

r-process in neutron star mergers

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第3回研究会

September 23-25, 2014, Atagawa, Japan



Flash Info

■ Pilots' strike action from 15 to 26 September 2014

Flight	Original Departure	Original Arrival	
AF272 cancelled	10:50 - 2014年9月23日 パリ, シャルル・ド・ゴール空港 (CDG) - フランス	06:00 - 2014年9月24日 東京, 羽田空港 (HND) - 日本	▼
AF276	13:40 - 2014年9月23日 パリ, シャルル・ド・ゴール空港 (CDG) - フランス	08:35 - 2014年9月24日 東京, 成田空港 (NRT) - 日本	▼
AF284	22:20 - 2014年9月23日 パリ, シャルル・ド・ゴール空港 (CDG) - フランス	16:55 - 2014年9月24日 東京, 成田空港 (NRT) - 日本	▼
AF274 cancelled	23:25 - 2014年9月23日 パリ, シャルル・ド・ゴール空港 (CDG) - フランス	18:20 - 2014年9月24日 東京, 羽田空港 (HND) - 日本	▼

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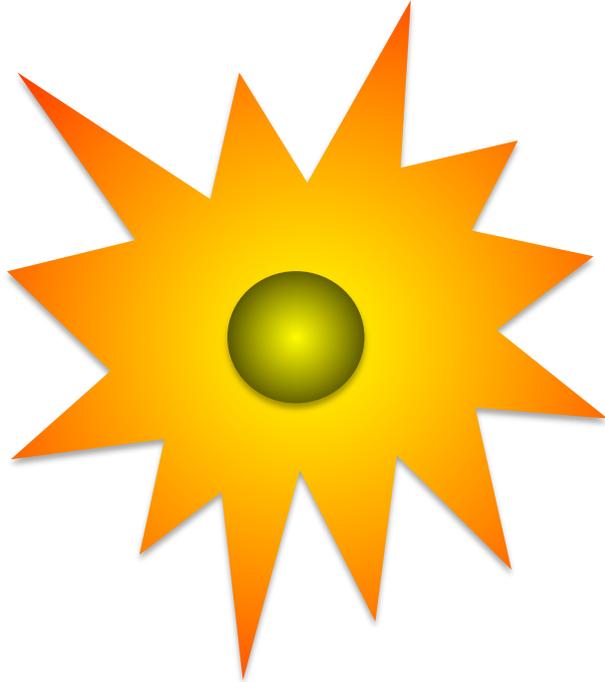


1. overview

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



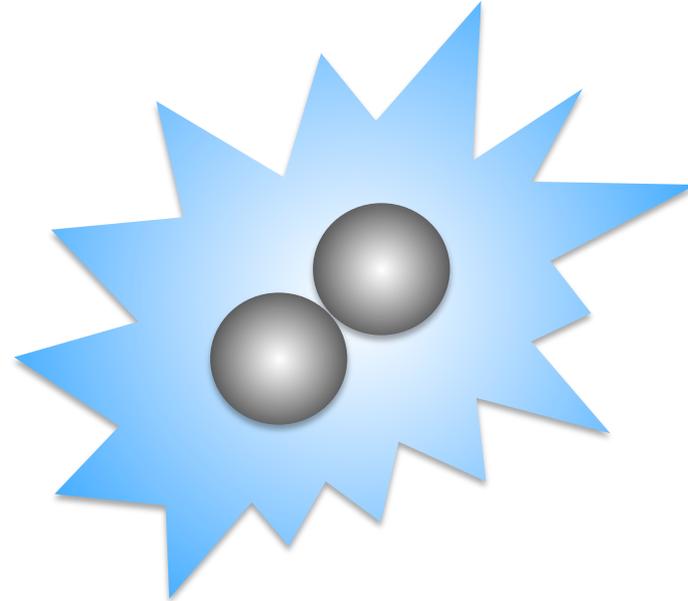
popular r-process scenarios



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

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

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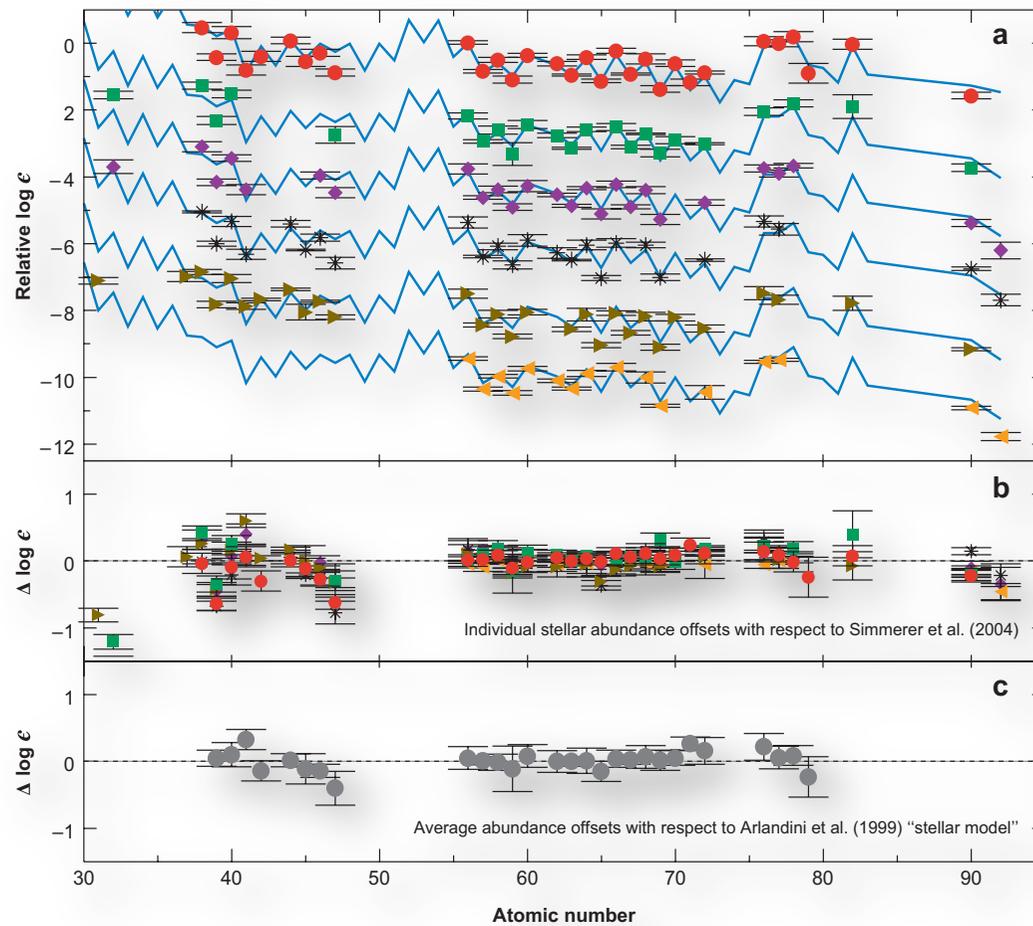
neutron-star mergers
(since Lattimer+1974;
Symbalisty+1982)

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

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r-process in the early Galaxy



- CS 22892-052: Sneden et al. (2003)
- HD 115444: Westin et al. (2000)
- ◆ BD+17°324817: Cowan et al. (2002)
- * CS 31082-001: Hill et al. (2002)
- ▶ HD 221170: Ivans et al. (2006)
- ◀ HE 1523-0901: Frebel et al. (2007)

Sneden+2008

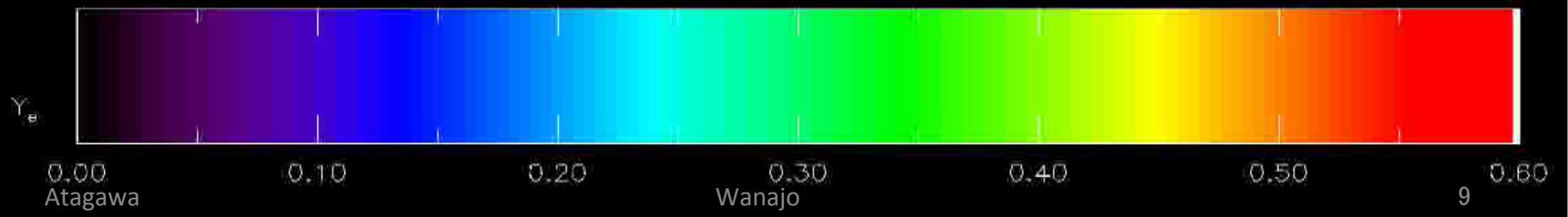
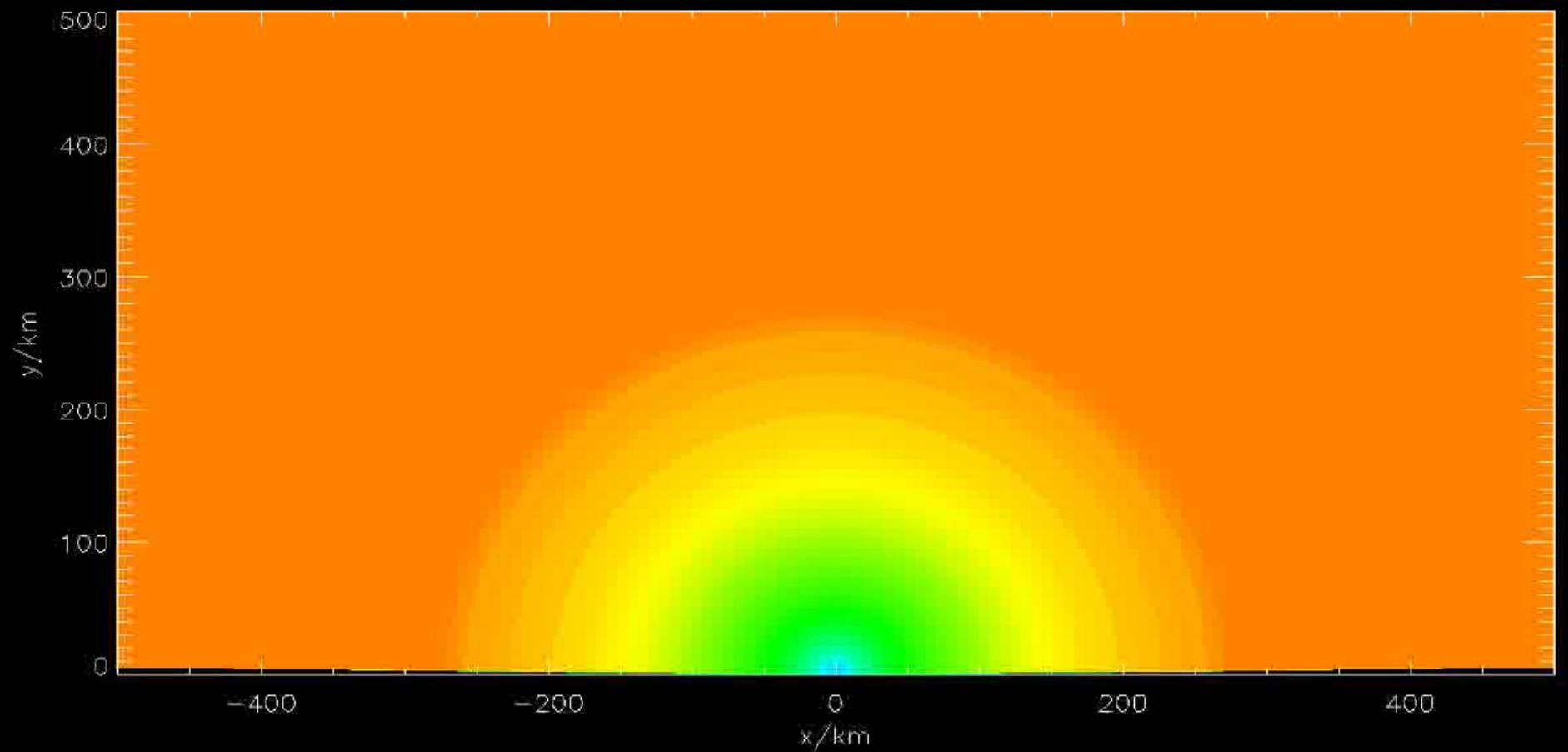
all r-rich Galactic halo stars show remarkable agreement with the solar r-pattern

