Dynamical Fission in r-process Nucleosynthesis

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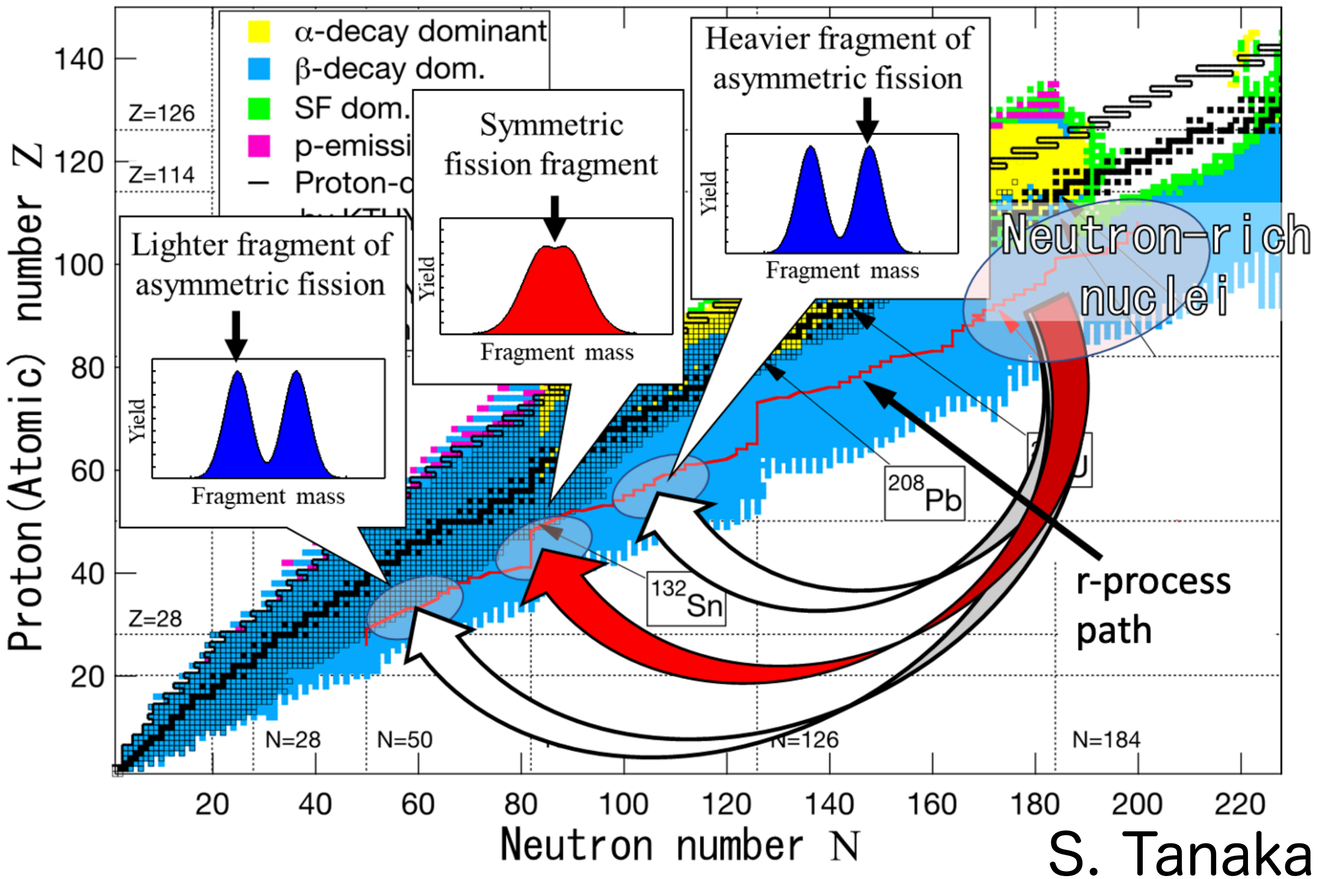
KOGAKUIN UNIVERSITY 東京大学 THE UNIVERSITY OF TOKYO CNS RIKEN PRI 科研費 KAKENHI

Fission in r-process nucleosynthesis

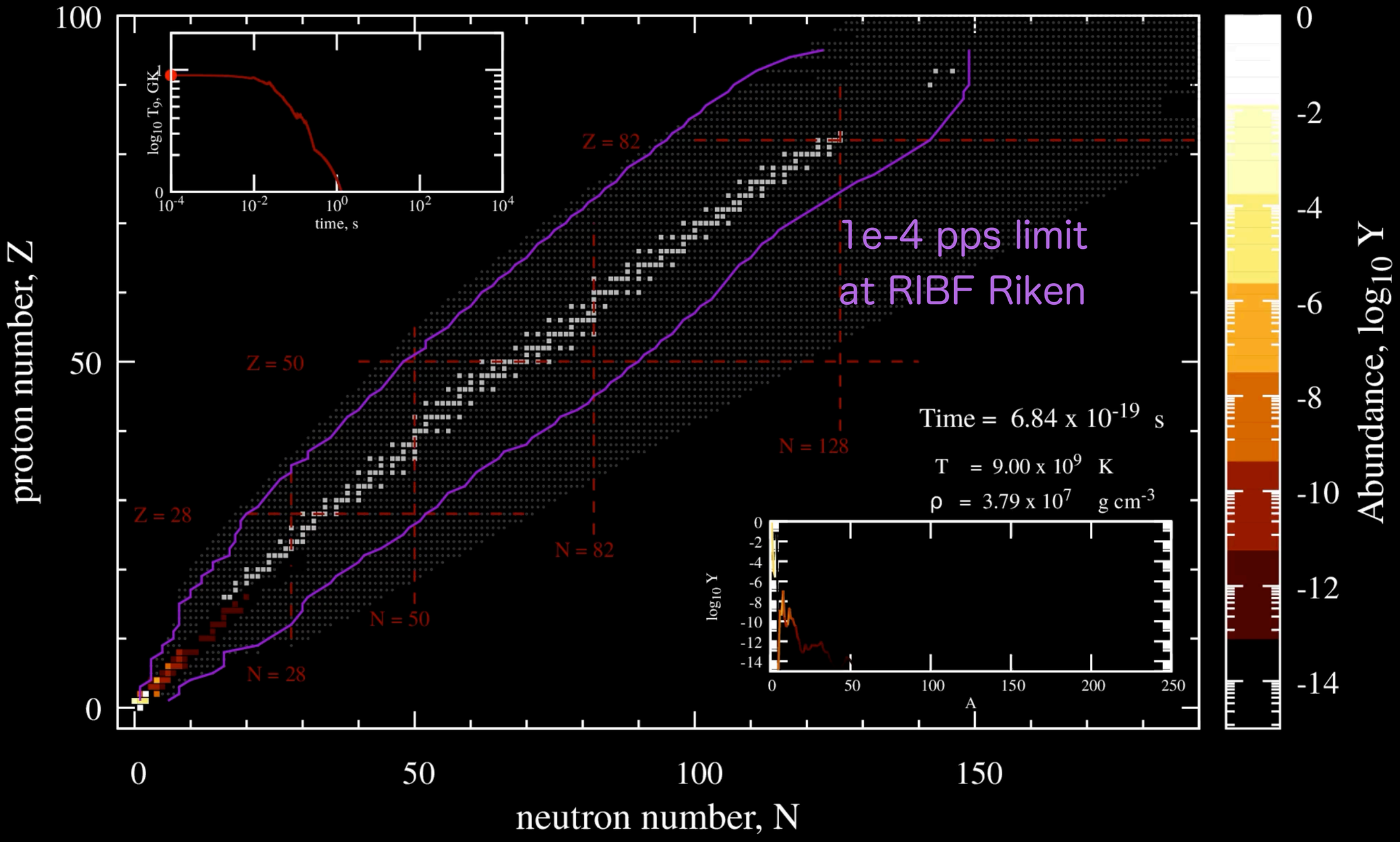
- **Fission**
  - A nuclear decay of heavy nuclei (e.g., U)
  - includes spontaneous fission and induced fission (by β-decay, n-capture)

- **Role in astrophysical nucleosynthesis**
  - The r-process may be the only process that produces U and other actinides
  - Competes with β-decay and (n,g), leading to termination of the r-process
  - Fission yields contribute to the production of intermediate-mass r-process nuclei
  - Radioactive decay and fission can provide energy sources for kilonovae from neutron-star mergers

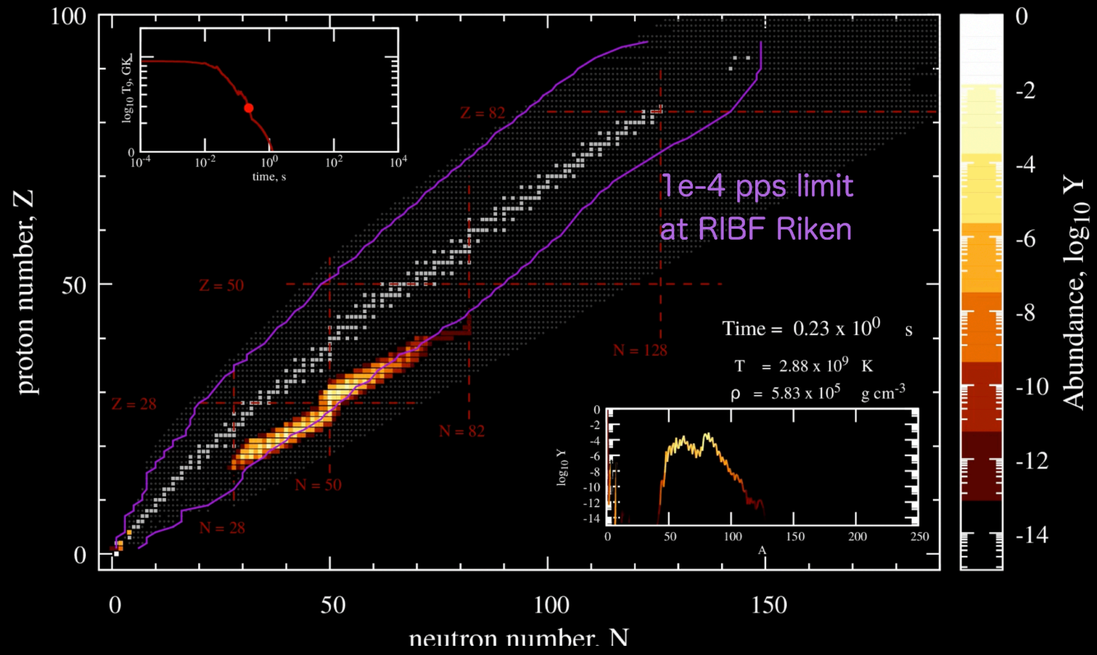
fission in the r-process

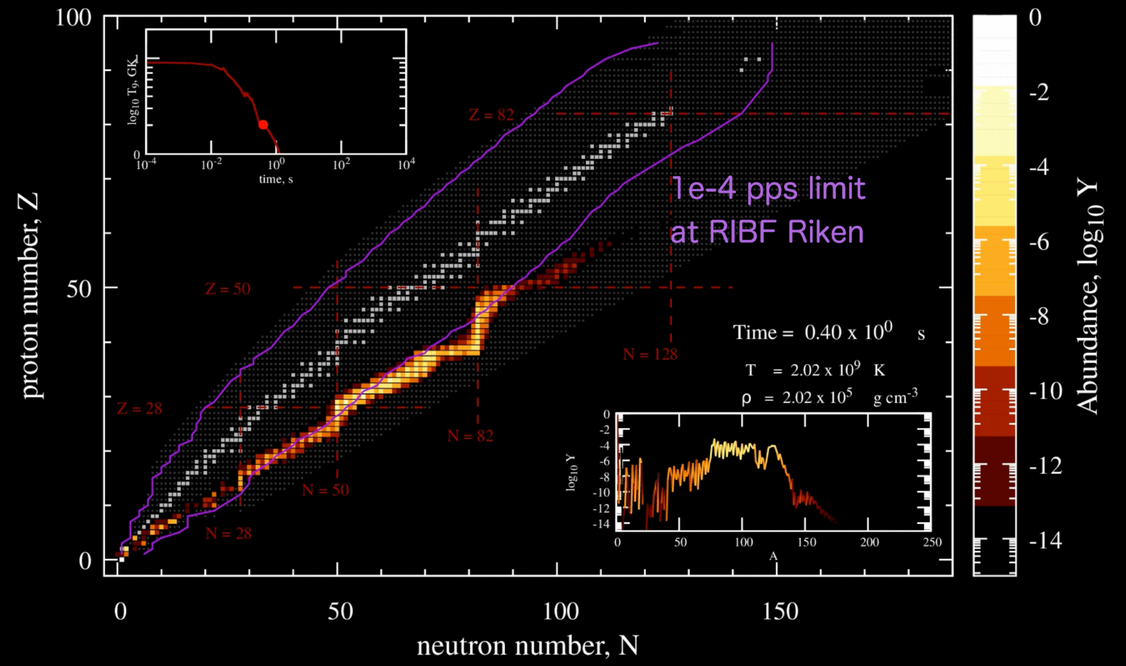


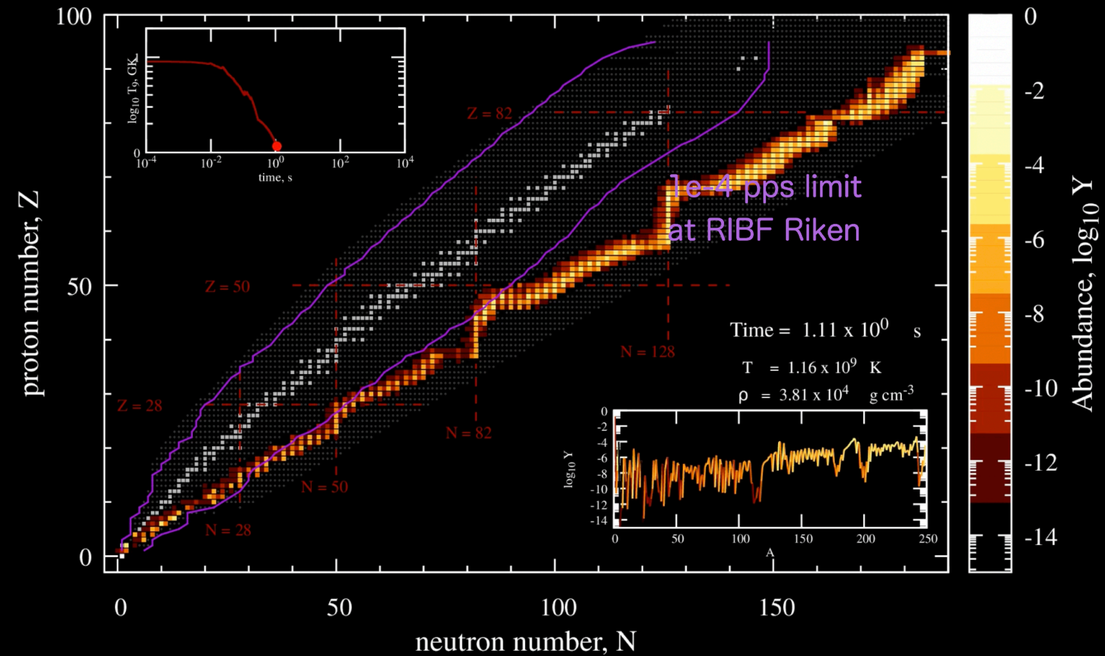
r-Process simulation

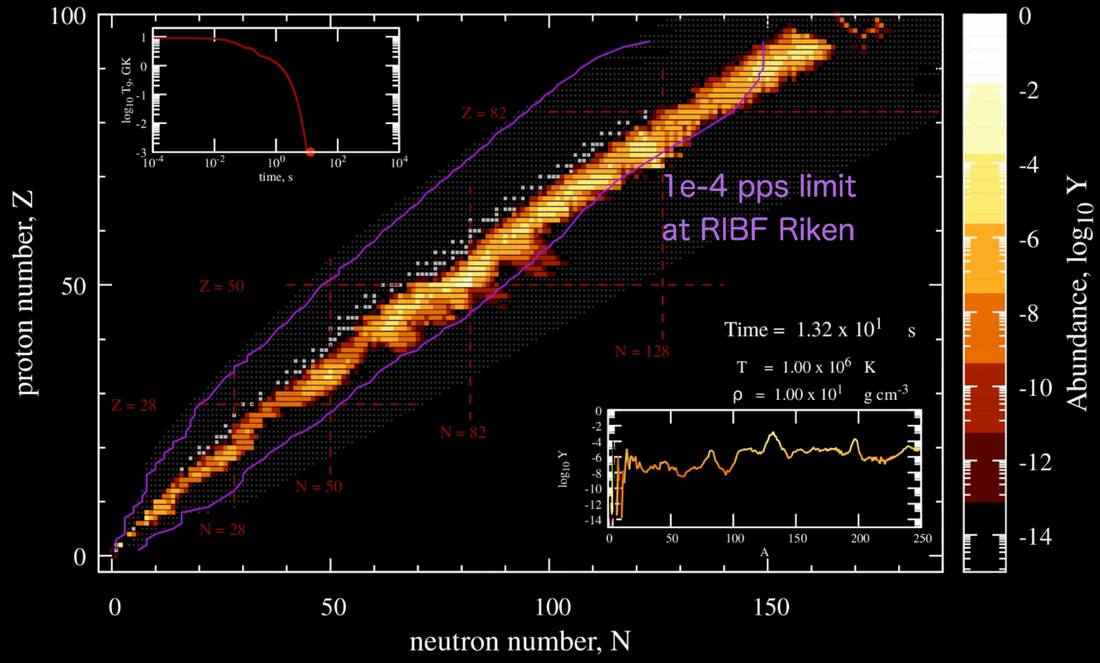


r-Process simulation

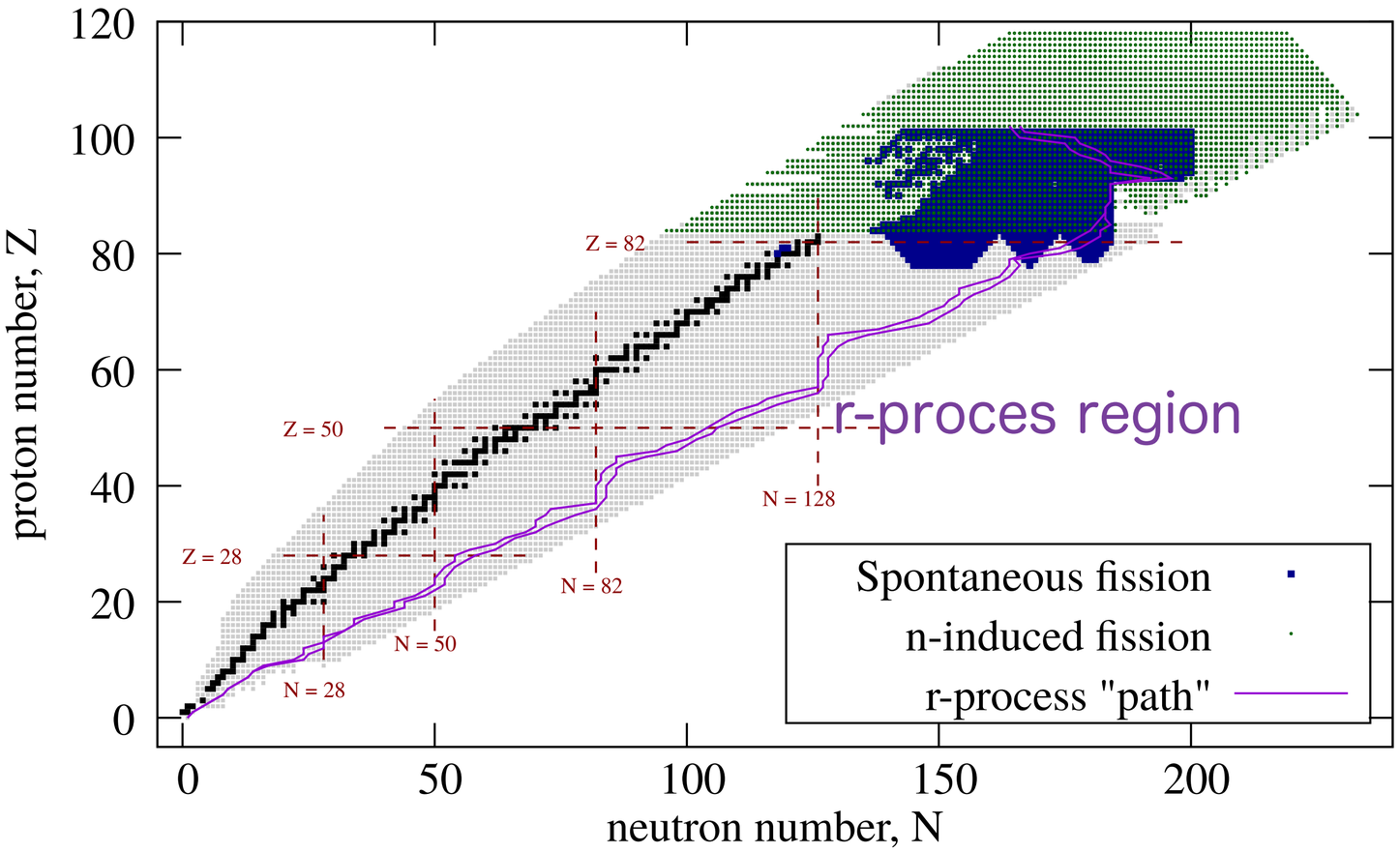




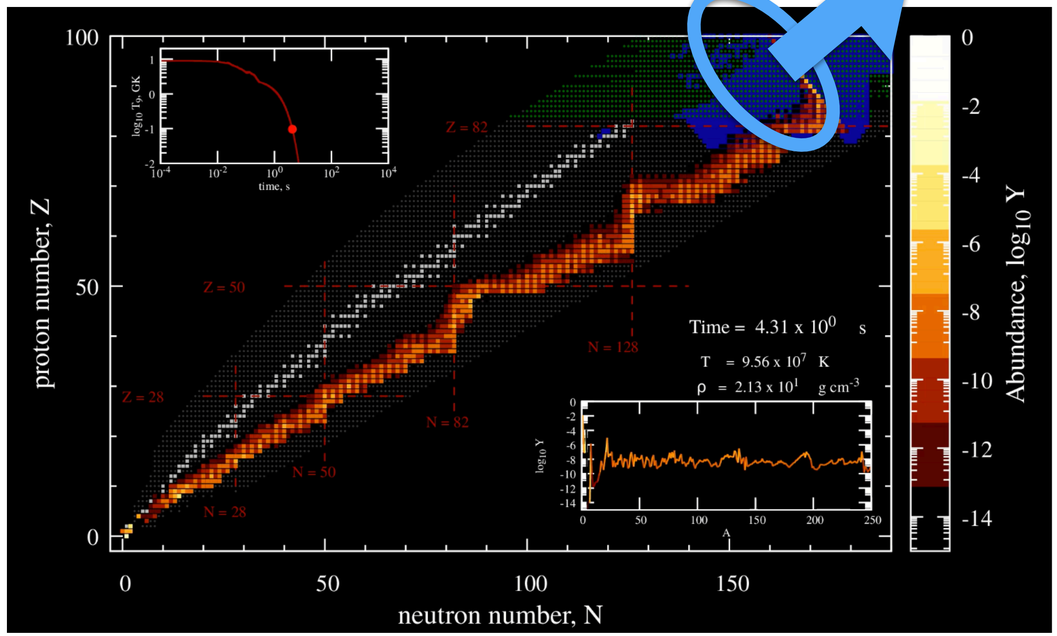




Fission nuclei on the NZ-plane



fission: OFF (unphysical)

