# Astrophysical studies with Split-Pole spectrometer at the ALTO facility

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# Nucleosynthesis studies with Split-Pole

Experimental study of nucleosynthesis: (Coll.: CSNSM, York, Algeria, GANIL, ...)

- AGB stars and the $^{13}C(\alpha,n)^{16}O$ reaction
  $\rightarrow$ $^{13}C(^{7}Li,t)^{16}O$ — M. Pellegriti, F. Hammache et al, PRC Rapid (2008)
- Massive stars and the $^{12}C(\alpha,\gamma)^{16}O$ reaction
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- Big-Bang nucleosynthesis and the $^{7}Li$ cosmological problem
  $\rightarrow$ $^{10,11}B(^{3}He,t)^{10,11}C$ — F. Hammache et al, PRC Rapid (2013)
- Massive stars and $^{26}Al$ nucleosynthesis
  $\rightarrow$ $^{27}Al(p,p')^{27}Al(p|\alpha)$ — S. Benamara, N. de Séréville et al, PRC (2014)
- $^{19}Ne$ spectroscopy for classical novae & X-ray bursts
  $\rightarrow$ $^{19}F(^{3}He,t)^{19}Ne(p|\alpha)$ — J. Riley, A. M. Laird, N. de Séréville, under analysis
- Massive stars & SNIa and the $^{12}C$ + $^{12}C$ reaction
  $\rightarrow$ $^{24}Mg(p,p')^{24}Mg$ — V. Guimares, I. Stefan, under analysis
- Massive stars and $^{15}N$ nucleosynthesis
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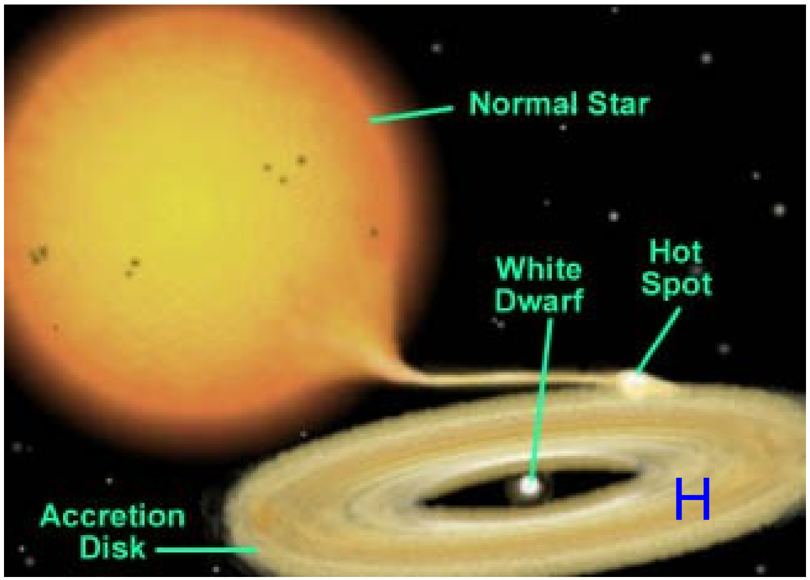
# Classical novae and γ-ray emission

## Final evolution of a close binary system




- Accretion of H-rich material on the WD from its companion star
- Thermonuclear runaway in convective envelope
- Expansion and shell ejection

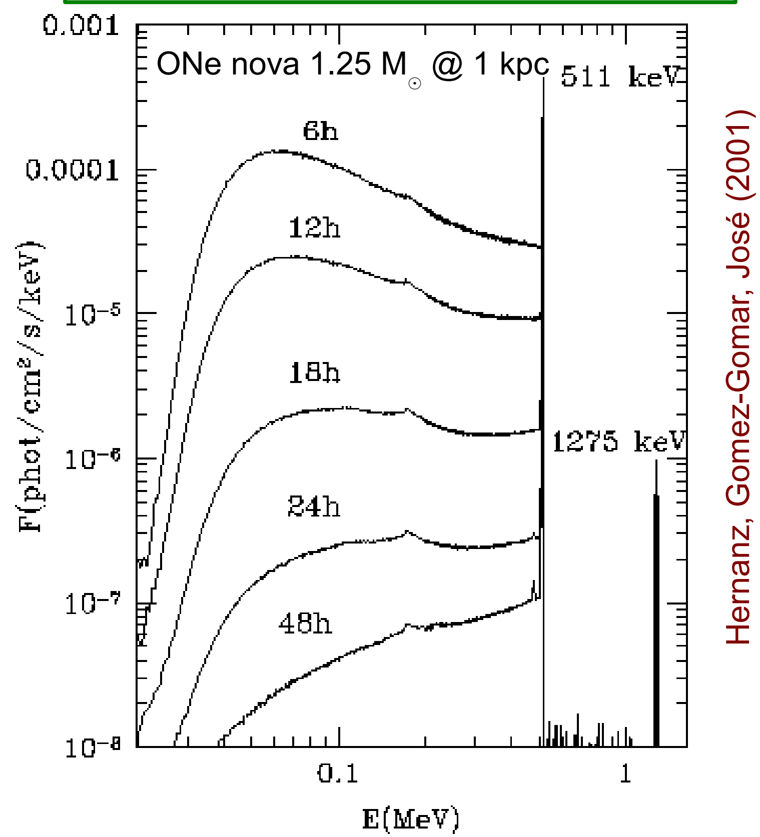
## Constraint models

- Multi wavelengths observations
- γ-ray observations
  - → isotopic abundances
  - → explosion mechanism, novae rate ejected shell properties ...

## Observations and predictions

- $E_\gamma$ > 100 MeV (FERMI/LAT) Abdo et al. Science (2010)
- γ-ray lines ($^{7}$Be, $^{18}$F, $^{22}$Na, $^{26}$Al)

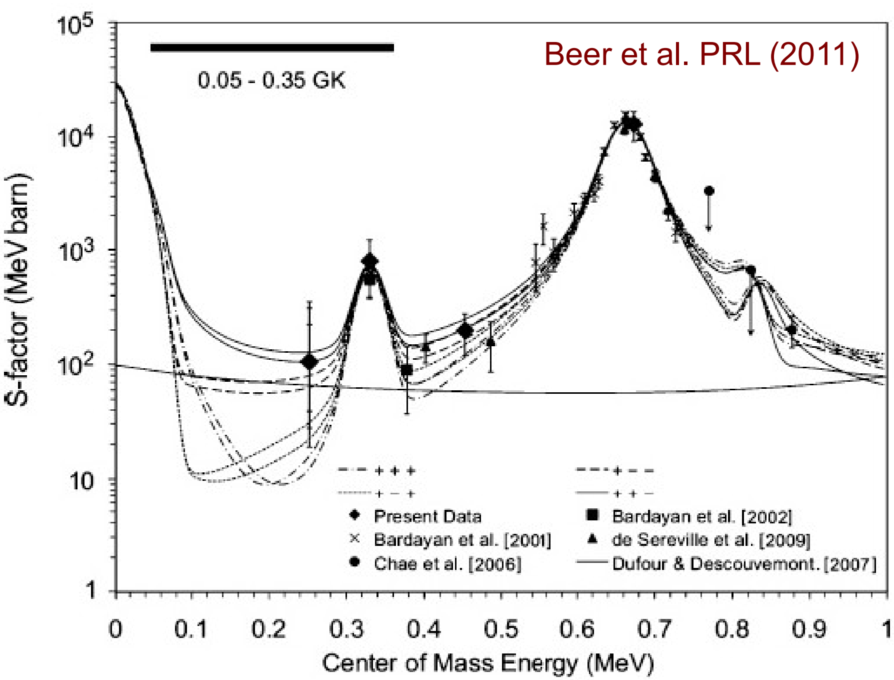
$^{18}$F ($T_{1/2}$ = 158 min) predicted emission




$^{18}$F yield depends crucially on uncertain $^{18}$F(p,α)$^{15}$O reaction

# $^{18}F(p,\alpha)^{15}O$ (some) recent studies

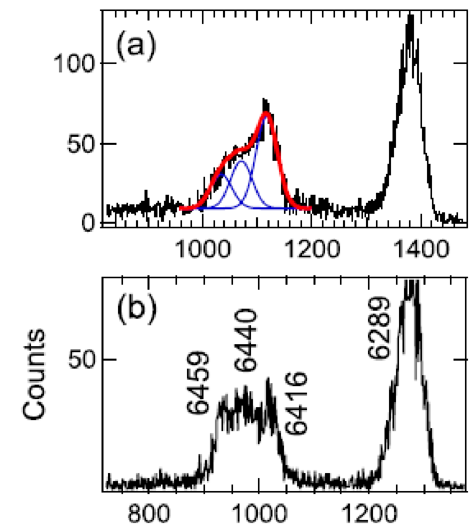
$^{18}F(p,\alpha)^{15}O$ is the focus of intensive investigation since more than two decades




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

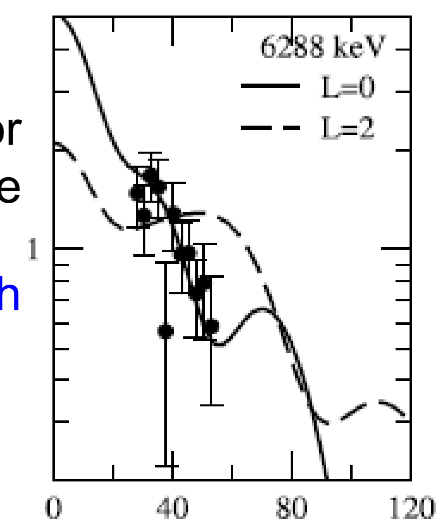
$^{19}F(^{3}He,t)^{19}Ne$ @ MLL
- 3 states above $p+^{18}F$
  - 5 keV (3/2-, 5/2+)
  - 29 keV (11/2+)
  - 48 keV (5/2-)
  
  → no 3/2+!




