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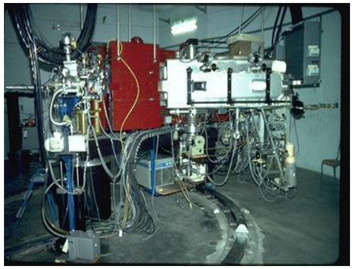
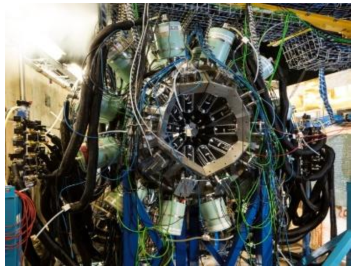
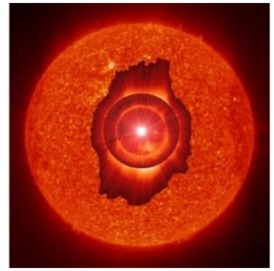
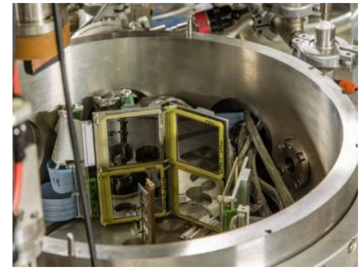
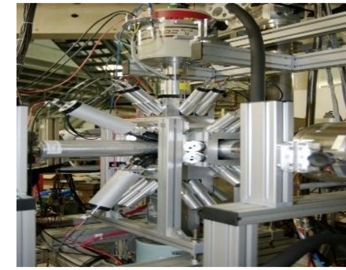
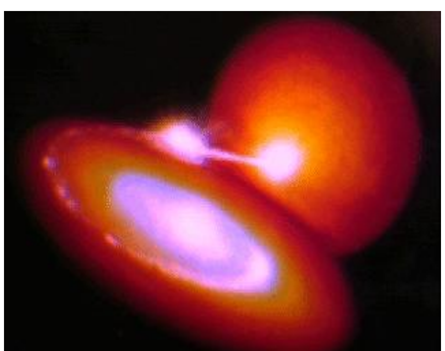
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

UNIVERSITÉ PARIS SUD

université PARIS-SACLAY

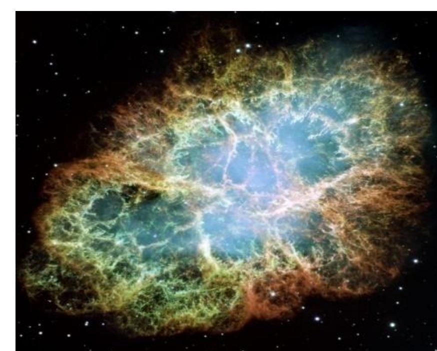






Nuclear astrophysics projects @ ALTO facility

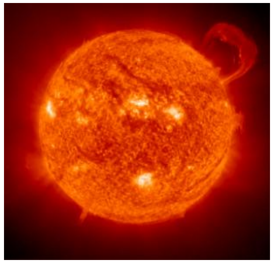


Faïrouz Hammache
IPN-Orsay

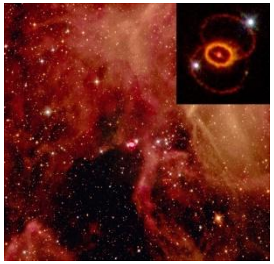
1st meeting of LIA – Subatomic Physics : from theory to applications
São José Dos Campos 12-13 June 2018



