Fission in R-Process Calculations and the Position of the Third Peak

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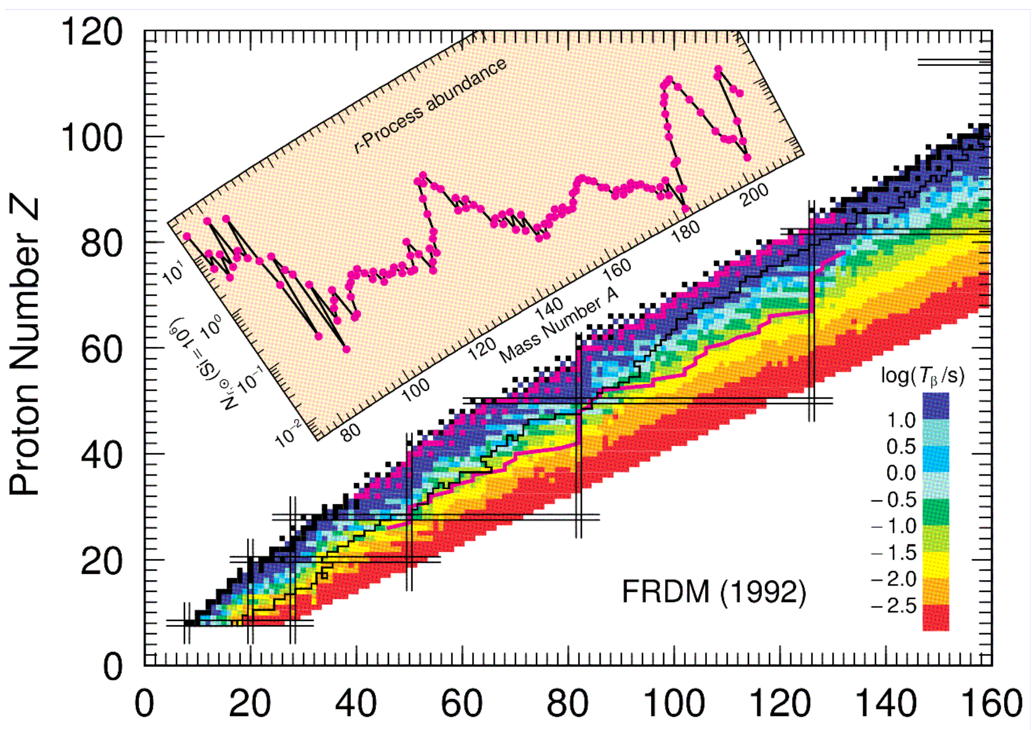
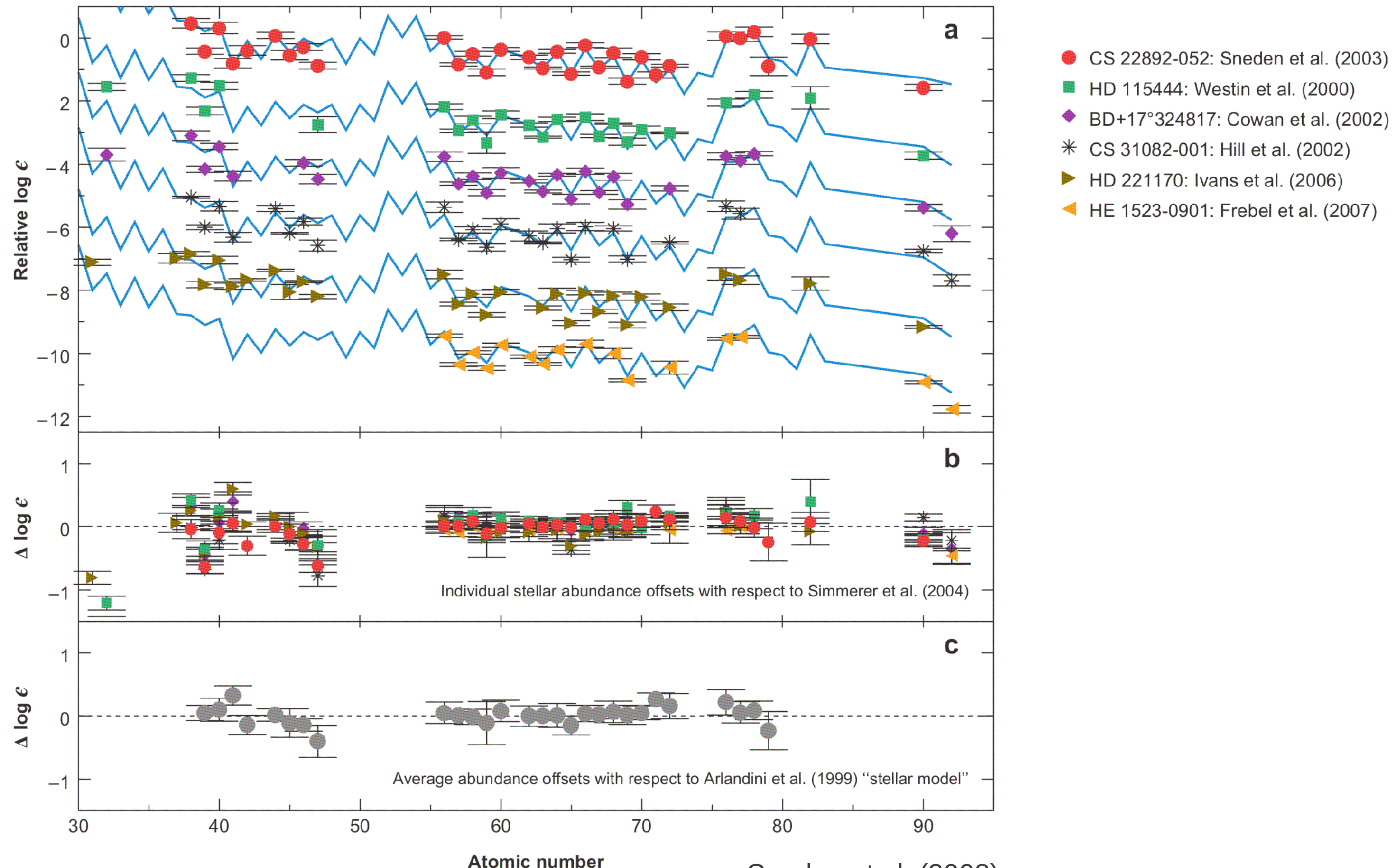
The R-Process

- $\tau_{(n,\gamma)} \ll \tau_\beta$
- path runs through very neutron-rich part of nuclear chart → still many uncertainties in nuclear properties



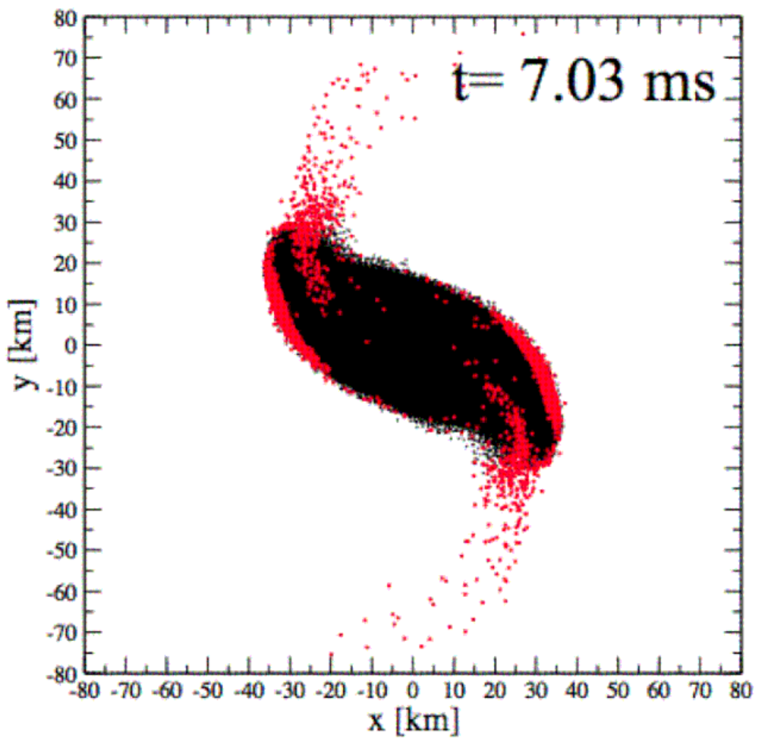
Möller et al. (1997)

