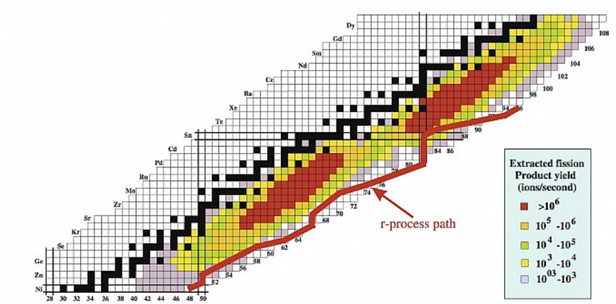
Nuclear physics measurements for the r-process

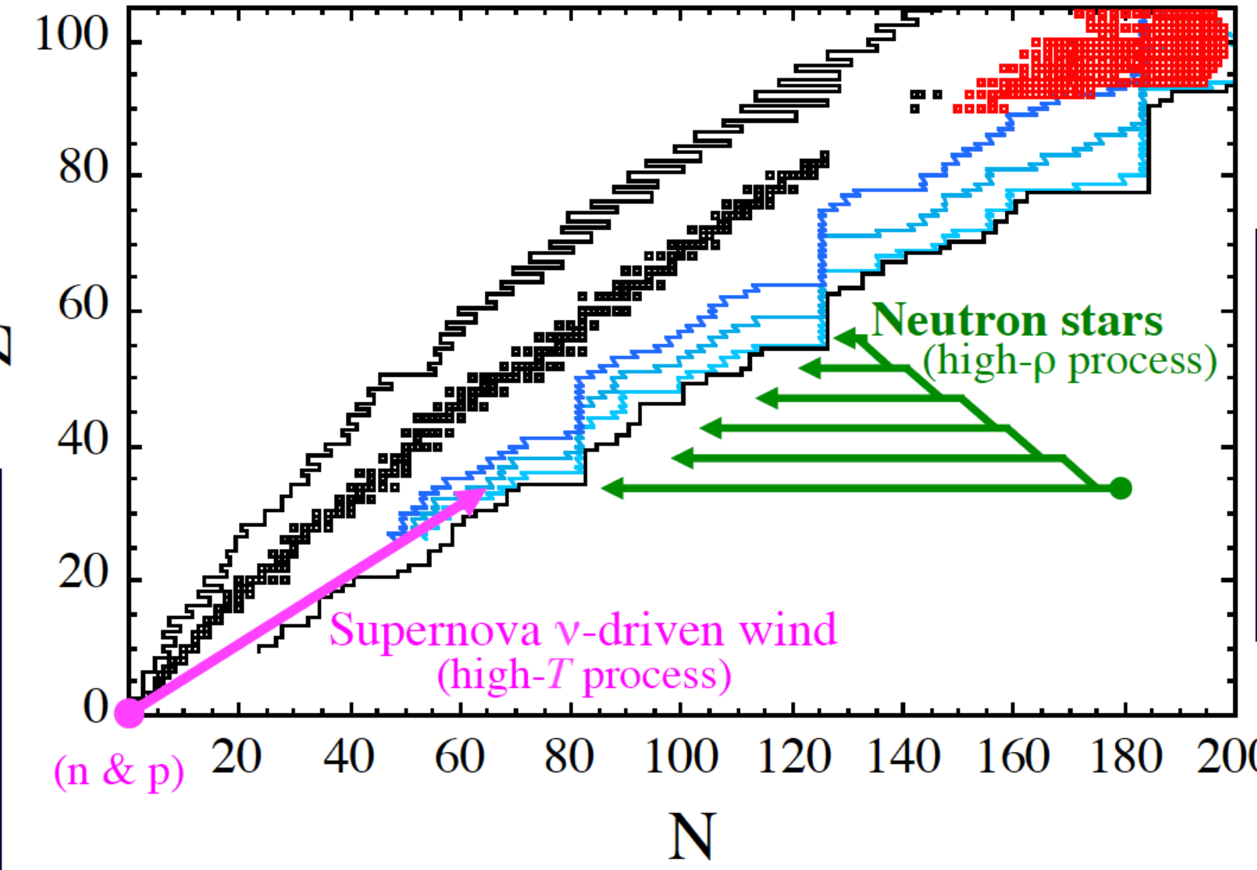
Beyhan BASTIN (GANIL)

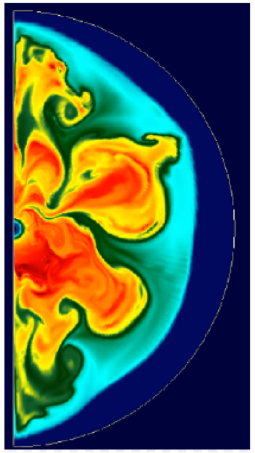
Production of half of the heavy elements (>Fe)

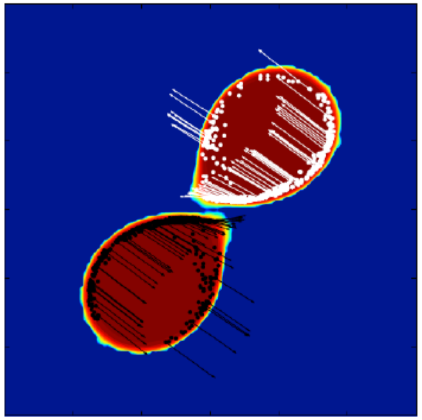
temperature	**$1\text{-}2\times10^{9}$ K (→ E_n<100 keV)**
timescale	**~ seconds**
neutron density	**$10^{20}\text{-}10^{24}$ cm^{-3}**
possible stellar sites	**type II supernovae / neutron star mergers**



ALTO / SPIRAL2-phase2





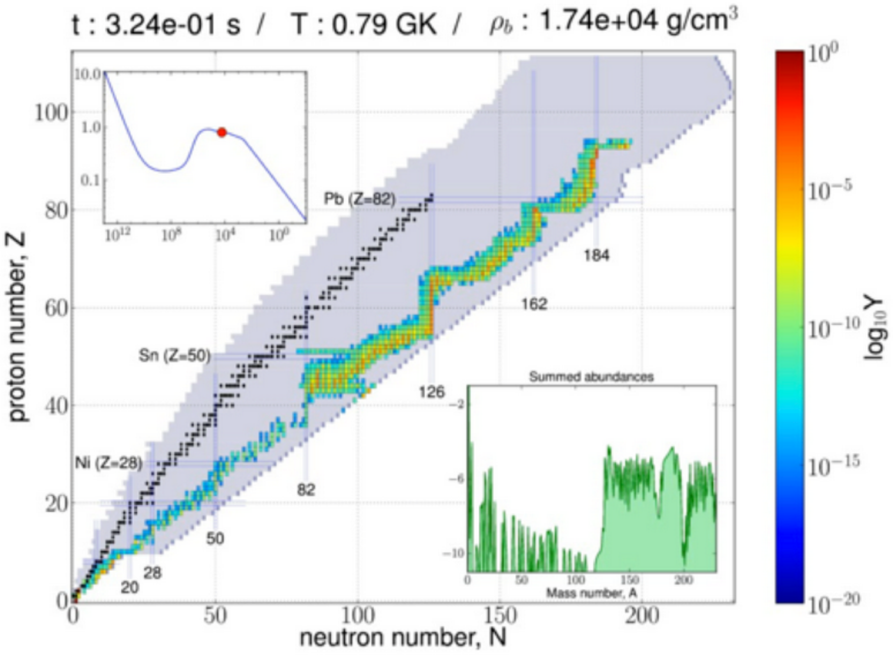


S. Goriely, Ecole Joliot Curie 2016

Which nuclei are concerned? Depends on the site

Nucleosynthesis for dynamic ejecta

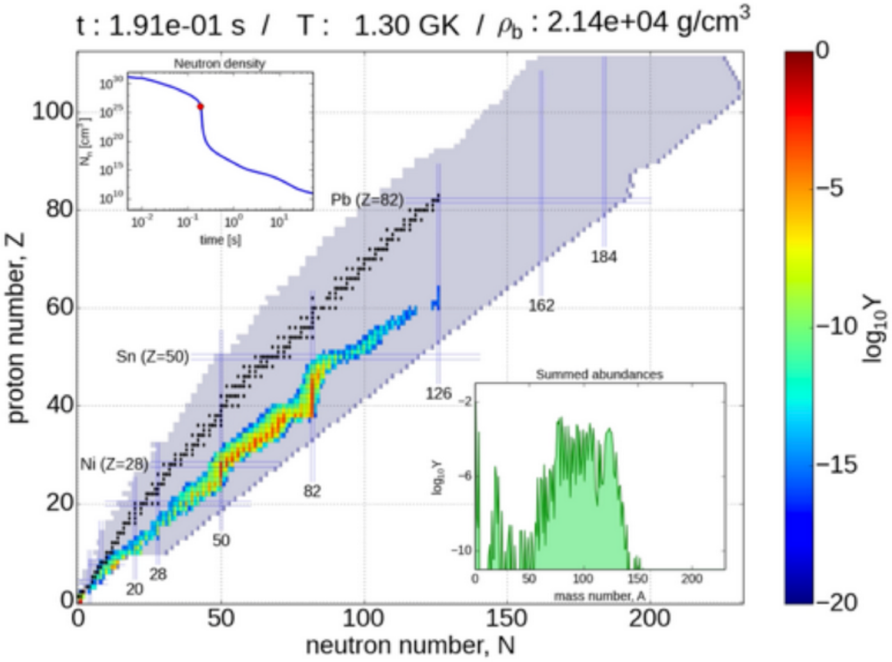
(snapshot; Korobkin et al. 2012)



- extremely neutron-rich (Ye ≈ 0.04)
- close to neutron drip-line
- extending to very large neutron (N≈ 200) and proton numbers (Z≈ 90)
- forging the heaviest elements (A>130) in the Universe (e.g. gold and platinum)

Nucleosynthesis for neutrino-driven winds

(snapshot; Martin et al. 2015)



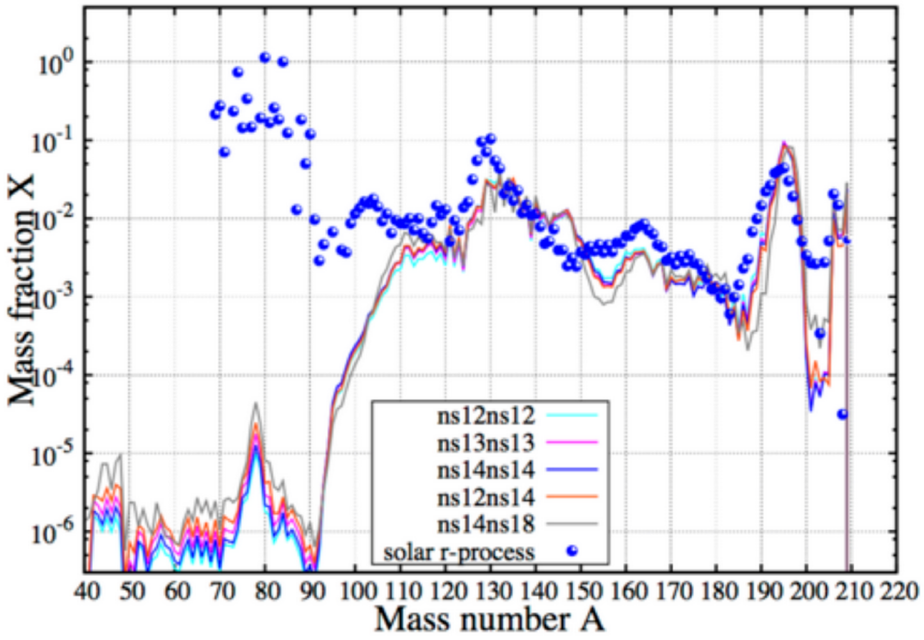
- neutron-rich, broad distribution (0.2< Ye < 0.4)
- further away from neutron drip-line
- extending to moderately large neutron and proton number
- forging heavy elements, but usually with nucleon numbers A < 130

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

• Which nuclei are concerned? Depends on the site

Nucleosynthesis for dynamic ejecta

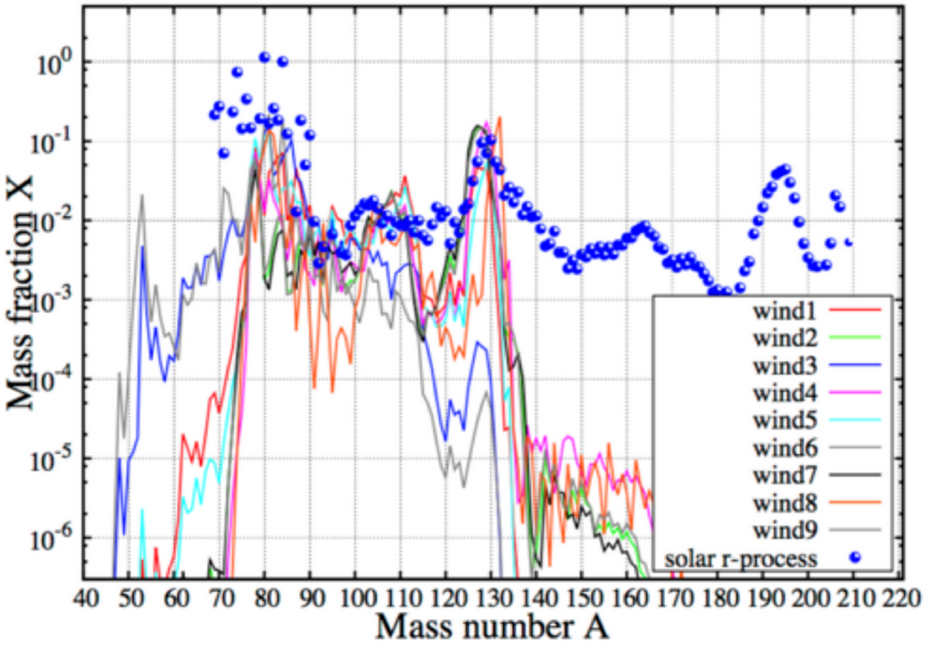
(Rosswog et al. 2017)



- the heaviest elements, A>130
- robustly producing the “platinum peak” at A= 195
- very little variation between different mergers

Nucleosynthesis for neutrino-driven winds

(Rosswog et al. 2017)

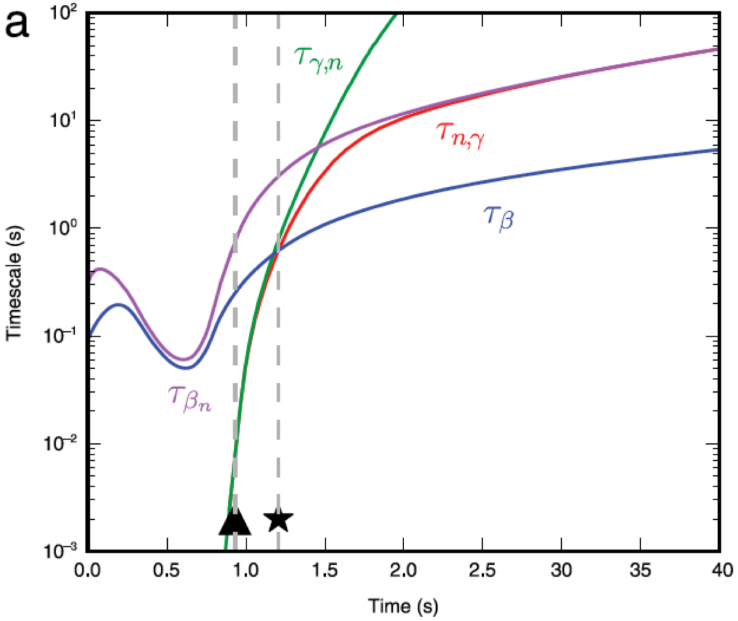


- lighter r-process elements, A <130
- large variation between different astrophysical events expected

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

• Which nuclear processes are involved?

