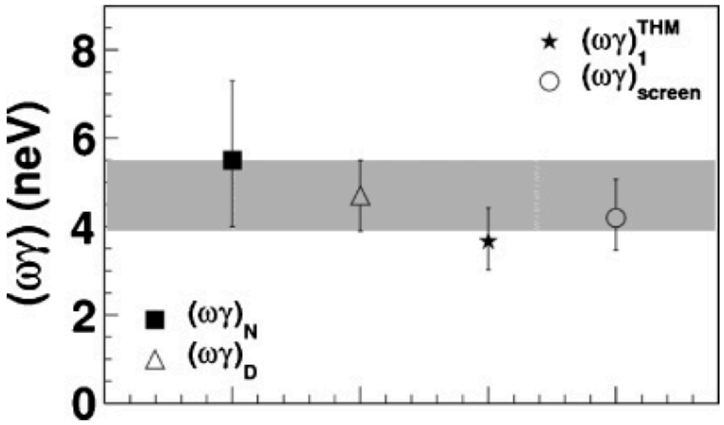
Sergi et al, Phys Rev C 82 (2010) 032801



Extraction of:

✓ **Resonance energies: E_{R1}=65±5 keV and E_{R2}=183±5 keV.**

✓ **Peak value of the two resonances: N_1=0.170±0.025 and N_2=0.220±0.031, used to derive the resonance strengths ωγ (case of narrow resonances).**



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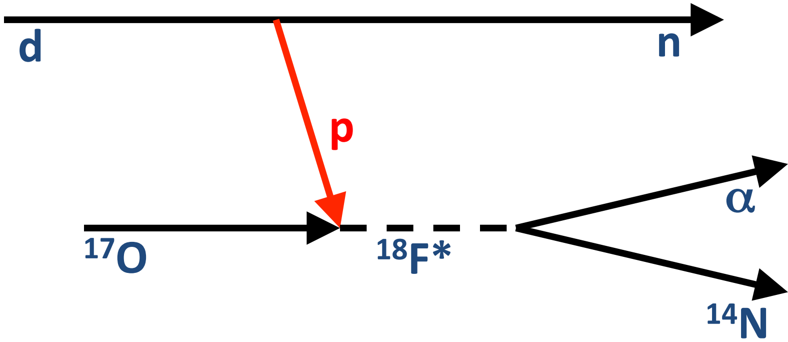

