Binary merger simulation in numerical relativity in our group

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Our current activity: Summary

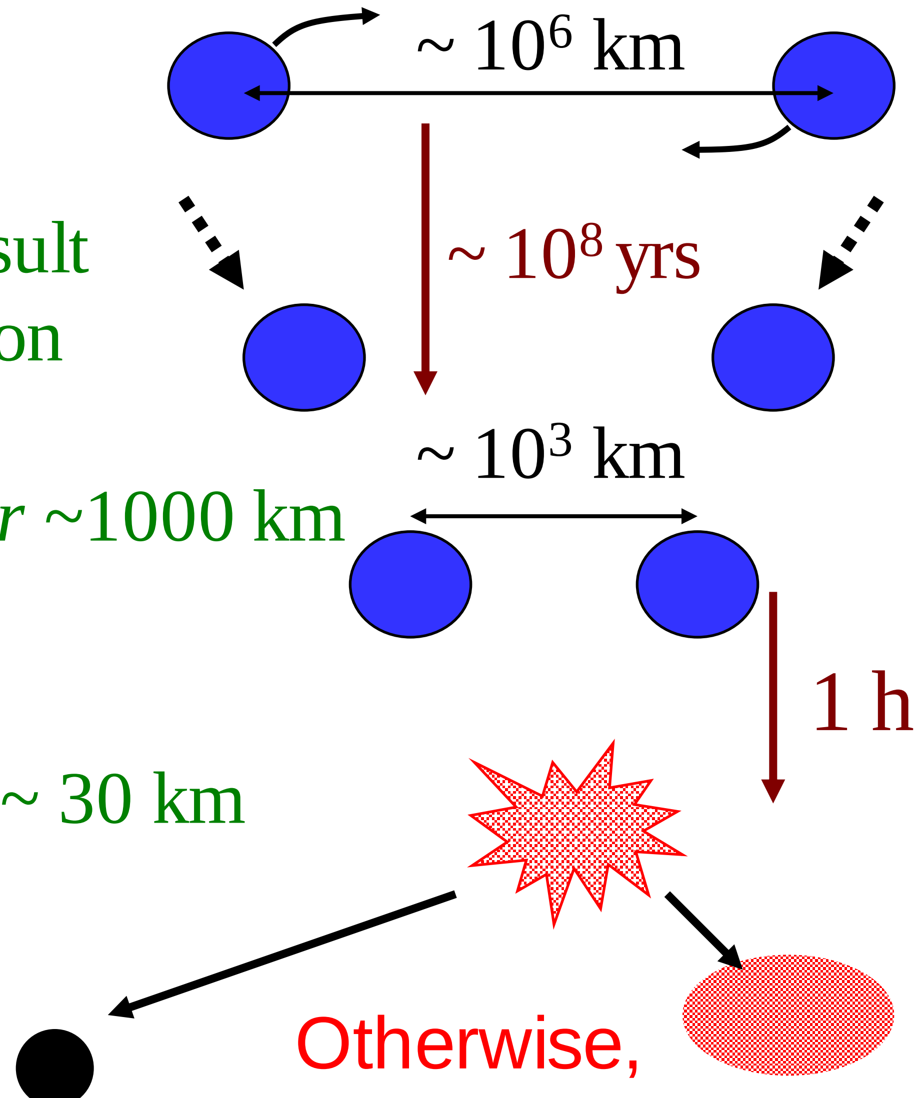
- NS-NS by Kiuchi, Sekiguchi, & Shibata, in partial collaboration with UWM (Taniguchi, Friedman, …) & with Baiotti
- BH-NS by Kyutoku, Shibata in collaboration with Taniguchi
- Stellar collapse by Sekiguchi & Kiuchi
- Pop III collapse to BH by Sekiguchi, Suwa
- GRMHD by Kiuchi & Shibata, and Baiotti
- Higher-dimensional NR by Shibata, Okawa with Yoshino (Alberta, CA)

Evolution of NS-NS

Inspiral

- At formation
- Evolve as a result of GW emission
- Last 1 hour at $r \sim 1000$ km

Merger starts when $r \sim 30$ km

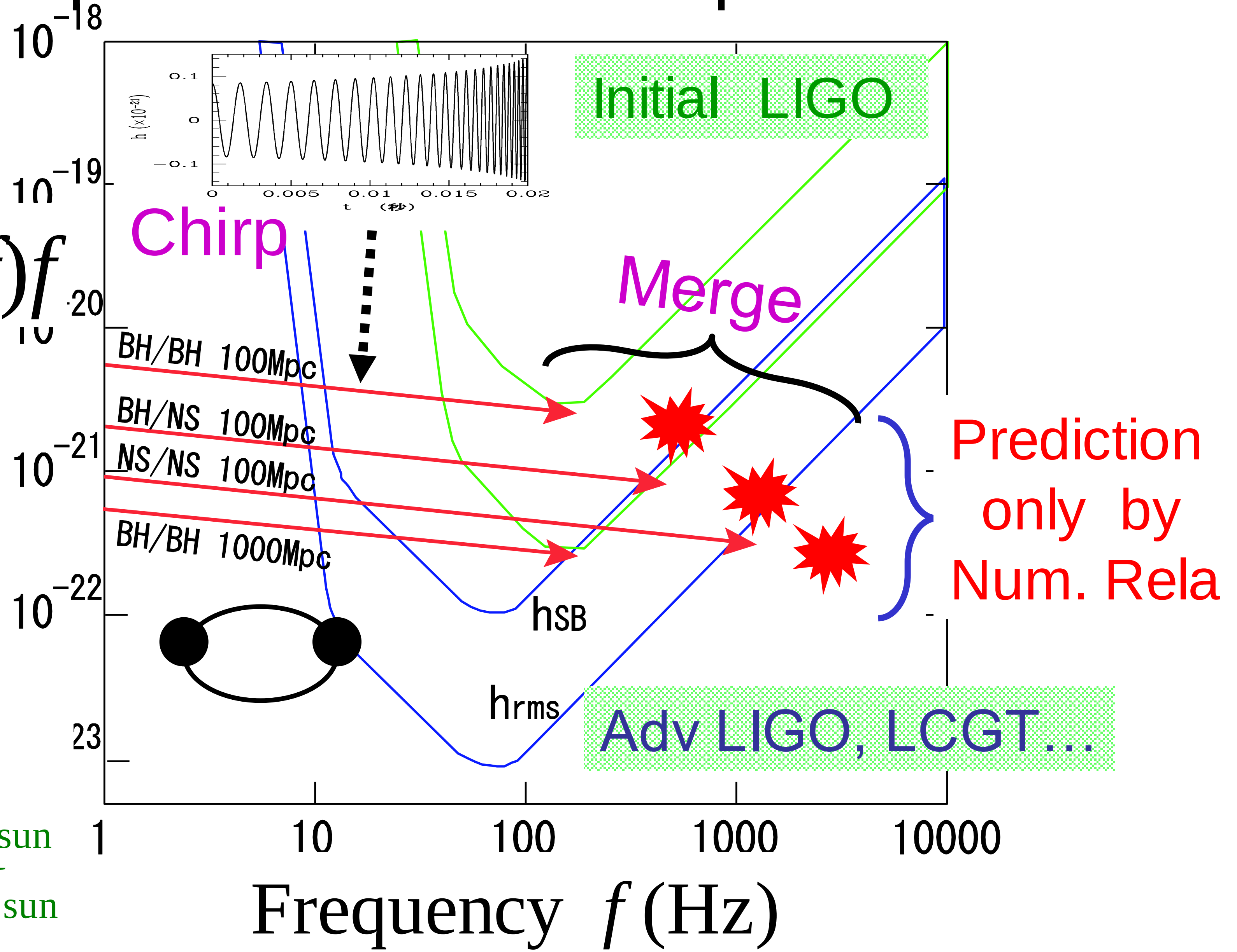


If mass is high enough, a black hole is formed

Otherwise, "hypermasive NS"

GW spectrum from compact binaries

$$h = h(f)f$$



Assume
BH=$10M_{sun}$
NS=$1.4M_{sun}$

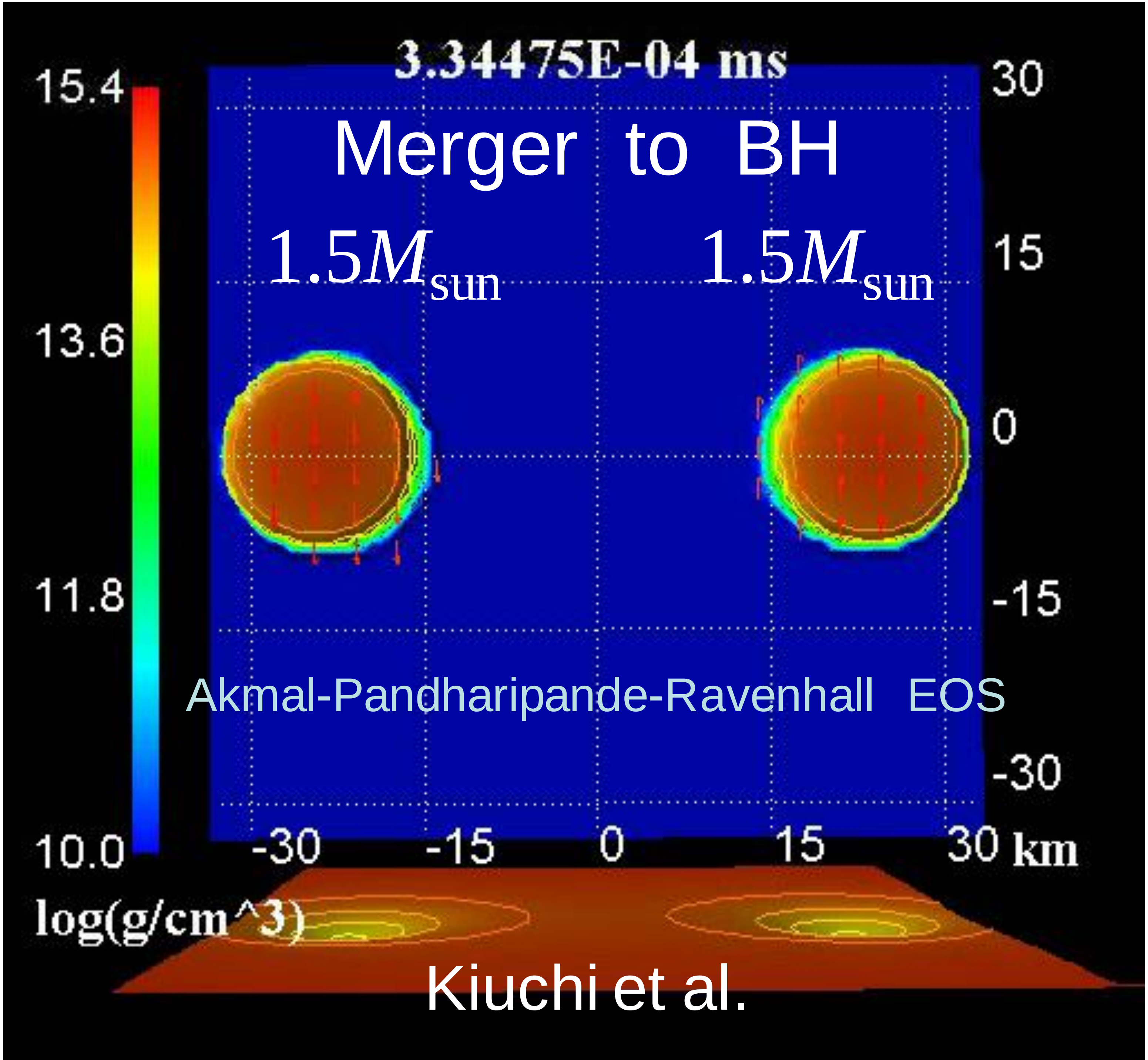
Thermal condition of NS 1

- Inspiral phase = NS is cold;
  For NS's age > 10^7 yrs,
  $T < 10^5$ K ~ 10 eV ≪ E_F ~ 100 MeV
  → NS should be modeled by cold EOS
  (but it is still unknown; need systematic survey)
- Merger phase: By shock heating, T rapidly increases by many orders of magnitude;
  $kT \sim 0.1$—$0.2\, E_F$
  → Finite temperature effects, Y_e, neutrino thermal pressure, neutrino cooling, etc could play an important role
  (but there are only a few EOSs)