Laird et al. PRL (2013)

$^{20}Ne(p,d)^{19}Ne$ @ HRIBF
- $J^{\Pi}$ = 1/2+ ($\ell$ = 0) for subthreshold resonance at -122 keV
- Maybe a doublet or high spin state (J > 3/2)

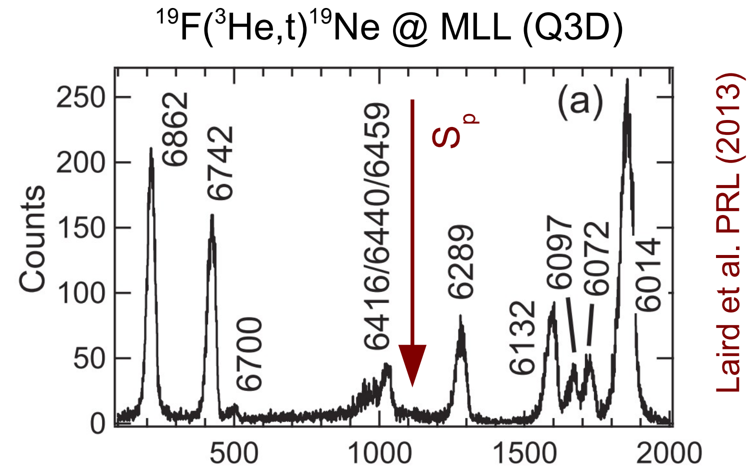
Laird et al. PRL (2013)




Bardayan et al. PLB (2015)

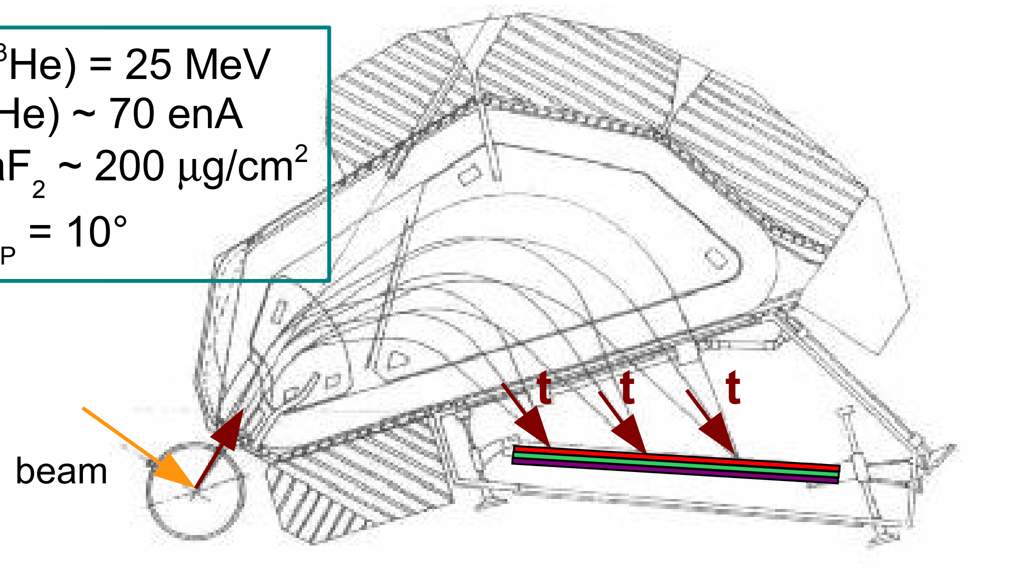
# Experimental set-up

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



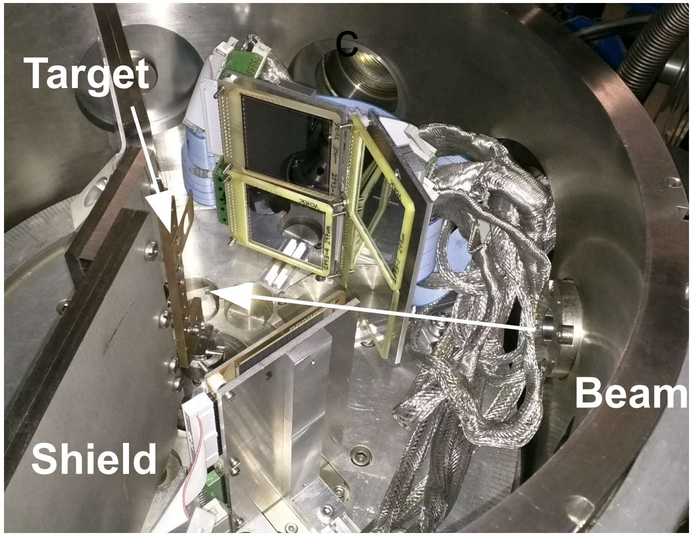

Split-Pole $\Delta E/E \sim 10^{-4}$

$E(^{3}He)$ = 25 MeV
$I(^{3}He)$ ~ 70 enA
$CaF_2$ ~ 200 $\mu g/cm^2$
$\Theta_{SP}$ = 10°




Focal-plane detector:

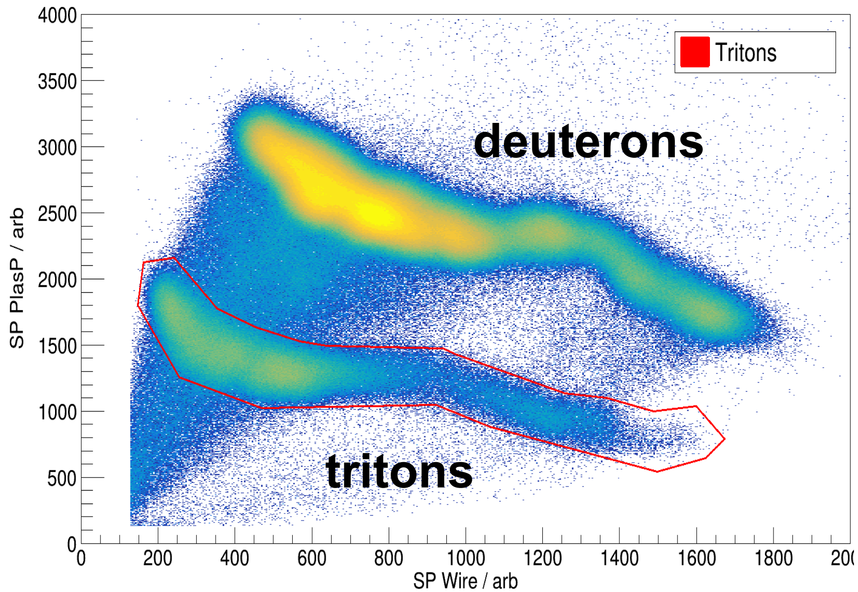
- Position sensitive gas chamber ($B\rho$)
- $\Delta E$ proportional gas counter (PID)
- E plastic scintillator (PID + ToF)




- 6 W1 (16+16) DSSSDs
  → angular distribution measurement
- $\varepsilon$ ~ 15%, $\Delta E$ ~ 20 keV
- Thick shield between 0° FC and DSSSDs

