Topic 1
The formation (and structure) of r-process nuclei

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Topic 1 – r-process nuclei

✓ What can / should be meaured

→ Observables

✓ What astrophysical observations are needed to cross-check and verify the measurements

✓ What is the impact

→ How do the nuclear-induced uncertainties compare to other sources of uncertainty

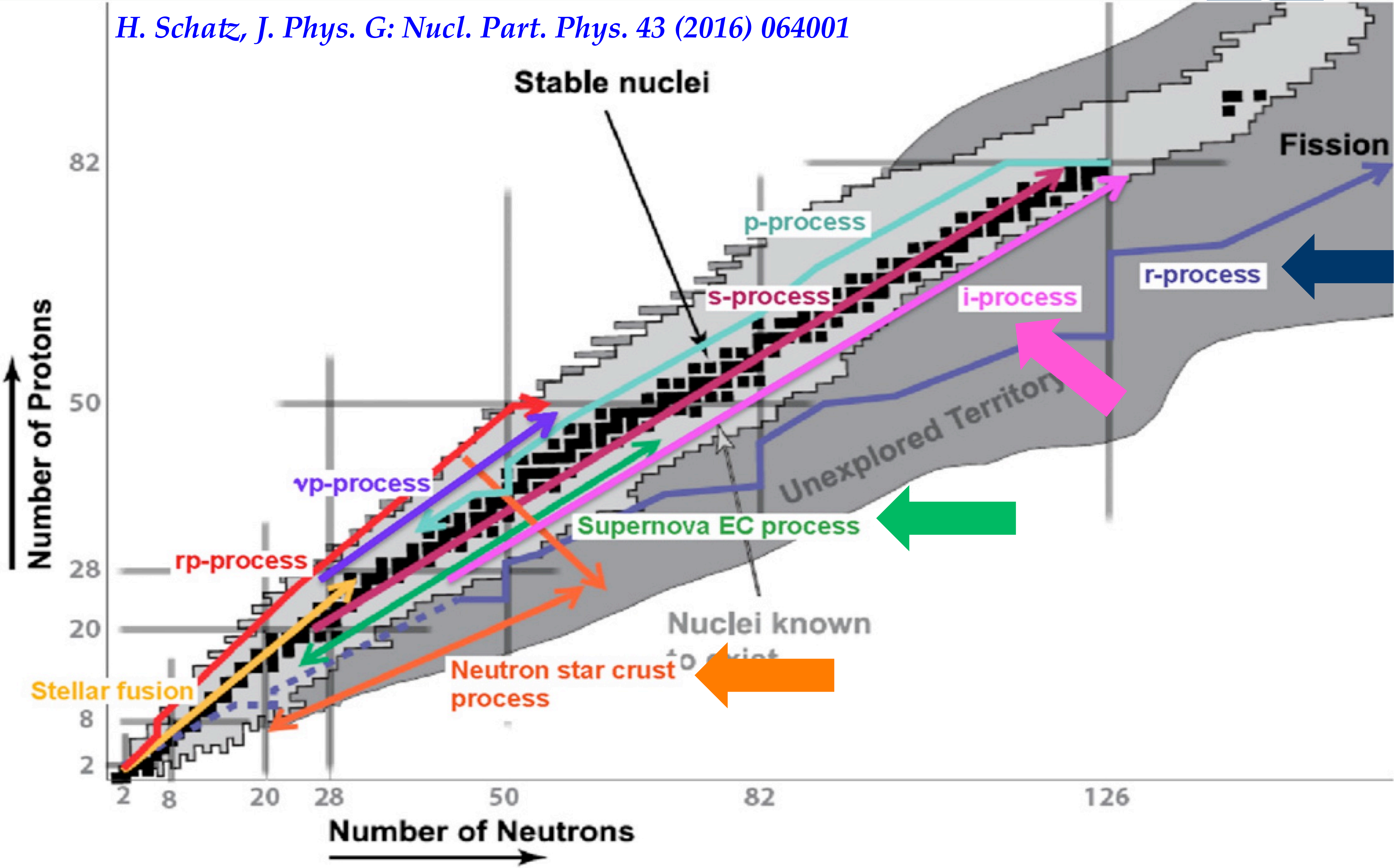
✓ What can be done at EURISOL-DF

→ How does it compare to Fragmentation facilities

✓ What may be reached at EURISOL

A. Kankainen - Astrophysical processes

H. Schatz, J. Phys. G: Nucl. Part. Phys. 43 (2016) 064001



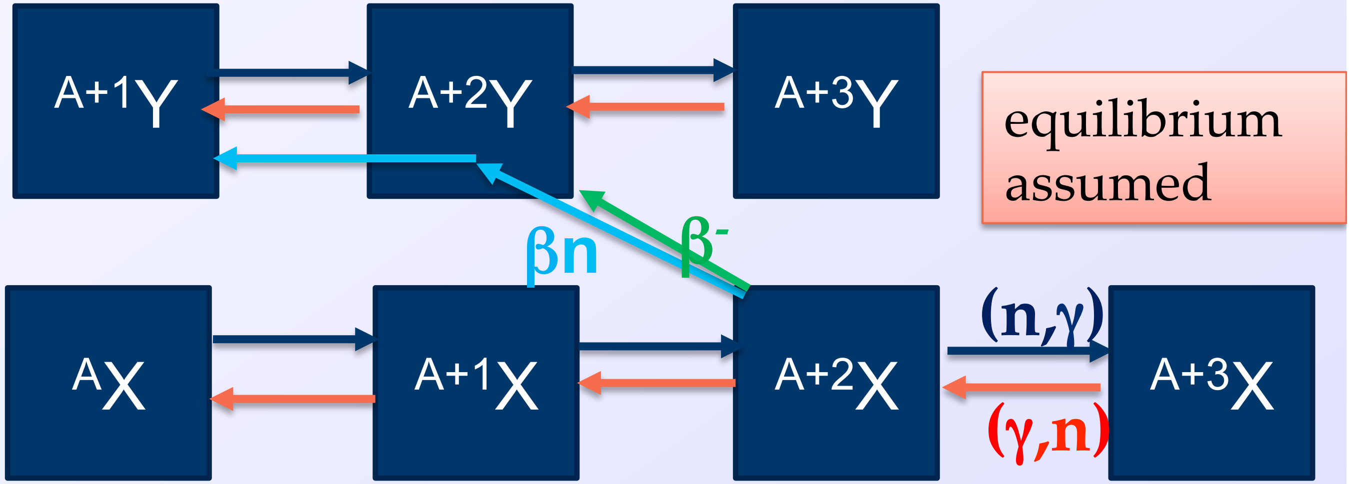
Nuclear properties and the r-process

Weak r process (A < 120)

- ν-driven winds from proto-neutron star in core-collapse supernovae
- Also in neutron star mergers
  N.V. Tanvir et al., Astrophys. J. Lett. 848, L27 (2017)

Main r process (A > 120)

- Merger of two neutron stars confirmed by GW170817, GRB 170817A&AT2017gfo; see e.g. *Astrophys. J. Lett. 848, L12 (2017)*
- neutron star – black hole mergers?
- Other sites, such as magnetars?