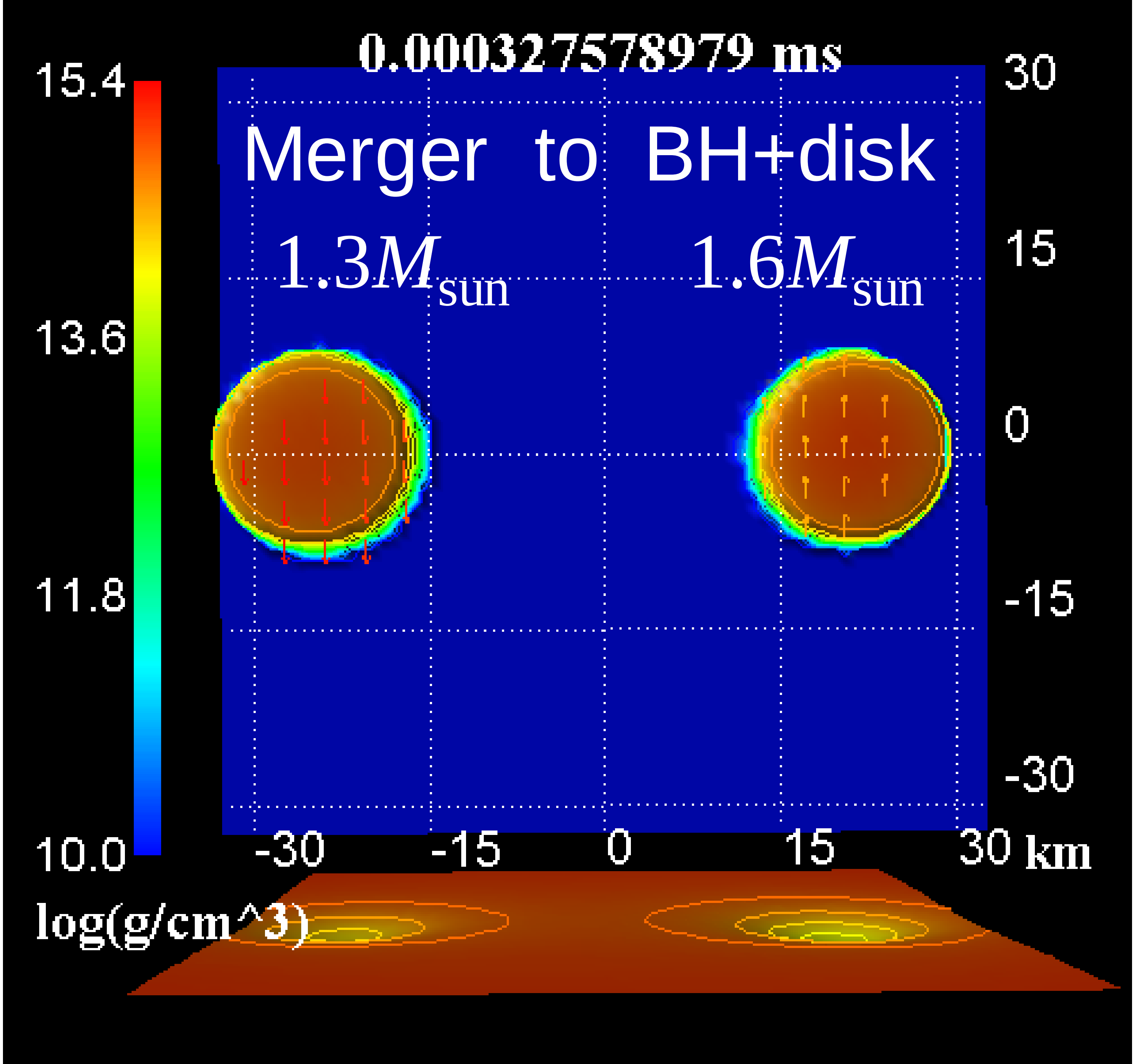
Thermal condition of NS 2

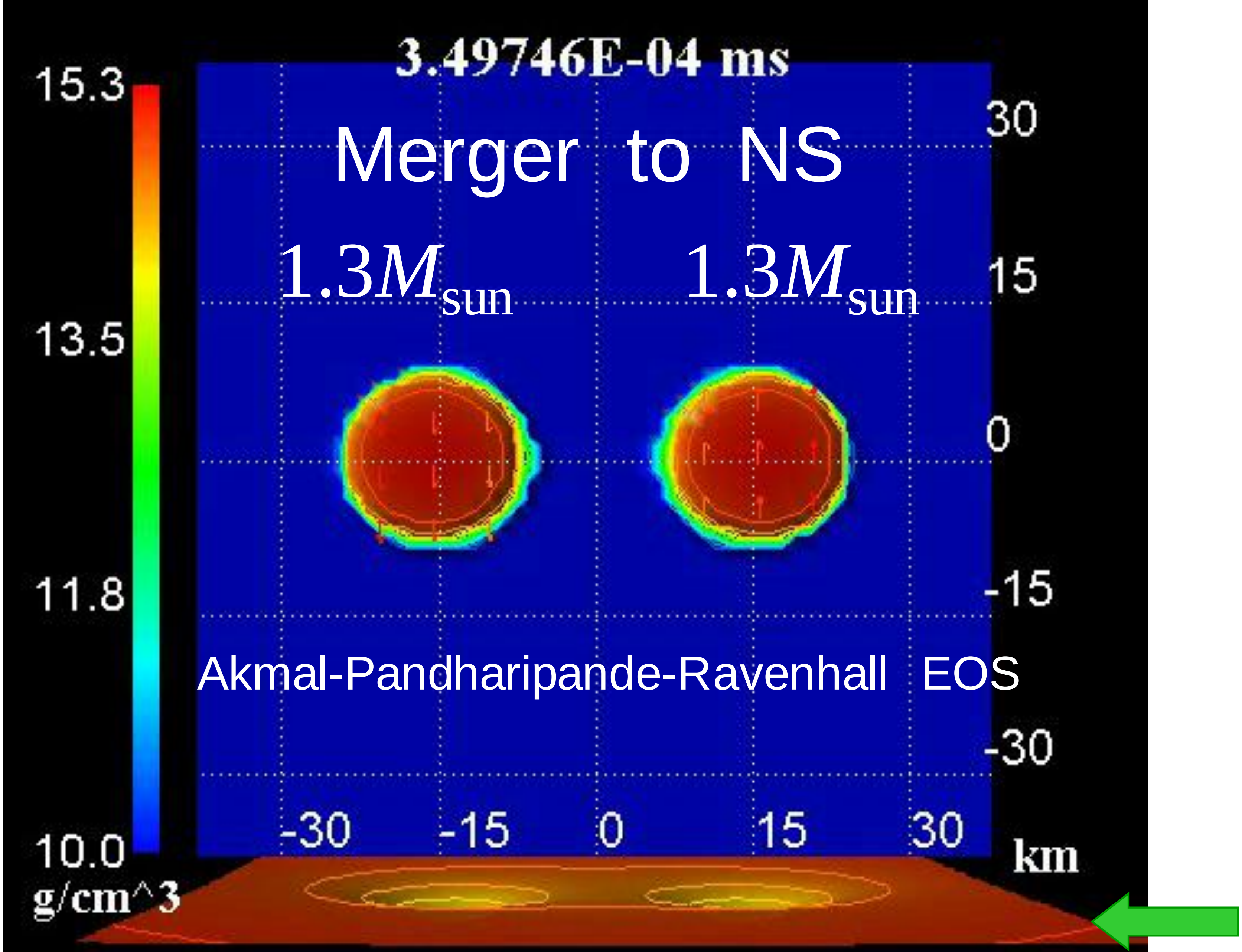
- After merger: two possibilities

1. BH is formed in a dynamical time → Effects of EOS and neutrino cooling would be minor correction (but for BH accretion disks, realistic EOS & neutrino cooling/heating would be important)
2. Hypermassive NS is formed → Continuous shock heating, longterm neutrino cooling (& magnetic instabilities) are obviously important; detailed modeling is required



3.34475E-04 ms
Merger to BH
1.5M_{sun}
1.5M_{sun}
15.4
13.6
11.8
10.0
log(g/cm^3)
30
15
0
-15
-30
-30
-15
0
15
30 km
Akmal-Pandharipande-Ravenhall EOS
Kiuchi et al.


0.000327578979 ms
Merger to BH+disk
1.3M_{sun}
1.6M_{sun}
15.4
13.6
11.8
10.0
log(g/cm^3)
30
15
0
-15
-30
-30
-15
0
15
30 km



Shibata & Taniguchi, PRD 73, 064027 (2006)

Three approaches of our study

1. Inspiral + Early merger with cold EOSs
   → Detailed classification of gravitational waveforms for late inspiral + early merger phases to clarify their dependence on NS's cold EOSs
2. Inspiral + prompt BH formation
   → The same as 1 (but for BH accretion disks, see 3)
3. Inspiral + Merger + Hypermassive NS
   → Finite temperature EOS + neutrino cooling (and B-fields); study for GRBs

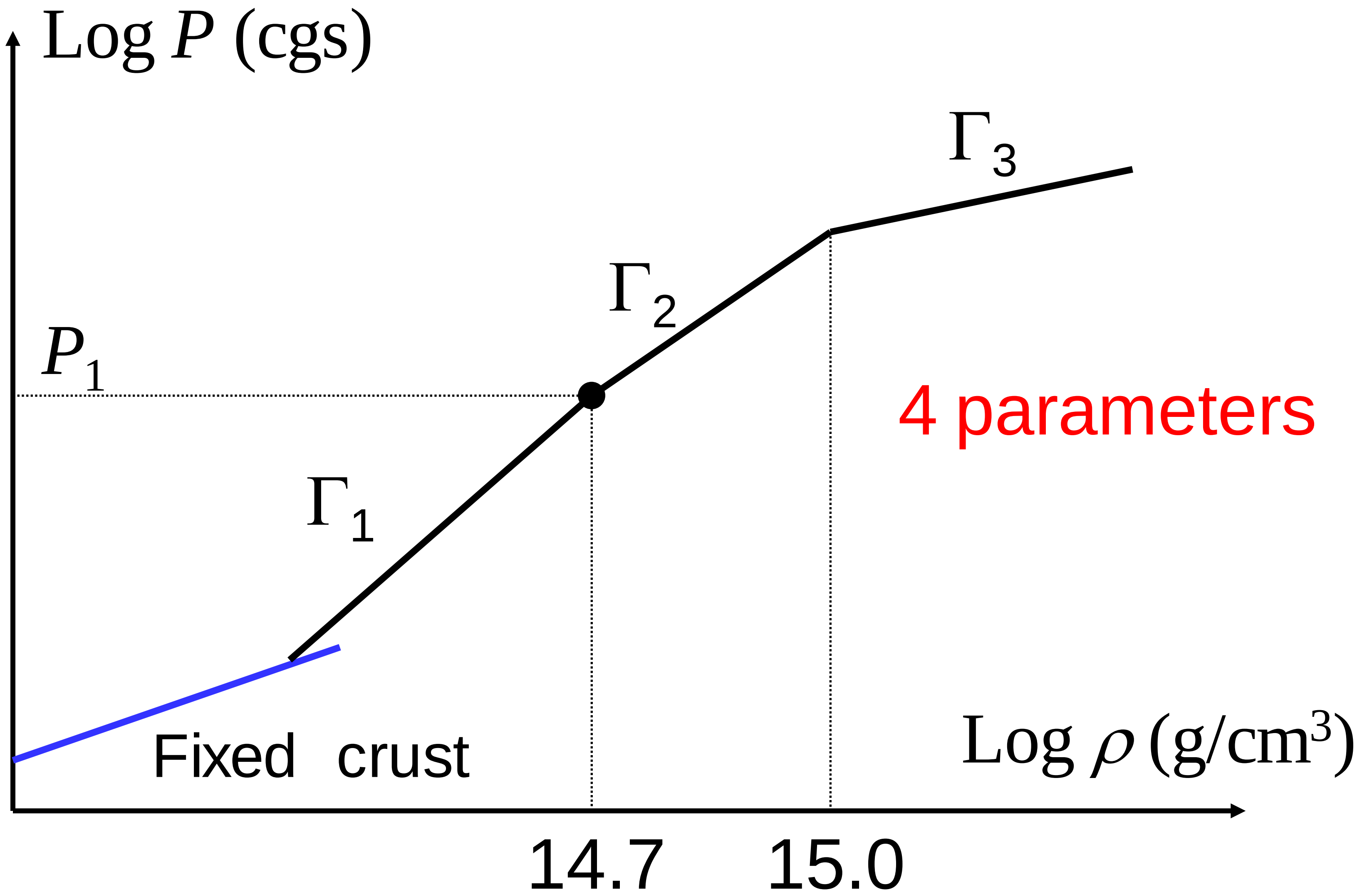
For BH-NS

- Inspiral + Early merger with cold EOSs → Detailed classification of gravitational waveforms for late inspiral + early merger phases to clarify their dependence on NS's cold EOSs
- Inspiral + BH accretion disk → Finite temperature EOS + neutrino cooling (and B-fields); study for GRB

