Max-Planck-Institut
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Workshop on Binary Neutron Star Mergers
Thessaloniki, Greece, May 27–29, 2015

Mass Ejection, Outflows, and r-Process Nucleosynthesis in Compact Binary Mergers

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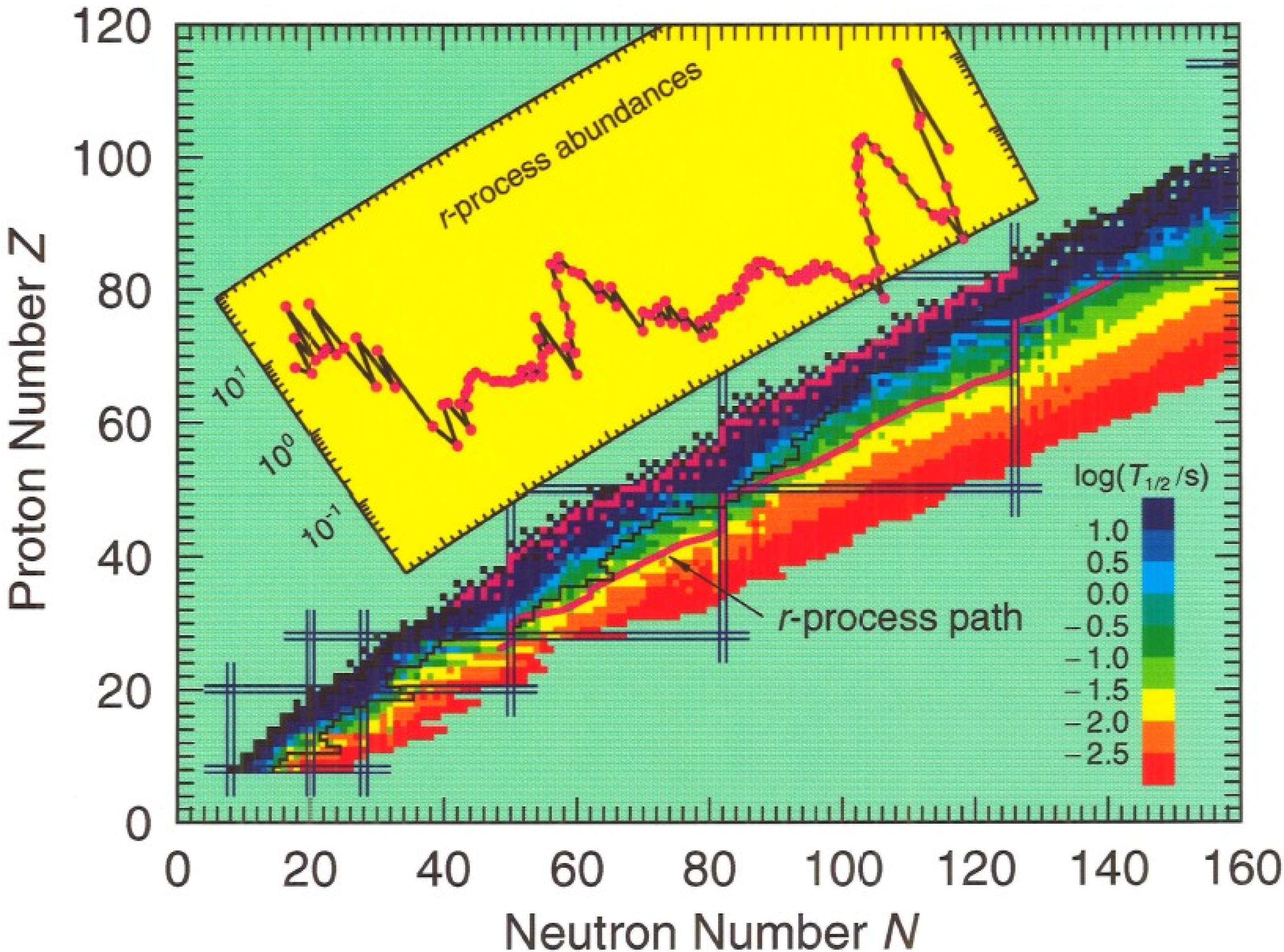
Max Planck Institute for Astrophysics, Garching

Outline

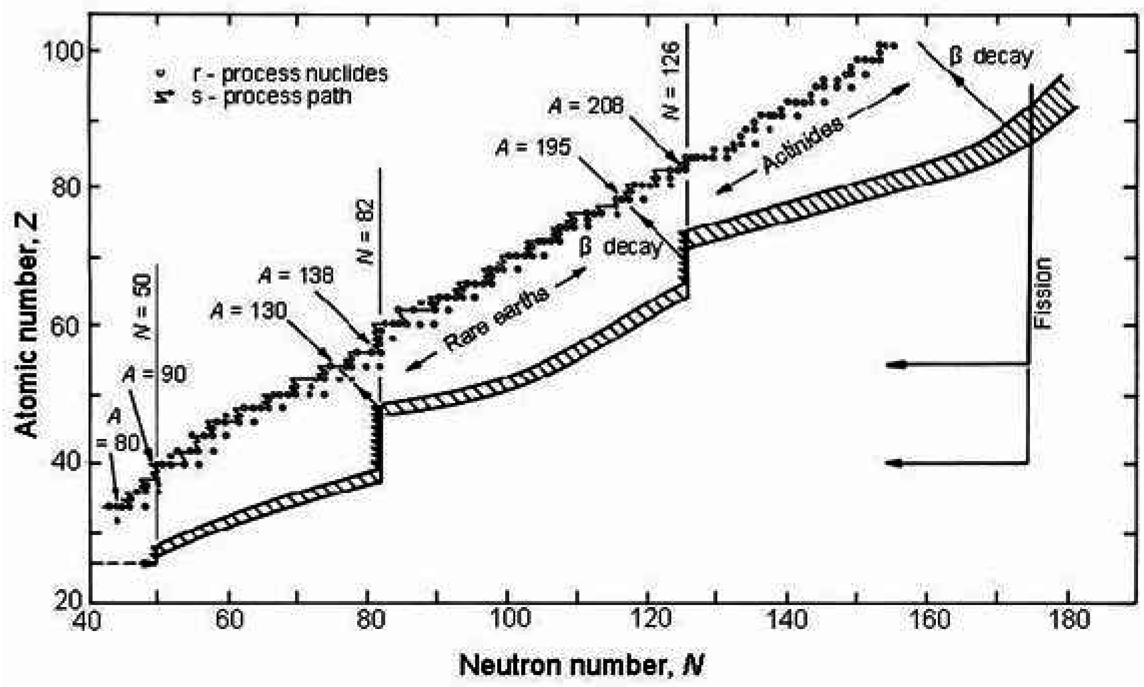
- Introduction: The r-process riddle
- Supernovae as candidate sites of r-processing
- Neutron star mergers as likely sites of r-process production

s- and r-Process Nucleosynthesis



Courtesy: K.-L. Kratz

s- and r-Process Nucleosynthesis



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

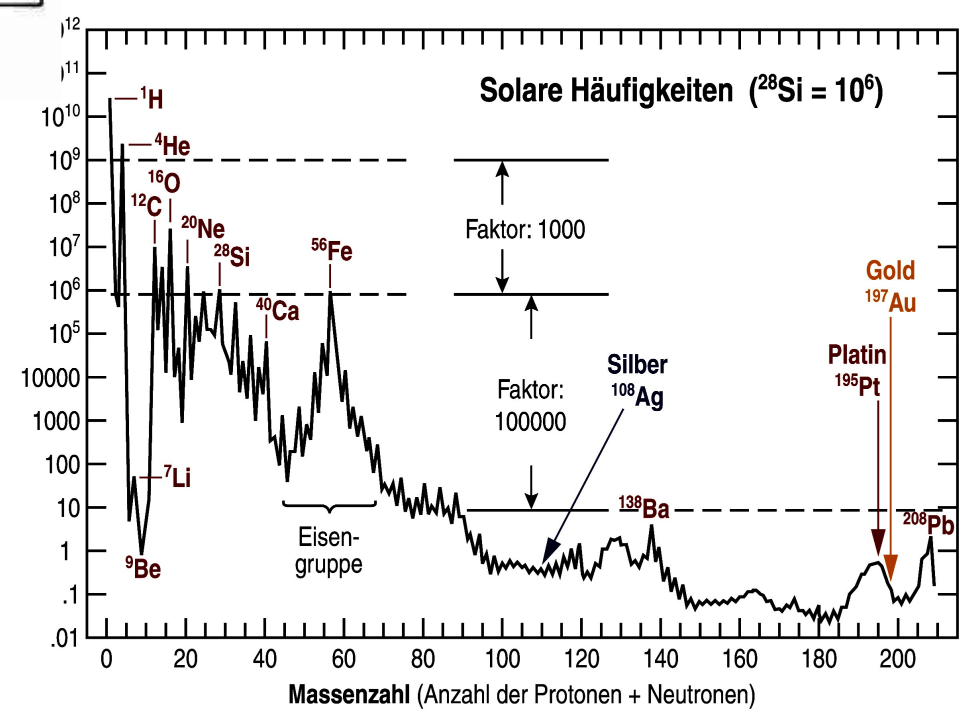
One of greatest mysteries of nuclear astrophysics.

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

n-capture timescale << ß-decay timescale

→ high neutron densities required

→ explosive event(s)

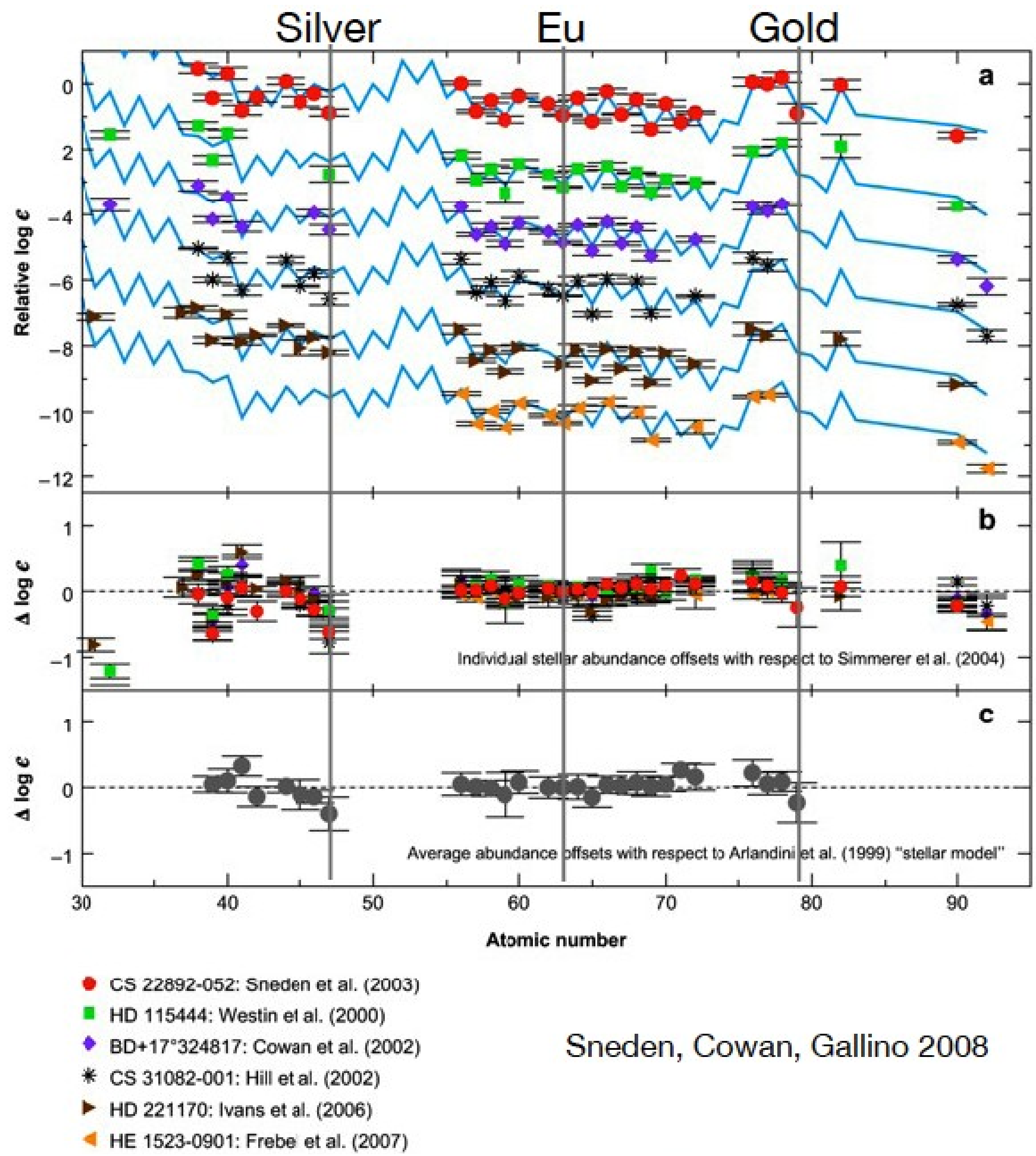


R-Process Elements in Ultra Metal-Poor Stars

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

Uniform pattern for 56 < Z < 83

Larger scatter for Z < 50



Sneden, Cowan, Gallino 2008

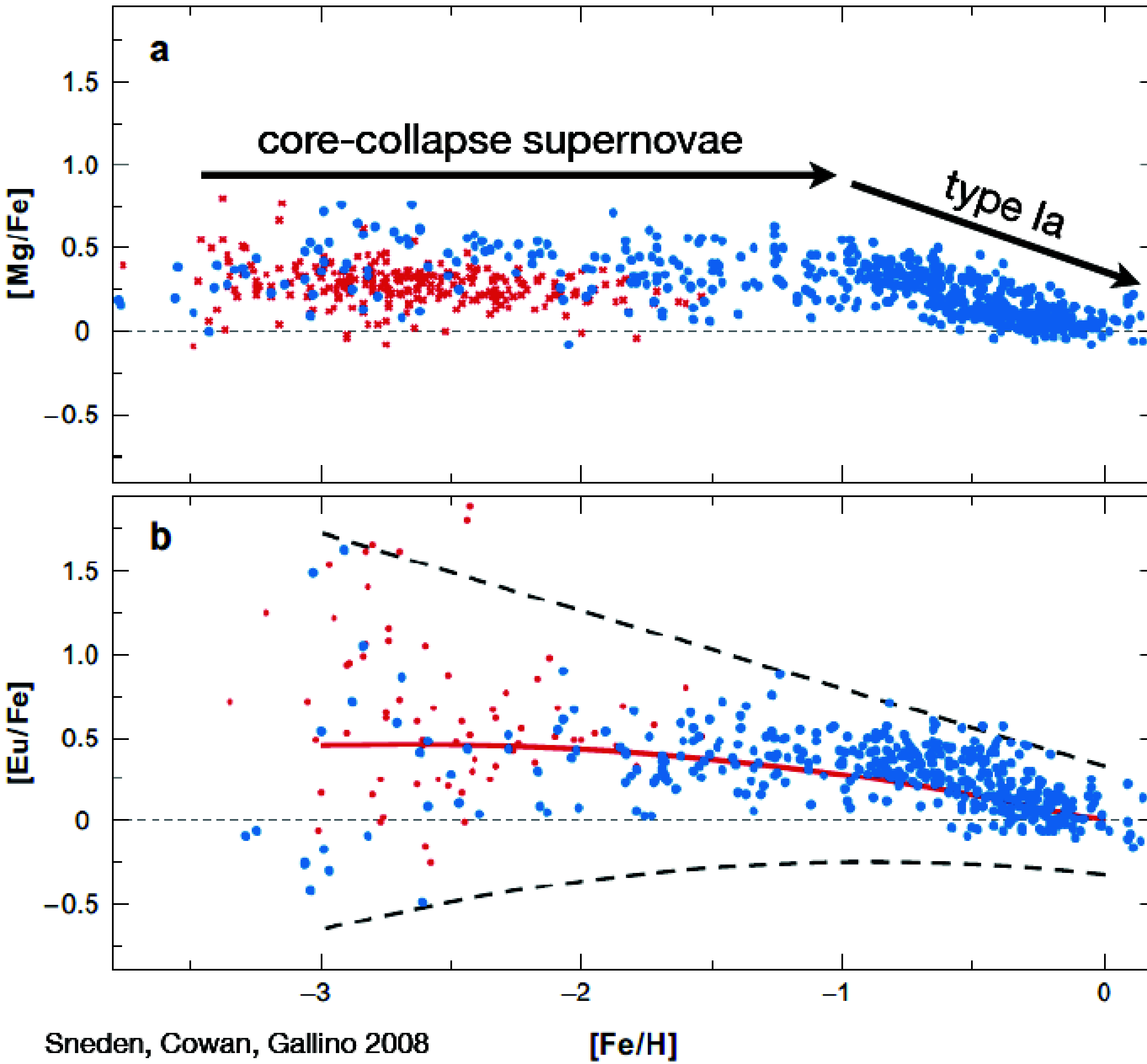
Metallicity Evolution of R-Element Enrichment

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

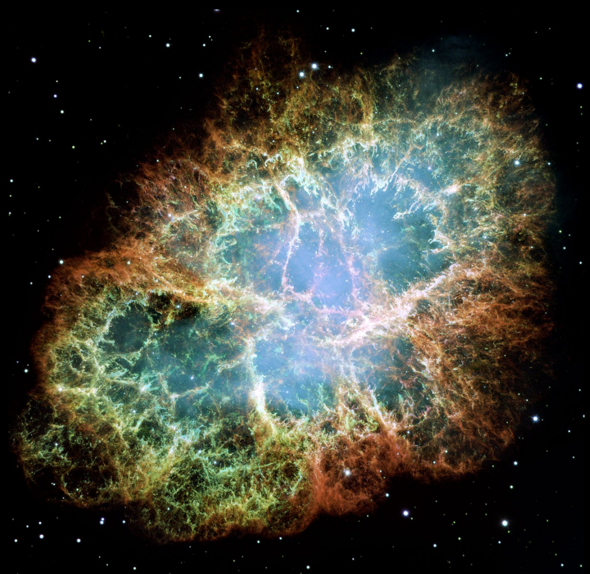
- Physical conditions of the ejecta <——>

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

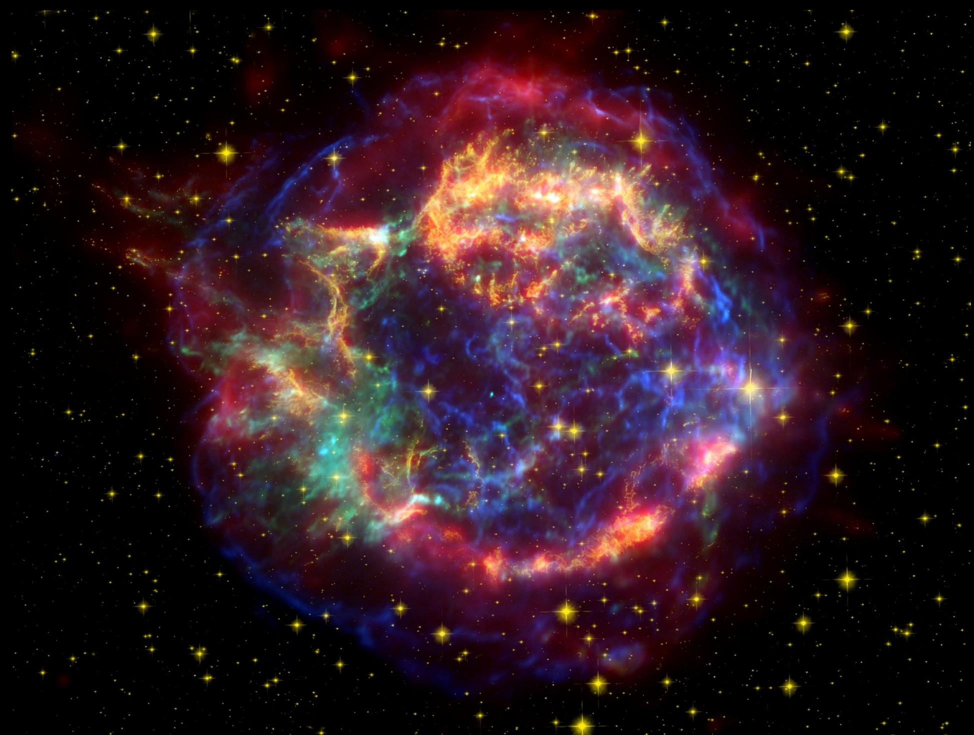
- Ejecta mass and frequency of source <——>
  Main source or sub-dominant contributor?

- Element enrichment history of Galaxy <——>
  Can one astrophysical source explain all observations?