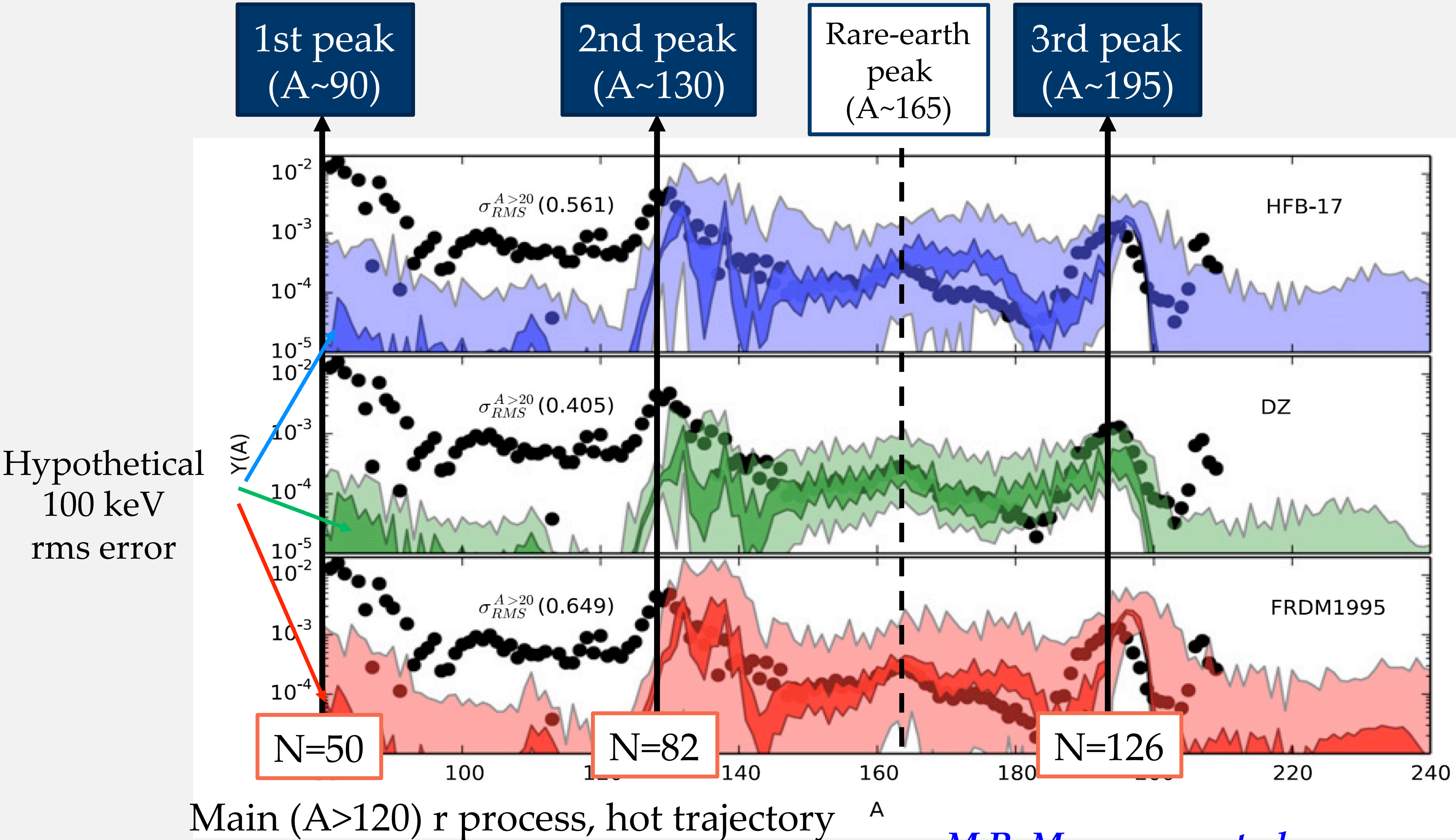
Classic r-process assuming (n,γ)-(γ,n) equilibrium:
- ➢ Isotopic abundances (waiting points) set by S_n (masses)
- ➢ Elemental abundances set by beta-decay half-lives
- ➢ Smoothening → ß-delayed neutron decays

- masses
- Beta-decay $T_{1/2}$
- P_n values

- (n,γ) rates excited states
- Fission

A. Kankainen

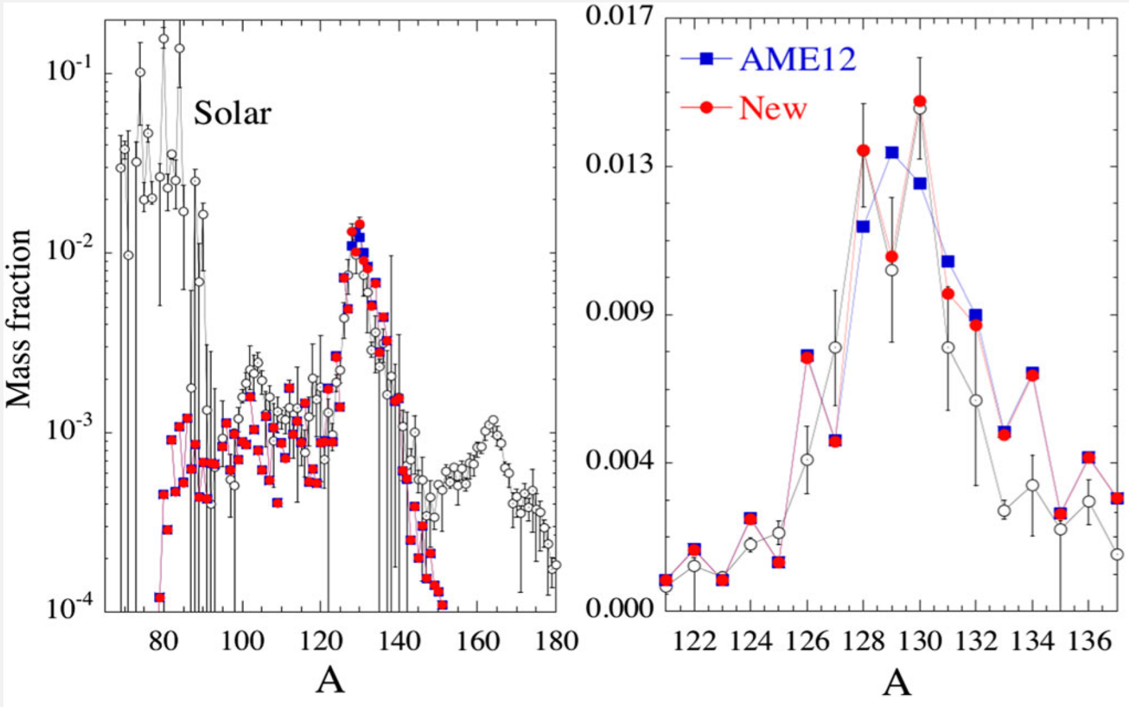
Masses: r-process abundances



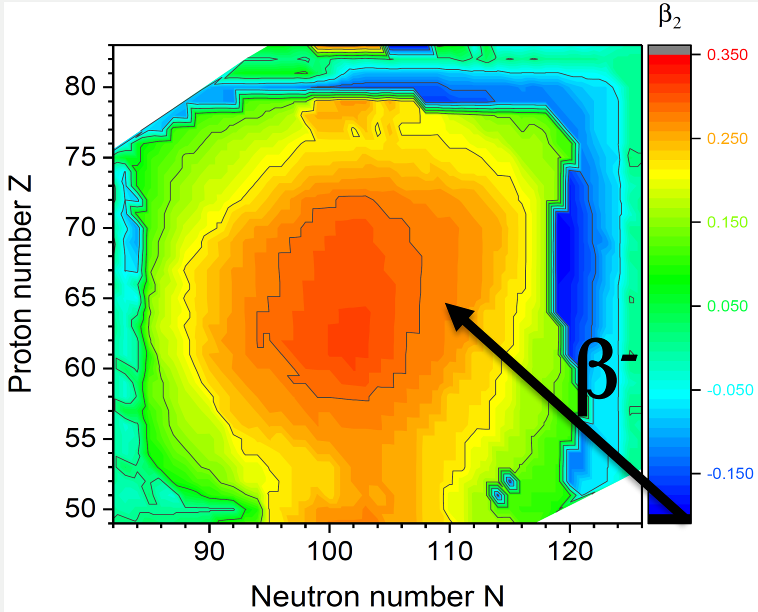
M.R. Mumpower et al.,
Progr. Part. Nucl. Phys. 86 (2016) 86

