Dynamical mass ejection from binary compact-star mergers

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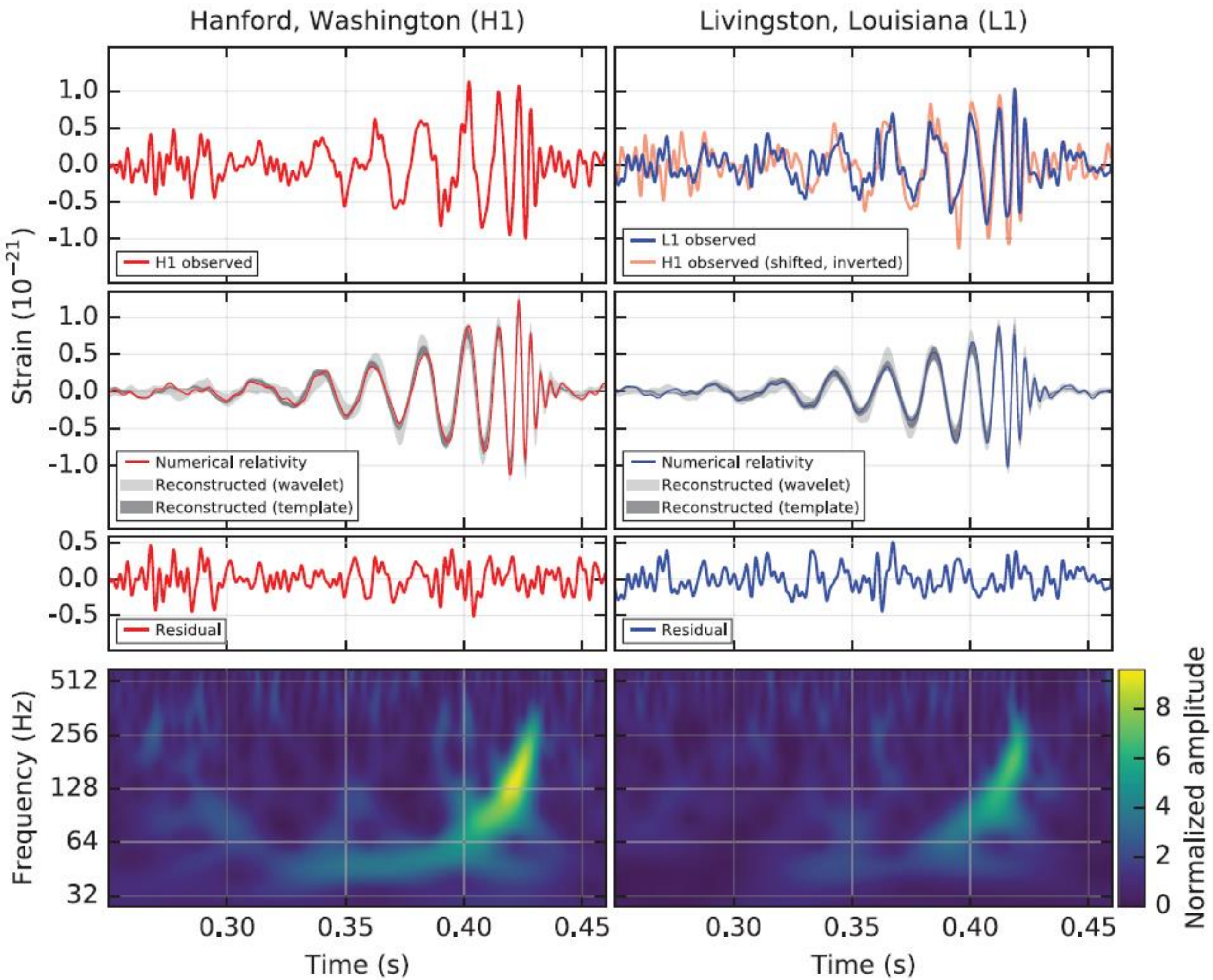
with K. Kiuchi, K. Kyutoku, M. Shibata, S. Wanajo, N. Nishimura, and K. Taniguchi

Toward GW astronomy



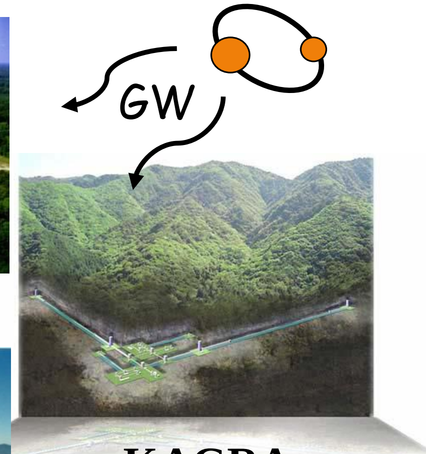
Abbott et al. 2016

Introduction

Toward GW detection and GW astronomy

Advanced LIGO

Advanced Virgo



KAGRA

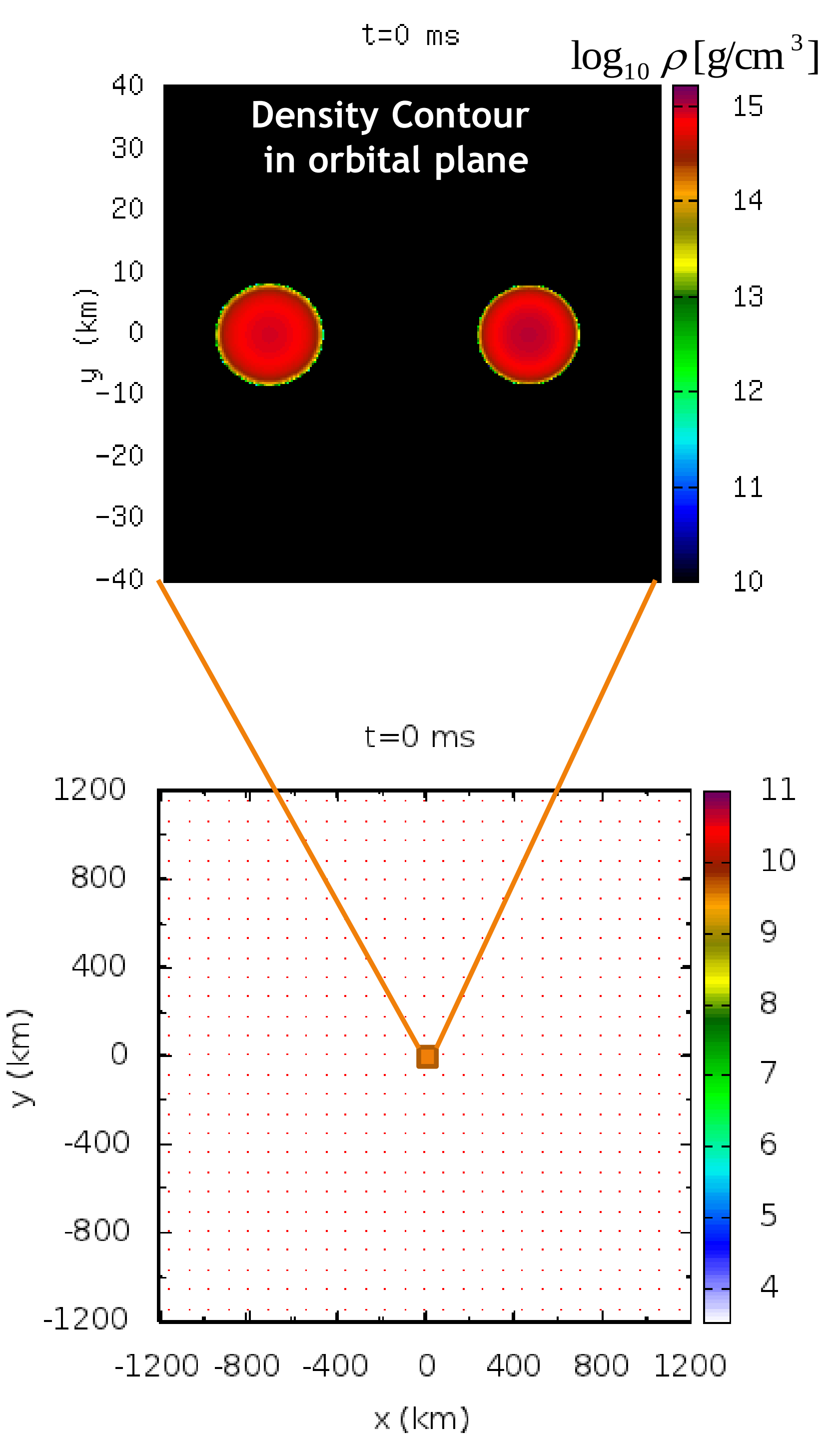
One of the most promising source
merger of compact-star binary with NS

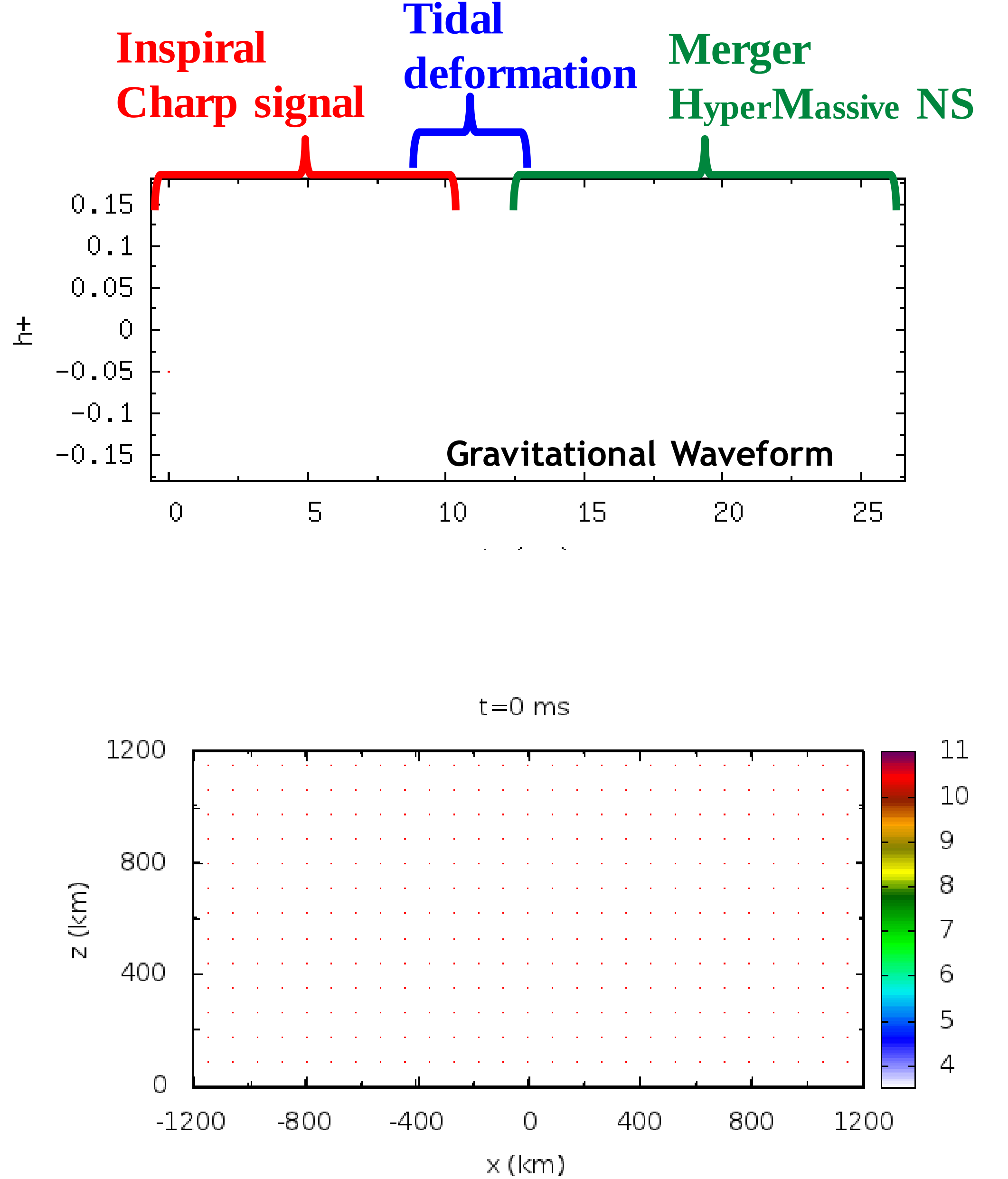
- Expected event rate ~ a few ×10 / yr
- Matched filter : huge parameter space
  - Location, time, distance, etc.
- Identification of EM counterpart
  - Reducing parameter space (effectively S/N↑)
- First detection may be near the threshold
  - Multi-messenger confirmation

- **Complementary information for GW astronomy**
  - **Gravitational waves: physics of the binary system**
    - Mass, radius, orbit, NS EoS, BH formation
  - **EM detection: Astrophysical environment**
    - Redshift, host galaxy, NS EoS

- Dynamical mass ejection from NS-NS
  - Main topic

- Dynamical mass ejection from **BH**-NS
  - Discuss briefly later



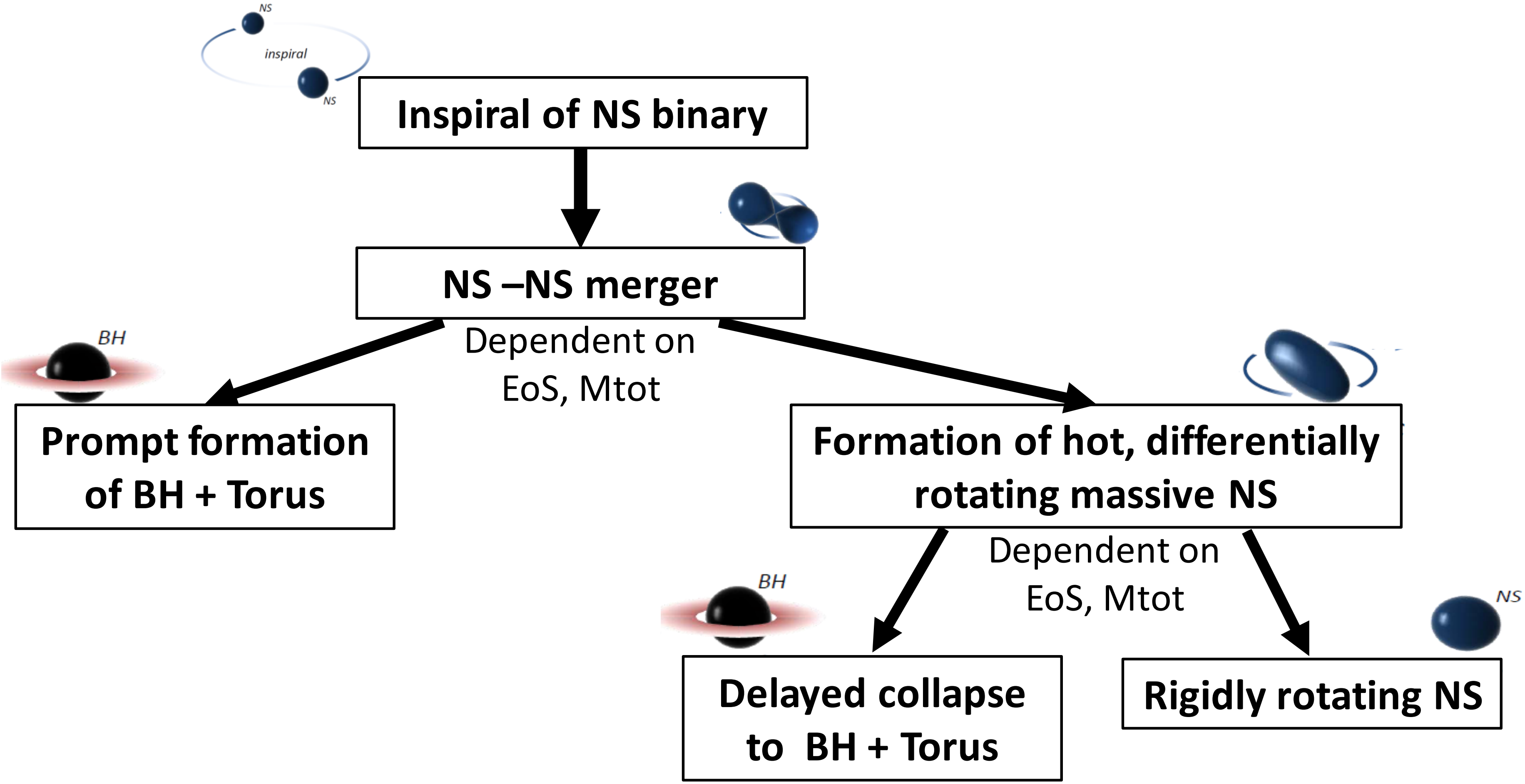


Animation by Hotokezaka

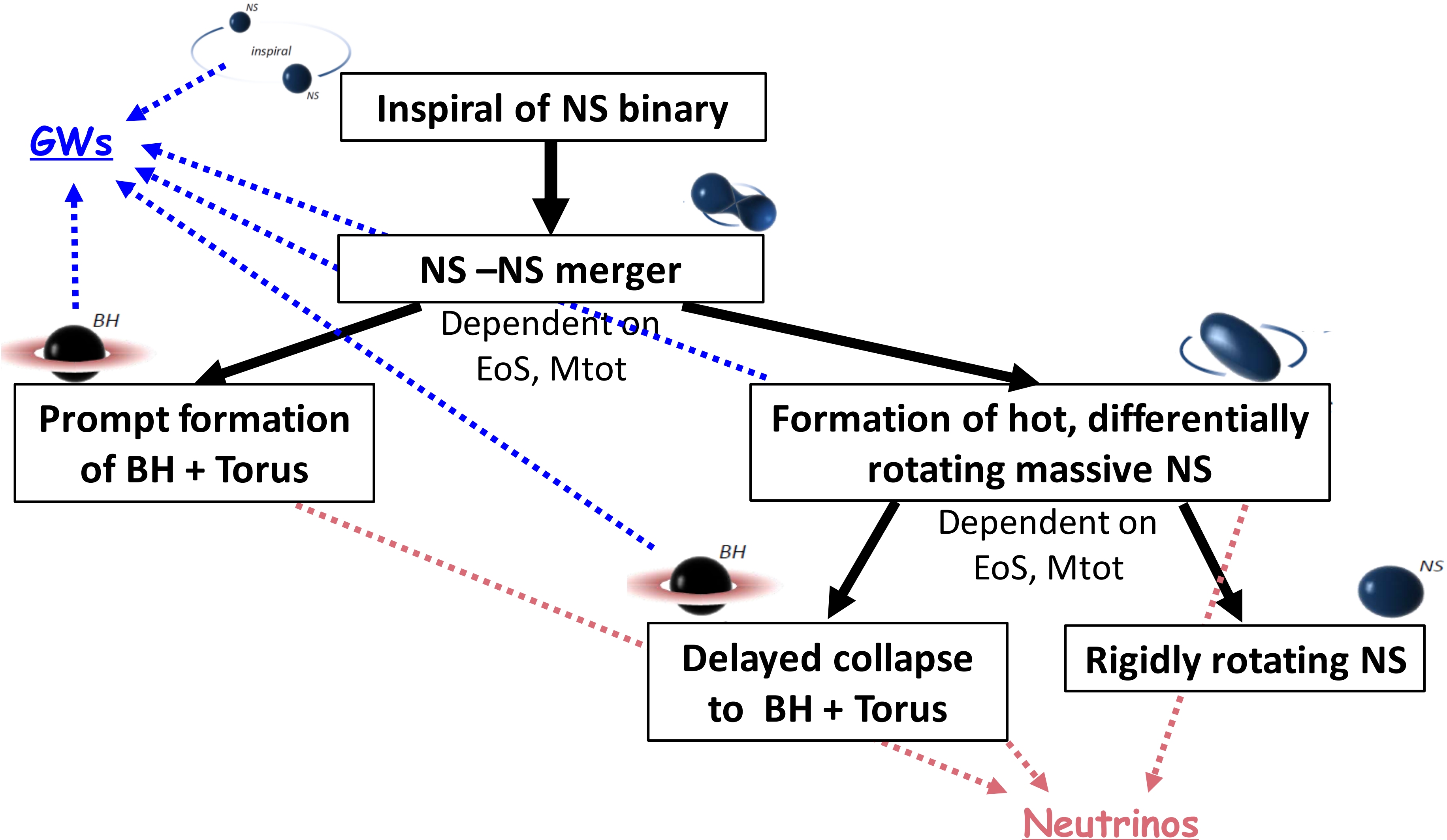
Sekiguchi et al. PRL (2011a, 2011b)
Kiuchi et al. PRL (2010); Hotokezaka et al. (2013)