❖ r-process should have operated in the early Galaxy;
SNe 😊, mergers 😞 ?

❖ astrophysical models should reproduce the "universal" solar-like r-process pattern (for $Z \geq 40$; $A \geq 90$)

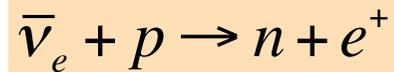
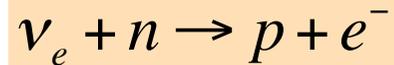
8.8 M_{\odot} self-consistently exploding electron-capture supernova

simulation by Bernhard Müller



SN neutrino wind: not so neutron-rich

❖ Y_e is determined by



❖ equilibrium value is

$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e} \varepsilon_{\bar{\nu}_e} - 2\Delta}{L_{\nu_e} \varepsilon_{\nu_e} + 2\Delta} \right]^{-1},$$

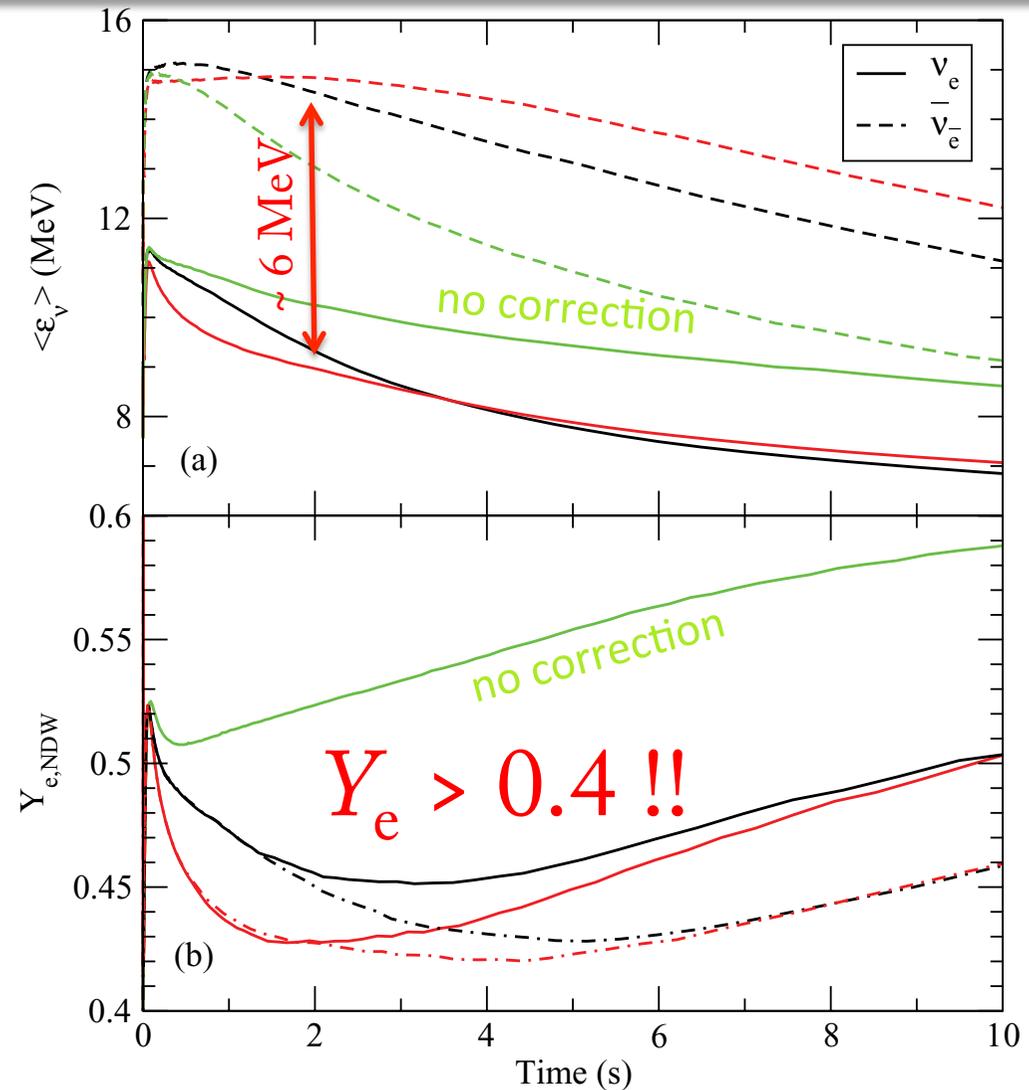
$$\Delta = M_n - M_p \approx 1.29 \text{ MeV}$$

❖ for $Y_e < 0.5$ (i.e., n-rich)

$$\varepsilon_{\bar{\nu}_e} - \varepsilon_{\nu_e} > 4\Delta \sim 5 \text{ MeV}$$

$$\text{if } L_{\bar{\nu}_e} \approx L_{\nu_e}$$

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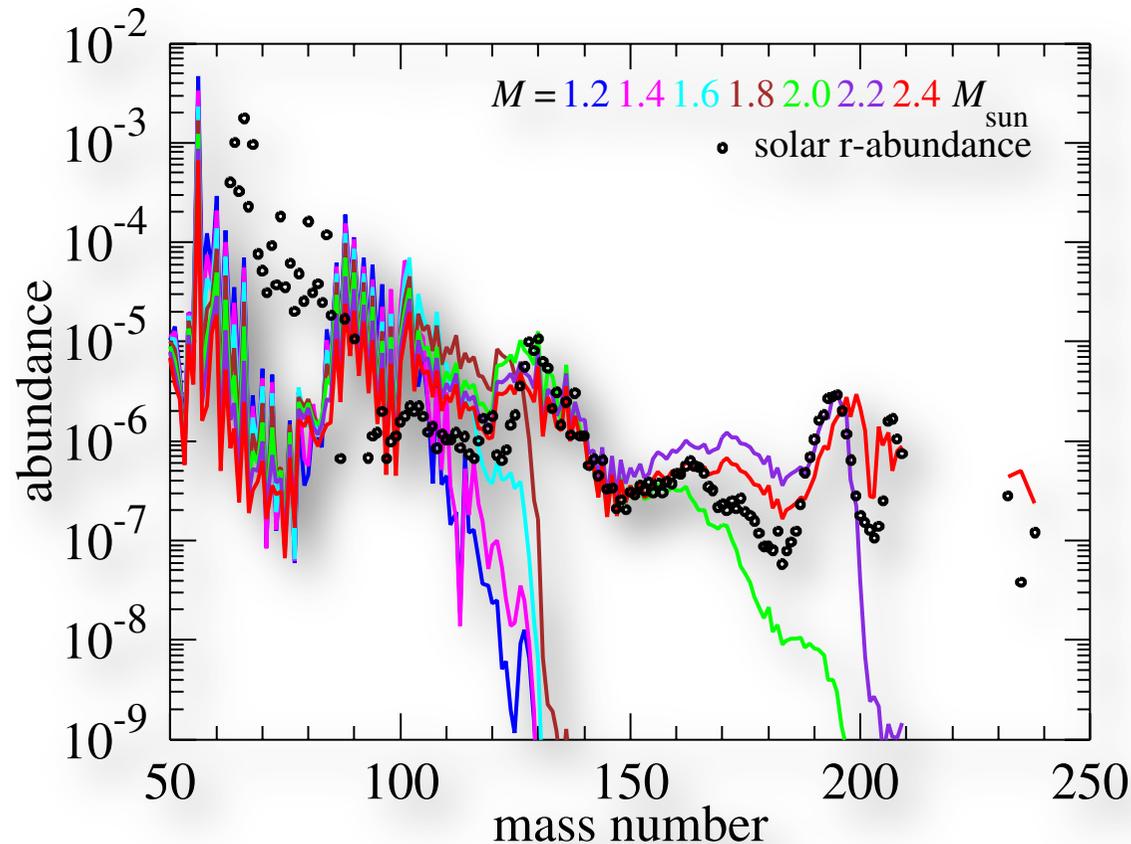


Roberts+2012

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is the answer blowing in the wind?



