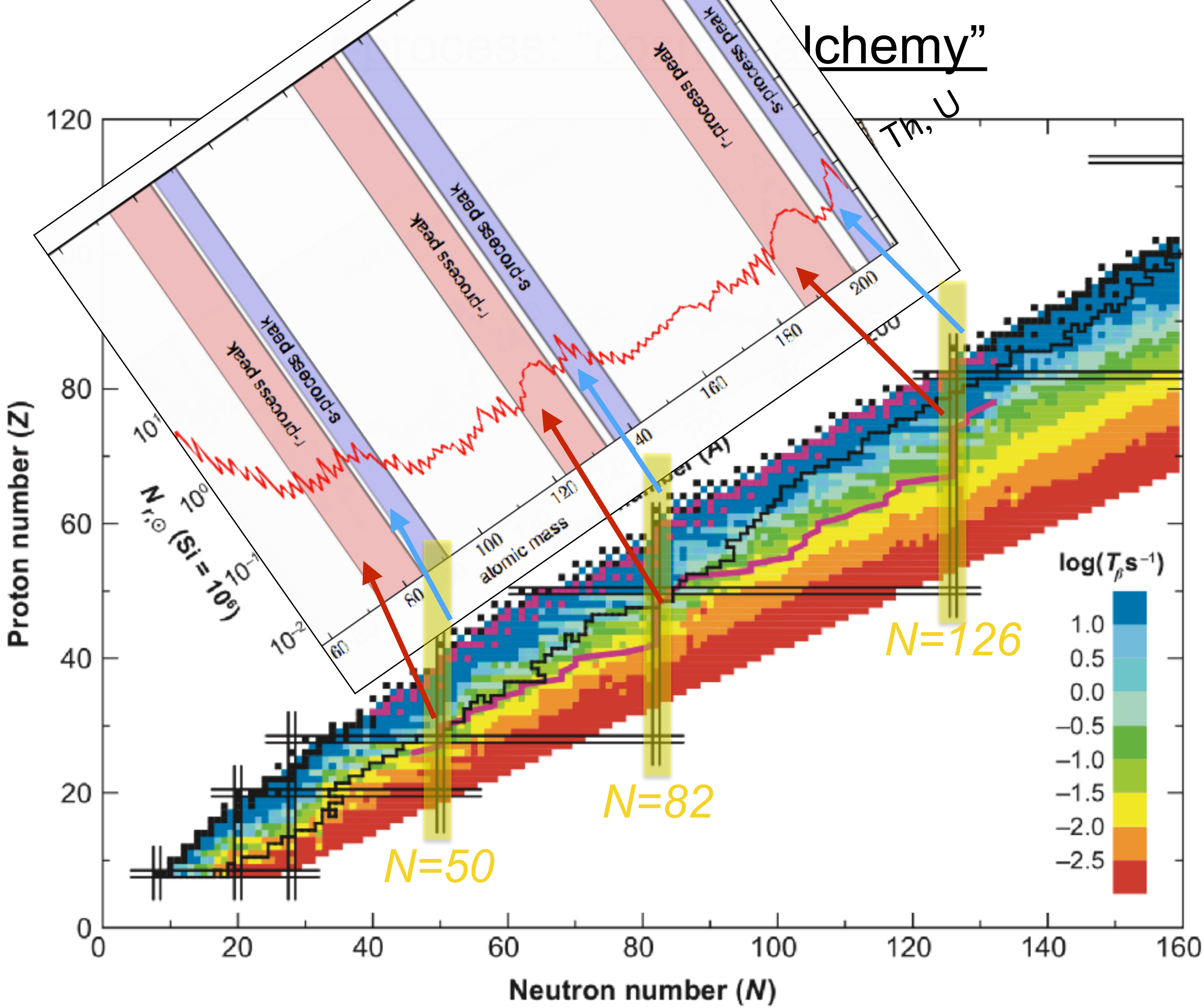
Observational signatures of r-process jets in core-collapse supernovae

Nobuya Nishimura
YITP, Kyoto University

CGP Center for Gravitational Physics Yukawa Institute for Theoretical Physics
YITP YUKAWA INSTITUTE FOR THEORETICAL PHYSICS
京都大学 KYOTO UNIVERSITY
計算基礎科学連携拠点 JICFuS Joint Institute for Computational Fundamental Science
京 K computer

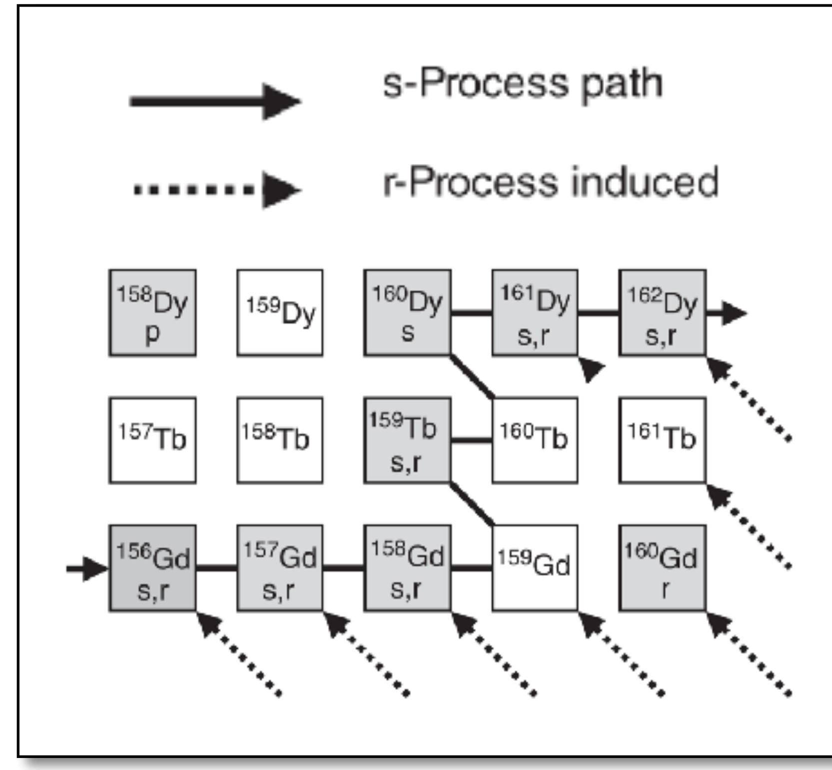

lchemy”
Th, U
Proton number (Z)
Neutron number (N)
log(T_βs^{-1})
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
N=50
N=82
N=126
r-process peak
s-process peak
$N_{r,\odot}$ (Si = 10^6)
atomic mass
0
20
40
60
80
100
120
140
160

The rapid-neutron-capture process

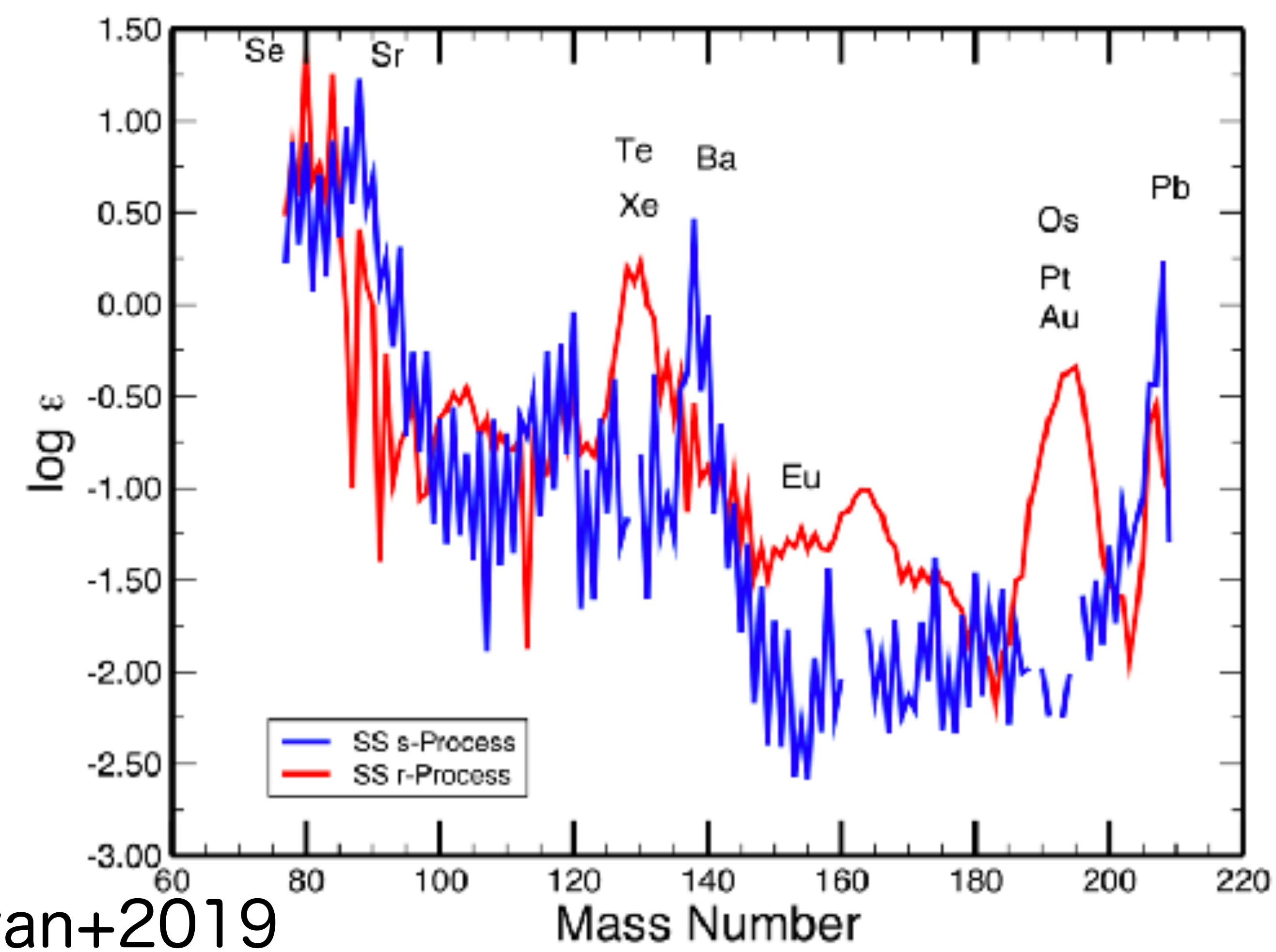
- rapid n capture vs. β-decay
  $N_n \sim 10^{23}$ /cm^3

($N_n \sim 10^5$ /cm^3 for the slow process)

- the nucleosynthesis "path" goes to very neutron-rich nuclei



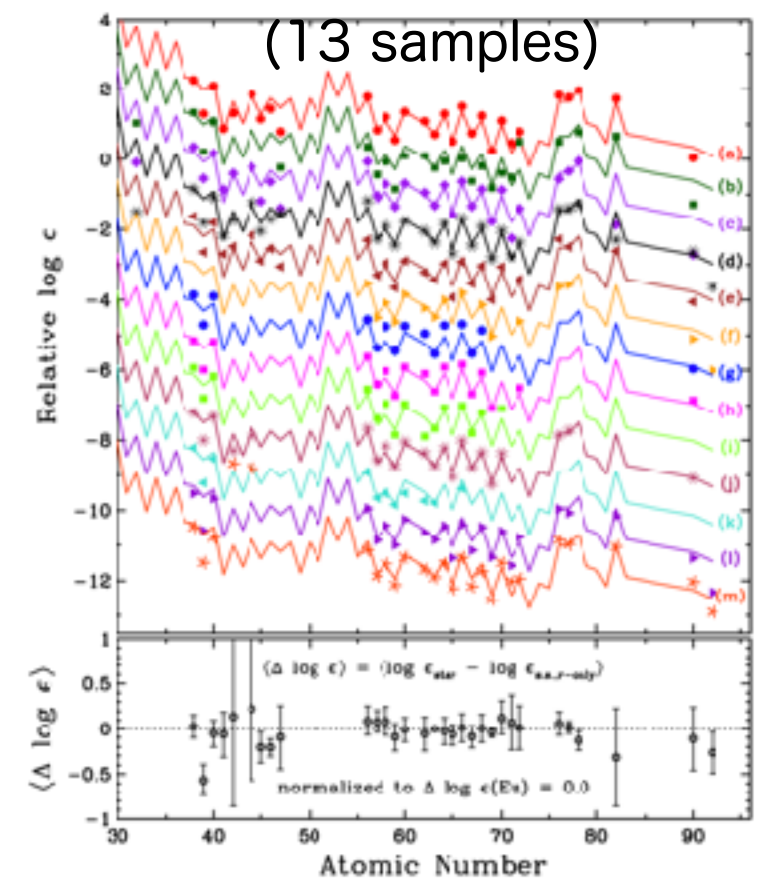
"solar r" ≈ [solar obs.] - "s-proc. calc."



Cowan+2019

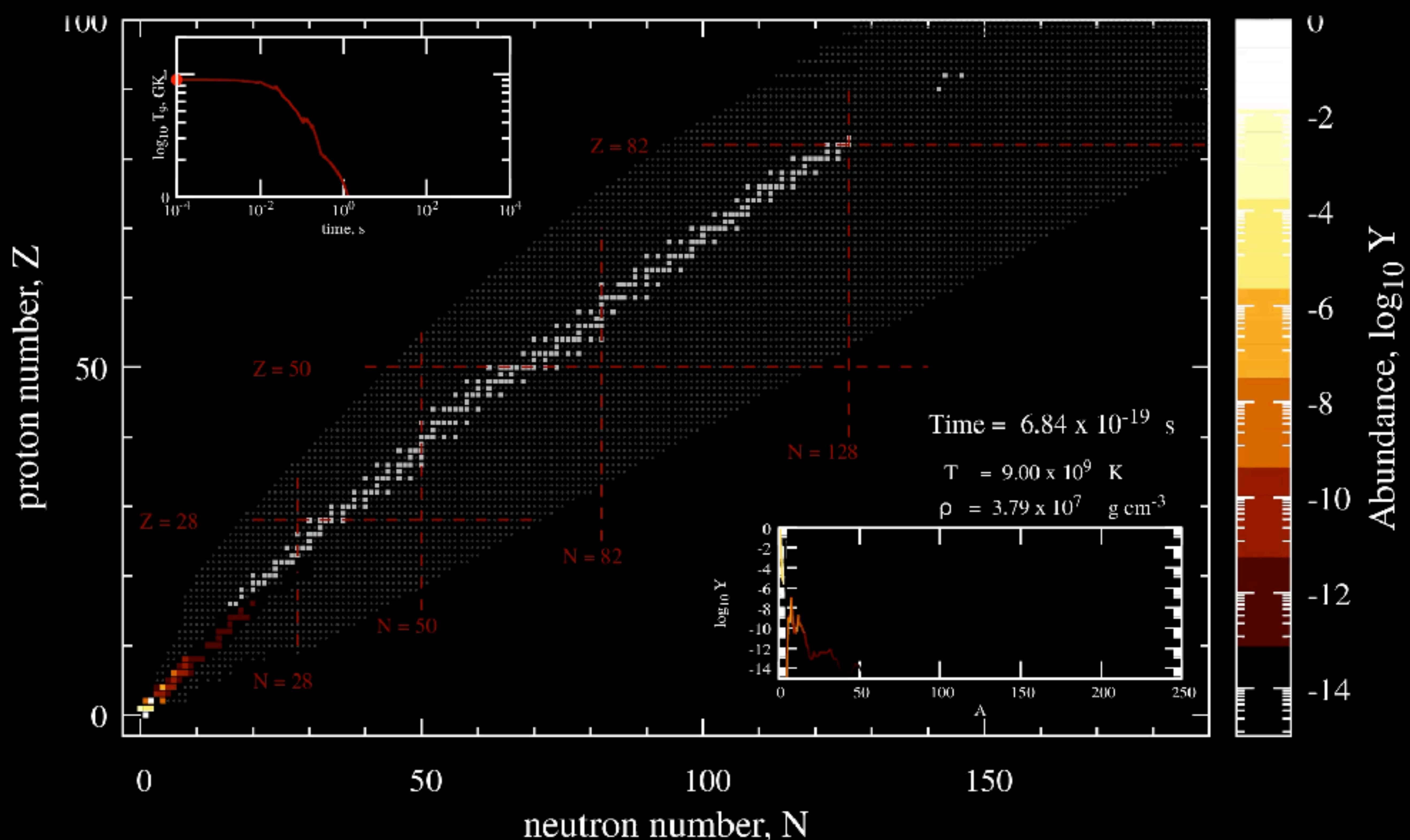
metal-poor halo stars

(13 samples)

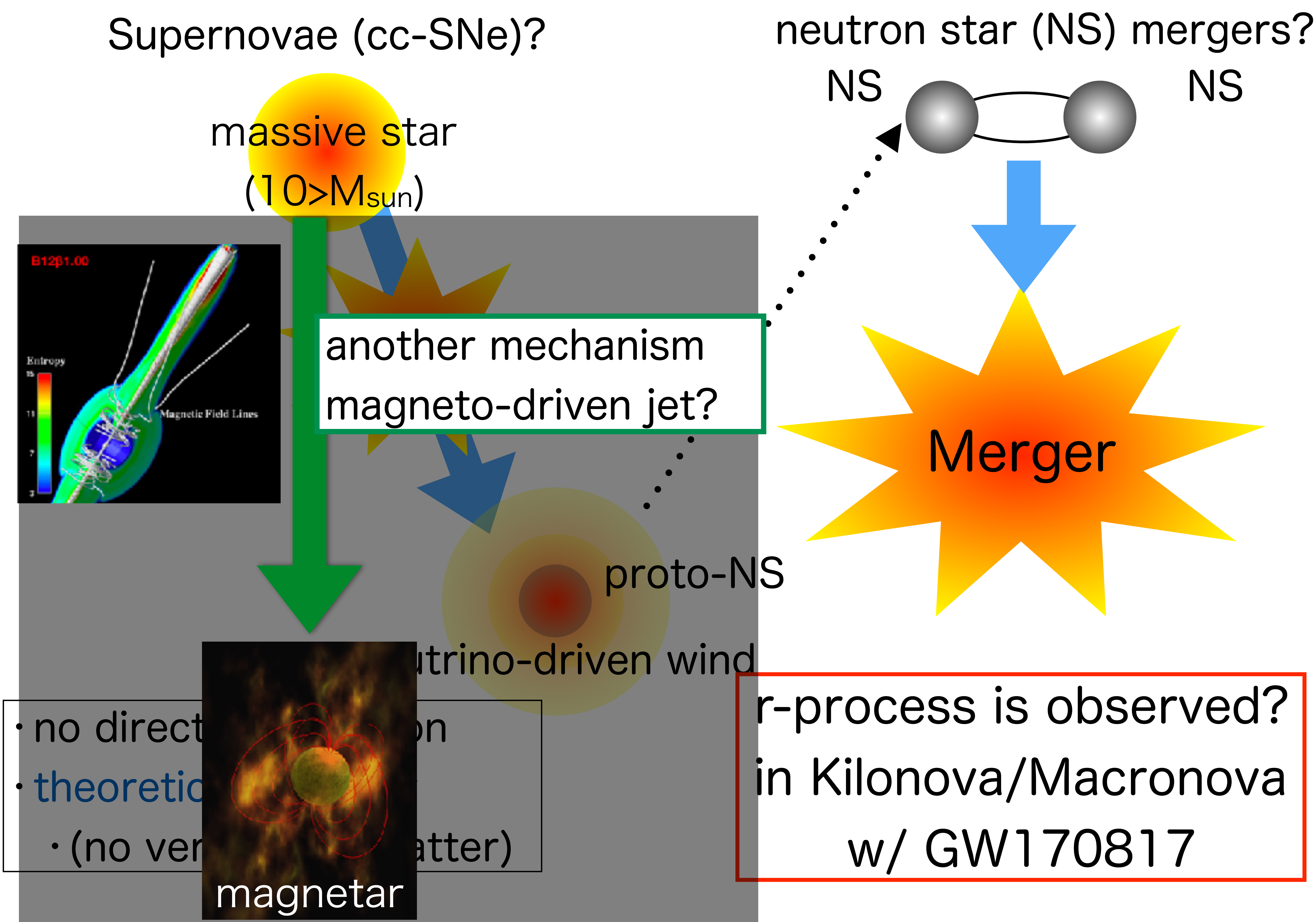


Cowan+2019

r-process nucleosynthesis "flow"



Astronomical site(s) of the r-process



Talk plan

- Introduction
  - MR-driven “jet” supernovae?
- Production of r-process nuclei
  - central engine and abundances
  - (vs. r-process observation in metal-poor stars)
- Ejection of r-process nuclei
  - shock propagation and r-nuclei ejection
- (uncertainties due to nuclear-physics inputs)
- Summary

References

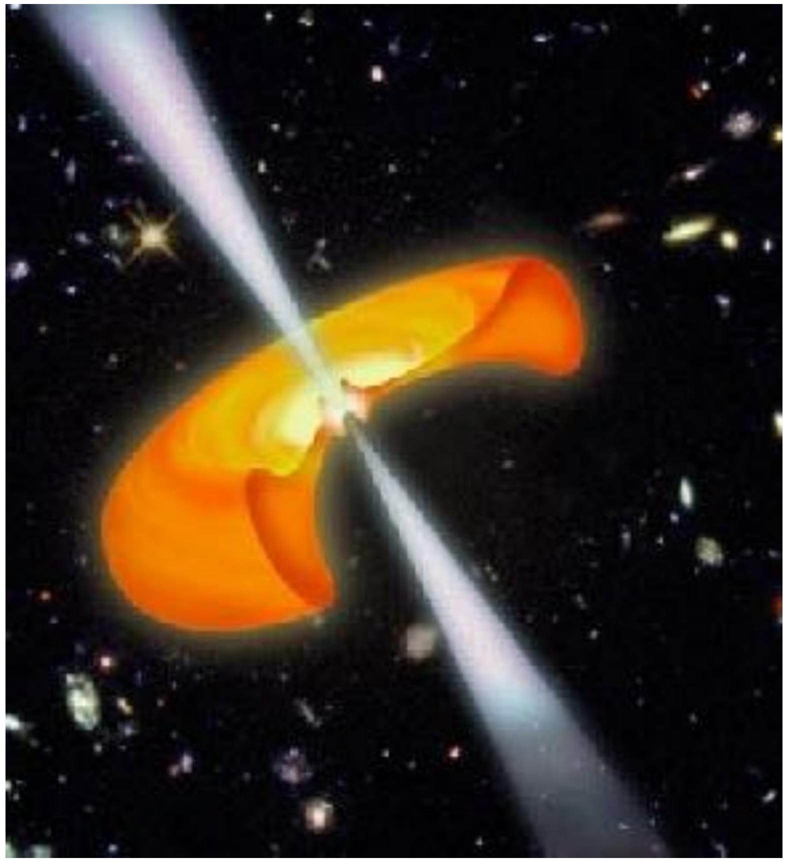
- Winteler+NN+(2012) ApJL 750:L22
- NN, Takiwaki, Thielemann (2015) ApJ 810:109
- Tsujimoto & NN (2015) ApJL 810:L10
- NN, Sawai, Takiwaki+(2017) ApJL 836:L21
- Tsujimoto & NN (2018) ApJL 863:L27

