26 Nov. 2023, N3AS-RIKEN WS

The impacts of nuclear-physics uncertainties on heavy-element nucleosynthesis

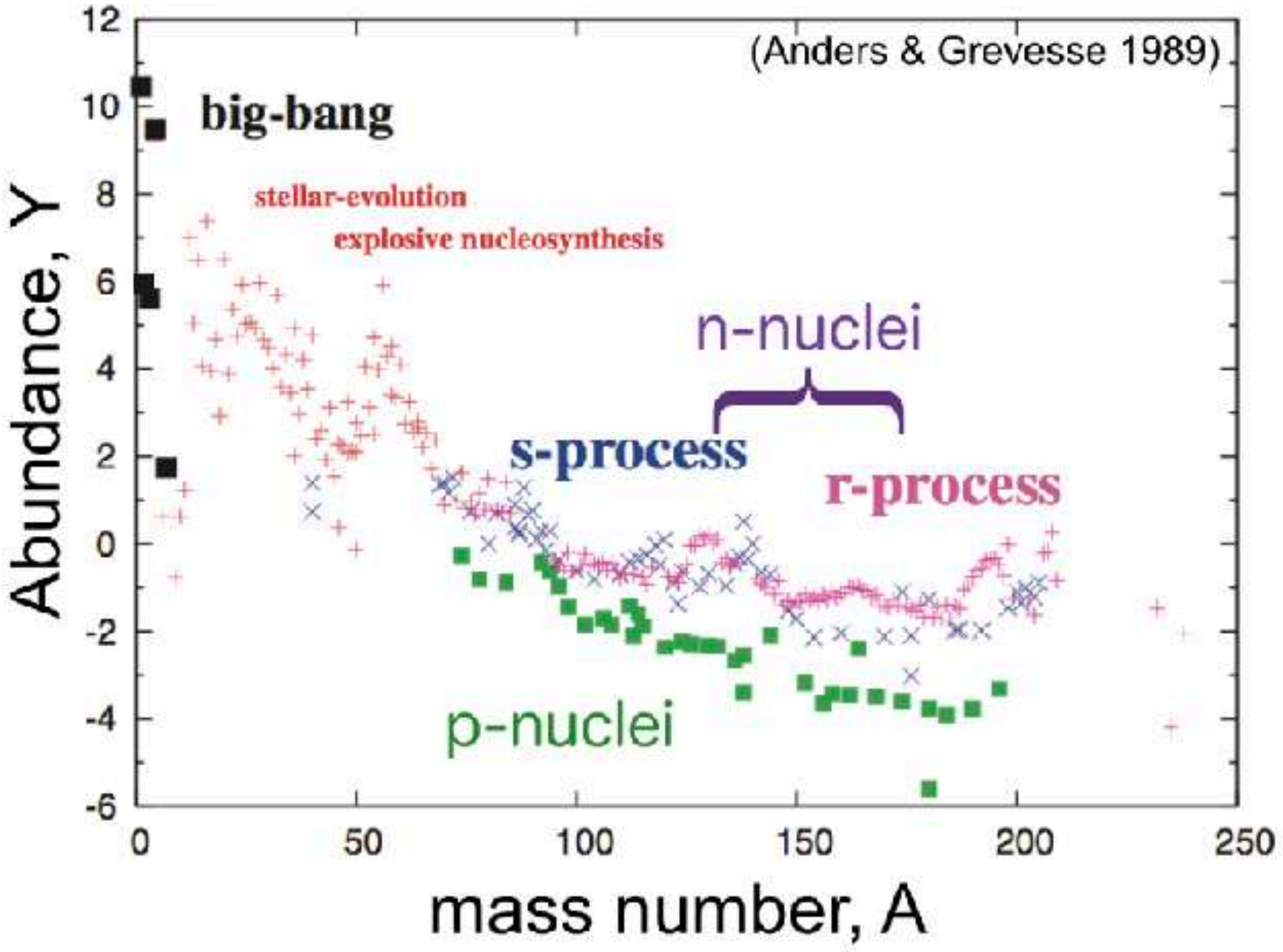
Nobuya Nishimura

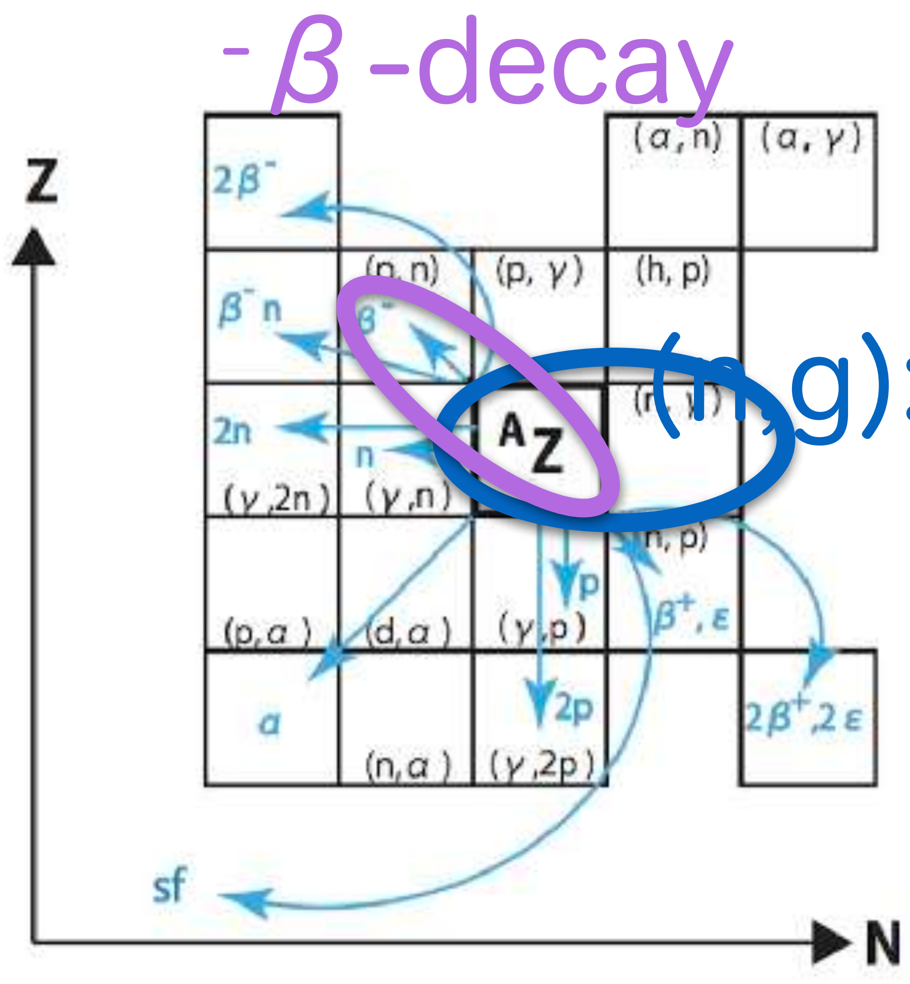
RIKEN (CPR/RNC)

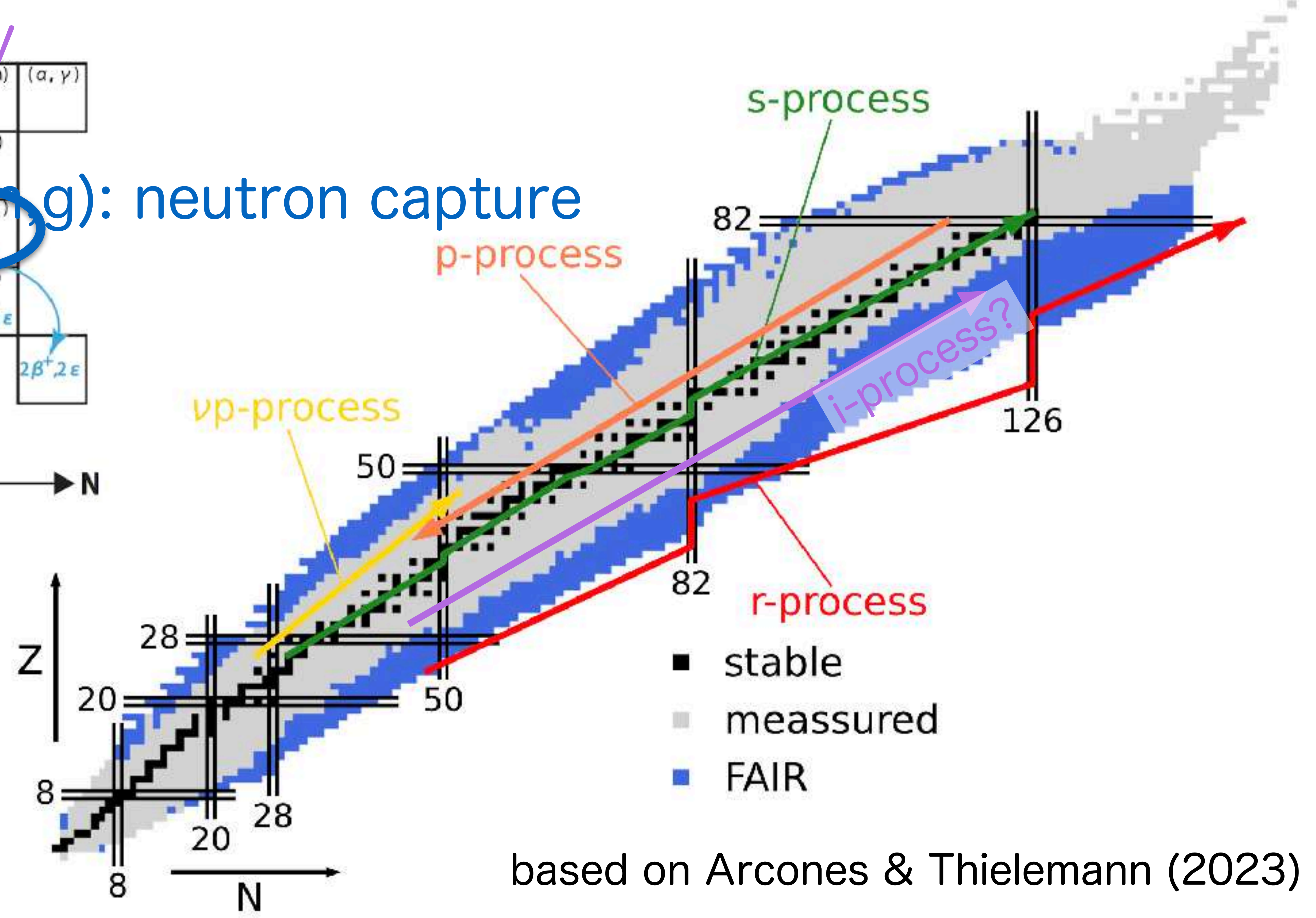
Cosmic nucleosynthesis beyond Iron

・regular nuclear burnings in stars synthesize elements up to Fe
・trans-Fe, classically 3 classes: s-process, r-process, “p-process”
・each group originates individual nucleosynthesis process
(s/r process, p process (+rp/νp process) + subclasses)

solar abundances

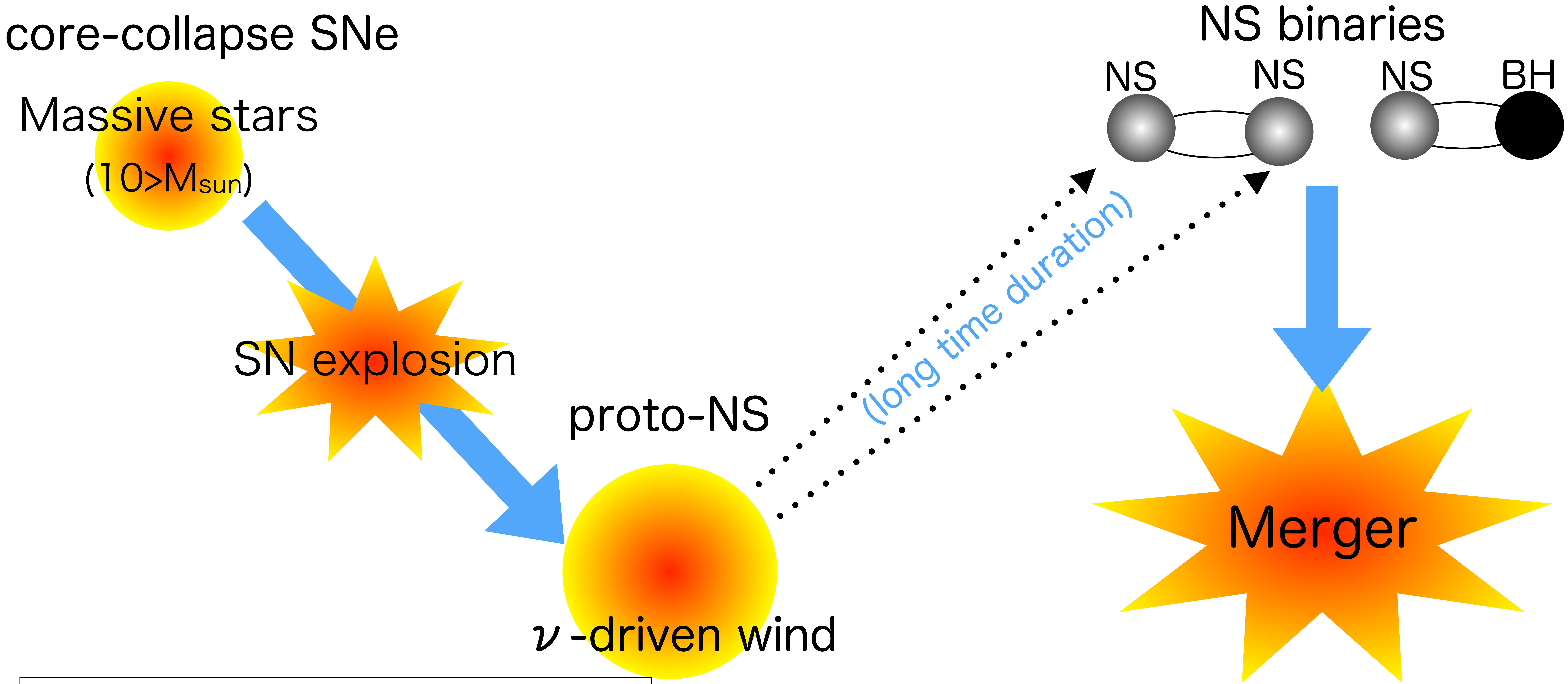






based on Arcones & Thielemann (2023)

Astrophysical r-process sites

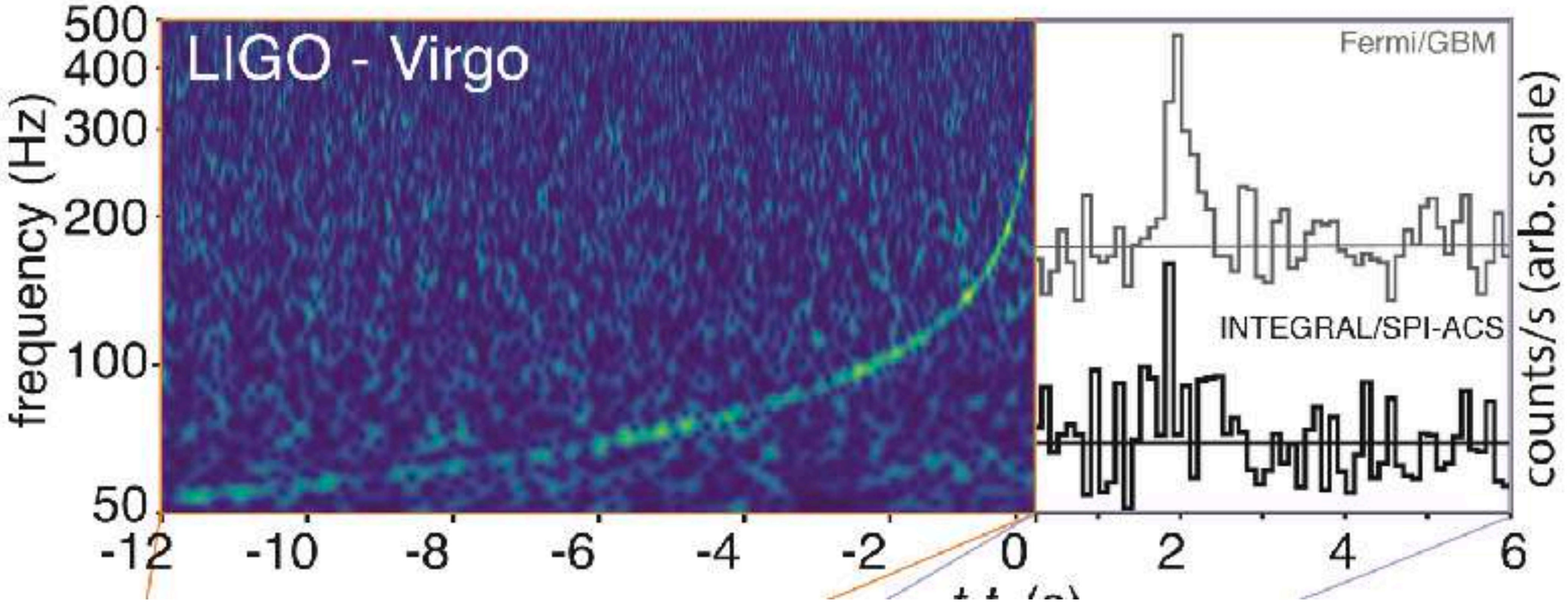


- NO direct r-process observation
- Theoretically difficult
  - not very neutron-rich

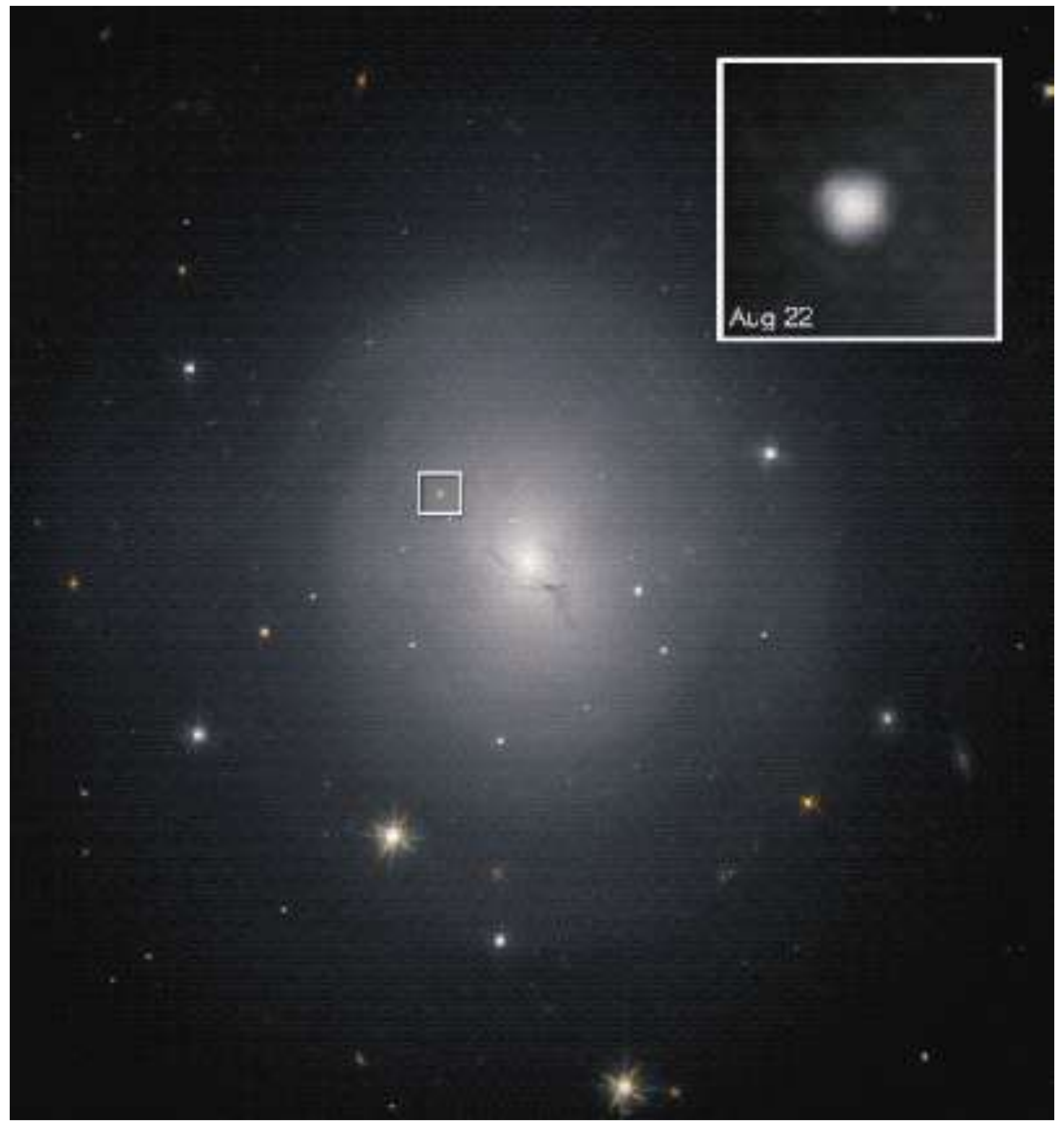
The “observational” evidence with gravitational waves (GW170817)

“Observation” of r-process nucleosynthesis

GW from NS-NS merger
Abbot+(2017)

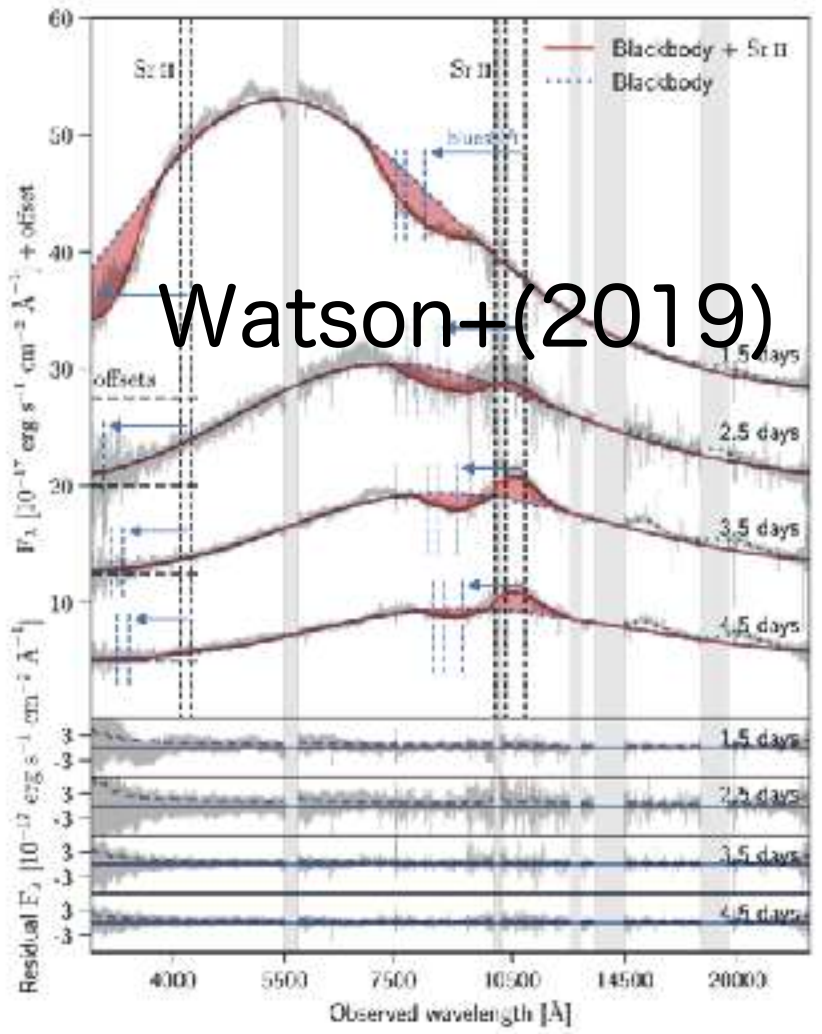


“kilonova"



NASA and ESA

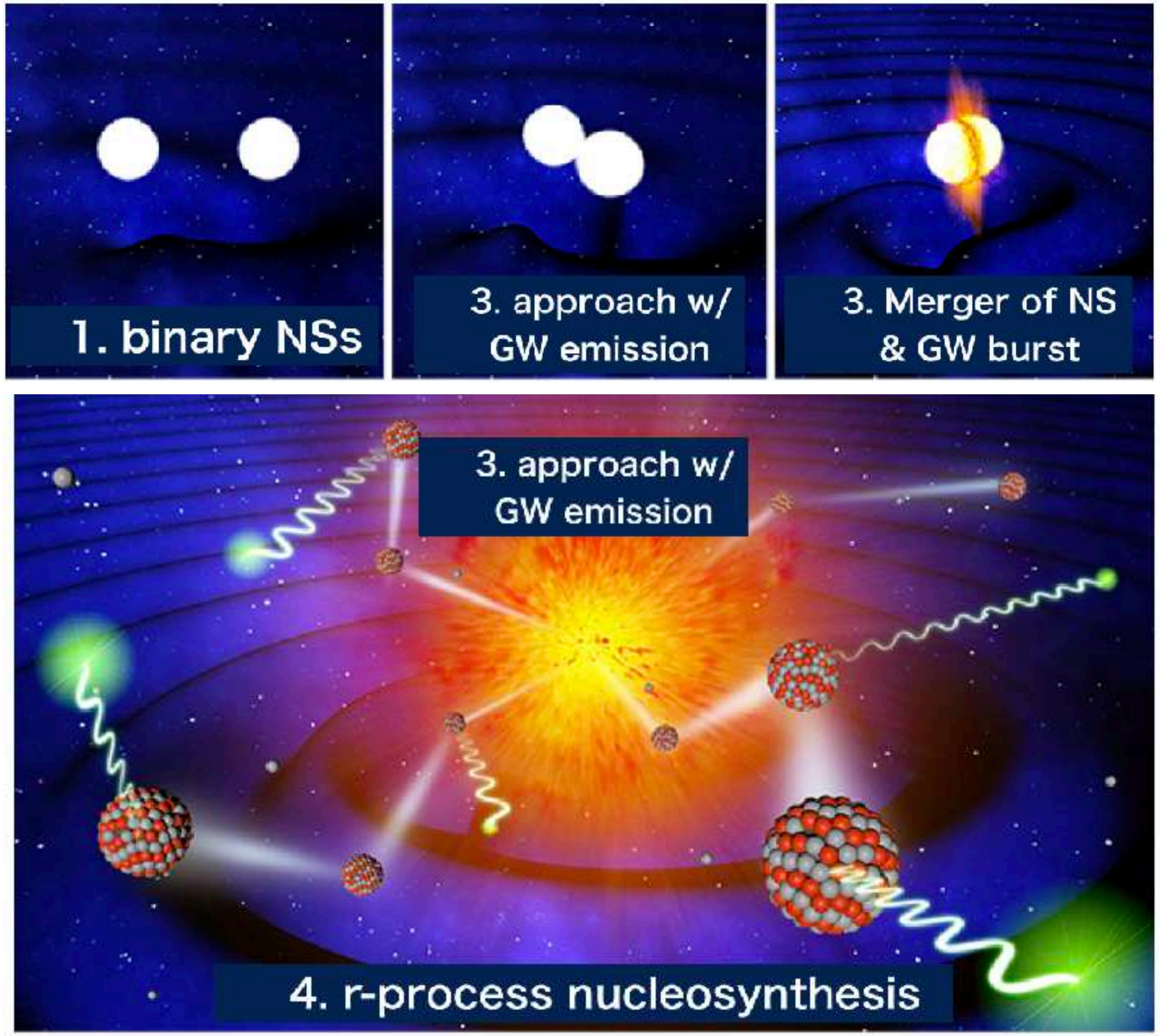
identification of Sr



Watson+(2019)

and La??
(Domoto+2022)

NS mergers and r-process senario



©NAOJ

Talk plan

1. **νp-process in "regular" core-collapse SNe**
   - Nucleosynthesis in p-rich ejecta: possible solution of "Mo problem"
   - Key reactions for the Mo isotope ratio of lighter p-isotopes
2. **r-process in "peculiar" core-collapse SNe**
   - Background: magneto-rotational cc-SNe
   - possibilities of the r-process and observational signature
3. **r-process in NS mergers** (see also S. Tanaka's Poster)
   - Nuclear fission in the NS-merger r-process
   - A new method: dynamical fission + post-fission evolution
   - impacts of n-emission for n-rich isotopes

1. νp-process in Core-collapse supernovae

- Rauscher, NN+(2016), MNRAS 463 4153
- NN+(2018), MNRAS 474 3133
- NN+(2019), MNRAS 489 1379

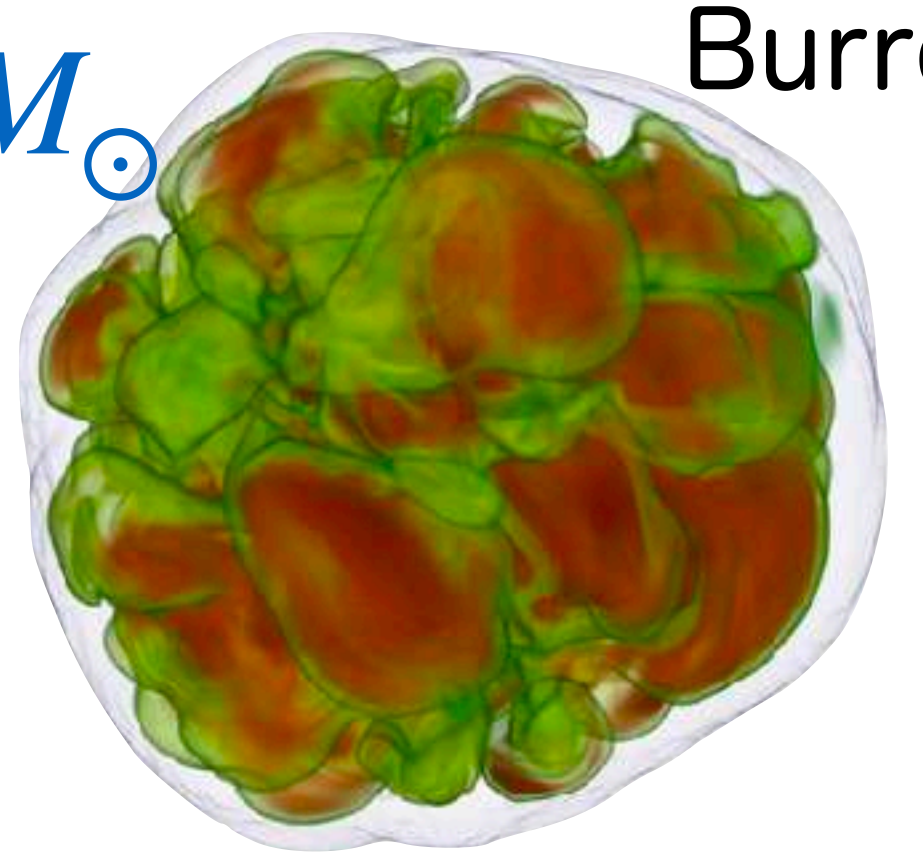
Proton-rich matter in cc-SNe

around the SN core: neutron-rich? → NO, due to neutrino heating
(strong magnetic explosion?, if you want to see the r-process → next topic)

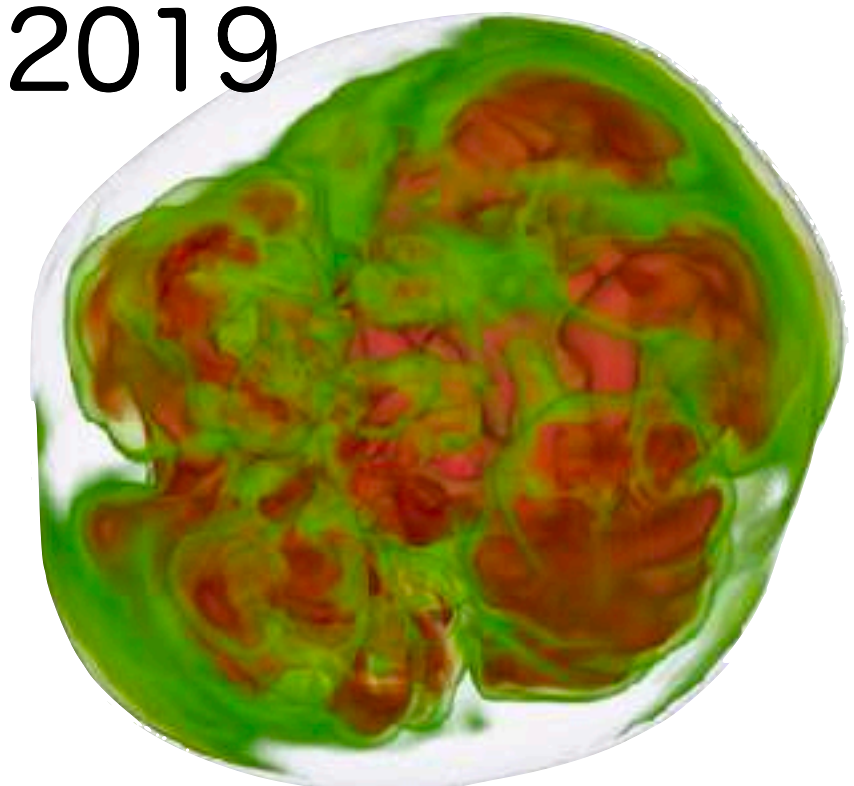
$\nu_e + n \rightarrow p + e^-$ & $\bar{\nu}_e + p \rightarrow n + e^+$

