Applications of β-decay Total Absorption Gamma-ray Spectroscopy to Astrophysics

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- The TAGS technique
- Constraints on (n,γ) cross-section estimates for the r-process
- Improvement of $T_{1/2}$ and P_n predictions for the 3rd r-process peak
- EC/β+ rates for the rp-process

Total Absorption Gamma-ray Spectroscopy Technique

Goal:

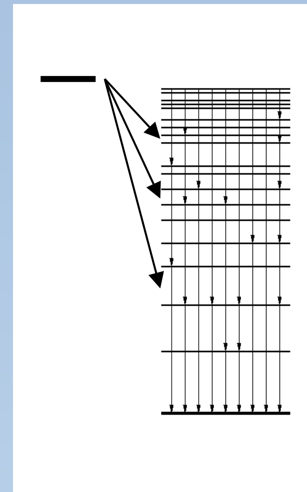
- Counting β-decays to a level from the γ-rays emitted

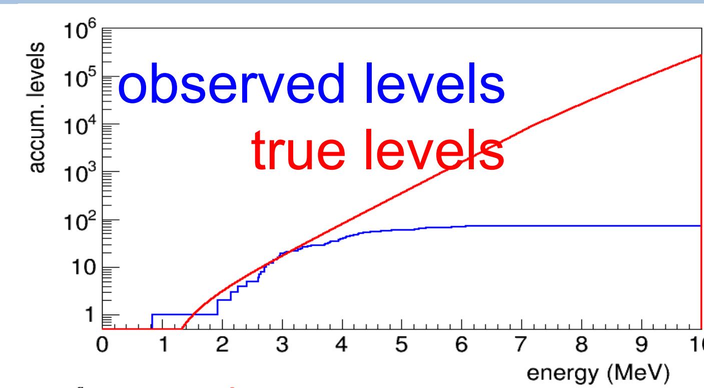
Problem:

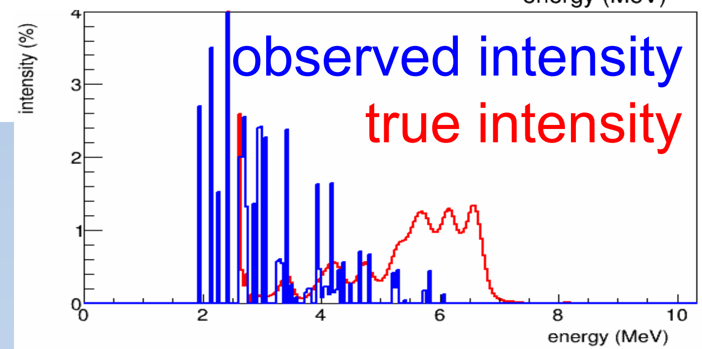
- The limited efficiency of HPGe detectors together with the complex de-excitation path: ***Pandemonium effect***

Solution:

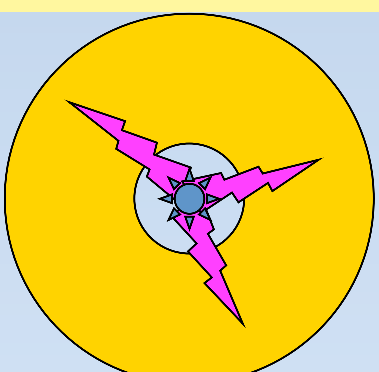
- Measure the full γ-ray cascade with a calorimeter



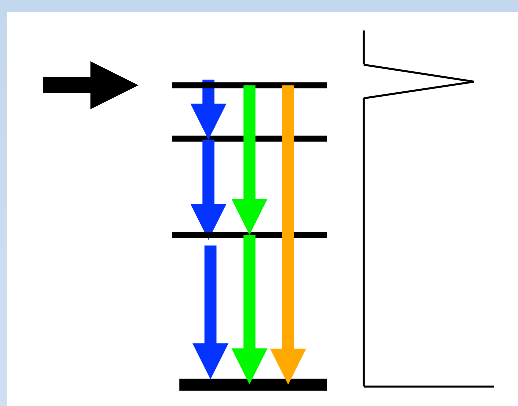




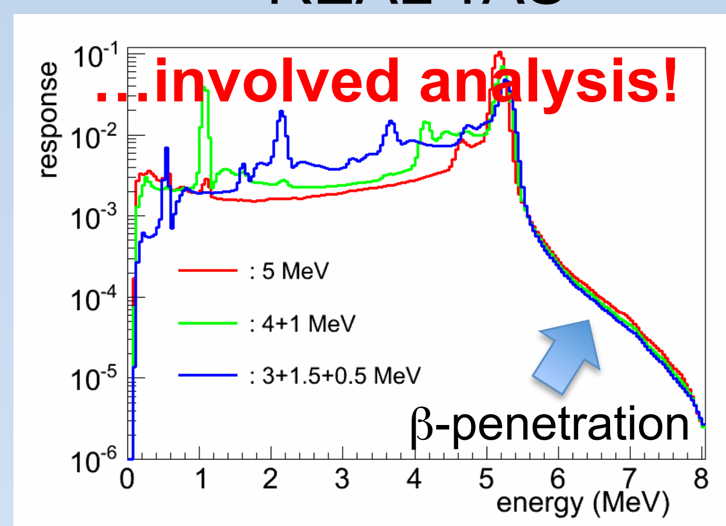
Duke+,NPA151,1970



IDEAL TAS



REAL TAS

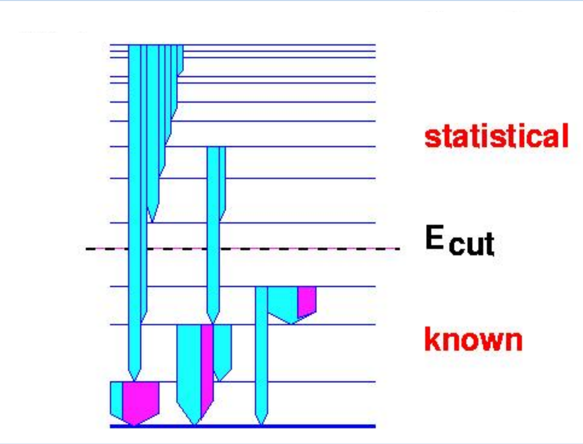


The TAGS analysis in a nutshell

1) Reduce the analysis to a **linear inverse problem** taking the b.r. as parameters:

$$d_i = \sum_j R_{ij}(\mathbf{b}) \cdot f_j$$

2) Make a reasonable choice of b.r. matrix: we use the **nuclear statistical model** plus **known level-scheme**



3) Construct the spectrometer response using **MC simulations**: need to make **careful calibrations**

$$\mathbf{r_j} = \sum_{k=0}^{j-1} b_{jk} \gamma_{\mathbf{jk}} \otimes \mathbf{r_k}$$

$$\mathbf{R_j} = \beta_j \otimes \mathbf{r_j}$$

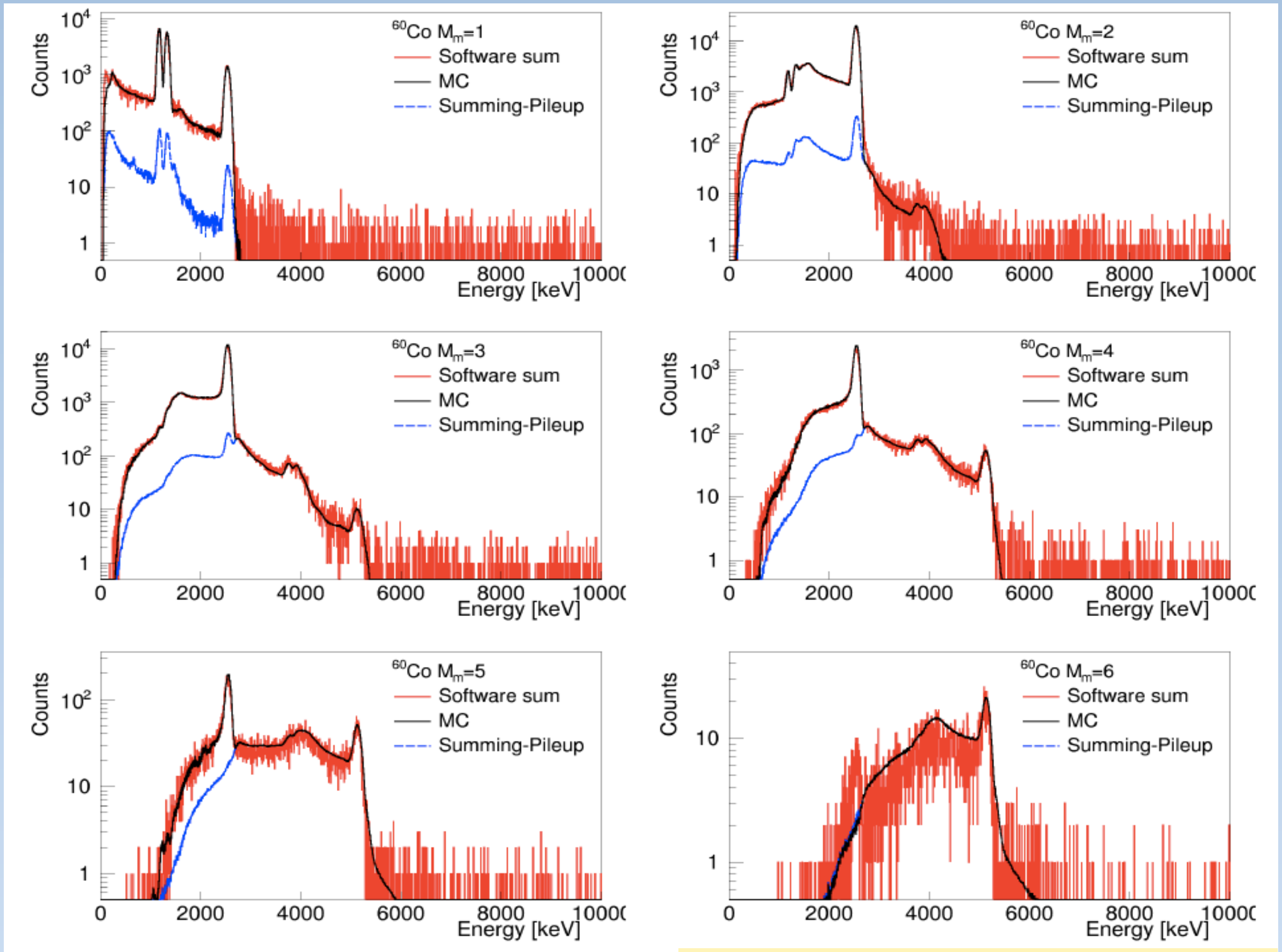
4) Apply any suitable (**deconvolution**) algorithm: we use the EM method

