r-process in neutron star mergers

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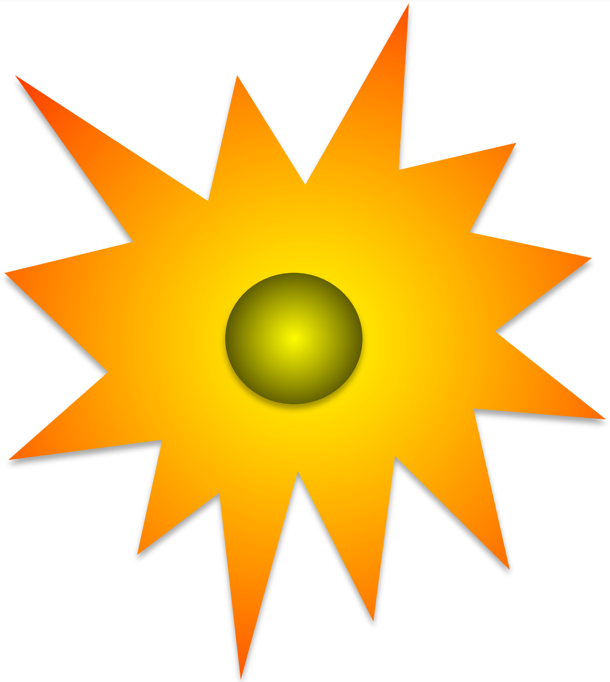
1. overview

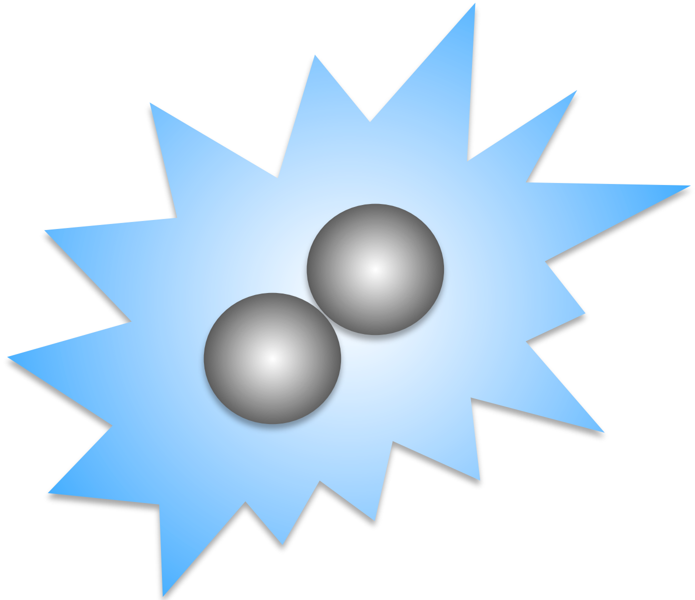
origin of gold (r-process elements) is still unknown…

popular r-process scenarios



core-collapse supernovae
(since Burbidge+1957;
Cameron 1957)

- n-rich ejecta nearby proto-NS
- not promising according to recent studies



neutron-star mergers
(since Lattimer+1974;
Symbalisty+1982)

- n-rich ejecta from coalescing NS-NS or BH-NS
- few nucleosynthesis studies

SN ejecta: not so neutron-rich…

- Y_e is determined by

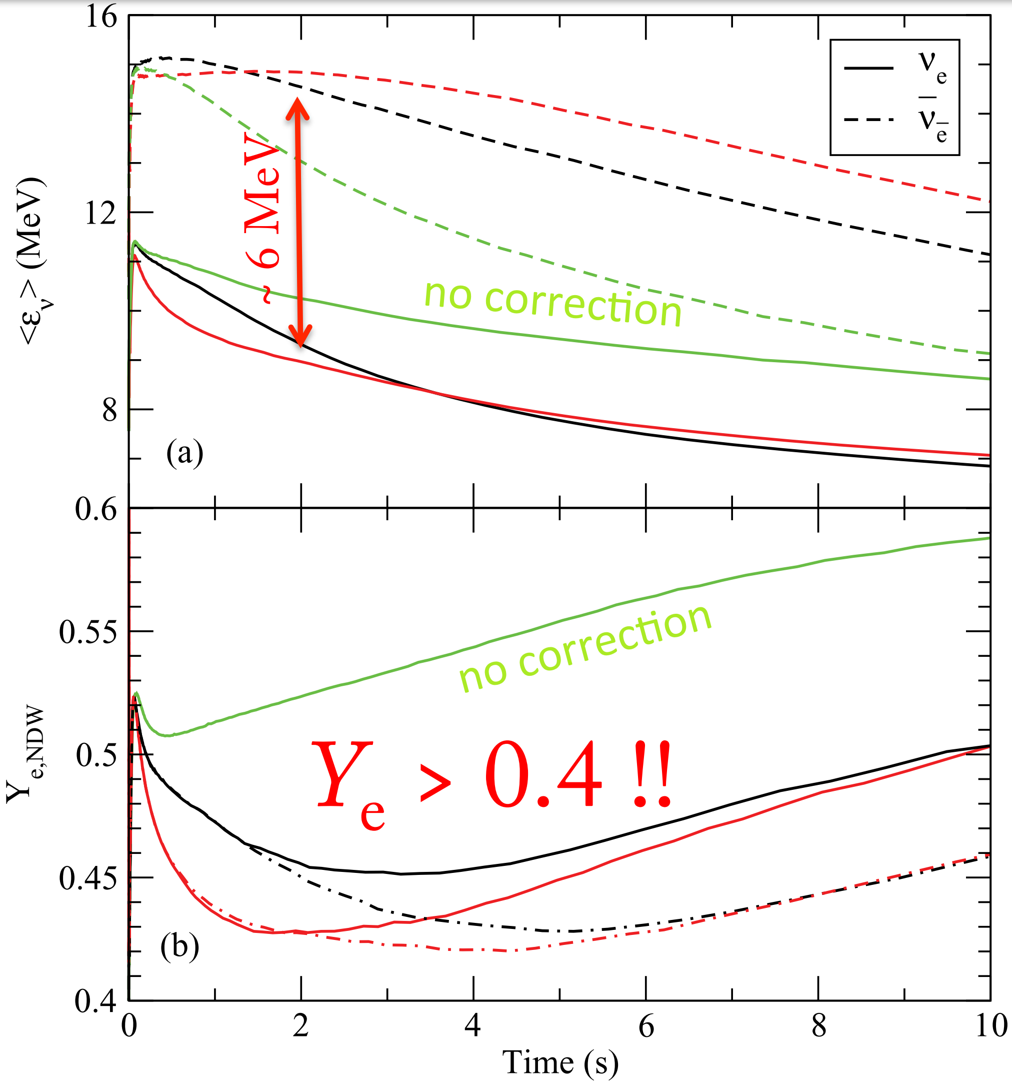
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

- equilibrium value is

$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}e}}{L_{\nu e}} \frac{\varepsilon_{\bar{\nu}e} - 2\Delta}{\varepsilon_{\nu e} + 2\Delta}\right]^{-1},$$
$$\Delta = M_n - M_p \approx 1.29 \text{ MeV}$$

- for $Y_e < 0.5$ (i.e., n-rich)

$$\varepsilon_{\bar{\nu}e} - \varepsilon_{\nu e} > 4\Delta \sim 5 \text{ MeV}$$
$$\text{if } L_{\bar{\nu}e} \approx L_{\nu e}$$

