Nucleosynthesis: State of the art & open questions

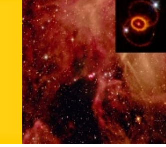
Faïrouz Hammache (IPN-Orsay)

for **GT4** (**Quel est l'apport de la physique nucléaire à la compréhension de l'astrophysique?**)

Assemblée générale du GdR RESANET

Orsay, 10-11/12/2018

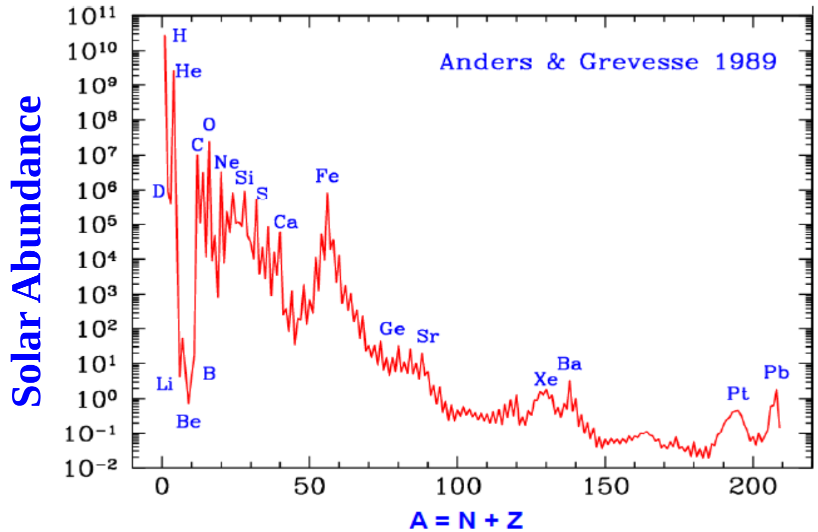
NUCLEAR ASTROPHYSICS



- How do stars form and evolve?
- What powers the stars?
- What is the origin of the elements?

Which nucleosynthesis processes at work?

- What is the nature of matter under extreme conditions?

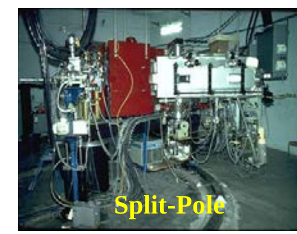


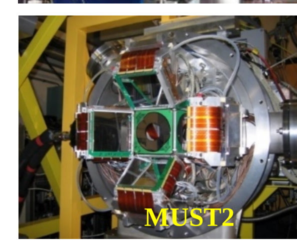
Observations (astronomy & geology)

KEY for understanding

Nuclear Physics
Synthesis of nuclei

Astrophysics modelling
(BBN & stellar modelling)





1st joint meeting GT4-GdR RESANET and OG

24-25 September 2018 (Observatoire de Paris)

French community: Naturally interdisciplinary nuclear physics, astrophysics and theoretical physics → IN2P3, INP, INSU

Nucleosynthesis

- Experiments for key reactions : CSNSM, IPNO, GANIL, CENBG, IPHC
- Stellar abundance observations : GEPI, CENBG, CSNSM
- Modelling : IAP, LUPM, CSNSM

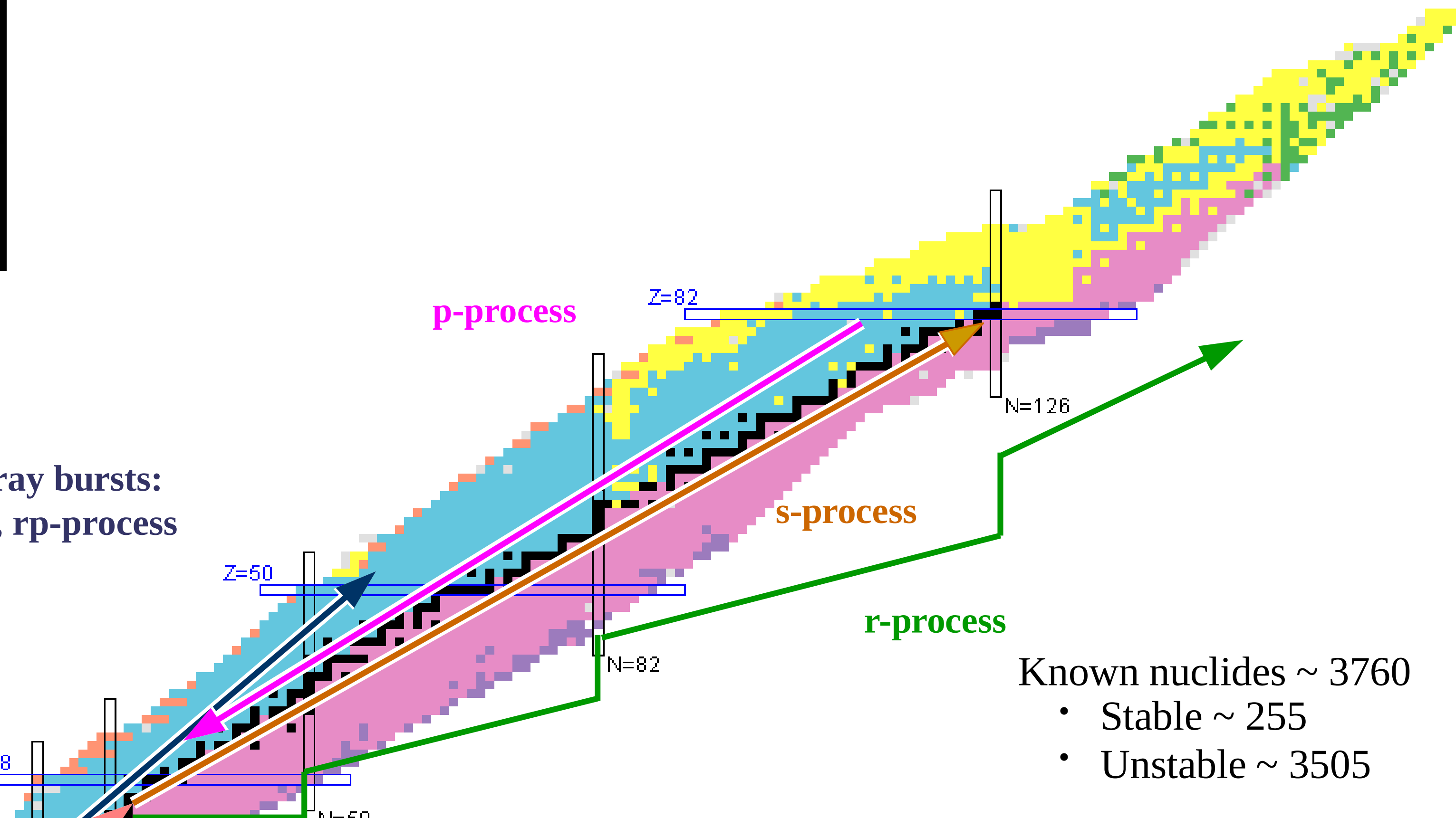
Compact objects

- Dense matter modelling : LPC, IPNL, GANIL, IPNO, LUTH
- Experiments (heavy-ion collisions) : : GANIL, Subatech, LPC
- Observations : Nançay, IRAP, IPAG, CENBG, Obs. Strasbourg, AIM
- Modelling : LUTH, AIM, IPNL, IAP

Strong connection with gravitational waves (GdR OG), detection of binary neutron star mergers by Virgo/LIGO

Around 50 participants at the meeting

Nuclear landscape and astrophysical processes



Known nuclides ~ 3760

- Stable ~ 255
- Unstable ~ 3505

Big-Bang nucleosynthesis: Achievements & open questions

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

- (BBN+CMB) predictions (D, ^3He, ^4He) ≅ observations

BUT higher precision is needed for $D(p,\gamma)^3He$ to be comparable with D observation precision (1.2%) Cook 2018

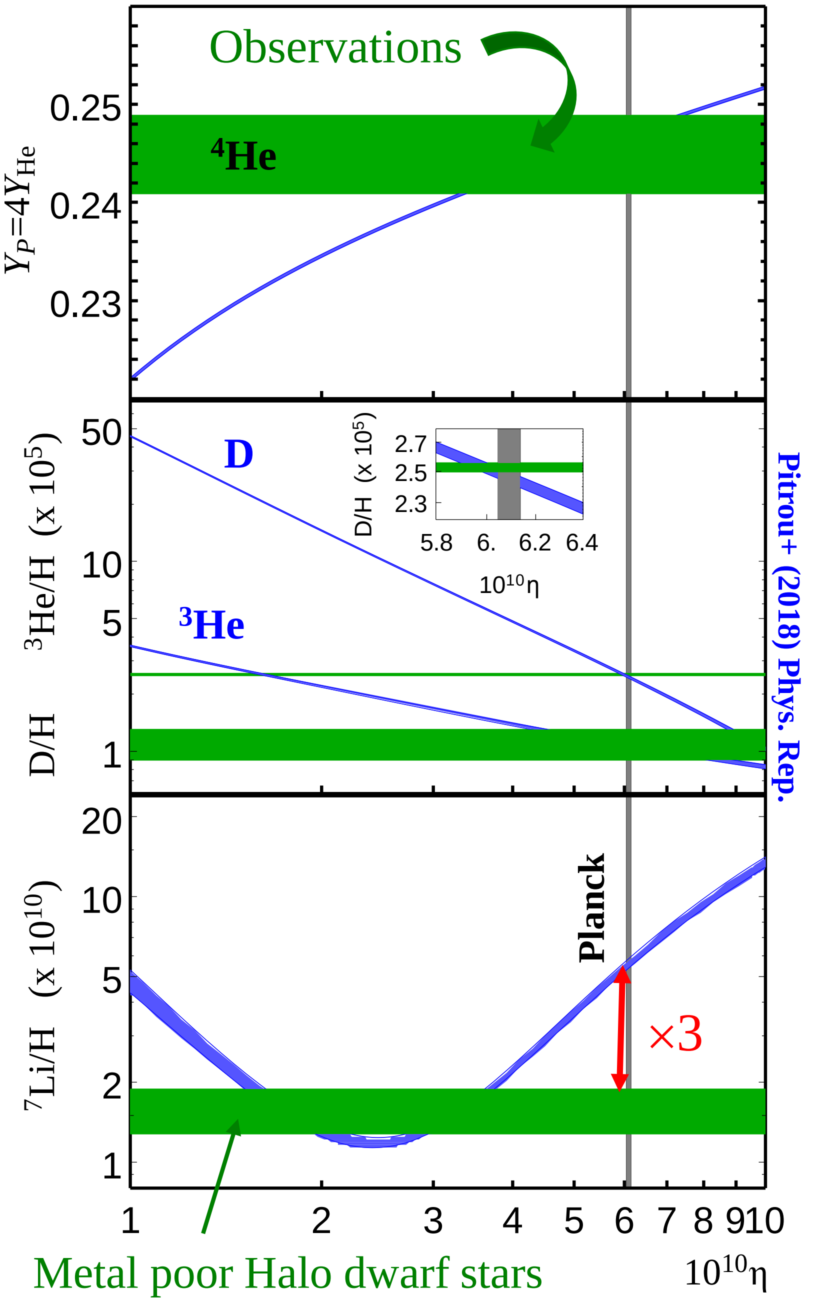
- **^{7}Li problem** : $(^7Li/H)_{BBN}$/ $(^7Li/H)_{obs}$ **≈ 3 !!!**