Production of r-process nuclei

the central engine of MR-SNe

・NN, Takiwaki & Thielemann (2015) ApJ
・NN, Sawai, Takiwaki+(2017) ApJL

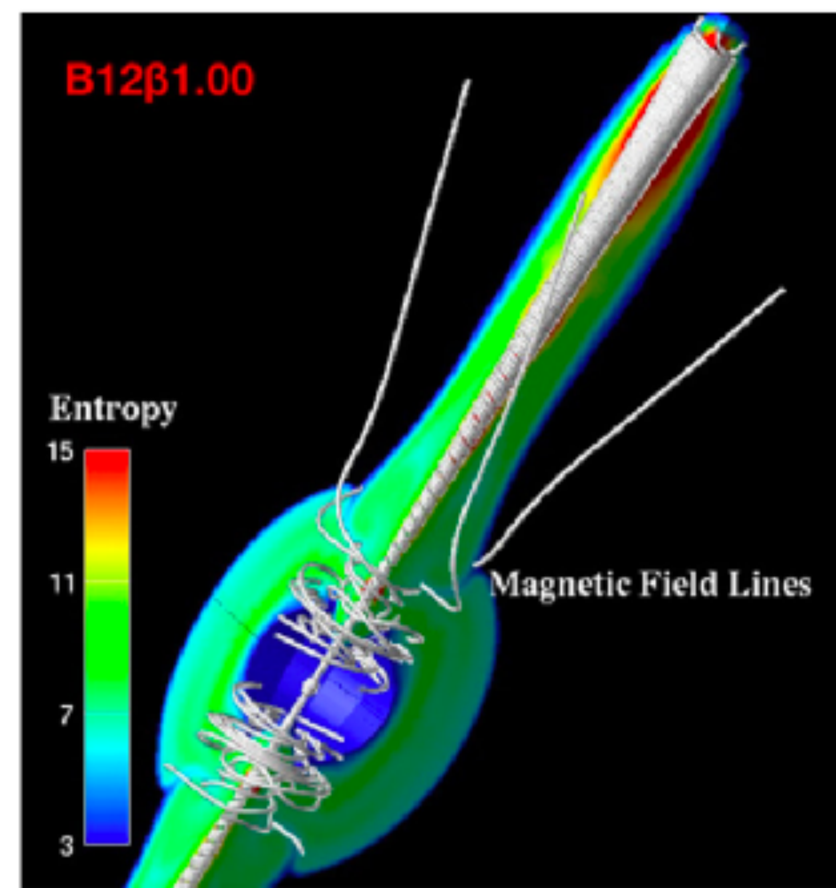
r-Process in magneto-rotational supernovae



hypernova/jet-like SN

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

NN+2015

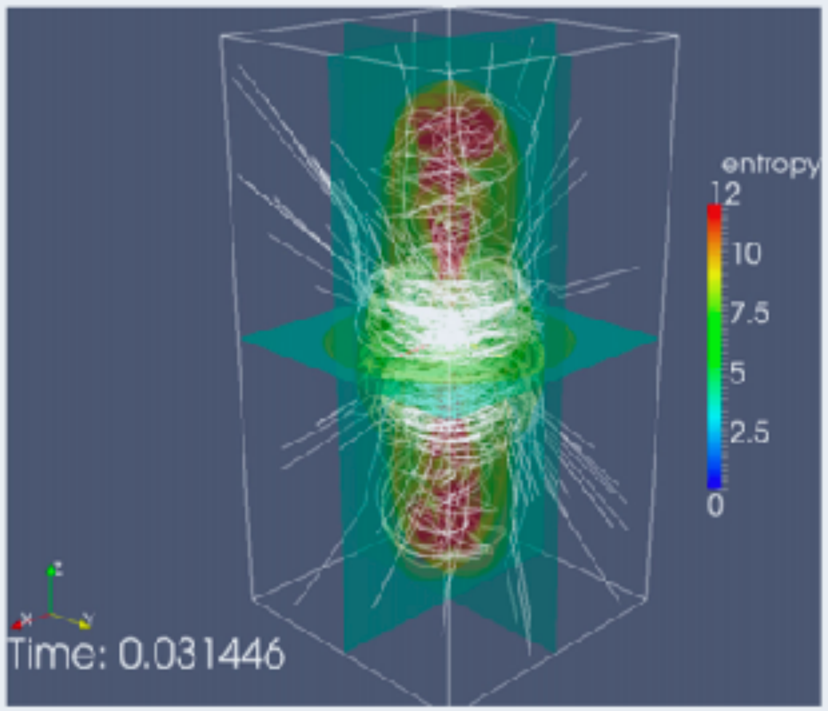


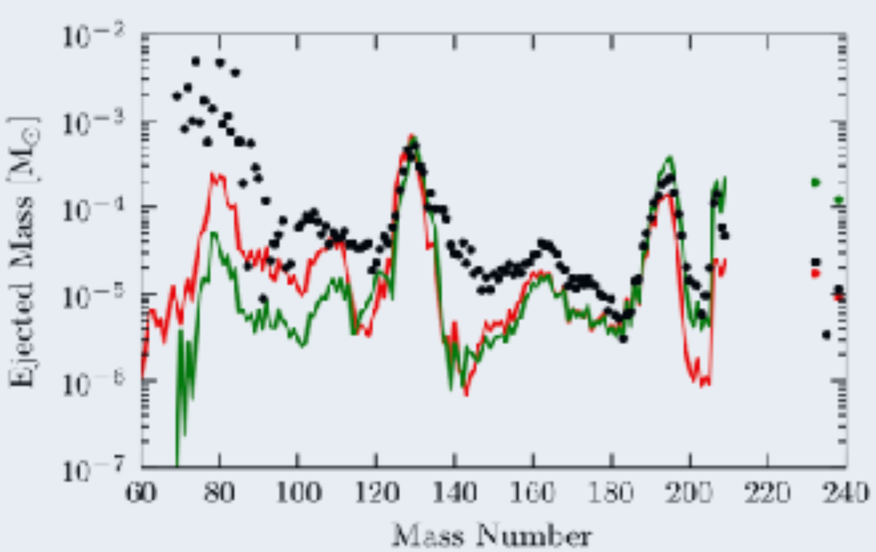
- MR-SNe (magnetar formation)
  - “the classics”: Symbalisty(1984), Cameron(2003)
  - 2D: Nishimura+NN+(2006); NN+(2012,2015,2017)
  - 3D: Winteler+NN+(2012); Mösta+(2014,2018), Halevi&Mösta(2018)
- “Collapsar model” (BH + disk + jet)
  - 2D: Fujimoto+(2007); Fujimoto, NN, Hashimoto(2009);
  - Ono+(2009, 2012)

3D effects on jet-propagation

strong jet in 3D

Winteler+NN+(2012)

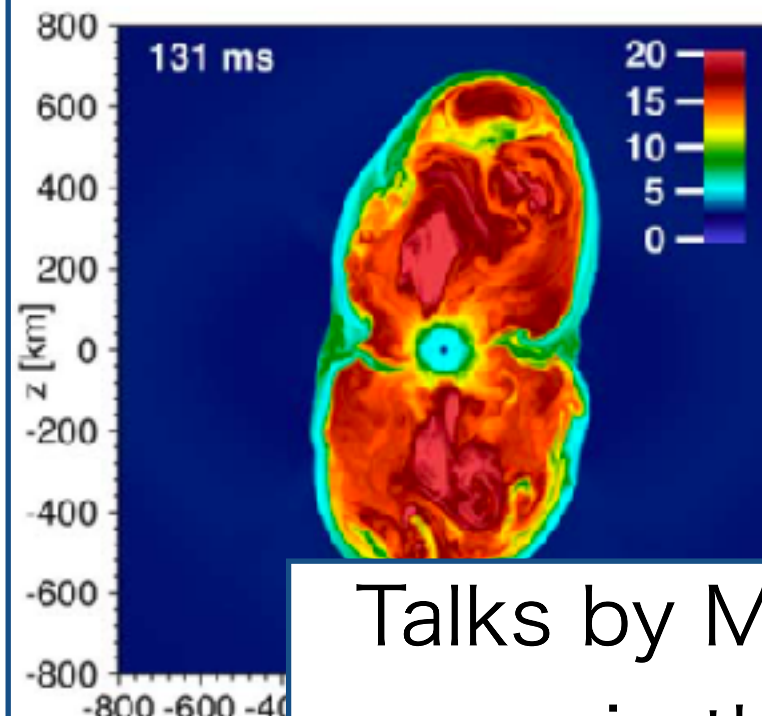


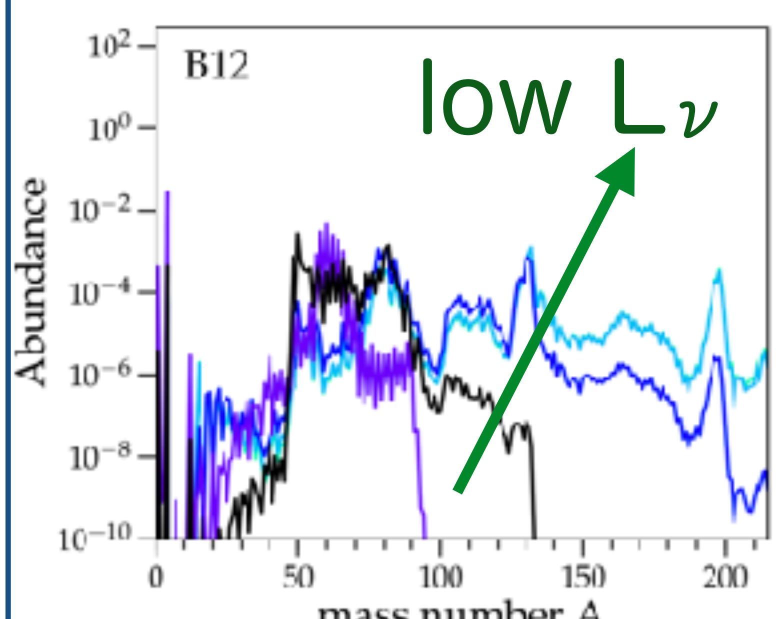


*difference is due to uncertainty

deformation by hydro-instability

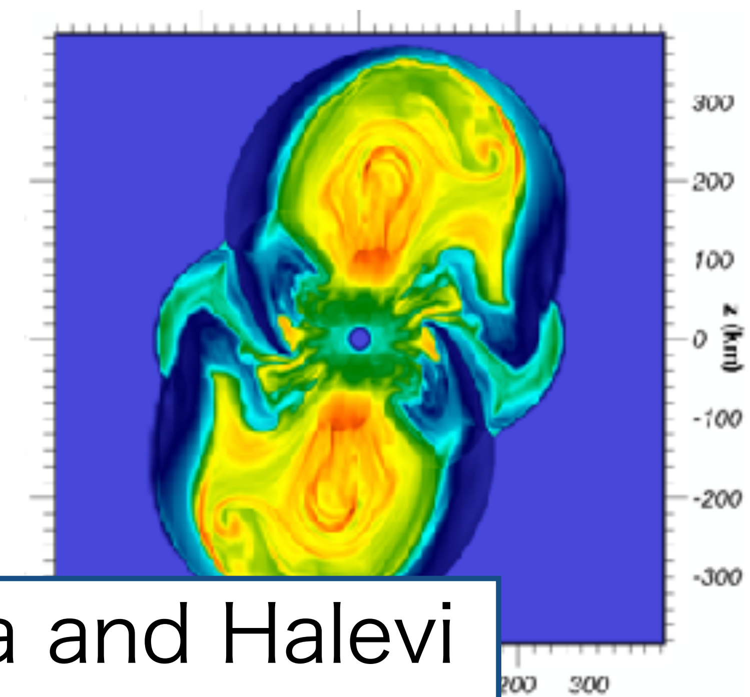
Mösta+(2018)

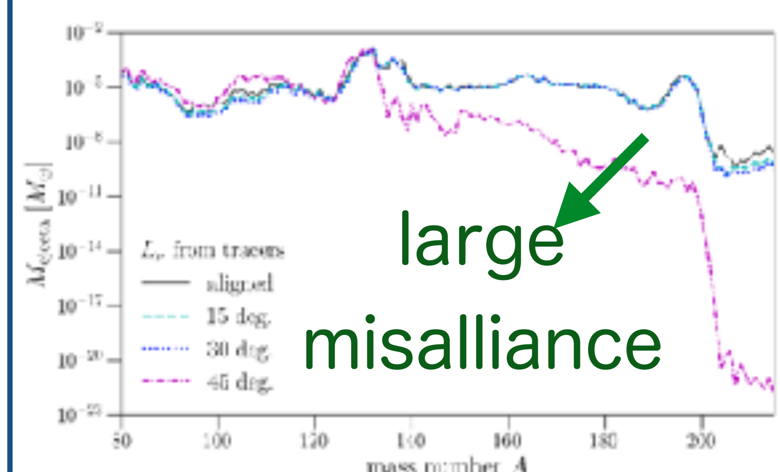




misalliance of B-filed and rotation

Halevi&Mösta(2018)



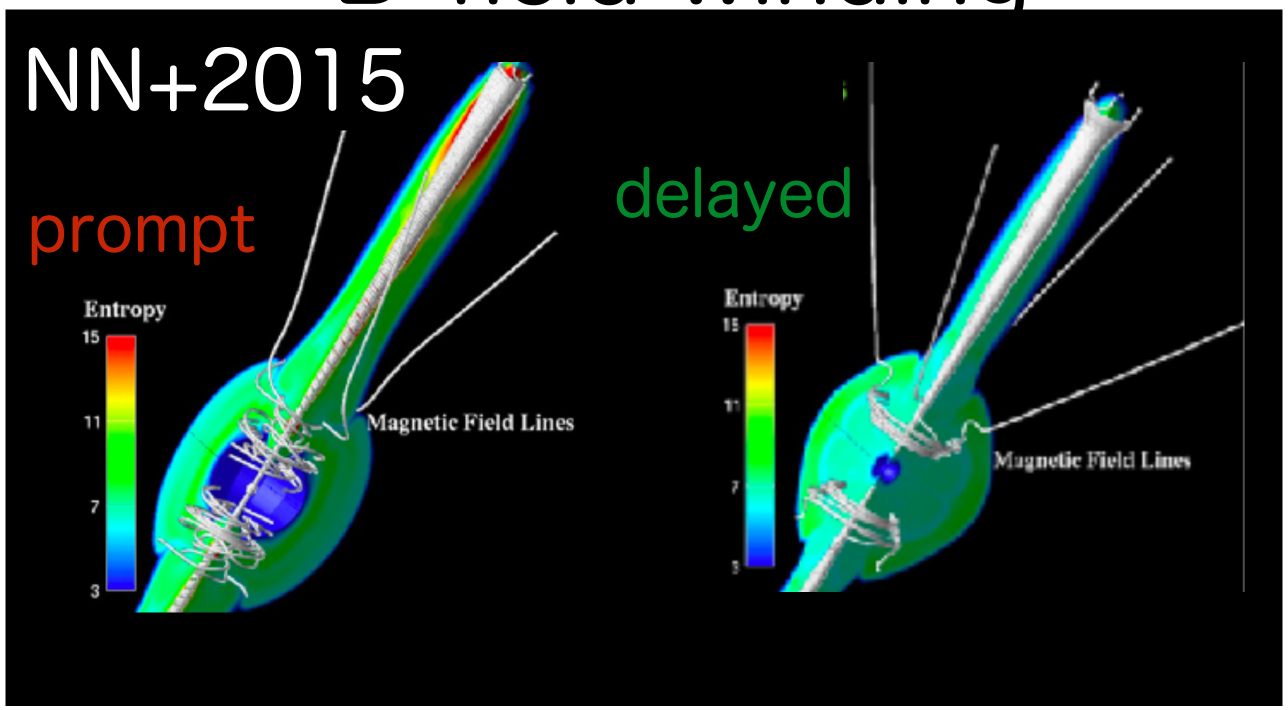


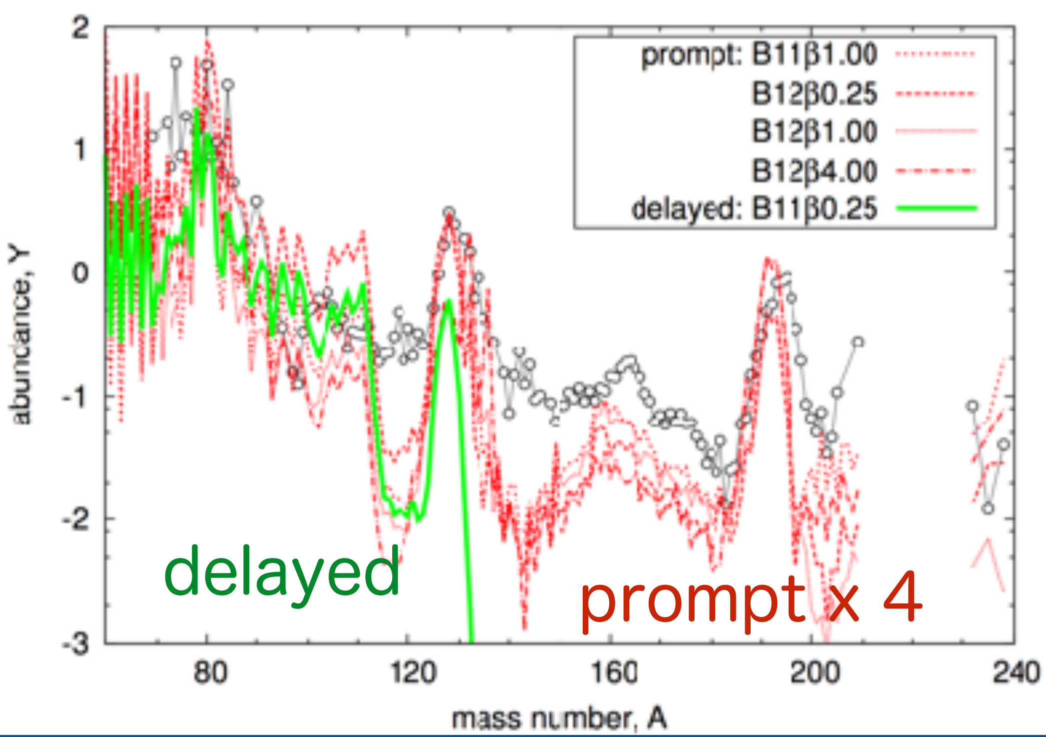
Talks by Mösta and Halevi in this week?

magnetic-field enhancement process?

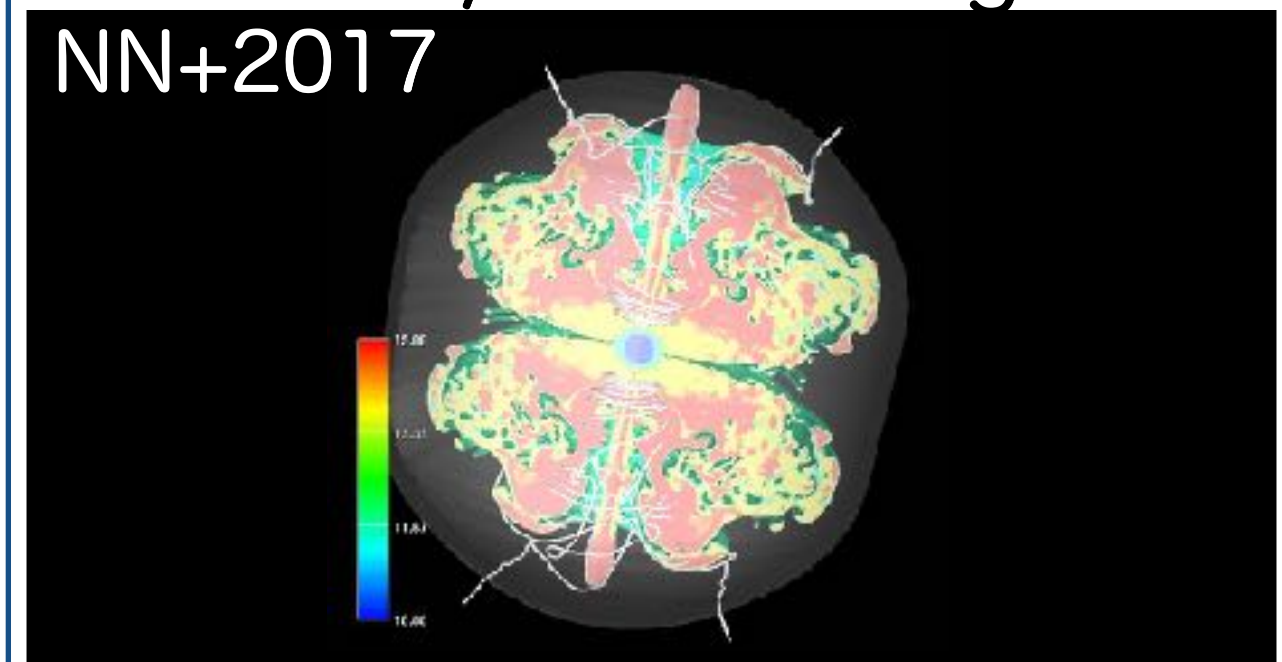
axi-symmetric (2D); long-term, high-resolution

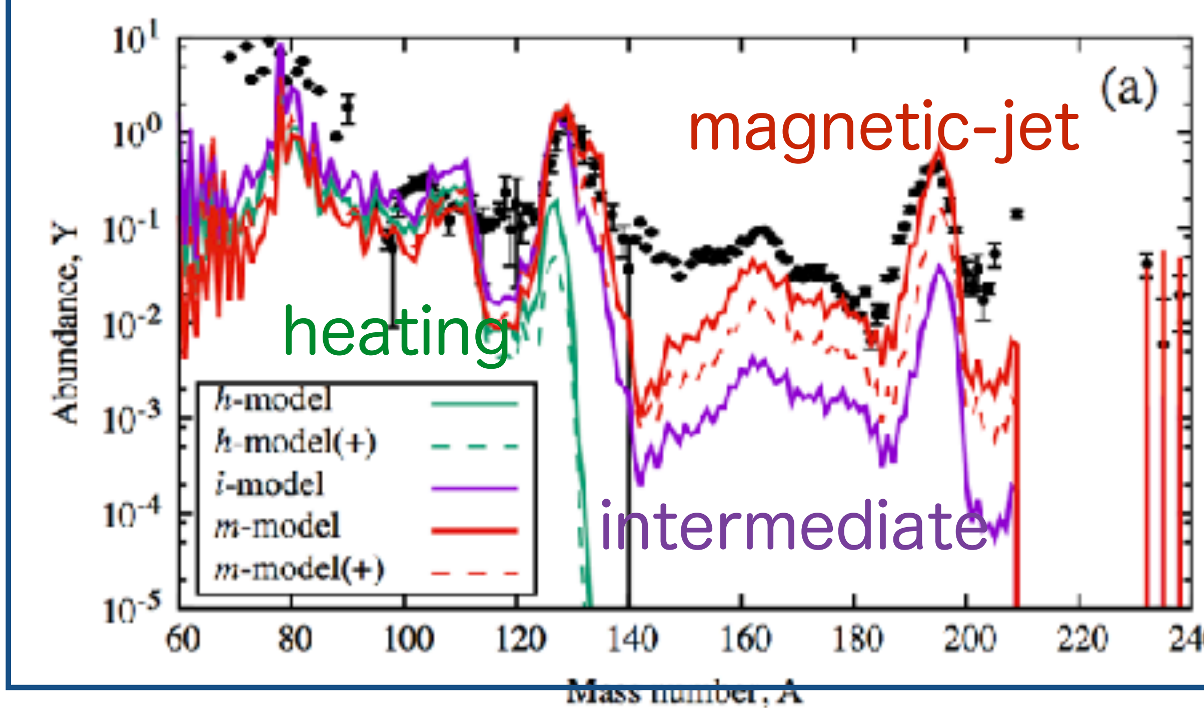
B-field winding





MRI w/ ν-heating



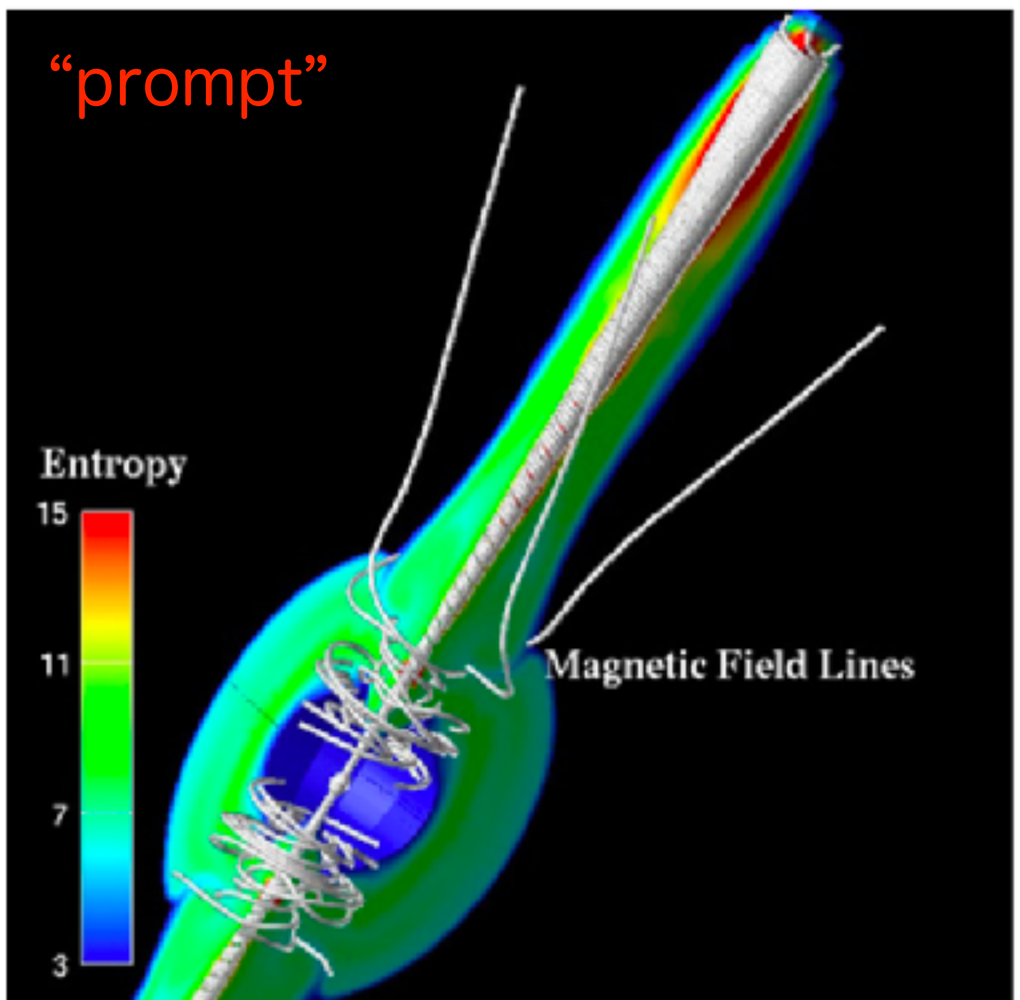


Various r-process in several jet SNe

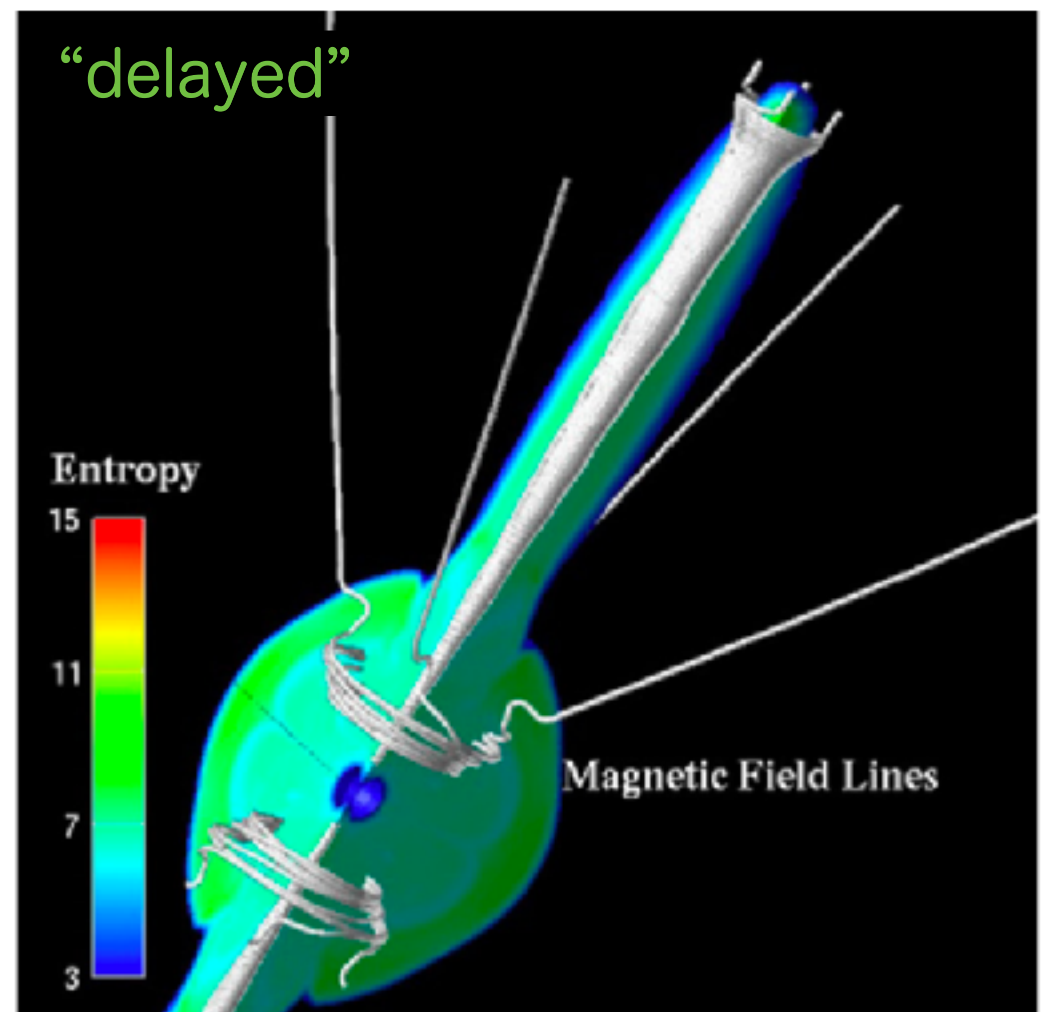
2D-hydro w/ parametric rotation & B-fields