NUCLEAR ASTROPHYSICS

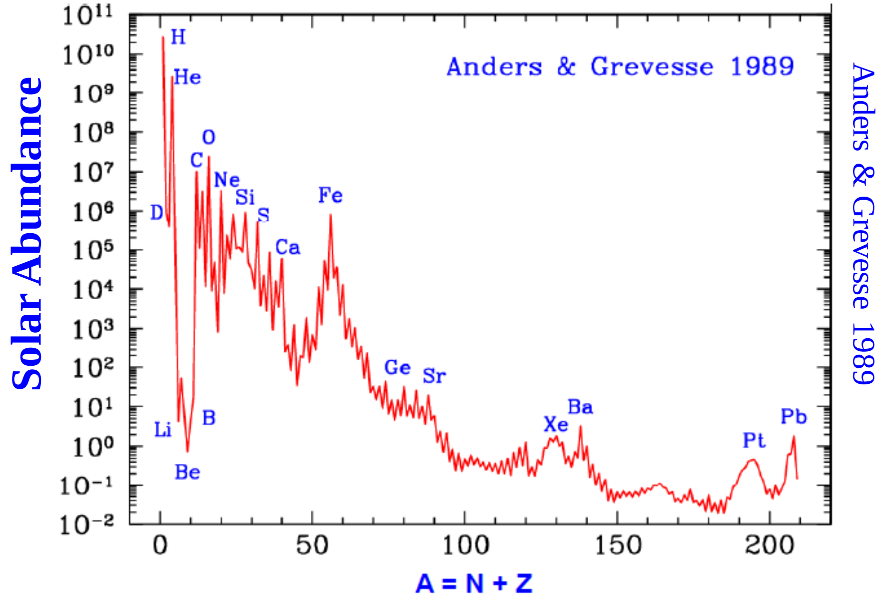


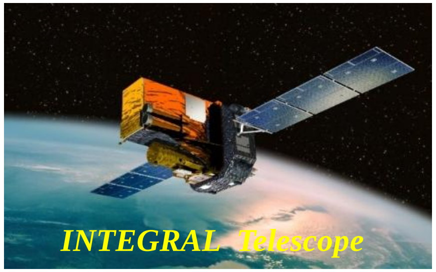
- study energy generation processes in stars
- study nucleosynthesis of the elements



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

Which nucleosynthesis processes at work?



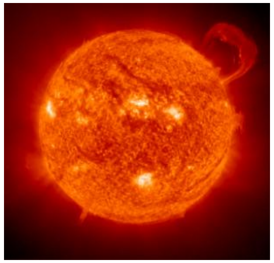


Observations (astronomy & geology),
Modelling & **NUCLEAR PHYSICS**

⬇

KEY for understanding

NUCLEAR ASTROPHYSICS



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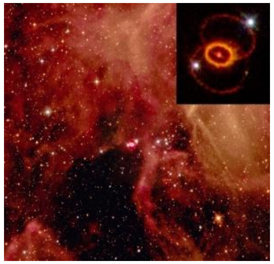

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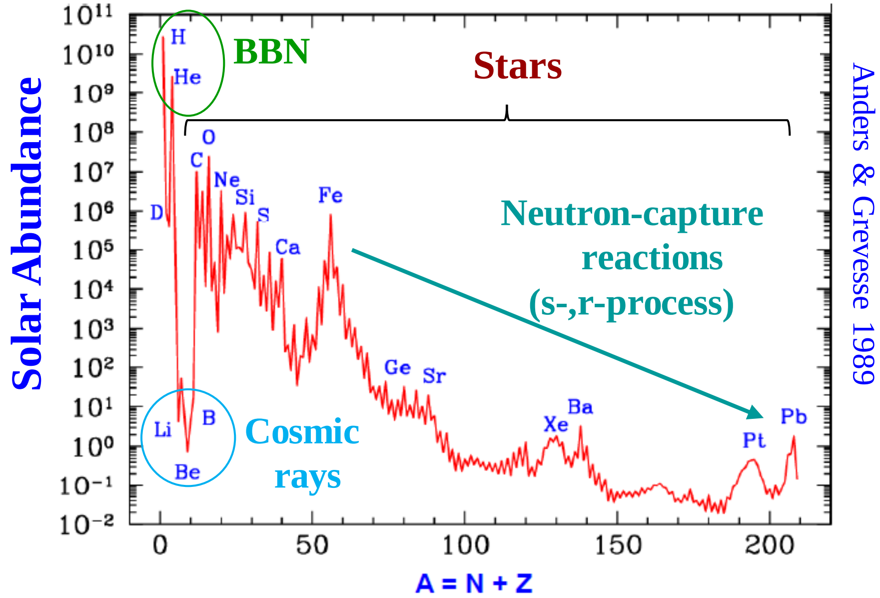

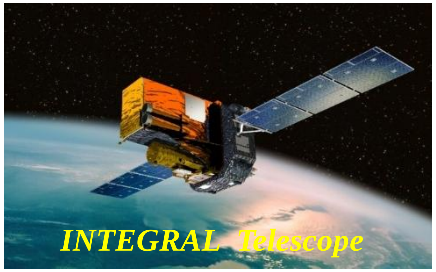

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KEY for understanding

From nuclear physics to abundances

Improving the knowledge of the nucleosynthesis processes at work in the universe & the understanding of stellar evolution

Nuclear physics Experiments & theory

Needed inputs: cross-sections, **nuclear spectroscopic properties (Ex, J, partial decay widths)** , masses, β-decays,…)

Reaction rate

Astrophysics Modelling

Network calculations (BBN & stellar evolution modelling, nucleosynthesis)

Abundances

Observations

(On earth, meteorites, satellites,…)

Abundances

The ALTO facility

e-LINAC
50 MeV / 10 μA
~10^{11} fissions/s

TANDEM
V_T = 14 MV
p, d, ^{3,4}He,
^{6,7}Li, …, ^{14}C, ...

