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Compact Stars and Gravitational Waves
Yukawa Institute for Theoretical Physics, Kyoto Univ., Oct. 31–Nov. 4, 2016

Where do the r-process Elements Come From?

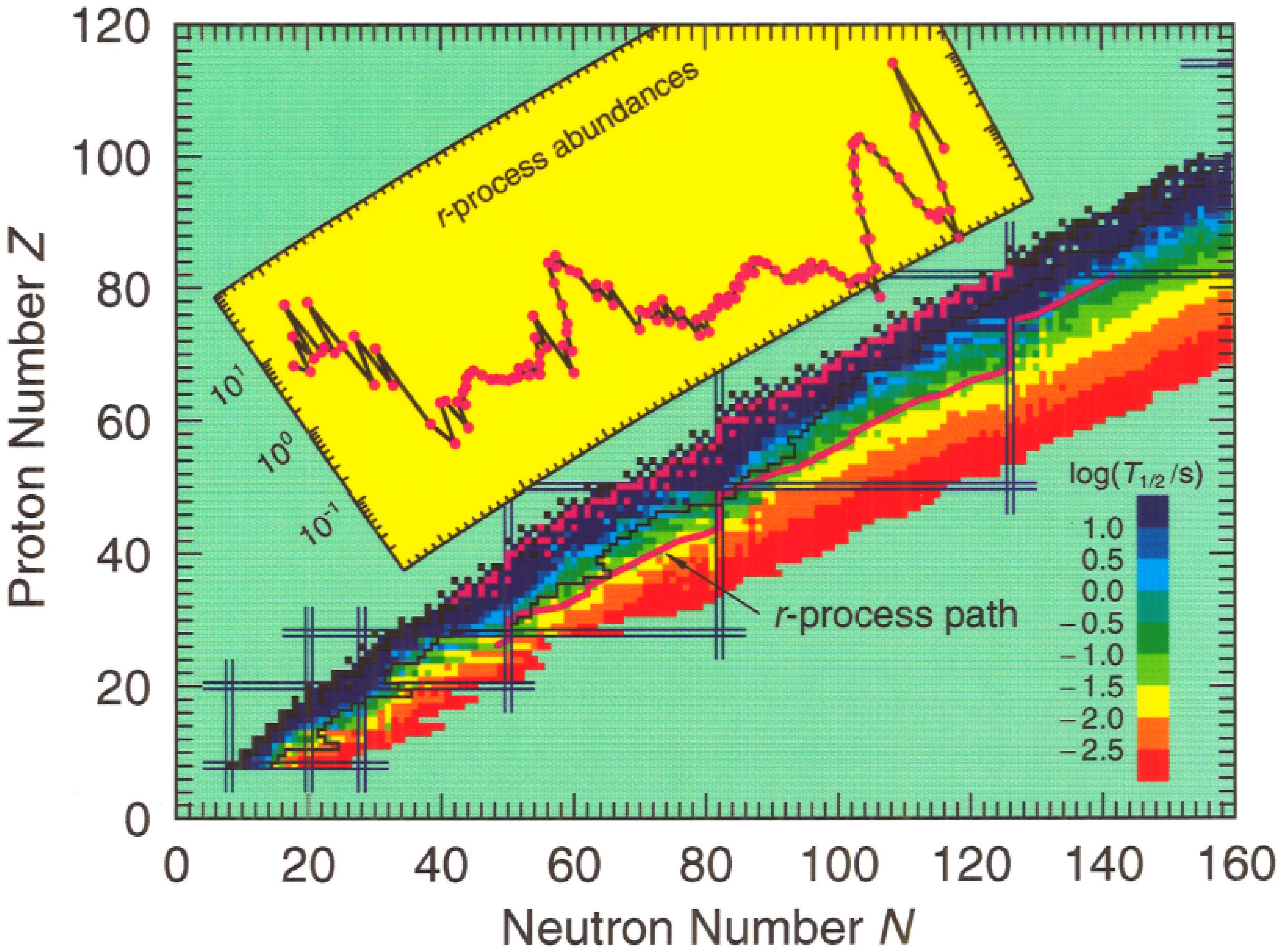
Astrophysical Source Models and Implications

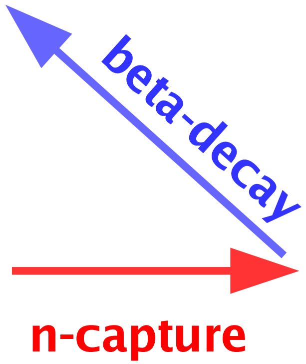
Hans-Thomas Janka
Max Planck Institute for Astrophysics, Garching

Outline

- Introduction: The r-process riddle
- Supernovae as candidate sites of r-processing
- Neutron star mergers as likely sites of r-process production
- Theoretical caveats and observational constraints

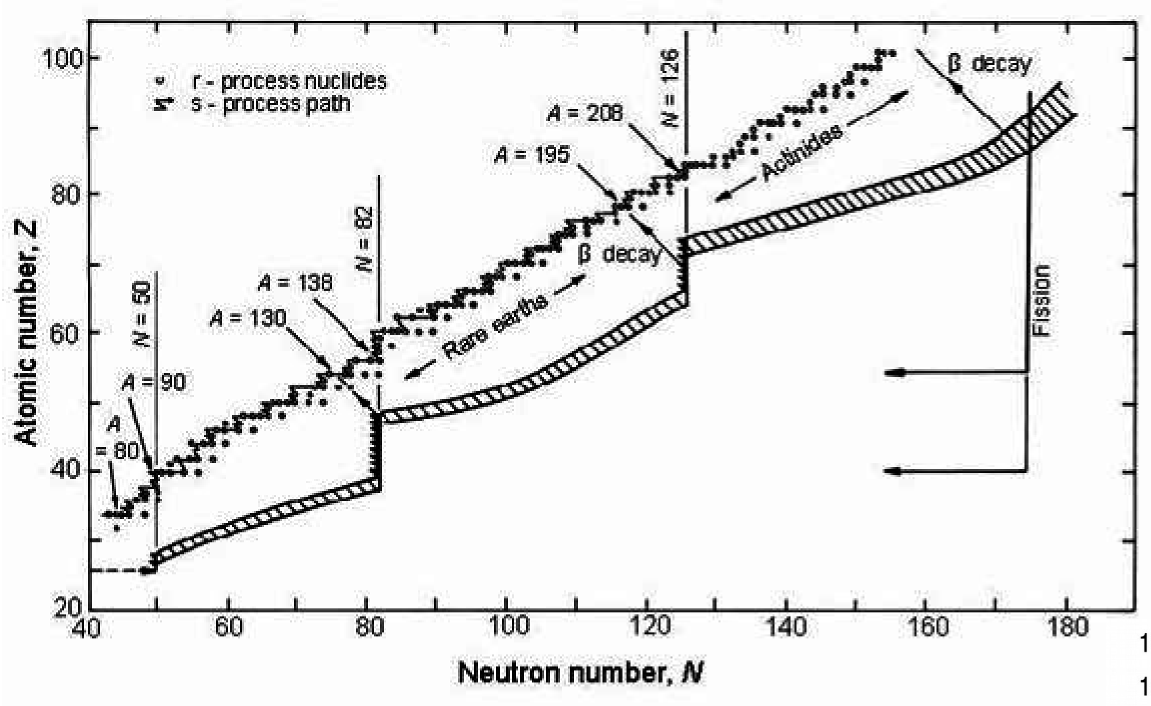
s- and r-Process Nucleosynthesis





Courtesy: K.-L. Kratz

s- and r-process Nucleosynthesis



Astrophysical site(s) of r-process are still unknown;

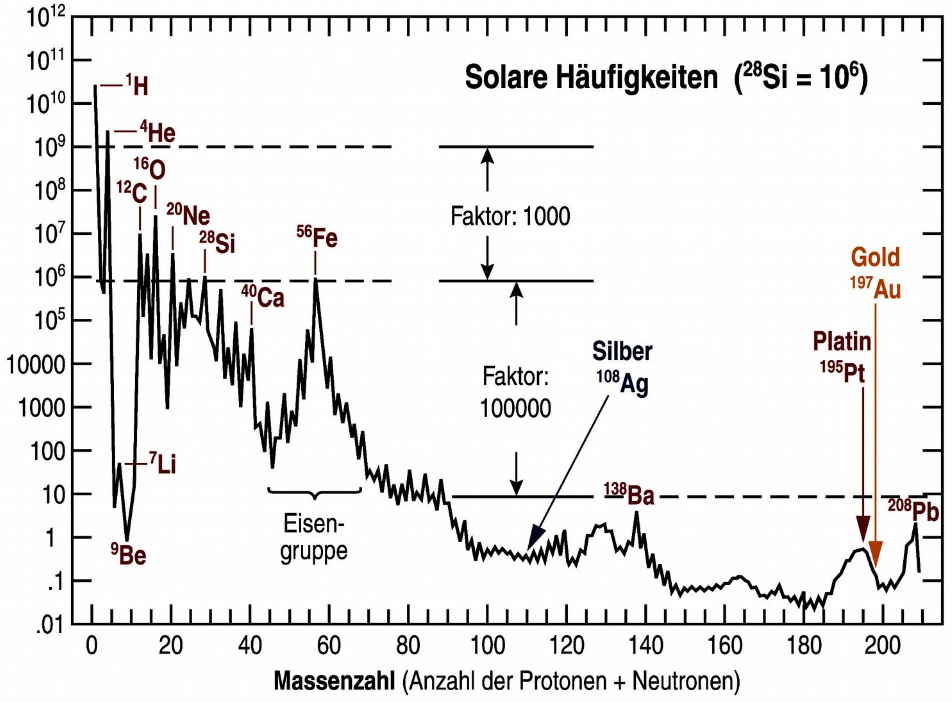
One of greatest mysteries of nuclear astrophysics.

Rapid neutron-capture process (r-process) is responsible for production of ~50% of n-rich nuclei heavier than iron.

n-capture timescale << beta-decay timescale

→ **high n-densities needed (> 10^{25} cm^{-3})**

→ **explosive events**



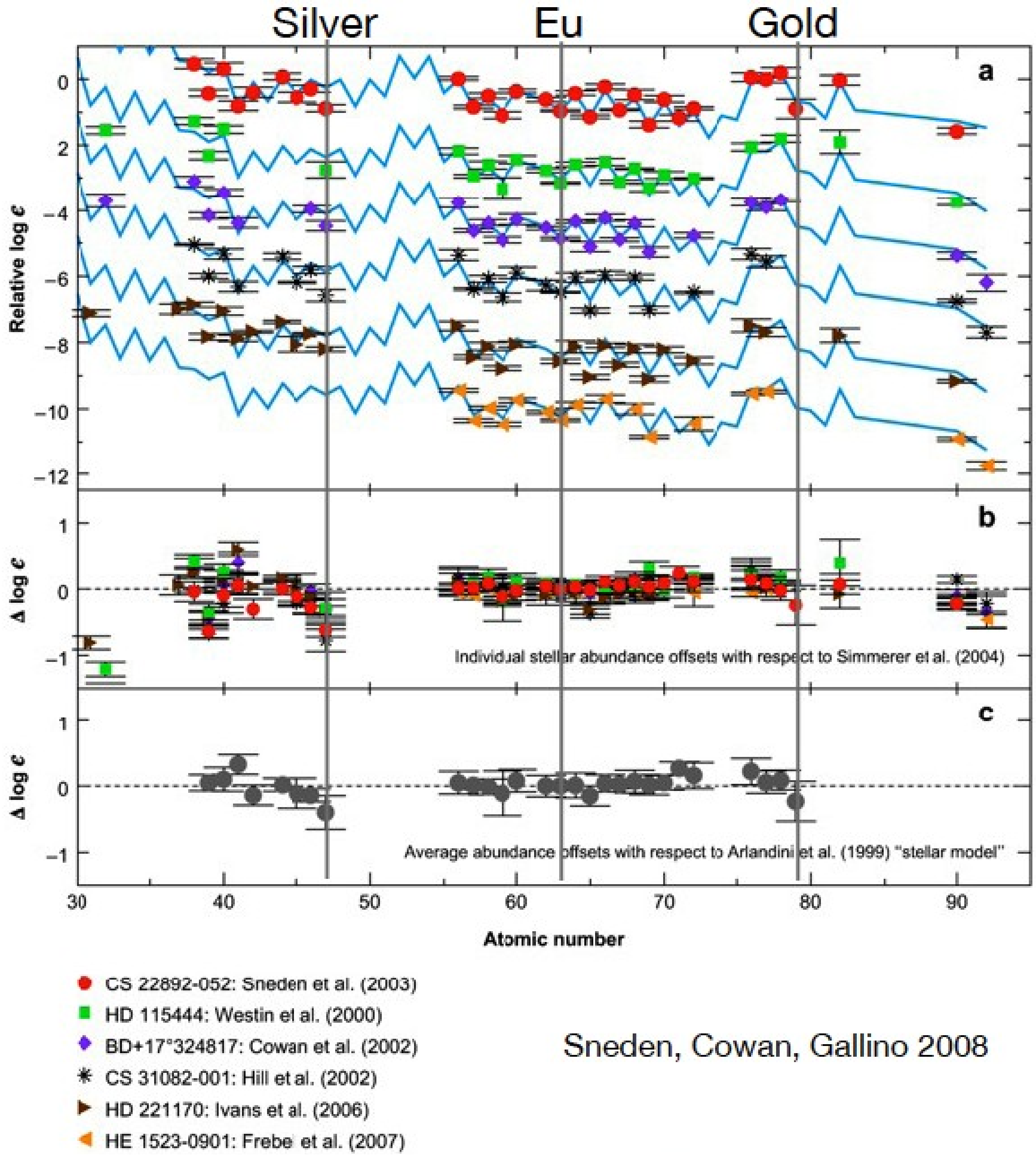
r-Process Elements in Ultra Metal-poor Stars

Elemental r-process abundances in ultra metal-poor (UMP) stars compared to solar distribution

Uniform pattern for 56 < Z < 83

Larger scatter for Z < 50

UMP stars with elemental abundances only up to Ag are observed.



Sneden, Cowan, Gallino 2008

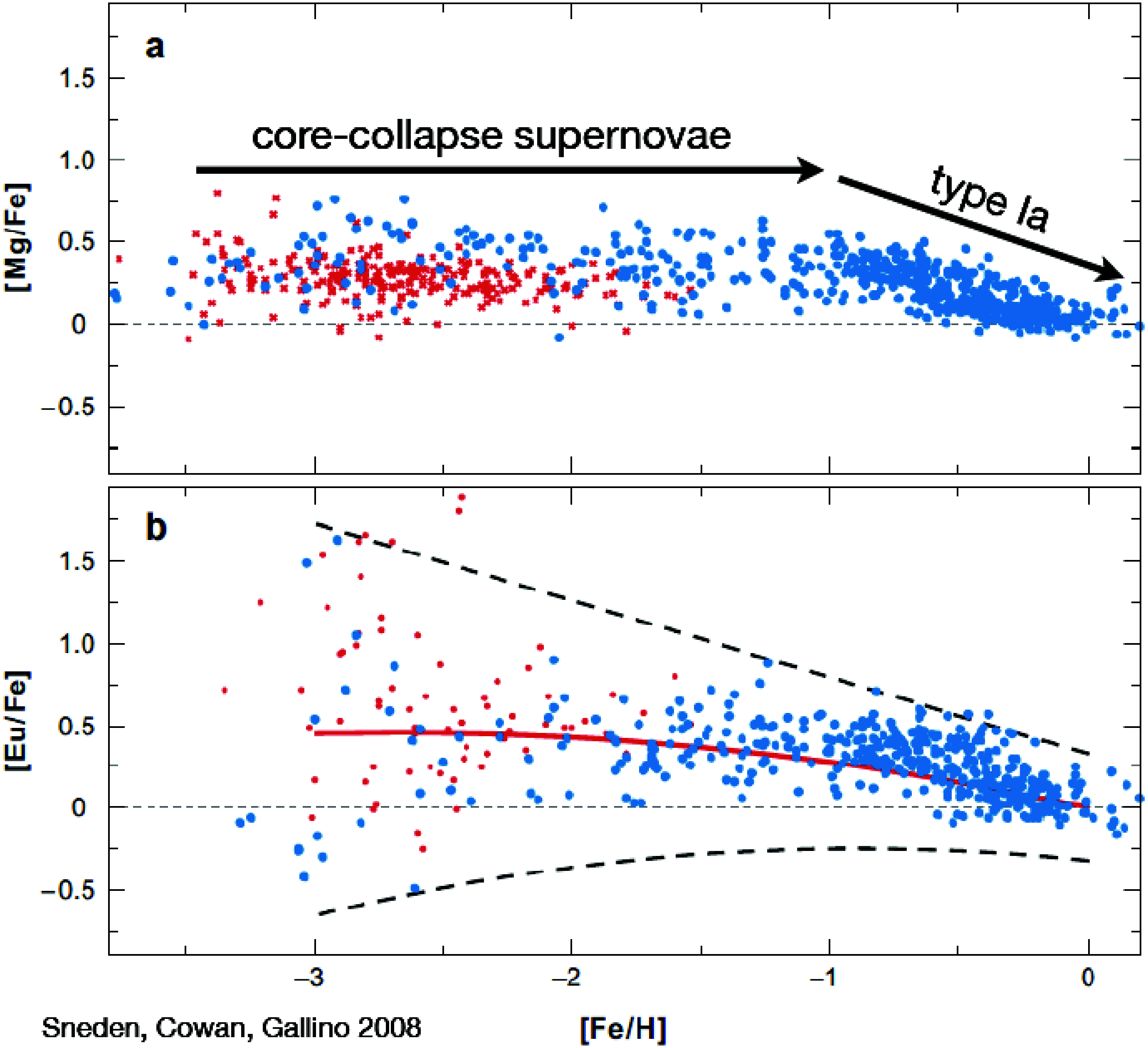
Metallicity Evolution of r-element Enrichment

Fe and Mg produced in same site: core-collapse supernovae

Significant [Eu/Fe] scatter at low metallicities [Fe/H]

r-process production is rare in early galaxy

Mg and Fe production is not tightly coupled to r-process production



Sneden, Cowan, Gallino 2008

r-process Sources: Basic Questions

- Physical conditions of the ejecta <——>

  Source of "weak" or "strong" r-process?
  Can solar r-abundances be produced "robustly"?

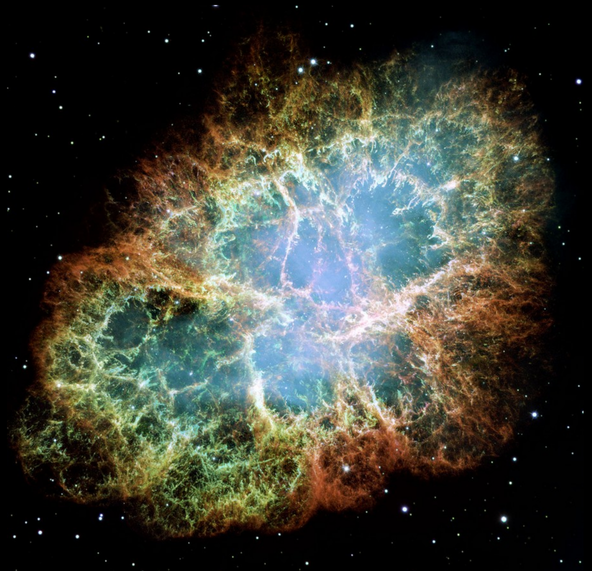
- Ejecta mass and frequency of source <——>

  Main source or sub-dominant contributor?

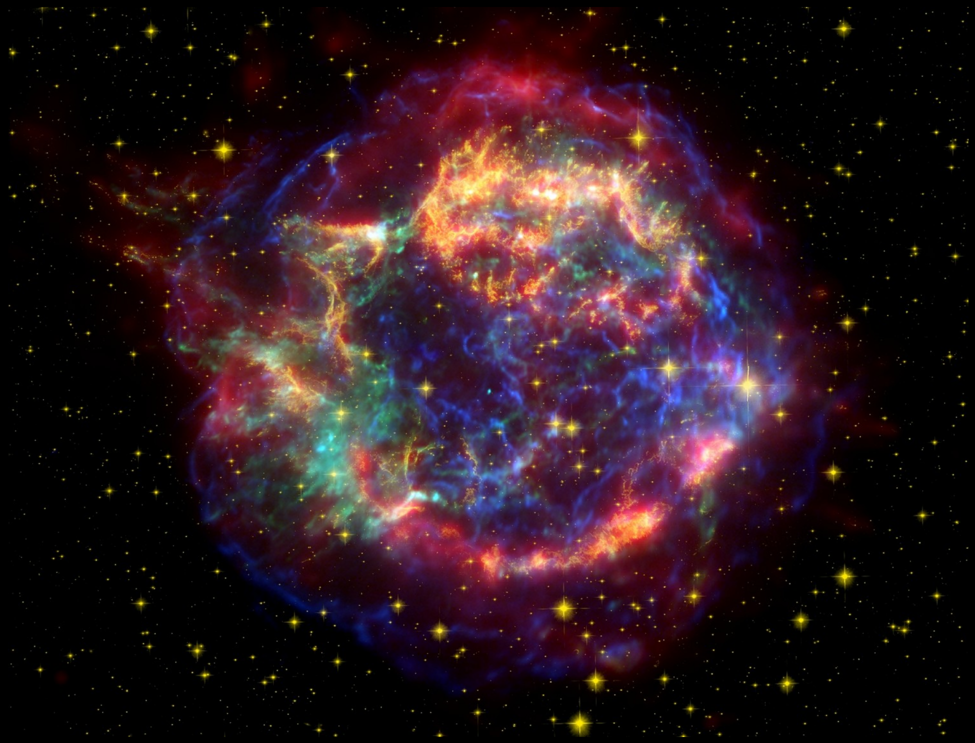
- Element enrichment history of Galaxy <——>

  Can one astrophysical source explain all observations?

