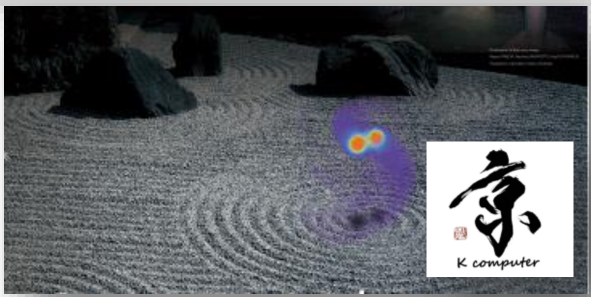
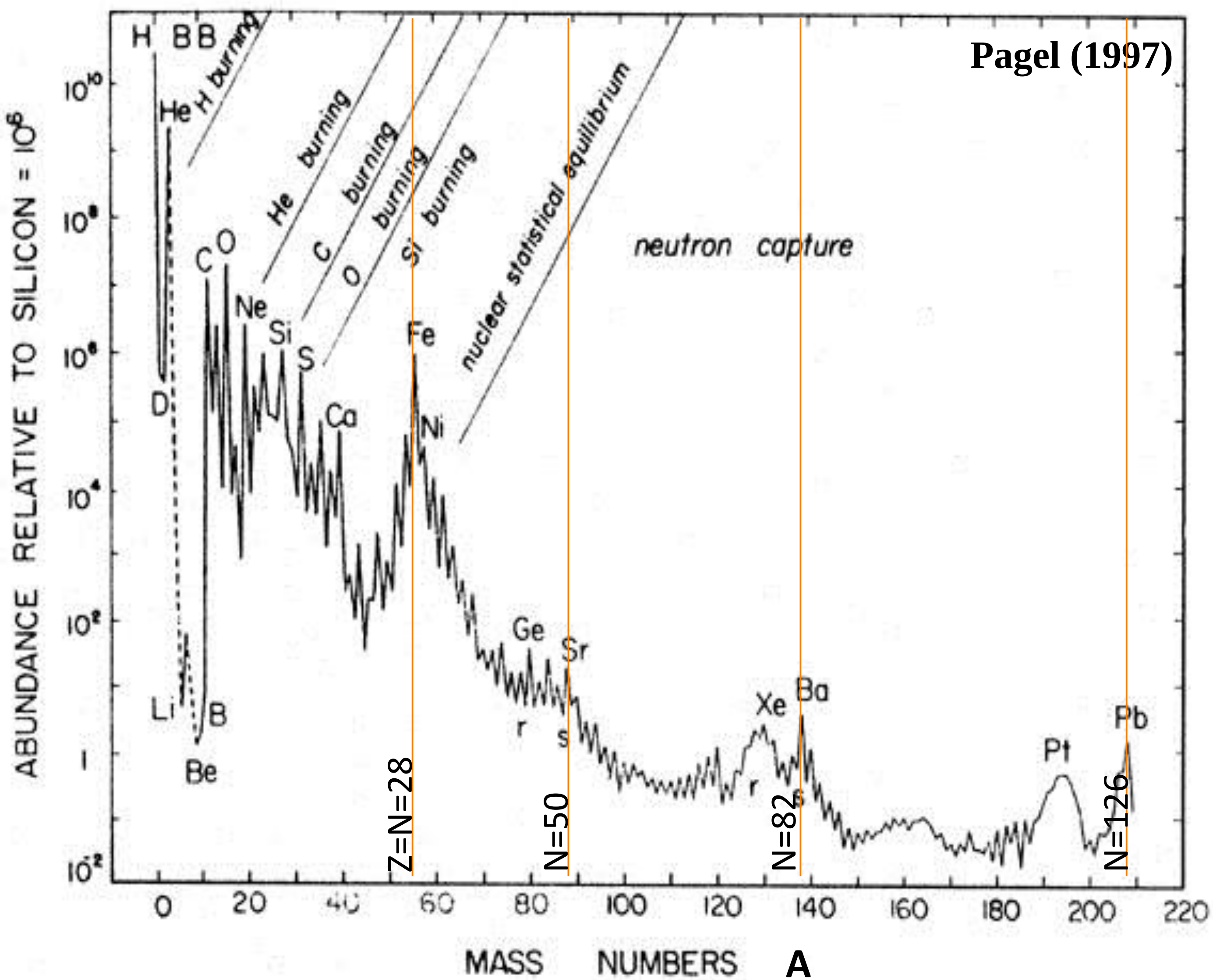


Mass ejection from compact binary merger and r-process nucleosynthesis

Yuichiro Sekiguchi (Toho University)

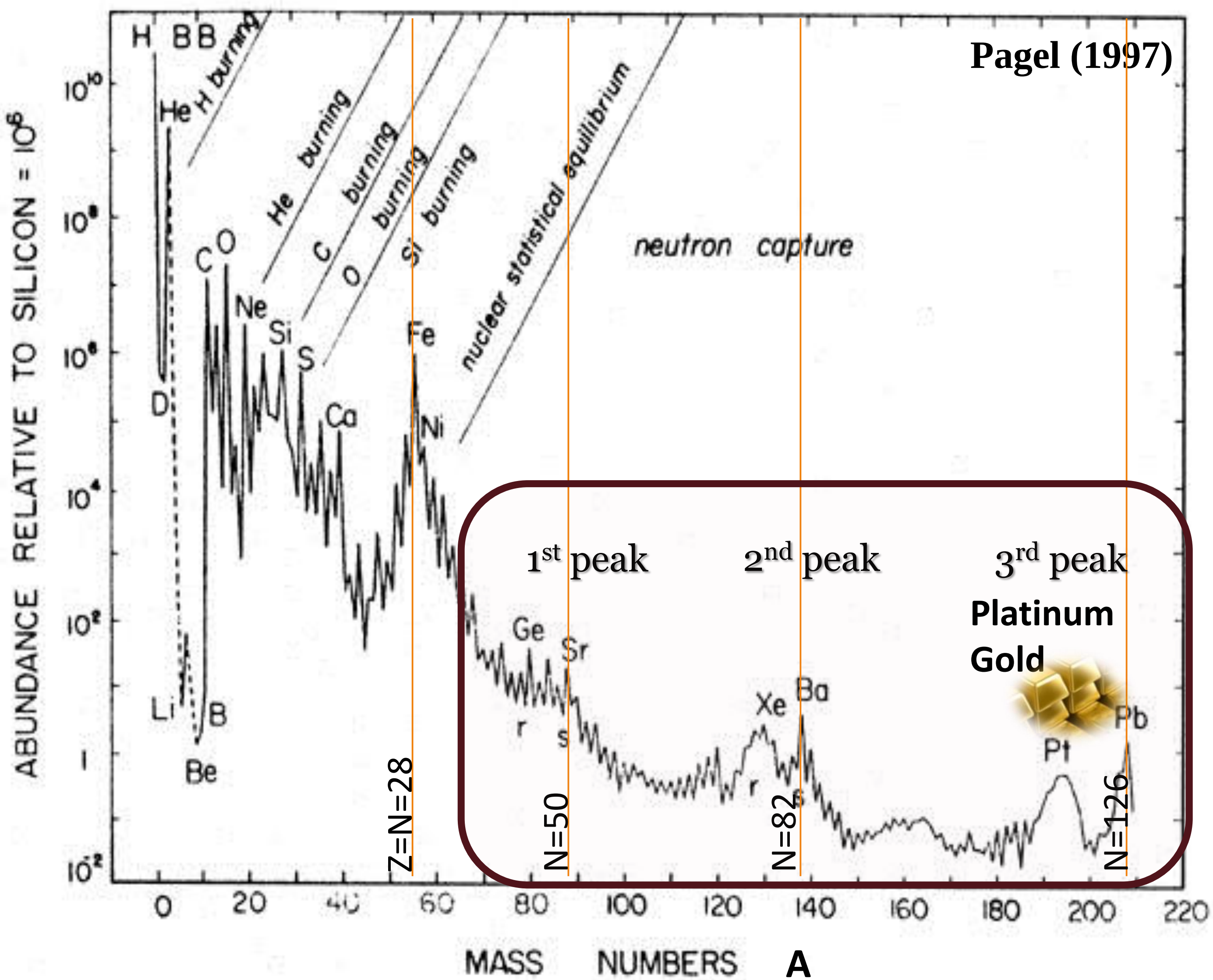
S. Wanajo, N. Nishimura, K. Kyutoku, M. Tanaka, K. Hotokezaka, H. Nagakura, K. Kiuchi, M. Shibata, K. Taniguchi

Solar abundance of nuclei



- <u>Basic feature :</u> exponential decay with mass number + constant tail
- <u>Characteristic features:</u>
- Peak in iron-group
- Deficient of D, Li, Be, and B
- Enhancement of α-nuclei (C, O, Ne, Si,..)

Solar abundance of nuclei



- **Basic feature :** exponential decay with mass number + constant tail
- **Characteristic features:**
- Peak in iron-group
- Deficient of D, Li, Be, and B
- Enhancement of α-nuclei (C, O, Ne, Si,..)
- **Peaks in heavier region associated with n-magic numbers,**
- **made by neutron capture processes**

Neutron capture processes:
free from Coulomb barrier

$n + (Z,N) \Rightarrow (Z,N+1)$

n-capture versus **β-decay**

$(Z,N+1) \Rightarrow (Z+1,N) + e + \bar{\nu}_e$

$\tau_n < \tau_\beta$

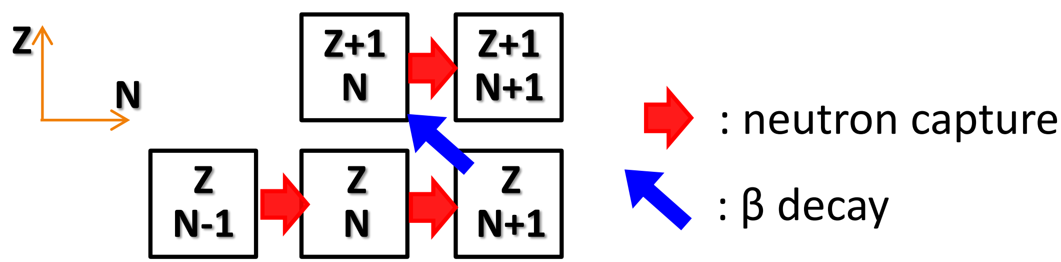
rapid neutron-capture process
(r-process)

large neutron densities
- Can synthesize all heavy nuclei

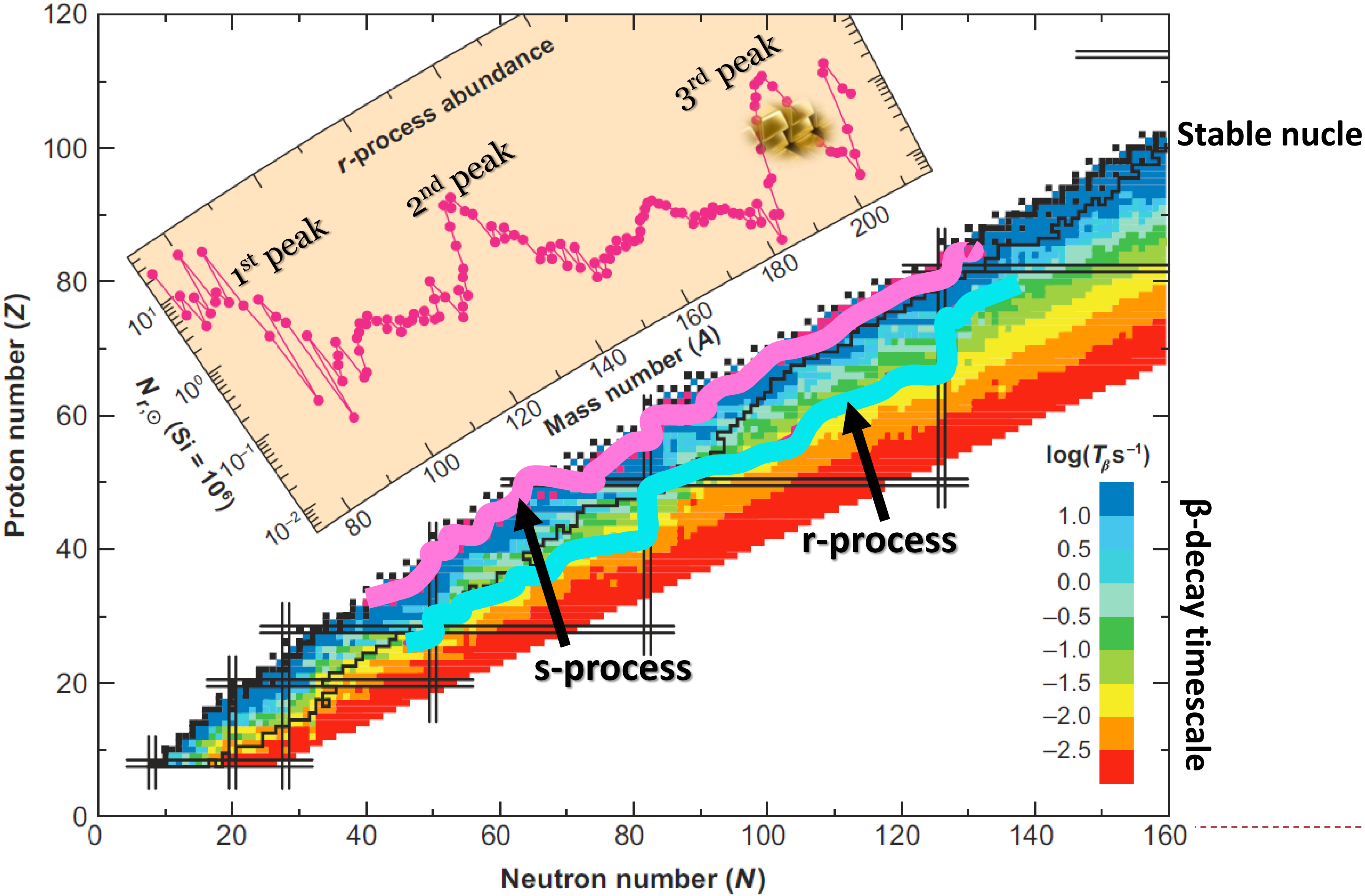
$\tau_n > \tau_\beta$

slow neutron-capture process
(s-process)

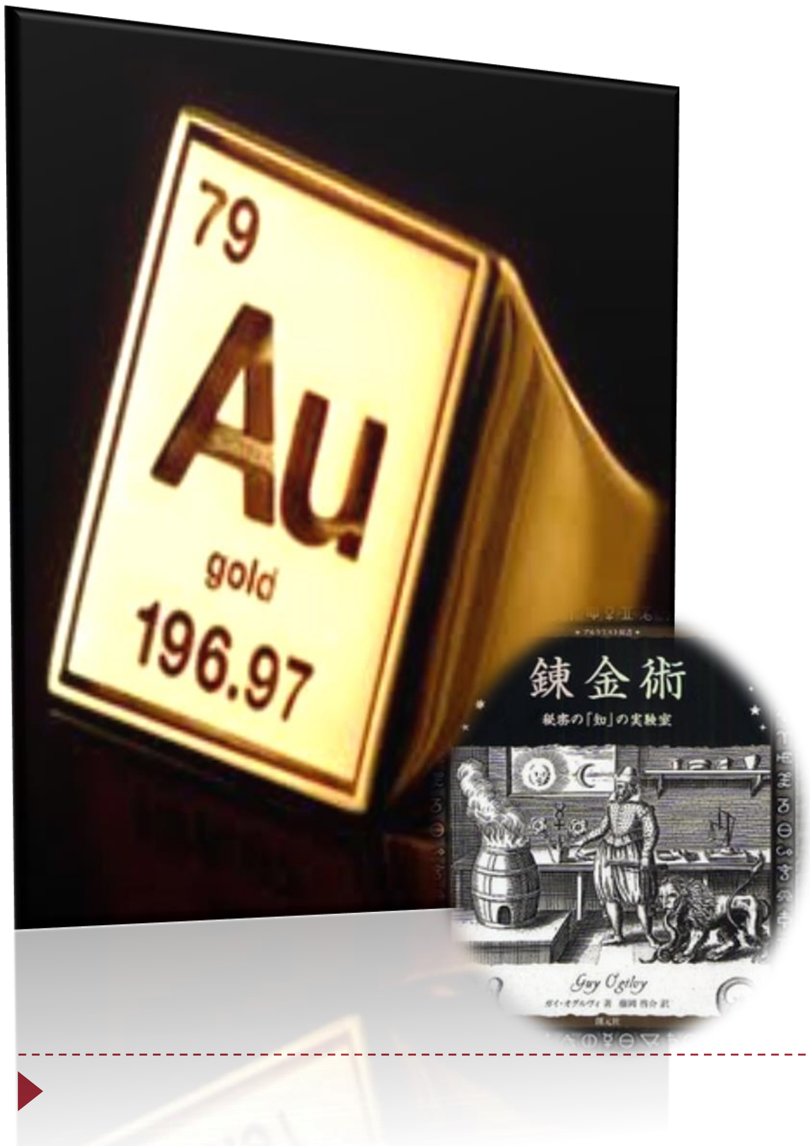
moderate neutron densities
- does not synthesize all heavy nuclei
- terminates at Pb, Bi



s-process / r-process path



To be an alchemist : recipe to cook gold



- Neutron capture : packing neutrons into ‘seed’ nuclei

  $n + (Z,N) \Rightarrow (Z,N+1)$

  - Large #neutron/#seed ratio is required
  - A(gold) – A (seed) ~ 100
- **(1) Low electron fraction Ye**
  - Ye = number of electrons per baryon ~ # of proton ~ 1 - # of neutron
  - To have a large number of free neutrons
- **(2) Higher entropy per baryon**
  - To slow the seed nuclei production
- **(3) Short expansion timescale**
  - To freeze seed production with rapid decrease of temperature

What is the cite of r-process ?

- **<u>Supernova (SN) explosion + PNS ν-driven wind : (*Burbidge et al. 1957*)</u>**
  - Nice review by Thomas Janka and Luc Roberts
    - Smaller entropy/per baryon than previously expected (e.g., Janka et al. 1997)
      - Previous expectation (s/kB > 200) => recent update s/kB ~ 100-150
    - difficulty in preserving n-rich condition (Roberts et al. 2010, 2012; Wanajo 2013)
      - Neutrinos from PNS make the flow towards proton rich side via weak interactions
  - difficulty in satisfying the universality of the abundance pattern of r-process rich stars

- **<u>NS-NS(/BH) binary merger: (*Lattimer & Schramm 1974*)</u>**
  - problems in terms of chemical evolution (Argust et al. 2004)
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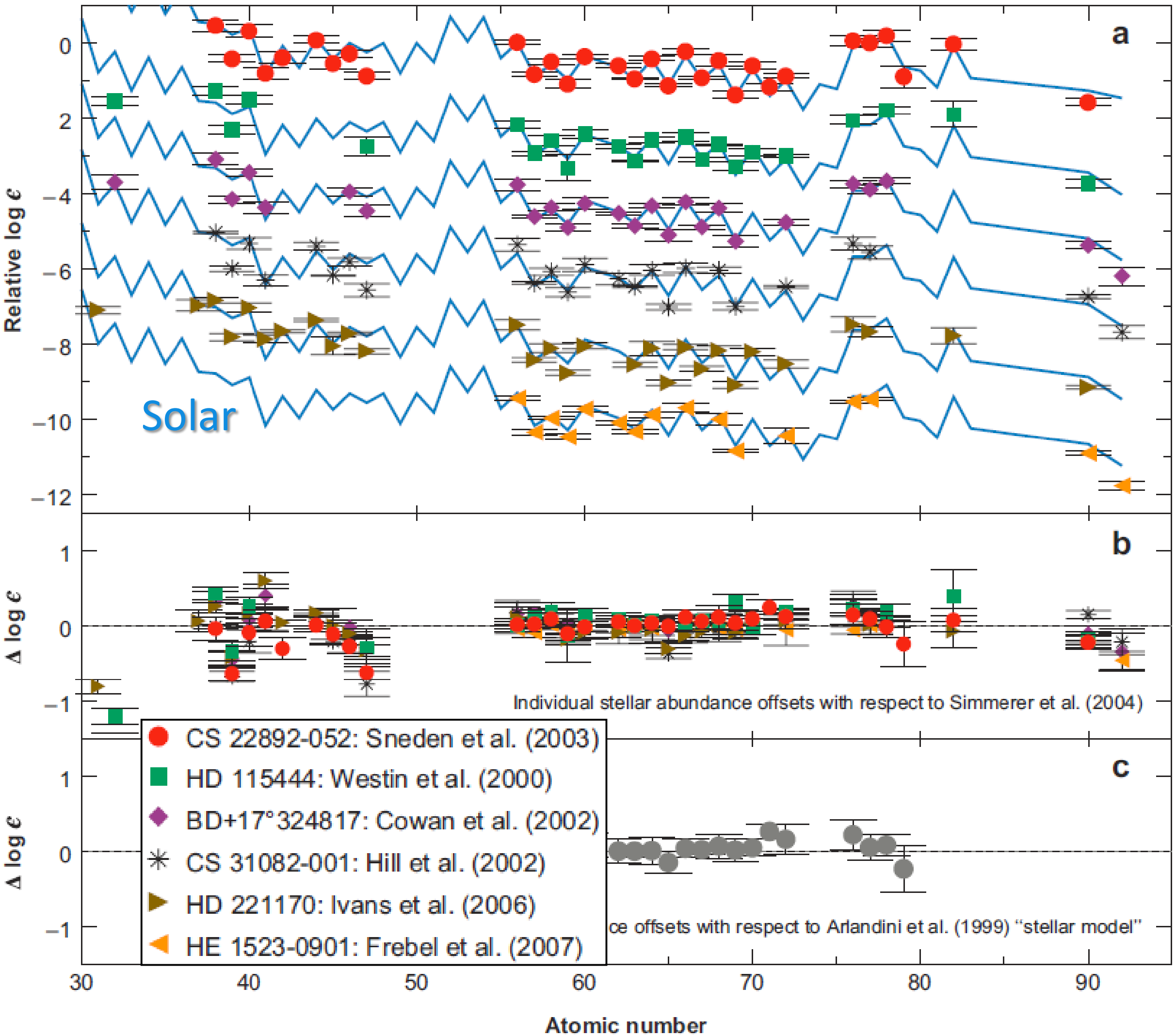
  - Good news by Piran
  - How about the universality : too neutron rich ejecta ?
  - What is the ejecta mass ?
    - Topic of this talk

