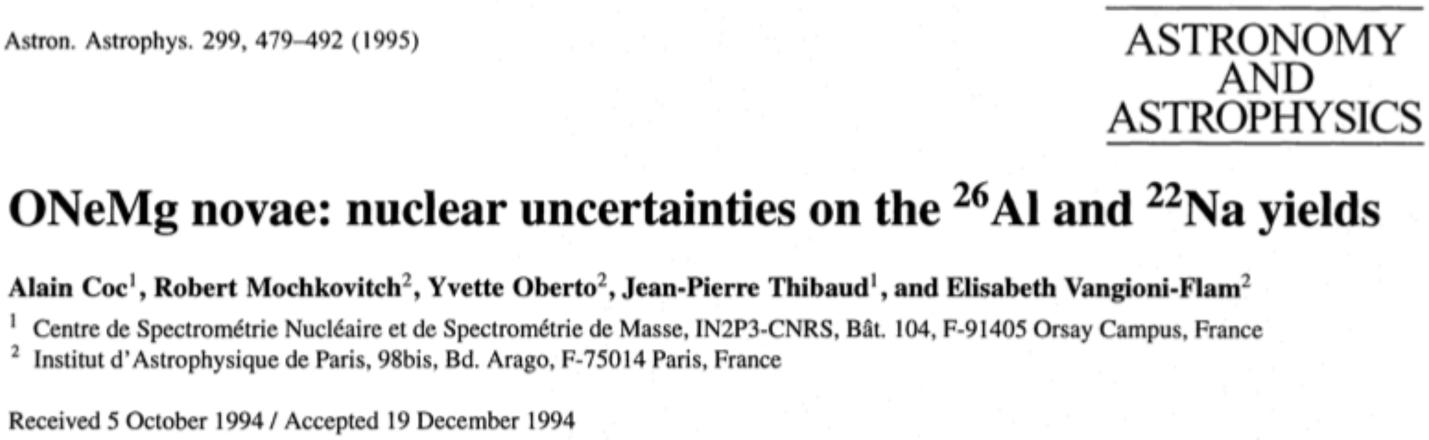
Some nuclear aspects of nova nucleosynthesis

Alain Coc
(**C**entre de **S**ciences **N**ucléaires et de **S**ciences de la **M**atière, Orsay)

Nicolas de Séréville
(**I**nstitut de **P**hysique **N**ucléaires d'Orsay)



Astron. Astrophys. 299, 479–492 (1995)

ASTRONOMY
AND
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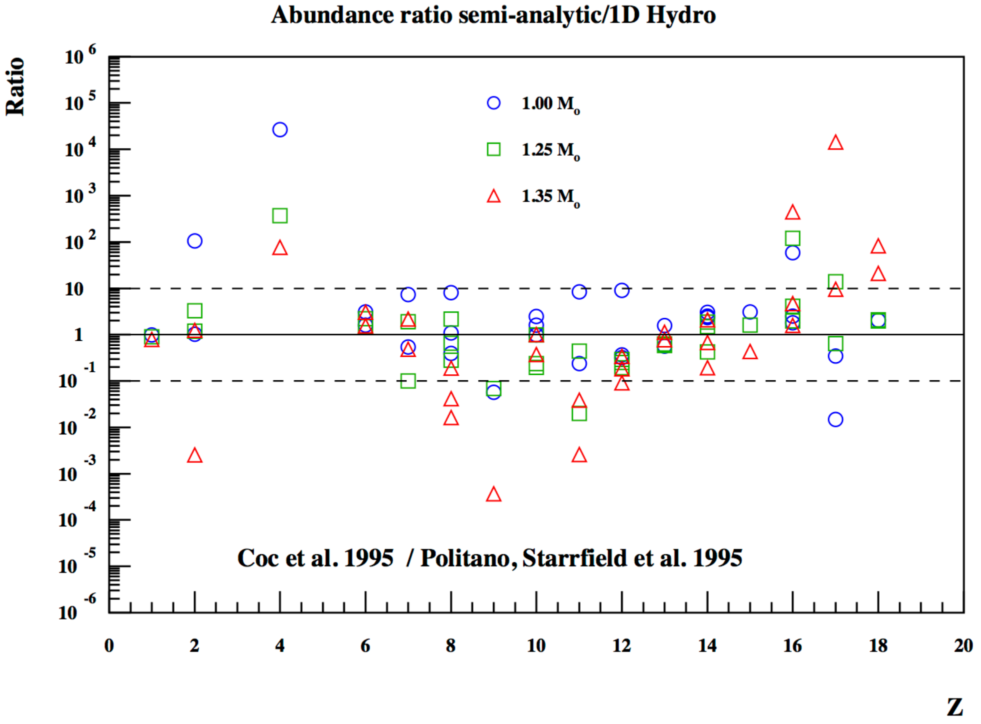
ONeMg novae: nuclear uncertainties on the ^{26}Al and ^{22}Na yields

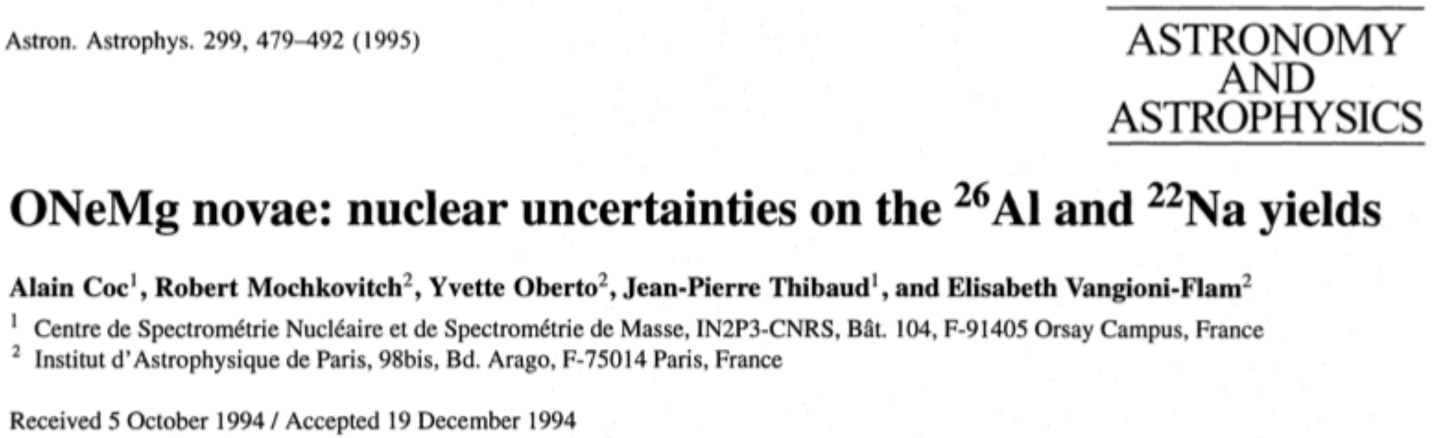
Alain Coc[1], **Robert Mochkovitch**[2], **Yvette Oberto**[2], **Jean-Pierre Thibaud**[1], and **Elisabeth Vangioni-Flam**[2]

[1] Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS, Bât. 104, F-91405 Orsay Campus, France
[2] Institut d'Astrophysique de Paris, 98bis, Bd. Arago, F-75014 Paris, France

Received 5 October 1994 / Accepted 19 December 1994



- Comparison between semi-analytic model of *McDonald 1983* and 1-D hydrocode from *Politano, Starrfield et al. 1995*
- Poor agreement (?)



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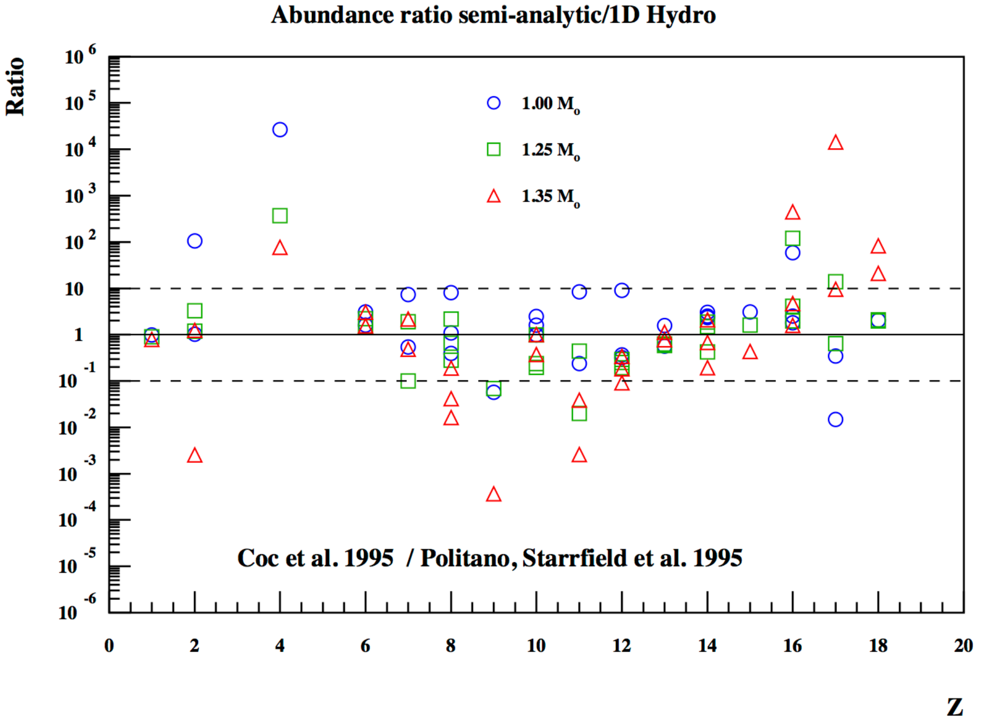
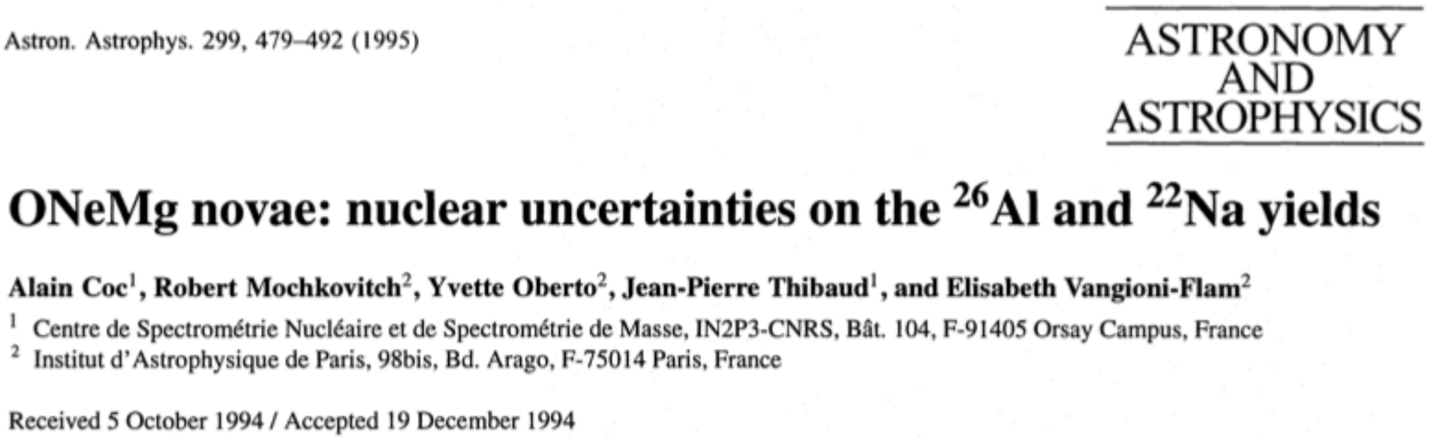


- Comparison between semi-analytic model of *McDonald 1983* and 1-D hydrocode from *Politano, Starrfield et al. 1995*
- Excellent agreement! *[Robert, Elisabeth & Michel (Cassé)]*



Astron. Astrophys. 299, 479–492 (1995)

ASTRONOMY
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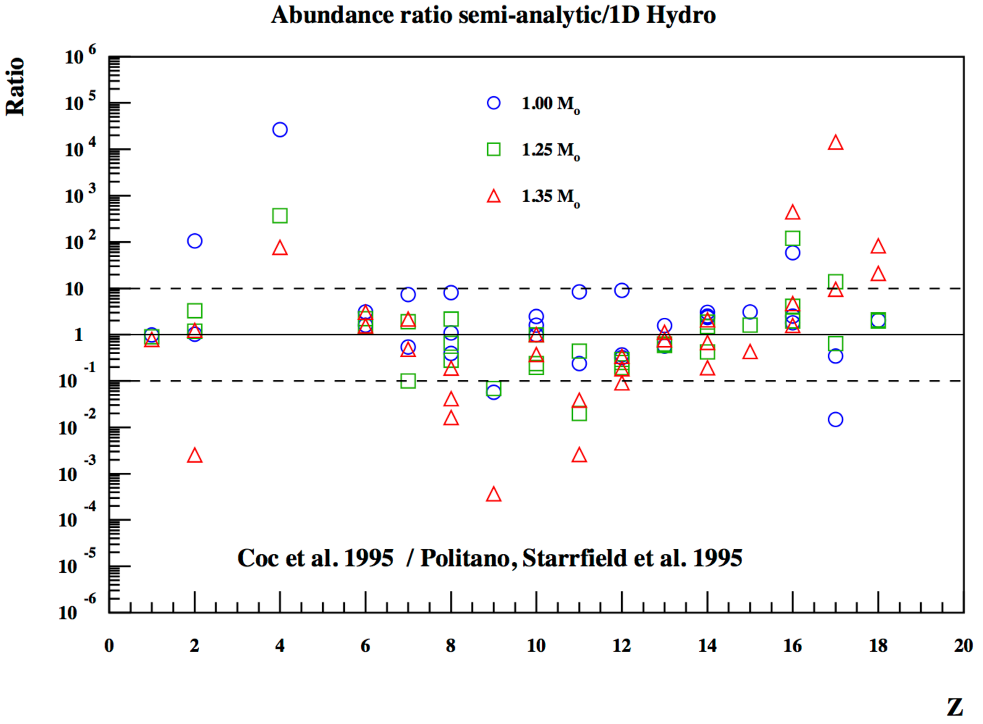
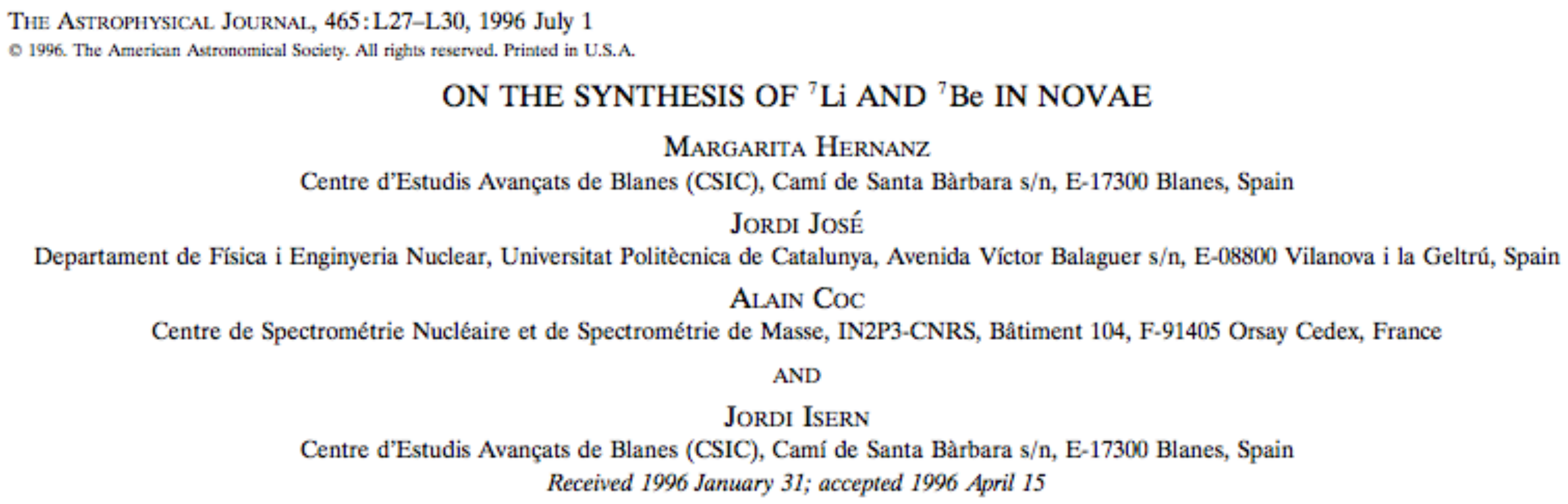