The Alto facility: stable beams

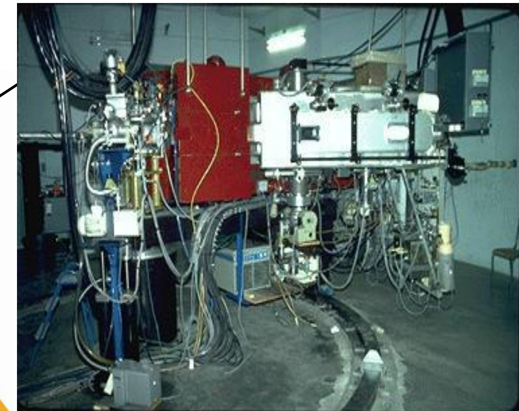
γ-spectroscopy

LICORNE

Multipurpose

BACCHUS Spectrometer

SPLIT-POLE Spectrometer



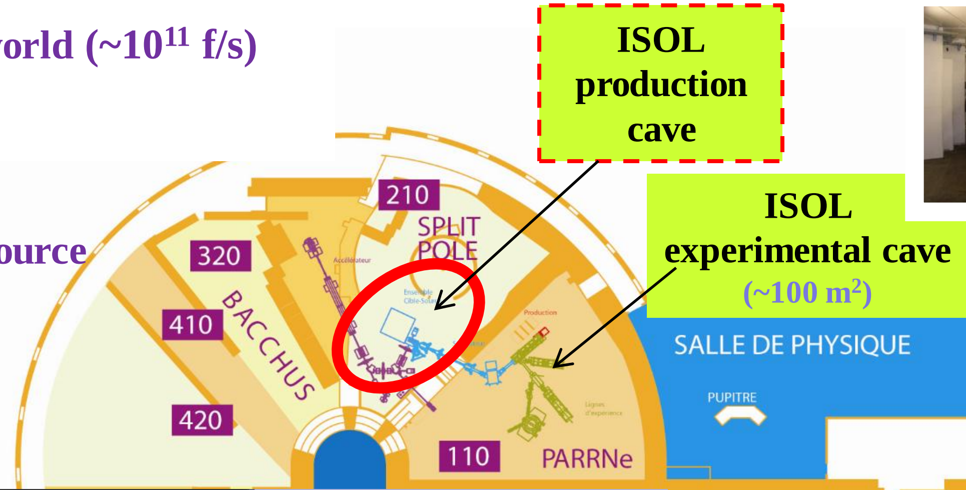
Standard Tandem beams

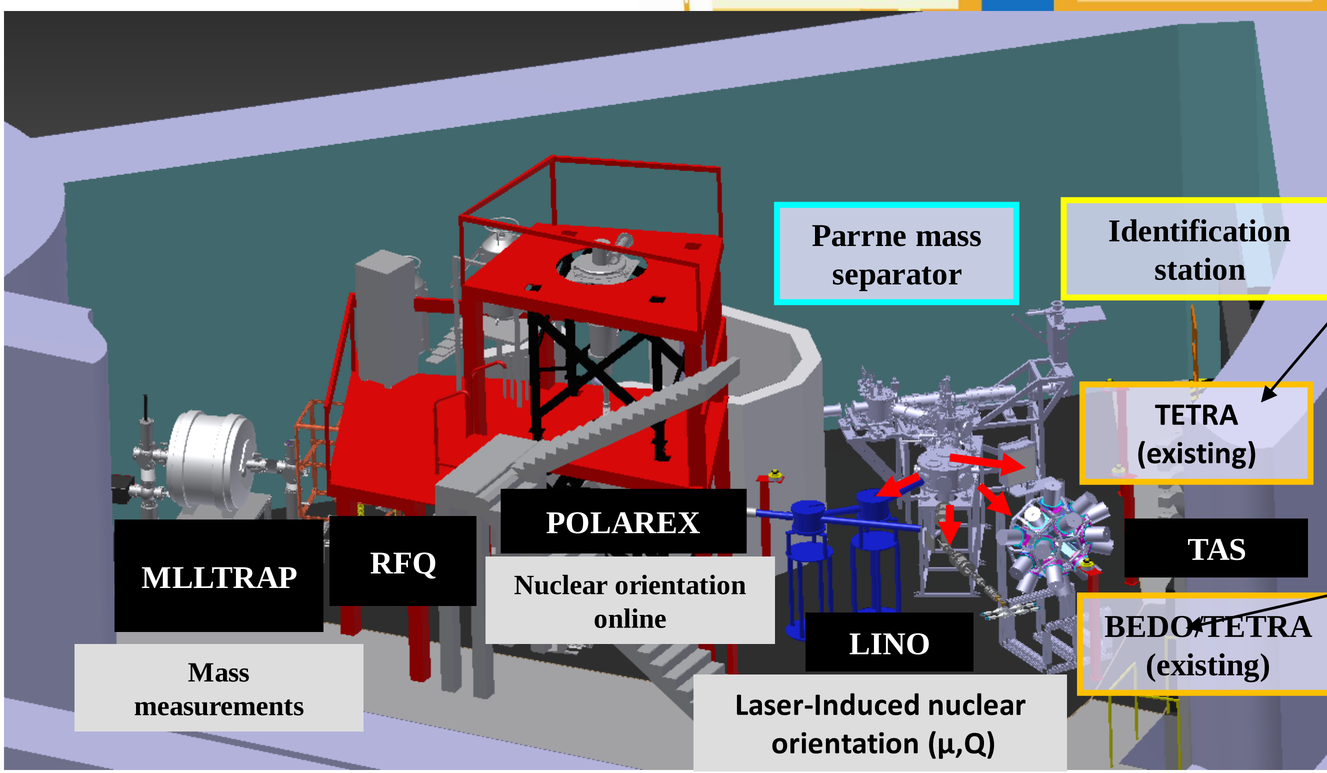
- from **H, ^{3}He, ^{4}He, ..., ^{14}C, ...** up to **^{127}I**
- terminal voltage: from **< 1 MV** up to **14.5 MV**
- beam pulsing: pulse width **1 – 2 ns**; repetition rate – **200 ns** or more
- **new ions source** purchased for higher intensity of difficult beams (Mg, Ca)

