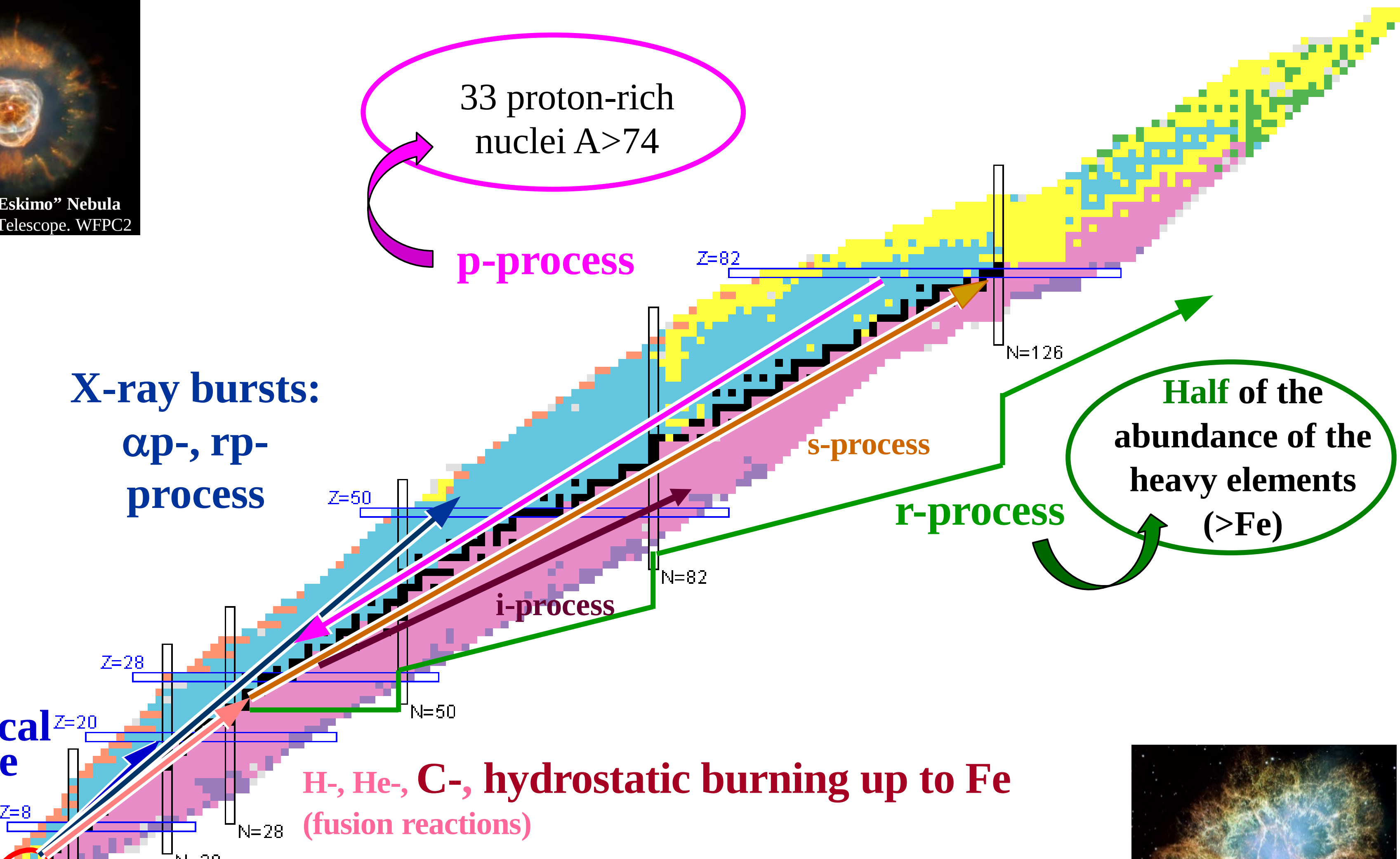
Nuclear Physics and Nuclear Astrophysics Town Hall meeting

Abbaye aux Dames, Caen, 30-31/01/2020

Nucleosynthesis & origin of elements

Faïrouz Hammache (IJCLab)
for
the nucleosynthesis community

Nuclear landscape and astrophysical processes

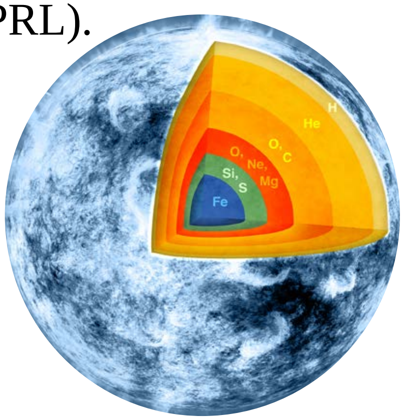


Quiescent nucleosynthesis in massive stars ($M > 8\ M_{\odot}$)

IPHC: <u>S. Courtin</u>, D. Curien, M. Heine, M. Moukkadam, J. Nippert; **IPNO**: S. Della Negra, F. Hammache, N. de Séréville