(NN+2015, based on Takiwaki+2009)

- **Strong (prompt)-jets**
  - very n-rich from the inside of the PSN (strong e^--capture)
- **Weaker (delayed) jets**
  - less neutron-rich due to strong neutrino absorption



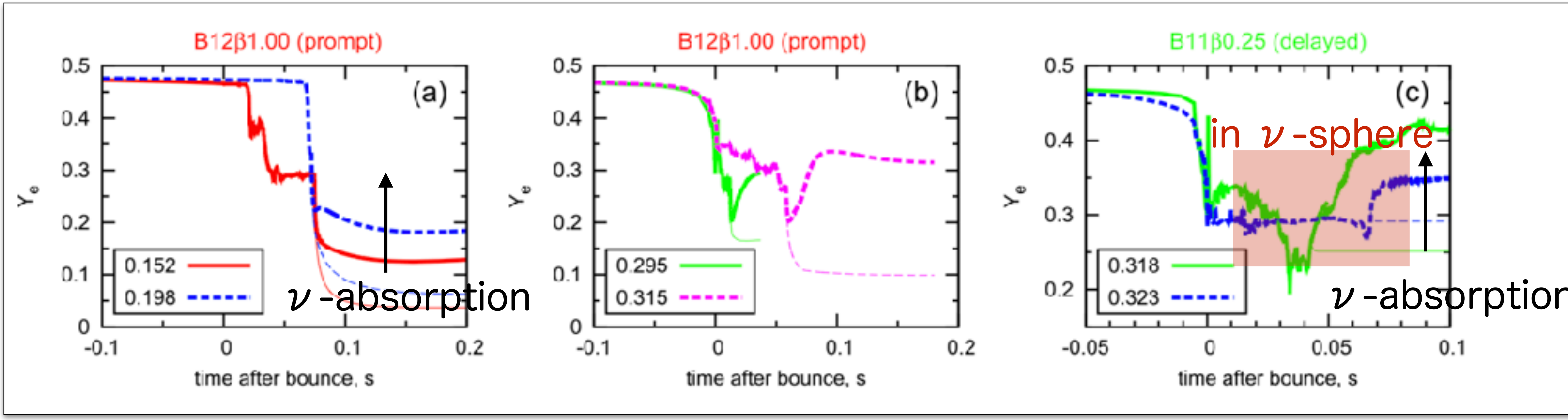
VS



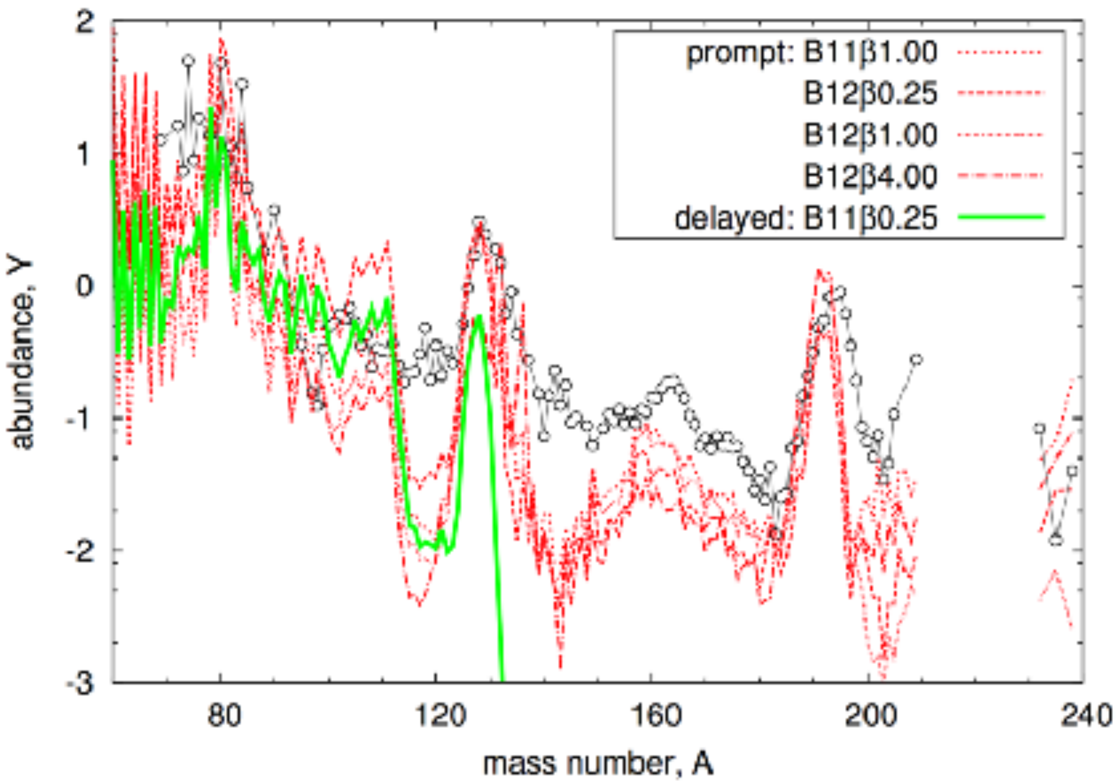
Various r-process in several jet SNe

very neutron-rich matter in SN core ("proto-magnetar")

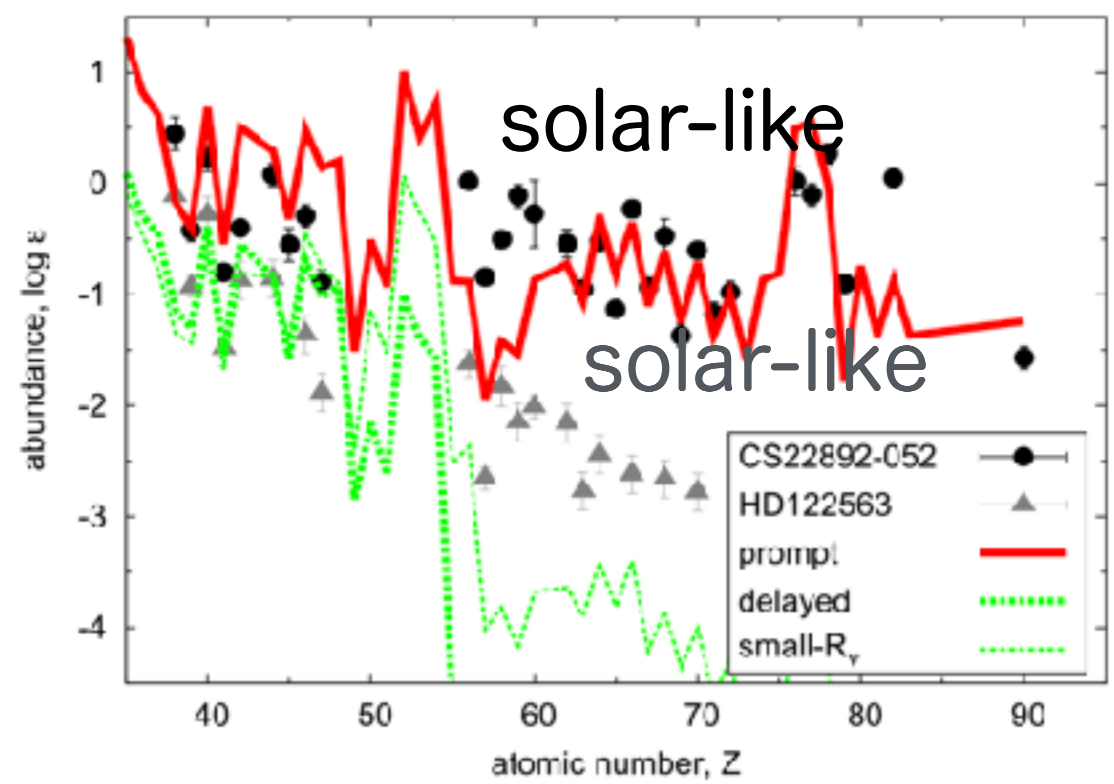
significant effect of e⁻-capture (off β-equilibrium)



solar r



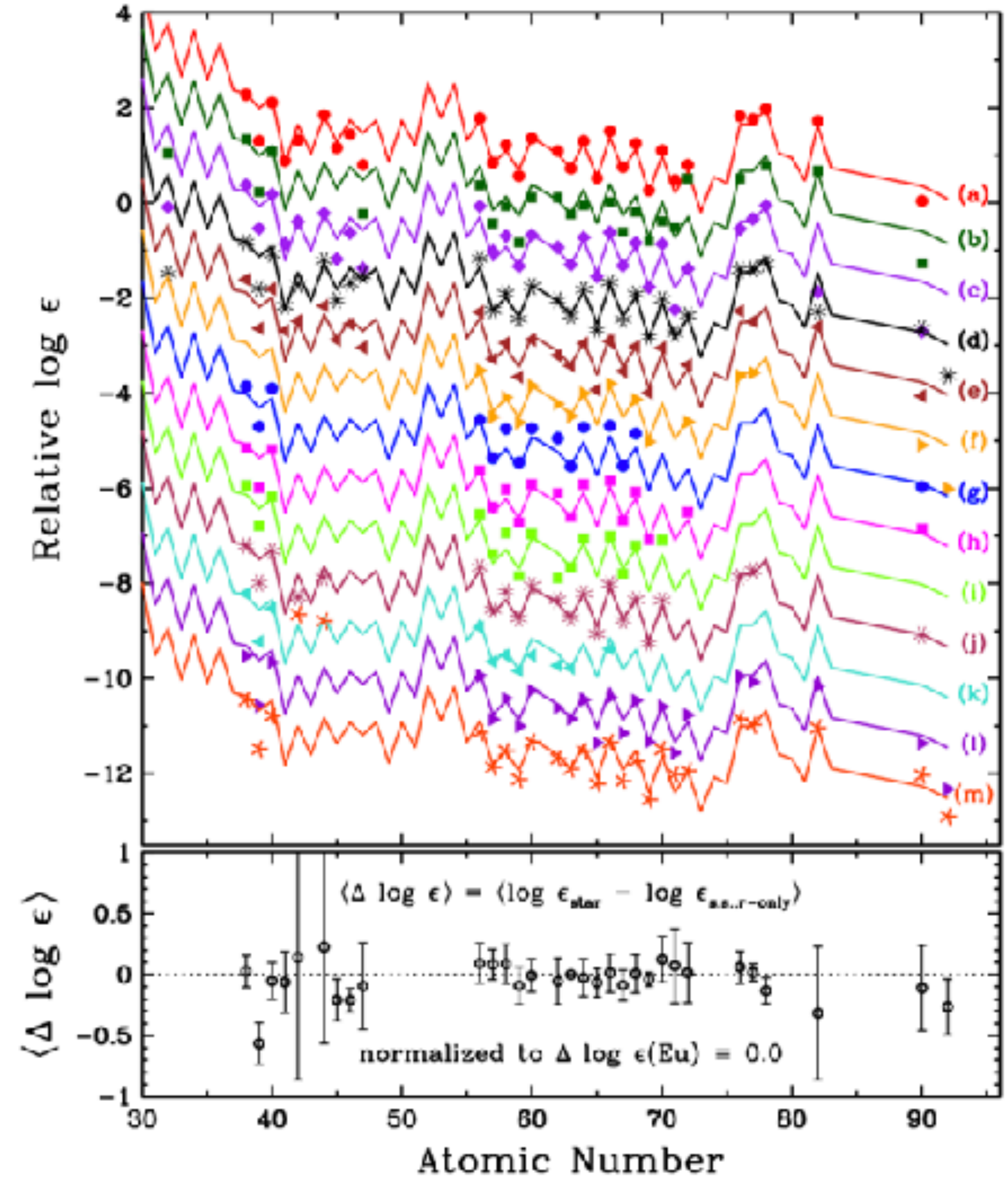
metal-poor stars



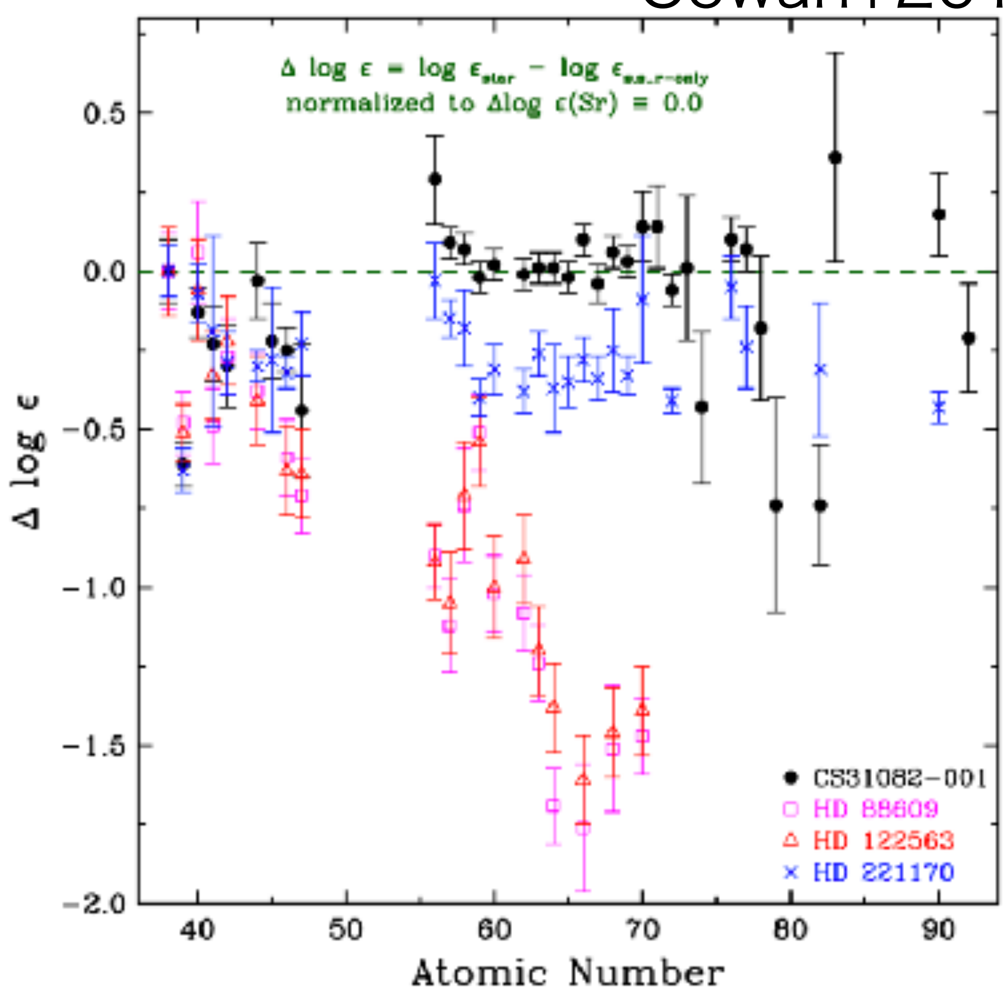
Diversity in metal-poor star abundances?

Cowan+2019

- many r-rich Galactic halo stars show the solar r-pattern
- r-process has happened from the early Galaxy
- astrophysical models reproduce this common pattern (Z>40; A>90)



Cowan+2019



- However, growing evidence for “weak” r-process patterns (e.g., Honda+2006)

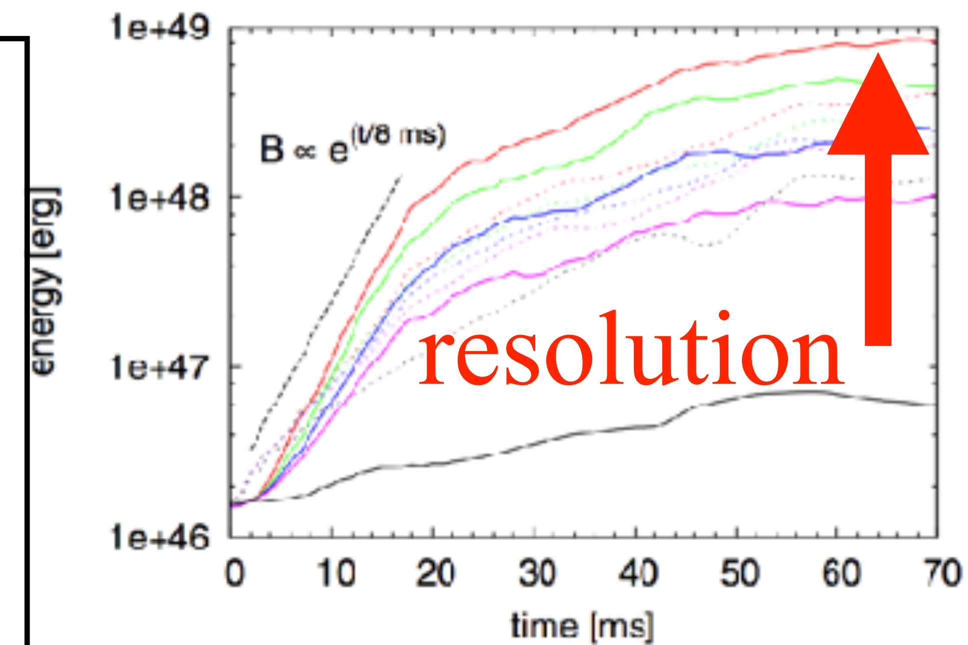
Magneto-rotational instability in CC-SN

Sawai & Yamada (2014, 2016)

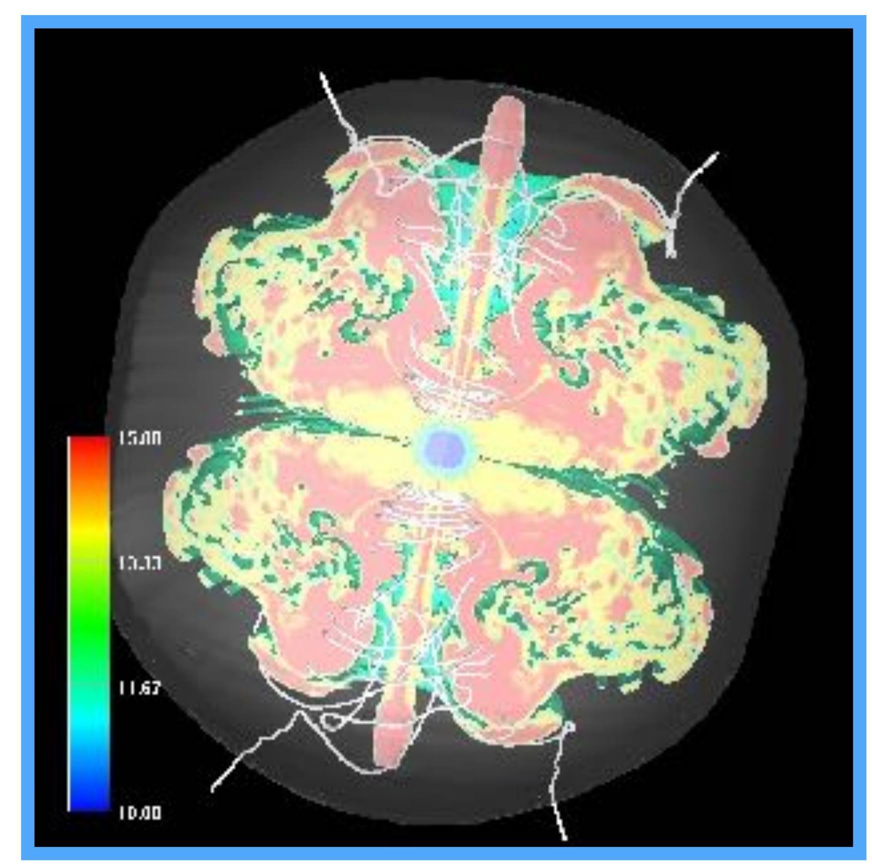
- MR-hydro code (山桜: “YAMAZAKURA”)
- MRI enhance B-fields of the core
- neutrino-heating also affects explosion
- 2D axisymmetric
- initial condition:
  - $15M_{sun}$ (Fe: $1.4M_{sun}$) (Woosley&Heger1995)
  - rotation (core): 2.7 rad/s
  - B-fields: 2×10^{11} G (B flux: 7×10^{27} cm^2G)

    —> magnetar candidate

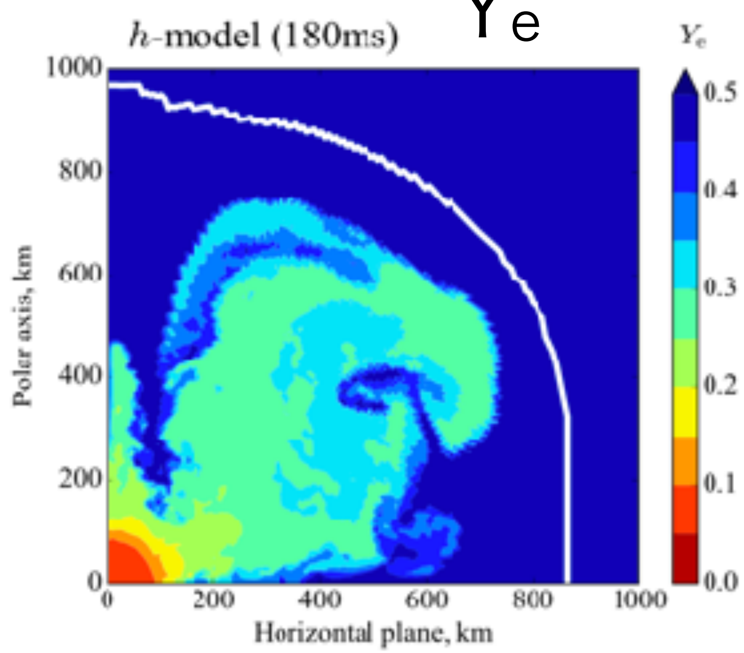
Δr_{min} = 100, 50, 25, 12.5 m



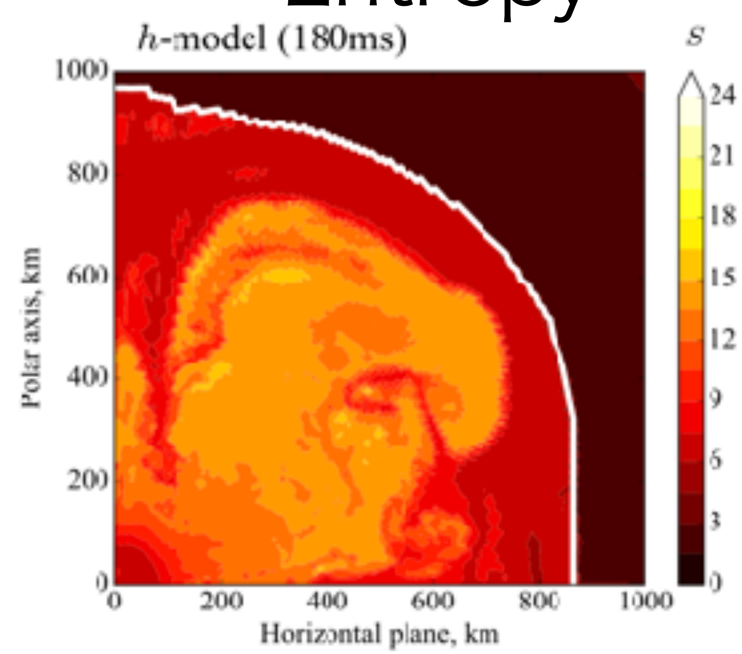
Entropy + B-fields(3D)



Ye



Entropy

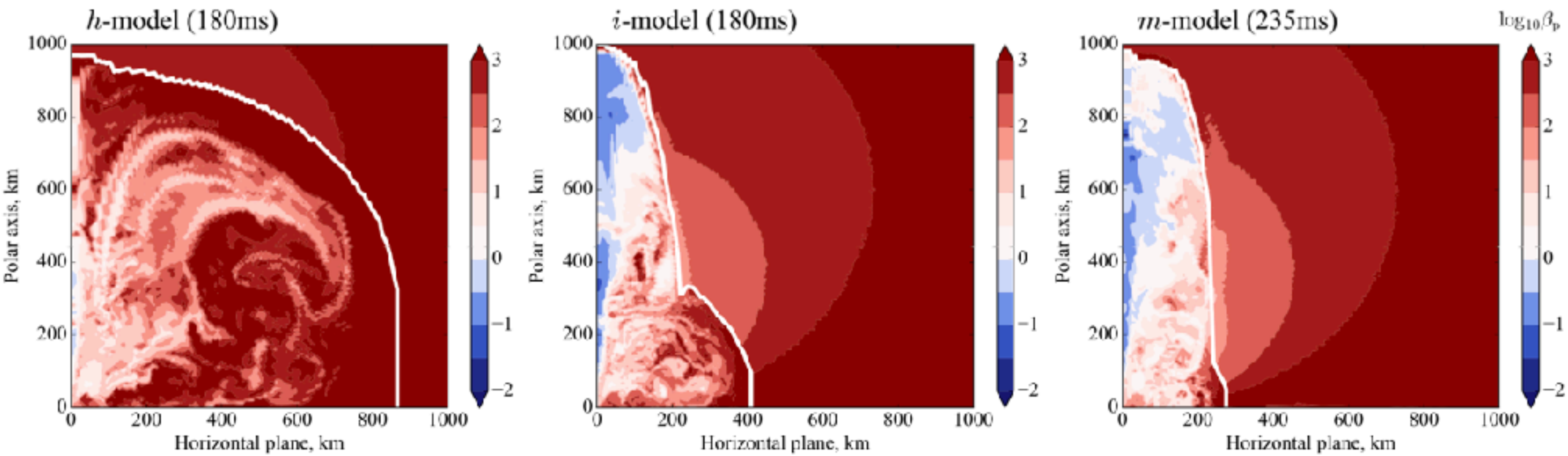


Need those strong initial B-fields?

