Study of stellar nucleosynthesis using radioactive beams at GANIL

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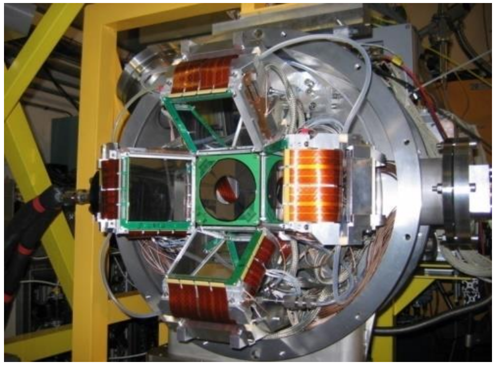
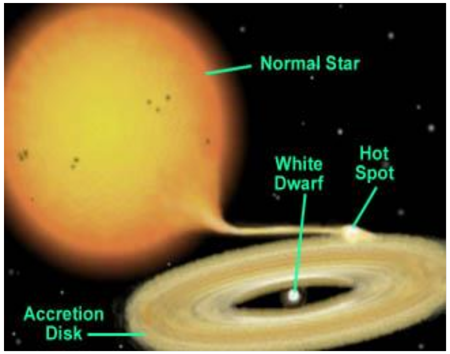
Joint LIA COLL-AGAIN, COPIGAL, and POLITA workshop LNS Catania, April 26-29, 2016

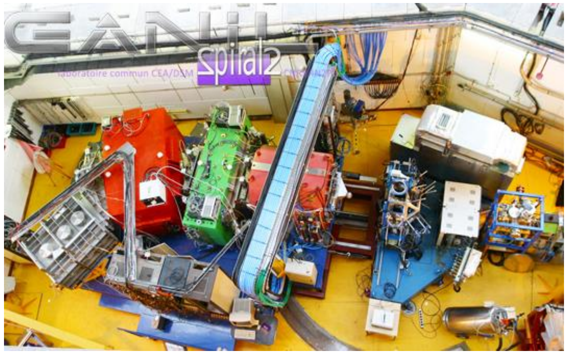
Nuclear astrophysics @ GANIL

- ^{60}Fe nucleosynthesis & γ-ray astronomy
  Coll. IPN-GANIL-IRFU-CSNSM-RIKEN
  S.Giron, F. Hammache, N. de Séréville, P. Roussel et al. Ph.D. thesis & paper in progress





- ^{18}F nucleosynthesis in novae
  → 2 experiments
  Coll. GANIL-Edimbourgh-IPN-York-CSNSM
  • F. Boulay, B. Bastin, F. de Oliveira et al.
  Ph.D. thesis & paper in progress
  • D. J. Mountford, A. Murphy et al. PRC 2012



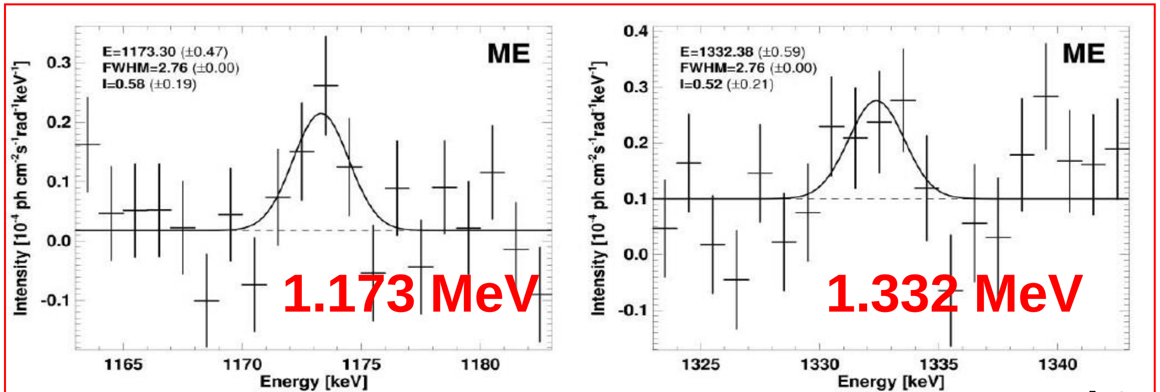
- Electron screening effect on β-decay studies
  Coll. GANIL-VINCA-LPC-Bucharest-IPN-CSNSM-CEA-CRISMAT
  P. Ujic, F. de Oliveira, M. Lewitowicz et al. PRL 2013

- Test experiment for direct measurements of $\sigma_{(\alpha,g)}$ of p-nuclei using the Wien Filter of LISE
  Coll. NCSR(Demokritos)-GANIL

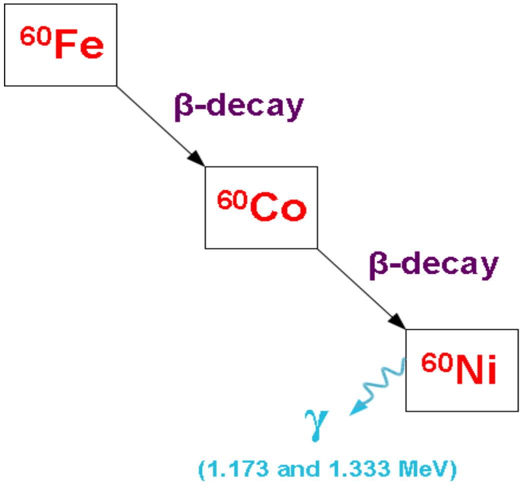
^{60}Fe nucleosynthesis & γ-ray astronomy

Detection of ^{60}Fe by **RHESSI (2004)** & **INTEGRAL (2007)**

^{60}Fe ($T_{1/2}$=2.6 10^6 yr)



Wang et al. 07

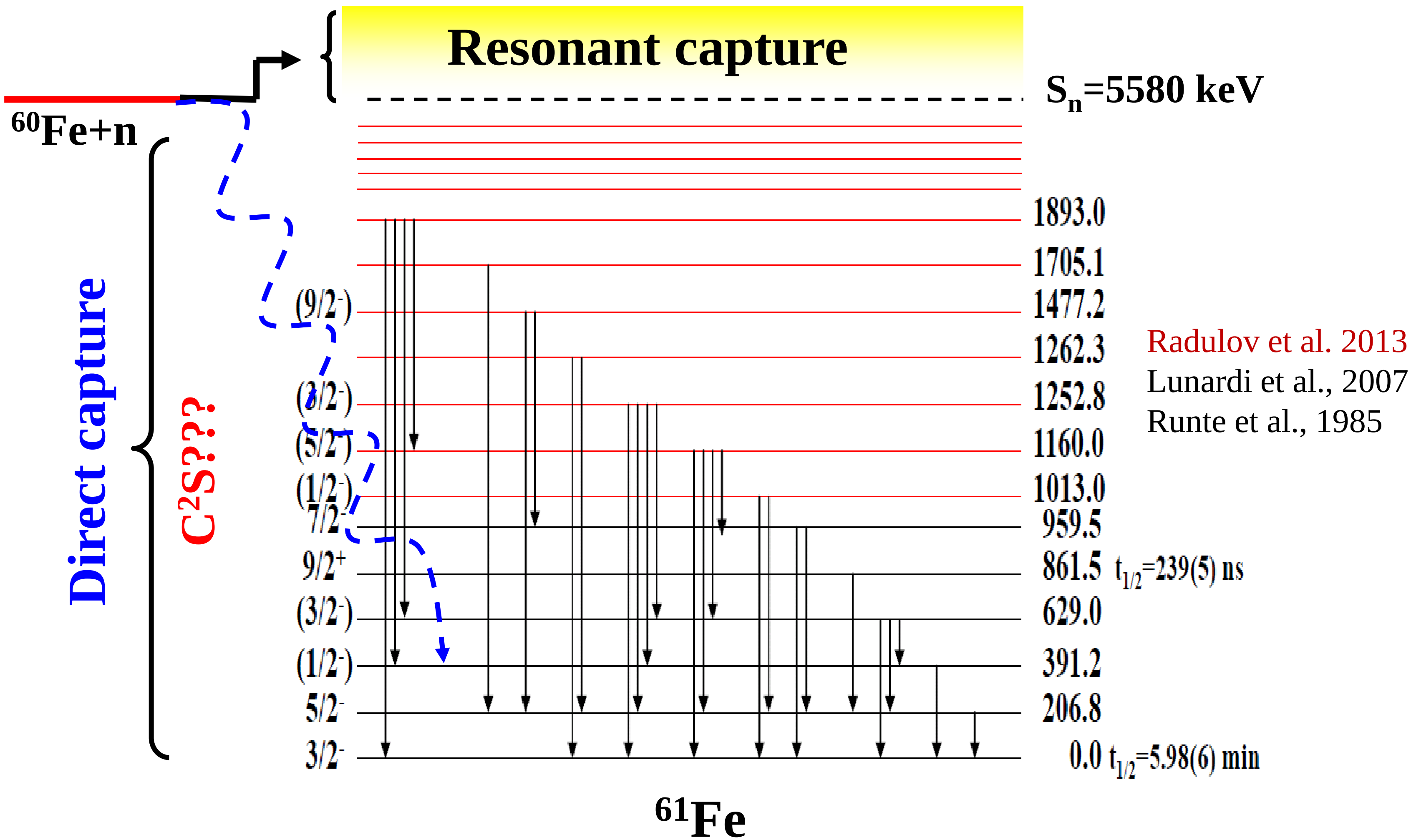


^{60}Fe mainly produced in massive stars & released in ISM by subsequent Core Collapse supernovae type II → **Stellar model test**