5) Study the effect of different b.r assumptions, MC simulations and other **systematic errors**

NIM: A430(1999)p333, A571(2007)p728, A571(2007)p719

The new segmented TAS: multiplicity distributions

^{60}Co

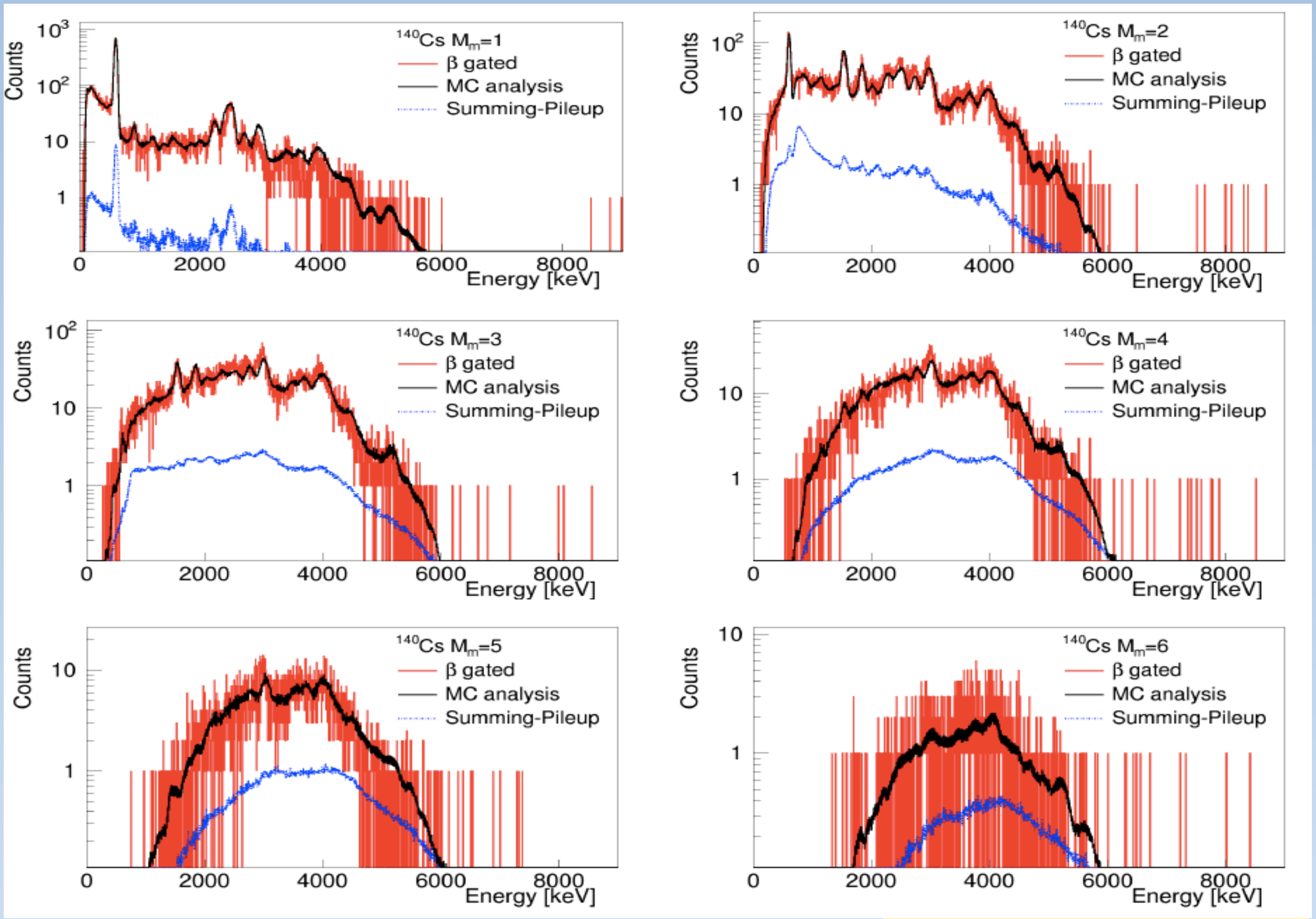


V. Guadilla+,NIMB376(2016)334

Known sources: more restrictive verification of Geant4 response simulation and of summing-pileup calculation

The new segmented TAS: multiplicity distributions

^{140}Cs

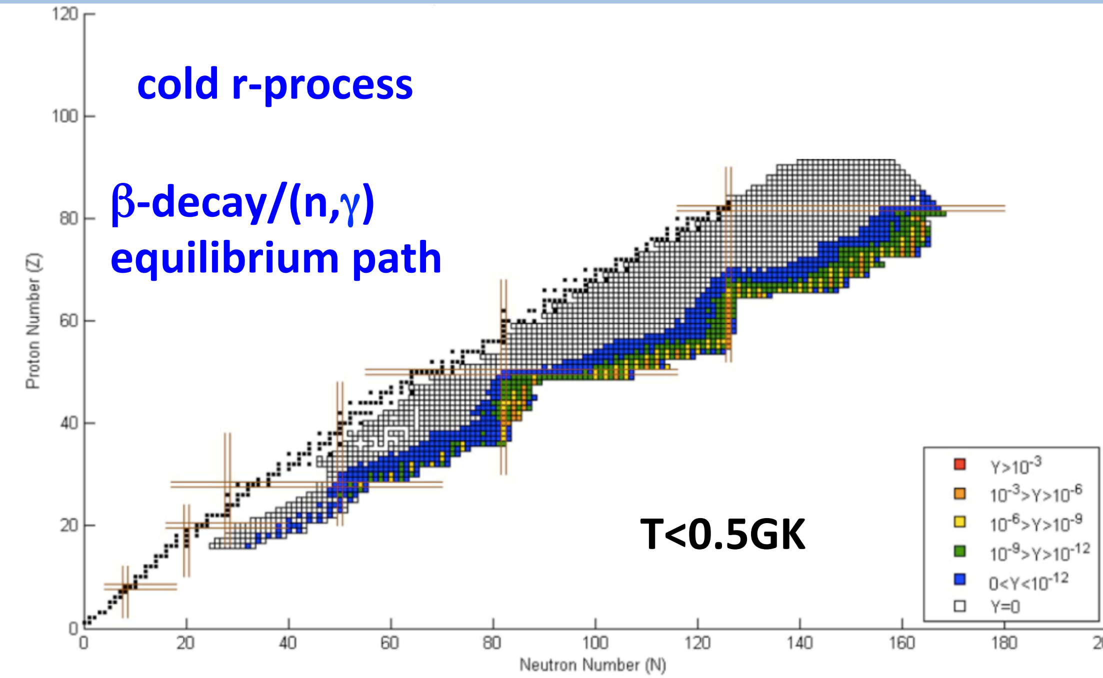


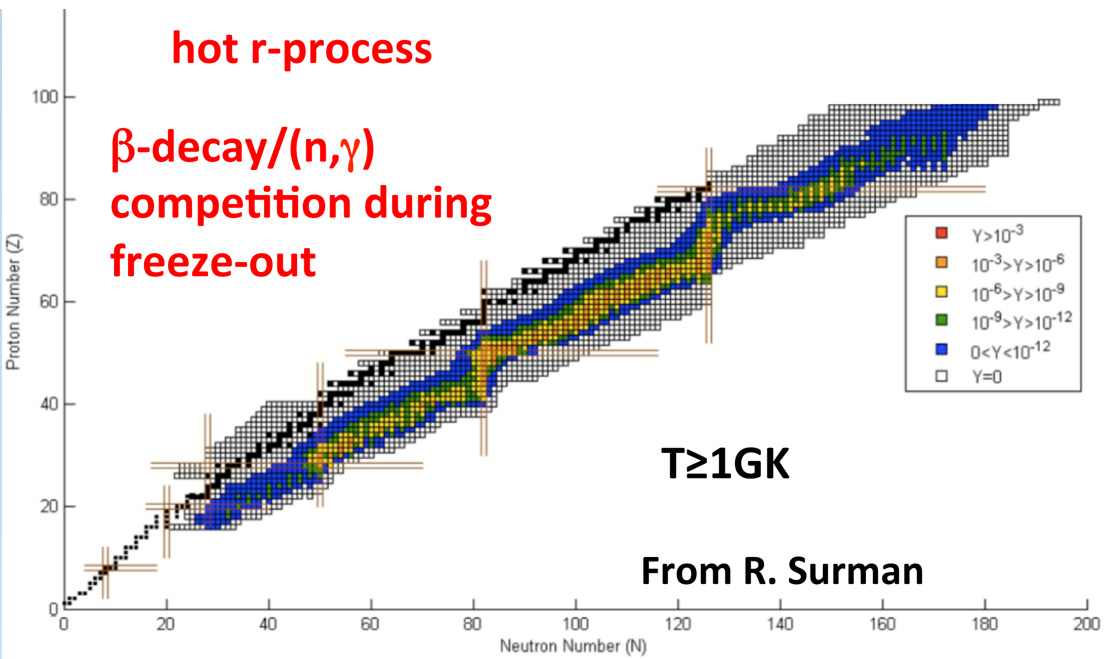
V. Guadilla, PhD Thesis

Unknown decays: verification/improvement of branching ratio matrix

Constraints on (n,γ) cross-section estimates for the r-process from γ de-excitation of neutron unbound states populated in β-decay (β-delayed neutron emitters)

