Nucleosynthesis in magneto-rotational driven supernovae

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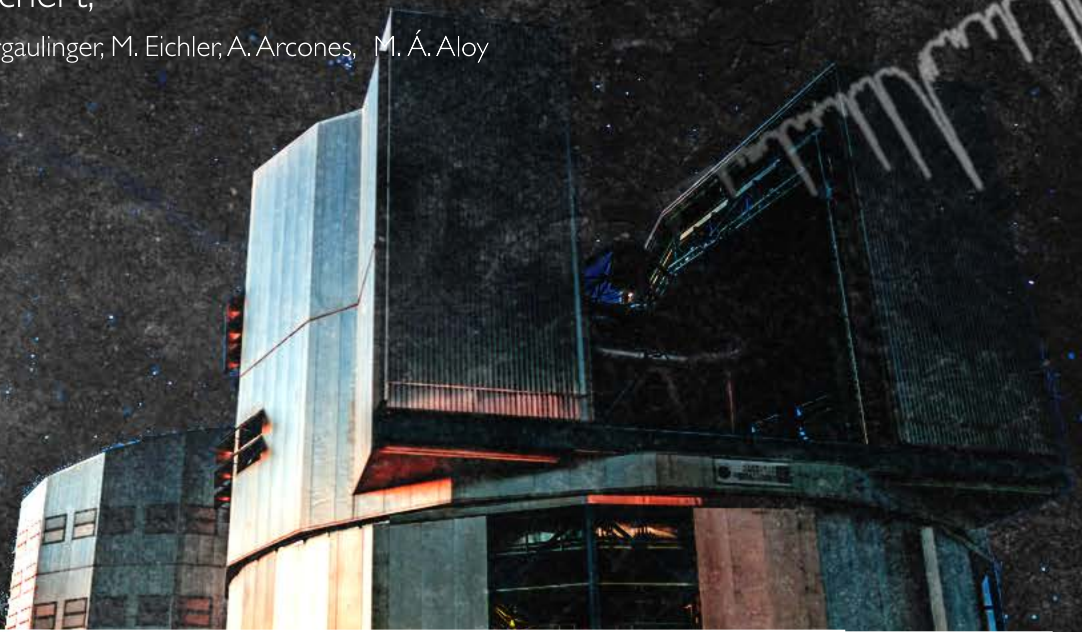

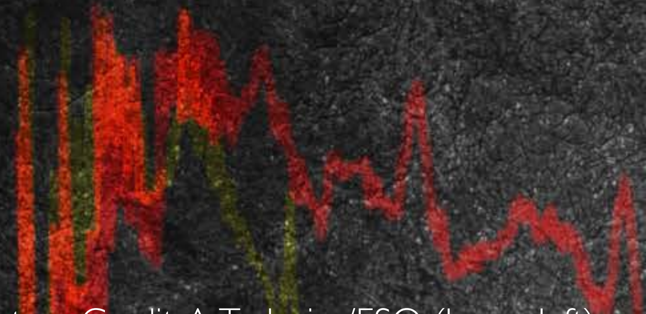

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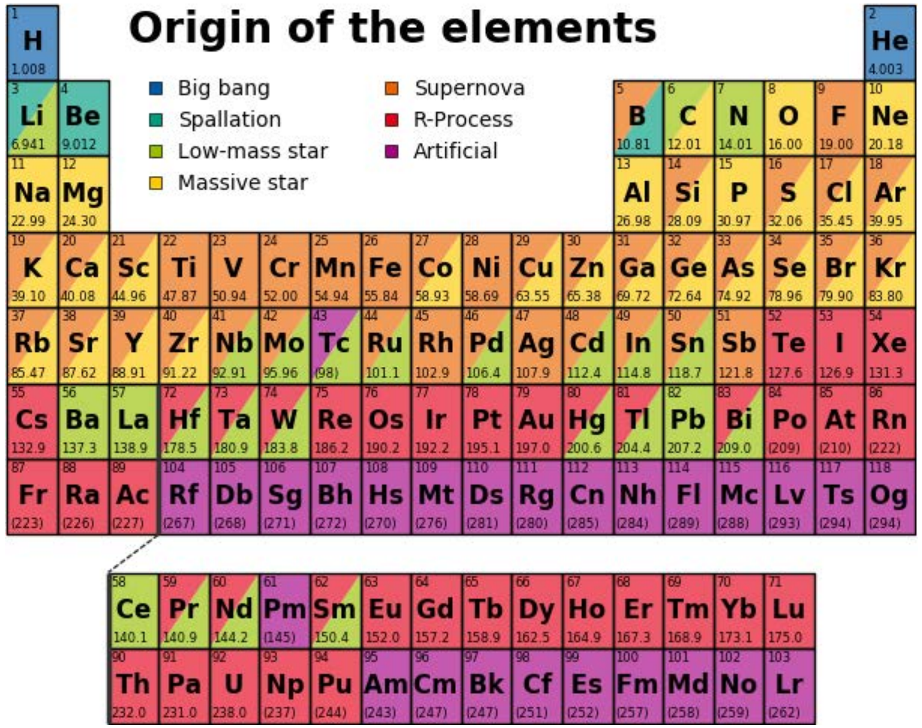
Picture Credit: A. Tudorica/ESO (lower left), M. Obergaulinger (middle right)

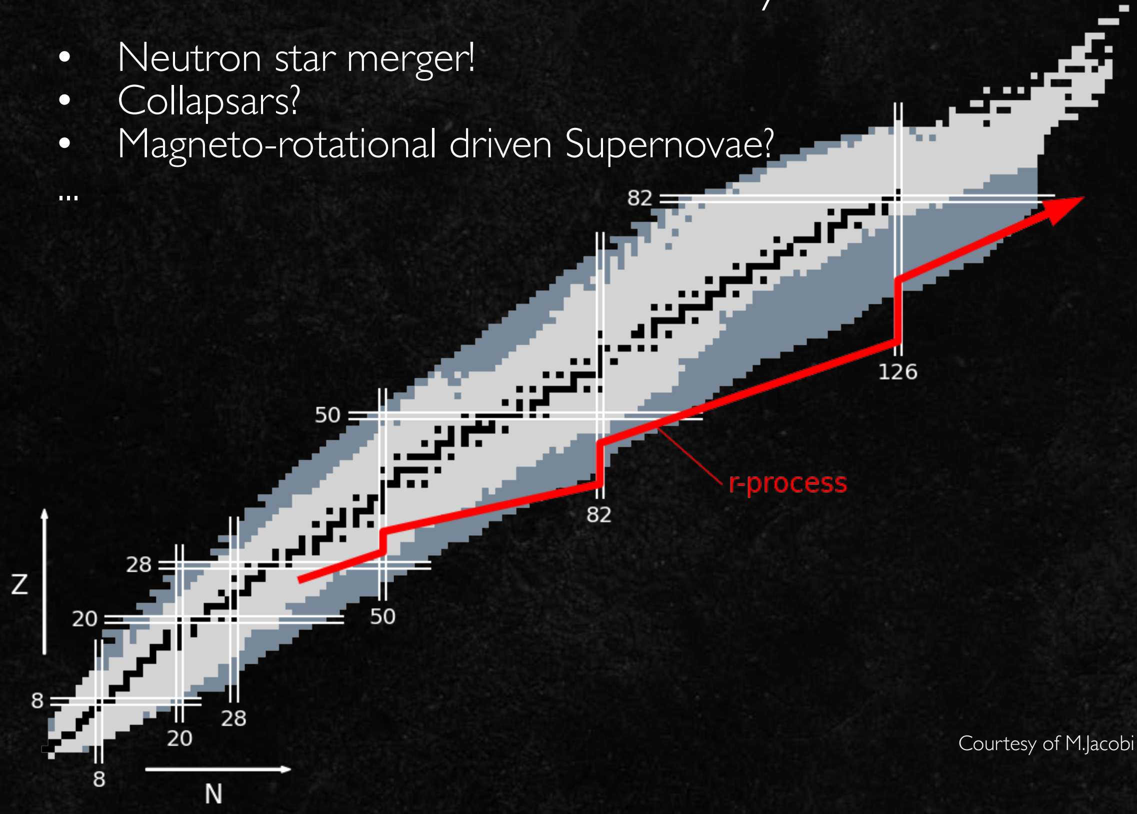
The production of heavy elements



Neutron-rich environments necessary

- Neutron star merger!
- Collapsars?
- Magneto-rotational driven Supernovae?

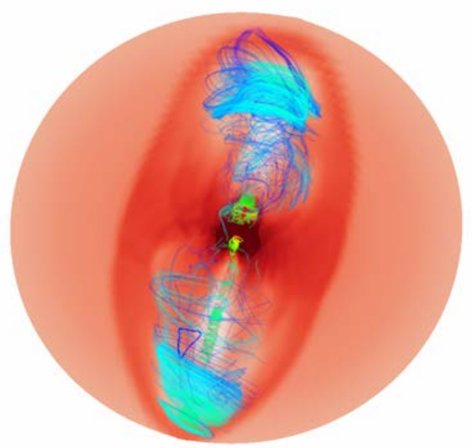
...



Courtesy of M.Jacobi

What are the conditions for an r-process?

Why MRD-SNe?



