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科研費
KAKENHI
重力波天体の多様な観測による宇宙物理学の新展開
New development in astrophysics through multimessenger observations of gravitational wave sources

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Dynamical mass ejection from BNS merger and r-process nucleosynthesis

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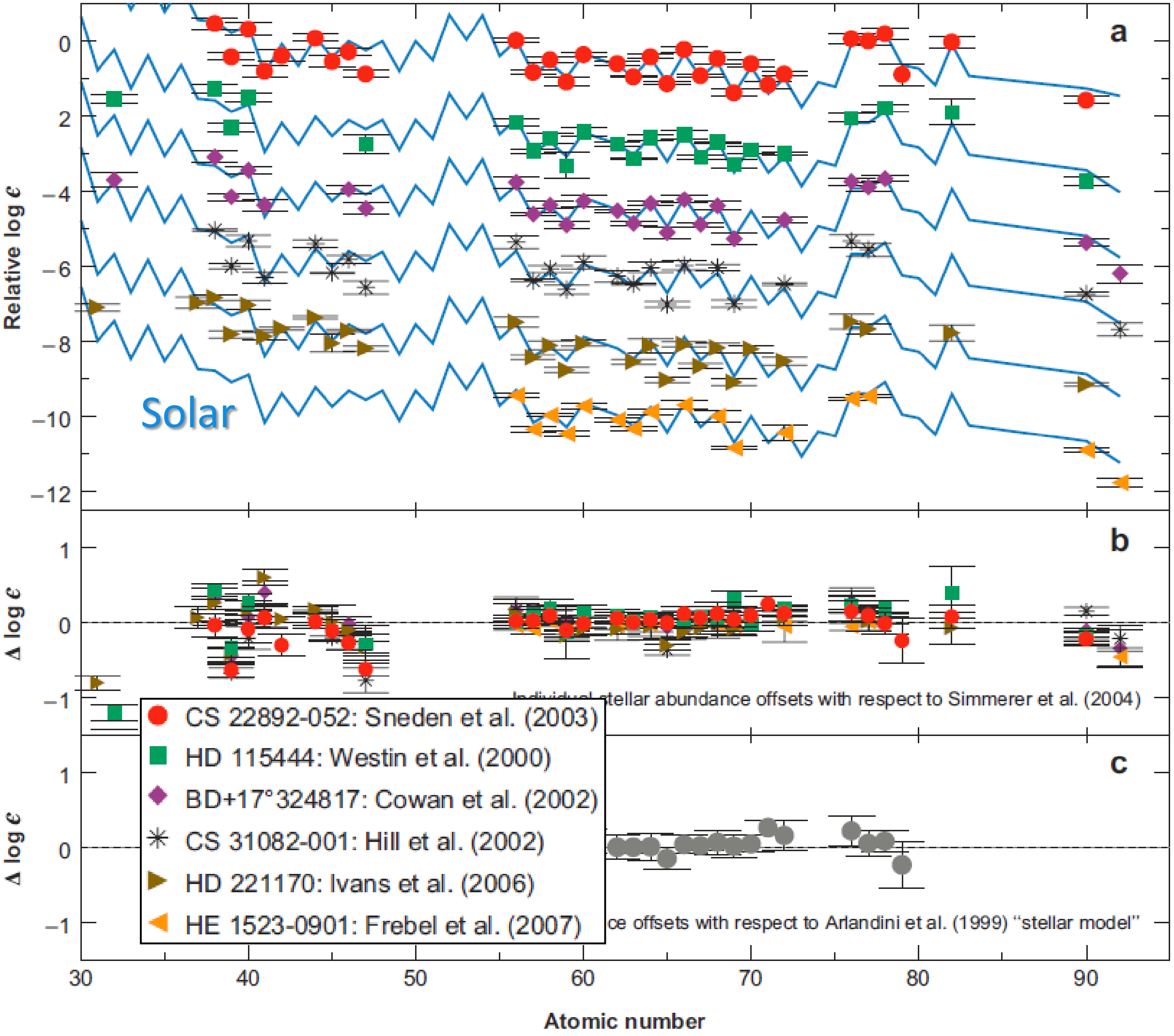
What is the cite of r-process ?

- **Supernova (SN) explosion (+ PNS ν-driven wind) : (*Burbidge et al. 1957*)**
  - Review by Frohlich
    - Entropy is not so high as previously expacted
    - difficulty in preserving n-rich condition (Roberts et al. 2010, 2012)
  - difficulty in satisfying the universality
  - Bad news from Piran

- **NS-NS(/BH) binary merger: (*Lattimer & Schramm 1974*)**
  - problem in chemical evolution (Argust et al. 2004)
    - Resolution by Ishimaru et al. (2015); Hirai et al. in prep.
  - difficulty in satisfying the universality : too neutron rich ejecta
    - Topic of this talk
  - Good news by Piran

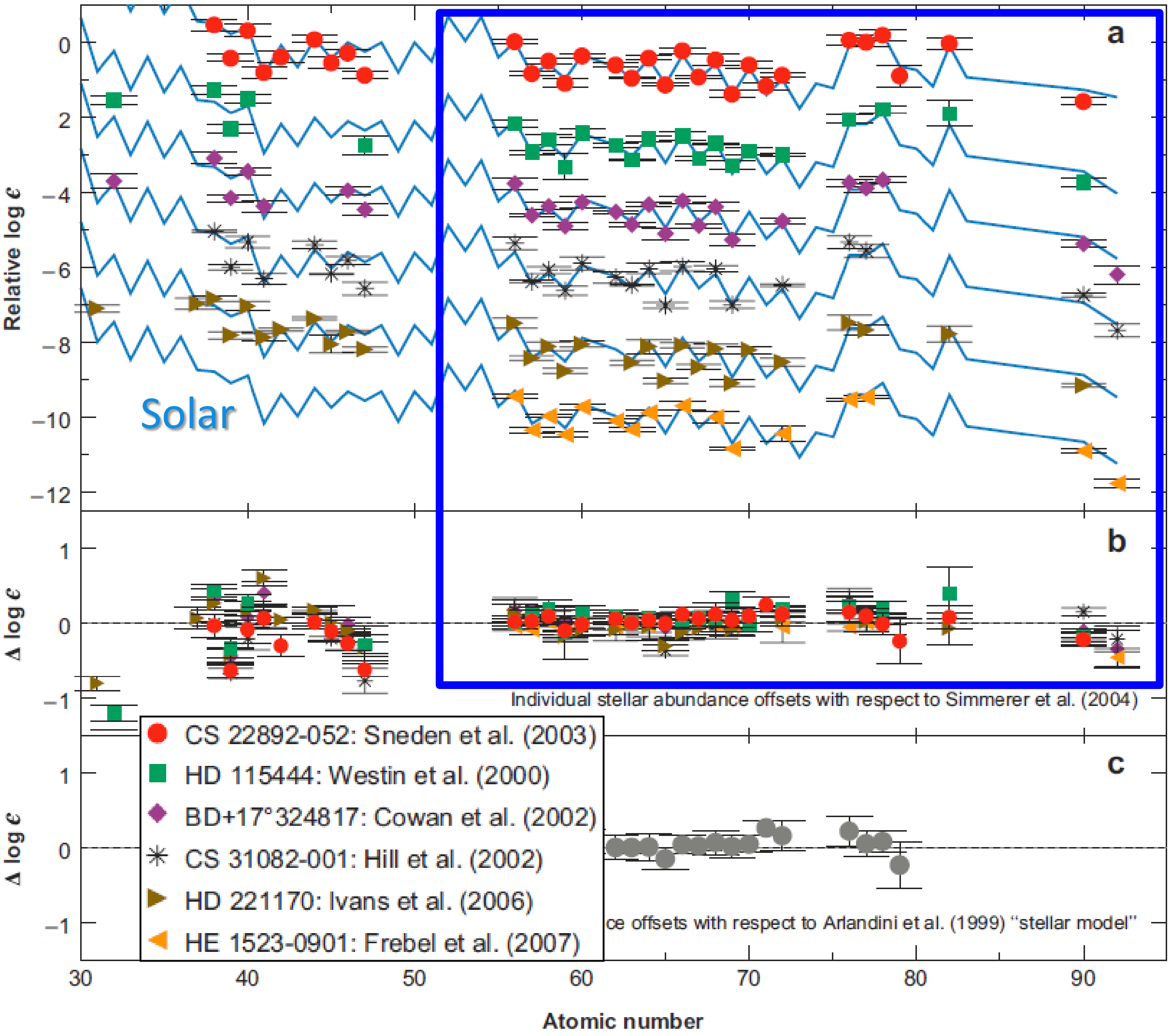
Key observations : Universality



- Abundance pattern comparison :
  - r-rich low metallicity stars
  - Solar neighborhood
- Low metallicity suggests
  - Such stars experience a few r-process events
  - Such stars preserve the original pattern of the r-process events (chemical fossil)

- Sneden et al. (2008)

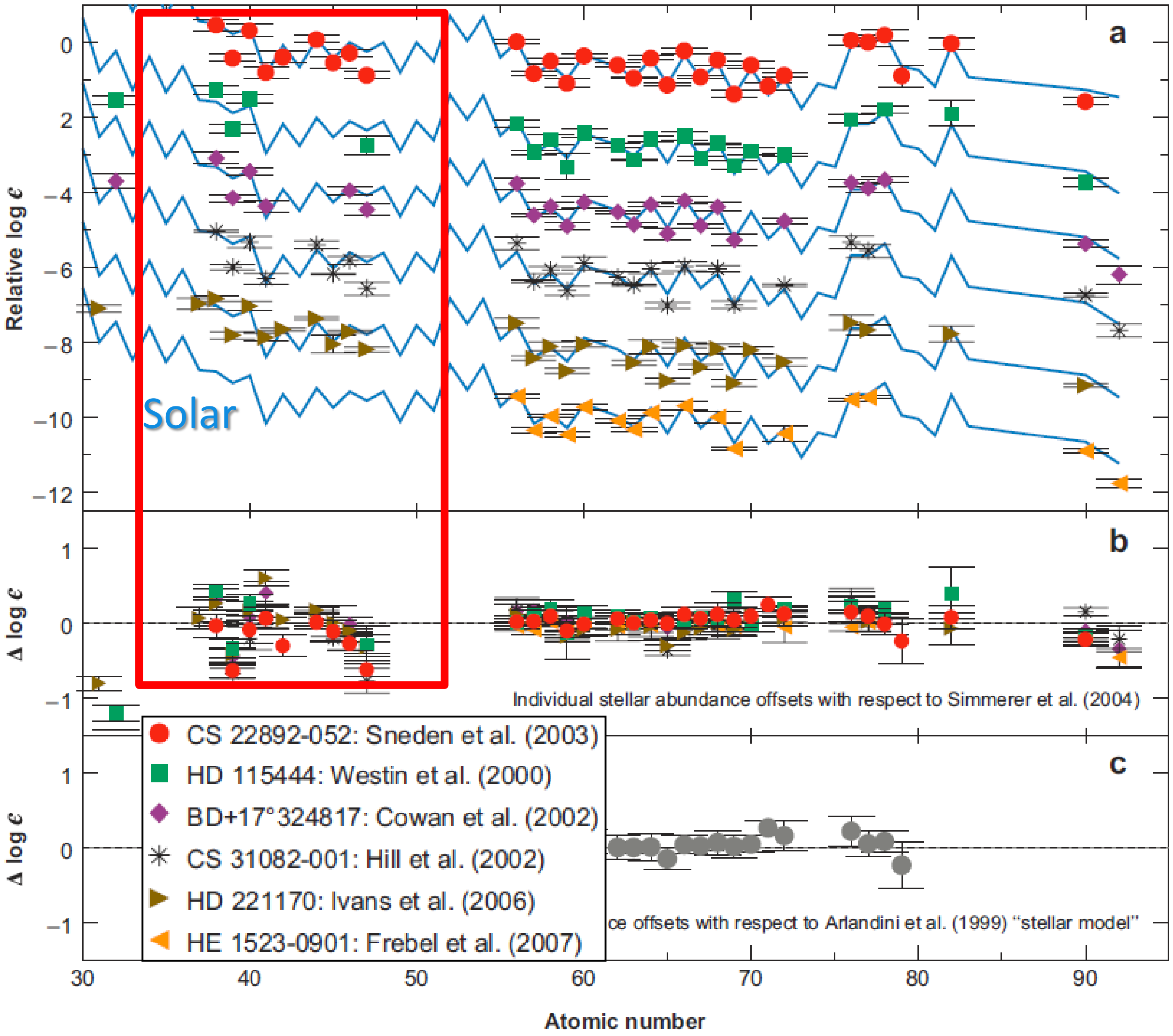
Key observations : Universality



- The solar and chemical fossil patterns agree well for Z >~ 55
- suggests that r-process event synthesize heavy elements with a pattern similar to solar pattern (Univsersality)

- Sneden et al. (2008)

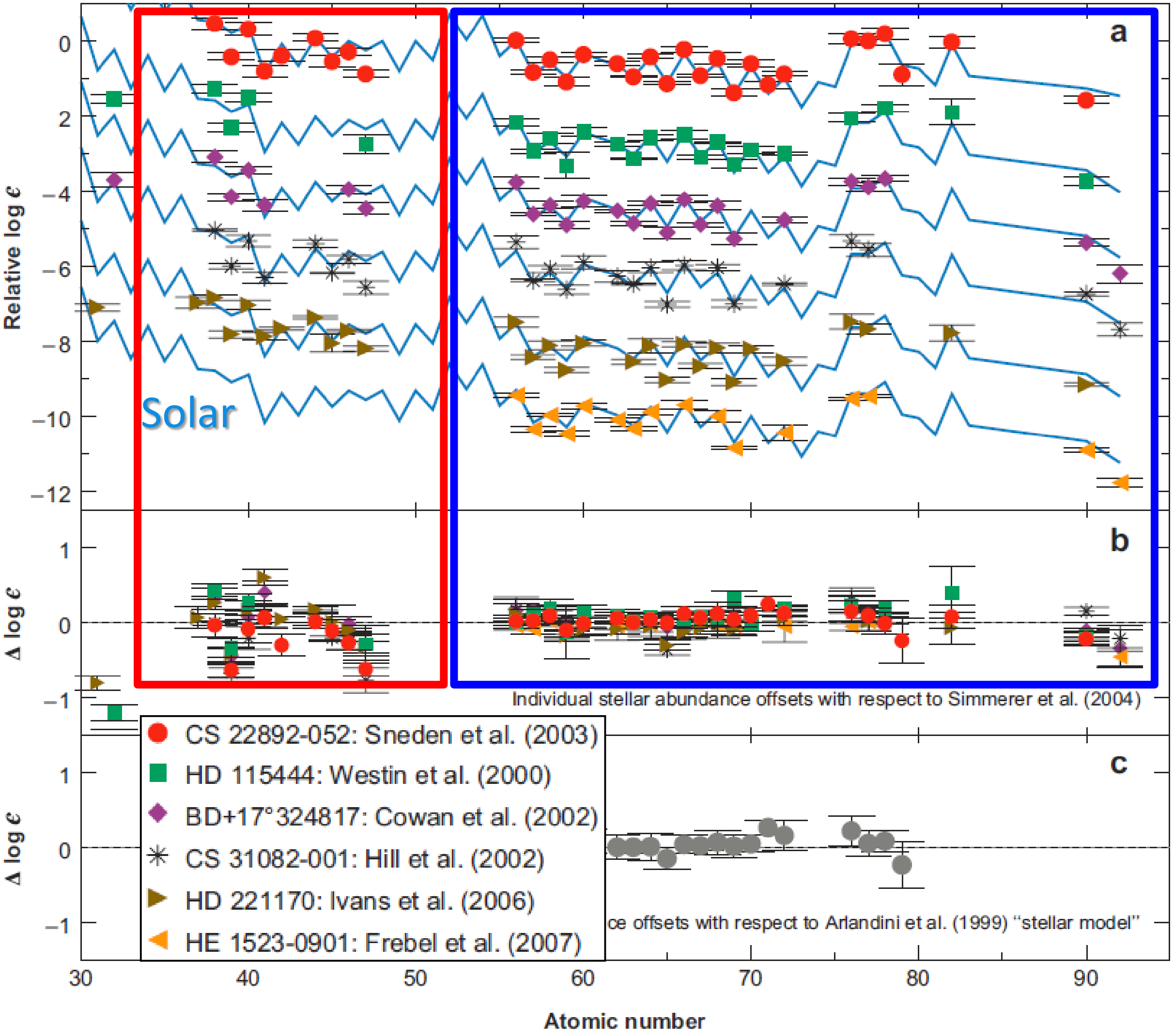
Key observations : Universality



- The patterns agree approximately for 35 < Z < 50 but show some diversity (factor of few)

