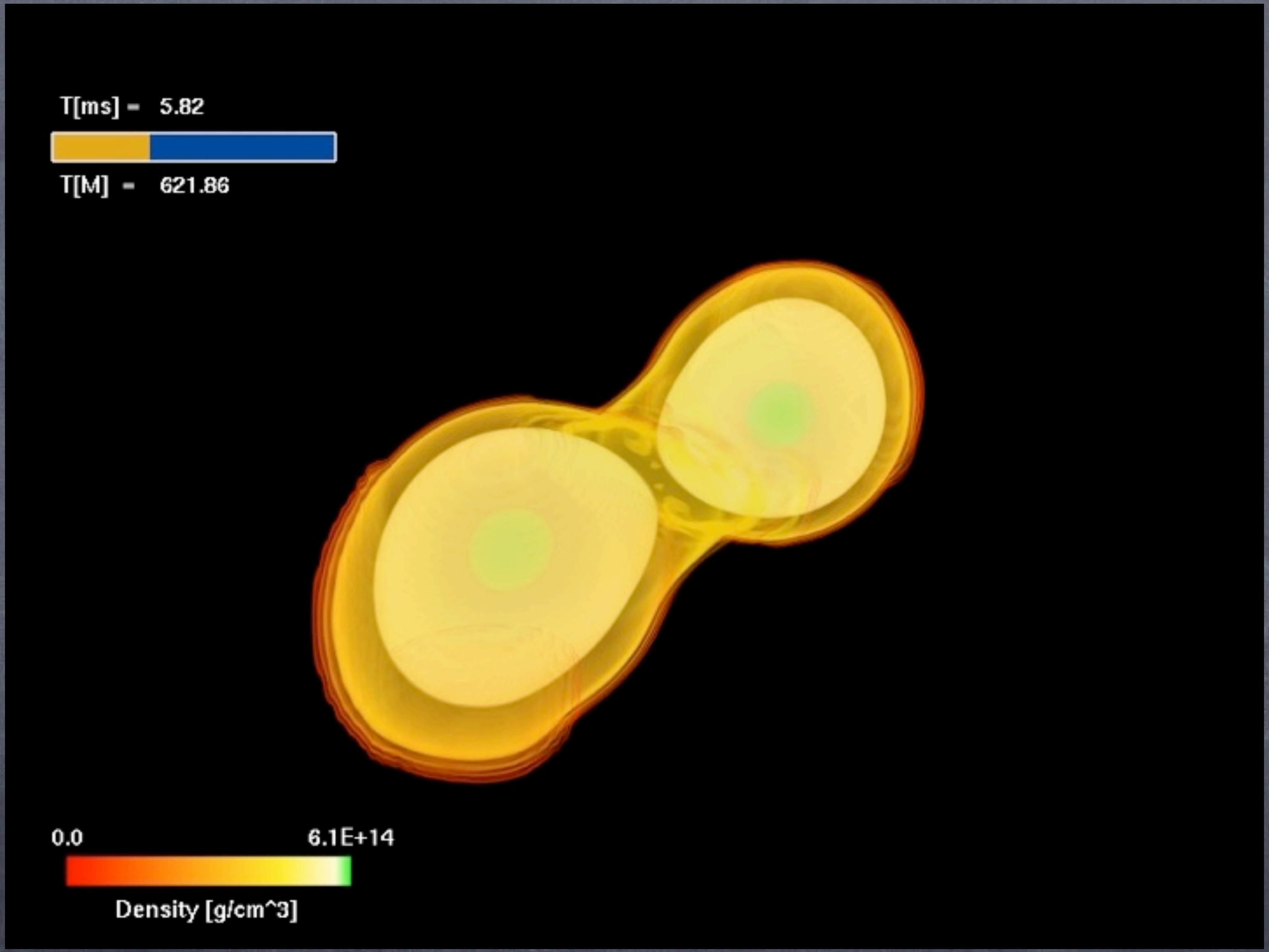
General Relativistic Simulations of Compact Binaries



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Plan of the Talk

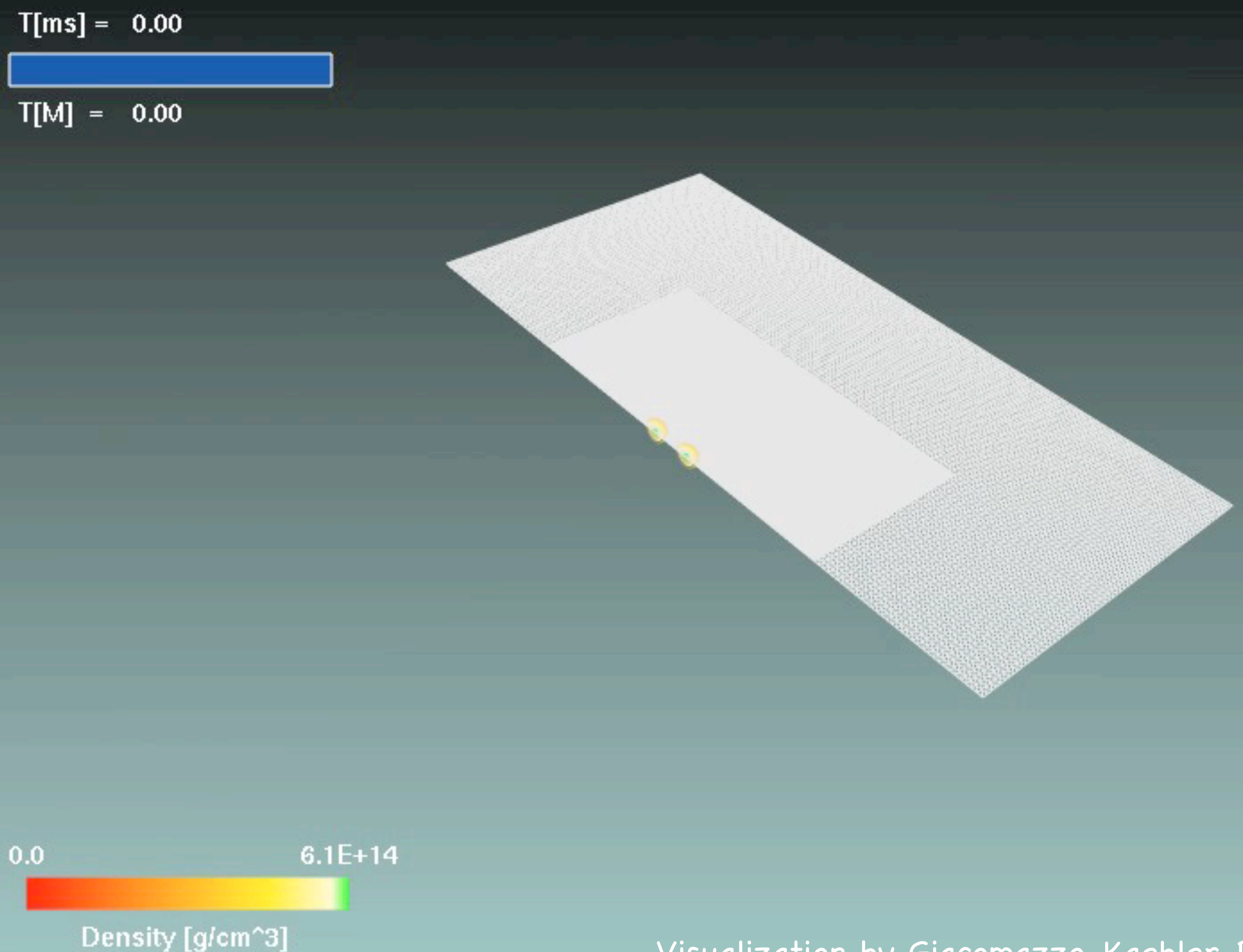
- Gravitational Waves
  - Binary Neutron Stars
  - Mixed Binary Systems (NS-BH)
- EM counterparts
  - Tori formation in BNS and NS-BH mergers
  - EM signals from BBH

BNS simulations: state of the art

- GRHD (only most recent papers listed)
  - Shibata et al 2005: FPS and SLy EOSs
  - Shibata & Taniguchi 2006: APR and SLy EOSs
  - Anderson et al 2008: AMR, ideal fluid EOS
  - Baiotti et al 2008, 2009: AMR, ideal fluid EOS, long-term post-merger evolution
  - Yamamoto et al 2008: AMR, ideal fluid EOS
  - Read et al 2009: piecewise polytropic EOSs
  - Kiuchi et al 2009: long-term inspiral, APR EOS
  - Rezzolla et al 2010: AMR, ideal fluid, tori formation
- GRMHD (all the papers listed...)
  - Anderson et al 2008: AMR, ideal fluid EOS
  - Liu et al 2008: ideal fluid EOS
  - Giacomazzo et al 2009: AMR, ideal fluid EOS

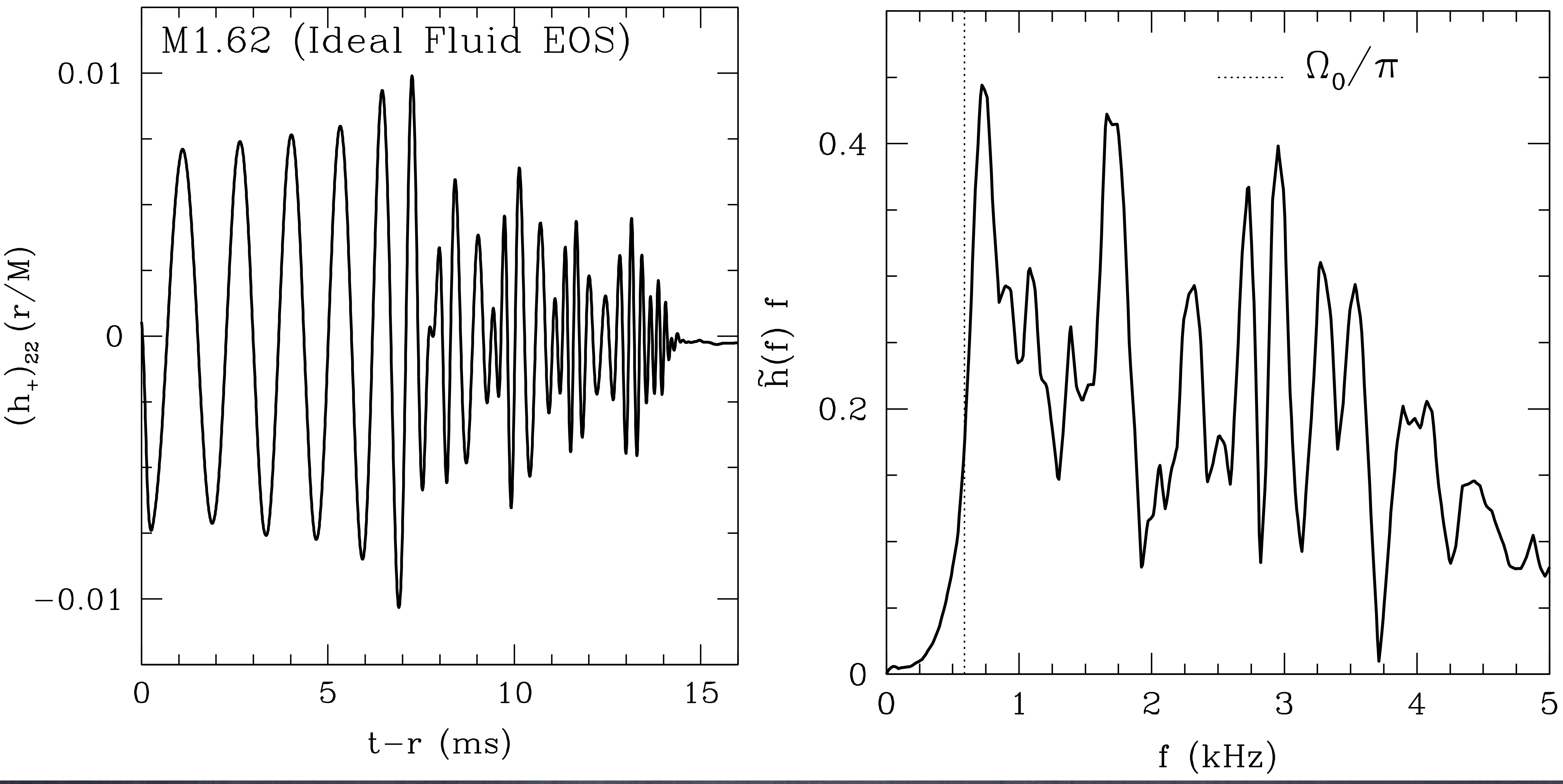
Ideal Fluid EOS: High-Mass BNS (M_1=M_2=1.6)

Visualization by Giacomazzo, Kaehler, Rezzolla



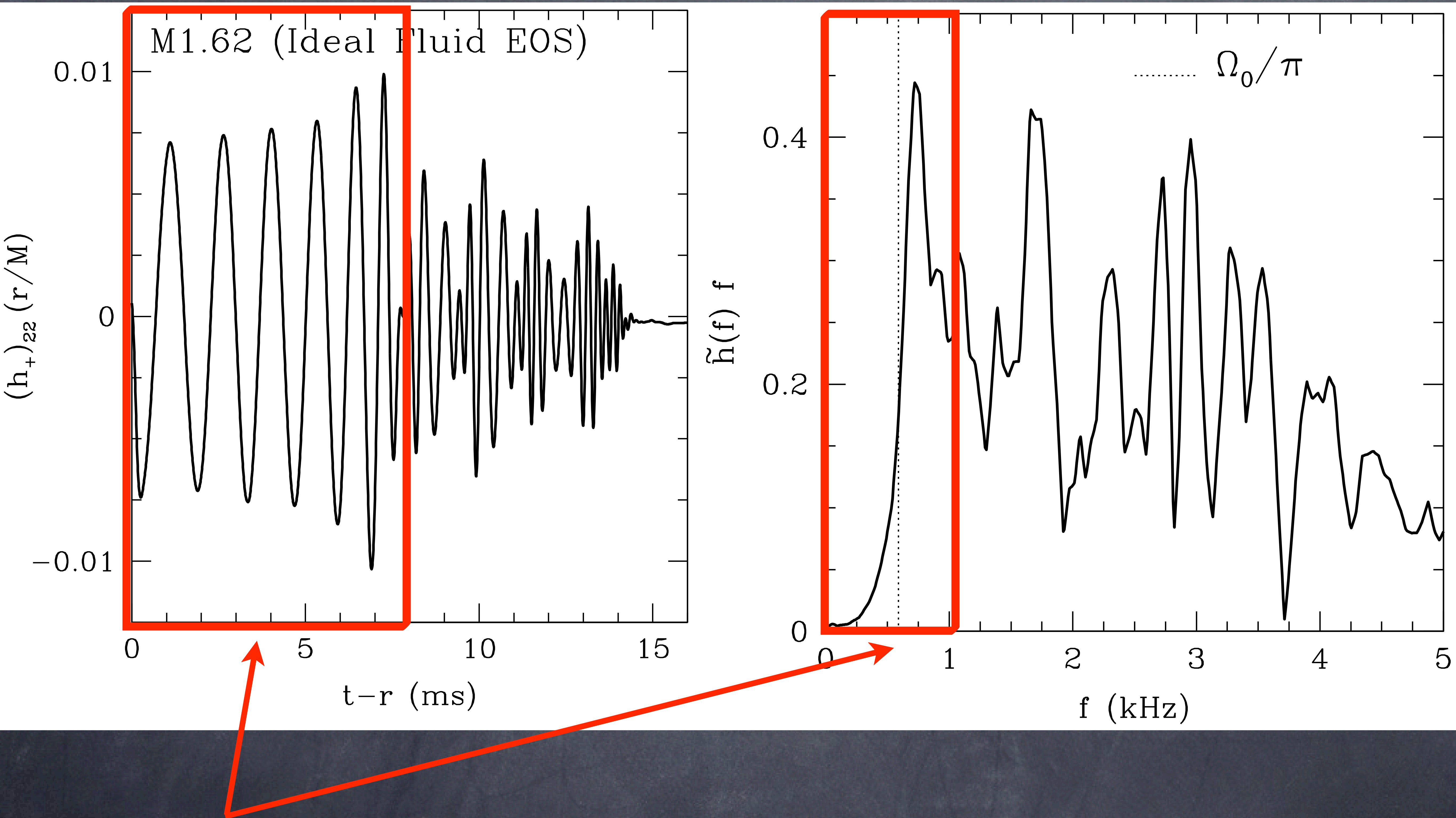
Visualization by Giacomazzo, Kaehler, Rezzolla