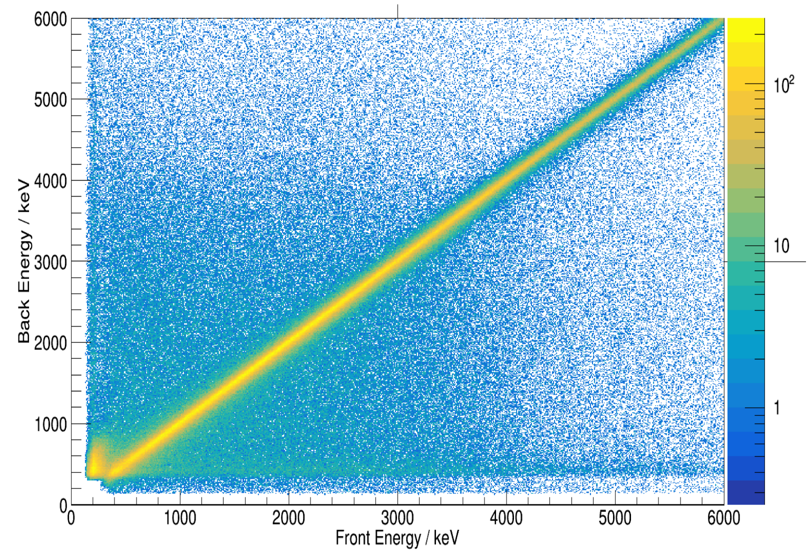
# Coincidence events selection

## Particle identification in Split-Pole

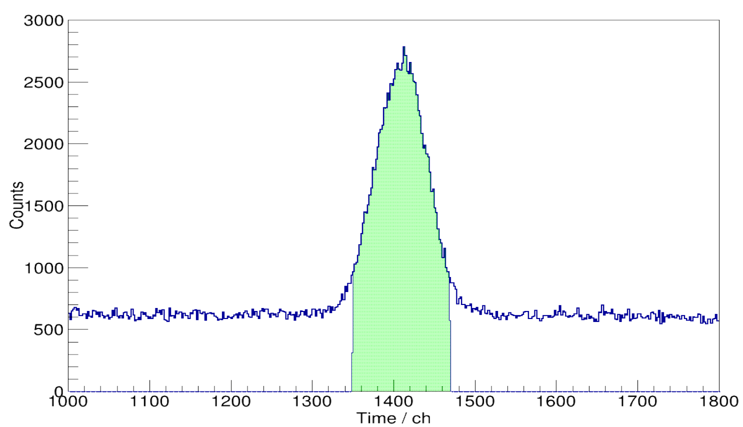



## DSSSD good event selection

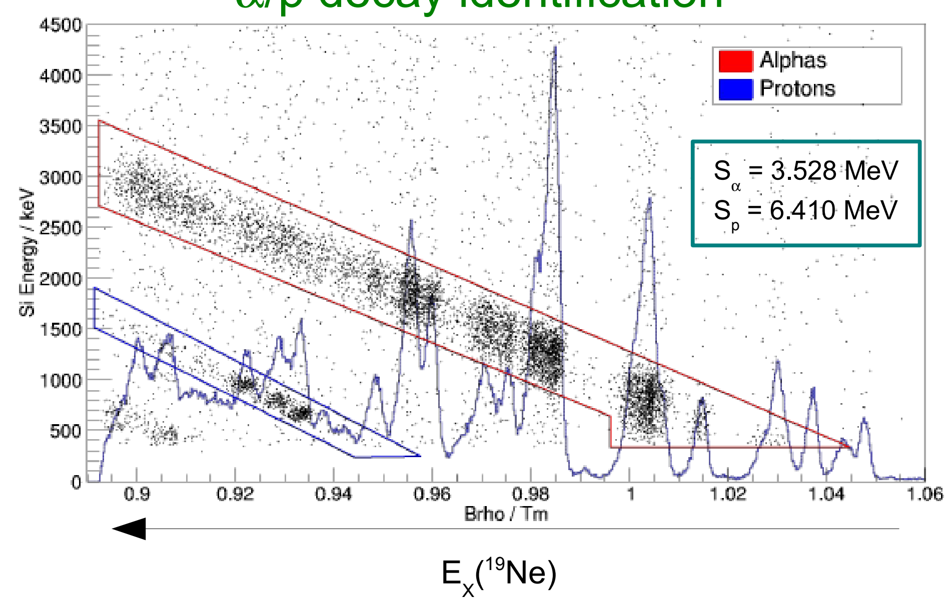
Equal energy in front/back channels



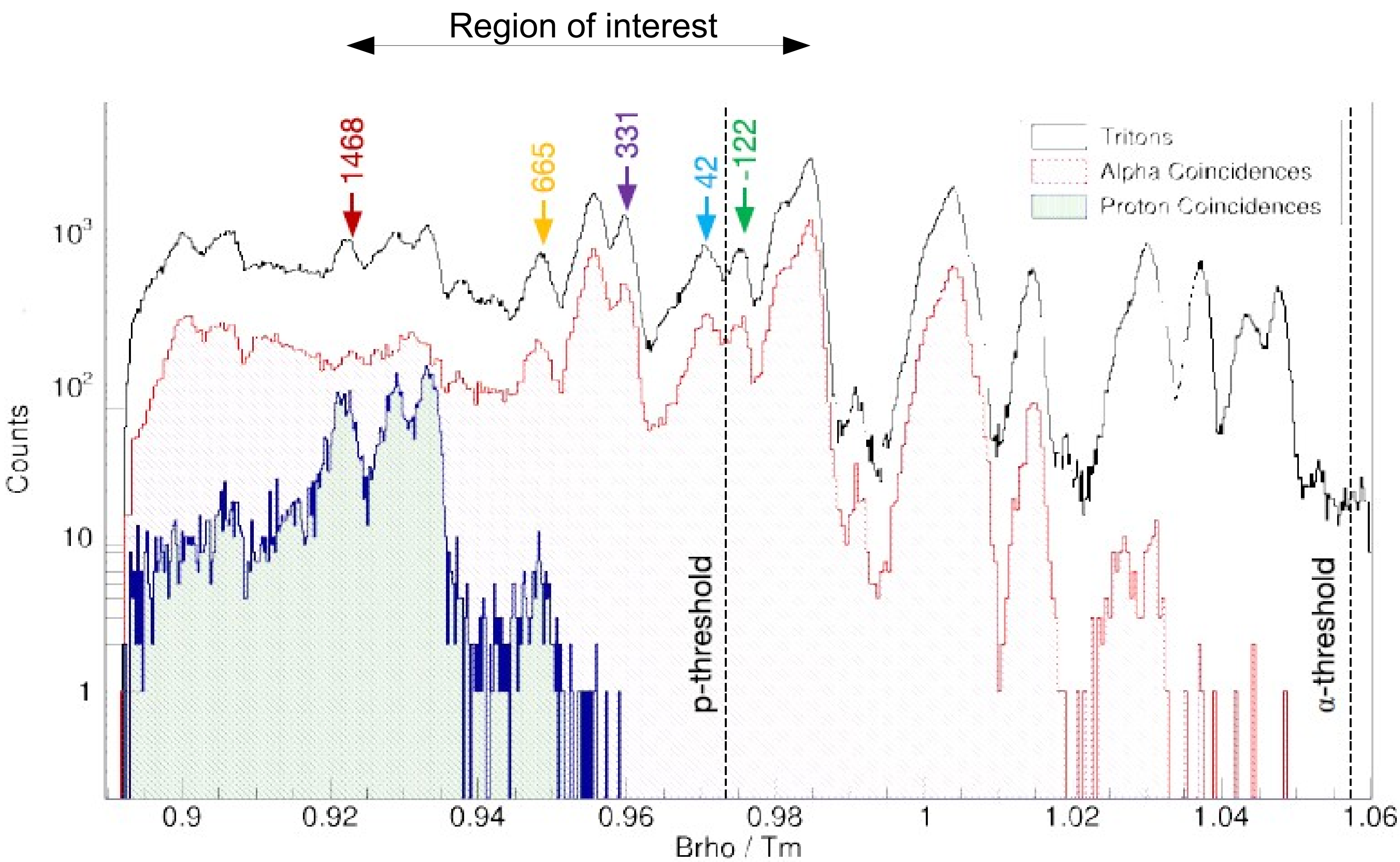

## Coincidence events (ToF selection)




## α/p decay identification



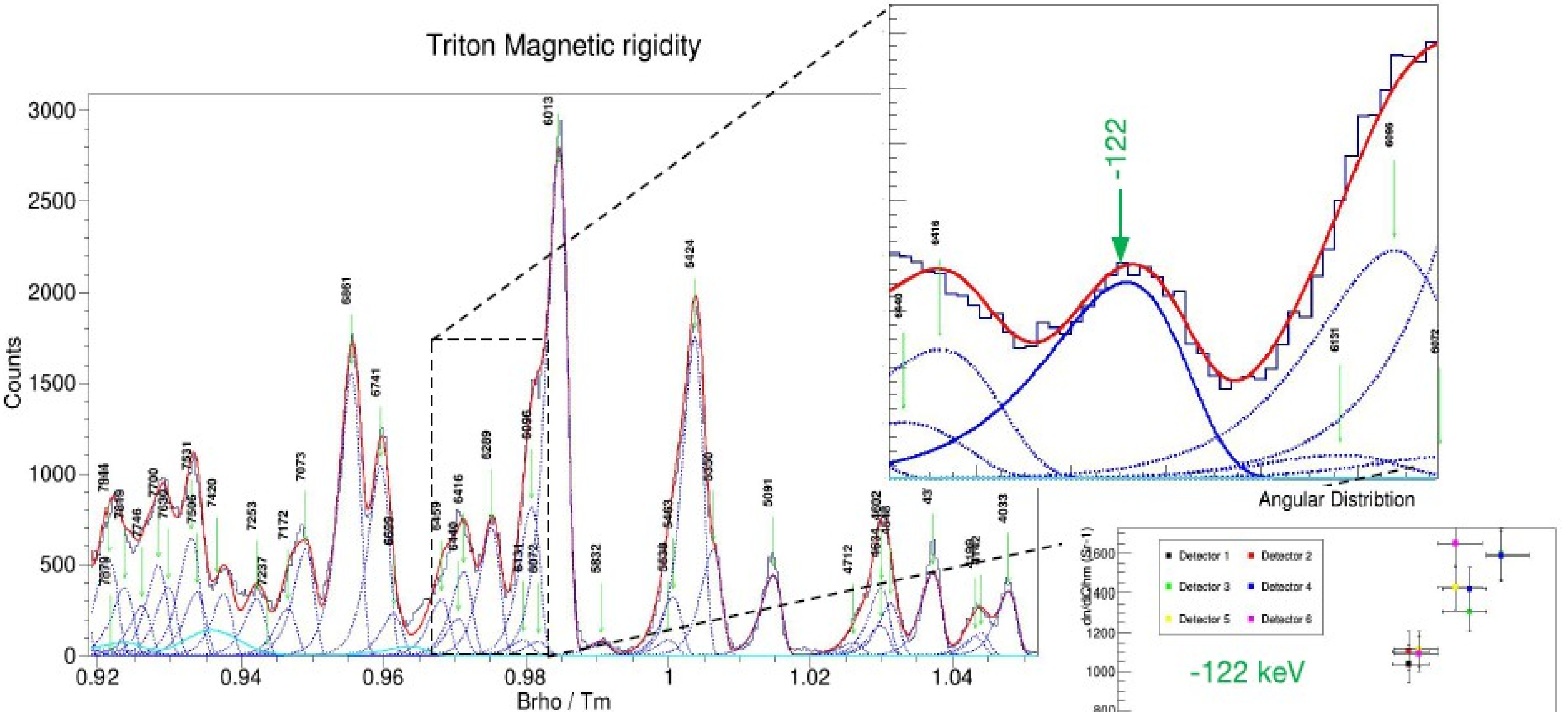
# Coincidence spectra




- Key resonances are easily observed
- Branching ratio determination

BR = "(coinc / $\varepsilon_{geom}$)" / singles

# Angular correlations



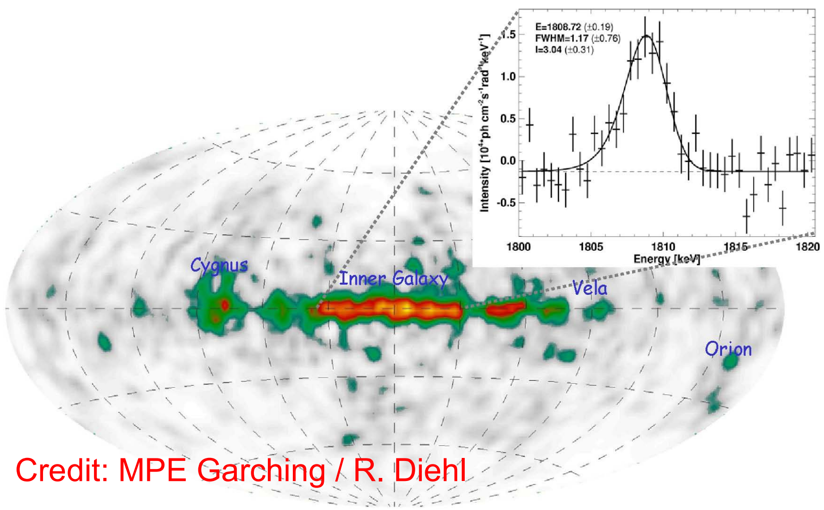

- Fit of single spectrum with same width (exp. resolution)
- Angular correlation are getting extracted
  → Branching ratio determination and constraints on $J^{\Pi}$

J. Riley, A. M. Laird, NdS, under analysis

