Nuclear measurements for astrophysics

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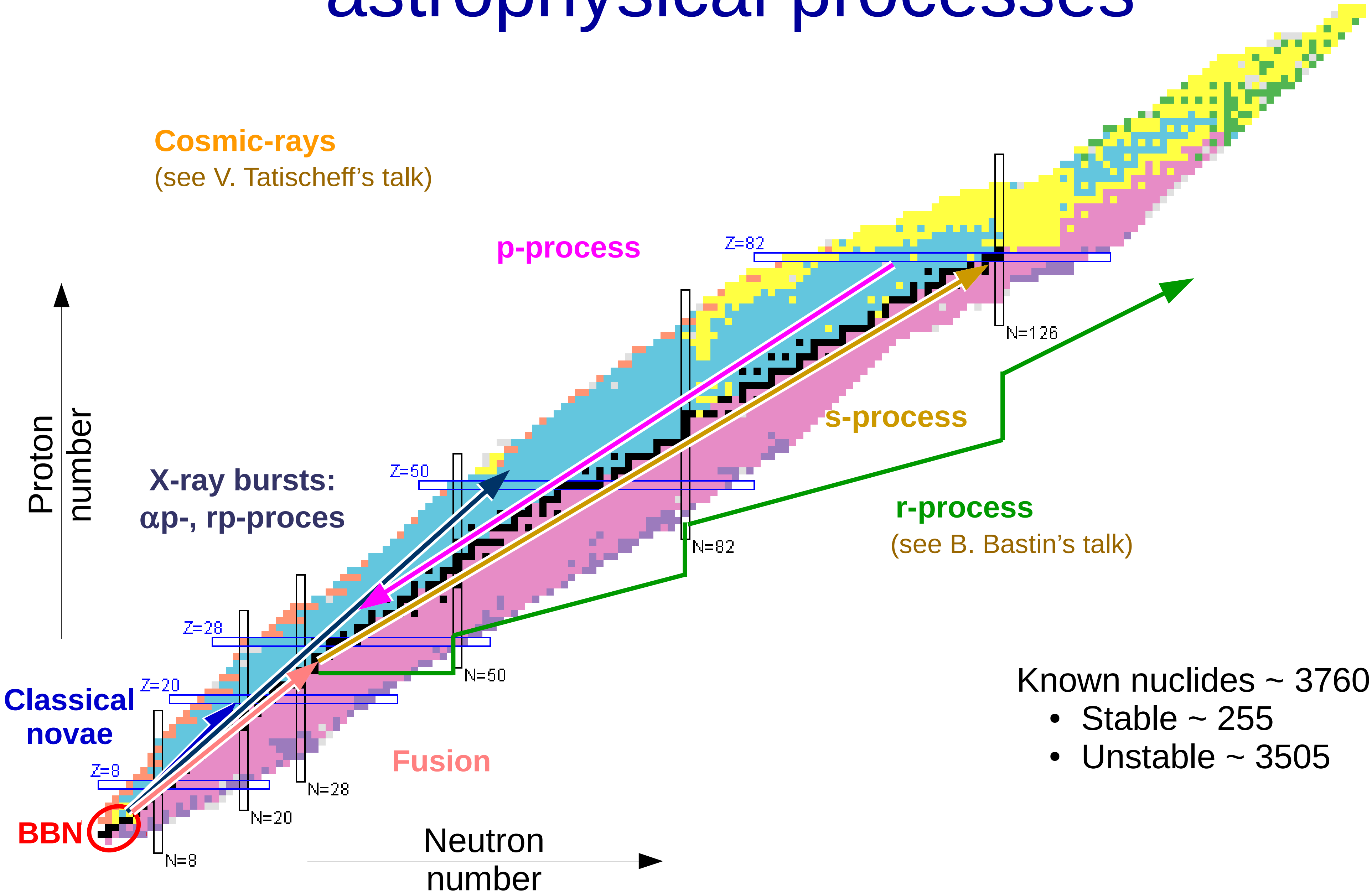
- Nucleosynthetic processes and key nuclear reactions
- Specificity of charged particle reactions & experimental approaches
- A (few) selected cases in BBN, explosive burning, massive stars and globular clusters

Réunion groupes de travail GdR Resanet et OG, Observatoire de Paris, September 24th - 25th

Nuclear landscape and astrophysical processes



Known nuclides ~ 3760

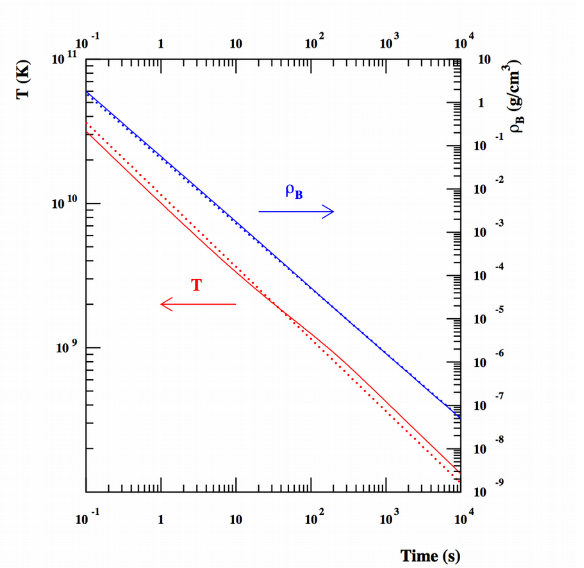
- Stable ~ 255
- Unstable ~ 3505

What are the key reactions?

Approach: sensitivity studies using post-processing Monte Carlo calculations

Method:

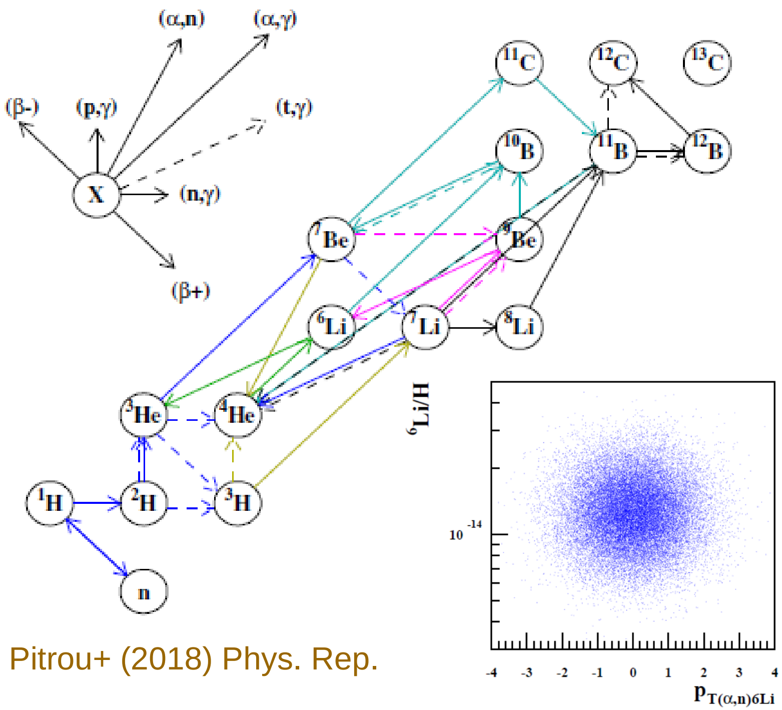
- Full hydrodynamical calculations still time consuming
- Use representative time-dependent density and temperature profiles
- Every reaction rate is sampled according to its uncertainty distribution



Criteria:

- Significant impact on energy generation or nucleosynthesis
- Search for correlations between isotopic yields and reaction rates

BBN nuclear network



Pitrou+ (2018) Phys. Rep.

