Understanding Neutron Stars with ET

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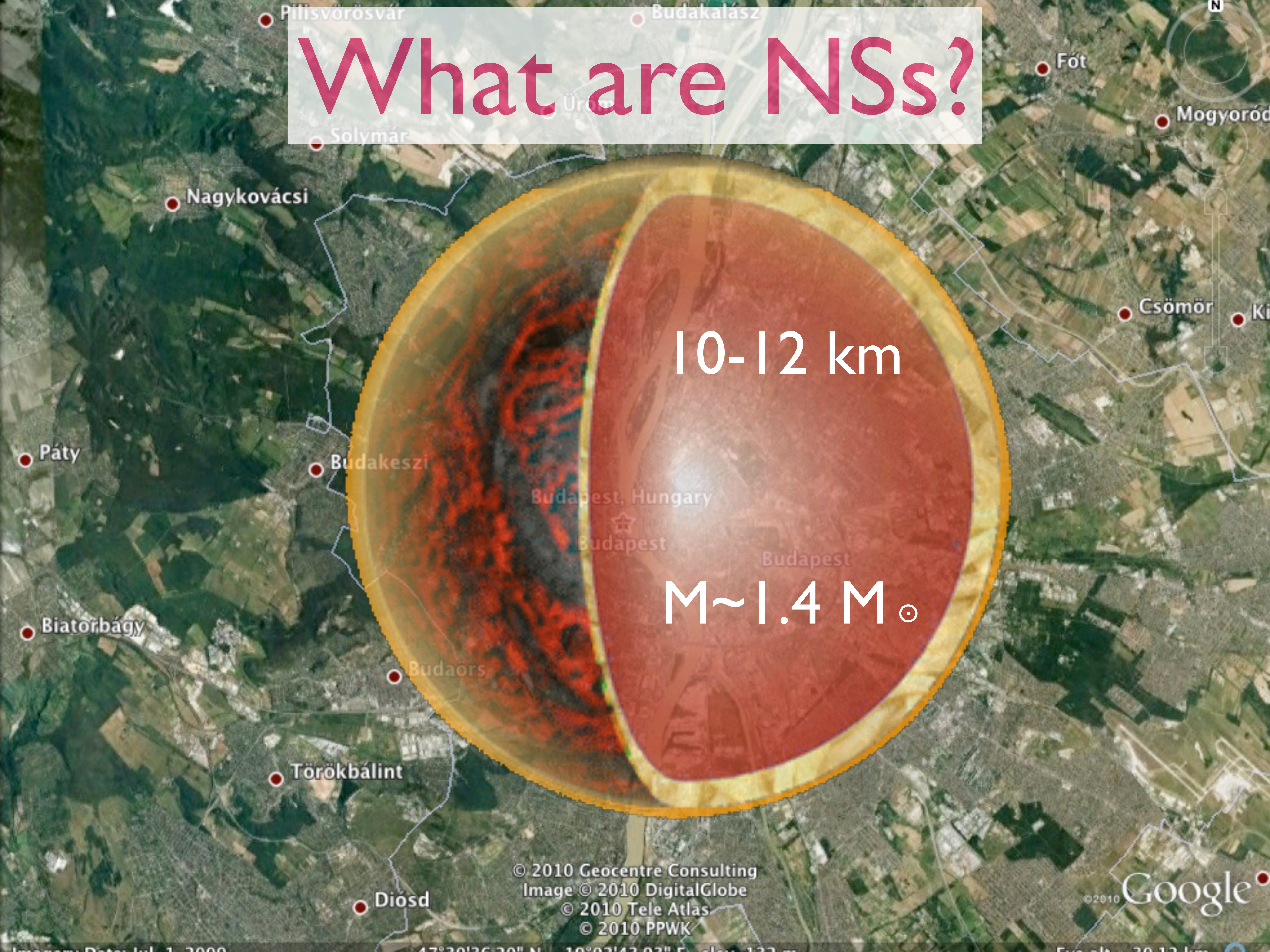
Plan of the talk

- What are neutron stars (NSs)?
- NSs as unique opportunities for GW Astronomy
- The holy grail of nuclear physics
- How ET can make the difference

What are NSs?


10-12 km
M~1.4 $M_\odot$
Pilisvörösvár
Budakalász
Fót
Mogyoród
Solymár
Nagykovácsi
Csömör
Páty
Budakeszi
Budapest, Hungary
Budapest
Budapest
Biatorbágy
Budaörs
Törökbálint
Diósd
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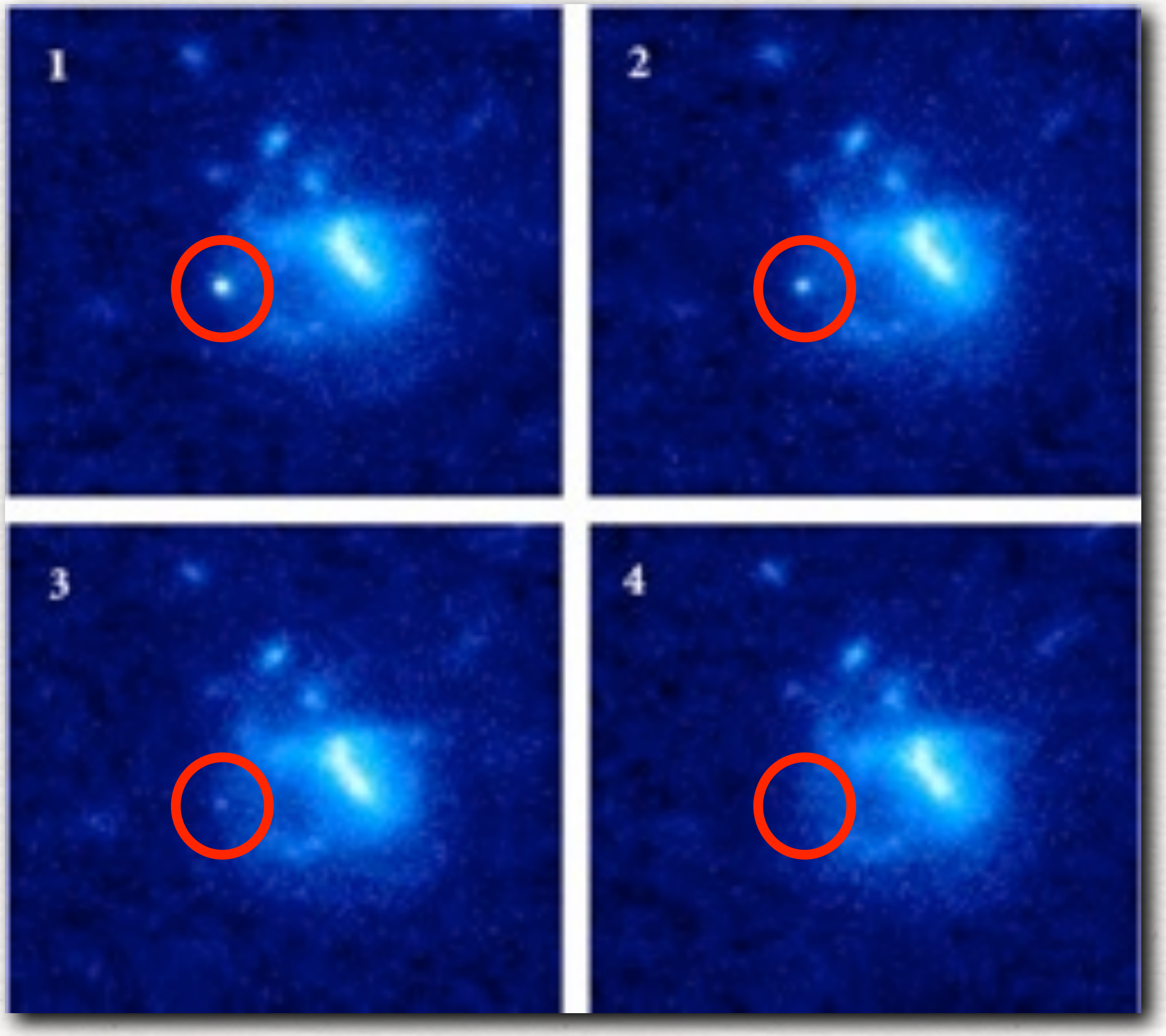
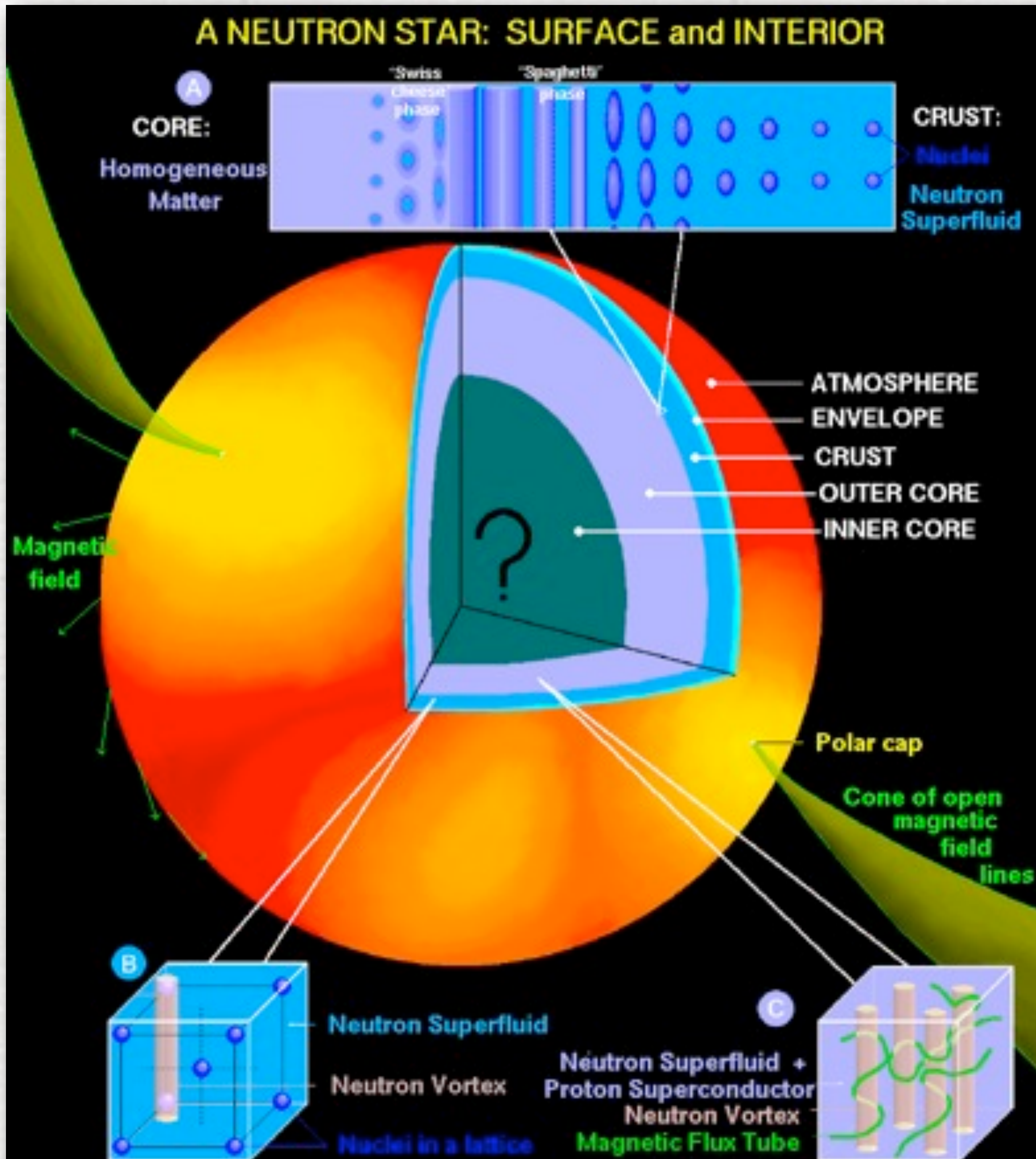
Why investigate binary neutron stars?