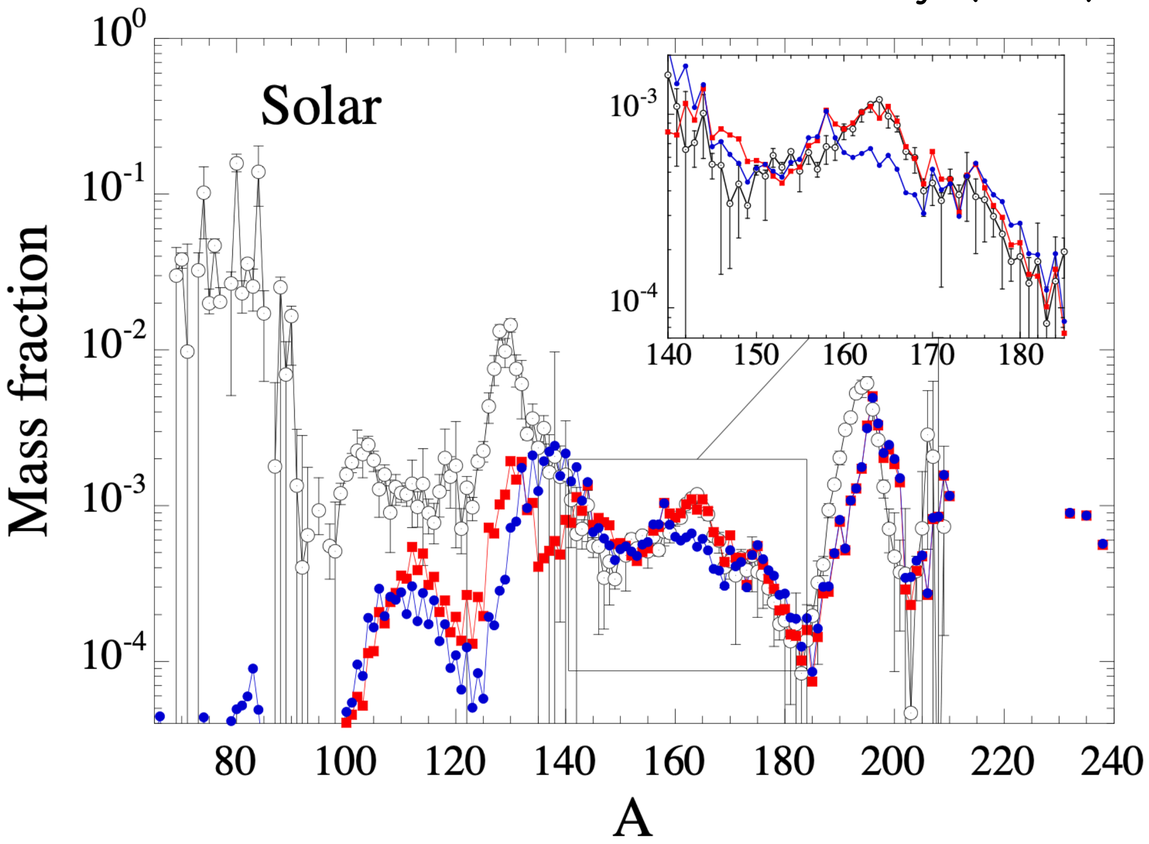


Nuclear fission in the r-process

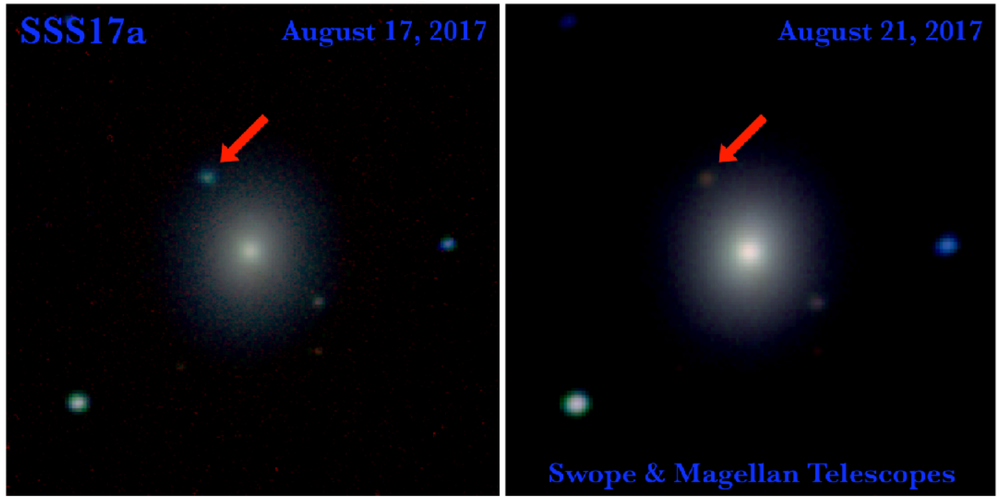
r-process → fission : termination, heating source of “kilonovae”

fission → r-process : unique natural source, beyond accelerator experiments

Goriely+(2013)

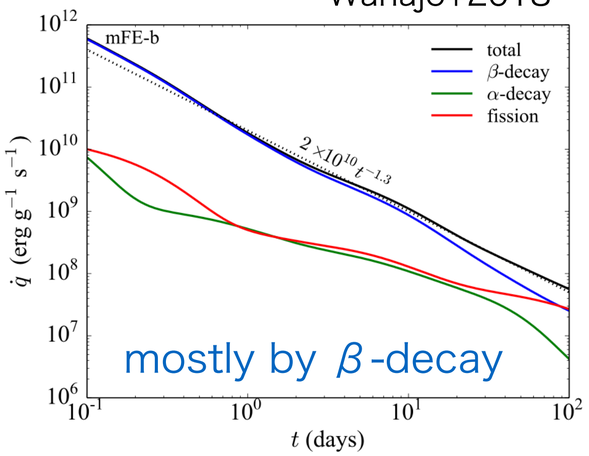


NS merger (kilonova)

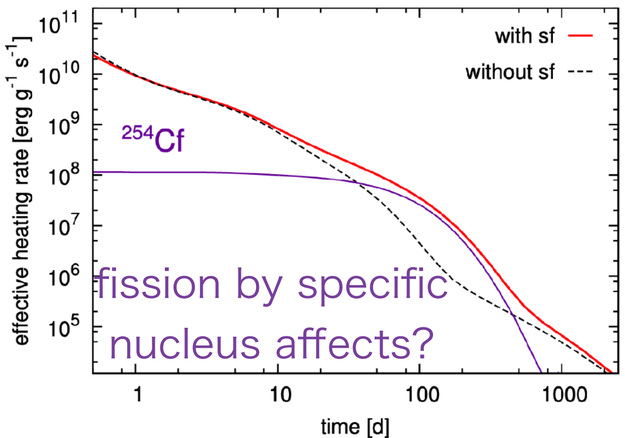


light curve

Wanajo+2018



Zhu+2018



Talk plan

- **Fission in r-process**
  - r-process is only nucleosynthesis process fission happens
  - several astronomical observations

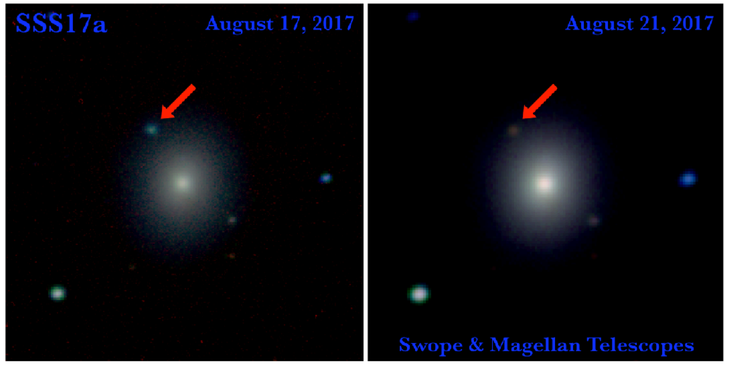
- **Recent progresses in astrophysics**
  - Compact binary merger simulations and r-process
  - Actinide-boost metal-poor stars

- **Theoretical fission data for the r-process**
  - need for database: fission & n emission for U isotopes
  - (impacts on the r-process)

Recent progresses in astrophysics

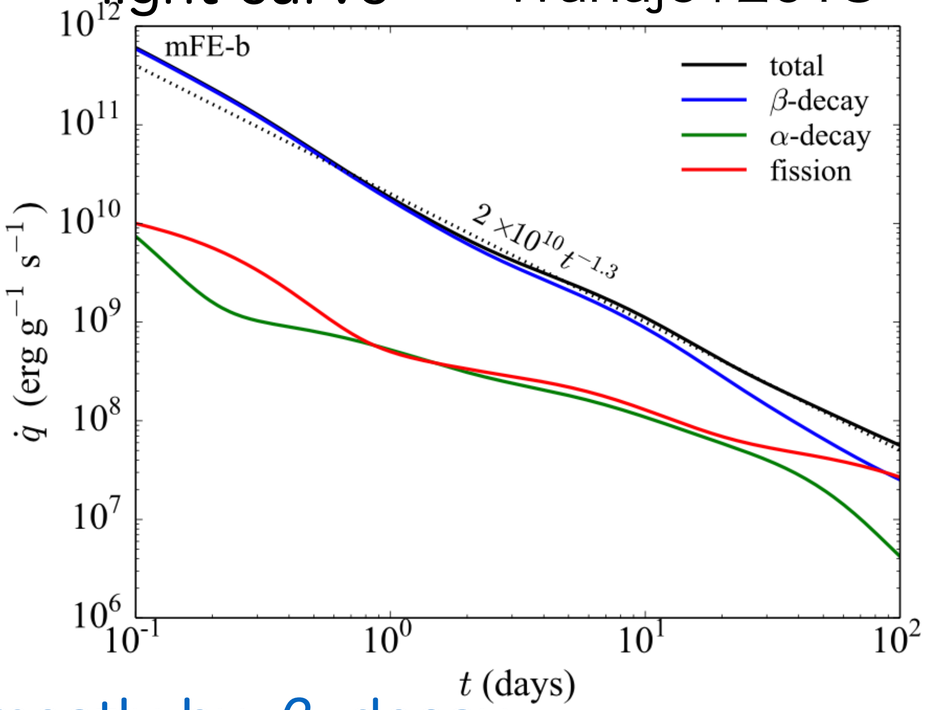
Nuclear fission in the r-process: kilonovae

NS merger (kilonova)



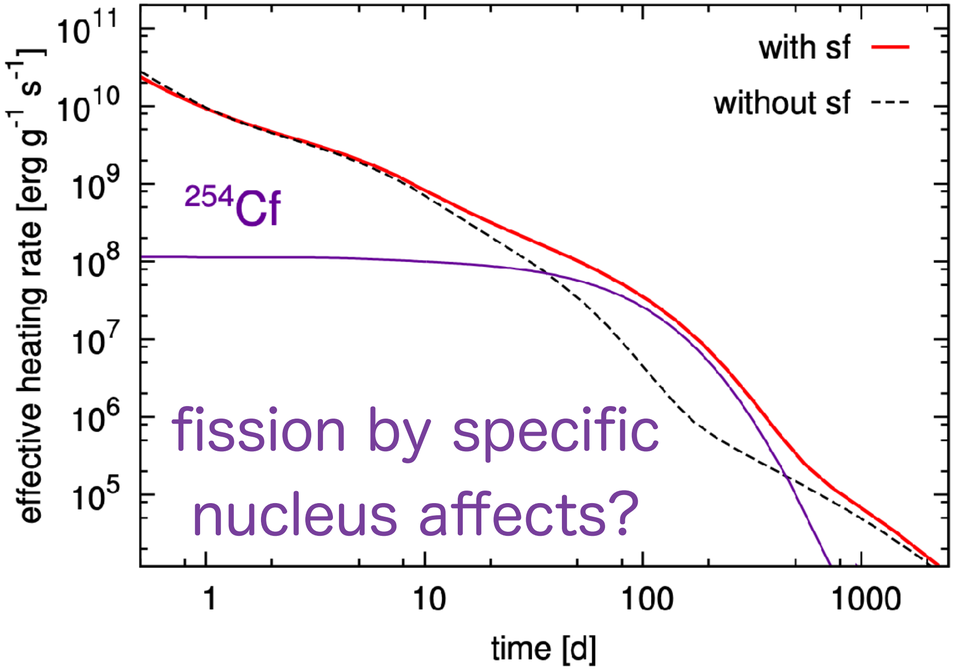
r-process → fission : heating source of “kilonovae”

light curve Wanajo+2018



mostly by β-decay

light curve Zhu+2018

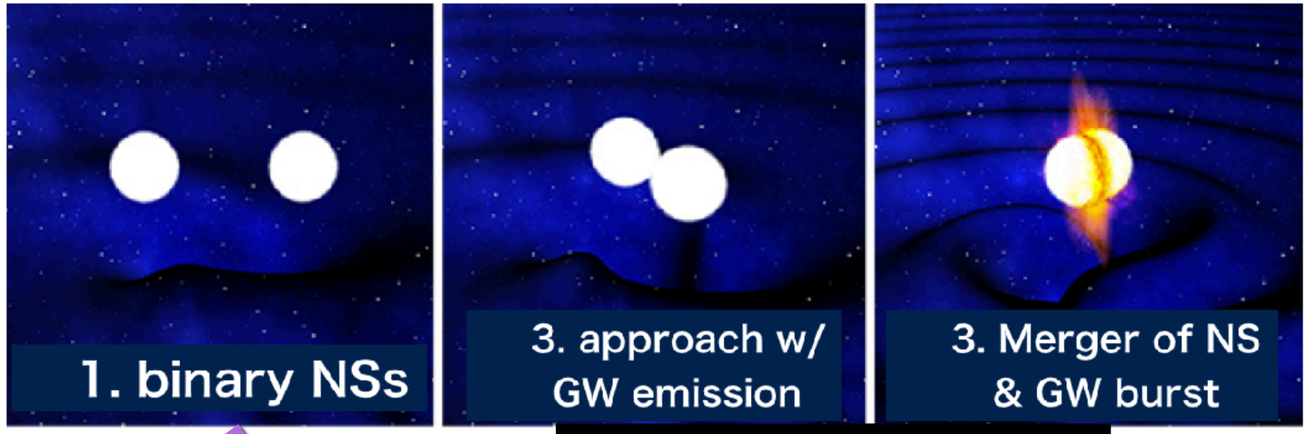


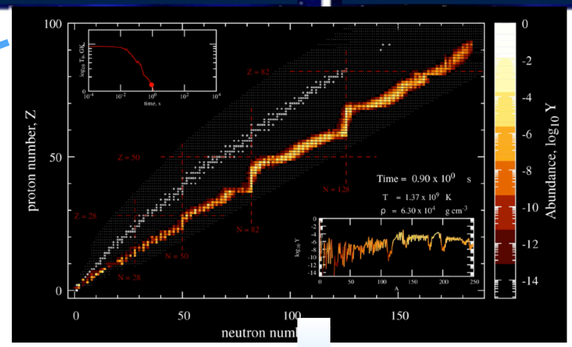
NS mergers and "kilonova”

credit NAOJ

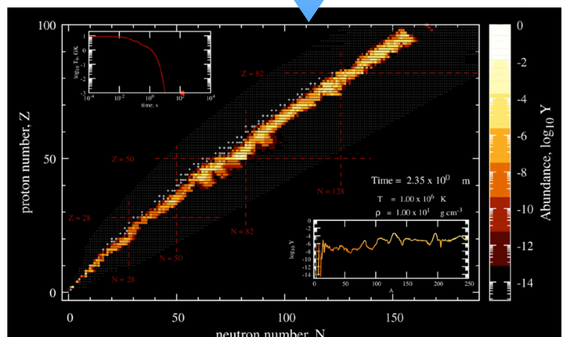
SN explosion

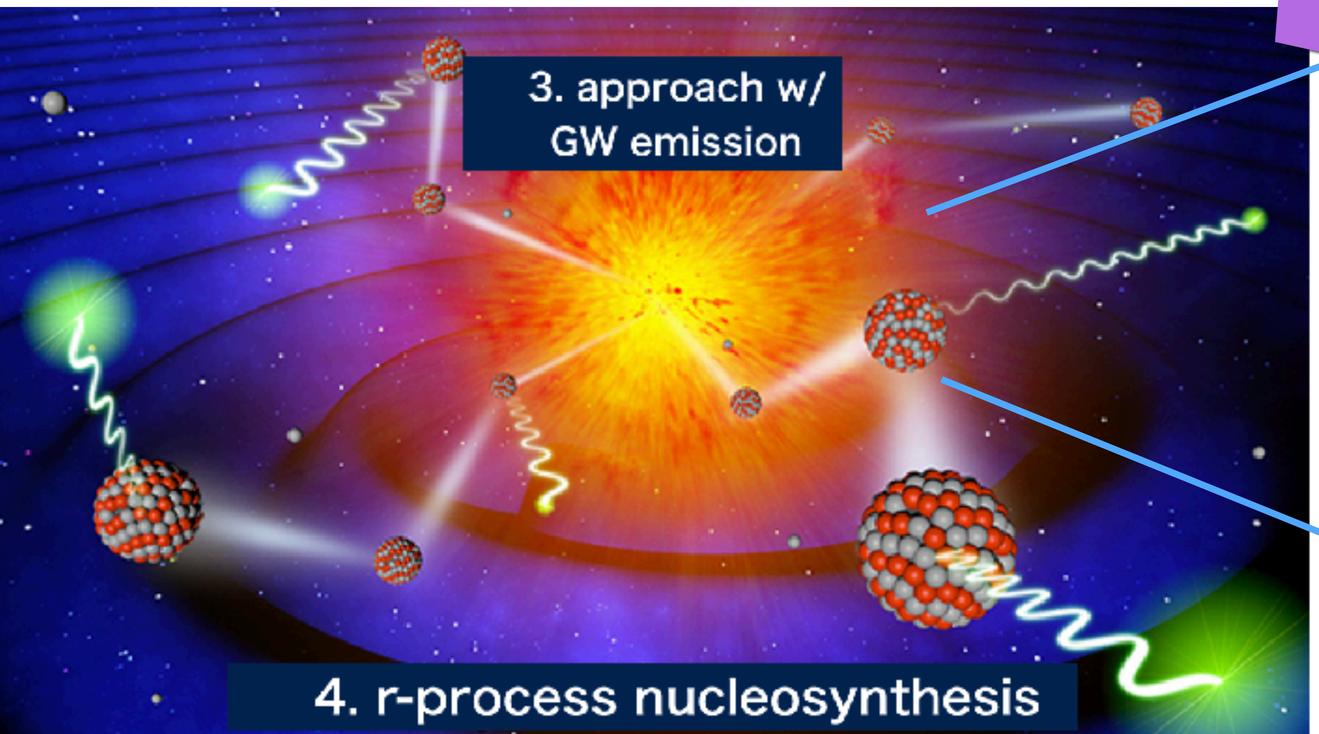
Neutron star





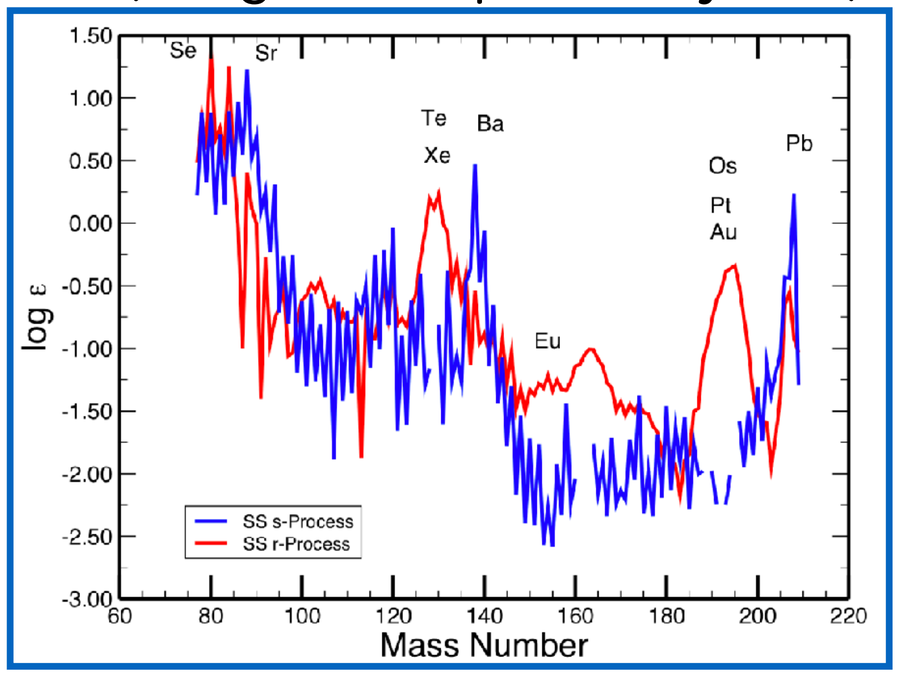
radio active decays of r-process elements