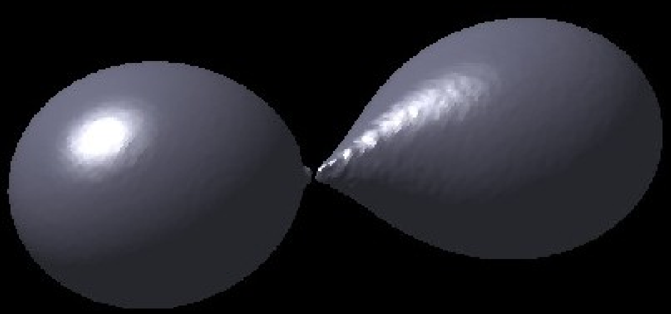
Explosive Origins of Heavy Elements



Supernova 1054



Supernova ~1680



Neutron Star Merger

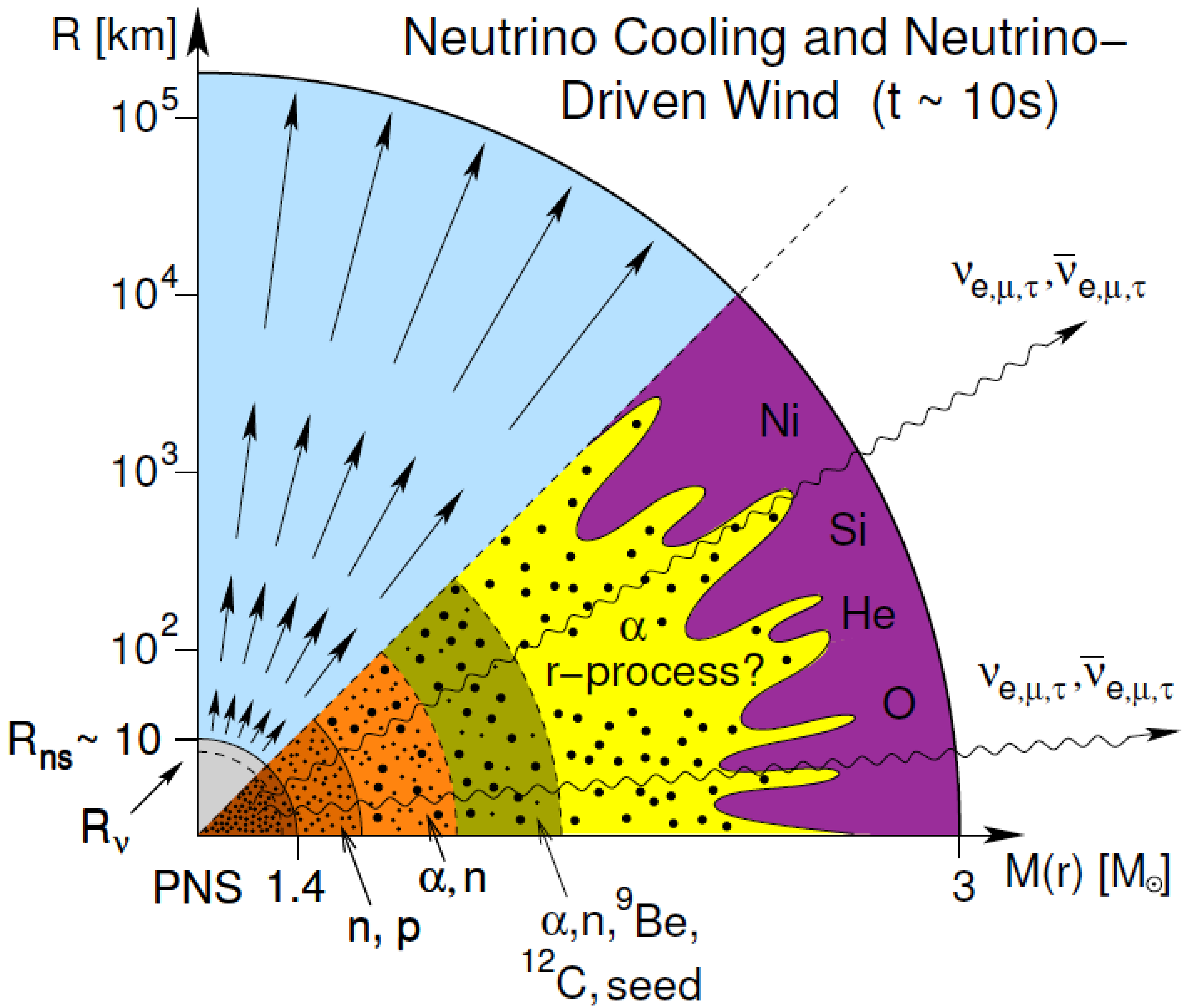
Supernovae as Potential Site of r-Process Element Production

R-Process Scenarios in Supernovae

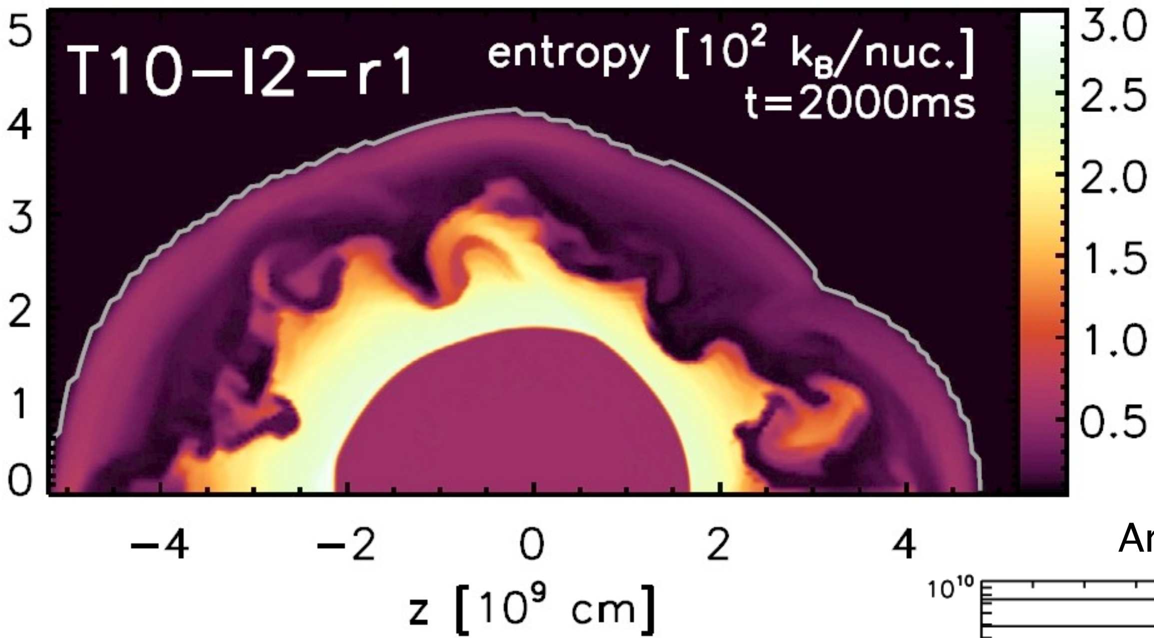
- Dynamical ejecta of prompt explosions (of O-Ne-Mg cores) (Hillebrandt, Takahashi & Kodama 1976; Wheeler, Cowan & Hillebrandt 1998; Wanajo 2002)
- He-shell exposed to intense neutrino flux (Epstein, Colgate, & Haxton 1988; Banerjee et al. 2011)
- Neutrino-driven wind from proto-neutron stars (Woosley et al. 1994)
- C+O layer of O-Ne-Mg-core ("electron-capture") supernovae (Ning, Qian & Meyer 2007)
- Magnetohydrodynamic jets of rare core-collapse supernovae (Winteler et al. 2013, Nishimura et al.)
- Ejection of fallback material (Fryer et al. 2006)

- Some more...?

Neutrino-Driven Wind from Proto-Neutron Stars

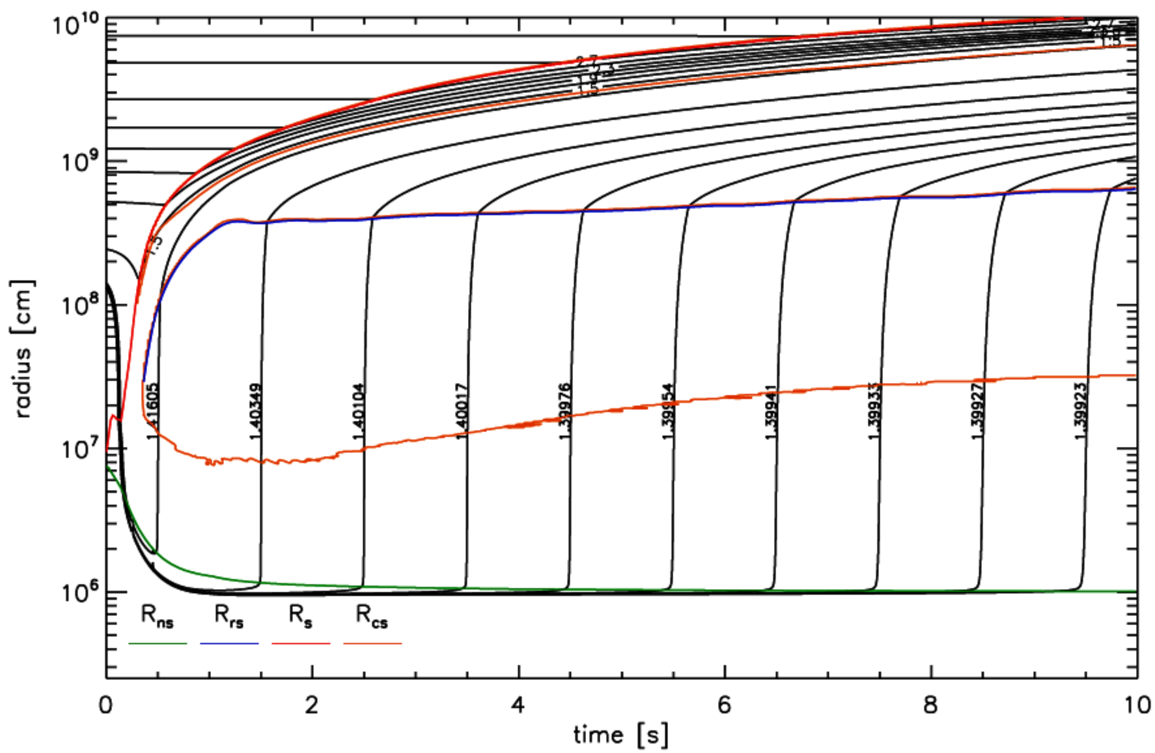


Neutrino-Driven Wind from Proto-Neutron Stars



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:

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

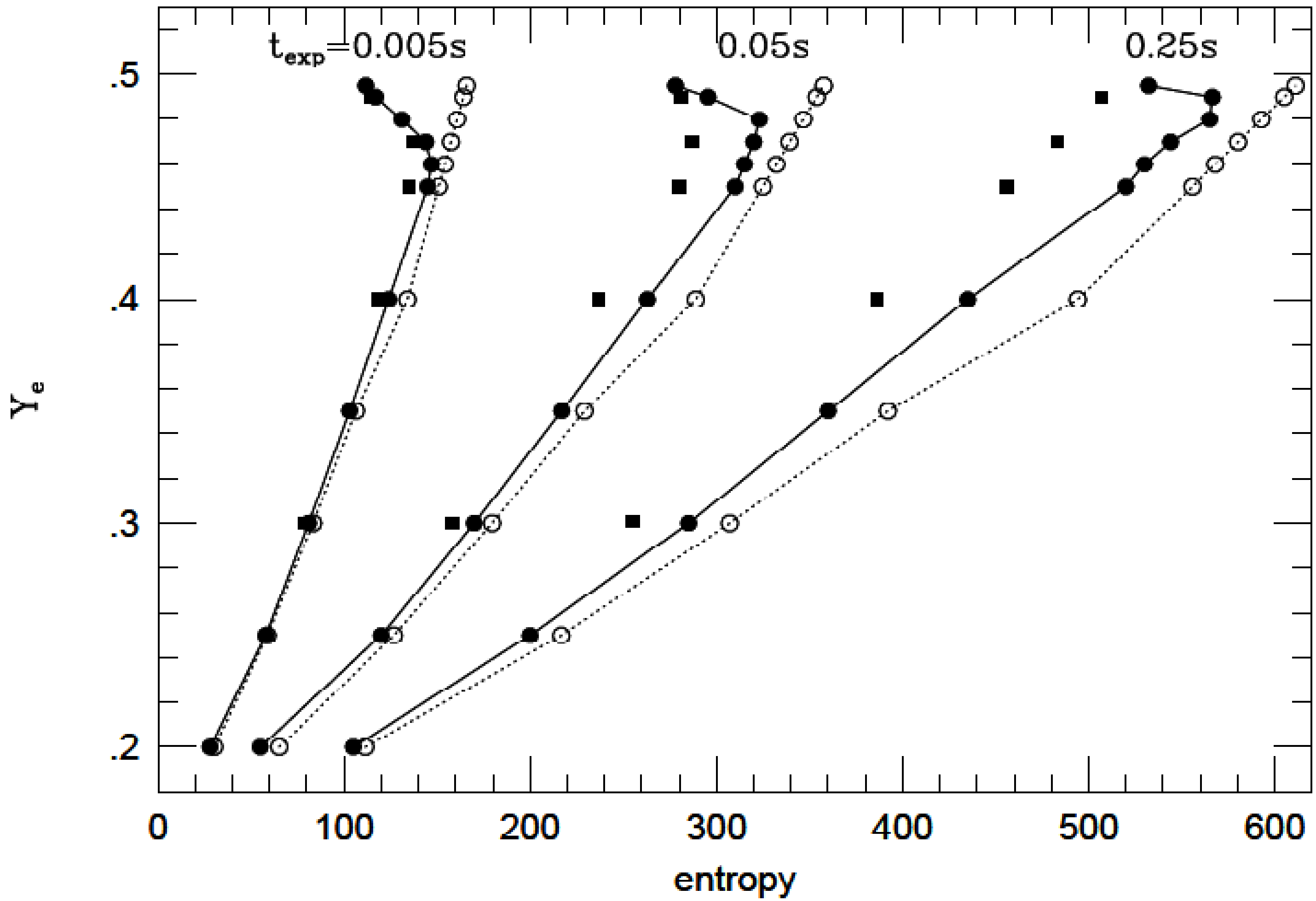
$$\boxed{Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta)}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta)}\right]^{-1}}$$

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

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

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

Requirements for strong r-Process Including Third Abundance Peak



(Hoffman, Woosley & Qian 2007)

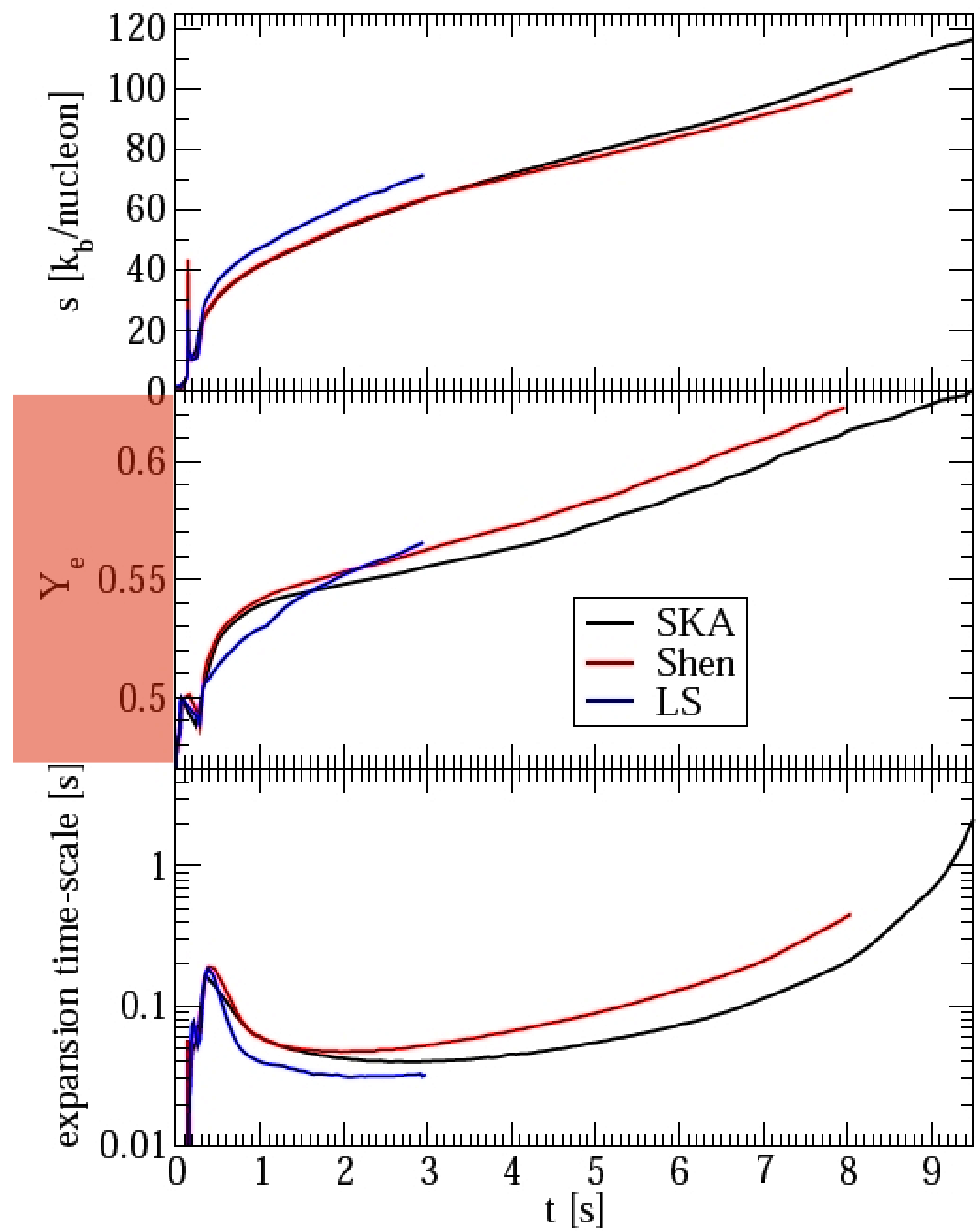
FIG. 10.—The combinations of Y_e, entropy, and expansion time required for the production of the $A \sim 195$ *r*-process peak nuclei. Circles connected by lines are for various fixed expansion times. Shown are the values derived in the numerical study using equation (7) (*filled circles*) and those 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

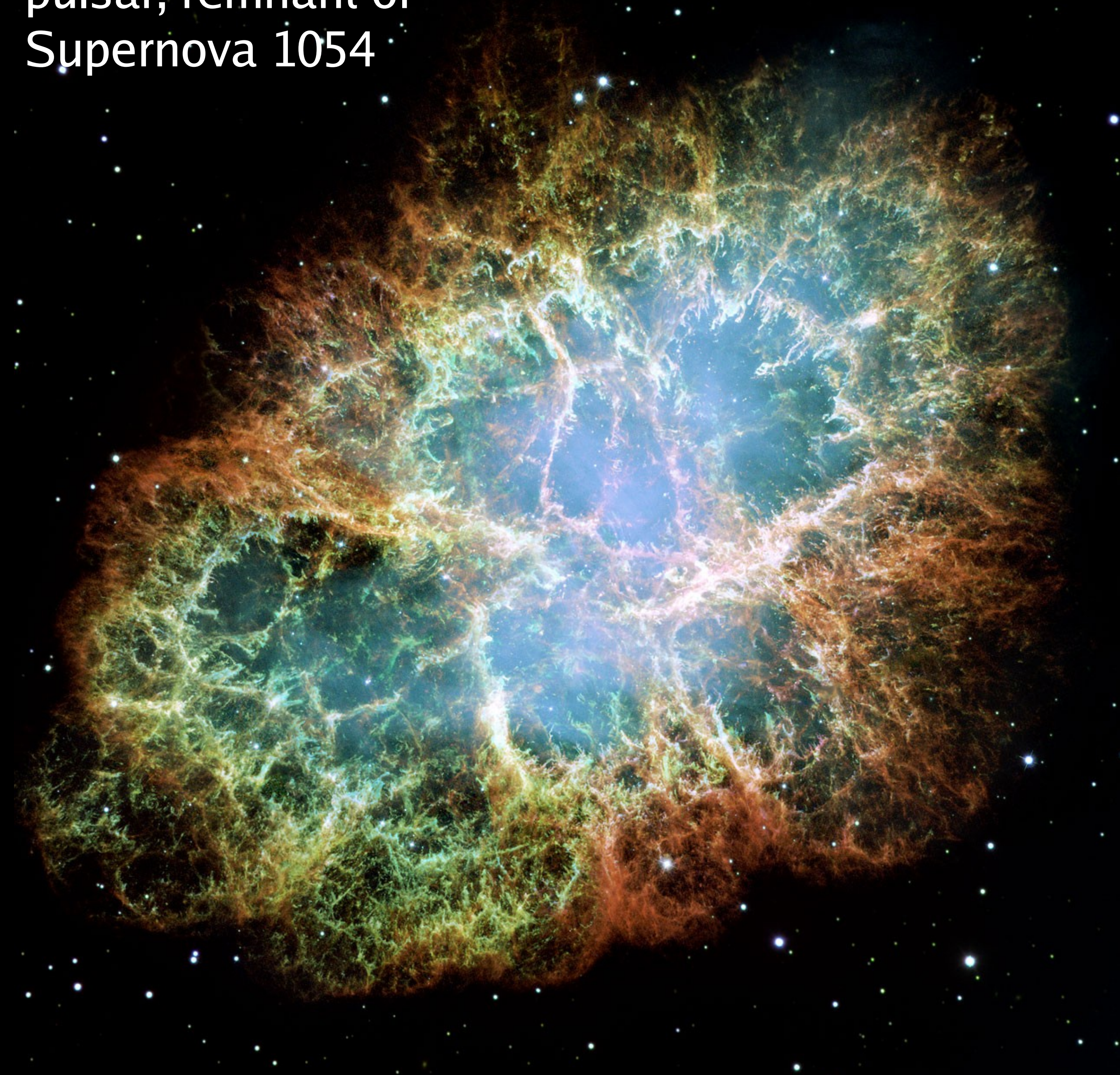
- Neutrino-driven wind remains p-rich for >10 seconds!
- No r-process in the late neutrino-driven wind!
- Holds also for more massive progenitos (Fischer et al. 2009)

Hüdepohl (Diploma Thesis 2009);
Hüdepohl et al. (PRL 104 (2010); arXiv:0912:0260)

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



CRAB Nebula with pulsar, remnant of Supernova 1054



Explosion properties:

$E_{exp} \sim 10^{50}$ erg = 0.1 bethe

$M_{Ni} \sim 0.003\ M_{sun}$

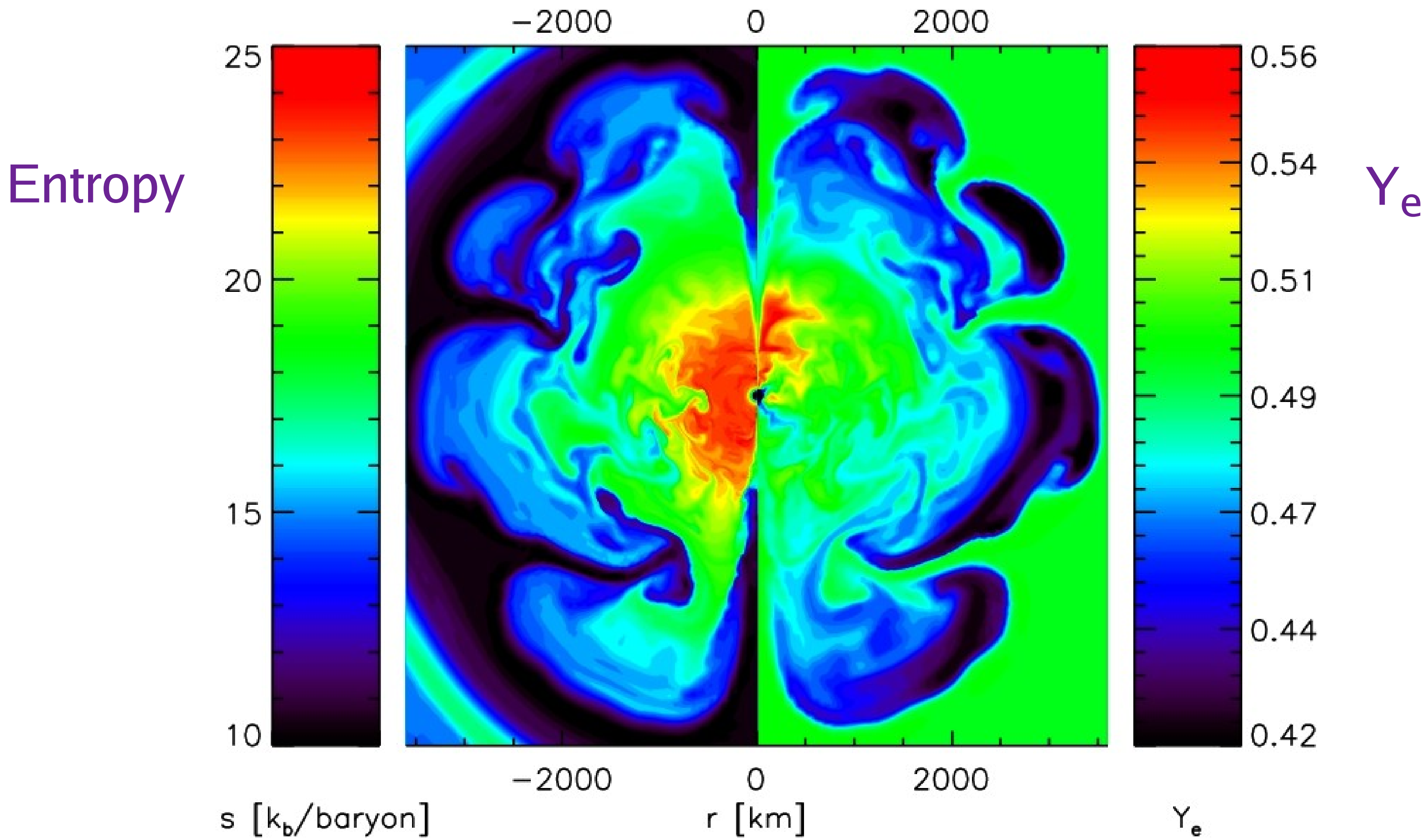
Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with CRAB (SN1054)

(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 leads to slight increase of explosion energy, causes explosion asymmetries, and ejects n-rich matter!