Problem: varying B-fields/rotation
—> requires MRI convergence for each case
and comparison among models are difficult
Adopt: varying L_ν —> effective strength of B-fields in explosion dynamics

heating-dominated | intermediate | magnetically-dominated

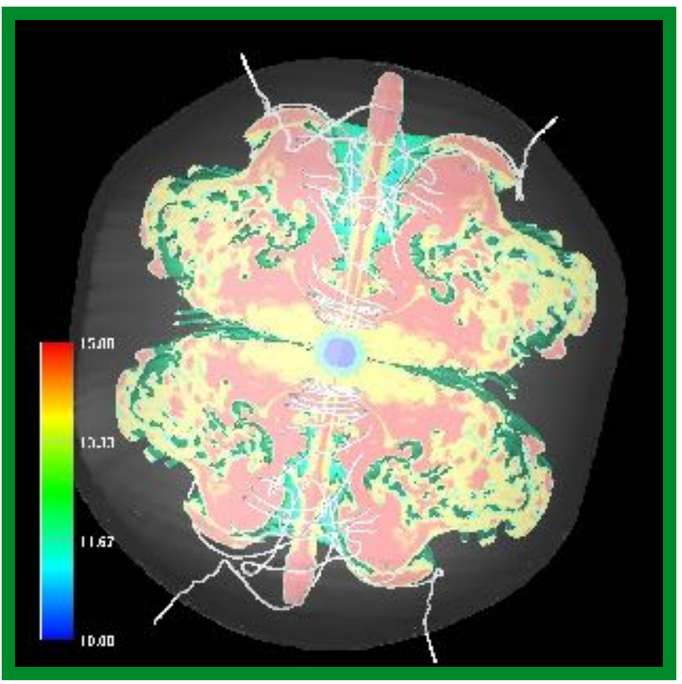
plasma-β



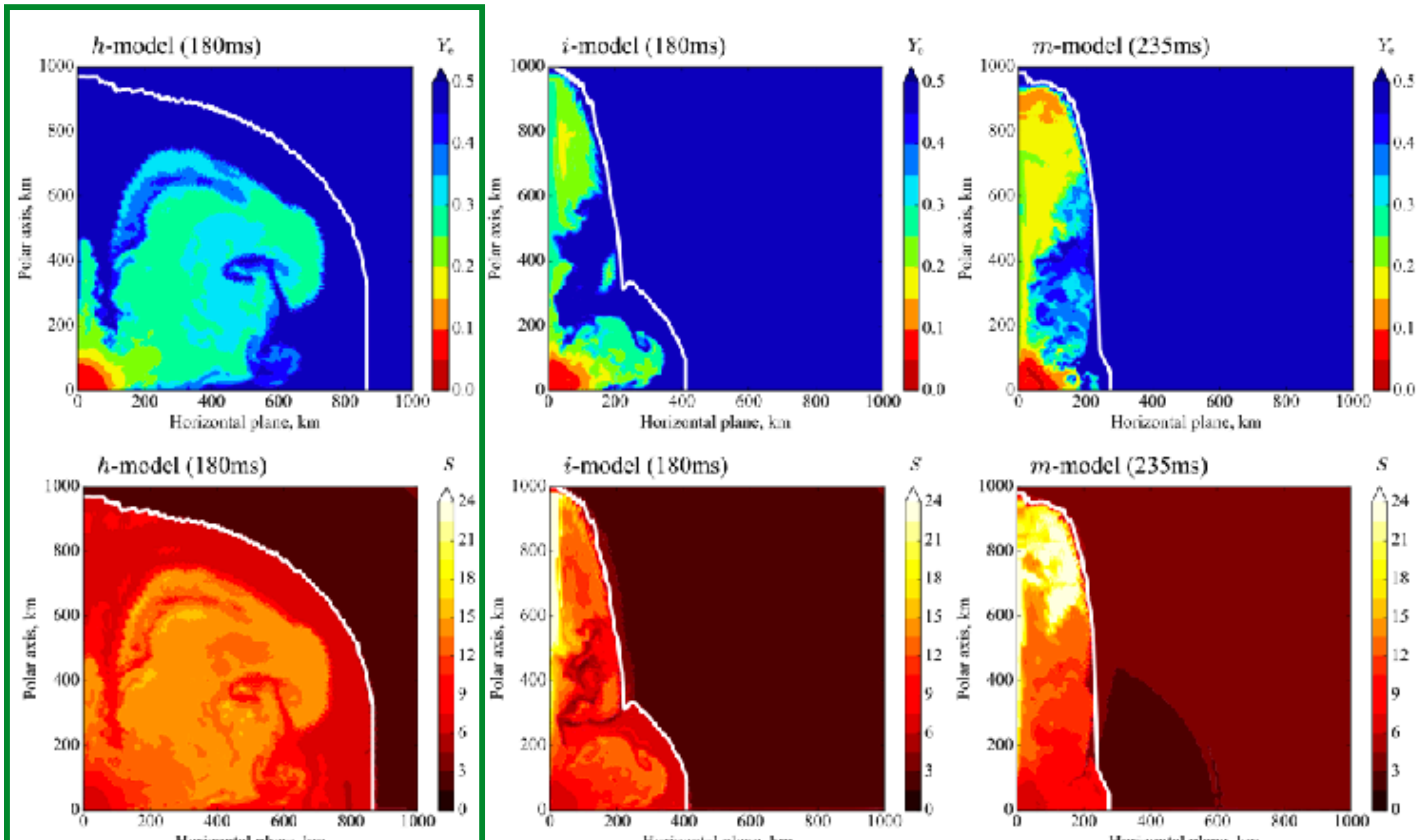
Need those strong initial B-fields?

heating-dominated ⟷ intermediate ⟷ magnetically-dominated

heating-dominated



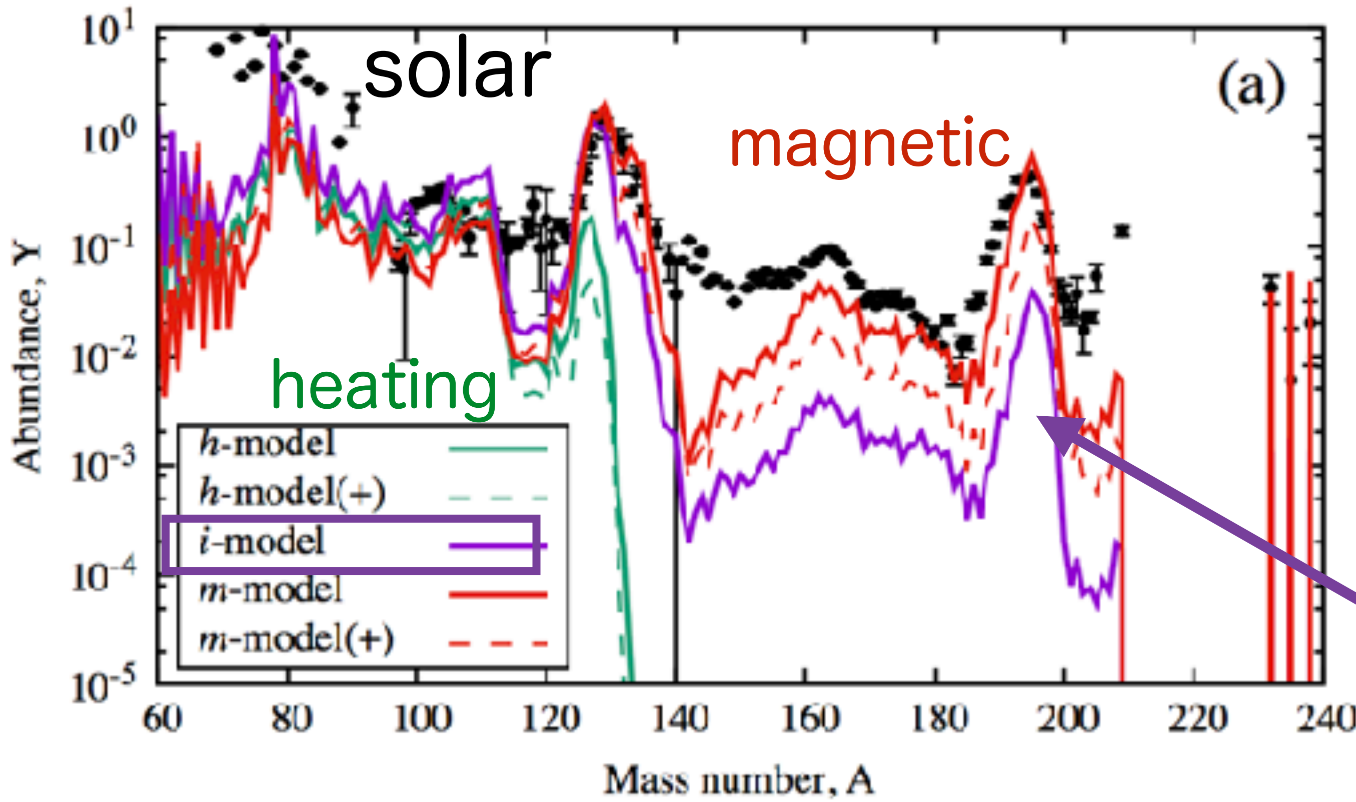
Y_e

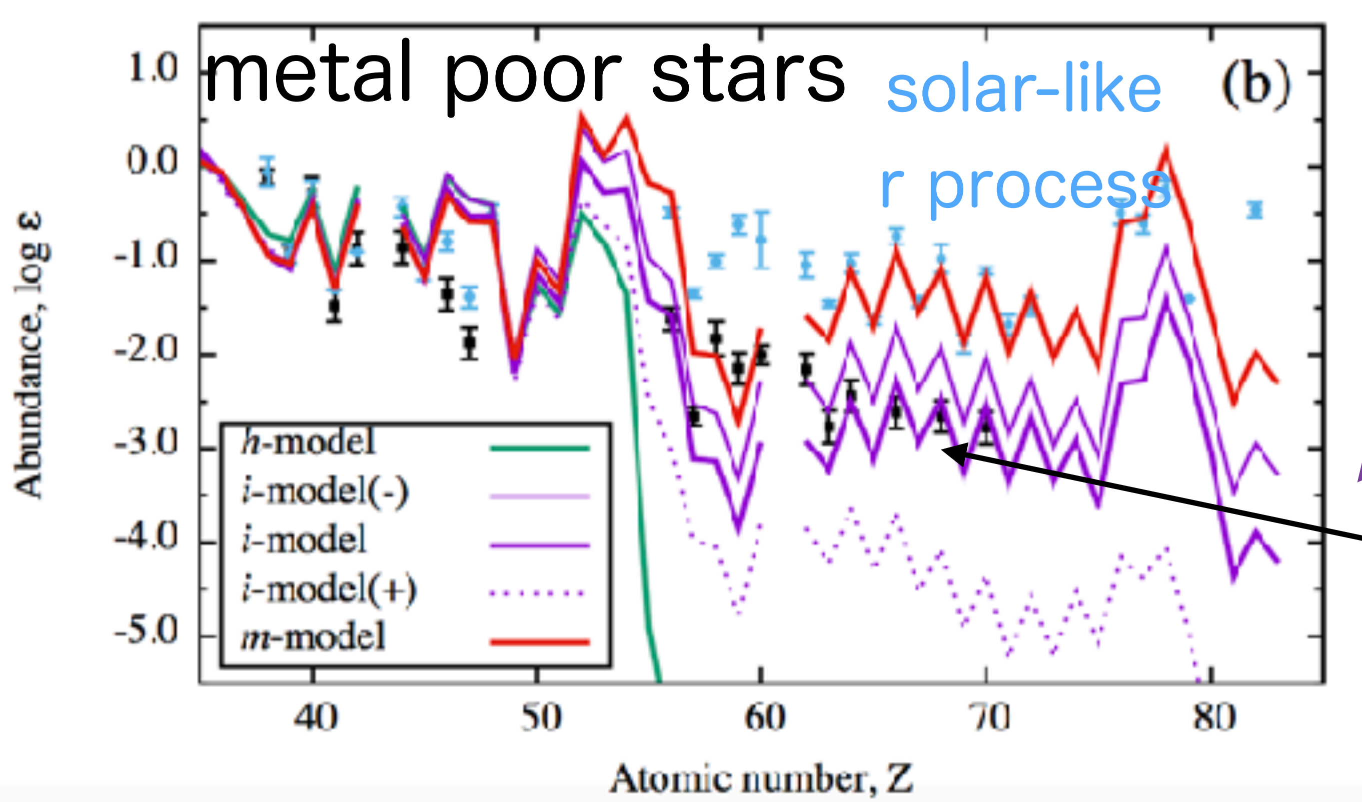


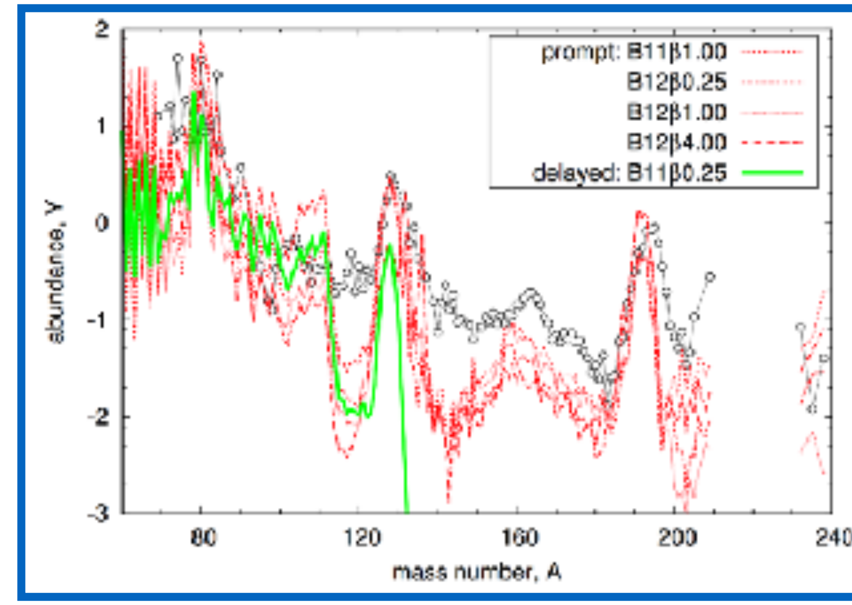
Entropy, S

r-process abundances

NN+(2017), based on Sawai models







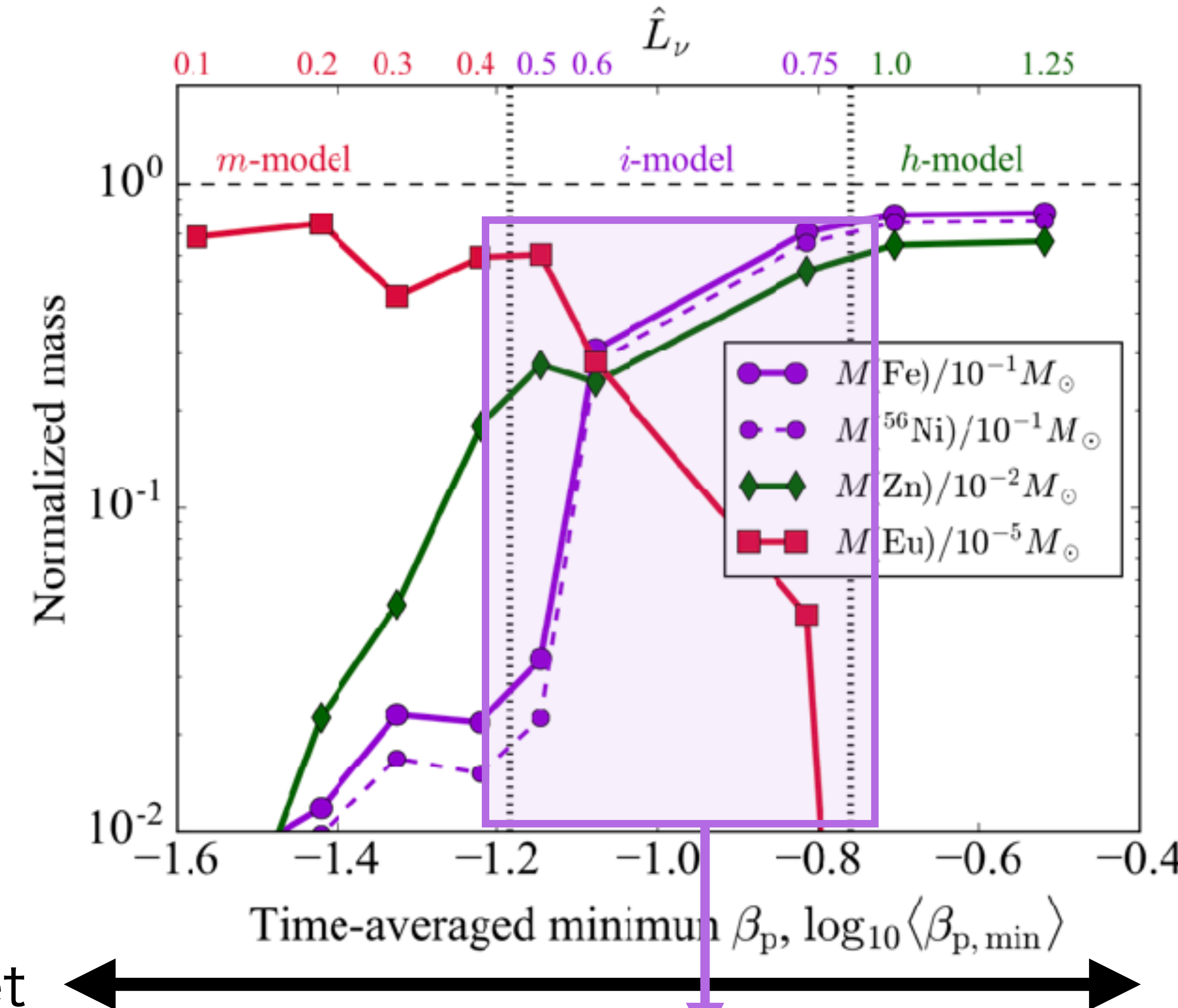
prompt vs delayed

(NN+2015, Takiwaki models)

"intermediate" r-process?

"weak" heavy r pattern
HD122563 (Honda+2006)

Alternative r-process sources in early galaxy?



"intermediate" r-process?

discussion on GCE
(several Talks in this WS)

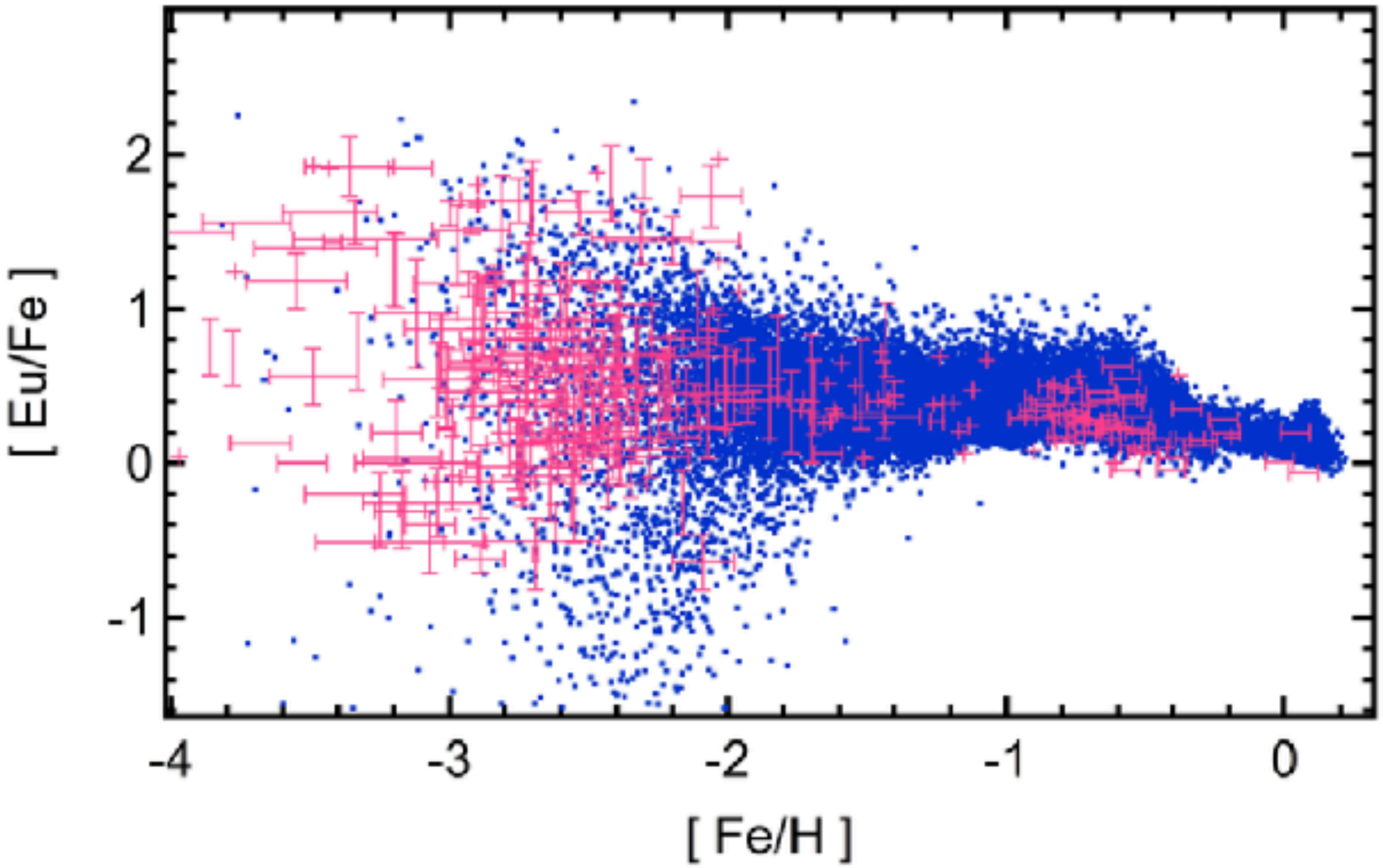
nucleosynthesis yields:
github.com/nnobuya/mrsn

Multiple r-process sources in GCE?