Shibata et al. 2005,2006
Sekiguchi et al, 2011
Hotokezaka et al. 2013

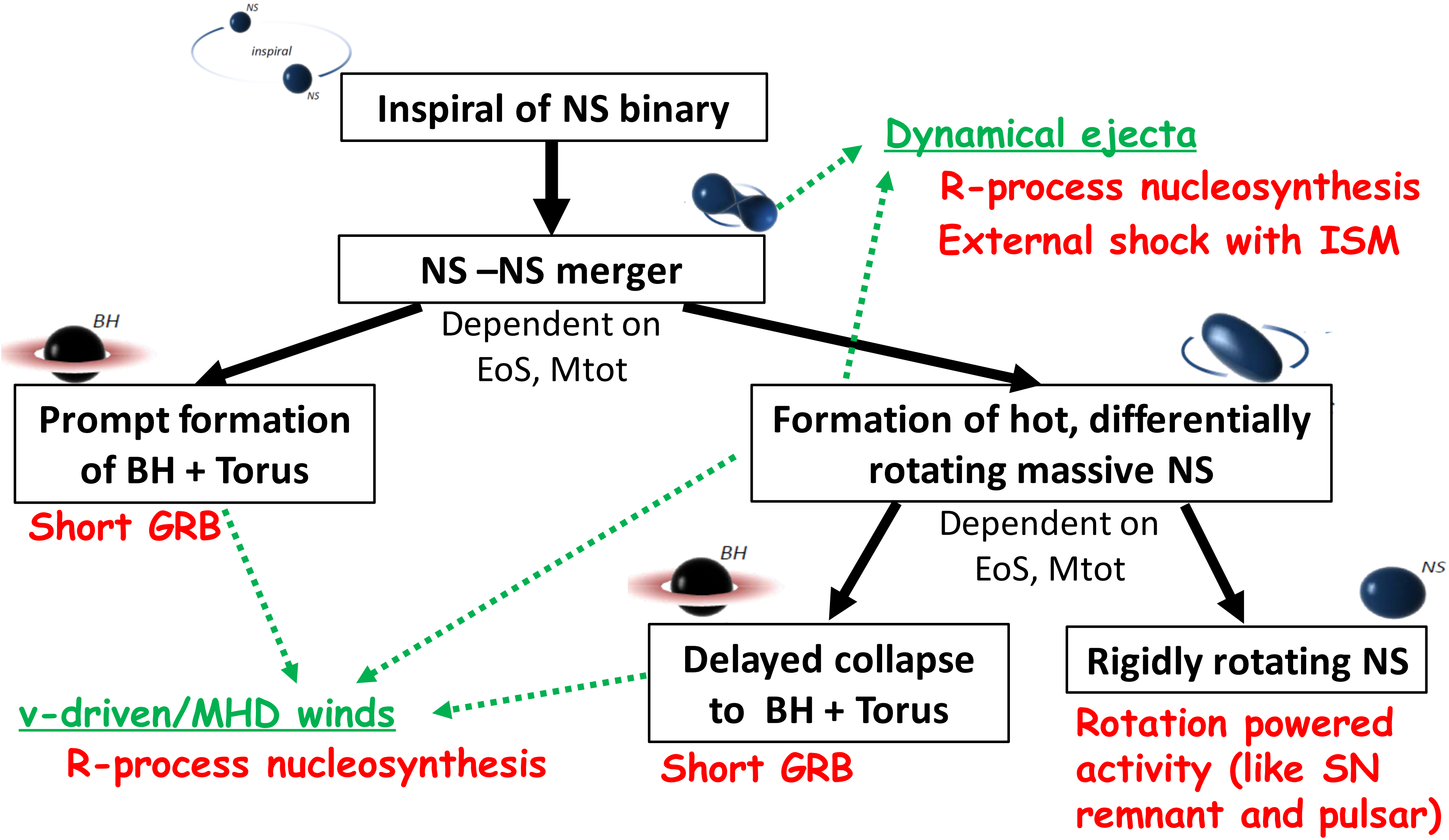
Evolution of NS-NS mergers



Messengers of NS-NS mergers



Messengers of NS-NS mergers



Possible EM counterparts : Similarities to SNe

- **Supernovae**
  - **Long GRBs**
    - Prompt (γ), afterglow (X to Radio)
  - **Supernova remnants**
    - Synchrotron: Ejecta-ISM interaction
    - Activities Powered by Pulsar
  - **Radioactive decay of ^{56}Ni**
    - produced in the explosive ejecta
    - Optical
  - **Classification by spectra**
  - **Shock breakout**
    - UV ~ X. (e.g. Tominaga+ 2009)

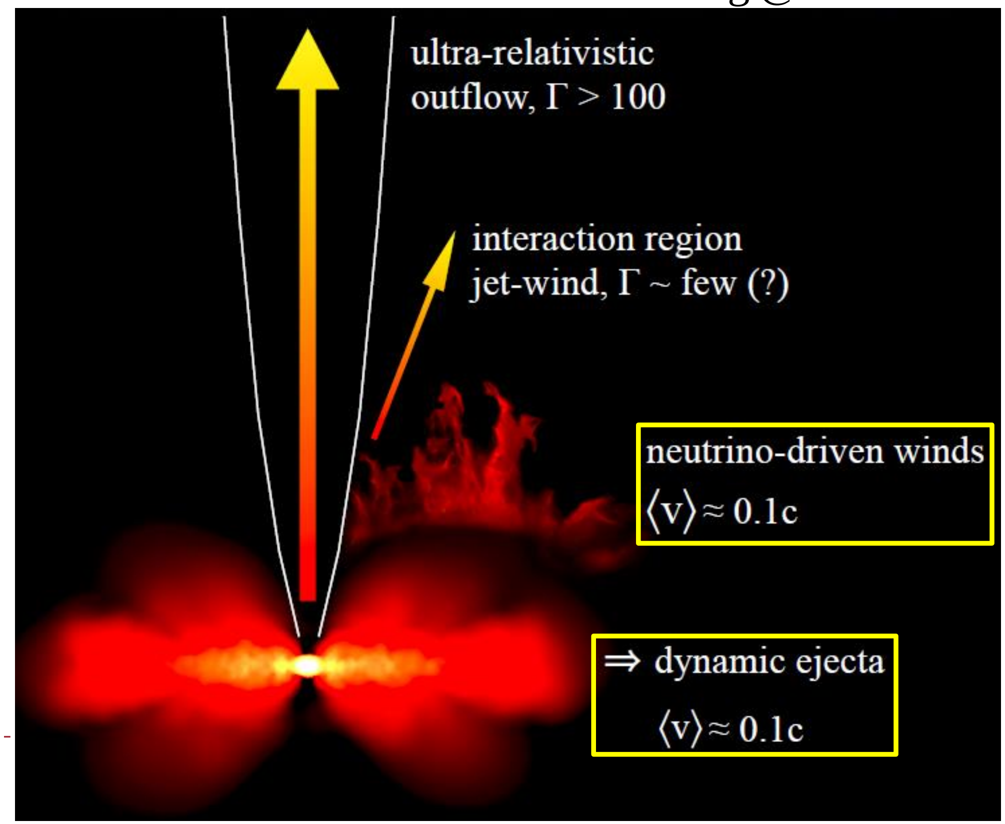
- **Merger of NS-NS, BH-NS**
  - **Short GRBs**
    - Prompt (γ), afterglow (X to radio)
  - **Merger remnants**
    - Radio Flare: Ejecta-ISM interaction
    - Powered by Massive NS ? (Zhang 2013)
  - **Decay of r-process elements**
    - Proceeds in the n-rich ejecta
    - Opticall-IR : Macronova
  - **Classification by spectra ???**
  - **Merger Shock breakout**
    - X-ray : Kyutoku et al. (2012)

See also Metzger & Berger (2012)

SGRB and Quest for 4π emission

- Jets of short GRBs may be collimated in general
- Jet opening angle estimated from the jet break
  - SGRB111020A : $\theta_j \sim$ 3-8° (Fong et al. 2012)
  - SGRB051121A : $\theta_j \sim$ 7° (Burrows et al. 2006)
  - Most of GRB Jets are expected to be Off-Axis ⇒ **very faint**
  - There will be GW-events without SGRB counterparts
- We need 4π emission events
  - Associated with 4π ejecta
    - **Dynamical ejecta**
    - **neutrino-driven/MHD winds**
    - **Late-time disk dissolution**
      - Fernandez & Metzger 2013

Rosswog @ YKIS2013



Radio flare from Ejecta-ISM interaction

- External shock with inter stellar matter (ISM) : a 4π emission
- Synchrotron radiation becomes most luminous when ejecta mass = swept-up ISM mass: for typical values (Nakar & Piran 2011)

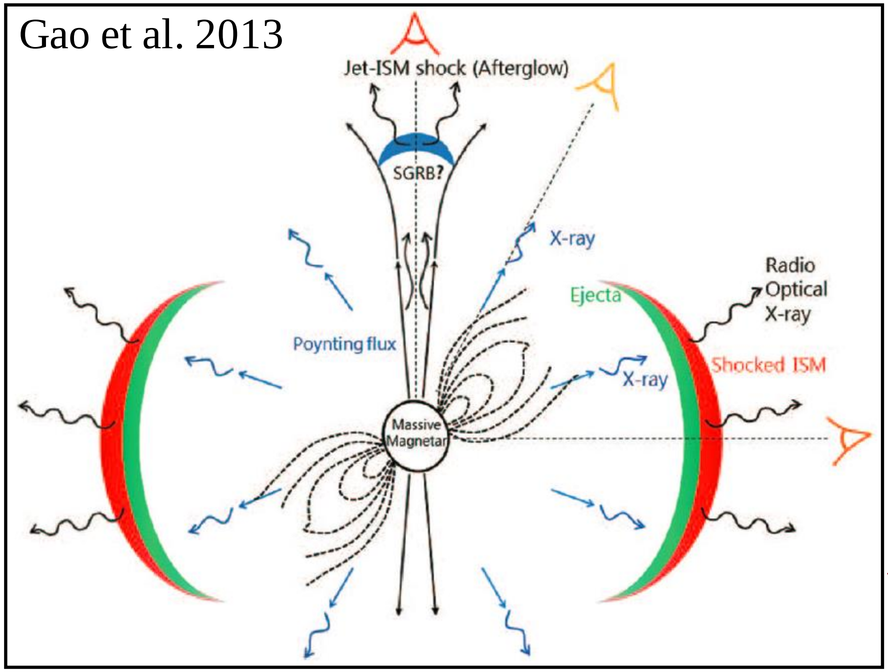
$$t_{\rm peak} \sim 4\ {\rm yrs} \left(\frac{E_{\rm ejecta}}{10^{50}\,{\rm ergs}}\right)^{1/3} \left(\frac{n_{\rm ISM}}{1\,{\rm cm}^{-3}}\right)^{-1/3} \left(\frac{v_{\rm ejecta}}{0.2c}\right)^{-5/3}$$

$$F_\nu \sim 0.1\,{\rm mJy} \left(\frac{E_{\rm ejecta}}{10^{50}\,{\rm ergs}}\right) \left(\frac{n_{\rm ISM}}{1\,{\rm cm}^{-3}}\right)^{0.9} \left(\frac{v_{\rm ejecta}}{0.2c}\right)^{2.8} \left(\frac{D}{200\,{\rm Mpc}}\right)^{-2} \left(\frac{\nu_{\rm obs}}{1.4\,{\rm GHz}}\right)^{-0.75}$$

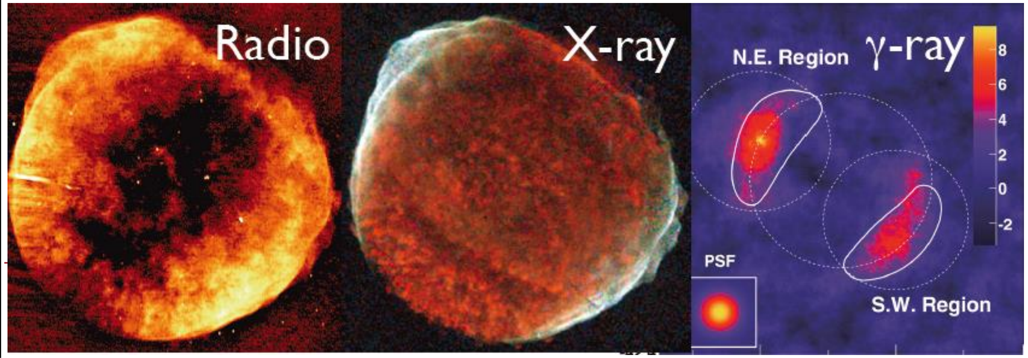
- ISM density may be much smaller : according to recent SGRB obs.
  - $\mathbf{n_{ISM} \sim 0.01\text{-}0.1\ cm^{-3}}$ for SGRB 111020A (Fong et al. 2012)
  - $\mathbf{n_{IMS} \sim 0.0001\text{-}1\ cm^{-3}}$ for SGRB 111117A (Margutti et al. 2012)
- Radio flare may be less bright and shine in a very late time : Not very suited as EM counterparts of GWs

Rotation powered activities ?

- If a **stable massive NS** is survived, additional EM emissions powered by NS-rotation may be expected (Metzger et al. 2011; Zhang 2013; Gao et al. 2013)
  - Compared to normal pulsars, rapid rotation (P~ms), strong B-fields (B~10^{15} G)
- **However, such additional emissions may be not very frequent :**
  - Nuclear theory : hard to make such a very stiff EoS with Mmax > 2.4Msolar
  - SGRB : if central engine of SGRB is BH + Disk, frequent formation of the massive NS may lead to too much mergers (only low mass NS merger ?)



- ~1/3 of SGBRs may have late-time activity
  - which could be originated in the massive SN
- Most of them are short duration < O(100s)
  - Collapse to a BH ?
  - shorter than the spin down timescale > 1000s



Macronova

- Merger ejecta will be very neutron rich: rapid neutron capture (r-process)

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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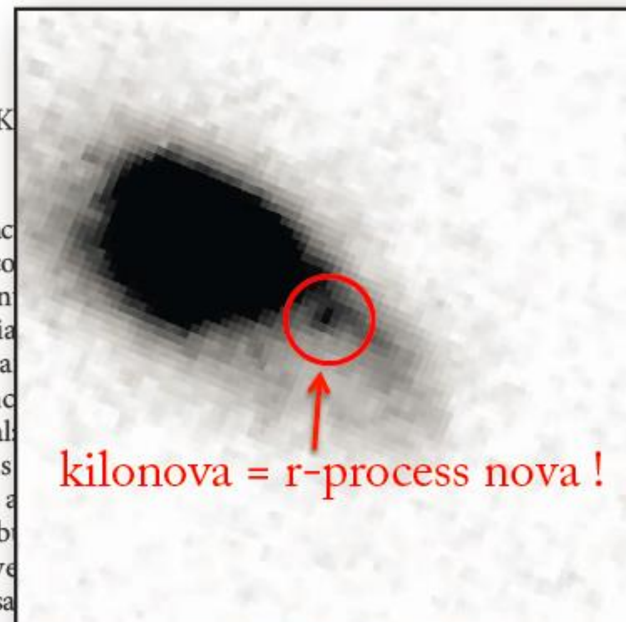

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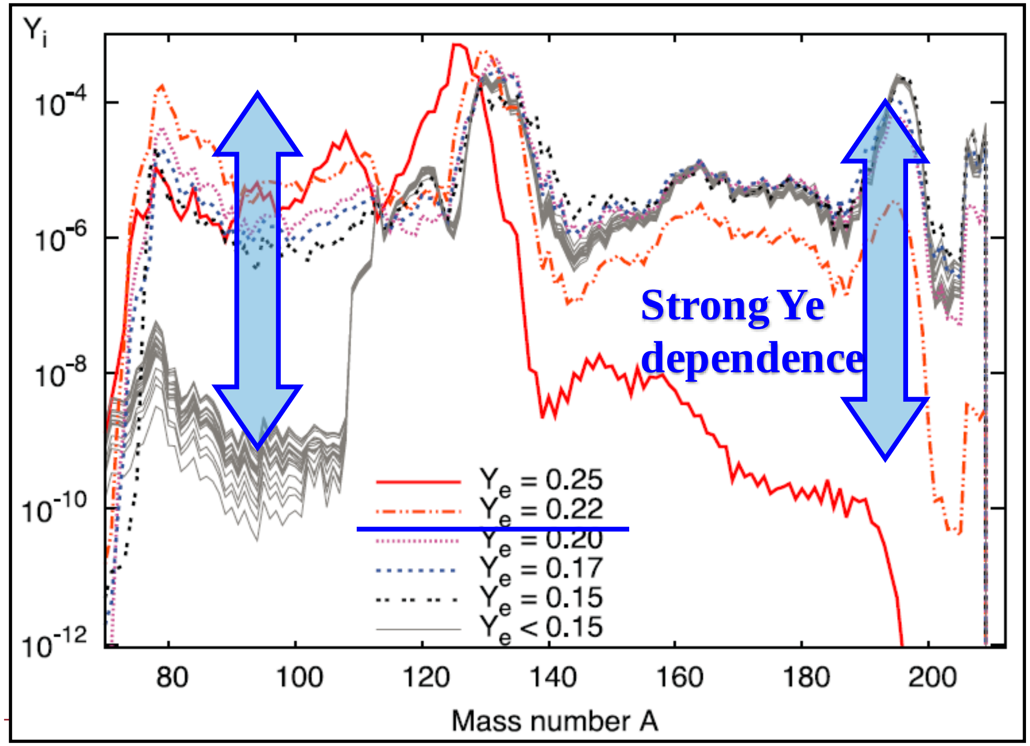
Importance of Ye in the r-process

