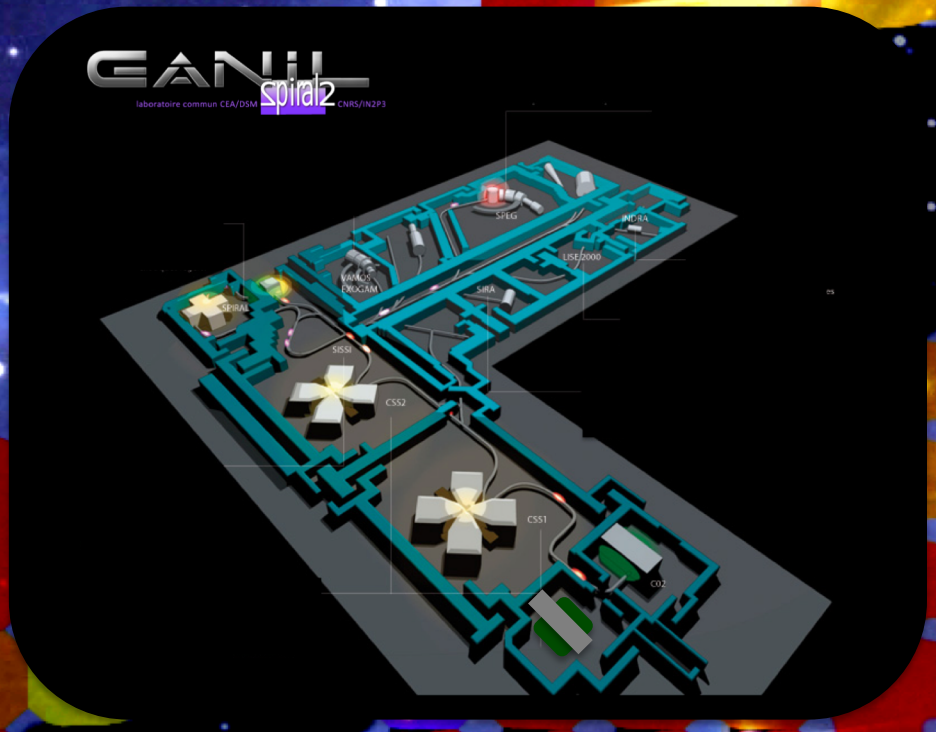
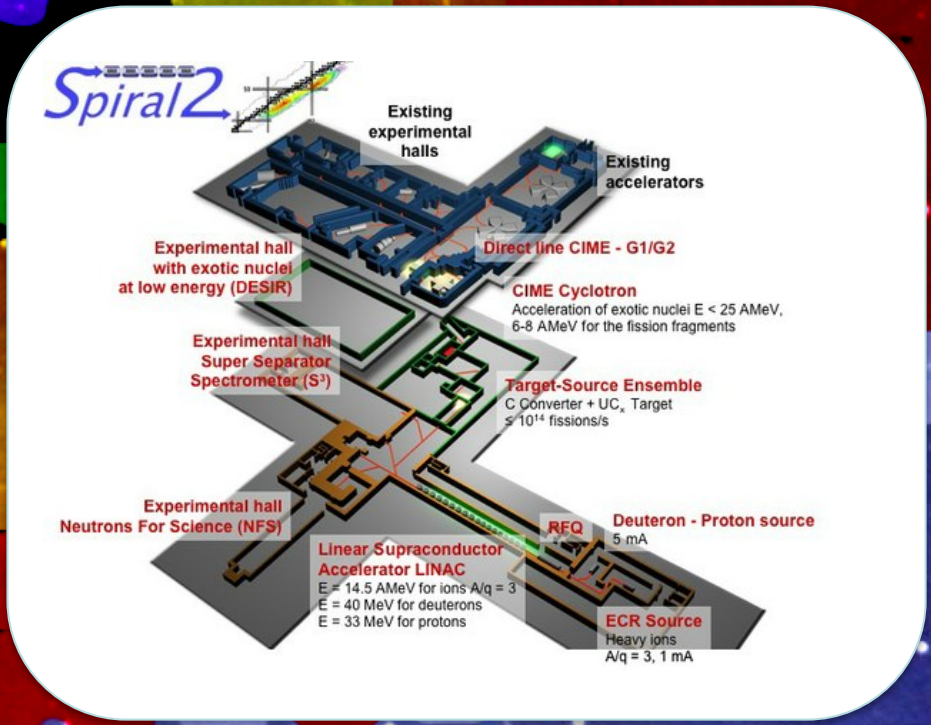
# Nuclear astrophysics studies at GANIL-SPIRAL2




**Caen**

- ❑ **GANIL-SPIRAL1** **Stable-Radioactive** beams **Cyclotrons**
  Accelerated stable-radioactive HI beams on light/heavy targets
  **Novae, X-ray bursts, p-process, e- screening**
- ❑ **GANIL-SPIRAL2 (phase1)** **Stable and n** beams **LINAC**
  Very intense accelerated stable LI / HI beams and n-beams on light/heavy targets
  **p-process, X-ray bursts, s-process, novae, dark energy**
- ❑ **GANIL-SPIRAL2 (phase2)** **Radioactive** beams **Cyclotrons**
  Very intense (accelerated) radioactive HI beams on light/heavy targets or for GS/decay studies
  **r-process, core-collapse supernovae**

**Beyhan BASTIN**

# Nuclear measurements for astrophysics @ GANIL

## The last 10 years experiments : Nuclear Astrophysics & proton drip line

(9 Ph.D. Thesis)

| | |
|---|---|
| E400S: F. de Oliveira, L. Achouri et al. | EPJA24 |
| E442S: I. Stefan et al. | PRC 90 |
| E521S: F. de Grancey et al., | PRB758 |
| E521aS: M. Assié et al. | PLB721 |
| E456S: 47Ar L. Gaudefroy, O. Sorlin et al., | EPJA27 |
| E530: 60Fe(d,p) S. Giron, F. Hammache et al. | Under analysis |
| E560S: M. Aliotta et al. | Problem |
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| E563: S. Harissopulos et al. | Scheduled |
| E578S: P. Ujic et al. | PRL110 |
| E568S: P. Ujic et al. | PRC96 |
| E641S: B. Bastin et al. | To be submitted |