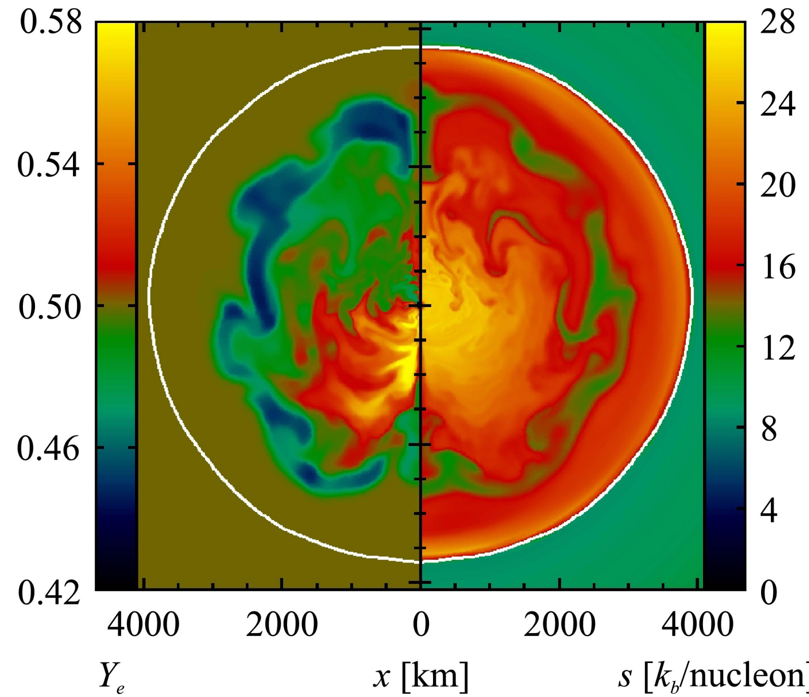
t = 0.262 s after core bounce

Nucleosynthesis in Neutrino-Heated SN Ejecta

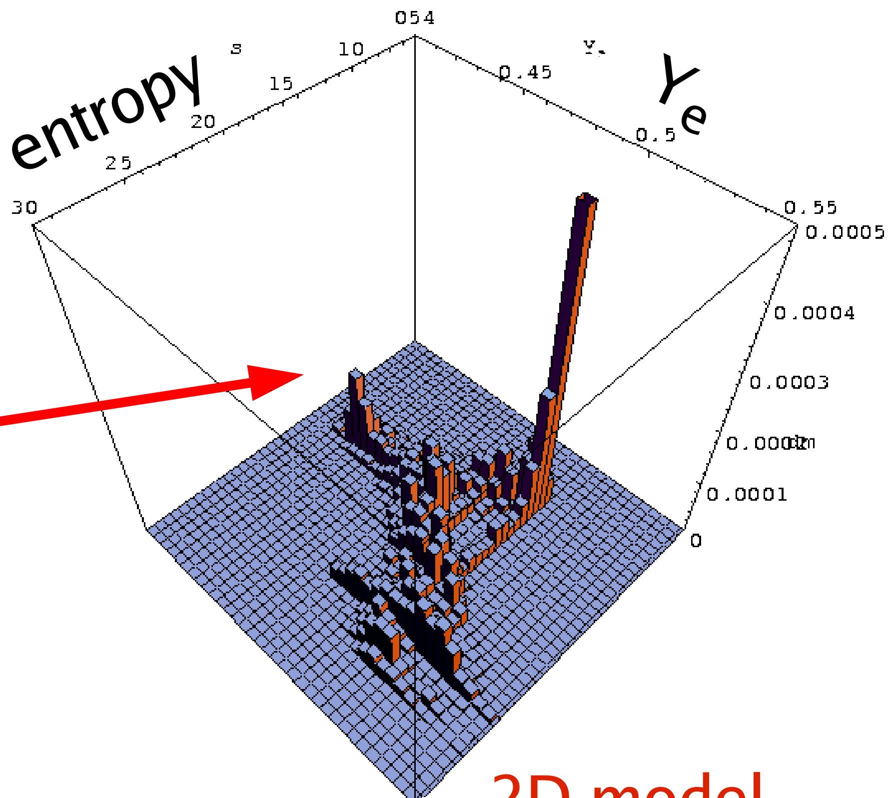
Convectively ejected n-rich matter makes ONeMg-core and low-mass Fe-core supernovae an interesting source of nuclei between the iron group and N = 50 (from Zn to Zr), possibly also of weak r-process nuclei.

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

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

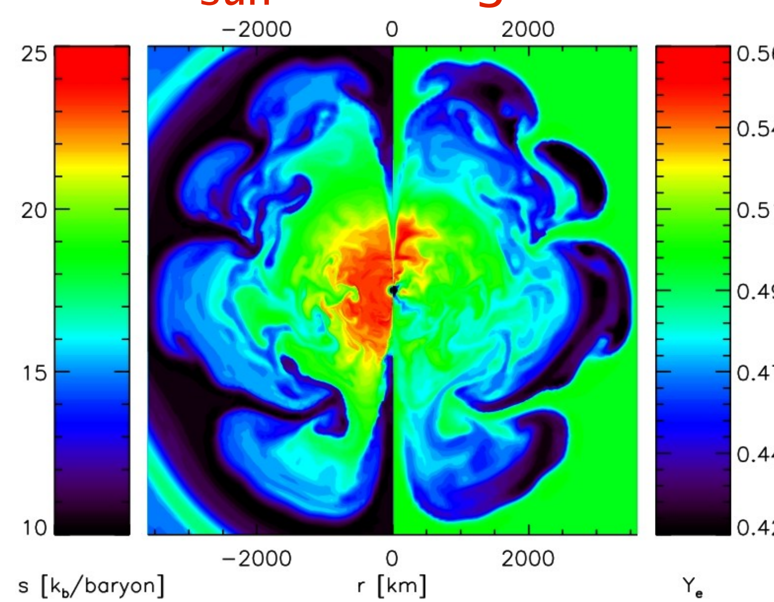


n-rich matter

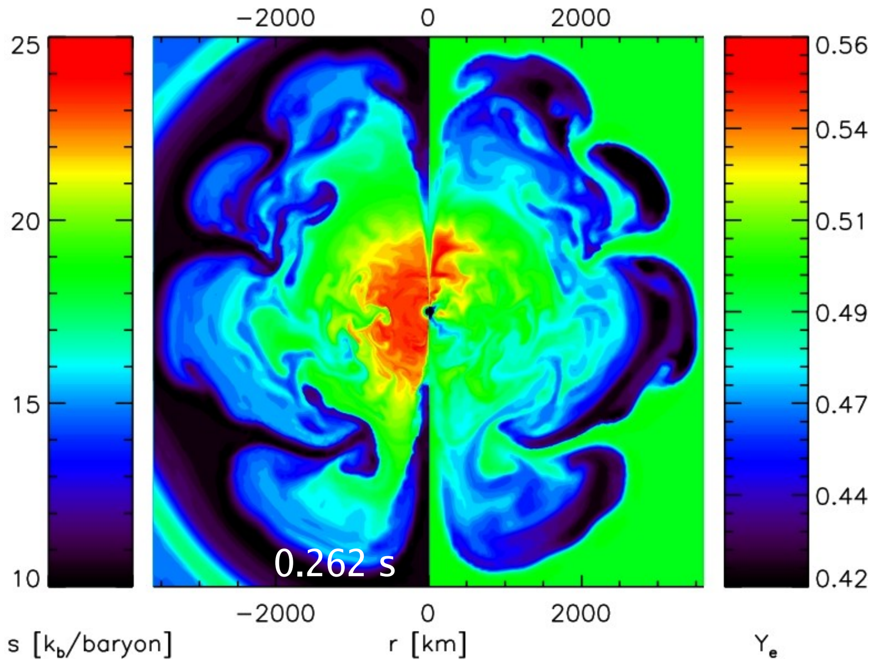


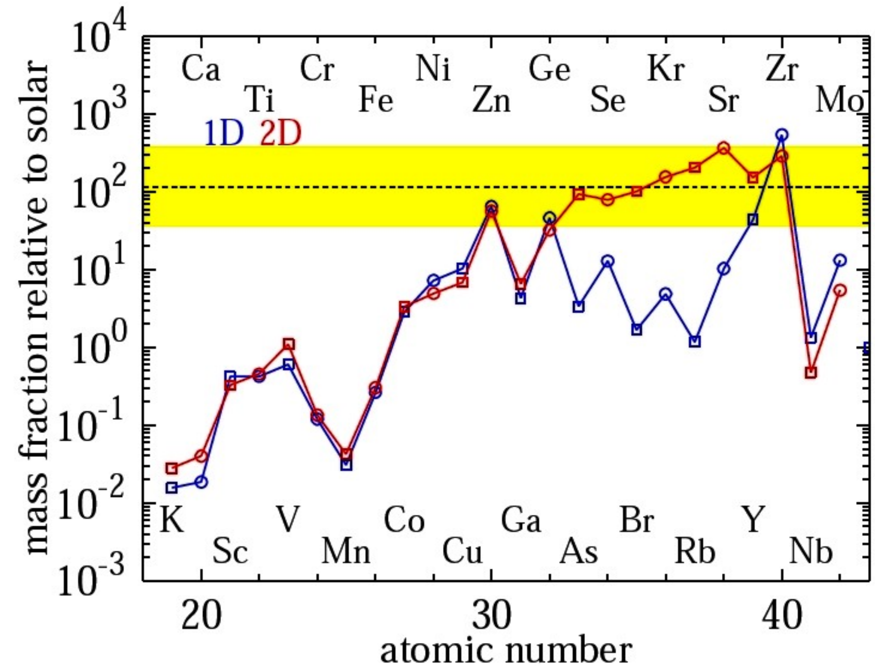
2D model

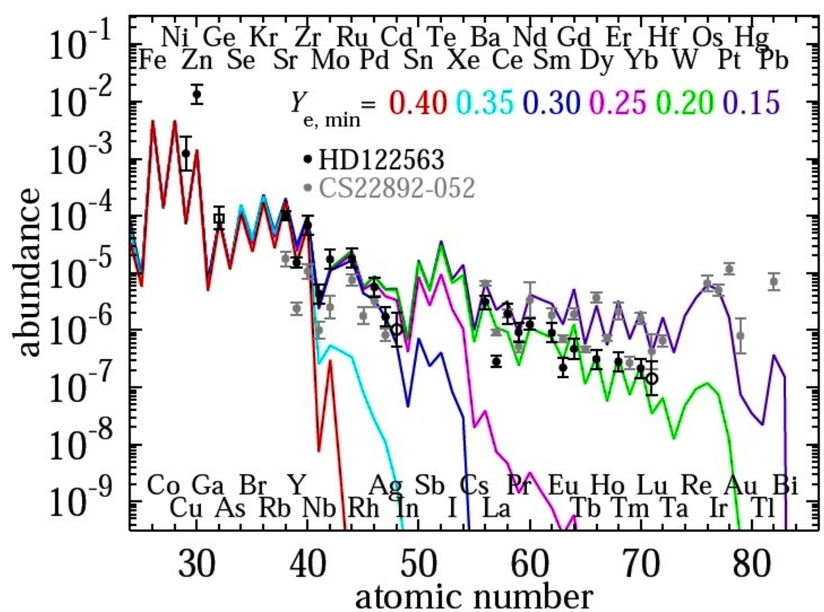
8.8 M_{sun} O-Ne-Mg core SN



Nucleosynthesis in O-Ne-Mg Core SNe







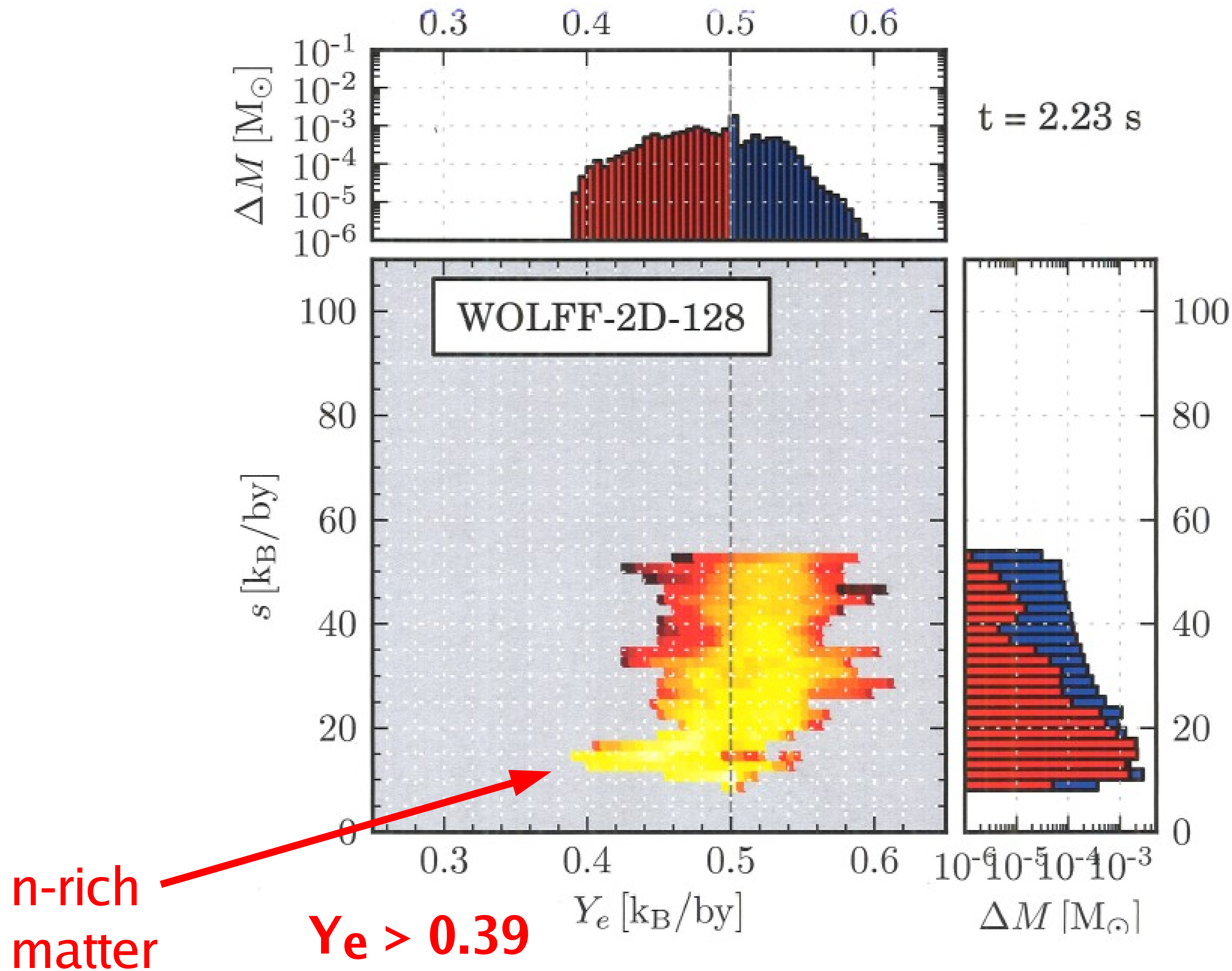
Convectively ejected n-rich matter makes ONeMg-core supernovae an interesting source of nuclei between iron group and N = 50 (from Zn to Zr).

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)

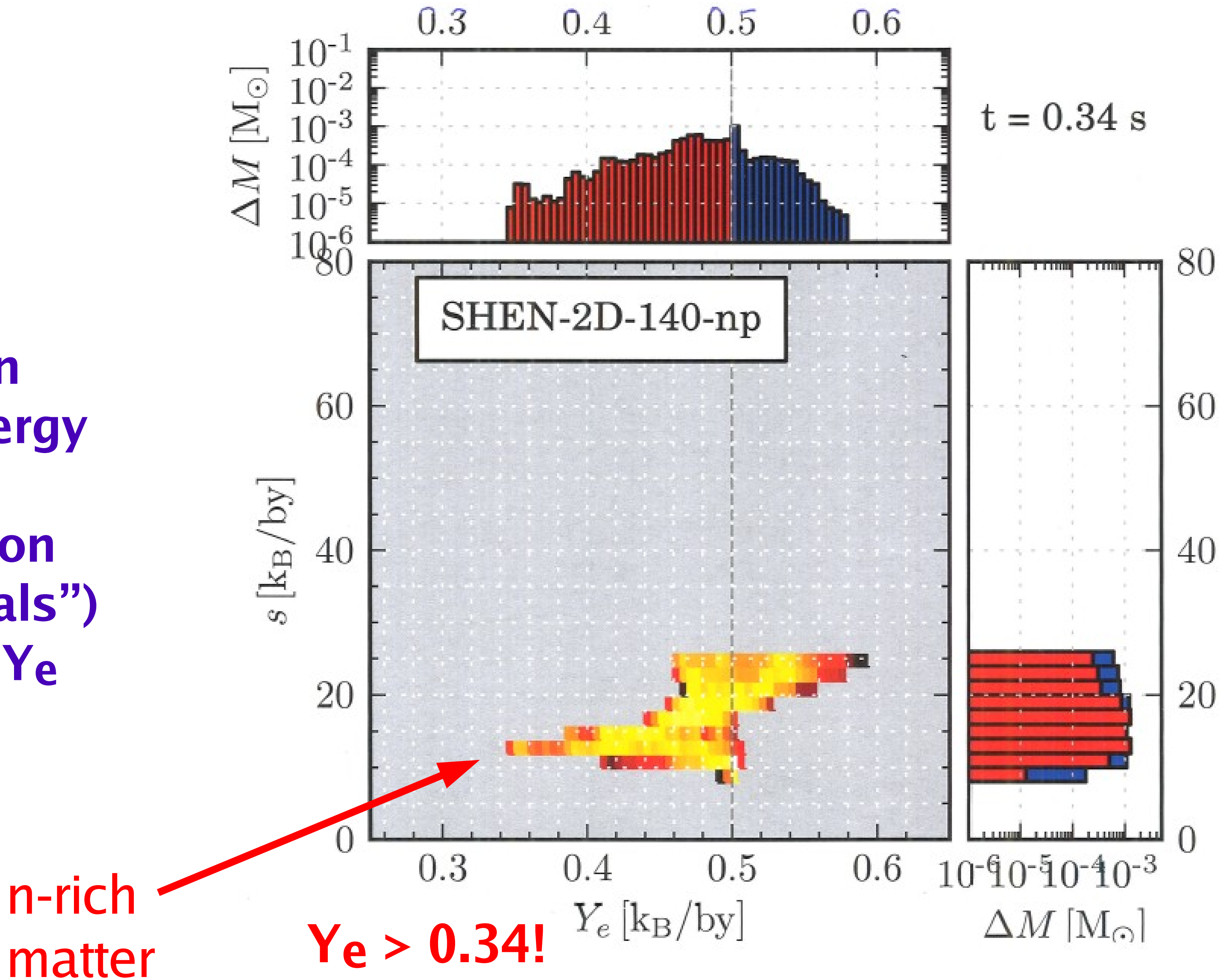
Ejecta Conditions in O-Ne-Mg Core SNe



Janina v. Groote, PhD Thesis

Ejecta Conditions in O-Ne-Mg Core SNe

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



Y_e > 0.34!

Janina v. Groote, PhD Thesis

Ejecta Conditions in O-Ne-Mg Core SNe

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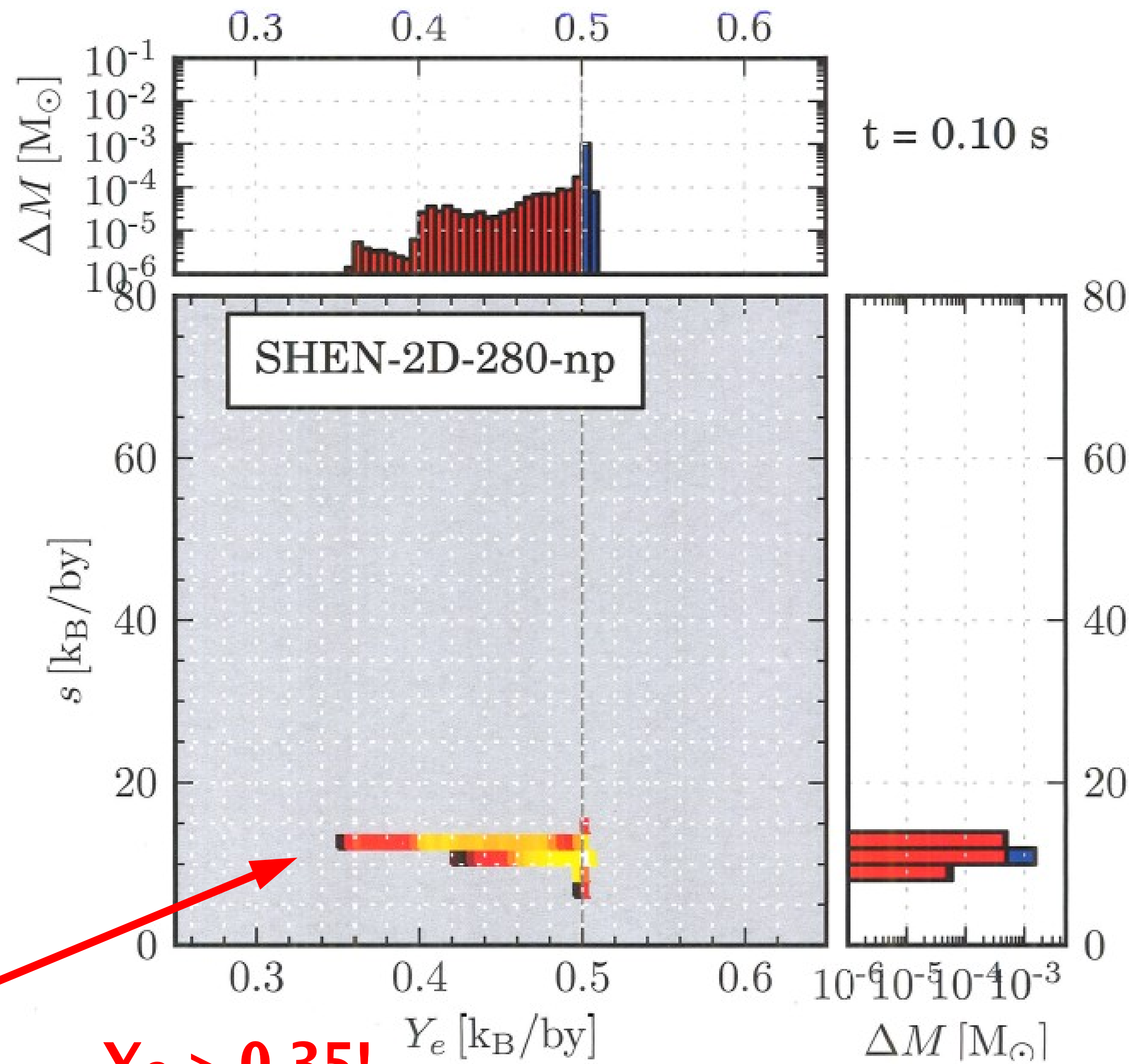