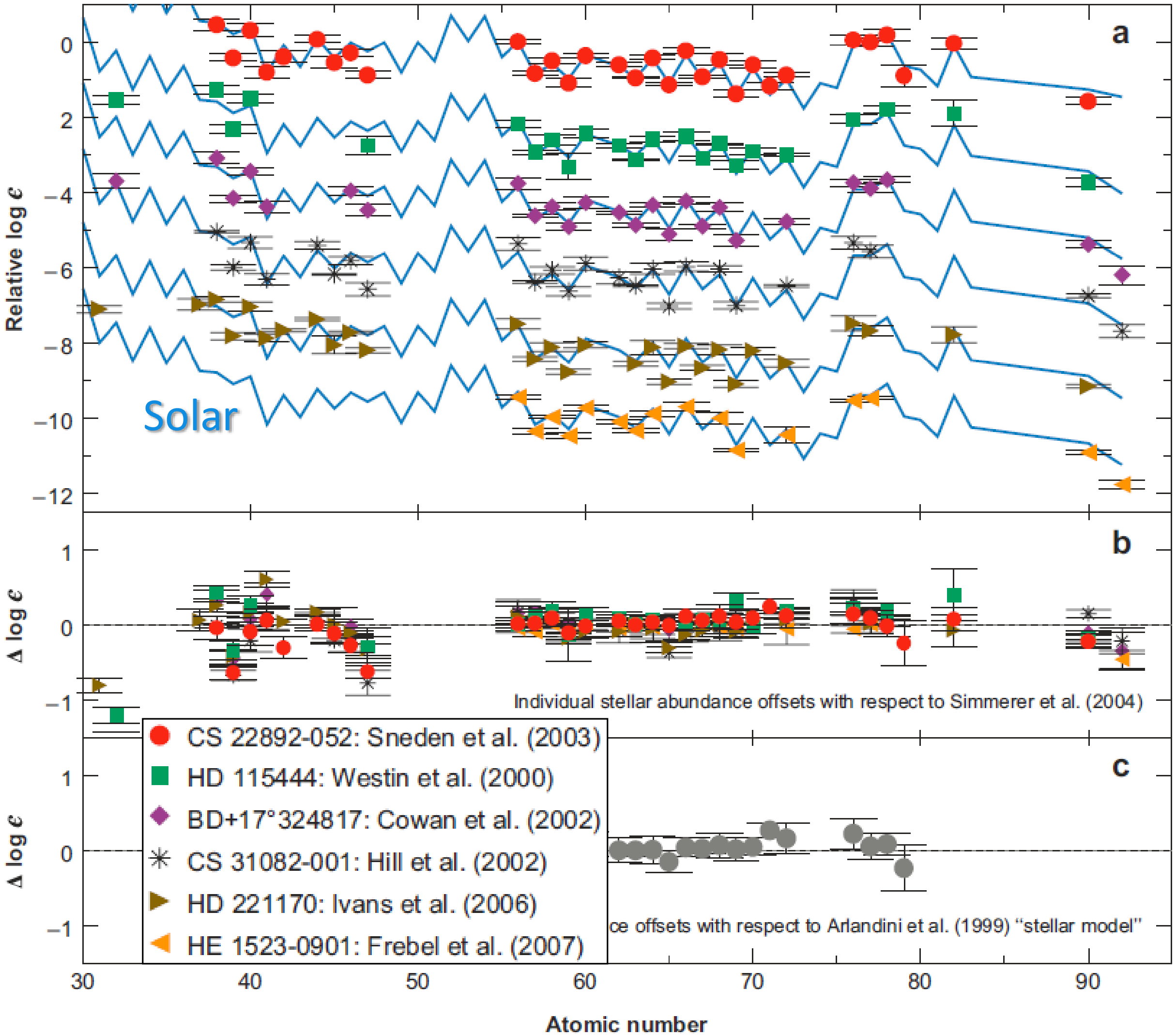
- **Electron fraction (Ye) is the key parameter : <u>Ye ~ 0.2-0.25 is critical threshold</u>**
  - Ye < 0.2-0.25 : strong r-process ⇒ nuclei with A>130
  - Ye > 0.2-0.25 : weak r-process ⇒ nuclei with A< 130
  - Different decay heat and opacity for them (Smaller κ for smaller A: Grossman et al. 2013 Kasen et al. 2015)
- **Neutrino-matter interaction**
  - **<u>Ye can be changed</u>**
  - Two reactions which increase Ye
  - Positron capture : $n + e^{+} \rightarrow p + \bar{\nu}_e$
    - **Important for higher temperature**
      ∵ there are more positrons
  - Neutrino capture : $n + \nu_e \rightarrow p + e^{-}$
    - Copious neutrinos are emitted
    - NS matter is neutron rich
    - Not considered in the previous studies (need neutrino transfer)



Korobkin et al. 2012

Key observations for r-process : Universality

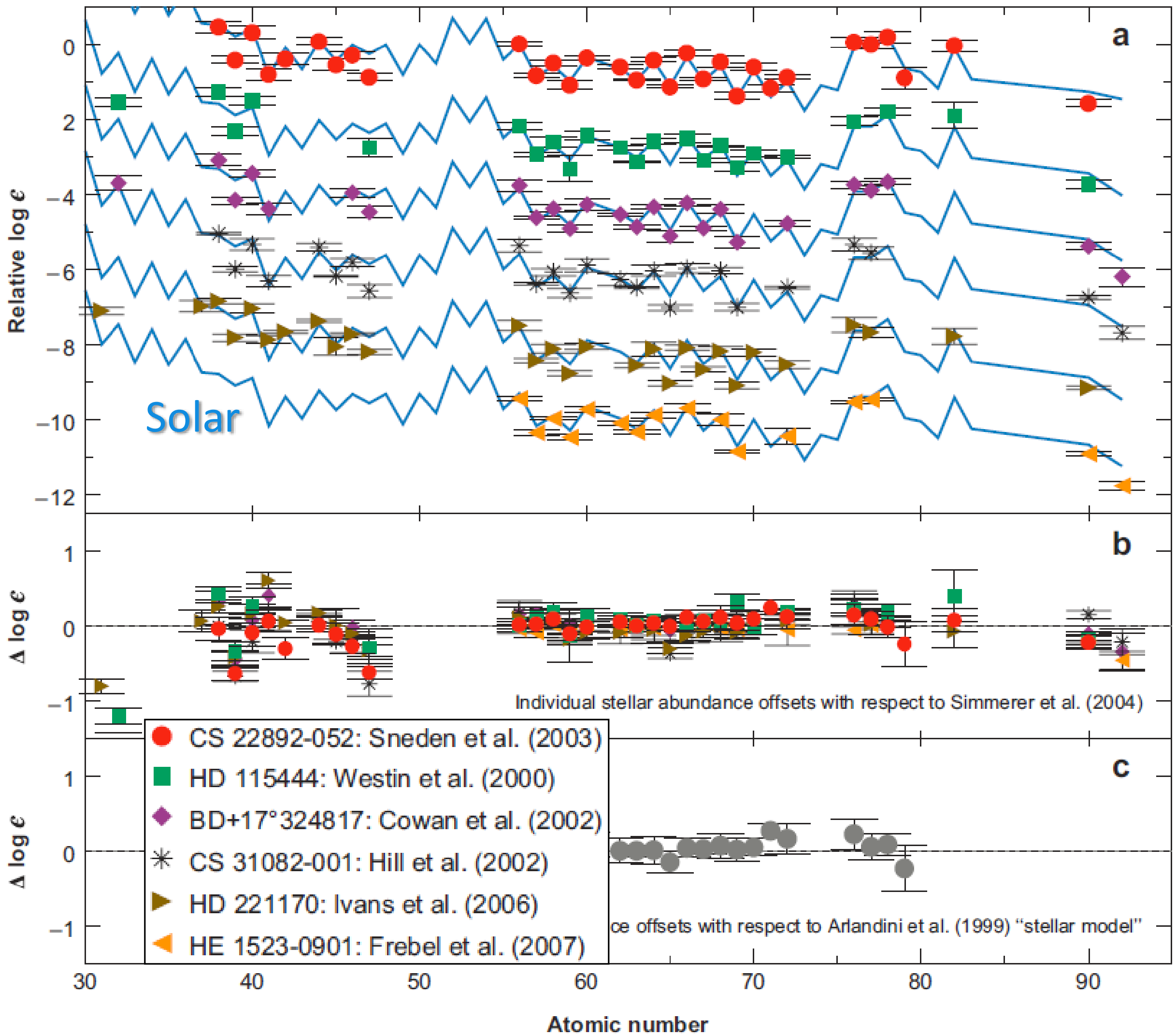
solar pattern = event by event r-process pattern



- 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 for r-process : Universality
solar pattern = event by event r-process pattern



- Sneden et al. (2008)

- The solar and chemical fossil r-process element patterns agree well
- suggests that <u>r-process event synthesize heavy elements with a pattern similar to solar pattern (Univsersality)</u>
- Low metallicity !!
- Universality should be achieved before chemical enrichment
  - Should not rely on many events
  - **Single event has to satisfy the universality**

Dynamical mass ejection from NS-NS

With 'Universality' point of view :

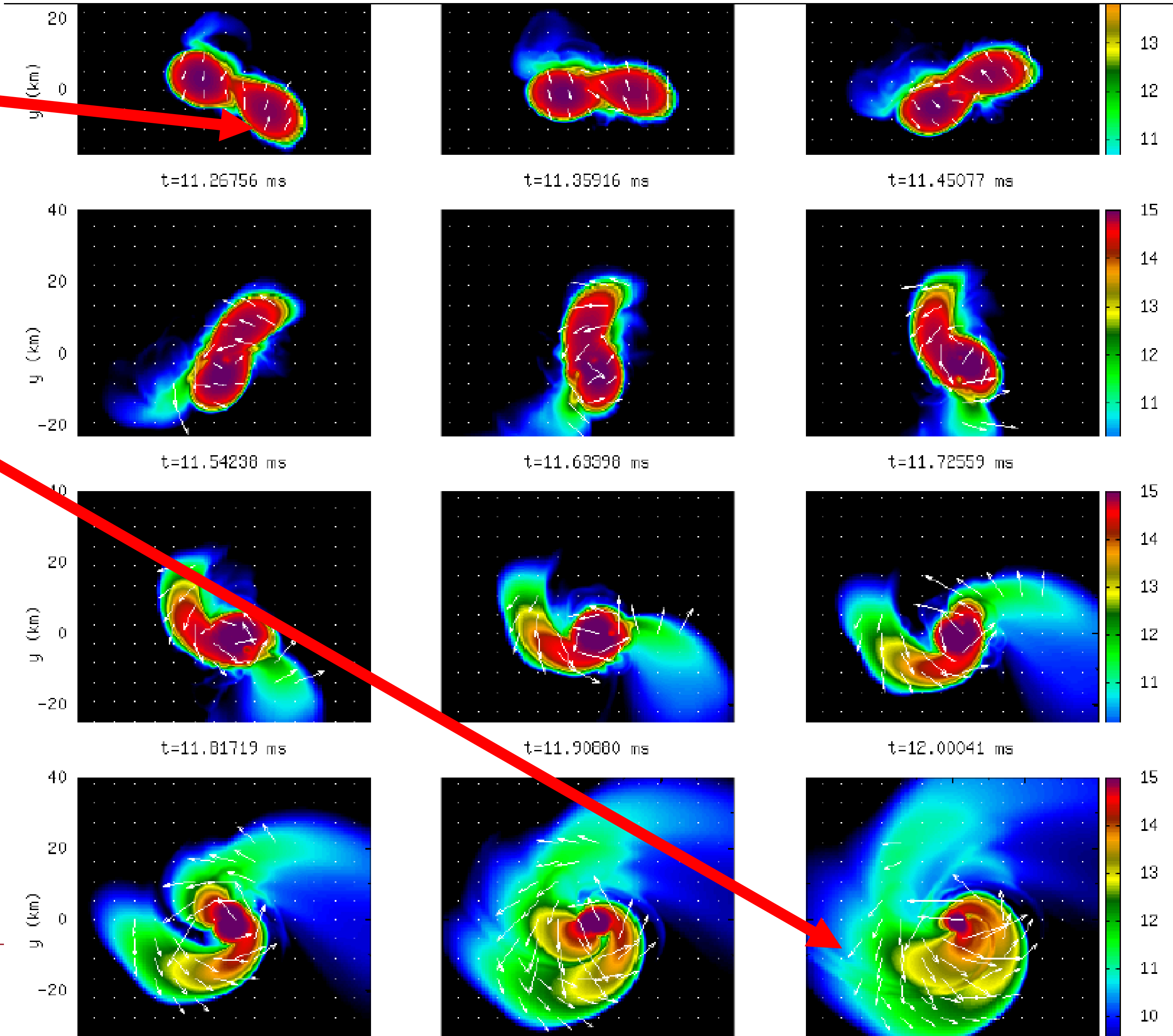
NS-NS merger ejecta: too neutron-rich ?

- 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

Hotokezaka et al. (2013)

- 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~0), no shock heating, rapid expansion (fast T drop), no time to change Ye by weak interactions

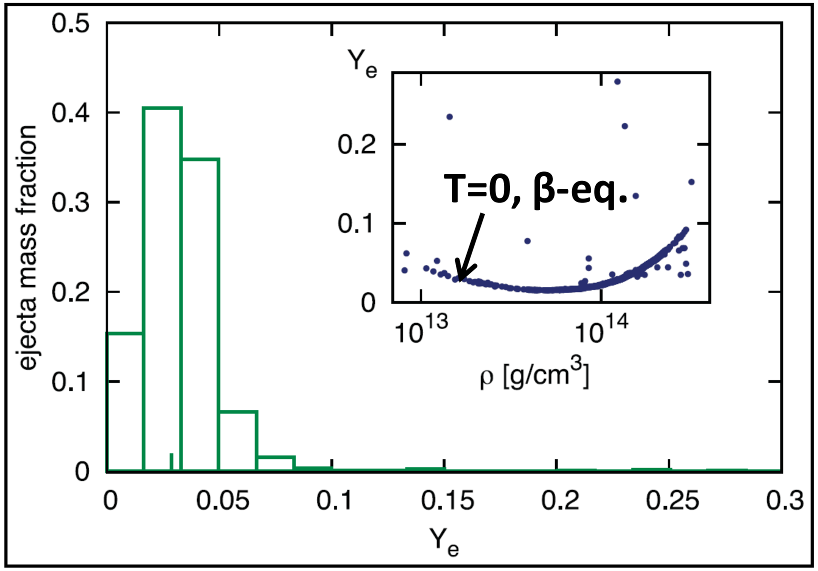


Density contour
[log (g/cm³)]

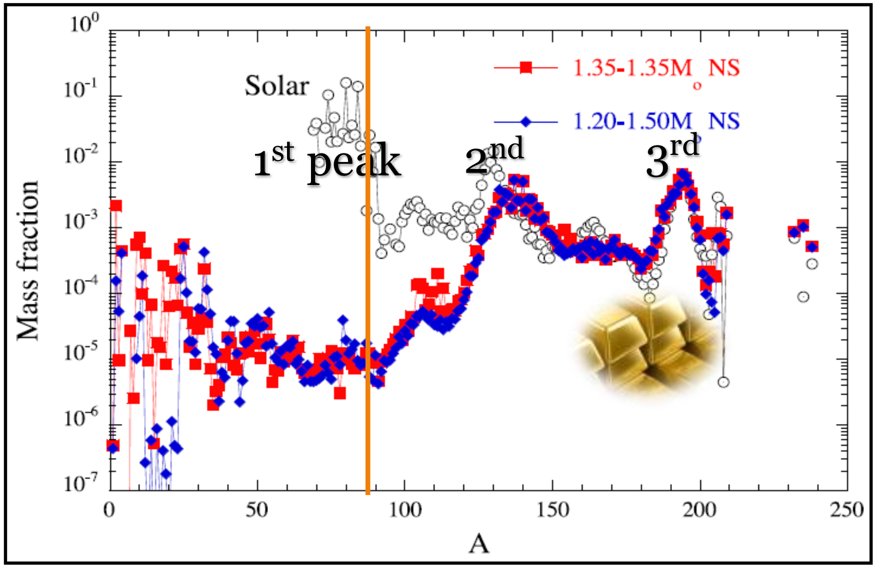
With 'Universality' point of view :

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



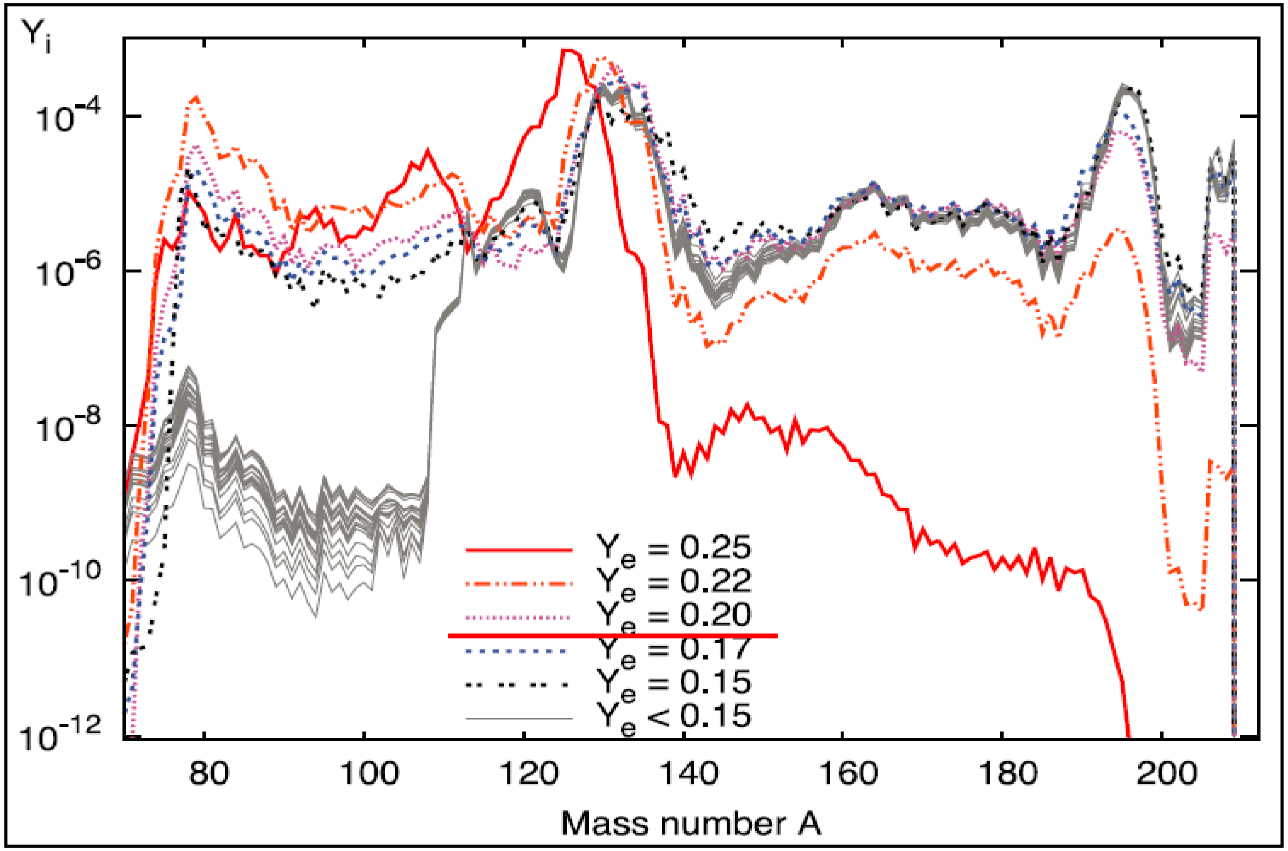
Korobkin et al. (2012) MNRAS 426 1940



Goriely et al. (2011) ApJL 738 32

How to satisfy the universality

- **Electron fraction (Ye) is a key parameter : <u>Ye ~ 0.2 is critical threshold</u>**
  - 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