…

**SPIRAL1 beams most of the time**

**+ Indirectly related experiments (nuclear dynamics etc…)**

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…

**SPIRAL1 beams most of the time**

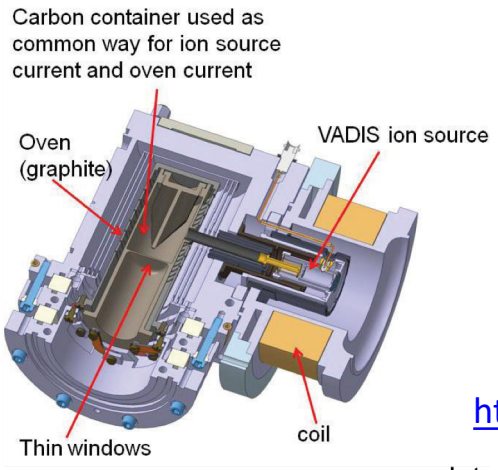
**Novae** **CC SNII** **p-process** **$^{46,48}$Ca isotopic anomalies (meteorite)**

**e- screening** **X-ray burters** **2p emission**

***Light nuclei : CNO, Hot CNO rp-process***

**+ Indirectly related experiments (nuclear dynamics etc…)**

# Nuclear measurements for astrophysics @ GANIL

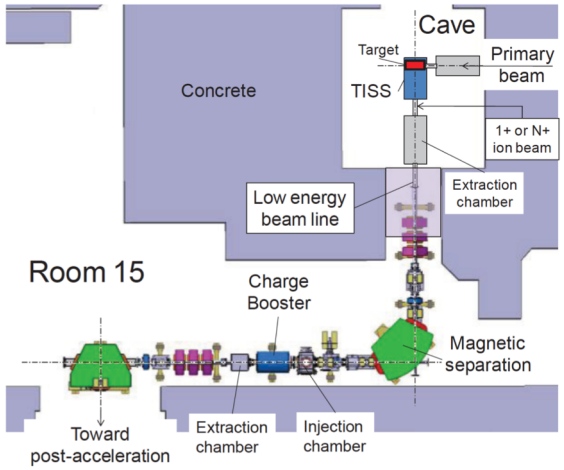


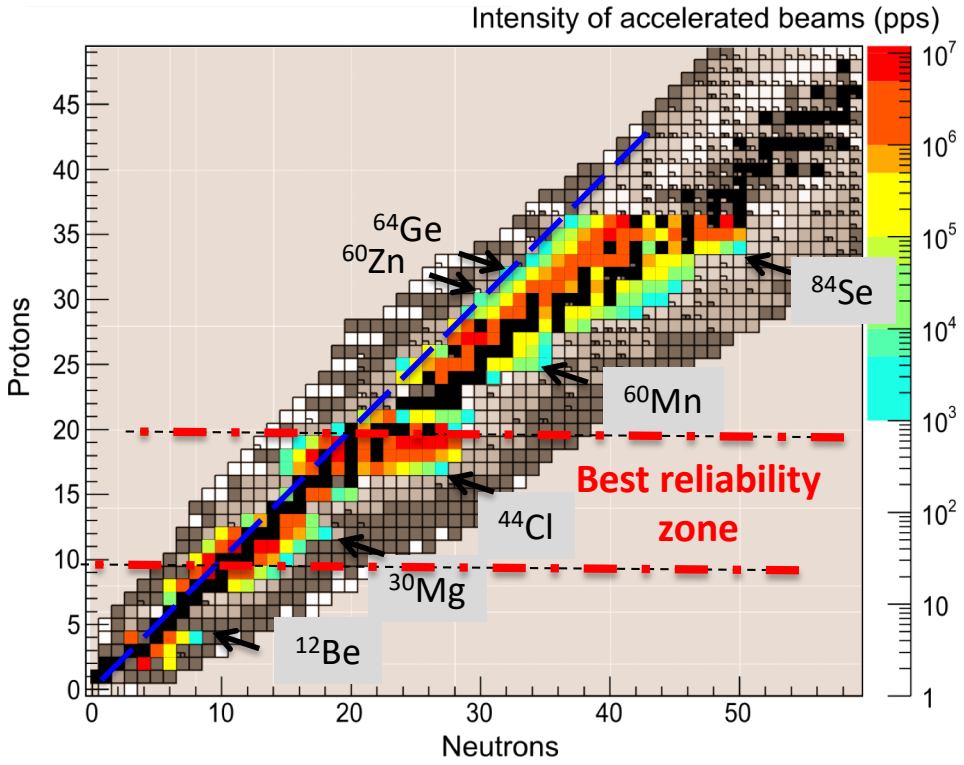

## New perspectives : beams from SPIRAL1 upgrade

**Target + FEBIAD + Booster**

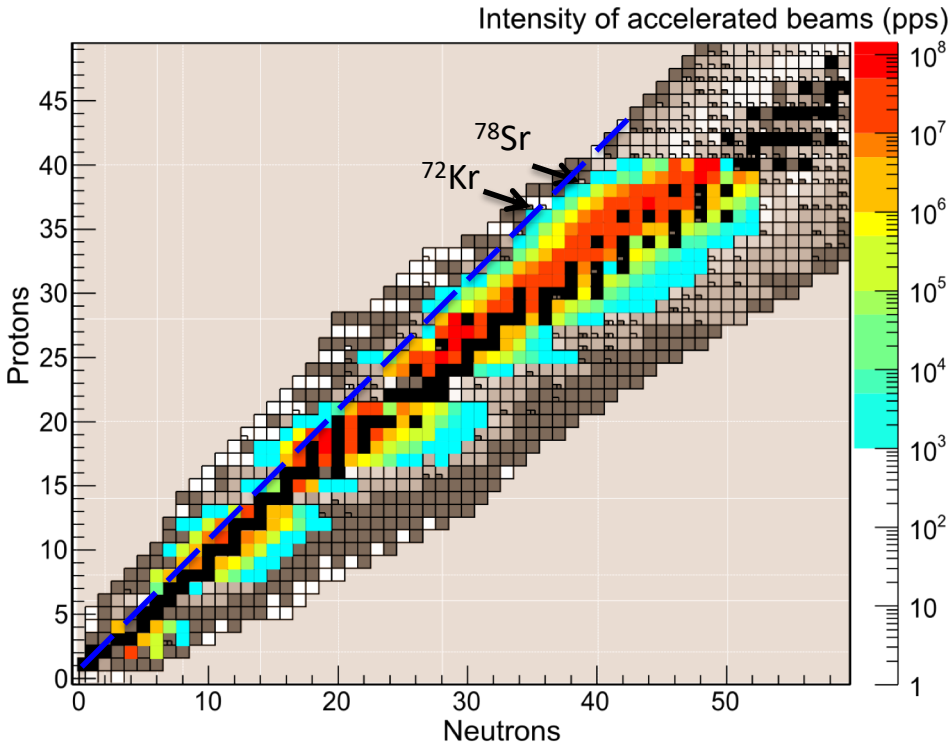
