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Possible observational properties of r-process nucleosynthesis in jet-driven core-collapse supernovae

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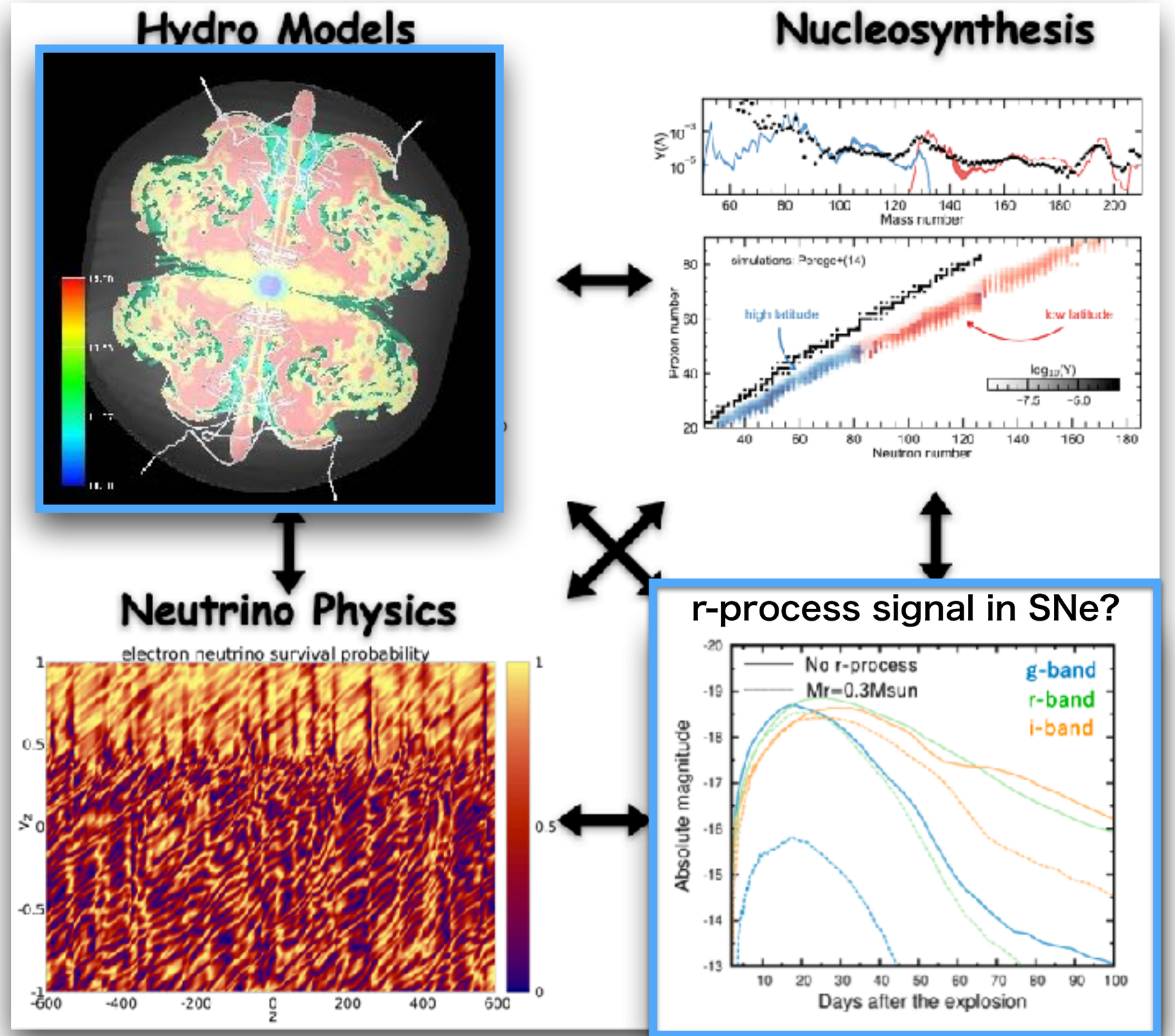
Remnants of ~~neutron star mergers~~
core-collapse SNe with the r-process?



Talk plan

- r-process in Jet-driven cc-SNe
  - central engine and ejection of r-process elements
  - shock propagation and r-nuclei ejection
  - Signatures in SN light-curves?
- Nuclear physics uncertainty
- Summary

References

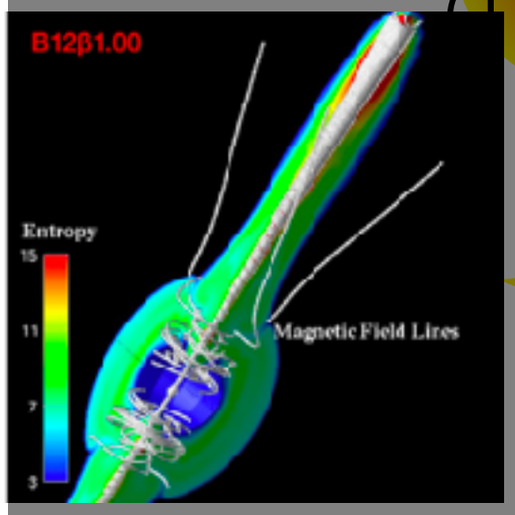
- Winteler+NN+(2012) ApJL 750:L22
- NN, Takiwaki, Thielemann (2015) ApJ 810:109
- Tsujimoto & NN (2015) ApJL 810:L10
- NN, Sawai, Takiwaki+(2017) ApJL 836:L21
- Tsujimoto & NN (2018) ApJL 863:L27
- NN, Matsumoto+, in prep.
- Hasegawa+NN+, in prep.

Astrophysical r-process sites

core-collapse SNe

Massive stars

(1(>M_{sun})



Magneto-rotational driven Supernovae

proto-NS

utrino-driven wind

・NO direc ion

・Theoreti lt

・not ver rich

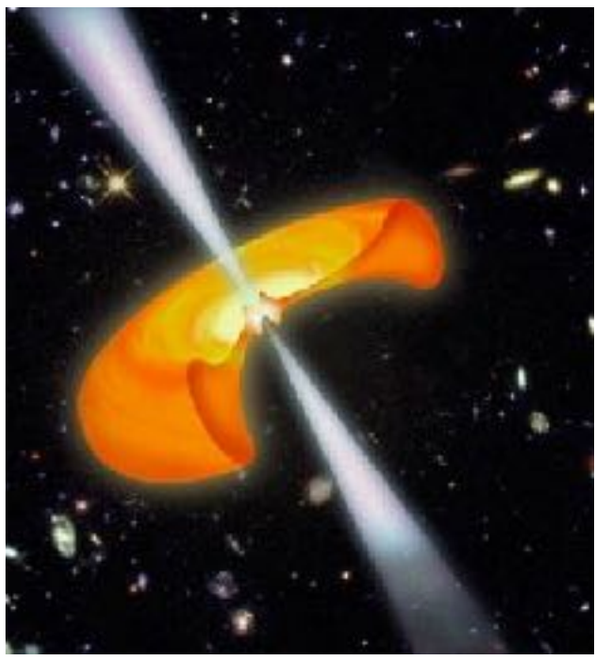
NS-NS binaries

NS NS

Merger

r-process was “observed” with GW170817

Magneto-rotational SN scenario

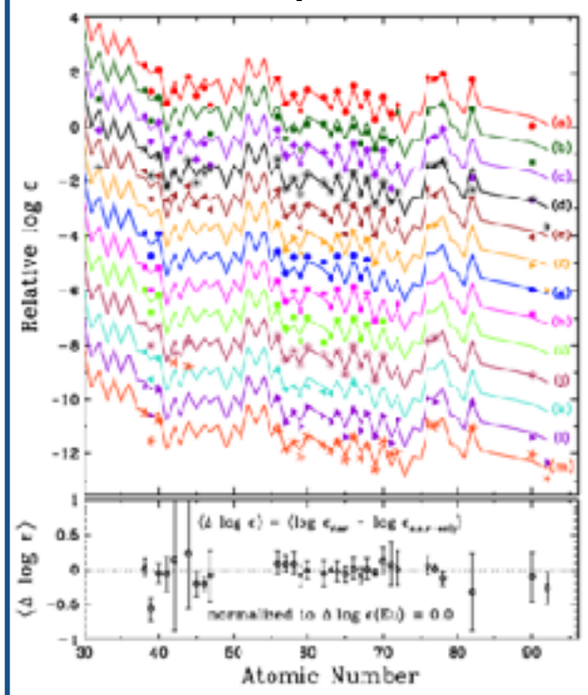


hypernova/jet-like SN

- 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 pattern in metal-poor stars
- can be rare 1%
- Galactic chemical evolution
  - large DTD problem of NS mergers?
- needs external sources?
  - MR-SNe, hypernovae, “collapsars”??
  (see, Wehmeyer+2015, Tsujimoto&NN 2015,
  Cescutti+2017, Siegel+2019, Kobayashi+2020 etc.)

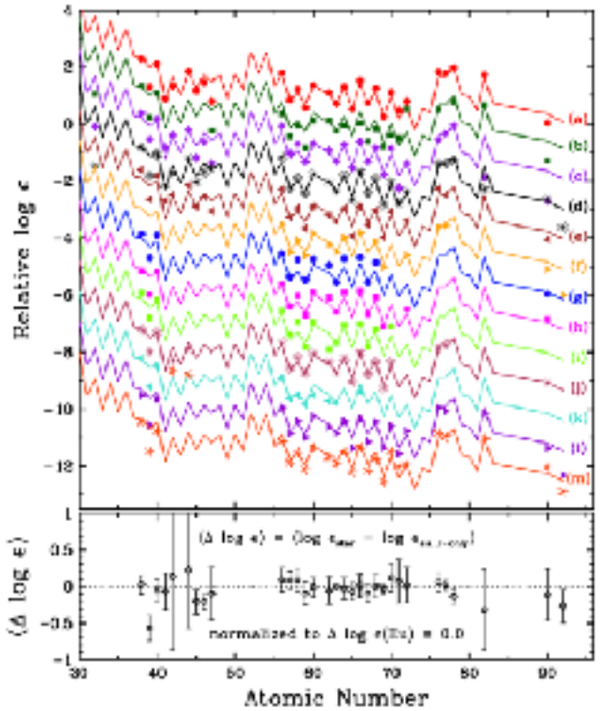
r-process
in metal-poor stars



Cowan+2021

r-Process-rich stars and GCE

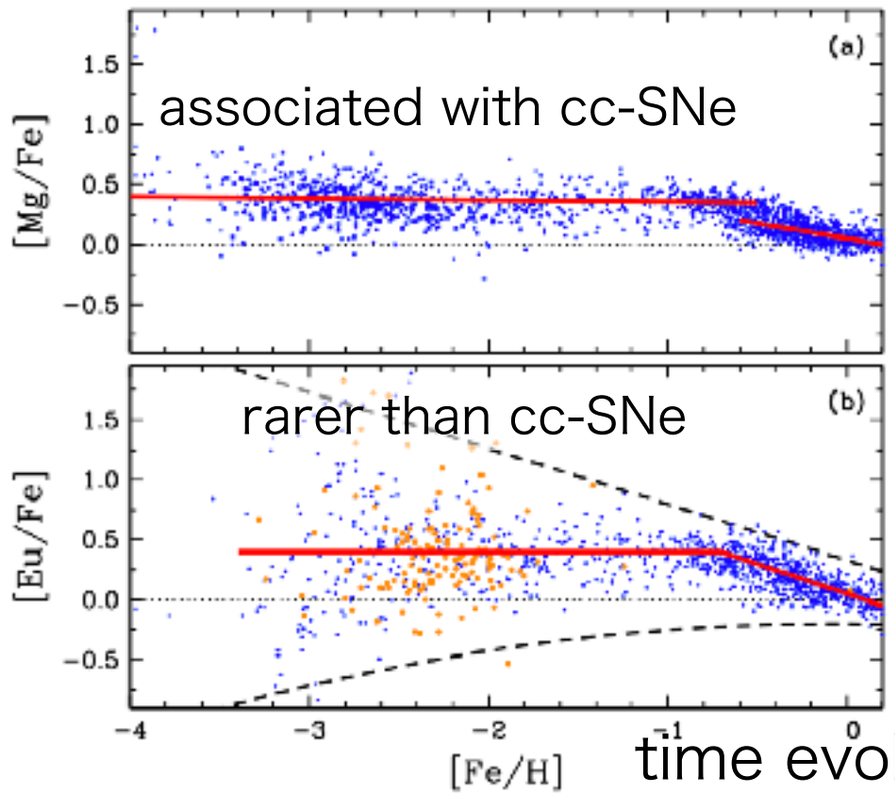
Galactic halo stars



solar-like r-process patten

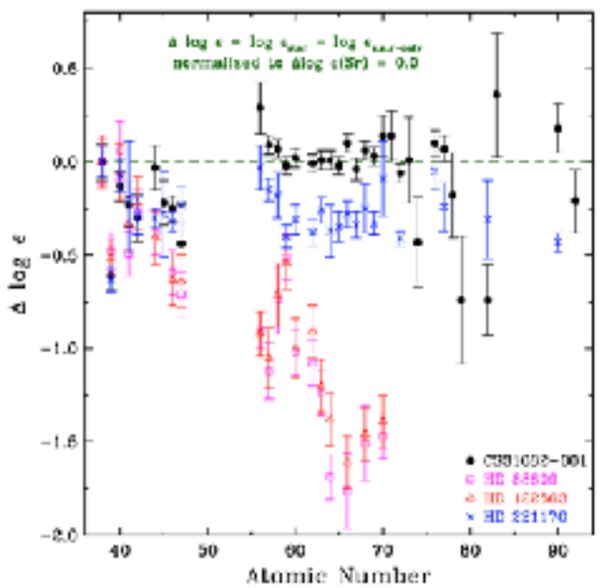
r-process elements

production event vs. SNe Cowan+2021



time evolution

“weak” r-process patten



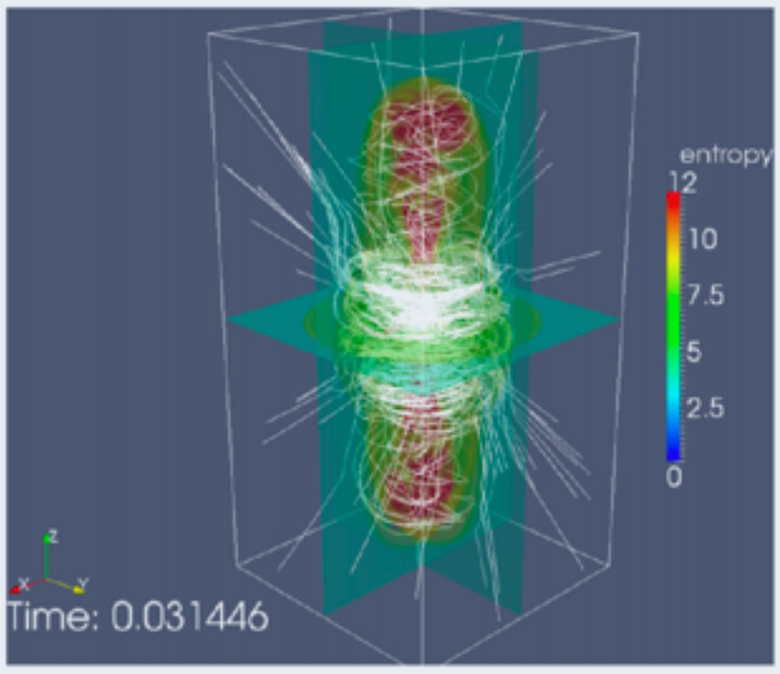
Galactic chemical evolution

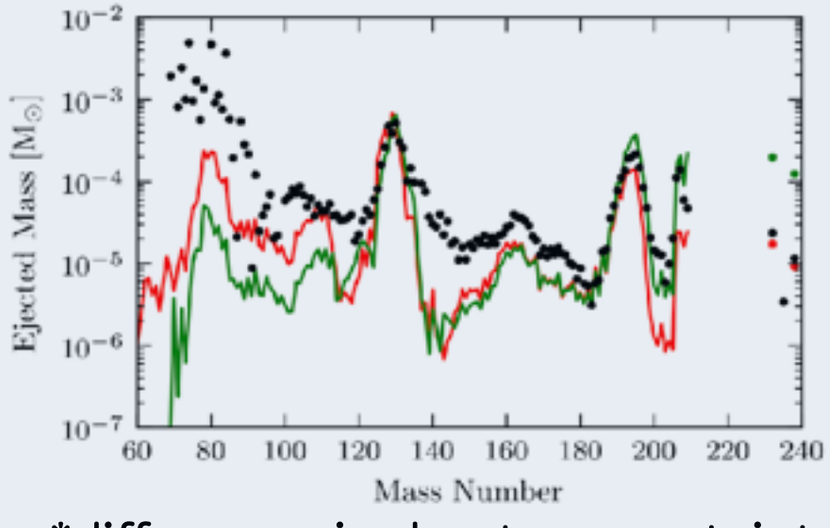
- NS-NS mergers can be the main source (many papers, e.g., Wanajo+2021)
- but, it needs alternative source? (e.g, Cote+2019)
  → Rare cc-SNe events? (collapsars??)
  - GCE of dSph by Tsujimoto & NN (2015, 2018)
  - frequency: 0.5 % of CC-SNe; large mass: ～10^{-5} M_{sun}

3D effects on jets and r-process

strong jet in 3D

Winteler+NN+(2012)

