Binary source modelling for ET

Luciano Rezzolla

Albert Einstein Institute, Potsdam, Germany

Dept. of Physics and Astronomy, Louisiana State Univ. Louisiana, USA

ET-ILIAS meeting, Nov. 24-25 2008, Cascina, Italy

What NR can do for ET and viceversa

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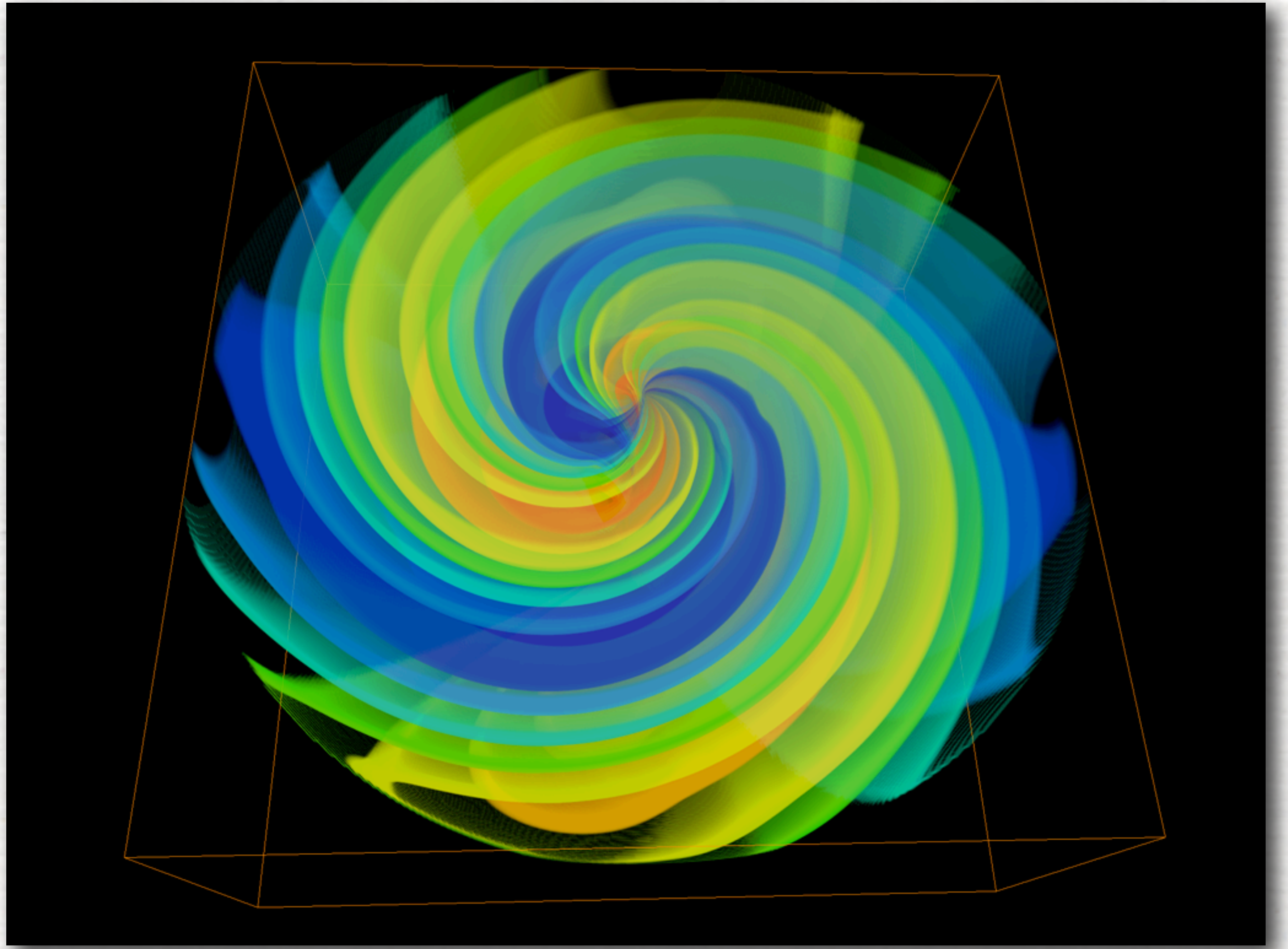
Plan of the talk

- What NR can do for ET
- Some representative examples
  - binary black holes:
    - hybrid waveforms for unequal-mass non-spinning
    - SNR for equal-mass spinning
  - binary neutron stars:
    - deciphering the EOS
    - connecting GW and EM emission from GRBs

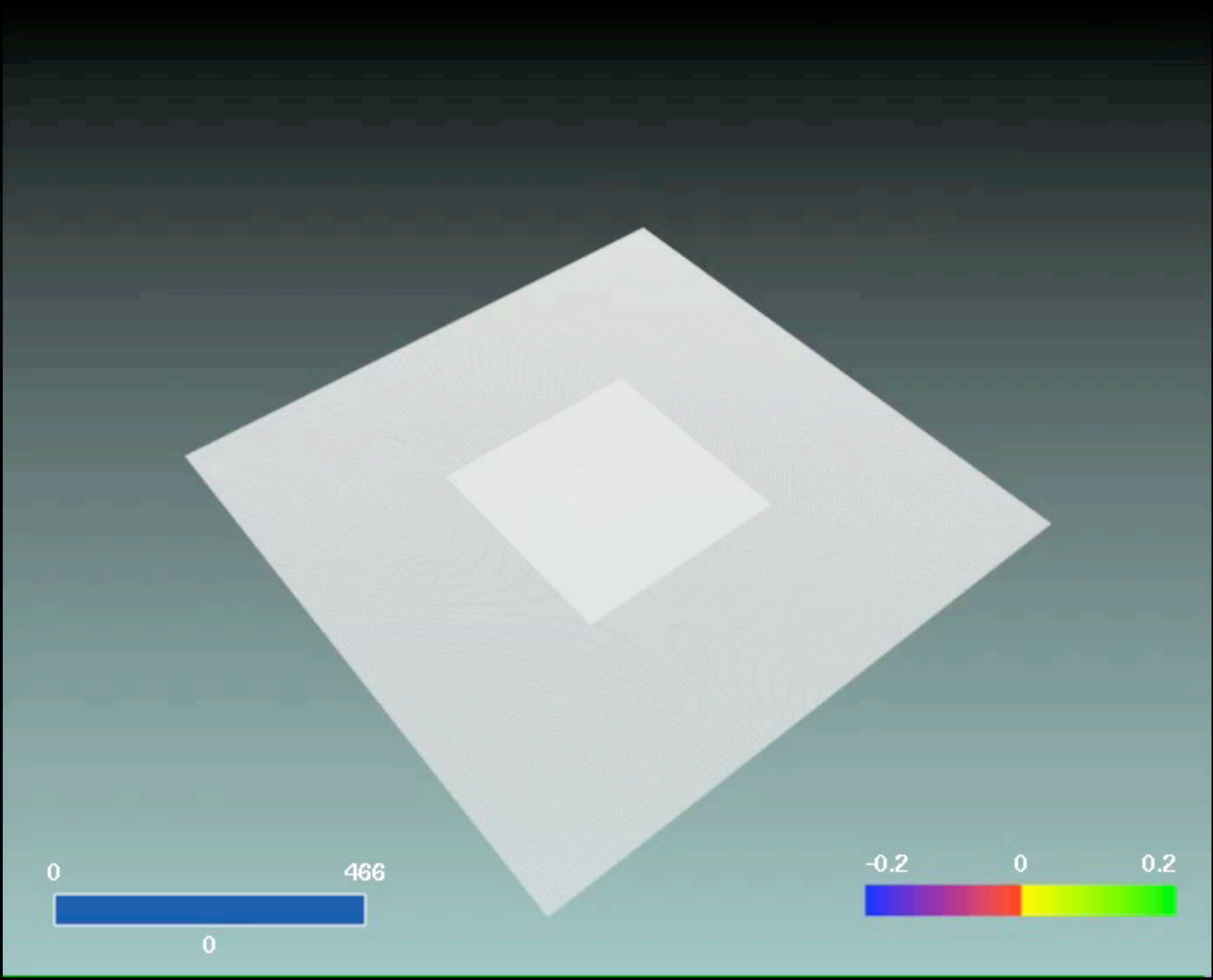
Modelling binary black holes

Ajith et al. 2007, CQG
Ajith et al. 2008, PRD
Riesswig et al. 2008



In collaboration with:

- GW group AEI Hannover
- GW group AEI Potsdam
- Numrel group Jena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466
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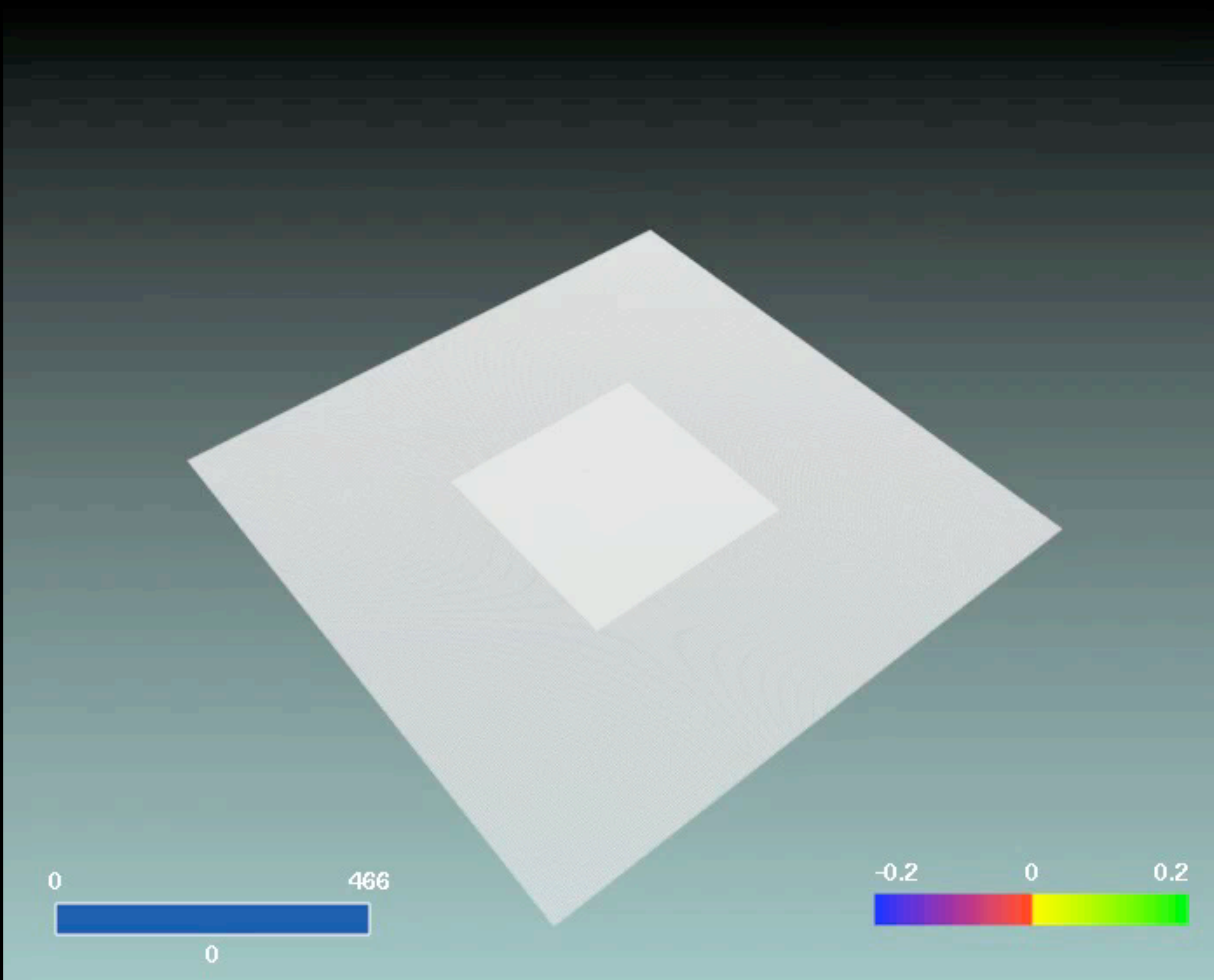

Animation by R. Kaehler, LR

Hybrid waveforms: the motivations

- There is no fundamental obstacle to long-term (i.e. covering ~ 10+ orbits) NR calculations of the three stages of the binary evolution: inspiral, merger and ringdown

- Yet, NR simulations are computationally expensive and building a template bank out of them is prohibitive and awkard

- Present data-analysis pipelines employ phenomenological template: analytic, fast, and collect most of the information

- In the past phenomenological templates have been built using approximations and a certain amount of heuristics

- Ideally phenomenological templates should be built upon modelling NR waveforms for the three stages.

The basic logic...

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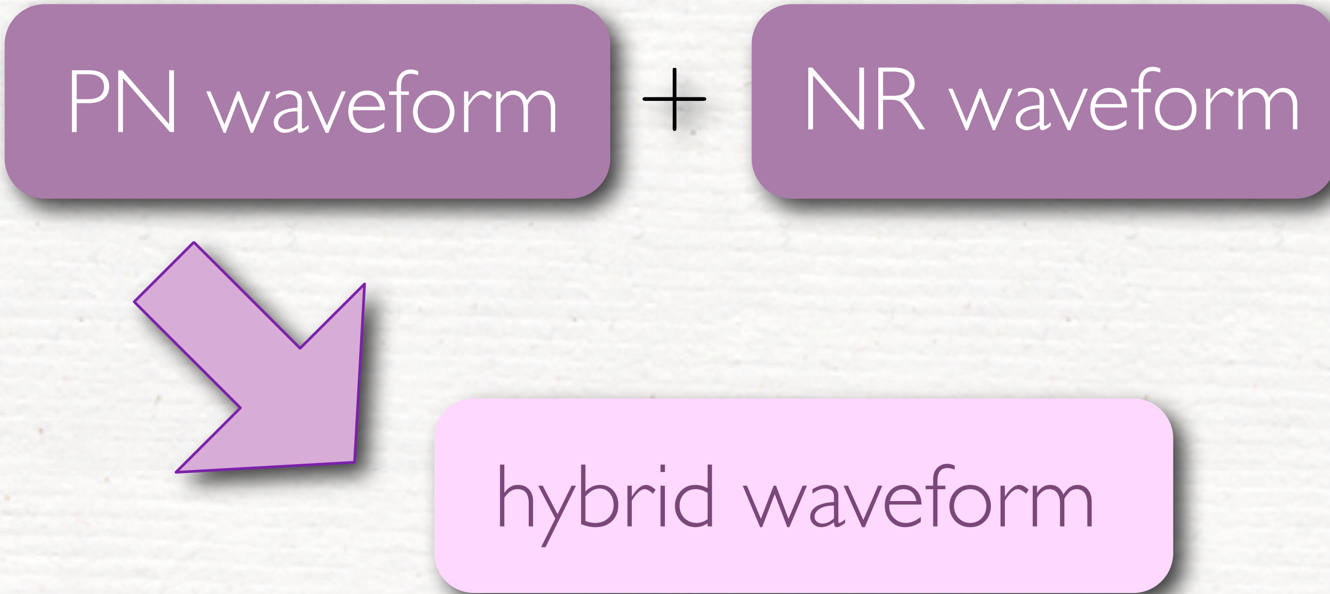
PN waveform + NR waveform

The basic logic...



The basic logic...