GWs from BNS



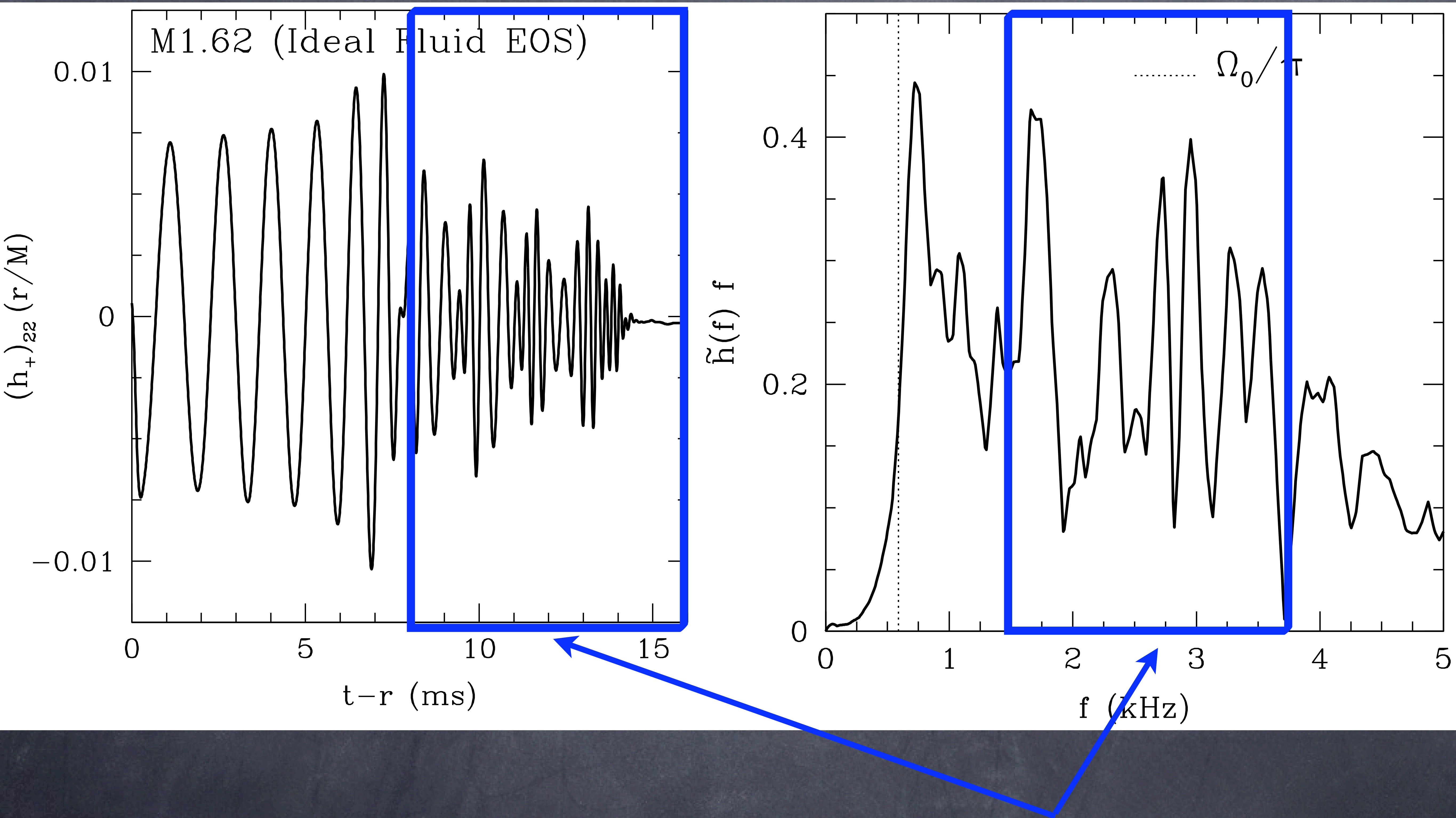
M1.62 (Ideal Fluid EOS)
0.01
0
−0.01
$(h_+)_{22}\,(r/M)$
0
5
10
15
t−r (ms)
Ω_0/π
0.4
0.2
0
$\tilde{h}(f)\,f$
0
1
2
3
4
5
f (kHz)