- Comparison between semi-analytic model of *McDonald 1983* and 1-D hydrocode from *Politano, Starrfield et al. 1995*
- Excellent agreement! *[Robert, Elisabeth & Michel (Cassé)]*
- (One of ?) the first study of the impact of nuclear uncertainties in novae
- Followed* over the years with *Margarita* and *Jordi* 1-D hydrocode to keep buzzy** (now for >20 years) the nuclear physics community!

* ^{7}Be/Li (1996), ^{26}Al (1997), ^{26}Al, ^{22}Na (1997), ^{18}F (1999; 2000), Si-Ca (2001)
** ^{17}O+p, ^{18}F+p, ^{21,22}Na(p,γ)^{22,23}Mg, ^{25}Al(p,γ)^{15}O, ^{30}P(p,γ)^{31}S,….



The Astrophysical Journal, 465:L27–L30, 1996 July 1

ON THE SYNTHESIS OF ^{7}Li AND ^{7}Be IN NOVAE

Margarita Hernanz
Centre d'Estudis Avançats de Blanes (CSIC), Camí de Santa Bàrbara s/n, E-17300 Blanes, Spain
Jordi José
Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, Avenida Víctor Balaguer s/n, E-08800 Vilanova i la Geltrú, Spain
Alain Coc
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS, Bâtiment 104, F-91405 Orsay Cedex, France
and
Jordi Isern
Centre d'Estudis Avançats de Blanes (CSIC), Camí de Santa Bàrbara s/n, E-17300 Blanes, Spain

Received 1996 January 31; accepted 1996 April 15

Predictions:

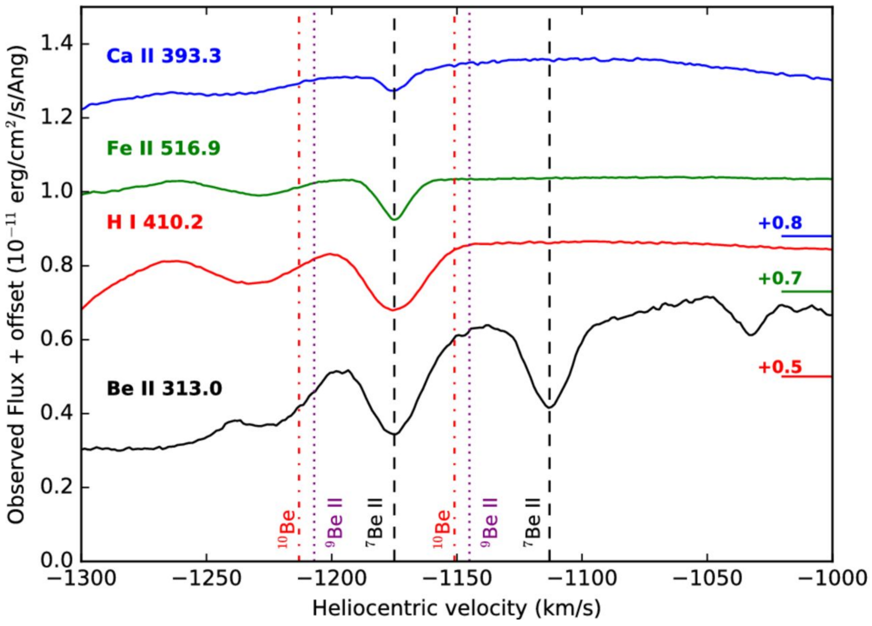
- ^{7}Be(^{7}Li) production : X = $(6.0\text{-}7.9)\times10^{-7}$ ONe $(3.1\text{-}8.2)\times10^{-6}$ CO ⇒ 20 / 150 $M_\odot$ galactic Li
- γ-detectability at $d \lesssim 0.5$ kpc

Observations:

- No γ-detection
- Atomic lines of ^{7}Be observed in 3 nova *[Tajitsu +2015;2016; Molaro+2016]* and of ^{7}Li in one *[Izzo+2015]* at higher levels than predictions

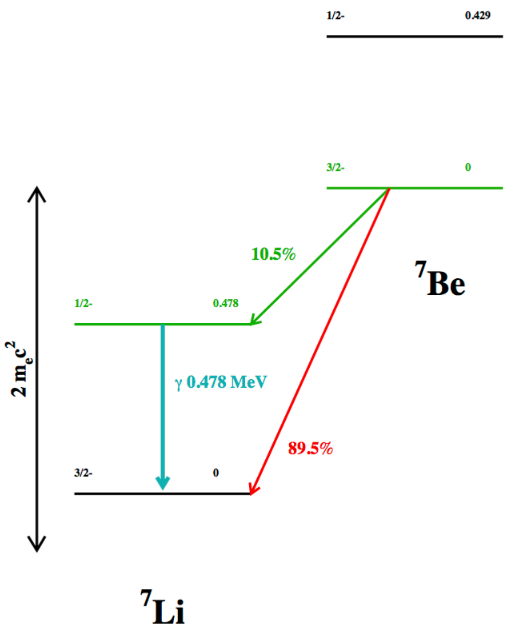
After the big bang "lithium problem" the nova lithium problem?

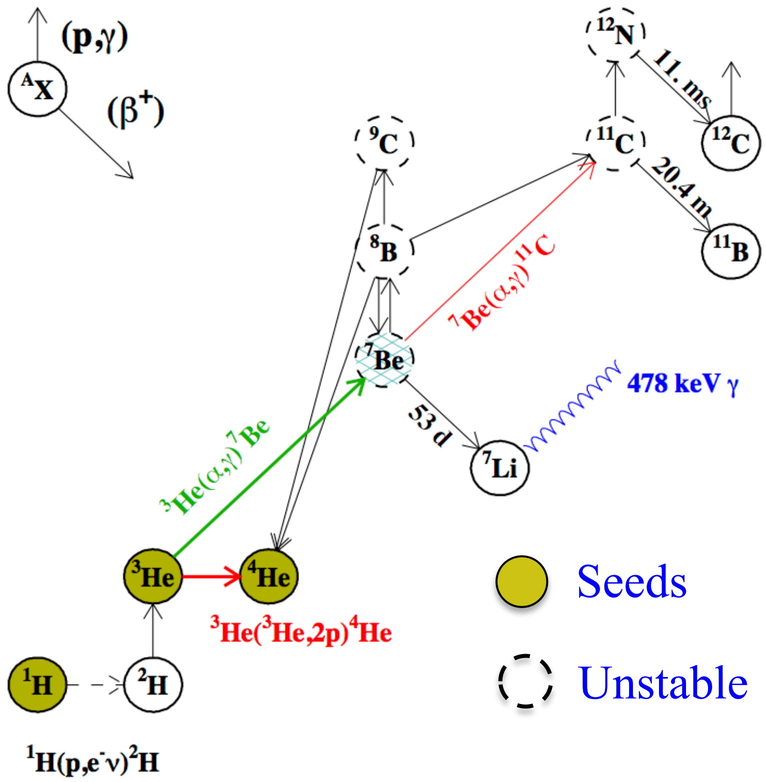
Nova Sagittarii 2015 No. 2 *[Molaro+2016]*



^{7}Be decay (e-capture, $\tau_{1/2}$=53 days) to ^{7}Li

- (10% B.R.) 478 keV γ-ray emission
- Stellar source of Li together with AGB and besides BBN and GCR





- Produced
  - From initial ^{3}He through ^{3}He(α,γ)^{7}Be
- Destructed/limited
  - Not so much by ^{7}Be(α,γ)^{11}C (Coulomb barrier)
  - By ^{7}Be(p,γ)^{8}B at low *T*, but hindered by photo-disintegration at high *T* (very low *Q*-value: 0.136 MeV). Requires a fast rise in temperature (CO versus ONe Novae)
  - By diverting the flow from its ^{3}He source through ^{3}He(^{3}He,2p)^{4}He

A toy model at constant $T = 100$ MK and $\rho = 10^3$ g/cm^3

$$\boxed{\frac{\mathrm{d}Y_3}{\mathrm{d}t} = -\lambda Y_3 - \mu Y_3^2}$$

$$\frac{\mathrm{d}Y_7}{\mathrm{d}t} = +\lambda Y_3 \quad \Rightarrow \quad \boxed{Y_7(t) = \int_0^t \lambda Y_3(t)\,\mathrm{d}t}$$

Y's = ^{3}He, ^{4}He, and ^{7}Be molar fraction

$$\lambda \equiv Y_4 \rho N_A \langle \sigma v \rangle_{^3\mathrm{He}+^4\mathrm{He}\rightarrow^7\mathrm{Be}+\gamma}$$

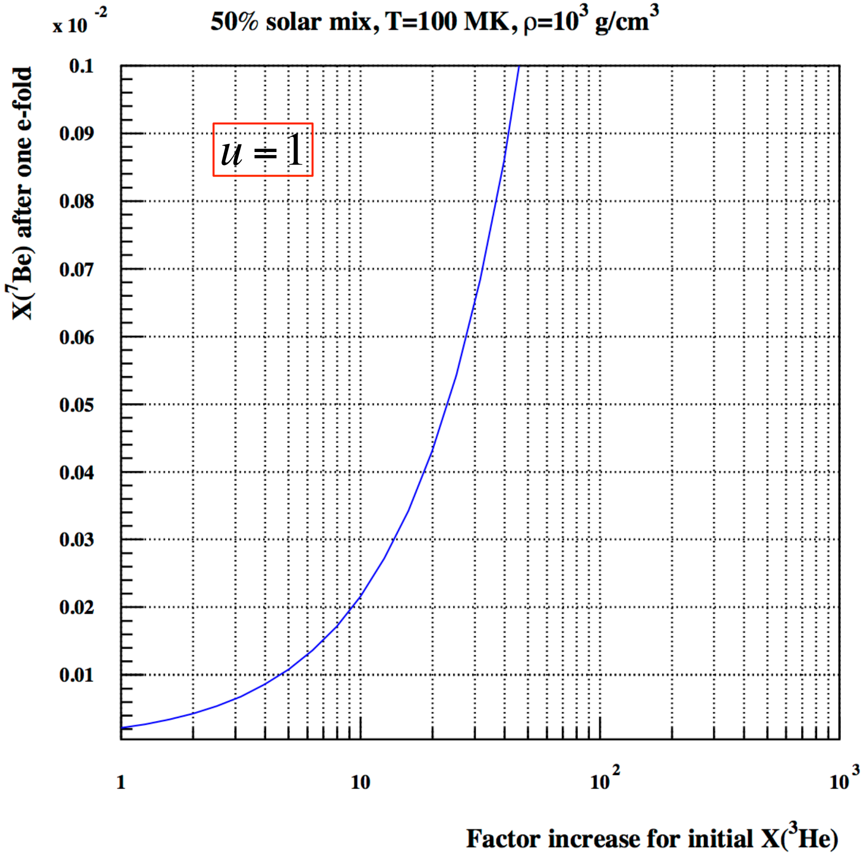
$$\mu \equiv \frac{1}{2!} \rho N_A \langle \sigma v \rangle_{^3\mathrm{He}+^3\mathrm{He}\rightarrow^4\mathrm{He}+2\mathrm{p}}$$

Without ^{3}He(^{3}He,2p)^{4}He

$$\boxed{Y_3(u) = Y_3(0)\exp(-u)}$$

$$\boxed{Y_7(u) = Y_3(0)\left[1-\exp(-u)\right]}$$

$$u \equiv \lambda t$$



A toy model at constant T = 100 MK and $\rho = 10^3$ g/cm^3

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$$\boxed{Y_3(u) = Y_3(0)\exp(-u)}$$