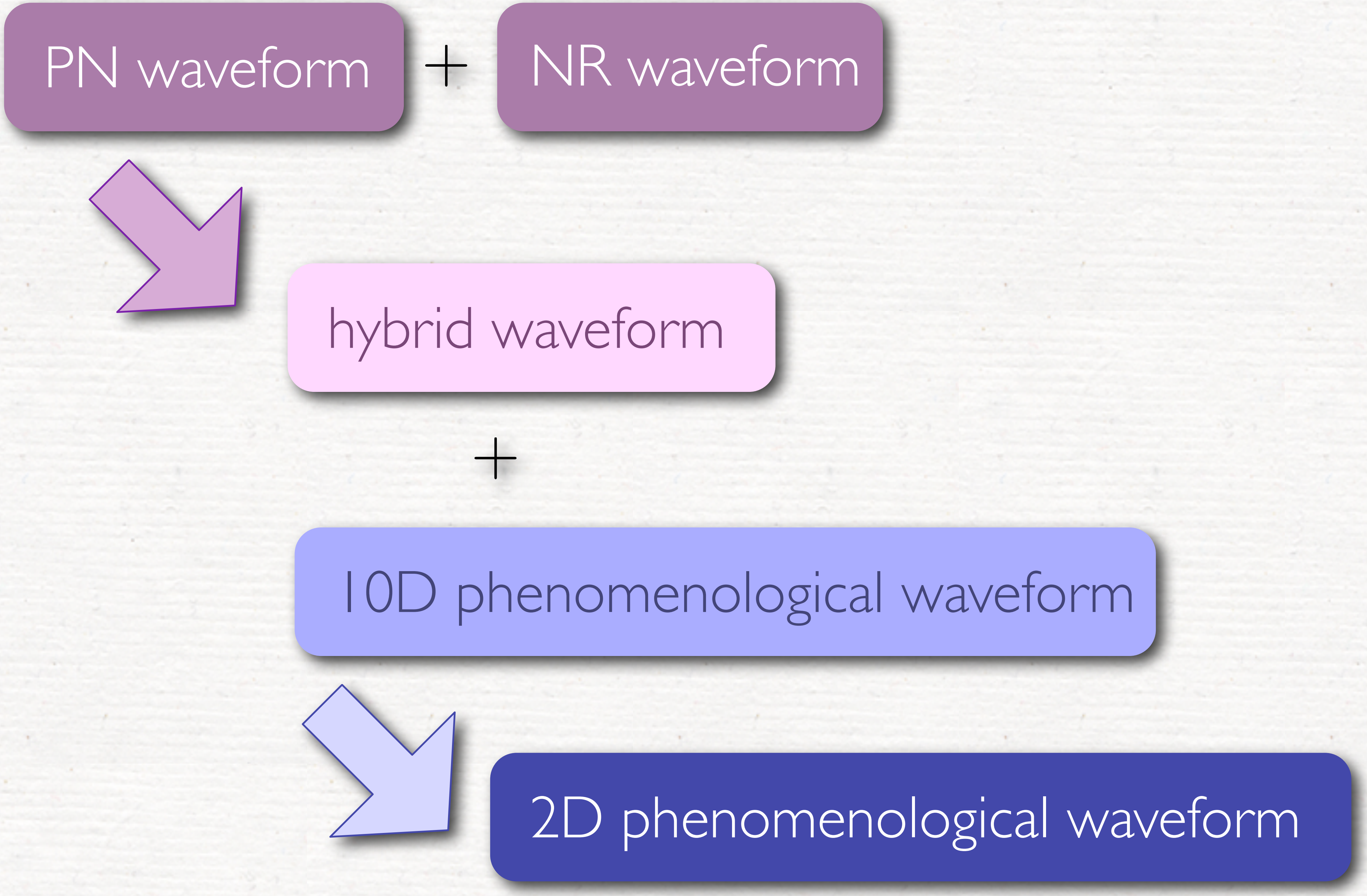
PN waveform + NR waveform

hybrid waveform

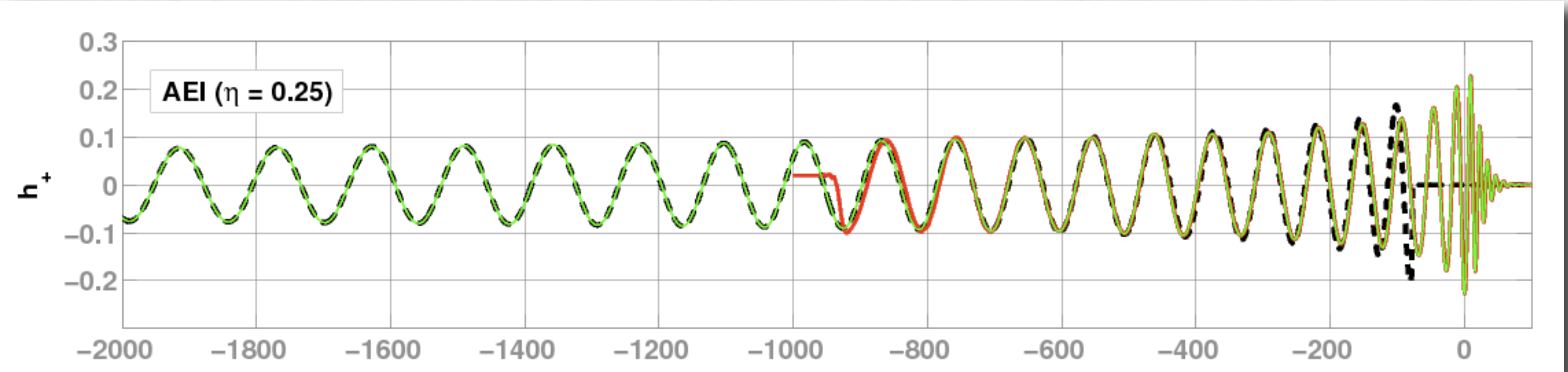
+

10D phenomenological waveform

The basic logic...



A hybrid waveform in practice...



Red line is the numrel waveform

Black dashed line is the 3.5PN waveform

Green line is the hybrid waveform

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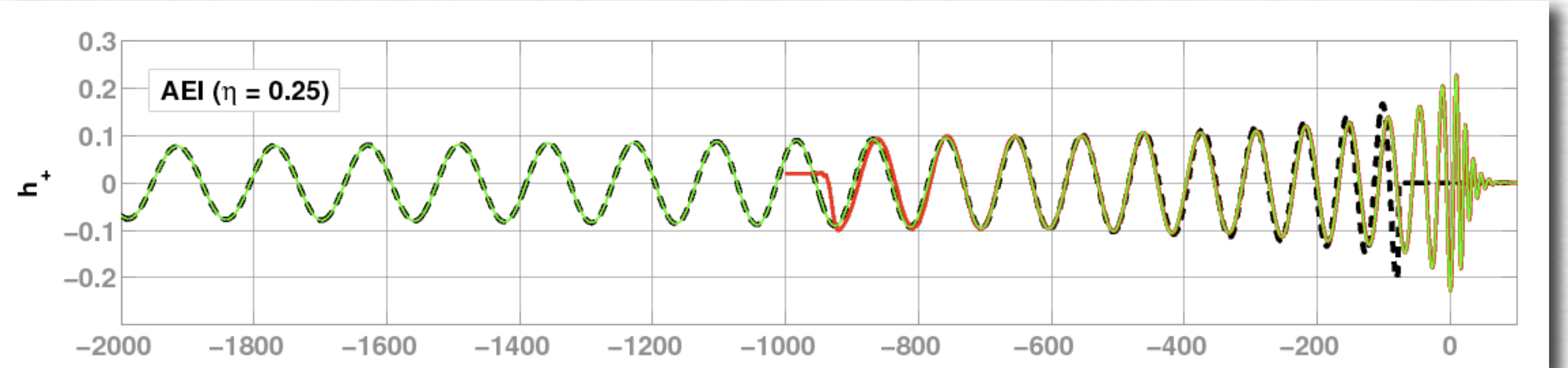

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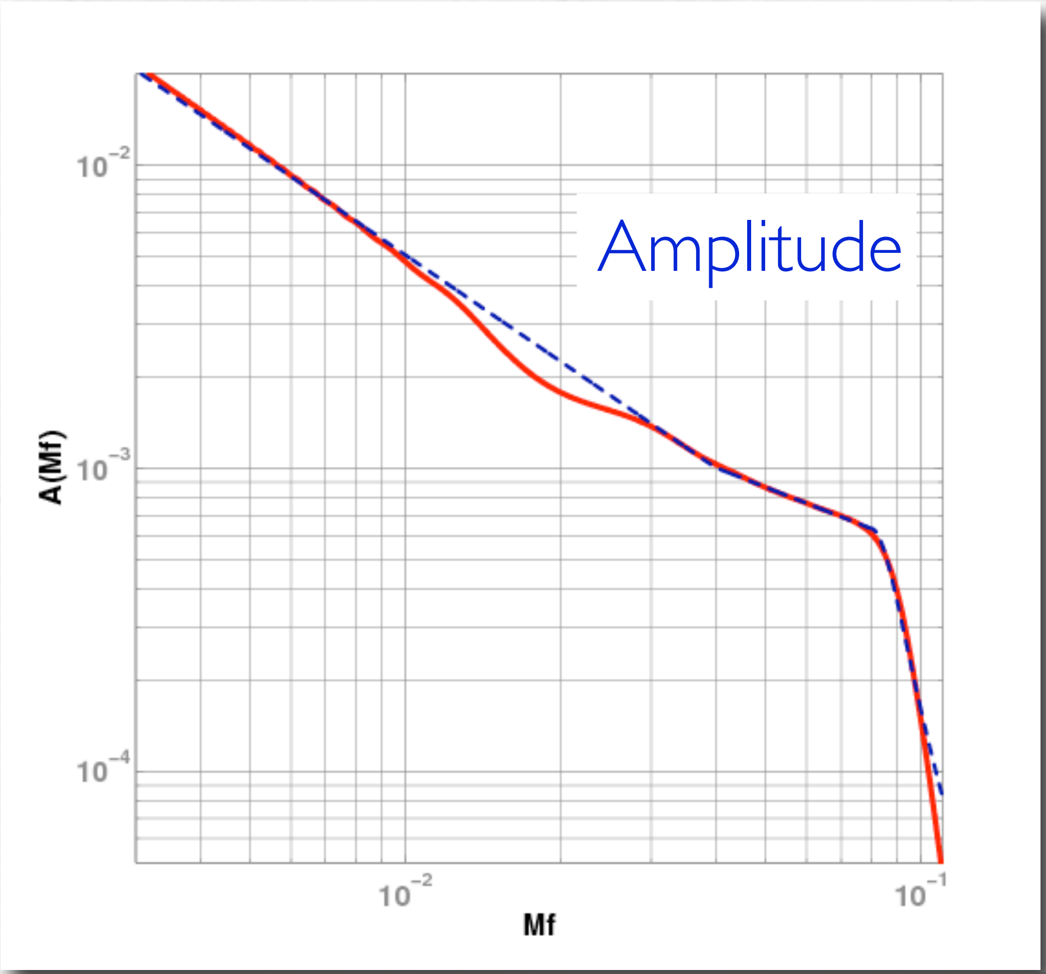
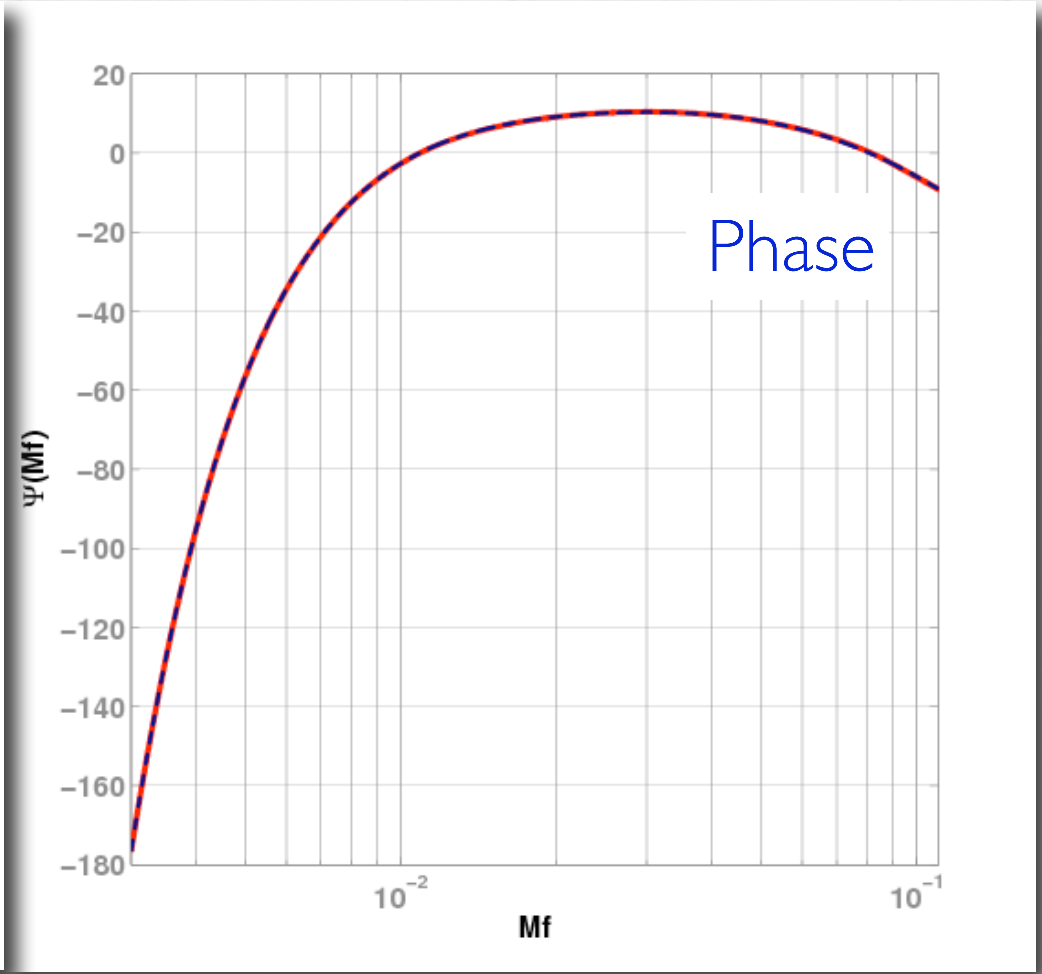
Once the hybrid waveform is computed, it can be parametrized in the Fourier domain via 10 phenomenological parameters (4 for the amplitude, 6 for the phase).