GWs from BNS



contribution
from the inspiral

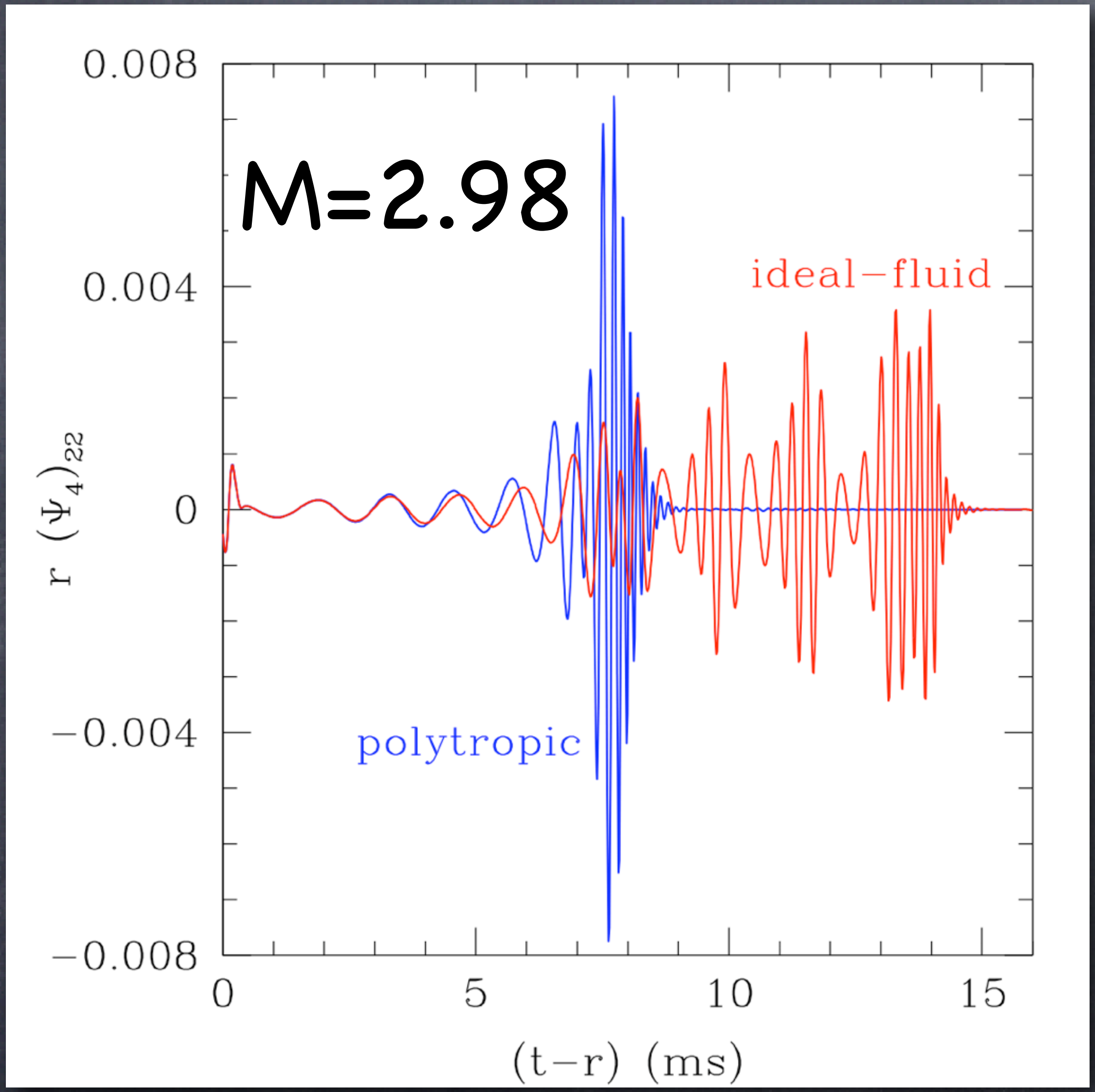
GWs from BNS

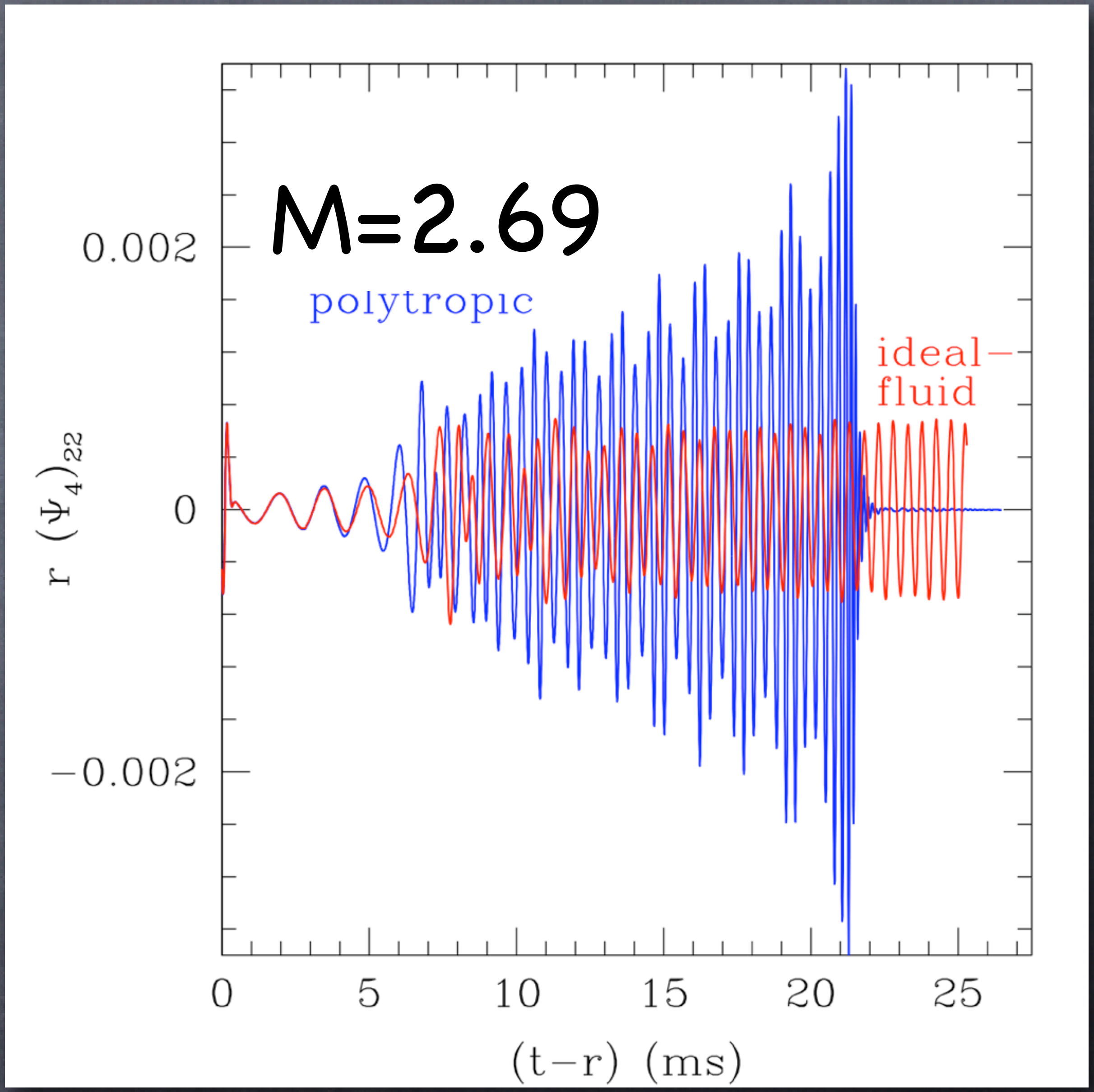


contribution
from the HMNS

GWs from BNS: The Role of Mass and EOS

Baiotti, Giacomazzo, Rezzolla 2008

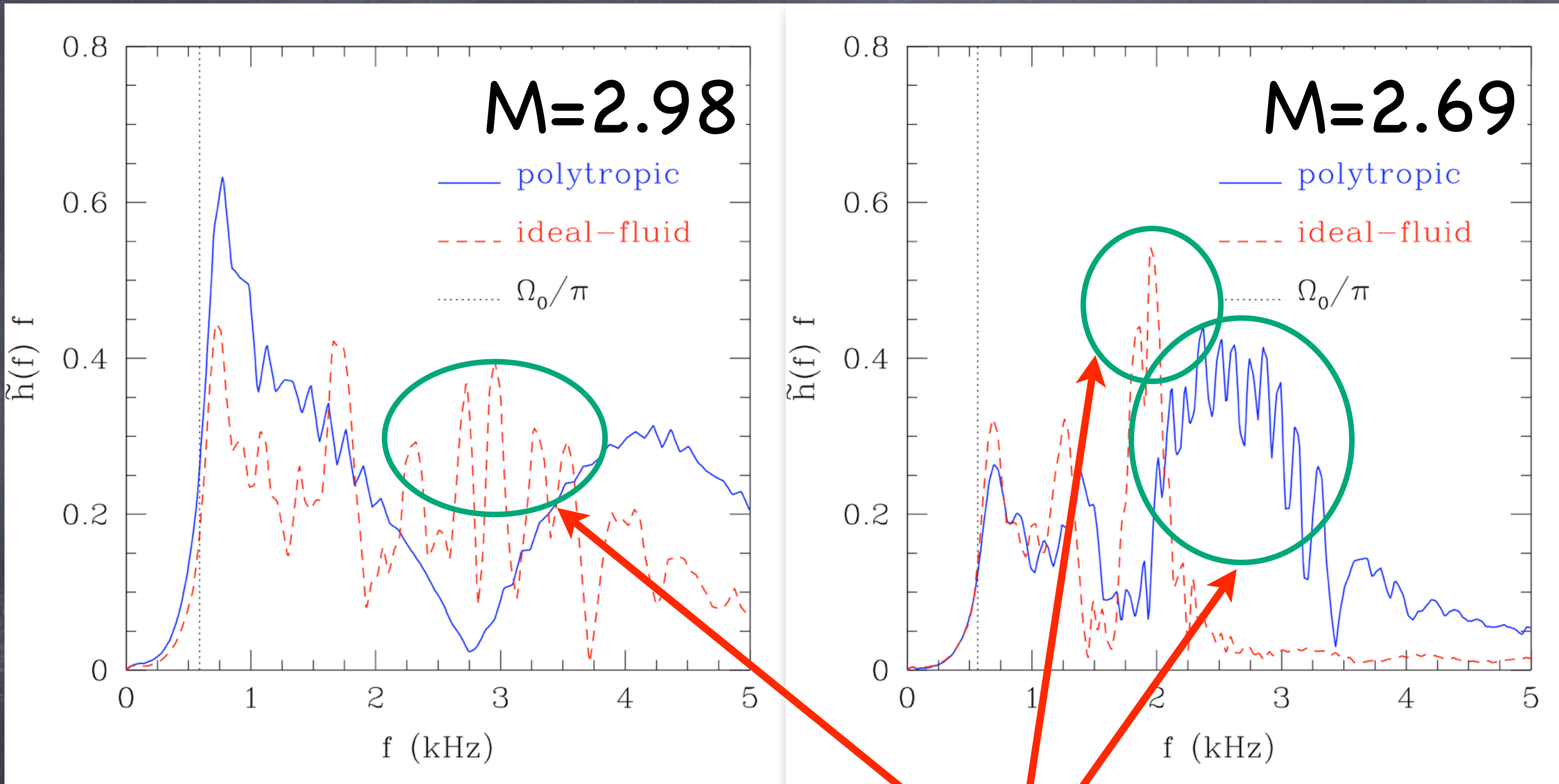




Kiuchi et al 2009 (APR EOS): prompt collapse to BH when M>2.8-2.9.

GWs from BNSs

Baiotti, Giacomazzo, Rezzolla 2008



The pre-merger dynamics is very similar; the post-merger phase is very different

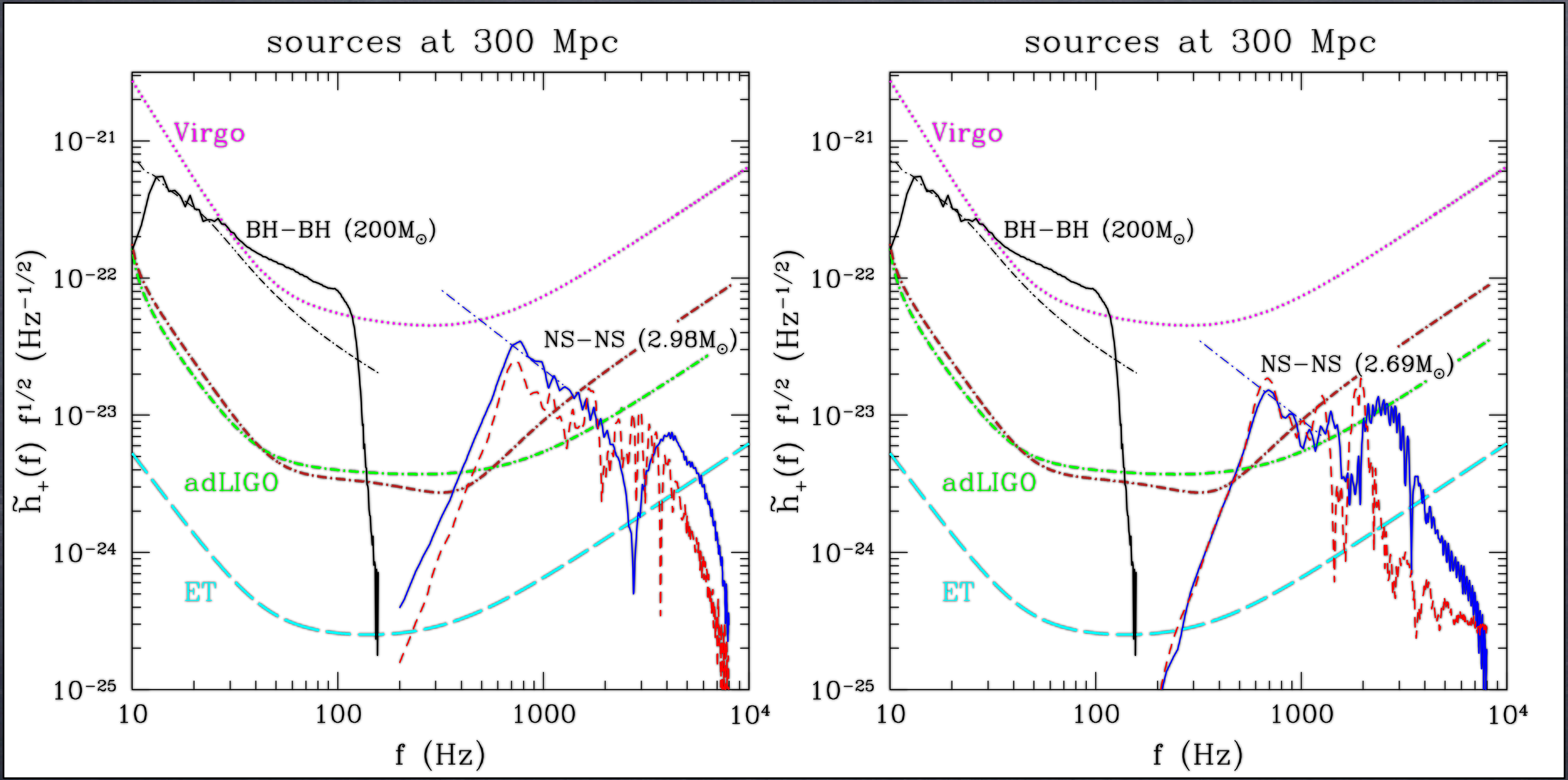
Contributions from the post-merger evolution

HMNS emits GW signal at 2-4kHz (depending on the EOS)

Detectability of the post-merger phase

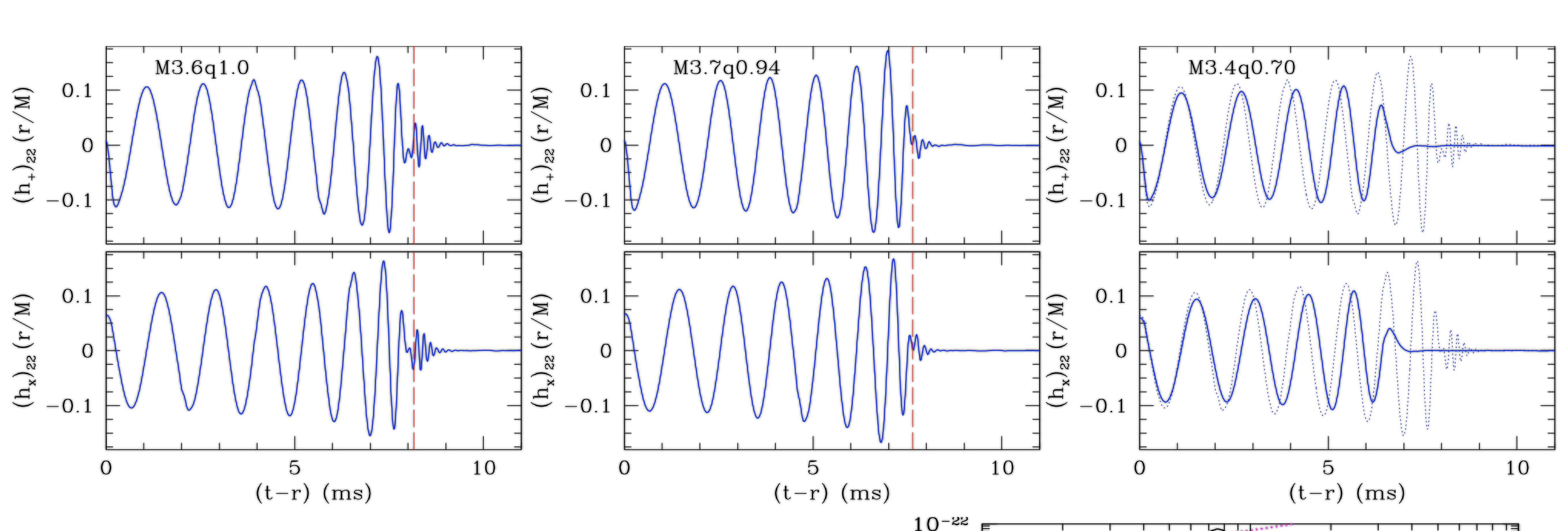
M=2.98 M=2.69

Andersson et al 2009



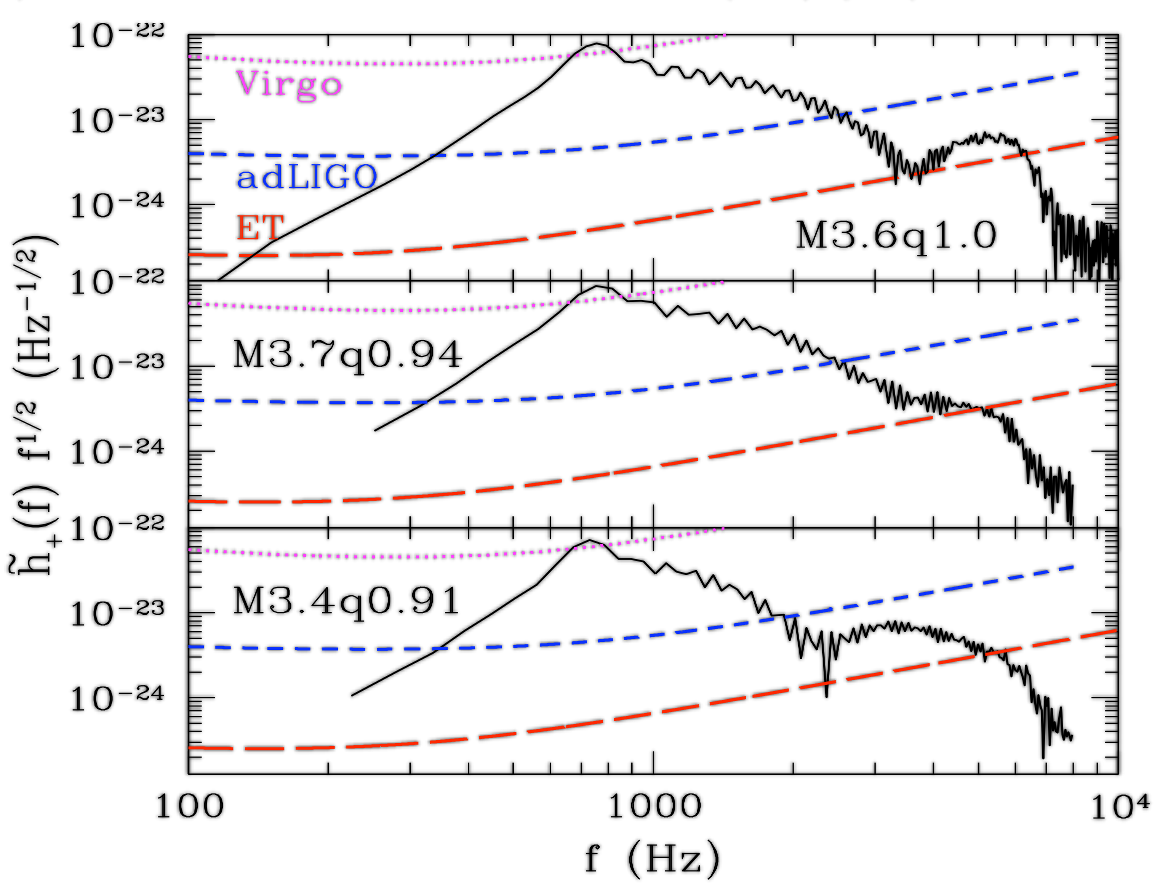
Note that in both cases the post-merger phase is almost invisible to current and advanced LIGO/Virgo detectors.