Courtesy of M. Obergaulinger

Neutrinos:

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

Field amplifying mechanisms:

- Compression ($\sim\rho^{2/3}$, flux conservation, e.g., Käppeli 2013)
- Differential rotation (field winding, e.g., Wheeler 2000,2002, Käppeli 2013)
- Magnetorotational instability (e.g., Balbus & Hawley 1991, 1998, Obergaulinger et al. 2009)
- Convection and the stationary accretion shock instability (e.g., Thompson & Duncan 1993, Raynaud et al. 2020)

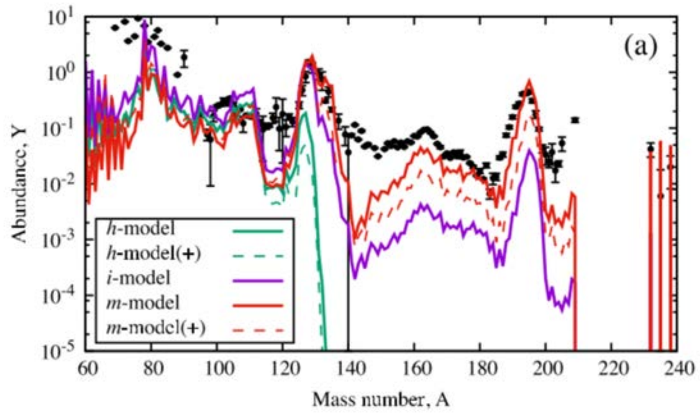
Previous studies

S. Nishimura et al. 2006

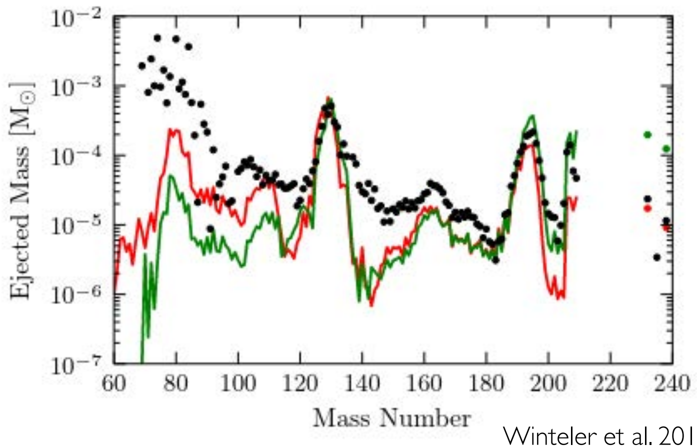
2D
No neutrino transport
~400 ms

Winteler et al. 2012

3D
Spectral leakage
~33 ms



Nishimura et al. 2017



Winteler et al. 2012

N. Nishimura et al. 2015

2D
Leakage
~33-100 ms

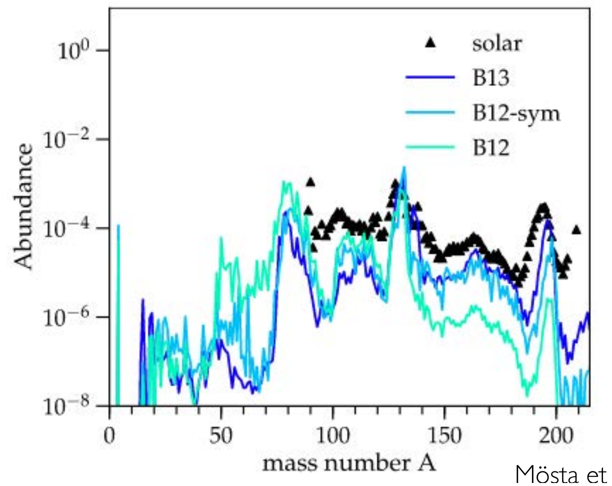
N. Nishimura et al. 2017

2D
Light bulb
~235 ms

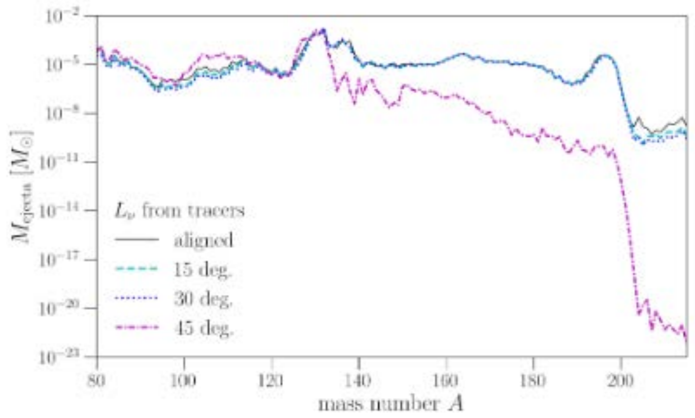
Previous studies

Mösta et al. 2018

Sym. 3D, Full 3D
Leakage
~20-110 ms



Mösta et al. 2018



Halevi & Mösta 2018

Halevi & Mösta 2018

Sym. 3D
Leakage
~20-49 ms

Magneto-rotational driven SNe

Simulation setup

(Obergaulinger & Aloy 2017, 2020)

- Long-time
  (900 – 2540 ms)
- Sophisticated neutrino treatment
  (M1)
- 2D
- Parametrized magnetic field / from stellar evolution model

Magnetorotational core collapse of possible GRB progenitors. I. Explosion mechanisms.

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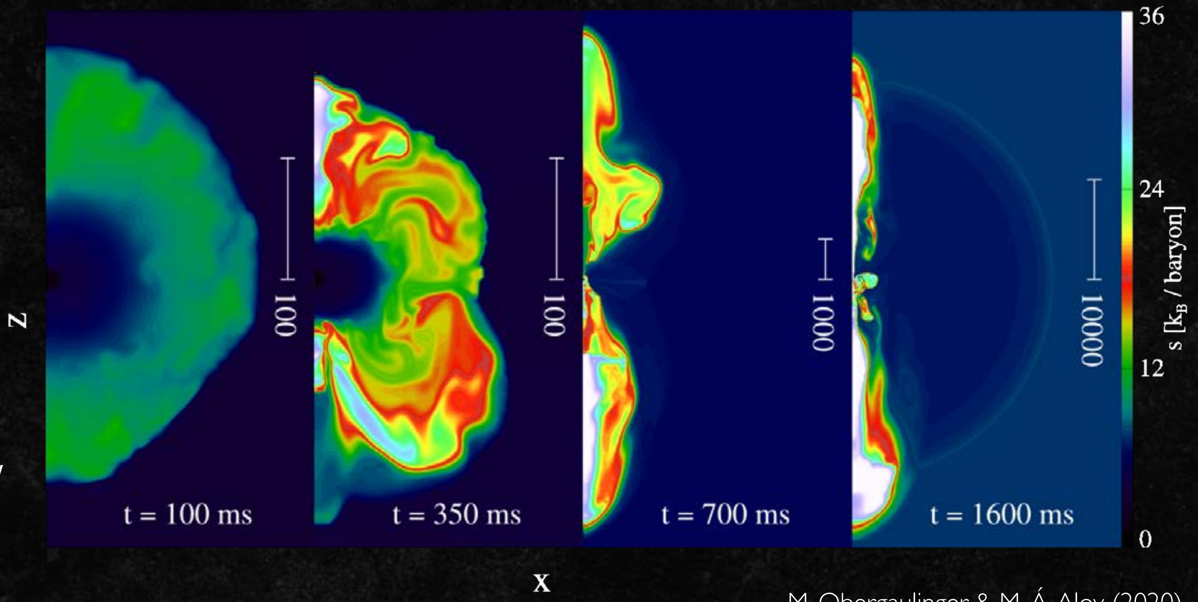
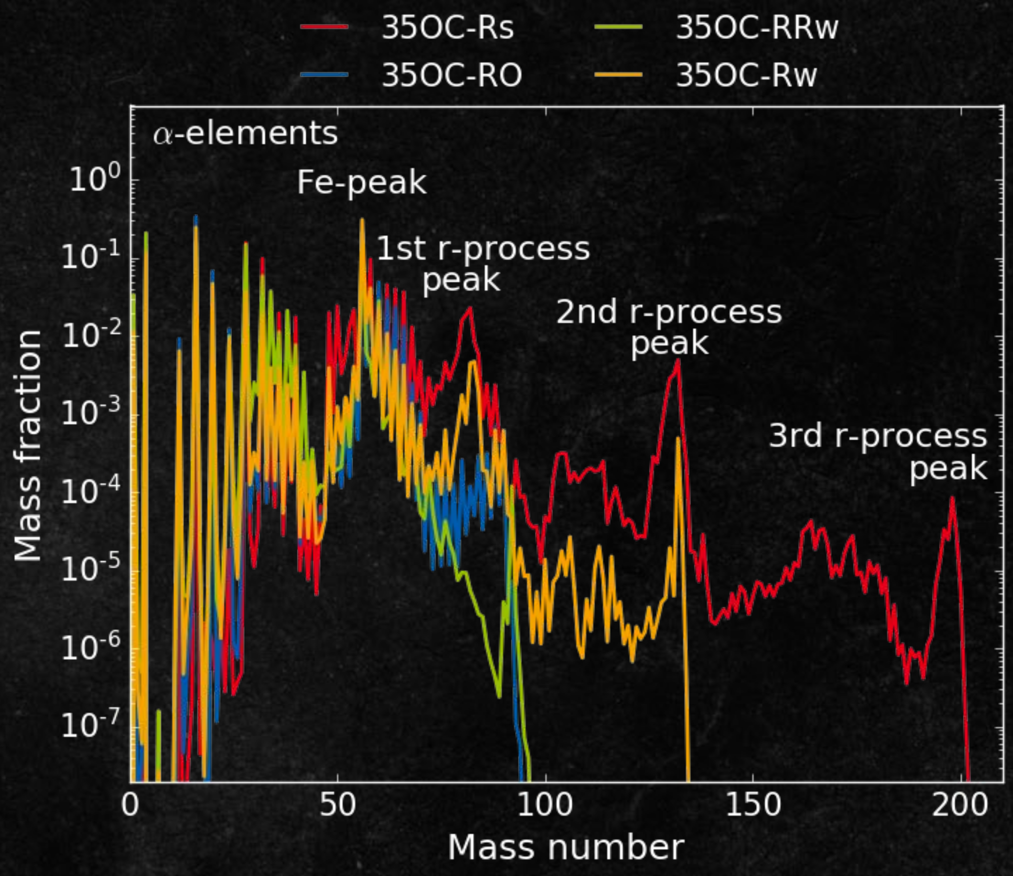
14 January 2020