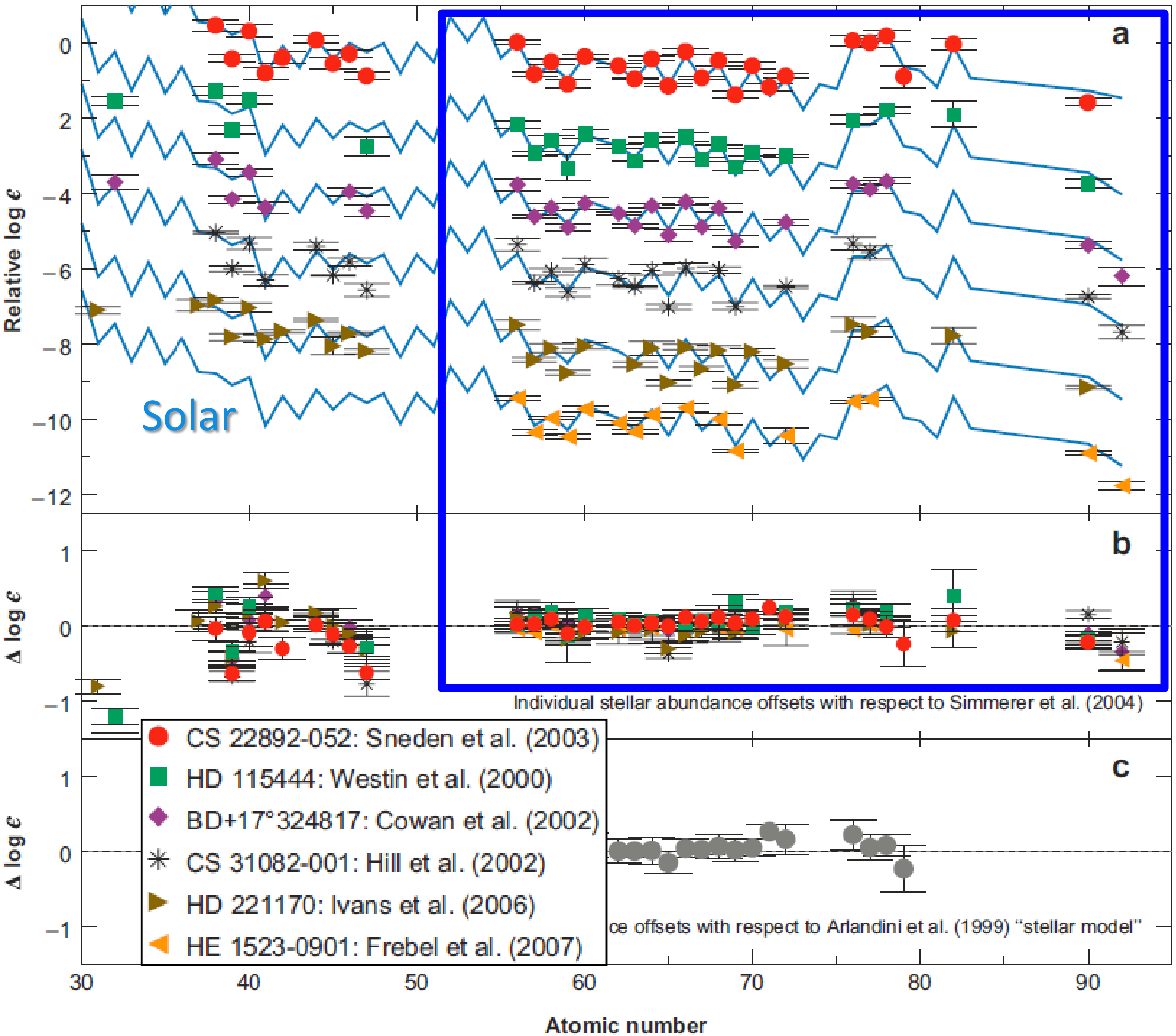
Key observations : Universality



- **Abundance pattern comparison :**
  - r-rich low metallicity stars
  - Solar neighborhood
- **Low metallicity suggests**
  - Such stars experience a few r-process events
  - preserve the pattern of the r-process events (chemical fossil)
    - Not the mixture of many events

- Sneden et al. (2008)

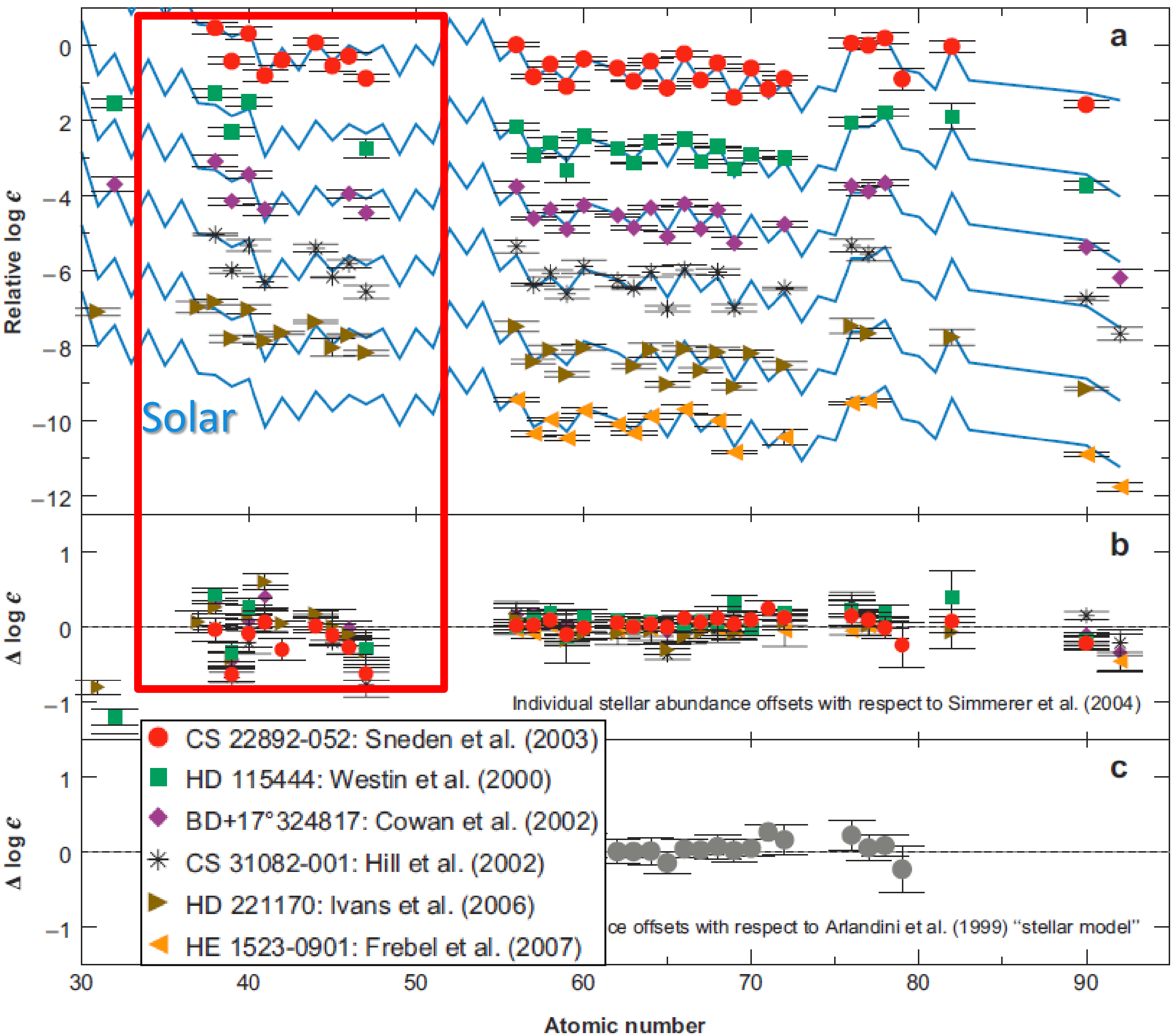
Key observations : Universality



- **The abundance patterns agree well for Z >~ 55**
- suggests that <u>r-process event synthesize heavy elements with a pattern similar to solar pattern (Univsersality)</u>

- Sneden et al. (2008)

Key observations : Universality



- **The patterns agree approximately for 35 < Z < 50 but show some diversity (factor of few)**
- **Weakly universal ?**
- **We also consider this 'weak universality'**

- Sneden et al. (2008)

What is the cite of r-process ?

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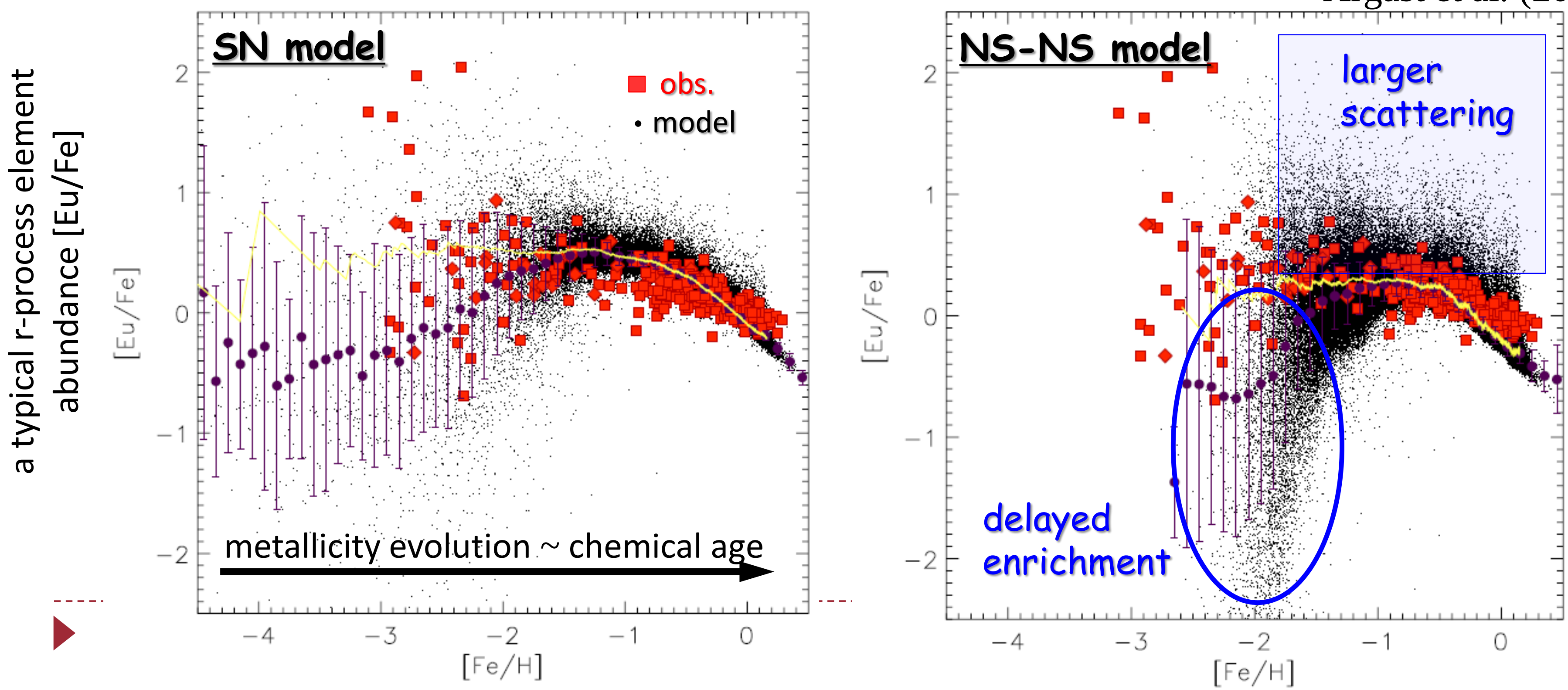
e.g., Matteucci et al. 2014, MNRAS, 438, 2177; Komiya et al. 2014, ApJ, 783, 132,
Tsujimoto & Shigeyama, A&A, 565, L5

Chemical evolution of galaxies

- **NS-NS/BH binary merger was observationally disfavored (*Argast et al. 2004*)**
  - Too slow appearance of r-process elements
    - long merger time ~ 100Myr
  - Too large scattering
    - low event rate (~ $10^{-5\sim-4}$/yr/gal) and larger mass per event

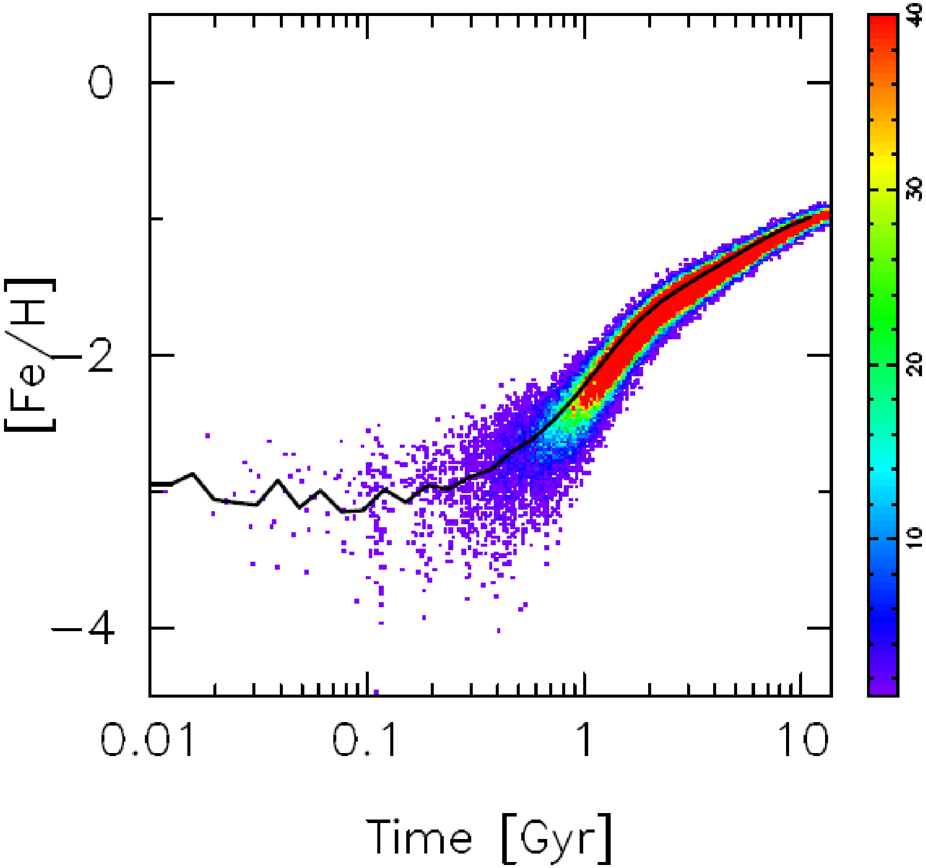
Argast et al. (2004)



Chemical evolution of galaxies

- **A resolution of the problem in the chemical evolution model (*Hirai et al. 2015; Ishimaru et al. 2015*)**
  - Hierarchical merging paradigm : dwarf spheroidal galaxies are building block of the normal galaxies
    - [Fe/H] does not increase in the dwarf galaxies due to shallower gravitational potential
    - **It takes ~ 300 Myr for [Fe/H] to start increasing**
  - Mixing in the star formation region (SNe feedback)
    - **Reduces the dispersion of [Eu/Fe]**
  - **NS-NS mergers with merger time ~ 300 Myr can reproduce the observed [Eu/Fe]**

Hirai et al. (2015)



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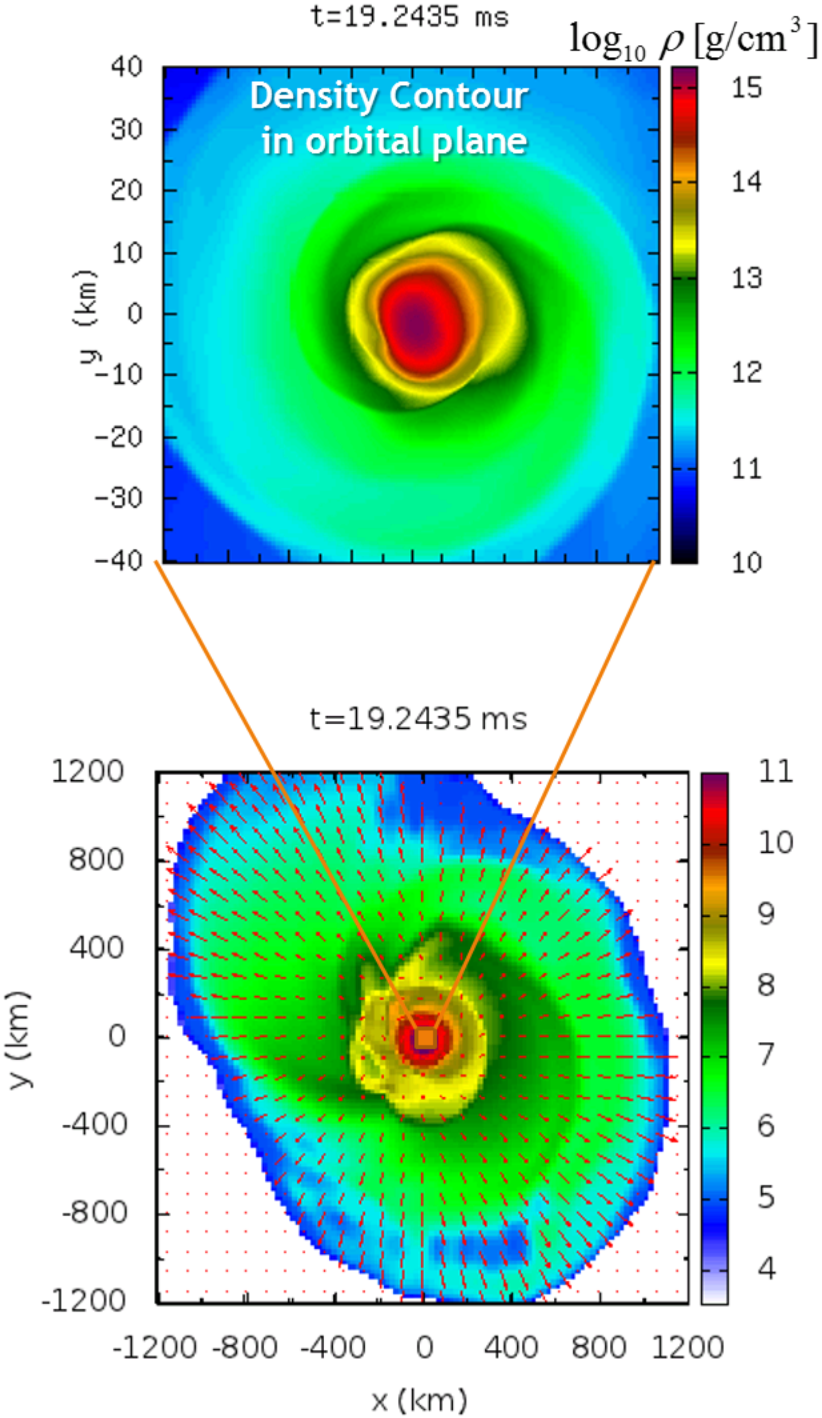
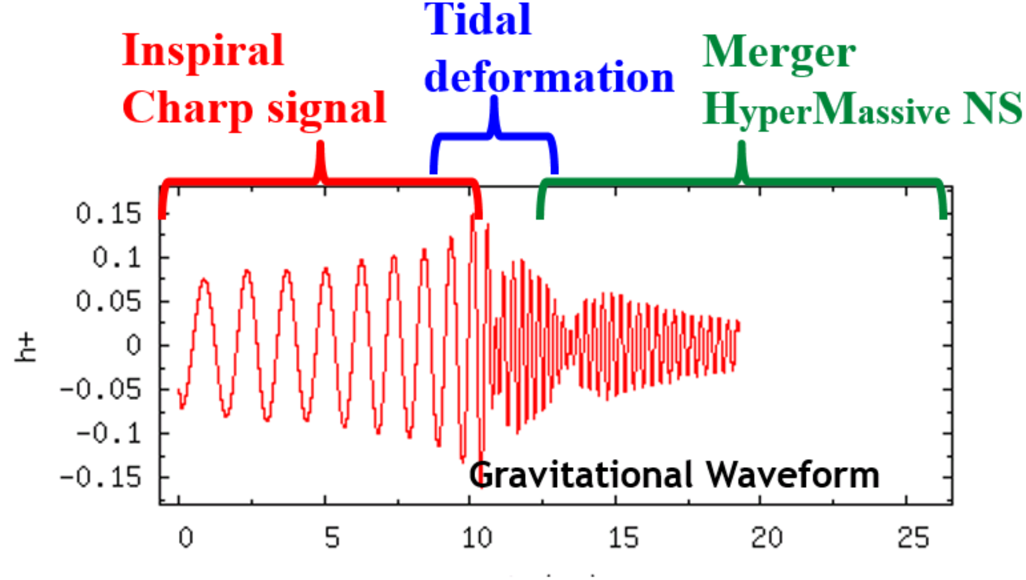
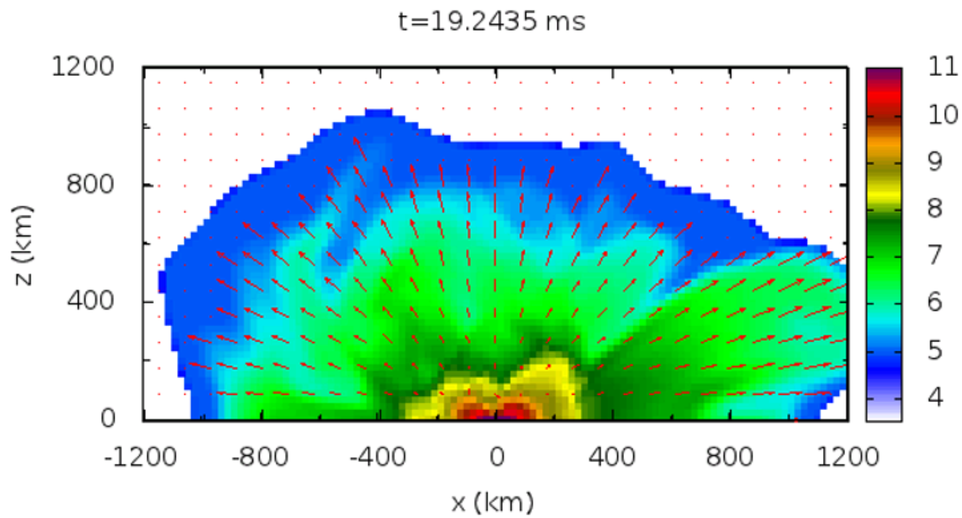