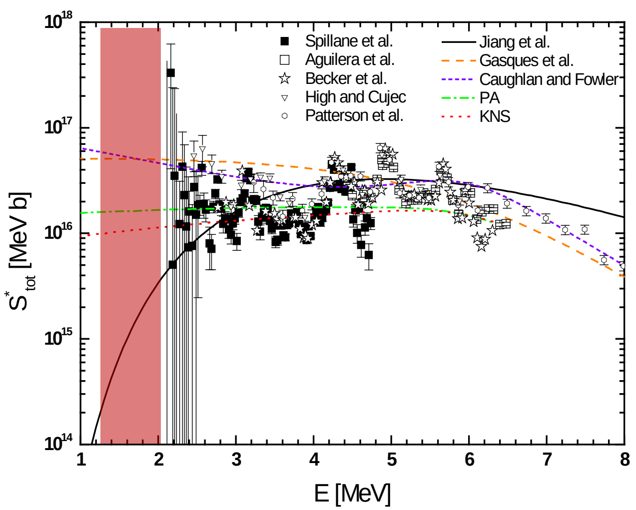
Key reactions : $^{12}C+^{12}C$ (the grail), $^{16}O+^{16}O$, $^{12}C+^{16}O$ …

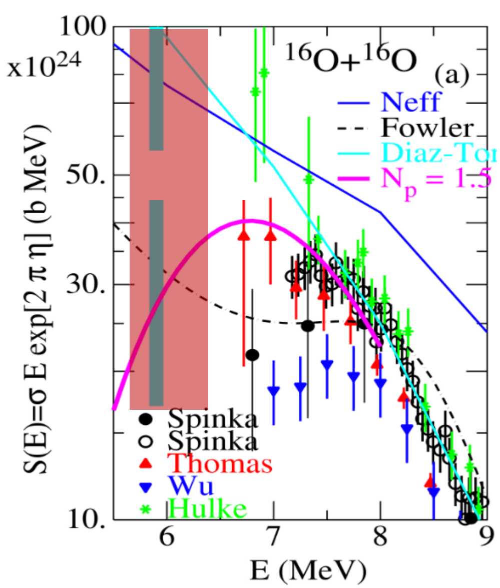
- Direct data scarce in the Gamow window,
- Possible strong effects of resonances and/or hindrance -> major impact on the stellar evolution,
- … pioneering results from the STELLA collaboration (G. Fruet et al. sub. to PRL).



Projects : $^{12}C+^{12}C$, $^{16}O+^{16}O$, $^{12}C+^{16}O$ → accurate fusion data down to Gamow window

- High intensity stable beams ($I \geq 10\ \mu A$) at low energies,
- Specific targets,
- Coincidence technique (high efficiencies, good timing).

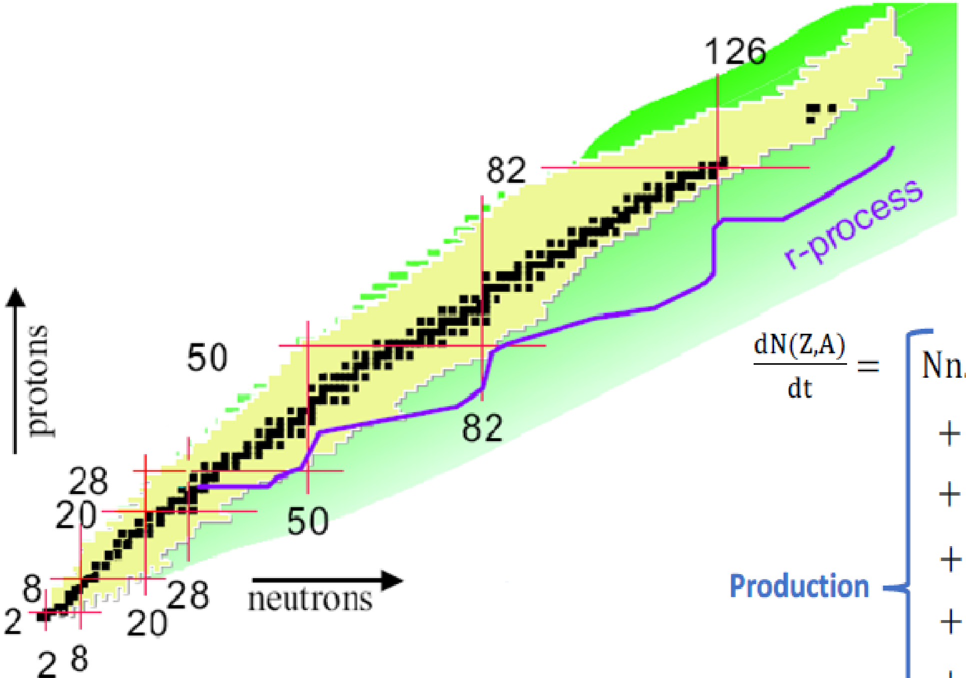




STELLA experiment at **Andromède** (IPHC, IPNO, GANIL, York, Surrey)
M. Heine et al., Nim A 903 (2018) 1

r-process nucleosynthesis

Which nuclear properties to measure/constrain?