Production of **^{60}Fe** depends strongly on the uncertain ^{59}Fe(n,γ)^{60}Fe & **^{60}Fe(n,γ)^{61}Fe** cross sections

$^{60}Fe(n,\gamma)^{61}Fe$ status

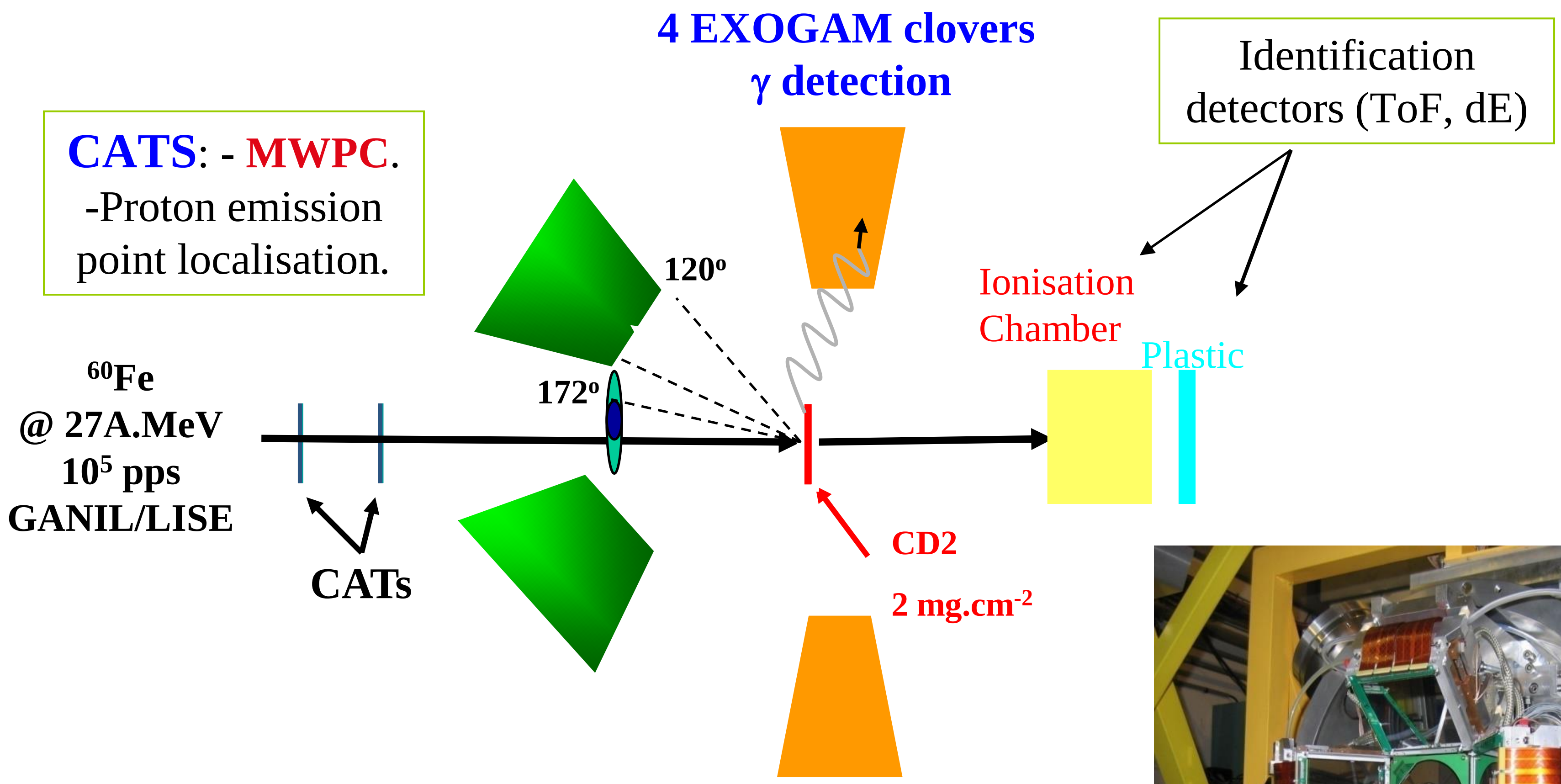
Reaction rate: HF calculations (resonant capture) + shell-model (direct capture)

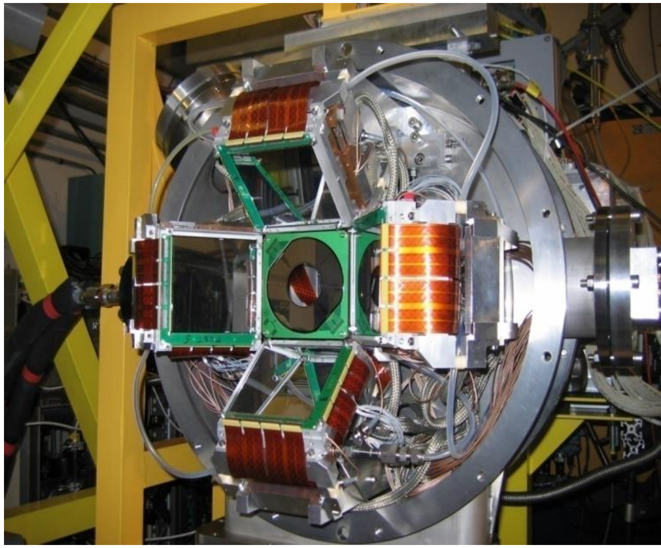


Direct $\sigma_{60Fe(n,\gamma)61Fe}$ $\rightarrow$ E_x, l & C^2S of ^{61}Fe $\rightarrow$ (d,p) transfer reaction

Study of the direct component $^{60}Fe(n,\gamma)^{61}Fe$ via $^{2}H(^{60}Fe,p\gamma)^{61}Fe$ transfer reaction @ LISE/GANIL

(Collaboration IPNO/GANIL/IRFU/IPHC/LPC/CSNSM/RIKEN/GSI/LISBOA)