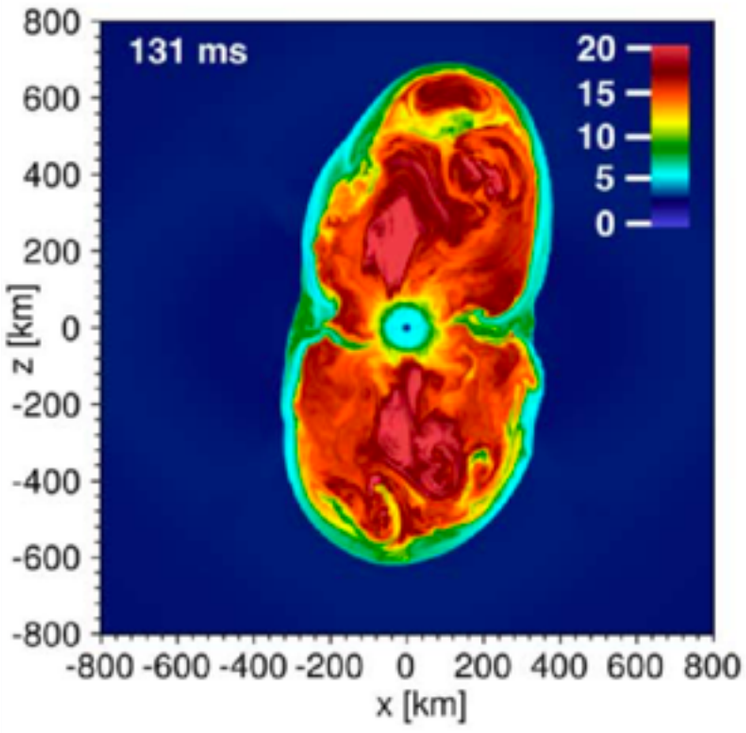


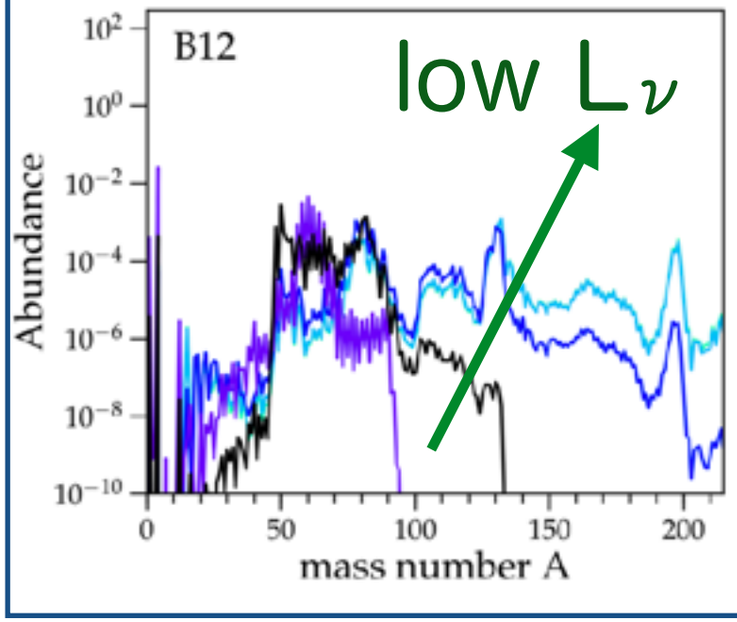


*difference is due to uncertainty

deformation by hydro-instability

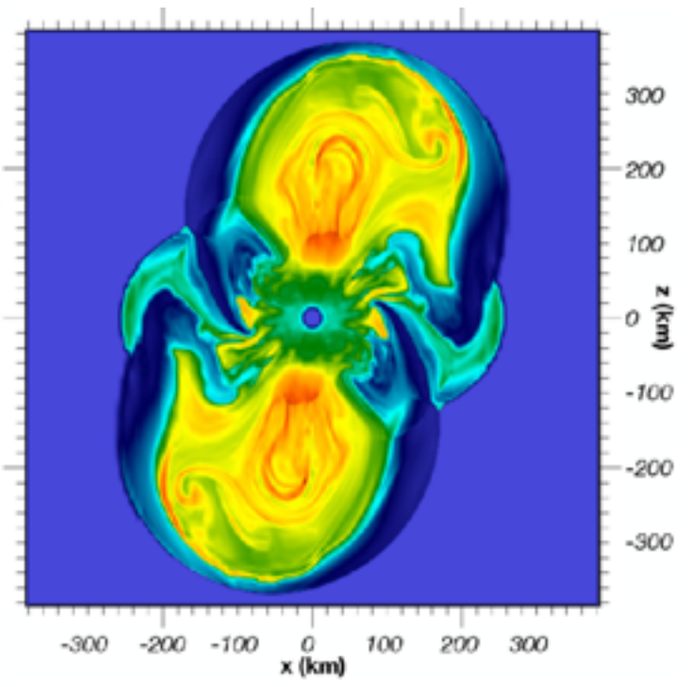
Mösta+(2018)

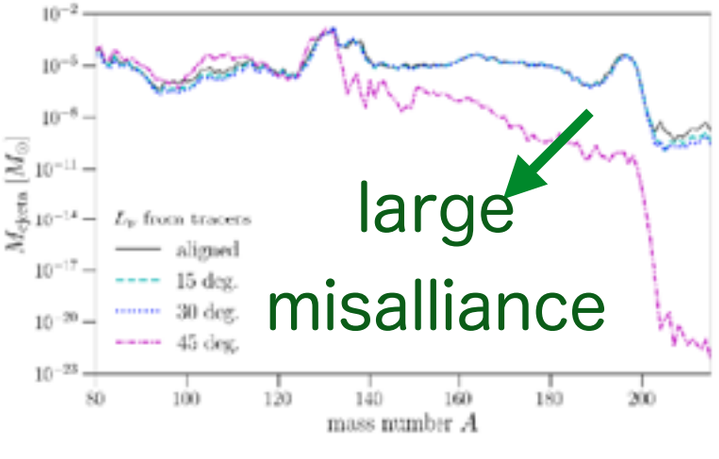




misalliance of B-filed and rotation

Halevi&Mösta(2018)

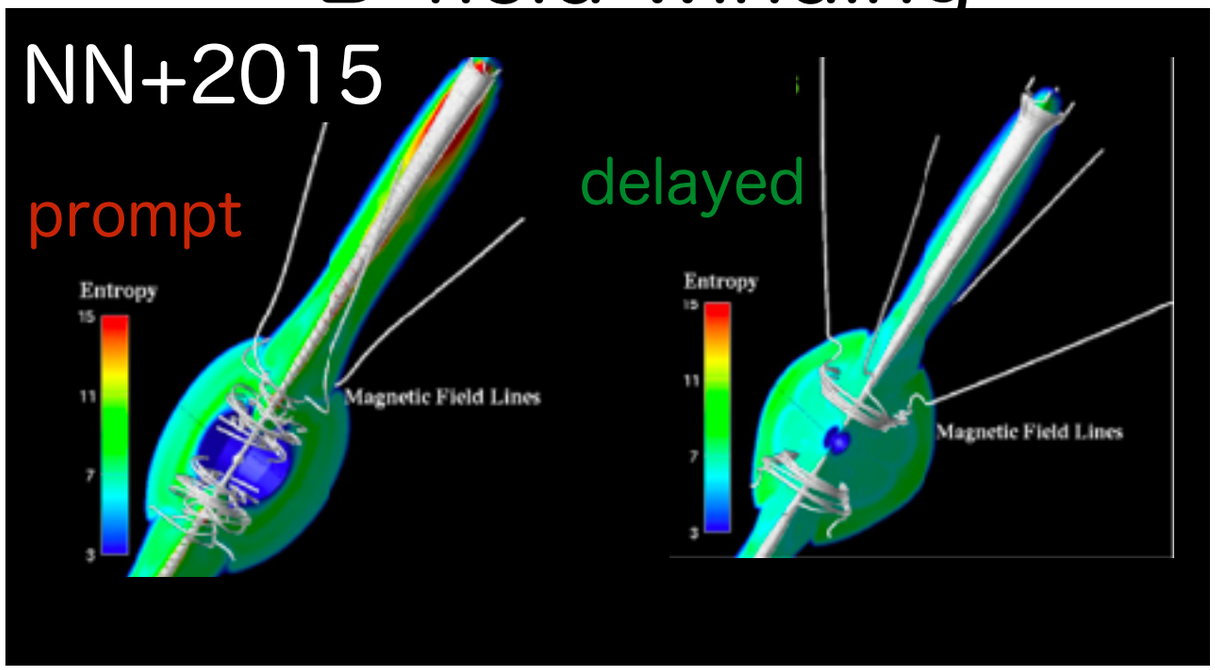


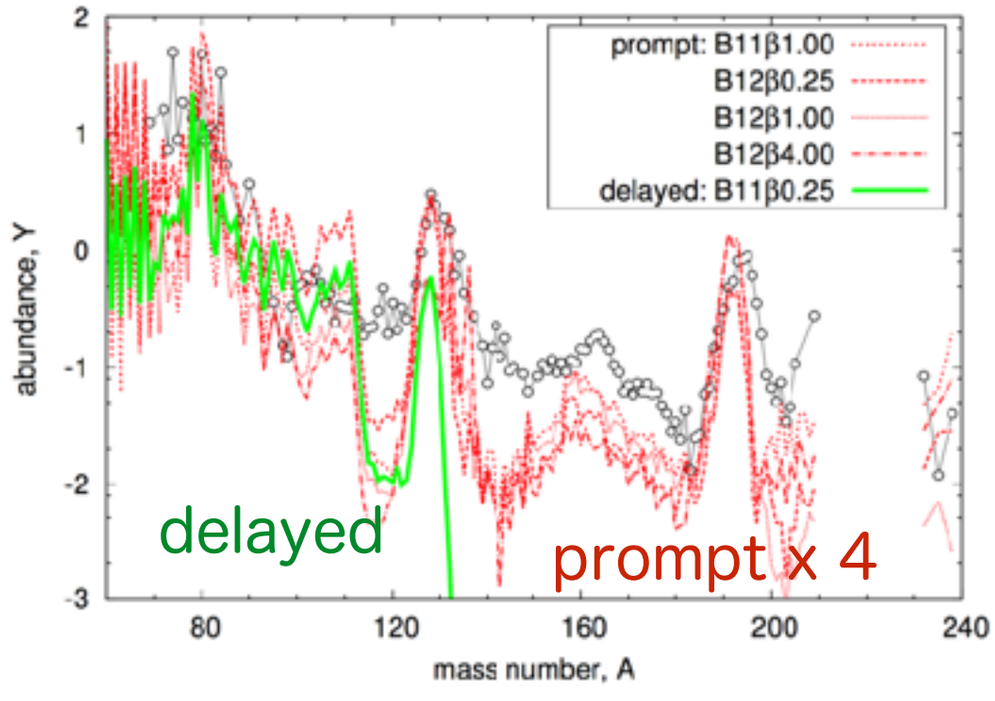


Magnetic-field amplification process?

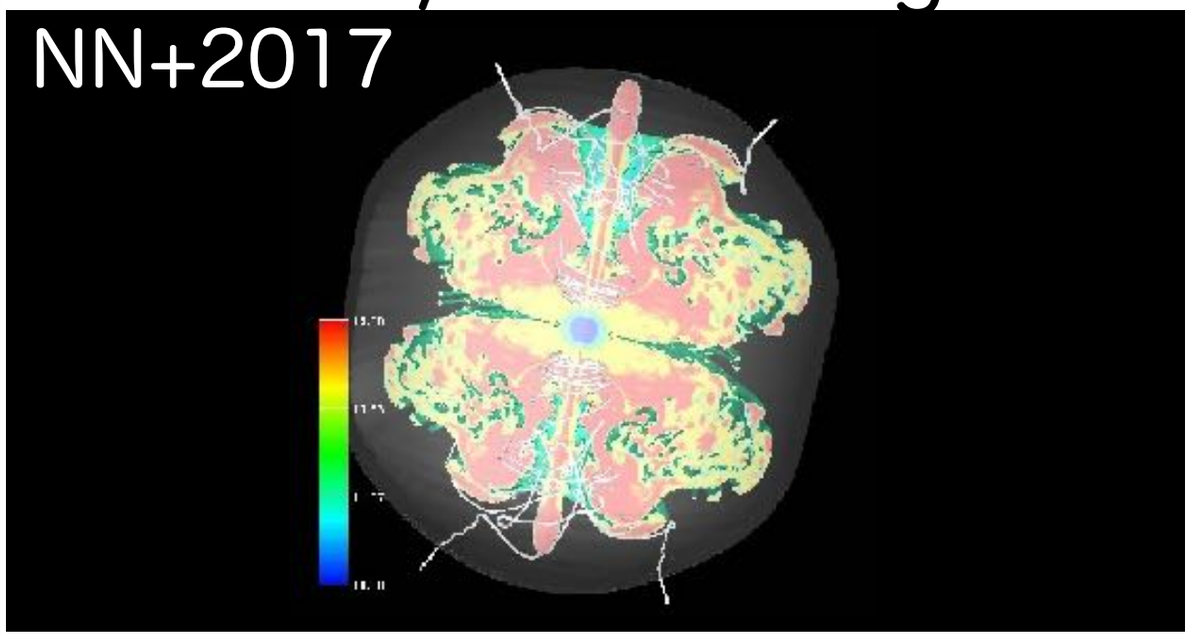
axisymmetric (2D); long-term, high-resolution

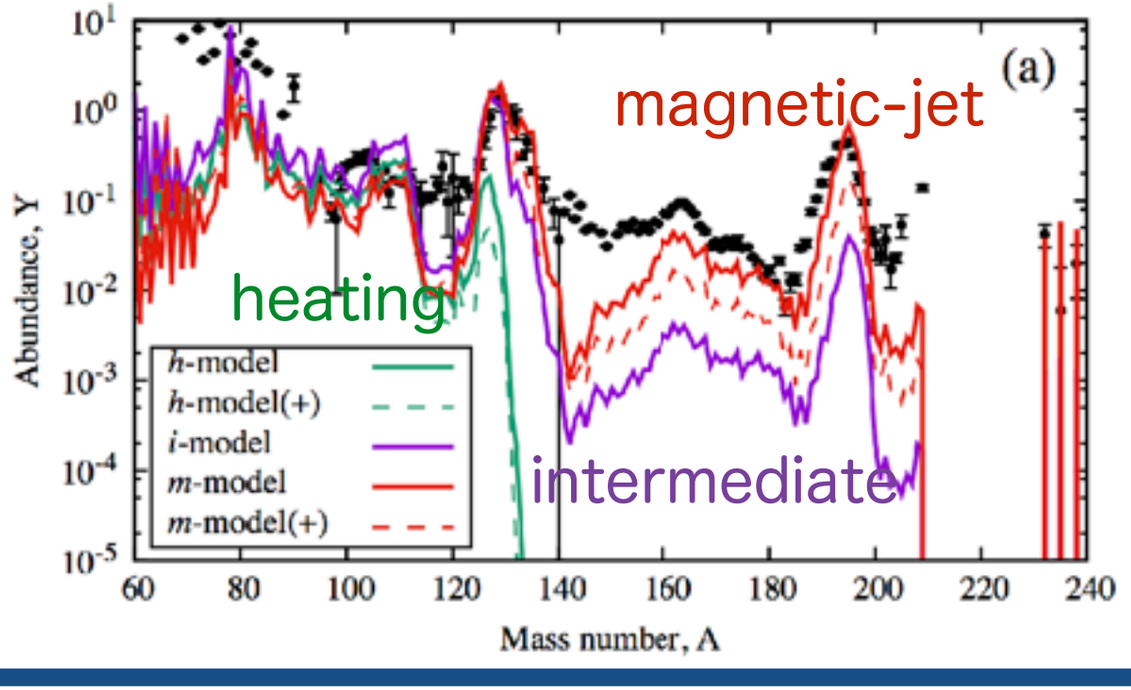
B-field winding





MRI w/ ν-heating



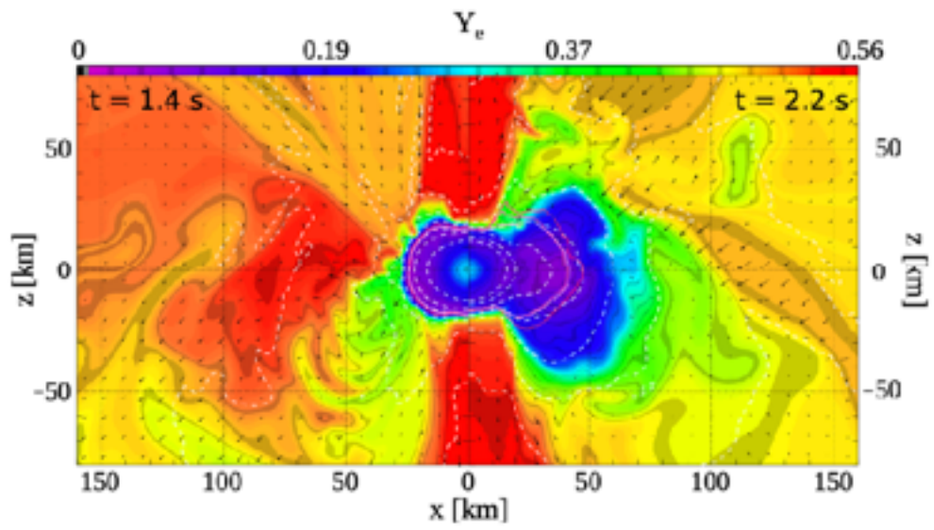


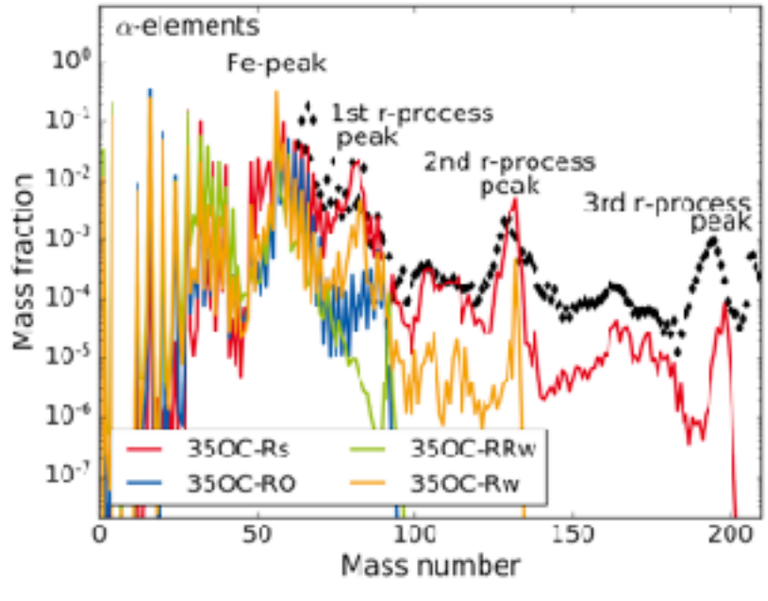
Magneto-driven but with ν-heating?

axi-symmetric (2D) w/ detailed ν-transport

Reichert+2021, 2022

(based on Obergaulinger+2020)





Brief summary: MR-SNe

- MR-SNe are (still) possible r-process sites
- However, strong magnetic jet explosions are required to produce heavy r-process elements?
  - difficult for “canonical” progenitors and MHD conditions
    → initial rapid rotation and strong magnetic fields?