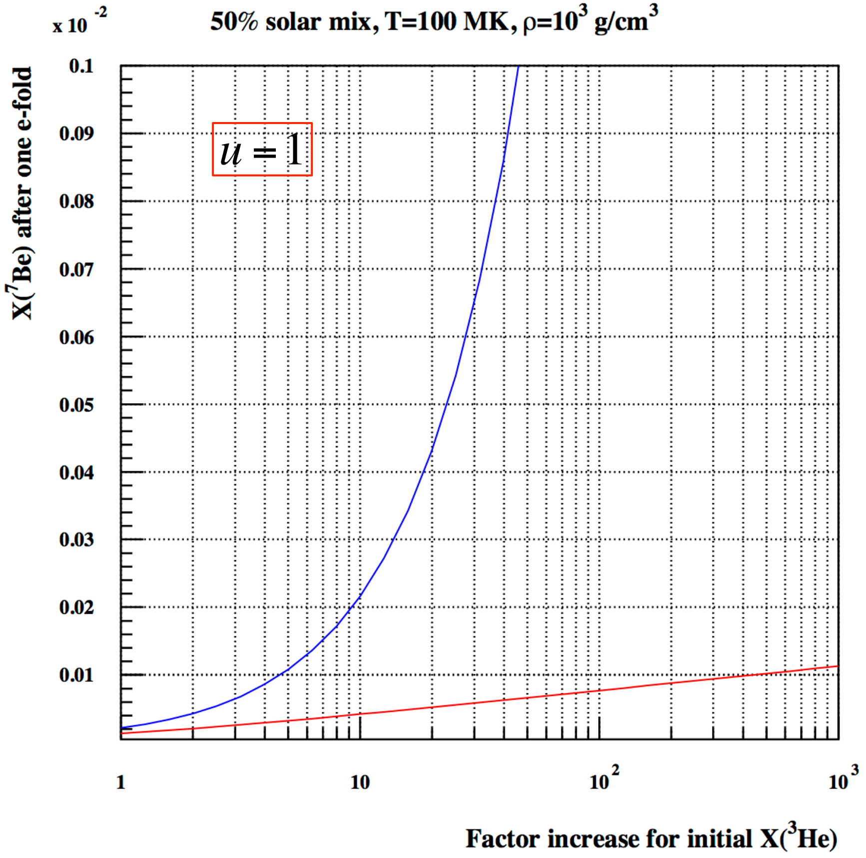
$$\boxed{Y_7(u) = Y_3(0)\left[1-\exp(-u)\right]}$$

$$u \equiv \lambda t$$

With ^{3}He(^{3}He,2p)^{4}He

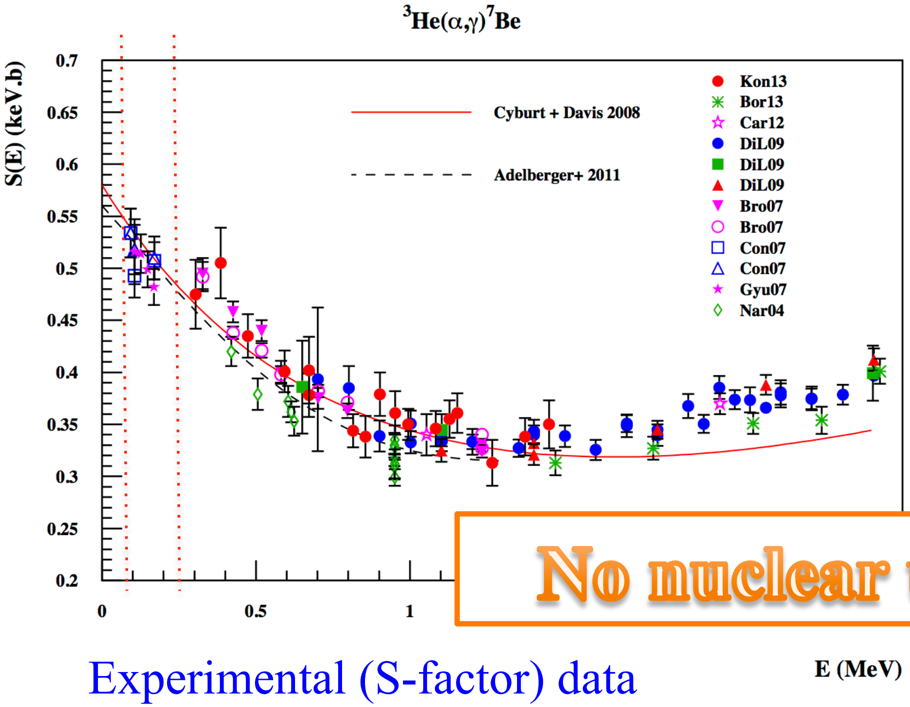
$$Y_3(u) = \frac{A\lambda}{\exp(+u) - A\mu} \qquad \boxed{A = \frac{Y_3(0)}{\lambda + \mu Y_3(0)}}$$

$$\boxed{Y_7(u) = \frac{\lambda}{\mu}\left[\ln\left(\frac{e^u - \mu A}{1-\mu A}\right) - u\right]}$$

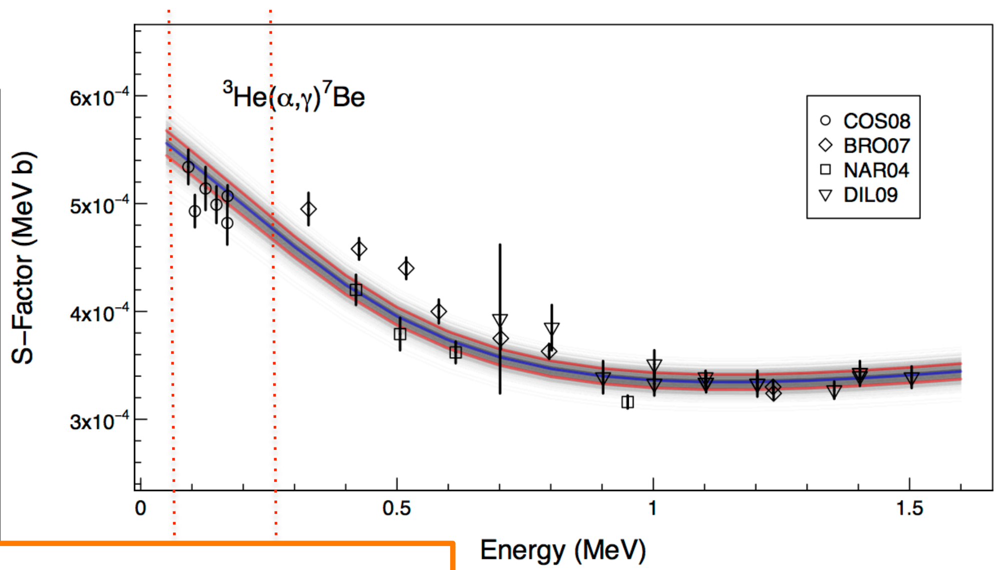


Logarithmic dependence on initial ^{3}He abundance

[Boffin+ 1993]

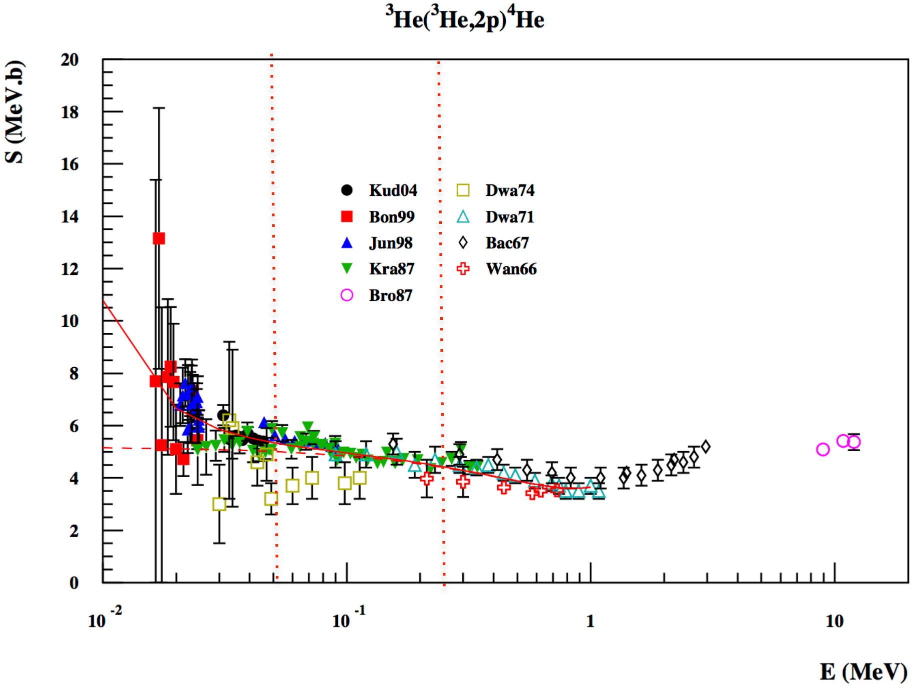


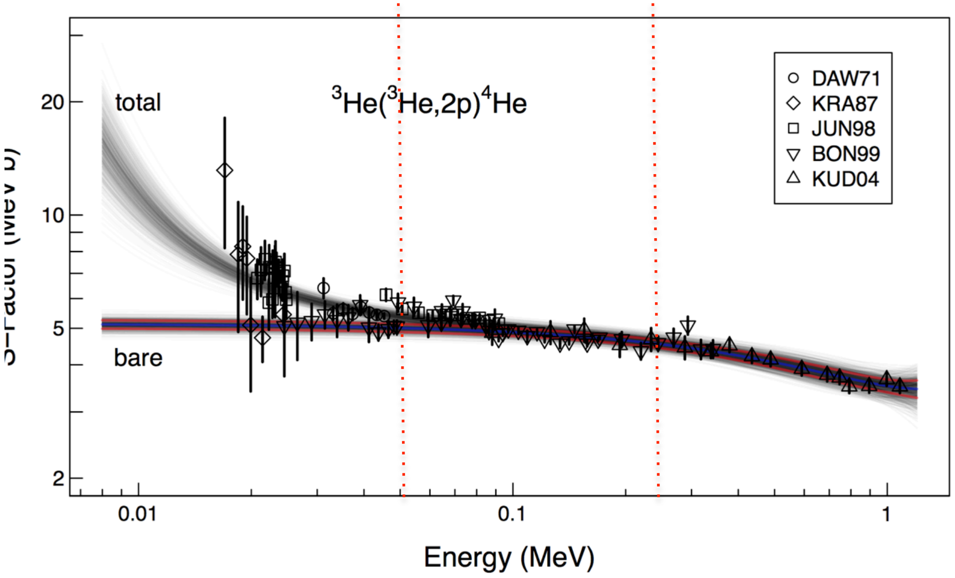
No nuclear uncertainty



Experimental (S-factor) data

Recent re-evaluation *[Iliadis, Anderson, Coc, Timmes & Starrfield 2016]*





THE ASTROPHYSICAL JOURNAL, 526:L97–L100, 1999 December 1

GAMMA-RAY EMISSION FROM NOVAE RELATED TO POSITRON ANNIHILATION: CONSTRAINTS ON ITS OBSERVABILITY POSED BY NEW EXPERIMENTAL NUCLEAR DATA

MARGARITA HERNANZ,[1] JORDI JOSÉ,[1,2] ALAIN COC,[3] JORDI GÓMEZ-GOMAR,[1] AND JORDI ISERN[1]
Received 1999 July 23; accepted 1999 October 5; published 1999 October 29

Astron. Astrophys. 357, 561–571 (2000)

ASTRONOMY
AND
ASTROPHYSICS

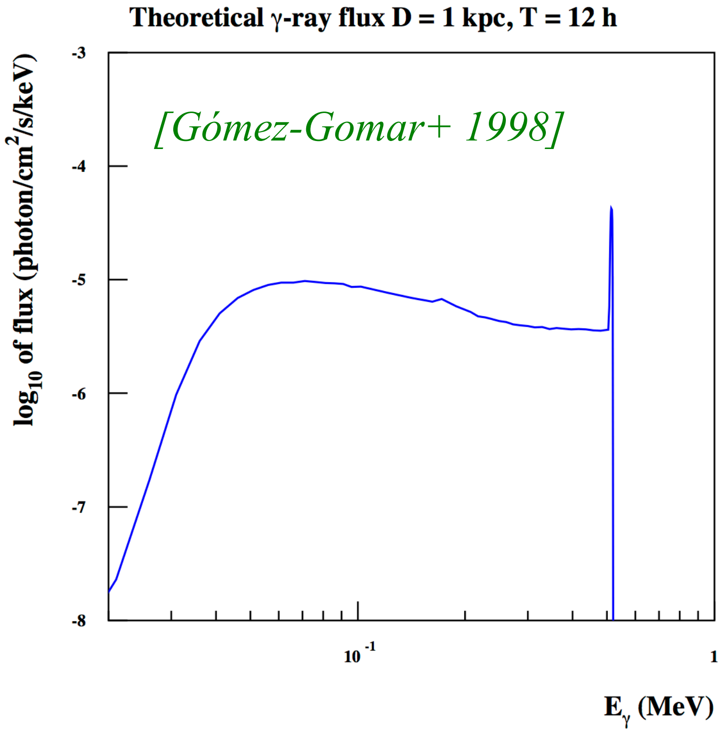
Influence of new reaction rates on ^{18}F production in novae

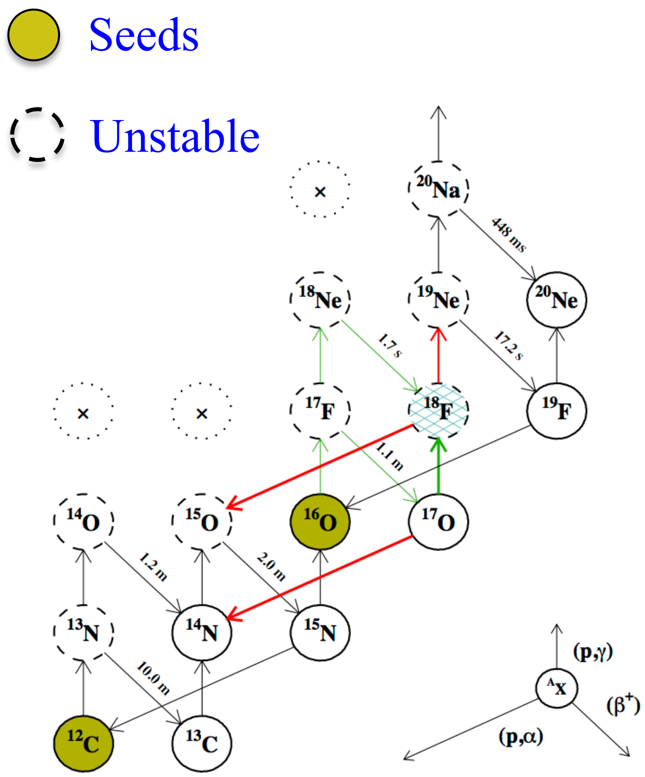
A. Coc[1], M. Hernanz[2], J. José[2,3], and J.-P. Thibaud[1]

[1] Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS and Université Paris Sud, Bâtiment 104, 91405 Orsay Campus, France
[2] Institut d'Estudis Espacials de Catalunya/CSIC, Edifici Nexus-201, C/Gran Capità 2-4, 08034 Barcelona, Spain
[3] Departament de Física i Enginyeria Nuclear (UPC), Avinguda Víctor Balaguer, s/n, 08800 Vilanova i la Geltrú (Barcelona), Spain