Abundance weighted timescales of important channels during the freeze-out phase for a hot r-process



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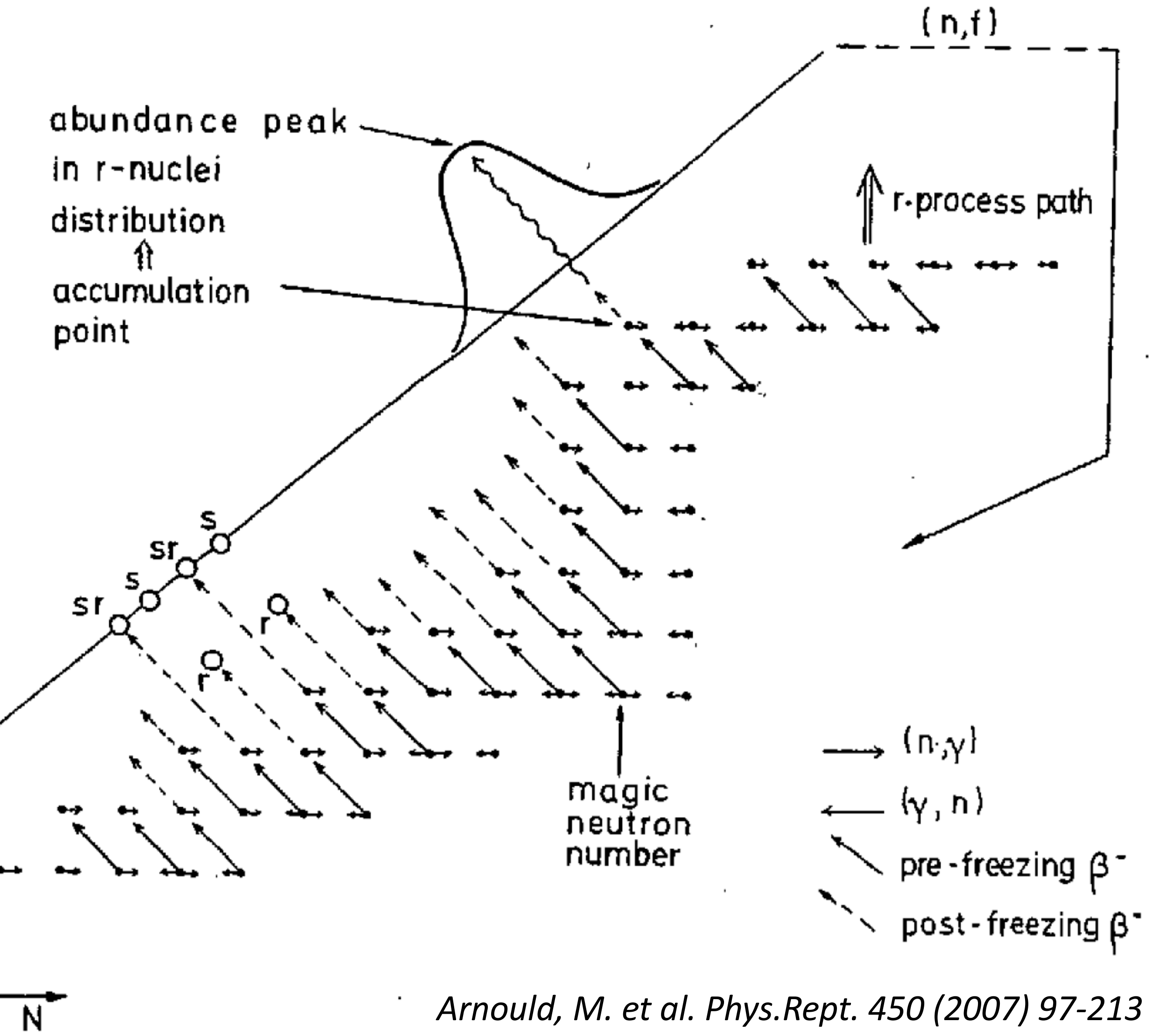
Schematic scheme of the r process



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• Which properties to measure / to constraint?

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

$$\frac{\mathrm{dN(Z,A)}}{\mathrm{dt}} =$$

Production

$$\begin{aligned}
&\mathrm{Nn.\,N(Z, A-1).} < \sigma\nu >_{\mathrm{Z,A-1}} && \rightarrow \text{(n,}\gamma\text{) reaction}\\
&+\mathrm{N(Z, A+1).}\,\lambda_{\gamma,\mathrm{n}}^{\mathrm{Z,A+1}} && \rightarrow (\gamma\text{,n) reaction}\\
&+\mathrm{N(Z-1, A).}\,\lambda_{\beta}^{\mathrm{Z-1,A}} && \rightarrow \beta\text{ decay}\\
&+\textstyle\sum_{\mathrm{k=1}}^{3}\mathrm{N(Z-1, A+k).}\,\lambda_{\beta\mathrm{kn}}^{\mathrm{Z,A+1}} && \rightarrow \beta\text{ –delayed k neutron emission}\\
&+\mathrm{N(Z+2, A+4).}\,\lambda_{\alpha}^{\mathrm{Z+2,A+4}} && \rightarrow \alpha\text{ decay}\\
&+\textstyle\sum_{\mathrm{f}}\ \mathrm{q}_{\mathrm{Z_f,Af}}\mathrm{(Z,A).}\,\lambda_{f}^{Z_f,Af}\,\mathrm{.N(Z_f,A_f)} && \rightarrow \text{spontaneous fission}\\
&+\textstyle\sum_{\mathrm{f}}\ \mathrm{q}_{\mathrm{Z_f,Af}}\mathrm{(Z,A).}\,\lambda_{f}^{Z_f-1,A_f}\mathrm{.N(Z_f\text{-}1,A_f)} && \rightarrow \beta\text{–delayed fission}\\
&+\textstyle\sum_{\mathrm{f}}\ \mathrm{q}_{\mathrm{Z_f,Af}}\mathrm{(Z,A).}\,\lambda_{f}^{Z_f,Af-1}\mathrm{.N(Z_f,A_f\text{-}1)} && \rightarrow \text{n-induced fission}
\end{aligned}$$

Destruction

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

+ γ induced fission

+ neutrino interactions with nuclei for some scenarios

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+\,\mathrm{N(Z, A+1).\,\lambda_{\gamma,n}^{Z,A+1}} & \rightarrow \textbf{(}\boldsymbol{\gamma}\textbf{,n) reaction} \\
+\,\mathrm{N(Z-1, A).\,\lambda_{\beta}^{Z-1,A}} & \rightarrow \boldsymbol{\beta}\textbf{ decay} \\
+\sum_{\mathrm{k=1}}^{3}\mathrm{N(Z-1, A+k).\,\lambda_{\beta kn}^{Z,A+1}} & \rightarrow \boldsymbol{\beta}\textbf{ –delayed k neutron emission} \\
+\,\mathrm{N(Z+2, A+4).\,\lambda_{\alpha}^{Z+2,A+4}} & \rightarrow \boldsymbol{\alpha}\textbf{ decay} \\
+\sum_{\mathrm{f}}\mathrm{q_{Z_f,Af}(Z,A).}\,\lambda_{f}^{Z_f,Af}\,\mathrm{.N(Z_f,A_f)} & \rightarrow \textbf{spontaneous fission} \\
+\sum_{\mathrm{f}}\mathrm{q_{Z_f,Af}(Z,A).}\,\lambda_{f}^{Z_f-1,A_f}\mathrm{.N(Z_f\text{-}1,A_f)} & \rightarrow \boldsymbol{\beta}\textbf{–delayed fission} \\
+\sum_{\mathrm{f}}\mathrm{q_{Z_f,Af}(Z,A).}\,\lambda_{f}^{Z_f,Af-1}\mathrm{.N(Z_f,A_f\text{-}1)} & \rightarrow \textbf{n-induced fission}
\end{array}\right.$$

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

+ γ induced fission

+ neutrino interactions with nuclei for some scenarios

=> Masses, β-decay properties, neutron capture rates, fission rates

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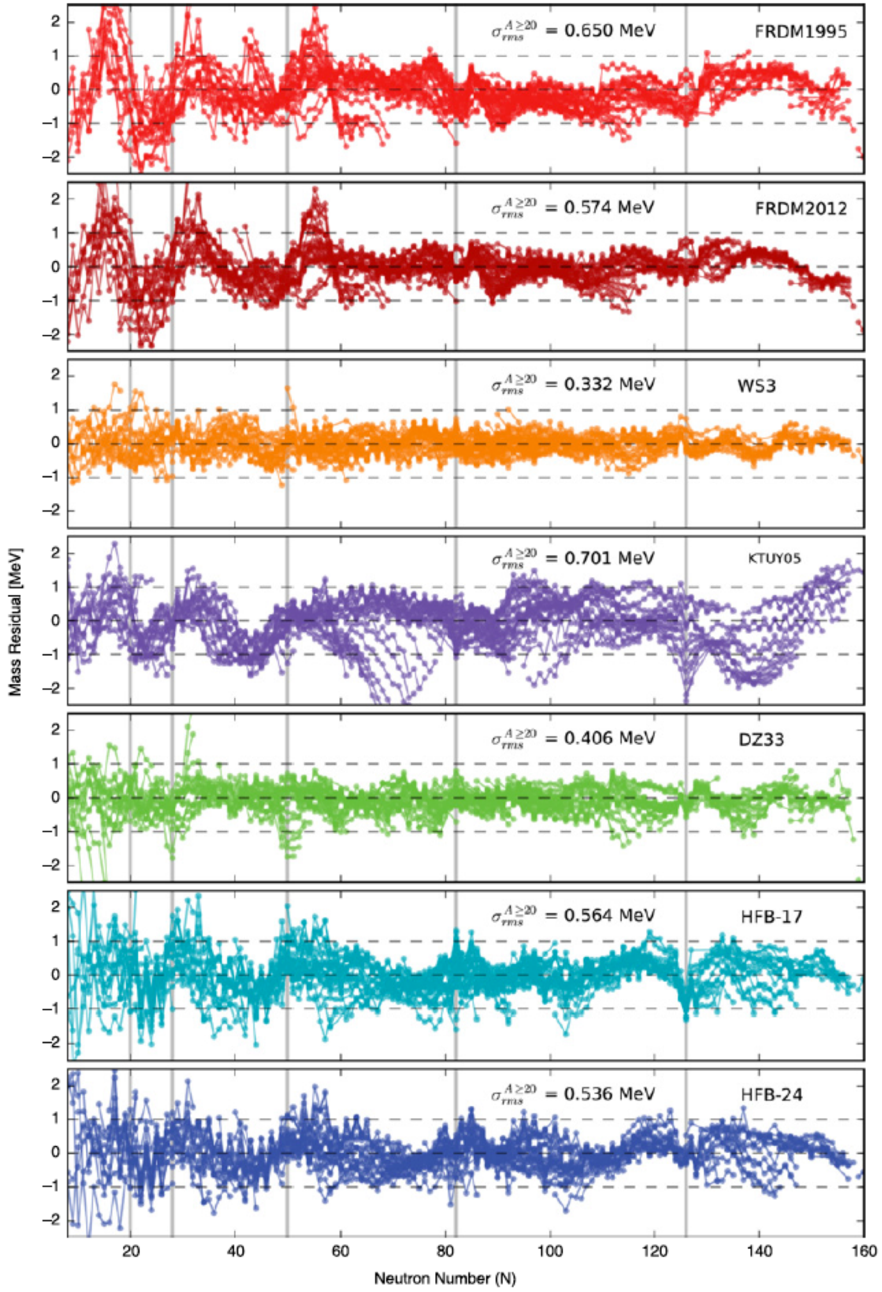
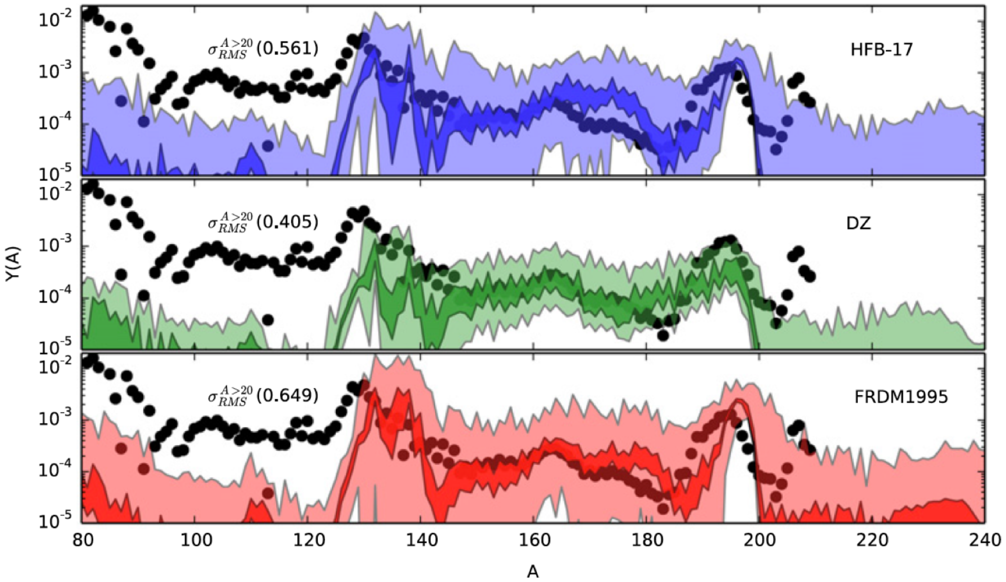
- **Masses**