A suitable fitting procedure allows one to reduce them to the 2 physical ones: M mass of the binary and the symmetric mass-ratio ν

Solid lines are hybrid waveforms

Dashed lines are phenomenological waveforms

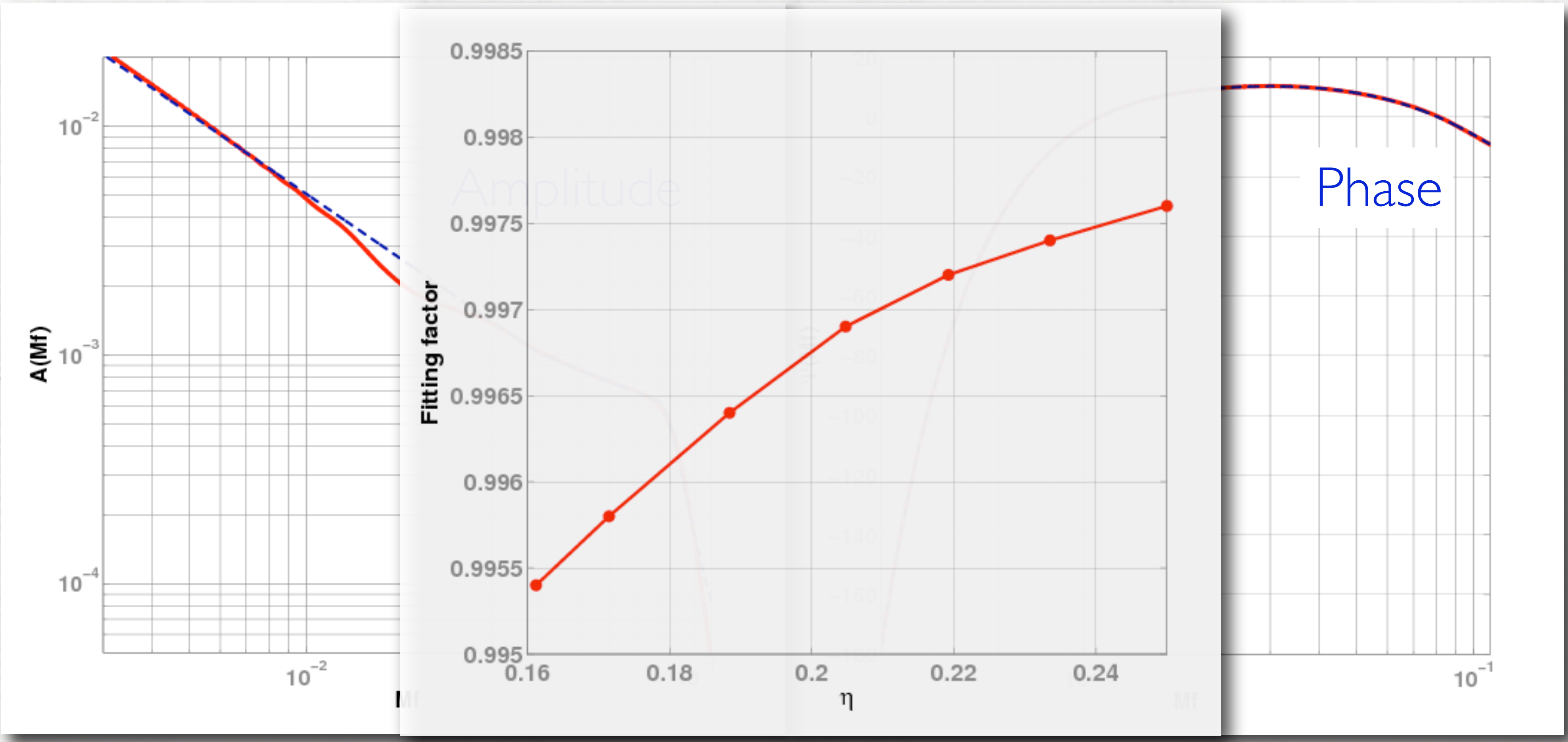




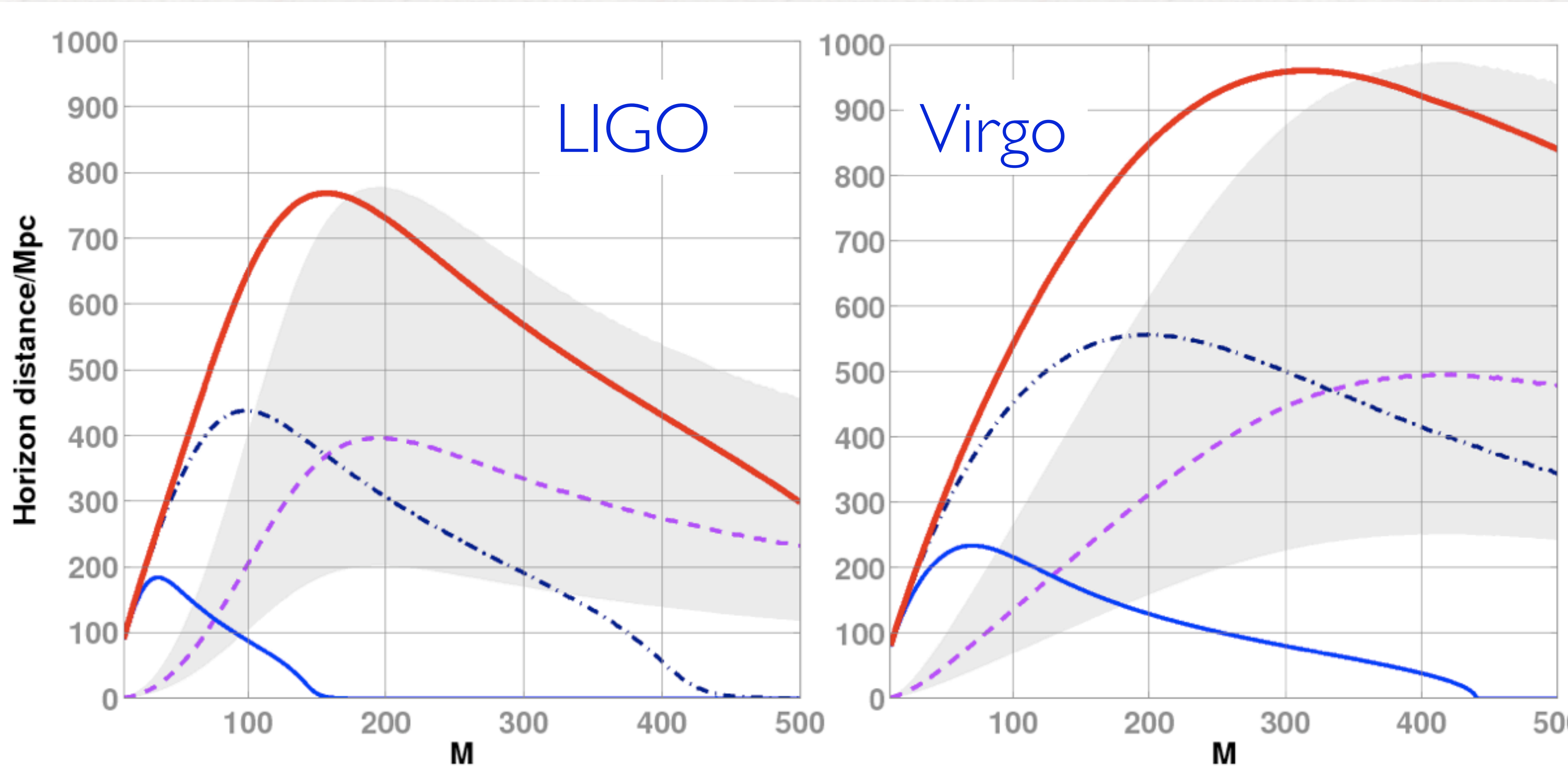
Solid lines are hybrid waveforms

Dashed lines are phenomenological waveforms

Fitting Factor: measures deviations between two waveforms; should be larger than 97%; here is > 99%



What is this good for?



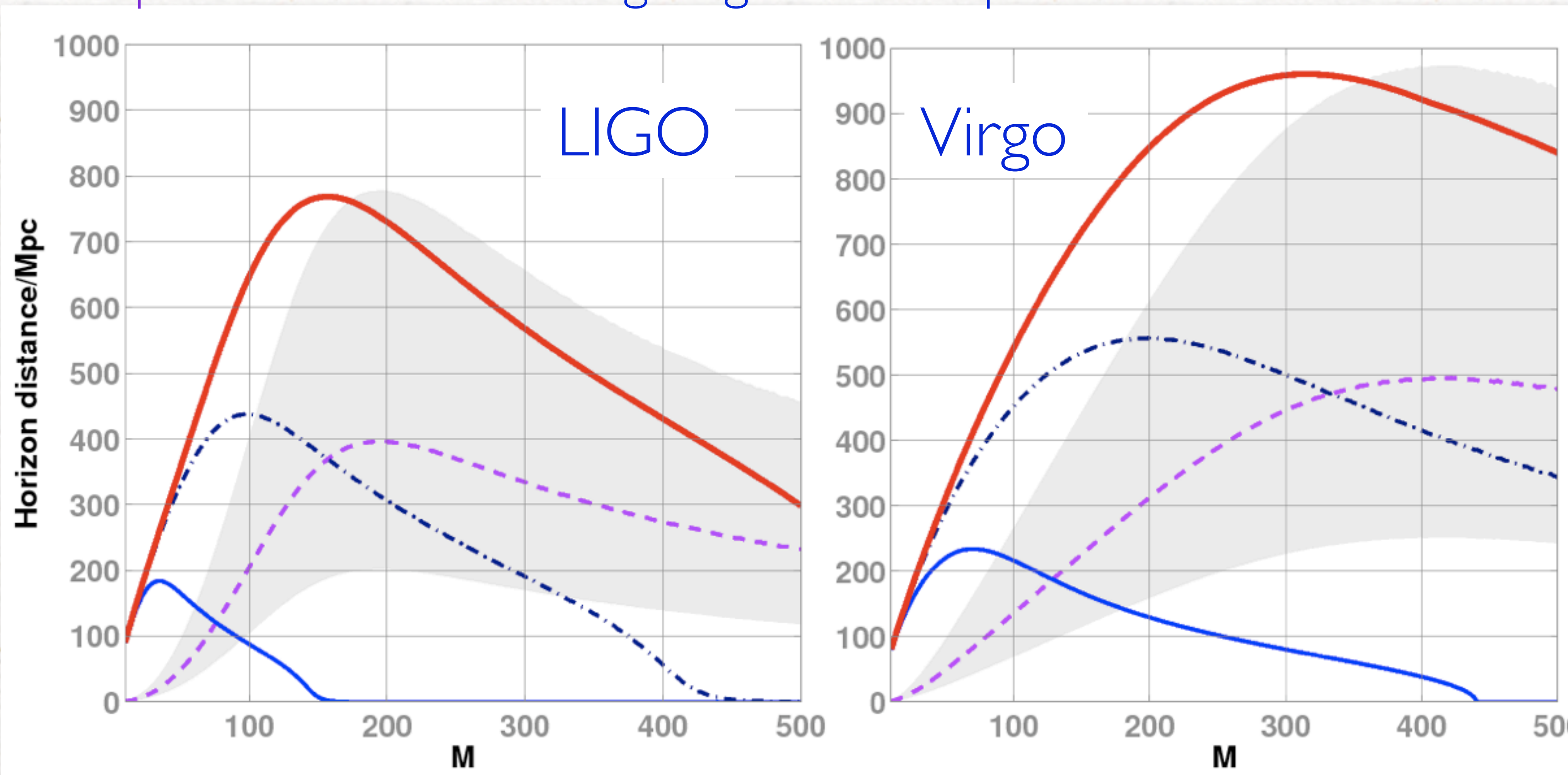
What is this good for?

Red line is the complete (inspiral, merger, ringdown) template

Blue line is the PN template truncated at ISCO

Black dot-dashed line is EOB template truncated at light-ring

Purple dashed line is using ringdown templates



SNR for equal-mass **spinning** binaries

Given a precise portion of the space of parameters (e.g. equal-mass, aligned spinning binaries) it is possible to compute generic SNRs by "stitching" PN, and NR waveforms.

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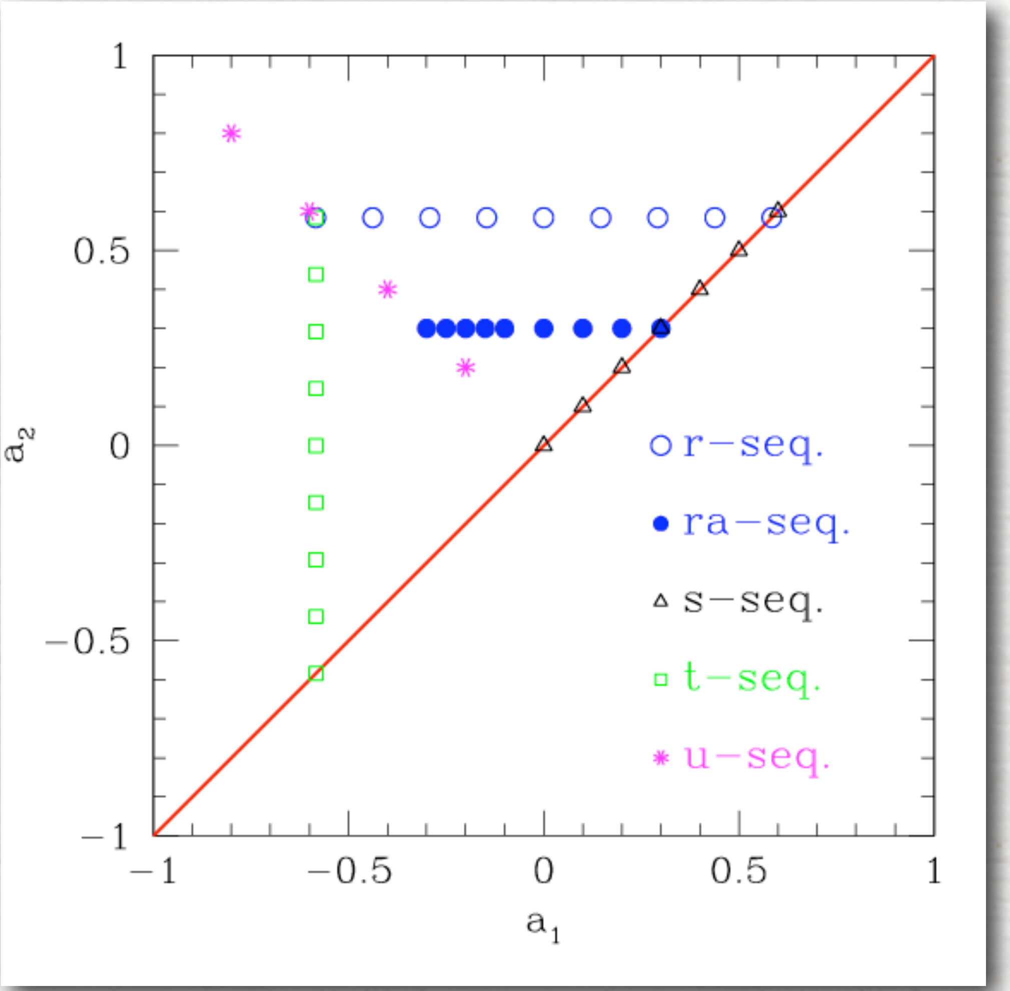