GWs form unequal mass BNSs

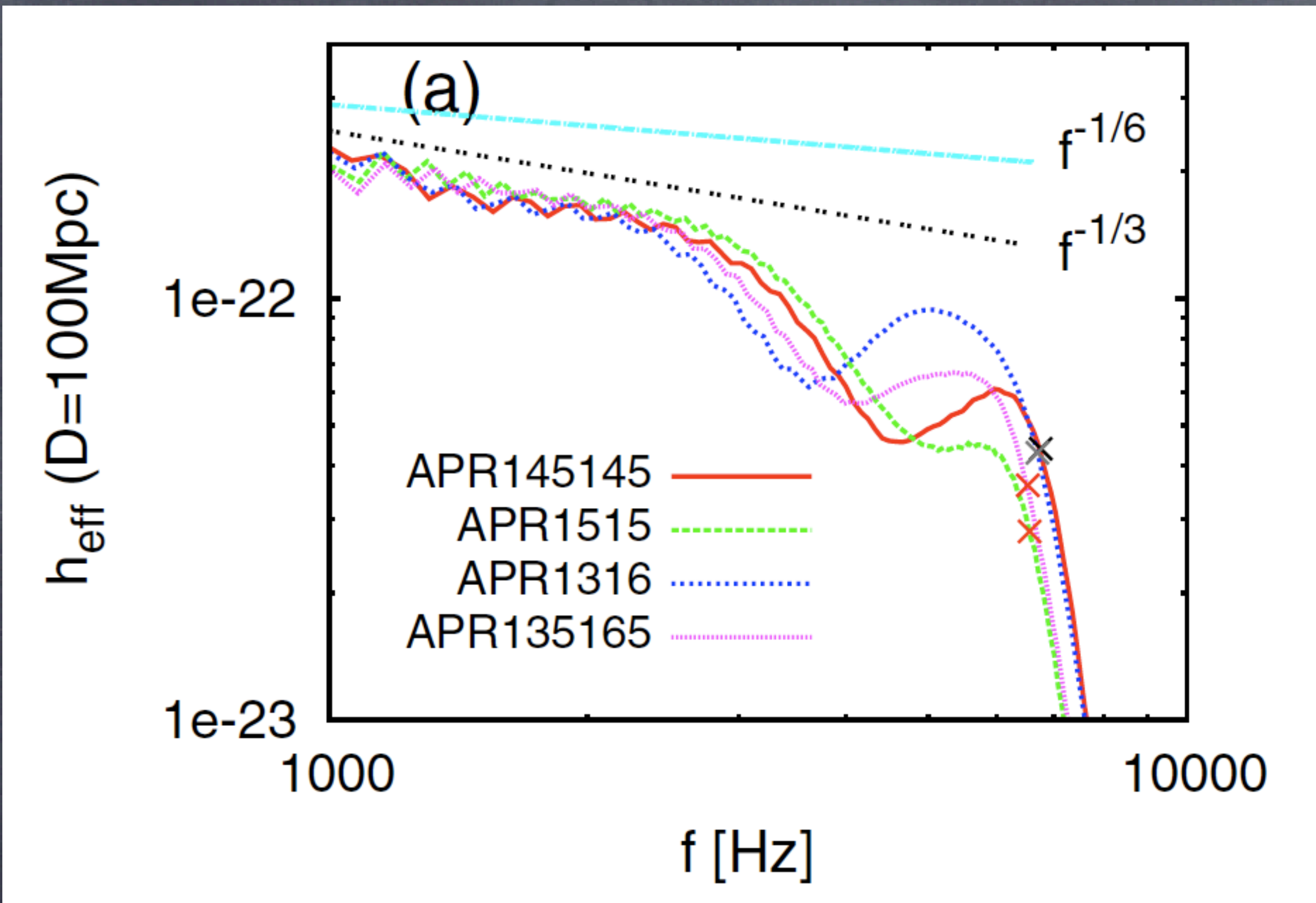


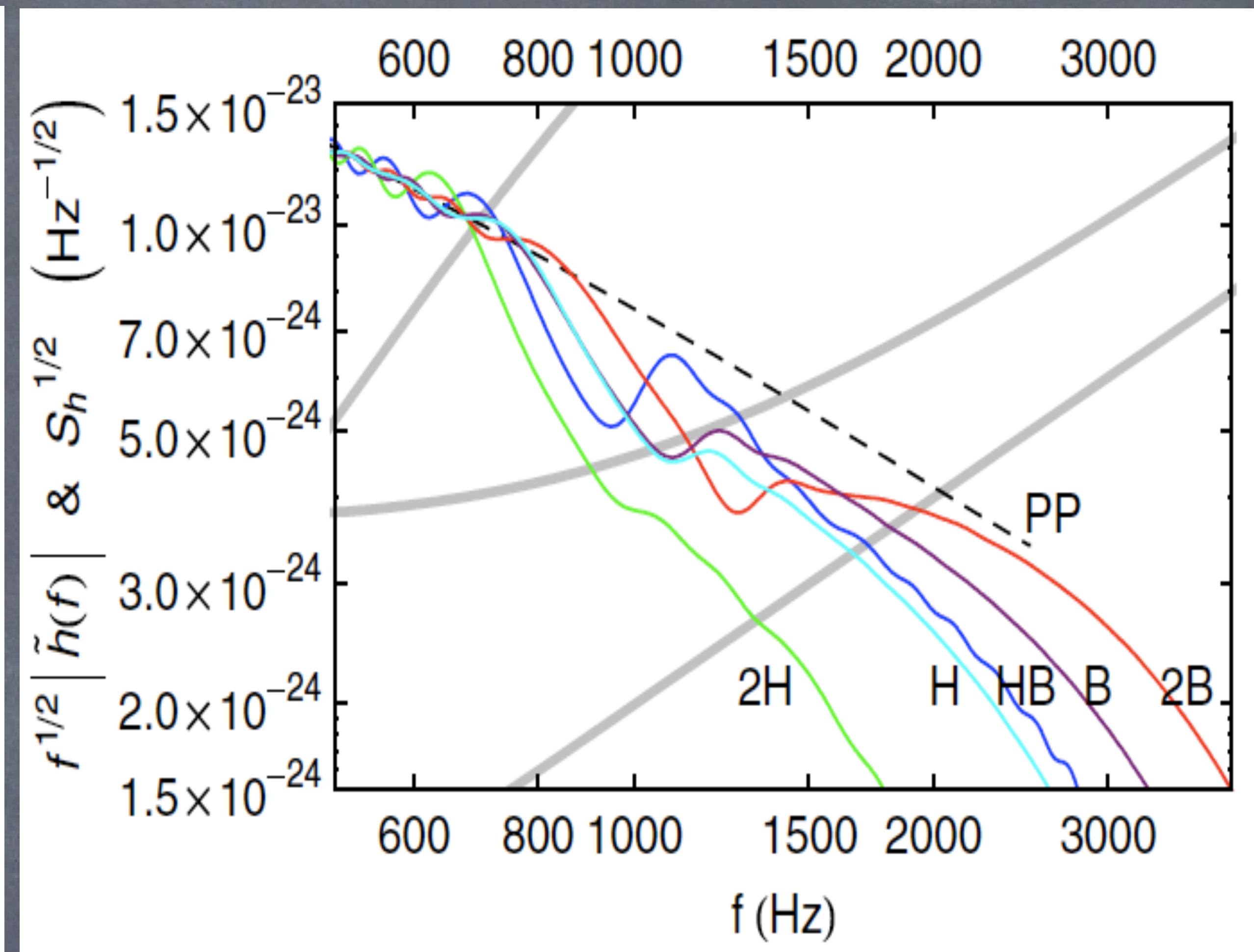
Rezzolla et al 2010: computed GWs from 6 unequal-mass binaries with ideal fluid EOS.

SNR@100Mpc>40 for ET!



Detectability of mass-ratio and EoS





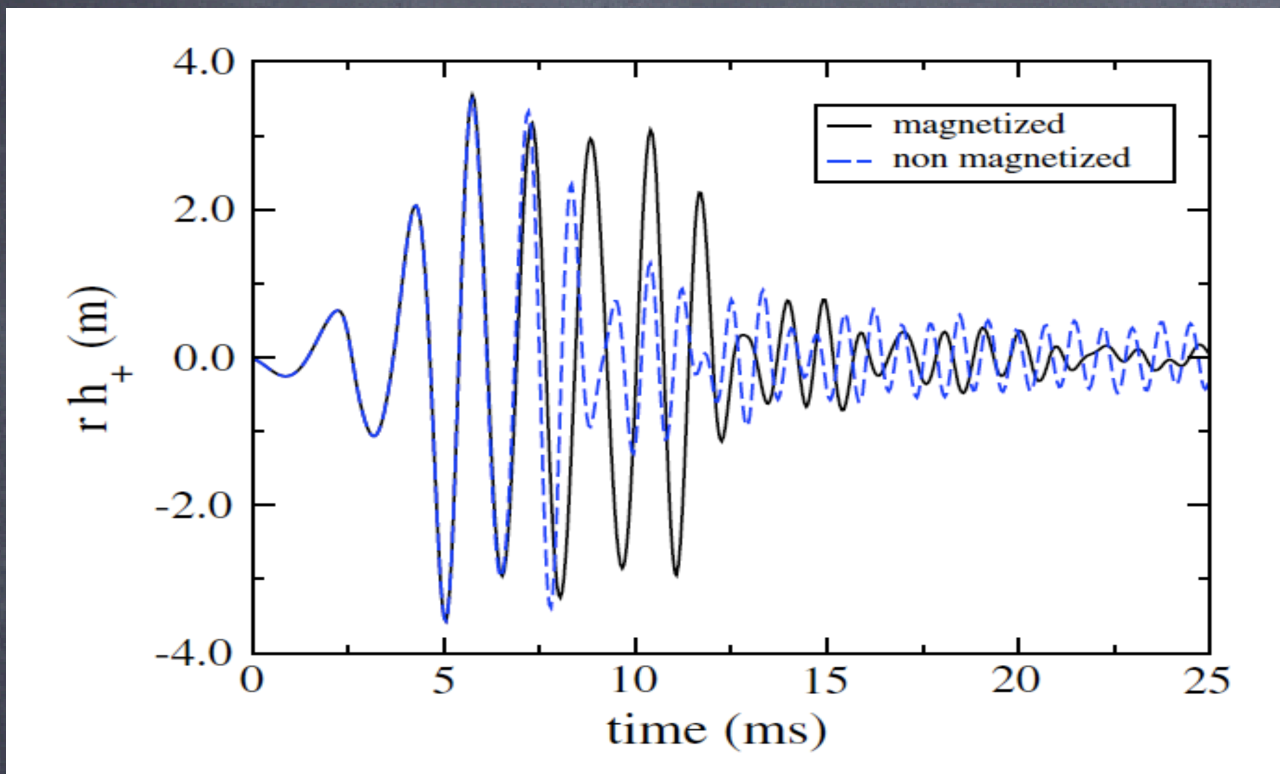
Kiuchi et al 2009

A hump in the post-merger GW PSD can be observed at high frequencies.
It could be used to constrain mass ratio.

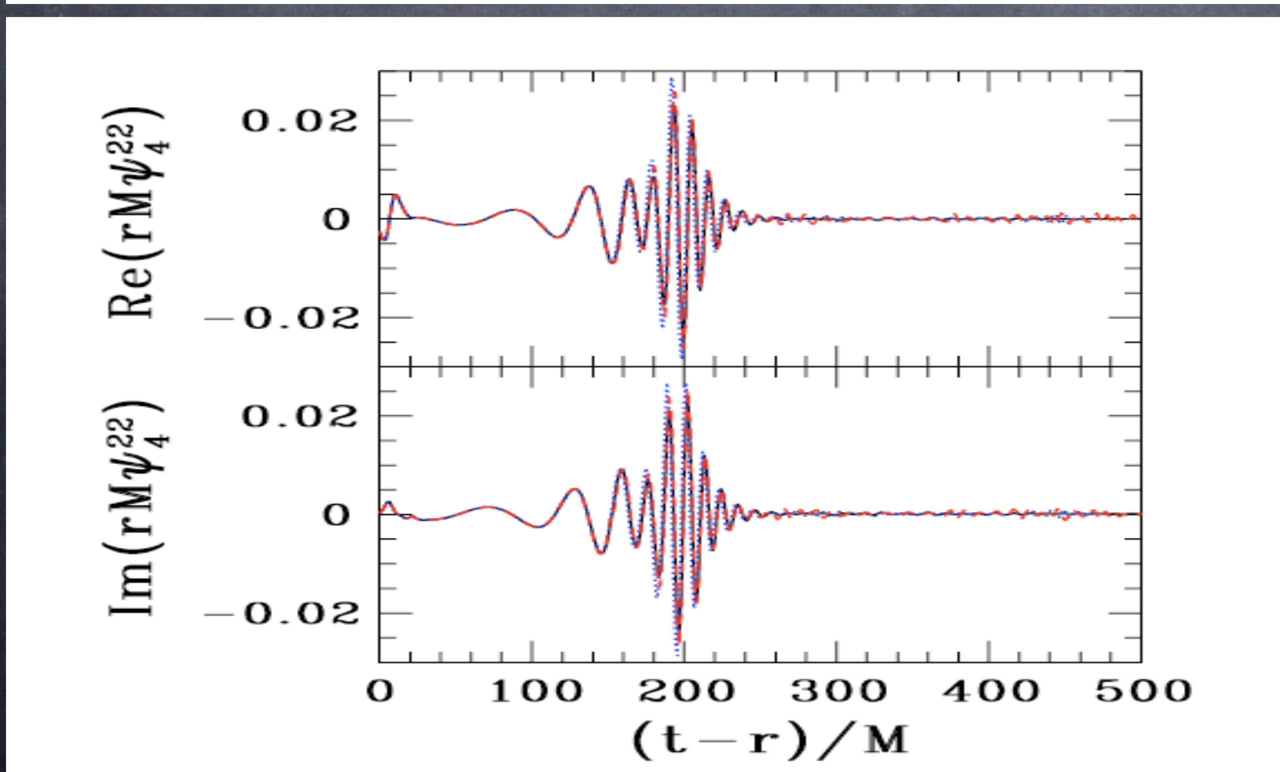
Read et al 2009

Deviation from PP can be detected in the inspiral for advanced Ligo or ET.
Radius could be measured with an accuracy of ~1km

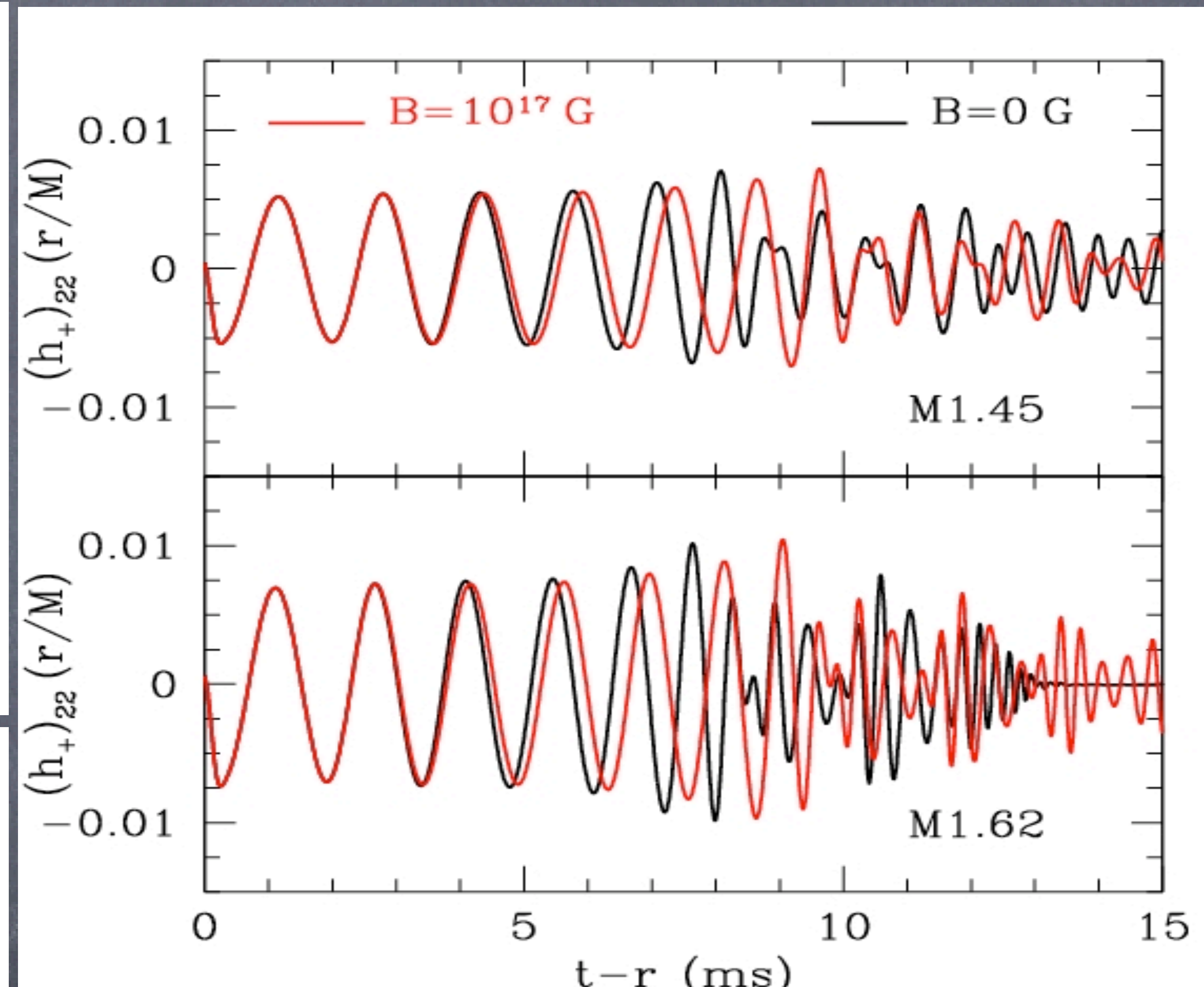
GWs from BNS: The Role of Magnetic Fields