Importance of (n,γ) in r-process nucleosynthesis beyond iron



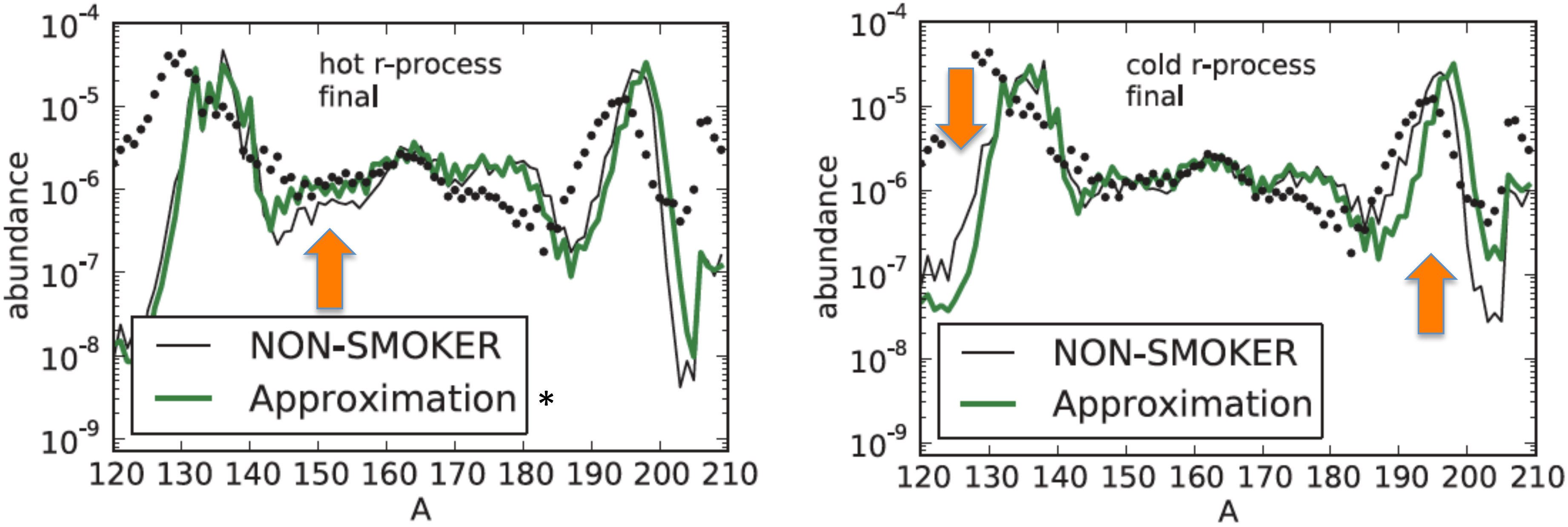


From R. Surman

(n,γ) cross-sections do not play a role in the classical picture of a hot r-process with instantaneous freeze-out, however they need to be considered under non-equilibrium conditions (Goriely, PLB436, 1998), this is the case, for example, for the cold r-process (Wanajo, ApJL666, 2007), and during freeze-out for the hot r-process (Surman+, PRC64, 2001; Rauscher, NPA758, 2005)

Sensitivity of abundance calculations to (n,γ) cross-sections

Arcones+, PRC83(2011)045809

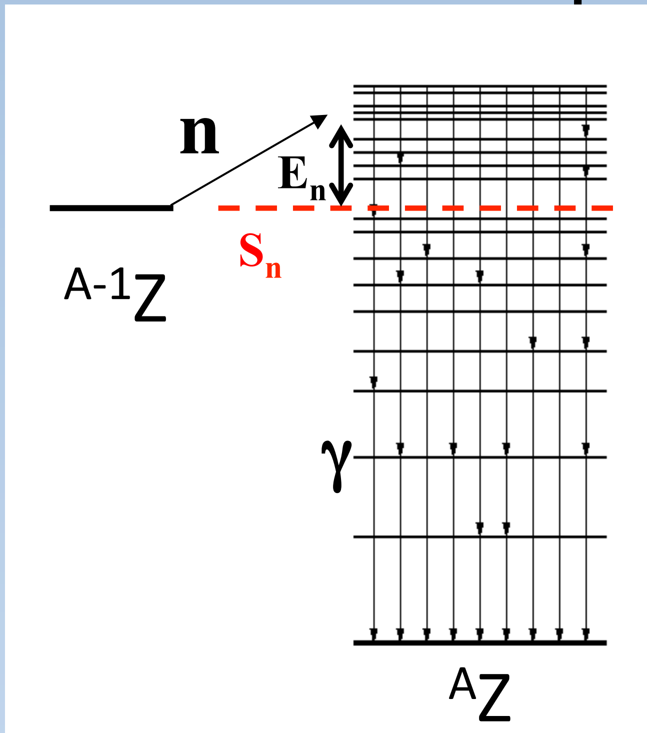


* Approximation: semi-empirical formula (Michaud+, PRC2, 1970)

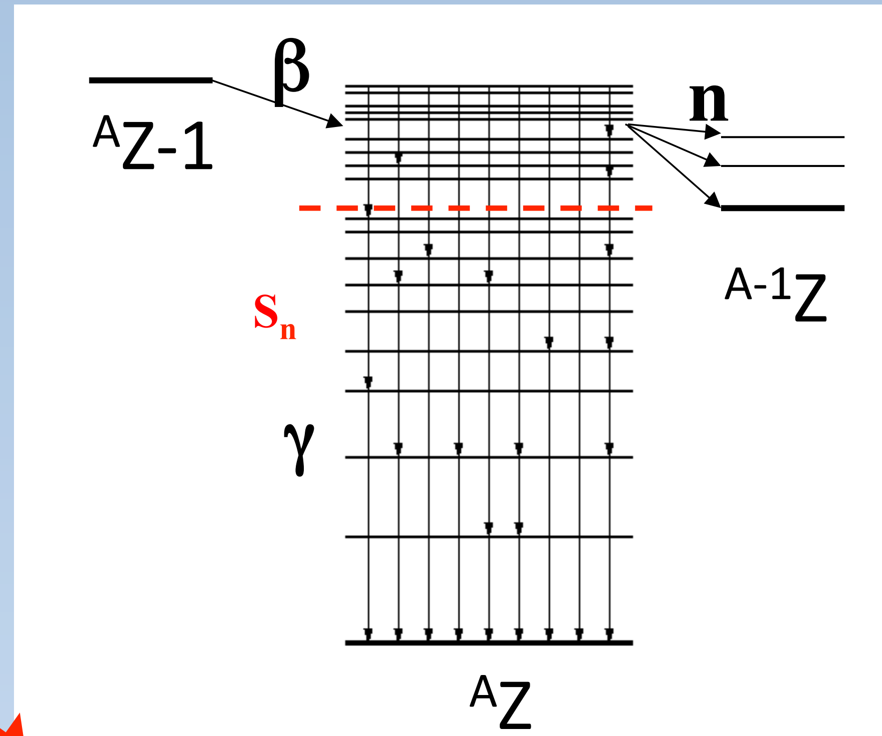
- However these cross sections are not measurable: the CN part is taken from Hauser-Feshbach statistical model calculations
- Parameters (NLD, PSF, NTC) for the H-F calculations are obtained from data close to stability
- **How reliable are (n,γ) HF estimations far from stability?**
- Surrogate reactions with ion beams cannot go very exotic

Analogy between (n,γ) and βn

Radiative neutron capture:



Beta delayed neutron emission:



$$\sigma_\gamma(E_n) = \frac{4\pi}{k^2} g_J \frac{\Gamma_\gamma \Gamma_n}{\Gamma_\gamma + \Gamma_n} \Phi(E_n)$$

$$I_{\beta\gamma}(E_x) = \frac{\Gamma_\gamma}{\Gamma_\gamma + \Gamma_n} T_{1/2} f(Q_\beta - E_x) S_\beta(E_x)$$

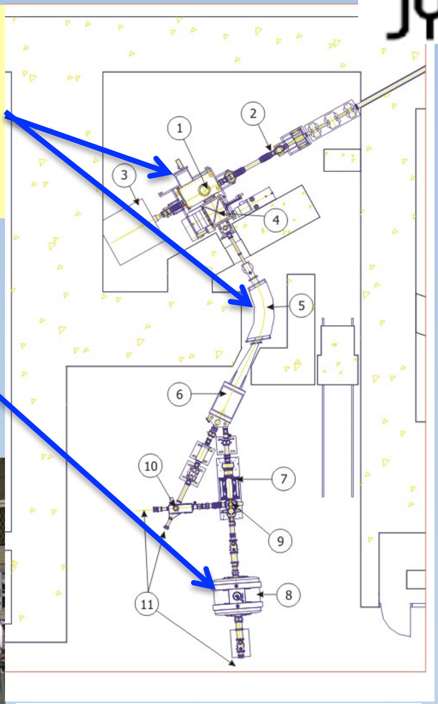
- But, it is difficult to observe γ-emission from states above S_n populated in β-decay: intensity fragmented over many cascades
- Only few γ-rays in a handful of isotopes have been observed in HPGe spectroscopy ➔ TAGS technique

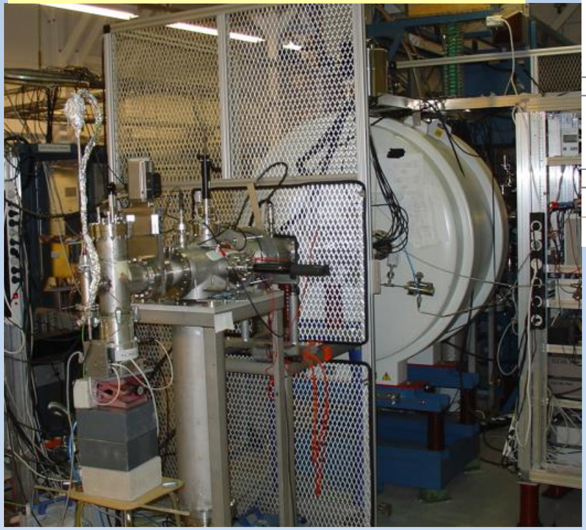
1^{st} Experiment:

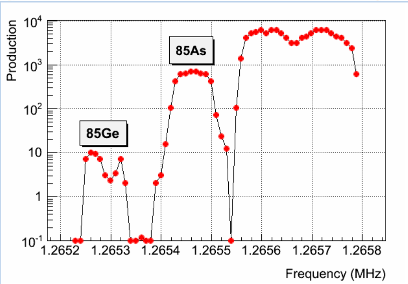
JYFL Accelerator Laboratory

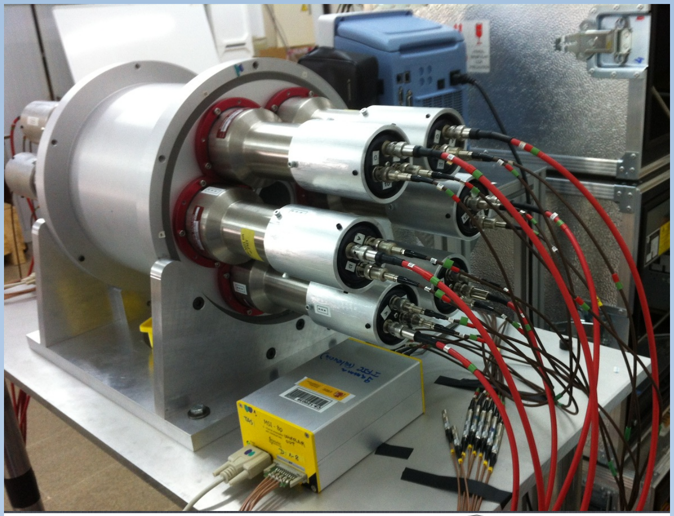
IGISOL separator **+ ion guide** source: refractory elements