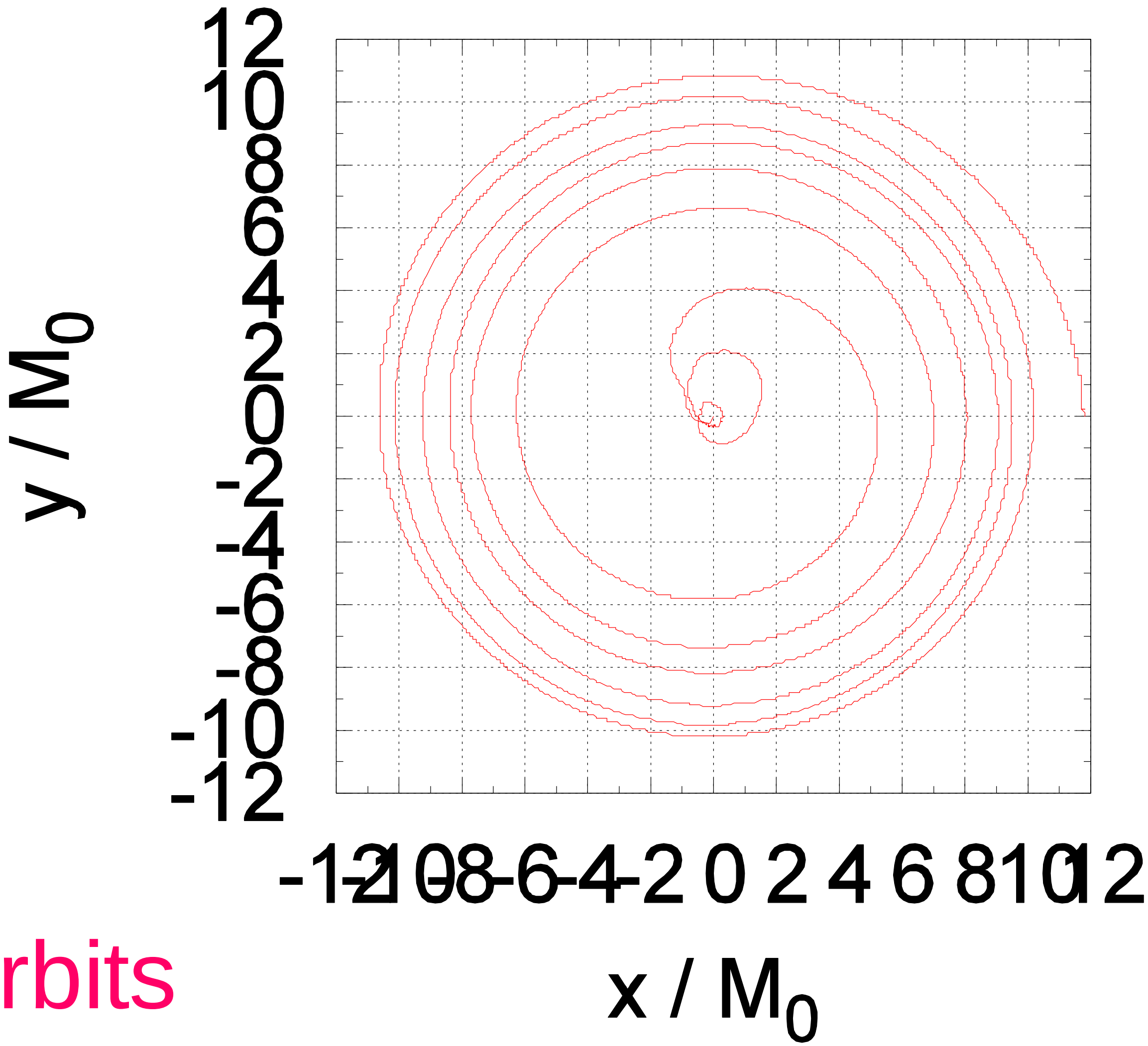
§ NS-NS: Current activity 1

- Category 1: Study with piecewise polytrope $P = K_i \rho^{\Gamma i}$ for $\rho_i < \rho < \rho_{i+1}$ (Cold EOS)
- Piecewise polytrope with 4 parameters is a good approximation for many EOSs (Read et al. PRD79, 2009; UWM group)
- Goal: To clarify gravitational waveforms from late inspiral to early merger phases, and their dependence on EOSs