Yield predictions accelerated beams

https://indico.in2p3.fr/event/12296/material/3/0.pdf



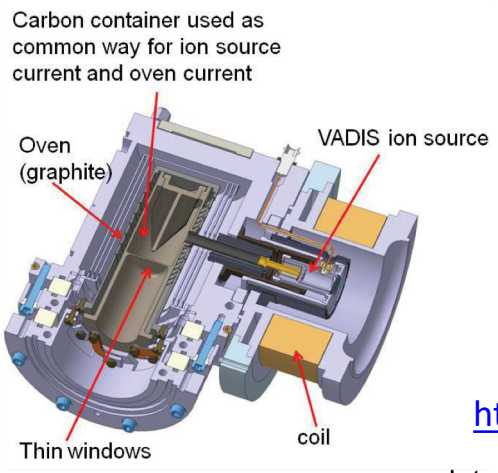

**SPIRAL: Expected production from 12C target**




**SPIRAL: Expected production by target fragmentation**

Best accelerated intensities from fragmentation of SiC, CaO, NiO, Nb targets using 2E13 12C @ 95AMeV.

# Nuclear measurements for astrophysics @ GANIL

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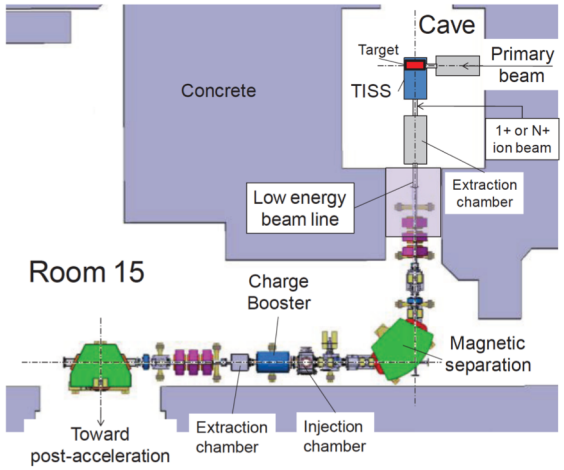


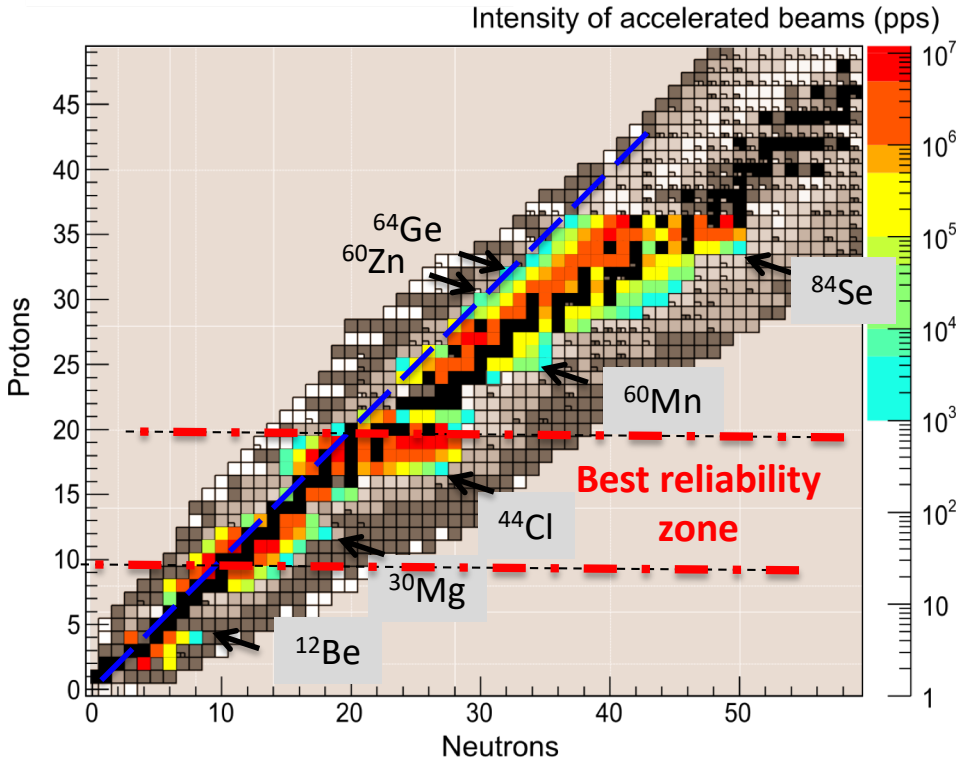


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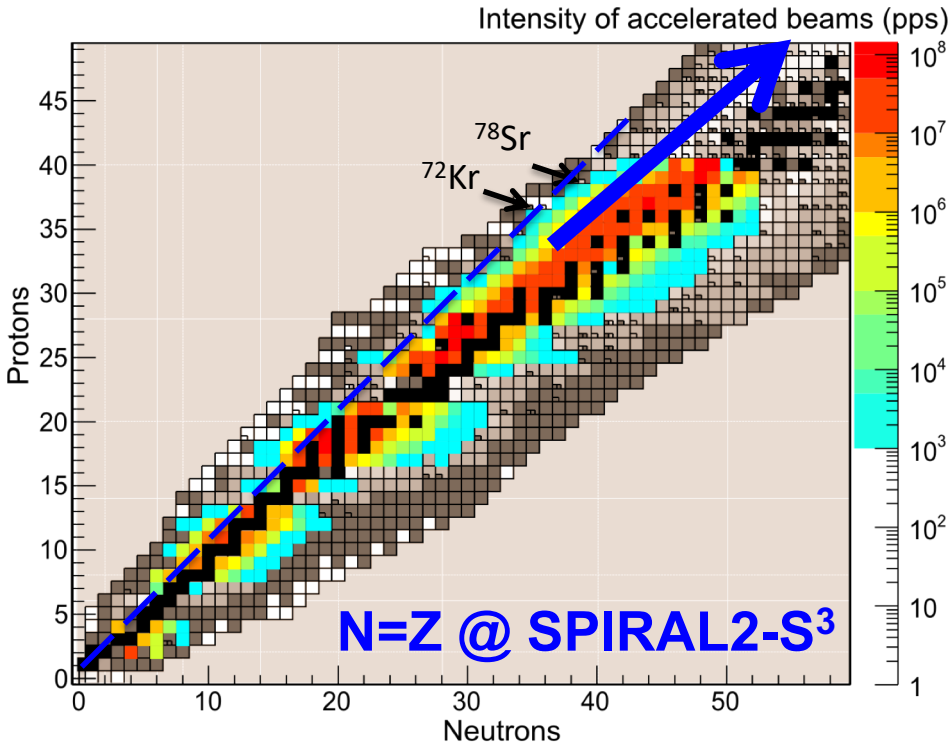


