Progress of the r-process theory in the era of nuclear experiments and astronomical observations

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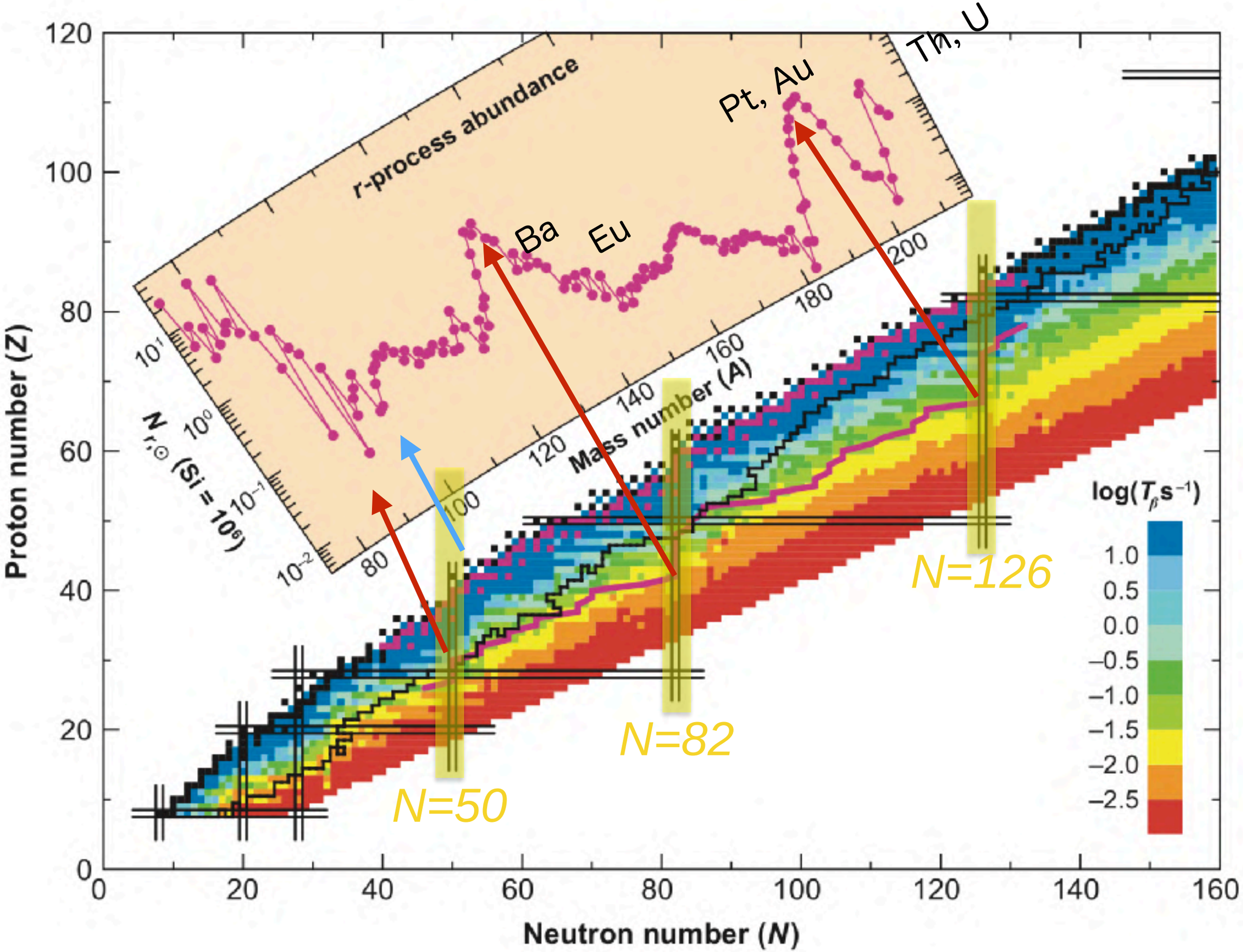
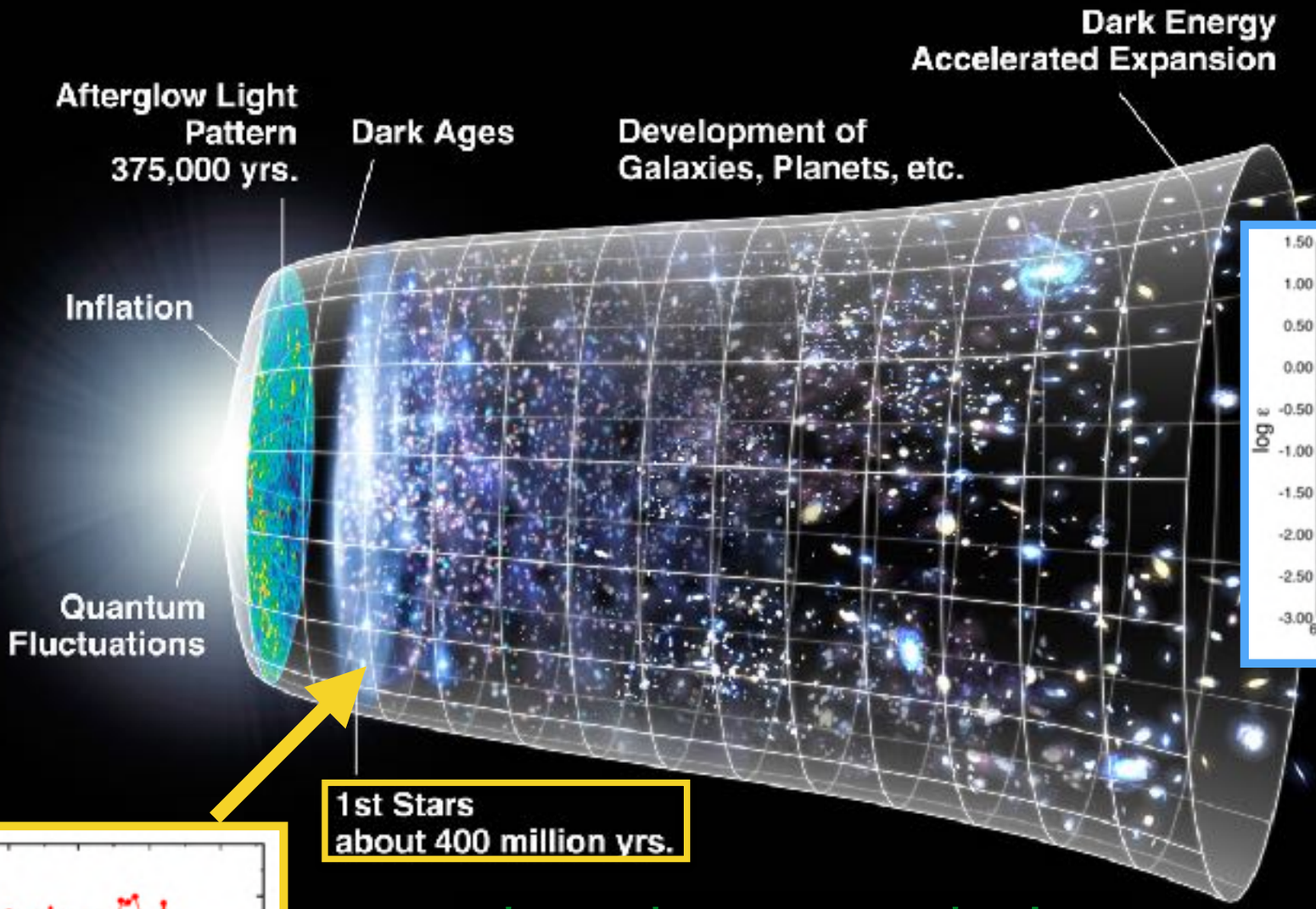
Astrophysical Big-bang, CPR, RIKEN

& Radioactive Isotope Physics, RNC, RIKEN

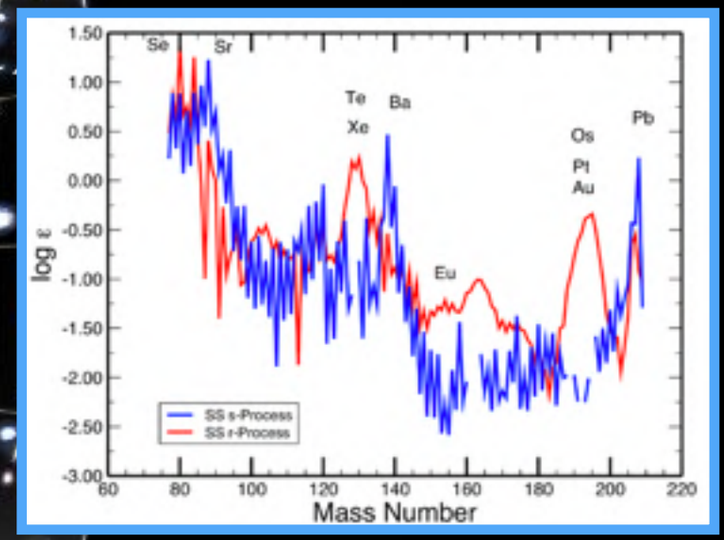
Nucleosynthesis beyond Iron



Evolution of r-process elements

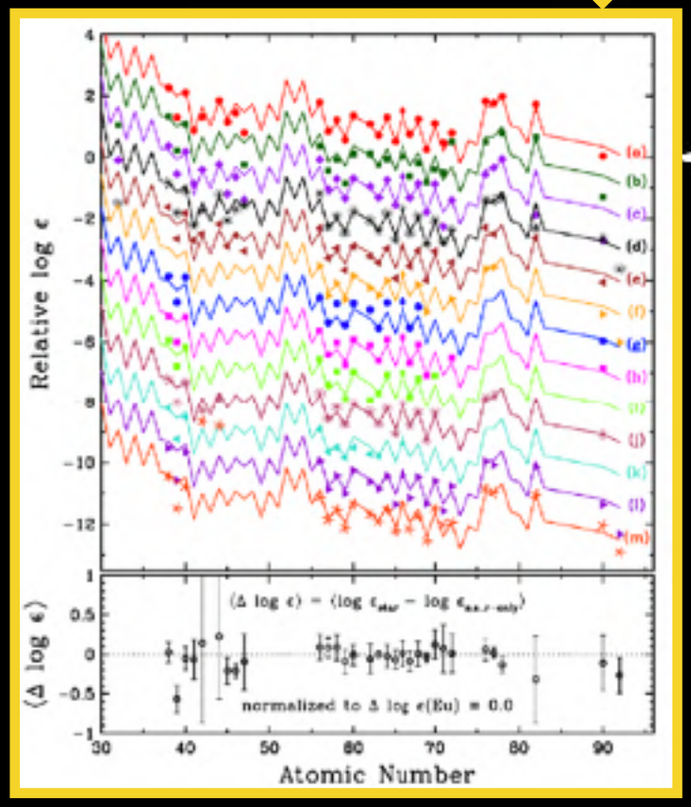


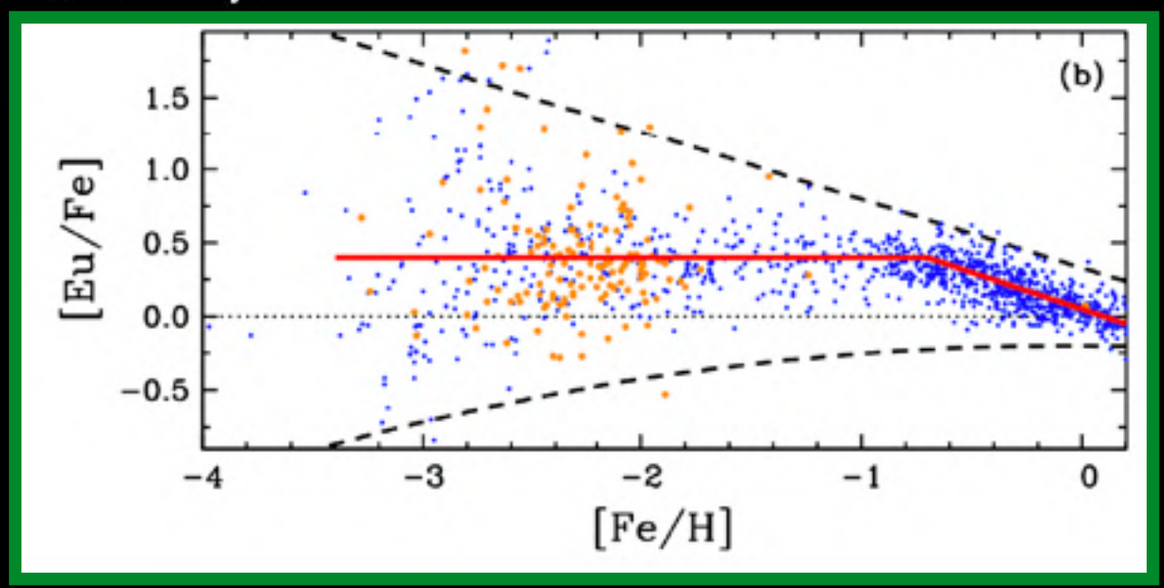
solar abundances



abundance evolution

13.77 billion years





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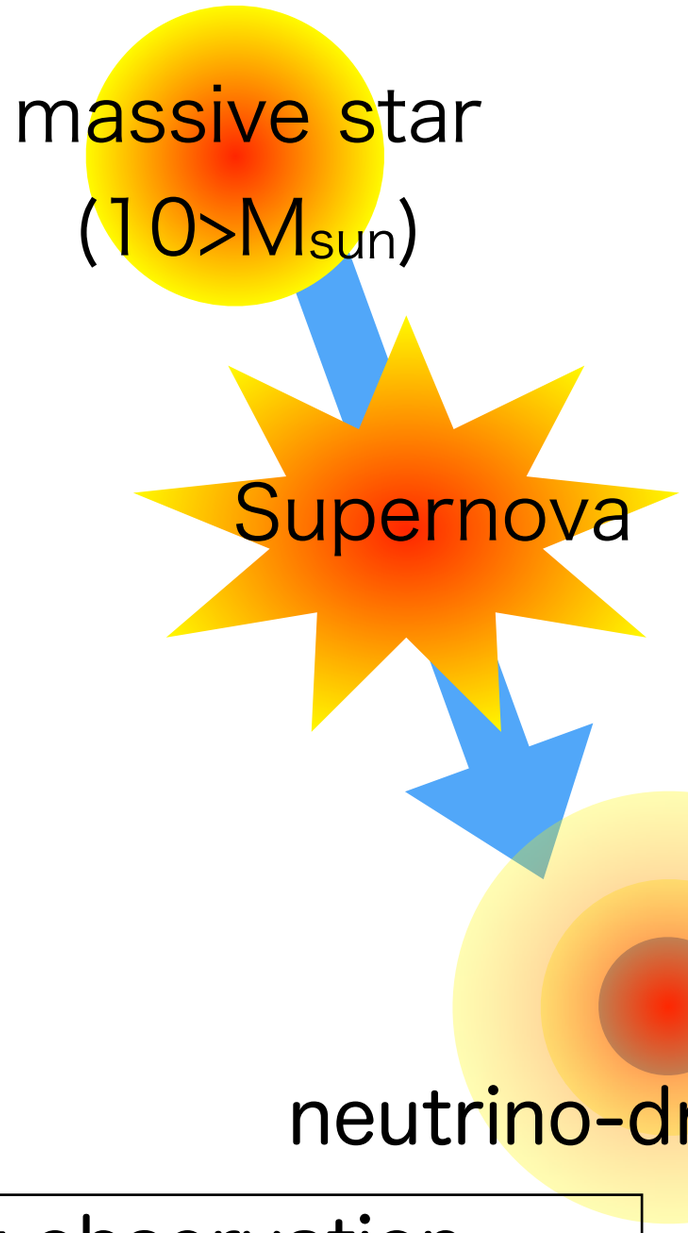
- **Summary**

PART 1:
Astrophysics

“Observation of the NS merger and impacts on the r-process studies”