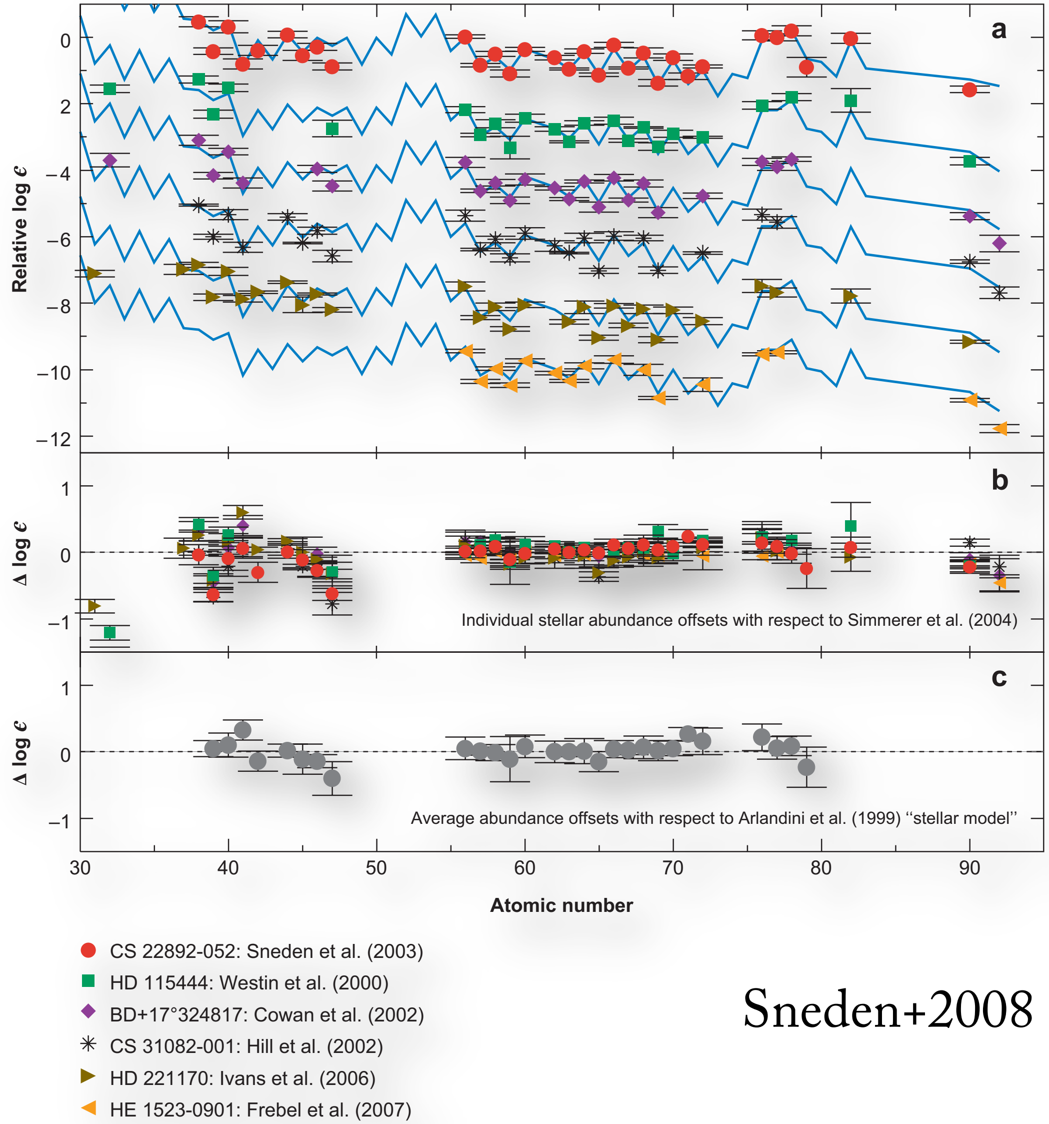


Roberts+2012

supernovae can be the origin only if …

the explosion is not due to neutrino heating (but, e.g., magneto-rotational jet; Winteler+2012) or our knowledge of neutrino physics is insufficient.

r-process in the early Galaxy



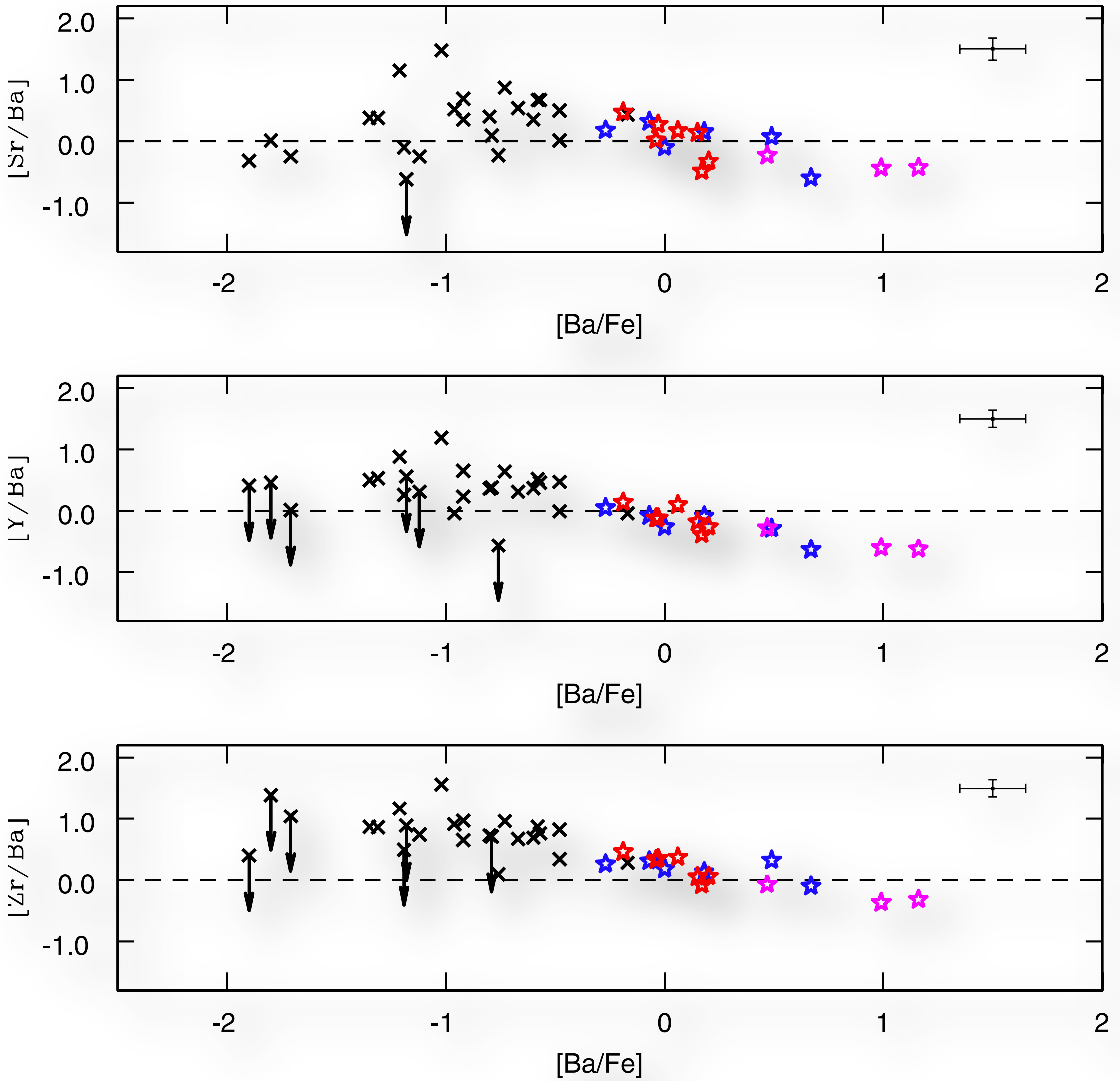
Sneden+2008

all r-rich Galactic halo stars show remarkable agreement with the solar r-pattern

- r-process should have operated in the early Galaxy; SNe 😃, mergers 😢 ?
- astrophysical models should reproduce the "universal" solar-like r-process pattern (for $Z \geq 40$; $A \geq 90$)

constraint to light-to-heavy r-ratio

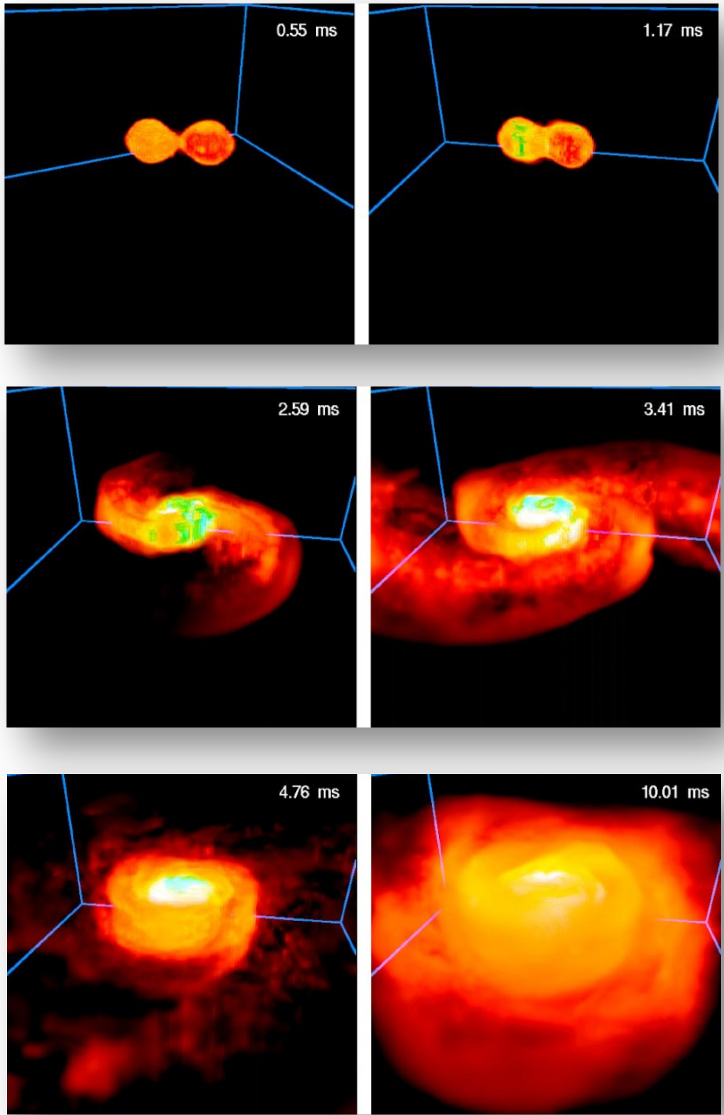
Siqueira Mello+…+ Wanajo 2014



VLT observations give tight constraint for light-to-heavy r-abundances (here [Sr, Y, Zr/Ba])

- [light-r/heavy-r] ≥ -0.3; no stars below this constraint
- “the r-process” must make lighter r-elements with similar portion

NS merger scenario: most promising?