Abundance variation of a given $^{A}_{Z}X$ nucleus:

Production

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

Destruction

$$\begin{cases} -N(Z,A).\left|N_n.<\sigma v>_{Z,A} + \lambda_{\gamma,n}^{Z,A} + \lambda_{\beta}^{Z,A} + \sum_{k=1}^{3} \lambda_{\beta kn}^{Z,A}\right| \\ -N(Z,A).\left|\lambda_{\alpha}^{Z,A} + \lambda_{f}^{Z,A} + \lambda_{\beta f}^{Z,A} + \lambda_{nf}^{Z,A}\right| \end{cases}$$

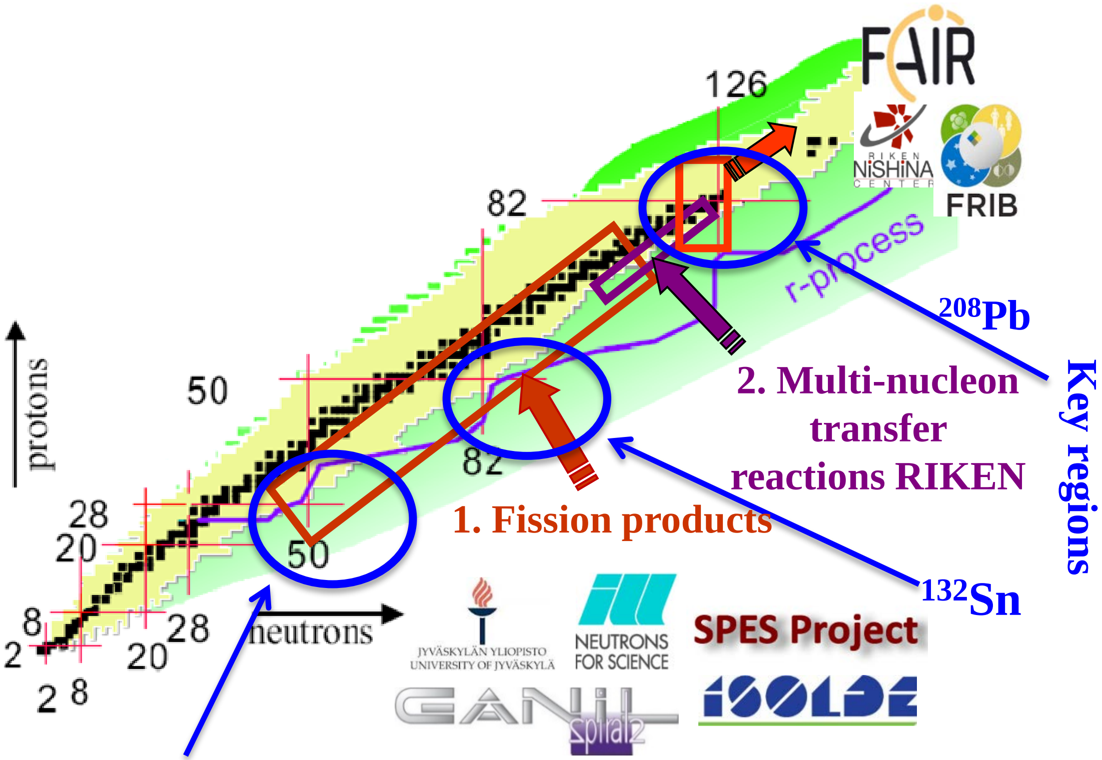
$+\gamma$ induced fission

➔ **Masses** **(L. Caceres talk)** **, β-decay properties, neutron capture rates, fission rates,...**

M. Arnould et al., Phys. Rep 450 (2007) 97

β-decay properties measurements for r-process nucleosynthesis

CENBG: **T. Kurtukian**, P. Ascher, B. Blank, S. Grévy; *IJCLab:* **R. Lozeva**, D. Lunney, E. Minaya Ramirez



- ❑ **M**easurements of nuclei in the mass region N~126

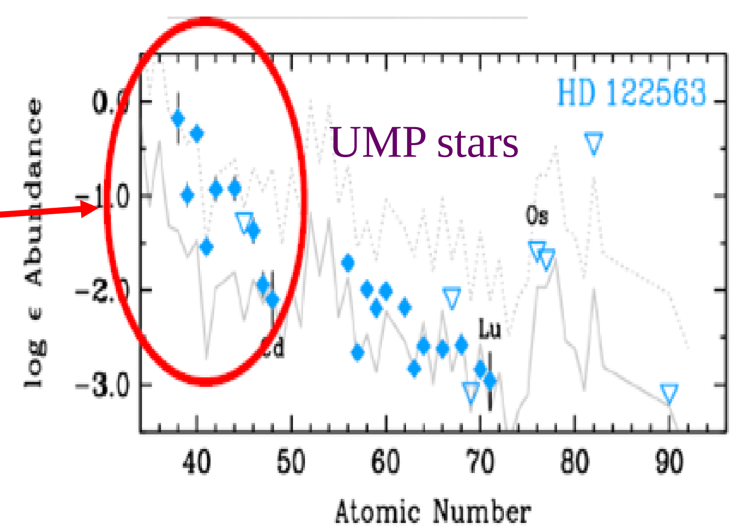
→ **N~127** isotones, **^{206}Au**, **^{205}Pt**, **^{204}Ir** & **^{203}Os** : **KISS/RIKEN**