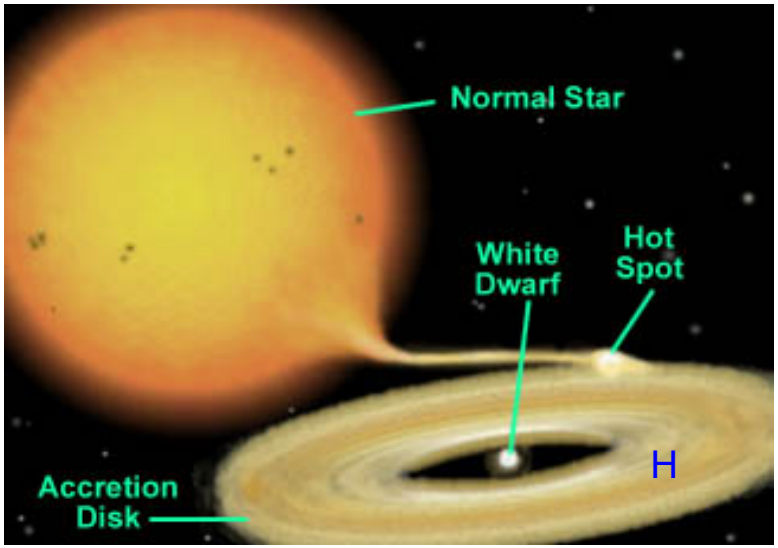

**SPIRAL: Expected production by target fragmentation**

Best accelerated intensities from fragmentation of SiC, CaO, NiO, Nb targets using 2E13 12C @ 95AMeV.

# (1) Nova Explosions and X-Ray Bursts

## *Classical nova and gamma 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

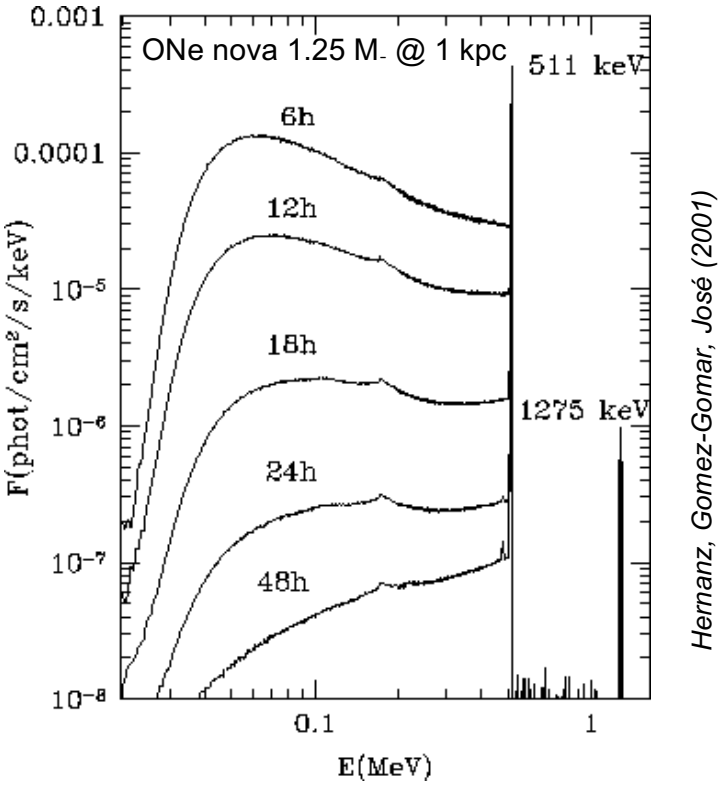
### Constraints on models

- 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

*Beyhan BASTIN (GANIL)*

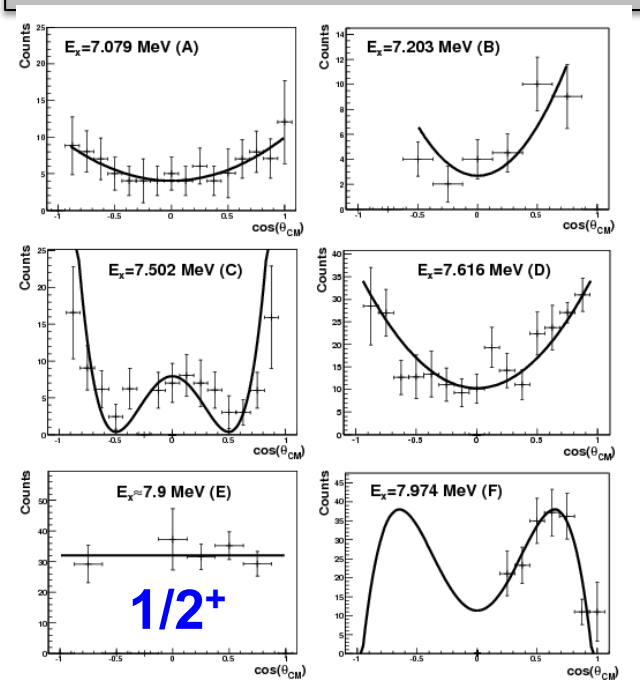
# (1) Nova Explosions and X-Ray Bursts

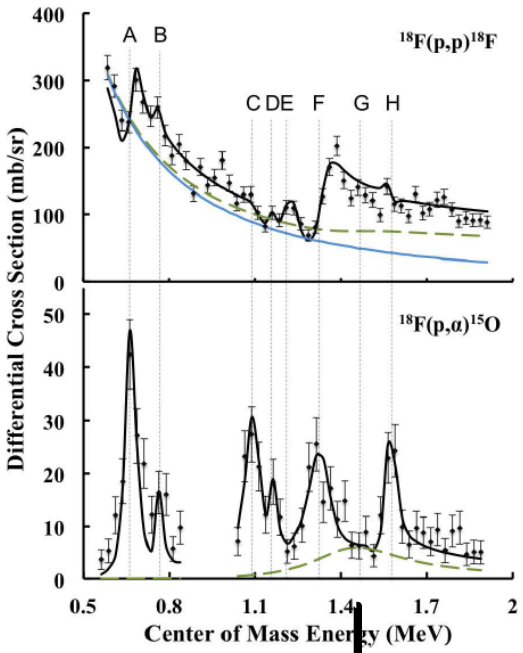
## *Precise direct and indirect measurements of the $^{18}F(p,\alpha)^{15}O$ reaction rate*