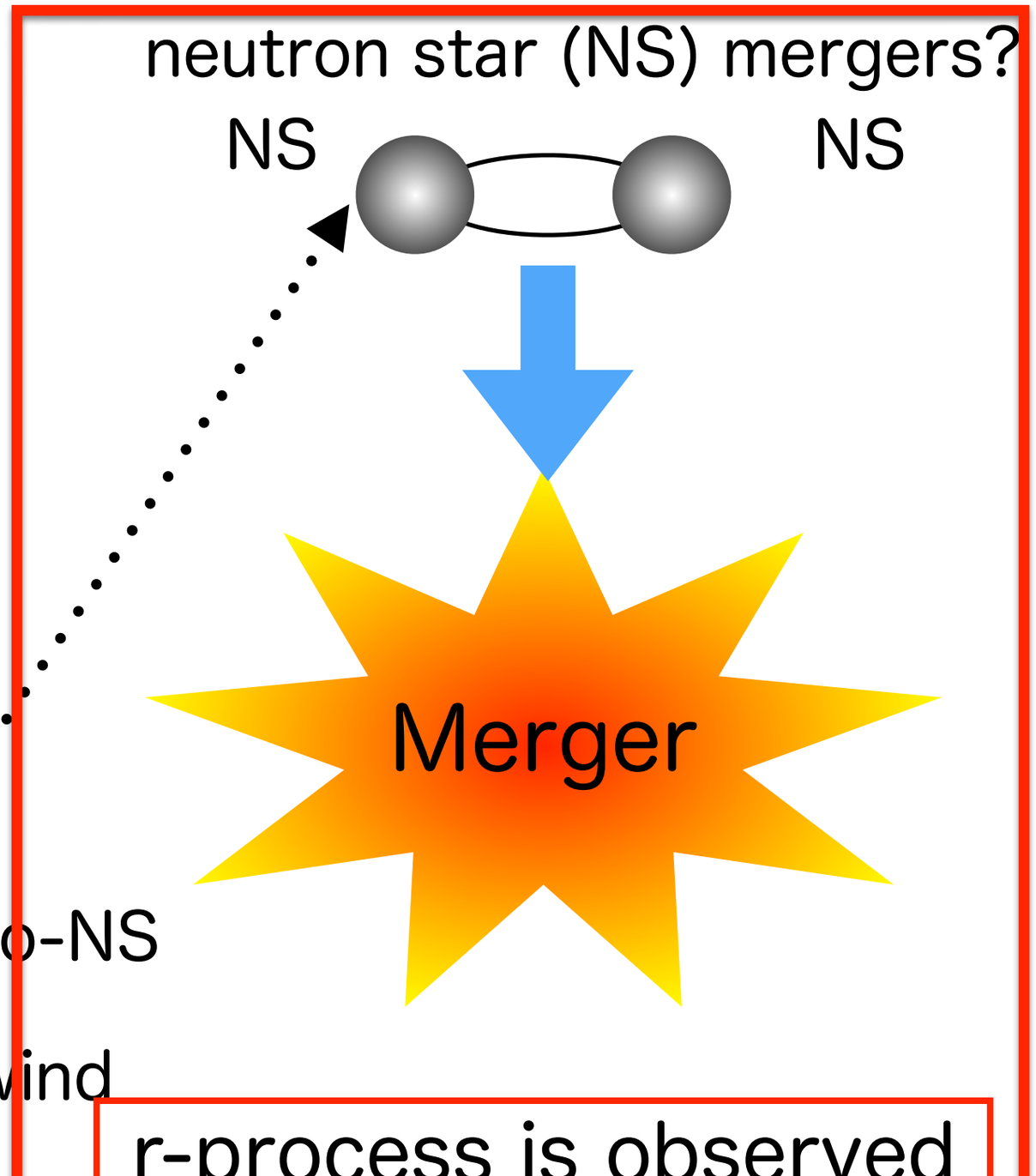
Astronomical site(s) of the r-process

Supernovae (cc-SNe)?



- no direct observation
- theoretical difficulty
  - (no very n-rich matter)

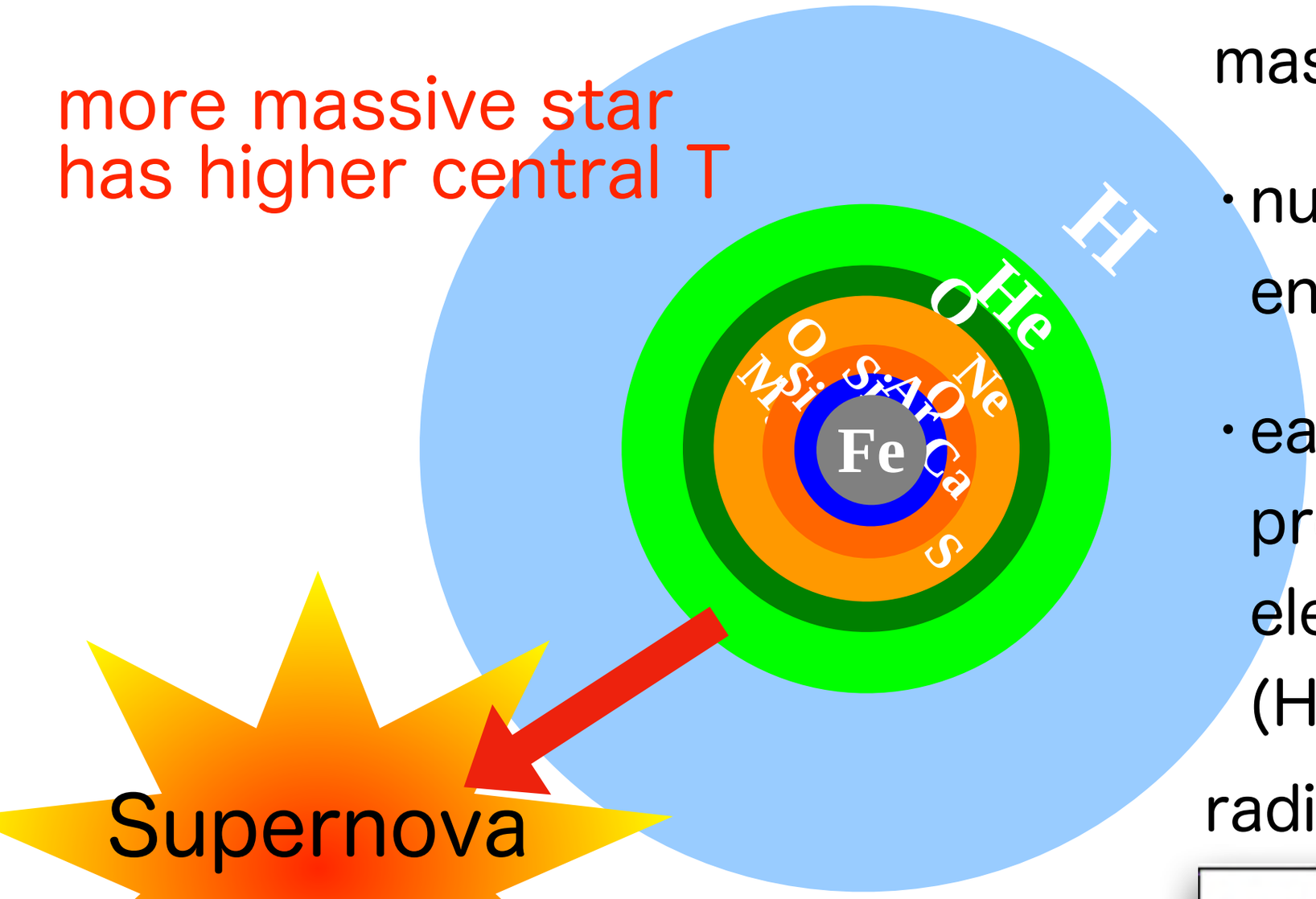
neutron star (NS) mergers?



r-process is observed
in Kilonova/Macronova
w/ GW170817

Core-collapse supernova

more massive star
has higher central T

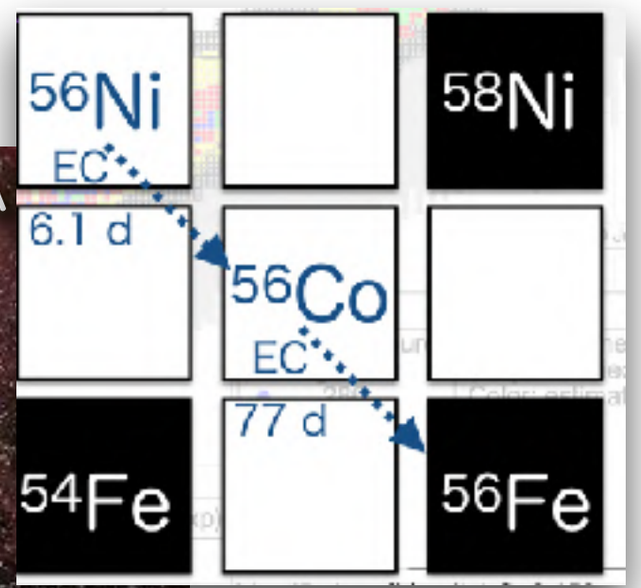


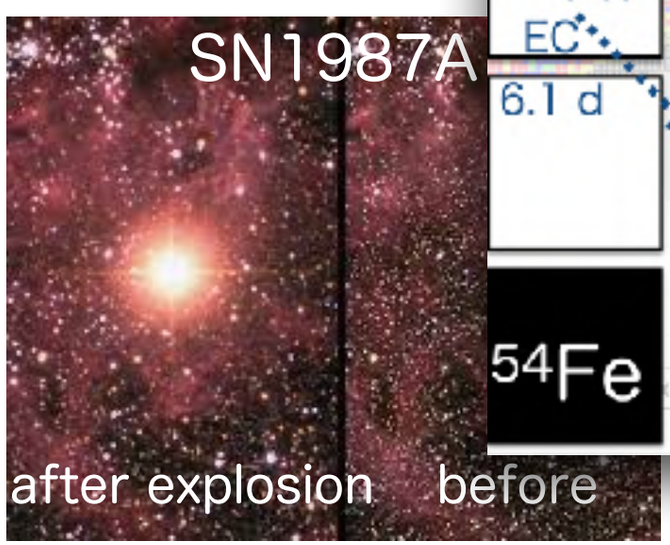
explosive nucleosynthesis
(radioactive iron-group nuclei)

massive stars (>10 M_{sun})

- nuclear reactions supply energy (brightness)
- each burning process produces heavier elements as “ashes”
  (H→He→C→O→ … →Fe)