M. Obergaulinger & M. Á. Aloy (2020)

Integrated abundances



Reichert et al. 2021a

35OC-RO (ordinary) – Mostly iron and first r-process peak

35OC-Rw (weak) – Second r-process peak

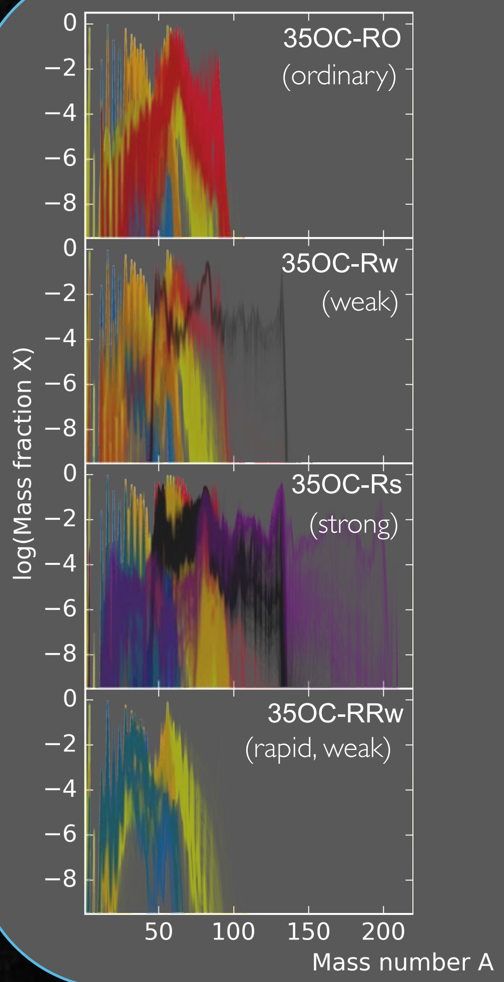
35OC-Rs (strong) – Third r-process peak

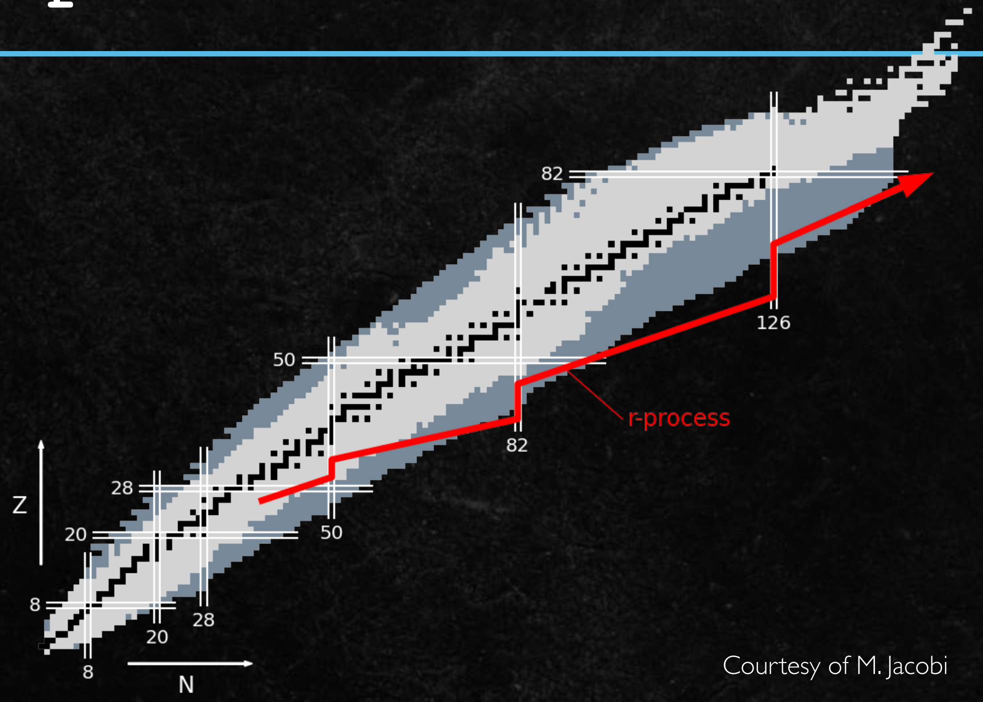
35OC-RRw (rapid, weak) – Mostly iron

Magnetic fields favor the conditions for heavy elements while rotation act against it

c.f., Nishimura et al. 2006, Winteler et al. 2012, Nishimura et al. 2015/2017, Mösta et al. 2018, Halevi & Mösta 2018, Meynet & Maeder 2017, Marrasi et al. 2019

Individual tracer particles



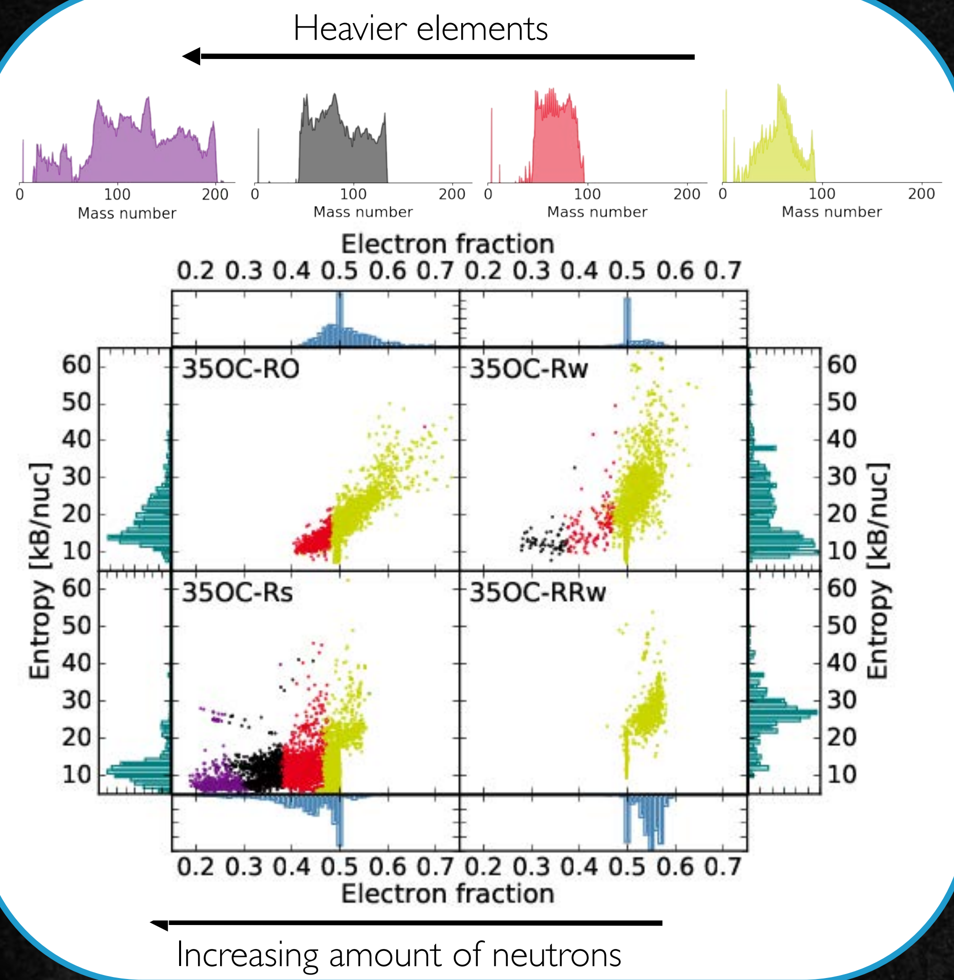


Courtesy of M. Jacobi

- Many tracers result in a similar final abundance pattern
- Tracers are separated into groups based on the abundances
- Magic numbers are bottlenecks

