94 β-Decay Half-Lives of Neutron-Rich $_{55}$Cs to $_{67}$Ho: Experimental Feedback and Evaluation of the *r*-Process Rare-Earth Peak Formation

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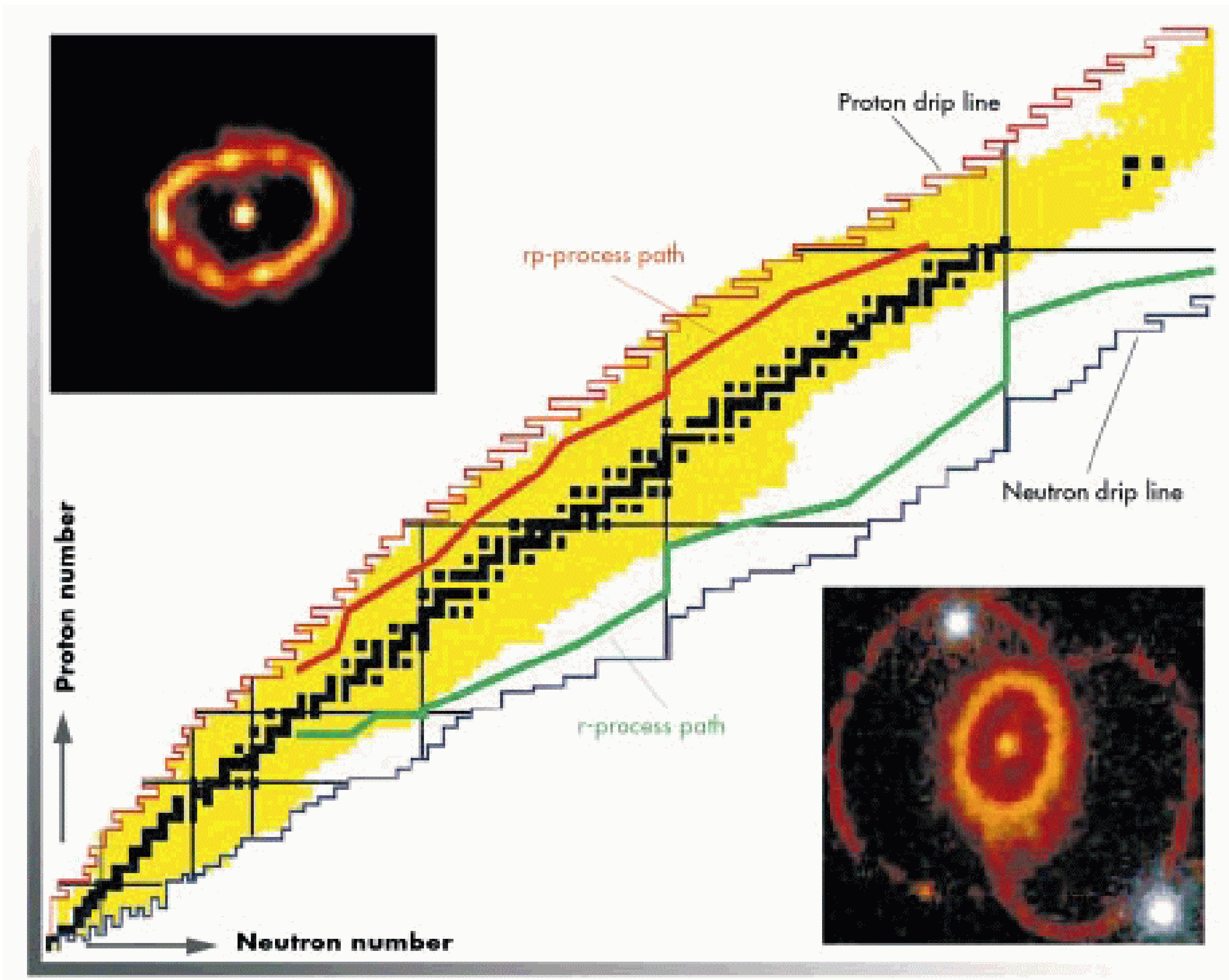
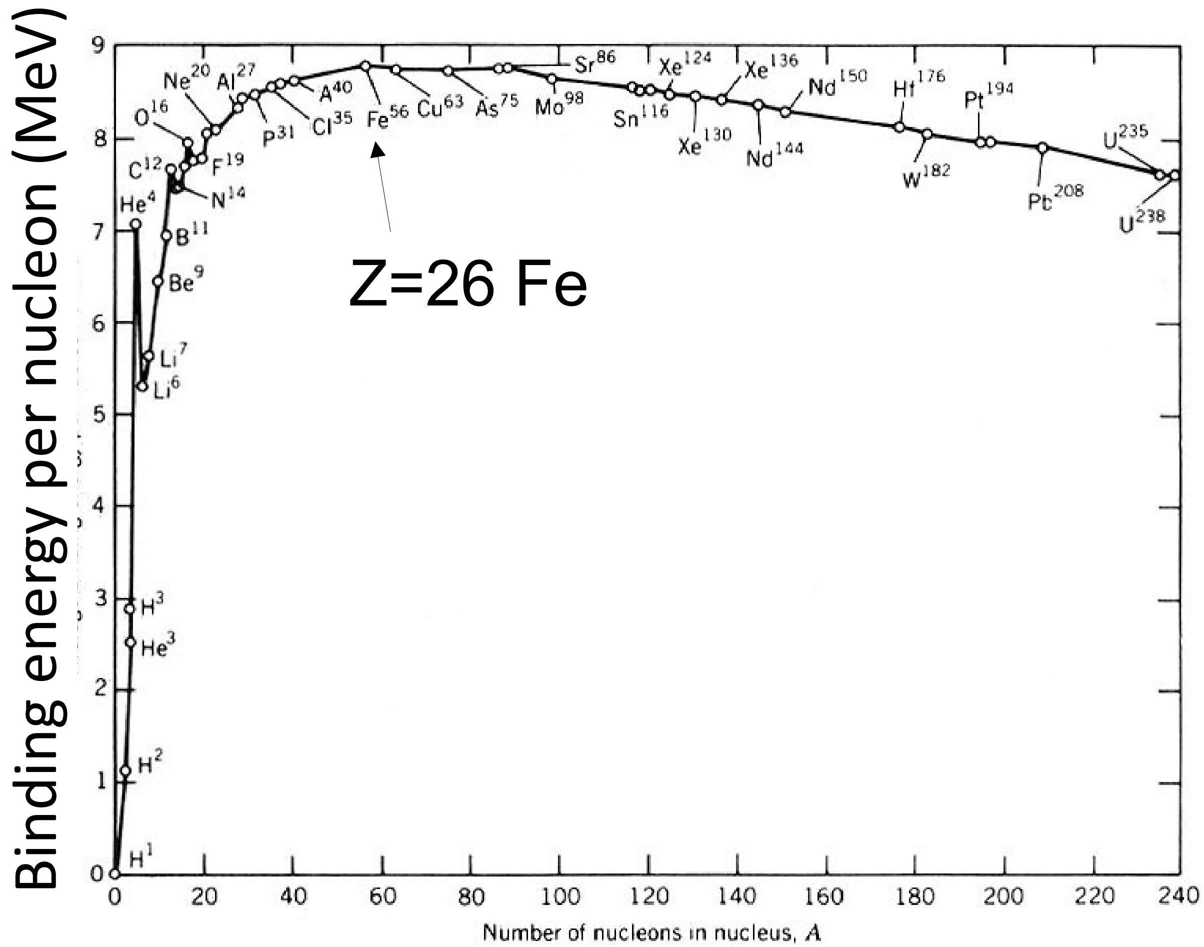
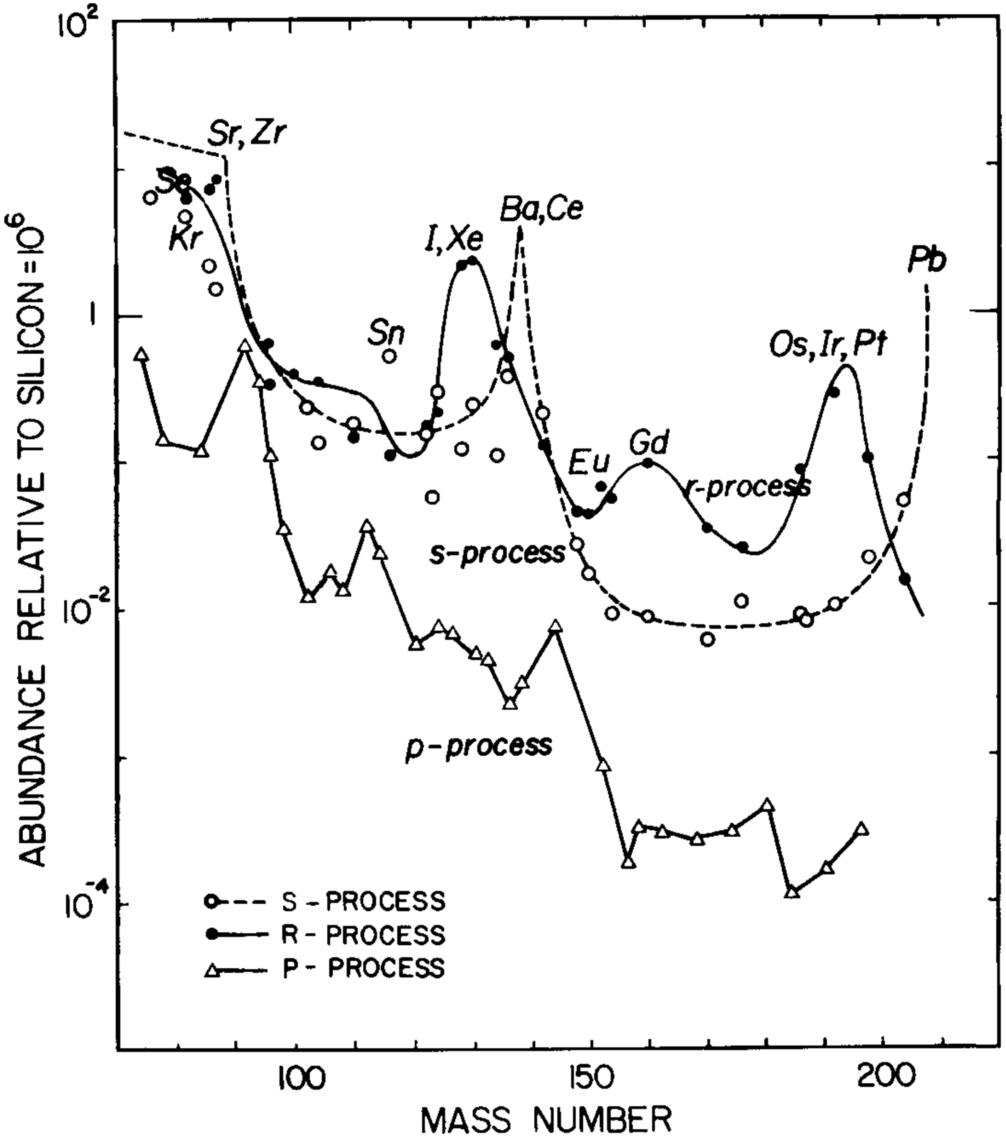