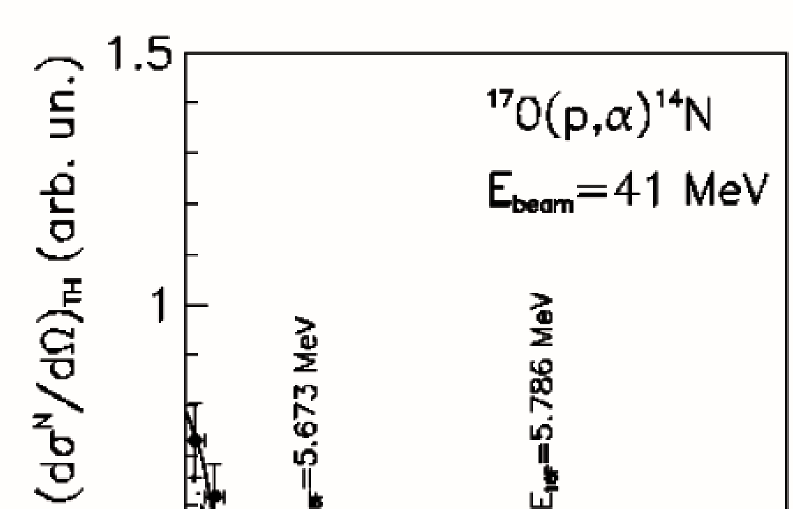

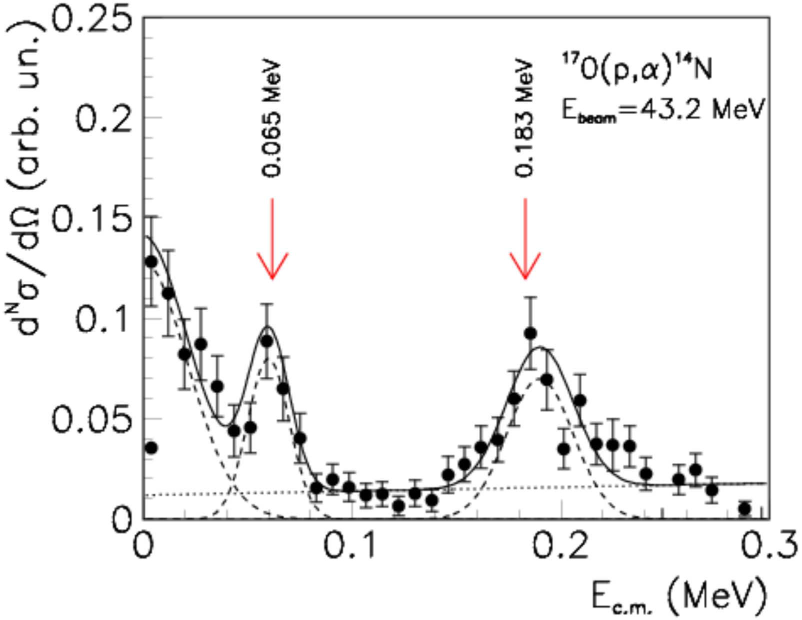

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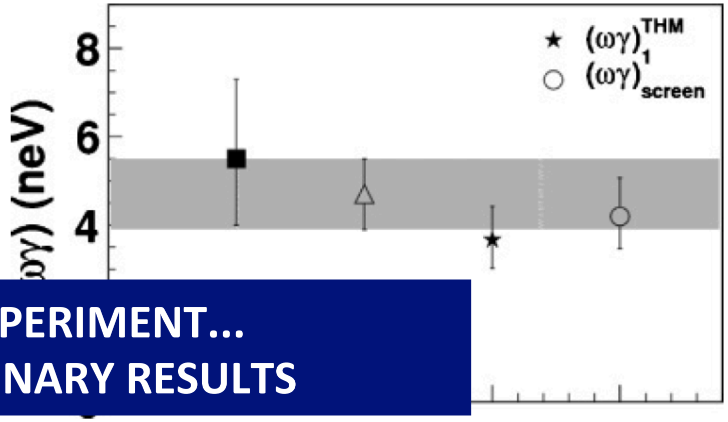
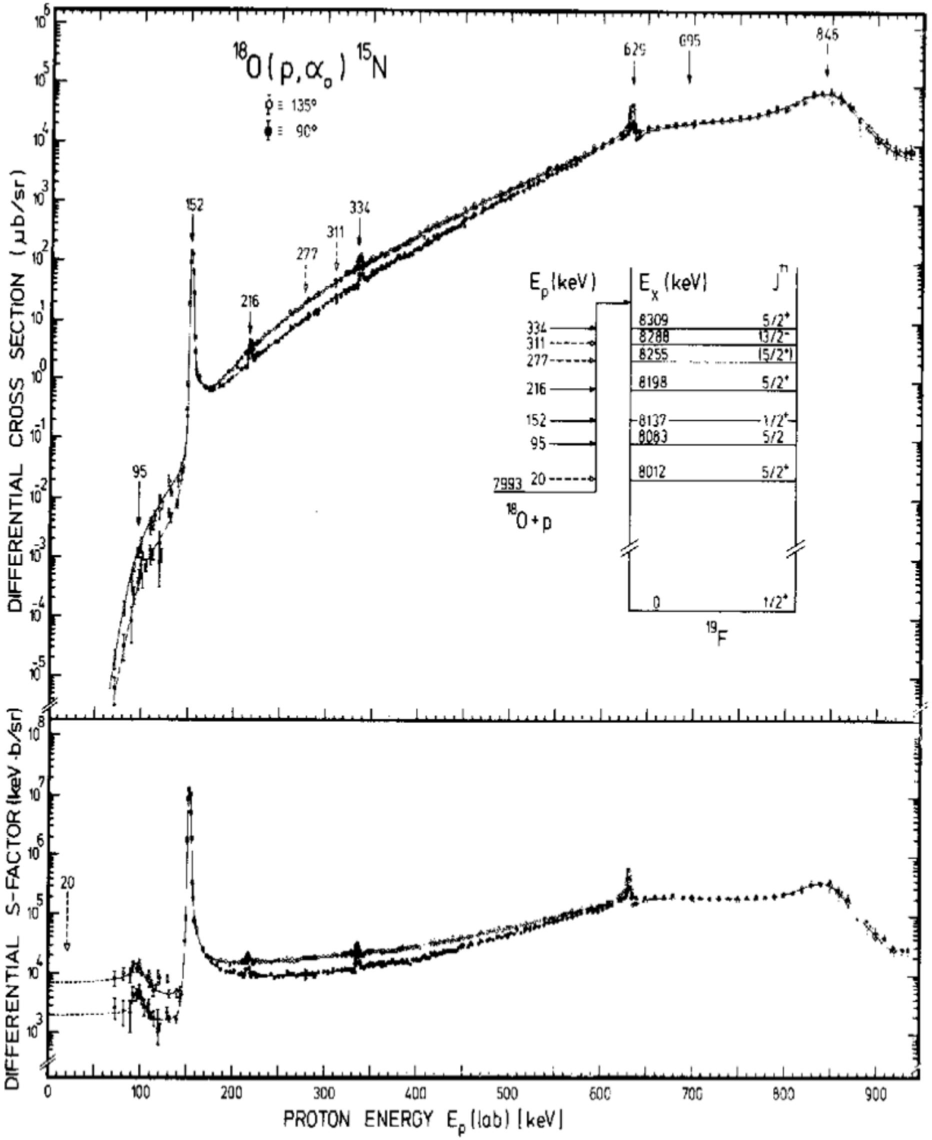