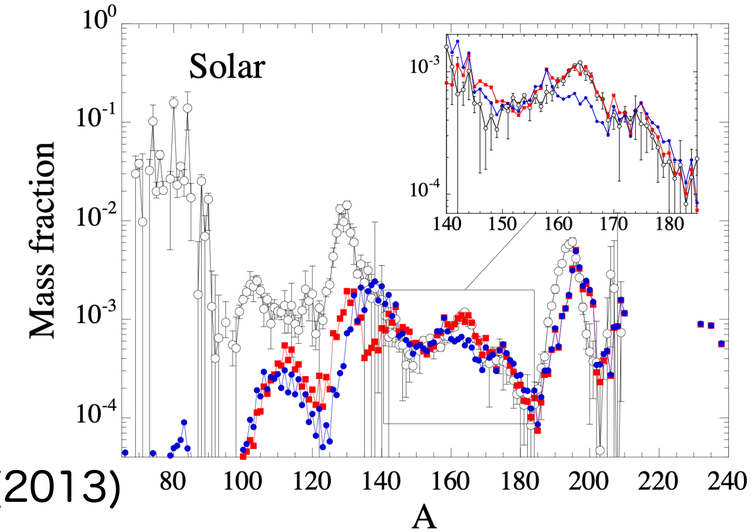




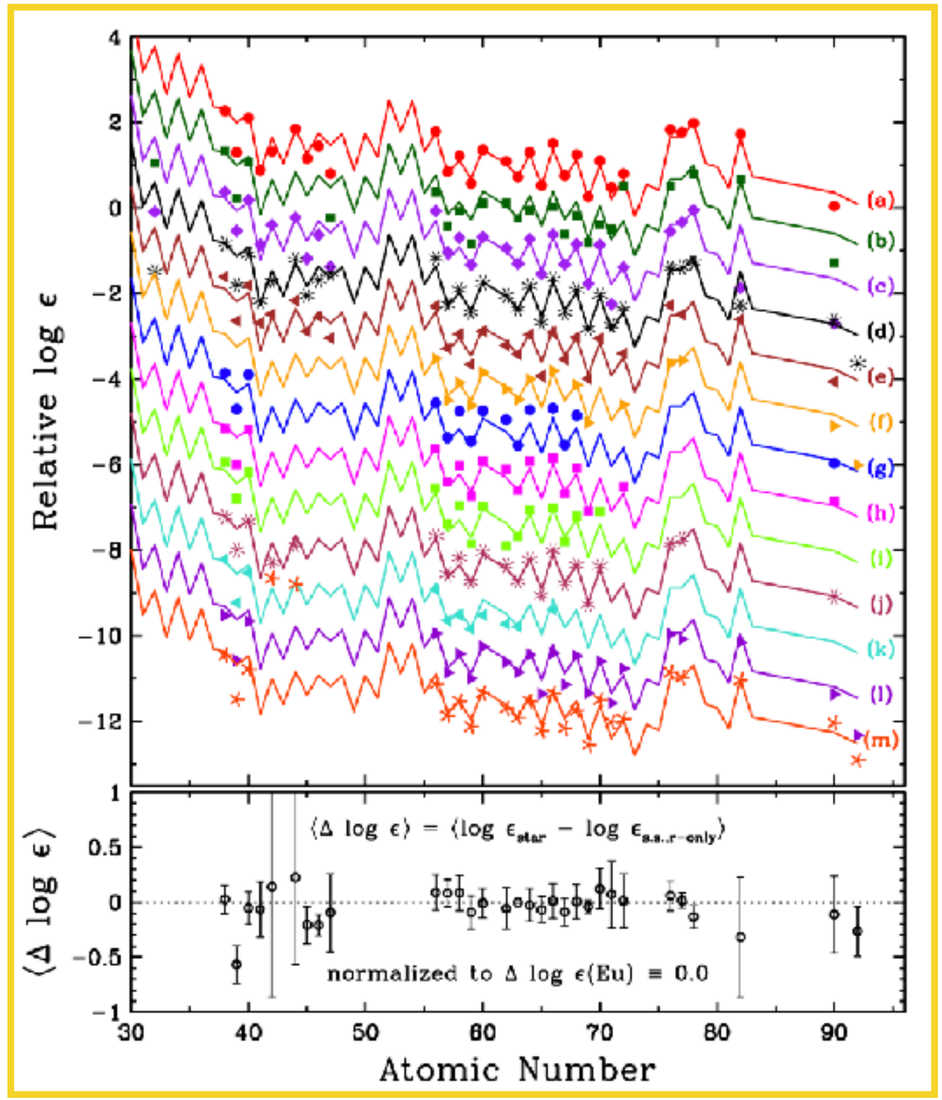
Nuclear fission in the r-process: abundances

the solar abundances
(integrated r-process yields)



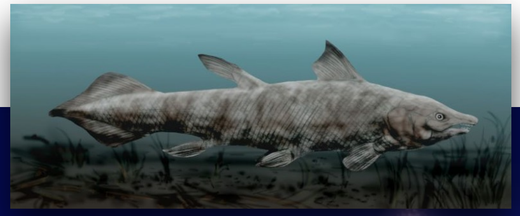


Goriely+(2013)



Metal-poor stars and “Galactic Archaeology“

fossils



present day

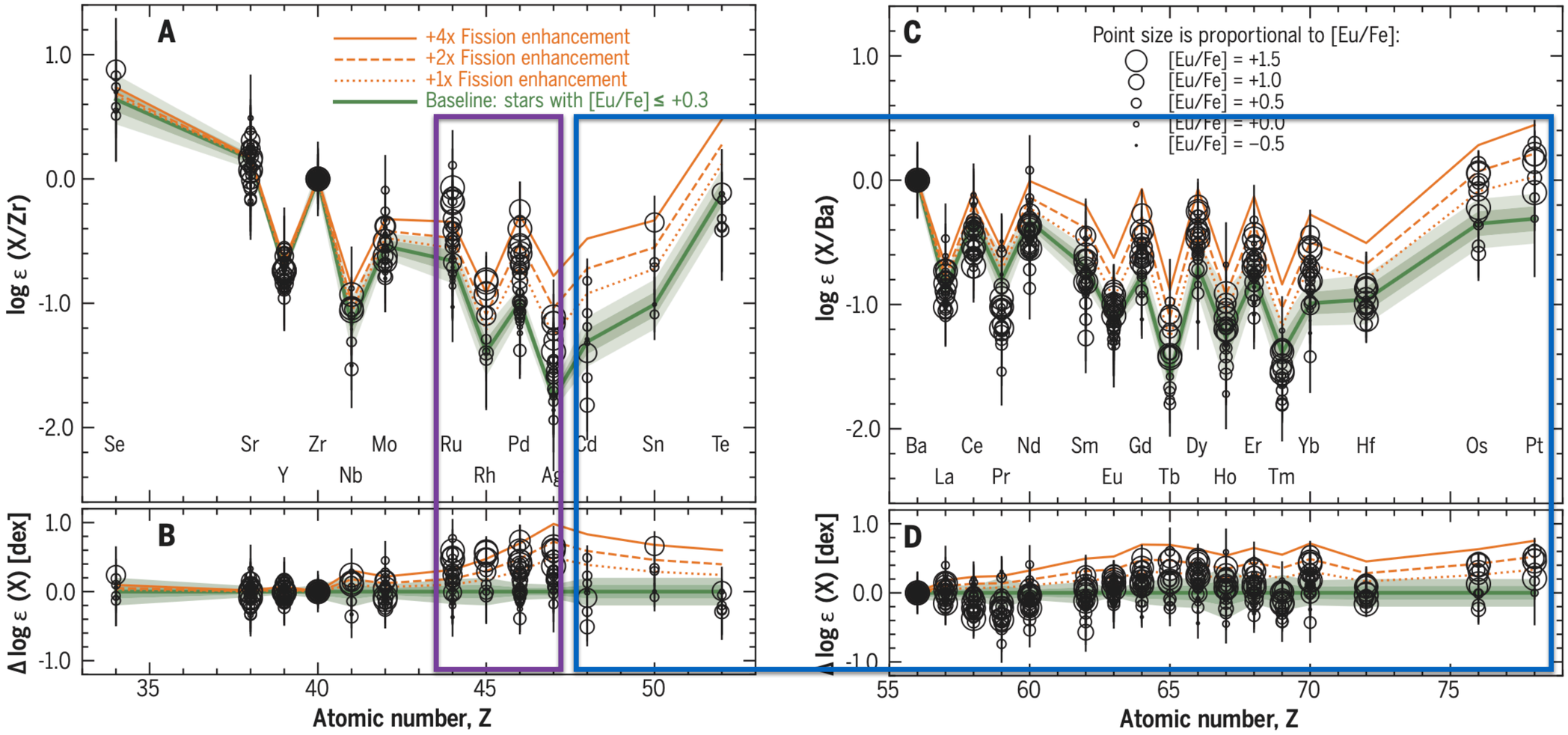
Credit: Pearson Education Inc.

Fission yields in metal-poor stars

・42 r-process enhanced metal-poor stars

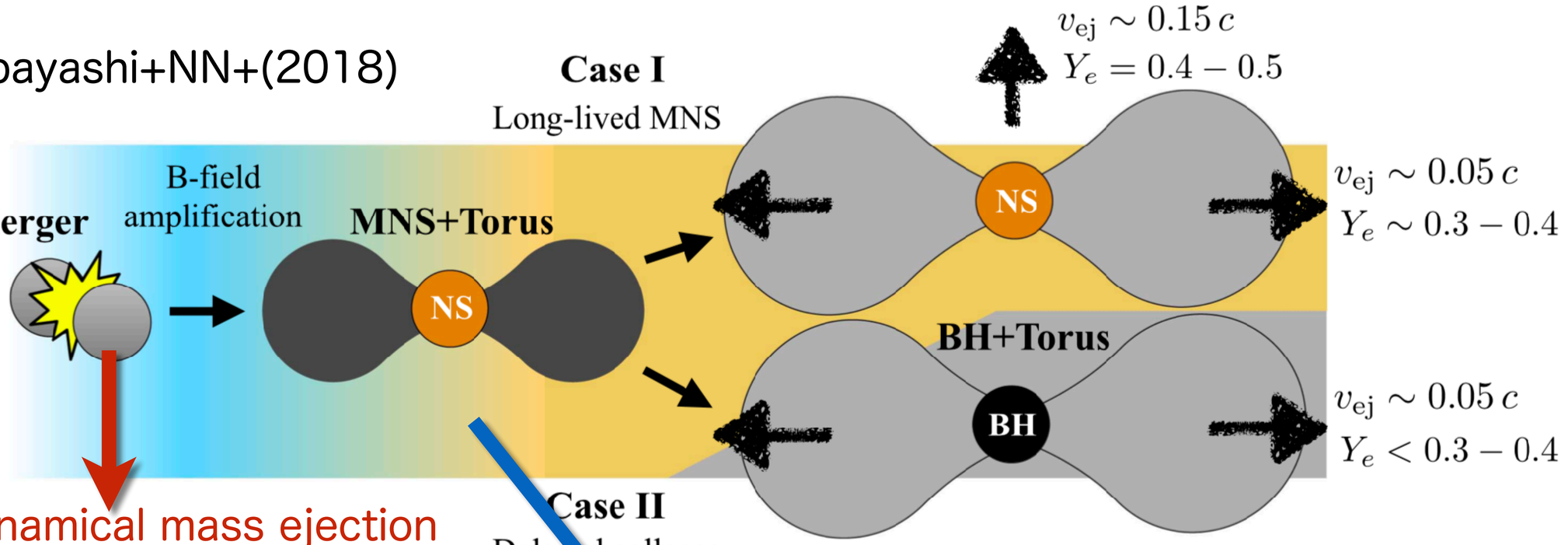
・Z = 44—47 elements correlate with 48 ≦ Z ≦ 78 and A > 150

Roederer+(2023) Science 382 (6675)

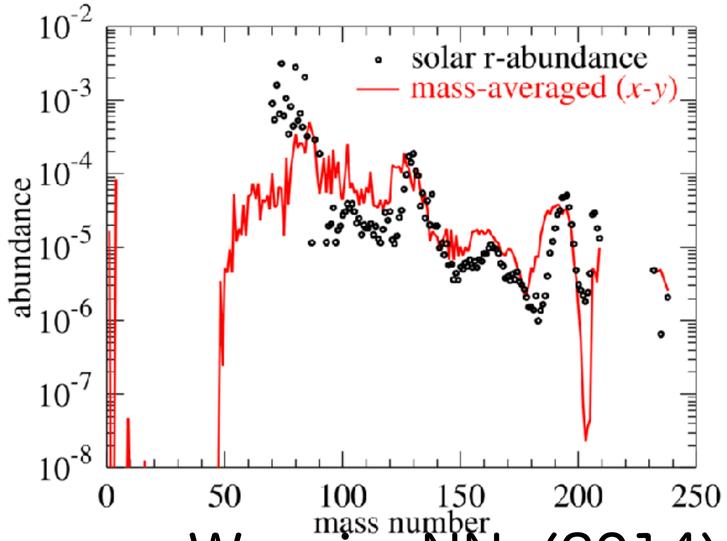


r-process in NS—NS mergers: dynamical + post-merger

Fujibayashi+NN+(2018)

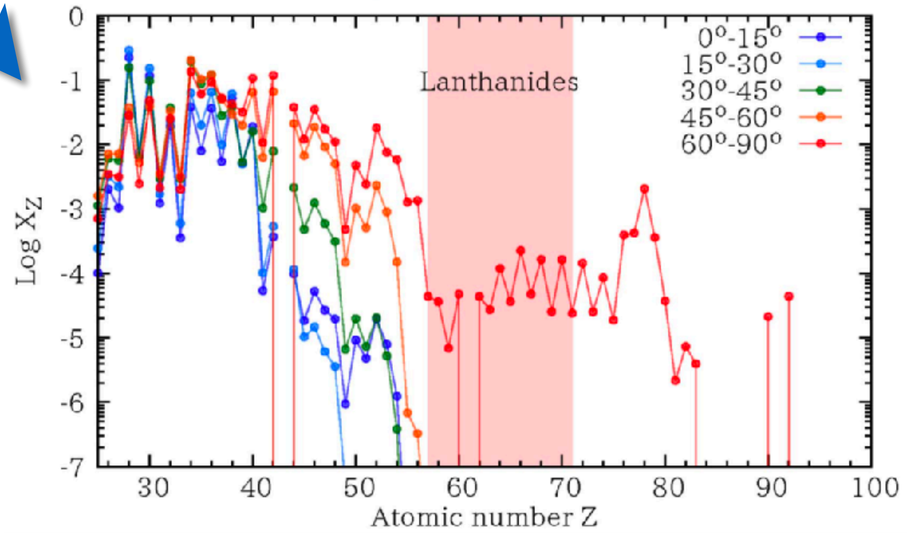


dynamical mass ejection



Wanajo+NN+(2014)

post-merger

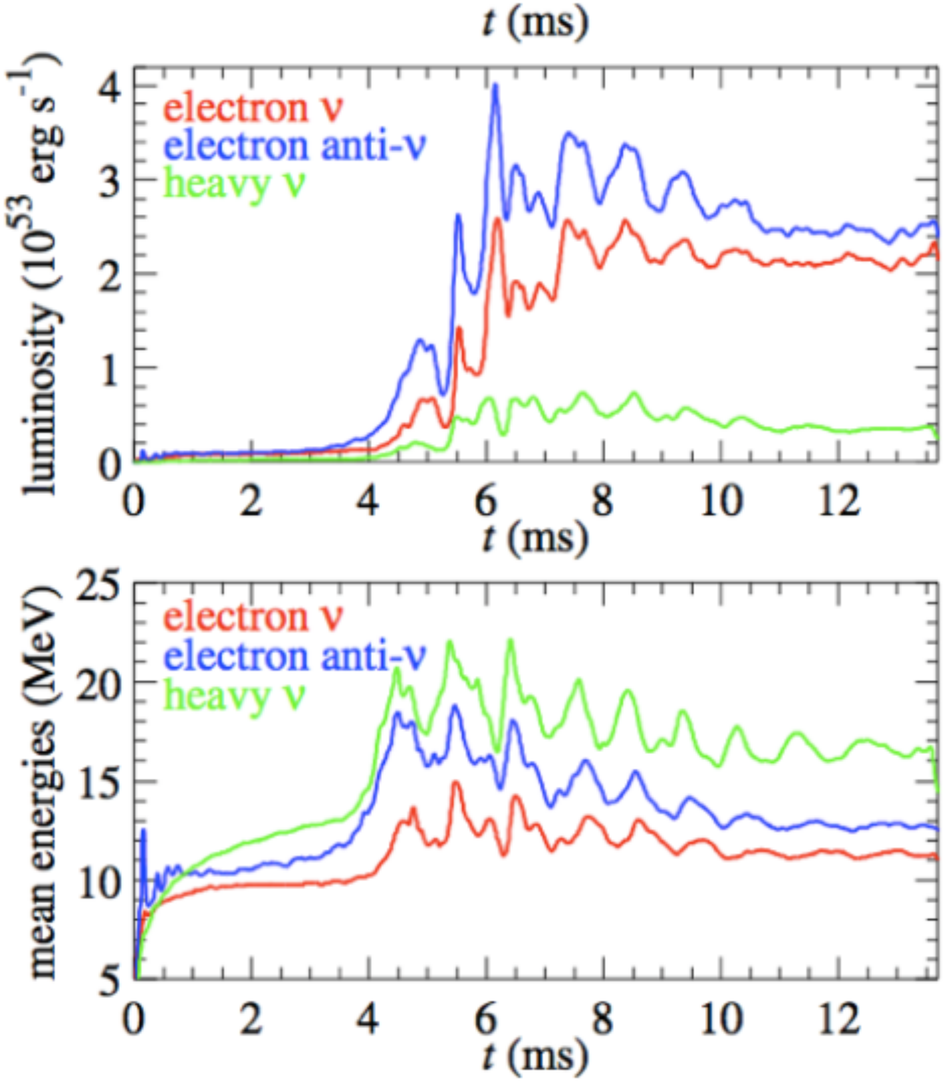


lighter r-nuclei
(lanthanide poor)

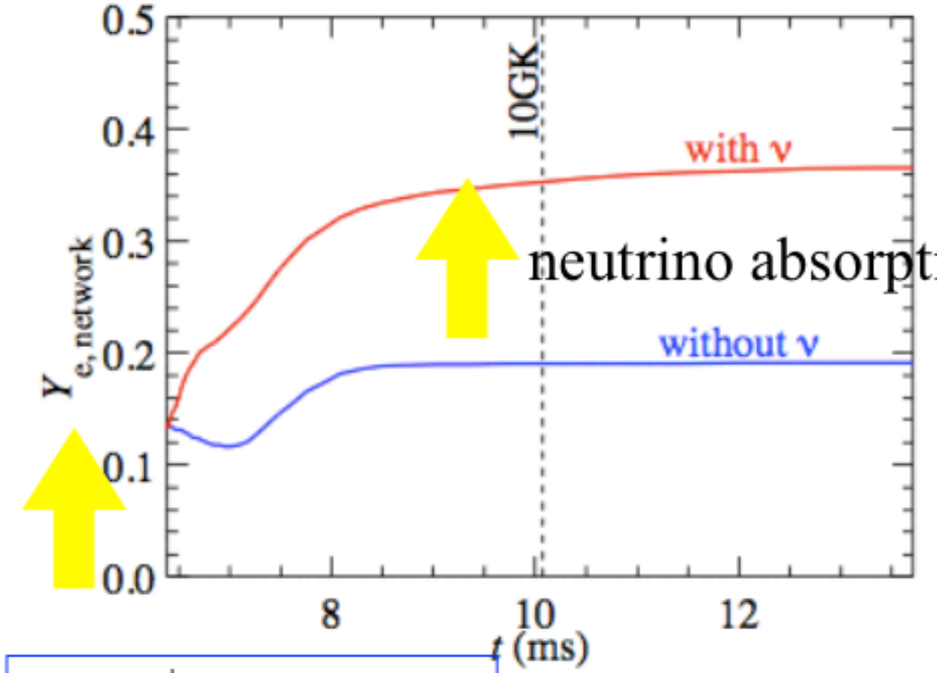
lanthanide
Z=57–71

Y_e change by the neutrino burst

"Protonization" Burst



Ye changes due to positron capture and neutrino absorption

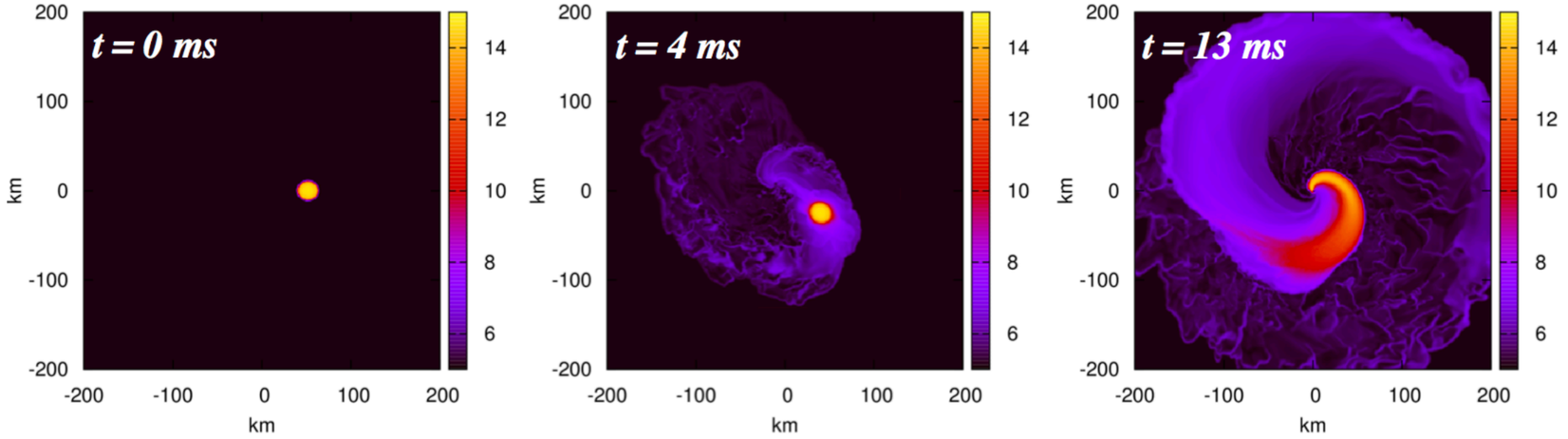


$$n + e^+ \rightarrow p + \overline{\nu_e}$$

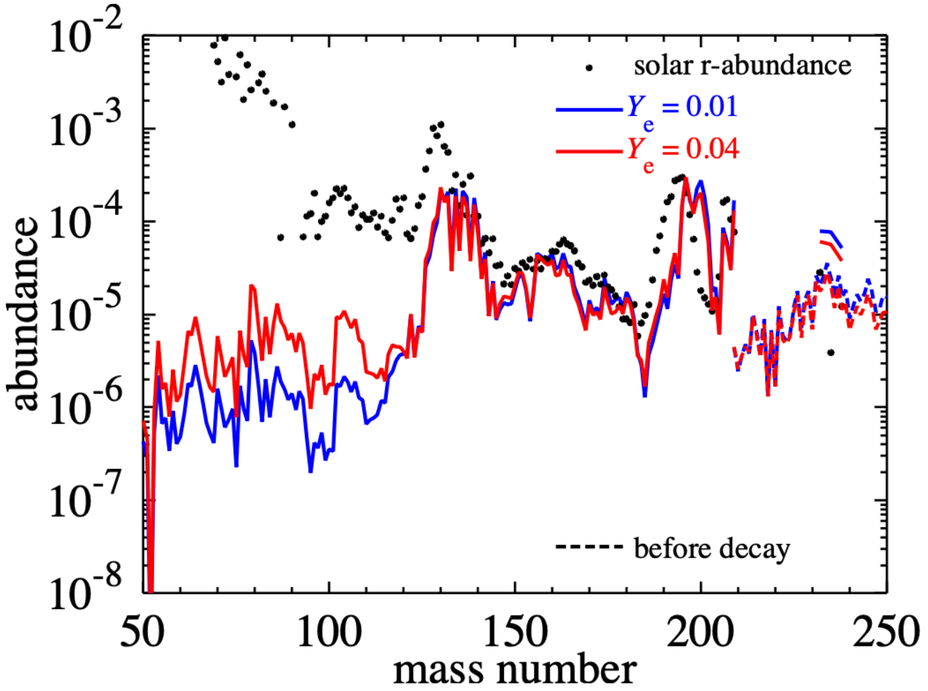
Wanajo+NN+(2014)

Stronger fission in BH—NS?