NS mergers cannot explain early chemical evolution of r-process elements, e.g., Eu?
→ shorter delay time or another source

comprehensive GCE analysis after GW170817 (e.g., Côté+2018)

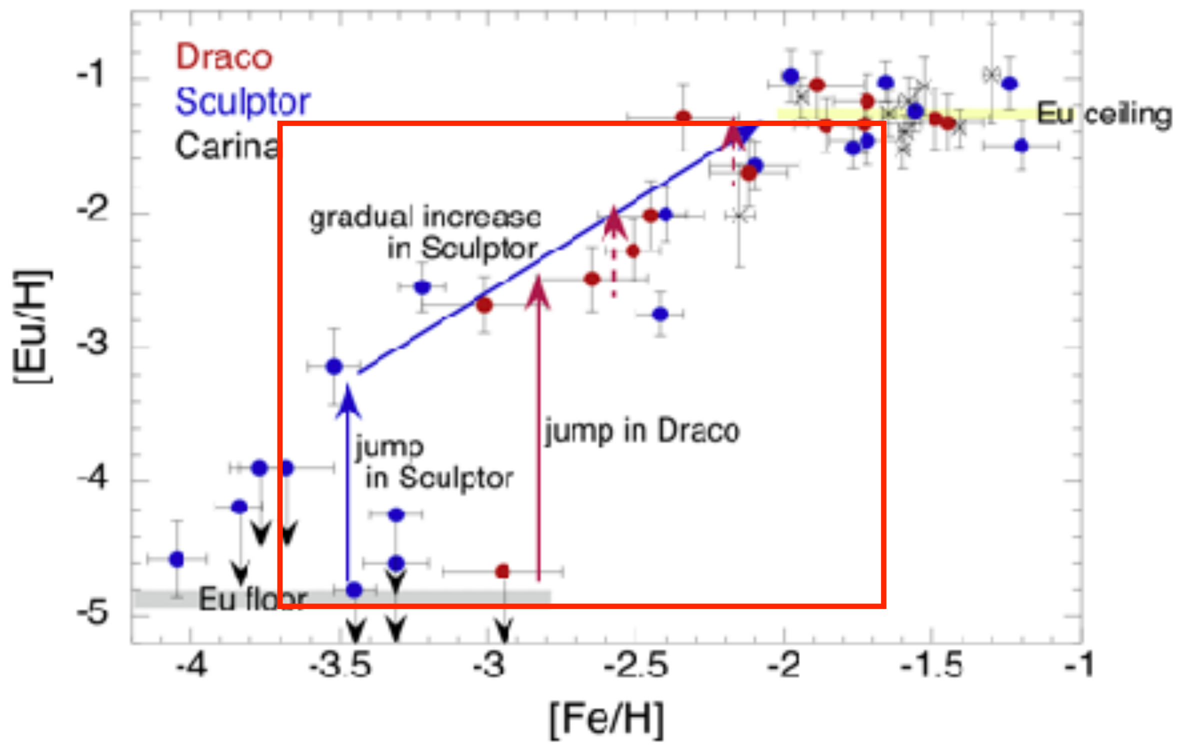
Wehmeyer+(2015,2019): different event rates for MR-SNe



0.1%

NS mergers
+ MR-SNe

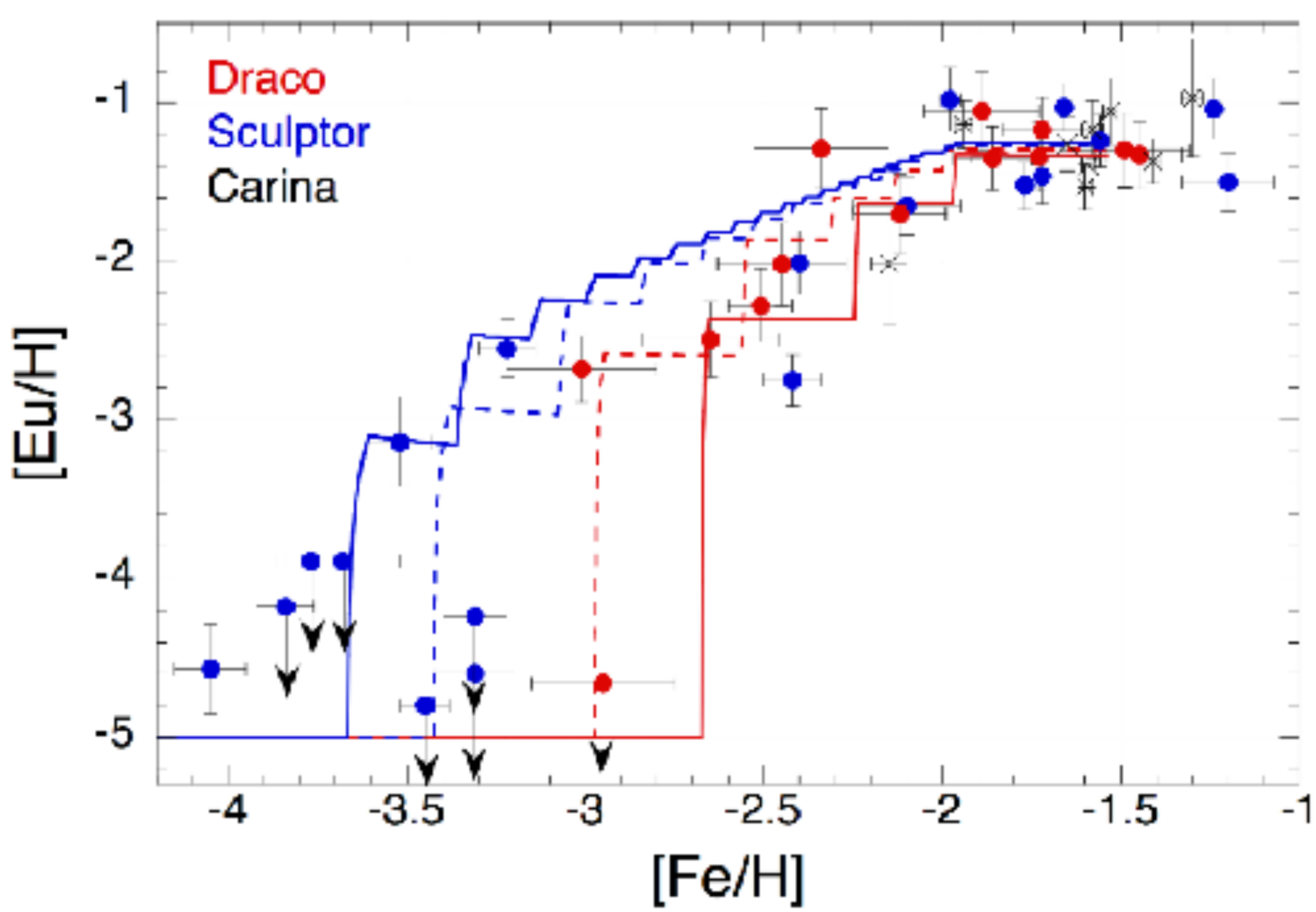
Eu evolution by MR-SNe in dSph galaxies



Chemical evolution models
Tsujimoto & NN (2015)

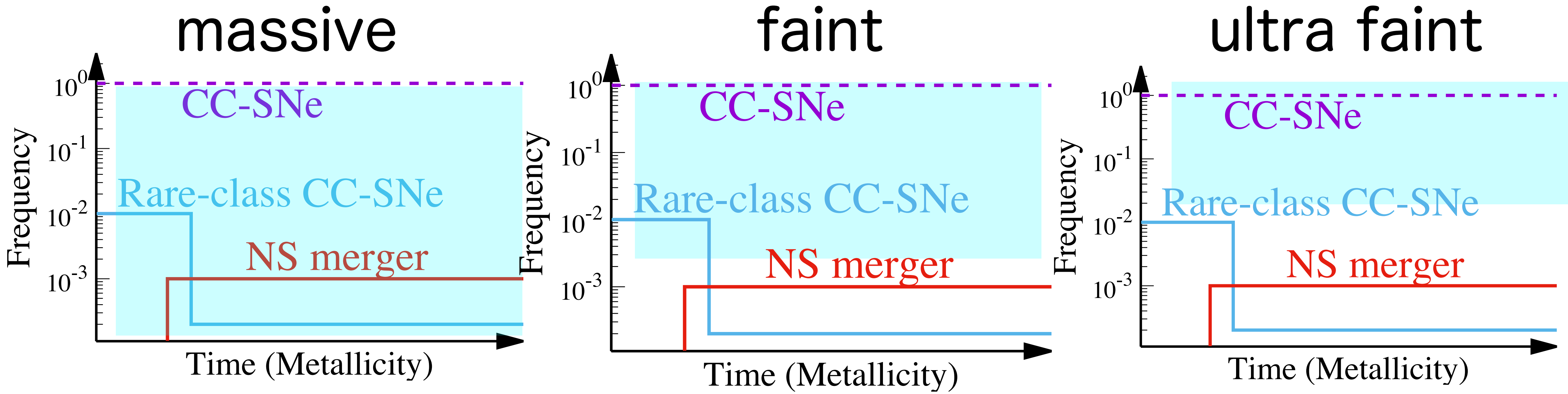
GCE models suggest:
- event rate: 0.5 % of CC-SNe
- large Eu ejection: ～10^{-5} M_{sun}

agree with our MR-SN models (e.g. NN+2015, 2017)

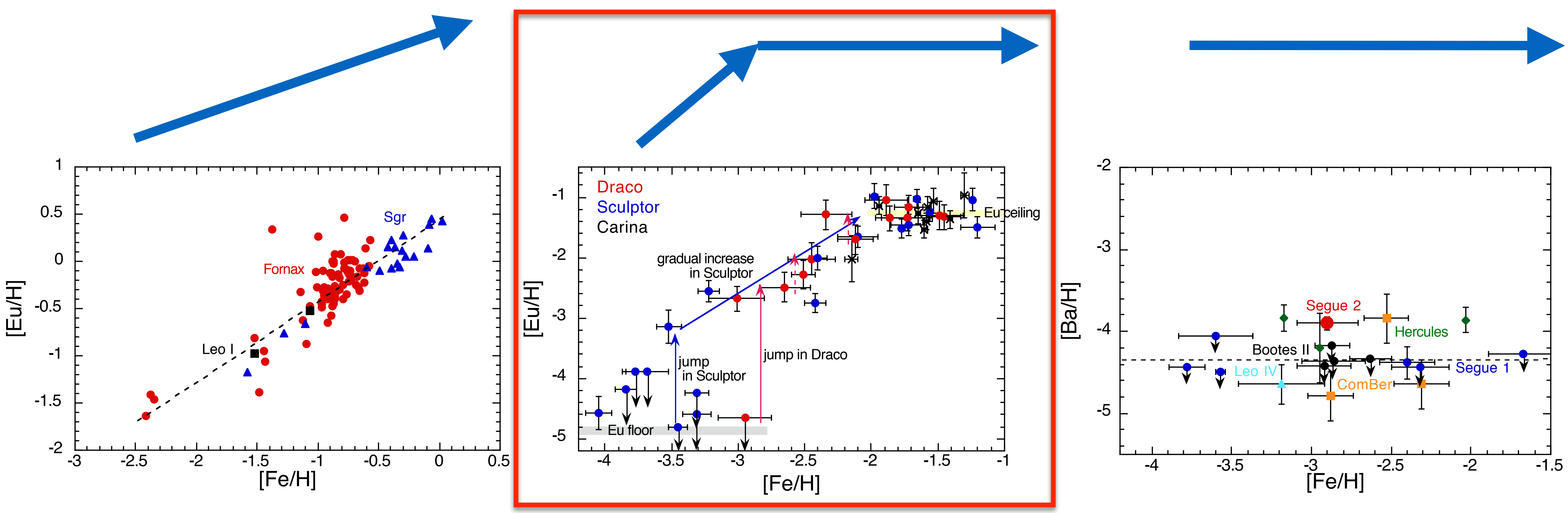


increase of Eu,
which are not explained
by NS-NS mergers

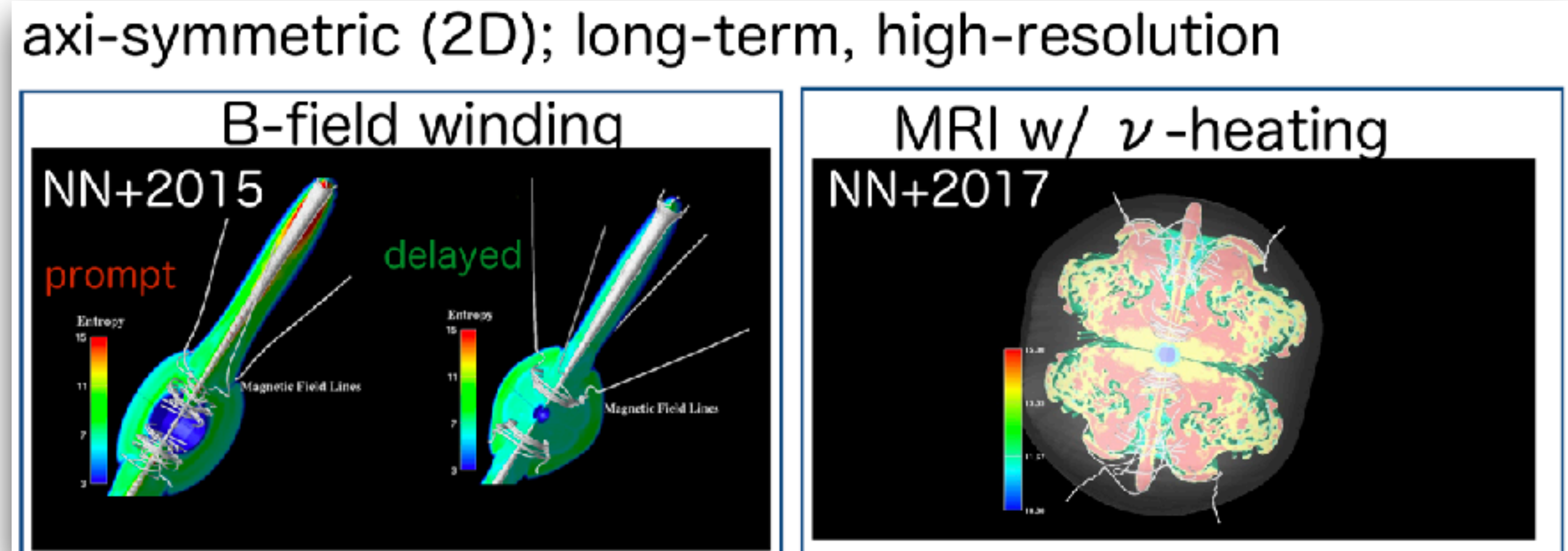
What we learned from faint dwarf galaxies



r-process abundance feature



How to get such n-rich ejecta?



energetic (high density, large mass ejection)
and fast ejection of material by strong jets

more "realistic" conditions

- multi-D (deformation)
- weaker B fields (w/ enhancement)

Short 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

We want to discuss possible "observational" properties of such events: r-process-jet supernovae.

long-term evolution of r-process ejection

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

Ejection of r-process nuclei

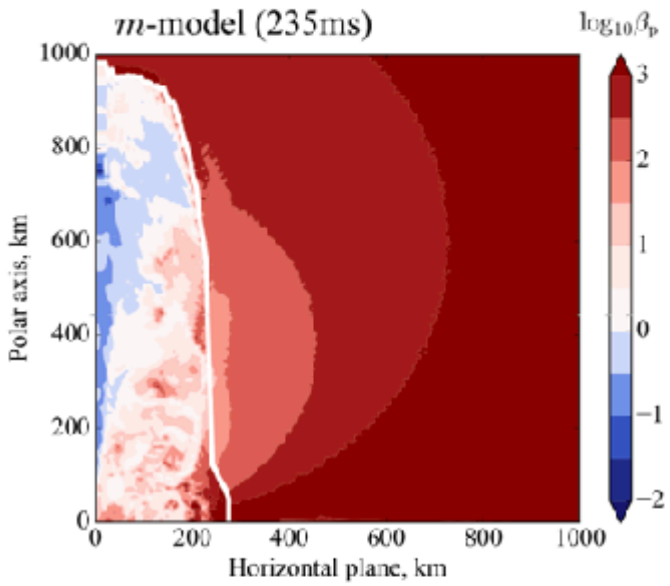
from engine to remnant

Collaboration with

J. Matsumoto, H. Sawai and T. Takiwaki

Strong-magnetic jet: (strong r)

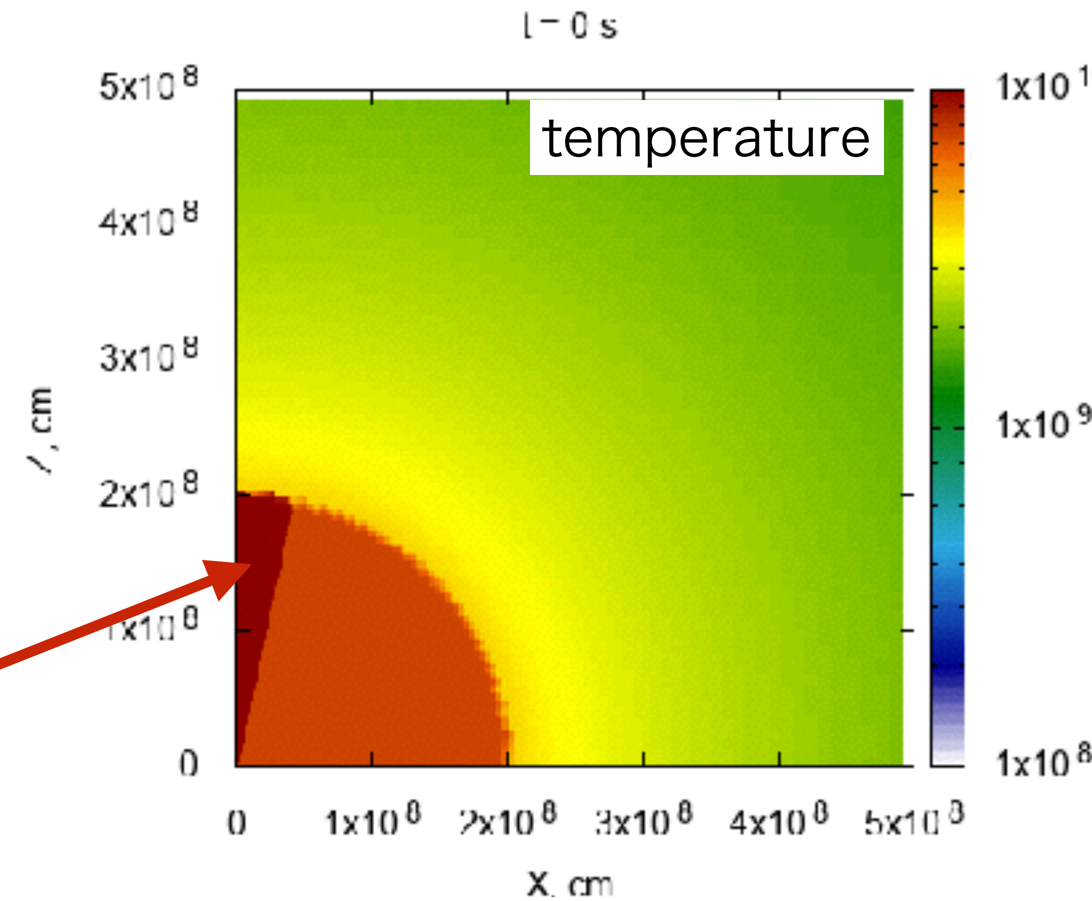
NN, Sawai+2017



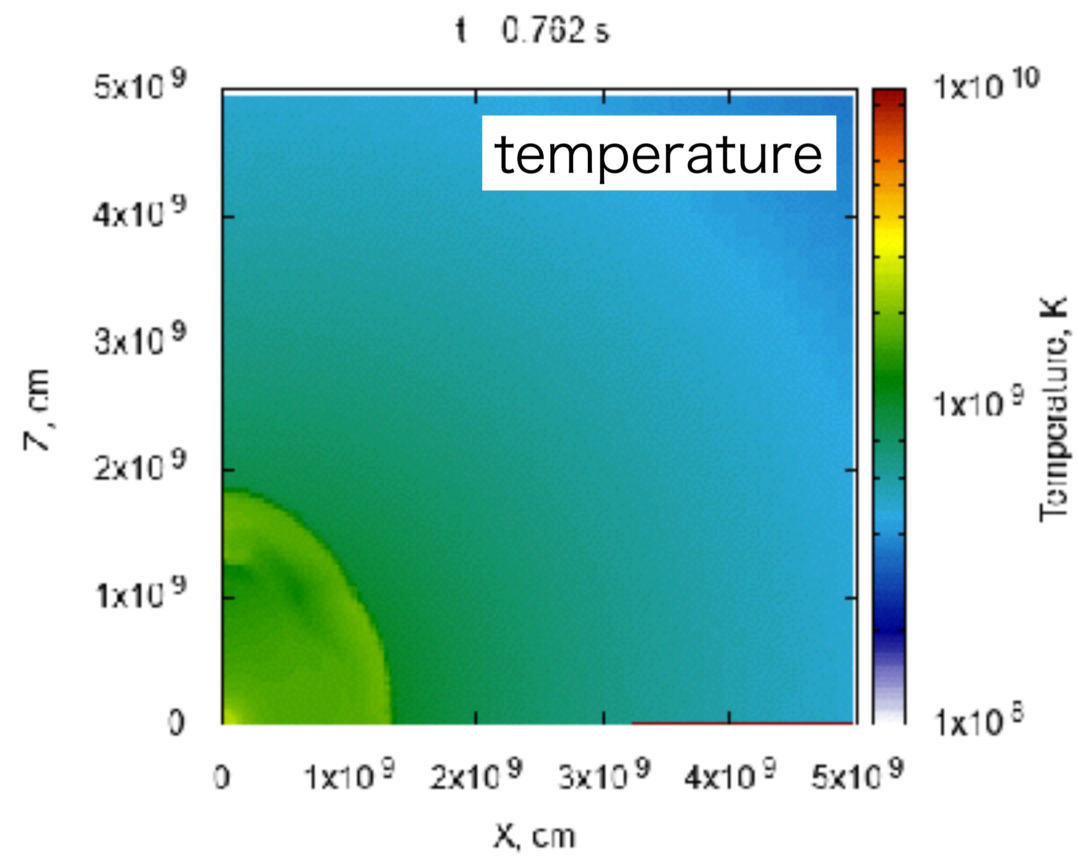
10^8 cm

x 5

$E_{jet} = 10^{51}$ erg



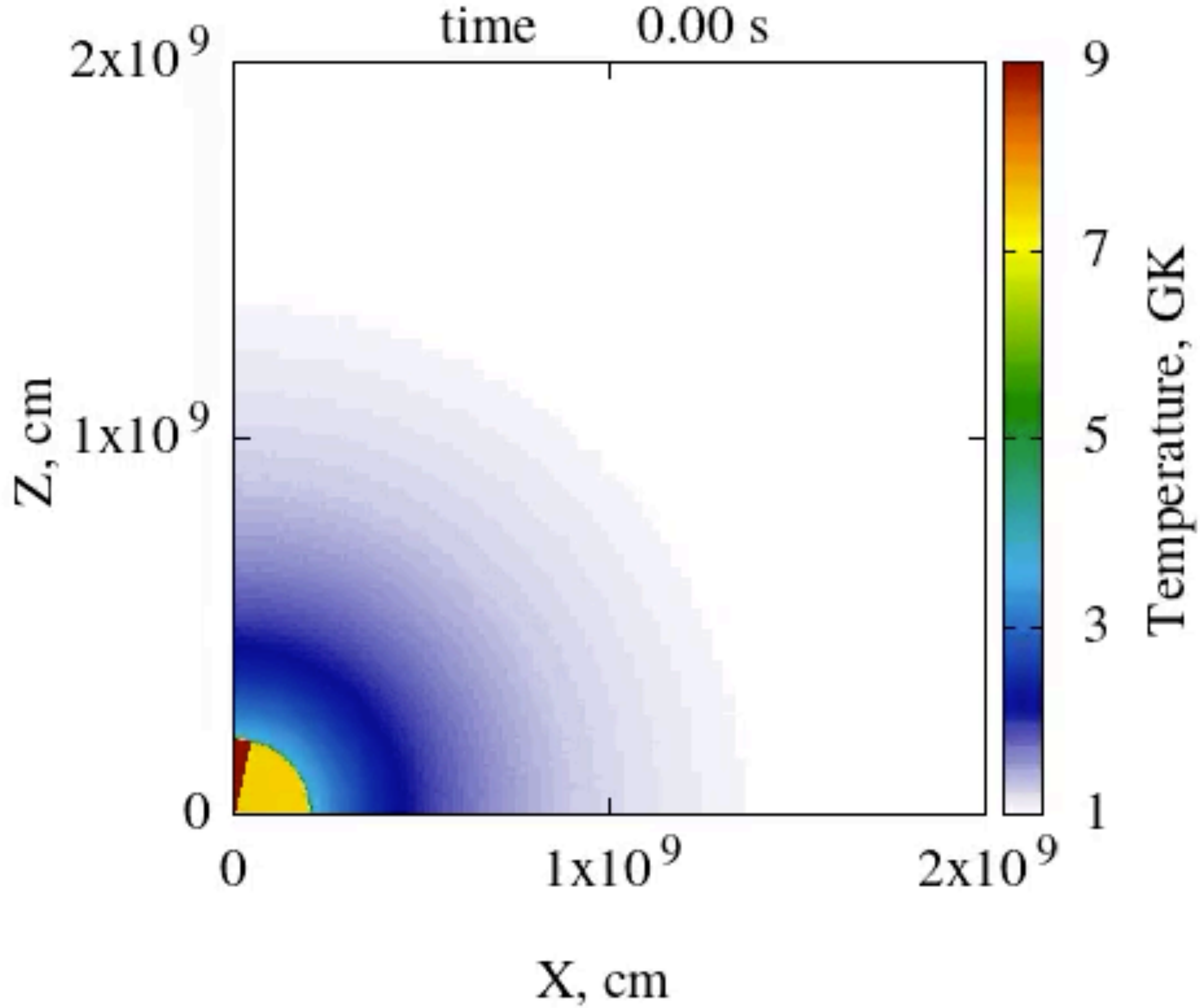
x 10



- hydrodynamics w/o B-fields
- "jet" injection
- Wolf-Rayet (no H-layer)