Reichert et al. 2021a

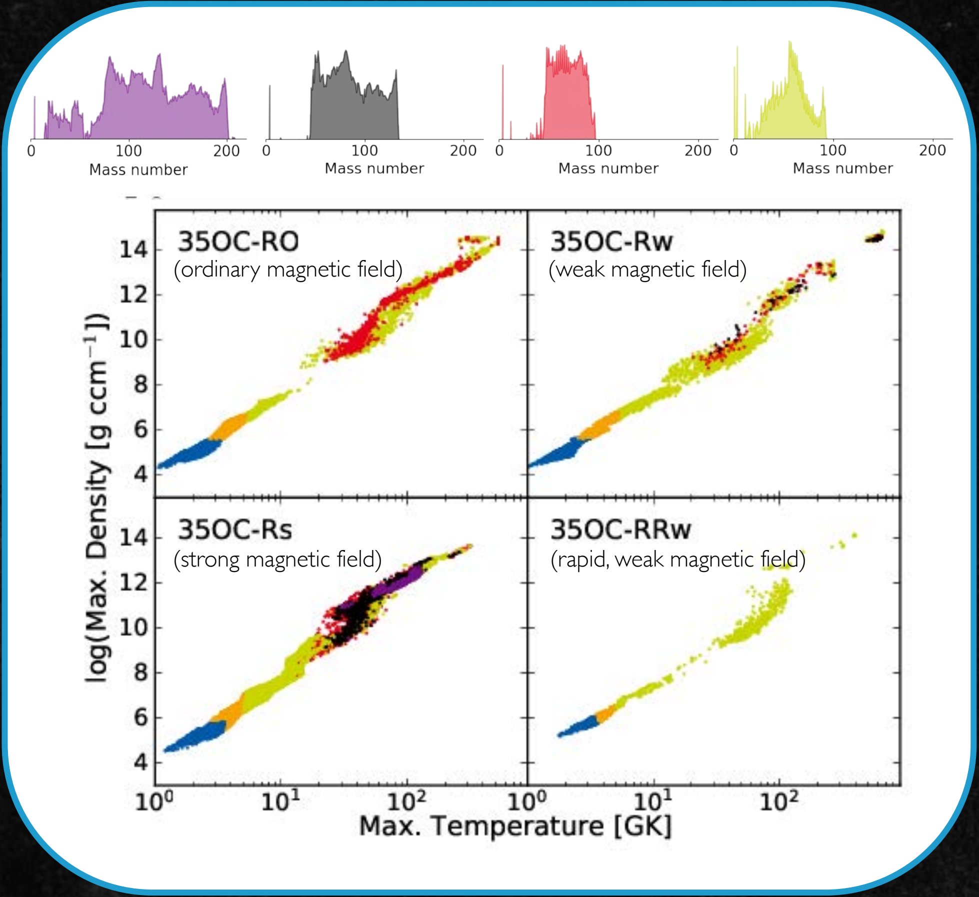
Neutron richness



- $Y_e = \dfrac{n_p}{n_p + n_n}$
- Electron fraction is key parameter
- Event hosts neutron rich, but also proton rich conditions
- Strong magnetic field achieves electron fractions ~0.2

Reichert et al. 2021a

Neutrons and timescales



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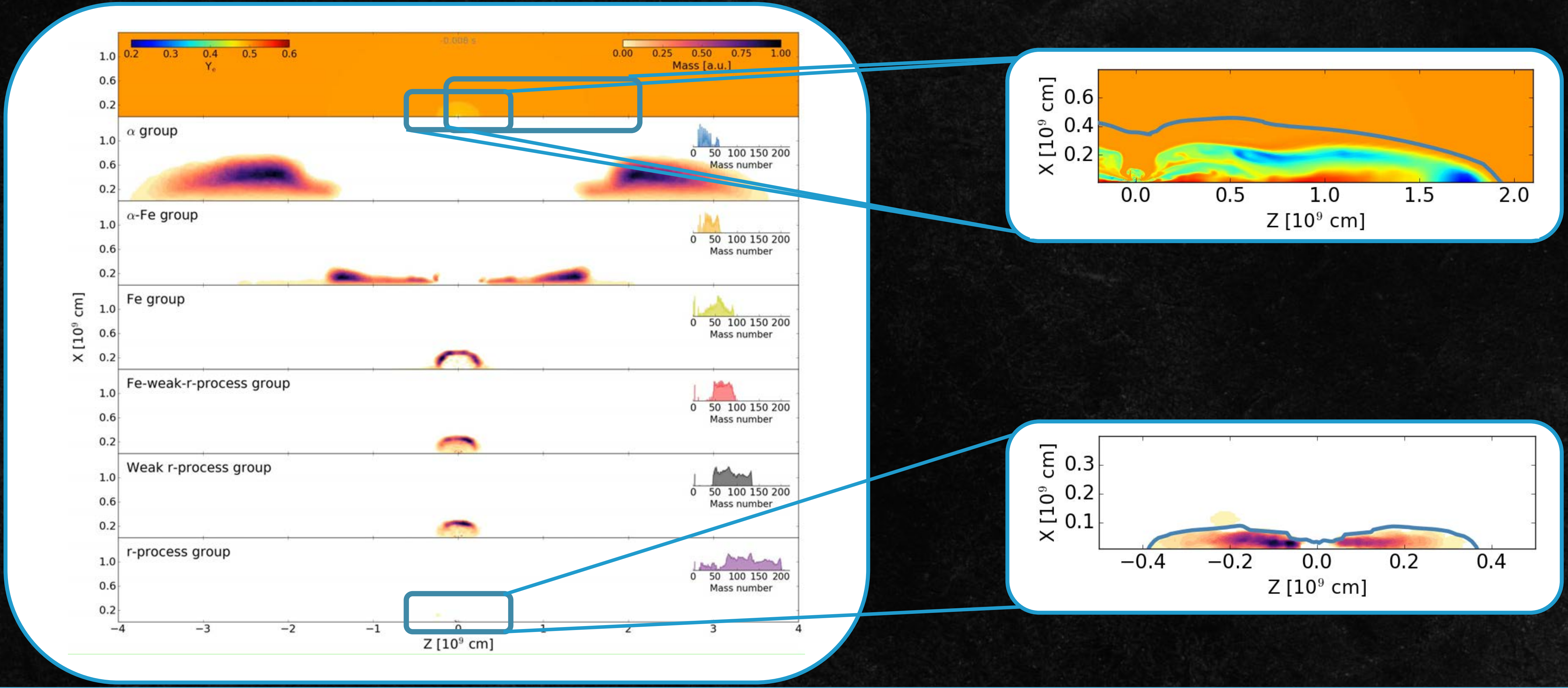
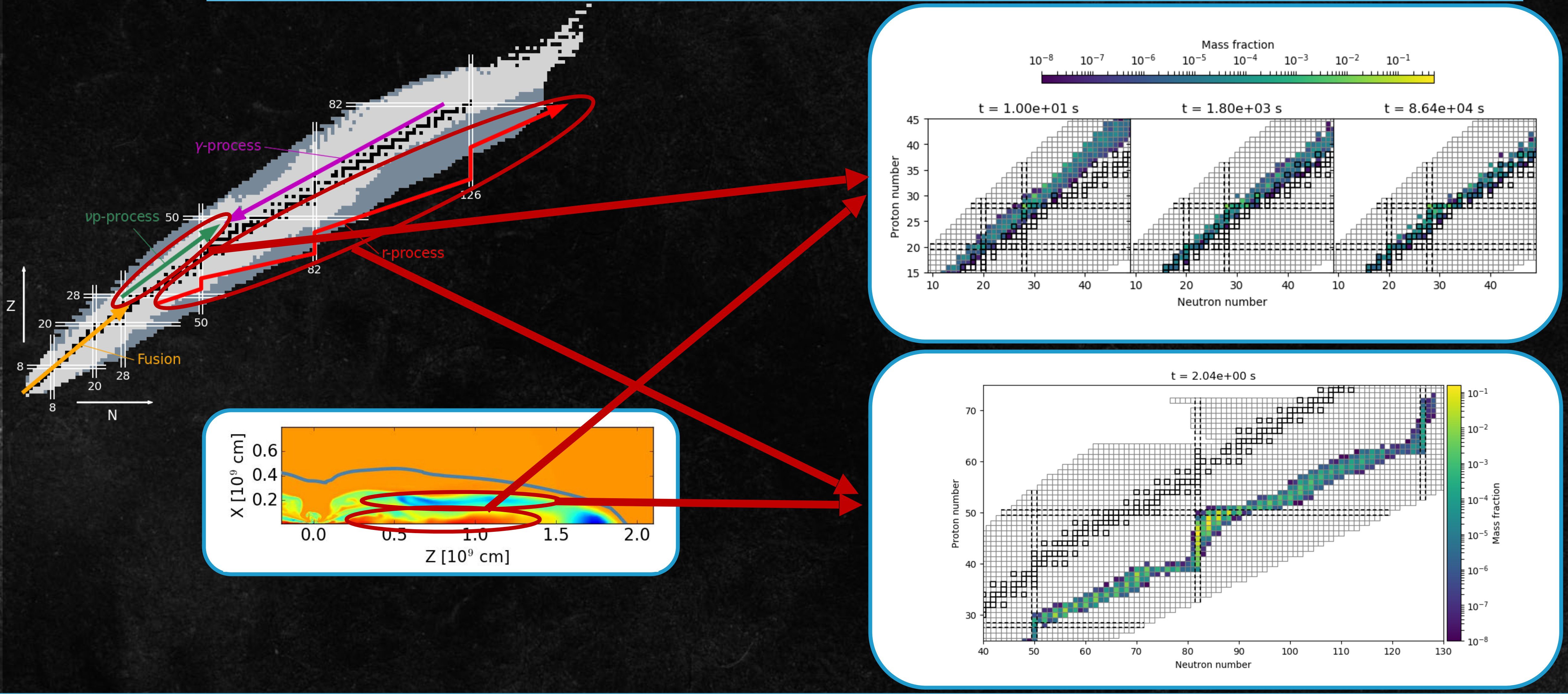
Reichert et al. 2021a