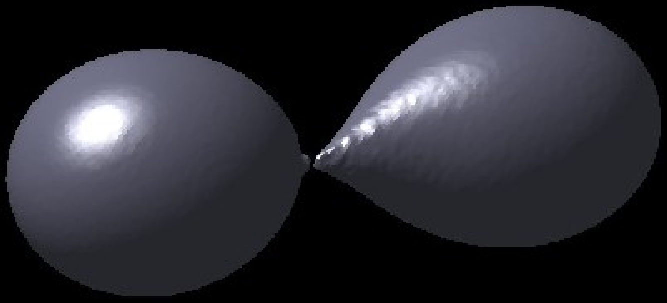
Explosive Origins of Heavy Elements



Supernova 1054



Supernova ~1680



Neutron Star Merger

Supernovae as Potential Site of r-process Element Production

r-process Scenarios in Supernovae

- Dynamical ejecta of prompt explosions (of O-Ne-Mg cores)
  (Hillebrandt, Takahashi & Kodama 1976; Wheeler, Cowan & Hillebrandt 1998; Wanajo 2002)
- C+O layer of O-Ne-Mg-core ("electron-capture") supernovae
  (Ning, Qian & Meyer 2007)
- He-shell exposed to intense neutrino flux
  (Epstein, Colgate, & Haxton 1988; Banerjee et al. 2011)
- Re-ejection of fallback material in SNe
  (Fryer et al. 2006)

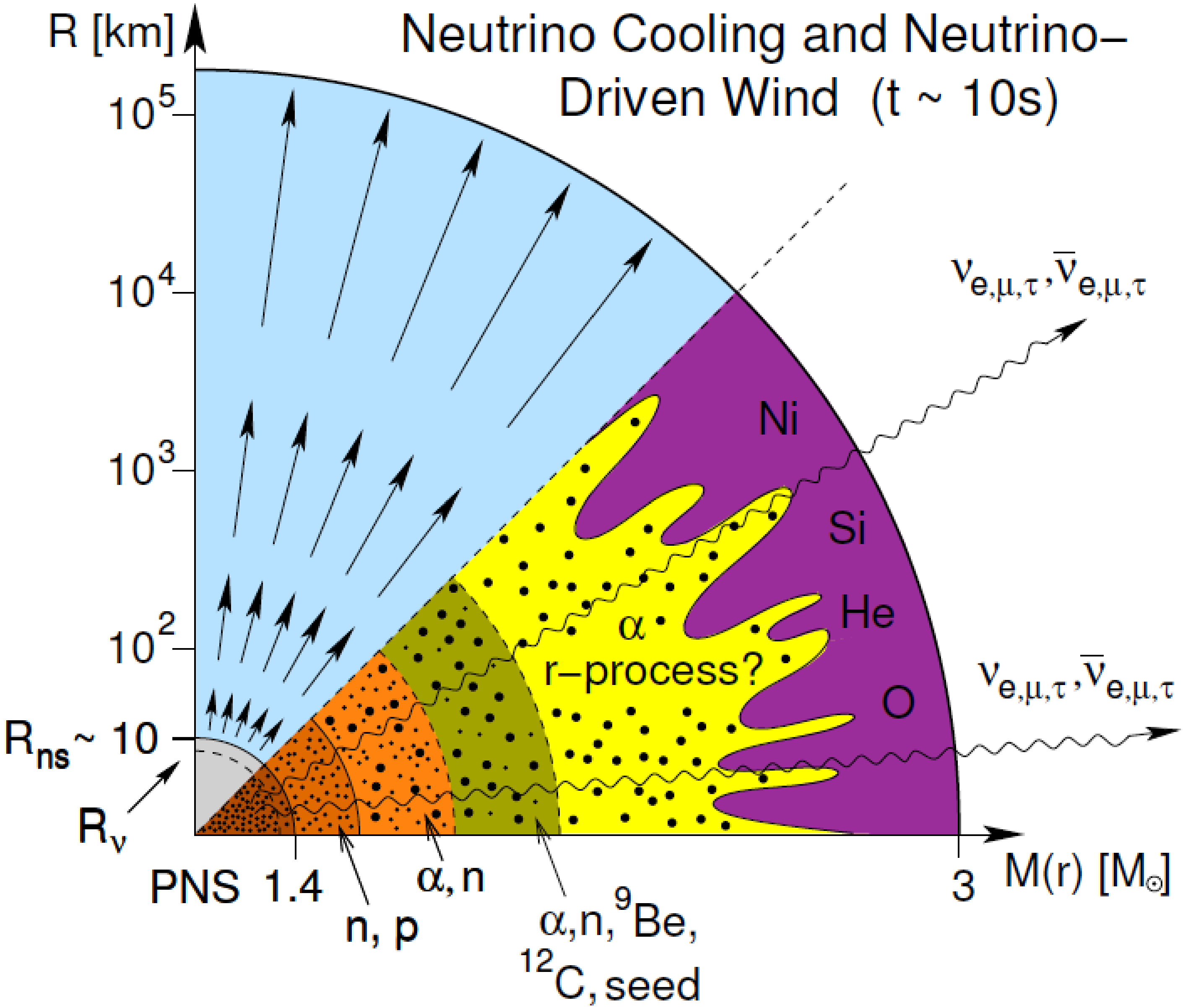
- Neutrino-driven wind from proto-neutron stars
  (Woosley et al. 1994, Takahashi et al. 2014)
- Magnetohydrodynamic jets of rare core-collapse SNe
  (Winteler et al. 2013, Nishimura et al.)

- Some more...?

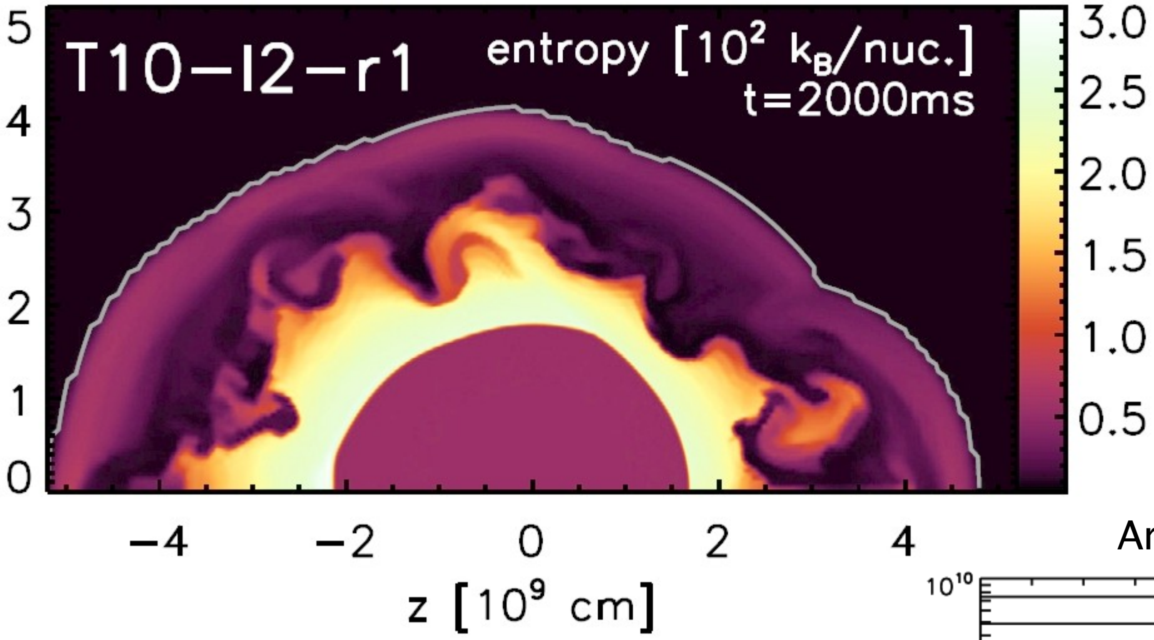
All of these suggested scenarios have severe problems

Nevertheless,
SNe *cannot* be excluded
as sites of heavy r-processing
on grounds of theoretical models!

Neutrino-Driven Wind from Proto-neutron Stars

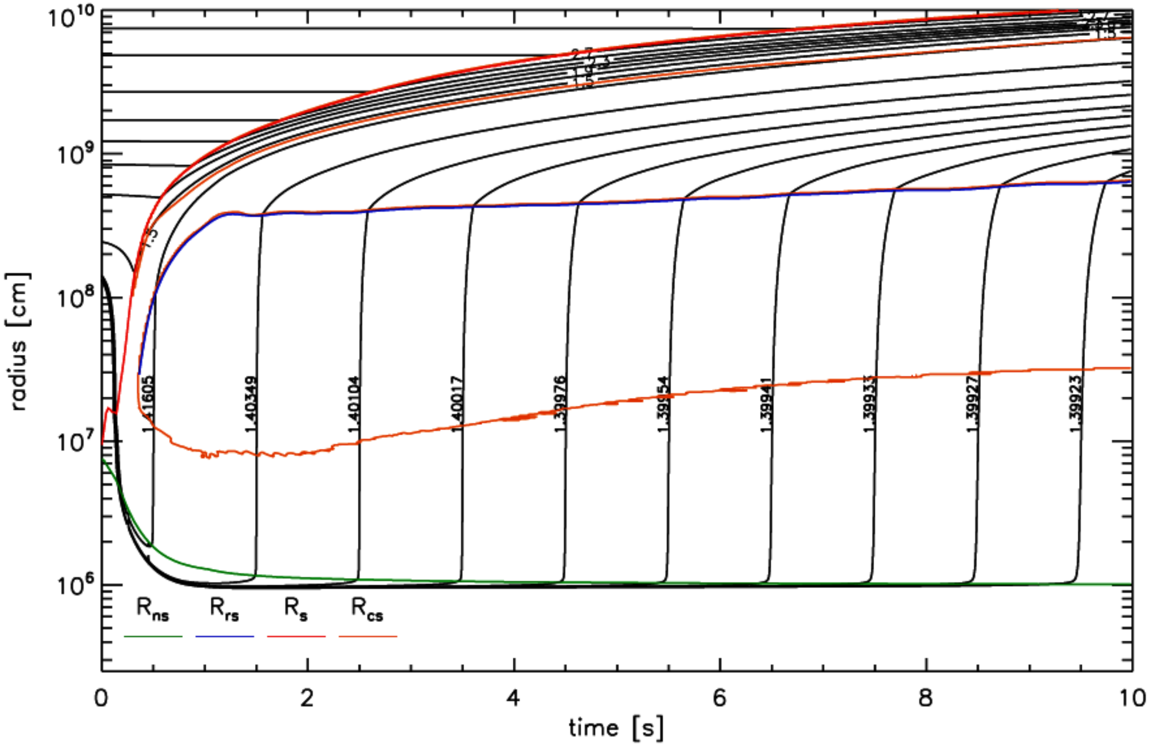


Neutrino-Driven Wind from Proto-neutron Stars



Arcones & Janka, (A&A 526 (2011) A160)

Arcones, Janka, & Scheck (A&A 467 (2007) 1227)



Nucleosynthesis in Neutrino-heated Ejecta

Crucial parameters for nucleosynthesis in neutrino-driven outflows:

* Electron-to-baryon ratio Y_e (<---> neutron excess)
* Entropy (<----> ratio of (temperature)^3 to density)
* Expansion timescale

Determined by the interaction of stellar gas with neutrinos from nascent neutron star:

$$\begin{aligned} \nu_e + n &\to e^- + p \\ \bar{\nu}_e + p &\to e^+ + n \end{aligned}$$

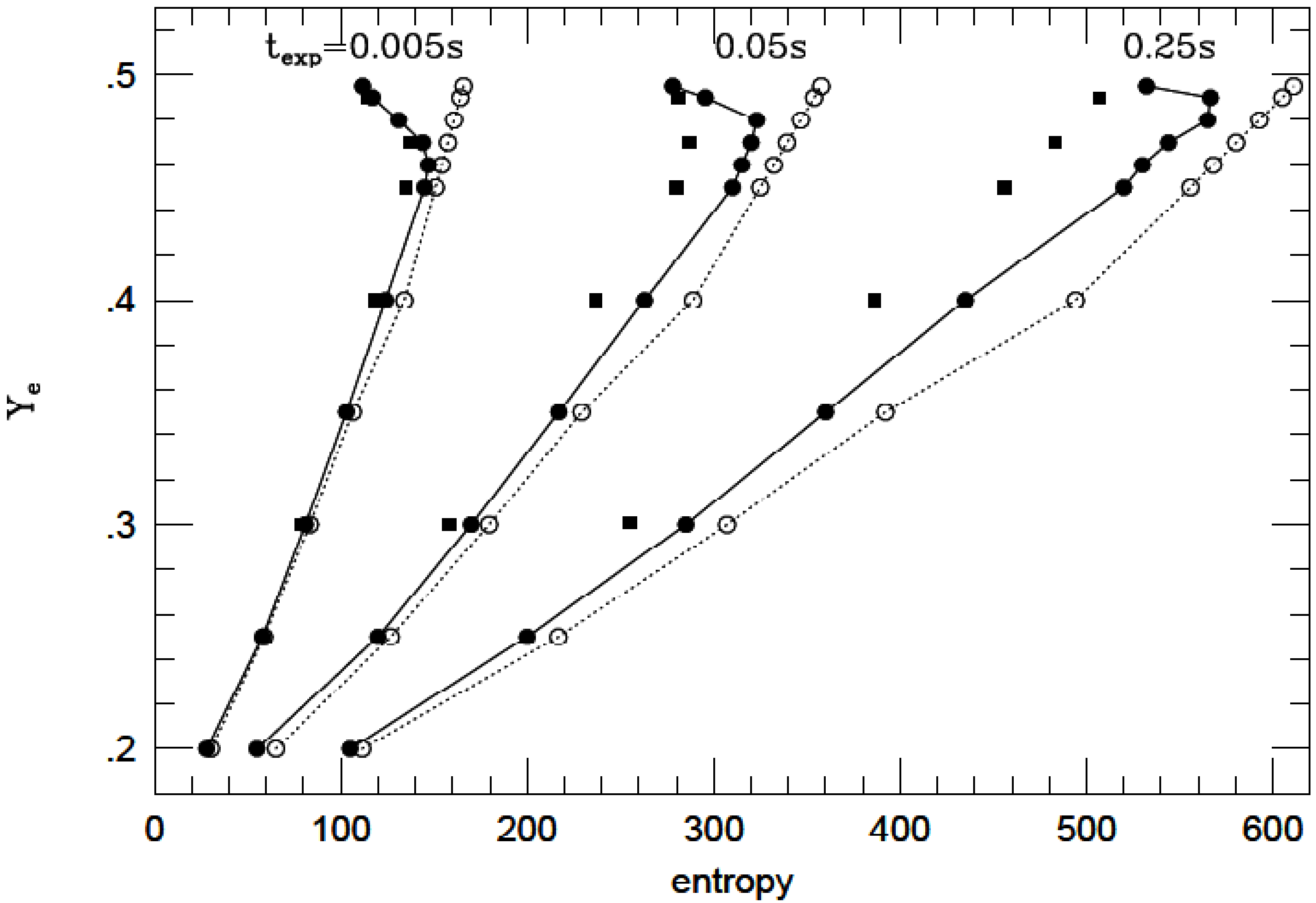
$$\boxed{Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta)}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta)}\right]^{-1}}$$

with $\epsilon_\nu = \dfrac{\langle\epsilon_\nu^2\rangle}{\langle\epsilon_\nu\rangle}$ and $\Delta = (m_n - m_p)c^2 \approx 1.29\,\mathrm{MeV}$.

If $L_{\bar{\nu}_e} \approx L_{\nu_e}$, one needs for $Y_e < 0.5$ (i.e. neutron excess):

$$\boxed{\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} > 4\Delta.}$$

Requirements for Strong r-process Including Third Abundance Peak



(Hoffman, Woosley & Qian 1997)

(similar:
Ohnishi et al. 1999, Thompson et al. 2001)

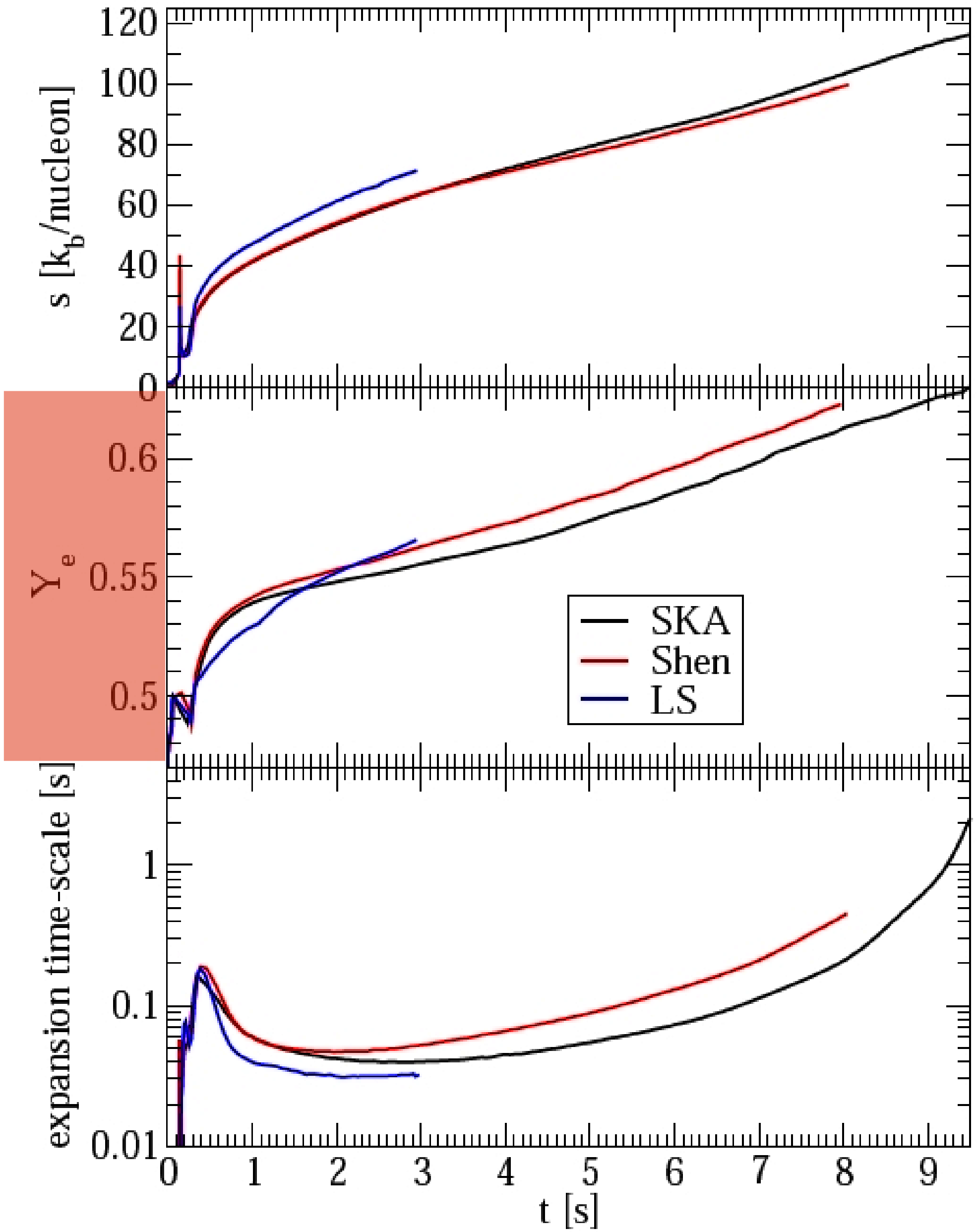
FIG. 10.—The combinations of Y_e, entropy, and expansion time required for the production of the $A \sim 195$ *r*-process peak nuclei. Circles connected by lines are for various fixed expansion times. Shown are the values derived in the numerical study using equation (7) (*filled circles*) and those from the analytic approximation (eqs. [20a] and [20b], *open circles*). The filled squares represent results from the numerical survey that used an exact adiabatic equation of state.