^{18}F decay (positron emission, $\tau_{1/2}$=108 mn) to ^{18}O

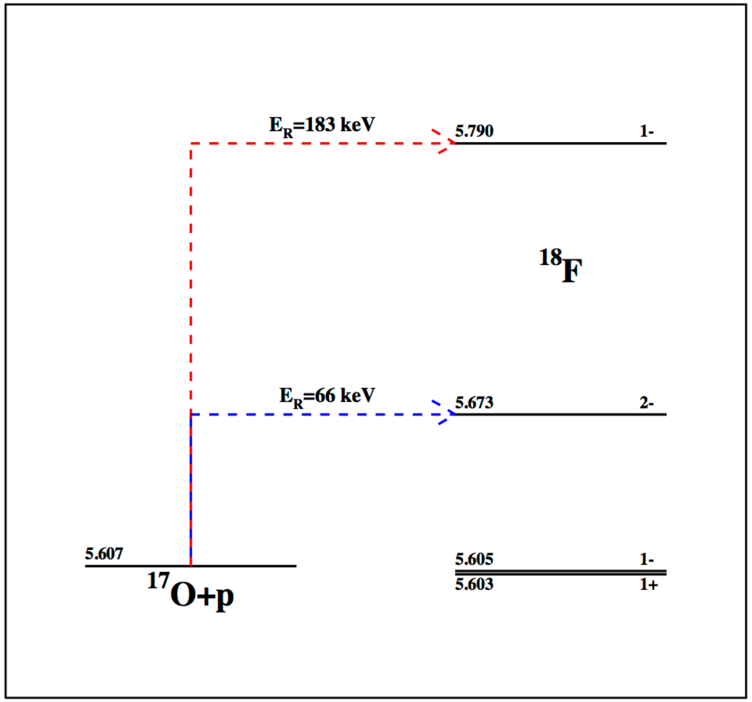
- Electron-positron annihilation 511 keV γ-ray + continuum emission

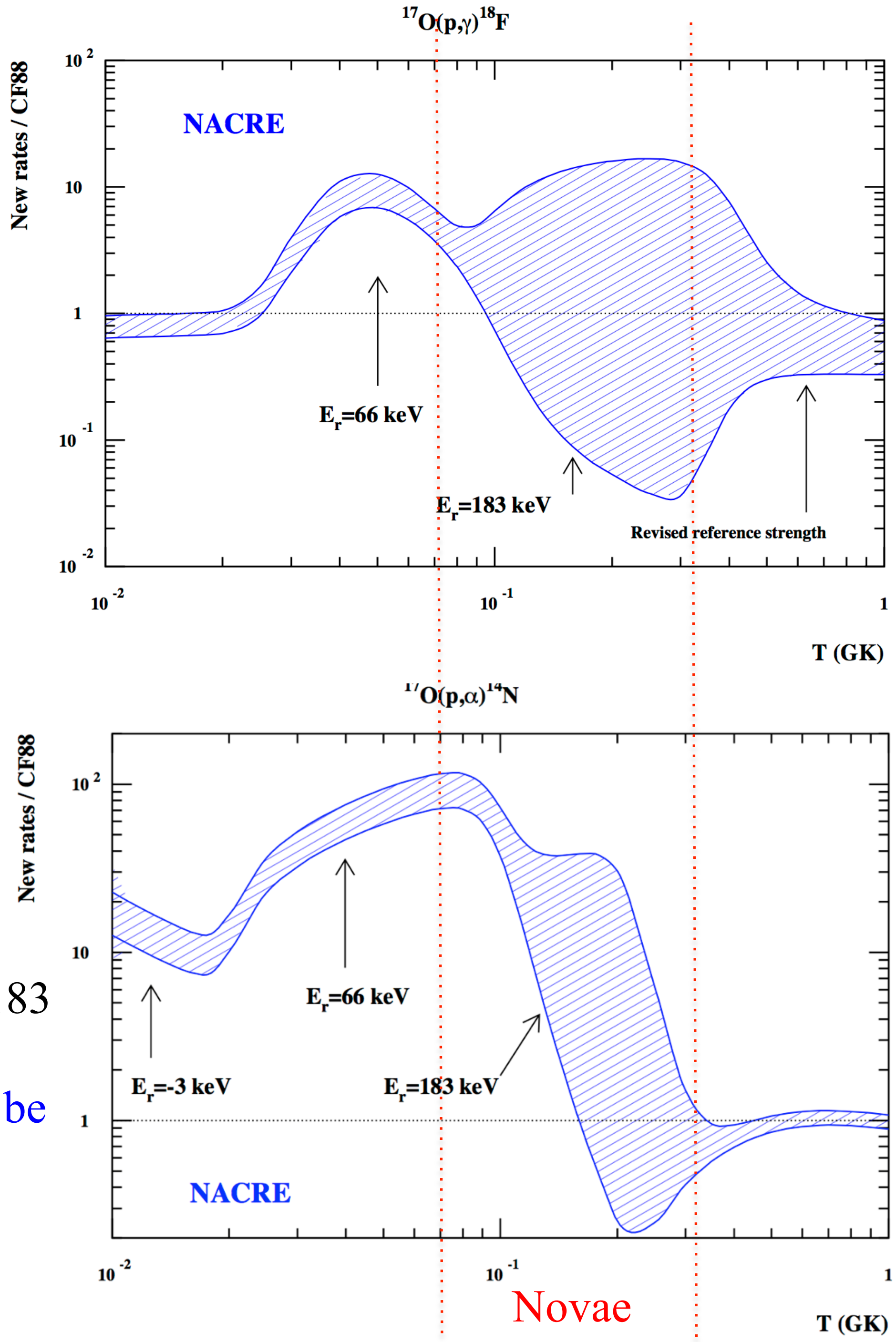




- Producted
  - From initial ^{16}O, mainly through ^{16}O(p,γ)^{17}F(β+)^{17}O(p,γ)^{18}F
- Destructed/limited
  - Mainly by ^{18}F(p,α)^{15}O [^{18}F(p,γ)^{19}Ne negligible]
  - By diverting the flow through ^{17}O by ^{17}O(p,α)^{14}N
- Main stellar source of ^{17}O
- Large nuclear uncertainty in 2000

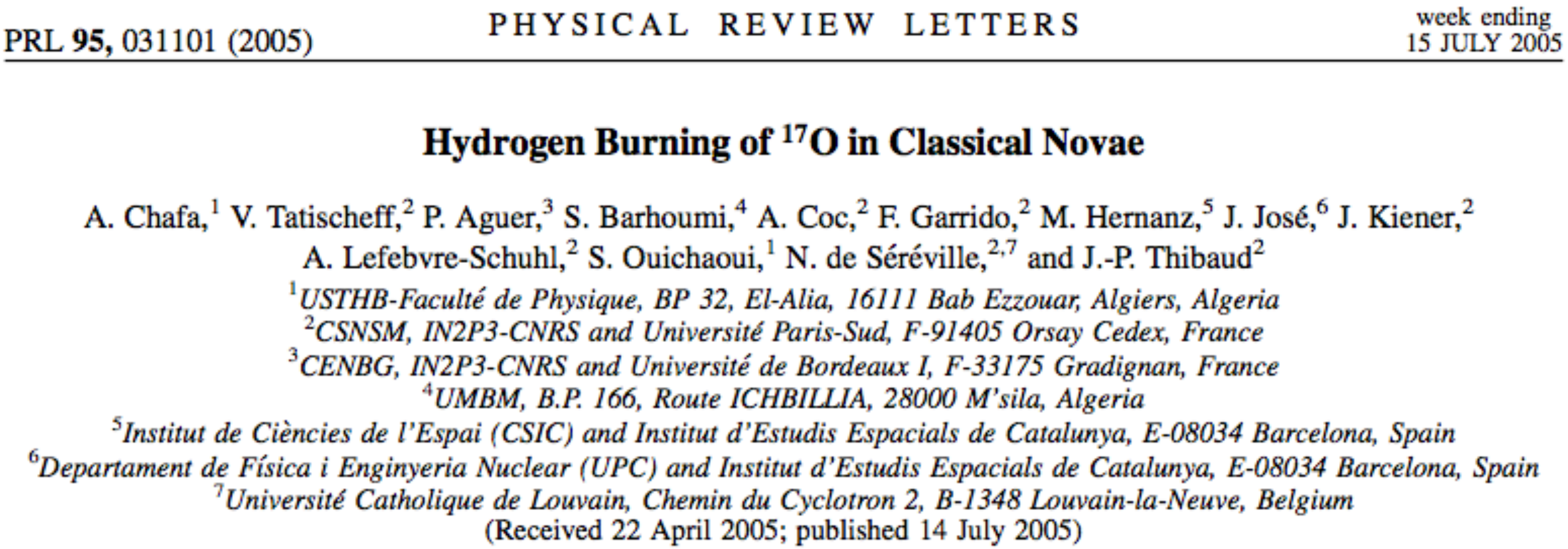
Uncertainties in the $^{17}O(p,\gamma)^{18}F$ and $^{17}O(p,\alpha)^{14}N$ reaction rates (NACRE evaluation by *Angulo+ 1999*)





Unknown strength of a resonance around $E_R = 183$ keV

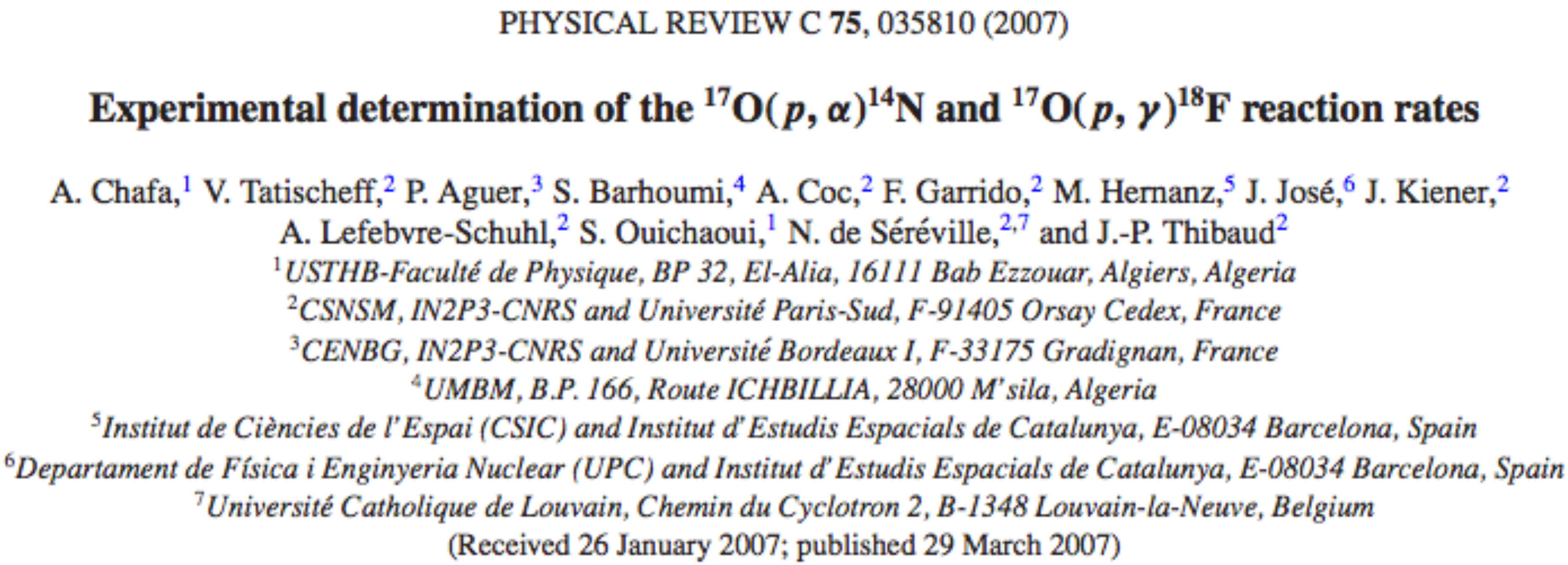
- ➢ “Well known” at that time to be too small to be measured in the (p,α) channel!
- ➢ But the resonance energy and total width from the literature were all wrong!



PRL **95,** 031101 (2005) PHYSICAL REVIEW LETTERS week ending 15 JULY 2005

Hydrogen Burning of ^{17}O in Classical Novae

A. Chafa,[1] V. Tatischeff,[2] P. Aguer,[3] S. Barhoumi,[4] A. Coc,[2] F. Garrido,[2] M. Hernanz,[5] J. José,[6] J. Kiener,[2]
A. Lefebvre-Schuhl,[2] S. Ouichaoui,[1] N. de Séréville,[2,7] and J.-P. Thibaud[2]
[1]*USTHB-Faculté de Physique, BP 32, El-Alia, 16111 Bab Ezzouar, Algiers, Algeria*
[2]*CSNSM, IN2P3-CNRS and Université Paris-Sud, F-91405 Orsay Cedex, France*
[3]*CENBG, IN2P3-CNRS and Université de Bordeaux I, F-33175 Gradignan, France*
[4]*UMBM, B.P. 166, Route ICHBILLIA, 28000 M'sila, Algeria*
[5]*Institut de Ciències de l'Espai (CSIC) and Institut d'Estudis Espacials de Catalunya, E-08034 Barcelona, Spain*
[6]*Departament de Física i Enginyeria Nuclear (UPC) and Institut d'Estudis Espacials de Catalunya, E-08034 Barcelona, Spain*
[7]*Université Catholique de Louvain, Chemin du Cyclotron 2, B-1348 Louvain-la-Neuve, Belgium*
(Received 22 April 2005; published 14 July 2005)



PHYSICAL REVIEW C **75**, 035810 (2007)

Experimental determination of the ^{17}O$(p, \alpha)^{14}$N and ^{17}O$(p, \gamma)^{18}$F reaction rates