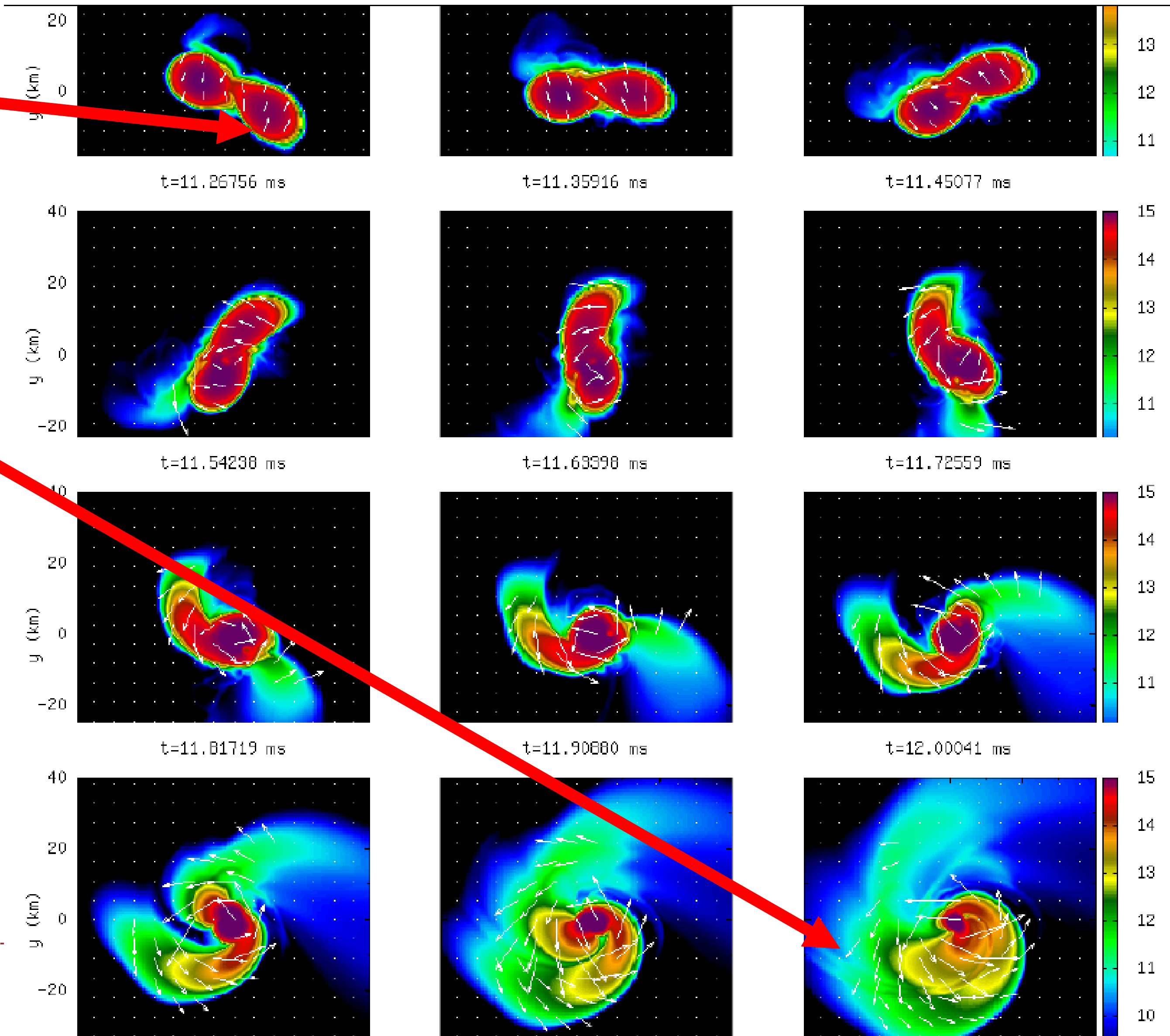
Animation by Hotokezaka

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

Dynamical Mass ejection from NS-NS merger (1): Tidal components

Korobkin et al. 2012; Rosswog et al. 2013; Hotokezaka et al. 2013; Bauswein 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

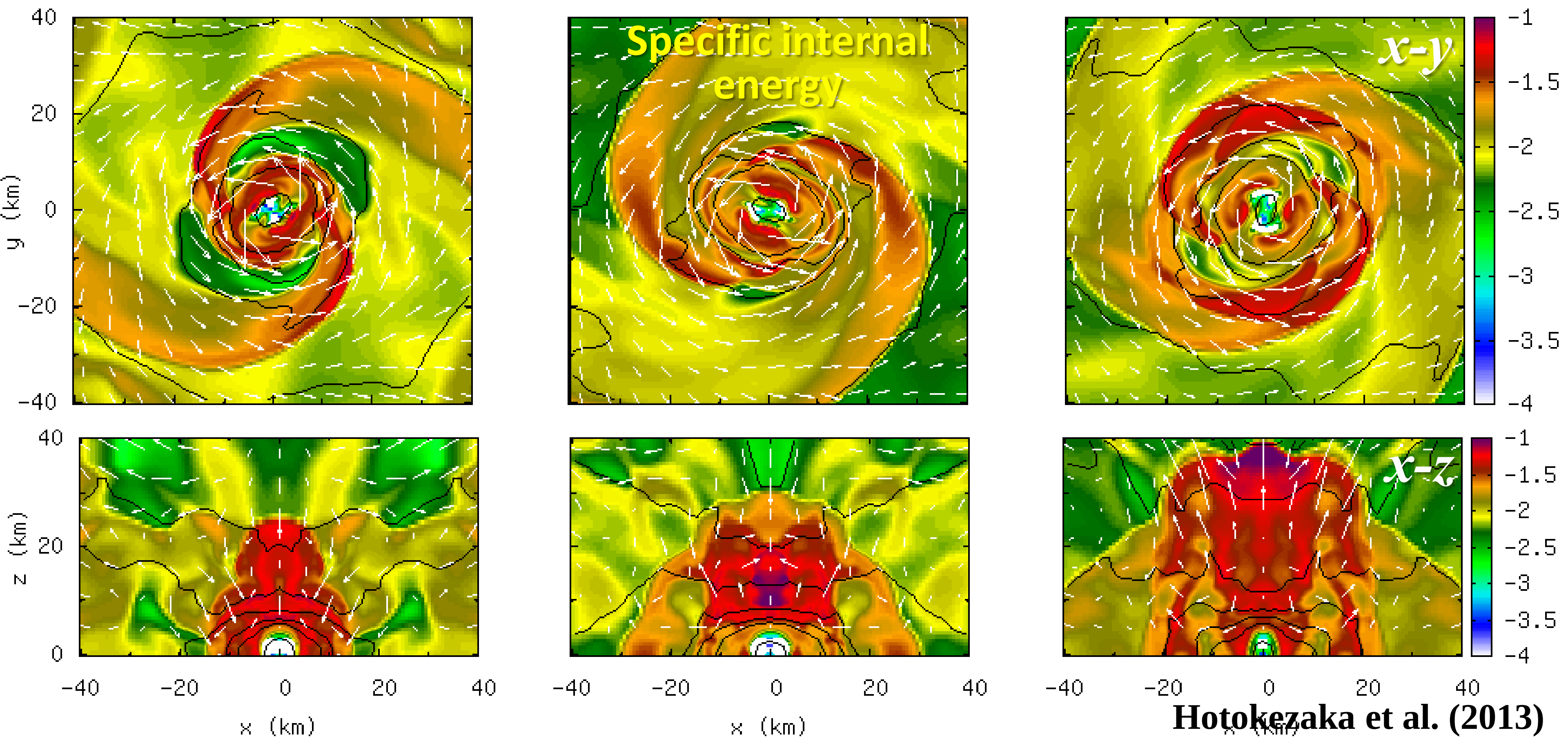


Density contour
[log (g/cm^3)]

Dynamical Mass ejection from NS-NS merger (2): Shock driven components

Hotokezaka et al. 2013; Bauswein et al. 2013

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



Hotokezaka et al. (2013)

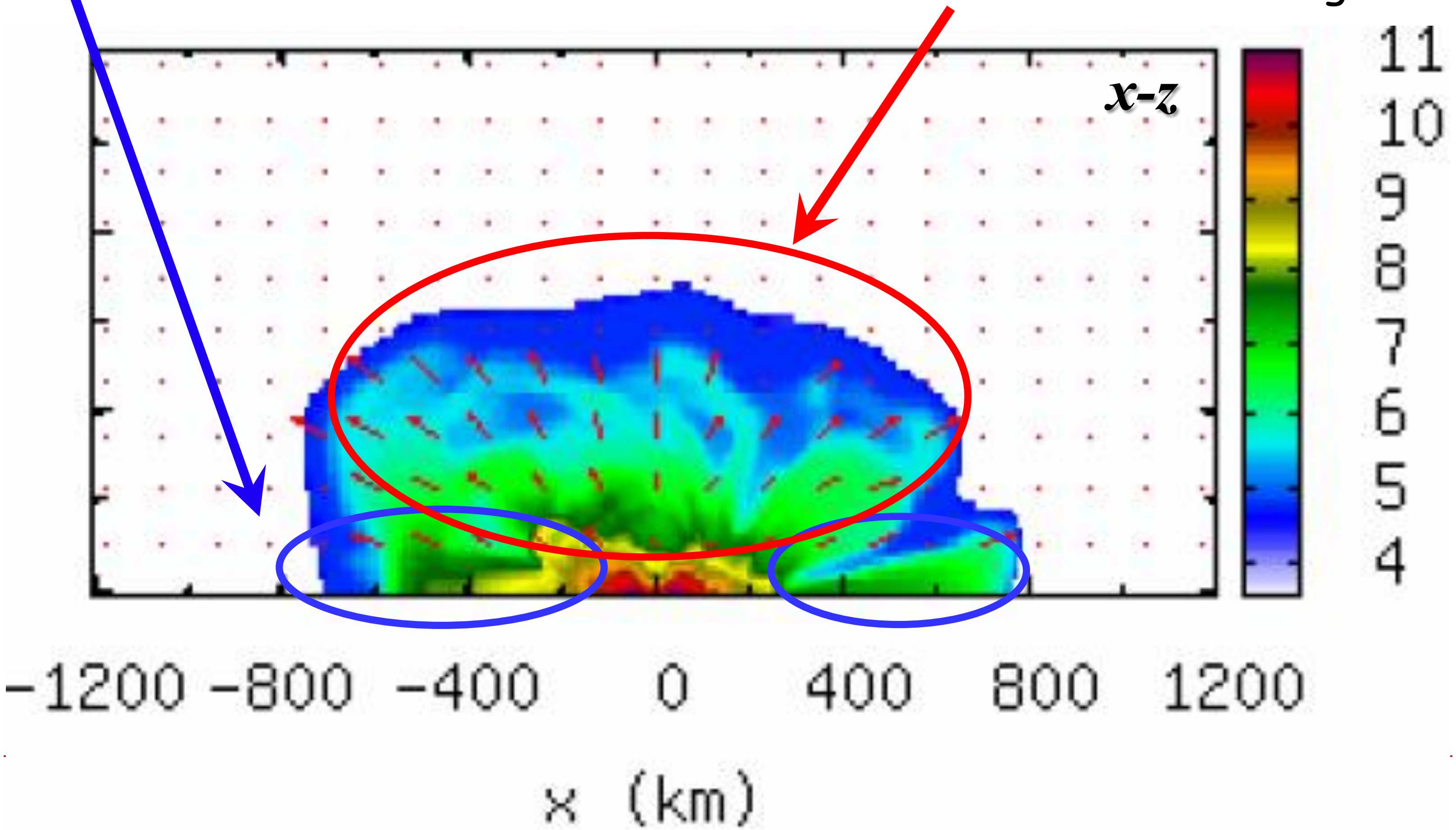
Dynamical mass ejection from NS-NS merger

- **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



(Expected) Mass ejection mechanism & EOS

- <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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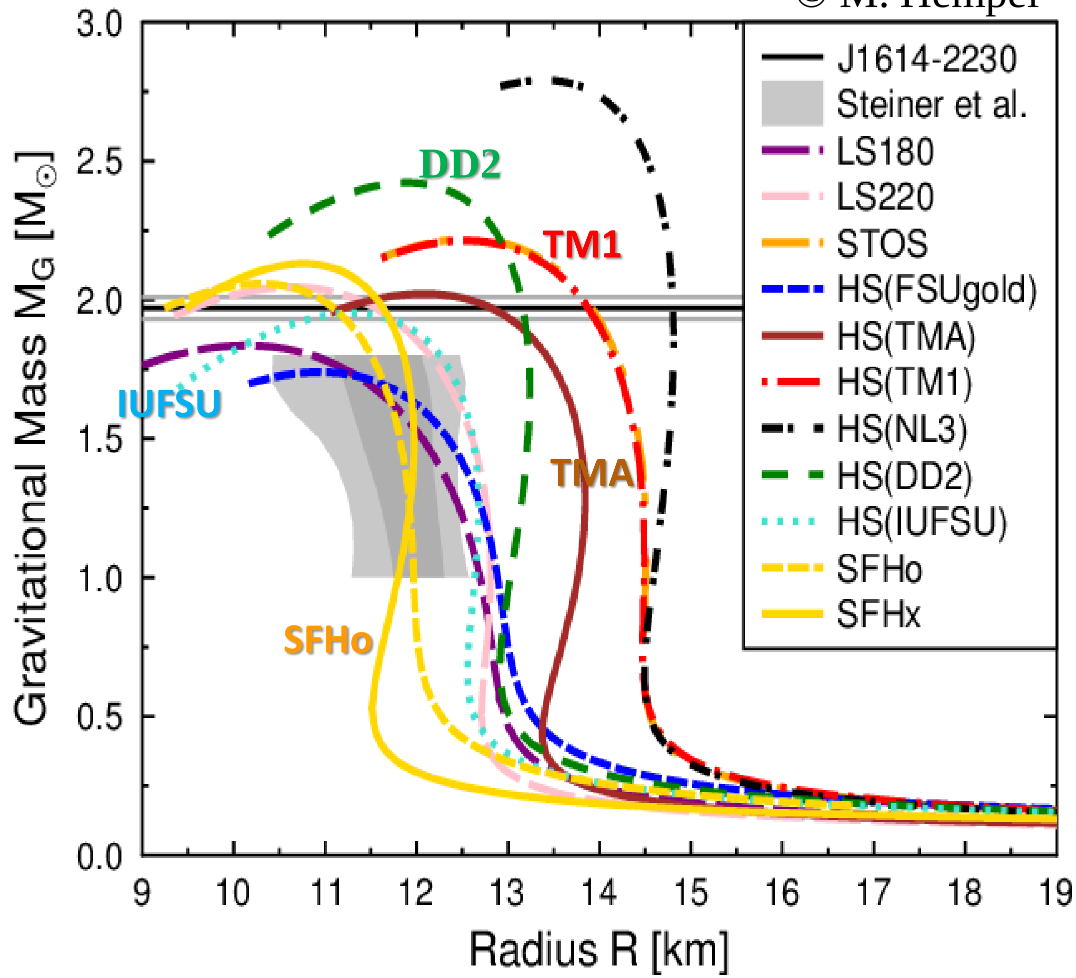
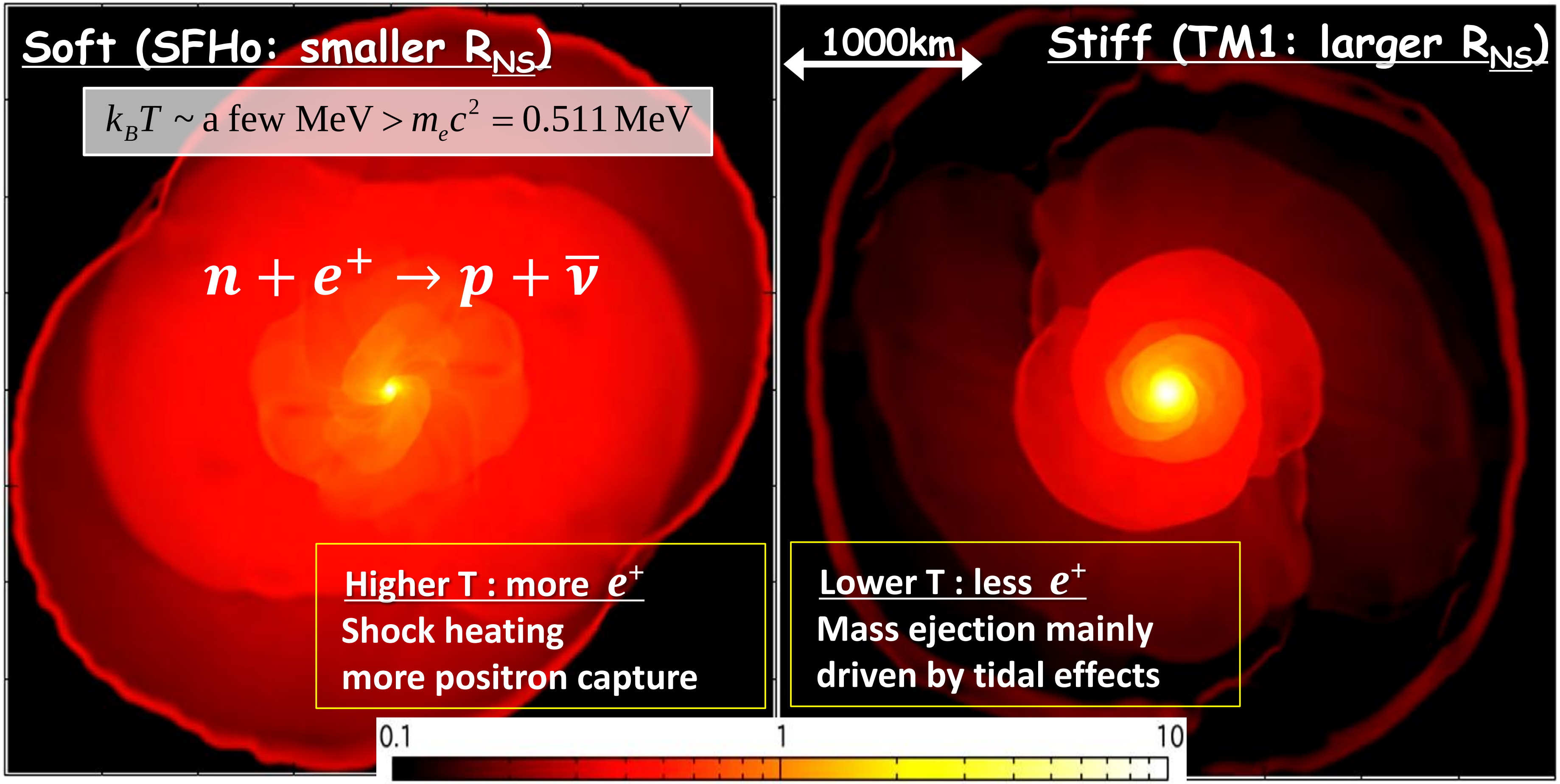


Soft(SFHo) vs. Stiff(TM1): Ejecta temperature

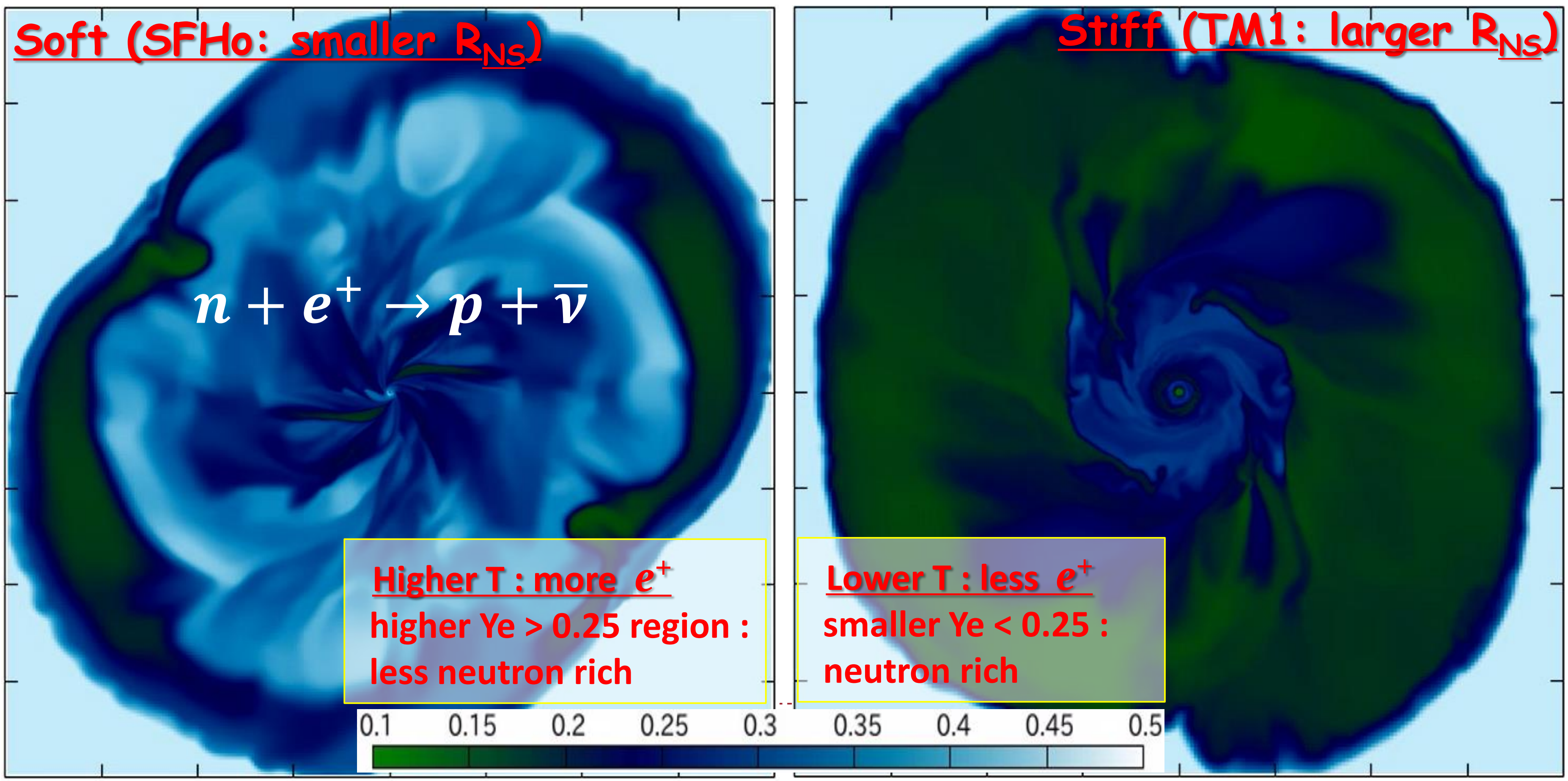
- Soft (SFHo): temperature of unbound ejecta is higher (as 1MeV) due to the shock heating, and produce copious positrons
- Stiff (TM1): temperature is much lower



Sekiguchi et al PRD (2015)