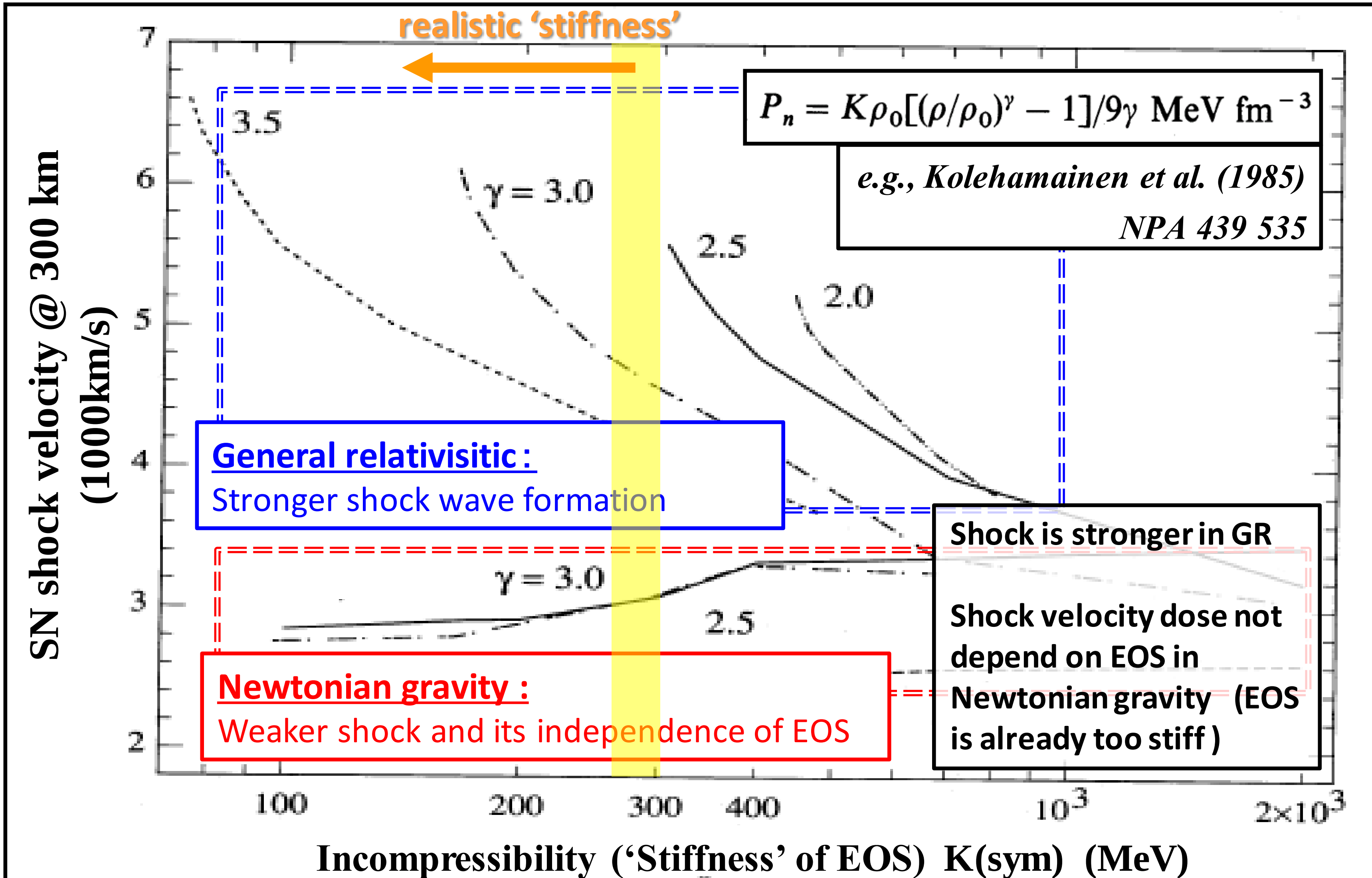
- Korobkin et al. 2012

How to satisfy the universality

- Introduce new ejecta components
  - Neutrino driven winds from the remnant system
    - 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
- Take into account effects of both GR and weak interaction in the dynamical ejecta (this talk)

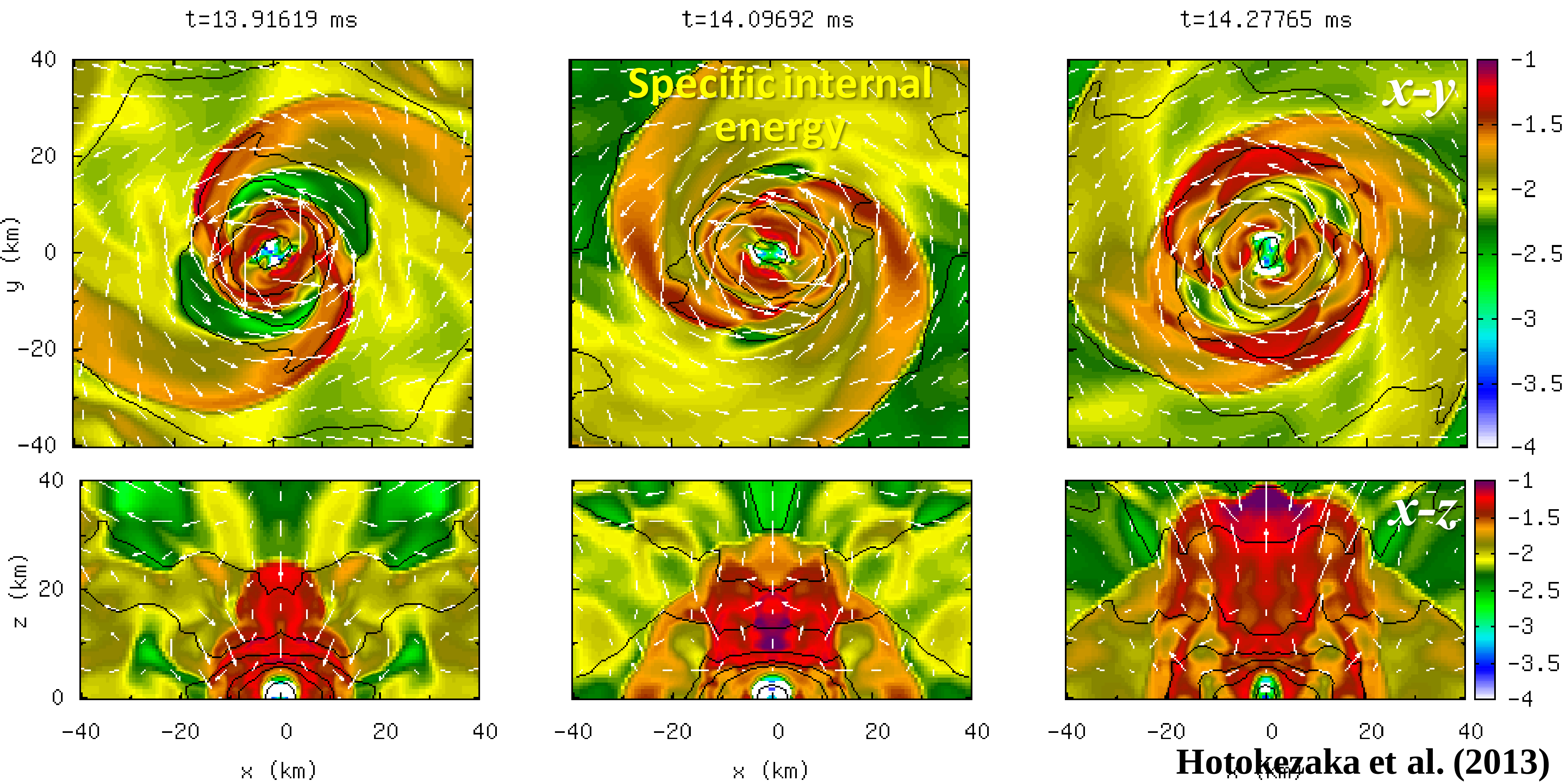
What will change if you include GR and microphysics (1) : Stronger shock in GR

van Riper (1988) ApJ 326 235



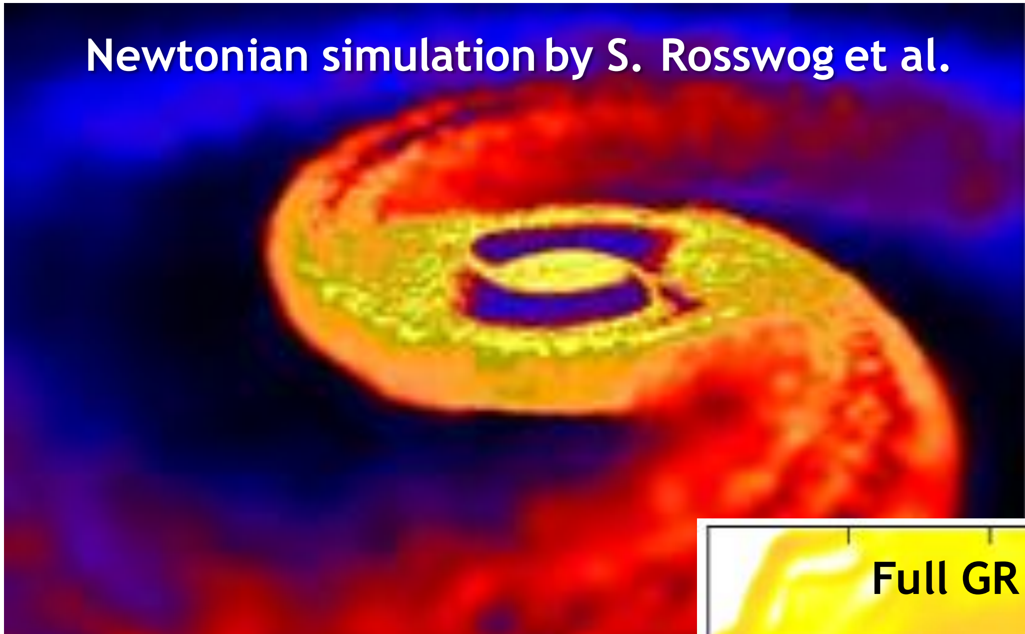
Mass ejection from BNS merger (2): Shock driven components

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

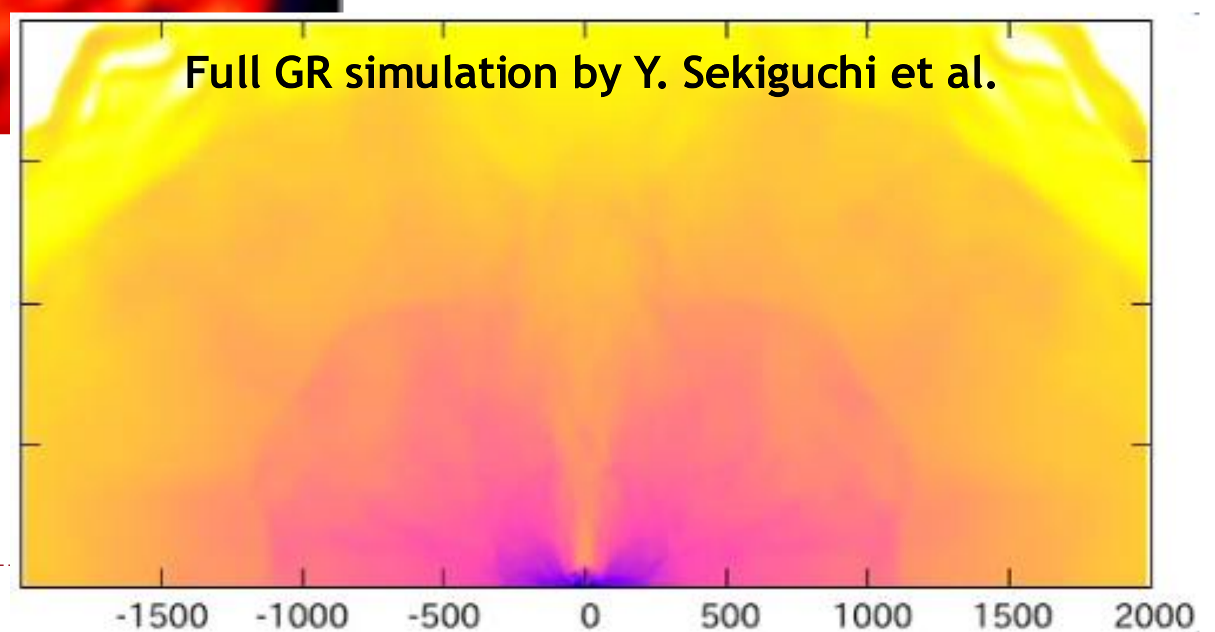


Hotokezaka et al. (2013)

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



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



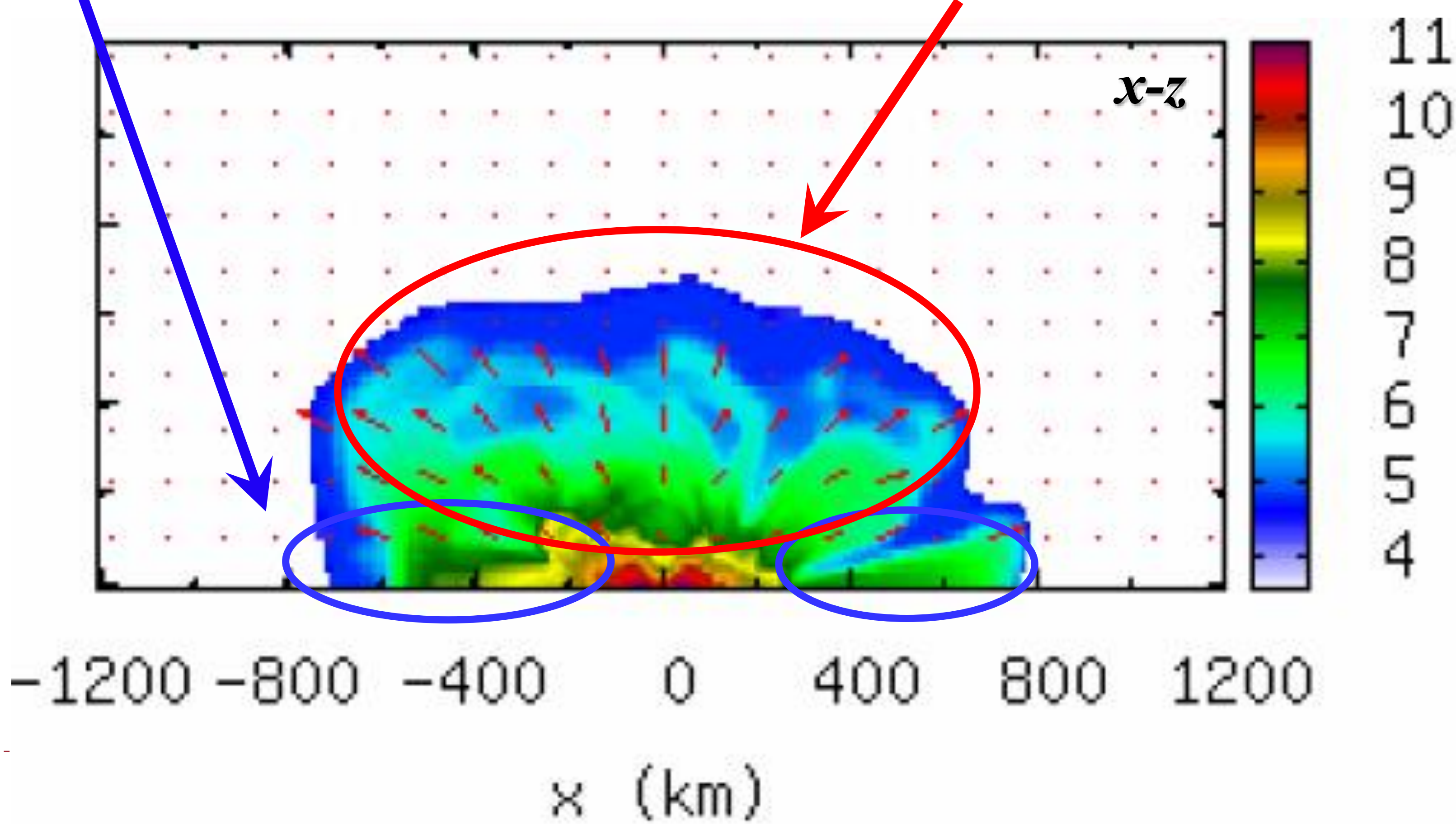
What will change if you include GR and microphysics (2) :
Ye can change via weak interaction

- **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

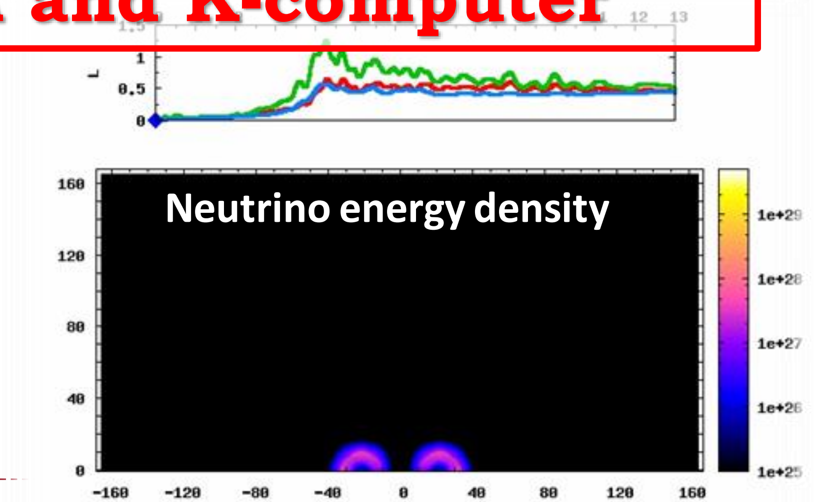


Previous studies and our study

- **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 M1 closure

BNS merger simulations with multiple EOS, different mass ratio, and switch-on and –off neutrino interactions become accessible thanks to XC30 in CfCA and K-computer