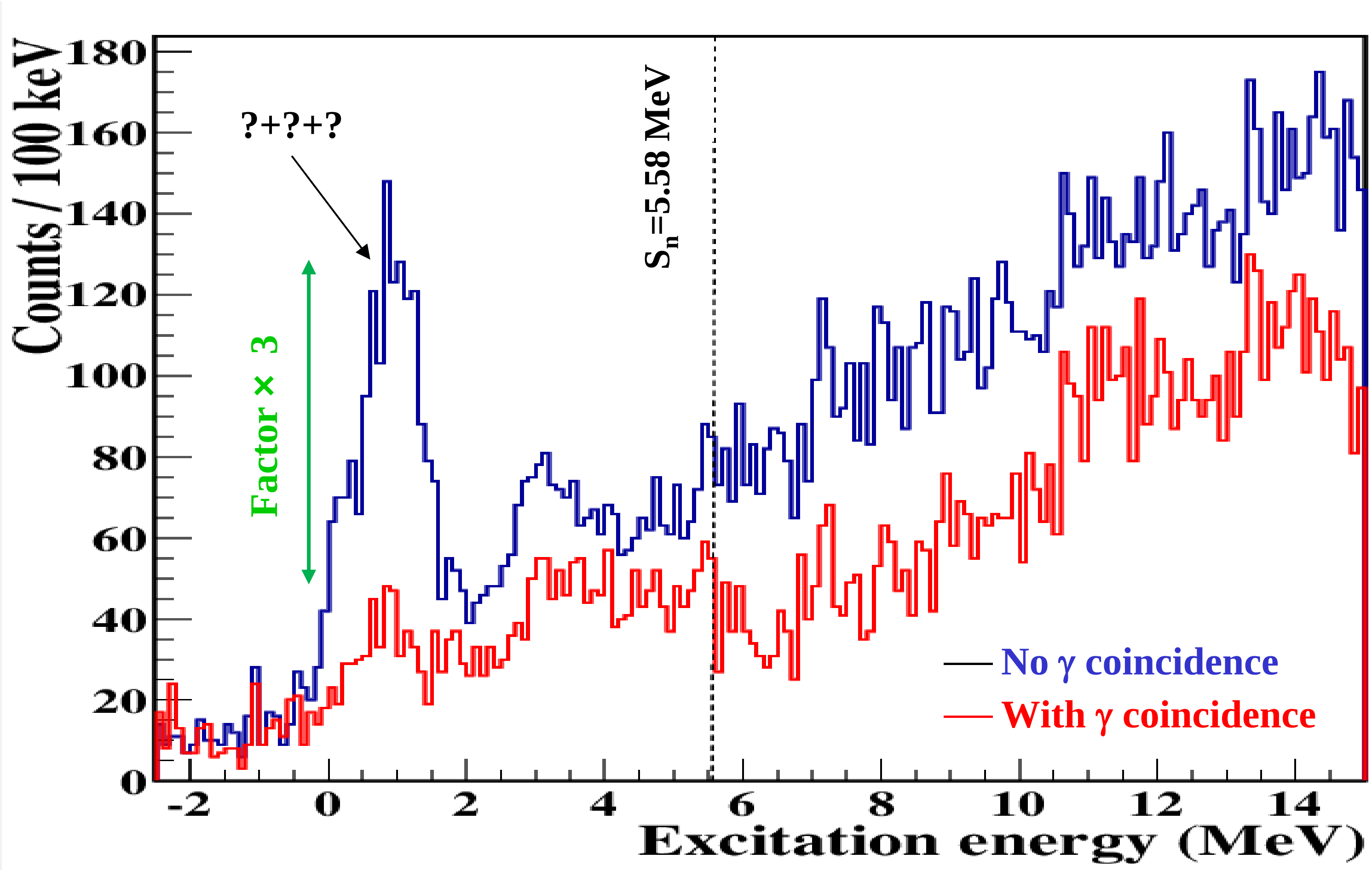


MUST2 : -**Si Strips (300µm)** + **SiLi** (4.5 mm) detectors.

- Proton **impact localisation.**
- Proton **energy** measurement.

S1: Si annular detector (500 µm, 64 strips in Θ and 16 in Φ)

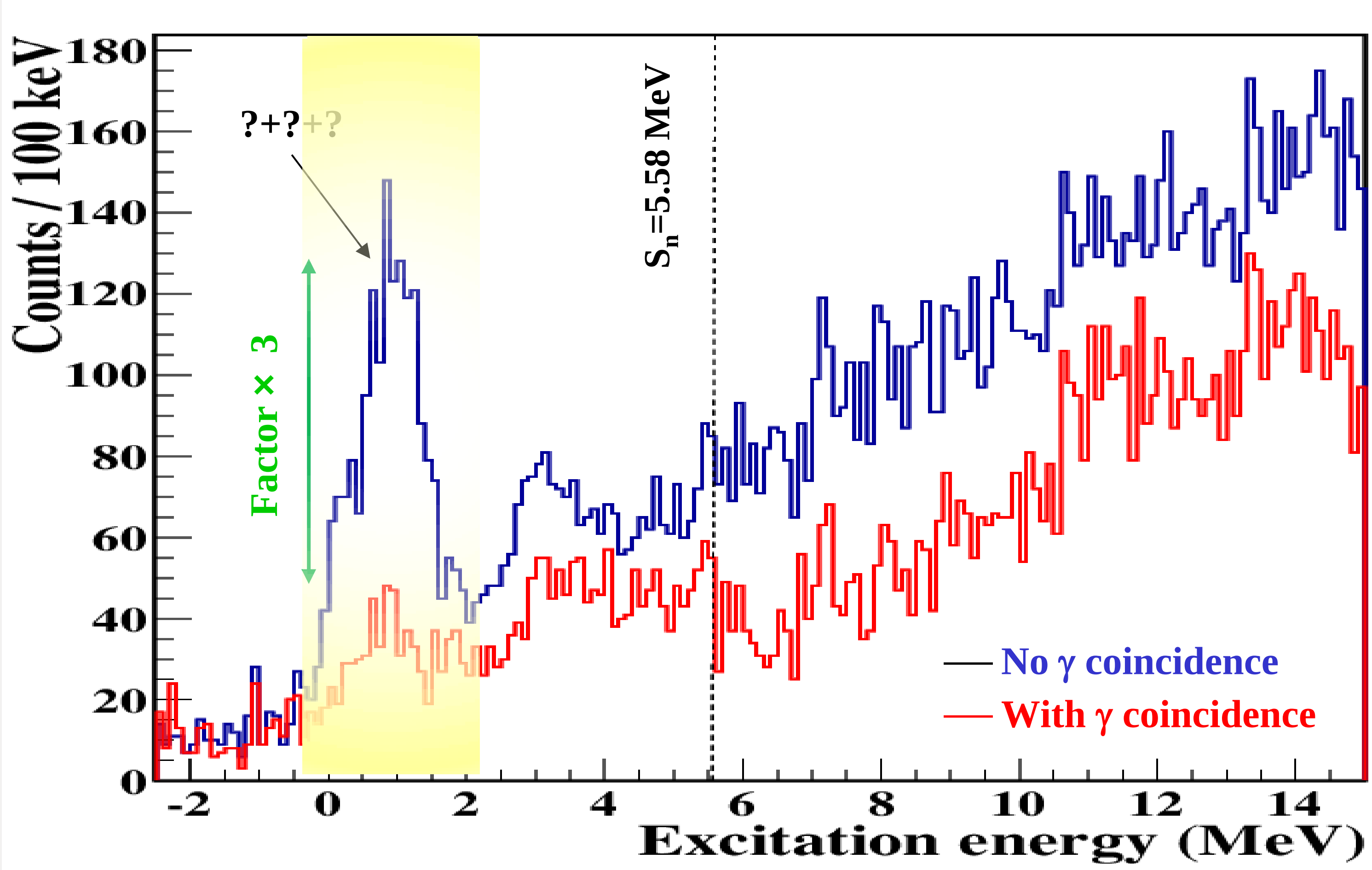
Experimental Results: ^{61}Fe excitation energy spectrum



- FWHM(peak) > 800 keV (expected energy resolution) ➔ population of 2-3 states
- Population of the 861 keV (J^{π}=9/2+) isomeric state (τ=239 ns)

S. Giron PhD. thesis

Experimental Results: ^{61}Fe excitation energy spectrum



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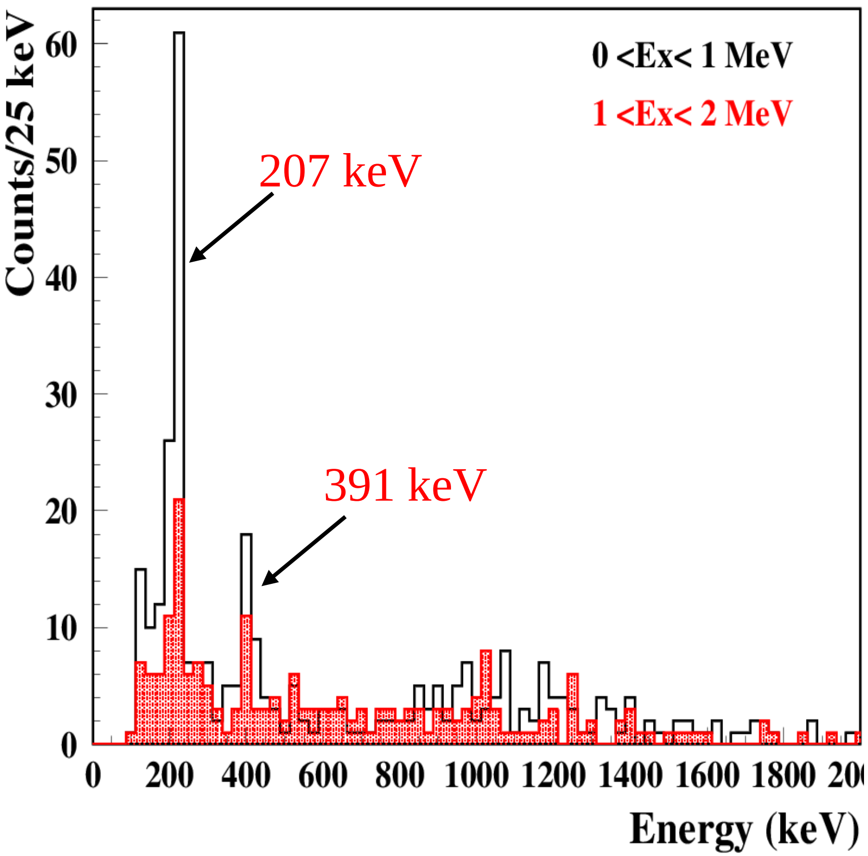
S. Giron PhD. thesis