**Discovery of a New Broad Resonance in $^{19}Ne$: Implications for the Destruction of the Cosmic -Ray Emitter $^{18}F$**
*J.C. Dalouzy Ph.D. thesis 2008*
*J.C. Dalouzy et al, PRL 102, 162503 (2009)*

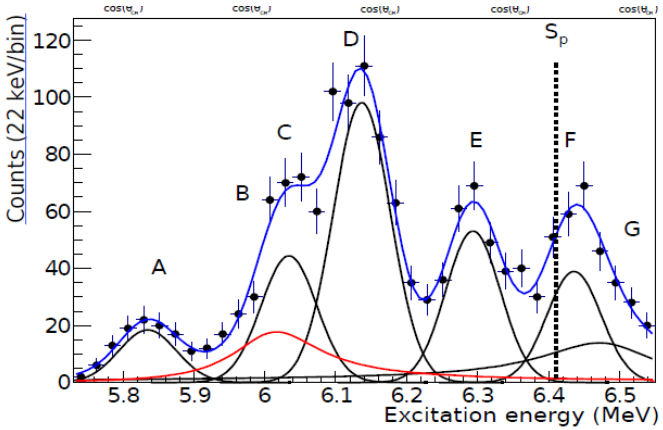
**E560S: Direct Measurement of $^{18}F(p,\gamma)^{15}O$ and $^{18}F(p,p)^{18}F$**
University of Edinburgh
Mountford et al., PRC, 85, 022801 (2012)

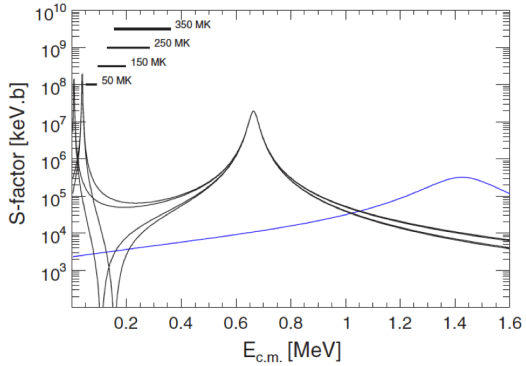
**E641S: A new broad resonance in $^{19}Ne$ relevant for the study of novae**
*F. Boulay Ph.D. thesis 2015*
F. Boulay et al., to be submitted to PRL



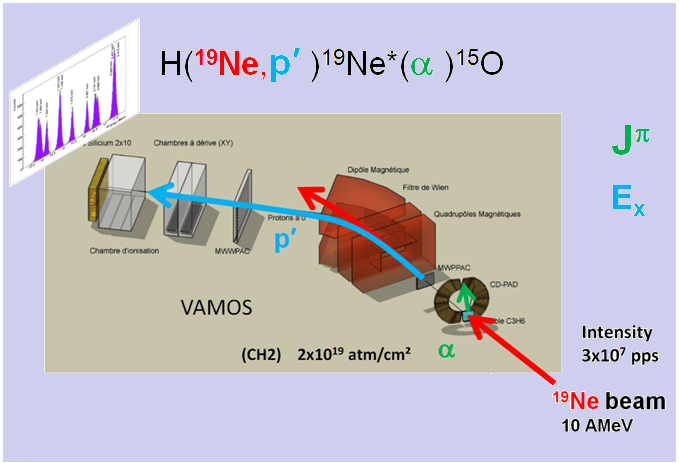




**Hint for a new broad resonance below Sp?**




Confirmed the result



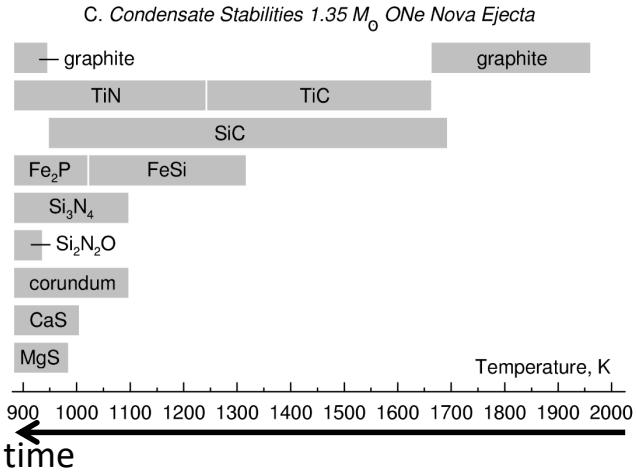

*Beyhan BASTIN (GANIL)*

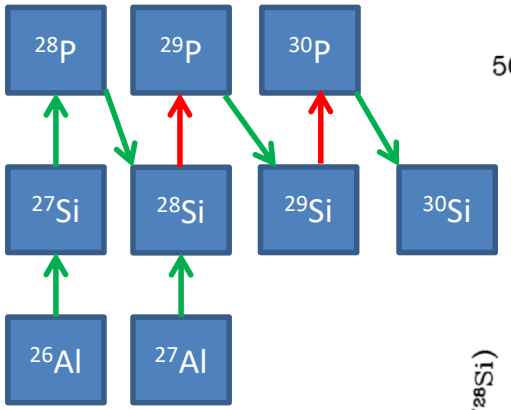
# (1) Nova Explosions and X-Ray Bursts

***Precise direct measurements of the key $^{28}Si(p,\gamma)^{29}P$ and $^{29}Si(p,\gamma)^{30}P$ reaction rates to understand the origin of presolar nova grains***