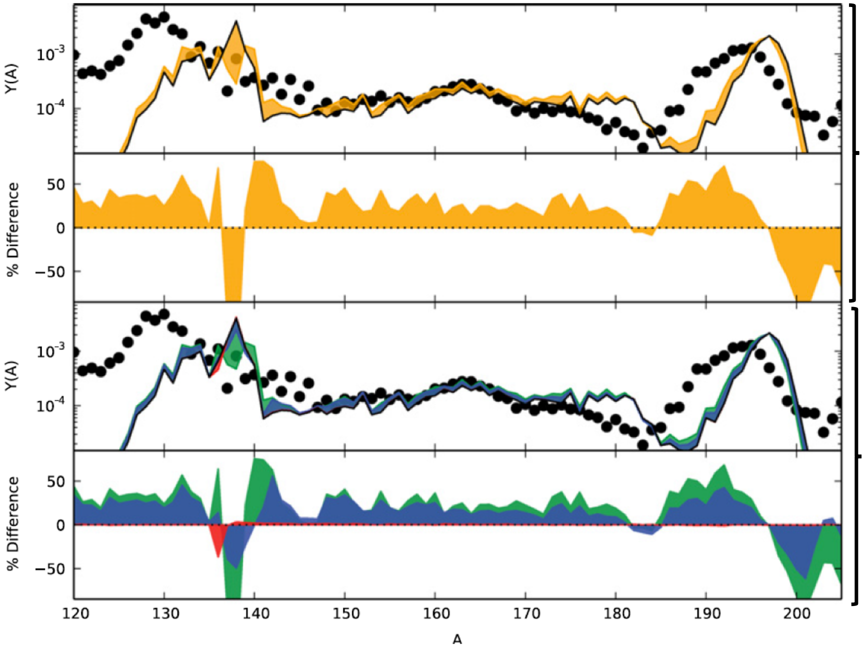
Predictions / AME 2012



Abundance varitions = f (mass model)
(hot r-process trajectory)



Change in final r-process abundances
when m(^{140}Sn) is increased by 500 keV (FRDM15)



all mass dependencies considered

only propagating changes to :

--- n-capture
--- **β-decay**
--- **(γ,n) rates**

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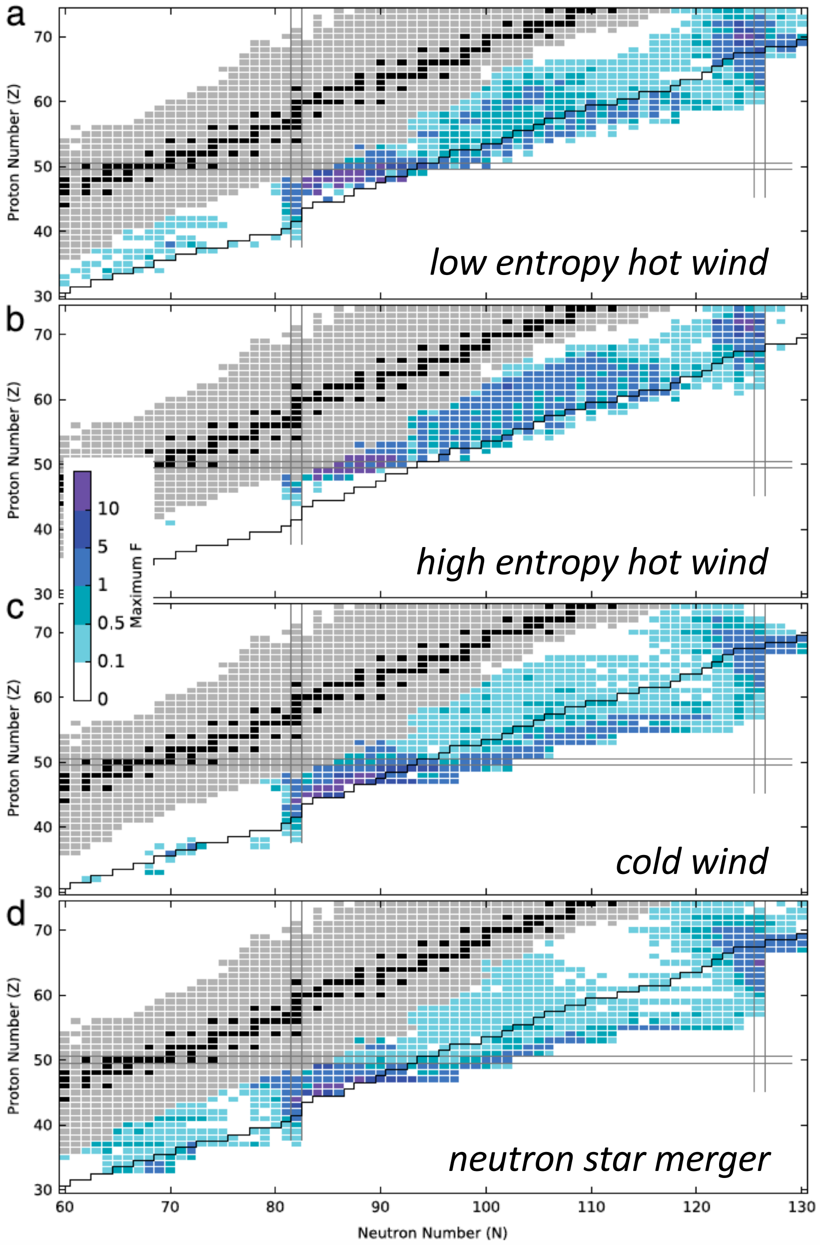
- **Masses**

mass variations of +/- 500MeV (FRDM12) = f (astro conditions)



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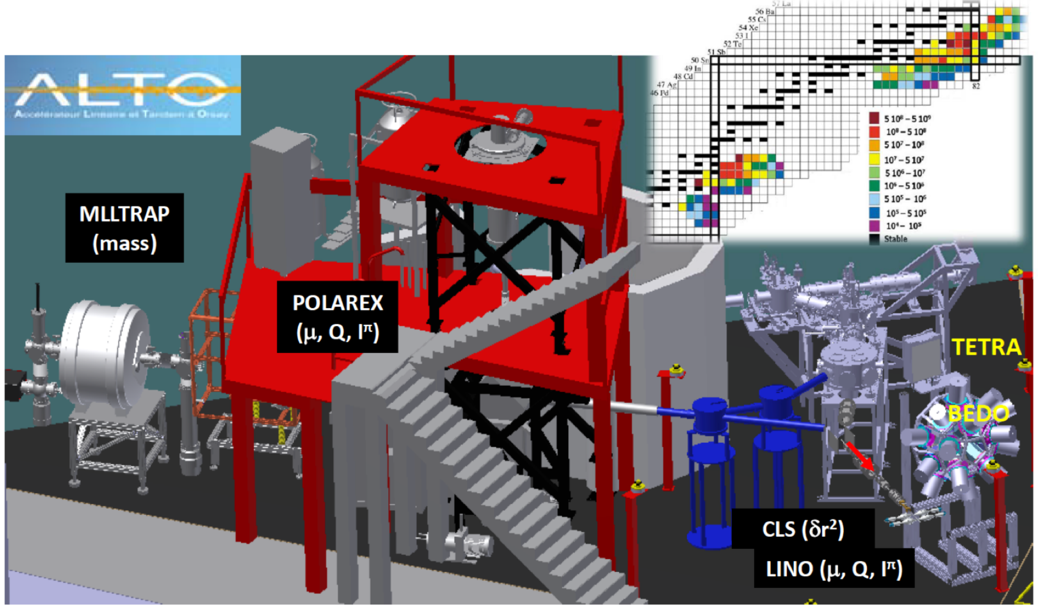
Modern precise mass measurement techniques

	Penning Trap	MR-TOF	TOF in RING
Quantity	cyclotron freq. abs. mass	TOF in Mirrors rel. mass	TOF in RING rel. mass
Accuracy determination	$<10^{-7}$ (MRP ∝ $T_{1/2}$)	$<10^{-6}$ (MRP:>200,000)	$<10^{-6}$ (MRP: ?)
meas. period	~10ms - 1s	~1ms	~100μs
practical lifetime, intensity limit	10~100ms <0.1 cps	1~10ms <0.01 cps	<1ms 1 c/day ?
status	established	development	future tech.
operation	not difficult	simple	unknown/difficult
competition	ISOLDE, MSU,ANL, JYFL, etc	None on-line	GSI-ESR
Calibration	Perfect (calib. ^{12}C)	easy (isobar)	difficult (same A/Z)

In Europe : exp. mainly @ ISOLDE / JYFL / GSI

Soon also in France : Alto (+ SPIRAL2-phase)



2017-2019; fort soutien de l'IN2P3

E. Minaya et al., mass-program (Ag) + in-trap spec (2019)

• Which properties to measure / to constraint?

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

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\textbf{Production} & \left\{ \begin{array}{l}
\mathrm{Nn.\,N(Z,A-1).} < \sigma\nu >_{\mathrm{Z,A-1}} \qquad \rightarrow \text{(n,}\gamma\text{) reaction} \\
+\,\mathrm{N(Z,A+1).}\,\lambda_{\gamma,\mathrm{n}}^{\mathrm{Z,A+1}} \qquad \rightarrow (\gamma\text{,n) reaction} \\
\boxed{\begin{array}{l}
+\,\mathrm{N(Z-1,A).}\,\lambda_{\beta}^{\mathrm{Z-1,A}} \qquad \rightarrow \beta \text{ decay} \\
+\sum_{\mathrm{k=1}}^{3} \mathrm{N(Z-1,A+k).}\,\lambda_{\beta\mathrm{kn}}^{\mathrm{Z,A+1}} \qquad \rightarrow \beta \text{ –delayed k neutron emission}
\end{array}} \\
+\,\mathrm{N(Z+2,A+4).}\,\lambda_{\alpha}^{\mathrm{Z+2,A+4}} \qquad \rightarrow \alpha \text{ decay} \\
+\,\sum_{\mathrm{f}}\ \mathrm{q}_{\mathrm{Z_f,Af}}\mathrm{(Z,A).}\,\lambda_{f}^{Z_f,Af}\ \mathrm{.N(Z_f,A_f)} \qquad \rightarrow \text{spontaneous fission} \\
+\,\sum_{\mathrm{f}}\ \mathrm{q}_{\mathrm{Z_f,Af}}\mathrm{(Z,A).}\,\lambda_{f}^{Z_f-1,A_f}\mathrm{.N(Z_f\text{-}1,A_f)} \qquad \rightarrow \beta\text{–delayed fission} \\
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\end{array} \right. \\
\textbf{Destruction} & \left\{ \begin{array}{l}
-\mathrm{N(Z,A).}\left|\mathrm{N_n.} < \sigma\nu >_{\mathrm{Z,A}} + \lambda_{\gamma,\mathrm{n}}^{\mathrm{Z,A}} + \boxed{\lambda_{\beta}^{\mathrm{Z,A}} + \sum_{\mathrm{k=1}}^{3} \lambda_{\beta\mathrm{kn}}^{\mathrm{Z,A}}}\right| \\
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\end{array} \right.
\end{array}$$

$+\ \gamma$ induced fission

$+$ neutrino interactions with nuclei for some scenarios

=> Masses, β-decay properties, neutron capture rates, fission rates

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- **β-decay properties**

☐ β-decay half-lives

$$\frac{1}{T_{1/2}} = \sum_{0\leq E_i\leq Q_\beta} S_\beta(E_i).\,f(Z,\mathbf{Q_\beta}\text{-}E_i)$$

- $S_\beta(E_i)$: b-strength function
- $f(Z,Q_\beta\text{-}E_i)$: Fermi function
- Q_β = M(Z,N)-M(Z+1,N-1)

