Can nuclear physics solve "the missing gold problem" in the evolution of Galaxy?

Nobuya Nishimura

（西村 信哉）

CNS, The University of Tokyo

Talk plan

- Astrophysics part:
  a brief summary on the missing problem in GCE, or a bit ironical overview from nucleosynthesis person
- Nucleosynthesis part:
  - production of 3rd r-process peaks)
  - basics: production of r-process peaks
  - previous and on-going studies
  - MC-based sensitivity study
- Summary and perspective (personal)

1. Astrophysics part:

“The missing gold problem” in GCE

Evolution of r-process elements

Dark Energy
Accelerated Expansion

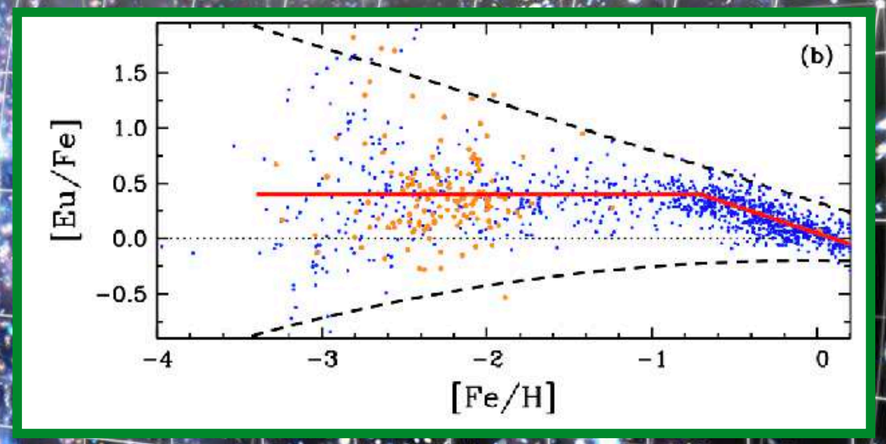
Afterglow Light
Pattern
375,000 yrs.

Dark Ages

Development of
Galaxies, Planets, etc.

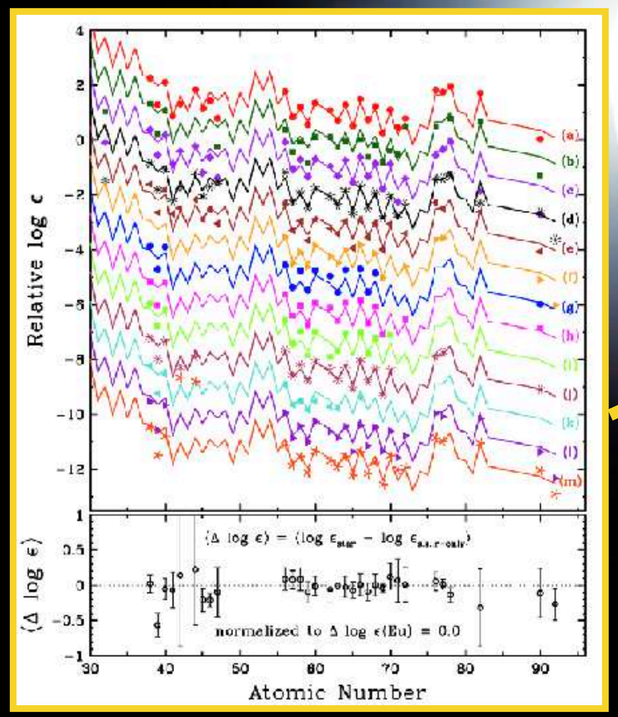
abundance evolution

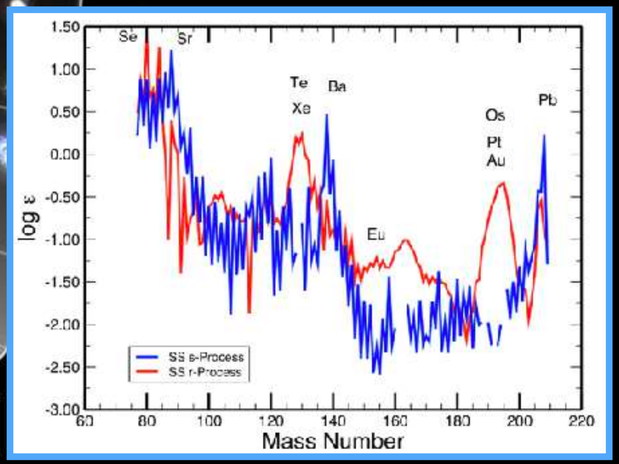
Inflation



WMAP

solar abundances





1st Stars
about 400 million yrs.

Big Bang Expansion

13.77 billion years

Galactic Chemical Evolution (GCE)

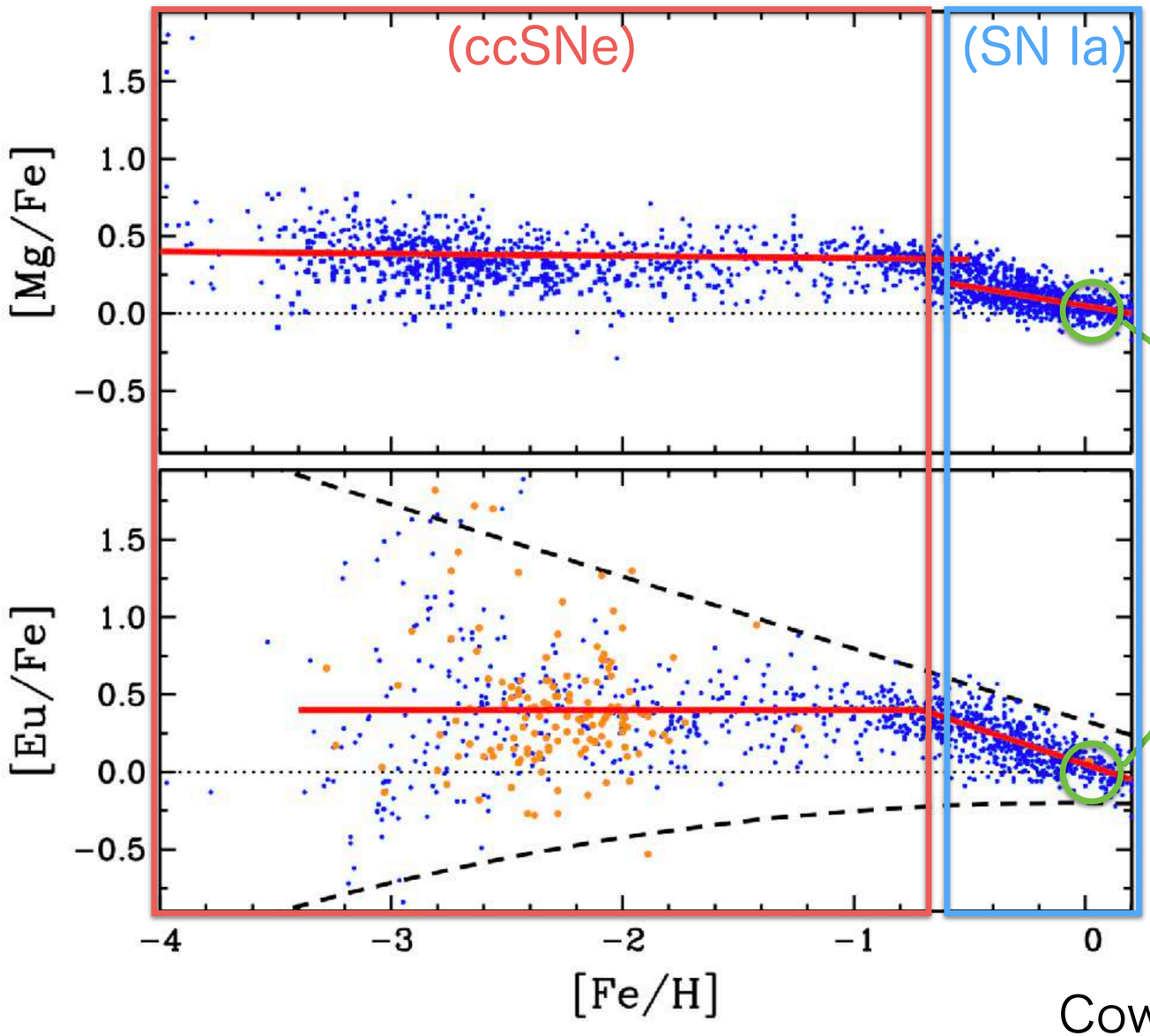
Galactic halo stars

massive stars (ccSNe)

low mass stars (SN Ia)

regular SN/stellar yields

r-process elements



Solar

Cowan+2019

Iron (time evolution)