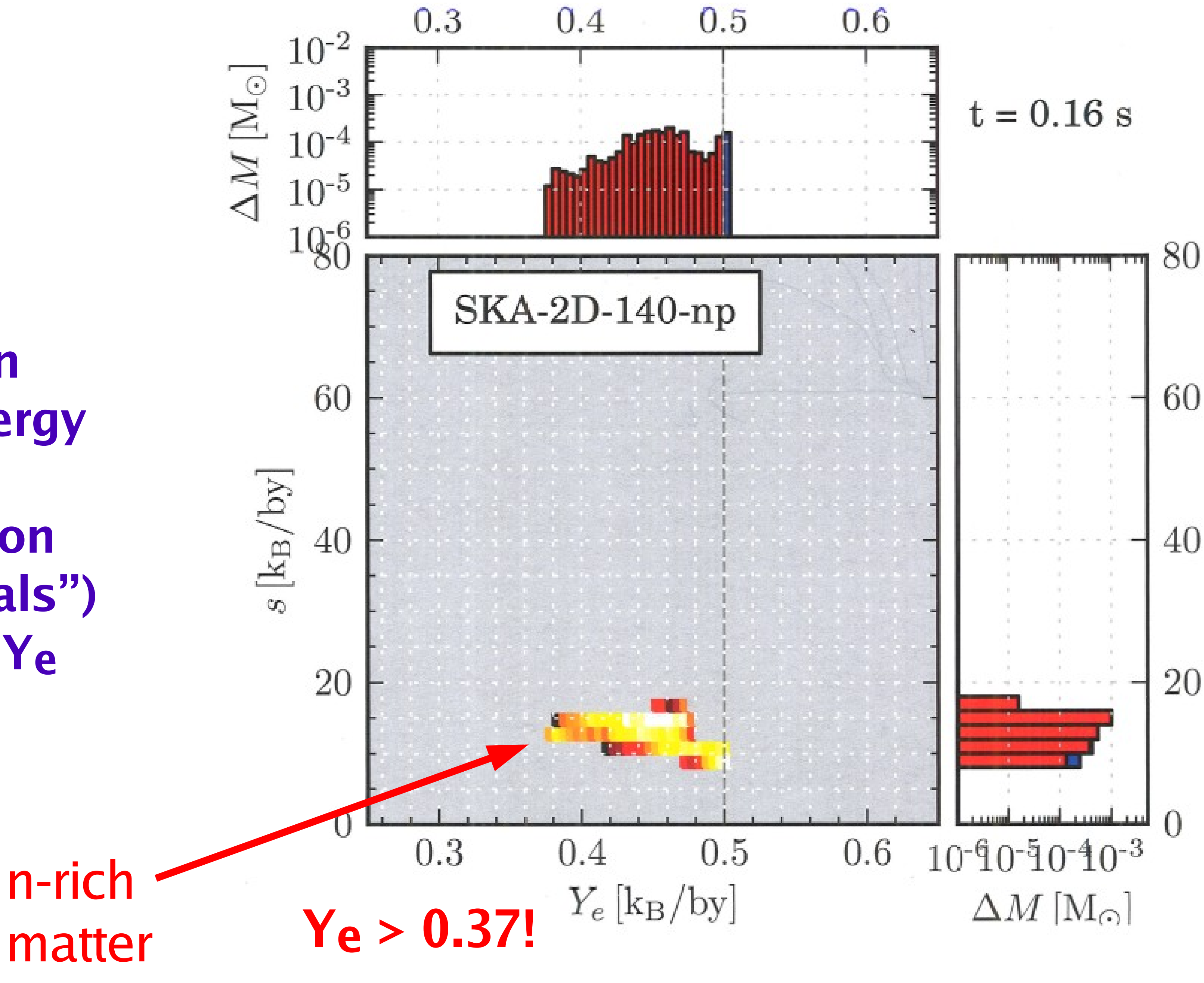
Janina v. Groote, PhD Thesis

n-rich matter

Y_e > 0.35!

Ejecta Conditions in O-Ne-Mg Core SNe

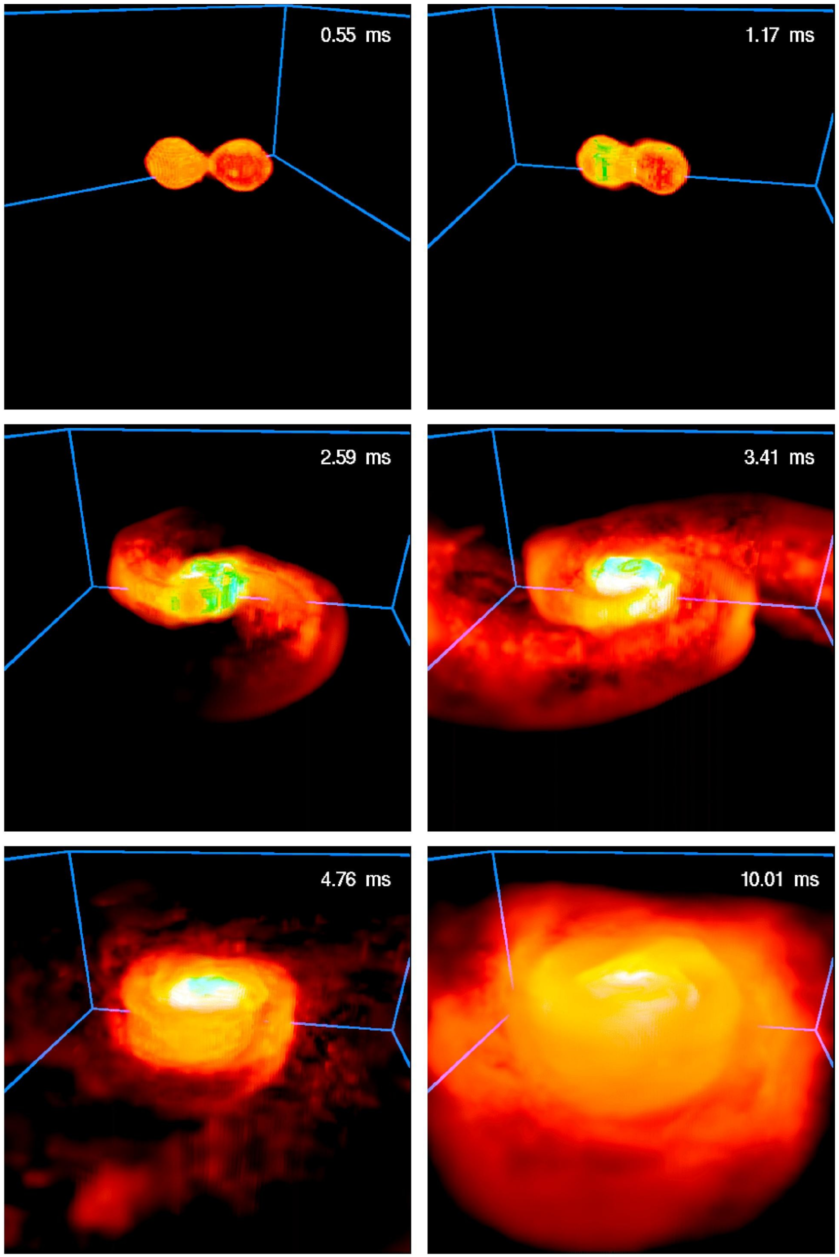
Nucleon self-energy shifts ("nucleon potentials") reduce Y_e

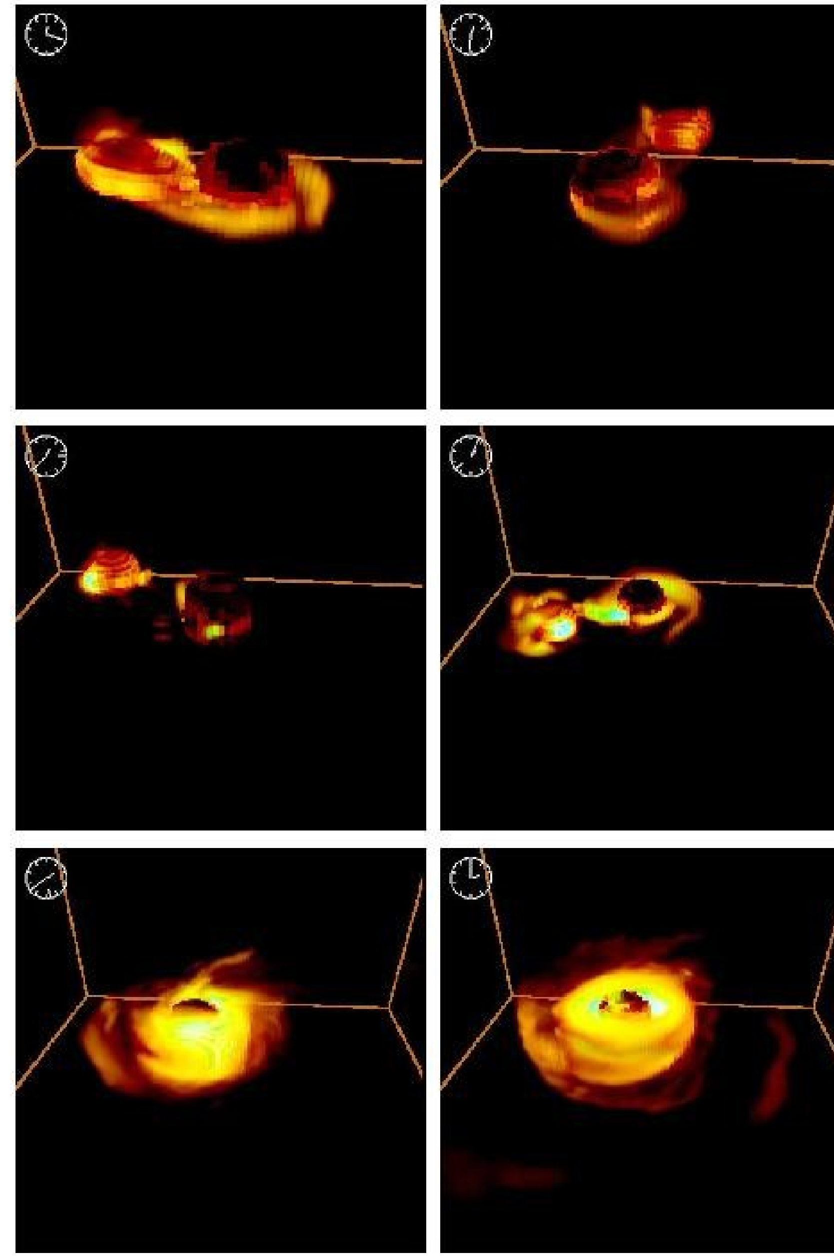


Janina v. Groote, PhD Thesis

Compact Binary Mergers as Origin of r-Process Elements

NS+NS/BH Mergers

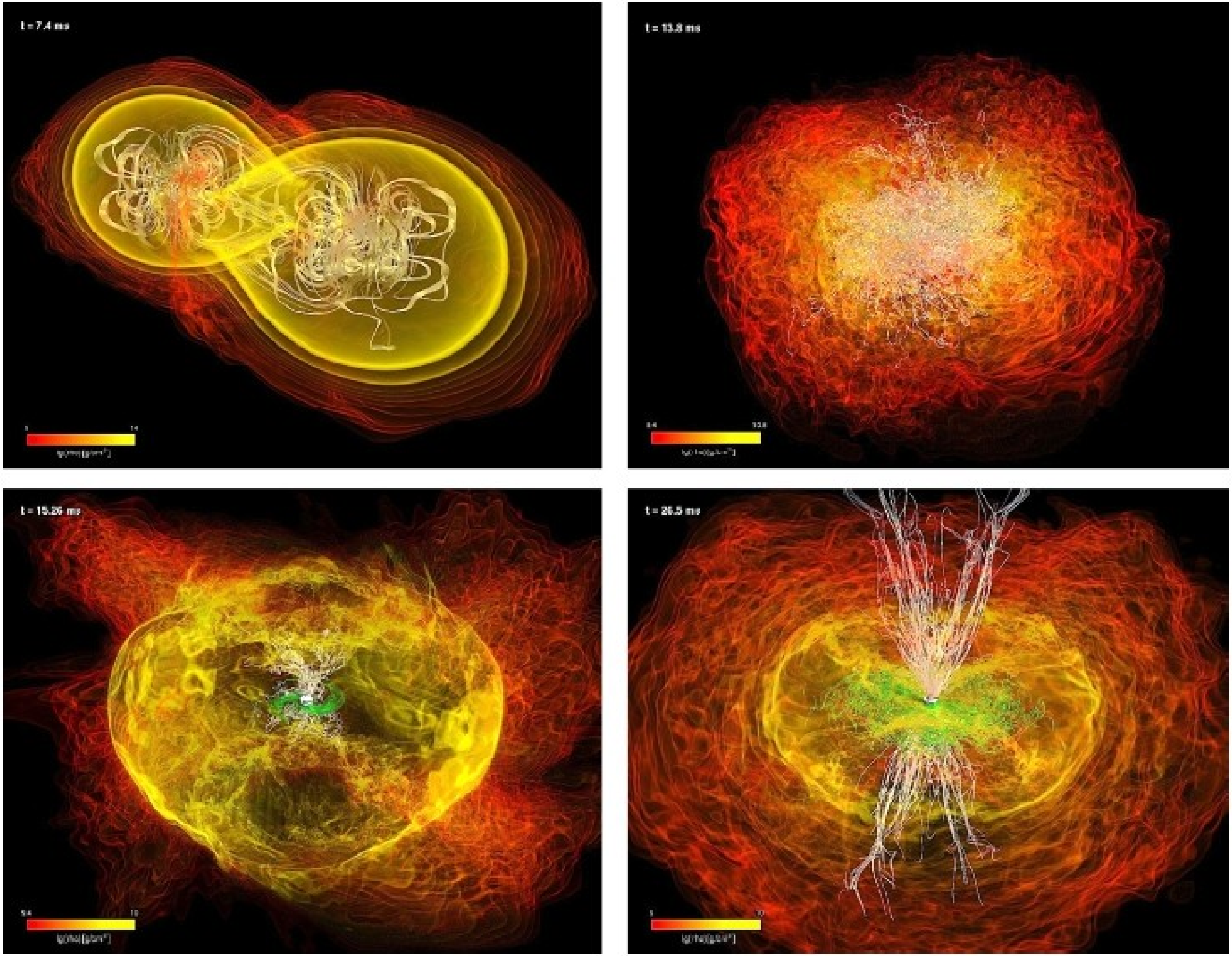




Ruffert et al.
Rosswog et al.
Oechslin et al.
Shibata et al.
Rezzolla et al.
Rasio et al.
Lehner et al.
Foucart et al.

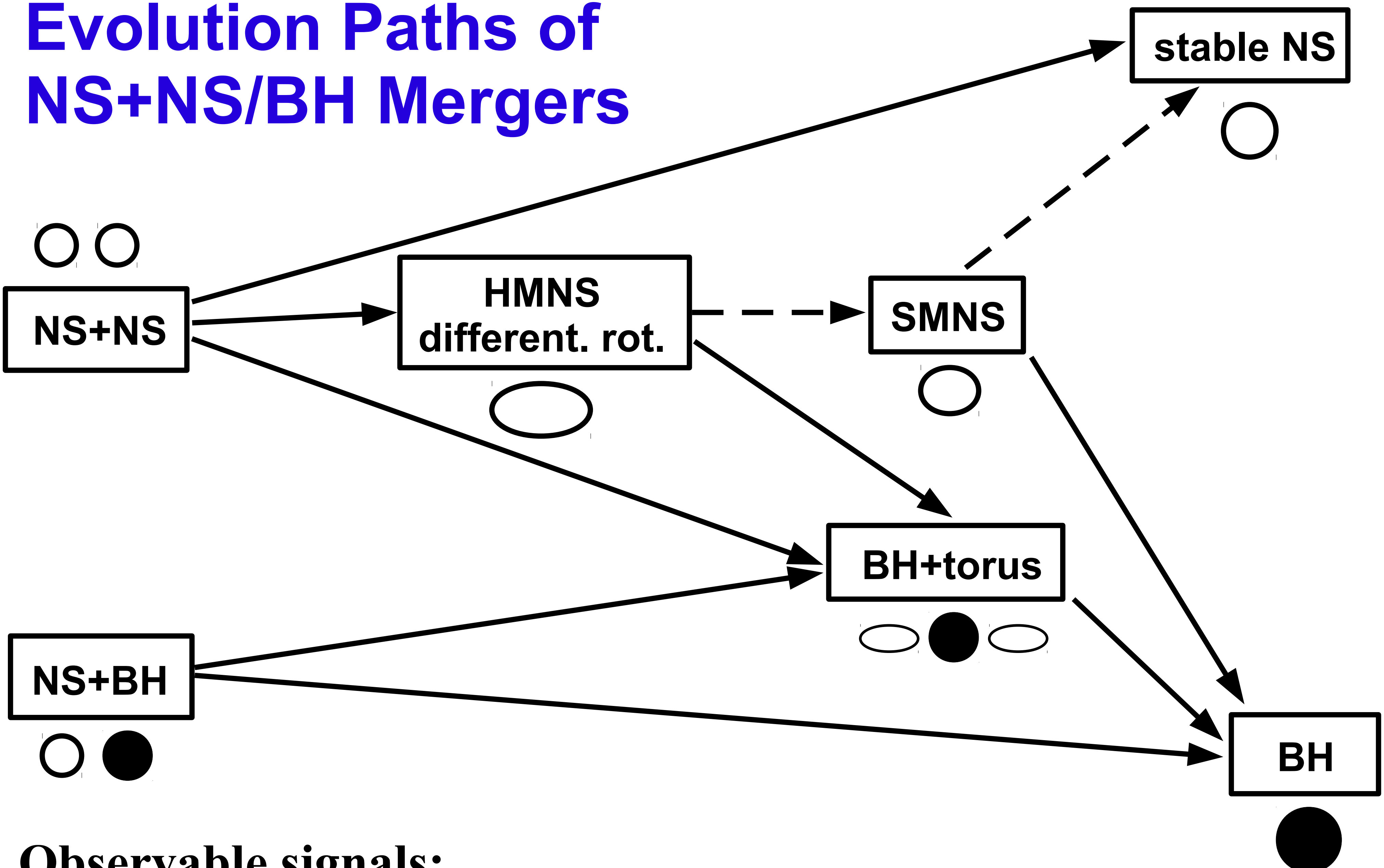
etc.

Extreme Magnetic Field Amplification



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

Evolution Paths of NS+NS/BH Mergers



Observable signals:

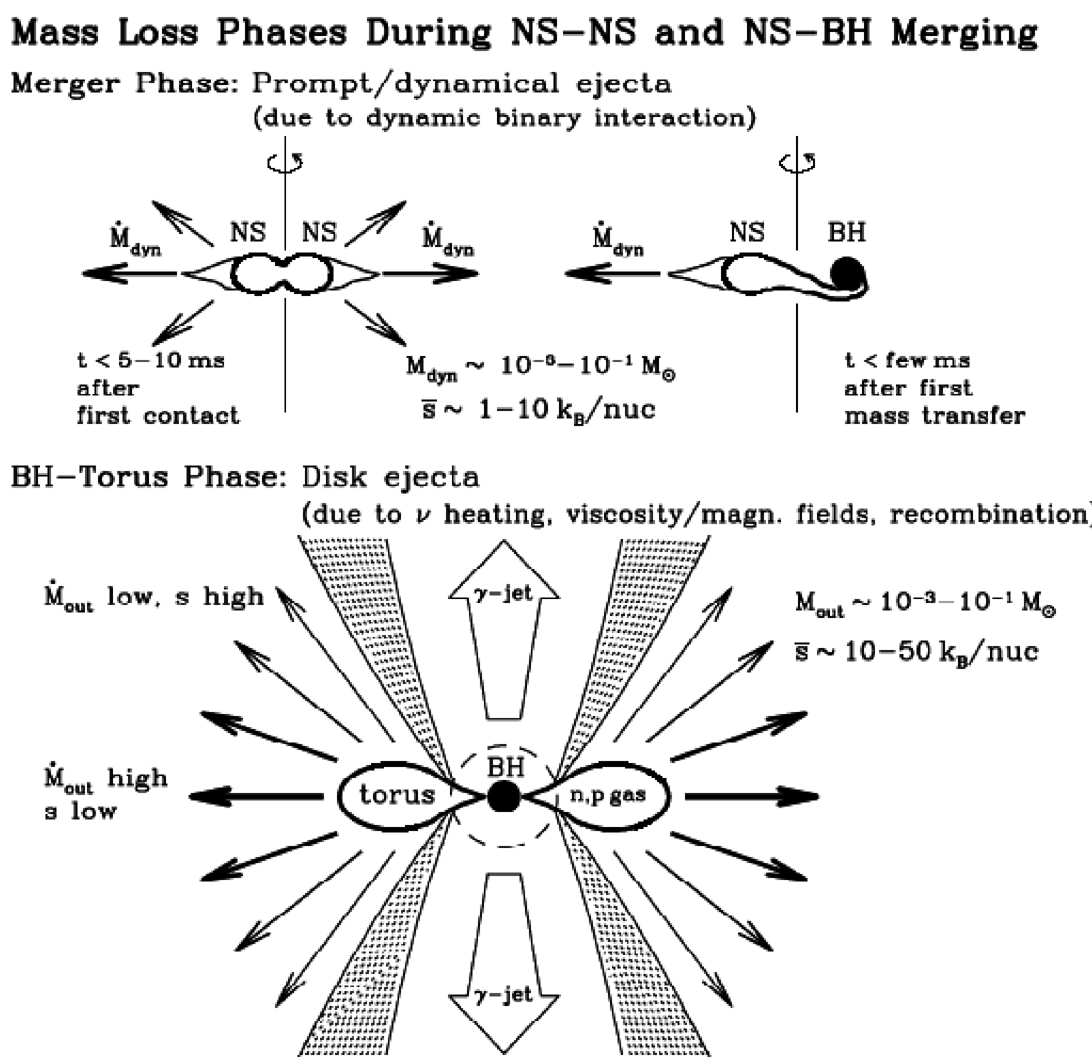
Gravitational waves, neutrinos, gamma-ray bursts,
mass ejection, r-process elements, electromag. transients