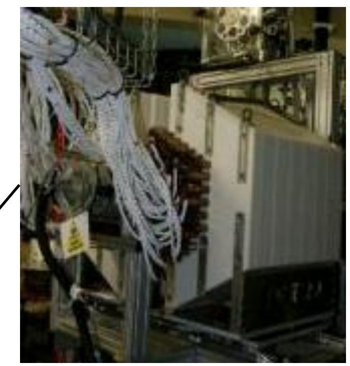
The Alto facility: radioactive beams

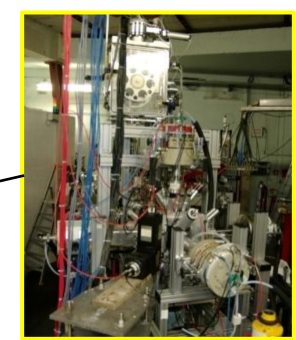
First photofission ISOL facility in the world (~10^{11} f/s)

- **50 MeV** & **10 µA** e^- beam
- UCx target (~70g, ~140 pellets)
- Z selection with: **Surface/LASER ion source**
- Mass Selection with PARRNe magnet



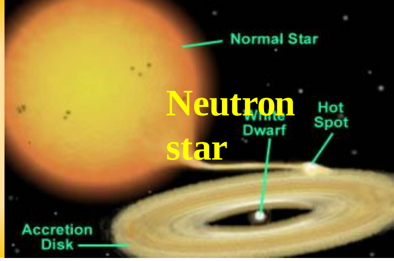






Beta decay spectroscopy

Projects with stable beams: γ-ray measurements for hydrogen burning in novae/X-ray bursts