# $^{26}$Al observations

$^{26}$Al ($T_{1/2}$ = 7.4 $10^5$ yr): $\quad {}^{26}Al \xrightarrow{\beta+} {}^{26}Mg^* \xrightarrow[1.809\ MeV]{\gamma} {}^{26}Mg$

## γ-rays observations




Credit: MPE Garching / R. Diehl

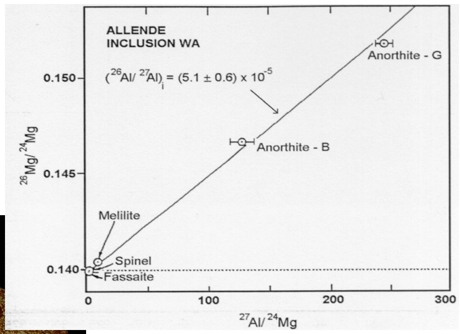
- Cumulative emission in the galactic plane
- Steady state mass of $^{26}$Al:
  → 2.8 ± 0.8 $M_\odot$ (Diehl et al. 2006)

## Stellar sources:

- ccSN, Wolf-Rayet phase
- AGB, classical novae

## Meteoritic observations

Refractory inclusions CAIs





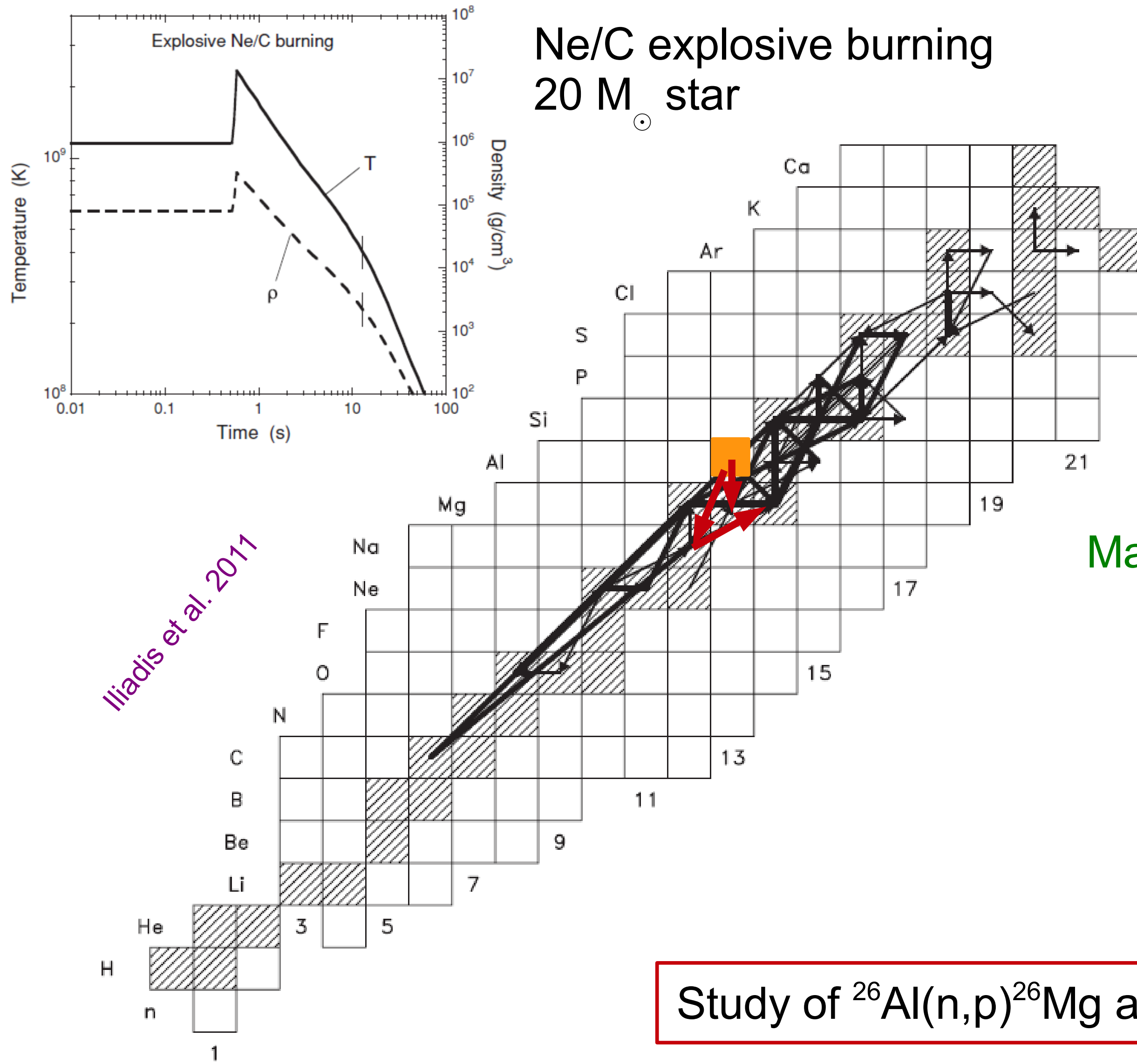
$^{26}$Al/$^{27}$Al = 5x$10^{-5}$ in Early SS

## Astrophysical context of SS formation

- Last minute stellar nucleosynthesis event:
  → ccSN (Cameron et al. 1995)
  → WR (Tatischeff et al. 2011)
  → AGB (Busso et al. 2003)

Good understanding of $^{26}$Al nucleosynthesis in massive stars needed

# $^{26}$Al nucleosynthesis in massive stars




Iliadis et al. 2011

Sensitivity study:

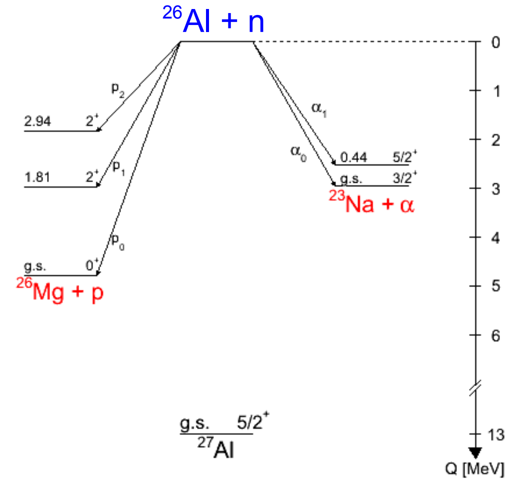
- Post-processing
  → (ρ,T) from Limongi et al. 06
- Nuclear reaction network
  → 175 isotopes ($^1$H - $^{40}$Ca)
  → 1650 interactions
- Burning phases
  → xNe/C, shell C/Ne, core H

Main results:

| Reaction | Site[b] | Temperature[c] |
|---|---|---|
| $^{26}Al^t(n,p)^{26}Mg$ | xNe/C; C/Ne | ≈2.3; ≈1.4 |
| $^{25}Mg(\alpha,n)^{28}Si$ | xNe/C | ≈2.3 |
| $^{24}Mg(n,\gamma)^{25}Mg$ | xNe/C; C/Ne | ≈2.3; ≈1.4 |
| $^{23}Na(\alpha,p)^{26}Mg$ | C/Ne | ≈1.4 |
| $^{26}Al^t(n,\alpha)^{23}Na$ | xNe/C; C/Ne | ≈2.3; ≈1.4 |
| $^{27}Al(\alpha,p)^{30}Si$ | xNe/C | ≈2.3 |
| $^{29}Si(\alpha,n)^{32}S$ | xNe/C | ≈2.3 |
| $^{26}Mg(\alpha,n)^{29}Si$ | C/Ne | ≈1.4 |

Study of $^{26}$Al(n,p)$^{26}$Mg and $^{26}$Al(n,α)$^{23}$Na reactions

# $^{26}$Al + n reactions status




## Resonances of interest:

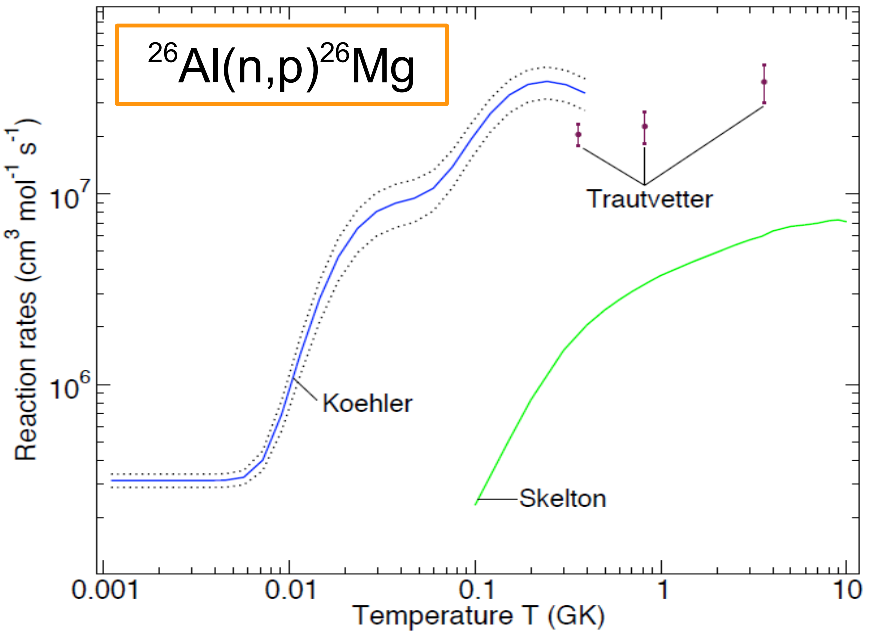
- $S_n < E_X < S_n + 500$ keV ($T_9 = 2.3$)
- s-wave neutron capture $J^\pi = 9/2^+, 11/2^+$
- p-wave neutron capture $J^\pi = 7/2^-, .., 13/2^-$

## Dedicated measurements:

- Time-reverse reactions
  → $^{26}$Mg(p,n) & $^{23}$Na(α,n) Skelton et al. 1987
- $^{26}$Al + n direct measurements
  → $^{26}$Al(n,p)$^{26}$Mg
  - Trautvetter et al. 1986
    $k_BT$ up to 71 keV + $E_n$ < 350 keV
  - Koehler et al. 1997
    $E_n$ up to 70 keV: $E_R$ = 5.9 keV and 33.7 keV

  → $^{26}$Al(n,α)$^{23}$Na
  - Koehler et al. 1997
    $E_n$ up to 10 keV: $E_R$ = 5.9 keV
  - de Smet et al.2007
    $E_n$ up to 100 keV: 6 resonances

## Reaction rate: Oginni et al. 2011




Lack of spectroscopic information ($E_X$, Jπ, $\Gamma_{tot}$, $\Gamma_p$, $\Gamma_\alpha$, $\Gamma_n$) above $S_n$

# Experimental method and set-up

Extend $^{27}$Al spectroscopy above $S_n$:

- Determine level energies accurately
- Determine branching ratio: $\Gamma_p / \Gamma_{tot}$ and $\Gamma_\alpha/\Gamma_{tot}$
- Spins and/or $l_n$ of resonances

Inelastic reaction: $^{27}$Al(p,p')$^{27}$Al*

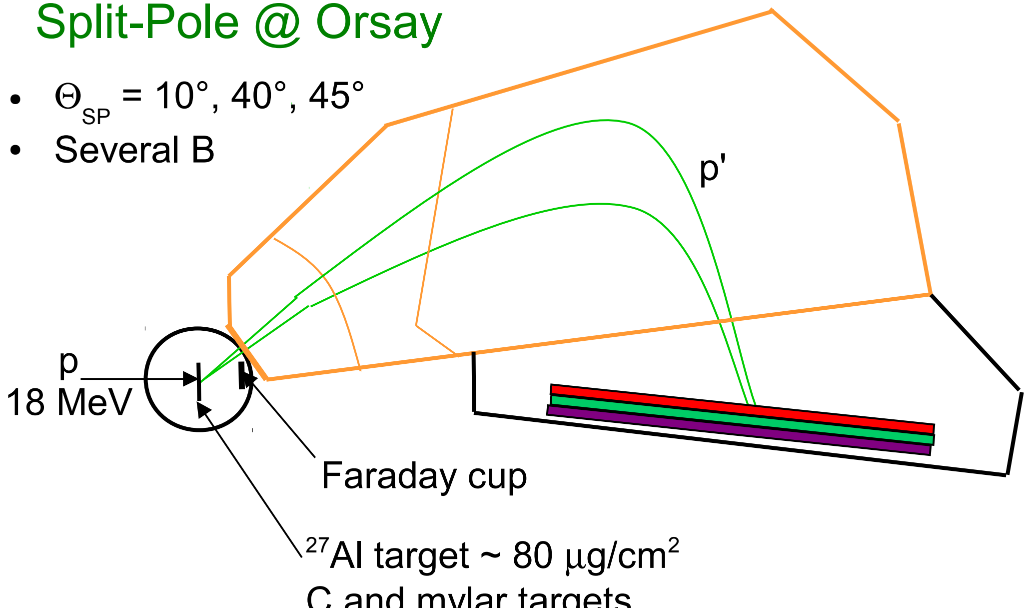
→ non selective reaction

→ all known $^{27}$Al high-spins (J > 7/2) levels have been observed in (p,p') measurements (Doekes et al. 1971, Moss et al. 1976)

