Optical properties of magneto-rotational jet-driven supernovae associated with r-process nucleosynthesis

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Astrophysical r-process sites

core-collapse SNe

Massive stars

(10>M_{sun})

SN explosion

proto-NS

ν-driven wind

NS binaries

NS NS NS BH

Merger

・NO direct r-process observation

・Theoretically difficult

・not very neutron-rich

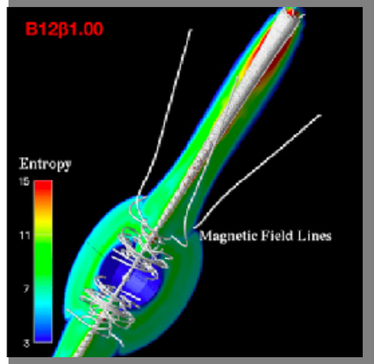
r-process was “observed” with GW170817

Astrophysical r-process sites

core-collapse SNe

Massive stars

(10>M_{sun})



Magneto-rotational driven explosion

roto-NS

ν -driven wind

・NO ess observation

・The icult

・no n-rich

NS binaries

NS NS NS BH

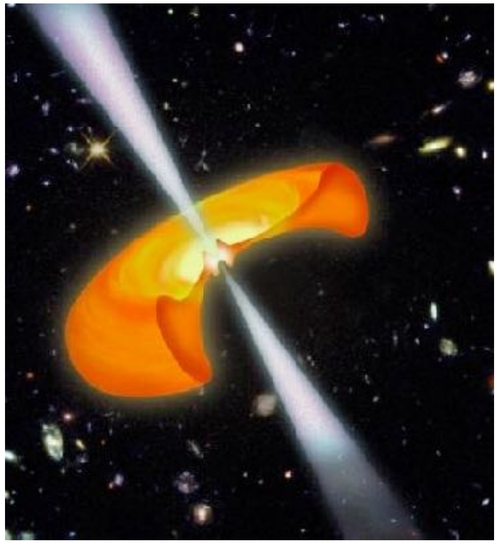
Merger

r-process was “observed” with GW170817

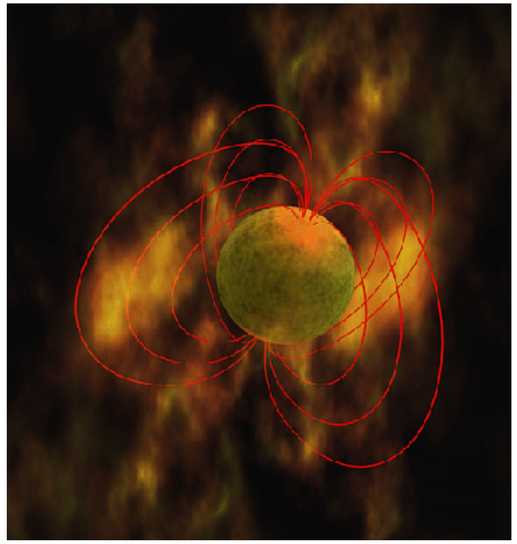
1. Magneto-rotational SNe a brief overview

- 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

Magneto-rotational SN scenario



hypernova/jet-like SN



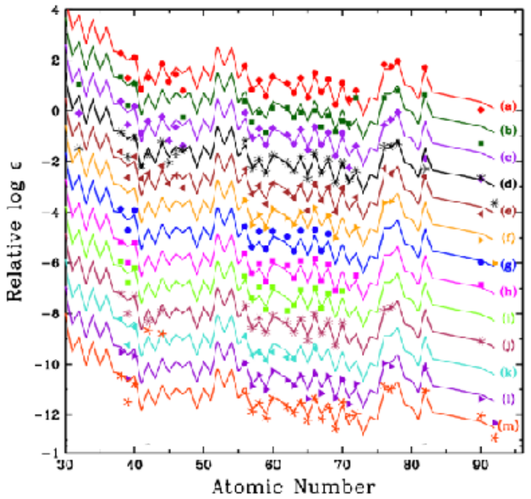
magnetars

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

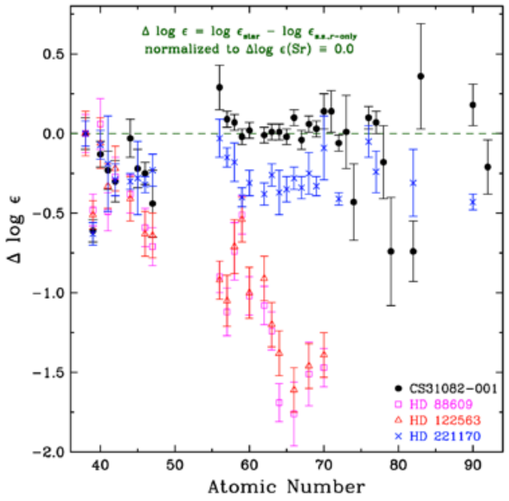
- variety of r-process patterns in metal-poor stars
- can be rare ~ 1% of ccSN rate
- Galactic chemical evolution
  - needed as external sources with NS mergers?
  - MR-SNe, “hypernovae”, collapsars etc.??

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

r-process in MP stars



“weak” r-process?



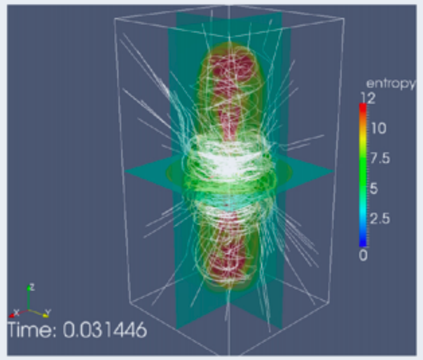
Cowan+2021

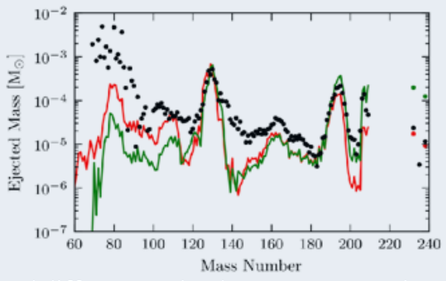
r-Process studies with SN models

- 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)

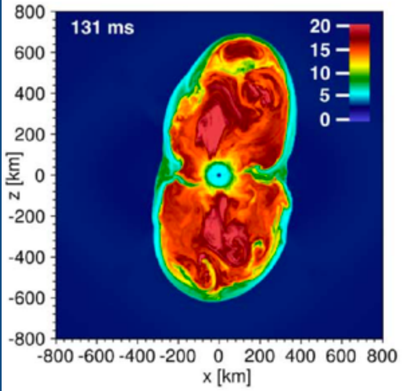


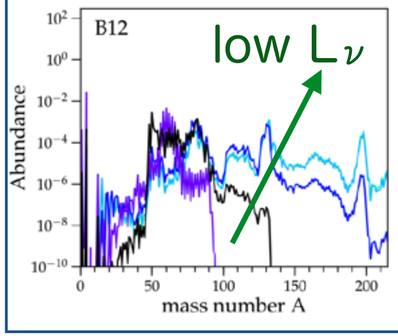


*difference is due to uncertainty

hydro-instability

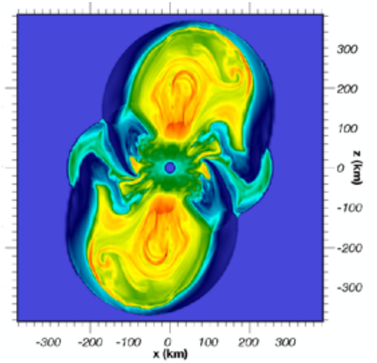
Mösta+(2018)