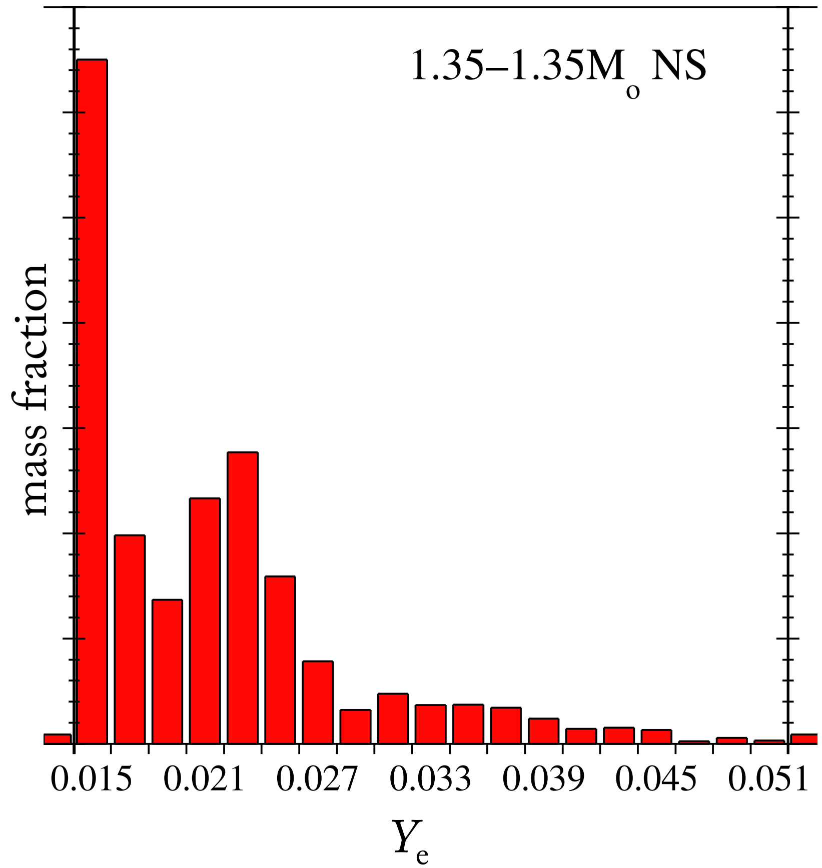


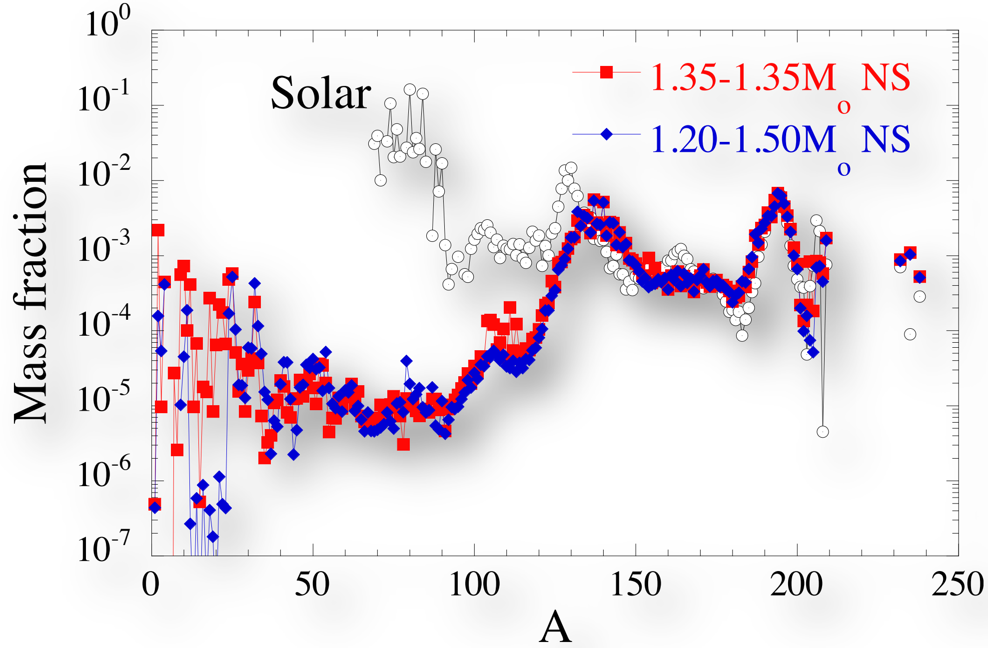
www.mpa-garching.mpg.de

- coalescence of binary NSs expected ~ 10 – 100 per Myr in the Galaxy (also possible sources of short GRB)
- first ~ 0.1 seconds
  dynamical ejection of n-rich matter with M_{ej} ~ 10^{-3} – 10^{-2} $M_\odot$
- next ~ 1 second
  neutrino or viscously driven wind from the BH accretion torus with M_{ej} ~ 10^{-3} – 10^{-2} $M_\odot$

previous works: too neutron-rich ?

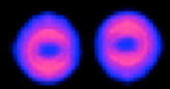
Goriely+2011 (also similar results by Korobkin+2011; Rosswog+2013)





tidal (or weakly shocked) ejection of "pure" n-matter with $Y_e < 0.1$

- ❖ strong r-process leading to fission cycling
- ❖ severe problem: only $A > 130$; another source is needed for the lighter counterpart

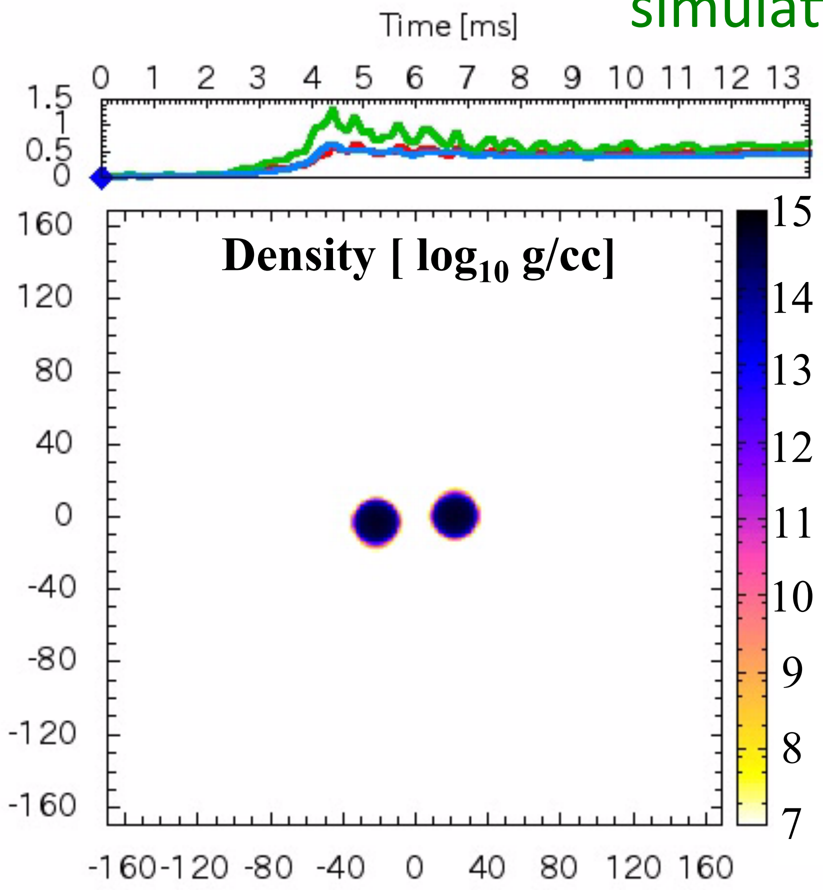


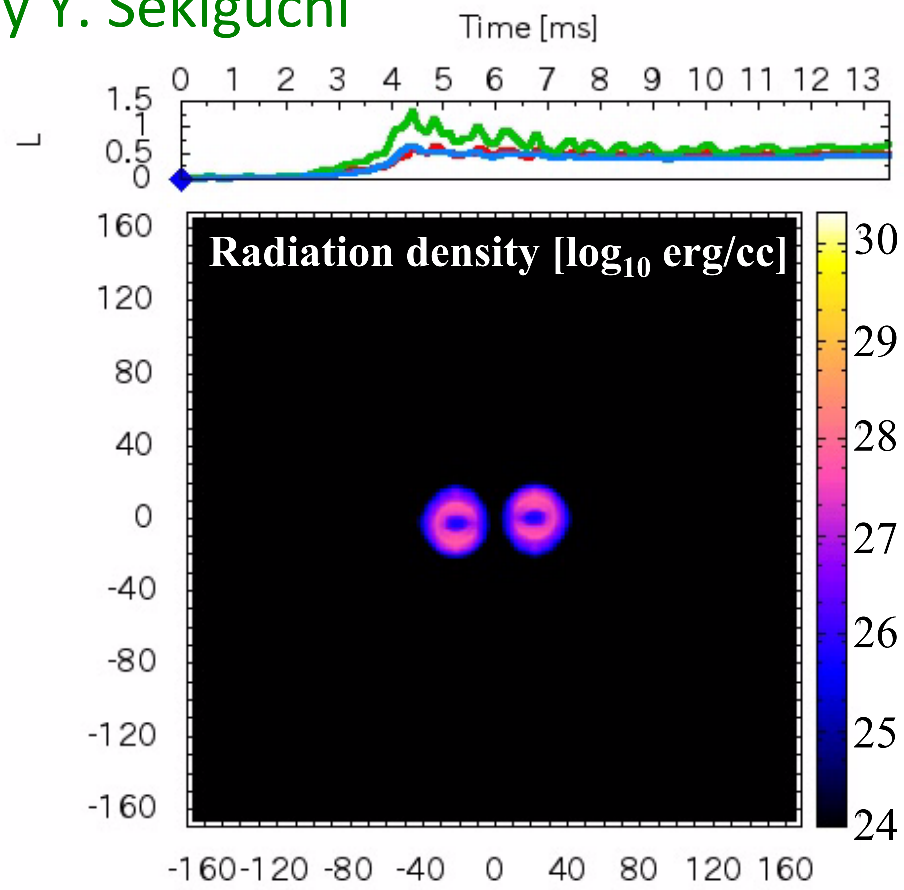
2. mergers with GR and ν

first simulation with full-GR and ν

- Approximate solution by Thorne's Moment scheme with a closure relation
- Leakage + Neutrino heating (absorption on proton/neutron) included