Nucleosynthesis in O-Ne-Mg Core Winds

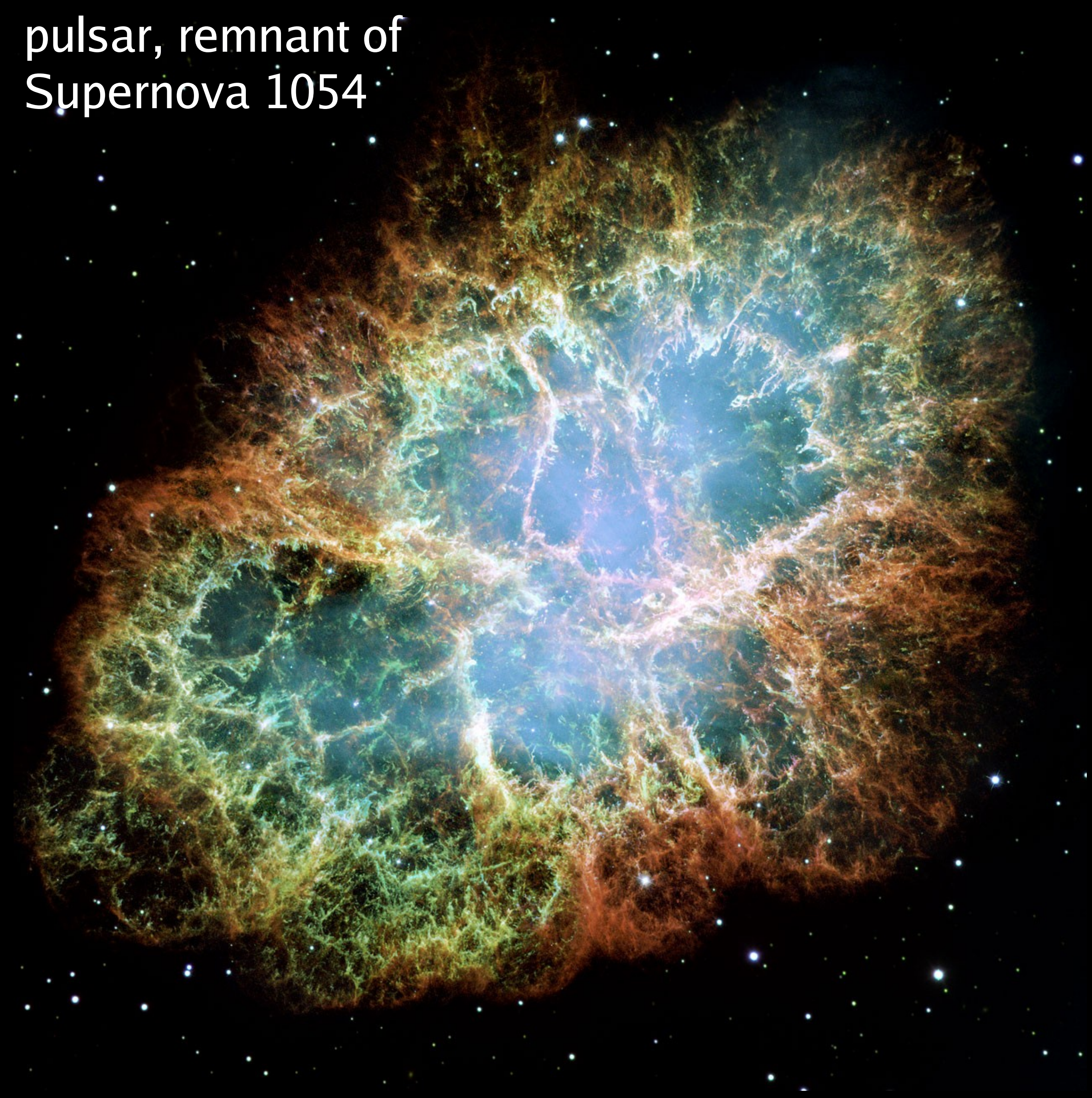
- Neutrino-driven wind remains p-rich for >10 seconds!
- No r-process in the late neutrino-driven wind!
- Holds also for more massive progenitos

Hüdepohl (Diploma Thesis 2009)
Hüdepohl et al. (PRL 104 (2010)
Fischer et al. (2010)
Roberts & Woosley (2010)
Roberts et al. (2012, 2013)
Fischer et al. (2013)
Martinez-Pinedo et al. (2014)
Mirizzi, Tamborra, THJ et al. (2016)

No favorable conditions for a strong r-process in ONeMg-core explosions and neutrino-driven winds of PNSs!



Hüdepohl (Diploma Thesis 2009)



CRAB Nebula with pulsar, remnant of Supernova 1054

Explosion properties:

E_{exp} ~ 10^{50} erg = 0.1 bethe
M_{Ni} ~ 0.003 M_{sun}

Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with CRAB (SN1054)

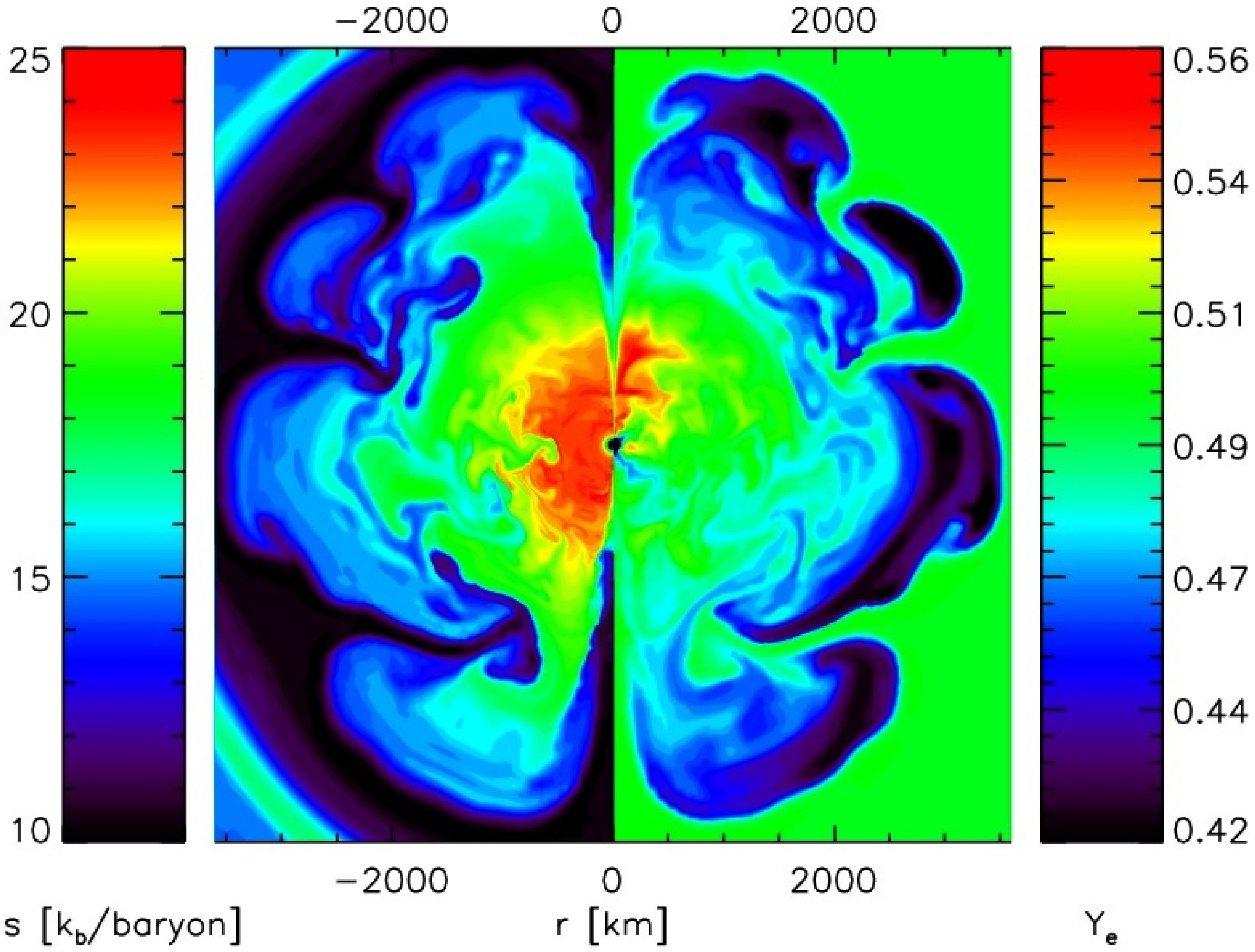
(Nomoto et al., Nature, 1982;
Hillebrandt, A&A, 1982)

Might also explain other low-luminosity supernovae (e.g. SN1997D, 2008S, 2008HA)

2D SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

Convection causes explosion asymmetries, leads to slight increase of explosion energy, and the ejection of n-rich matter!

Entropy



Y_e

(Wanajo, THJ, Müller, ApJL 726, (2011) L15)

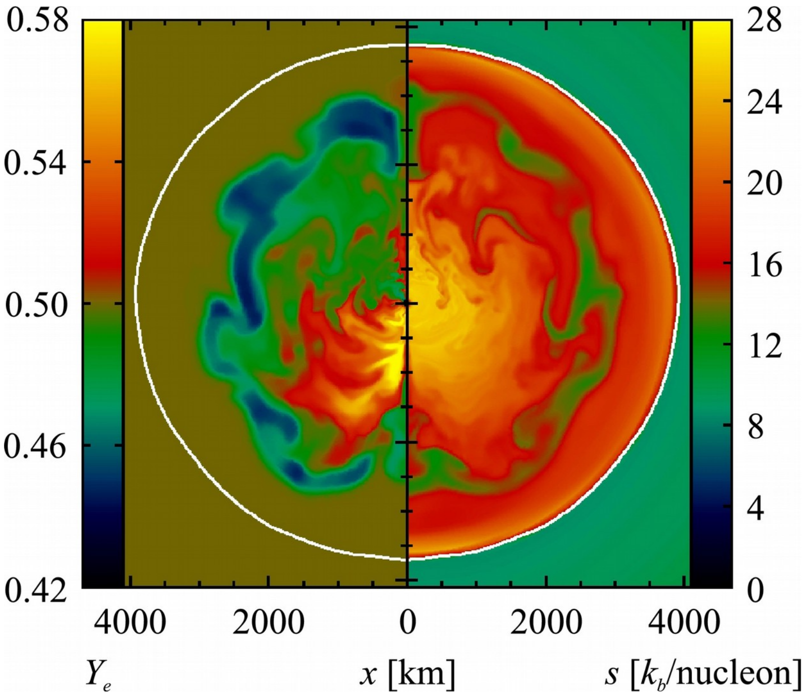
t = 0.262 s after core bounce

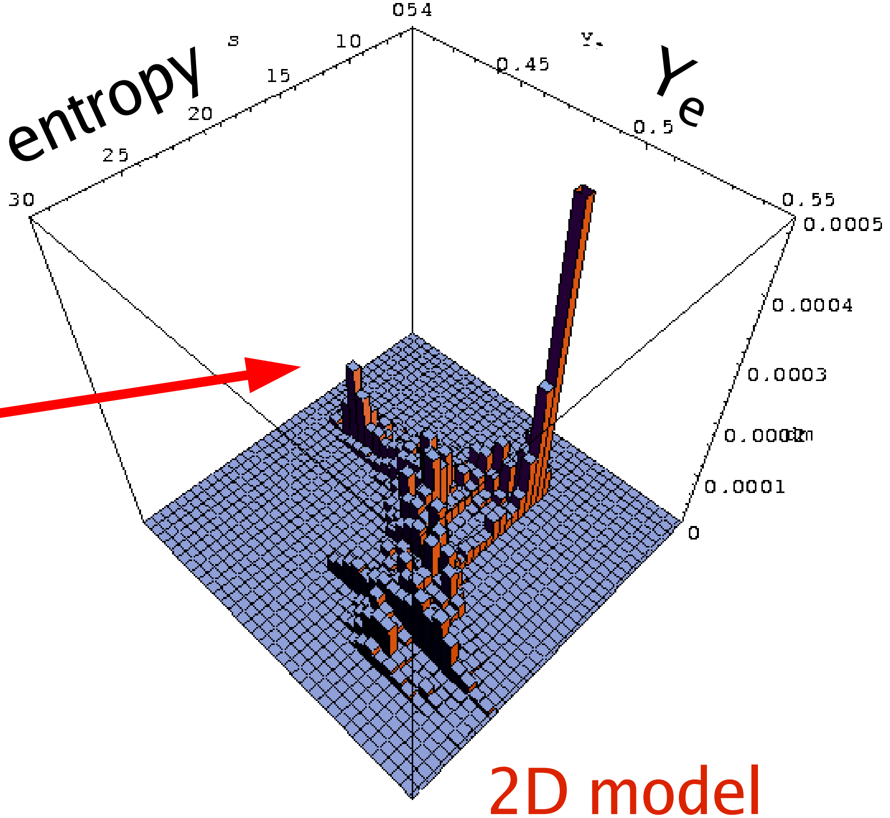
Nucleosynthesis in Neutrino-heated SN Ejecta

Convectively ejected n-rich matter makes ONeMg-core and low-mass Fe-core supernovae an interesting source of nuclei between the iron group and N = 50 (from Zn to Zr), possibly also of weak r-process nuclei.

(Wanajo, THJ, Müller, ApJL 726, (2011) L15)

9.6 M_{sun} (z=0) Fe core SN

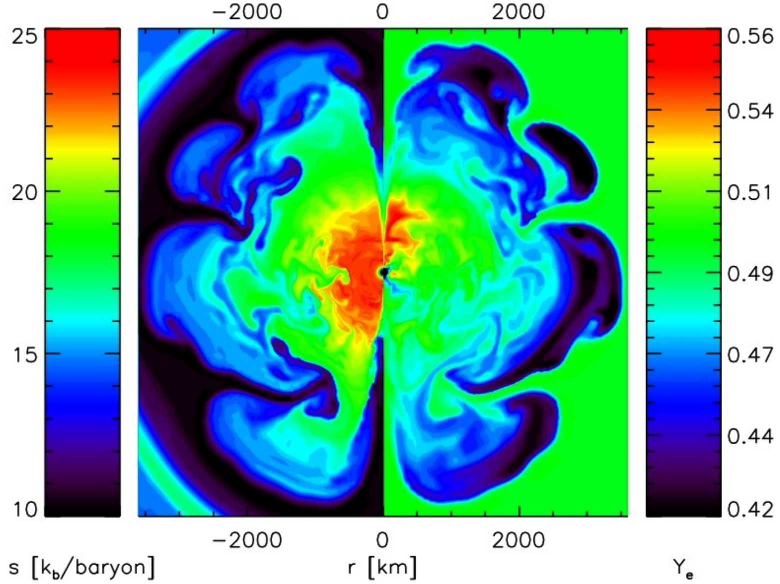




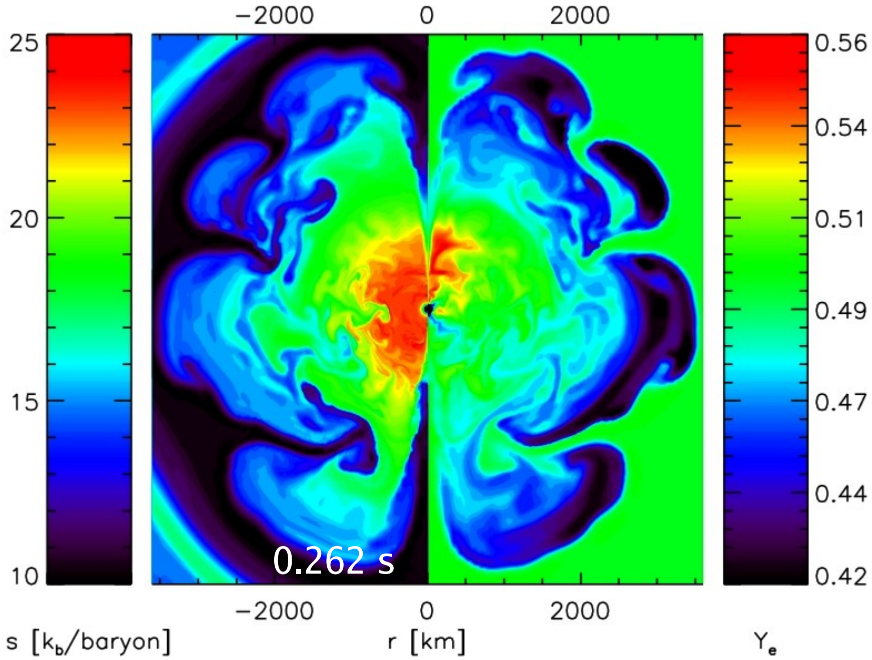
n-rich matter

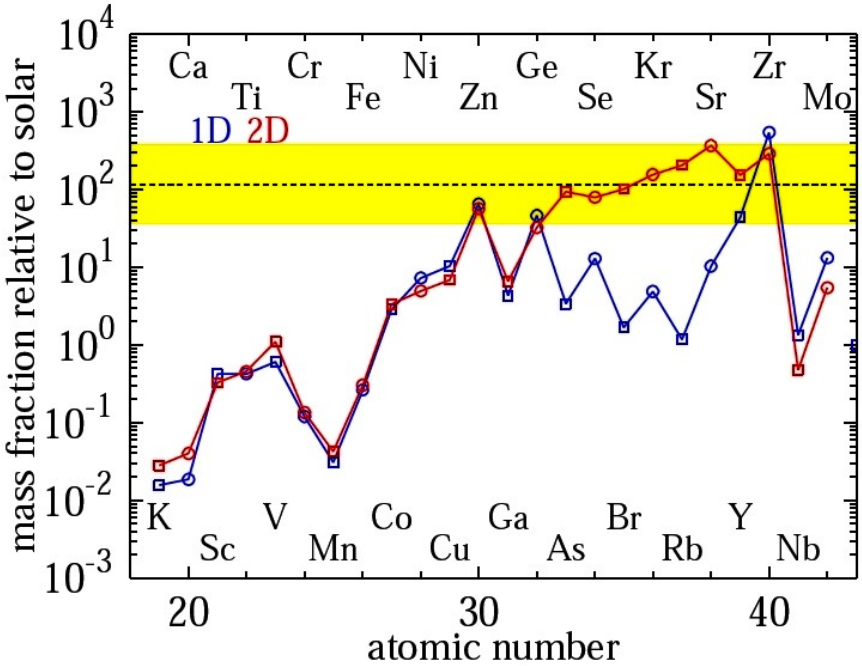
2D model

8.8 M_{sun} O-Ne-Mg core SN



Nucleosynthesis in O-Ne-Mg Core SNe

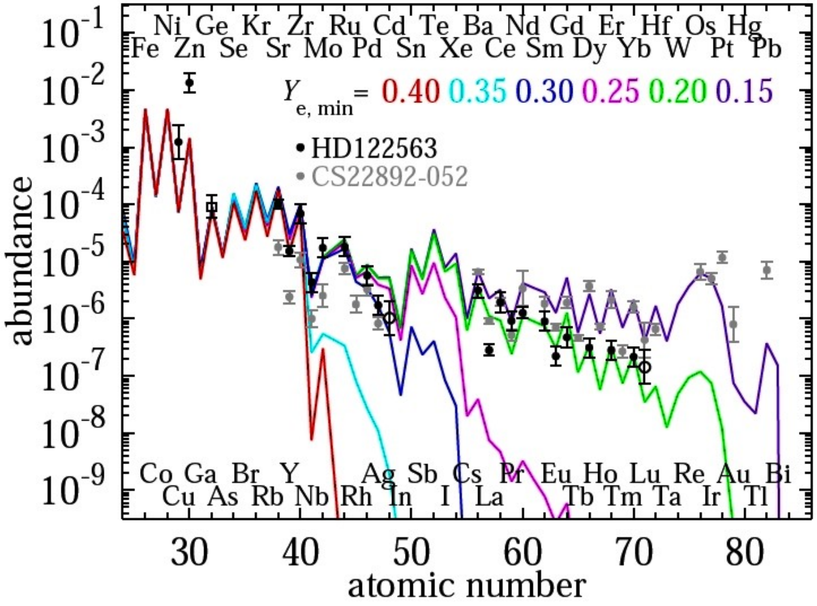




Convectively ejected n-rich matter makes ONeMg-core supernovae an interesting source of nuclei between iron group and N = 50 (from Zn to Zr).

Models in very good agreement with Ge, Sr, Y, Zr abundances observed in r-process deficient Galactic halo stars.

If tiny amounts of matter with Y_e down to 0.30–0.35 were also ejected, a weak r-process may yield elements up to Pd, Ag, and Cd.