Investigated solutions to ^{7}Li problem:

- ^{7}Li stellar destruction ? → need uniform destruction all over the Spite plateau region
- Physics beyond standard model?
- Nuclear physics? ^{7}Li produced via ^{7}Be EC

→ Nuclear reaction rates of the main reactions producing and destroying ^{7}Be are well know

→ Secondary destruction channels were investigated:
$^7Be+d \rightarrow {}^9B^*$, 7Be+n → $^8Be^* \rightarrow 2\alpha$
$^7Be+{}^3He \rightarrow$ **$^{10}C^*$** & $^7Be+{}^4He \rightarrow$ **$^{11}C^*$** **(IPNO)**



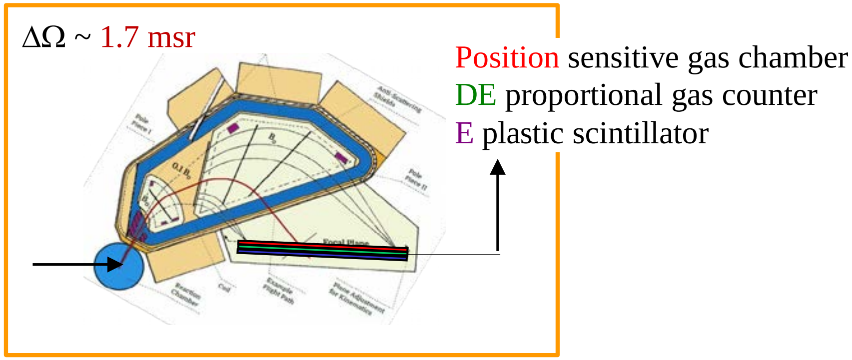
Big-Bang nucleosynthesis: Achievements & open questions

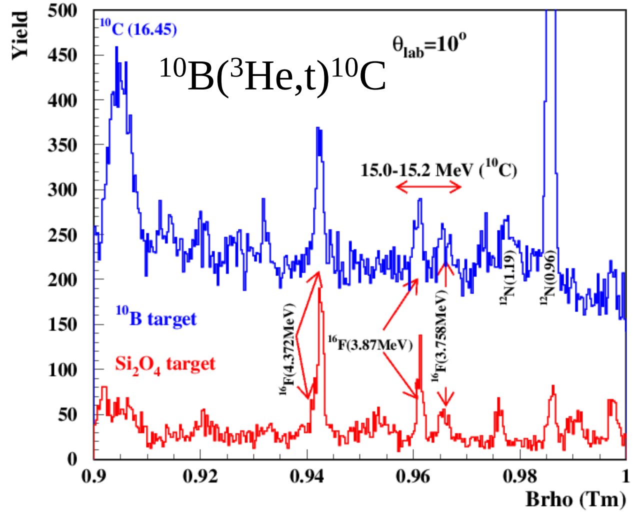
- Search for missing ^{10}C & ^{11}C resonant states @ IPN Orsay

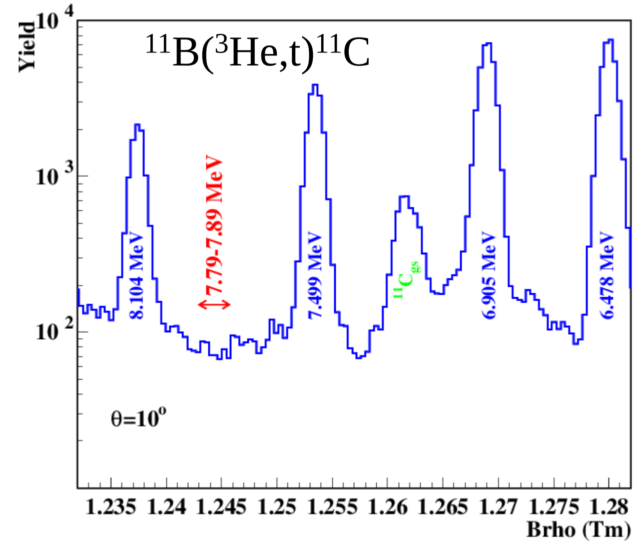
→ population via charge exchange reaction ^{10}B(^{3}He,t)^{10}C & ^{11}B(^{3}He,t)^{11}C

→ ^{3}He beam delivered by the Tandem of Alto facility

→ Experimental setup: Split-Pole (high resolution magnetic spectrometer)







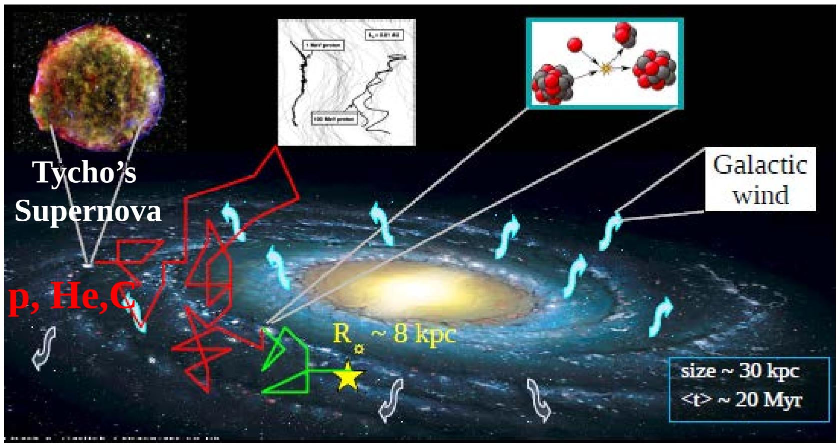
Hammache+(2013) PRC (R)

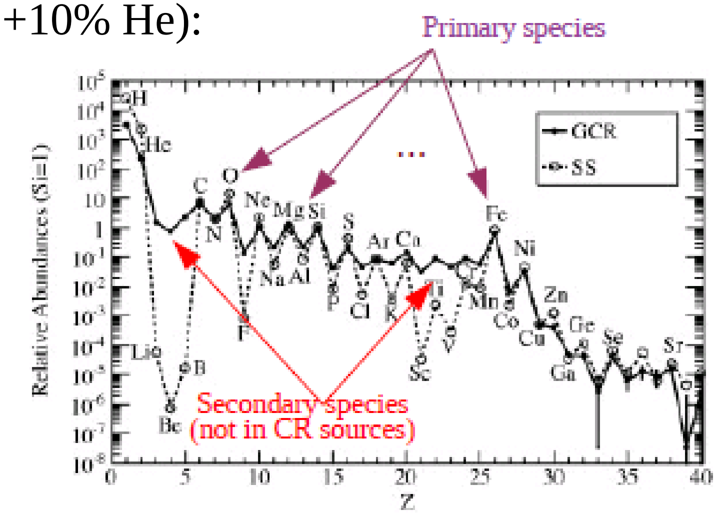
- No additional state in ^{10}C & ^{11}C
- If present, any ^{10}C (1-,2-) state should have $\Gamma_{total} \geq$ 590 keV (95% CL)
- New ^{7}Be(^{3}He,p)^{9}B and ^{7}Be(^{3}He,α)^{6}Be reaction rates → no impact on ^{7}Li production

→ ^{7}Be + ^{3,4}He reaction channels don't alleviate ^{7}Li problem, neither ^{7}Be + d & ^{7}Be+n channels **Barbagallo+(2016) PRL**