- We know they exist (as opposed to binary BHs) and are among the strongest sources of GWs
- Despite almost 40 years of observations with all possible instruments (radio, IF, optical, X and gamma) we still don't know their internal structure and composition.
- We expect them to be related to SGRBs: most luminous phenomena in the universe with energies released are huge: 10^{50-51} erg. Equivalent to what released by the whole Galaxy over ~ 1year.
- Also in this case, decades of observations have produced vast phenomenology but no self-consistent model yet

The holy grail of nuclear physics

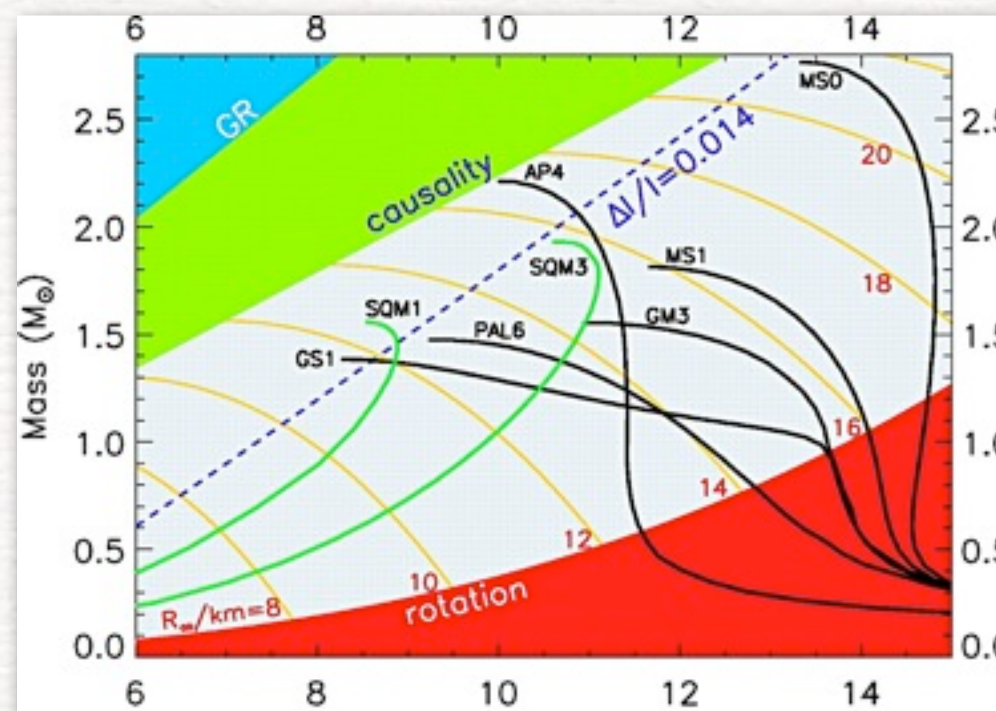
D. Page



Very little is known about the interior structure and composition of NSs, although there is no lack of models...

Main difficulties:

- astronomical observations cannot really provide the radi (but masses)
- nuclear data limited to heavy ions (ten orders of magnitude difference)
- EM observations reveal properties from the surface and different EOSs yield a NS with the same radius and mass
- determining NS EOS would reveal properties of matter at nuclear densities (not possible on Earth laboratories)



Lattimer & Prakash (2004)

The two-body problem: GR

Modelling binary black holes (BHs) and binary neutron stars (BNSs) is very different and not because the eqs are different

In the case of BHs we know what to **expect**:

BH + BH ⟶ BH + gravitational waves (GWs)

In the case of NSs the question is more **subtle** because in general the merger will lead to an hyper-massive neutron star (HMNS), namely a self-gravitating object in metastable equilibrium:

NS + NS ⟶ HMNS + GWs + **... ?** ⟶ BH + GWs

It's in the intermediate stage that all the physics and complications are; the rewards are however high (GRBs, nuclear physics, etc).

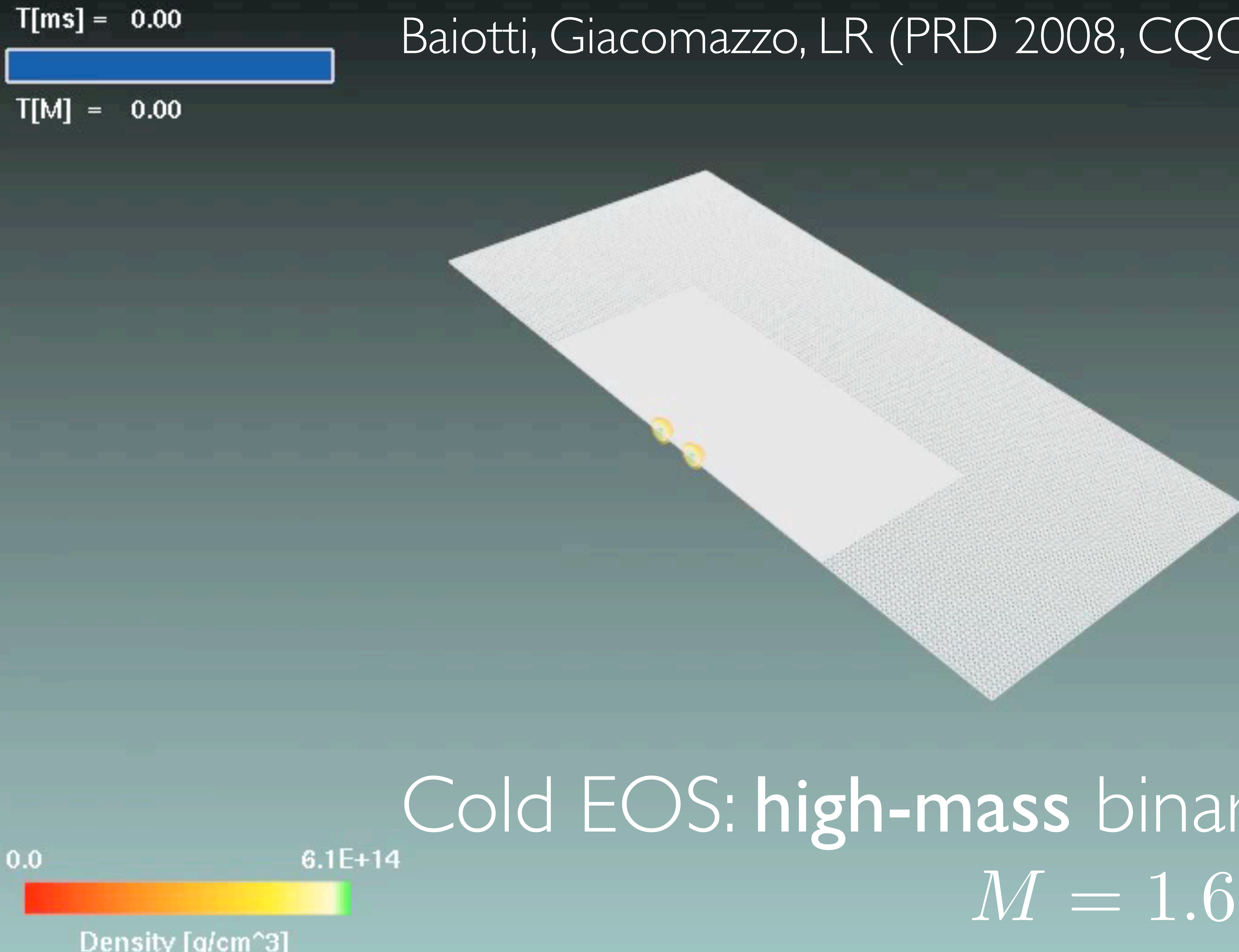
"merger $\longrightarrow$ HMNS $\longrightarrow$ BH + torus"

Quantitative differences are produced by:

- **differences induced by the gravitational MASS:**
  a binary with smaller mass will produce a HMNS further away from the stability threshold to gravitational collapse
- **differences induced by the EOS ("cold" or "hot"):**
  an EOS with large thermal capacity (ie hotter after merger) will lead to a HMNS with more pressure support
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; lead to prompt BH and ejection
- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or added magnetic pressure can change the structure of the HMNS
- **differences induced by RADIATIVE PROCESSES:**
  radiative losses could alter the equilibrium of the HMNS

Animations: Kaehler, Giacomazzo, LR

Baiotti, Giacomazzo, LR (PRD 2008, CQG 2008)