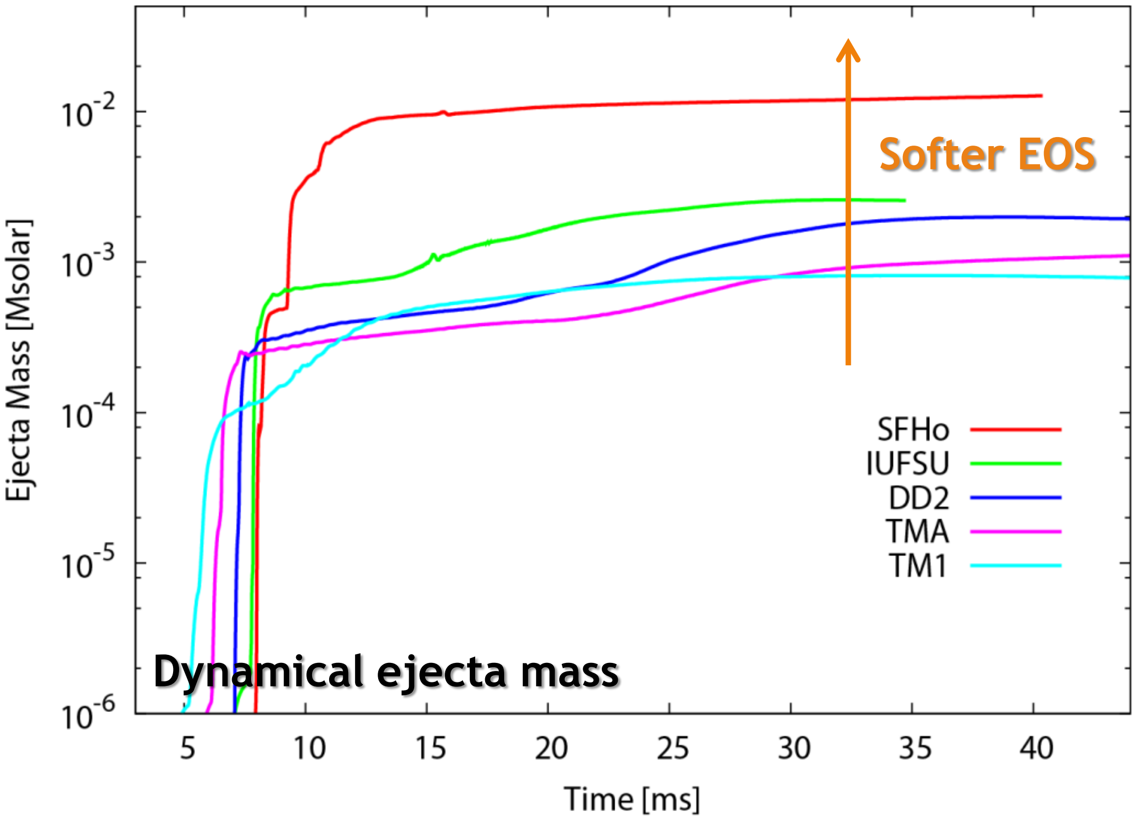
Soft(SFHo) vs. Stiff(TM1): Ejecta Ye = 1- Yn

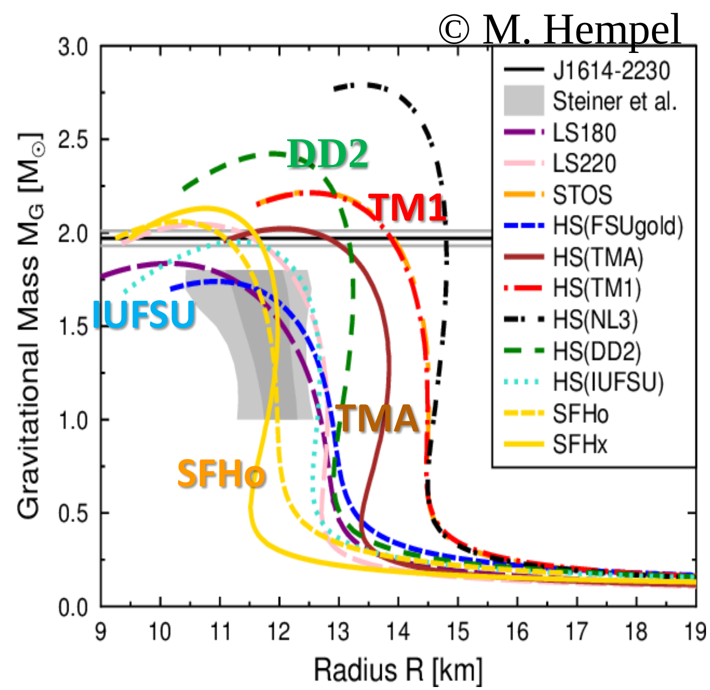
- Soft (SFHo): In the shocked regions, Ye >> 0.2 by weak processes
- Stiff (TM1): Ye is low as < 0.2 (only strong r-process expected)



Sekiguchi et al. 2015; Bauswein et al. 2013; Radice 2016 ; Lehner et al. 2016

EOS dependence : 1.35-1.35 NS-NS

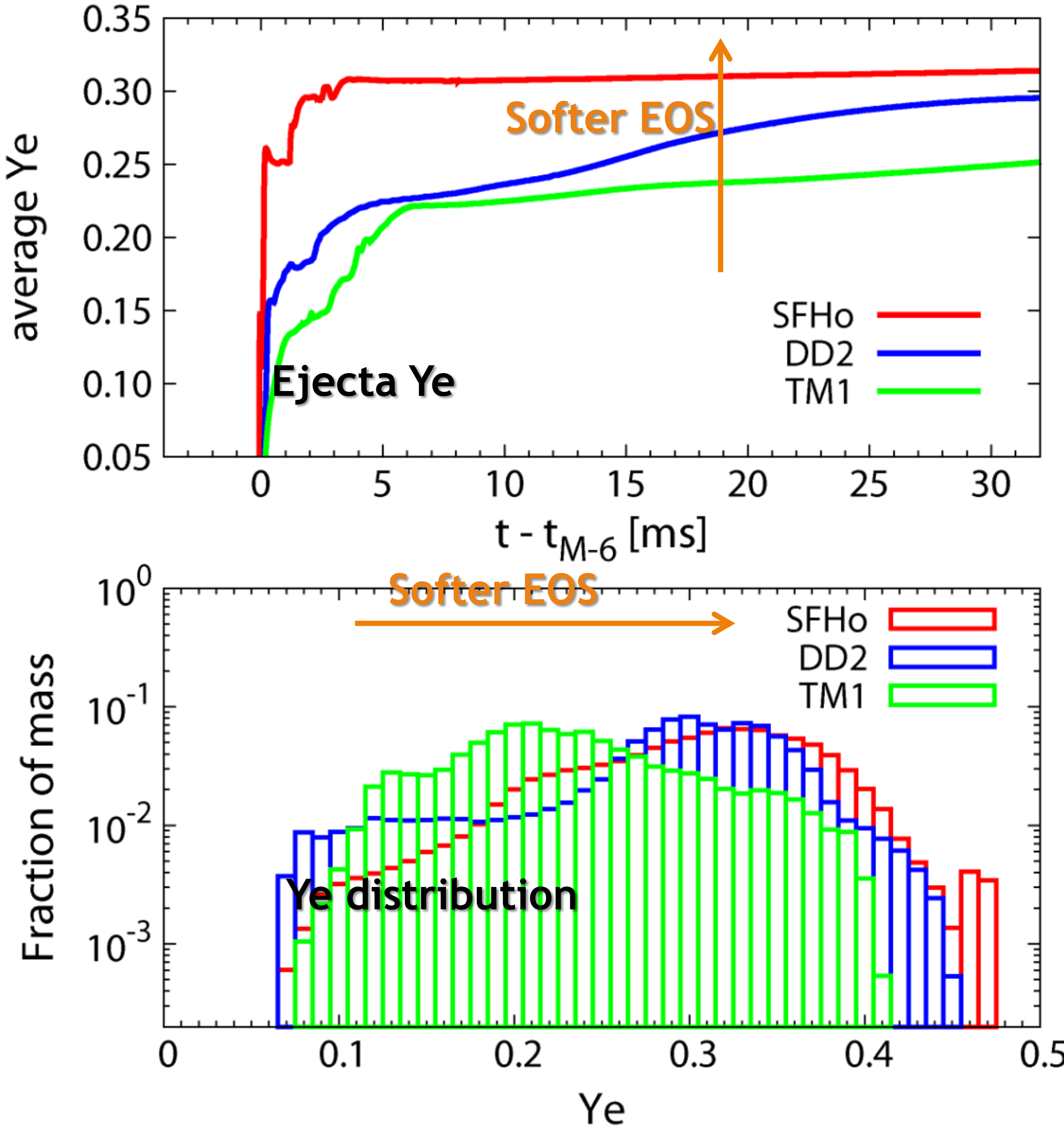




- Mej is larger for softer EOS : importance of shock heating and GR
- **Only SFHo achieves Mej ~ 0.01 Msun :** required by the total amount of r-process elements and flux of the 'kilonova' event (GRB 130603B)

EOS dependence : 1.35-1.35 NS-NS

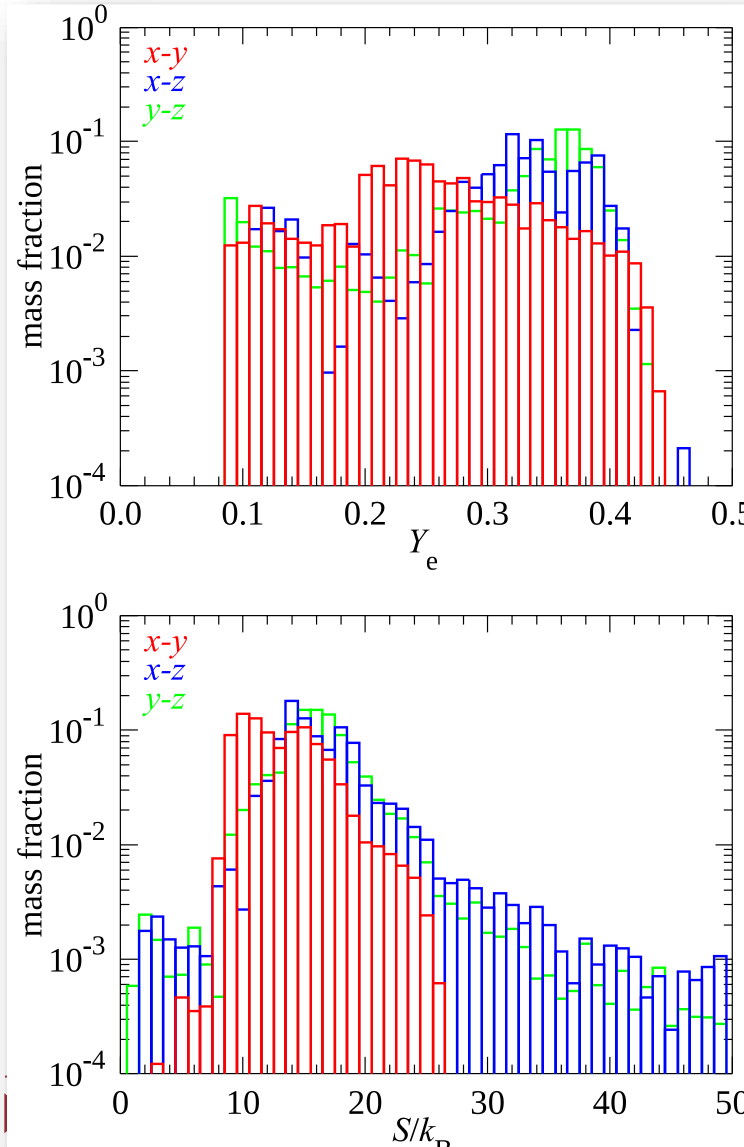
- Mass averaged Ye of the ejecta is larger for softer EOS
- But still neutron rich
- Ye distribution of the ejecta is broad irrespective of EOS
- **There are ejecta components with larger Ye**

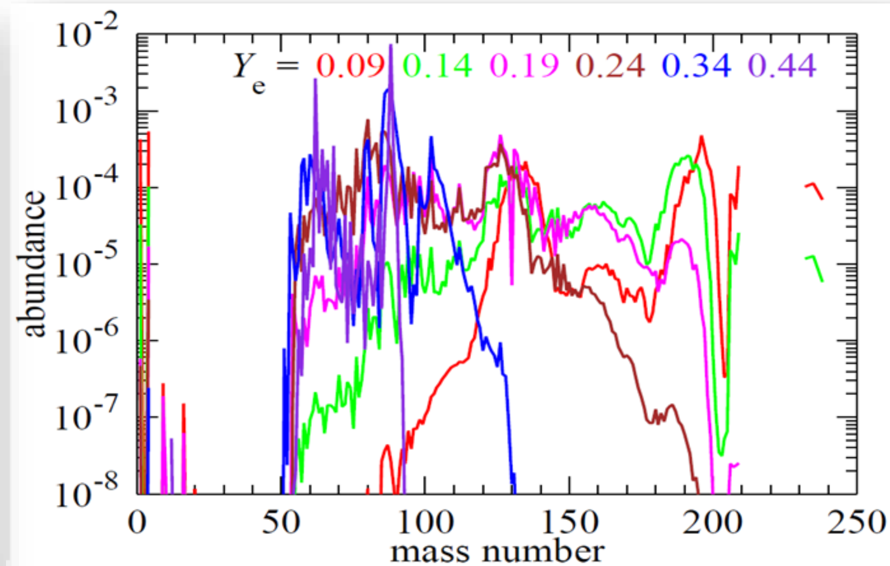


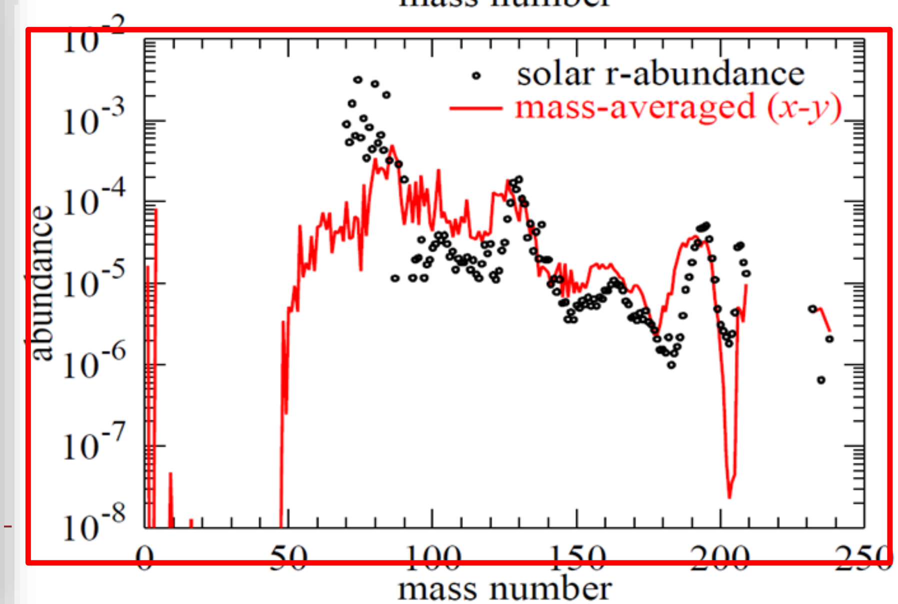
Wanajo, Sekiguchi et al. ApJL (2014)

Achievement of the universality

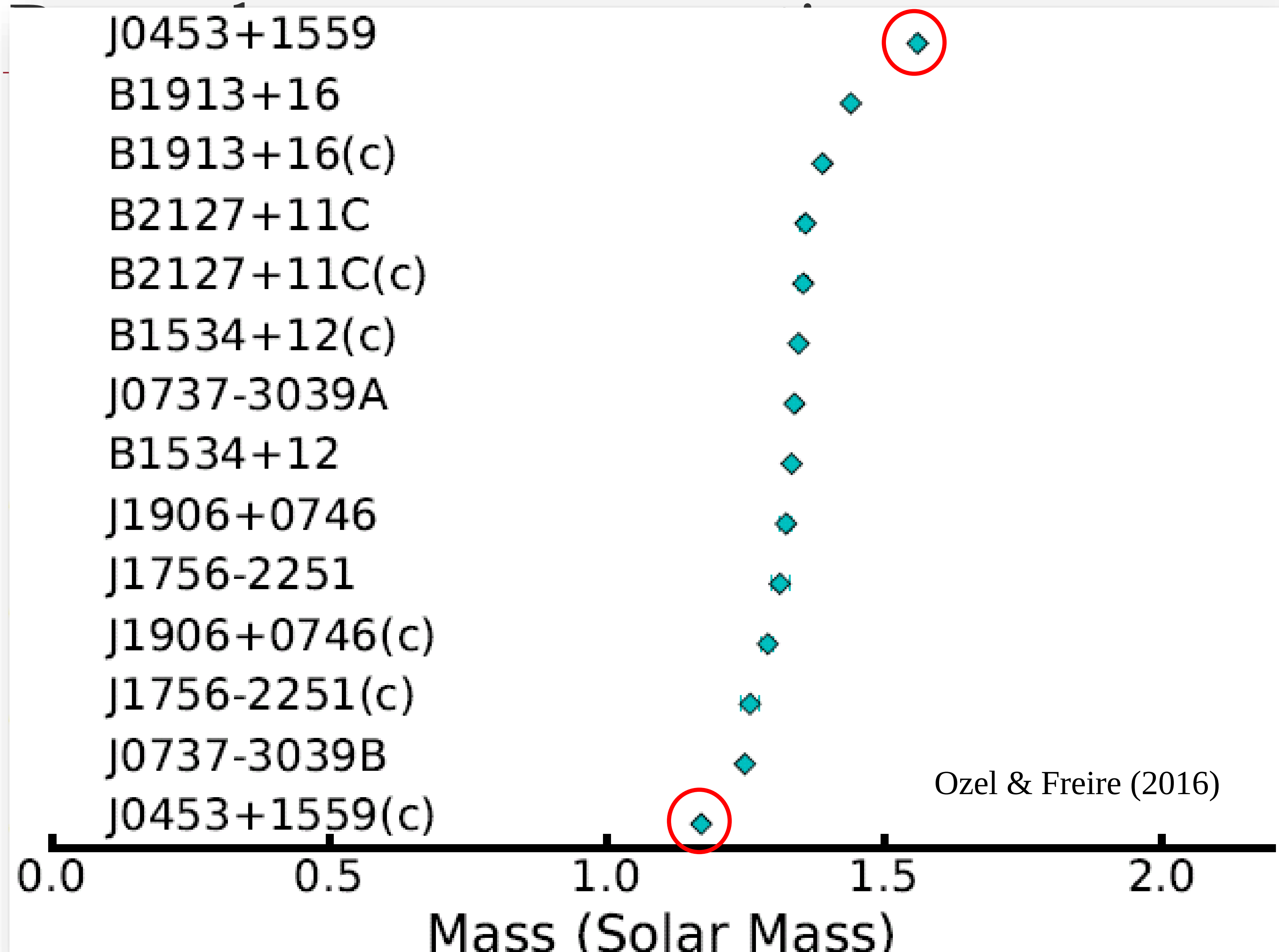
(soft EOS (SFHo), equal mass (1.35-1.35))







Sekiguchi et al. 2016; Bauswein et al. 2013; Lehner et al. 2016



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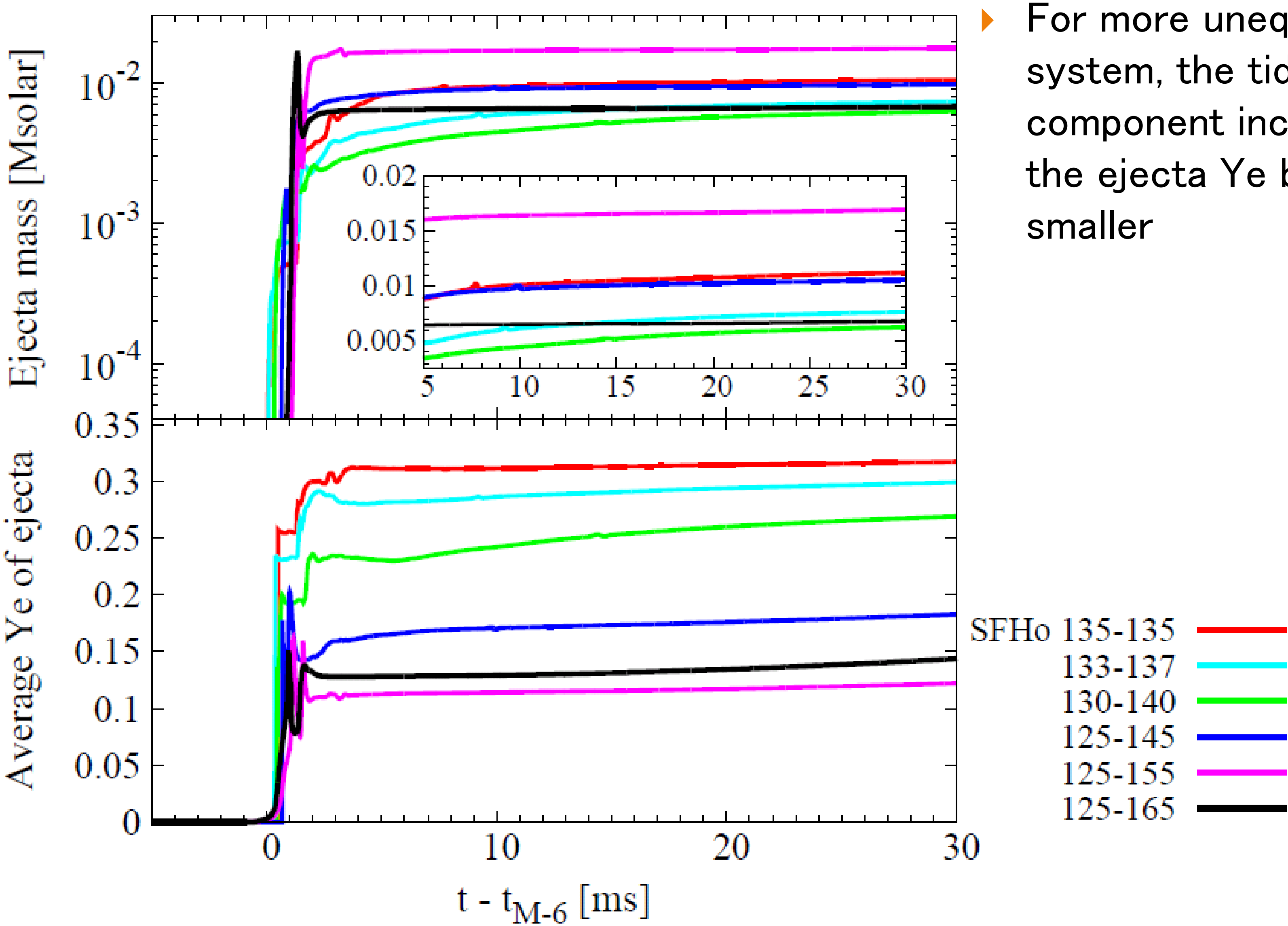
Dependence on mass ratio