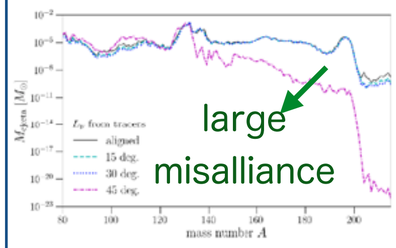




rotation vs. B-field misalliance

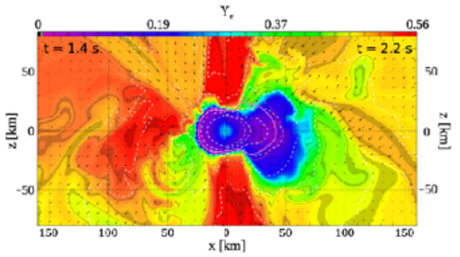
Halevi & Mösta(2018)

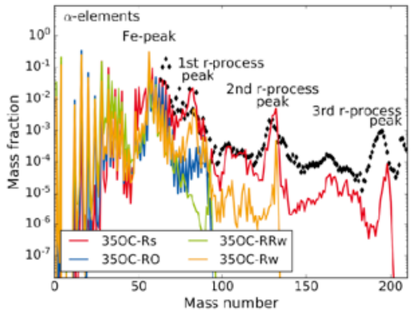




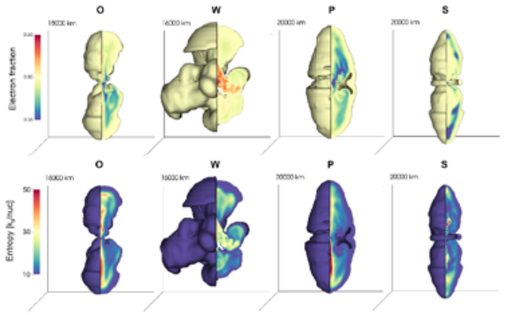
advanced neutrino transport

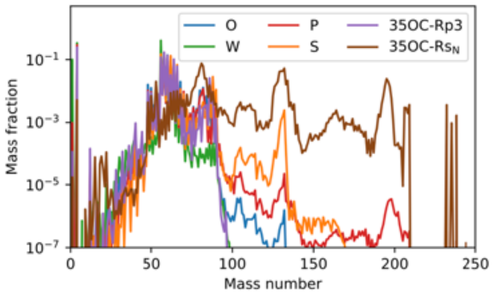
Reichert+2021, 2022
(w/ Obergaulinger+2020)





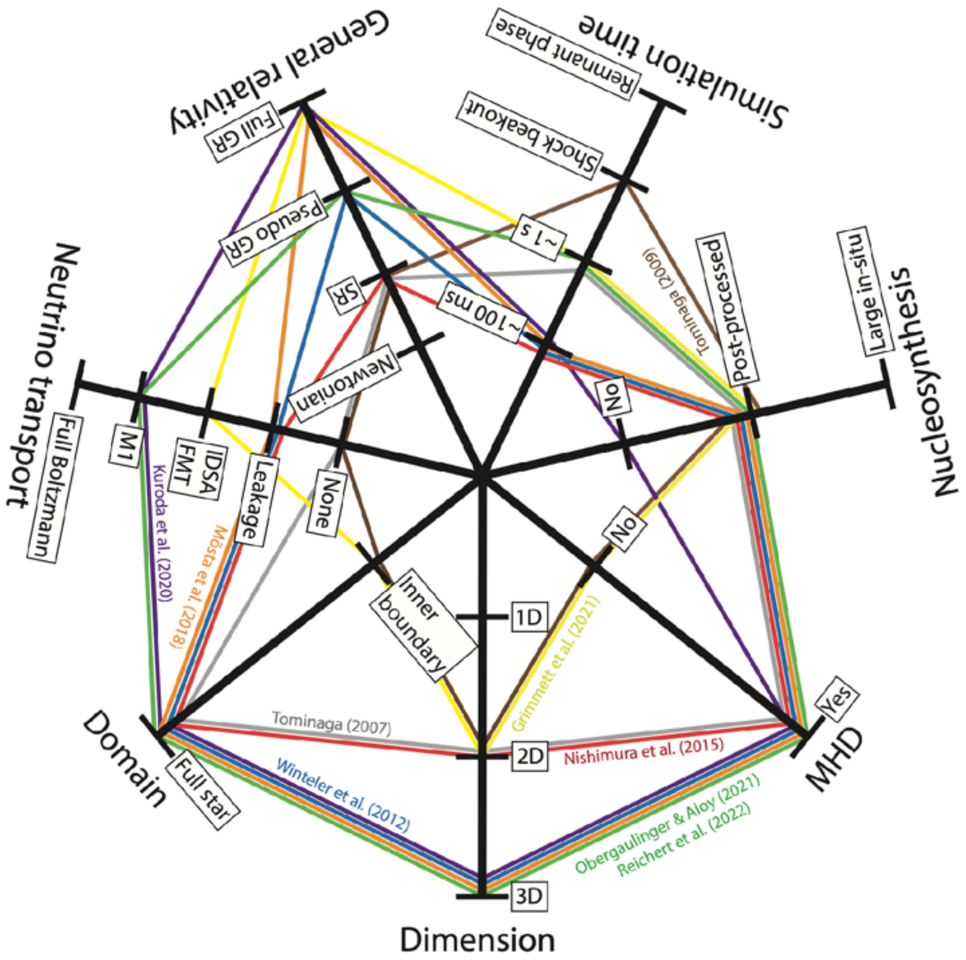
Reichert+2023





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
- ….