How are heavy elements created? ….. can't be just fusion



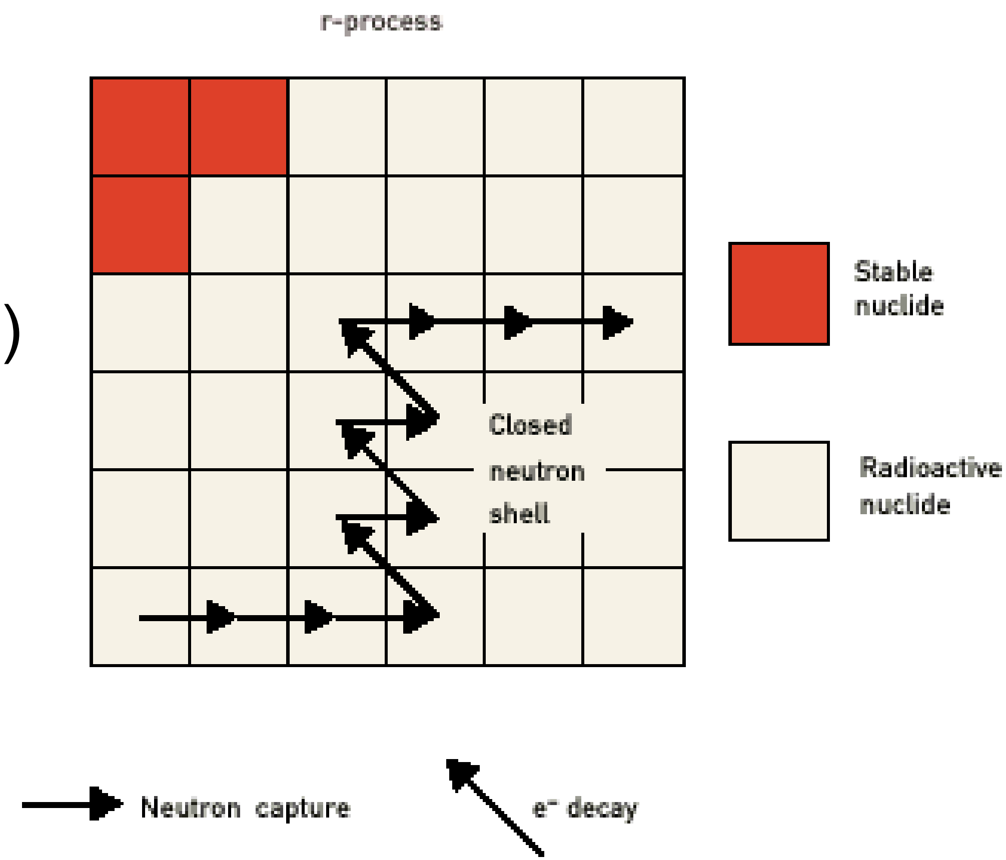
How are the heavy elements (Z>26) on Earth created?



- ~50 % r-process
- What are the necessary r-process astrophysical conditions?
- What is the important nuclear structure input ($T_{1/2}$, Q_β, P_n, …..)?

What is the r-process?

- Successive neutron captures by a seed nucleus in a very high neutron flux (10^{24} n/cm^3)
- (n,γ), (γ,n) reactions
- β decay



Nucleosynthesis in the r-process

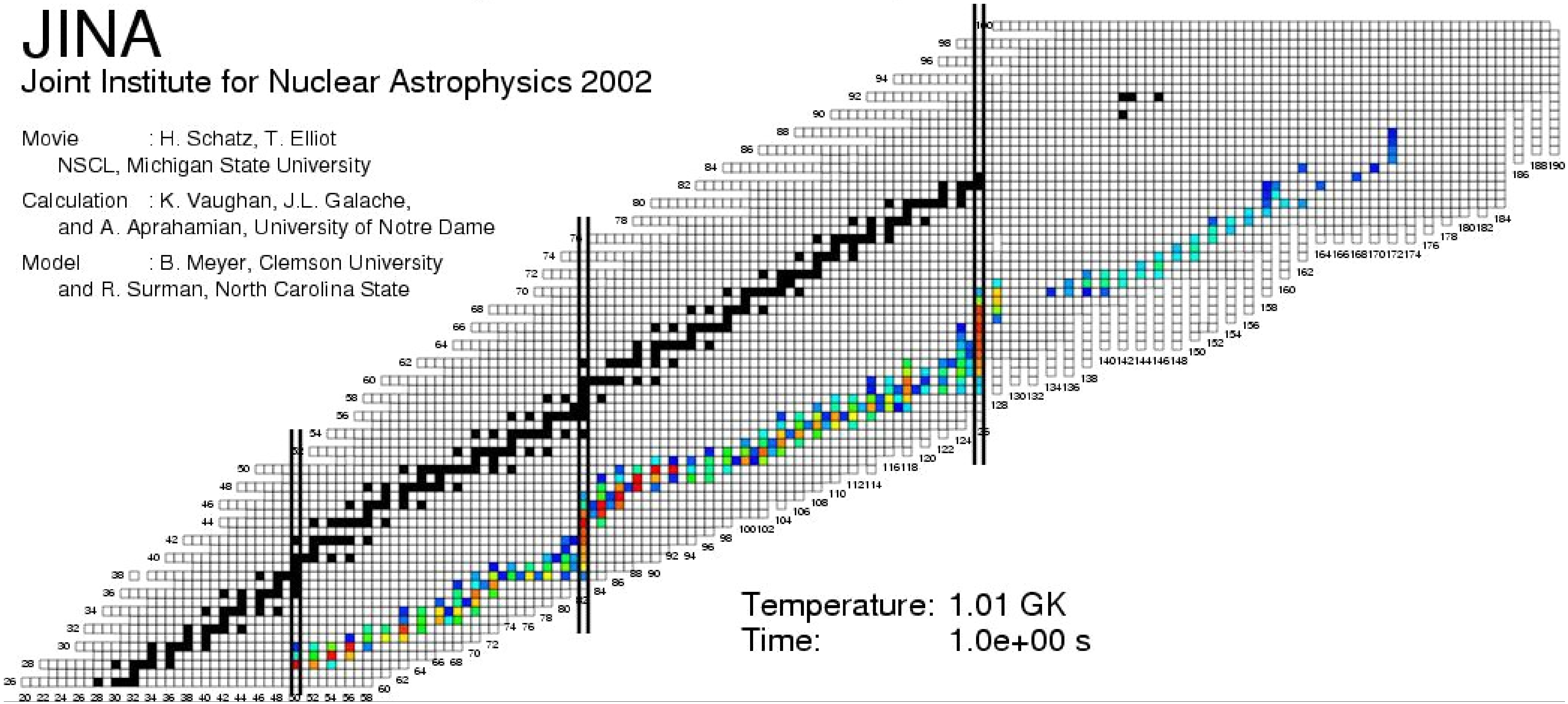
JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, T. Elliot
NSCL, Michigan State University