Wanajo 2013

- ❖ only very massive proto-NSs ($> 2.2 M_{\odot}$) make the heavy r-elements
- ❖ typical proto-NSs ($< 2.0 M_{\odot}$) probably make weak r-elements ($A \sim 90 - 130$)

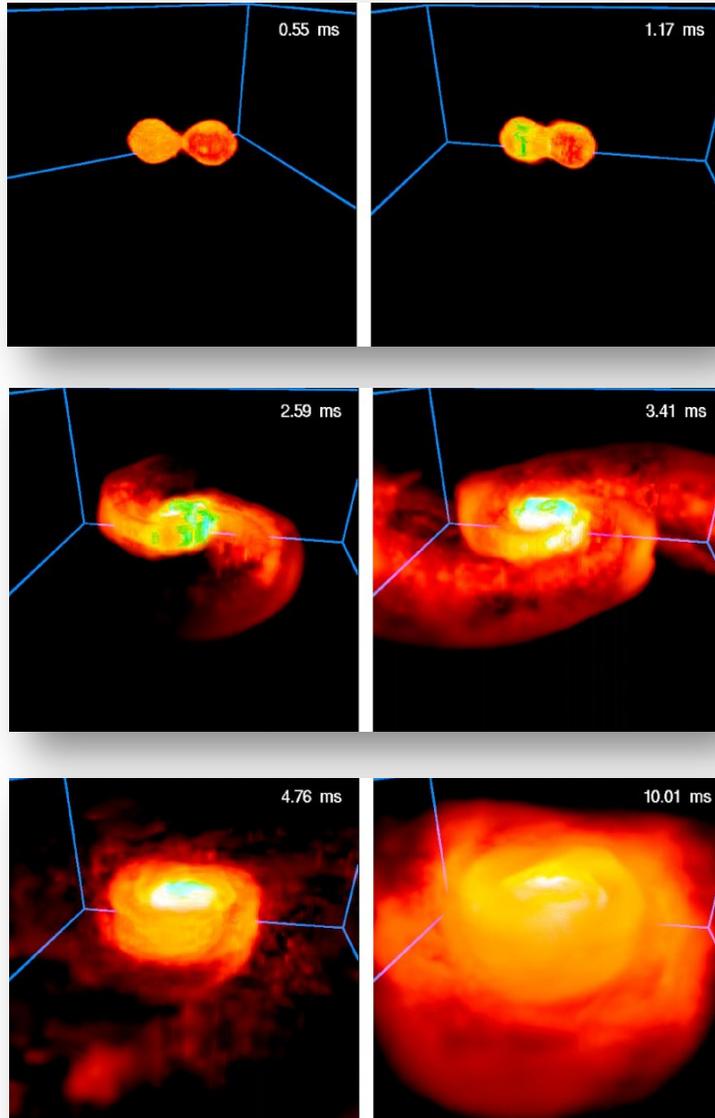
supernovae can be the origin only if ...

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

CAUTION!!! EXPLOSION MECHANISM IS STILL UNCLEAR...

NS merger scenario: most promising?

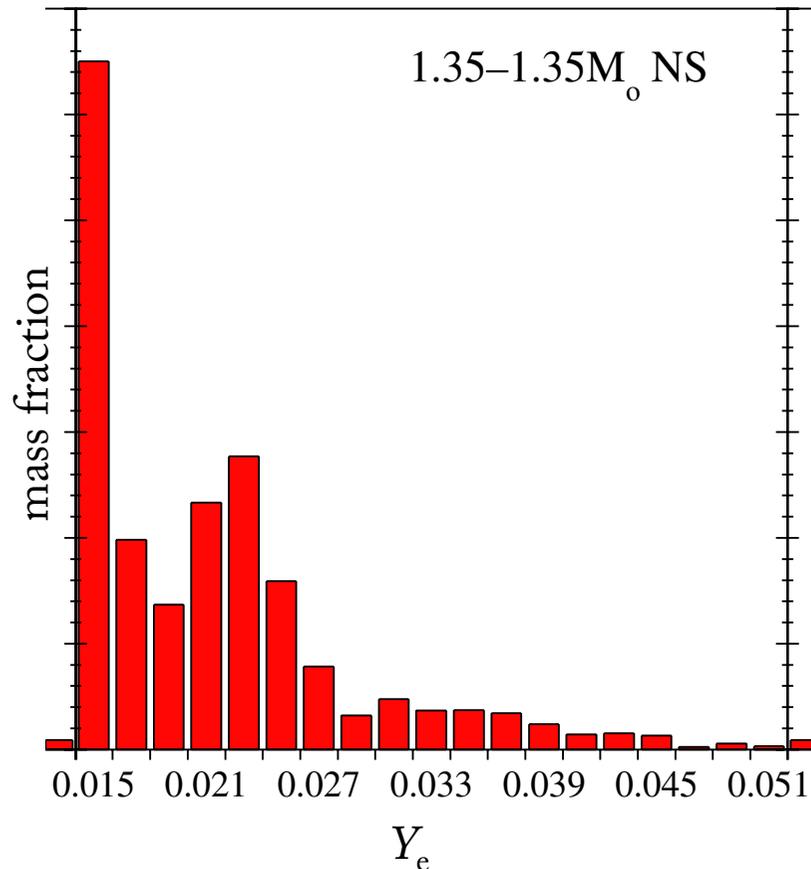
www.mpa-garching.mpg.de



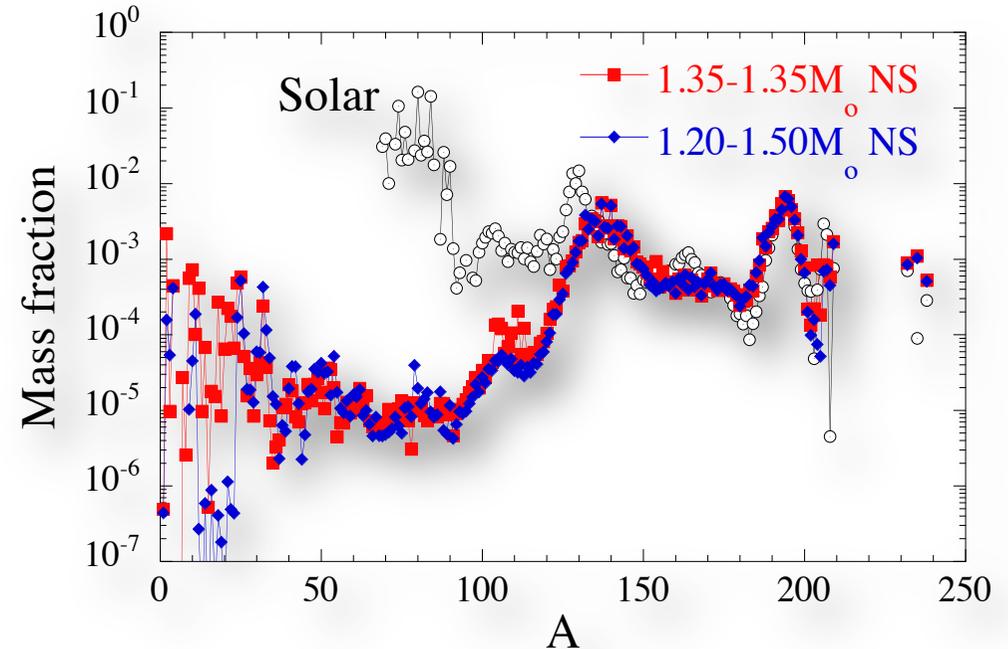
- ❖ coalescence of binary NSs
expected $\sim 10 - 100$ per Myr in
the Galaxy (also possible sources
of short GRB)
- ❖ first ~ 0.1 seconds
dynamical ejection of n-rich
matter up to $M_{\text{ej}} \sim 10^{-2} M_{\odot}$
- ❖ next ~ 1 second
neutrino or viscously driven wind
from the BH accretion torus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

previous works: too neutron-rich ?

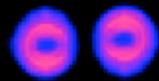
Goriely+2011 (also similar results by Korobkin+2011; Rosswog+2013)