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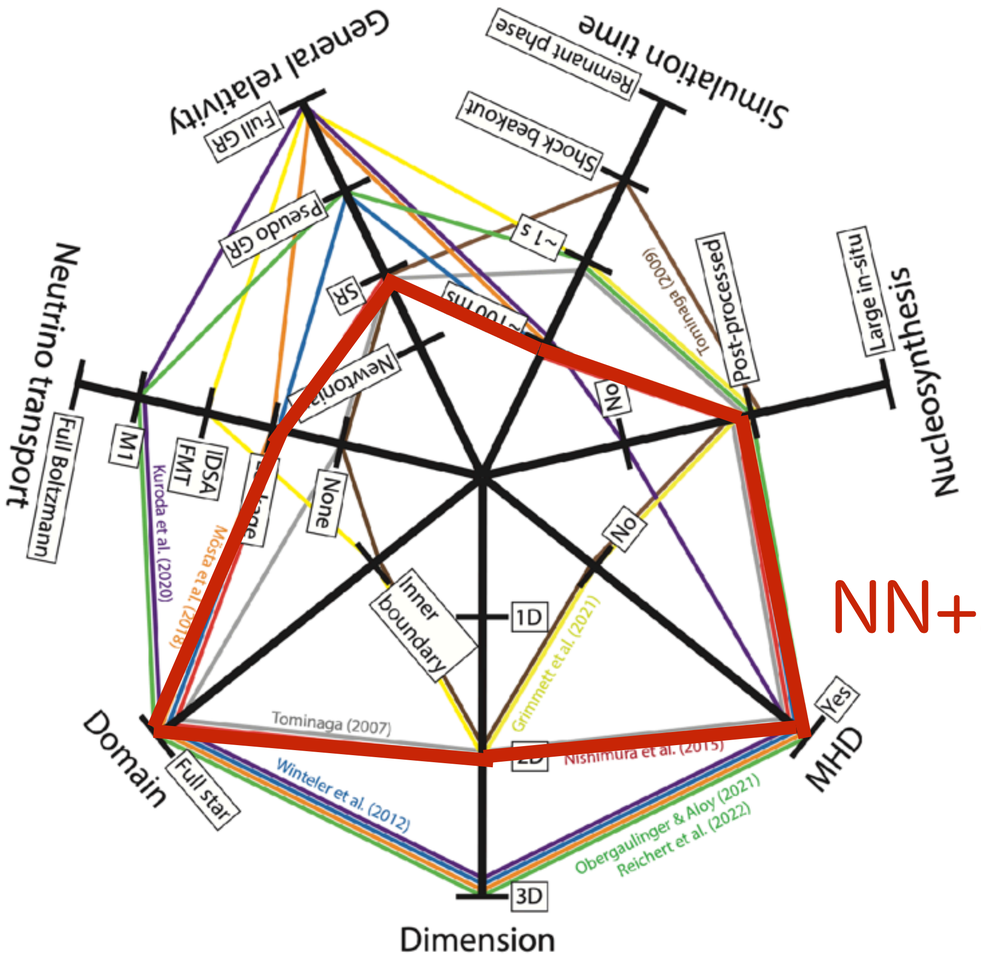

NN+2015

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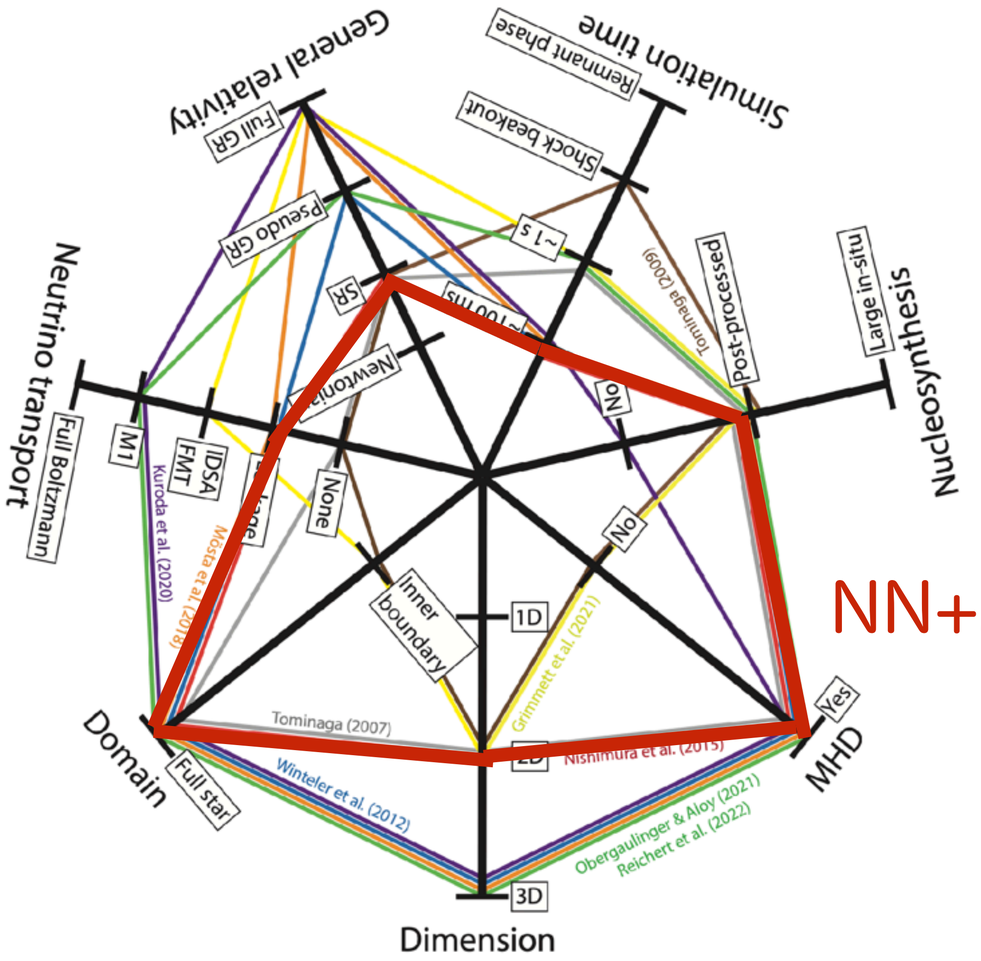

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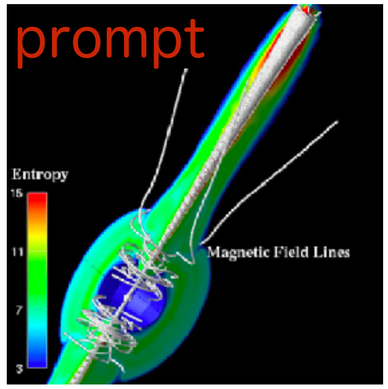
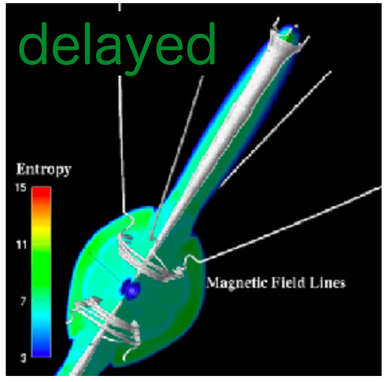
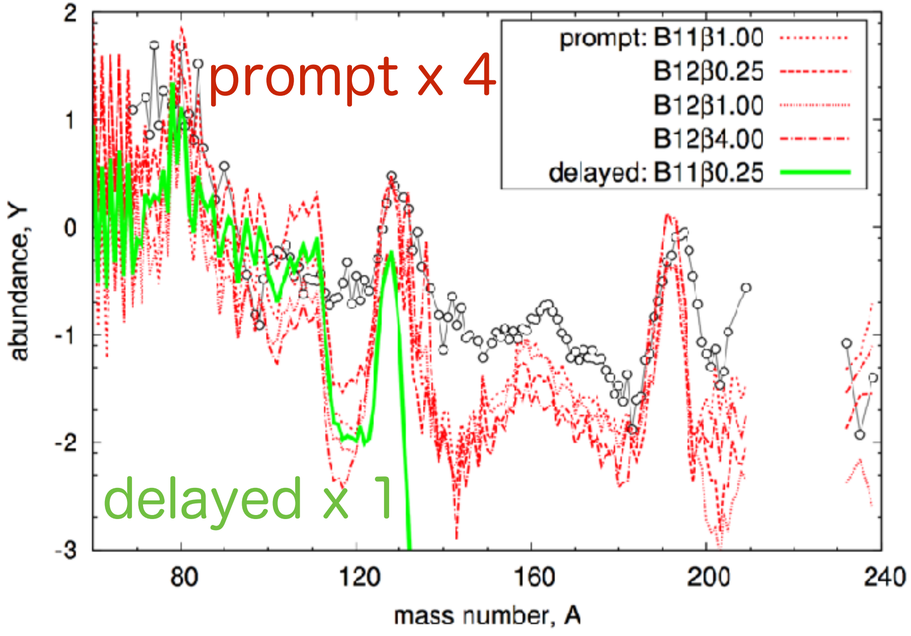