- Single measurement ⇒ State energies

Split-Pole @ Orsay

- $\Theta_{SP}$ = 10°, 40°, 45°
- Several B

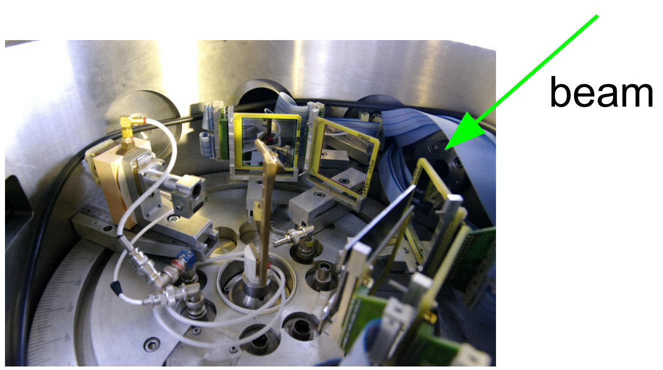



- Coincidence measurement

→ $^{27}$Al(p,p')$^{27}$Al*(p)$^{26}$Mg

→ $^{27}$Al(p,p')$^{27}$Al*($\alpha$)$^{23}$Na

⇒ branching ratios



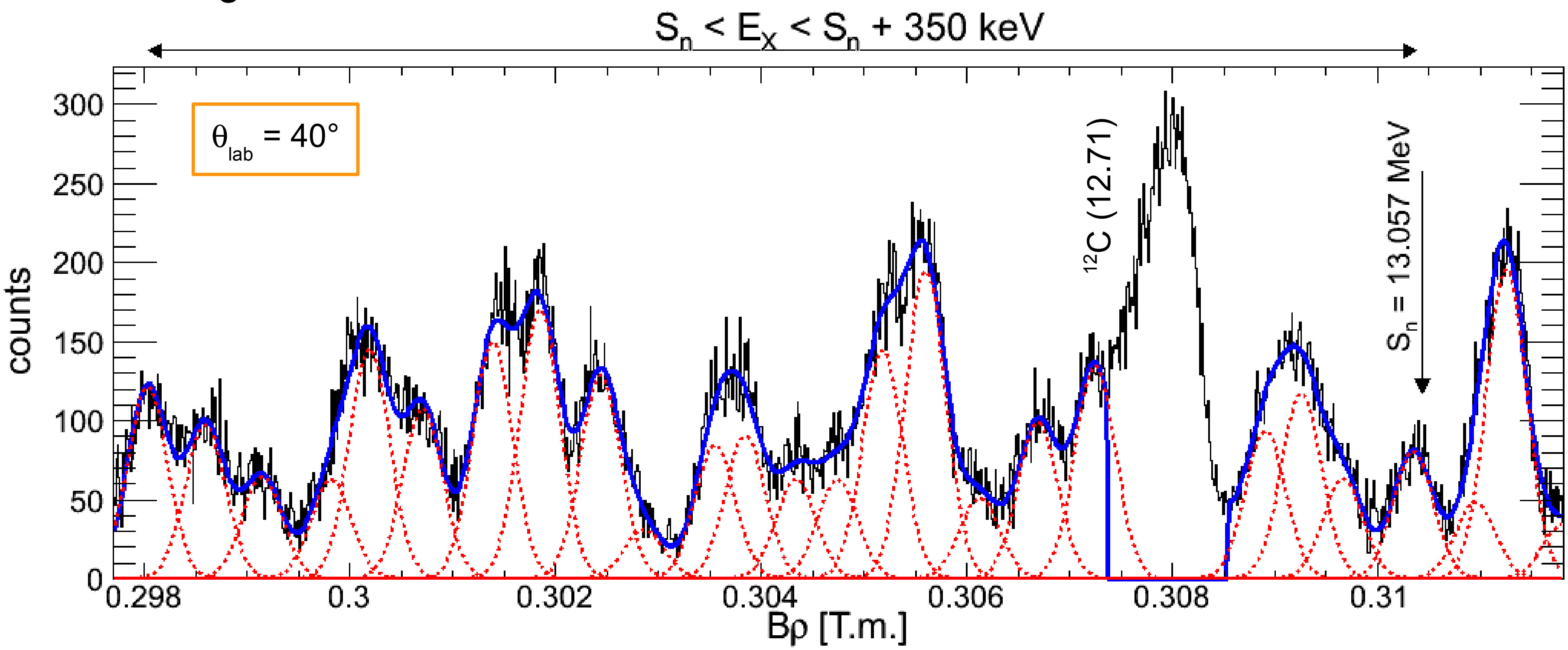
# $^{27}$Al levels above neutron threshold

Deconvolution above neutron threshold:

- C contamination → energy resolution 12 keV
- Background subtraction

Deconvolution robustness:

- Similar deconvolution at 10°



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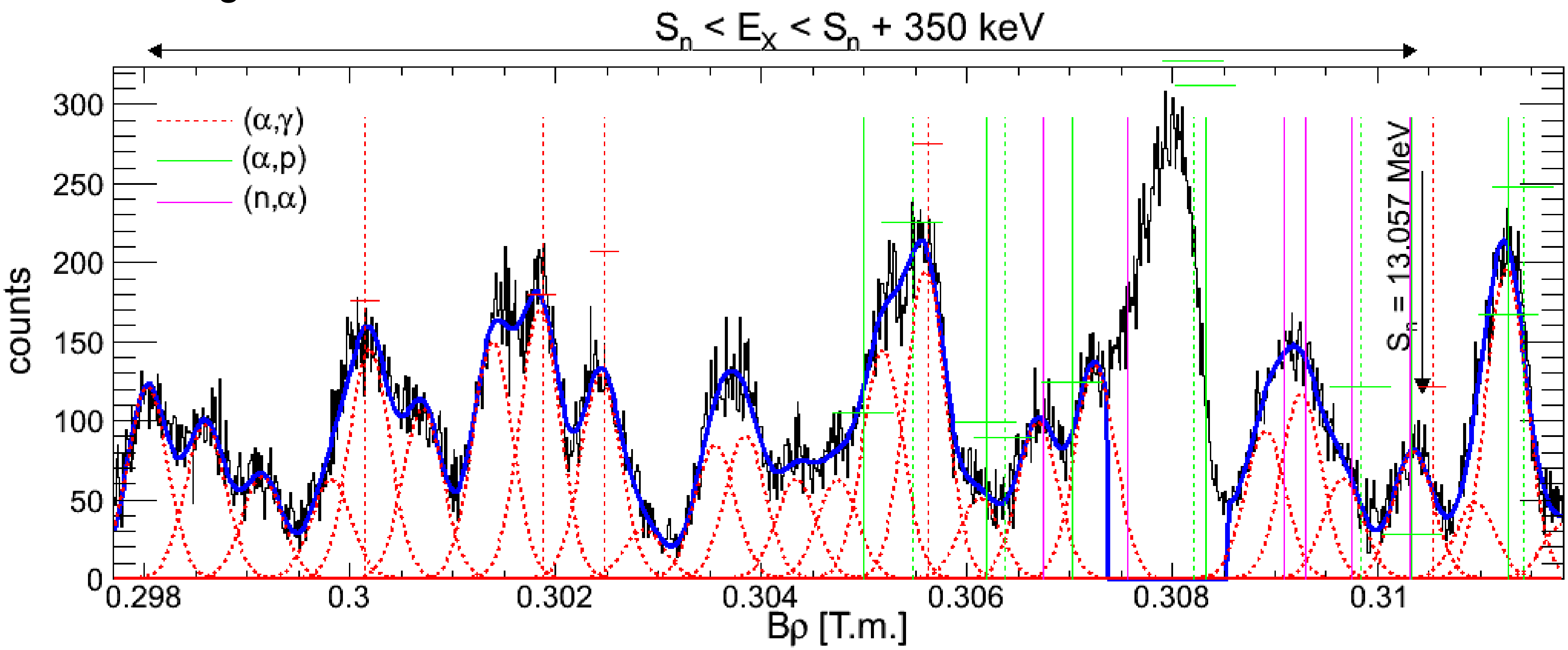



Comparison with known levels:

- Very good agreement with $^{23}Na(\alpha,\gamma)^{27}Al$
- Very good agreement with $^{26}Al(n,\alpha)^{23}Na$
- Marginal agreement with $^{23}Na(\alpha,p)^{26}Mg$

(de Voigt et al. 1971, de Smet et al. 2007, Whitmire et al. 1974)

→ more than 30 new resonances above $S_n$!

Resonance's spins?

- (α,γ) and (n,α) preferentially populate high-spins (J>7/2)

→ new resonances probably have low-spins

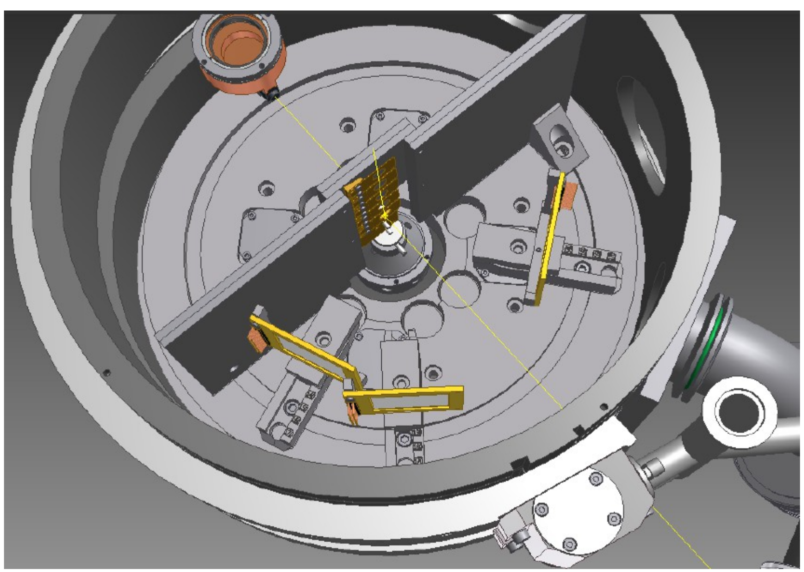
S. Benamara, NdS, A. M. Laird, PRC 2014

# Coincidence measurement

(Orsay – Barcelona – York set-up)