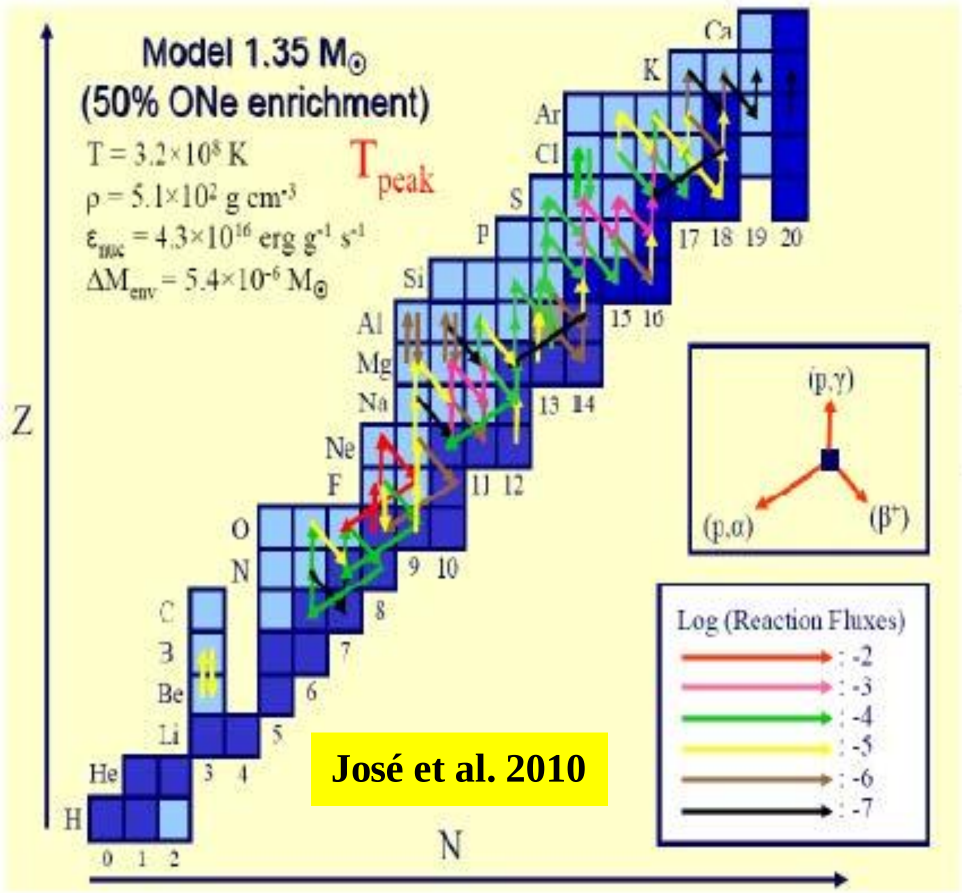


Hydrogen-burning in novae/ X-ray bursts scenarios - rates dominated by narrow resonances typically within a few 100s of keV above the threshold

γ widths dominate due to low energy for Coulomb-barrier penetration

Need information on the energies, spins & parities of these states to work out which ones are potentially important

γ-ray decay information is one of the best ways to do this



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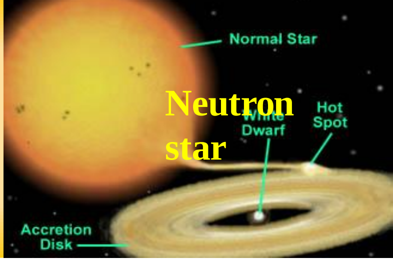

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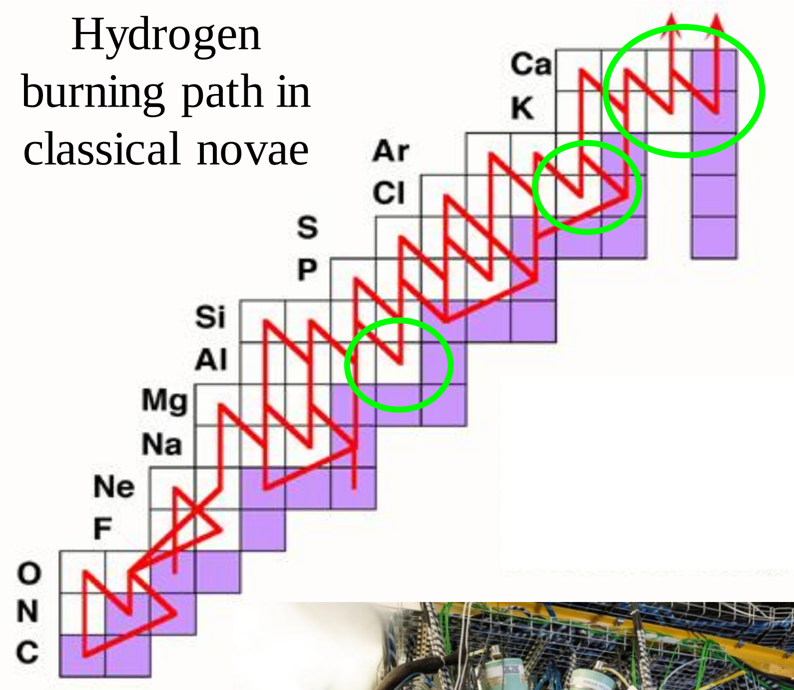
$$N_A\langle\sigma v\rangle \propto \omega\ \Gamma_p\Gamma_\gamma/\Gamma * \exp(-11.605\ E_r / T_9)$$

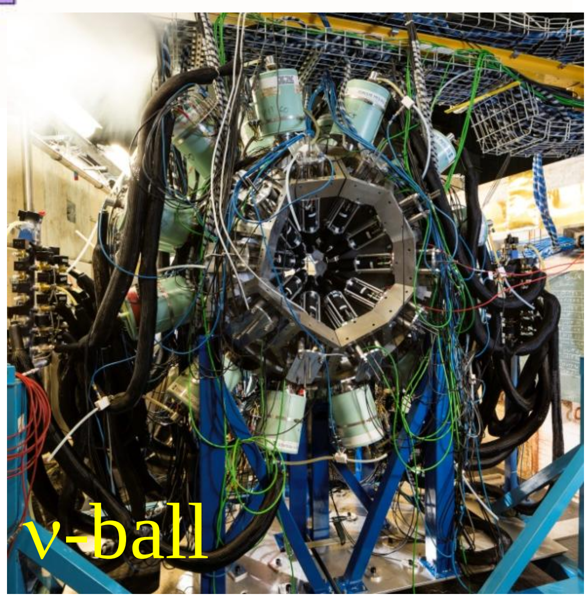
Spin factor = $(2J+1)/((2j_1+1)(2j_2+1))$

$$\Gamma_p = 2\ \gamma^2\ P_L(E),$$

P_L is the penetrability for orbital angular momentum, L, and varies strongly with the orbital angular momentum – only low L are astrophysically important

Physics cases for hydrogen burning





Resonances in ^{38}K, ^{39}K, ^{39}Ca which contribute to burning in massive stars/novae (e.g. globular cluster pollution scenarios) - all accessible via ^{39}K+p reactions (e.g. (p,d), (p,p'), (p,pn), (p,n))
P.Adsley et al.