Neutron Star Mergers as Production Sites of Ejecta & Heavy Elements

Compact binary mergers

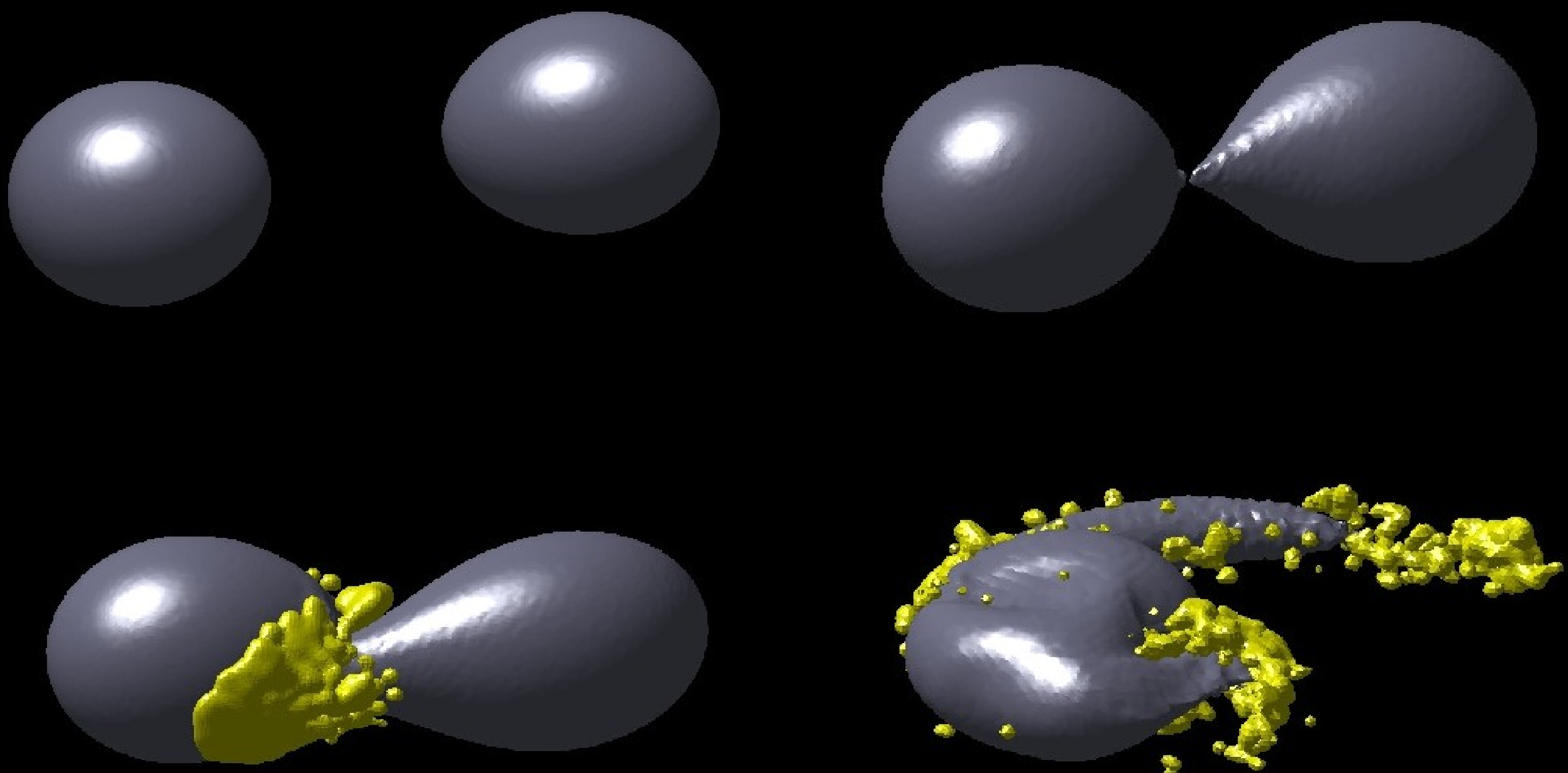
- are likely sources of short gamma-ray bursts
  (Paczynski, Jaroszynski, etc.)
- are among strongest sources of gravitational waves
- are potential production sites of r-process nuclei
  (Lattimer & Schramm 1974, 1976; Lattimer et al. 1977; Meyer 1989)
- May be observable transient sources of optical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

  and radio flares (Piran & Nakar 2011)



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

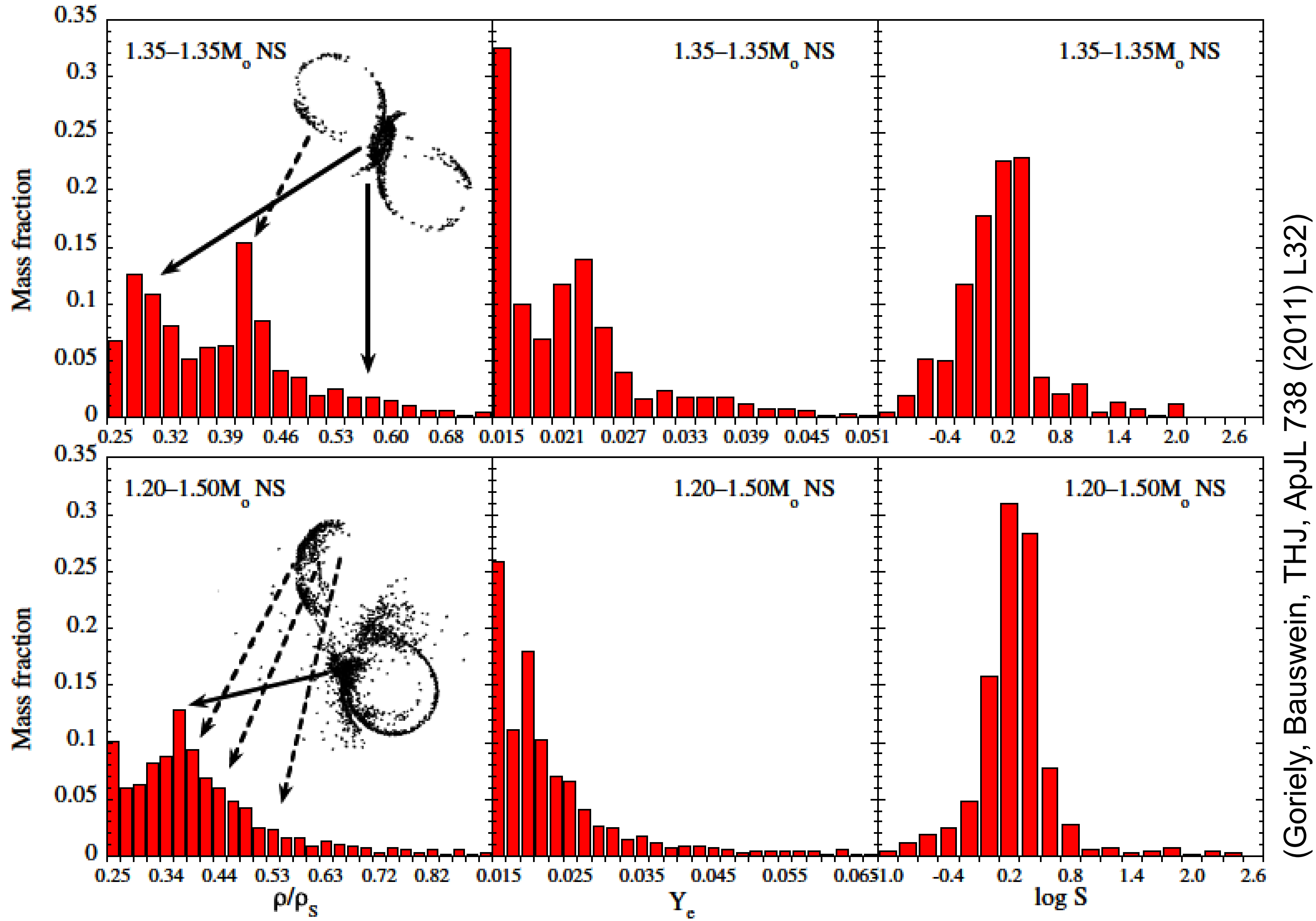
Dynamical Mass Ejection in NS-NS Mergers



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

Asymmetric NS-NS merger

Properties of Dynamical Merger Ejecta

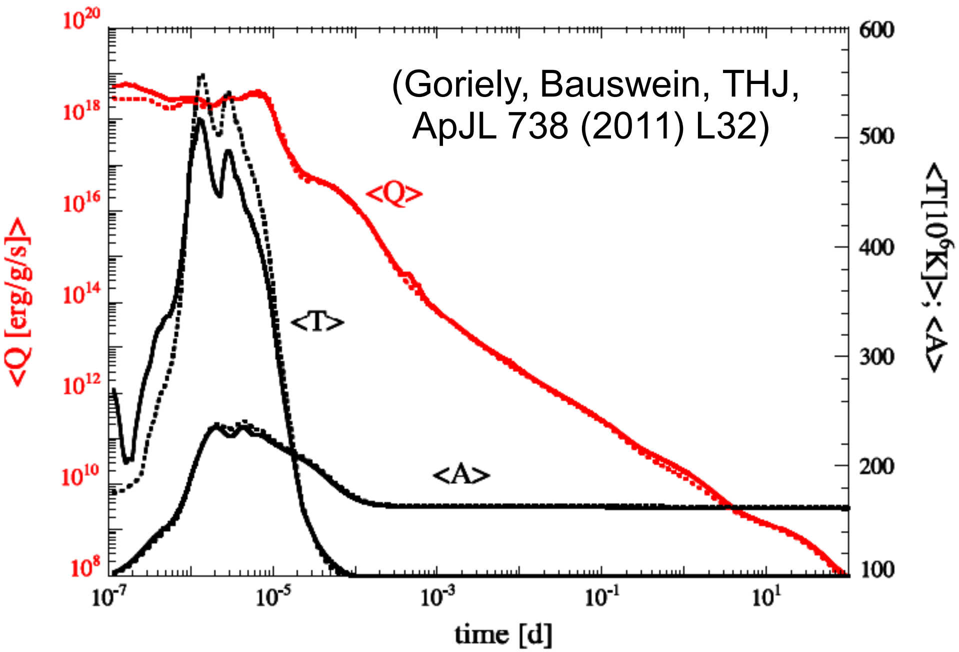


Symmetric NS-NS merger

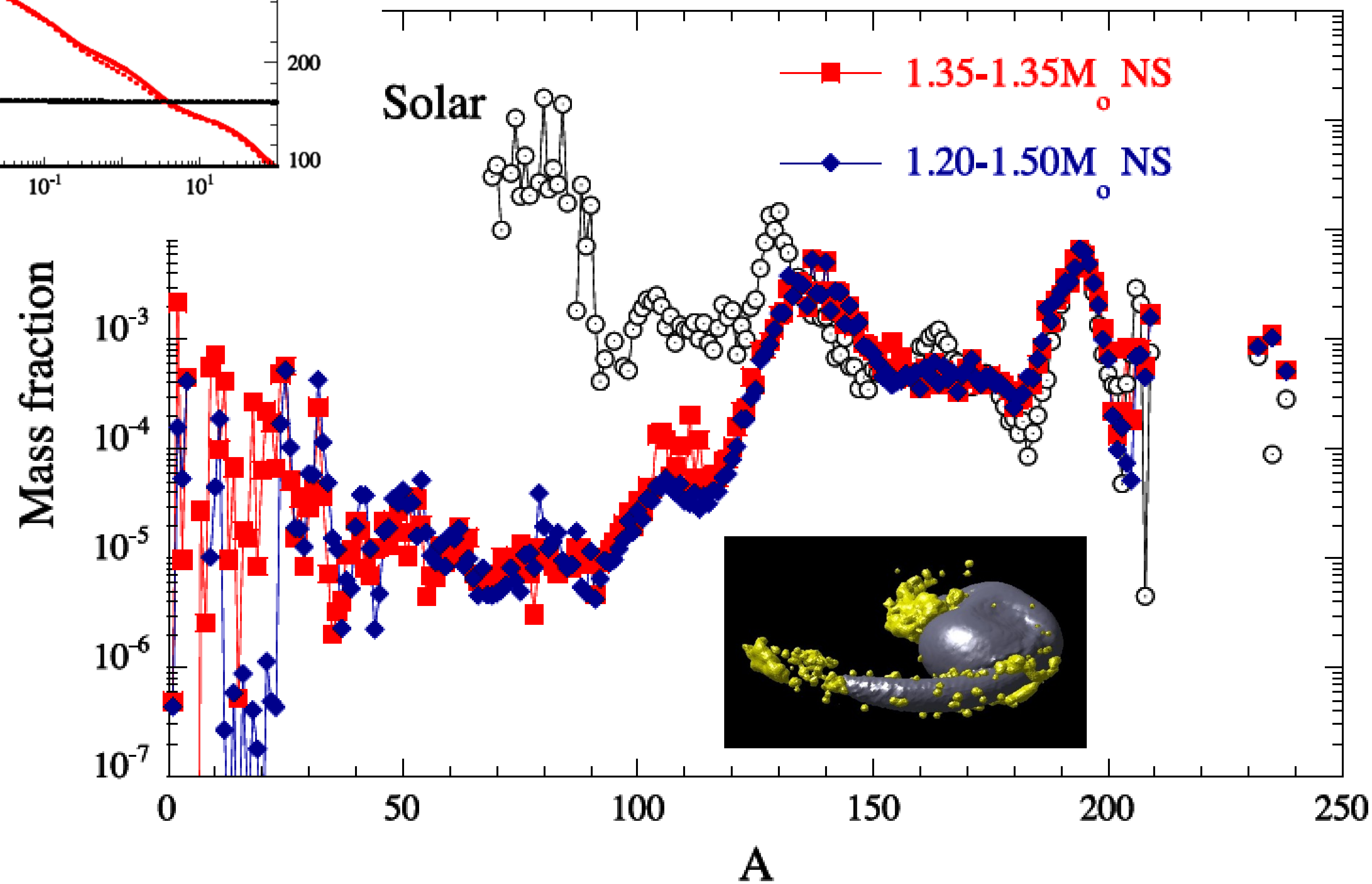
Asymmetric NS-NS merger

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

Nucleosynthesis in Dynamical Merger Ejecta



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

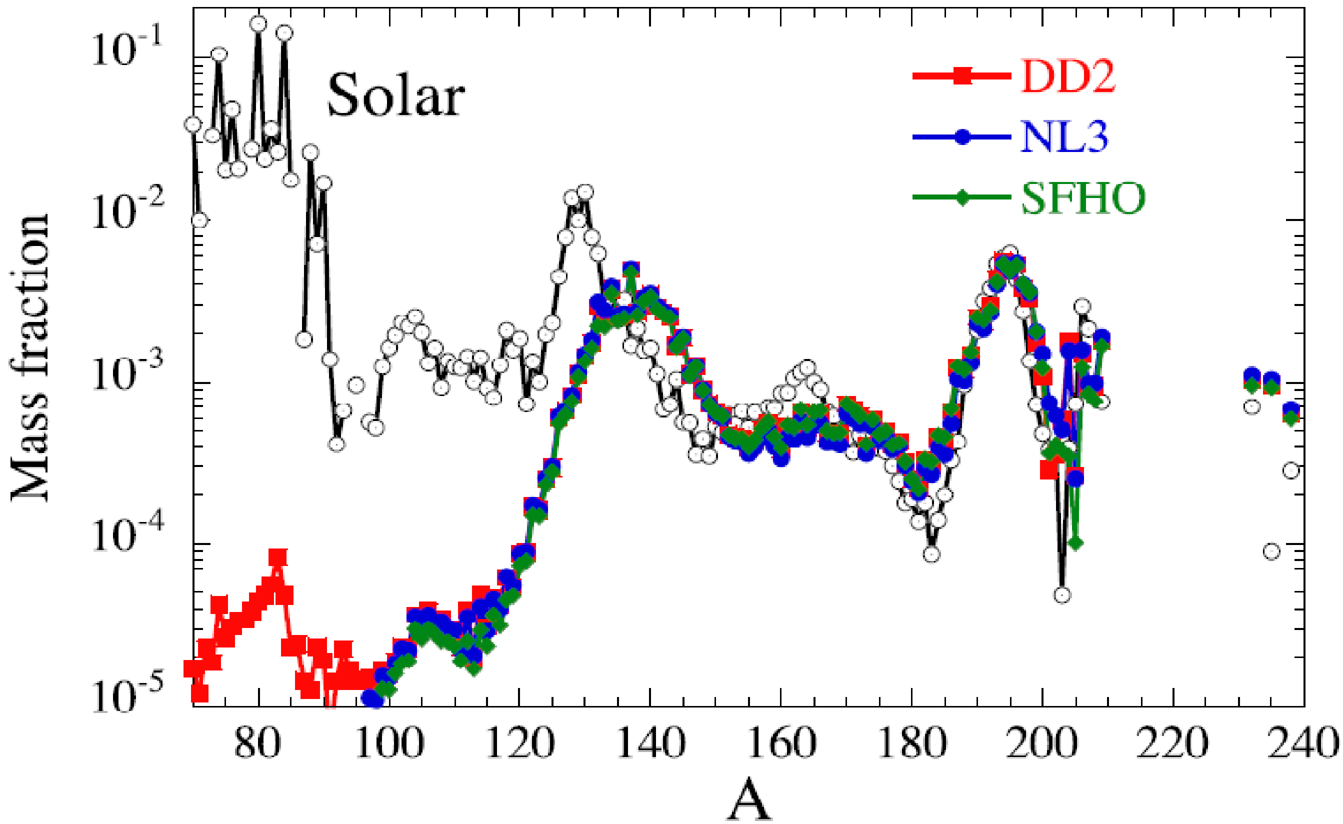


Per merger event 10^{-3}–10^{-2} M_{sun} are ejected.

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

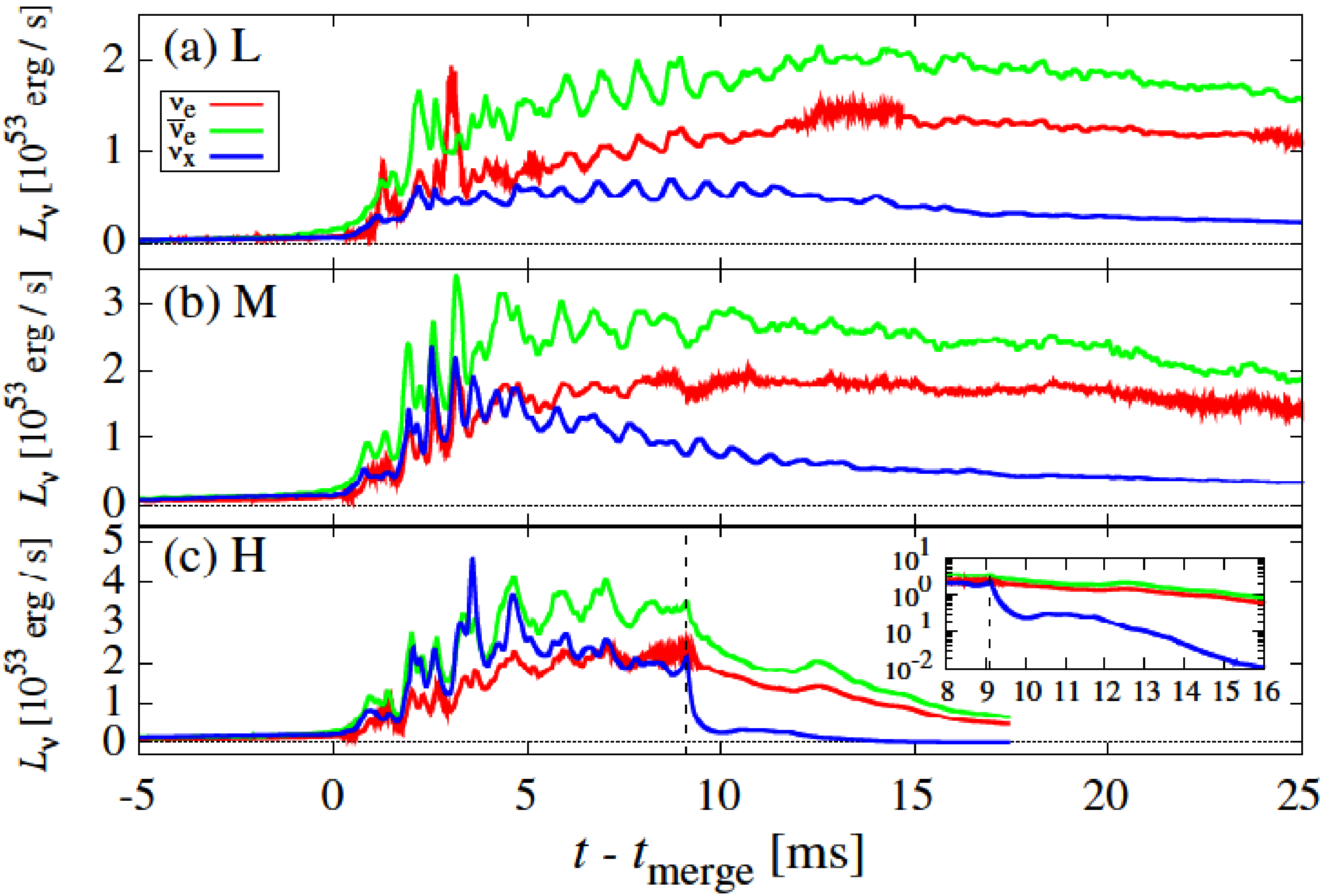
for 1.35-1.35 binaries (most abundant in binary population)



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??
- Radioactive decays power optical transient

Neutrinos



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

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:

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

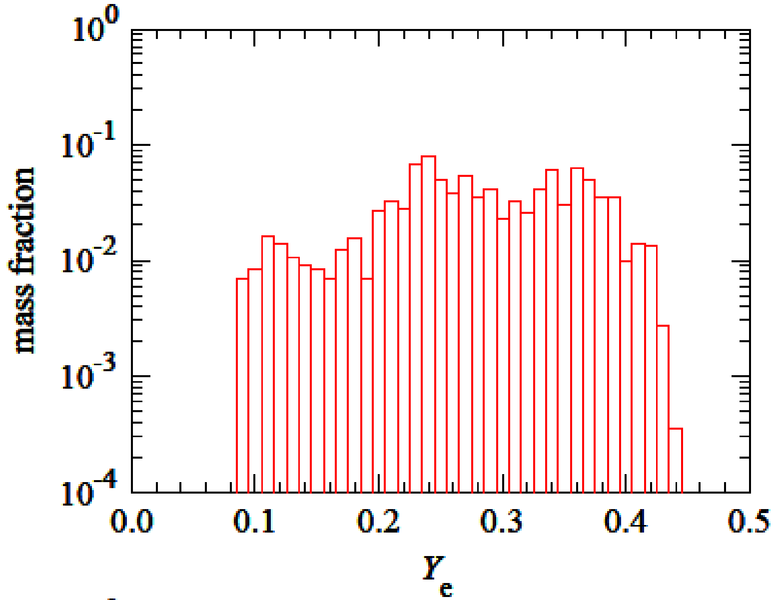
$$\boxed{Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta)}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta)}\right]^{-1}}$$

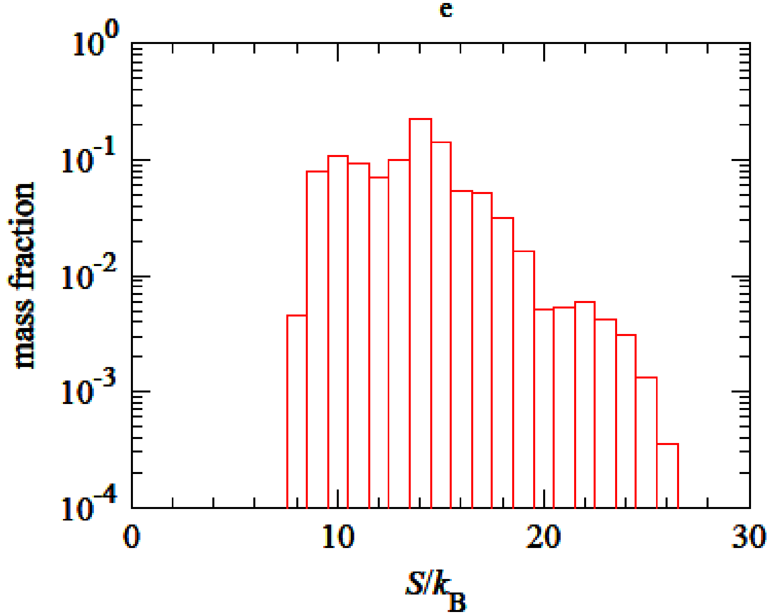
$$\text{with} \quad \epsilon_\nu = \frac{\langle \epsilon_\nu^2 \rangle}{\langle \epsilon_\nu \rangle} \quad \text{and} \quad \Delta = (m_n - m_p)c^2 \approx 1.29\,\mathrm{MeV}.$$

