Merger of binary neutron stars: mass ejection

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Why NS-NS mergers are important ?

1. **Most promising sources of gravitational waves for LIGO/VIRGO/KAGRA**
2. Invaluable **laboratory for studying high-density nuclear matter**
3. Promising origins of **short-hard GRBs**
4. Sources of strong transient **EM emission**
5. Possible site for **r-process heavy elements**

Predicting the merger event requires numerical relativity

Our latest activity

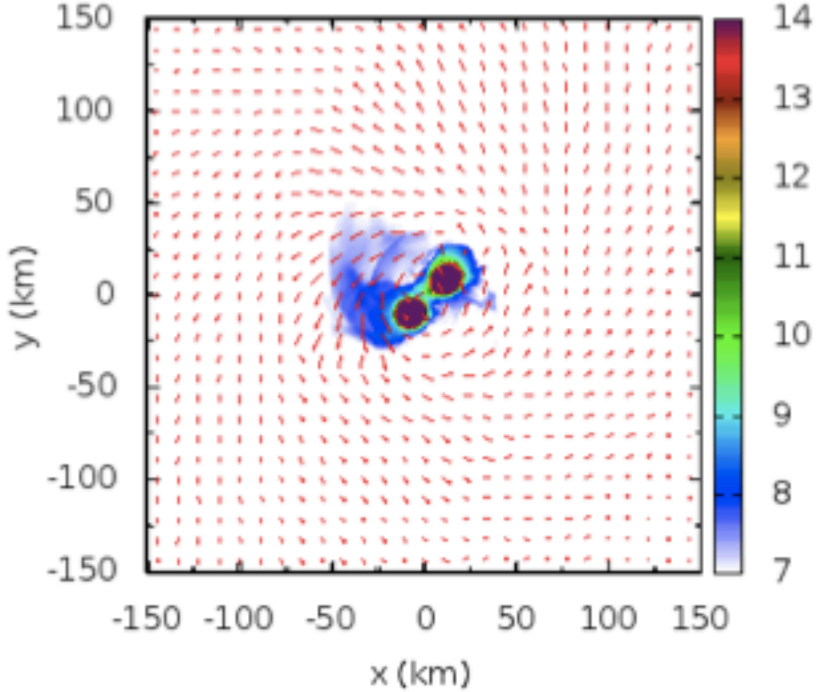
1. Neutrino radiation-hydro & r-process nucleosynthesis (Sekiguchi et al. + Wanajo….)
2. High-resolution GRMHD simulations (Kiuchi et al.)
3. Longterm, low-eccentricity evolution of NS-NS inspiral & merger (Hotokezaka et al. → GW session)

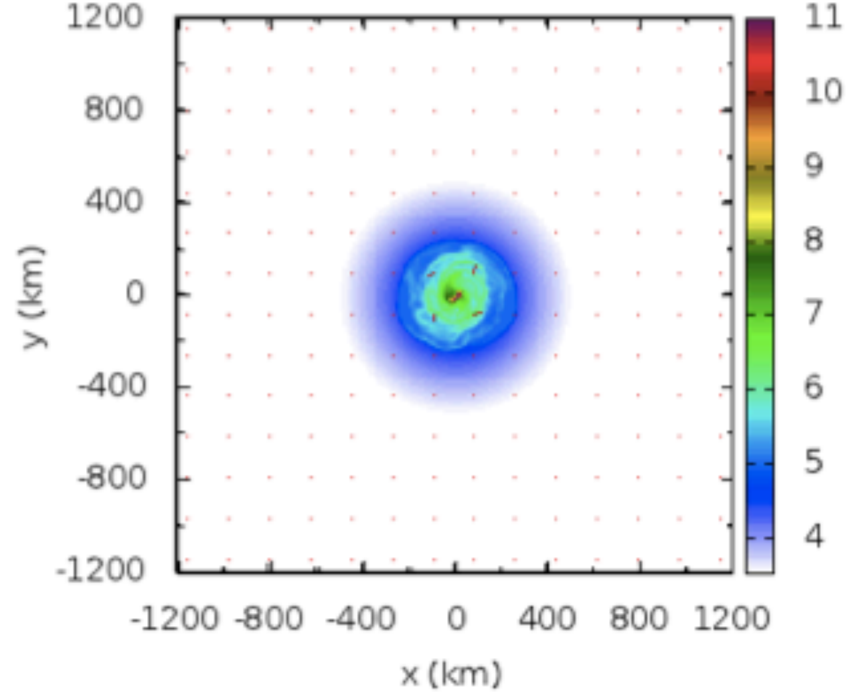
I will talk on the 1st & 2nd topics focusing particularly on mass ejection