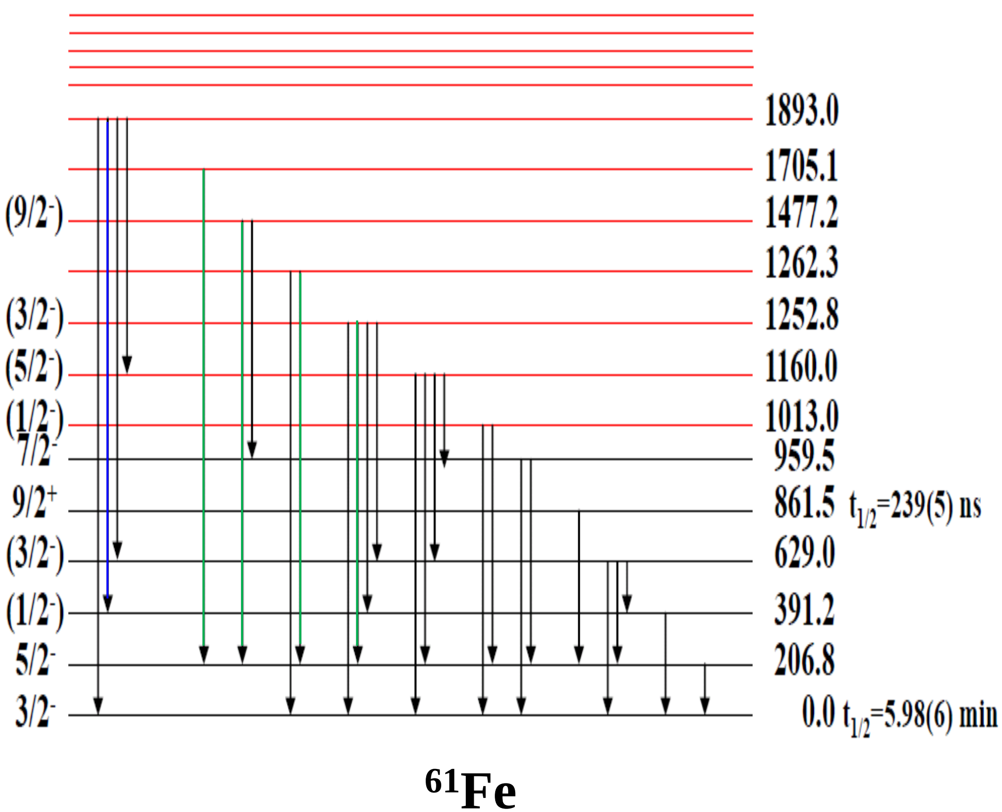
Experimental Results : γ-ray spectra (1st peak)

γ-ray spectra



Results of β decay of ^{61}Mn to ^{61}Fe levels

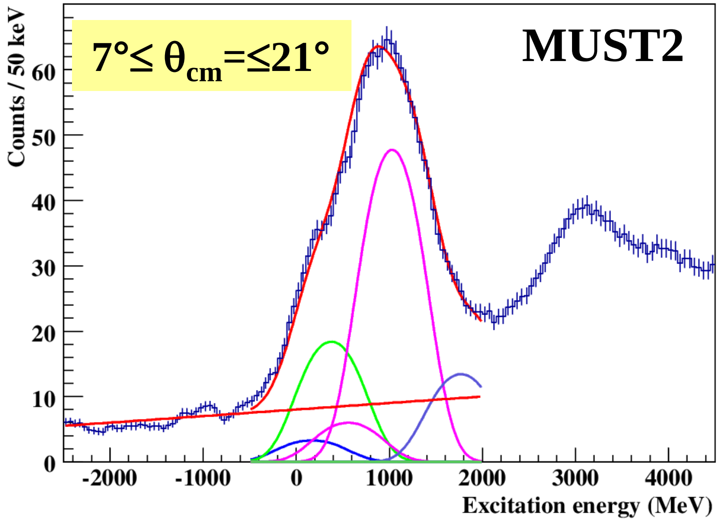
Radulov et al. PRC88, 014307 (2013)

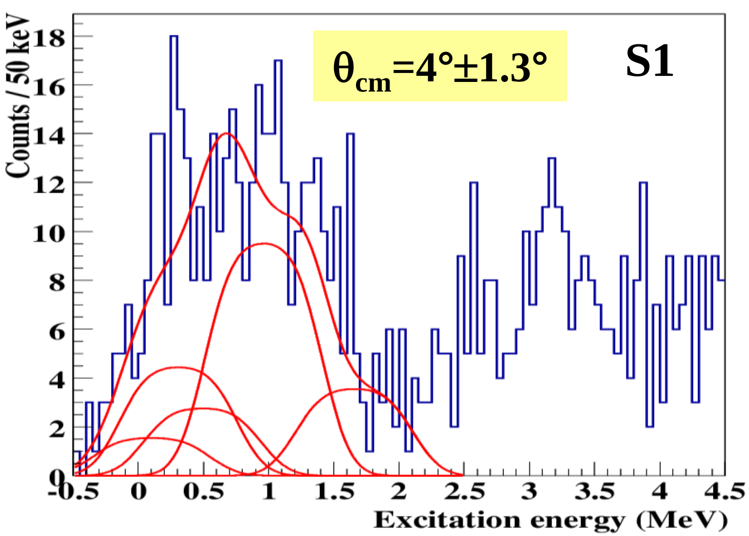


- Population of **207 & 391 keV** states in the 1st peak
- No clear identification of the γ-ray partners of the 207 & 391 keV transitions in the range 1 MeV <Ex<2 MeV → large background, low statistics (low cross sections, efficiency ↘)

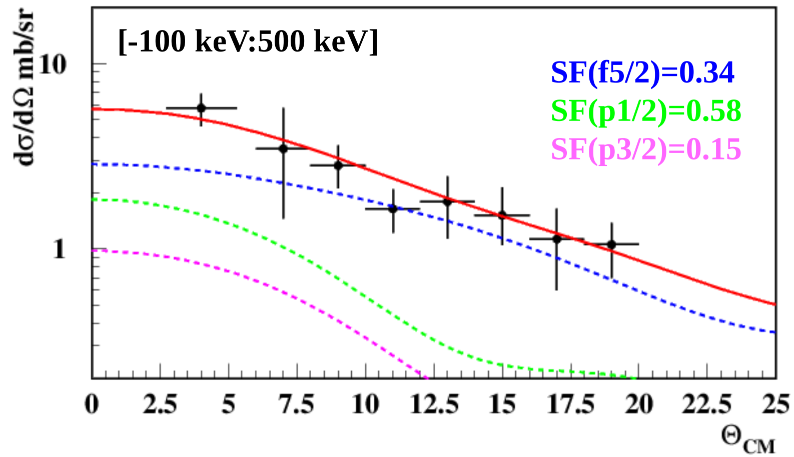
Experimental Results: Spectroscopic factors

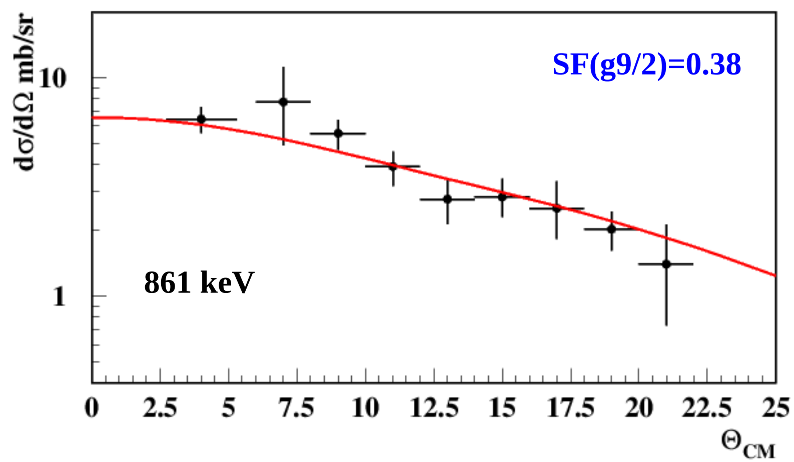
Deconvolution with: **gs, 207, 391, 861 keV** & a higher level ~ ”1600 keV”