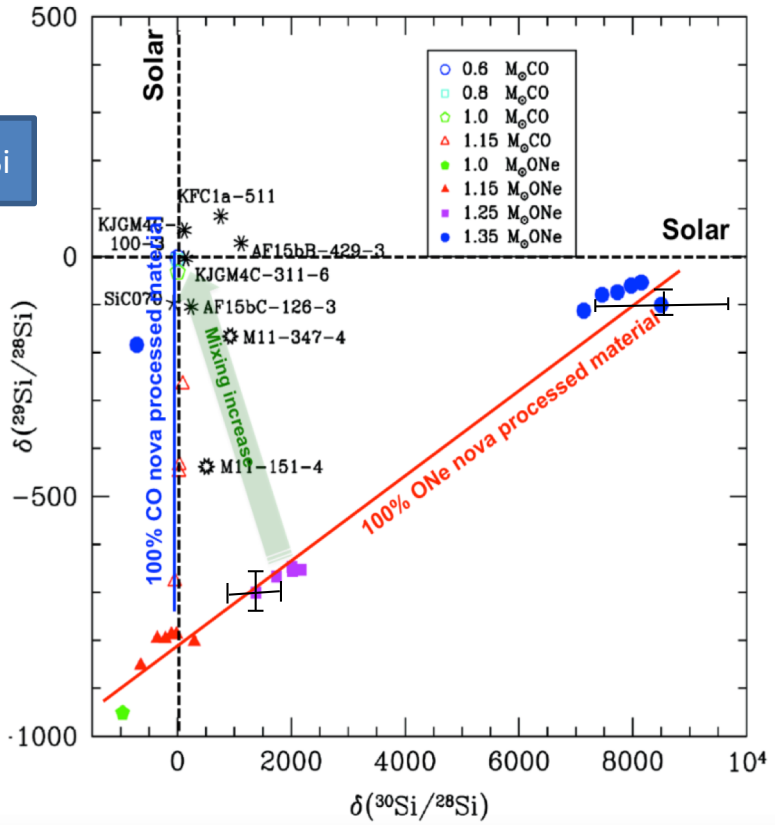
***E719 : F. Boulay, B. Bastin, J. Mrazek et al.***

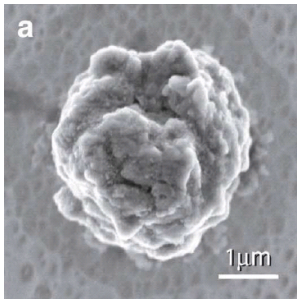
J.Jose Astrophysical. Journal., 612:414–428, (2004)




Destruction reactions
$^{28}Si(p,\gamma)^{29}P$, $^{29}Si(p,\gamma)^{30}P$

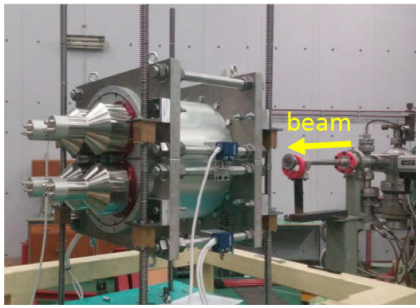



Presolar SiC grain

7 micrometeorties collected on Earth are identified coming from nova explosion

- **Abundances of $^{28,29,30}Si$**
- **Mixing of shells and envelop**




Necessity to constrain the reaction rates $^{28}Si(p,\gamma)^{29}P$ and $^{29}Si(p,\gamma)^{30}P$ which have currently 21 % and 30 % uncertainties.

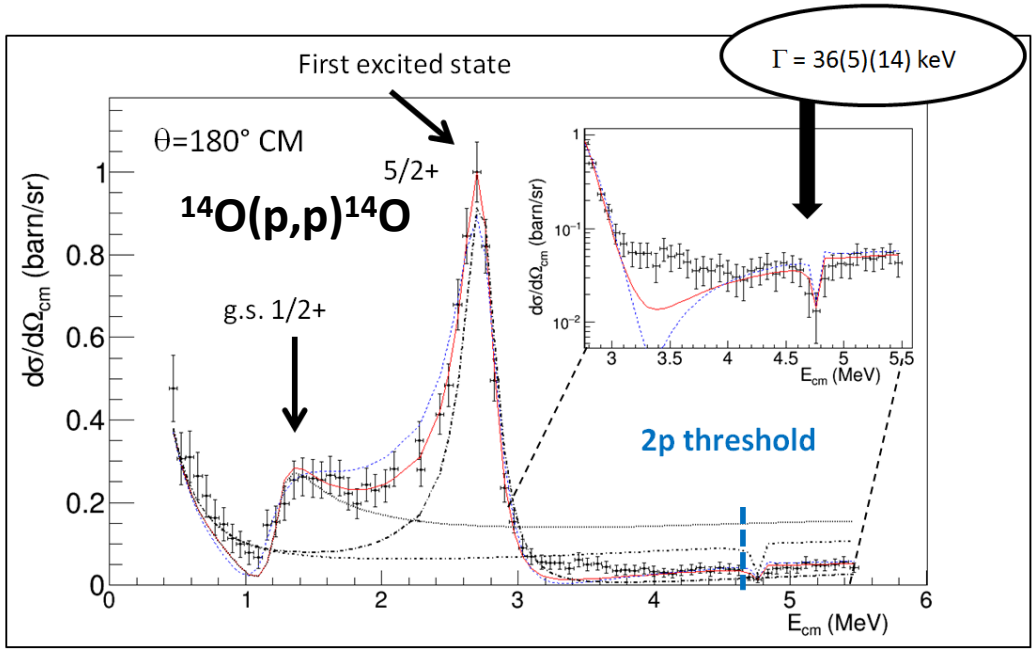
In-beam $\gamma$ summing with the Neoptolemos setup from Demokritos

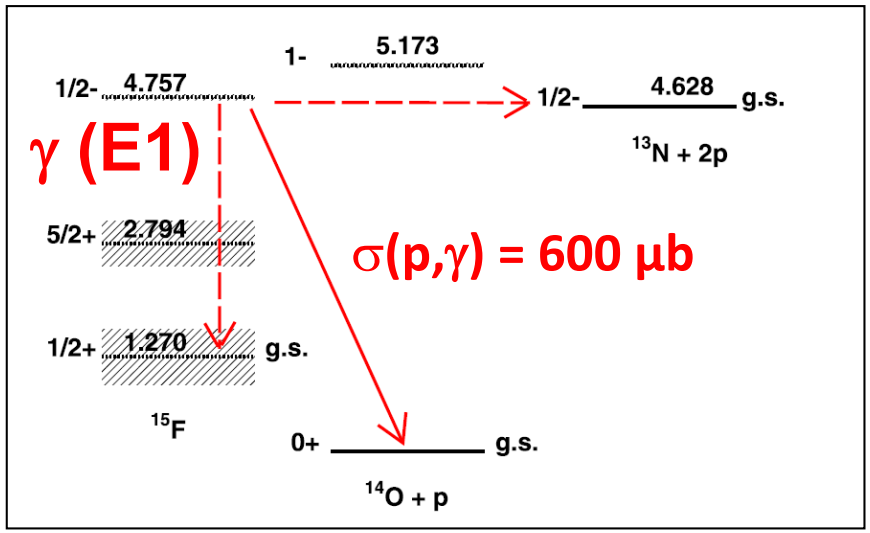
*Beyhan BASTIN (GANIL)*

# (1) Nova Explosions and X-Ray Bursts

## *Search for ?-transition in the unbound $^{15}$F (XRBs)*

***E744 : I. Stefan, V. Girard Alcindor, F. de Oliveira et al.***




**We observed a narrow resonance in $^{15}$F**
De Grancey, F., Mercenne, A. . et al PLB, 758, 26-31. (2016)
A ½- state located above the Coulomb barrier and just above the 2p emission threshold.