- dependence on rotation and B-fields
- B-fields application by winding



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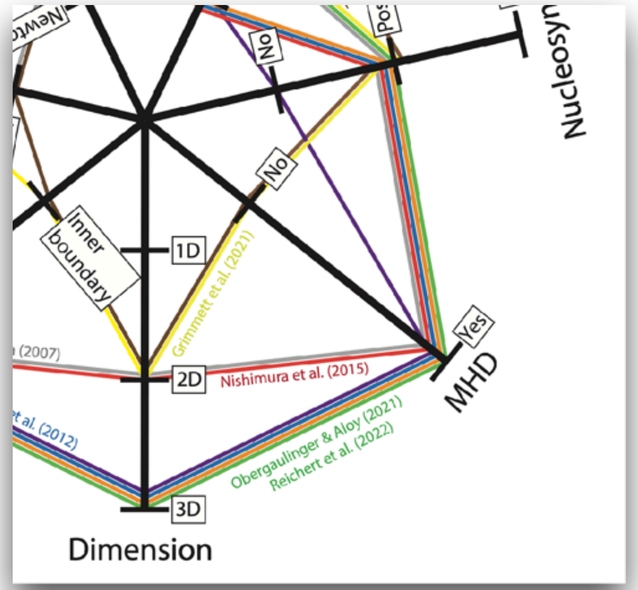

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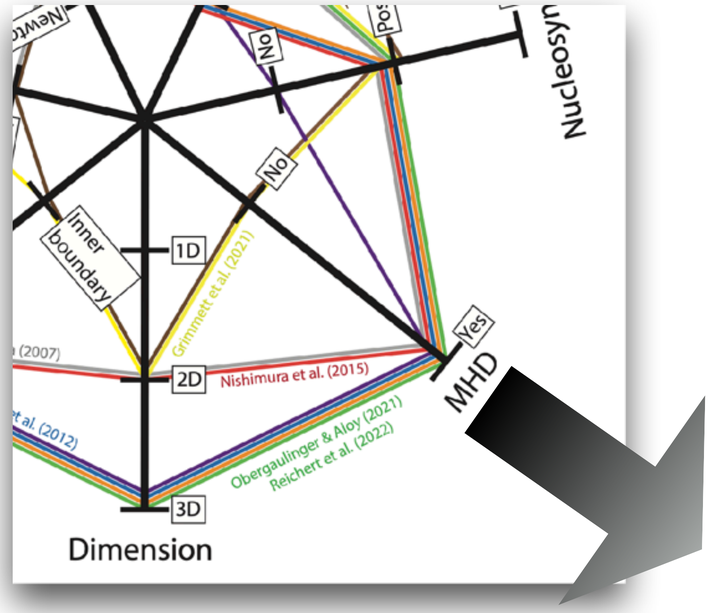
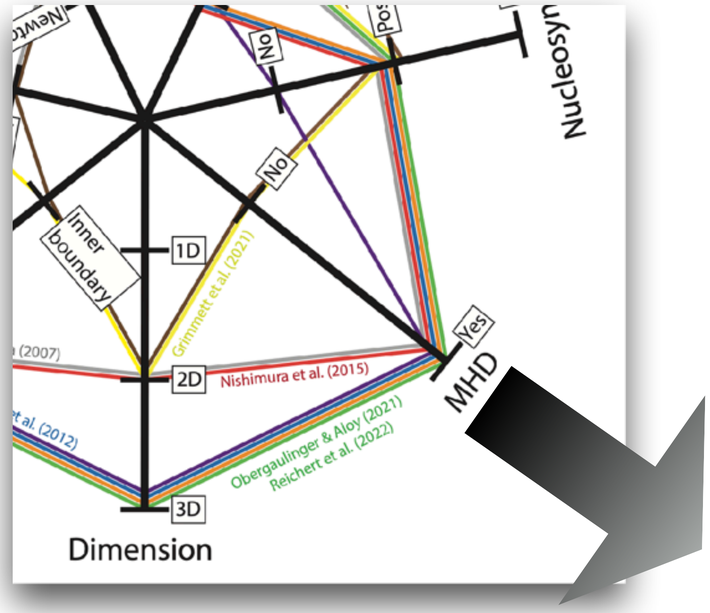


・<u>High resolution MHD</u>
(local B-field amplification)
・MRI
・magnetic turbulence
・・・・