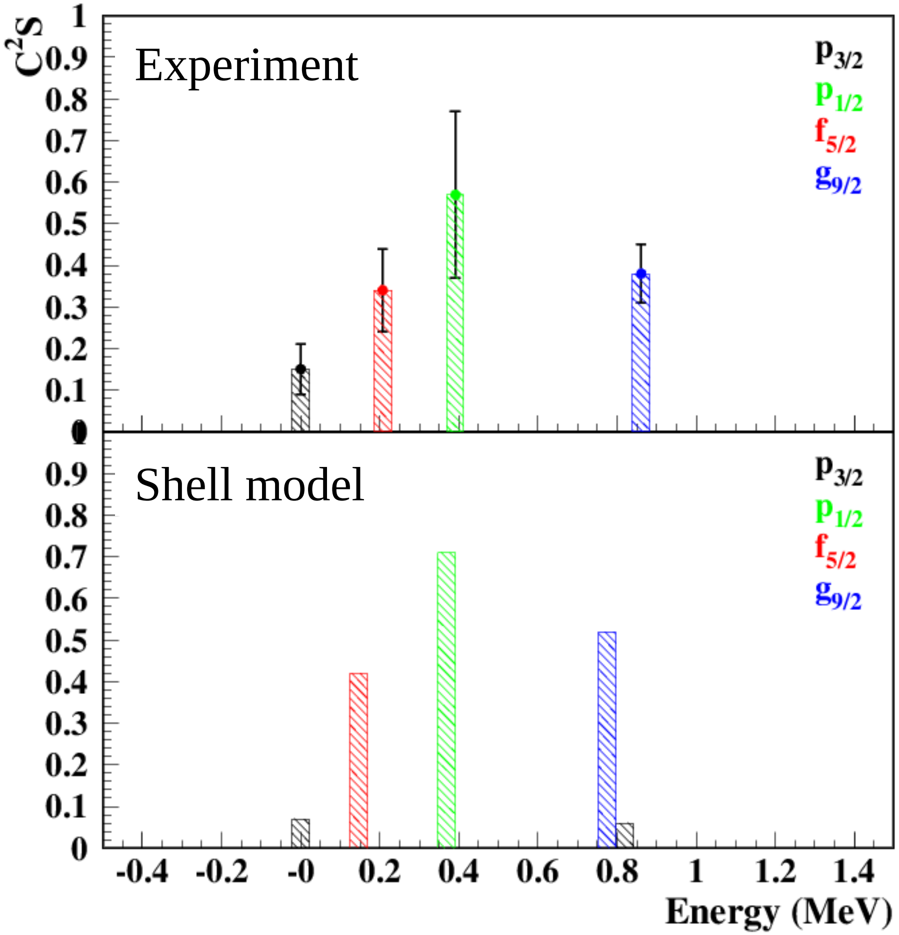
Zero-range ADWA calculations





S =**0.15±0.06** (p3/2 gs)
S =**0.34±0.10** (f5/2 207 keV)
S =**0.58±0.20** (p1/2 391 keV)
S =**0.38±0.07** (g9/2 861 keV)

Comparison with shell model calculations



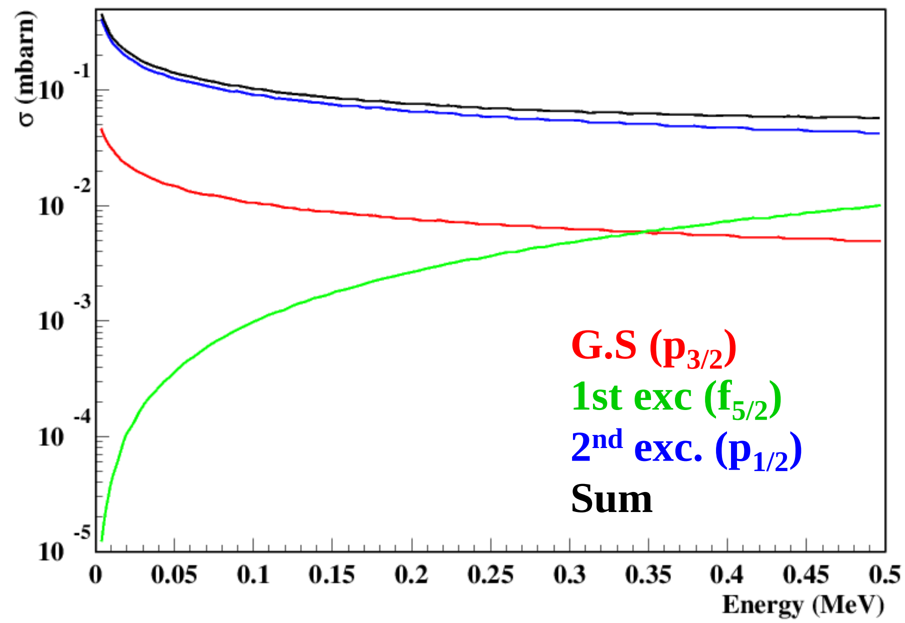
Very **good agreement** between SM predictions (**K.Sieja**) & experimental results

→ **SM calculations are reliable in this mass region**

Direct $\sigma_{^{60}Fe(n,\gamma)^{61}Fe}$

$$\sigma_{(n,\gamma)} = \sum_i C_i^2 S_i \sigma_i^{DC} = \sum_i C_i^2 S_i \left| \int_{r=0}^{\infty} \phi_f \theta_{em} \phi_i d\vec{r} \right|^2$$

TEDCA code: K.Krauss

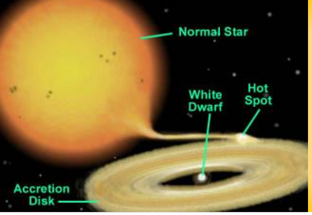


@ 25 keV:

σ_{total}=10 mbarn (Activation measurement)

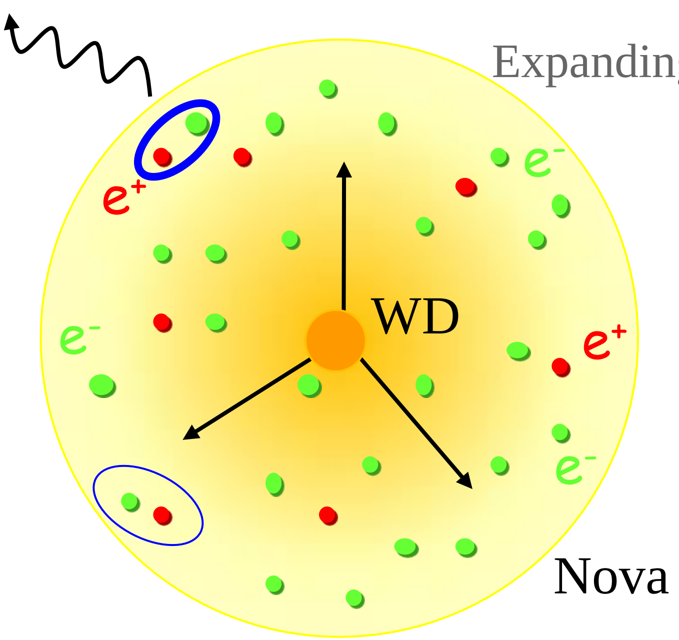
This work: σ_{direct} =0.2 mbarn → **2%** (total)

→**Resonant capture dominates**



^{18}F nucleosynthesis & novae

^{18}F ($T_{1/2}$ = 2h) β+ emitter
→ e+ e- interaction
→ Main contributor to 511 keV γ-rays during nova outburst



Uncertainty ≈ 40 on the γ-ray flux

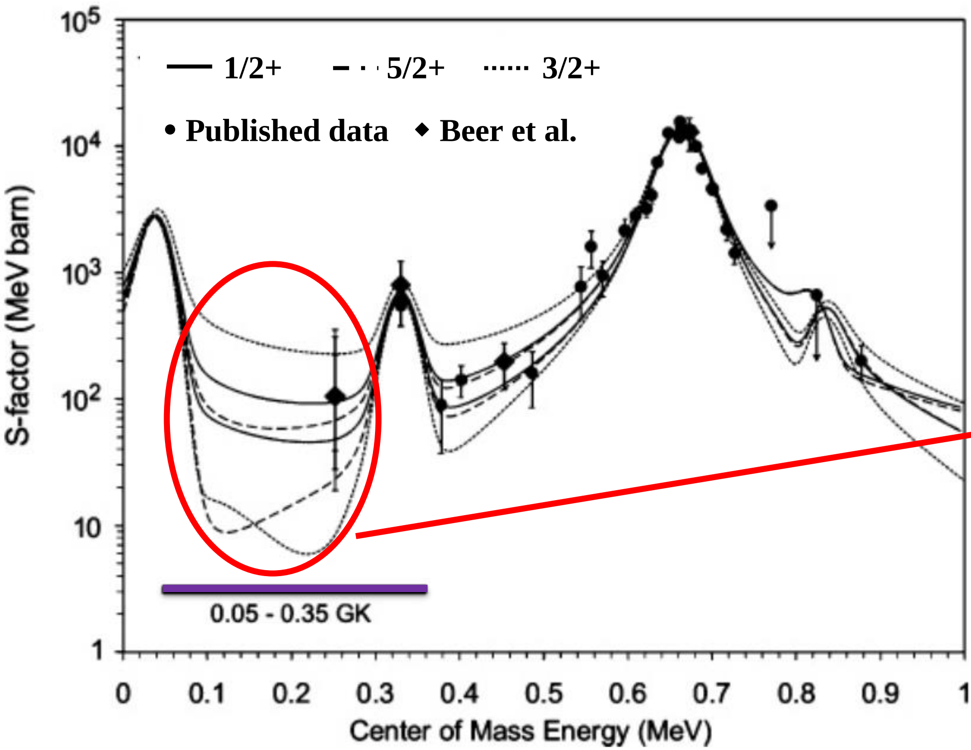
- The detection of the 511 keV radiation would provide insight into nova mechanism
- The amount of ^{18}F produced in nova explosion depends critically on the rates of $^{18}F(p,\alpha)^{15}O$ & $^{18}F(p,\gamma)^{19}Ne$ @ T = 1-4×10^8 K
- The competition between $^{18}F(p,\alpha)^{15}O$ and ^{18}F β-decay has consequences on a possible observation of the 511 keV γ-ray from novae (ex: Integral): *not yet detected*

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

Direct measurements

- Cross section of ^{18}F +p (inverse kinematics)
  - Low beam intensity
  - Beam impurities (^{18}O)
  - Low cross section

Mountford et al. 2012
Beer et al. 2011
de Séréville et al. 2009
Chae et al. 2006
Bardayan et al. 2003