Low-lying/isomeric state to and from which capture can take place c.f. ^{34}Cl and ^{26}Al

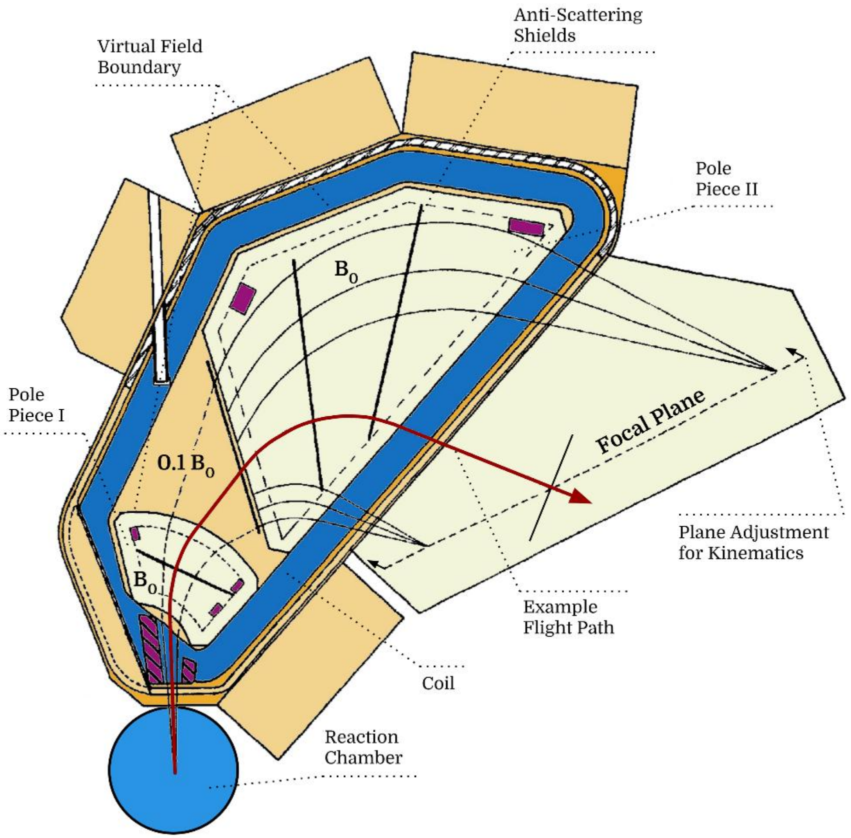
States relevant for rp-process in X-ray bursts also accessible for some cases - e.g. ^{59}Cu(p,γ)^{60}Zn by ^{58}Ni(^{3}He,n))^{60}Zn

→ γ-ray measurements using
ν-ball setup-like (34 Ge detectors+ 36 $LaBr_3$)
actually available at ALTO

Projects with stable beams: Split-Pole measurements

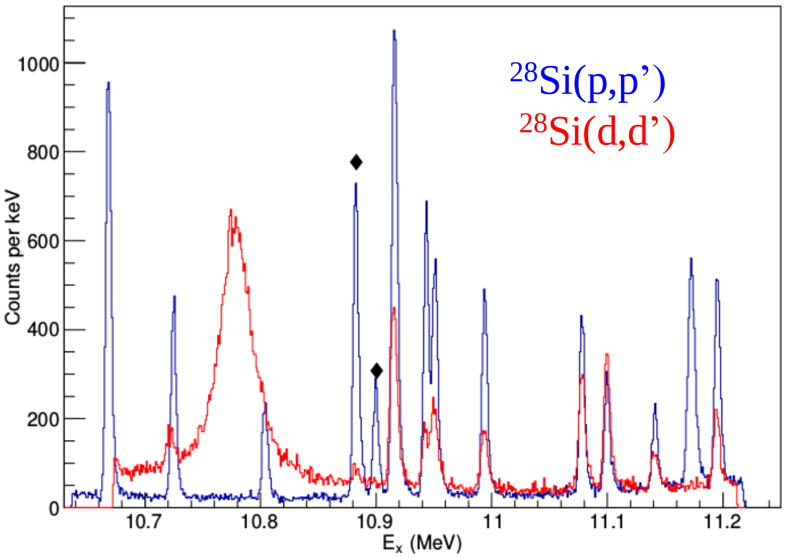
Split-Pole spectrometer

- $\Delta\Omega \sim 1.7$ msr
- $\Delta E/E \sim 5 \times 10^{-4}$



Most of the nuclear astrophysics projects performed these last 10 years at ALTO used Split-Pole spectrometer (see N. de Séréville talk)