The solution has very likely to be found outside nuclear physics

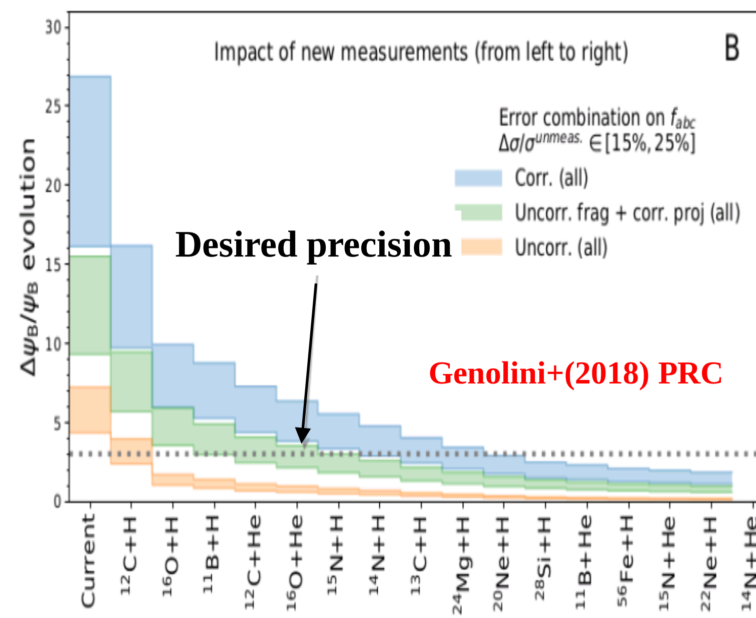
Cosmic ray spallation in Inter-Stellar Medium (ISM ~90% H +10% He): heavier nuclei (CNO) broken by interaction with p or α particle $\rightarrow$ Li, Be, B





Bauch+(2014) AdSR

(projectile+target) to measure with high priority



- A correct interpretation of the high precision (3 %) galactic cosmic ray measurements (AMS,..) in the Gev/n – TeV/n range could possibly lead to discoveries of new physics **but** interpretation limited by insufficient quality of the XS data (20%)
- ~few % accuracy required on key channels (100 MeV/n to multi-GeV/n) $\rightarrow$ **experimentally challenging**
- Need of improved models

D. Maurin talk

Carbon burning nucleosynthesis: Achievements & open questions

Carbon burning is a crucial phase in the stellar nucleosynthesis in massive stars ($M \geq 8\ M_{\odot}$)

- $^{12}C+^{12}C$ reaction rate uncertainties (several order of magnitudes) have effects on the subsequent evolution & nucleosynthesis in massive stars

- A large $^{12}C+^{12}C$ rate affects

→ the s-process elements in massive stars: it produces a significant proportion of Kr, Sr, Y, Zr, Mo, Ru, Pd and Cd **Bennett +(2012) Mon. Not. R. Astron.**

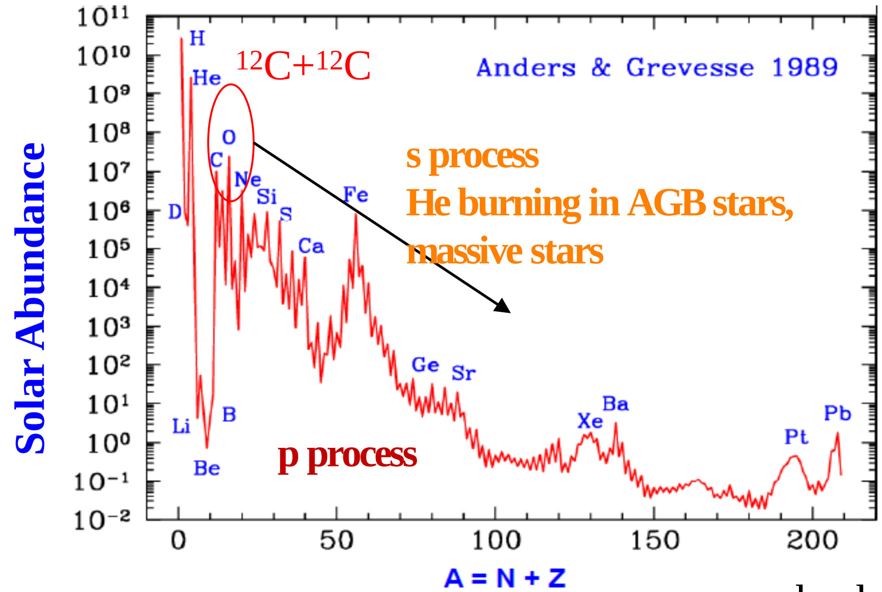
→ The explosive p-process nucleosynthesis in massive stars **Pignatari +(2013) Astrophys. J.**

- $\sigma(^{12}C+^{12}C)$ extremely small: pb-nb

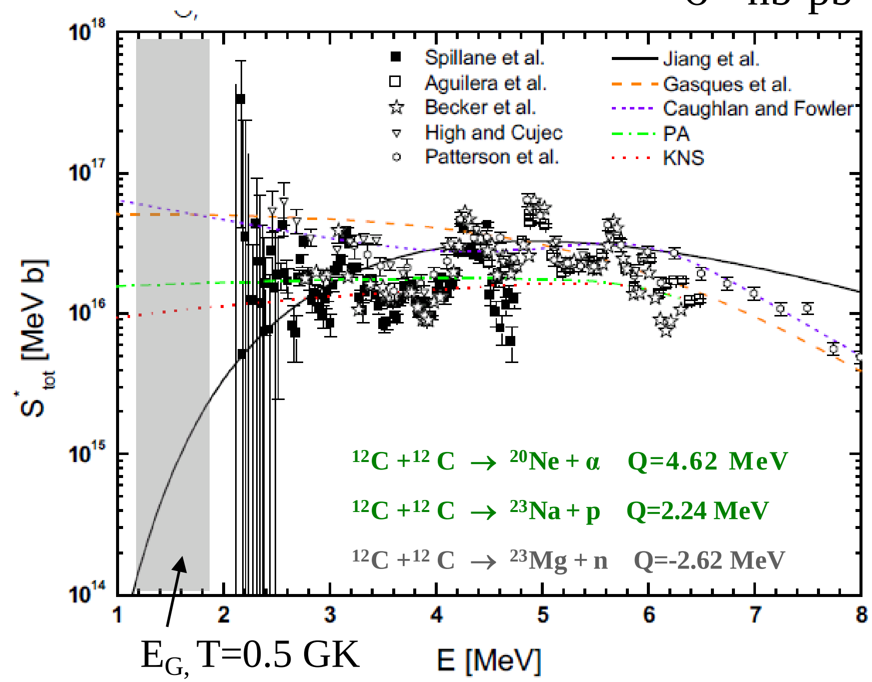
→ extremely sensitive to background

→ extrapolation with various trends

→ Crucial role of resonances, impact on the reaction rate? **Tumino+(2018) Nature (THM experiment)** → very controversial results

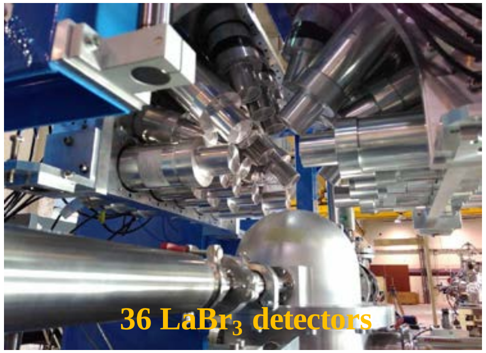


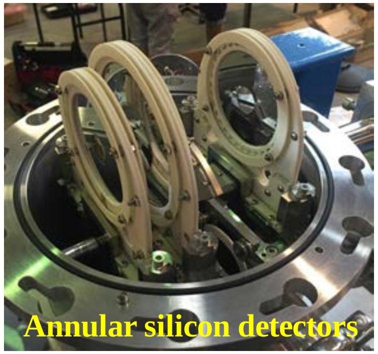
σ~ nb-pb

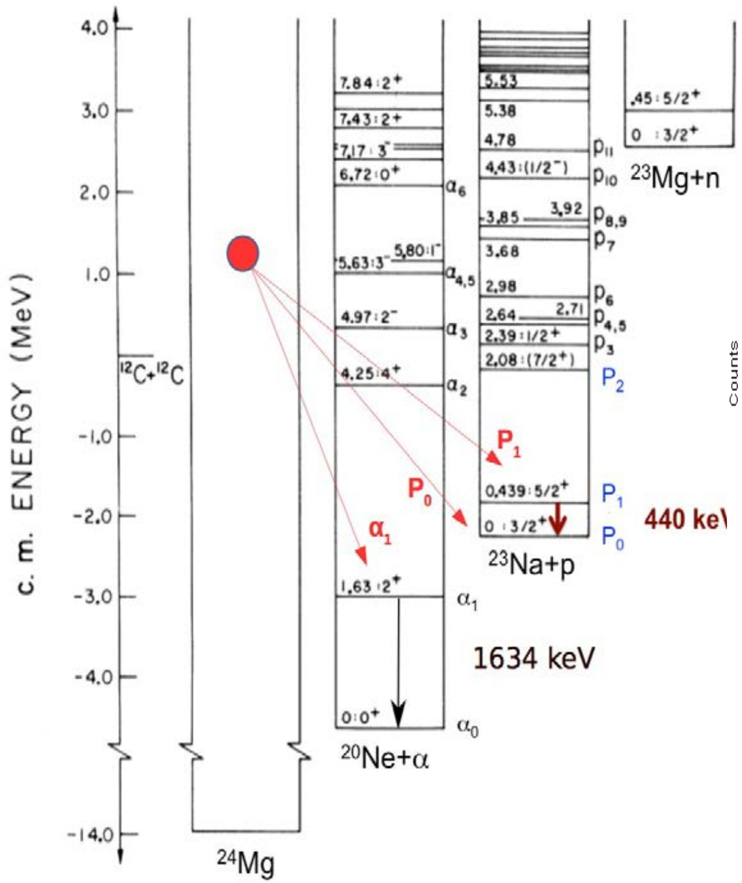


The Stella project: Direct $^{12}C+^{12}C$ cross-section measurements @ ANDROMEDE **Courtin+(2017)**