r-Process studies with SN models

Obergaulinger & Reichert 2023



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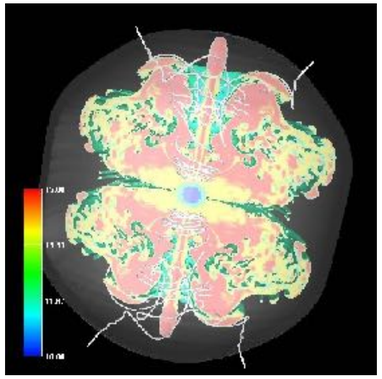
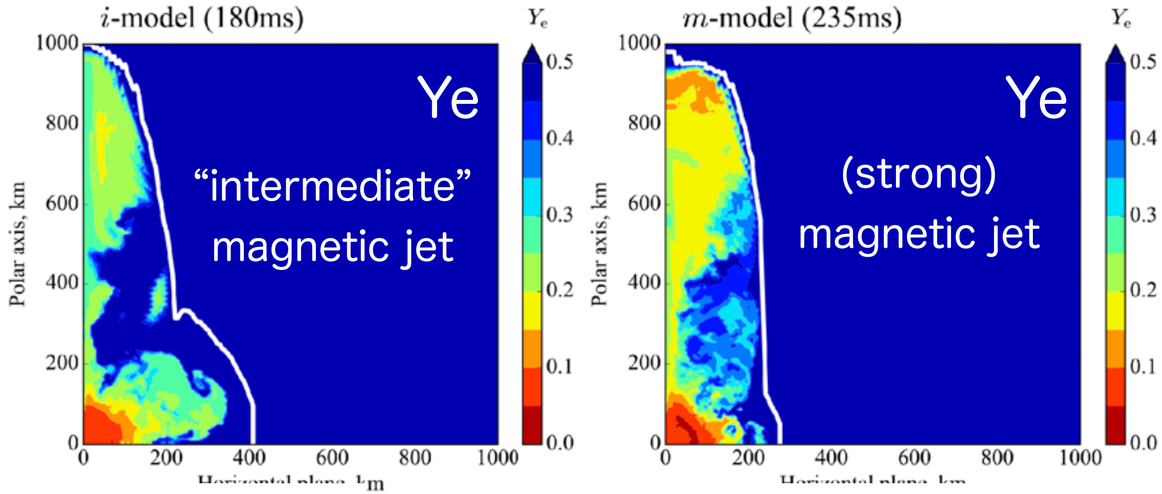
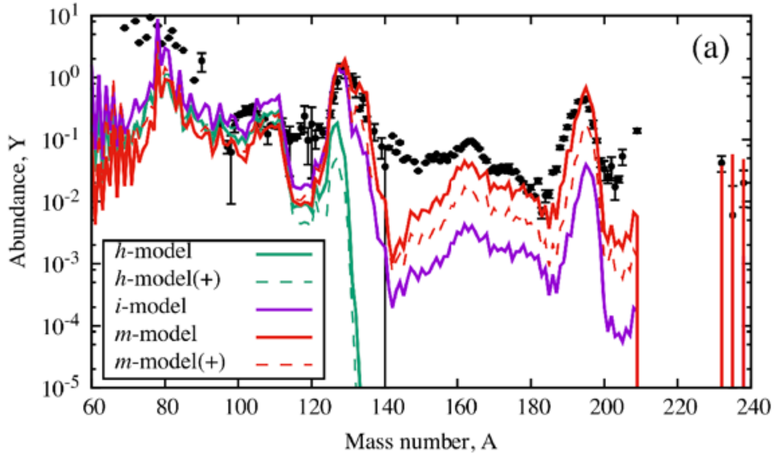
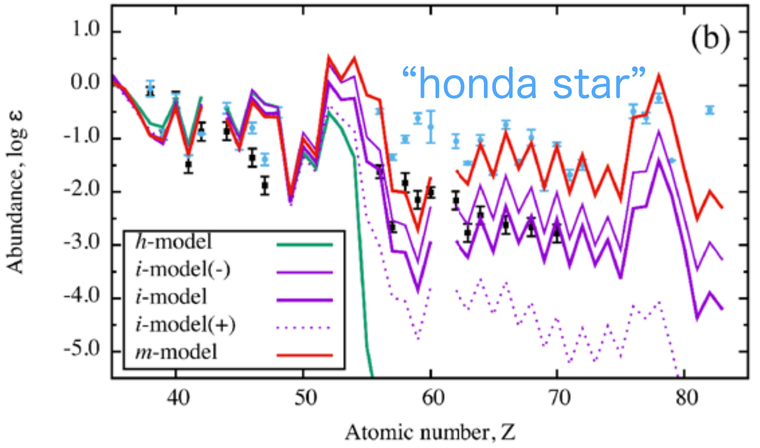
NN+2017



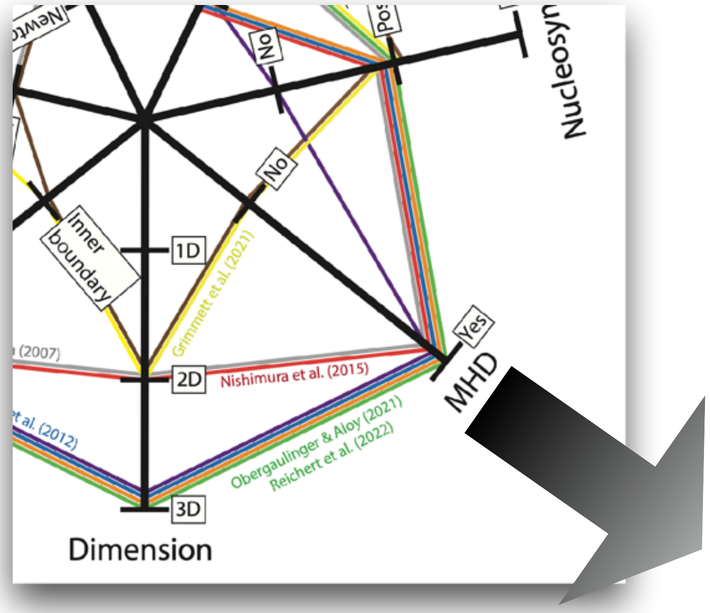






r-Process studies with SN models

Obergaulinger & Reichert 2023



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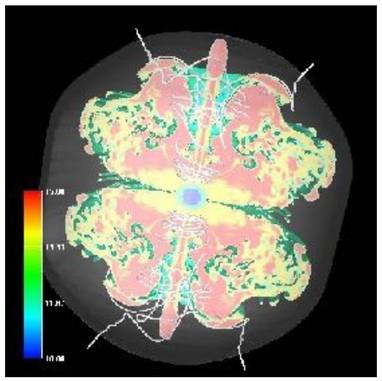
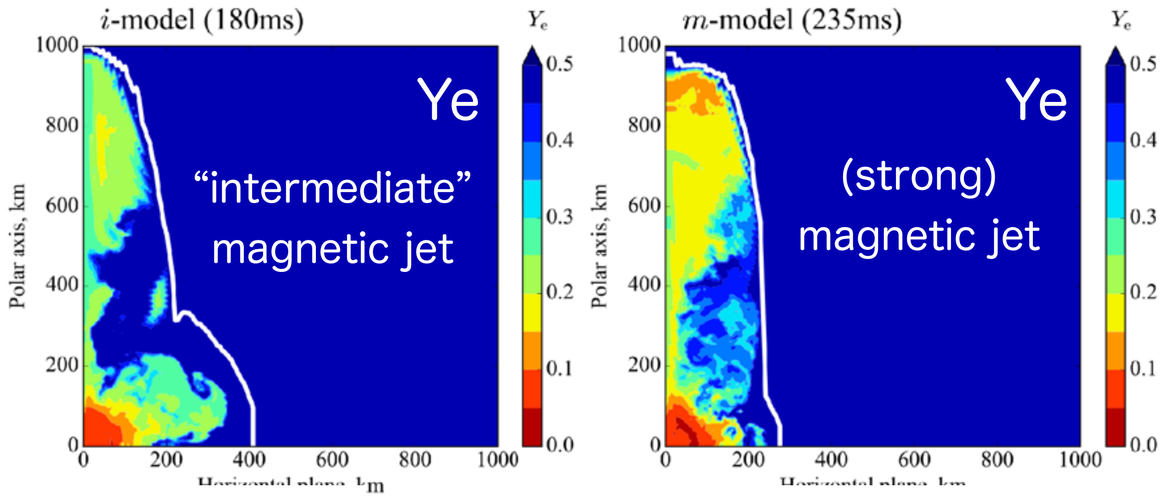
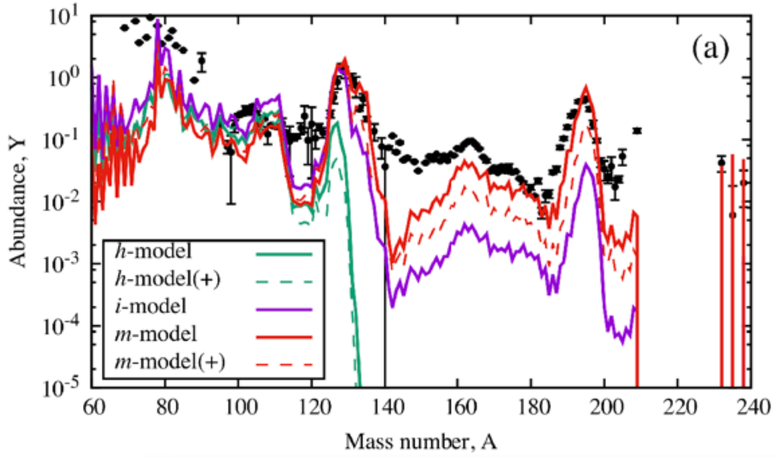
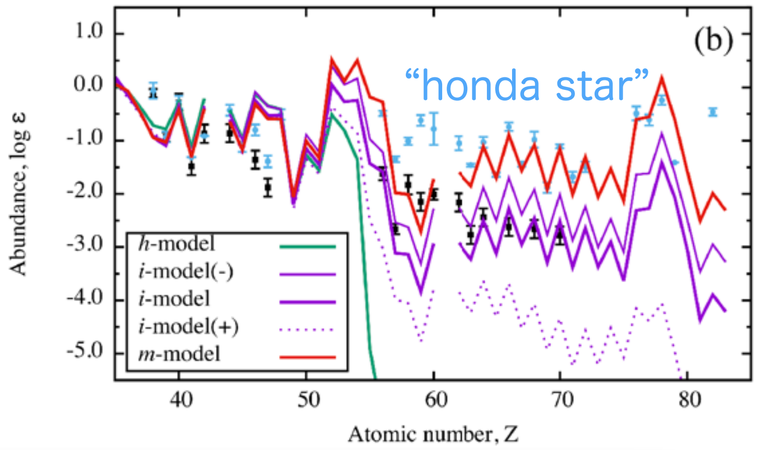