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

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

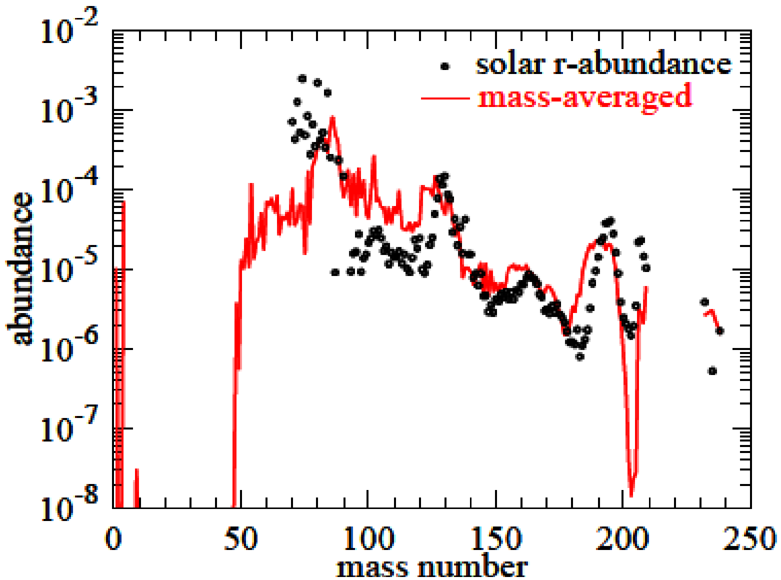
Nucleosynthesis in Neutrino-Processed Merger Ejecta





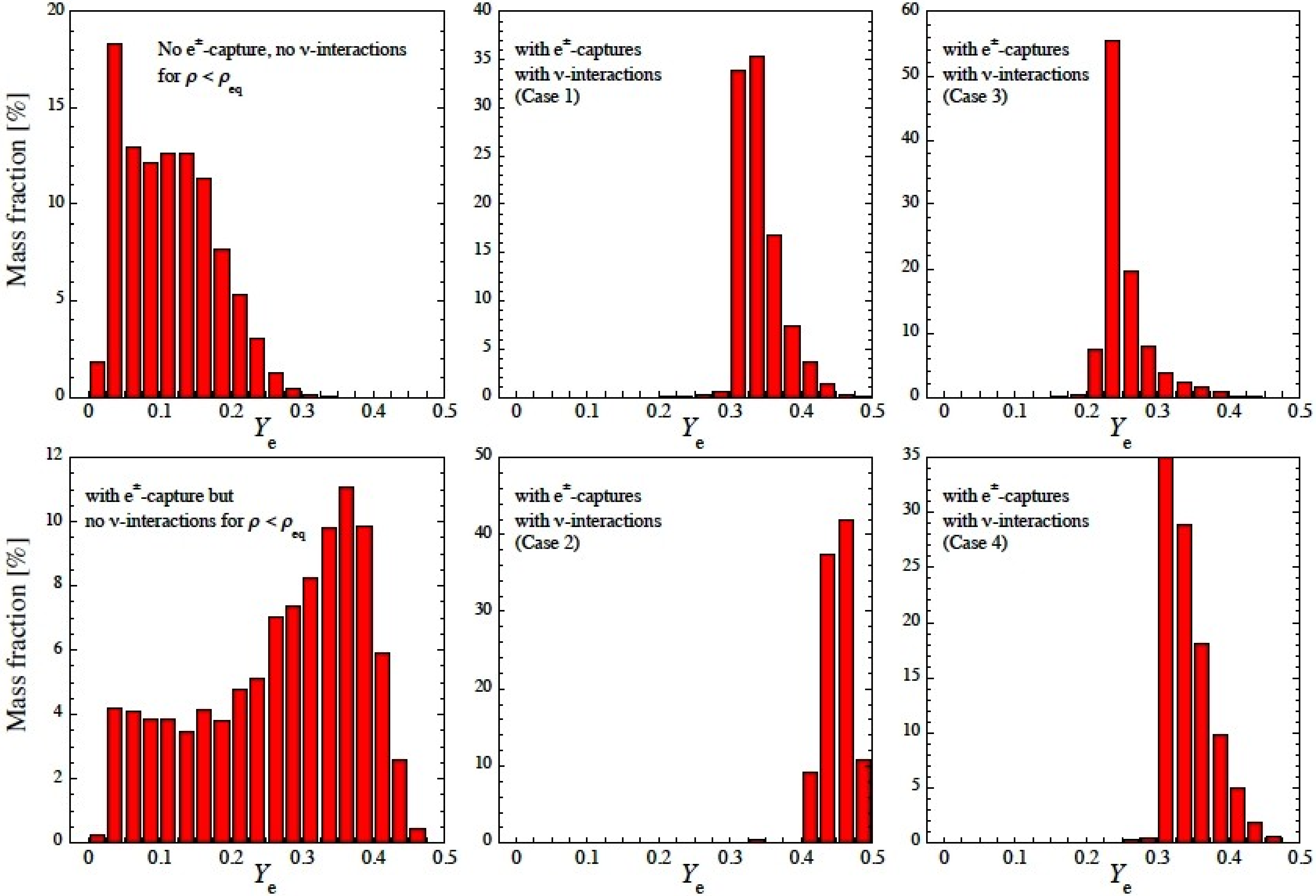
(Wanajo et al., ApJL 789 (2014) L39)

- 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.



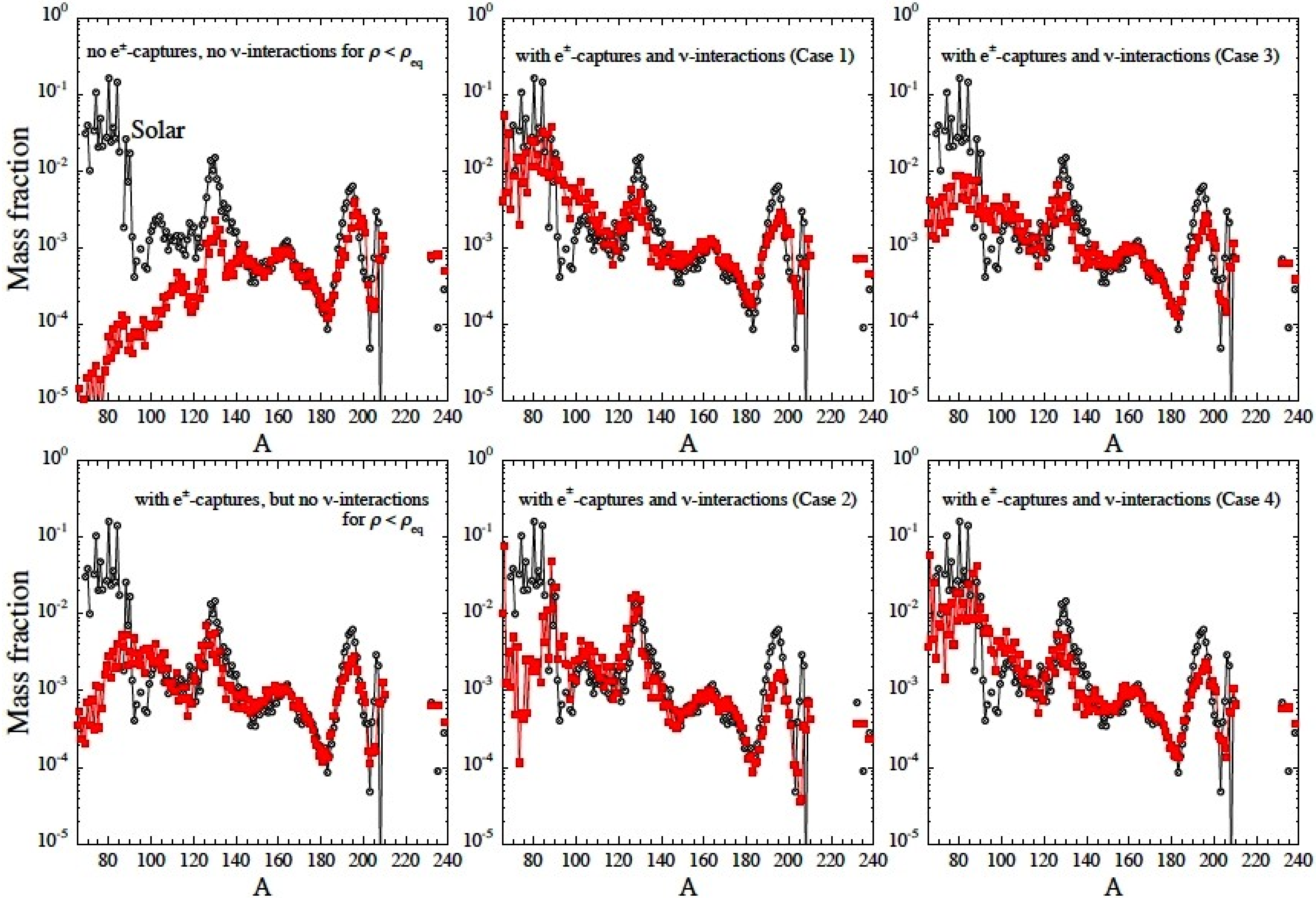
→ **see also M. Shibata's talk of yesterday**

Nucleosynthesis in Neutrino-Processed Merger Ejecta



(Goriely et al., arXiv:1504.04377)

Nucleosynthesis in Neutrino-Processed Merger Ejecta



(Goriely et al., arXiv:1504.04377)

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

Mass of r-Process vs. α-particles vs. Fe-group

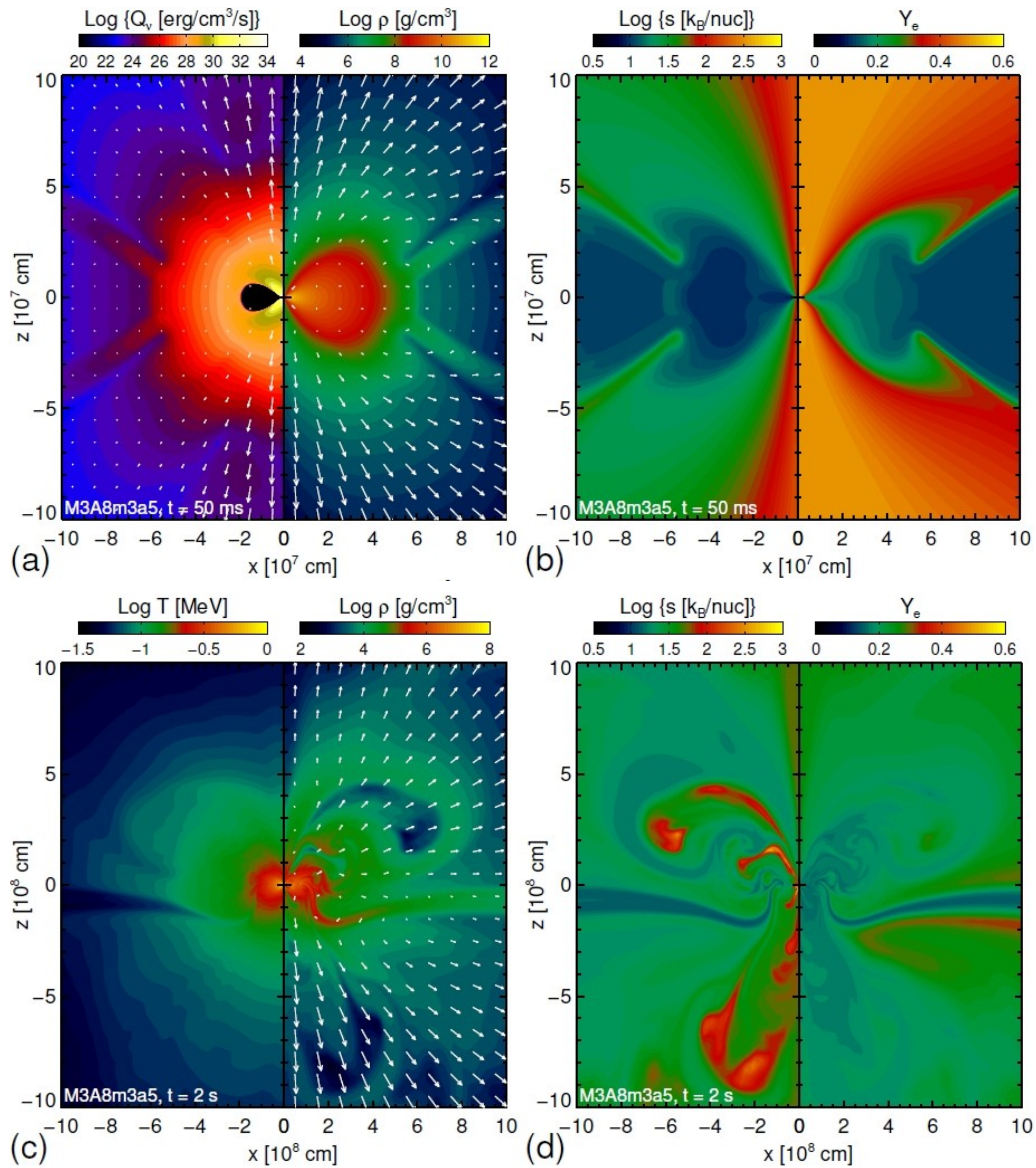
- **Depends on EoS** **(cf. Sekiguchi et al. 2015)**
- **Depends also on viewing direction, merger system and system parameters, phase of mass ejection**
- **Potentially depends on neutrino flavor oscillations**
  (cf. Malkus et al. 2012, Caballero et al. 2012)

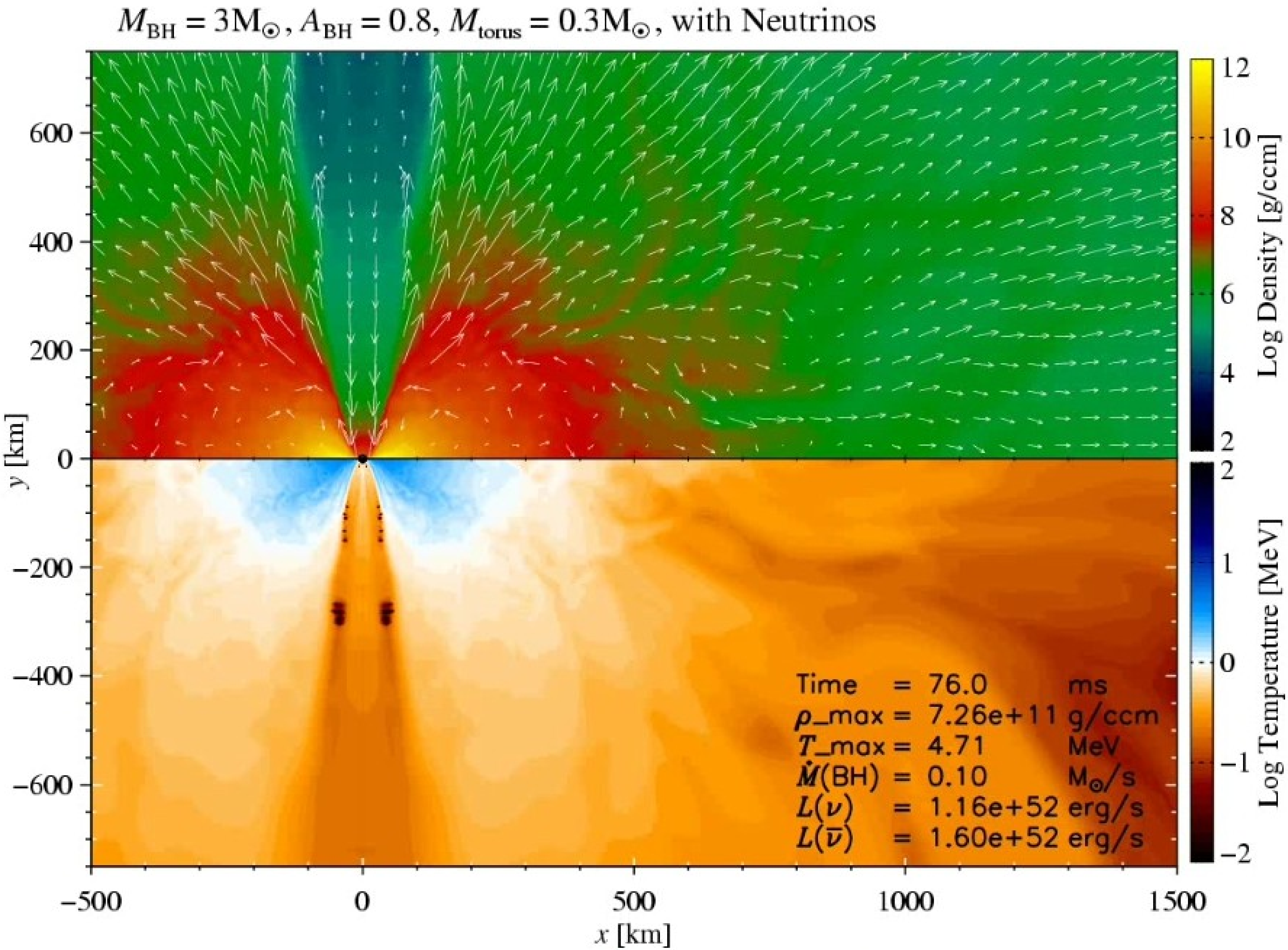
BH-Torus Outflows

- 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)



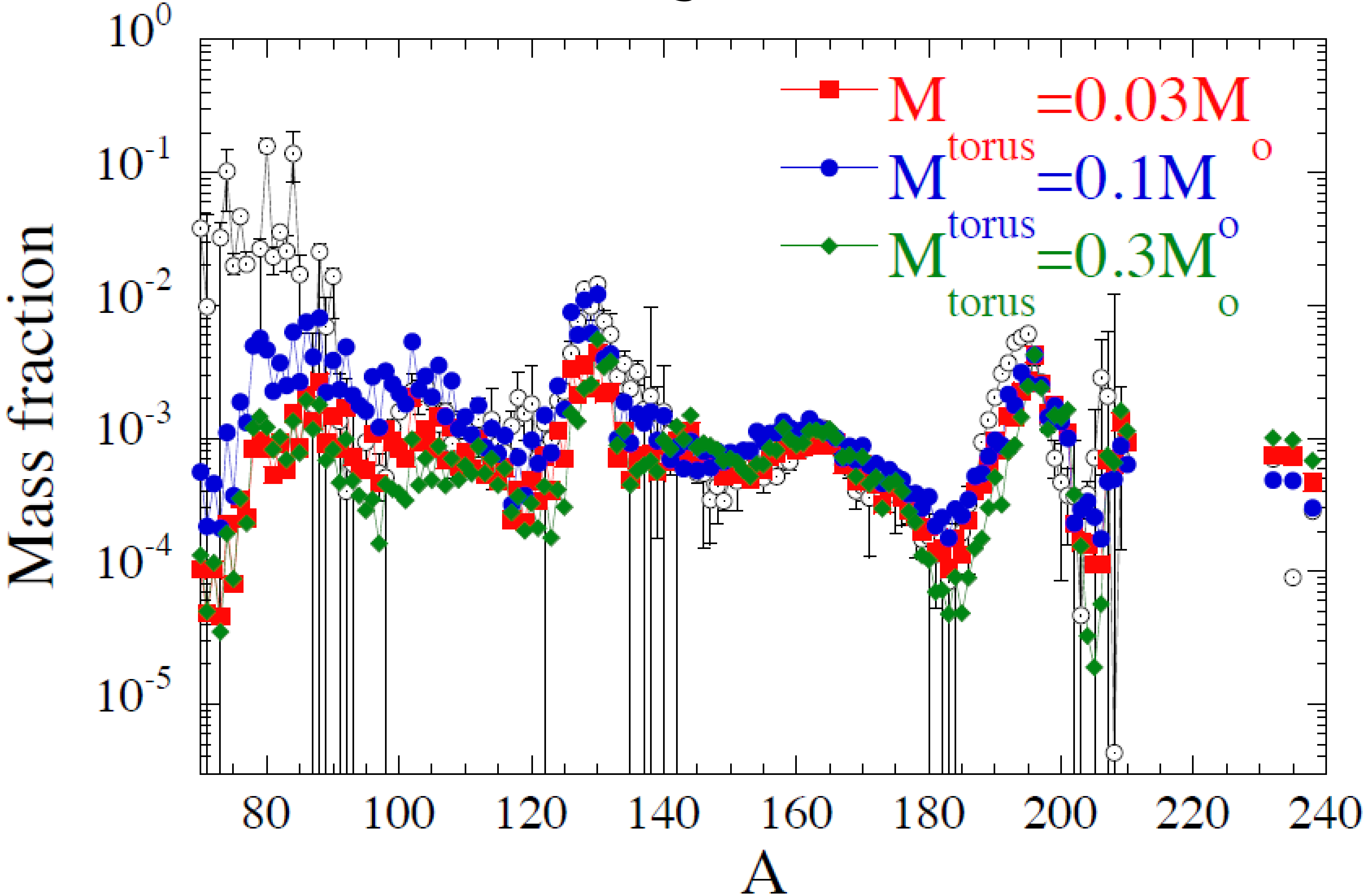


Magnetohydrodynamic simulation

(Just, PhD Thesis 2012)

R-process Nucleosynthesis

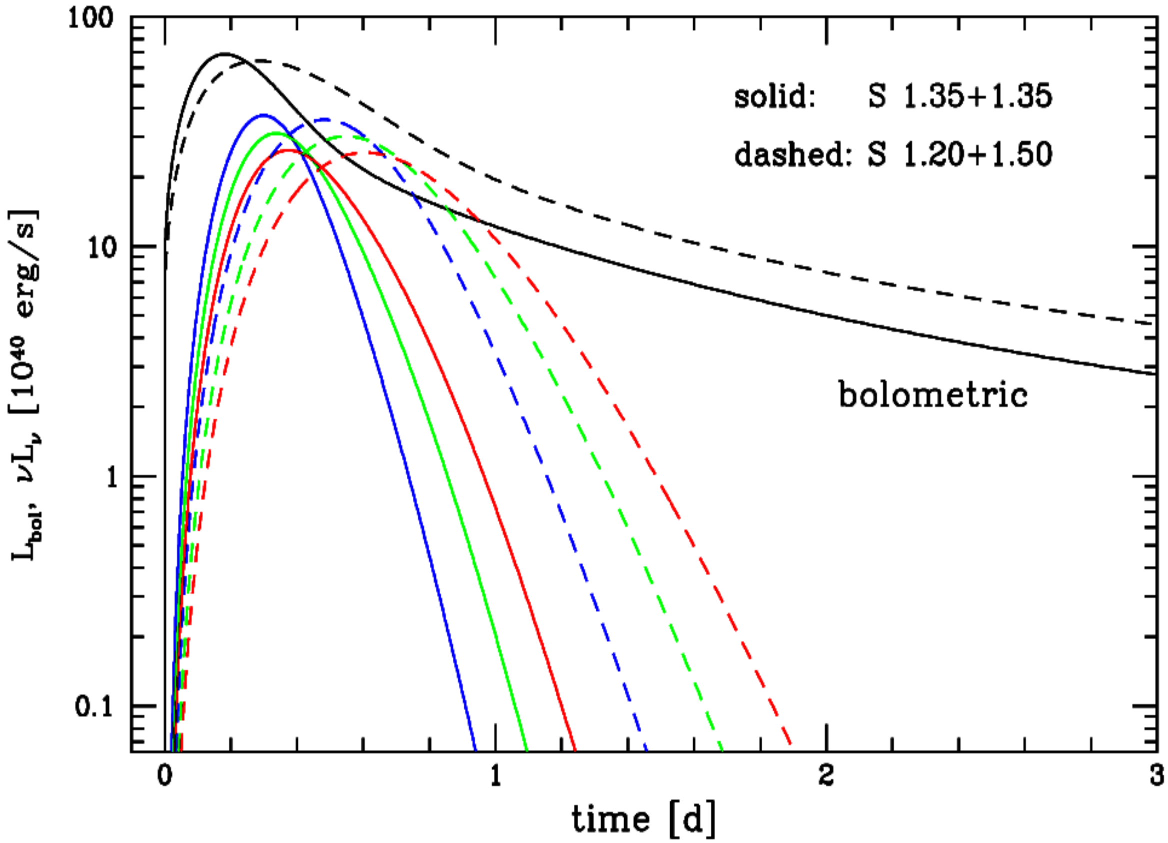
for NS+NS merger + BH-torus remnant



Just, Ardevol Pulpillo, Bauswein, Goriely & THJ, MNRAS 448 (2015) 541

Electromagnetic Transients: Light Curve

Goriely, Bauswein & THJ, ApJL (2011)