Indirect measurements

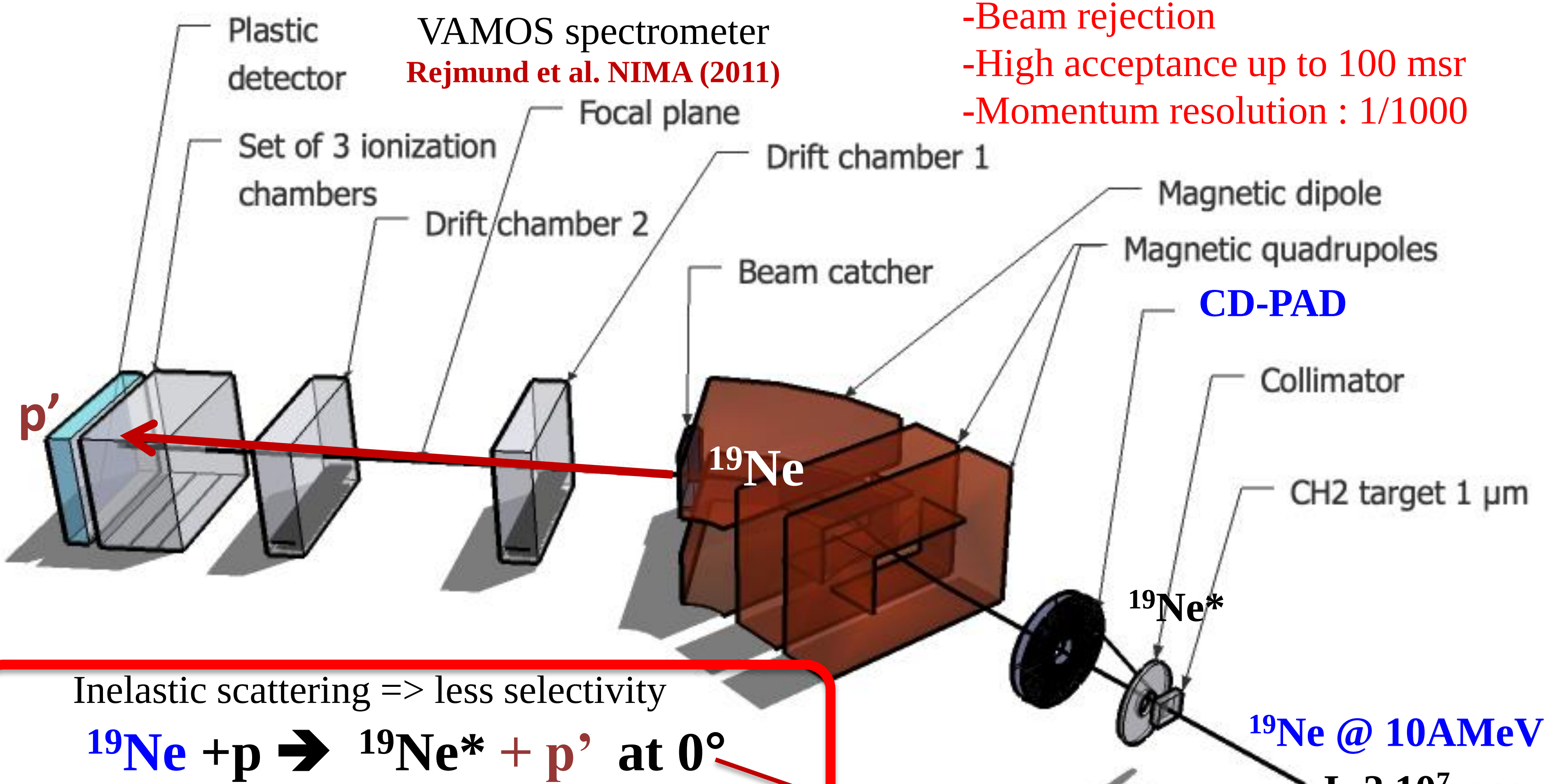
- Study of ^{19}**Ne** or the mirror nucleus ^{19}**F** → properties (**Ex, Spin, width**) close to proton threshold

- **Cherubini et al. 2015 (THM)**
- **Laird et al. 2013 (Transfer)**
- **Adekola et al. 2011 (Transfer)**
- **Dalouzy et al. 2009 (Inelastic scattering)**
- **Murphy et al. 2009 (Resonant elastic scattering)**
- **de Séréville et al. 2007 (Transfer)**
- **Bardayan et al. 2001 (Transfer)**
- **Utku et al. 1998 (Transfer)**

Large uncertainties on the astrophysical S-factor at the Gamow peak: **factor ~ 40**
→ Ambiguities in the spin assignment

Experimental Setup

- Beam rejection
- High acceptance up to 100 msr
- Momentum resolution : 1/1000



Inelastic scattering => less selectivity

^{19}Ne +p → ^{19}Ne* + p’ at 0° → Ex, Γ

10 MeV/u

S_p = 6.41 MeV

S_a = 3.52 MeV

γ

^{19}Ne

p’’ + ^{18}F

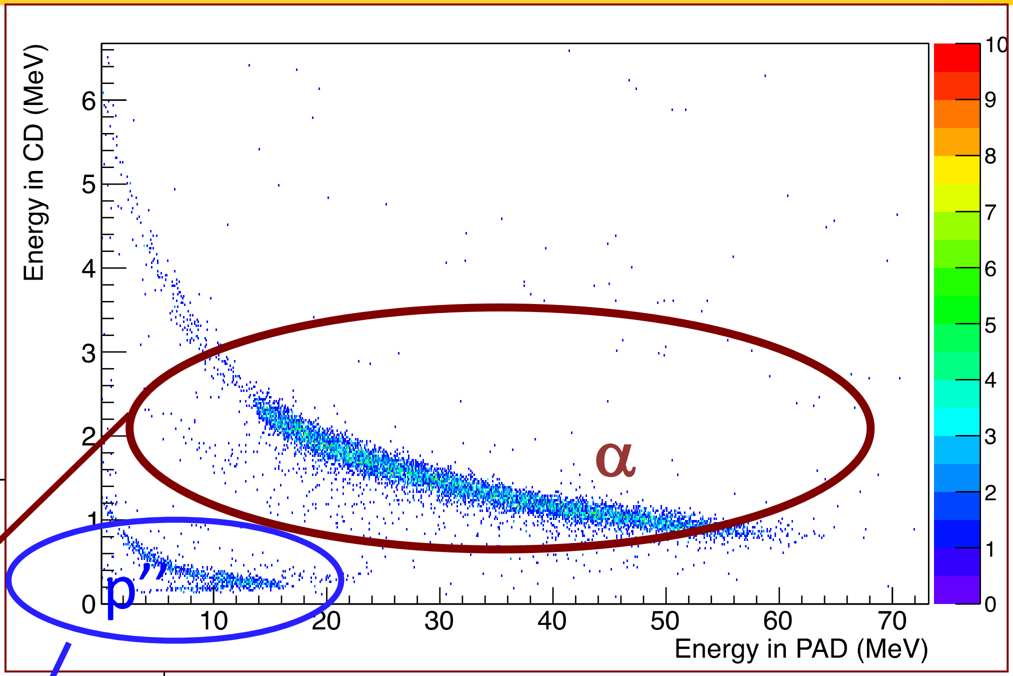
α + ^{15}O

Detected in **CD-PAD**

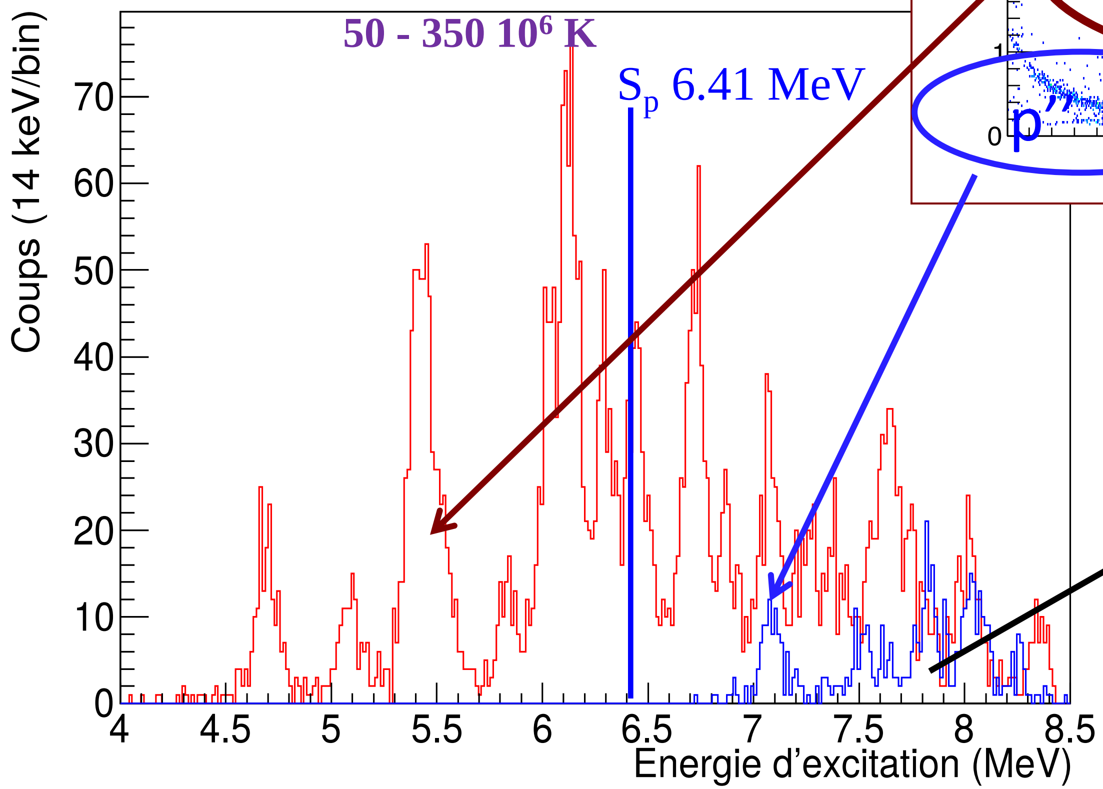
Angular correlations → **J**
Decay branching ratios