The Astrophysical Journal Letters, 836:L21 (6pp), 2017 February 20
https://doi.org/10.3847/2041-8213/aa5dee

ir-process??

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

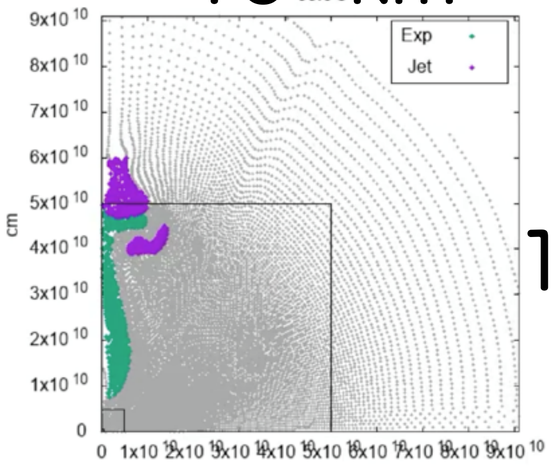
N. Nishimura (西村信哉)[1,6], H. Sawai (澤井秀朋)[2,3], T. Takiwaki (滝脇知也)[4], S. Yamada (山田章一)[3], and F.-K. Thielemann[5]

2. Toward SN light-curves

Hasegawa, Tanaka, NN+2022 (NIC XVI Proceedings)
Hasegawa, Tanaka, NN+2023, in prep.

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

10^5 km



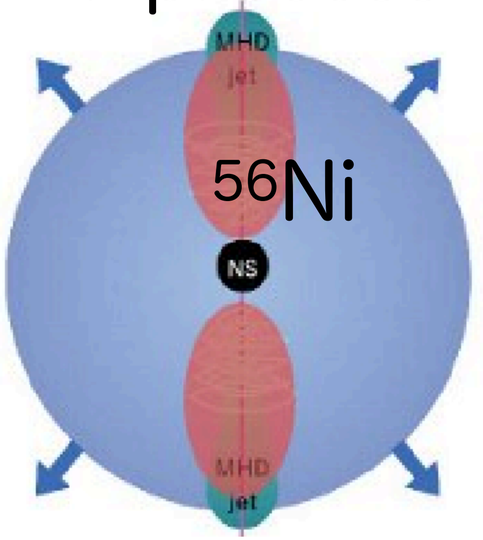
$t_{68.0\,s}$

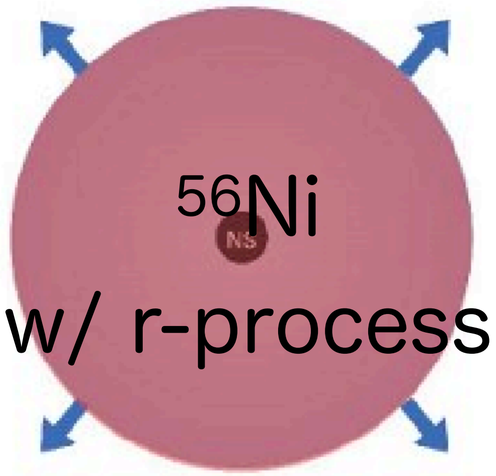
cm ～100 s

light curves

10^5 km

r-process





later phase ～ days — yrs

- 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)