radioactive decay



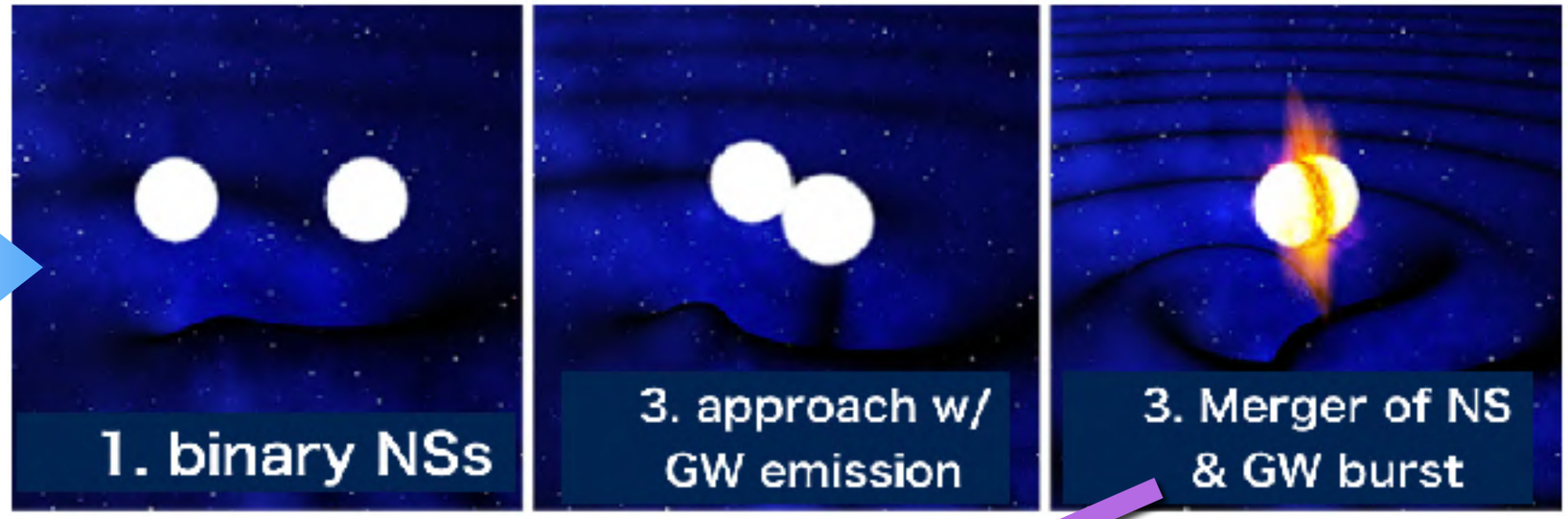


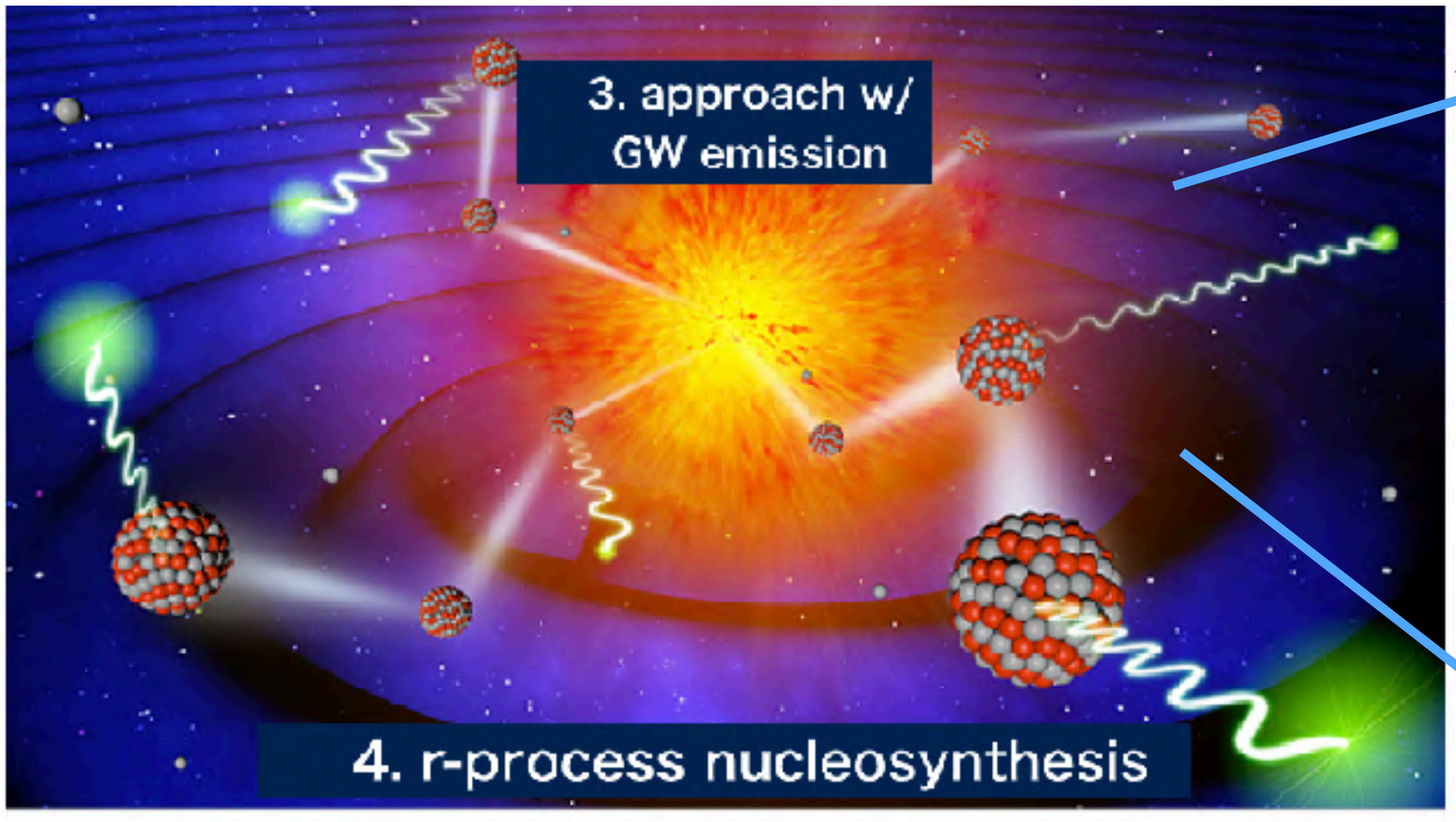
“Kilonova” with NS merger

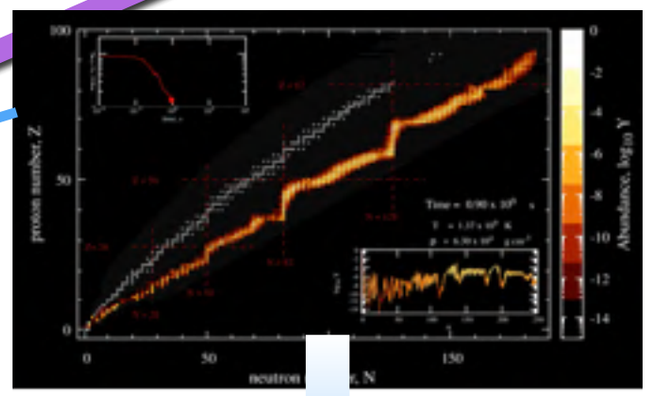
credit NAOJ

SN explosion

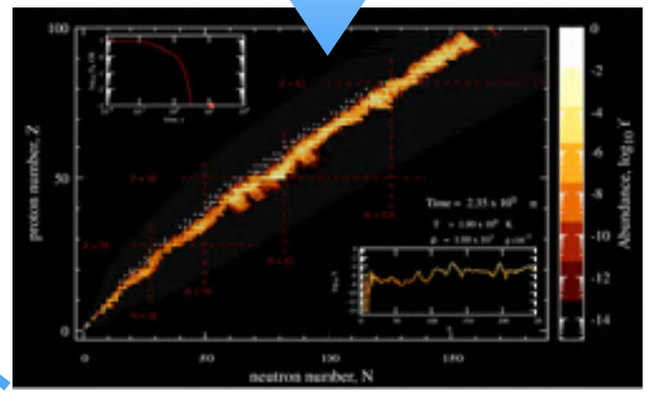
Neutron star







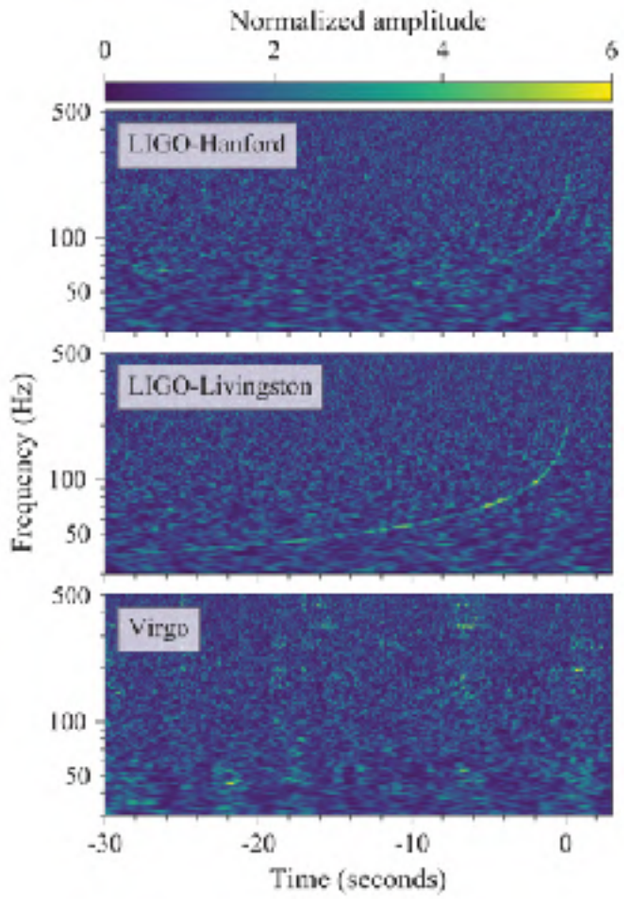
radio active decays of r-process elements



The kilonova with GW

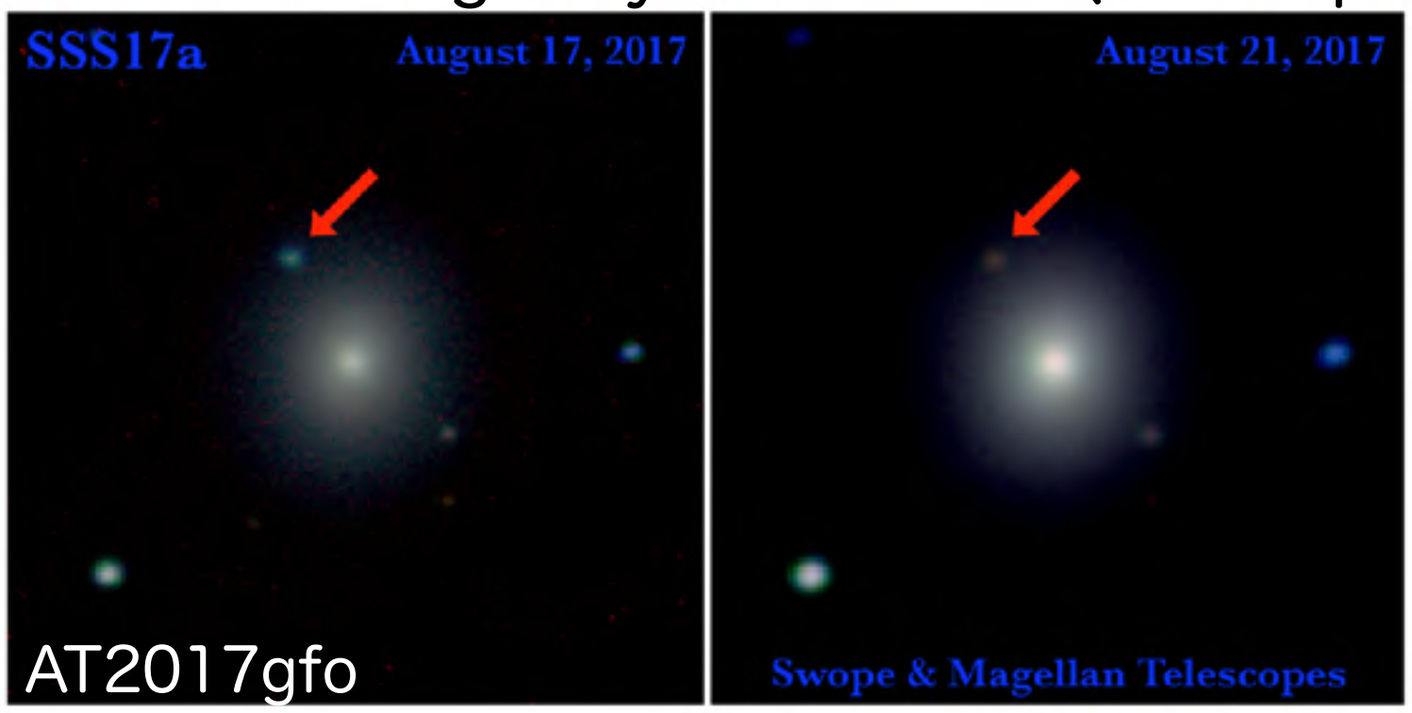
- The electromagnetic transient associated with the NS merger
- “kilo”(1000)-nova: 1000 times brighter than nova (fainter than SNe)
- Energy source? —> radioactive decays (e.g, β, α & fission etc.) of neutron-rich nuclei made by r-process nucleosynthesis

GW170817 (17. Aug. 2017)



GW signal

Electromagnetic counterpart
= kilonova (AT2017gfo) was observed
host galaxy: NGC4993 (39.5Mpc)



by Magellan telescope; Drout+2017, Science

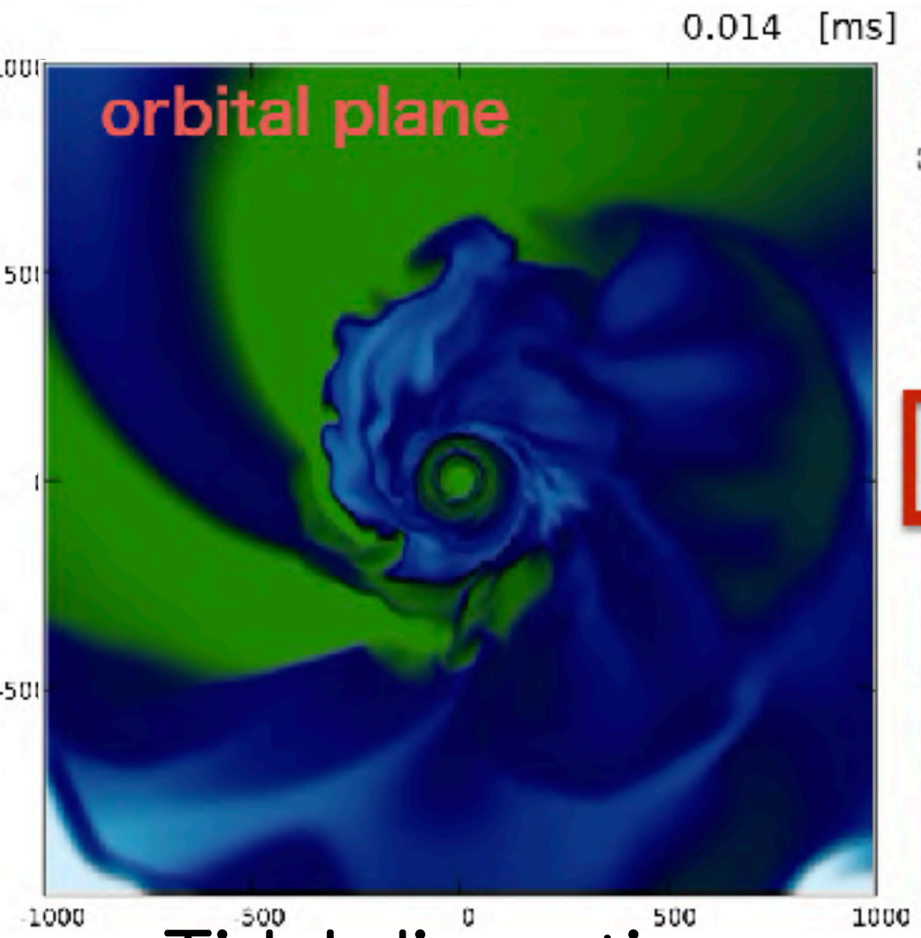
The r-process in dynamical ejecta

dynamical ejecta

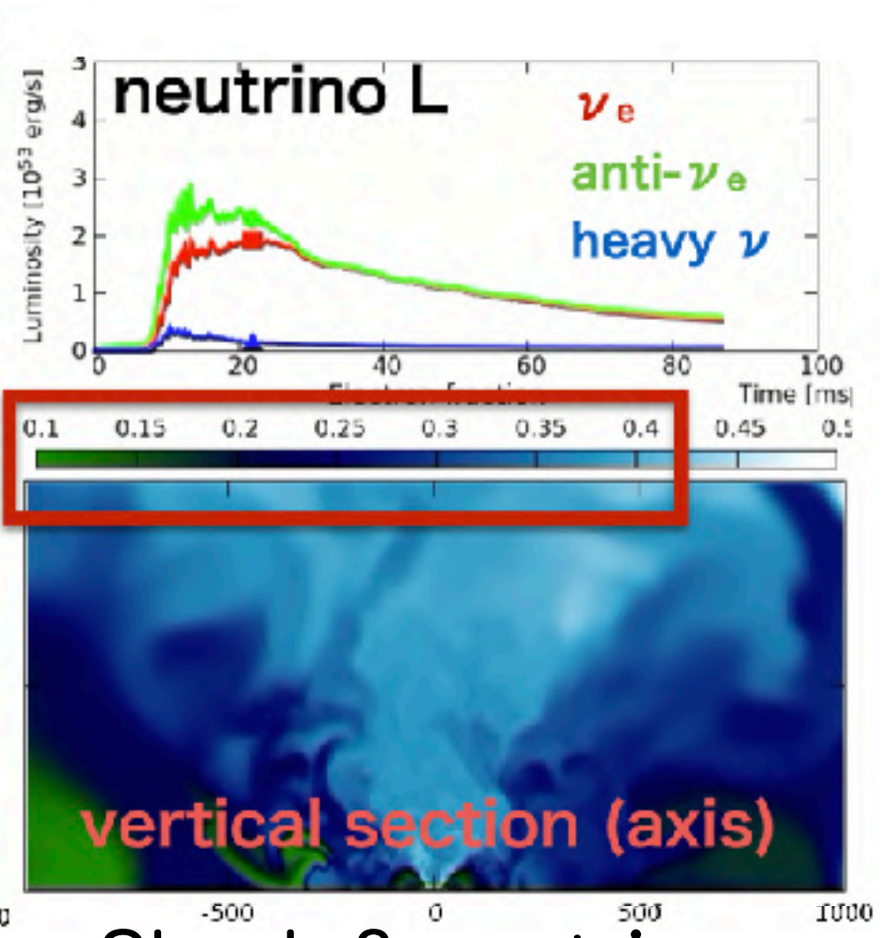
Y_e evolution

$$\left(Y_{\rm e} = \frac{N_{\rm p,\,all}}{N_{\rm p,\,all} + N_{\rm n,\,all}} \right)$$

based on 3D hydro
(Sekiguchi+2015)