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



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

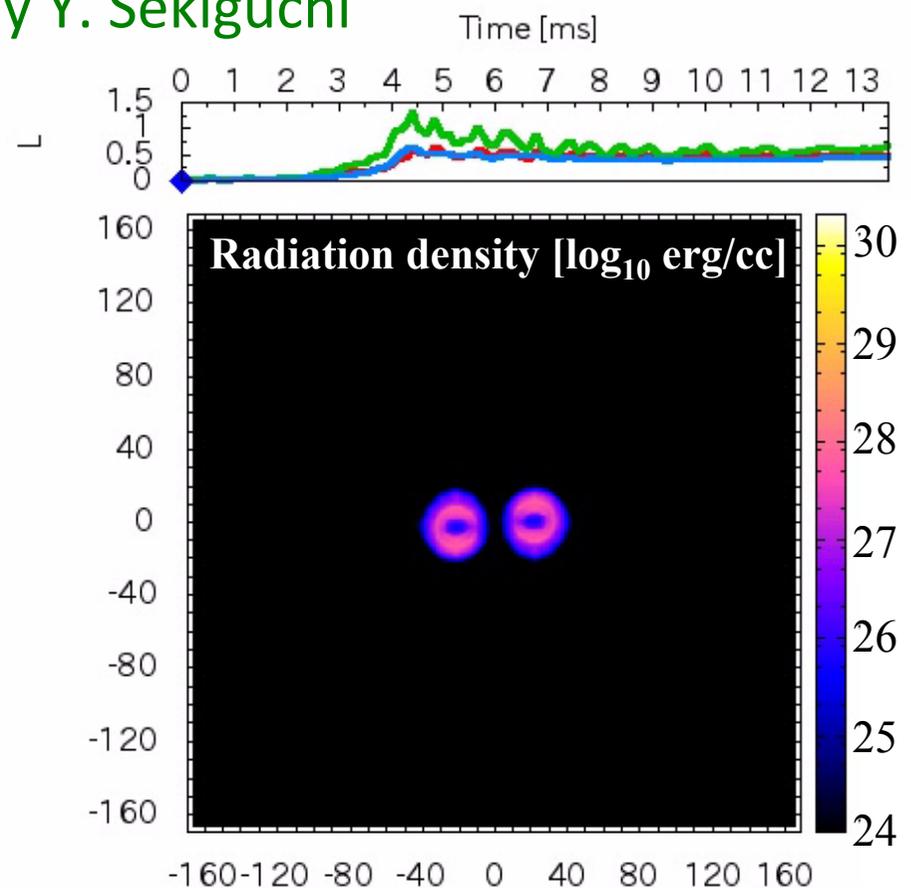
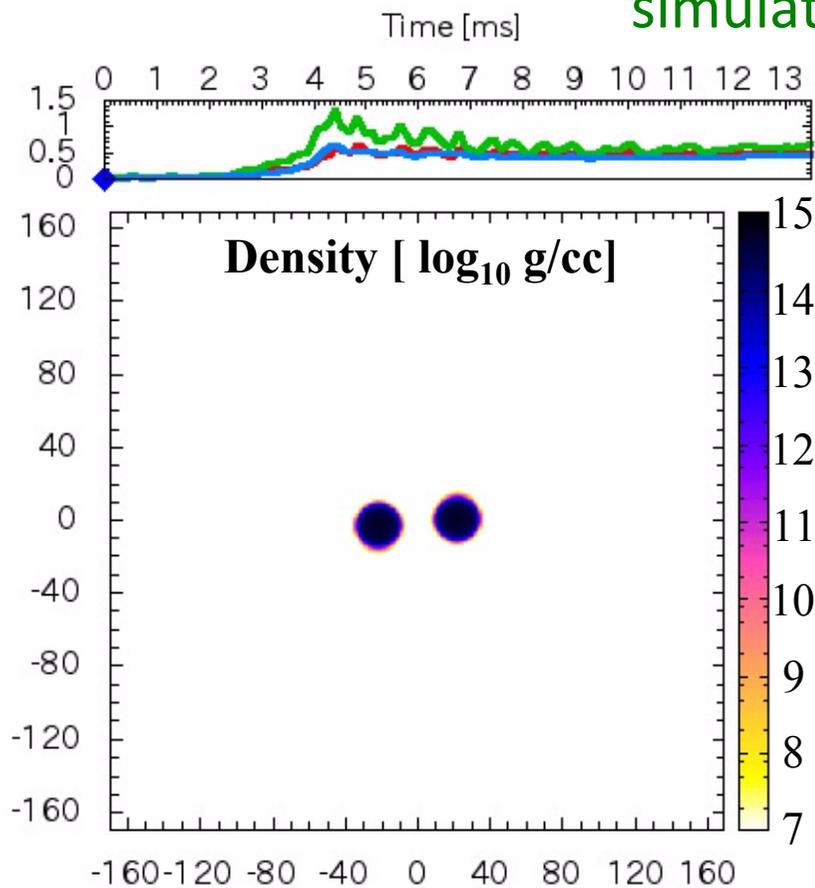


2. mergers with GR and ν

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

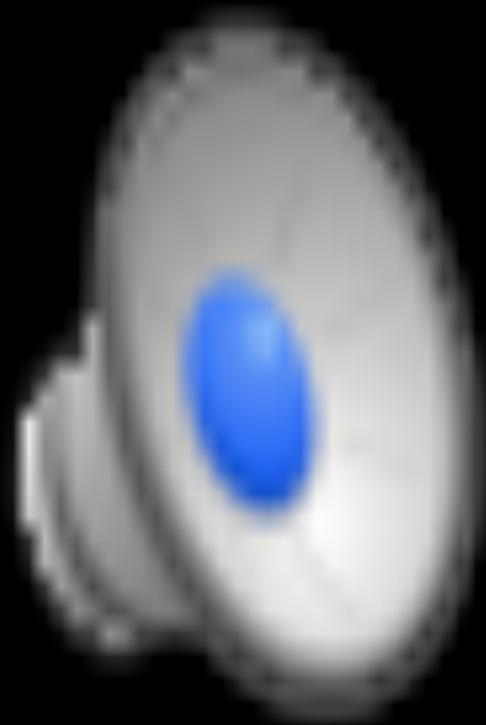
simulation by Y. Sekiguchi



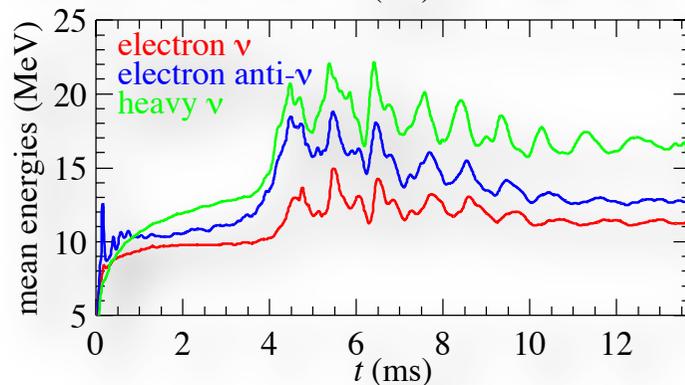
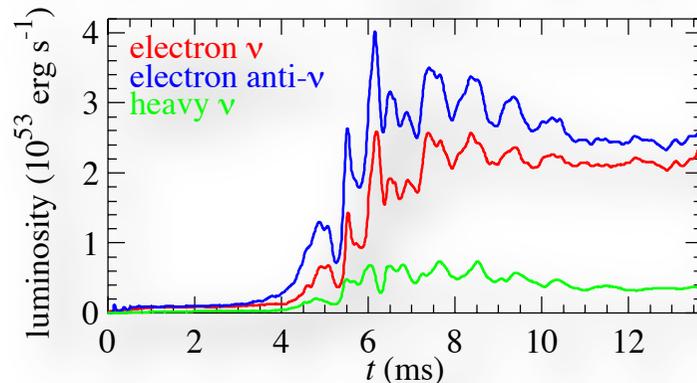
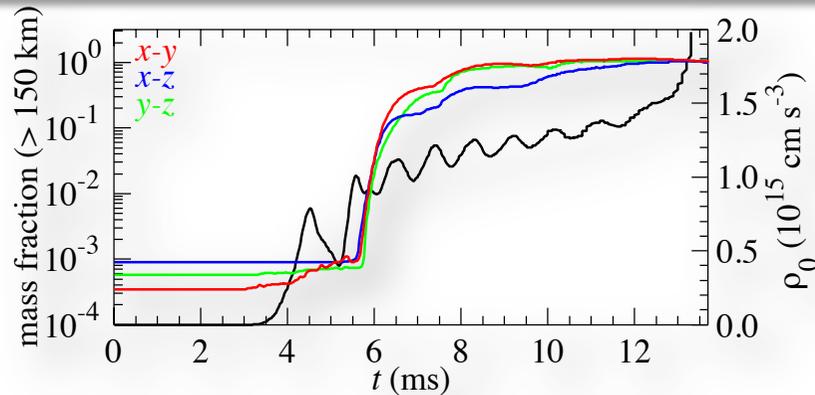
1.3+1.3 M_{\odot} neutron star merger with full-GR and neutrino transport (SFHo)

simulation by Yuichiro Sekiguchi





neutrino properties (Steiner's EOS)

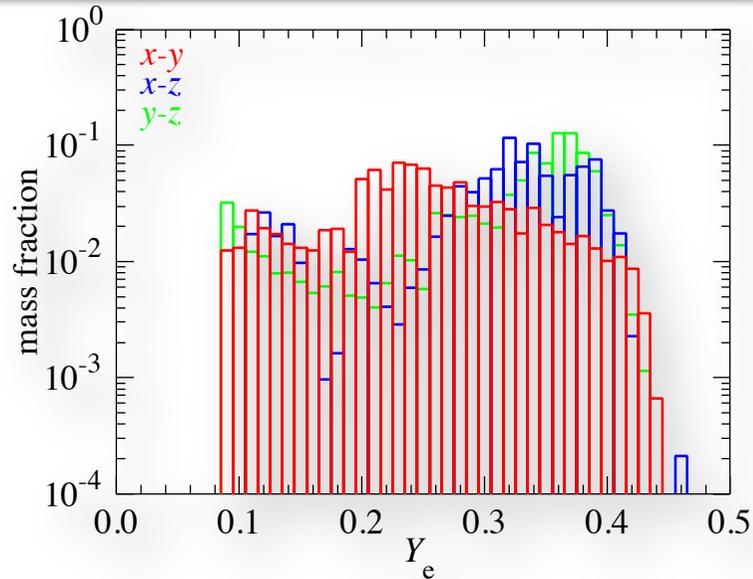


❖ mass ejection before (40%) and after (60%) HMNS formation; 70% ejecta reside near orbital