The second r-process peak and the ^{132}Sn region and rare-earth peak

Impact on the r process: Cd masses



D. Atanasov et al., PRL 115, 232501 (2015)



FRDM2012
P. Möller et al., ADNDT 109-110, 1 (2016)

- Forms during the freezeout phase when matter decays back to the stability
- **Midshell, different origin of the peak**
- Deformation maximum and/or deformed shell gap may drive abundances to create the rare earth peak and/or fission recycling?

NEED MASSES TO EXPLORE THIS!

Beta-decay: P_n & P_{2n} et al.

Smoothen r-process abundance pattern

BELEN at IGISOL: pure beams

- β2n emission of ^{136}Sb

  R. Caballero-Folch et al., EPJ Web of Conferences 146, 01005 (2017)

- βn emission of ^{135}Sb, ^{137,138}Te, $^{138\text{-}140}$I

  J. Agramunt et al., EPJ Web of Conferences 146, 01004 (2017)

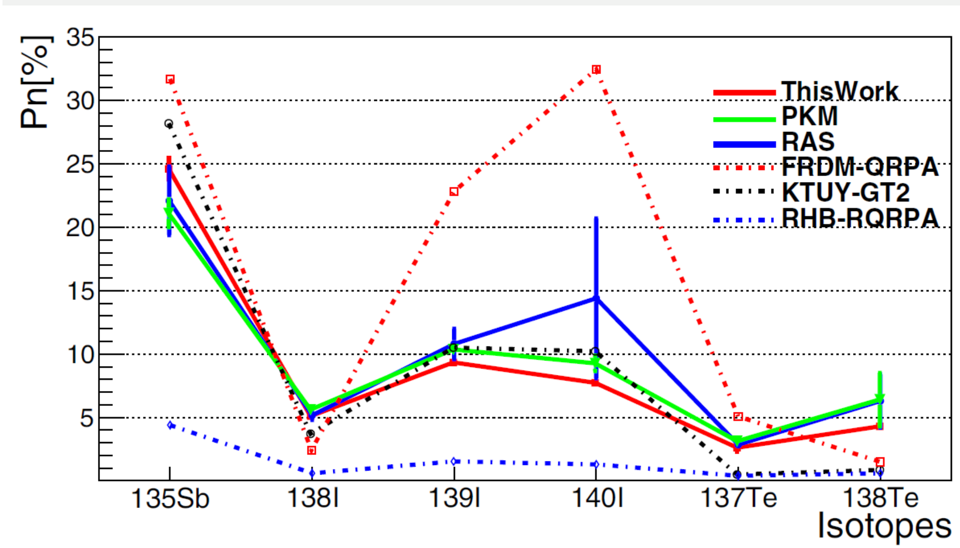
- Half-lives: long-living isomeric states? Identification of the states?
- First-forbidden beta decays relevant for the r process
- GT strengths for EC rates (inverse of beta decay) for core collapse and neutron star crust processes

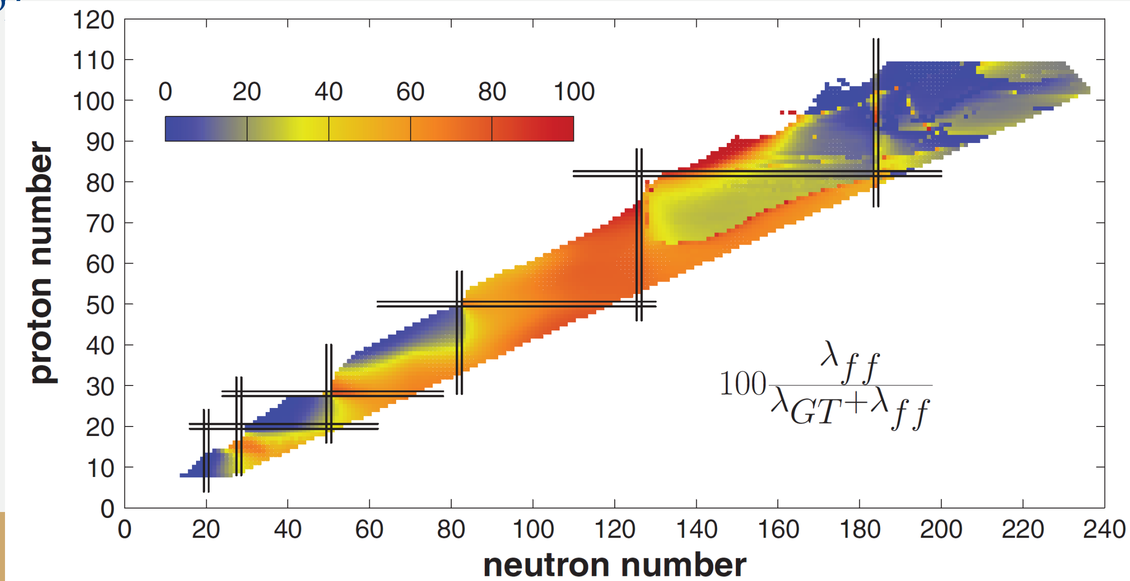
FRDM+QRPA approach

T. Marketin et al., PRC 93, 025805 (2016)

PKM= Pfeiffer et al., Prog. Nucl. Energy 41, 39 (2002)

RAS = Rudstam et al., Atom. Data Nucl. Data Tables 53, 1(1993)





O. Sorlin - Determination of neutron capture rates

What for ? : r process freeze-out, neutron bursts, cooling of neutron stars

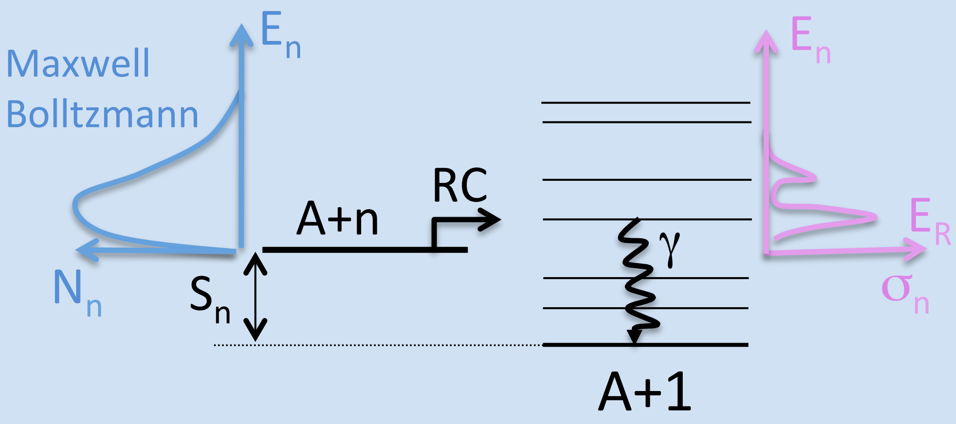
Far from stability, around closed shells