Coc+ (2014) JCAP

Some recent Monte Carlo sensitivity studies

Astrophysical process / site	Reference
BBN	Coc+ (2014) JCAP
Classical novae	Iliadis+ (2002) ApJS
X-ray burst	Parikh+ (2008) ApJS
Main *s*-process	Cescutti+ (2018) MNRAS
Weak *s*-process	Nishimura+ (2017) MNRAS
p-process	Rauscher+ (2016) MNRAS Nishimura+ (2017) MNRAS
r-process	Munpower+ (2016) PPNP

Nuclear ingredients

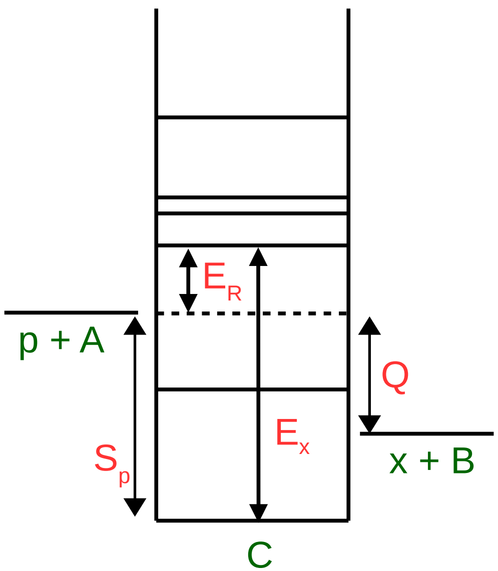
Nucleosynthesis network depends on several rates

- Charged-particle and neutron induced reaction rates
- Neutrino and photon interaction rates
- β-decay rates
- Electron capture rates

Thermonuclear reaction rate: $$N_A < \sigma v >= \sqrt{\frac{8}{\pi\mu}} \frac{N_A}{(kT)^{3/2}} \int_0^\infty \sigma(E) E e^{(-E/k_B T)} dE$$

Two-body reaction

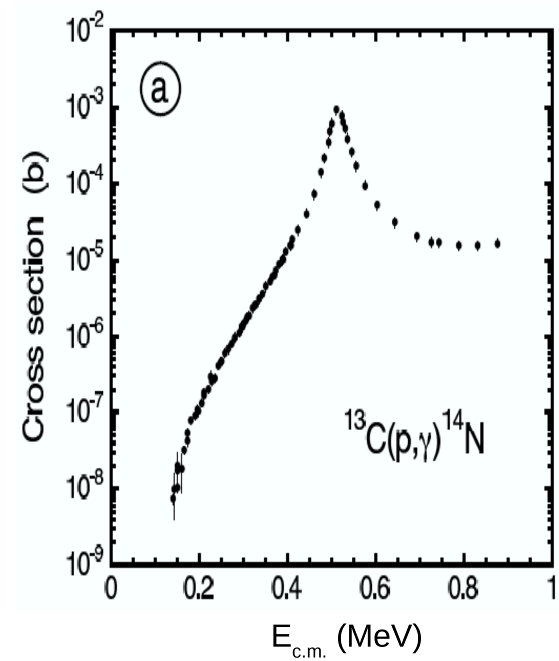
p + A → C → x + B



Resonant case (Breit Wigner):

$$\sigma(E) = \pi \lambda^2 \omega \frac{\Gamma_p(E)\Gamma_x(E+Q)}{(E-E_R)^2 + \Gamma_{tot}{}^2(E)/4}$$

- Resonance energy: $E_R = E_x - S_p$
- Spin factor: ω μ $(2J_R + 1)$
- Partial widths (Γ_p, Γ_x) and total width ($\Gamma_{tot} = \Gamma_p + \Gamma_x + \ldots$)
- Q-value: $Q = (m_p + m_A - m_x - m_B)c^2$

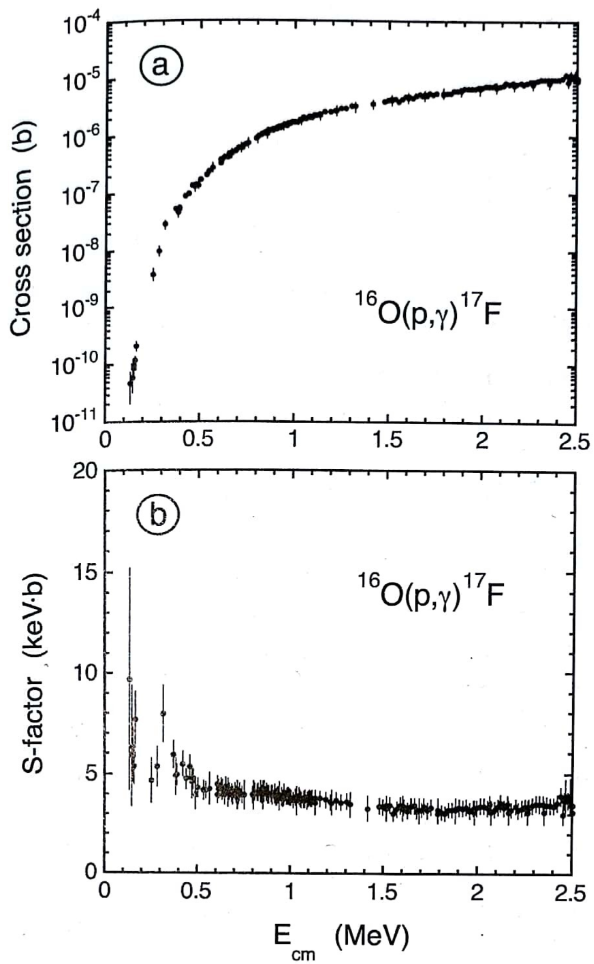


Iliadis (2007) Nuclear Physics of Stars

Charged particles reaction

Astrophysical energies are much below the Coulomb barrier
e.g. quiescent burning: E ~ 100's keV << B_C ~ MeV

Rapidly varying small cross-section

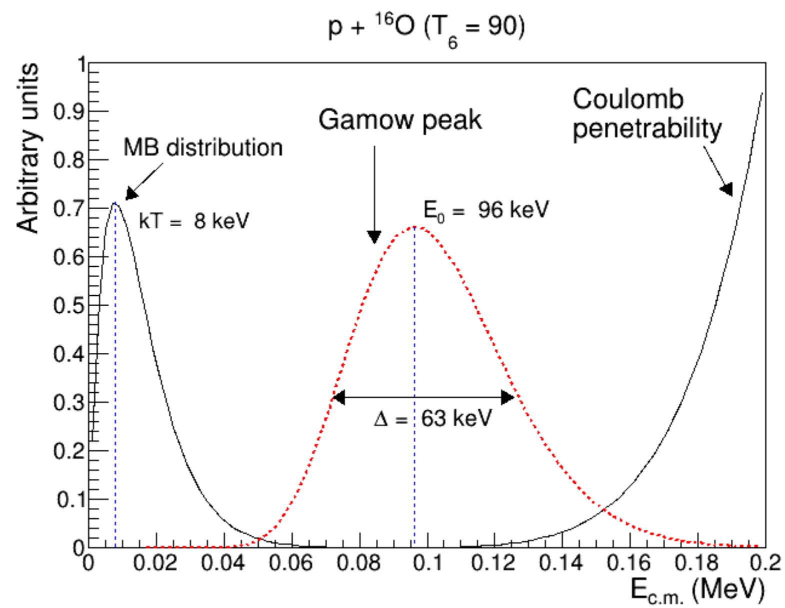


Iliadis (2007) Nuclear Physics of Stars

Astrophysical S-factor

$$S(E) = \sigma(E) E \exp(2\pi\eta)$$

Gamow window



Extremely small cross-sections

- 10^{-18} barns < σ < 10^{-9} barn
- $^{16}O(p,\gamma)^{17}F$ Iliadis+ (2008) PRC
  - S(90 keV) = 7.6 MeV.mb
    → σ = 6x10^{-13} barn
  - ~ 5 counts per day (but background!)

Major experimental challenge

Experimental methods

Direct approach

- Measurements as low in energy as possible
  → (very) low cross-sections ✗

- Main issue: background
  - Beam induced: target impurities, collimators, …
  - Non beam induced: cosmic muons, natural background, neutron-induced reactions

- Main challenge: improve signal-to-noise ratio
  - Very long measurements (weeks, months, …)
  - Ultra pure targets
  - High beam intensities (target heating effects)
  - High detection efficiency

- How to reduce background?
  - Measure underground with shielding → e.g. LUNA
  - Coincidence measurements → e.g. STELLA (see S. Courtin's talk)
  - Recoil mass separator → e.g. DRAGON

Indirect approach

- Measurements with "high" incident energies
  → higher cross-sections ✓

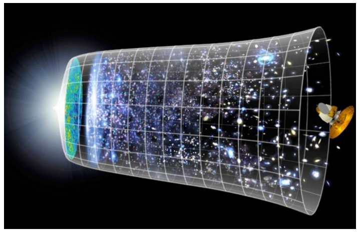
- Possibility to use stable beams to study nuclei relatively close to the valley of stability

- Experimental conditions are somehow less constraining

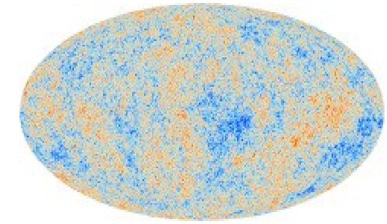
- Main drawback:
  - Model dependent ✗
  - Sensitivity to the parameter models

- Need to combine different approaches:
  - Transfer reactions → E_x, Γ_i
  - Resonant elastic scattering → E_x, Γ_i, Γ_{tot}, J^π
  - Trojan Hose Method → S(E)
  - Coulomb dissociation, ANC, ...