Tidal disruption

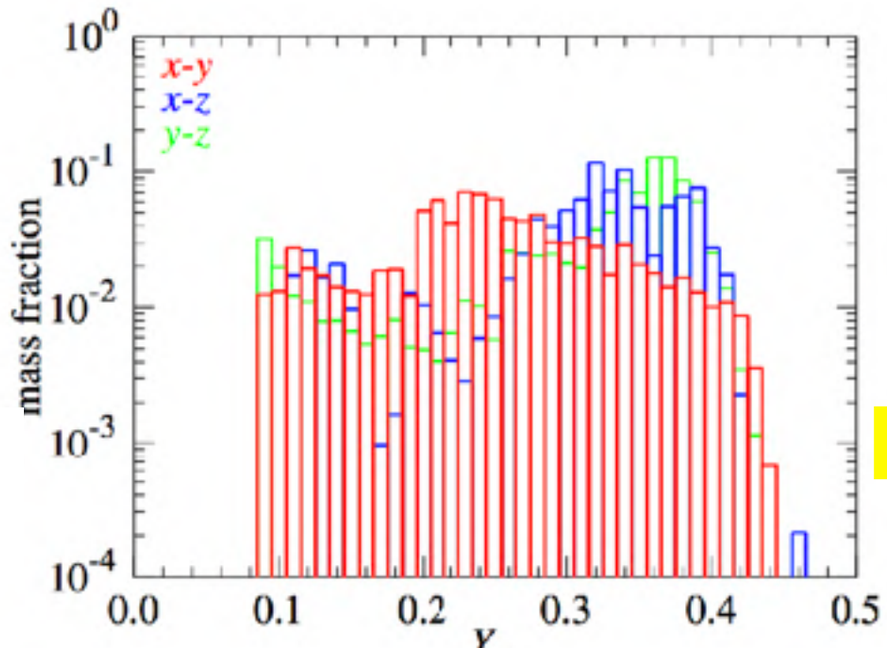


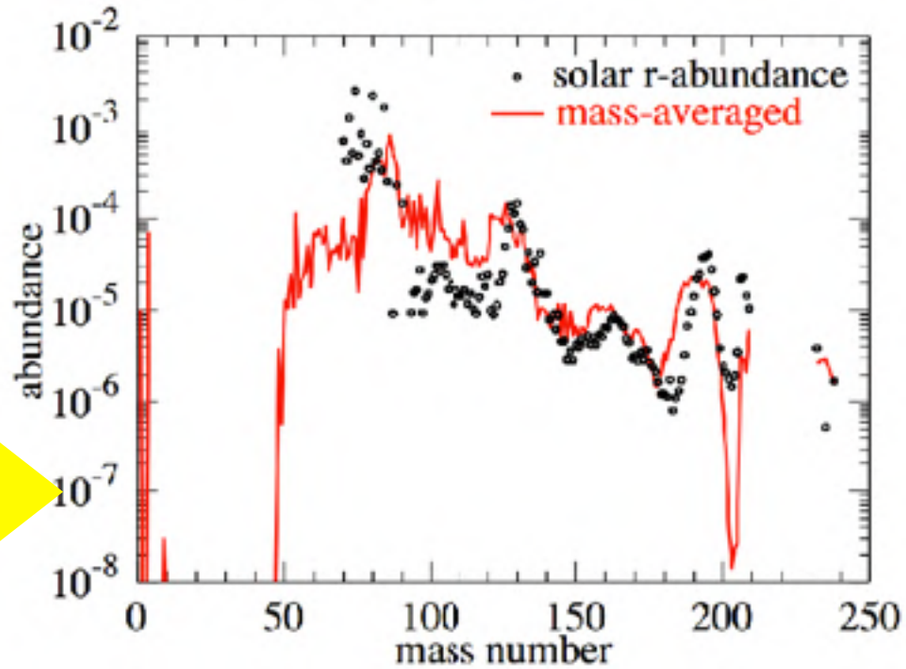
Shock & neutrino

Wanajo+NN+2014, ApJL

Y_e changes
(increase)
by neutrino

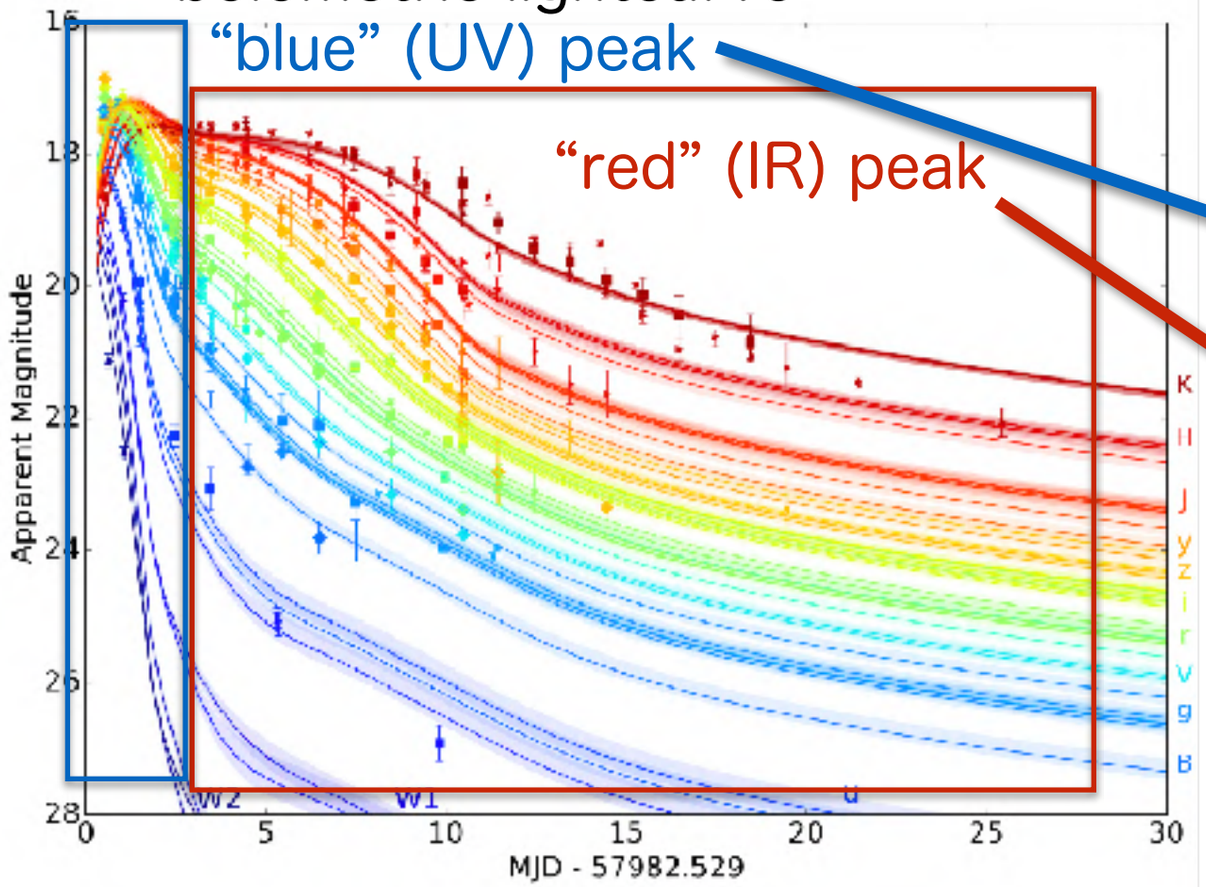
$$\bar{\nu}_e + p \rightleftarrows e^+ + n$$
$$\nu_e + n \rightleftarrows e^- + p$$





kilonova (AT2017gfo) lightcurve

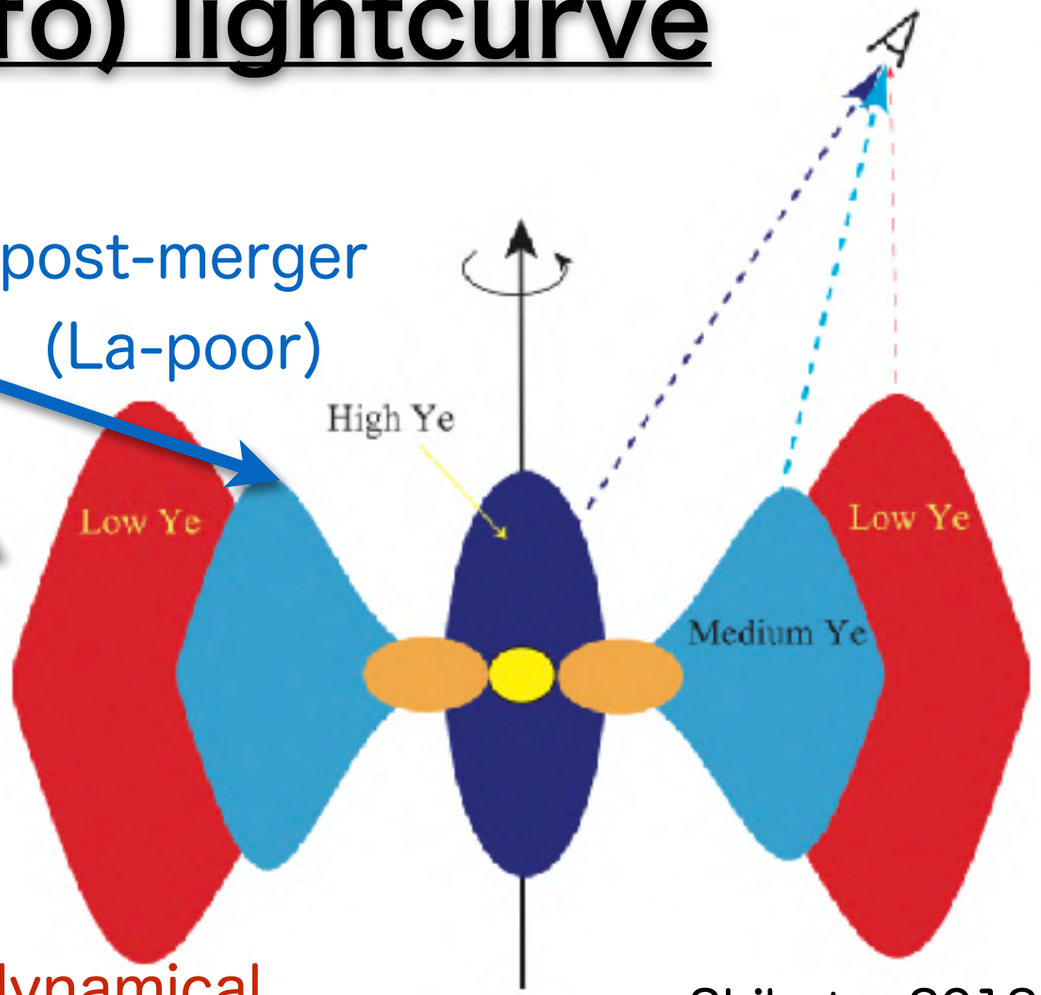
bolometric lightcurve



time, day

Villar et al. 2018

post-merger
(La-poor)



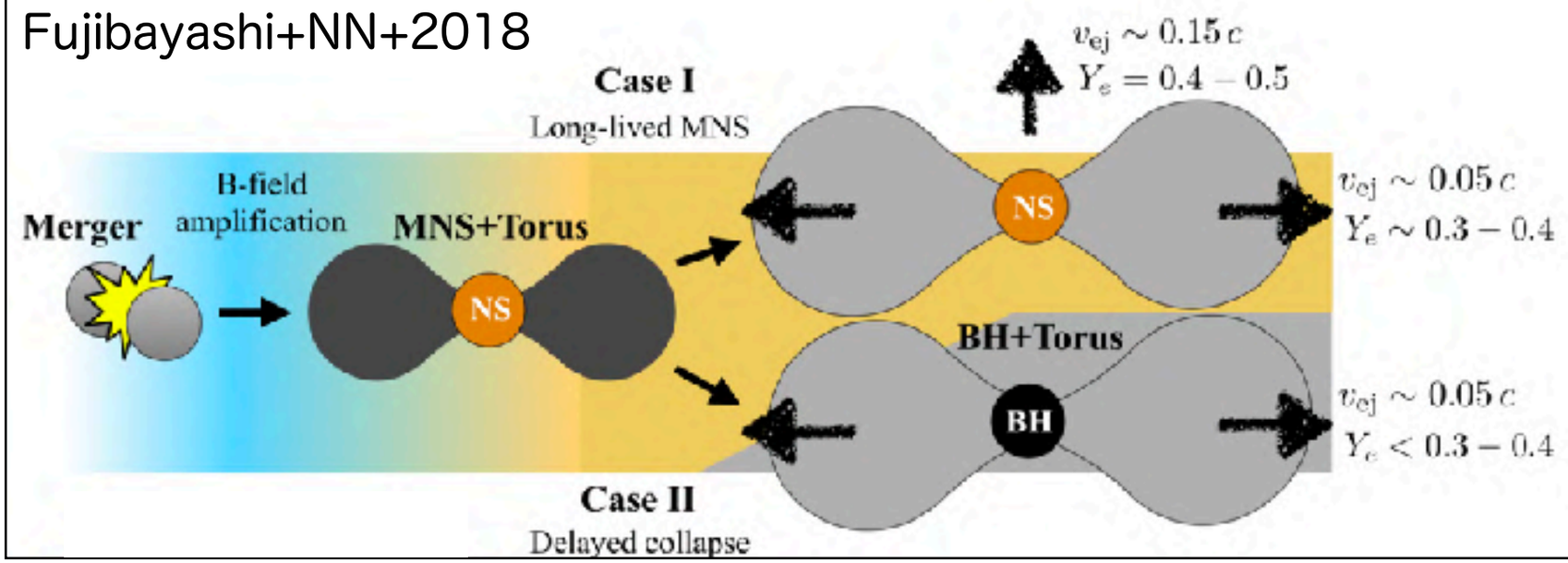
Shibata+2018

dynamical
(La-rich)

the NS-NS merger scenario studied by hydrodynamical simulations

see a review,
e.g., Shibata+2018
(many papers)

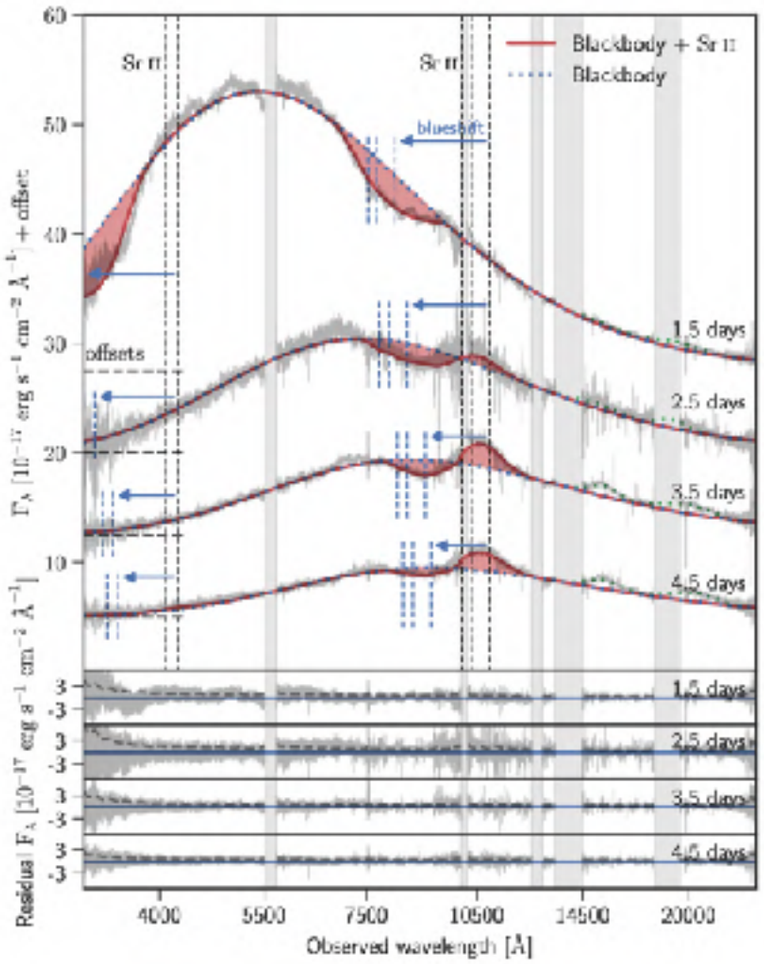
Fujibayashi+NN+2018



Kilonova remnant

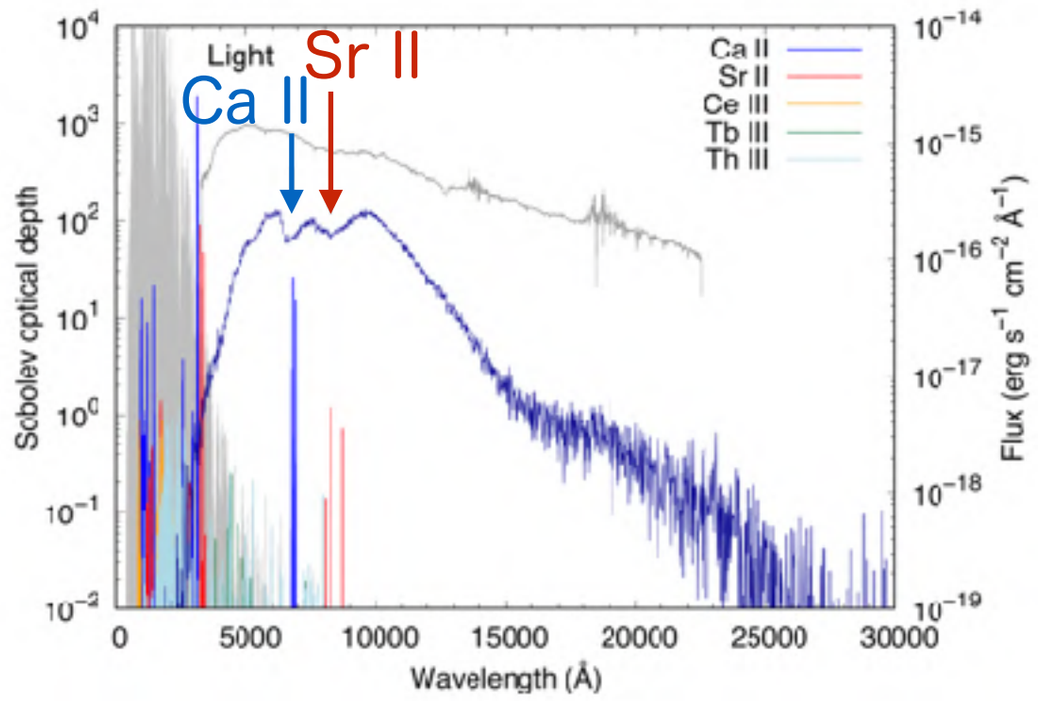
Possibility of other elements?