Shen EoS;

Light curves from one-zone ejecta modell

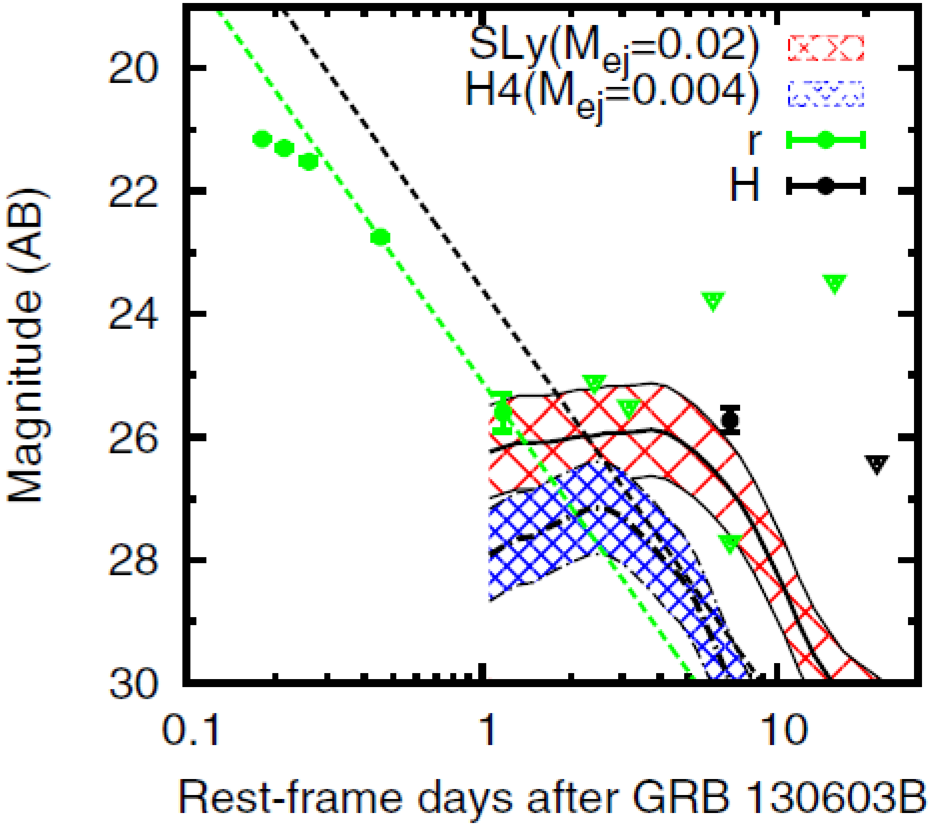
Estimates: $L_{bolo} \sim 7.5{*}10^{41}$ erg/s $\kappa^{-1/2}$ $(v/0.1c)^{1/2}$ $(M_{ejecta}/10^{-2}M_{sun})^{1/2}$

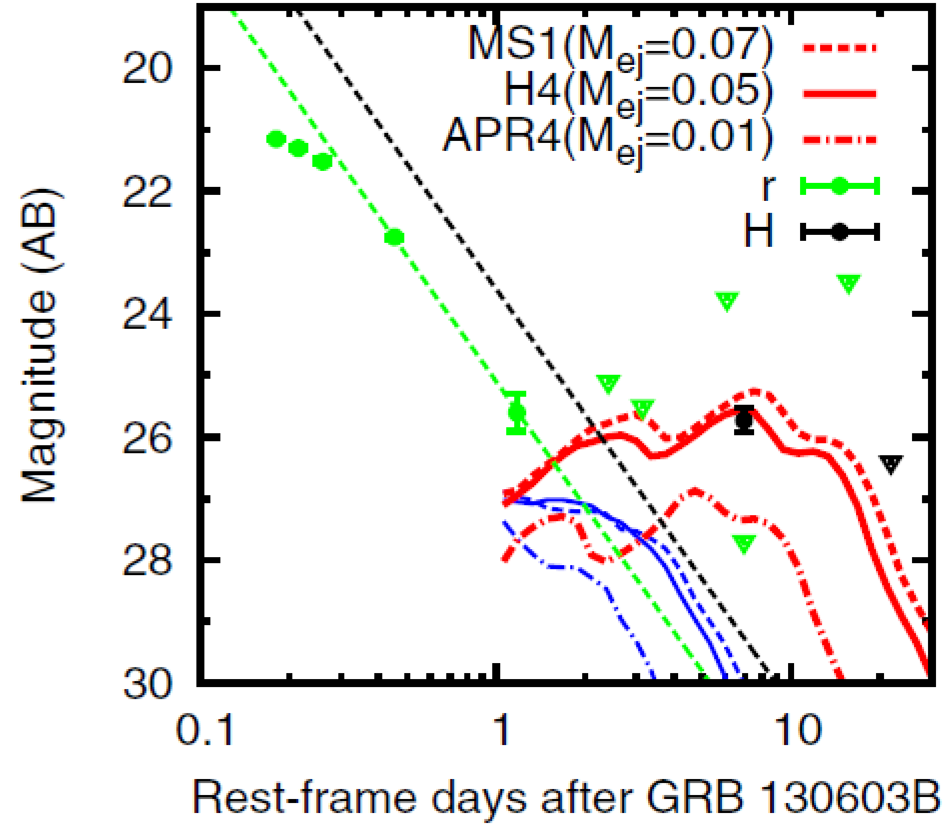
$t_{peak} \sim 0.5$ d $\kappa^{1/2}$ $(v/0.1c)^{-1/2}$ $(M_{ejecta}/10^{-2}M_{sun})^{1/2}$

$T_{eff} \sim 1.4{*}10^{4}$ K $\kappa^{-3/8}$ $(v/0.1c)^{-1/8}$ $(M_{ejecta}/10^{-2}M_{sun})^{-1/8}$

→ **see also following talk by B. Metzger**

Infrared Transient of GRB 130603B and NS EOS Implications





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

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

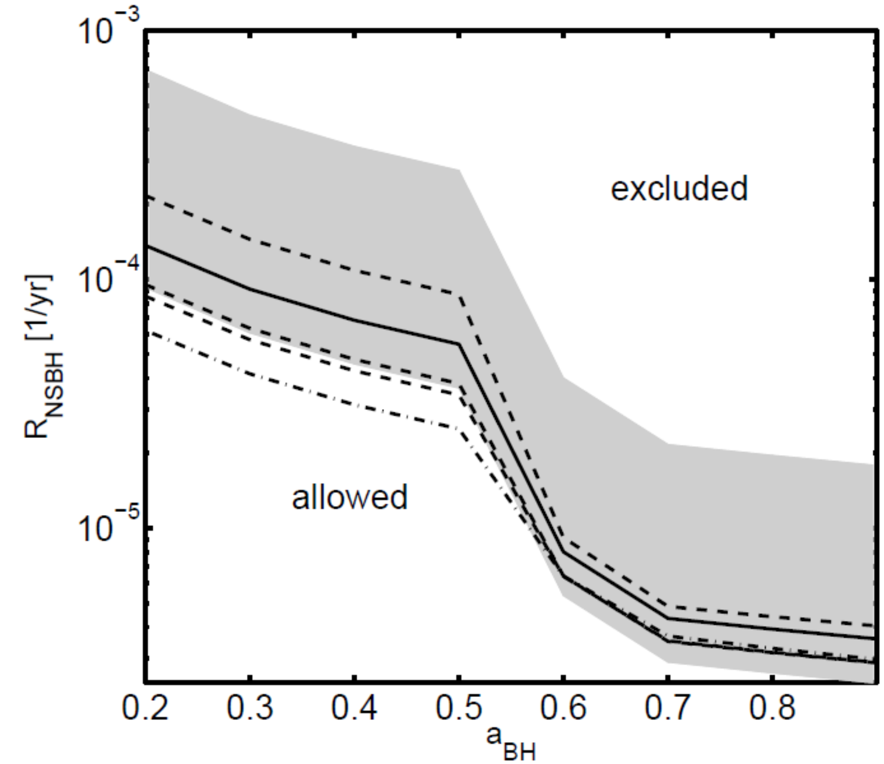
Hotokezaka et al., ApJ (2013)

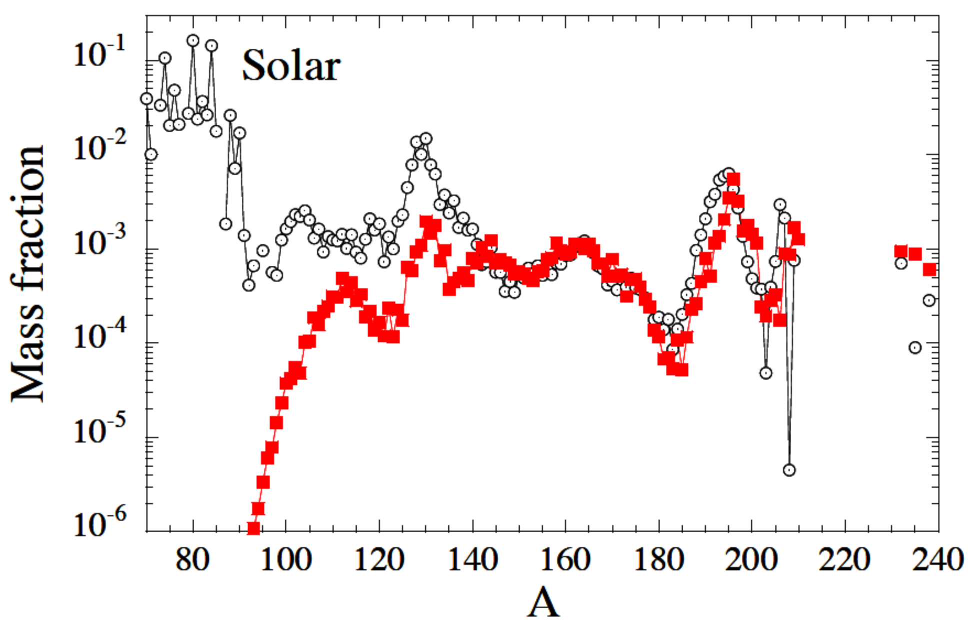
Constraints on NS-BH Merger Rate by R-Process Production

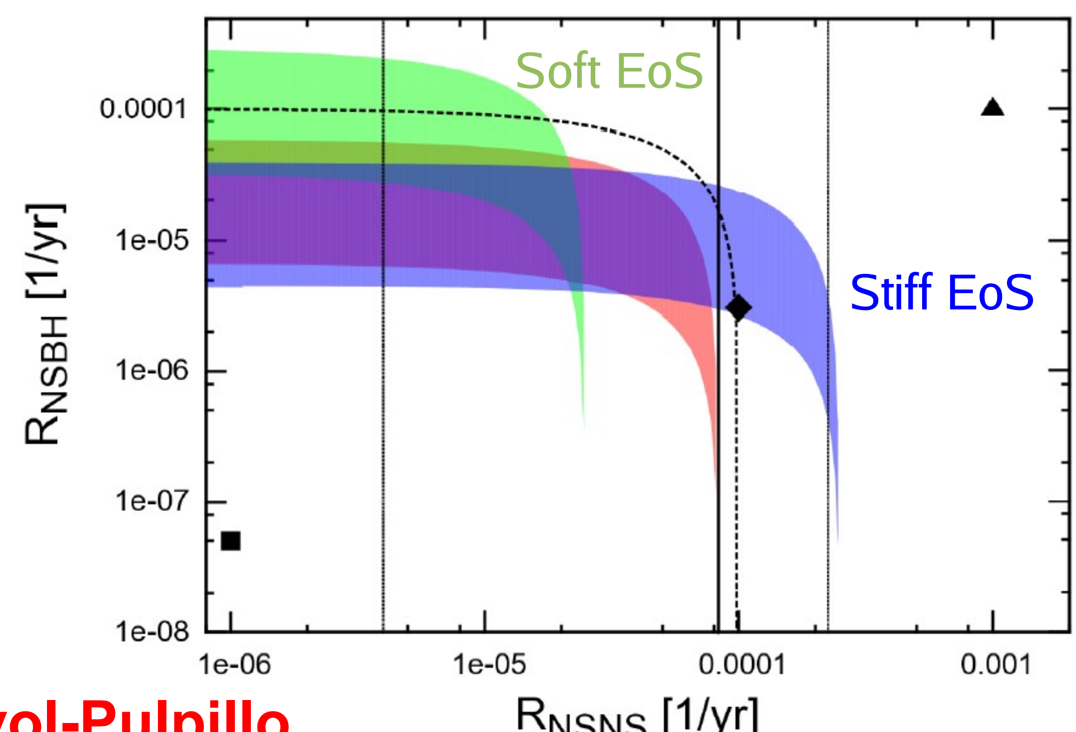
TABLE 1
EJECTA MASSES

a_{BH} \ M_{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_{BH}, initial BH spin a_{BH}, NS mass 1.35 $M_\odot$, and DD2 EoS.







Bauswein et al., ApJL 795 (2014) L9

see also talk by R. Ardevol-Pulpillo

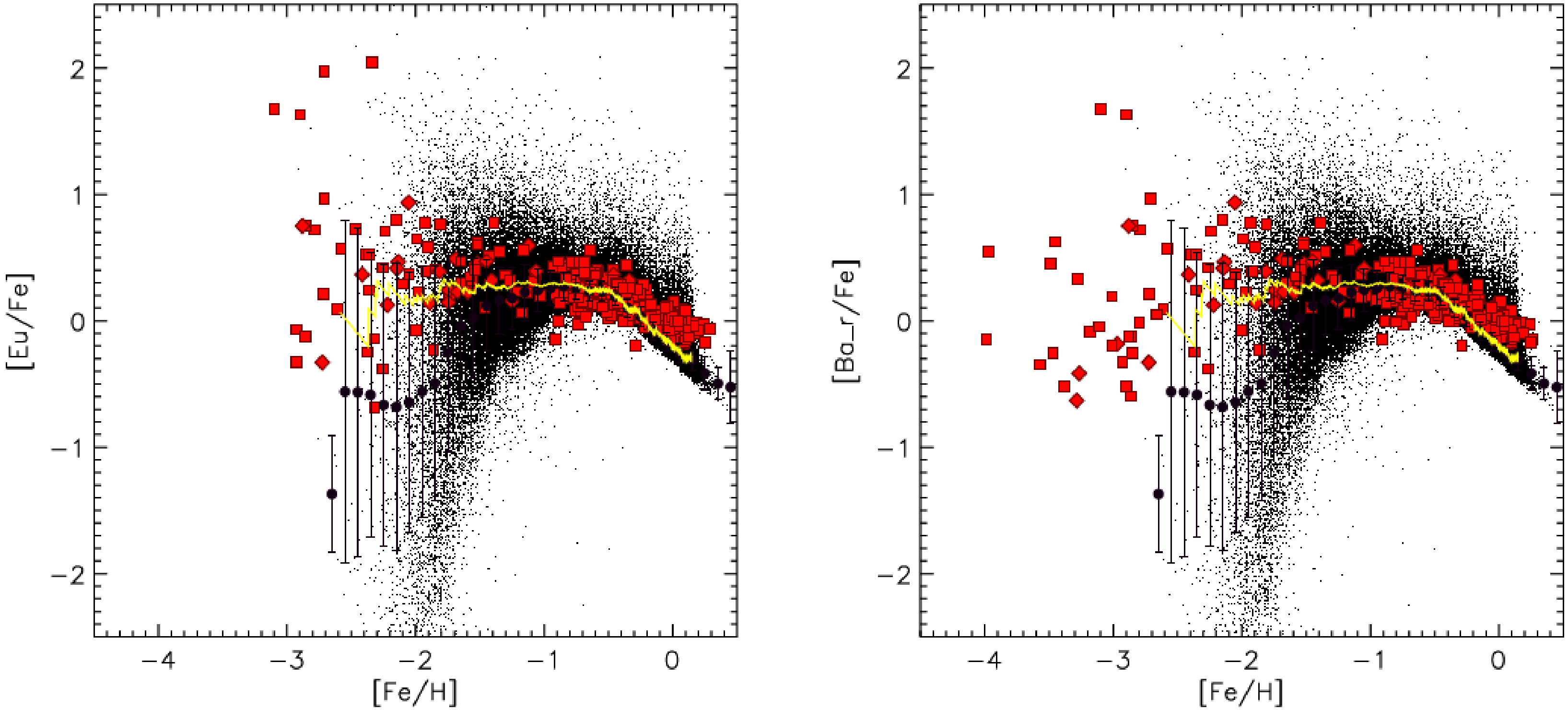
Summary and Conclusions

- 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 insensitive/weakly sensitive to EoS,
  but for NS-NS mergers depends on neutrino emission (and absorption) —> relevance for ejecta opacity!
- Chemogalactic implications require careful studies with detailed hydrodynamical models of Galaxy evolution

R-process Sources

- Having identified one source does not exclude existence of other sources.

The ISM Mixing Problem



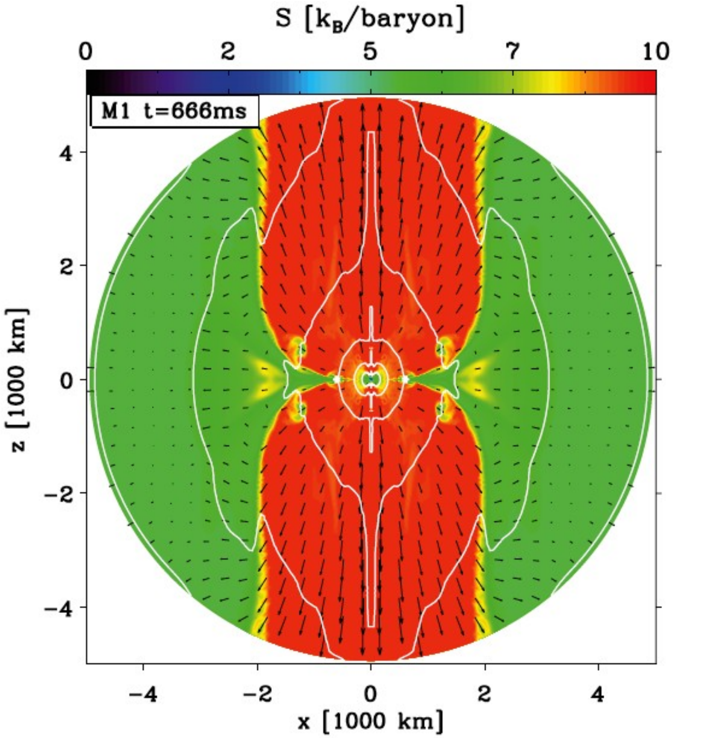
(Argast et al., A&A 416 (2004) 997)

Fig. 4. Evolution of [Eu/Fe] and [Ba^r/Fe] abundances as a function of metallicity [Fe/H]. NSM with a rate of 2×10^{-4} yr^{-1}, a coalescence timescale of 10^6 yr and 10^{-3} $M_\odot$ of ejected r-process matter are assumed to be the dominating r-process sources. Black dots denote model stars, observations are marked by filled squares and diamonds (see text). Average ISM abundances are marked by a continuous line. Filled circles with error bars denote average abundances of model stars and their standard deviation in [Fe/H] bins with binsize 0.1 dex.

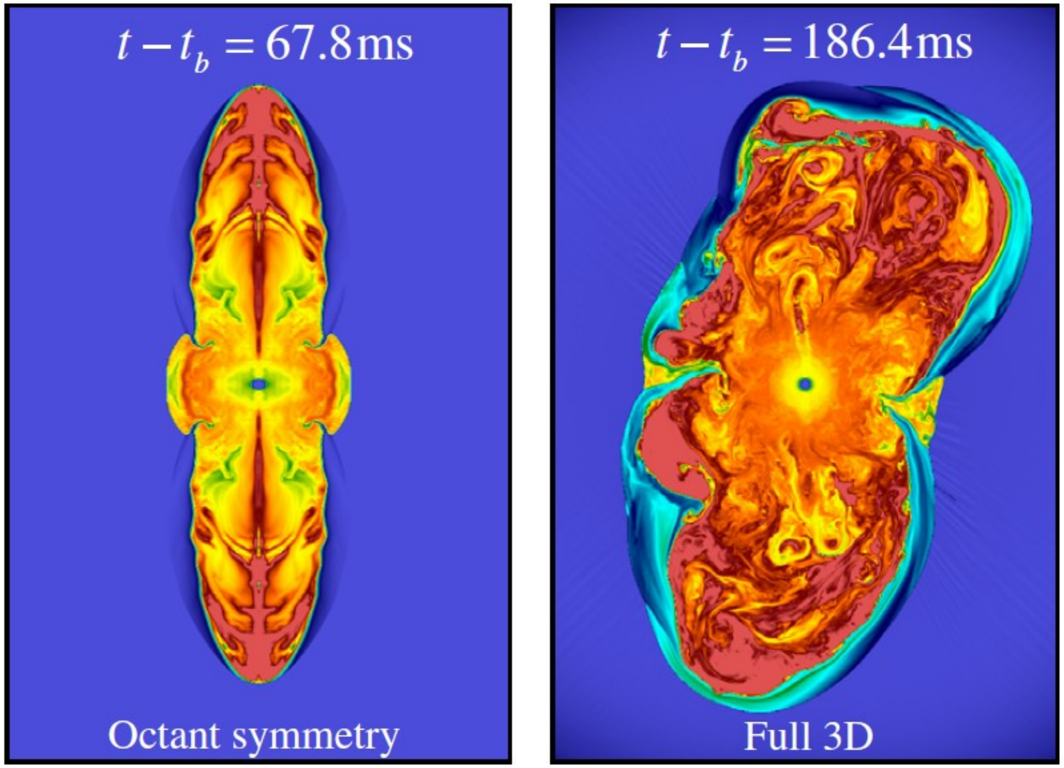
(see also Wehmeyer et al., arXiv:1501.07749)

Jet-Supernova Models as r-Process Sites?