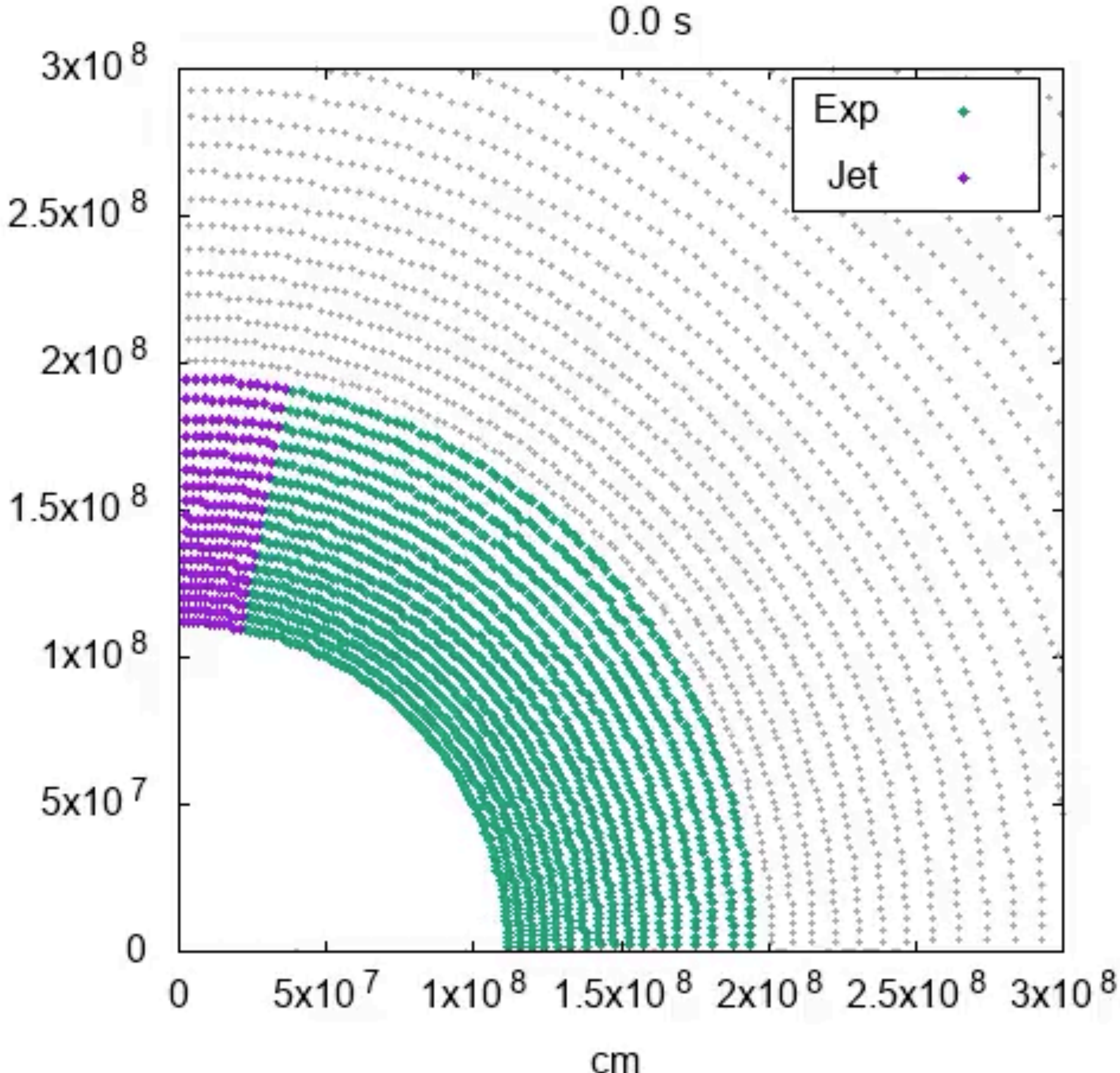
hydrodynamical simulation by J. Matsumoto

Strong-magnetic jet: (strong r)



jet-SN explosion

Lagrangian "tracer particles"



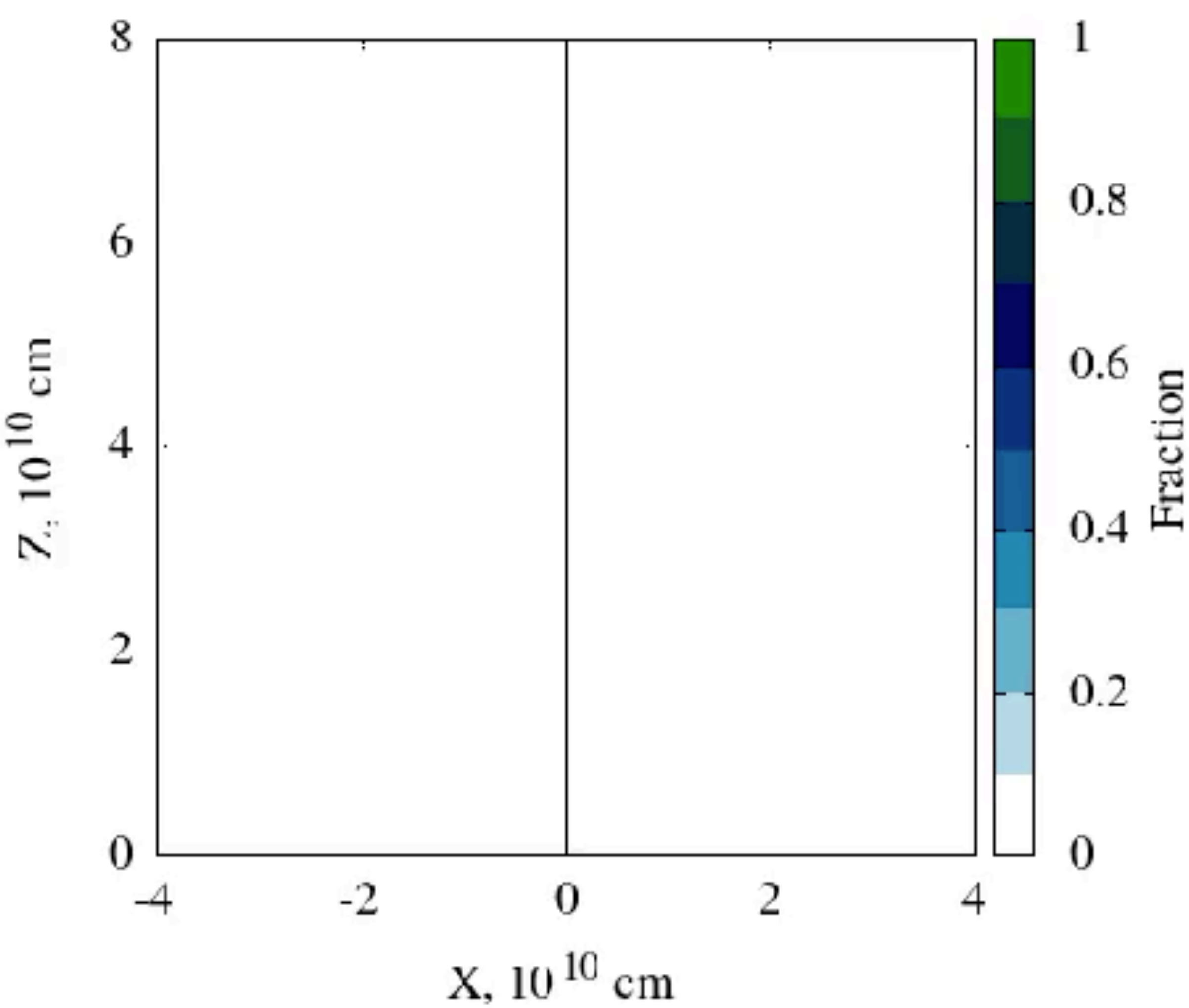
MR-SNe simulations

1000 km (10^8 cm)

Weker magnetic-jet: intermediate r

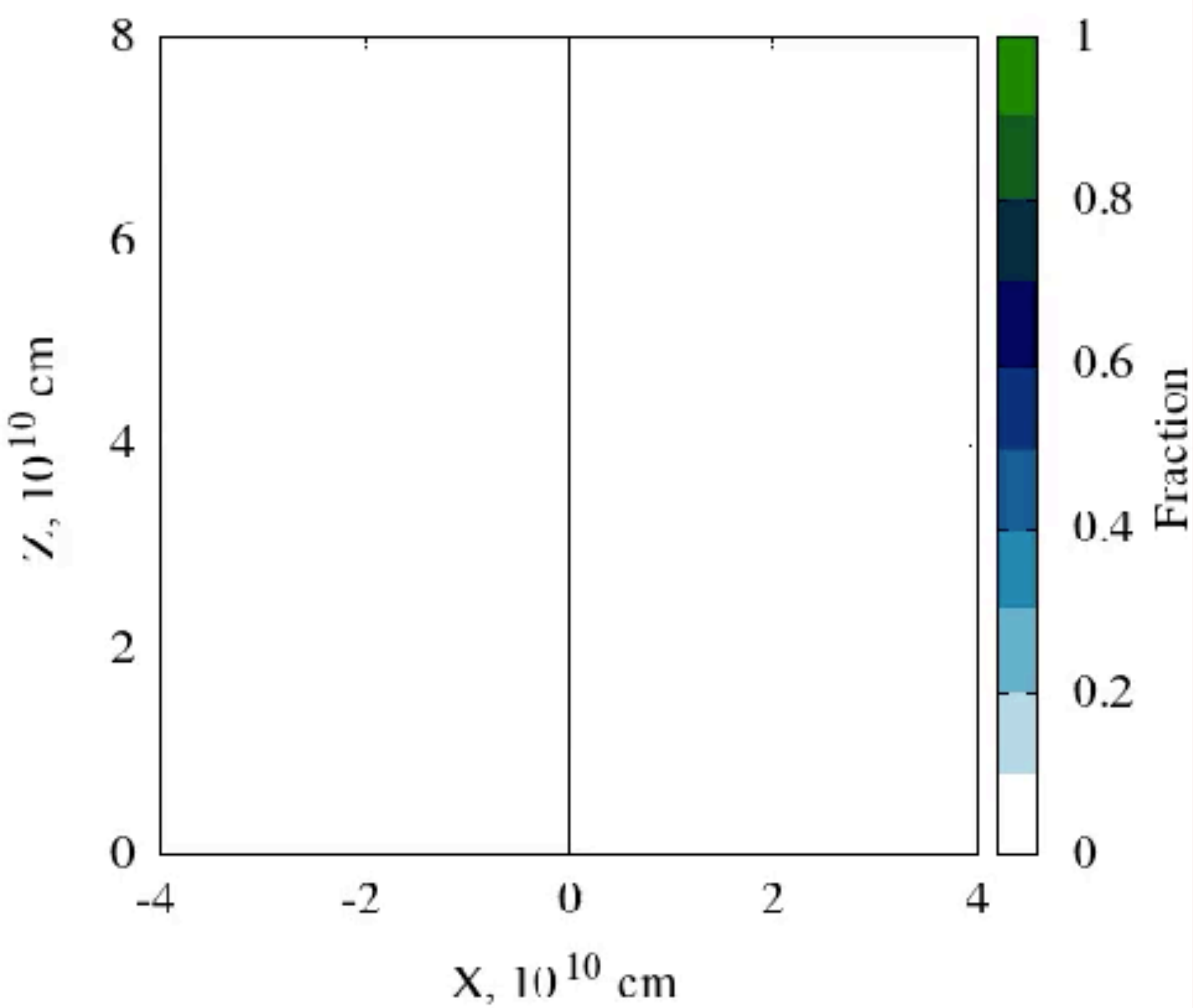
weak magnetic jet

medium n-rich very n-rich

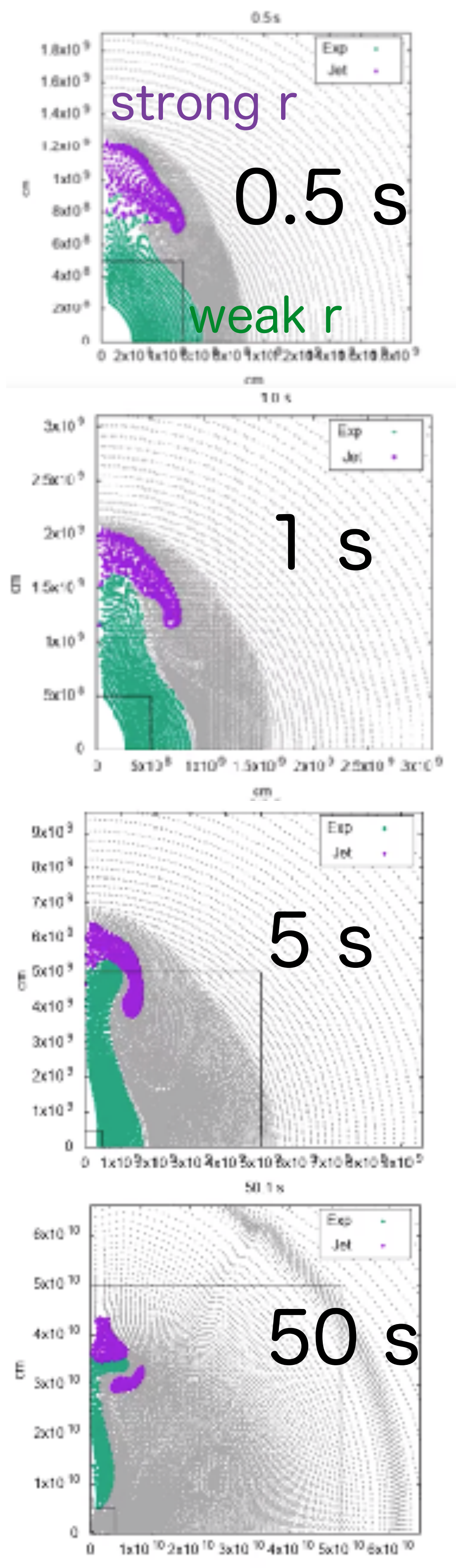


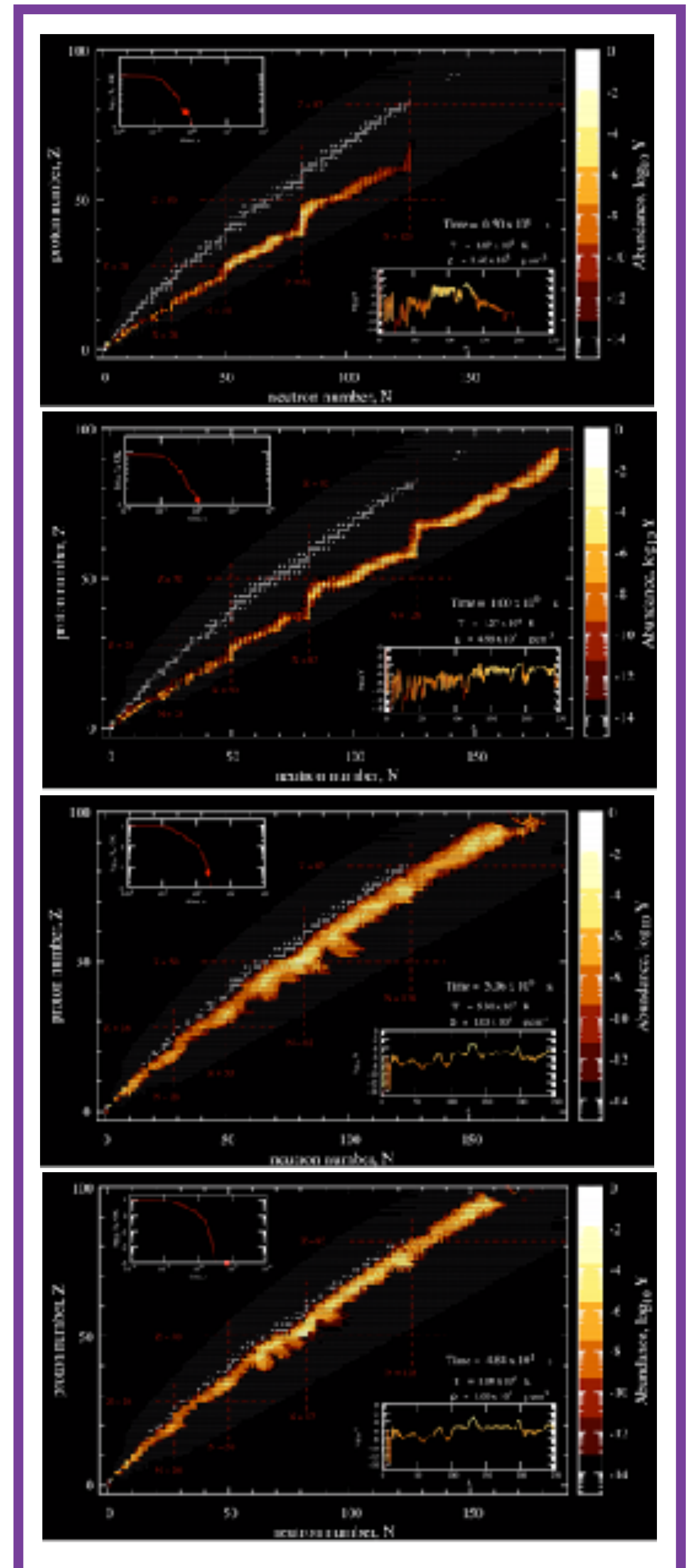
strong magnetic jet

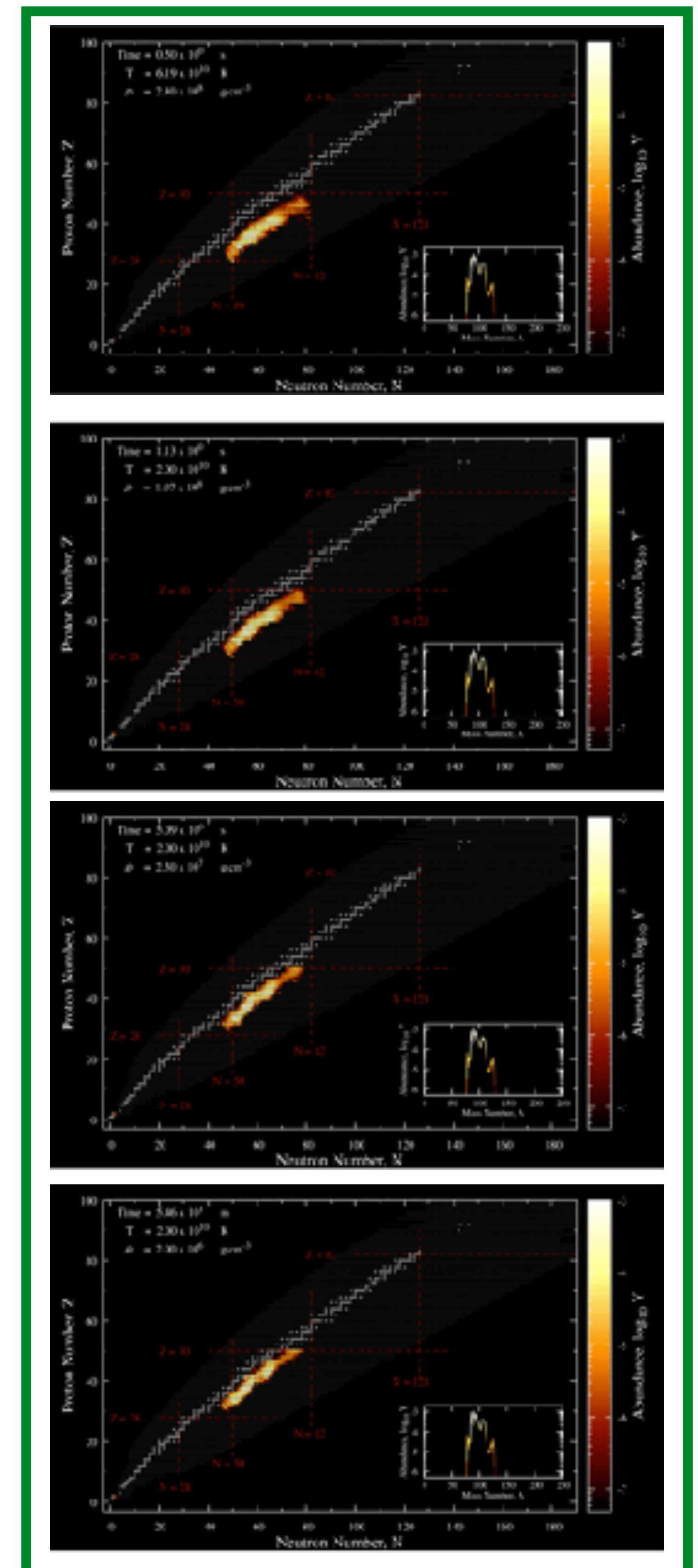
medium n-rich very n-rich



Evolution of hydro vs r-process







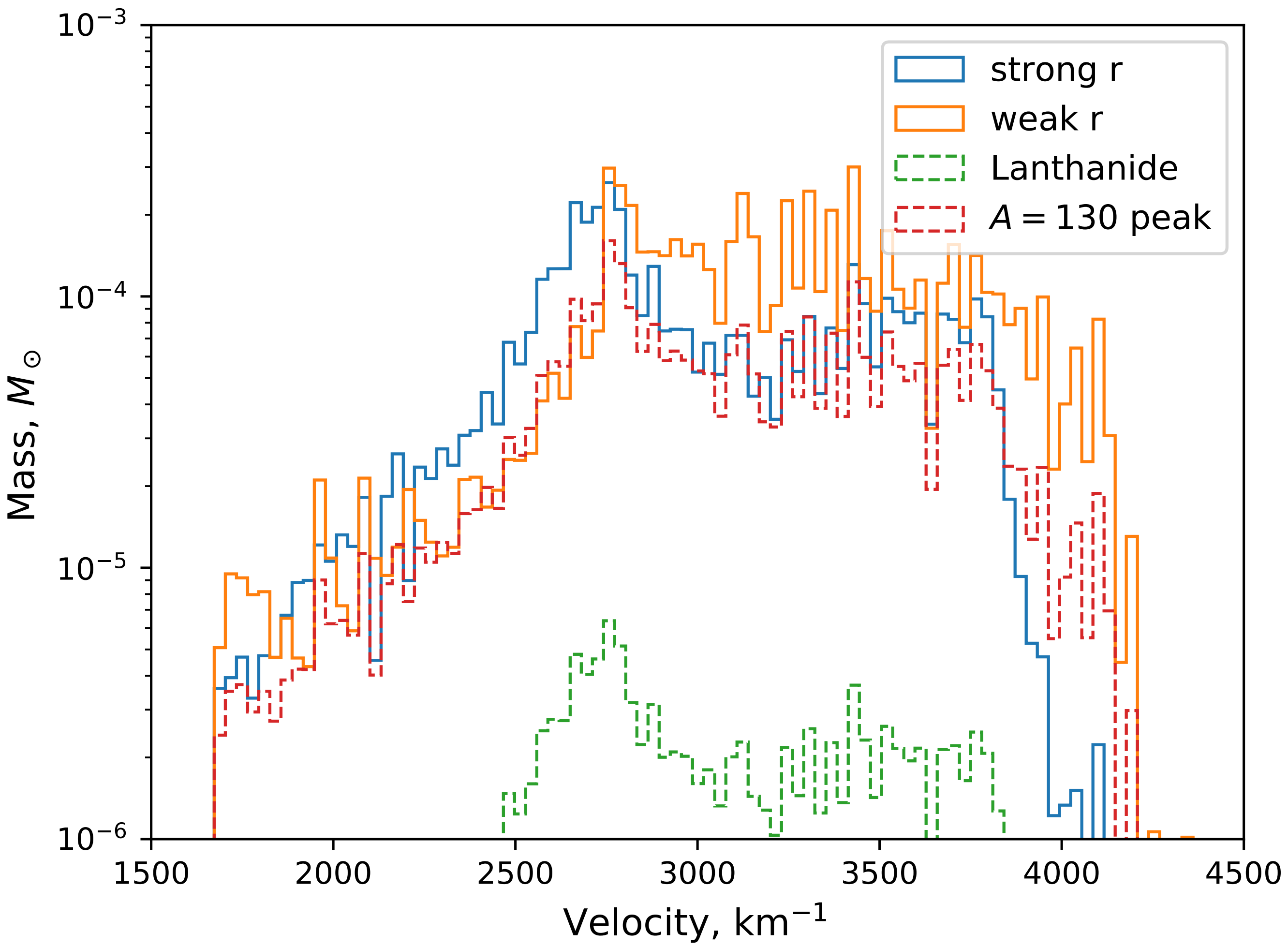
Elemental distribution in ejecta

based on the nucleosynthesis condition of NN+2017:

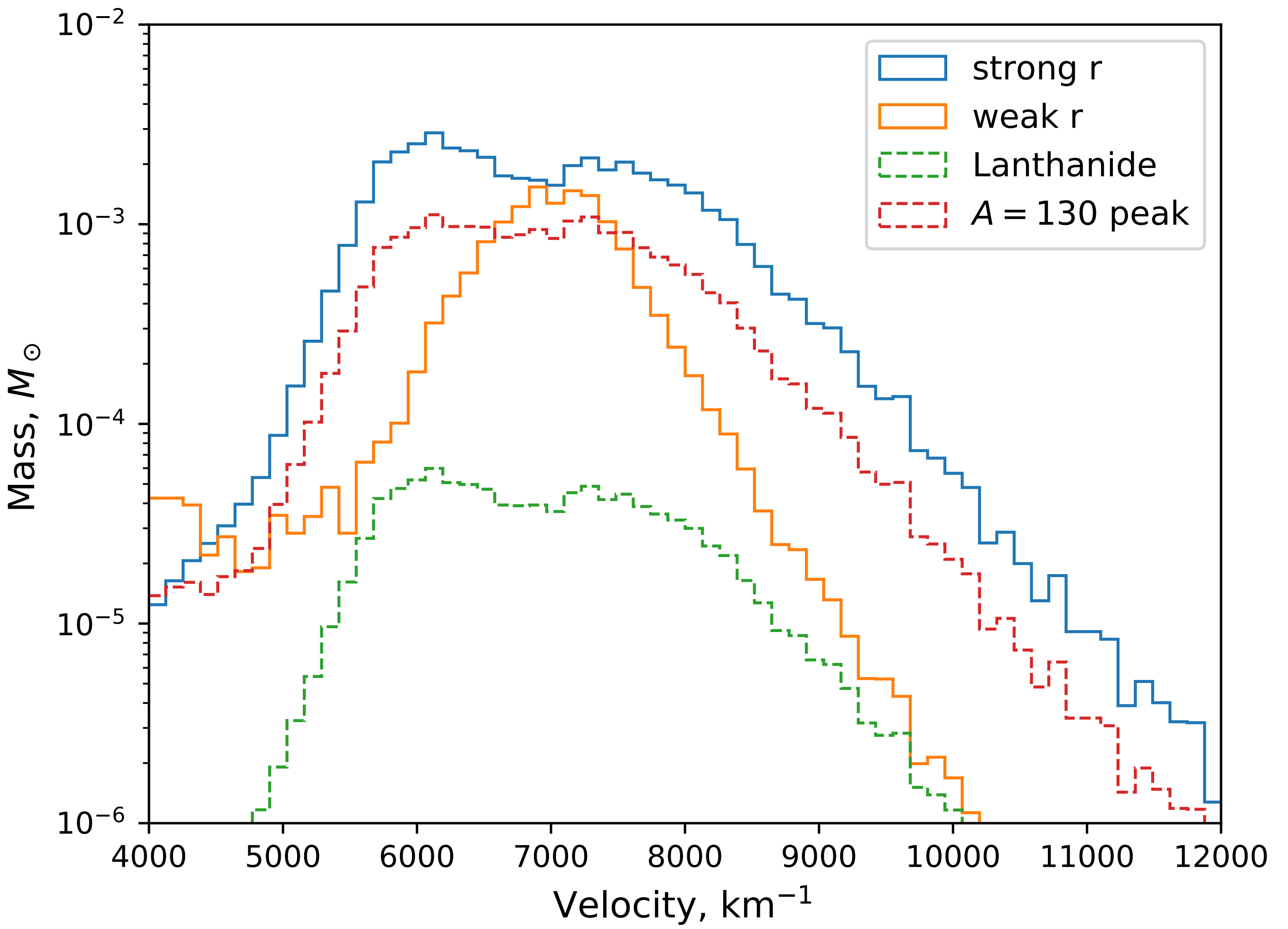
very n-rich —> strong r

medium n-rich —> "intermediate r"

weak magnetic jet



stronger magnetic jet



—> Future observation will provide new insights?

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

We want to discuss possible "observational" properties of such events: r-process-jet supernovae.

- <u>Hydrodynamical simulation of jet-SNe (w/ r-nuclei)</u>
  - 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

Uncertainties in the nuclear-physics "input"

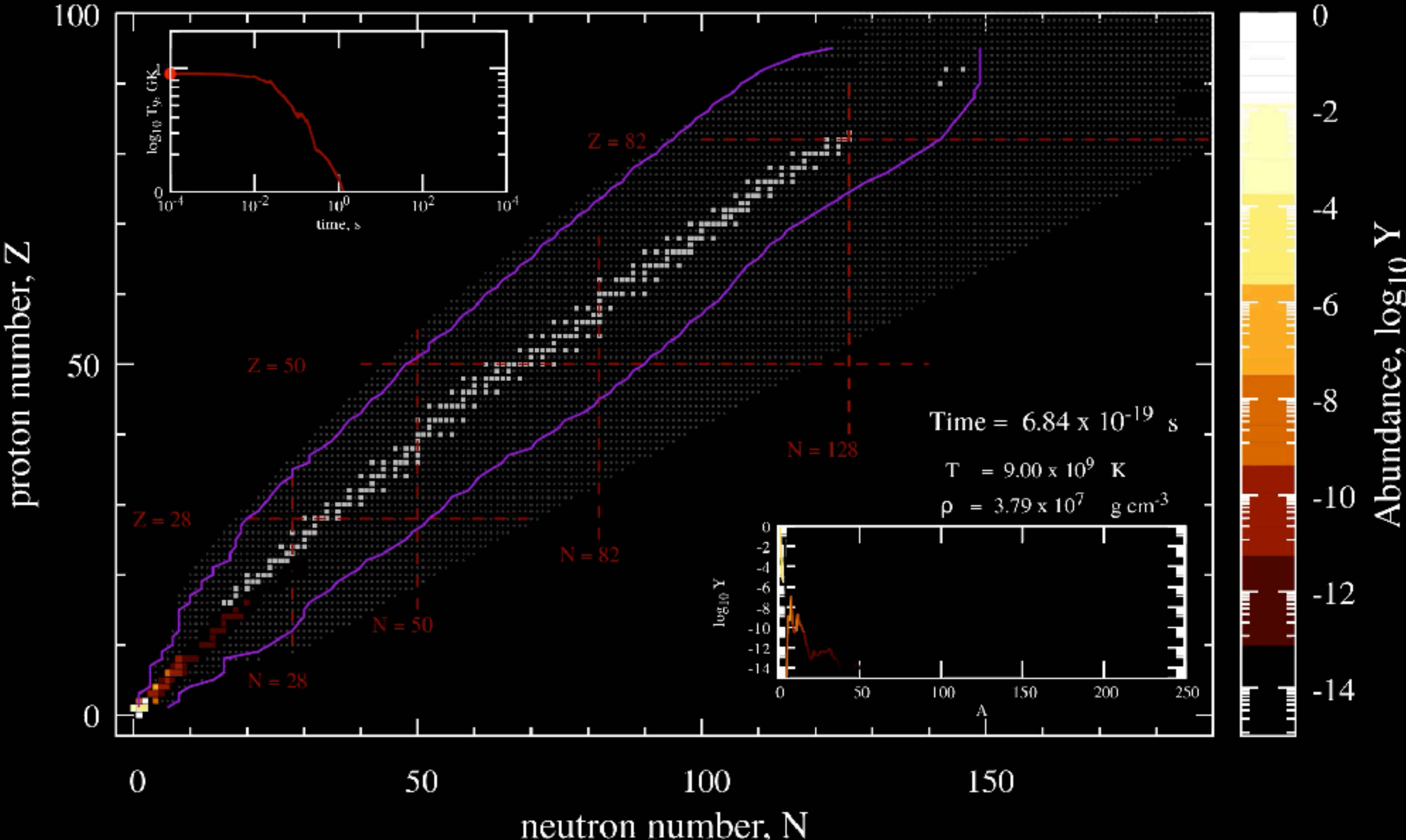
impacts on the r-process

Collaboration with

T.Rauscher, R. Hirschi, G. Cescutti, A. Murphy

r-process nucleosynthesis "flow"

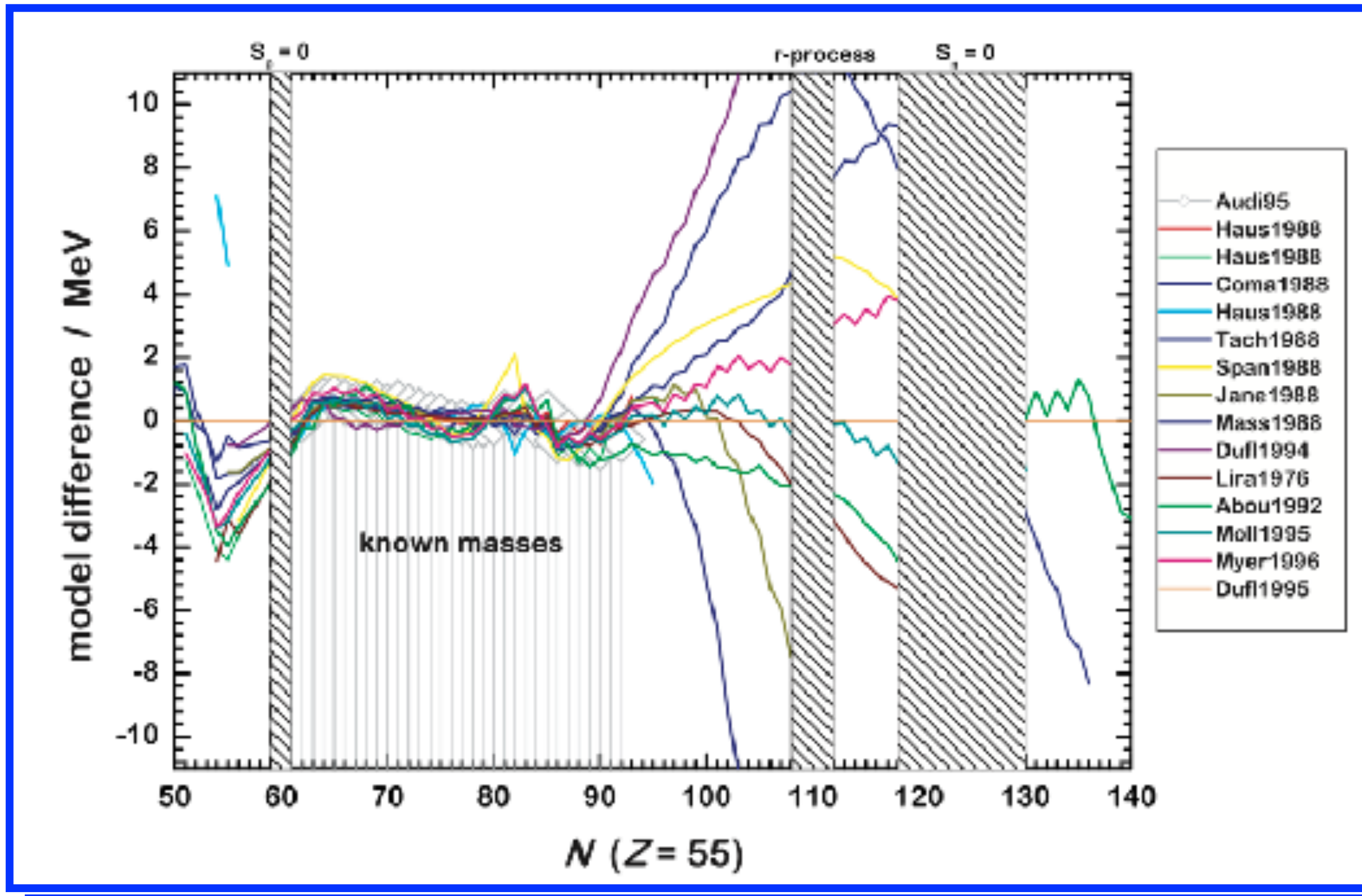
RIBF (1e-4 pps limit)



Theoretical uncertanities

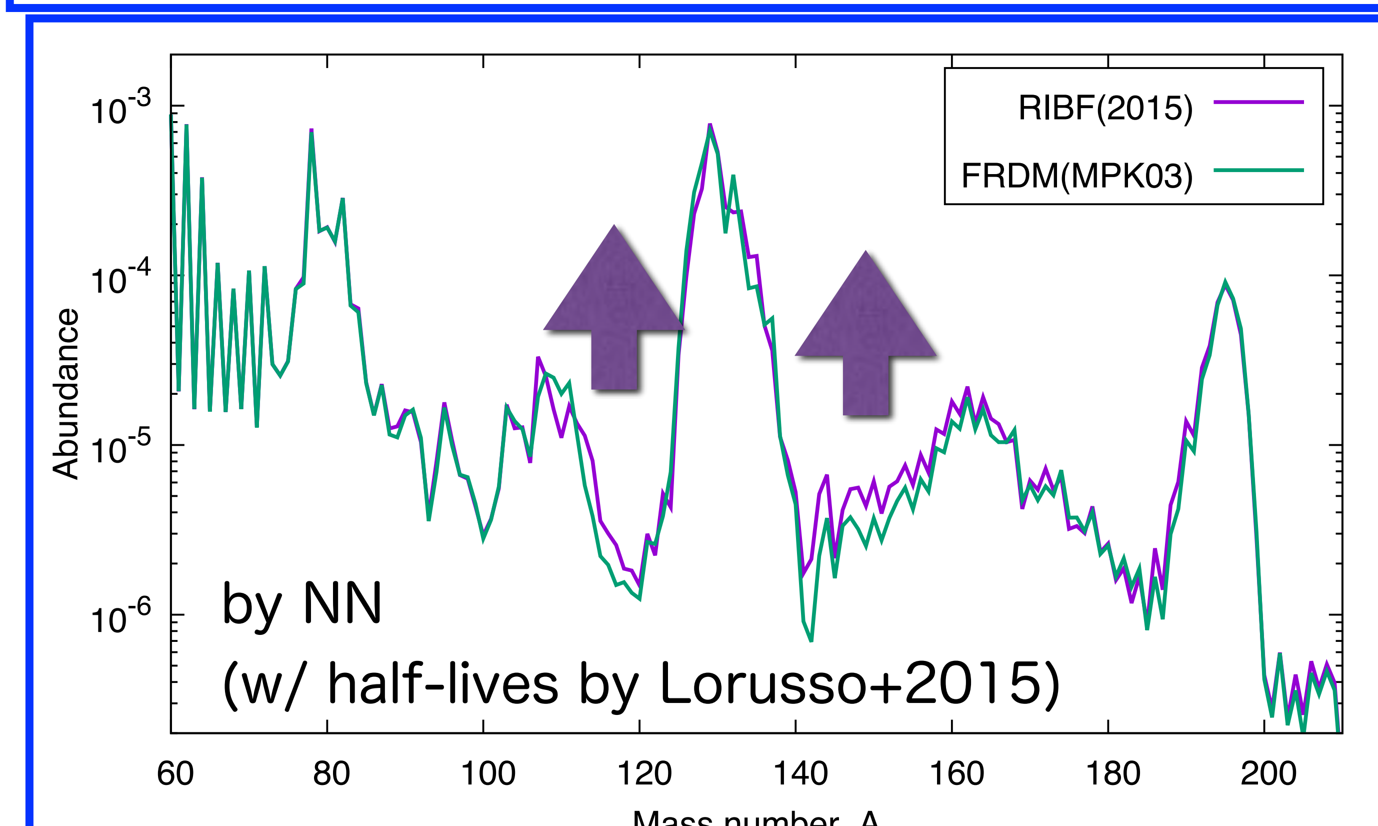
mass formula

Large uncertainty in the r-process range



β-decay

Recent experiments reach only limited region



* In addition, reaction and fission rates are not well determined

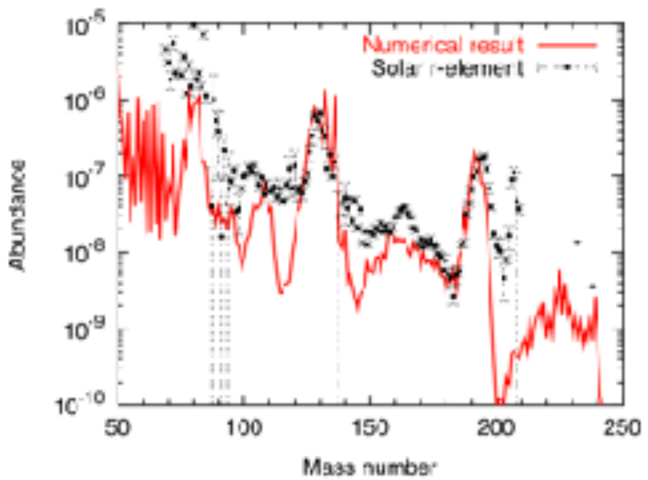
Uncertainty studies

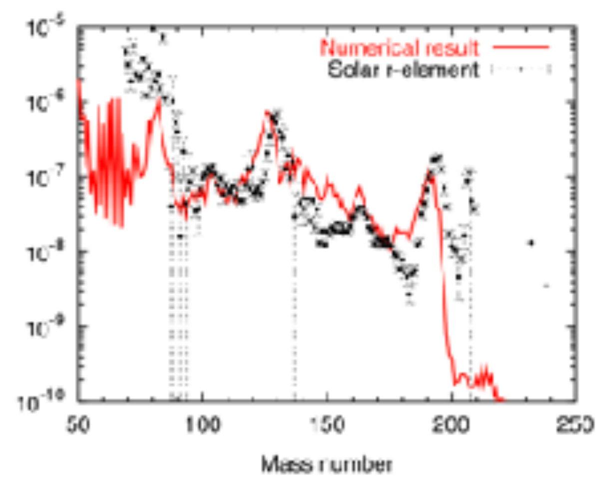
nuclear mass (+reaction and decay rates

FRDM(’92 → ’12)

FRDM

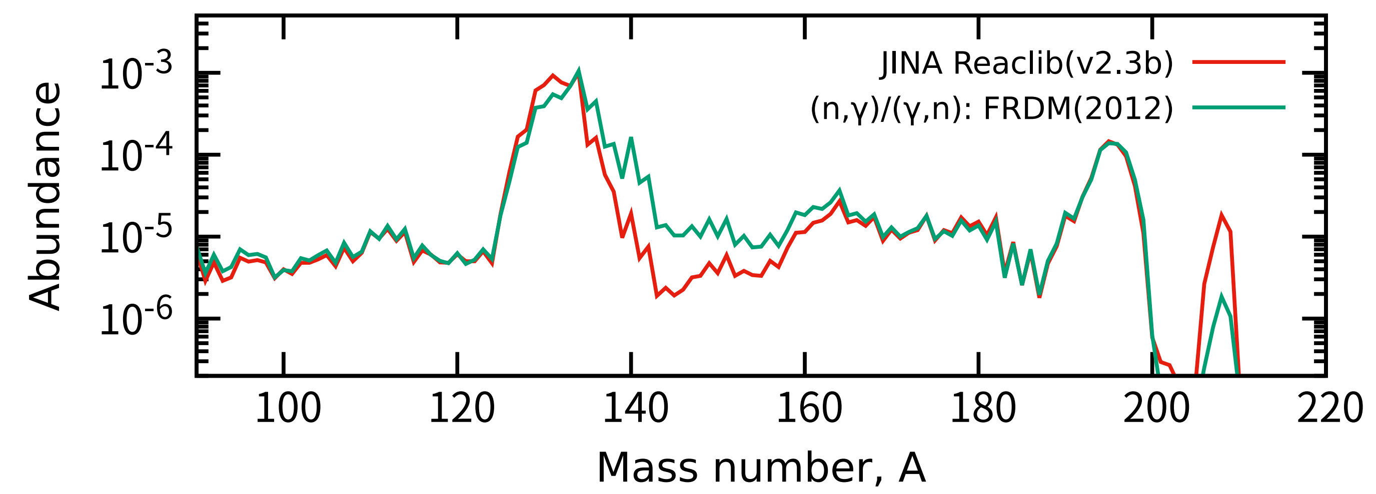
ETFSI





Nishimura+2006

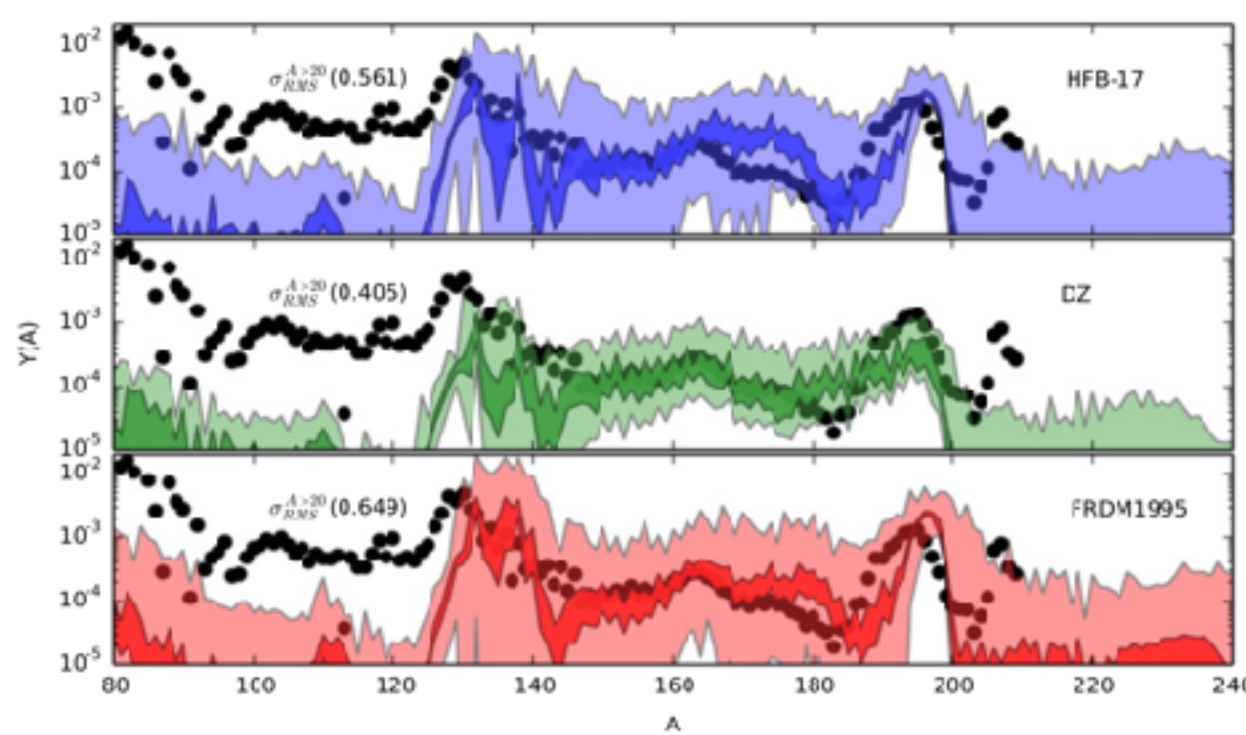
S=100 k_B/nucleon



by NN (test calculation

Comprehensive studies (by Monte-Carlo)
reaction/decay rate uncertainty due to mass

Mumpower+2015



Monte-Carlo network code

Piz Buin (mountain)