$E_n \approx kT \approx$ 100 keV for T $\approx 10^9$K

- $S_n(A+1)$ is small
- Few states contribute, mainly low L
- Resonant or / and Direct capture

Other methods needed for nuclei in between shell closures -> level density and γ-strengths

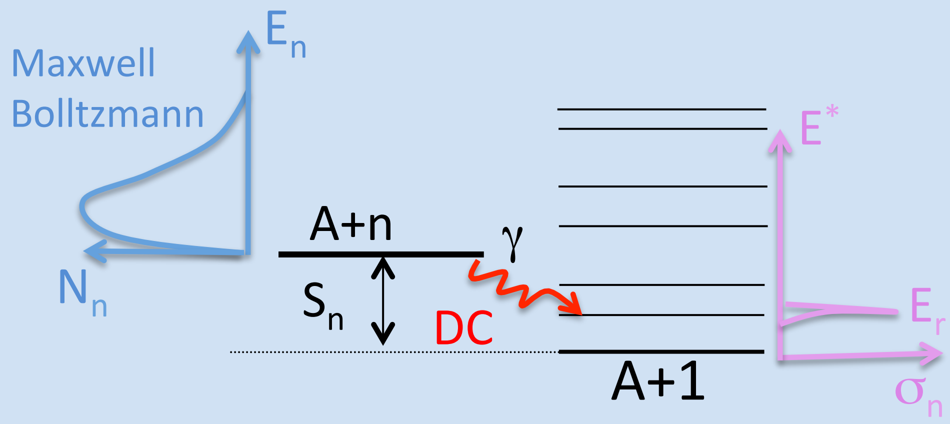
Resonant capture



$$\sigma_{BW}(E) = \omega(J_1,J_2,J)\,\pi\lambda^2 \frac{\Gamma_n \Gamma_\gamma}{(E-E_R)^2+(\Gamma_{tot}/2)^2}$$

Measure E_R, Γ_n and Γ_γ

Direct capture



$$\frac{d\sigma}{d\Omega} \approx S \left| \int \Phi_f \, \theta_{EM} \, \Phi_i \, d\vec{r} \right|^2$$