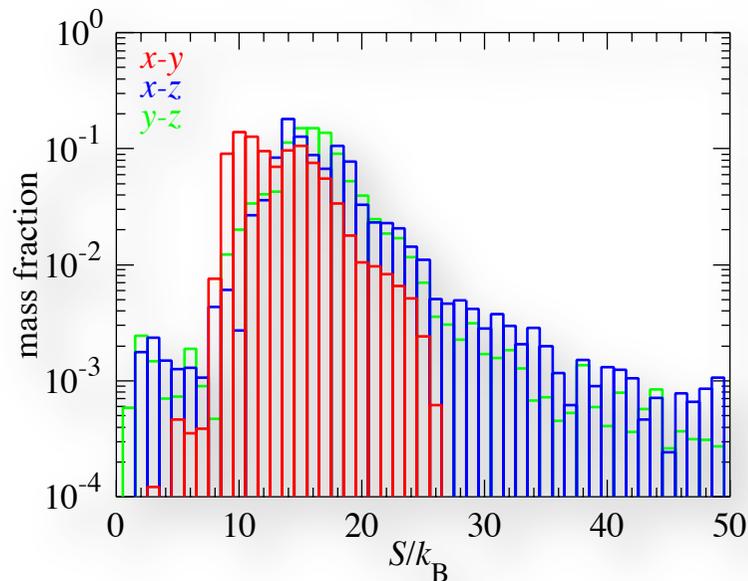
❖ neutrino luminosities similar between ν_e and anti- ν_e

❖ neutrino mean energies similar between ν_e and anti- ν_e

nucleosynthesis in the NS ejecta

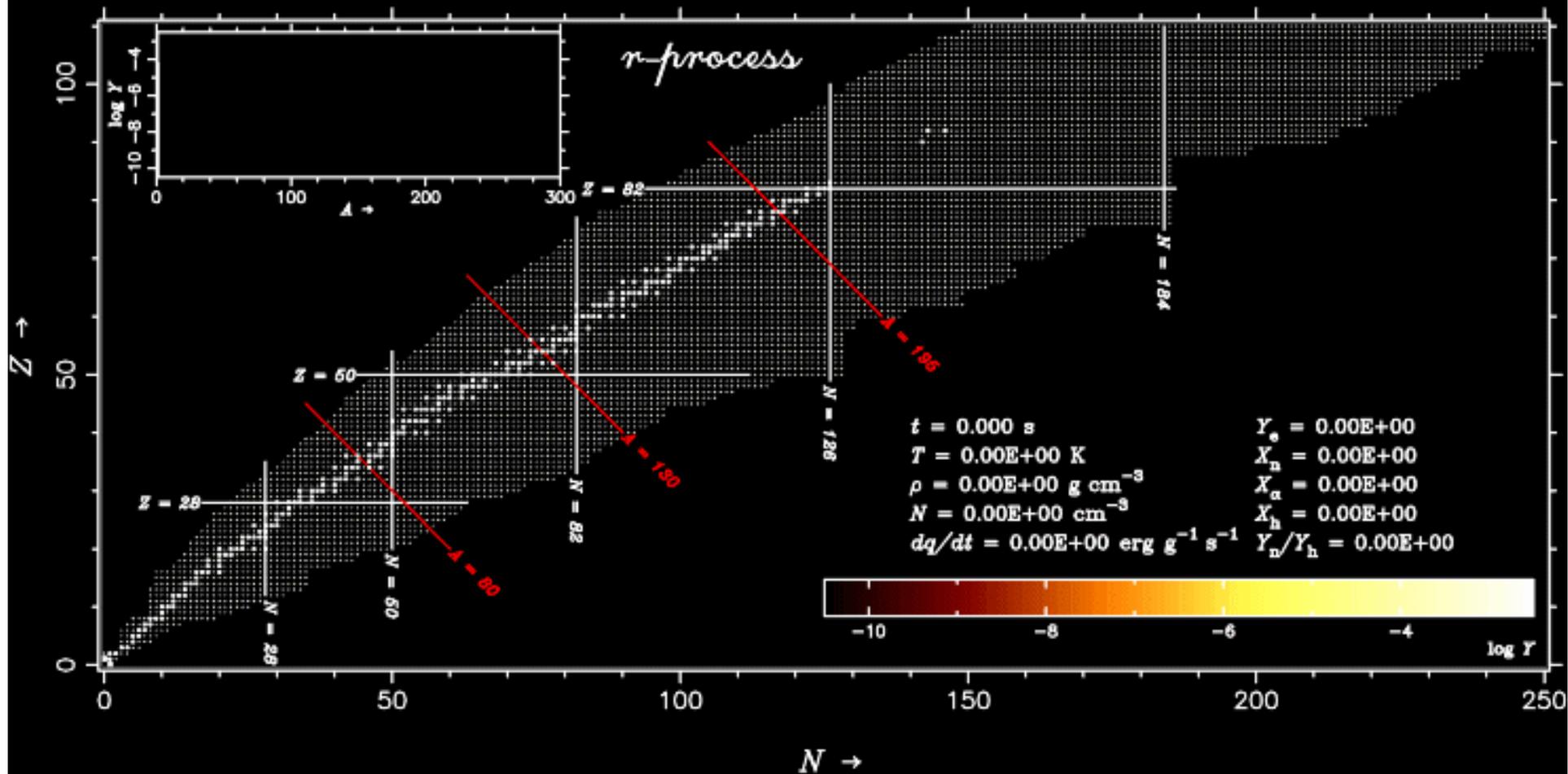


- ❖ higher and wider range of Y_e ($= 0.09-0.45$) in contrast to previous cases ($Y_e = 0.01-0.05$)

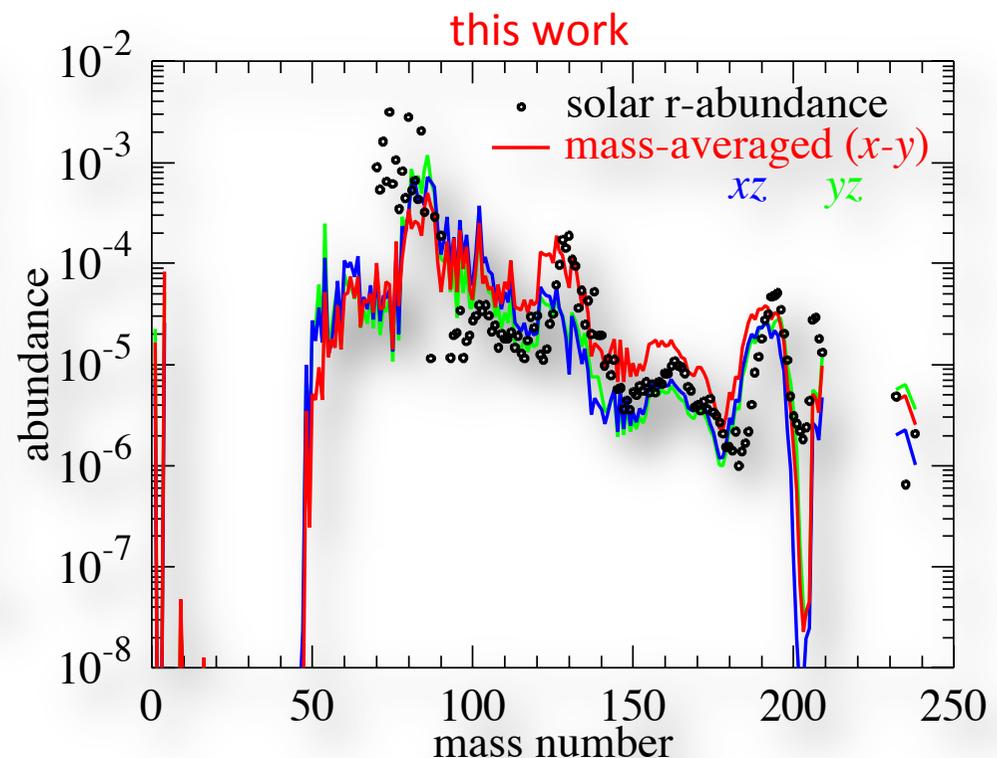
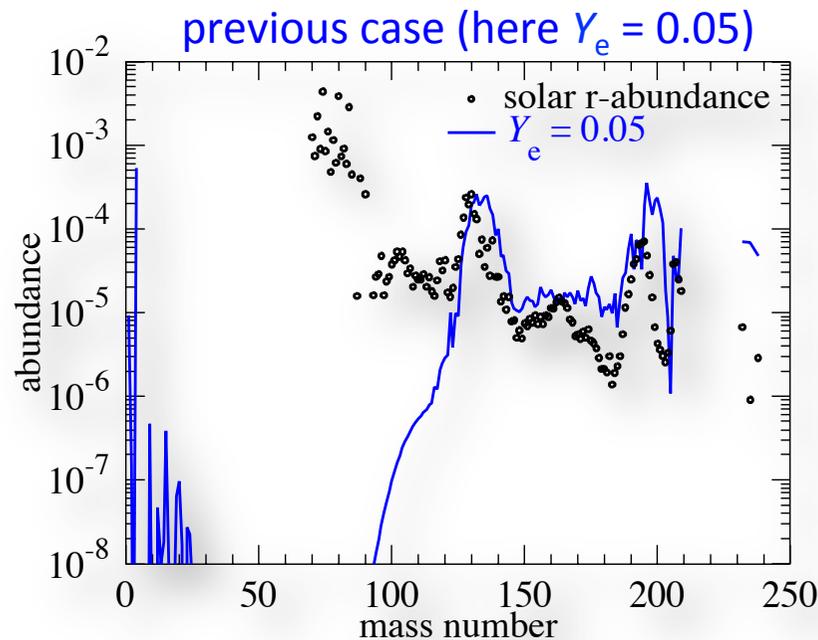