We want to discuss possible “observational” properties of such events (if happened): r-process-jet supernovae.

long-term evolution of r-process ejection

(propagation of r-process-rich ejecta in the progenitor)

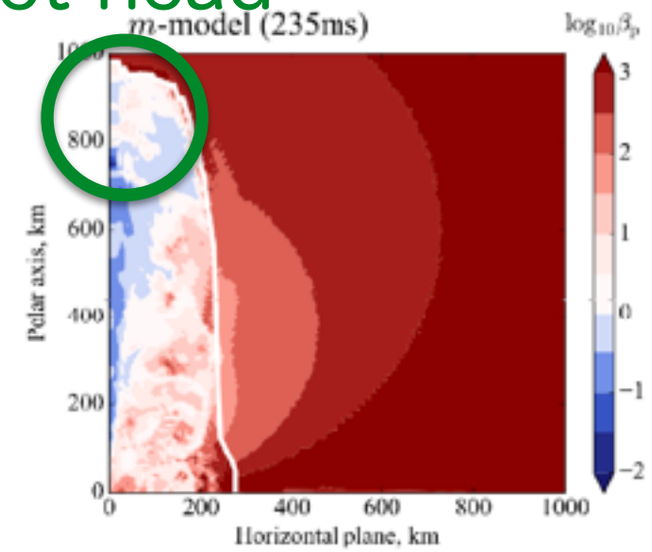
From the central engine to the SN remnant phase

NN, Matsumoto+, in prep.

jet-propagation with r-process

NN, Sawai+2017

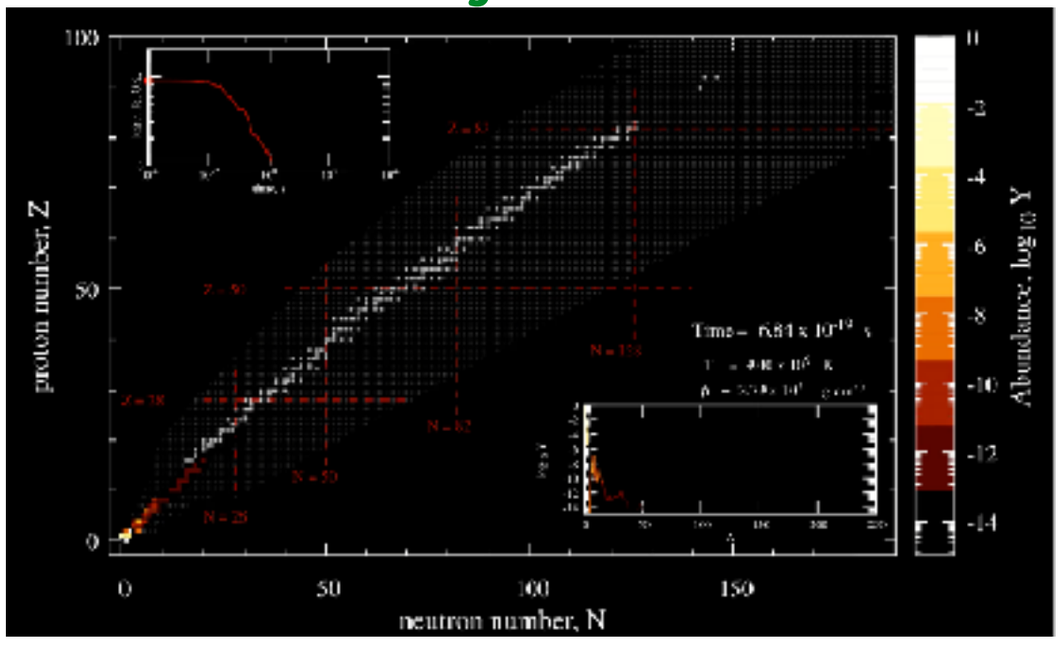
jet head



1,000 km

composition

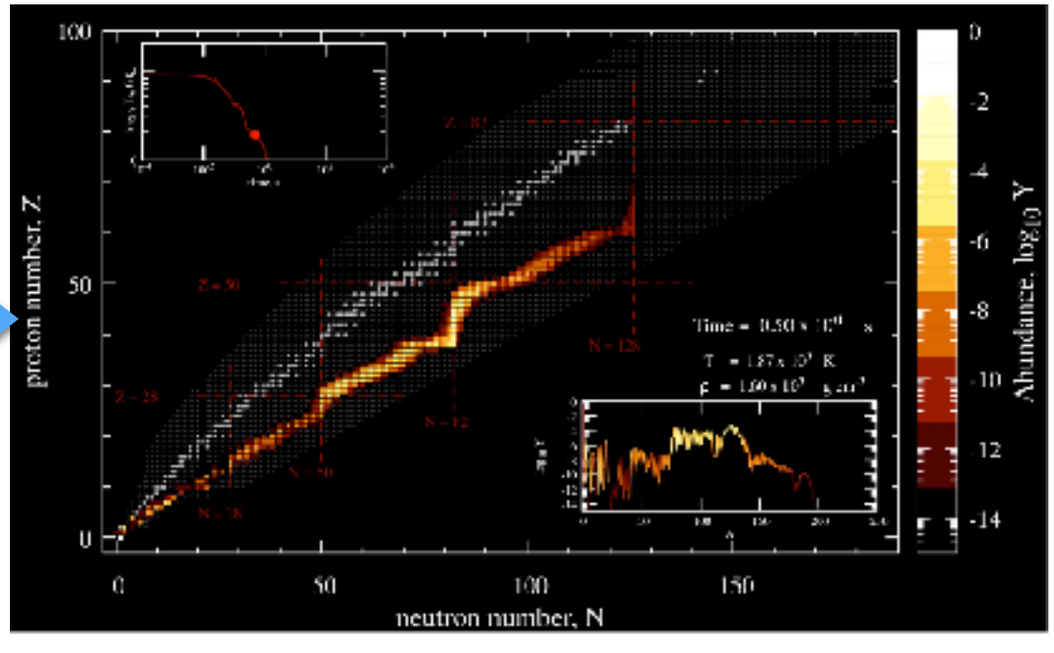
of the jet-head



20,000 km

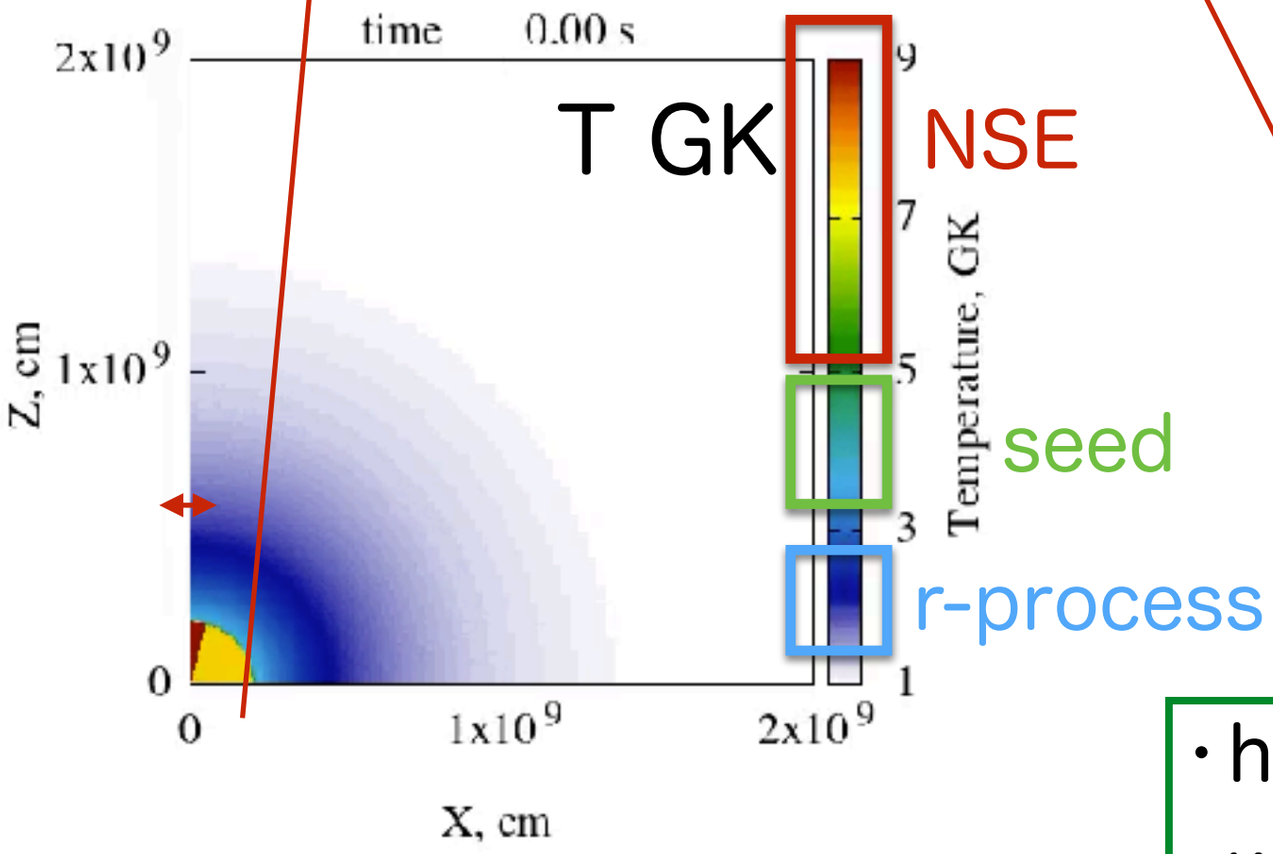
(simplified) hydro-dynamics simulations

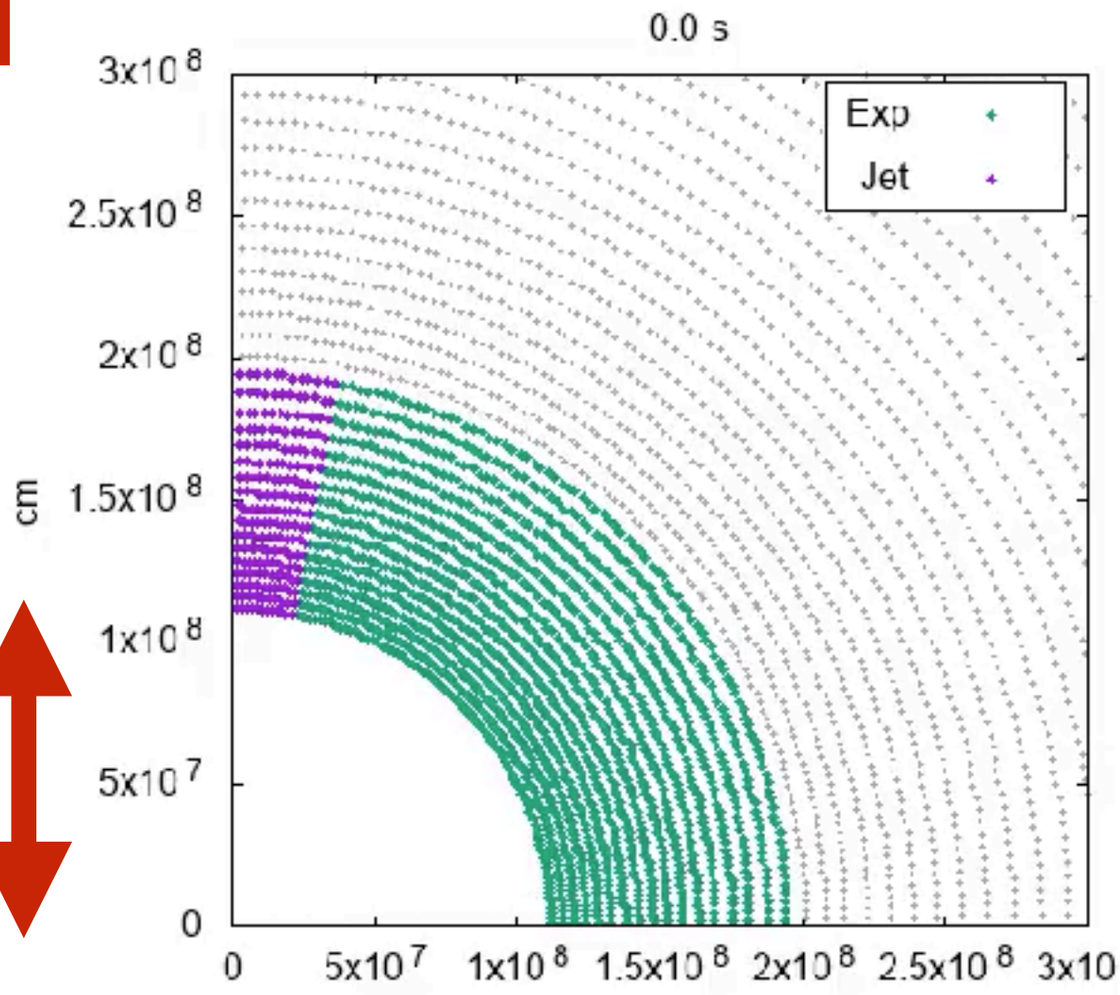
1,000 km composition



Jet-induced SN with the r-process

Central engine (MHD simulation)
1000 km (10^8 cm)



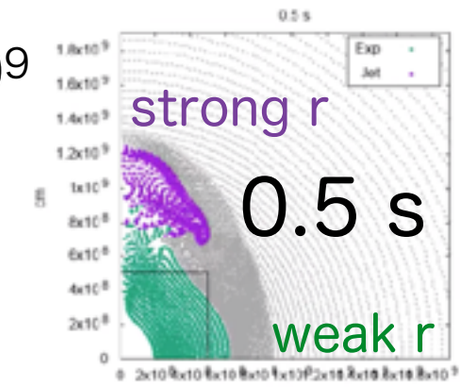


hydrodynamics code
Matsumoto et al. (2012, 2013)

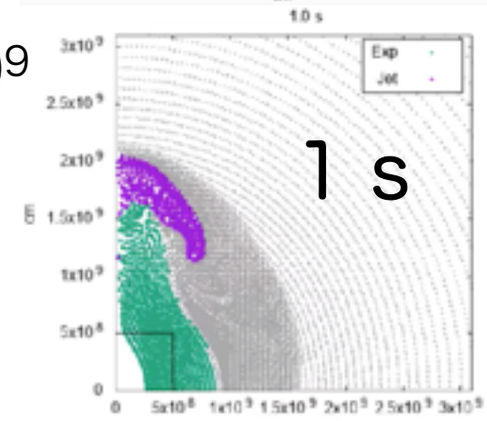
- hydrodynamics w/o B-fields
- “jet” injection
- $16M_{sun}$ Wolf-Rayet (no H-layer)