NN+(2016): NPA6 conference proceedings



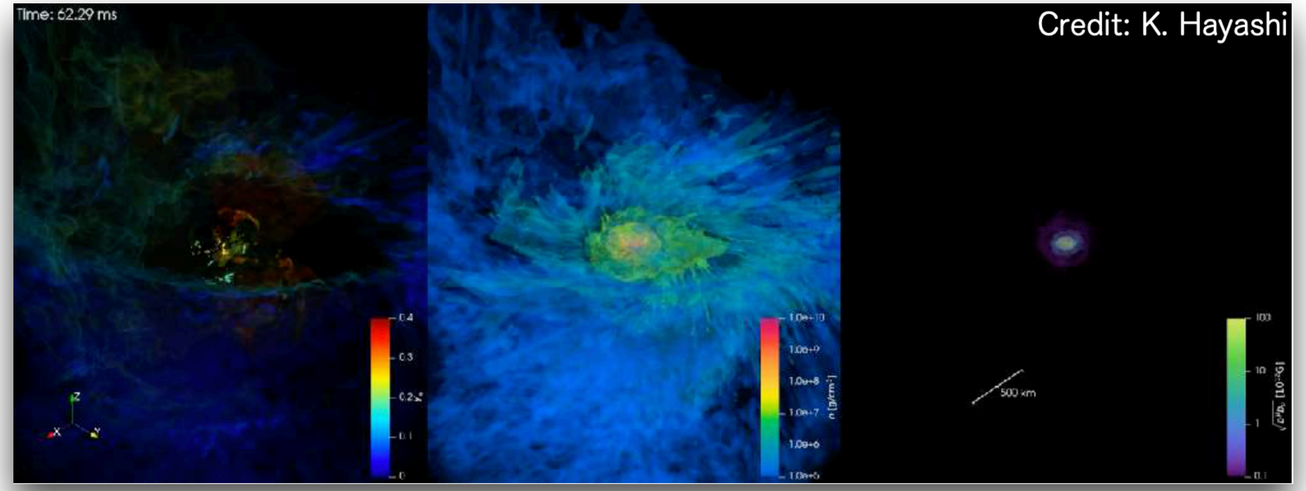
dynamical ejection due to tidal disruption:
keeps very n-rich matter of cold NSs
→ strong r-processes with fission cycling



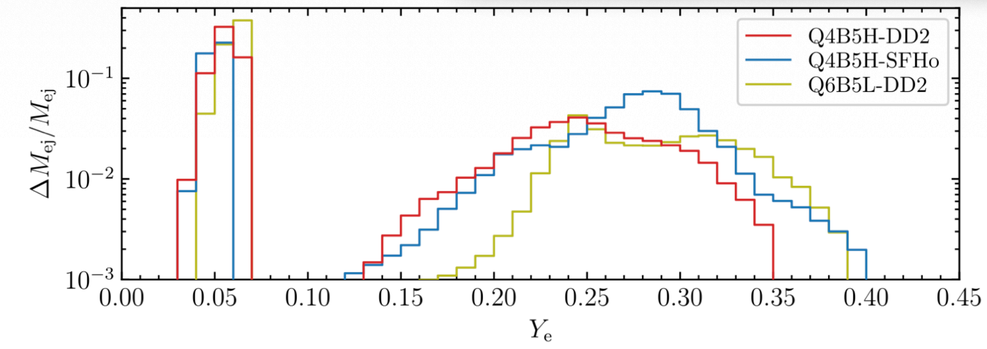
Nuclear fission in r-process nucleosynthesis

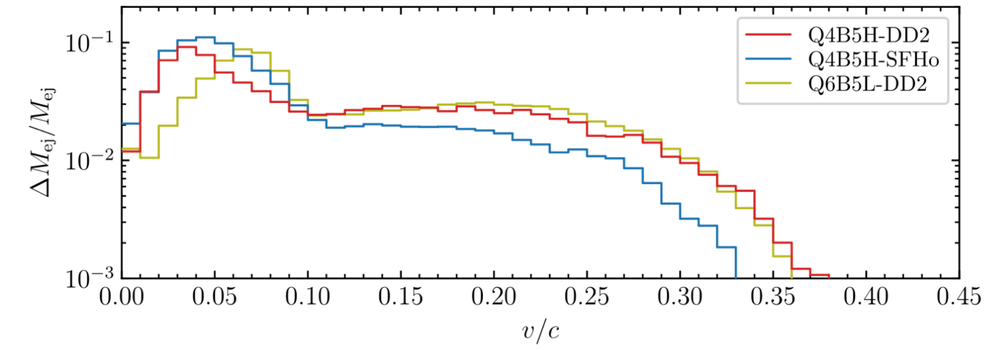
BH-NS simulation

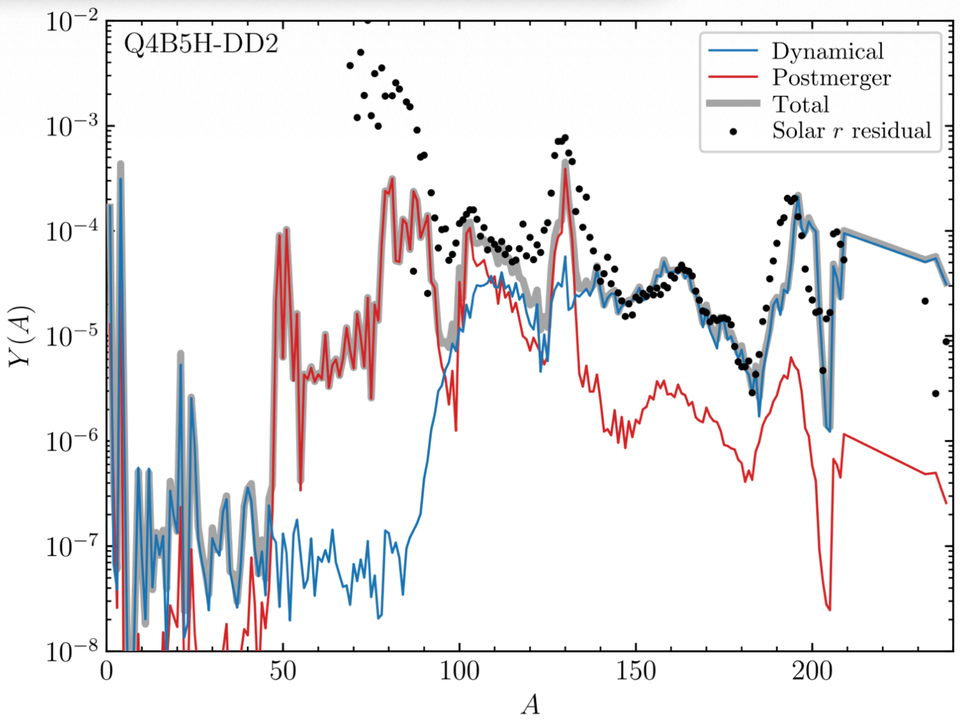
Wanajo+(2024)



different EOS



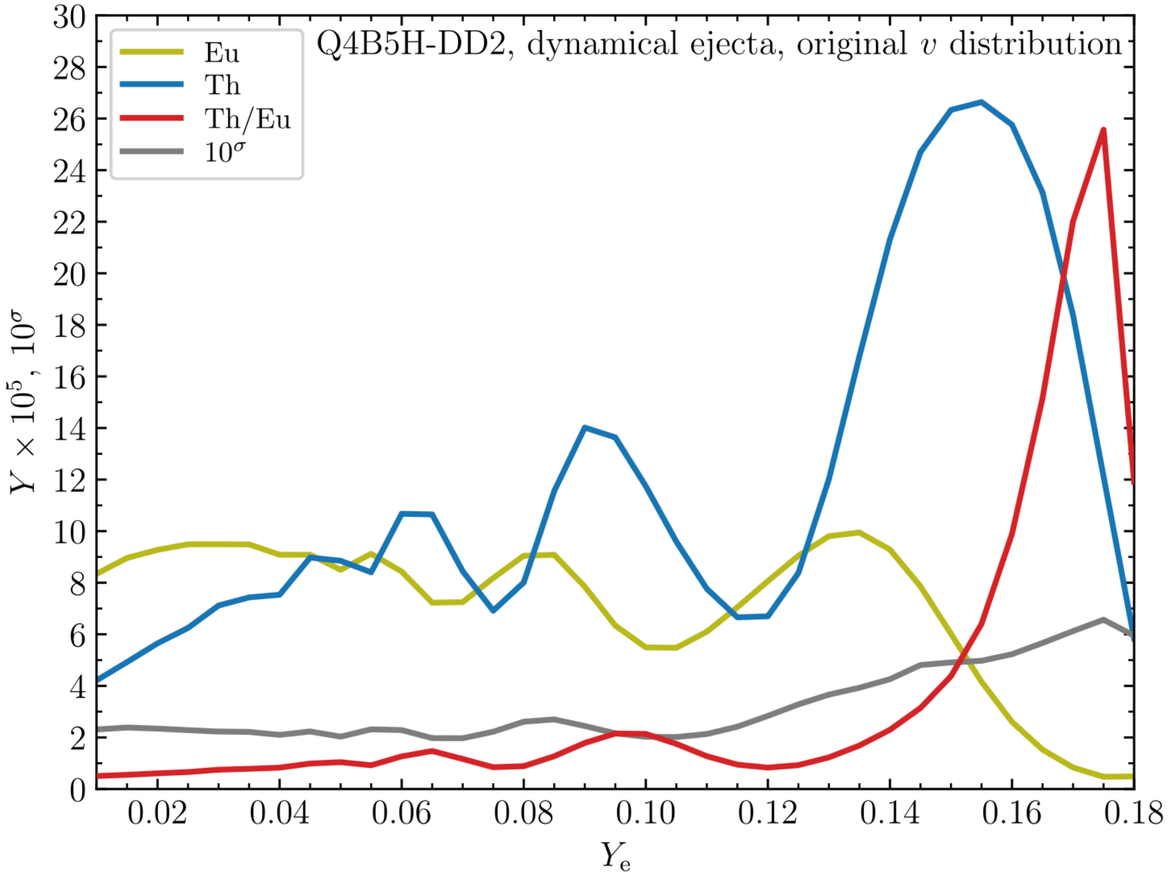


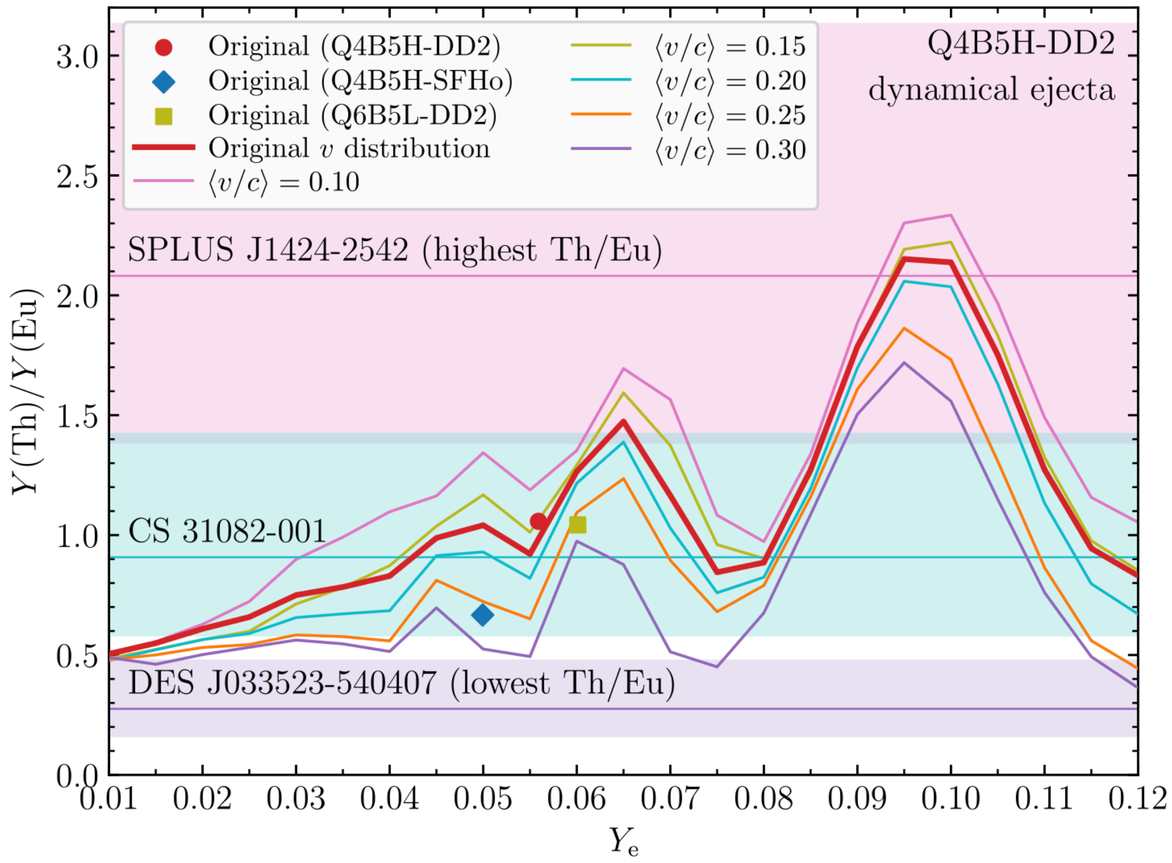


Nuclear fission in r-process nucleosynthesis

Abundance comparison to actinides-boost stars
(not the solar abundances)

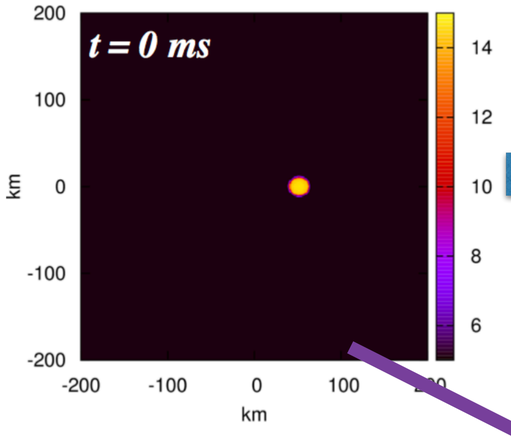
Wanajo+(2024)



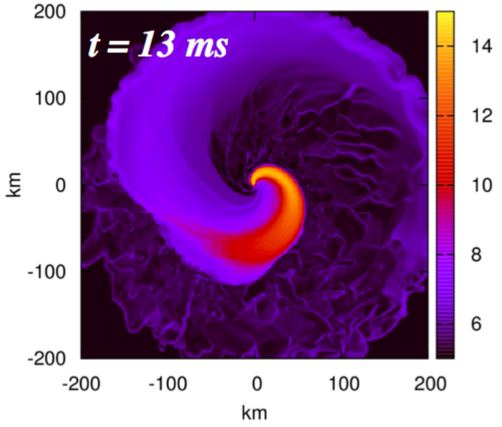


Constraint on the NS EOS

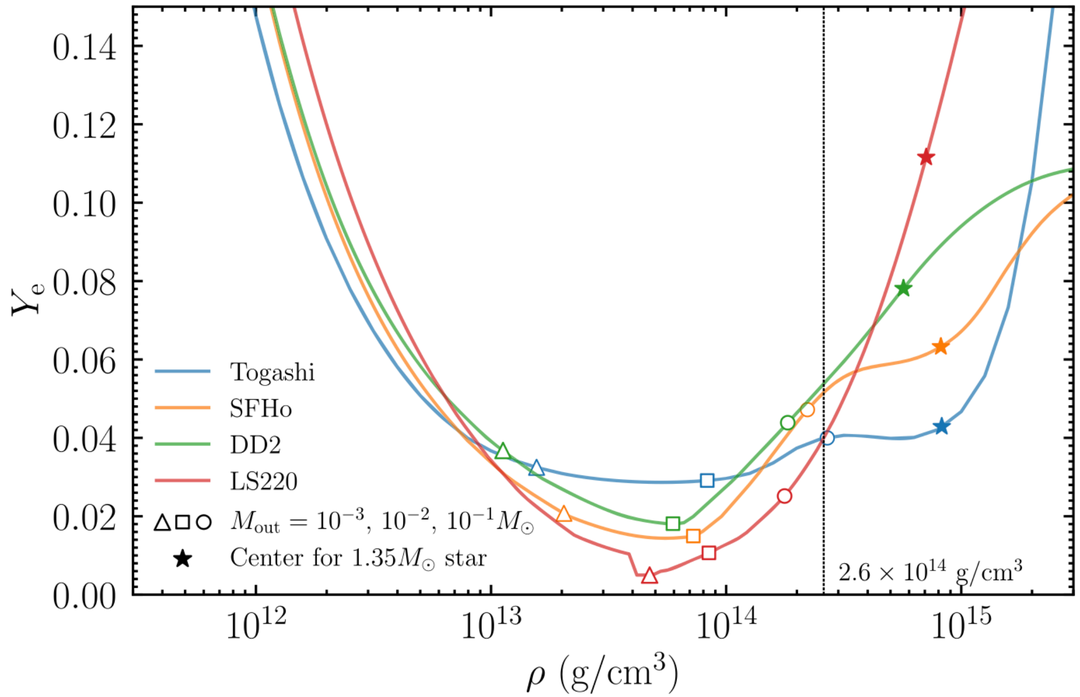
cold NS matter
the lowest Y_e

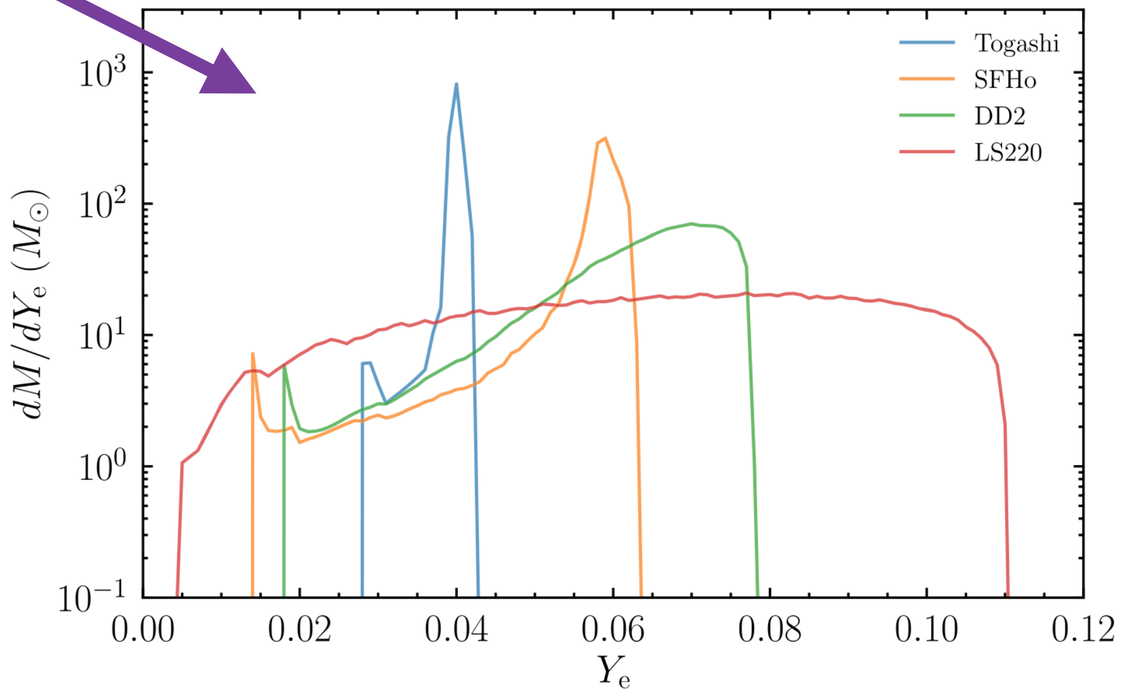


merger/explosion
increase Y_e



Wanajo+(2024)





Theoretical fission data for the r-process

in collaboration with Kindai U+ Group

- S.Tanaka, NN, Minato & Aritomo PRC 108 054607 (2023)
- C.Tahara (Master Thesis, Kindai U, FY2025)
- K. Miyake (undergraduate project, FY2026)
- S.Takagi, NN+, in prep.