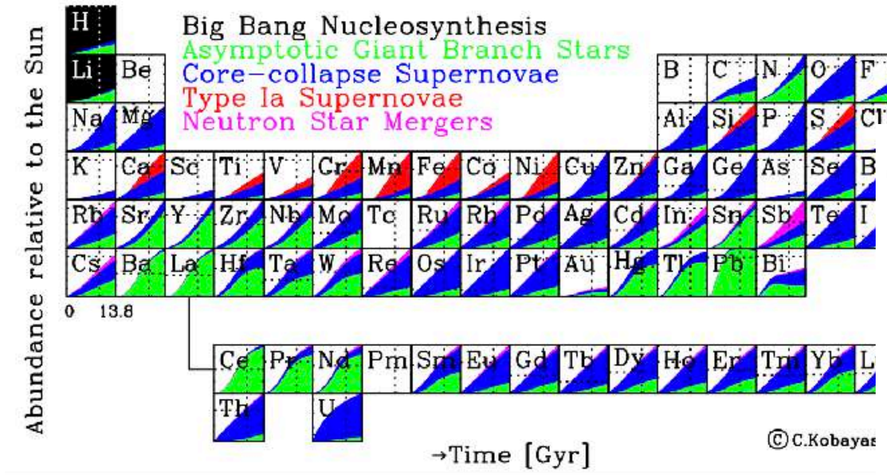
The beginning of the story

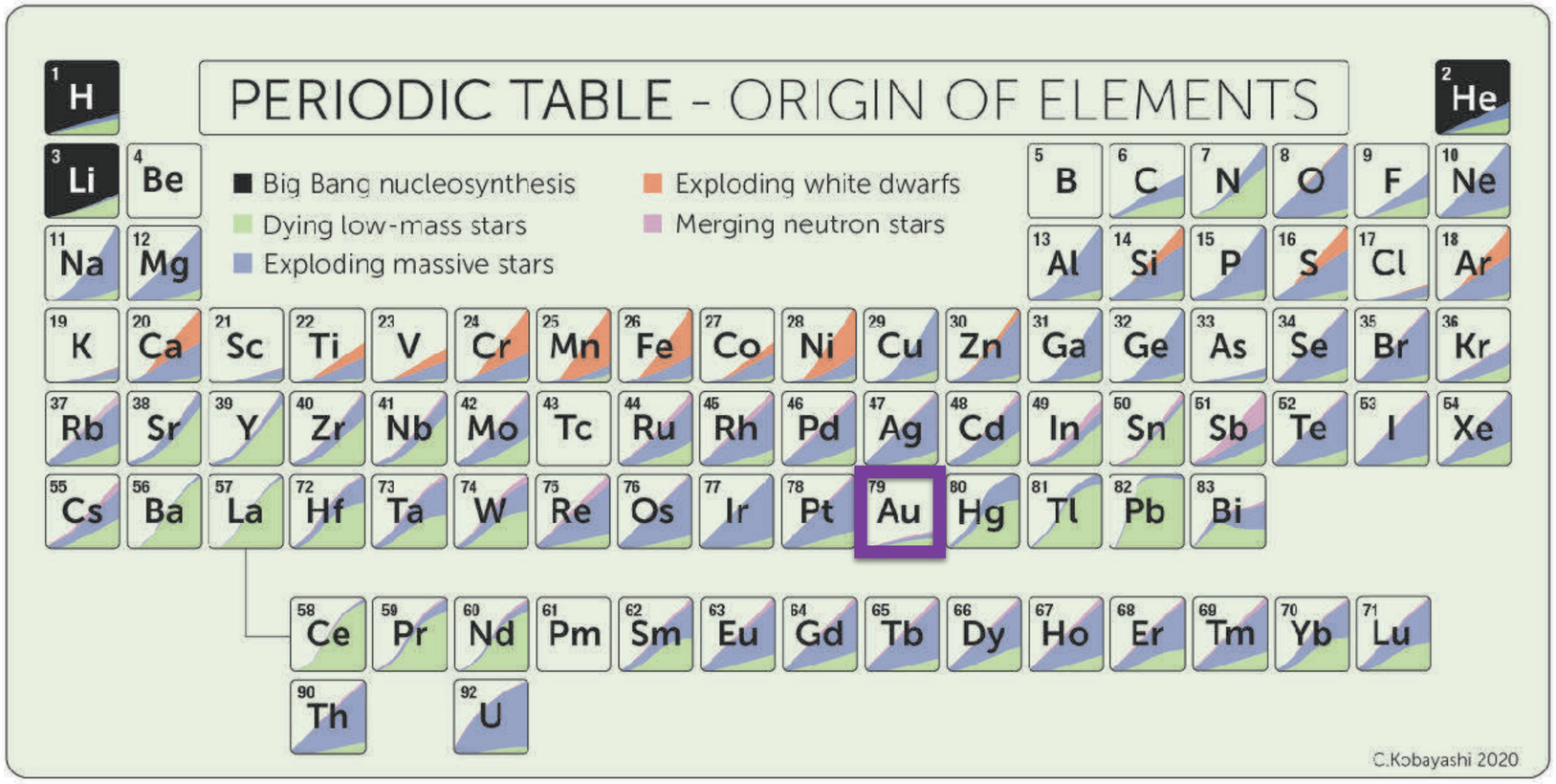
C. Kobayashi, A. Karakas, M. Lugaro, ApJ 2020

“The origin of Elements from Carbon to Uranium”

・challenge to explain all the isotopes in GCE (Galactic Chemical Evolution)

・they assume supernovae are the main source of r-process (than NS mergers)