Hydrodynamics vs r-process

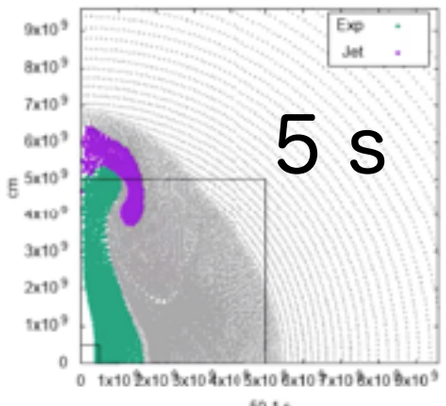
~2x10⁹ km



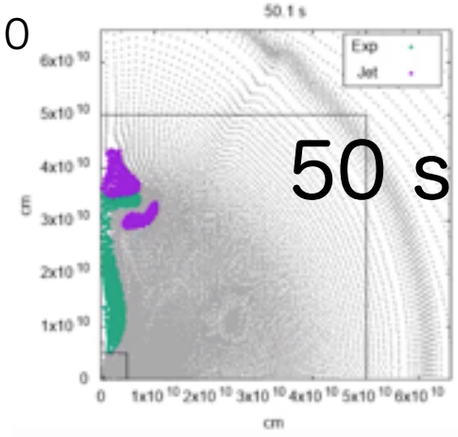
~3x10⁹ km



~10¹⁰ km



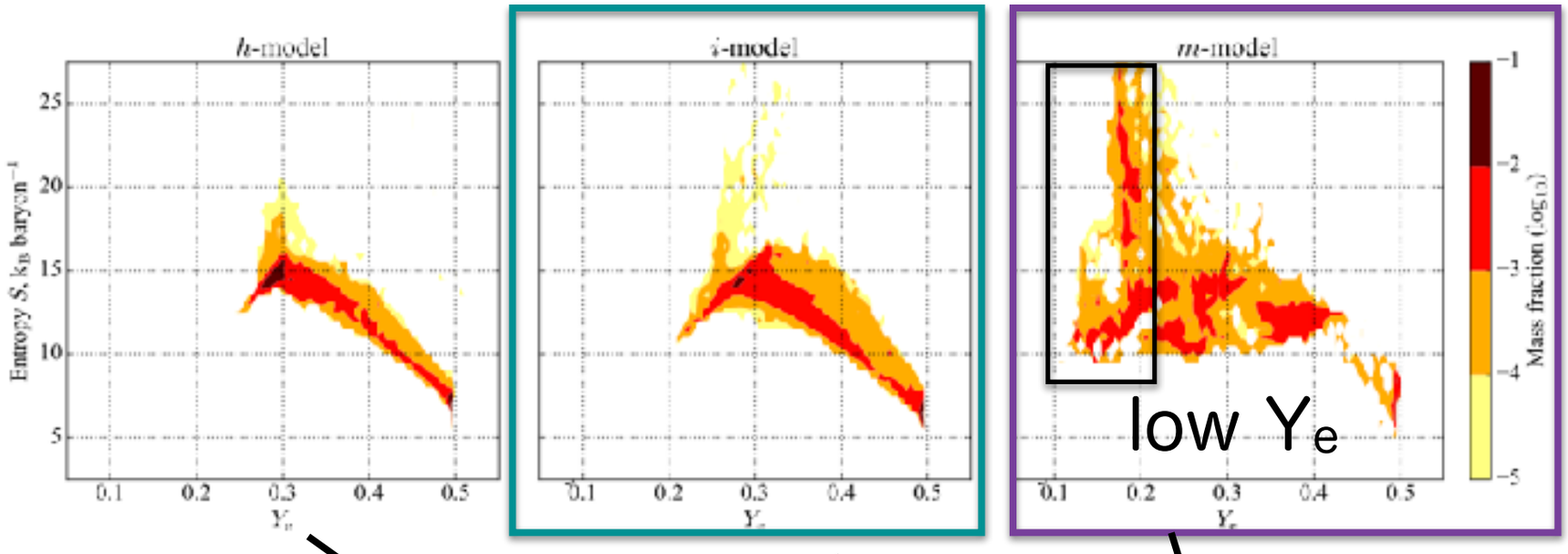
~7x10¹⁰ km



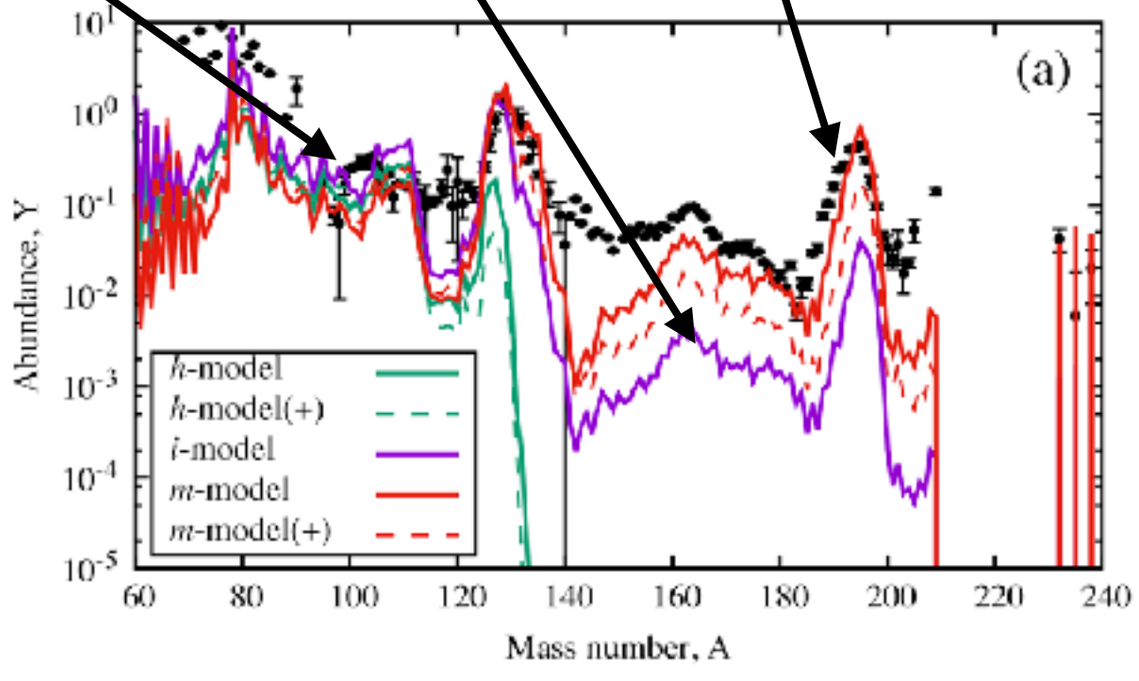
initial composition?

Y_e/n-richiness

NN+2017

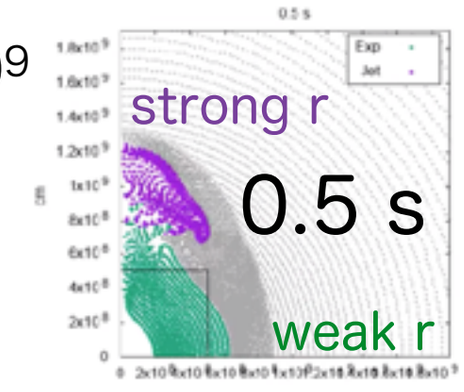


NN+2017

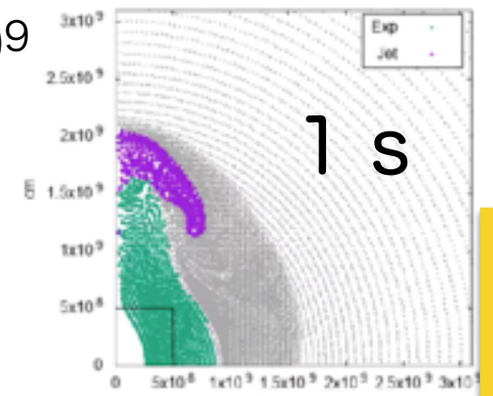


Hydrodynamics vs r-process

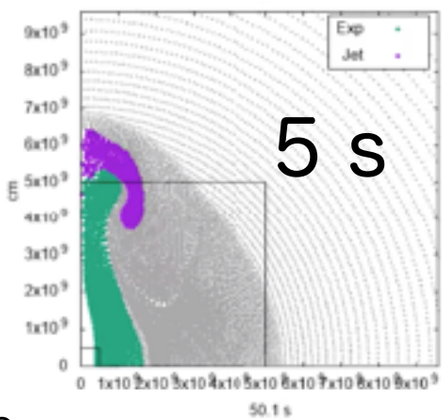
~2x10⁹ km



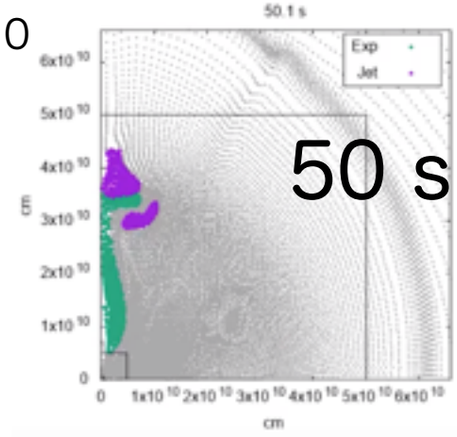
~3x10⁹ km



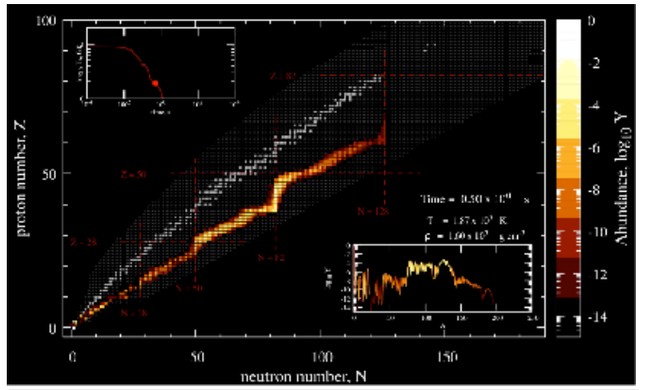
~10¹⁰ km

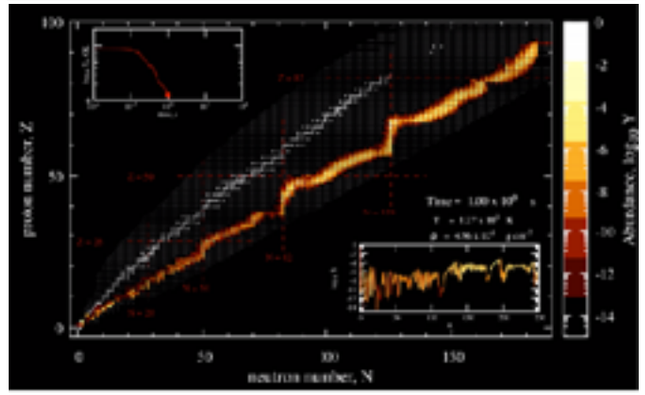


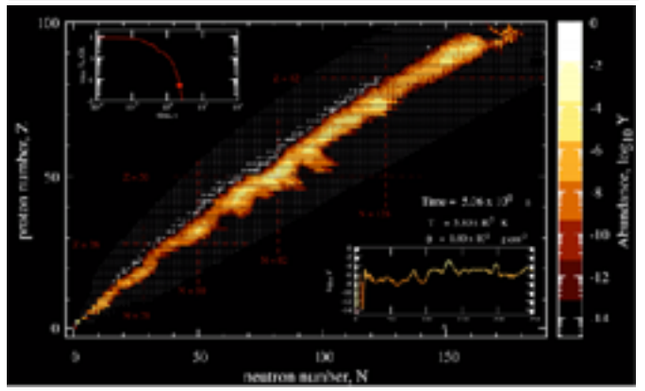
~7x10¹⁰ km

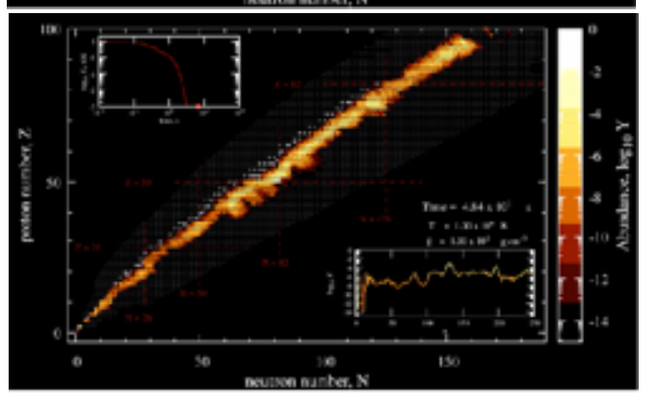


strong r

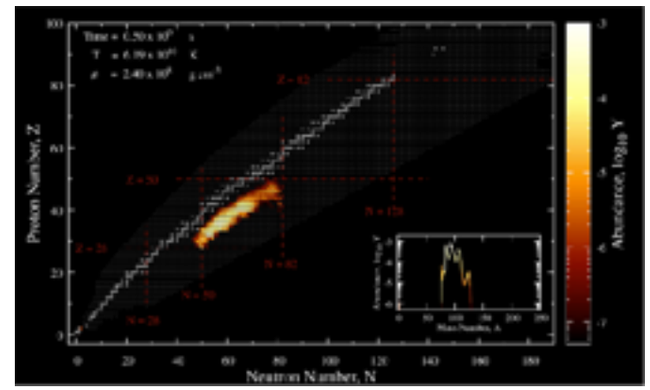


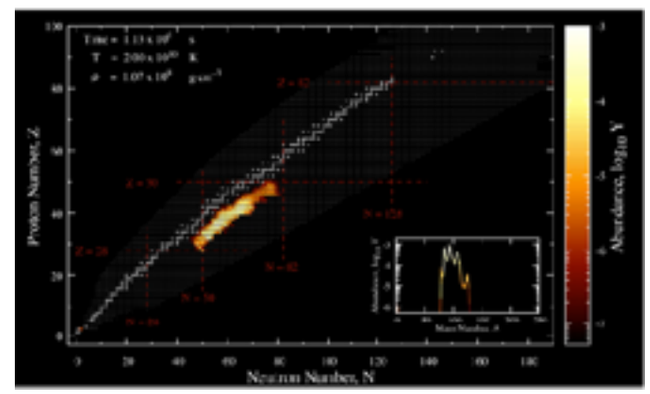


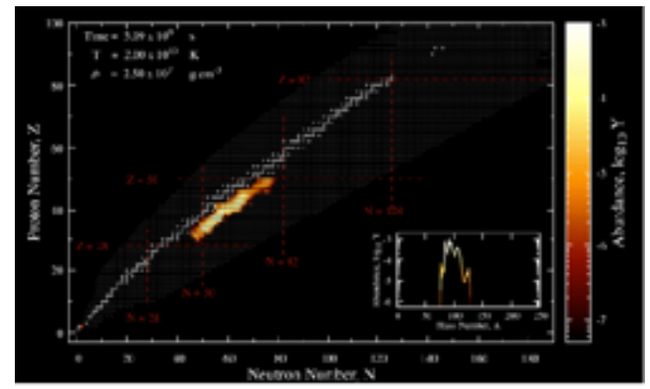


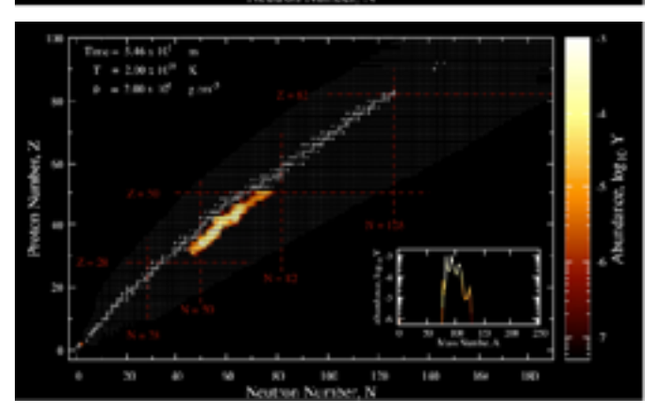


weak r









weak r

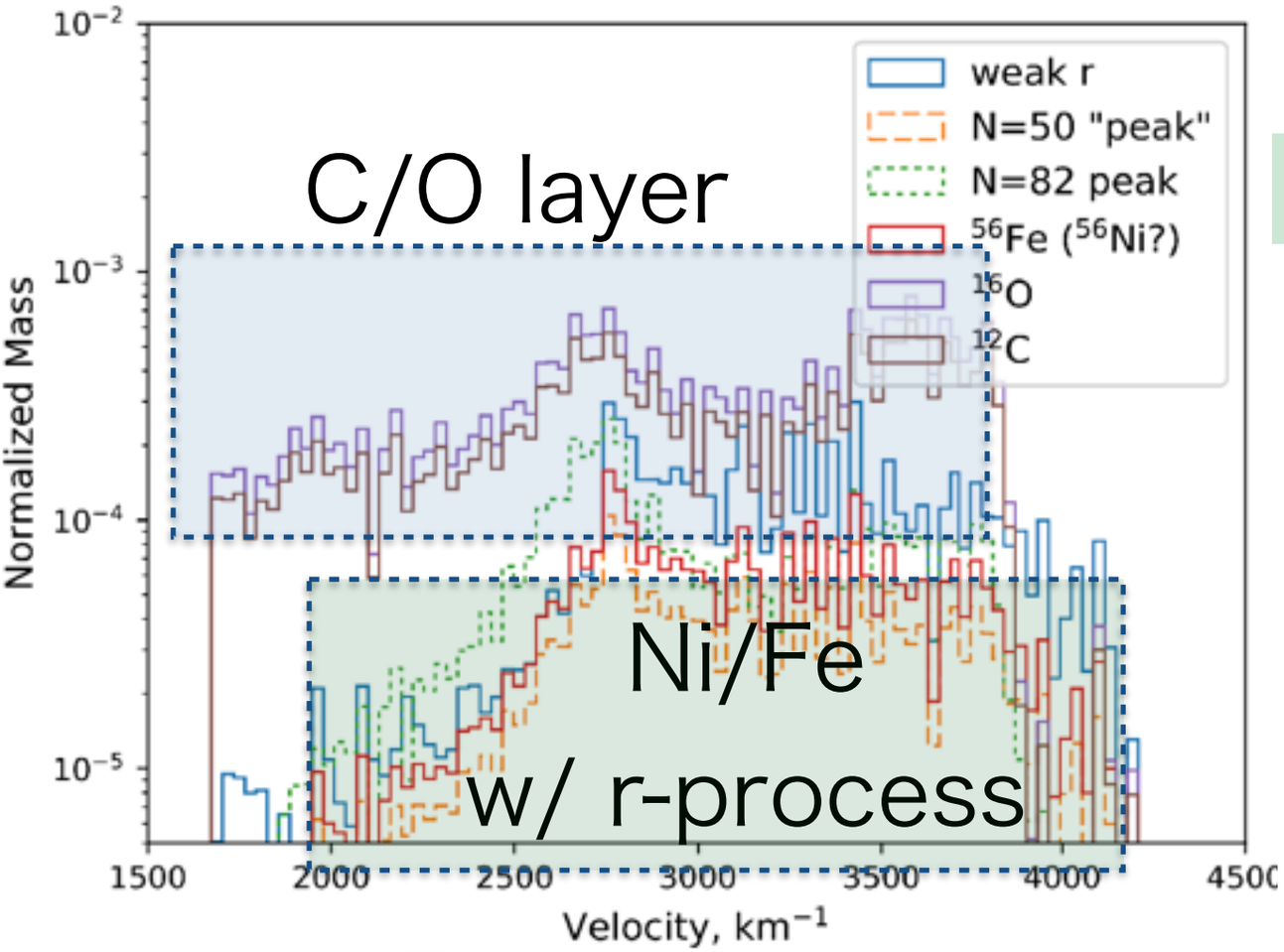
Elemental distribution in ejecta

based on the nucleosynthesis condition of NN+2017:

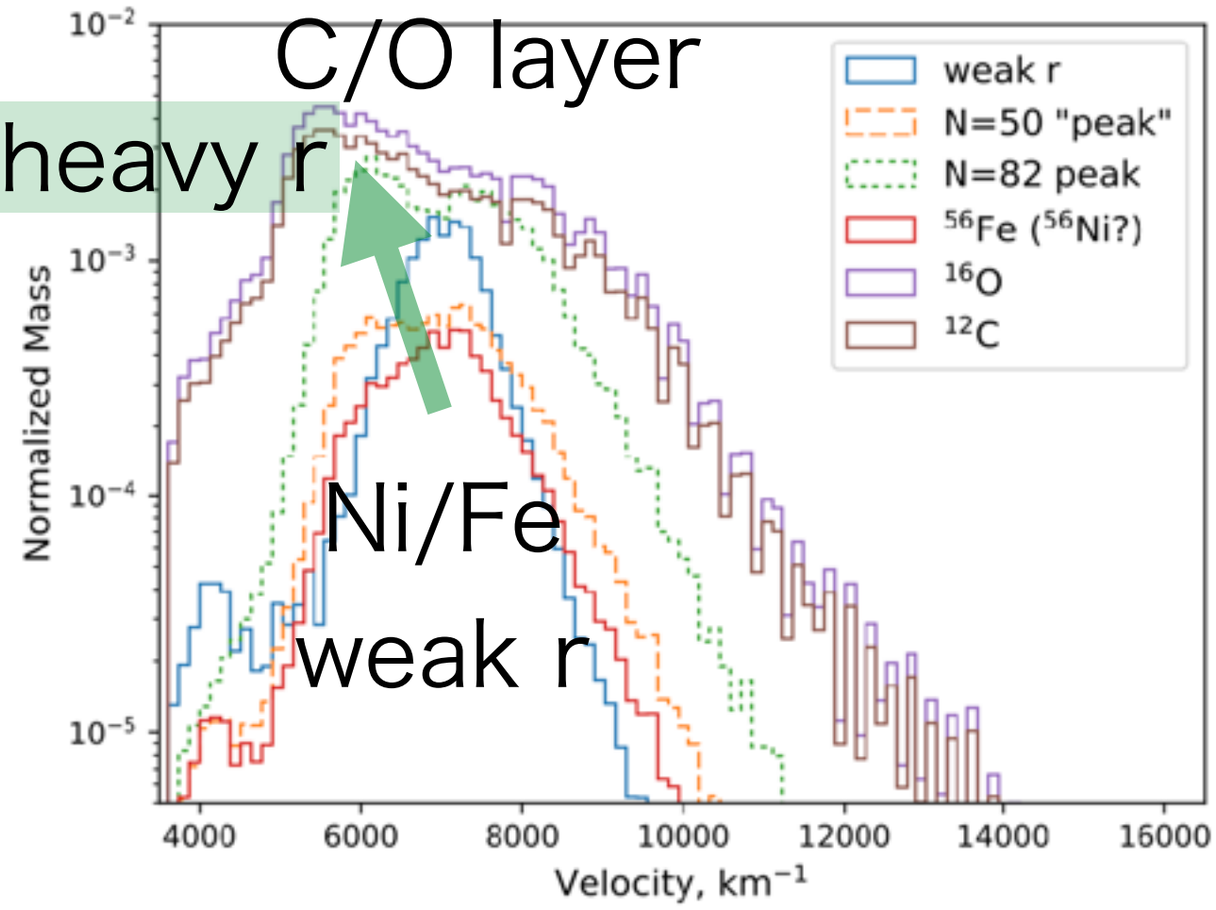
strong jet with very n-rich (strong r)

weaker jet with medium n-rich (“intermediate r”)

weaker magnetic jet



stronger magnetic jet



—> Future observation will provide new insights?

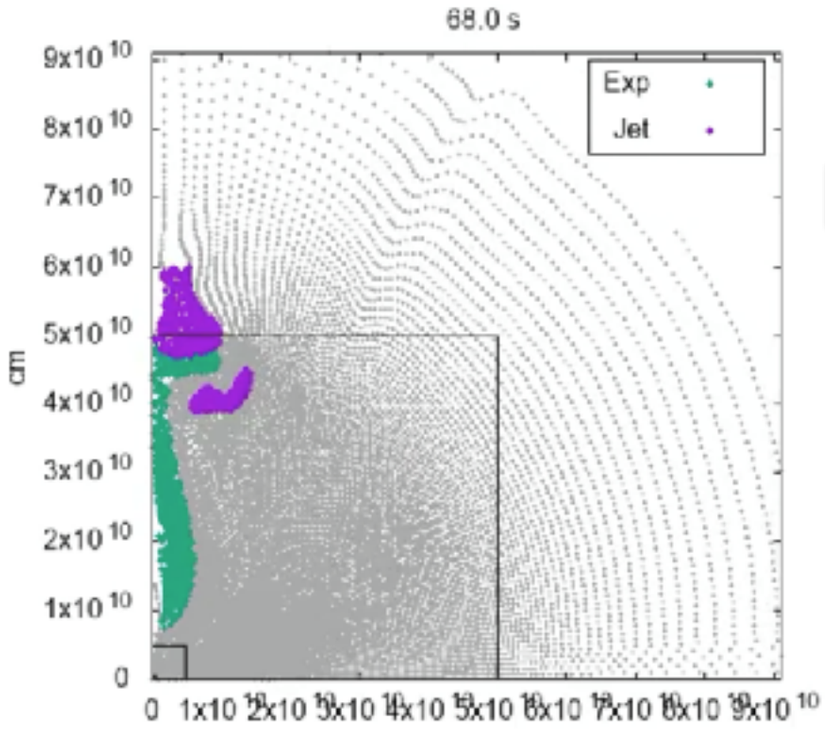
(r-process SN remnant?)

Toward optical SN light curves

- direct observation of r-process elements
  - only one kilonova with the NS-NS merger (GW170817)
    - Sr in the remnant (Watson+2019)
  - identified by GW waves
- No direct r-process observation in cc-SNe
  - but, a lot of cc-SNe are observed
    - including peculiar SNe associated with GRB, SLSNe, …
  - Can we find any traces of r-process nucleosynthesis?

Hasegawa+NN+, in prep.

Another approach: search by optical observation



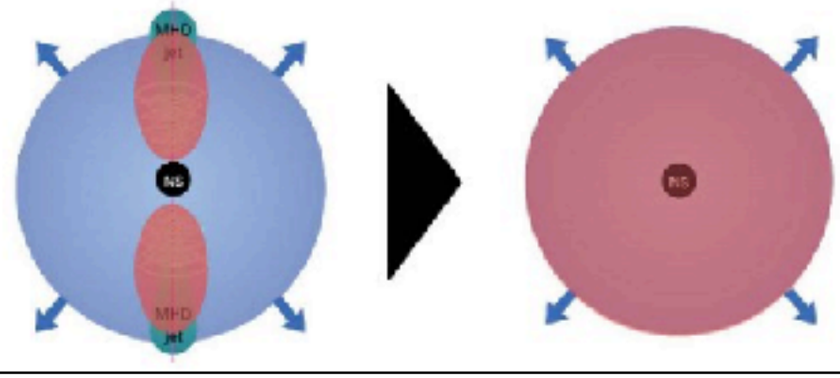
SN light-curves

much more later phase
～ days

Progenitor (Sukhbold et al. 2016)	ZAMS：45 Msun Just before the collapse：13 Msun
1D hydrodynamics & nucleosynthesis calculation (blcode, Ott et al. 2014)	Kinetic energy : 10^{52} erg => M(56Ni) ~ 0.3 Msun
r-process elements	Solar abundance and uniform distribution

- 1D Radiative Transfer simulation (Tanaka & Hotokezaka 2013)
  - Calculate the absorption coefficients of the b-b transition of all the elements
  - Assume LTE
  - Mass of r-process elements

: Mr = 0, 0.1, 0.3, 0.6, 0.9, 1.2 Msun



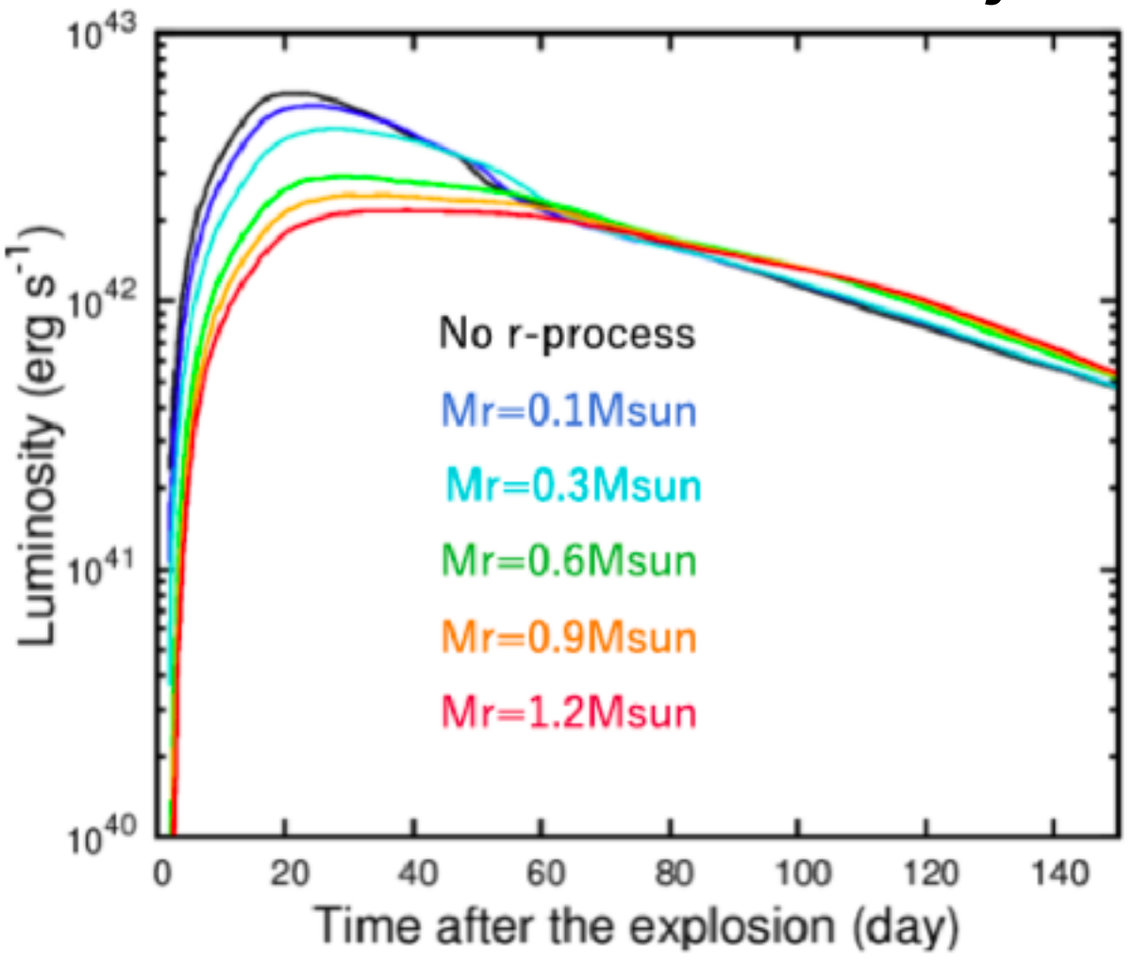
GRB associated SN: r-process contamination

various r-process masses

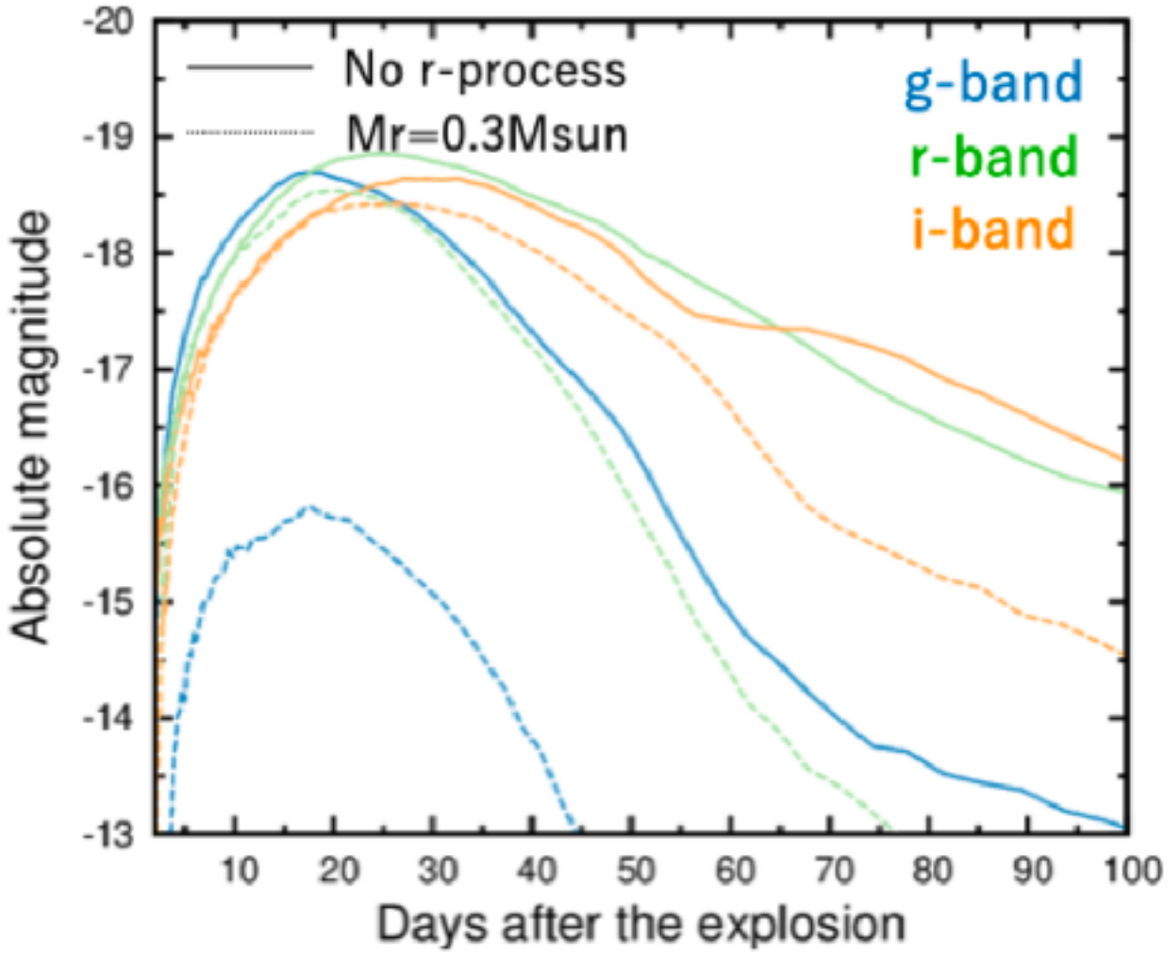
with $M(^{56}Ni) = 0.36\ M_{sun}$ ($E_{exp} = 10^{52}$ erg)