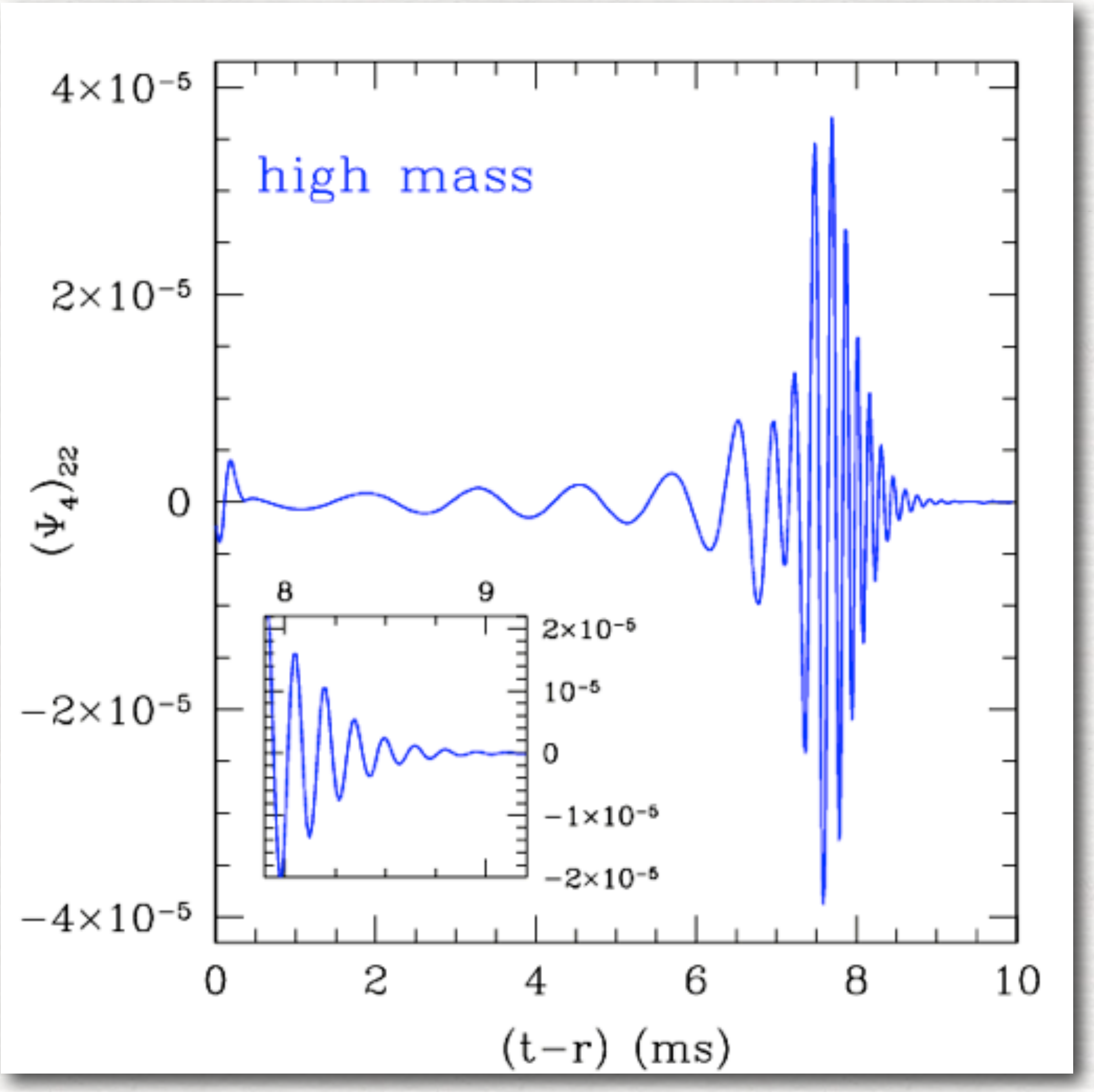


Cold EOS: **high-mass** binary

$$M = 1.6\, M_{\odot}$$

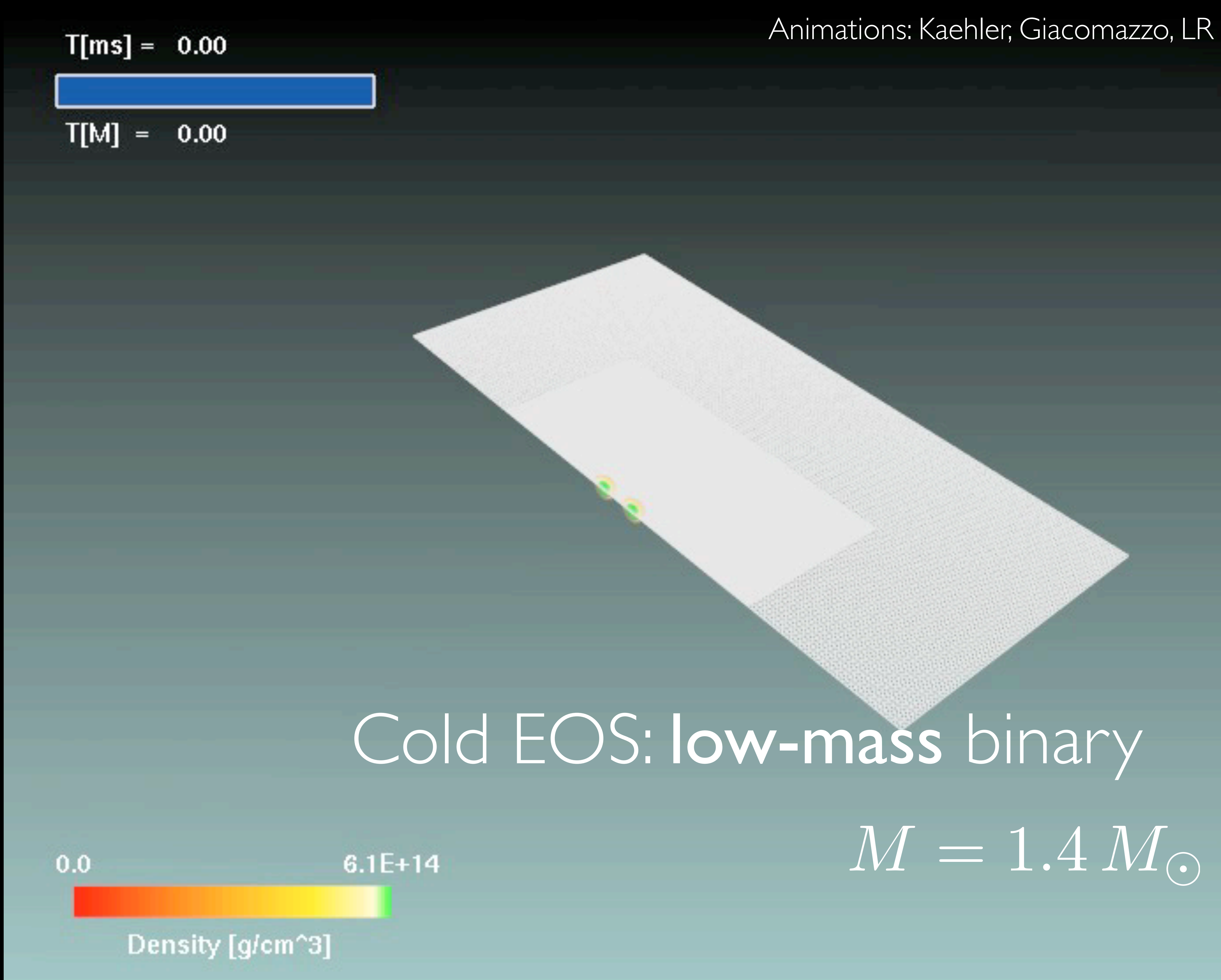
Waveforms: cold EOS

high-mass binary



inspiral is "immediately" followed by the collapse to BH and ringdown

Animations: Kaehler, Giacomazzo, LR



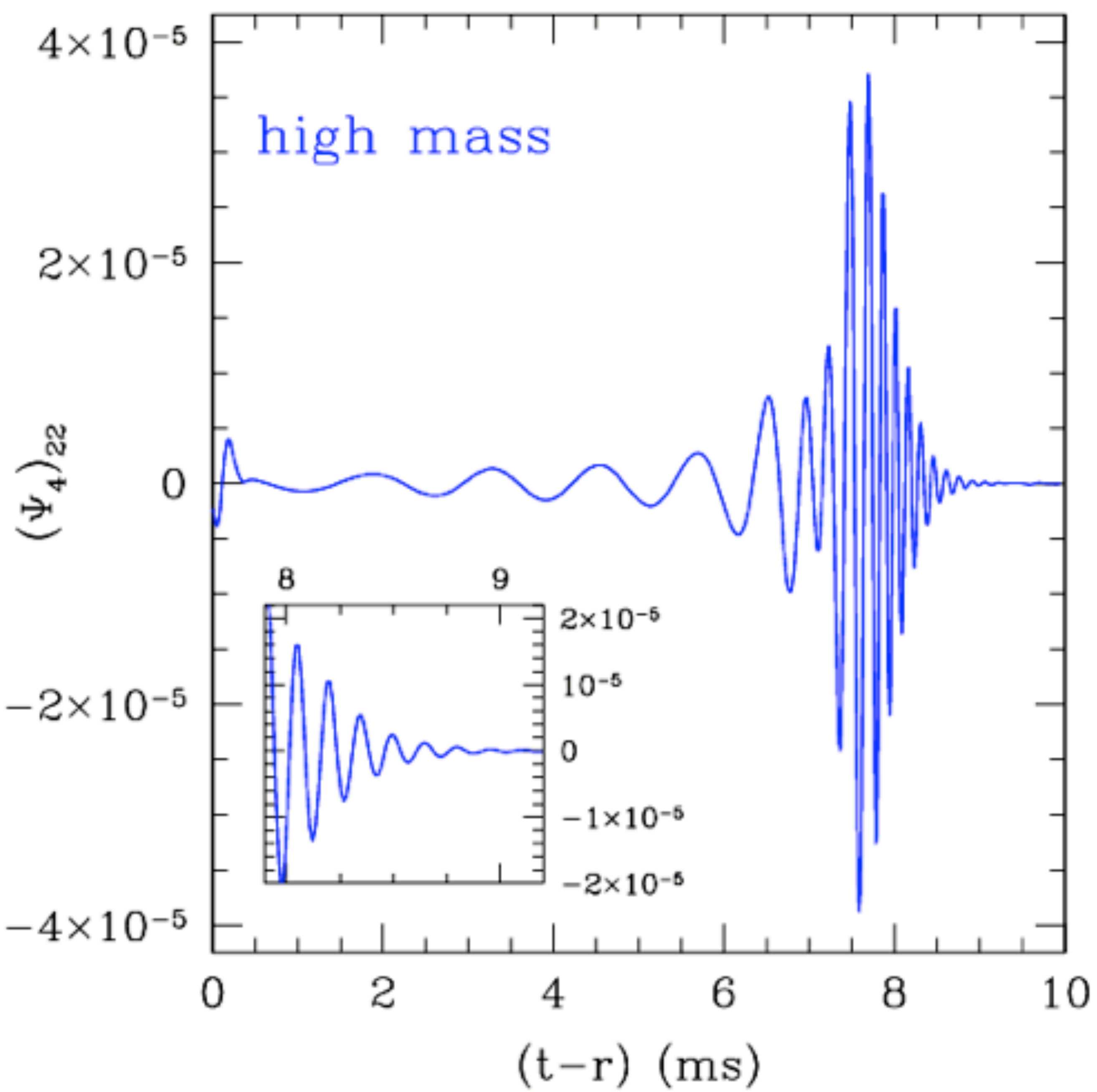
Cold EOS: **low-mass** binary

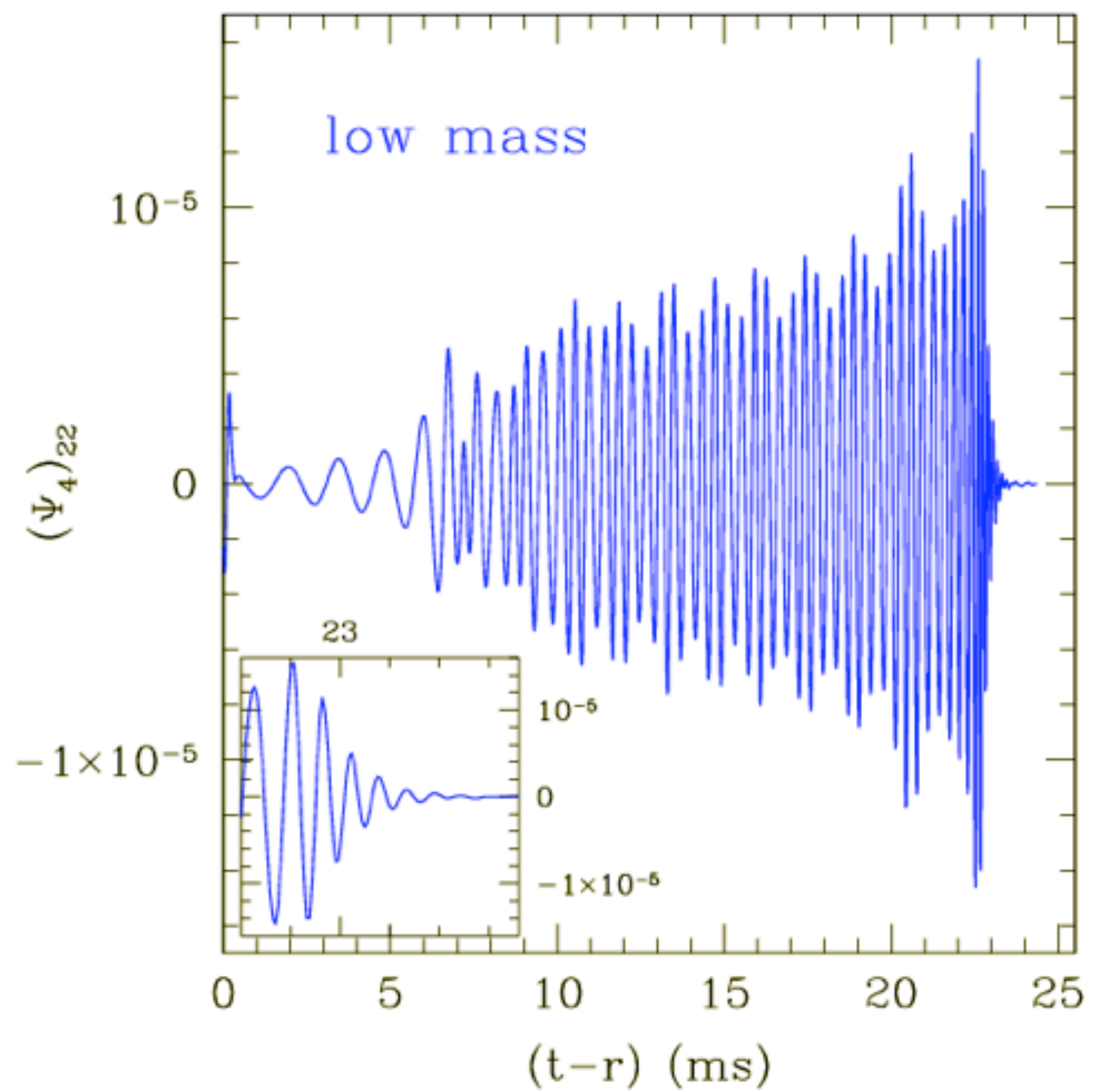
$$M = 1.4\, M_{\odot}$$

Waveforms: cold EOS

high-mass binary

low-mass binary

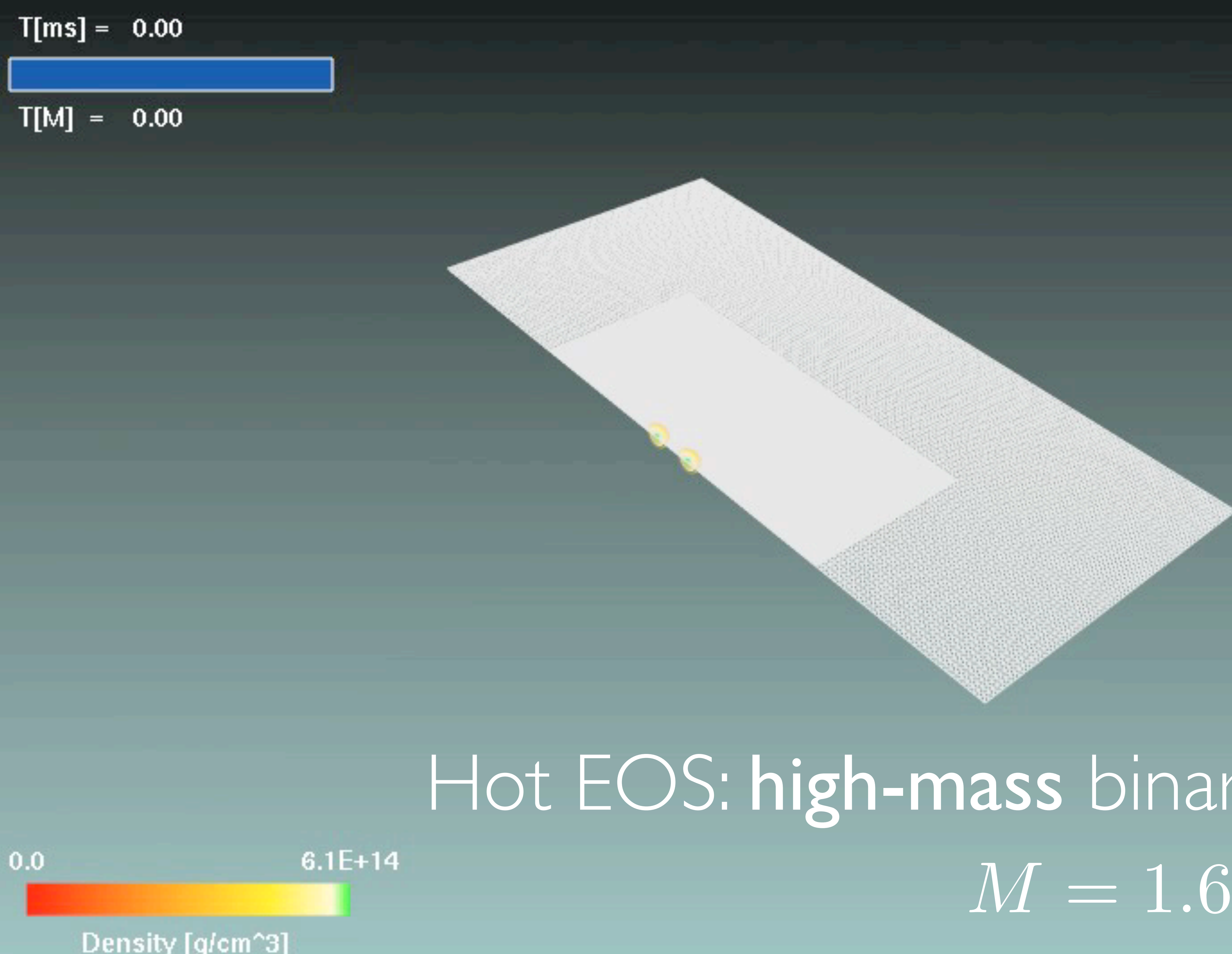




inspiral is "immediately" followed by the collapse to BH and ringdown

development of a bar-deformed NS leads to a long gw signal

Animations: Kaehler, Giacomazzo, Rezzolla



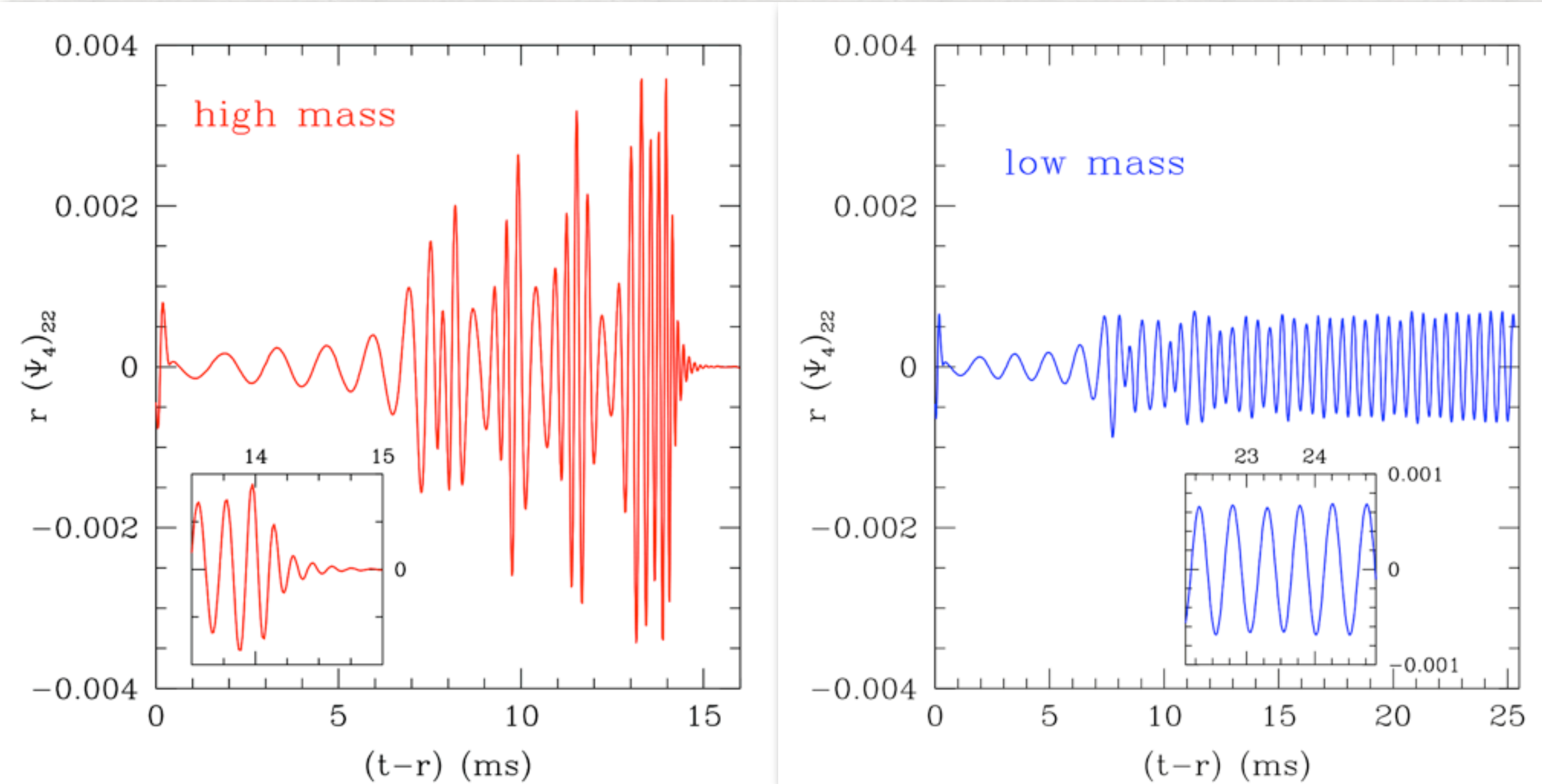
Hot EOS: **high-mass** binary

$M = 1.6\, M_{\odot}$

Waveforms: hot EOS

high-mass binary

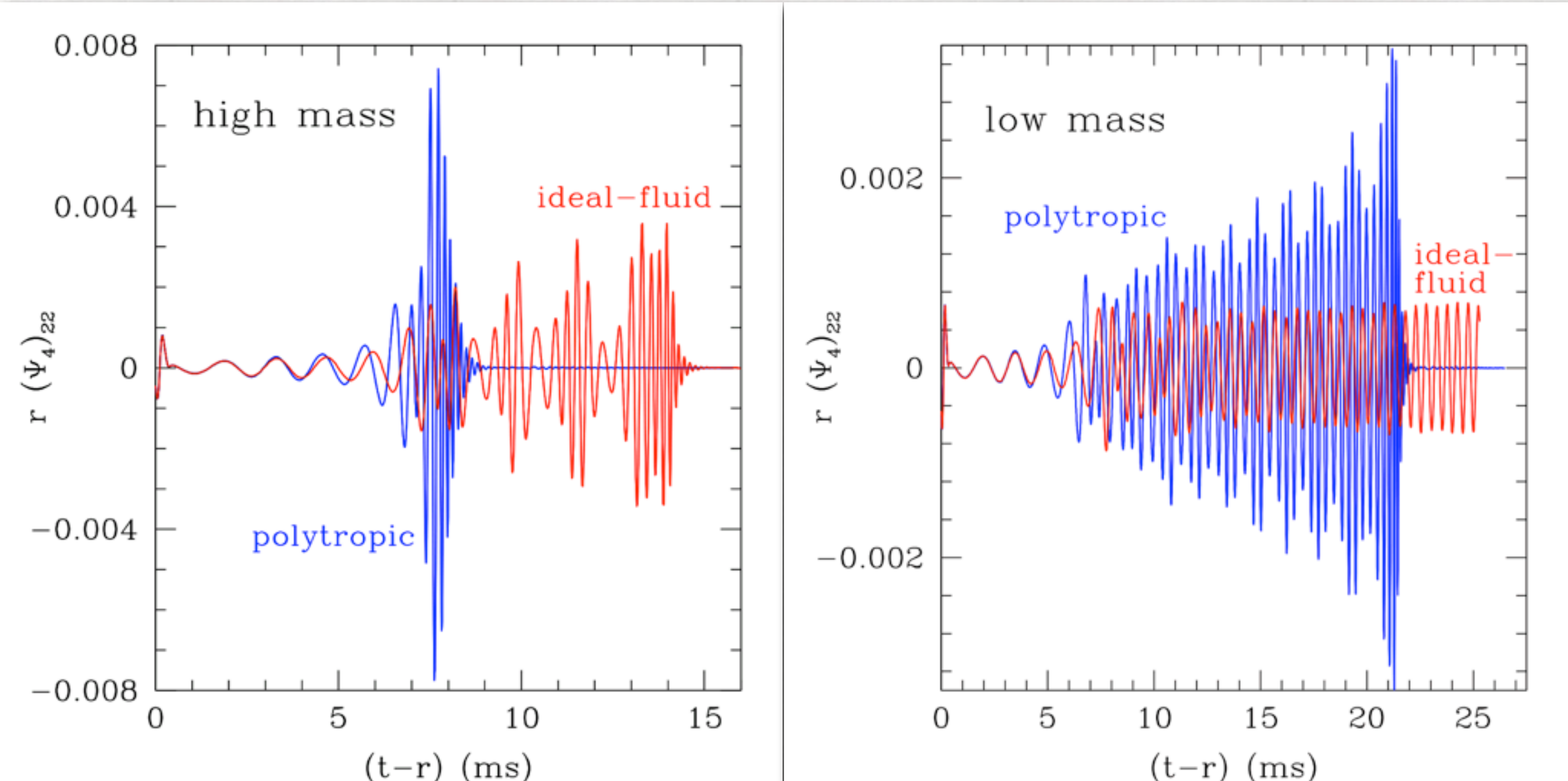
low-mass binary



high internal energy (temperature) of the HMNS prevents a prompt collapse