Bound state — Folding potential

θ_{EM}: E1,M1 operators strongly dominant

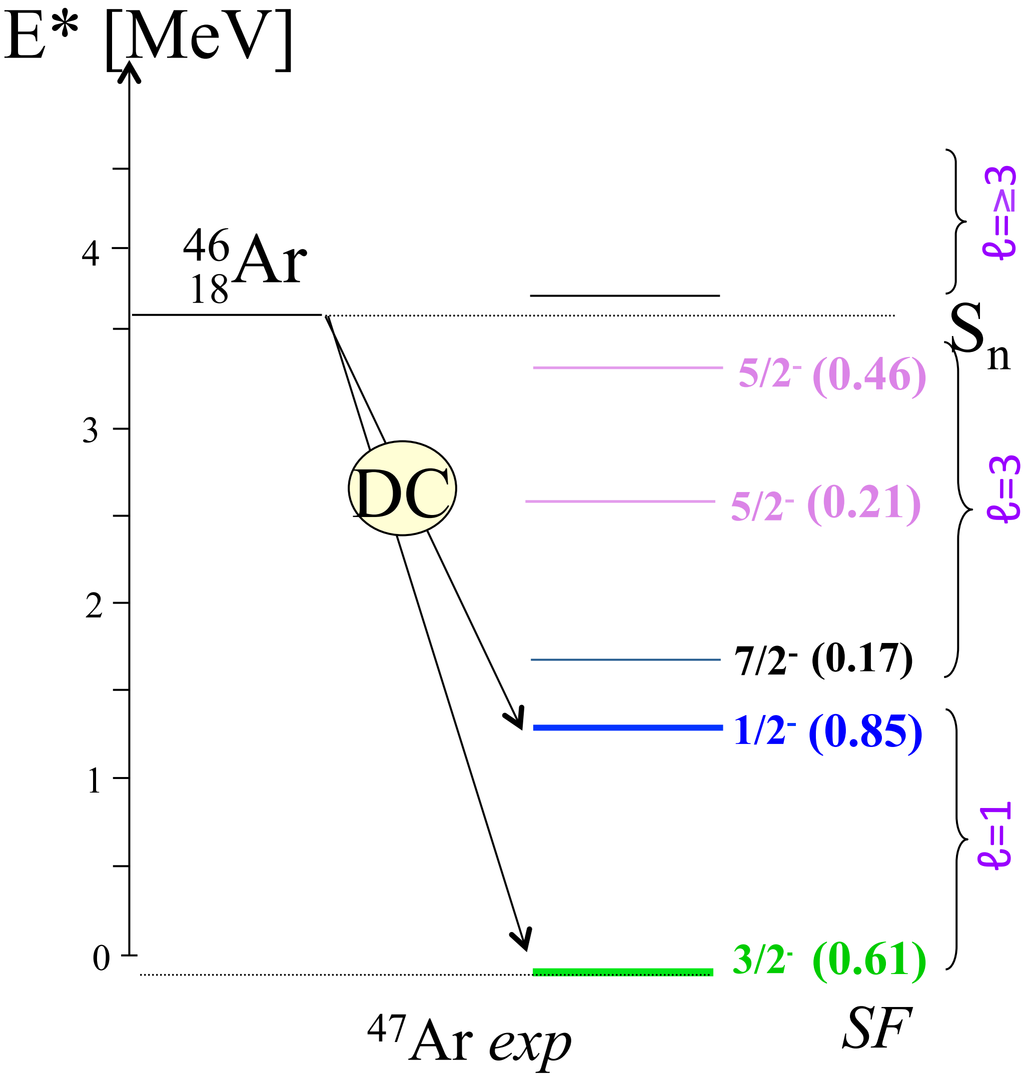
Determine J, L, S, E_r, S_n

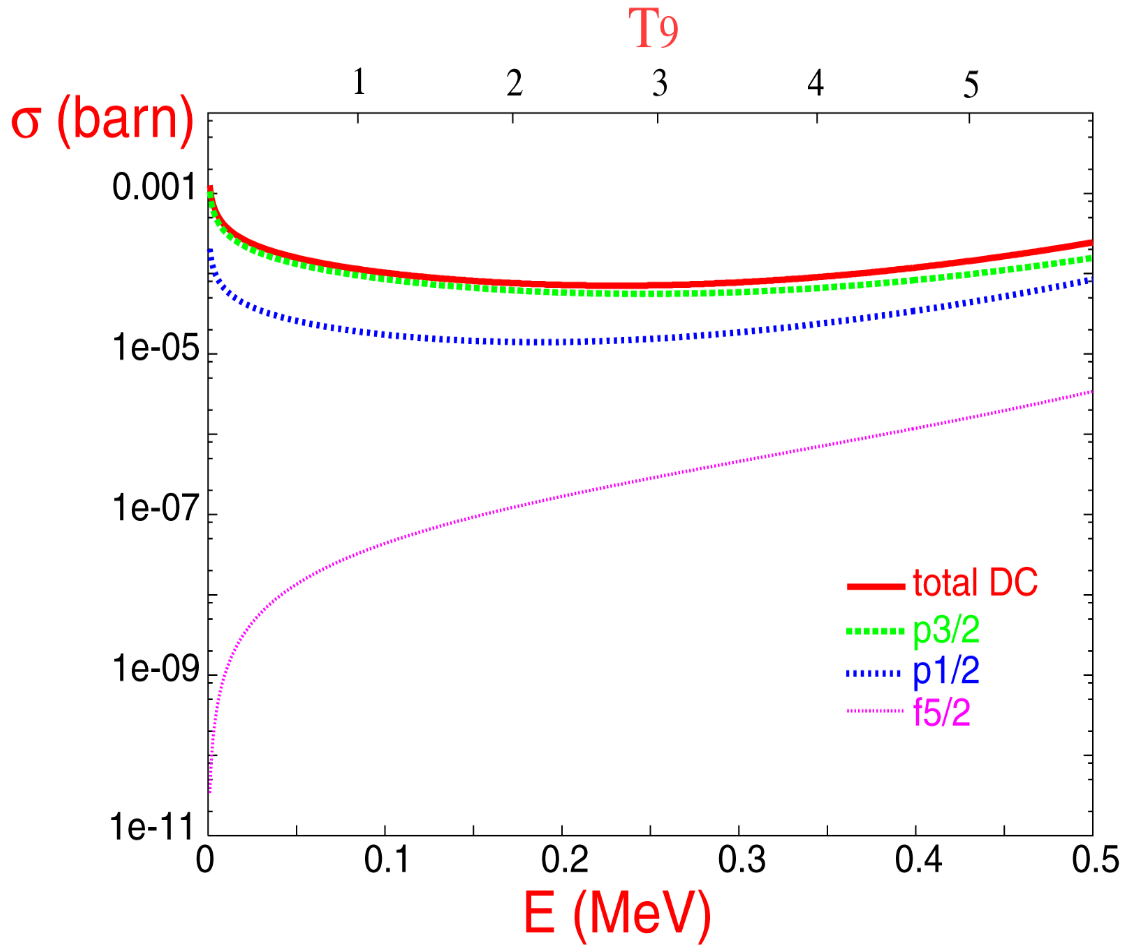
Transfer (d,p) reactions can provide S_n, E, L, SF required for n captures

Comparison of (n,γ) versus (d,p)-derived cross section (Kraussmann et al. PRC 53 (1996))

Choose the appropriate energy for momentum matching (v/c~0.1) , RIB of ~10^5pps

Neutron capture rate at N=28 (^{46}Ar)





(d,p) access to E*, SF, spins → derive (n,γ) stellar rates

Direct capture (E1) with $\ell_n = 0$ on *p* states dominates

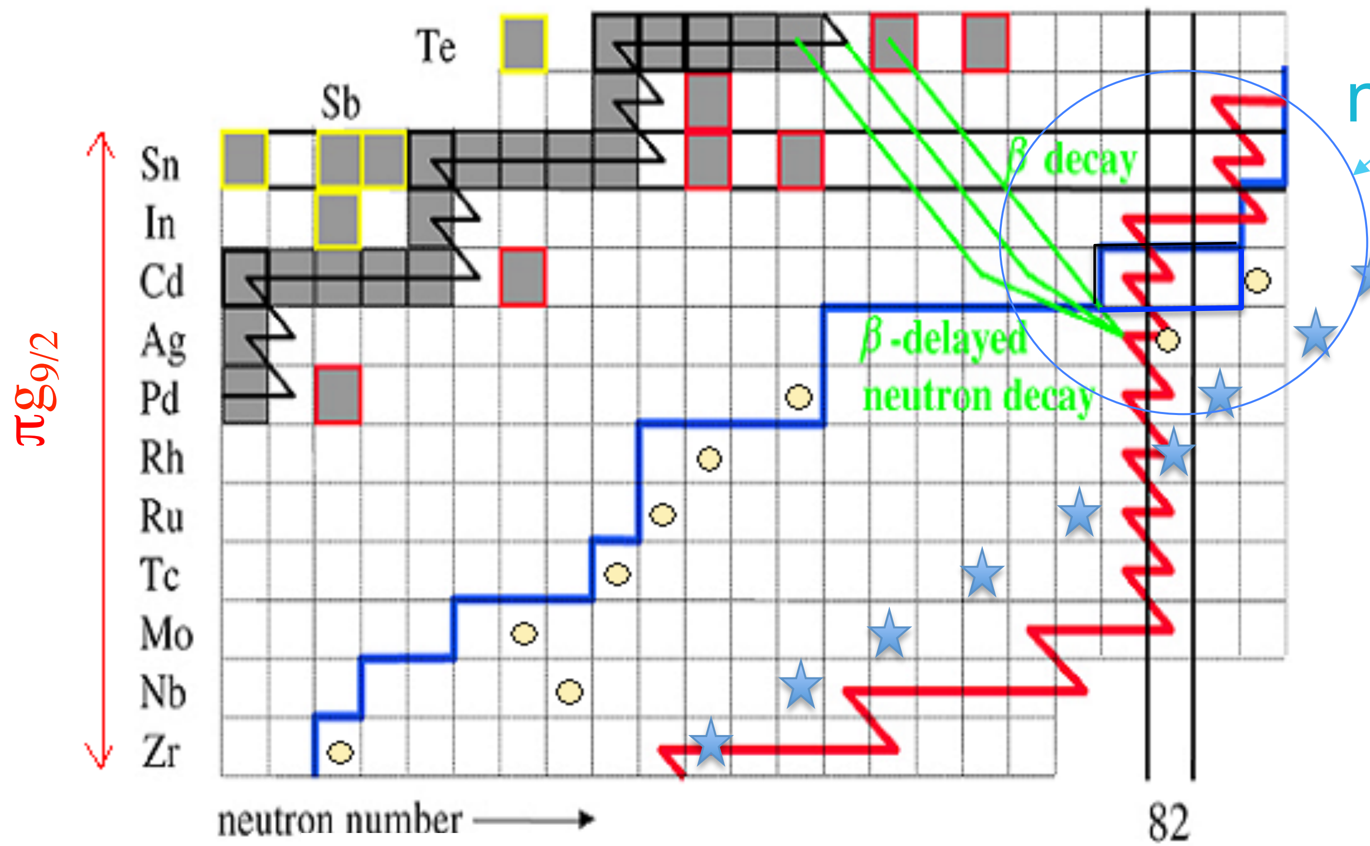
Speed up neutron-captures at the N=28 closed shell

Favor the enhancement of ^{48}Ca over that of ^{46}Ca using d_n= 3 10^{19}-^{21} cm^{-3}

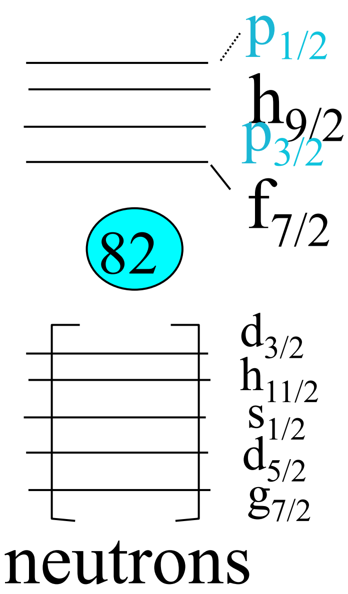
O. Sorlin et al. CR Phys 4 (2003)
L. Gaudefroy et al., EPJA (2006)

Neutron capture rate at N=82

Shuffle the material to more neutron-rich when the star expands
Could modify the shape of the r process peak
Play a role in weak r process conditions