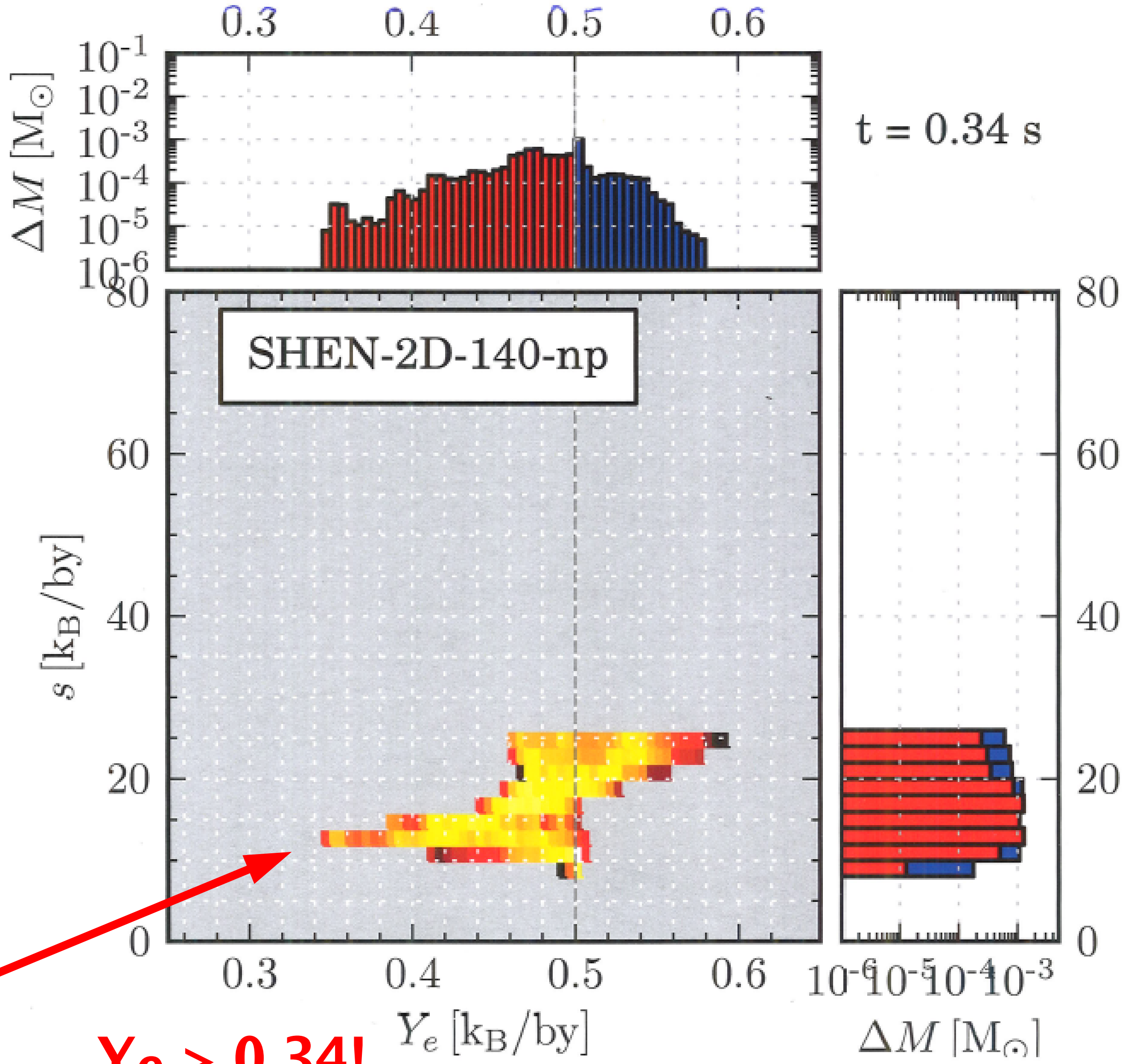


(Wanajo, Janka, & Müller, ApJ Letters 726 (2011) L15)

Ejecta Conditions in O-Ne-Mg Core SNe

2D GR models

Nucleon self-energy shifts ("nucleon potentials") slightly reduce minimal Y_e



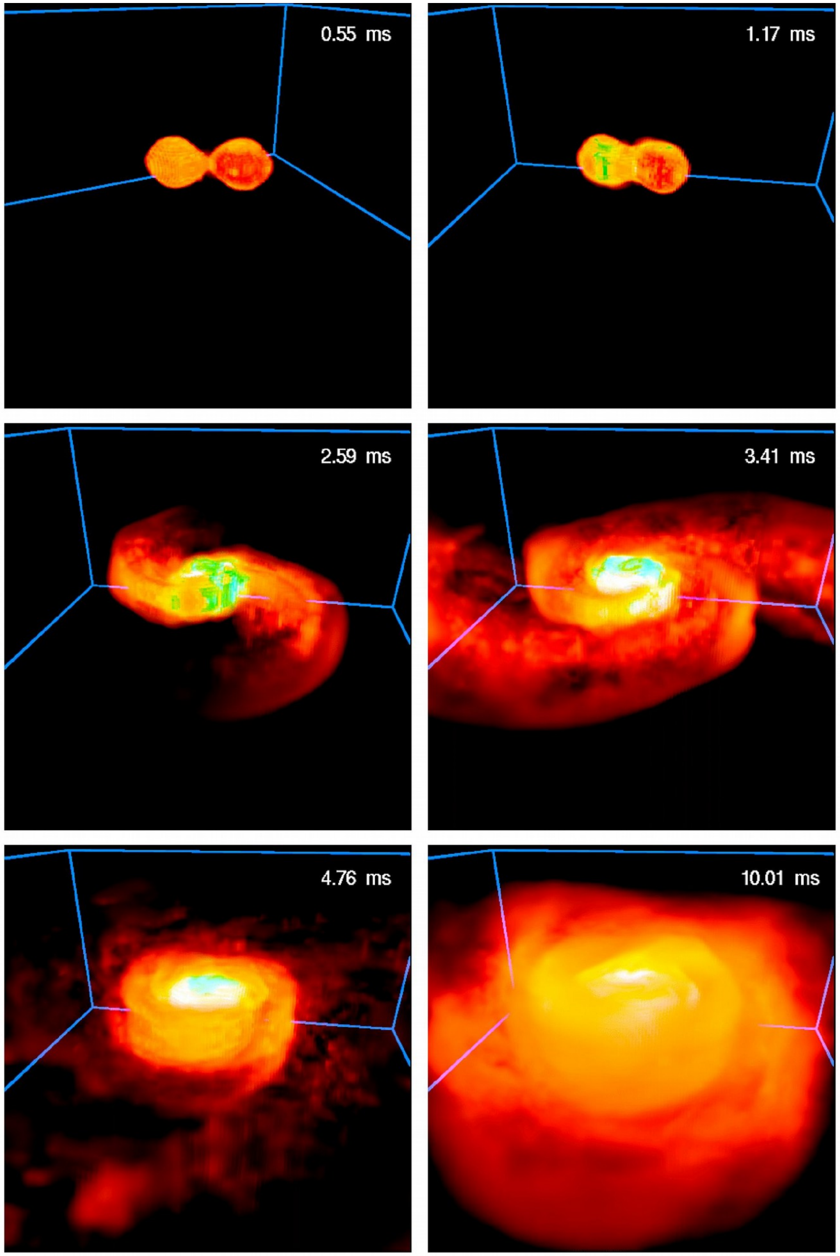
n-rich matter

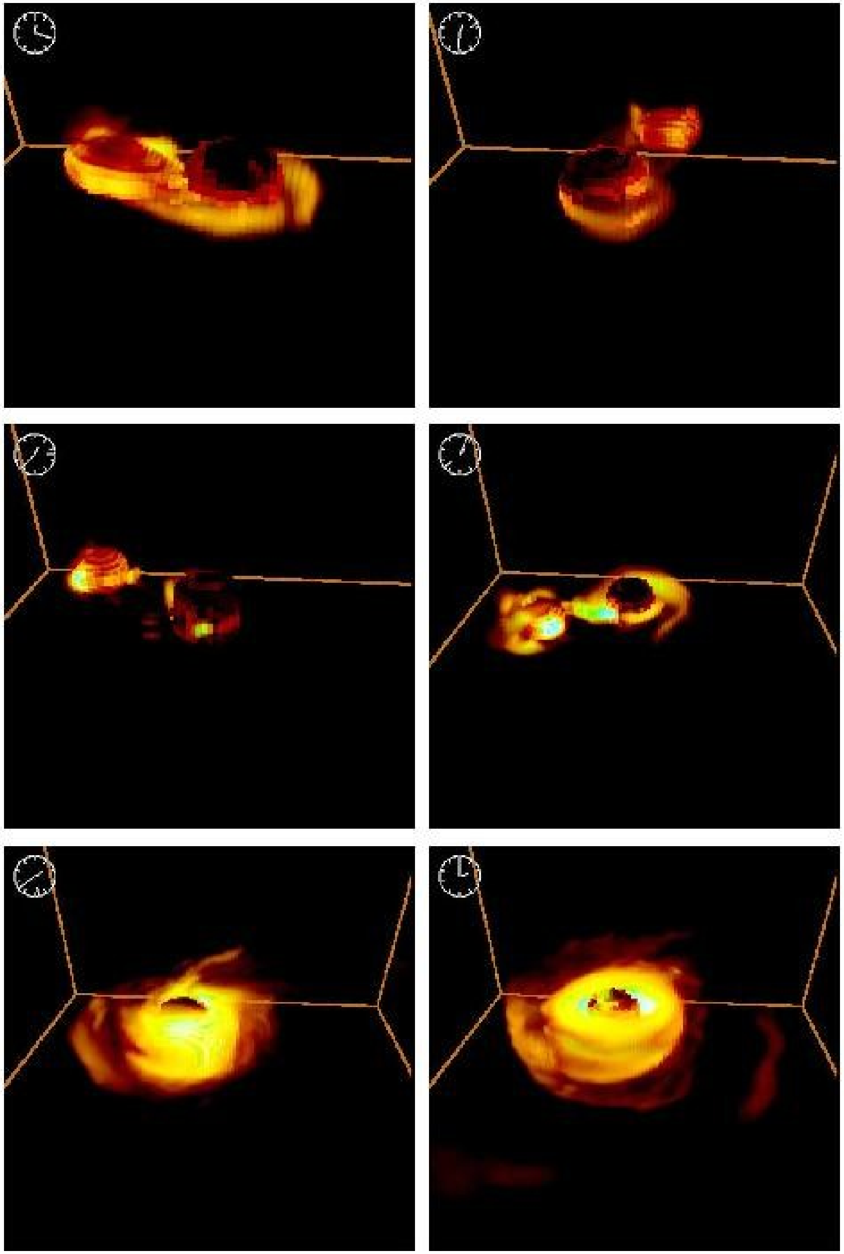
$Y_e > 0.34$!

Janina v. Groote, PhD Thesis (2014)

Compact Binary Mergers as Origin of r-Process Elements

NS+NS/BH Mergers

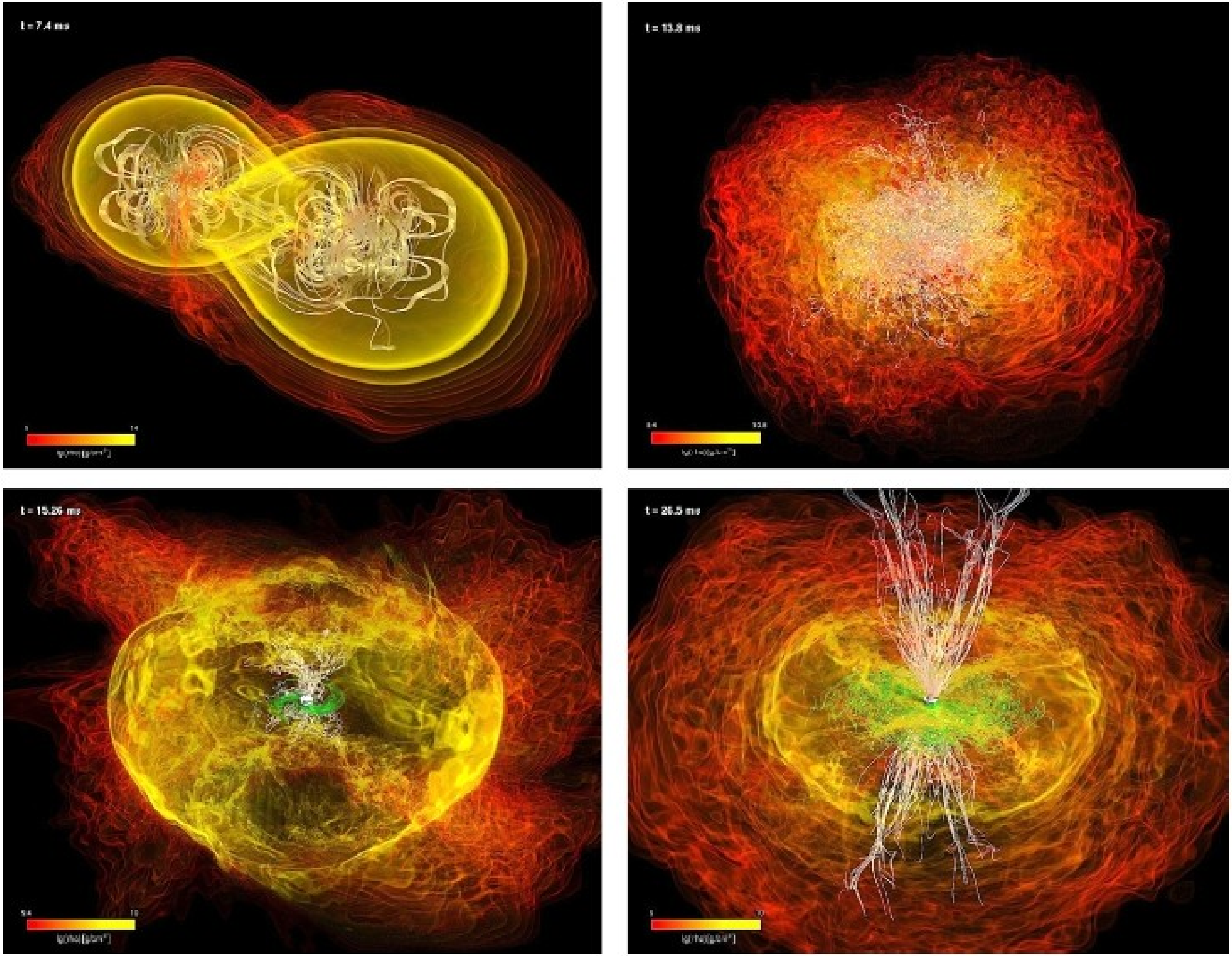




Ruffert et al.
Rosswog et al.
Oechslin et al.
Shibata et al.
Rezzolla et al.
Rasio et al.
Lehner et al.
Foucart et al.

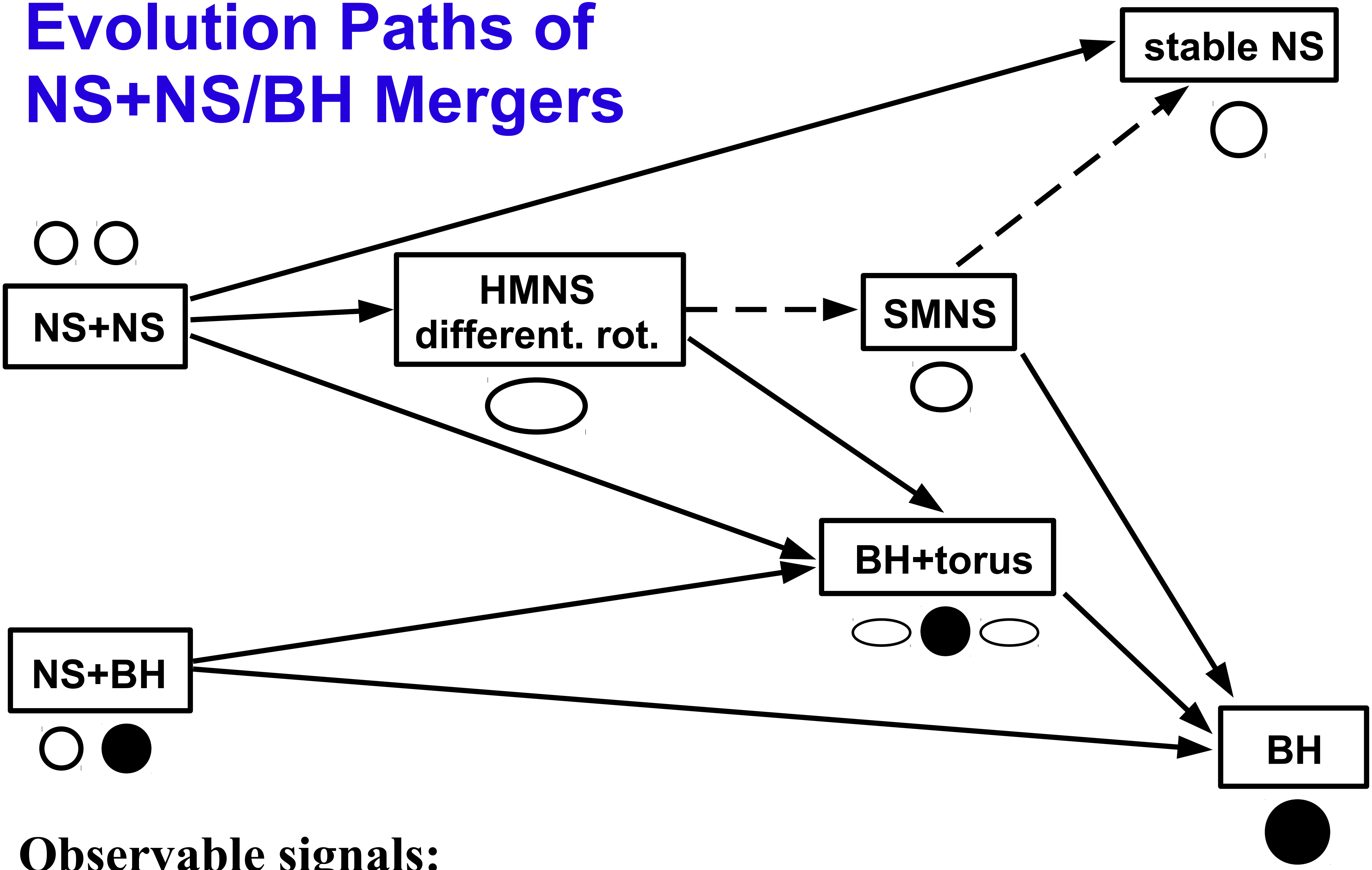
etc.

Extreme Magnetic Field Amplification



Rezzolla, Giacomazzo, Baiotti, et al., ApJL (2011)

Evolution Paths of NS+NS/BH Mergers



stable NS

NS+NS

HMNS
different. rot.

SMNS

BH+torus

NS+BH

BH

Observable signals:

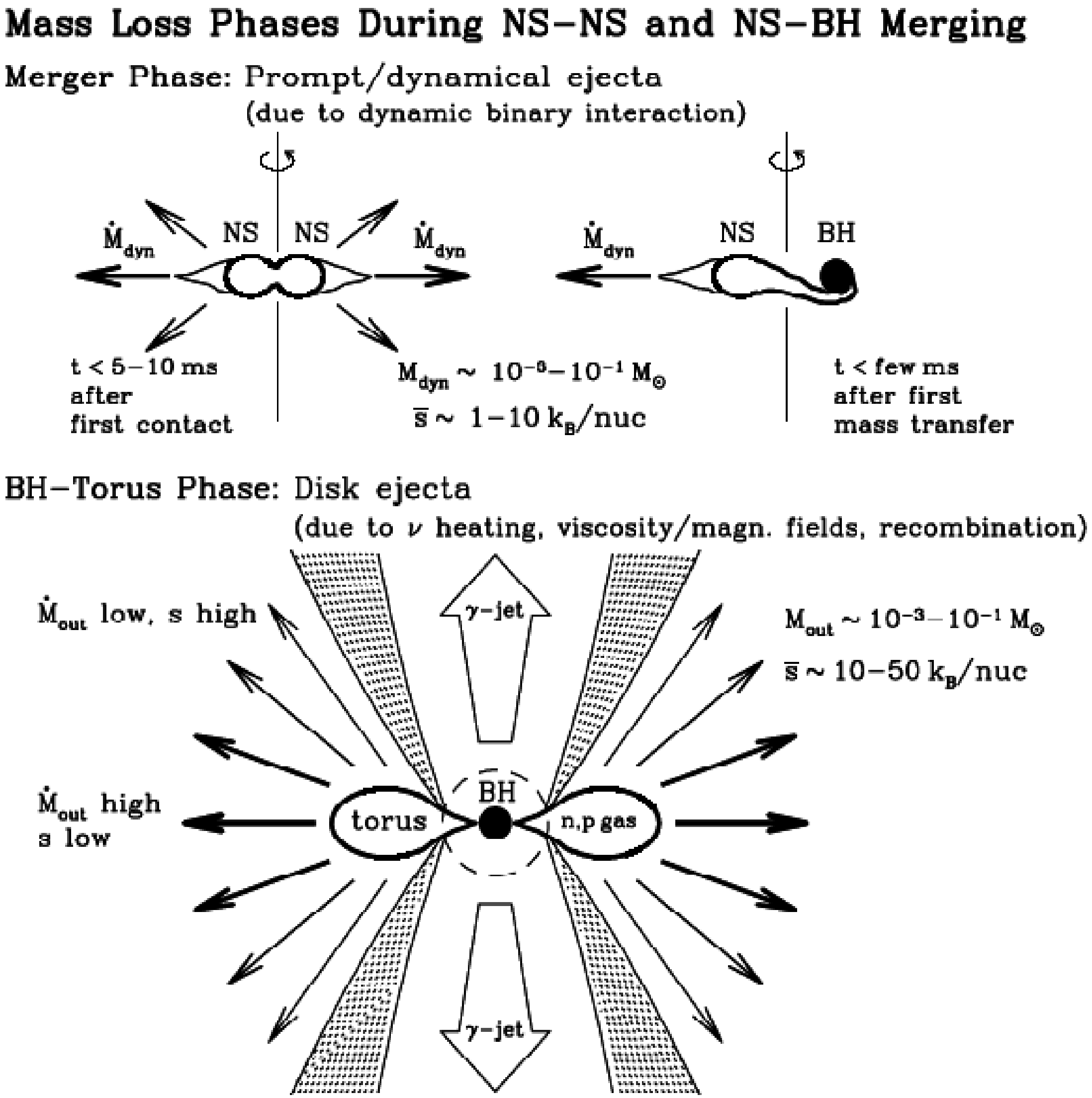
Gravitational waves, neutrinos, gamma-ray bursts,
mass ejection, r-process elements, electromag. transients

Neutron Star Mergers as Production Sites of Ejecta & Heavy Elements

Compact binary mergers

- are likely sources of short gamma-ray bursts
  (Paczynski, Jaroszynski, etc.)
- are among strongest sources of gravitational waves
- are potential production sites of r-process nuclei
  (Lattimer & Schramm 1974, 1976; Lattimer et al. 1977; Meyer 1989, Freiburghaus et al. 1999)
- May be observable transient sources of optical radiation
  (Li & Paczynski 1998, Kulkarni 2005, Metzger et al. 2010, Roberts et al. 2011)

  and radio flares (Piran & Nakar 2011)