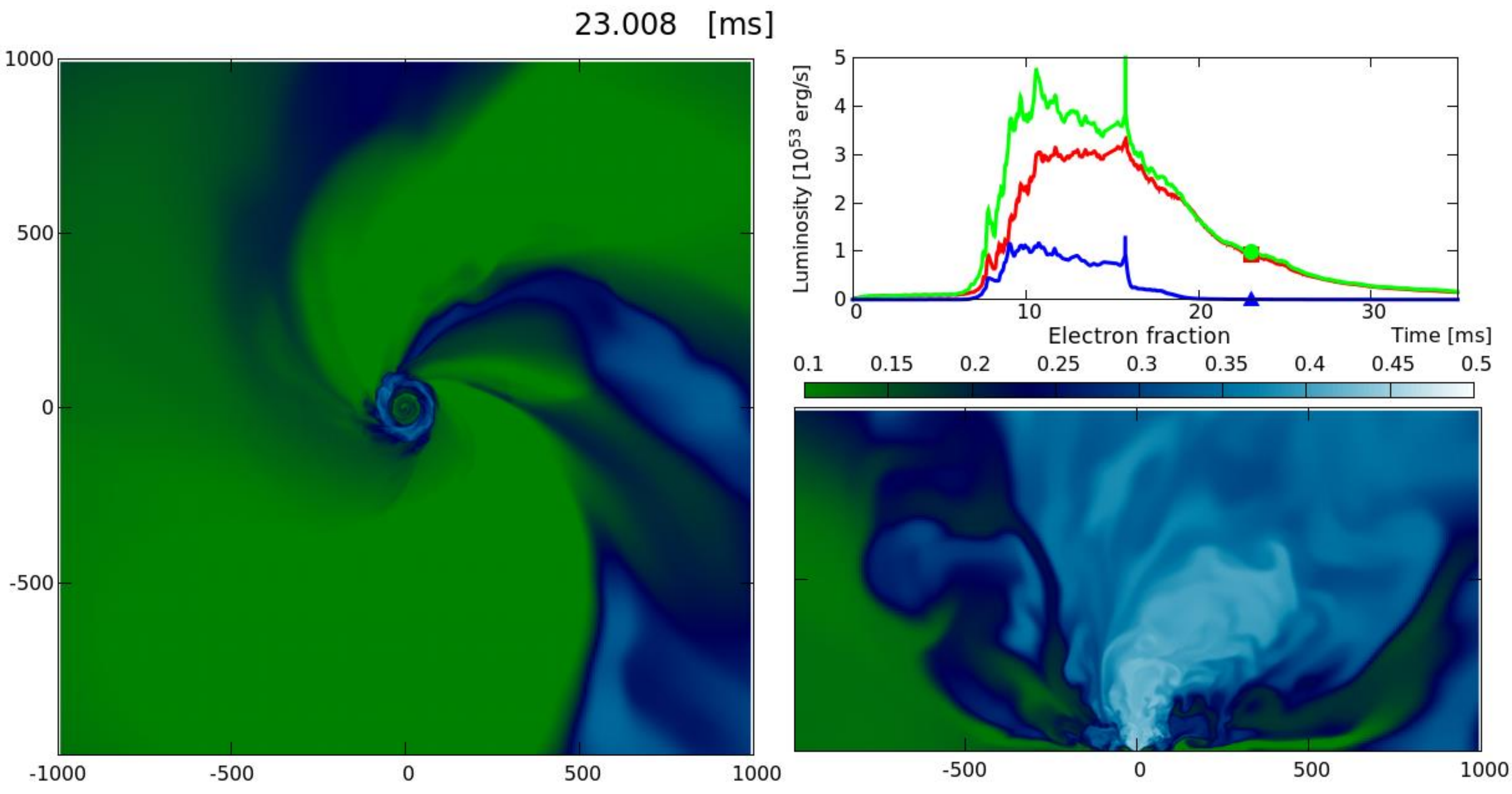


- For more unequal mass system, the tidal ejecta component increases and the ejecta Ye becomes smaller

Sekiguchi et al. 2016; Bauswein et al. 2013; Lehner et al. 2016

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

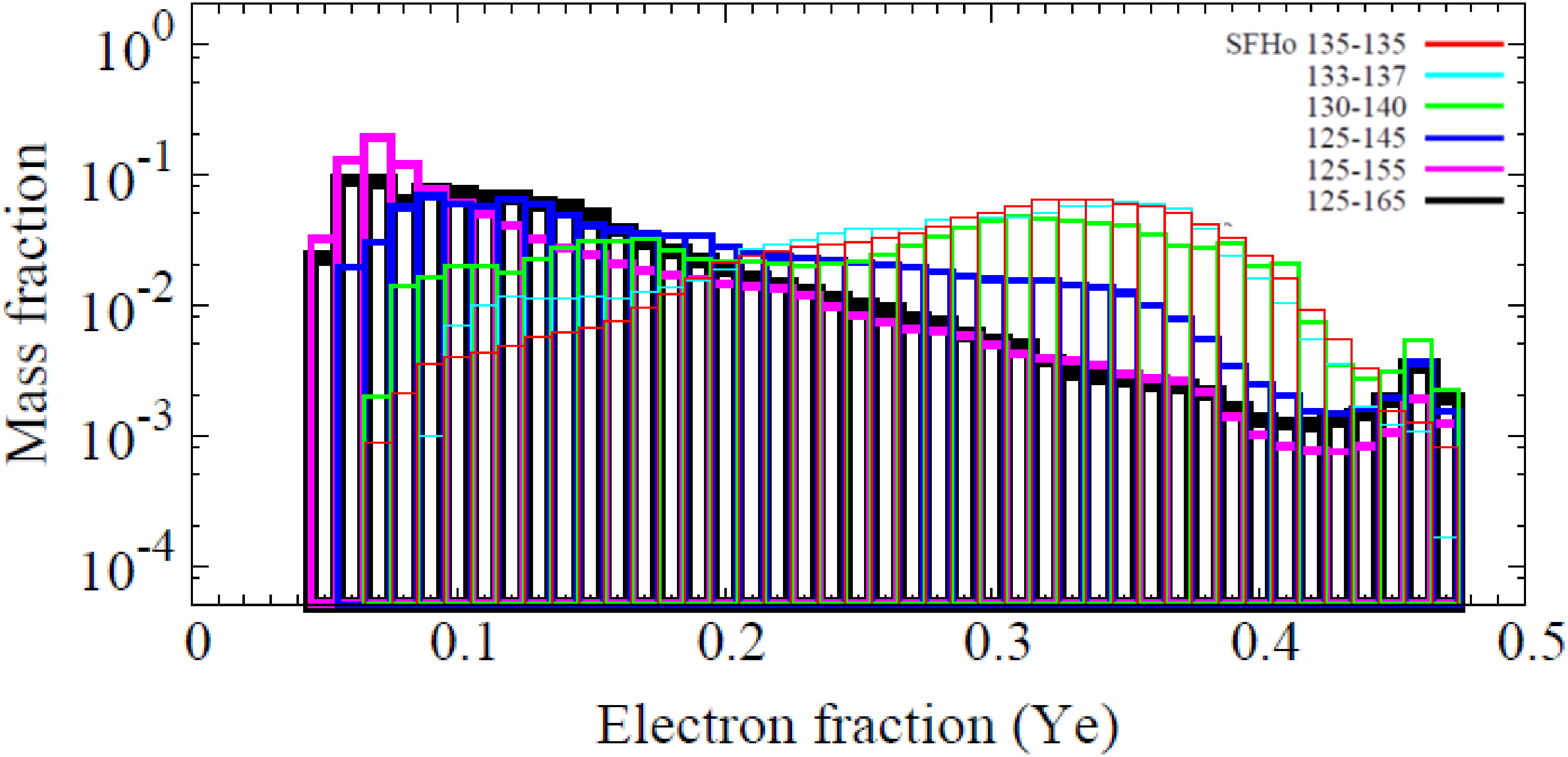
- Orbital plane : Tidal effects play a role, ejecta is neutron rich
- Meridian plane : shock + neutrinos play roles, ejecta less neutron rich



Sekiguchi et al. 2016; Bauswein et al. 2013; Lehner et al. 2016

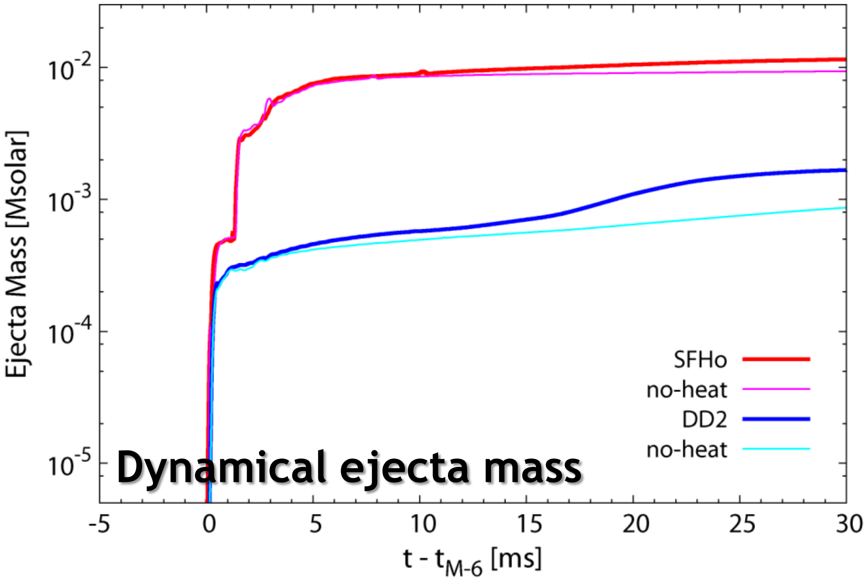
Dependence on mass ratio

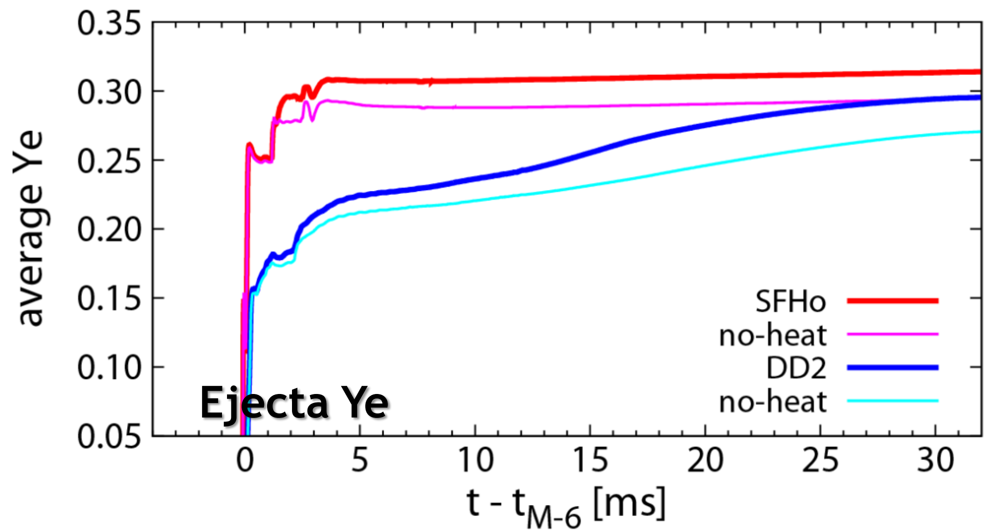
- Ye distribution is still wide if mass ratio is not very far from unity
  - For mass ratio larger than 1.25-1.45 model, Ye distributes in smaller values



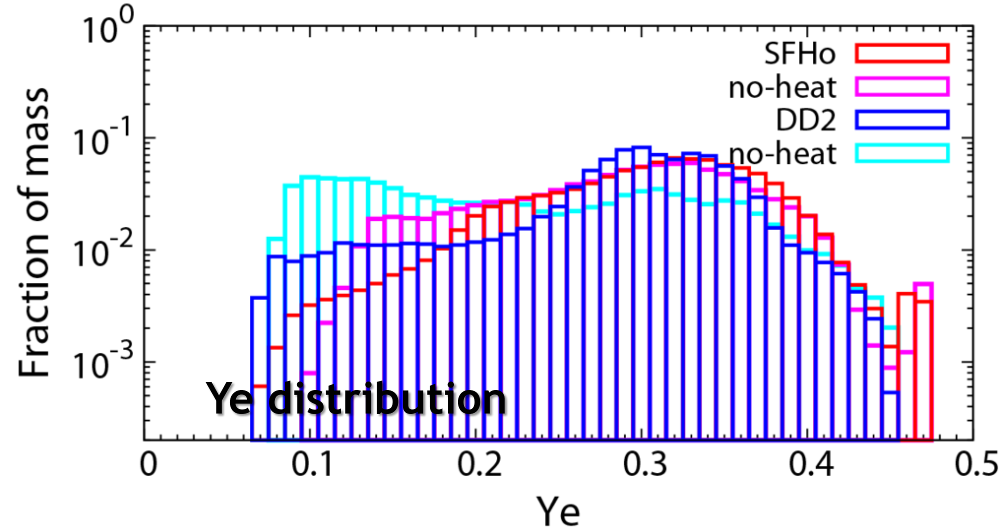
Sekiguchi et al. 2015; Prego et al. 2014; Goriely et al. 2015; Martin et al. 2015; Foucart et al. 2016

Importance of neutrino absorption





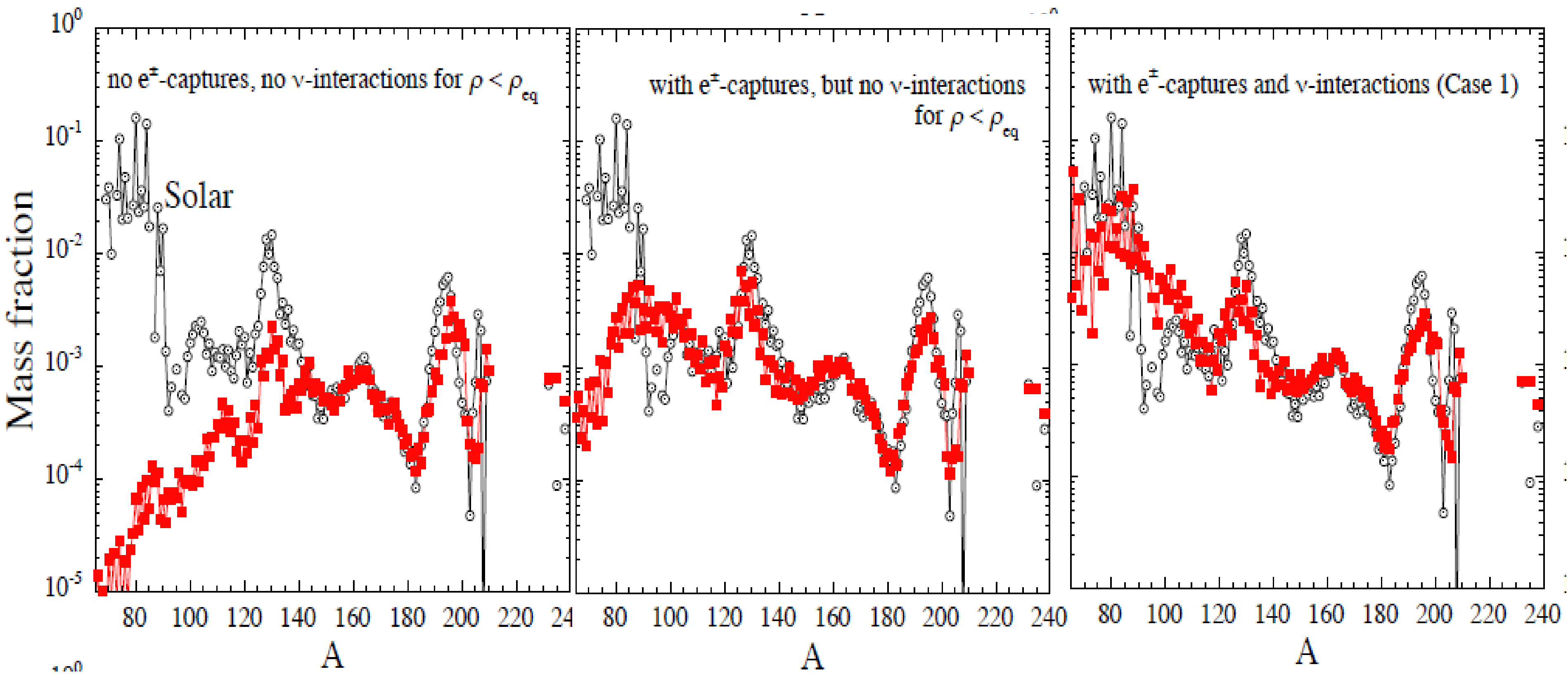
- Amount of ejecta mass can be increased order of 10^{-3} Msun
- Average Ye can change 0.02~0.03 depending on EOS : effect is stronger for stiffer EOS with which HMNS survive in a longer time



Goriely et al. 2015

Importance of weak interactions

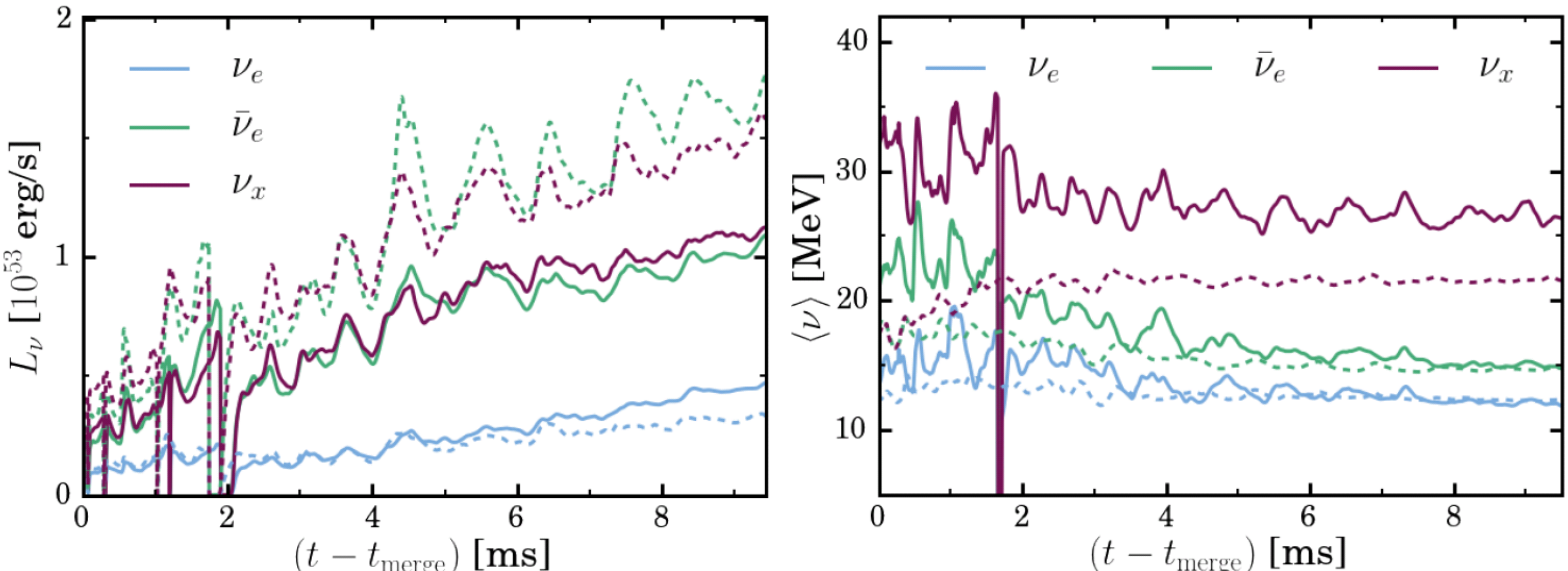
- Goriely et al. 2015 studied in more detail the effects of weak interaction on the resulting r-process pattern
- e± captures fill in the gap in A = 90-130
- Neutrino absorption contributes to synthesize the 1st peak



Foucart et al. 2016

Importance of neutrino energy estimate

- There is also uncertainty in the neutrino energy estimate in gray neutrino transport codes which are currently available
- Foucart et al. developed an improved method of neutrino average energy estimation based on a conserved neutrino number density
- Impact is small for the dynamical ejecta mass but large for the ejecta Ye
  - The previous estimate predict strong r-process (lanthanoid) in the polar region