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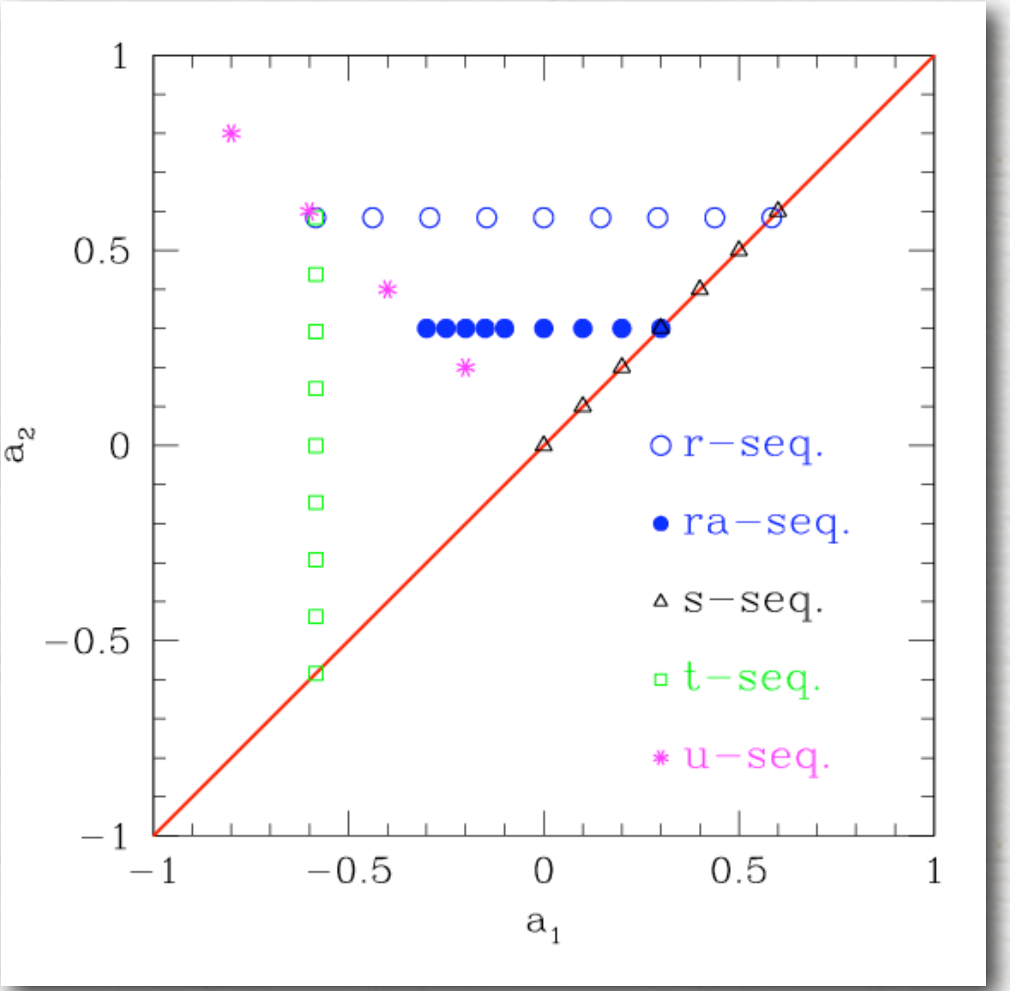
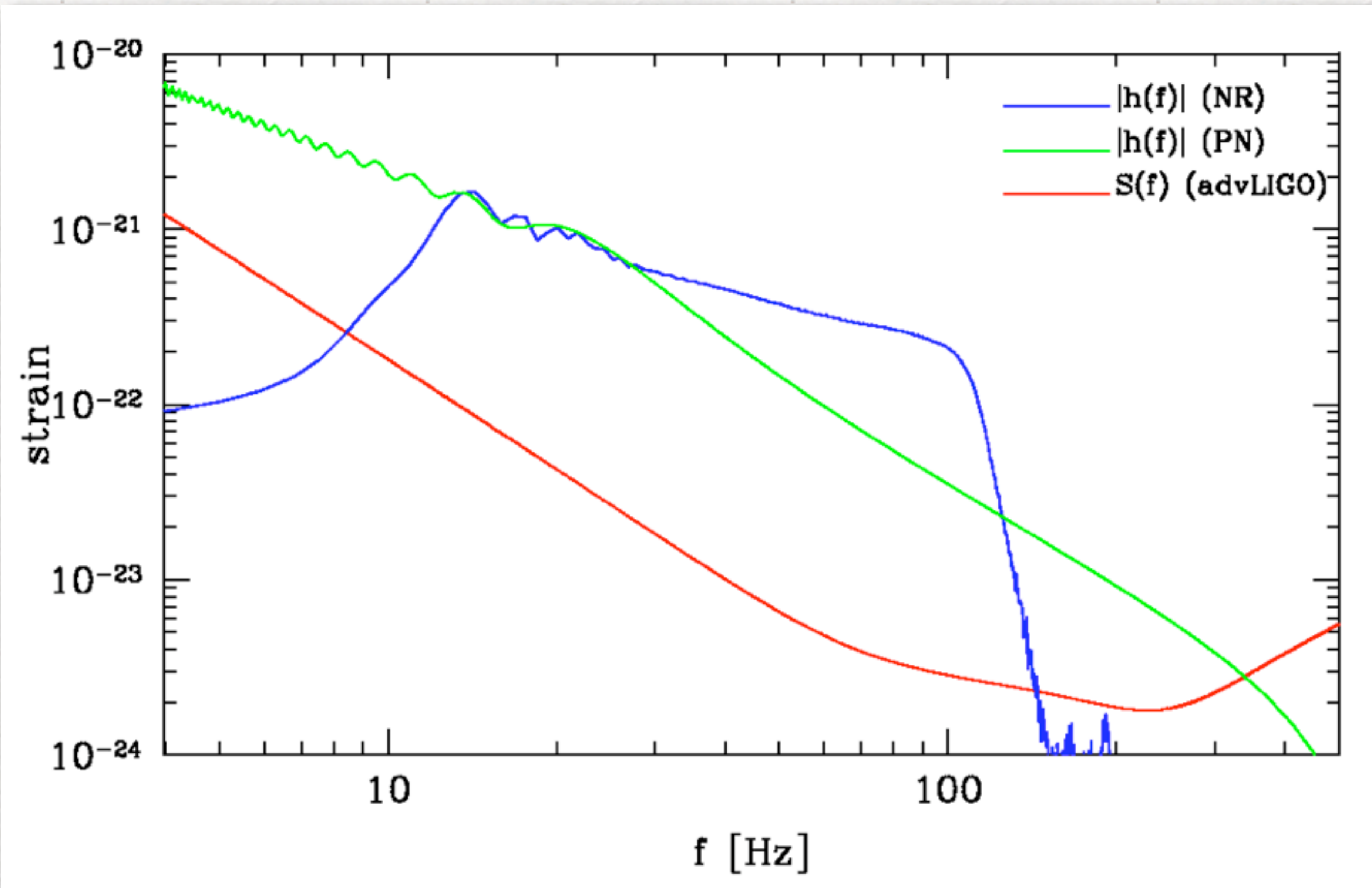


In practice, we cover the "spin diagram" with suitably chosen sequences and evaluate the SNR for different detectors and different masses.

Particularly relevant is the SW-NE diagonal: $a_1 = a_2$ and thus spanning the case of accelerated inspiral $a_1 = a_2 < 0$ and of decelerated inspiral ("hang-up") $a_1 = a_2 > 0$

The "stitching" is made in frequency space and at a precise "glueing" frequency. Proper windowing removes additional high-and low-frequency artifacts from the NR waveform.



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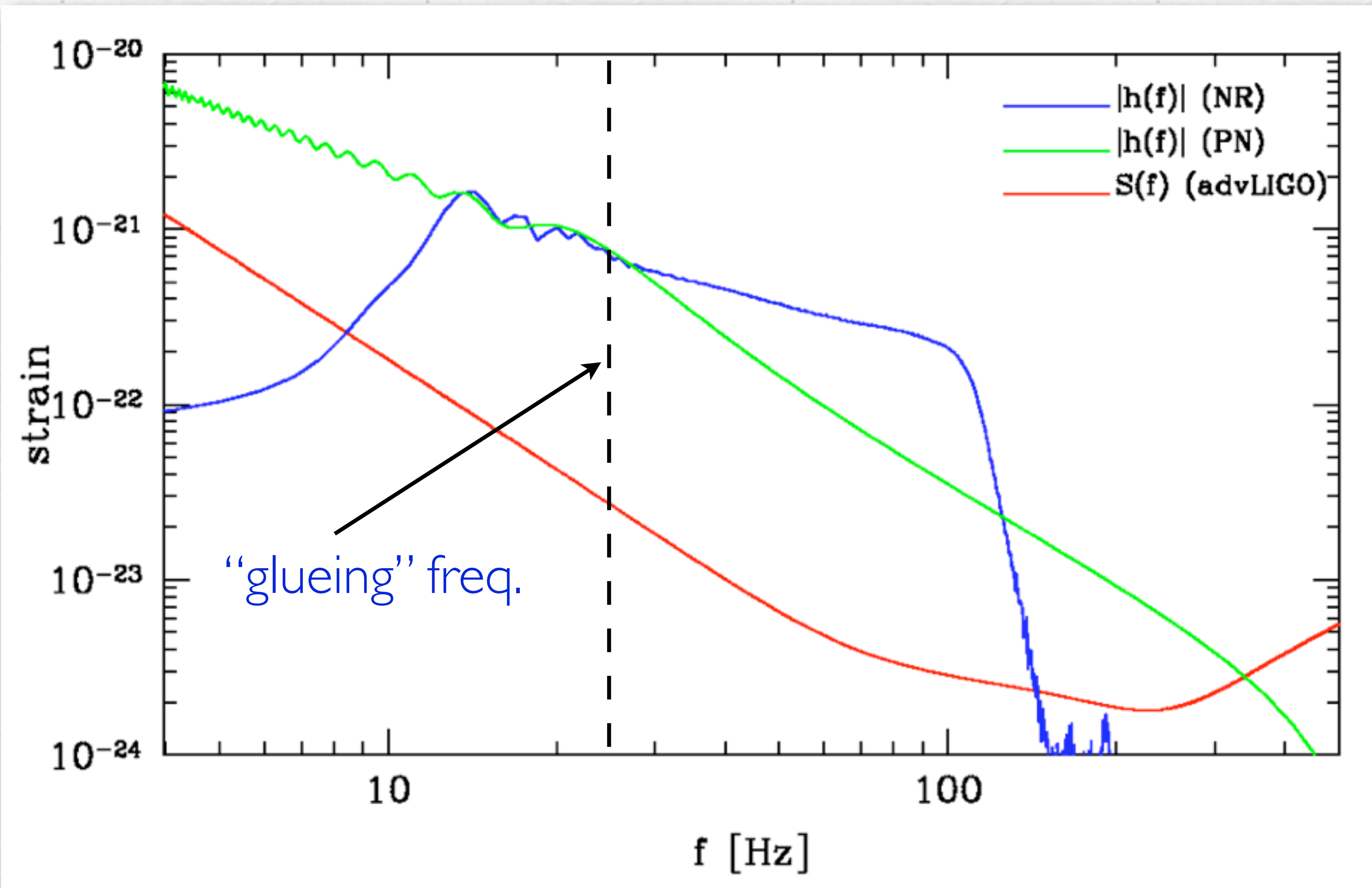
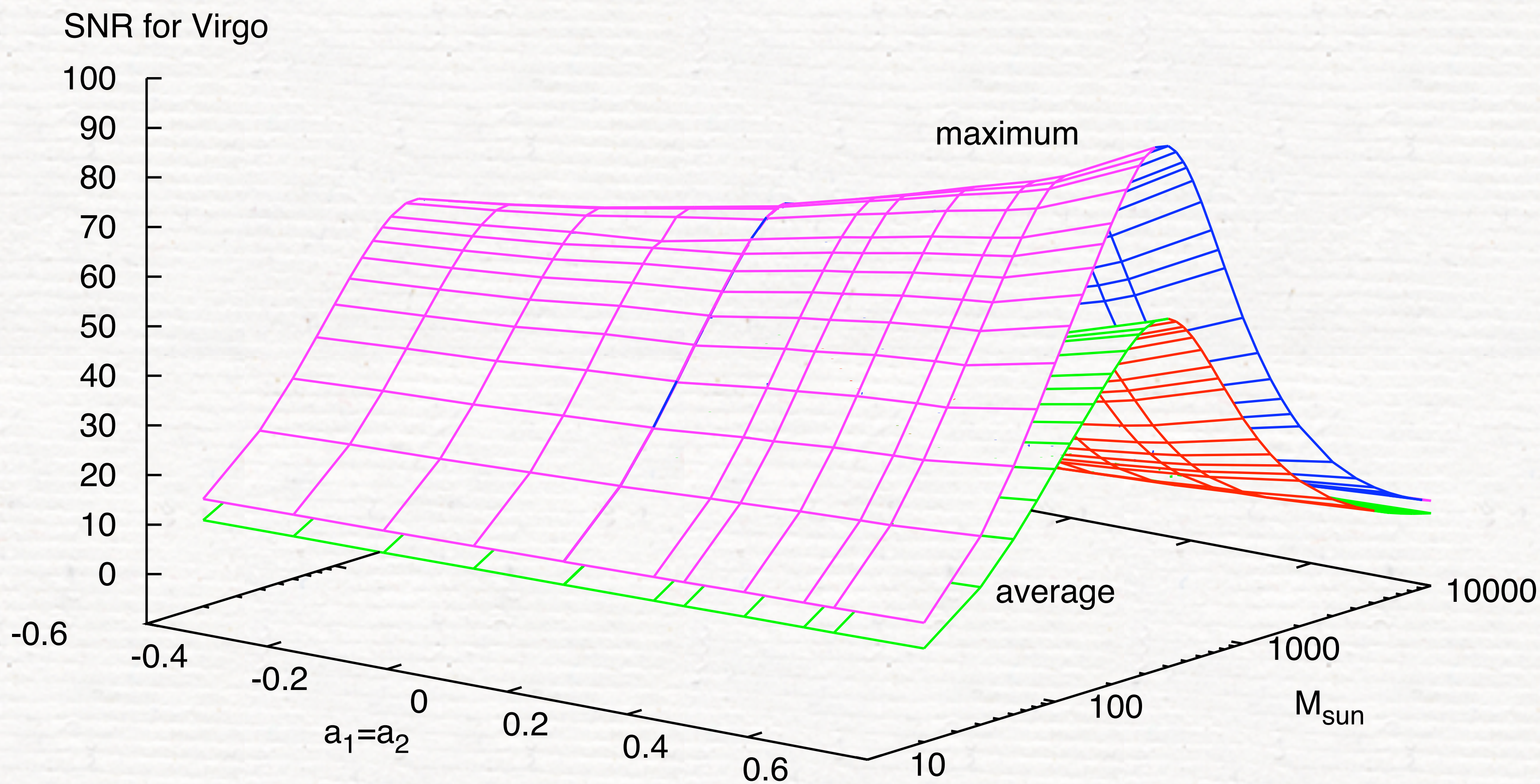


The end result can be shown as a function of the initial spins and masses for each detector



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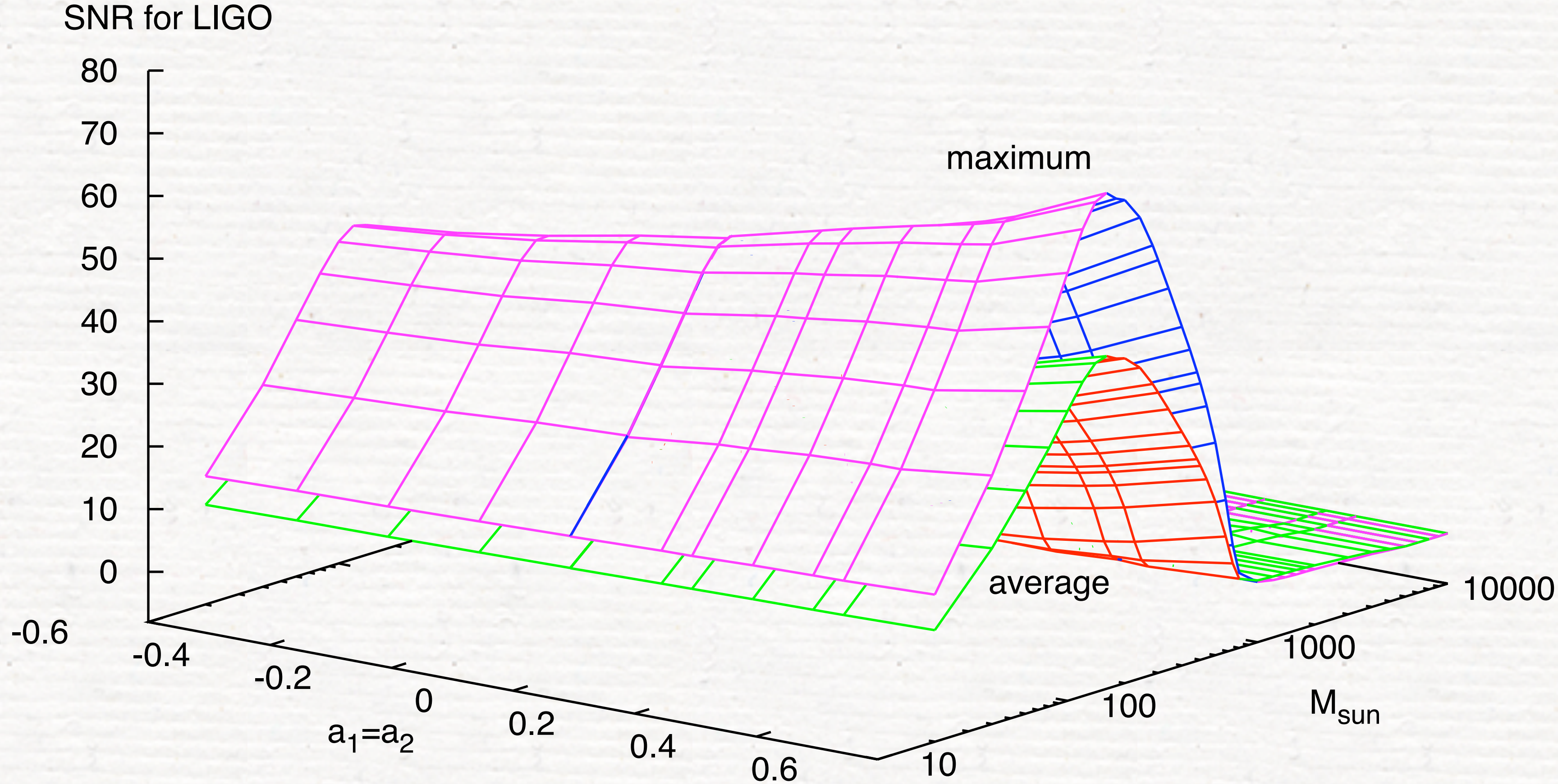