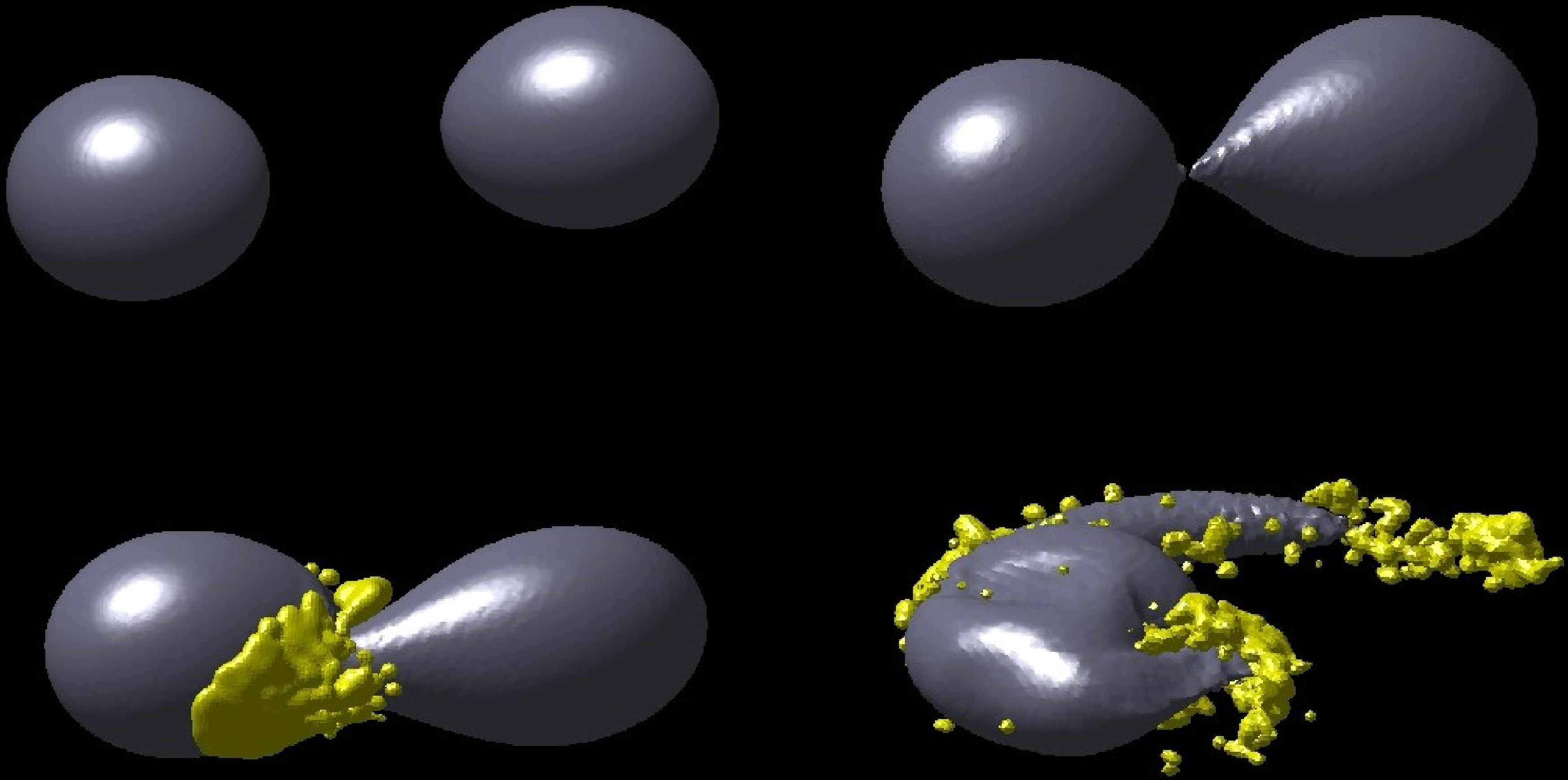

Mass Loss Phases During NS−NS and NS−BH Merging

Merger Phase: Prompt/dynamical ejecta
(due to dynamic binary interaction)

BH−Torus Phase: Disk ejecta
(due to ν heating, viscosity/magn. fields, recombination)

(Ruffert & Janka 1999; Just et al., MNRAS 448 (2015) 541)

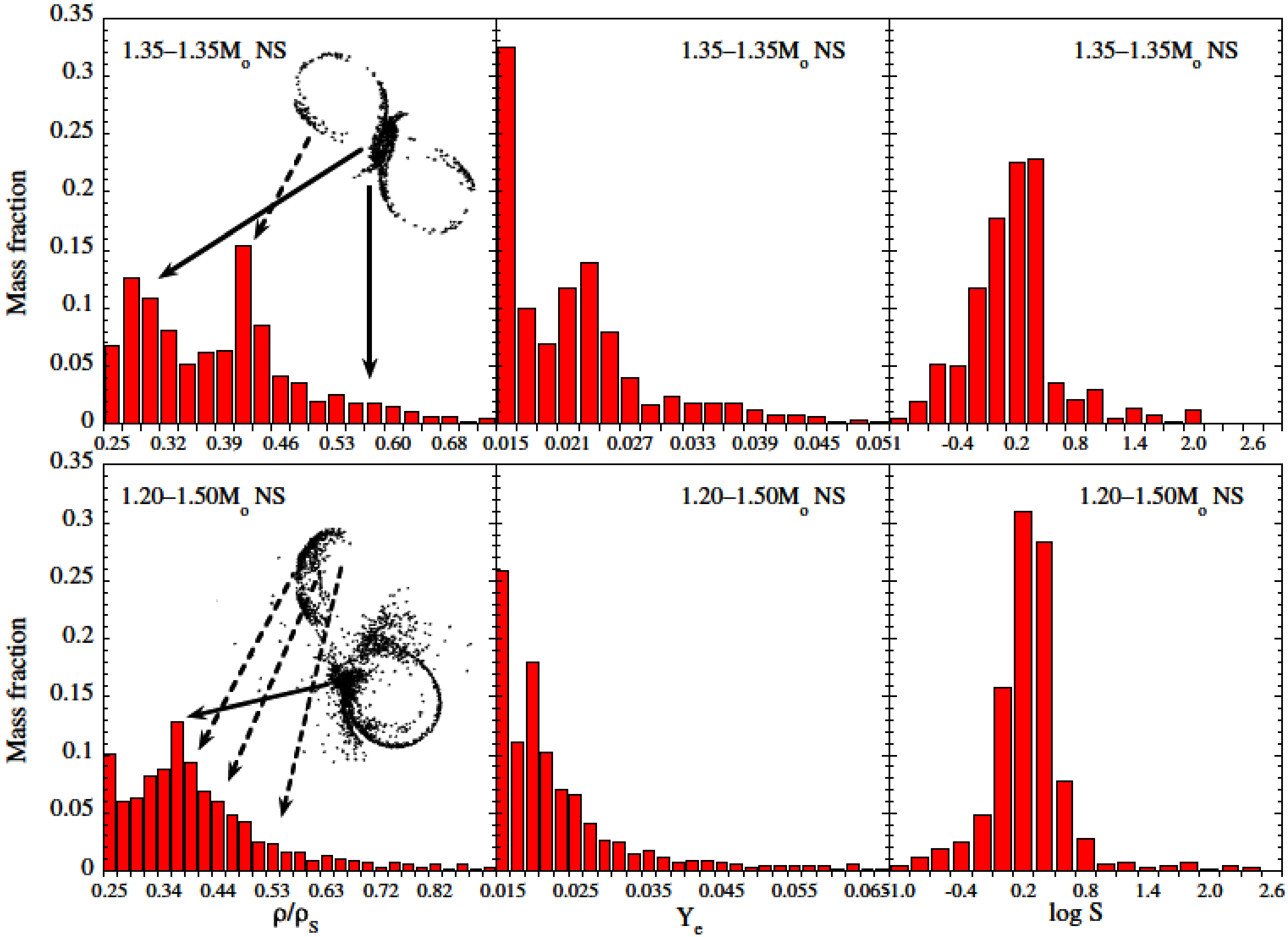
Dynamical Mass Ejection in NS-NS Mergers



(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

Asymmetric NS-NS merger

Properties of Dynamical Merger Ejecta



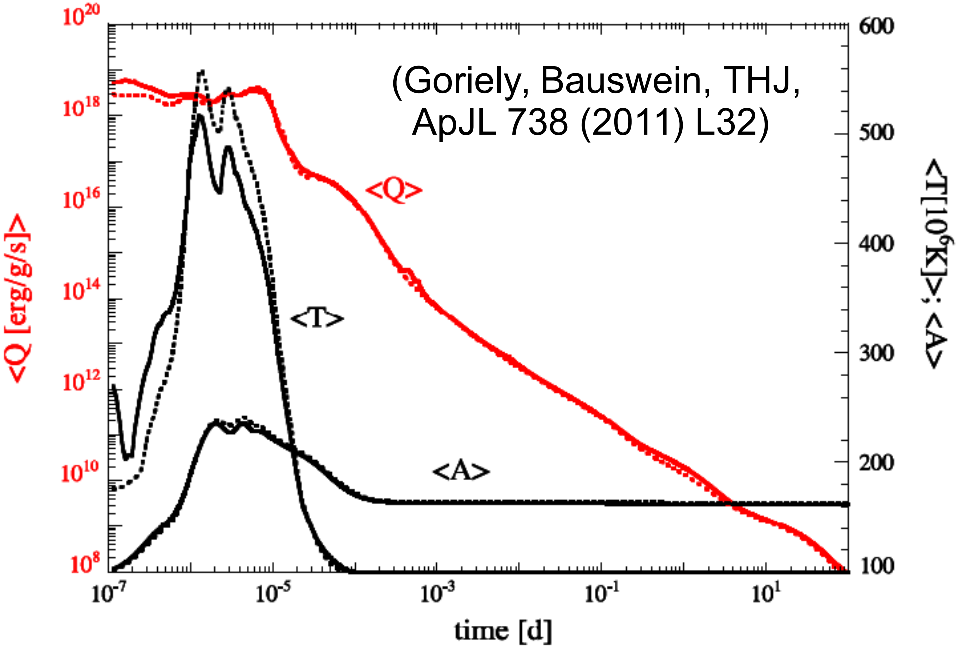
(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

Symmetric NS-NS merger

Asymmetric NS-NS merger

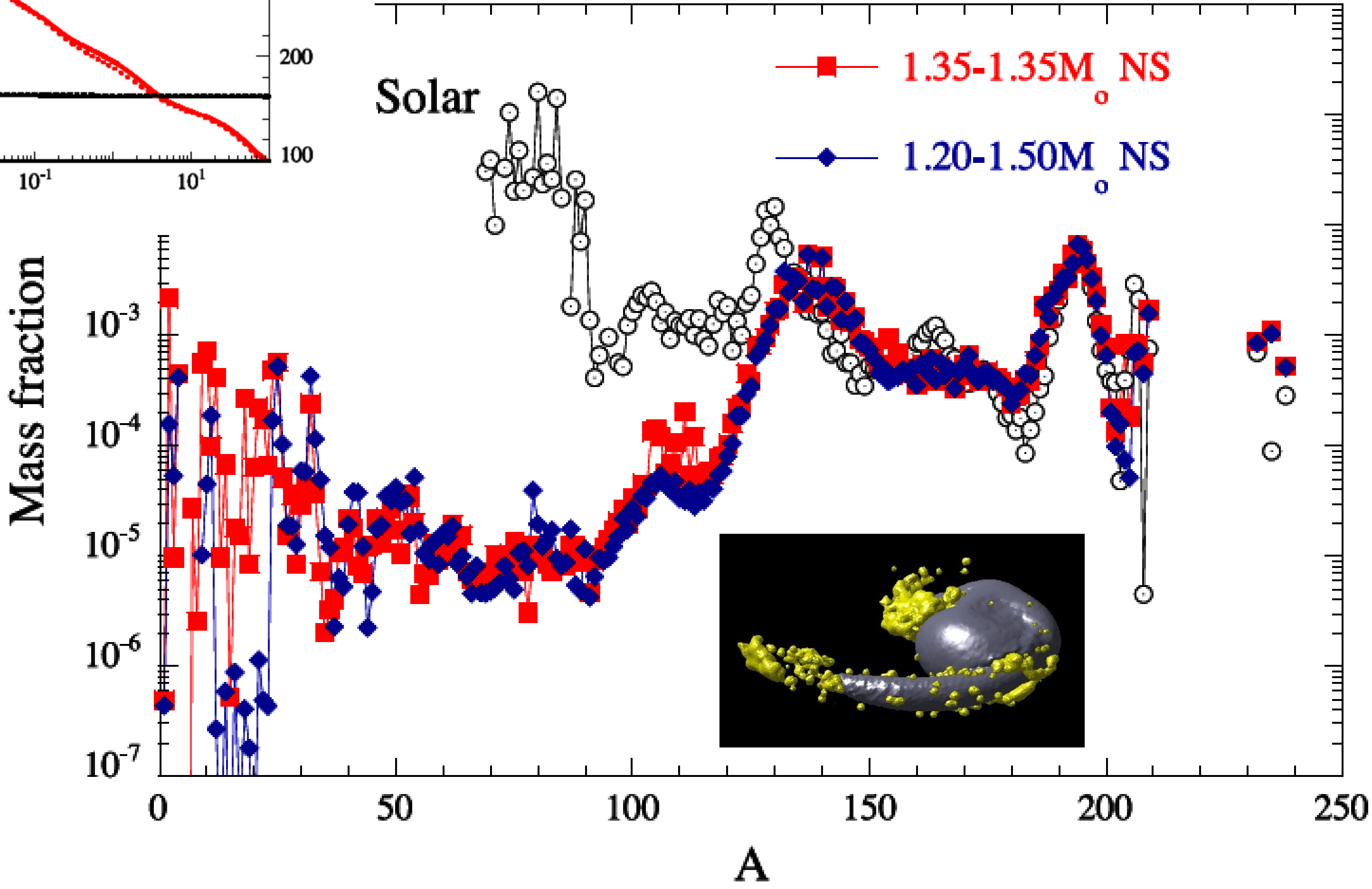
- Still unclear influence of neutrinos on ejecta Y_e
- Can depend on NS compactness and therefore EOS

Nucleosynthesis in Dynamical Merger Ejecta



(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

During r-processing fission recycling takes place and produces roughly solar abundances for A > 130.

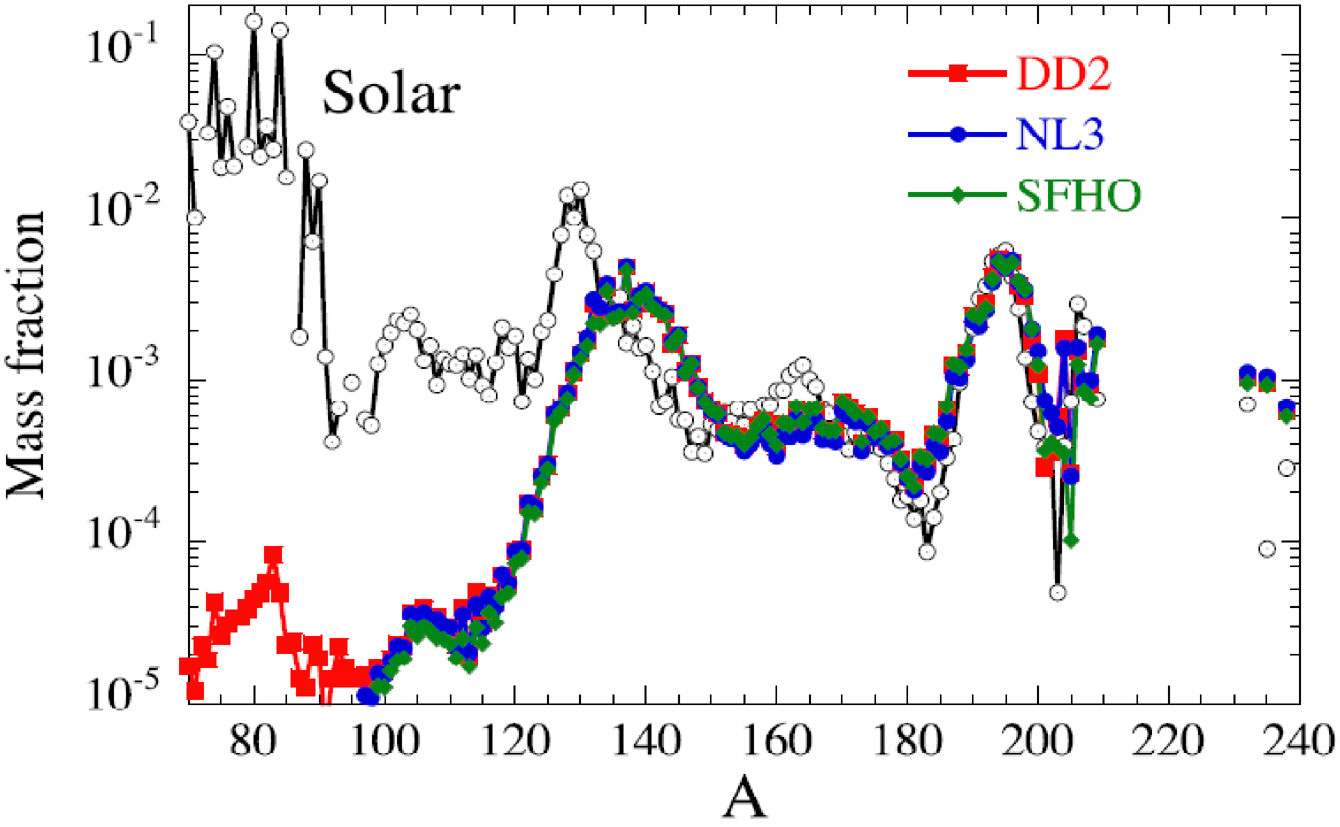


Per merger event 10^{-3}–10^{-2} M_{sun} are ejected.

With rate of 10^{-5} events per year and galaxy, NS mergers could be the main source of heavy r-process material.

r-process Nucleosynthesis

for 1.35-1.35 binaries **(most abundant in binary population)**



Goriely, Bauswein & THJ, ApJ 773 (2013) 78

- Robust r-process with solar abundance above A ~130
- Insensitive to high-density equation of state?
- Caveat: neutrinos !!

Nucleosynthesis in Neutrino-heated Ejecta

Crucial parameters for nucleosynthesis in neutrino-irradiated outflows:

* Electron-to-baryon ratio Y_e (<---> neutron excess)
* Entropy (<----> ratio of (temperature)^3 to density)
* Expansion timescale

Determined by the interaction of stellar gas with neutrinos from radiating merger remnant:

$$\begin{aligned} \nu_\mathrm{e} + n &\rightarrow e^- + p \\ \bar{\nu}_\mathrm{e} + p &\rightarrow e^+ + n \end{aligned}$$

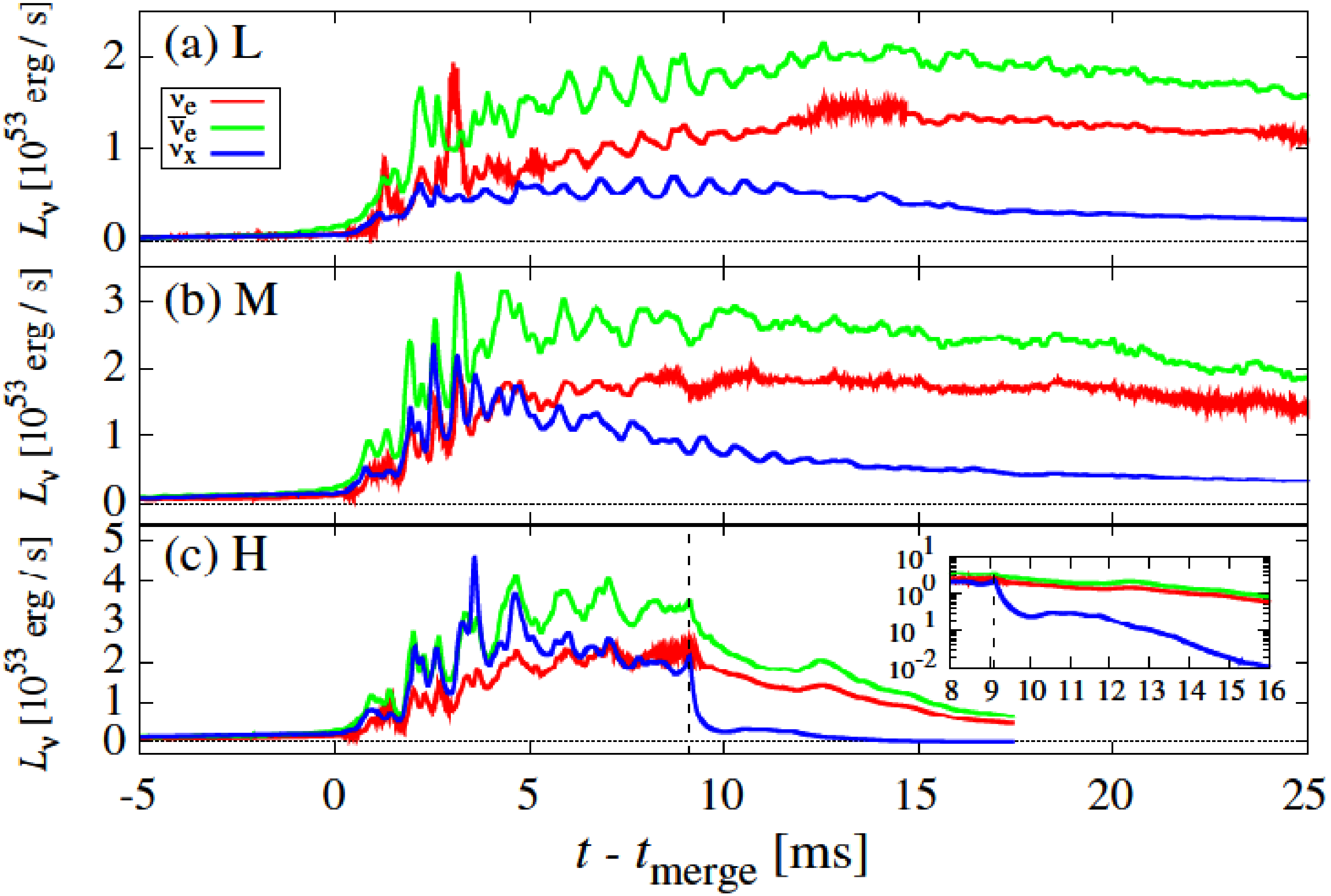
$$\boxed{Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta)}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta)}\right]^{-1}}$$

$$\text{with} \quad \epsilon_\nu = \frac{\langle\epsilon_\nu^2\rangle}{\langle\epsilon_\nu\rangle} \quad \text{and} \quad \Delta = (m_n - m_p)c^2 \approx 1.29\,\mathrm{MeV}.$$