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



Dessart et al., ApJL 673 (2008) L43
Winteler et al., ApJL 750 (2012) L22

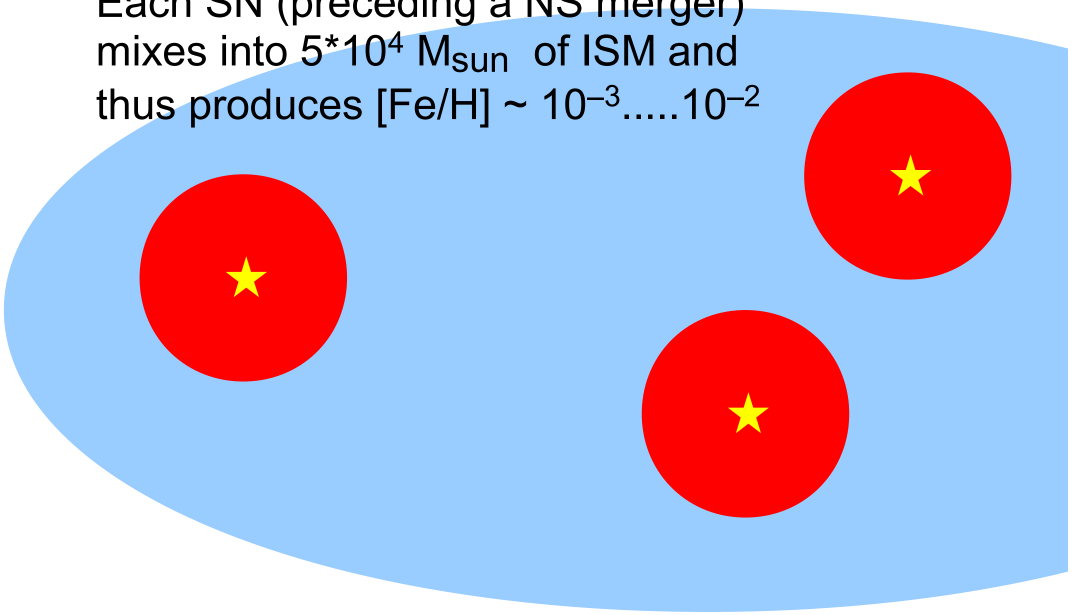


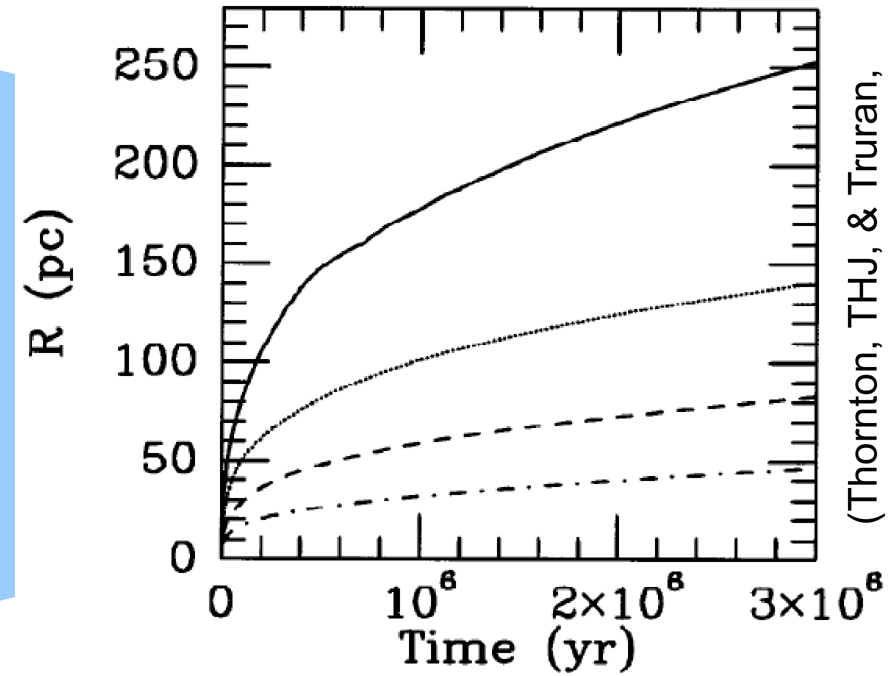
Mösta et al., ApJL 785 (2014) L29

The ISM Mixing Problem

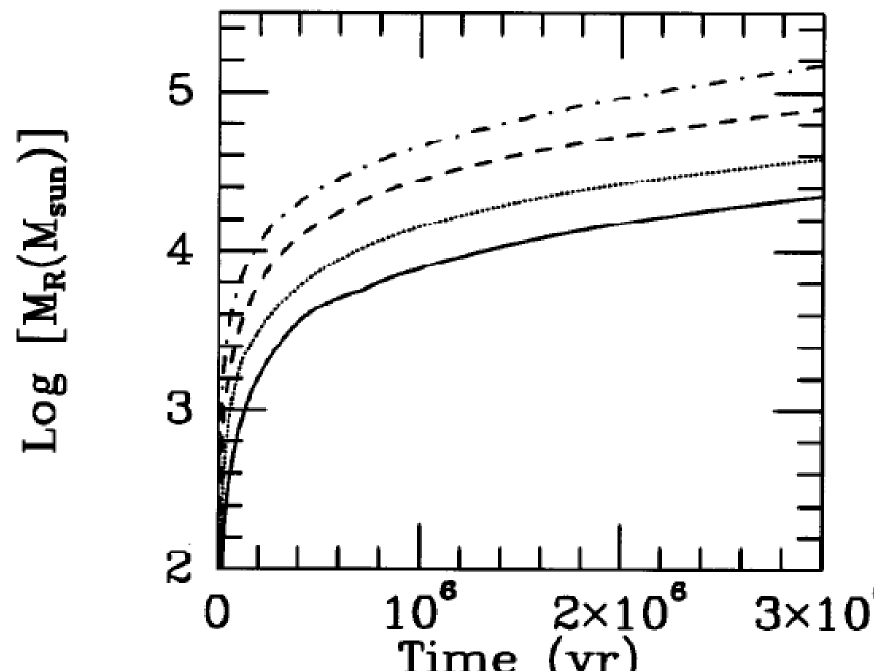
Chemogalactic Enrichment History

Each SN (preceding a NS merger) mixes into $5*10^4$ M_{sun} of ISM and thus produces [Fe/H] ~ 10^{-3}.....10^{-2}





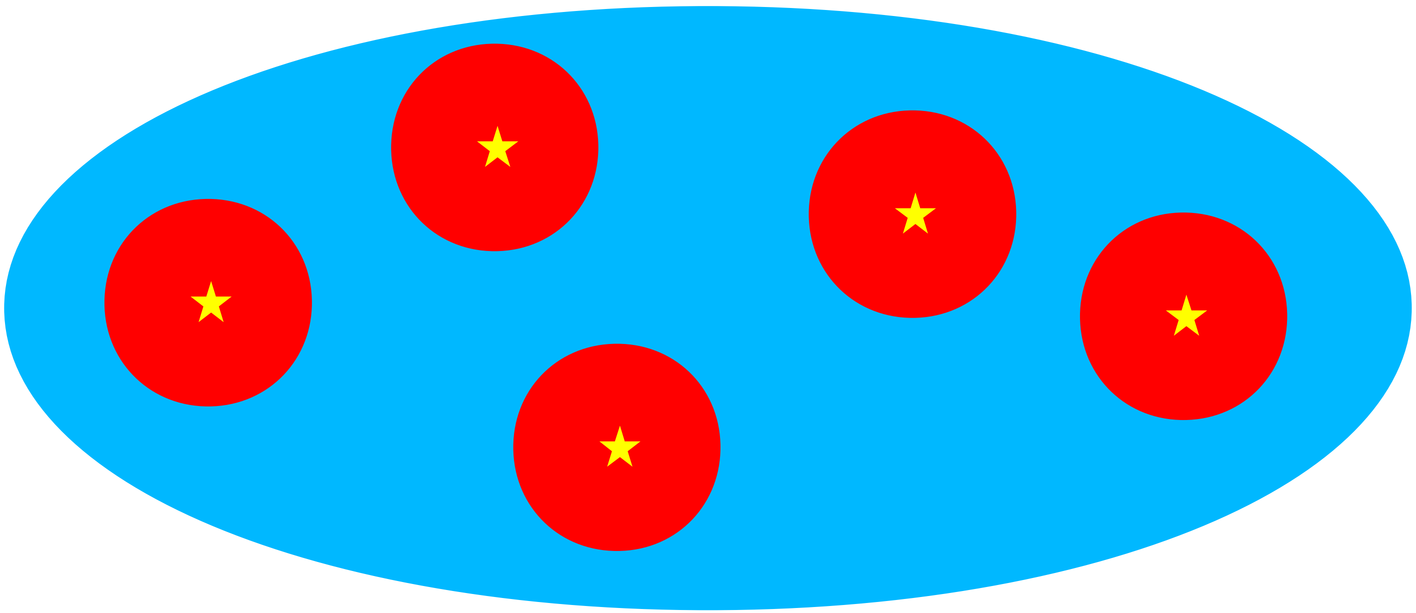
(Thornton, THJ, & Truran, ApJ 500 (1998) 95)



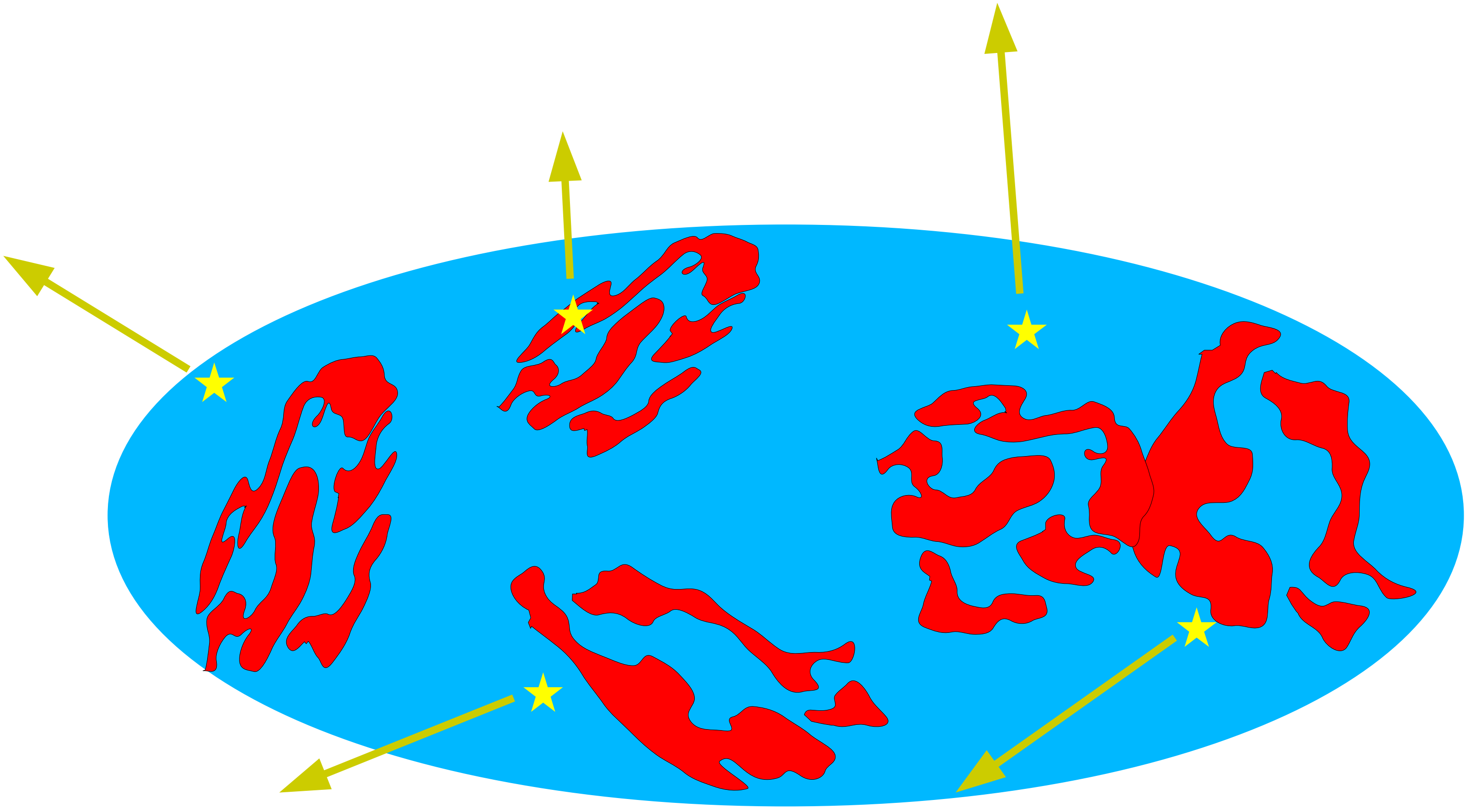
Argast et al. (A&A 416 (2004) 997 :

SN events pollute the neighbouring ISM with their nucleosynthesis products and sweep up the material in a spherical, chemically well mixed shell. Here, it is assumed that each SN pollutes $\approx 5 \times 10^4\ M_\odot$ of ISM (Ryan et al. 1996; Shigeyama & Tsujimoto 1998). Stars which form out of material enriched by a *single* SN II show an element abundance pattern that is characteristic of the yields for the particular progenitor of this SN II. This will lead to a large scatter in element abundance ratios ([el/Fe]) as long as local inhomogeneities caused by SN II events dominate the halo ISM. As time progresses, supernova remnants overlap and the abundance pattern in each cell approaches the average defined by SN II yield patterns for different progenitor masses and the IMF. This leads to a decrease of the scatter in element abundance ratios at later times.

But : **Highly idealized picture of Galactic chemical enrichment dynamics and history**

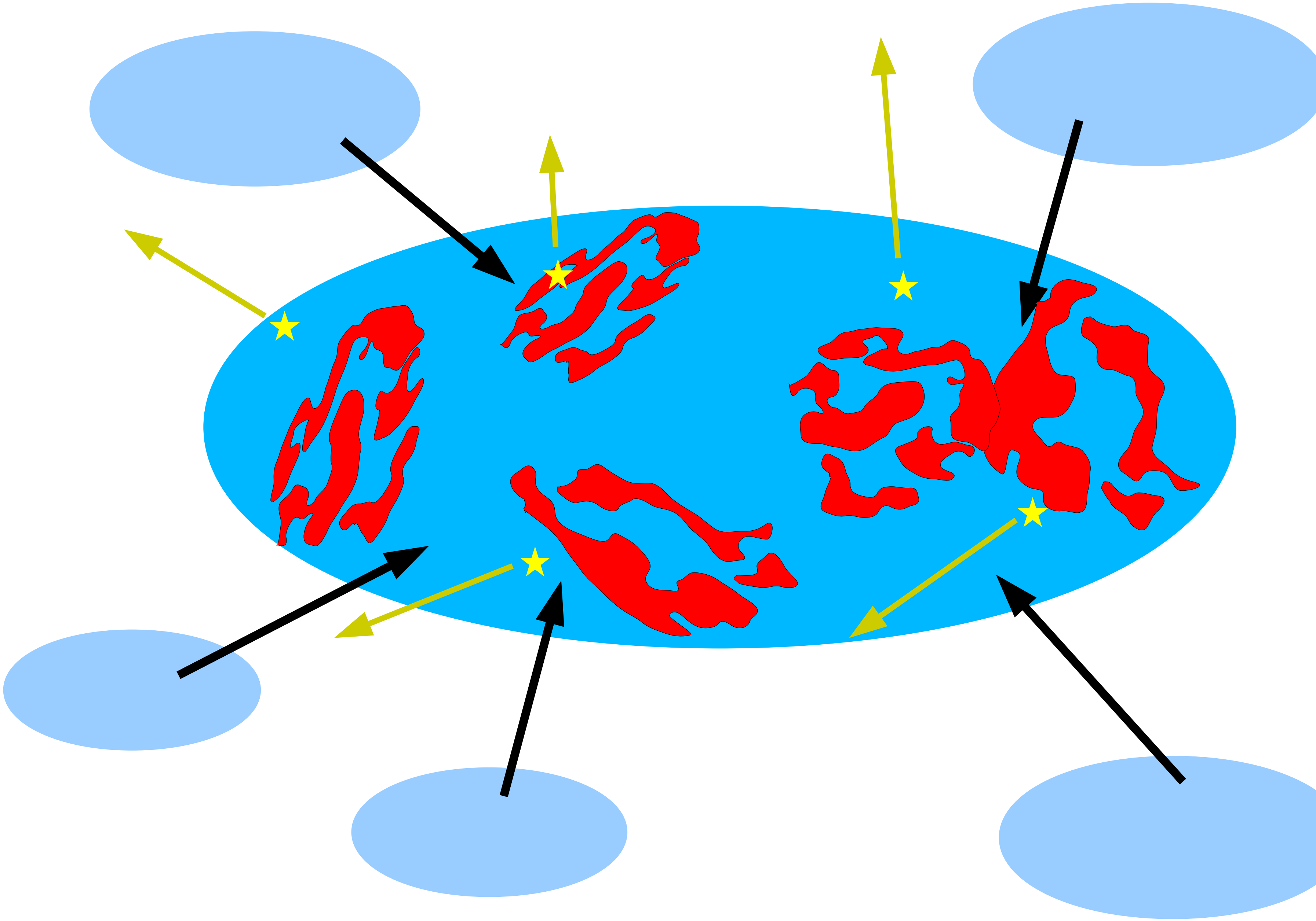


What can large-scale flows in the Galaxy and NS kick velocities do?



Dwarf spheriodals and sub-halos mergers with Galaxy can change relation between time and metallicity; reduce SN metal enrichment preceding first NS mergers to [Fe/H] ~ 10^{-4}.....10^{-3}

(Prantzos 2006; Ishimaru et al. 2015, Vangioni et al. 2015; van de Voort 2015)



Chemogalactic Enrichment History

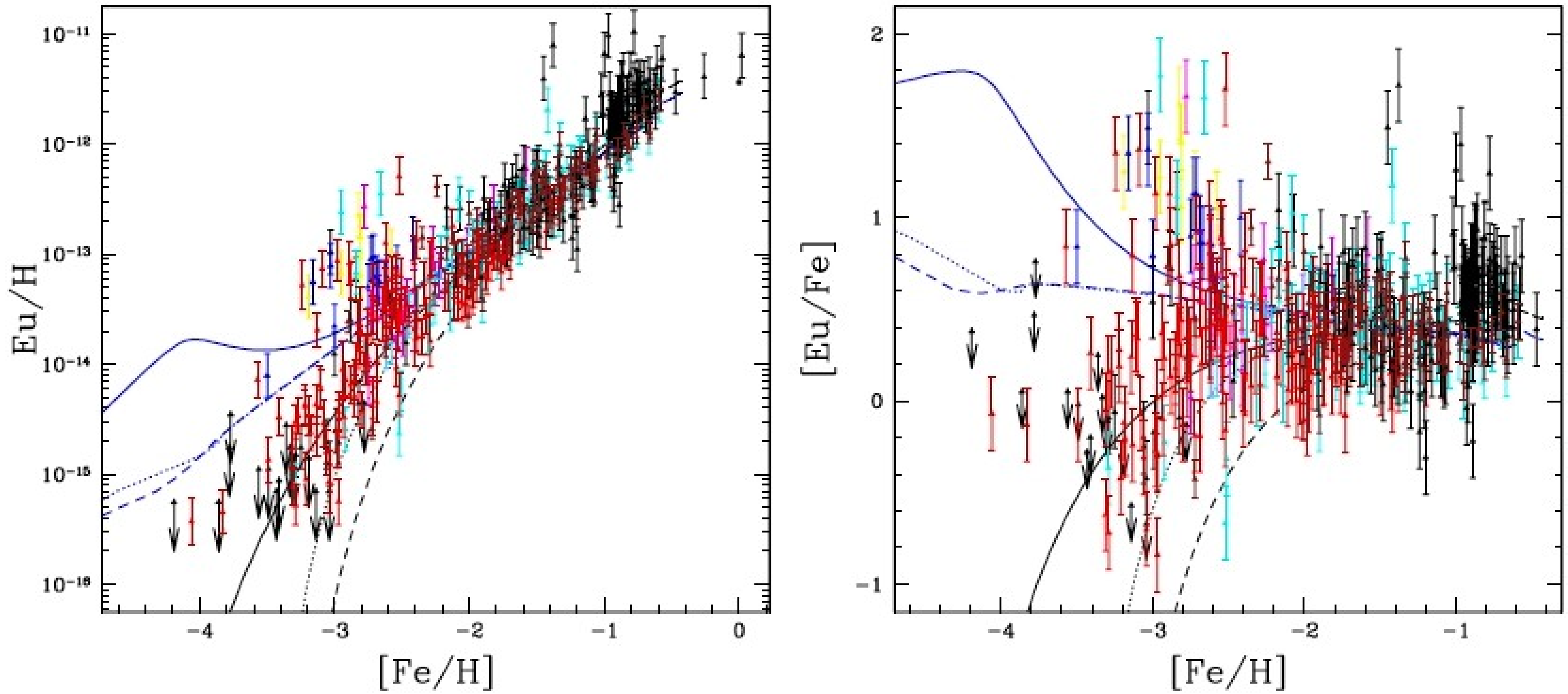


Fig. 5. Cosmic evolution of Eu: comparison between the two possible astrophysical sites (1) Eu/H and [Eu/Fe] vs [Fe/H]. Evolution of Eu/H and [Eu/Fe] as a function of [Fe/H] either in the CCSN (blue lines) or in the NSM (black lines) scenario. The evolution is computed for the three SFR modes considered in the present study, SFR1 (solid lines), SFR2 (dotted lines), SFR3 (dashed lines). In the CCSN scenario, the Eu yield is $10^{-7}\ M_\odot$ per supernova. In the NSM scenario, the Eu yield is $7 \times 10^{-5}\ M_\odot$ per merger, the fraction of binary compact objects is $\alpha = 0.002$ and the coalescence timescale is $\Delta t_{\mathrm{NSM}} = 0.2$ Gyr. Data points come from different references: black points and upper limits at low metallicity from François et al. (2007), brown points at higher metallicity from Simmerer et al. (2004), yellow from Barklem et al. (2005), magenta from Ren et al. (2012), red from Roederer et al. (2010, 2014a,b), heavy blue points from Roederer et al. (2014c). The bulk of black points at high metallicity come from dwarf spheroidal systems (Shertone, Côté & Stetson, 2001; Shertone, et al., 2003; Geilser et al., 2005; Cohen and Huang, 2009; Letarte et al., 2010; Starkenburg et al., 2013; McWilliam et al., 2013).

Vangioni et al., arXiv:1501.01115

Supernovae

- ✔ Exist, frequent, known rate, onset early in galaxy
- ✗ Small r-mass mass/event
- ✔ Chemogalactic role well understood
- ✗ Inner ejecta exposed to intense neutrino fluxes, increase Ye
- ✗ Ejecta conditions highly variable, neutrino-driven wind sensitive to Mns, Rns, neutrino properties, strong B-fields, wave-heating, sterile neutrinos,....
- ✗ Speculative scenarios:
  - O-Ne-Mg core surface
  - He shell (secondary process)
  - MHD jets
  - SN fallback-ejection

Mergers

- ✗ Exist, rare, rate uncertain
- ✔ Ejecta more mass/event
- ✗ Chemogalactic role not well studied
- ✔ Prompt mass ejection very fast: neutrinos do not harm much
- ✔ "Robust" r-process, outcome independent of numerics/group
- ✔ Scenario can be directly confirmed by observations (macro-nova)
- ✔ Sufficient variability for "outliers" and event scatter