NEW EXPERIMENT...
PRELIMINARY RESULTS

The $^{18}O(p,\alpha)^{15}N$ reaction



~50 resonances in the 0-7 MeV region

The main contribution to the reaction rate is given by the resonances:

1- 20 keV $J^\pi=5/2^+$
2- 144 keV $J^\pi=1/2^+$ (well established)
3- 656 keV $J^\pi=1/2^+$

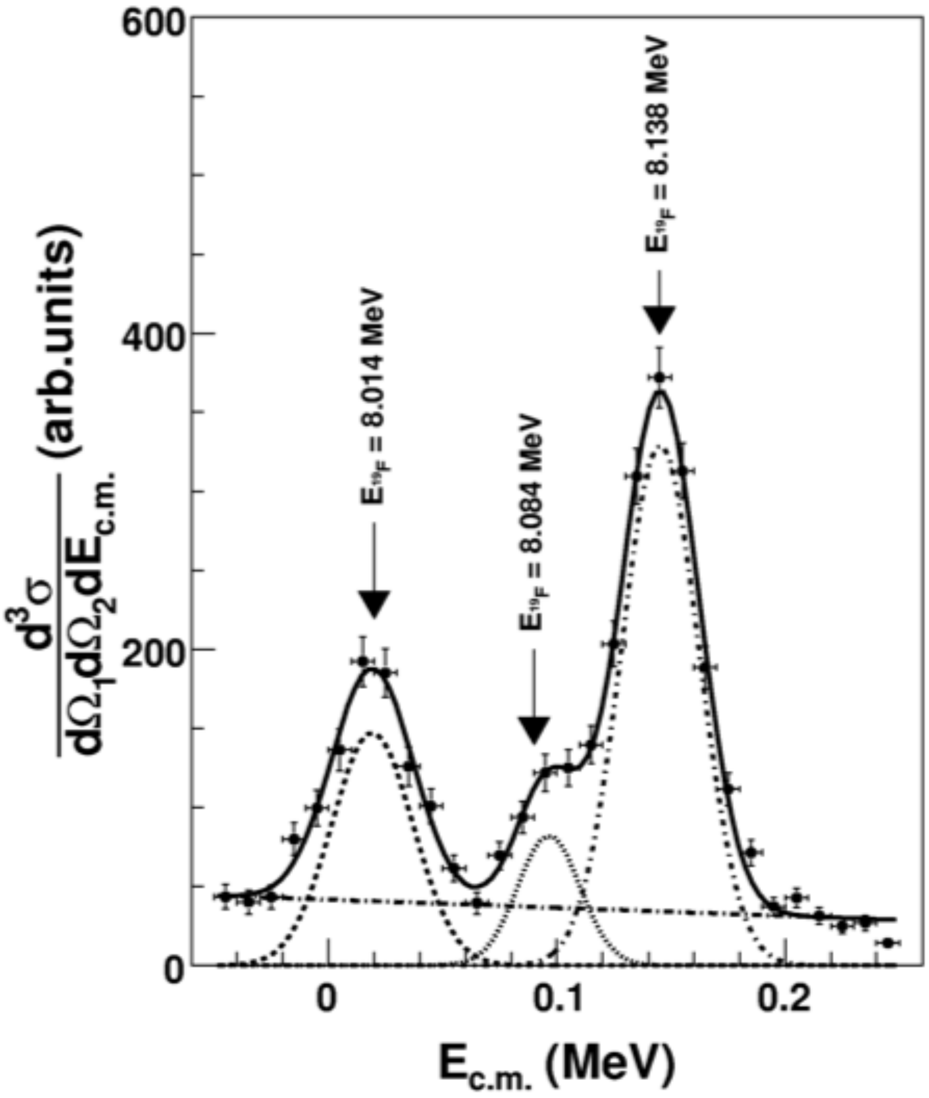
20 keV resonance parameters are deduced from an indirect measurement