Spatial distribution

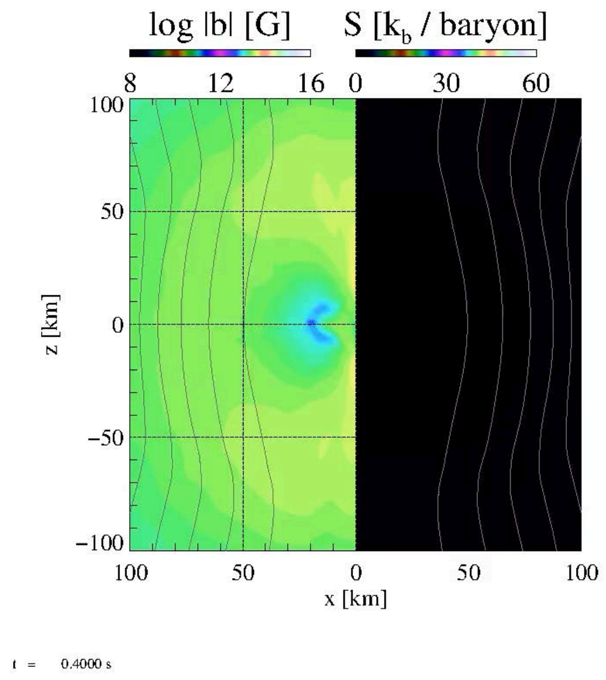


The diverse nucleosynthetic conditions

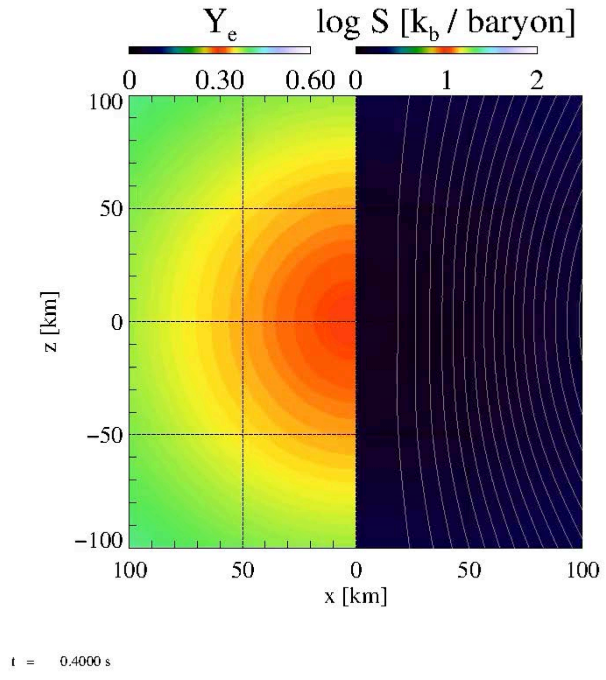


Comparison, 35OC-RO vs 35OC-Rs

35OC-RO

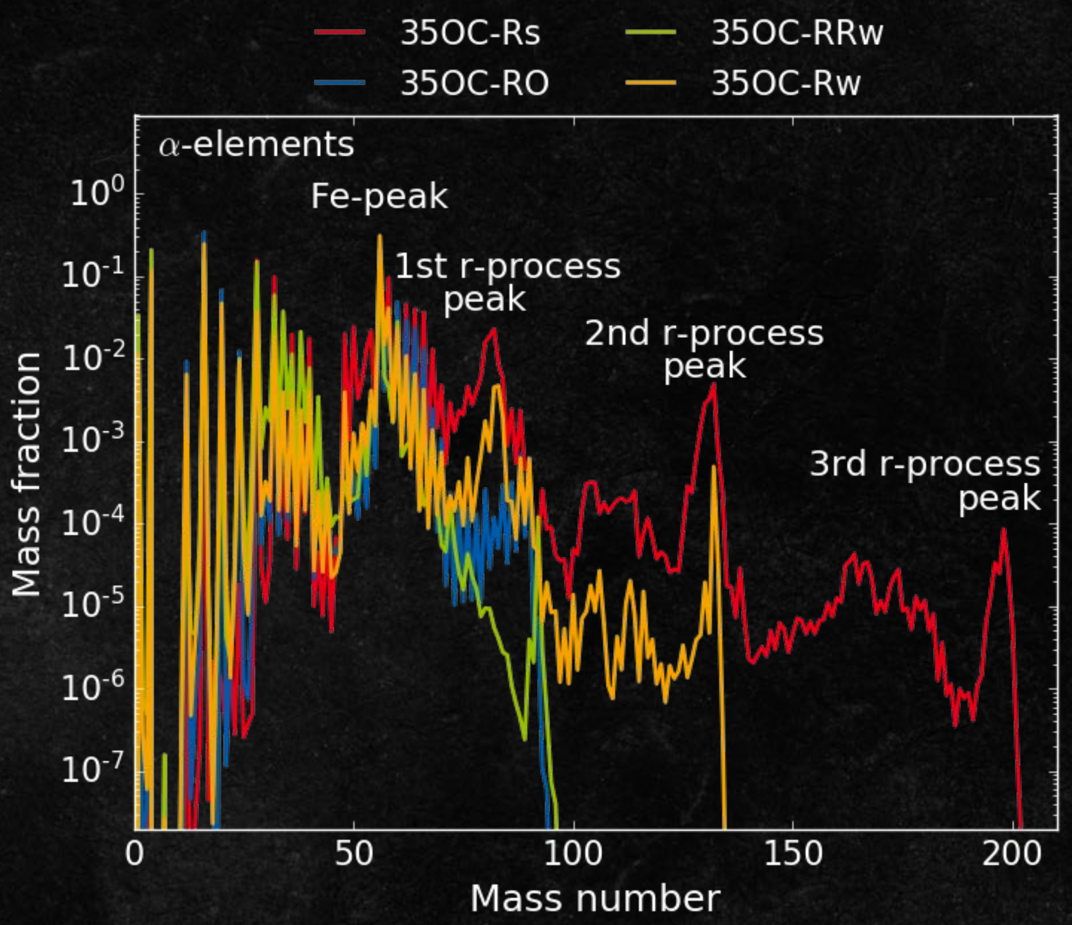


35OC-Rs



Courtesy of M. Obergaulinger

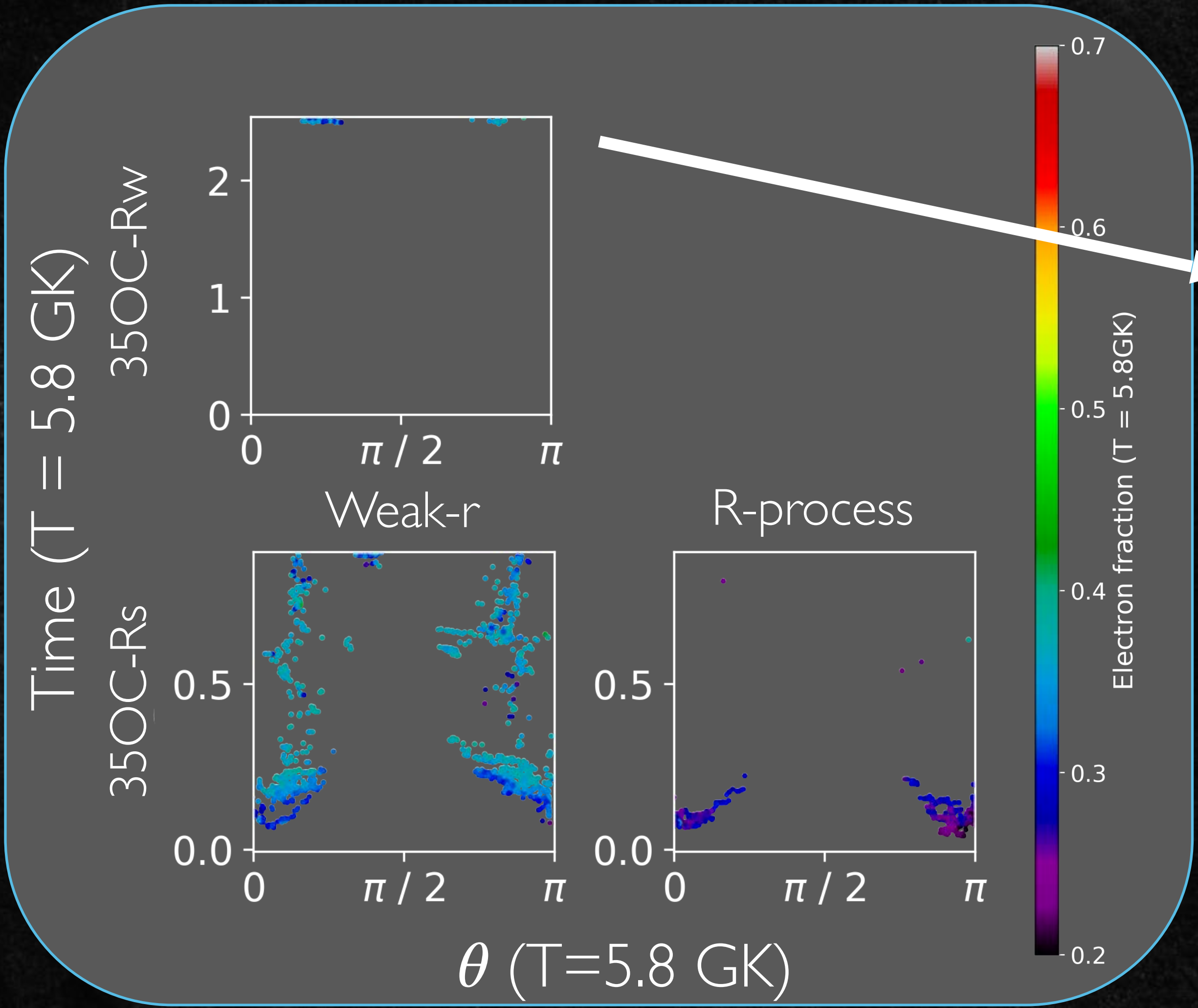
Model 35OC-Rw

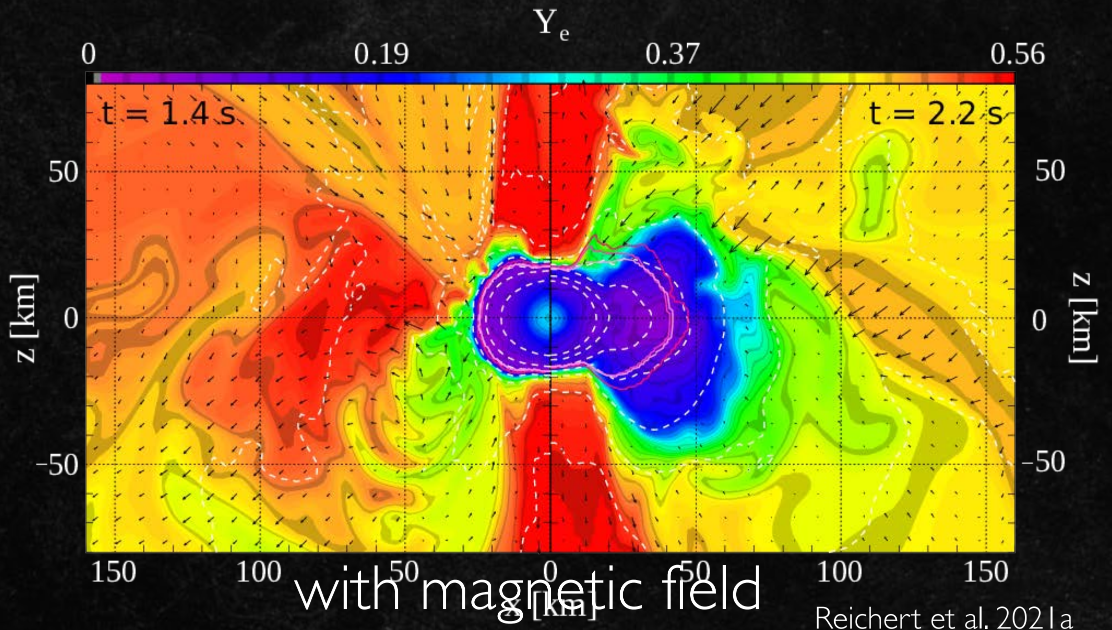


Why is the amount of heavy synthesized elements not monotonic with magnetic field strength?

Reichert et al. 2021a

Model 35OC-Rw