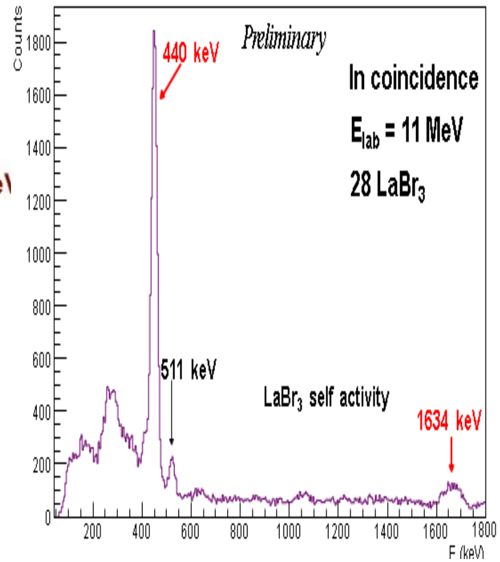
→ γ-particle coincidence measurement
→ rotating target system I > 1pμA
→ Measurements down to E_{cm} ~ 2.1 MeV



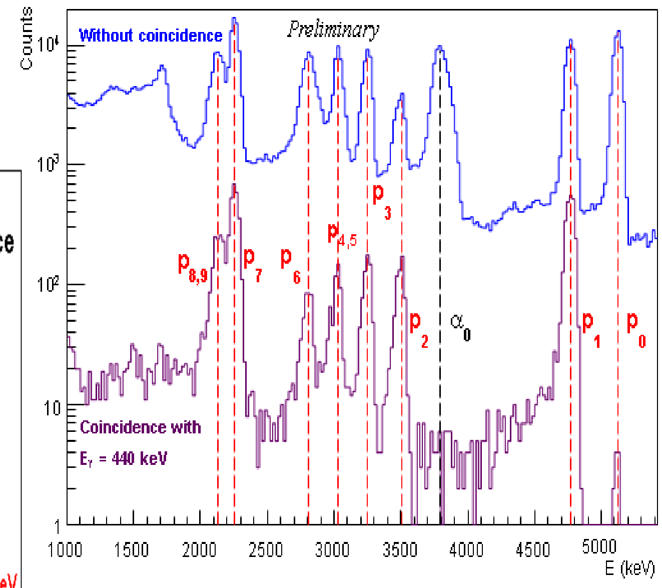




γ-ray spectrum



Particle spectrum

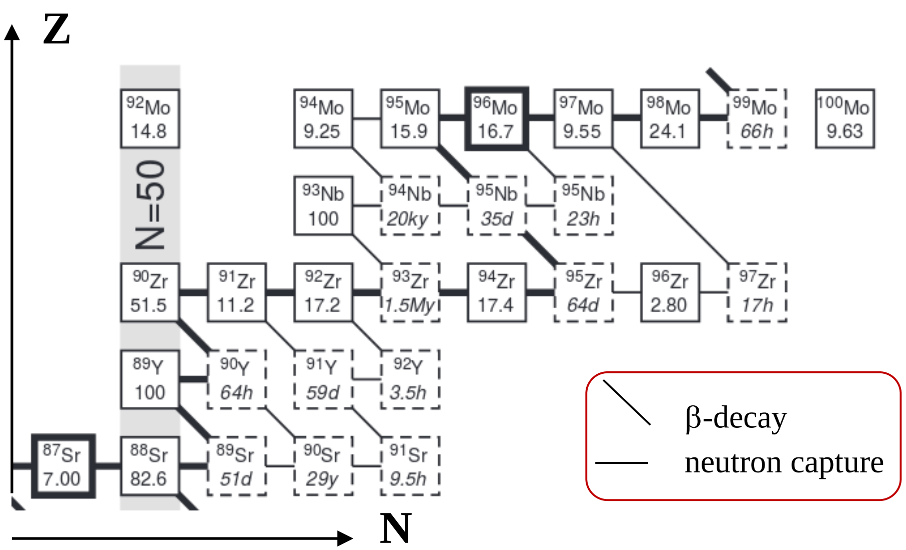


Analysis being finalized

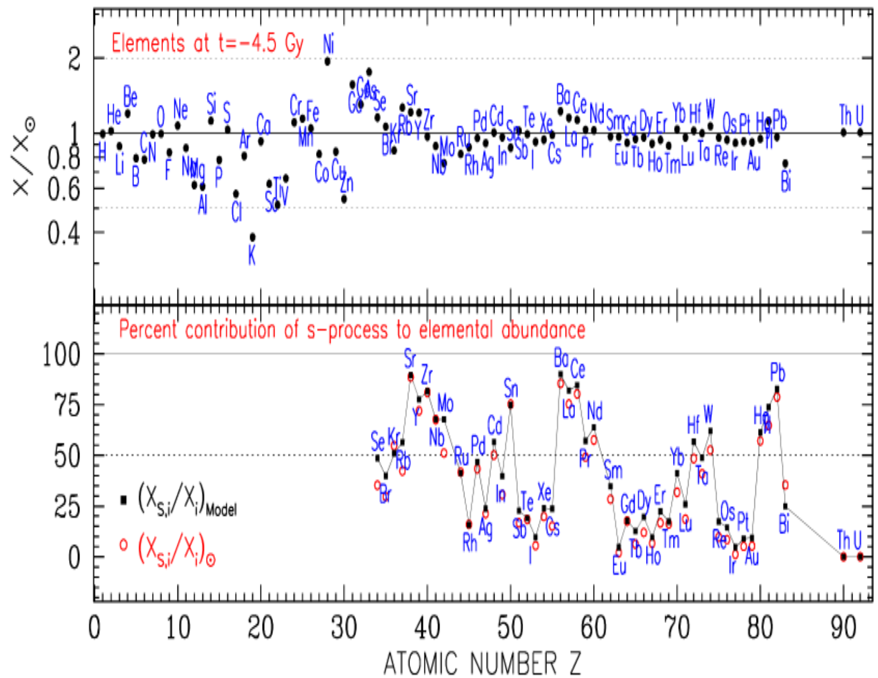
S. Courtin talk

s-process nucleosynthesis: Achievements & open questions

<u>s-process</u> (s = slow neutron capture process) → production of half of the abundance of heavy elements



Galactic chemical evolution calculation



Prantzos+(2018) MNRAS

- Weak s-process : production of 60<A<90 elements in massive stars (T~0.35GK-1GK) & intermediate-mass AGB star (T~0.35 GK)

  → main neutron source $^{22}Ne(\alpha,n)^{25}Mg$

- Main s-process : production of 90<A<209 elements in low-mass AGB stars 1-3 $M_{\odot}$ (T~0.1 GK)

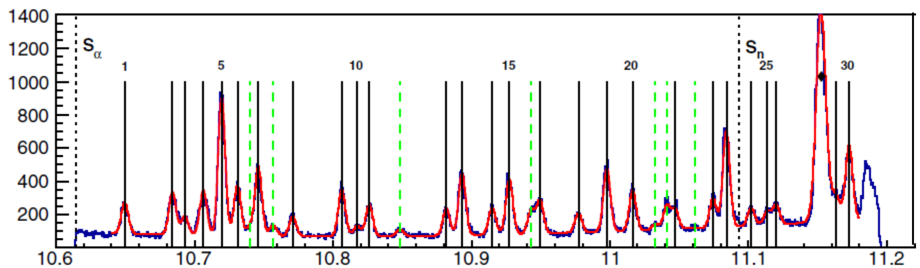
  → main neutron source $^{13}C(\alpha,n)^{16}O$

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

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

Most important reactions with large uncertainties:

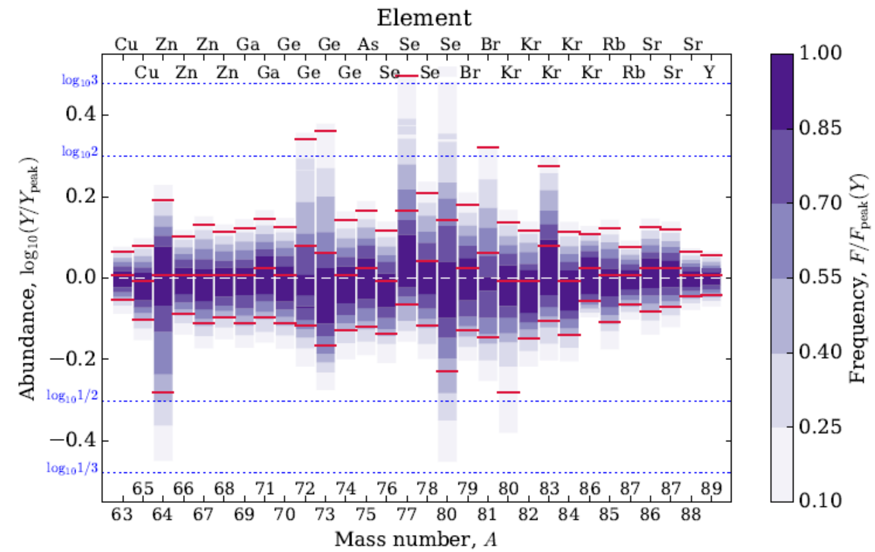
$^{22}Ne(\alpha,n)^{25}Mg$ → main neutron source
→ competition with $^{22}Ne(\alpha,\gamma)^{26}Mg$
→ $^{26}Mg(p,p')^{26}Mg^*$ @ MLL-Munich



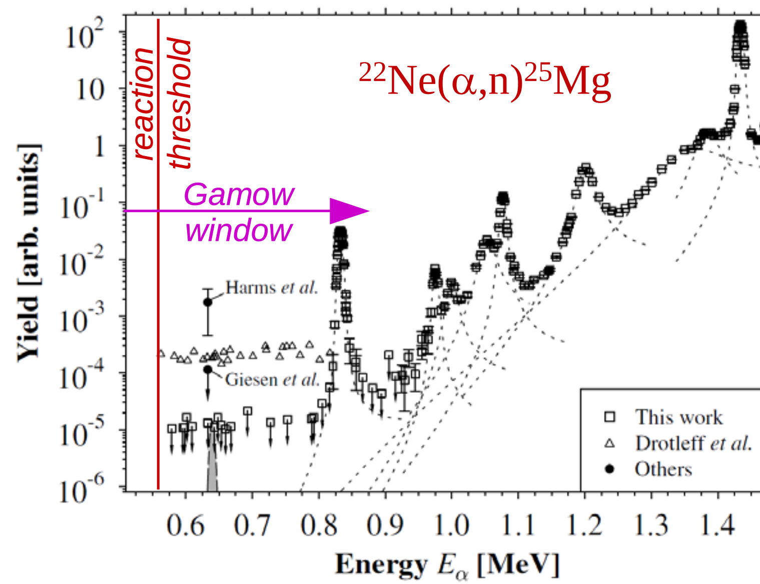
Adsley+(2018) PRC

→ $^{22}Ne(^{7}Li,t)^{26}Mg$ @ ALTO (Split-Pole & gas cell)