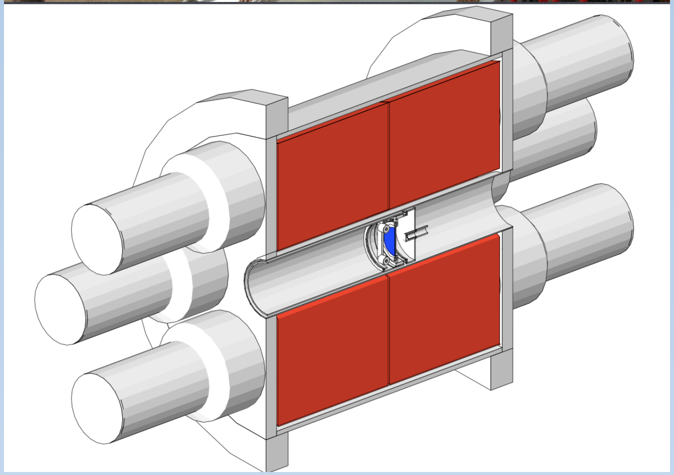
JYFLTRAP Penning trap: isotopic purification









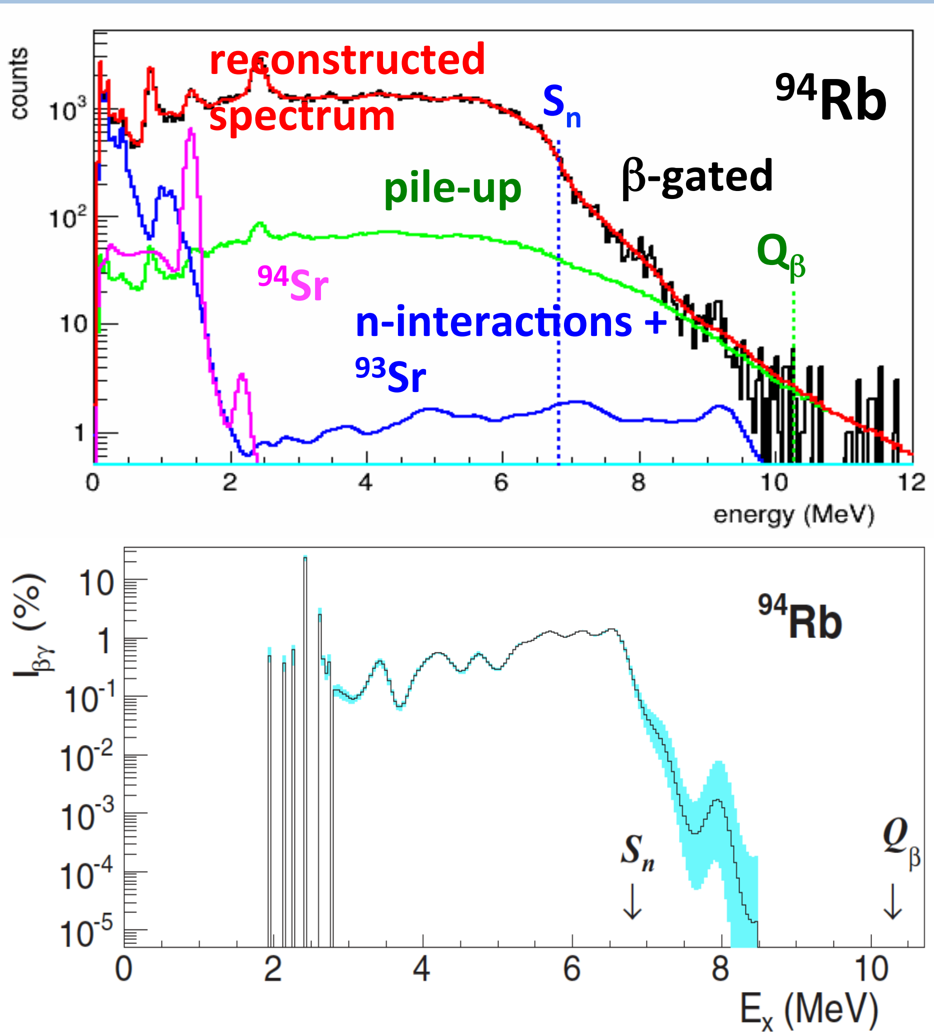


"Rocinante" TAS

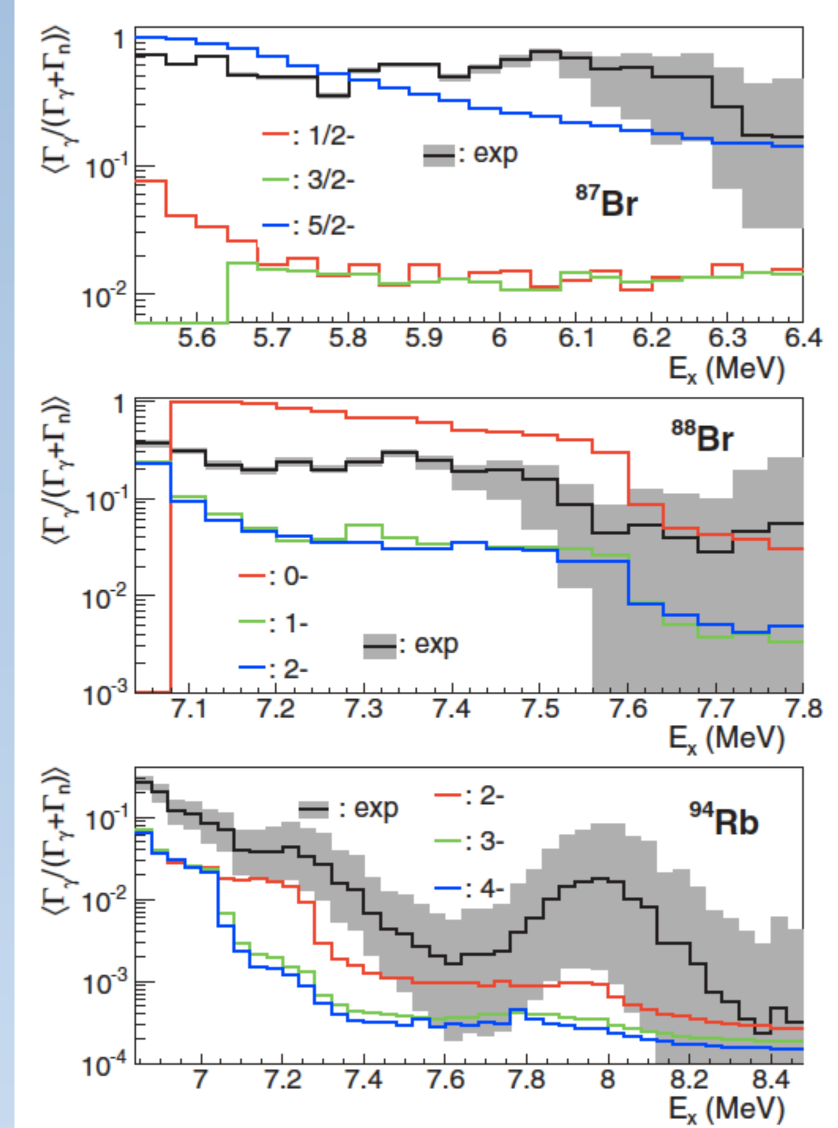
- **Compact 12-fold segmented BaF_2 spectrometer + Si-detector**
- **Low neutron sensitivity**
- **Cascade multiplicity information**

Isotope	P_n (%)	S_n (MeV)	Q_β (MeV)
^{87}Br	2.43(14)	5.515(3)	6.818(3)
^{88}Br	6.75(18)	7.053(3)	8.975(4)
^{94}Rb	10.24(21)	6.828(10)	10.281(8)

Results:



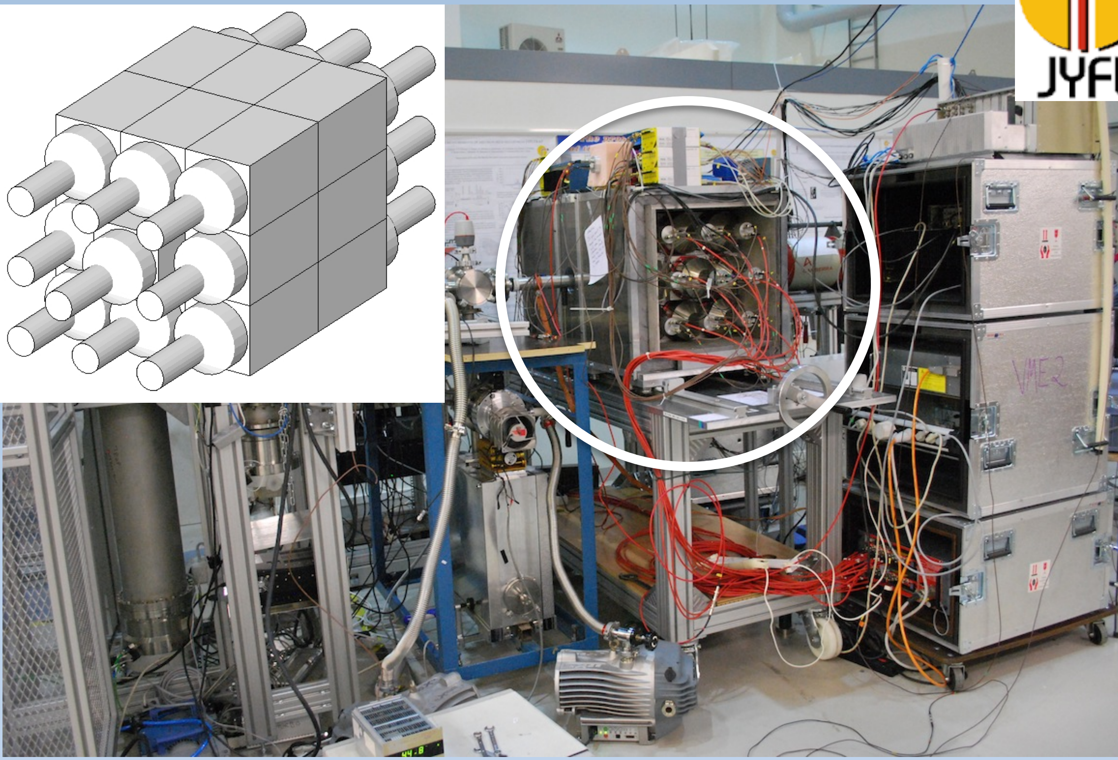
(%)	$\Sigma I_{\beta n}=P_n$	$\Sigma I_{\beta\gamma}=P_\gamma$
^{87}Br	2.43(14)	3.5(5)
^{88}Br	6.75(18)	1.59(25)
^{94}Rb	10.24(21)	0.53(25)