Sr (Z=38) observation
in the remnant
→ primary production
of trans-Fe nuclei



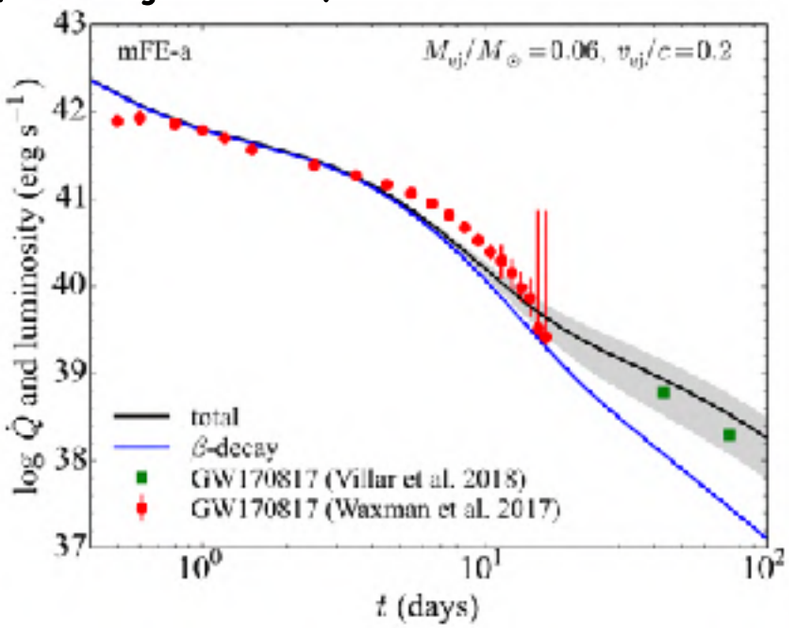
Watson+2019 Nature

theoretical models (Domoto+2021)

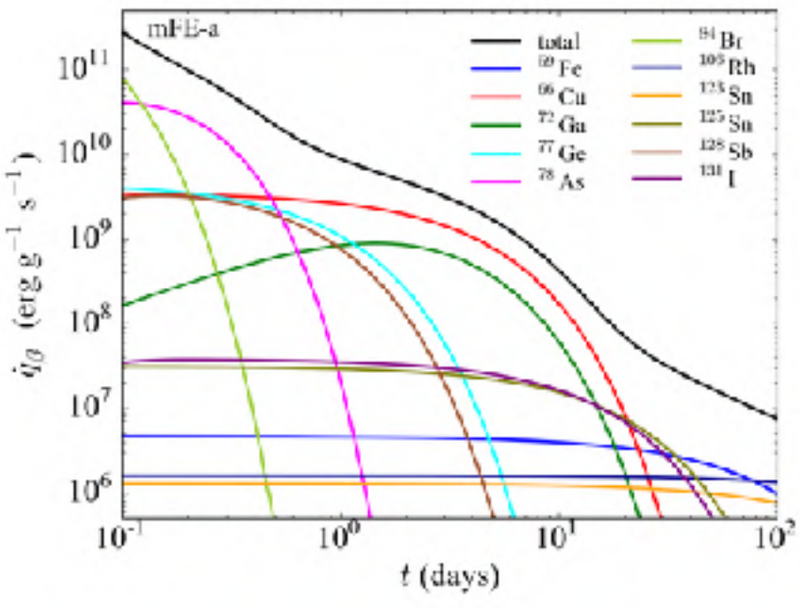


Contribution to the lightcurve?

(Wanajo2018)

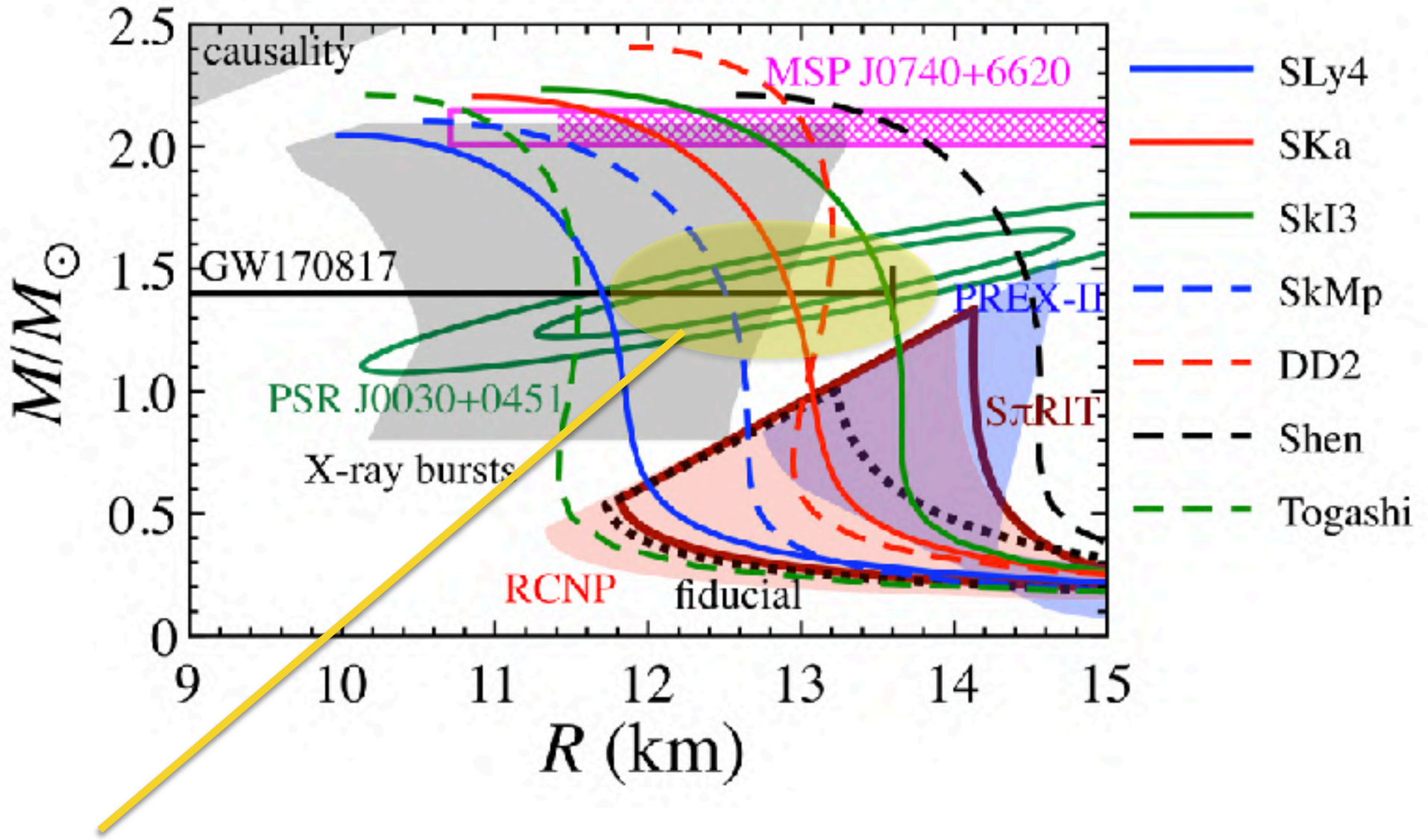


beta-decay



NS EOS and r-process?

Sotani, NN, Naito (2022)



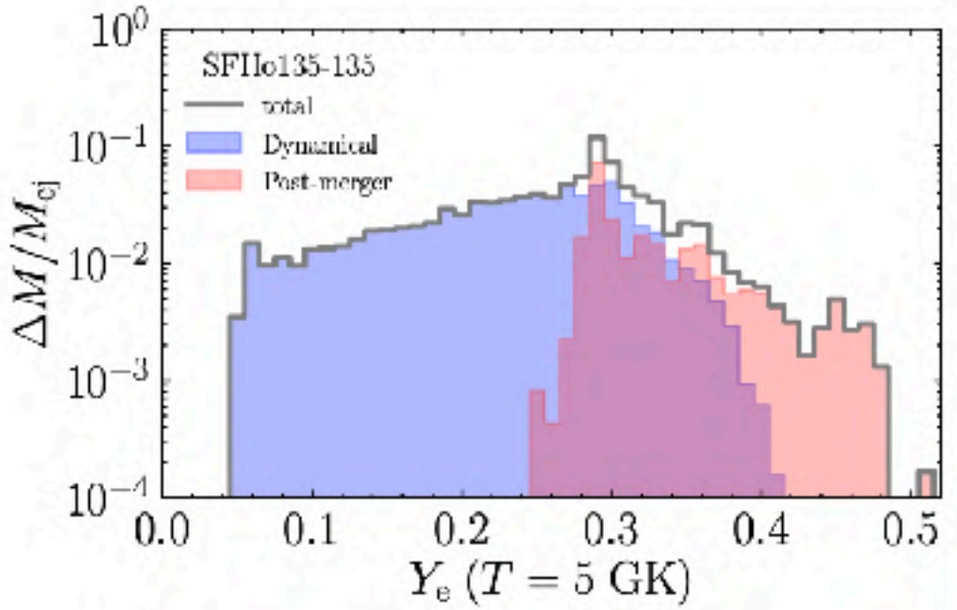
Additional constraints via the r-process?

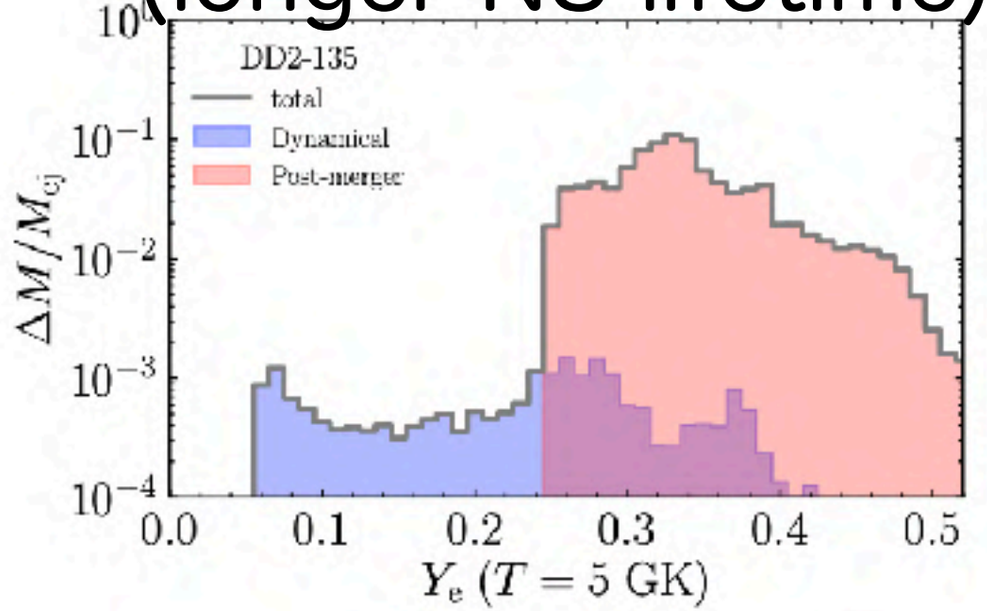
- the NS lifetime (collapse to BH)
- r-process abundance patterns?

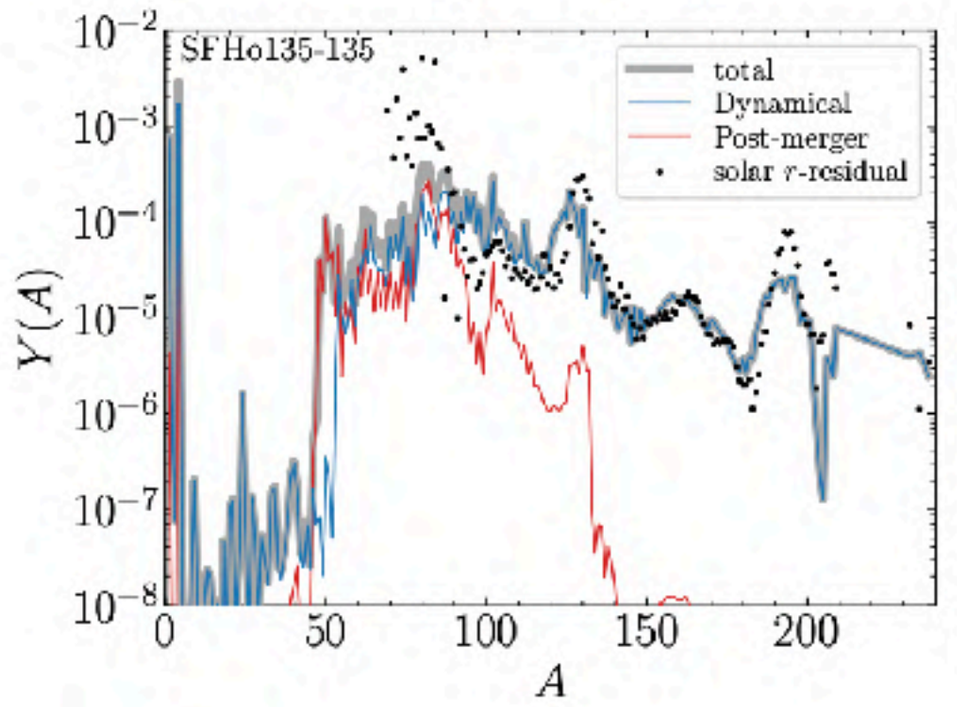
EOS dependence of the r-process

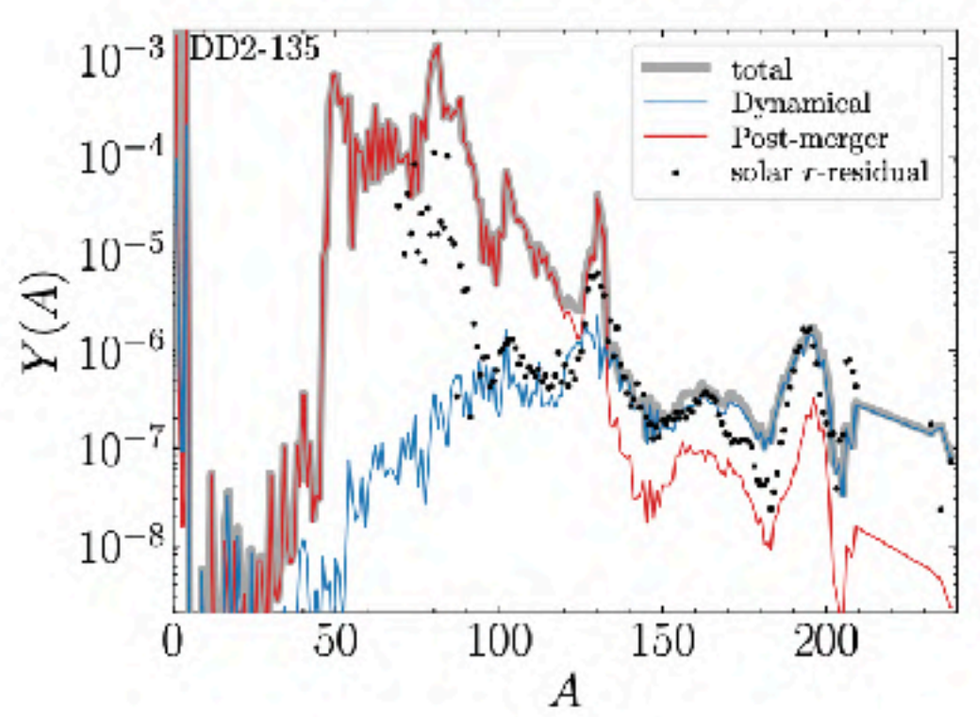
soft EOS

stiff EOS
(longer NS lifetime)









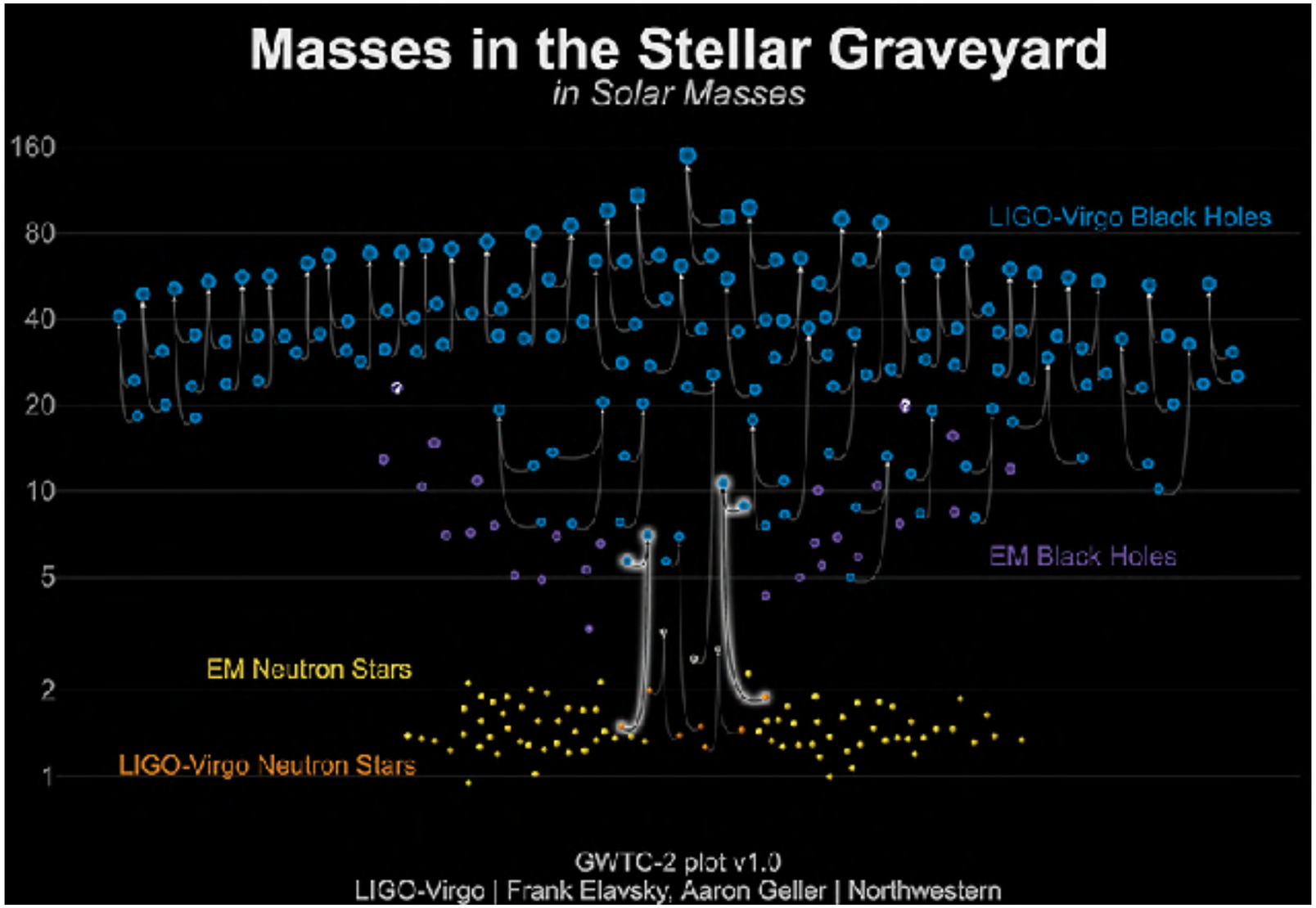
Fujibayashi+(2022)

+ and also they depend on the NS mass ration

NS-BH?