Direct measurements should be performed whenever possible



Big-Bang Nucleosynthesis

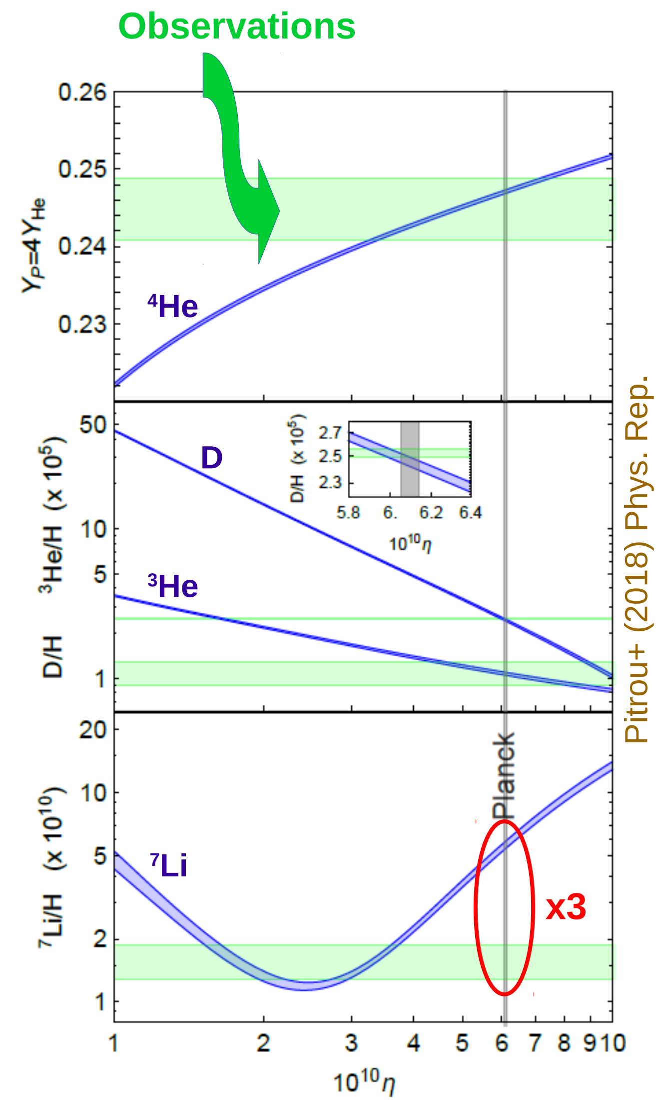


Primordial nucleosynthesis (**BBN**) of light elements is one of the three observational pillars of the Big Bang model with the expansion of the Universe and the Cosmic Microwave Background (**CMB**) radiation

- When T ≤ 10^9 K → BBN begins:
  - D, ^{4}He, ^{3}He, ^{7}Li synthesized via nuclear reactions
  - Abundances depend on $\Omega_B h^2$
- (BBN+CMB) predictions for ^{3}He, ^{4}He agree with observations
  - D: recent 1% precision abundance determination Cooke+ (2018) ApJ
    Undergoing D(p,γ) measurement at LUNA Zavatarelli et al.
  - ^{7}Li: $(^7\text{Li/H})_{BBN} / (^7\text{Li/H})_{obs}$ → **3 !!!**
- Attempts to solve the ^{7}Li problem:
  - Stellar atmosphere model? New ^{7}Li stellar mechanism destruction? Physics beyond the standard model?
  - Nuclear solution? ^{7}Li produced by ^{7}Be EC
    - Additional ^{7}Be destruction channels?
      - $^7\text{Be} + {^3\text{He}} \rightarrow {^{10}\text{C}^*}$
      - $^7\text{Be} + {^4\text{He}} \rightarrow {^{11}\text{C}^*}$

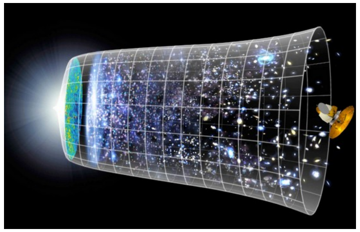
Hypothetical states?

Chakraborty+ (2011) PRD

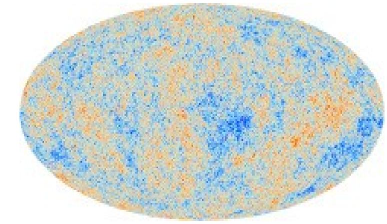


The ALTO facility

Accélérateur Linéaire
et TANDEM à Orsay



Search for missing ^{10,11}C states

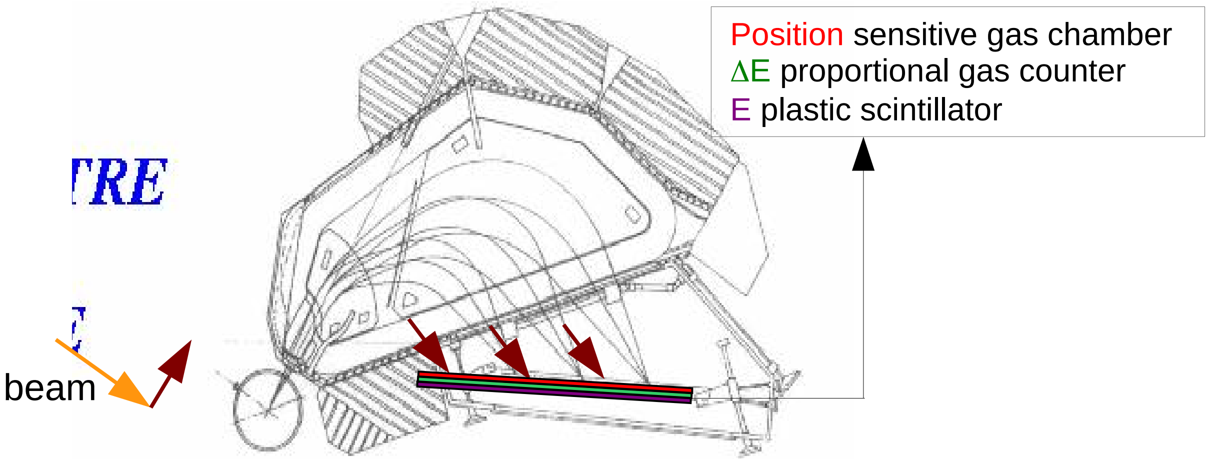


Experimental details:

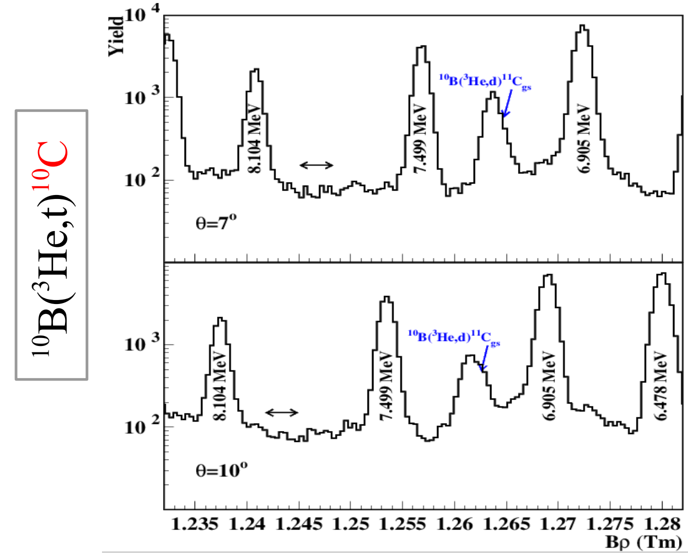
- Charge exchange reactions:
  → $^{10}B(^3He,t)^{10}C$ & $^{11}B(^3He,t)^{11}C$ @ 35 MeV
- Targets: ^{10}B/Au, ^{nat}B (80% ^{11}B), ^{12}C, Si_2O_4, ^{197}Au
- Beam intensity: 100 pnA

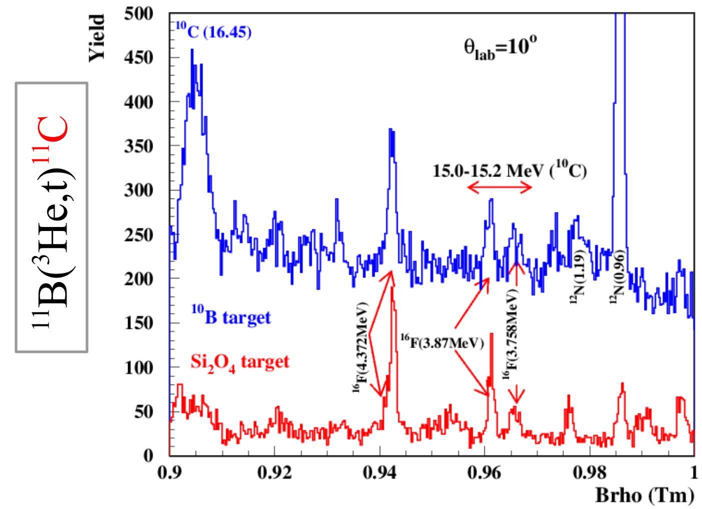
Enge Split-Pole (magnetic spectrometer):

- $\Delta E/E = 5 \times 10^{-4}$
- $\Delta\Omega$ = 1.7 msr (or more, but aberrations)