A. Chafa,[1] V. Tatischeff,[2] P. Aguer,[3] S. Barhoumi,[4] A. Coc,[2] F. Garrido,[2] M. Hernanz,[5] J. José,[6] J. Kiener,[2]
A. Lefebvre-Schuhl,[2] S. Ouichaoui,[1] N. de Séréville,[2,7] and J.-P. Thibaud[2]
[1]*USTHB-Faculté de Physique, BP 32, El-Alia, 16111 Bab Ezzouar, Algiers, Algeria*
[2]*CSNSM, IN2P3-CNRS and Université Paris-Sud, F-91405 Orsay Cedex, France*
[3]*CENBG, IN2P3-CNRS and Université Bordeaux I, F-33175 Gradignan, France*
[4]*UMBM, B.P. 166, Route ICHBILLIA, 28000 M'sila, Algeria*
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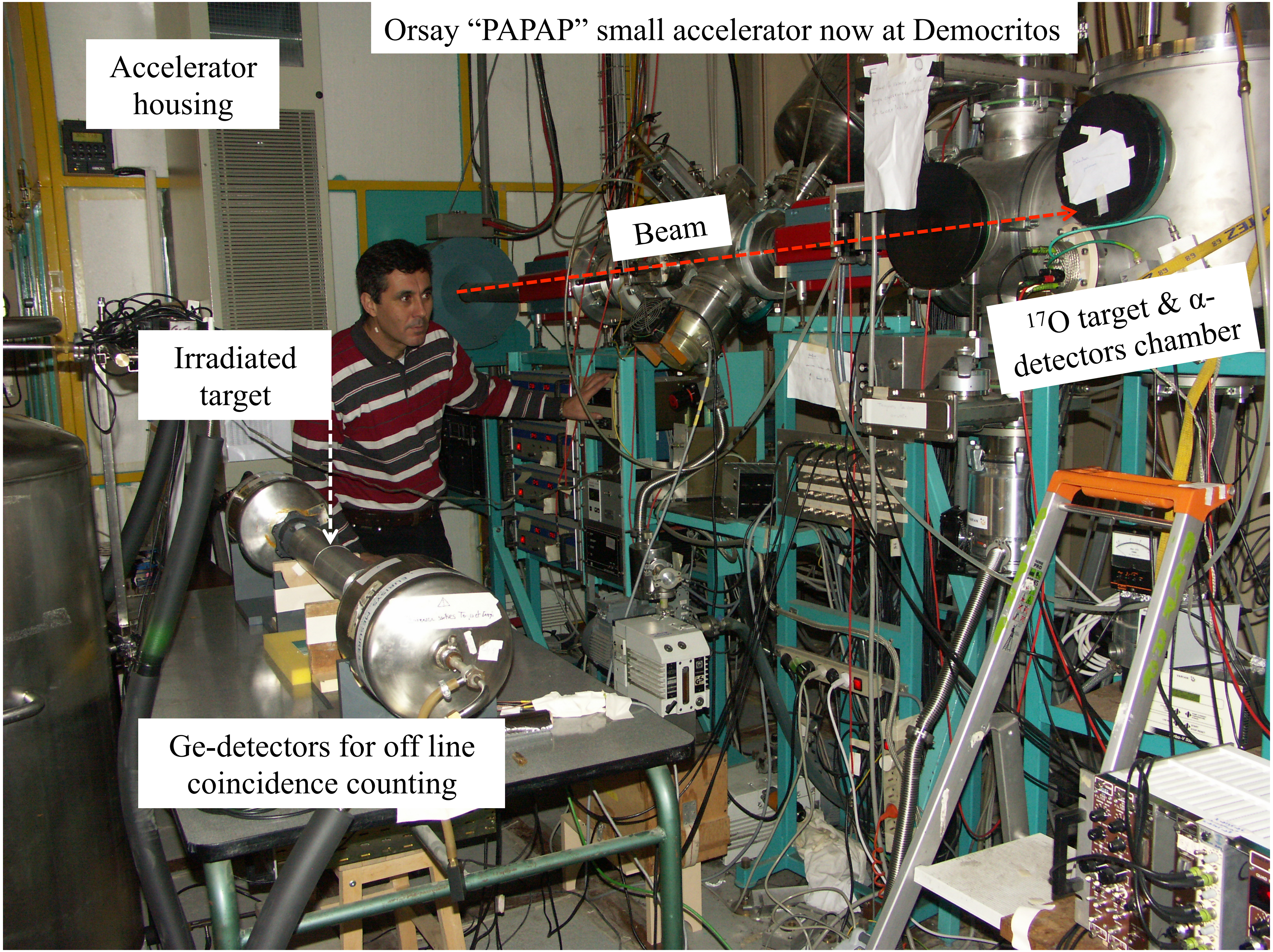
[7]*Université Catholique de Louvain, Chemin du Cyclotron 2, B-1348 Louvain-la-Neuve, Belgium*
(Received 26 January 2007; published 29 March 2007)

Orsay “PAPAP” small accelerator now at Democritos



Accelerator housing

Beam

Irradiated target

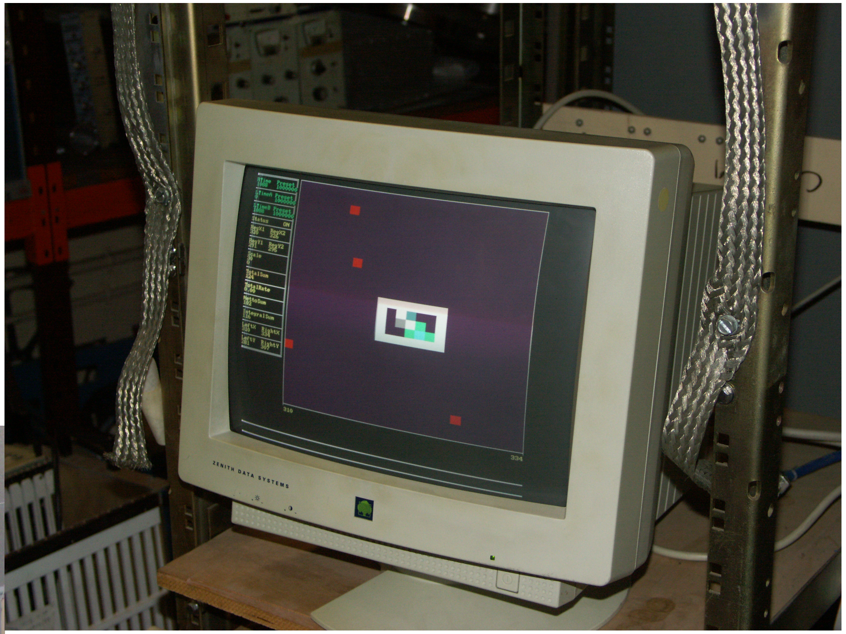
^{17}O target & α-detectors chamber

Ge-detectors for off line coincidence counting

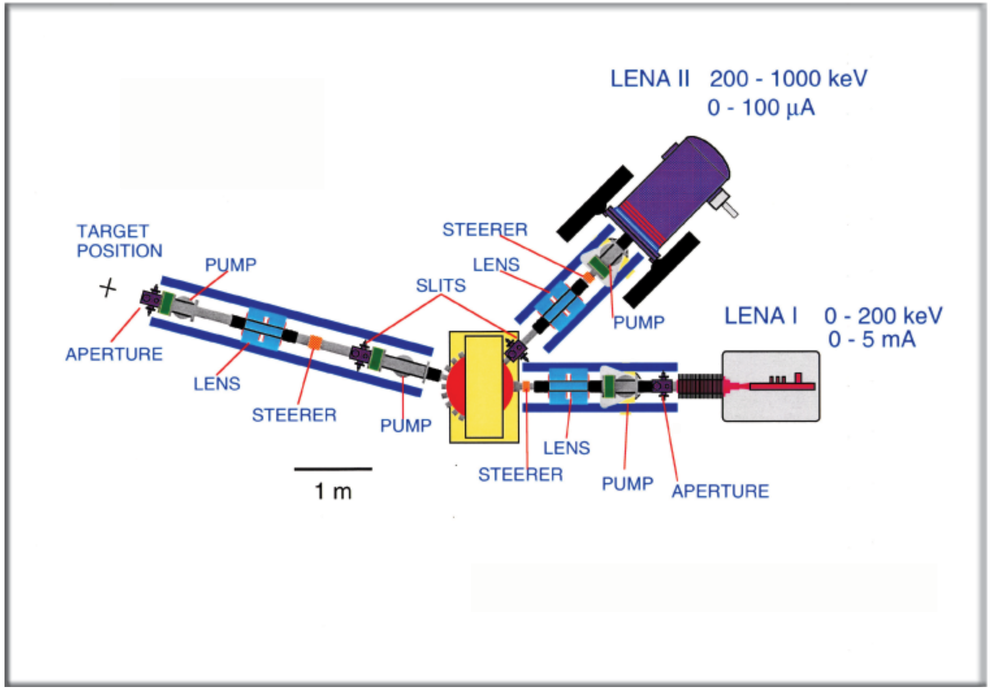
Resonance strength measured:

- By activation and ^{18}F decay followed by e+e- →γγ off-line coincidence counting for the (p,γ) channel!
- Directly for the (p,α) channel, “impossible” measurement

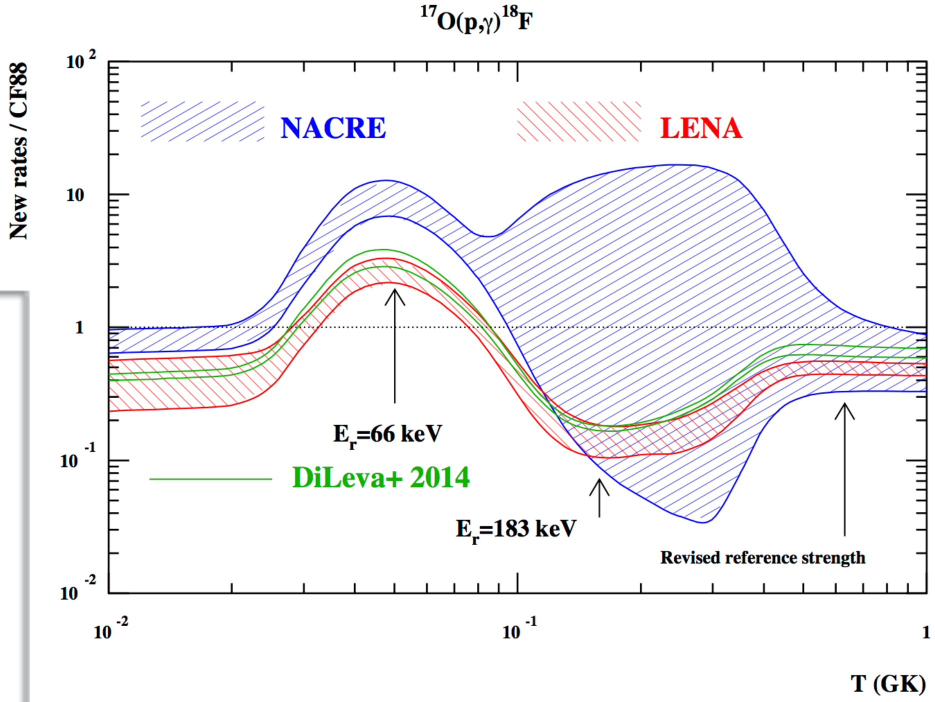
The “highly sophisticated” coincidence system

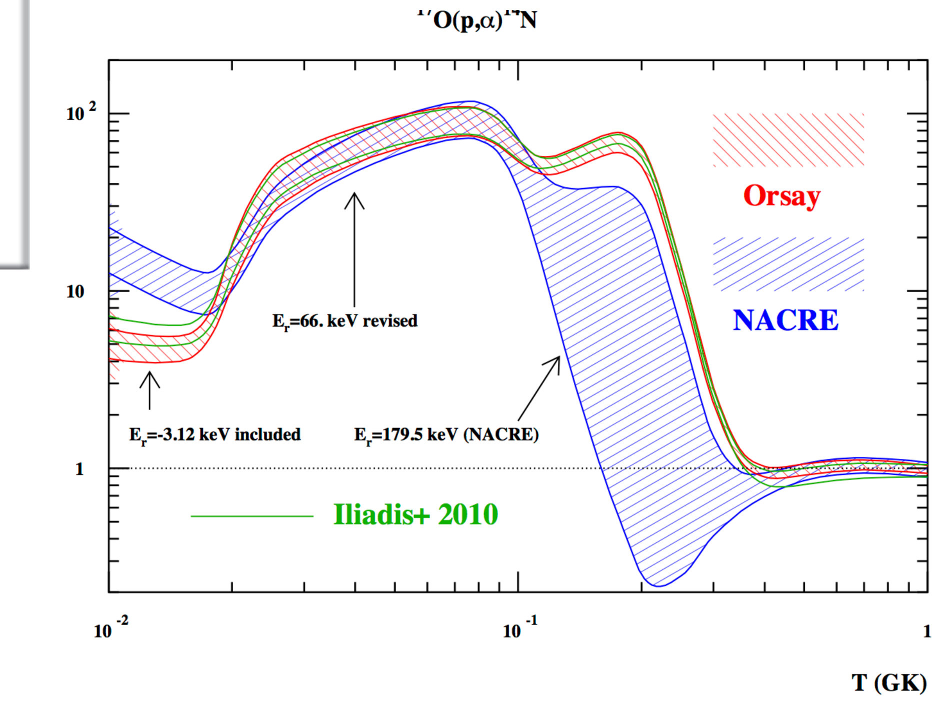


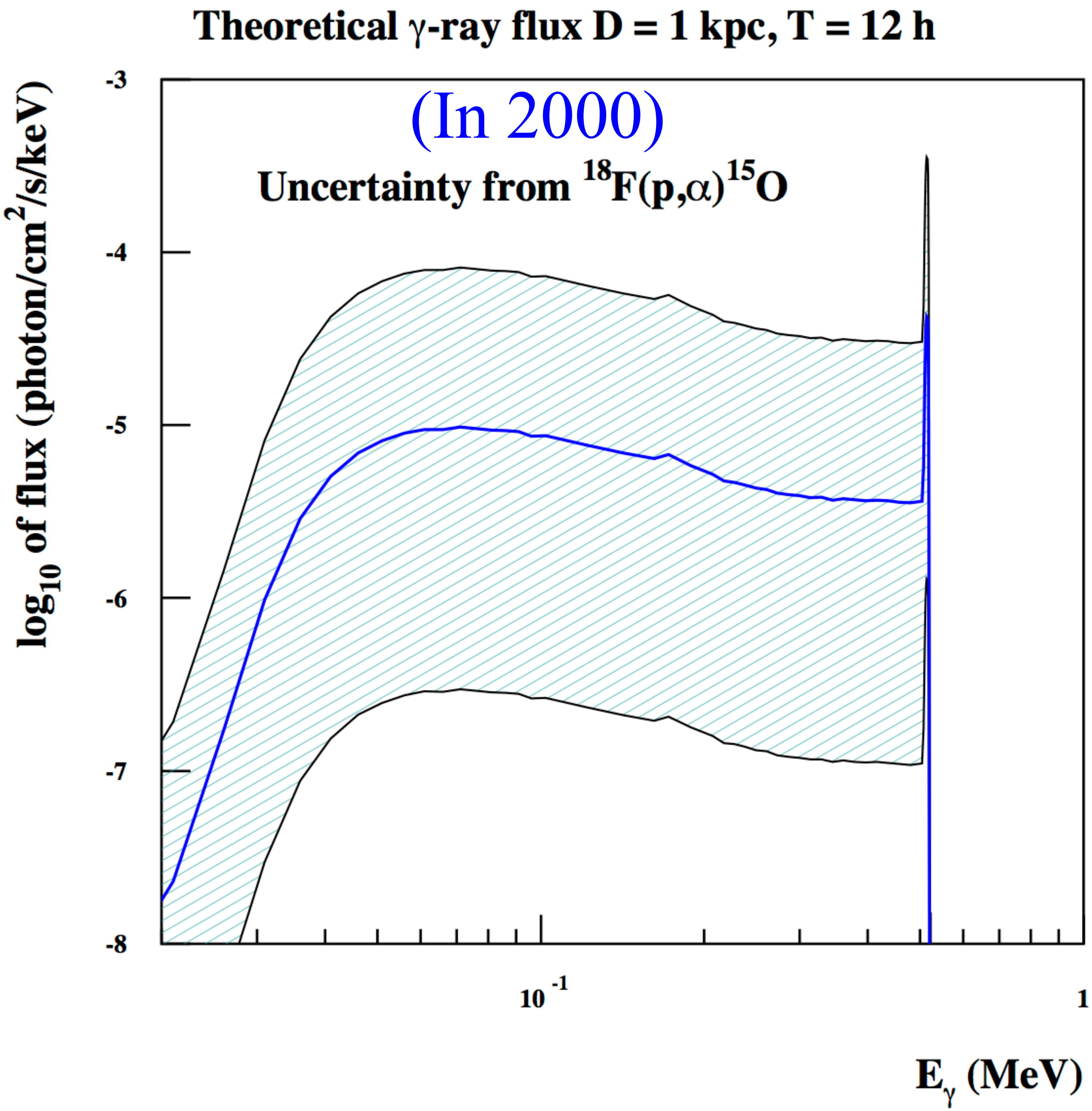
- Several experiments confirmed the Orsay PAPAP *[Chafa+ 2005; 2007]* and Duke LENA *[Fox+ 2004; 2005]* (simultaneous) results



- Just after a few (≈5) years, both ^{17}O+p rates were known with a precision sufficient for nova modeling see the *Iliadis+ 2010* evaluation of reaction rates.
- Not the case after ≈20 years for the ^{18}F+p (and other) reaction rates!