Dynamical mass ejection at merger

Model : $1.2M_{sun} - 1.5M_{sun}$, EOS=APR4, R ~11 km

Equatorial plane





Hotokezaka + PRD 2013

Dynamical mass ejection at merger

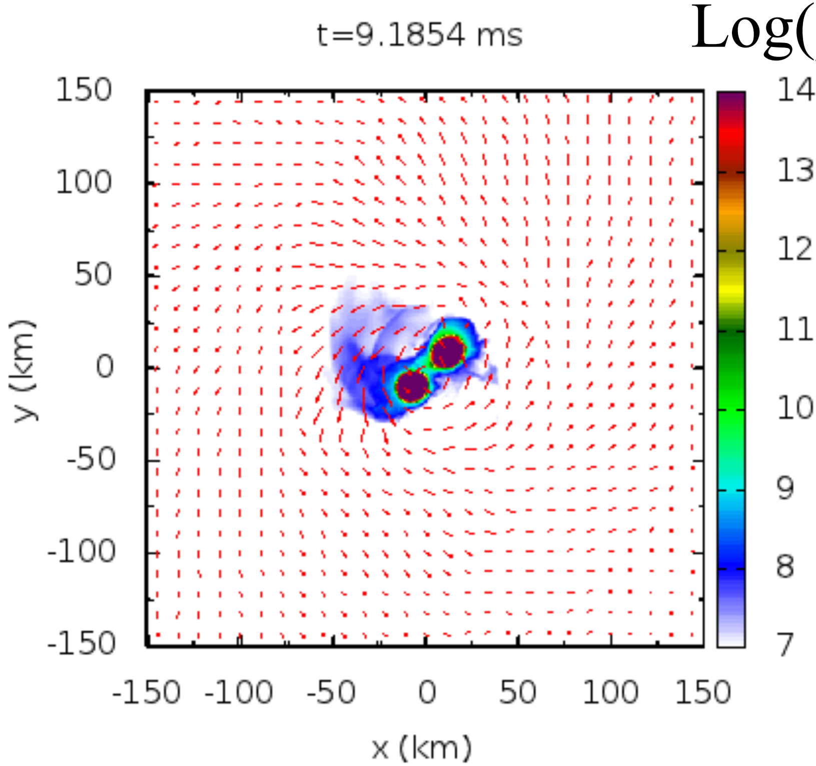
Model : $1.2M_{sun} - 1.5M_{sun}$, EOS=APR4, R ~11 km

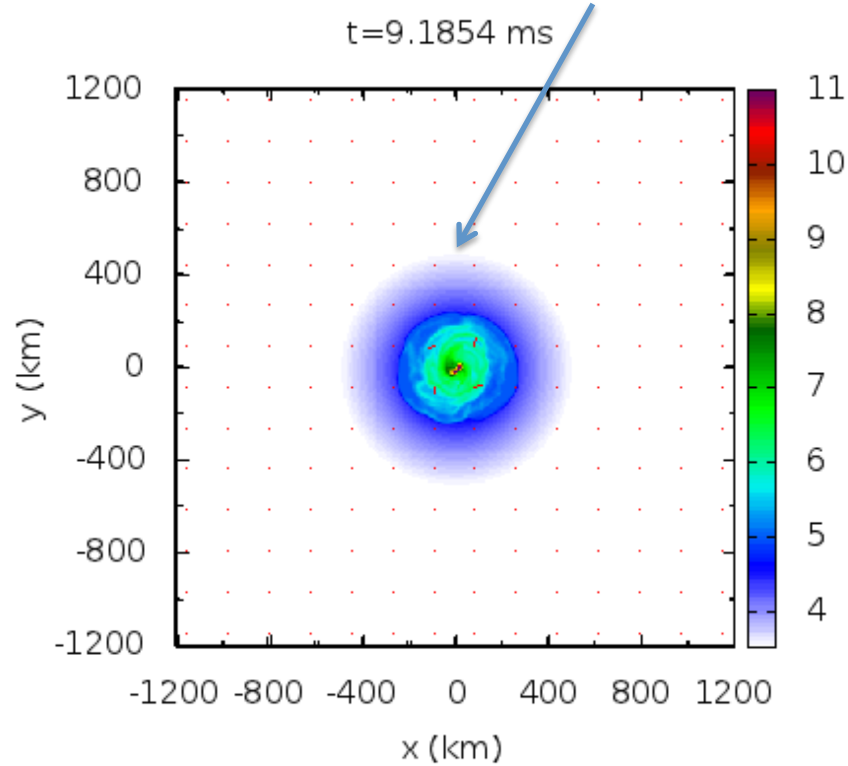
Equatorial plane

300 * 300 km

Head speed $v \sim 0.8c$

Log(ρ g/cc)