Hammache, Adsley+(end 2019)



Nishimura+ (2016) MNRAS

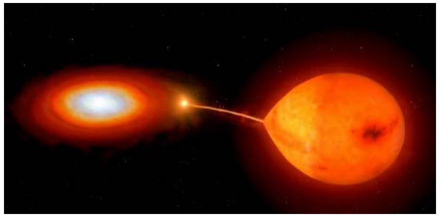


Jaeger+ (2001) PRL

$^{17}O(\alpha,n)^{20}Ne$ →neutron recycling in low Z rotating stars from the $^{16}O(n,\gamma)^{17}O$ neutron poison reaction?
→ in competition with $^{17}O(\alpha,\gamma)^{21}Ne$
→ $^{17}O(^{7}Li,t)^{21}Ne$ @ MLL-Munich (Q3D)

Hammache, Lamia+(2019)

Classical novae nucleosynthesis: Achievements & open questions



- Novae produced by runaway nuclear fusion at the surface of a white dwarf accreting the H rich material of its companion star

Nova cygni 1992

directly in the nova Gamow window. The remaining uncertainties for nova nucleosynthesis involve only a handful of reaction rates, particularly $^{18}F(p,\alpha)$, $^{25}Al(p,\gamma)$ and $^{30}P(p,\gamma)$, for which several experiments are being conducted (or have been proposed) at different facilities **José+ (2007)**

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

Classical novae are γ-ray emitters and dust producers

$^{30}P(p,\gamma)^{31}S$: paternity of novae grains **Meyer+ (ALTO)**

$^{25}Al(p,\gamma)^{26}Si$: contribution to galactic ^{26}Al **Boulay+ (GANIL)**

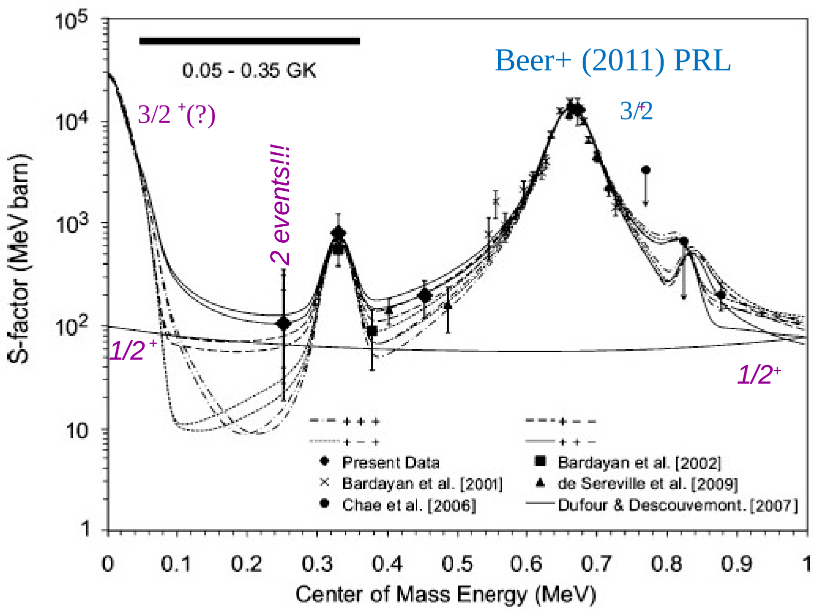
$^{18}F(p,\alpha)^{15}O$: γ-ray emission $\leq$ 511 keV **Riley+(ALTO)**

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

Interference effects in Gamow peak

- $3/2^+$ resonances: "8, 38keV" & 665 keV
- $1/2^+$ resonances: **sub-threshold**+1.45 MeV

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



N. de Séréville talk

Classical novae nucleosynthesis: Achievements & open questions

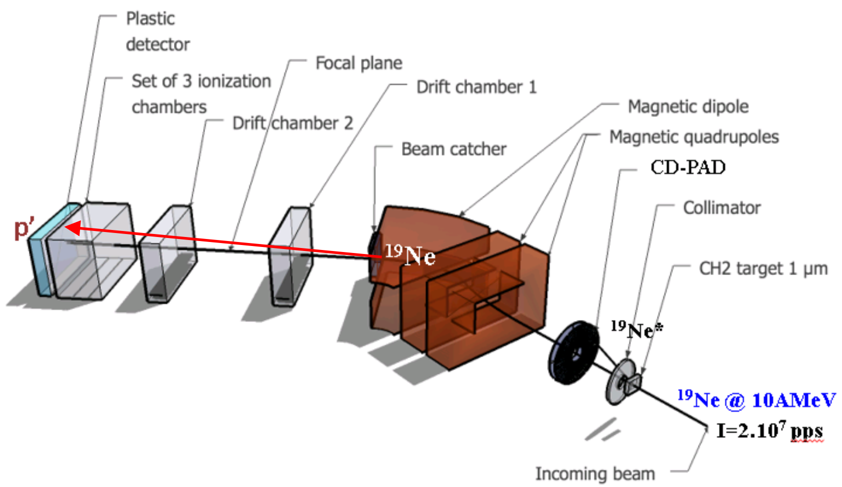
Search of the $1/2^+$ sub-threshold state

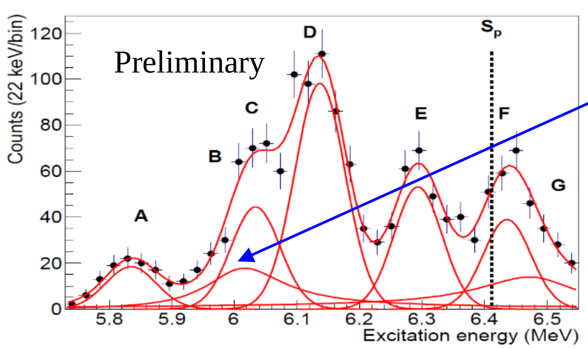
GANIL: $^{19}Ne(p,p')^{19}Ne^*$ inelastic scattering reaction in inverse kinematics: $^{19}Ne + p \rightarrow {}^{19}Ne^* + p'$ at 0°

$\rightarrow p + {}^{18}F$

$\rightarrow \alpha + {}^{15}O$

VAMOS spectrometer





1st evidence for a new state

$E_x \sim 6.02$ MeV

$J^\pi = ?$

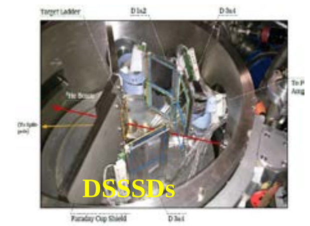
Boulay+(to be submitted)

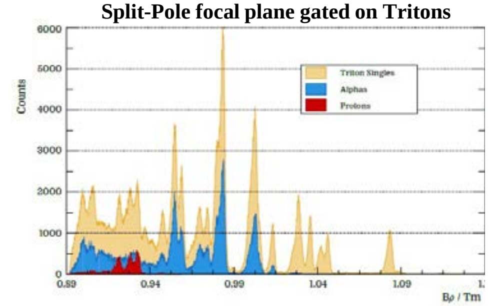
ALTO: Charge exchange reaction $^{19}F(^3He,t)^{19}Ne^*$

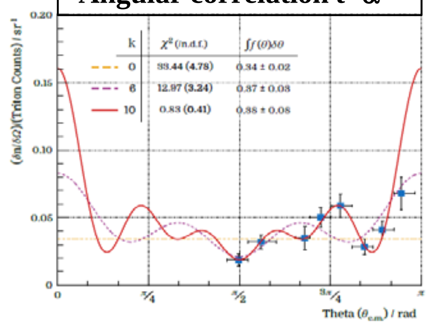
$\rightarrow p + {}^{18}F$

$\rightarrow \alpha + {}^{15}O$

Split-Pole spectrometer + 6 DSSSDs



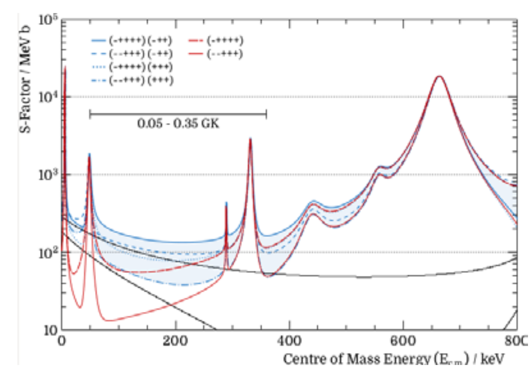




Ex = 6289 keV (E = -122 keV)

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

- New state observed at 6.08 MeV

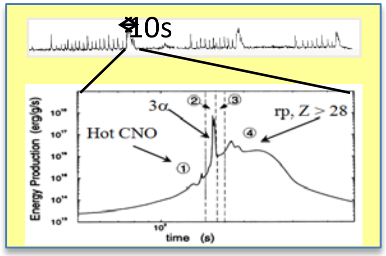


Blue: calculations with $1/2^+$ sub-threshold state

Red: with $9/2^+$ state

Riley+(to be submitted)