- 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

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

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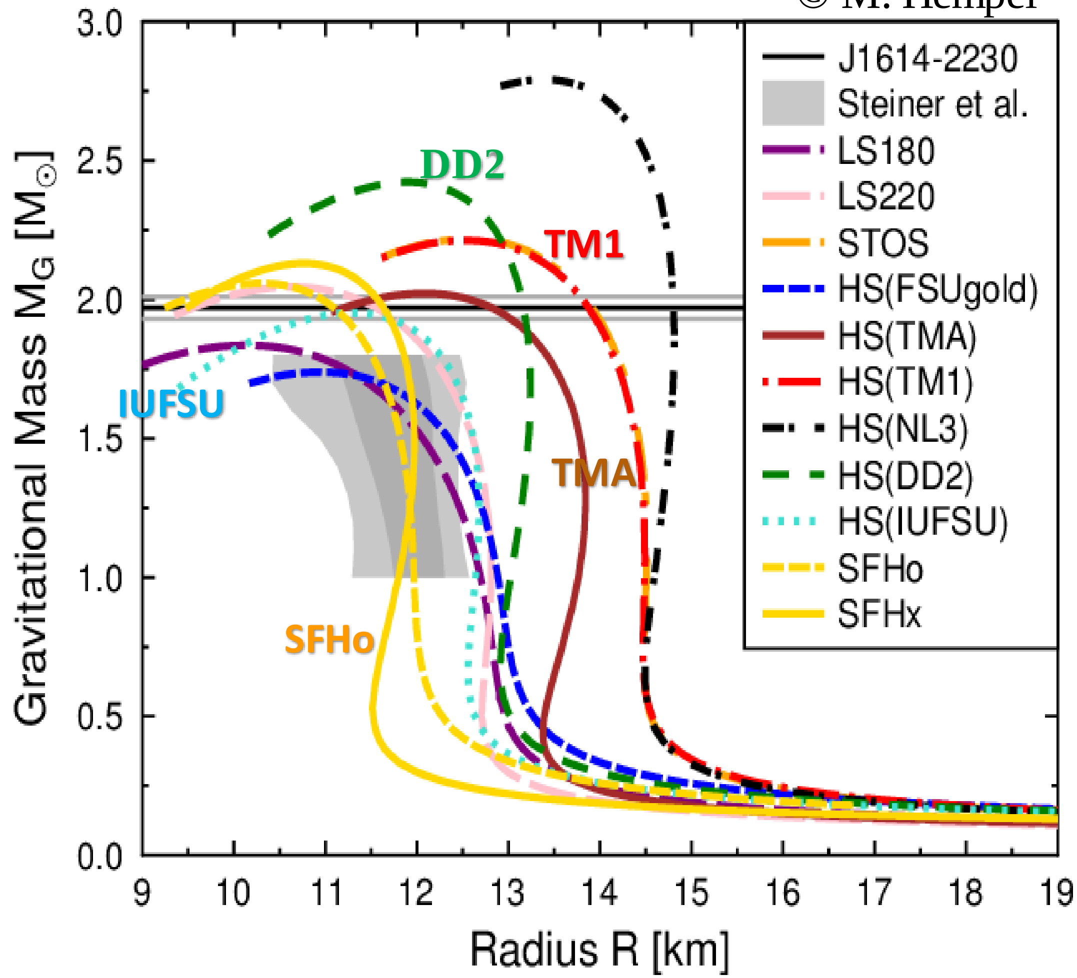
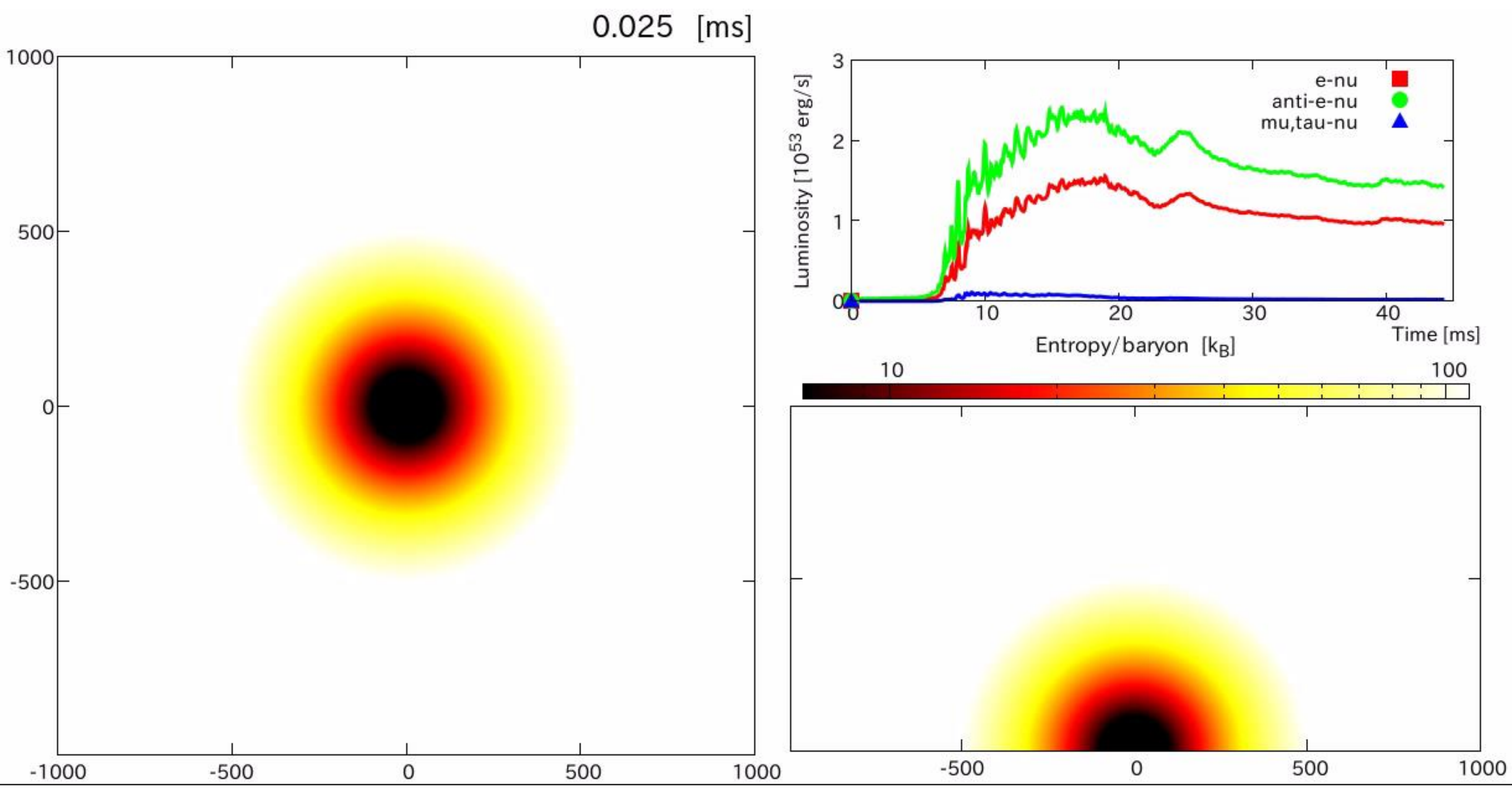
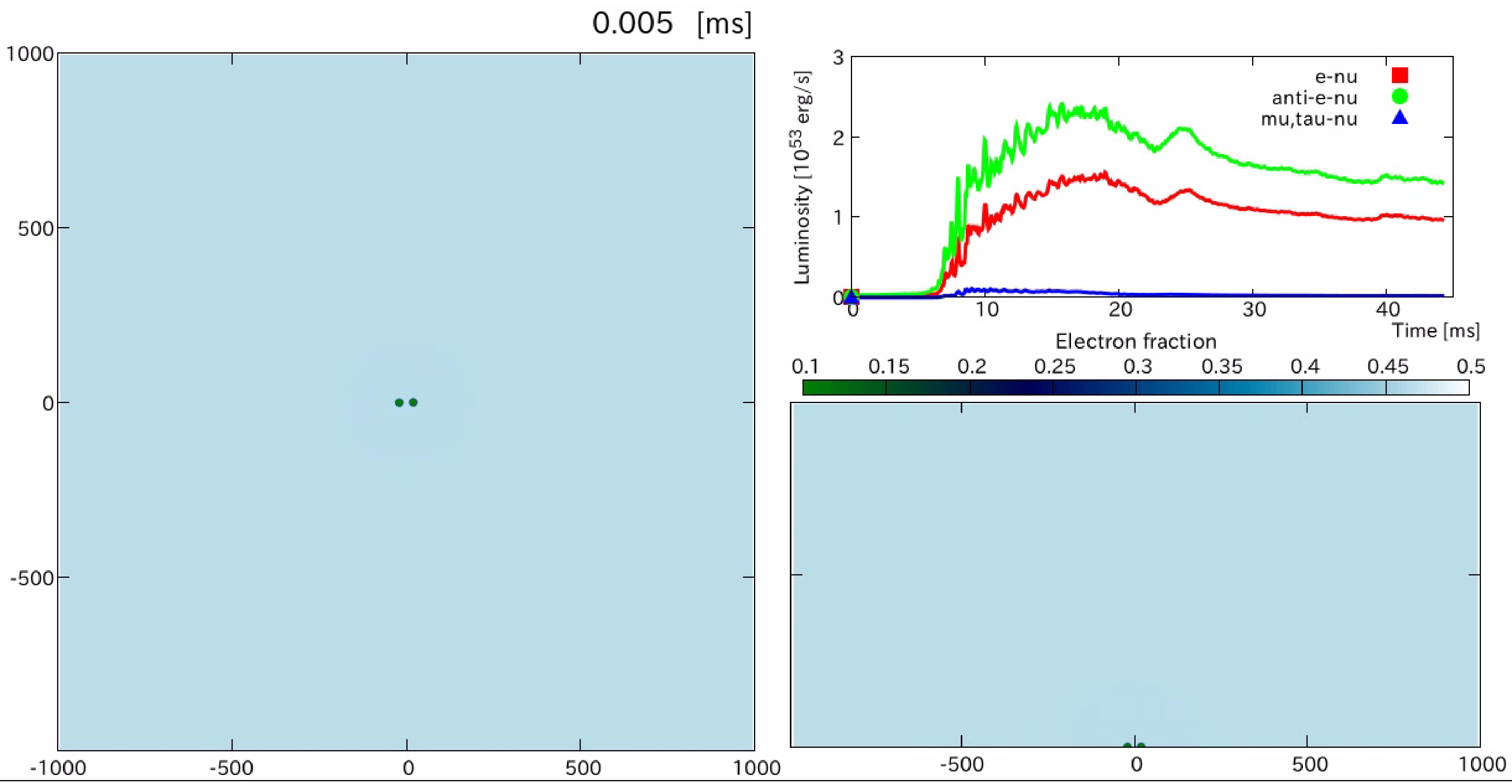


See also, Bauswein et al. (2013); Just et al. (2014)

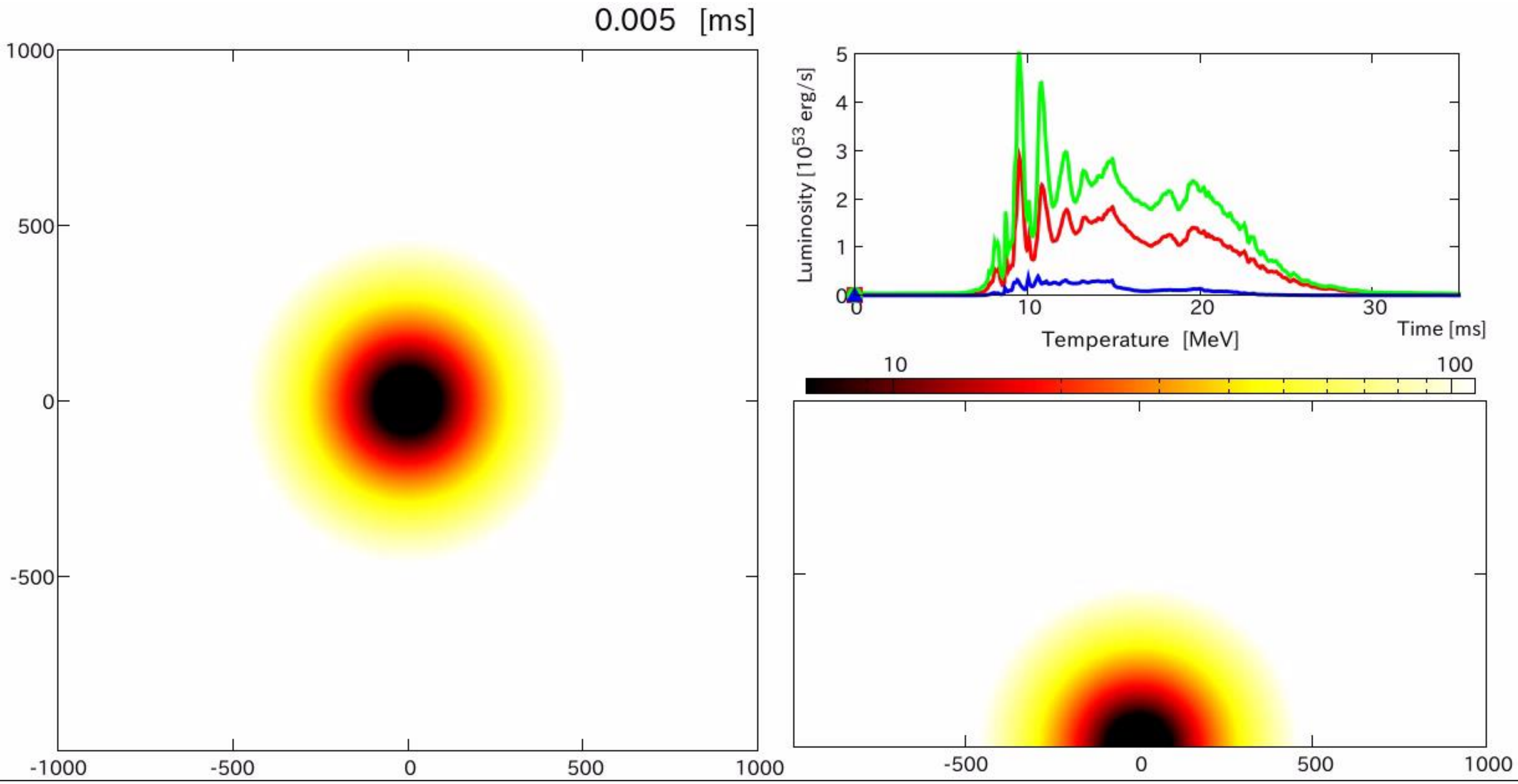
Entropy per baryon : DD2
relatively **stiff**, tidal component dominated



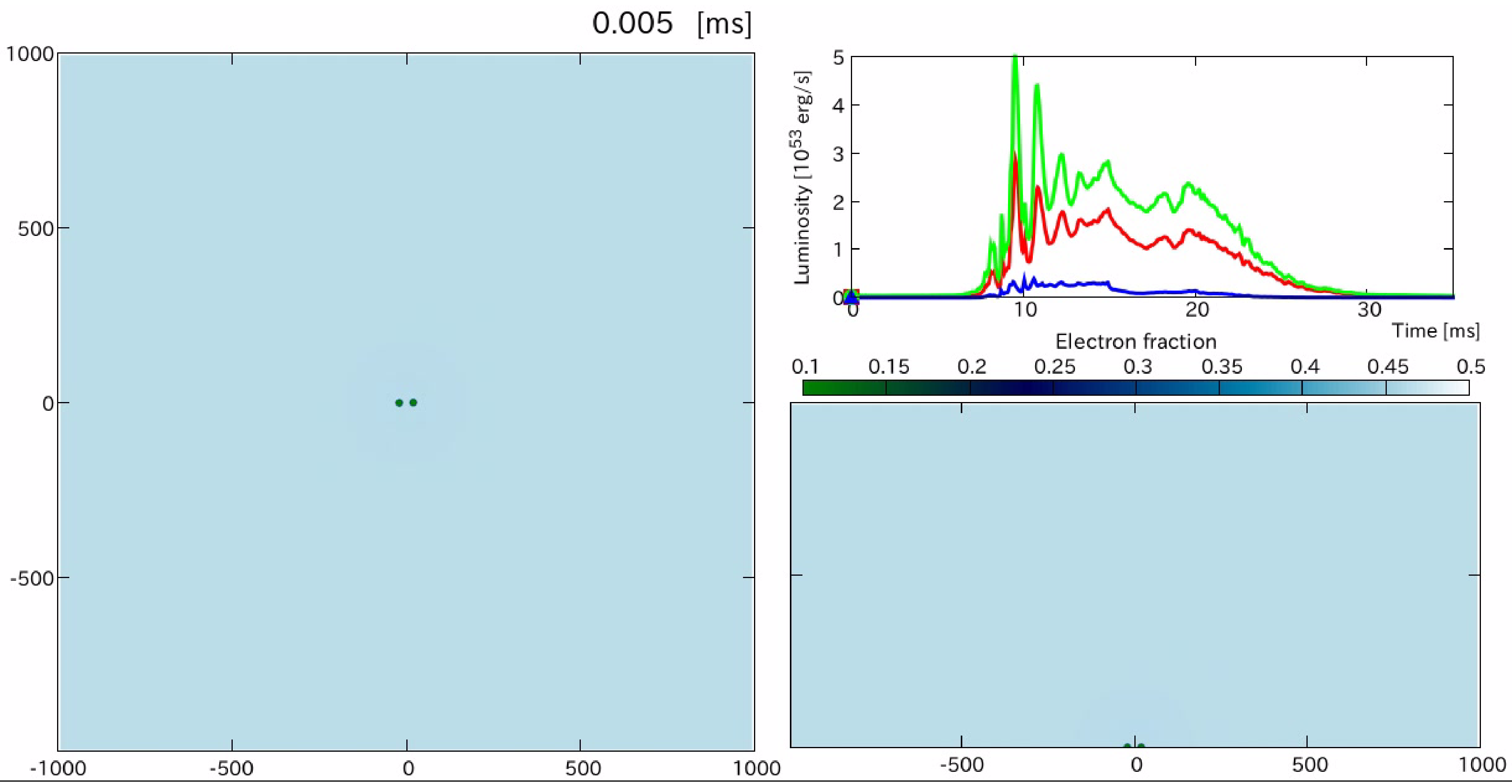
Ye : DD2
relatively **stiff**, tidal component dominated