no BH produced: the HMNS evolves on longer (radiation-reaction) timescale

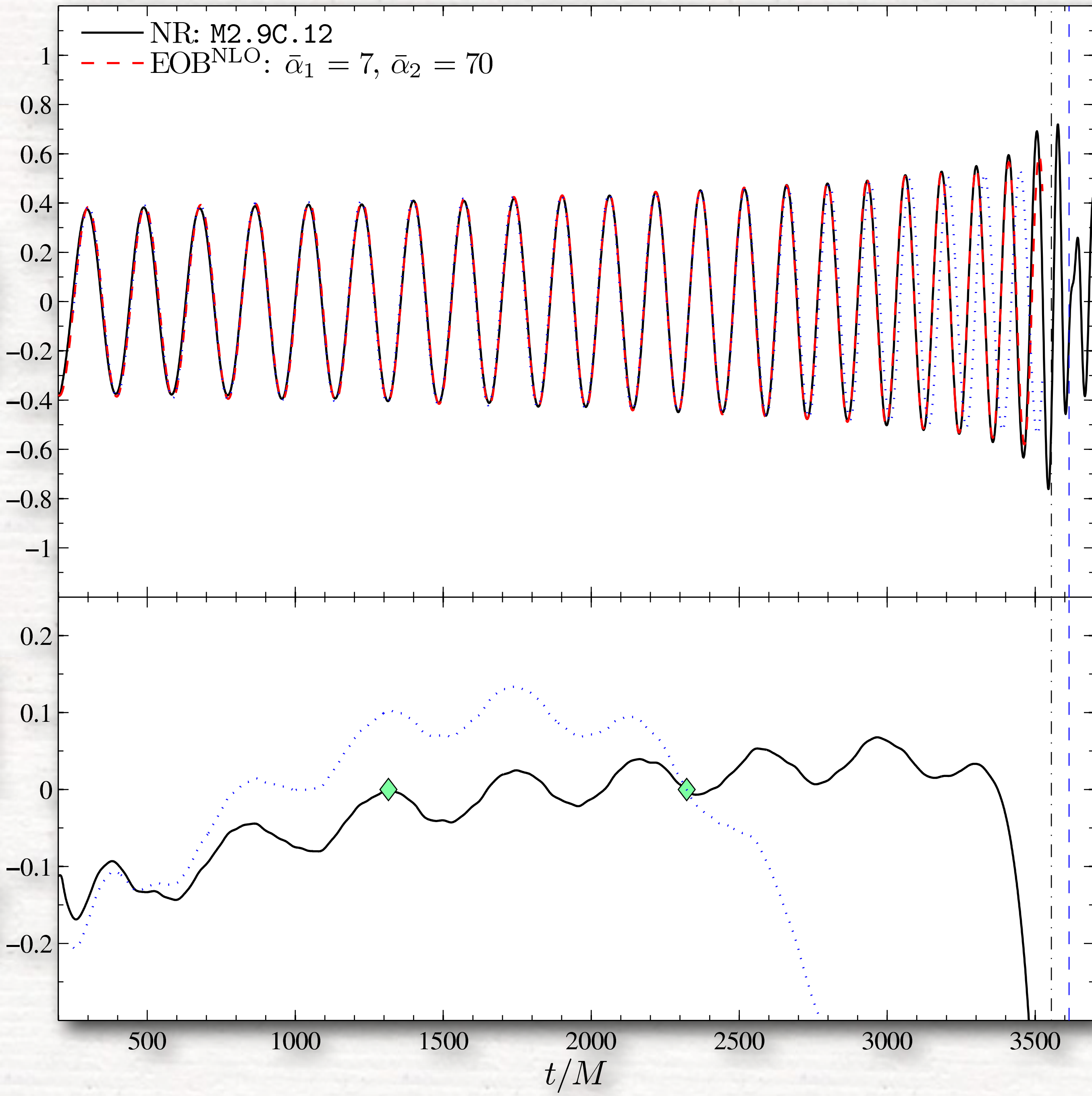
Imprint of the EOS: **hot** vs **cold**



Overall, a smaller initial mass and a hot EOS have the same effect: prolong the life of the HMNS and delay collapse to BH.

Good news related with the **inspiral**

Determining the properties of the EOS is rather difficult.
Tidal effects are important and about twice as strong as expected from Love number (Newtonian, GR) (Baiotti et al 2010)



This emerges from the comparison between the longest inspiral to date and a EOB modelling extended to include tidal effects.
The match is good only for

$$\kappa_\ell^{T,\mathrm{eff}} \simeq (2.0 - 2.5)\kappa_\ell^T$$

Bad news related with the **inspiral**

In addition, because these effects become most important in the very last few orbits, the differences among different EOSs are small: $\lambda \sim 1$.