X-ray burst nucleosynthesis: Achievements & open questions

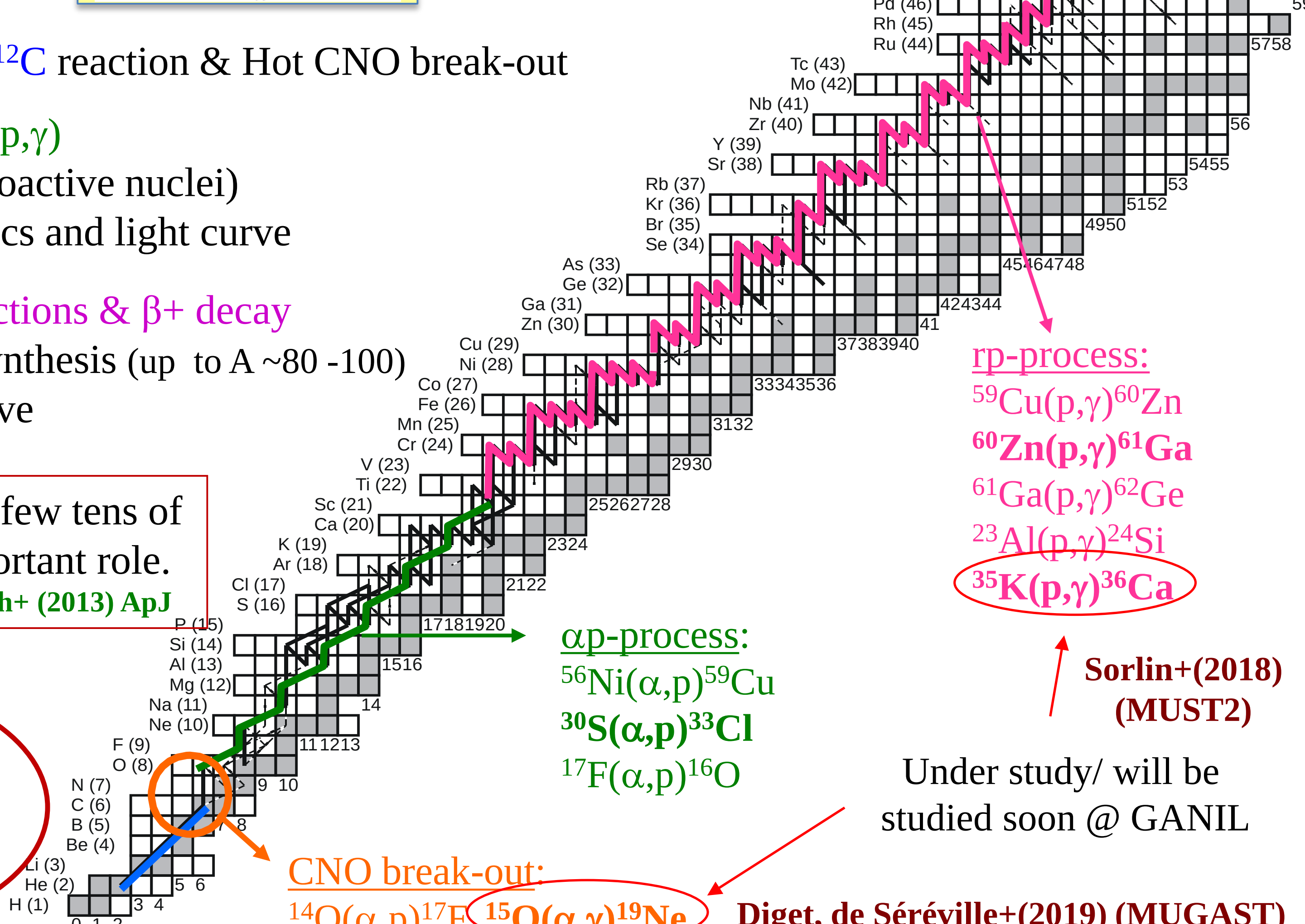


$T \sim 10^9$ K

$\rho \sim 10^6$ g cm^{-3}

- Triggered by 3α → ^{12}C reaction & Hot CNO break-out
- (α,p) process: (α,p)(p,γ)
  - Up to A< 60 (radioactive nuclei)
  - Impact on energetics and light curve
- rp-process: (p,γ) reactions & β+ decay
  - impact on nucleosynthesis (up to A ~80 -100)
  - impact on light curve

Sensitivity studies → few tens of reactions play an important role.
Cyburt+(2016) ApJ, A. Parikh+ (2013) ApJ



rp-process:
^{59}Cu(p,γ)^{60}Zn
^{60}Zn(p,γ)^{61}Ga
^{61}Ga(p,γ)^{62}Ge
^{23}Al(p,γ)^{24}Si
^{35}K(p,γ)^{36}Ca

Sorlin+(2018) (MUST2)

αp-process:
^{56}Ni(α,p)^{59}Cu
^{30}S(α,p)^{33}Cl
^{17}F(α,p)^{16}O

Under study/ will be studied soon @ GANIL

CNO break-out:
^{14}O(α,p)^{17}F, **^{15}O(α,γ)^{19}Ne**

Diget, de Séréville+(2019) (MUGAST)

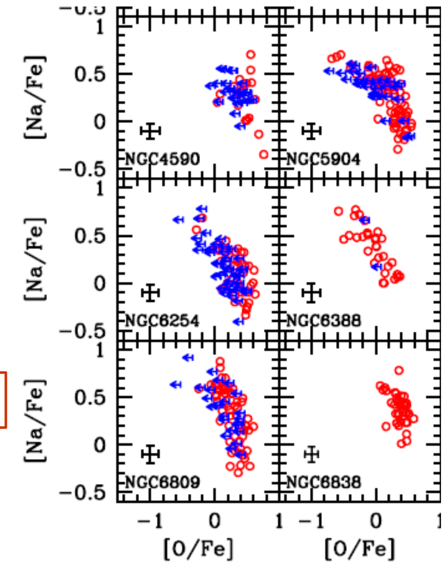
Need beam development & beam time

Globular clusters nucleosynthesis: Achievements & open questions

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 & nucleosynthetic products are mixed with pristine GC gas **Prantzos+ (2007) A&A, (2017) A&A**

Na-O anticorrelation



Carretta+ (2007) ApJL

Nature of 1st generation of stars? AGB, fast rotating massive stars, ...

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

Case of NGC 2419

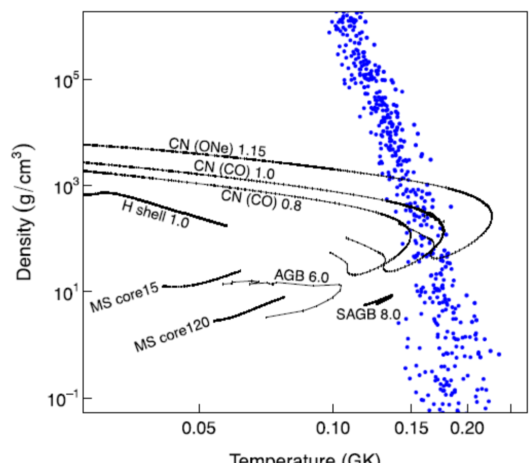
- Observation of Mg-K anticorrelation

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:

Dermigny+ (2016) ApJ

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

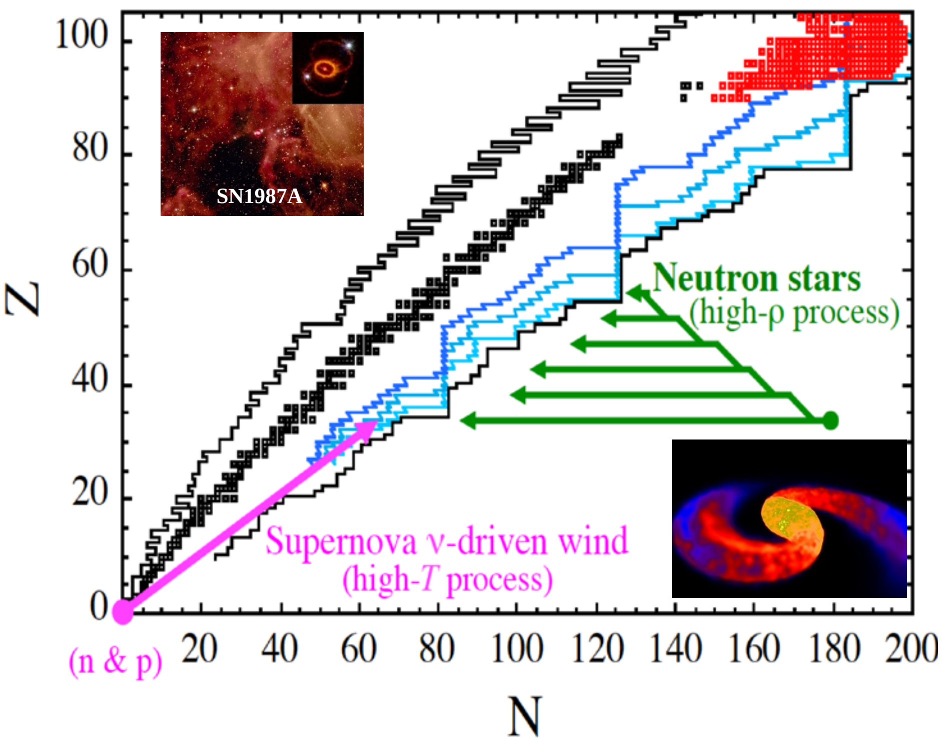
de Séréville, Adsley+(2019)
(DRAGON @ TRIUMF & MLL@ MUNICH)