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State

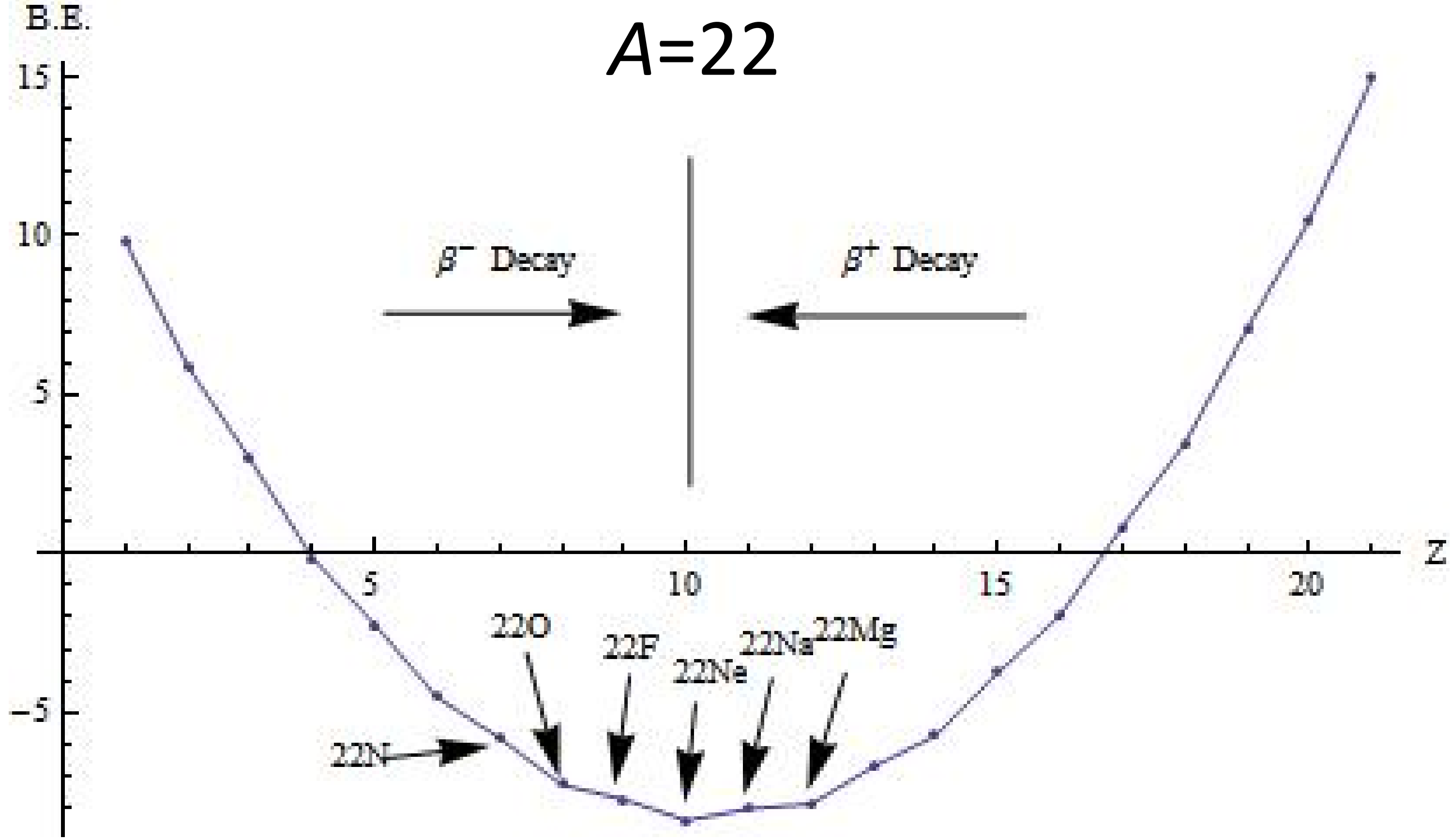


Astrophysical conditions

process	conditions	timescale	site
s-process (n-capture, ...)	T~ 0.1 GK τ_n~ 1-1000 yr, $n_n \sim 10^{7-8}$/cm^3	10^2 yr and 10^{5-6} yrs	Massive stars (weak) Low mass AGB stars (main)
r-process (n-capture, ...)	T~1-2 GK $\tau_n \sim \mu$s, $n_n \sim 10^{24}$ /cm^3	< 1s	Type II Supernovae ? Neutron Star Mergers ?
p-process ((γ,n), ...)	T~2-3 GK	~1s	Type II Supernovae

- Recent articles cast doubt that the conditions for the r-process can be found in the core collapse of a Type-II supernovae
- Difficult to probe these astrophysical conditions (T, n_n, τ_n) ……. but we can experimentally measure many parts of the nuclear structure input

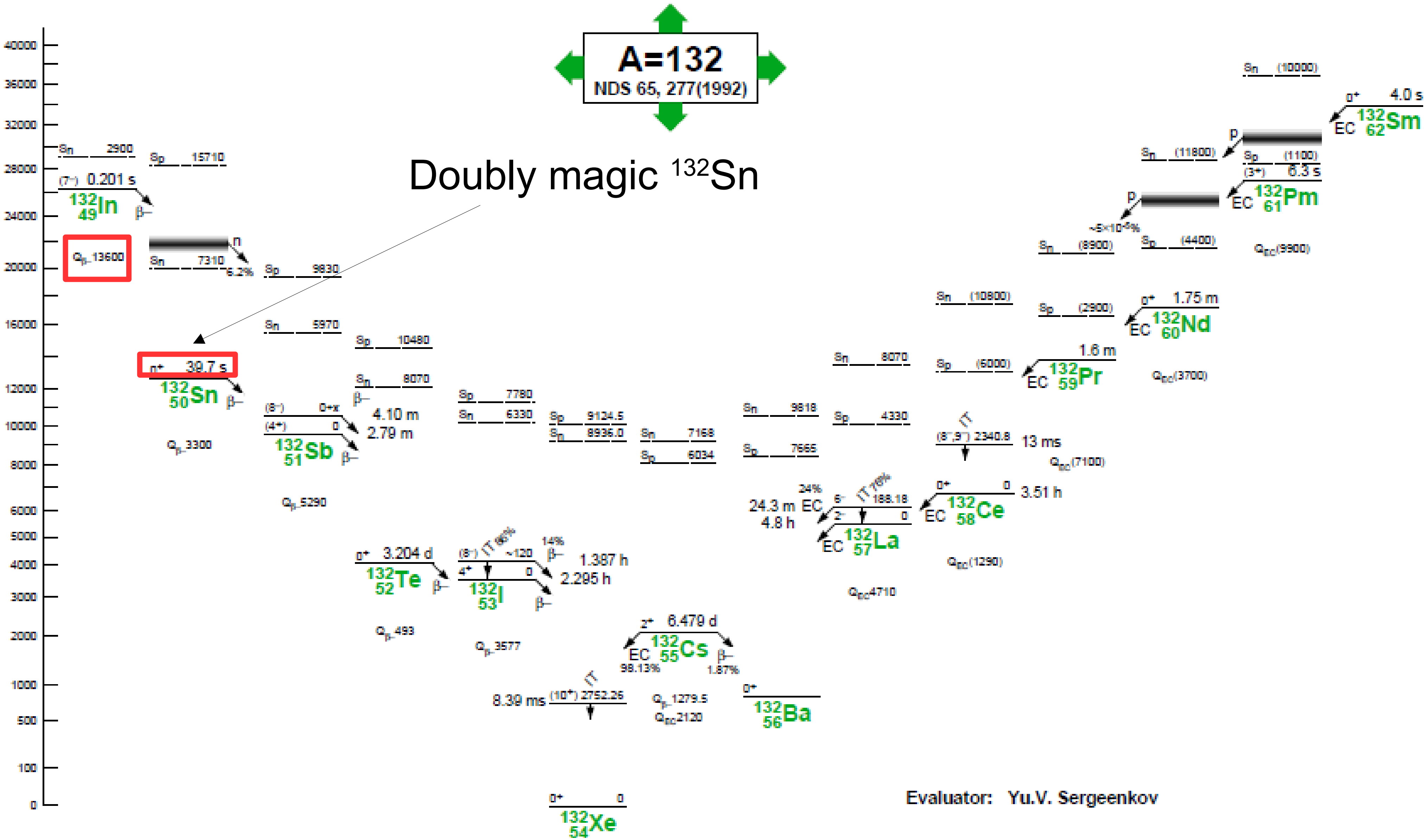
Why are nuclei radioactive?



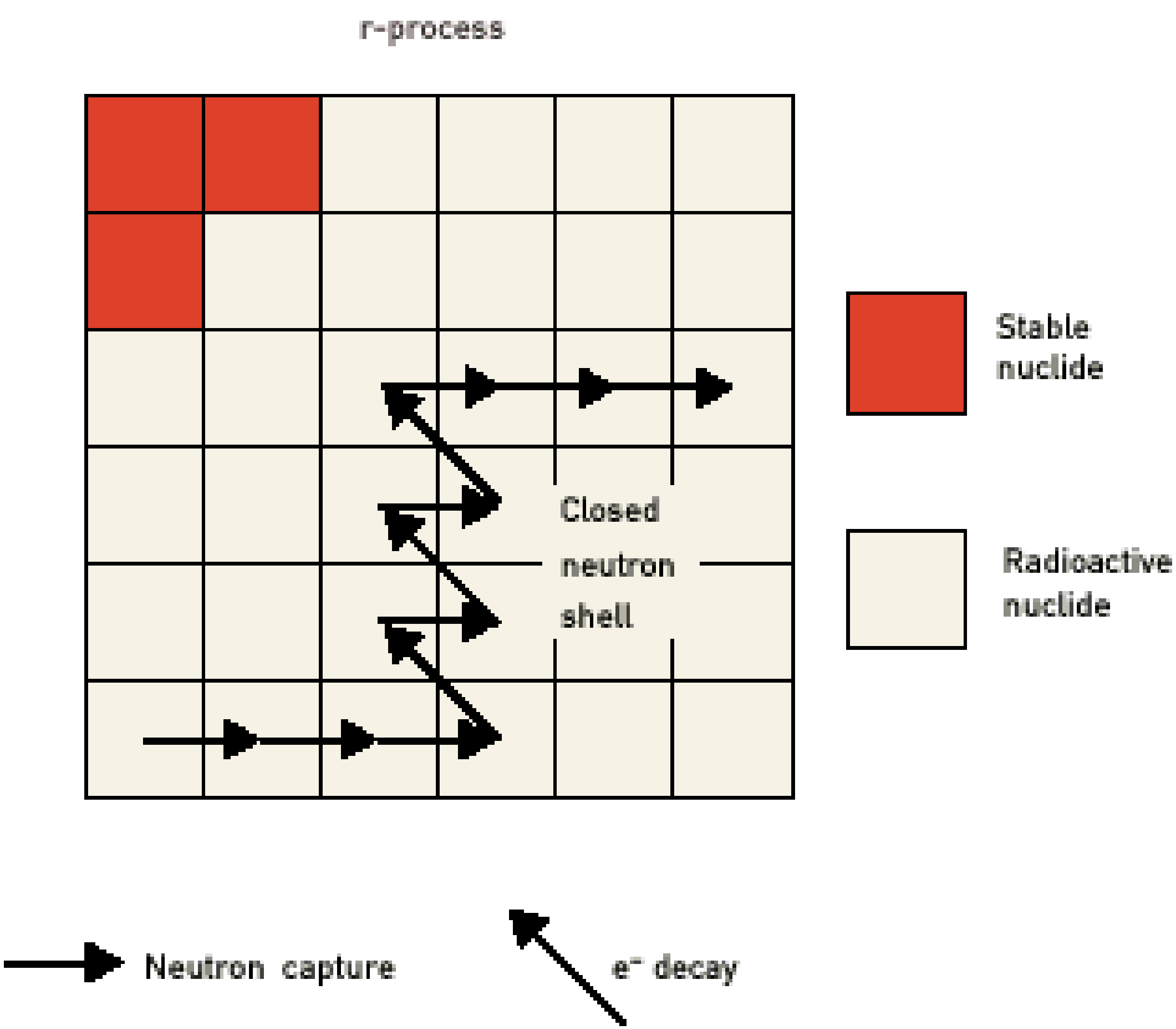
- Nuclei will always try to maximise their binding energy, and can do so via radioactive $\beta^{+/-}$ decay