Piecewise polytrpoe by UWM

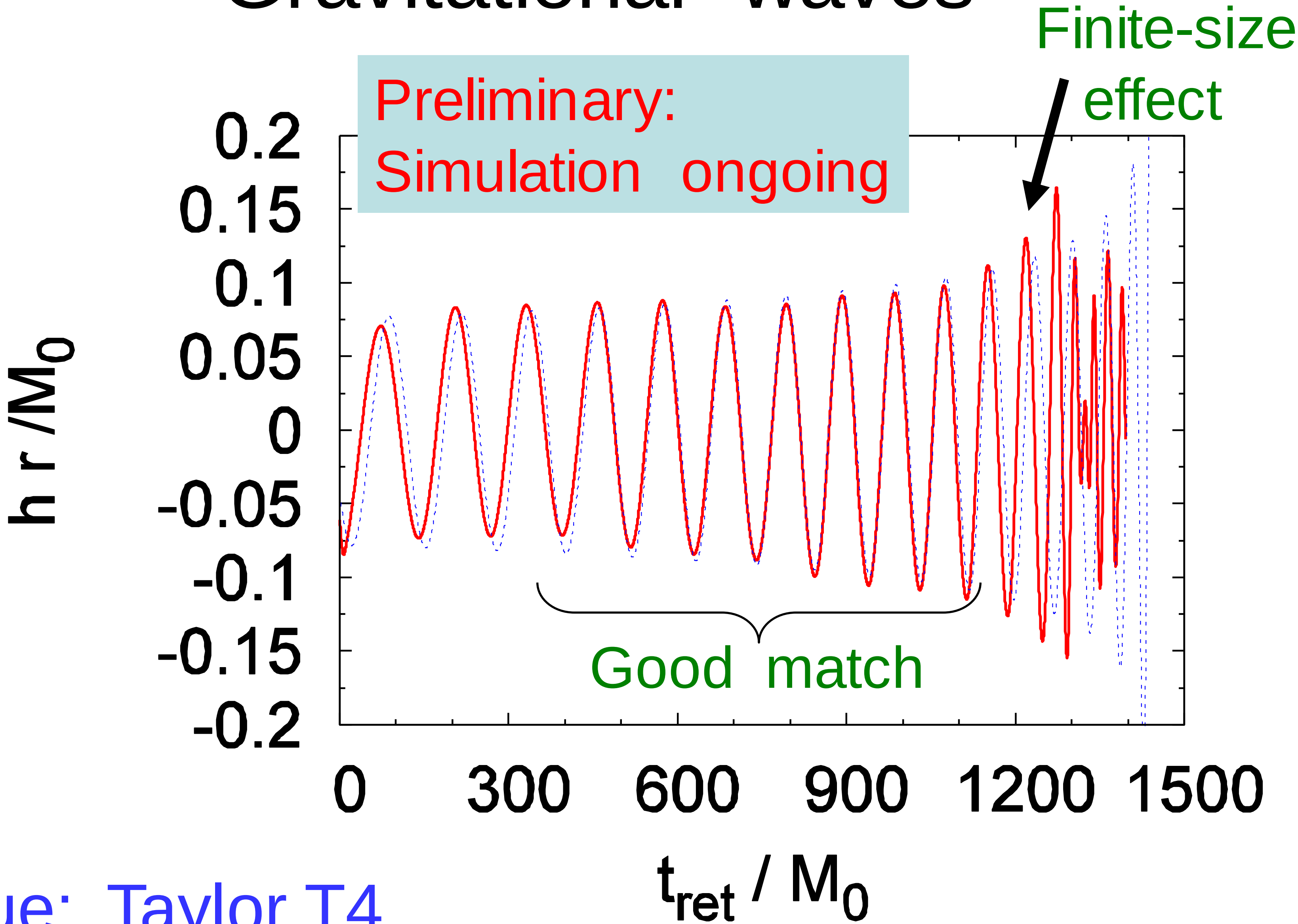


A result of longterm evolution



6.5 orbits

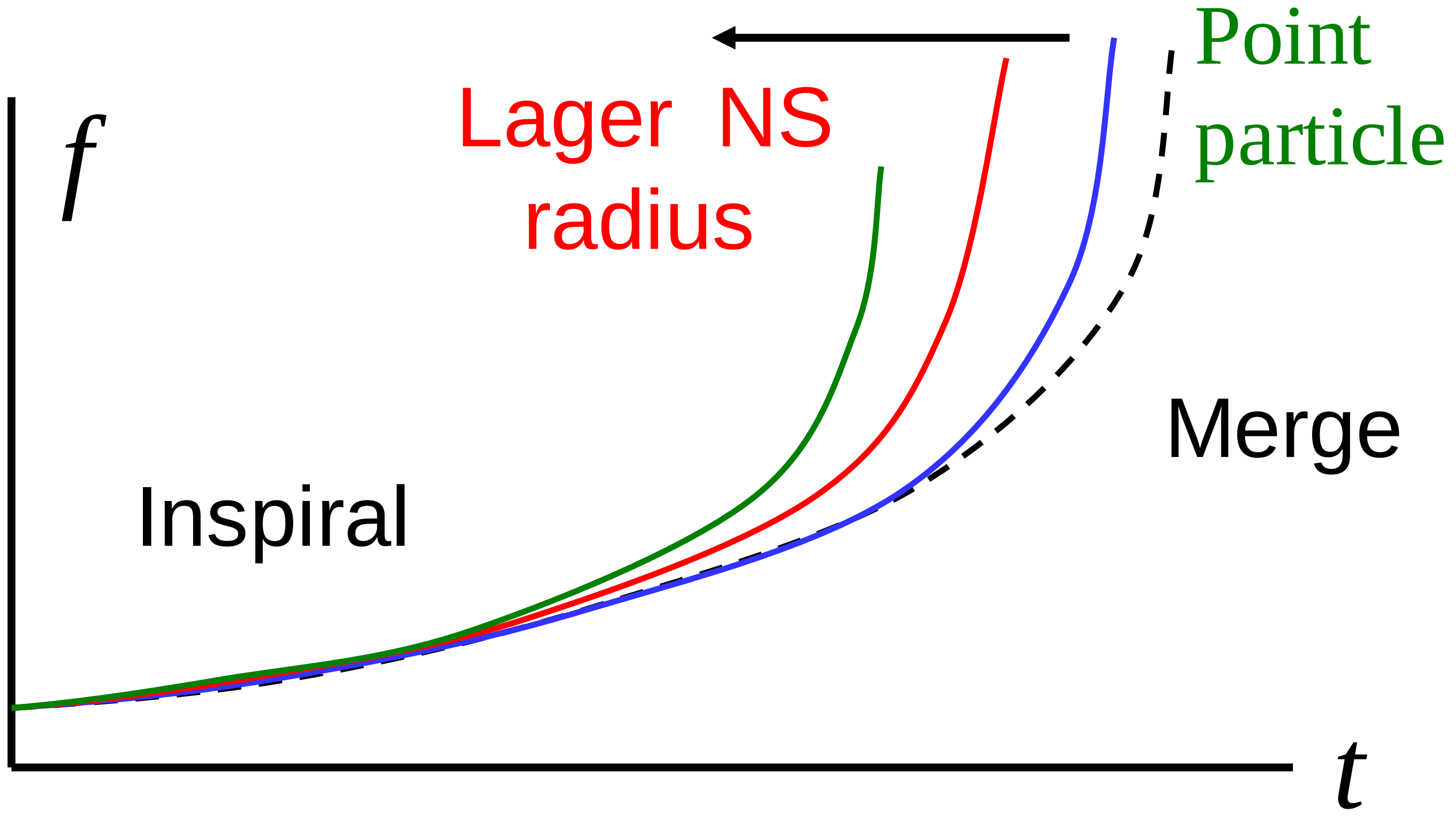
Gravitational waves



Blue: Taylor T4

Expected results

E.g., Gravitational wave frequency as a function of time for a given mass

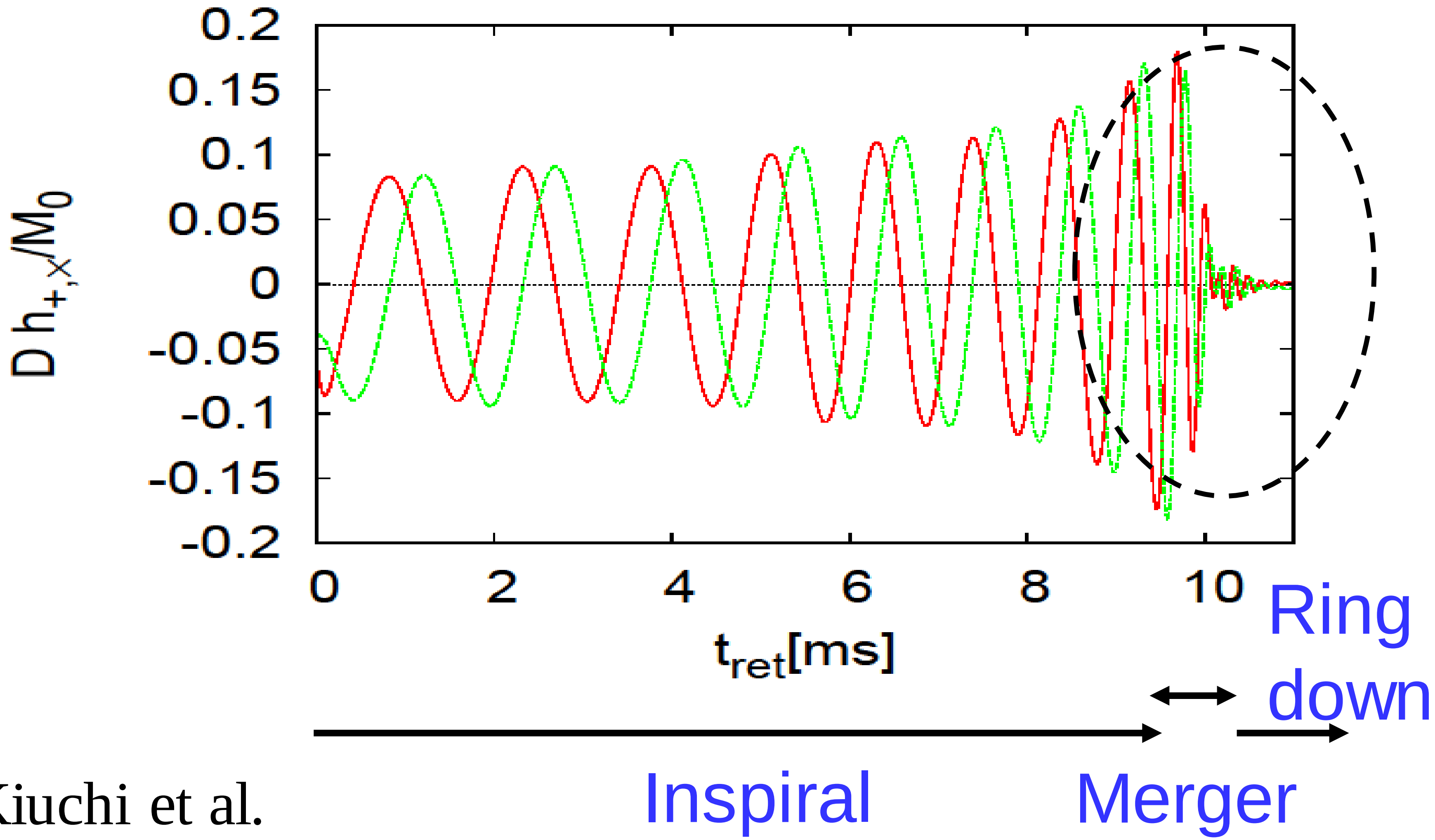


§ NS-NS: Current activity 2

- Category 2: Study with Cold EOS (+ rough correction for finite-temperature part) to clarify gravitational waveforms for BH formation case

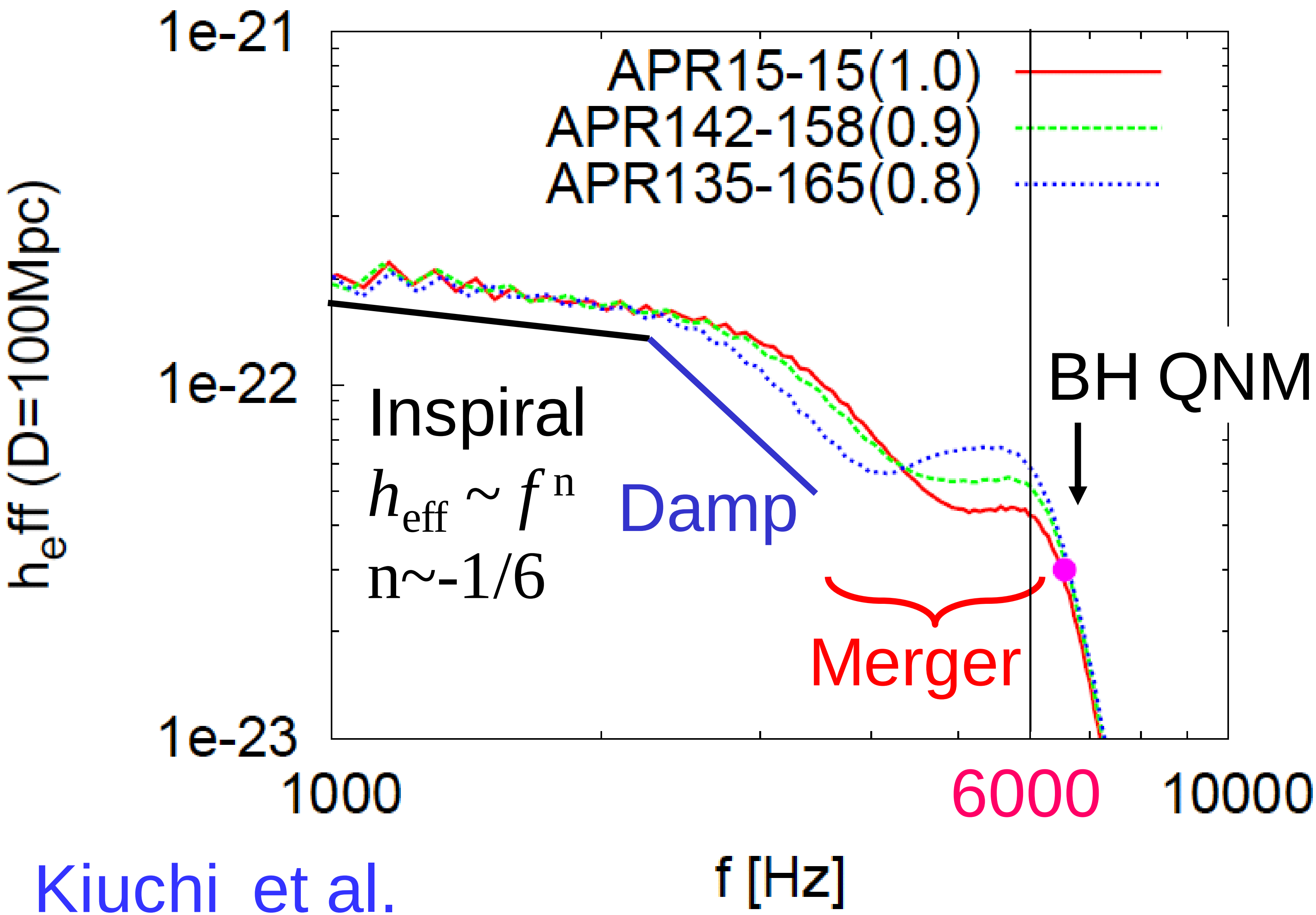
Kiuchi et al. 2009

Gravitational waveform for black hole formation case

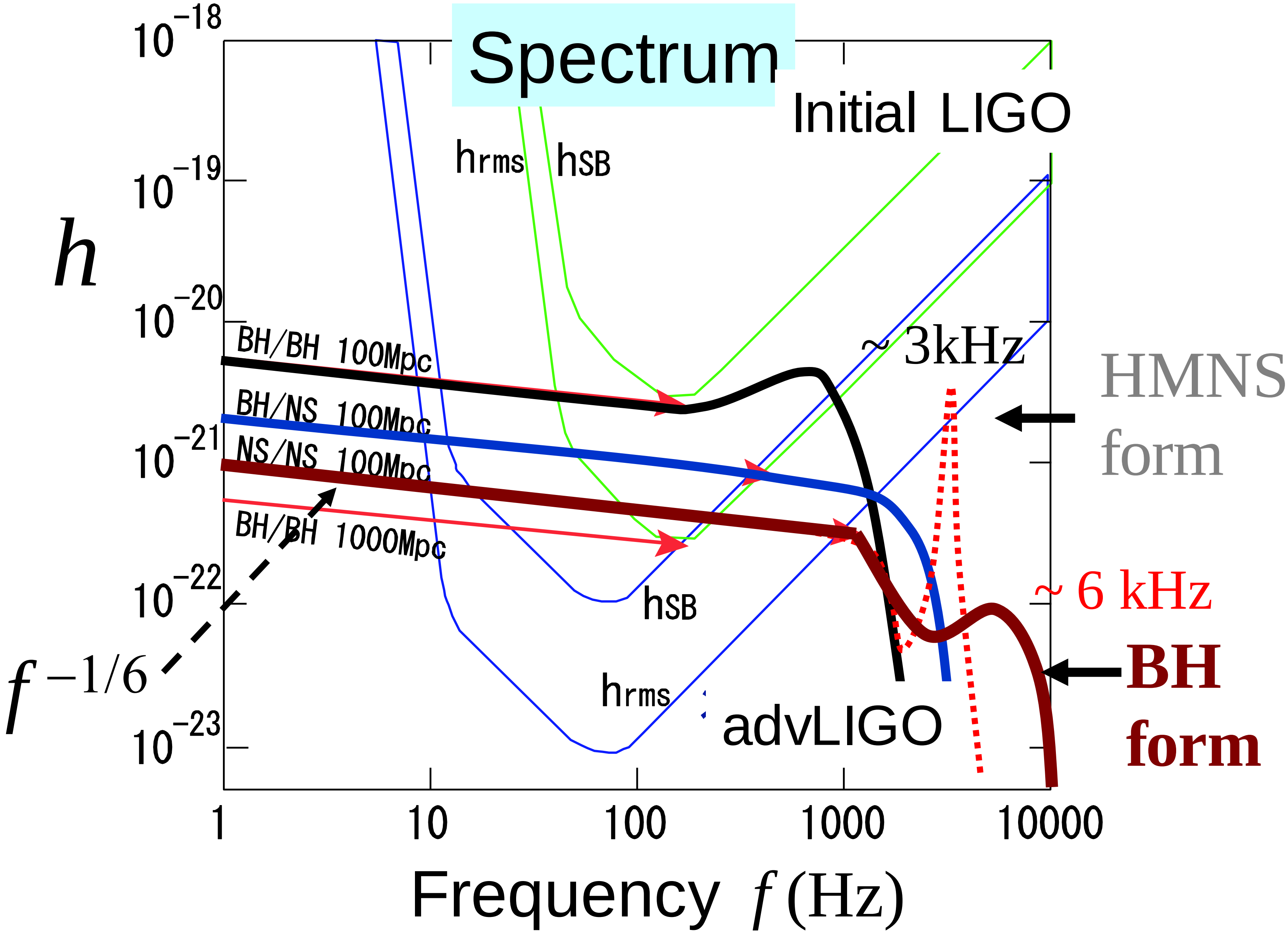


Kiuchi et al.