Results: Excitation energy, width and branching ratio

Energy resolution σ = 33 to 39 keV limited by the target thickness (1 μm)
(Dalouzy et *al.* PRL 2009 got σ = 59 keV)



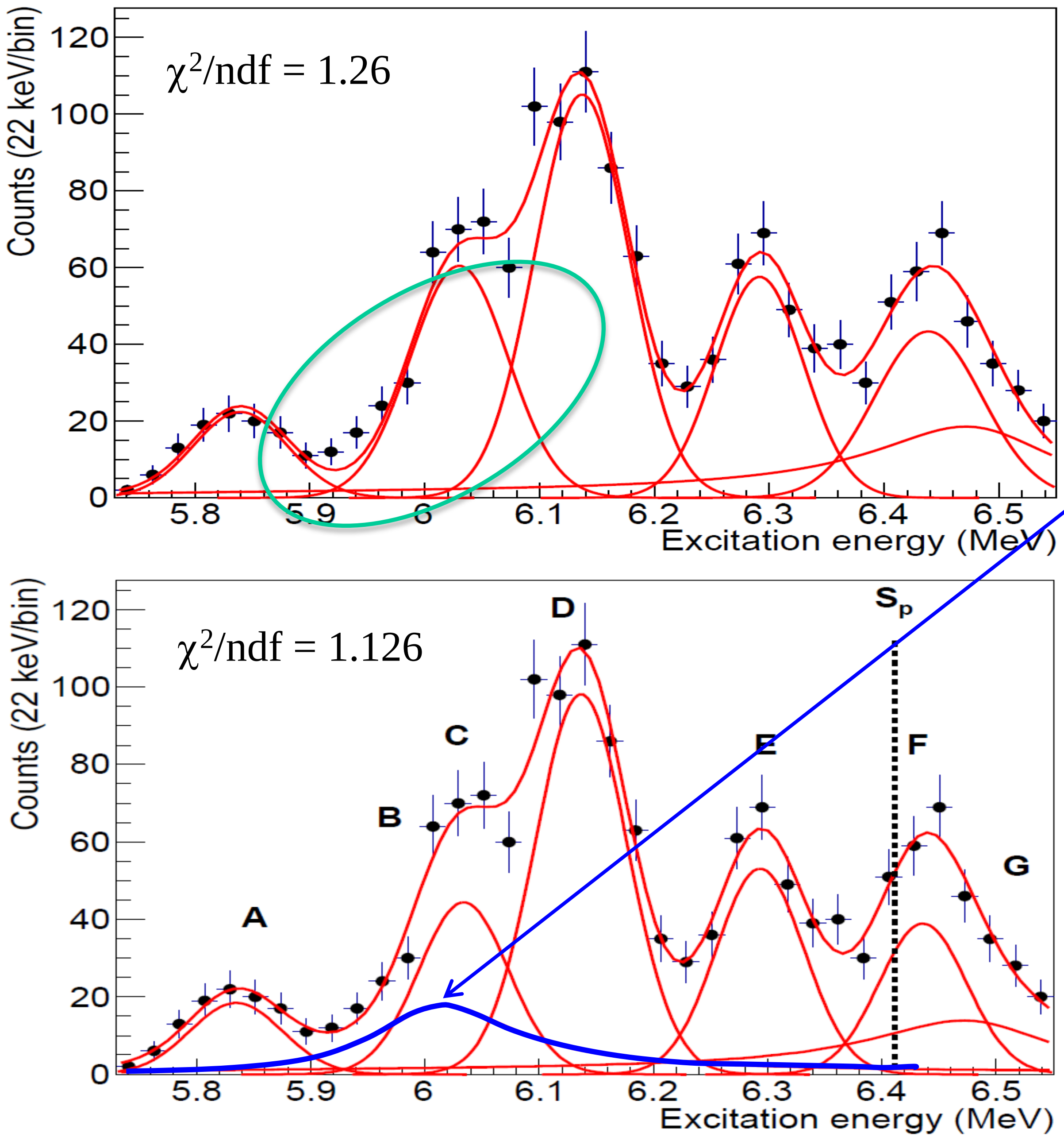
Coincidence spectra



Low background
Extraction of branching ratios and partial widths

F. Boulay Ph.D. thesis

Results: Analysis of key states



1 evidence for a new state

E_x = **6.02(1) MeV**

Γ_α = **110(26) keV**

Result compatible with Descouvemont & Dufour theoretical prediction

E_x = 6 MeV

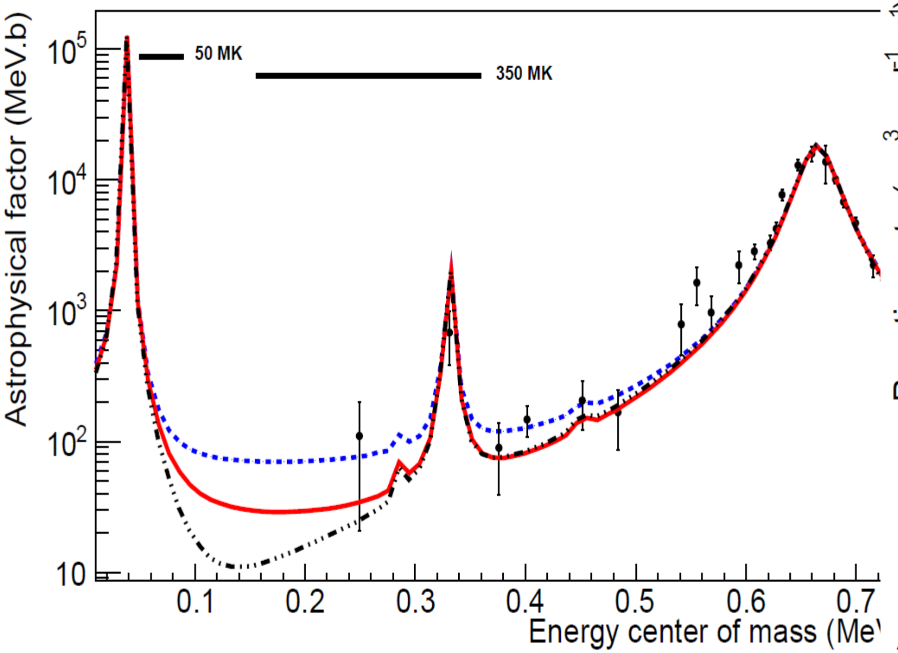
Γ_α = 231 keV

$J^\pi = 1/2^+$

Astrophysical S-factor & reaction rate

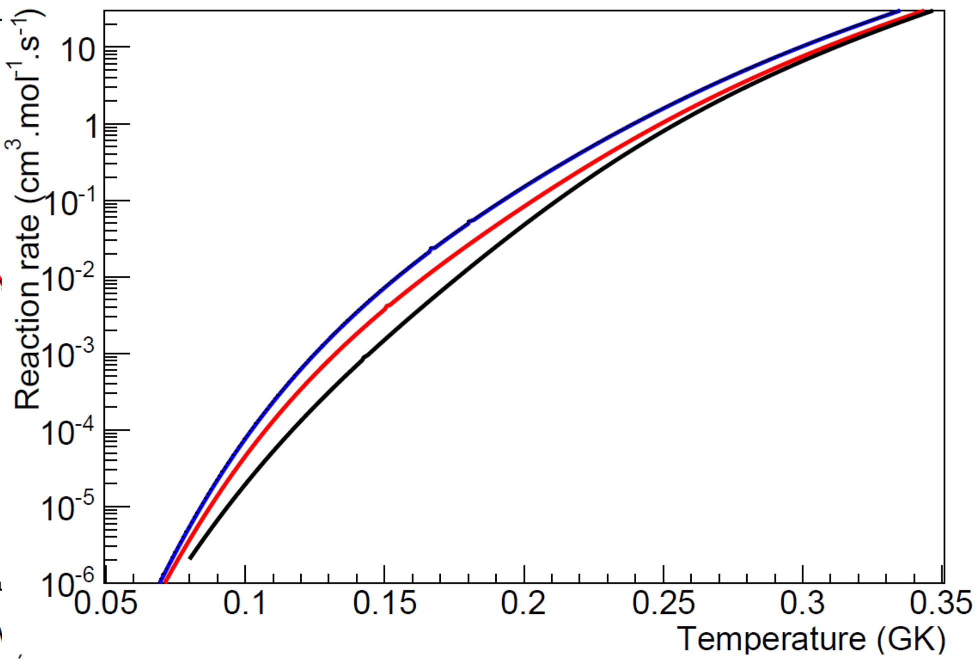
$^{18}F(p,\alpha)^{15}O$ astrophysical S-factor