If $L_{\bar{\nu}_e} \approx L_{\nu_e}$, one needs for $Y_e < 0.5$ (i.e. neutron excess):

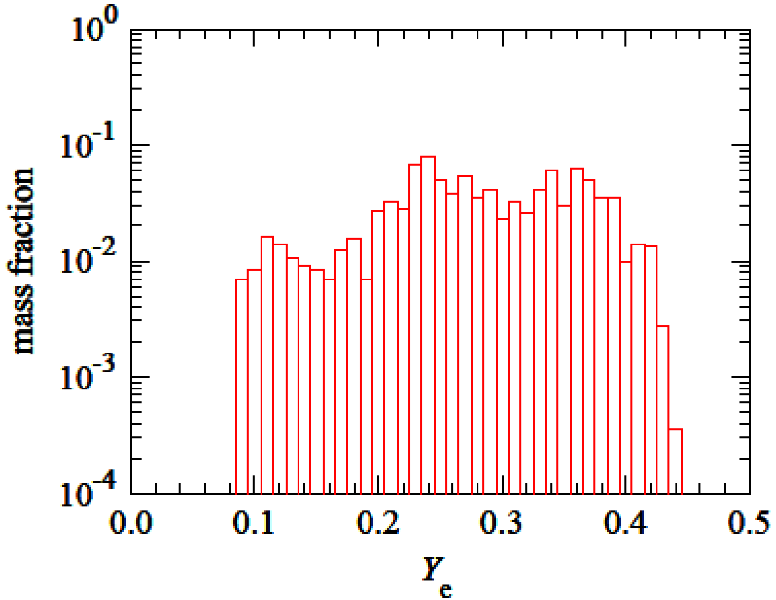
$$\boxed{\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} > 4\Delta.}$$

Neutrino Emission During NS Merging



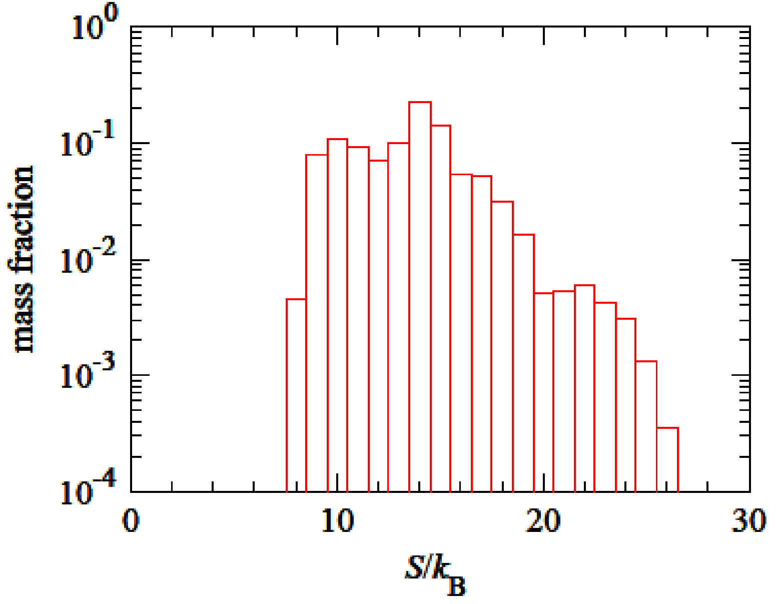
Sekiguchi et al., PRL 107, 051102 (2011)

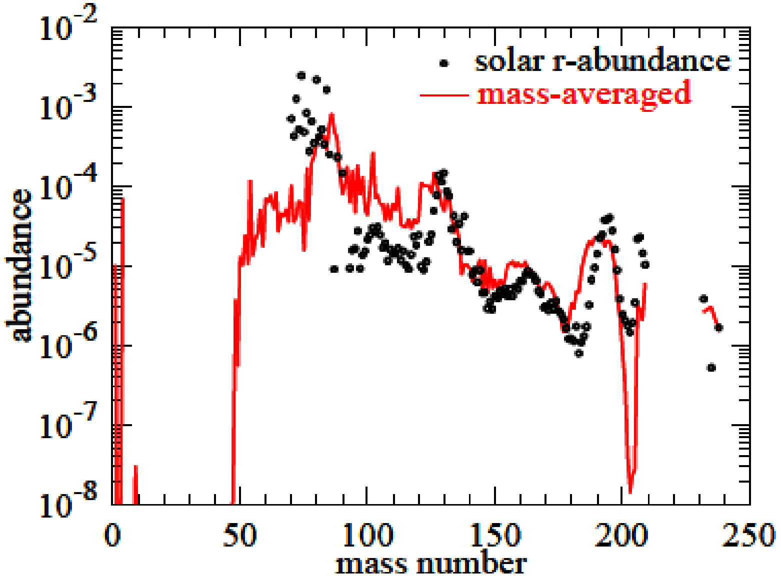
Nucleosynthesis in Neutrino-processed Merger Ejecta



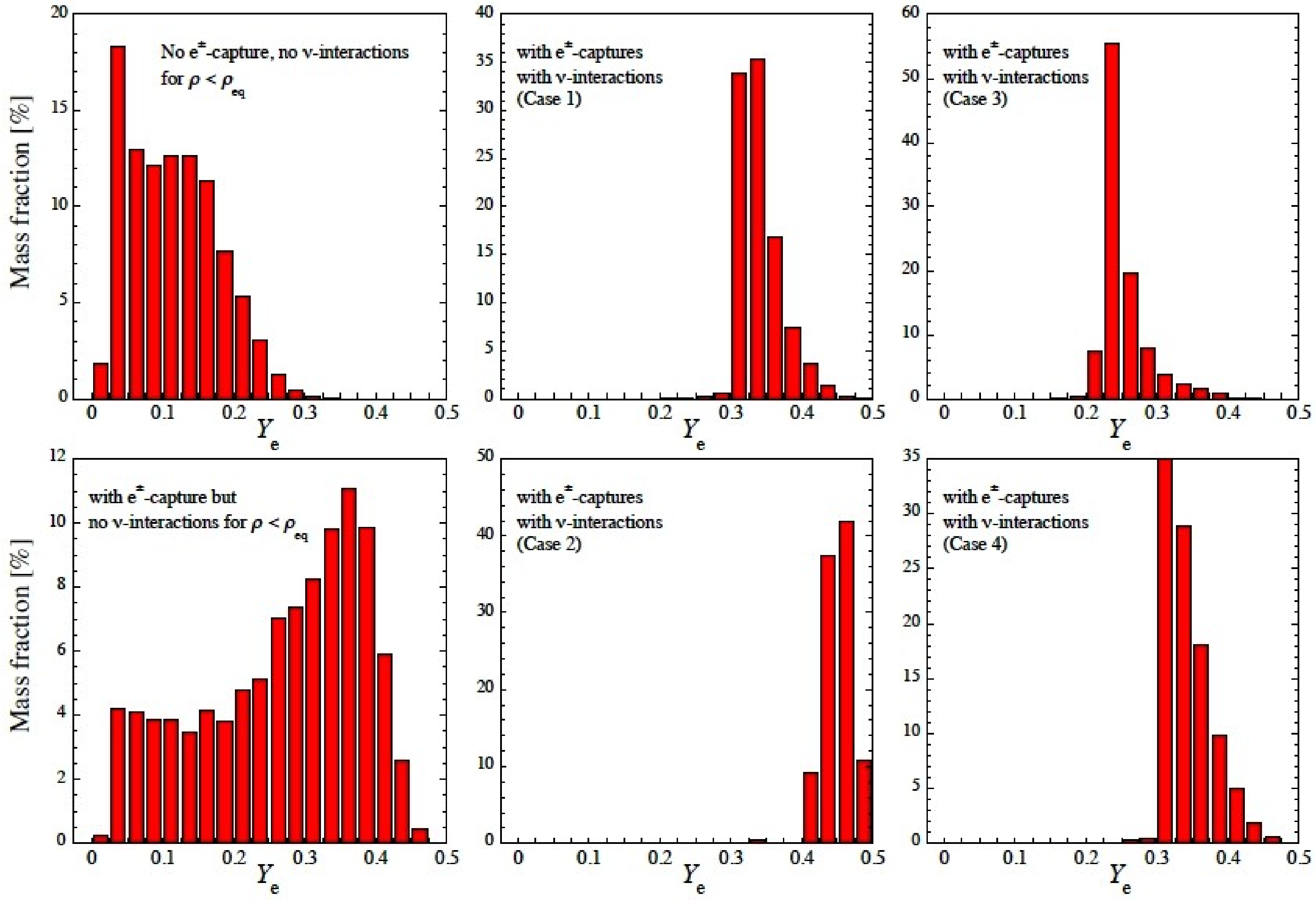
(Wanajo et al., ApJL 789 (2014) L39)

- Compact NSs produce strongly shock-heated ejecta.
- Electron fraction increases considerably in hot ejecta, mostly due to positron capture.
- Heavy r-process is still produced, but also A < 130 nuclei.



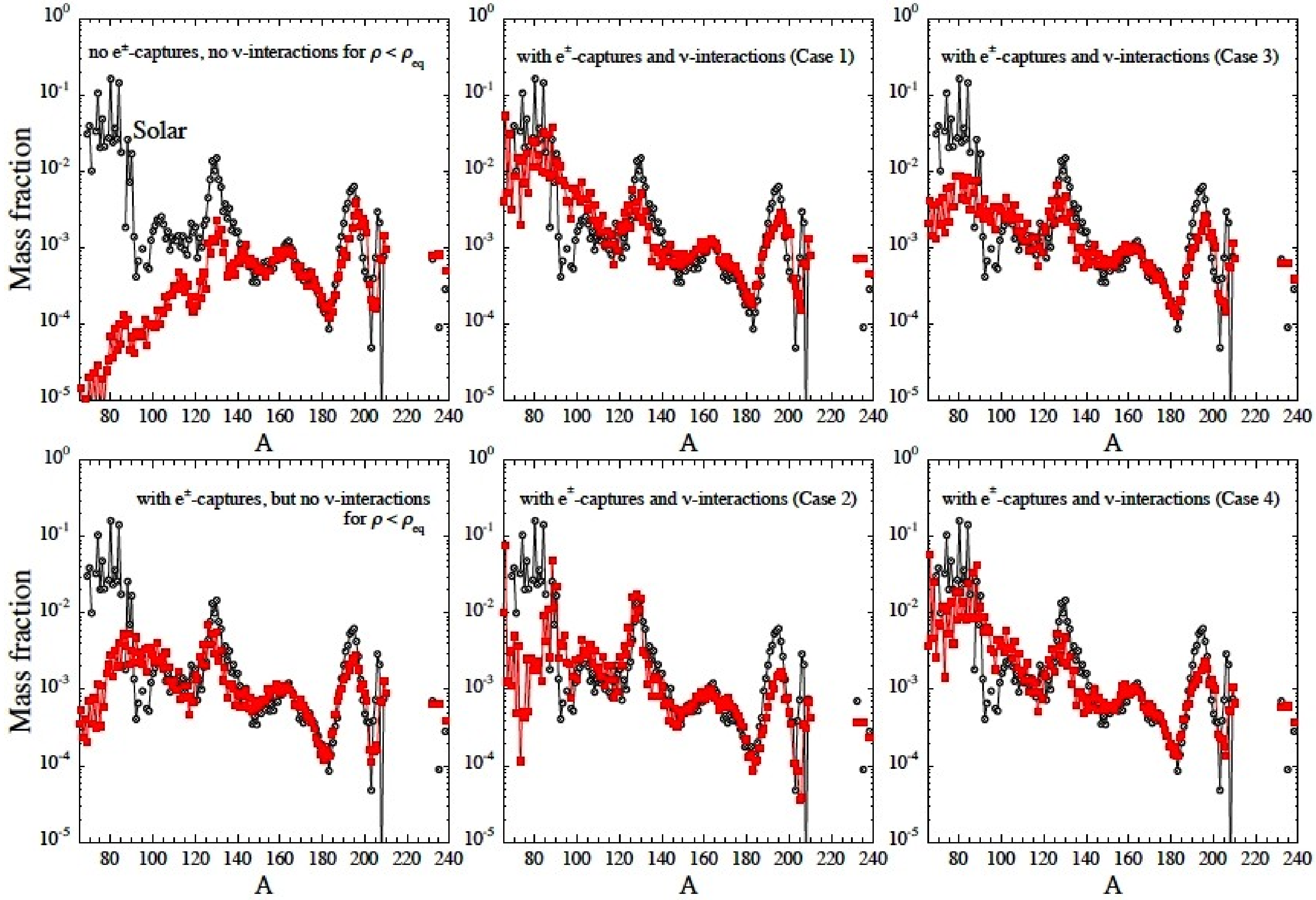


Nucleosynthesis in Neutrino-processed Merger Ejecta



(Goriely et al., MNRAS 452 (2015) 3894)

Nucleosynthesis in Neutrino-processed Merger Ejecta



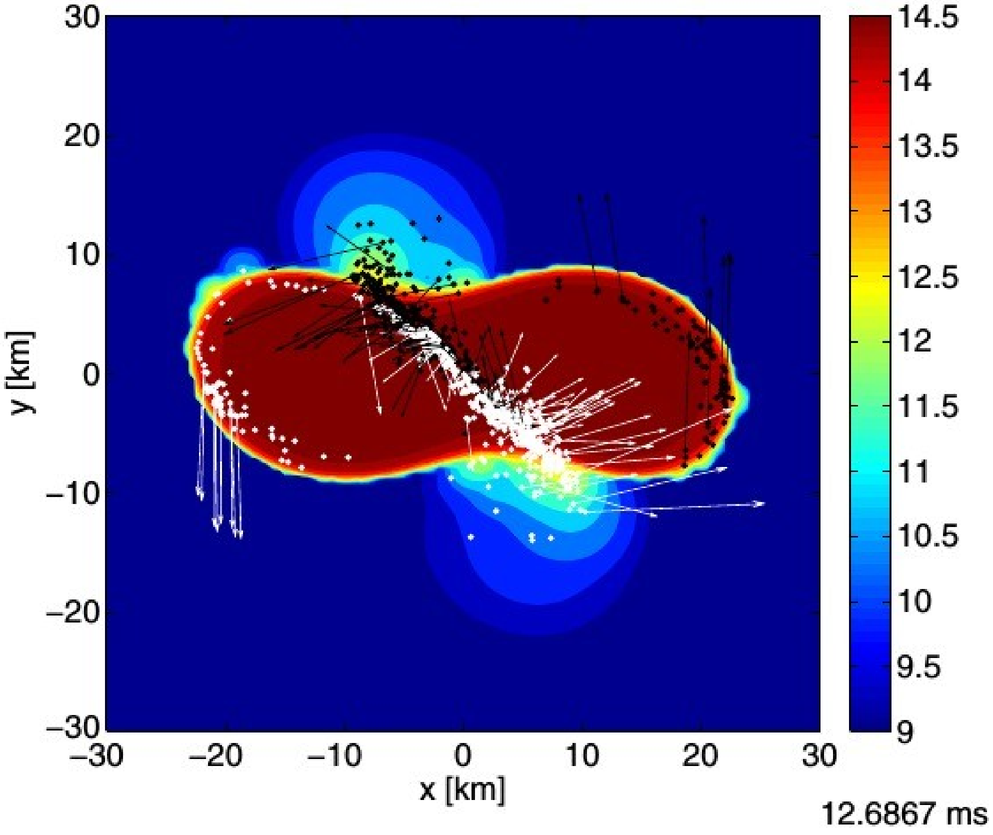
(Goriely et al., MNRAS 452 (2015) 3894)

Mass of r-material varies between some percent and ~70%

(also: Roberts et al. 2016, Foucart et al. 2016)

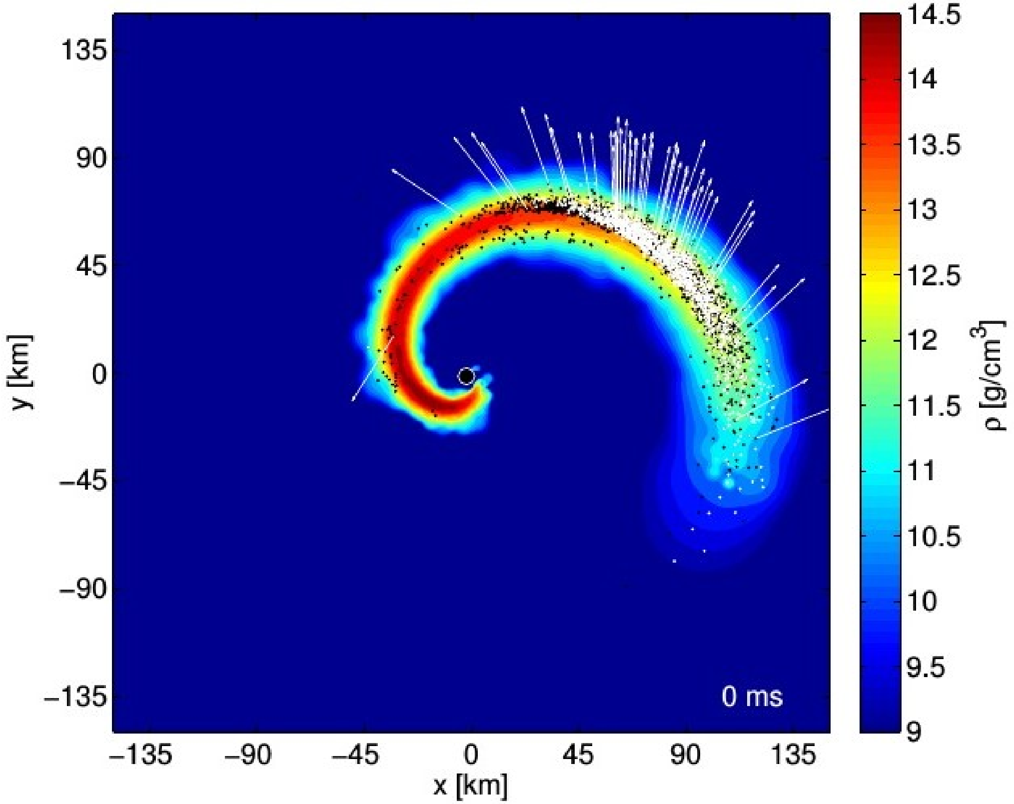
Dynamical Mass Ejection in Compact Binary Mergers

Symmetric NS-NS merger



(Bauswein, Goriely, THJ, ApJ 773 (2013) 78)

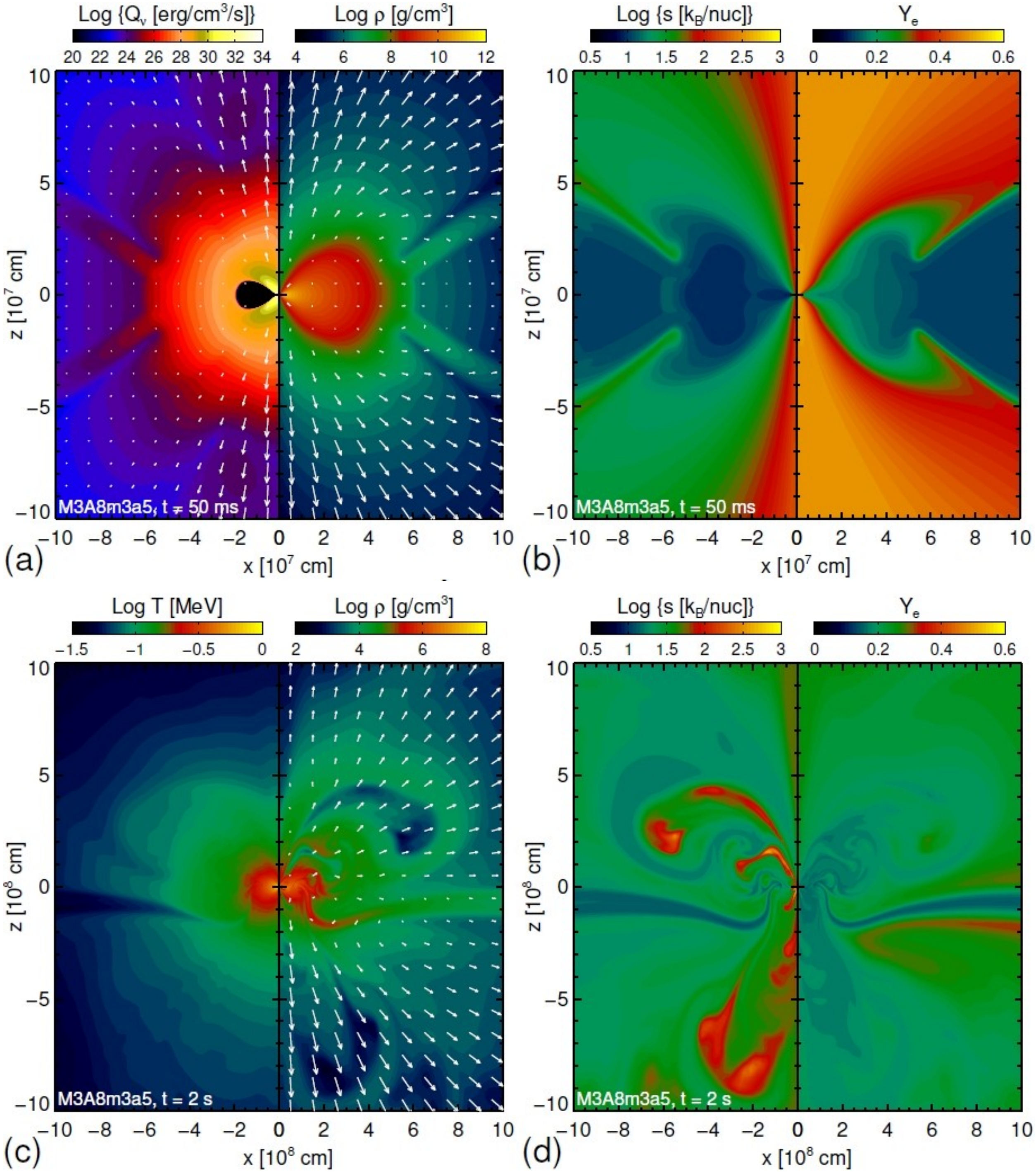
NS-BH merger



(Just et al., MNRAS 448 (2015) 541)

BH-torus Outflows

- Hydrodynamical 2D models of BH-torus evolution.
  (Just, PhD Thesis 2012)
- New Newtonian MHD-code with 2D, energy-dependent neutrino transport based on two-moment closure scheme.
  (Obergaulinger, PhD Thesis 2008)
- BH treated by Artemova-Novikov potential.
- Diplayed model based on Shakura-Sunyaev α-viscosity
- MHD yields turbulent tori !