The 656 keV resonance provides a significant contribution to the reaction rate both at low and high temperatures. The strength and FWHM of the 656 keV are very uncertain

Subthreshold resonance at 7.9 MeV

Lorentz-Wirzba et al, Nucl. Phys. A313 (1979) 346

The $^{18}O(p,\alpha)^{15}N$ reaction



La Cognata et al, Phys Rev Lett 101 (2008) 152501

Present case: narrow resonances.
THM data are smoothed out because of 17 keV energy spread

The energies and the ωγ parameters are obtained from the fit of the experimental three-body cross section.

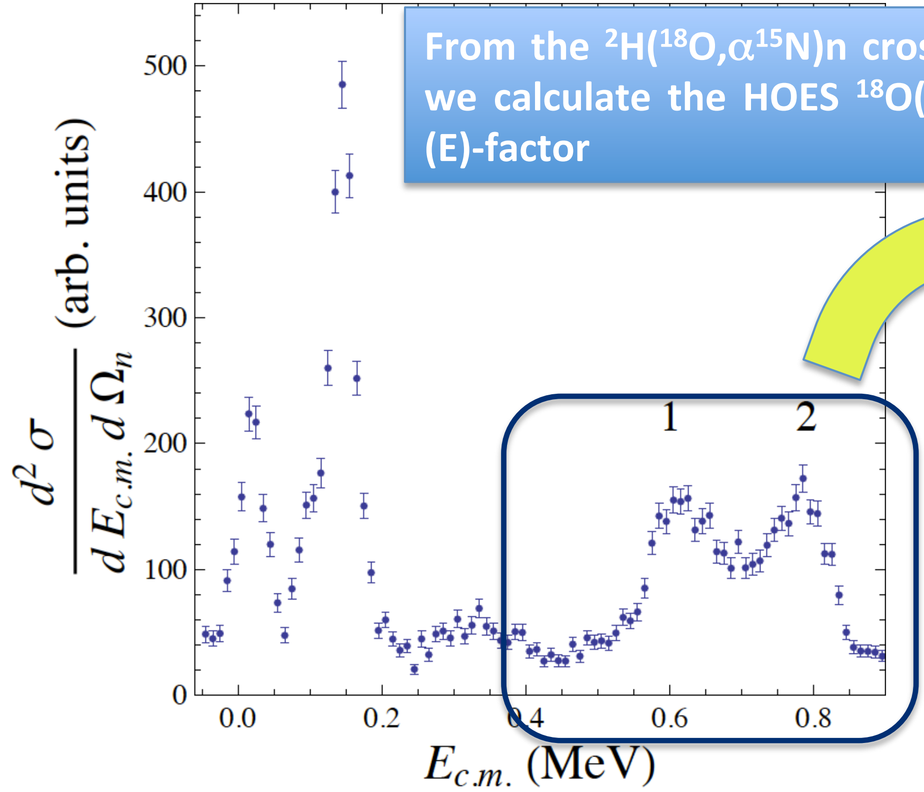
Absolute values are obtained by normalizing to the well known resonance at 144 keV

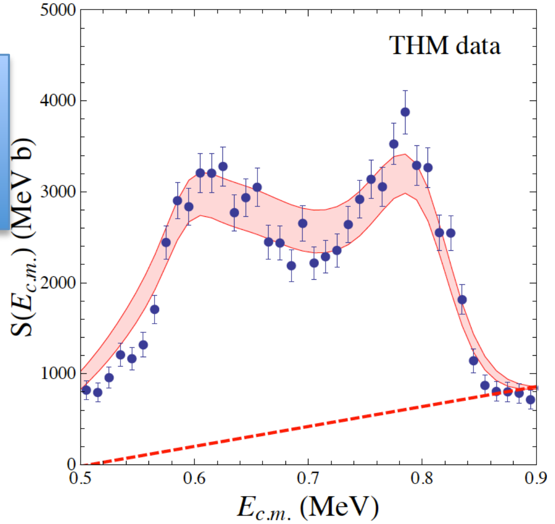
$$(\omega\gamma)_i = \frac{\omega_i}{\omega_3}\frac{\Gamma_{p_i}(E_{R_i})}{|M_i(E_{R_i})|^2}\frac{|M_3(E_{R_3})|^2}{\Gamma_{p_3}(E_{R_3})}\frac{N_i}{N_3}(\omega\gamma)_3.$$