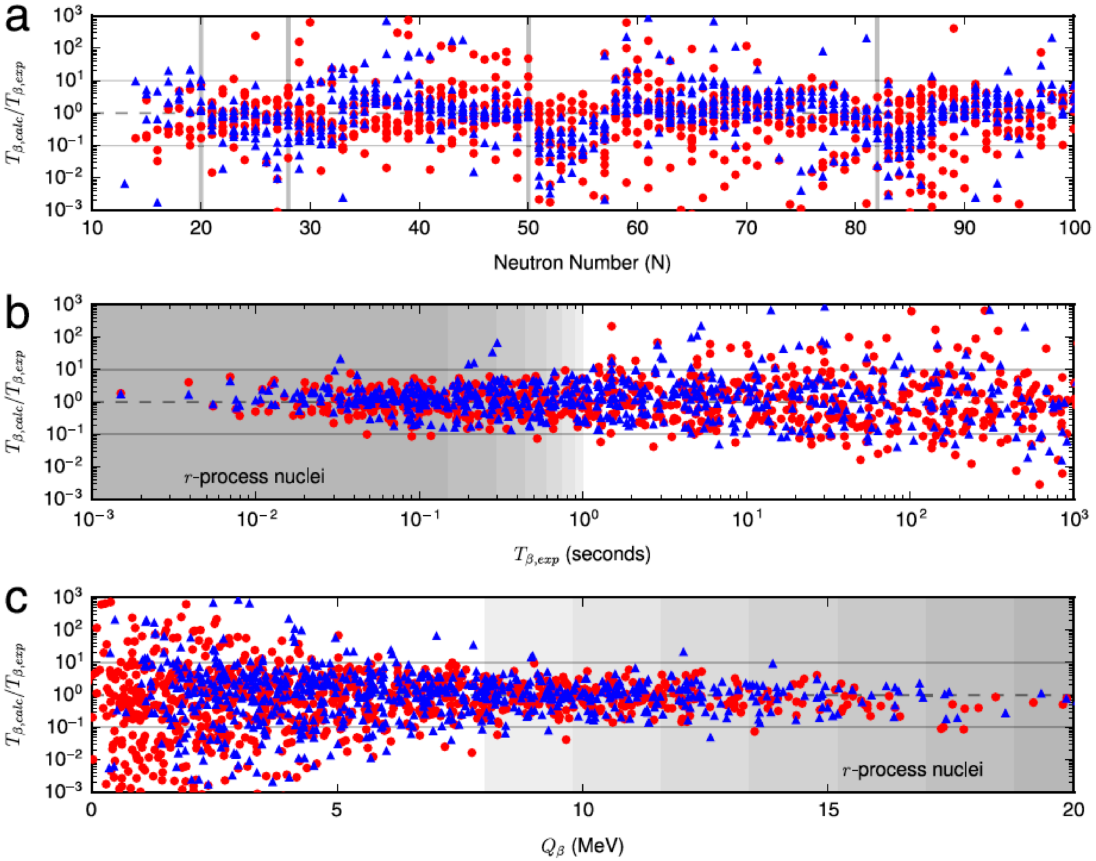
☐ β-delayed neutron emission probability

$$\boldsymbol{P_n} = \frac{\sum_{S_n\leq E_i\leq Q_\beta} S_\beta\,(E_i).\,f(Z,\mathbf{Q_\beta}-E_i)}{\sum_{0\leq E_i\leq Q_\beta} S_\beta\,(E_i).\,f(Z,\mathbf{Q_\beta}-E_i)}$$

Theory / Experiment

● QRPA + FRDM95 (Q-values) / NNDC

● Gross theory + KTUY05 (Q-values) / NNDC



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- Discrepancies for longest $T_{1/2}$, due to phase space factor, which goes $(Q_\beta\text{-}\,E_i)^5$

- less than factor 10 for short half-lives

- *A. Algora, M. Fallot et al.,* total absorption spectroscopy (Sn and In)
- *A. Gottardo et al.,* Beta delayed neutron spectroscopy…

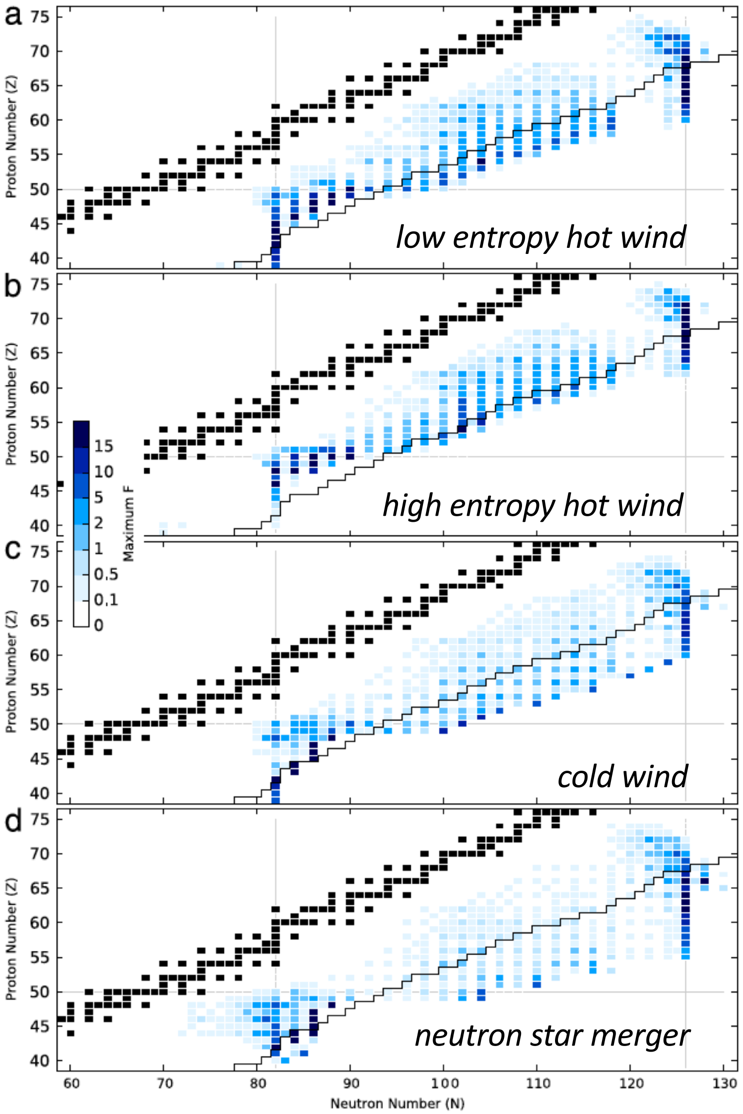
$\Rightarrow$ **Experimental measurements using TAS, Bedo, MONSTER, VANDLE…**

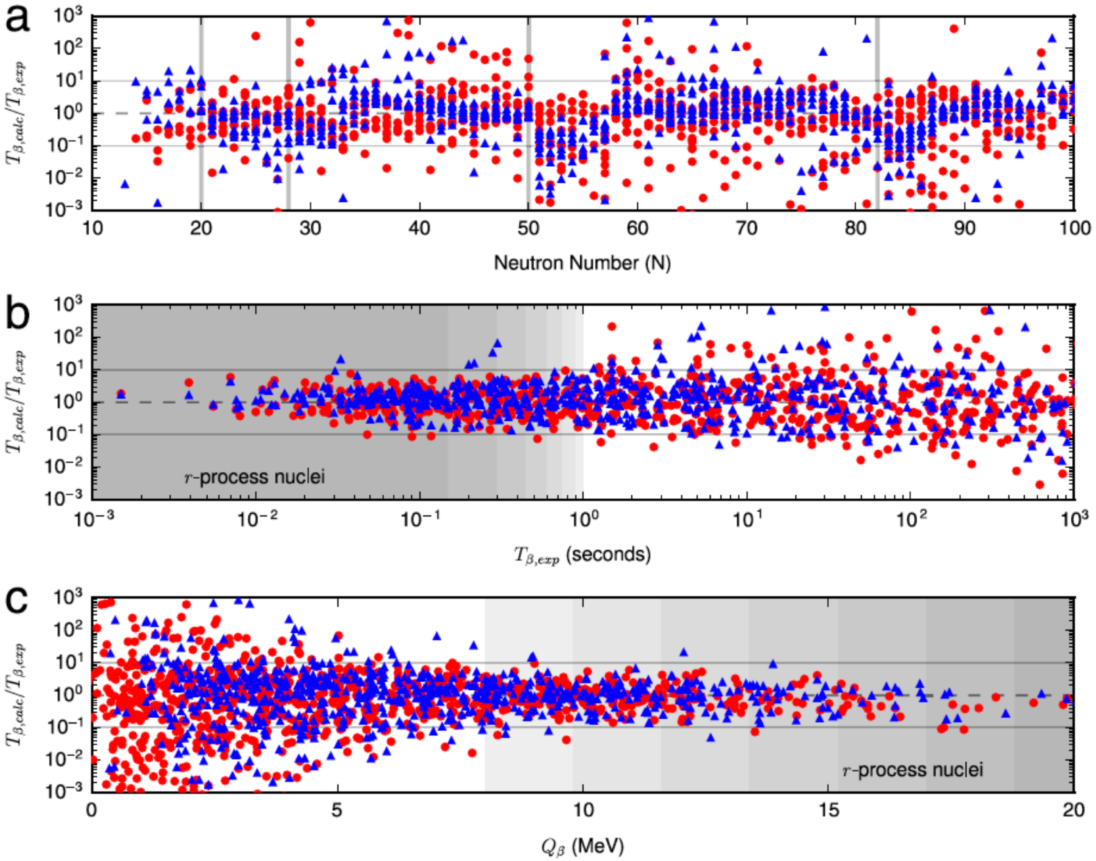
- # β-decay properties

$T_{1/2}$ variation of factor 10 (QRPA+AME95/FRDM) = f (astro conditions)

Theory / Experiment

- QRPA + FRDM95 (Q-values) / NNDC
- Gross theory + KTUY05 (Q-values) / NNDC





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- *A. Algora, M. Fallot et al.,* total absoprtion spectroscopy (Sn and In)
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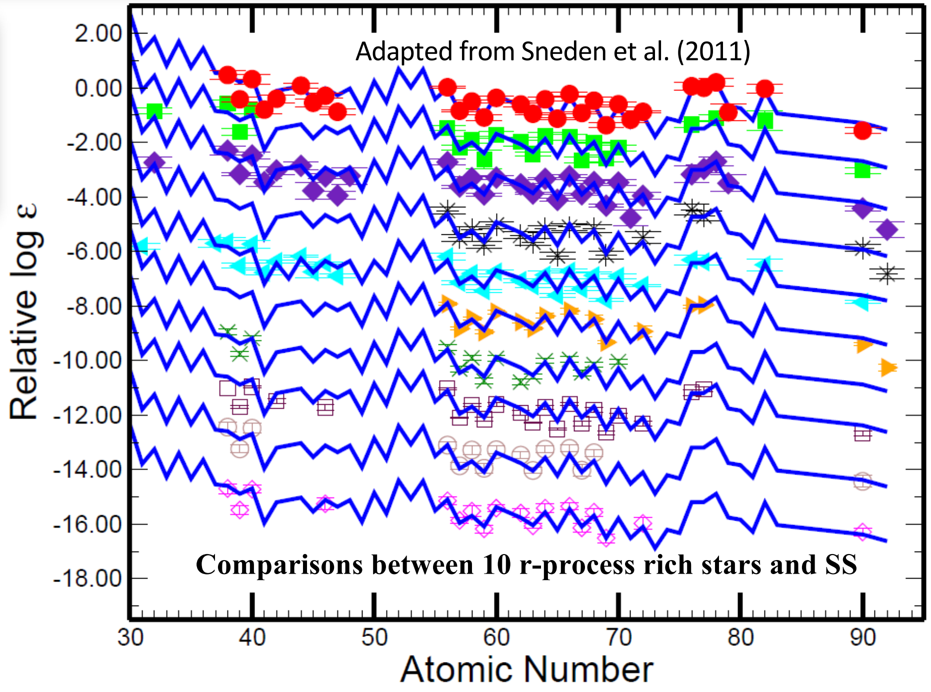
$\Rightarrow$ **Experimental measurements using TAS, Bedo, MONSTER, VANDLE…**

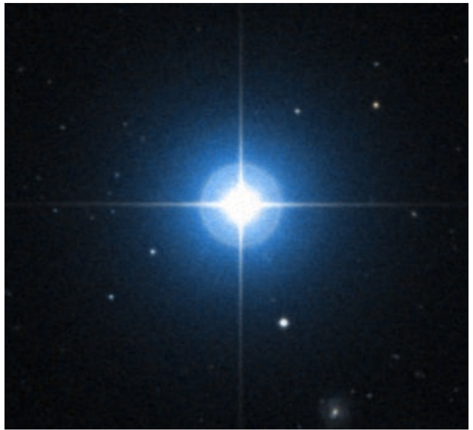
« Measurement of the decay characteristics of ^{90}Se relevant to the r-process nucleosynthesis »

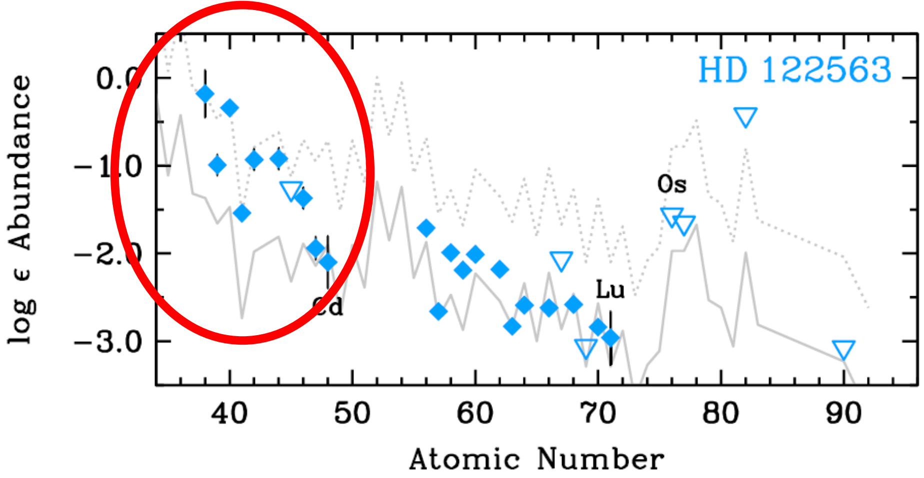
Letter of Intent from T. Kurtukian Nieto (CENBG)

UMP giants stars provide crucial constraints to the stellar nucleosynthesis.

Its elemental abundances are consistent with the solar r-process elemental distribution.







Overproduction of stable Sr, Y, and Zr isotopes in some UMP, compared to the SS r-process pattern.