- AZURE R-matrix code
- New ½+ broad resonance (this work)
- New ½+ resonance **Dalouzy et al. 2009**



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

$$\langle\sigma\upsilon\rangle_G = \sqrt{\frac{8}{\pi\mu}}\frac{1}{(k_bT)^{3/2}}\int_0^\infty E\sigma(E)\exp\left(\frac{-E}{k_bT}\right)dE$$



Lowest S-factor **Illiadis *et al.* NPA 2010**
with ½+ (+ -)
with the same sign of interference

Lowest rate **Illiadis *et al.* NPA 2010**
with ½+ (+ -)
with the same sign of interference

Astrophysical impact

Hernanz,Gomez-Gomar, José ,Coc (2001)

^{18}F detection limit for ONe 1.15 $M_{\odot}$ is 3.7 kpc

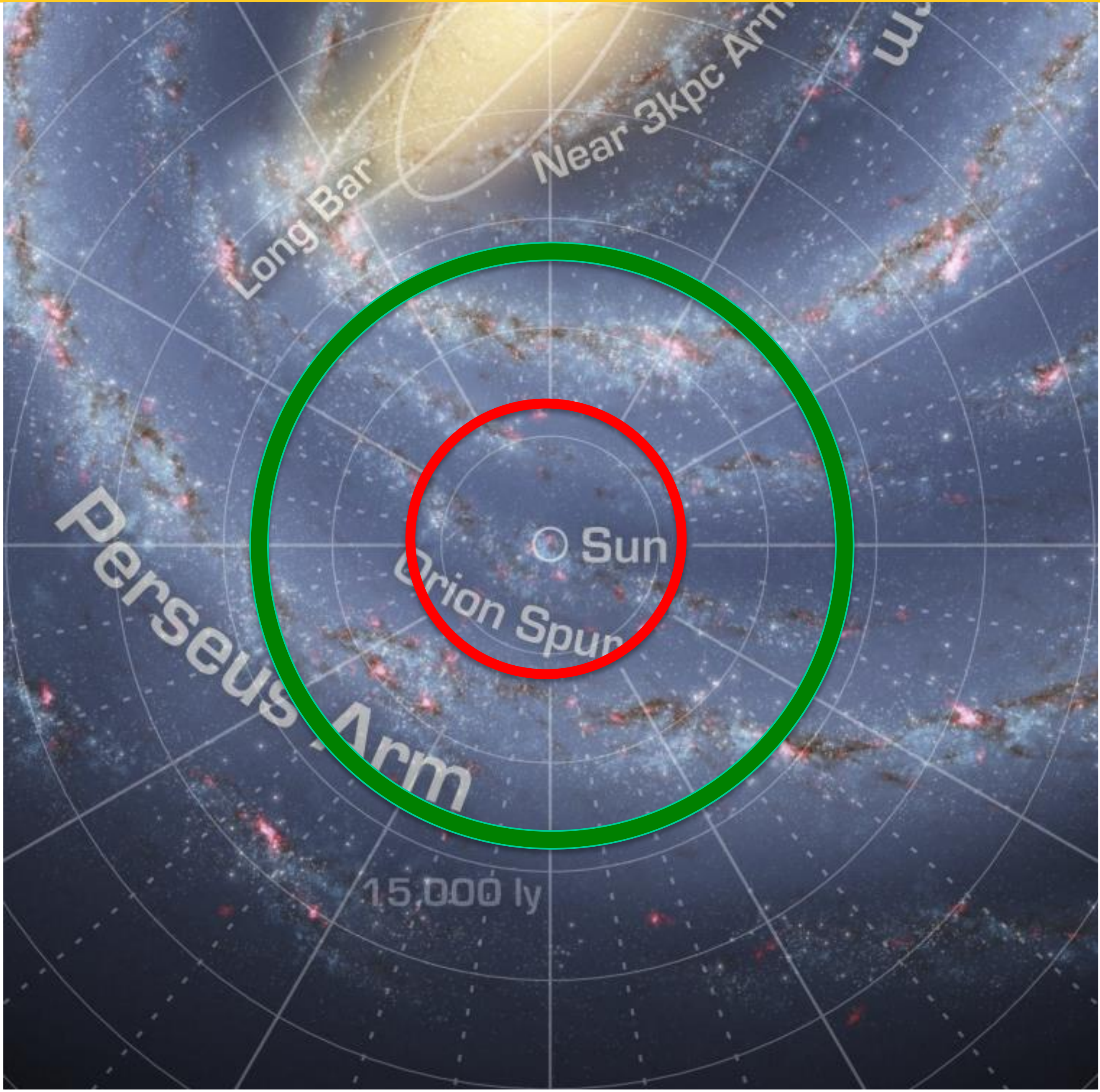
With N times less ^{18}F → limit radius of detectability reduces by $N^{1/2}$

This work: **N=5 → 1.7 kpc**

Nova detection probability for INTEGRAL :

- galaxy 30 novae per year
- 4 novae per decade

F. Boulay Ph. D. thesis



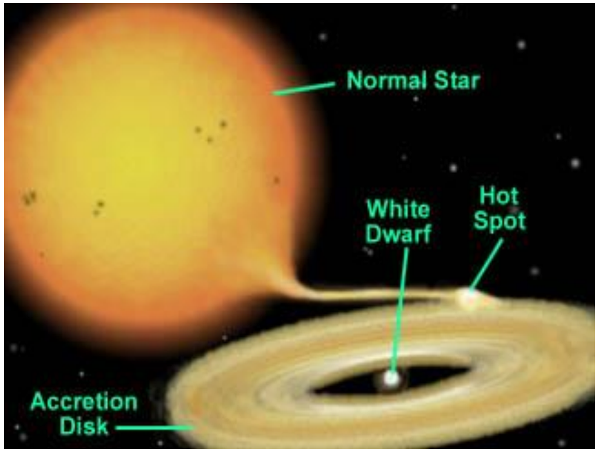
Perspectives @ GANIL

Study of key nuclear reactions involved in explosive nucleosynthesis with the new SPIRAL1 beams, new setups (ACTAR, MUGAST, …),…

Novae:

- using radioactive beams (SPIRAL1)

→ $^{25}Al(p,\gamma)^{26}Si$
→ $^{30}P(p,\gamma)^{31}S$
} Indirect measurements



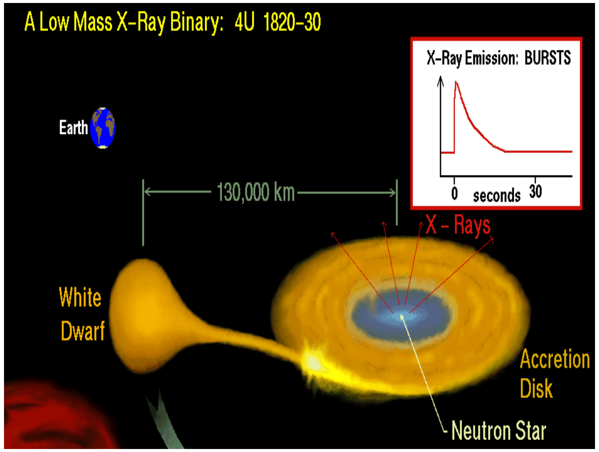
- using high intense proton beams of NFS

→ $^{28}Si(p,\gamma)^{29}P$
→ $^{29}Si(p,\gamma)^{30}P$
} Direct measurements

X-ray bursts:

- using radioactive beams (SPIRAL1 & LISE)

→ key (α,p) reactions at waiting points
→ key (p,γ) reactions at waiting points
} Direct & Indirect measurements



Collaborations

FRANCE

- IPN, Orsay
- GANIL, Caen
- CEA, IRFU, Saclay
- CSNSM, Orsay
- LPC, Caen
- IPHC, Strasbourg

UK

- University of Edinburgh
- University of York

SPAIN

- University of Huelva
- University of Santiago de Compostel

ROMANIA

- IFIN/HH,rez institires Bucharest

SERBIA

- VINCA Institute, Belgrade

CZECH REPUBLIC

- NRI, Rez

POLAND

- Niewodniczanski Institute, Krakow

GERMANY

- GSI, Darmstadt

PORTUGAL

- CFNU, Lisboa

JAPAN

- RIKEN, Wako