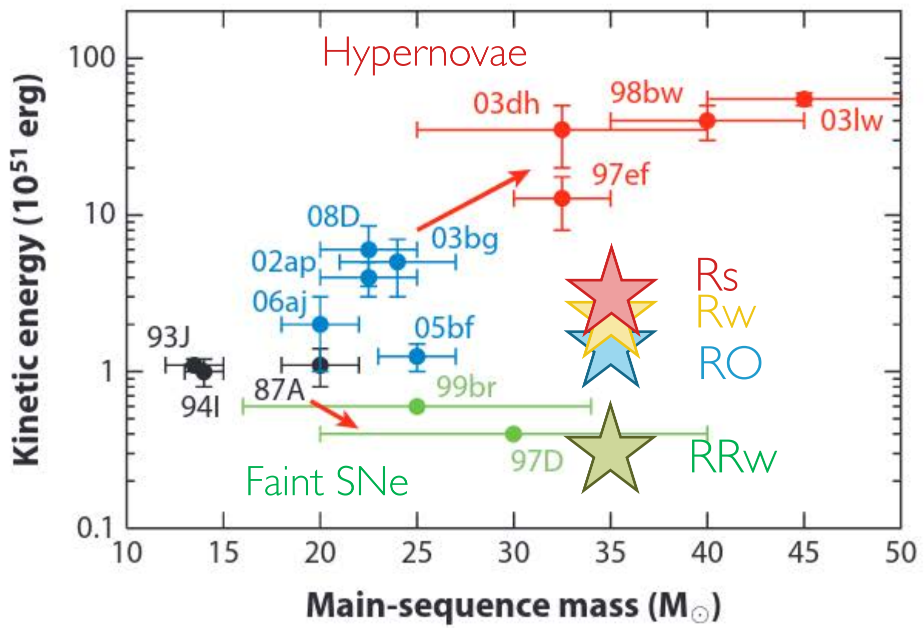


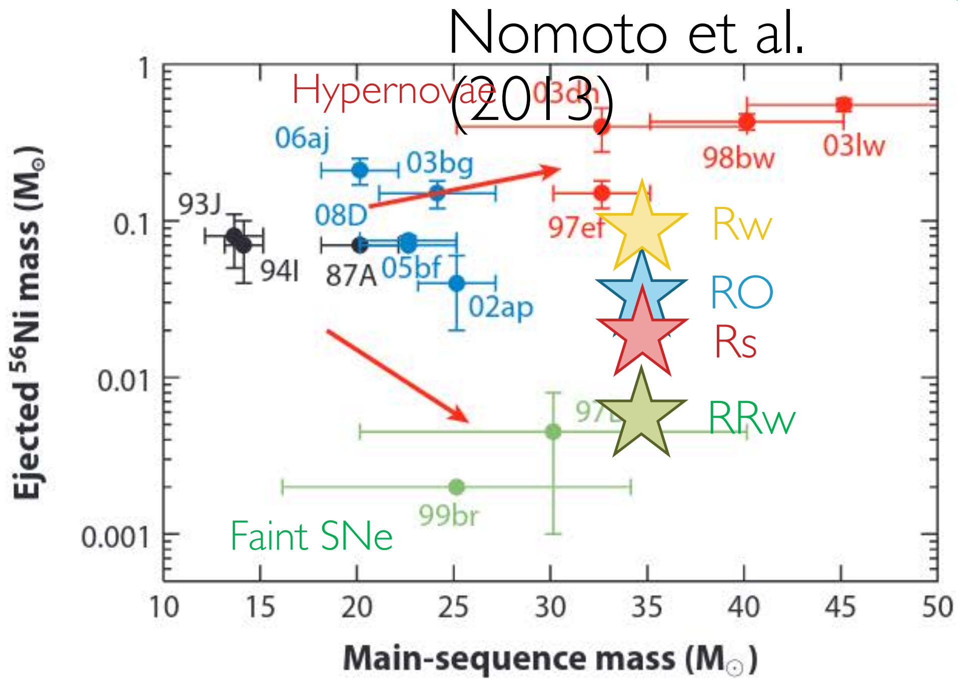
with magnetic field strength?

Reichert et al. 2021a

Long time simulations are crucial to catch all relevant nucleosynthetic features! (see also Aloy & Obergaulinger 2021)

Comparison to observations: ^{56}Ni

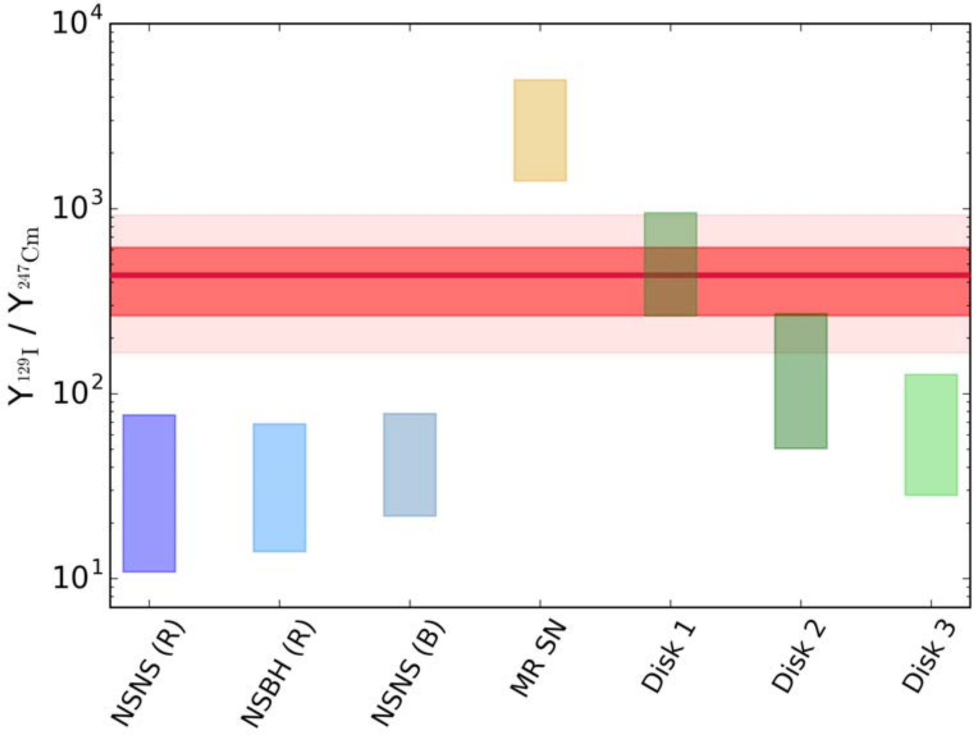




	35OC-RO	35OC-Rw	35OC-Rs	35OC-RRw
Energy (erg)	1.78×10^{51}	2.80×10^{51}	4.16×10^{51}	0.21×10^{51}
^{56}Ni	4.73×10^{-2}	1.21×10^{-1}	2.54×10^{-2}	7.32×10^{-3}