→ **N~126 : FAIR**

- ❑ Measurements of nuclei in the mass region **N~82 → RIKEN, Jyväskylä**

- ❑ β decay properties (**$T_{1/2}$ & P_n**) of very neutron rich **Ge, As** & **Se** isotopes have a direct impact on the production of Sr, Y, and Zr

→measurements @ **ALTO**, **SPES**, **ILL**



- ❑ Technical development → **4π electron detector**: Leptonic-TPC for low decay rates & very short $T_{1/2} \leq 100$ ms

Pygmy resonance measurements for r-process nucleosynthesis

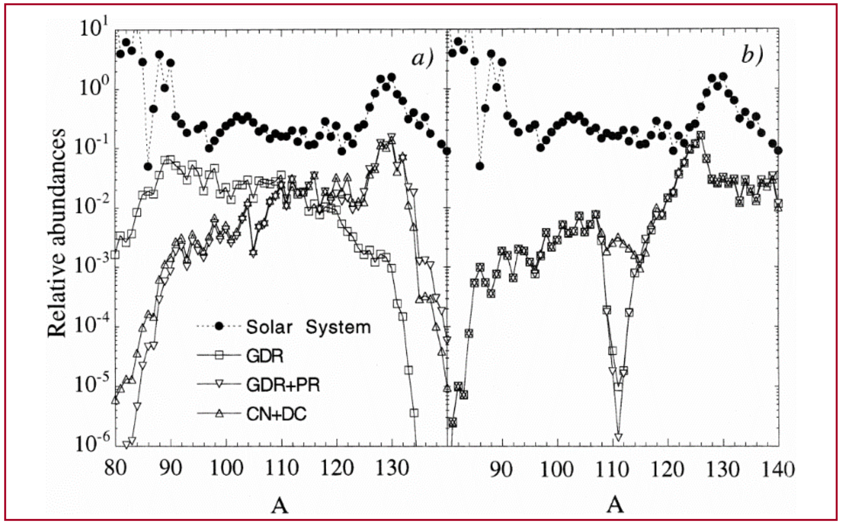
IJCLab: **<u>I. Matea</u>**, Y. Blumenfeld; ***GANIL***: O. Sorlin, ***LPC***: J. Gibelin; ***Subatech***: M. Fallot

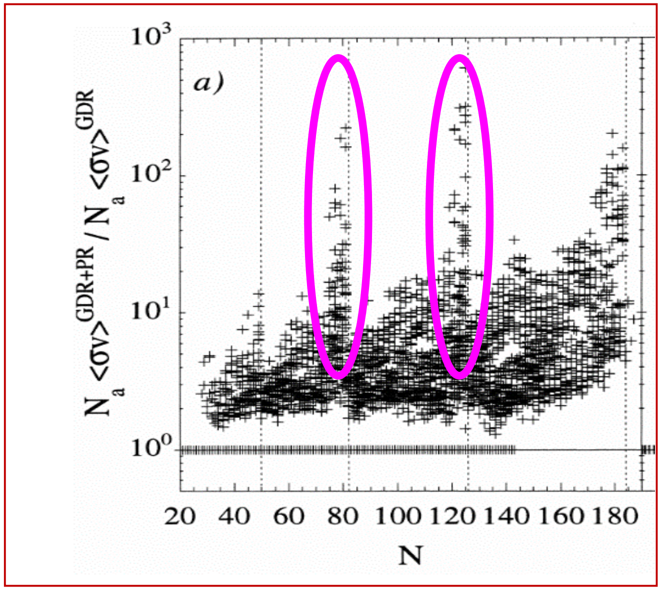
- The energy balance in the nuclear reactions networks may change significantly the nuclear abundances of heavy nuclei if one includes pygmy resonances **Bertulani 2019**

- The presence of PR near neutron threshold tends to enhance (n,γ) rates → strong impact on the r-process nucleosynthesis in the mass region **A~130, N~ 82 & N~126** **Goriely 98**

- But large uncertainties affect the predictions of PR characteristics (Electric dipole strength function, excitation energy,..) **Goriely 98**

- Experimental studies of PR characteristics via Coulomb excitation & inelastic particle scattering reactions on heavy targets RIKEN, GANIL, GSI