Entropy per baryon : SFHo
relatively **soft**, multiple shock components

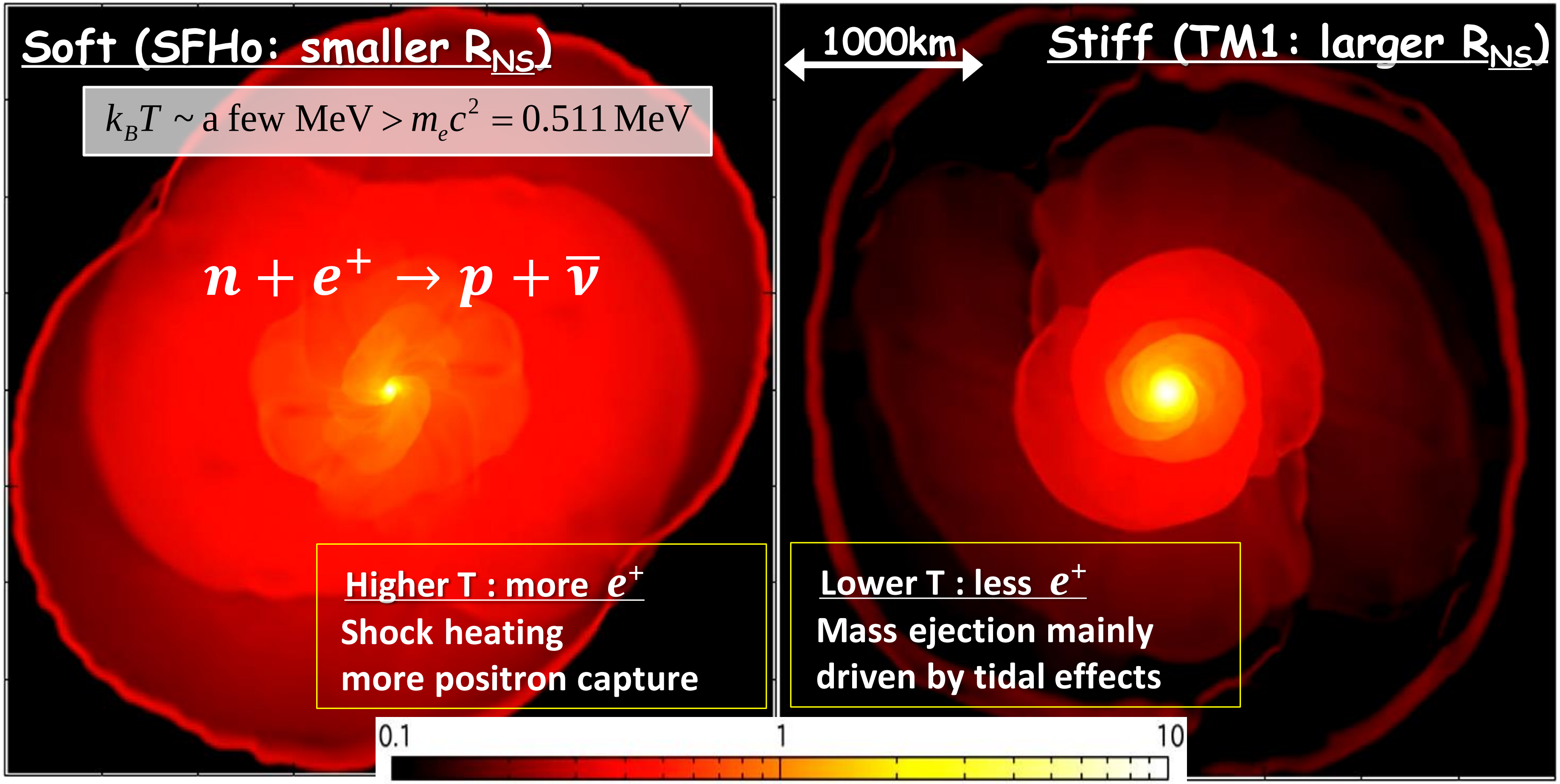


Ye : SFHo
relatively **soft**, multiple shock components



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

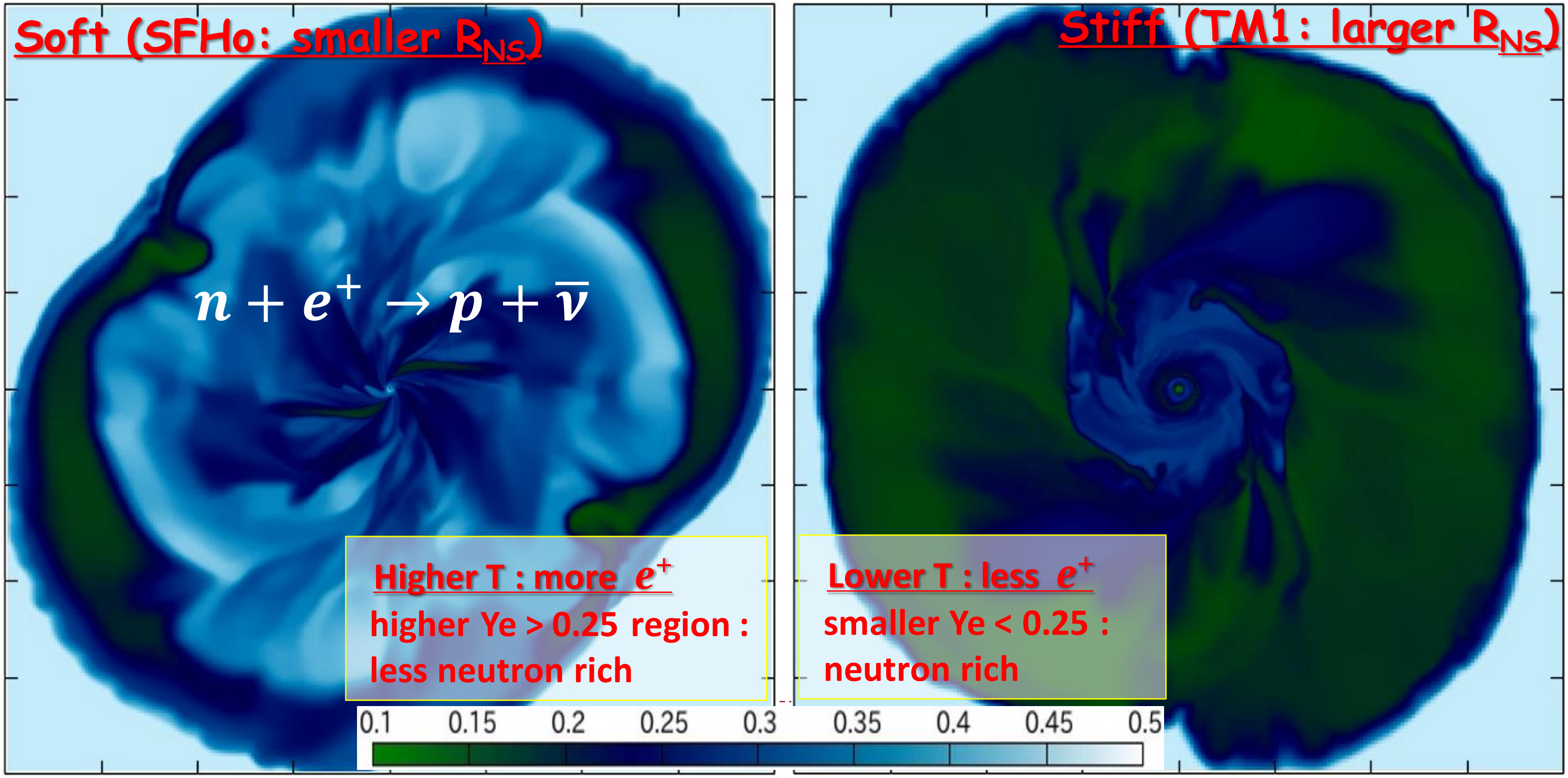
- Soft (SFHo): temperature of unbound ejecta is higher (as 1MeV) due to the shock heating, and produce copious positrons
- Stiff (TM1): temperature is much lower



Sekiguchi et al PRD (2015)

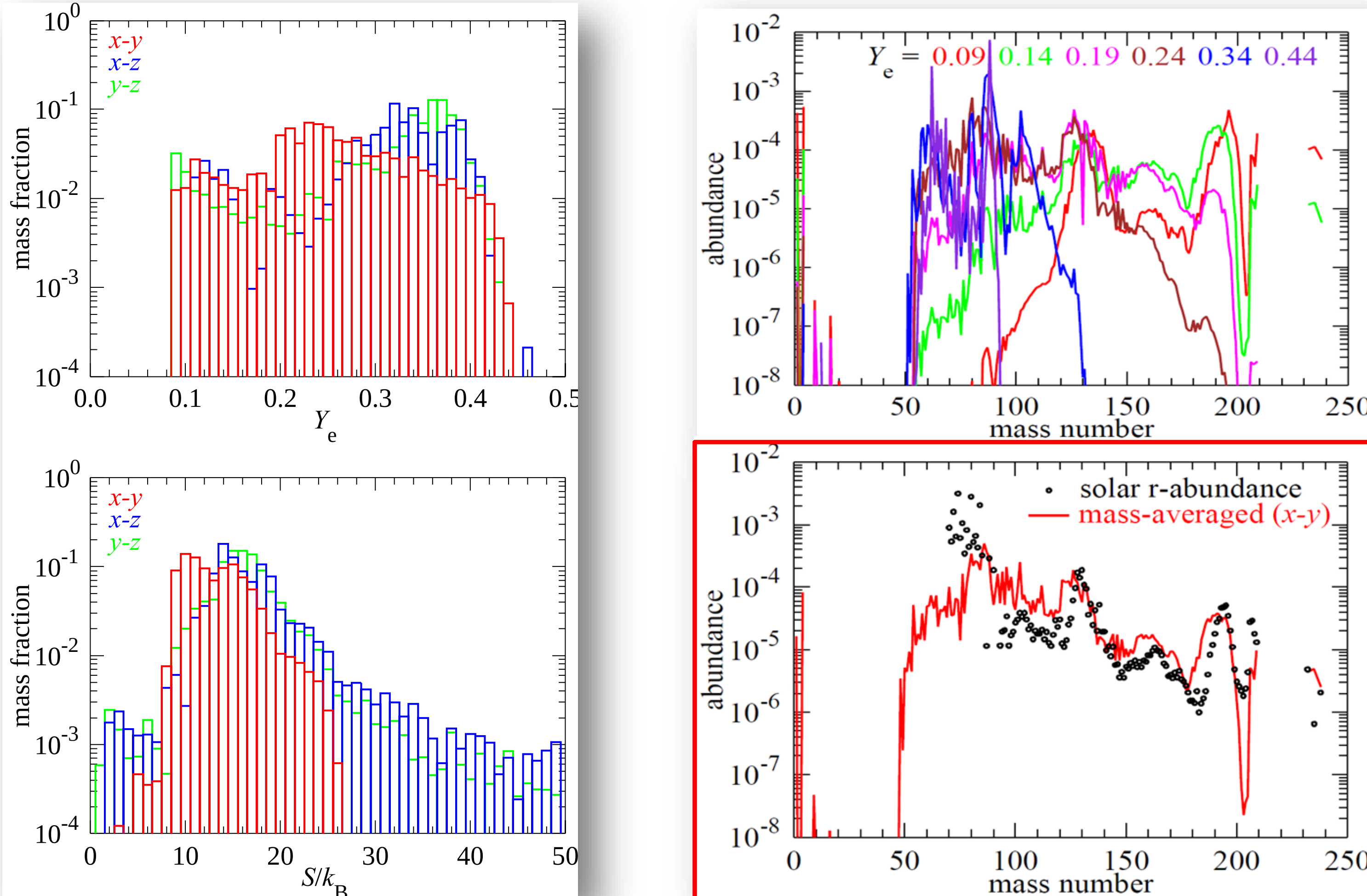
Soft(SFHo) vs. Stiff(TM1): Ejecta Ye = 1- Yn

- 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)



Achievement of the universality

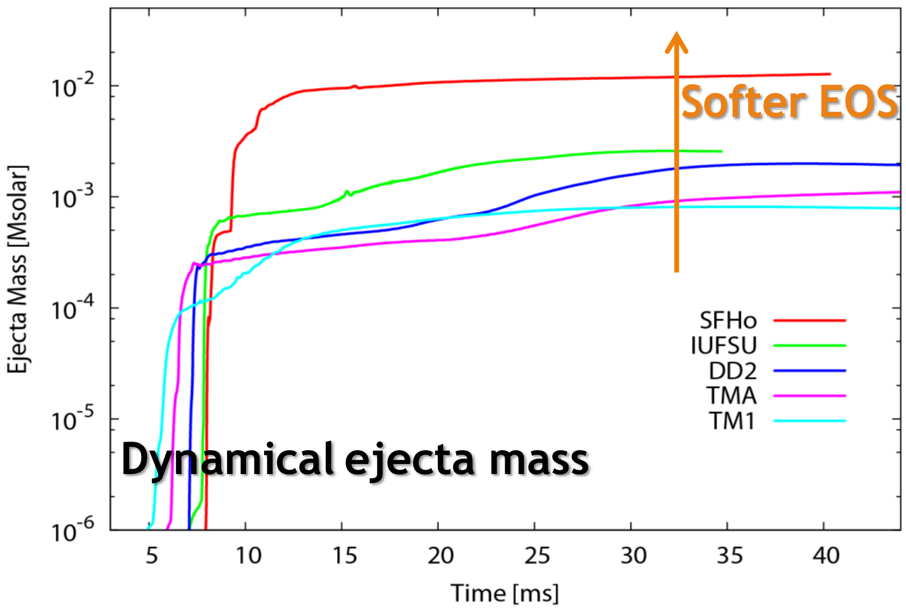
(soft EOS (SFHo), equal mass (1.35-1.35))

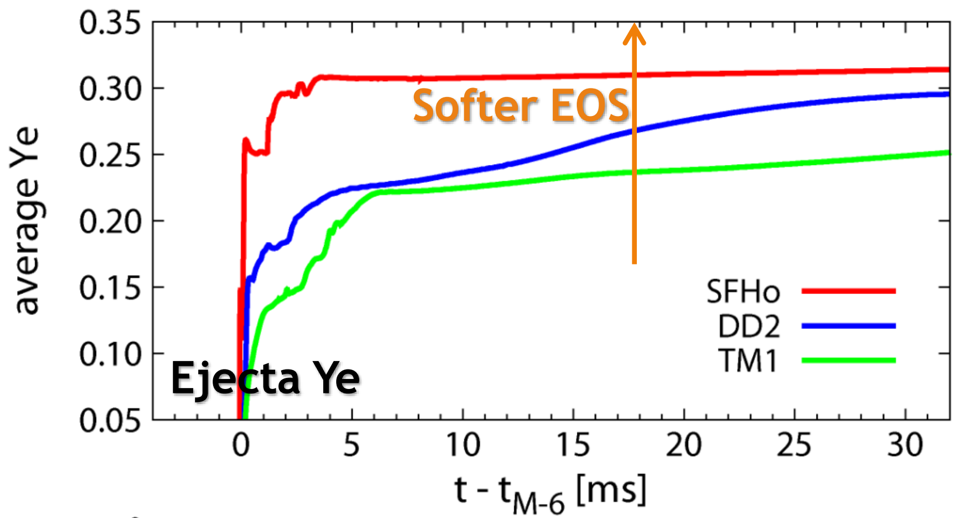


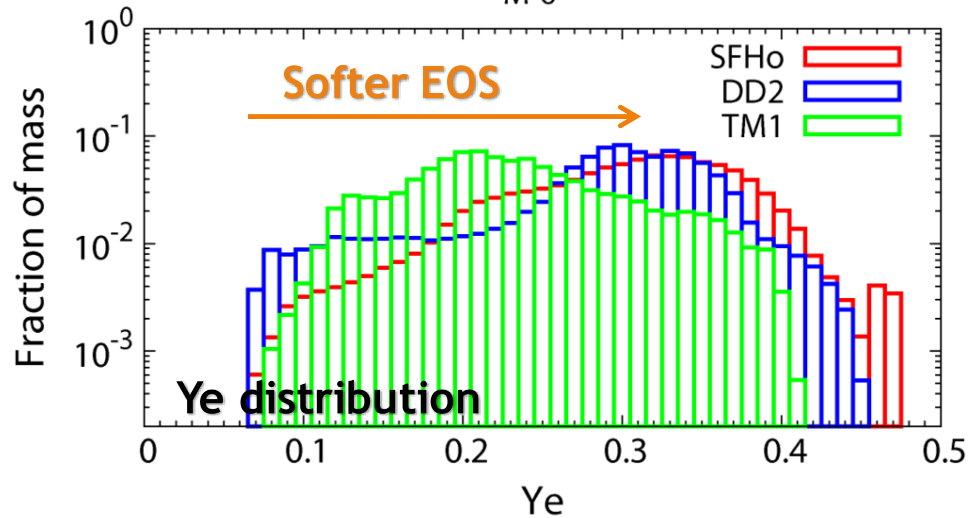
- The Ye-distribution histogram has a broad, flat structure (*Wanajo, Sekiguchi, et al. (2014)*.)
  - Mixture of all Ye gives a good agreement with the solar abundance !
  - Robustness of Universality (dependence on binary parameters)

Sekiguchi et al PRD (2015)