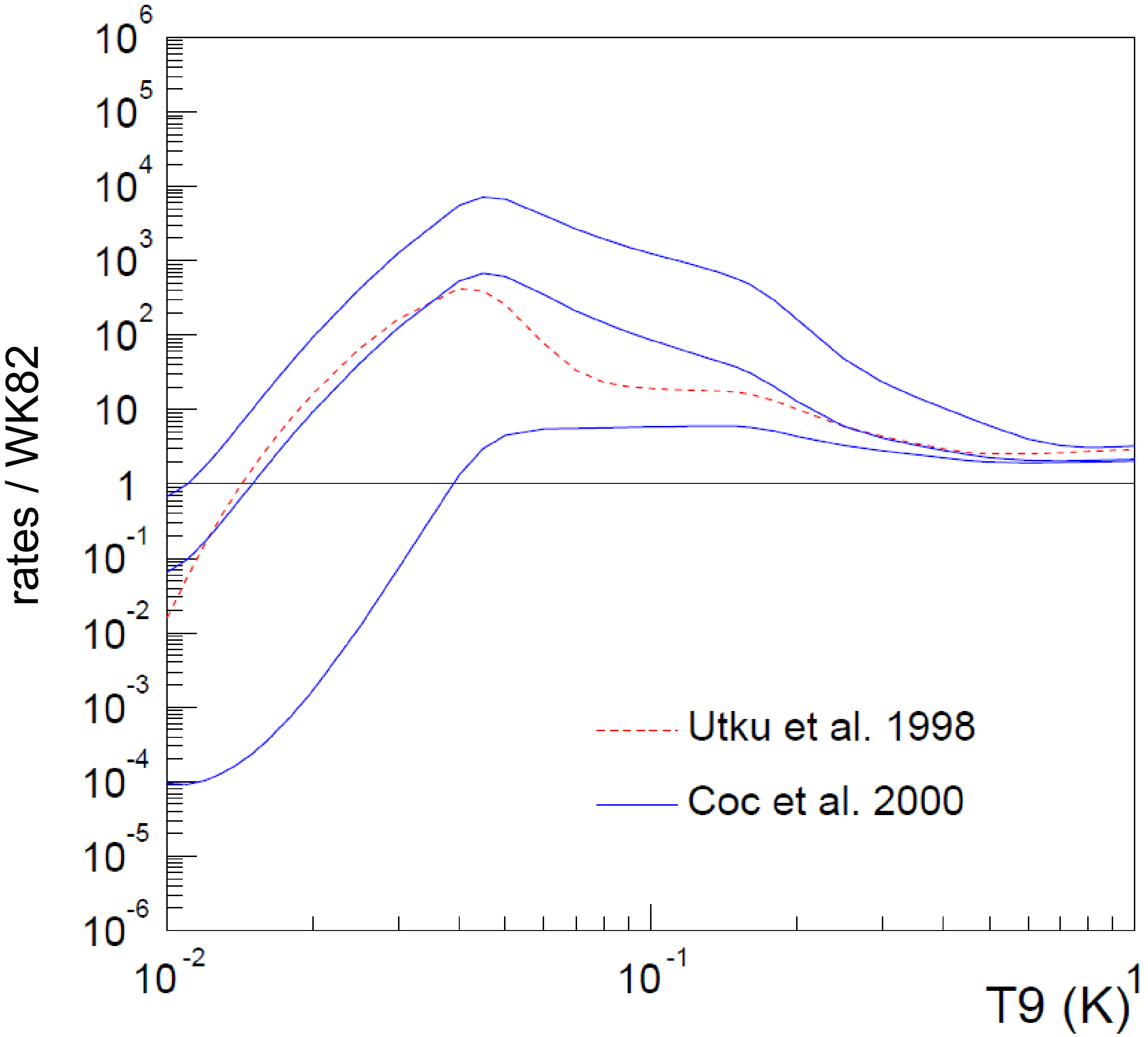




Theoretical γ-ray flux D = 1 kpc, T = 12 h

(In 2000)

$^{18}F(p,\alpha)^{15}O$ reaction rate (~ 2000)



- WK82 (Wiescher & Kettner) reaction rate used in first γ-ray emission calculations

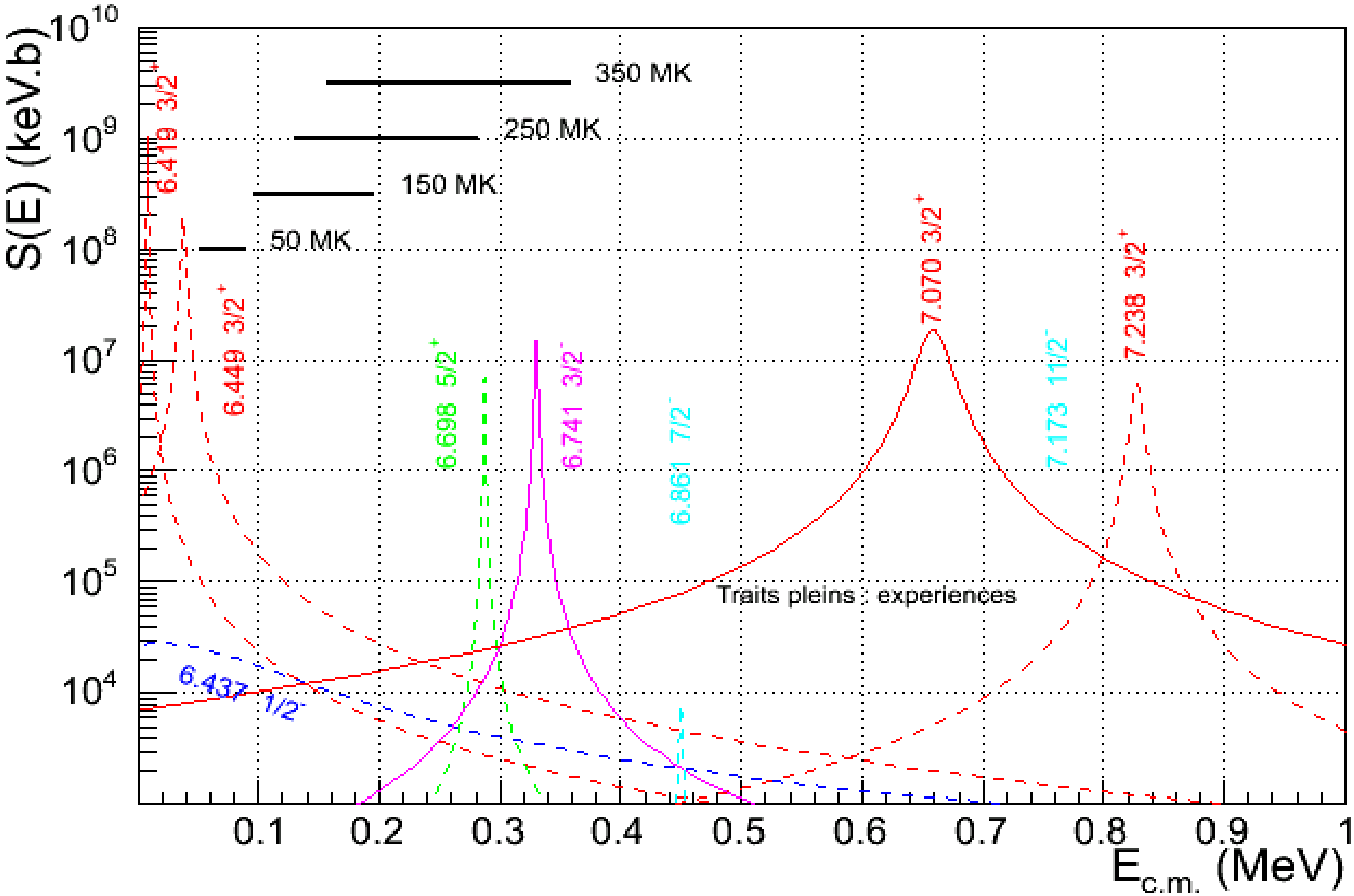
  Gomez-Gomar et al. MNRAS (1998)

- Max / min reaction rates are obtained when contribution of resonances are maximized or minimized

- 3 orders of magnitude uncertainty at T = 100 MK

- Factor 300 on γ-ray flux predictions at and below 511 keV

^{18}F(p,α)^{15}O S-factor (~ 2000)



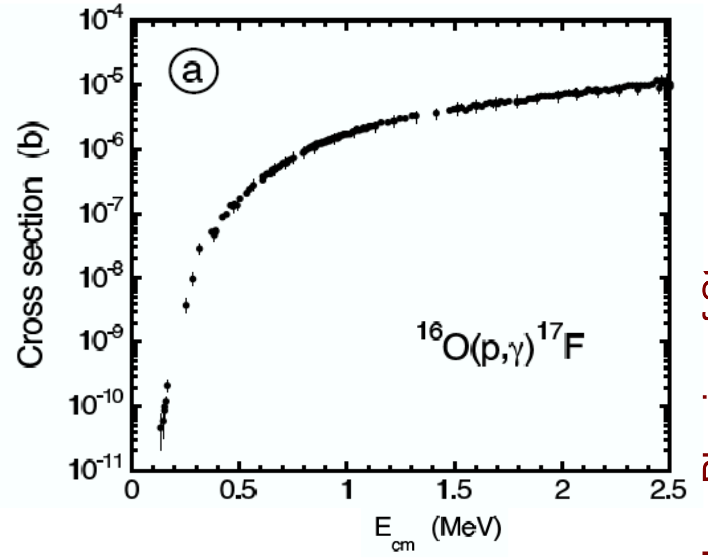
- Astrophysical S-factor: $S(E) = \sigma(E)Ee^{2\pi\eta} \propto \Gamma_p\Gamma_\alpha/\Gamma_{tot}$
- Unknown proton width
- Tentative spin / parity assignment
- Missing ^{19}Ne states when compared to ^{19}F mirror nucleus

Cross-section determination

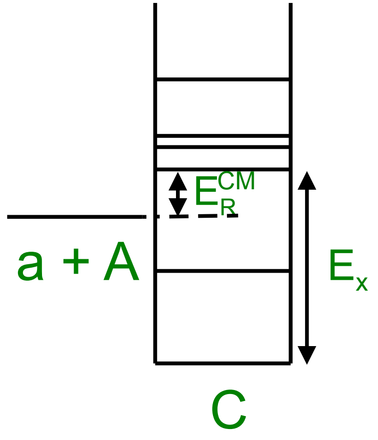
$$N_A < \sigma v >= \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty E\sigma(E)e^{-E/kT}dE$$

Direct measurement [a + A → b + B]

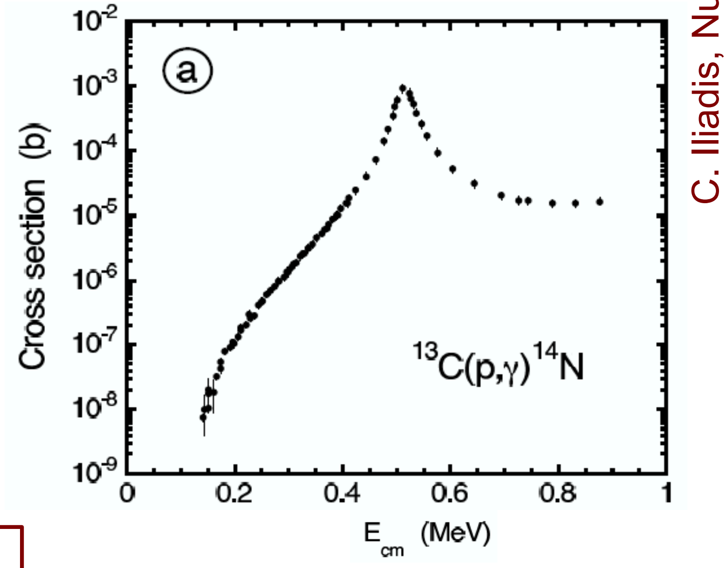
- Very low cross-section at small energies (Coulomb penetrability)
- High beam intensity (difficult when radioactive species)
- Dedicated experimental set-up to reduce background (recoil separator, underground measurement, coincidence measurement, ...)