PHYSICAL REVIEW C **108**, 054607 (2023)

Postfission properties of uranium isotopes: A hybrid method with Langevin dynamics and the Hauser-Feshbach statistical model

S. Tanaka (田中翔也),[1,*] N. Nishimura (西村信哉),[2,1,†] F. Minato (湊太志),[3,1,‡] and Y. Aritomo (有友嘉浩)[4,§]

田中 (Ta-naka): 4th
1,293,000

西村 (Nishi-mura): 44th
297,000

Dynamical fission model: Langevin w/ Kindai G

see also an overview talk by Aritomo

$$V(q,\ell,T) = V_{LDM}(q) + \frac{\hbar^2\ell(\ell+1)}{2I(q)} + V_{SH}(q,T)$$

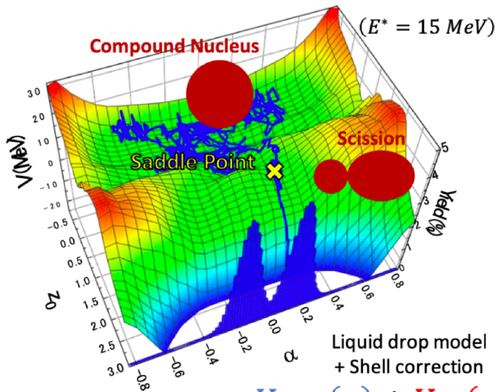
$$V_{LDM}(q) = E_S(q) + E_C(q)$$

$$V_{SH}(q,T) = E^0_{shell}(q)\Phi(T)$$

Temperature dependent factor

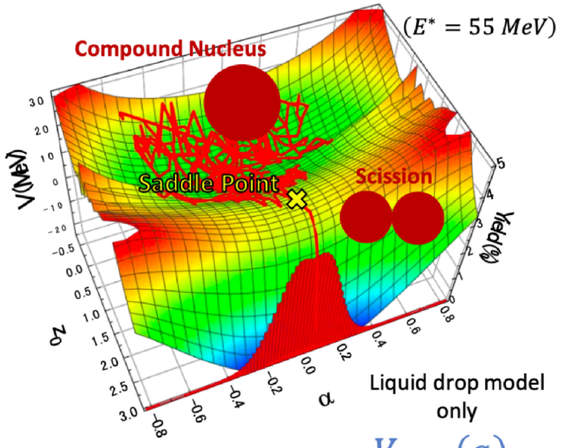
$$\Phi(T) = \exp(-\frac{aT^2}{E_d}) \quad E_d = 20[MeV]$$

(a) At low excitation energy



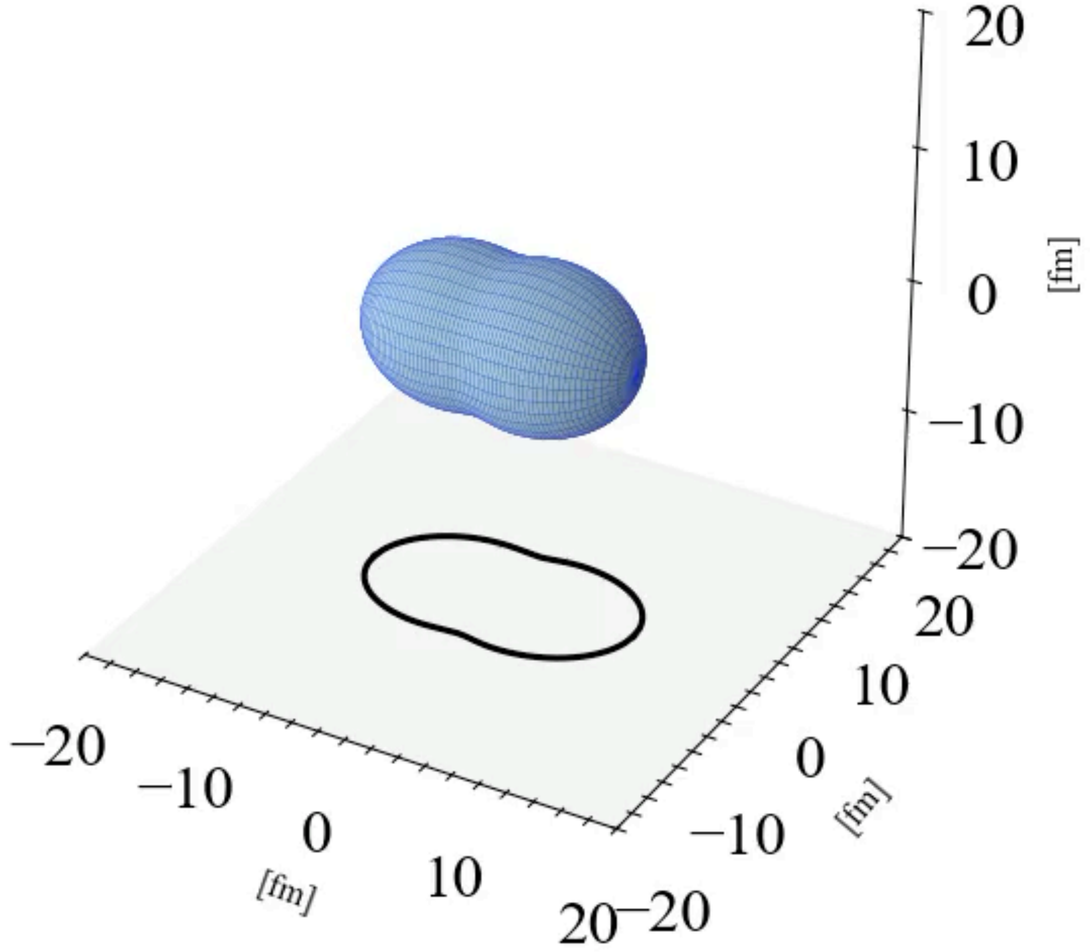
$V_{LDM}(q) + V_{SH}(q,T)$

(b) At high excitation energy



$V_{LDM}(q)$

Z, fm



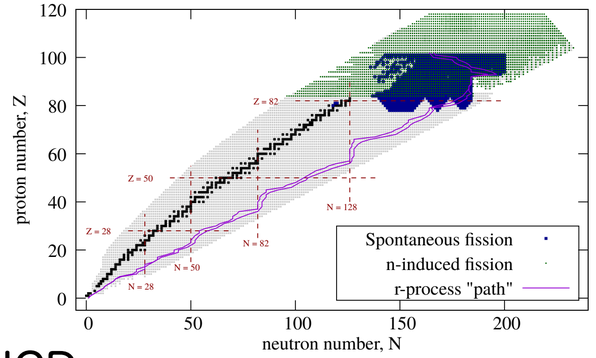
Fission theory: dynamical calculations

fission distribution by Langevin calculations

KUDAF (ver 0.1, in prep.)

(Kindai University Database of Dynamical Fission yields)

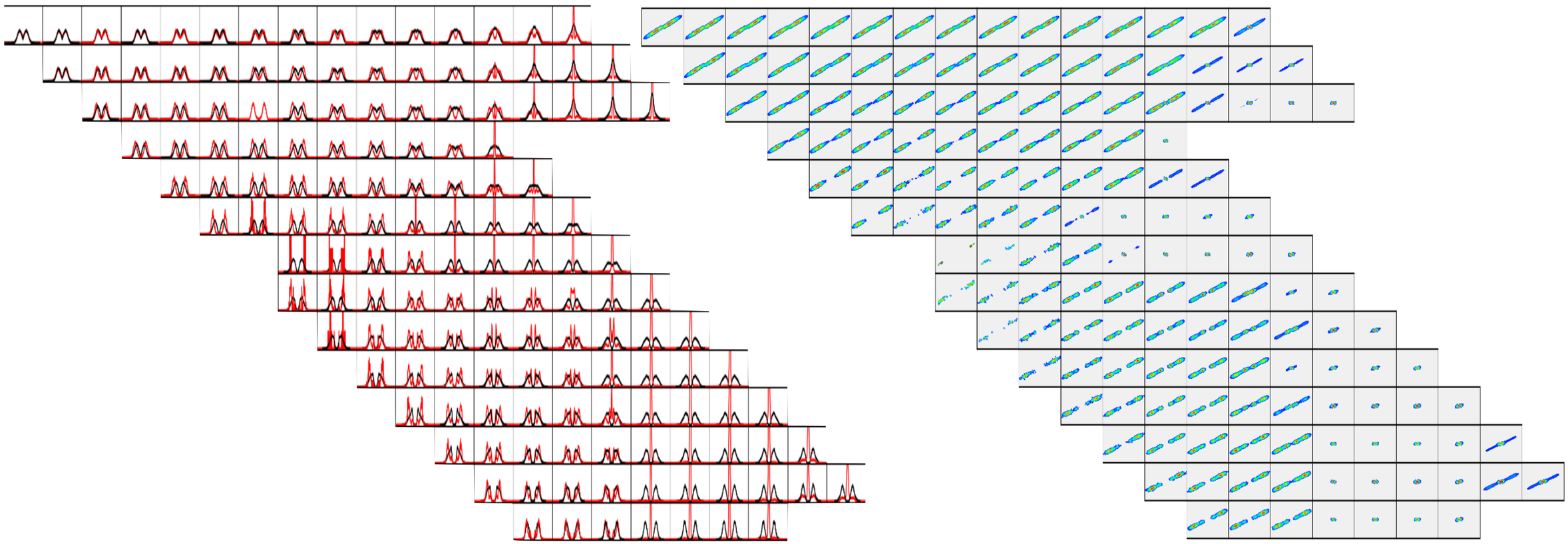
NN with Tanaka, Aritomo (Kindai U Group)



Fm

KUDAF vs GEF

Fission distribution with UCD

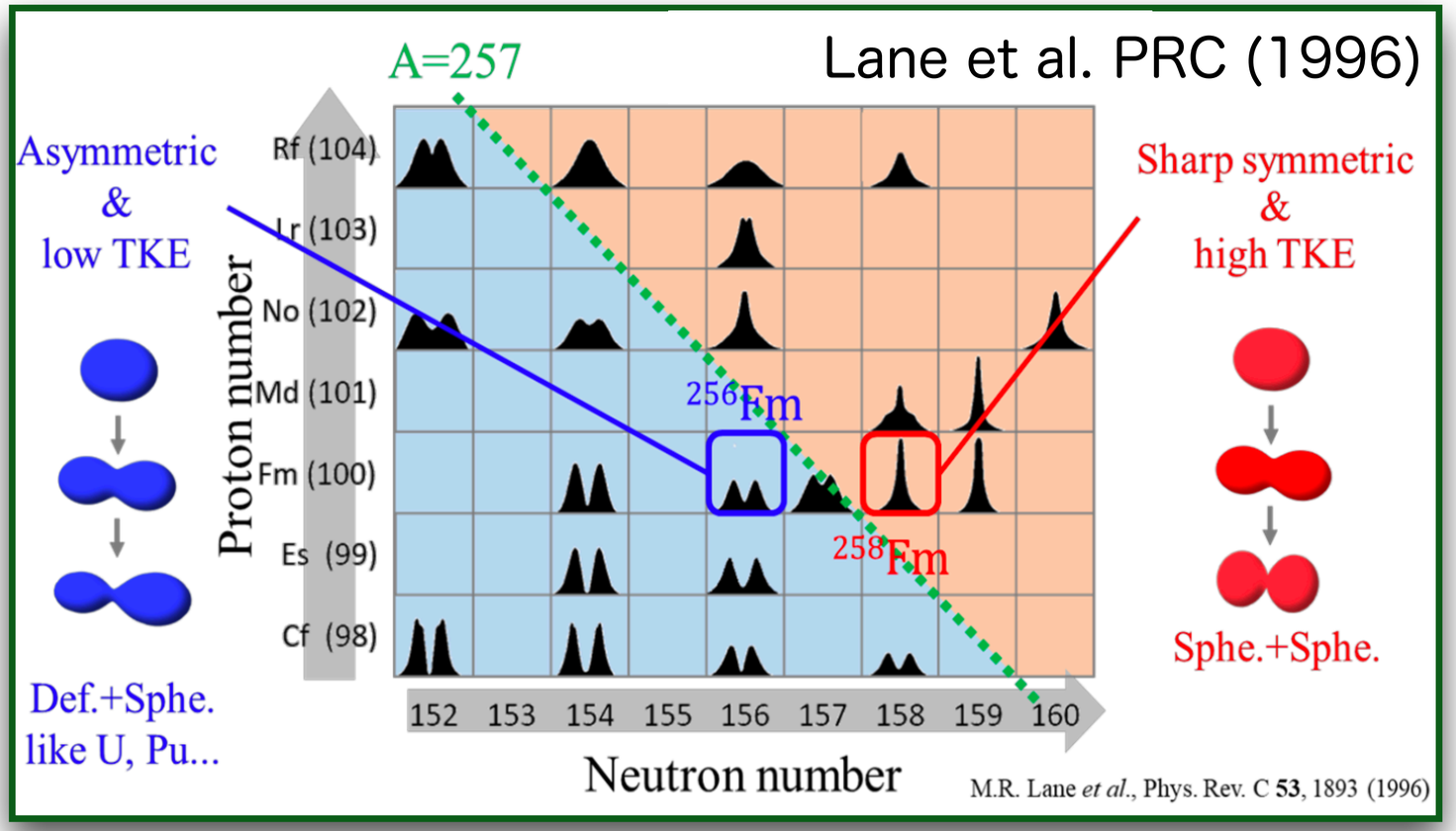


U

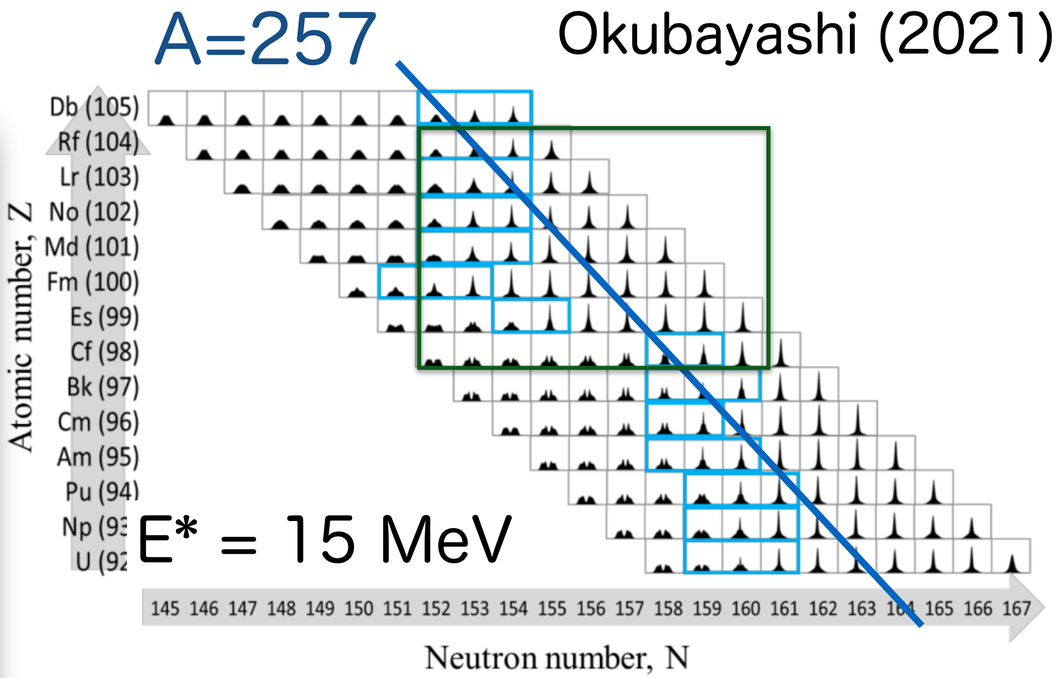
n-rich r-process region

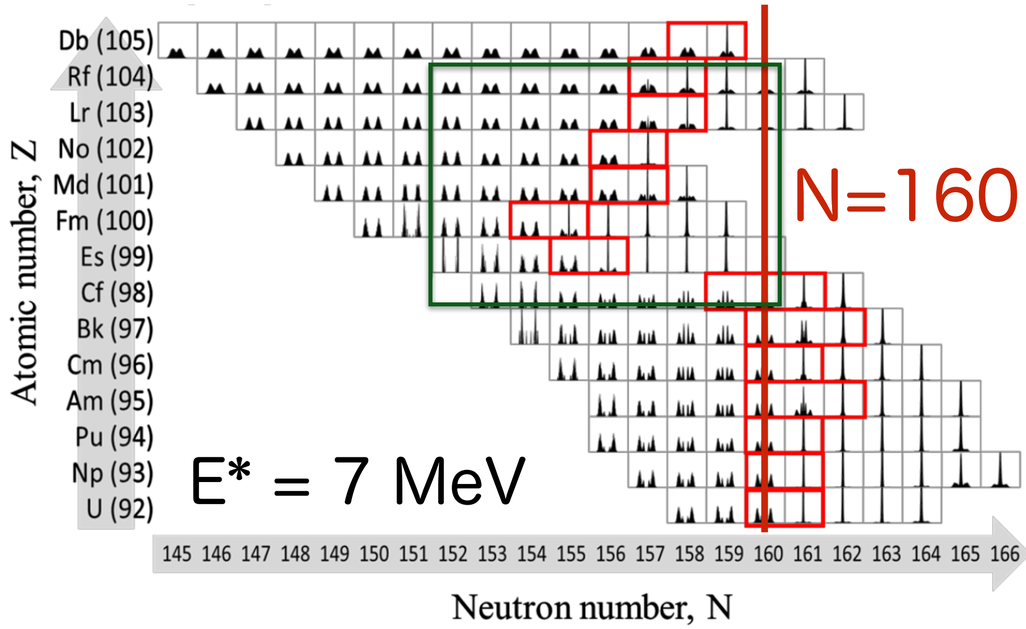
calculated by I.Nishimura, Takagi, Miyasakai