Universal spectrum for BH formation



Kiuchi et al.



Assume BH： $10M_{sun}$、NS: $1.4M_{sun}$

§ NS-NS: Current activity 3

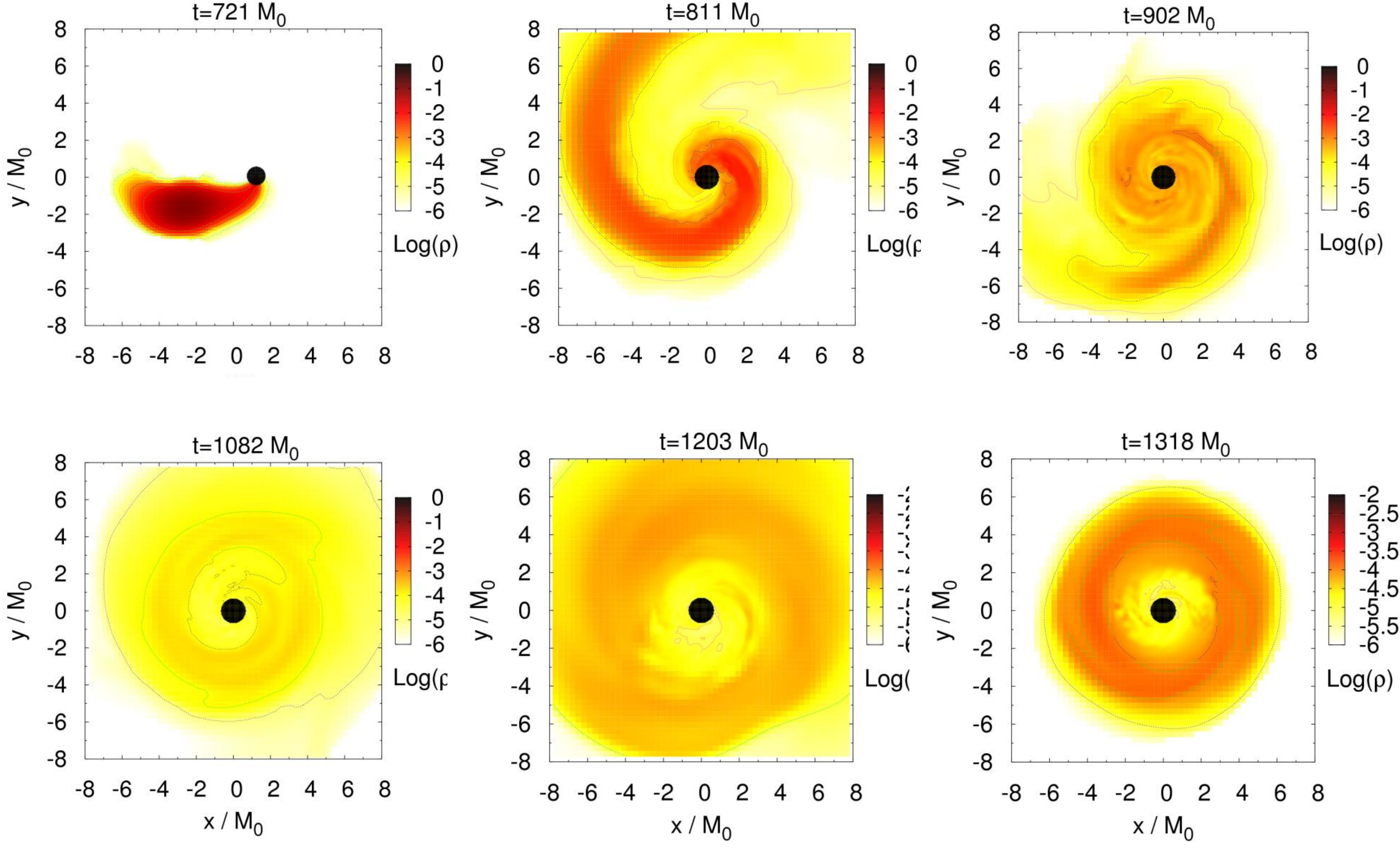
- Category 3: Study with finite-temperature EOS + some neutrino physics
- The purpose is to clarify the detail in the merger phase; evolution of hypermassive neutron stars and possible relation between short GRB (Challenge)

Sekiguchi will talk details
of our implementation tomorrow

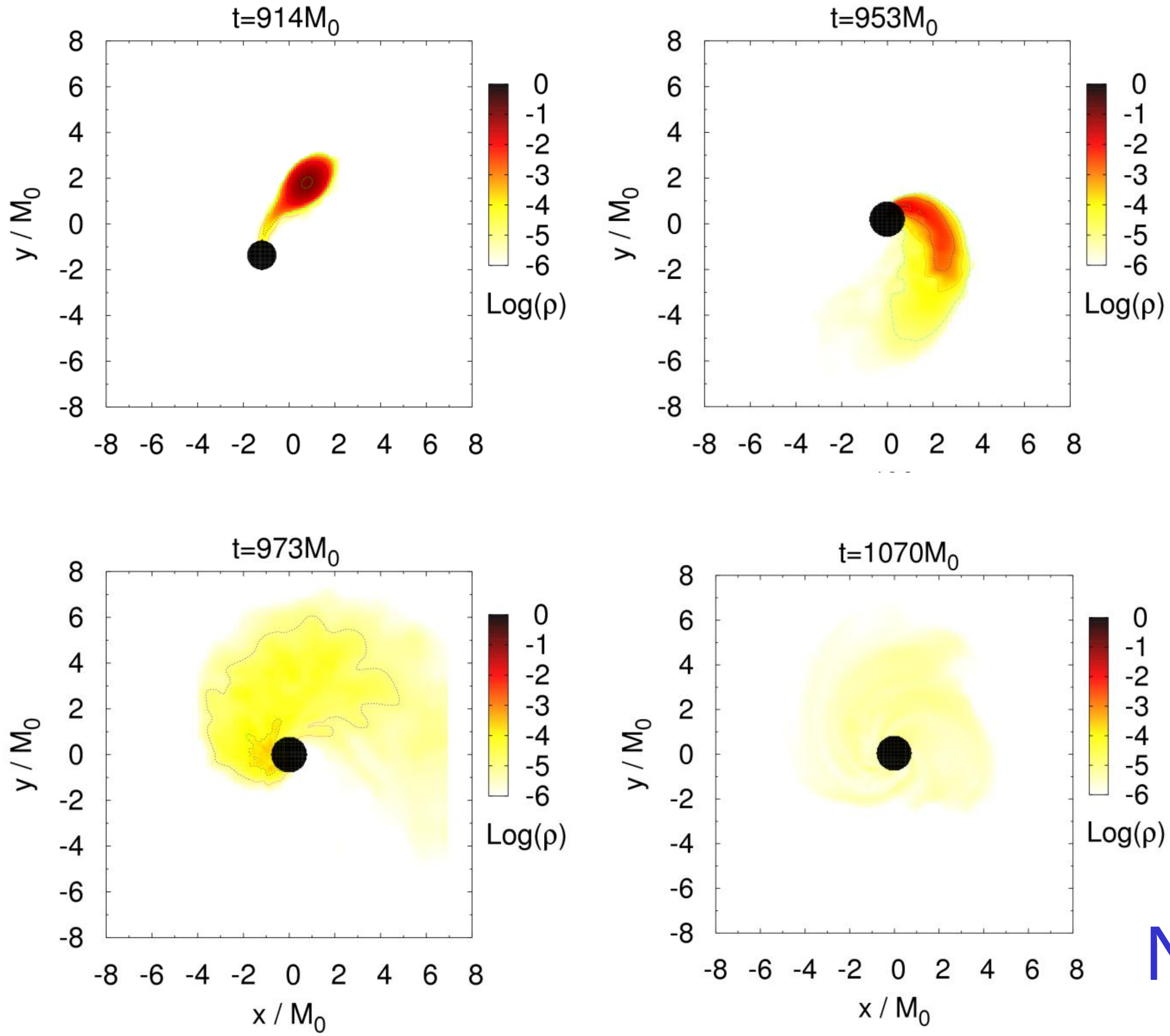
§ BH-NS: Current activity

- We are also interested in gravitational waveforms in the late inspiral and merger phases
- Survey for waveforms using piecewise polytropic EOSs (by Kyutoku & Shibata)