Comparison with HF calculations

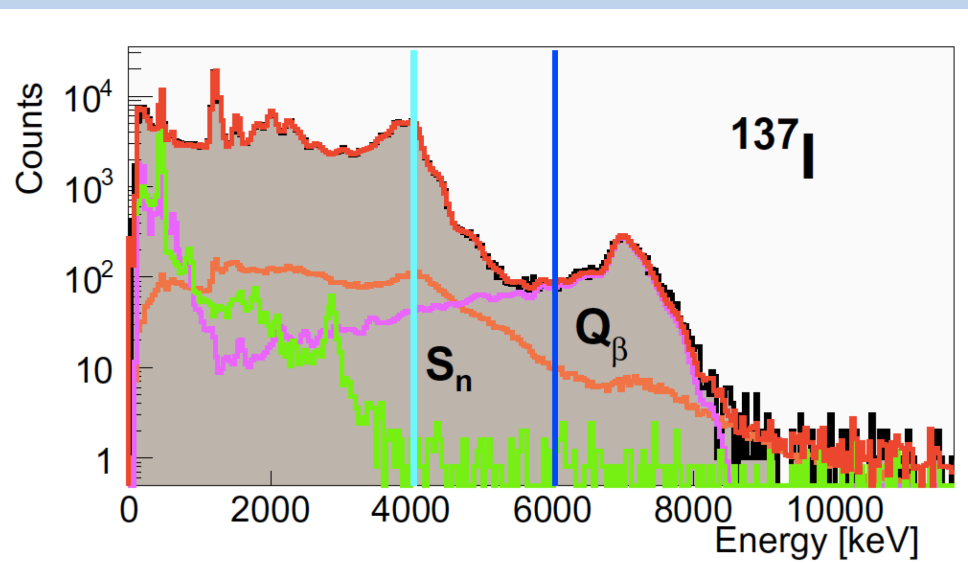
J.L. Tain+, PRL115(2015)062502
E. Valencia+, PRC95(2017)024320
E. Valencia, PhD Thesis, U. Valencia

2^{nd} Experiment:



DTAS spectrometer

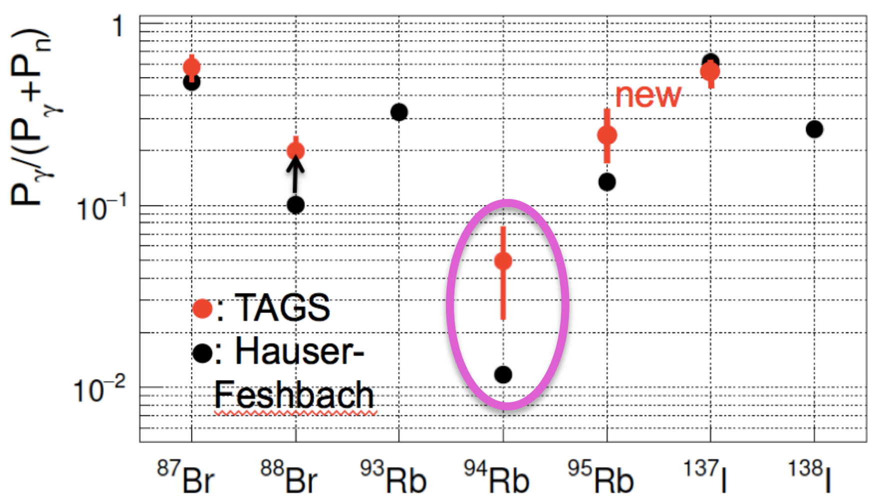
- 18-fold modular NaI(Tl) spectrometer + Plastic-detector
- Good efficiency and energy resolution
- High neutron sensitivity
- Developed for FAIR/NUSTAR



$^{95}Rb, ^{137}I, ^{138}I$

V. Guadilla+, NIMB376(2016)
V. Guadilla, PhD Thesis, U. Valencia
L. Le Meur, PhD Thesis, U. Nantes

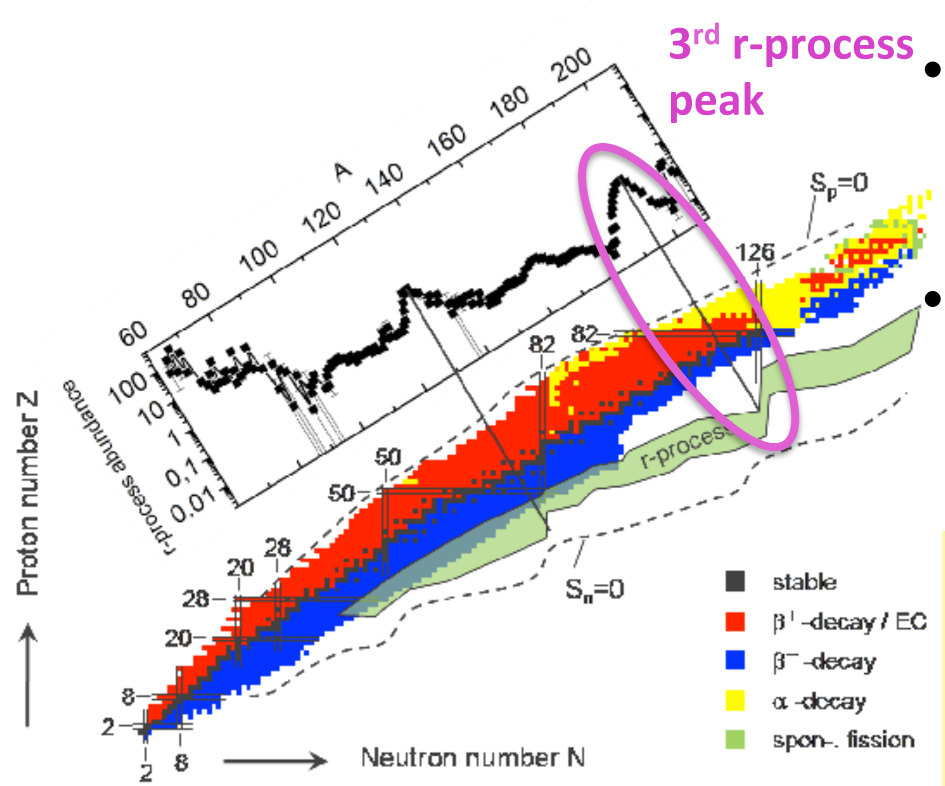
Summary of results:



Parent	Daughter J^π_{GT}	Final $J^\pi_{g.s.}$	Final E_x^{1st} [keV]
^{87}Br	$3/2^-, \mathbf{5/2^-}, \mathbf{7/2^-}$	0^+	1565
^{88}Br	$\mathbf{0^-}, 1^-, 2^-$	$5/2^+$	532
^{93}Rb	$3/2^-, \mathbf{5/2^-}, \mathbf{7/2^-}$	0^+	815
^{94}Rb	$2^-, 3^-, 4^-$	$5/2^+$	213
^{95}Rb	$3/2^-, \mathbf{5/2^-}, \mathbf{7/2^-}$	0^+	837
^{137}I	$5/2^+, \mathbf{7/2^+}, \mathbf{9/2^+}$	0^+	1313
^{138}I	$\mathbf{0^-}, 1^-, 2^-$	$7/2^-$	601

- In all cases, except one, the large $\Gamma_\gamma/\Gamma_{tot}$ can be explained as due to the large hindrance of neutron emission because of the large orbital angular momentum required
- For ^{94}Rb: the result indicates either a large enhancement of Γ_γ, with impact on (n,γ), or a large hindrance of Γ_n, or both
- Recently it has been proposed (Dungan+, PRC93(2016): ^{19}O; Spyrou+, PRL117(2016): ^{70}Co) that the small overlap between initial and final states (spectroscopic factor) is the reason for neutron emission hindrance
- Does this apply to ^{94}Rb decay?

Improved half-lives and β-delayed neutron emission probabilities estimates for the 3^{rd} r-process peak



- Most of the nuclei formed are out of current experimental reach.
- $T_{1/2}$ and P_n for r-process network calculations are thus taken from β-strength calculations

$$\frac{1}{T_{1/2}} = \int_0^{Q_\beta} f\left(Q_\beta - E_x\right) S_\beta\left(E_x\right) dE_x$$

$$P_n = T_{1/2} \int_{S_n}^{Q_\beta} \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma} f\left(Q_\beta - E_x\right) S_\beta\left(E_x\right) dE_x$$

β-strength (theory):

$$S_\beta^{th}\left(E_x\right) = \frac{1}{D} \frac{4\pi}{g_V^2} B_{i\to f}$$

$$B_{i\to f} = \frac{1}{2J_i + 1} \left| \left\langle f \left\| M_{\lambda\pi}^{\beta} \right\| i \right\rangle \right|^2$$

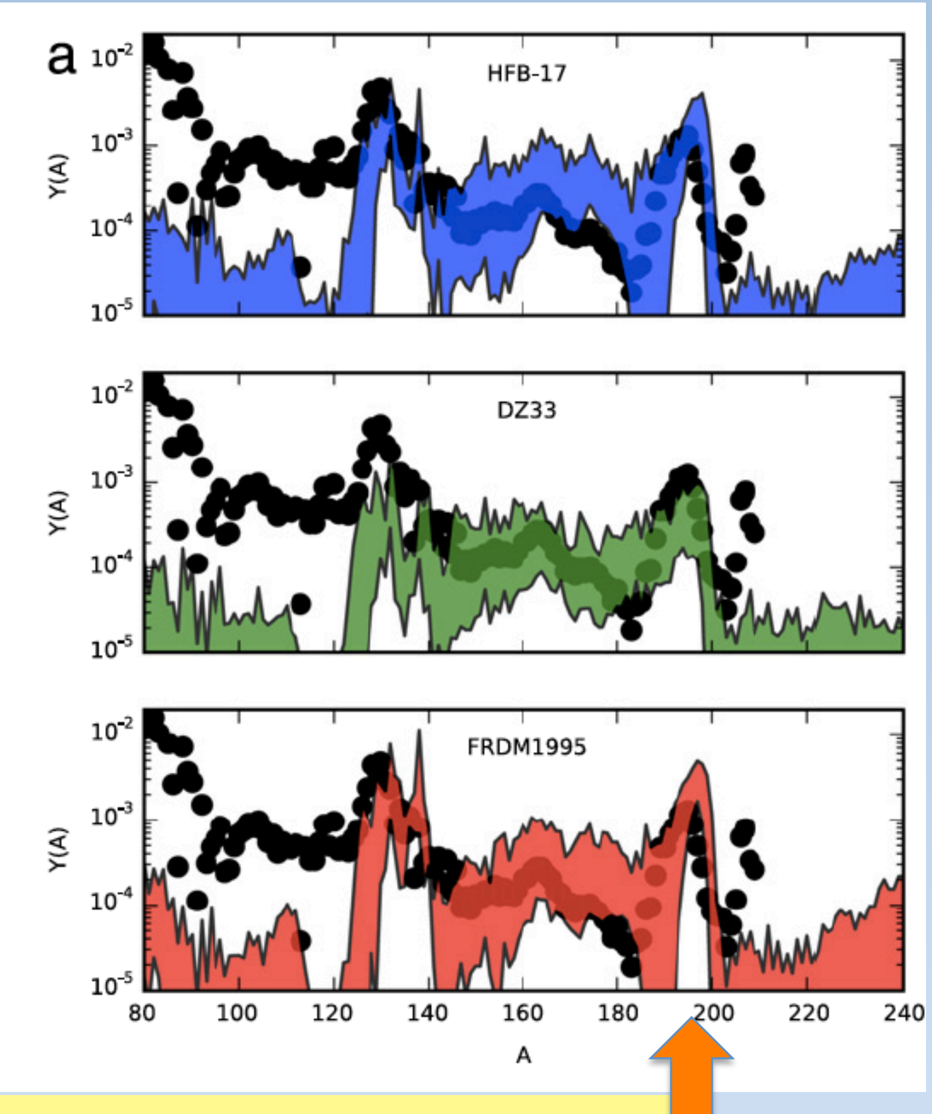
β-strength (experiment):

$$S_\beta^{\exp}\left(E_x\right) = \frac{1}{T_{1/2}} \frac{I_\beta\left(E_x\right)}{f\left(Q_\beta - E_x\right)}$$

How good are these calculations?