Enge, (1979) NIM 162
Spencer & Enge, (1967) NIM 49

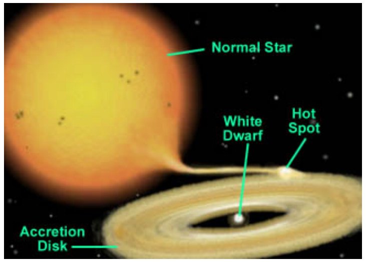




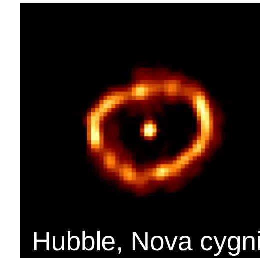
Hammache+ (2013) PRC(R)

- No additional states in ^{10}C nor ^{11}C
- If present, any $^{10}C(1^-$ or $2^-)$ state should have Γ_{tot} > 590 keV (95% CL)
- New $^7Be(^3He,p)^9B$ and $^7Be(^3He,\alpha)^6Be$ reaction rates → no impact on ^{7}Li production

$\boxed{\text{}^7\text{Be} + {}^{3,4}\text{He reaction channels don't alleviate } {}^7\text{Li problem}}$



Classical novae and ^{18}F nucleosynthesis



> directly in the nova Gamow window. The remaining uncertainties for nova nucleosynthesis involve only a handful of reaction rates, particularly ^{18}F(p,α), ^{25}Al(p,γ) and ^{30}P(p,γ), for which several experiments are being conducted (or have been proposed) at different facilities

José+ (2007)

→ soon the first stellar explosions with all reaction rates based on experimental information

Classical novae are γ-ray emitters and dust producers

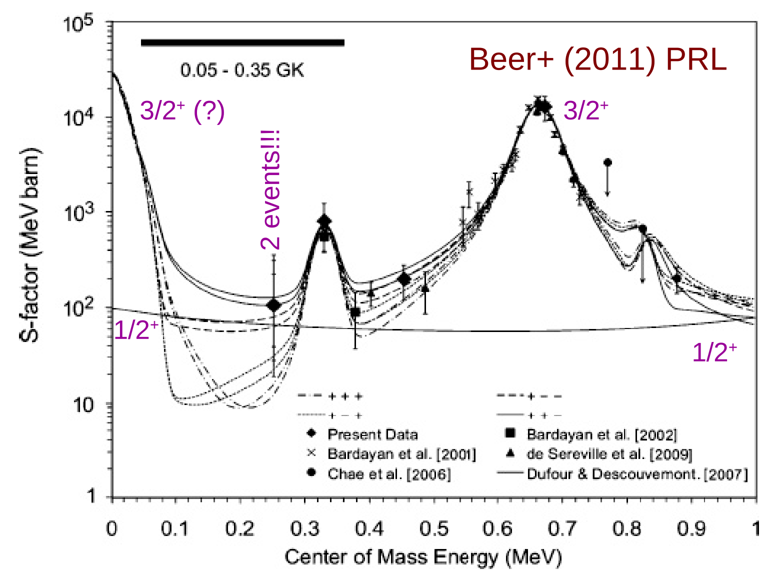
- ^{30}P(p,γ)^{31}S: paternity of novae grains
- ^{25}Al(p,γ)^{26}Si: contribution to galactic ^{26}Al
- ^{18}F(p,α)^{15}O: γ-ray emission ≤ 511 keV

γ-ray observations

- Access to isotopic abundances
- Explosion mechanism
- Novae rate
- Properties of ejected envelope ($T_{1/2}$(^{18}F) ≈2h)

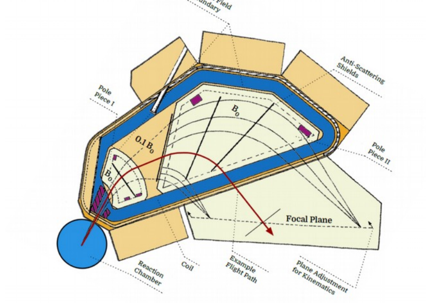
^{18}F yield depends crucially on the uncertain ^{18}F(p,α)^{15}O reaction

^{18}F(p,α)^{15}O astrophysical S-factor

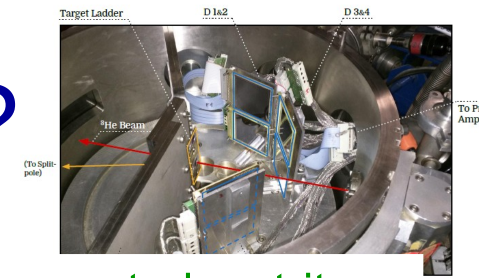


Interference effects in Gamow peak

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



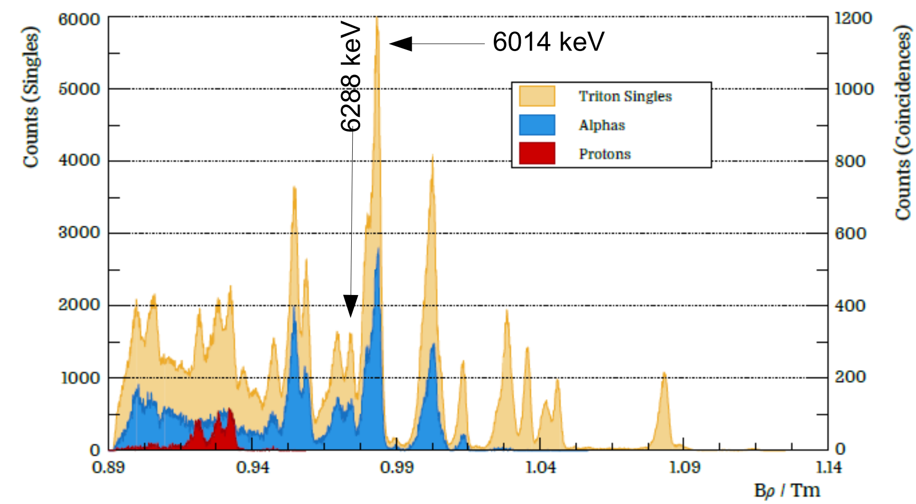
Sub-threshold 1/2⁺ state?



Experimental set-up @ ALTO

- 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.
  → Split-Pole spectrometer
- Coincidence measurement, ^{19}Ne states decay via α/p emission.
  → charged particle detection array (DSSSD)

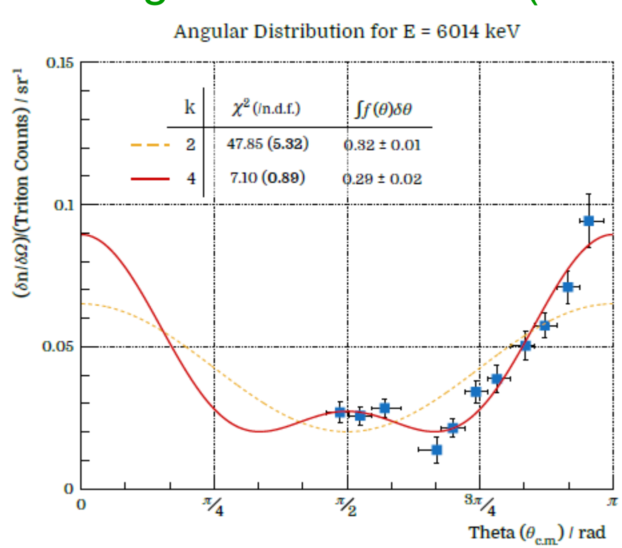
Split-Pole focal plane gated on tritons



Angular correlations (t + α)

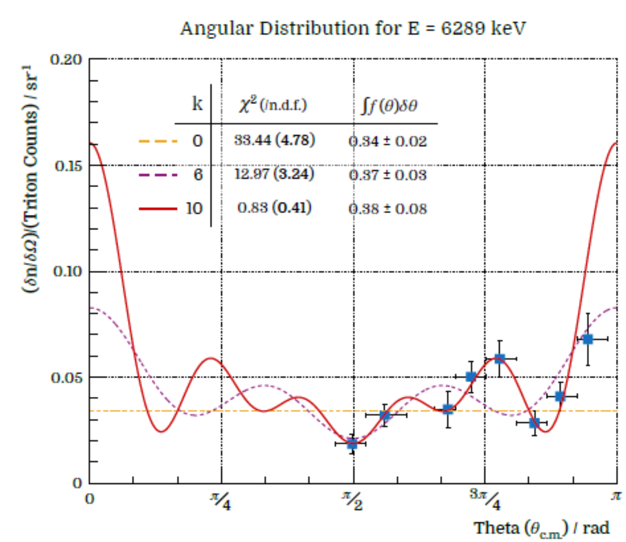
Legendre polynomial governed by J^{π}

J^{π}	$k_{max} = 2l$
1/2+	0
1/2-	2
3/2+	2
3/2-	4
5/2+	4
5/2-	6
7/2+	6
7/2-	8



$E_x = 6014$ keV

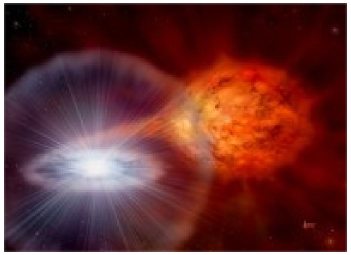
- Test case, known 3/2- state
- In agreement with J^{Π} = 3/2-