$$B = a_v A - a_s A^{2/3} - a_c Z(Z-1) A^{-1/3} - a_{sym} (A-2Z)^2/A + \delta$$

Effect of Neutron Shell Closures

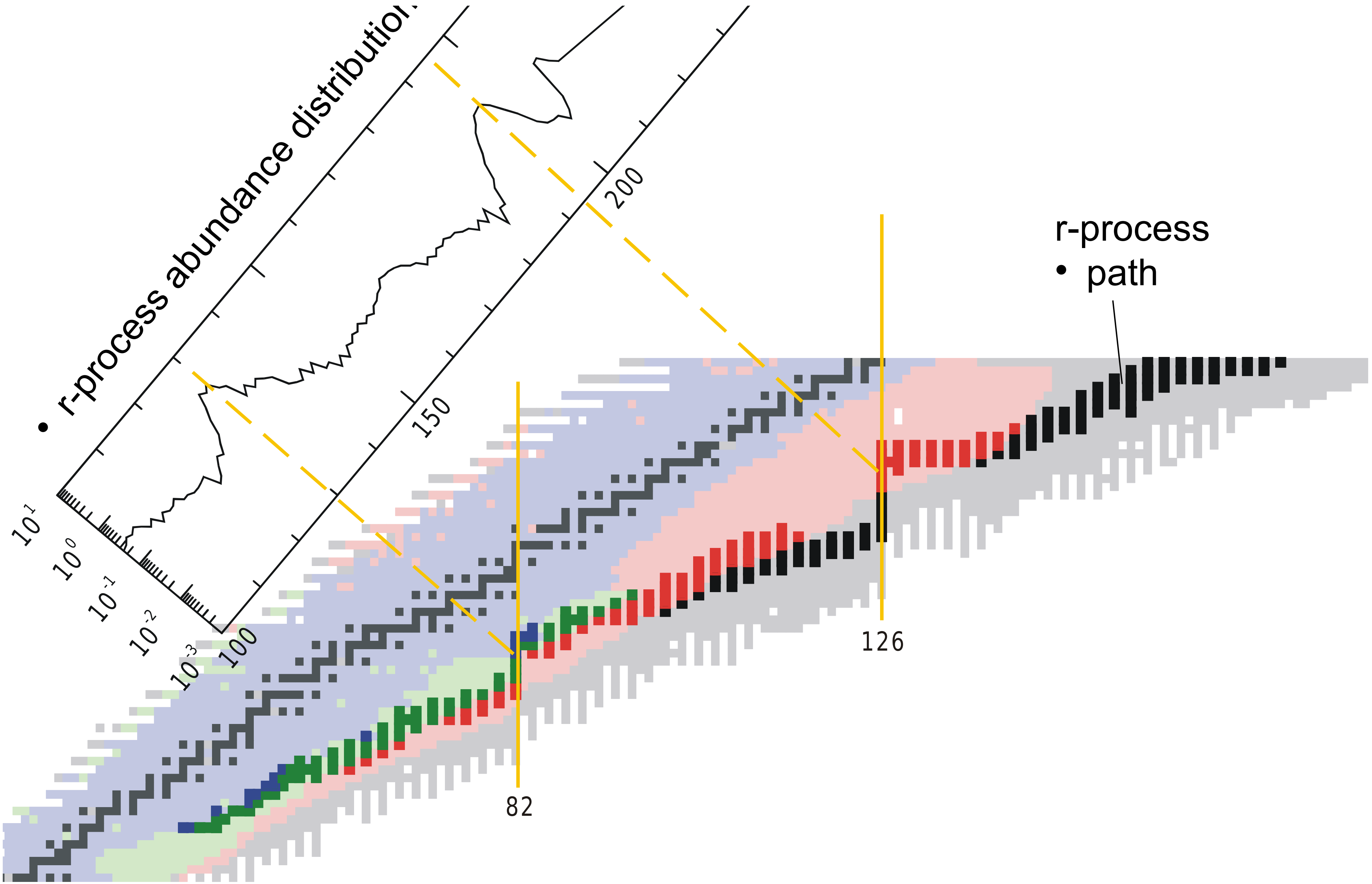


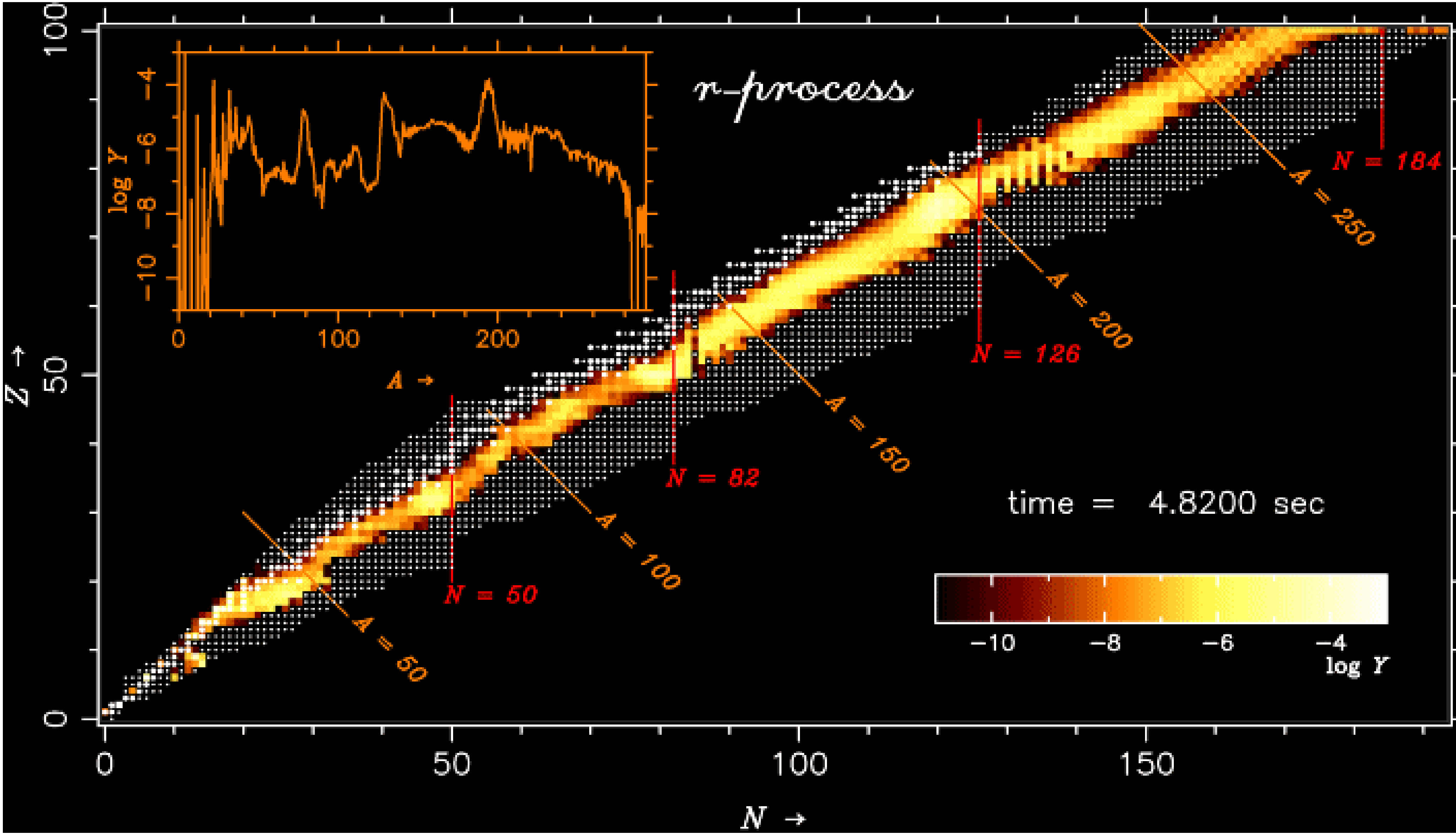
Effect of Neutron Shell Closures
-creates reaction waiting point



- Longer $T_{1/2}$ than neighbours
- Next neutron capture less probable
- High Q_β values of parent