## Experimental conditions:

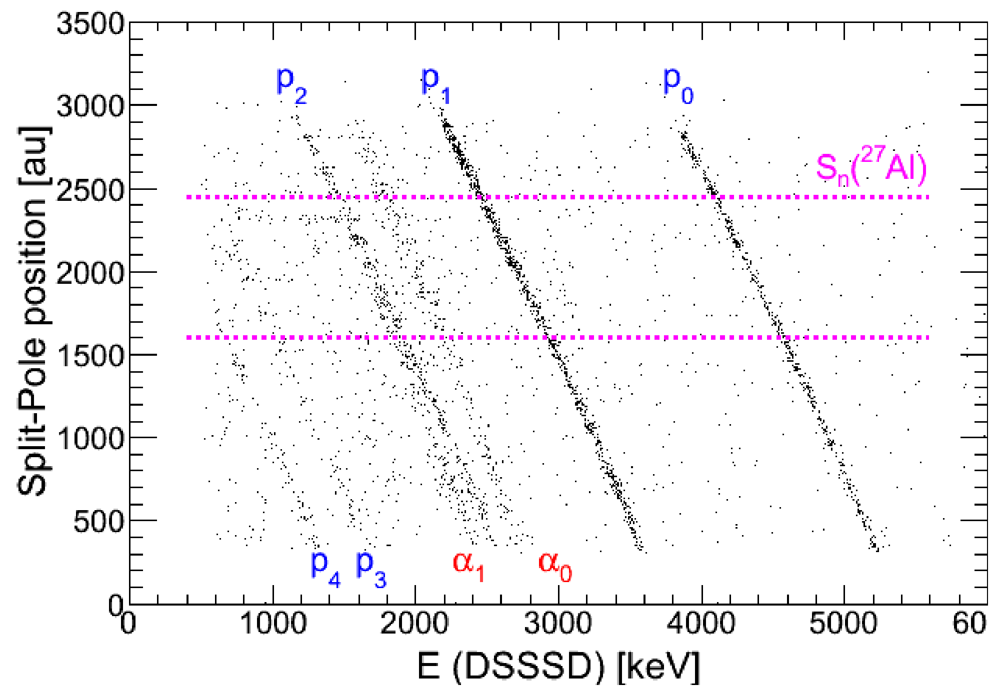
- 3 W-type DSSSDs
  → 16 + 16 strips ($\Delta E$ ~ 20 keV FWHM)
- close geometry around the target
  → d ~ 11-12 cm, $\varepsilon$ ~ 4%
- Very low background environment
- Thick shield to reduce induced background from faraday cup @ 0 degree
- Beam intensity up to 100 nA



## Event selection:

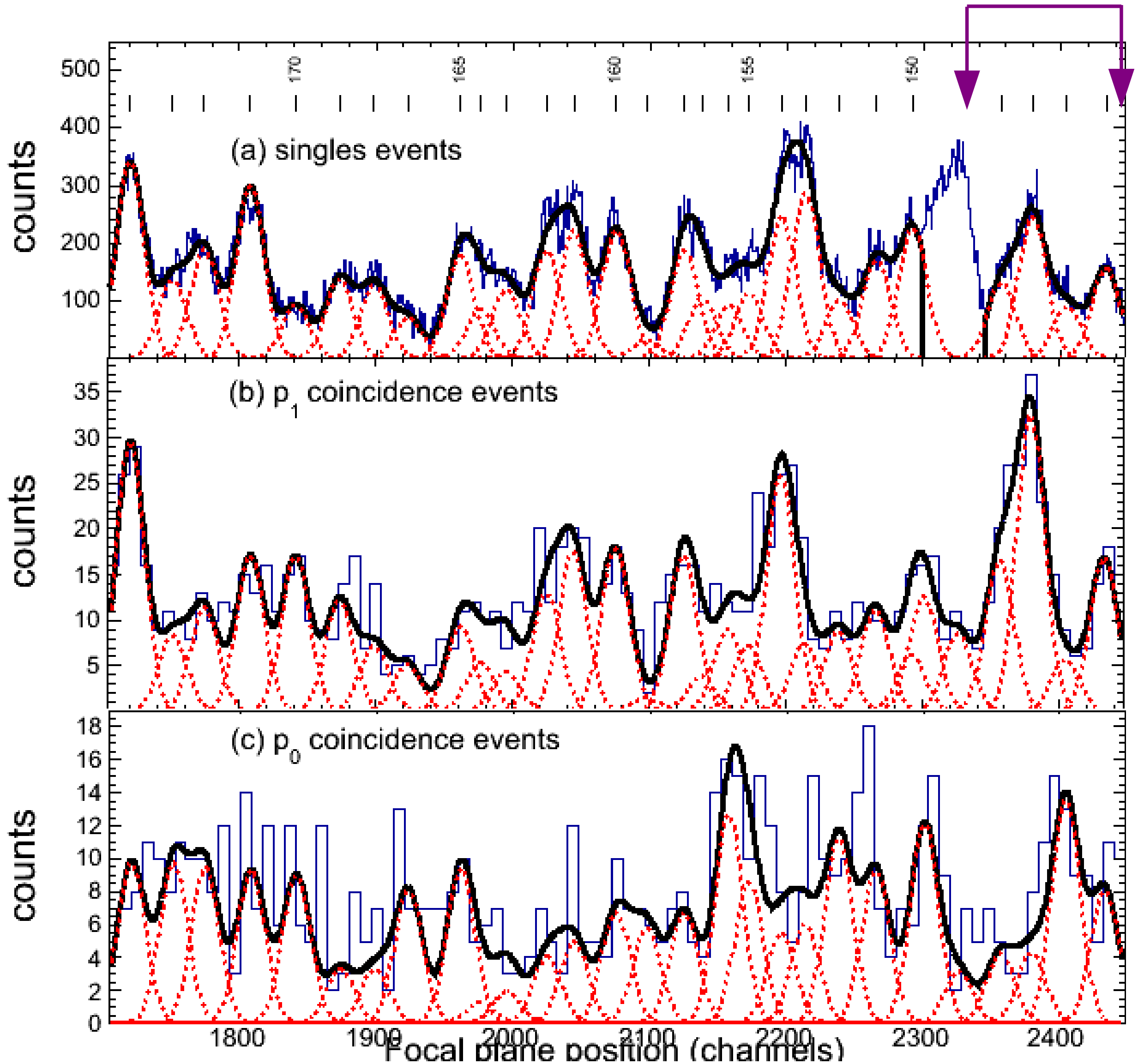
- Split-Pole proton selection
- Time of flight between FP plastic and DSSSDs
- Energy front v.s. back in DSSSDs

## Coincidence spectrum:




$^{26}Al(n,p)^{26}Mg$ dominated by $(n,p_1)$ component

# Branching ratios




Branching ratios for first resonances above neutron threshold:

| $E_R$ (keV) | 5.87 | 21.98 | 34.95 | 41.30 |
|---|---|---|---|---|
| BR (%) p0 | 17 (4) | 50 (9) | 5 (2) | 11 (4) |
| BR (%) p1 | 34 (5) | 21 (7) | 44 (5) | 41 (7) |

- Statistical uncertainty (15 – 40%)
- Isotropic emission assumption (20%)
- Background subtraction (20%)

Constrains on spin of resonance by comparing BR(p1)/BR(p0) ratio and penetrability calculations:

Case of resonance at 34.95 keV

de Smet et al. → 9/2+ - 11/2+ (s-wave)

Present work → BR(p1) / BR(p0) = 8.8 (3)

Penetrability ratios:

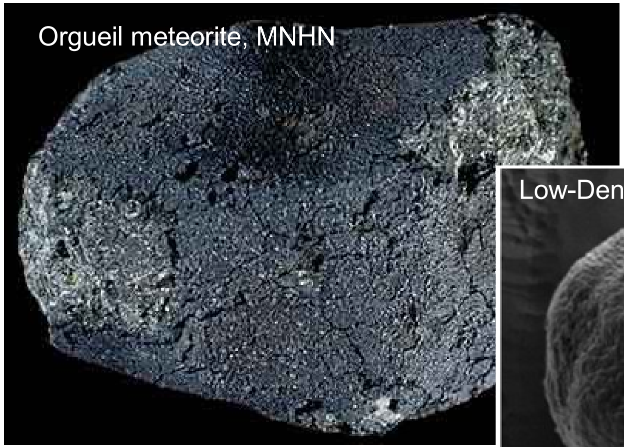
→ P(p1) / P(p0) = 6.3 (9/2+)

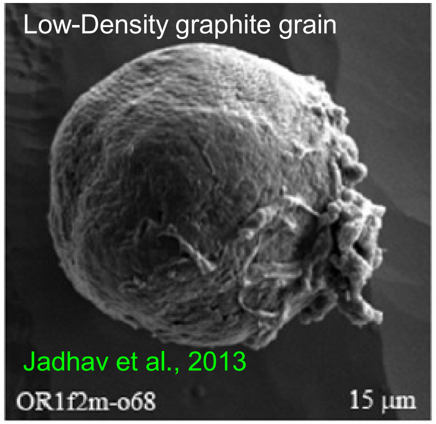
→ P(p1) / P(p0) = 16.4 (11/2+)

P. Adsley, NdS, A. M. Laird in preparation

# Explosive nucleosynthesis of $^{15}$N in massive stars

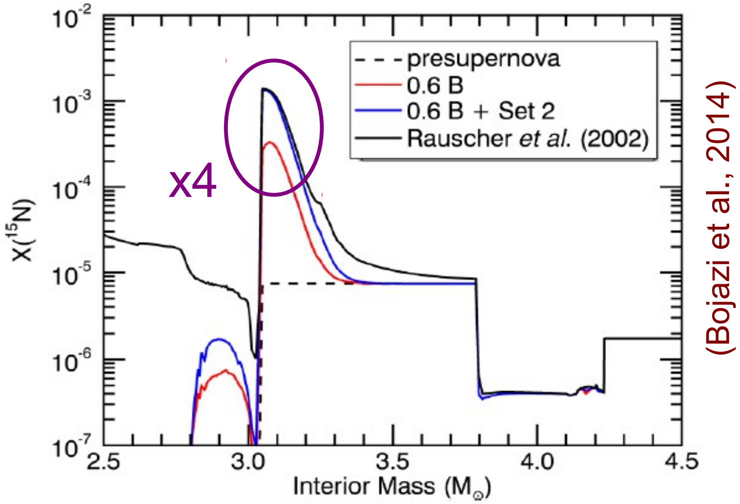

- Massive stars ($M > 8\,M_\odot$) play a key role in the chemical and dynamical evolution of our galaxy.
- Material from these stars is brought to Earth in presolar grains embedded in meteorites.