GW200105, GW200115

→ no kilonova event was observed



NS-BH must have different nucleosynthesis signatures:

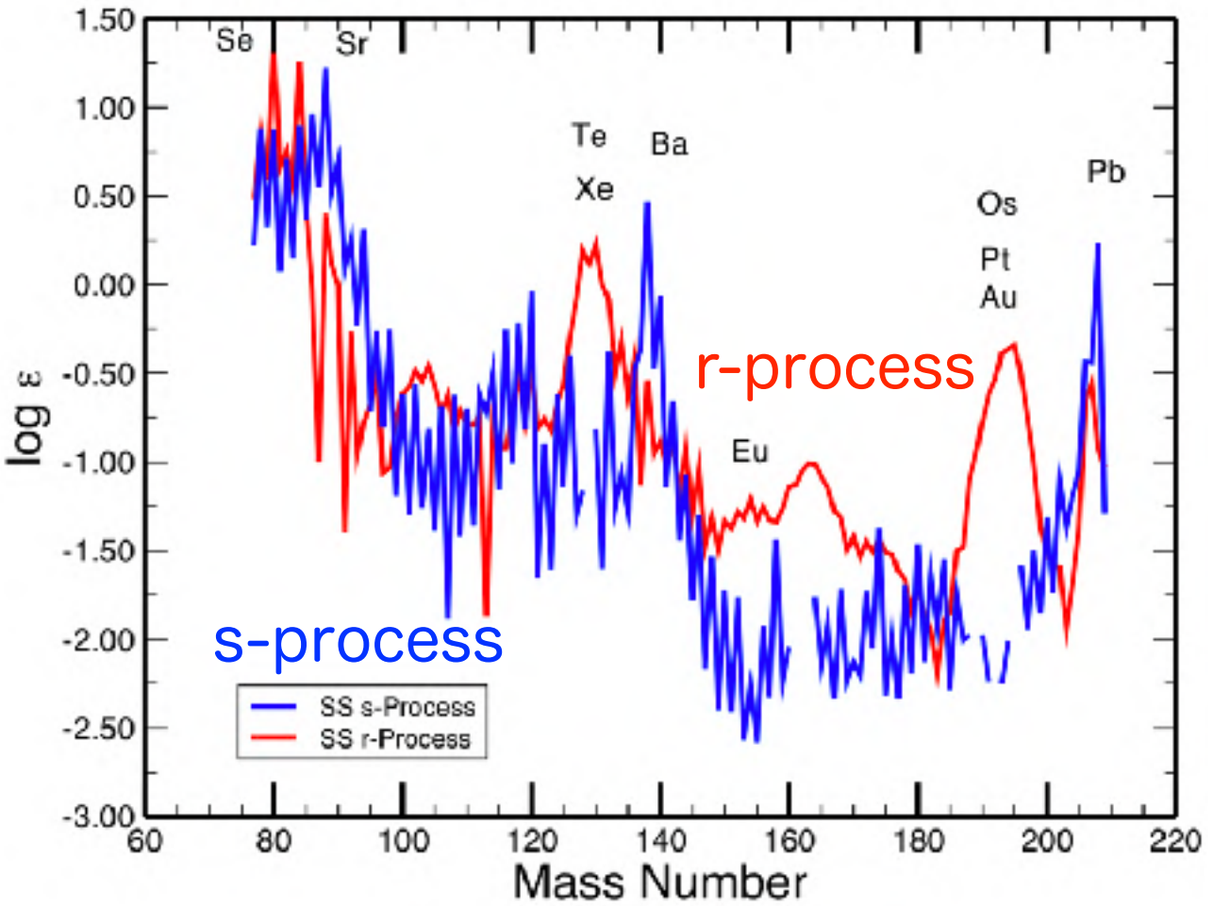
can be very strong r-process→ actinide boost stars?

(see, Tsujimoto, NN, Kyutoku 2020, ApJ)

r-Process in metal-poor stars

Soar abundances

Cowan&Thieleman(2004)



"solar r-process"

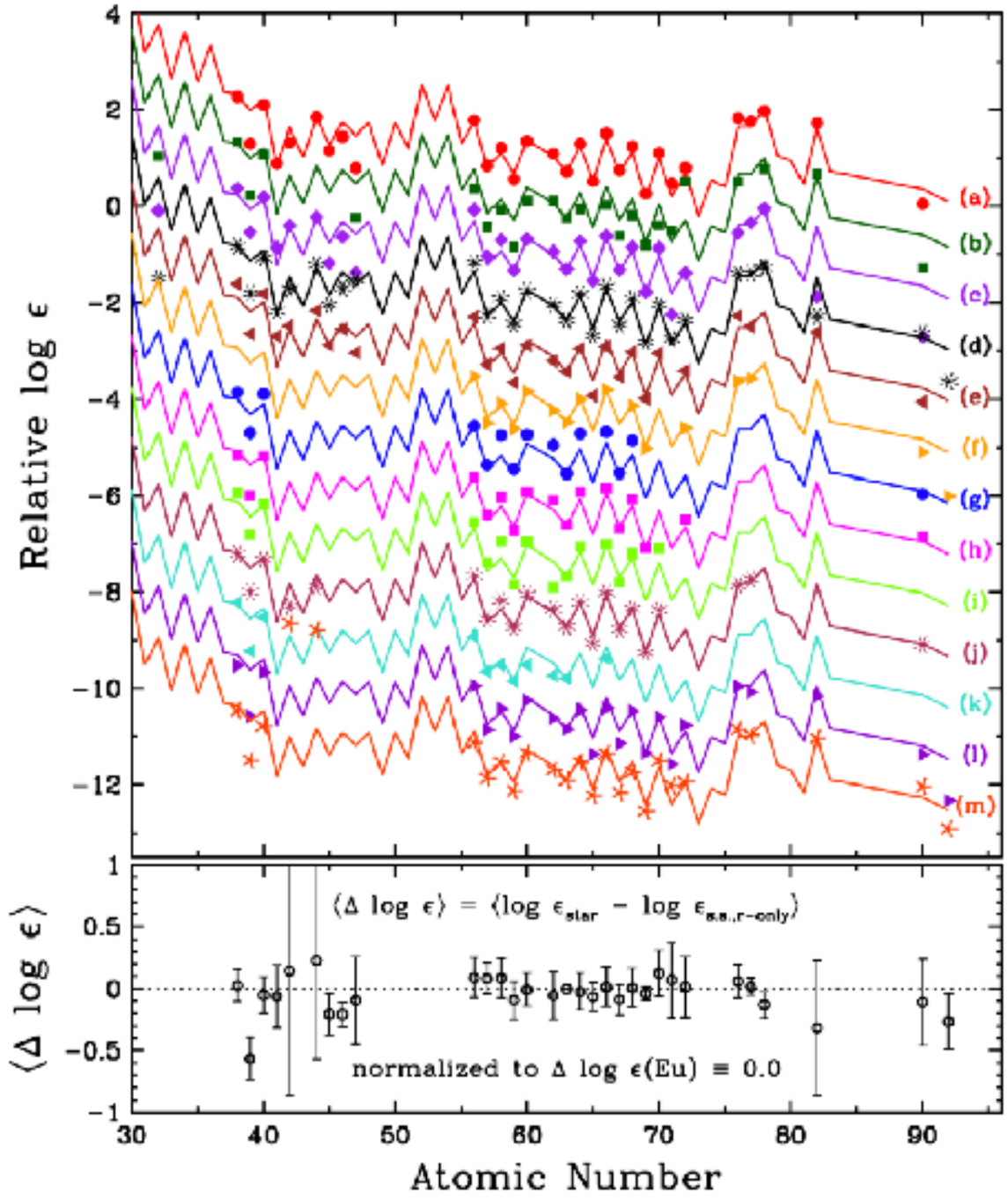
= "solar abundances"

- "s-process calculation"

Cowan+2021

Galactic halo stars

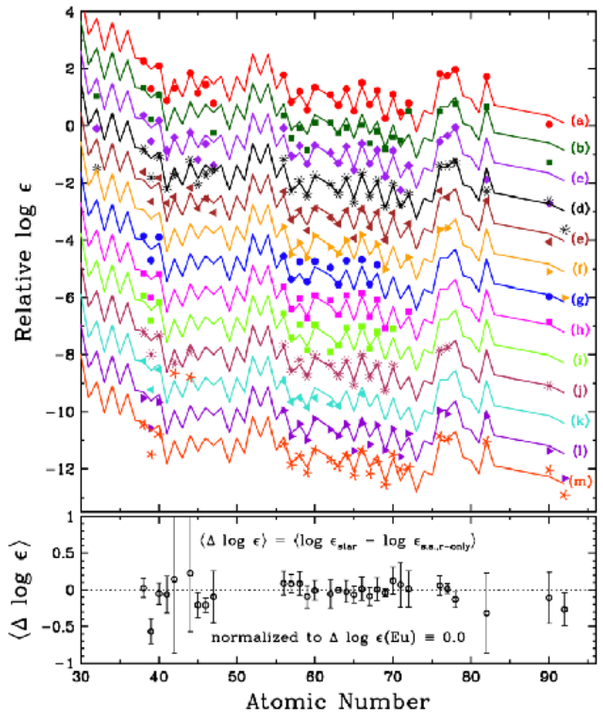
solar-like r-process patten



r-Process-rich stars and GCE

Cowan+2021

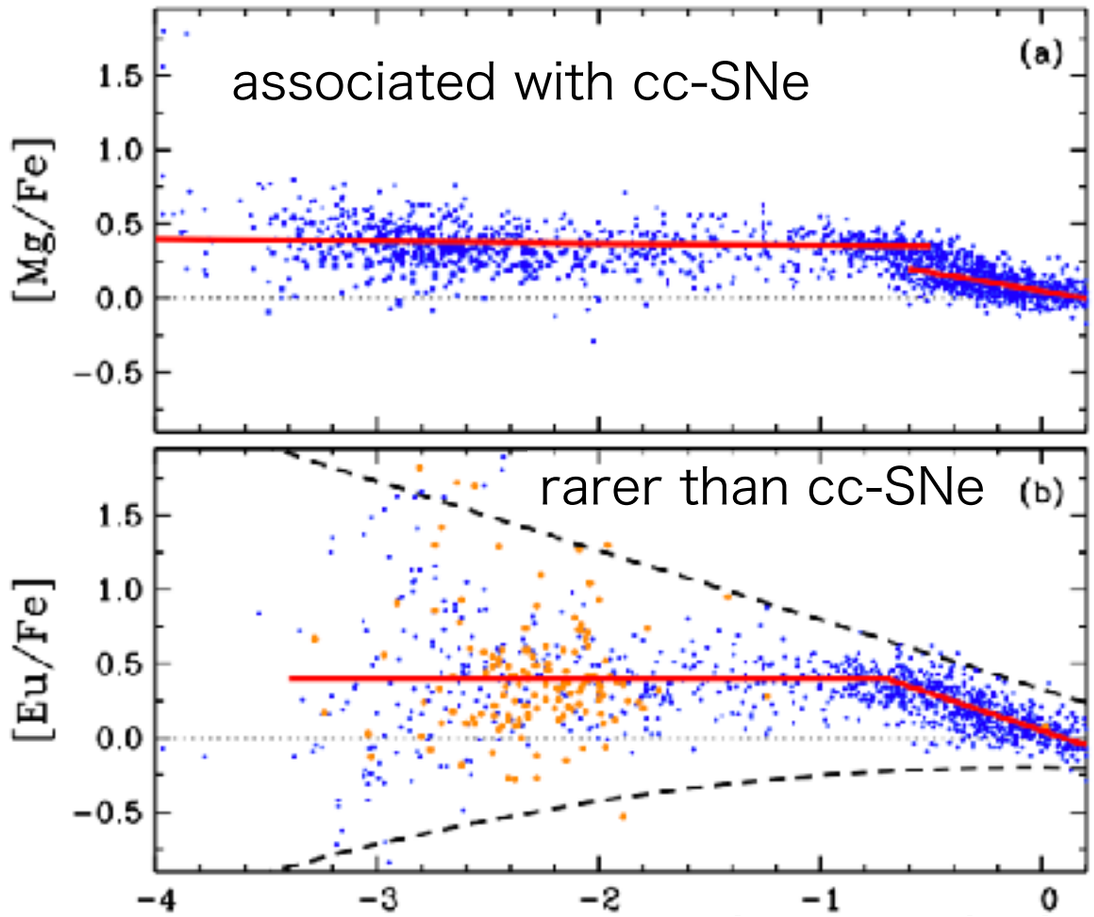
Galactic halo stars



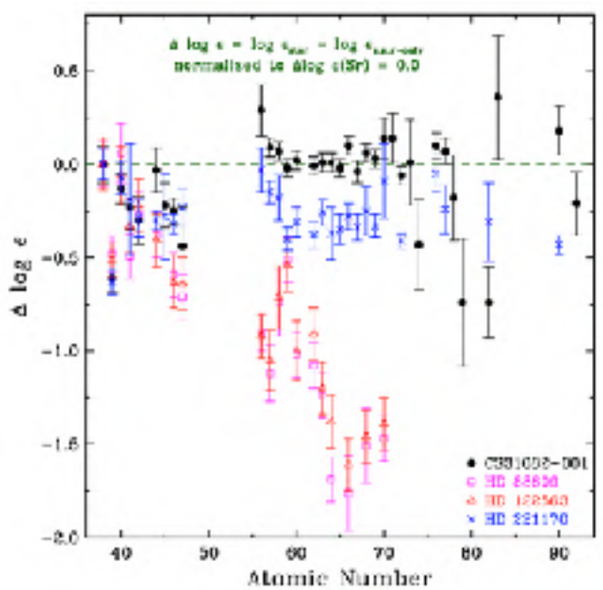
solar-like r-process patten

r-process elements

production event vs. SNe



"weak" r-process patten



Galactic chemical evolution

- NS-NS mergers can be the main source (many papers, e.g., Wanajo+2021)
- but, it needs alternative source? (e.g, Cote+2019)
  → Rare cc-SNe event?
  - GCE of dSph by Tsujimoto & NN (2015, 2018)
  - frequency: 0.5 % of CC-SNe; large mass: ～10^{-5} M_{sun}

Short summary

- Observation of NS-NS mergers in GWs and EM waves
  - kilonova was observed (identified) (GW170817)
  - distinction of “color” of kilonova
    = a clue of r-process composition
  - Sr in the remnant
    = primary production by r-process
- Further theoretical studies are ongoing
  - more presice models
  - which is the dominant decay source (in each epoch)?