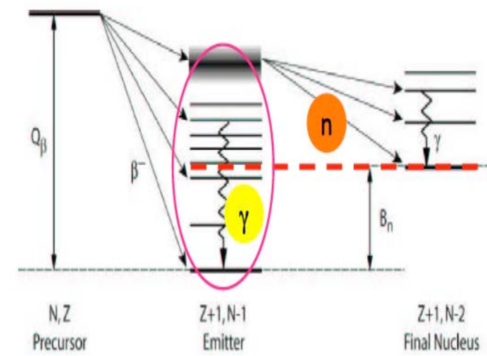


TAGS experiments for r-process & Core-collapse SNe studies

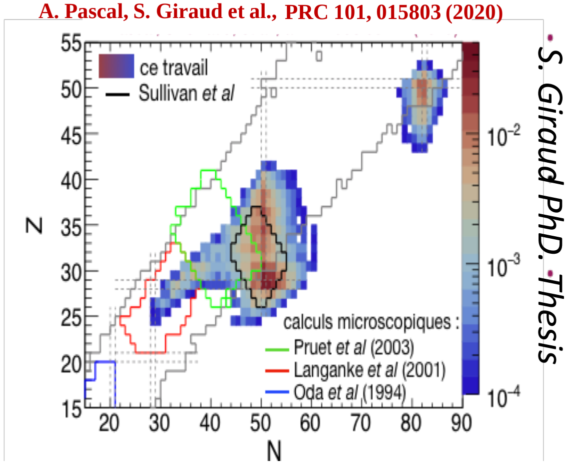
Subatech: M. Estienne, **M. Fallot**, A. Porta; ***GANIL:*** **B.Bastin**, A. Fantina, F. de Oliveira; ***IJCLAB:*** **I. Matea**
LPC Caen: **F. Gulminelli**

❑ r-process:

- β-decay of delayed neutron emitters as a "surrogate" of the (n,γ) reaction: **enhanced Γγ** measured in some nuclei **impacting (n,γ)** cross sections => **general trend ?**
  → around & beyond ^{132}**Sn** nuclei (**ALTO, Jyväskylä, ISOLDE**)
- Probe the presence **of low-lying collective modes with β-decay** as it impacts the r-process paths → mass region close to ^{78}**Ni** & ^{132}**Sn**
- PR population via β decay of very neutron rich nuclei at ALTO, SPES, Jyväskylä, ISOLDE



A. Pascal, S. Giraud et al., PRC 101, 015803 (2020)



S. Giraud PhD. Thesis

❑ Core-collapse SNe:

→ Study the electron capture properties of key nuclei around ^{78}**Ni** and ^{126}**Pd** which play an important role in core-collapse supernovae @ **IGISOL** & **ALTO**

❑ ^{44}**Ti production rate**: probes the **innermost shells** of the SN explosion → measure the γ emission from unbound proton states in key nuclei to constrain reaction rates playing a role in the ^{44}Ti abundance

❑ Technical upgrade & development :

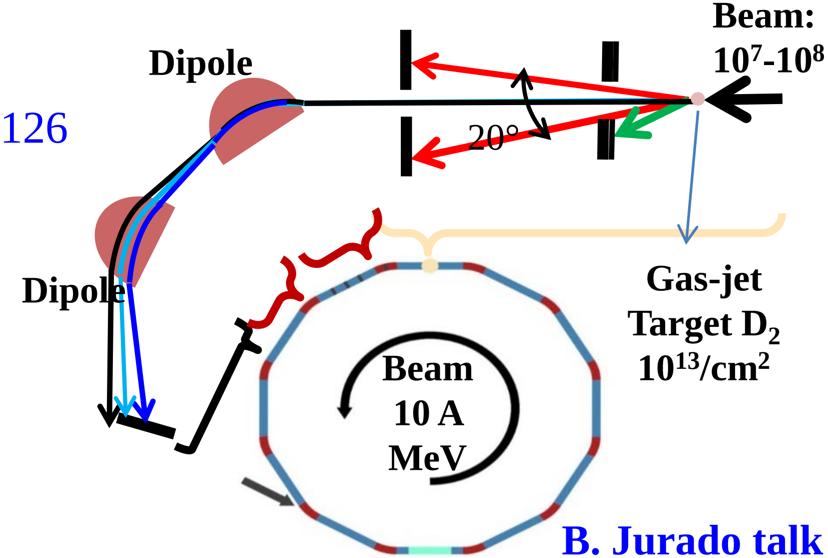
→ 32 LaBr3 for angular distributions & neutron-γ discrimination & the associated Faster electronics

CRYRING measurements for r-process & i-process

CENBG: **<u>B. Jurado</u>**, P. Marini, L. Mathieu, I. Tsekhanovich ***; IJCLab*****:** L. Audouin ; ***CEA-DAM:*** A. Chatillon, L. Gaudefroy, V. Meot, O.Roig, J. Taieb