Indirect measurement [a + A → C → b + B]



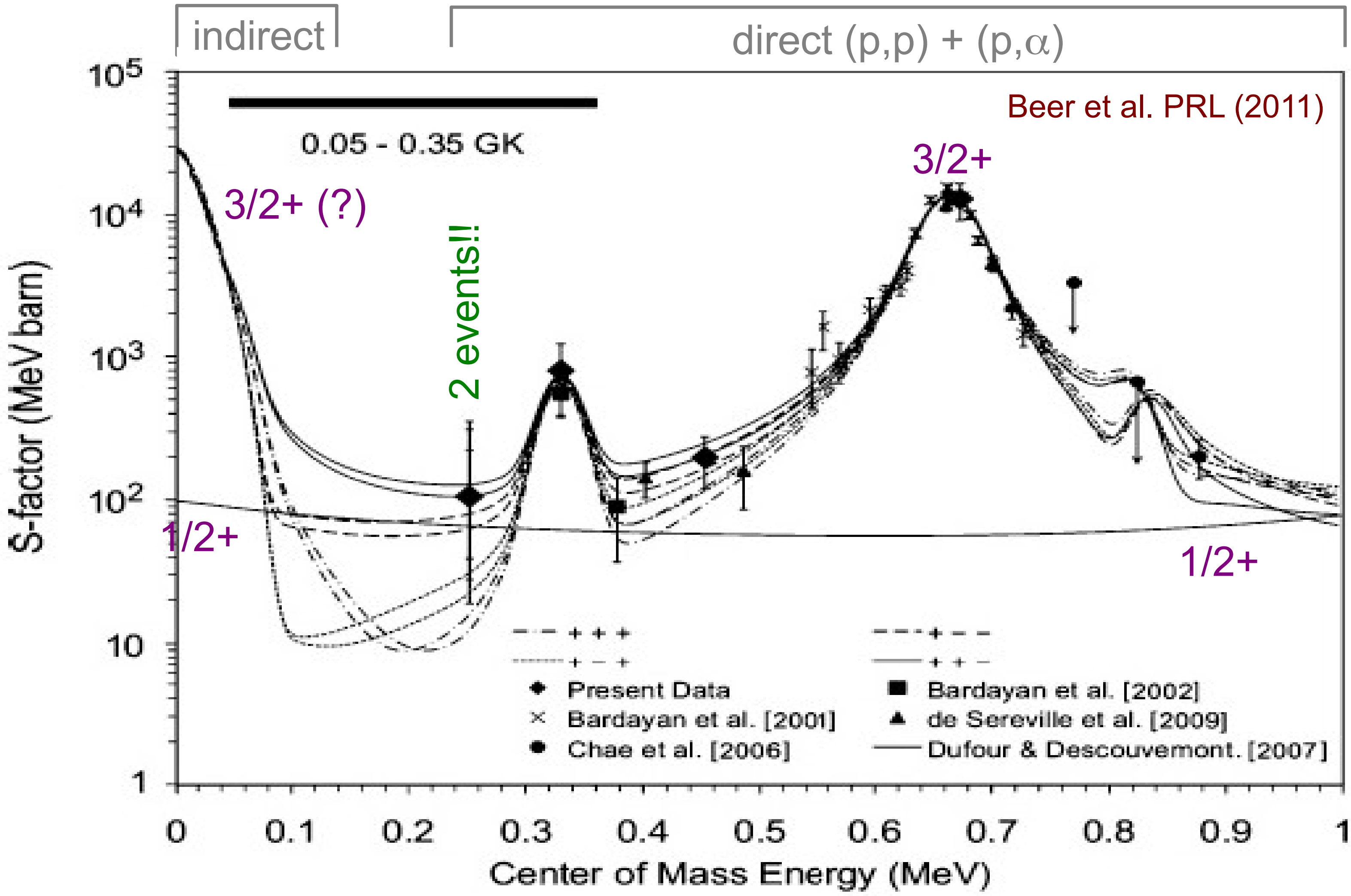
- High cross-section
- Determine properties of compound nucleus states
  - Energy
  - Spin / parity
  - Total width
  - Partial widths



C. Iliadis, Nuclear Physics of Stars

Direct measurements should be performed whenever possible

$^{18}F(p,\alpha)^{15}O$ S-factor (~ 2010)


Beer et al. PRL (2011)

Direct measurement in Gamow peak

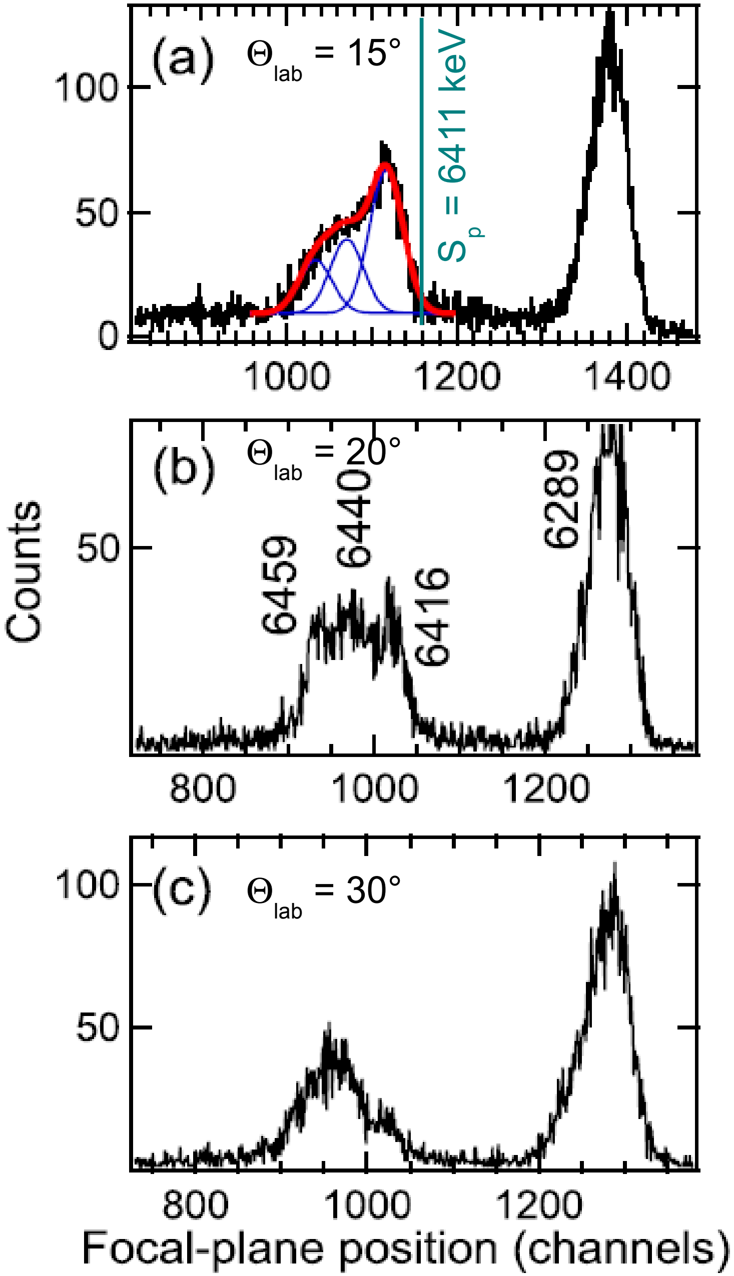
- Large error bar (statistics)
- Need for lower energy data

Interference effects in Gamow peak

- 3/2+ resonances: “8, 38keV” (?) and 665 keV
- 1/2+ resonances: sub-threshold + 1.45 MeV

Where are the $3/2^+$ states close to the ^{18}F + p threshold?

- Very high resolution measurement using the Q3D magnetic spectrometer at MLL (Munich) → resolution 14 keV (FWHM)
- Population of the ^{19}Ne states using the charge exchange ^{19}F(^{3}He,t)^{19}Ne reaction (E = 25 MeV, CaF_2 50 $\mu g/cm^2$)
- Three resonances above ^{18}F + p threshold at 5, 29 and 48 keV instead of the two previously assumed at 8 and 38 keV
- Angular distributions not consistent with $3/2^+$ states
- The uncertainty associated with the 48 keV resonance only results in a factor ~2 uncertainty in the final ^{18}F yield

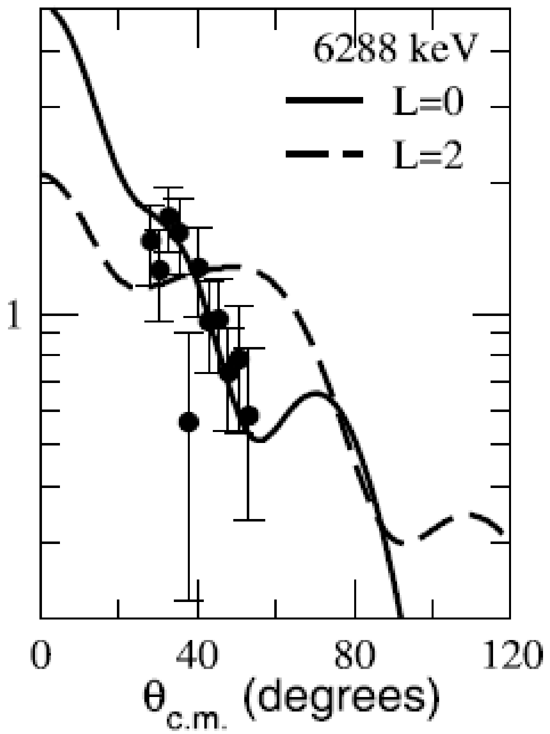


Laird et al. PRL (2013)

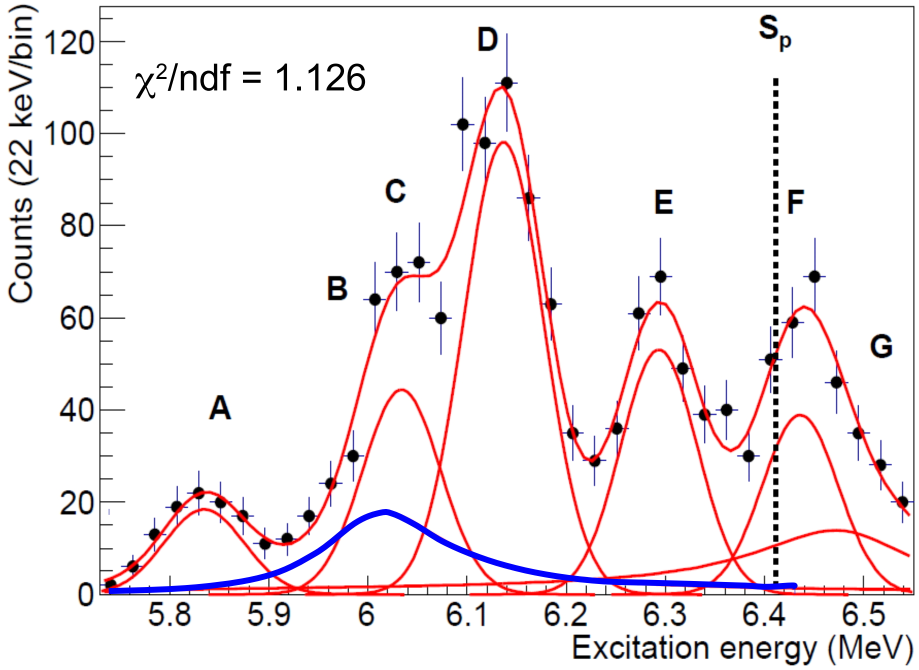
Sub-threshold $1/2^+$ resonances?

^{20}Ne(p,d)^{19}Ne @ HRIBF

Bardayan et al. PLB (2015)



^{19}Ne(p,p')^{19}Ne(α)^{15}O @ GANIL



Boulay et al. to be submitted

- $J^{\Pi} = 1/2+$ ($\ell = 0$) for sub-threshold resonance at -122 keV
- But, maybe a doublet or high spin state ($J > 3/2$)

Laird et al. PRL (2013)

- Evidence for new state at 6.02 (1) MeV [Γ_α = 120 (26) keV]

Dufour et al. NPA (2007)

- In line with theoretical predictions
- Reaction rate 5 times larger than previously → ^{18}F yields reduced by a factor 2-4

$^{18}F(p,\alpha)^{15}O$

Where do we stand? Where do we go?

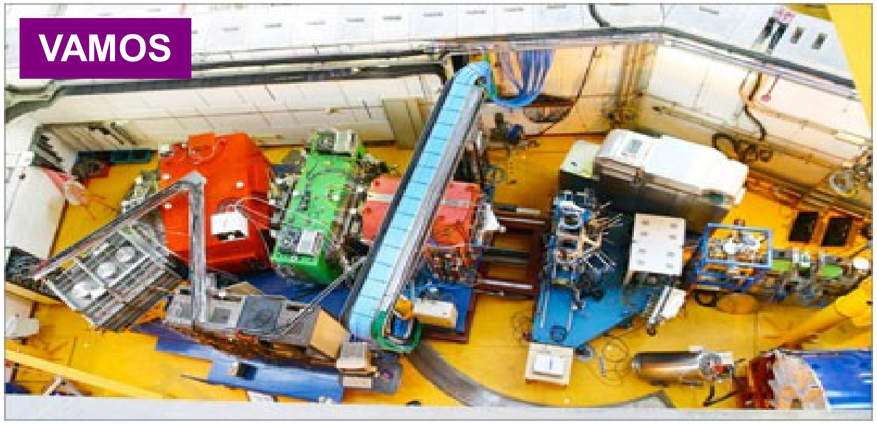
- Since Coc et al. 2000, more than 25 peer reviewed experimental papers, more than 6 PhDs!

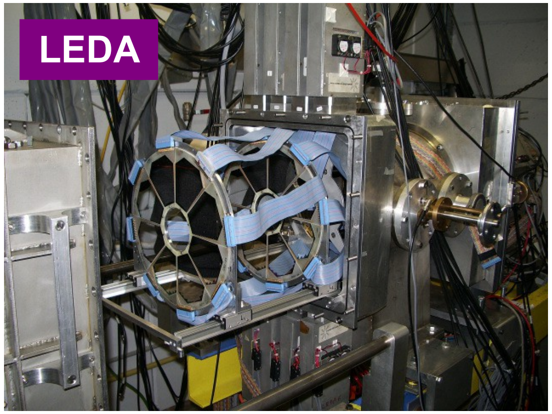
- Many experimental approaches
  - Direct measurements
  - Indirect measurements (transfer, charge exchange, Trojan Horse Method…)

- Many facilities
  - Stable beams: Orsay (France), Munich (Germany), ORNL (USA), Yale (USA), ...
  - Radioactive Ion Beams: Louvain-la-Neuve (Belgium), ORNL (USA), TRIUMF (Canada), GANIL (France), CNS (Japan), ...

- Many experimental setups
  - Charged particle array, γ-ray array, magnetic spectrometer, ...

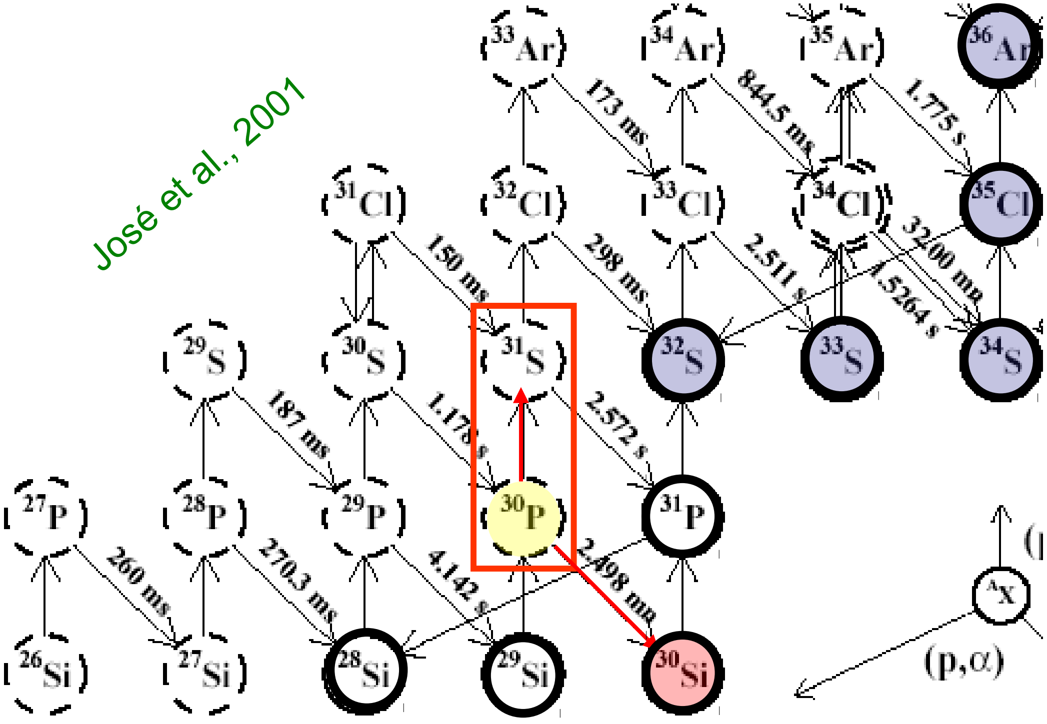
Still difficult to give a reliable reaction rate!