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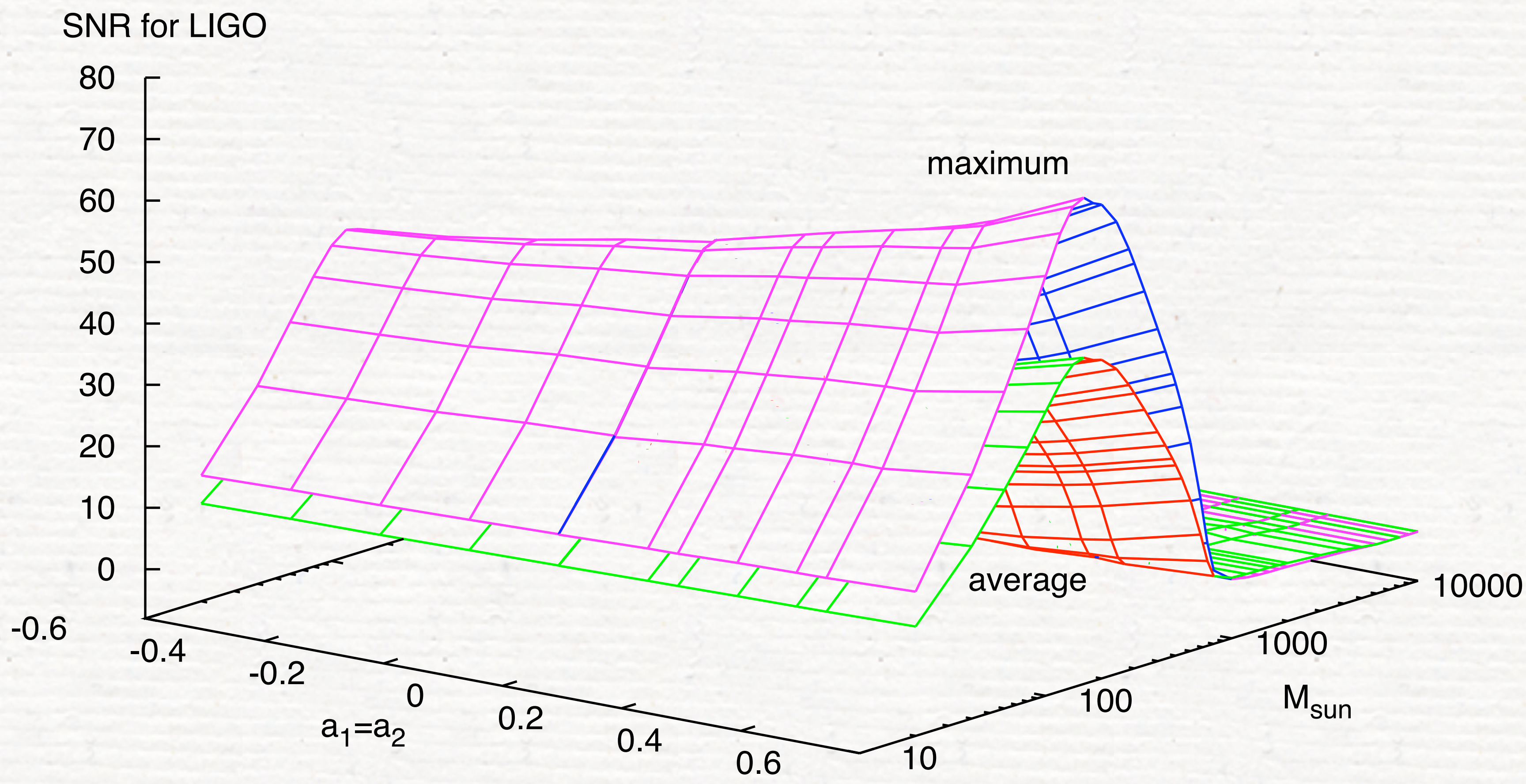
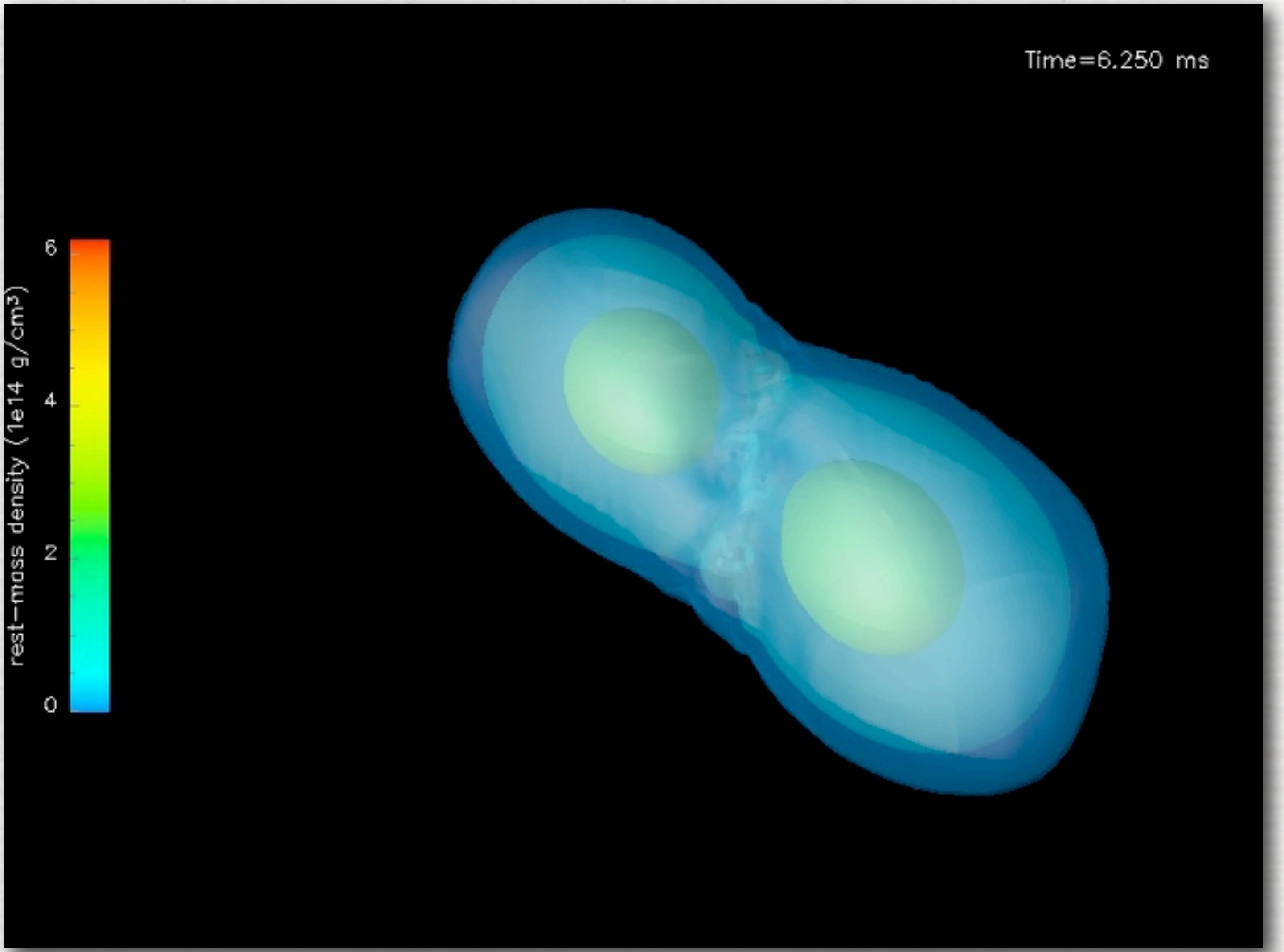


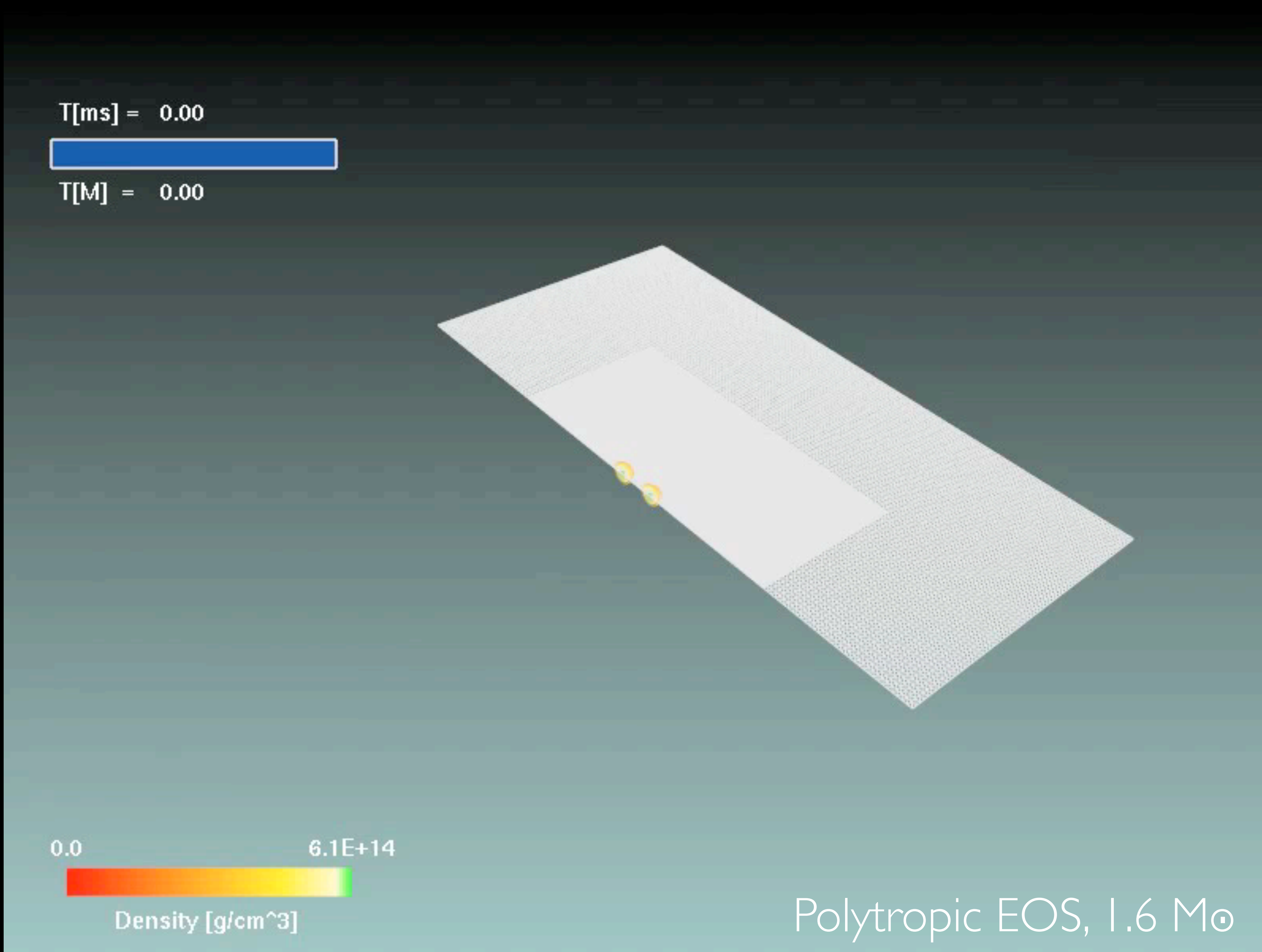
Overall, large aligned spins $a_1 = a_2 \sim 1$ have a SNR which is twice as large as the antialigned spins $a_1 = a_2 \sim -1$. The explanation is obvious: ~ four times the number of cycles