$9M_\odot$

Burrows+2019



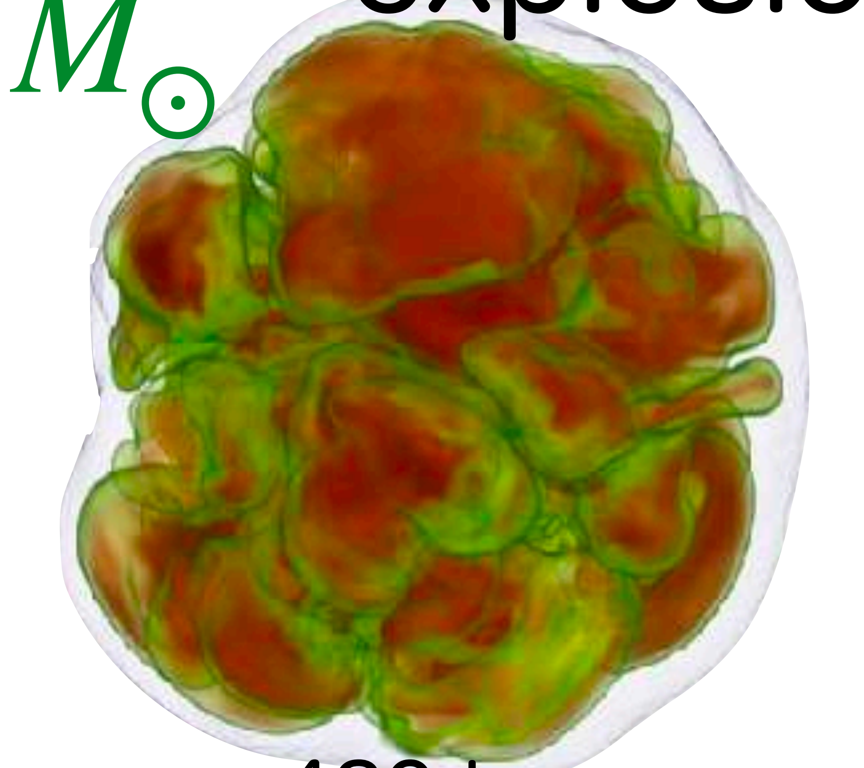
400 km



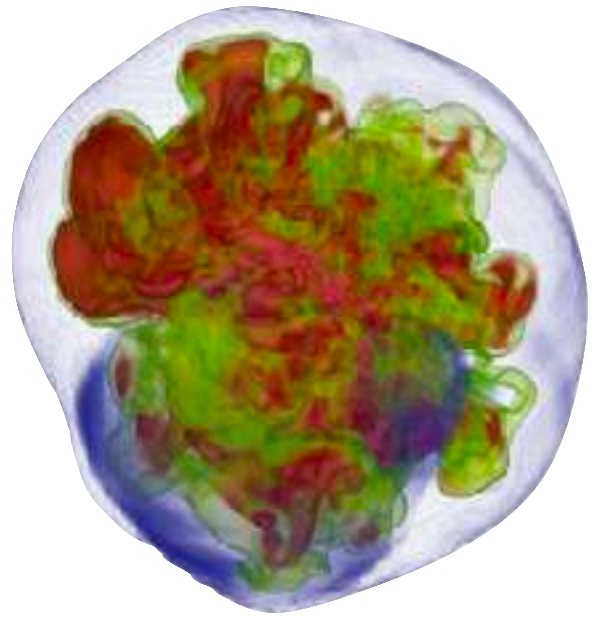
6000 km

explosion by ν heating

$11M_\odot$



420 km

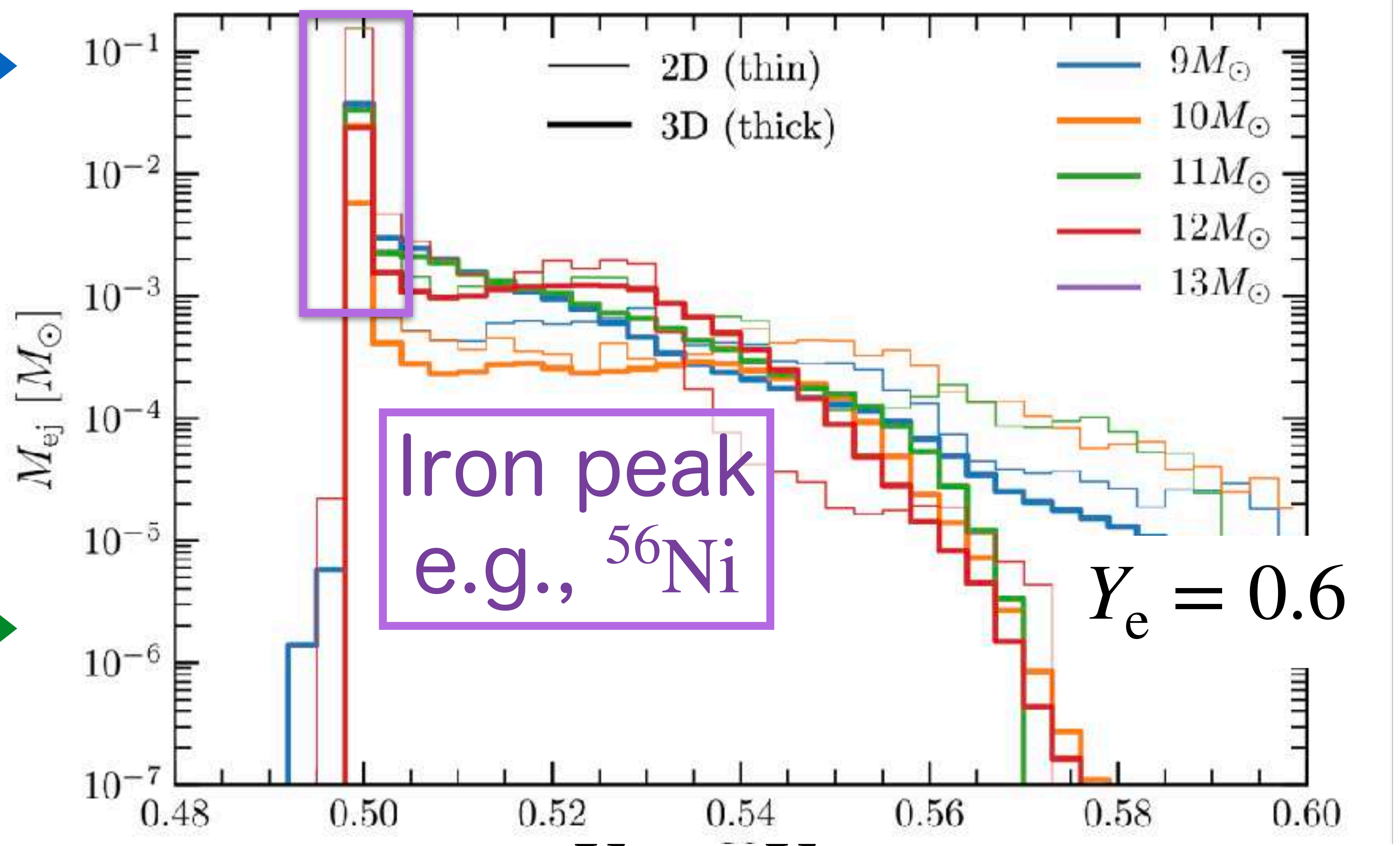


4200 km

Y_e tail reaches proton-rich?

can exceed $Y_e = 0.6$

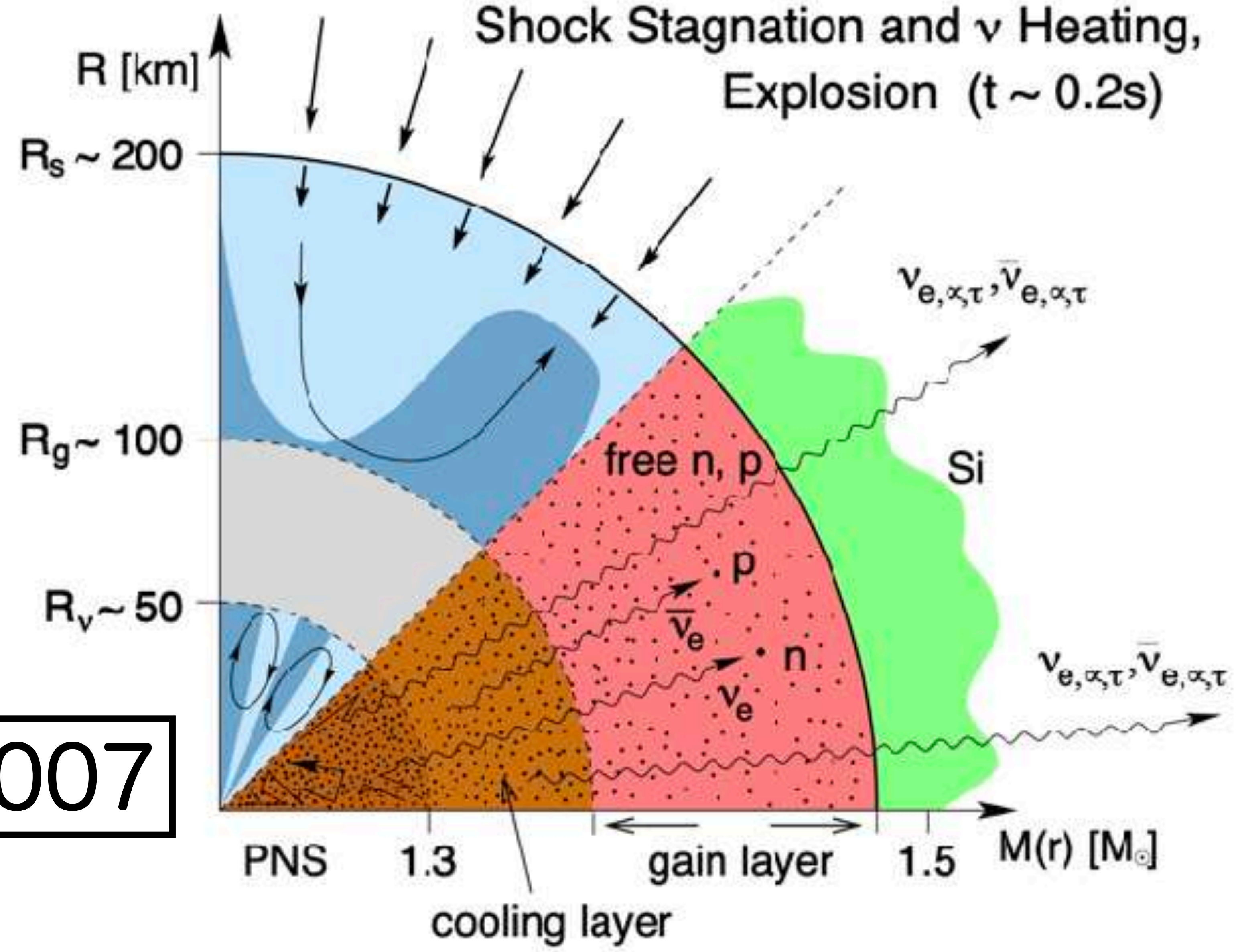
(several group, e.g., K. Nakamura+)



$Y_e \sim Y_p$ Burrows+2019

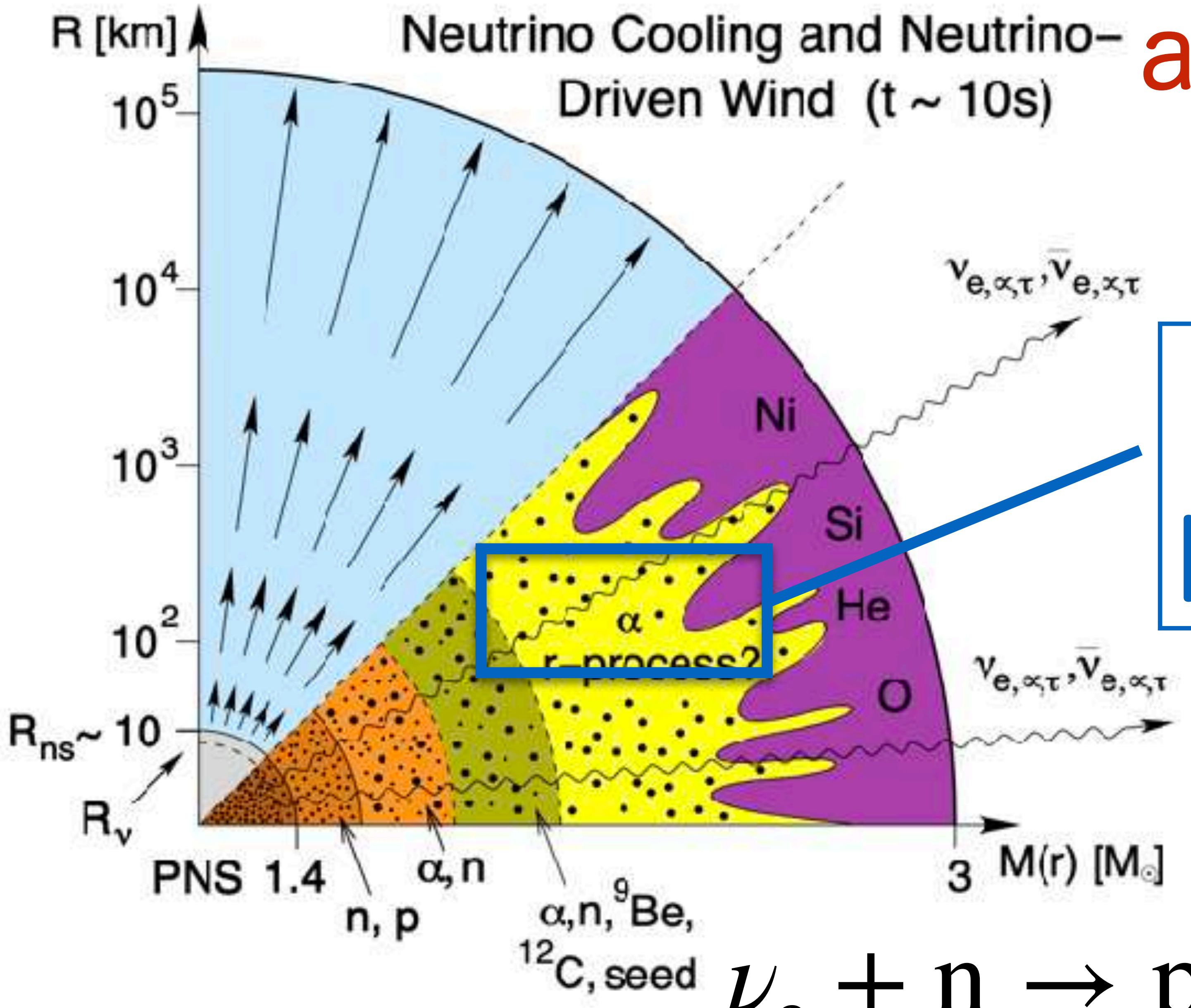
νp-process: p-capture accelerated by the ν-reaction

ν heating and explosion



Janka+2007

proto-NS cooling and ν-driven wind

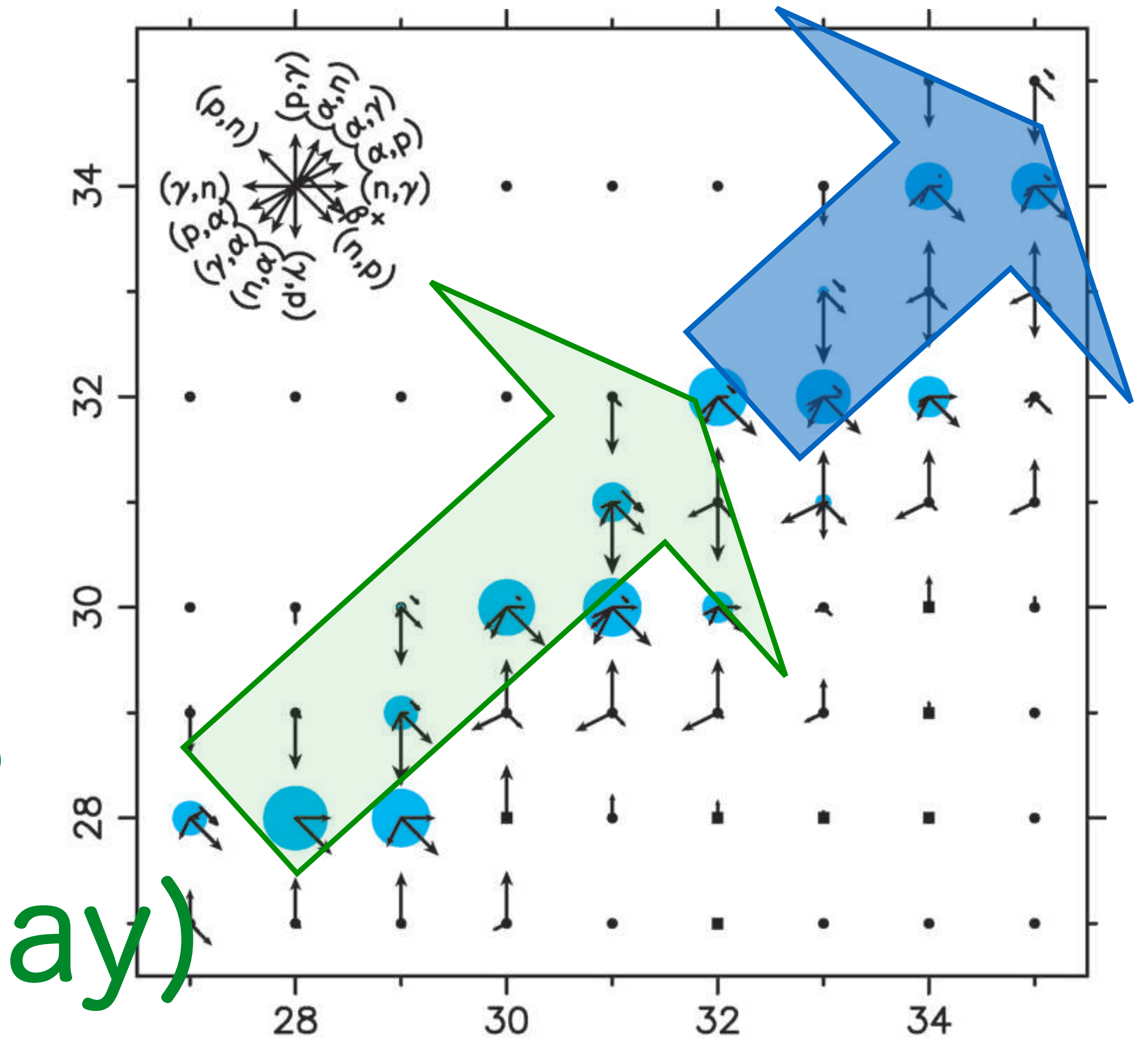


r-process if n-rich but p-rich conditions?

$\nu_e + n \rightarrow p + e^- \ \& \ \bar{\nu}_e + p \rightarrow n + e^+$

・α recombination: initiated by triple-α immediately reaches Fe peak (^{56}Ni)

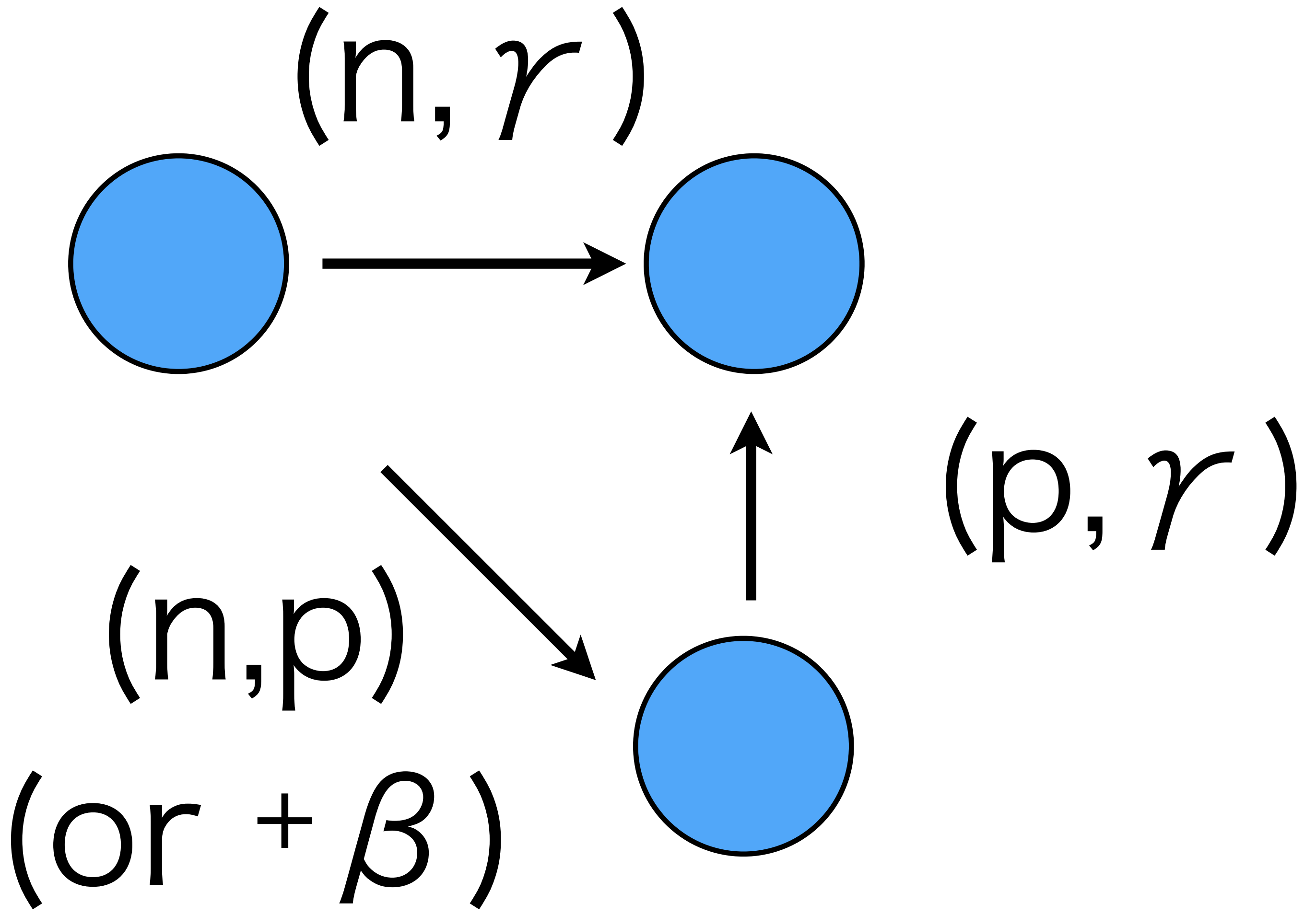
・sequence of (p,g) and β^+ decay



^{64}Ge: half-life ~ 1 min.

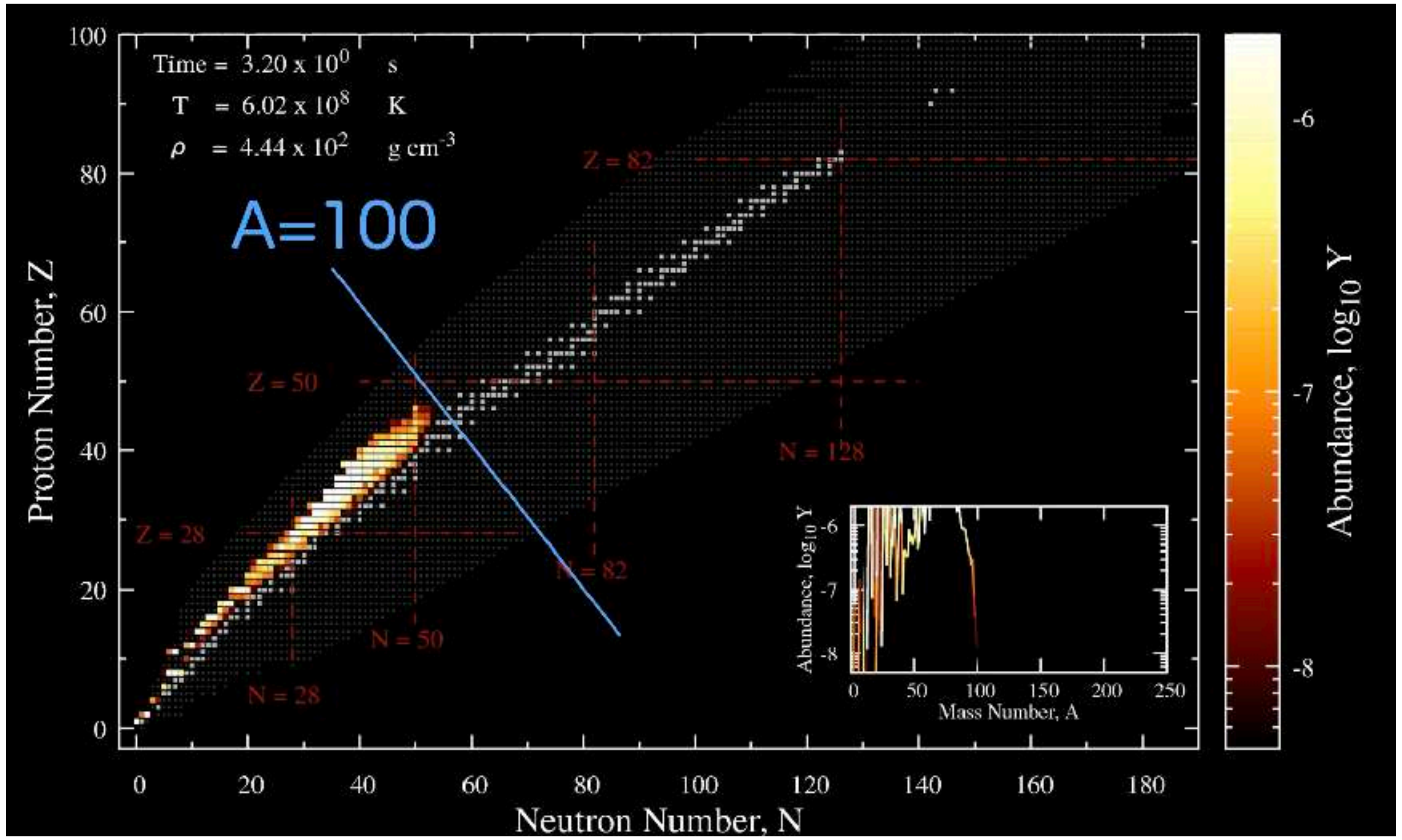
explosion time scale ~ s

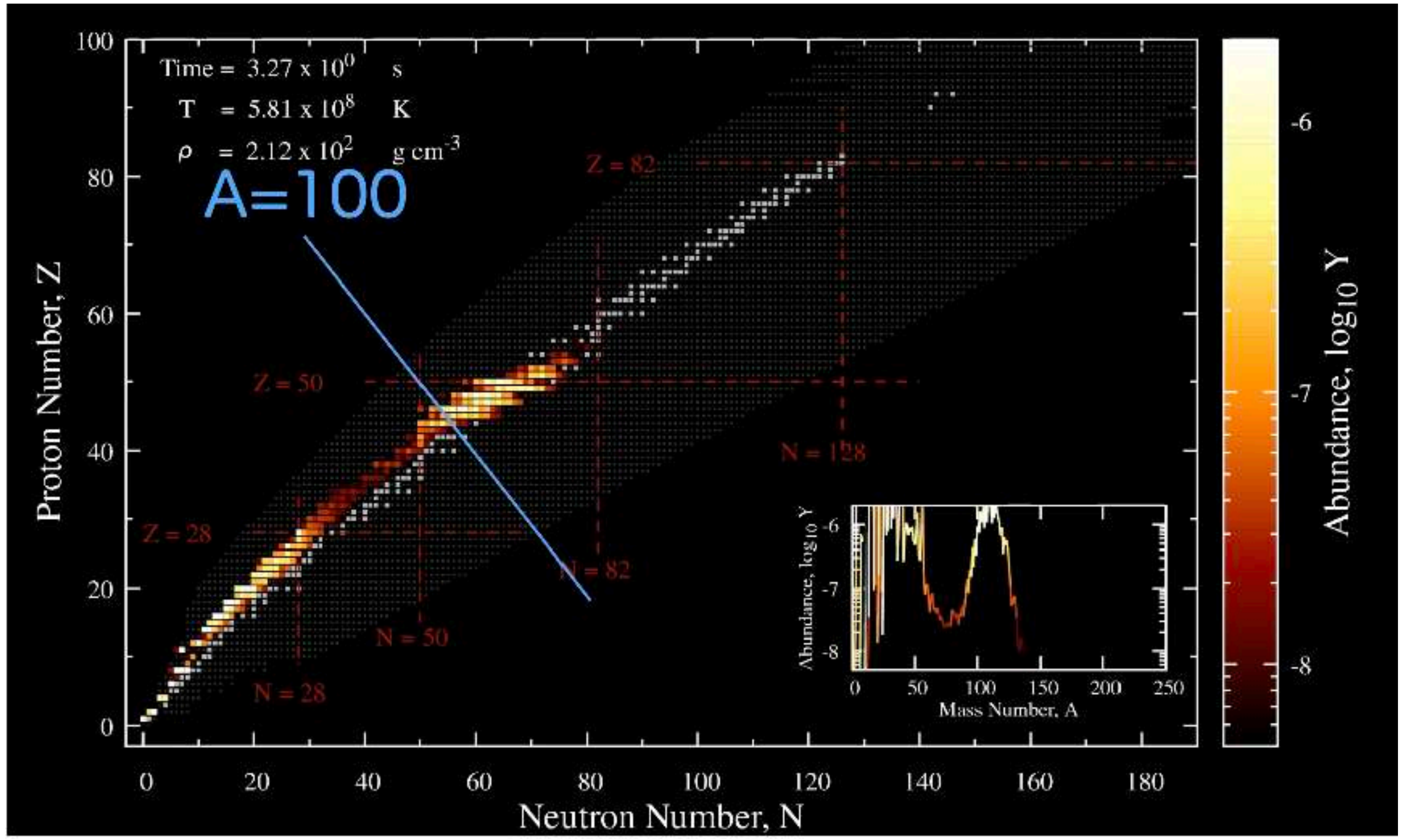
(stalls by waiting β decay)



Nucleosynthesis simulations

νp-process ("initial" $Y_e \sim 0.6$) | stronger νp-process ("initial" $Y_e \sim 0.7$)





NN+2019

※1D wind model with parameters suggested by SN simulations

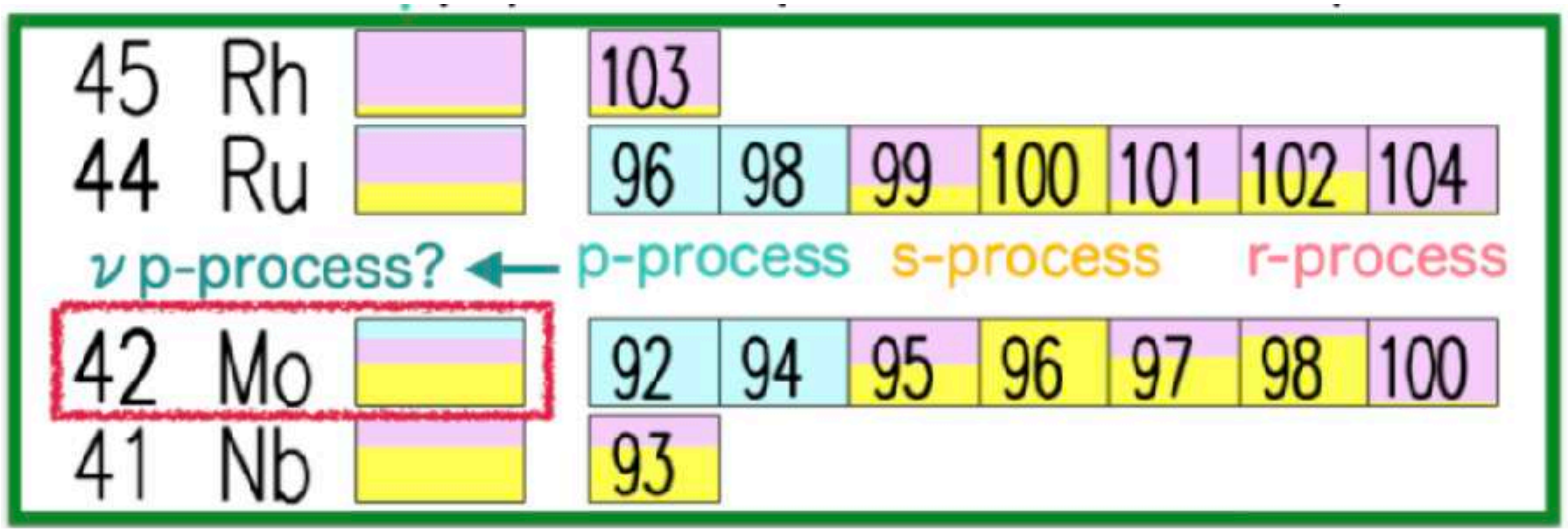
Can the νp-process happen in realistic cc-SNe?