❑ Fission rate predictions for r-process

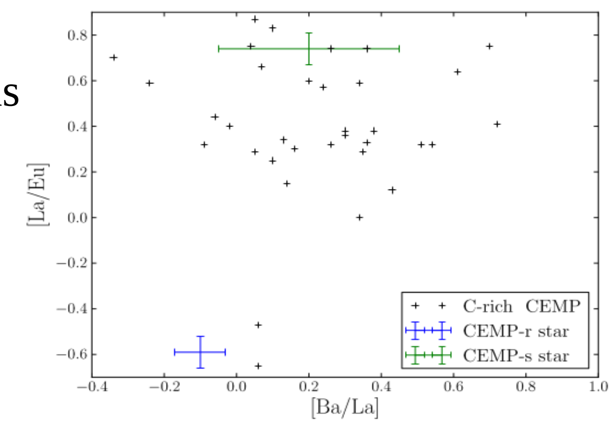
→ Measure fission probabilities of actinides close to N~126
→ impact of shell closure and the change of neutron numbers on fissions probabilities
→ constrain fission models
→ reliable fission models for fission rate predictions near N~184 for r-process



B. Jurado talk

❑ Intermediate neutron capture process (i-process)

→ to explain some CEMP-r/s stars ([C/Fe]>1 objects) observations
→ Active in Post-AGB stars
→ plays an important role in Pop III stars
→ (n,γ) XS on **^{135}I**, **^{137}Xe**, **^{136,139}Cs**,**^{140}Ba** have strong impact on La/Eu and Ba/La ratios & i-process understanding **Bertoli+2013**
➔ use of **(d,p) surrogate** reaction to deduce (n,γ) XS



Study of the p-process

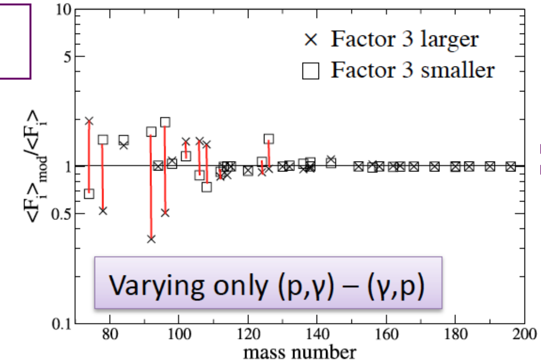
GANIL : **B. Bastin**, **F. de Oliveira Santos** et J.-C. Thomas. *IP2I* : **C. Ducoin**, **B. Rebeiro**, J. Dudouet, D. Guinet, N. Redon, O. Stezowski ; *IJCLab* : F. Hammache et N. De Séréville. *LPC Caen* : L. Achouri

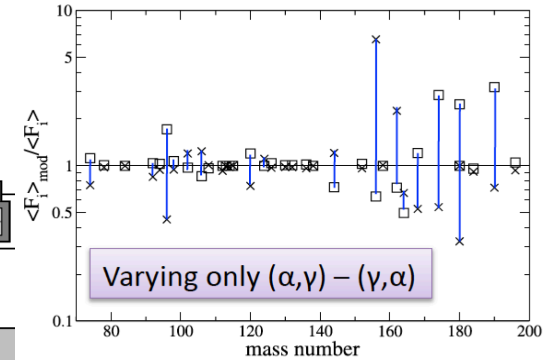
- ~ 2000 nuclei involved, (γ,n), (γ,p), (γ,α), n-, p-, α-captures

✓ Major source of uncertainty for (α,γ) (γ,α) reaction rates estimations in HF calculations: → discrepancies between OMP3 (2012) et AV (2014) OPs → α-optical potential measurements @ Splitpole Orsay **(B. Rebeiro et al.)**

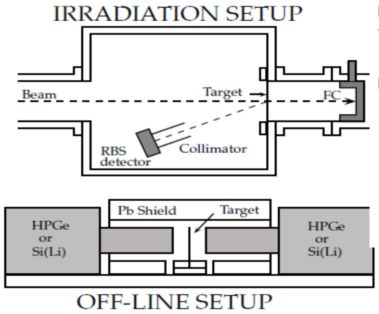
✓ Activation & direct measurements @ NFS foreseen (LOI) **(B. Bastin, C. Ducoin, B. Rebeiro et al.)**

LINAC : Emin = 0.75 MeV, High p & He intensity : 5 mA!!!!