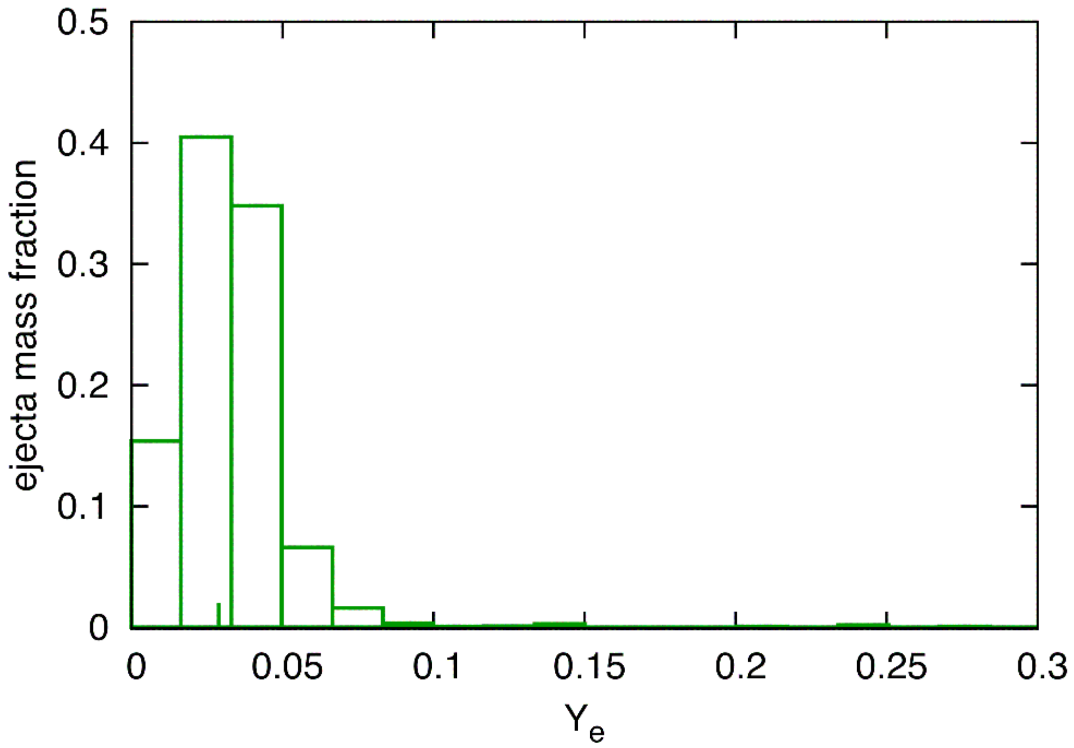
Robustness of the (strong) R-Process



Sneden et al. (2008)

Neutron Star Mergers as R-Process Sites





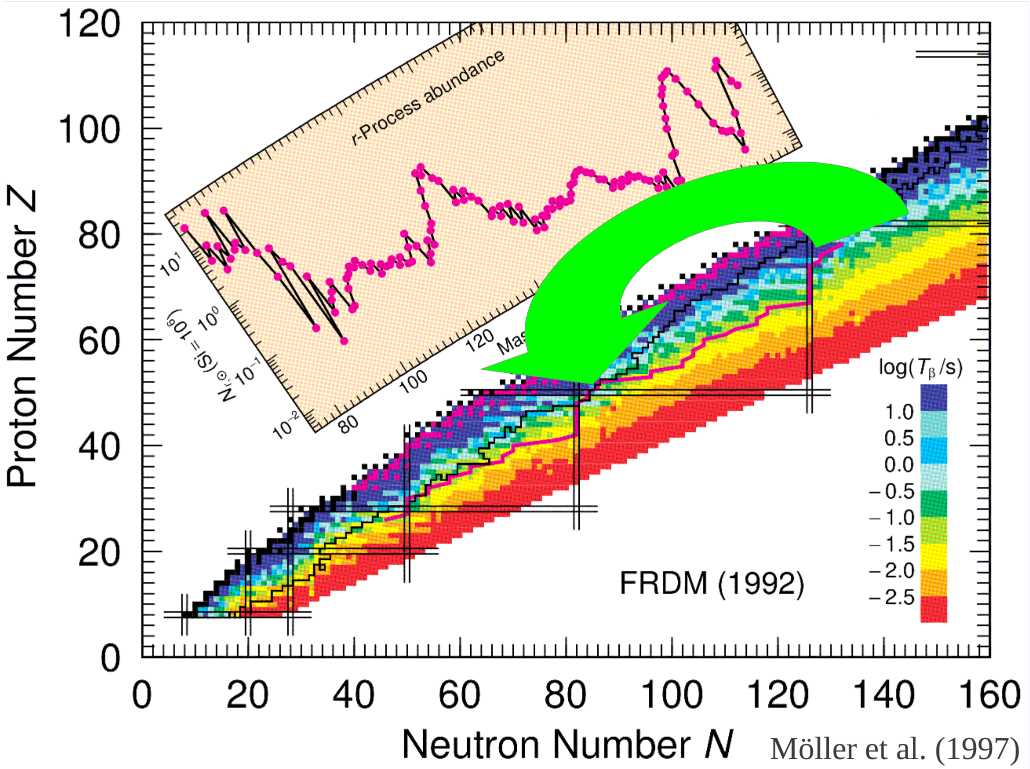
Korobkin et al. (2012)

Fission in the R-Process

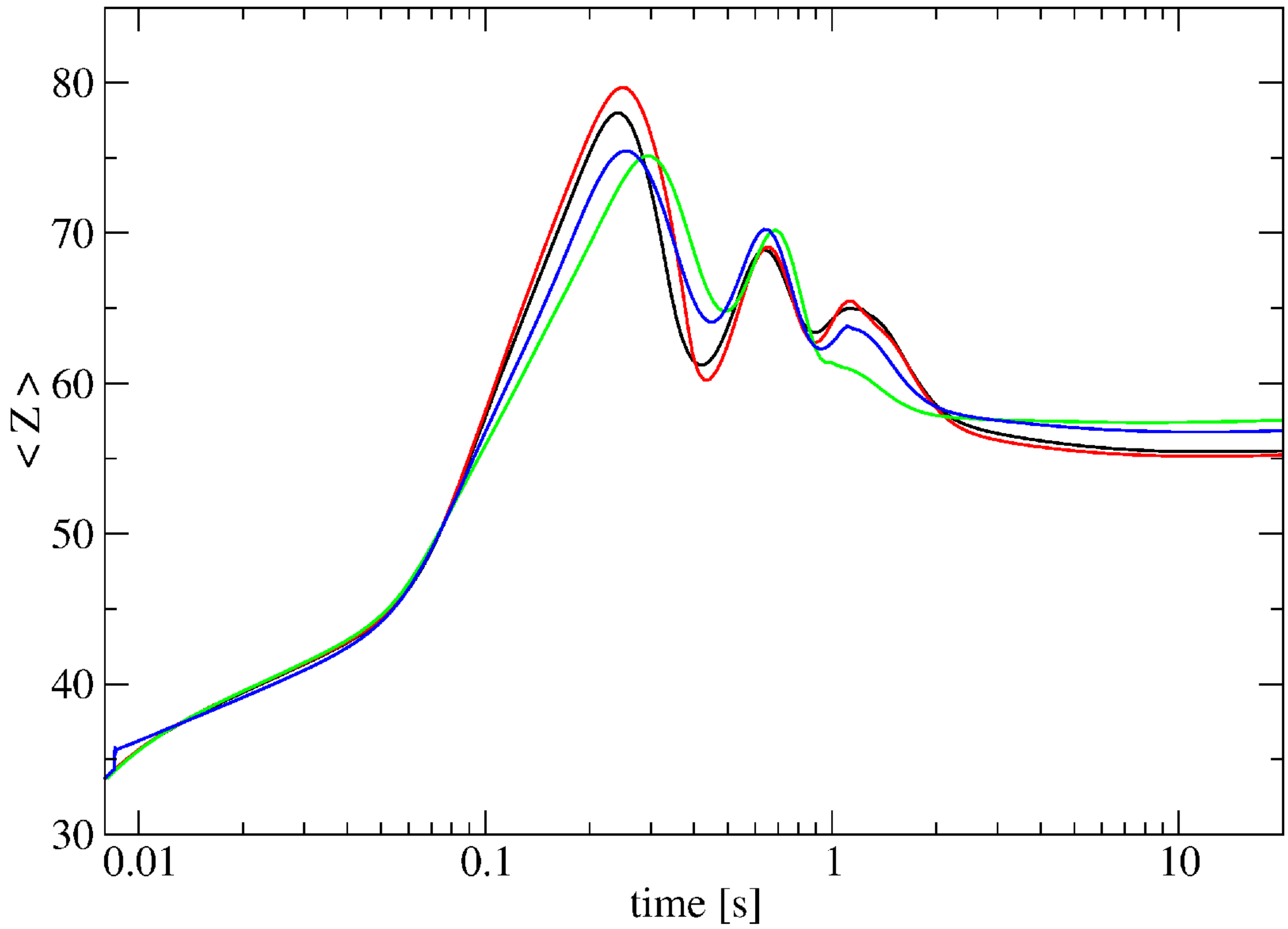
at the end of the r-process path nuclei become unstable and undergo fission