$E_x = 6289$ keV (E_R = -122 keV)

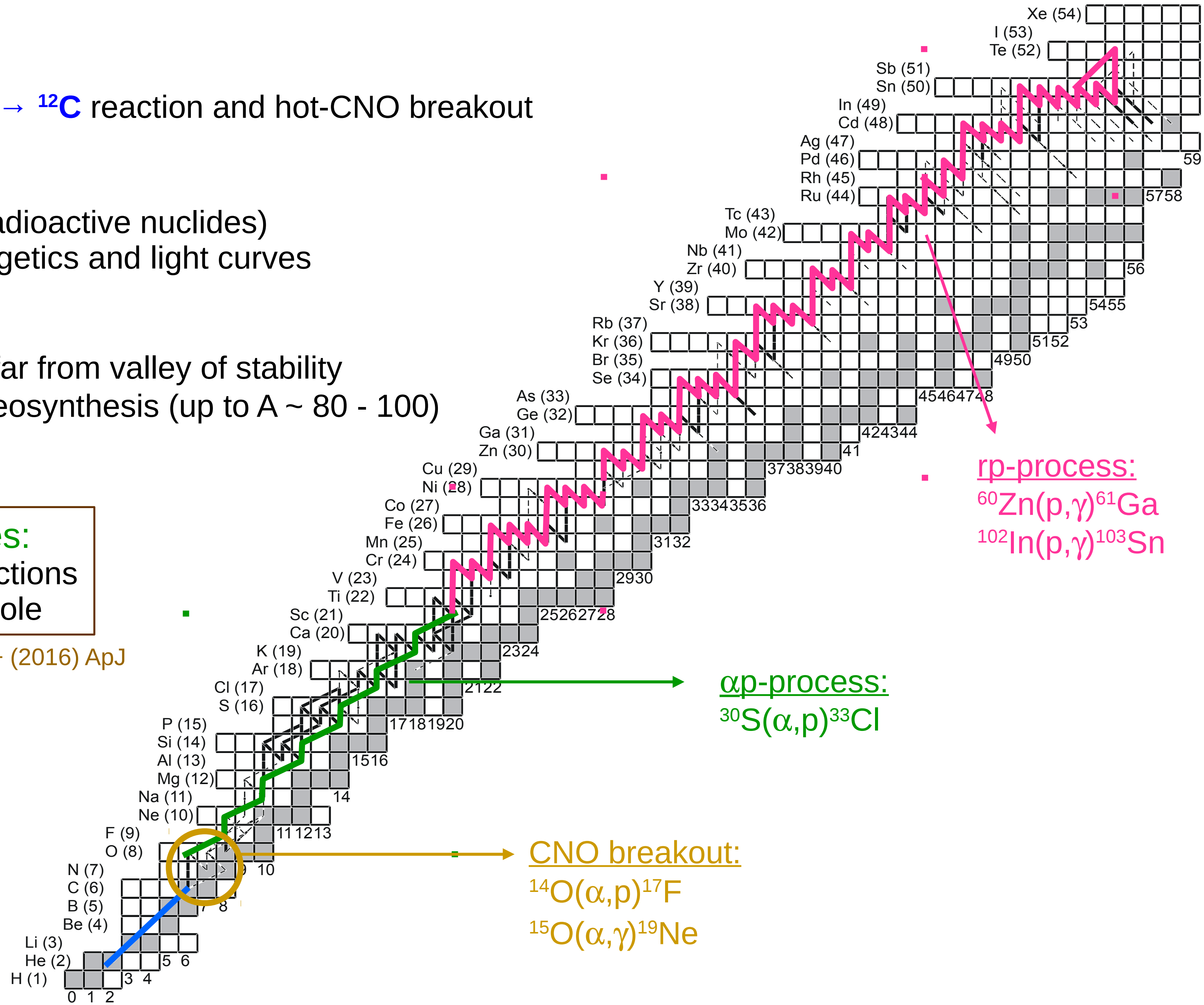
- Not compatible with 1/2+ (isotropy)
- Would indicate high spin or multiplet

J. Riley, A. M. Laird et al., to be submitted



X-ray bursts nucleosynthesis

- **Triggered by 3α → ^{12}C** reaction and hot-CNO breakout
- **(α,p) process**
  - Up to A < 35 (radioactive nuclides)
  - Impact on energetics and light curves
- ***rp*-process**
  - (p,γ) reactions far from valley of stability
  - Impact on nucleosynthesis (up to A ~ 80 - 100)



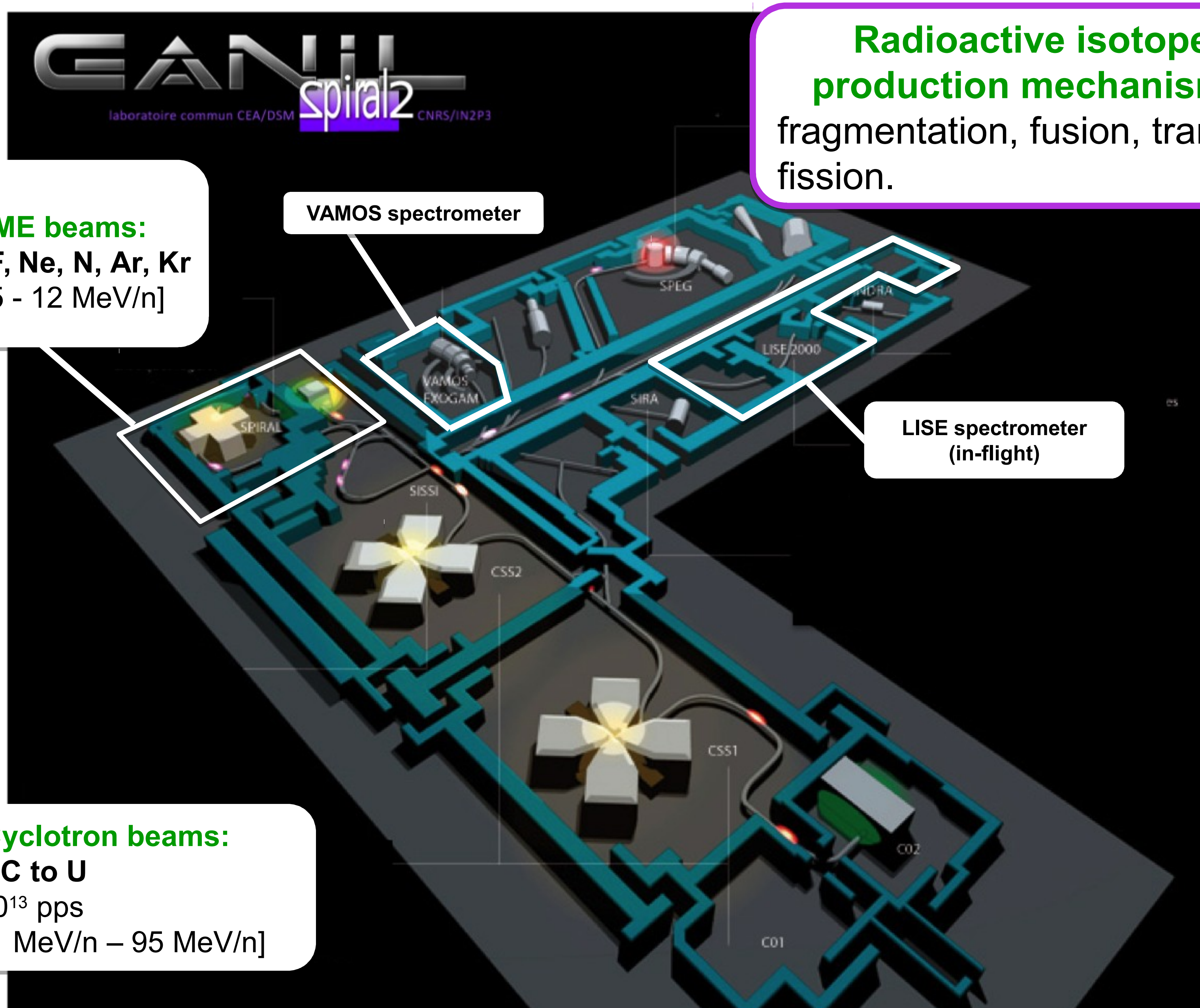
Sensitivity studies:
→ few tens of reactions play an important role

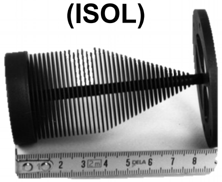
Parikh+ (2008) ApJ, Cyburt+ (2016) ApJ

The GANIL facility

Grand Accélérateur National d'Ions Lourds

Radioactive isotopes production mechanisms:
fragmentation, fusion, transfer, fission.