Anderson et al 2008



Liu et al 2008

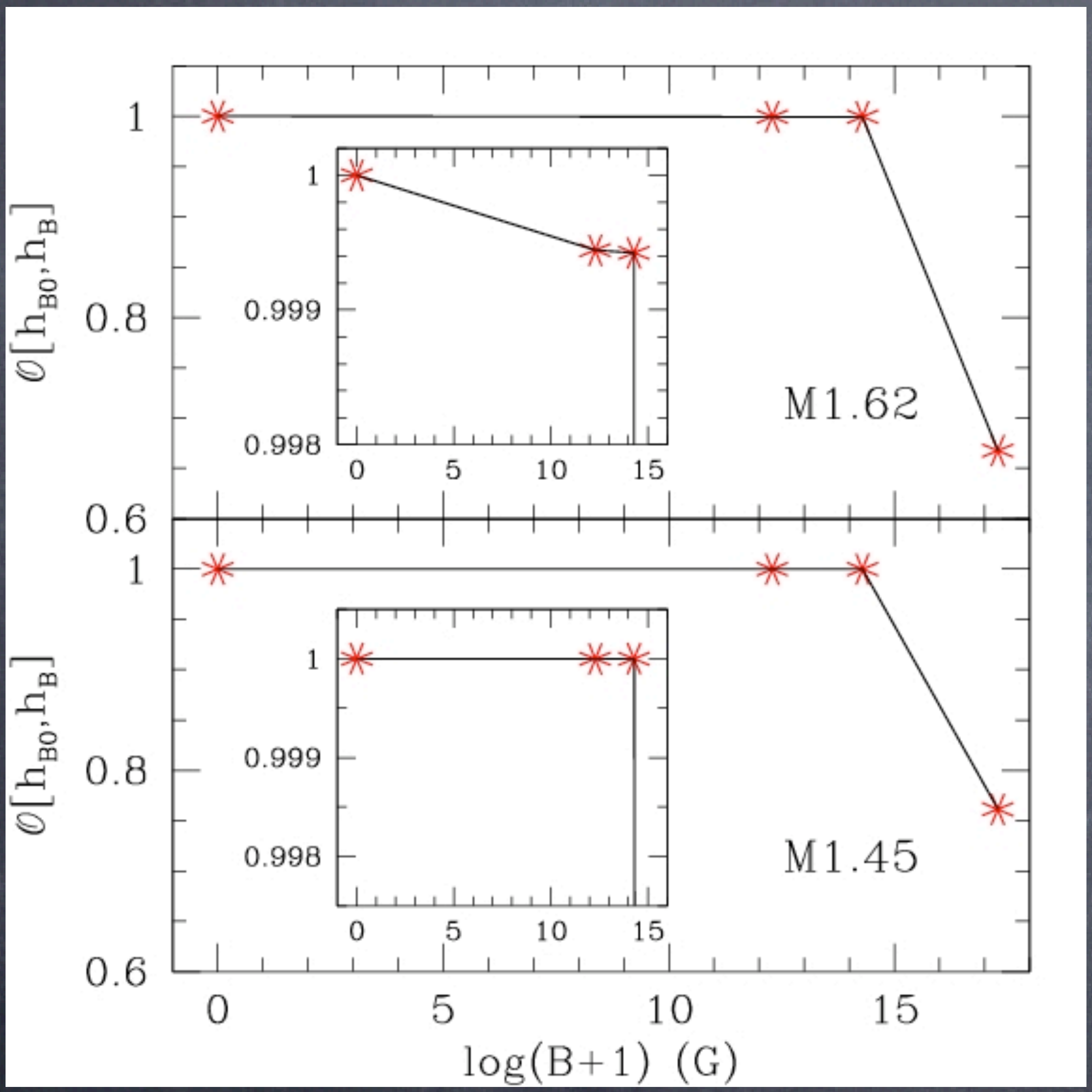


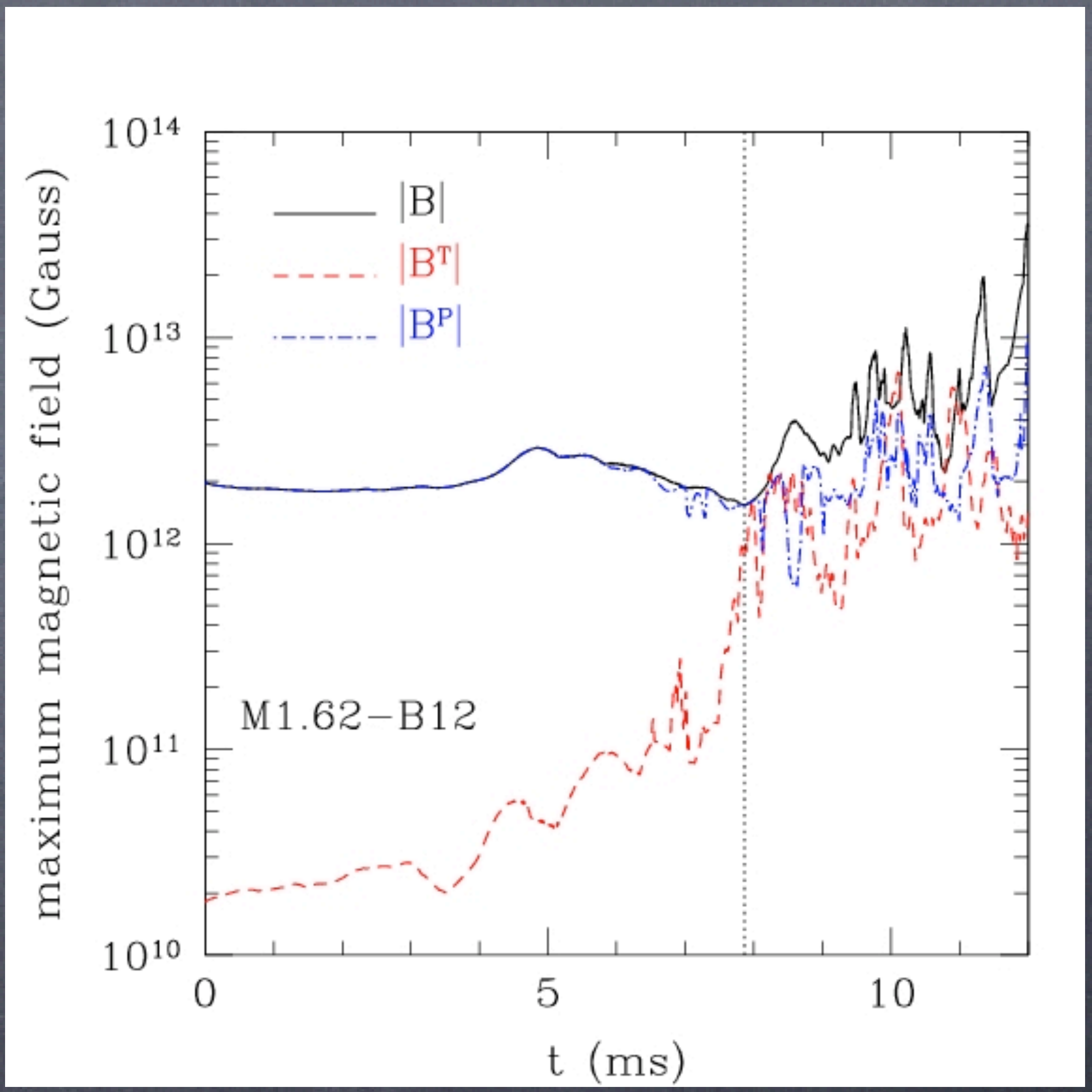
Giacomazzo et al 2009

BNSs with 10^{16}–10^{17} G

GWs from BNS: The Role of Magnetic Fields

Giacomazzo et al 2009





Effects in the inspiral can be detected only for very large and unrealistic magnetic fields

Magnetic field amplification because of KH instability may lead to effect in the post-merger also for lower values

BH-NS simulations: state of the art

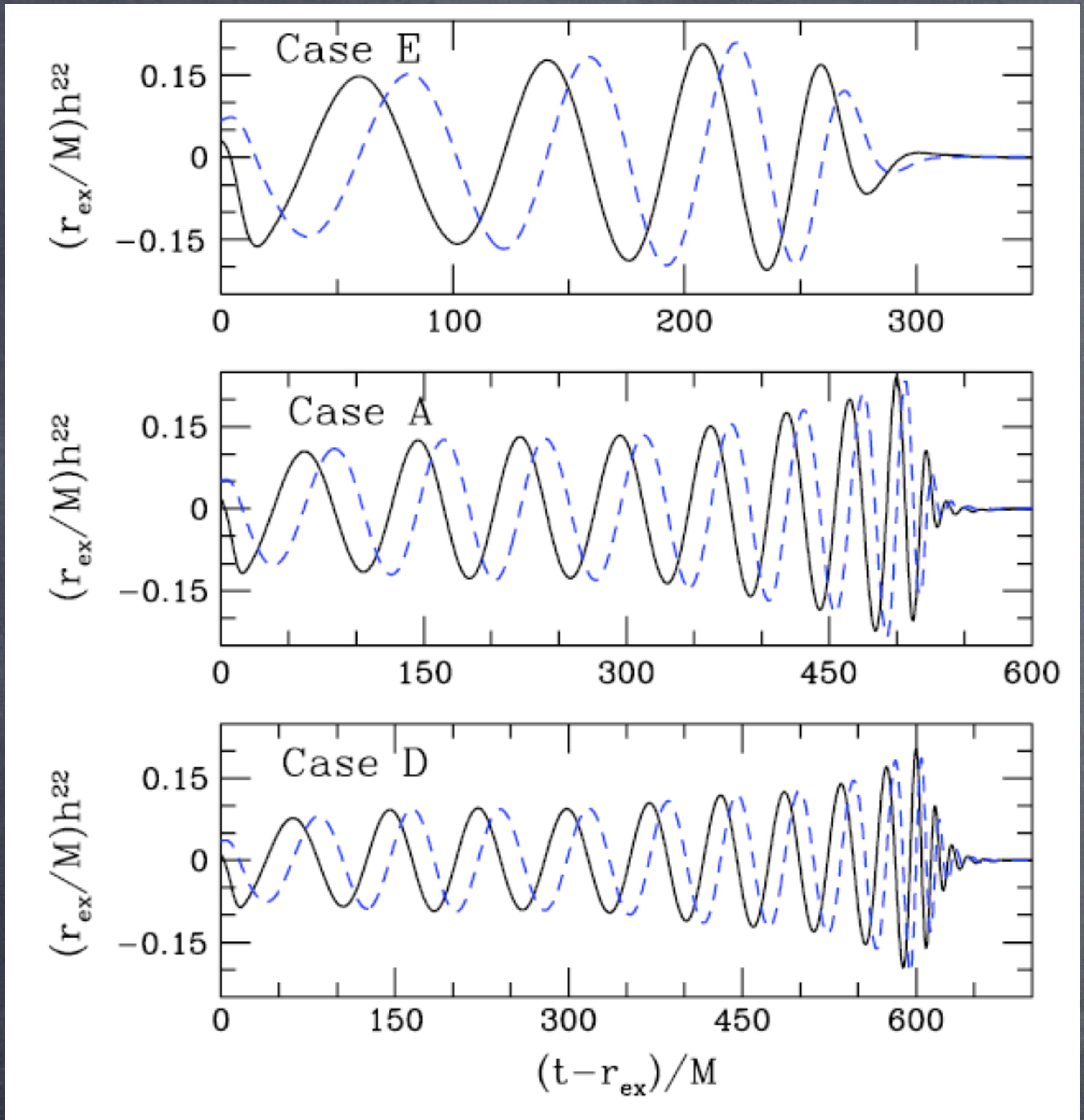
- GRHD
  - Shibata and Uryu 2006, 2007: ideal fluid, no spin
  - Shibata and Taniguchi 2008: ideal fluid, no spin
  - Etienne et al 2008: ideal fluid EOS, no spin
  - Duez et al 2008: ideal fluid EOS, no spin
  - Shibata et al 2009: AMR, ideal fluid EOS, no spin (long-inspiral phase)
  - Etienne et al 2009: AMR, ideal fluid EOS, with spin
  - Duez et al 2009: ideal fluid and Shen, with spin
- GRMHD
  - ----