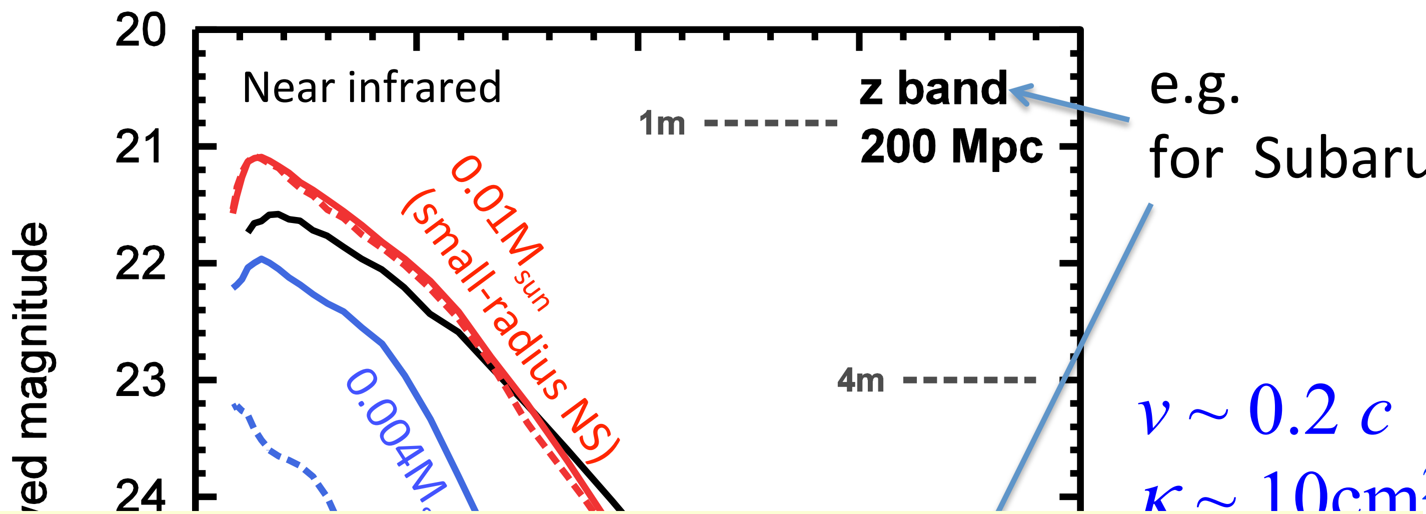




Ejecta mass ~ $0.01M_{sun}$, $v \sim 0.2c$ in average

Model luminosity curve of NS-NS @ 200Mpc

(Numerical-relativity + radiation transfer simulation
by M. Tanaka & Hotokezaka '13; also Kasen et al. '13)



$v \sim 0.2\,c$

$\kappa \sim 10\mathrm{cm}^2/\mathrm{g}$

- **For typical ejected mass 10^{-3}—10^{-2} M_{sun}, EM signal could be observed by 8m-class-telescopes for duration 1—10 days**

→ Need to quantify by better simulations: Mass, velocity & neutron-richness (→opacity)

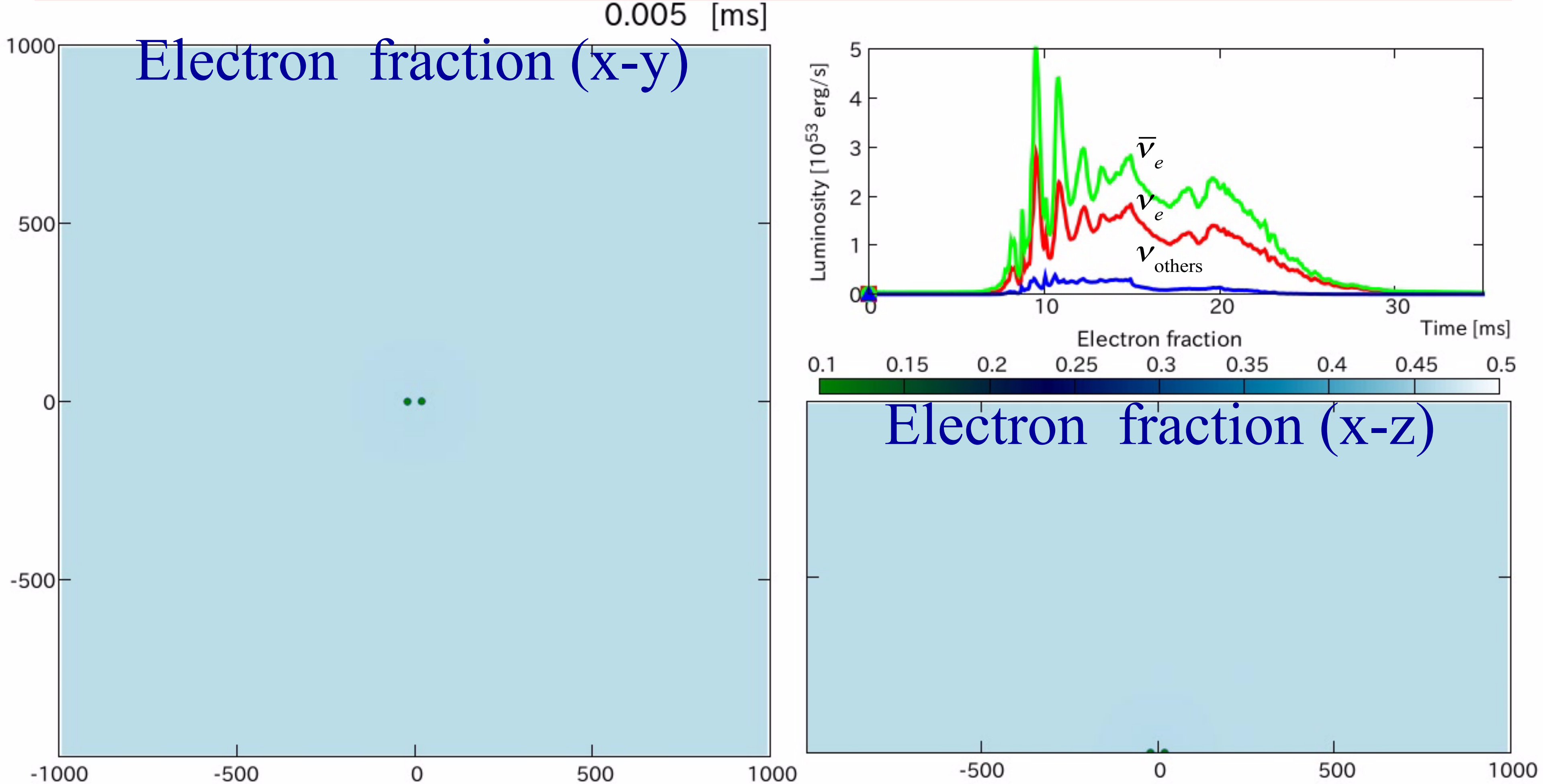
GR neutrino-radiation hydrodynamics

(Sekiguchi et al. PRD 2015)