ωγ (eV)	Present work	NACRE
20 keV	$8.3^{+3.8}_{-2.6}\ 10^{-19}$	$6^{+17}_{-5}\ 10^{-19}$
90 keV	$1.8 \pm 0.3\ 10^{-7}$	$1.6 \pm 0.5\ 10^{-7}$

Results and simultaneous R-matrix

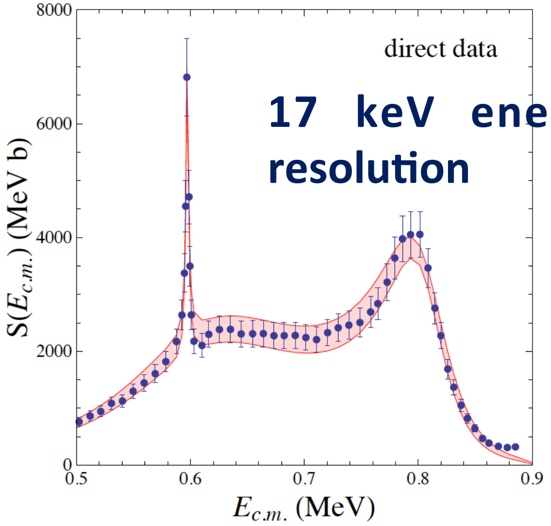
From the ^{2}H(^{18}O,α^{15}N)n cross section we calculate the HOES ^{18}O(p,α)^{15}N S (E)-factor





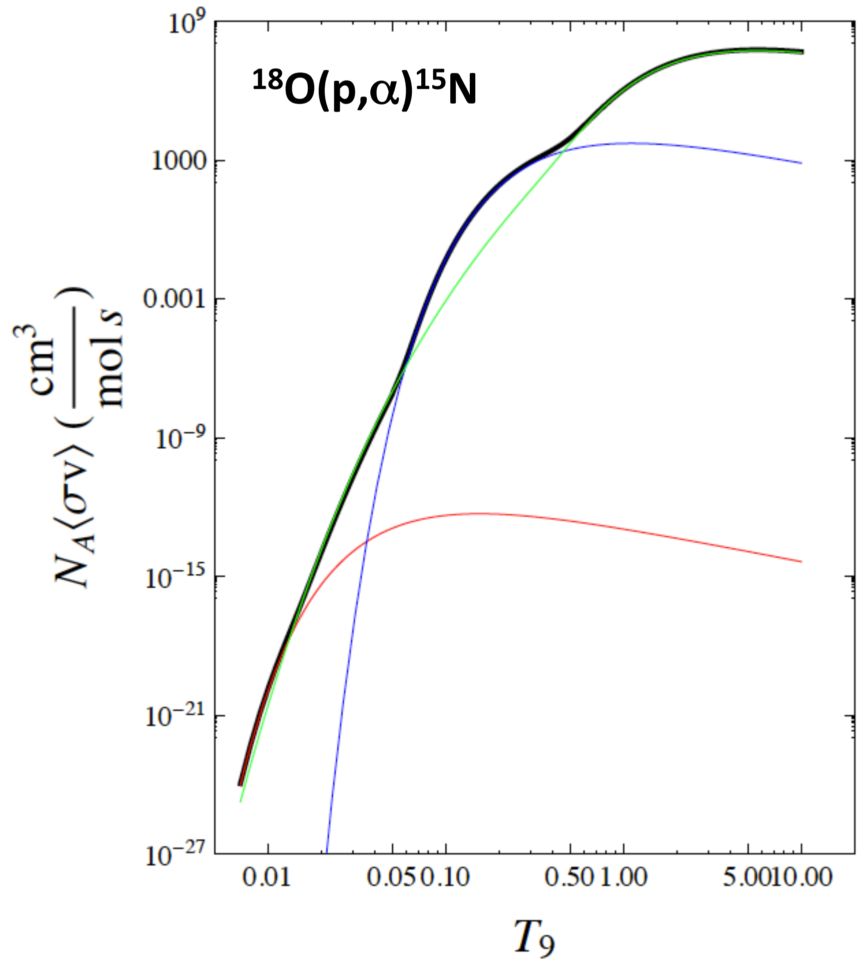
THM 2→3 cross section
1- 656 keV J$^{\pi}$=1/2^{+}
2- 799 keV J$^{\pi}$=1/2^{+}