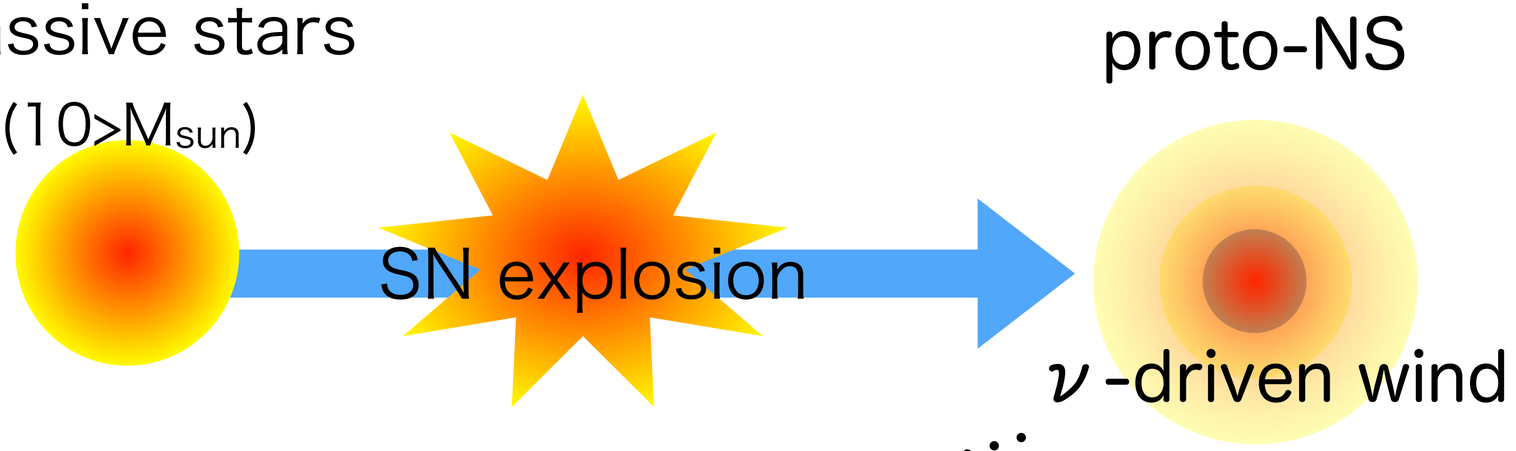




Astrophysical r-process sites

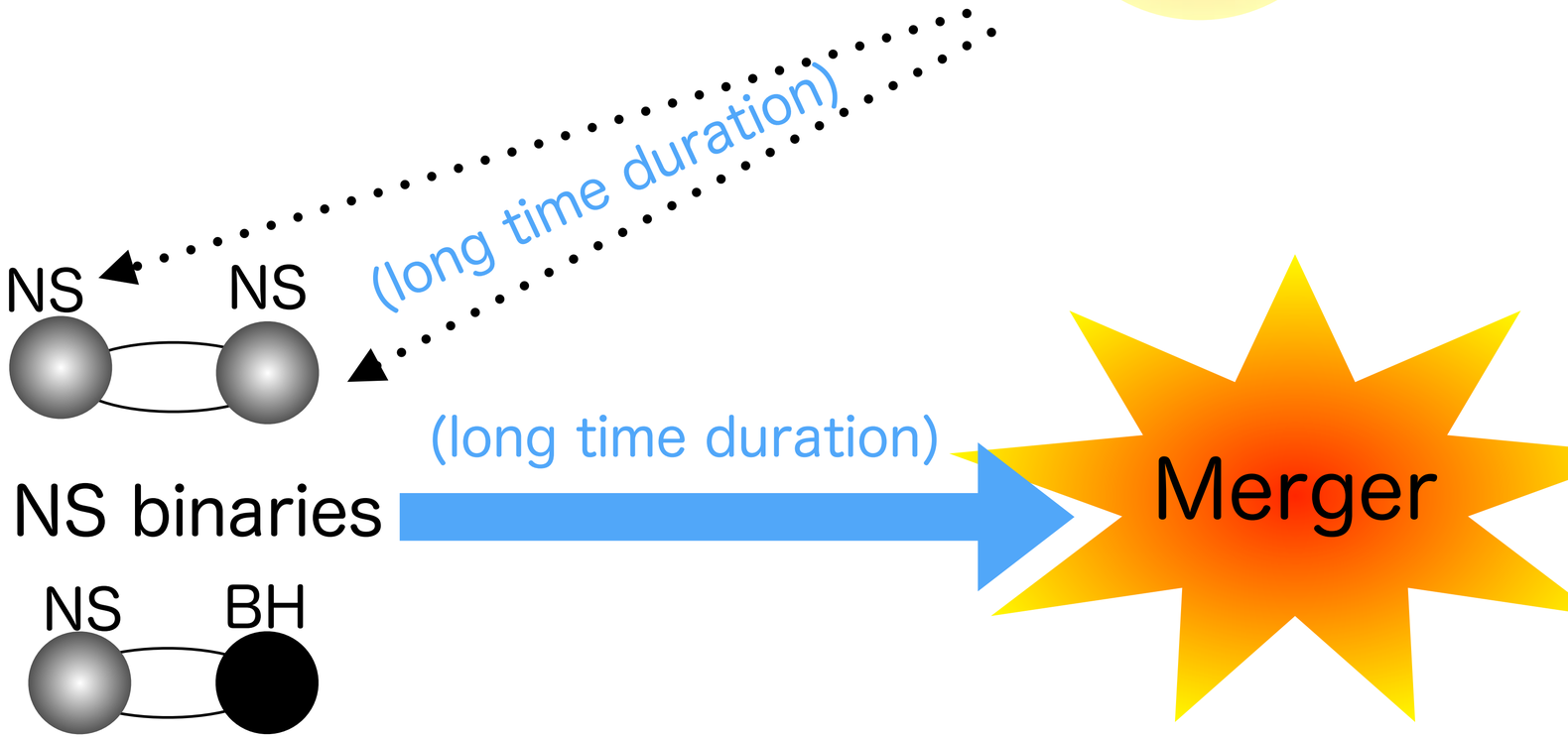
core-collapse SNe

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

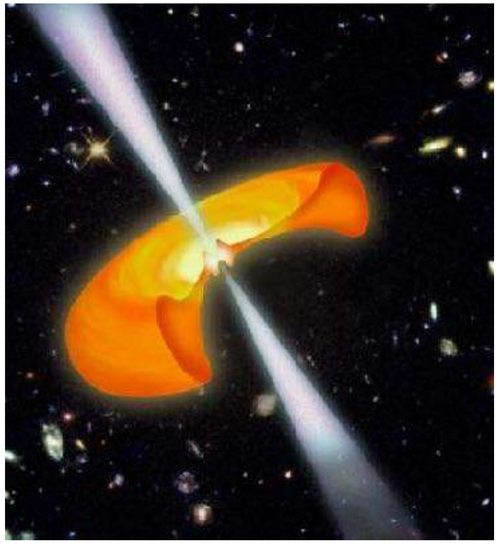


NS (binary) mergers

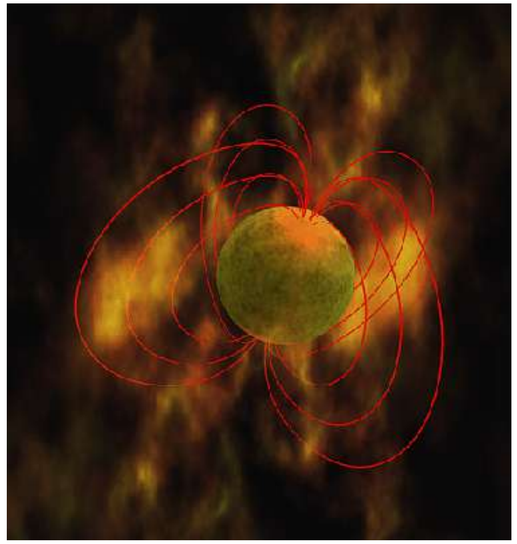
The “observational” evidence with gravitational waves (GW170817)



Magneto-rotational SN scenario



hypernova/jet-like SN



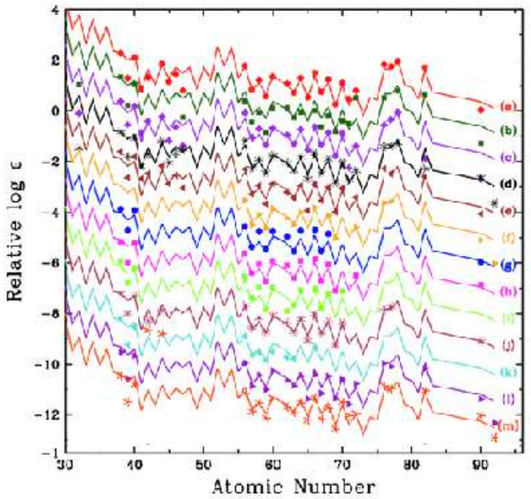
magnetars

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

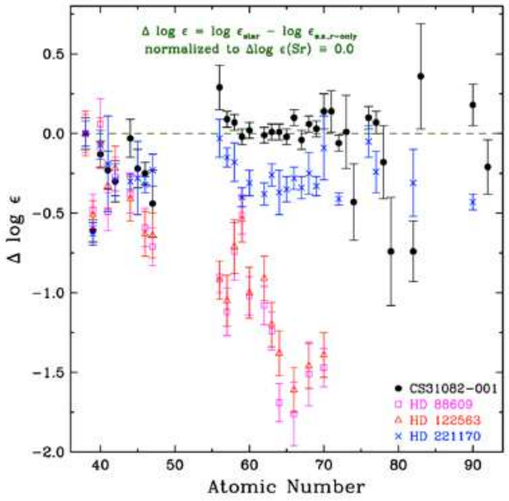
- variety of r-process patterns in metal-poor stars
- can be rare ～ 1% of ccSN rate
- Galactic chemical evolution
  - needed as external sources with NS mergers?
  - MR-SNe, “hypernovae”, collapsars etc.??

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

r-process in MP stars



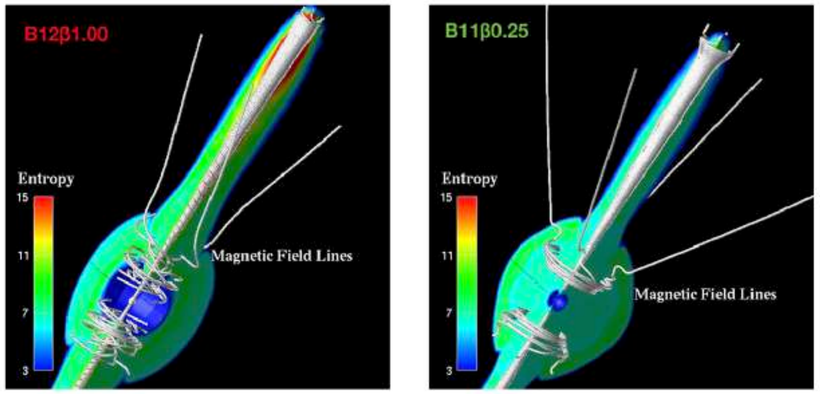
“weak” r-process?

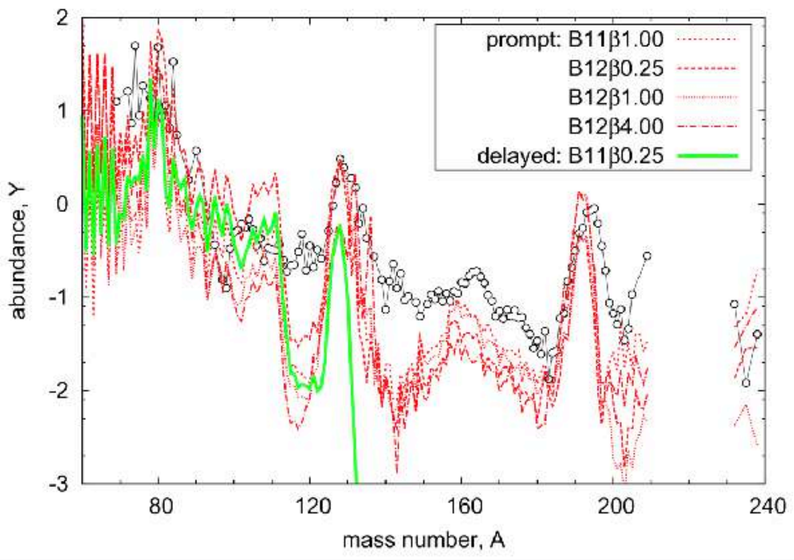


Cowan+2021

Prequel story?

Nishimura+(2015) ApJ

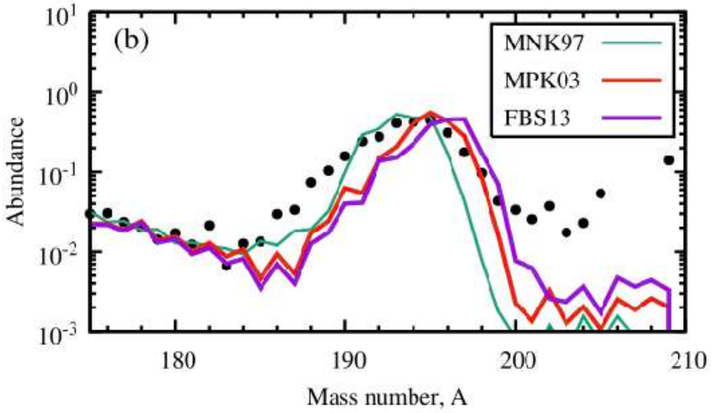




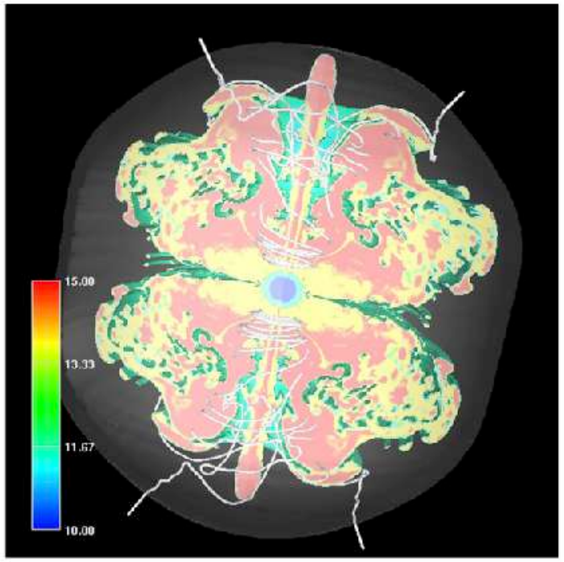
used by Kobayashi+2020

update my r-process calculations (β-decay)