- Sneden et al. (2008)

Key observations : Universality

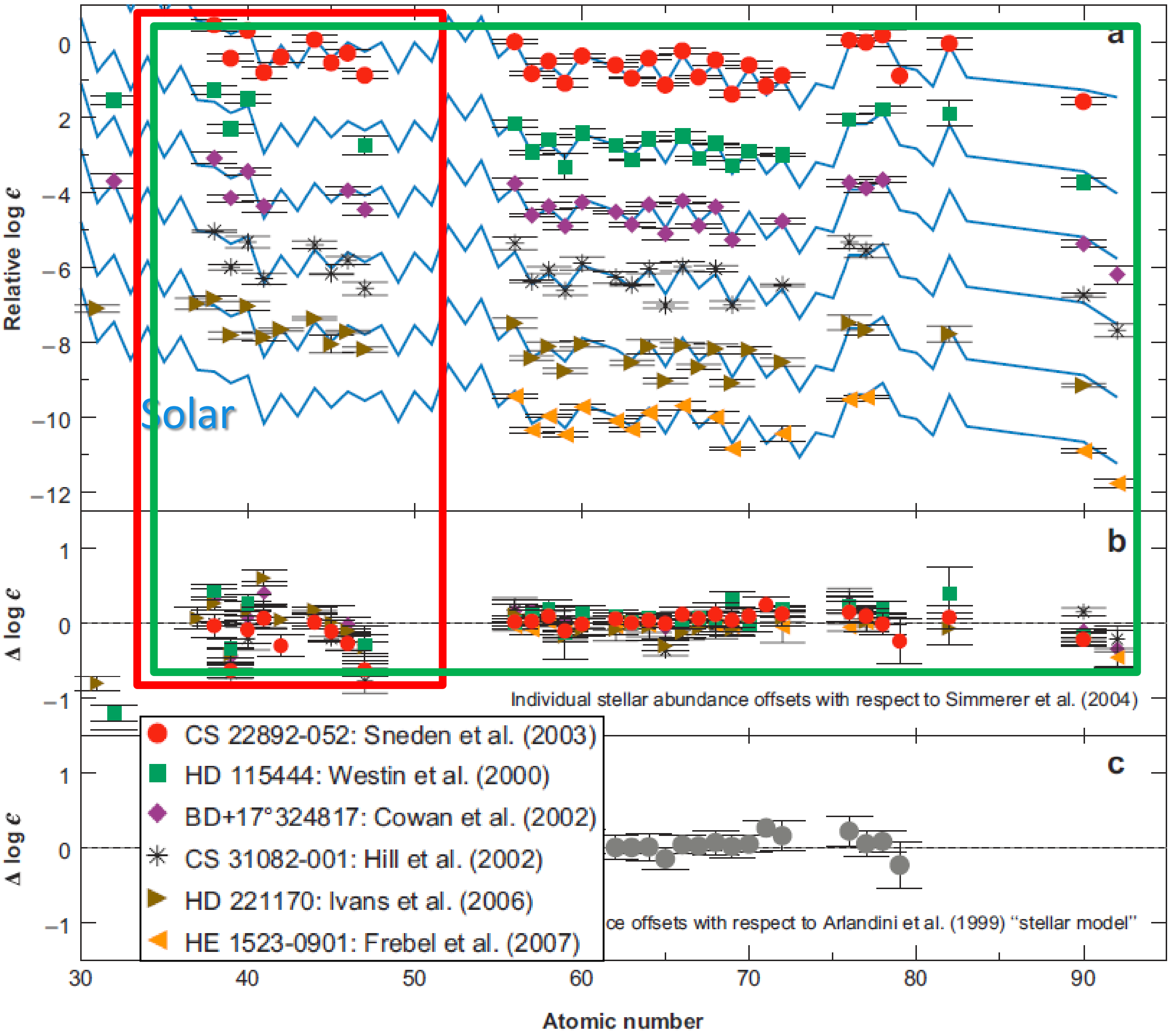


- (1) Multiple origins

  (1a) only light + only heavy

- Sneden et al. (2008)

Key observations : Universality



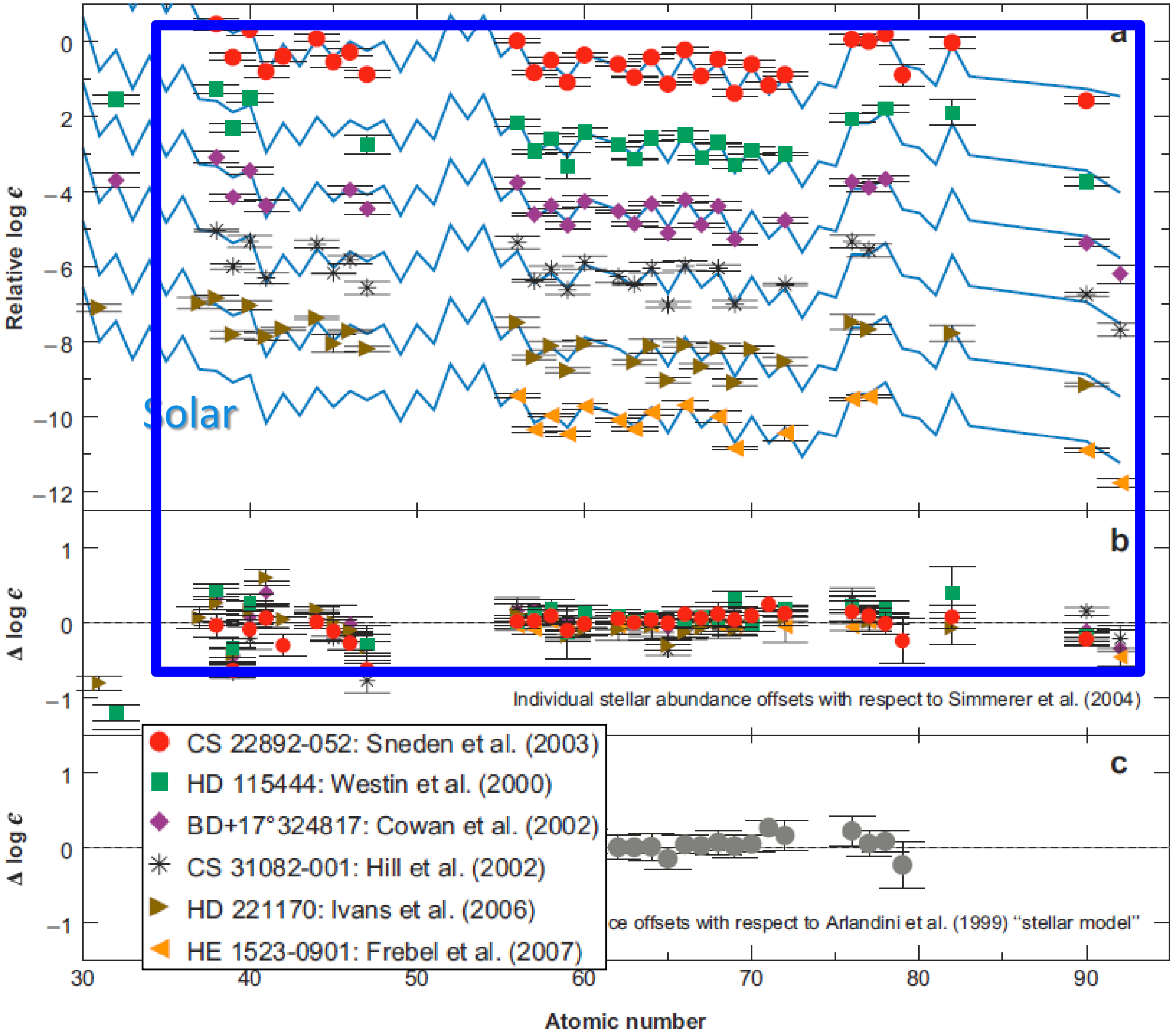
- (1) Multiple origins

  (1a) only light + only heavy

  (1b) only light + both

- Sneden et al. (2008)

Key observations : Universality



- (1) Multiple origins

  (1a) only light + only heavy

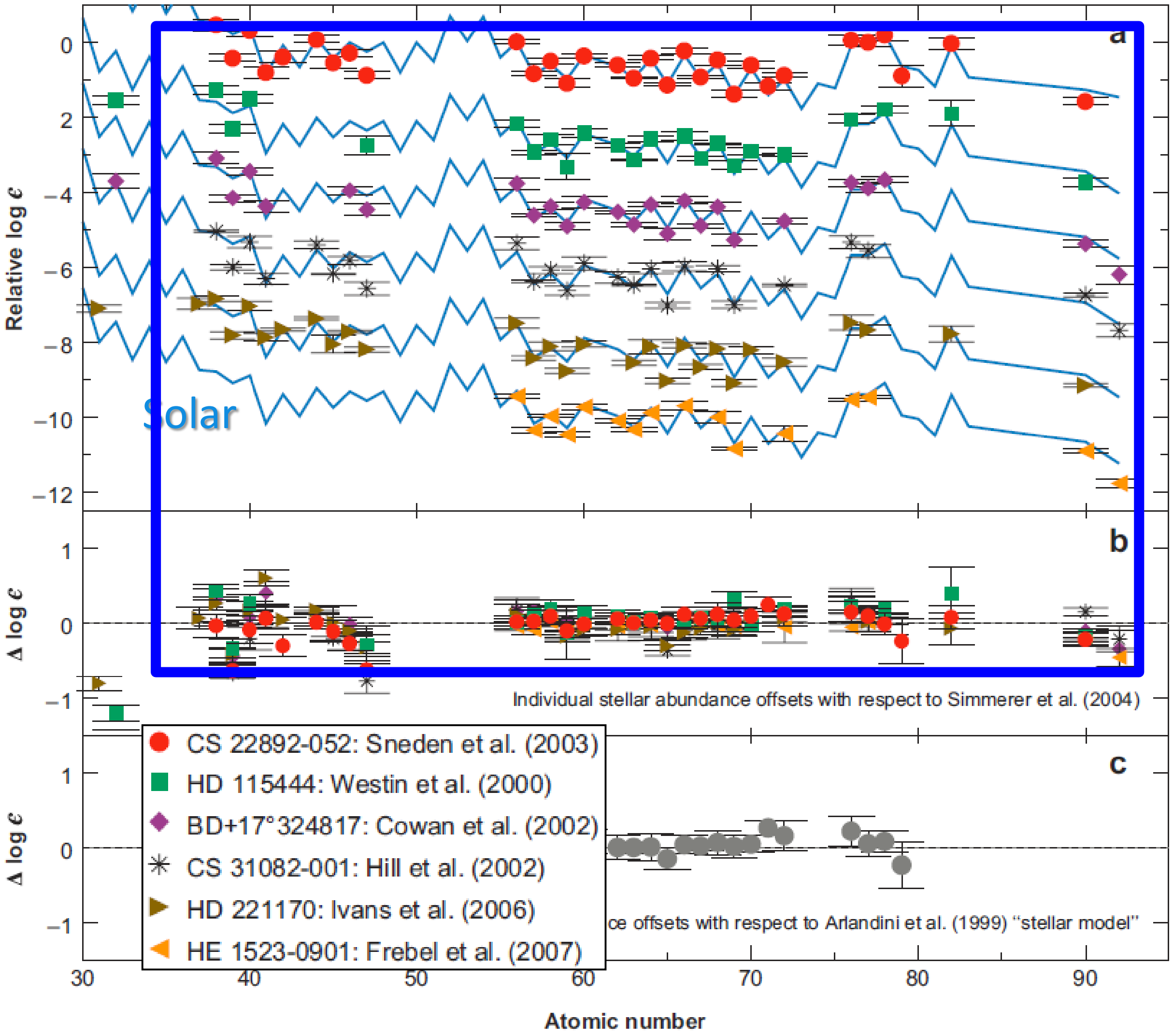
  (1b) only light + both

- (2) Single origin

  An event synthesize all the range with diversity in 35 < Z < 50 due to some reason

- Sneden et al. (2008)

Key observations : Universality



- (1) <u>Multiple origins</u>

  (1a) only light + only heavy

  (1b) only light + both

- (2) <u>Single origin</u>

  An event synthesize all the range with diversity in 35 < Z < 50 due to some reason

- Low metallicity
  - a few events should result in these pattern
  - Let us consider (2) single origin : NS-NS model

- Sneden et al. (2008)

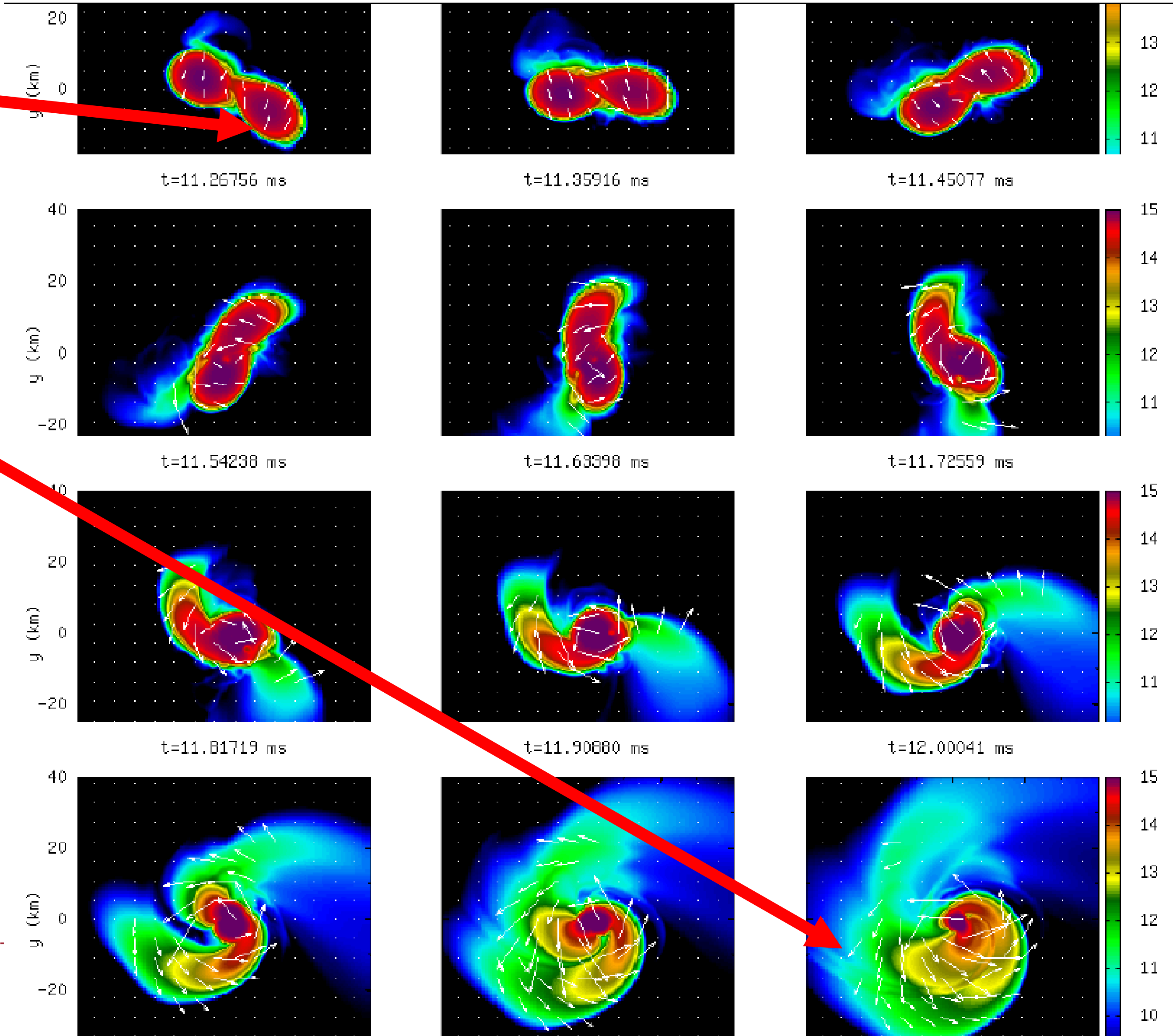
From the ‘Universality’ point of view :

NS-NS merger ejecta: too neutron-rich ?