simulation by Y. Sekiguchi





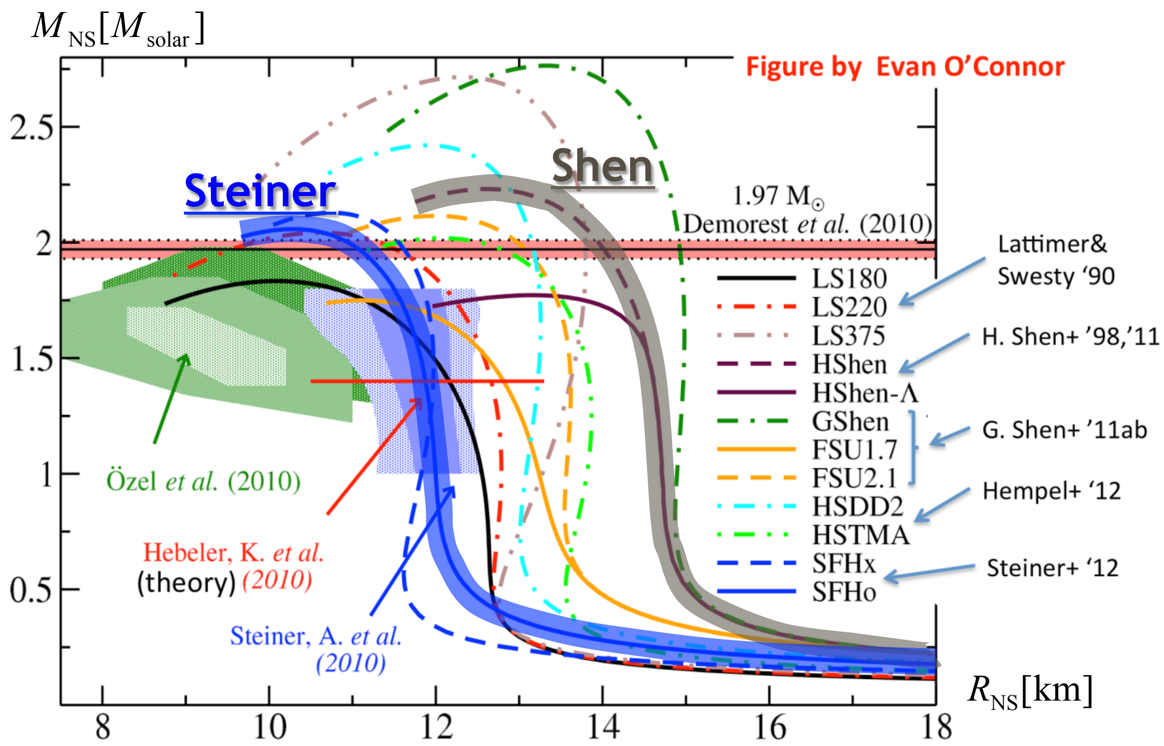
slide by Y. Sekiguchi

‘Robustness’ of r-process in NS-NS merger ?

- **Korobkin et al. 2012 :** Ye of the ejecta depends only weakly on the binary parameters so that r-process in the NS-NS is ‘robust’,
  - They adopted only one EoS (**Shen EoS**) : dependence on EoS is not explored
- **In This Study :** Comparison between **Steiner EoS** and **Shen EoS**

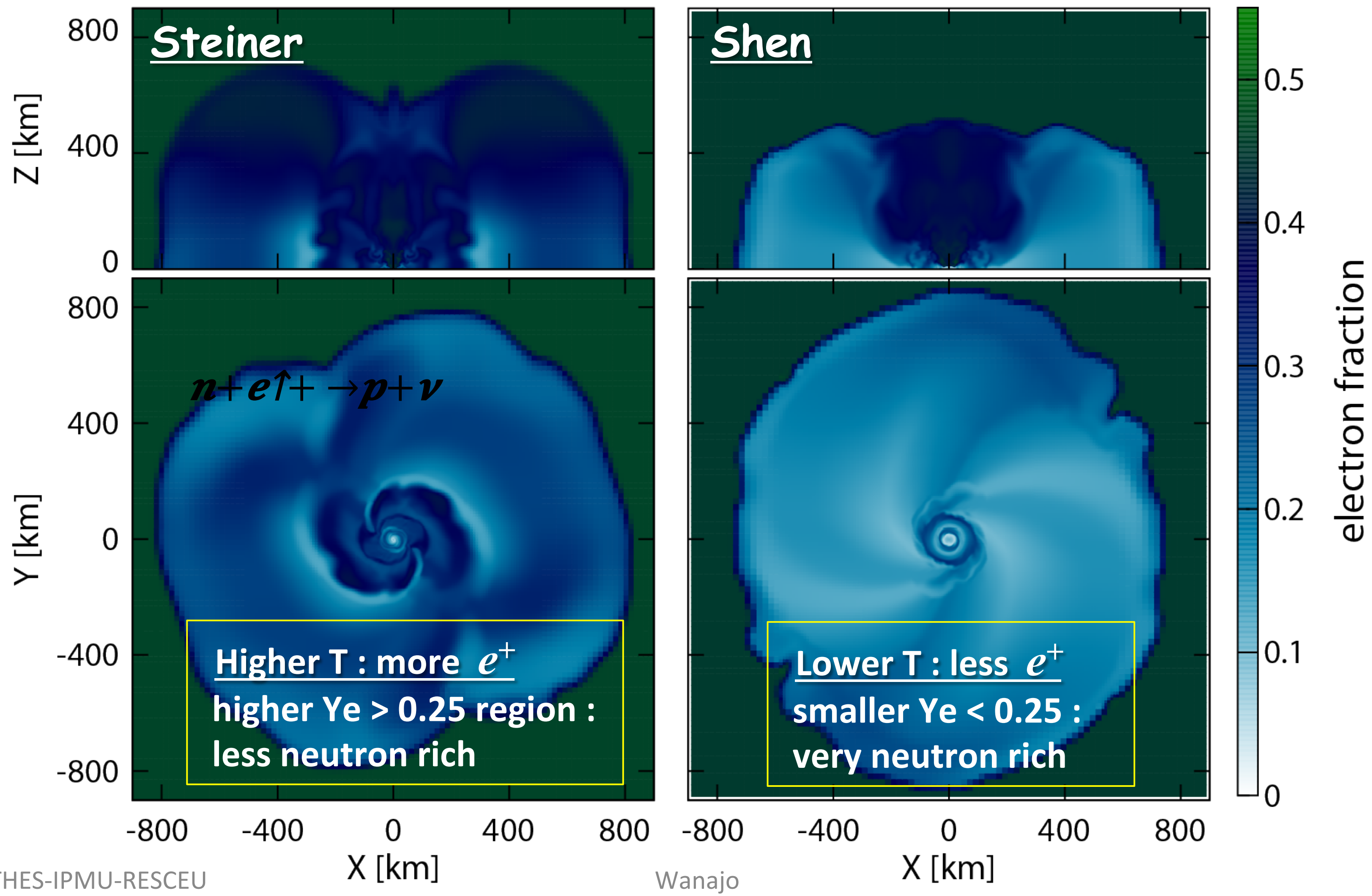
- **Shen EOS: ‘Stiffer’**
  - Larger NS radius
  - Mass ejection is driven mainly by Tidal force
- **Steiner EOS: ‘Softer’**
  - Smaller NS radius
  - Tidal effects are less important in mass ejection
  - Stronger bounce

$$F \sim k_{\rm EOS}\Delta x \sim M_{\rm NS},$$
$$E \sim k_{\rm EOS}(\Delta x)^2 \sim M_{\rm NS}^2 k_{\rm EOS}^{-1}$$