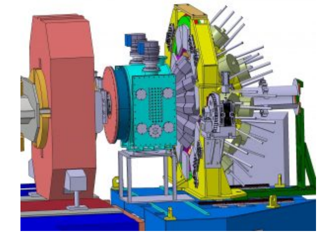
SPIRAL1 target (ISOL)

CIME beams:
He, O, F, Ne, N, Ar, Kr
E =[1.75 - 12 MeV/n]

Cyclotron beams:
from C to U
I $\leq 10^{13}$ pps
E = [1 MeV/n – 95 MeV/n]

Courtesy: B. Bastin

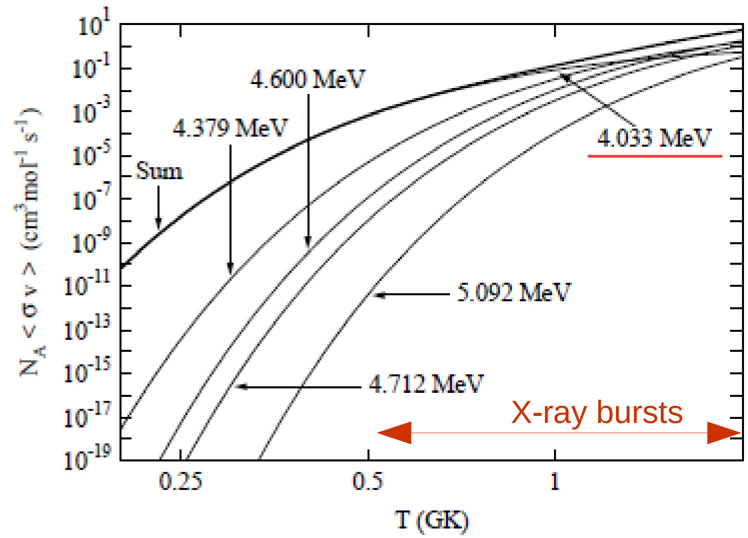
The $^{15}O(\alpha,\gamma)^{19}Ne$ reaction



Present status

- Gamow window: 0.5 – 2 MeV (0.5 – 1.5 GK)
- 4.033 MeV state dominates up to 1 GK
- $N_A < \sigma v > \propto (2J_R+1)\dfrac{\Gamma_\alpha \Gamma_\gamma}{\Gamma_{tot}} e^{-E_R/k_B T}$
- E_R, J^π: known
- $\Gamma_{tot} = \Gamma_\gamma \;\alpha\; 1/\tau$ with τ = 6.9 (15) fs Mythili+ (2008) PRC

Missing spectroscopic information: Γ_α in ^{19}Ne



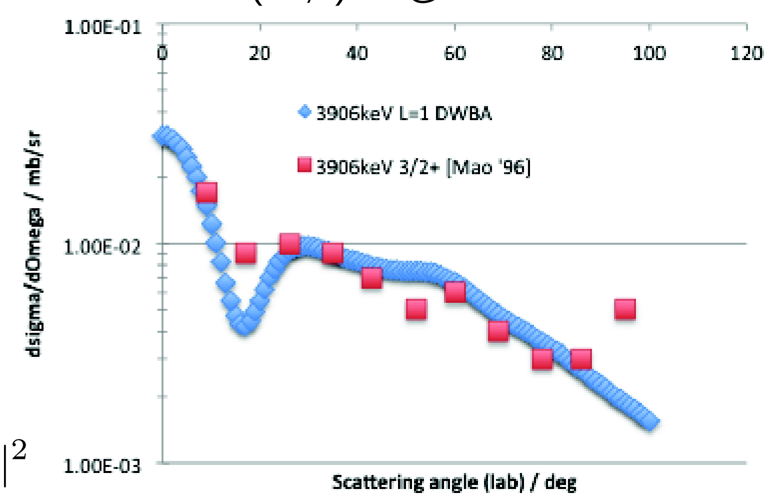
Davids+ (2003) PRC

Alpha-transfer reaction: $^{15}O(^6Li,d\gamma)^{19}Ne_{4.033}$ in inverse kinematics

Diget+ exp. accepted

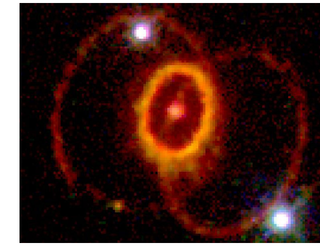
- Intense ^{15}O RIB ~ 10^7 pps @ 4.7 MeV/u
- State of the art detection system
  - VAMOS magnetic spectrometer
    → reaction channel identification (^{19}Ne)
  - AGATA γ-ray spectrometer
    → identification of the 4.033 MeV state
  - MUGAST charged particle array
    → angular distribution measurement

$^{15}N(^6Li,d)^{19}F$ @ 3.7 MeV/u



$$\left.\frac{d\sigma}{d\Omega}\right)_{exp} = C^2 S_\alpha \left.\frac{d\sigma}{d\Omega}\right)_{DWBA} \rightarrow \quad \Gamma_\alpha = 2P_L(r,E)\frac{\hbar^2 r}{2\mu} C^2 S_\alpha \; |\phi(r)|^2$$

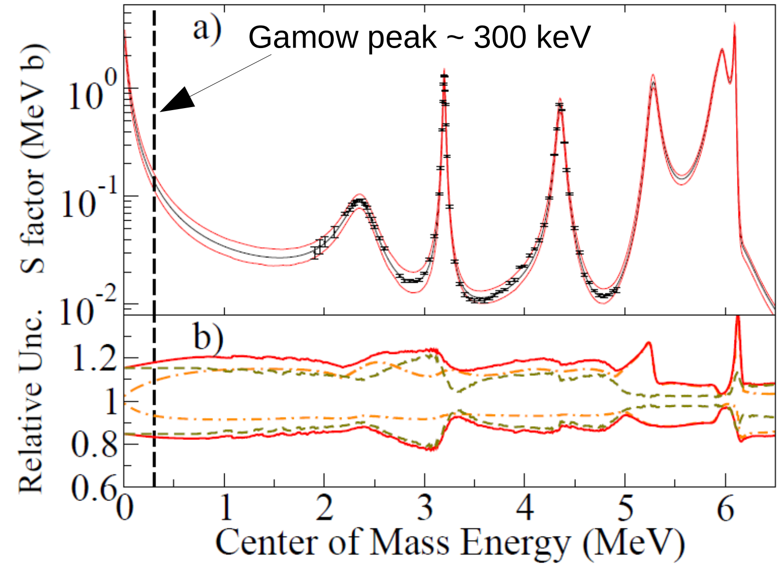
Massive stars



The $^{12}C(\alpha,\gamma)^{16}O$ reaction → Holy Graal

- Determines C/O abundance in stars
- Impact on the stellar core sizes (Fe, Si, O)
  - Consequence on supernovae explosions
  - Nature of compact remnant formed

$^{12}C(\alpha,\gamma)^{16}O$



deBoer+ (2017) Review Modern Physics

Advanced burning stages:

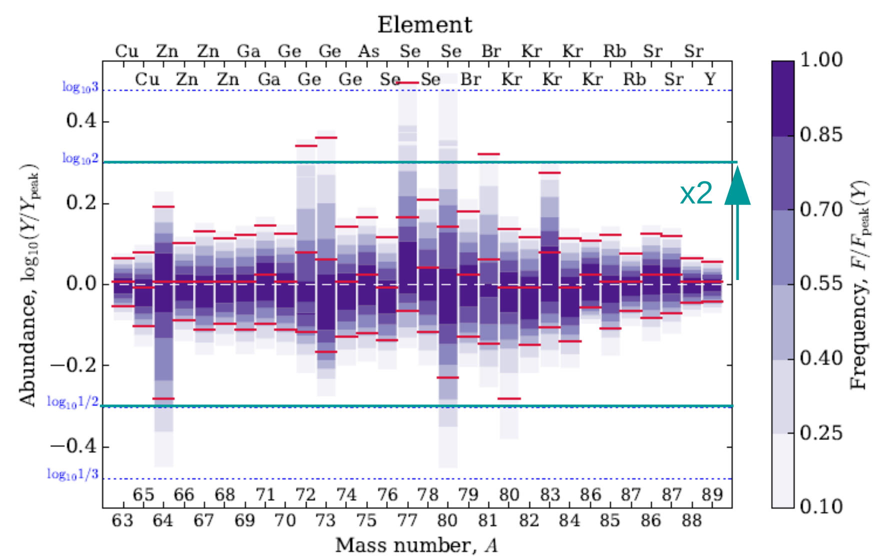
- The $^{12}C+^{12}C$ fusion reaction
- ...

see S. Courtin's talk

Weak *s*-process: production of nuclides up to A ~ 90

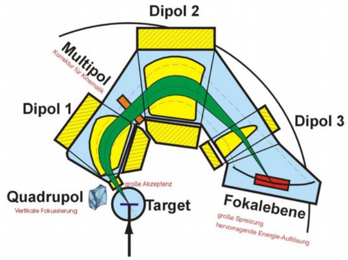
- Small abundance uncertainty (~ 30 %) for most of the elements → 10 influencial reactions identified (above Fe)

- Most important reactions:
  - $^{22}Ne(\alpha,n)^{25}Mg$ & $^{22}Ne(\alpha,\gamma)^{26}Mg$
    → neutron source
  - $^{17}O(\alpha,n)^{20}Ne$ & $^{17}O(\alpha,\gamma)^{21}Ne$
    → neutron recycling in low Z rotating stars from the $^{16}O(n,\gamma)^{17}O$ neutron poison reaction?