Modelling binary neutron stars

Baiotti, et al. 2008, PRD



Polytropic EOS, 1.6 $M_\odot$



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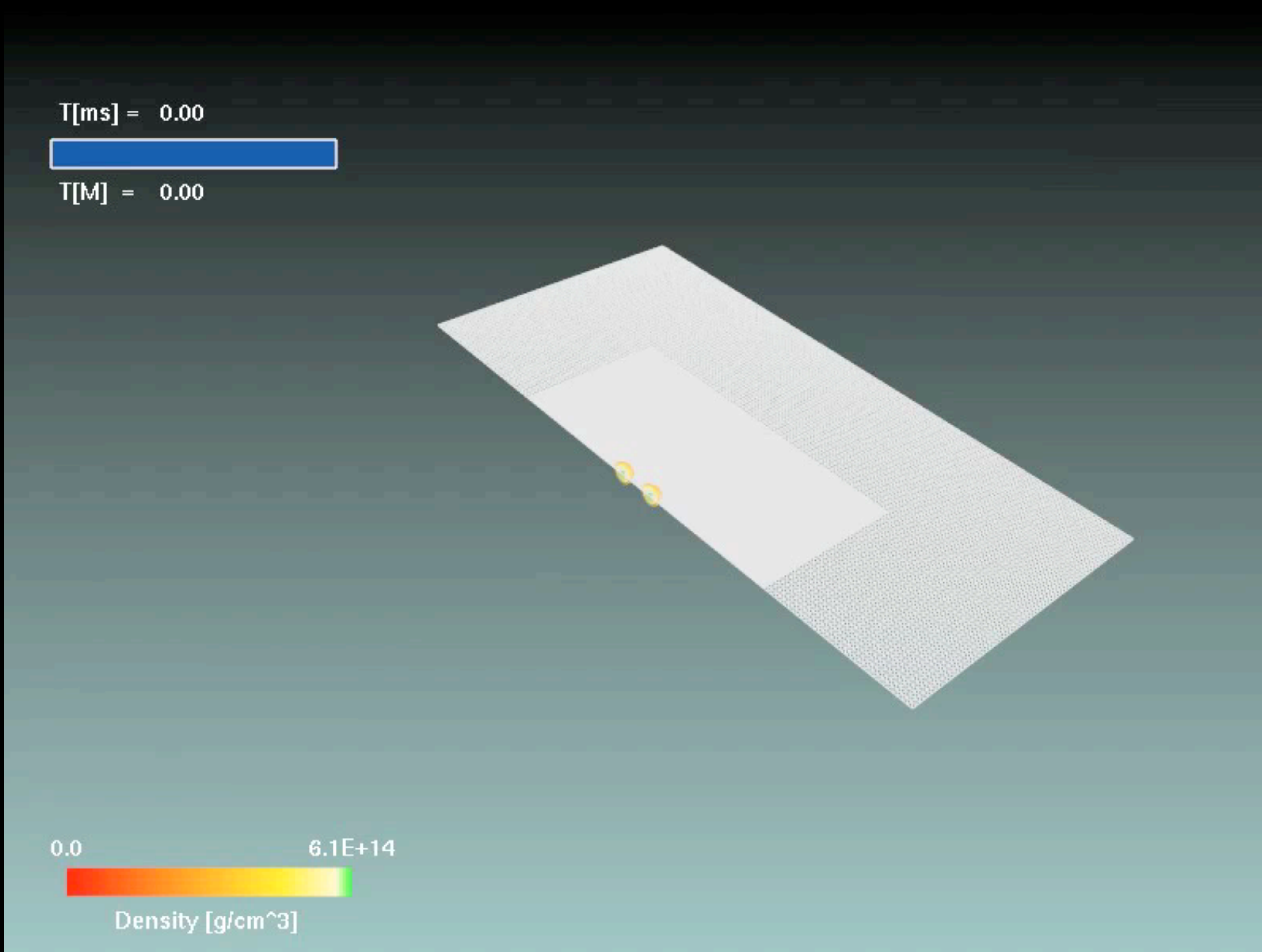
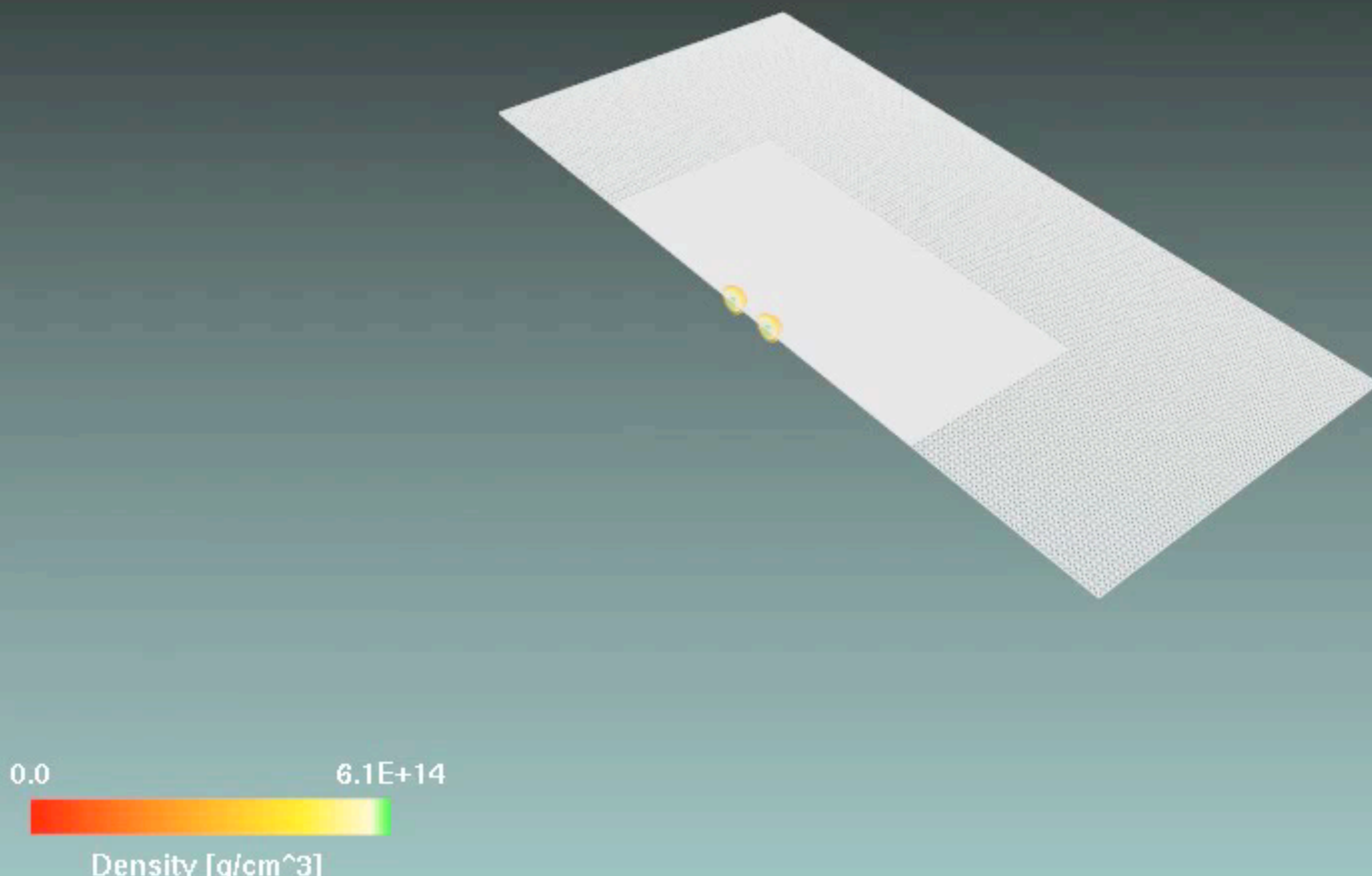
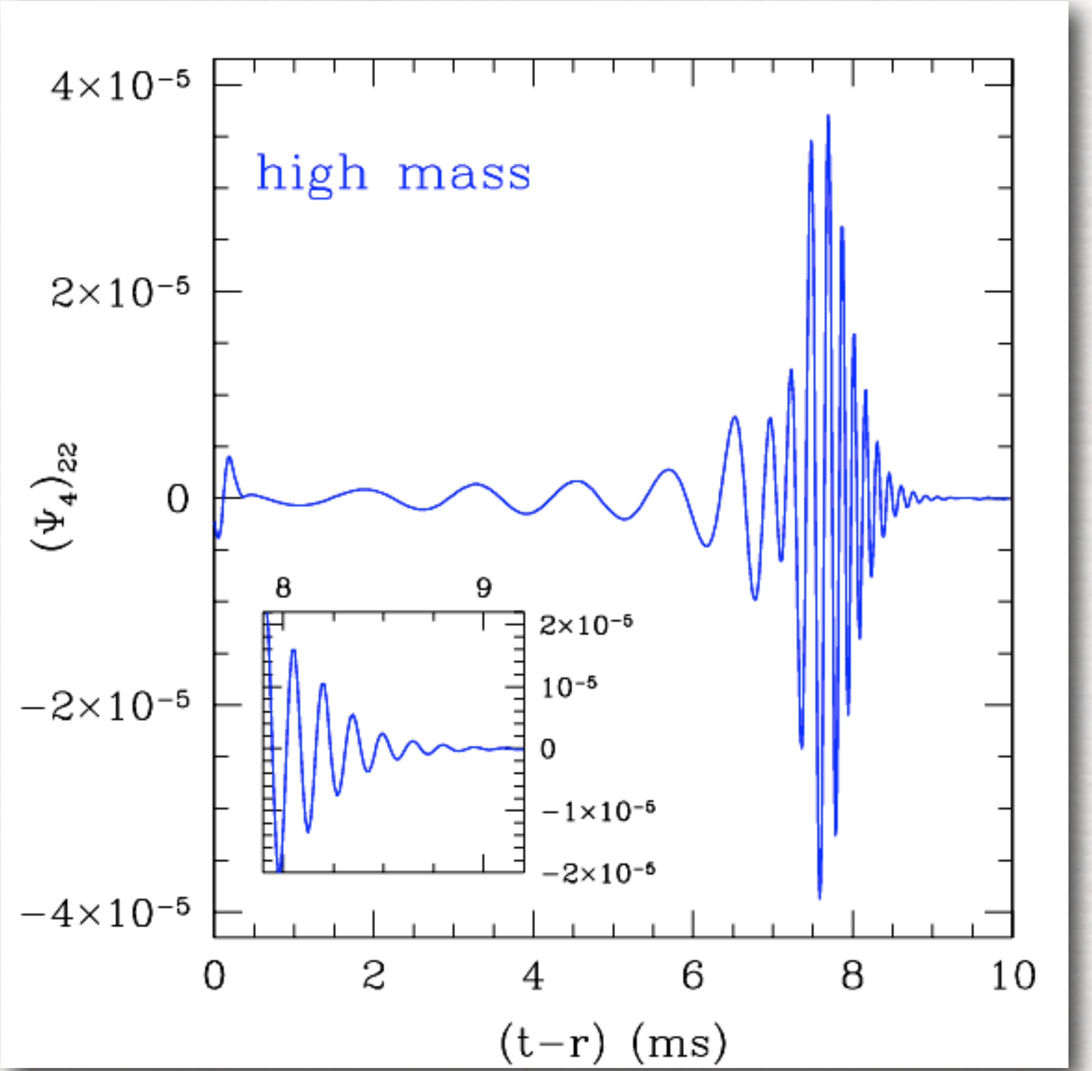

T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]

A hot, low-density torus is produced orbiting around the bh. This is what expected in short GRBs.



Waveforms: polytropic EOS

high-mass binary



first time the full signal from the formation to a bh has been computed

Waveforms: polytropic EOS

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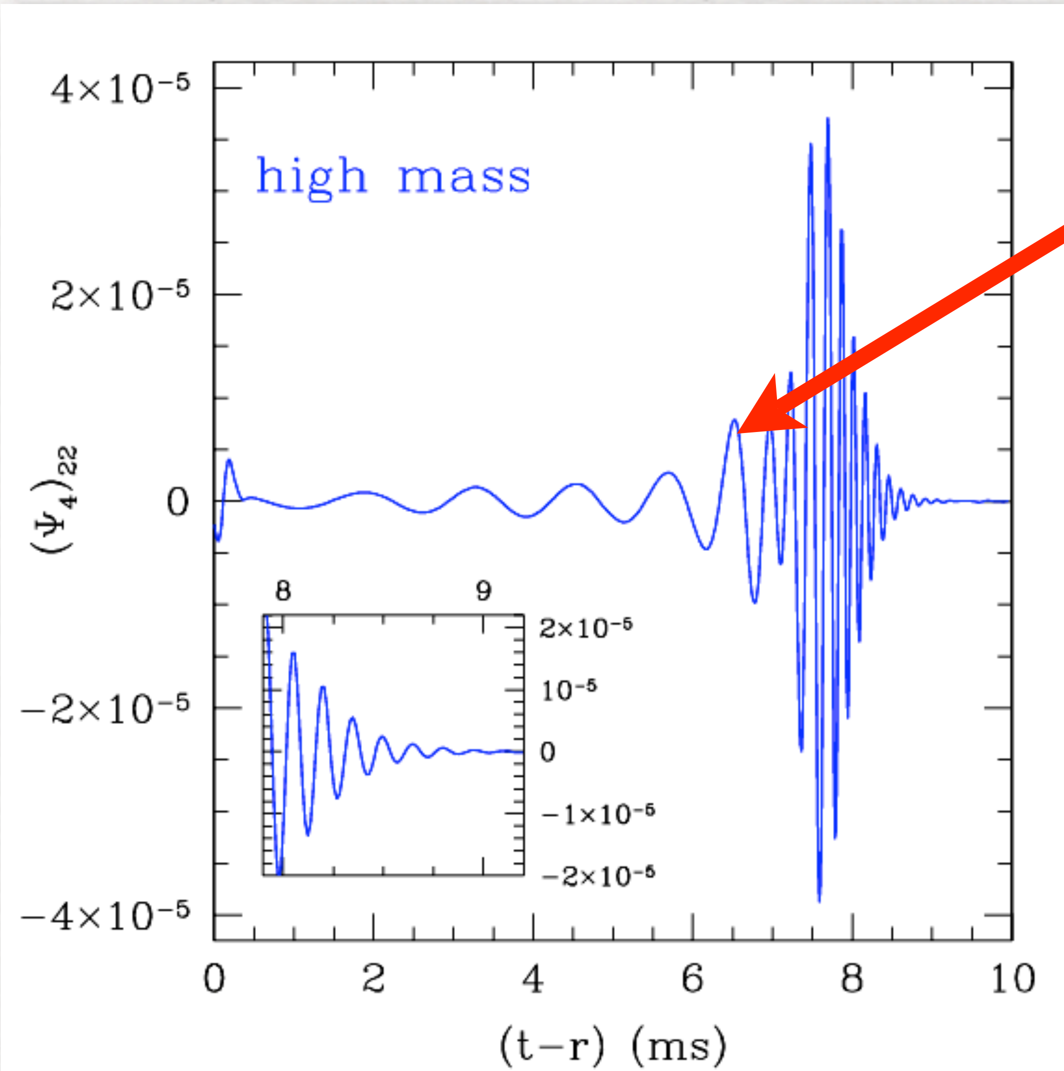

Merger

first time the full signal from the formation to a bh has been computed

Waveforms: polytropic EOS

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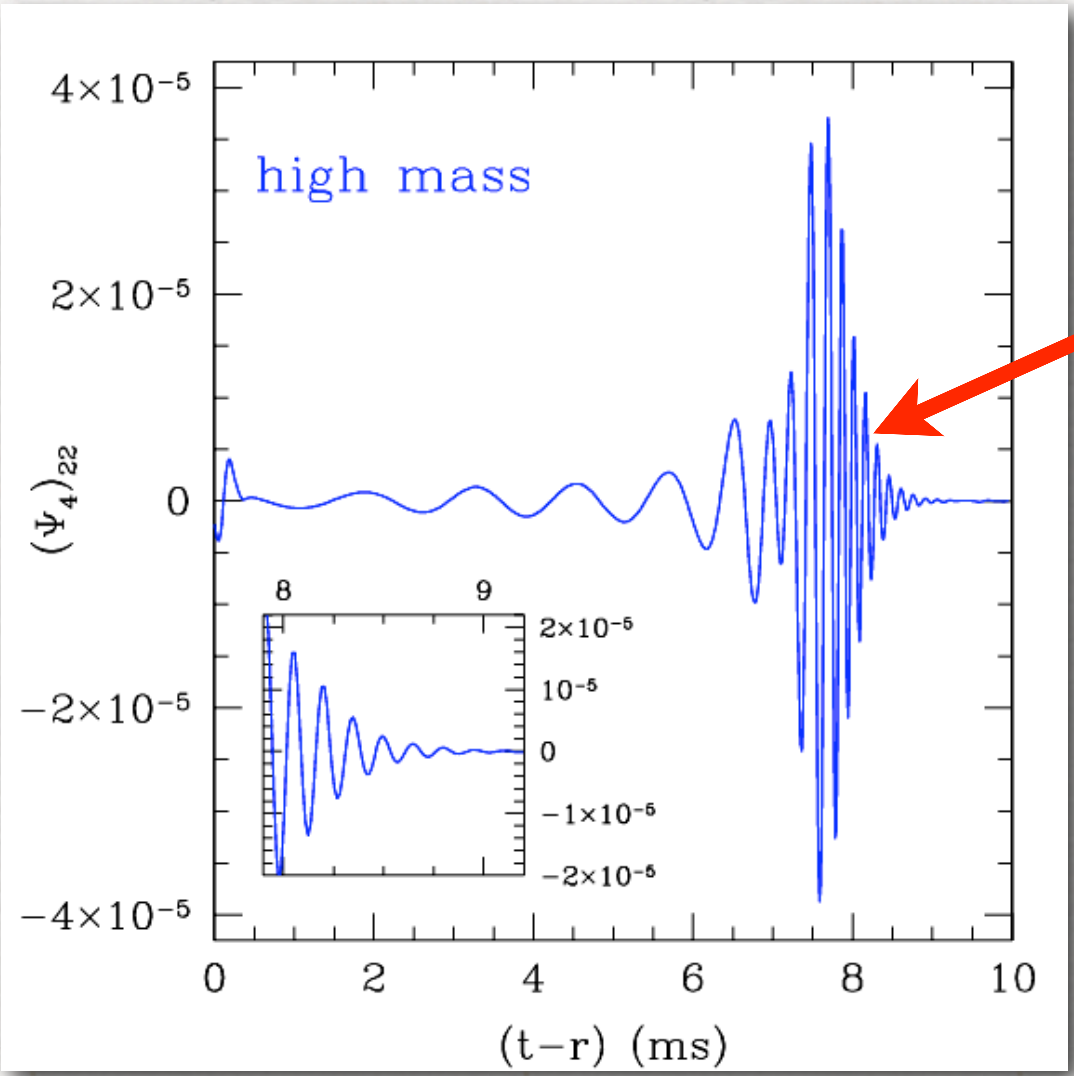

Collapse to BH

first time the full signal from the formation to a bh has been computed

The behaviour:

“merger → *HMNS* → *BH + torus”*

is general but only qualitatively

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- **differences in the mass for the same EOS:**

a binary with smaller mass will produce a HMNS which is further away from the stability threshold and will collapse at a later time

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"merger → HMNS → BH + torus"