- ❖ higher and wider range of entropy per baryon ($= 0-50$) in contrast to previous cases ($= 0-3$)

$$Y_e = 0.09$$



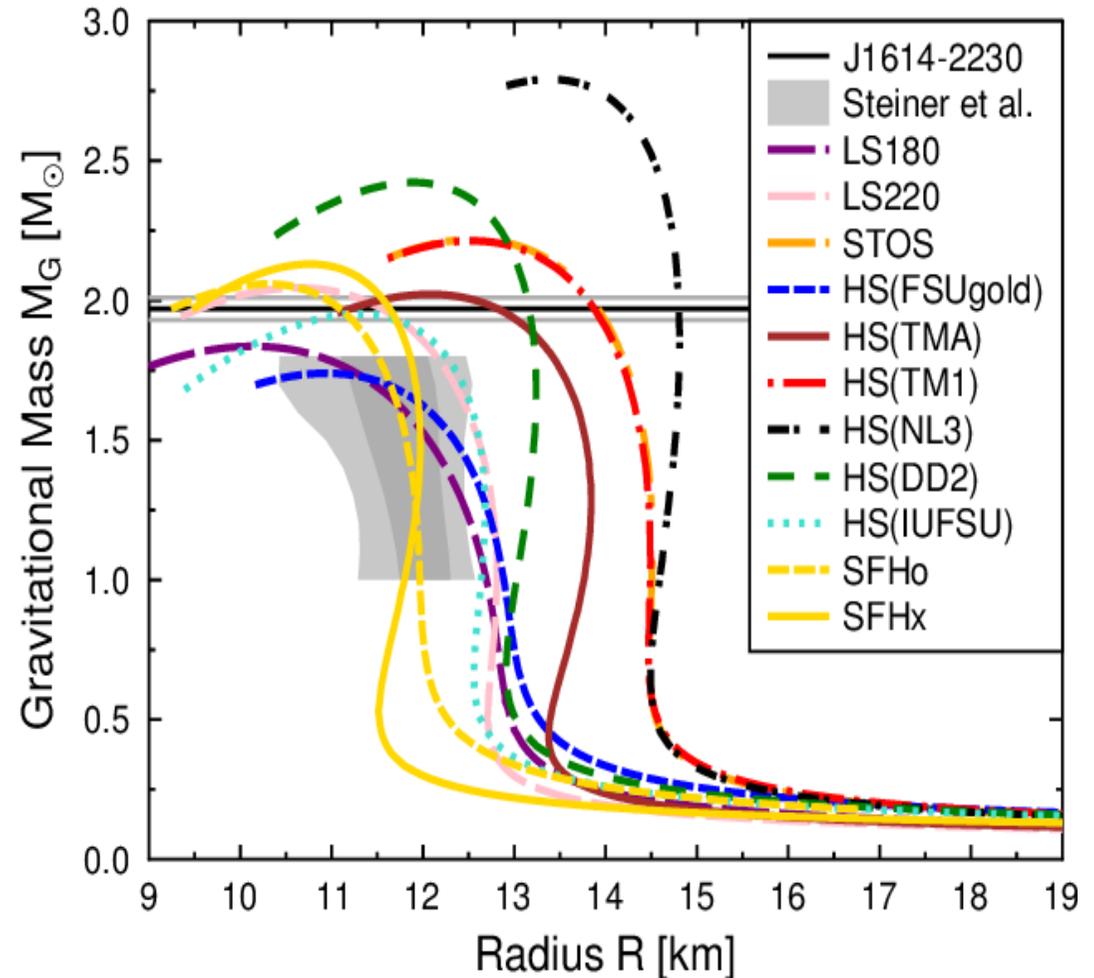
mass-integrated abundances



- ❖ previous case: not in agreement with solar r-pattern
 - need additional sources for $A < 130$ and even $A \sim 130$ elements
- ❖ this work: reasonable agreement with solar r-pattern for $A = 90-240$
 - no need of additional (e.g., BH-torus) sources for light r-elements
 - no fission recycling in this case

Dynamical mass ejection mechanism & EOS

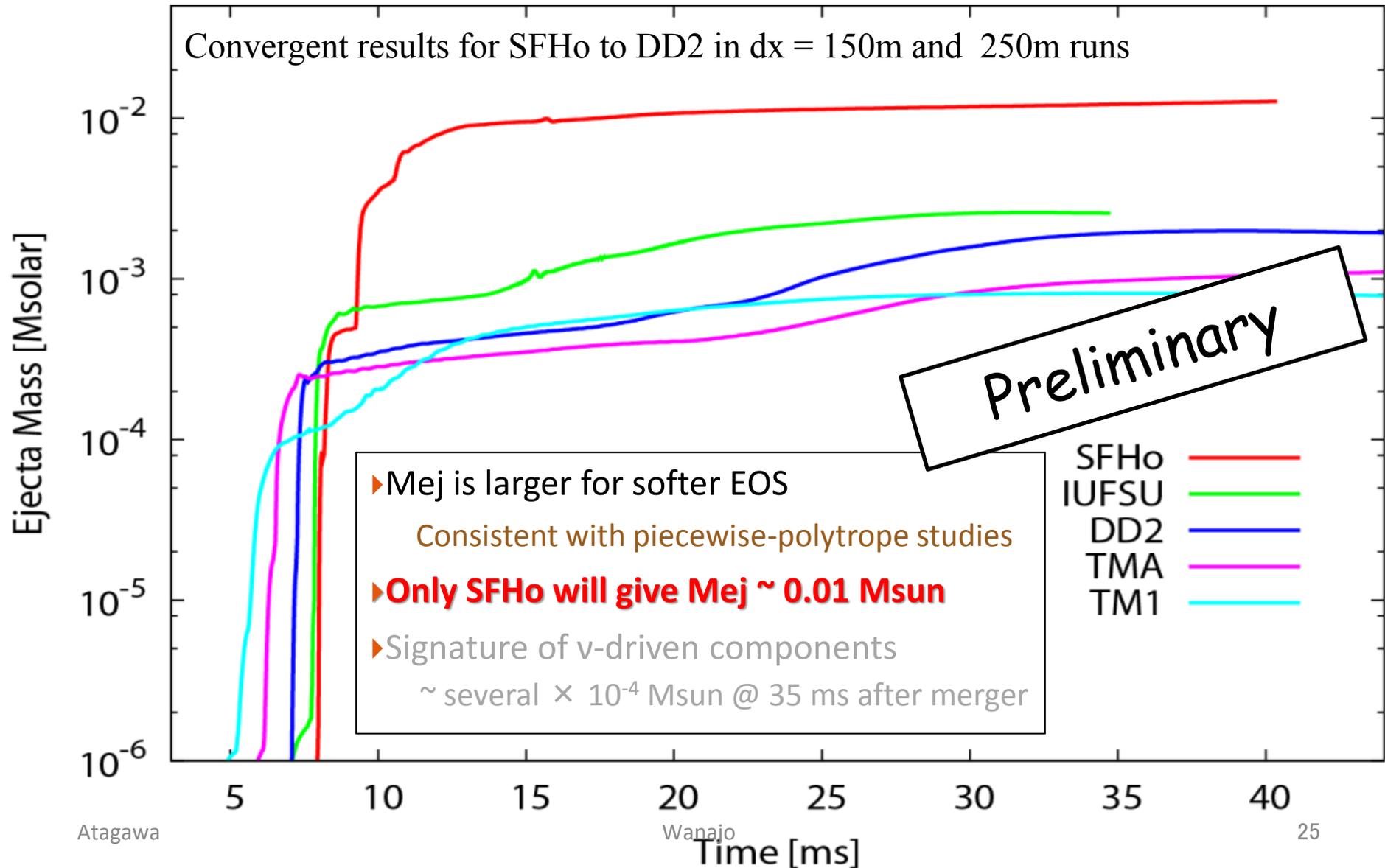
- ▶ ‘Stiffer EOS’
 - ▶ **TM1, TMA**
 - ▶ R_{NS} : lager
 - ▶ Tidal-driven dominant
 - ▶ **Ejecta consist of low T & Y_e NS matter**
- ▶ ‘Intermediate EOS’
 - ▶ **DD2**
- ▶ ‘Softer EOS’
 - ▶ **SFHo, IUFSU**
 - ▶ R_{NS} : smaller
 - ▶ Tidal-driven less dominant
 - ▶ Shock-driven dominant
 - ▶ **Y_e can change via weak processes**



See also, Hotokezaka et al. (2013); Bauswein et al. (2013); Just et al. (2014)