r-process rich → high opacity → fainter & red

bolometric luminosity



light curves

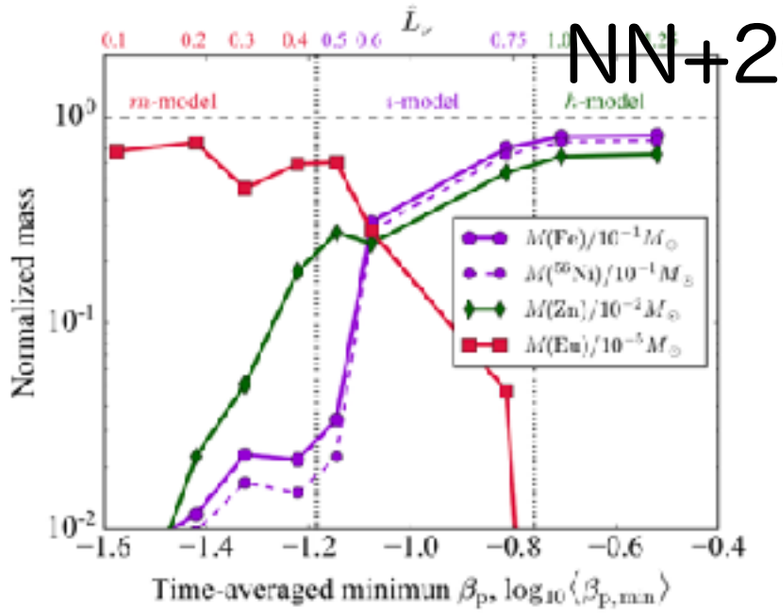


Hasegawa+NN+ 2022

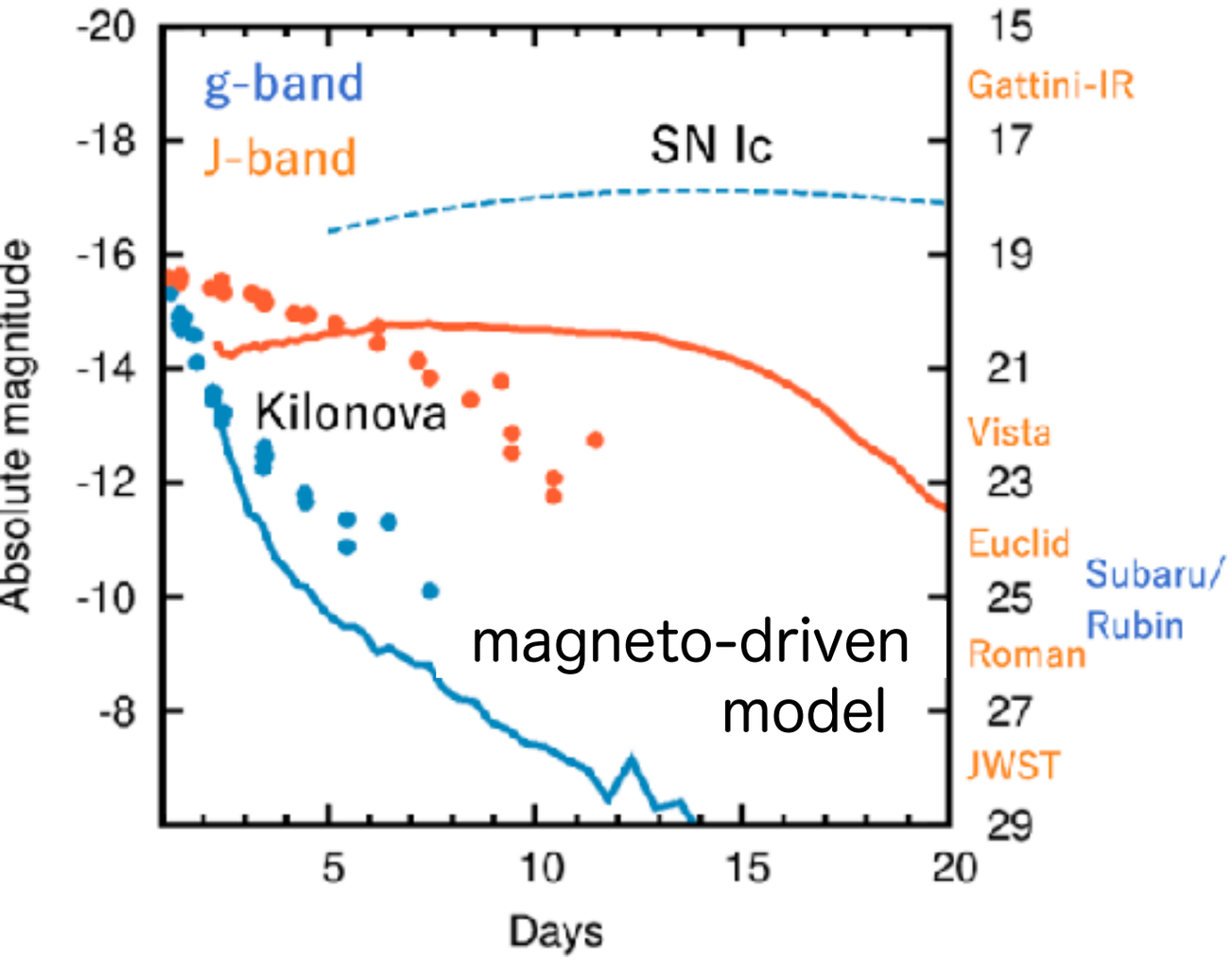
Another approach: search by optical observation

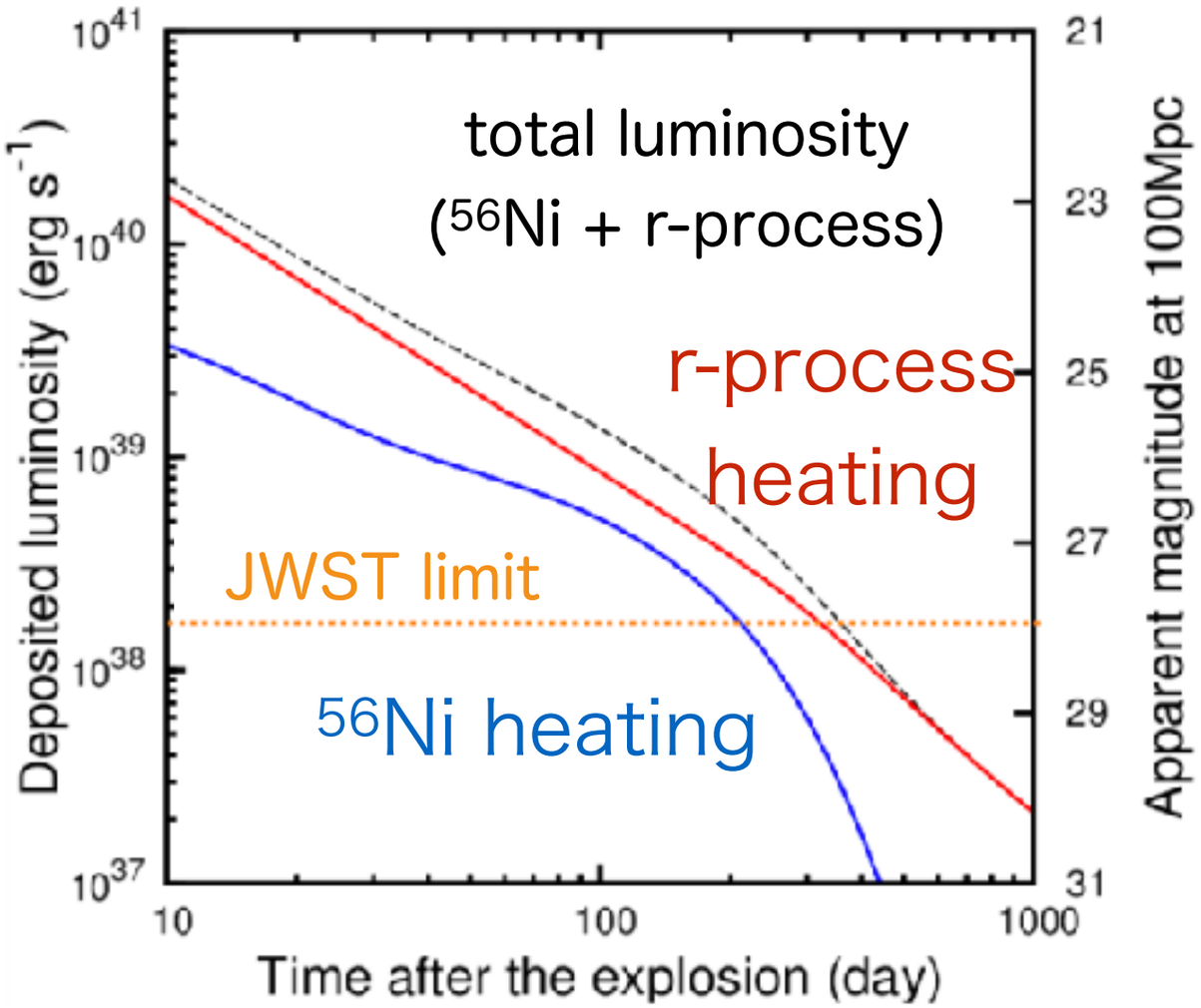
MR-SN simulations suggestlower ^{56}Ni for r-process-rich model?

- **r-process heating ∝ $t^{-1.3}$ ($1.1 \times 10^{-2}\ M_{sun}$)**
- **^{56}Ni heating ∝ exp(- t / τ) ($1.0 \times 10^{-4}\ M_{sun}$)**



NN+2017



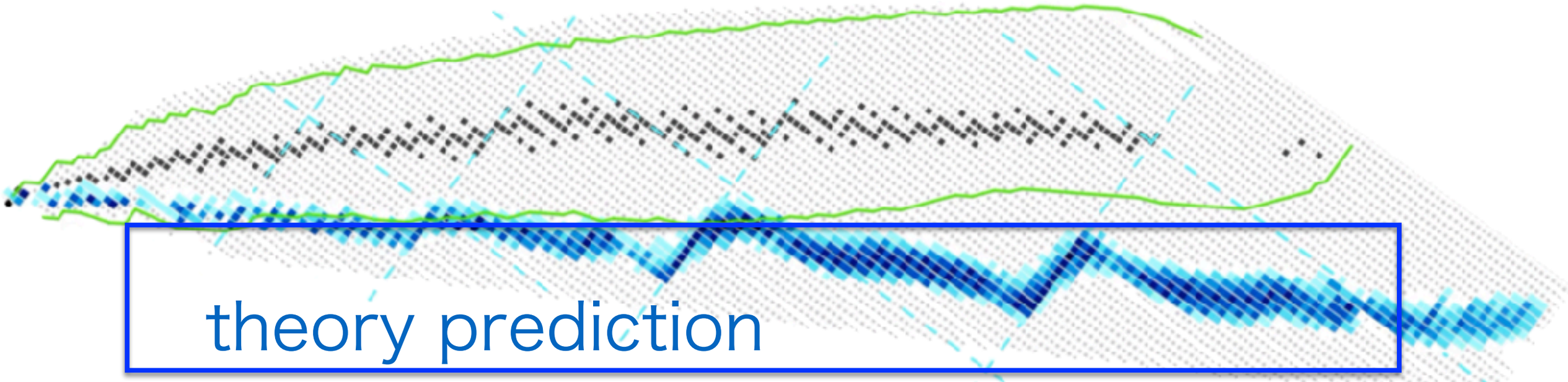


Hasegawa+NN+ 2022

Nuclear-physics uncertainty

Theoretical Prediction

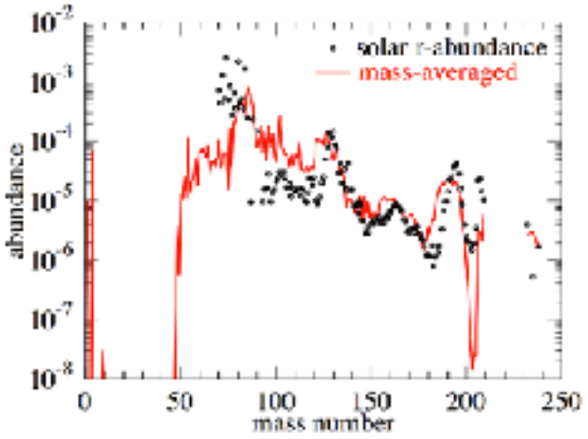
r-process path is beyond experimental accessible region



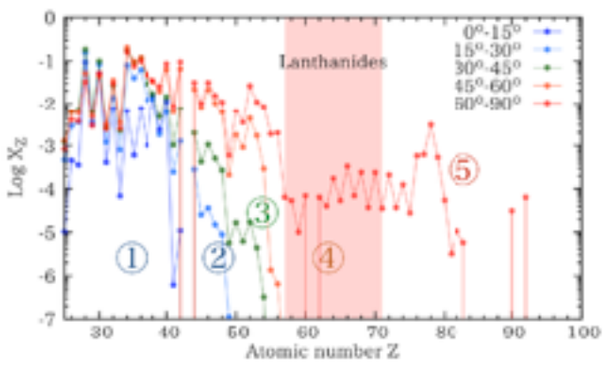
astrophysics

reliability??

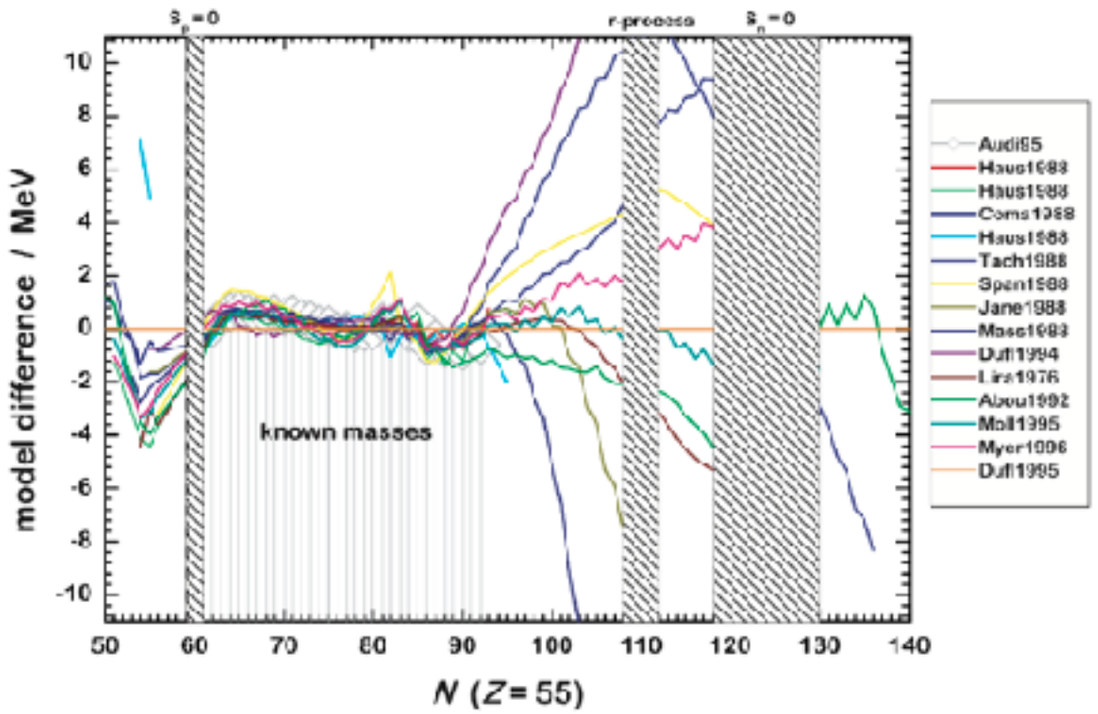
large uncertainty in theory



Wanajo+NN+(2014)



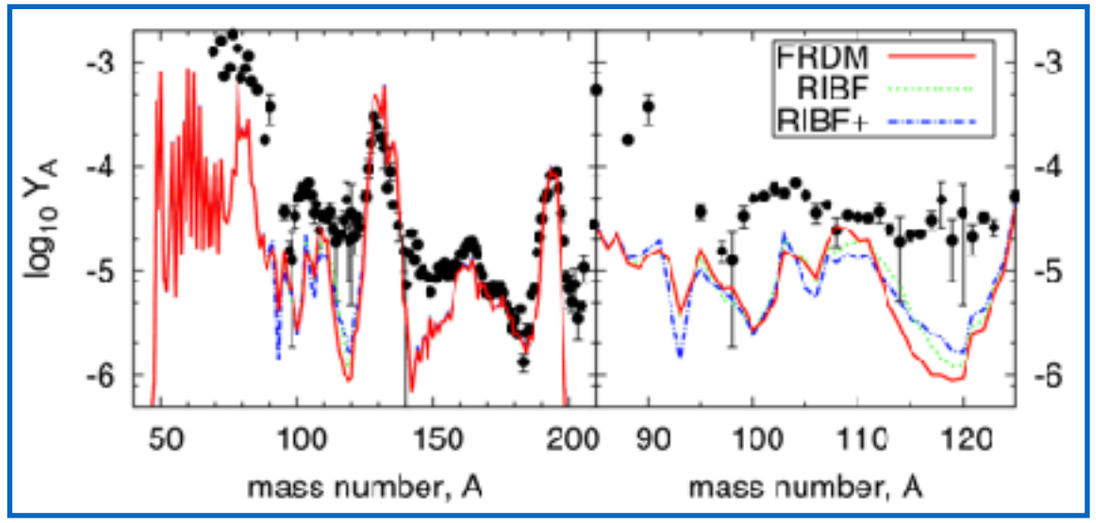
Fujibayashi+NN+(2018)



Beta-decay: BRIKEN Experiments

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

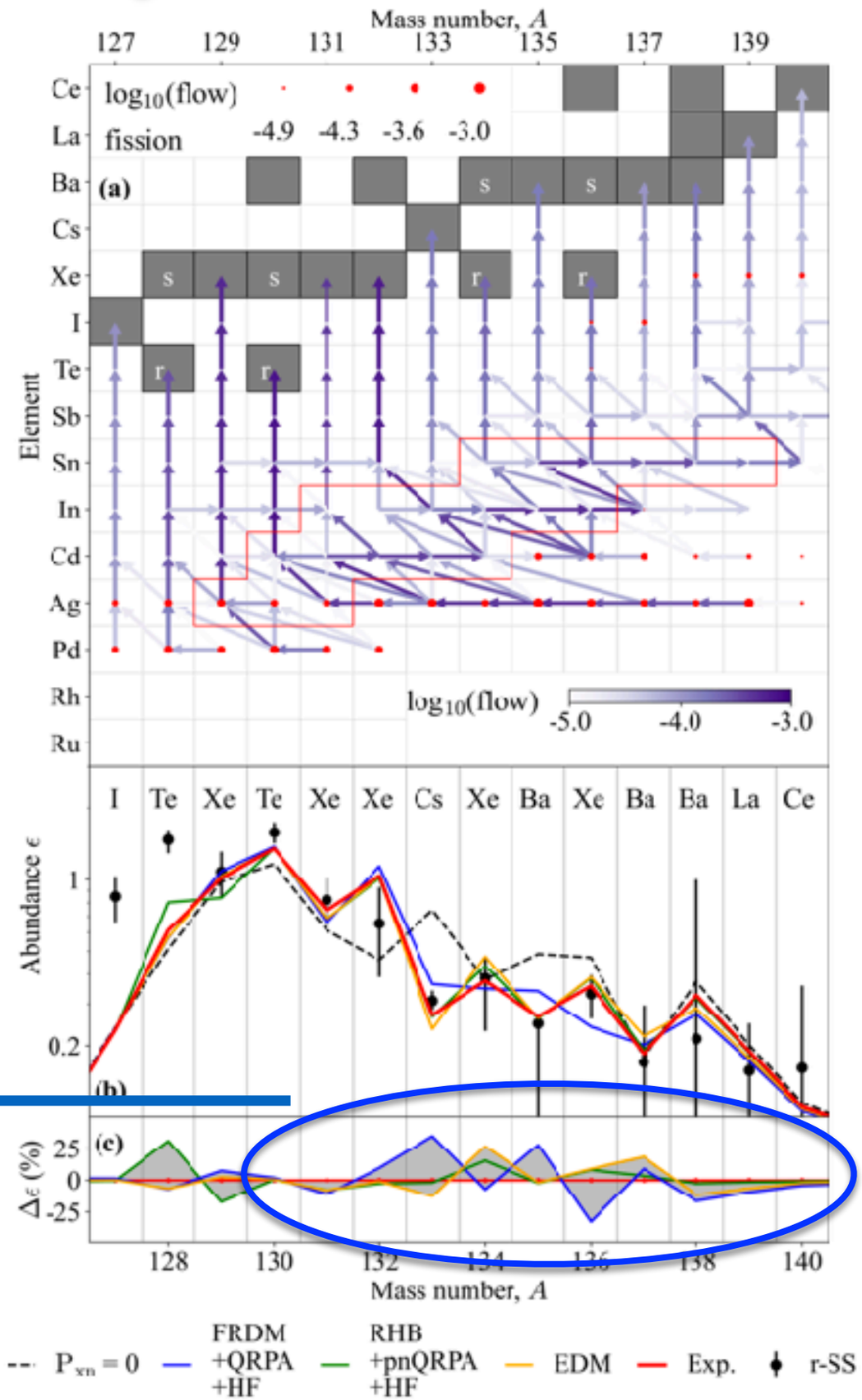
NN+2012



<u>n-emission:</u>

New results of BRIKEN (P_n 20 isotopes)
Pong, S.Nishimura+NN+(2022), PRL (in press)

<u>impacts on Cs, Xe, Ba</u>
robust impacts on the abundances from solar-system to metal-poor stars (early universe)



Monte-Carlo network code

- Monte-Carlo framework
  - PizBuin MC-driver
    (developed by Rauscher & NN)
  - a simple “Brute-force” approach
  - parallelized by OpenMP for shared memory architectures
    (paralleled easily, but harder debugging. . .)