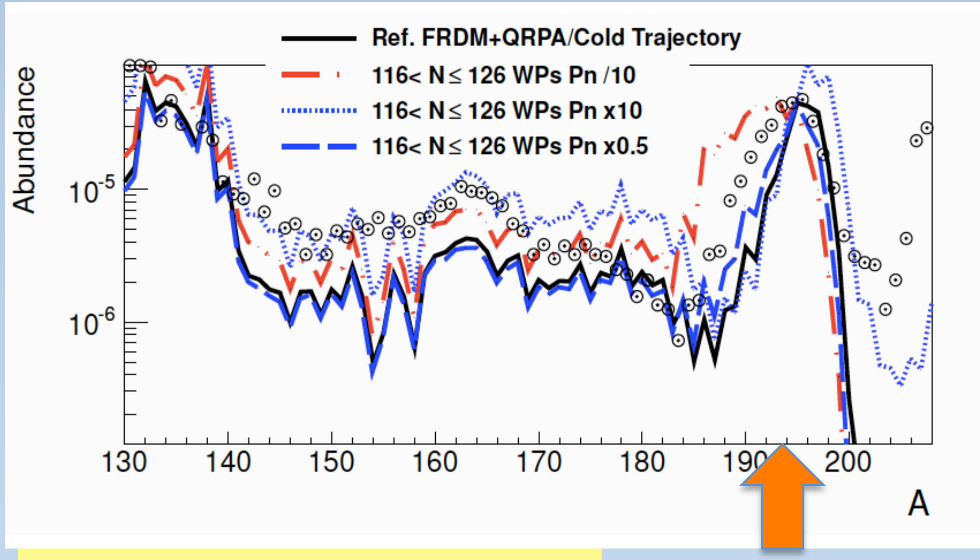
Abundance calculations are sensitive to uncertainties in the parameters:

$T_{1/2}$ (hot r-process)



Mumpower+, PPNP86(2016)

P_n (cold r-process)

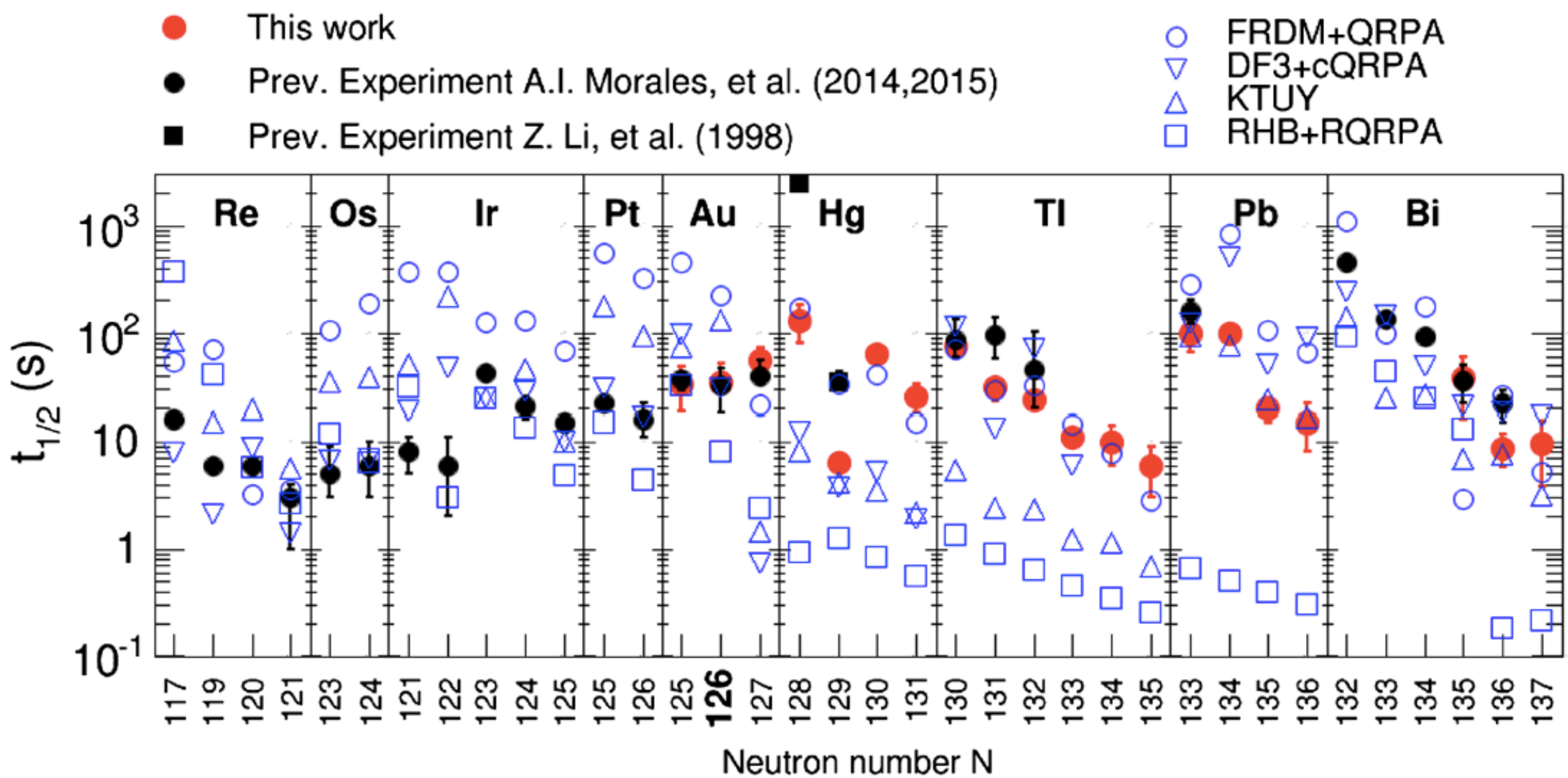


Domingo-Pardo+, JPhysConfSer665(2016)

Typically the quality of the theoretical models is assessed through the comparison of calculated and measured $T_{1/2}$ and P_n

- ☆ :Kurtukian+, NPA827(2009)
- ☆ :Benzoni+, PLB715(2012)
- ☆ :Morales+, PRL113(2014)
- ☆ :Caballero+, PRL117(2016)

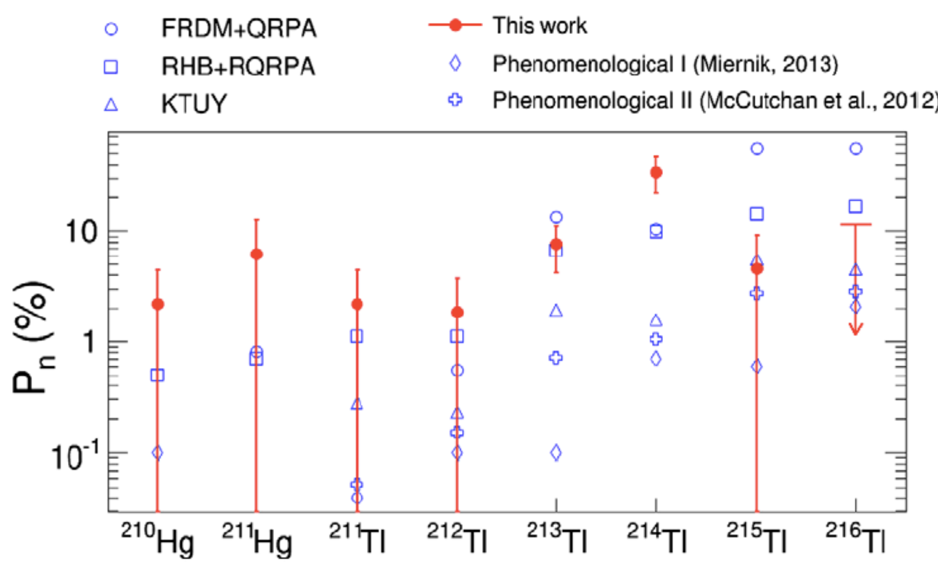
Status of experimental knowledge in the region



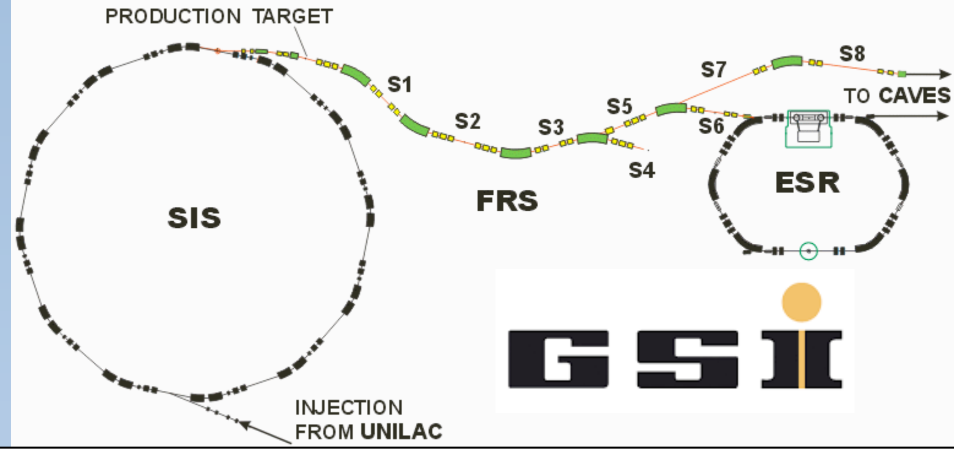
Caballero+, PRL117(2016)
Caballero+, PRC95(2017)