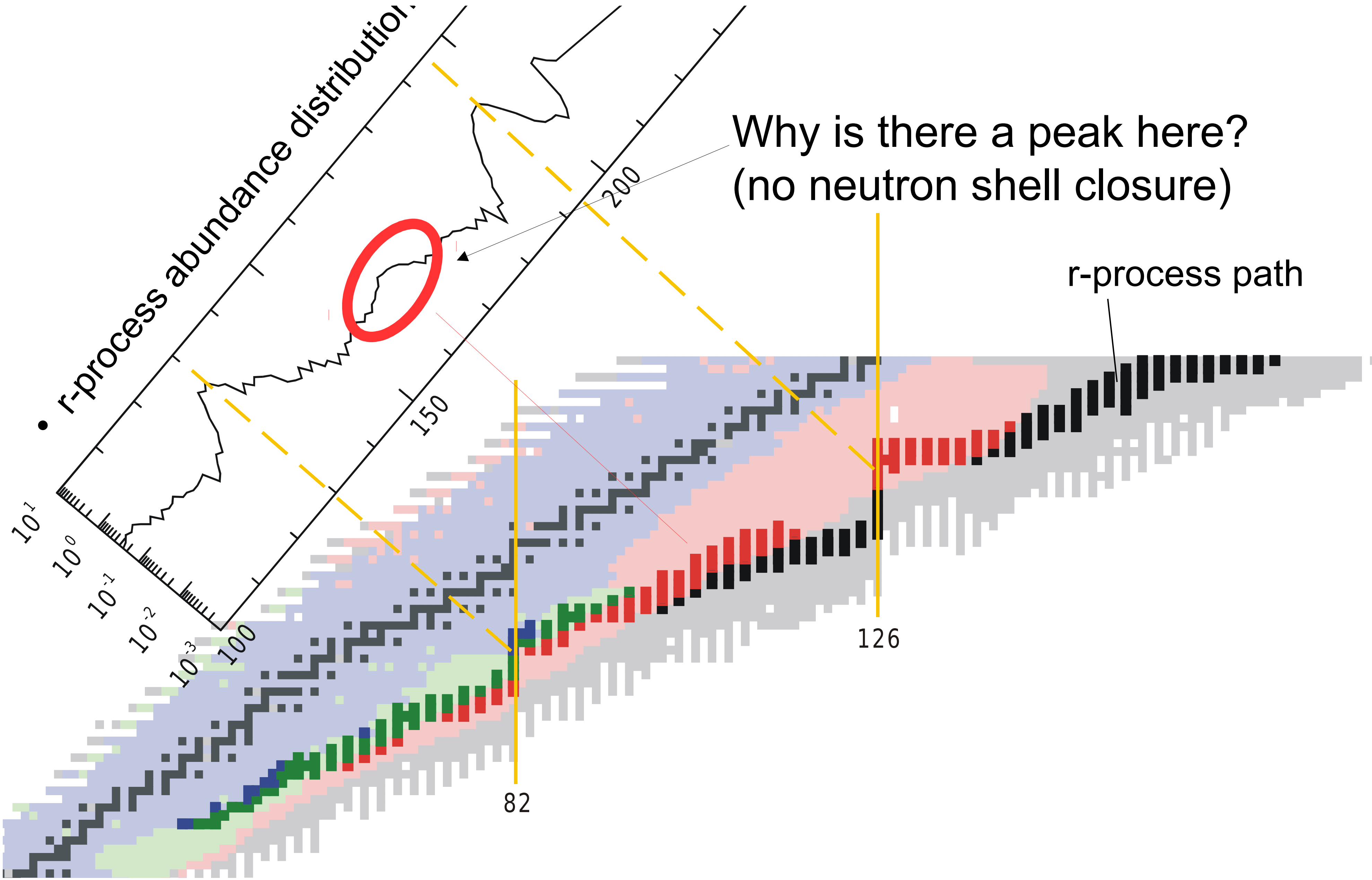
- The r-process path



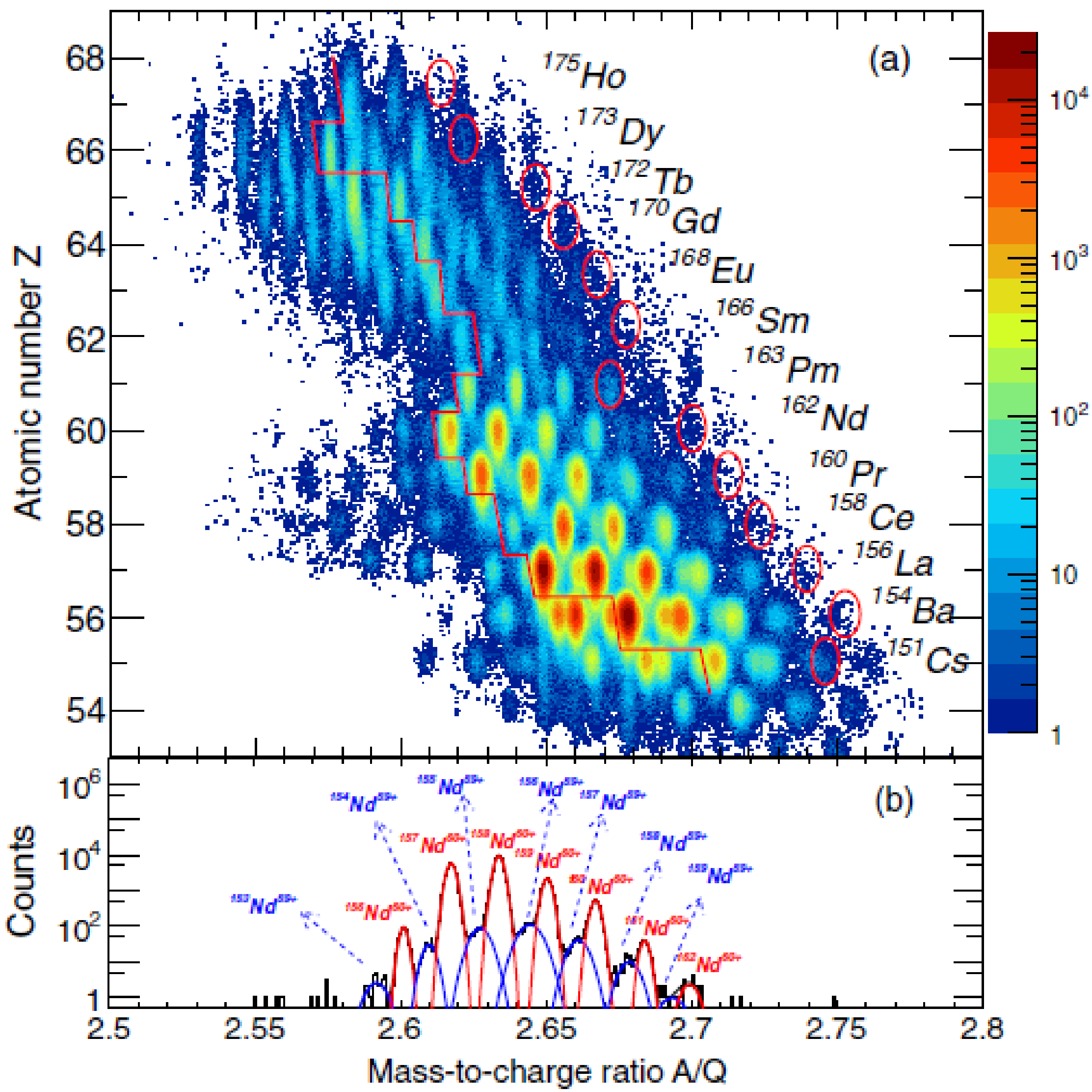


r-process
time = 4.8200 sec
N = 50
N = 82
N = 126
N = 184
A = 50
A = 100
A = 150
A = 200
A = 250
log Y
A →
Z →
N →
−10
−8
−6
−4
0
50
100
150
200