- Goriely et al. 2011; Bauswein et al. 2013
  - Approx. GR SPH sim. **without** weak interactions
  - No way to change Ye => ejecta remains n-rich (initial low Ye)
  - See also post-process calculation of weak interactions
- Korobkin et al. 2012; Rosswog et al. 2013
  - Newtonian SPH sim. with neutrino
  - **tidal mass ejection (explained in the next slide)** of ‘pure’ neutron star matter
- Ejecta is very n-rich with Ye < 0.1

Mass ejection from BNS merger (1) : Tidal torque + centrifugal force

- Less massive NS is tidally deformed
- Angular momentum transfer by spiral arm and swing-by
- A part of matter is ejected along the orbital plane
- **reflects low Ye of cold NS** (β-eq. at $T\sim 0$), no shock heating, rapid expansion (fast T drop), no time to change Ye by weak interactions

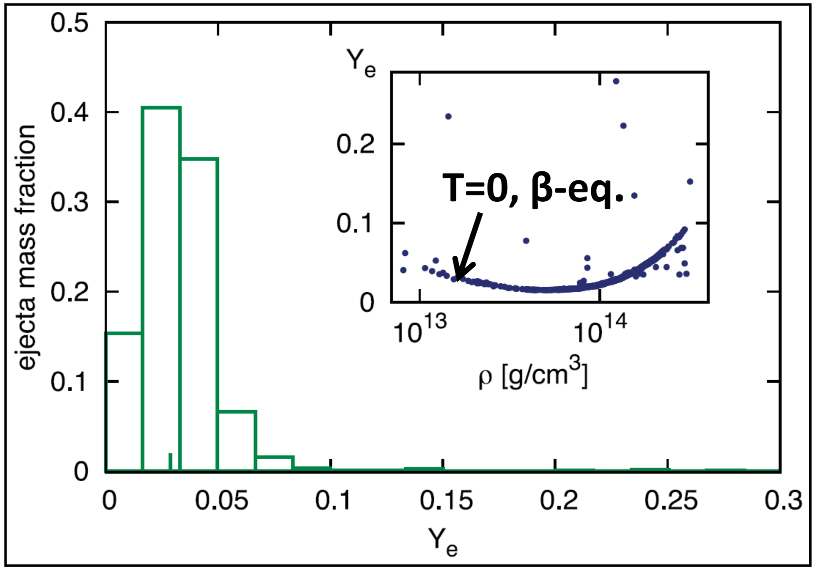


Hotokezaka et al. (2013)

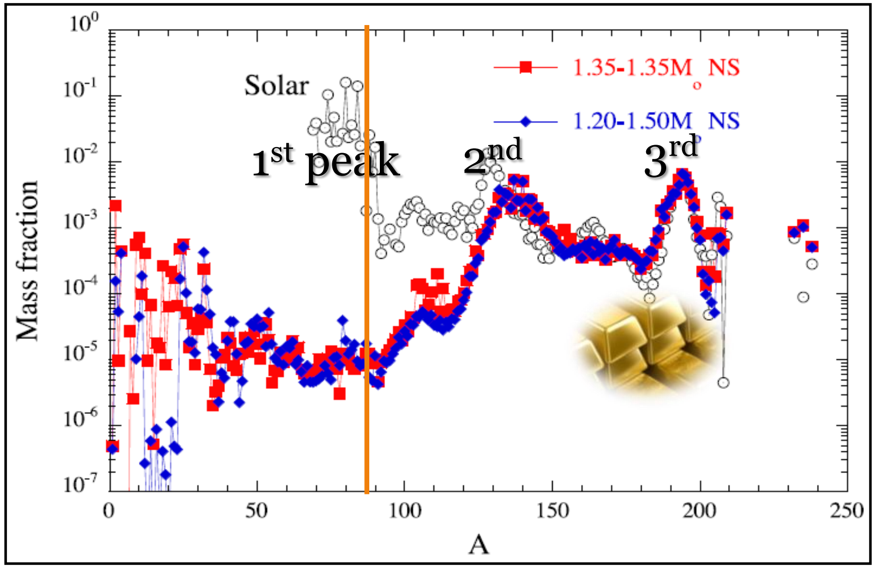
Density contour
[log (g/cm^3)]

From the ‘Universality’ point of view :
NS-NS merger ejecta: too neutron-rich ?

- **Korobkin et al. 2012; Rosswog et al. 2013; see also Goriely et al. 2011**
  - tidal mass ejection of ‘pure’ neutron star matter (very n-rich) with Ye < 0.1
    - Ye is that of T=0, β-equilibrium
  - strong r-process with fission recycling only 2nd (A~130; N=82) and 3rd (A~195; N=126) peaks are produced (few nuclei in A=90-120)
  - the resulting abundance pattern does not satisfy universality in A=90-120



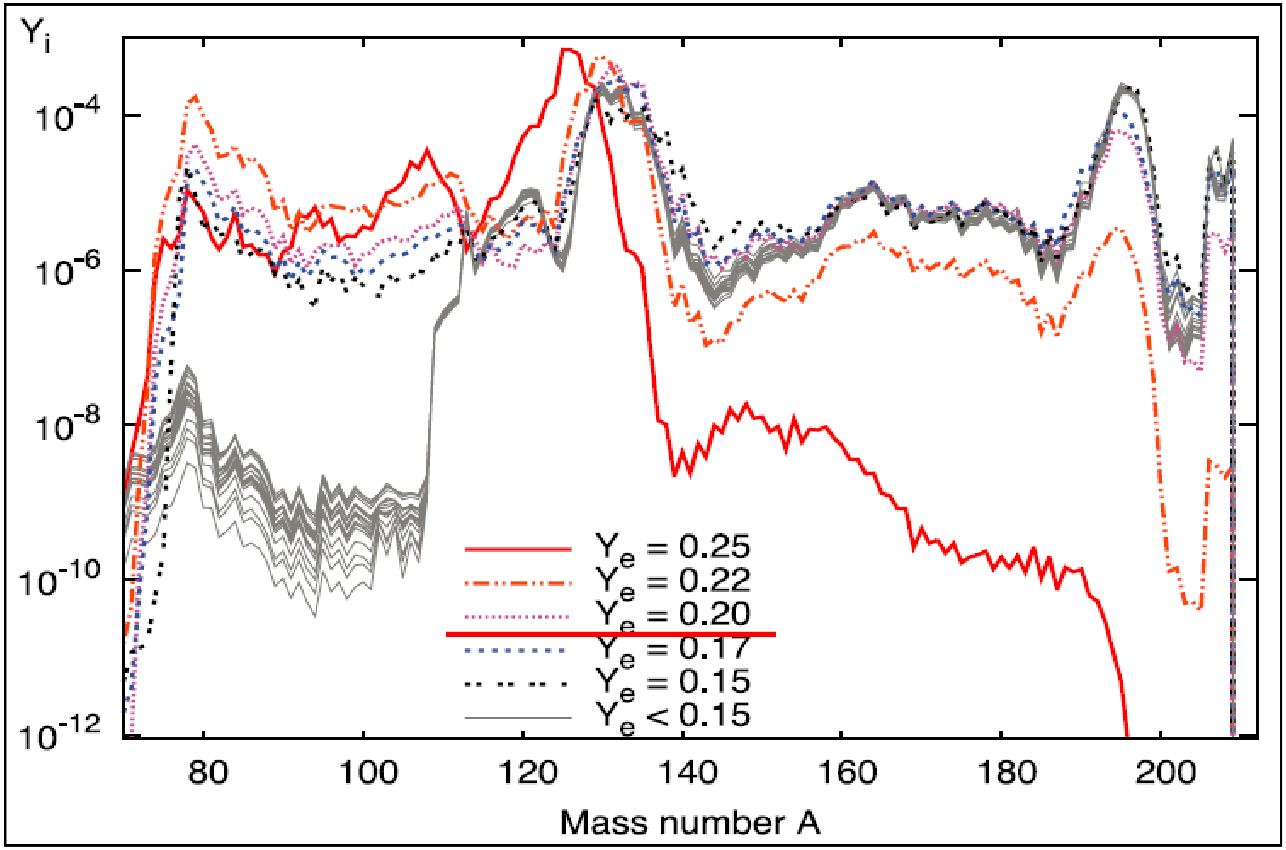
Korobkin et al. (2012) MNRAS 426 1940



Goriely et al. (2011) ApJL 738 32

How to satisfy the universality

- **Electron fraction (Ye) is a key parameter : Ye ~ 0.2 is critical threshold**
  - Ye < 0.2 : strong r-process ⇒ nuclei with A>130 (the pattern is robust)
  - Ye > 0.2 : weak r-process ⇒ nuclei with A< 130 (for larger Ye, nuclei with smaller A)



We need ejecta with higher Ye

- Korobkin et al. 2012

How to satisfy the universality

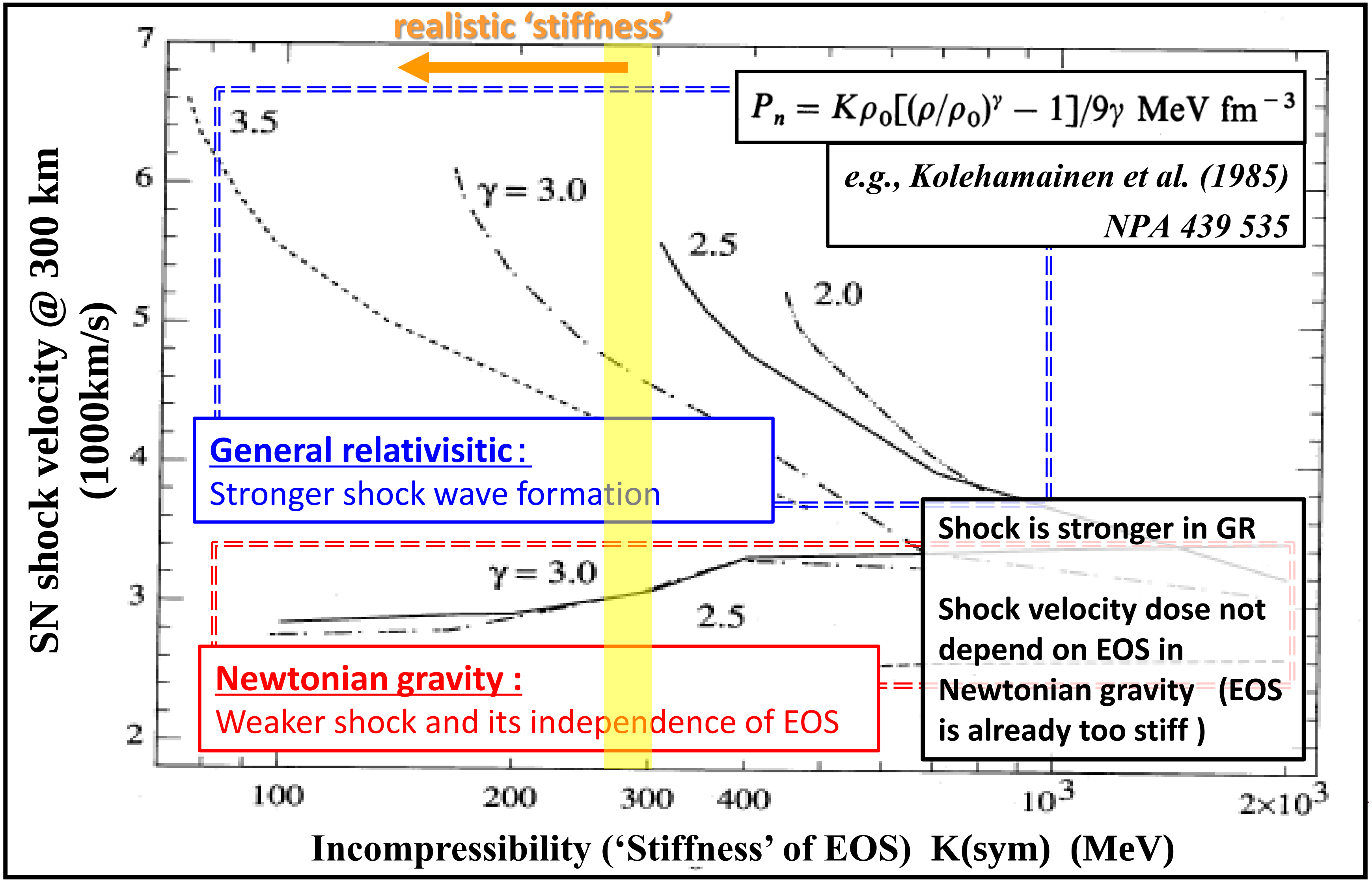
- Introduce new ejecta components
  - Neutrino driven winds from the remnant system
    - Perego’s talk, Krobkin’s talk
    - Dessart et al. (2009); Grossman et al. (2014); Perego et al. (2014); Just et al. (2015)
  - late time disk/torus disintegration
    - Fernandez & Metzger (2013)
  - It is not clear whether it is possible to satisfy the universality robustly

How to satisfy the universality

- Introduce new ejecta components
  - Neutrino driven winds from the remnant system
    - Dessart et al. (2009); Grossman et al. (2014); Perego et al. (2014); Just et al. (2015)
  - late time disk/torus disintegration
    - Fernandez & Metzger (2013)
- Take into account effects of both GR and weak interaction in the dynamical ejecta (this talk)

What will change if you include GR and microphysics (1) : Stronger shock in GR

van Riper (1988) ApJ 326 235



$$P_n = K\rho_0[(\rho/\rho_0)^\gamma - 1]/9\gamma \ \mathrm{MeV\ fm}^{-3}$$

e.g., Kolehamainen et al. (1985) NPA 439 535

General relativisitic :
Stronger shock wave formation

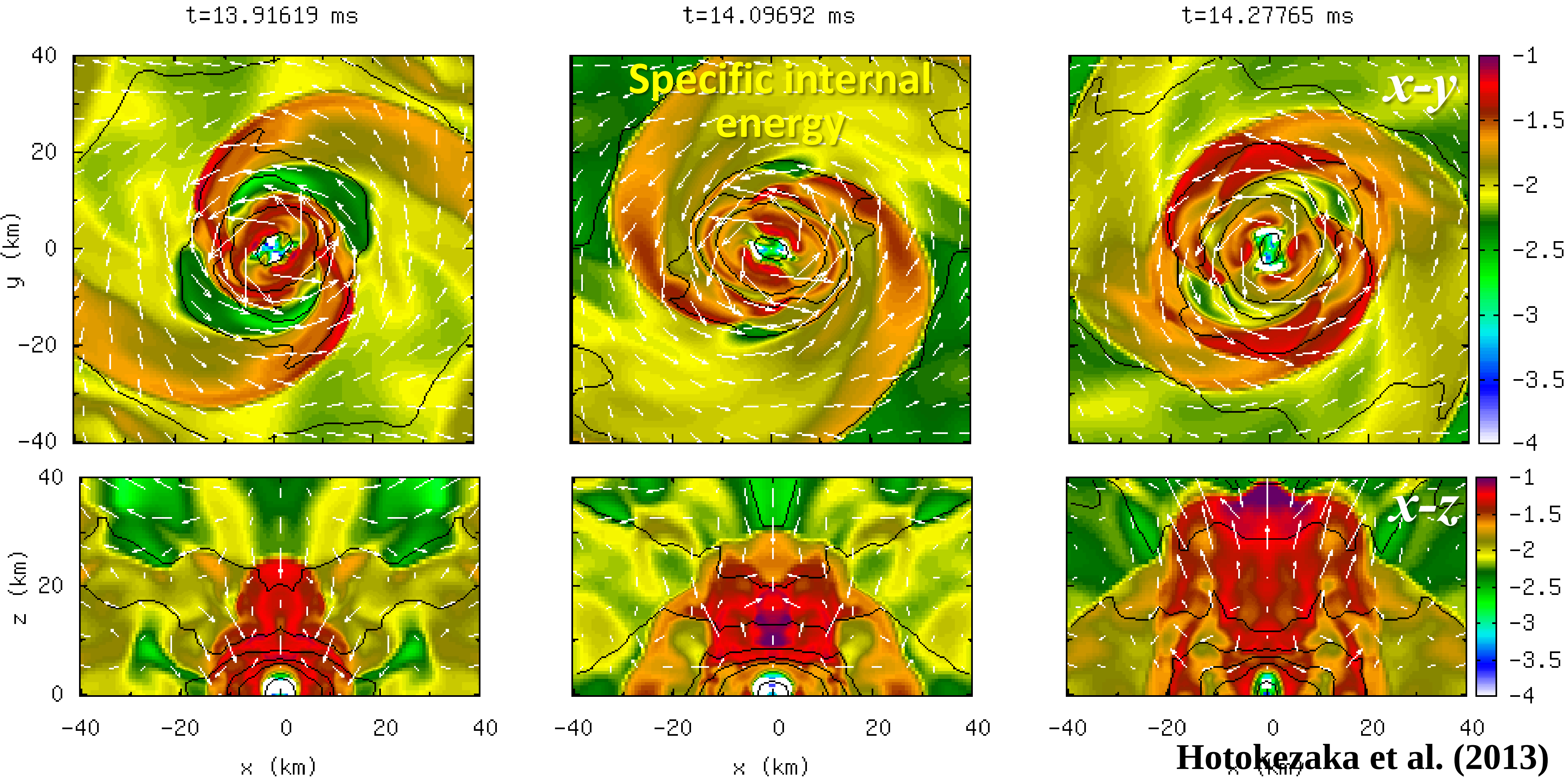
Newtonian gravity :
Weaker shock and its independence of EOS