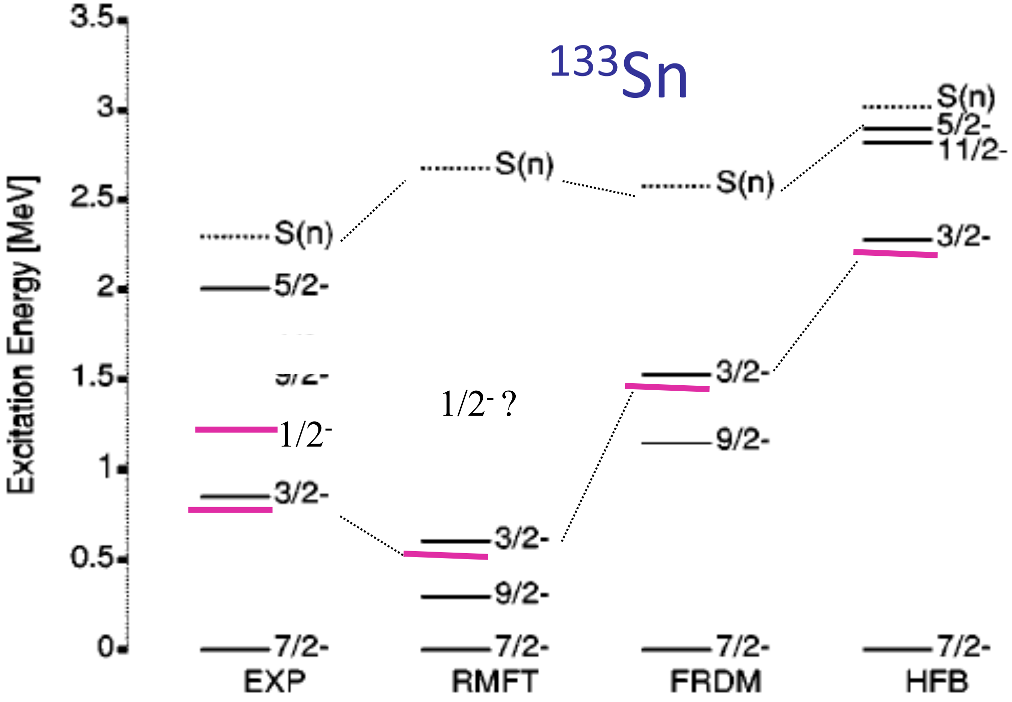
n capture rates important



○ $T_{1/2}$ until 2013
★ $T_{1/2}$ new RIKEN data
— Limits of mass measurements

Same p orbits present ..

Neutron captures at the N=82 shell closure

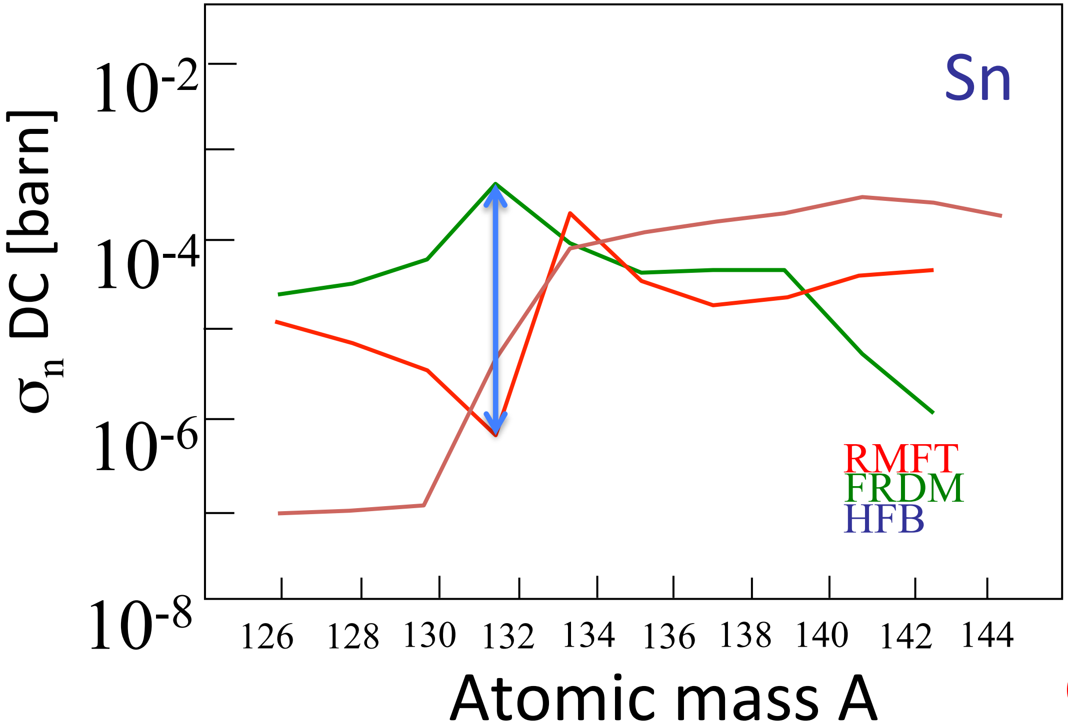


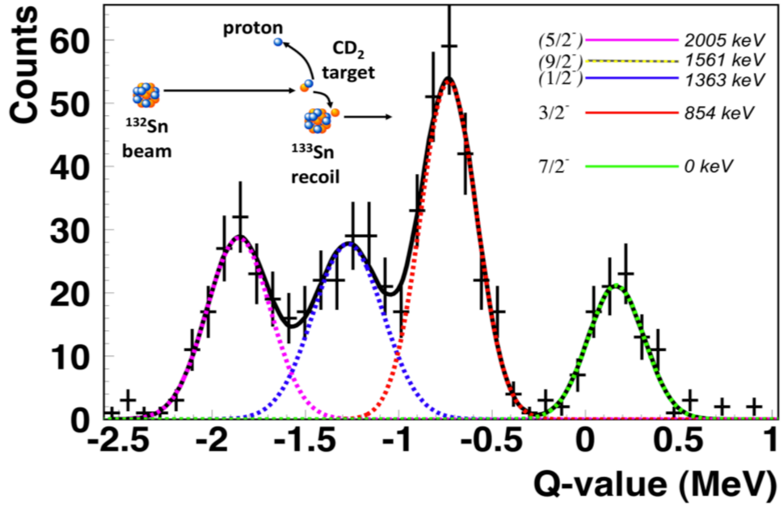
Same cross sections at ^{132}Sn, by chance!