Nishimura+ (2016) MNRAS

The ^{22}Ne + α reactions

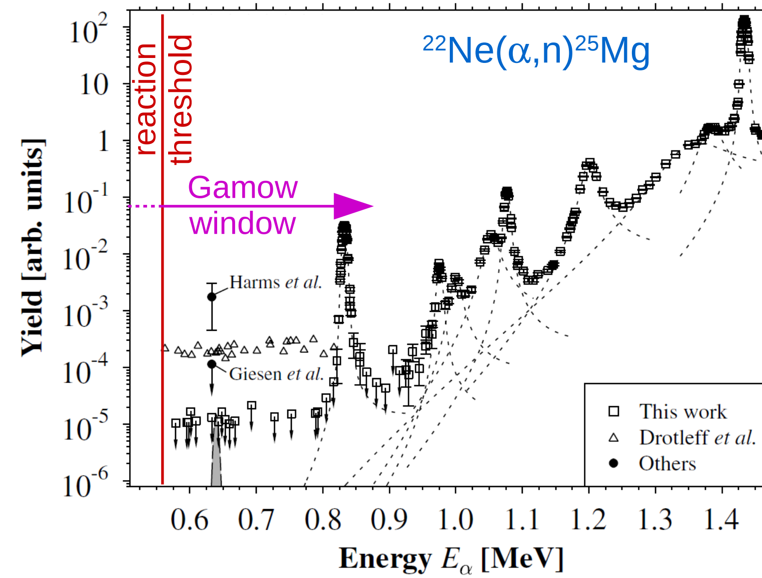


Present status

- Negative Q-value: - 478 keV
- Gamow window: 600 ± 150 keV (central He burning)

- Direct measurement down to n+^{25}Mg threshold
  → BUT only upper limit below E_R = 702 keV resonance

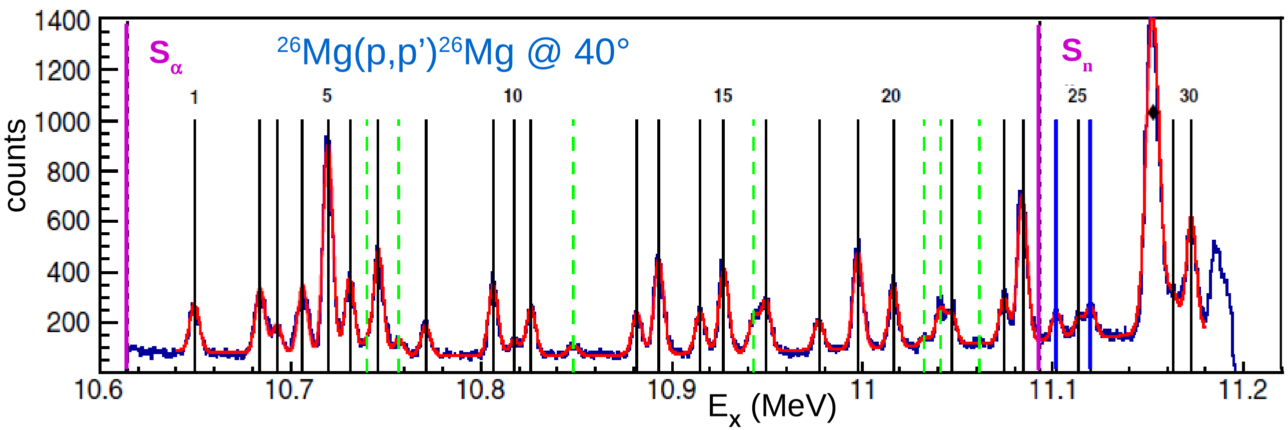
- ^{22}Ne + α reaction rates rely on spectroscopic properties of ^{26}Mg states
  → BUT inconsistent number of states, J^{Π}, Γ_{α}
  (see Longland+ (2012) PRC for a review)



Jaeger+ (2001) PRL

Recent & future indirect studies

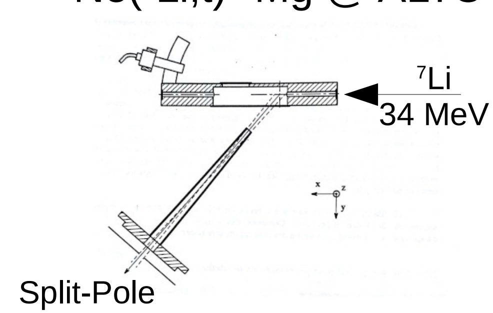
- Very high resolution measurement (Q3D @ MLL)



Adsley+ (2018) PRC

- Confirmation of suggested states above α+^{22}Ne threshold
- New ^{26}Mg states observed above n+^{25}Mg threshold: nature?

- Determination of Γ_α(^{26}Mg)
  → ^{22}Ne(^{7}Li,t)^{26}Mg @ ALTO

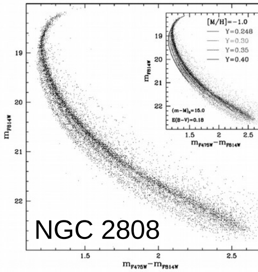


Development of a gas cell

(see De Oliveira, PhD thesis)

Hammache+ exp. accepted

Globular clusters & elemental anomalies



It is now commonly accepted that globular clusters (GC) are made of multiple generations implying several episodes of star formation

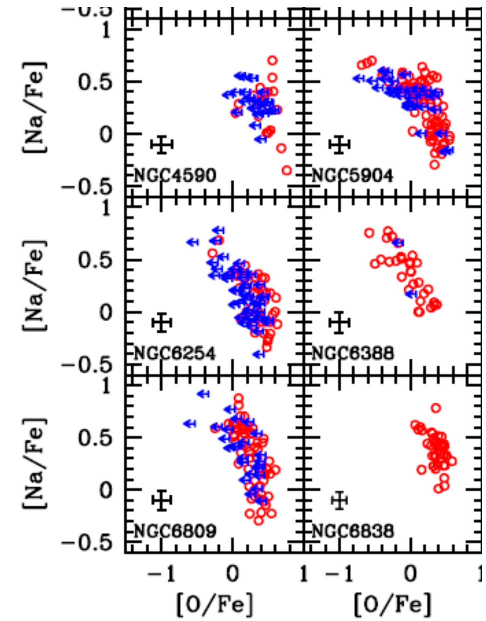
- Abundance anticorrelation C-N, O-Na, Mg-Al
- Observed in red giant stars where temperature is too low to alter abundances

- Observations reproduced if 1st generation of star burns hydrogen at ~ 75 MK and nucleosynthetic products are mixed with pristine GC gas Prantzos+ (2007) A&A, (2017) A&A

Nature of 1st generation of stars? AGB, FRMS, ...

(see Charbonnel (2016) EAS Pub. Ser. 80 for a review)

Na-O anticorrelation



Carretta+ (2007) ApJL

Case of NGC 2419

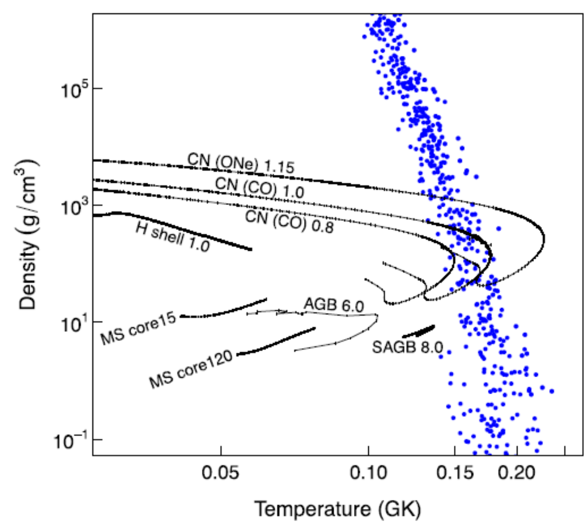
- Observation of Mg-K anticorrelation

Case of NGC 2808

- Observation of K-O anticorrelation
- Observation of K-Na correlation

Need for higher temperatures ~ 180 MK

Iliadis+ (2016) ApJ, Prantzos+ (2017) A&A

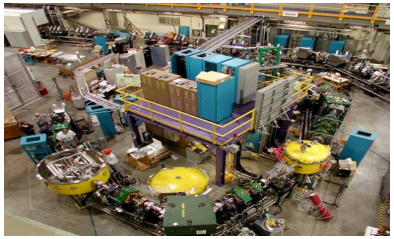


Iliadis+ (2016) ApJ

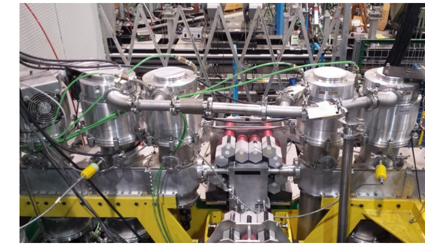
Sensitivity of the T-ρ locus to reaction rates