$(M/R)_{NS}=0.145,\ M_{BH}/M_{NS}=2$



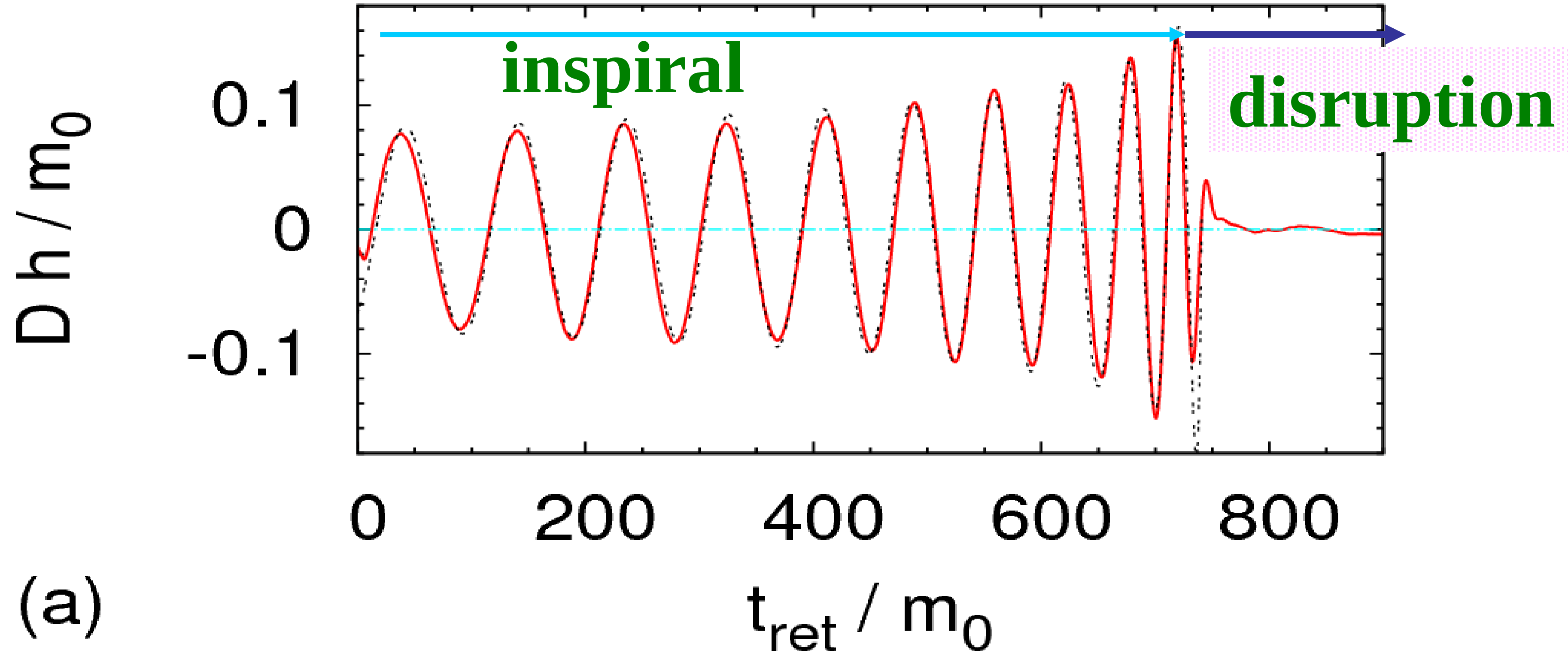
$(M/R)_{NS}$=0.145, M_{BH}/M_{NS}=4



No disk

Gravitational waveforms

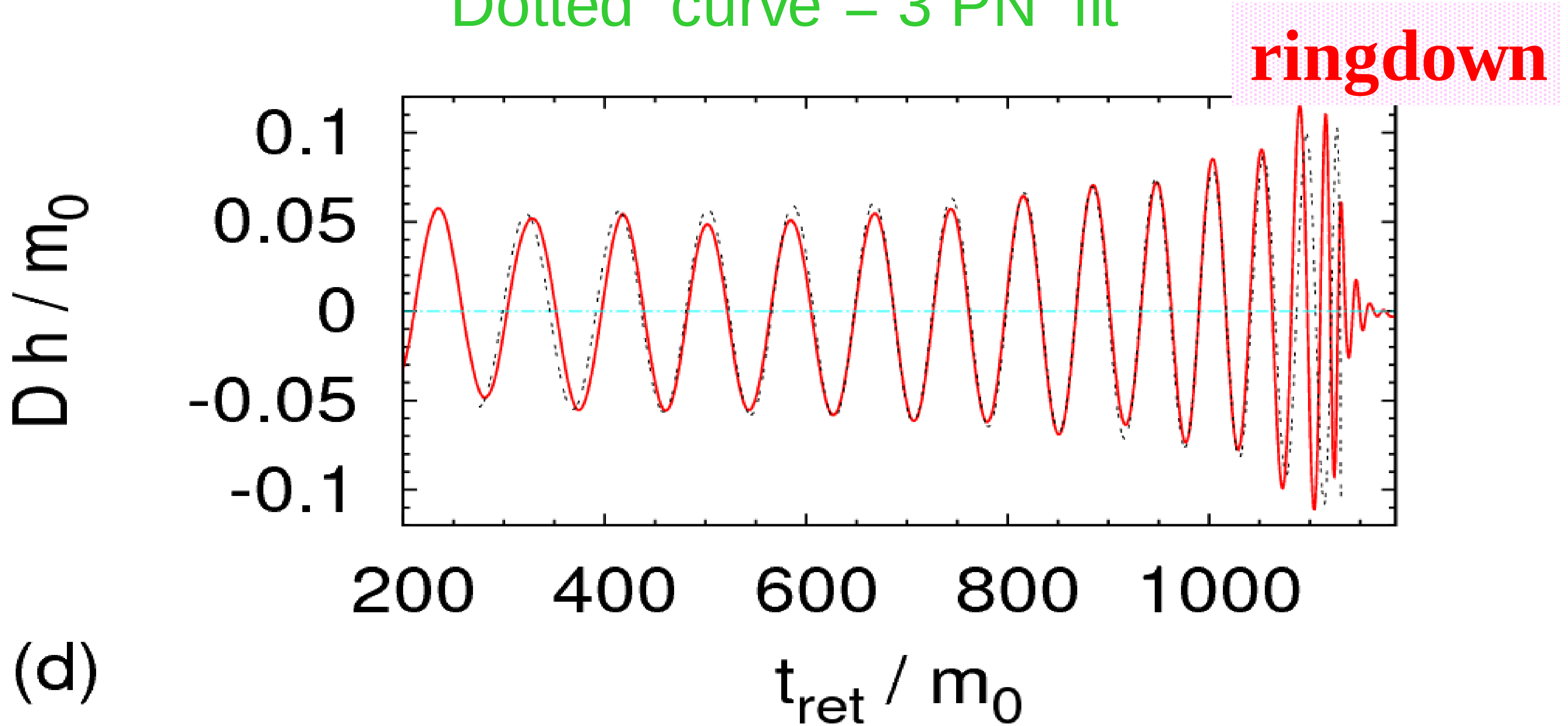
Dotted curve = 3 PN fit



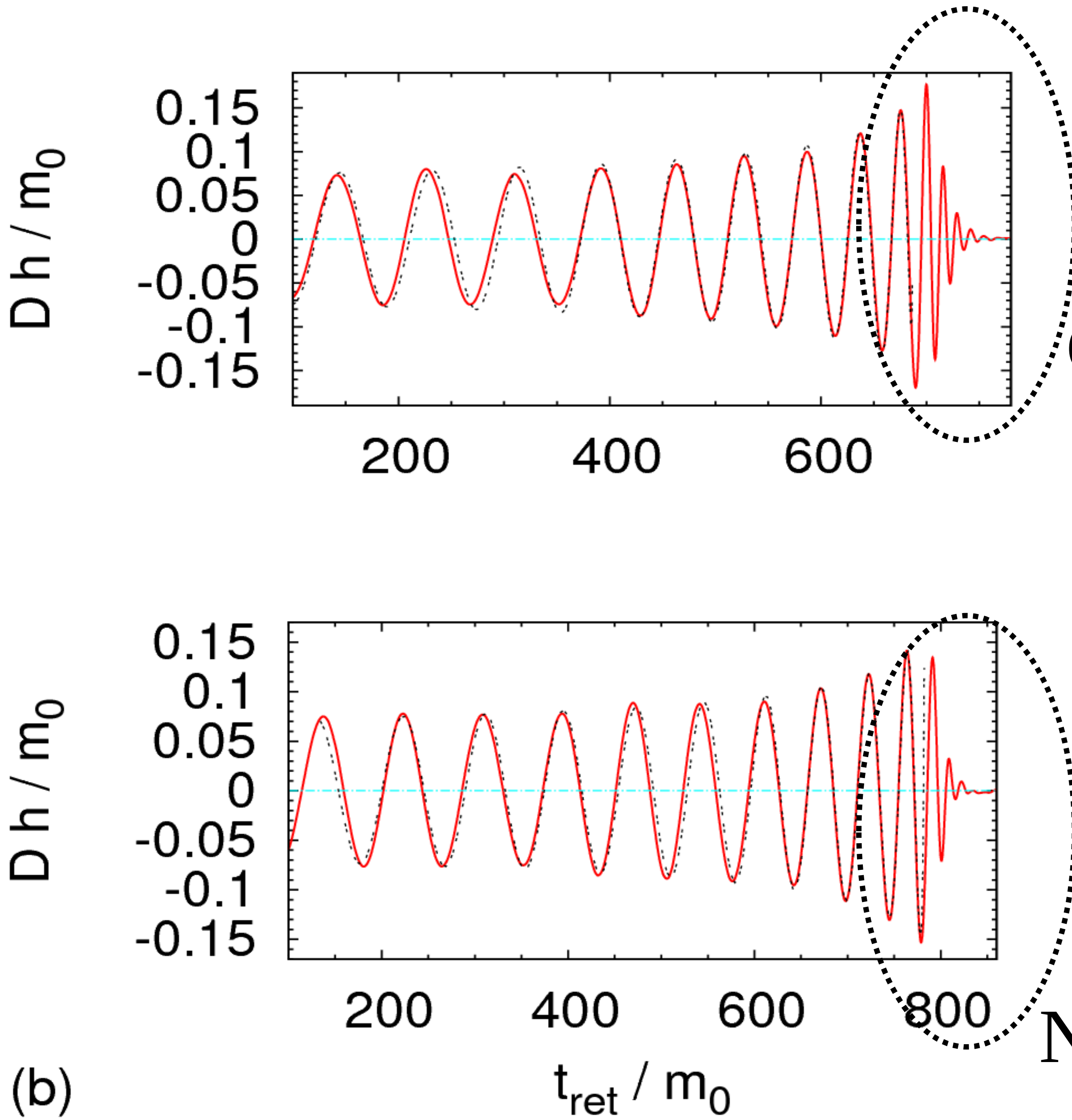
$(M/R)_{NS}=0.145, M_{BH}/M_{NS}=2$

Gravitational waveforms

Dotted curve = 3 PN fit



$(M/R)_{NS}=0.145, M_{BH}/M_{NS}=5$



$(M/R)_{NS}$=0.178

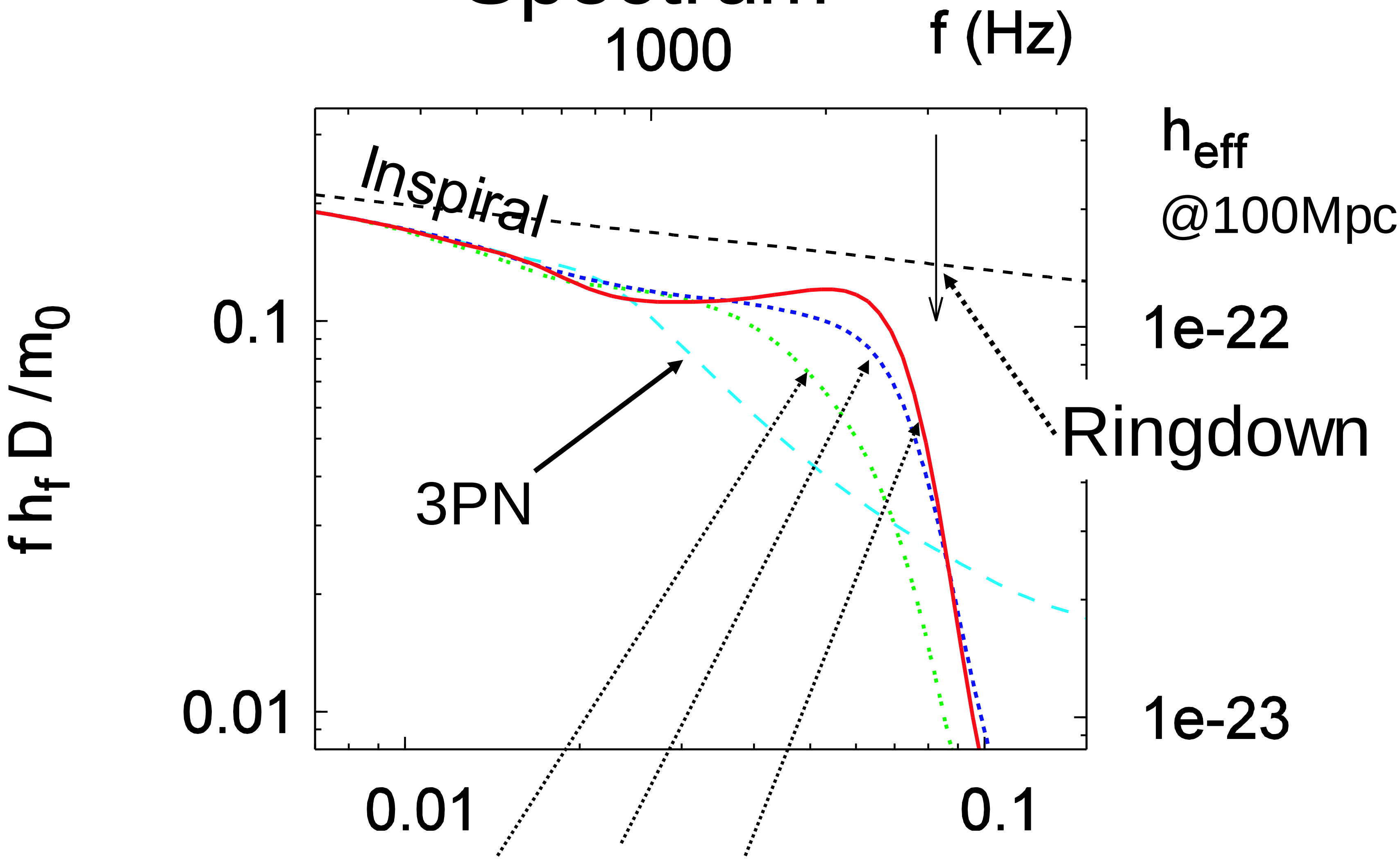
Clear ringdown

M_{BH}/M_{NS}=3

$(M/R)_{NS}$=0.145

Not very clear

Spectrum

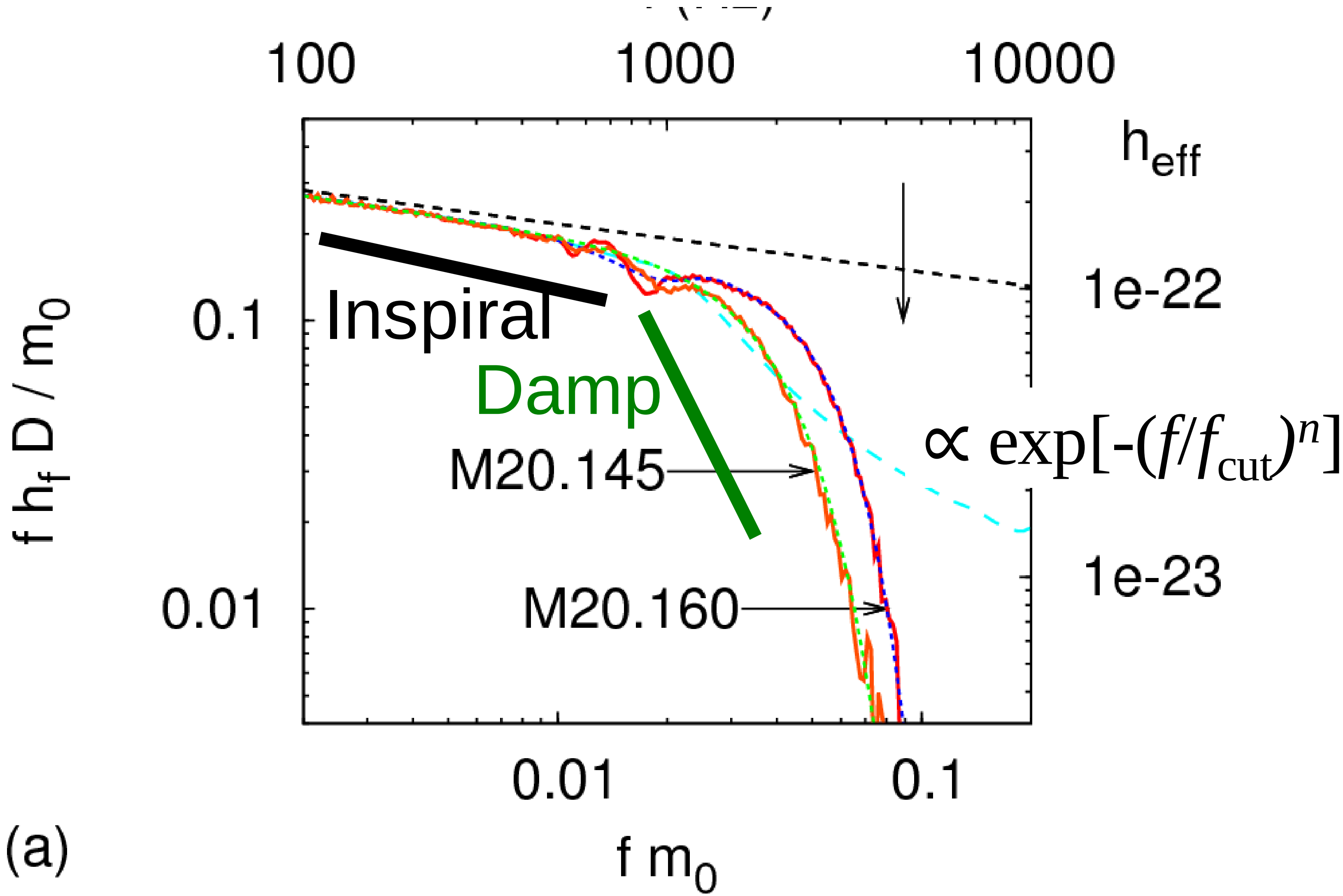