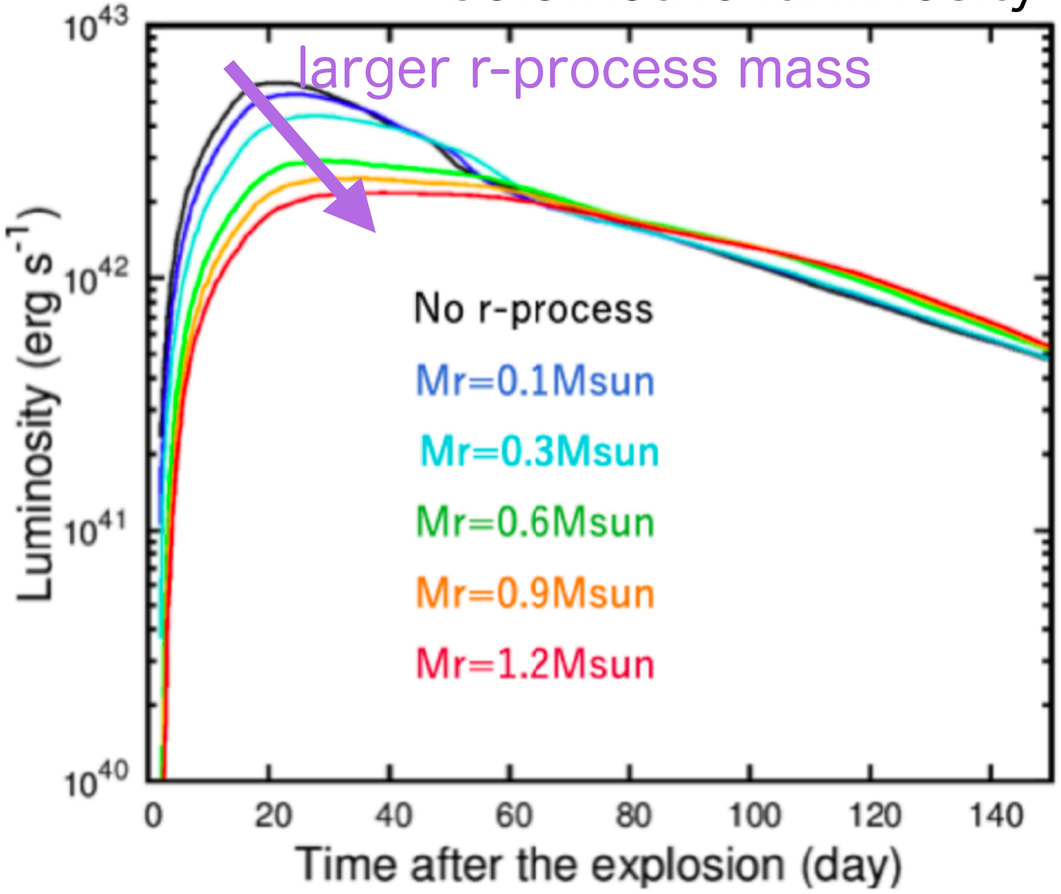
GRB (hypernova) associated SNe

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}

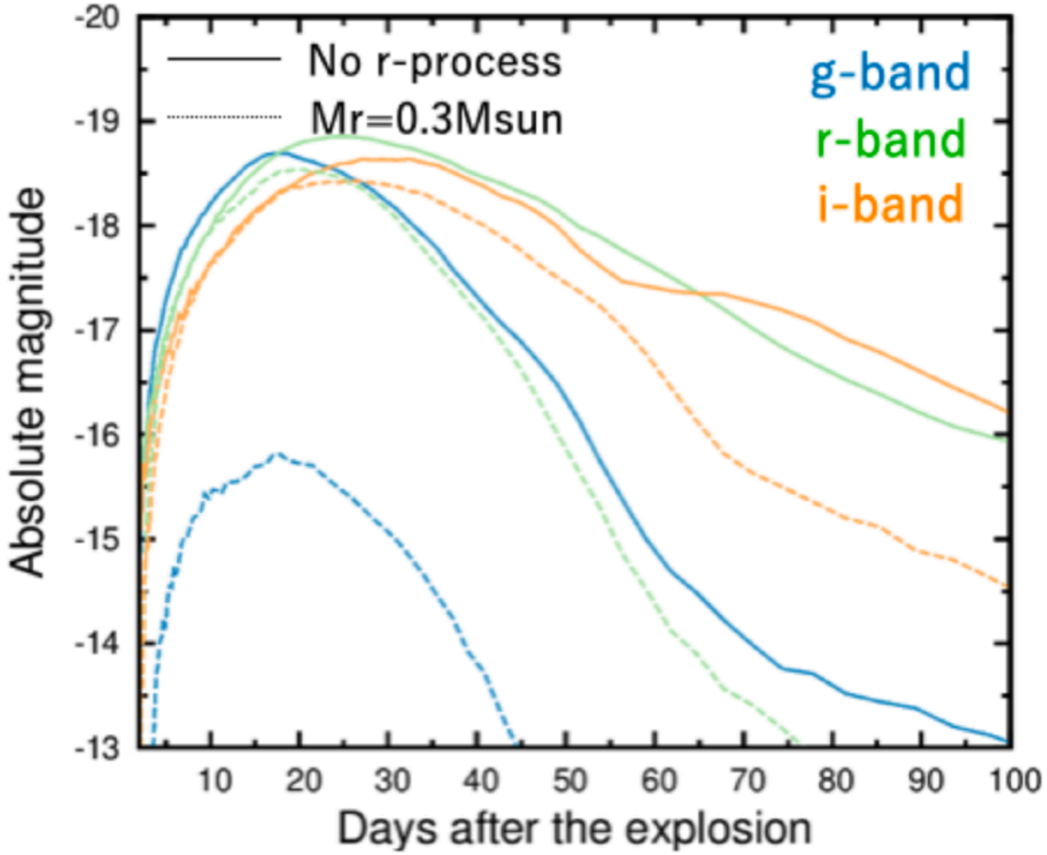
→ r-process rich → high opacity → fainter & red

Hasegawa+NN+ 2022

bolometric luminosity

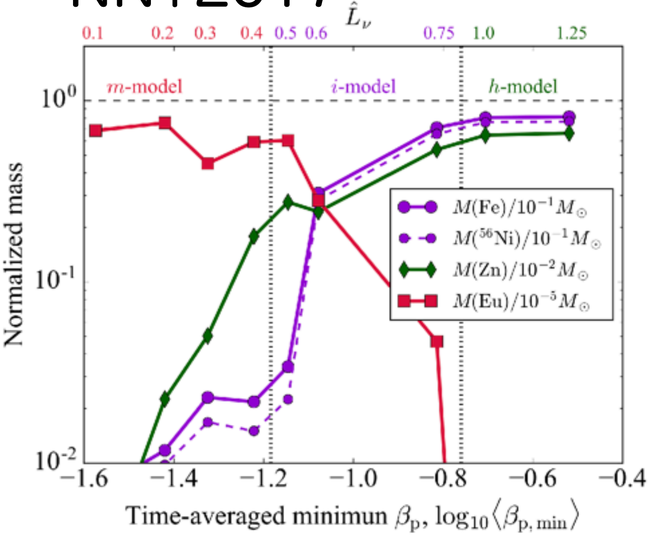


light curves



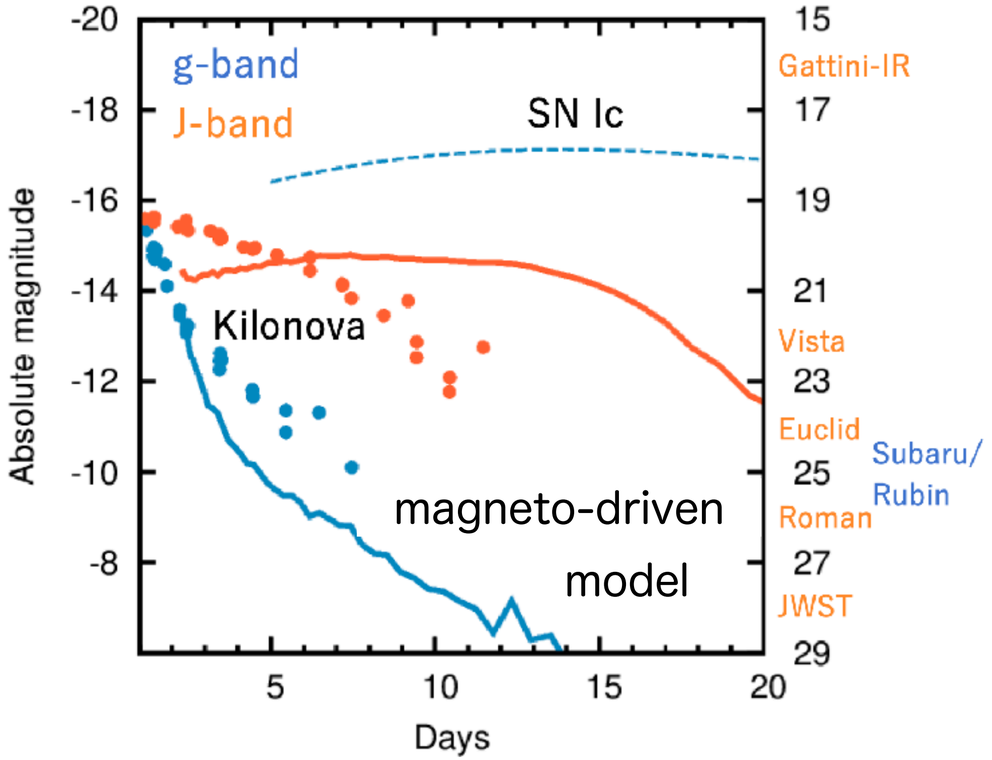
Identification in SN observations?