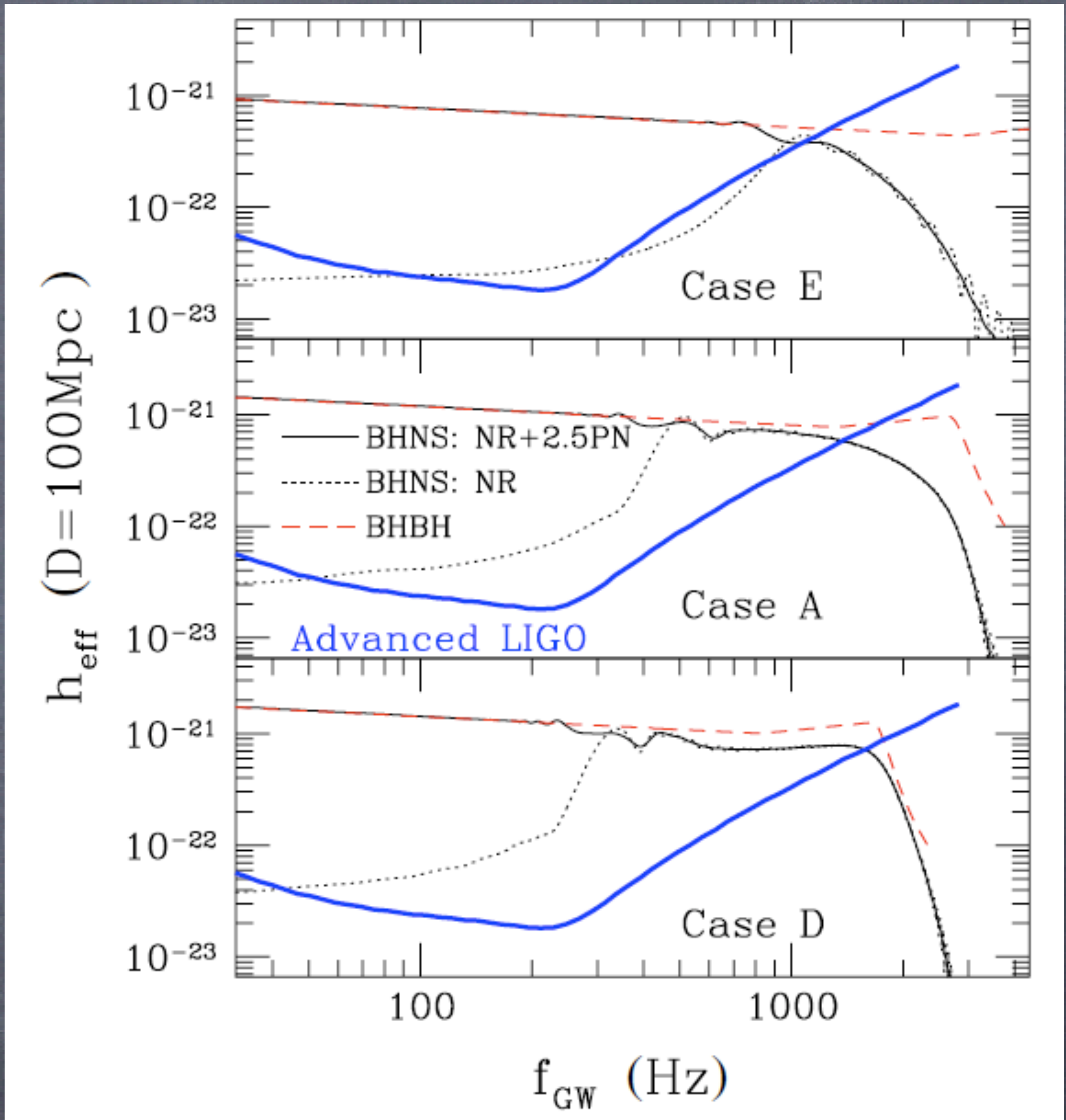
BH-NS: Classification of GWs

- Shibata et al 2009 defined 3 types of GWs:
  - type I: NS disrupted outside ISCO. Only inspiral signal.
  - type II: mass transfer near ISCO. Both inspiral and merger are present in the GWs.
  - type III: no disruption. GWs very similar to BBH and composed by inspiral, merger and ringdown.
- Classification depends on mass-ratio and NS compactness (type III for $Q>3$, type II for $2<Q<3$, type I for $Q<2$)
- GW cutoff frequency can be used to measure mass-ratio and NS compactness (except for type III signals)

BH-NS vs BBH: no spin

Etienne et al 2009



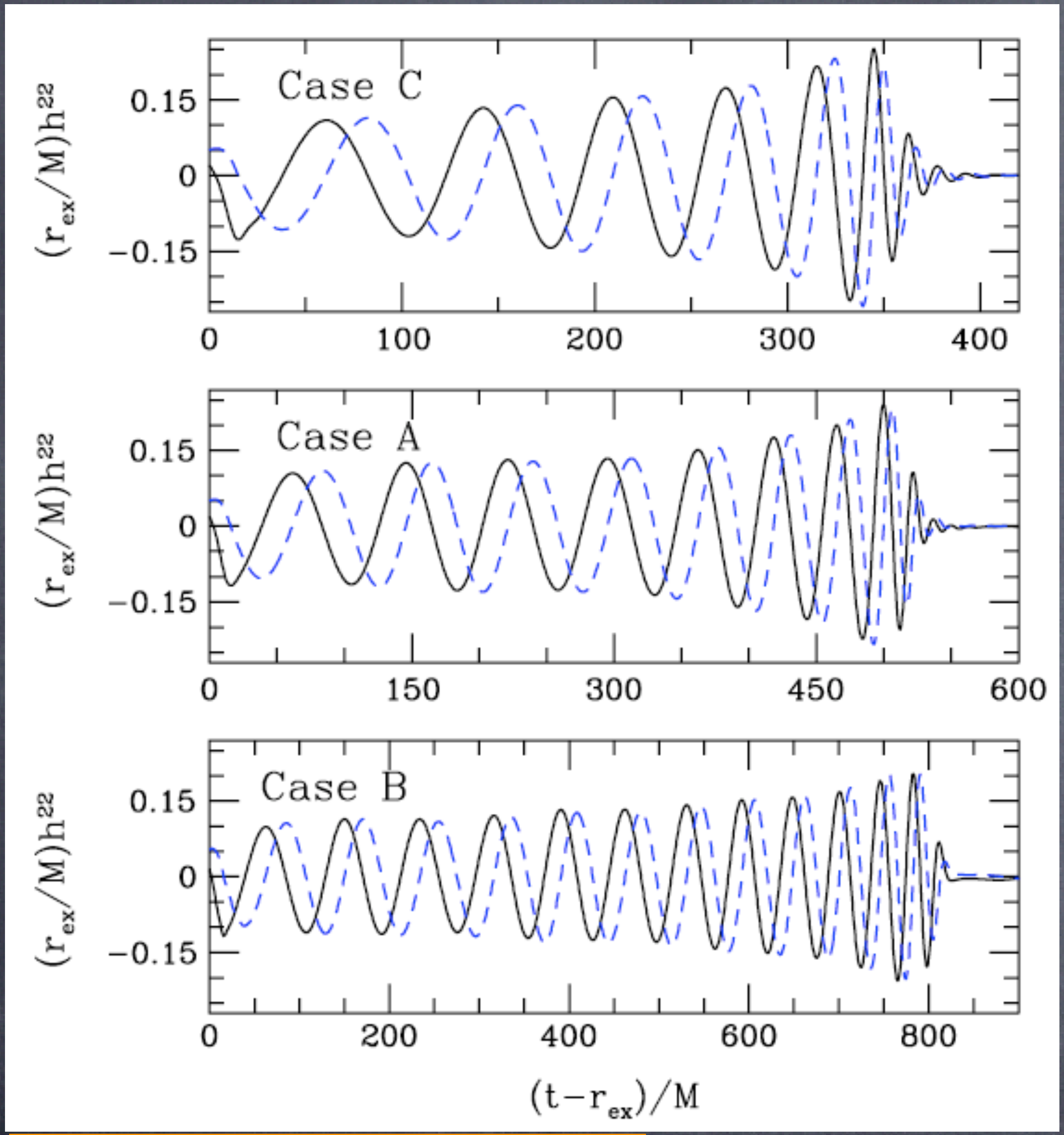


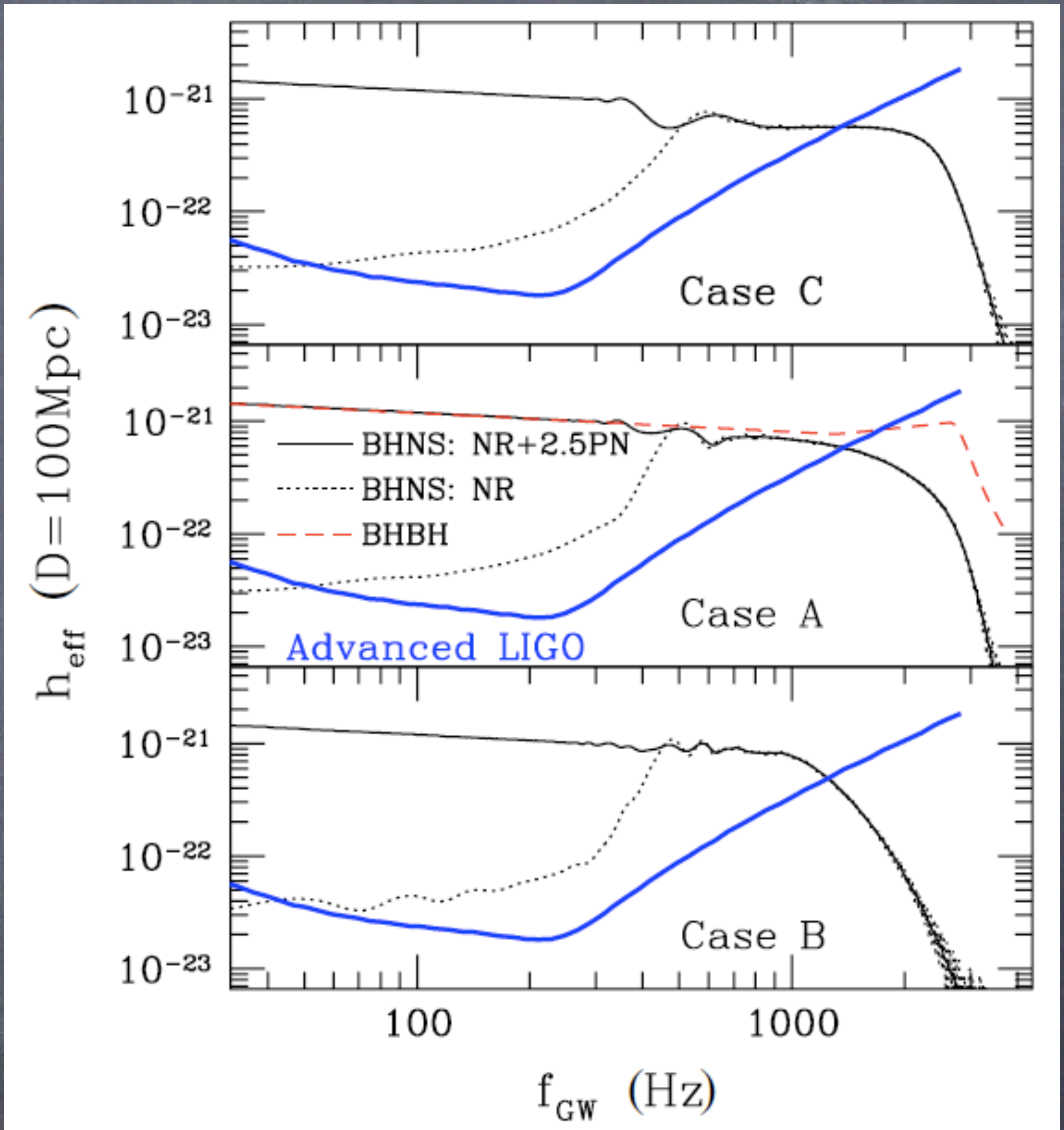
E: Q=1
A: Q=3
D: Q=5

Difficult to detect difference with BBH. Note how when increasing Q the frequency cutoff gets close to the one for BBH.

GW from BH-NS: role of BH spin

Etienne et al 2009





C: Q=3, a=-0.5

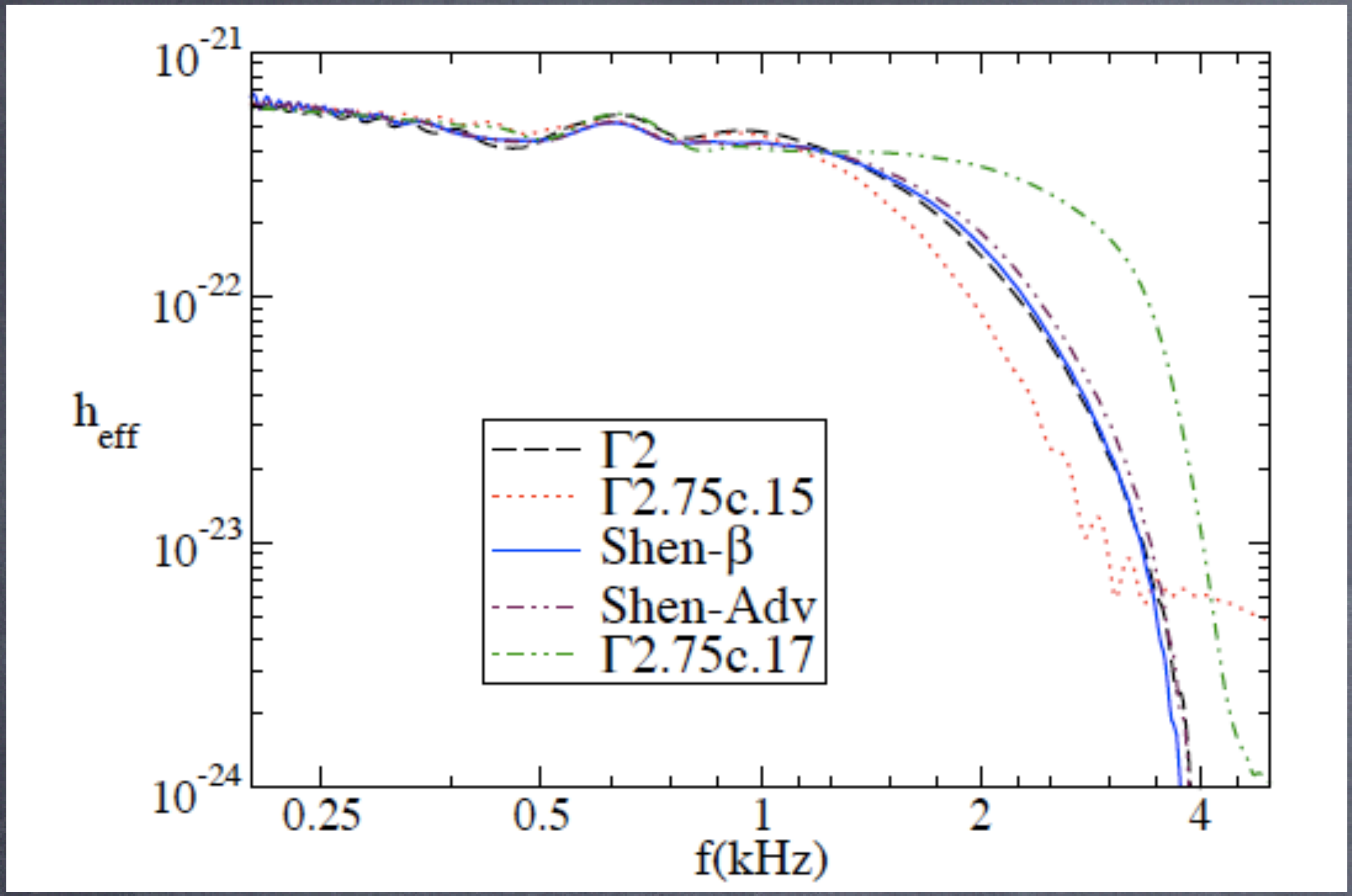
A: Q=3, a=0

B: Q=3, a=0.75

Ringdown signal gets smaller with higher BH spin because of larger disk formation.

GWs from BH-NS: role of the EOS

Duez et al 2009



Q=3, a=0.5, M_{NS}=1.55$M_{\odot}$

First simulation in full GR to study realistic EOS effects on NS-BH system.