$(M/R)_{NS}$=0.145, 160, 178, M_{BH}/M_{NS}=3

Summary

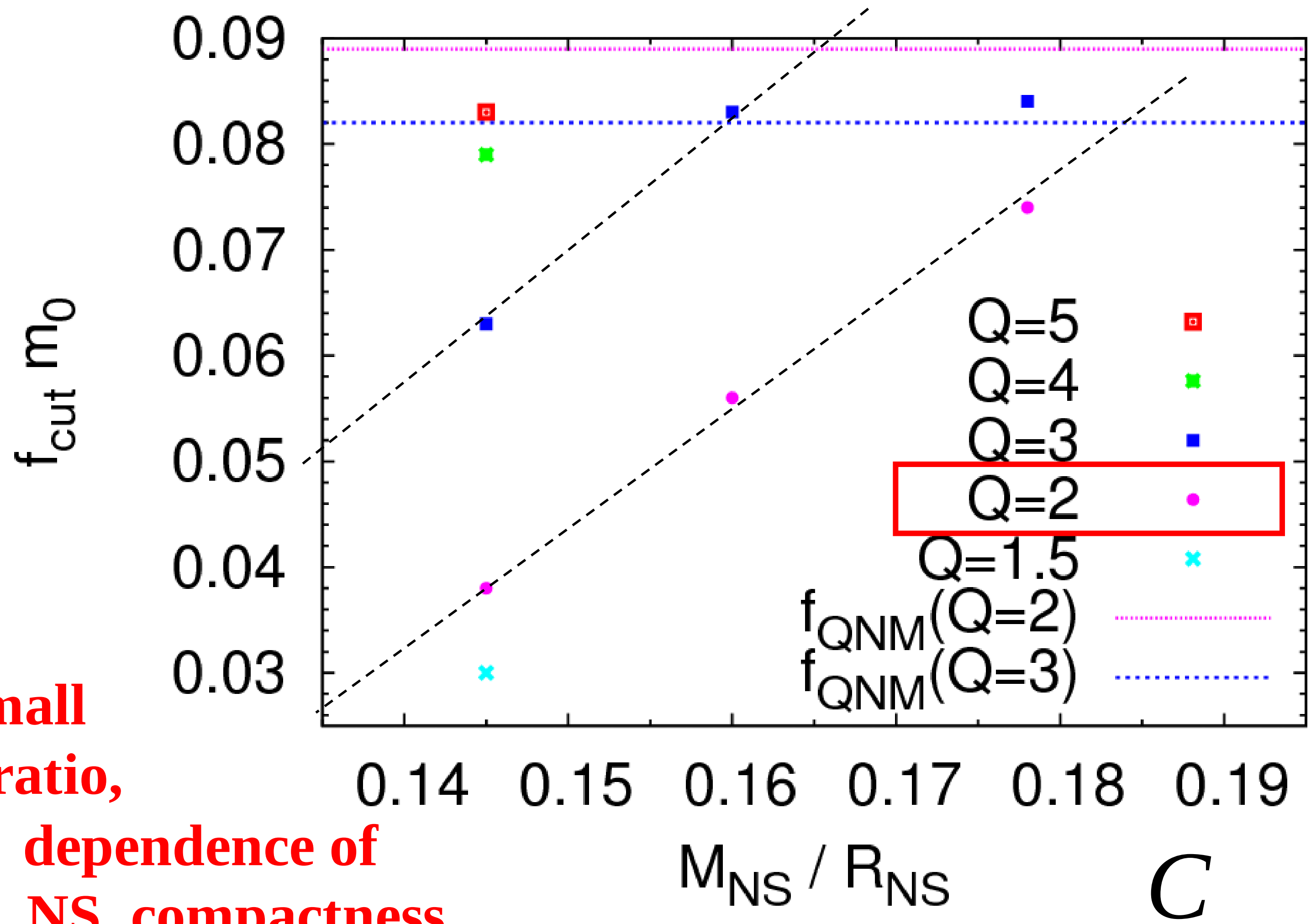
- Many simulations are ongoing for NS-NS and BH-NS. Our current primary purpose is to clarify gravitational waveforms
- In 3—5 years, a variety of theoretical waveforms will be derived.
- Implementation of finite-temperature EOS & some neutrino physics + transfer was started by Sekiguchi
  → One of challenges for PFlops machine in the next ~ 5 years

Typical spectrum



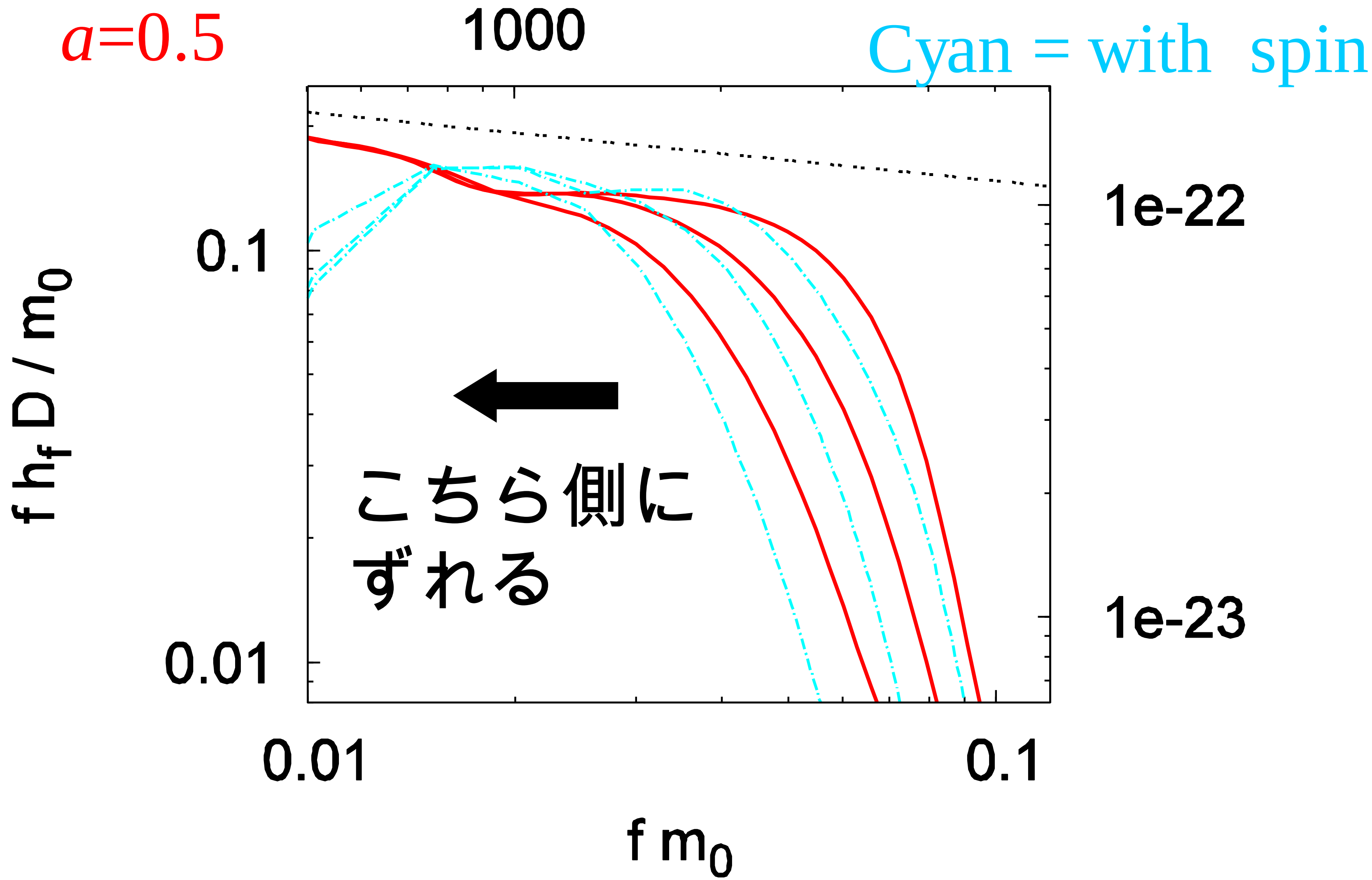
$(M/R)_{NS}$=0.145, M_{BH}/M_{NS}=2

Relation between Compactness (*C*) and mass ratio (*O*)