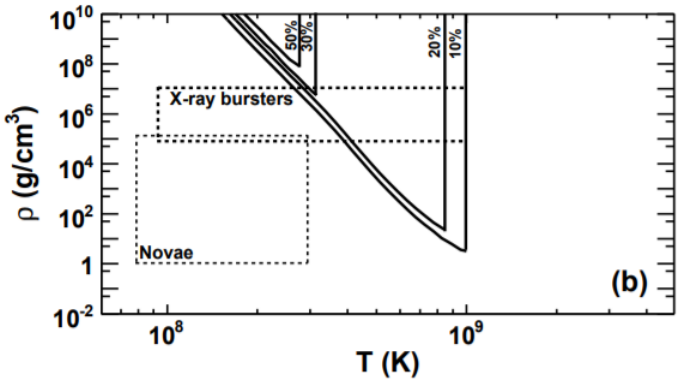
**A new experiment accepted at GANIL/SPIRAL1**
Search for γ-transition in this unbound nucleus. We propose to measure $^{14}$O(p,g)$^{15}$F(p)$^{14}$O

**Motivations:**

- Conflicting theoretical predictions
- Could have applications in astrophysics

**Idea:**

**$^{13}$N(2p,γp) can compete with $^{13}$N(p,γ) at high density. Same idea with $^{15}$O(p,γ e$^{+}$)$^{16}$O in X-ray bursts -> ρ=f(T) when this rr represents 10 to 50 % of the total reaction flux initiated by 15O**




*J. Casal et al. PR C 94 (2016) / I. Stefan et al. arXiv.org > nucl-ex/0603020*

# (2) Core-Collapse Supernovae

## *Modeling, dissipative collisions at GANIL, masses around $^{78}$Ni @ JYFL/SPIRAL2 and decay studies at SPIRAL2*

❖ **Dissipative collisions**

- ✓ **Constraint on the eos of asymmetric nuclear matter – conditions reigning in the neutrinosphere. Input for the model developed by the group**

**Heavy ions collisions** studies **at GANIL** with FAZIA coupled to INDRA (vaporisation in light clusters of highly excited neutron-rich systems:

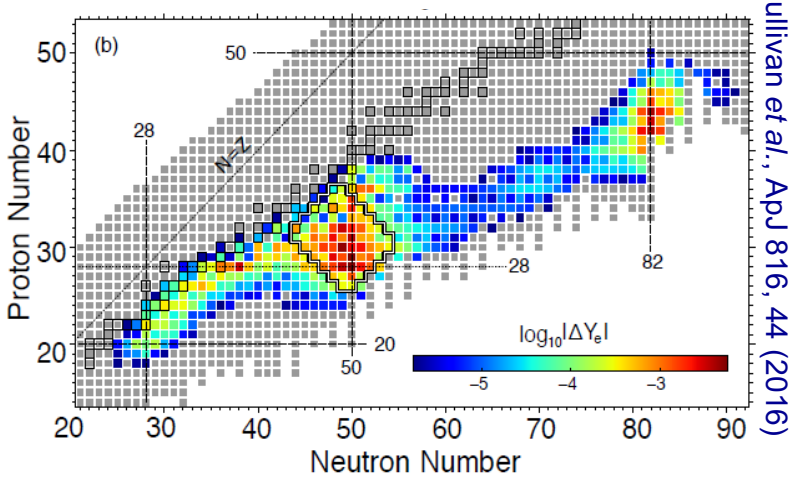
$^{48}$Ca + $^{48}$Ca @ different energies (for example)

❖ Very **precise mass measurements** (less than ~100 KeV) are necessary in **the model developed by the local group (A. Fantina & F. Gulminelli)** for the computation of :

- ✓ **Q value in EC** rates
- ✓ **EoS – composition of SN matter**

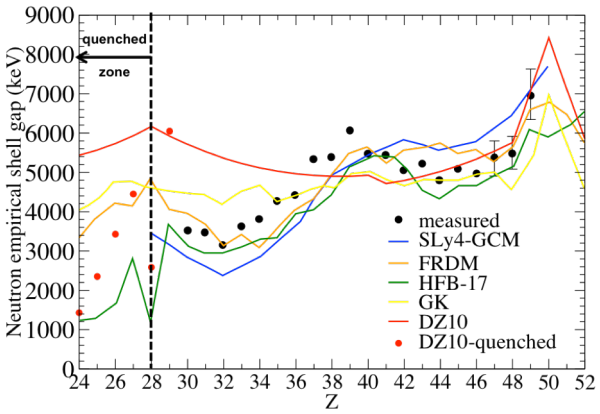
***(coll. with** Universidade Federal de Santa Catarina, Brazil)*

❖ Which nuclei matter ?

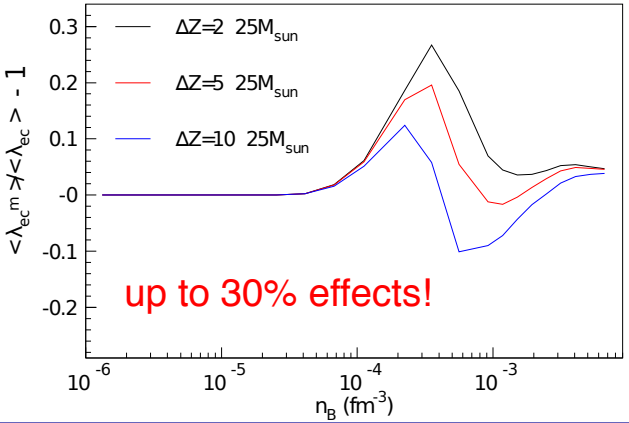



Sullivan *et al.*, ApJ 816, 44 (2016)

❖ Exotic nuclei around N=50 (**$^{78}$Ni**) and N=82 (**$^{128}$Pd**) dominate because predicted to be magic.