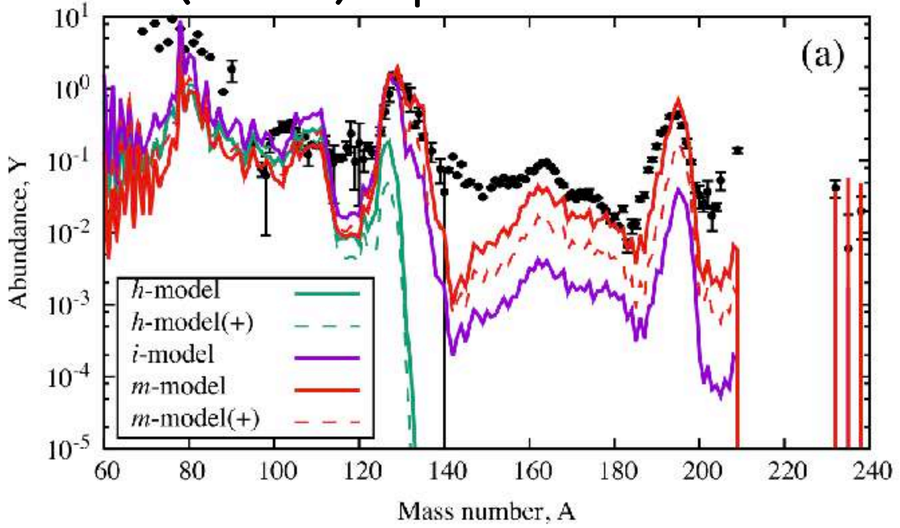
NN+2016, PLB (2016)



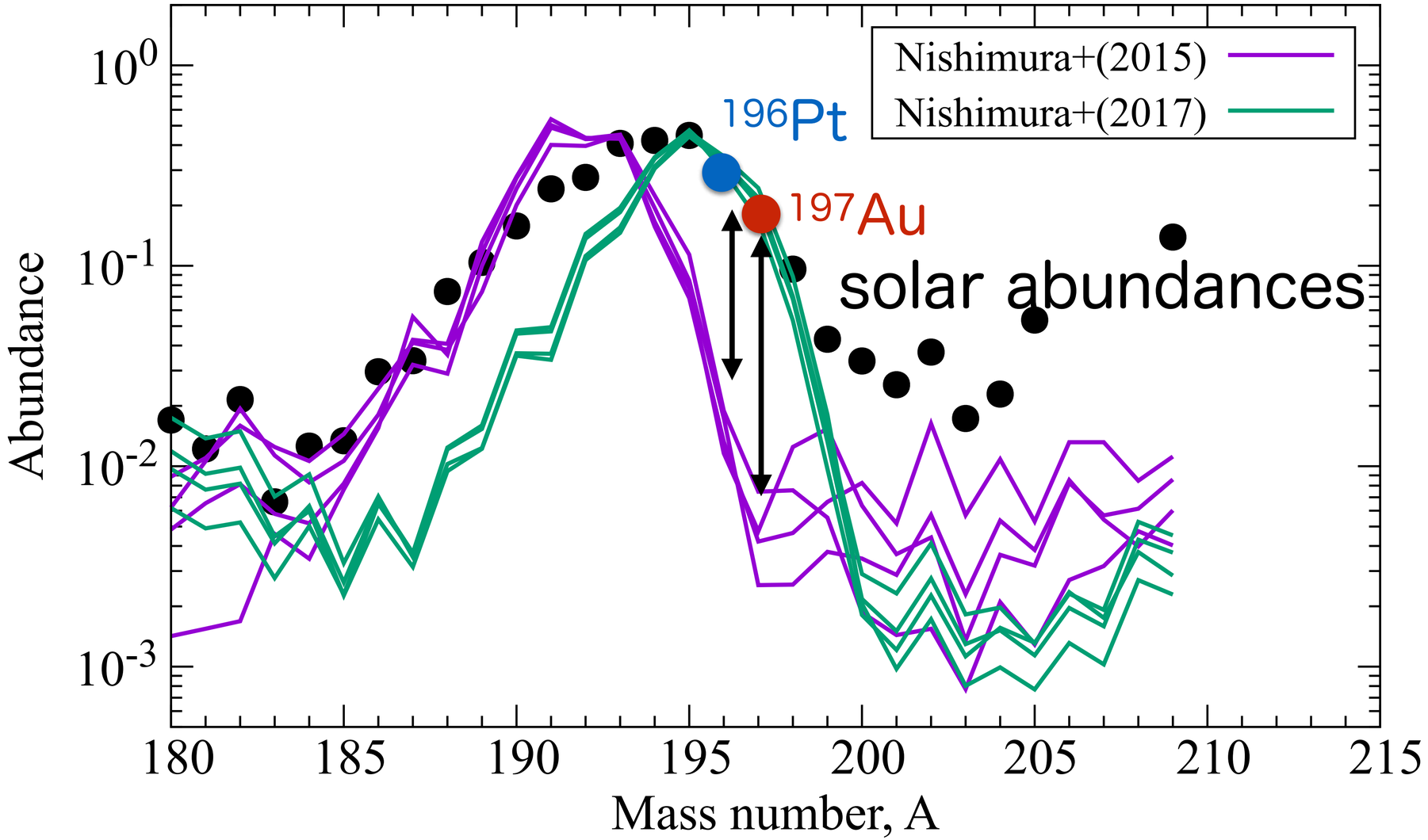
comparison of different beta-decay rates



Nishimura+(2017) ApJL

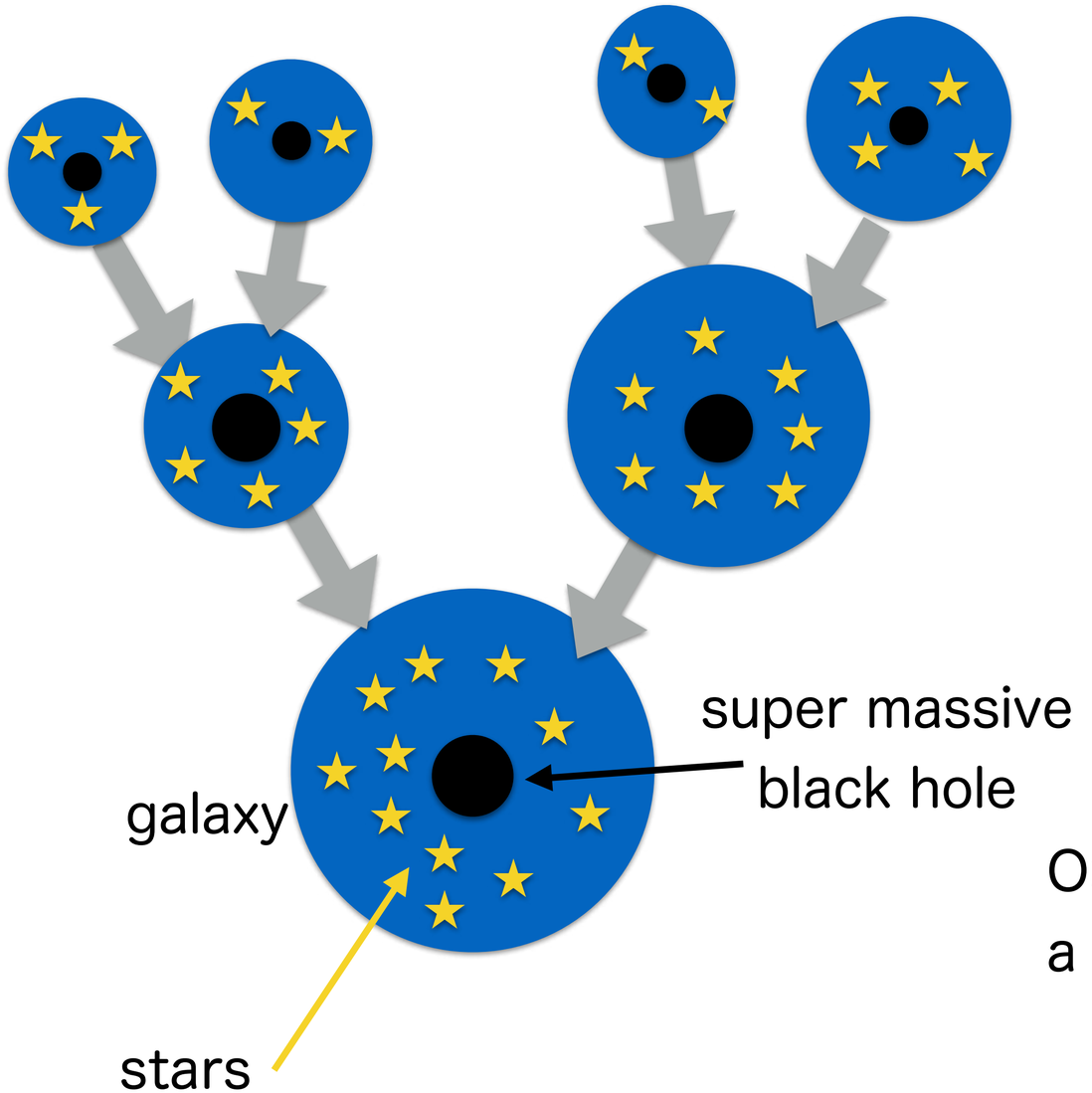


Prequel story?