N. de Séréville talk

r-process nucleosynthesis: Achievements & open questions

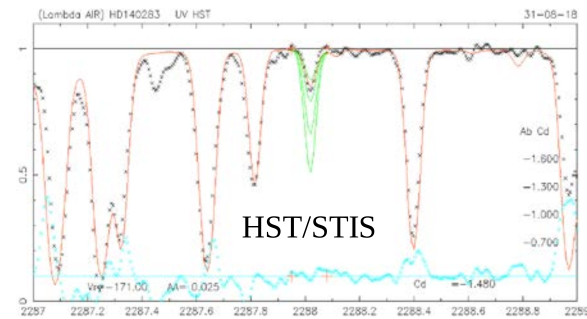
Production of half of the heavy elements (>Fe)

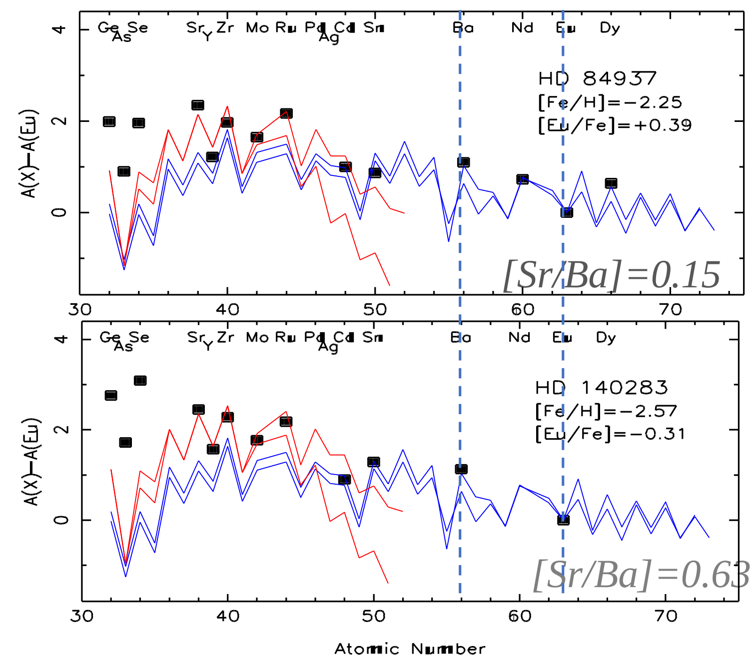
temperature	1-2× 10^9 K
timescale	~seconds
neutron density	10^{20}-10^{24} cm^{-3}
possible stellar sites	Type II supernovae/ Neutron star mergers



Abundance of Ge up to Dy in 4 metal-poor stars

high resolution spectra in the far UV 189 nm - 304nm





Barbuy, Peterson & Spite (2018)

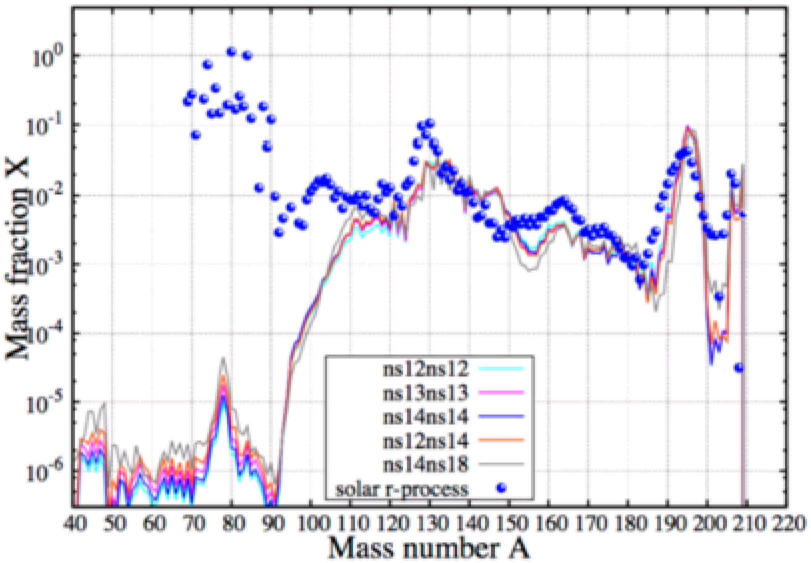
blue line : main r-process

red line : weak-r process **Wanajo, 2013**

r-process nucleosynthesis: Achievements & open questions

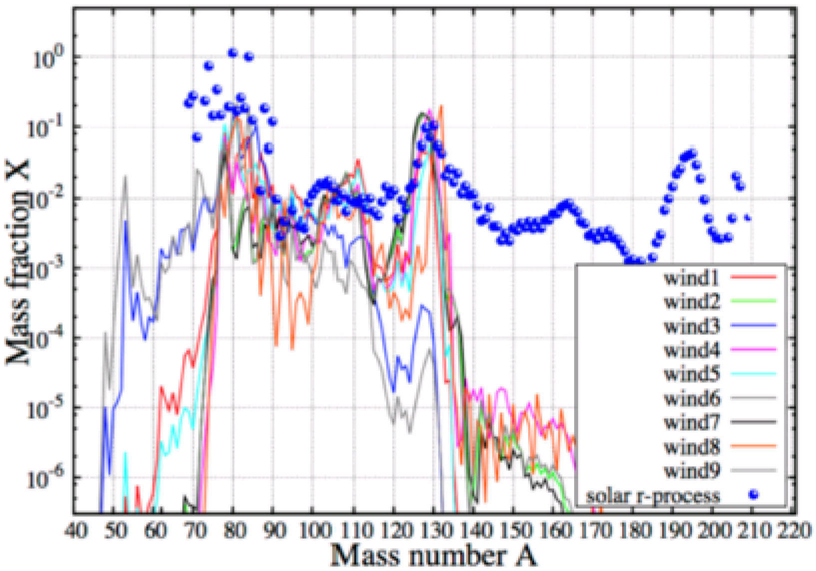
- **Which nuclei are concerned? Depends on the site**

Nucleosynthesis for dynamic ejecta
Rosswog+(2017)



- The heaviest elements A>130
- Robustly producing the "platinum peak" at A=195
- Very little variation between different mergers

Nucleosynthesis for neutrino-driven wind
Rosswog+(2017)

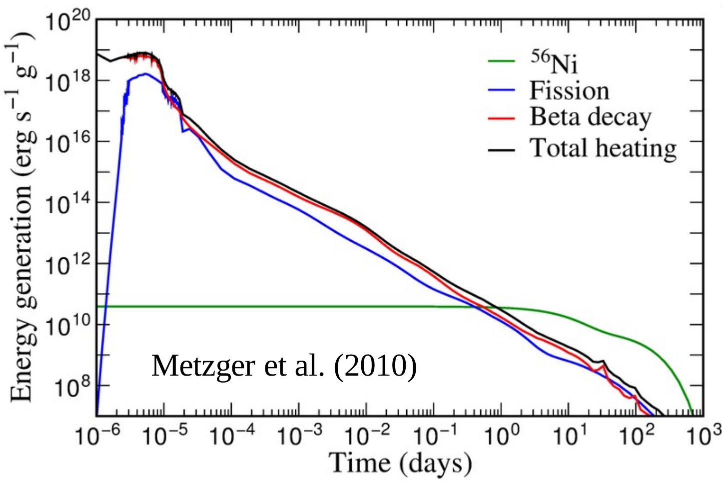


- Lighter r-process elements, A<130
- Large variation between different astrophysical events expected

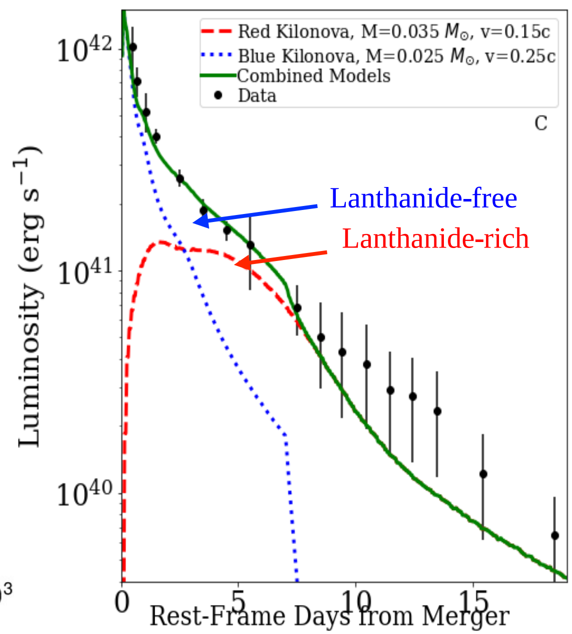
http://compact-merger.astro.su.se/Macronovae_04_2017.html

B. Bastin talk

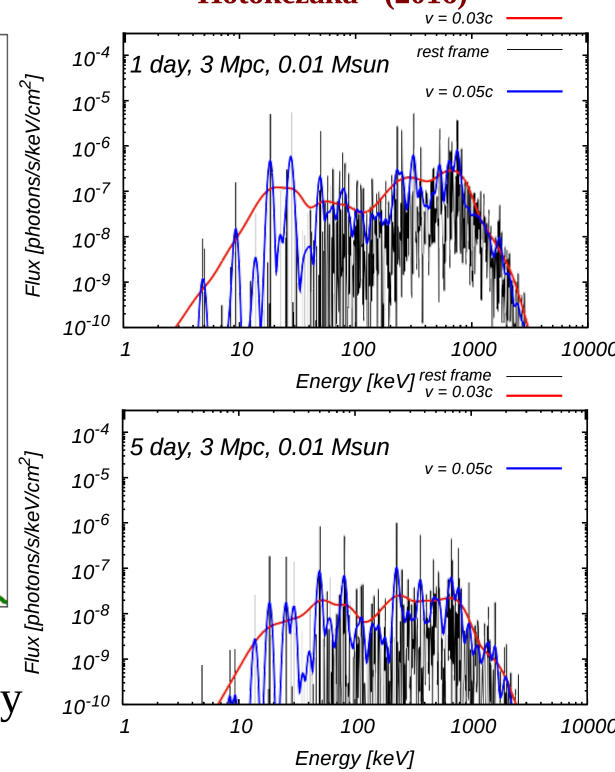
Neutron star mergers & Kilonova



SSS17a (Kilpatrick +2017)