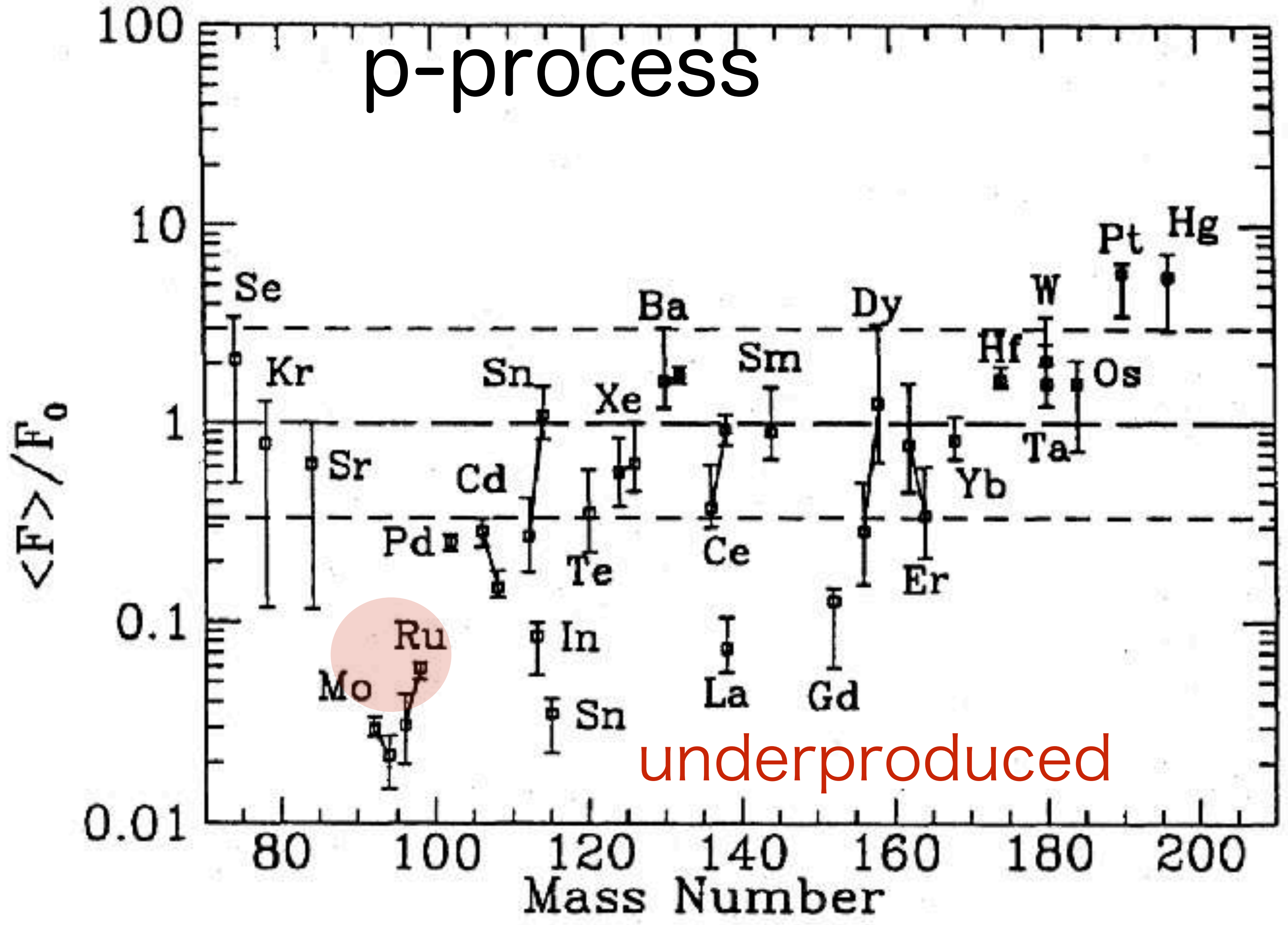
→ surely happen, but how far it reaches (heavy nuclei) remains unsolved

→ a major source of p-rich nuclei in cc-SNe

"Molybdenum (Mo) problem" (lighter p-nuclei)

35 neutron-deficient isotope

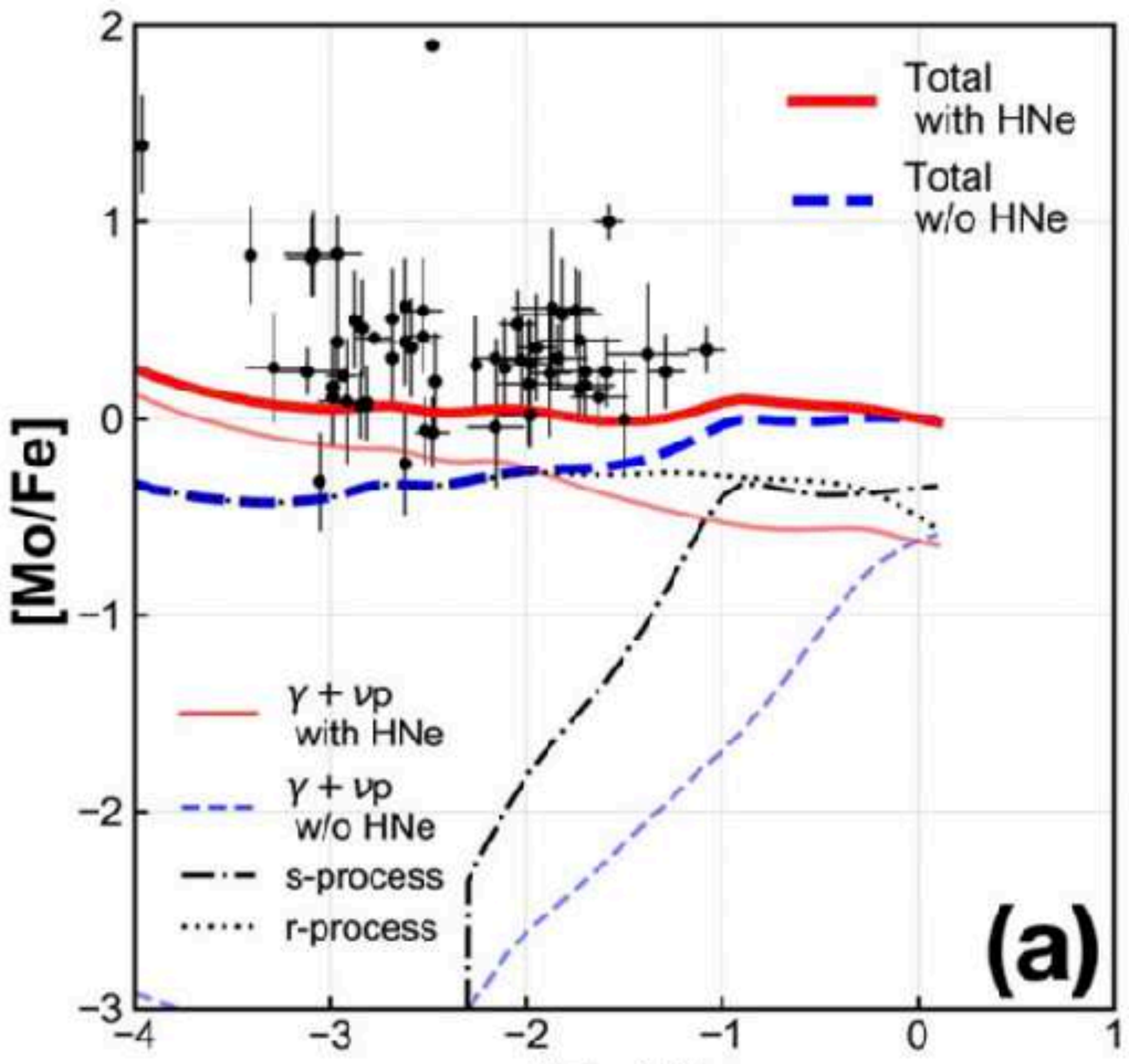




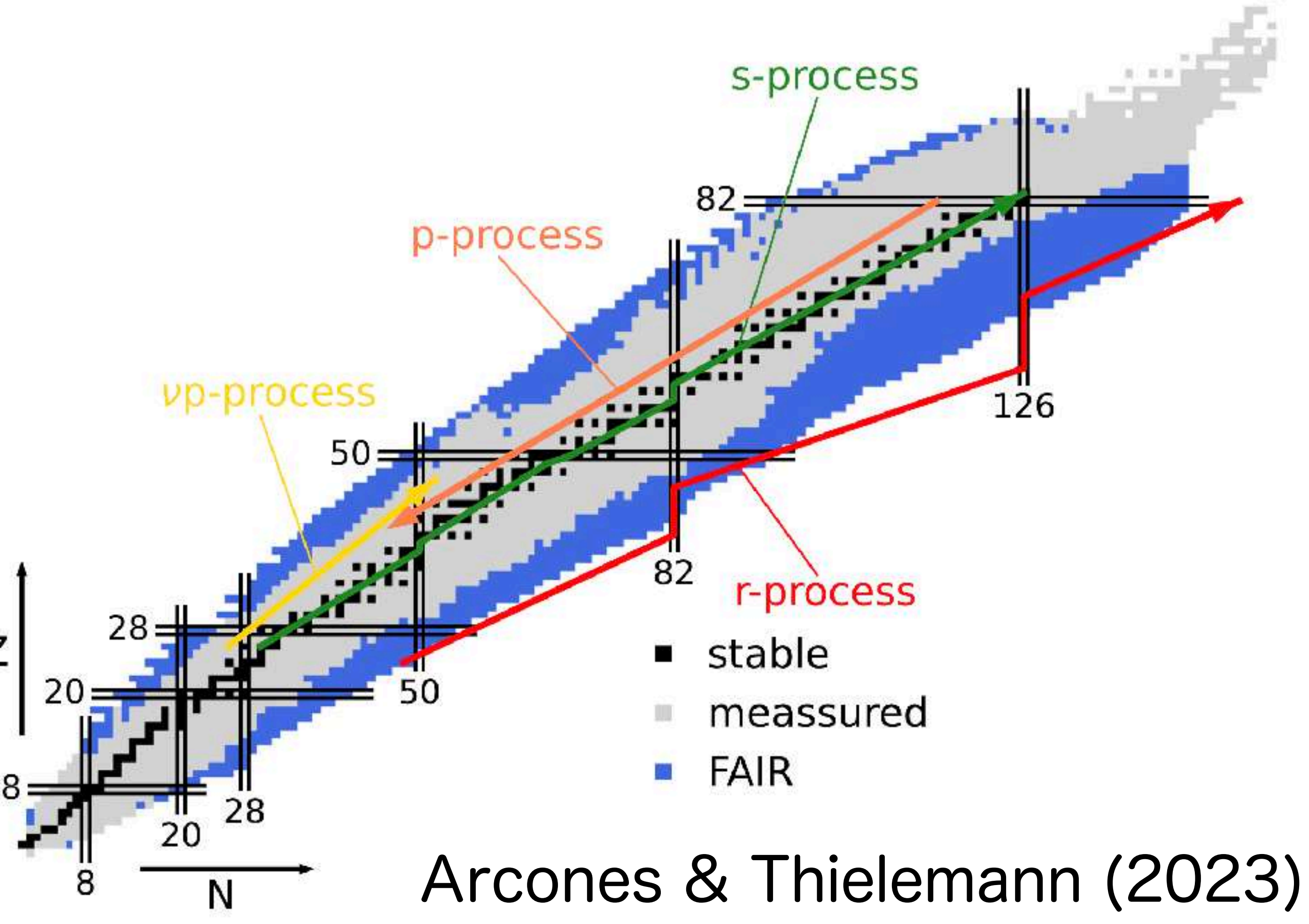
ν p-process in GCE

(see, Travaglio+2018 for the entire p-nuclei)

Sasaki+(2022)



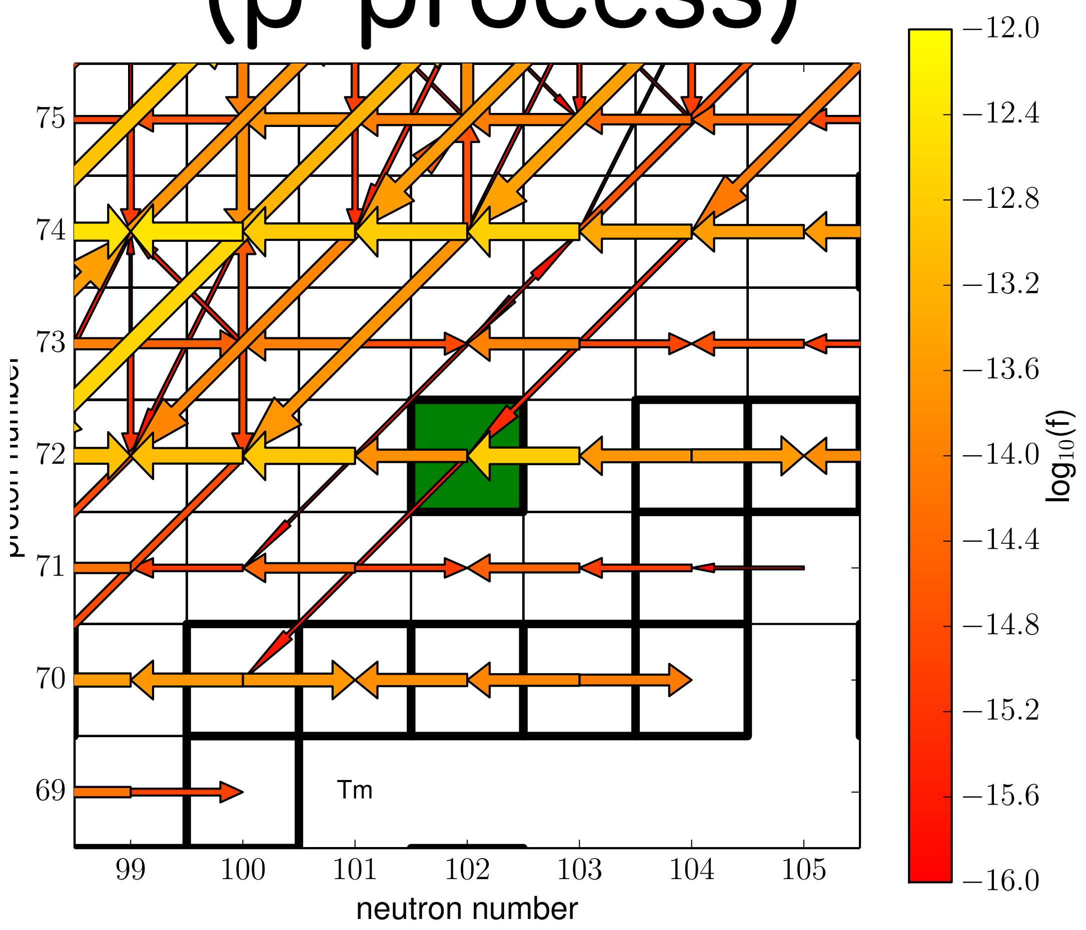
Key reactions in heavy-element nucleosynthesis

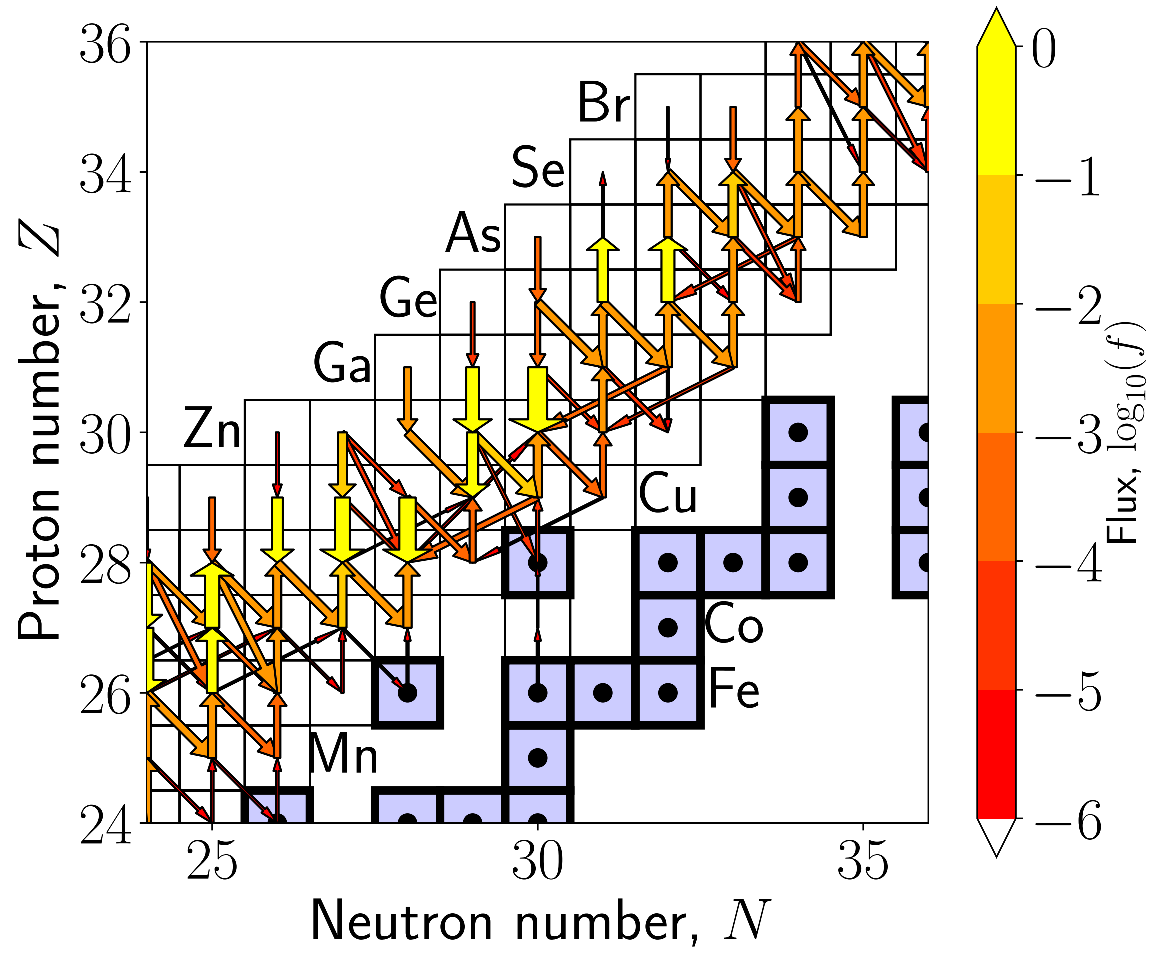


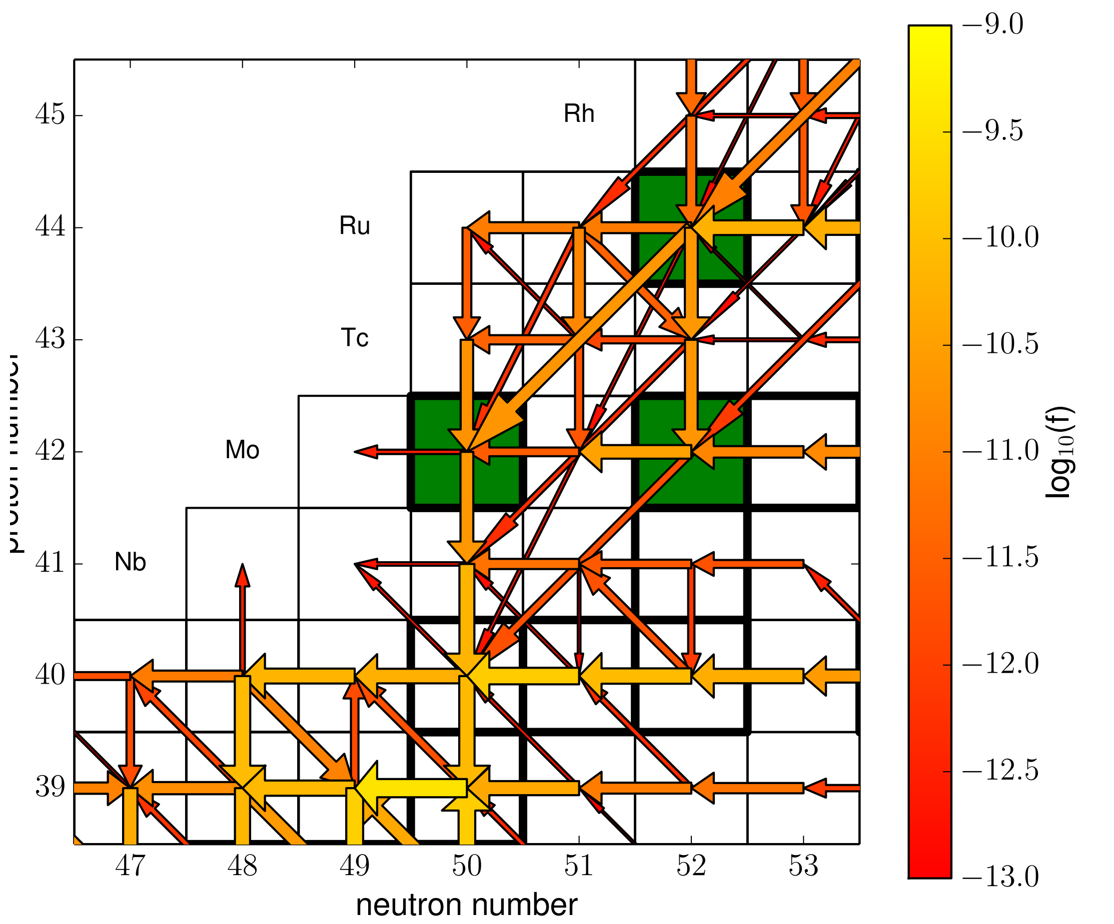
Arcones & Thielemann (2023)

reaction “flows” in several nucleosynthesis

(p-process)







Our approach with

Rauscher (U Basel), Hirshi (Keele U)

reaction/decay uncertainty

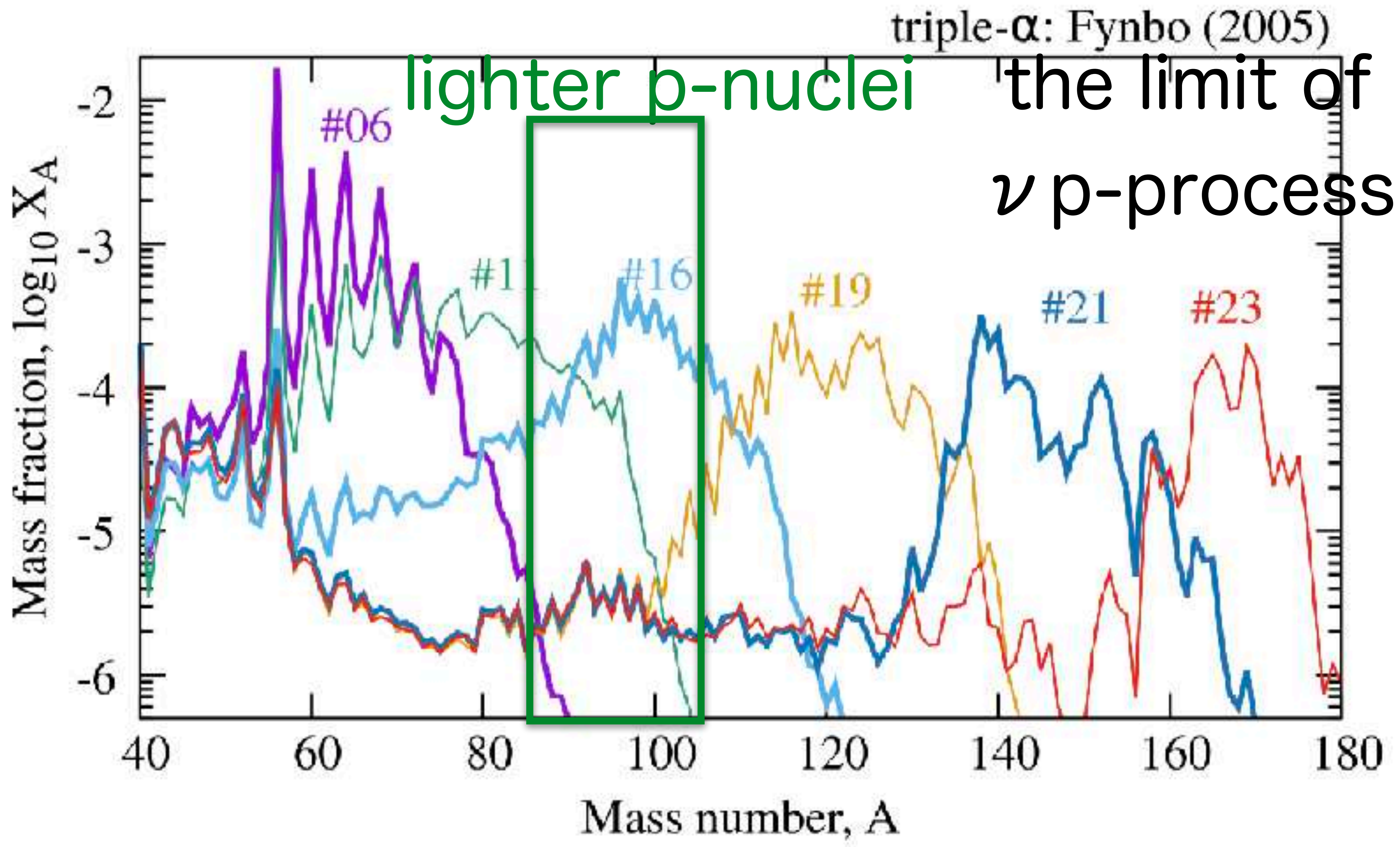
Monte-Carlo
statistical analysis

observation

uncertainty

- s-process
  - weak s: massive stars (NN+2017)
    → n_TOF experiments
  - main s: low mass stars (Cescutti, Hirsch, NN+2018)
- p-process → TRIUMF experiments
  - core-collapse supernovae (Rauscher, NN+2016)
  - Type Ia supernovae (NN+2018)
- νp-process (NN+2019) → RIBF experiments

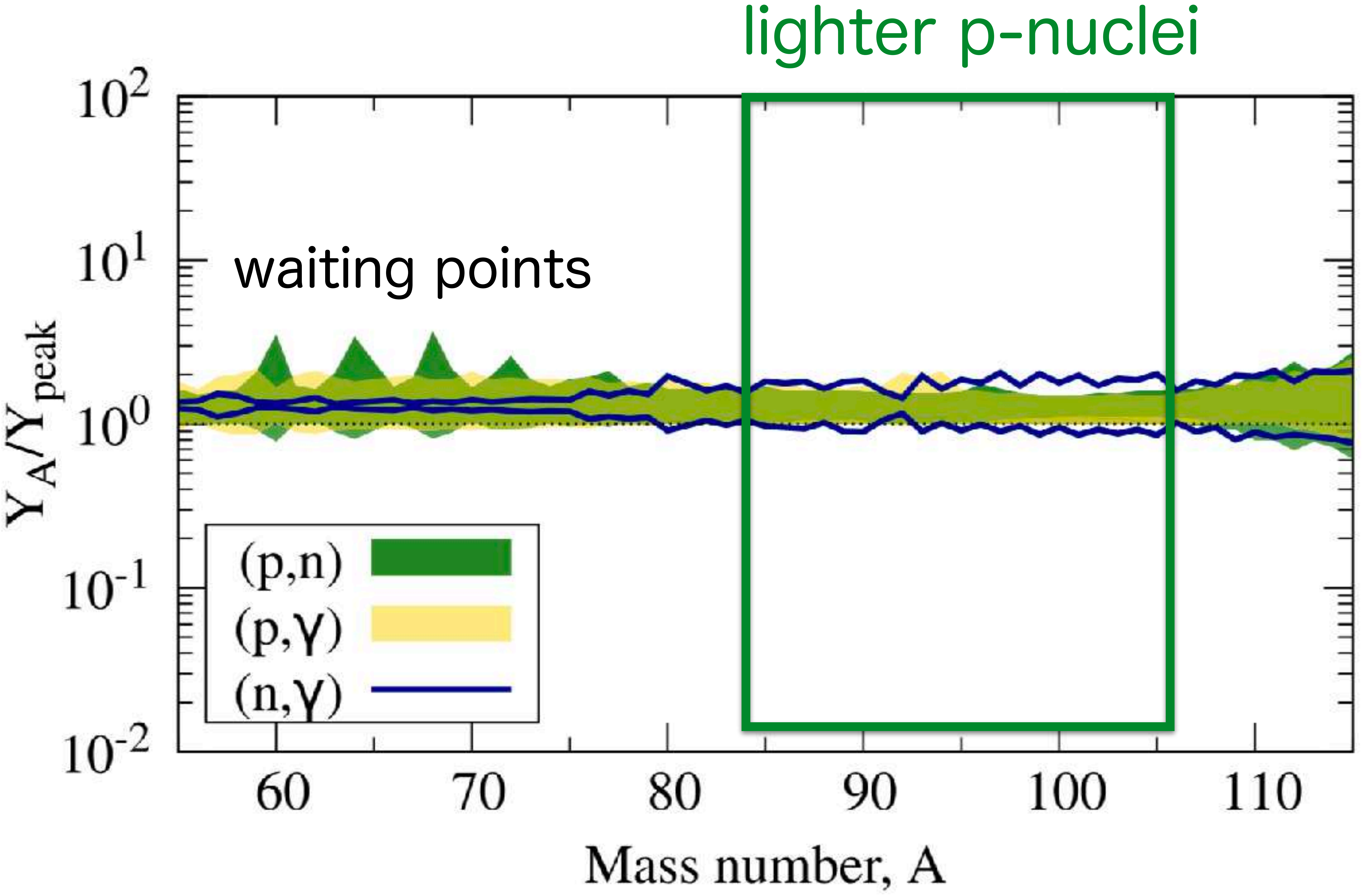
Uncertainty by individual reaction types



uncertainty range

Reaction	upper	lower
(n,γ)	2.0	2.0
(p,γ)	2.0	3.0
(p,n)	2.0	3.0
(α,γ)	2.0	10.0
(α,n)	2.0	10.0
(α,p)	2.0	10.0

consider uncertainty of all reactions except for w/o triple-α and ^{56}Ni(n,p)