→ if the neutron density is still high enough, the r-process continues with the fission products as new seed nuclei

fission probability of heavy nuclei and fission fragment distribution shape the r-process reaction path and have an effect on the final abundances

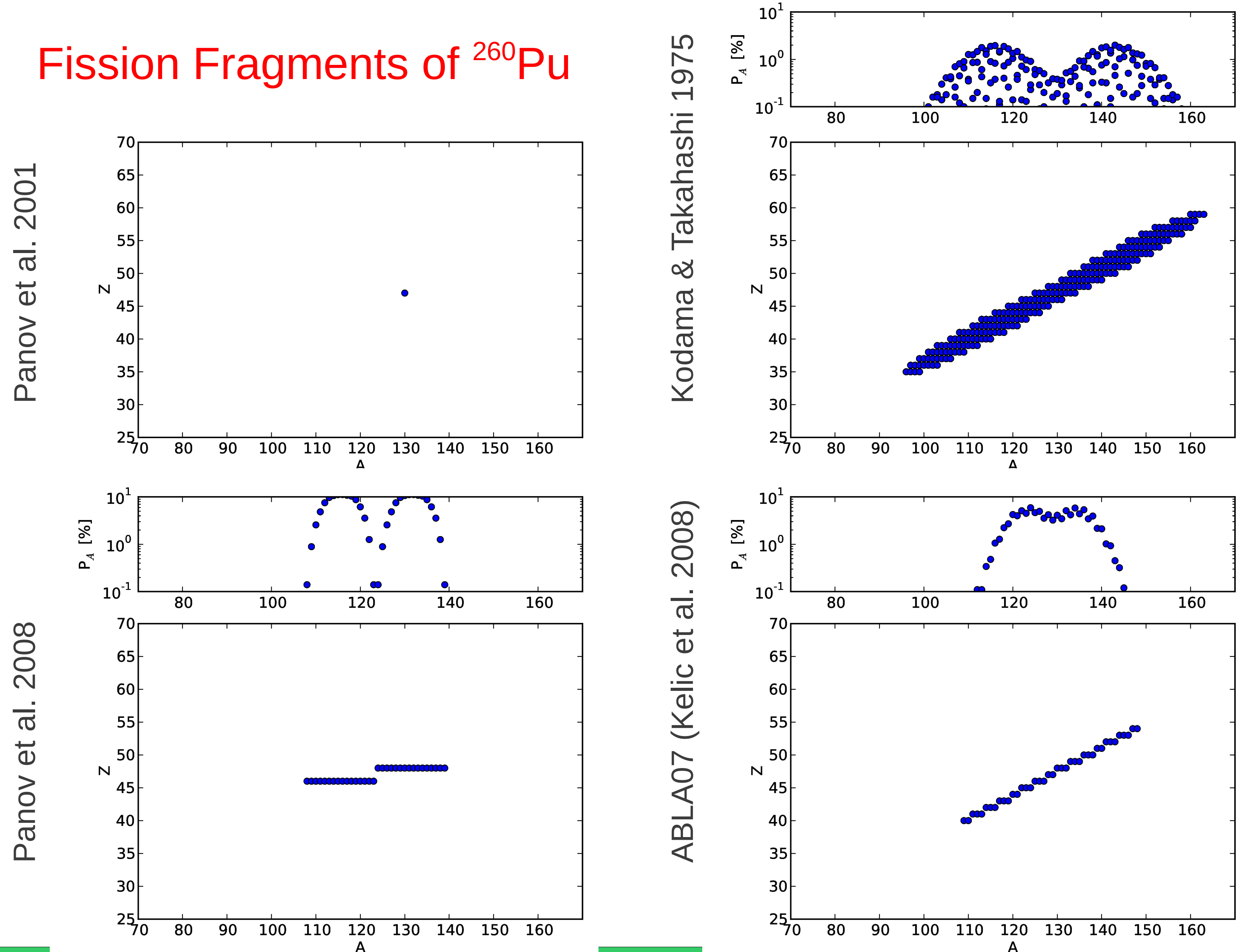


Fission Cycles in Neutron Star Mergers



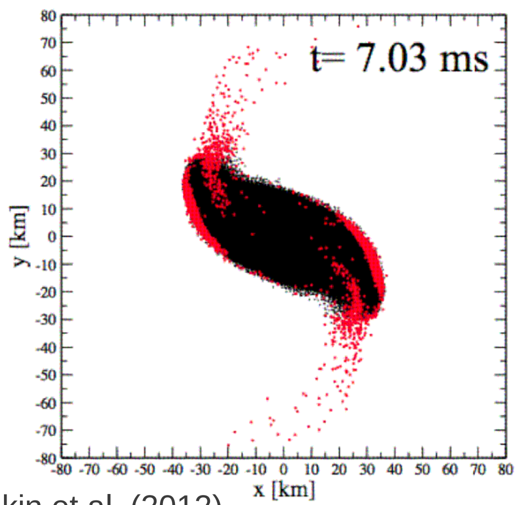
Fission Fragment Distribution Models

Fission Fragments of ^{260}Pu



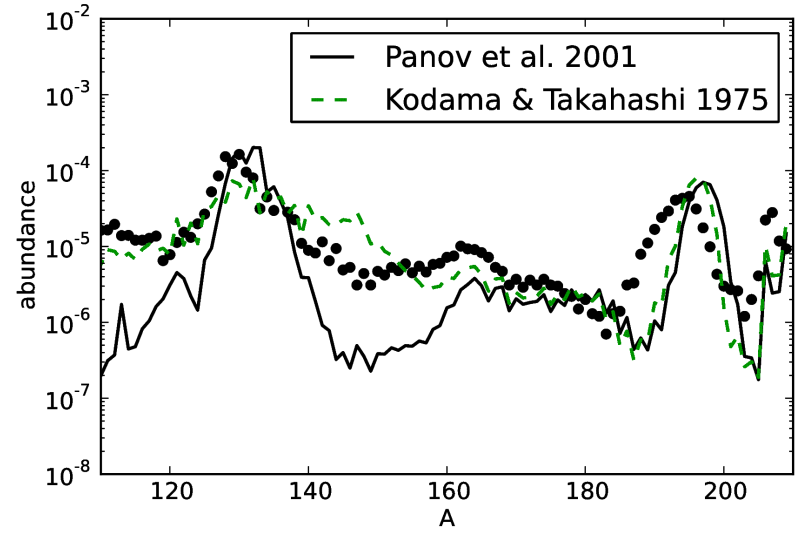
R-Process in Neutron Star Mergers

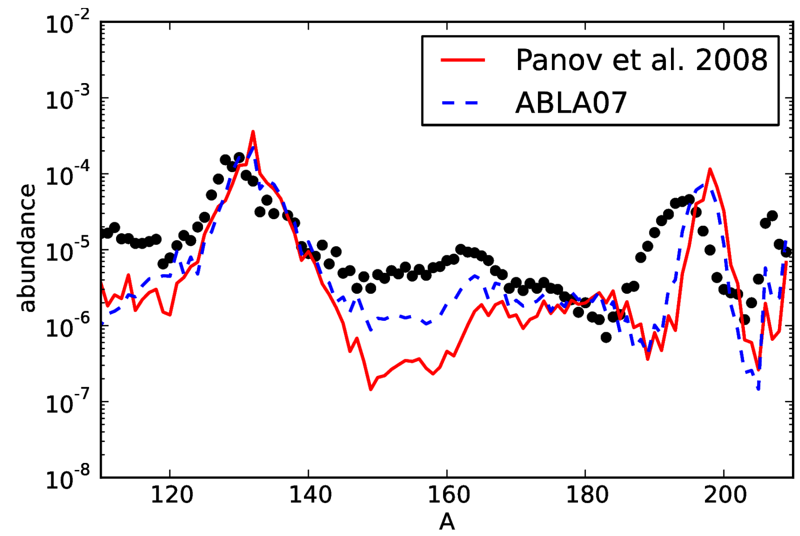
- trajectories from a neutron star merger with two 1.4 $M_\odot$ neutron stars (Rosswog, Piran & Nakar, 2013; Korobkin et al., 2012)
- trajectories include “interaction” as well as “tidal” components ($0.03 \leq Y_e \leq 0.05$)
- Reaclib, FRDM
- difference between fission fragment distribution models mainly around and after 2nd peak
- 3rd peak shifted to the right for all models