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

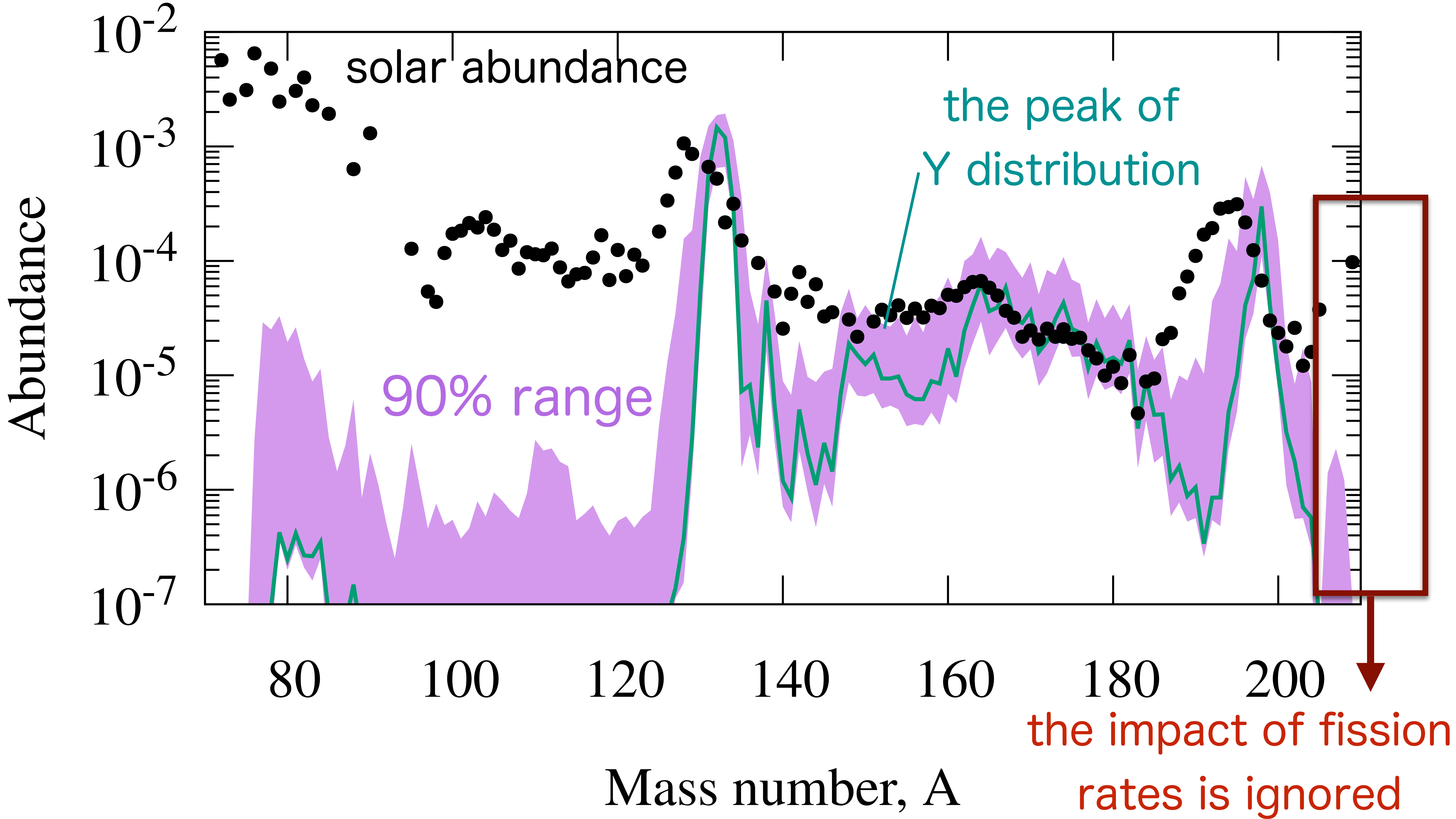
References

- Rauscher, NN+2016, MNRAS 463
- NN+2017, MNRAS 469
- NN+2018, MNRAS 474
- Cescutti, Hirschi, NN+2018, MNRAS 478
- NN+2019, MNRAS 389

Rate uncertainty: (n,g) and β-decay

rate uncertainty range: (n,g) x0.02/x50, β-decay x0.05/x20

uncertainty region (90% probability) of r-process



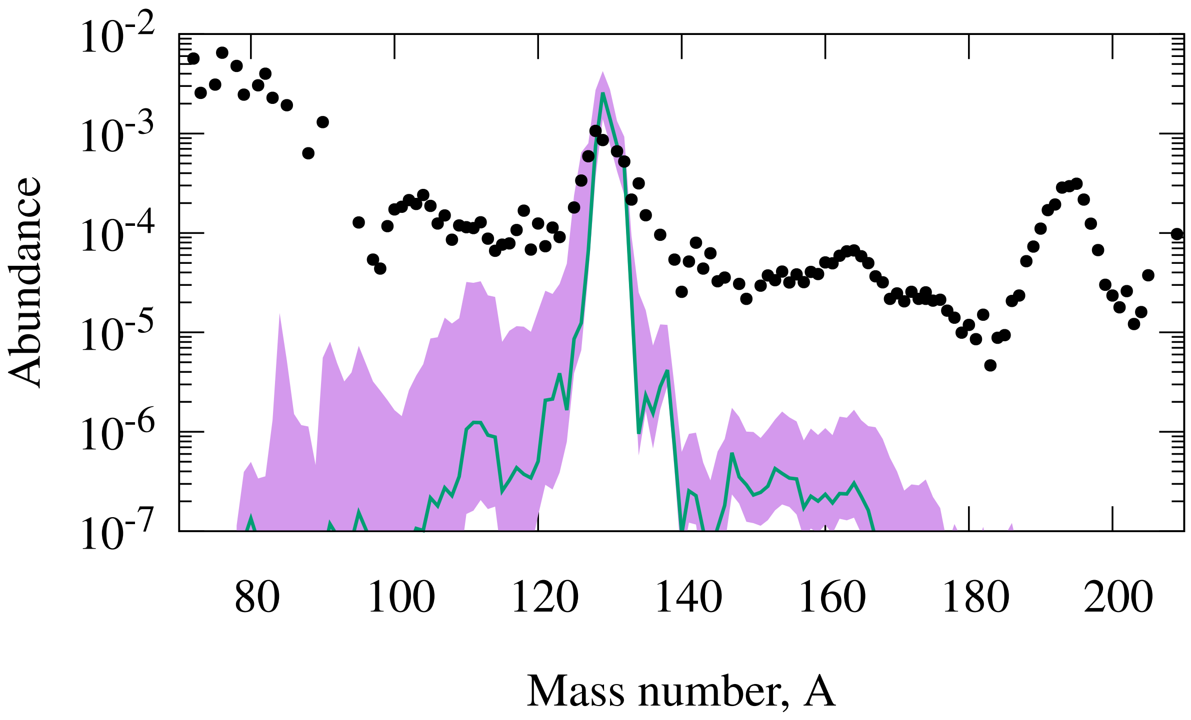
Rate uncertainty: (n,g) and β-decay

rate uncertainty range: (n,g) x0.02/x50, β-decay x0.05/x20

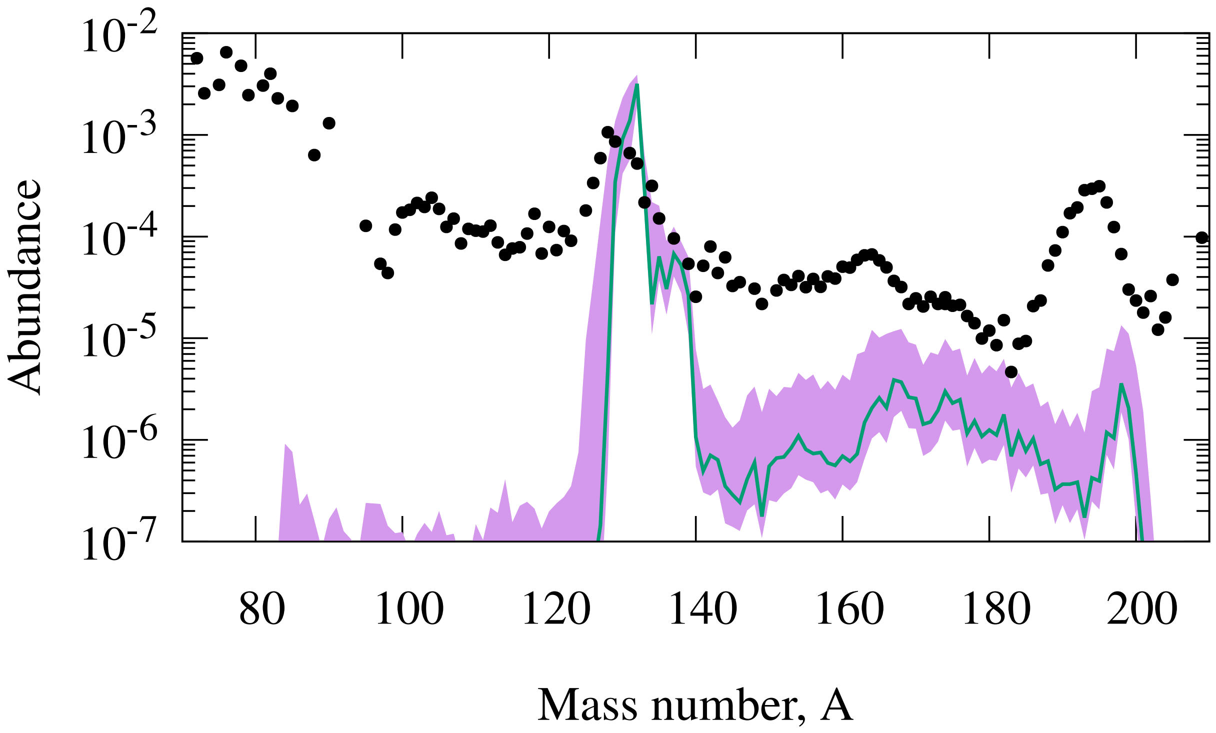
uncertainty region (90% probability) of r-process

different "trajectories" (astrophysical environments)

weak r



intermediate r



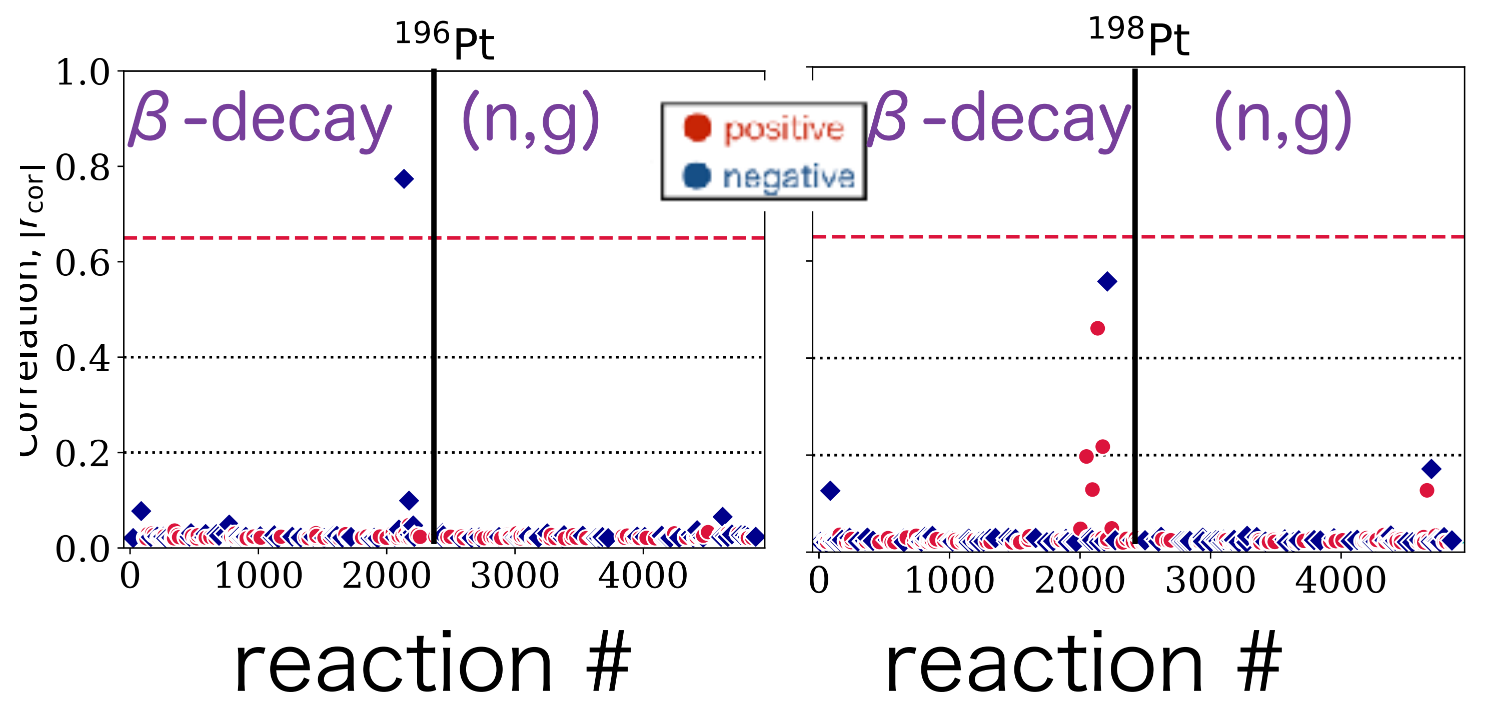
Key reactions?: r-process

"correlation analysis"

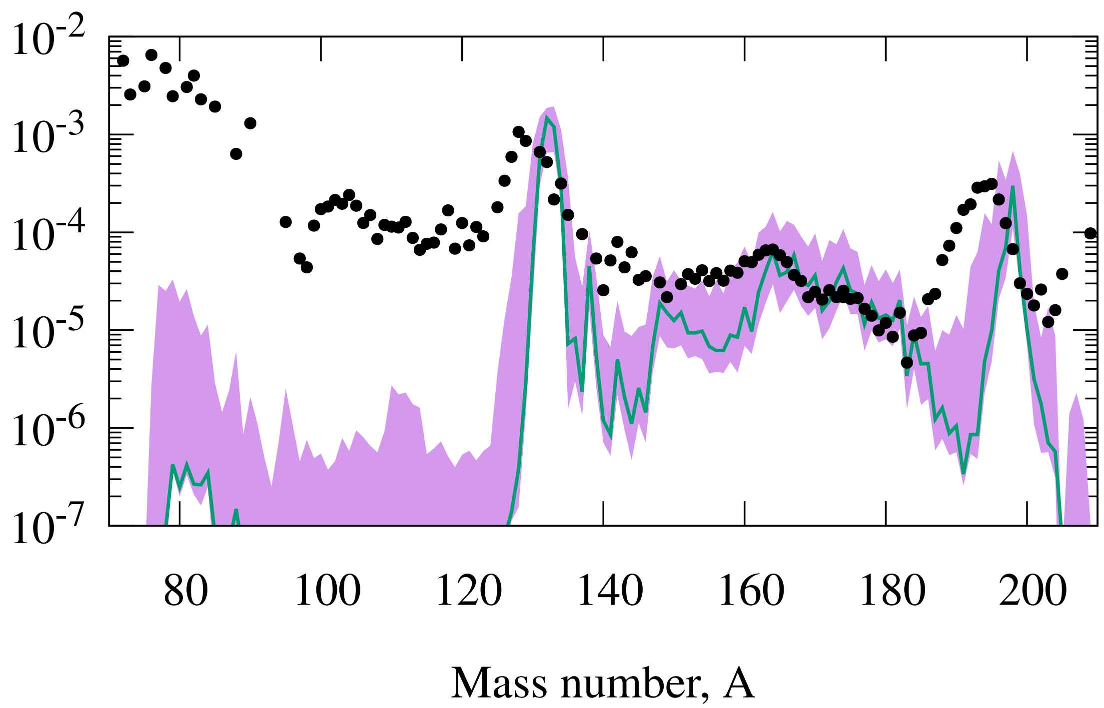
β-decay : 130Cd, 134In
134Sn, 196Yb, 197Lu

→ not many key reactions
(can be smaller than astrophysical uncertainty)

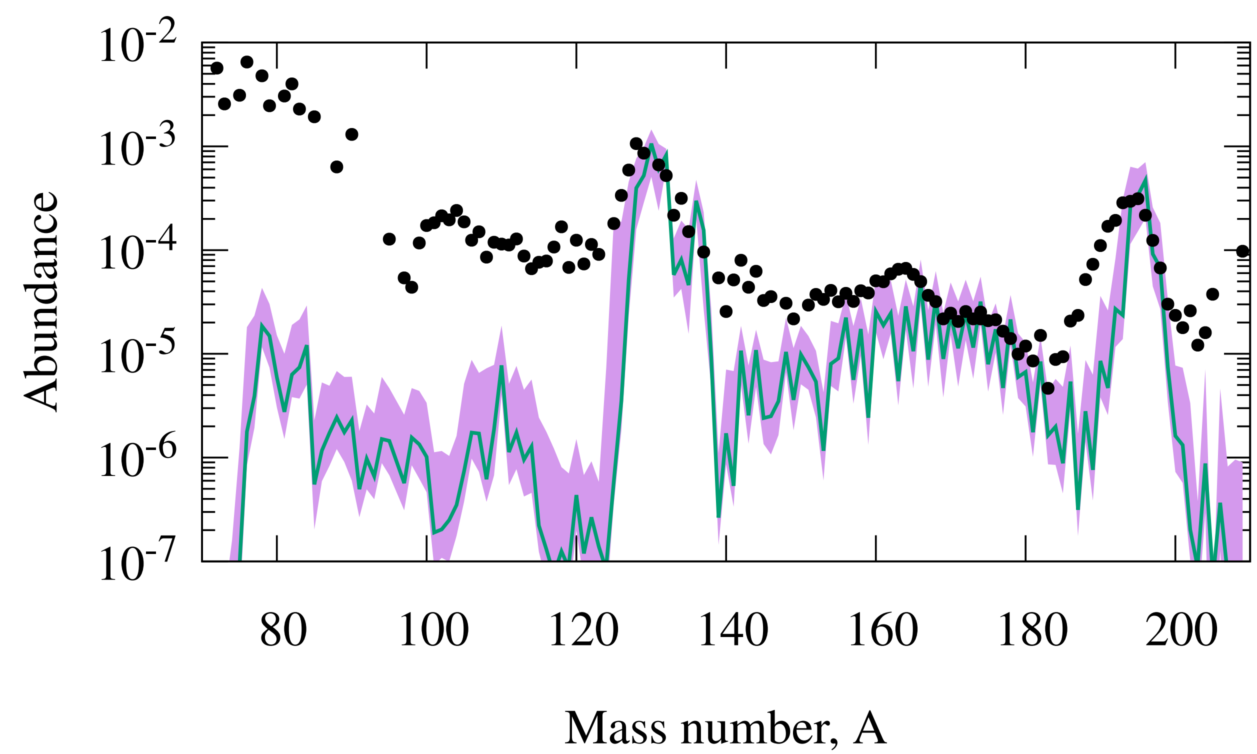
relevant reactions (n-cap & β-decay) 4897



357 rates (mainly β-decay) have effects (if not very strong)

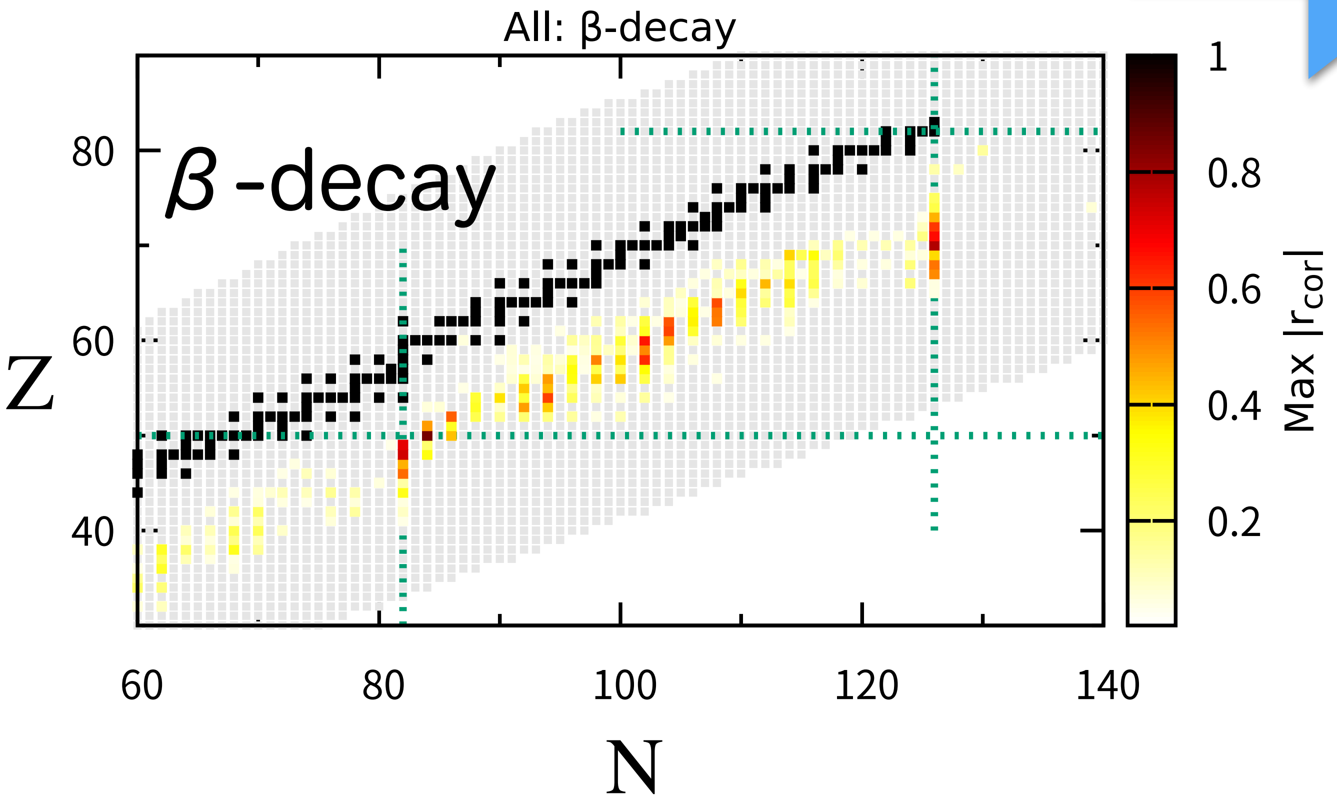


fixing 357 rates

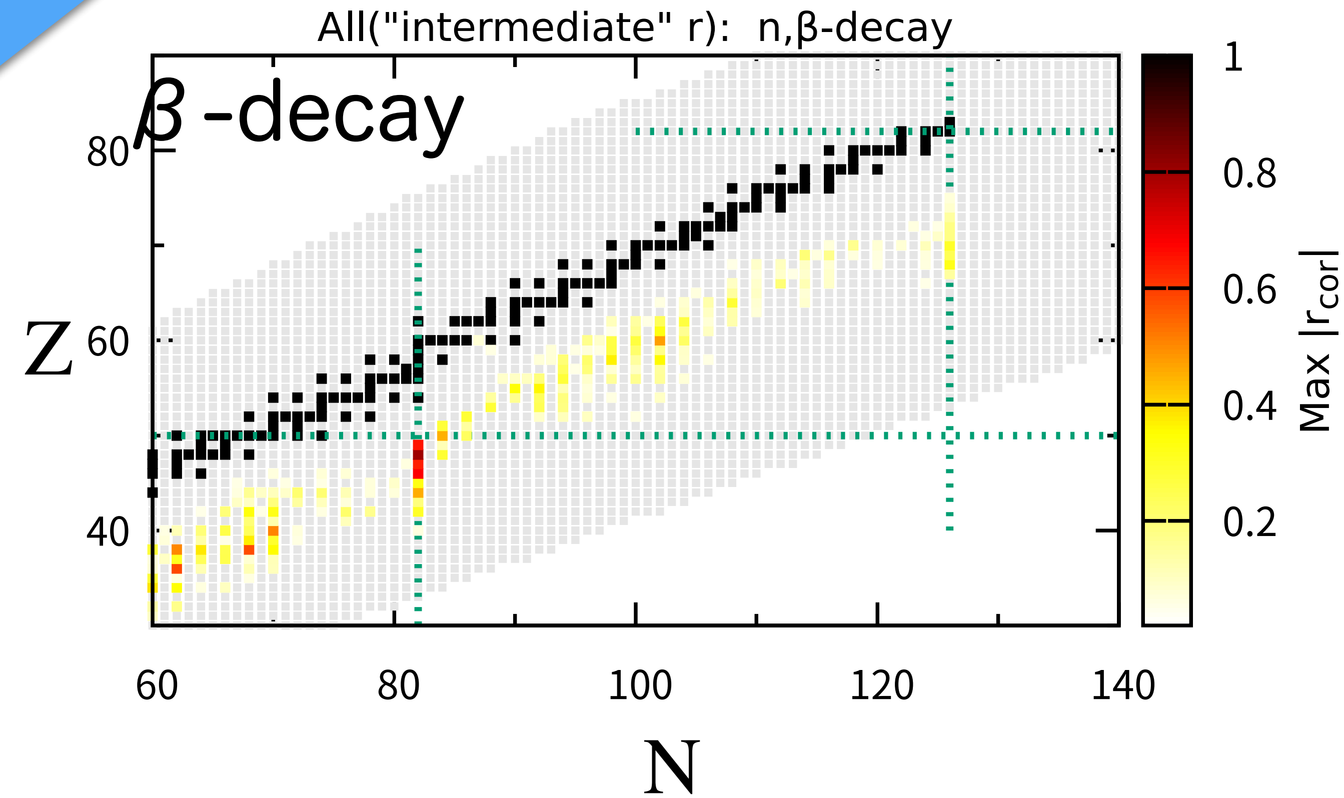


“Key” reactions for different models

strong r



intermediate r



Summary:

- r-process calculations have a large uncertainty due to nuclear mass, reaction rates and decay rates
- the impacts of such uncertainties may change in different astrophysical conditions for the r-process