TABLE II: The rms measurement error in various binary parameters (chirp mass $\mathcal{M}$, dimensionless reduced mass η, and weighted average $\tilde{\lambda}$ of the tidal deformabilities) for a range of total mass M and mass ratio m_2/m_1, together with the signal to noise ratio ρ, using only the information in the portion of the inspiral signal between 10 Hz $\leq f \leq$ 450 Hz. The distance is set at 100 Mpc, and the amplitude is averaged over sky position and relative inclination.

Advanced LIGO

M ($M_\odot$)	m_2/m_1	$\Delta\mathcal{M}/\mathcal{M}$	$\Delta\eta/\eta$	$\Delta\tilde{\lambda}(10^{36}\,\mathrm{g\,cm^2\,s^2})$	ρ
2.0	1.0	0.00028	0.073	8.4	27
2.8	1.0	0.00037	0.055	19.3	35
3.4	1.0	0.00046	0.047	31.3	41
2.0	0.7	0.00026	0.058	8.2	26
2.8	0.7	0.00027	0.058	18.9	35
3.4	0.7	0.00028	0.055	30.5	41
2.8	0.5	0.00037	0.06	17.8	33

Einstein Telescope

M ($M_\odot$)	m_2/m_1	$\Delta\mathcal{M}/\mathcal{M}$	$\Delta\eta/\eta$	$\Delta\tilde{\lambda}(10^{36}\,\mathrm{g\,cm^2\,s^2})$	ρ
2.0	1.0	0.000015	0.0058	0.70	354
2.8	1.0	0.000021	0.0043	1.60	469
3.4	1.0	0.000025	0.0038	2.58	552
2.0	0.7	0.000015	0.0058	0.68	349
2.8	0.7	0.000021	0.0045	1.56	462
3.4	0.7	0.000025	0.0038	2.52	543
2.8	0.5	0.000020	0.0048	1.46	442

The estimated uncertainty $\Delta\lambda$ for a binary neutron star inspiral at 100 Mpc using the advanced LIGO sensitivity below 450 Hz is greater than the largest values of λ except for very low-mass binaries (Hinderer et al 2010).

The prospects are better for ET but $\Delta\lambda/\lambda \sim 1$. Confined to the inspiral, ET will **rule out** some EOSs at best.

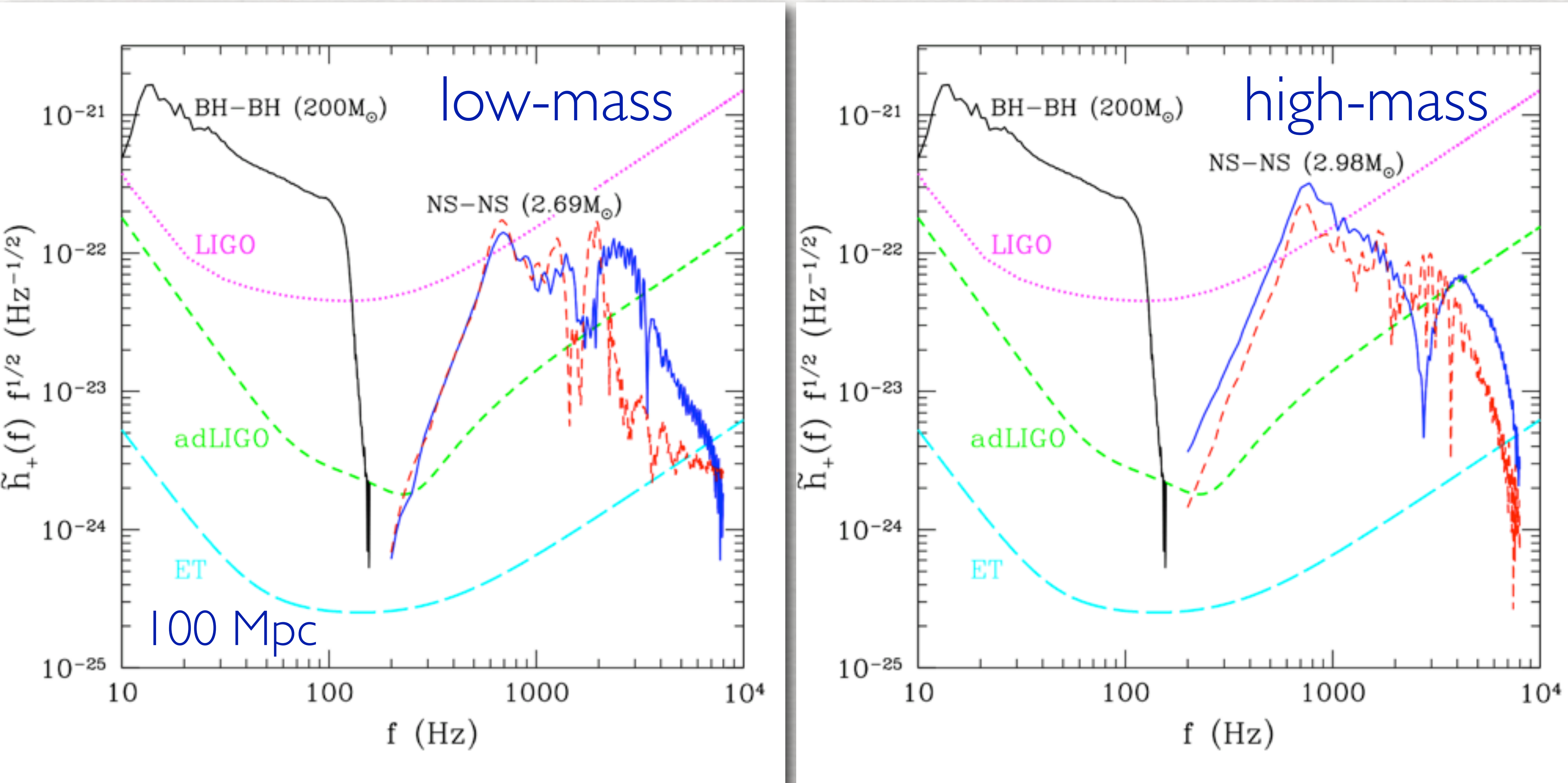
On the importance of the HMNS stage

- The HMNS stage is essential to extract information about the EOS but comes at the cost of being a high-frequency signal.
- With sufficiently sensitive detectors, GWs will work as the Rosetta stone to decipher the NS interior.
- But what is sufficiently sensitive? Considering the last few orbits, the HMNS stage and the ringdown:

SNR (Virgo/LIGO): **~ 0.3**
SNR (advVirgo/LIGO): **~ 2**
SNR (ET): **~ 40**

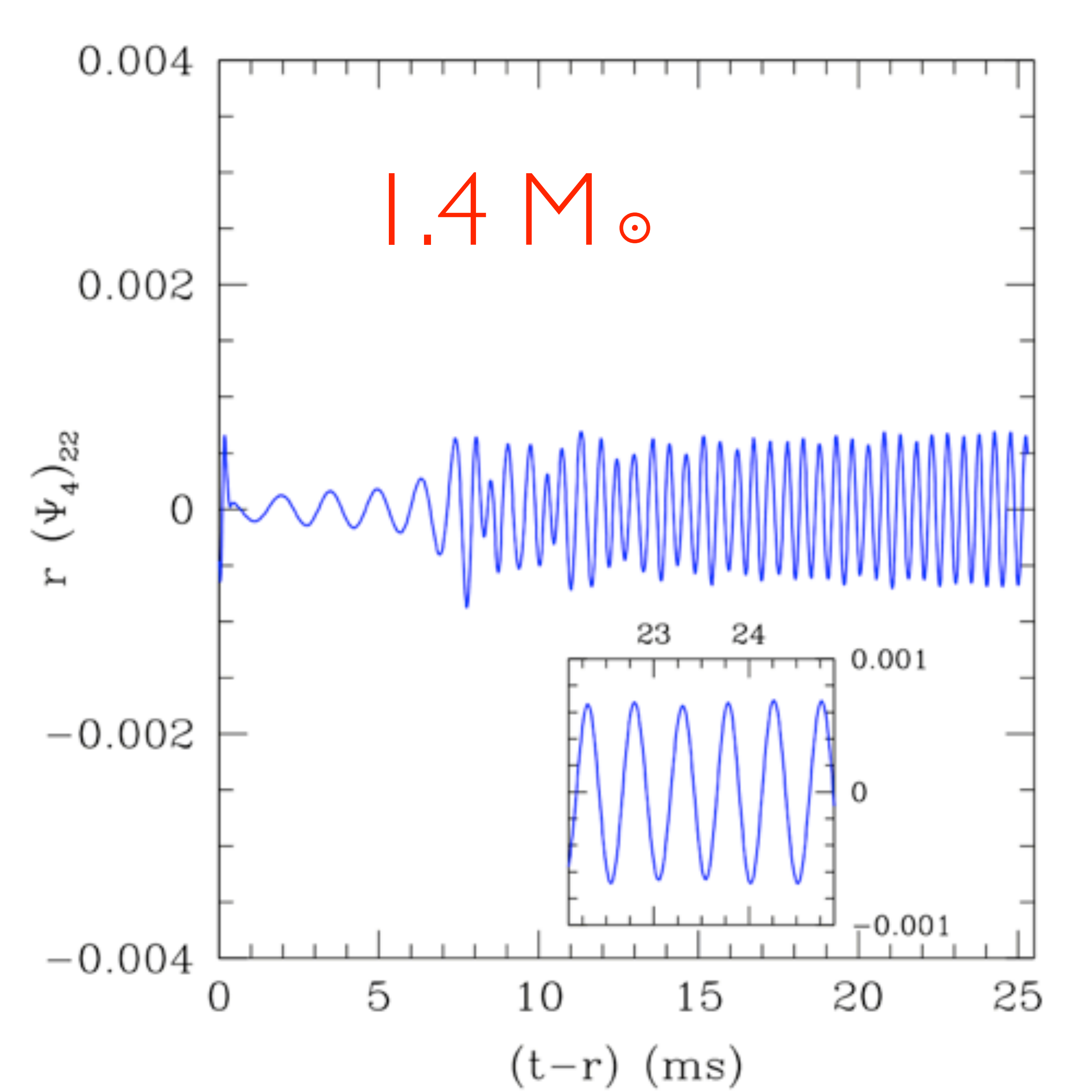
Imprint of the EOS: frequency domain

Andersson et al. (GRG 2009)



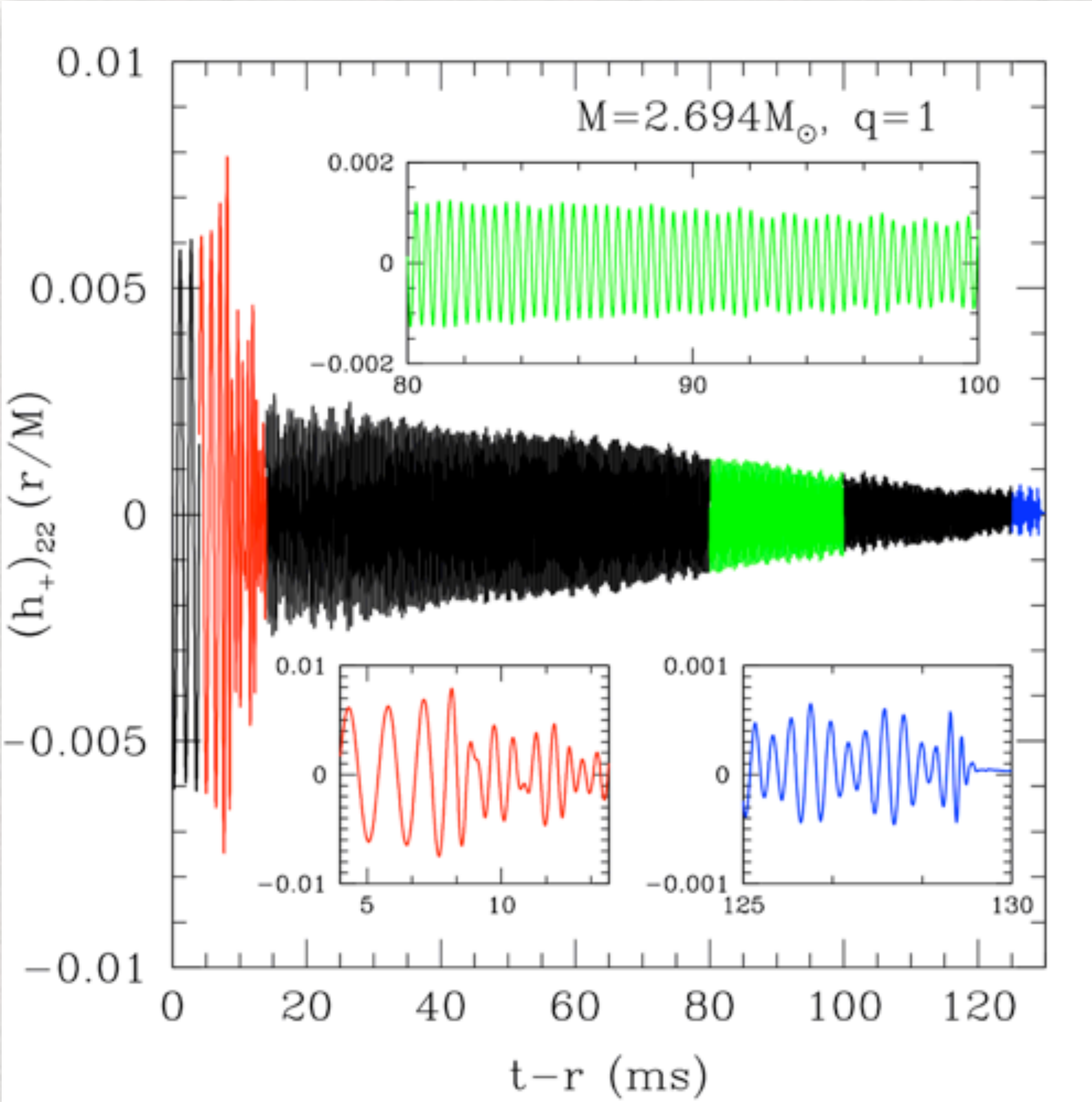
A comparison in the frequency space clarifies the additional complexity and richness of GWs from NSs