- Einstein's eq : BSSN + puncture (+ locally add Z4c)
- Radiation : Leakage + covariant truncated moment scheme with M1 closure (gray) for heating
- EOS : SFHo, IUFSU, DD2, TMA, TM1
- Grid size : 580*580*290*9 level (fixed mesh refinement) with Δx~150 m for the finest domain
- CPU time : 500-700k node-hours by K-computer with ~7000 cores (864 nodes)
- Binary mass : 1.30-1.30, 1.35-1.35, 1.30-1.40, 1.25-1.45

High temperature $\Rightarrow \gamma\gamma \rightarrow e^- + e^+, \quad n + e^+ \rightarrow p + \bar{\nu}_e$

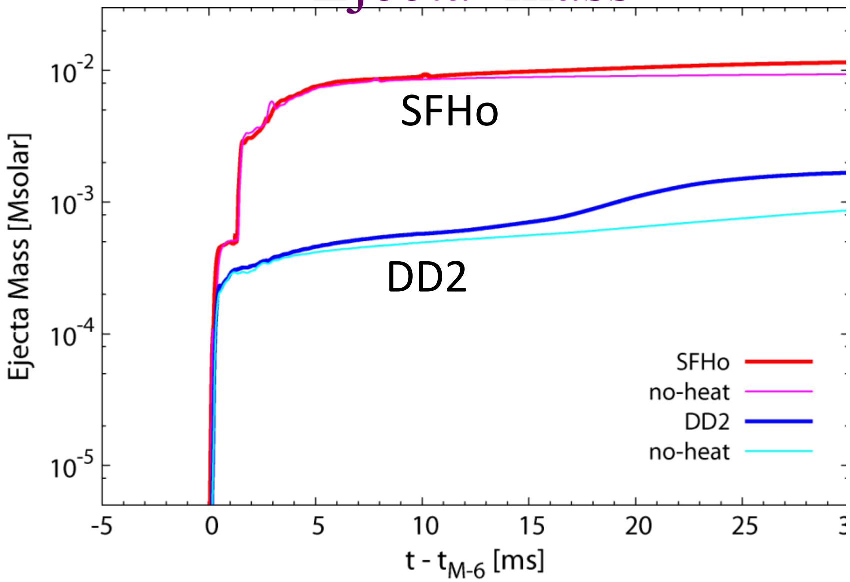
Neutron heating $\Rightarrow n + \nu_e \rightarrow p + e^-$



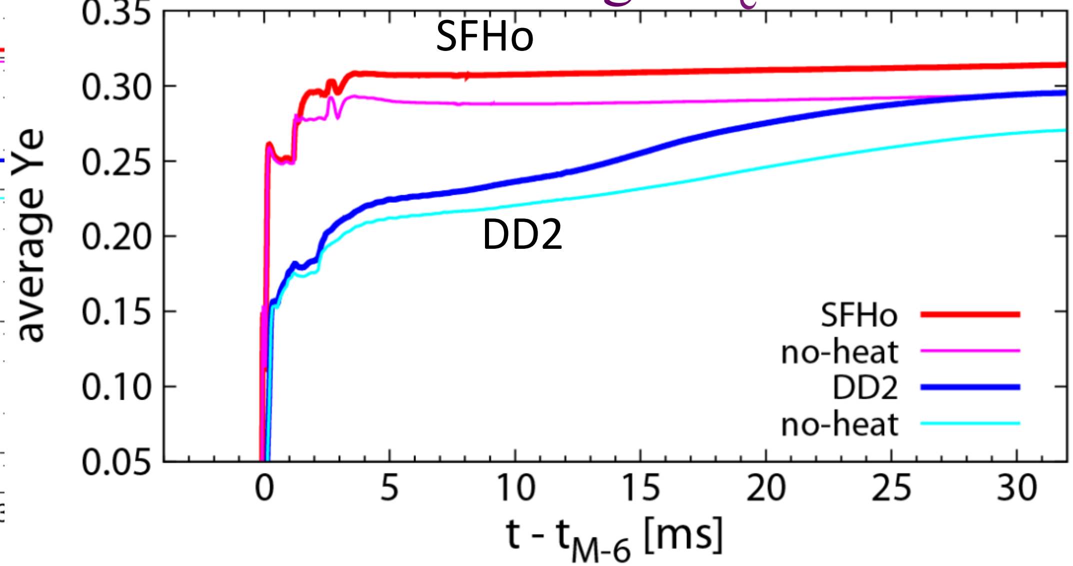
Sekiguchi et al. (2015)