Shock is stronger in GR

Shock velocity dose not depend on EOS in Newtonian gravity (EOS is already too stiff)

Mass ejection from BNS merger (2): Shock driven components

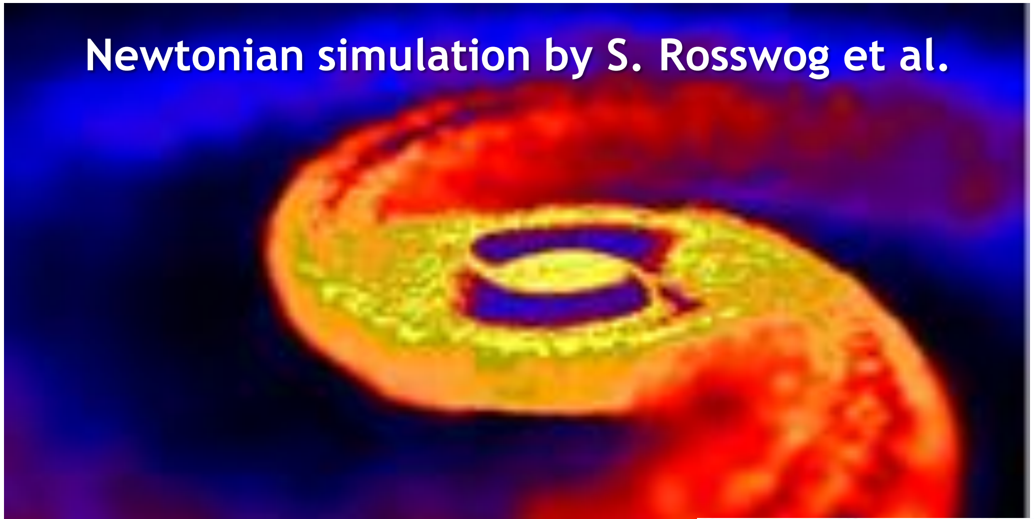
- Shocks occur due to oscillations of massive NS and collisions of spiral arms
- Isotropic mass ejection, higher temperature (weak interactions set in)



Hotokezaka et al. (2013)

What will change if you include GR and microphysics (1) :

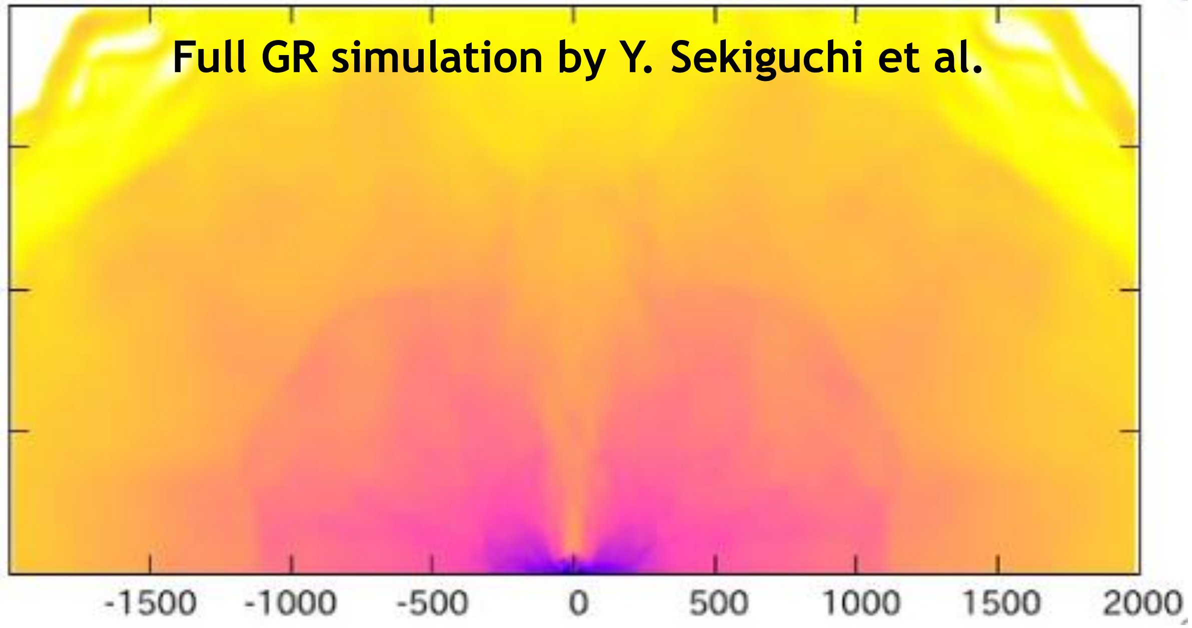
Stronger shock in GR



Newtonian simulation by S. Rosswog et al.

Almost no isotropic component (shock-driven) in Newtonian simulation

Only the tidal component



Full GR simulation by Y. Sekiguchi et al.

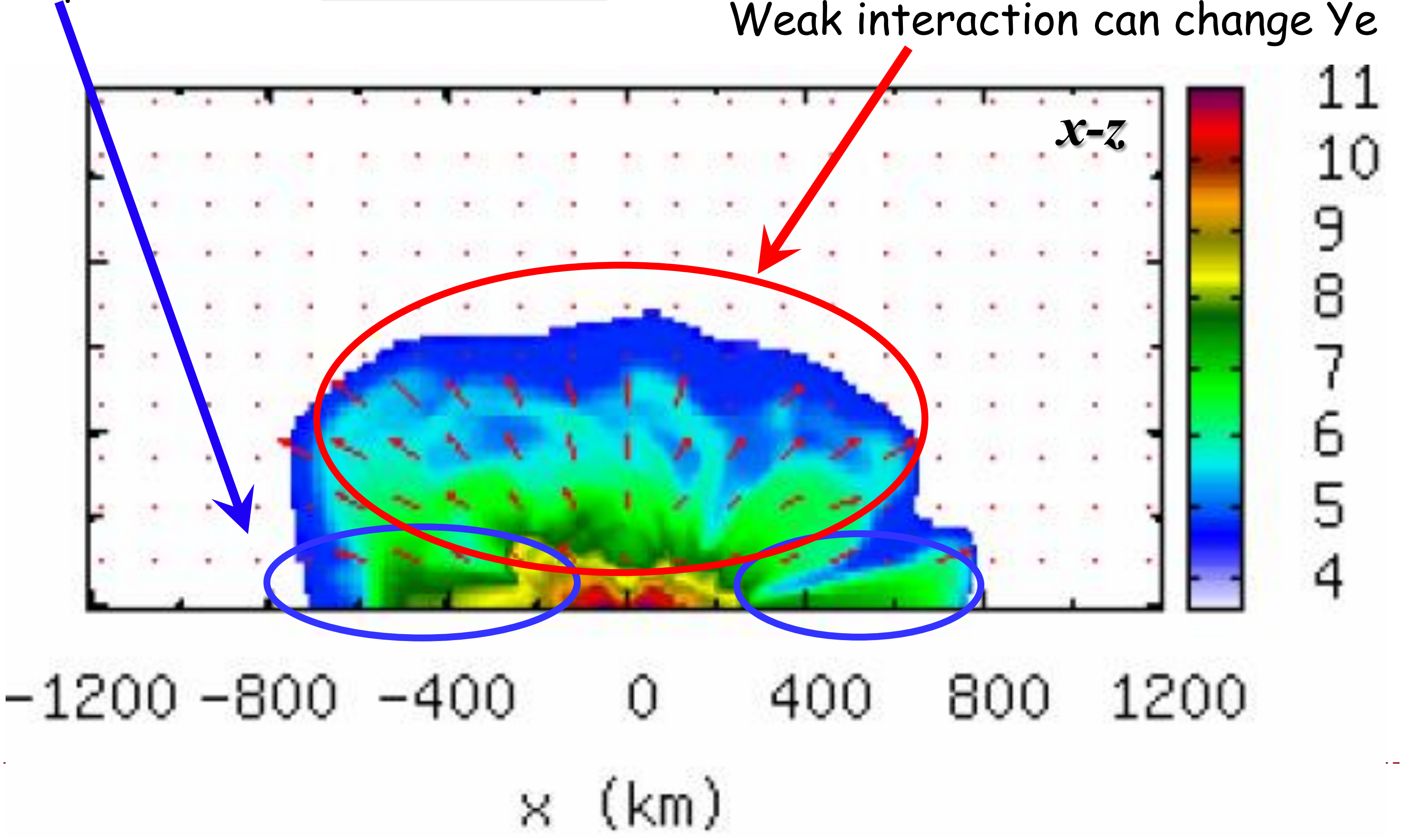
What will change if you include GR and microphysics (2) : Ye can change via weak interaction

- **Driven by tidal interactions**

  Consists of cold NS matter in β-equilibrium ⇒ **low Ye and T**

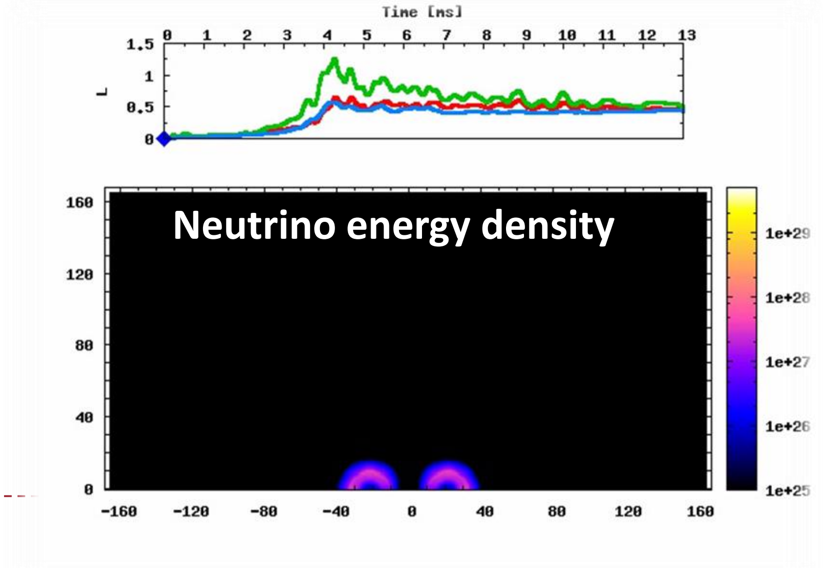
- **Driven by shocks**

  Consists of shock heated matter higher temperature =>
  Weak interaction can change Ye



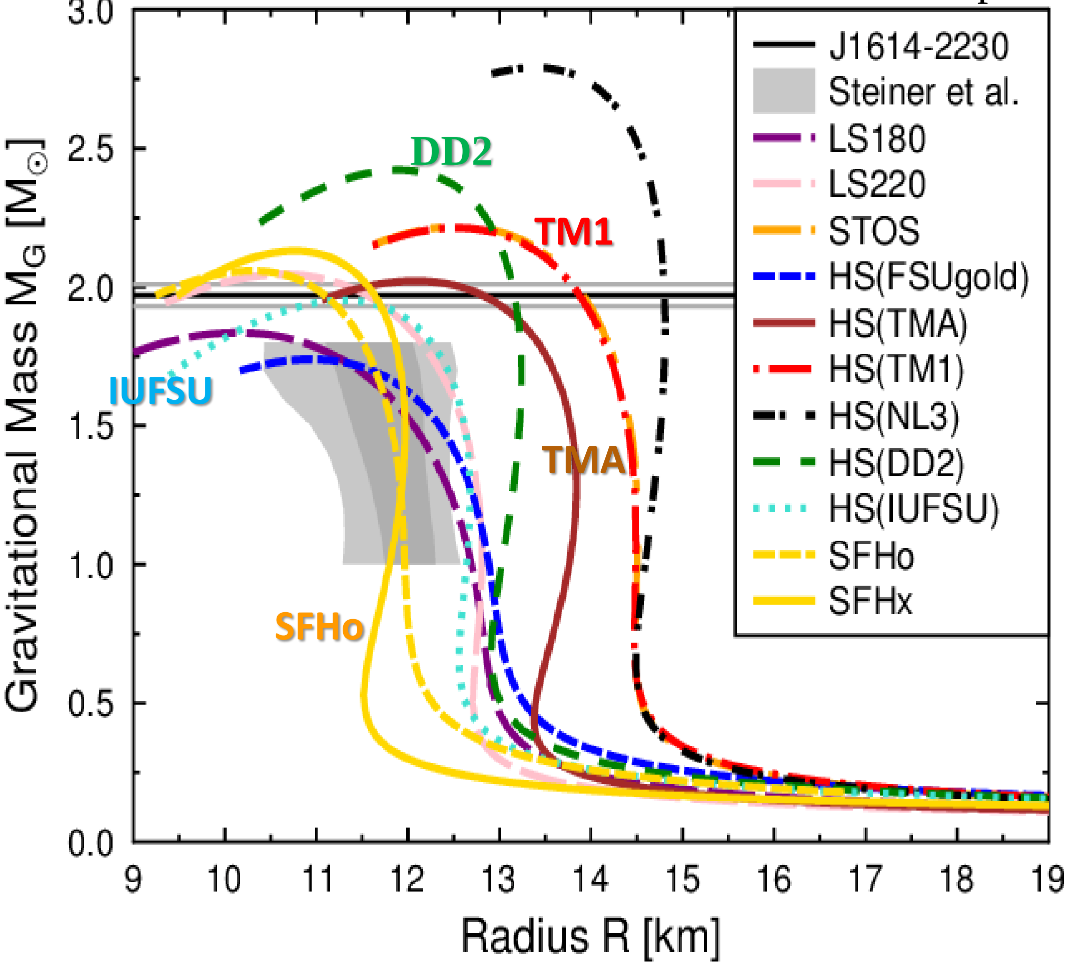
Previous studies and our study

- **Korobkin et al. 2012 :** Newtonian SPH simulations with neutrinos
- **Bauswein et al. 2013:** Relativistic SPH simulations with many EOS but without neutronos
- **This Study :** Full GR, approximate gray radiation hydrodynamics simulation with multiple EOS and neutrinos (brief summary of code is in appendix of lecture note)
  - Einstein's equations: Puncture-BSSN/Z4c formalism
  - GR radiation-hydrodynamics (*neutrino heating can be approximately treated*)
    - Advection terms : Truncated Moment scheme (*Shibata et al. 2011*)
      - EOS : any tabulated EOS with 3D smooth connection to Timmes EOS
      - gray or multi-energy but advection in energy is not included
      - Fully covariant and relativistic M-1 closure
    - Source terms : two options
      - Implicit treatment : Bruenn's prescription
      - Explicit treatment : trapped/streaming ν's
        - e-captures: thermal unblocking/weak magnetism; NSE rate
        - Iso-energy scattering : recoil, Coulomb, finite size
        - e±annihilation, plasmon decay, bremsstrahlung
        - diffusion rate (Rosswog & Liebendoerfer 2004)
        - two (beta- and non-beta) EOS method
    - Lepton conservation equations