EOS dependence : 1.35-1.35 NS-NS





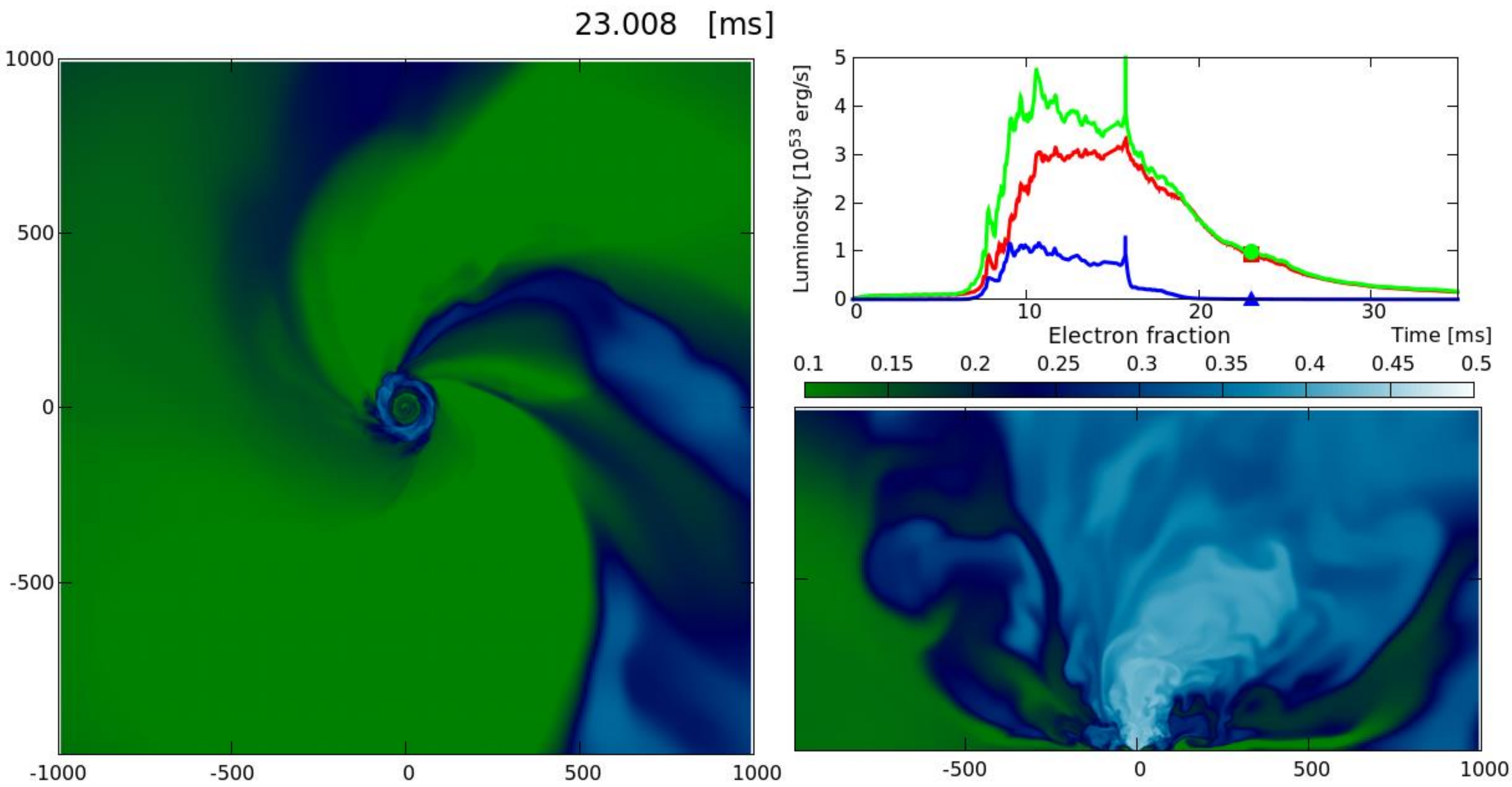


- Mej is larger for softer EOS

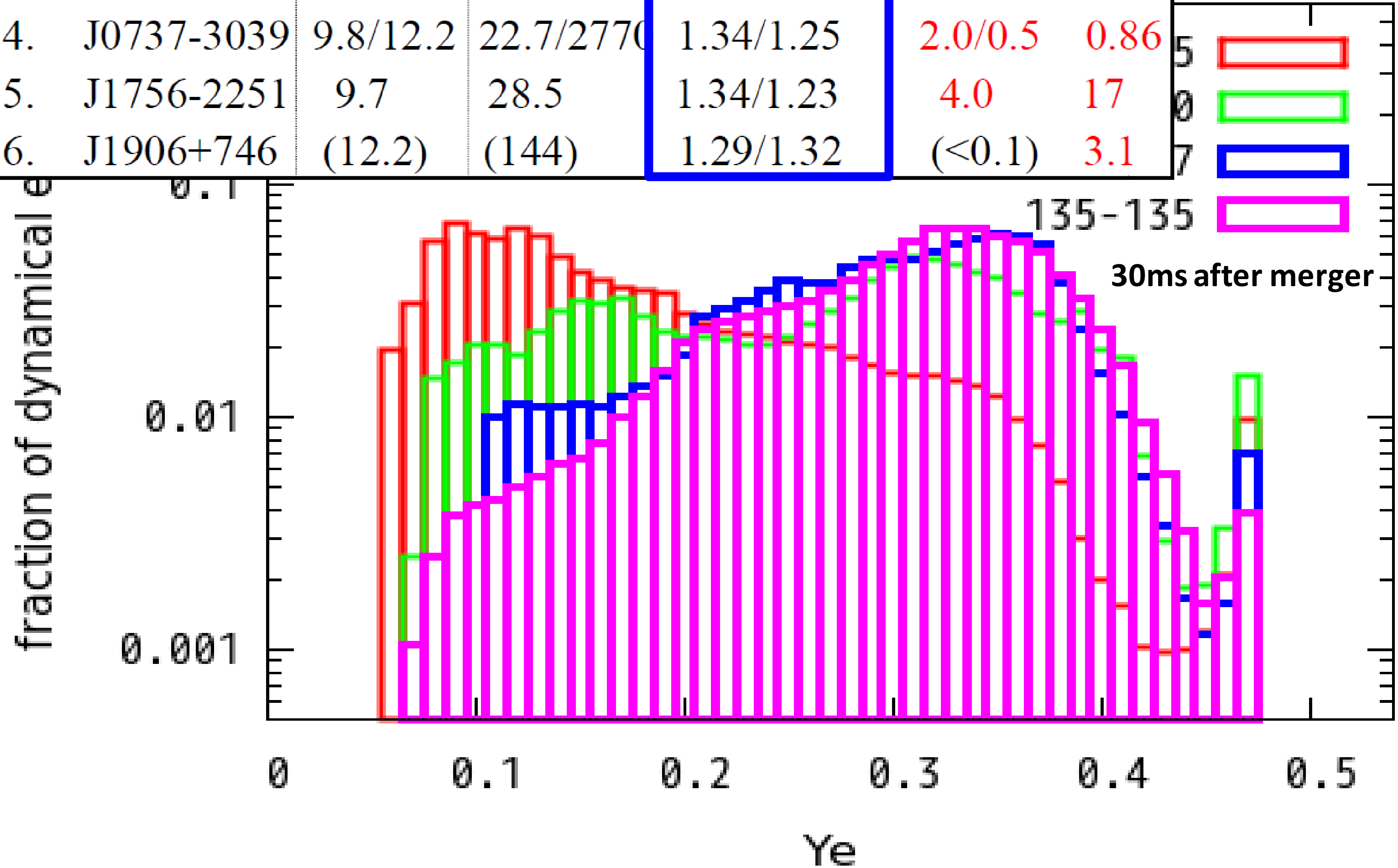
  Consistent with piecewise-polytrope studies
- **Only SFHo will give Mej ~ 0.01 Msun**
- a value required by the total amount of r-process elements and flux of the 'macronova' event (GRB 130603B)

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

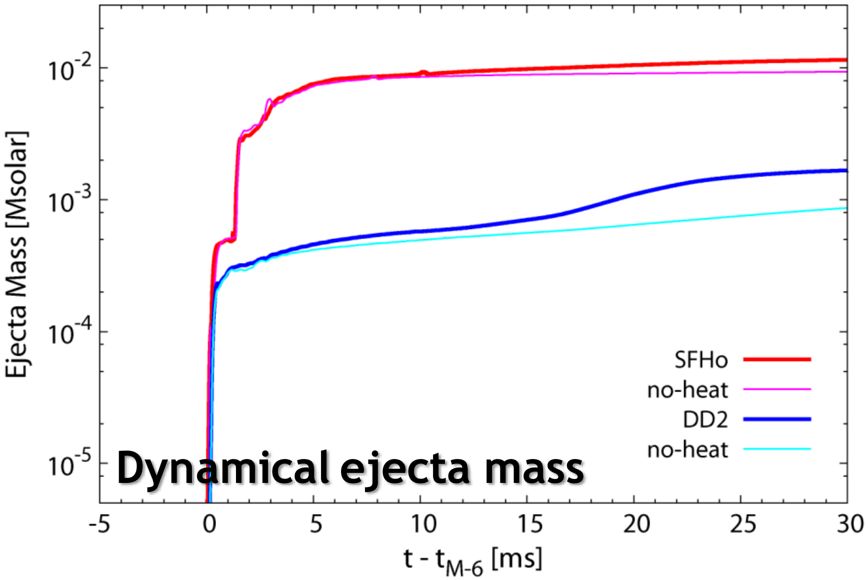


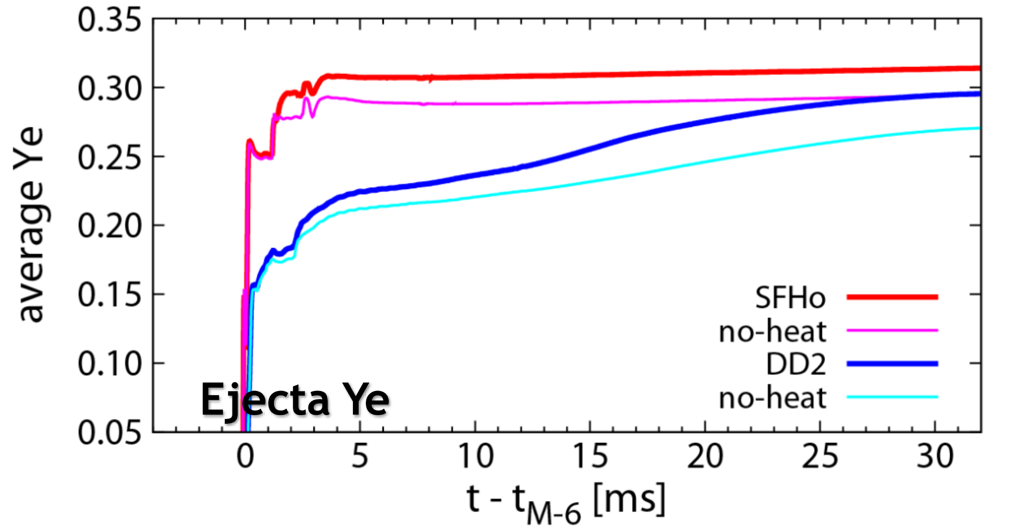
	PSR	log B(G)	$P_{\rm rot}$ (ms)	$M(M_{\rm sun})$	$T_{\rm Mag}$	$T_{\rm GW}$
1.	B1913+16	10.4	59.0	1.441/1.387	1.0	3.0
2.	B1534+12	10.0	37.9	1.333/1.345	2.5	27
3.	B2127+11C	10.7	30.5	1.36/1.35	1.0	2.2
4.	J0737-3039	9.8/12.2	22.7/2770	1.34/1.25	2.0/0.5	0.86
5.	J1756-2251	9.7	28.5	1.34/1.23	4.0	17
6.	J1906+746	(12.2)	(144)	1.29/1.32	(<0.1)	3.1

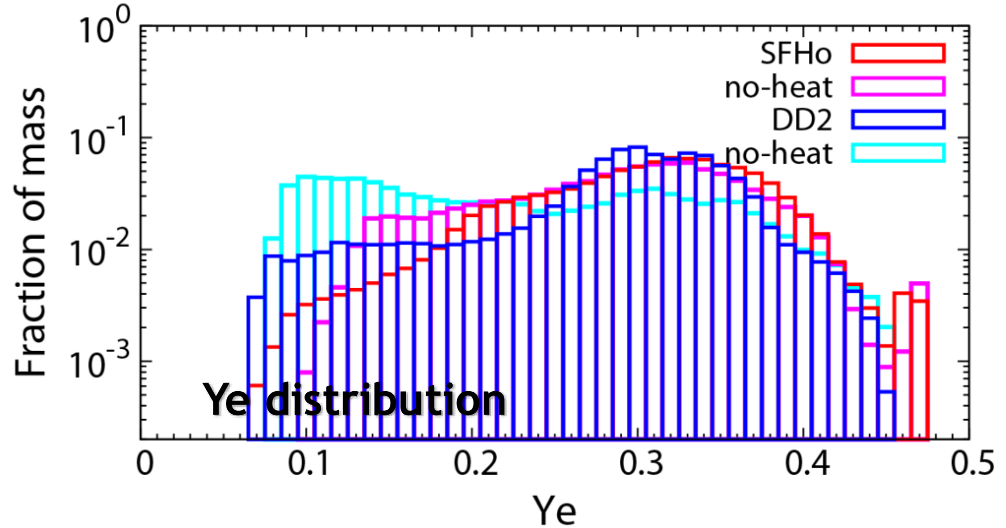


Sekiguchi et al PRD (2015); Prego et al. (2014); Just et al. (2014); Goriely et al. (2015); Martin et al. (2015)

Importance of neutrino absorption in dynamical mass ejection



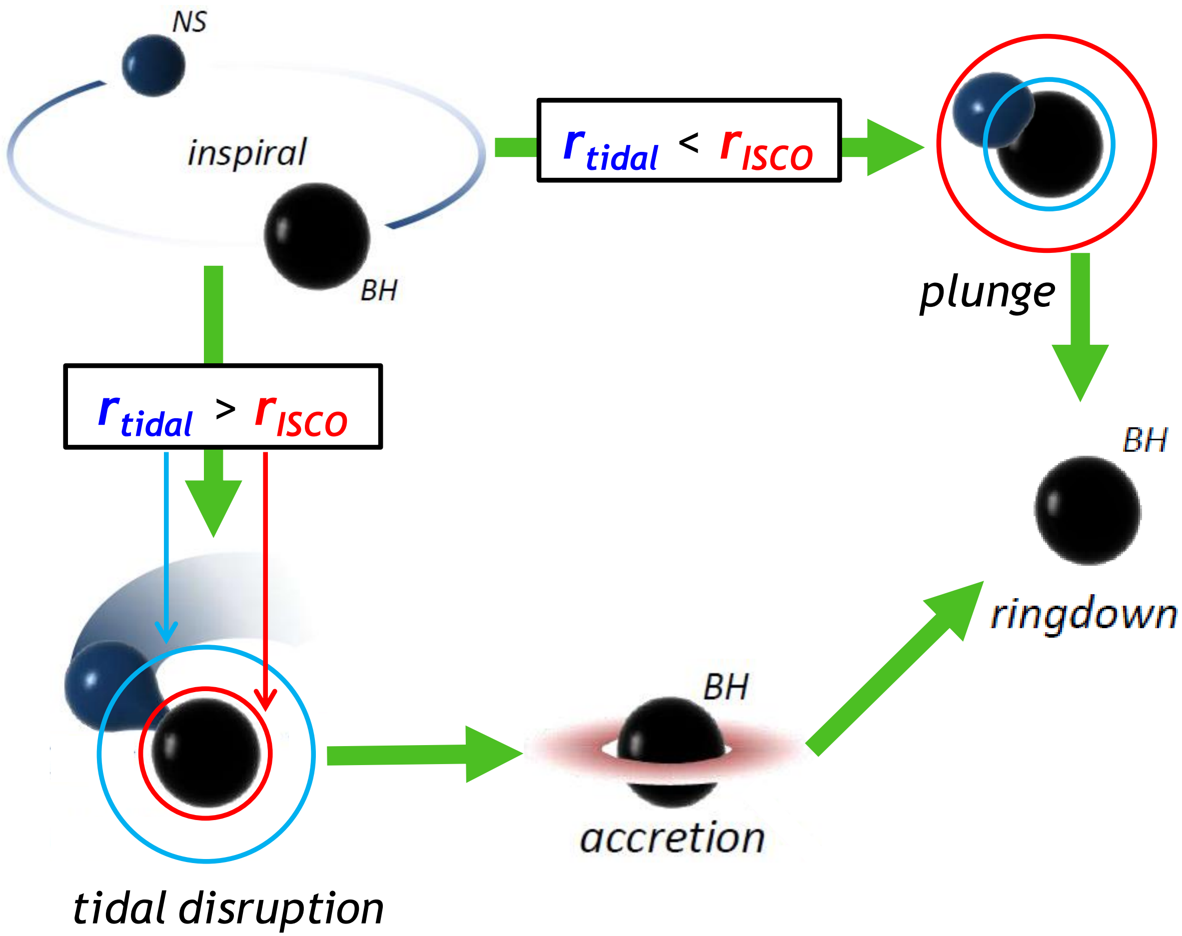




- Amount of ejecta mass can be increased order of 10^{-3} Msun
- Average Ye can change 0.02~0.03 depending on EOS : effect is stronger for stiffer EOS where HMNS survive in a longer time

Evolution of BH-NS

Shibata & Taniguchi (2008)
Kyutoku et al. (2010), (2011)



ISCO: innermost stable circular orbit

$$r_{\rm ISCO} = r_{\rm ISCO}(M_{\rm BH}, a_{\rm BH})$$

BH spin dependence

larger $a_{BH} \Rightarrow$ smaller r_{ISCO}

Tidal radius :

tidal force = self gravity of NS

$$\frac{r_{\rm tidal}}{M_{\rm BH}} = \left(\frac{M_{\rm NS}}{M_{\rm BH}}\right)^{2/3} \left(\frac{M_{\rm NS}}{R_{\rm NS}}\right)^{-1}$$

Compactness of NS
⇒ NS structure (EOS)

Imre Bartos, GECo, Columbia University
(Bartos et al. 2013, in prep.)

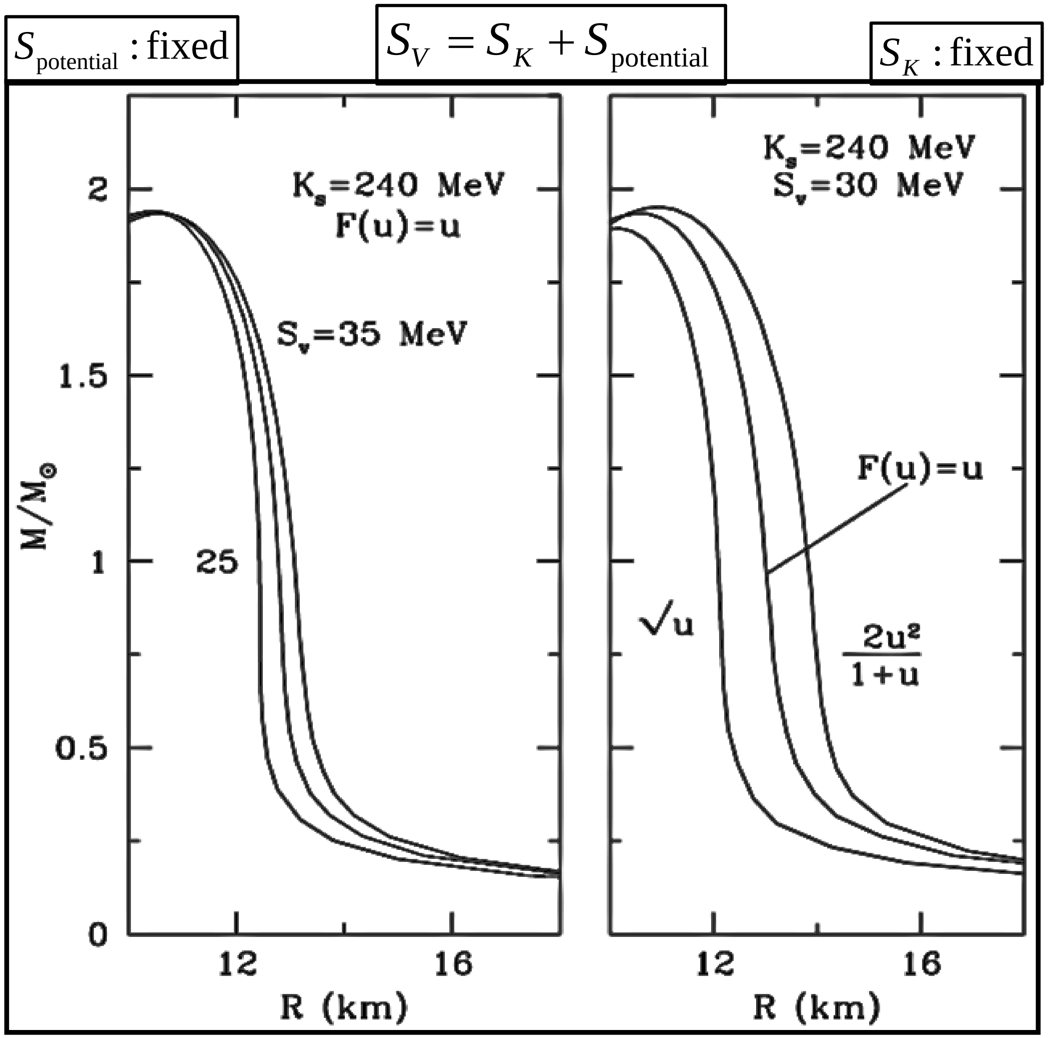
Symmetry energy and NS radius

- NS radius is sensitive to symmetry energy (@ρs)
  - empirical correlation for radius and pressure near the saturation density