Solid : improved energy estimate **Dashed: previous estimate**

Importance of neutrino energy estimate

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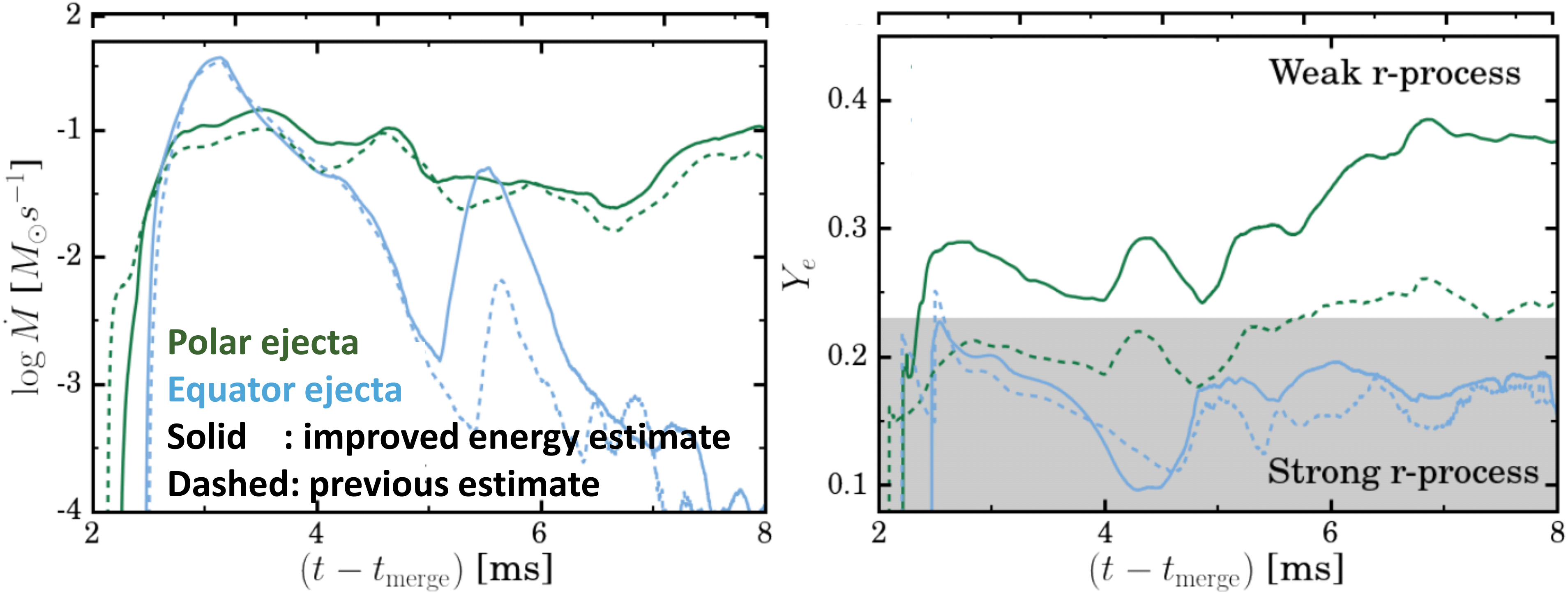
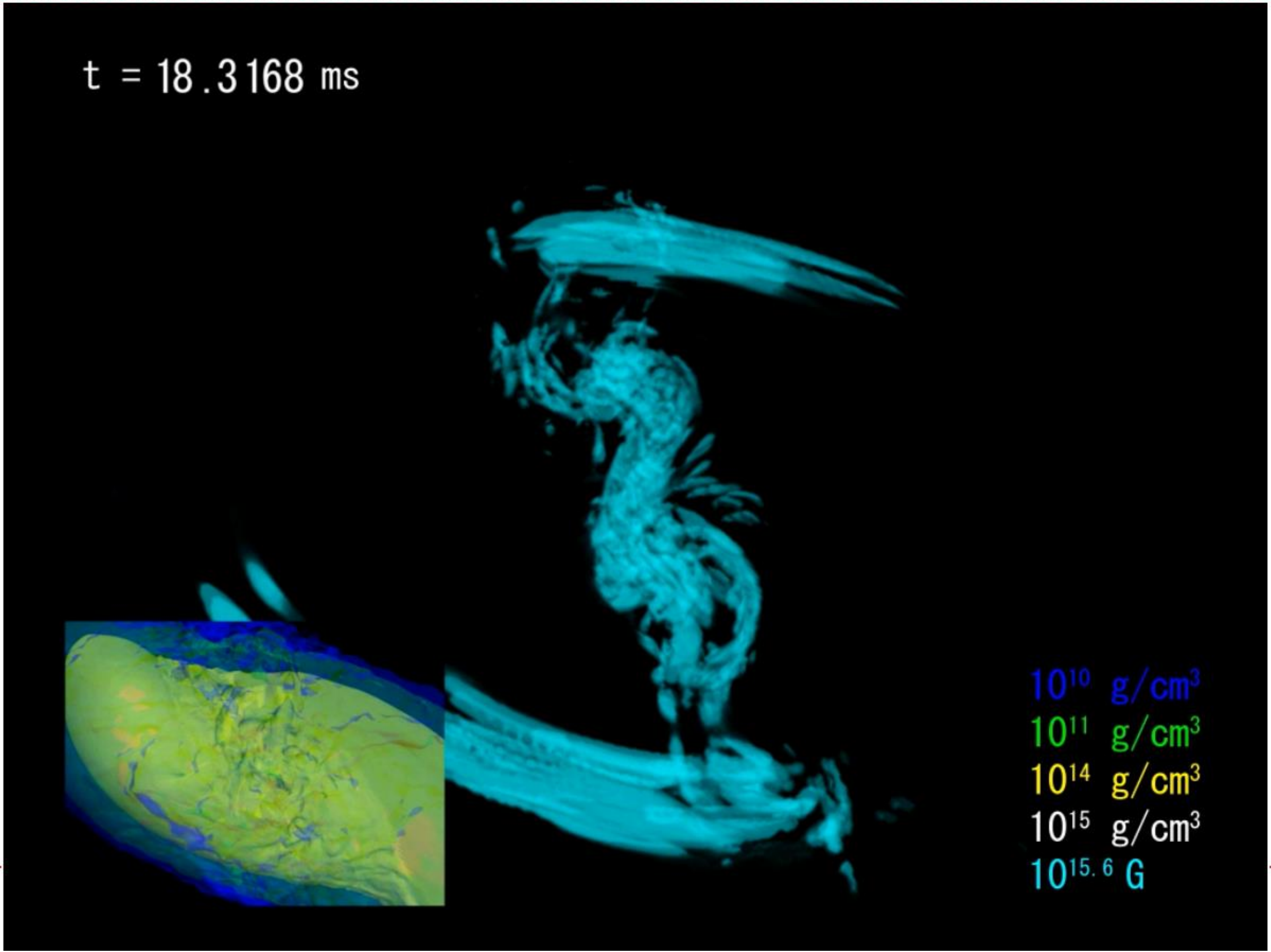
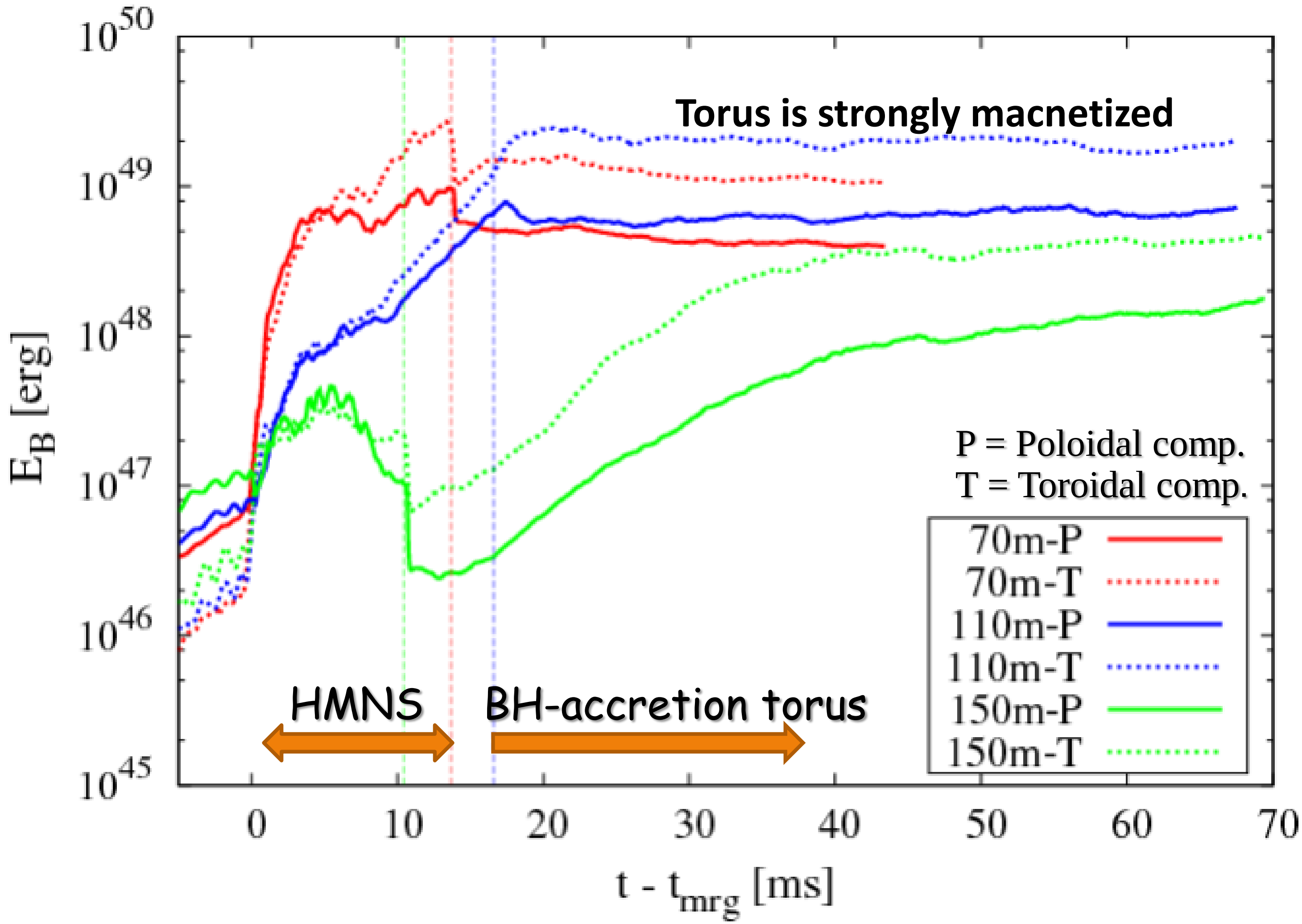


Kiuchi et al. (2014, 2015)

Importance of magnetic fields
Magnetized NS-NS merger simulation

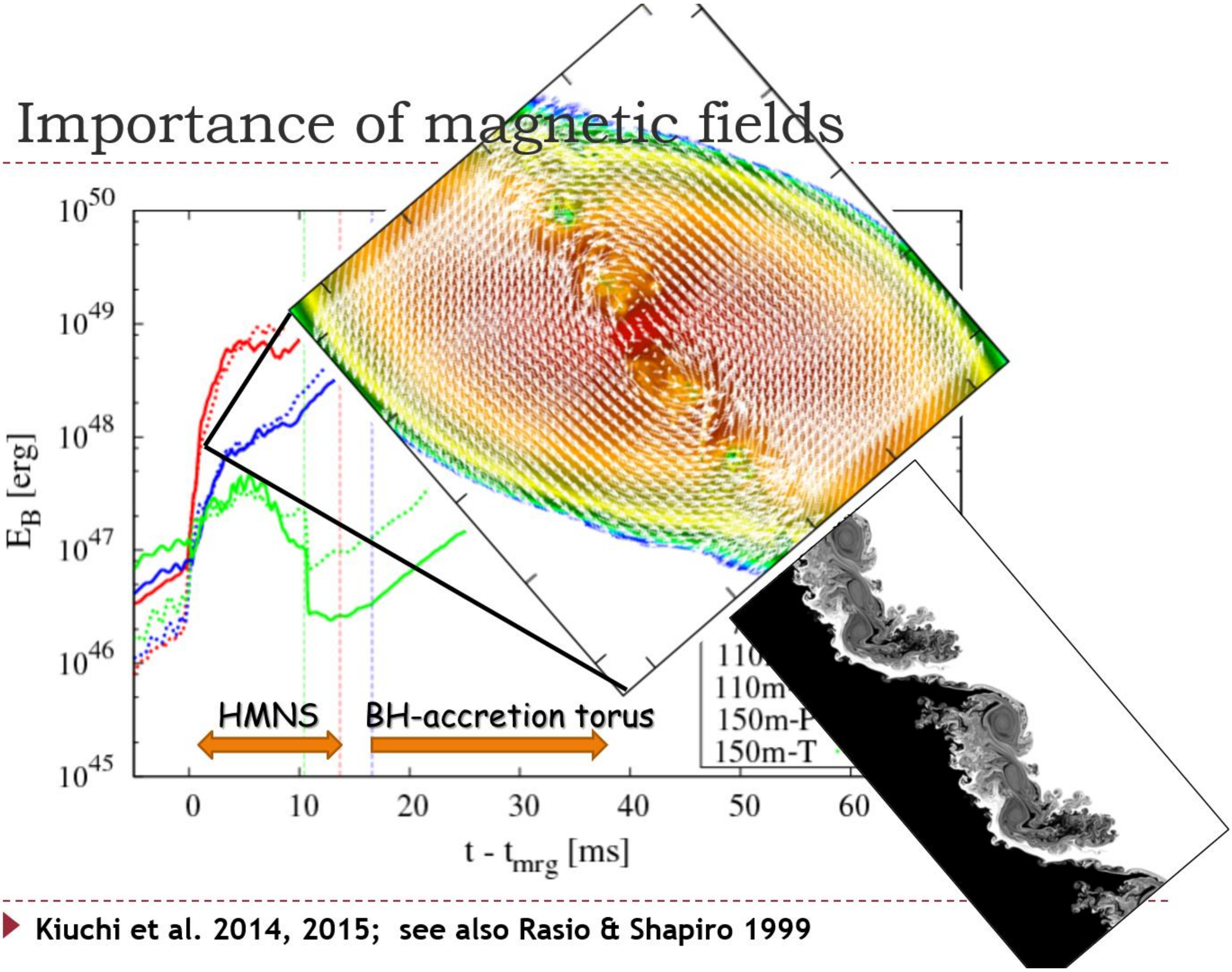


Importance of magnetic fields



- **Kiuchi et al. 2014, 2015; see also Rasio & Shapiro 1999**

Importance of magnetic fields



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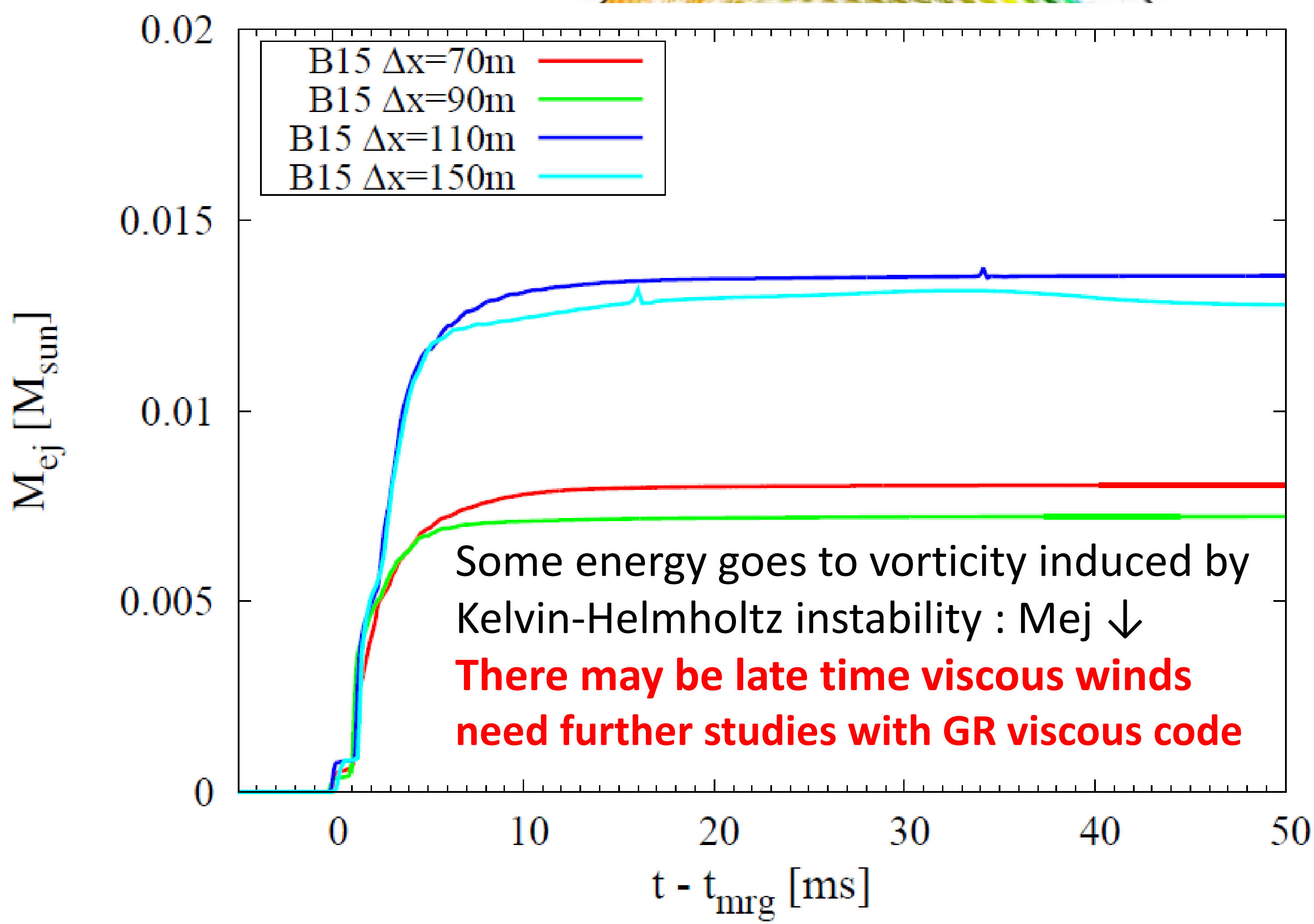
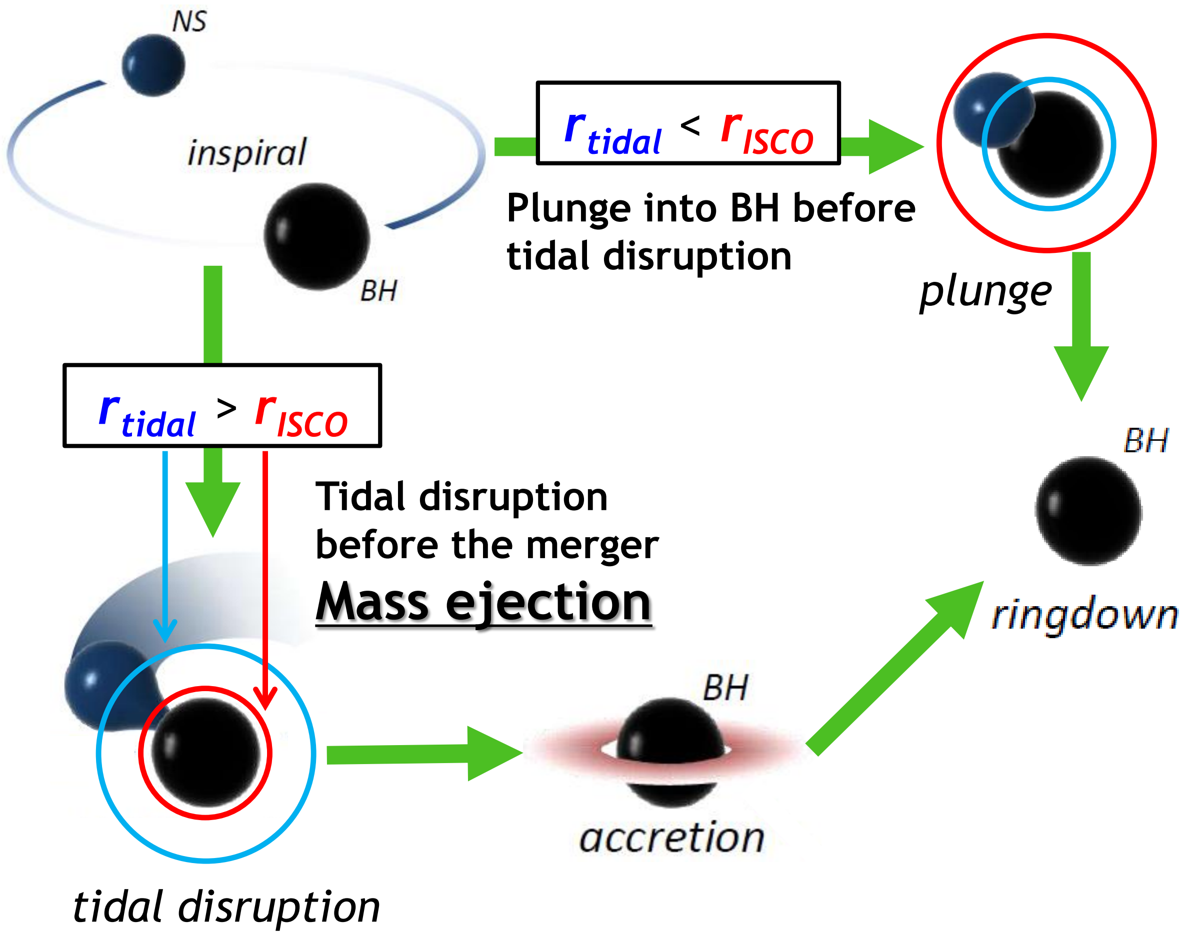


- **Kiuchi et al. 2014, 2015; see also Rasio & Shapiro 1999**

Shibata & Taniguchi (2008); Kyutoku et al. (2010, 2011)
Fourcart et al. (2014,2015); Kyutoku, YS et al. in prep

BH-NS merger



r_{ISCO}: **Innermost Stable Circular Orbit**

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

Depends on BH spin

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

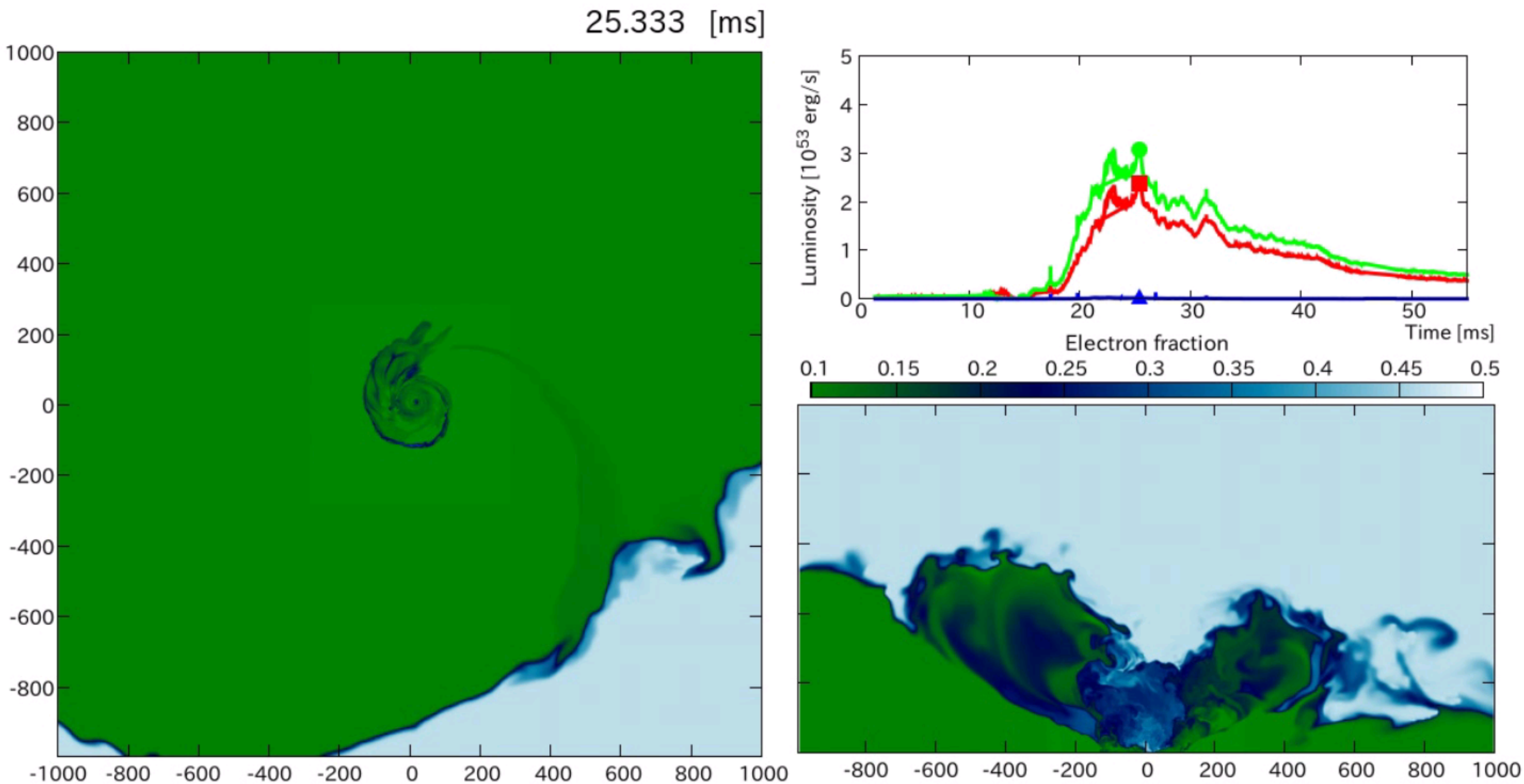
Tidal radius : r_{tidal}

tidal force = self gravity of NS

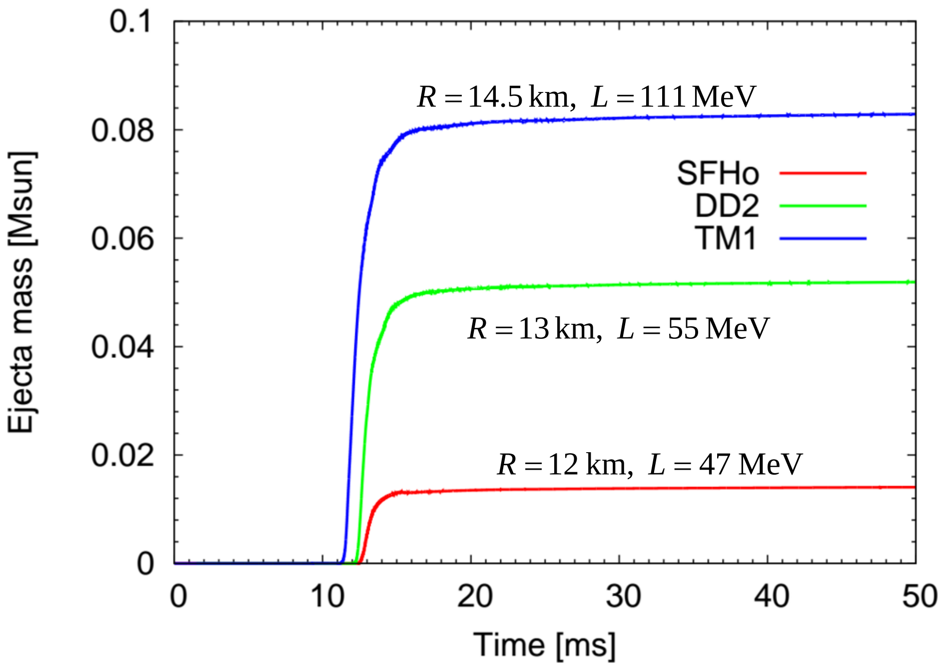
$$\frac{r_{\rm tidal}}{M_{\rm BH}} = \left(\frac{M_{\rm NS}}{M_{\rm BH}}\right)^{2/3} \left(\frac{M_{\rm NS}}{R_{\rm NS}}\right)^{-1}$$