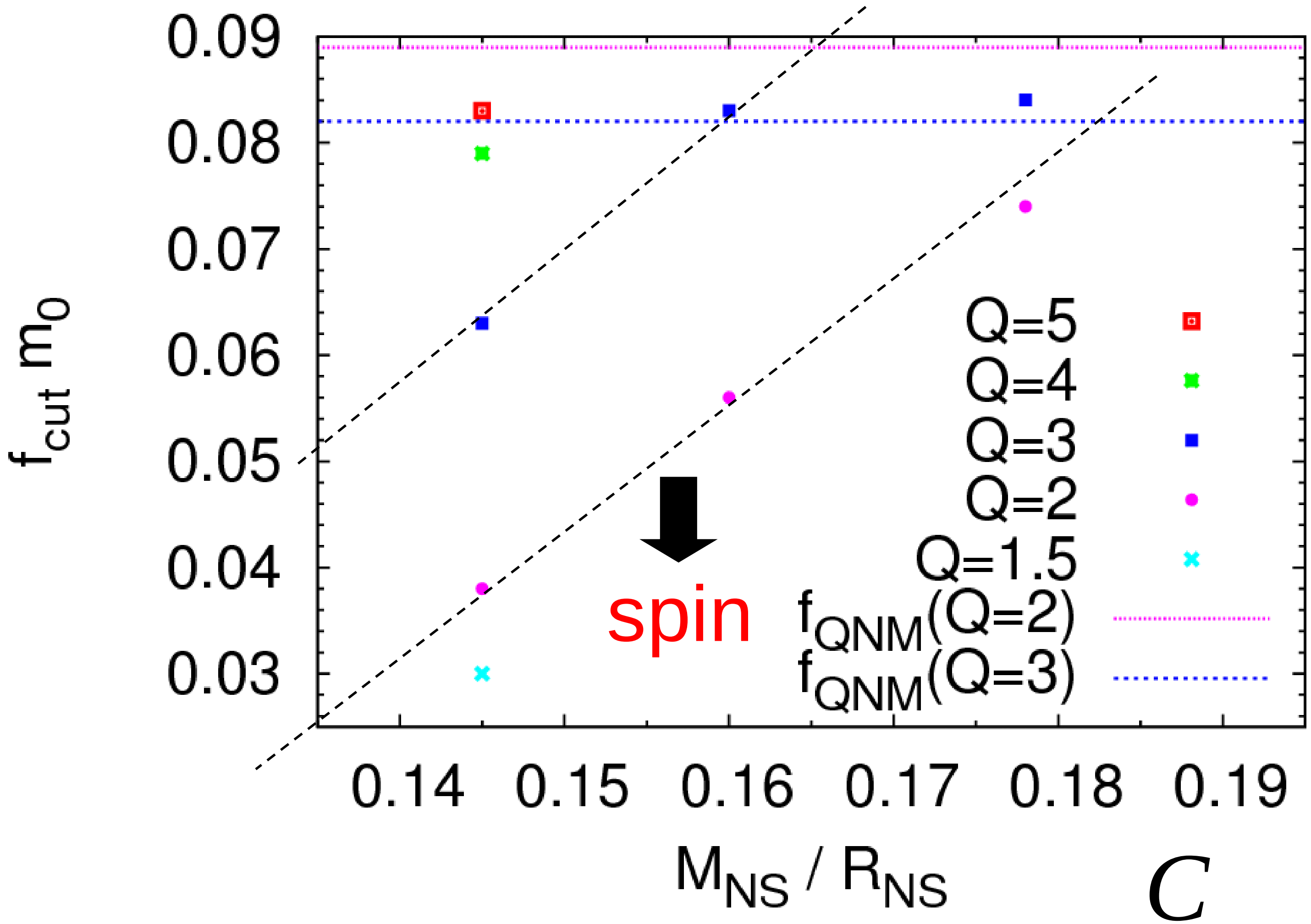


For small mass ratio, strong dependence of f_{cut} on NS compactness

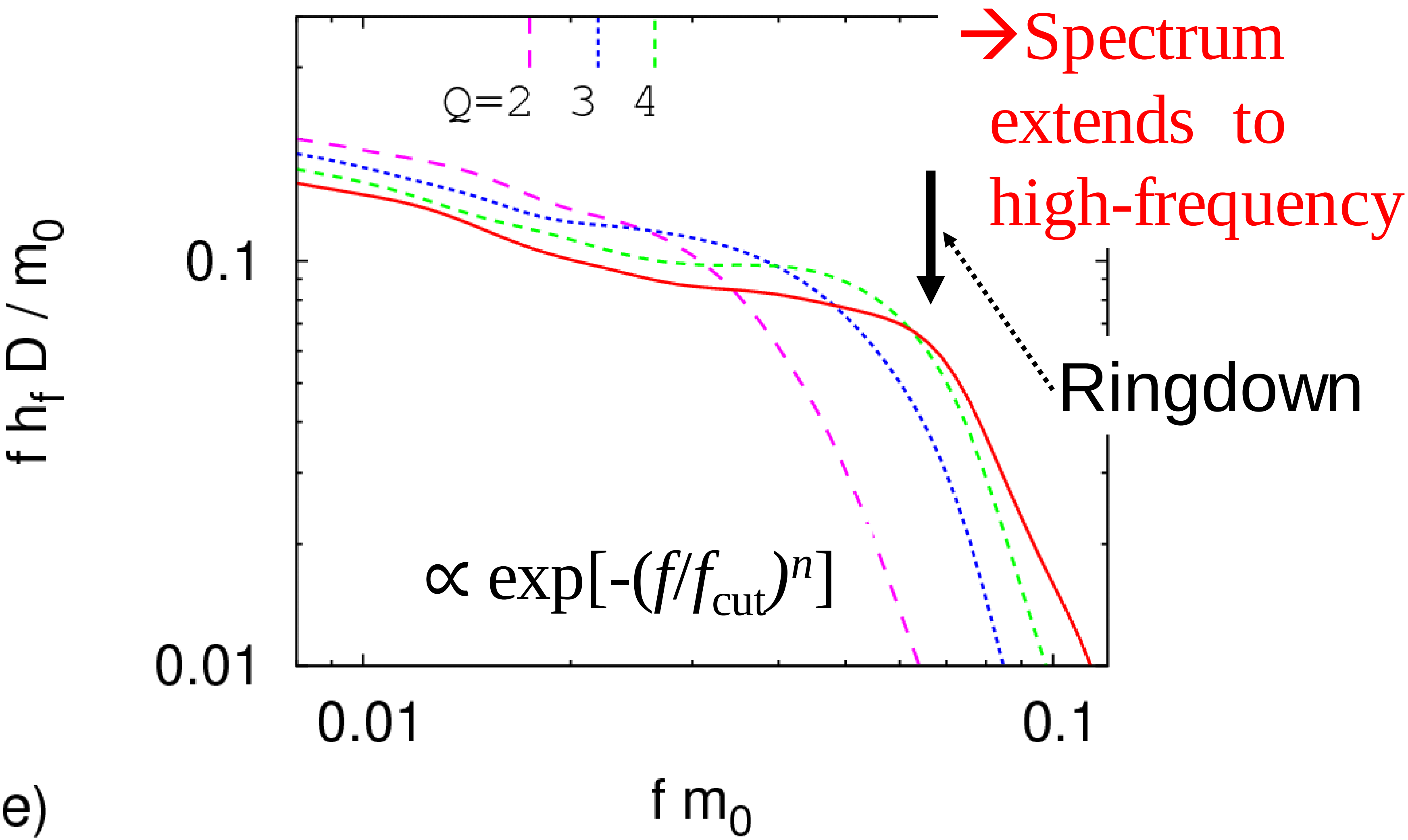
With spin: Q=2, C=0.145, 0.160, 0.178



Relation between Compactness (C) and mass ratio (Q)

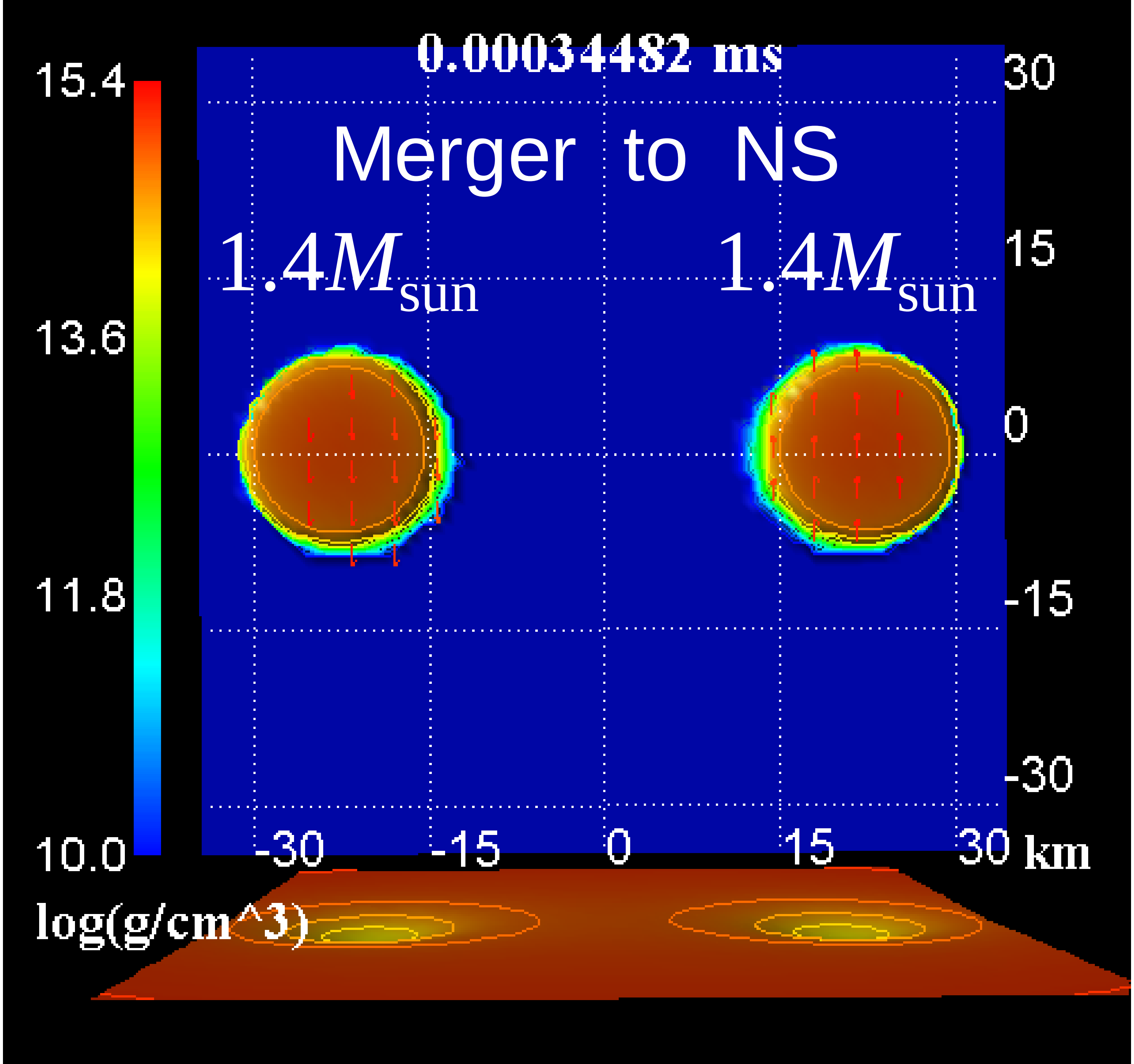


Spectrum



(e)

$(M/R)_{NS}$=0.145, M_{BH}/M_{NS}=2–5


0.00034482 ms
Merger to NS
$1.4M_{sun}$
$1.4M_{sun}$
15.4
13.6
11.8
10.0
log(g/cm^3)
30
15
0
-15
-30
-30
-15
0
15
30 km