Evolution of galaxy

Hierarchical structure formation



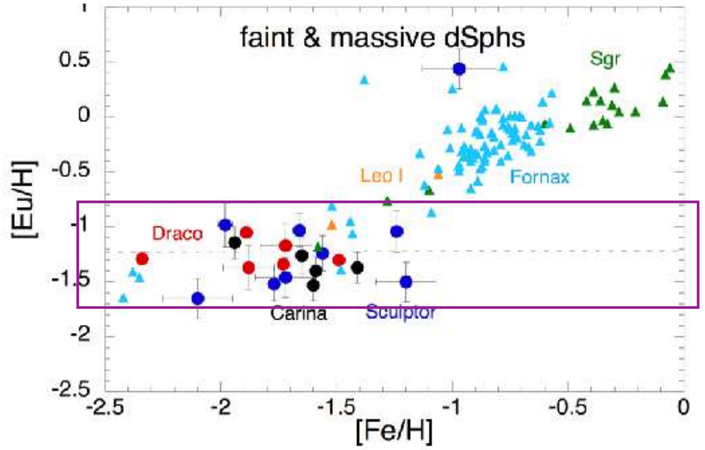
galaxy formation simulation

Takeda, Nukatani, Saito (2007)

Our Galaxy (Milky Way) was merged with
a dwarf galaxy (Gaia-Enceladus) 10 billion yrs ago

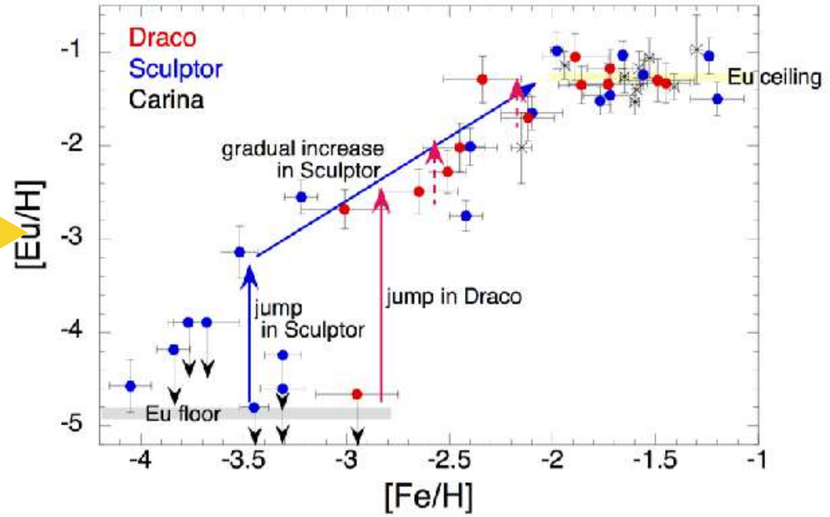
GCE: early dwarf spheroidal galaxies

Tsujimoto & Shigeyama A&A (2014)

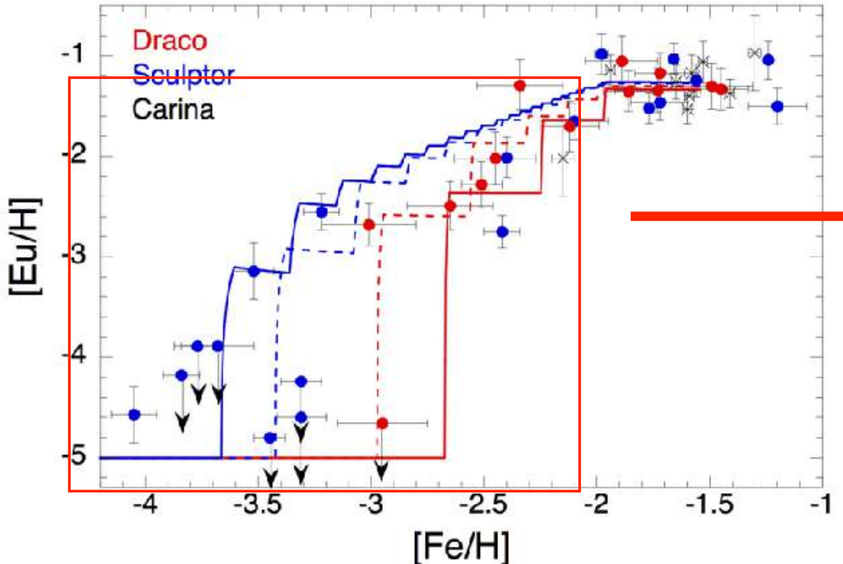


[Fe/H] < -2.5

Tsujimoto & NN ApJL (2015)
(see also, Tsujimoto+ PASJ 2015)



Tsujimoto & NN, ApJL (2015)



Chemical evolution models

GCE models suggest:
- rate event: 1/200 CC-SNe
- large Eu ejection: ~10^{-5} Msun

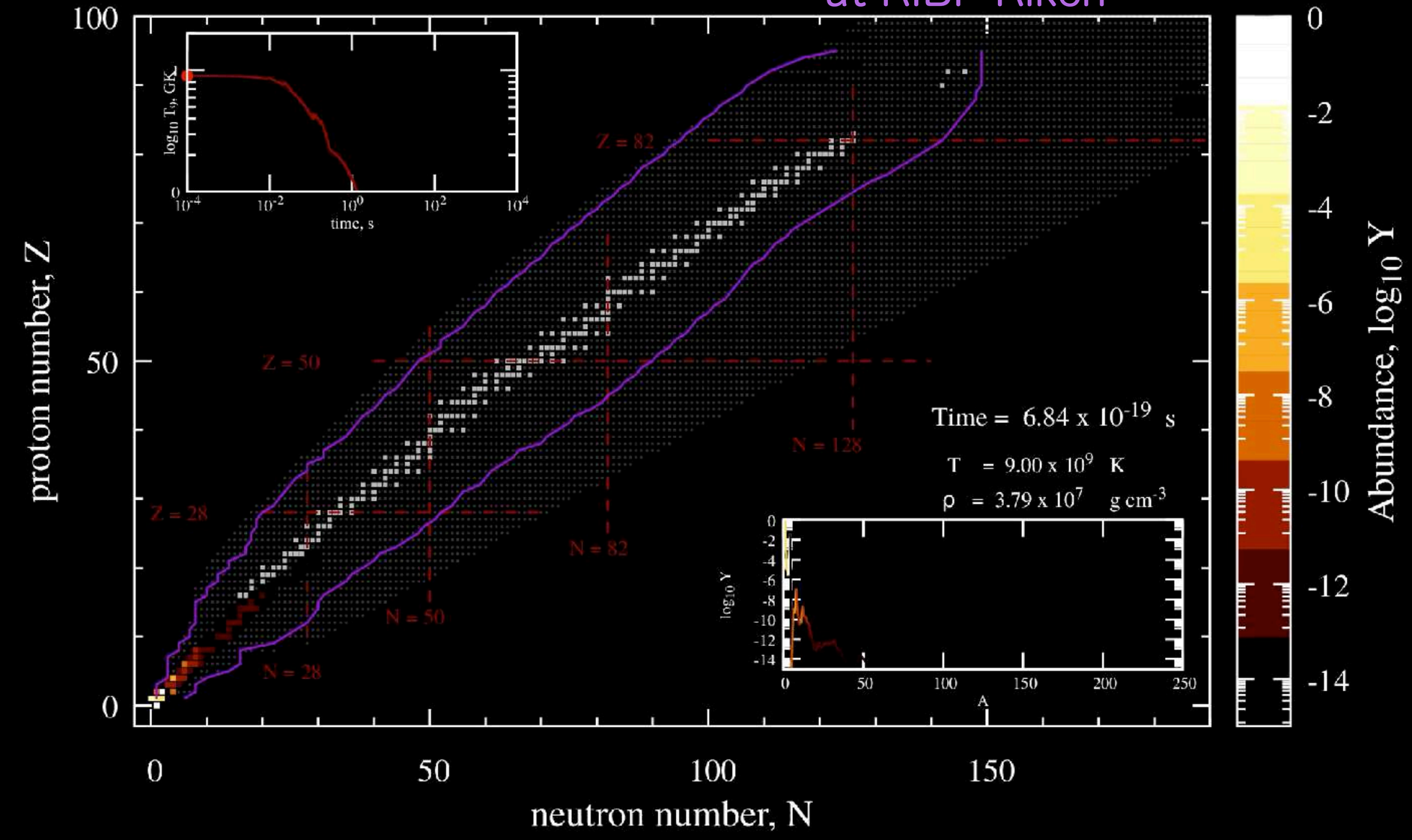
agree with our MR-SN models
(e.g. Nishimura+ 2015)