Adopted EOS & (expected) Mass ejection mechanism

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



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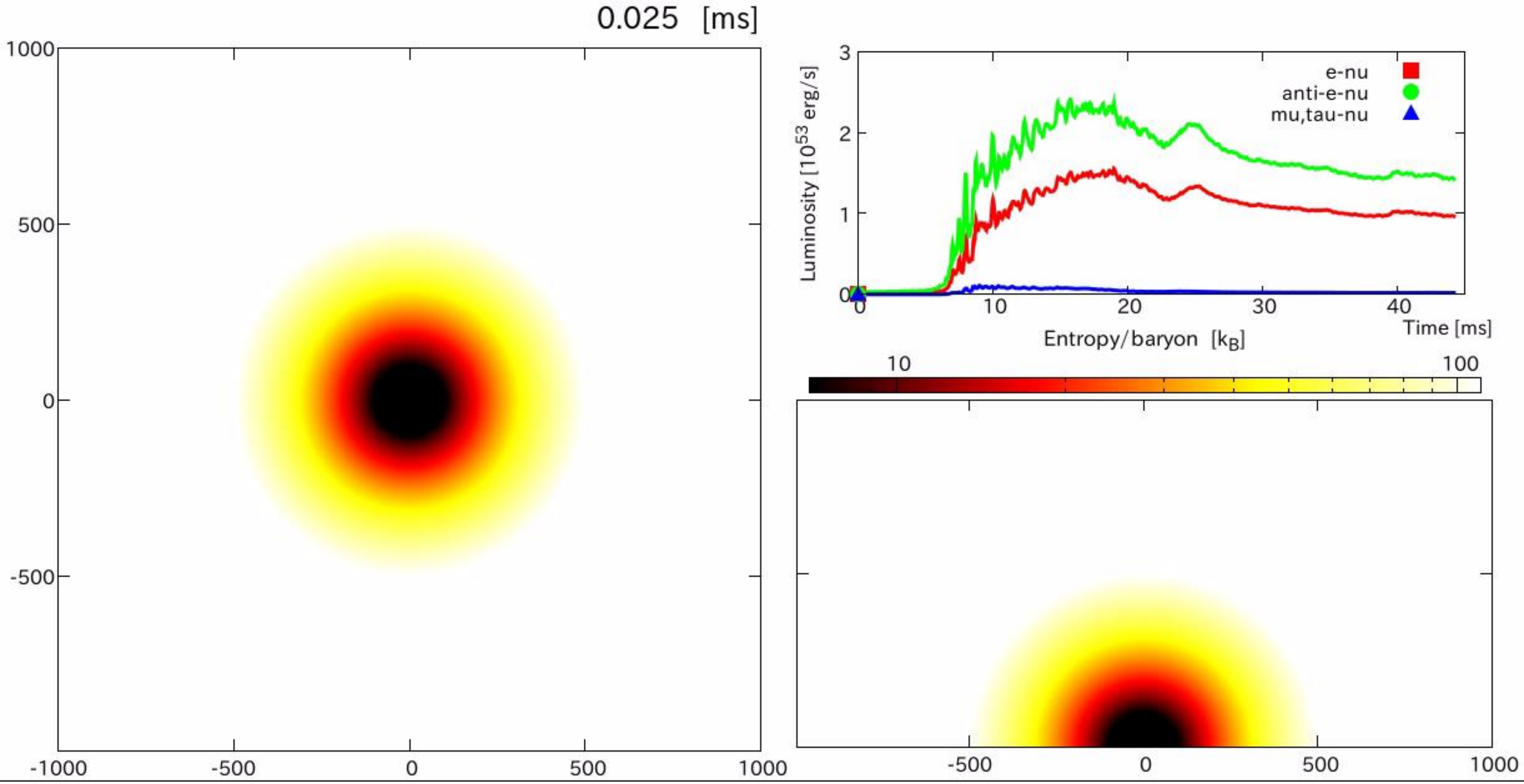
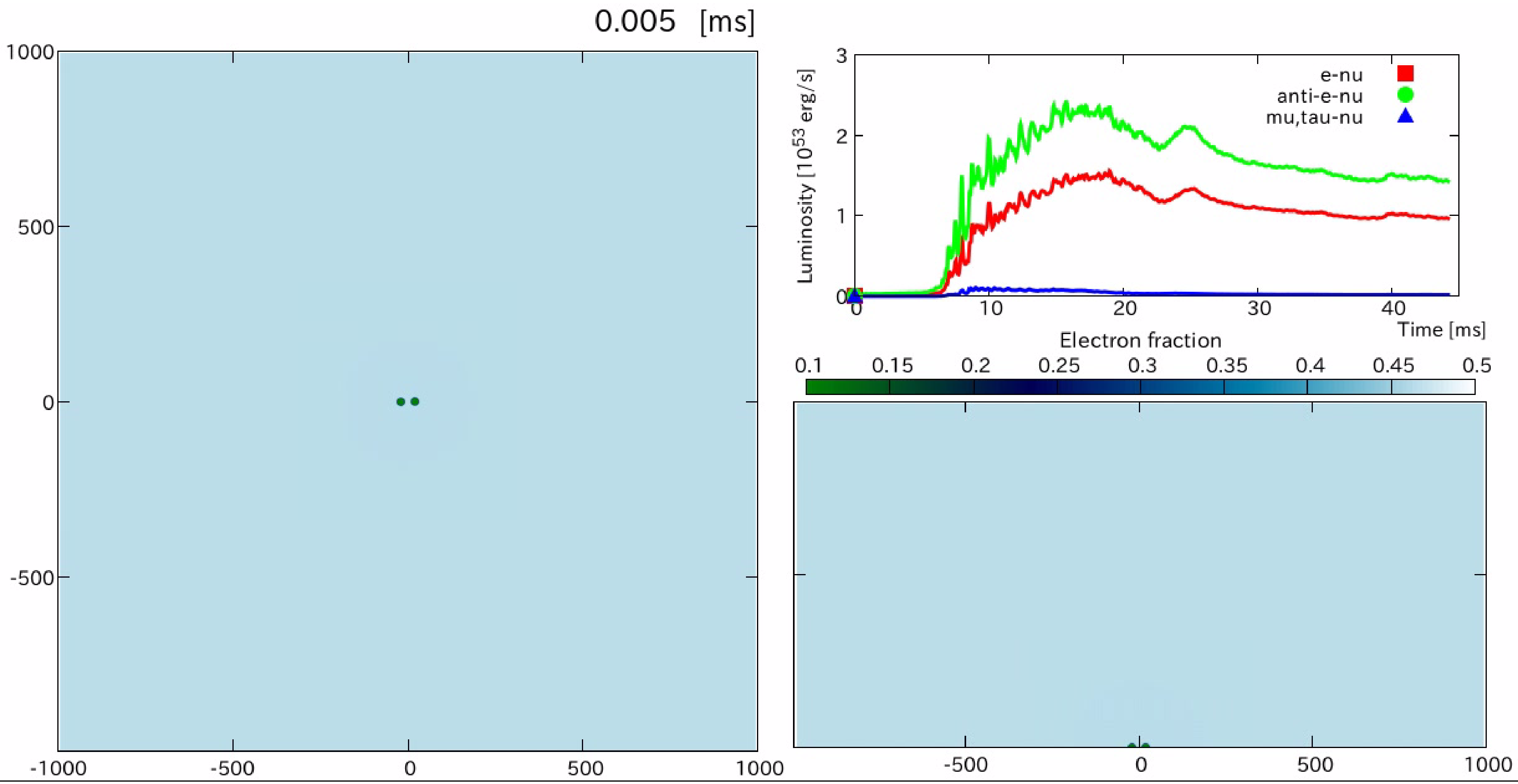
See also, Bauswein et al. (2013); Just et al. (2014)

Entropy per baryon : DD2
relatively **stiff**, tidal component dominated

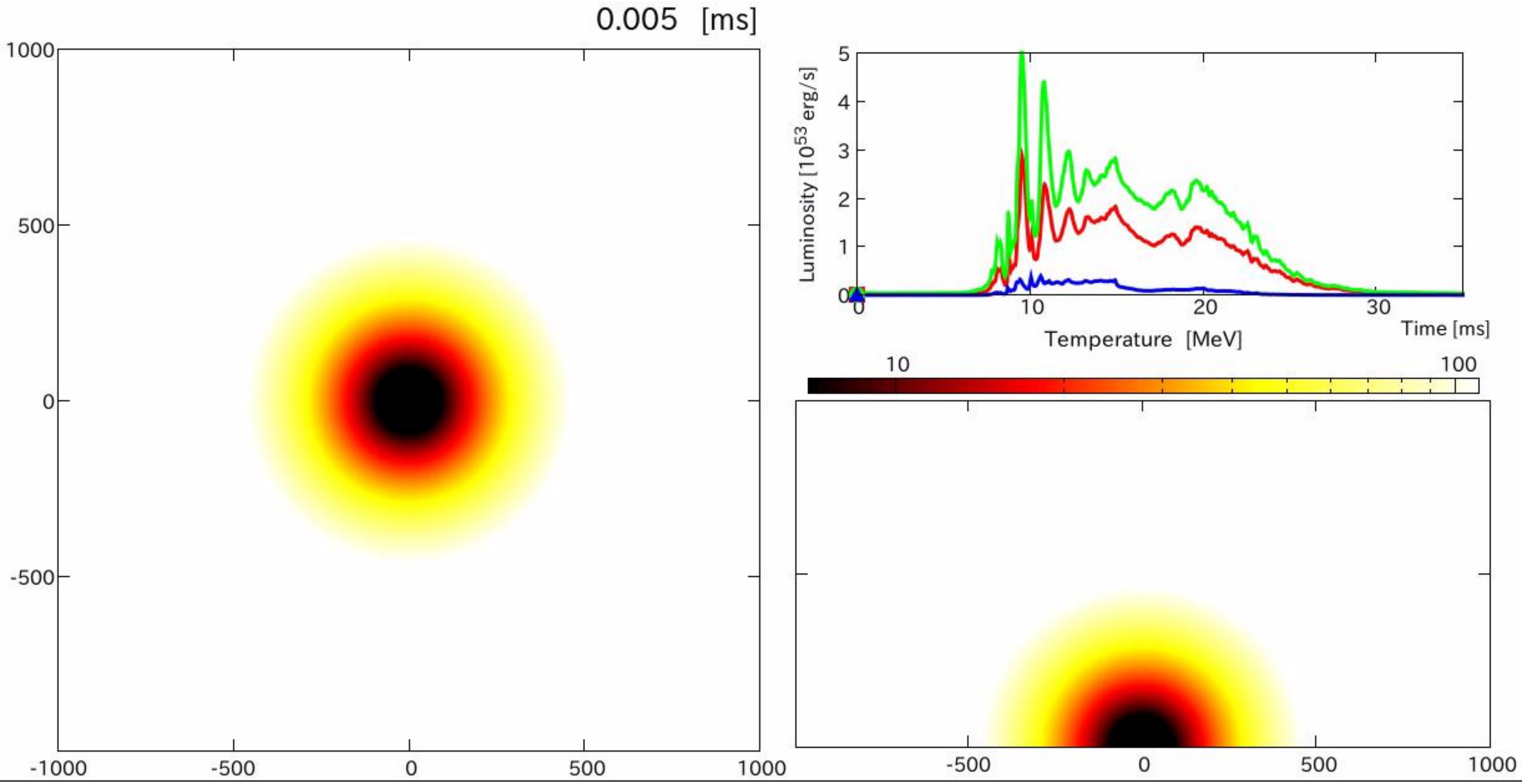


Ye : DD2
relatively **stiff**, tidal component dominated

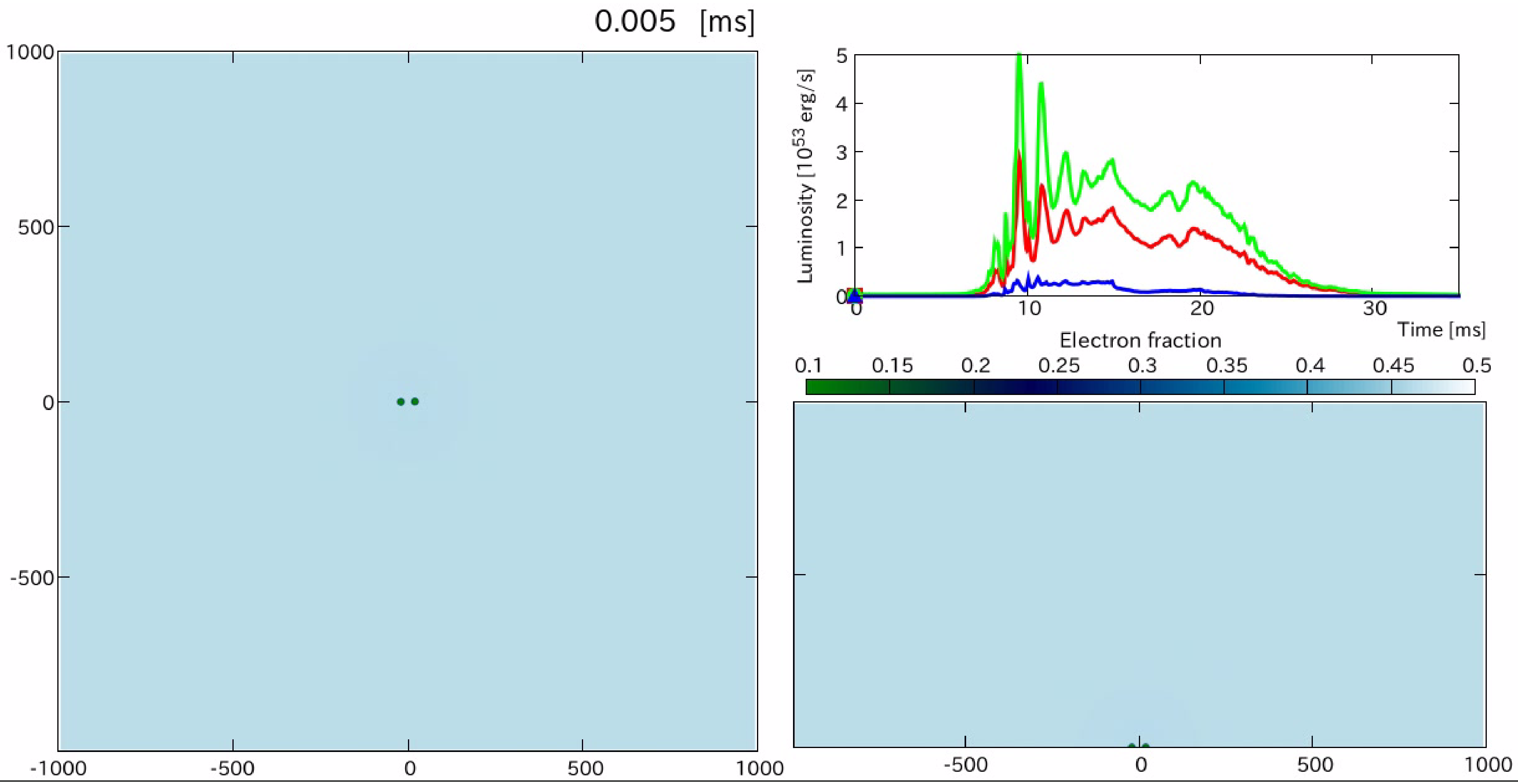


Entropy per baryon : SFHo

relatively **soft**, multiple shock components



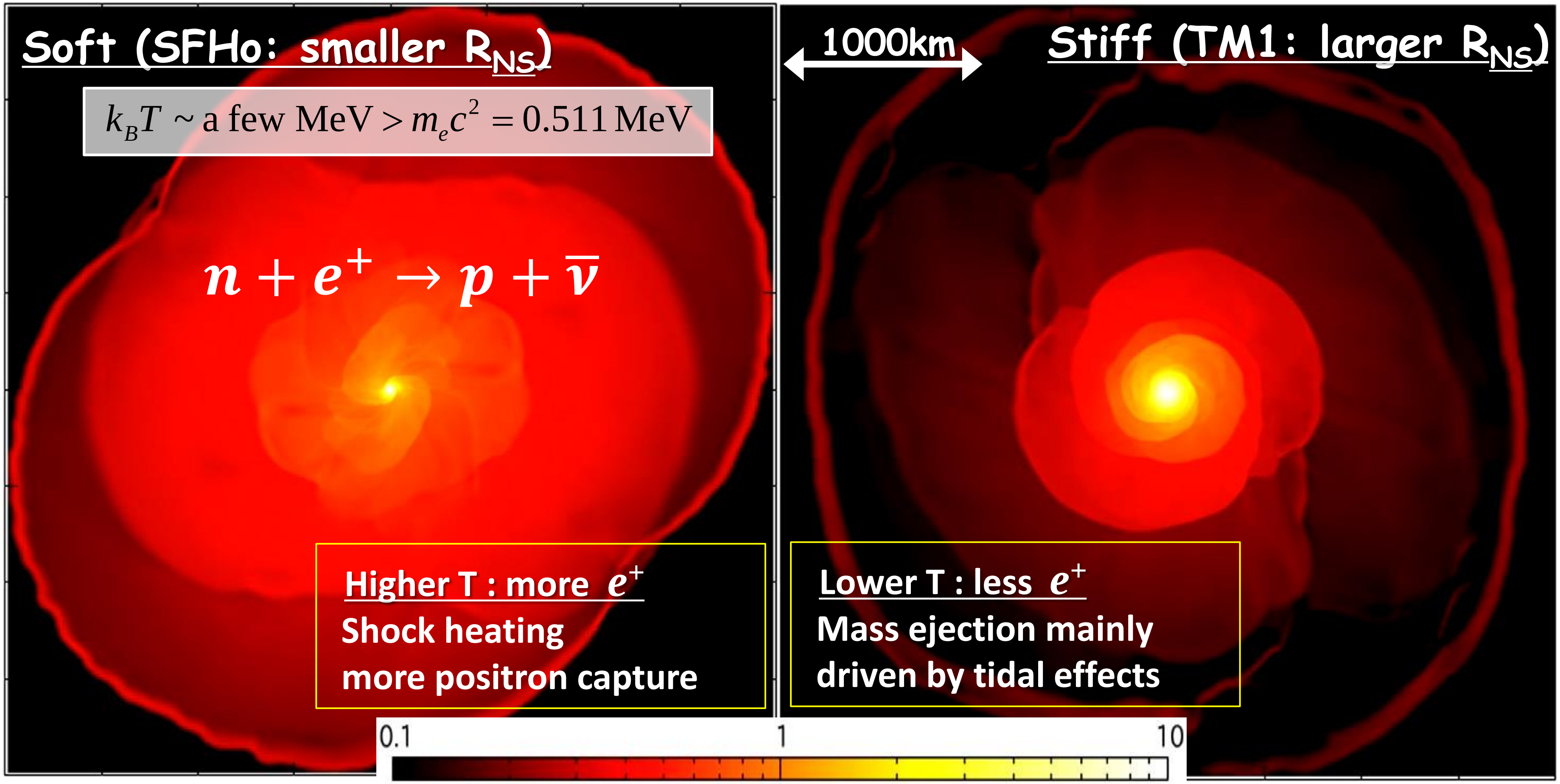
Ye : SFHo
relatively **soft**, multiple shock components