Symmetric-asymmetric transition: E*



see also talk by Nishio

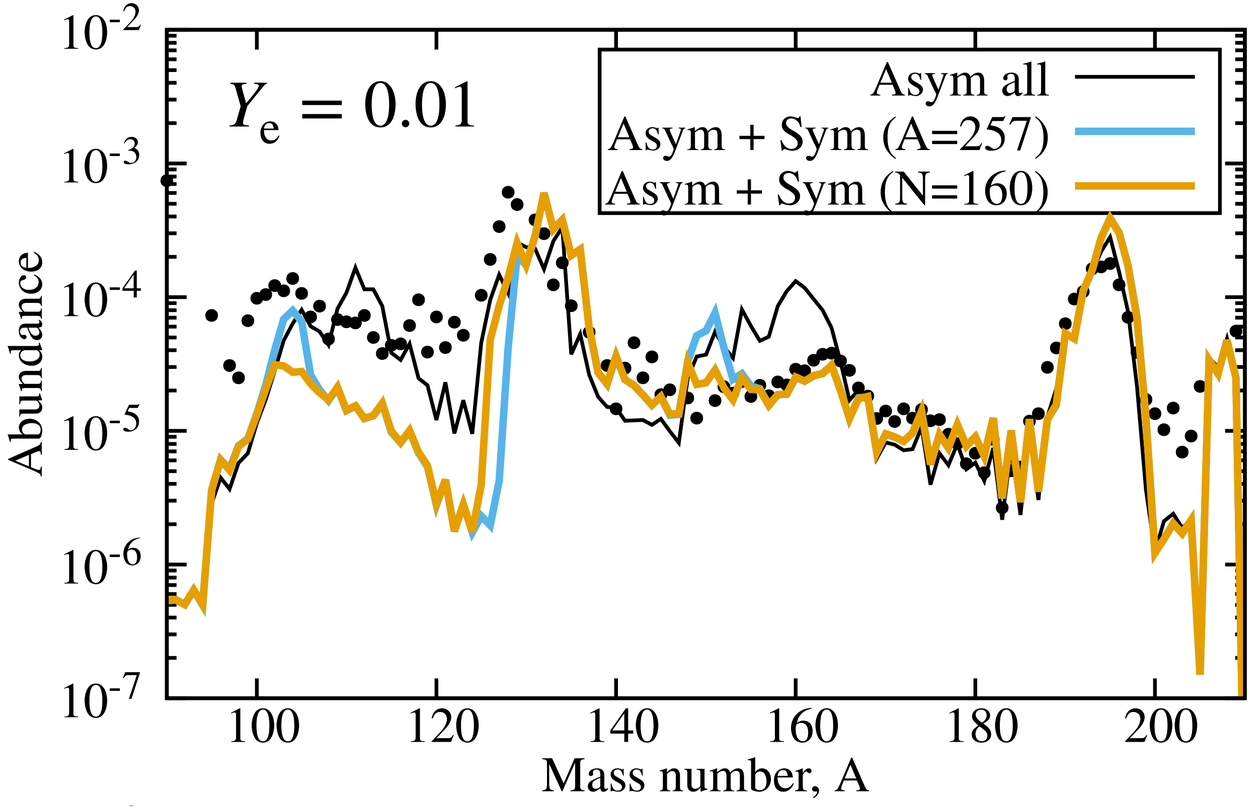


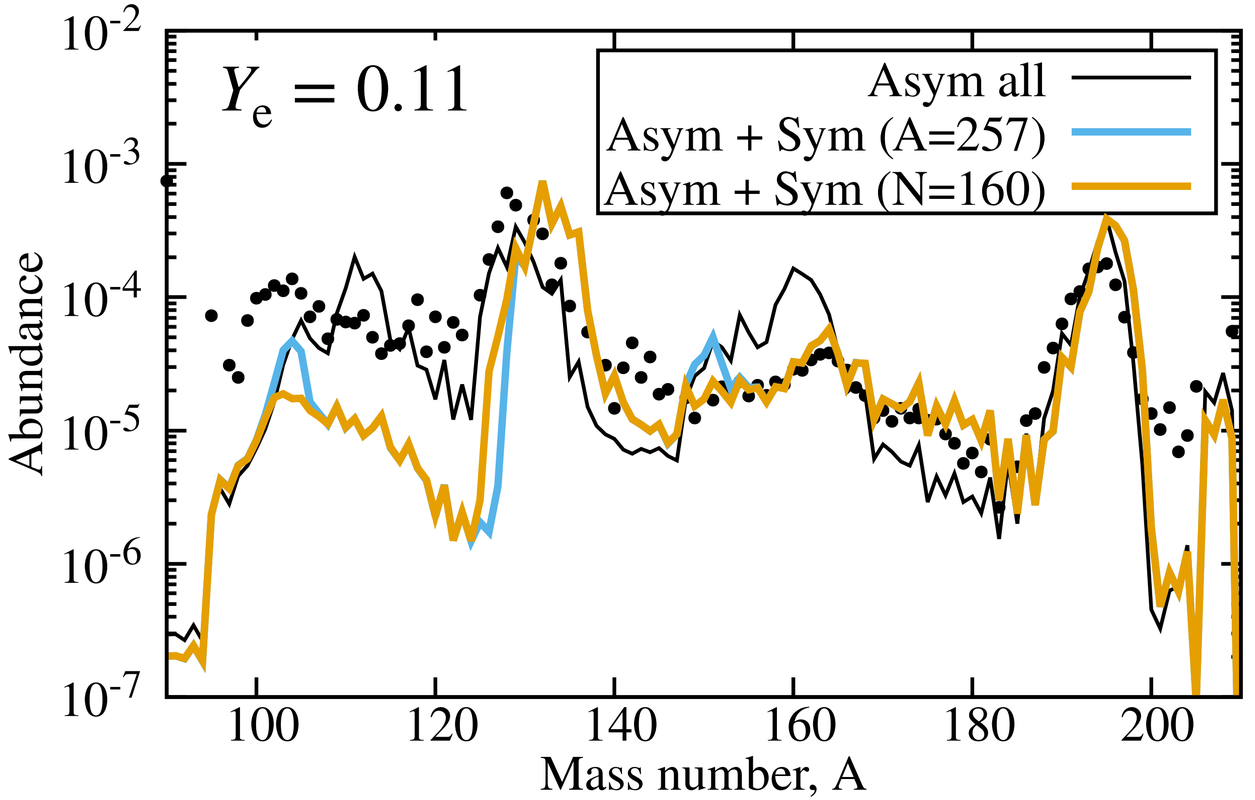


The impacts on the r-process

・Comparison: all asymmetric, asymmetric → symmetric A = 257 & N = 160

・very neutron-rich conditions, e.g., NS mergers





Comparison to several fission data

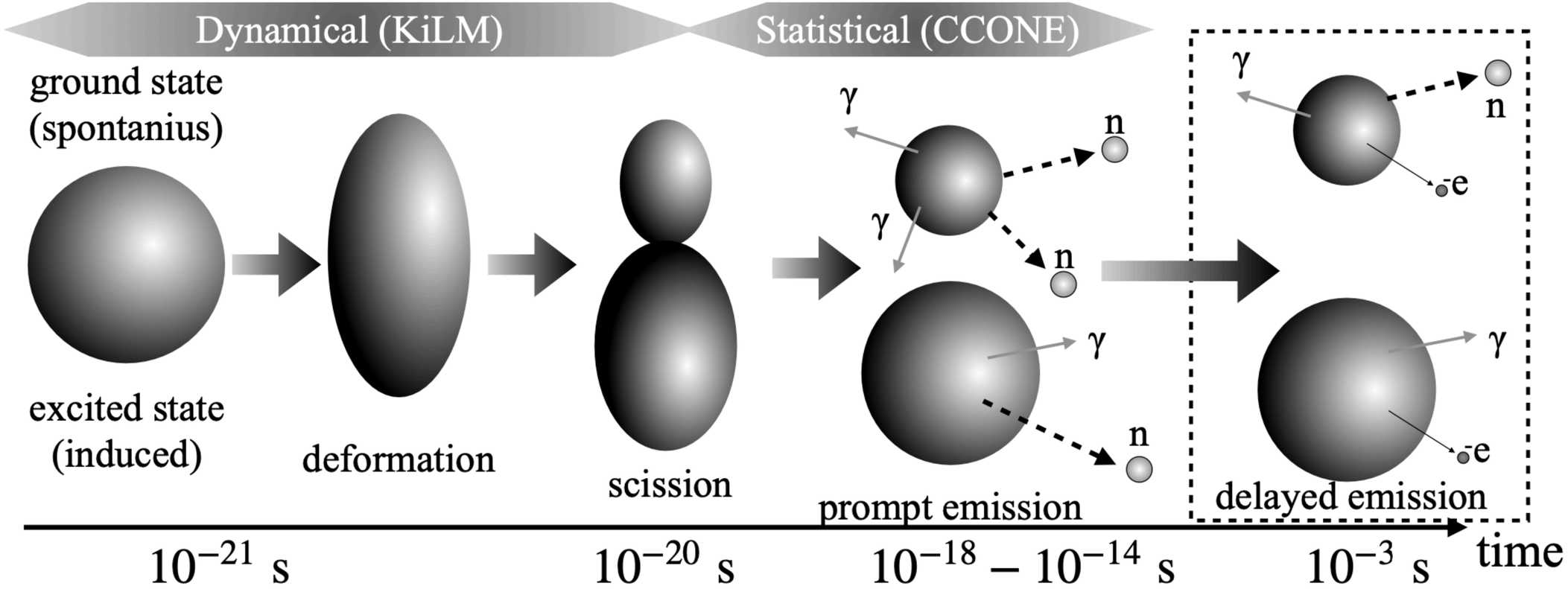
toward complete fission yields for r-process

theoretical data ↔ astrophysical nucleosynthesis

fission process has several experimental data → comparison

see also talk by Liu

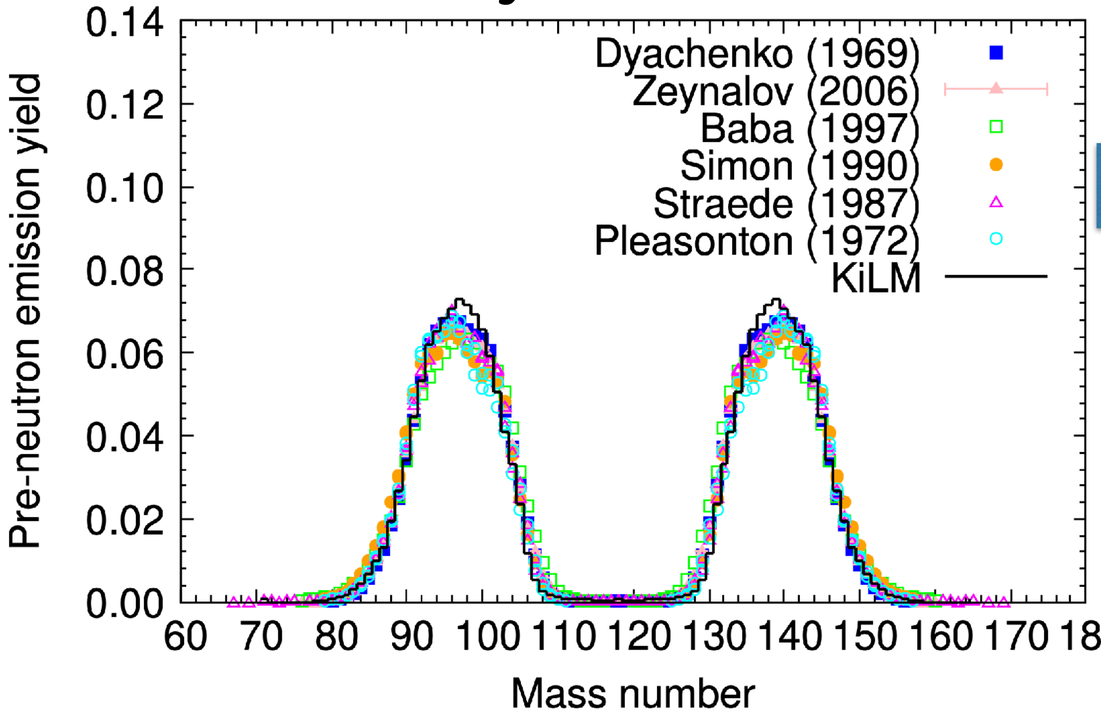
Tanaka, NN+2023



^{236}U : fission + n emission

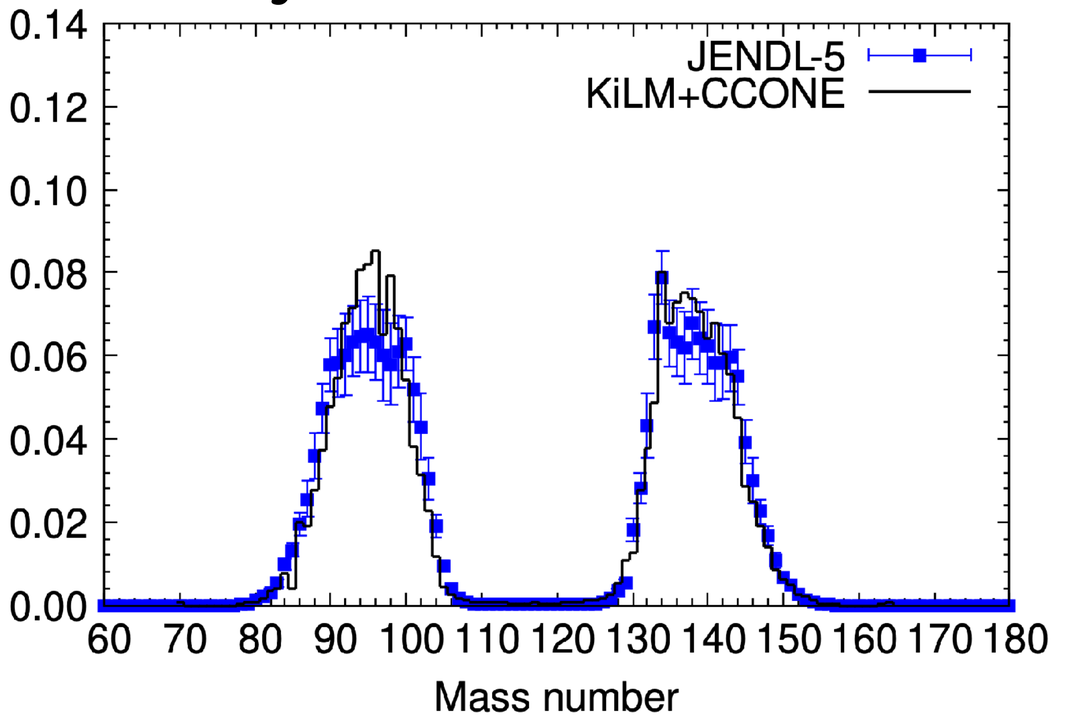
^{236}U (E^*=9 MeV)

primary fission yields
by KiLM



HF statistical model (CCONE)
Iwamoto et al.

independent fission yields
by KiLM + CCONE

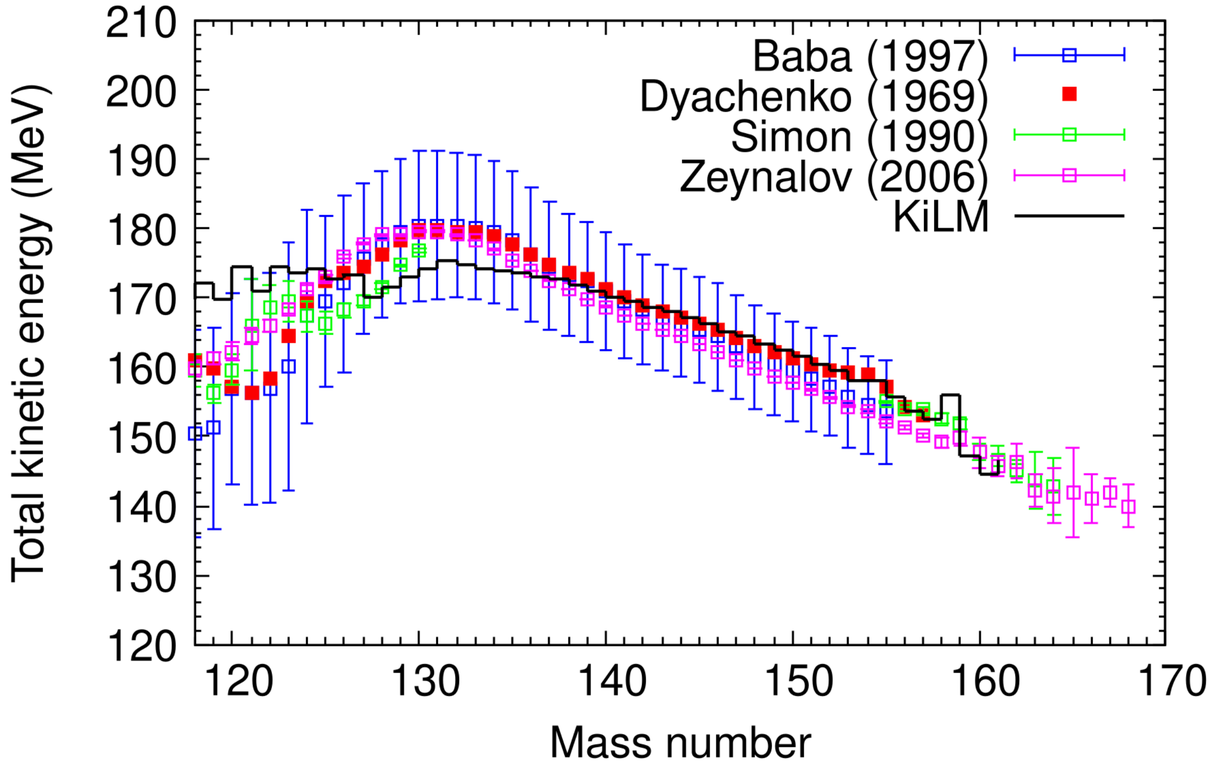


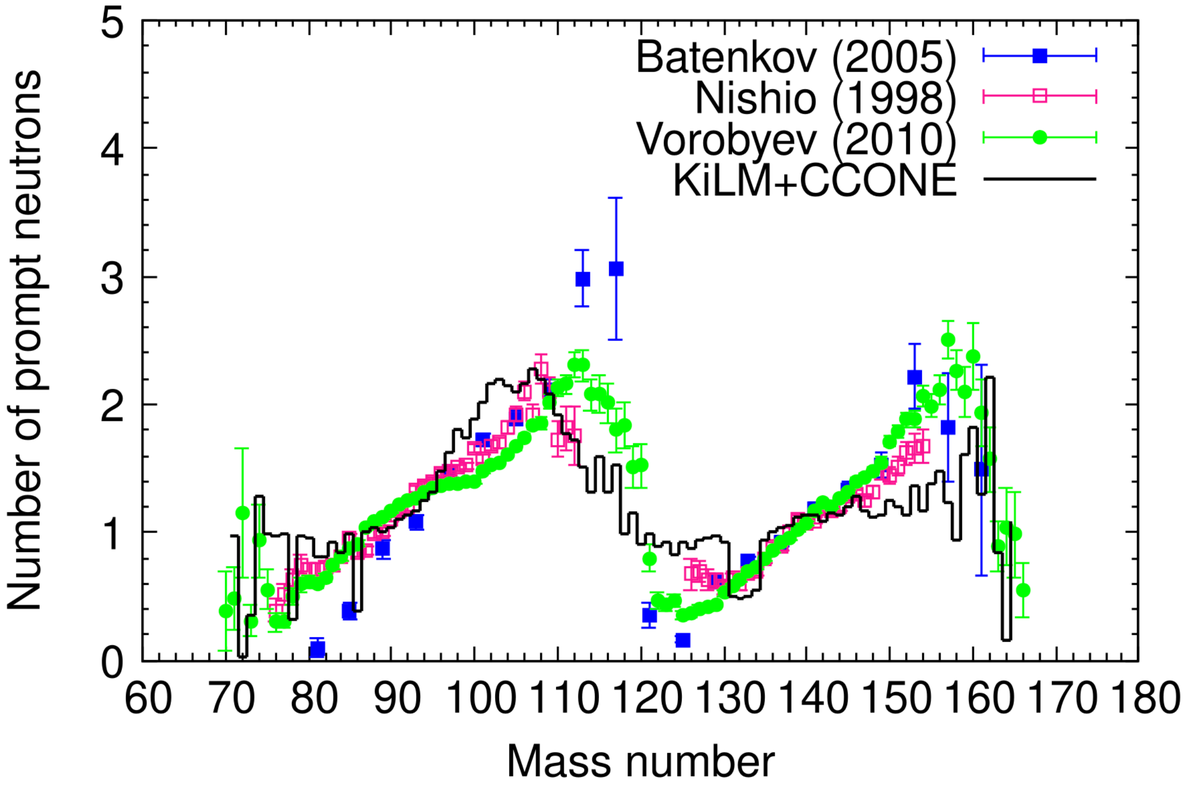
multiplicity $\langle n \rangle = 2.574$
(experiment : 2.413)

Tanaka, NN+2023

^{236}U : fission + n emission

^{236}U (E^*=9 MeV)





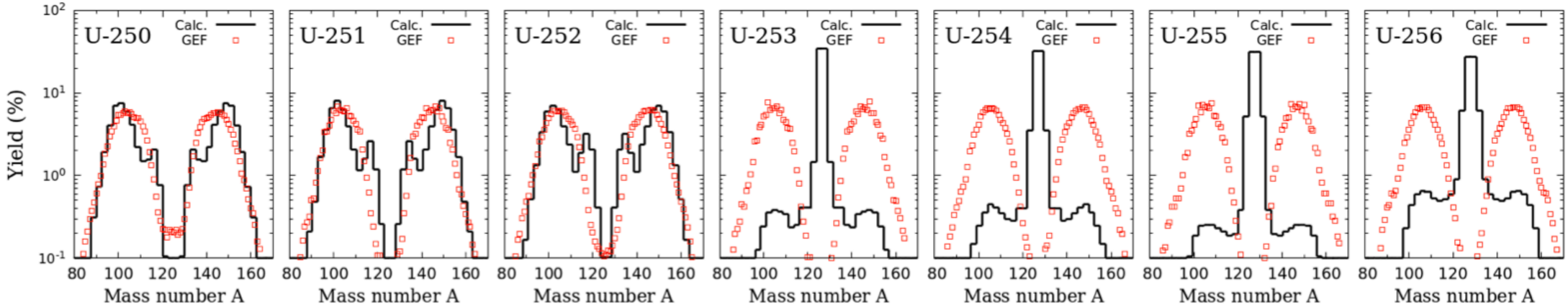
Tanaka, NN+2023

$^{250, 255}$U : fission + prompt n emission

KiLM

GEF

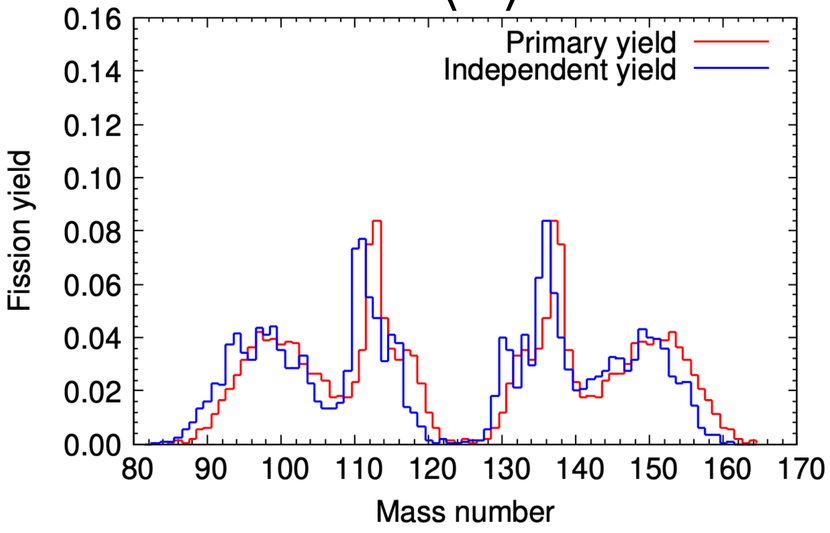
(Schmidt & Jurado)



$\langle n \rangle = 2.574$ for ^{236}U

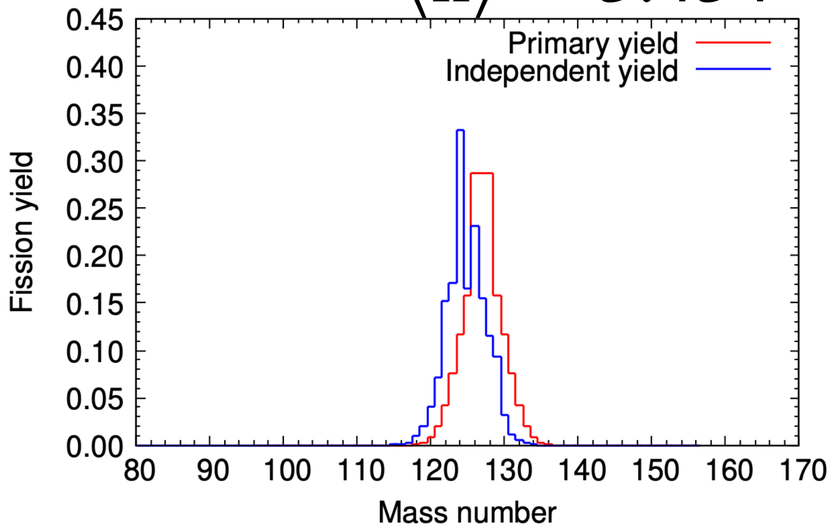
^{250}U (E* = 9 MeV)