B. Bastin (GANIL)

« Measurement of the decay characteristics of ^{90}Se relevant to the r-process nucleosynthesis »

Letter of Intent from T. Kurtukian Nieto (CENBG)

Z	88Zr	89Zr	90Zr	91Zr	92Zr	93Zr	94Zr	95Zr	96Zr	97Zr	98Zr	99Zr	100Zr	101Zr	102Zr	103Zr	104Zr
	87Y	88Y	89Y	90Y	91Y	92Y	93Y	94Y	95Y	96Y	97Y	98Y	99Y	100Y	101Y	102Y	103Y
38	86Sr	87Sr	88Sr	89Sr	90Sr	91Sr	92Sr	93Sr	94Sr	95Sr	96Sr	97Sr	98Sr	99Sr	100Sr	101Sr	102Sr
	85Rb	86Rb	87Rb	88Rb	89Rb	90Rb	91Rb	92Rb	93Rb	94Rb	95Rb	96Rb	97Rb	98Rb	99Rb	100Rb	101Rb
36	84Kr	85Kr	86Kr	87Kr	88Kr	89Kr	90Kr	91Kr	92Kr	93Kr	94Kr	95Kr	96Kr	97Kr	98Kr	99Kr	100Kr
	83Br	84Br	85Br	86Br	87Br	88Br	89Br	90Br	91Br	92Br	93Br	94Br	95Br	96Br	97Br	98Br	
34	82Se	83Se	84Se	85Se	86Se	87Se	88Se	89Se	90Se	91Se	92Se	93Se	94Se	95Se			
	81As	82As	83As	84As	85As	86As	87As	88As	89As	90As	91As	92As					
32	80Ge	81Ge	82Ge	83Ge	84Ge	85Ge	86Ge	87Ge	88Ge	89Ge	90Ge						
	48		50		52		54		56		58		60		62		N

^{88,89}Ge

$^{88,89,90?}$As

$^{90-92}$Se

β decay properties (half-lives and Pn) of neutron-rich Ge, As and Se isotopes have a direct influence on the production of Sr, Y, and Zr.

Some of these nuclei are accessible at ALTO (LoI 90Se T. Kurtukian-Nieto)

B. Bastin (GANIL)

Which properties to measure / to constraint?

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Production

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+\,\mathrm{N(Z,A+1).\,\lambda_{\gamma,n}^{Z,A+1}} & \rightarrow \mathbf{(\gamma,n)\ reaction}
\end{array}} & \\
+\,\mathrm{N(Z-1,A).\,\lambda_{\beta}^{Z-1,A}} & \rightarrow \mathbf{\beta\ decay} \\
+\sum_{k=1}^{3}\mathrm{N(Z-1,A+k).\,\lambda_{\beta kn}^{Z,A+1}} & \rightarrow \mathbf{\beta\text{–}delayed\ k\ neutron\ emission} \\
+\,\mathrm{N(Z+2,A+4).\,\lambda_{\alpha}^{Z+2,A+4}} & \rightarrow \mathbf{\alpha\ decay} \\
+\sum_{f}\mathrm{q_{Z_f,Af}(Z,A).}\,\lambda_{f}^{Z_f,Af}\,\mathrm{.N(Z_f,A_f)} & \rightarrow \mathbf{spontaneous\ fission} \\
+\sum_{f}\mathrm{q_{Z_f,Af}(Z,A).}\,\lambda_{f}^{Z_f-1,A_f}\mathrm{.N(Z_f\text{-}1,A_f)} & \rightarrow \mathbf{\beta\text{–}delayed\ fission} \\
+\sum_{f}\mathrm{q_{Z_f,Af}(Z,A).}\,\lambda_{f}^{Z_f,Af-1}\mathrm{.N(Z_f,A_f\text{-}1)} & \rightarrow \mathbf{n\text{-}induced\ fission}
\end{array}\right.$$

Destruction

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

$+\,\gamma$ induced fission

$+$ neutrino interactions with nuclei for some scenarios

=> Masses, β-decay properties, neutron capture rates, fission rates

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• Neutron capture and photodisintegration rates

Hauser-Feshbach statistical model

❑ The effective **stellar rate** of I + j → L + ι reaction at T (cm^3 s^{-1} mole^{-1}):

$$N_\mathrm{A}\langle\sigma v\rangle^*_{jl}(T) = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_\mathrm{A}}{(kT)^{3/2}\; G_I(T)} \int_0^\infty \sum_\mu \frac{(2J_I^\mu+1)}{(2J_I^0+1)} \sigma^\mu_{jl}(E) E \exp\left(-\frac{E+\varepsilon_I^\mu}{kT}\right) dE,$$

- N$_\mathrm{A}$: Avogadro number
- J : spin
- m : reduced mass
- E : relative energy
- G$_\mathrm{I}$: partition function
- ε : excitation energy of state μ ($\mu = 0$ for the ground state)

❑ **(n,γ) cross section:**

$$\sigma^\mu_{n,\gamma}(E) = \frac{\pi}{k^2\left(2J_I^\mu+1\right)(2J_n+1)} \sum_{J^\pi} (2J+1) \frac{T_n^\mu(J^\pi) T_\gamma(J^\pi)}{T_{tot}(J^\pi)},$$

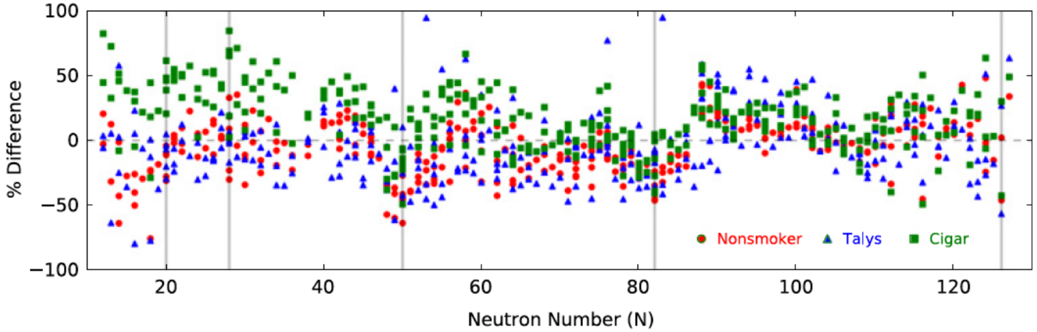
- k : neutron wave number
- T_n^μ and T_γ : transmission functions for the formation and decay channels
  => models of level densities & g-strength functions

❑ **Photo-dissociation rate:**

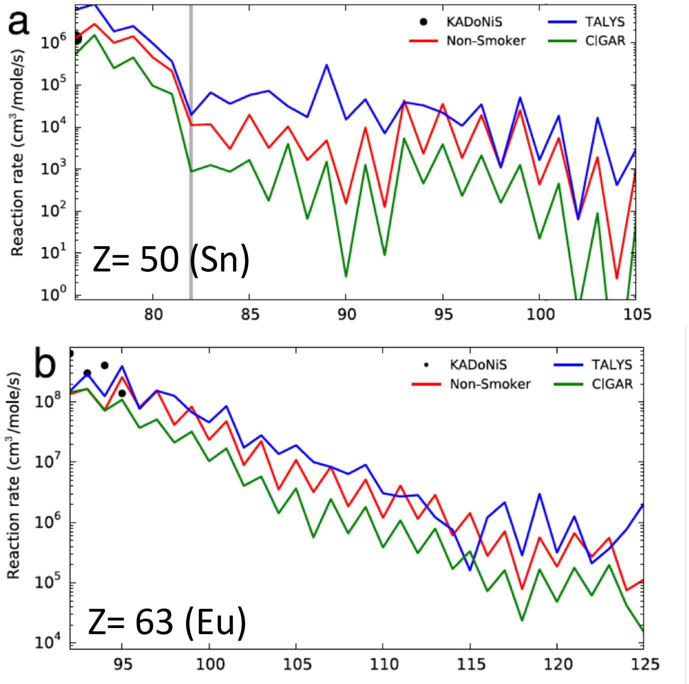
$$\lambda^*_{(\gamma,j)}(T) = \frac{(2J_I^0+1)(2J_j+1)}{(2J_L^0+1)} \frac{G_I(T)}{G_L(T)} \left(\frac{mkT}{2\pi\hbar^2}\right)^{3/2} \langle\sigma v\rangle^*_{(j,\gamma)}\; \mathrm{e}^{-Q_{j\gamma}/kT},$$

• Neutron capture and photodisintegration rates

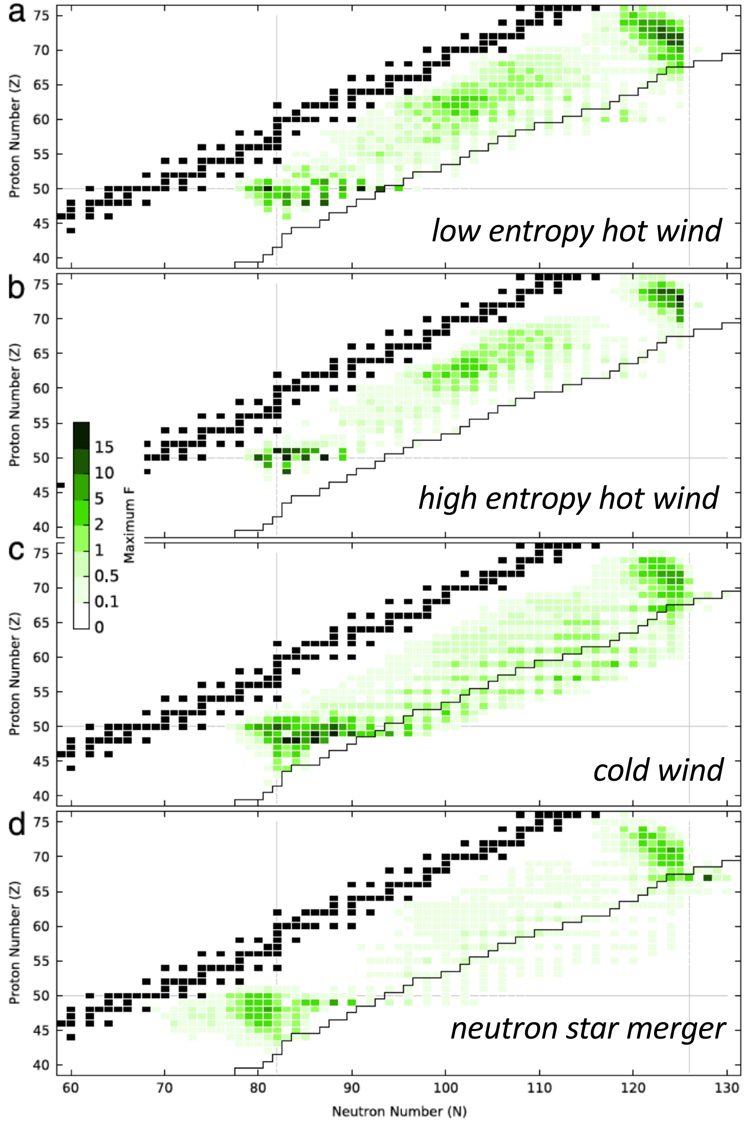
- ❑ **Difference between $\sigma_{HF\ model}$(n,γ) and $\sigma_{KADoNiS}$(n,γ)**



- ❑ **(n,γ) reaction rate at T_9=1.0**



(n,γ) rates variation of factor 100 = f (astro conditions)



M.R. Mumpower et al. Progr. in Part. and Nucl. Phy. 86 (2016) 86–126

- Measurements via surrogate method (ex : (d,p))
- β-Olso method => level density & γ-strength function

Exp. Project : on enhanced E1 strengths (impact in the gSF => photo-desintegration rate)

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

- # Which properties to measure / to constraint?

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

$$\frac{\mathrm{dN(Z,A)}}{\mathrm{dt}} = \begin{array}{l}
\textbf{Production}\left\{\begin{array}{ll}
\mathrm{Nn.\,N(Z,A-1).<\sigma\nu>_{Z,A-1}} & \to \text{(n,}\gamma\text{) reaction} \\
\mathrm{+\,N(Z,A+1).\,\lambda_{\gamma,n}^{Z,A+1}} & \to (\gamma\text{,n) reaction} \\
\mathrm{+\,N(Z-1,A).\,\lambda_{\beta}^{Z-1,A}} & \to \beta\text{ decay} \\
\mathrm{+\sum_{k=1}^{3} N(Z-1,A+k).\,\lambda_{\beta kn}^{Z,A+1}} & \to \beta\text{ –delayed k neutron emission} \\
\mathrm{+\,N(Z+2,A+4).\,\lambda_{\alpha}^{Z+2,A+4}} & \to \alpha\text{ decay} \\
\multicolumn{2}{l}{\boxed{\begin{array}{ll}
+\sum_{\mathrm{f}}\ \mathrm{q}_{\mathrm{Z_f,Af}}\mathrm{(Z,A)}.\,\lambda_{f}^{Z_f,Af}\ .\mathrm{N(Z_f,A_f)} & \to \text{spontaneous fission} \\
+\sum_{\mathrm{f}}\ \mathrm{q}_{\mathrm{Z_f,Af}}\mathrm{(Z,A)}.\,\lambda_{f}^{Z_f-1,A_f}.\mathrm{N(Z_f\text{-}1,A_f)} & \to \beta\text{–delayed fission} \\
+\sum_{\mathrm{f}}\ \mathrm{q}_{\mathrm{Z_f,Af}}\mathrm{(Z,A)}.\,\lambda_{f}^{Z_f,Af-1}.\mathrm{N(Z_f,A_f\text{-}1)} & \to \text{n-induced fission}
\end{array}}}
\end{array}\right. \\
\textbf{Destruction}\left\{\begin{array}{l}
\mathrm{-N(Z,A).\left[N_n.<\sigma\nu>_{Z,A}+\lambda_{\gamma,n}^{Z,A}+\lambda_{\beta}^{Z,A}+\sum_{k=1}^{3}\lambda_{\beta kn}^{Z,A}\right]} \\
\mathrm{-\,N(Z,A).\left[\lambda_{\alpha}^{Z,A}+\boxed{\lambda_{f}^{Z,A}+\lambda_{\beta f}^{Z,A}+\lambda_{nf}^{Z,A}}\right]}
\end{array}\right.
\end{array}$$

$\boxed{+\,\gamma\text{ induced fission}}$

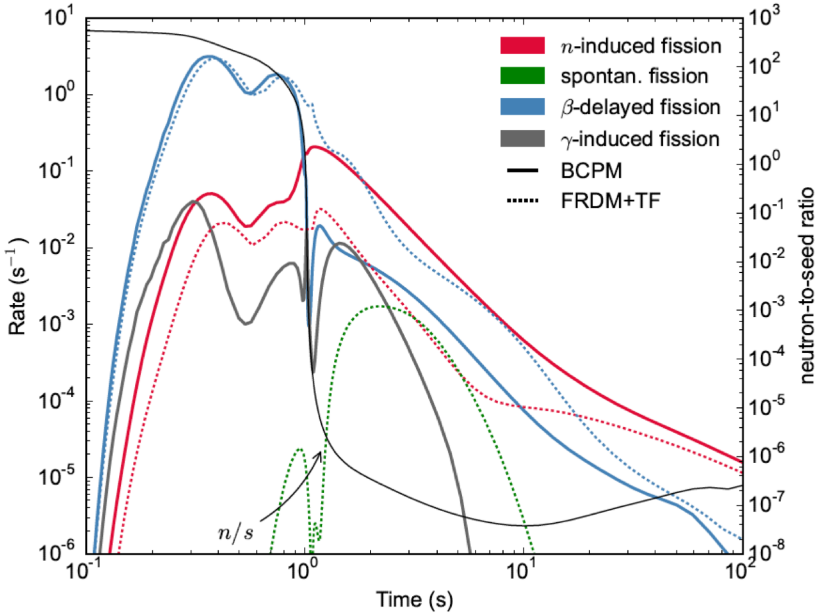
+ neutrino interactions with nuclei for some scenarios