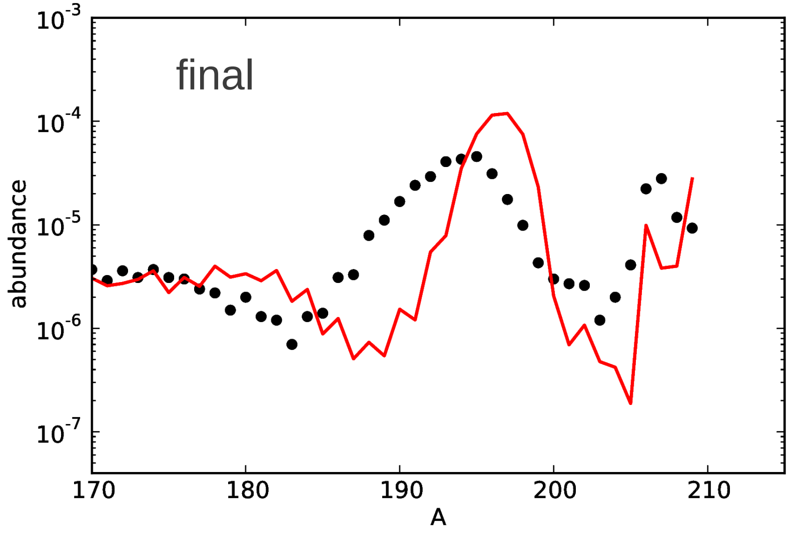
Korobkin et al. (2012)

solar r-abundances: Sneden et al. 2008

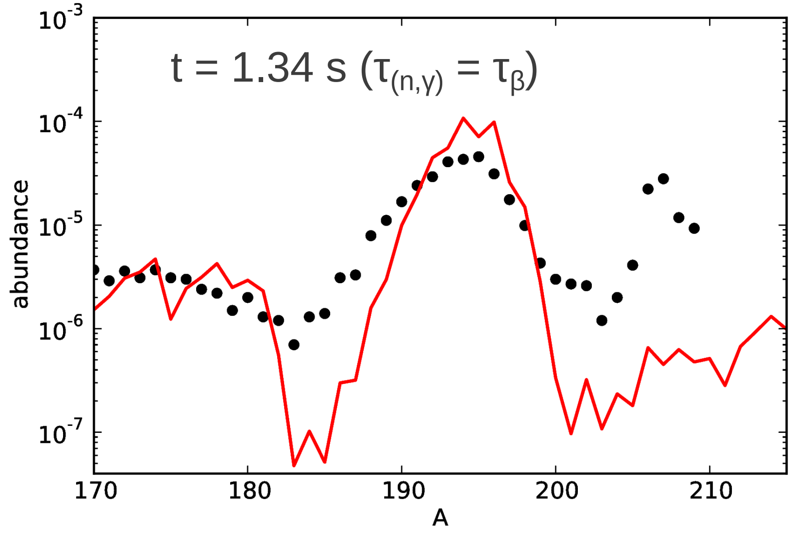




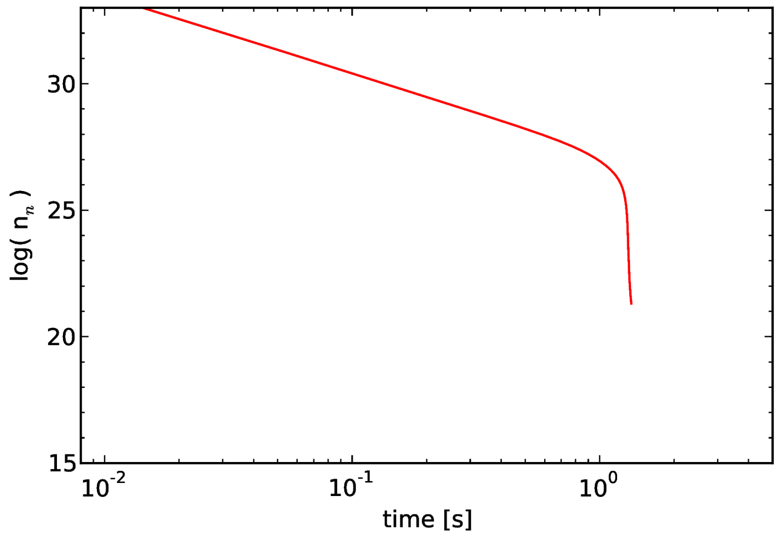
The Position of the Third Peak



- one trajectory from NSM previously discussed (ABLA07)
- snapshot at $\tau_{(n,\gamma)} = \tau_\beta$ reveals that peak shifts only when material decays to stability
- fission neutrons captured after that point



Neutron density n_n:

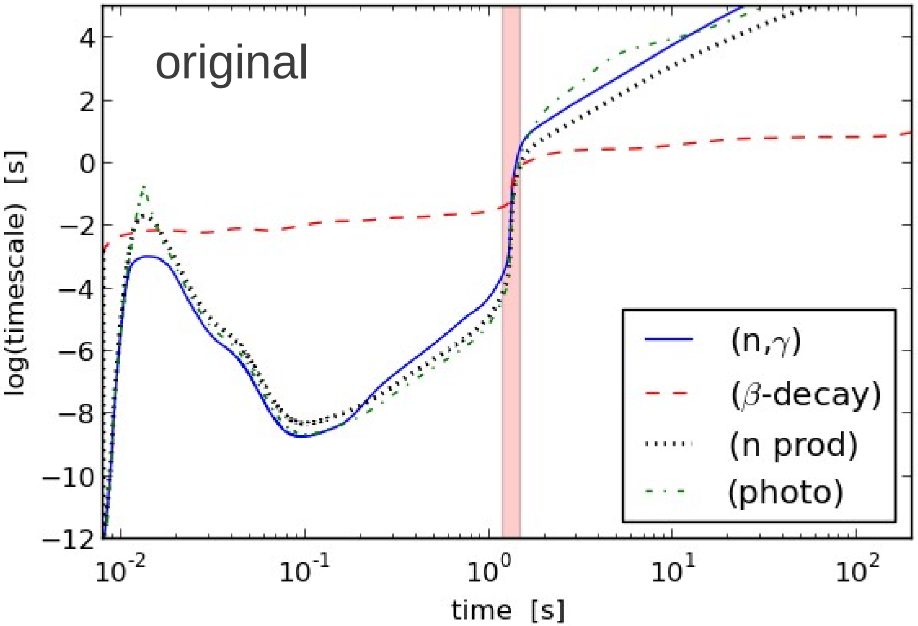


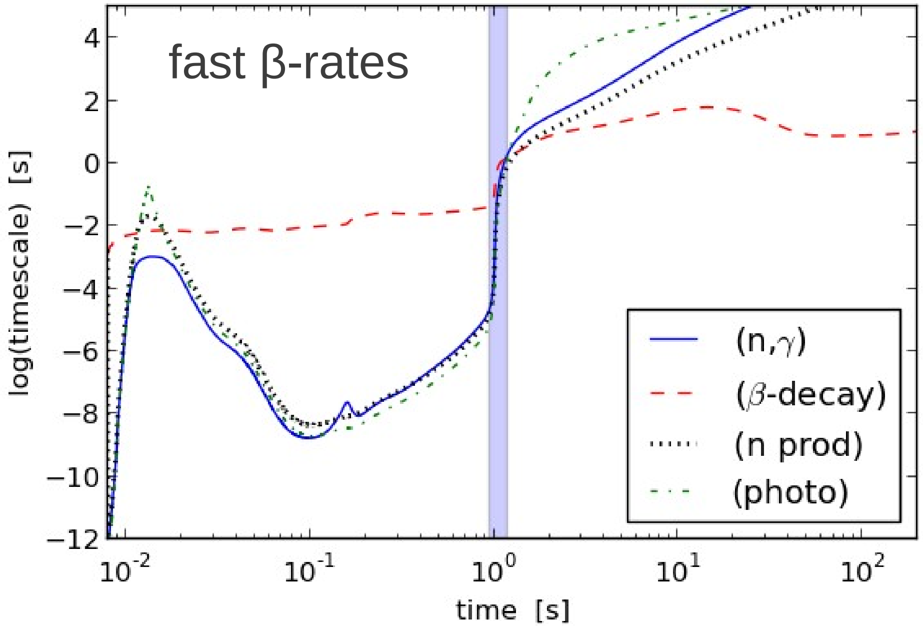
β-Decays in the R-Process

recent study of β-decay half-lives of r-process nuclei around N = 126 has shown that FRDM predictions might be off by a factor of more than 20 (Domingo-Pardo et al., 2013)

here: (artificial) acceleration of β-decays with subsequent neutron emission of heaviest elements (Z > 80) by a factor of 10