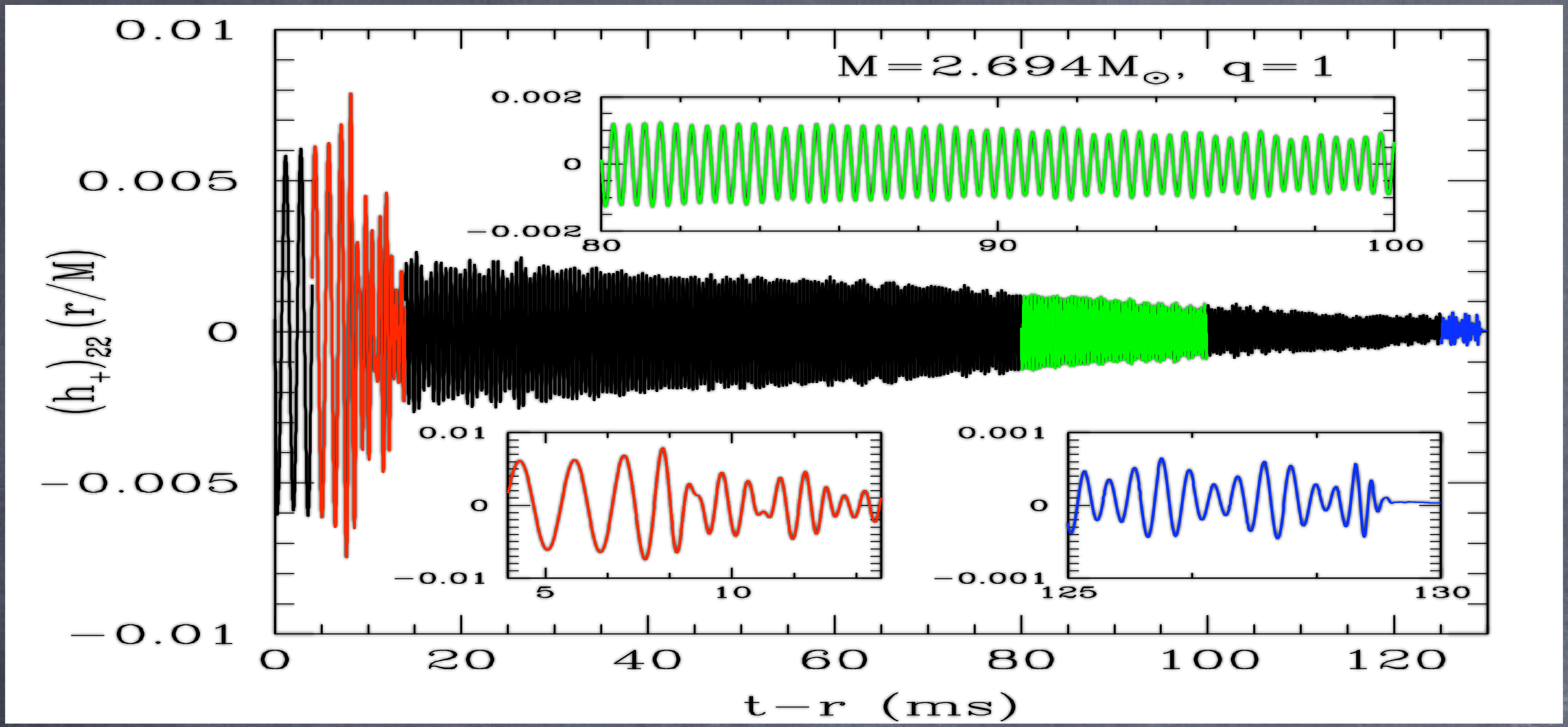
Differences in GWs appears for f>1kHz.

Very difficult for Adv Ligo to detect them.

NINJA-MATTER

ninja-matter@aei.mpg.de

Rezzolla et al 2010



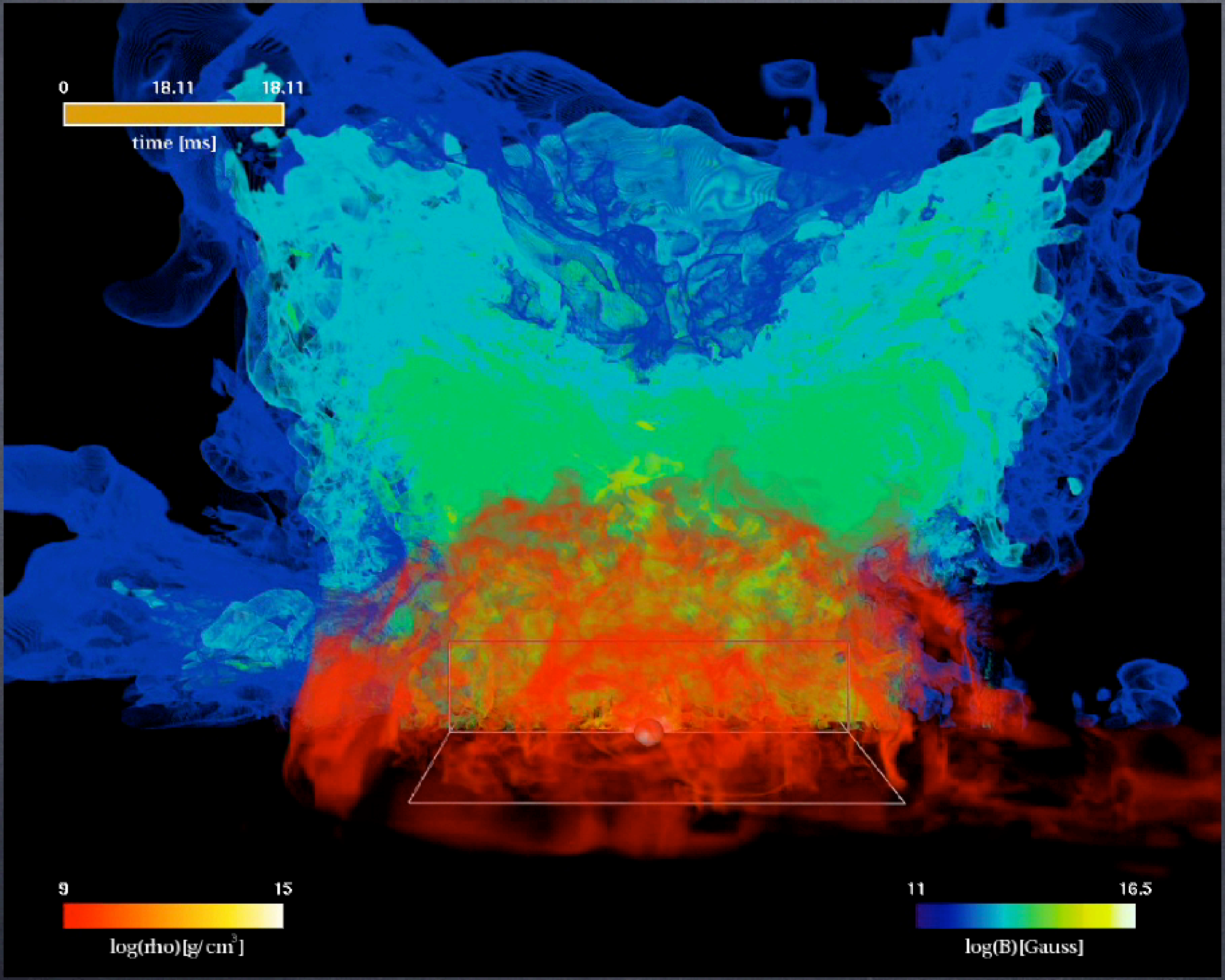
Example of a GW available for DA people if interested...

Several codes producing now GWs from BNS and NS-BH.

Interest by NR groups working on NS to start close interaction with DA. Several groups already involved in the project.

Shall we plan a more official NINJA-MATTER meeting? (next NRDA?)

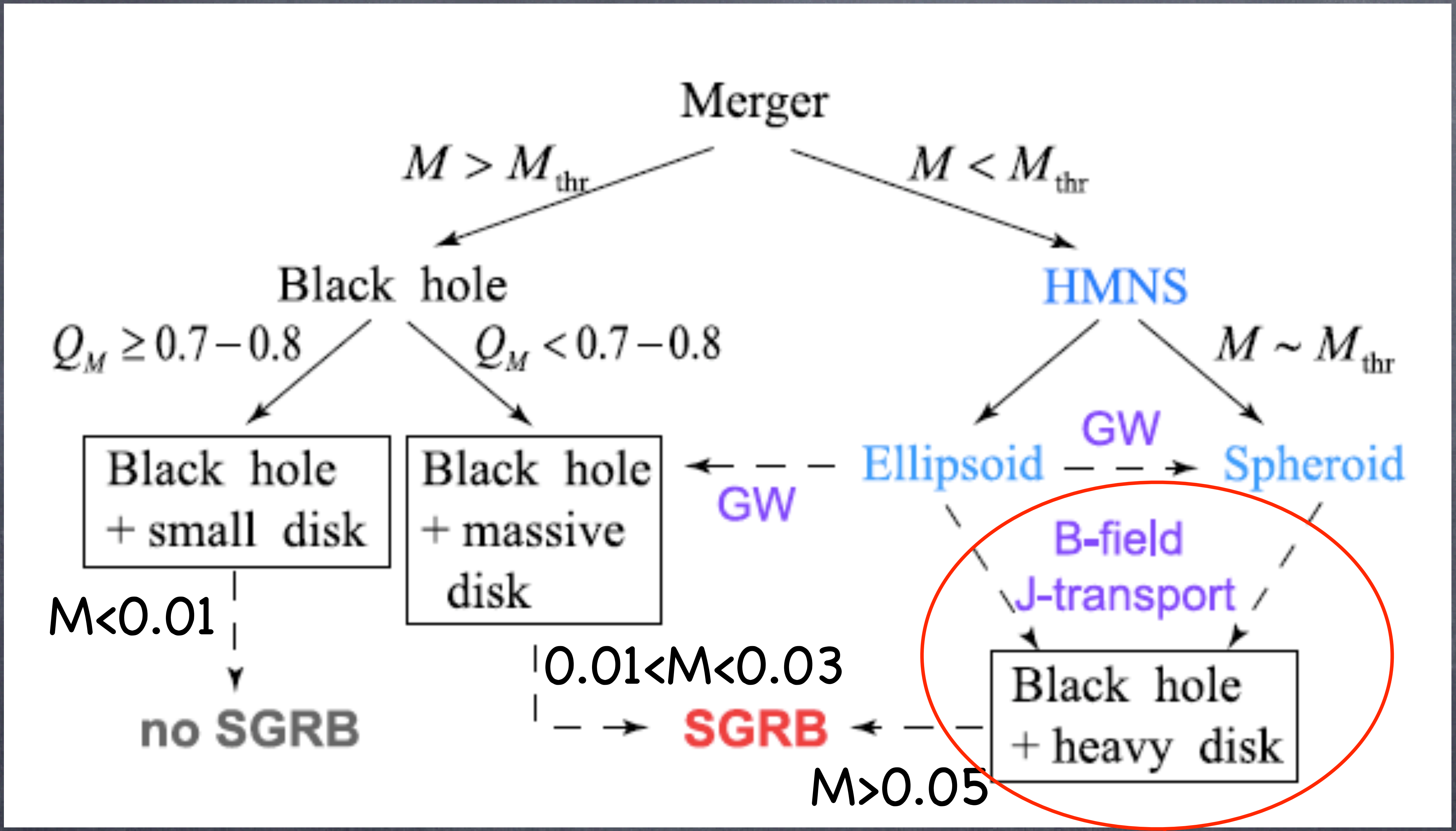
EM counterparts?