Differ by more than factor 100 at ^{130}Sn

-> important role of DC on p orbits

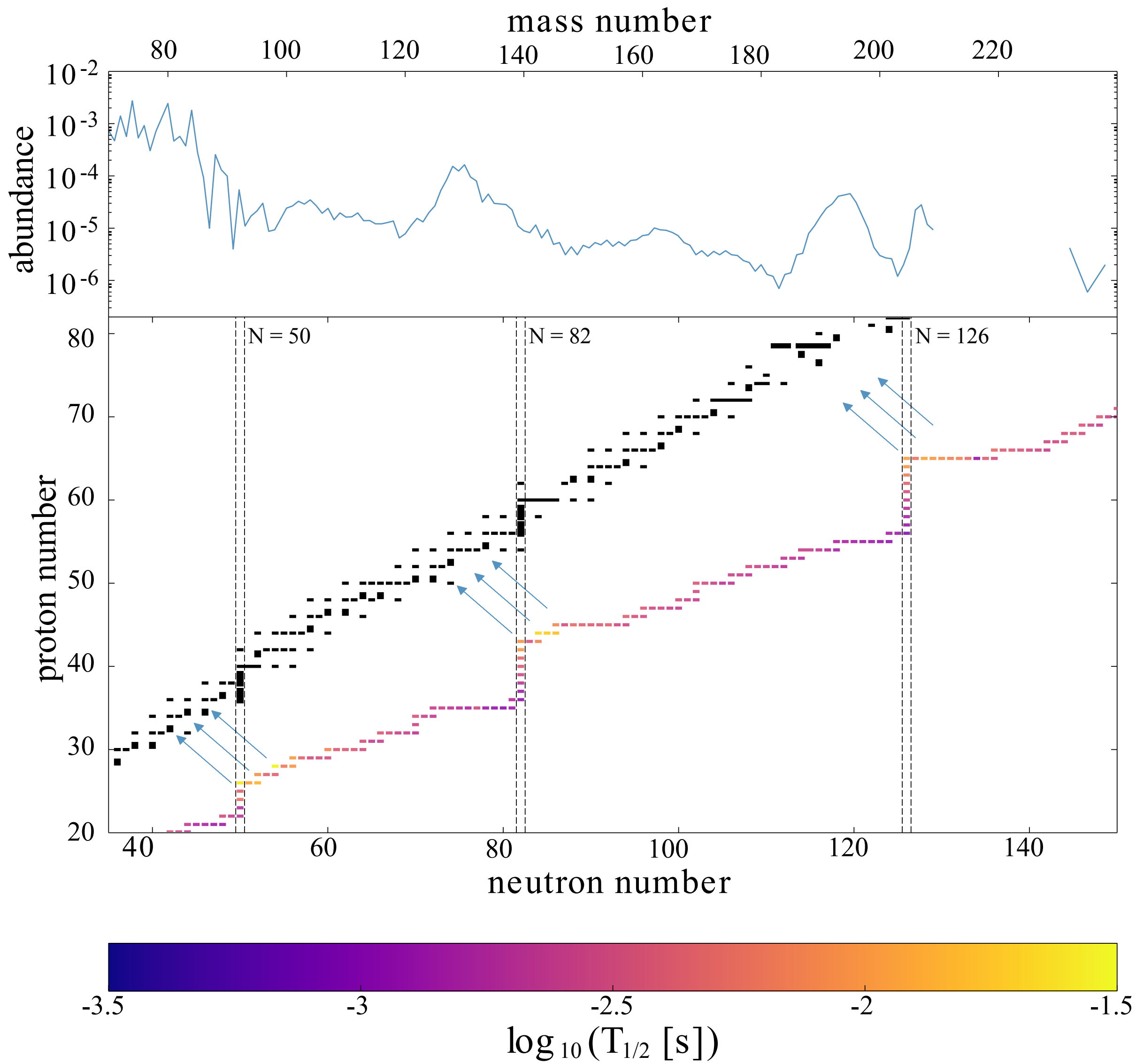
Rauscher et al. PRC 57(1998)





Jones et al. Nature 465 (2010)

Go to heavier Sn or Cd in the future



Uncertainties for r-process calculations

Nuclear properties

- Masses
- neutron capture cross sections
- β-decay rates
- fission rates & fragment distribution

Hydrodinamical conditions

$$Y_e = \frac{n_p}{n_p + n_n}$$

temperatures and densities

expansion timescales

What is the relative weight of uncertainties?

Where does the r-process path run in (n,γ)-$(\gamma$,n) equilibrium?

detailed balance:

$$\lambda_{\gamma,n}(Z,A+1) = \frac{2G(Z,A)}{G(Z,A+1)} \left(\frac{A}{A+1}\right)^{3/2} \left(\frac{m_u kT}{2\pi\hbar^2}\right)^{3/2} \langle\sigma v\rangle_{n,\gamma}(Z,A) \exp[-S_n(Z,A+1)/kT]$$

$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{\langle\sigma v\rangle_{n,\gamma}(Z,A)}{\lambda_{\gamma,n}(Z,A+1)} n_n = \frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} n_n \exp[S_n(Z,A+1)/kT]$$

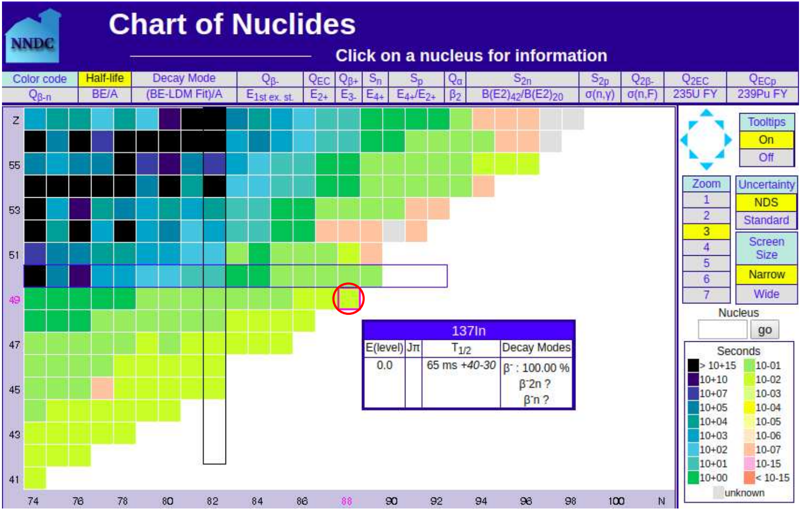
along any given isotopic chain, the isotope (Z,A) with maximum abundance can be estimated via

$$\frac{Y(Z,A+1)}{Y(Z,A)} = 1$$

$$S_n(Z,A+1) = -kT \ln\left[\frac{G(Z,A+1)}{2G(Z,A)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} n_n\right]$$

e.g., Thielemann, ME, et al. (2017)

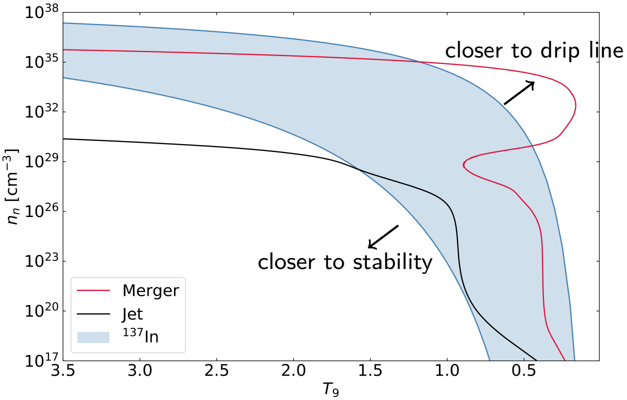
Example: ^{137}In



https://www.nndc.bnl.gov/nudat2/

Equilibrium conditions

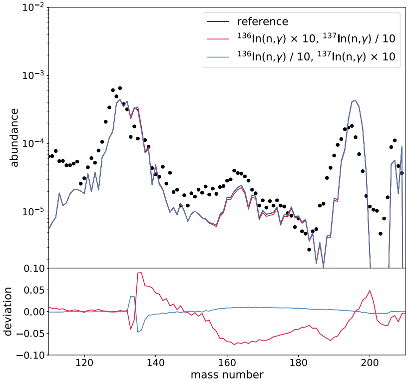
$$n_n = \frac{2G(Z,A)}{G(Z,A+1)} \left(\frac{A}{A+1}\right)^{3/2} \left(\frac{m_u kT}{2\pi\hbar^2}\right)^{3/2} \exp[-S_n(Z,A+1)/kT]$$