- Low-Density graphite grains carry isotopic anomalies typical from massive stars.
- What is the precise origin of the material (which layer)?
- Recent measurement of spatial correlation of $^{15}$N & $^{18}$O points toward the He layer. (Groopman et al., 2012)

- Sensitivity study for $^{15}$N production in case of explosion of a 15 $M_\odot$ star.



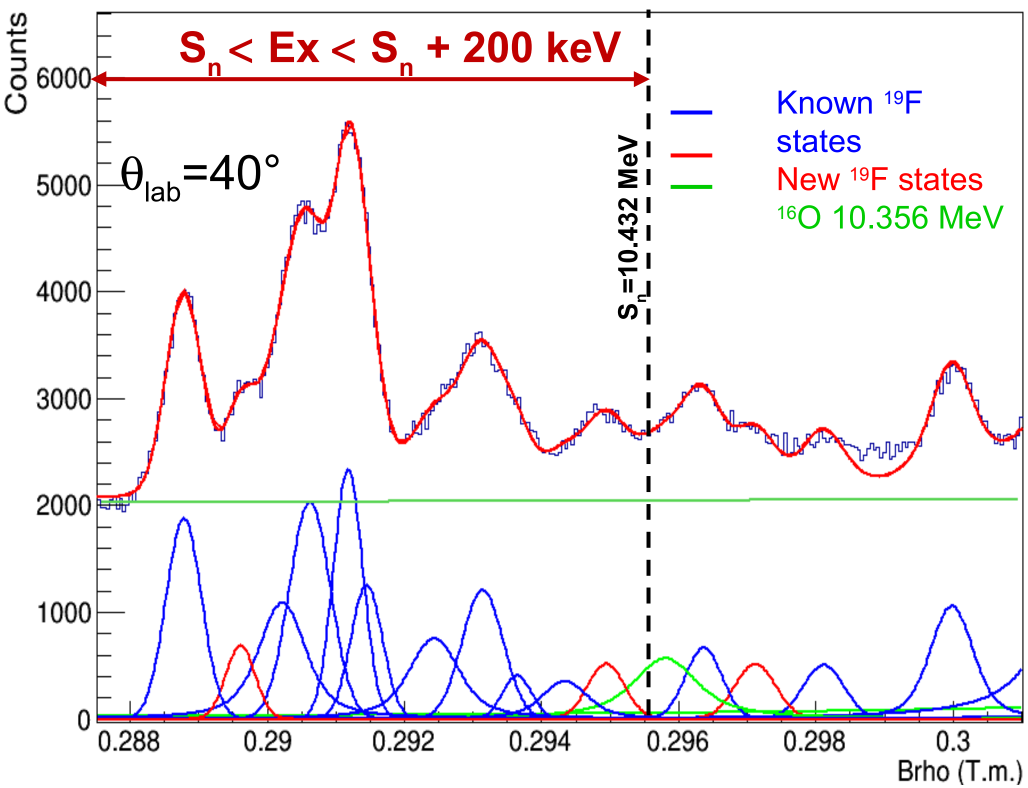

- Mainly due to uncertainty of 5 in the $^{18}$F(n,p)$^{18}$O rate and $^{18}$F(n,$\alpha$)$^{15}$N (based on Hauser-Feschbach calc.)

Lack of spectroscopic information in $^{19}$F nucleus above neutron threshold

# $^{19}$F levels above neutron threshold

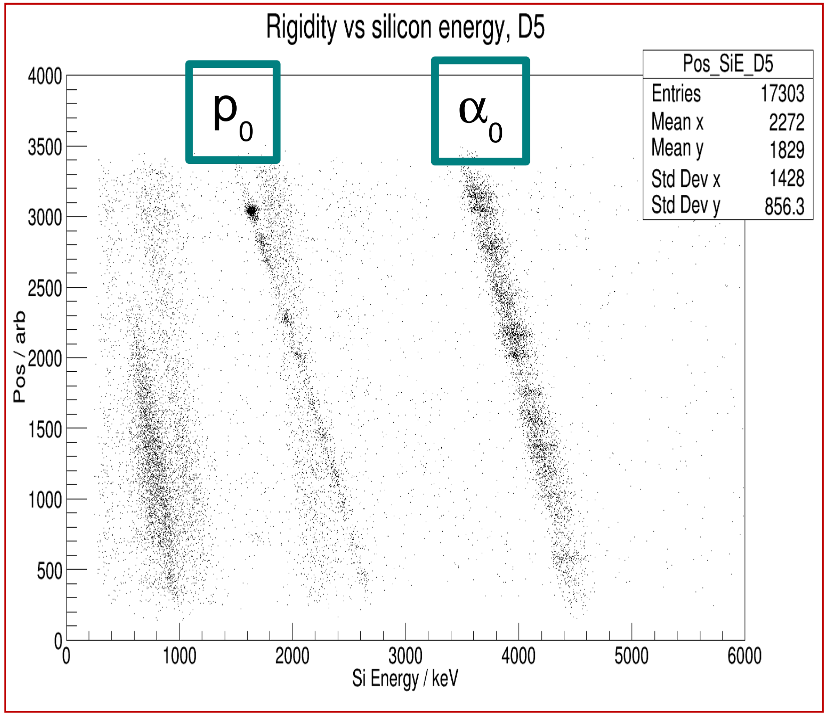
Coincidence measurement: $^{19}F(p,p')^{19}F^*(p|\alpha)$, E = 15 MeV, $\Theta_{SP}$ = 30°, 40°

Split-Pole inclusive spectrum



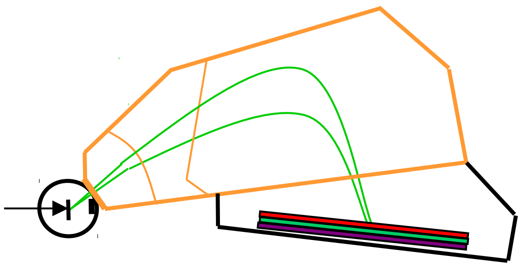

- Fit takes into account experimental resolution (16 keV) and natural width when needed
- Two new states above n+$^{18}$F

Coincidence spectrum (1 W1)

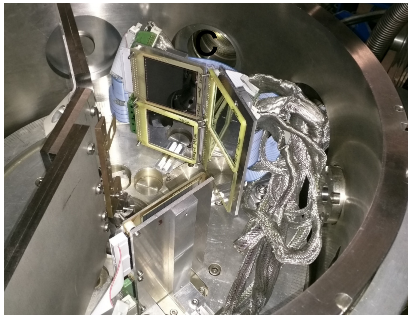



- Under analysis (F. Hammache)

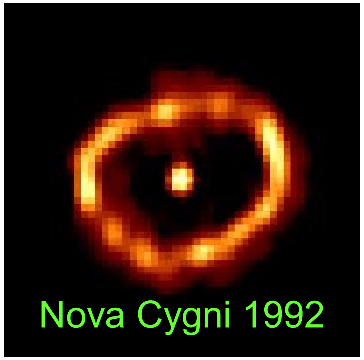
# Summary and perspectives



- Magnetic spectrometers (SP, Q3D) at TANDEM facilities well suited for indirect nuclear astrophysics studies:
  - → high-energy resolution measurements
  - → angular distribution measurements



- Efficient (~15%) silicon array coupled to Split-Pole
  - → angular correlation measurements
  - → spin and BR determination




- Mid-term program
  - → $^{22}$Na(p,$\gamma$)$^{23}$Mg reaction in classical novae (scheduled in 2 weeks)
  - → $^{30}$P(p,$\gamma$)$^{31}$S reaction in classical novae (accepted)
  - → $^{22}$Ne(p,$\gamma$)$^{23}$Na reaction in classical novae (accepted)
  - → ...

# Collaborators

S. Benamara, F. Hammache, N. de Séréville, I. Stefan...

P. Adsley, A. M. Laird, S. Fox, J. Riley...

A. Parikh