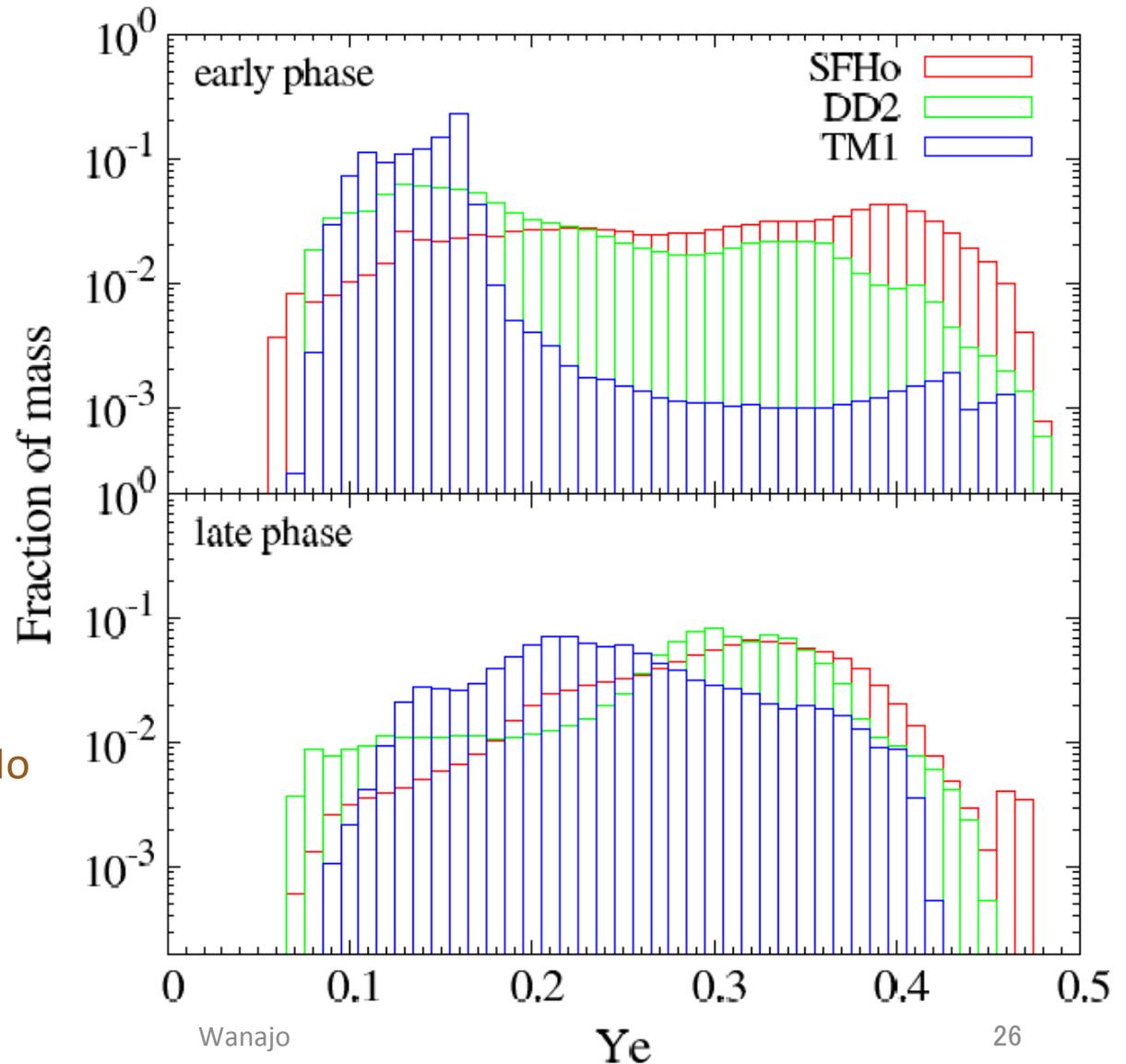
slide by Y. Sekiguchi

Dynamical Me_j depends strongly on EOS



EOS dependences

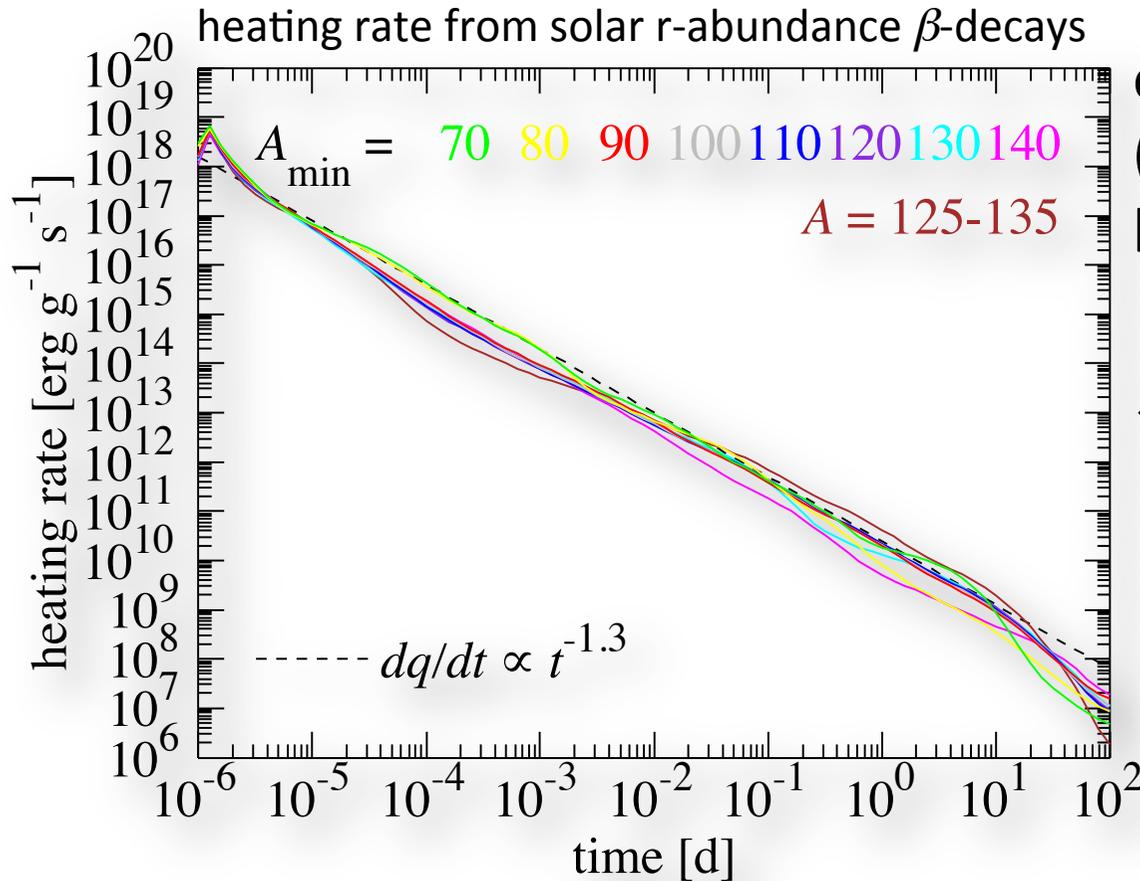
- ▶ All of EOS models show wide $Y_e(m)$ distribution in later phase
- ▶ The peak shifts higher Y_e for softer EOS
- ▶ Time evolution of the distribution due to weak interactions
 - ▶ e^+ (and ν) capture in SFHo
 - ▶ e^+/ν captures in DD2
 - ▶ ν capture in TM1





3. r-process novae (or goldnovae)

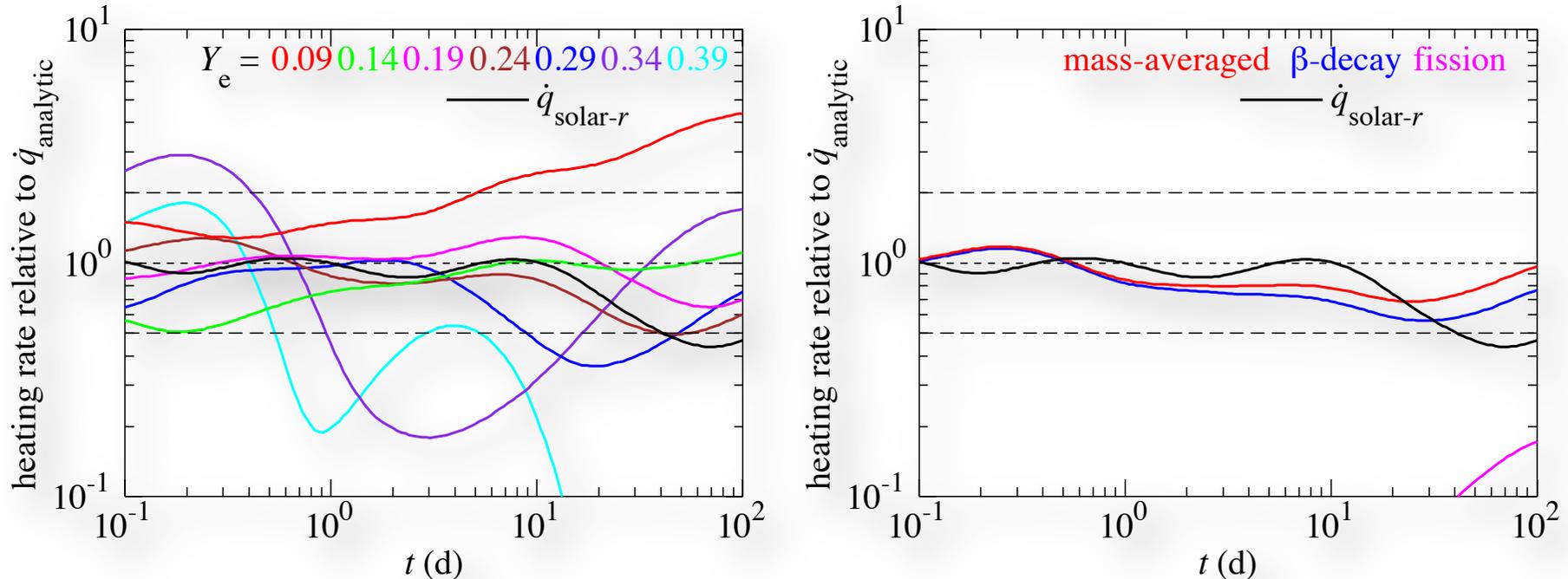
r-process novae (kilonovae)



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

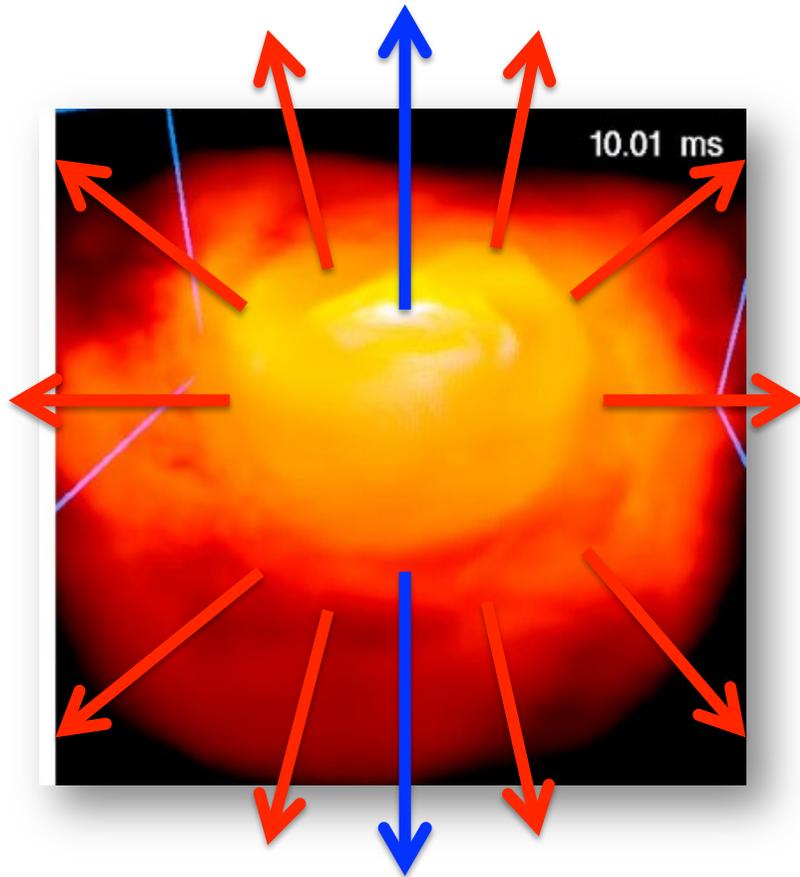
- ❖ heating from decays of radionuclides well scaled as $dq/dt \sim t^{-1.3}$