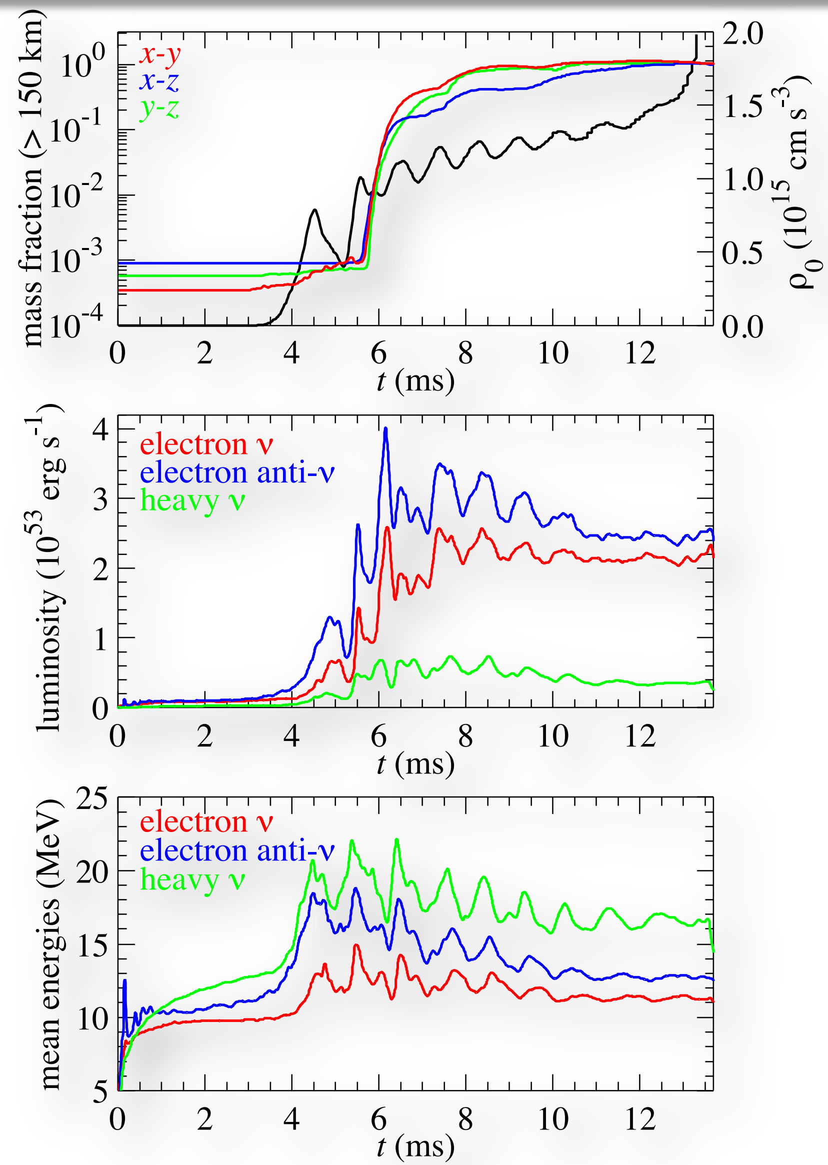


slide by Y. Sekiguchi

Composition depends on EOS

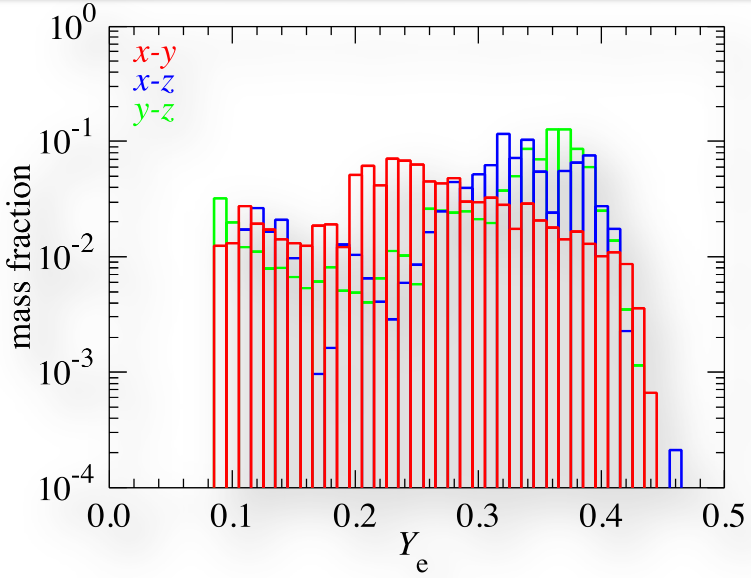


neutrino properties (Steiner's EOS)

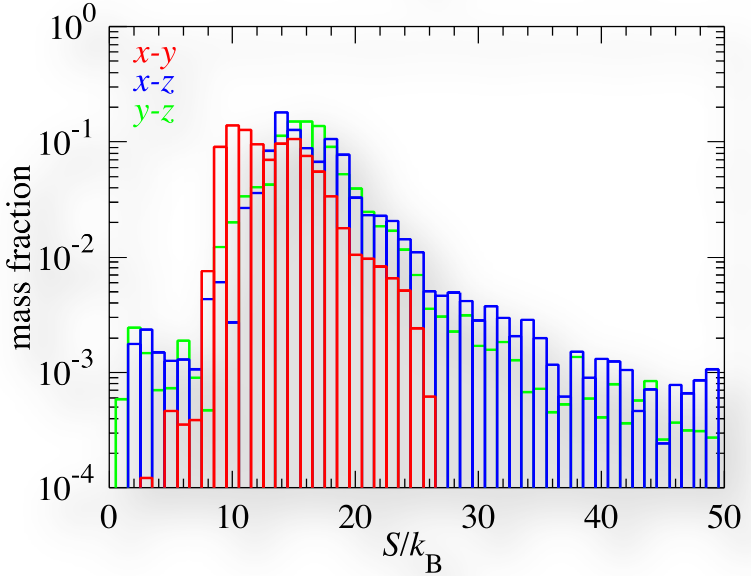


- ❖ mass ejection before (40%) and after (60%) HMNS formation; 70% ejecta reside near orbital
- ❖ neutrino luminosities similar between ν_e and anti-ν_e
- ❖ neutrino mean energies similar between ν_e and anti-ν_e

nucleosynthesis in the NS ejecta

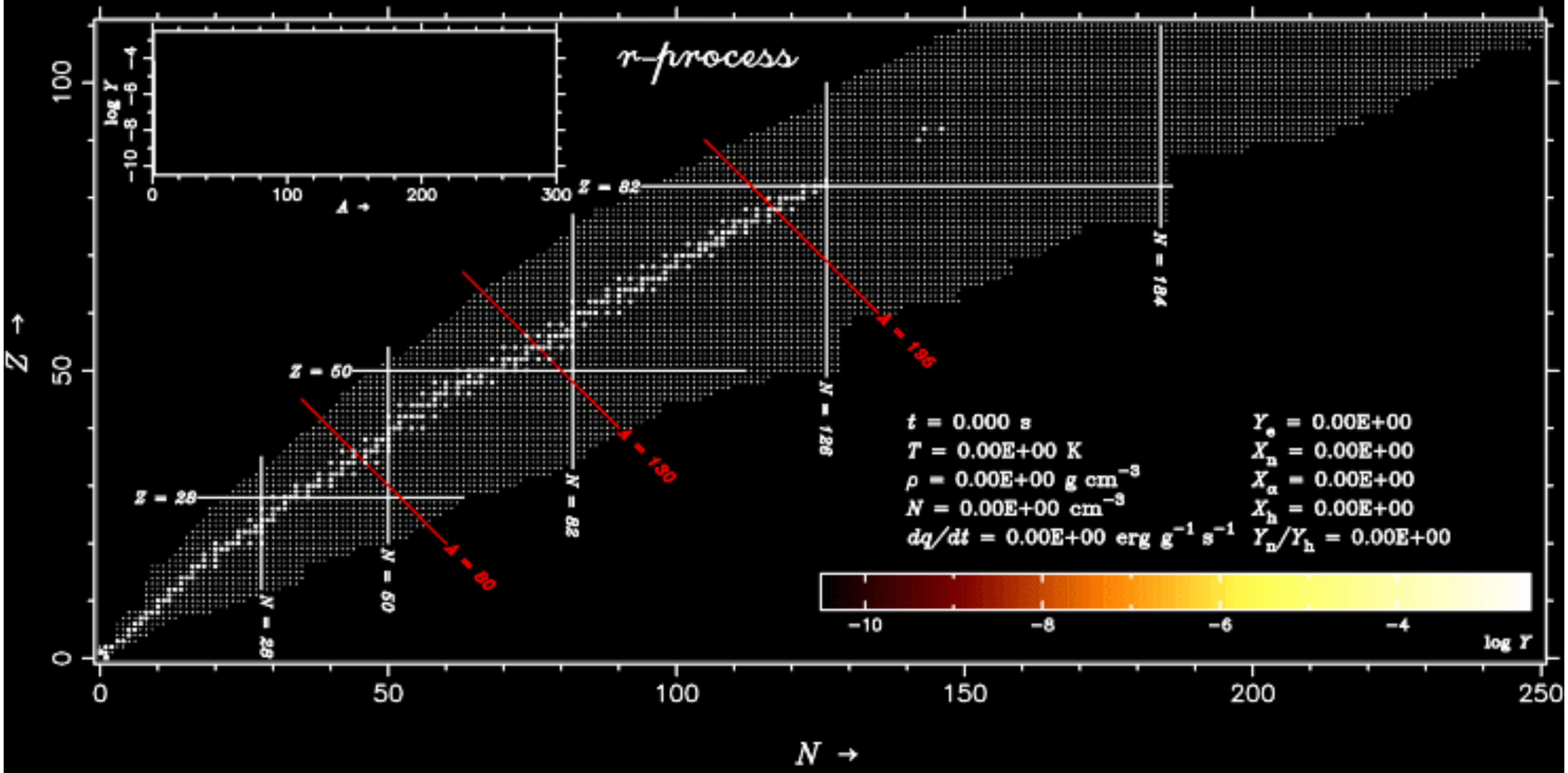


- higher and wider range of Y_e (= 0.09-0.45) in contrast to previous cases Y_e (= 0.01-0.05)