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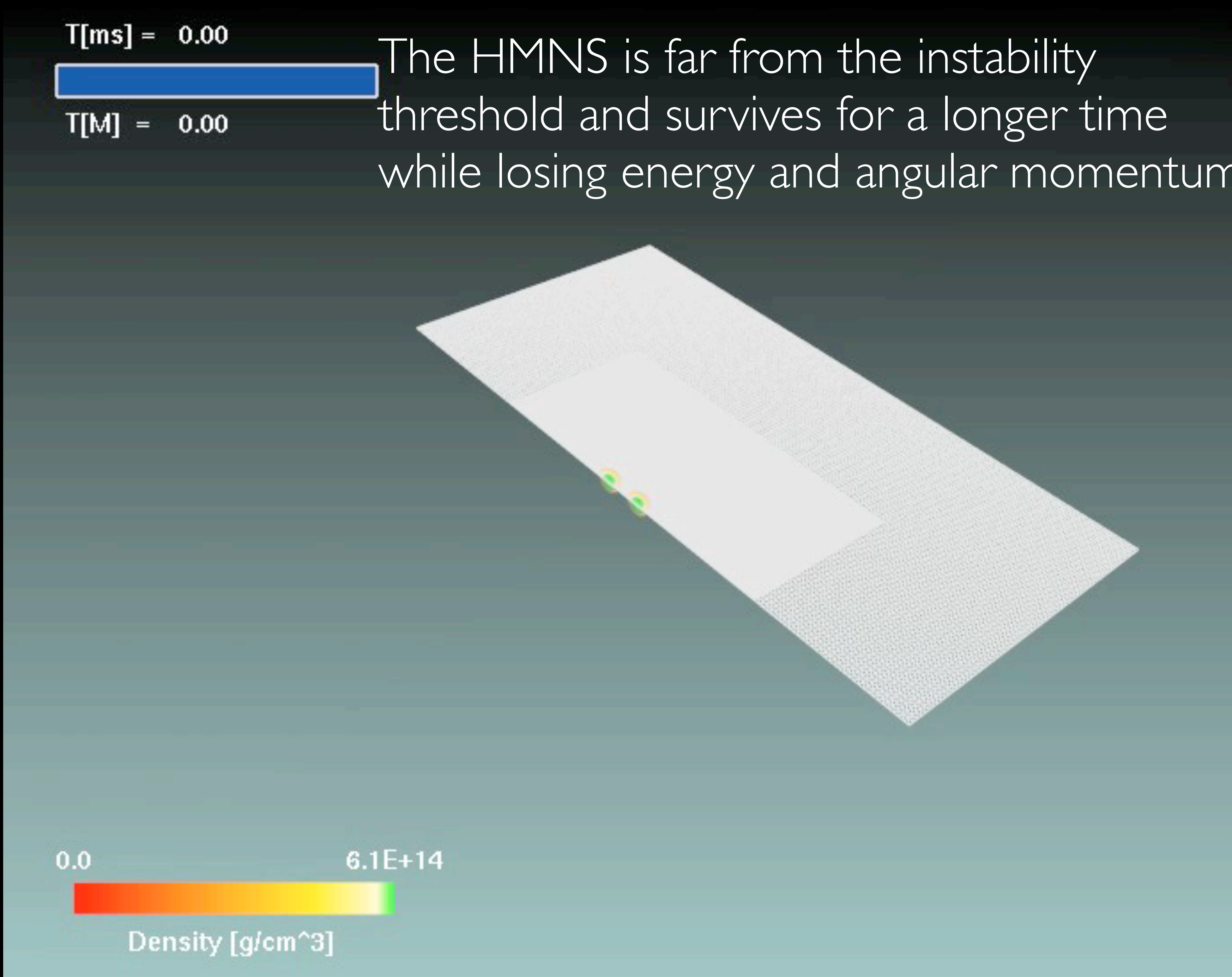
Quantitative differences are produced by:

- **differences in the mass for the same EOS:**
  a binary with smaller mass will produce a HMNS which is further away from the stability threshold and will collapse at a later time

- **differences in the EOS for the same mass:**
  a binary with an EOS allowing for a larger thermal internal energy (ie hotter after merger) will have an increased pressure support and will collapse at a later time

The HMNS is far from the instability threshold and survives for a longer time while losing energy and angular momentum



Waveforms: polytropic EOS

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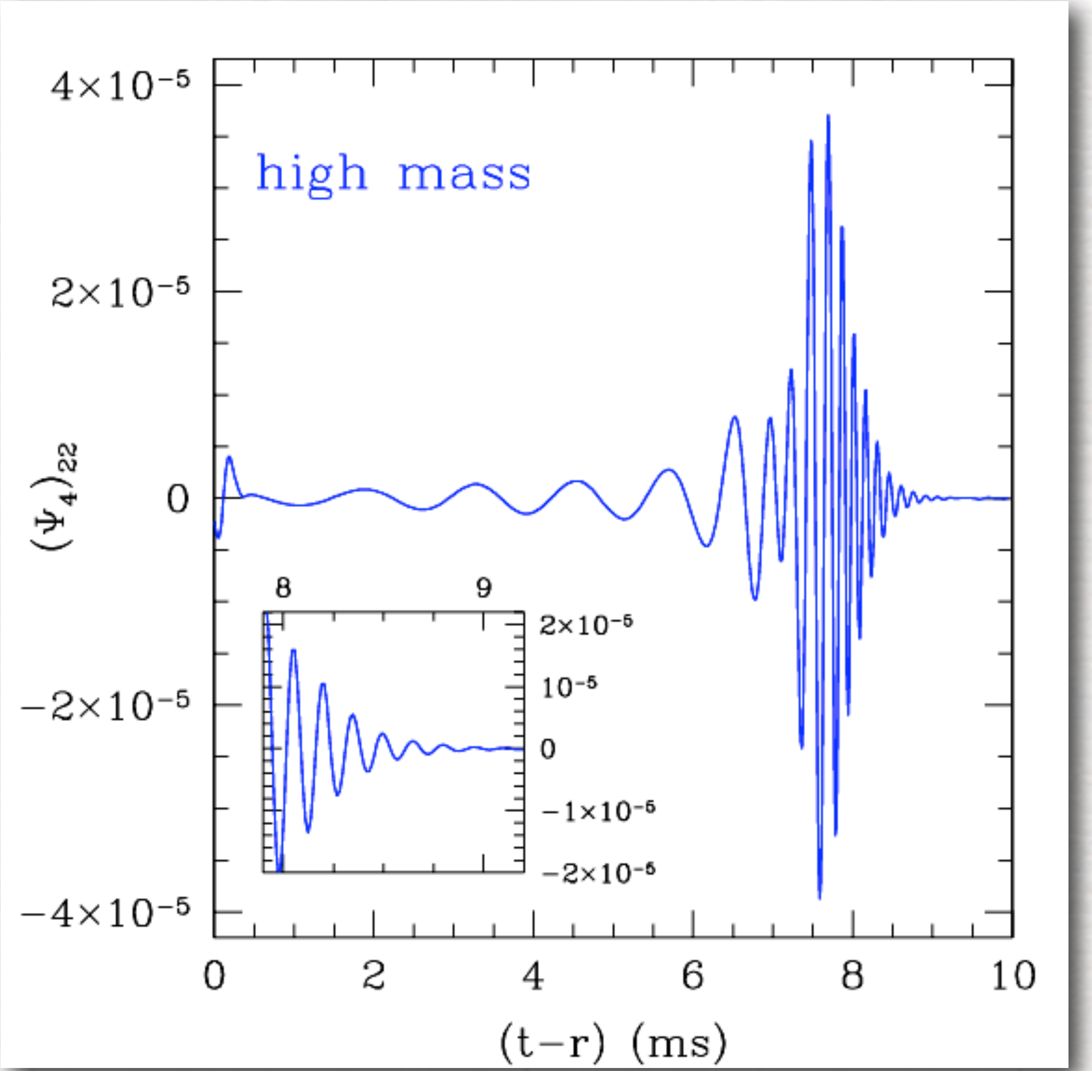

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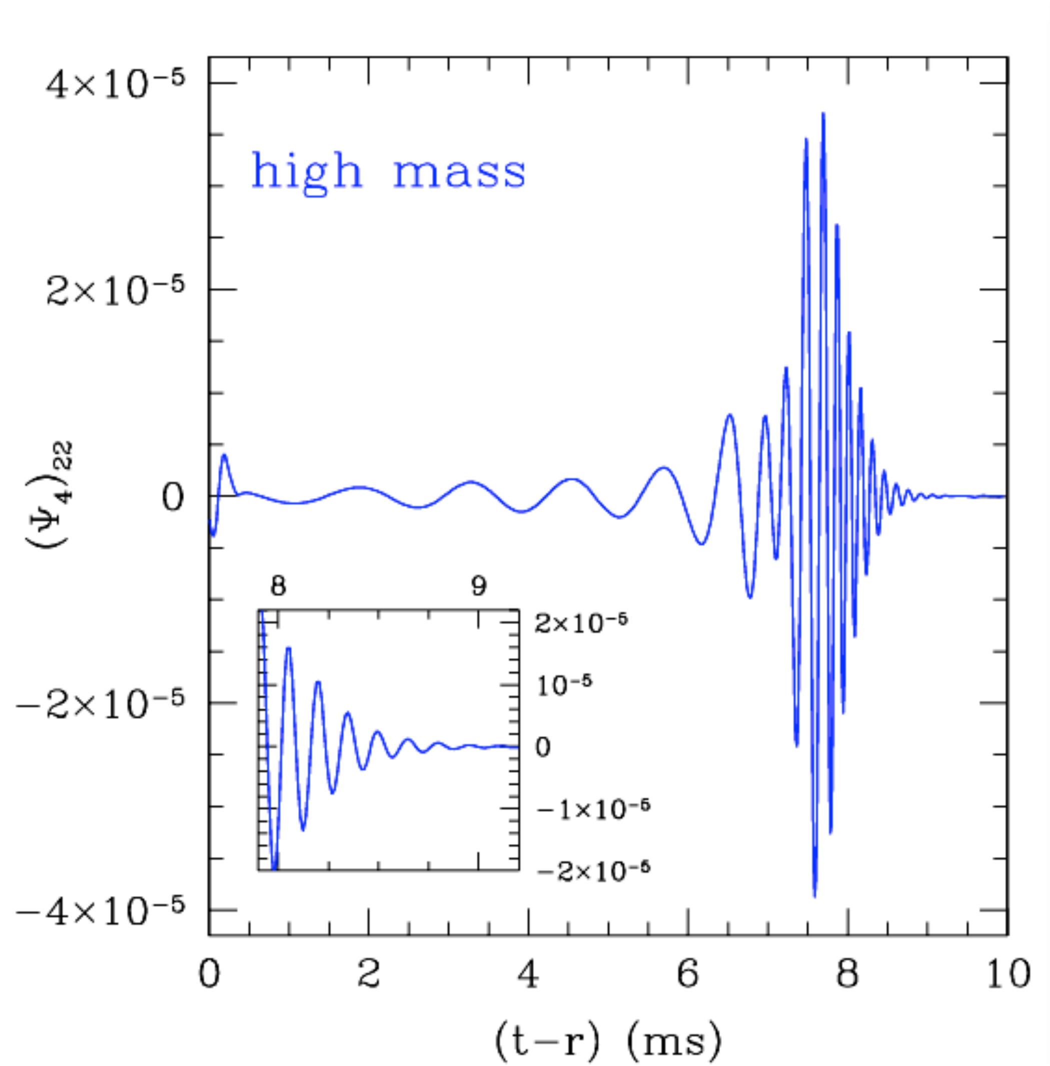
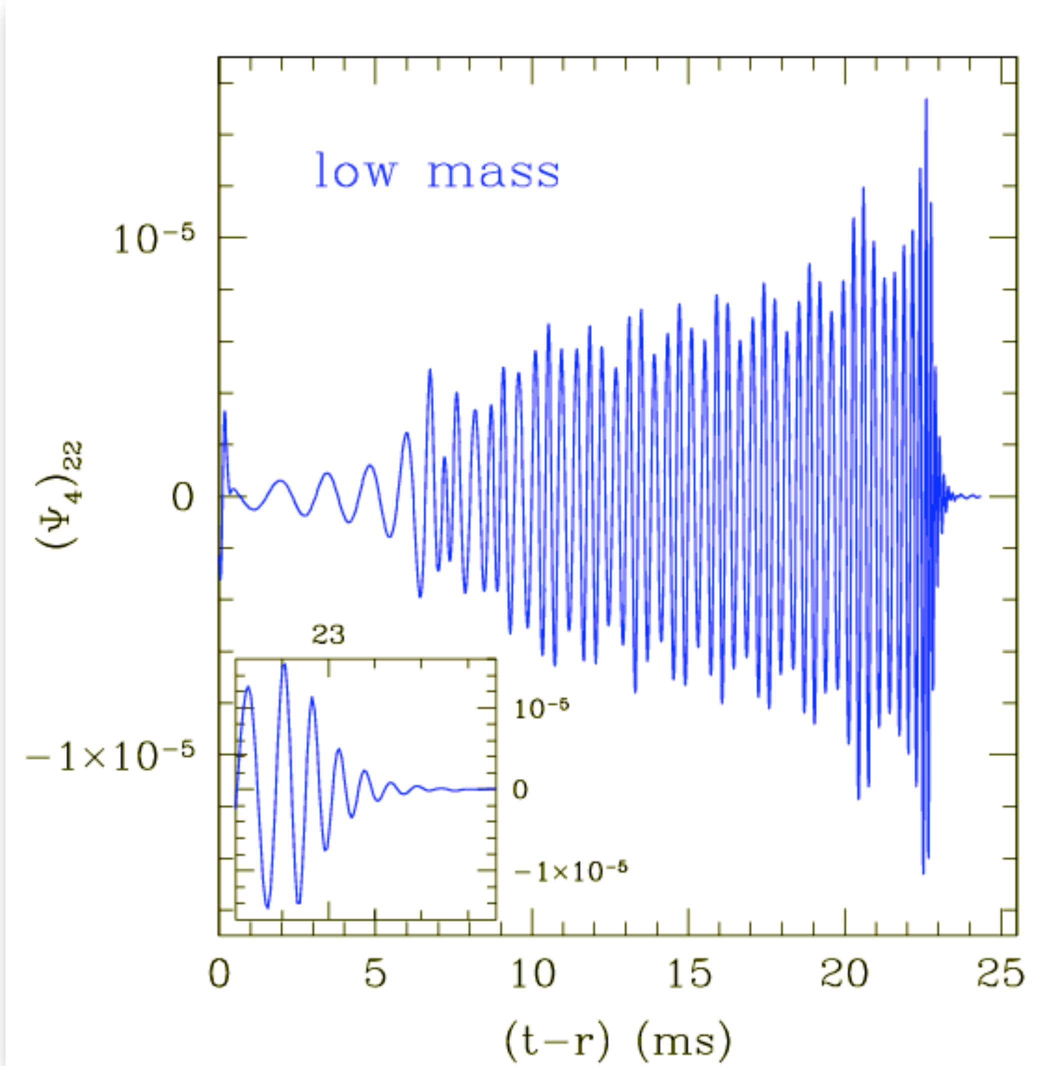


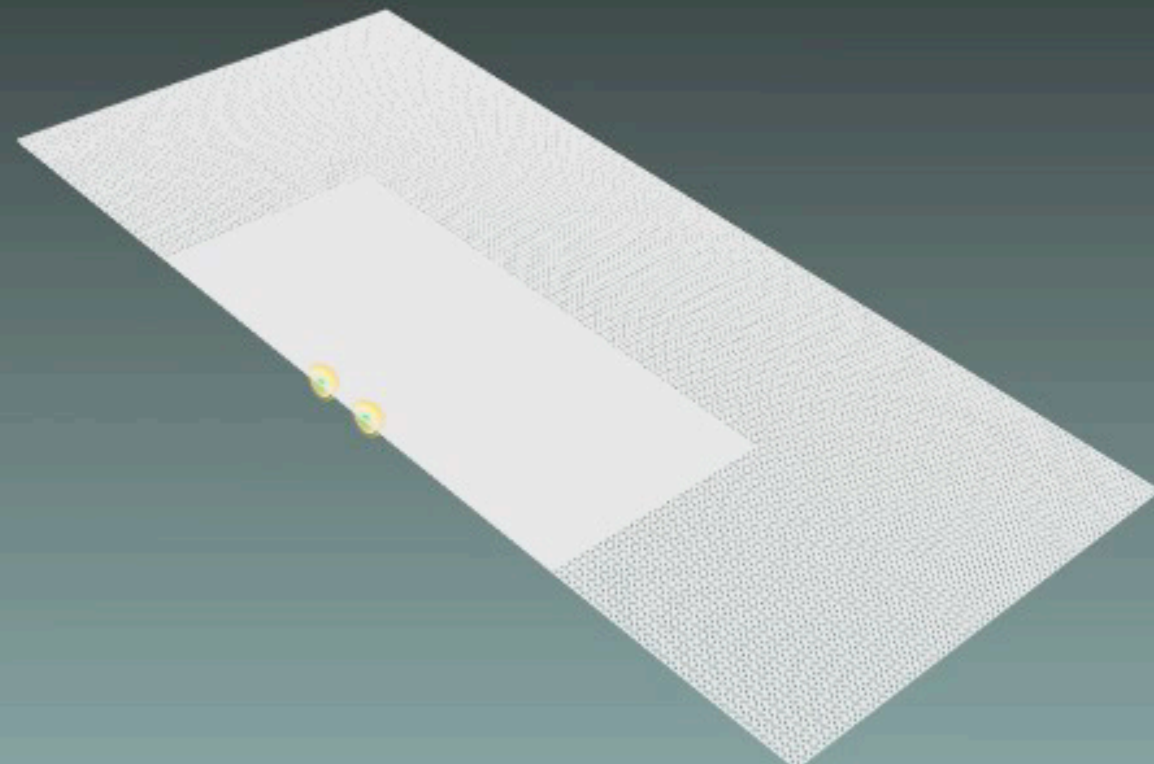
first time the full signal from the formation to a bh has been computed

low-mass binary



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

The HMNS is not close to the instability threshold and survives for a much longer time