=> Masses, β-decay properties, neutron capture rates, fission rates

Arnould, M. et al. Phys.Rept. 450 (2007) 97-213

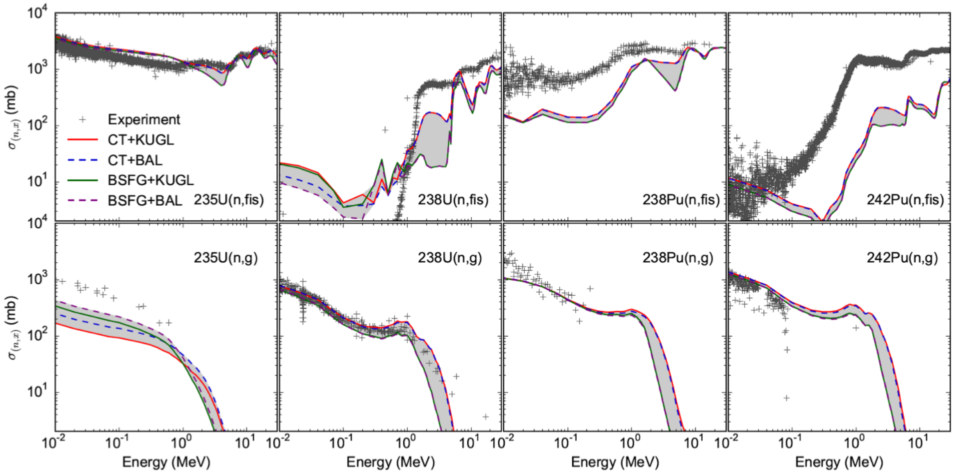
• Fission rates / fission distributions

☐ Evolution of different fission channels predicted by BCPM and FRDM+TF (neutron star mergers)

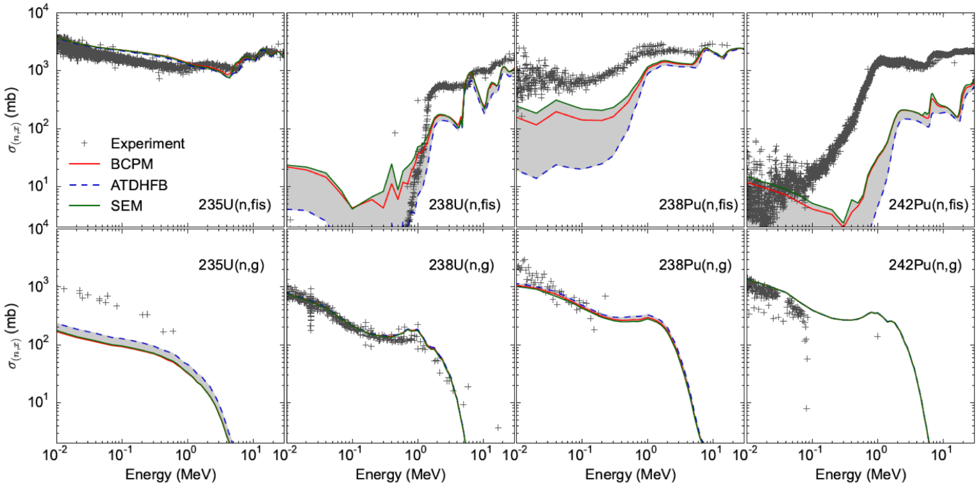


☐ Evolution of different n-induced fission and (n,γ) cross section for:

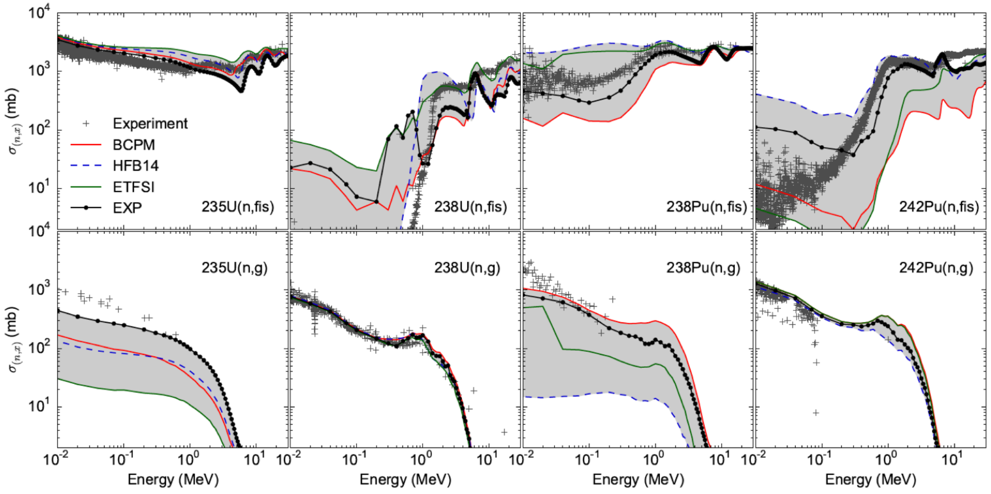
- Different combinations of level densities + gamma ray-strength



- Collective inertias schemes



- Sets of fission barriers

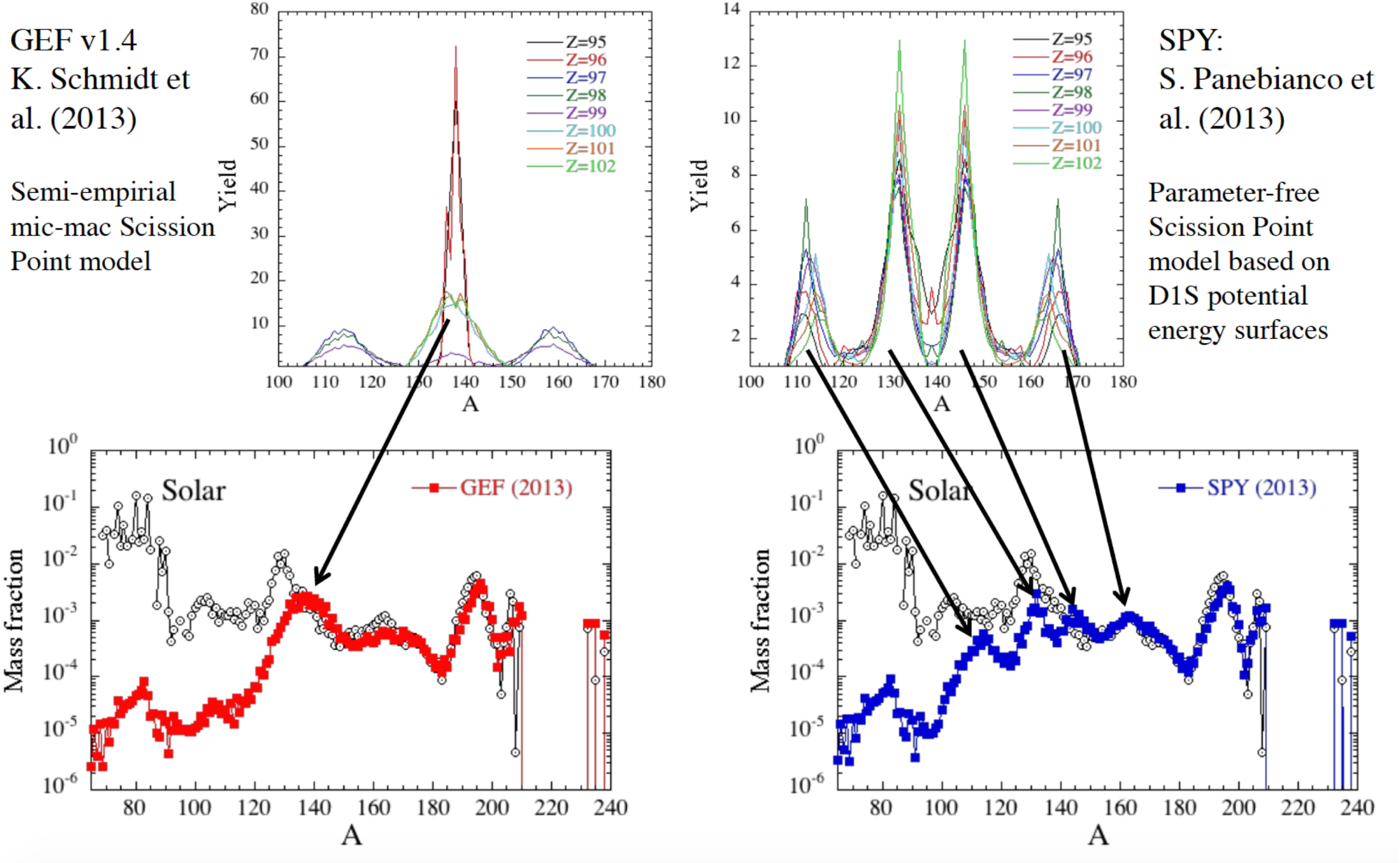


S. A. Giuliani, G. Martinez-Pinedo, L. M. Robledo 2018

- **Fission rates / fission distributions**

Sensitivity to the fission fragment distribution

along the A=278 isobar (from the N=184 closed shell)



GEF v1.4
K. Schmidt et al. (2013)

Semi-empirial mic-mac Scission Point model

SPY:
S. Panebianco et al. (2013)

Parameter-free Scission Point model based on D1S potential energy surfaces

S. Goriely, Ecole Joliot Curie 2016

Facilities in France : Licorne (ALTO), ILL, GANIL
+ Strong theoretical involvement : CENBG (GEF), CEA-DAM

Which properties to measure / to constraint?

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

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\text{Production}\left\{\begin{array}{lll}
\mathrm{Nn.\,N(Z,A-1).} < \sigma\nu >_{\mathrm{Z,A-1}} & & \rightarrow (\mathrm{n},\gamma)\text{ reaction} \\
+\,\mathrm{N(Z,A+1).}\,\lambda_{\gamma,\mathrm{n}}^{\mathrm{Z,A+1}} & & \rightarrow (\gamma,\mathrm{n})\text{ reaction} \\
+\,\mathrm{N(Z-1,A).}\,\lambda_{\beta}^{\mathrm{Z-1,A}} & & \rightarrow \beta\text{ decay} \\
+\sum_{\mathrm{k=1}}^{3}\mathrm{N(Z-1,A+k).}\,\lambda_{\beta\mathrm{kn}}^{\mathrm{Z,A+1}} & & \rightarrow \beta\text{ –delayed k neutron emission} \\
+\,\mathrm{N(Z+2,A+4).}\,\lambda_{\alpha}^{\mathrm{Z+2,A+4}} & & \rightarrow \alpha\text{ decay} \\
+\sum_{\mathrm{f}} q_{\mathrm{Z_f,Af}}\mathrm{(Z,A).}\,\lambda_f^{Z_f,Af}\,\mathrm{.N(Z_f,A_f)} & & \rightarrow \text{spontaneous fission} \\
+\sum_{\mathrm{f}} q_{\mathrm{Z_f,Af}}\mathrm{(Z,A).}\,\lambda_f^{Z_f-1,A_f}\mathrm{.N(Z_f\text{-}1,A_f)} & & \rightarrow \beta\text{–delayed fission} \\
+\sum_{\mathrm{f}} q_{\mathrm{Z_f,Af}}\mathrm{(Z,A).}\,\lambda_f^{Z_f,Af-1}\mathrm{.N(Z_f,A_f\text{-}1)} & & \rightarrow \text{n-induced fission}
\end{array}\right. \\
\text{Destruction}\left\{\begin{array}{l}
-\mathrm{N(Z,A).}\left[\mathrm{N_n.} < \sigma\nu >_{\mathrm{Z,A}} + \lambda_{\gamma,\mathrm{n}}^{\mathrm{Z,A}} + \lambda_{\beta}^{\mathrm{Z,A}} + \sum_{\mathrm{k=1}}^{3}\lambda_{\beta\mathrm{kn}}^{\mathrm{Z,A}}\right] \\
-\,\mathrm{N(Z,A).}\left[\lambda_{\alpha}^{\mathrm{Z,A}} + \lambda_{\mathrm{f}}^{\mathrm{Z,A}} + \lambda_{\beta\mathrm{f}}^{\mathrm{Z,A}} + \lambda_{\mathrm{nf}}^{\mathrm{Z,A}}\right]
\end{array}\right.
\end{array}$$

+ γ induced fission

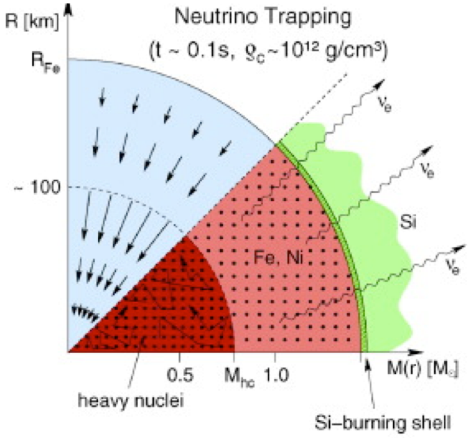
+ neutrino interactions with nuclei for some scenarios