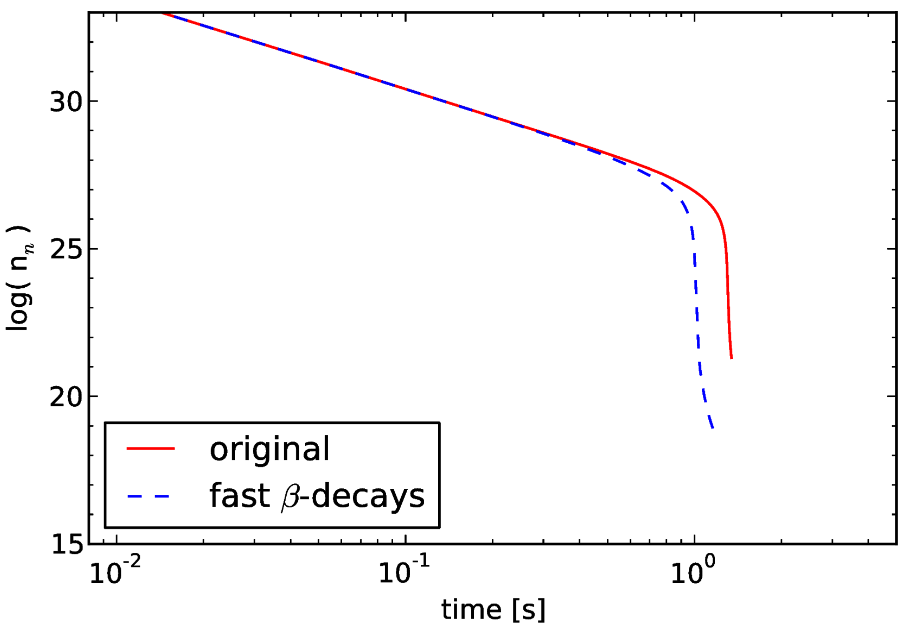
averaged timescales of neutron captures, β-decays, neutron production and photodissociations

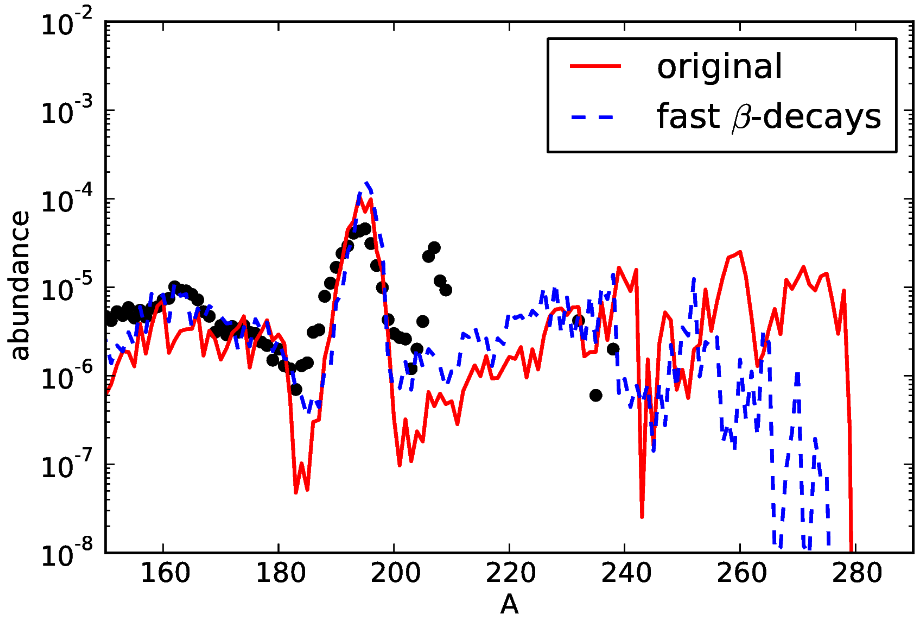




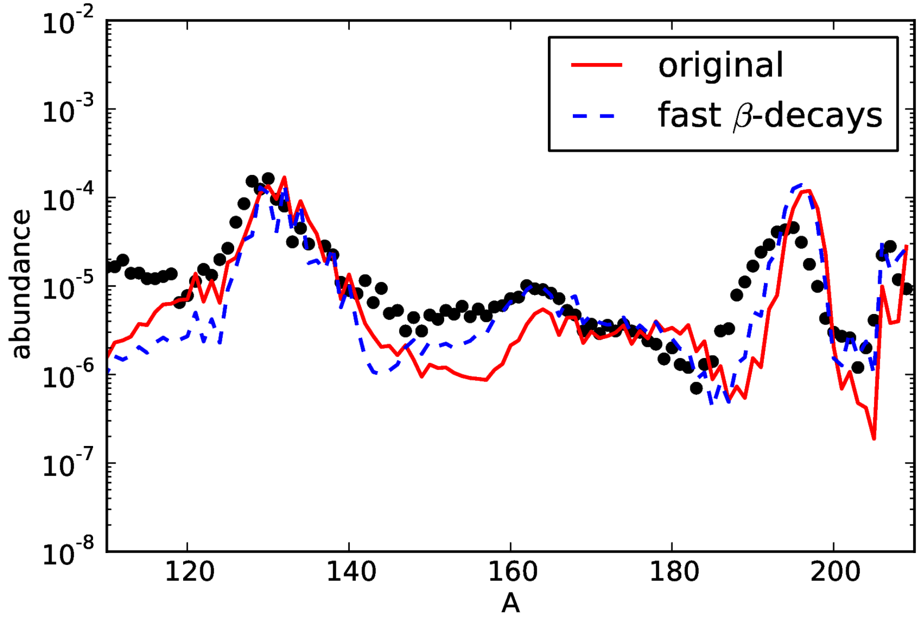
Comparison at $\tau_{(n,\gamma)} = \tau_\beta$

- snapshots at $\tau_{(n,\gamma)} = \tau_\beta$ (t = 1.34 and t = 1.16, respectively)
- abundances of A < 200 nuclei similar
- large differences in abundances of heaviest nuclei and neutron density

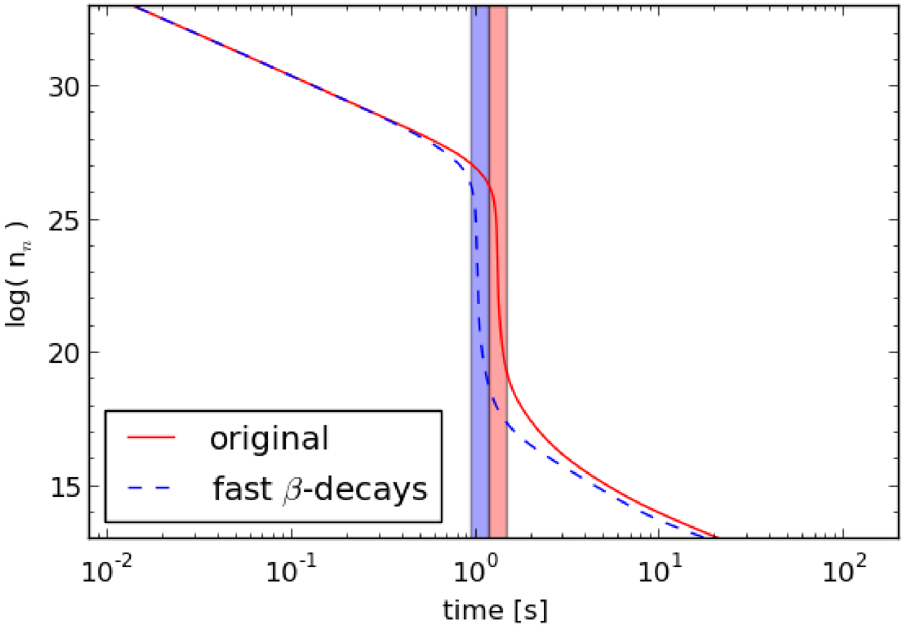




The Position of the 3rd Peak (NSM)