2. Nucleosynthesis part:

N = 126 isotones and production of the r-process 3rd peak

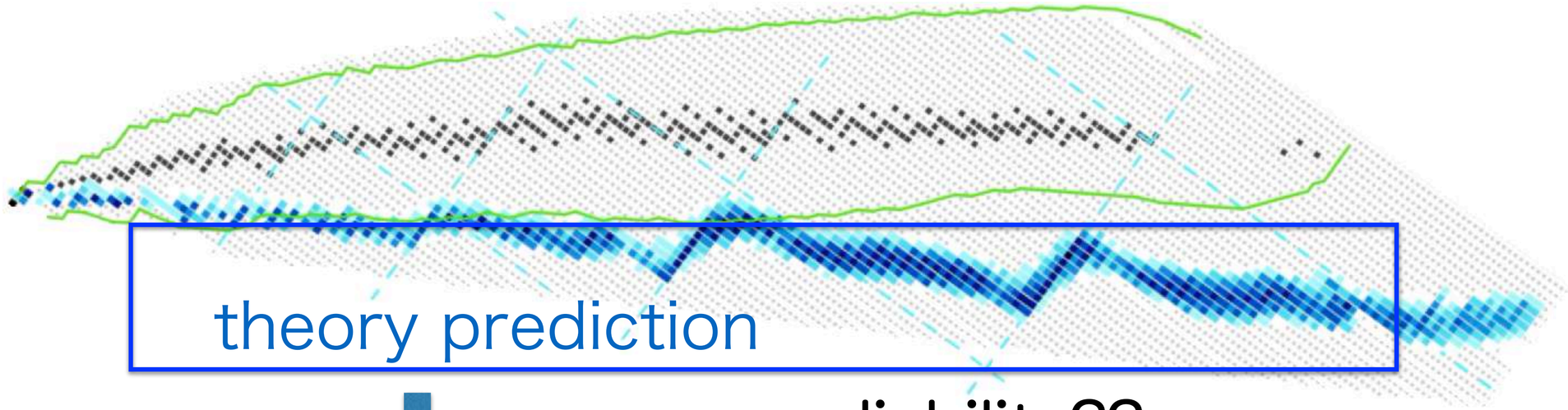
r-process nucleosynthesis “flow”

1e-4 pps limit
at RIBF Riken



Theoretical Prediction

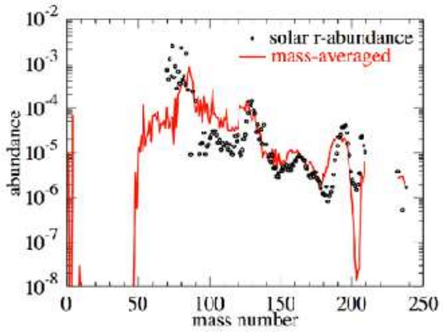
r-process path is beyond experimental accessible region

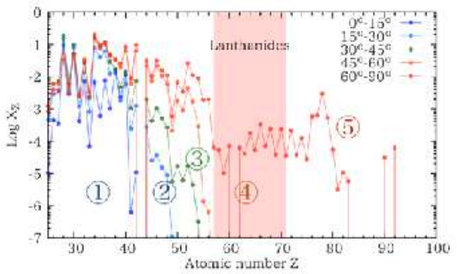


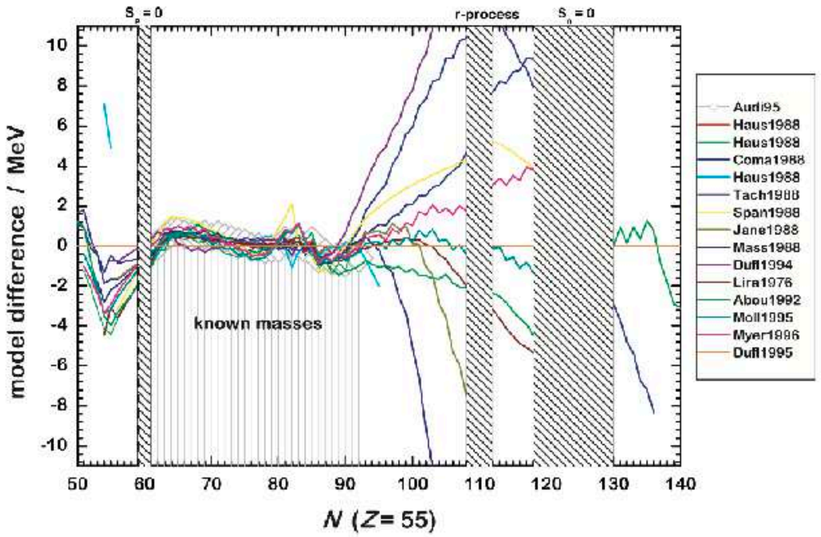
astrophysics

reliability??

large uncertainty in theory







Basics of the r-process

・nuclear physics

・“classical” solution : (n,γ)/(γ,n) equilibrium, waiting-point aprox.

① r-process path : (n,γ)/(γ,n) equilibrium → nuclear mass

② r-process abundance : half life (ratio) on the path → β decay

(abundance) / (β-decay half life) = constant

③ decay : smoothing by n-emission → β-delayed n emission

(fission of heavy nuclei : cannot consider?) → fission

① reverse reaction (photodissociation) is determined by the detailed balance :

$$\lambda_\gamma(Z,N) \propto T^{3/2} \exp\left[-\frac{S_n(Z,N)}{kT}\right] \langle \sigma v \rangle_{(Z,N-1)}$$

neutron separation E

neutron capture rate

r-process path = (n,γ) and (γ,n) balance

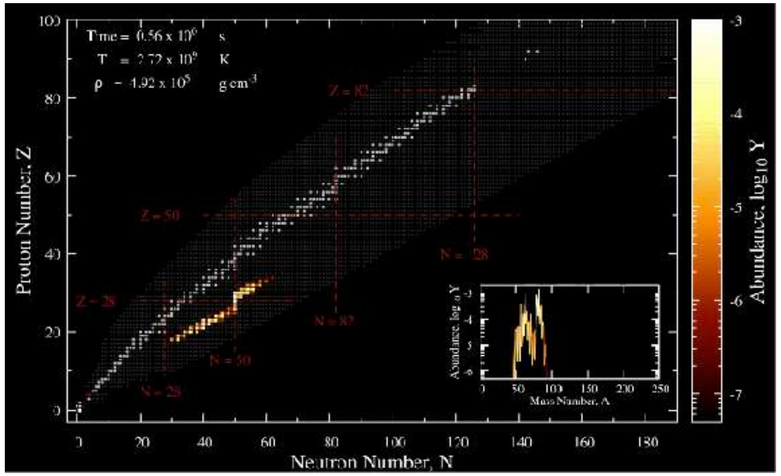
② abundance

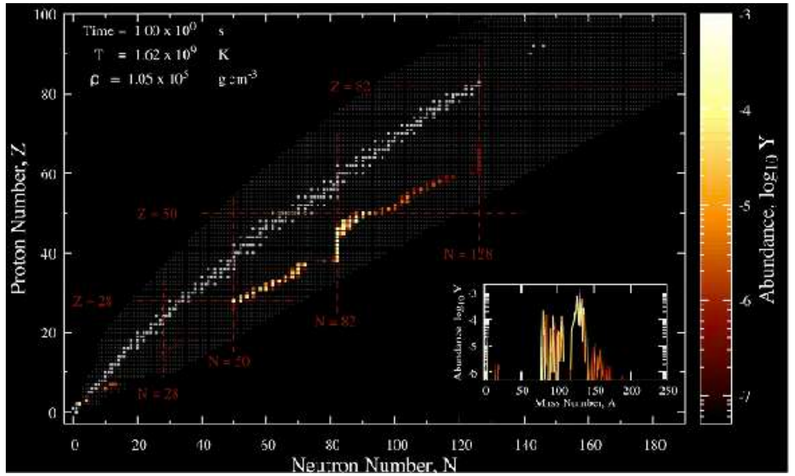
determined by the ratio of β-decay rate (half life) on the path;

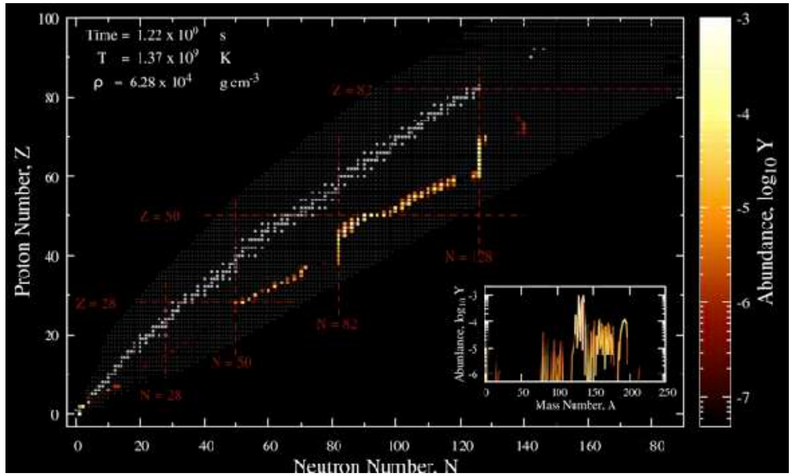
(in contract to the s-process determined by (n,g) rate)

Modern nucleosynthesis simulations

- Nuclear physics
  - method : calculations by nuclear reaction network
    - consider all possible reactions and decays
    - (n,g)/(g,n) partially achieved or not realized (cold r-process)
    - β-decay, (n,g), fission for a wide range of n-rich nuclei







r-process: nucleosynthesis mechanism

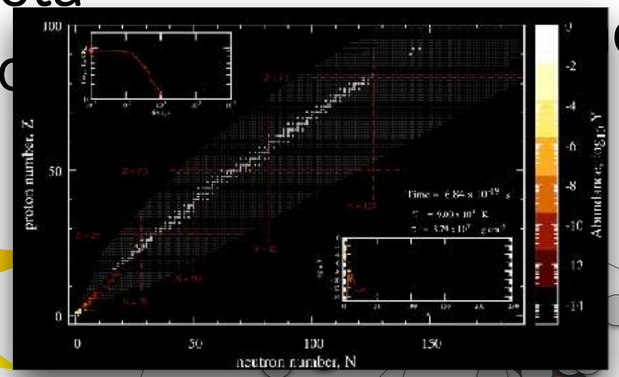
neutron-rich ejecta
in stellar explosio

① NSE (> 1 MeV)

d α)