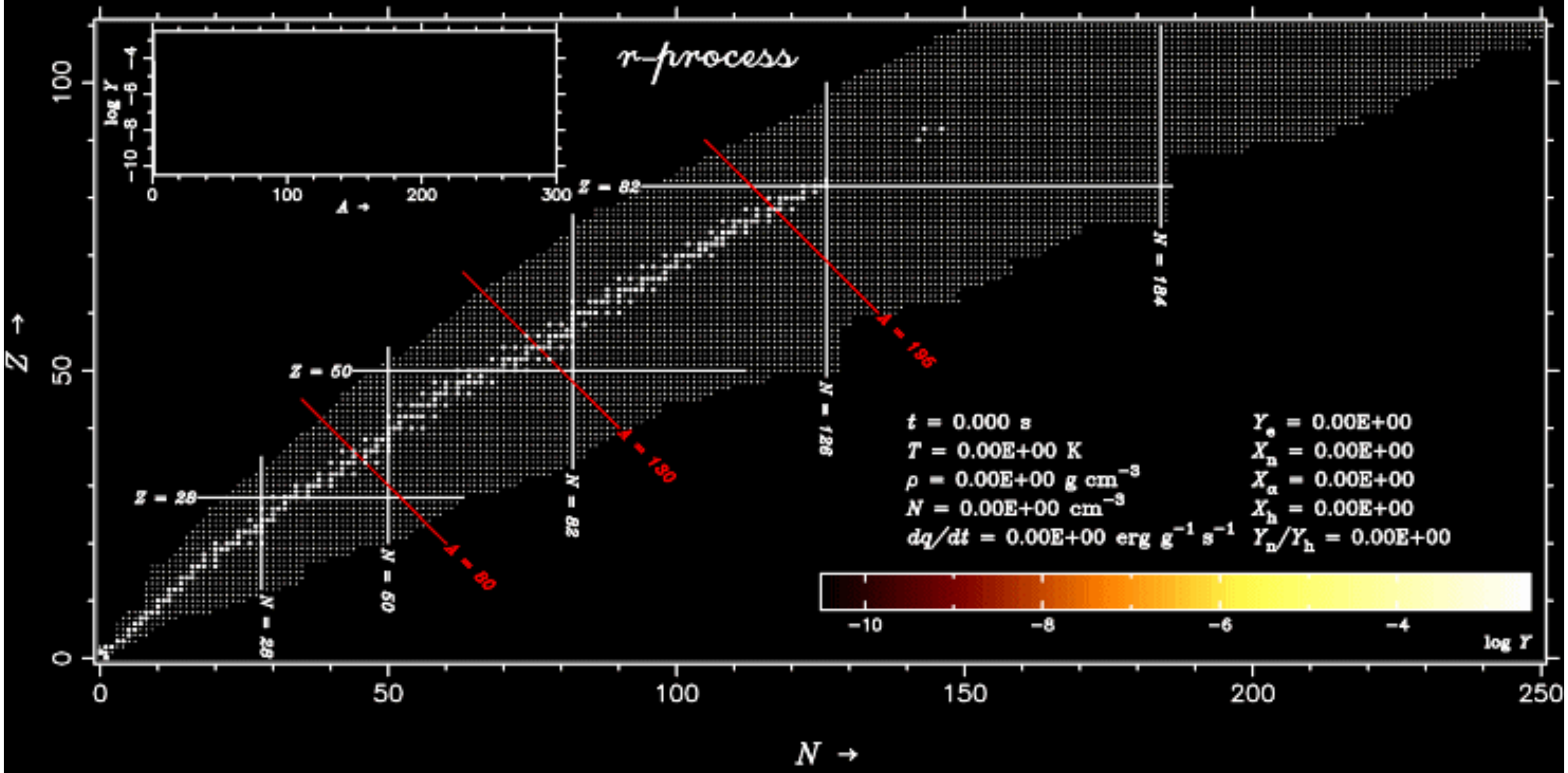
- higher and weder range of entropy per baryon (= 0-50) in contrast to previous cases (= 0-3)

$Y_e = 0.1$



r-process
log Y
A →
Z = 82
Z = 50
Z = 28
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 0.000 s
T = 0.00E+00 K
ρ = 0.00E+00 g cm^−3
N = 0.00E+00 cm^−3
dq/dt = 0.00E+00 erg g^−1 s^−1
Y_e = 0.00E+00
X_n = 0.00E+00
X_α = 0.00E+00
X_h = 0.00E+00
Y_n/Y_h = 0.00E+00
log Y
Z →
N →

Y_e = 0.2



r-process
log Y
A →
Z = 82
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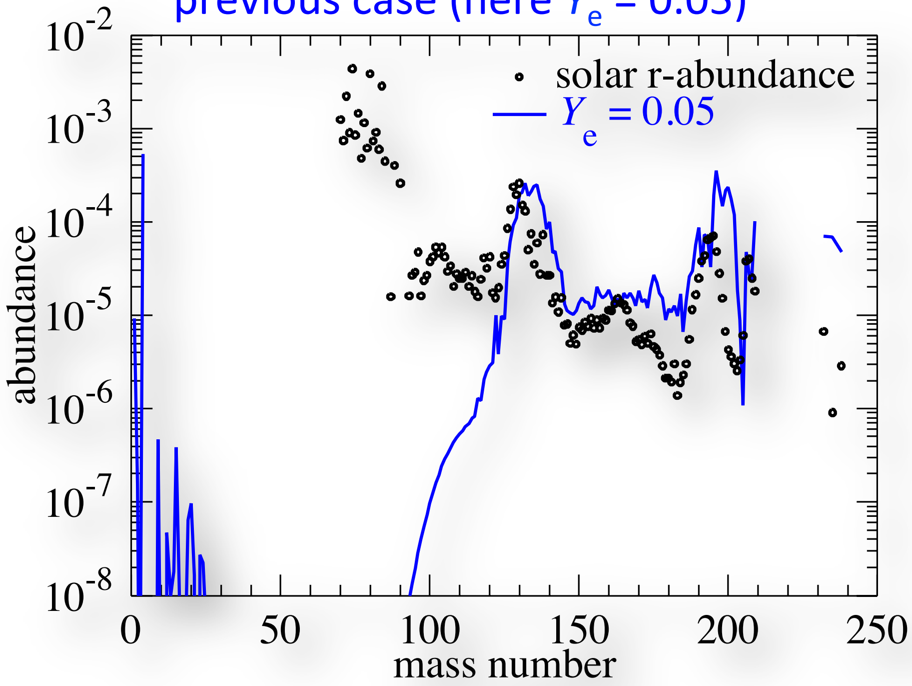
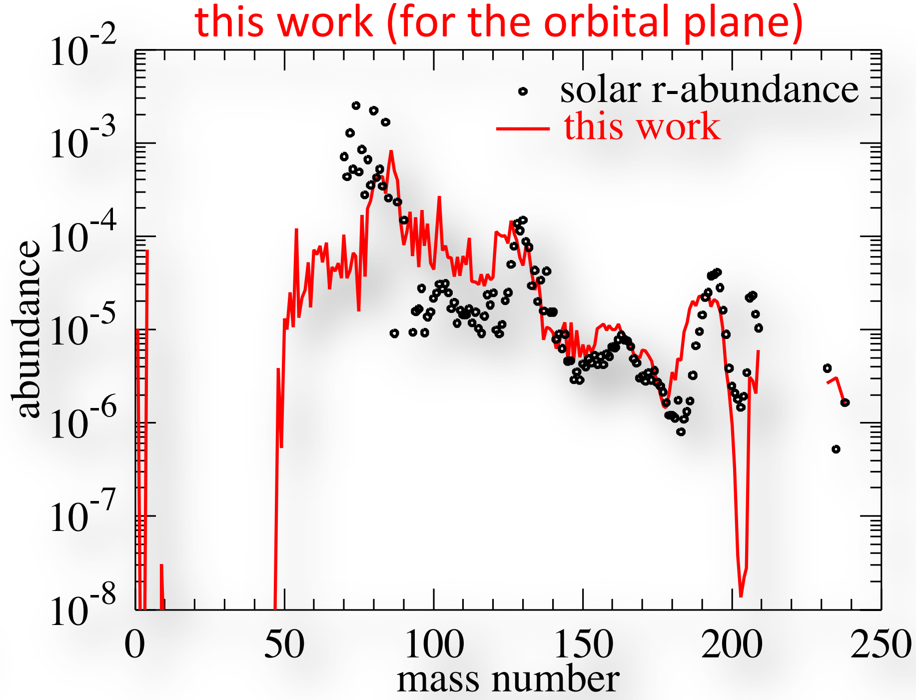
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 0.000 s
T = 0.00E+00 K
ρ = 0.00E+00 g cm⁻³
N = 0.00E+00 cm⁻³
dq/dt = 0.00E+00 erg g⁻¹ s⁻¹
Ye = 0.00E+00
Xn = 0.00E+00
Xα = 0.00E+00
Xh = 0.00E+00
Yn/Yh = 0.00E+00
log Y
Z →
N →

mass-integrated abundances

previous case (here Y_e = 0.05)