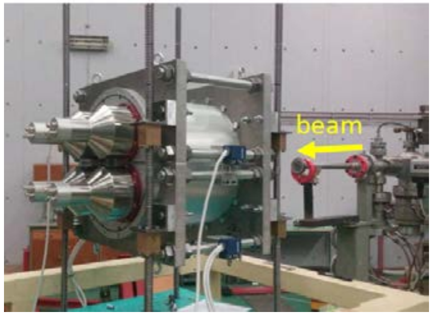
Rapp *et al.* AJ 653 (2006) 474

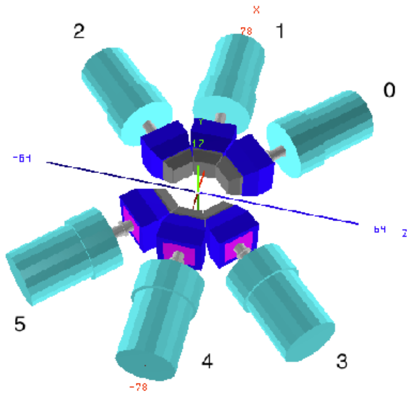


Critical p-process Reaction Rates
(list of day one experiments-easy cases)

(p,γ)	(p,n)	(α,γ)
^{72}Ge$(p,\gamma)^{73}$As	^{76}Ge$(p,n)^{76}$As	^{70}Ge$(\alpha,\gamma)^{74}$Se
^{74}Ge$(p,\gamma)^{75}$As	^{75}As$(p,n)^{75}$Se	^{92}Mo$(\alpha,\gamma)^{96}$Ru
^{77}Br$(p,\gamma)^{78}$Kr*	^{85}Rb$(p,n)^{85}$Sr	^{102}Pd$(\alpha,\gamma)^{106}$Cd
^{83}Rb$(p,\gamma)^{84}$Sr*	^{86}Kr$(p,n)^{86}$Rb	^{106}Cd$(\alpha,\gamma)^{110}$Sn

note : (p,γ) : 1.5 - 5.0 MeV (α,γ) : 3.5 - 11.0 MeV



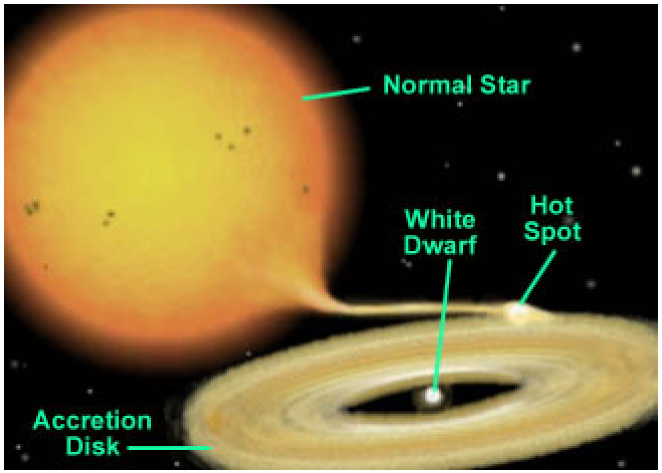


Experimental challenge under study :
use of radioactive targets!

Undersanding classical novae

IJCLab : **N. de Séréville**, **F. Hammache**, M. Assié, D. Beaumel, Y. Blumenfeld, I. Stefan ; *GANIL* : **B. Bastin**, F. de Oliveira Santos, O. Sorlin, J.-C. Thomas.

Novae: Thermonuclear runaway at the surface of a white dwarf in a close binary system



Mechanism well established but

- Ejected mass << observed mass
- Amount of mixing between accreted and white dwarf materials?

Contribution to ^{26}Al galactic γ-ray emission?

Key observational constraints: γ-ray emitters (γ-ray astronomy), isotopic abundances (presolar grains) and elemental abundances

First site with nucleosynthesis network based entirely on experimental data soon

Main remaining nuclear uncertainties: ^{18}**F**(p,α)^{15}O, ^{25}**Al**(p,γ)^{26}Si, ^{30}**P**(p,γ)^{31}S & ^{28,29}Si(**p**,γ)^{29,30}P

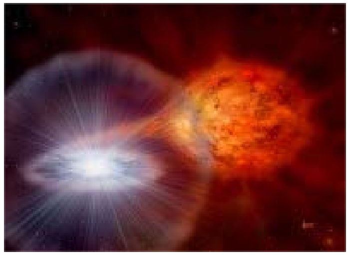
Experimental program needs

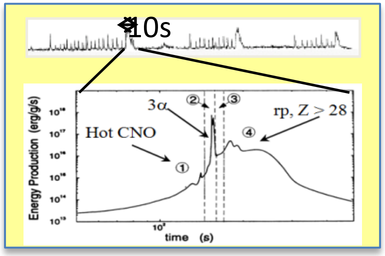
- Intense (>1e^{5} pps) RIBs (^{18}F, ^{25}Al, ^{30}P) at low (< 1 MeV/u) and intermediate energies (~10-15 MeV/u) at **GANIL** → **SPIRAL1** (development of new beams), **SPES**, **LISE-upgrade**
- Intense proton beam (~ 100 mA)
- High resolution spectrometer (Split-Pole) with stable beams (**Tandem-ALTO**)

X-ray burst nucleosynthesis

IJCLab : **F. Hammache**, **N. de Séréville**, M. Assié, D. Beaumel, Y. Blumenfeld, I. Stefan ; *GANIL* : **O. Sorlin**, B. Bastin, F. de Oliveira Santos, J.-C. Thomas; *Subatech:* M. Estienne, **M. Fallot**, A. Portal