→ these may be confirmed by future events??
(LIGO/Virgo/KAGRA O4, 2022?—)

other event? black hole—neutron star merger

- Observation of r-process abundances in metal-poor stars
  - galactic chemical evolution

PART 2:
Nuclear Physics

"Possible impacts of experimental progresses on the r-process"

a brief overview:

more details will be shown next week at RIKEN

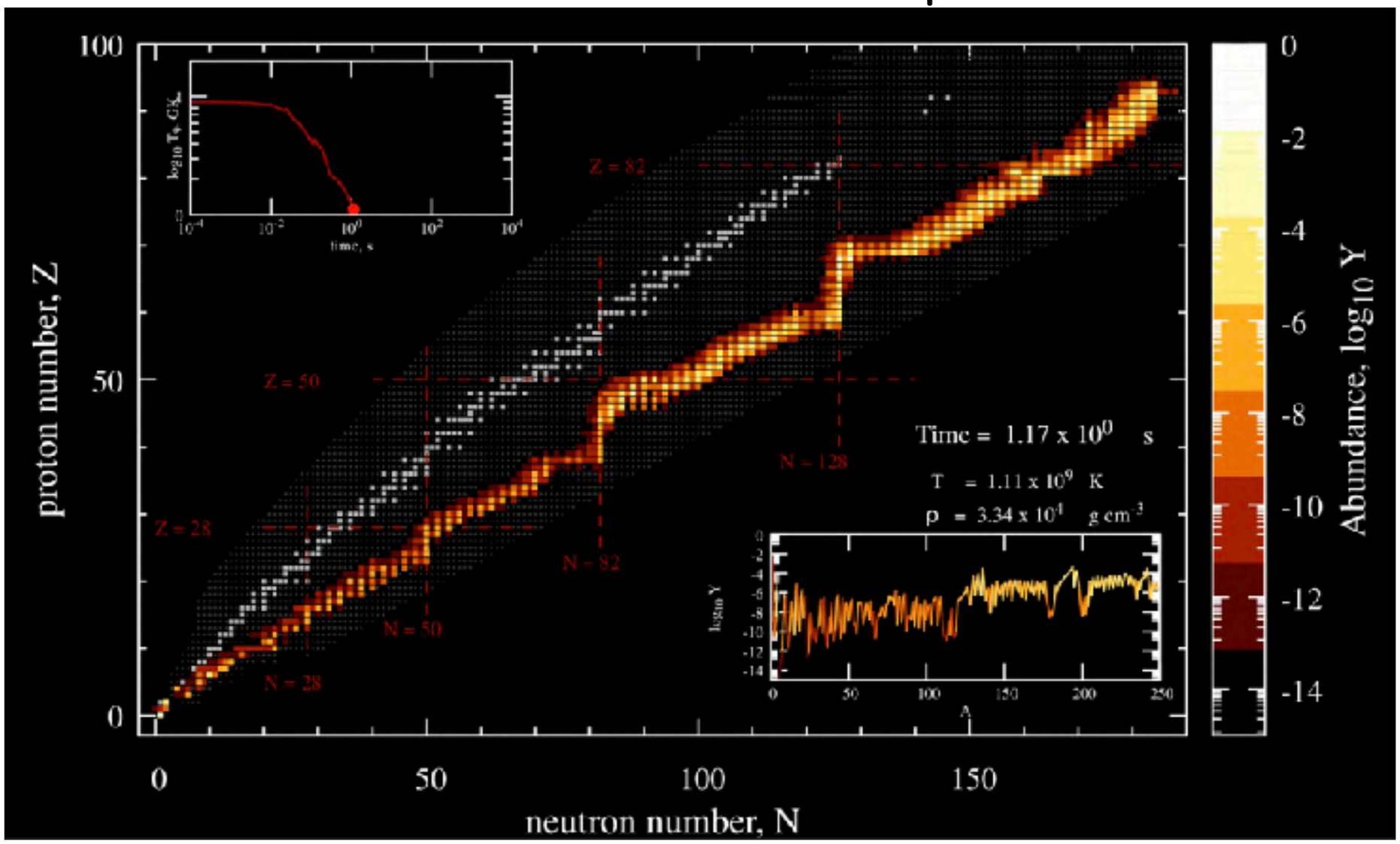
Nuclear Reaction Networks

Nuclear reaction networks

- tools for bridging nuclear physics to astrophysics
- consider all relevant reaction and decay rates:

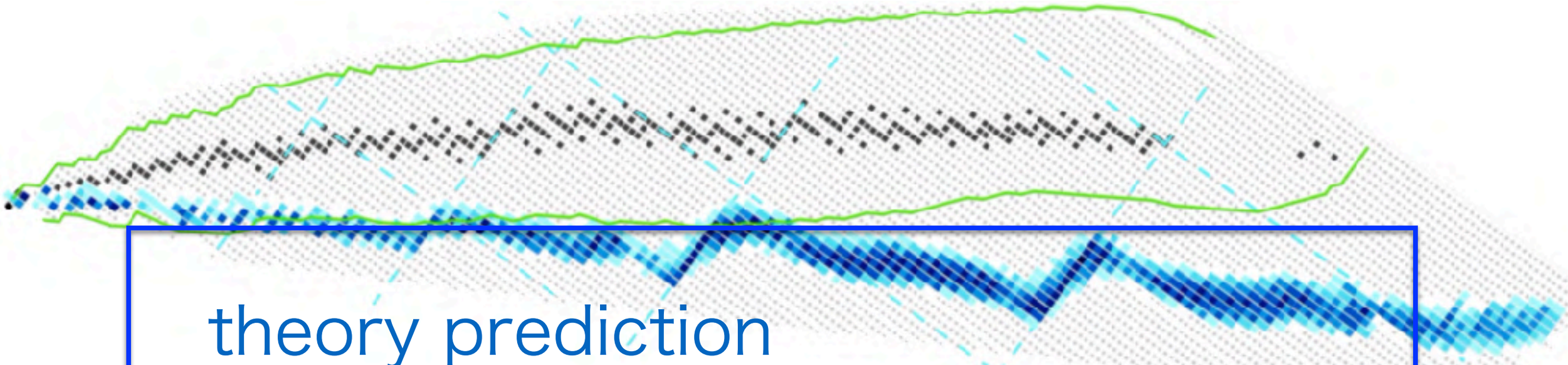
  (n,g)… and reverse reactions, α, β-decays, fission etc.
- "predict" r-process yields in astrophysical environments

r-process simulation



Theoretical Prediction

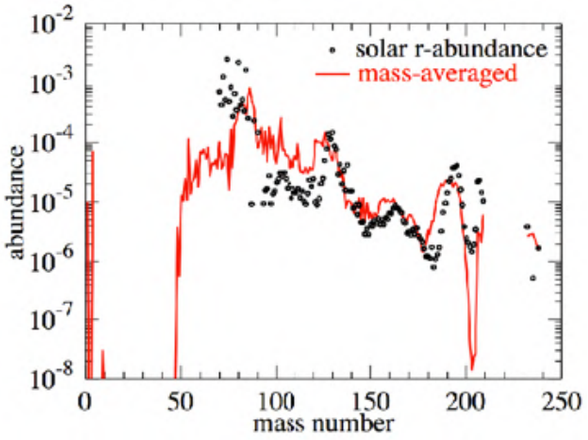
r-process path is beyond experimental accessible region

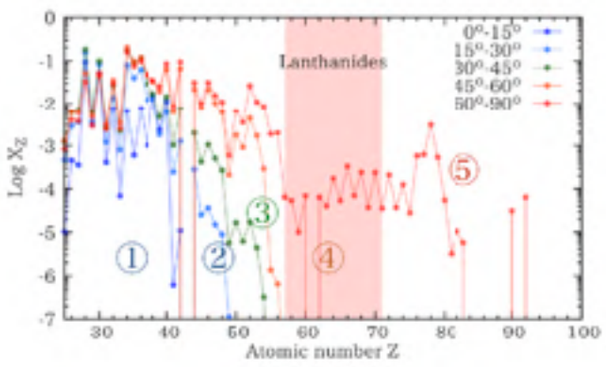


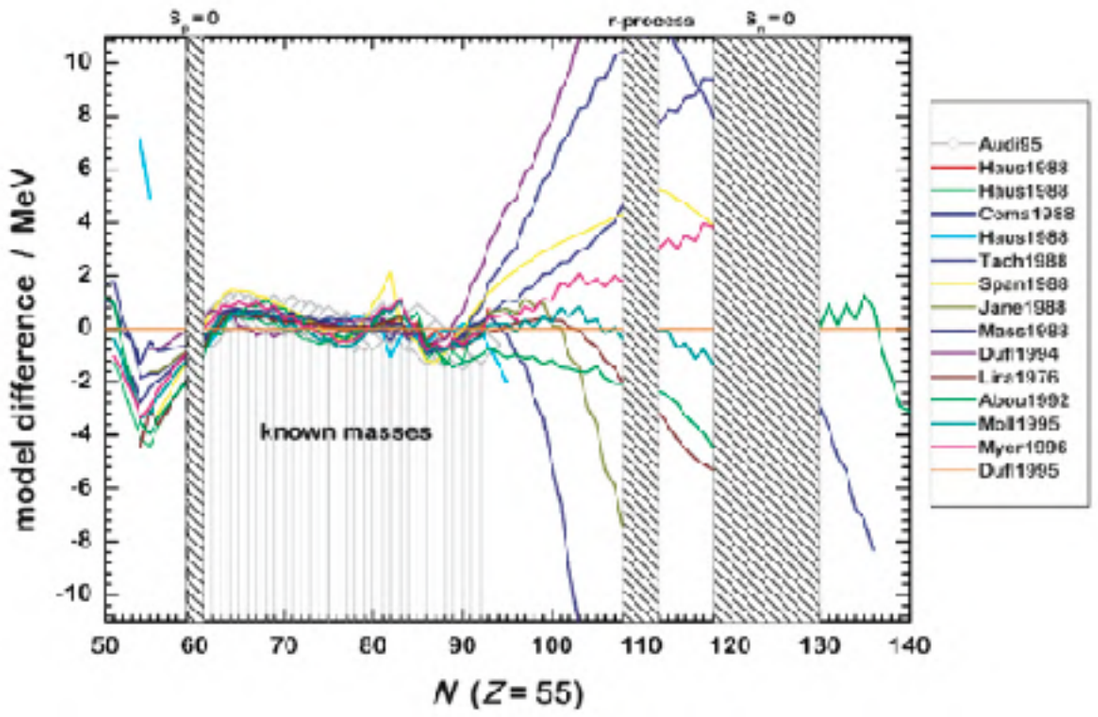
astrophysics

reliability??

large uncertainty in theory



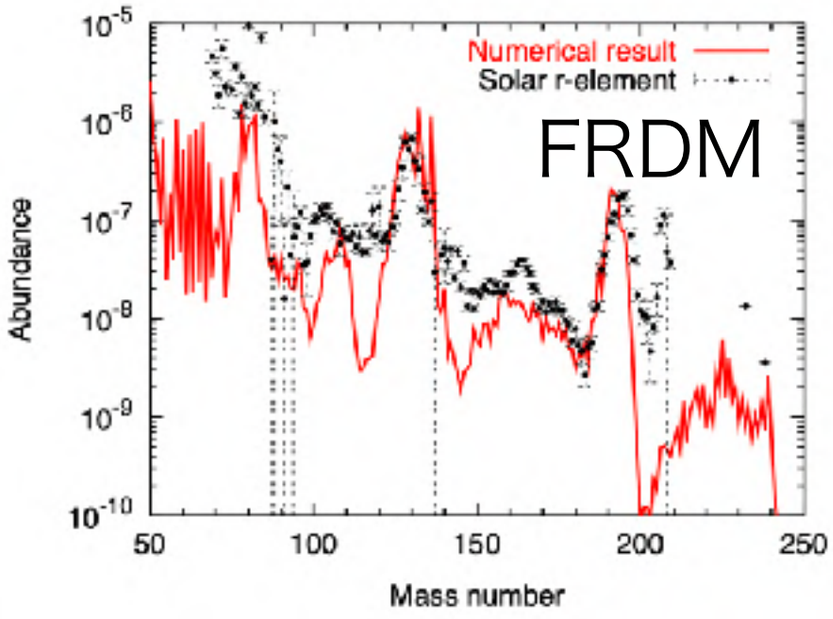


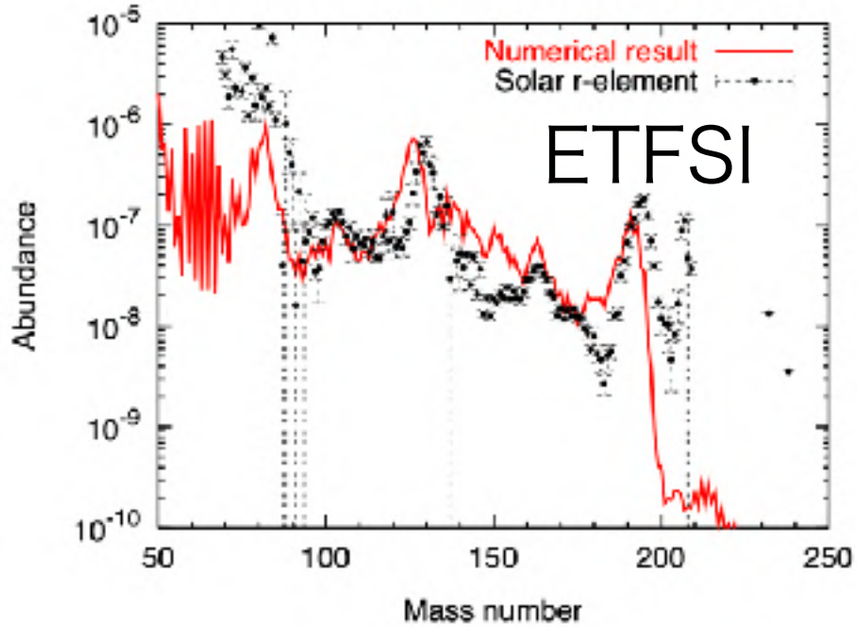


Theoretical Prediction

different theoretical masses (and decay rates)