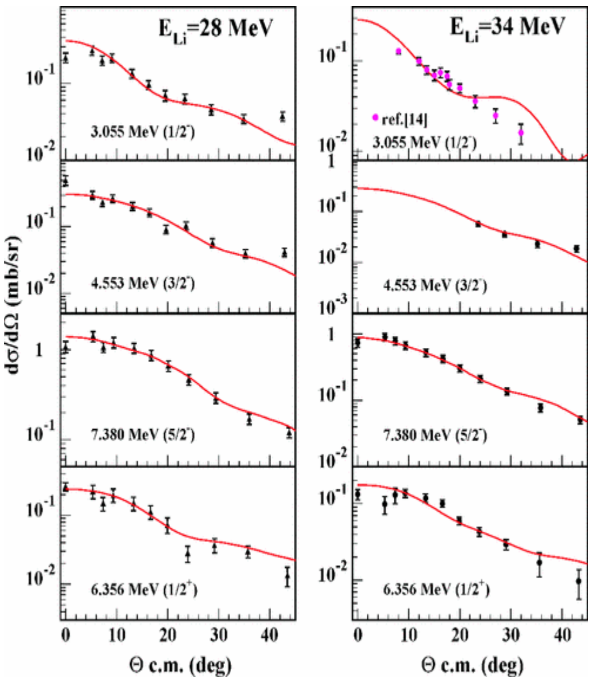
Combination of tandem+magnetic spectrograph ⇒ high-energy resolution measurement of a state



Two main ways - inelastic scattering and charge-exchange to find states and energies, and transfer reactions for spectroscopic factors (and therefore partial widths)

Transfer reaction measurements projects with Split-Pole

Pellegriti *et al.* PRC (R) (2008)



$^{13}C(^7Li,t)\,)^{17}O$ transfer reaction
↓
$^{13}C(\alpha,n)^{16}O$: s-process neutron source in low mass AGB stars

For alpha capture & proton capture reactions: $(^{6/7}Li,d/t)$ & $(^{3}He,d)$ are the most interesting options

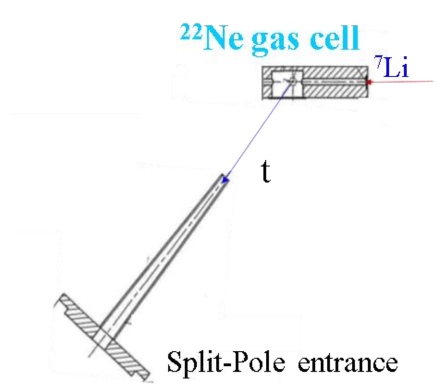
- $(^{3}He,d)$ gives access to proton widths
- $(^{6/7}Li,d/t)$ gives access to α-particle widths

Projects: Study of $^{18}O(\alpha,n)$ in CCSNe relevant to ^{15}N production & neon-burning reaction like $^{20}Ne(\alpha,\gamma)^{24}Mg$

- Coupling the magnet with **gas cell** makes reactions involving e.g. oxygen & neon possible.

<u>Accepted project in Orsay PAC 2018:</u>

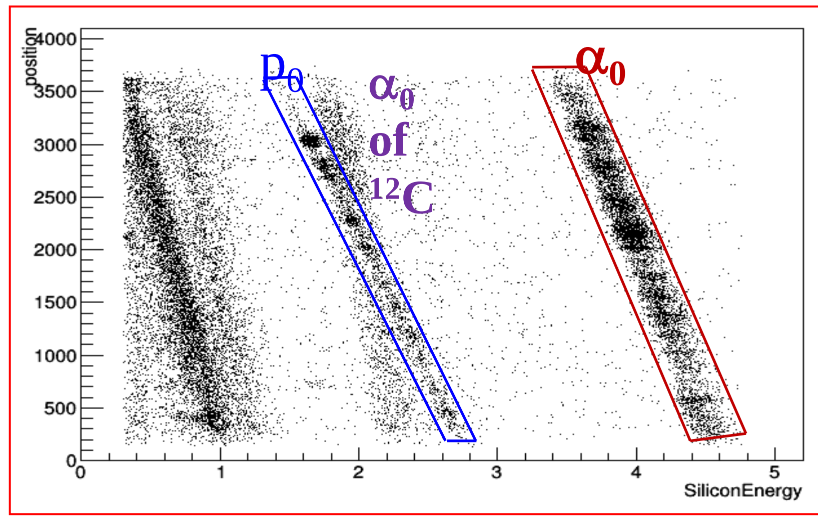
- Study of **$^{22}Ne(\alpha,n)$** reaction: main neutron source for the s-process in massive stars **(very high priority in nuclear astrophysics)** **(spokesperson: F. Hammache et al.)**