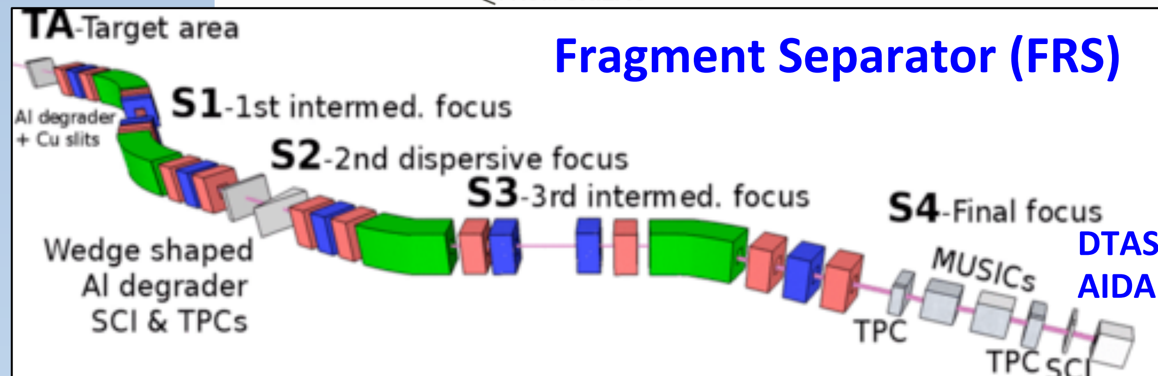
Experiment vs. Theory

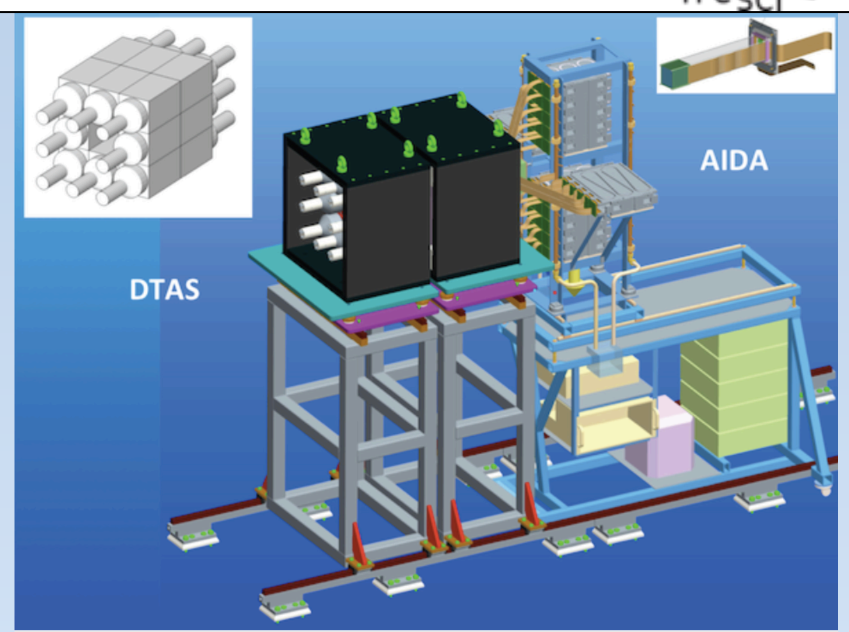
FRDM-QRPA: Moeller+, PRC67(2003)
DF3-cQRPA: Borzov, PhysAtNucl74(2011)
KTUY-GT2: Koura+/Tachibana+, ProgThPhys113(2005)
RHB-RQRPA: Marketin+,PRC87(2013)



- None of the models reproduce $T_{1/2}$ both above and below N=126
- Further insight can only be provided by comparison of the full β-strength
- A proposal (Morales, Nacher,Tain) has been presented to the GSI-PAC
- Using DTAS with AIDA implantation-decay array at the FRS
- Experiment 2018?



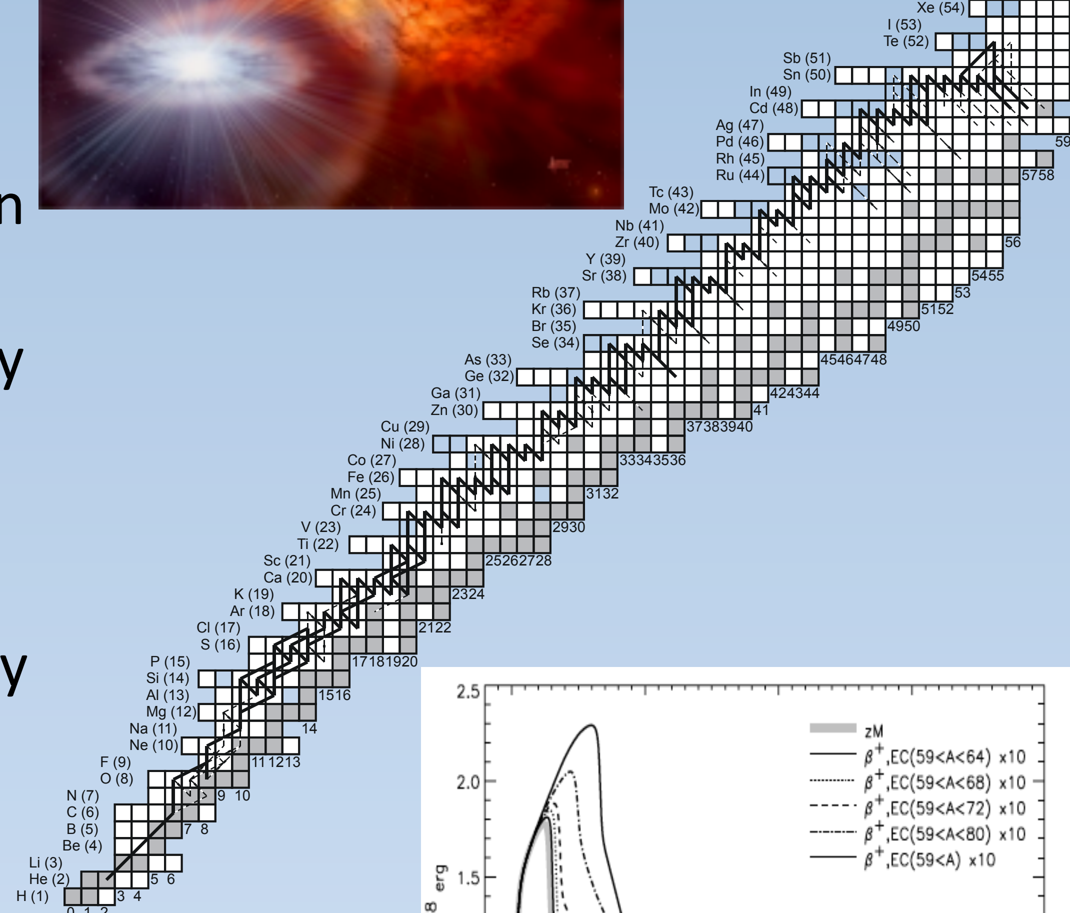


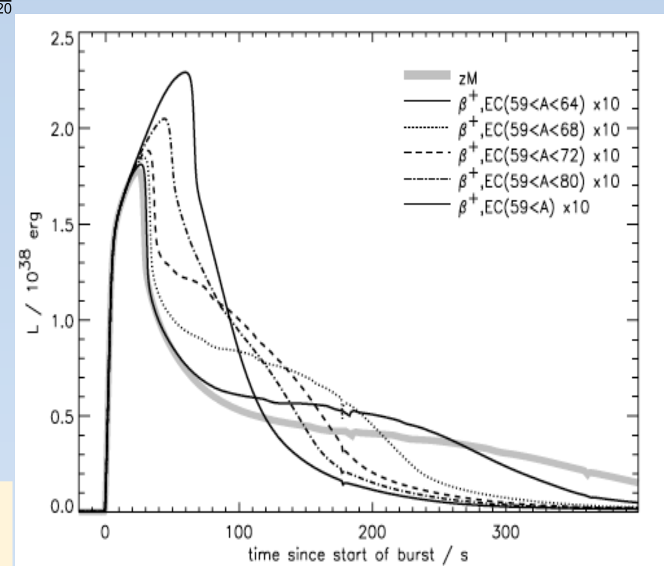


Impact of weak reaction rates on X-ray burst light yields (rp-process waiting point nuclei)

Type I X-ray bursts:

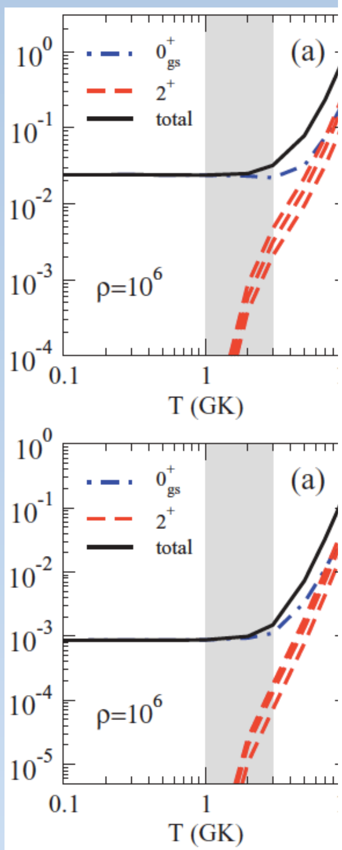
- Binary systems with a neutron star (NS) and a low mass companion
- H(He) enriched mass accretion on NS surface triggers thermonuclear runaway (X-ray burst)
- Site of rp-process: rapid (p,γ) reactions until N~Z nuclei are reached, then wait for β-decay
- Luminosity peaks at T=1-3 GK and $\rho_e=10^6$-10^7 mol/cm^3
- Sensitivity to β-decay rates