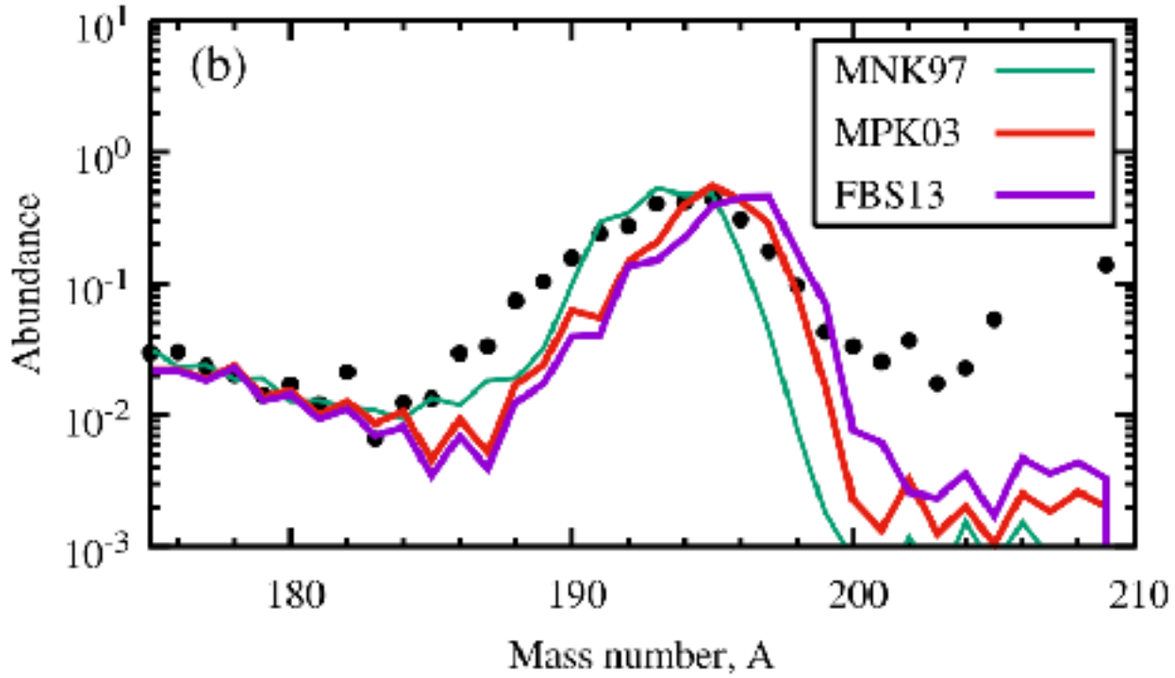
Nishimura+2006, ApJ

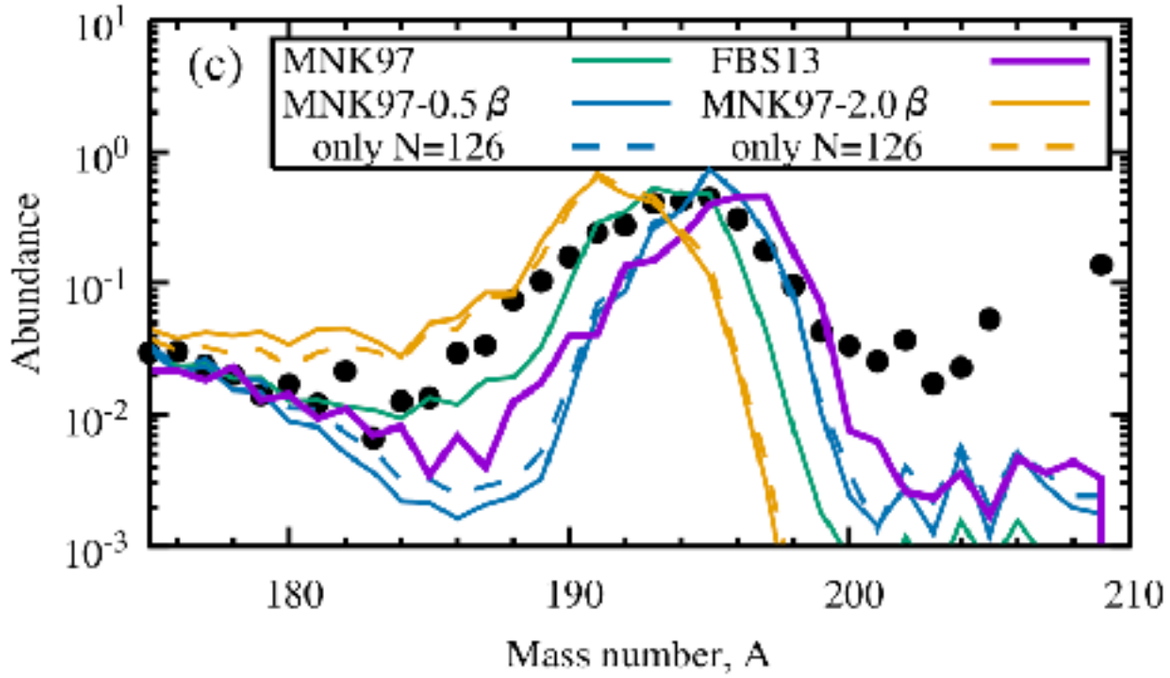




Impacts of the N = 126 β-decay half-lives on the r-process

NN+2016, PLB

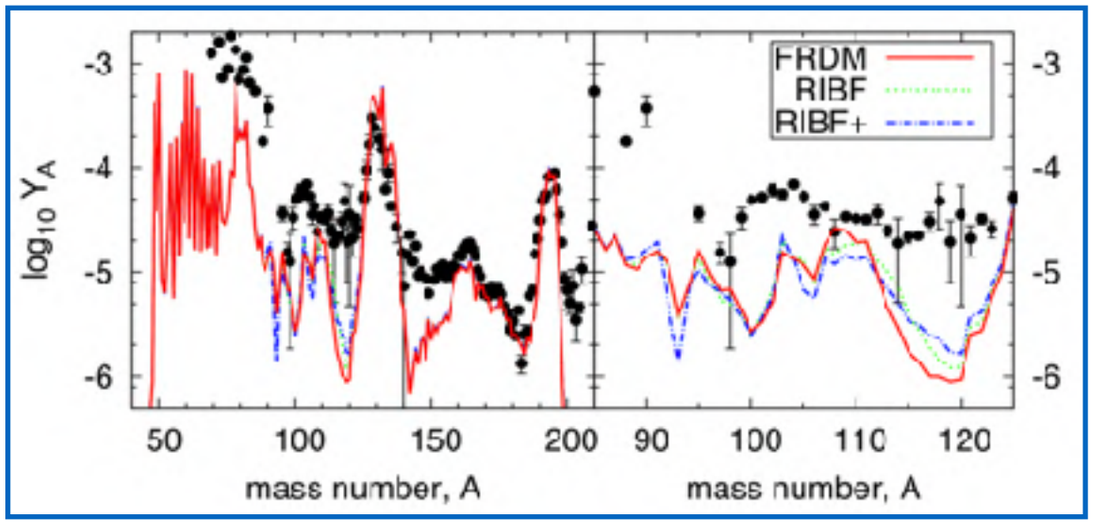




Beta-decay: BRIKEN Experiments

beta-decay half-life
experiments at RIBF
(led by S. Nishimura et al.)

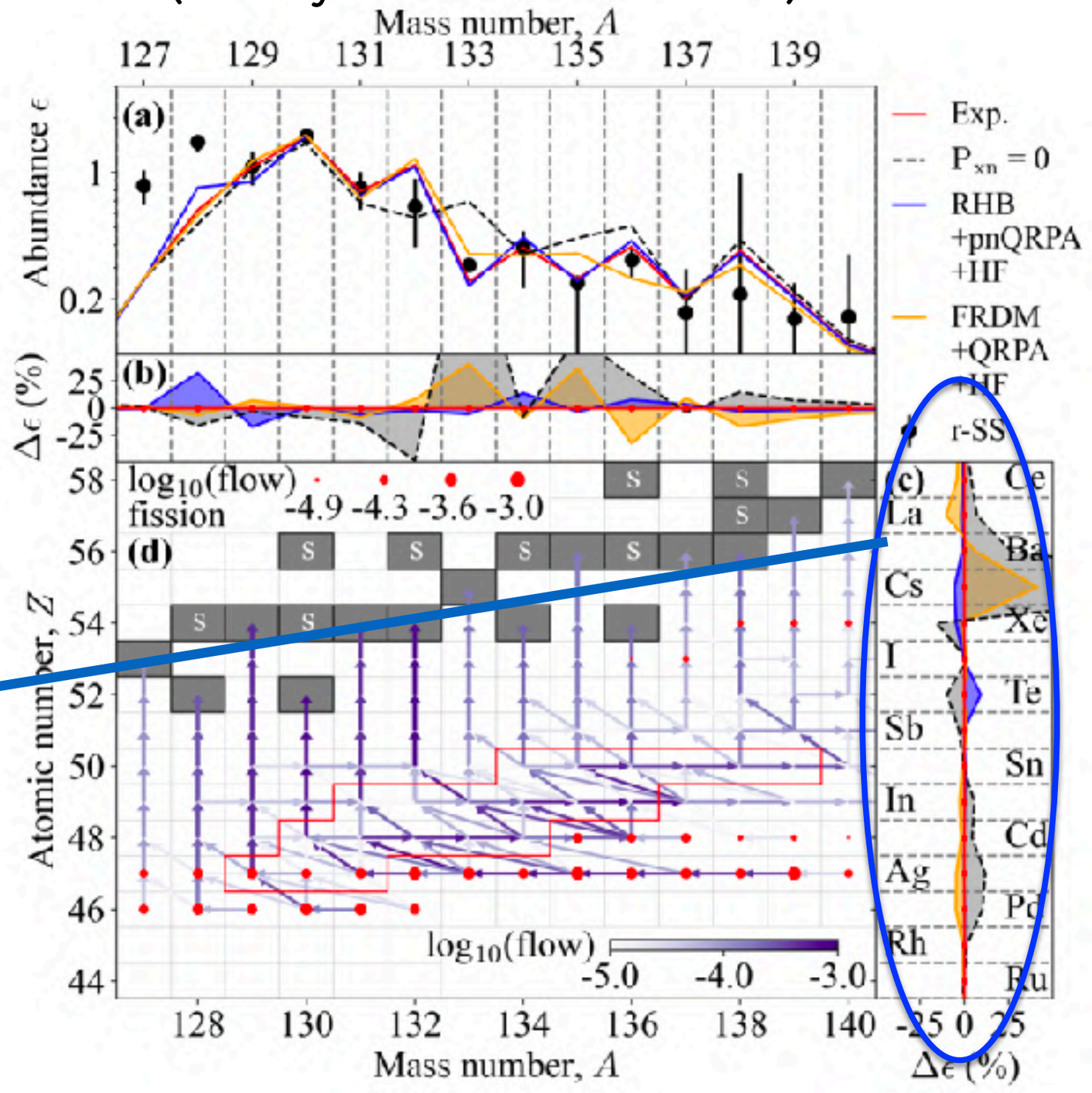
NN+2012



New results of BRIKEN (P_n 20 isotopes)

Pong, S.Nishimura+NN+(2022), in prep.
impacts on the r-process

(in very n-rich environment)



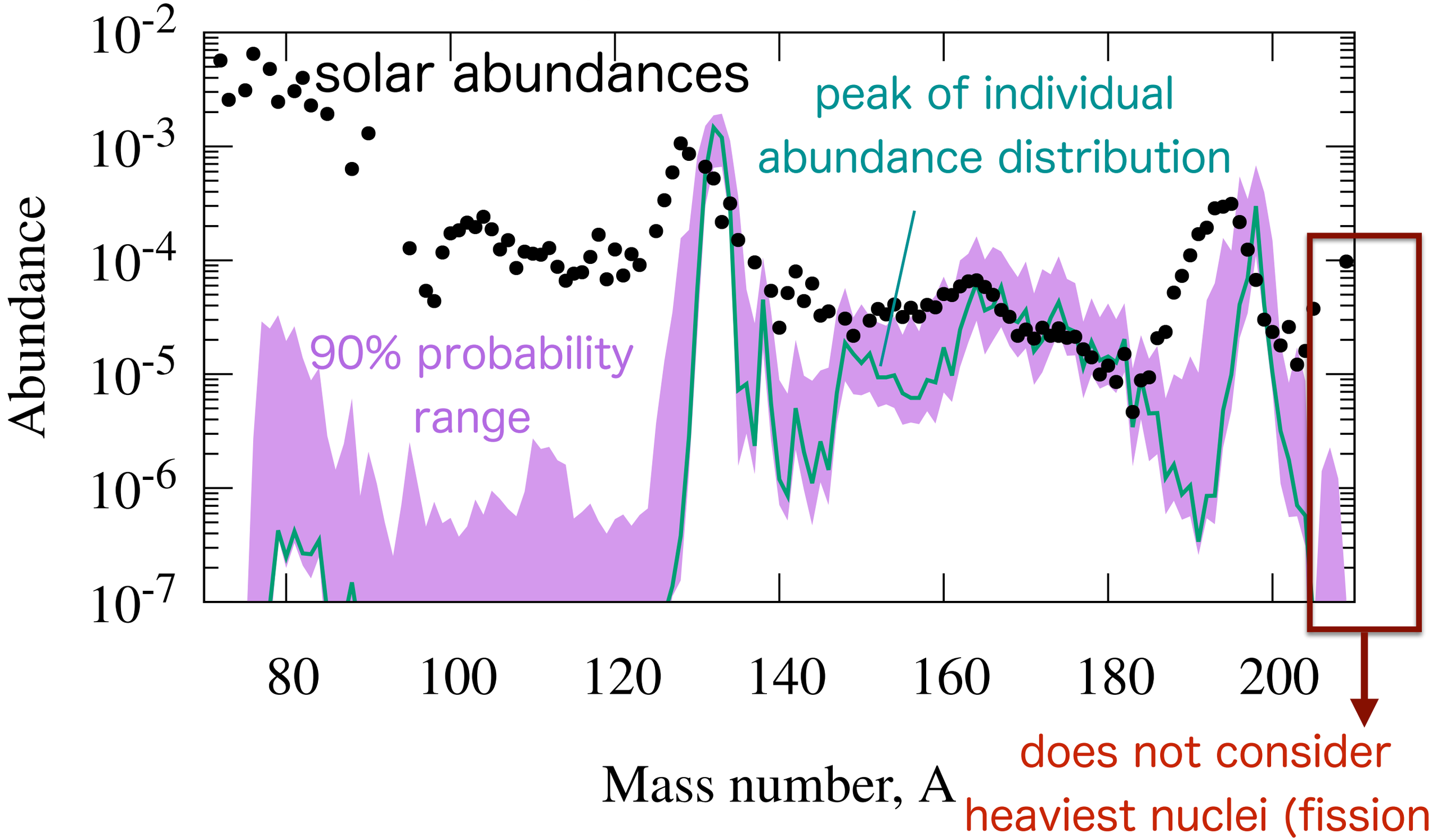
impacts on Cs?

important for early solar-system evolution

Collective uncertainties on the r-process

NN+2022, in prep.

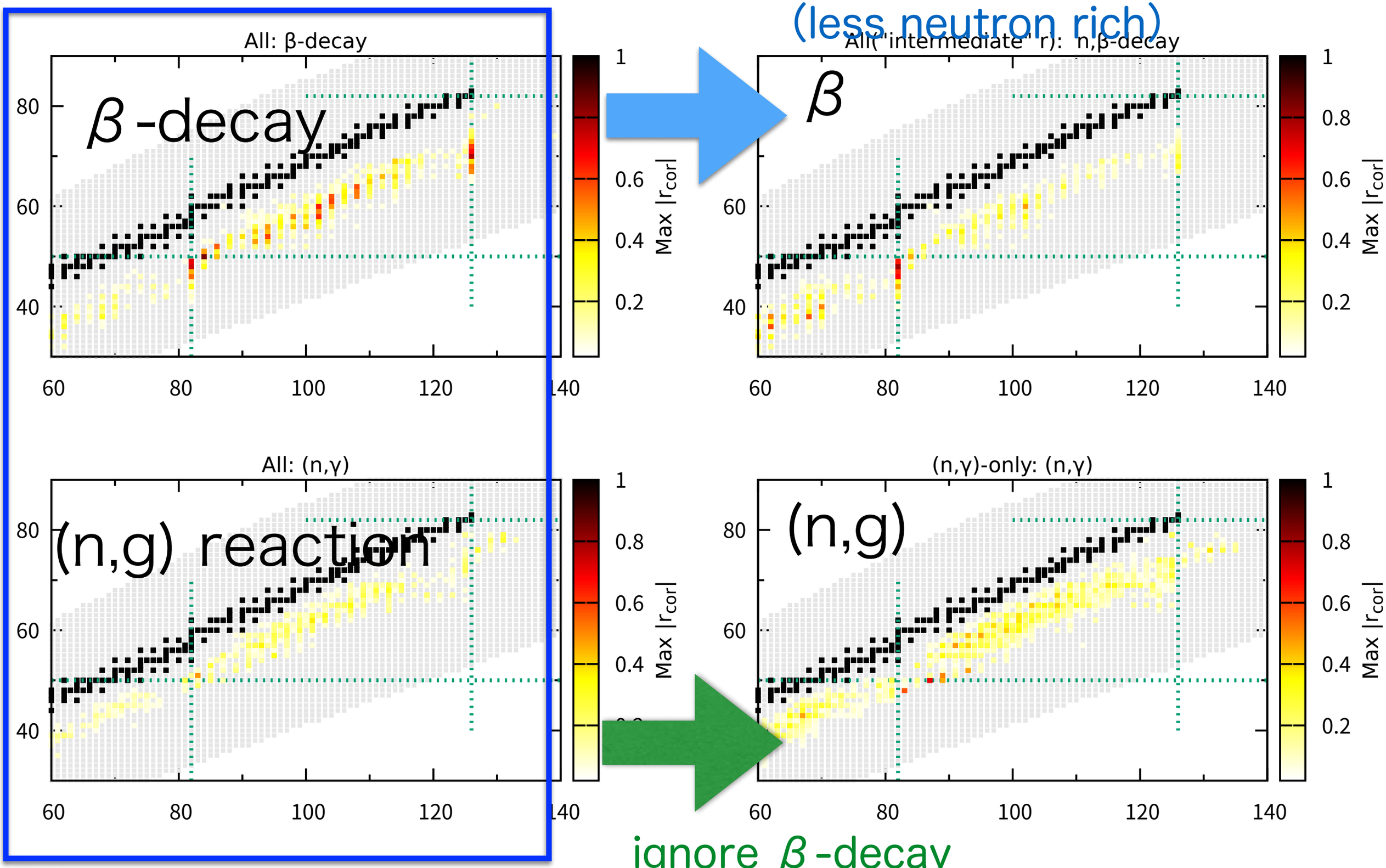
(n,g) x50, β x10



Individual impacts

weaker r-process (NN+2017)

(less neutron rich)



Summary

- NS-NS mergers may be the main site for the r-process
  - confirmed in the kilonova (GW170817)
  - dispersion and event rates agree with Eu evolution
- But, some difficulties in the early galaxies
  - several “variations”:
    weak r-process and actinide-boost stars
- Multiple r-process sources in GCE
  - rate types of SNe with r-process rich yields
    - detection of Sr in the remnant?
- Nuclear-physics uncertainties are still significant
  - experiments are approaching r-process region
  - but, most reaction and decay rates are rely on theory prediction

theoretical interpretation ⇆ observational constraint

- merger, SN models
- Galactic evolution
- abundances
- kilonova