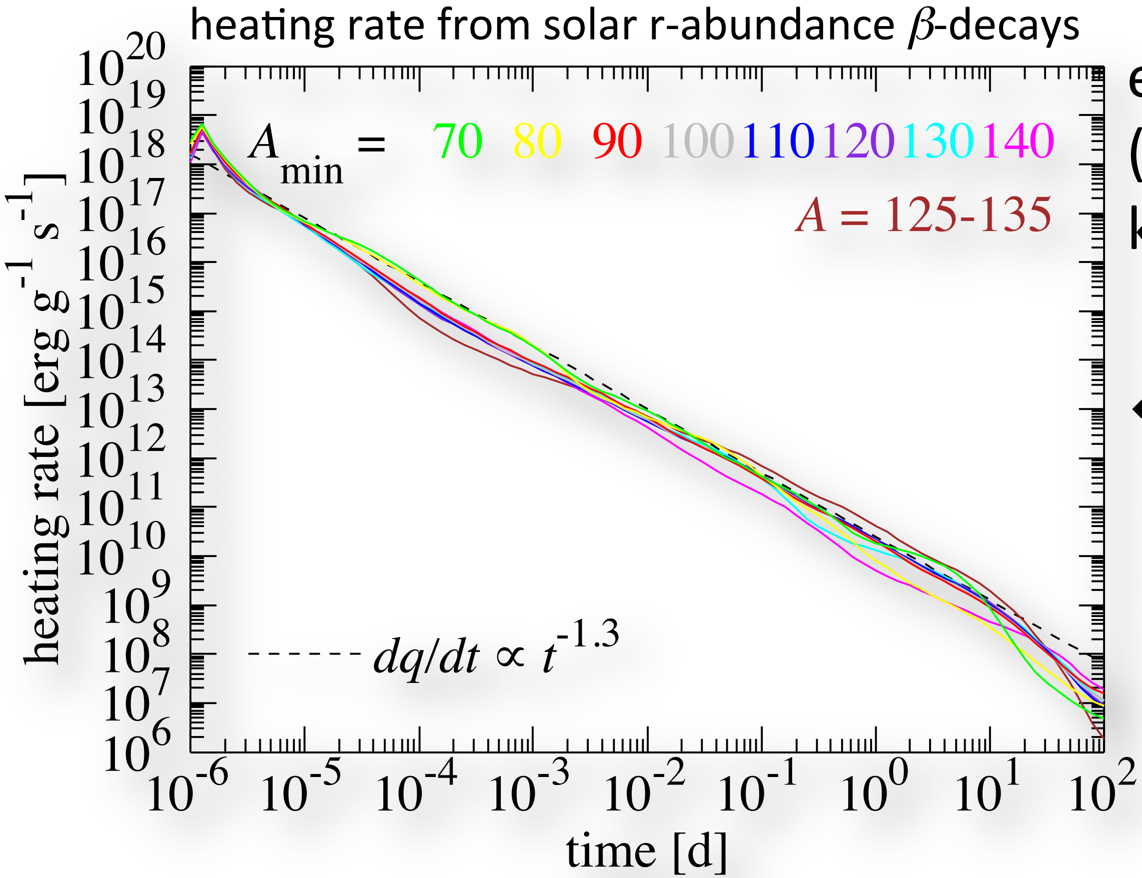
this work (for the orbital plane)



- previous case: not in agreement with solar r-pattern (e.g., for $A < 130$)
  → also the case for NS-NSs with stiff EOSs and BH-NSs
- this work: good agreement with solar r-pattern for A = 90-240
  → no need of additional (e.g., BH-torus) sources for light r-elements

3. r-process novae (or goldnovae)

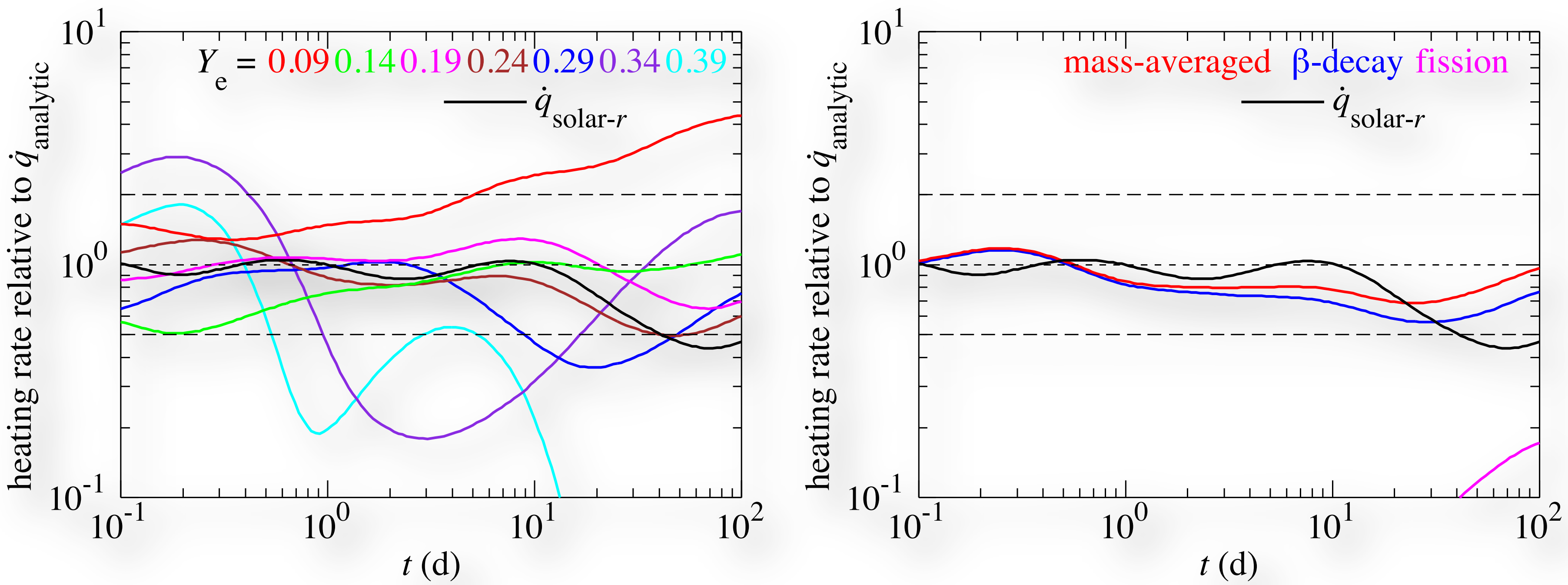
r-process novae (kilonovae)



electro-magnetic transients (macronova, Kulkarni 2005; kilonova, Metzger+2010)

- ❖ heating from decays of radionuclides well scaled as $dq/dt \sim t^{-1.3}$

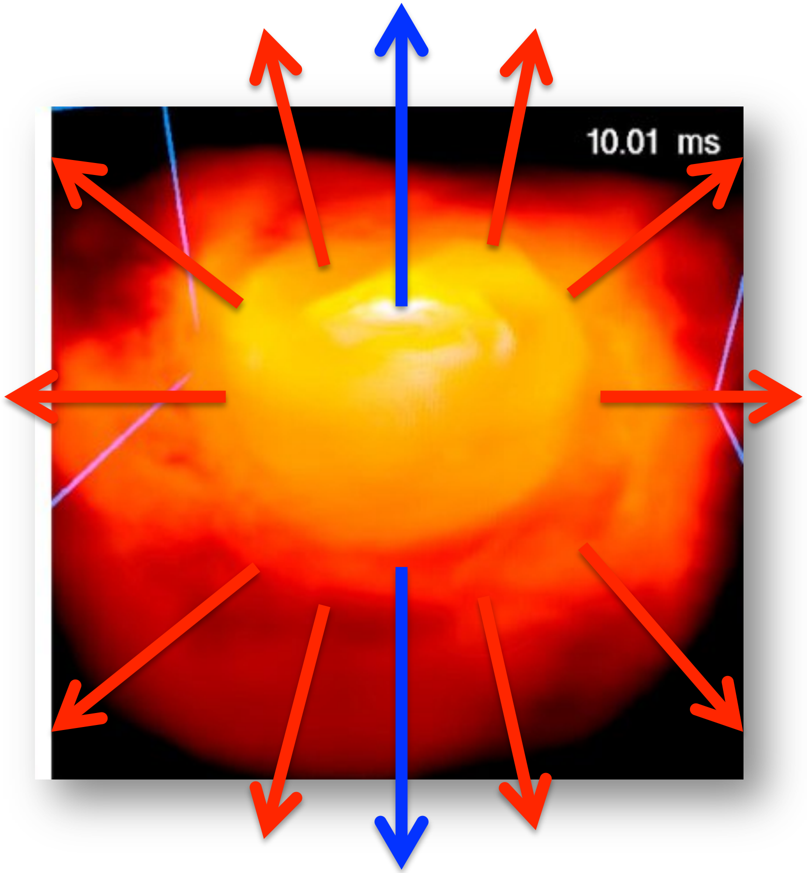
heating rate for the NS-NS ejecta



❖ heating rate for the mass-averaged abundances well fitted by the scaling law $dq/dt \sim t^{-1.3}$ (as well as by the solar r-pattern case)

❖ but dependent on Y_e; there might be directional (polar to equatorial) differences

EM counterparts of GW signals



GW signal can be spatially resolved only ~ 100 deg^2 by KAGRA/a.LIGO/ a.Virgo (from 2017)
→ EM counterparts are needed

- SGRBs
  events should be restricted due to narrow beaming

- r-process novae
  detectable (by, e.g., Subaru/HSC) from all directions!

already found?