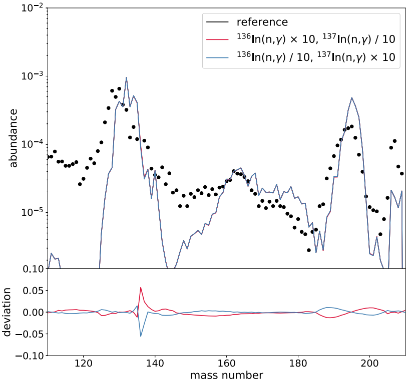
Merger: Rosswog et al. (2013)
Jet: Winteler et al. (2012)

^{137}In: (n,γ)-(γ,n) only

Neutron star merger

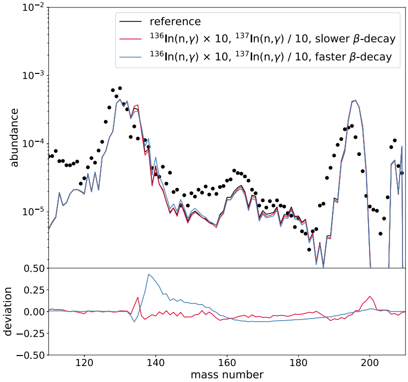


MHD SN (Jet)

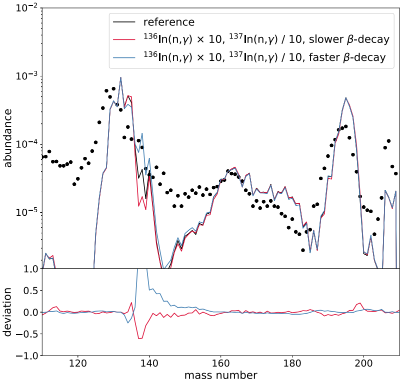


^{137}In: (n,γ)-(γ,n) and β-decay

Neutron star merger



MHD SN (Jet)



Summary

✓ r-process evolves in several stages where different effects are important

→ with nuclear heating always reaches (n,γ)-(γ,n) equilibrium

✓ r-process isotopes found if equilibrium holds

✓ late-stage n captures (freeze-out) possible (i-process…?)

✓ Regular observations of kilonovae will provide detailed information on nuclear composition of the ejecta

→ what can we learn from experimental measurements?

✓ Single-process isotopes

→ Eu, Ba

Summary

✓ Relevant properties of nuclear far from stability

→ masses, T1/2, Pn

→ neutron-capture rates on unstable nuclei

- case dependent, techniques?

✓ Understand processes in stars that can produce abundances

✓ EURISOL-DF (facilities)

→ pure, hiqh quality beams for mass measurements and beta decay studies

- complementarity…

→ isomers and their role in the r process

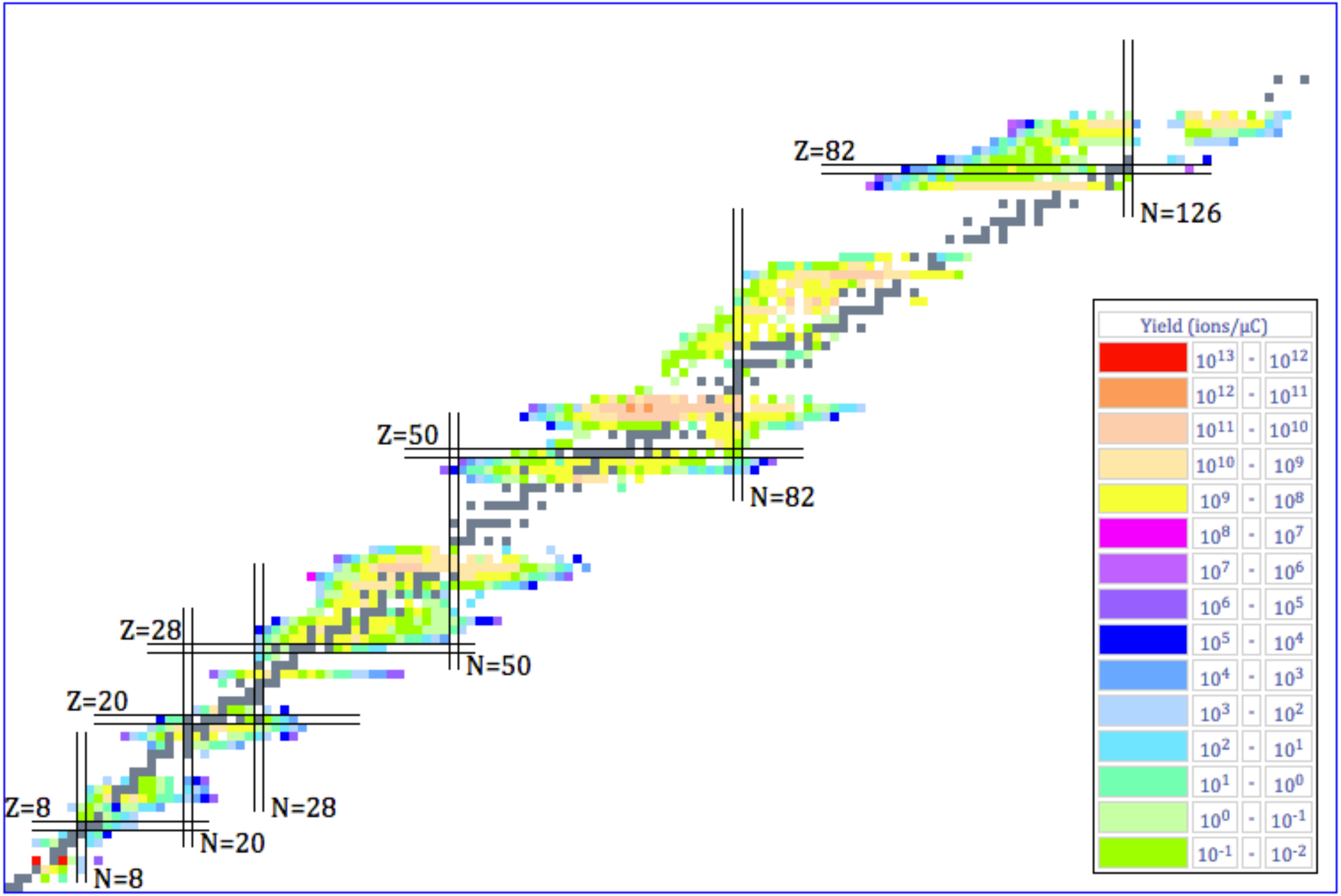
→ go further out to neutron-rich nuclei

EURISOL

EURISOL-DF

EURISOL-DF

But don't forget the fuel!!


Z=82
N=126
Z=50
N=82
Z=28
N=50
Z=20
N=28
Z=8
N=20
N=8
Yield (ions/μC)
10^13 - 10^12
10^12 - 10^11
10^11 - 10^10
10^10 - 10^9
10^9 - 10^8
10^8 - 10^7
10^7 - 10^6
10^6 - 10^5
10^5 - 10^4
10^4 - 10^3
10^3 - 10^2
10^2 - 10^1
10^1 - 10^0
10^0 - 10^-1
10^-1 - 10^-2

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