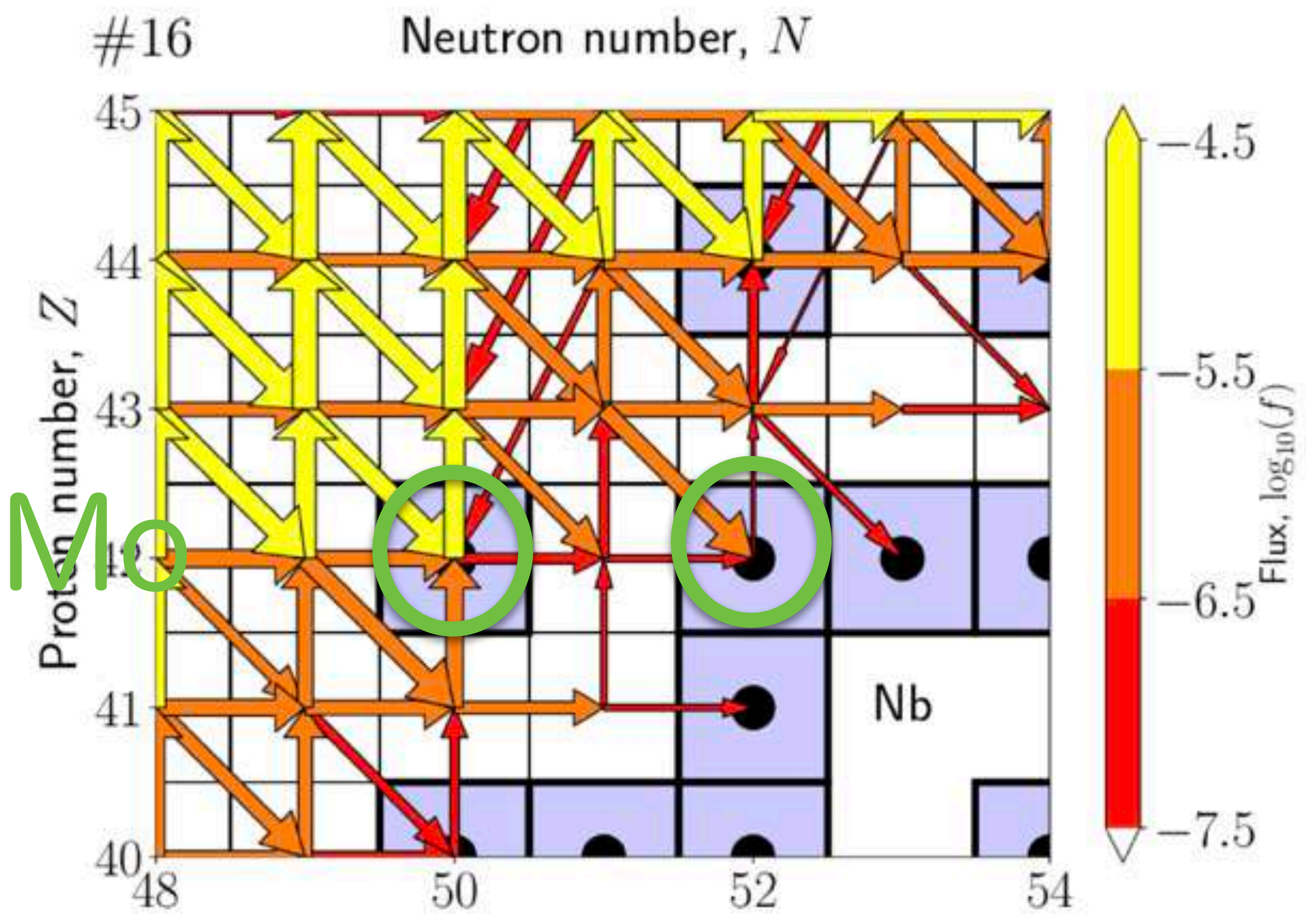


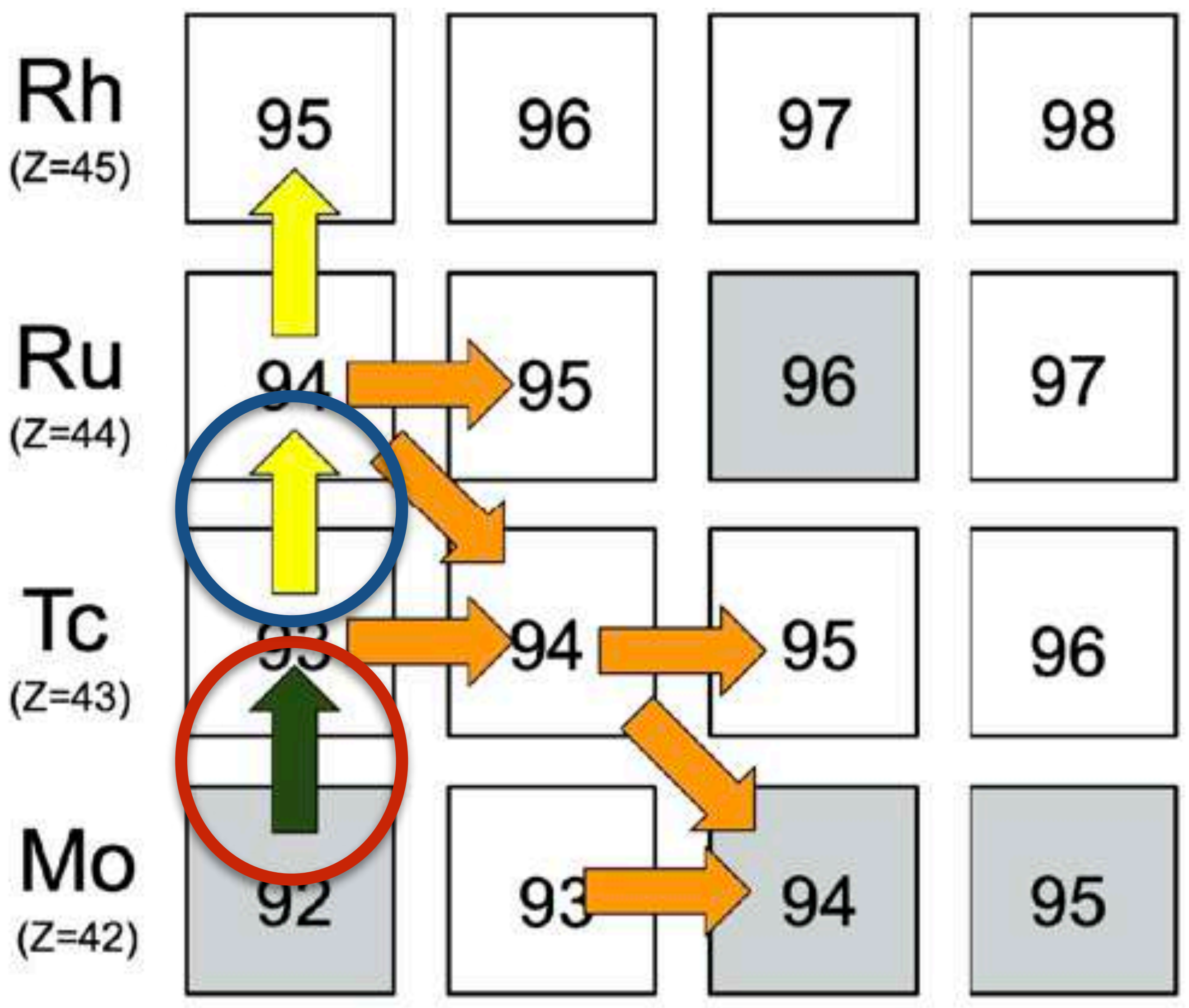
Solar isotopic ratios

the solar isotopic ratio (Lodders 2003): $/^{94}$Mo
^{92}Mo/^{94}Mo = 1.6, ^{84}Sr/^{94}Mo = 0.54, ^{78}Kr/^{94}Mo = 0.82

- ν p-process w/ updated masses?
  → still low ^{92}Mo/^{94}Mo (Xing+2018)
- nuclear reactions?
  - → 0.67 < ^{92}Mo/^{94}Mo < 2.79 for a specific model (NN+2019)

NN+2019



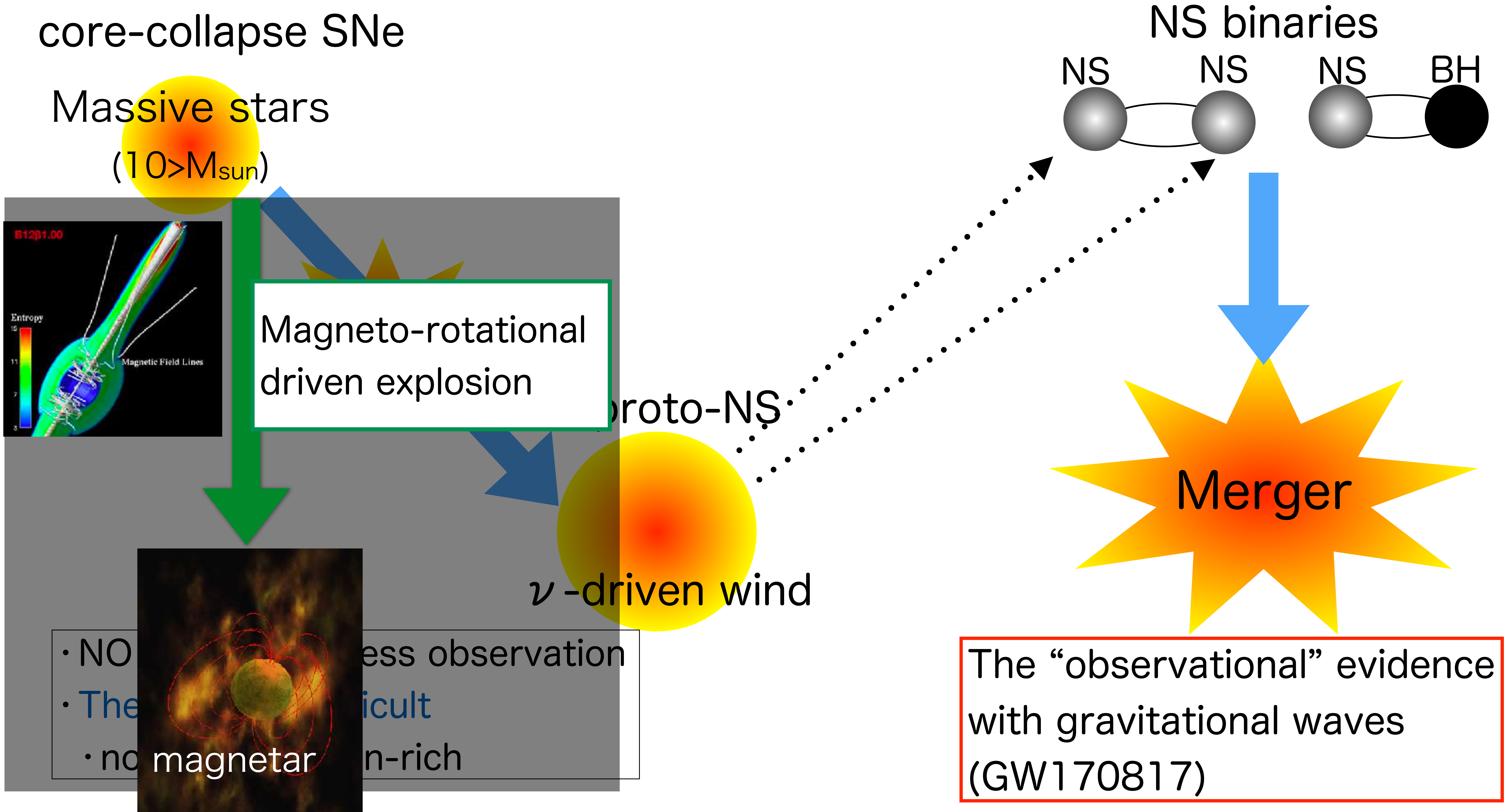


key reaction : ^{92}Mo(p,g)^{93}Tc
(next priority: ^{93}Tc(p,g)^{94}Ru)

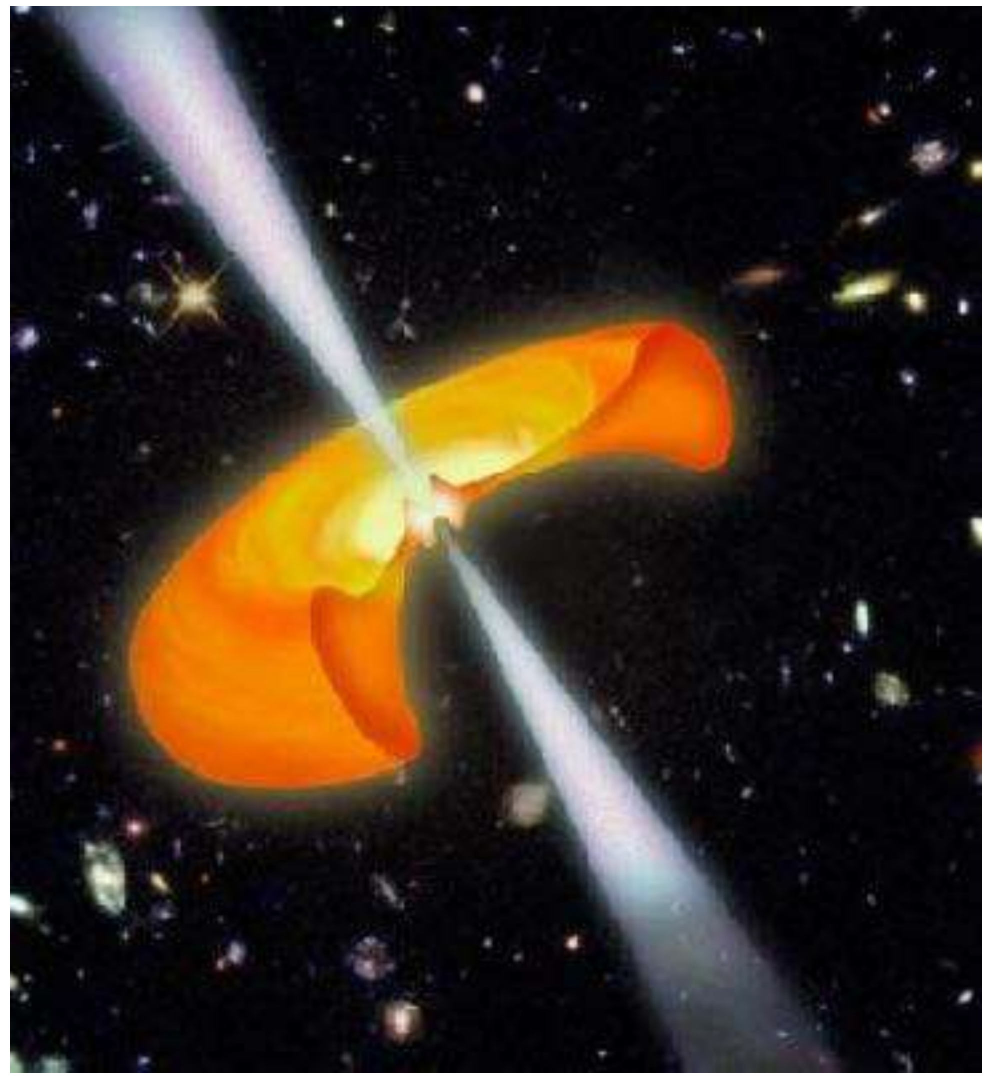
2. r-process in magneto-rotational SNe

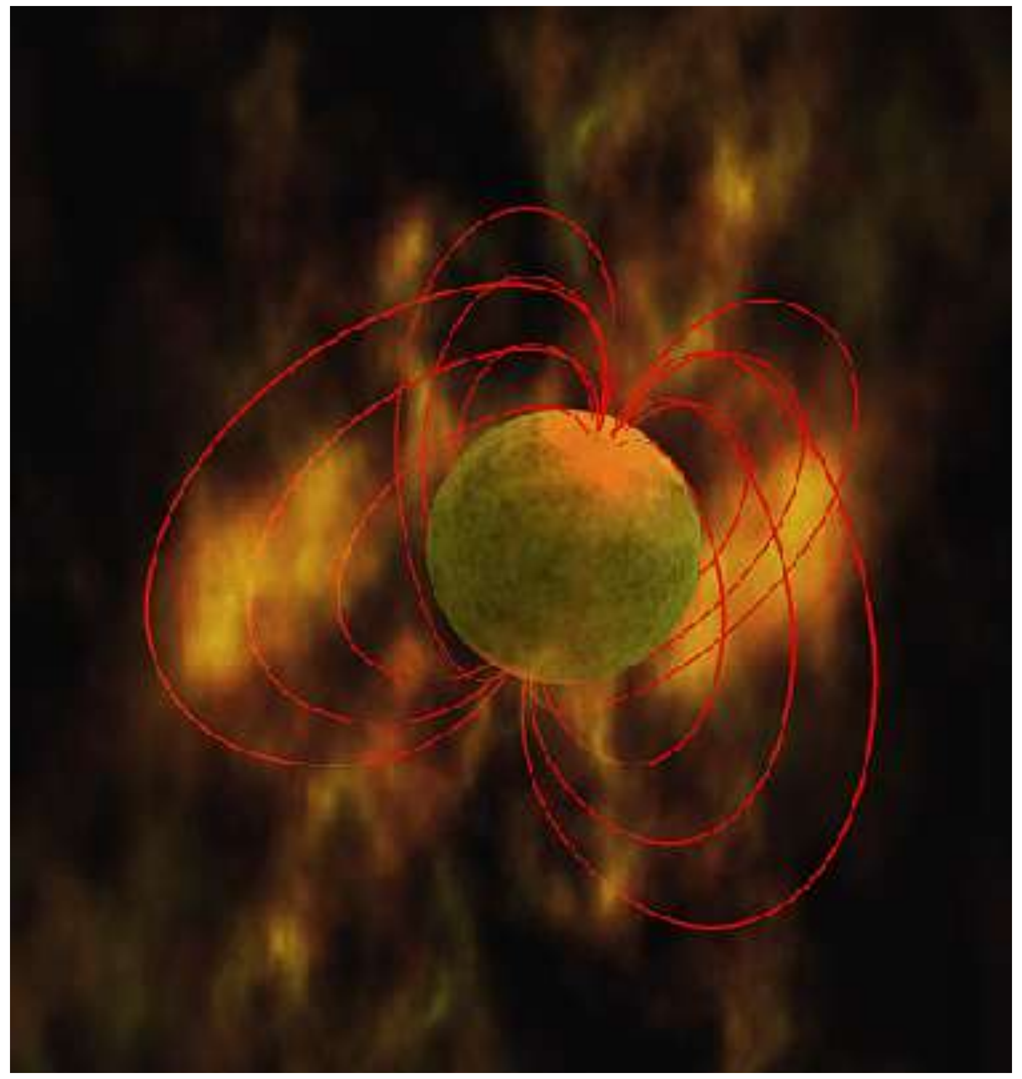
・Hasegawa, Tanaka, NN+, in prep.

Astrophysical r-process sites



Magneto-rotational SN scenario


hypernova/jet-like SN

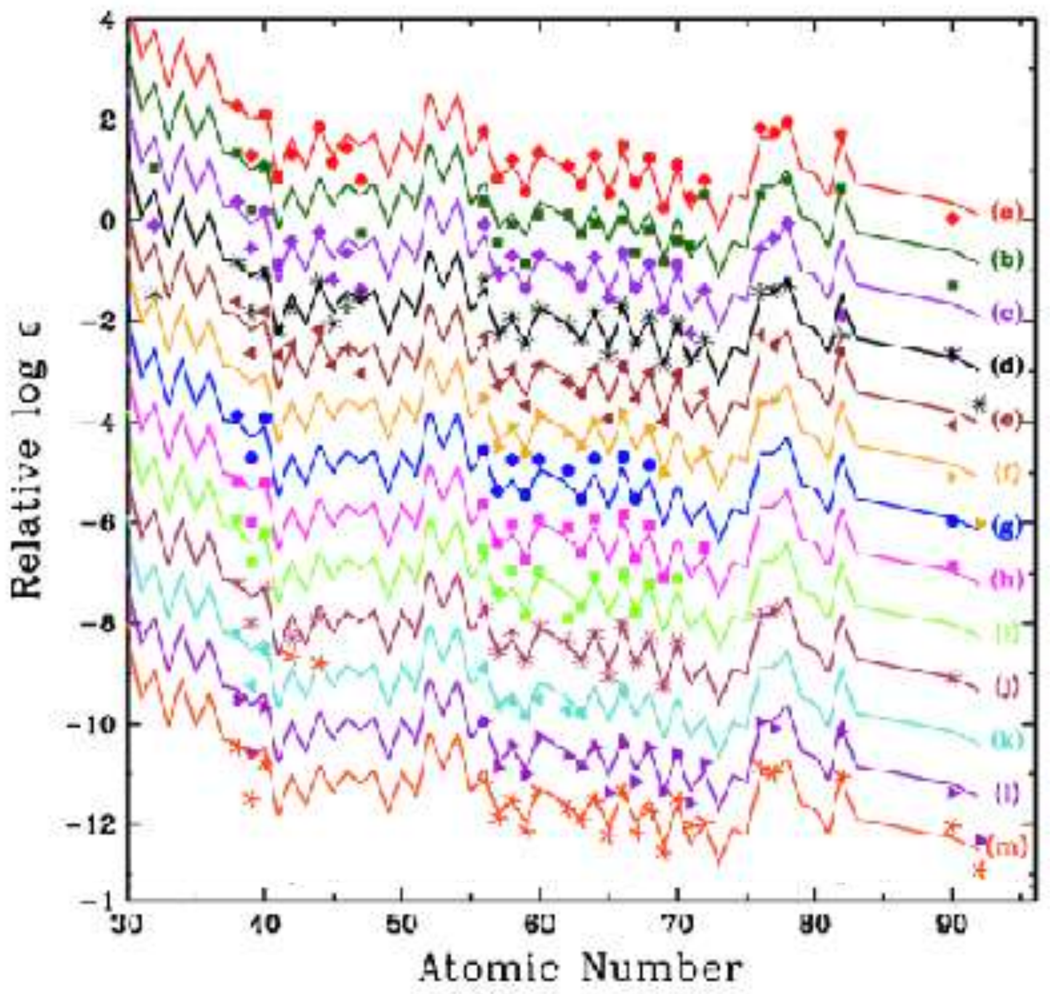

magnetars

- Magnetars
  - strong magnetic field ～10^{15} G
    (～1 % of all neutron stars)
- Magneto-driven Supernovae?
  - GRB central engine
  - Hypernovae?
  - (magnetar driven) Super luminous SNe?

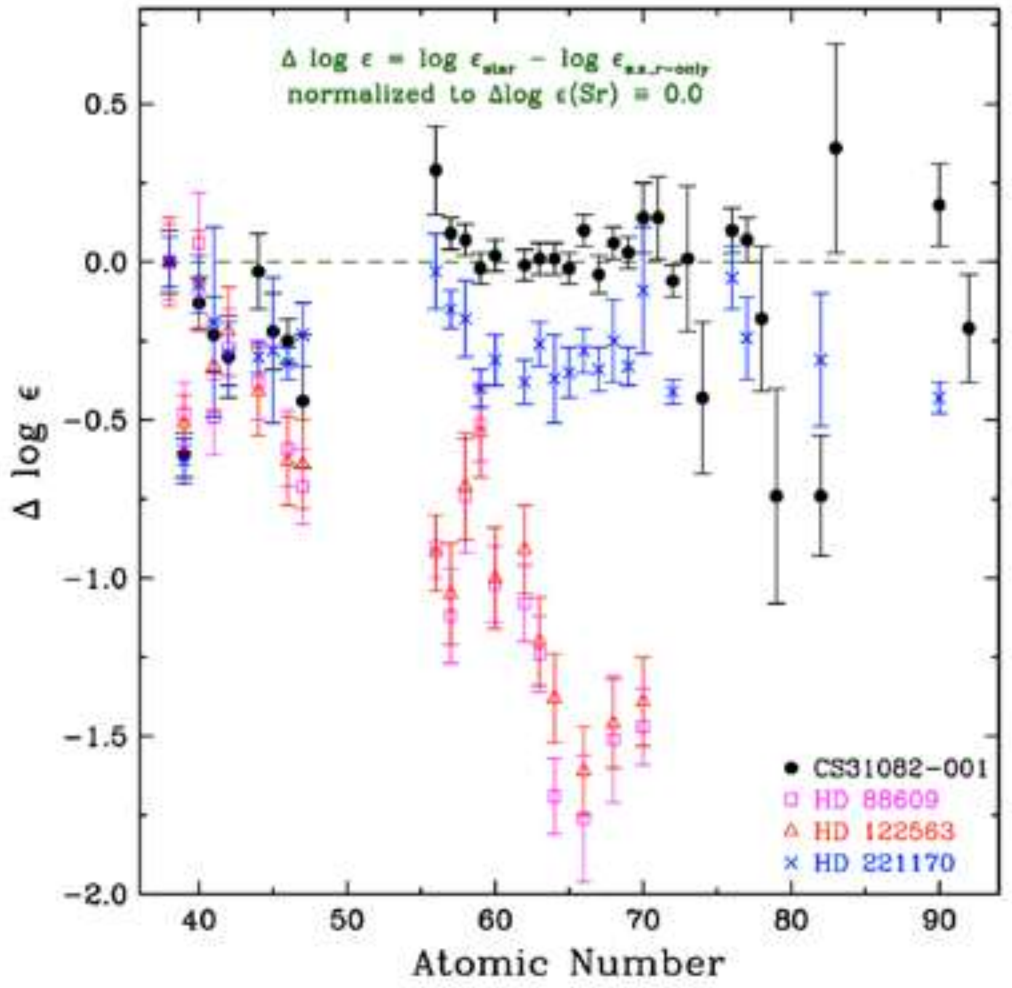
- variety of r-process patterns in metal-poor stars
- can be rare ～ 1% of ccSN rate
- Galactic chemical evolution
  - needed as external sources with NS mergers?
  - MR-SNe, "hypernovae", collapsars etc.??

  (see, e.g., Wehmeyer+2015, Tsujimoto&NN 2015, Cescutti+2017, Siegel+2019, Kobayashi+2020 etc.)

r-process in MP stars



"weak" r-process?



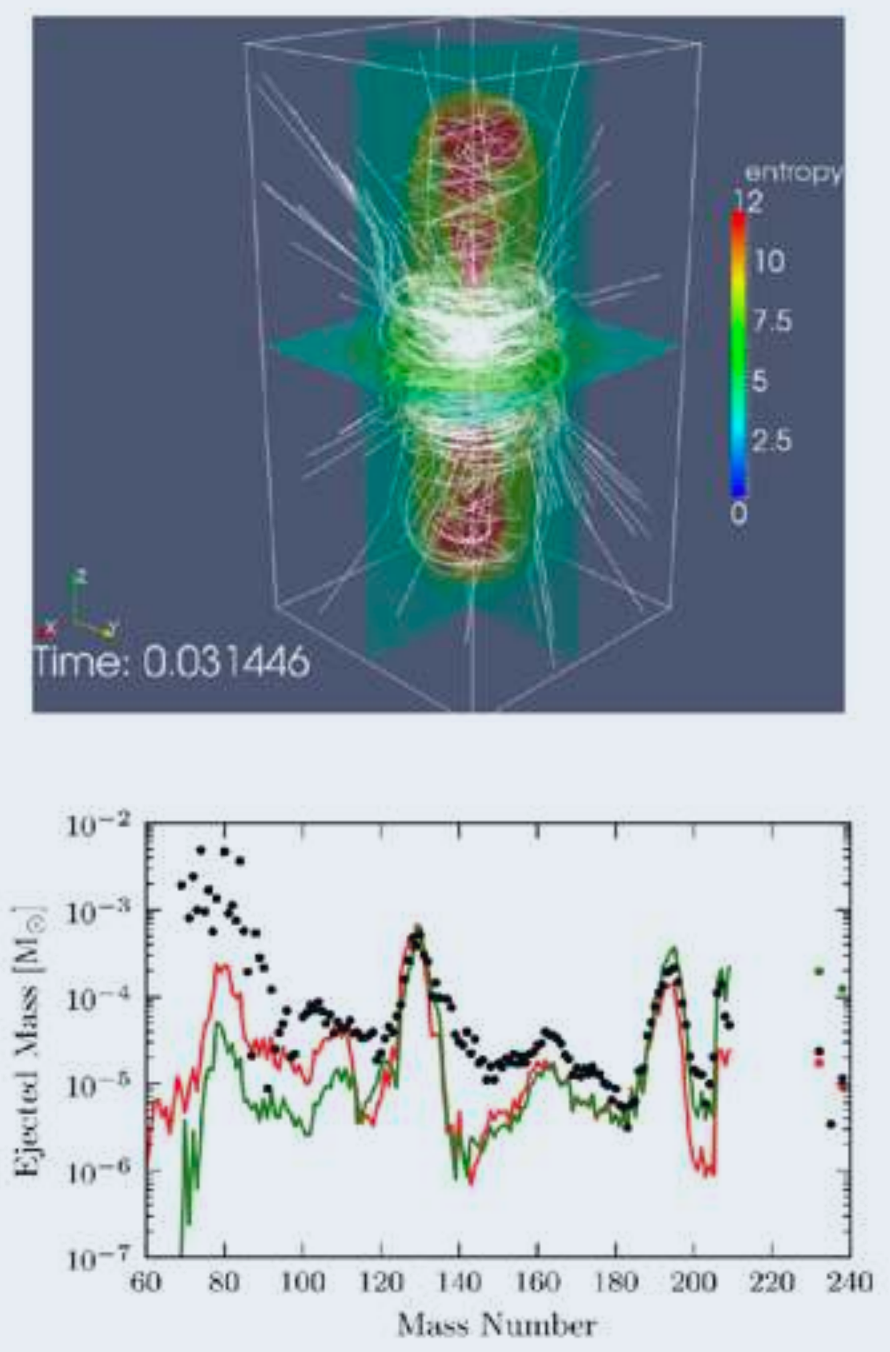
Cowan+2021

r-Process studies with SN models

- magneto-rotational driven cc-SN mechanism (non-standard explosions)
- strong magnetic jet may eject very neutron-rich matter (high e^- capture -> low Y_e)
- neutrino-heating is not predominant (but, still significant)

strong jet

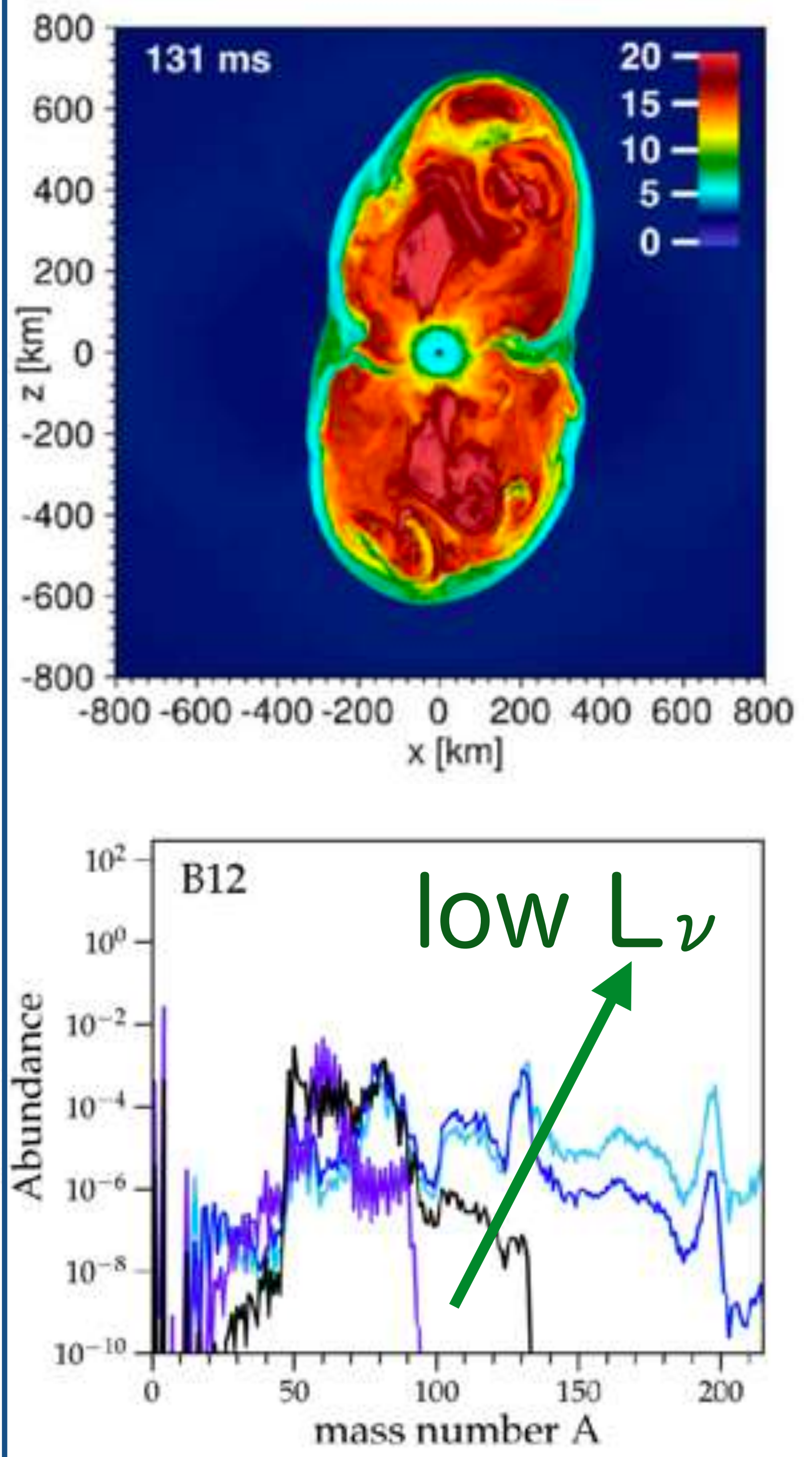
Winteler+NN+(2012)



*difference is due to uncertainty

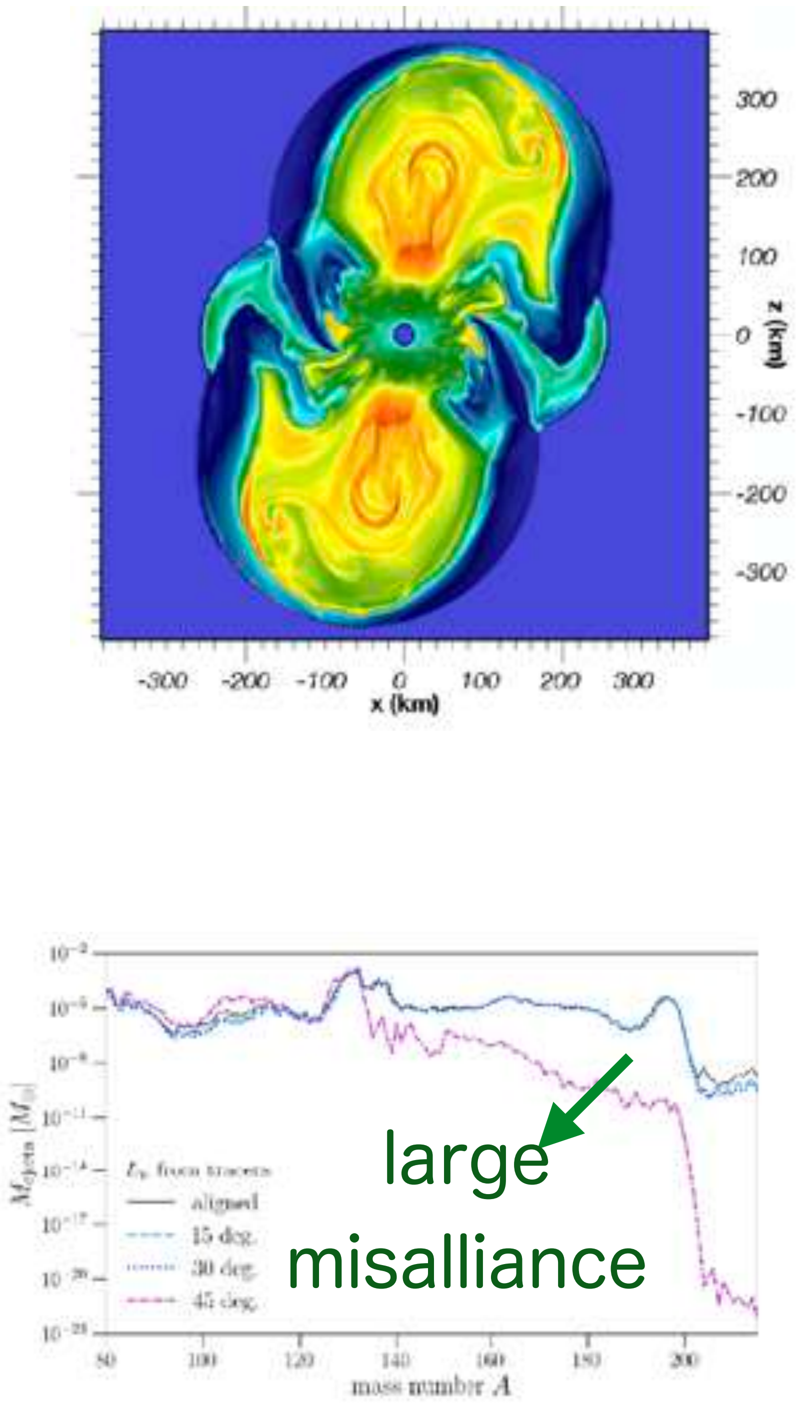
hydro-instability

Mösta+(2018)