$\langle n \rangle = 4.185$

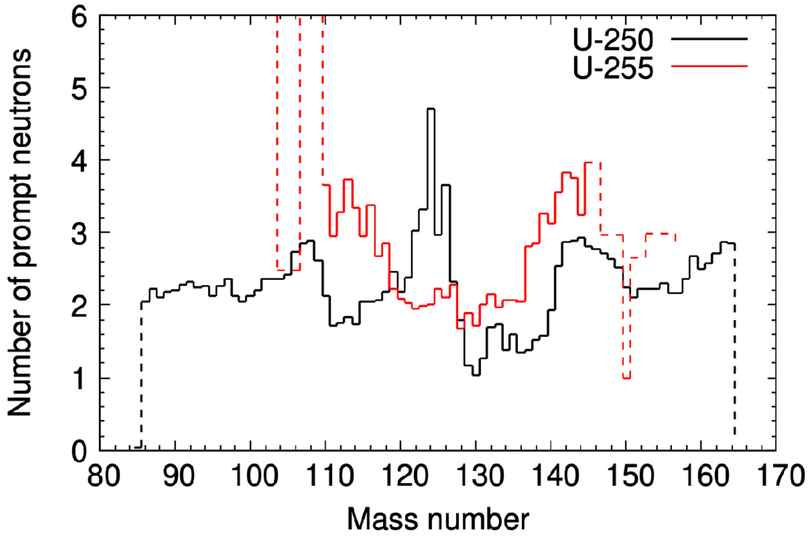


^{255}U (E* = 9 MeV)

$\langle n \rangle = 3.434$



number of n emission



Tanaka, NN+2023

Neck parameter: ε

Aritomo's slide

Two Center Shell Model

Neck parameter ε

$q(z, \delta, \alpha)$

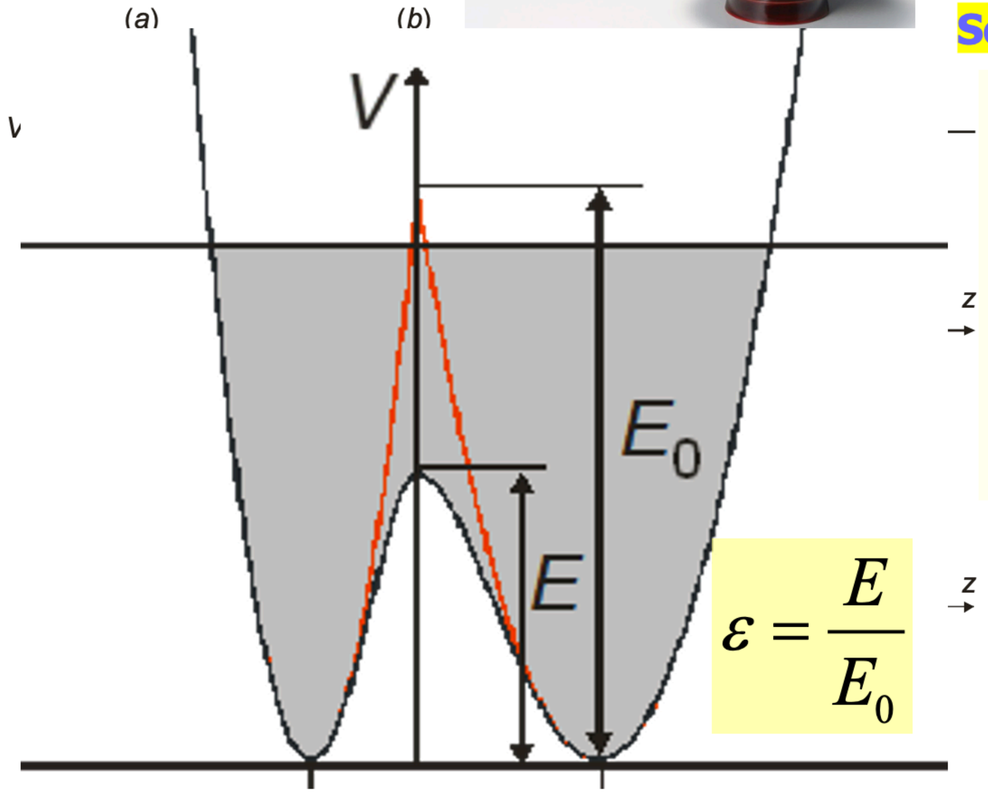
$+\varepsilon$

Distance const.

ε = 1.0

0.35

0.0



$$\varepsilon = \frac{E}{E_0}$$

Scission point

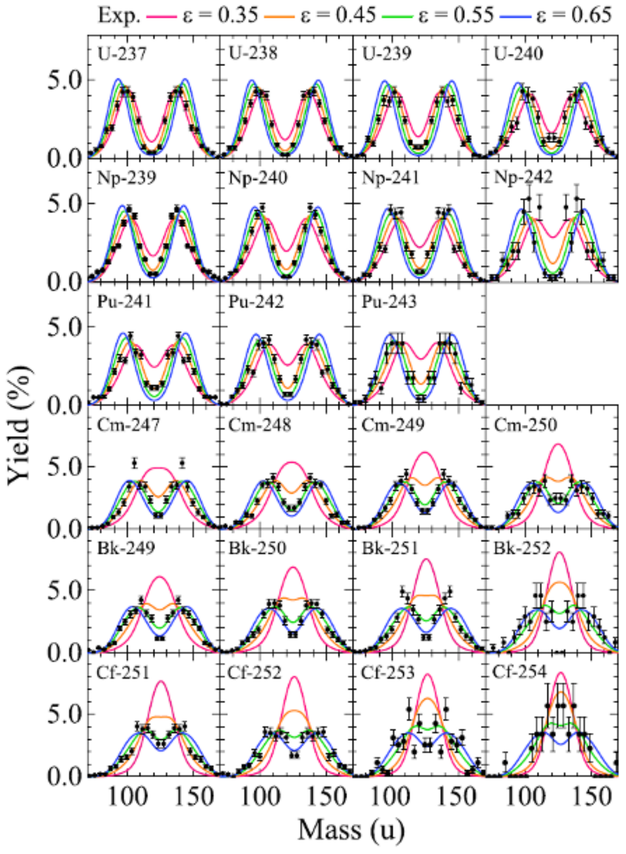
ε = 1.0

0.35

curvature

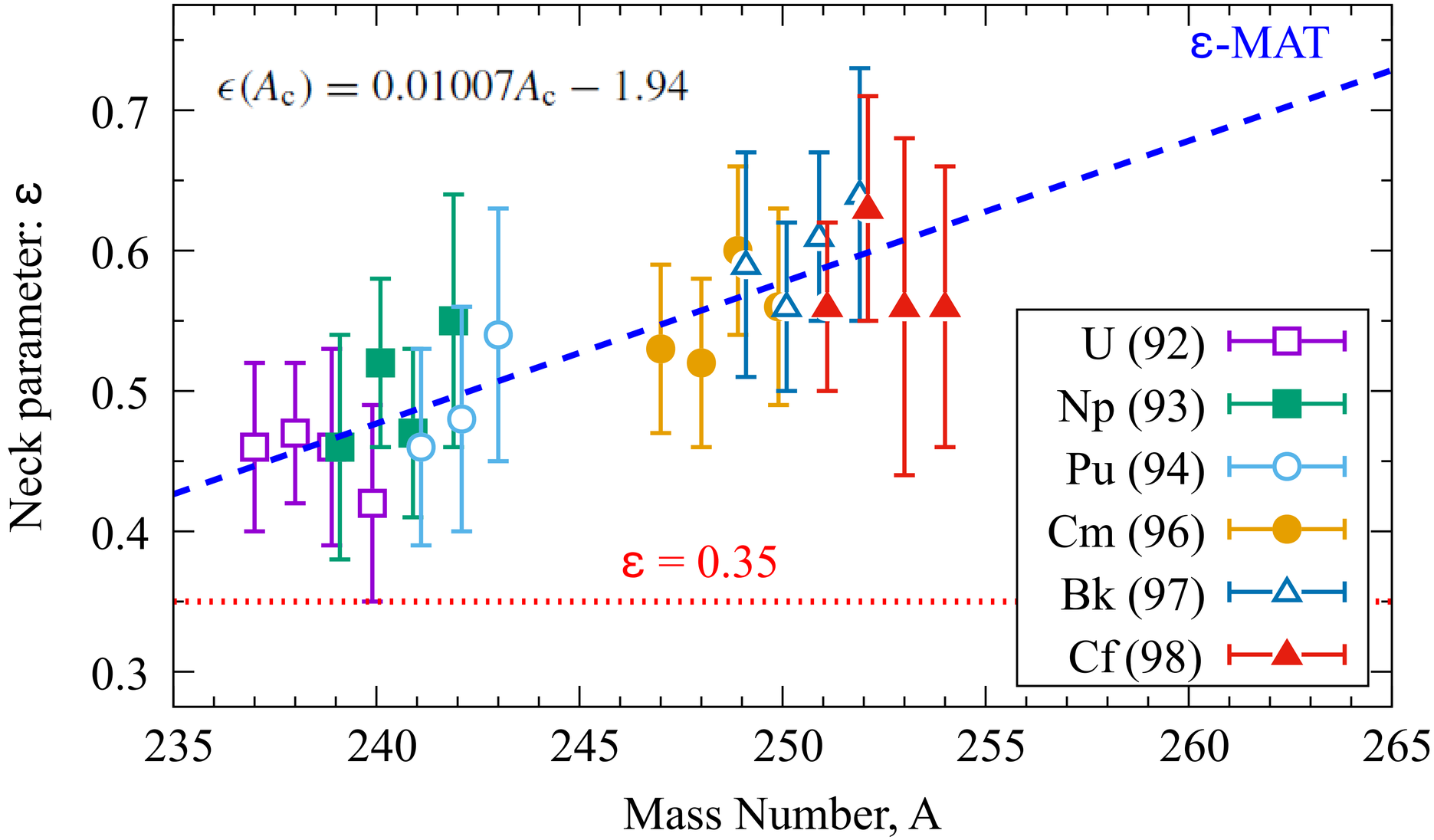
J. Maruhn and W. Greiner, Z. Phys, 1972

n multiplicity for neutron-rich U



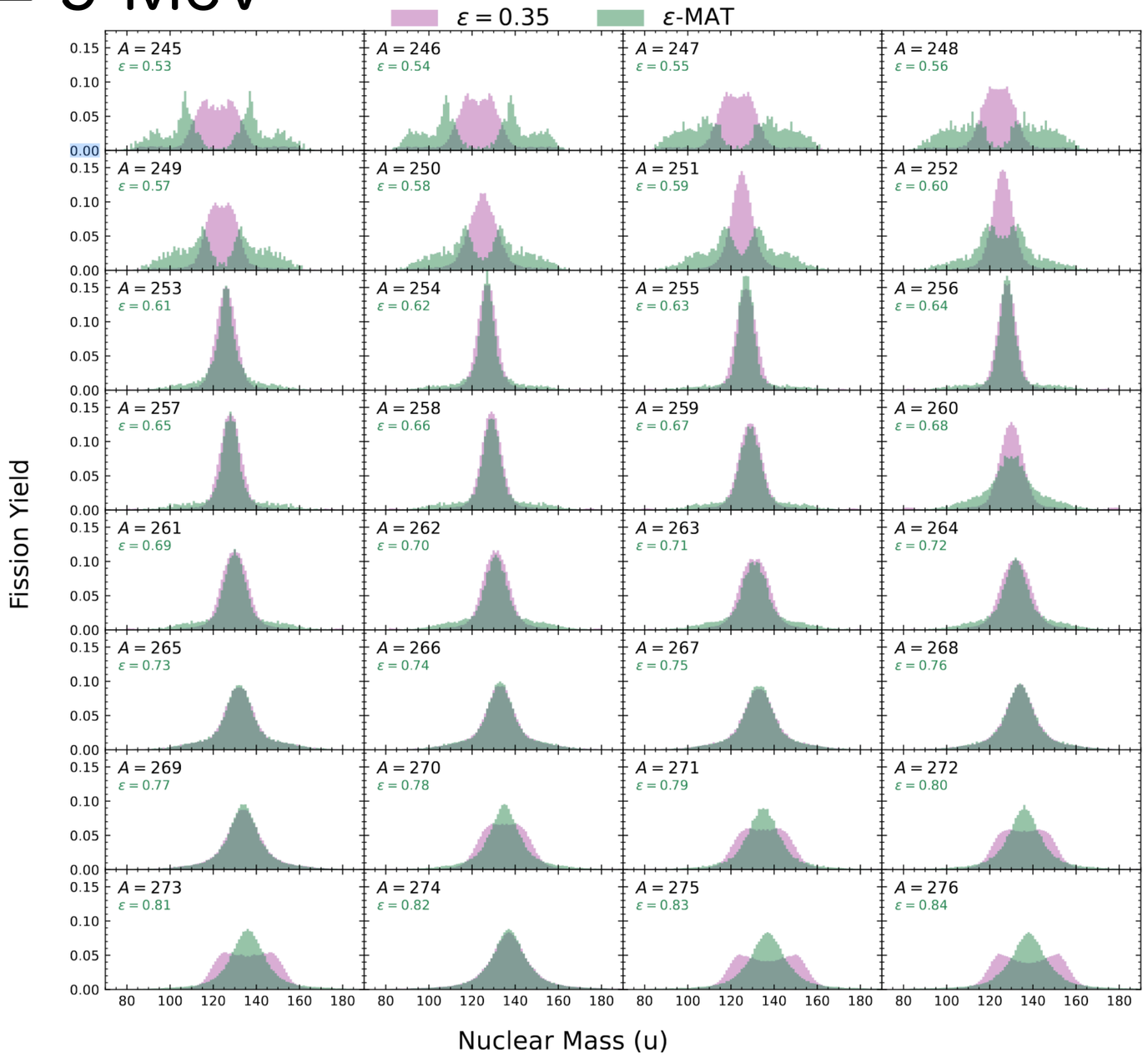
Miyamoto+2019

ε -MAT (Miyamoto, Aritomo, Tanaka et al.)