- The r-process path

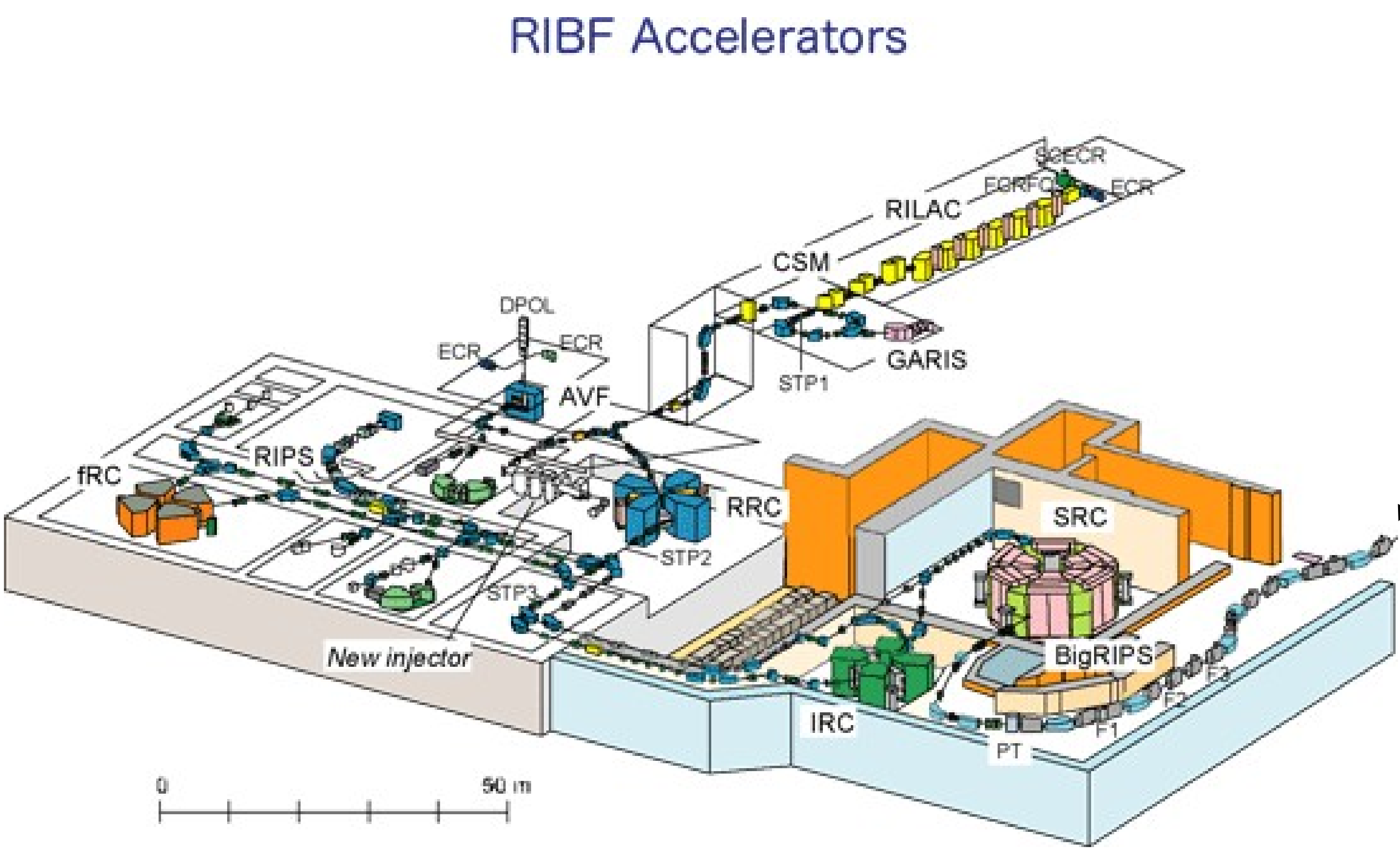


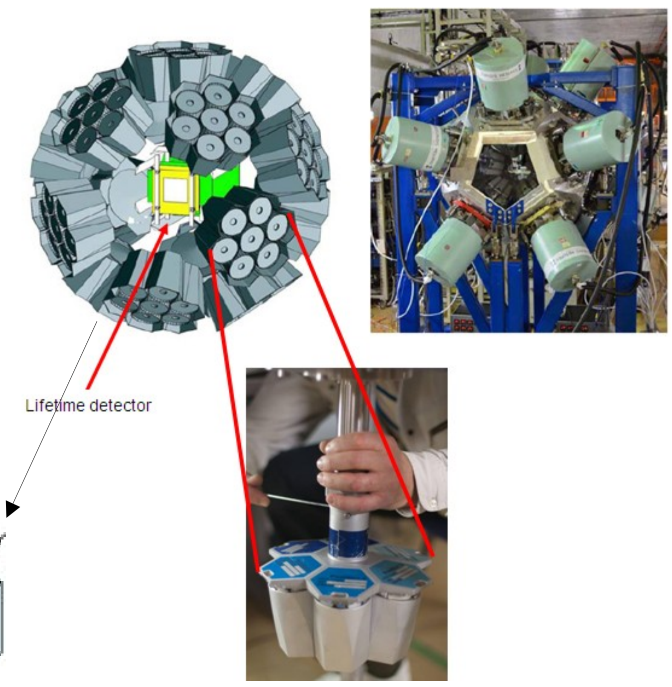
Provide nuclear structure input: $T_{1/2}$



- Produce neutron-rich nuclei with A~160 at RIBF RIKEN
- Participate in r-process "freeze out"
- Measure $T_{1/2}$, (β-decay properties, Pn, isomers ……)

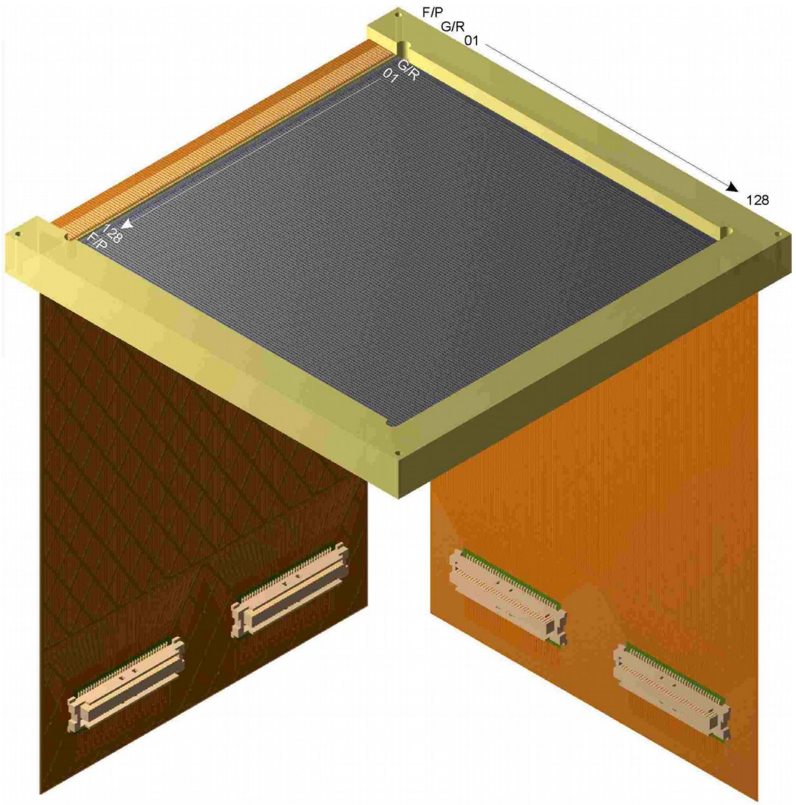
RIBF RIKEN In-flight fission of a 345 MeV/u ^{238}U beam



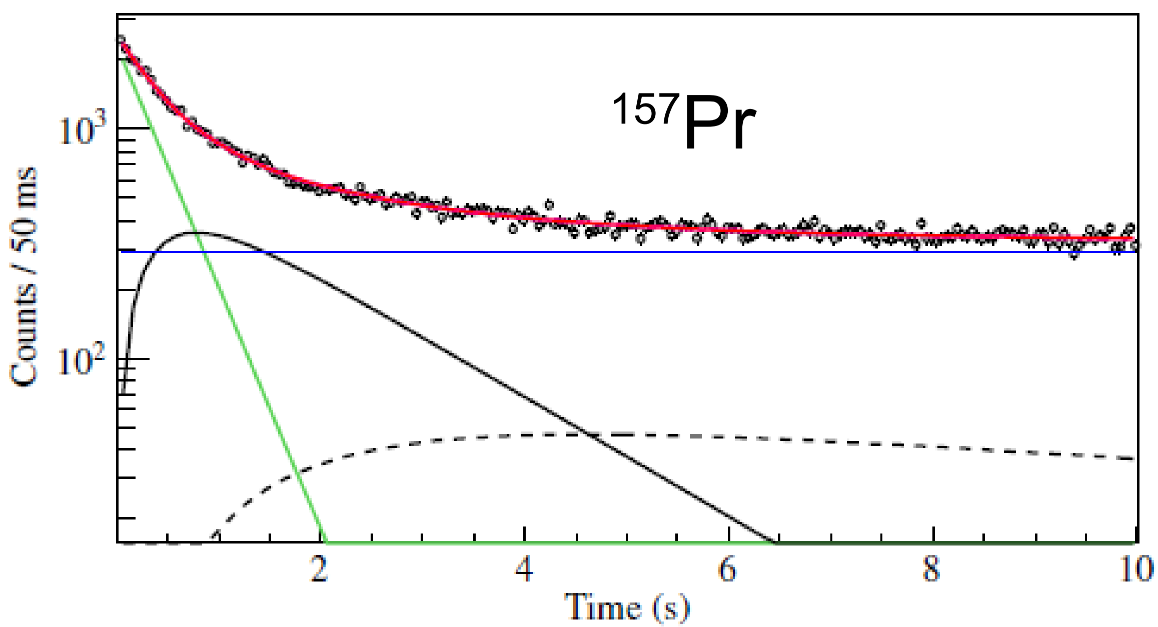


Implant in to DSSSD stack (WAS3ABI)