Visualization by Giacomazzo, Koppitz, Rezzolla

BNS: Torus Formation

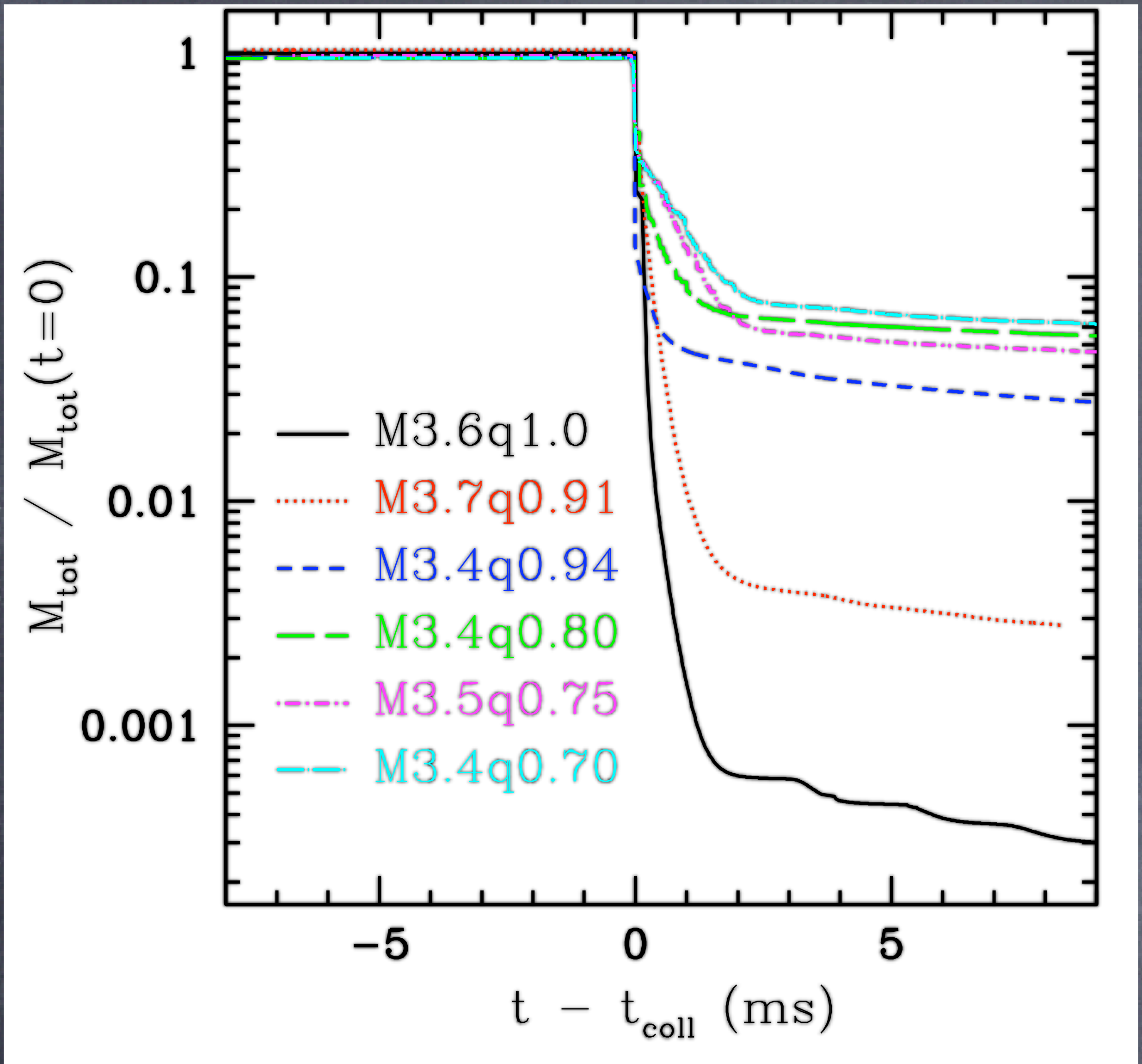
Shibata & Taniguchi 2006



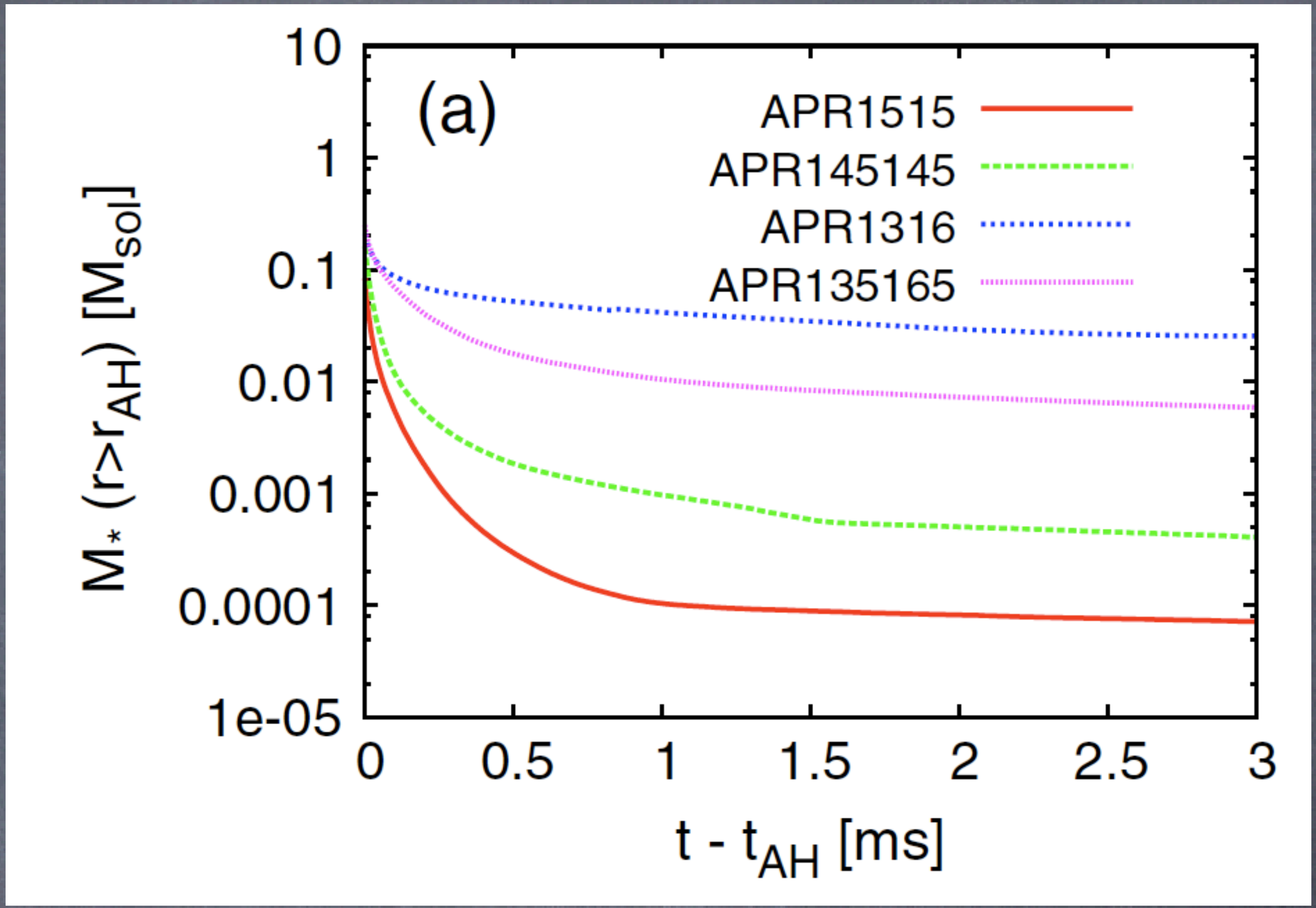
Kiuchi et al 2009:
M_{thr} is 2.8-2.9 for APR

Rezzolla et al 2010: M=0.11 after the collapse of an HMNS evolved for 120 ms

BNS: Torus Formation



Rezzolla et al 2010
ideal-fluid EOS and 2 orbits
M>0.1 for q≤0.8 for prompt collapse



Kiuchi et al 2009
APR EOS and 4 orbits
M>0.01 for q=0.8

In general BNS with higher total mass and higher mass-ratio produce smaller tori. BH spin J/M^2 is ~0.7−0.8.

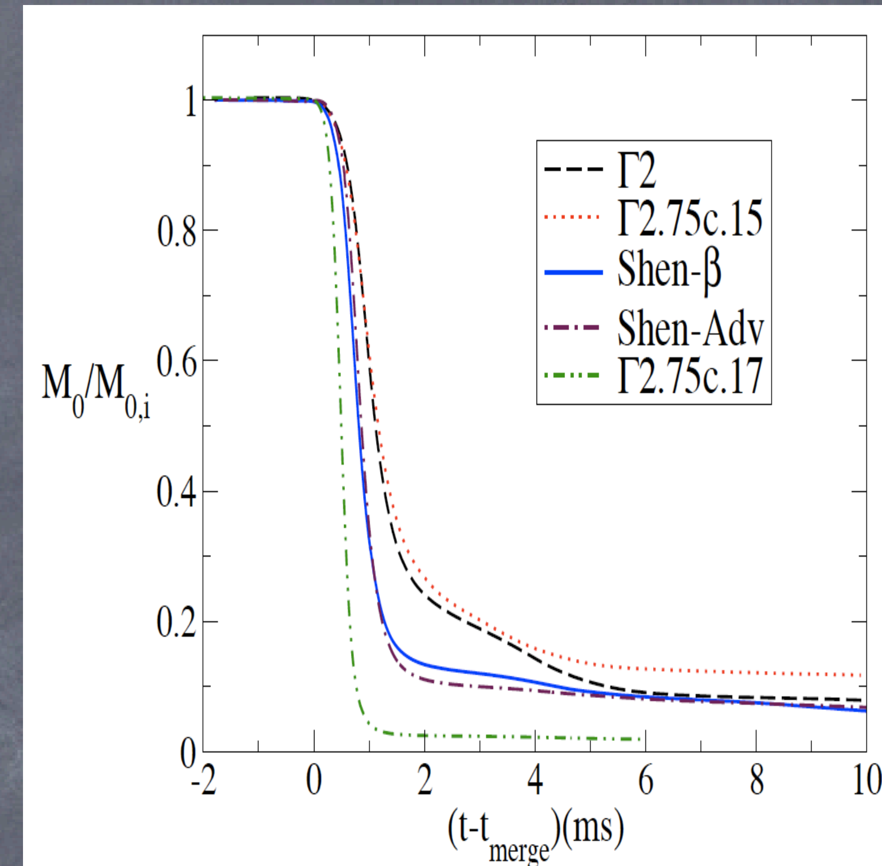
BH-NS: Torus Formation

Model	$M_{r>r_{AH}}/M_*$
M15.145	0.023
M20.145	0.010
M20.145N	0.011
M20.160	6×10^{-4}
M20.178	$<10^{-5}$
M30.145	$<10^{-5}$
M30.160	$<10^{-5}$
M30.178	$<10^{-5}$
M40.145	$<10^{-5}$
M50.145	$<10^{-5}$

Shibata et al 2009
- ideal fluid EOS
- no BH spin
- no disk for Q>2
- small disks

Case	$\tilde{a}$	q	M_{disk}/M_0
A	0.00	3.0	3.9%
A-MSep	0.00	3.0	3.8%
A-SSep	0.00	3.0	2.9%
B	0.75	3.0	15%
B-SSep	0.75	3.0	14.3%
C	−0.50	3.0	0.8%
D	0.00	5.0	0.8%
E	0.00	1.0	2.3%

Etienne et al 2009
- ideal fluid EOS
- BH with spin
- massive disk (M=0.2) for a=0.75



Duez et al 2009
- realistic EOS
- BH with spin (a=.5)
- mass ratio Q=3
- disk mass 10-20%

Tori produced with spinning BH could power SGRB

"wet" BBH simulations

- EM fields in vacuum
  - Palenzuela et al 2009a, 2009b
  - Moesta et al 2009
- particles
  - Van Meter et al 2009
- GRHD+BBH
  - Bode et al 2009
  - Farris et al 2009

Number of other works in Newtonian or full GR studying the effect of the final BH on the disk.

BBH+EM fields

Studied the effect of supermassive BBH on an initially uniform magnetic field (B=10^4G, M=10^8).

Palenzuela et al 2009a

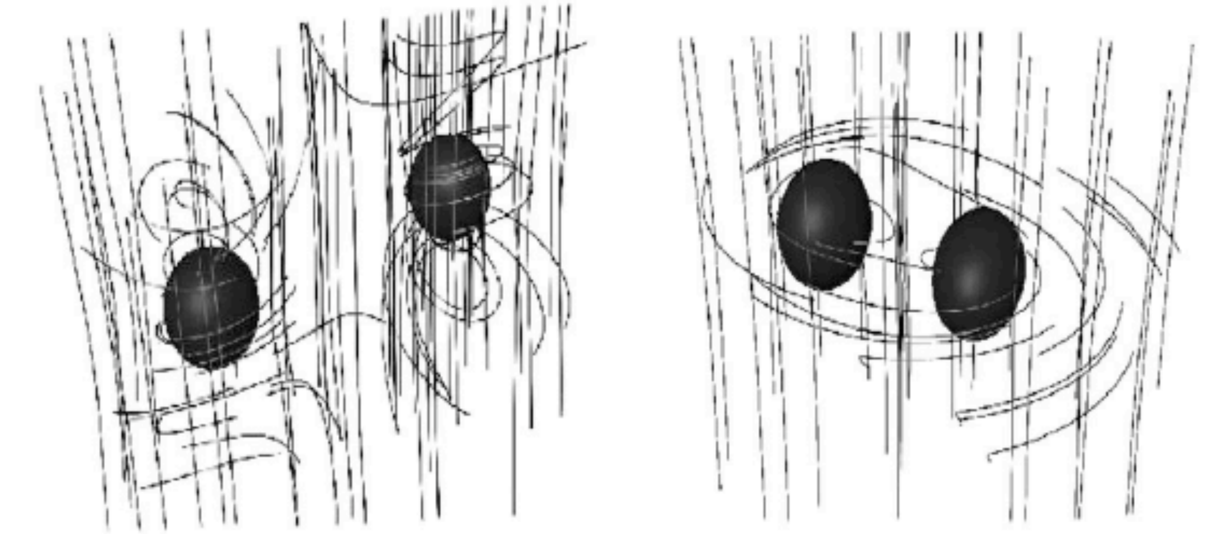
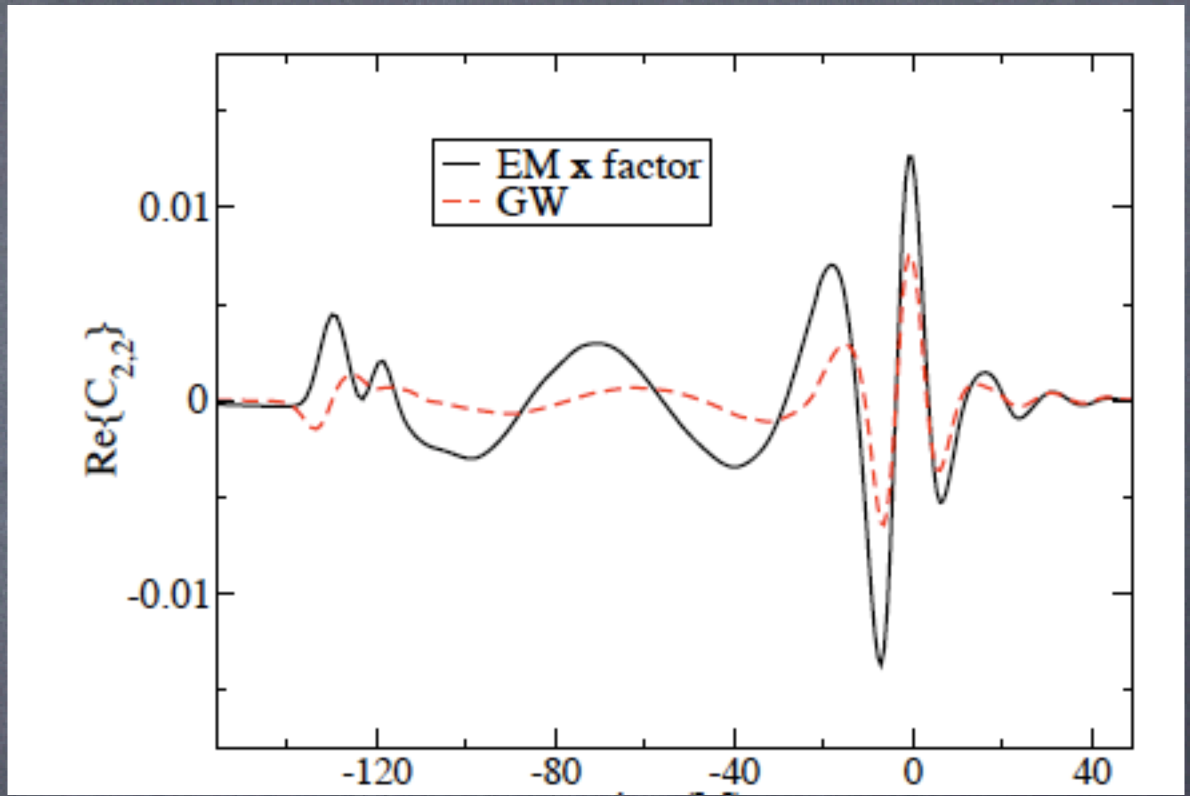


FIG. 2. Magnetic and electric field lines at $t \simeq -40M$, $-20M$ in 3D (the merger happens at $t = 0$). The electric field lines are twisted around the black hole, while the magnetic lines are mostly aligned with the z axis.

Palenzuela et al 2009b



EM signal similar to GW signal, but much lower energy

Moesta et al 2009: no possibility of direct detection of EM signal, but magnetic field could affect disk's dynamics.

Summary

- Numerical relativity is able to describe BNS and NS-BH mergers:
  - effect of realistic EOS currently investigated in full GR
  - massive tori from unequal mass BNS and NS-BH for spinning BHs
  - no radiation included (several groups working on it...)
  - magnetic field effects still poorly studied/understood (some work only in equal-mass BNS and/or only for too large fields)
  - numerical issues: accuracy & resolution (torus mass, KH, MRI,...), more generic initial conditions, error estimation...
  - long-term simulations are needed (longer inspiral, HMNS): massive use of computational resources is fundamental...
- Started several studies of possible EM counterparts from BBH