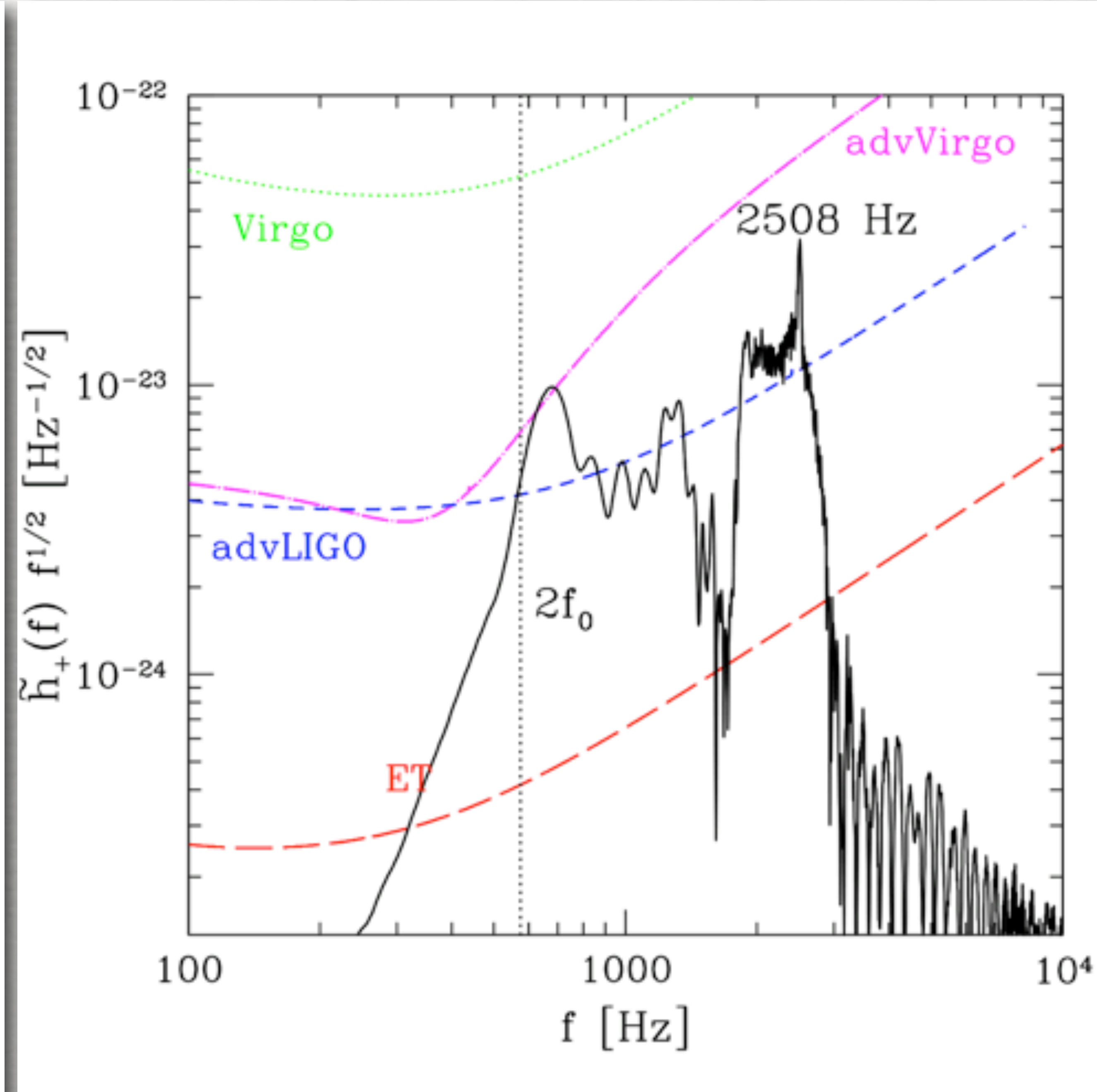
The advantages of the **post-merger**



Let's go back to something we have already seen: the merger of a low-mass binary. (1.4 M⊙) As discussed before, the HMNS is not massive enough to collapse immediately and it's losing angular momentum very slowly. However, it must collapse soon or later...

The advantages of the **post-merger**



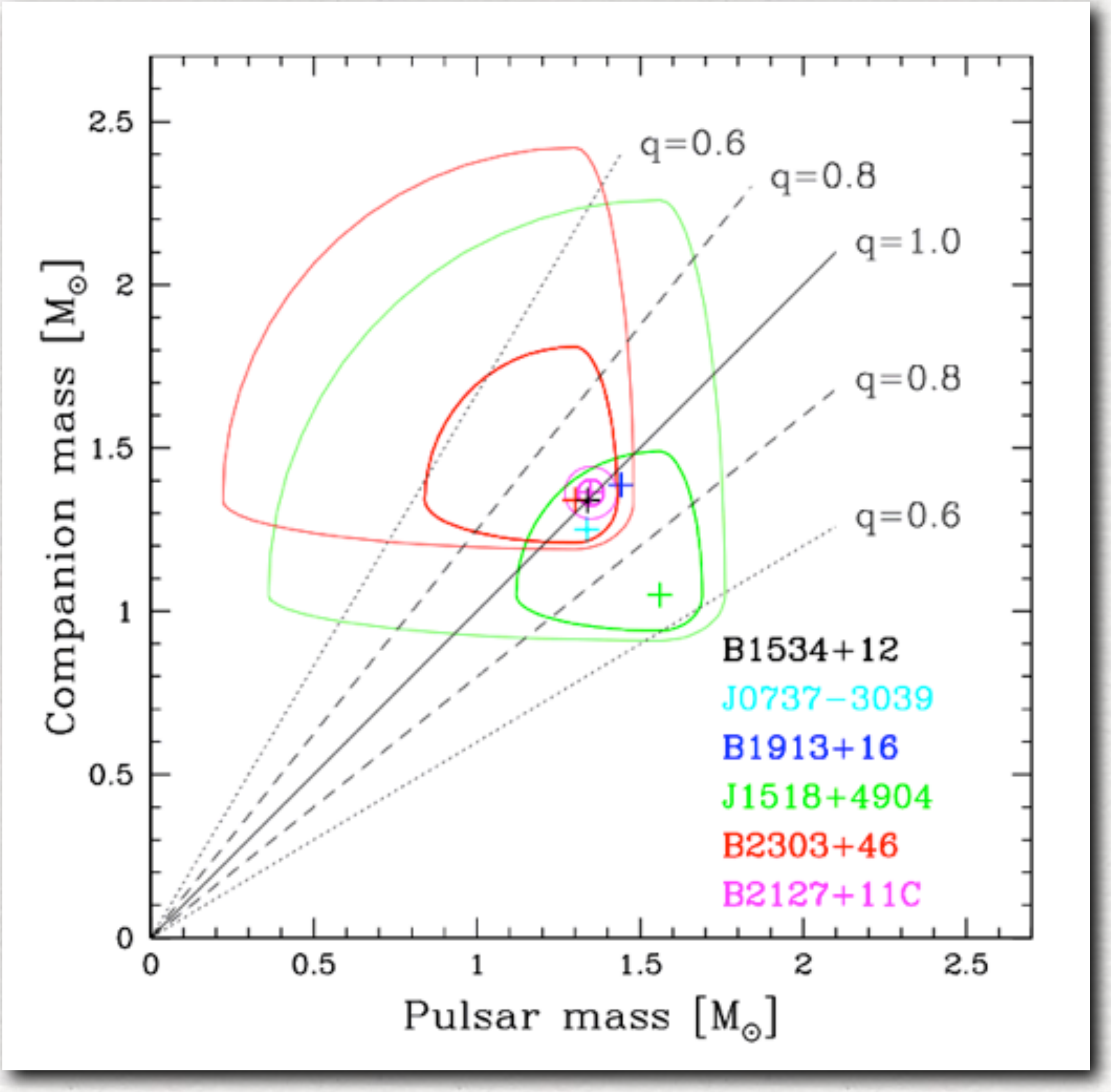


"Almost perfect" signal: high SNR, high stability in frequency, a unique fingerprint.

Not all instruments could exploit it: **ET clearly can!**

When the two masses are not equal...

In contrast to binary black holes, binary neutron stars do not show large variations in the mass ratio.

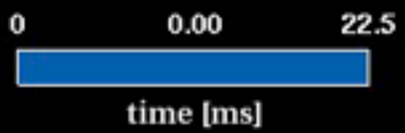


D. Gondek-Rosinska (2009)

M_1	M_2	
1.44	1.38	B1913+16
1.33	1.34	B1534+12
1.33	1.25	J0737-3039
1.40	1.18	J1756-2251
1.36	1.35	B2127+11C
1.35	1.26	J1906+0746
1.62	1.11	J1811-1736
1.56	1.05	J1518+4904
1.14	1.36	J1829+2456

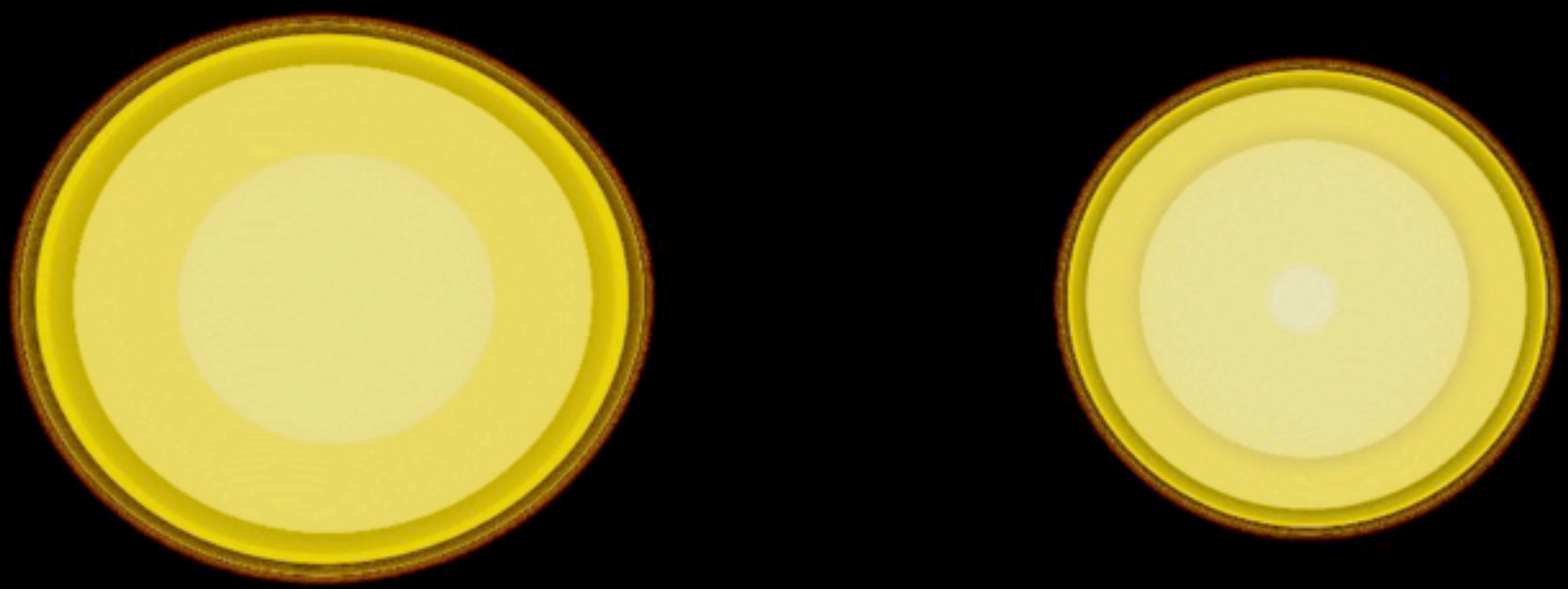
Such mass asymmetries are small and would be irrelevant for BHs.

They are important for NSs!