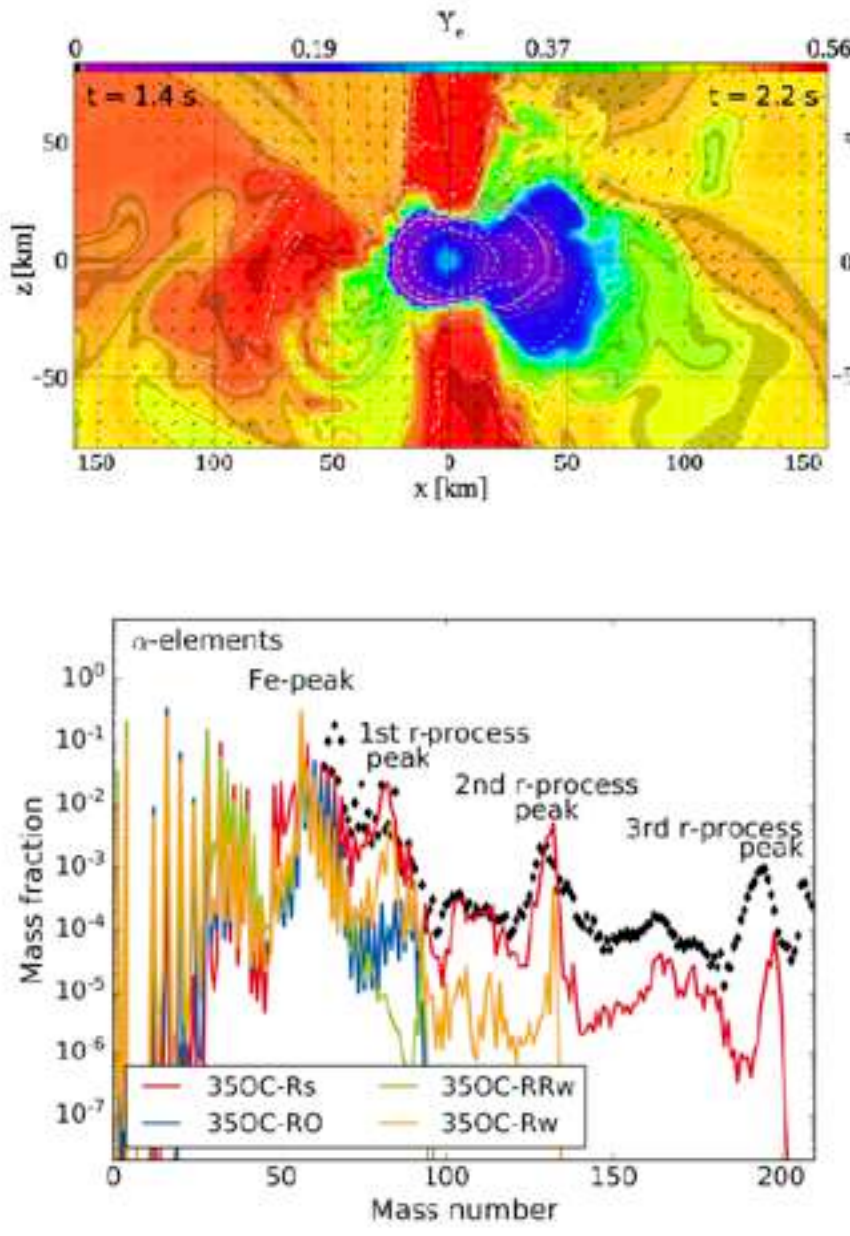
rotation vs. B-field misalliance

Halevi & Mösta(2018)

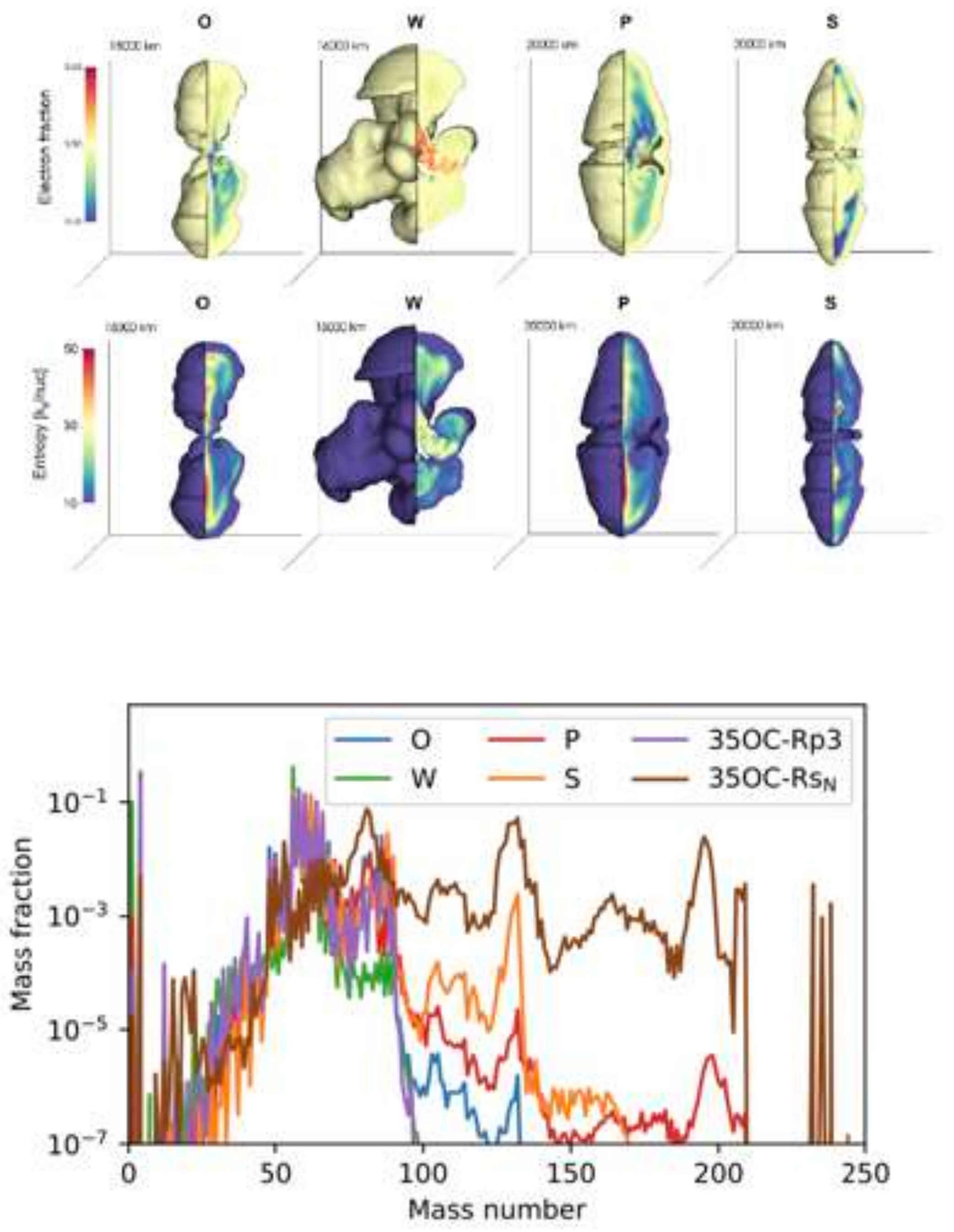


advanced neutrino transport

Reichert+2021, 2022
(w/ Obergaulinger+2020)

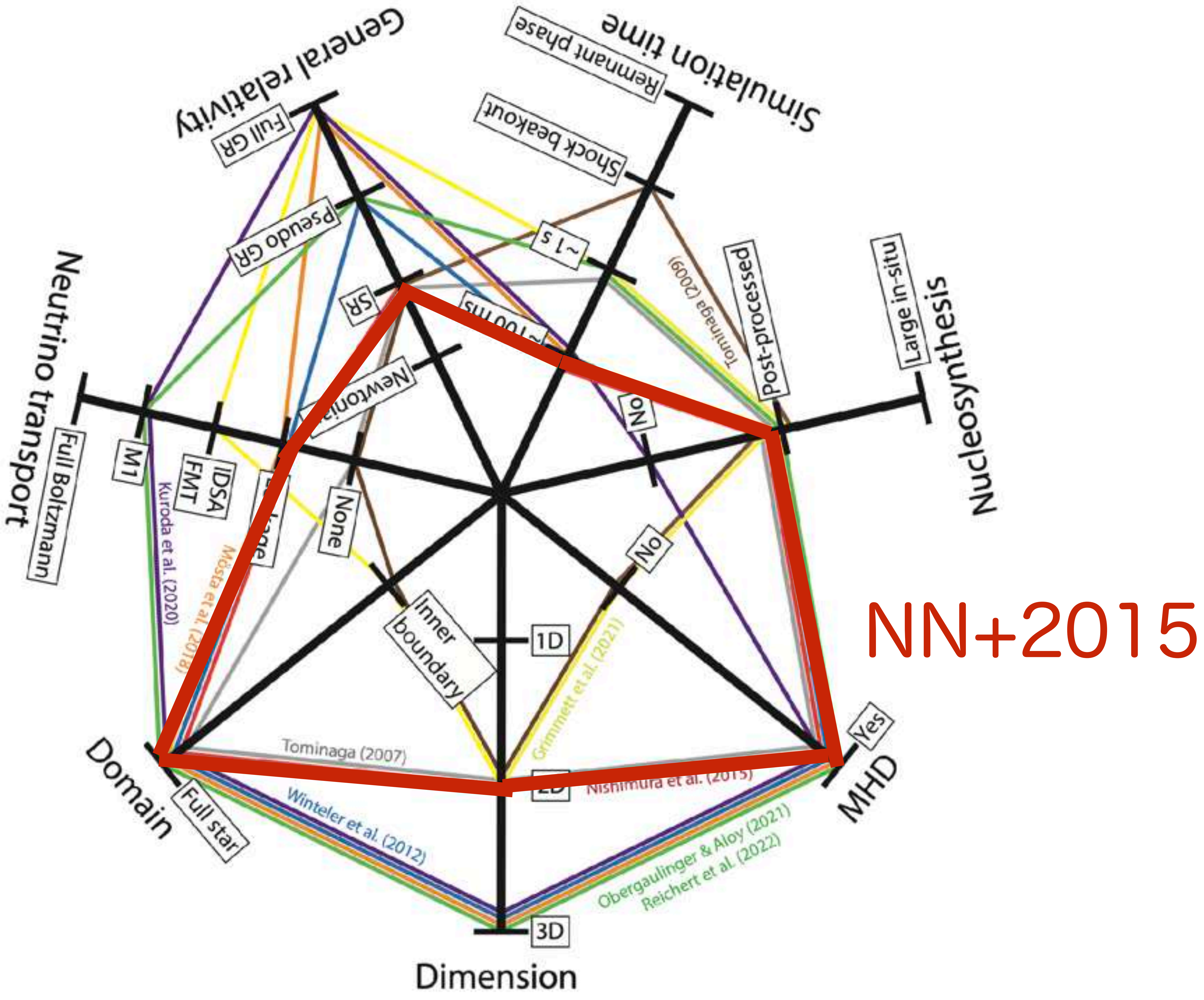


Reichert+2023



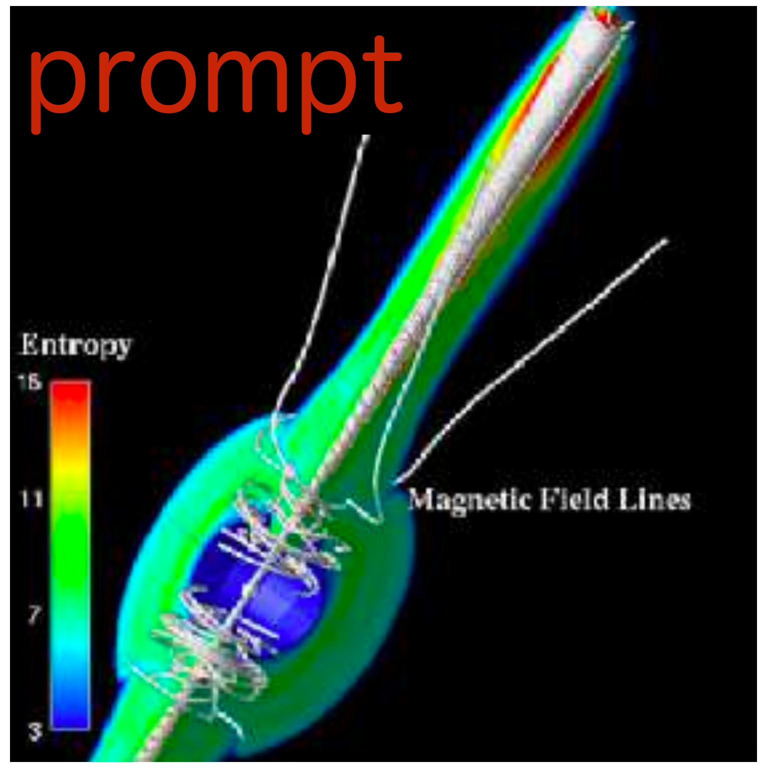
r-Process studies with SN models

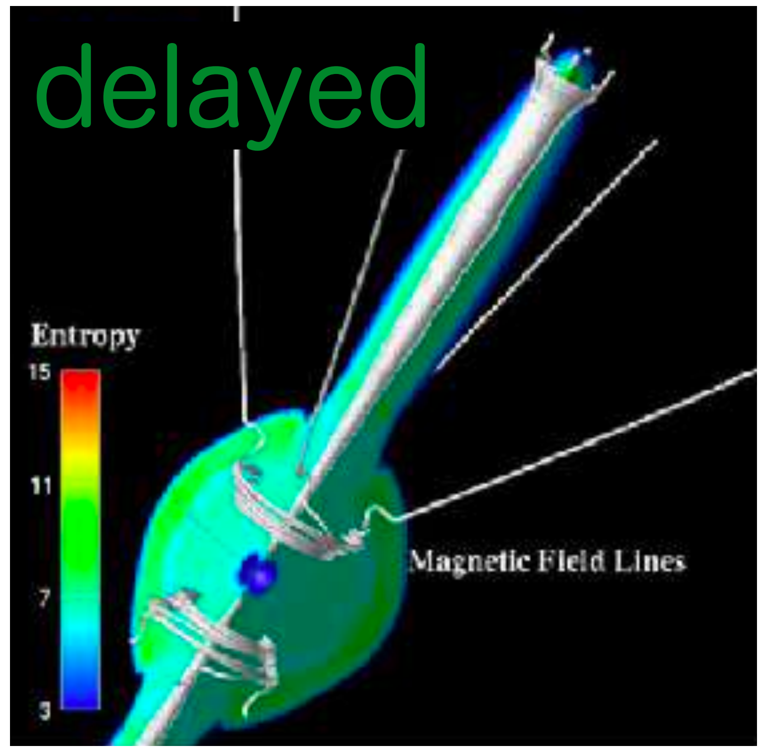
Obergaulinger & Reichert 2023



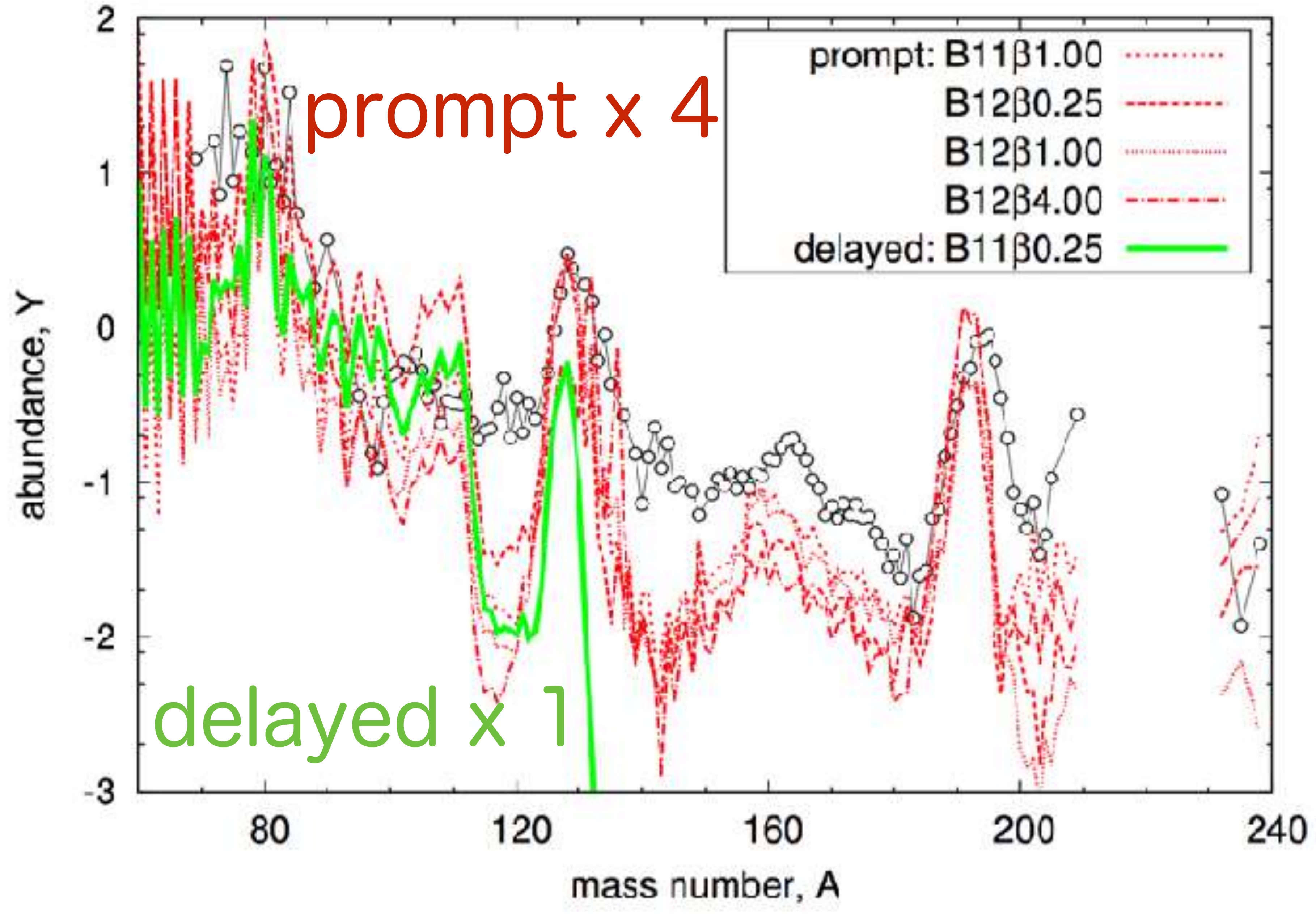
Multiple physics in explosion models

- multi-D MHD, general relativity
- neutron transport, weak reactions
- computational domain, time-scale
- nucleosynthesis
- ....



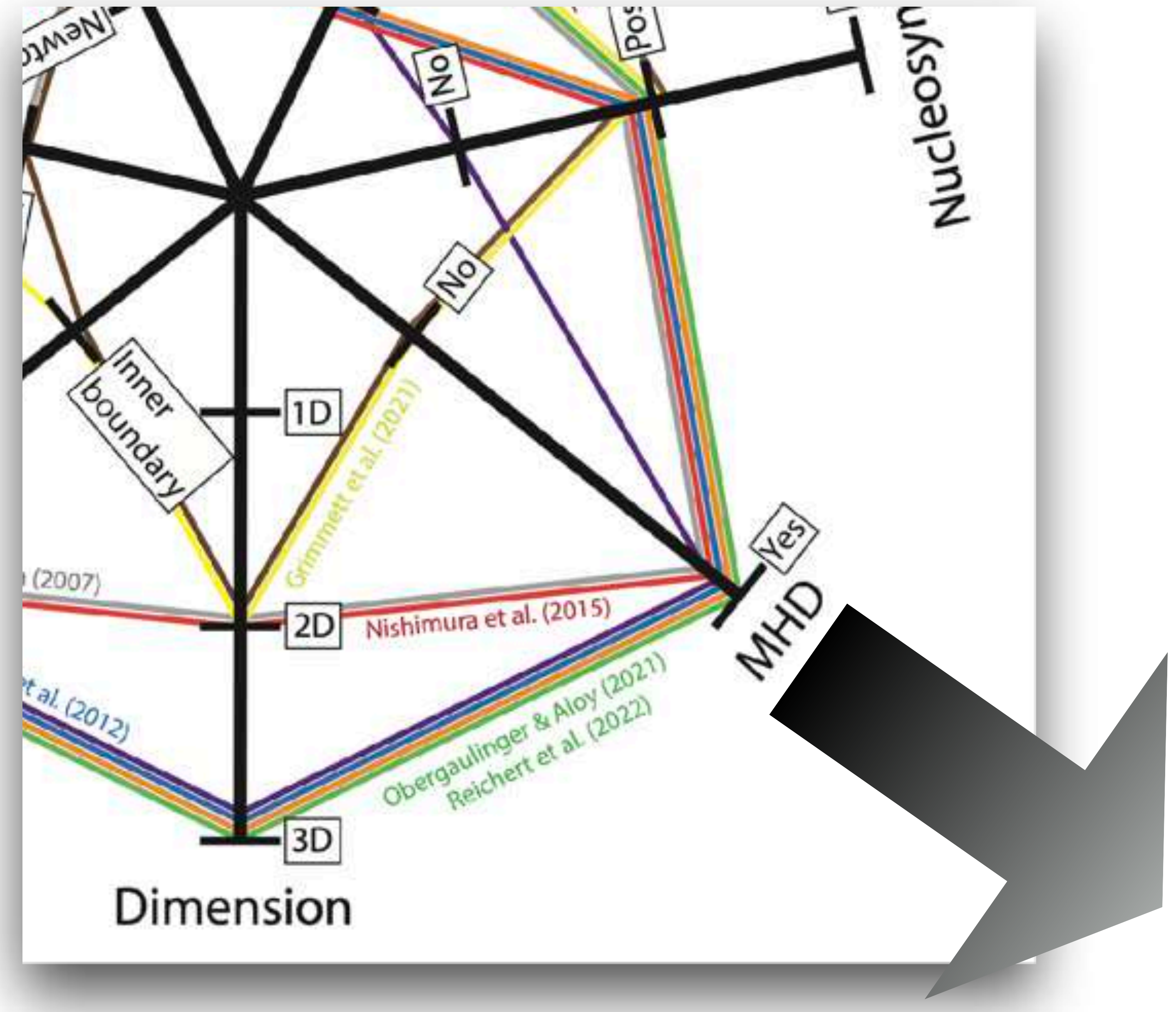


- dependence on rotation and B-fields
- B-fields application by winding



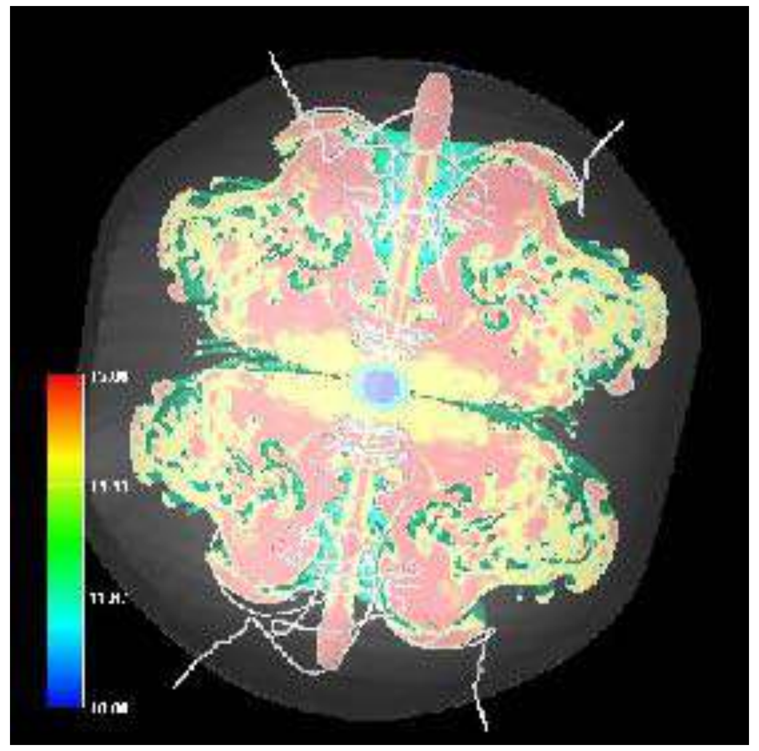
r-Process studies with SN models

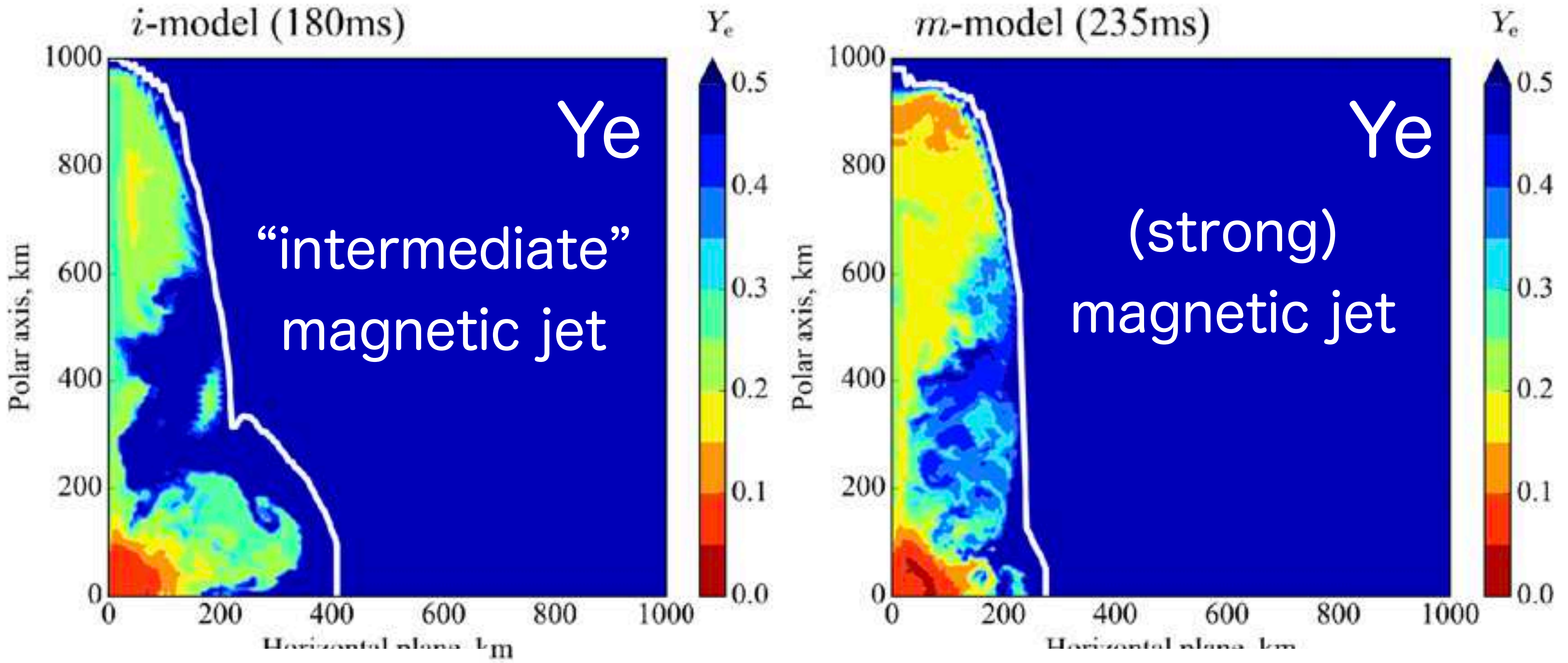
Obergaulinger & Reichert 2023

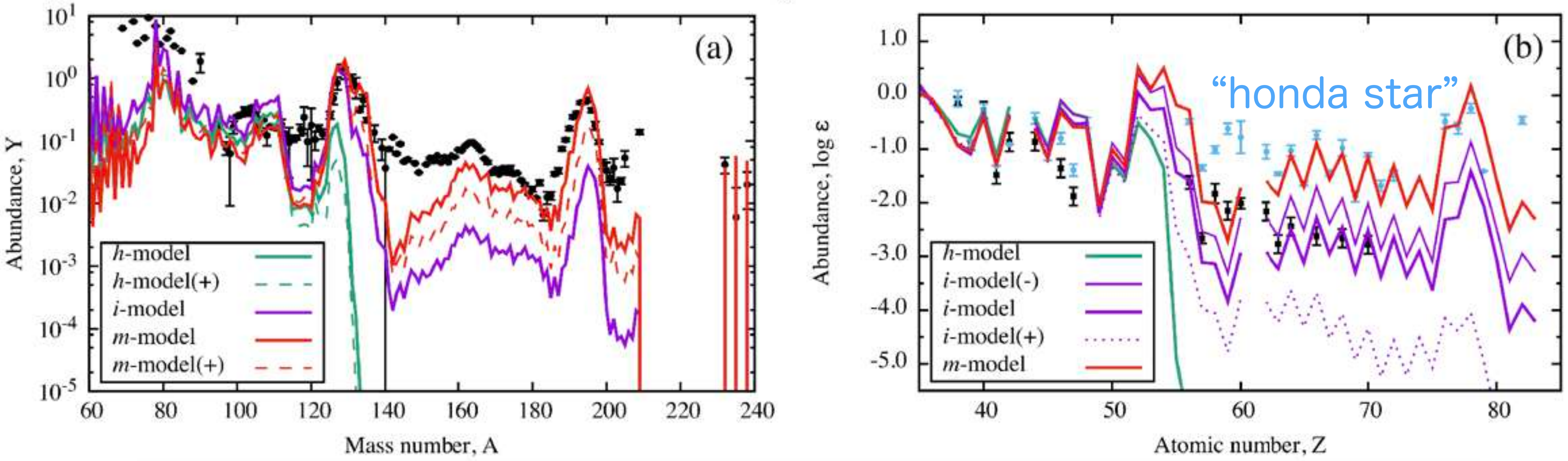


- High resolution MHD
  (local B-field amplification)
  - MRI
  - magnetic turbulence
  - ....

NN+2017







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https://doi.org/10.3847/2041-8213/aa5dee

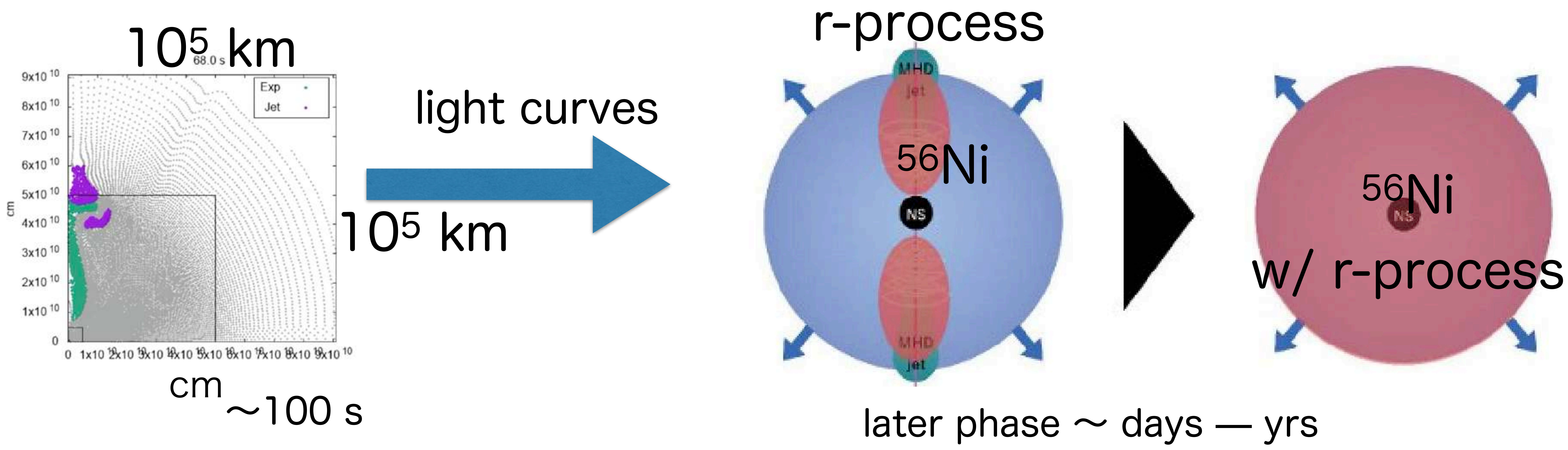
ir-process??