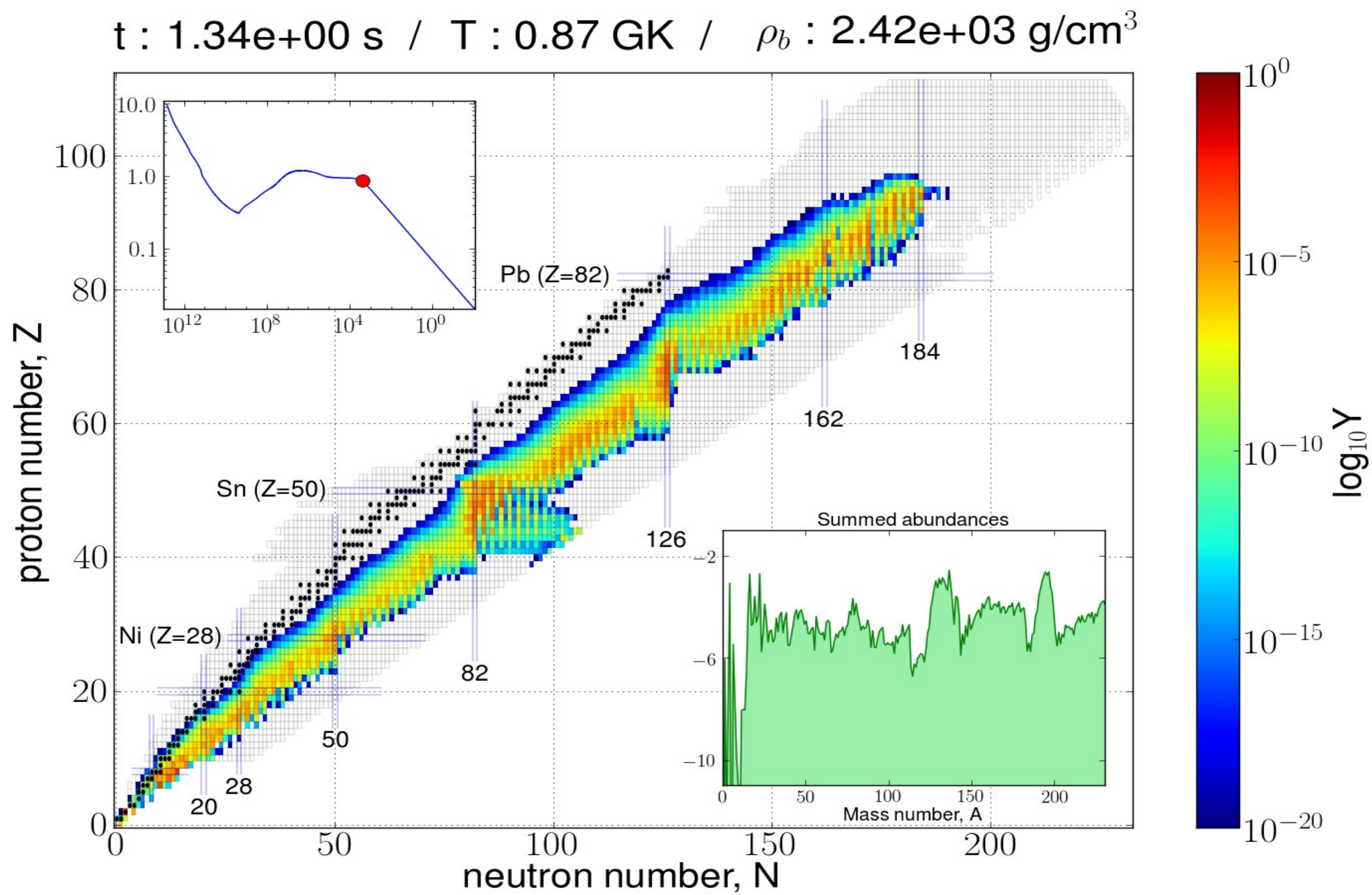


- β-decays with neutron emission of Z > 80 nuclei accelerated by a factor of 10
- FRDM
- ABLA07



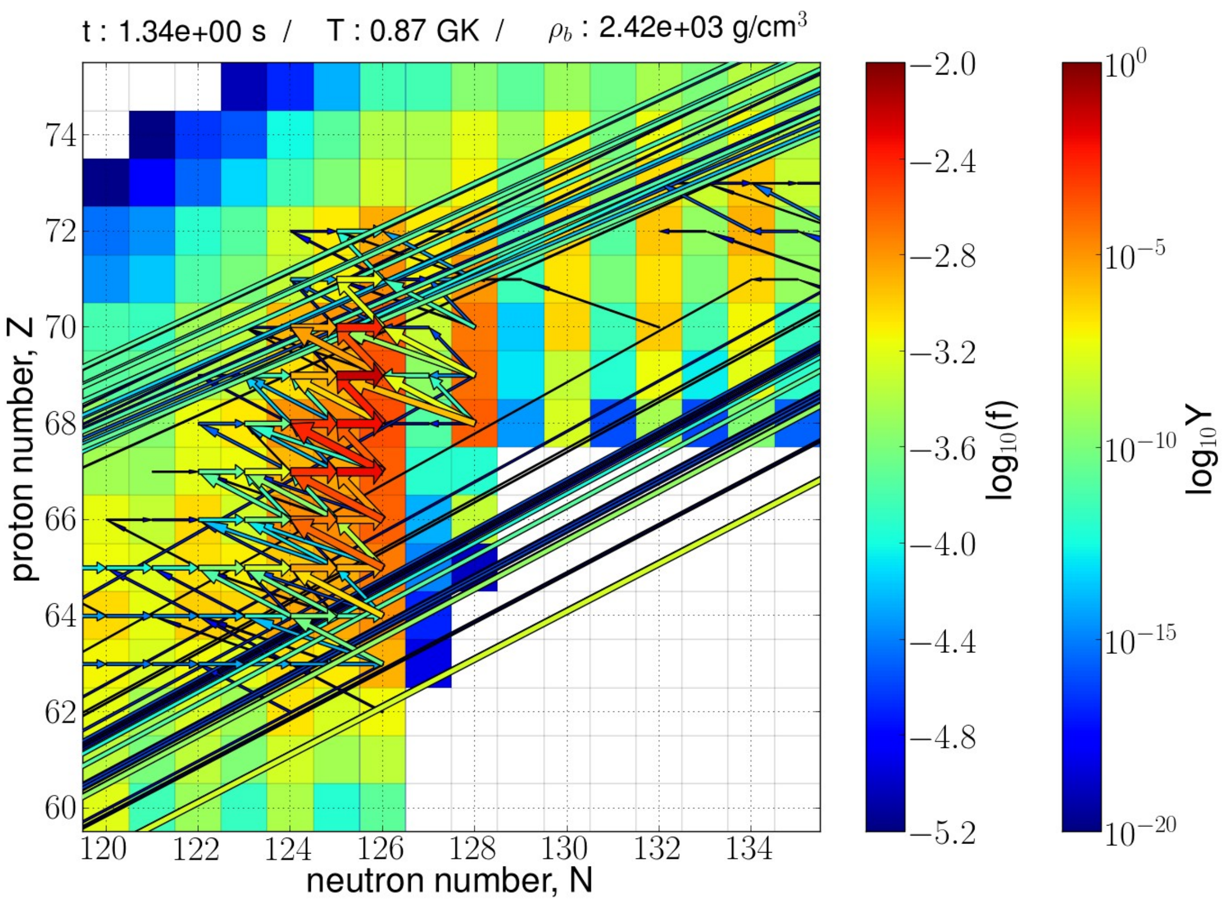
- fission neutrons from the last fission cycle enforce neutron captures
- affects mainly third peak and rare earths, second peak consists of neutron-rich fission fragments