Sekiguchi et al PRD (2015)

Soft(SFHo) vs. Stiff(TM1): Ejecta temperature

- Soft (SFHo): temperature of unbound ejecta is higher (as 1MeV) due to the shock heating, and produce copious positrons
- Stiff (TM1): temperature is much lower



$k_B T \sim$ a few MeV $> m_e c^2 = 0.511$ MeV

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

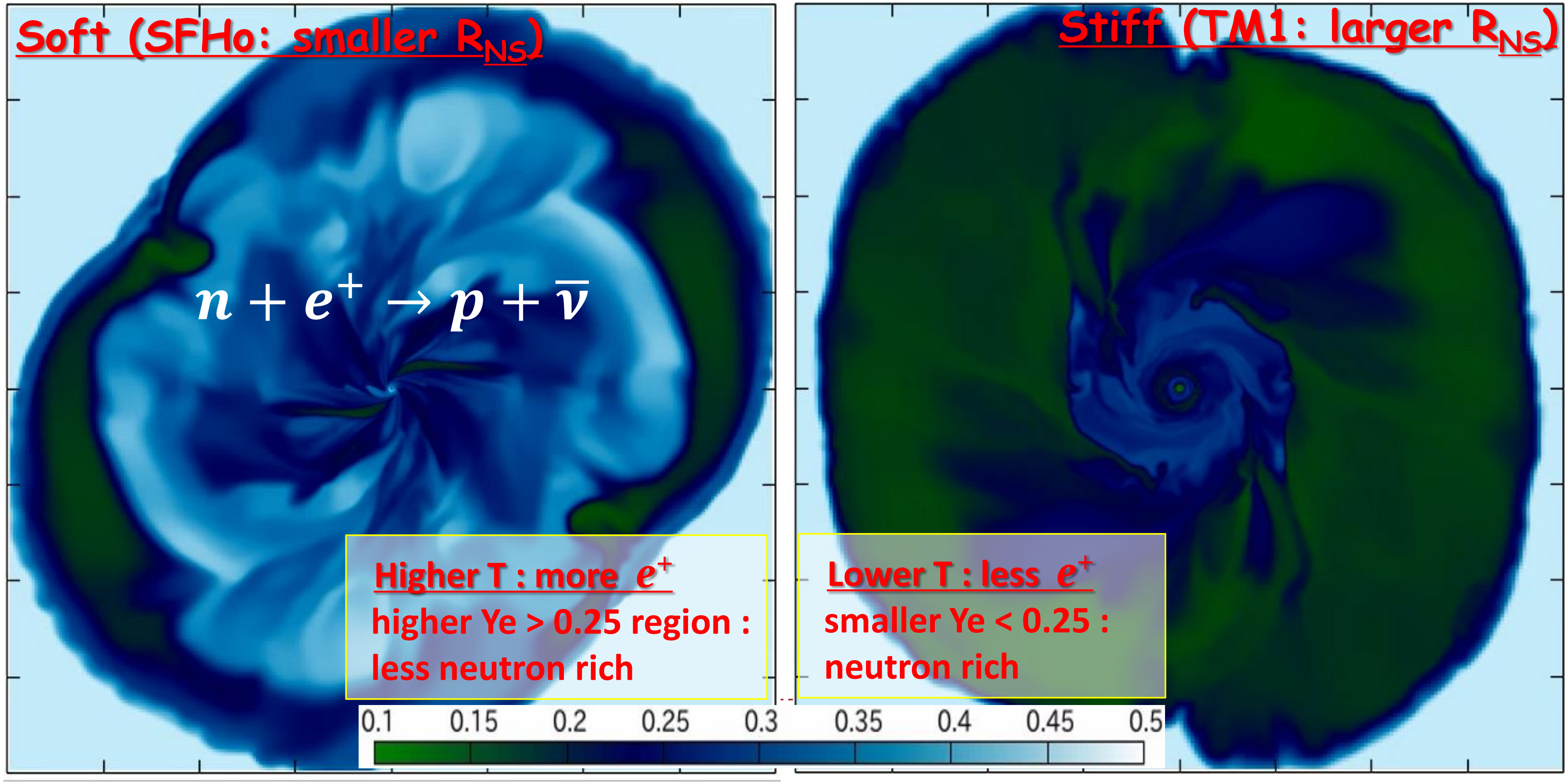
Higher T : more e^+
Shock heating
more positron capture

Lower T : less e^+
Mass ejection mainly driven by tidal effects

Sekiguchi et al PRD (2015)

Soft(SFHo) vs. Stiff(TM1): Ejecta Ye = 1- Yn

- Soft (SFHo): In the shocked regions, Ye >> 0.2 by weak processes
- Stiff (TM1): Ye is low as < 0.2 (only strong r-process expected)



Soft (SFHo: smaller R_{NS})

$$n + e^{+} \to p + \bar{\nu}$$

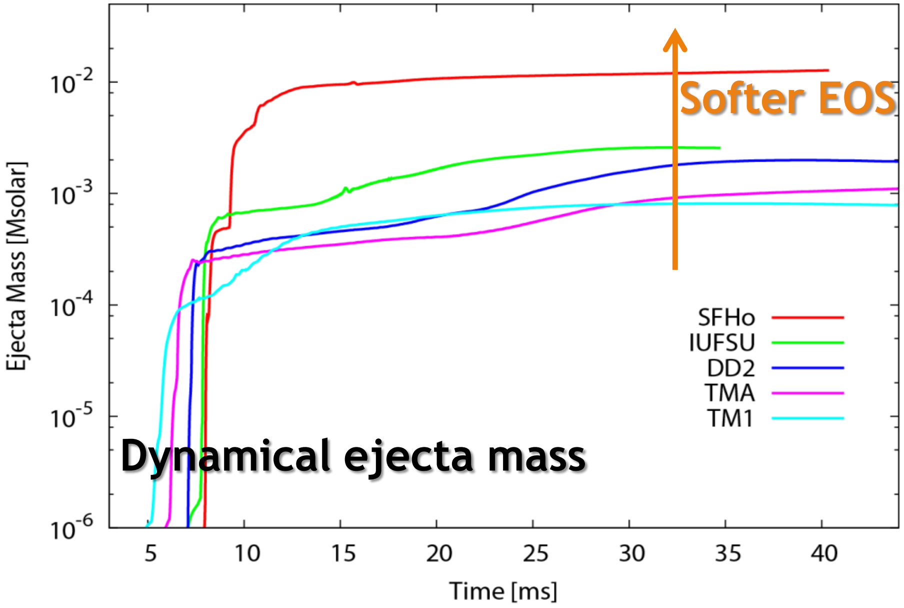
Stiff (TM1: larger R_{NS})

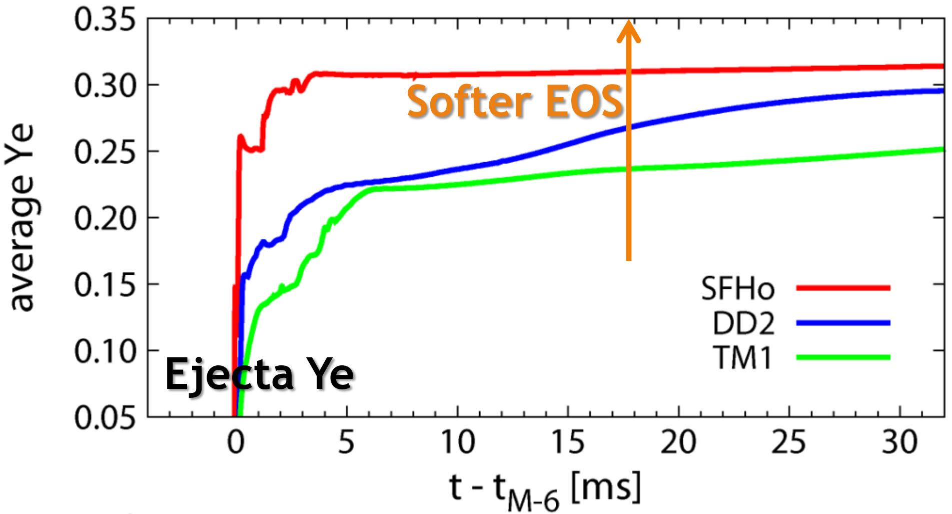
Higher T : more e^{+}
higher Ye > 0.25 region :
less neutron rich

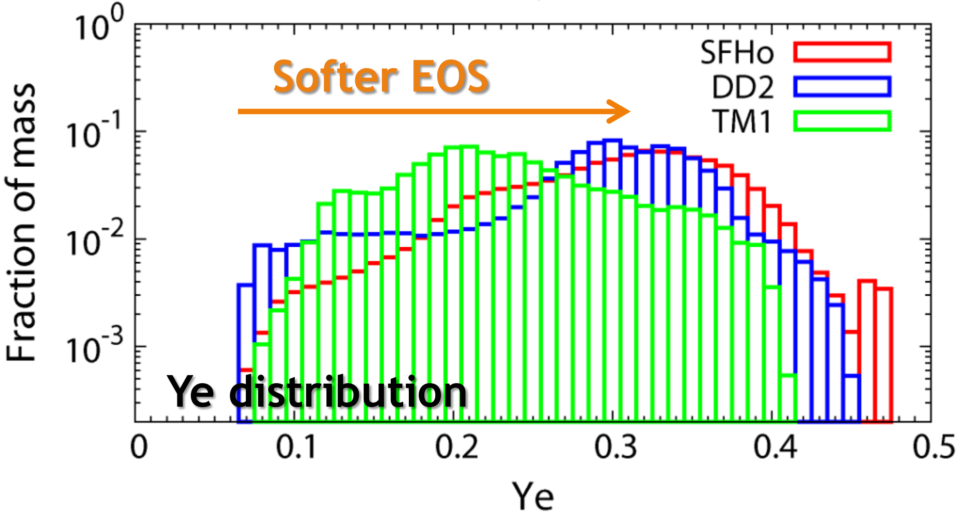
Lower T : less e^{+}
smaller Ye < 0.25 :
neutron rich

Sekiguchi et al PRD (2015)

EOS dependence : 1.35-1.35 NS-NS







- Mej is larger for softer EOS

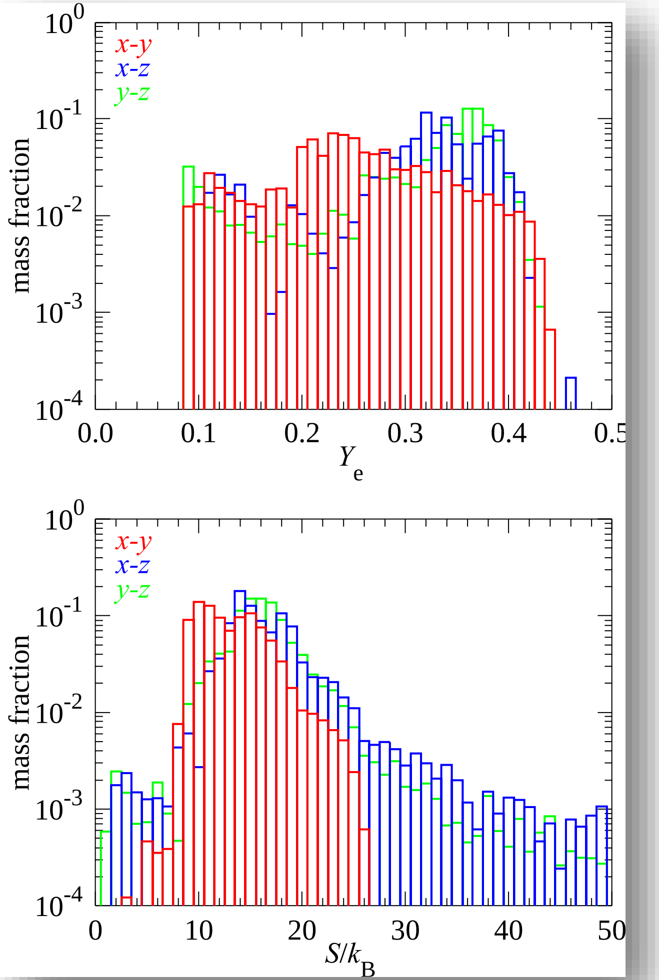
  Consistent with piecewise-polytrope studies

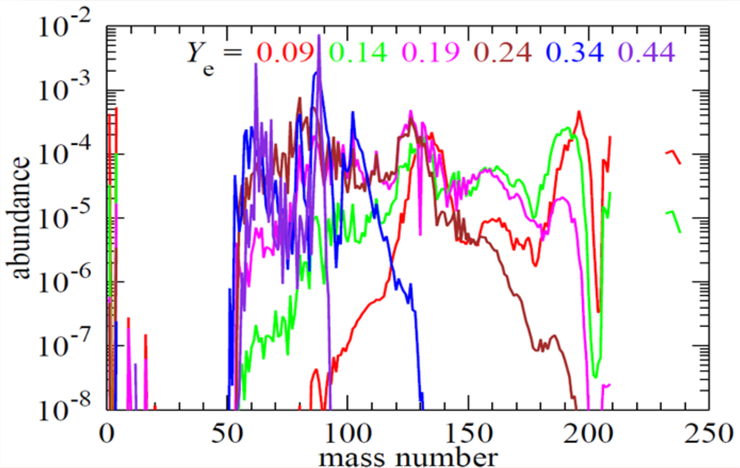
- **Only SFHo will give Mej ~ 0.01 Msun**
- a value required by the total amount of r-process elements and flux of the ‘macronova’ event (GRB 130603B)

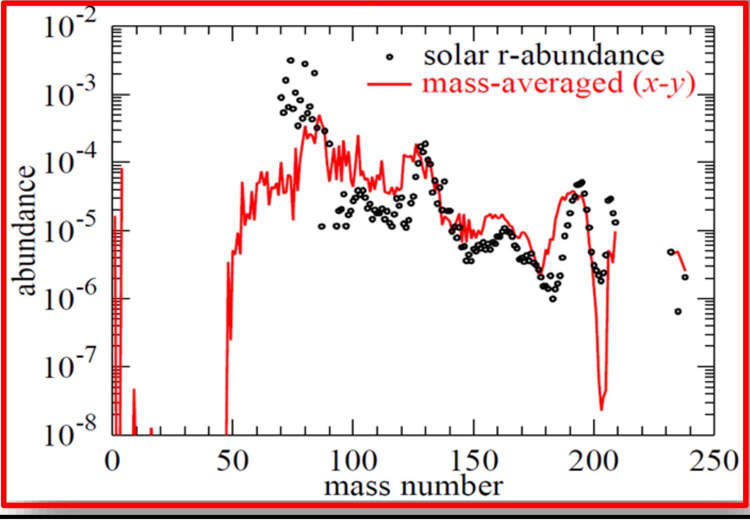
Wanajo, Sekiguchi et al. ApJL (2014)

Achievement of the universality

(soft EOS (SFHo), equal mass (1.35-1.35))