Piz Buin (mountain)

- Nuclear Reaction network
  - **Network solver:**
    - WinNet: the latest Basel network, Winteler+, 2012
  - **Reaction rates:**
    - Reaclib: (Rauscher & Thielemann 2000)
    - T-dependent beta-decay (Takahashi & Yokoi 1987, Goriely 1999)
  - **T-dependent uncertainty:**
    - Provided by Reaclib format, based on Rauscher 2012

Comprehensive uncertainty studies

- s-process
  - (n,g) and β-decay along the stable line
  - weak s: massive stars (NN+2017)
  - main s: AGB stars (Cescutti, Hirsch, NN+2018)
- p-process (gamma process)
  - several reactions on n-deficient nuclei (+photodissociation)
  - CC-SNe (Rauscher, NN+2016)
  - Type Ia SNe (NN+2018)
- ν p-process
  - ν-driven winds with CC-SNe (NN+2019)

larger uncertainty

- rp-process → NN, Dohi+, in prep.
- r-process → presented results

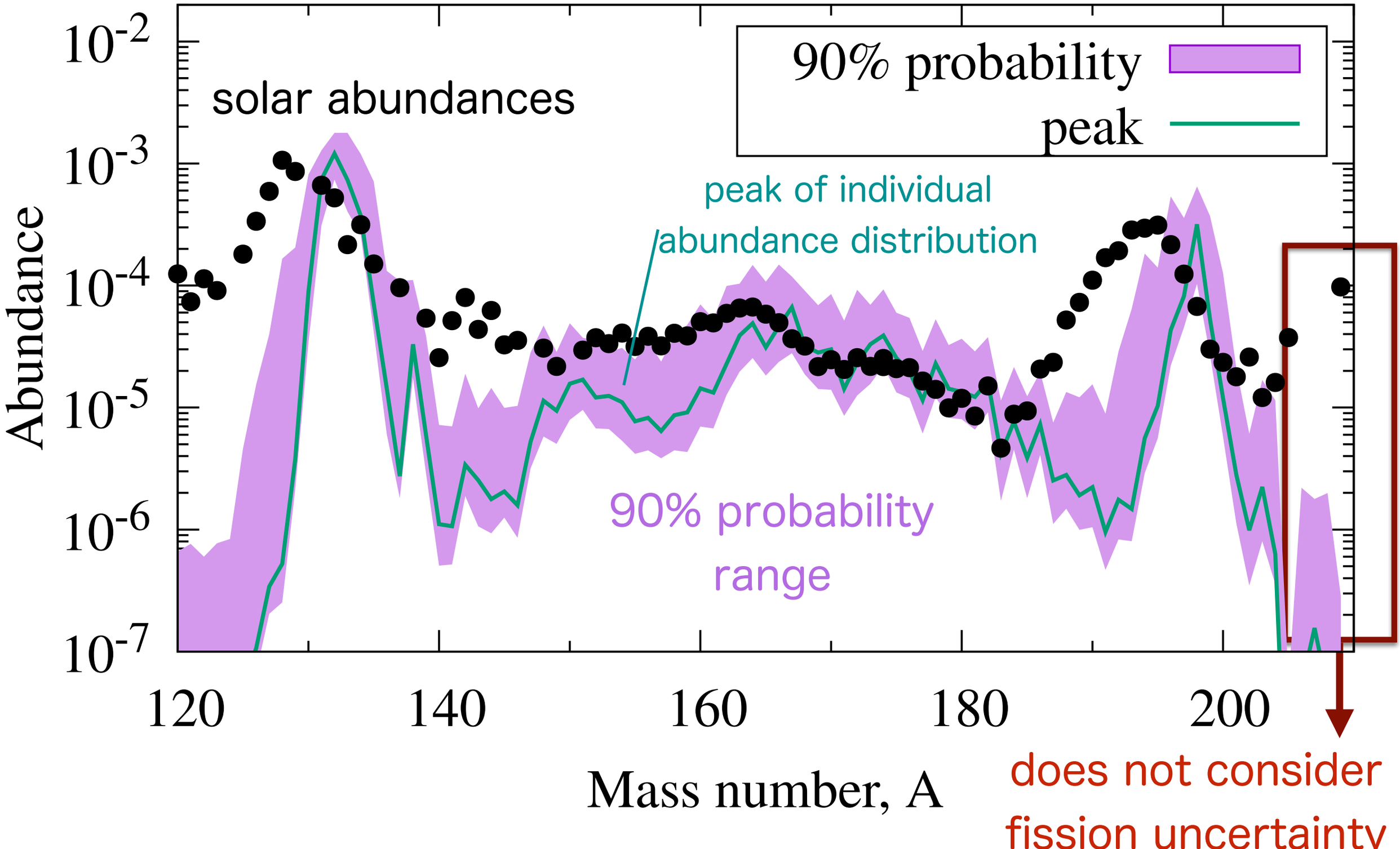
references

- Rauscher, NN+2016, MNRAS 463
- NN+2017, MNRAS 469
- NN+2018, MNRAS 474
- Cescutti, Hirschi, NN+2018, MNRAS 478
- NN+2019, MNRAS 489

Collective uncertainties on the r-process

NN+2022, in prep.

(n,g) x50, β x10



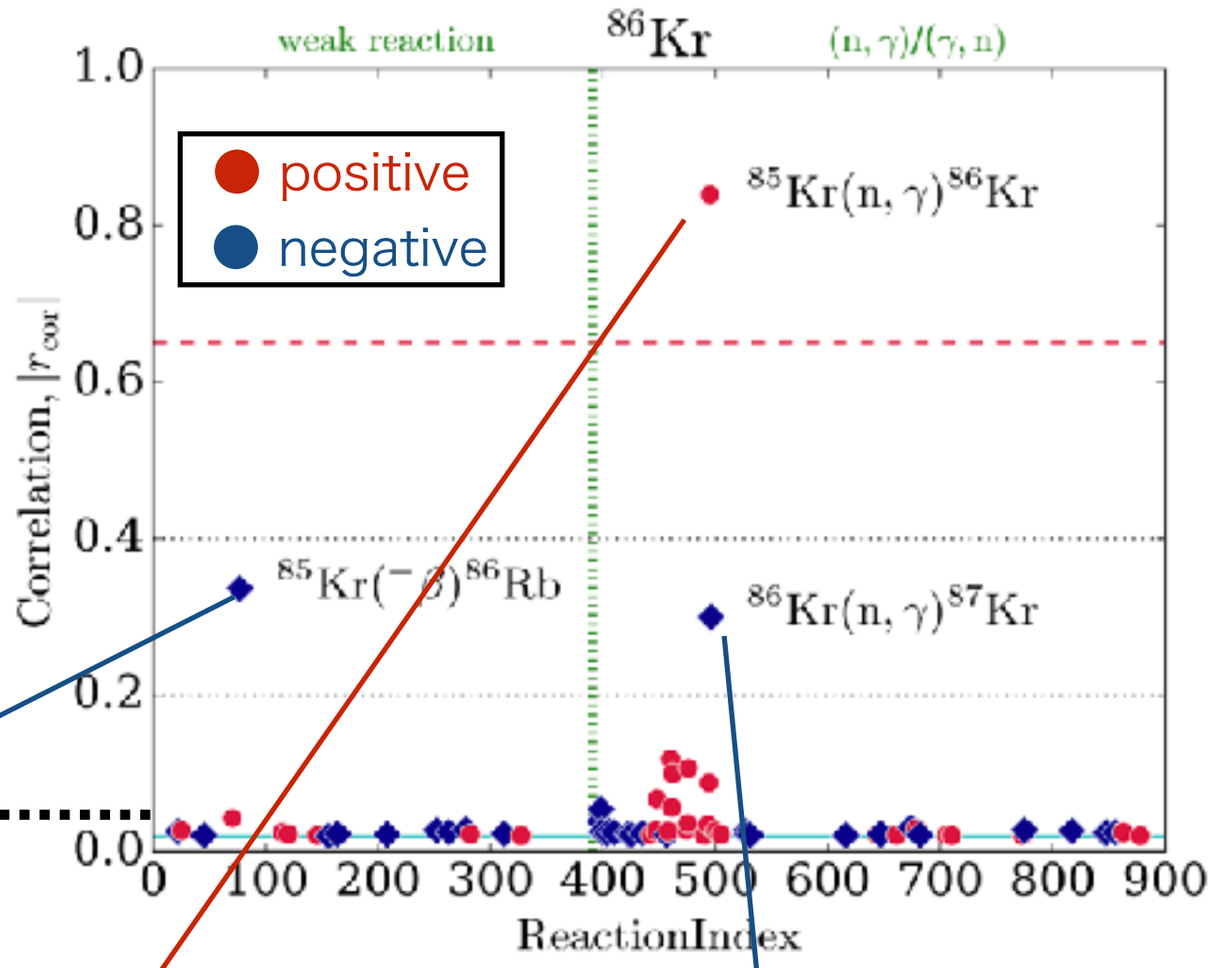
Evaluate “key” reactions

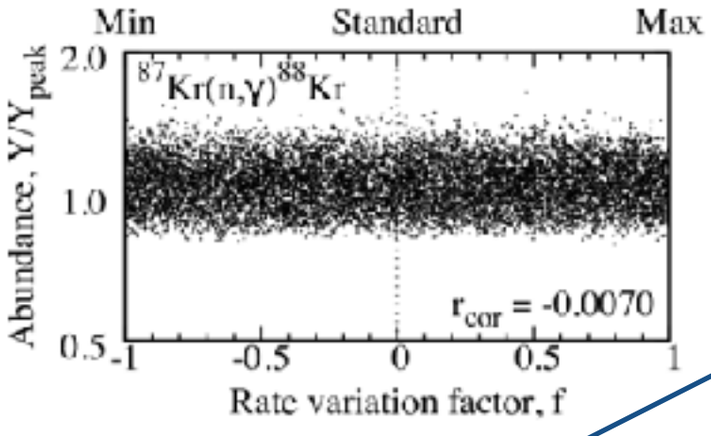
*the case of s-process

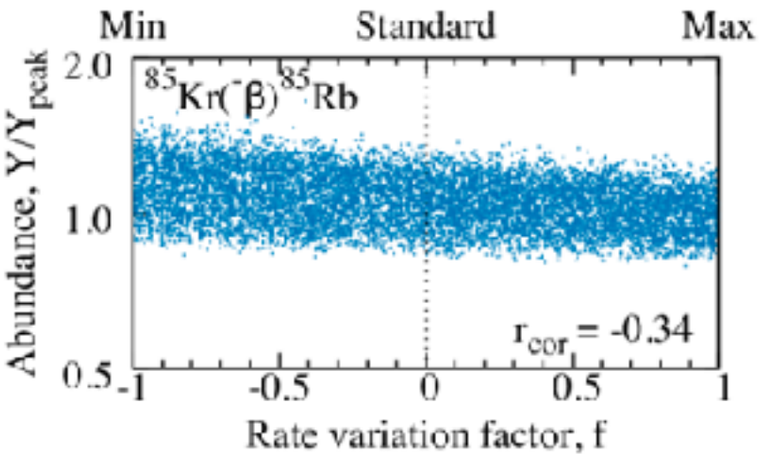
Pearson’s coefficient

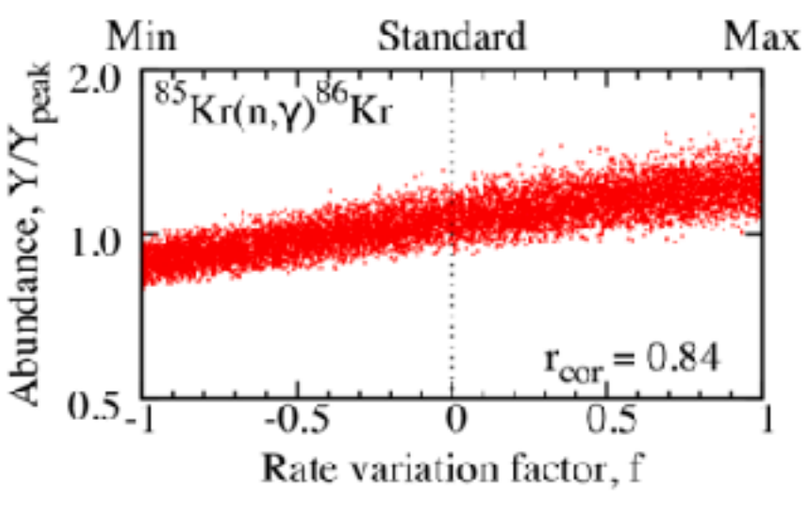
$$r_{\mathrm{Pearson}} = \frac{\sum_{i=1}^{k} (\tilde{x}_i - \overline{x})(\tilde{y}_i - \overline{y})}{\sqrt{\sum_{i=1}^{k} (\tilde{x}_i - \overline{x})^2} \sqrt{\sum_{i=1}^{k} (\tilde{y}_i - \overline{y})^2}}$$

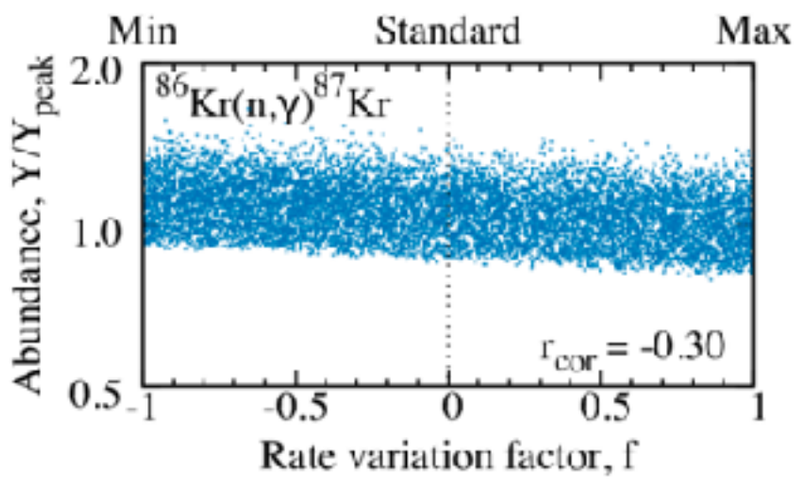
|r| > 0.65 → “strong”