Hotokezaka +(2016)



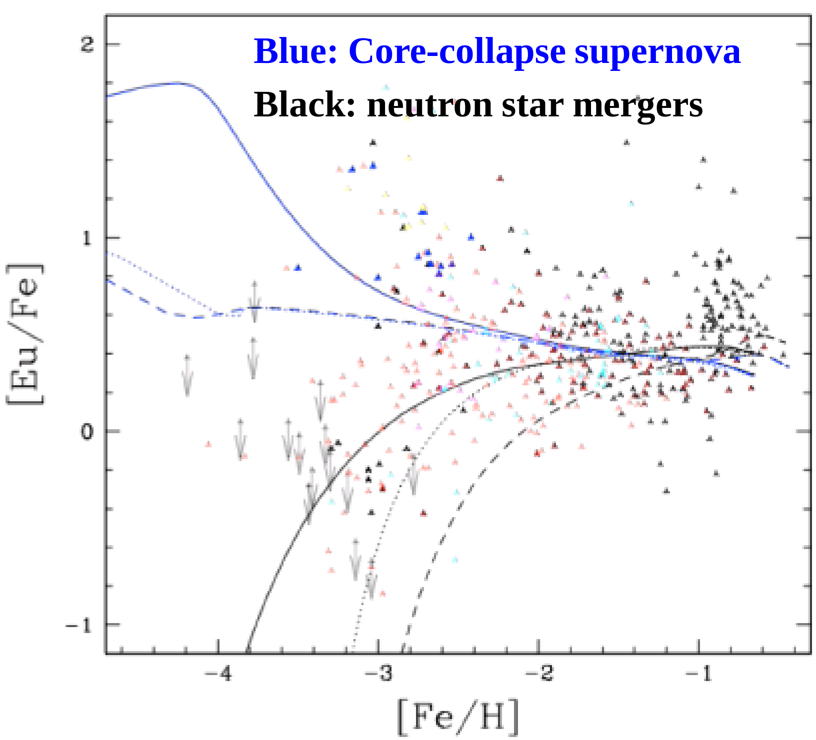
- Kilonova: UV-Optical-NIR transient powered by the radioactive decay of r-process nuclei **Metzger+(2010) & Li+(1989)**
- GW170817 (advanced LIGO and Virgo) associated with the short GRB 170817A (Fermi and INTEGRAL) and the optical/NIR transient SSS17a/AT2017gfo => kilonova
- Previous kilonovae suspected in GRBs 050709, 060614, 130603B
- Gamma-ray line emission detectable with the next-generation γ-ray observatories (e.g.e-ASTROGAM) to a distance <~12 Mpc **(Li 2018)** => ≈ 0.05 - 0.5 NS merger per century

V. Tatischeff talk

r-process nucleosynthesis: Achievements & open questions

Are NS-NS the main astrophysical site for the r-process?

- Constraints on the Merger Rate from the cosmic evolution of Eu (pure r-element)



Vangioni, Goriely, Daigne, François & Belczynski 2015

- ➢ The early cosmic evolution of Europium (pure r element) favors mergers as the main astrophysical site for the r process
- ➢ Supernovae over produce Eu at high z / low metallicity
- ➢ The early evolution is dominated by neutron star mergers with coalescence timescale ~100 Myr (range 50-200 Myr)
- ➢ More observations at very low metallicity are needed for a better constraint

F. Daigne talk

r-process nucleosynthesis: Achievements & open questions

Which properties to measure/constrain?

Abundance variation of a given $^A_Z X$ nucleus

Arnould+(2007) Phys.Rept

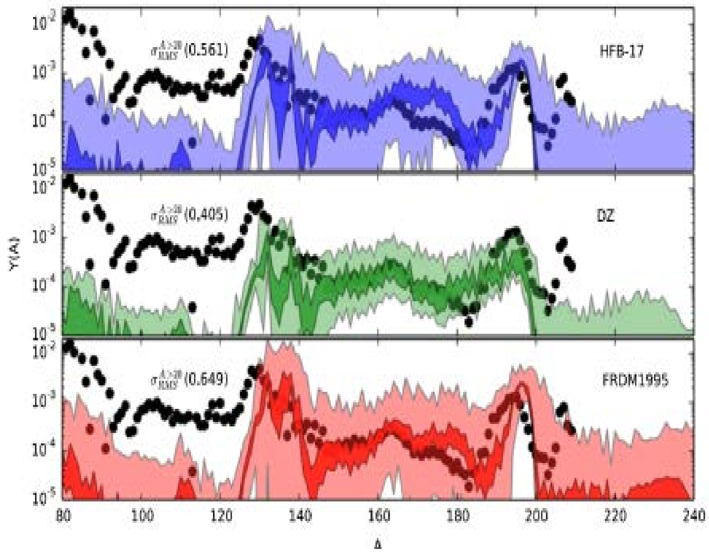
$$\frac{dN(Z,A)}{dt} = \begin{cases} N_n . N(Z,A-1). <\sigma v>_{Z,A-1} & \rightarrow (n,\gamma) \text{ reaction} \\ + N(Z,A+1). \lambda_{\gamma,n}^{Z,A+1} & \rightarrow (\gamma,n) \text{ reaction} \\ + N(Z-1,A). \lambda_{\beta}^{Z-1,A} & \rightarrow \beta \text{ decay} \\ + \sum_{k=1}^{3} N(Z-1,A+k). \lambda_{\beta kn}^{Z,A+1} & \rightarrow \beta\text{-delayed k neutron emission} \\ + N(Z+2,A+4). \lambda_{\alpha}^{Z+2,A+4} & \rightarrow \alpha \text{ decay} \\ + \sum_f q_{Z_f,A_f}(Z,A). \lambda_f^{Z_f,A_f} .N(Z_f,A_f) & \rightarrow \text{spontaneous fission} \\ + \sum_f q_{Z_f,A_f}(Z,A). \lambda_f^{Z_f-1,A_f} .N(Z_f-1,A_f) & \rightarrow \beta\text{-delayed fission} \\ + \sum_f q_{Z_f,A_f}(Z,A). \lambda_f^{Z_f,A_f-1} .N(Z_f,A_f-1) & \rightarrow \text{n-induced fission} \\ -N(Z,A). \left[N_n . <\sigma v>_{Z,A} + \lambda_{\gamma,n}^{Z,A} + \lambda_{\beta}^{Z,A} + \sum_{k=1}^{3} \lambda_{\beta kn}^{Z,A}\right] & \\ - N(Z,A). \left[\lambda_{\alpha}^{Z,A} + \lambda_{f}^{Z,A} + \lambda_{\beta f}^{Z,A} + \lambda_{nf}^{Z,A}\right] & \end{cases}$$

Production (first eight terms) / Destruction (last two terms)

+ γ induced fission
+ neutrino interactions with nuclei for some scenarios

⇒ **masses, β-decay properties, neutron capture rates, photo-disintegration rates, fission rates,…**

Abundance varitions = f (mass model)



- **Extensive mass measurements and decay studies are required**

- r-process : along the path with some priorities (to be clarified)
- Core-collapse : around ^{78}Ni and ^{126}Pd

- **Study of specific contributions**

- Fission rates and distribution (feedback)
- Enhanced E1 strengths (impact in the gSF => photo-desintegration rate)

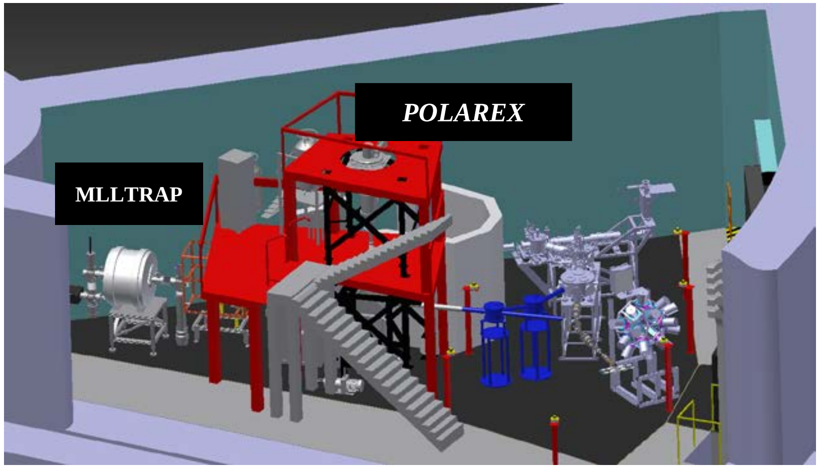
P. Adsley et al., Beta-delayed gamma emission (neutron-rich rare-earth nuclides)…

- **Possible working strategy :**

- Define list of key nuclei based on recent sensitivity studies.

Mumpower+(2016). Progr. in Part. and Nucl. Phy. 86

Mass measurements: soon in France @ Alto



E. Minaya et al., mass.program (Ag) + (2019)

B. Bastin talk

Summary

- The French community is present & very active in all the fields of nuclear astrophysics (Observations, astrophysics modelling, nuclear physics)
- The GDR will strengthen the already existing (since a long time) interactions between the actors of the different fields
- French community implied in all existing and future observation types (micrometeorites, UV, γ-rays,...)
- Many important reactions involved in various astrophysical sites and astrophysical processes were studied by the French community and/or will be studied soon in small and large scale facilities within international collaborations
- Need for proton rich radioactive beam development and beam time to study key reactions that were identified in X-ray bursts as well as classical-novae
- Need for production of more neutron rich radioactive isotopes at ALTO for masses and β-decay measurements and beams at GANIL (SPIRAL2-PHASE2 ???)