Properties of ejecta and dependence on EOS

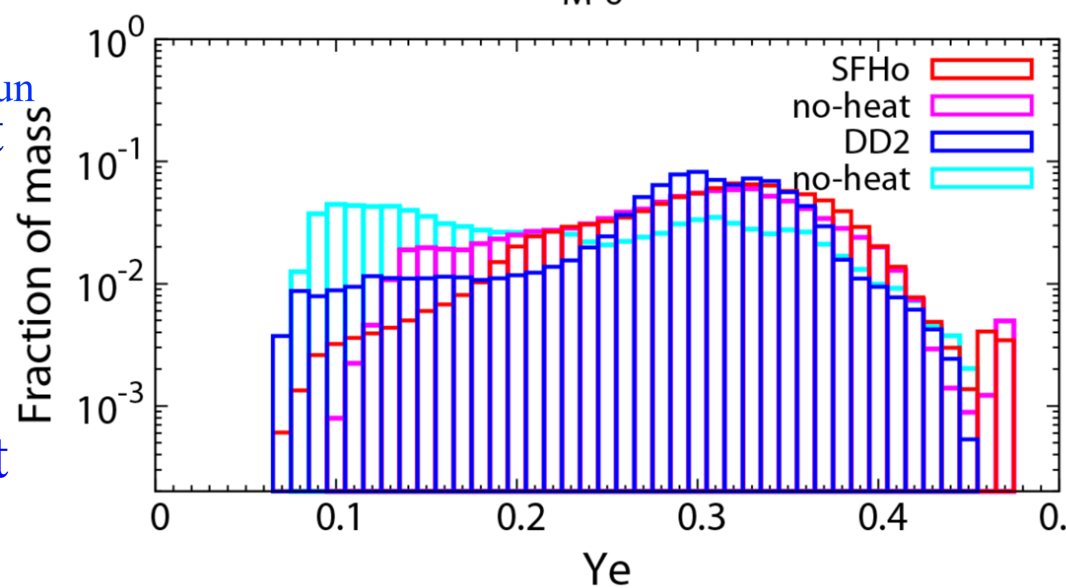
Ejecta mass



Average Y_e

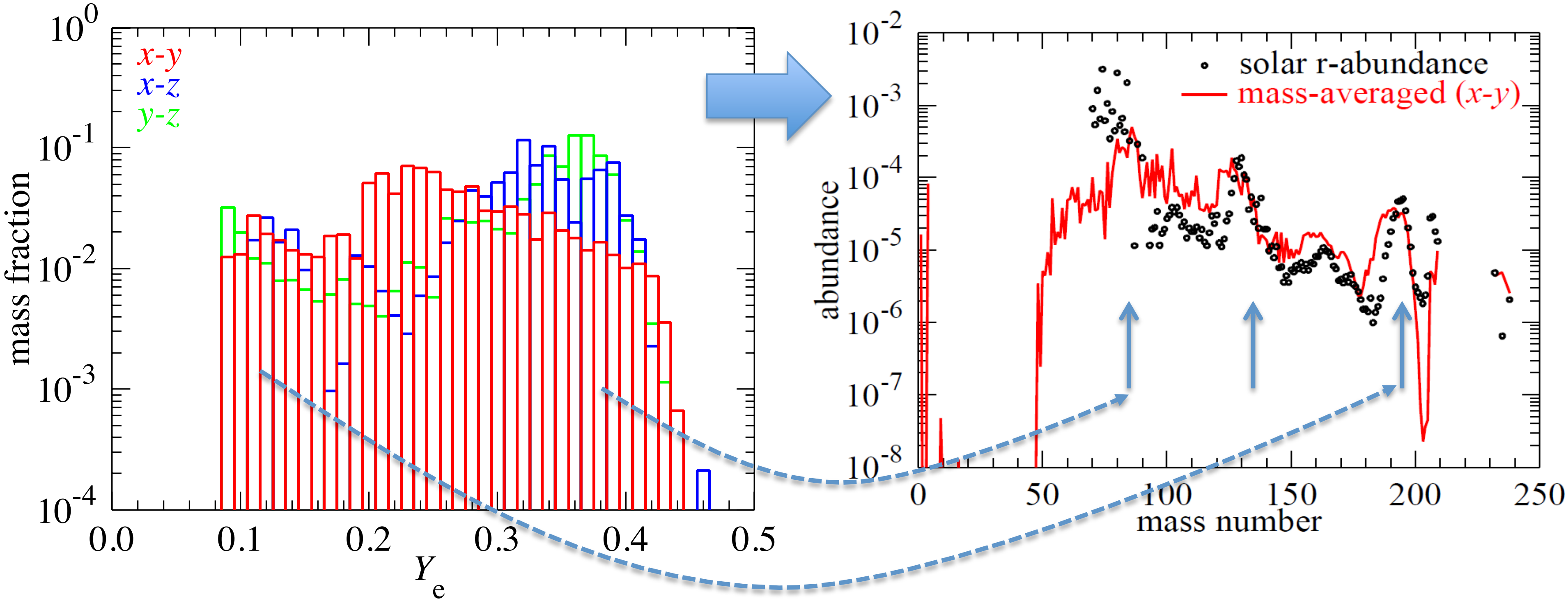


- Ejecta mass is $10^{-3} \sim 10^{-2} M_{sun}$
  → Good for EM counterpart
- Increase by $\sim 10^{-3}\ M_{sun}$ by neutrino heating
- Average $Y_e \sim 0.2$—0.3
- Neutrino heating increases it by 0.02—0.03
- **Broad distribution for Y_e**



Our first result

(Wanajo et al. ApJ 2014)