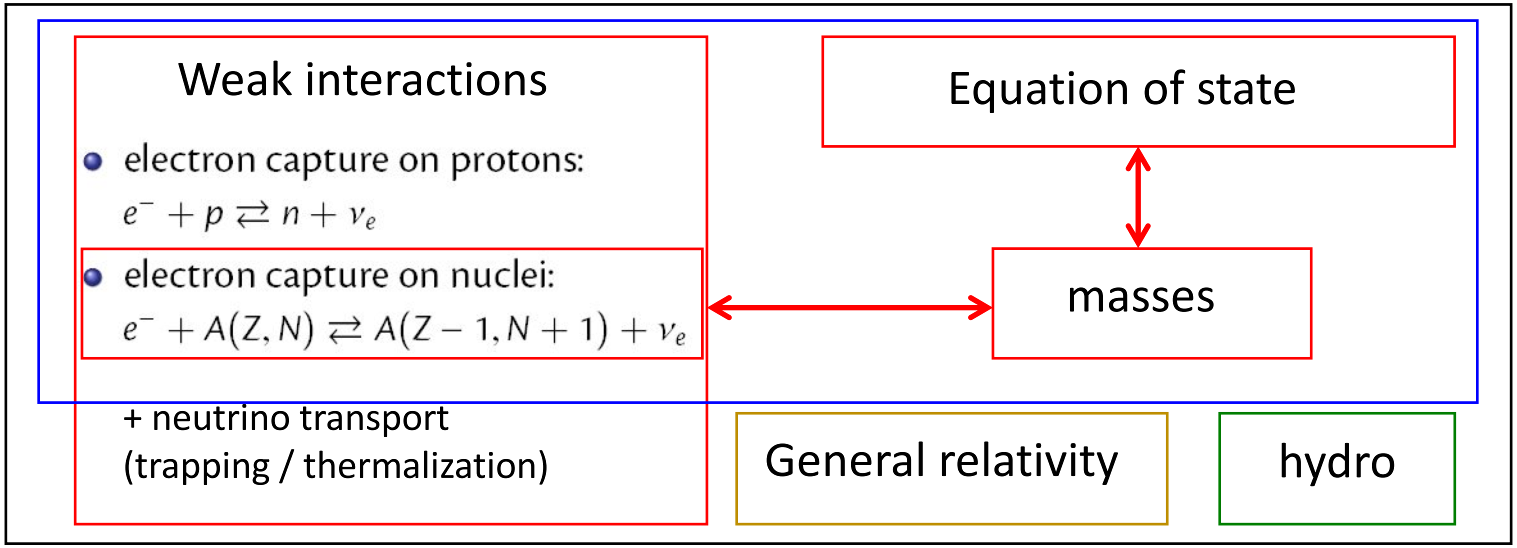
=> Masses, β-decay properties, neutron capture rates, fission rates

Arnould, M. et al. Phys.Rept. 450 (2007) 97-213

• Neutrino flux

core collapse





Weak interactions

- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$
- electron capture on nuclei:
  $e^- + A(Z,N) \rightleftarrows A(Z-1,N+1) + \nu_e$

+ neutrino transport
(trapping / thermalization)

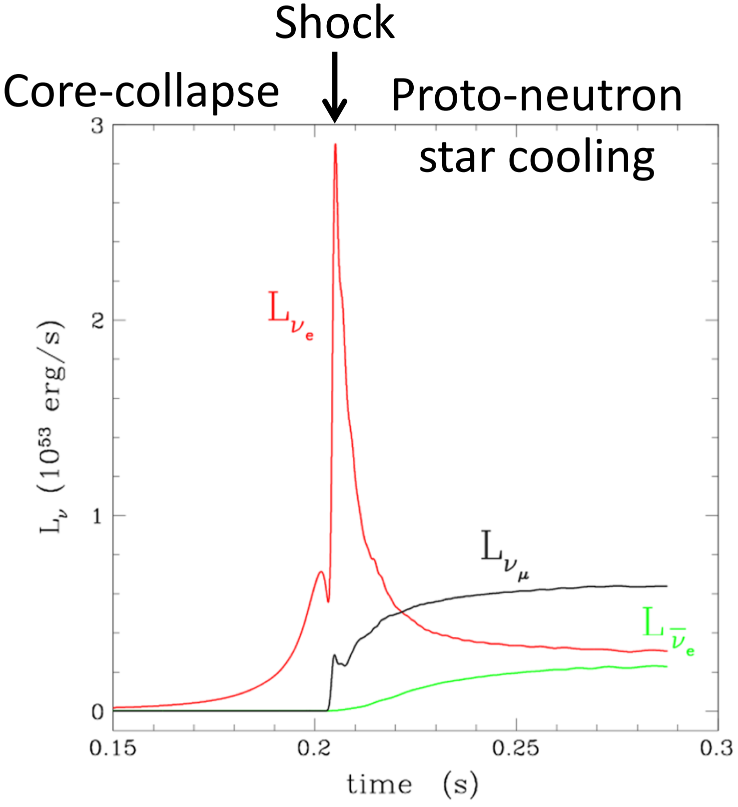
Equation of state

masses

General relativity

hydro

Time evolution of the ν luminosity



Shock

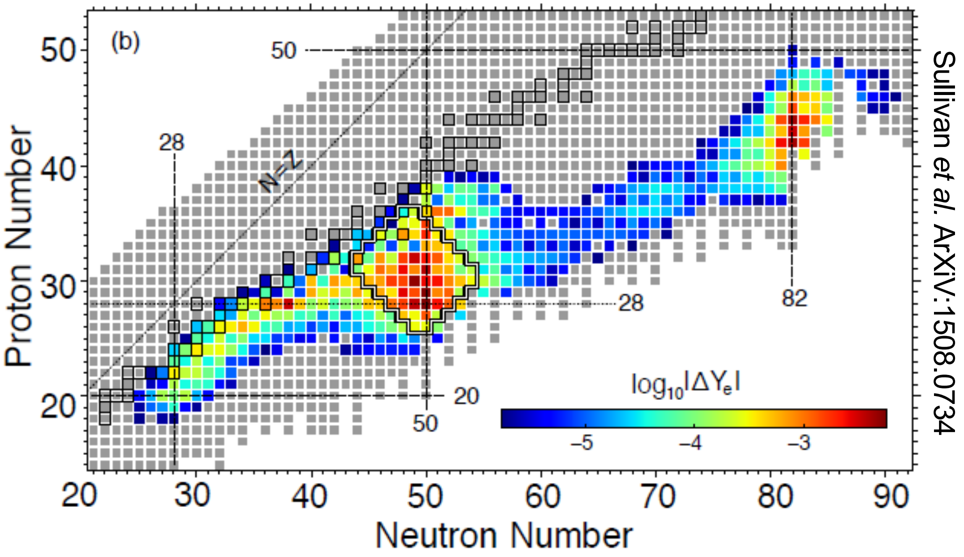
Core-collapse

Proto-neutron star cooling

Nuclear physics inputs

Influence the composition and ν_e rate

- EC : crucial all along the life of a star
  (particularly in massive stars → CCSN!)
- but: model uncertainties (especially in **n-rich nuclei**!)



Sullivan *et al.* ArXiV:1508.0734

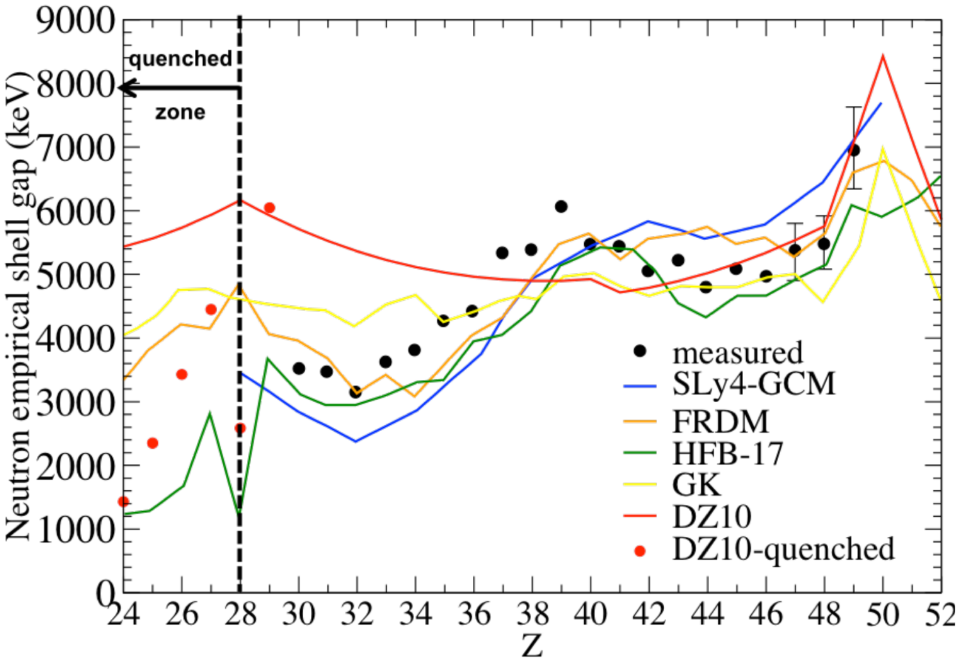
Study of core collapse supernovae (GANIL, LPCCaen, JYFL)

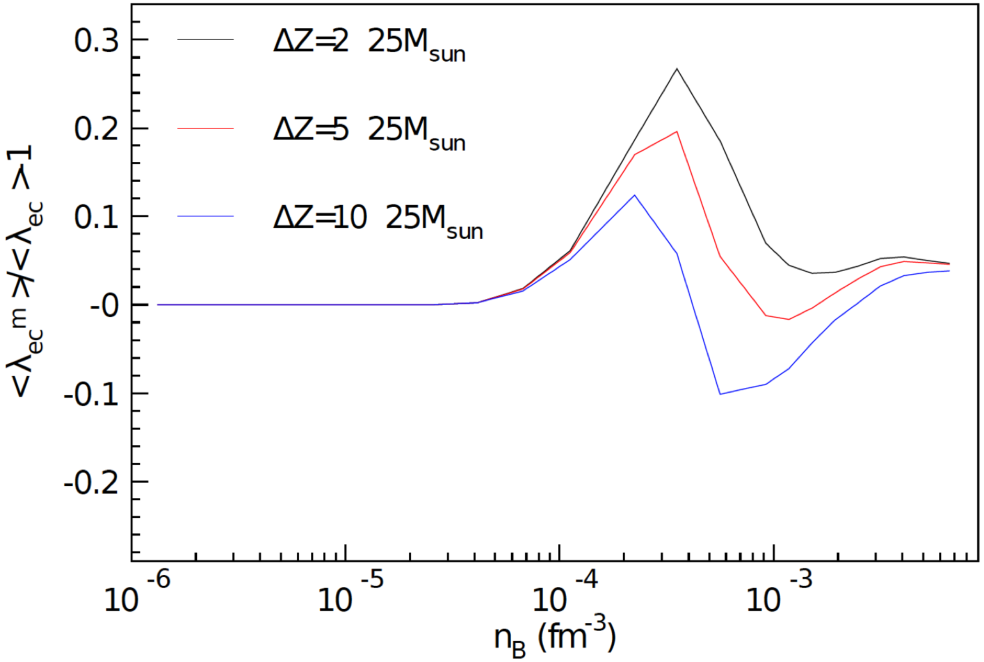
B. Bastin, A. Kankainen (experiment) / F. Gulminelli, A. Fantina (theory) et the collaboration

PhD thesis of S. Giraud (astrophysics) and L. Canete (nuclear structure)

Masses : impact on the EC rate

- Very precise mass values (within ~100 KeV) **are necessary for the computation of Q in EC**, but this is not all!
- Exotic nuclei around N=50 and N=82 dominate because they are predicted to be magic. **Magicity quenching would strongly affect EC.**





Ad. R. Raduta, Phys. Rev. C 93 (2016) 025803

Shell gap value will affect the electron capture rate very significantly!

Study of core collapse supernovae (GANIL, LPCCaen, JYFL)

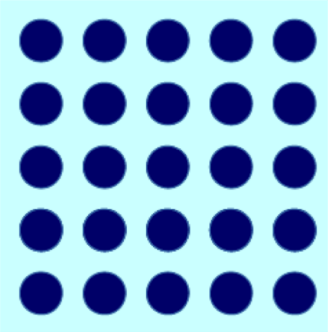
B. Bastin, A. Kankainen (experiment) / F. Gulminelli, A. Fantina (theory) et the collaboration

PhD thesis of S. Giraud (astrophysics) and L. Canete (nuclear structure)

Masses : impact on the nuclei distribution in SNII modelling (S. Giraud PhD)

$$\forall(T,Yp,\rho)\quad\begin{cases}10^{6} < \rho < 10^{15}\ \mathrm{g/cm^3}\\ 0.01 < T < 50\ \mathrm{MeV}\\ 0 < Y_p < 0.5\end{cases}$$

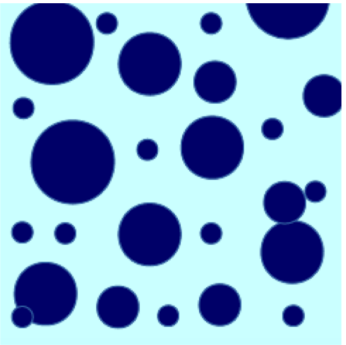
Single Nucleus Approximation (SNA)



$$F_{nuc} = F_{nuc}(\overline{A},\overline{Z})$$

But!at finite temperature more microstates states are populated

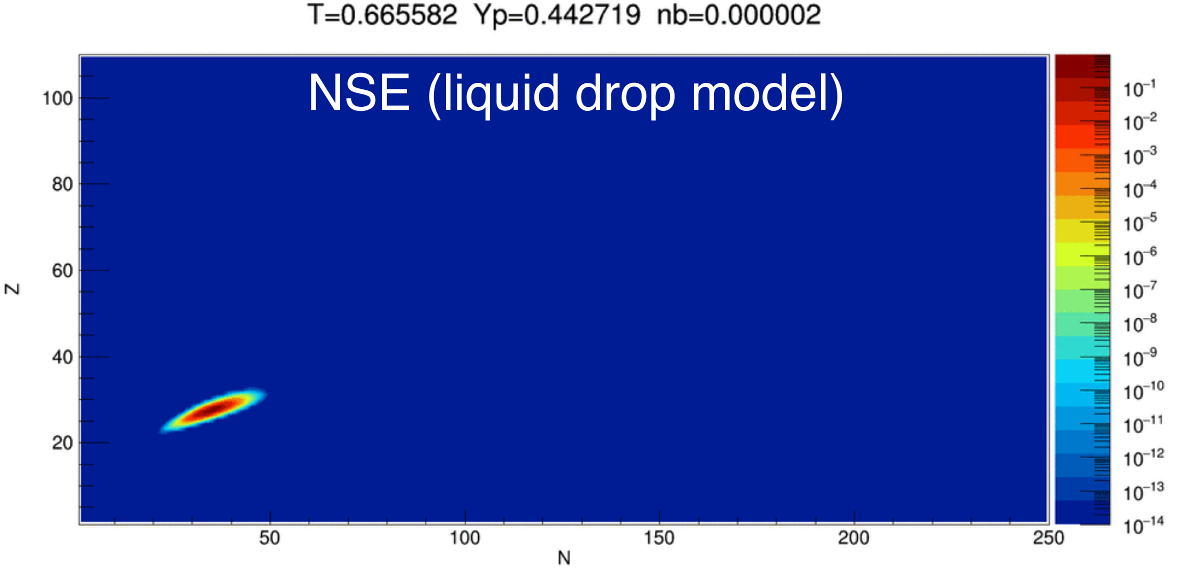
Nuclear Statistical Equilibrium (NSE)