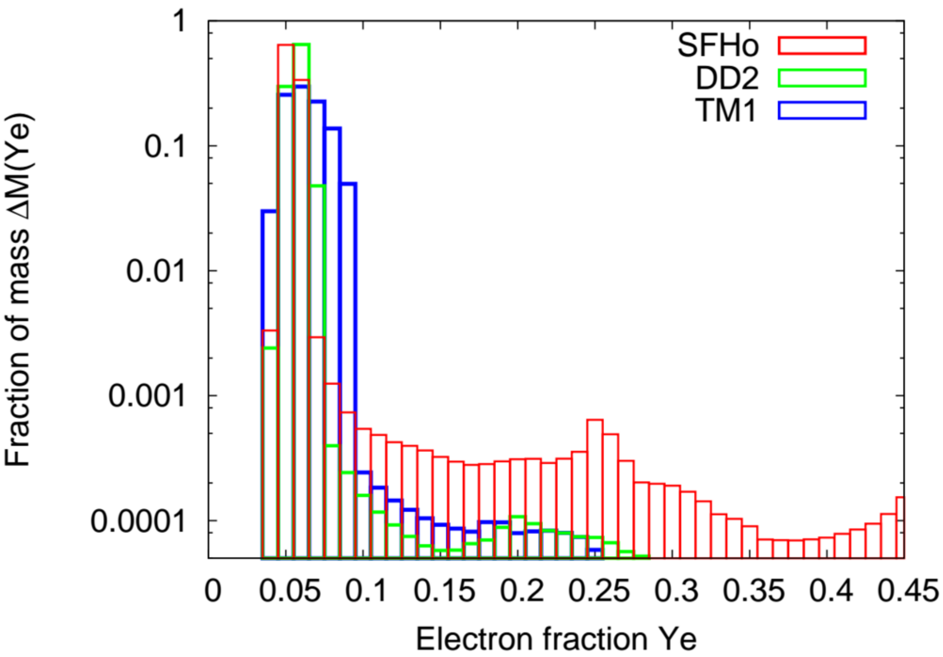
Depends on NS structure (EOS)

BH-NS merger dynamics (DD2 EOS: Ye)
$M_{BH}=5.4M_{sun}$, $M_{NS}=1.35M_{sun}$, $a_{BH}=0.75$



EOS dependence of the ejecta property

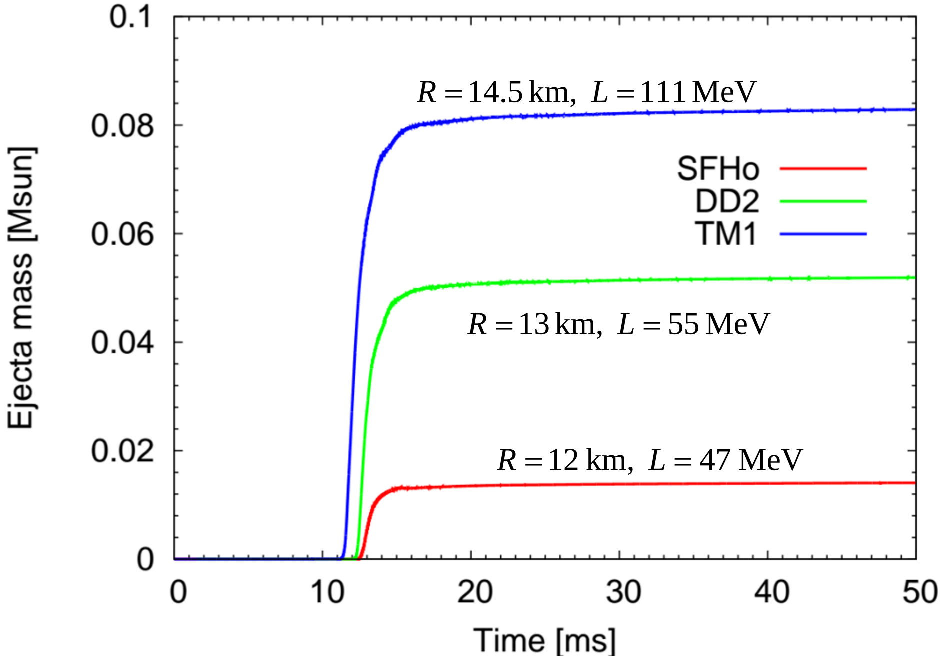


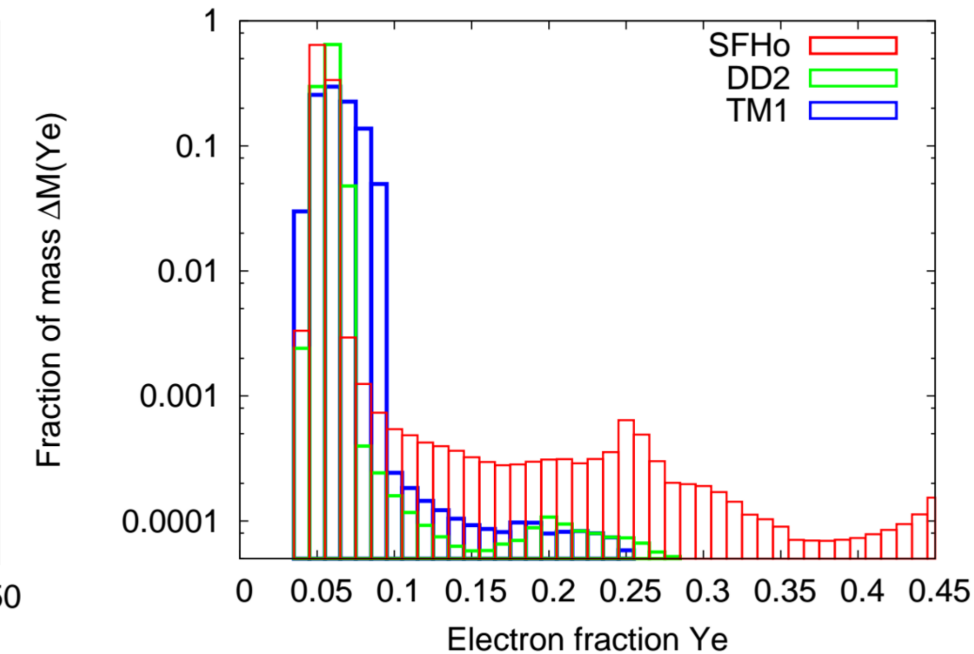


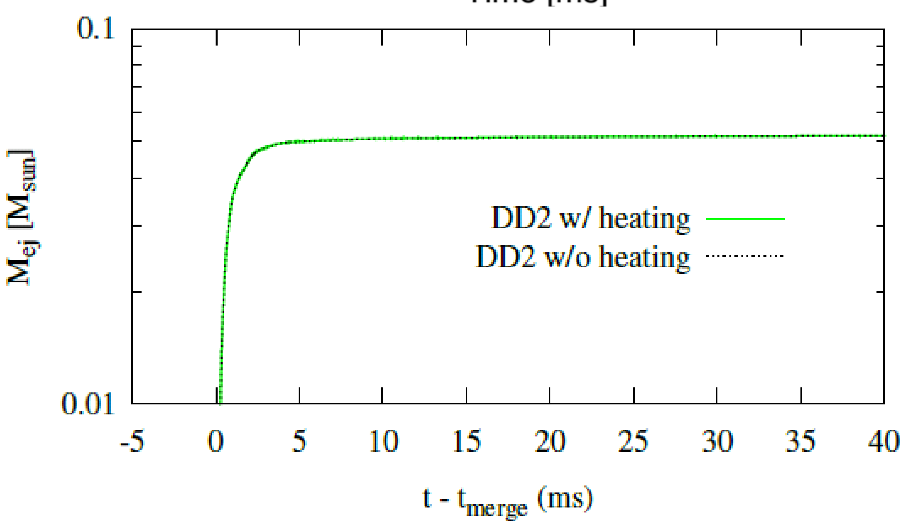
- The large amount of mass is tidally ejected
  - **Ejecta mass is larger for stiffer EOS (larger R_{NS})**
- Ejecta Ye is very small as < 0.1
  - Only strong r-process will occur : problem in terms of universality ??
- Effects of neutrino-matter interaction is very small

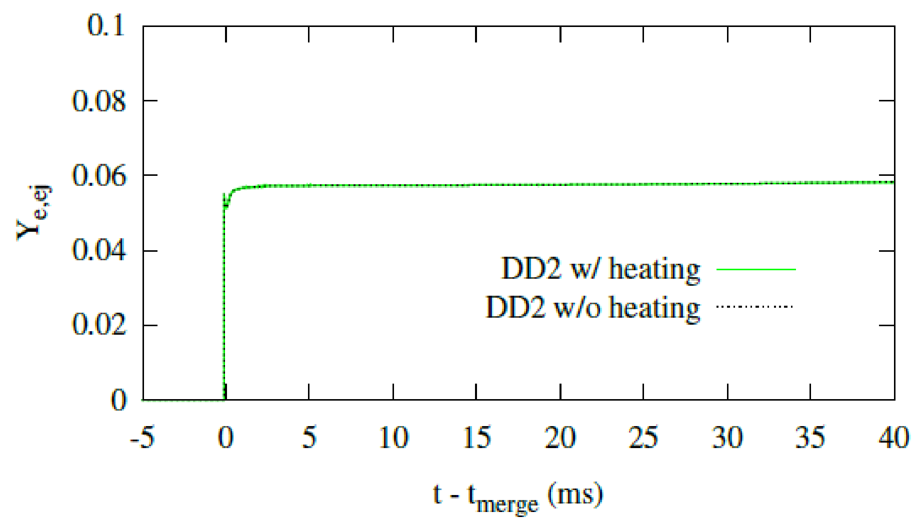
Fourcart et al. (2014,2015); Kyutoku, YS et al. in prep

EOS dependence of the ejecta property

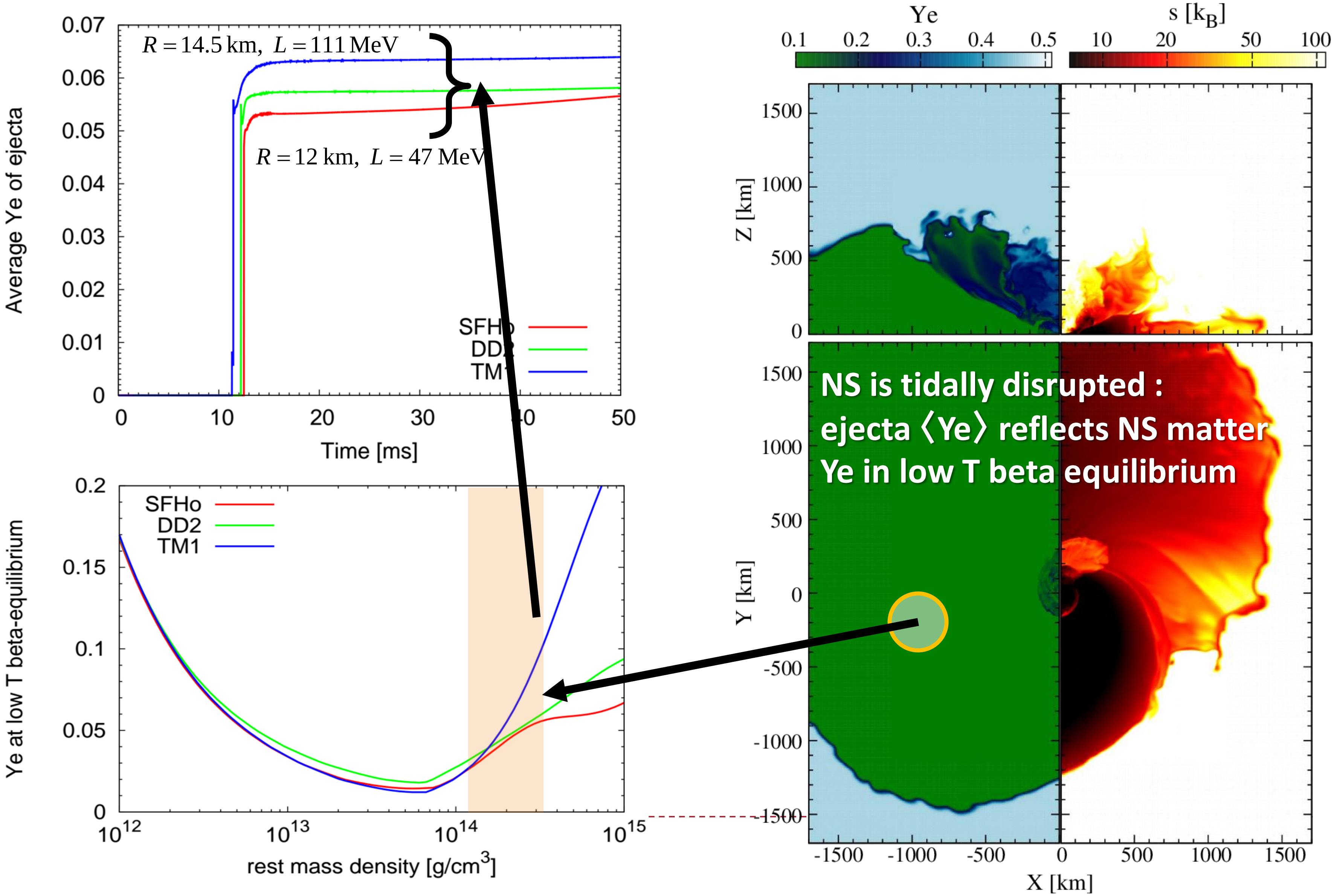






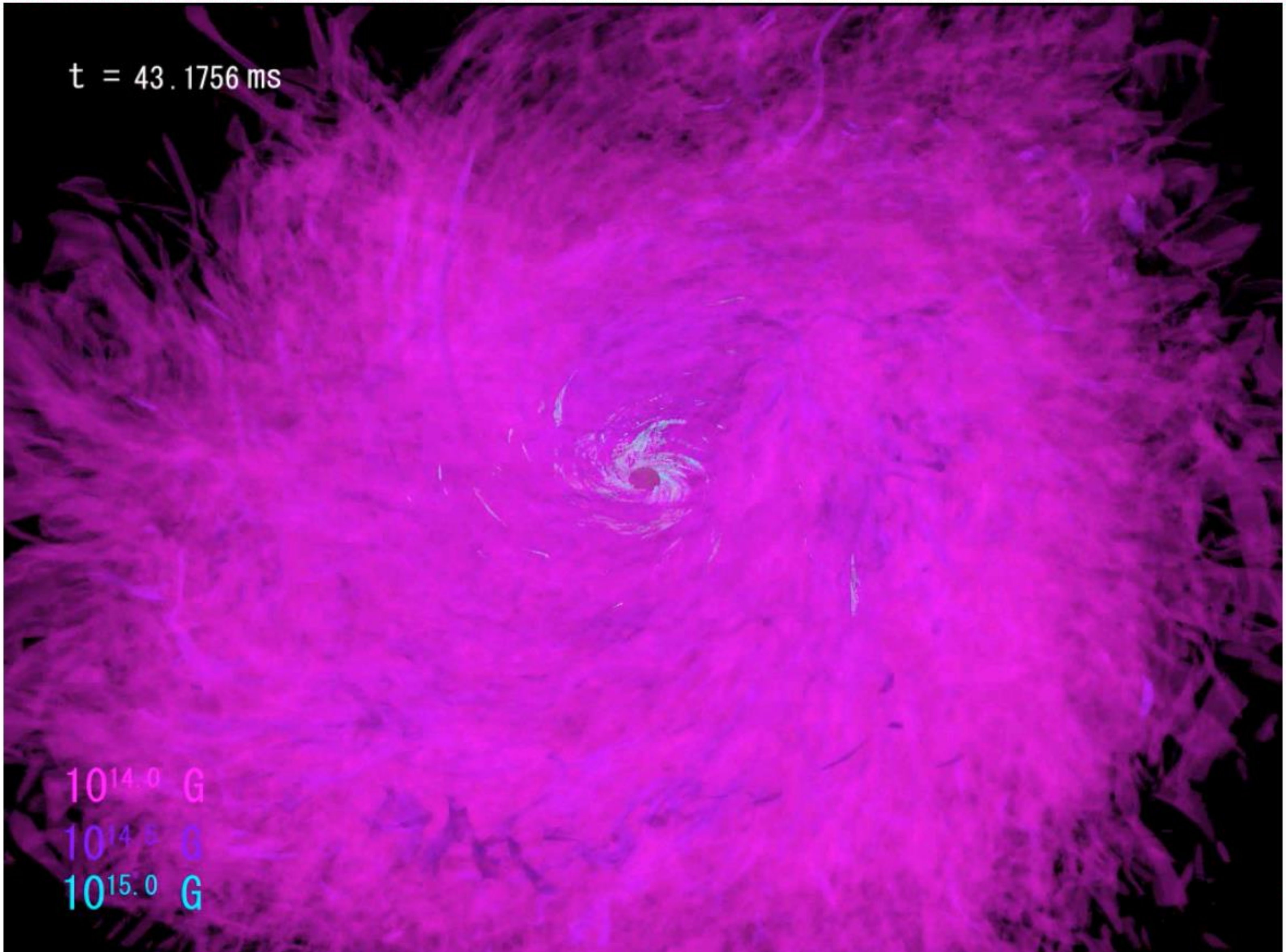


Ejecta Ye reflects the symmetry energy



Magnetically driven torus winds are very important in BH-NS !

Kiuchi et al. 2015



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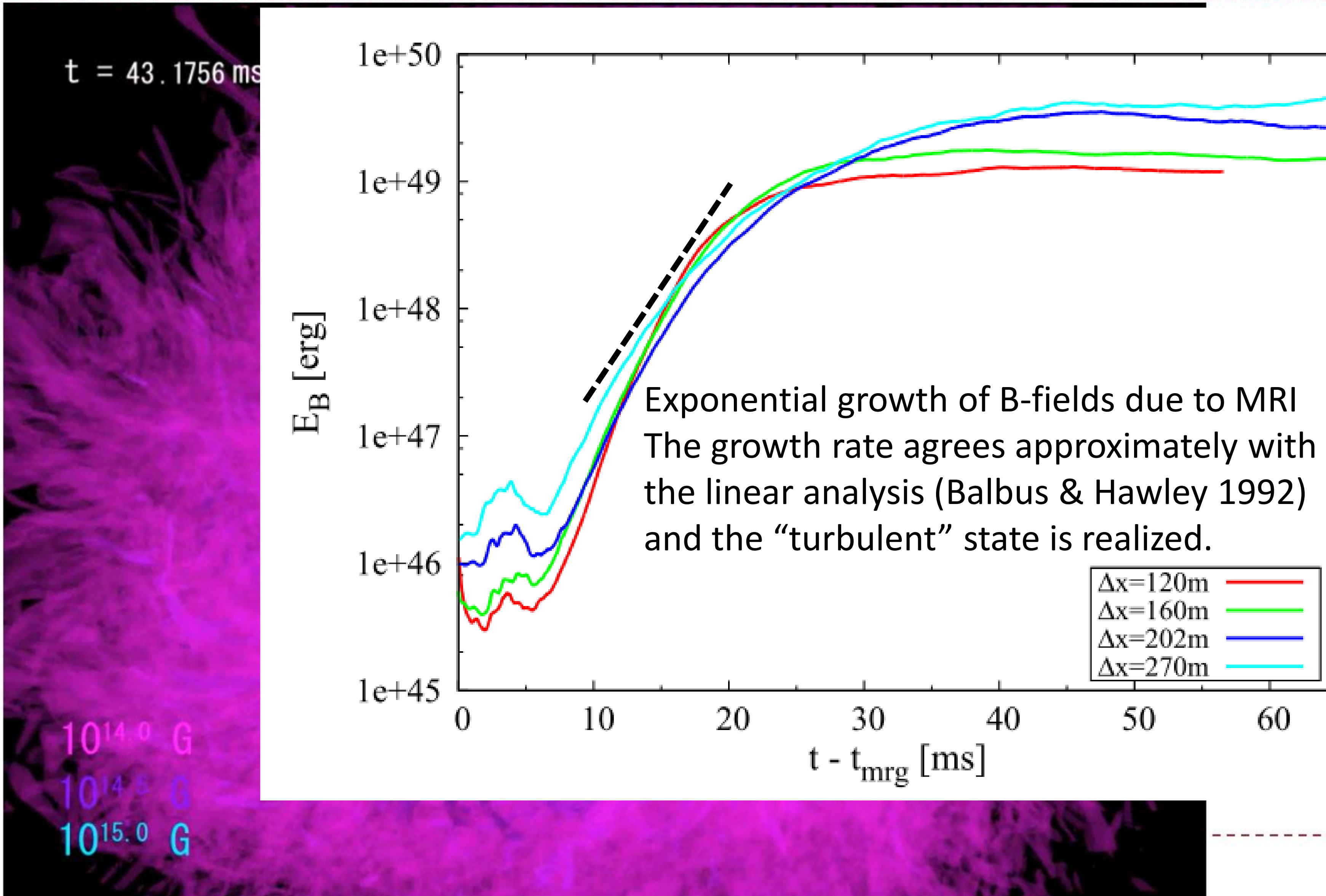