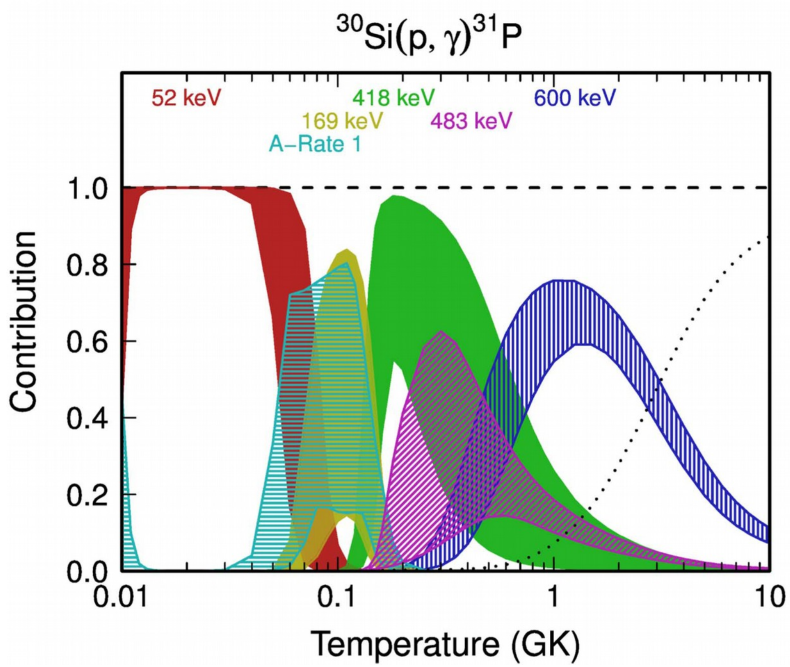
- Few reactions:
  - $^{37,38}Ar(p,\gamma)^{38,39}K$
  - $^{39}K(p,\gamma)^{40}Ca$
  - $^{30}Si(p,\gamma)^{31}P$

Dermigny+ (2016) ApJ



The $^{30}Si(p,\gamma)^{31}P$ case

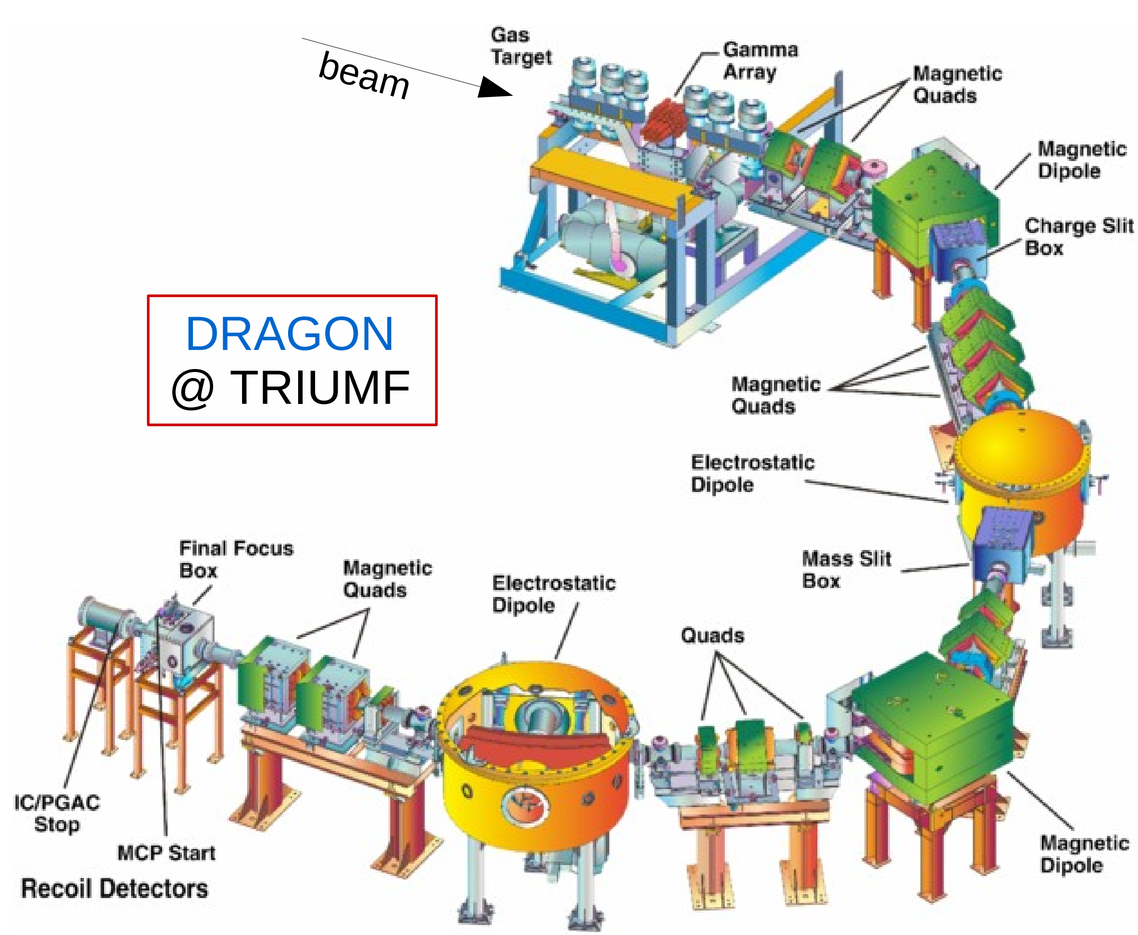




- Temperature range: 100 – 200 MK
- Most uncertain resonance: E_R = 418 keV (J^π unknown)
- Reaction rate for narrow resonance

$$N_A < \sigma v > \propto (\omega\gamma) e^{-E_R/k_B T}$$

DRAGON
@ TRIUMF



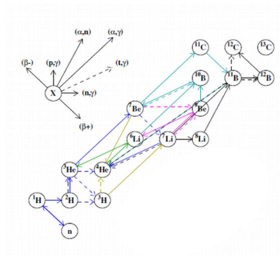
Direct measurement of the strength of the E = 418 keV resonance

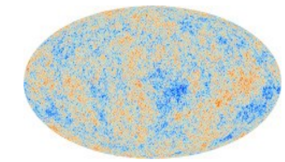
- Recoil mass separator: DRAGON
- Inverse kinematic (^{30}Si beam ~ 10^9 pps)
- “thick” H_2 windowless gas target (8 Torr)
- Estimated yield per incident ion ~ 10^{-10}
  → 30 coincident events / h

- Raw suppresion factor (p,γ) ~ 10^8 – 10^{13}

de Séréville+ exp. accepted

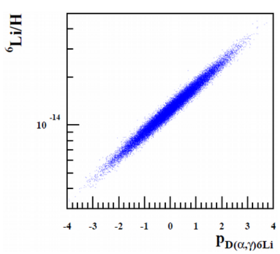
Summary

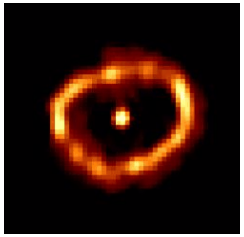




- Major nuclear reactions having strong impact on energetics and nucleosynthsesis of astrophysical sites/processes are identified

- Recent detailed sensitivity studies (*s*-, *r*-, *p*-process) to identify influencial reactions and possible overlooked reactions so far

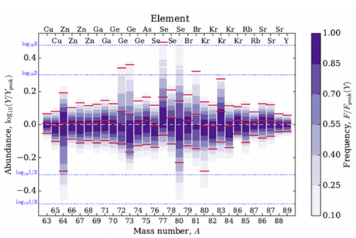


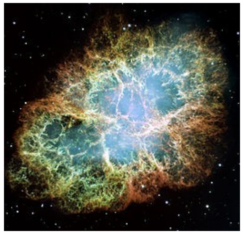


- One of the key ingredient is the thermonuclear reaction rate
- Crucial to give statistical meaningful reaction rates uncertainties

- Cross section is the key nuclear ingredient

- Two experimental approaches:
  - Direct measurements (very low cross section): σ, $\omega\gamma$
  - Indirect measurements (higher cross section but model dependent): E_X, J^π, Γ_i, Γ_{tot}





- Many nuclides are radioactive
  → development of challenging radioactive ion beams