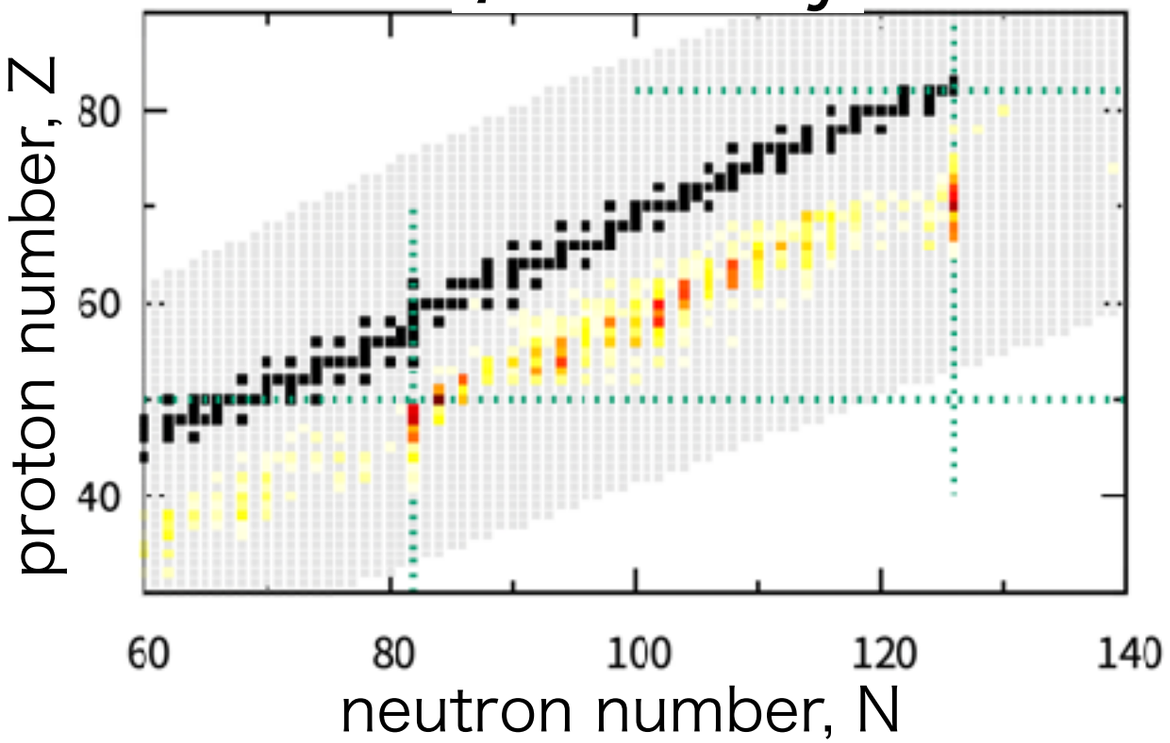




Individual impacts

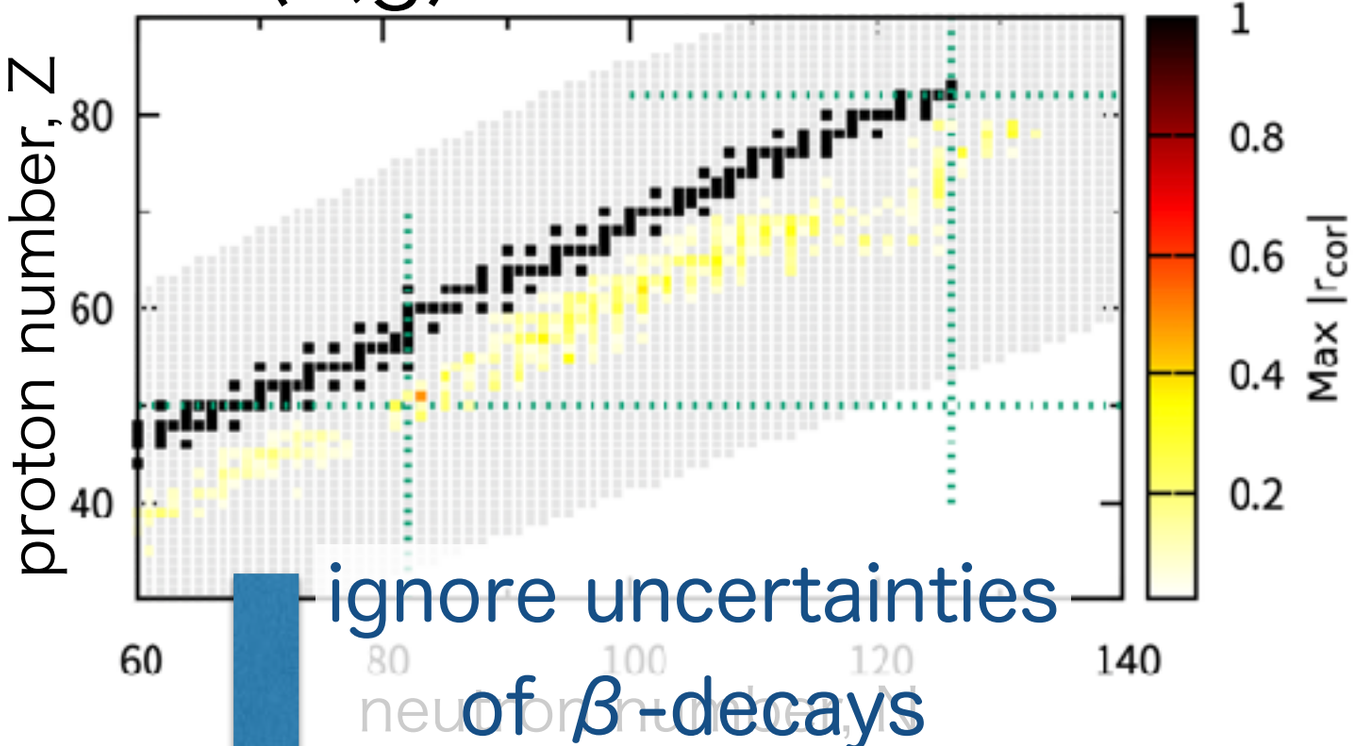
Impacts on the r-process of individual rates

β-decay



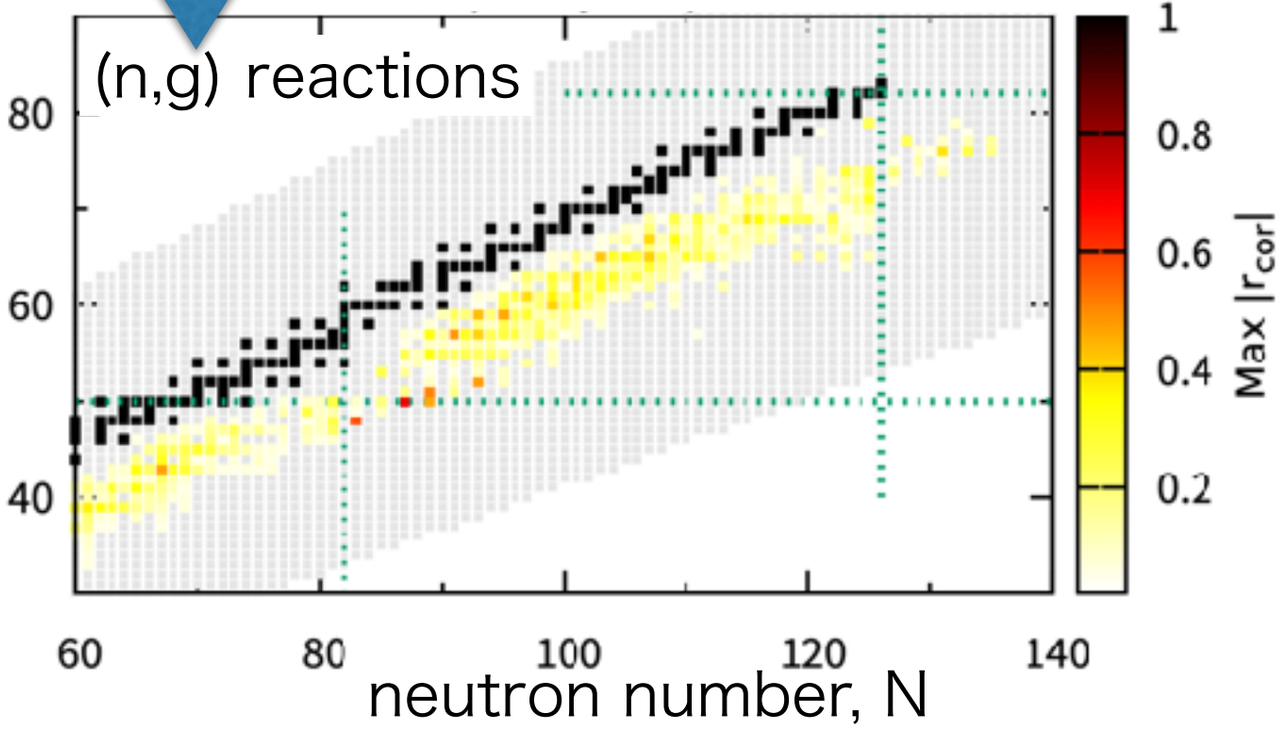
region around
Z=50, N=82
neutron-rich $_{50}$Sn
(relatively known)

(n,g) reactions

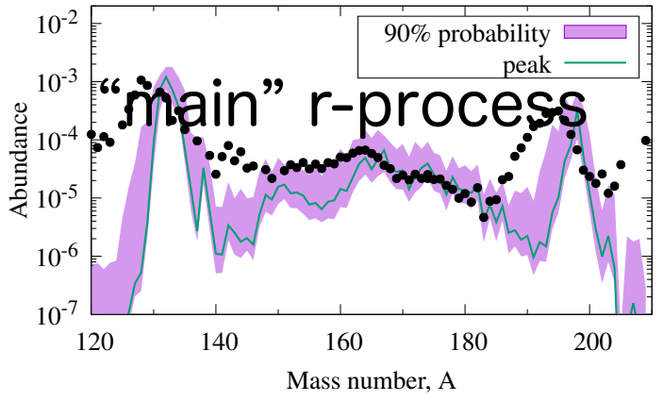


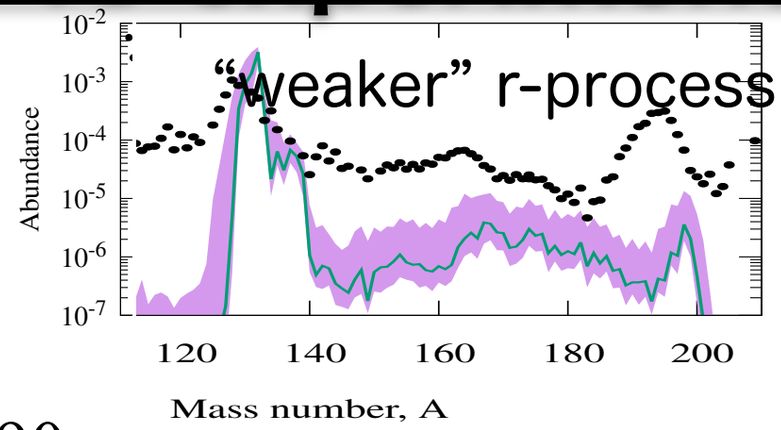
ignore uncertainties of β-decays

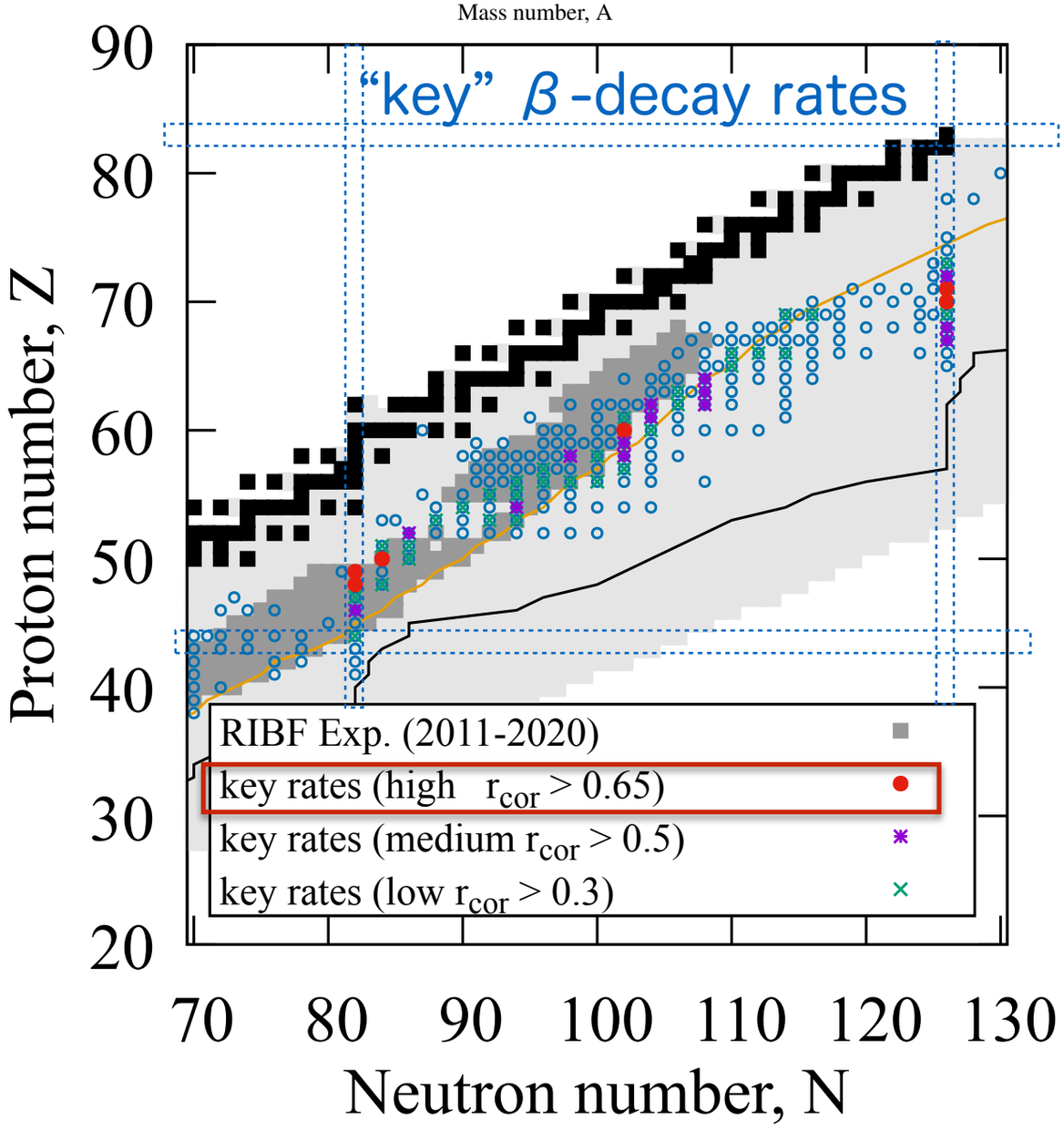
only (n,g) reactions

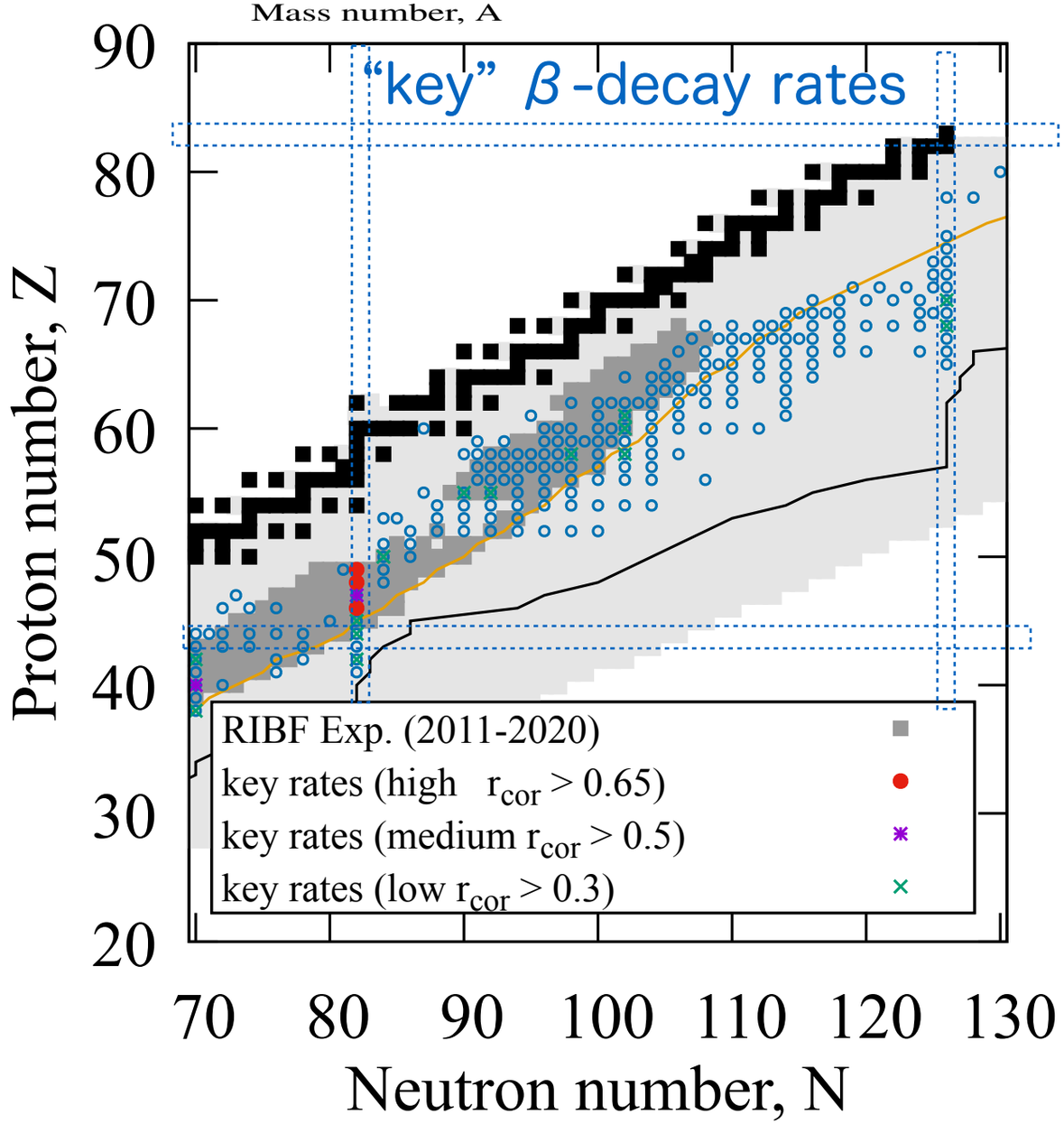


“key” β-decay rate vs experiments









→ more realistically, multi-zone (trajectories) uncertainty (e.g., NN+2018)

Summary

- MR-SNe are still possible sites for the r-process
- However, strong-magnetic jets are needed to produce heavier r-nuclei: unavailable so far in “realistic” progenitor/MHD set-up

possible “observational” properties?

- Hydrodynamical simulation of jet-SNe (w/ r-nuclei)
  - propagation of n-rich matter in outer layer with abundance evolution of r-process
  - Spacial abundance distribution can characterize explosion feature of central engine of MR-SNe
  - r-process contents may affect SN light-curve properties (if significantly produced compared)