CrossMark

The Intermediate r-process in Core-collapse Supernovae Driven by the Magneto-rotational Instability

N. Nishimura (西村信哉)[1,6], H. Sawai (澤井秀朋)[2,3], T. Takiwaki (滝脇知也)[4], S. Yamada (山田章一)[3], and F.-K. Thielemann[5]

Modeling light-curves with r-process-jet-SN



- 1D radiative hydrodynamics (Tanaka & Hotokezaka 2013)
  - LTE, b-b transition for all elements
  - ^{56}Ni production with explosion model —> model parameter
  - r-process is uniformly mixed in ejecta (free parameter)

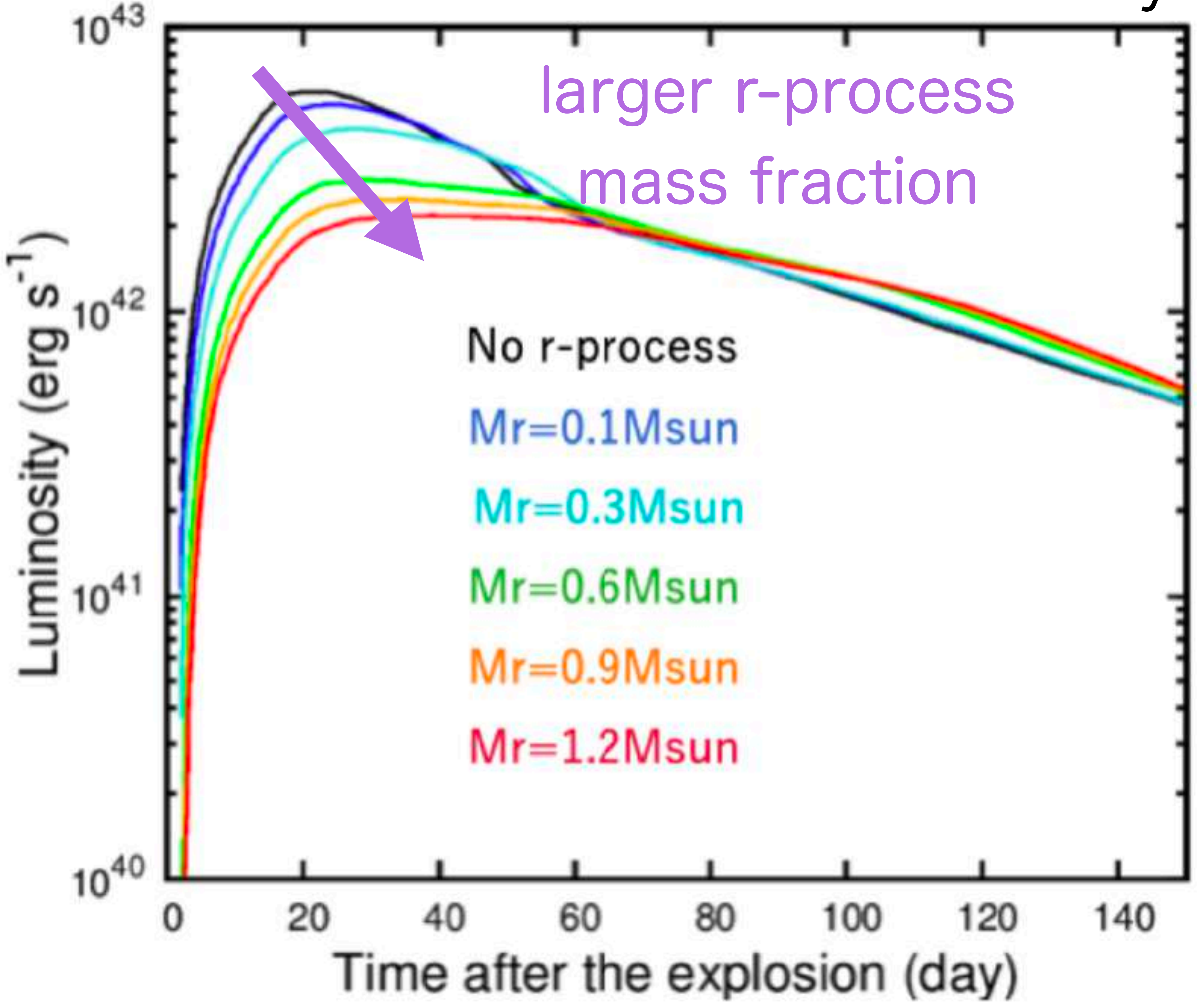
GRB (hypernova) associated SNe

bright SNe with high ^{56}Ni mass = 0.36 M_{sun} (E_{exp} = 10^{52} erg)
varying r-process mass M_r = 0, 0.1, 0.3, 0.6, 0.9, 1.2 M_{sun}

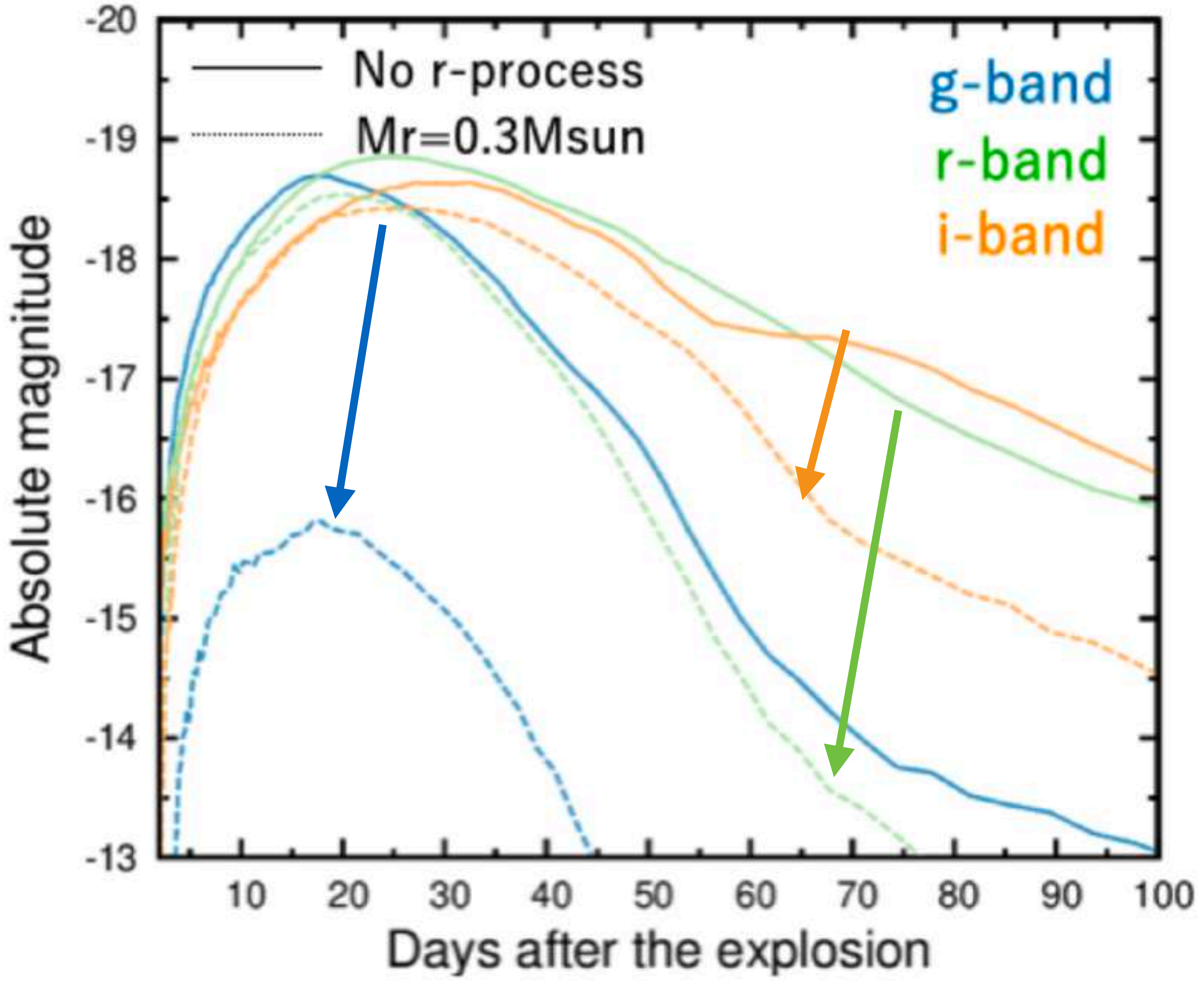
→ r-process rich → high opacity → fainter & red

Hasegawa+NN+ 2022

bolometric luminosity

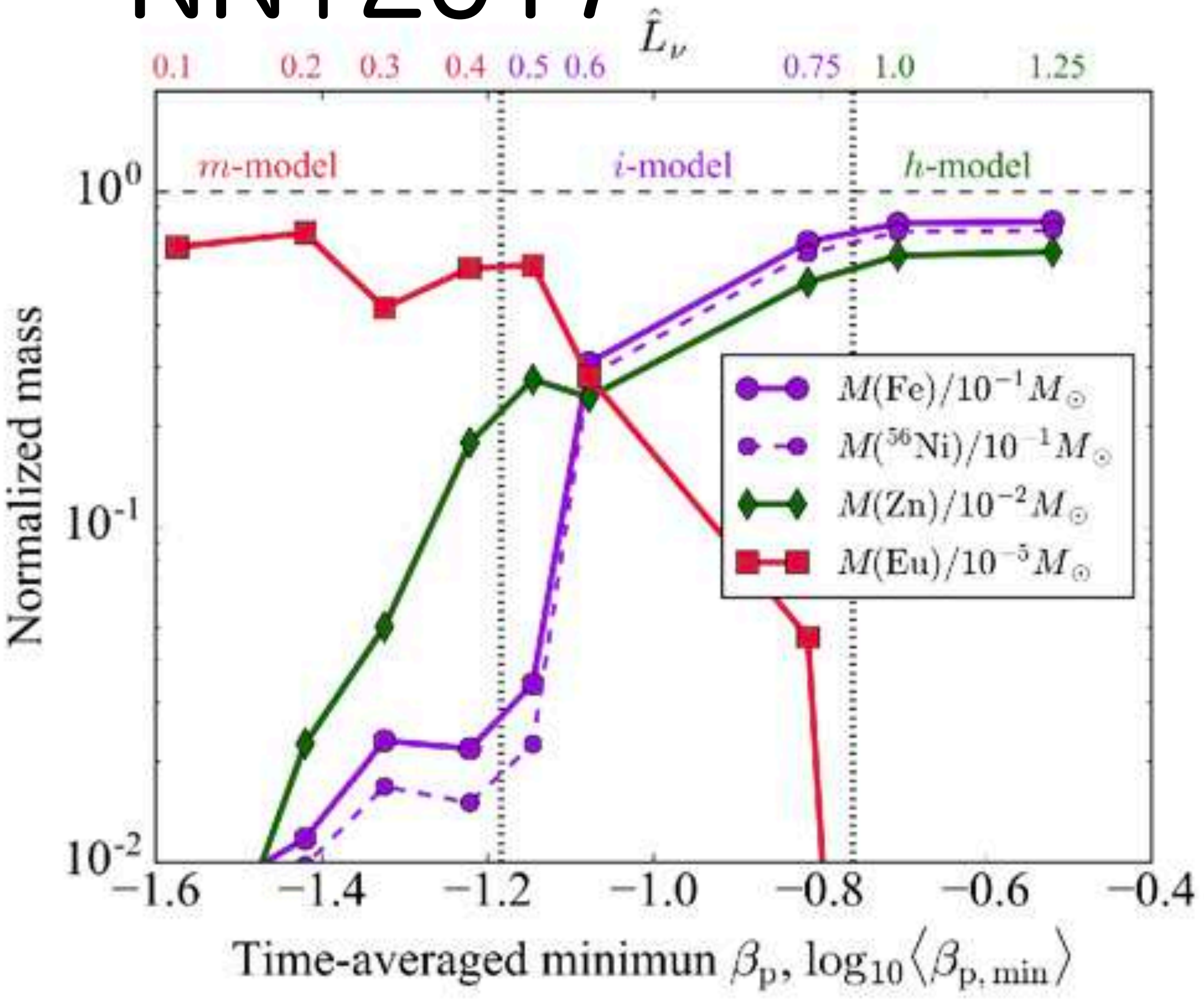


light curves



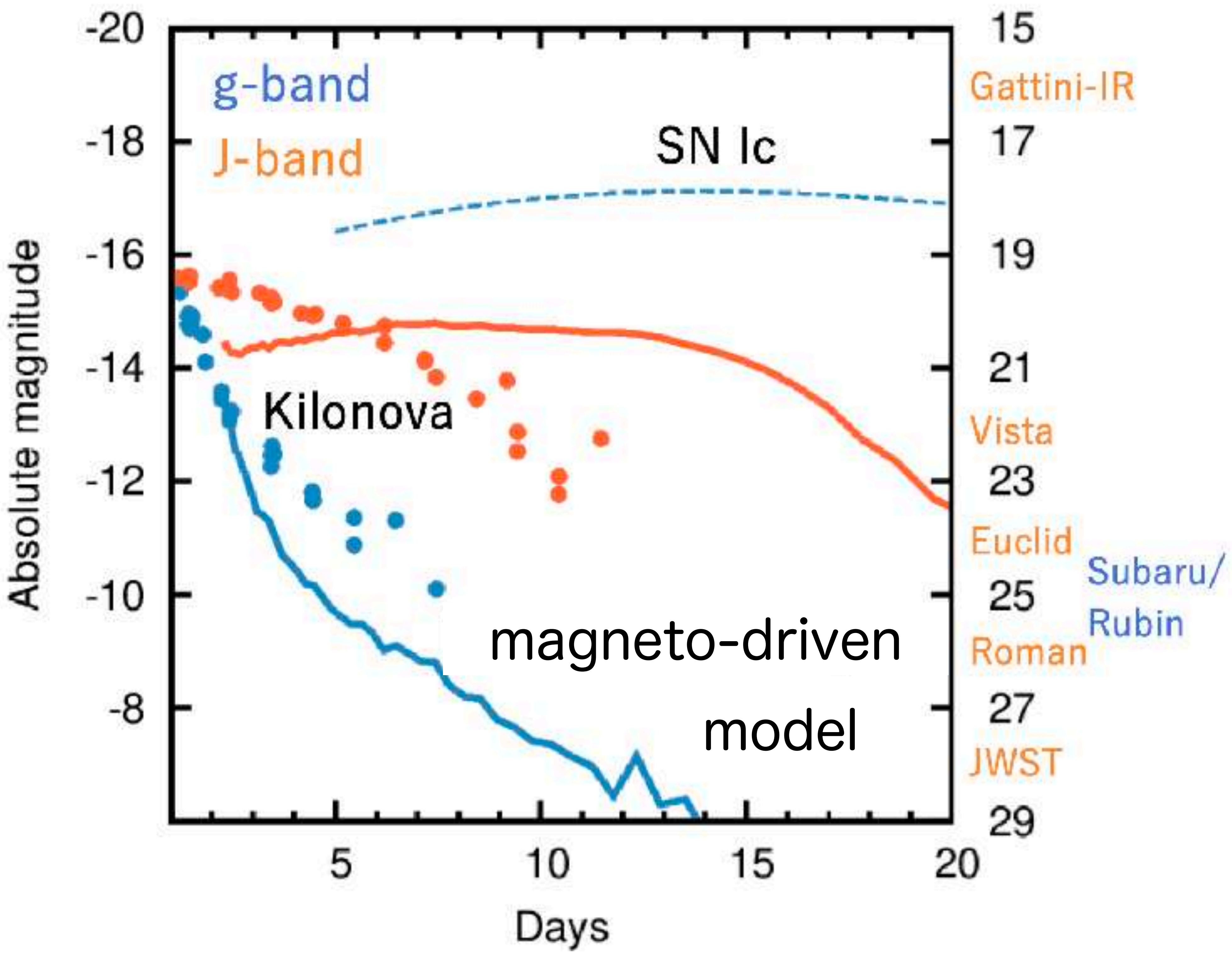
Identification in SN observations?

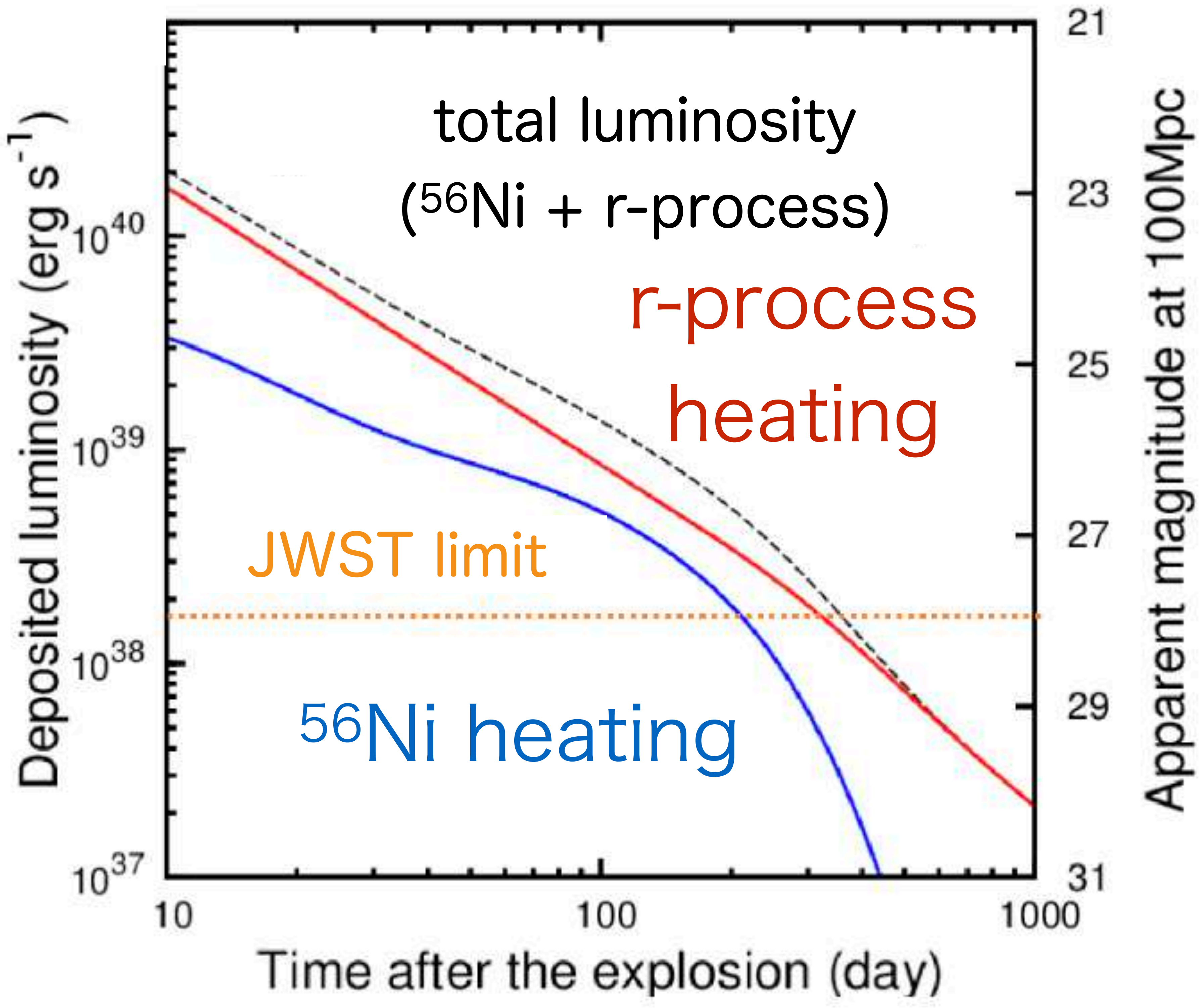
NN+2017



- NN+2017 suggests r-process-rich + ^{56}Ni poor ejecta
  - may occur if kinetic-driven (less heat-driven) jet expansion?
- We expect a significant r-process-decay heating (relative to ^{56}Ni)
  - ^{56}Ni heating $\propto \exp(-t/\tau)$: $M(^{56}\mathrm{Ni})1.1\times10^{-4}M_\odot$
  - r-process heating $\propto t^{-1.3}$: $M(\mathrm{r\ proc})1.1\times10^{-2}M_\odot$

Hasegawa, Tanaka, NN+, in prep.

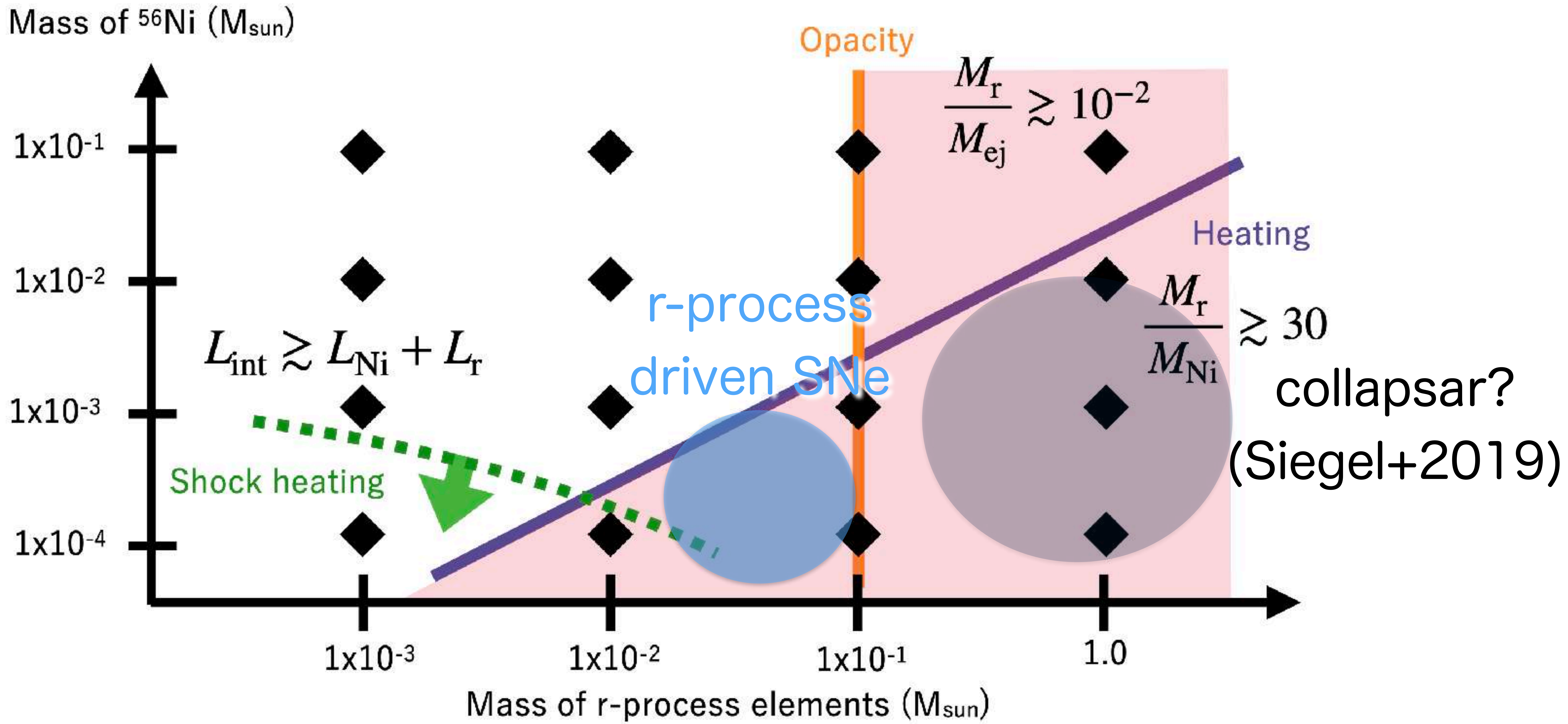




The overall feature: r-process vs ^{56}Ni

r-process is significant as

- opacity source if $M_r/M_{ejecta} > 10^{-2}$ → fainter and redder
- heating source if $M_r/M_{56Ni} > 30$ → than ^{56}Ni heating



3. r-process in neutron-star mergers

- only introducing our recent fission studies
- Tanaka, NN+(2023), Phys. Rev. C 108 054607
- See also the poster by Shoya Tanaka !


the NS merger and "kilonova"
credit NAOJ
SN
explosion
Neutron star
1. binary NSs
3. approach w/
GW emission
3. Merger of NS
& GW burst
3. approach w/
GW emission
4. r-process nucleosynthesis
radio active decays
of r-process elements

Nuclear fission in r-process nucleosynthesis

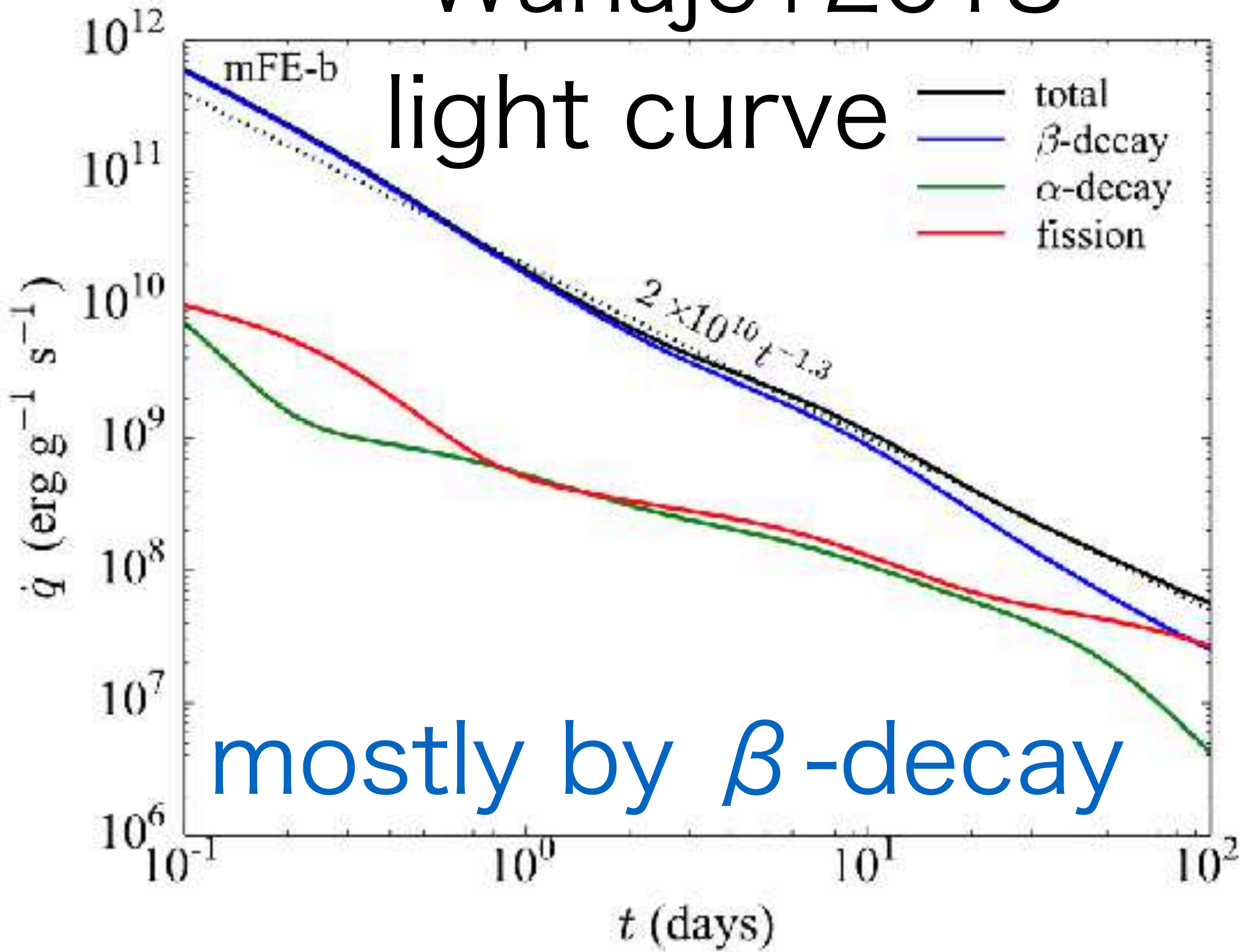
r-process → fission : termination, heating source of "kilonovae"
fission → r-process : unique natural source, beyond accelerator experiments

NS merger (kilonova)