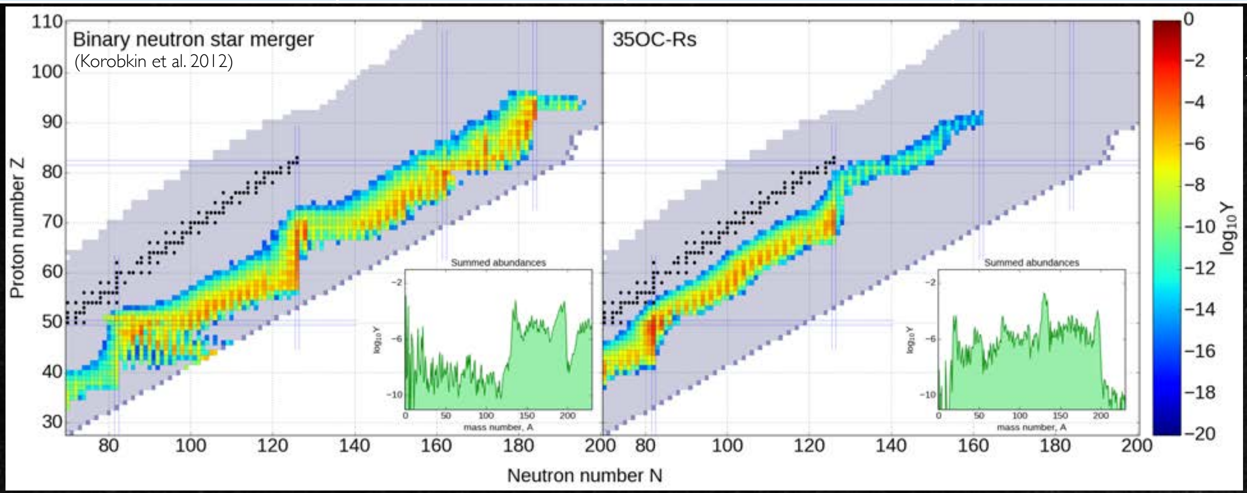
Not energetic enough, but explosion energy still not saturated
(see Obergaulinger & Aloy 2017,2020)

Comparison to observations: ^{129}I and ^{247}Cm



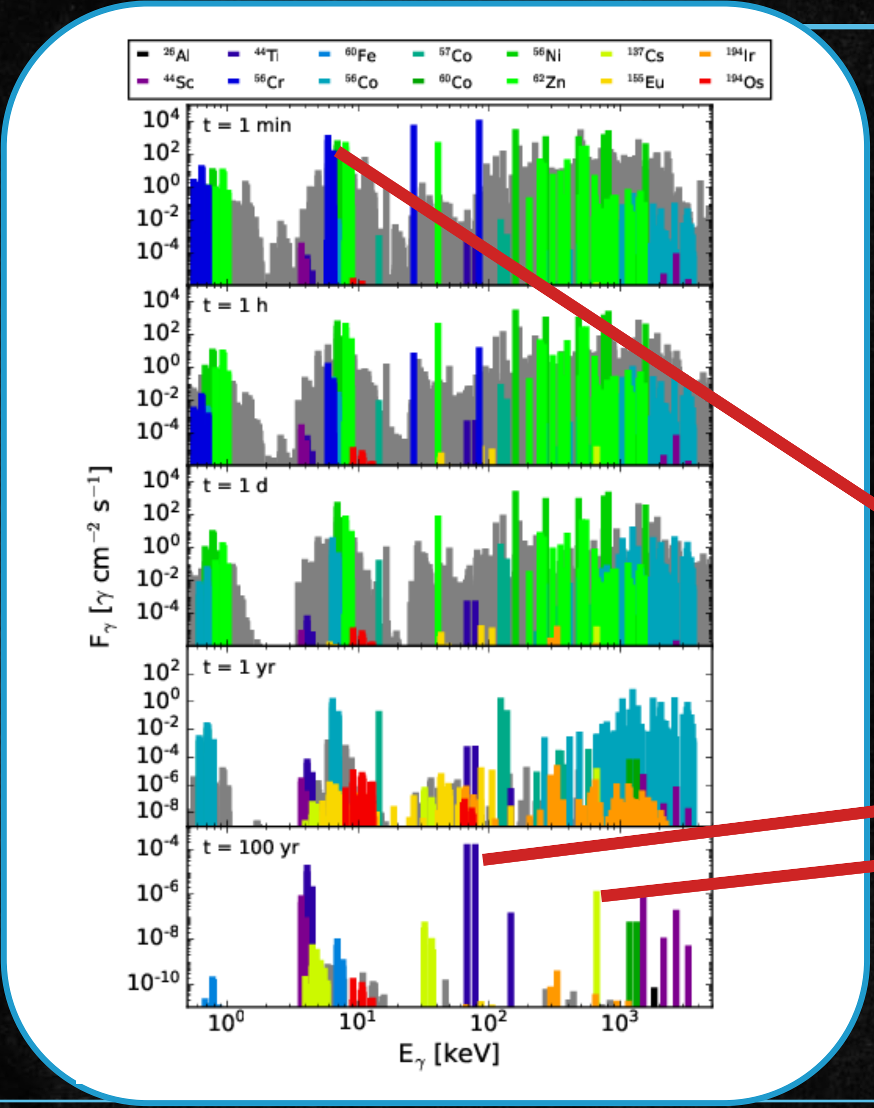
Model 35OC-Rs
(Strong magnetic field)

	FRDM	FRDM (D3C*)	Duflo-Zuker
Y(^{129}I)	6.93×10^{-4}	5.59×10^{-4}	2.43×10^{-4}
Y(^{247}Cm)	2.30×10^{-12}	9.63×10^{-10}	4.79×10^{-15}
Y(^{129}I)/Y(^{247}Cm)	5.77×10^{8}	1.11×10^{7}	9.71×10^{10}



2010

Comparison to observations: Gamma-rays

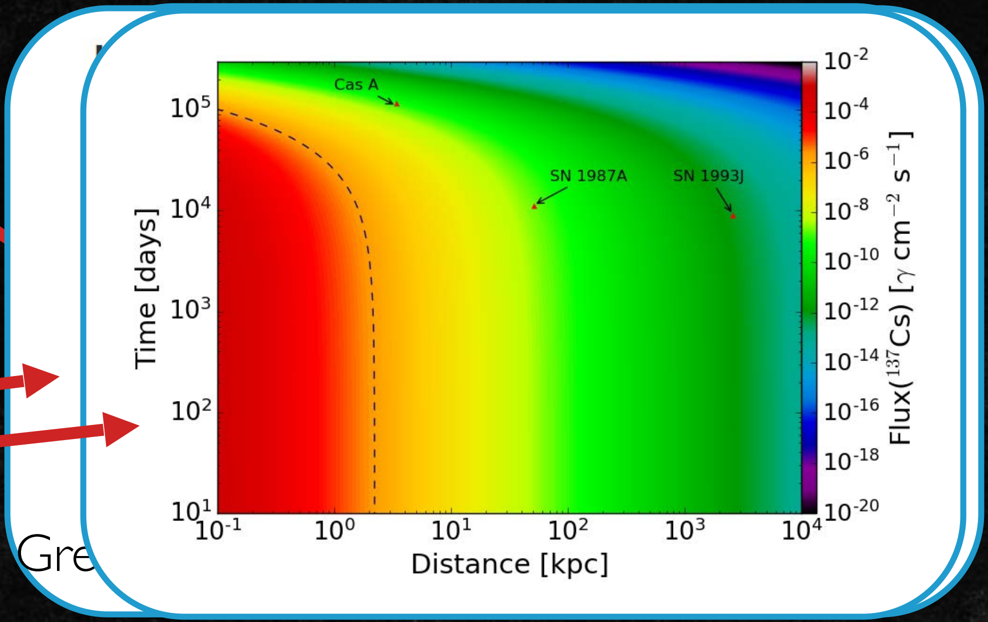


$$F_\gamma = \frac{N_A}{4\pi d^2}\frac{M_x}{A}\frac{I_\gamma}{\bar{\tau}}$$

e.g., Qian et al. (1998)