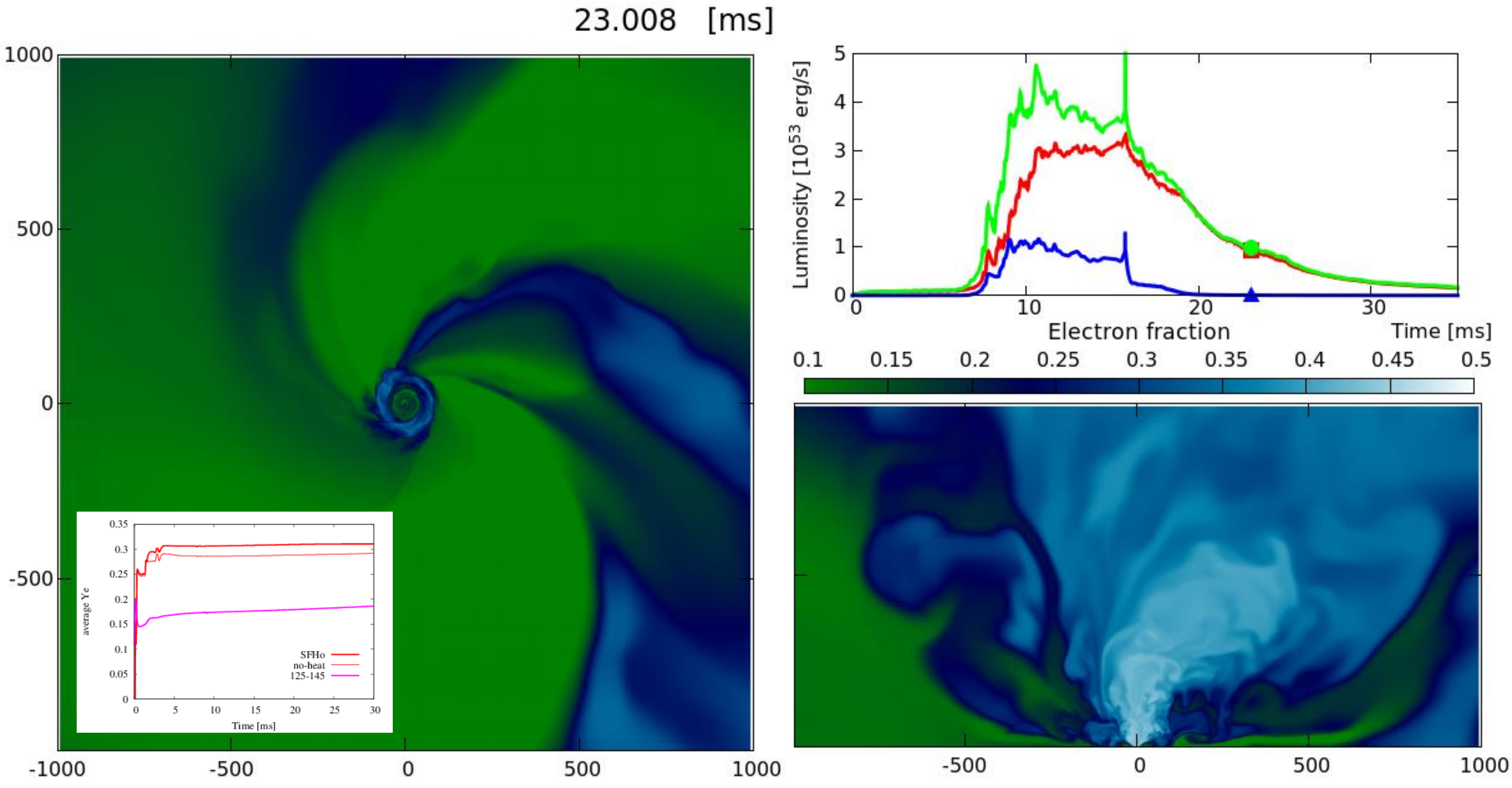




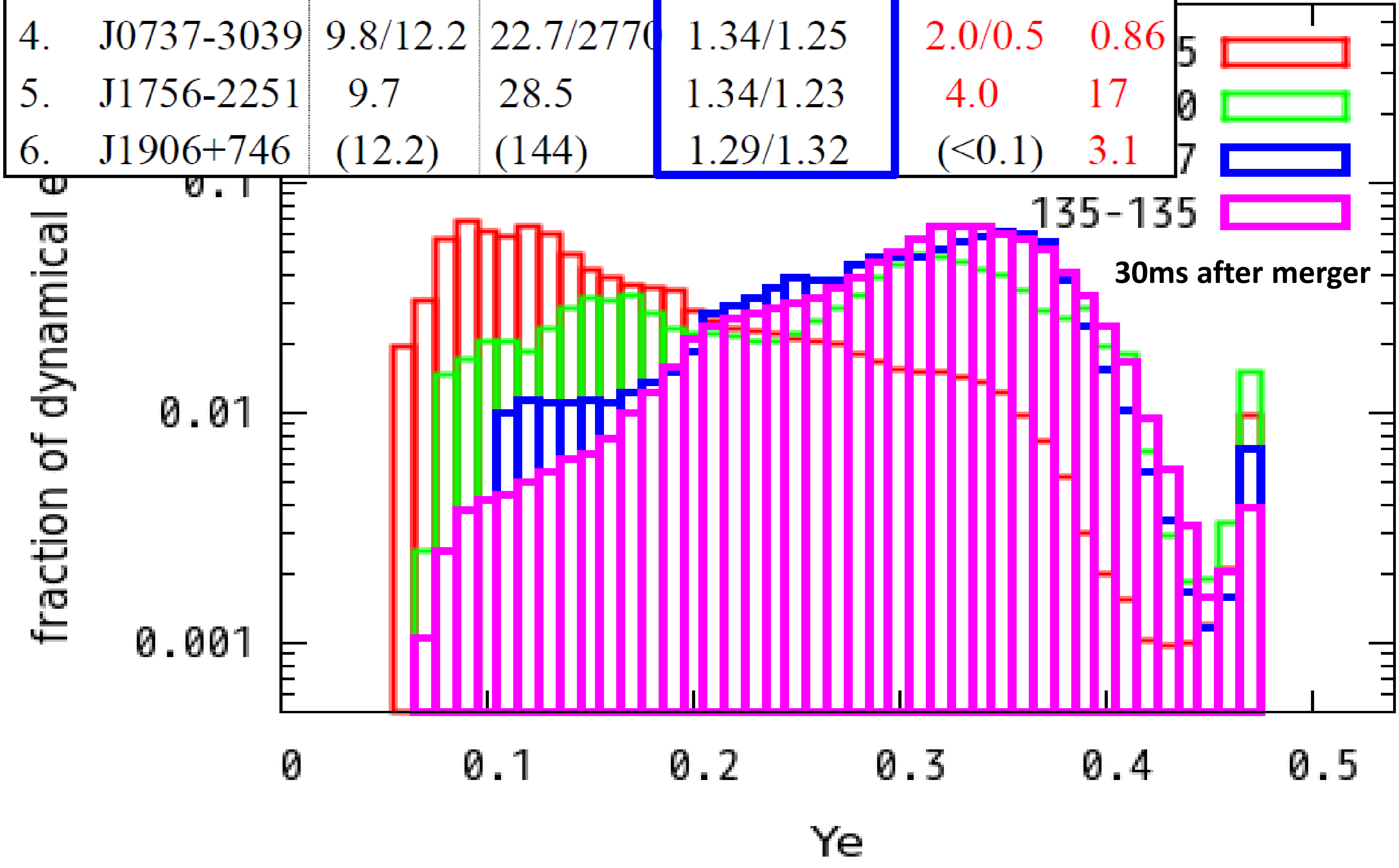
- The Ye-distribution histogram has a broad, flat structure (*Wanajo, Sekiguchi, et al. (2014)*.)
  - Mixture of all Ye gives a good agreement with the solar abundance !
  - Robustness of Universality (dependence on binary parameters)

Unequal mass NS-NS system: SFHo1.25-1.45

- Orbital plane : Tidal effects play a role, ejecta is neutron rich
- Meridian plane : shock + neutrinos play roles, ejecta less neutron rich

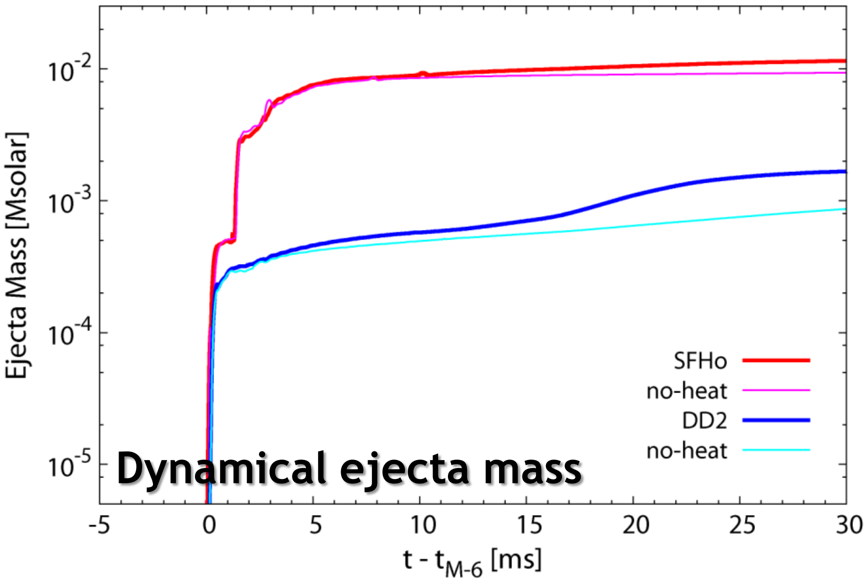


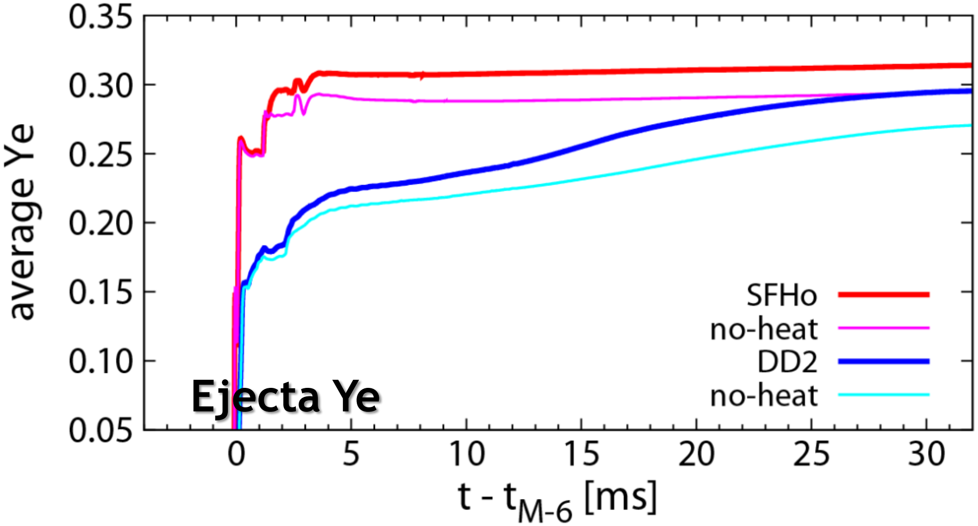
	PSR	log B(G)	$P_{\rm rot}$ (ms)	$M(M_{\rm sun})$	$T_{\rm Mag}$	$T_{\rm GW}$
1.	B1913+16	10.4	59.0	1.441/1.387	1.0	3.0
2.	B1534+12	10.0	37.9	1.333/1.345	2.5	27
3.	B2127+11C	10.7	30.5	1.36/1.35	1.0	2.2
4.	J0737-3039	9.8/12.2	22.7/277	1.34/1.25	2.0/0.5	0.86
5.	J1756-2251	9.7	28.5	1.34/1.23	4.0	17
6.	J1906+746	(12.2)	(144)	1.29/1.32	(<0.1)	3.1

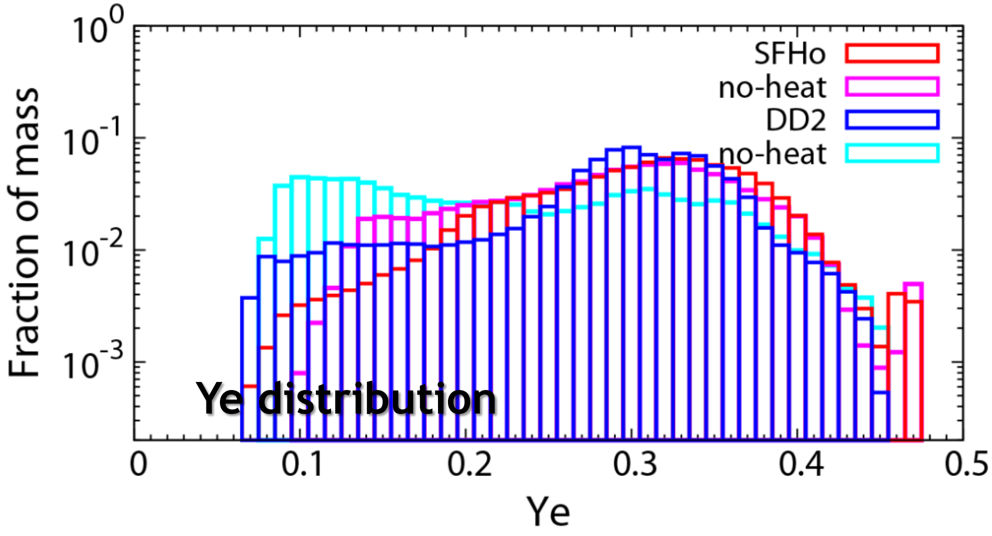


Sekiguchi et al PRD (2015); Prego et al. (2014); Just et al. (2014); Goriely et al. (2015); Martin et al. (2015)

Importance of neutrino heating (absorption)







- Amount of ejecta mass can be increased order of 10^{-3} Msun
- Average Ye can change 0.02~0.03 depending on EOS : effect is stronger for stiffer EOS where HMNS survive in a longer time

Summary

- Neutrino-Radiation-Hydrodynamics in numerical relativity is now feasible !
  - based on truncated moment formalism with M-1 closure
  - both implicit and explicit schemes can be adopted

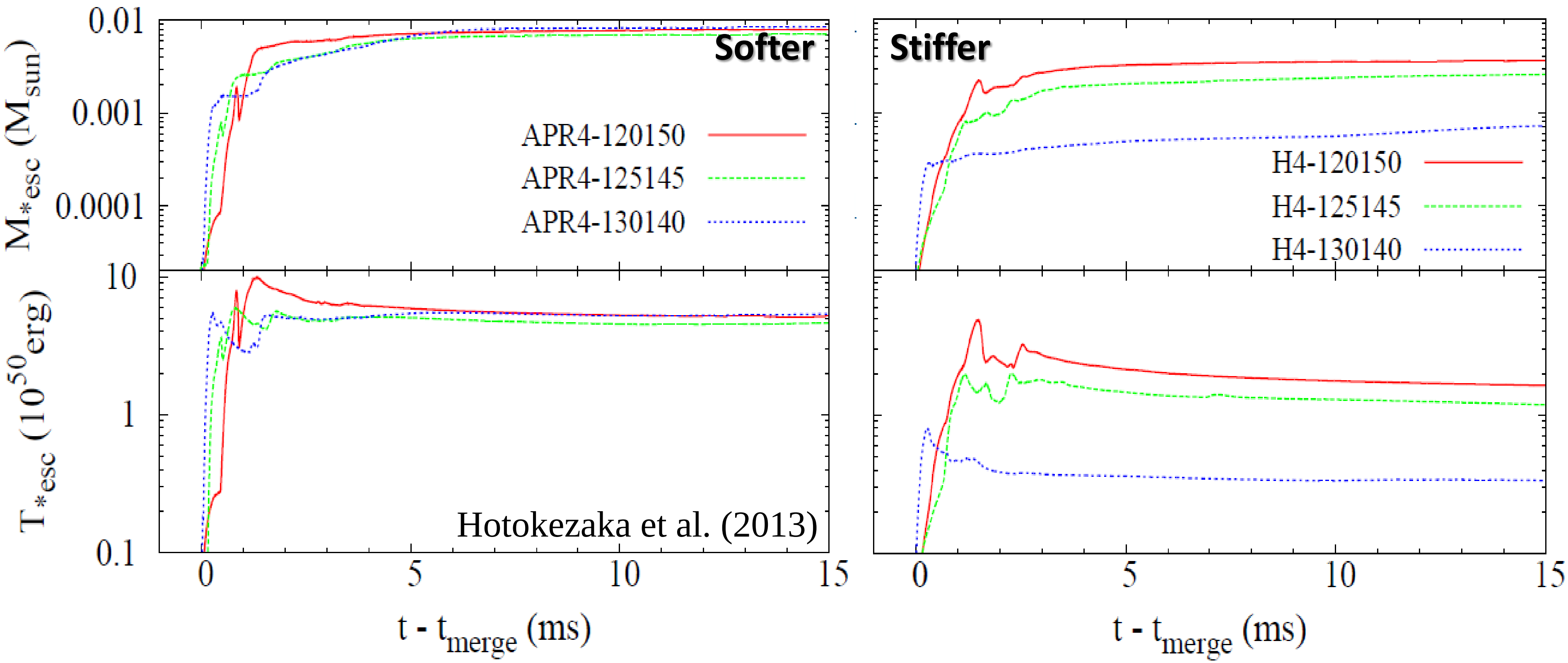
- **Importance of GR, neutrinos and EOS for r-process in BNS merger**
  - strong EOS dependence : challenge to the robustness (Korobkin et al. 2012)
  - For a softer EOS **shock heating** is more important and **ejecta *T* increases**
  - As a result, **positron capture** proceeds more and **ejecta Ye increases**
  - **Resulting r-process yield agrees well with the solar abundance**
  - BNS merger as origin of heavy elements ?