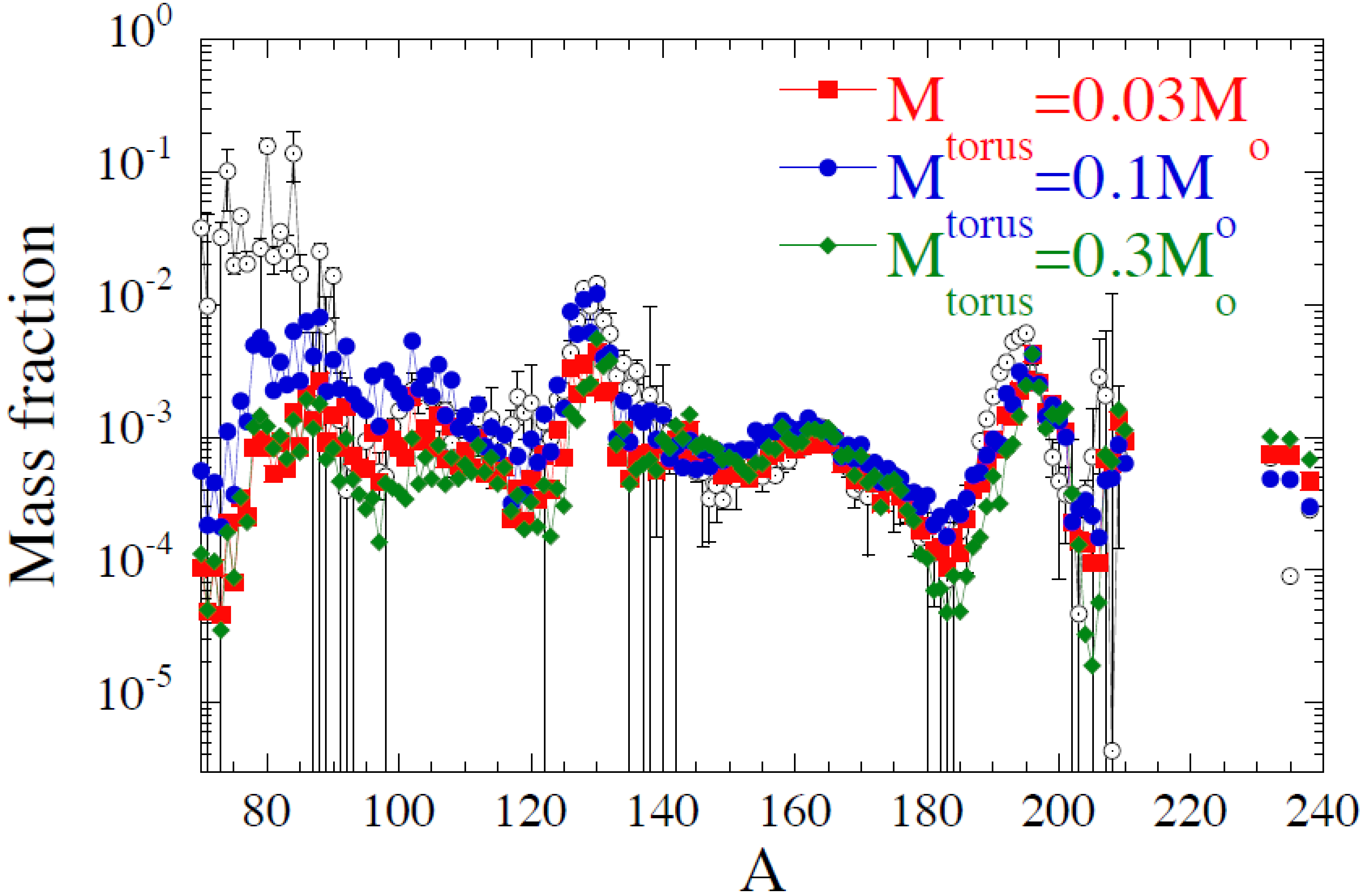


Just et al., MNRAS 448 (2015) 541

also: Fernández & Metzger (2013, 2014, 2015);
Perego et al. (2014), Martin et al. (2015) for outflows from HMNS remnants

r-process Nucleosynthesis

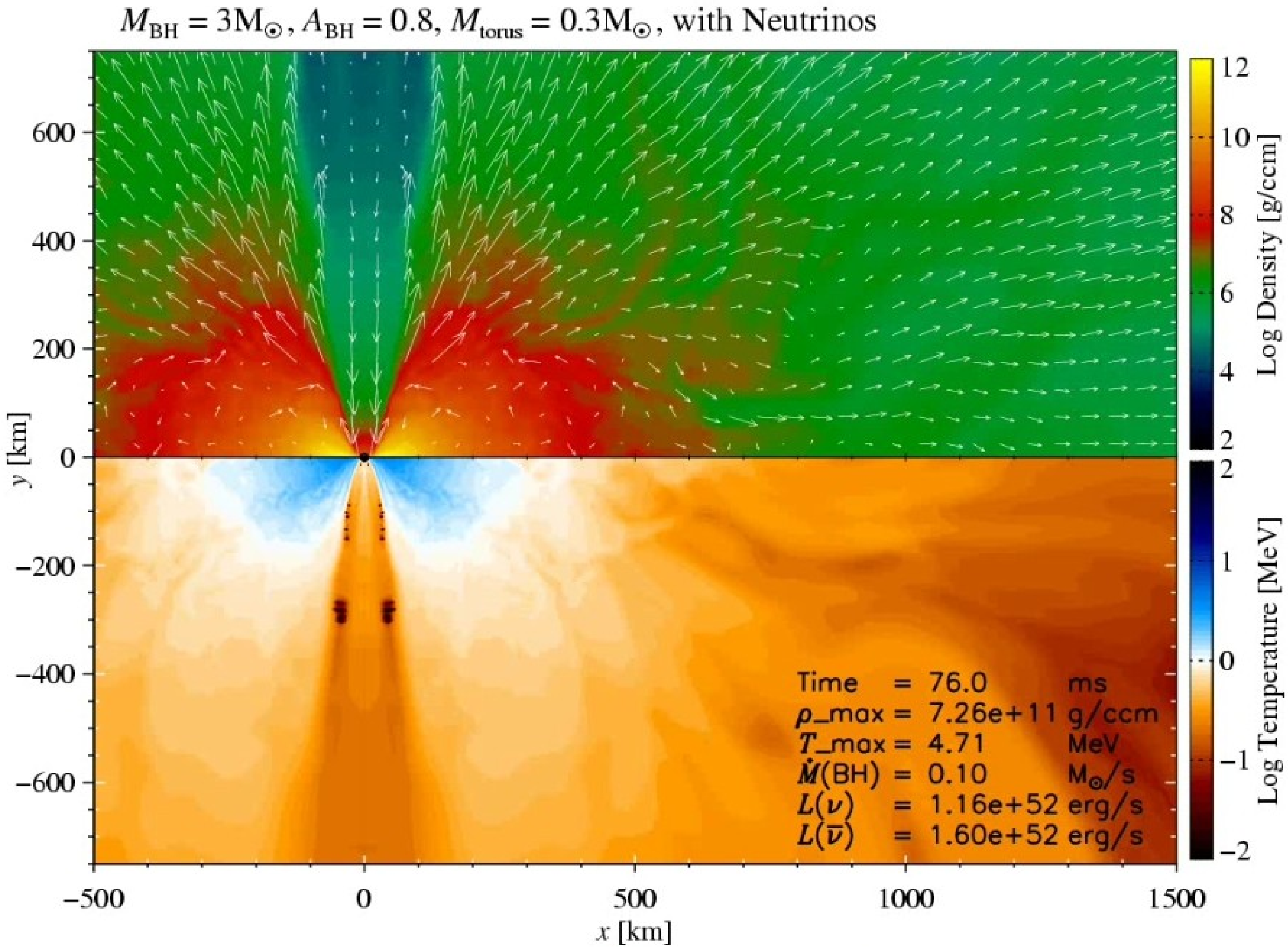
Ejecta from NS+NS merger + BH-torus remnant



(Just et al, MNRAS 448 (2015) 541)

For BH-disk ejecta, see also Wu+ (2016); for HMNS winds, see Perego+ (2014), Martin+ (2015)

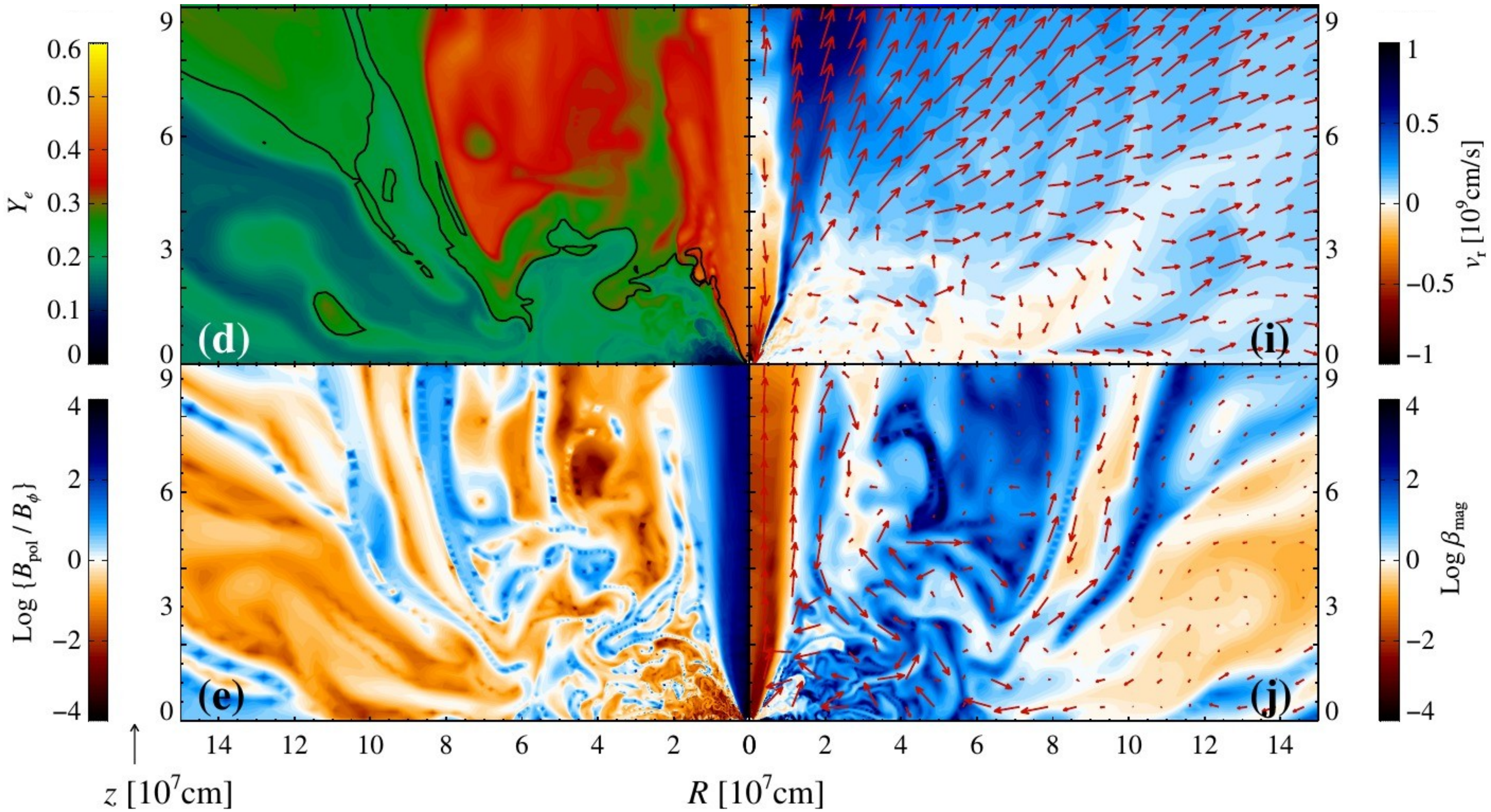
Outflows from Magnetized BH-torus



Magnetohydrodynamic simulation
With M1 ALCAR neutrino transport

(Just, PhD Thesis 2012)

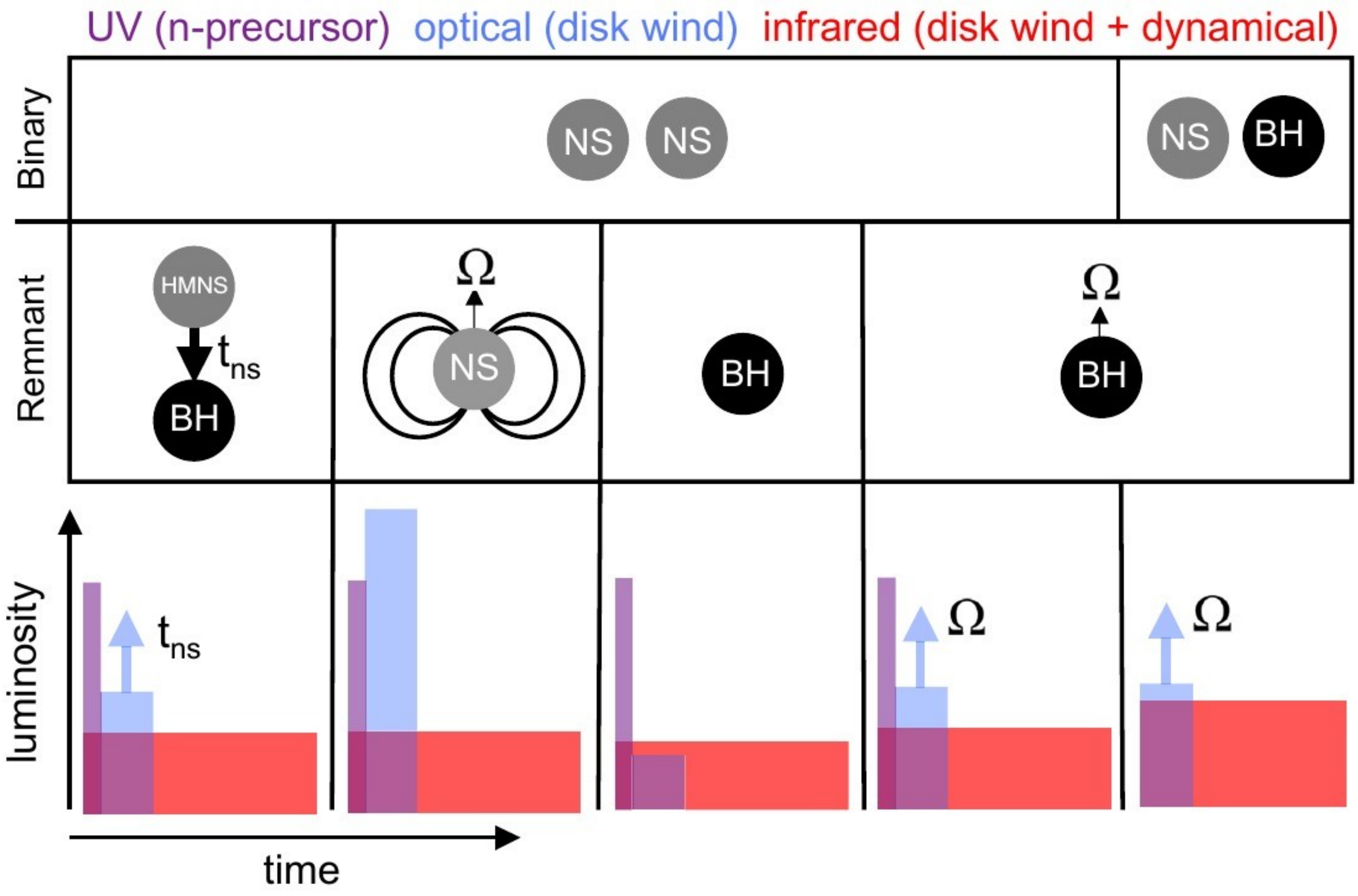
Outflows from Magnetized BH-torus



Magnetohydrodynamic simulation
With M1 ALCAR neutrino transport

(Just, PhD Thesis 2012)

Kilonovae from Outflows of Compact Binary Mergers



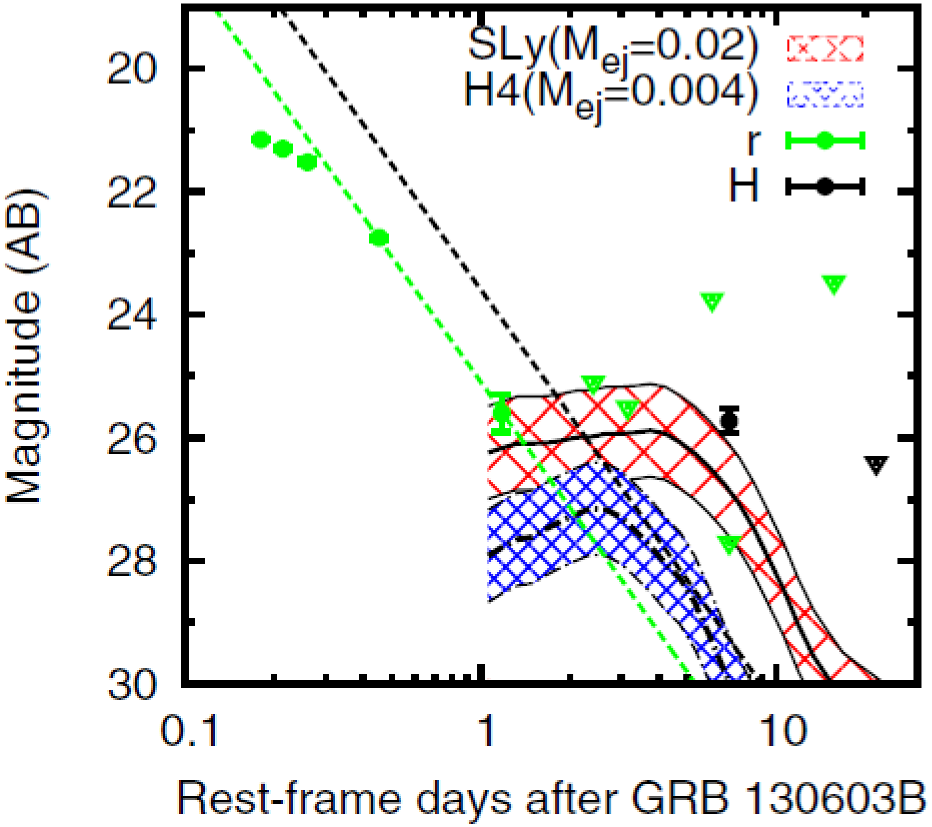
Kasen, Metzger, & Fernandez, MNRAS 450 (2015) 1777

Detailed light curve depends on: Binary parameters, viewing angle, nuclear EOS (→ determine mass and direction and time-dependent composition of ejecta);