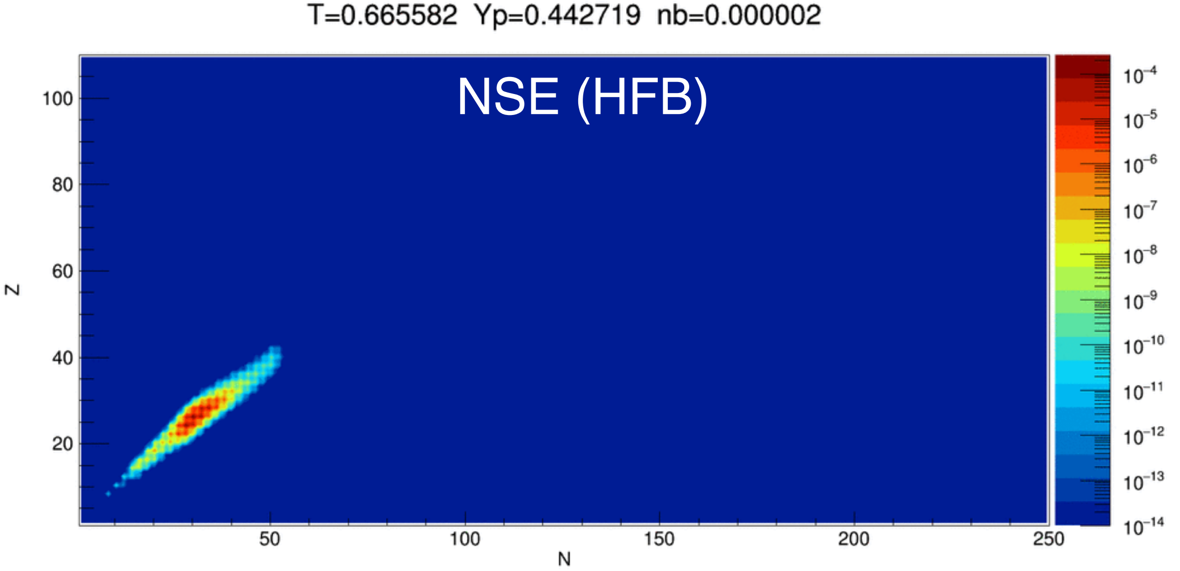


$$F_{nuc} = \underbrace{E(A,Z)}_{M(A,Z)-Nm_n-Zm_p} - TS(A,Z)$$

$$(LDM, HFB, \exp\ldots)$$

$$p(A,Z)\ \alpha\ \exp(-\beta.F)$$





Structure of nuclei around ^{78}Ni will affect the path => EC rate

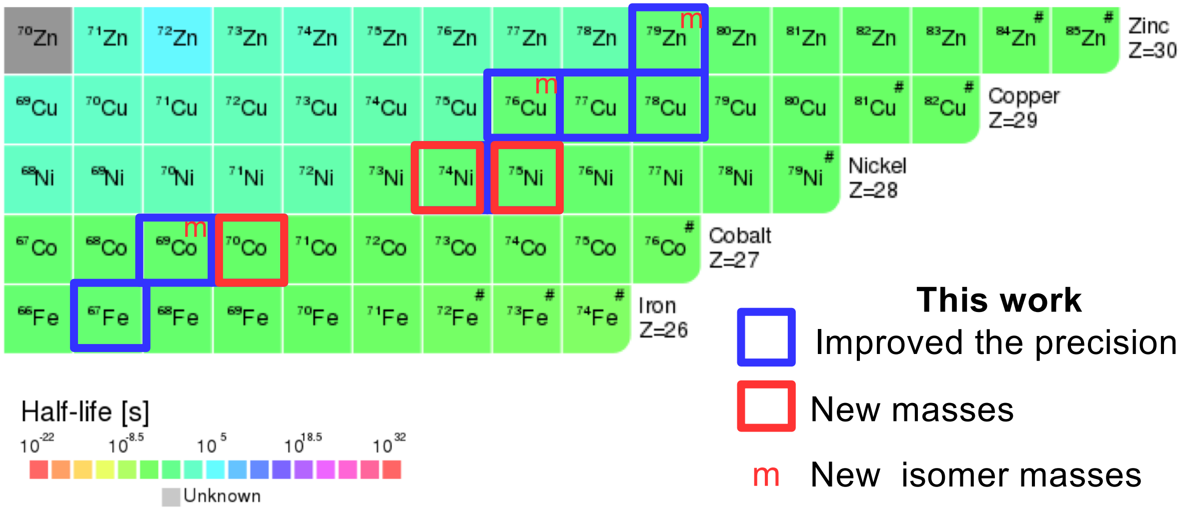
G. Grams, S. Giraud et al. PRC 97, 035807 (2018)

Study of core collapse supernovae (GANIL, LPCCaen, JYFL)

B. Bastin, A. Kankainen (experiment) / F. Gulminelli, A. Fantina (theory) et the collaboration

PhD thesis of S. Giraud (astrophysics) and L. Canete (nuclear structure)

New mass measurements around ^{78}Ni @ JYFL (Finland) :

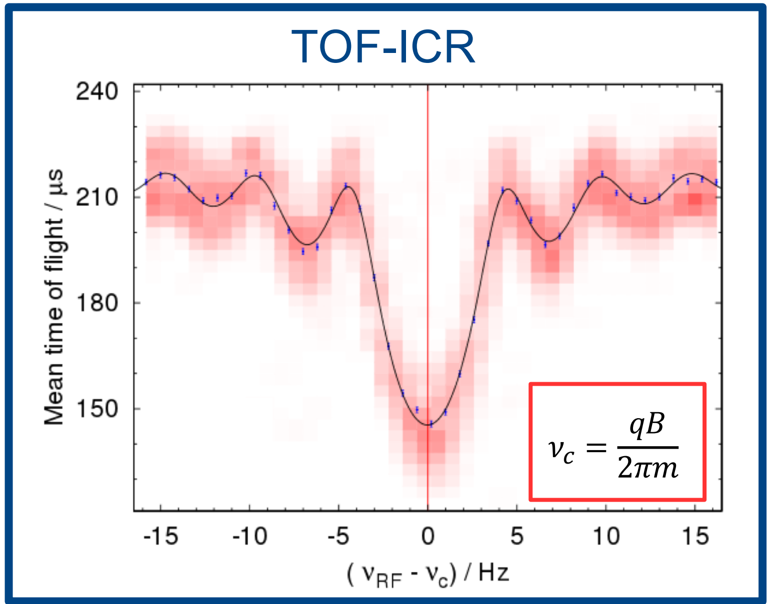


This work

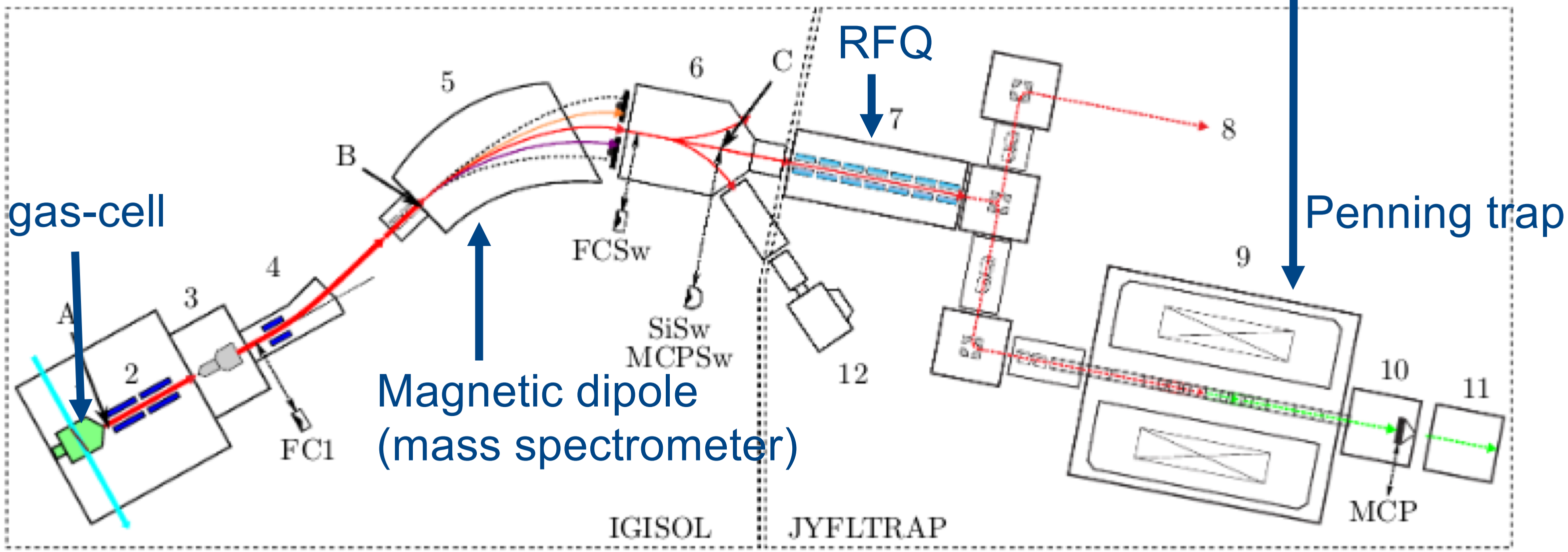
🟦 Improved the precision

🟥 New masses

m New isomer masses



$$\nu_c = \frac{qB}{2\pi m}$$



Summary

- **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.

“The impact of individual nuclear properties on r-process nucleosynthesis”

M.R. Mumpower et al. / Progress in Particle and Nuclear Physics 86 (2016) 86–126

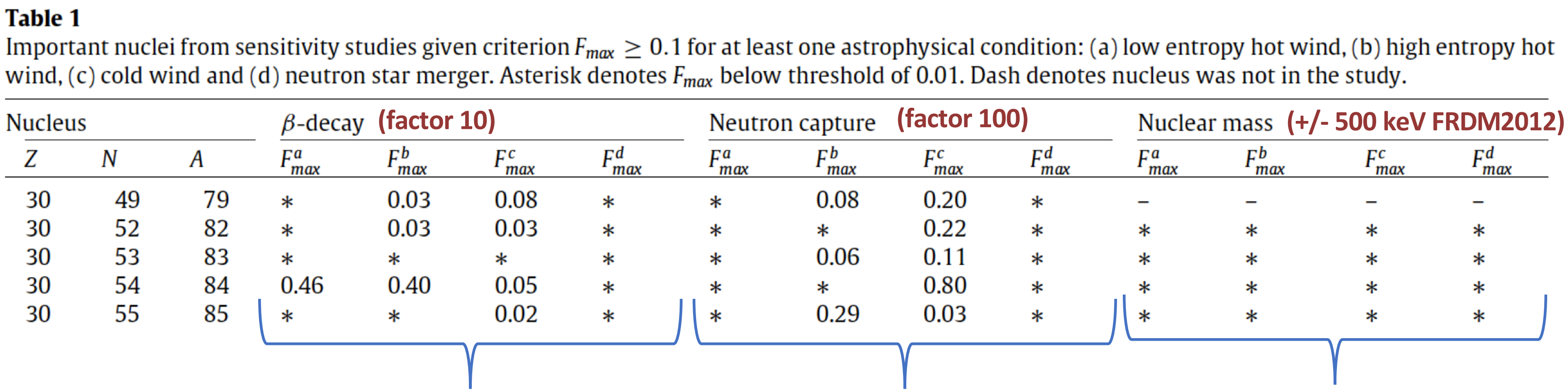


Table 1

Important nuclei from sensitivity studies given criterion $F_{max} \geq 0.1$ for at least one astrophysical condition: (a) low entropy hot wind, (b) high entropy hot wind, (c) cold wind and (d) neutron star merger. Asterisk denotes F_{max} below threshold of 0.01. Dash denotes nucleus was not in the study.

Nucleus			β-decay **(factor 10)**				Neutron capture **(factor 100)**				Nuclear mass **(+/- 500 keV FRDM2012)**			
Z	N	A	F^a_{max}	F^b_{max}	F^c_{max}	F^d_{max}	F^a_{max}	F^b_{max}	F^c_{max}	F^d_{max}	F^a_{max}	F^b_{max}	F^c_{max}	F^d_{max}
30	49	79	*	0.03	0.08	*	*	0.08	0.20	*	–	–	–	–
30	52	82	*	0.03	0.03	*	*	*	0.22	*	*	*	*	*
30	53	83	*	*	*	*	*	0.06	0.11	*	*	*	*	*
30	54	84	0.46	0.40	0.05	*	*	*	0.80	*	*	*	*	*
30	55	85	*	*	0.02	*	*	0.29	0.03	*	*	*	*	*

- $T_{1/2}$: progenitor abundances, Process speed
- β-delayed neutron emission branching : final abundances

Influential in the cold and merger cases (when photodissociation becomes negligible.)

Location of the path

- Discussion / validation during a specific workshop (atelier théorie CEA…) and synergy experiment-theory.