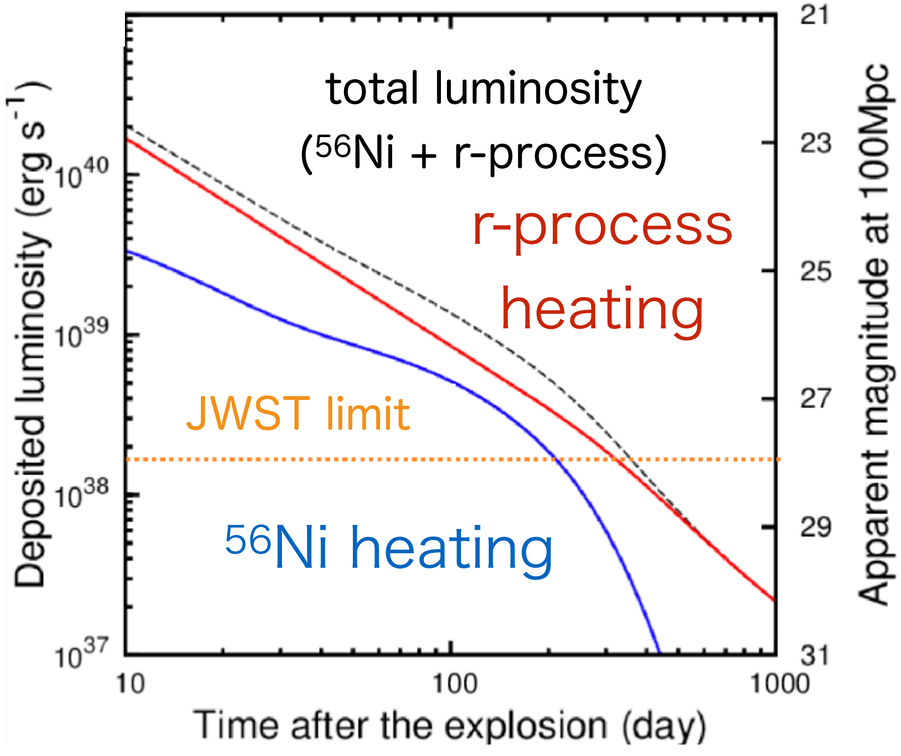
NN+2017



- 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+ 2023, in prep.

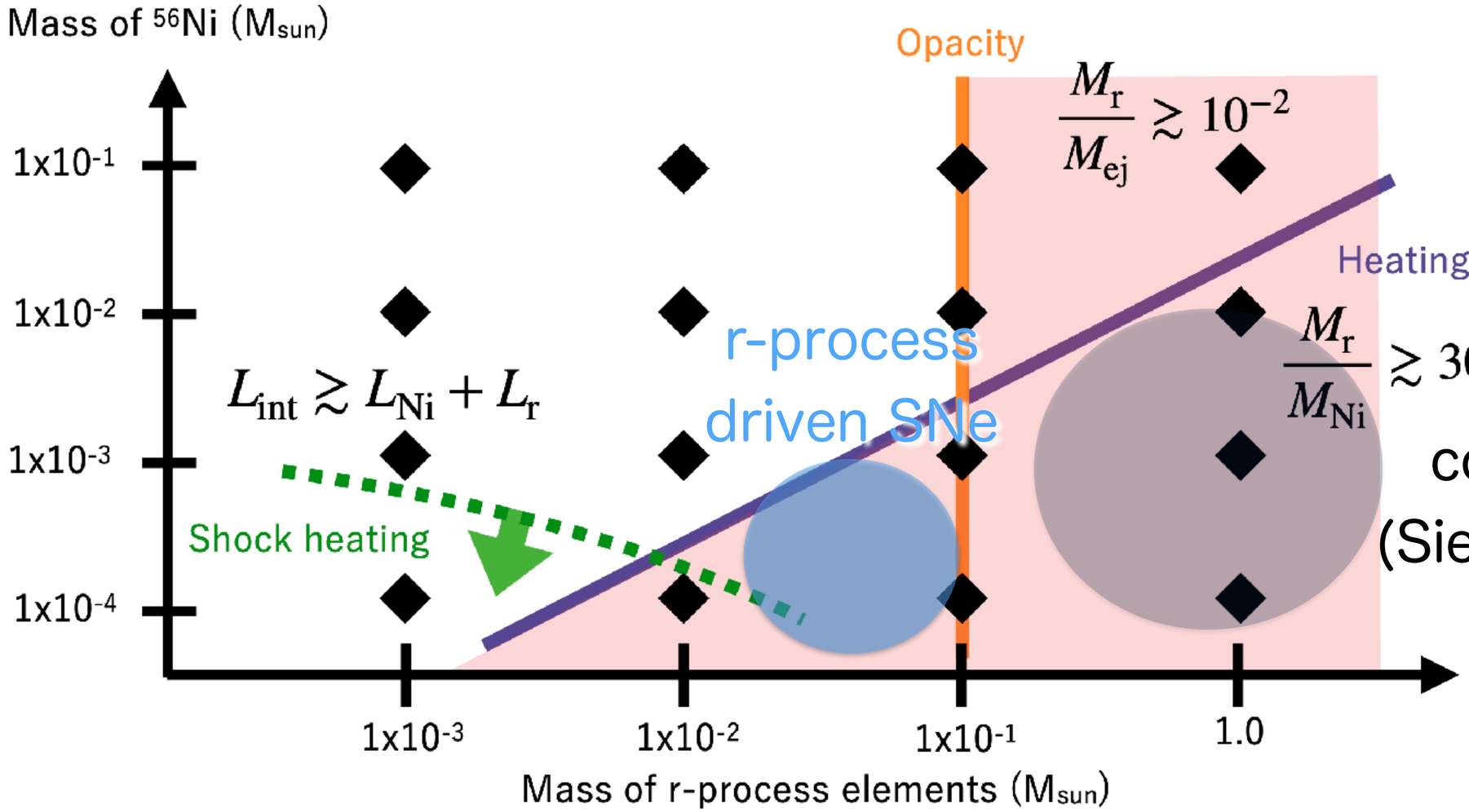




The overall feature: r-process vs ^{56}Ni

r-process is significant as

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



collapsar?
(Siegel+2019)

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

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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)