- Allows identified ions and their subsequent β decays to be correlated

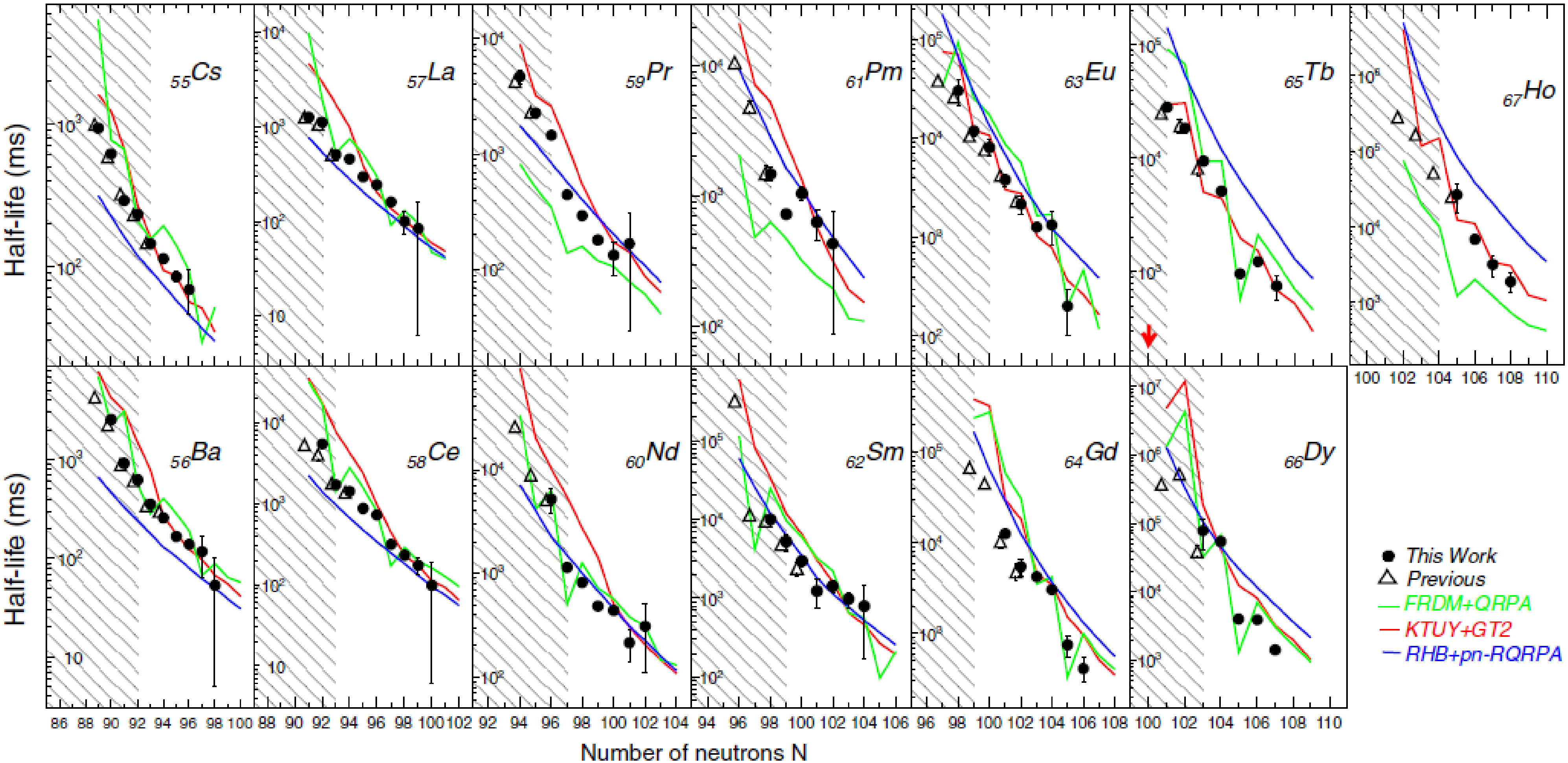


10000 pixels



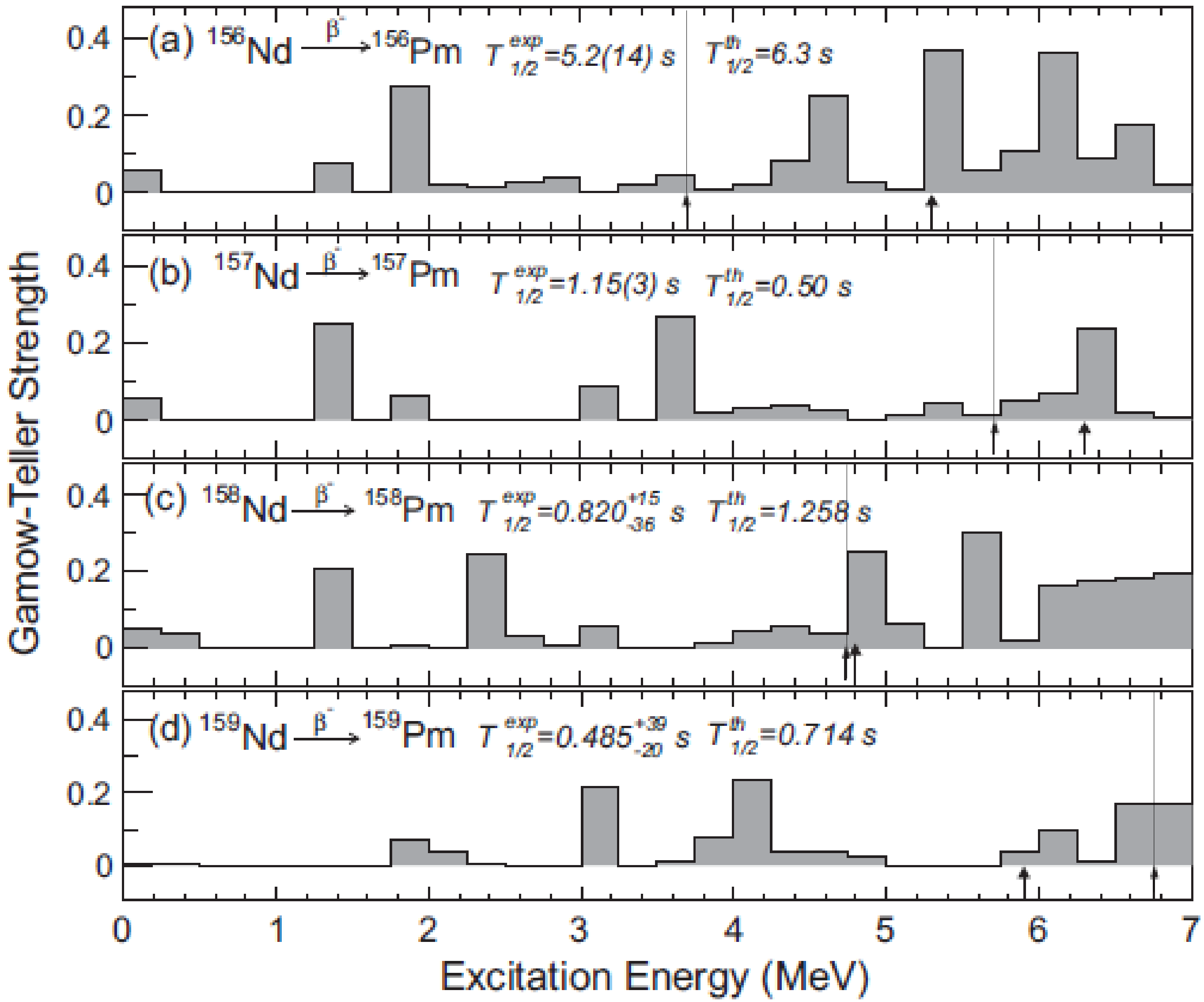
- Bateman equations (growth+decay)
- Fix known half lives of daughter, grand-daughter, etc. nuclei

Many new half-lives measured

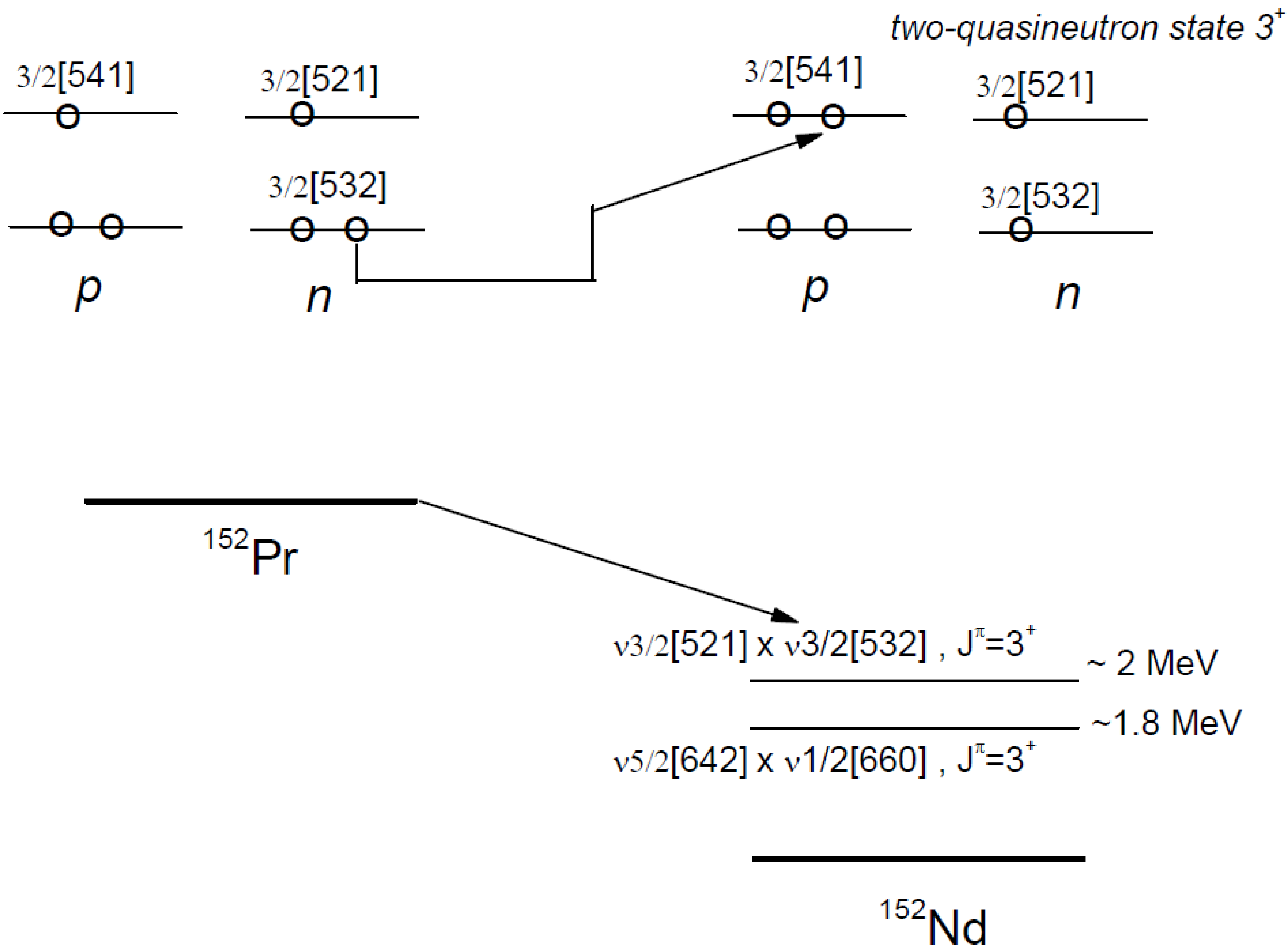


- Differences between measured and predicted half-lives are up to one order of magnitude