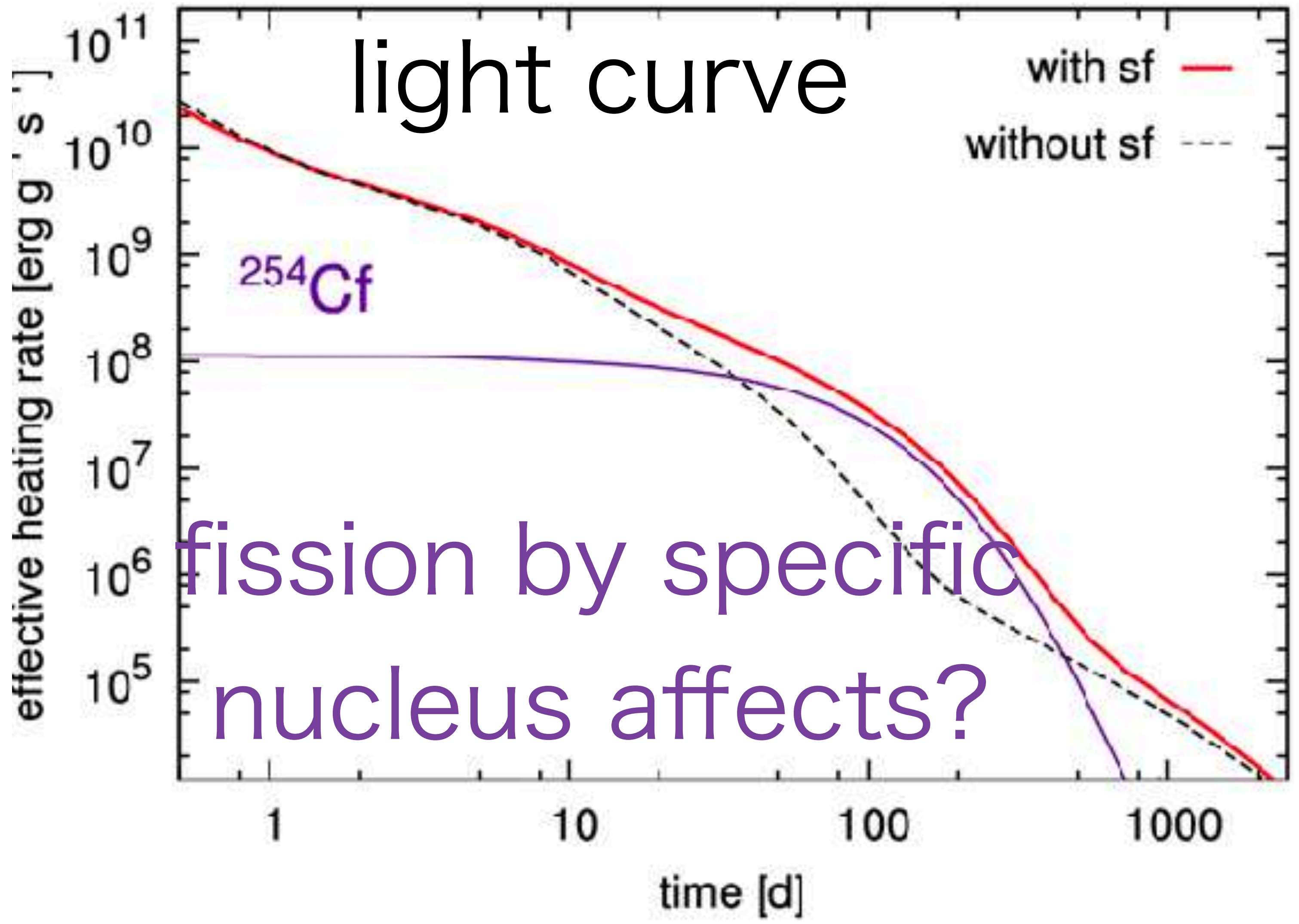
traditional NS merger calculations → too strong r-process
this problem was solved in modern simulations
e.g., Wanajo+NN+(2014)

strong fission recycle

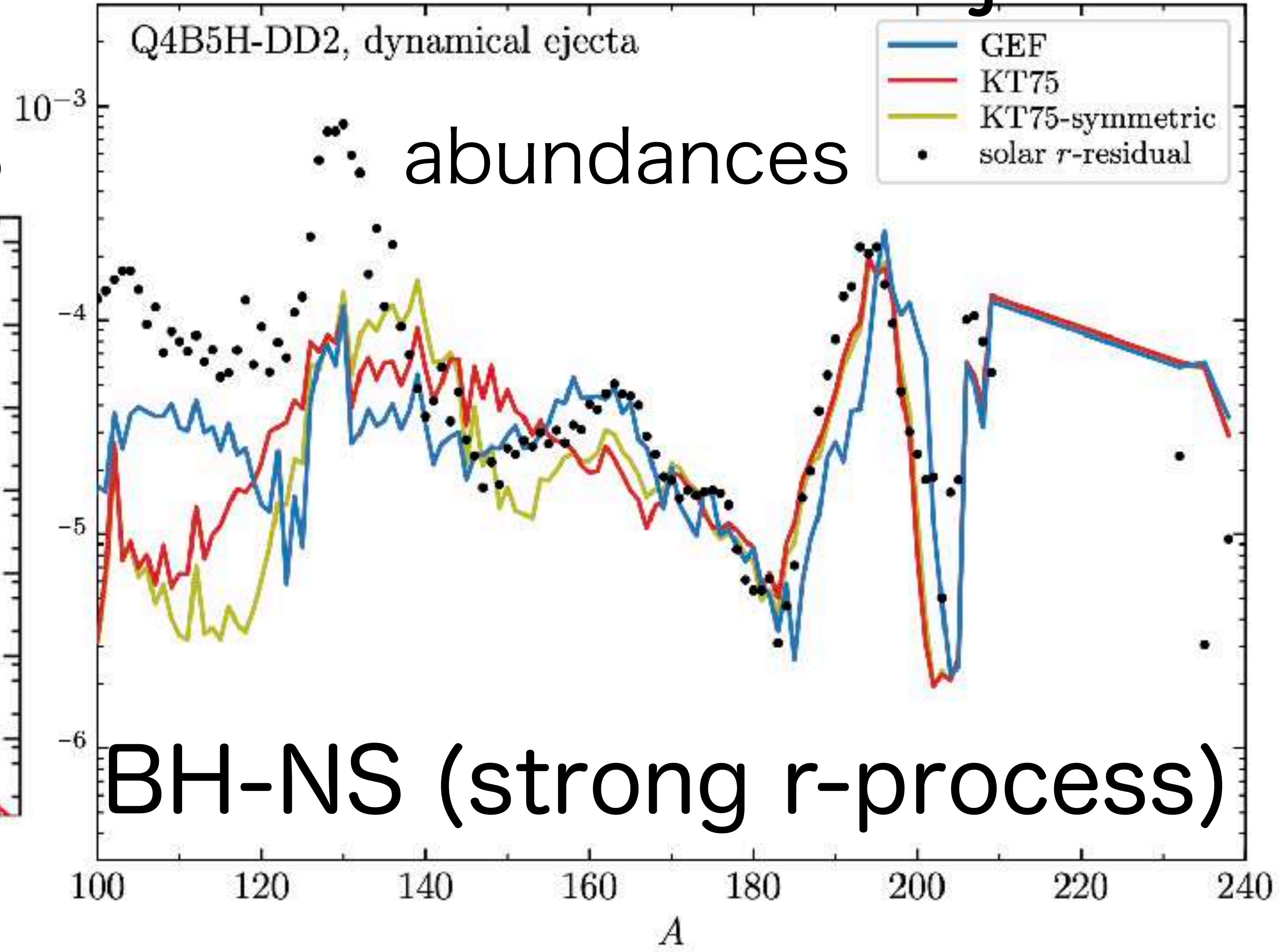
Wanajo+2018



Zhu+2018



Wanajo+2023



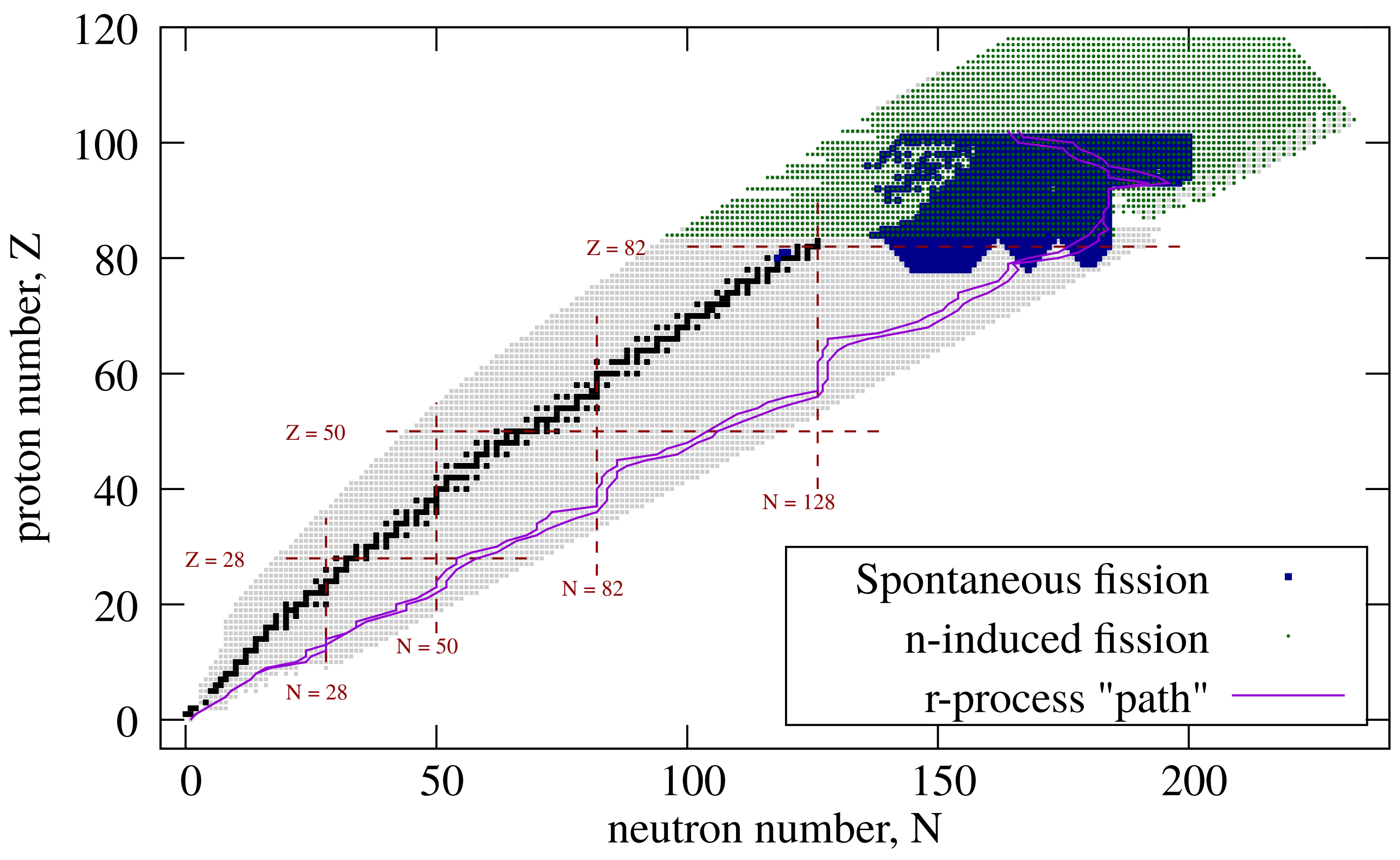
Theoretical fission yield distribution of n-rich nuclei

fission distribution by Langevin calculations

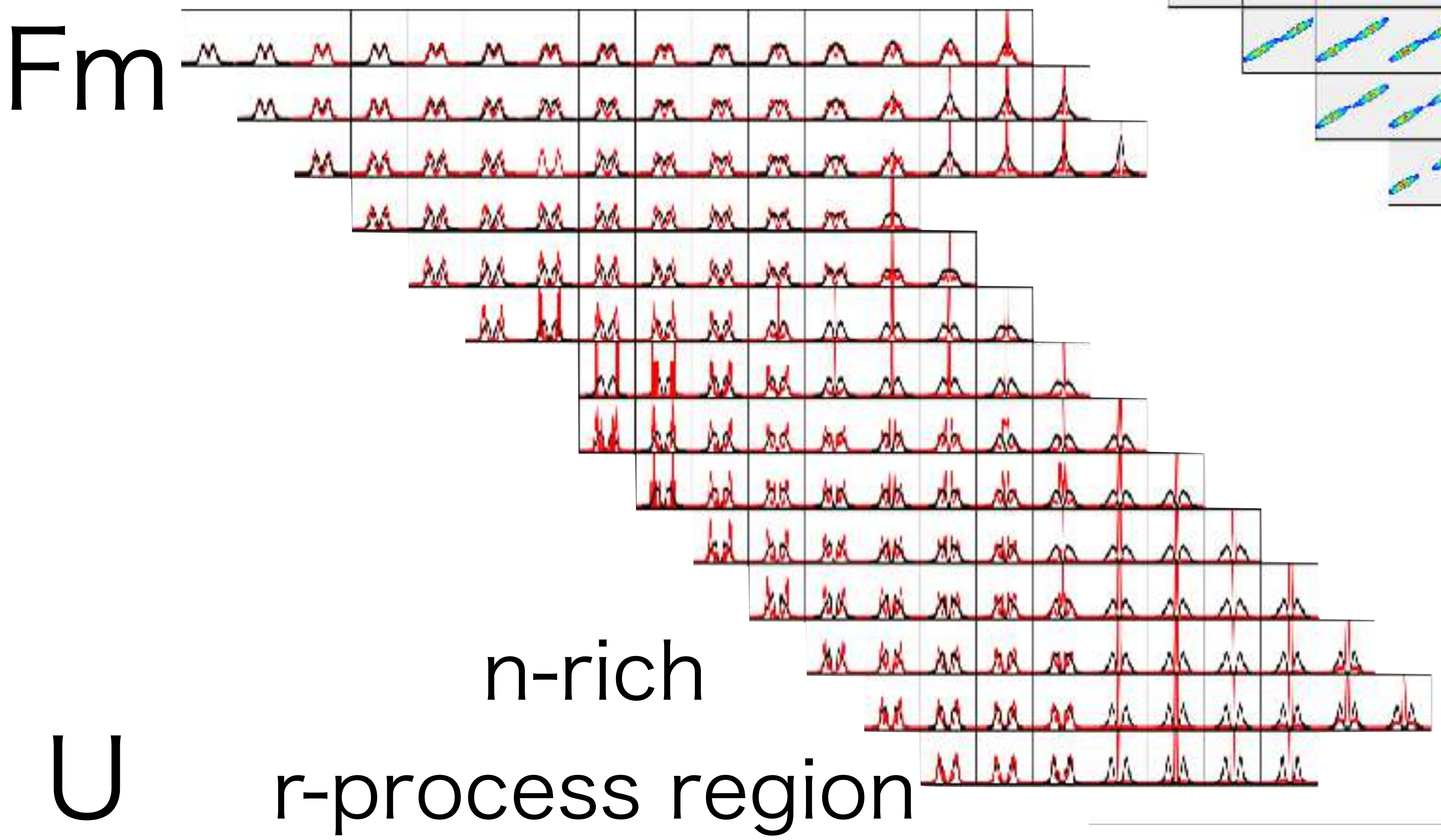
KUDAF database (in prep.)

(Kindai University DynAmical Fission yields)

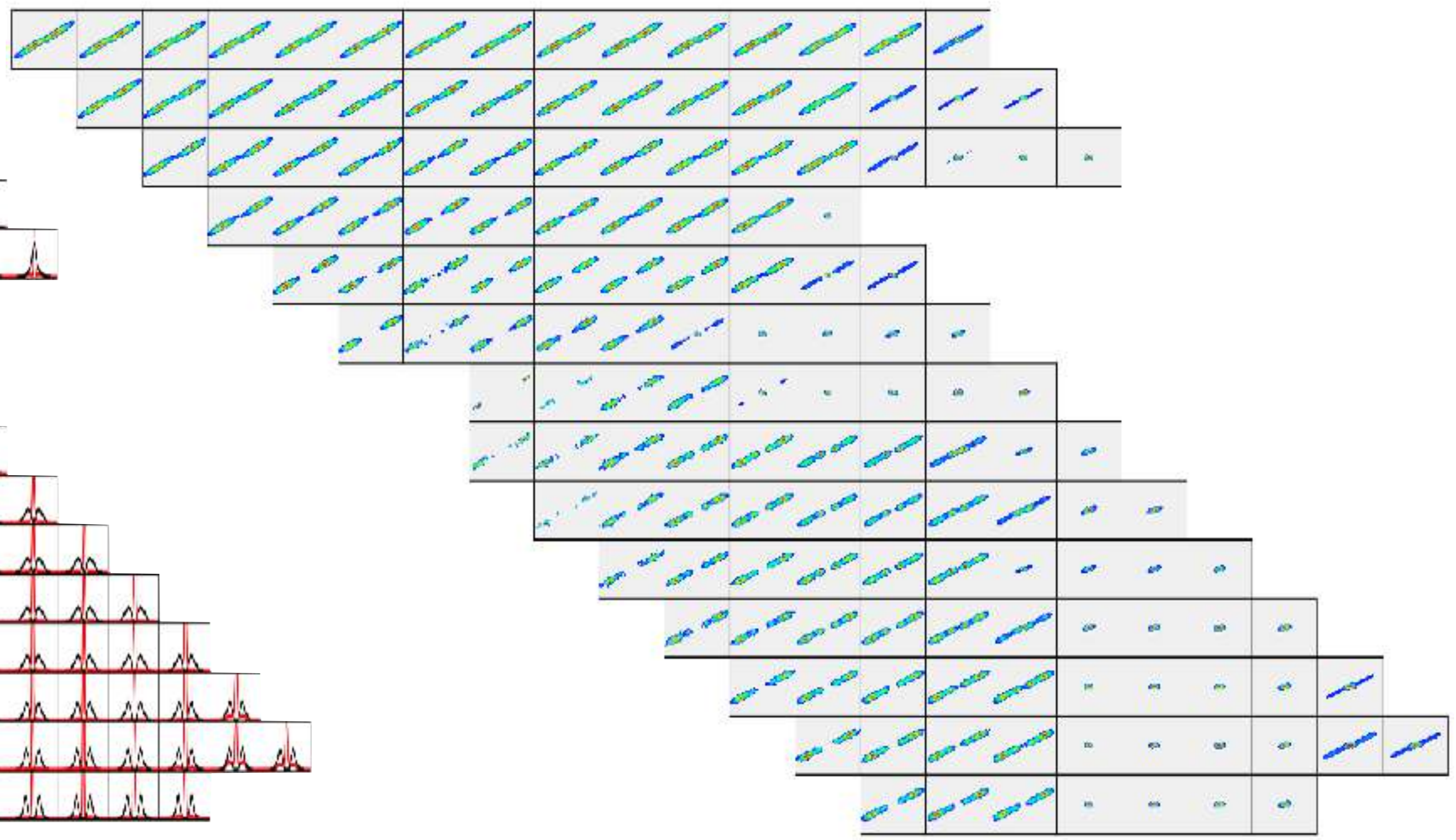
NN and Tanaka (RIKEN), Aritomo (Kindai U)



KUDAF vs GEF



Fission distribution with UCD



calculated by I.Nishimura, Takagi, Miyasakai

KiLM code : 3D two-center shell model

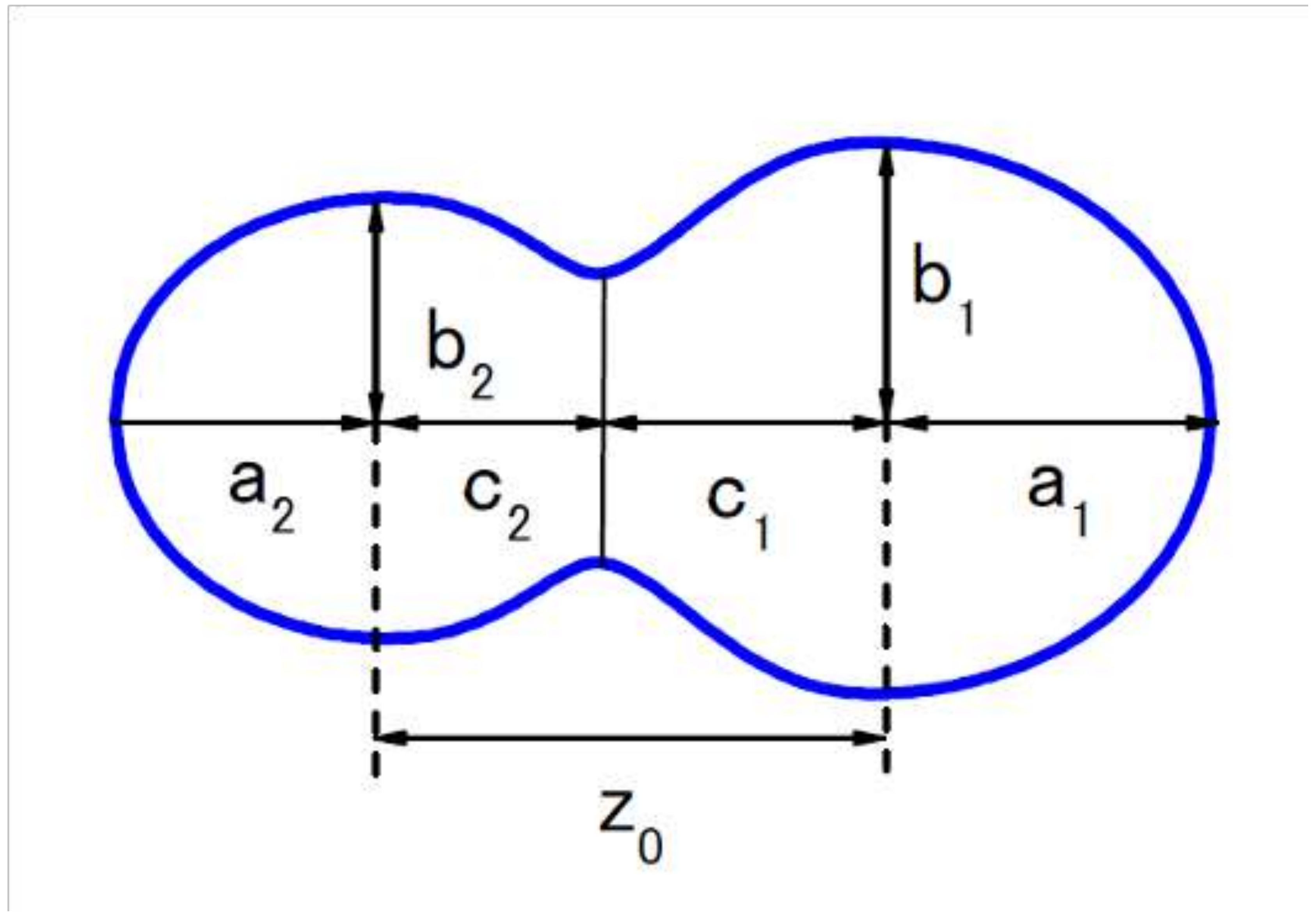
Two-center parametrization: $q\{z, \delta, \alpha\}$

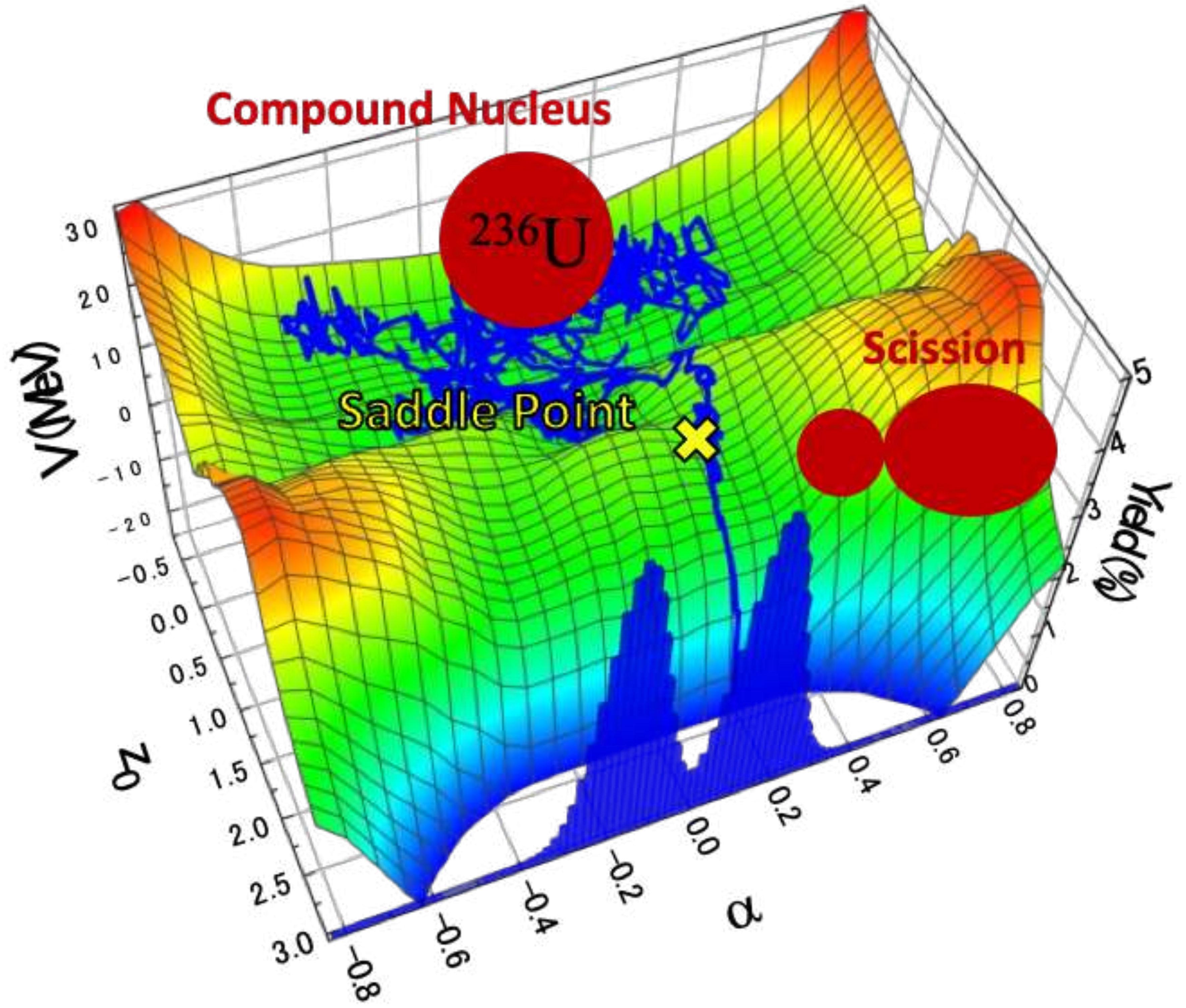
(Maruhn & Greiner 1972)

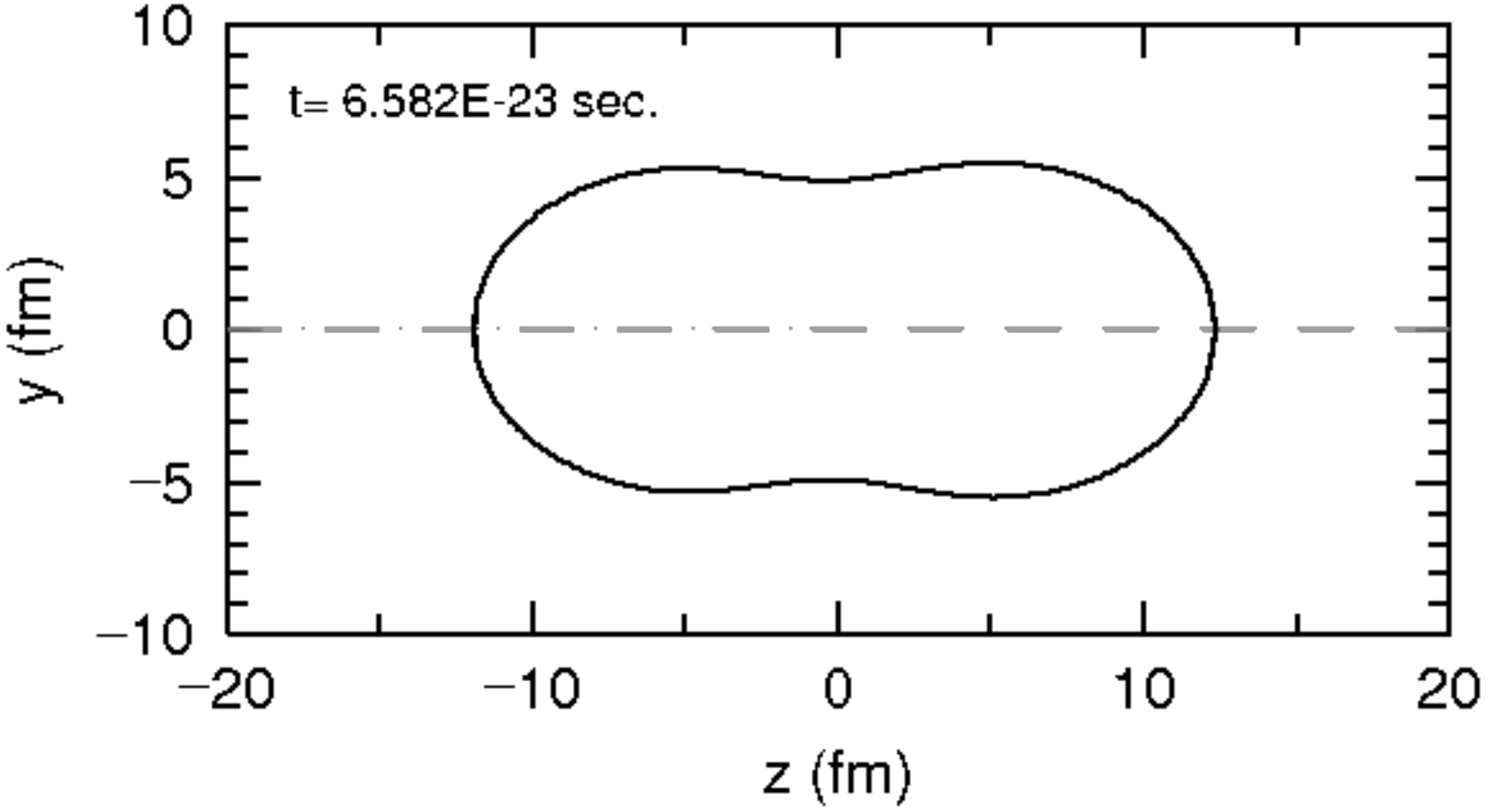
z : center of mass distance

δ : deformation

α : mass asymmetry







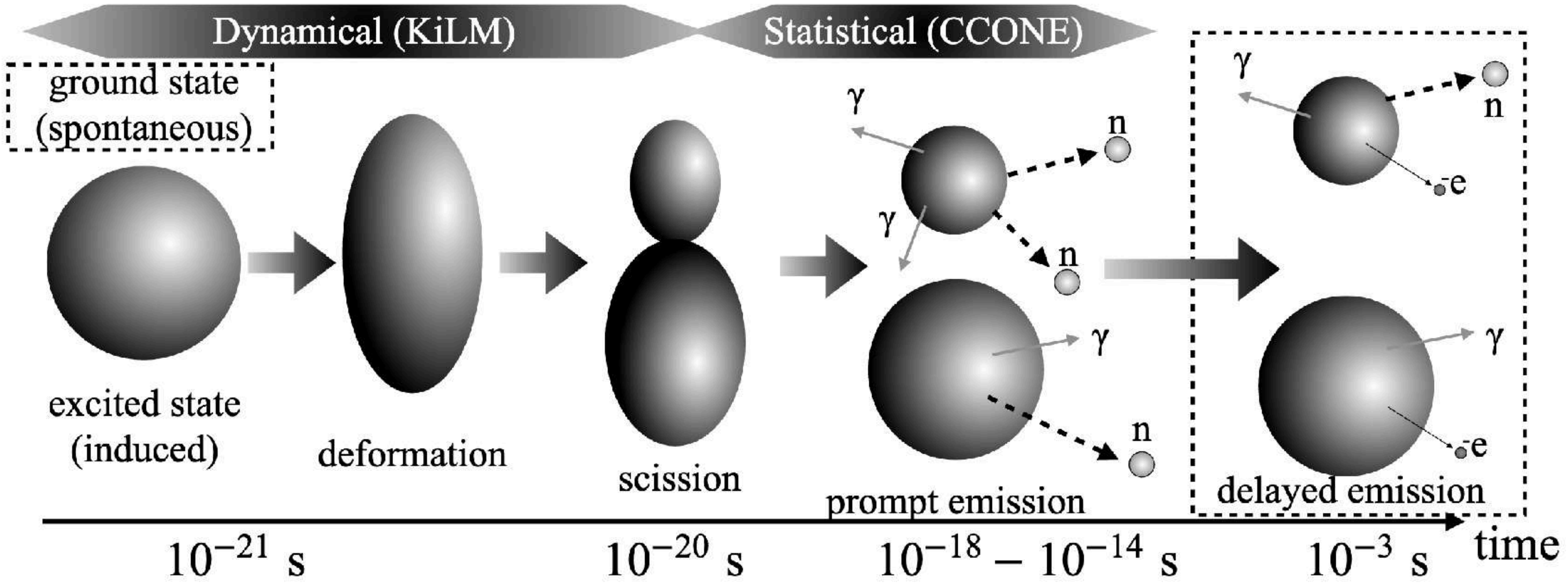
A hybrid method: dynamical + statical models