- **(α,p) process**: (α,p)(p,γ)
  - Up to A< 60
  - Impact on energetics and light curve





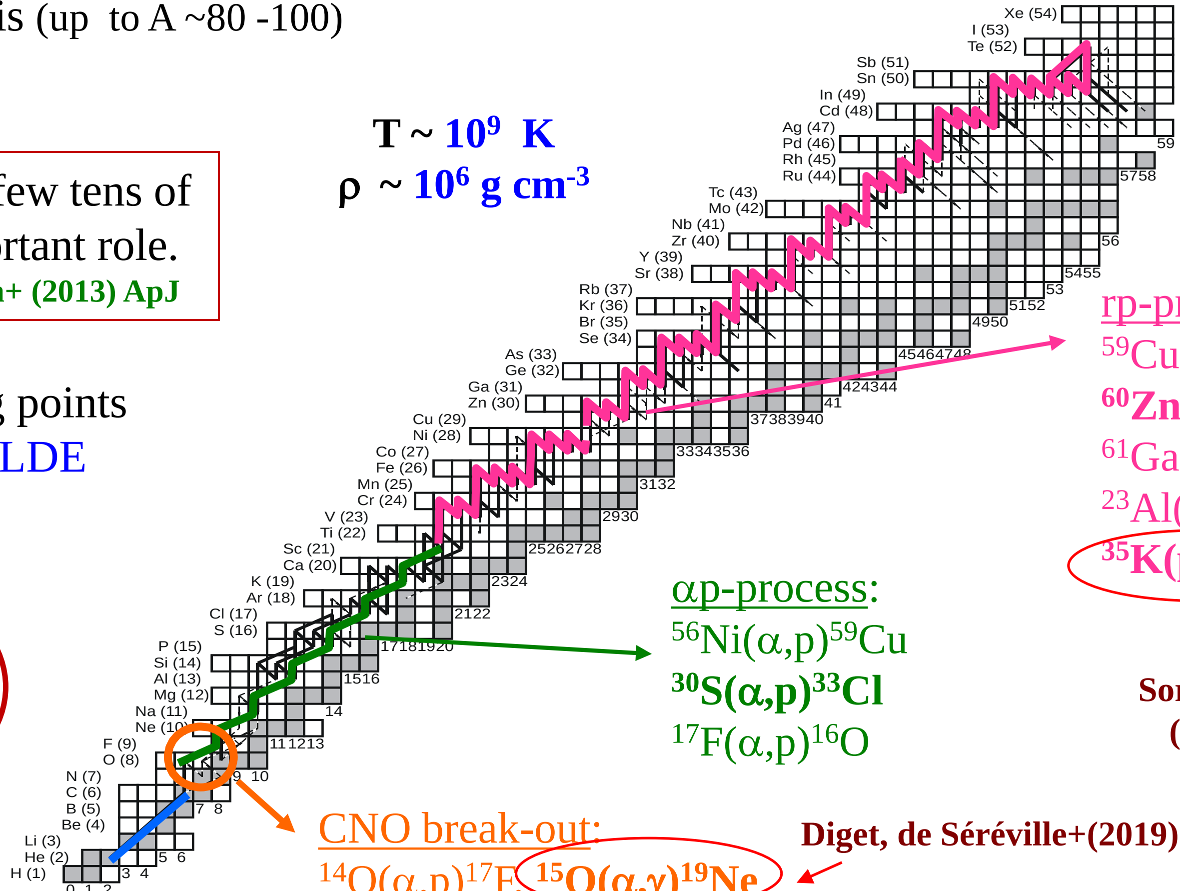
- **rp-process:** (p,γ) reactions & β+ decay
  - impact on nucleosynthesis (up to A ~80 -100)
  - impact on light curve

T ~ 10^9 K
ρ ~ 10^6 g cm^{-3}

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

β-decays at waiting points
→ TAGS @ ISOLDE

Need beam development @ GANIL



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

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

Diget, de Séréville+(2019) (MUGAST)

WANTED

Understand the origin of the elements & nucleosynthesis processes at work in the Universe

→ nuclear data (cross-sections & spectroscopic properties of the nuclei involved, masses, β- decays fission rates…) are needed for different processes in different astrophysical sites

- **Need of intense stable beams & accelerators of Tandem type (14 MV)**
- **Need of radioactive neutron rich and proton rich beam production in GANIL, ALTO, SPES, GSI,…**

  → high beam intensities ≥ 10^5 pps, good purity & 10-15 AMeV energy range for direct reaction studies
  → low beam energies < 1 MeV/u for direct measurements

- **Detection setups**

  → Upgrade of TAGS setup, 4π electron detector, detection setup building for CRYRING
  → Good identification detection system at 0° at LISE
  → Modernization of Split-Pole spectrometer & associated focal plan detection
  → γ-ray detectors development (PARIS type), charged particle detectors (MUGAST, GRIT)

- **Radioactive targets production & characterization**
- **Synergies with other contributions:**→ ISOL, Direct reactions, Fission, compact stars,…