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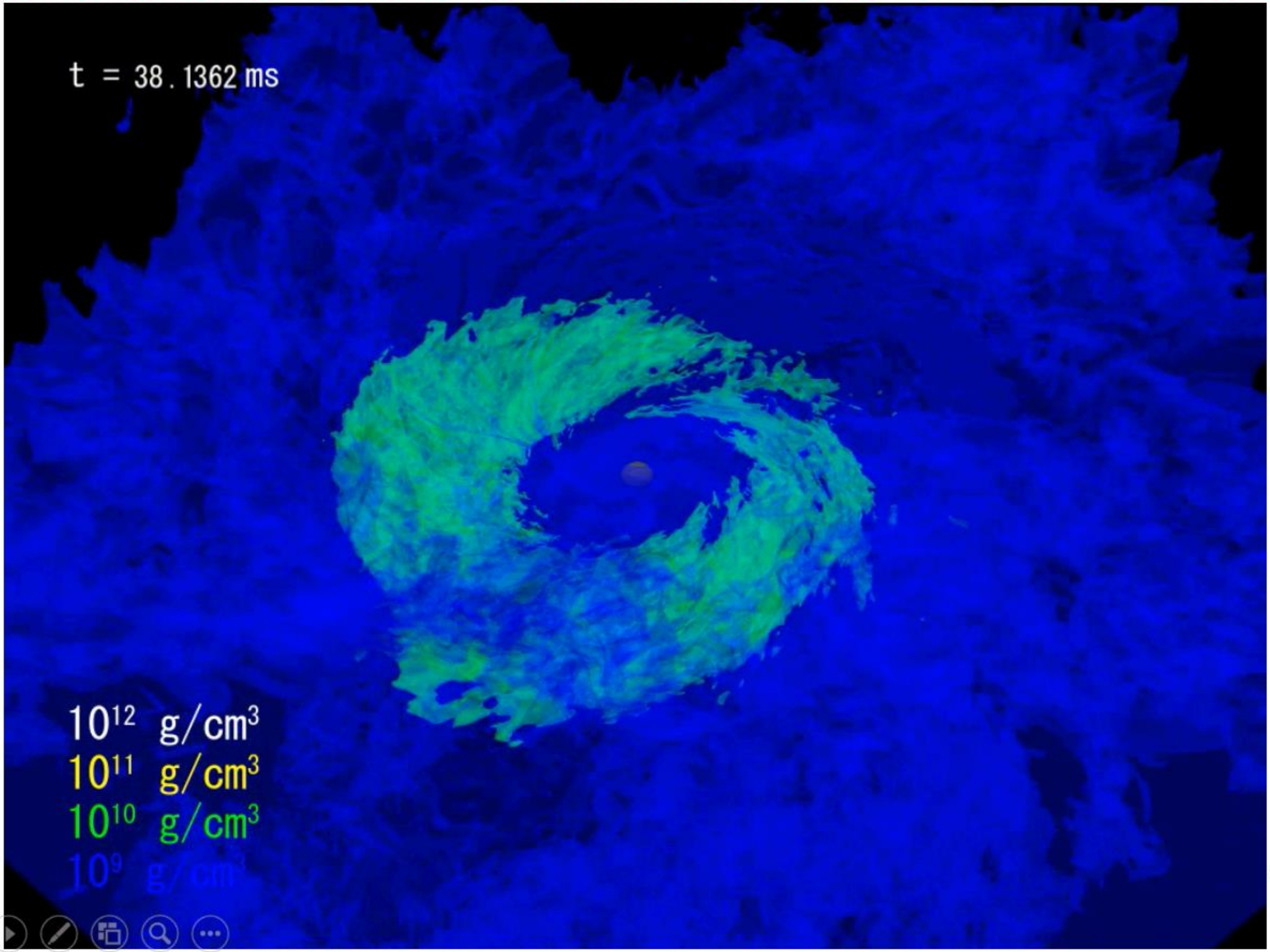

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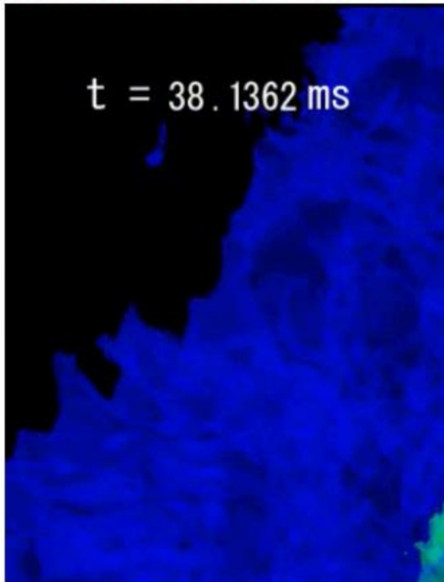
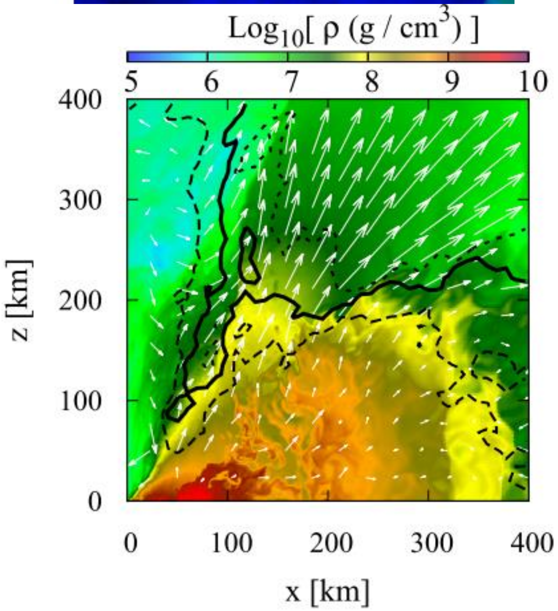
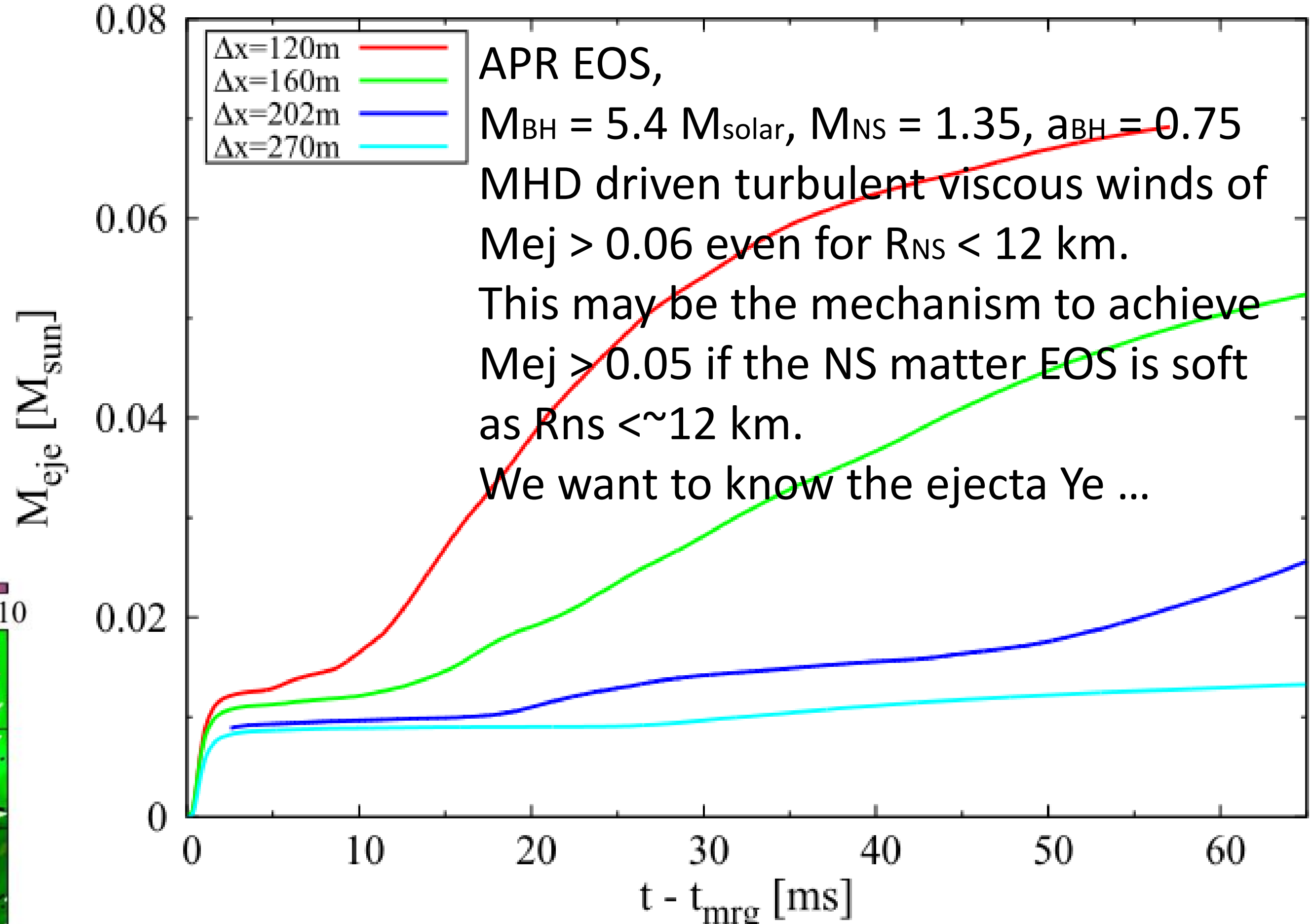






APR EOS,

M_{BH} = 5.4 M_{solar}, M_{NS} = 1.35, a_{BH} = 0.75

MHD driven turbulent viscous winds of

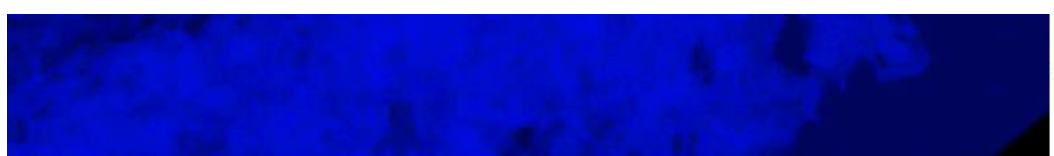
Mej > 0.06 even for R_{NS} < 12 km.

This may be the mechanism to achieve

Mej > 0.05 if the NS matter EOS is soft

as Rns <~12 km.

We want to know the ejecta Ye …



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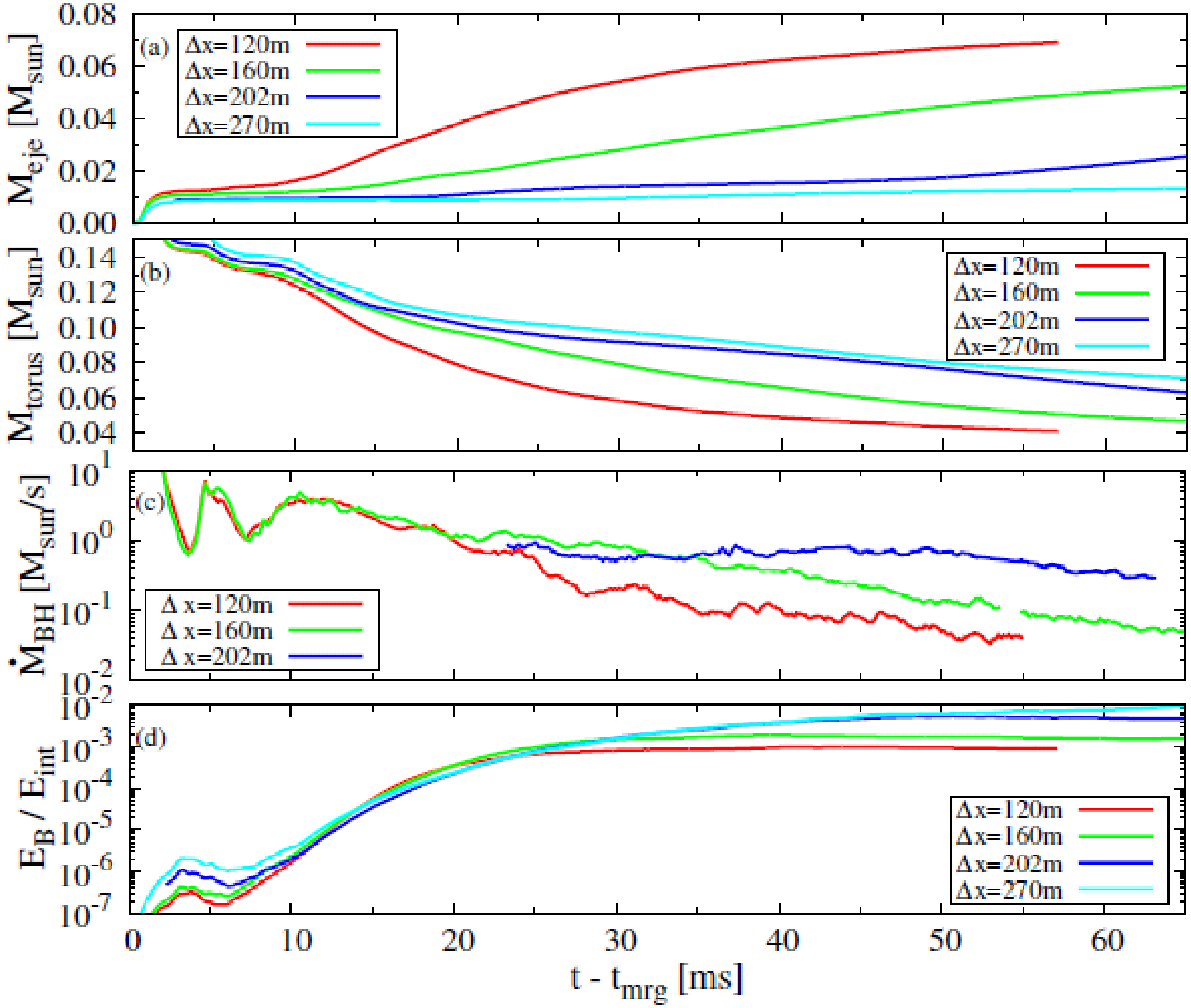
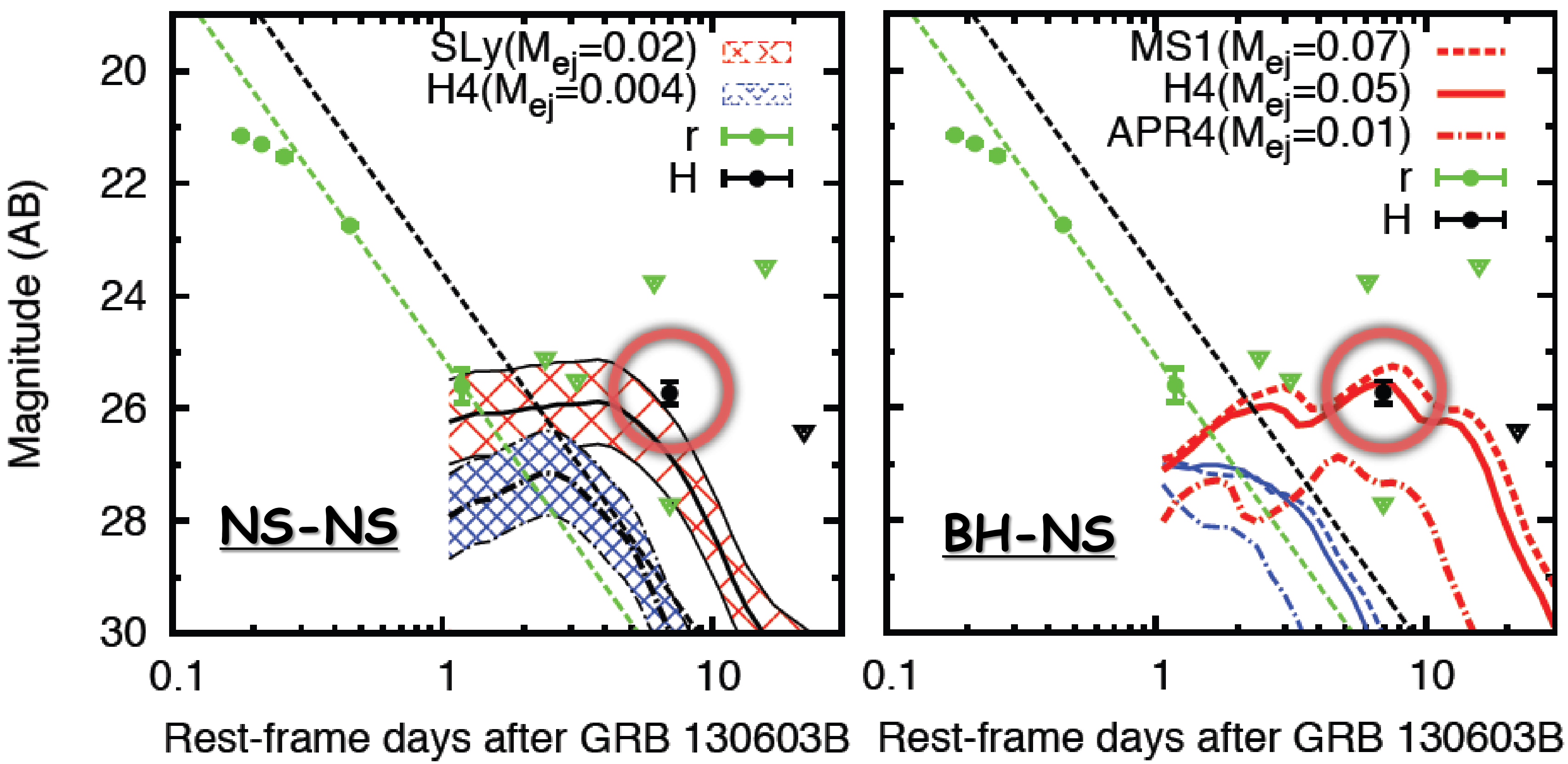


More than ~ 10% of the torus mass could be ejected
See also Just (2015)
Fernandez & Metzger (2014)

Kasen & Barnes (2013); Tanaka & Hotokezaka (2013); Hotokezaka et al. (2013); Tanaka et al. (2014)

'Macronova' modeling : NS-NS vs. BH-NS

- **NS-NS : Soft EOS is necessary** (shocks play a role)
- **BH-NS : Stiffer EOS is preferable** (tidal component is dominant)
- **Or large amount of MHD driven viscous winds are necessary !**
  - **In particular for macronova candidates with larger Mej**



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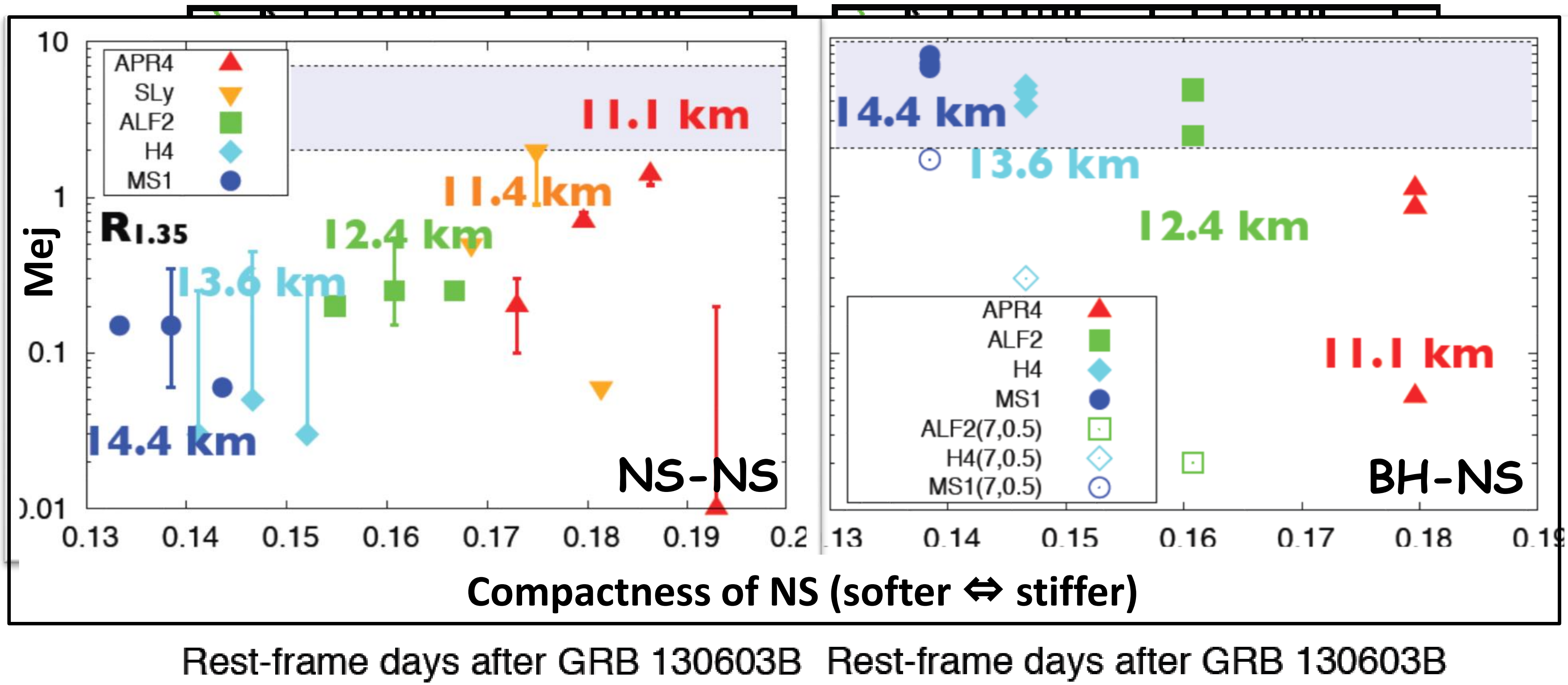

Summary

- NS-NS/BH mergers are good candidate of r-process nucleosynthesis cite
- The dynamical mass ejection from NS-NS mergers
  - The ejecta mass strongly depends on NS matter EOS
  - Mej ~0.01 Msun: only for soft EOS like SFHo, APR with Rns ~ 12km
  - Ye distribution is wide due to neutrino interactions irrespective of EOS and the so-called universality requirement can be satisfied.
  - Magnetic fields might play a role driving a MHD viscous winds
- The dynamical mass ejection from BH-NS mergers
  - The ejecta mass depends on NS matter EOS and BH parameters
  - Mej ~ 0.01 Msun for soft EOS like APR, with moderate BH spin
  - Magnetic fields will play a role driving a strong MHD viscous winds and more mass than expected may be ejected from the torus
- Conclusion: need further studies with GR viscous neutrino code !