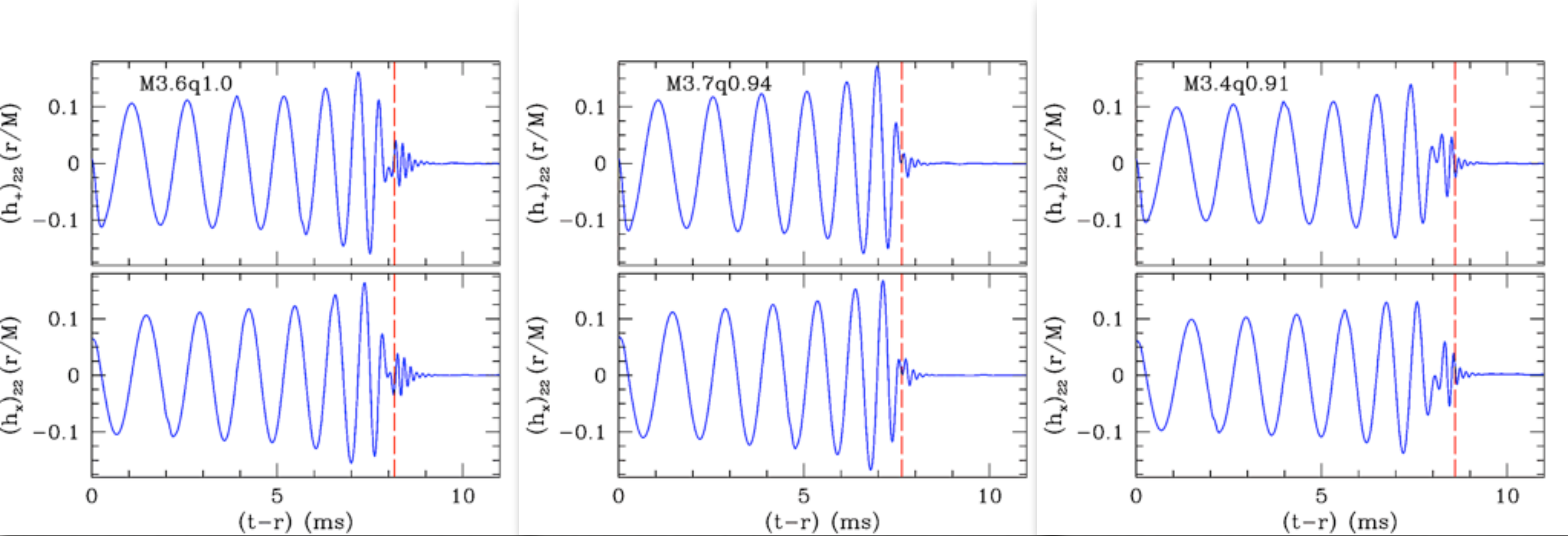
Animations: Giacomazzo, Koppitz, LR

Total mass : 3.37 $M_\odot$;   mass ratio :0.80;



- the torii are generically more massive
- the torii are generically more extended
- the torii tend to stable quasi-Keplerian configurations

Gravitational waveforms



- The waveforms are very simple with moderate modulation induced by mass asymmetry.
- No HMNS is produced and the QNM ringing (vertical line) is choked by the intense mass accretion rate (the BH cannot ringdown...). As a result: small-mass ratios are not promising signals to extract information about EOS

MHD: another context in which ET can make the difference

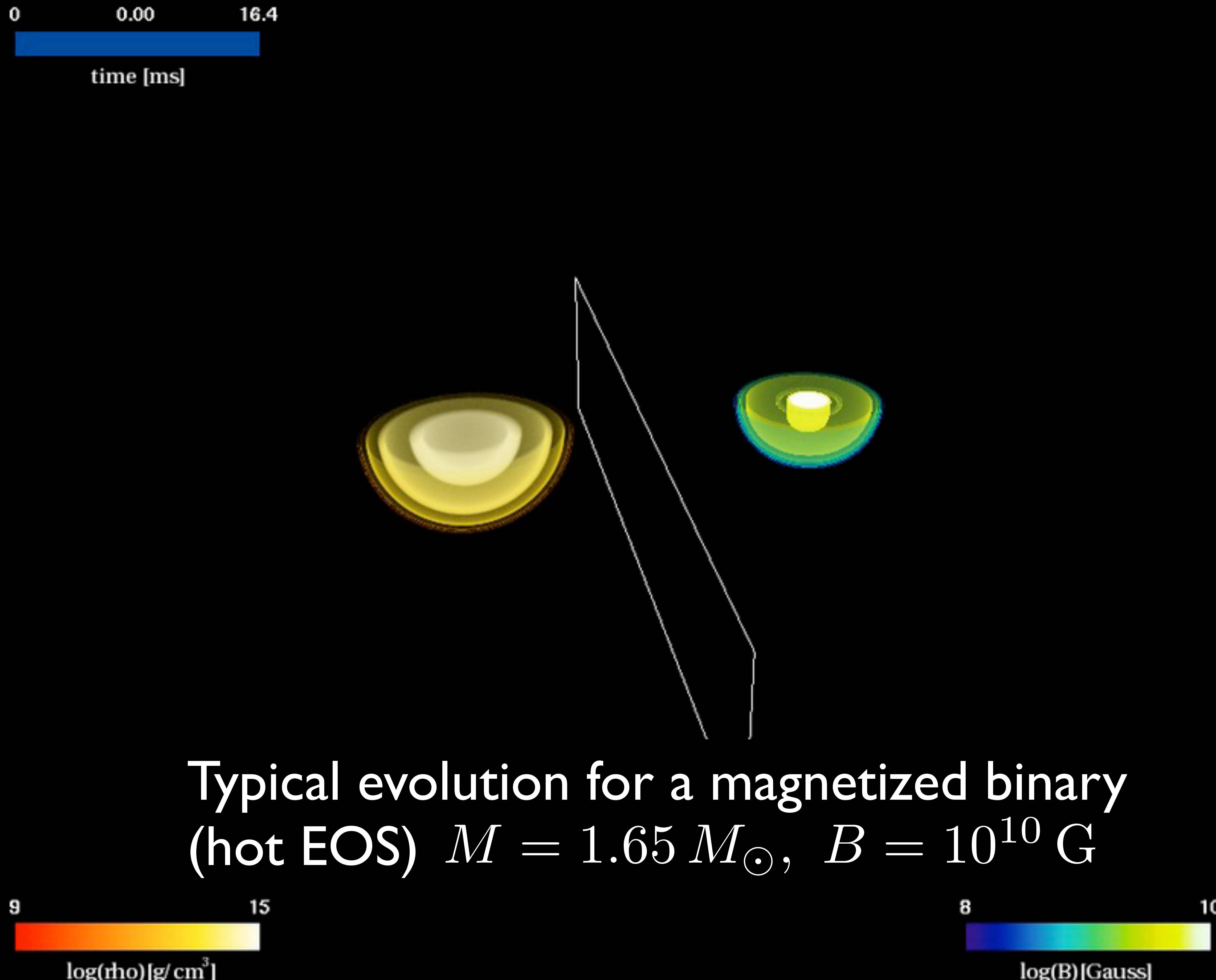
NSs have large magnetic fields but these have been traditionally neglected. It is natural to ask:

- can we detect B-fields during the inspiral?
- can we detect B-fields after the merger?
- how do B-fields influence the dynamics of the tori?

- This is not easy but can be done: relativistic hydrodynamics is extended to *ideal-MHD* (infinite conductivity).
- The B-fields are initially contained inside the stars: ie no magnetospheric effects.
- We have considered 12 binaries (low/high mass) with MFs:

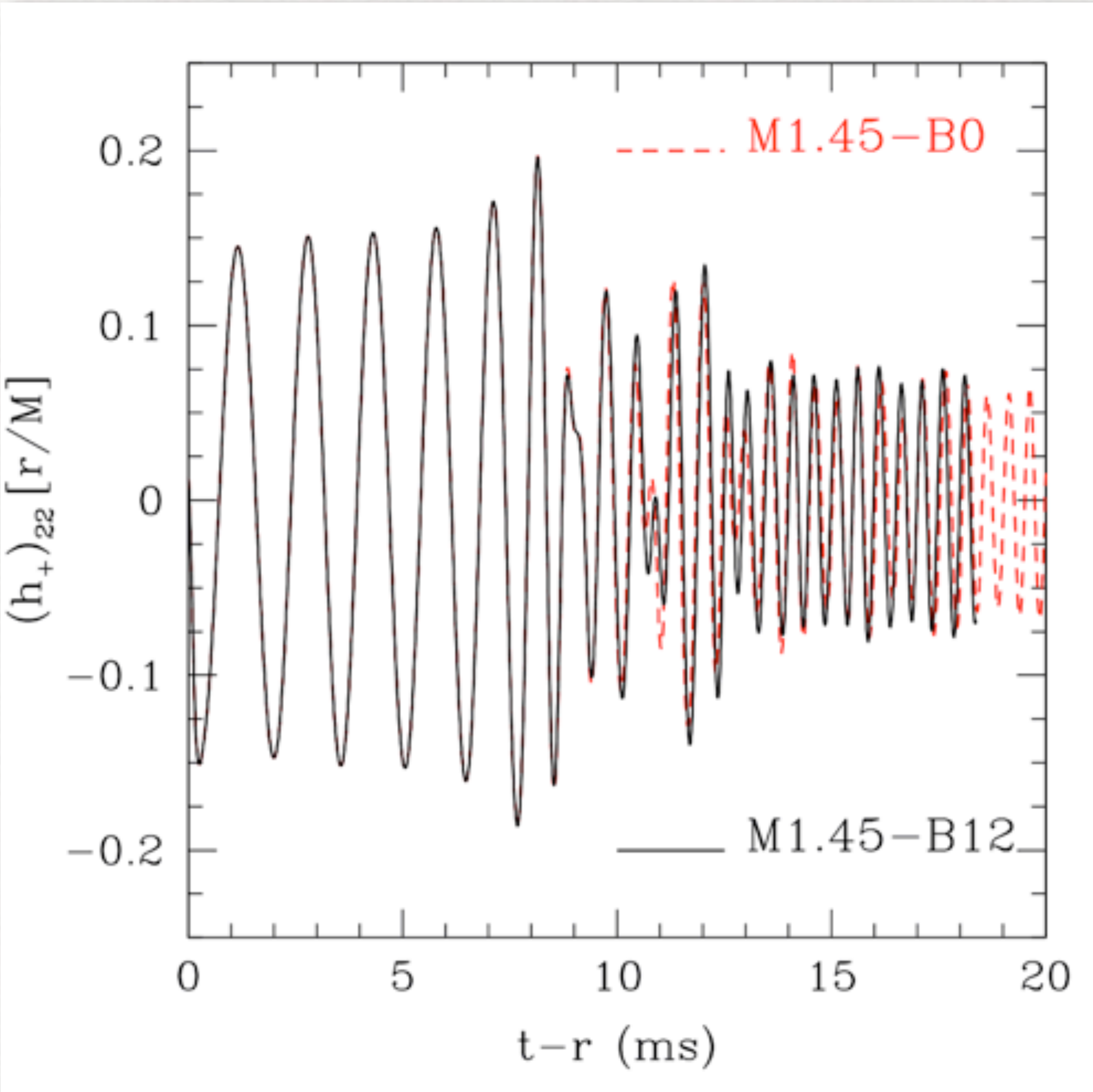
$$B = 0,\, 10^8,\, 10^{10},\, 10^{12},\, 10^{14},\, 10^{17}\ \mathrm{G}$$

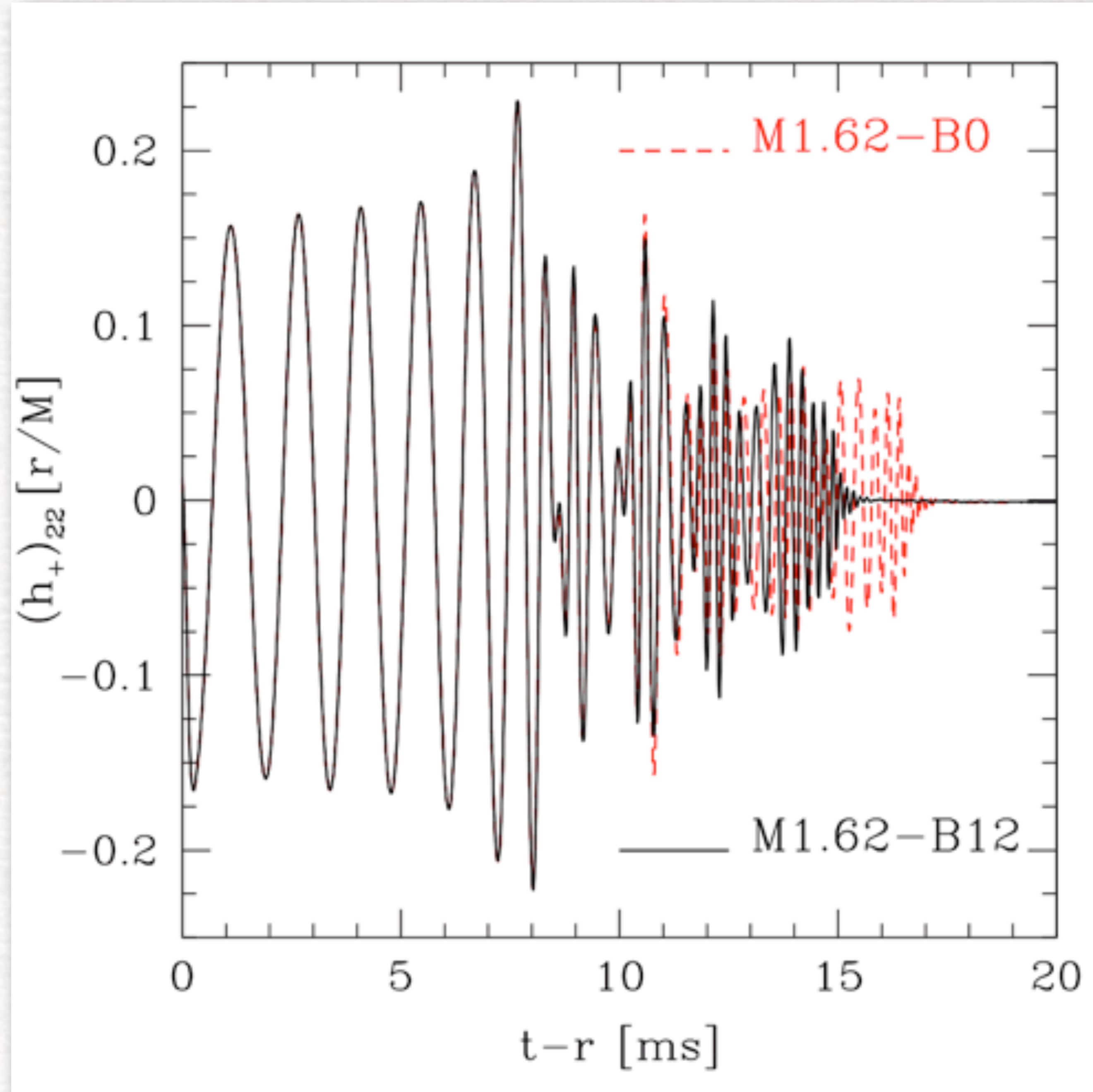
Animations: Koppitz, Giacomazzo, LR



Typical evolution for a magnetized binary (hot EOS) $M = 1.65\, M_{\odot},\ B = 10^{10}\,\mathrm{G}$