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 $\sim 100 \text{ deg}^2$ 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

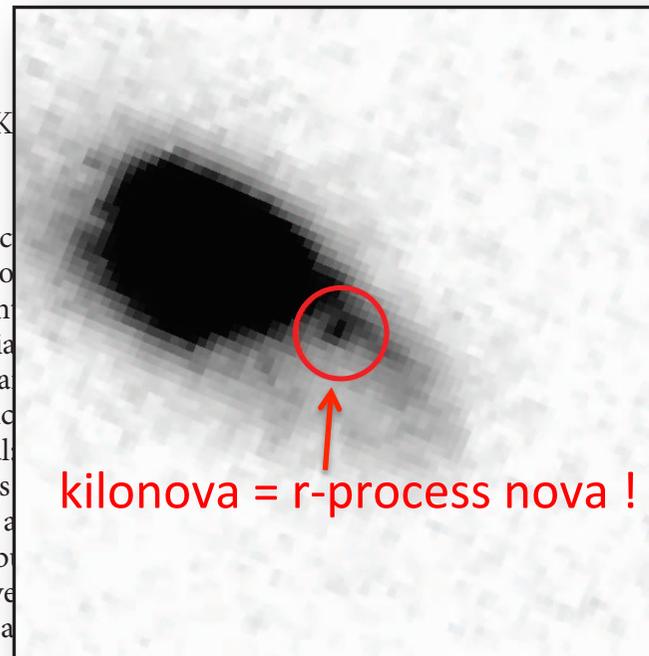
doi:10.1038/nature12505

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

N. R. Tanvir¹, A. J. Levan², A. S. Fruchter³, J. Hjorth⁴, R. A. Hounsell³, 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 galaxies³, 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 burst⁶⁻⁸. 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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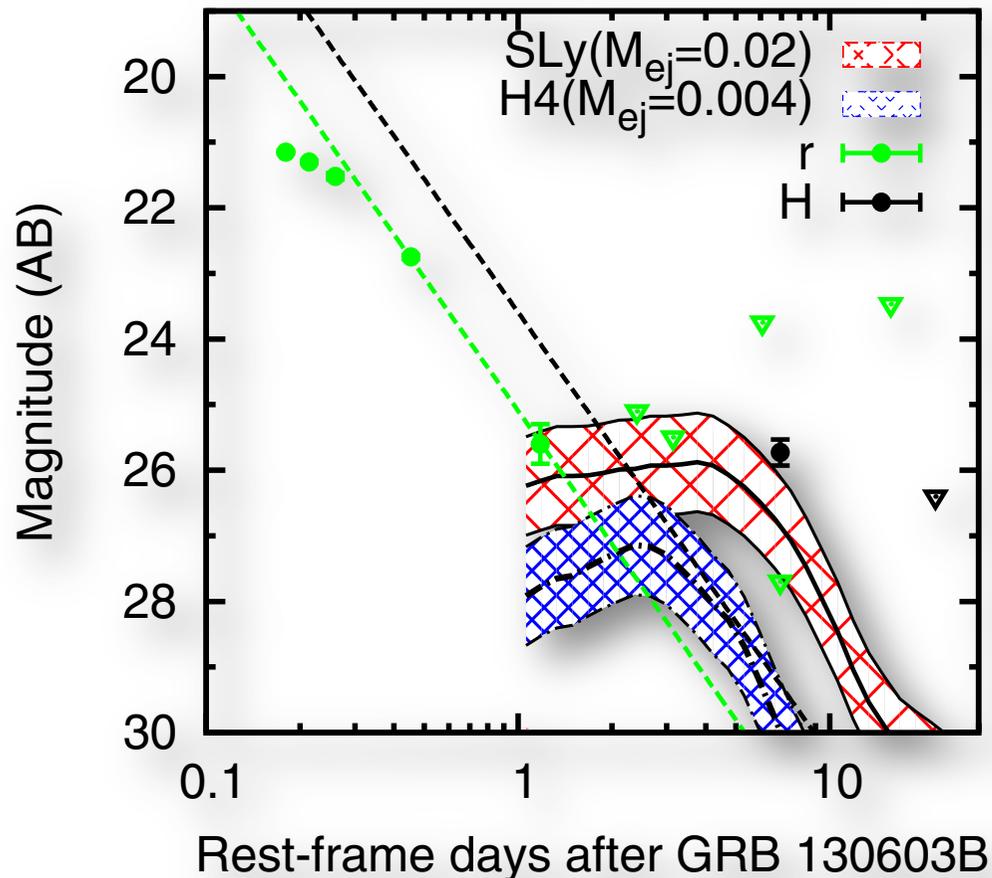


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Tanvir+2013, Nature, Aug. 29

r-process nova in the SGRB afterglow?

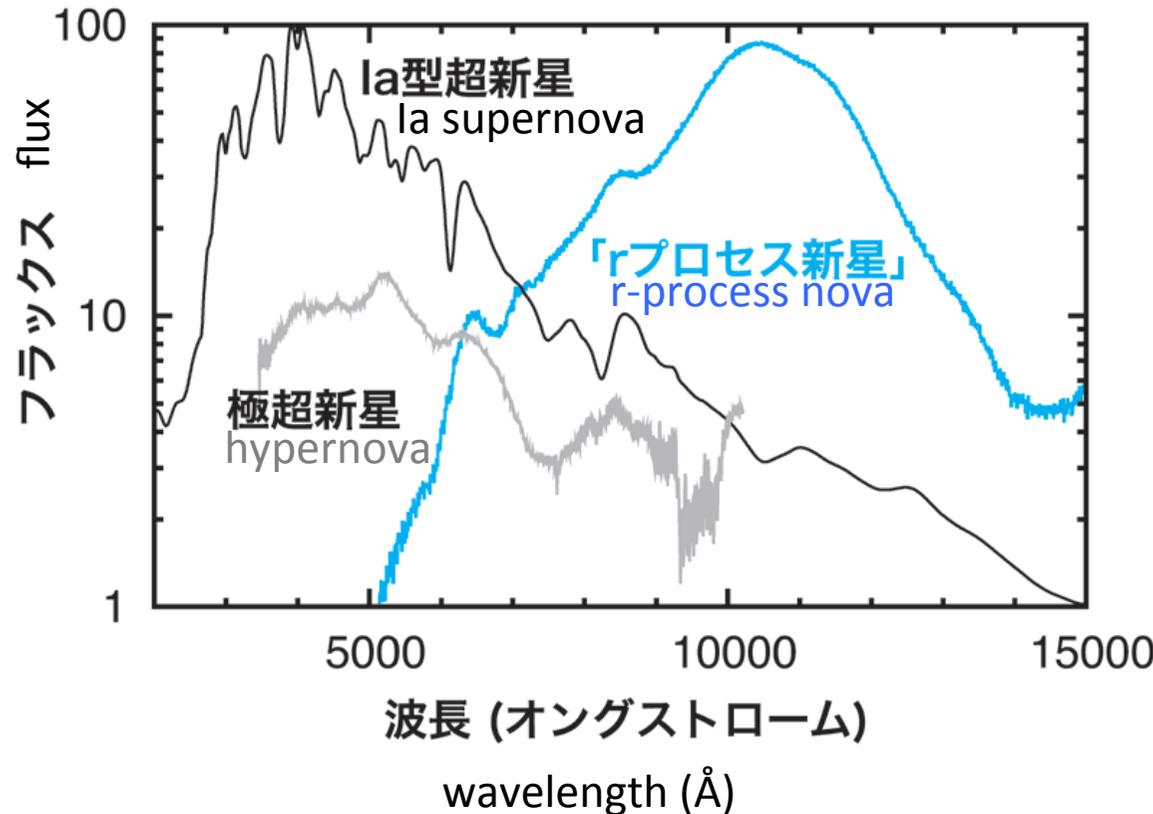
Hotokezaka+Tanaka...+Wanajo 2013;
NS+NS models



- ❖ 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

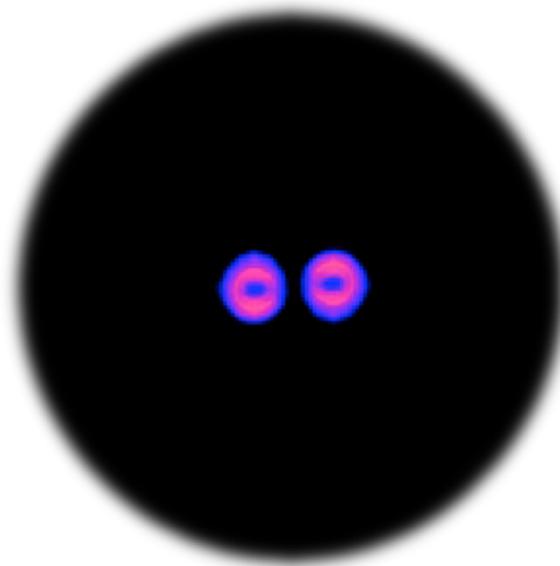


can we see r-abundances in the spectra?

❖ almost featureless because of too many bound-bound lines and Doppler shifts ($v/c \sim 0.1-0.3$)

❖ 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?