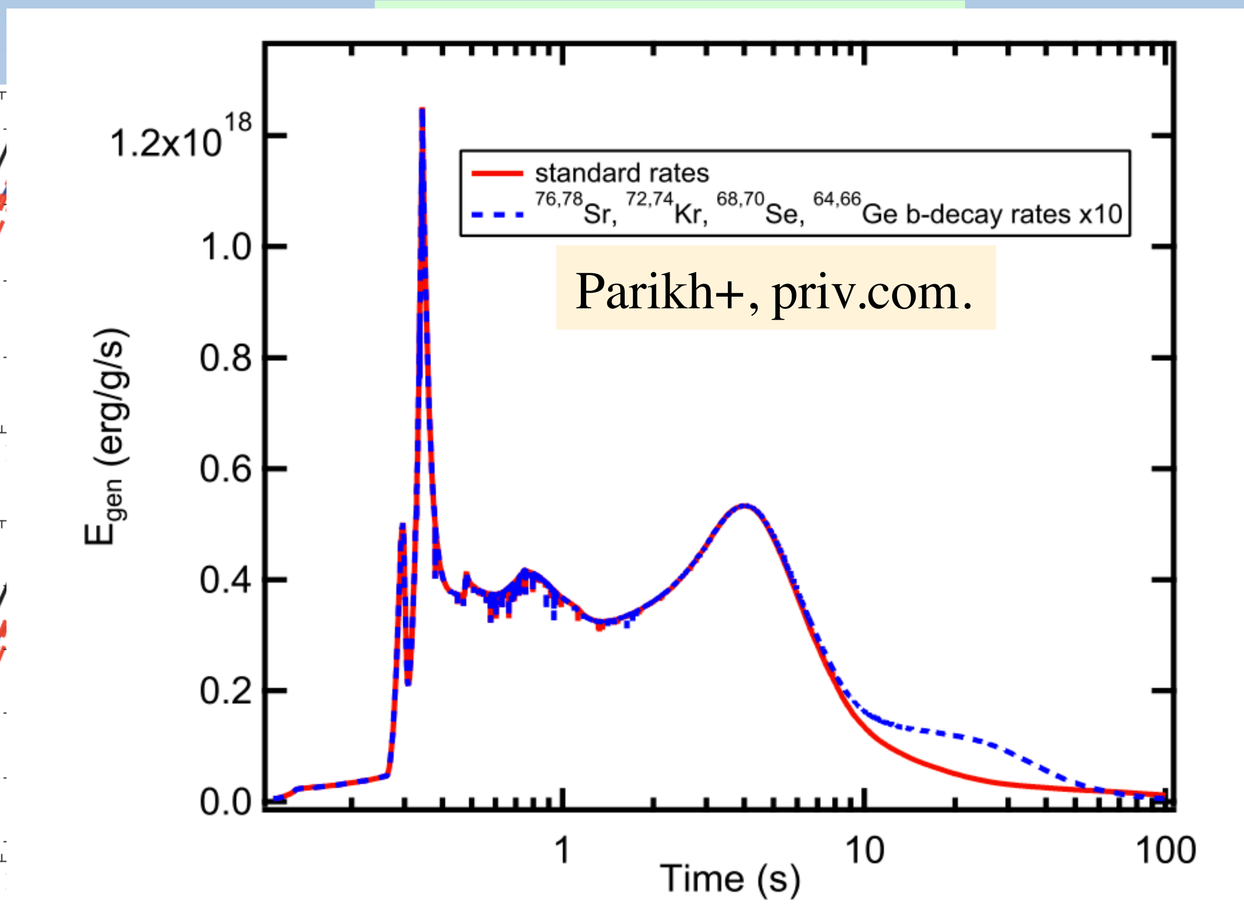


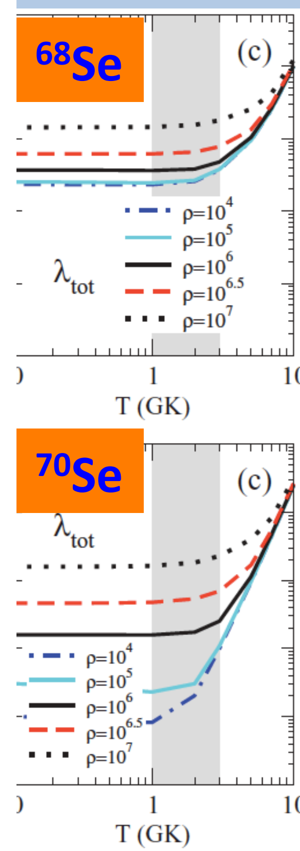


Woosley+, ApJS151(2004)

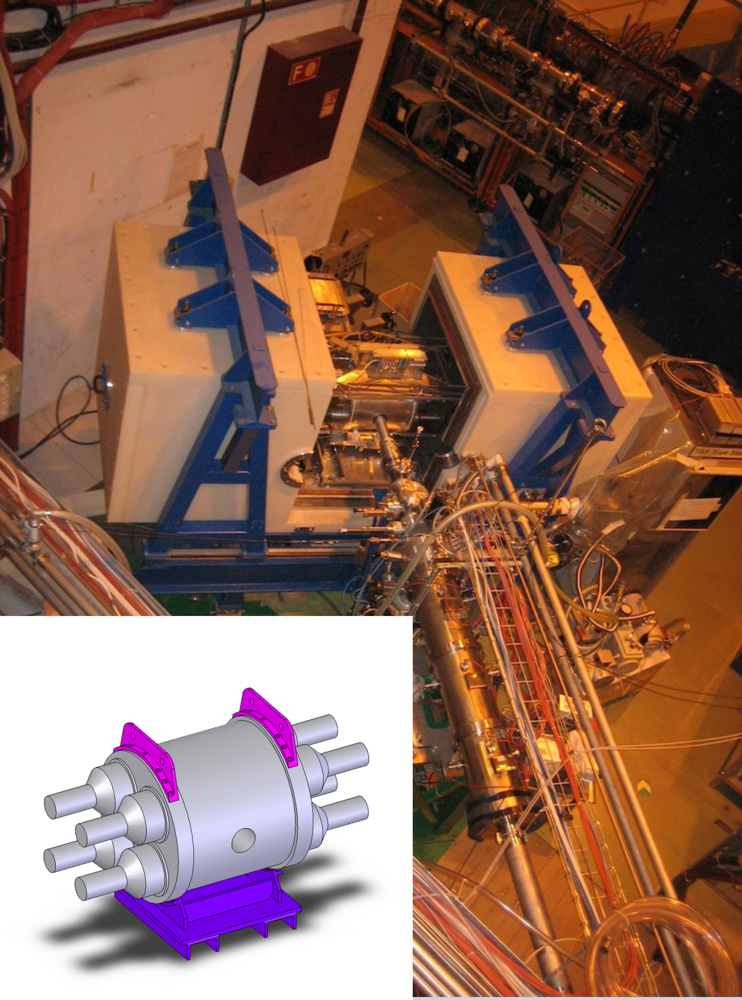
- Calculations (Sarriguren, PLB680(2009)) show that electron capture from the continuum (cEC) might dominate the decay rate in the stellar T and ρ_e conditions
- The effect is particular important for some isotopes (sensitive to β-strength)

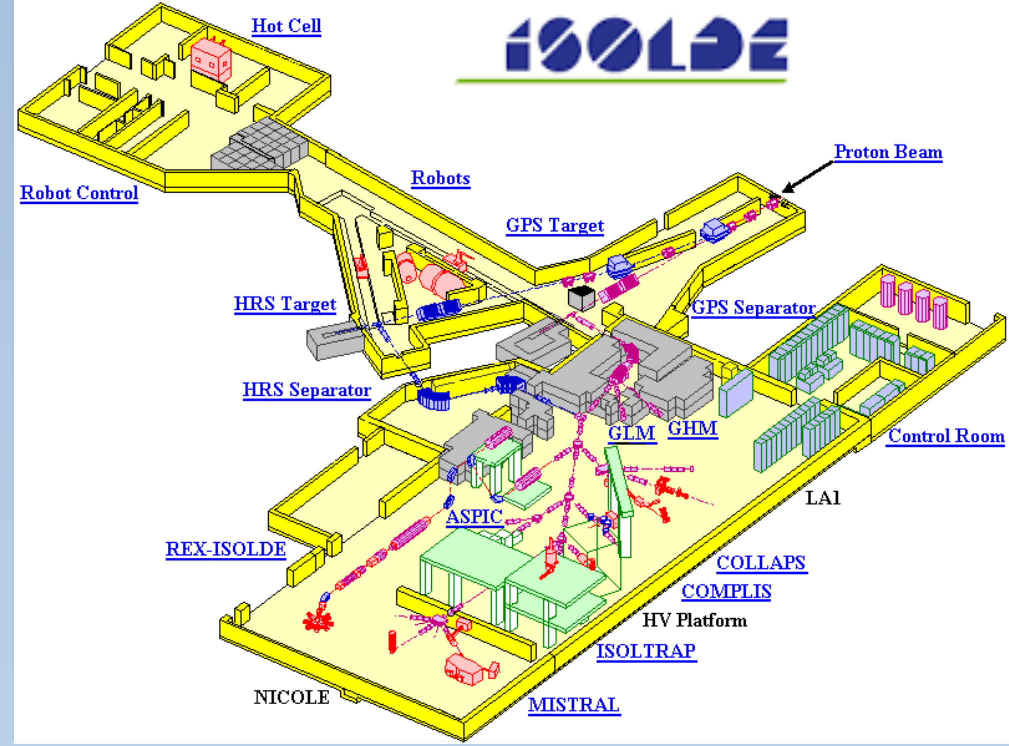






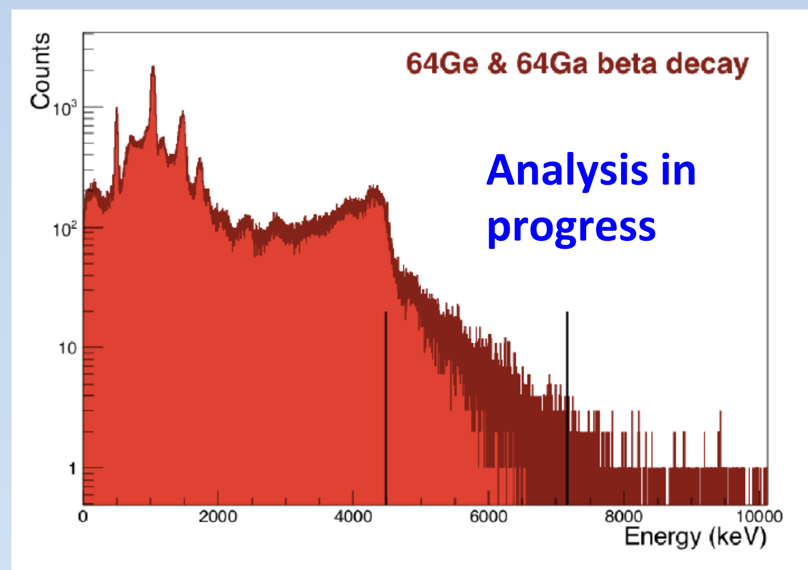
- Experiment (Nacher, Domingo-Pardo, Algora et al.) to verify the β-strength in terrestrial conditions for ^{64,66}Ge, ^{68,70}Se





“Lucrecia” TAS

- Single crystal NaI(Tl) spectrometer + Plastic-detector/X-ray detector
- Good efficiency and energy resolution



Conclusion:

- The TAGS technique is a powerful tool to explore the γ-ray emission in the full Q_β decay window
- It allows the verification of theoretical β-strength distributions and thus of calculations of weak rates in astrophysical processes (r and rp)
- It gives information on γ/neutron emission competition far from stability which can help to constrain (n,γ) rates

Collaborators:

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γ/n competition

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β-strength for the rp-process

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β-strength for the 3rd r-process peak

THANK YOU!