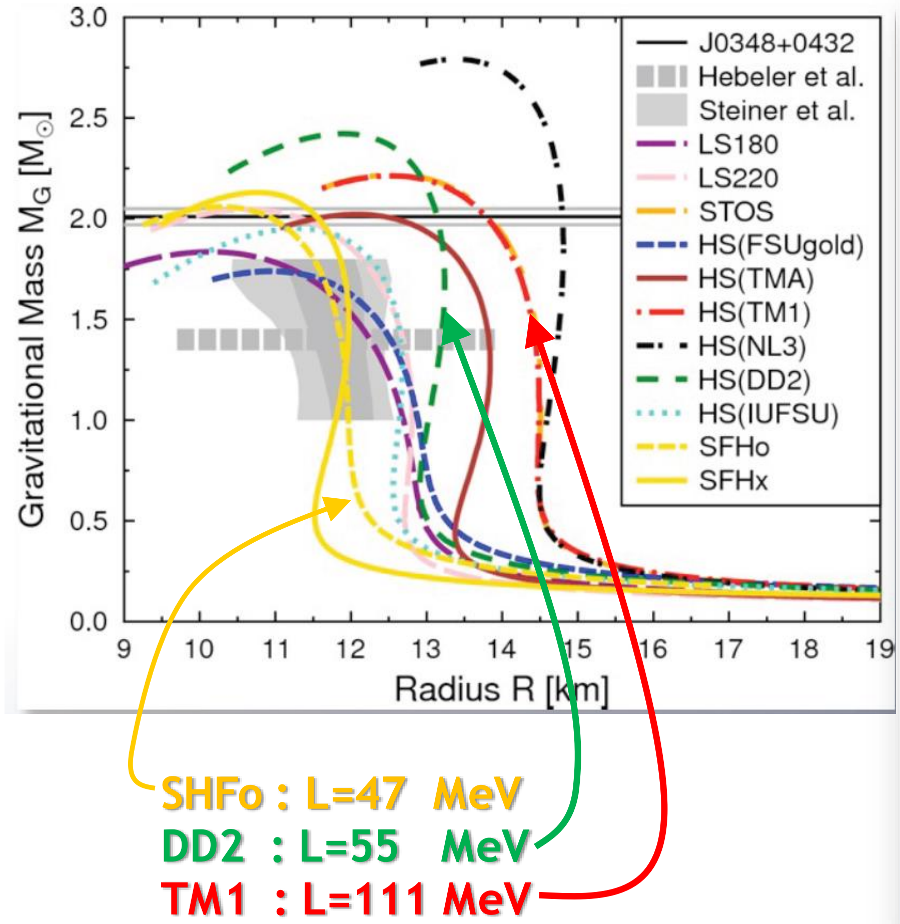
$$R_{NS}(n_S, M_{NS}) \approx C(n_S, M_{NS})\left(\frac{P(n_S)}{\text{MeV fm}^{-3}}\right)^{1/4}$$

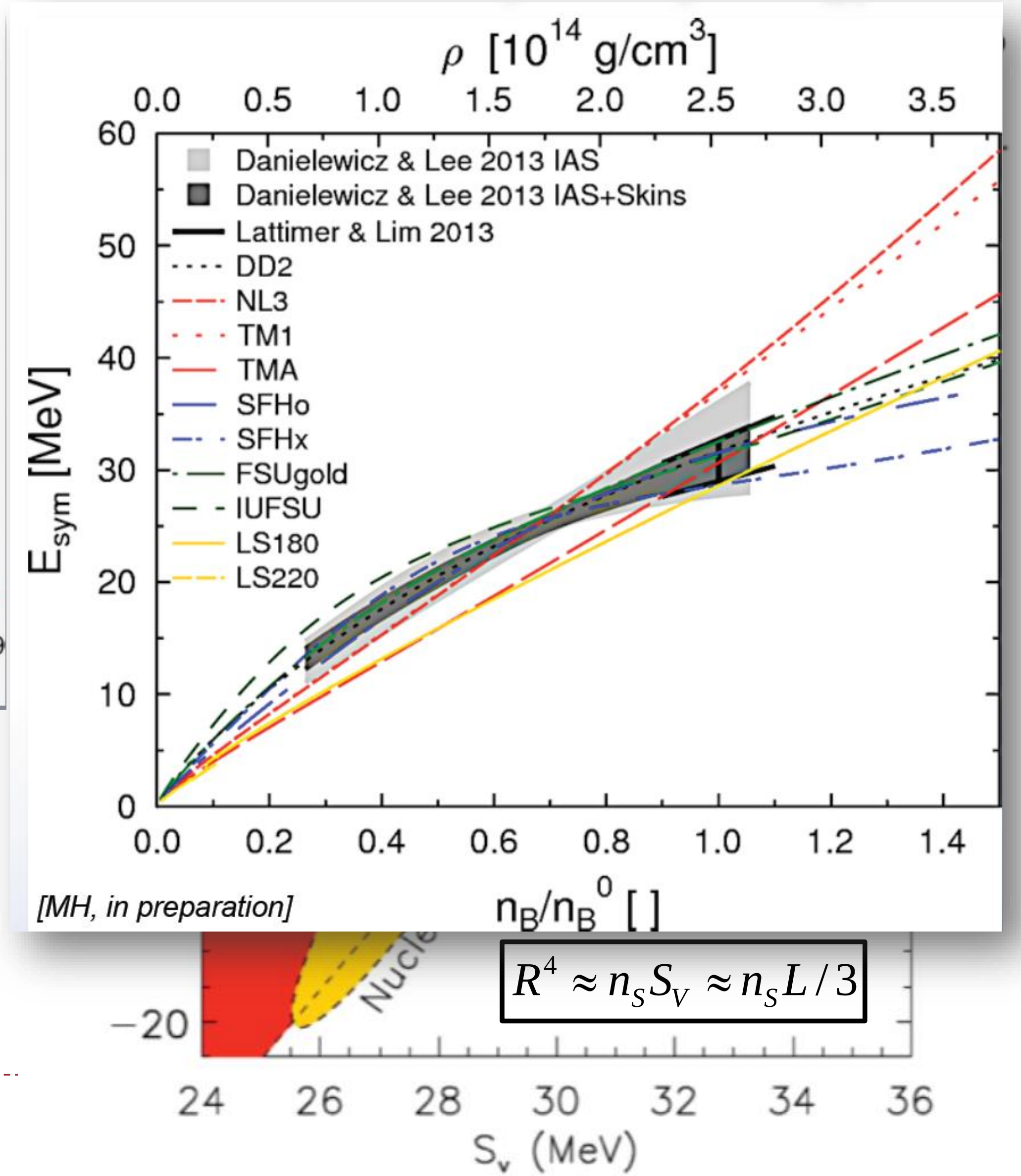
  - For pure neutron matter,
  - P @ saturation depends on symmetry energy

$$P(n_S, x=0) \propto L \approx S_V n_S$$



Symmetry energy of adopted EOS

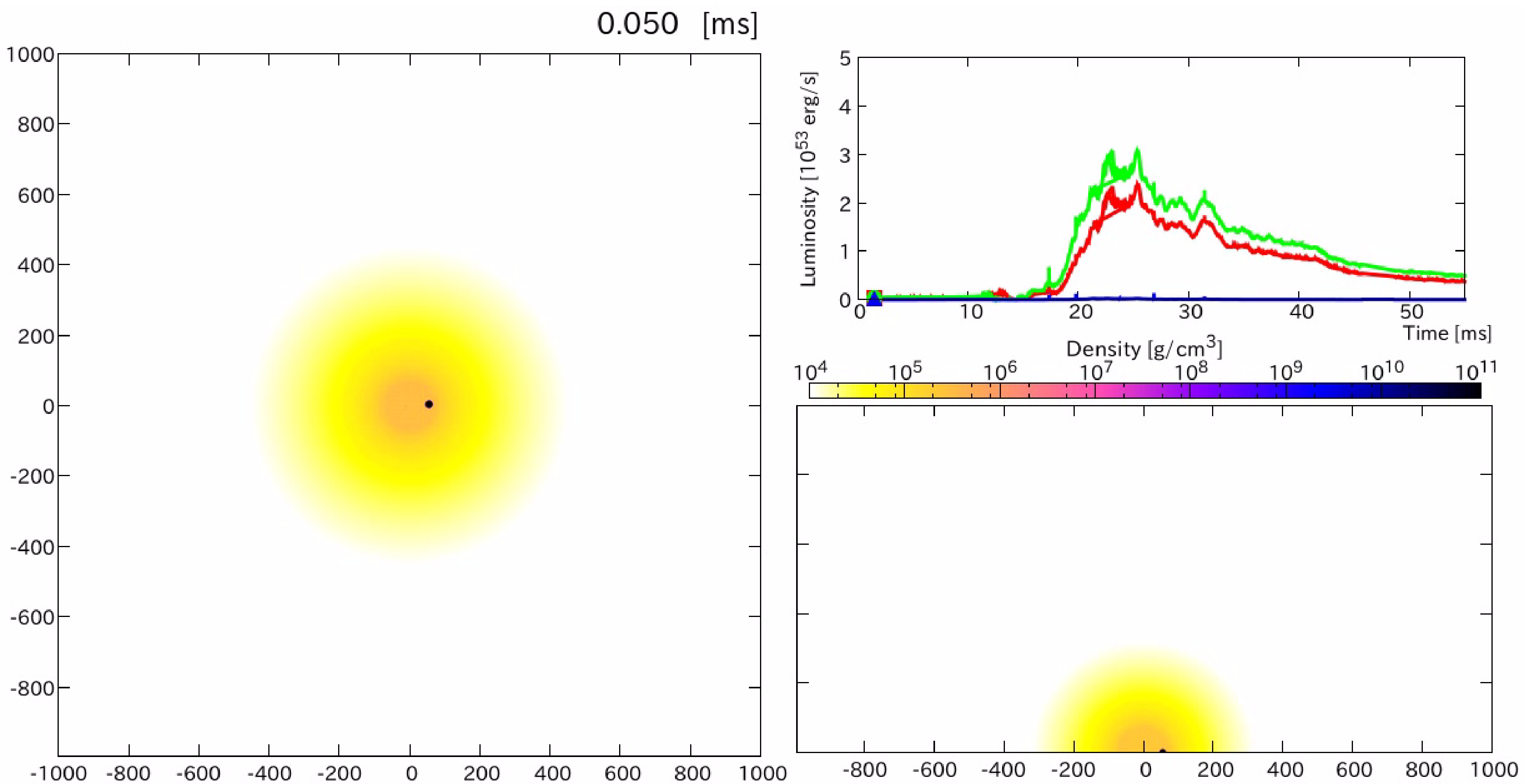




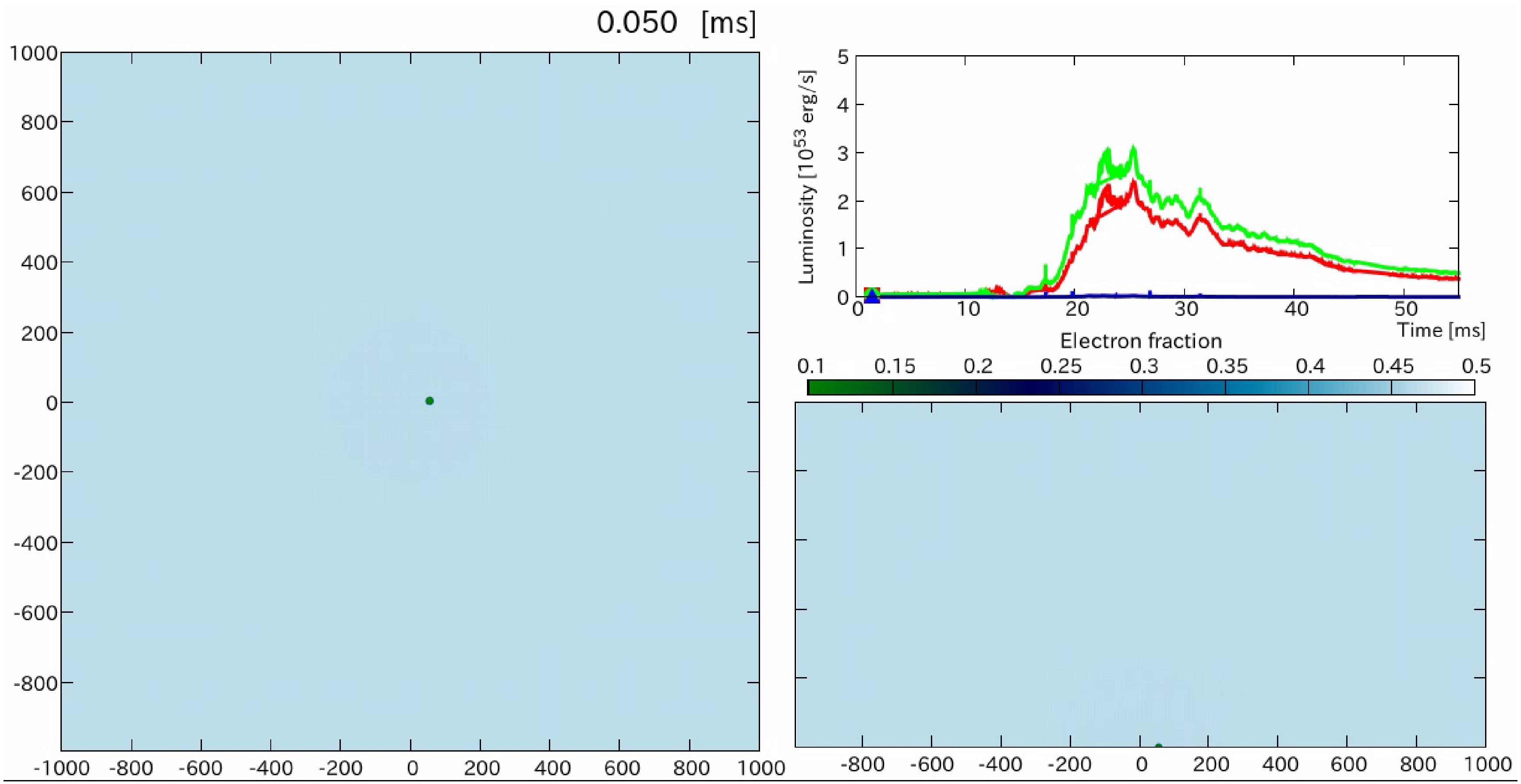
$$R^4 \approx n_S S_V \approx n_S L/3$$

BH-NS merger (DD2 EOS: density)

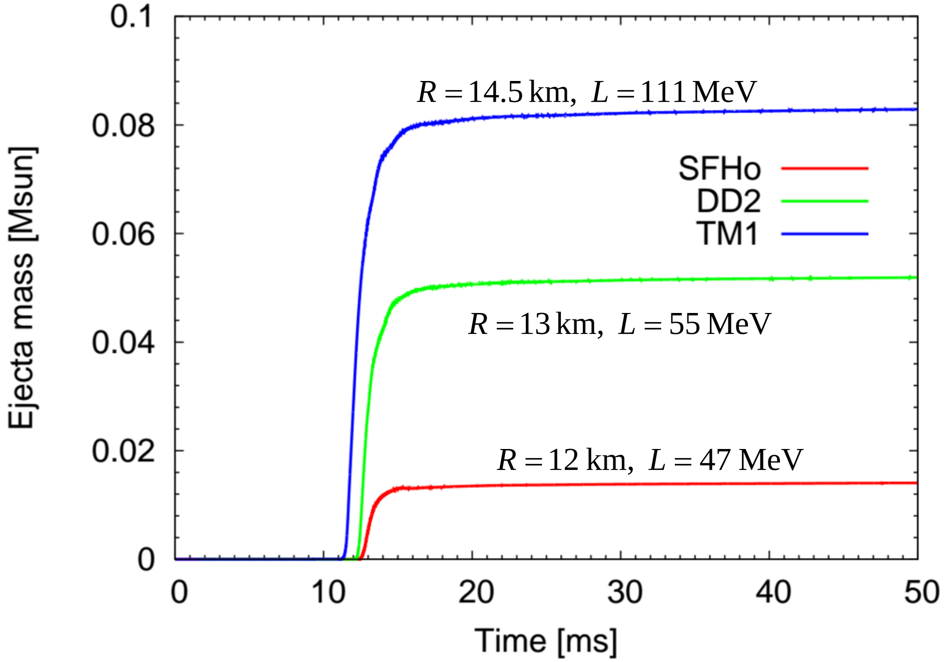
M_{BH}=5.5M_{sun}, M_{NS}=1.35M_{sun}, a_{BH}=0.75

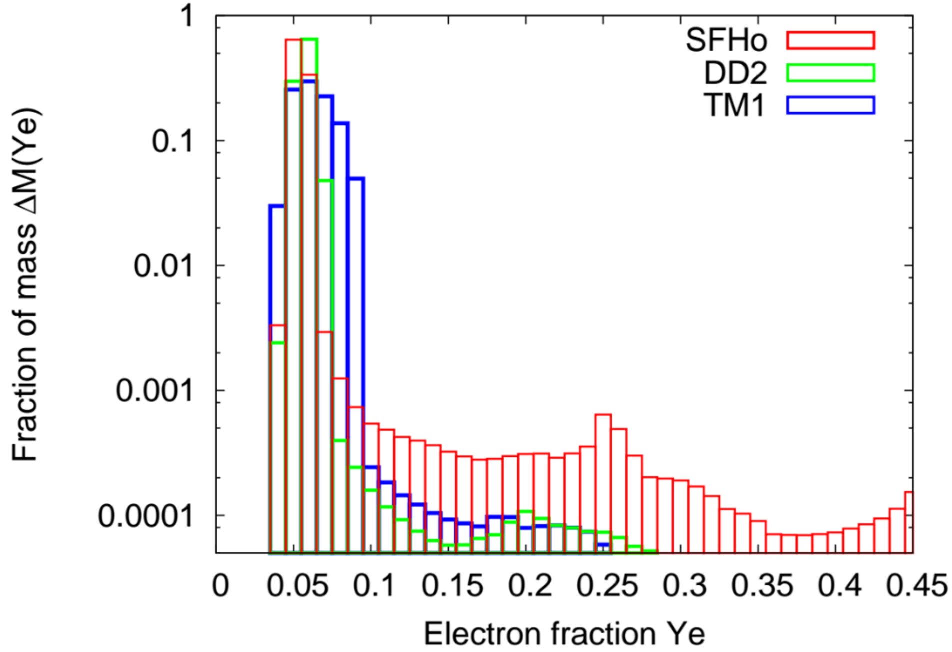


BH-NS merger (DD2 EOS: Ye)
$M_{BH}=5.5M_{sun}$, $M_{NS}=1.35M_{sun}$, $a_{BH}=0.75$



Properties of ejecta：EOS dependence





- Main mass ejection mechanism: tidal disruption of NS by BH ⇒ ejecta is very neutron rich
  - For lager R_{NS} (for stiff EOS or EOS with larger symmetry energy), ejecta mass is larger (promising as EM counterpart to GW)
- Neutrino heating effects less dominant
- Too neutron rich to satisfy the Universality
  - Need some additional ejecta components. (e.g., MHD driven winds: Kiuchi, YS, et al. 2015)

Not only ejecta mass but also ejecta Ye reflects the symmetry energy