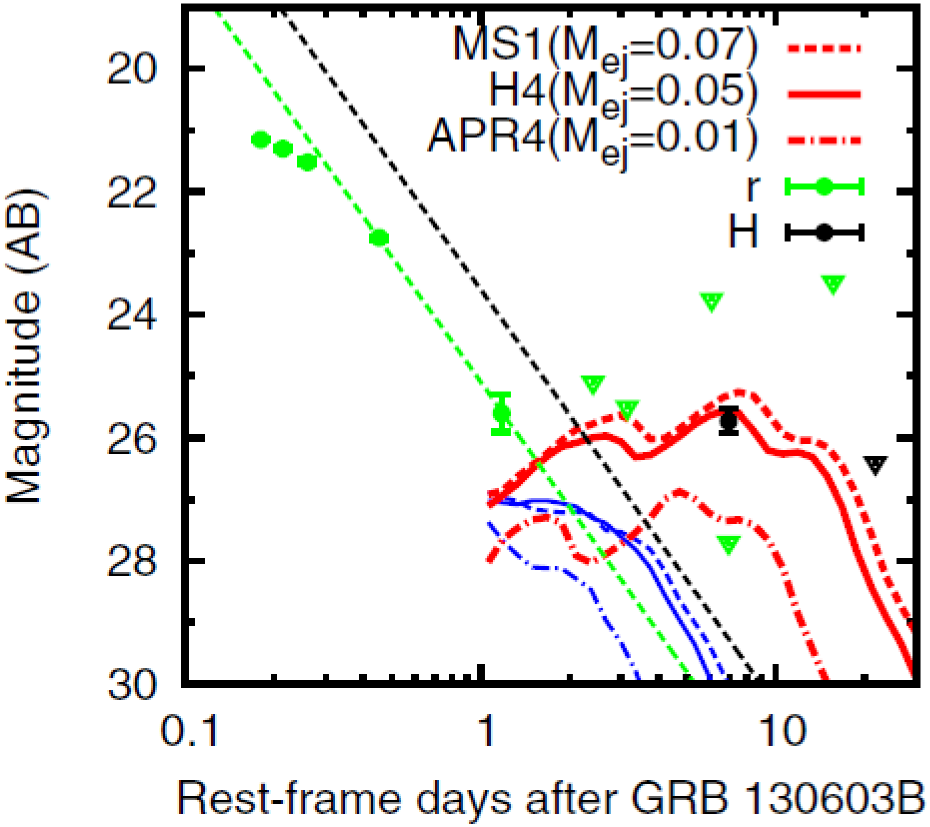
see excellent talk by Masuomi Tanaka yesterday

Infrared Transient of GRB 130603B and NS EOS Implications

Red OT data point: Tanvir et al. (2013); Berger et al. (2013)



Soft EOS with small NS radius
needed for NS+NS merger



Stiff EOS with large NS radius
needed for NS+BH merger

To account for rather large ejecta mass (Hotokezaka et al., ApJ 2013)

Observational Support for r-processing in Compact Binary Merger Ejecta:

- Suggestive cases of optical transients connected to GRBs

  (Tanvir+2013, Berger+2013, Yang+2015, Piran+2015;

  see talks by B. Zhang and T. Piran on Thursday)

- Measurement of live ^{244}Pu in deep-sea reservoirs on Earth hints to rarity of actinide production

  (Wallner et al., Nature Comm. 2015)

- ^{244}Pu abundance in early solar-system and in current ISM (as inferred from deep-sea measurement) are compatible with low-rate/high-yield NSM scenario

  (Hotokezaka, Piran, & Paul, Nature Physics 2015)

- Solar-like r-process (beyond Ba) enrichment of bright stars in ancient dwarf spheroidal galaxy Reticulum II points to single, rare production event consistent with NSM scenario

  (Ji et al., Nature 2016; arXiv:1607.07447; also Tsujimoto et al. 2015)

Compact Binary Merger Ejecta: Mass of r-process vs. α-particles vs. Fe-group

- Neutron excess in dynamical merger ejecta sensitive to EoS (Sekiguchi et al. 2015: currently best models; see talk on Friday)
- Detailed composition depends also on binary system and system parameters, viewing angle, phase of mass ejection
- Neutrino transport treatment needs further improvements in merger models (e.g., work by Sekiguchi+, Foucart+, Goriely+)
- Dependence on neutrino flavor oscillations is likely (e.g., Malkus et al. 2012, Caballero et al. 2012, Zhu et al. 2016, Frensel et al. 2016)

Constraints on NS-BH Merger Rate by r-process Production

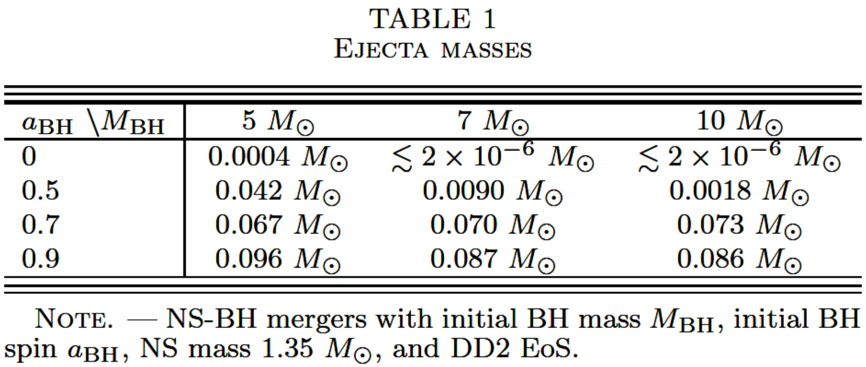
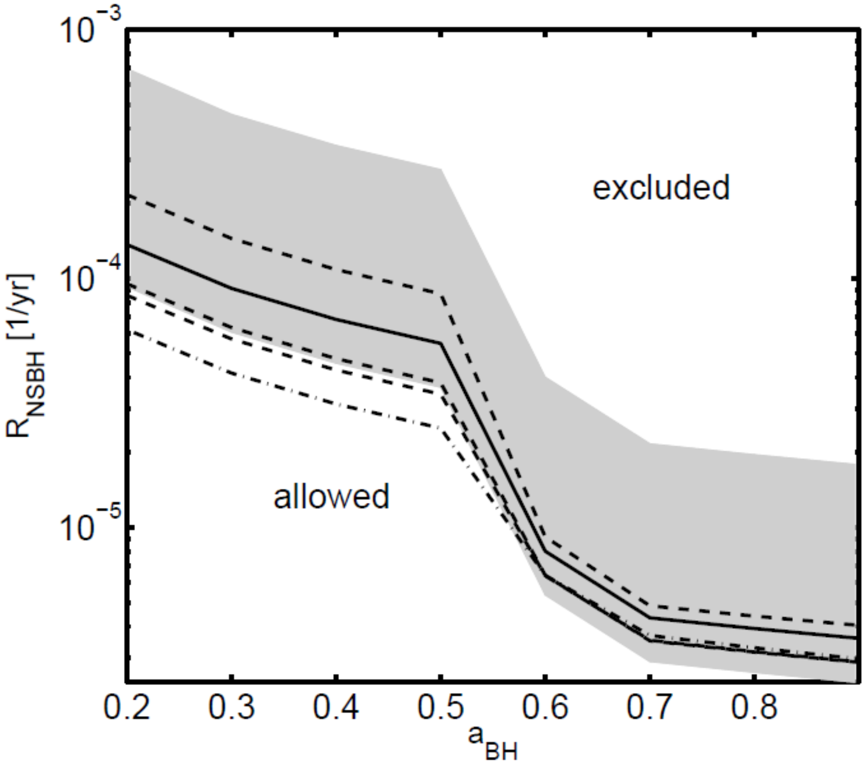
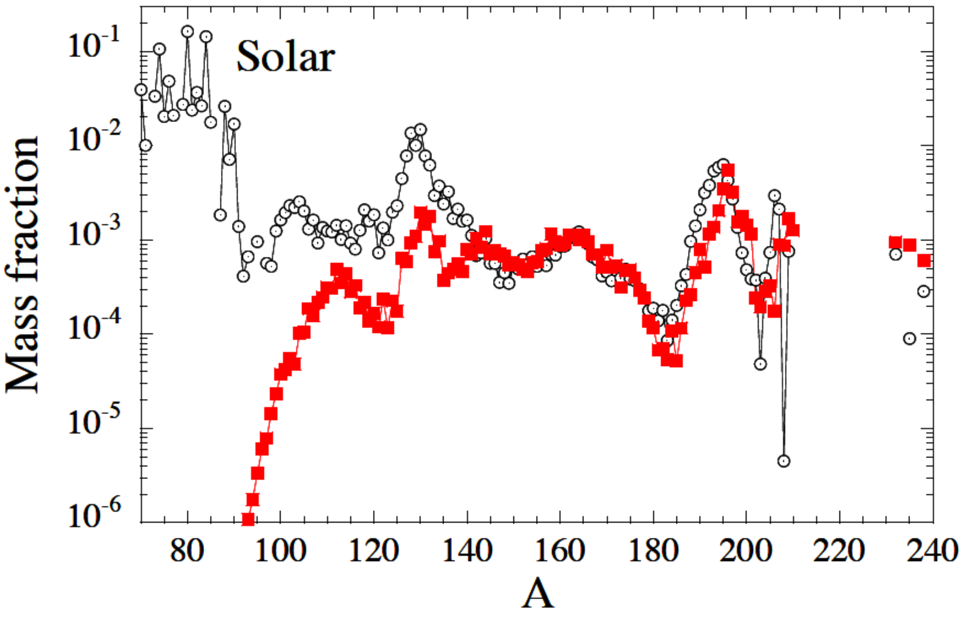


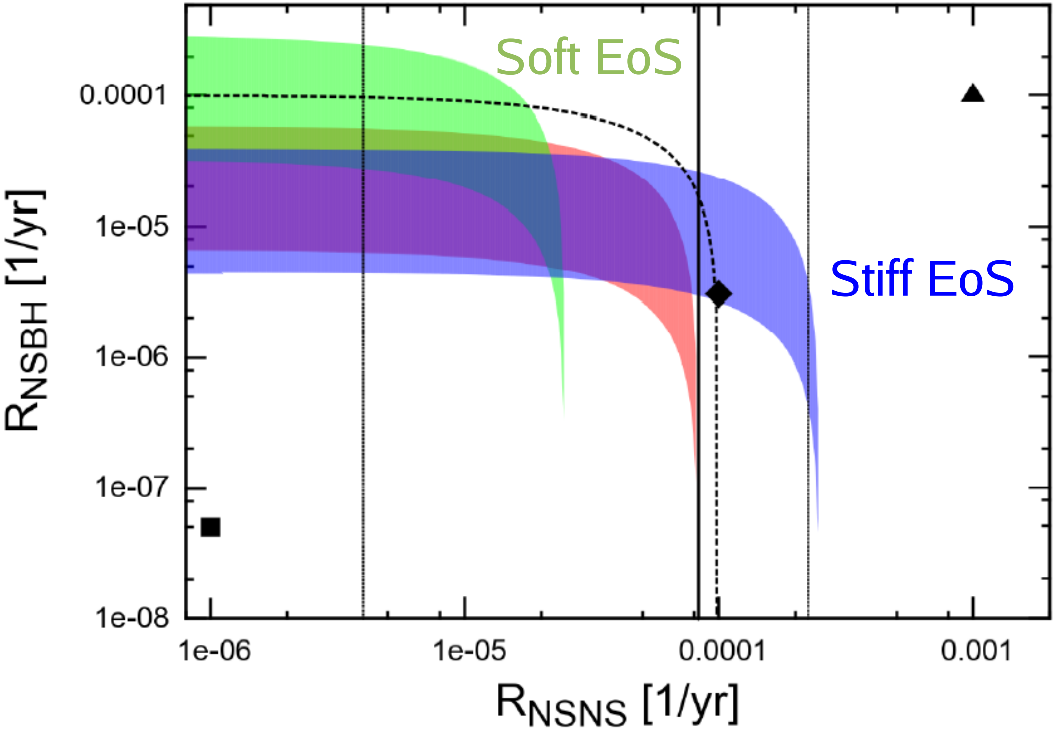
TABLE 1
EJECTA MASSES

$a_{\rm BH}$ \ $M_{\rm BH}$	$5\ M_\odot$	$7\ M_\odot$	$10\ M_\odot$
0	$0.0004\ M_\odot$	$\lesssim 2\times10^{-6}\ M_\odot$	$\lesssim 2\times10^{-6}\ M_\odot$
0.5	$0.042\ M_\odot$	$0.0090\ M_\odot$	$0.0018\ M_\odot$
0.7	$0.067\ M_\odot$	$0.070\ M_\odot$	$0.073\ M_\odot$
0.9	$0.096\ M_\odot$	$0.087\ M_\odot$	$0.086\ M_\odot$

NOTE. — NS-BH mergers with initial BH mass $M_{\rm BH}$, initial BH spin $a_{\rm BH}$, NS mass 1.35 $M_\odot$, and DD2 EoS.







Bauswein et al., ApJL 795 (2014) L9

r-process Sources

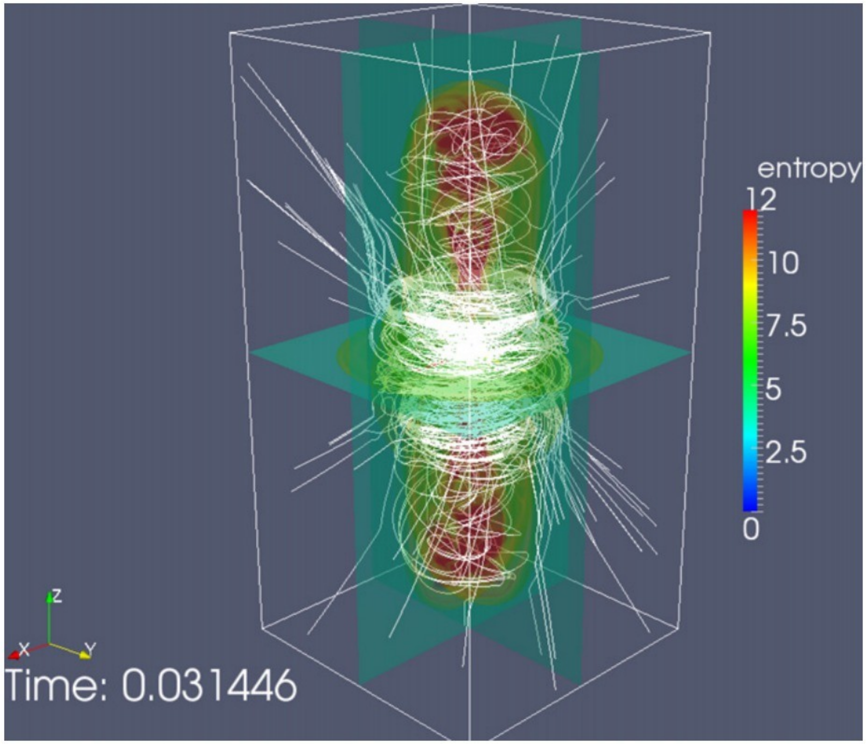
- Is there more than one heavy r-process source?

- Identification of one source does not exclude existence of other sources.

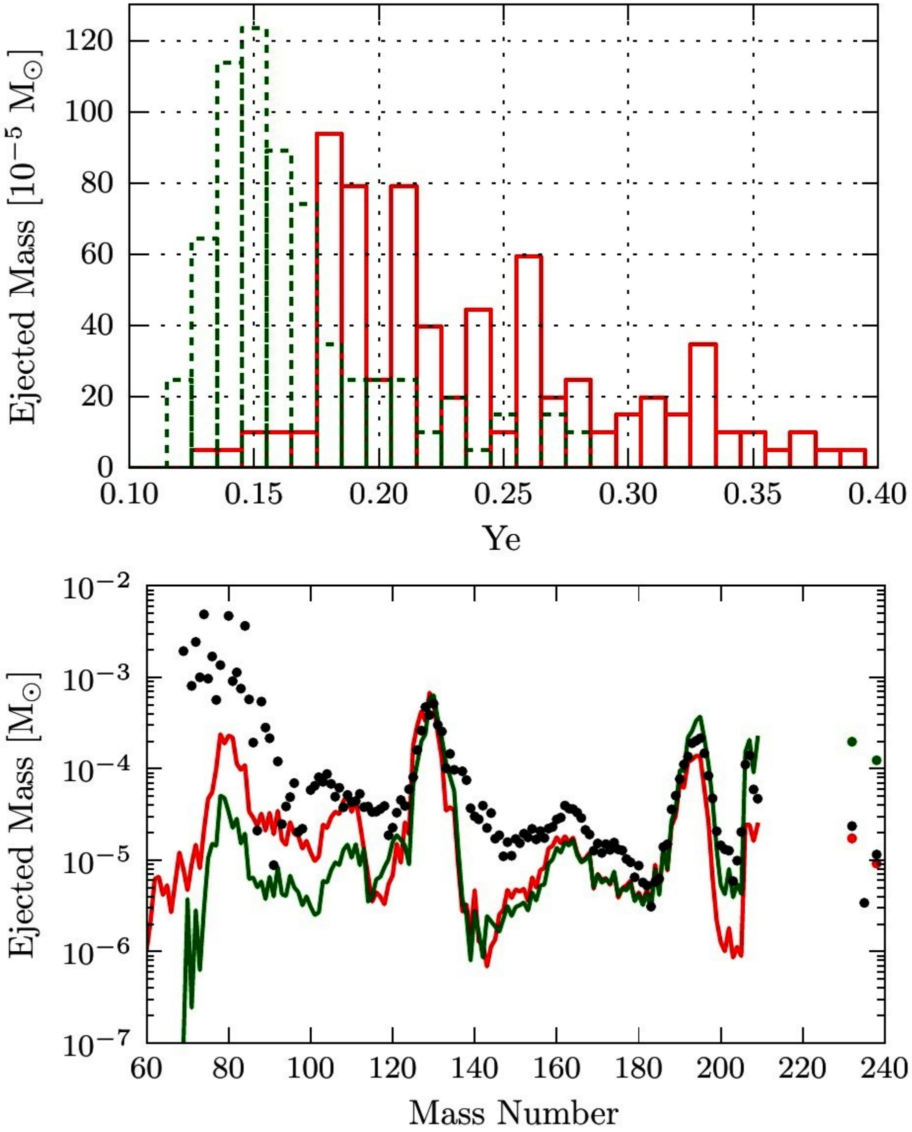
- Presence of small amounts of n-capture elements and [Sr/Ba] ratio in halo stars compared to stars in ultra-faint dwarf galaxies might suggest two different r-process sites (Ji et al., arXiv:1607.07447)

Jet-Supernova Models as r-process Sites?

- MHD-driven polar ‘jets”could sweep out n-rich matter.
- Requires extremely fast matter ejection, extremely rapid rotation and extremely strong magnetic fields in pre-collapse stellar cores.
- Should be very rare event; maybe 1 of 1000 stellar core collapses?



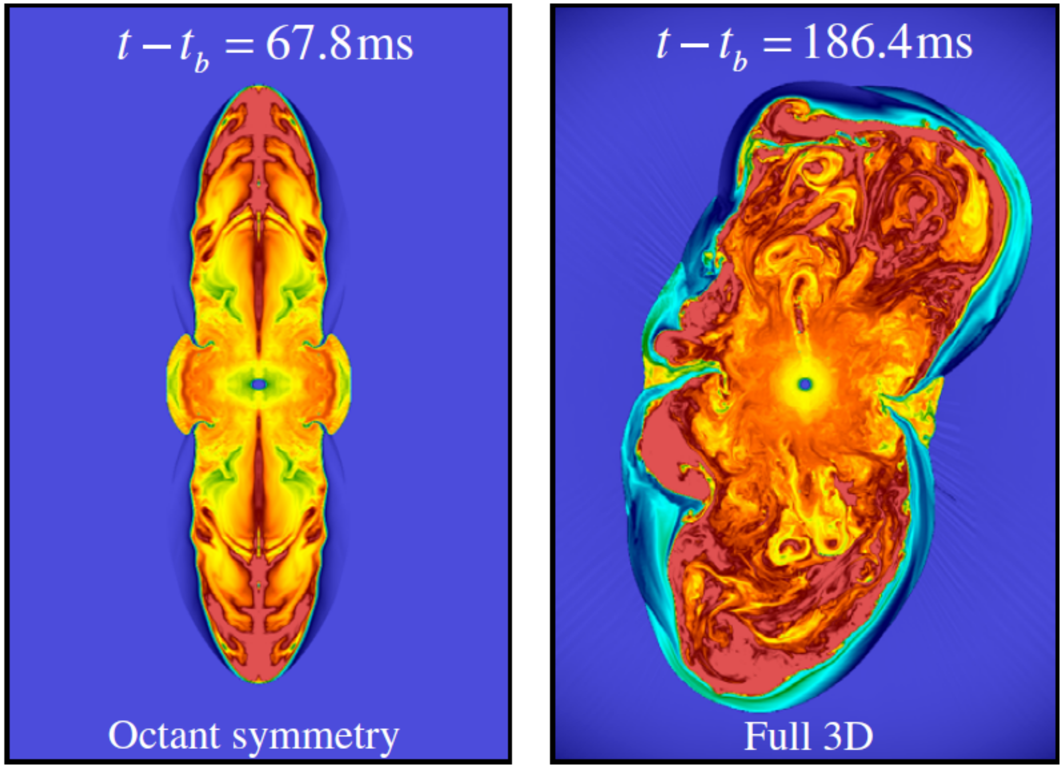
Winteler et al., ApJL 750 (2012) L22



Jet-Supernova Models as r-process Sites?

BUT:

- **MHD-driven polar "jets" in 3D develop kink instability.**
- **Assumed initial conditions not supported by stellar pre-collapse models.**
- **Dynamical scenario does not provide environment for robust r-process.**



Mösta et al., ApJL 785 (2014) L29

Summary and Conclusions

- Strong r-processing hard to achieve at supernova conditions.
- O-Ne-Mg core explosions are favorable sites for weak r-process.
- NS+NS/BH mergers are likely sites for strong r-process.
- Mass of NS+NS/BH merger ejecta sensitively depends on nuclear equation of state and BH spin.
- Properties of electromagnetic transients of compact object mergers are strongly and systematically affected by elemental composition of ejecta (cf. GRB130603B)
- Nucleosynthesis relatively weakly sensitive to EoS,
  but for NS-NS mergers depends on neutrino emission & absorption
  —> relevance for ejecta opacity!
- Chemogalactic implications require careful studies with detailed hydrodynamical models of Galaxy evolution