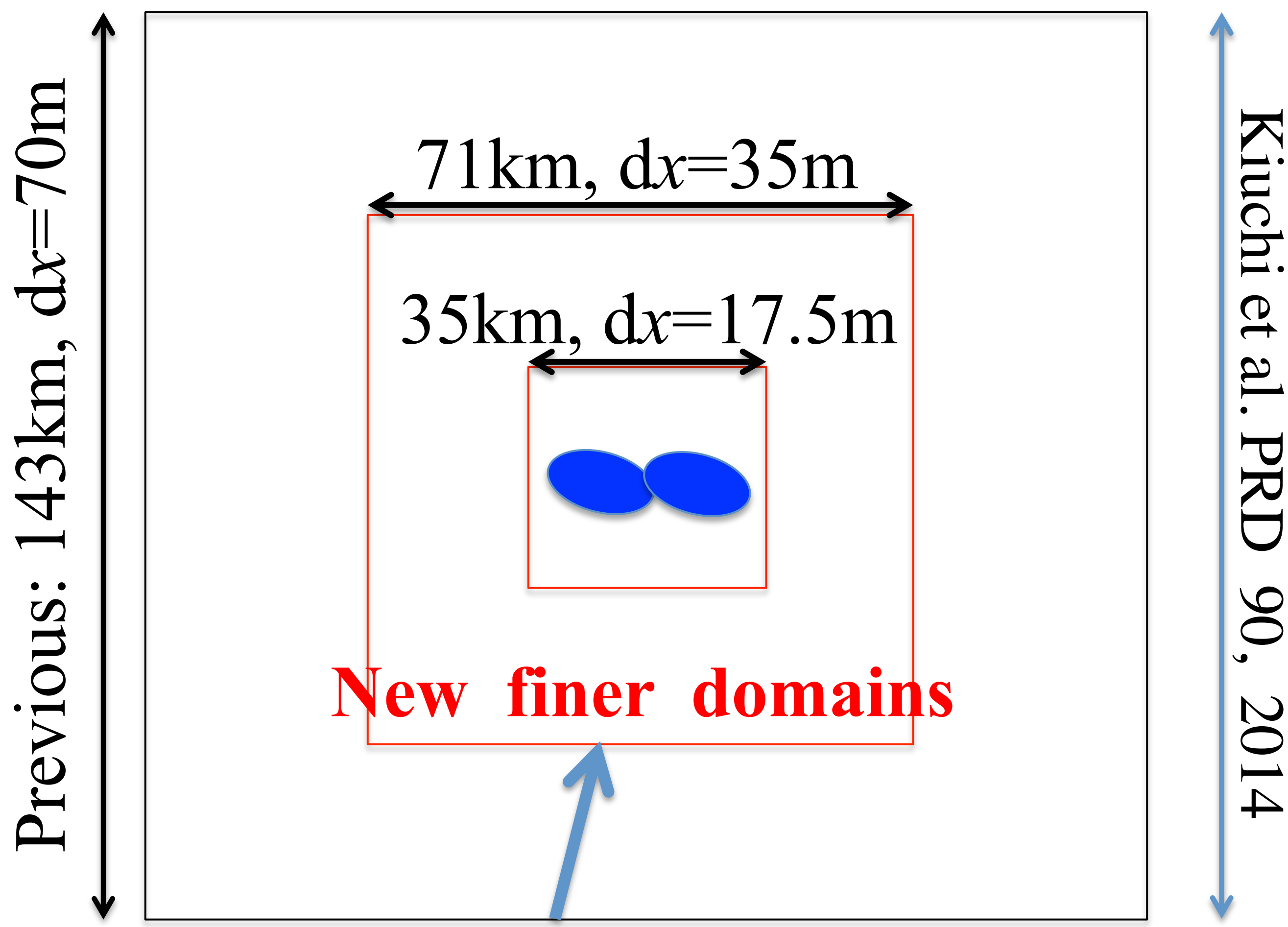


Broad distribution for Y_e could be suitable for reproducing wide abundance pattern

Project is ongoing by Wanajo, Nishimura, Sekiguchi+

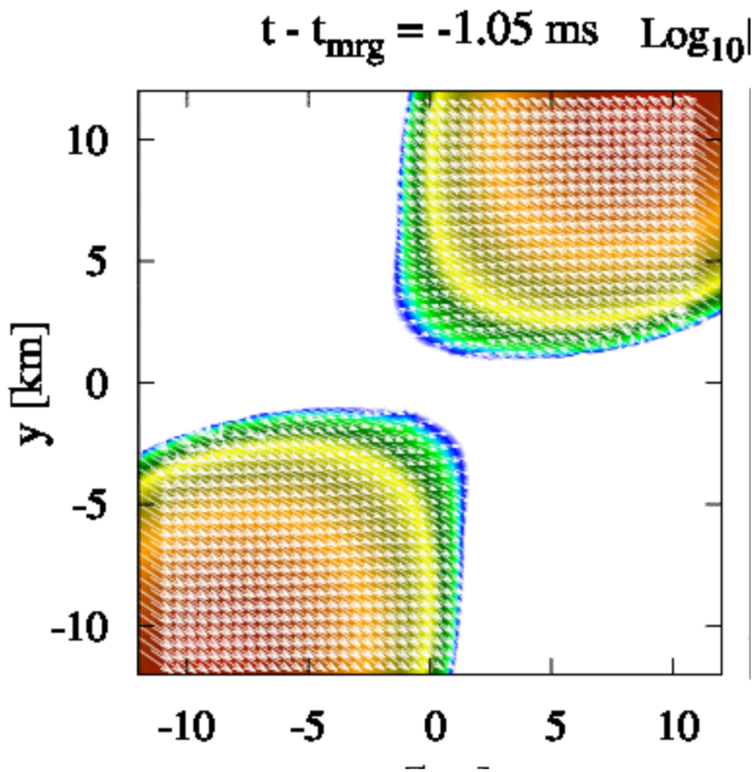
High-resolution GRMHD simulations: Exploring Kelvin-Helmholtz instability