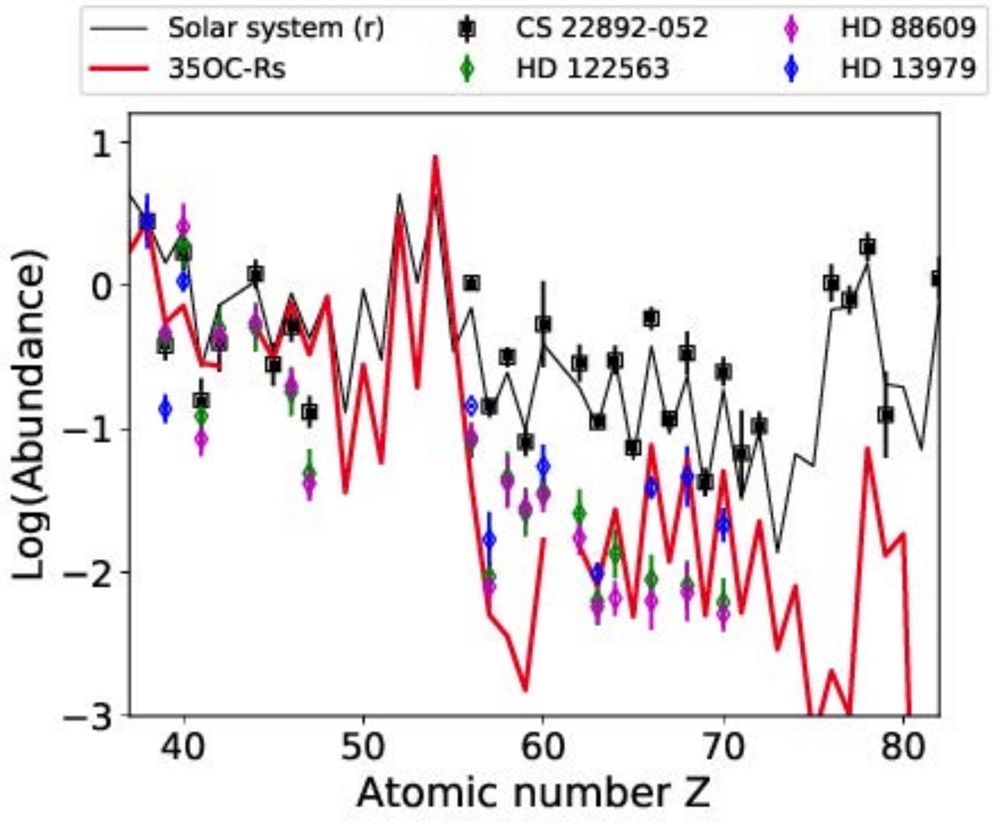
GRB 060904B

SN 1987A



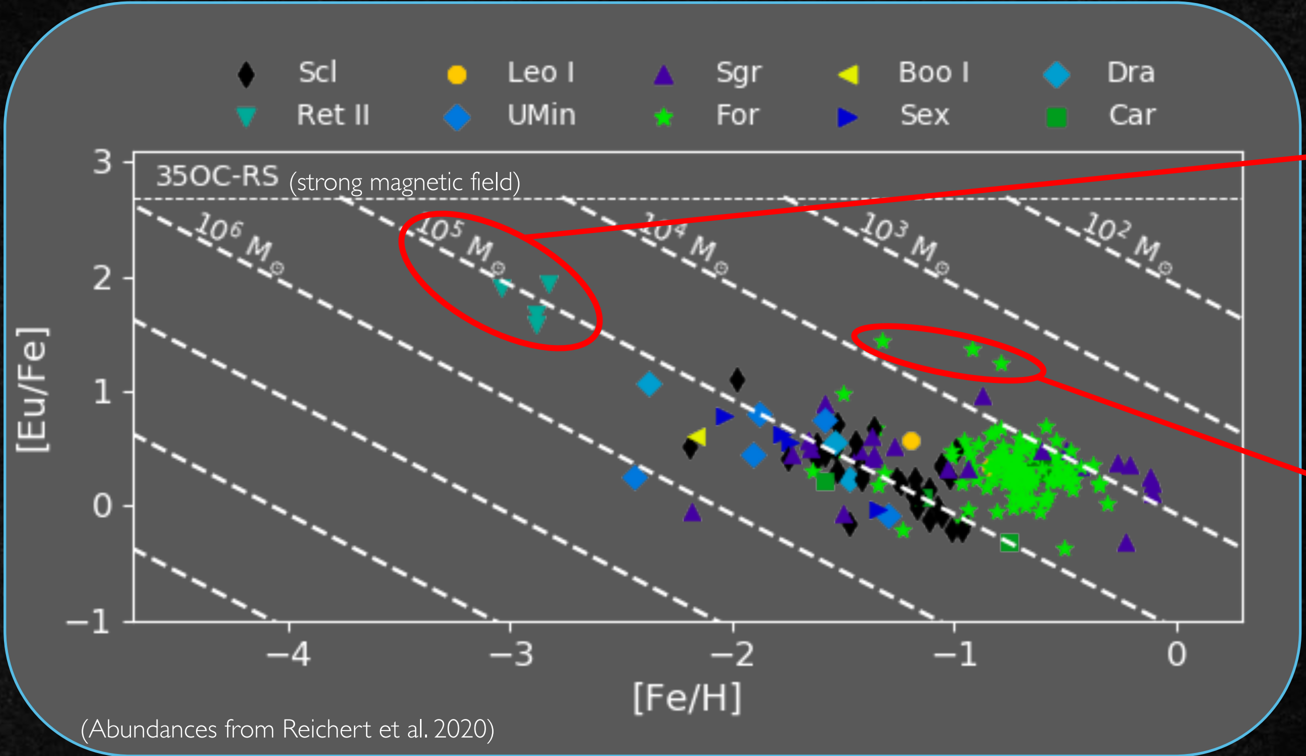
See also Qian & Wasserburg (1998), Ripley et al. (2014), Korobkin et al. (2020)

Comparison to observations: Abundances



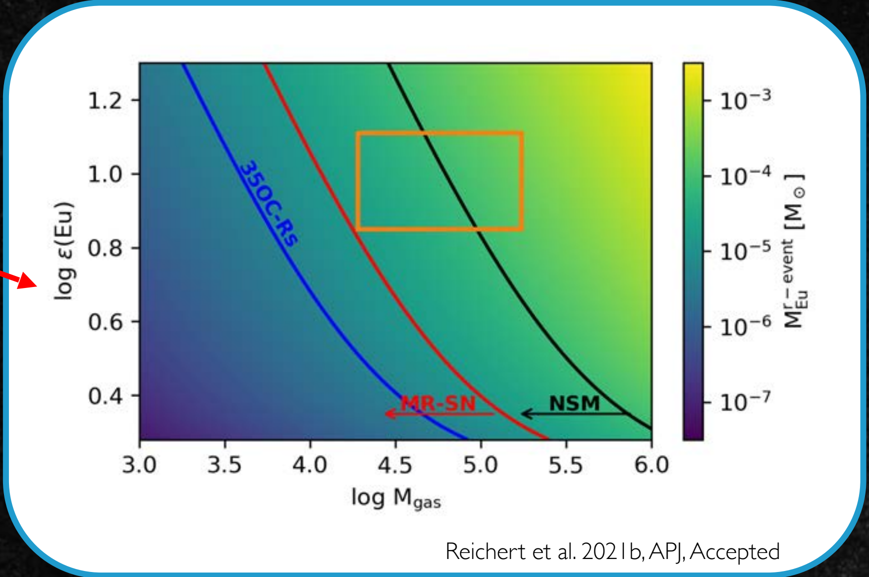
- Normalized to Sr
- Honda star kind of pattern
- Slightly shifted third r-process peak

Comparison to observations: Ejected Eu mass



$M(Eu)_{35OC\text{-}Rs} \sim 5 * 10^{-6} M_\odot$

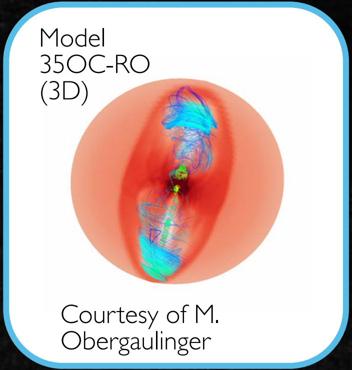
Mass of Ret II $\sim 2.4 * 10^5 M_\odot$
(Beniamini et al. 2016)

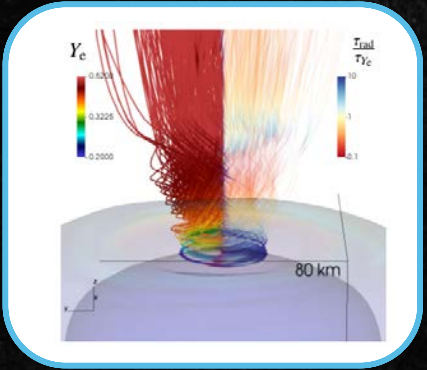


Summary

- First nucleosynthesis study with sophisticated neutrino transport
- Large variety of nucleosynthetic conditions
- Strong magnetic fields are still able to host the r-process
- Long time simulations extremely important
- Observables, isotopic ratios, gamma rays, abundances in stars

Future perspectives:





35OC-Rs (3D)
Obergaulinger & Aloy 2021

Thank you for your attention!