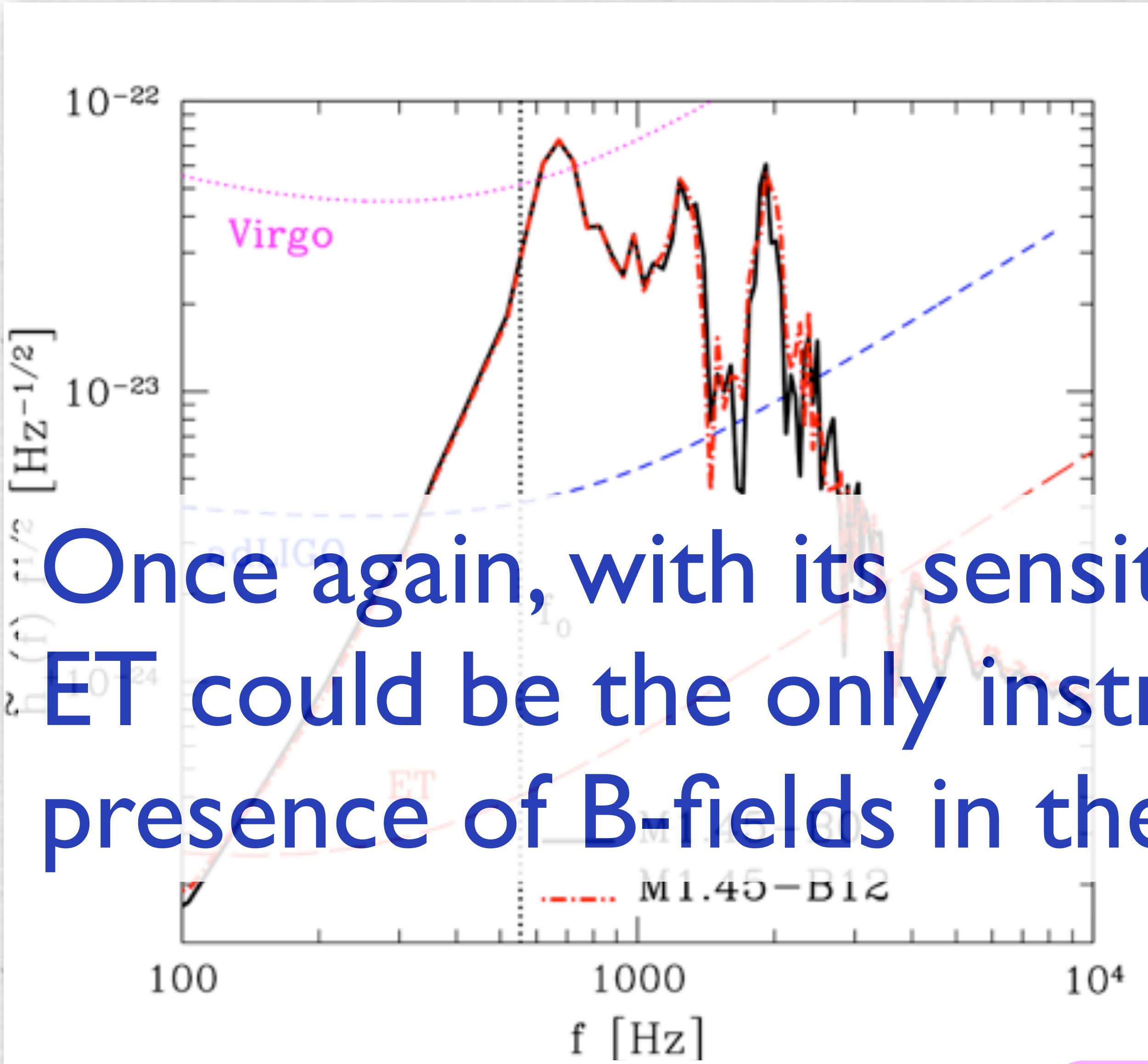
Imprint of the B-field: time domain

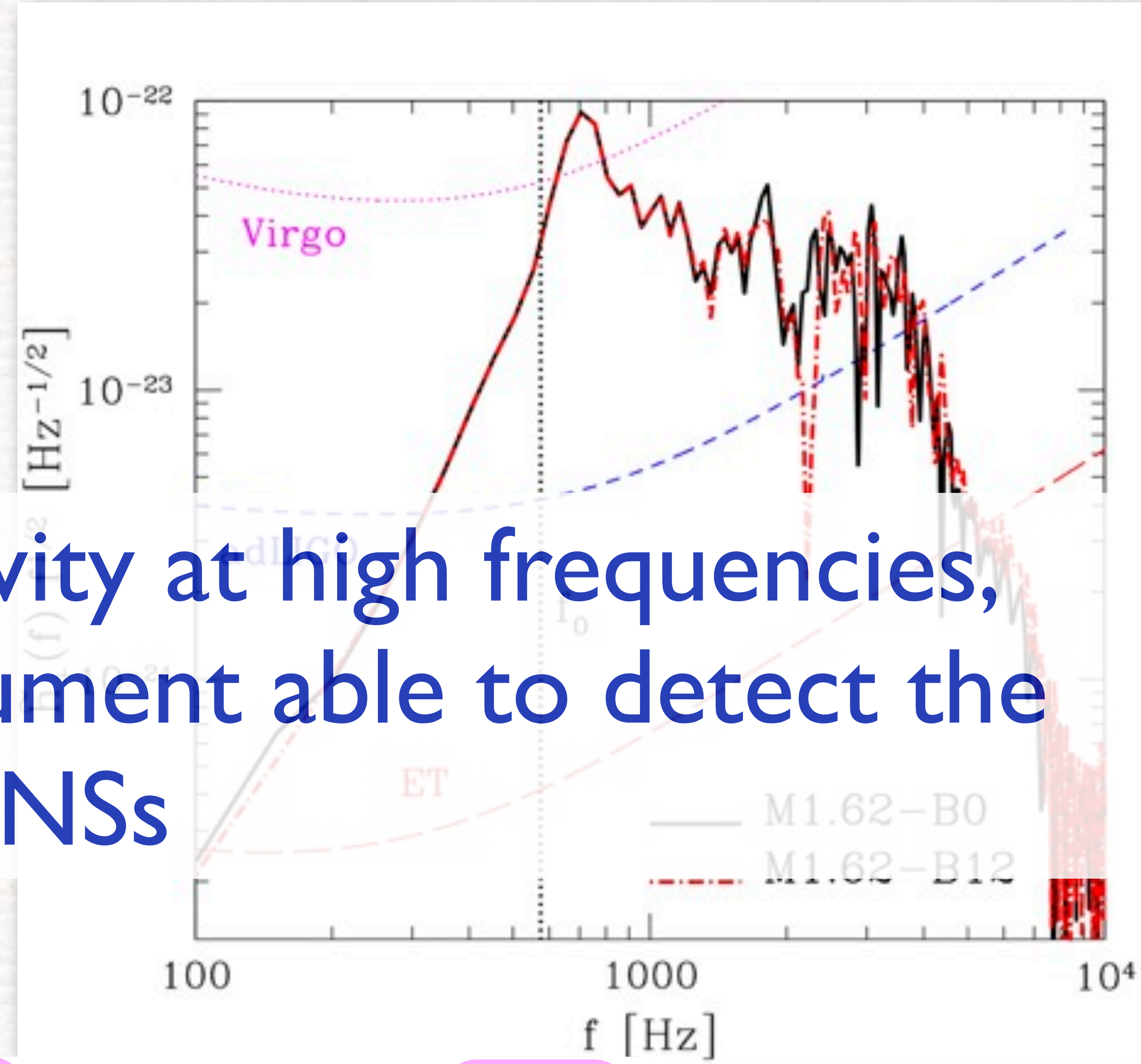




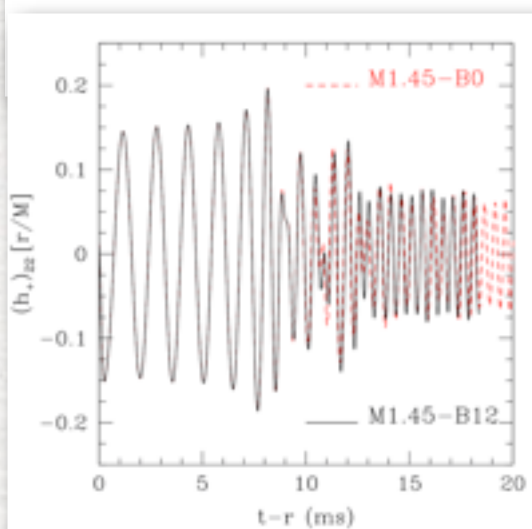
Clearly the differences during the **inspiral** are minute for realistic fields but can be large after the **merger**

Imprint of the B-field: frequency domain

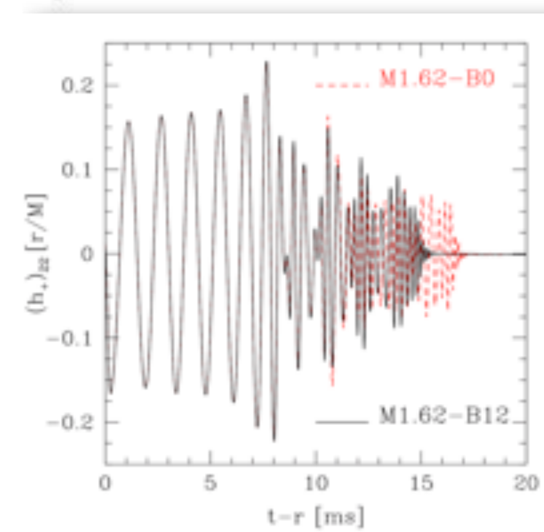




Once again, with its sensitivity at high frequencies, ET could be the only instrument able to detect the presence of B-fields in the NSs



Binary	$\mathcal{O}$	$\mathcal{O}_{\rm insp}$	$\mathcal{O}_{\rm postm}$	SNR AdvVirgo	SNR AdvLIGO	SNR ET
M1.45-B0	1.000	1.000	1.000	1.94	2.11	38.90
M1.45-B8	0.997	0.999	0.926	1.94	2.10	38.72
M1.45-B10	0.996	0.999	0.934	1.94	2.11	38.82
M1.45-B12	0.996	0.999	0.899	1.94	2.11	39.01
M1.62-B0	1.000	1.000	1.000	2.00	2.24	42.57
M1.62-B8	0.998	1.000	0.938	2.00	2.24	42.59
M1.62-B10	0.993	1.000	0.724	2.00	2.23	42.48
M1.62-B12	0.997	1.000	0.893	2.00	2.24	42.49



Conclusions

✳ Binary NSs, besides being prime sources of GWs represent marvelous laboratories where all physics is extreme.

✳ Detecting GWs from binary NSs will help reach holy grails in nuclear physics (EOS of nuclear matter) and in astrophysics (reveal the central engine of SGRBs)

✳All of this physics, however, comes at high costs:

- ★ a good part of the SNR is built at high frequencies ($f > 1$kHz)
- ★ tidal effects are strong and will distinguish different EOSs. However, using the inspiral only is hard (although not impossible) because tidal effects show up only very late
- ★ B-field corrections emerge only after the merger

✳ **None of these problems will be present for ET which will indeed allow us to understand NSs**