Split-Pole-DSSSD coincidence measurements

- Coincidence measurements is a useful method for getting charged-particle branching ratios for important astrophysical reactions
- Angular distributions of decaying particles for spin-parities

- Recent studies using Split-pole spectrometer coupled with an array of DSSSD in the reaction chamber include **^{27}Al, ^{19}F, ^{19}Ne, ^{31}S** (see **N. de Séréville talk**)



- Important cases :

  -Hydrogen burning → proton decay branching ratio of **^{38,39}K, ^{39}Ca**
  - ^{12}C+^{12}C fusion in massive stars→**^{24}Mg state decay** channels

Coincidence plot from the experiment:

^{19}F +p → ^{19}F* + p'

→ **p'' + ^{18}O**

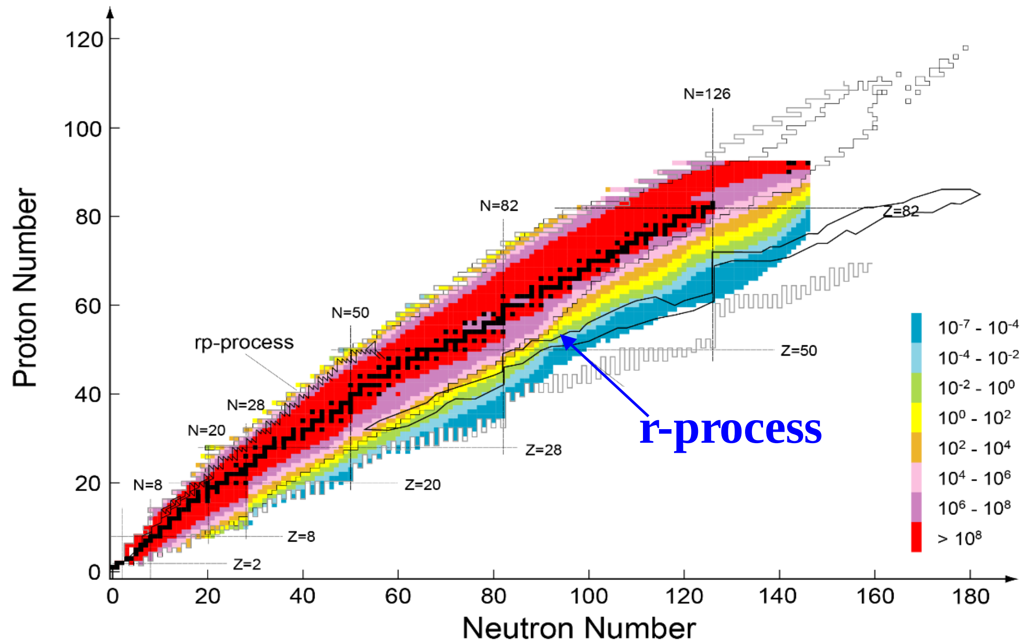
→ **α + ^{15}N**

P. Adsley, F. Hammache *et al.* ongoing analysis

Projects with radioactive beams: Study of the rapid neutron capture process

- ➢ Production of the half of the abundance of heavy elements

temperature	**1-2 ×10⁹ K**
/timescale	**~ seconds**
neutron density	**10^{20}-10^{24} cm^{-3}**
Possible stellar sites	type II supernovae
	neutron star mergers



- **Individual measurements will not affect the scenario**

=> need significant set of new inputs: masses, β-dcays, capture cross-sections

→ constrain the nuclear theoretical predictions

- **Example of projects:**
- Mass-program (Ag) **E. Minaya et al.**
- Measurements of the decay characteristics of ^{90}Se ($T_{1/2}$, β-delayed neutron emission…) **T. Kurtukian et al.**

} **Experimental measurements using MLLtrap, BEDO,TETRA …**

Conclusions

- ALTO – a small-scale facility for stable and radioactive beams that can provide physics results with considerable impact on nuclear astrophysics

- Stable beams:

  - Various key reactions can be studied via gamma-ray spectroscopy using γ-array setups such as ν-ball

  - Coupling a gas cell to the Split-Pole magnetic spectrometer will open opportunities for measurements of key (α,γ) & (α,n) reactions involving oxygen, neon, argon,…

- ISOL- Radioactive beams

  - Mass and β-decay measurements,… for the r-process studies can be performed with MLLTRAP, BEDO-TETRA setups

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You are welcome to join the projects

&

new ideas are welcome