Classical novae and the ^{30}P(p,γ)^{31}S reaction

Nucleosynthesis network (massive white dwarf)



José et al., 2001

Isotopic observations

→ a few SiC and graphite grains show isotopic ratio indicating a likely nova origin

→ high ^{30}Si/^{28}Si ratio

(Amari et al., 2001, Liu et al., 2016)

Elemental observations

→ provide constraints on peak temperature and mixing parameter

→ P/Al, O/S, S/Al, O/P and Si/H (uncertainty up to a factor of 6)

(Downen et al., 2013, Kelly et al. 2013)

Sensitivity studies

(José et al., 2001, Iliadis et al. 2002, Parikh et al. 2011)

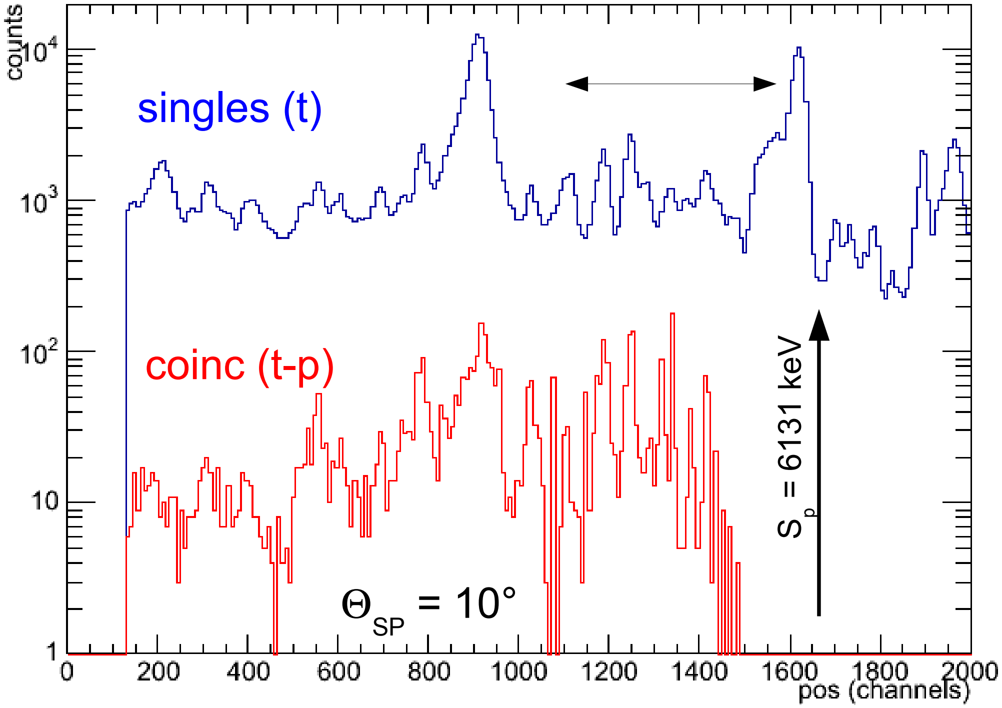
→ ^{30}P(p,γ)^{31}S

- gateway reaction for production of A = 30 – 38 elements
- abundance of these elements depends strongly on its reaction rate

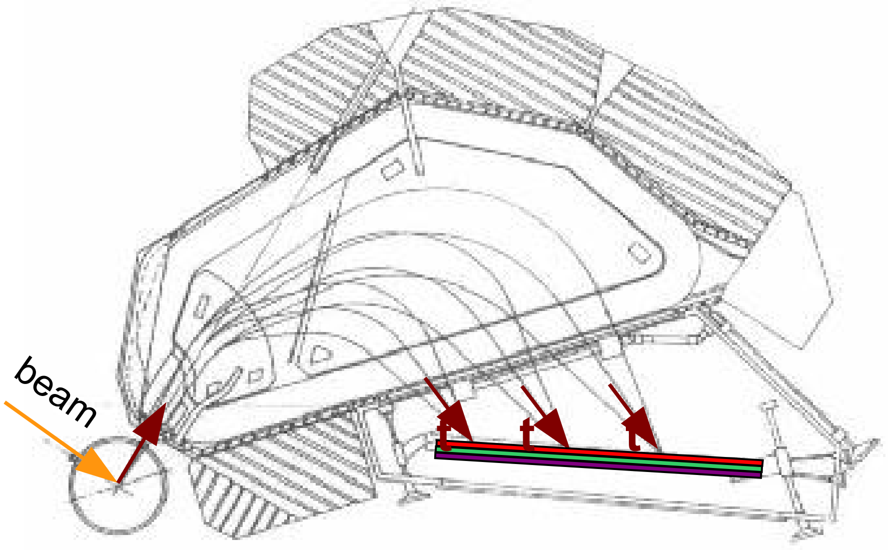
Experimental approach

- The (^{3}He,t) charge exchange reaction has already shown to be very little selective in populating ^{19}Ne excited states.
- Coincidence measurement, ^{31}S states decay via p emission

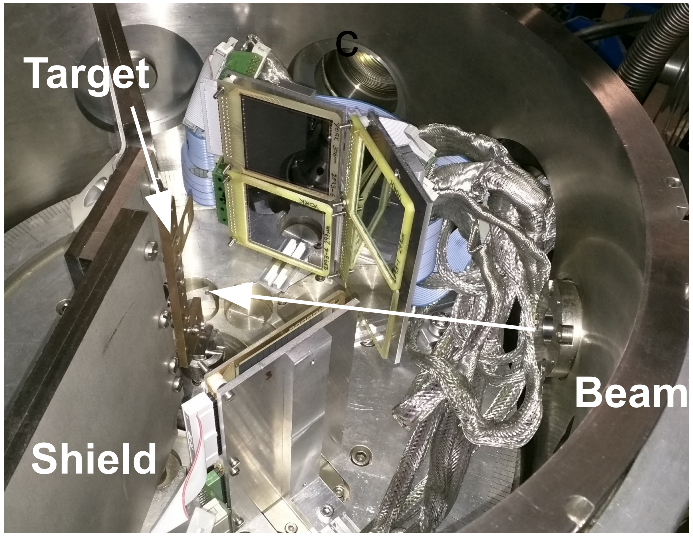
E(^{3}He) = 25 MeV I(^{3}He) ~ 100 enA ^{31}P ~ 60 μg/cm^{2}



Branching ratio determination (A. Meyer, PhD)

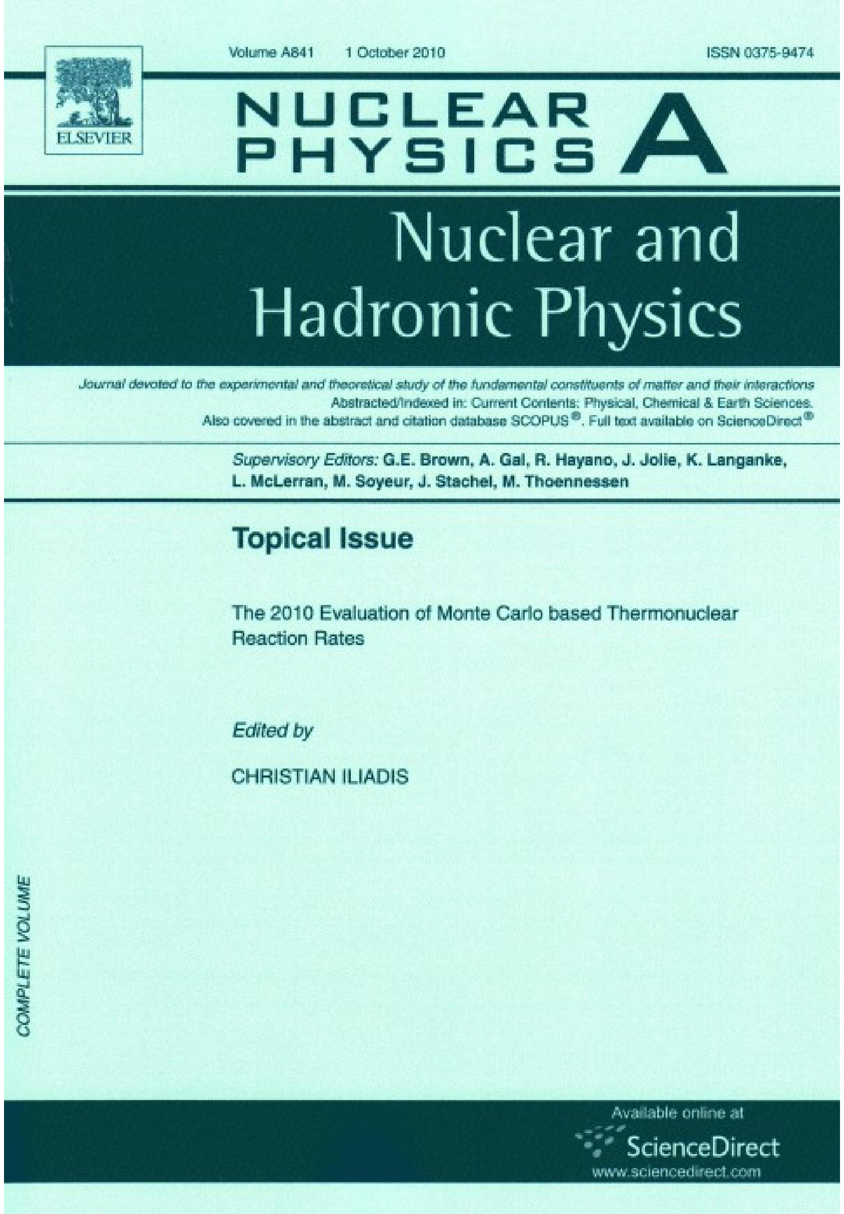


Split-Pole spectrometer ΔE/E ~ 10^{-4}



Silicon array (DSSSD) around target

End notes



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NUCLEAR PHYSICS A

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Topical Issue

The 2010 Evaluation of Monte Carlo based Thermonuclear Reaction Rates

Edited by

CHRISTIAN ILIADIS

COMPLETE VOLUME

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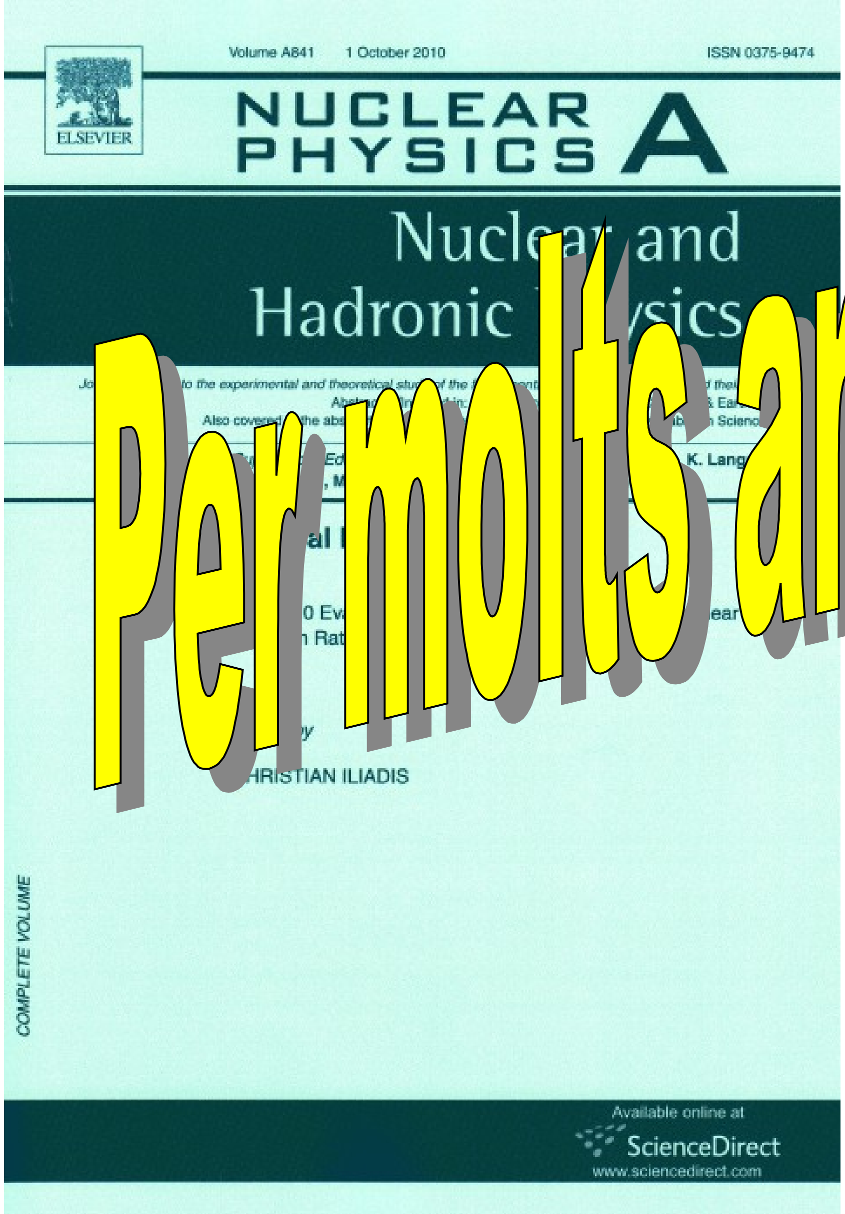
- Determination of cross section for a single nuclear reaction can be a (very) long task

- However, classical novae will become soon the first explosive site for which all nucleosynthesis network is based on experimental data.

- A few reactions are still the focus of strong experimental efforts
  - $^{18}F(p,\alpha)^{15}O$
  - $^{25}Al(p,\gamma)^{26}Si$
  - $^{30}P(p,\gamma)^{31}S$

End notes



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NUCLEAR PHYSICS A

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Per molts anys Margarita

- Classical novae will become soon the first explosive site for which all nucleosynthesis network is based on expe ntal data.

- A fe focus of strong exp
  - $^{18}F(p,\alpha)^{15}O$
  - $^{25}Al(p,\gamma)^{26}Si$
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