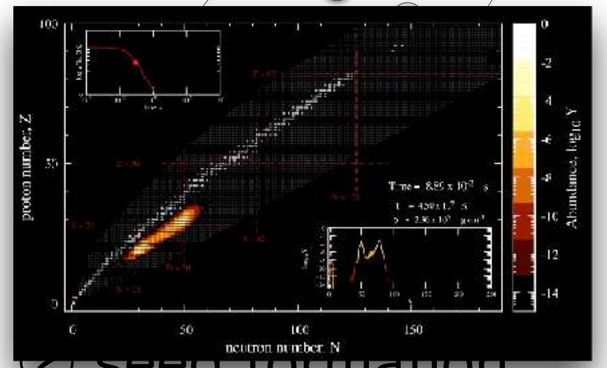
proton
neutron

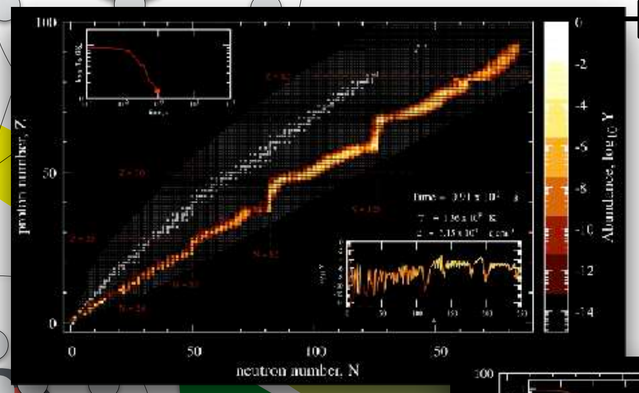
high T & ρ



③n-capture: A↑
(A,Z) → (A+1,Z)