LETTER

doi:10.1038/nature12505

A 'kilonova' associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. Hjorth[4], R. A. Hounsell[3], K

Short-duration γ-ray bursts are intense flashes of cosmic γ-rays, lasting less than about two seconds, whose origin is unclear[1,2]. The favoured hypothesis is that they are produced by a relativistic jet created by the merger of two compact stellar objects (specifically two neutron stars or a neutron star and a black hole). This is supported by indirect evidence such as the properties of their host galaxies[3], but unambiguous confirmation of the model is still lacking. Mergers of this kind are also expected to create significant quantities of neutron-rich radioactive species[4,5], whose decay should result in a faint transient, known as a 'kilonova', in the days following the burst[6–8]. Indeed, it is speculated that this mechanism may be the predominant source of stable r-process elements in the Universe[5,9].

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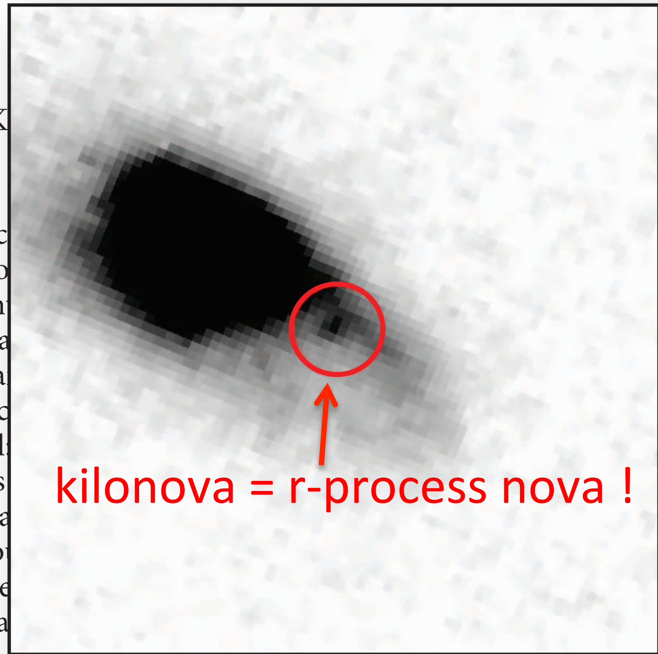
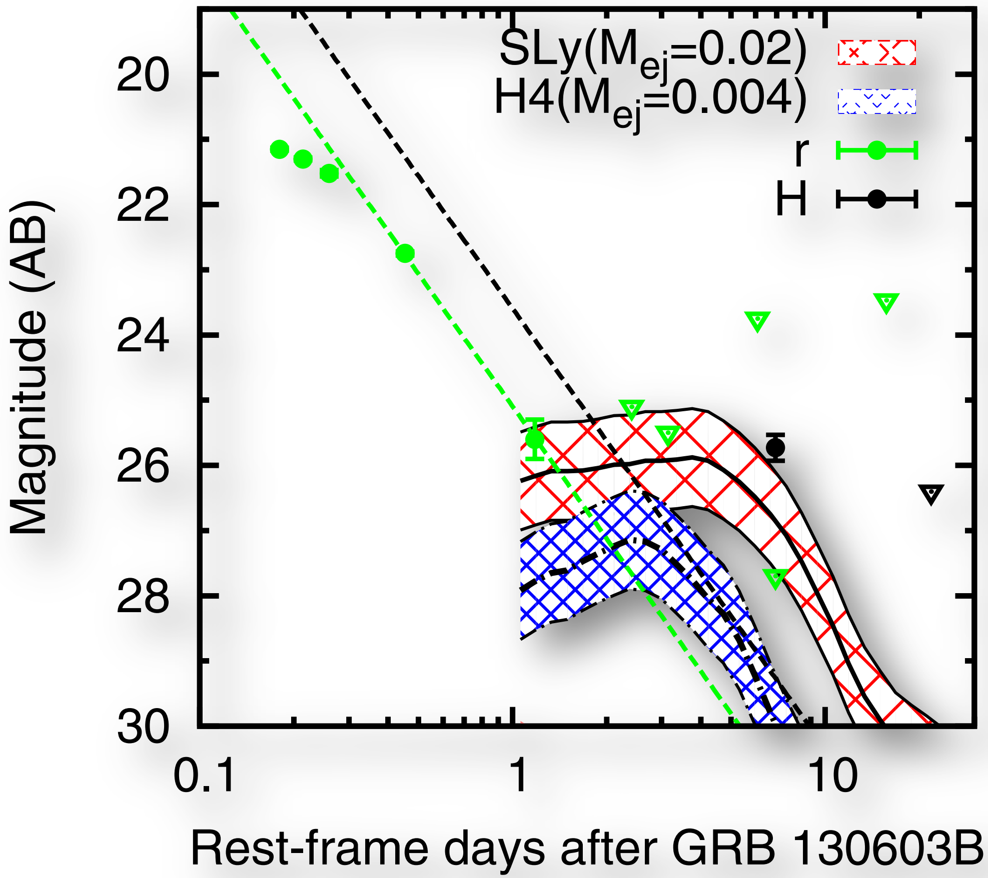


Tanvir+2013, Nature, Aug. 29

r-process nova in the SGRB afterglow?

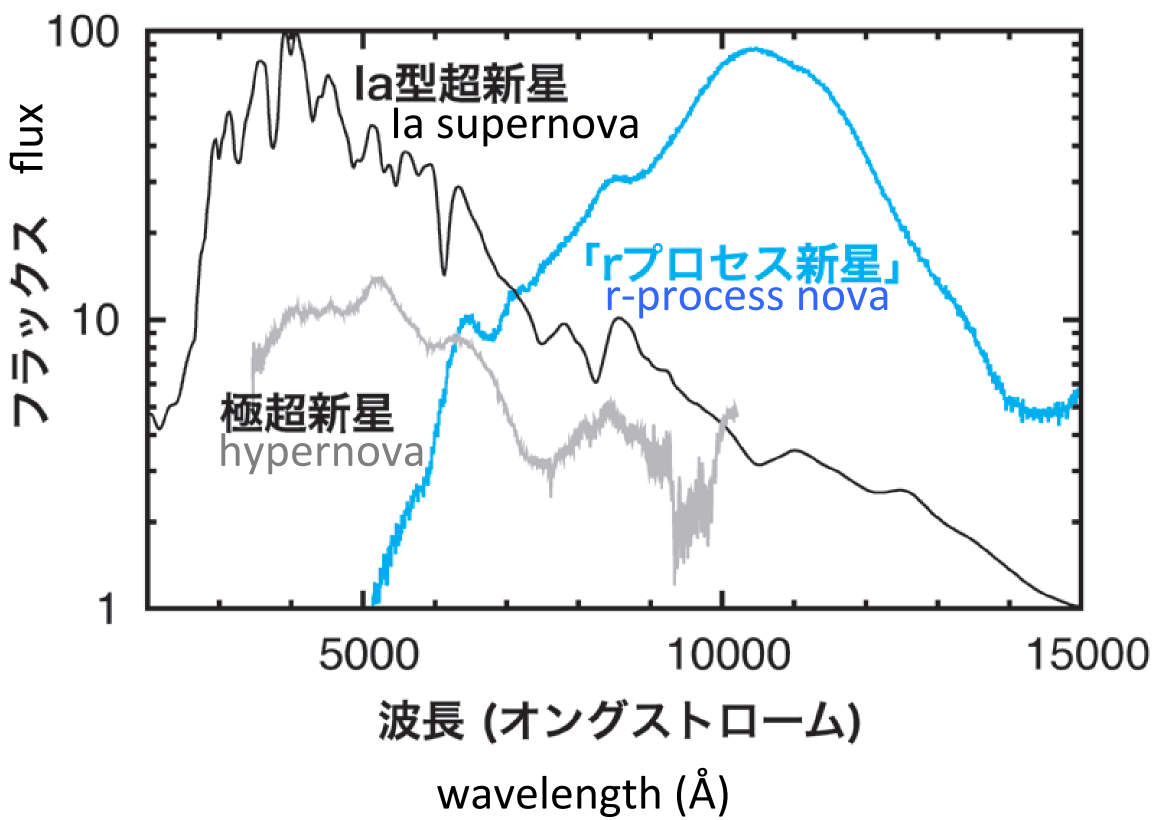
Hotokezaka+Tanaka…+Wanajo 2013;
NS+NS models



- ❖ late-time excess NIR flux requires an additional component (most likely an r-process nova)
- ❖ the excess NIR indicates the NS-NS ejecta with $M_{ej} \sim 0.02\ M_{\odot}$
- ❖ additional late-time red transients in SGRBs should be observed

what is a smoking gun of the r-process?

田中，天文月報2014年1月



can we see r-abundances in the spectra?

- almost featureless because of too many bound-bound lines and Doppler shifts (v/c ~ 0.1-0.3)

- identification of red, featureless spectral shape can be an unambiguous evidence of an r-process

summary and outlook

- ❖ NS mergers: very promising site of r-process
  - neutrinos play a crucial role (in particular for a soft EOS)
- ❖ still many things yet to be answered…
  - dependence on mass ratios of NSs and EOSs; how about BH-NS?
  - how the subsequent BH-tori contribute to the r-abundances?
  - can mergers be the origin of r-process elements in the Galaxy?