Fission yields: ε

E* = 9 MeV

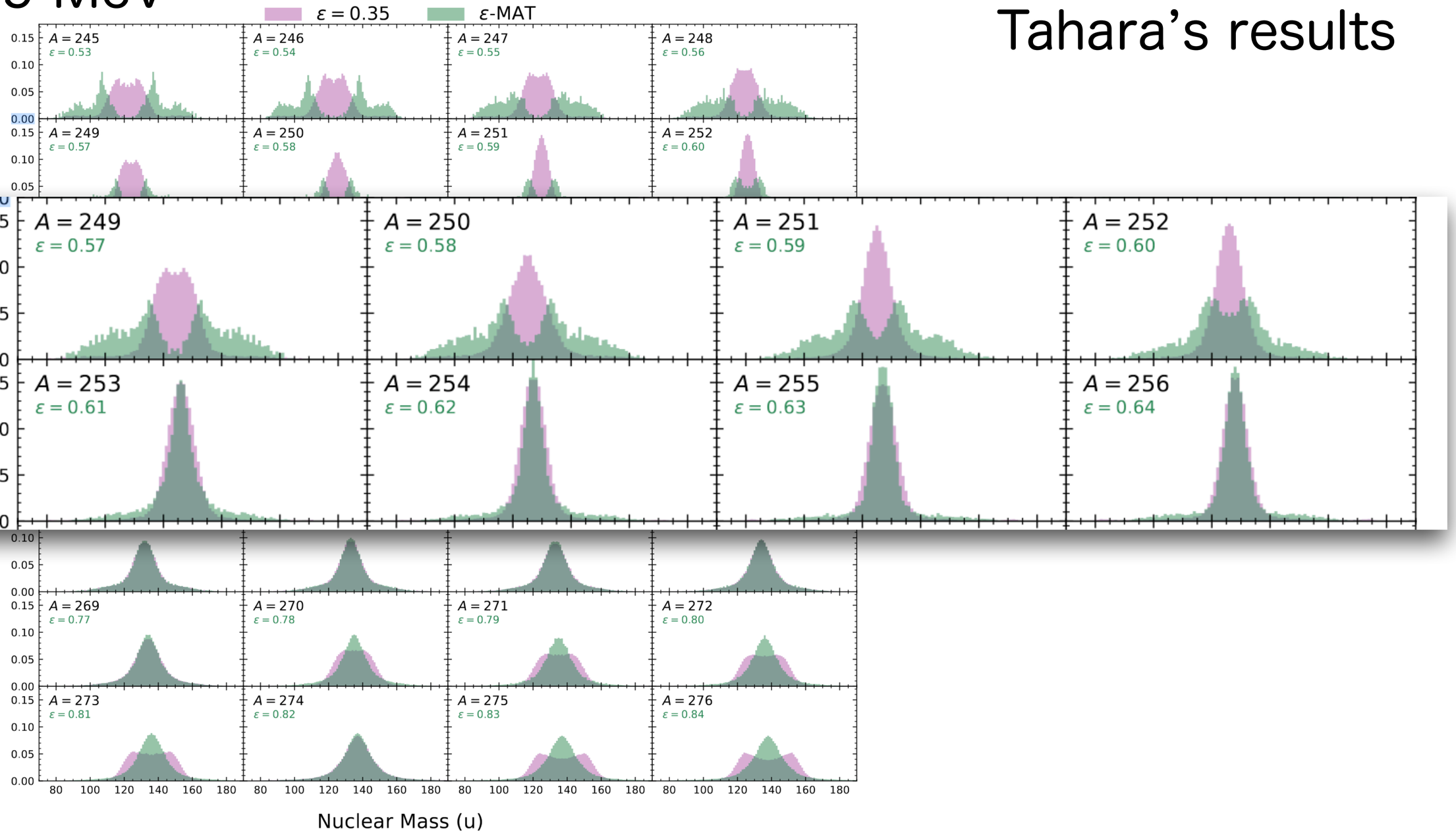


Tahara's results

Fission yields: ε

E* = 9 MeV

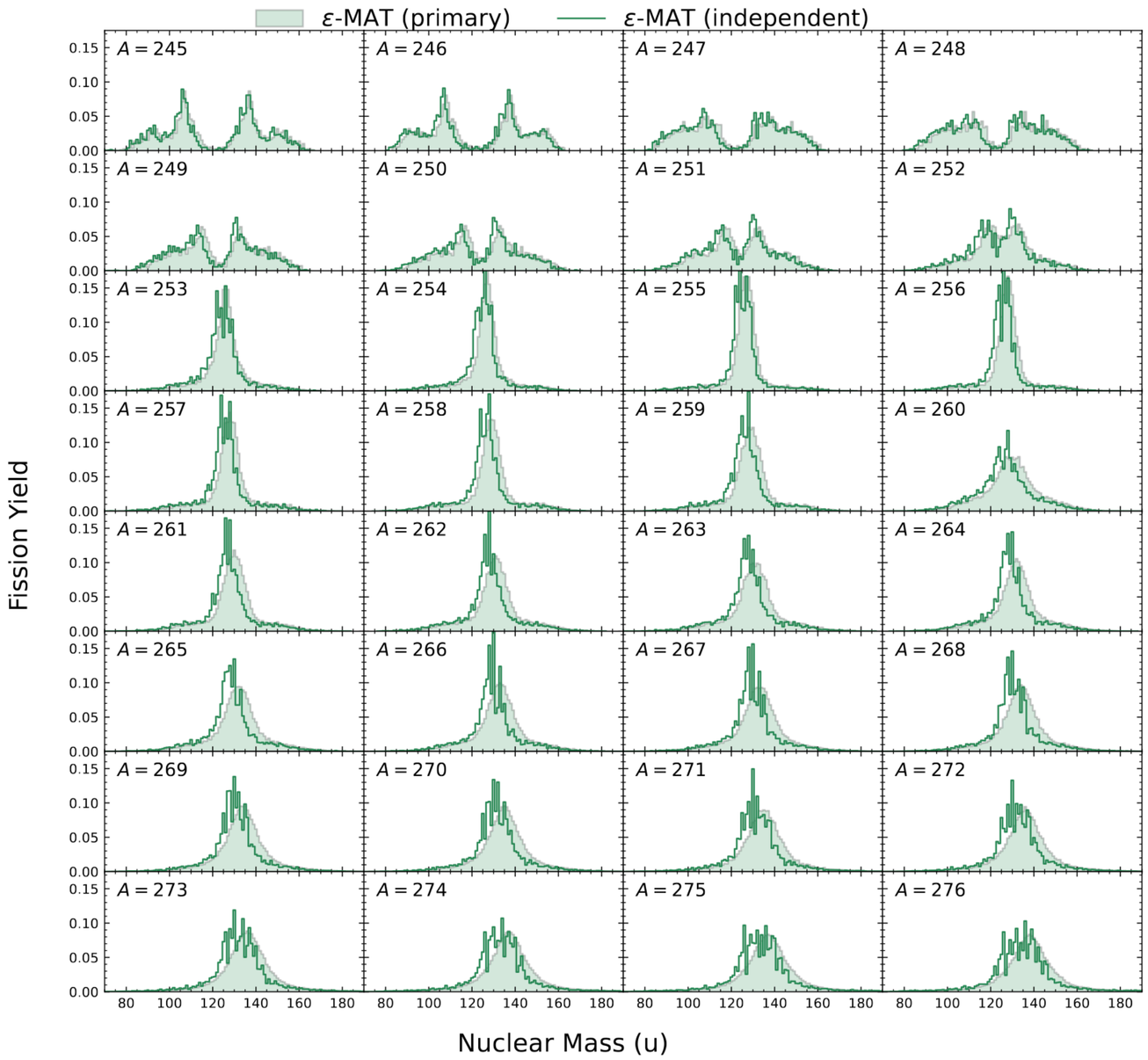
Tahara's results



independent fission yields

E* = 9 MeV

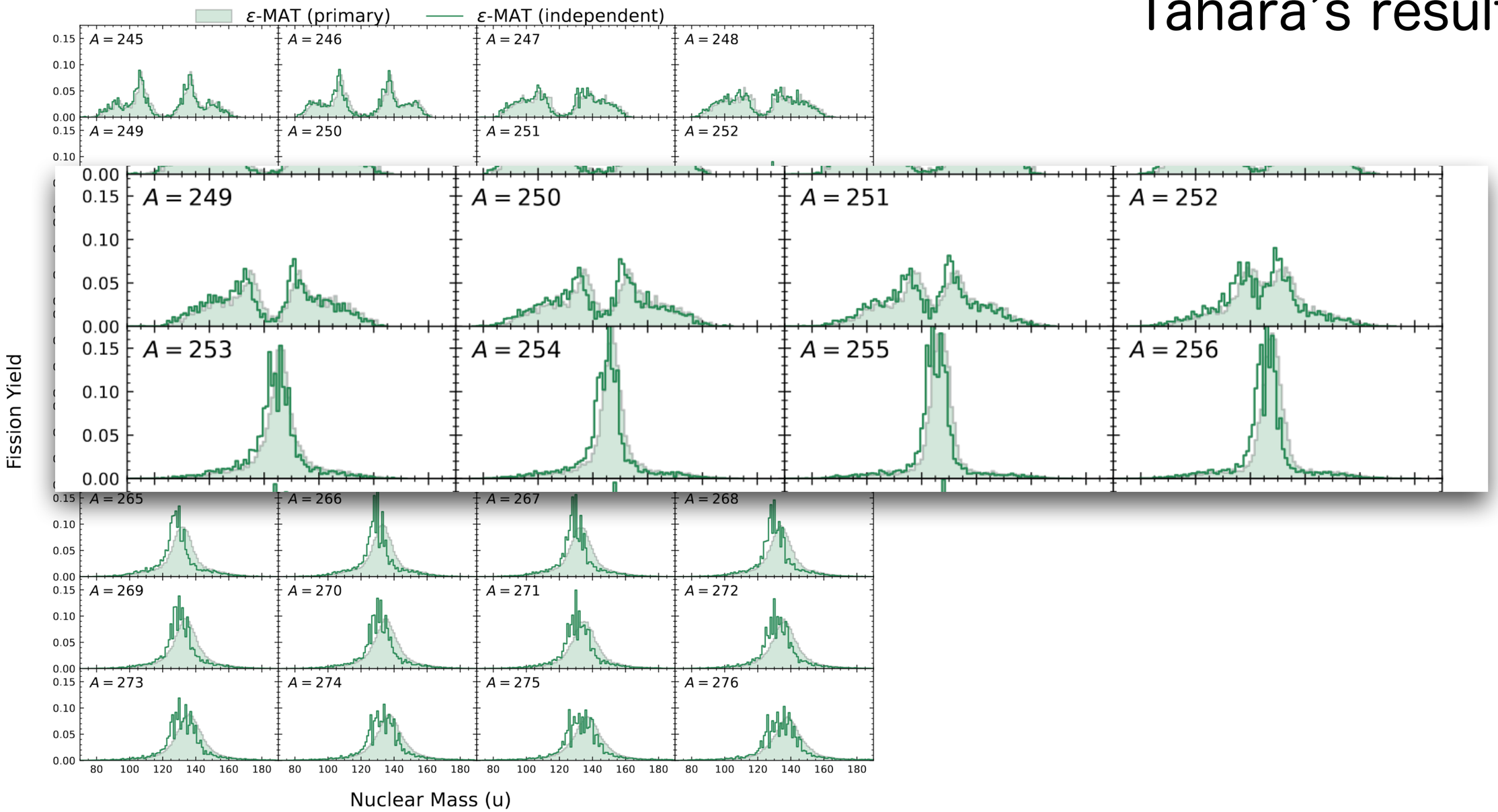
Tahara's results



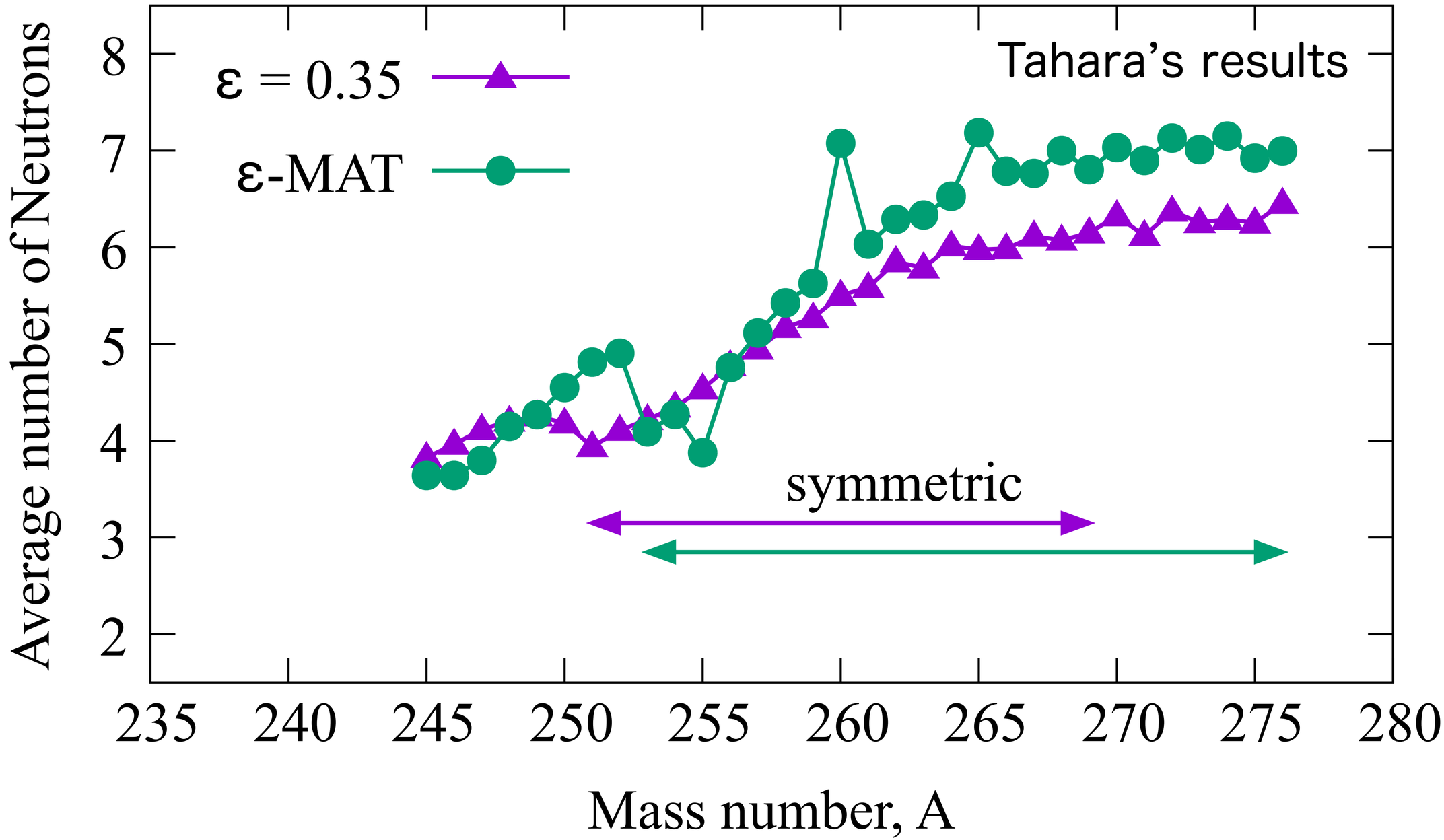
independent fission yields

E* = 9 MeV

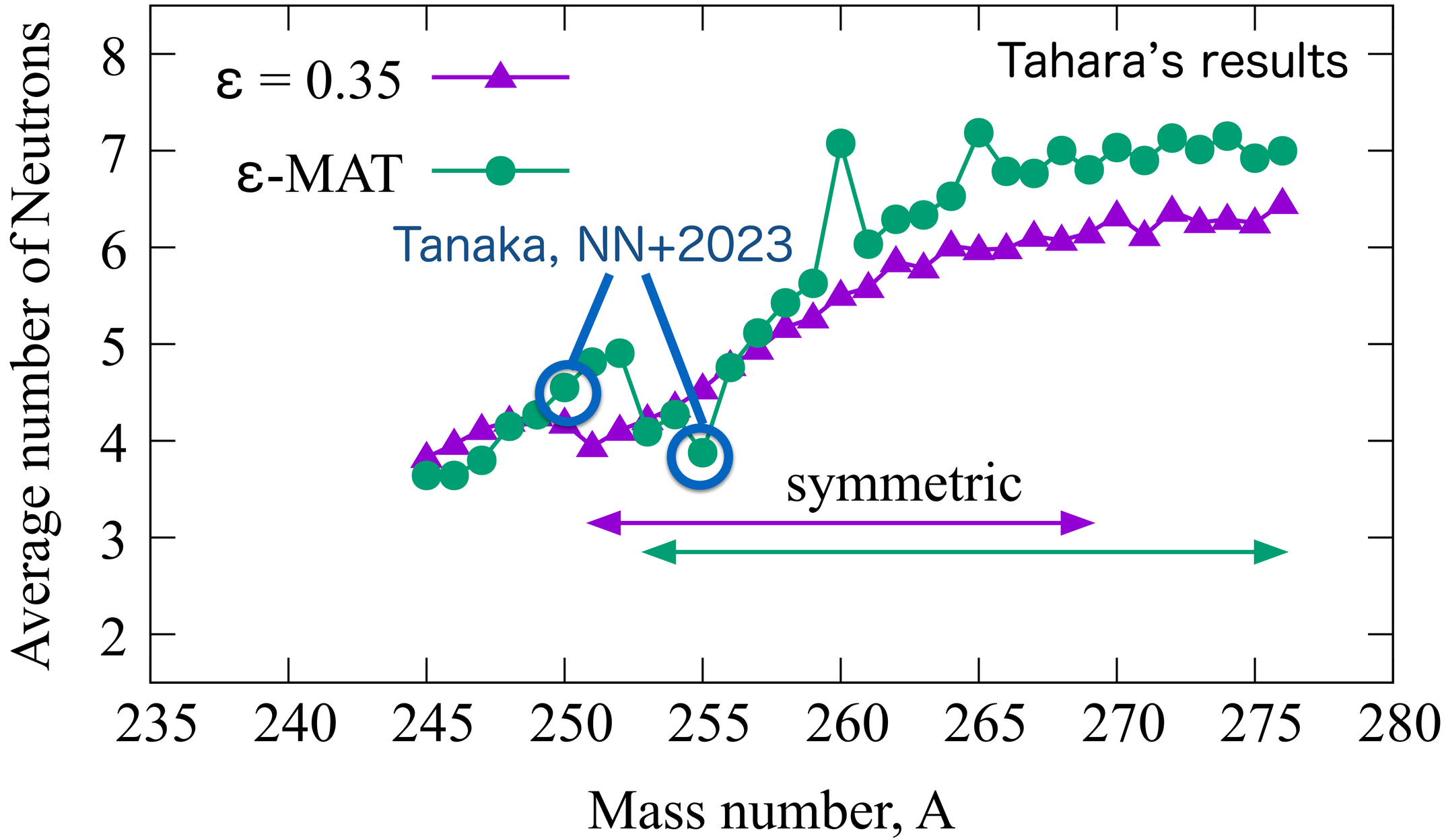
Tahara's results



Neutron multiplicity: different ε

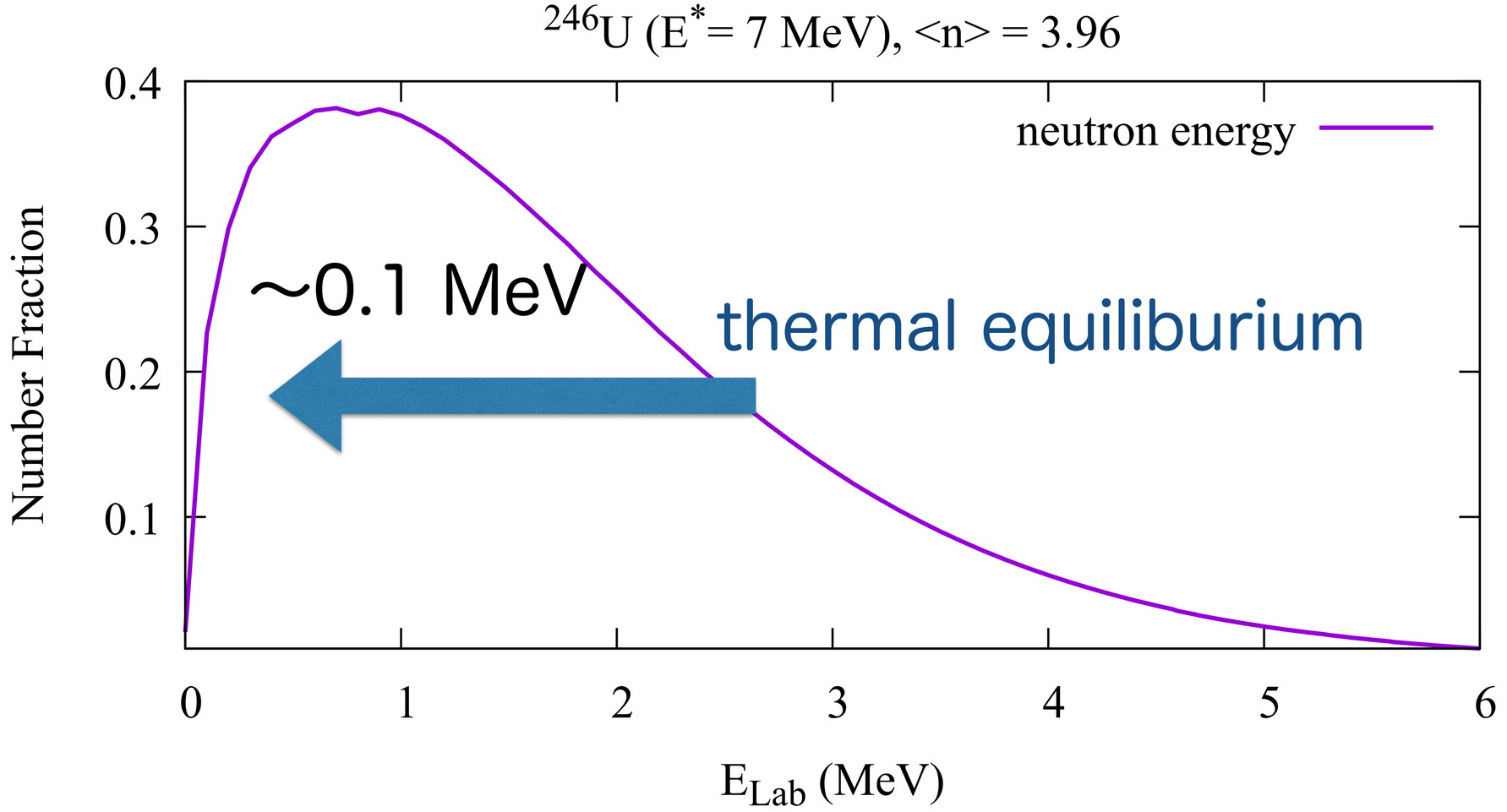


Neutron multiplicity: different ε



Energy of prompt neutron emission

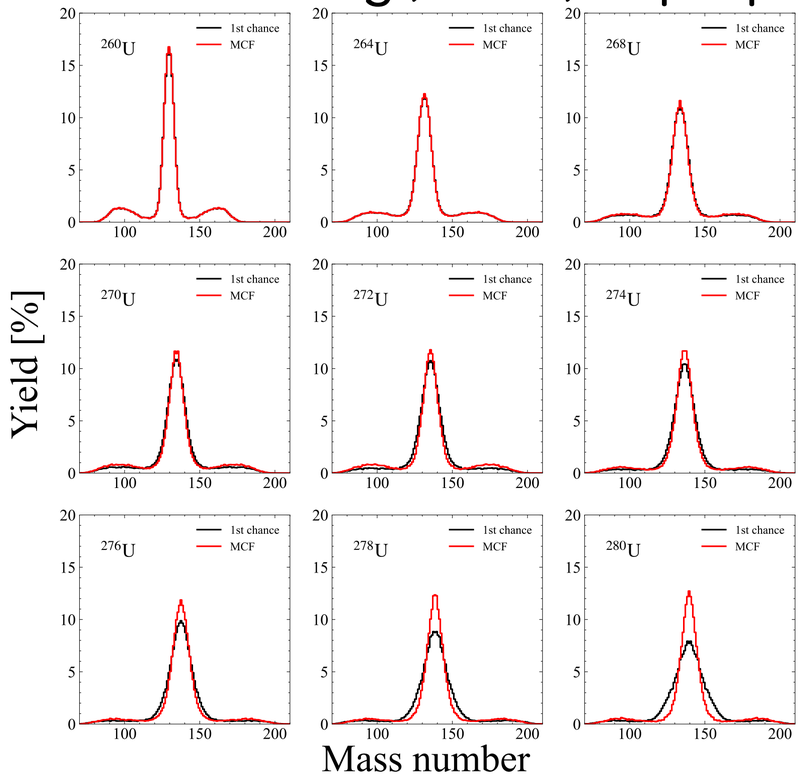
・Prompt emission neutrons have large energy > MeV
・They are considered to be immediately decreases 0.1 in r-process conditions
  ・but in the low density cases (low neutron number density)?
    → high-energy (n,f) and others? pecuiar observational signals??



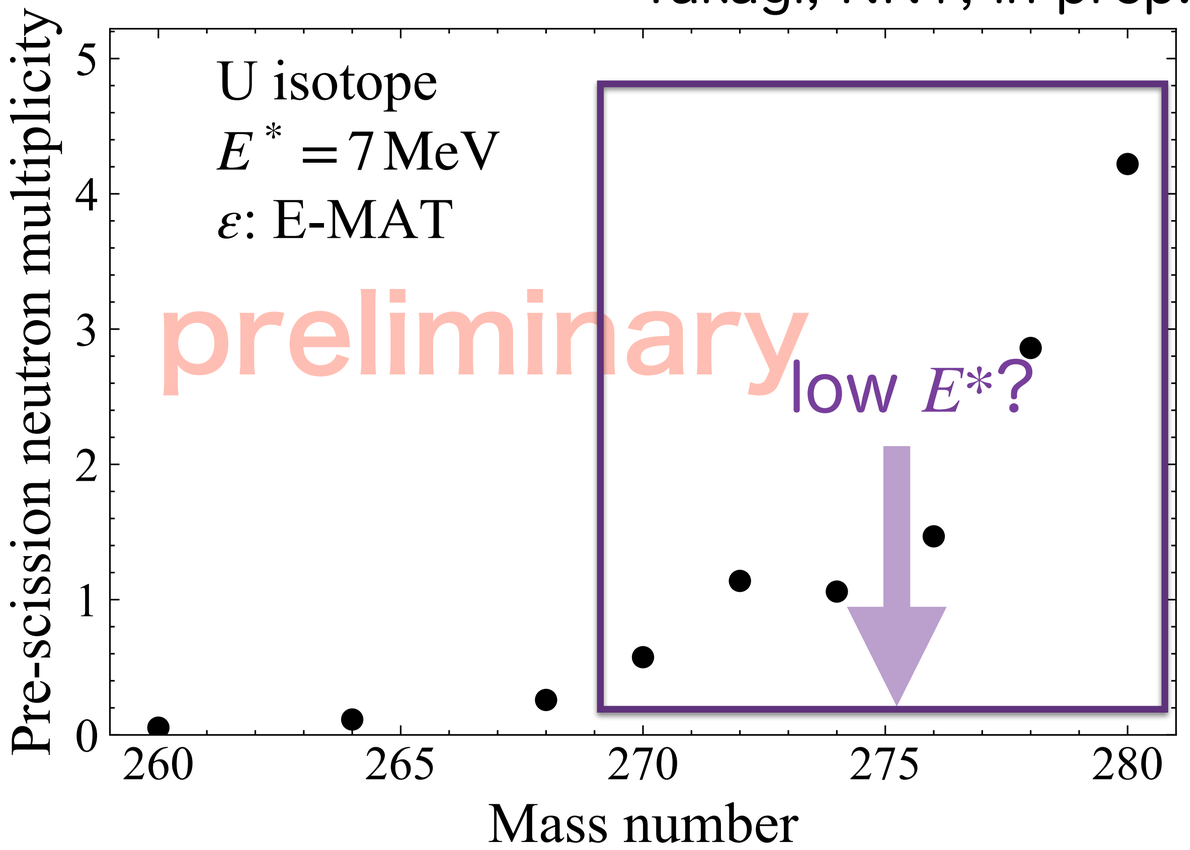
Multi-chance fission ?: neutron-rich U

- may be significant for very neutron-rich U ($E^* = 7\mathrm{MeV}$) : $A > 270$
  - may change the total neutron multiplicity
  - de-excitation: changes fission mode? suppresses n-induced fission?
  - but for lower E^* ? trans-U nad superheavy isotopes?

Takagi, NN+, in prep.



Takagi, NN+, in prep.



Summary

- **(background) Fission in r-process nucleosynthesis**
  - r-process is only nucleosynthesis process fission happens
  - several astronomical observations
    - NS mergers: a kilonova lightcurve
    - metal-poor stars: actinoide-boost, evidence of fission yields?

- **Dynamical fission calculations toward the r-process region**
  - n-rich U: symmetric distribution and larger neutron multiplicity
  - transition point to symmetric has impacts on the r-process
    - neutron emission?
    - (reliminary) multi-chance fission?