- Fixed mesh refinement: dx=70m→35m→17.5m

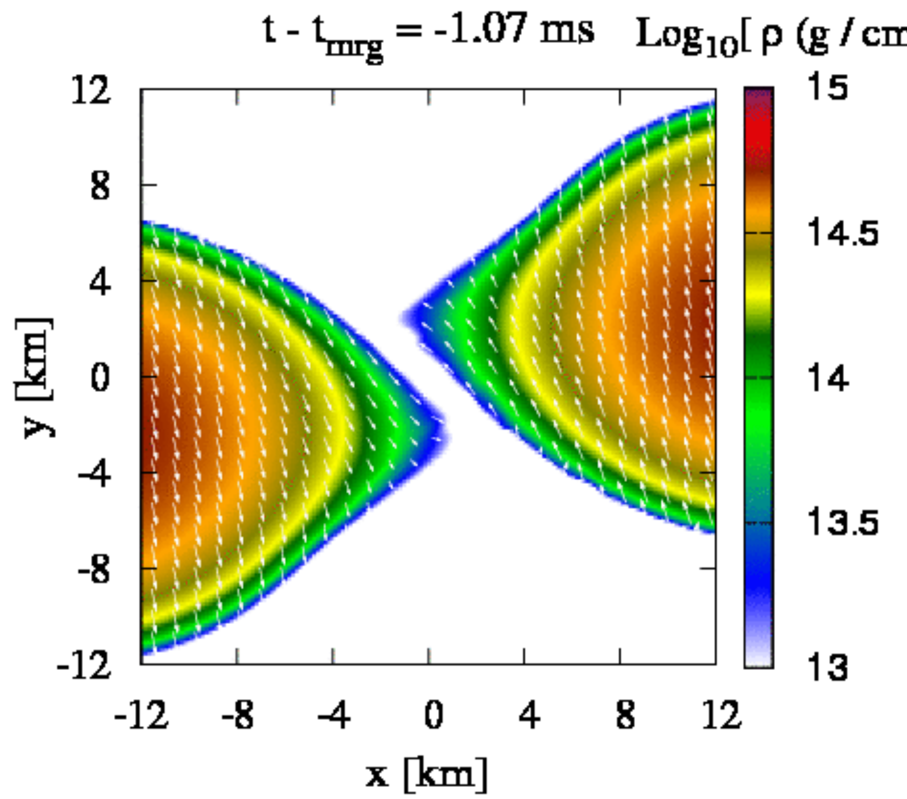


Kiuchi et al. PRD 2015

High-resolution GRMHD for NS-NS



Δx=17.5m

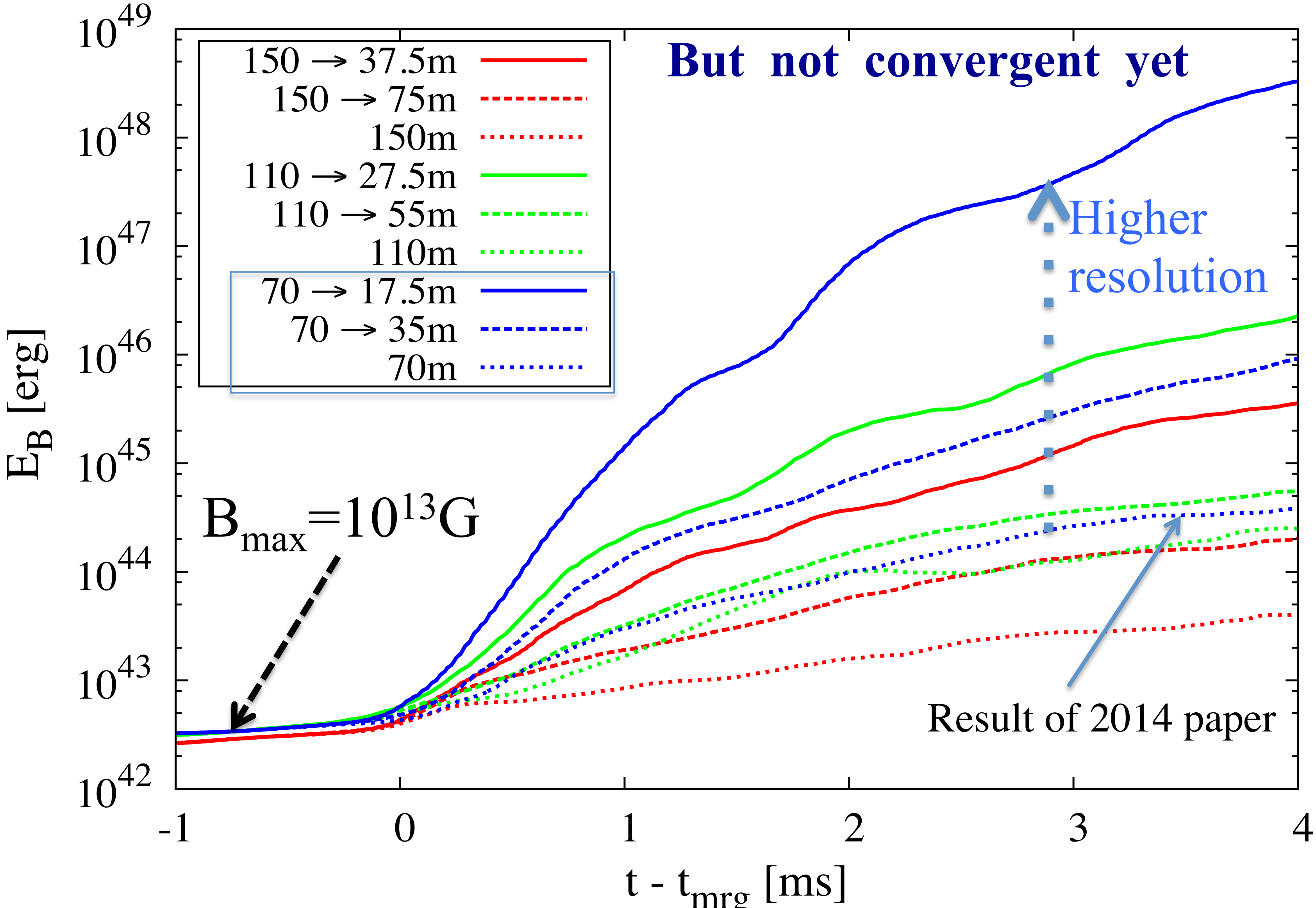


Δx=70m

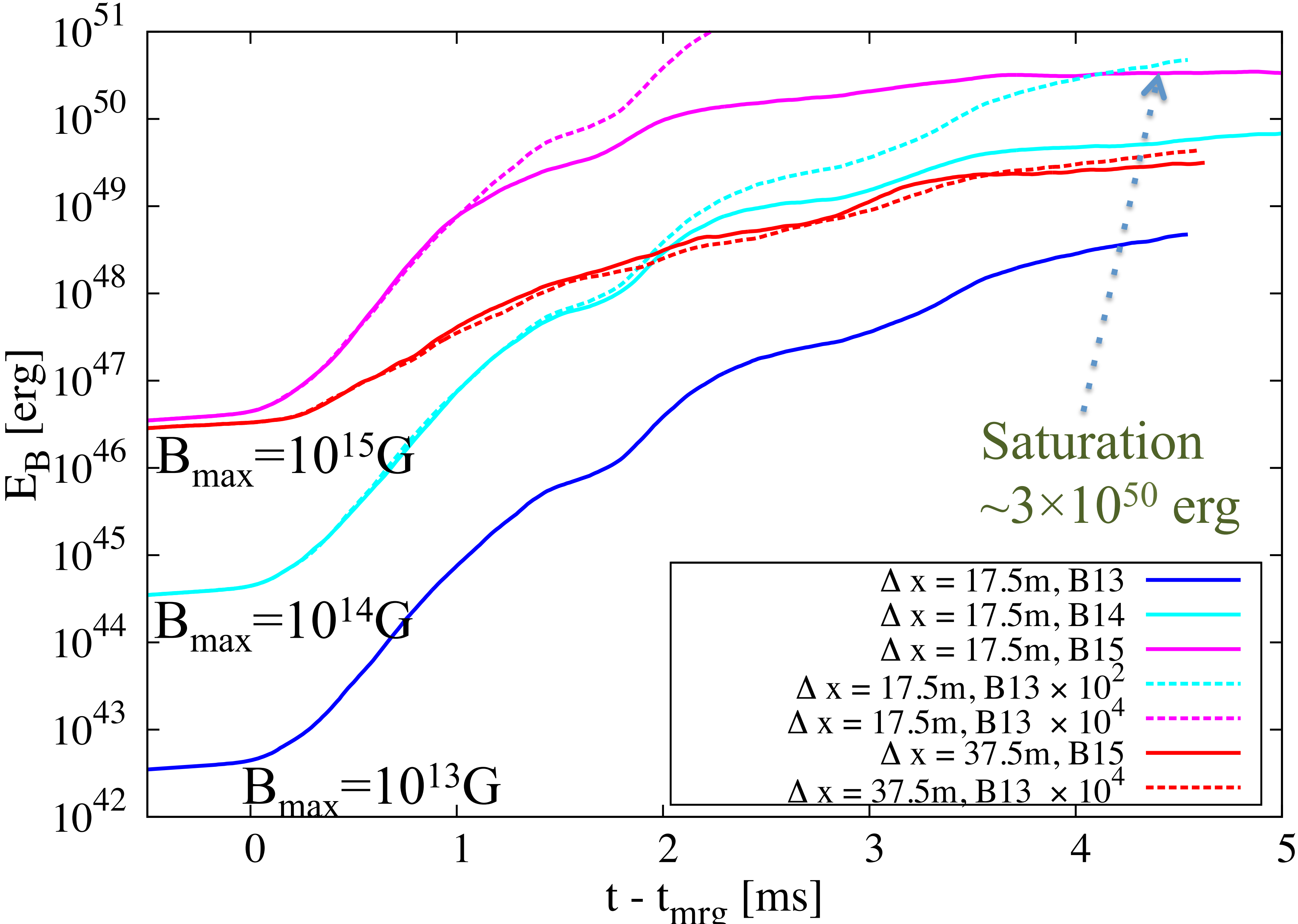
Enhancement of Kelvin-Helmholtz instability

→ Magnetic field is amplified by winding

Magnetic energy: resolution dependence



Magnetic energy: Amplified and saturated



Issues

- Magnetic fields are necessarily amplified
- Strong magnetic fields naturally formed could play a role in enhancing *effective viscosity*
- Does it induce mass ejection (for long-term evolution) ?
- If so, how large the mass and neutron richness ?

Important for EM counterpart prediction

Summary

- Substantial dynamical mass ejection is expected up to ~ 0.02 solar mass
  → promising EM counterpart as macronova
- Dynamical ejecta has broad neutron richness
  → suitable for r-process nucleosynthesis
- Magnetic fields should be significantly amplified during the early stage of the mergers
- Ejecta may be launched by MHD power
  → need higher-resolution or effective-viscosity study

Asymmetric cases: SFHo (in preparation)