Matter Composition at Freeze-out (NSM)

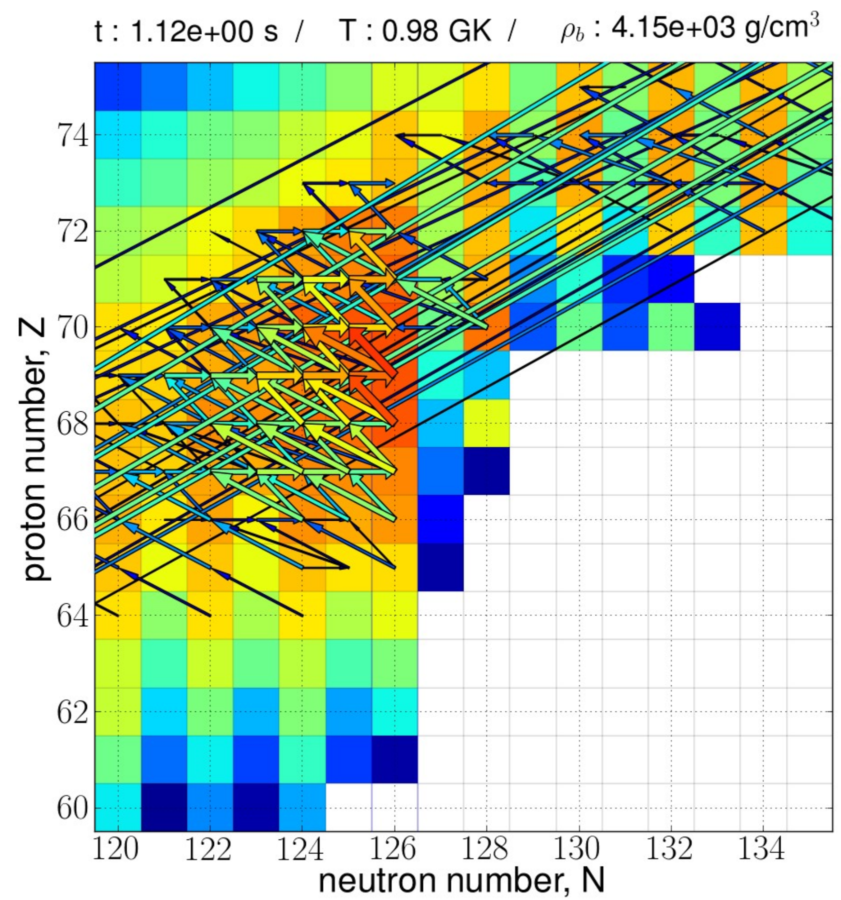


Matter Composition at Freeze-out (NSM)

original



fast β-rates

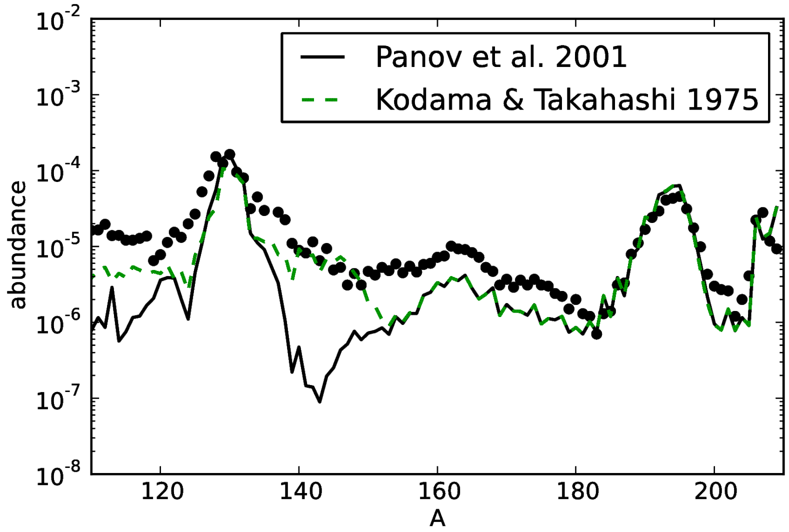


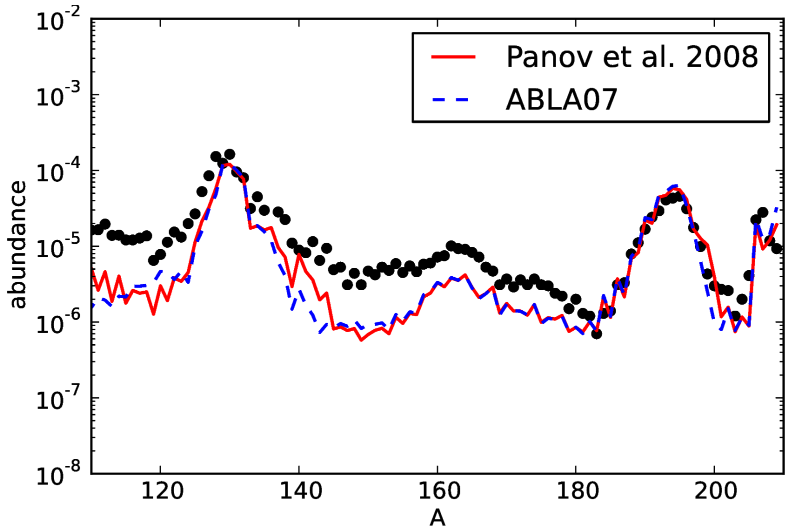
Conclusions

- the choice of the fission fragment distribution model has a major effect on the final abundances in NSM calculations, in particular the second peak
- in our NSM calculations, the 3rd peak is shifted towards heavier nuclei due to neutron captures after the r-process freeze-out
  - fission neutrons from last fission cycle are main culprits
  - time of r-process freeze-out is important
- in an earlier freeze-out, photodissociations can (partially) counter neutron captures, because temperature is higher
- unique problem of the FRDM?

R-Process in Jets of MHD Supernovae

- magneto-hydrodynamically driven supernova of a 15 $M_\odot$ star, ejects matter in two neutron-rich jets
- trajectories from Winteler et al. 2012
- $0.15 \leq Y_e \leq 0.35$
- FRDM
- only one fission cycle → mainly 2nd peak affected