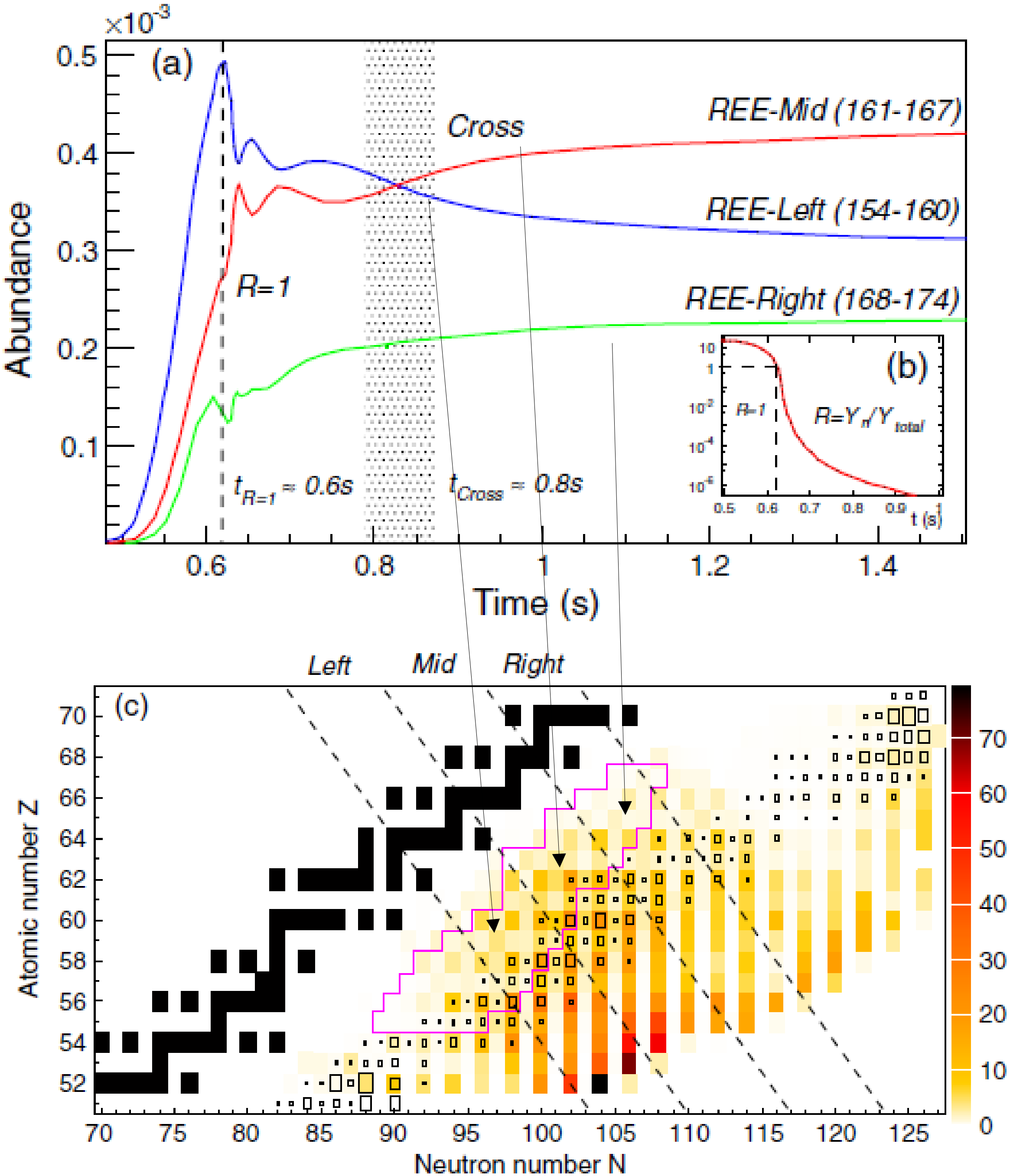
Half-lives depend on nuclear structure



Allowed unhindered β decays

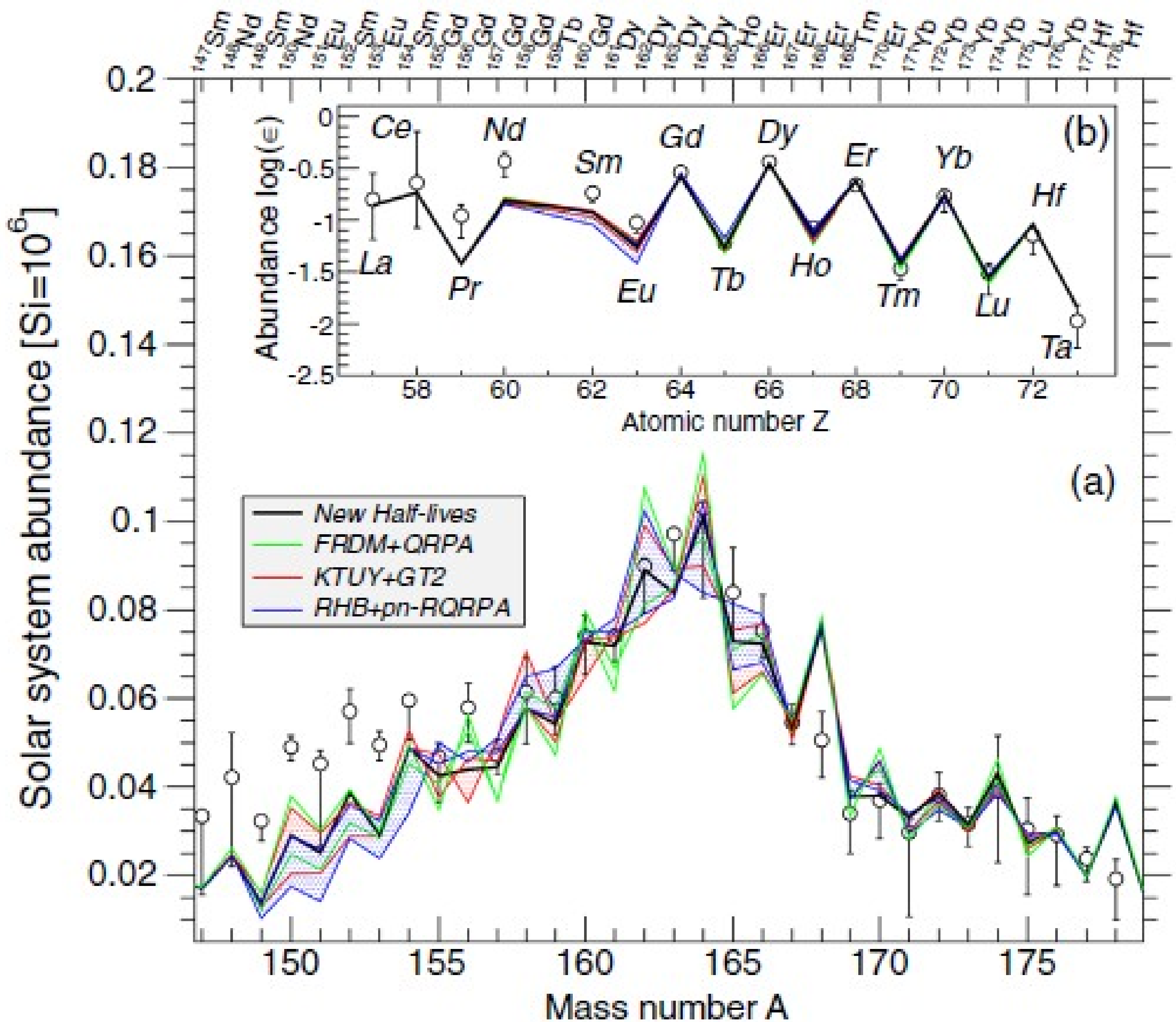


Predicted Abundances



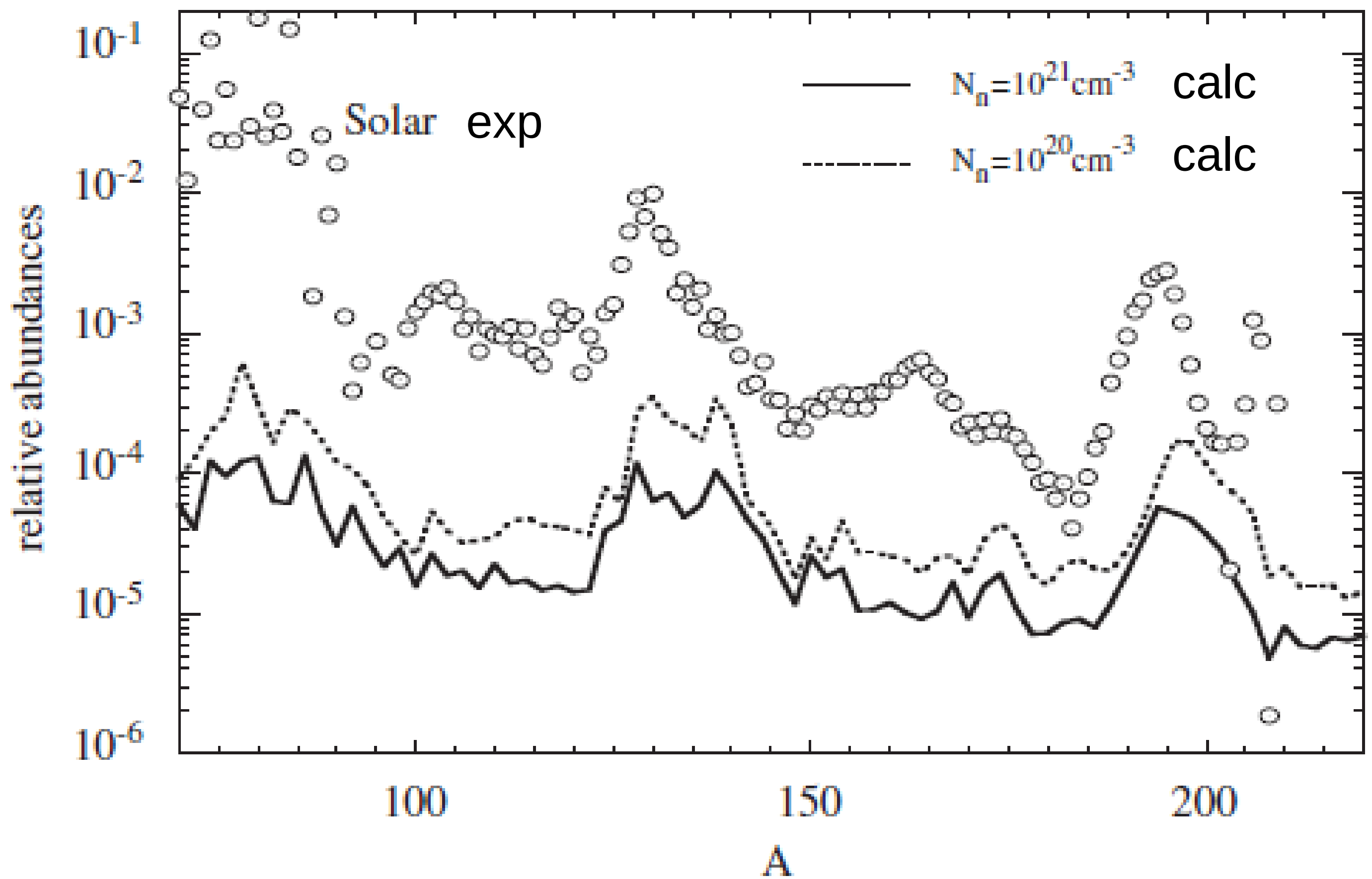
- Put the new exp. $T_{1/2}$ data back into the r-process simulations

Predicted Abundances



- Compare exp. data and different predictions
- More exp. data needed to reduce uncertainties, including masses, β-strength distributions, Pn values, fission yields …….

Outstanding problems



Agreement between theory and exp. around A~130, A~100 …… nuclear structure measurements can help