toward complete fission yields for r-process

theoretical data ↔ astrophysical nucleosynthesis

fission process has several experimental data → comparison

Tanaka, NN+2023

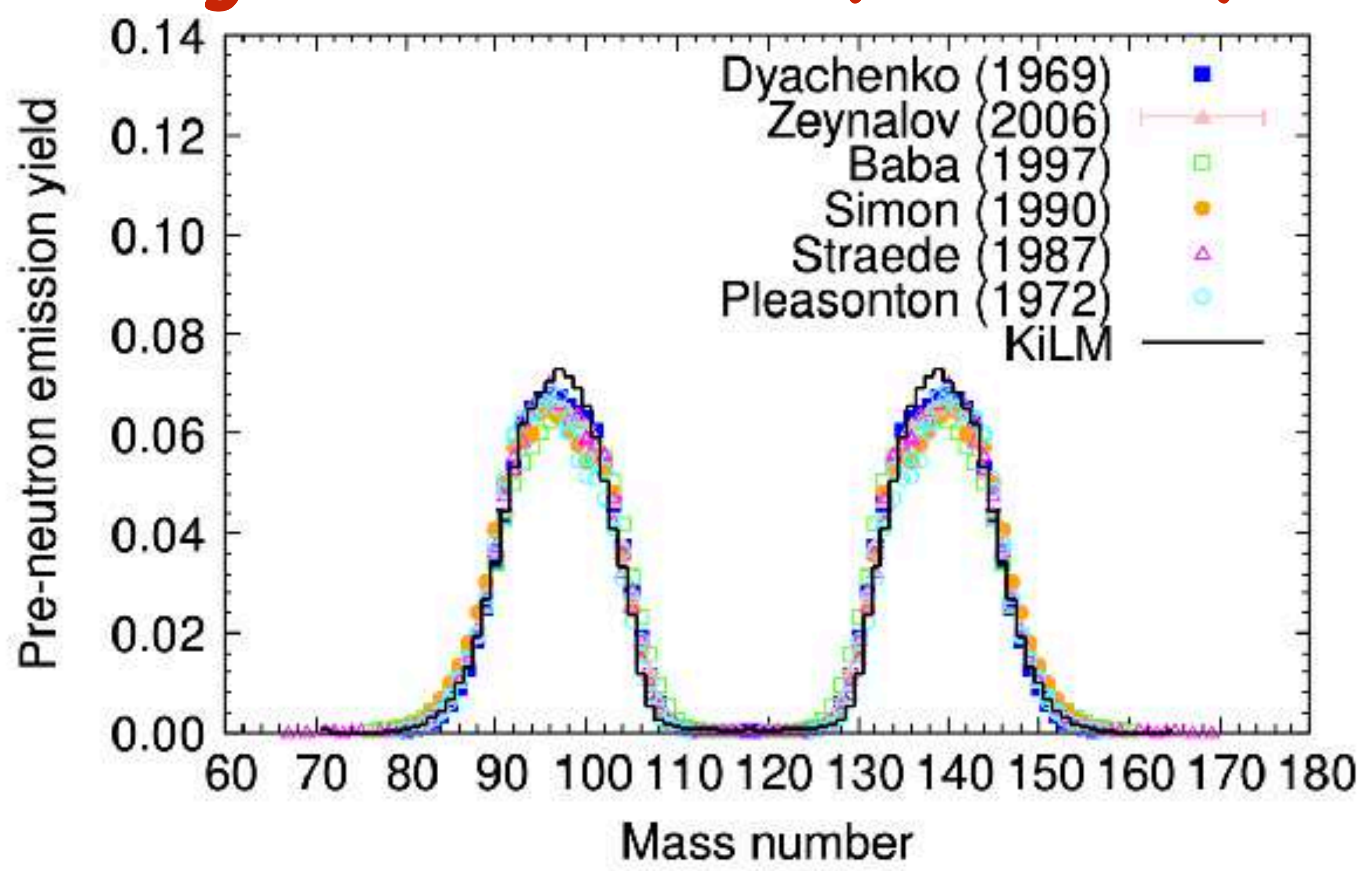


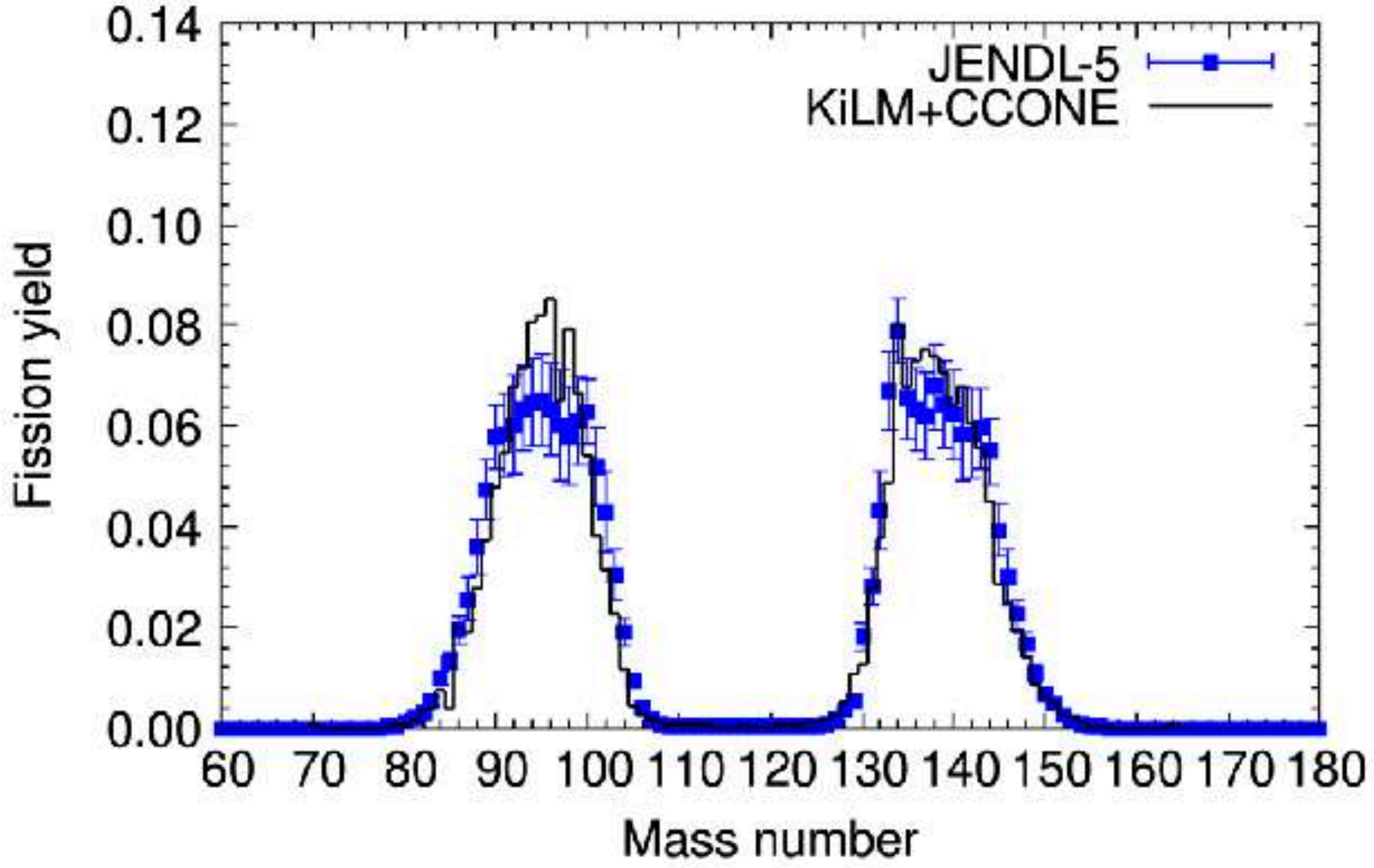
^{236}U : fission + n emission

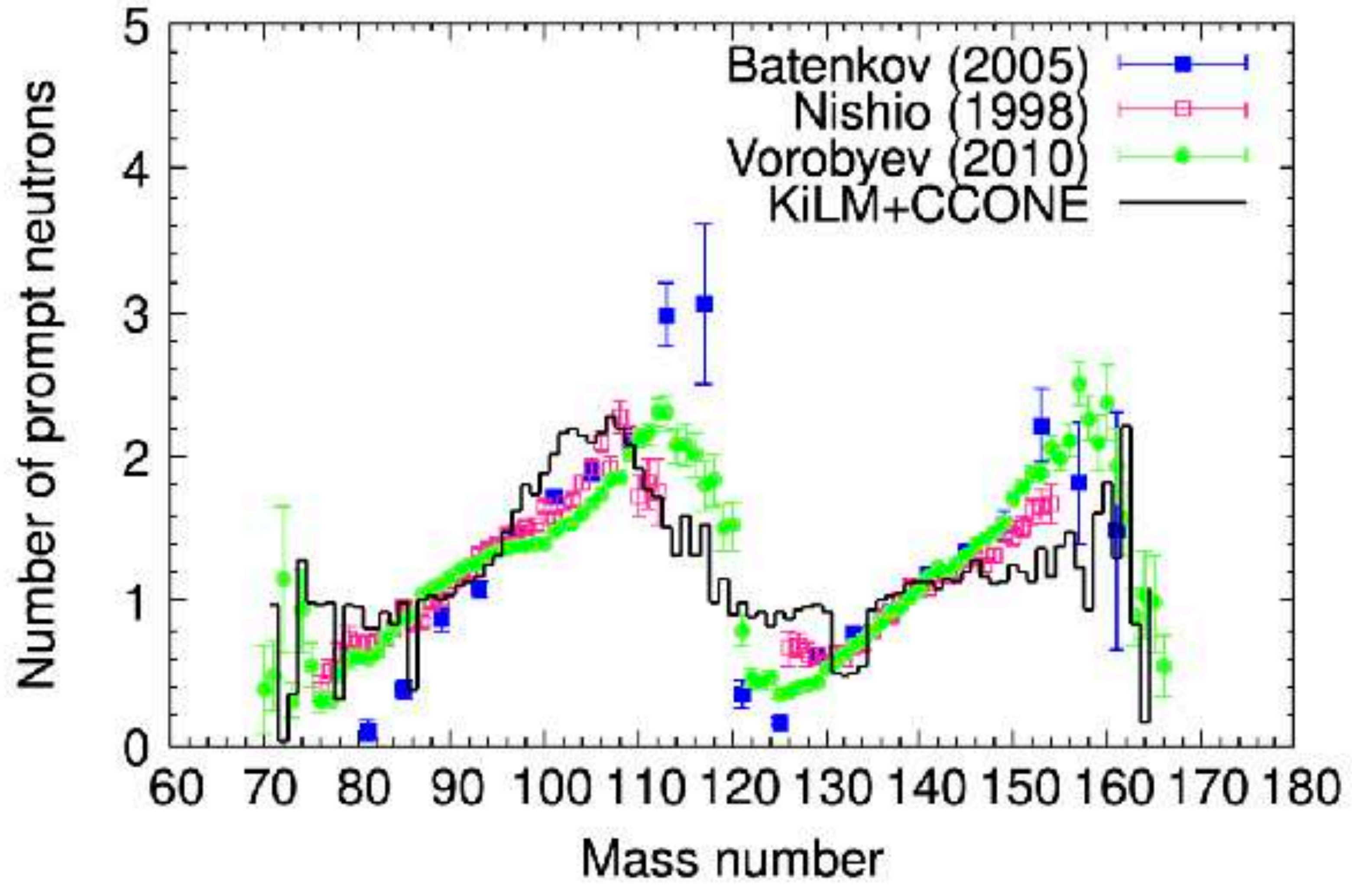
^{236}U (E^*=9 MeV)

Tanaka, NN+2023

dynamical (KiLM)





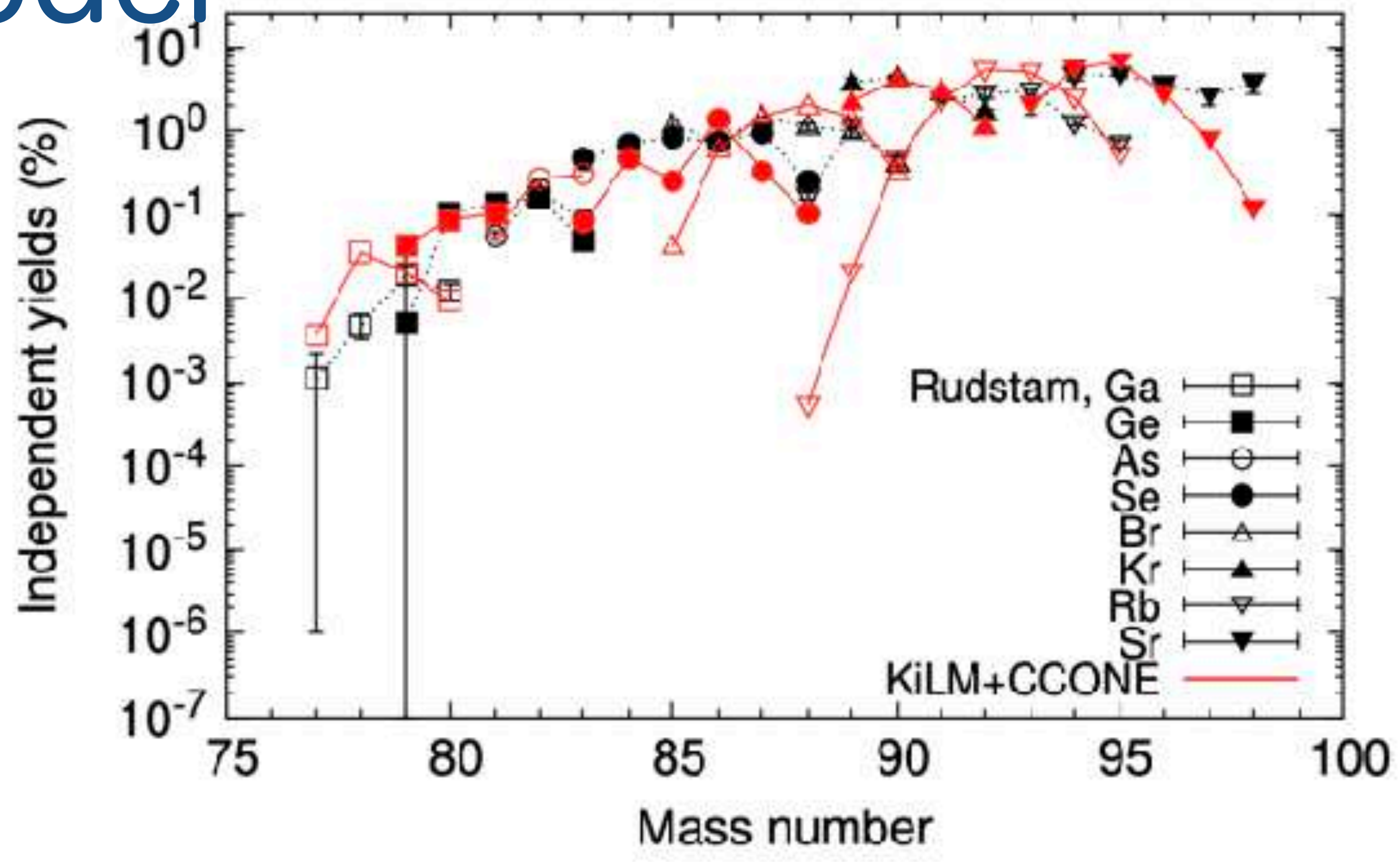


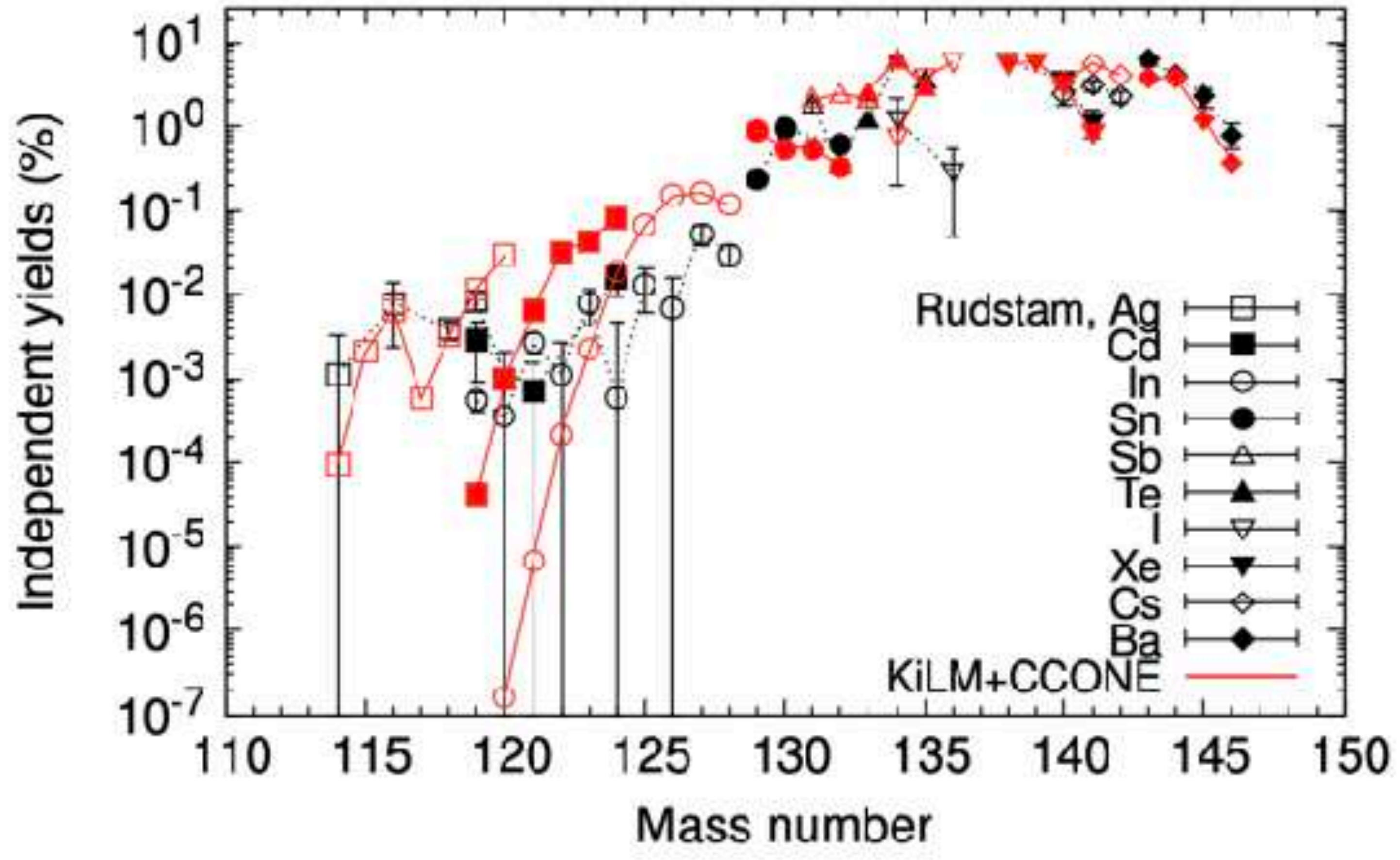
multiplicity $\langle n \rangle = 2.574$ (experiment : 2.413)

statistical model (CCONE)

identify isotopes with UCD

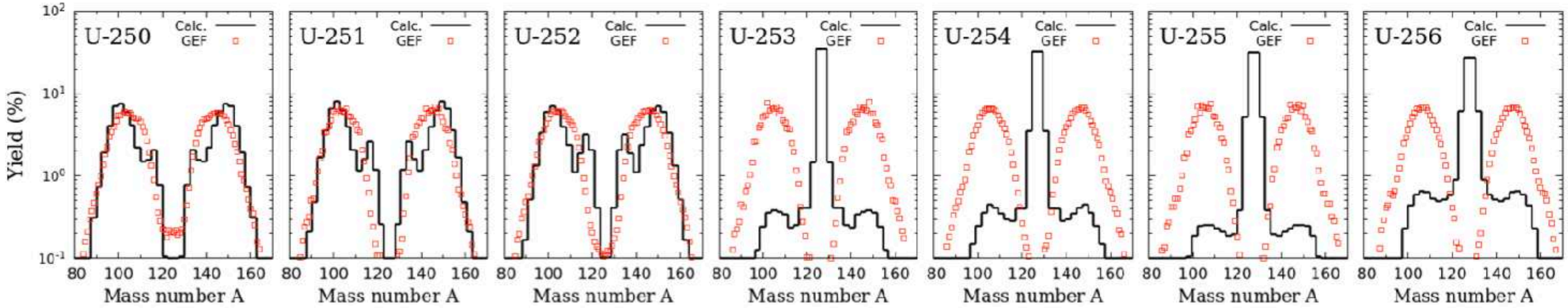
3D Langevin code "KiLM" code (Kindai U Langevin Model)





Nuclear fission of neutron-rich nuclei

GEF (red) vs. KiLM (dynamical model) (black)



→ affects r-process

Tanaka, NN+(2023)

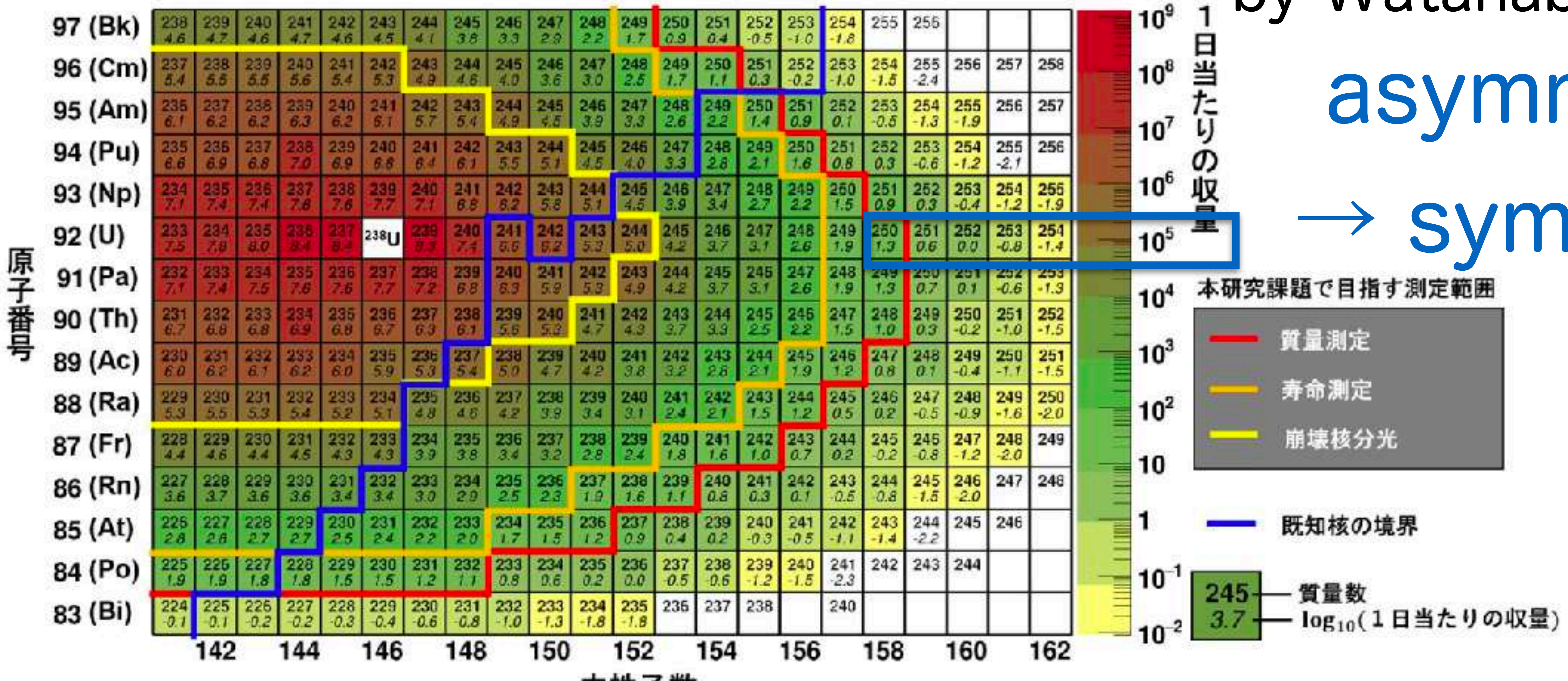
<u>future experiments (KISS II by KEK & RIKEN)</u>

toward neutron-rich U

by Watanabe（KEK)

asymmetric

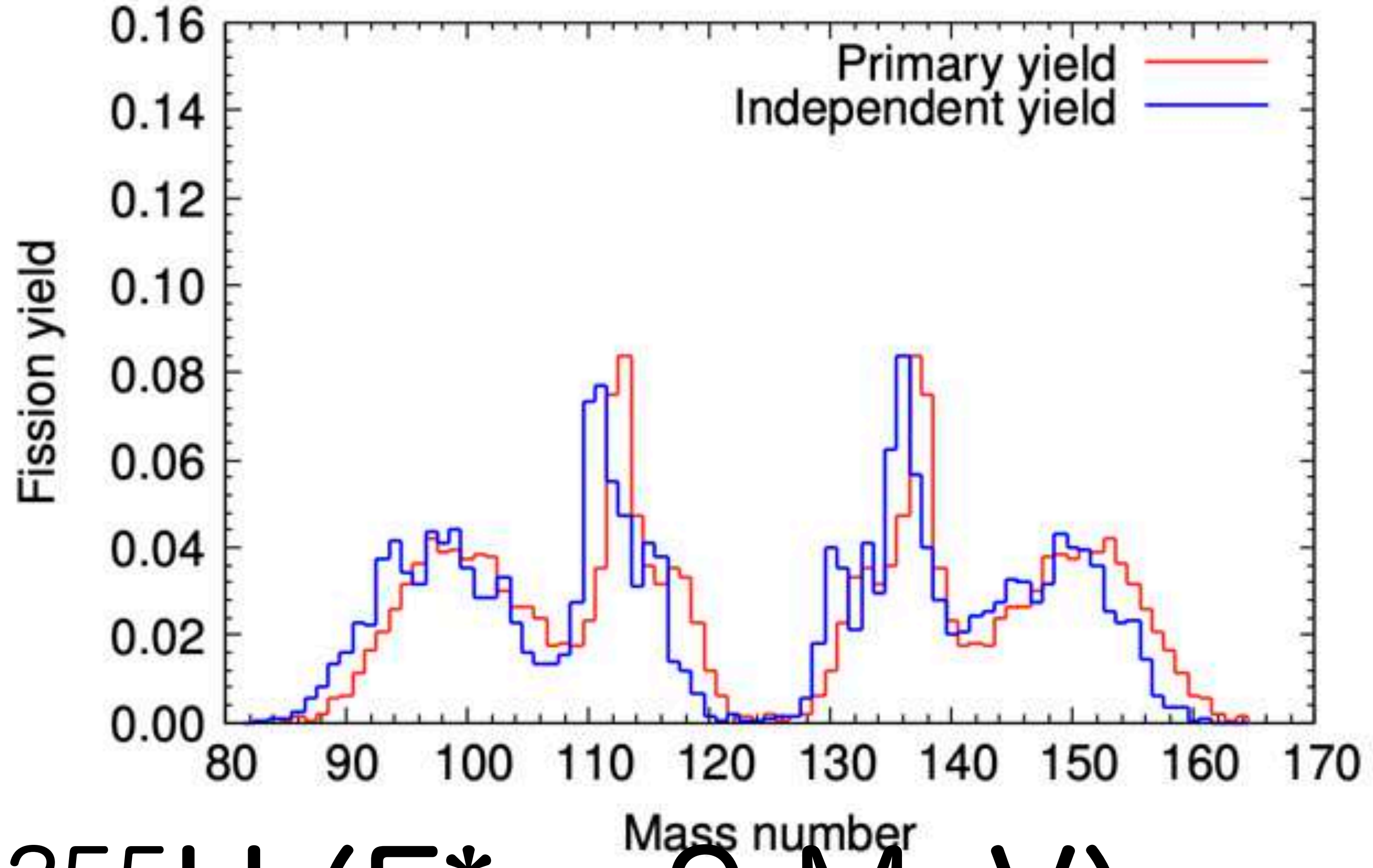
→ symmetric



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

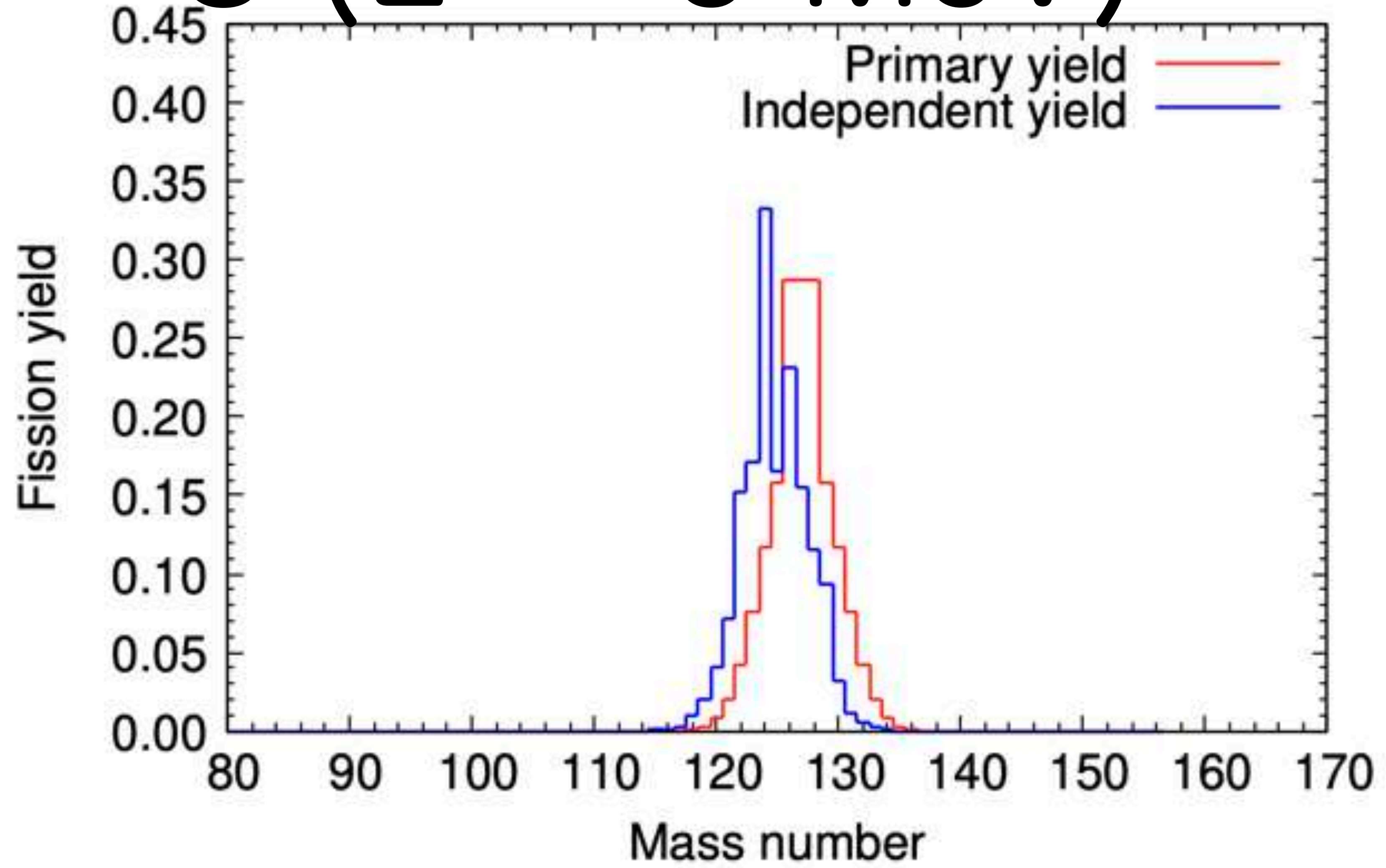
^{250}U (E^* = 9 MeV)

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



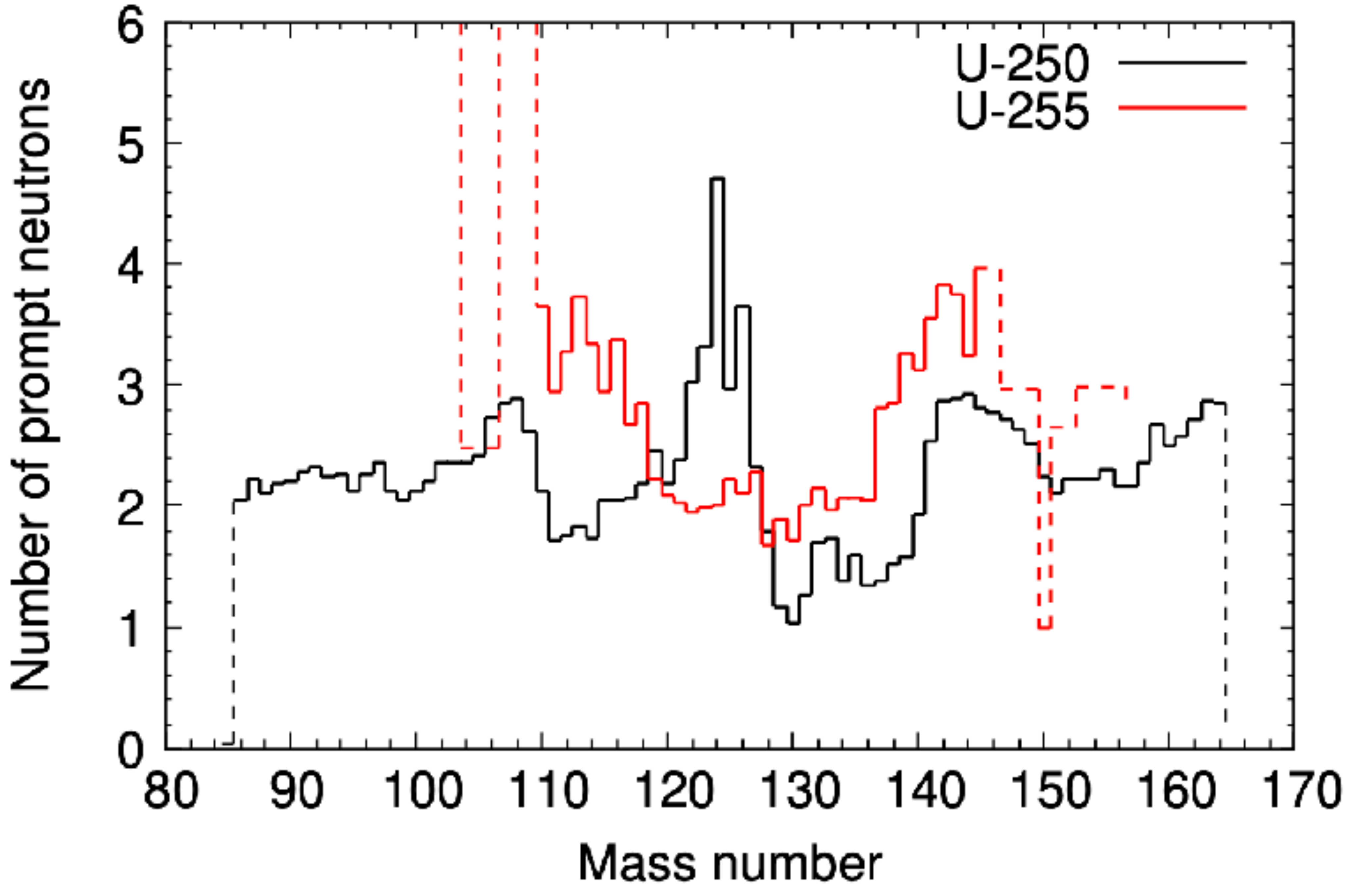
$\langle n \rangle = 4.185$

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



$\langle n \rangle = 3.434$

number of n emission



Tanaka, NN+2023

Summary

1. νp-process in core-collapse supernovae

・improving reaction rates may reproduce the solar ^{92}Mo/^{94}Mo

・key reactions of νp-process for determining ^{92}Mo/^{94}Mo :

first priority: ^{92}Mo(p,g)^{93}Tc (second ^{93}Tc(p,g)^{94}Ru)

2. r-process in magneto-rotational SNe

・possible alternative site, but still hypothetical

・We found a parameter region where the r-process can be identified in future optical observations

3. r-process in neutron-star mergers

・ ^{236}U : we reproduces experiments

・applying n-rich U: the difference of asymmetric to symmetric fission has impacts on the number of emitted neutrons <n>