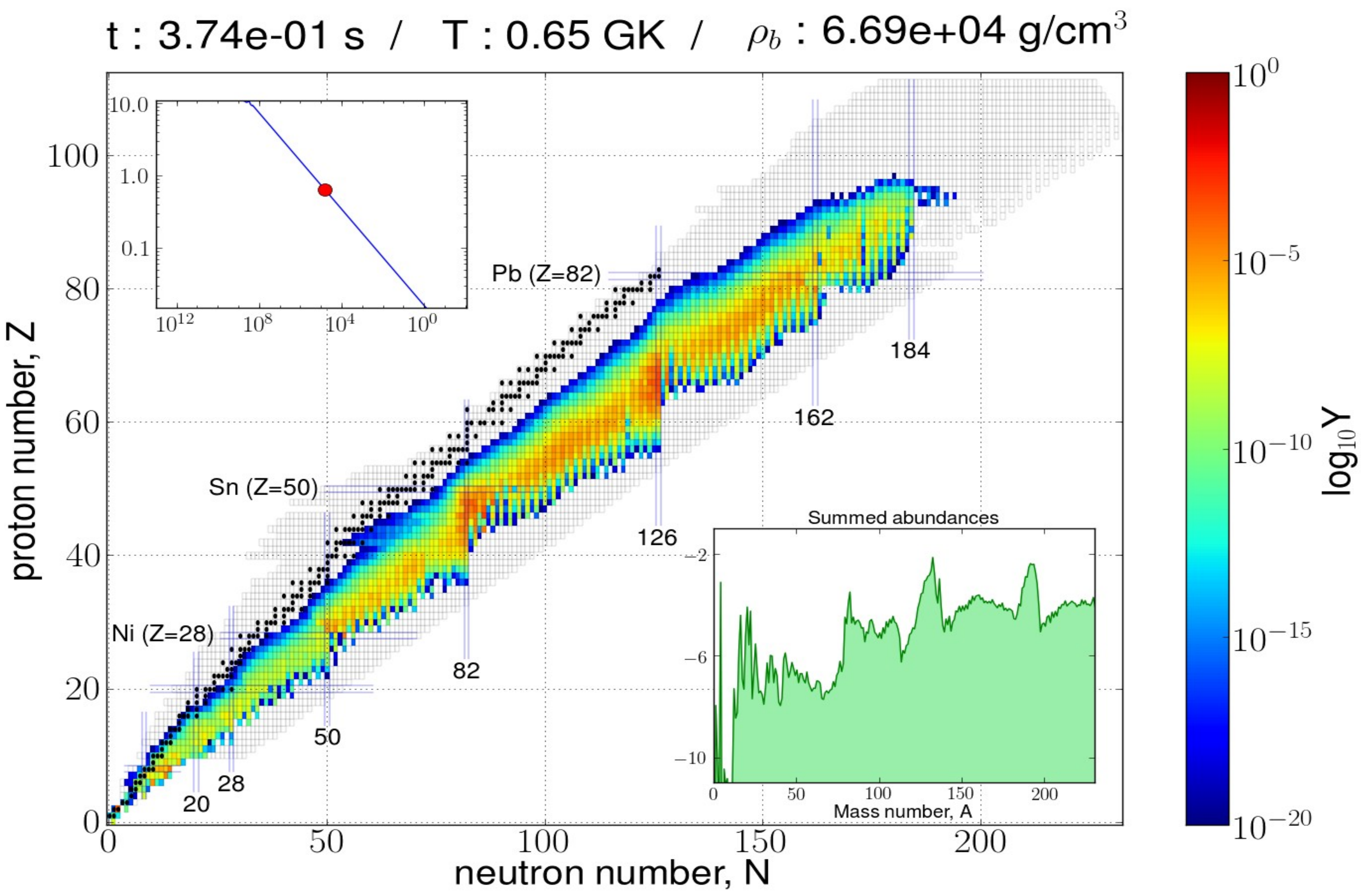




Our Network: Winnet

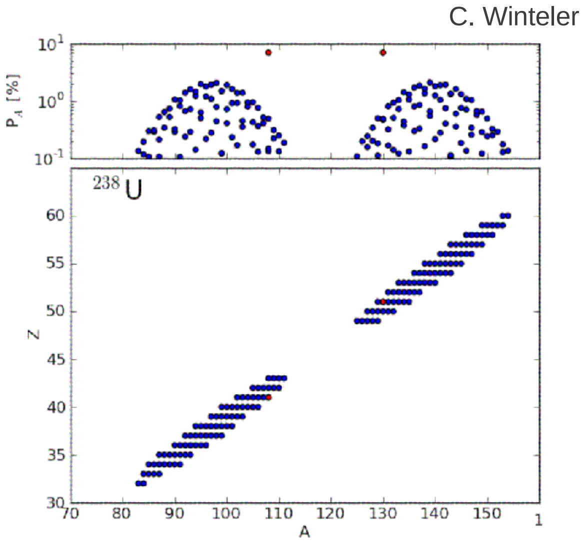
- includes around 6000 nuclei (7700 for ETFSI calculations)
- reaclib rates
- NSE while $T \geq 8$ GK
- Timmes et al. (1999) EoS
- thermonuclear heating implemented by O. Korobkin
- sparse matrix solver: PARDISO

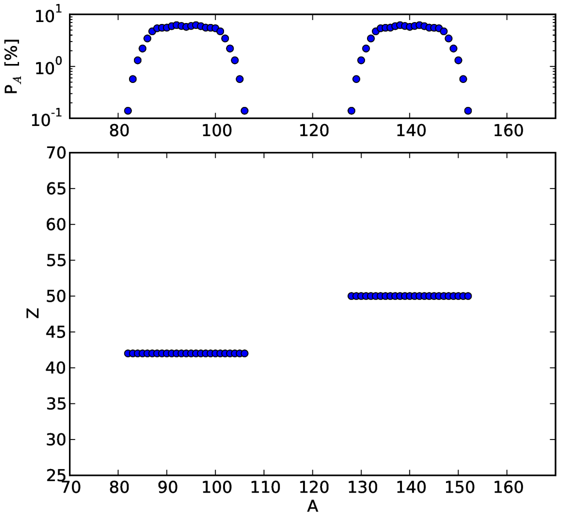
Matter Composition at Freeze-out (Jet)

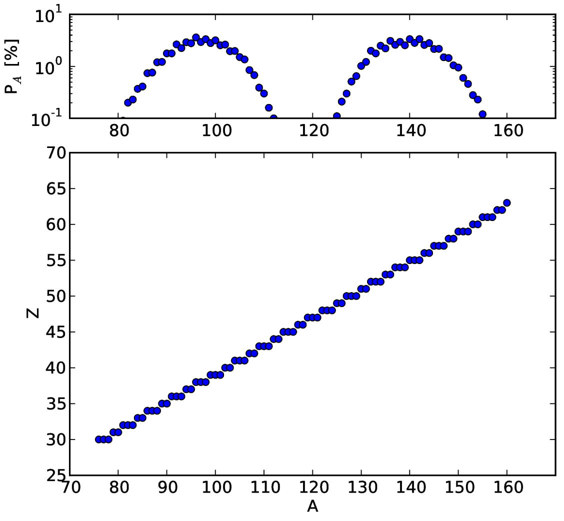


Fission Fragment Distribution Models

^{238}U







Panov et al. 2001 (red)
Kodama & Takahashi 1975 (blue)

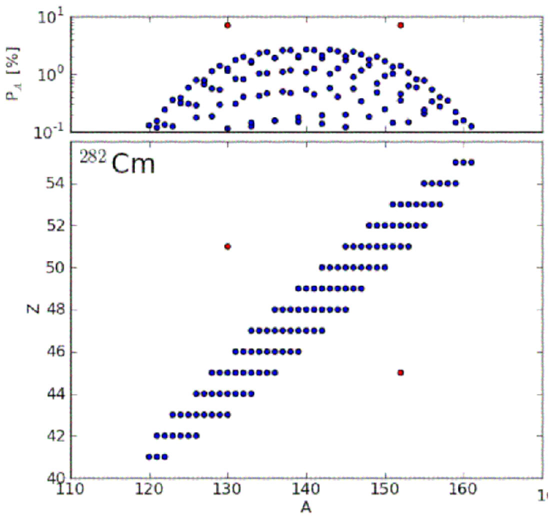
Panov et al. 2008

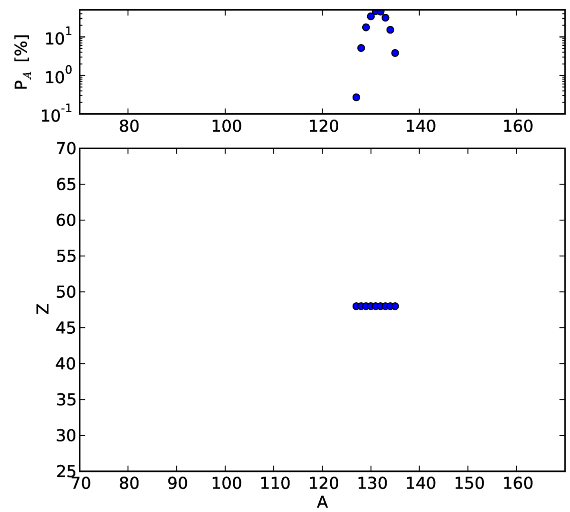
ABLA07 (Kelic)

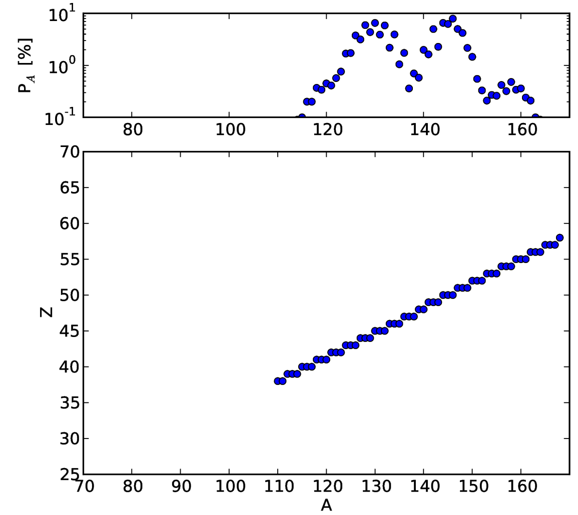
Fission Fragment Distribution Models

^{282}Cm

C. Winteler







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