→ **Magicity quenching would strongly affect EC.**




Mass measurements around **$^{78}$Ni @ JYFL** (2017) / **SPIRAL2** and **decay studies at SPIRAL2** :

**$^{67}$Fe, $^{69,70}$Co, $^{74,75}$Ni, $^{76,77,78}$Cu, $^{79}$Zn**

***(S. Giraud Phd thesis, modeling + exp.)***

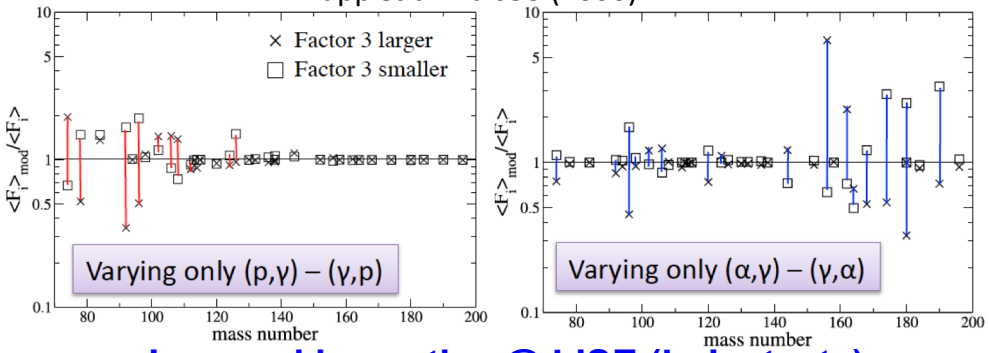
# (3) p-process

## *Direct measurements @ LISE & SPIRAL2/NFS*

- Abundance of 33 proton rich nuclei A ≥ 74
- Astrophysical site still in debate (O/Ne layer in ccSN, type Ia SN, np-process)
- ~ 2000 nuclei involved, (γ,n), (γ,p), (γ,α), n-, p-, α-captures

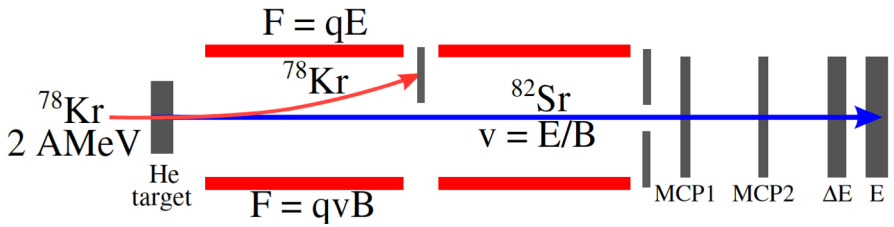
### Sensitivity studies:

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




### Inverse kinematics @ LISE (LoI + tests):

*loI : S. Harissopulos, F. de Oliveira et al.*




- Velocity selection → **beam rejection ~ $10^9$**
- Ideally collecting all charge states
- Dv ~ 5% between primary beam and CN
- July 2014: test of "windowless" gas target
→ new design to obtain N0 ≥$10^{16}$ cm-2
- ToF vs DE ID is possible with ChIO (up to $10^5$ pps)
- July 2015: 58Ni + p/a @ 4.7 AMeV

### 3 experimental campaigns @ NFS foreseen (LoI):

*loI : G. Randisi, I. Companis, B. Bastin, C. Ducoin et al.*

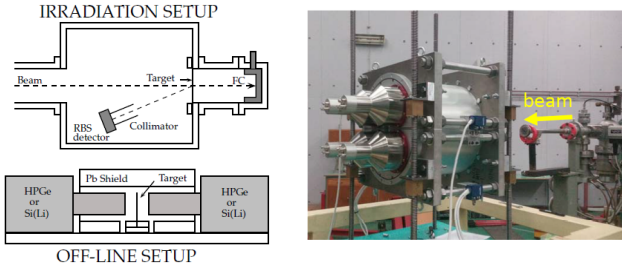
**LINAC : Emin = 0.75 MeV, High p & He intensity : 5 mA!!!!**

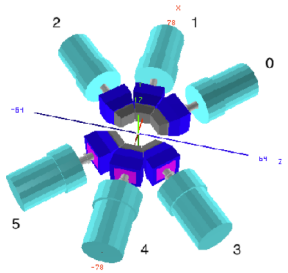
**Critical p-process Reaction Rates**
**(list of day one experiments-easy cases)**

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

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

**3 experimental campaigns foreseen :**
**Activation and 2 in-beam**



Workshop on p-process @ IPNL (Feb. 2017)

**Experiment challenge under study :**
**use of radioactive targets!**

# Nuclear astrophysics

*Adapted from Nupecc LRP 2017 : key properties to be constrained and facilities where measurements can be done*

## rp process

(p,γ), (α,p), (α,γ) at **GANIL-SPIRAL2**, FAIR/GSI, HIE-ISOLDE, SPES

Masses (traps, MR-TOF)

High-Resolution with **AGATA @ GANIL**, FAIR-NUSTAR, SPES, ISOLDE (?)

Novel TPC-based devices (**GANIL**) for $b_p$

Continuum EC + weak interaction strengths probed via β-decay (TAS) and CE studies

### Explosive hydrogen burning

Key reactions need to be measured!
- Spectroscopy and lifetime measurements with AGATA
- Inelastic scattering spectroscopy
- Transfer reactions

Mainly : ISOLDE and **GANIL-SPIRAL1 but also ALTO**

## s process

σ(n,γ) for key branching nuclei via:
- Coulomb dissociation ($R^3$B-LAND)
- surrogate mehods (CENBG and SPES)
- **Via (n,α) @ NFS**

Proof-of-principle for (n,γ) surrogate methods in rings

### Dark Energy (X boson @ **NFS**)

STELLAR EVOLUTION (C fusion @ **ANDROMEDE**)

## r process

Masses (traps, MR-TOF,ESR), half-lives, and beta-delayed neutrons

3rd r process peak and N=126 at NUSTAR(FAIR)

NUSTAR instruments being tested e.g. at RIKEN, **GANIL**, JYFL

In the medium-mass region (N=50, N=82) pure n-rich beams (ISOLDE, **GANIL-SPIRAL2**, SPES, JYFL, **ALTO**..)

### Core-collapse

Contraints on the eos, masses and GT response measure-ments needed around $^{78}$Ni and $^{128}$Pd

$^{44}$Ti and the mass cut

Currently : ISOLDE, Jyvaskyla and FRS-ESR + **ALTO**
Future : + SPES + **GANIL-SPIRAL2**

**→ Also astrochemistry program@ GANIL (CIMAP)**