- Future studies
  - Further investigation of EOS dependence
  - Long-term simulations to see neutrino heating effects
  - EM counterpart study based on r-process nucleosynthesis calculation
  - BH-NS, Collapsar, etc.

Appendix

Dynamical ejecta mass and mass ratio

- Dynamical ejecta mass basically increases as the mass ratio decreases
  - This is likely to be true for tidal-component
- For stiff EOS (less compact NS), mass ratio plays important role
  - For softer EOS (APR: more compact NS), ejecta mass is almost independent of mass ratio



Hotokezaka et al. (2013)

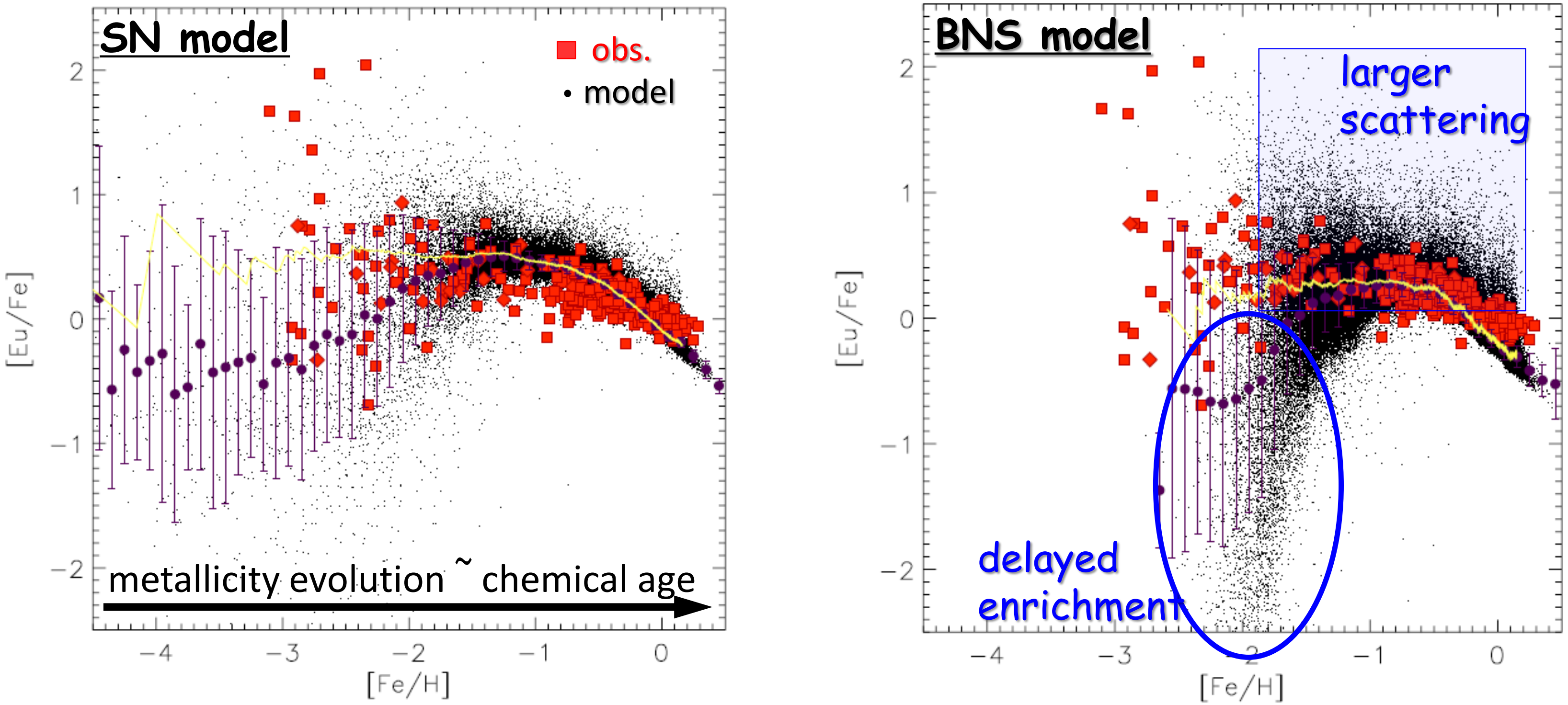
e.g., Matteucci et al. 2014, MNRAS, 438, 2177; Komiya et al. 2014, ApJ, 783, 132, Tsujimoto & Shigeyama, A&A, 565, L5

From a chemical evolution point of view

- **Two problems to be resolved (*Argast et al. 2004*)**
  - delayed appearance of r-process element (long merger time ~ 100Myr)
  - large star-to-star scattering (low event rate (~ 10^{-5}/yr/gal)

Argast et al. (2004)

a typical r-process element abundance (Eu)



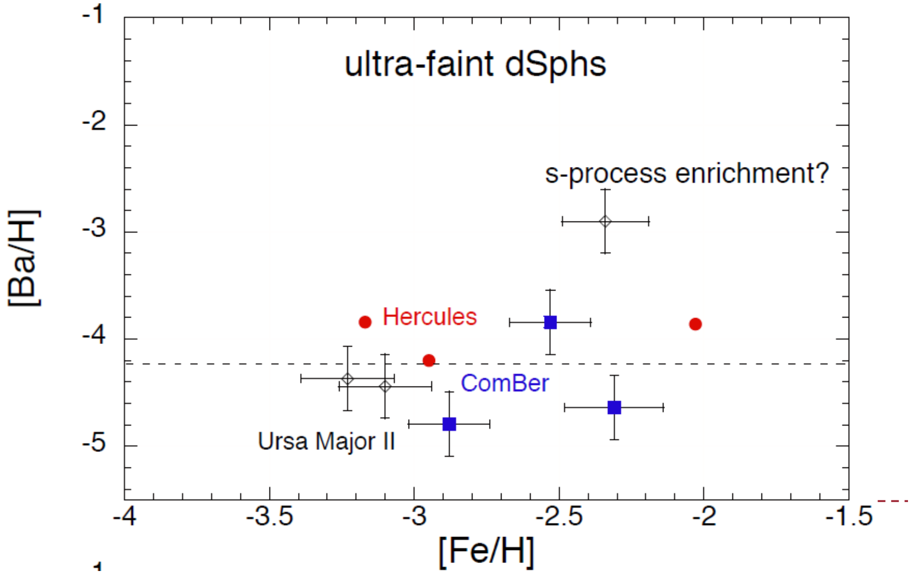
From a chemical evolution point of view

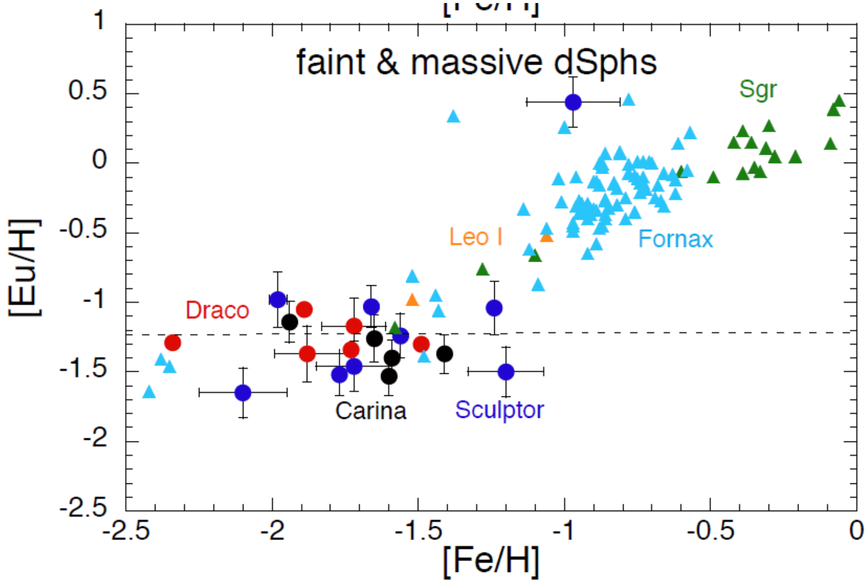
- Resolution of the delay time problem
  - due to merger time of ~ 100 Myr:
- In the dwarf galaxies, chemical enrichment is different from that in the ordinary galaxies due to less deep gravitational potential.
- Fe produced in SNe can escape from the dwarf galaxies more efficiently than normal galaxies
- => it takes more time for the dwarf galaxies to become Fe rich than in normal galaxies
- Studies taken into account this indicate that merger time of 100 Myr is not inconsistent with the observations (Ishimaru et al. 2015; Hirai et al. in prep.)

Observations of dwarf galaxies

- No enrichment of Eu in ultra dwarf galaxies but Fe increases
  - No r-process events (No Eu) but a number of SNe (Fe↑)
  - If SNe are the r-process cite, both Eu and Fe should increase
  - Suggest different origin for Fe and Eu
  - Enrichment of Eu in massive dwarfs
    - event rate is estimate as 1/1000 of SNe : consistent with BNS merger

Tsujimoto and Shigeyama (2014)





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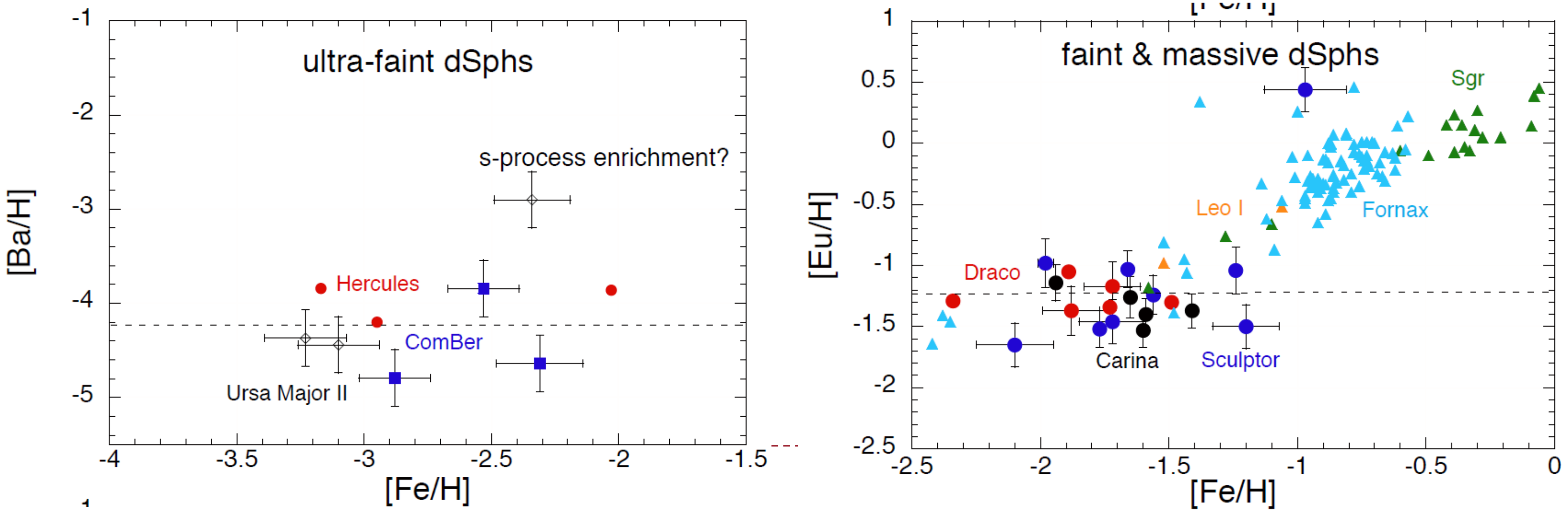
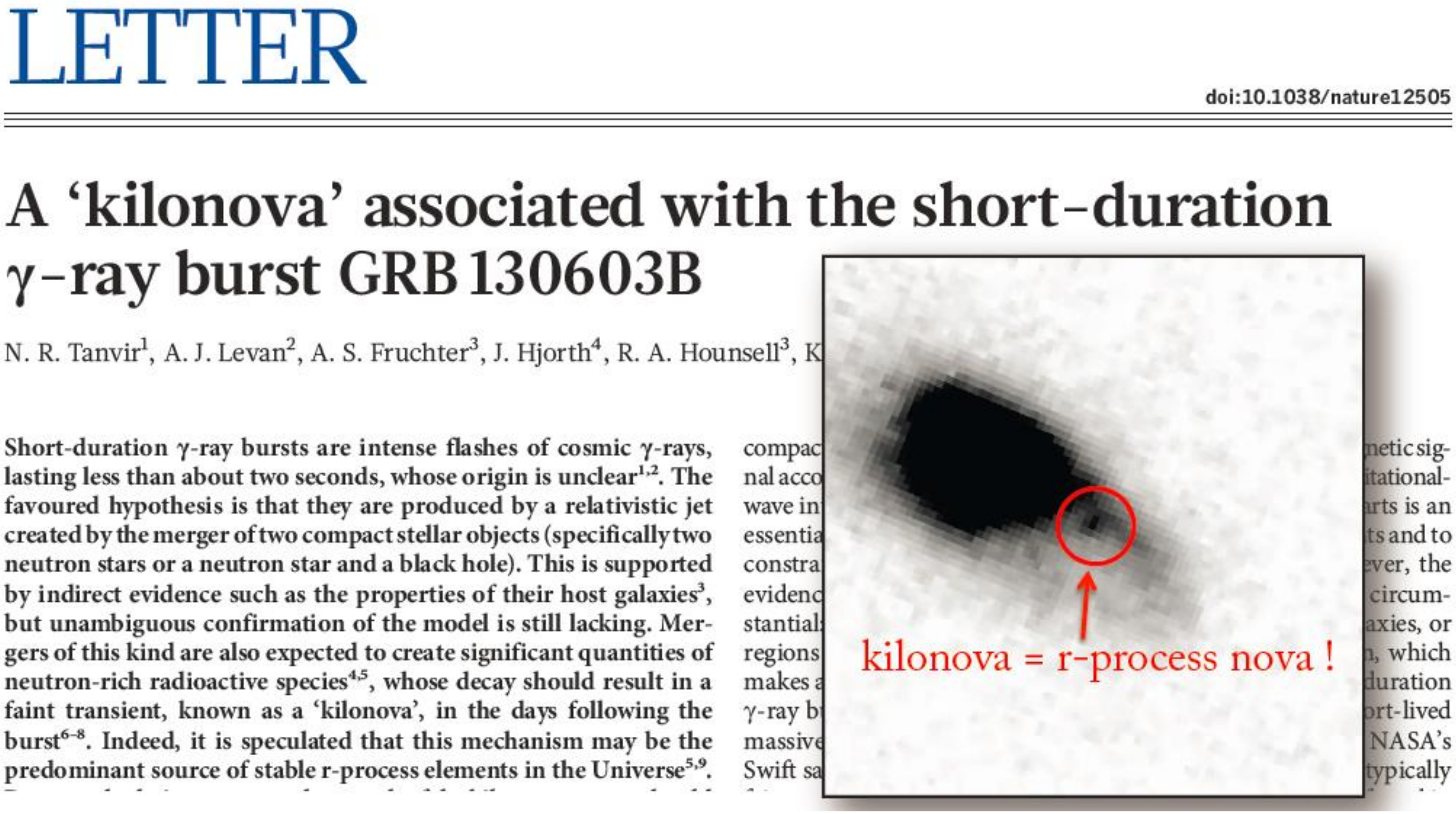


Further observational evidence ?
Kilo-nova/Macro-nova/r-process-nova

- **EM transients possibly powered by radioactivity of the r-process elements were expected (Li & Paczynski 1998) and found (important GW counterpart)**



LETTER

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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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kilonova = r-process nova !