⑤ β-decay
+fission

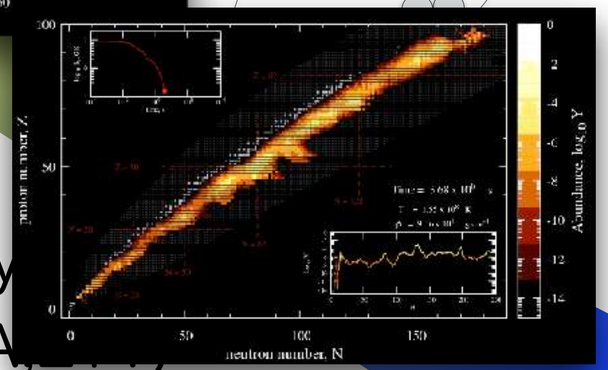




② seed formation
(α + recombination)
A ～ 100

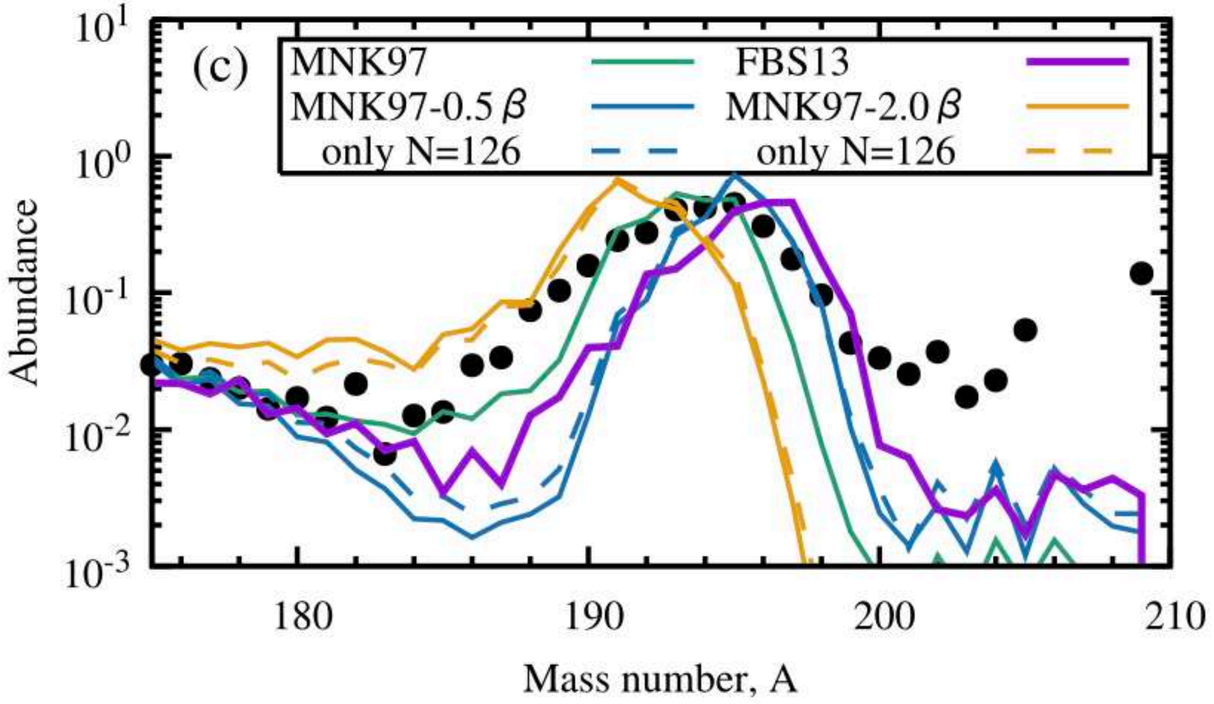
^{-}e

④β-decay
(A,Z) → (A

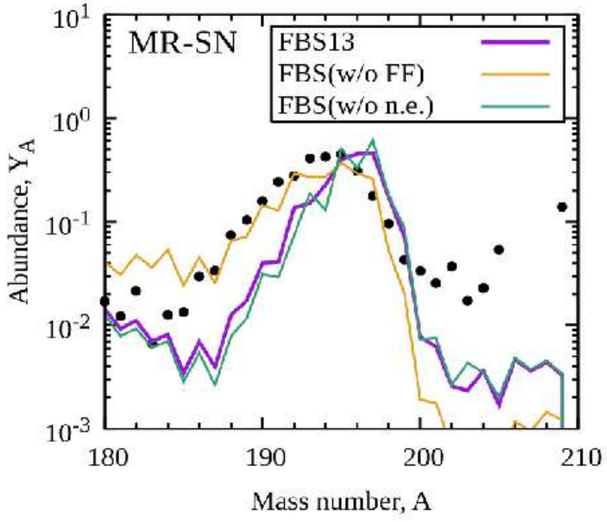


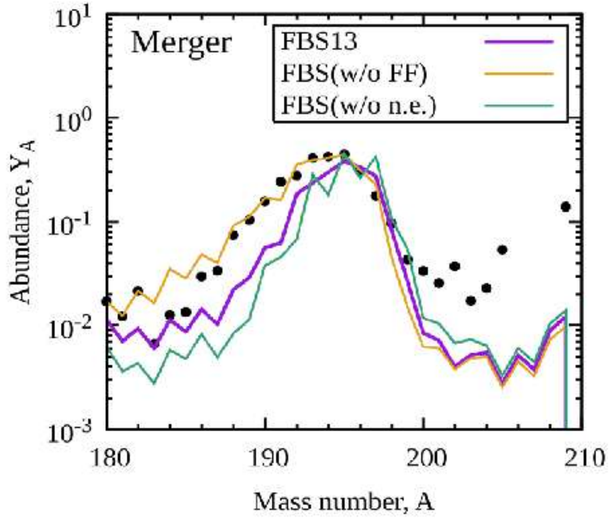
β-decay impacts on the 3rd peak

NN+2016



different astrophysics models

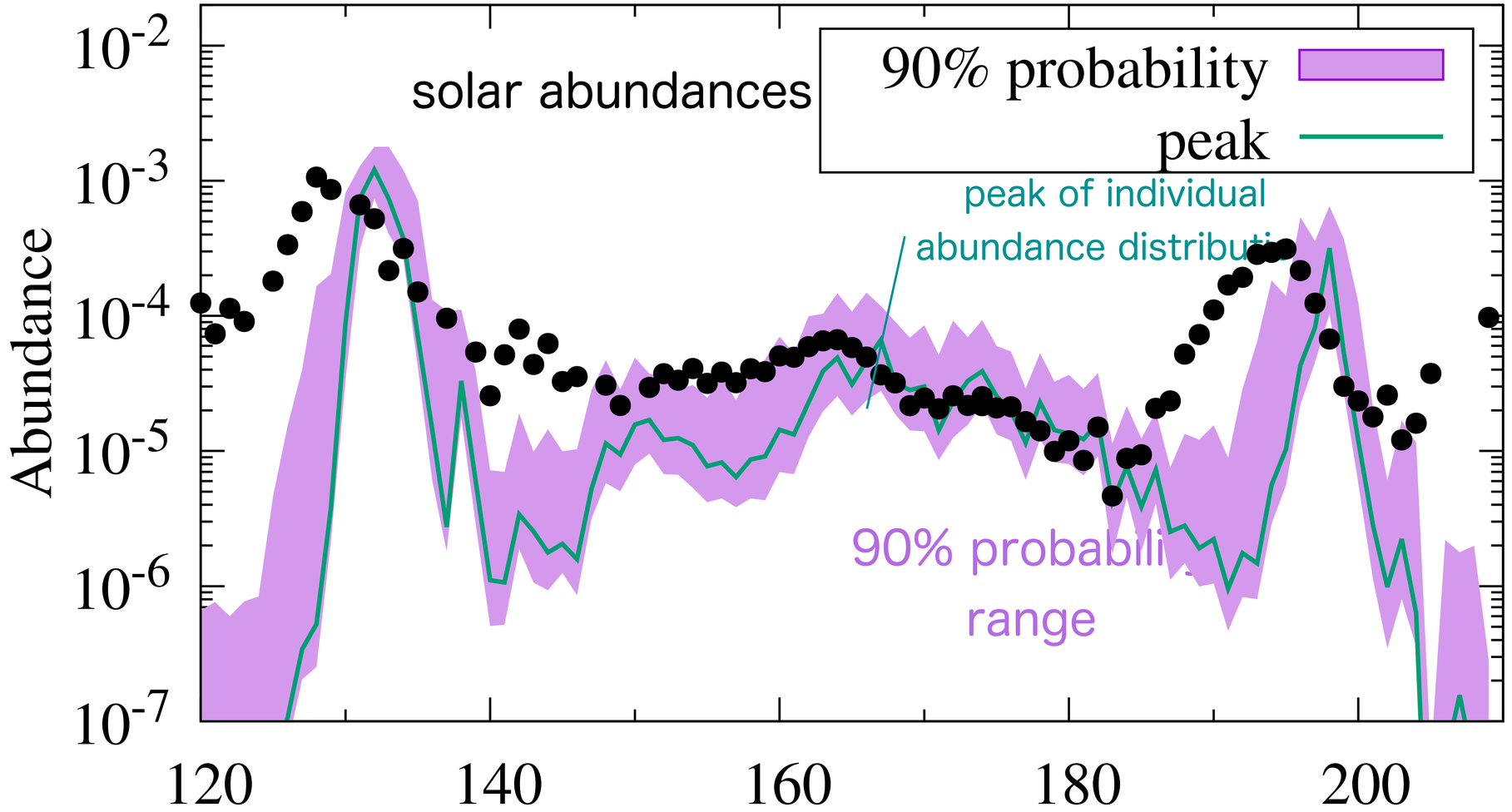




Collective uncertainties on the r-process

impacts on reaction/decay rate variation with MC nucleosynthesis

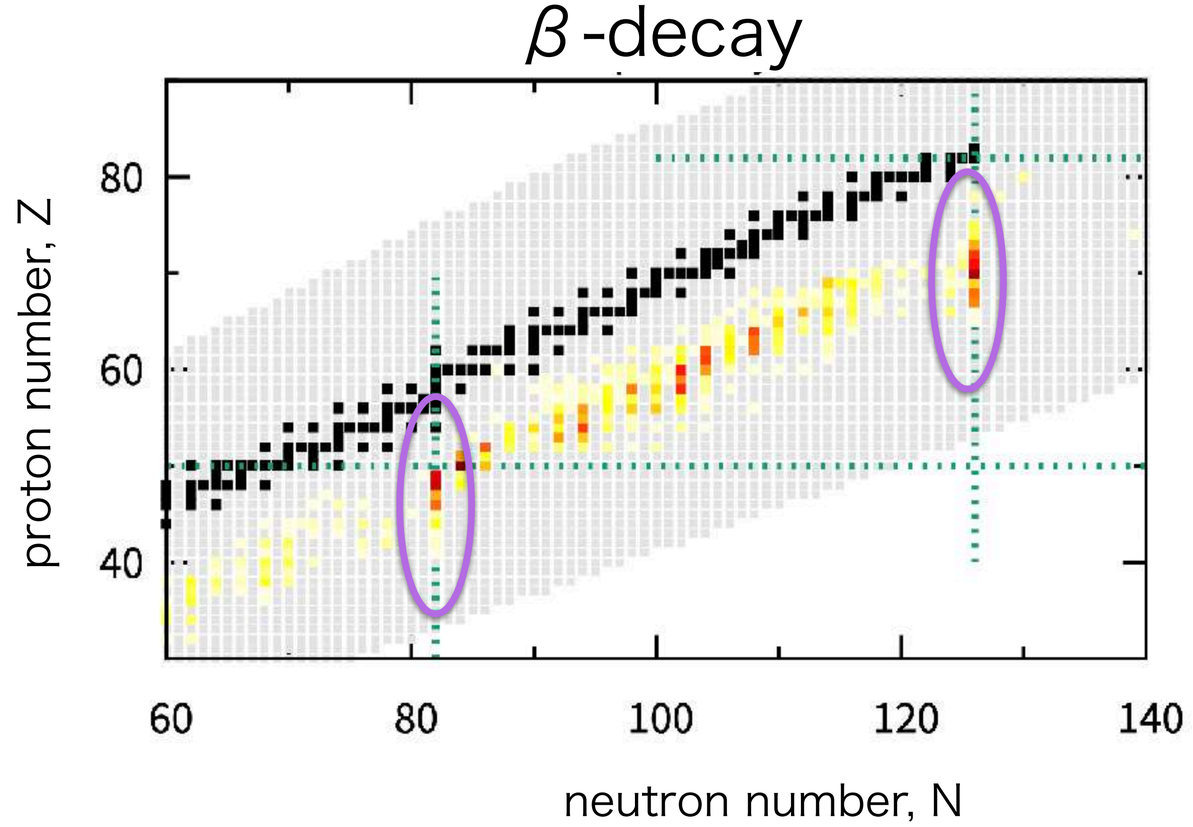
(n,g) x50, β x10

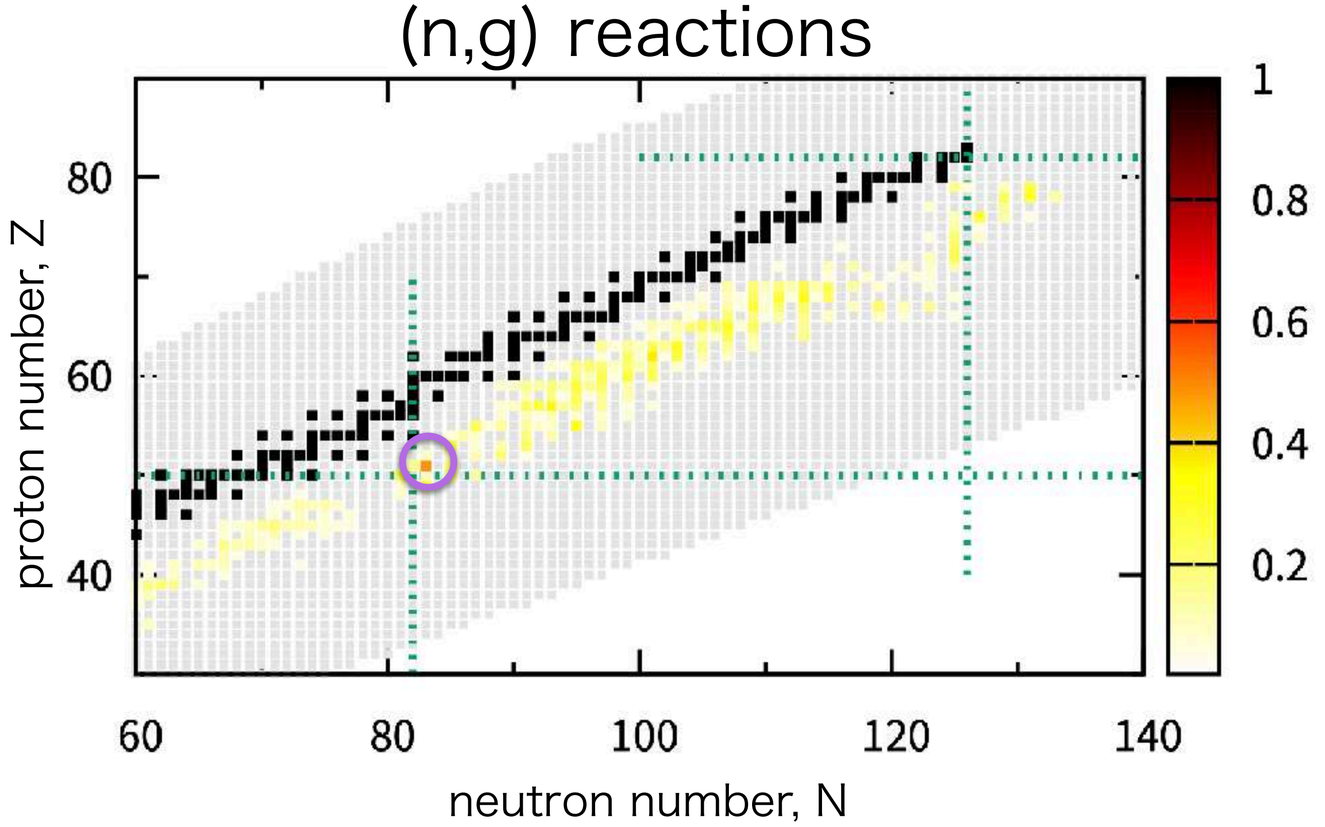


does not consider
heaviest nuclei (fission)

Individual impacts

Impacts on the r-process of individual rates





Summary and perspective(personal)

1. “The missing gold problem” in GCE

・It may be caused by “insufficient” theoretical prediction

・Though variation/differences by astrophysical parameters, significant underproduction of Au (gold) in some particular GCE studies would be improved by r-process prediction

・Anyway, Galactic chemical evolutions studies are difficult…

2. N = 126 halflives and the 3rd peak formation

・β decay of n-rich N = 126 isotones have significant impacts on the 3rd peak formation

・This is also (obviously) confirmed by comprehensive MC sensitivity calculation

→ investigations by improved “theory” data is also expected

3. Future perspective (personal)

・Recent theoretical progresses in Japanese community (DFT studies, Minato-san, Anil etc)

・Personally, although I had already done, it would be worth to revisit it now.

・I need to clear up any confusion (“the missing gold problem”) in the GCE study.