Strong interference pattern



17 keV energy resolution

The reaction rate: input for astrophysical computations



Thick black line:
Total reaction rate

Thin green line:
656+799 keV contribution

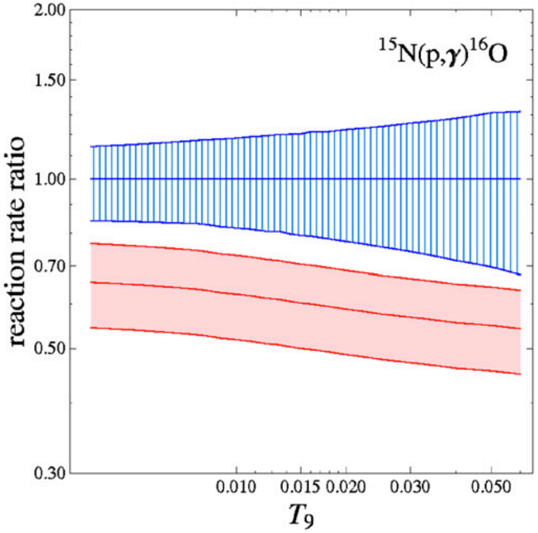
Thin blue line:
145 keV contribution

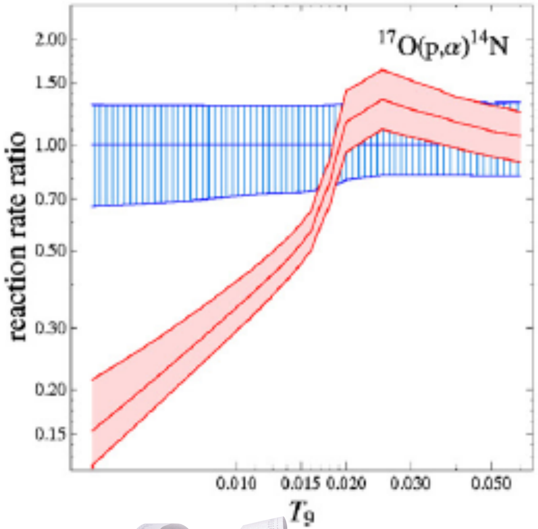
Thin red line:
20 keV contribution

The role of the broad 656 and 799 keV resonances is important both at high and low temperatures

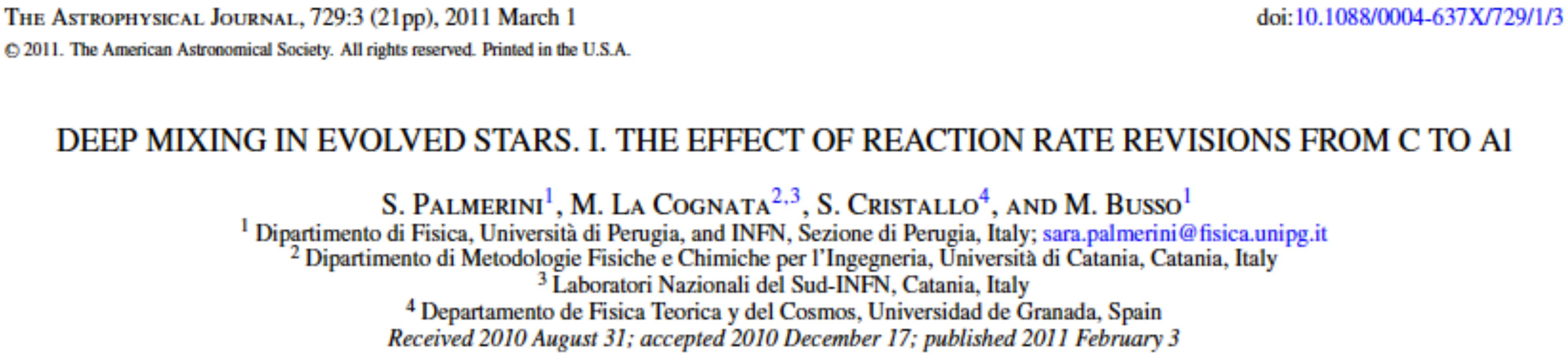
La Cognata et al, Astrophys J 723 (2010) 1512

Nuclear data as an input to astrophysics





Etc. … …



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DEEP MIXING IN EVOLVED STARS. I. THE EFFECT OF REACTION RATE REVISIONS FROM C TO Al

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