Waveforms: ideal-fluid EOS

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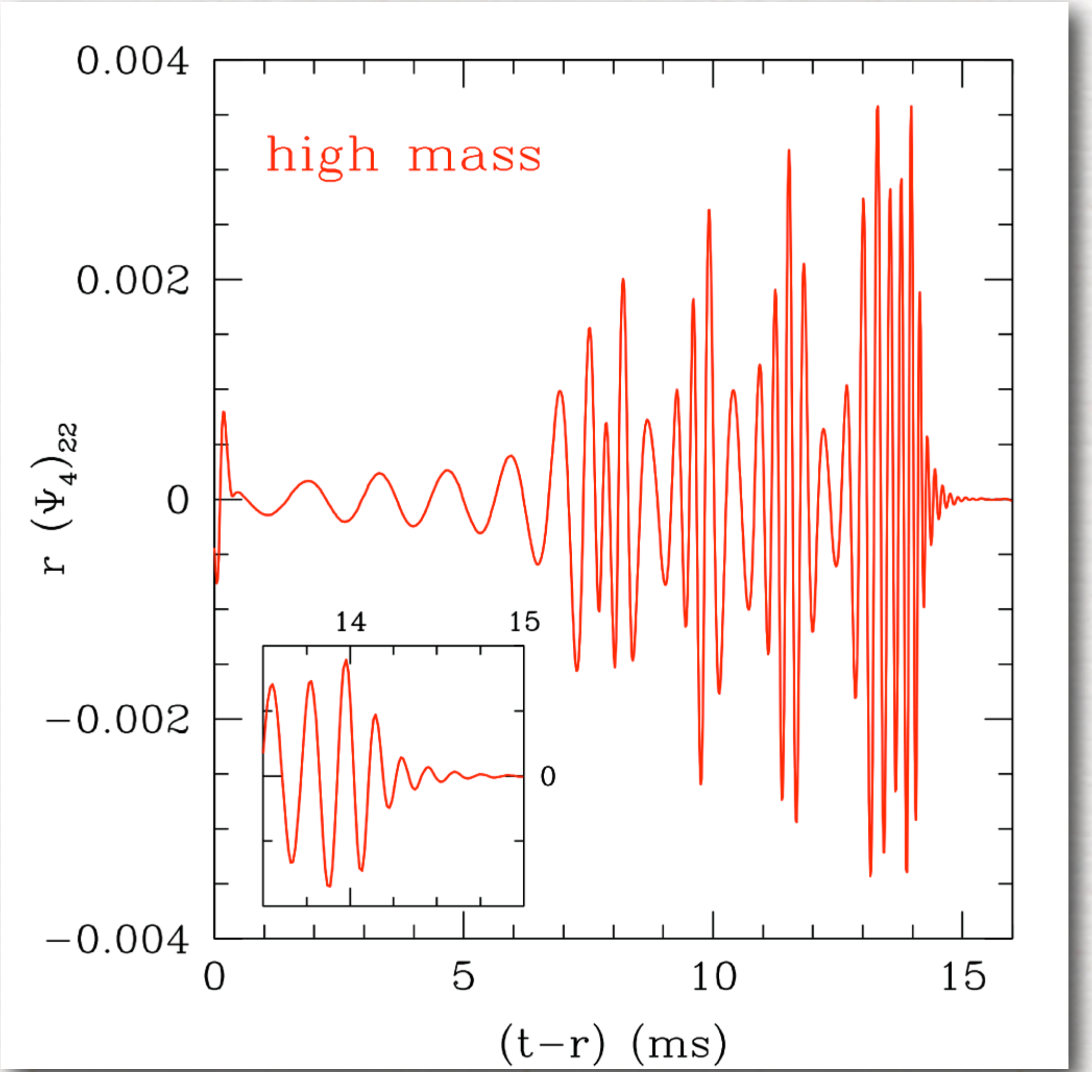
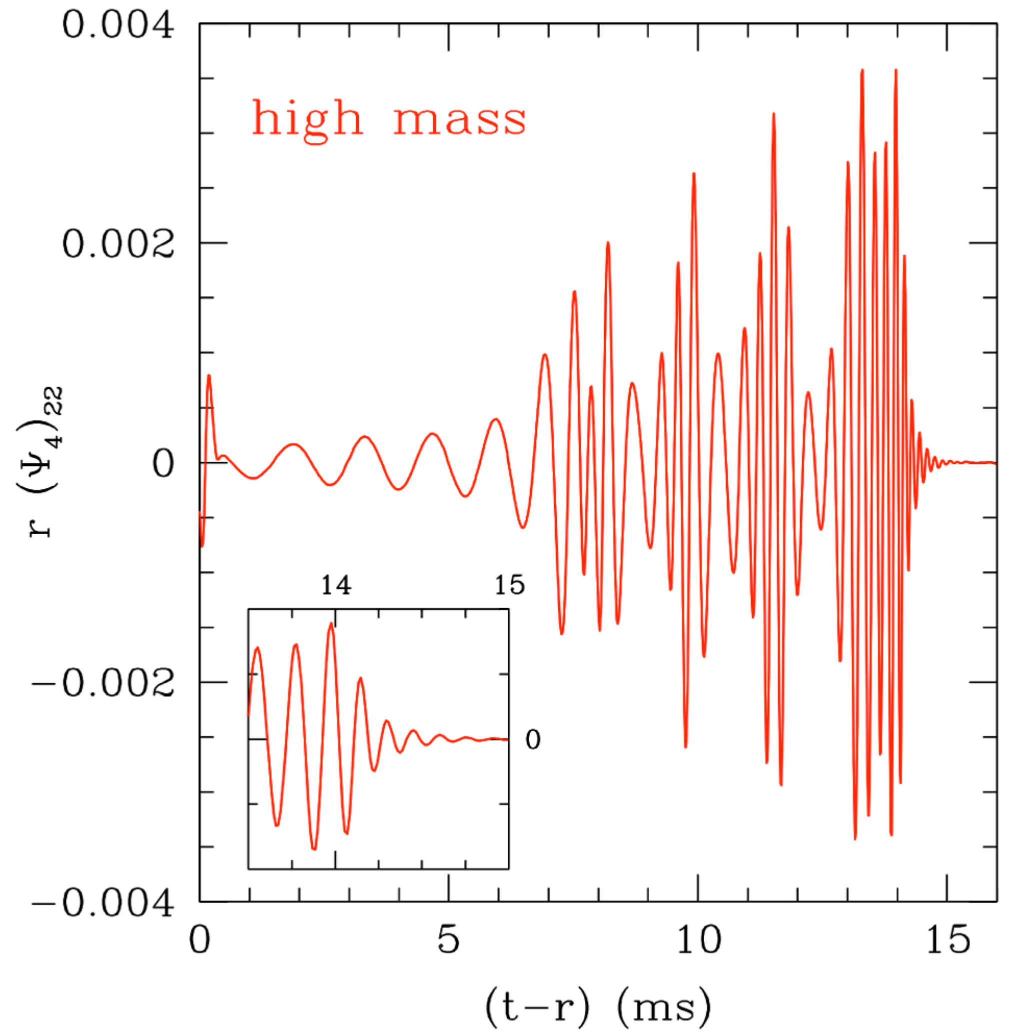
high-mass binary



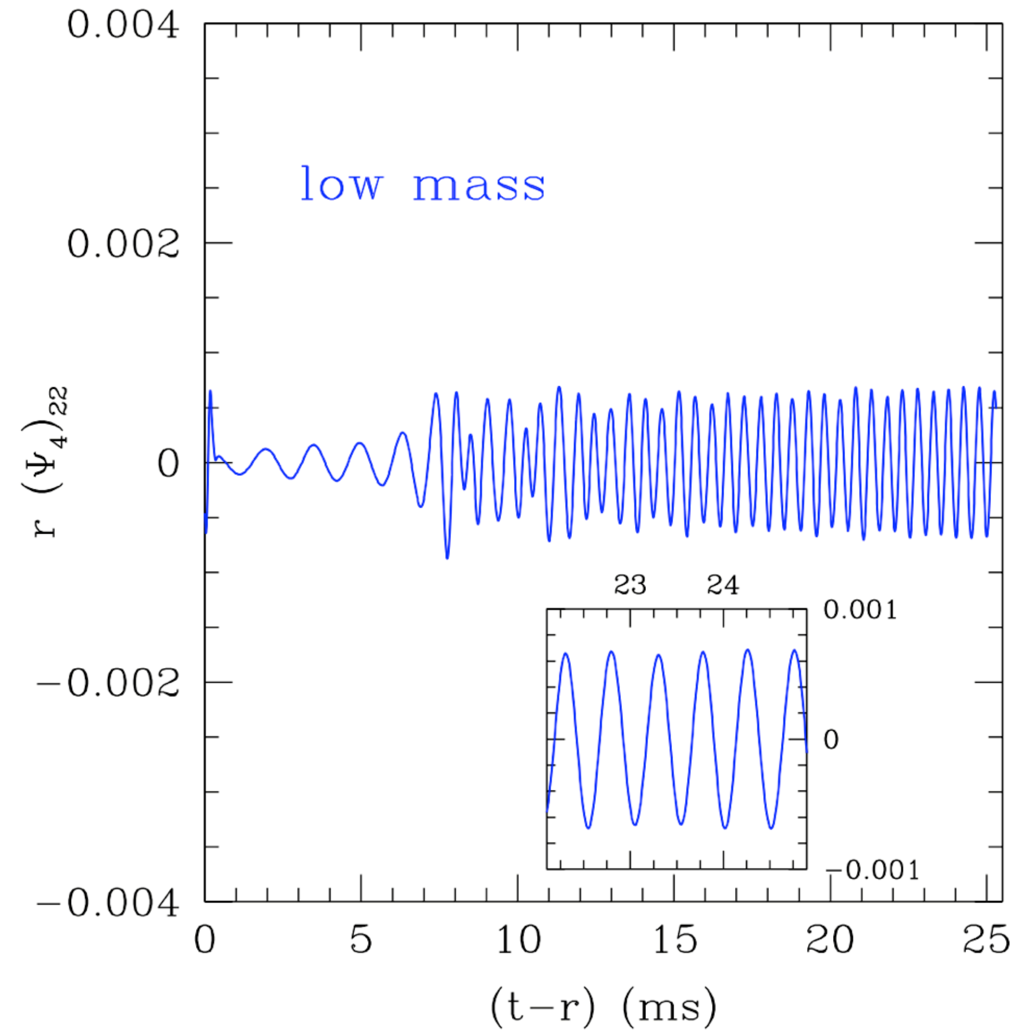
the high internal energy (temperature) of the HMNS prevents a prompt collapse

Waveforms: ideal-fluid EOS

high-mass binary



low-mass binary



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the HMNS evolves on longer (radiation-reaction) timescale

Waveforms: ideal-fluid EOS

high-mass binary

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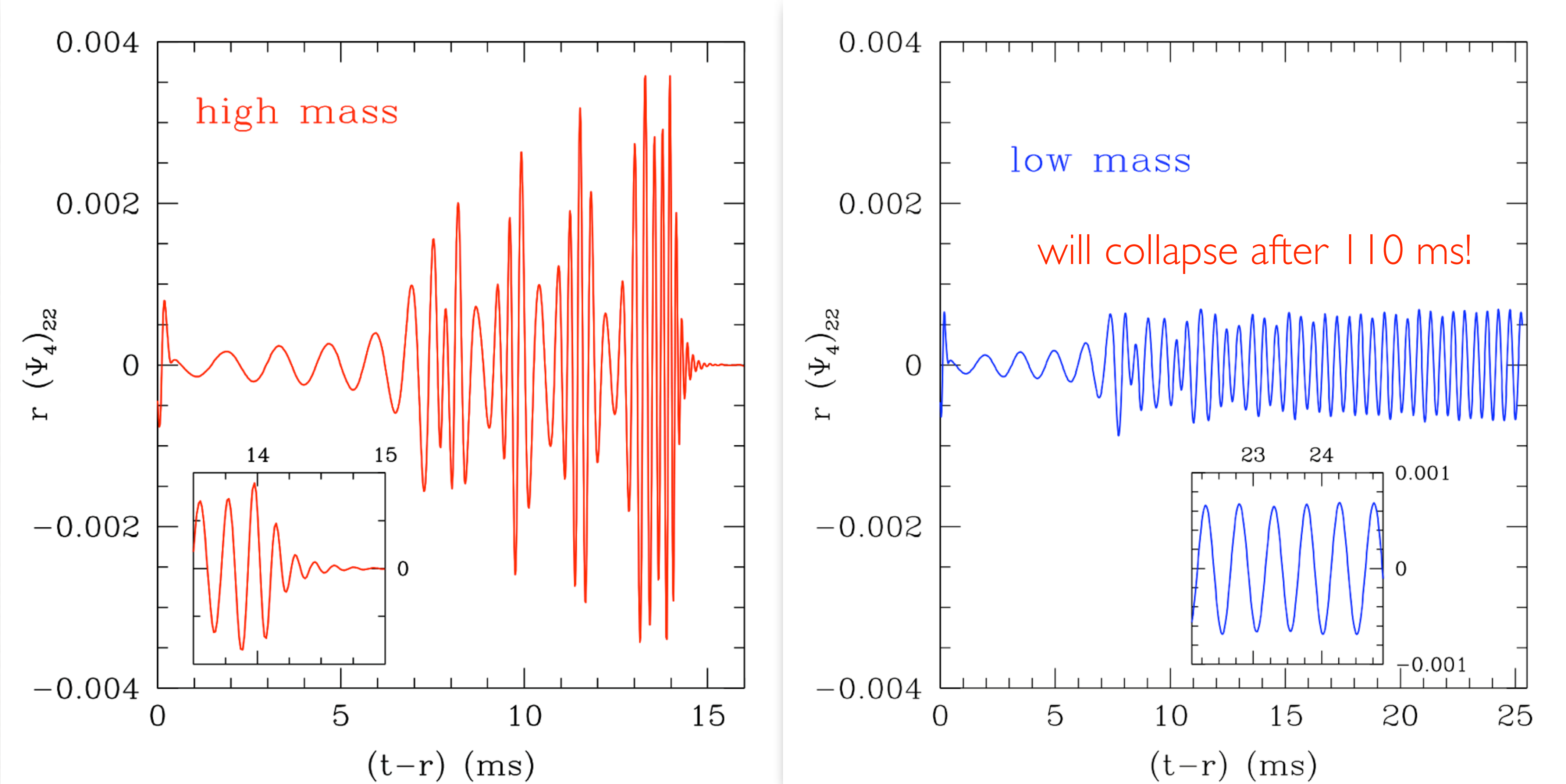

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Imprint of the EOS: Ideal-fluid vs polytropic

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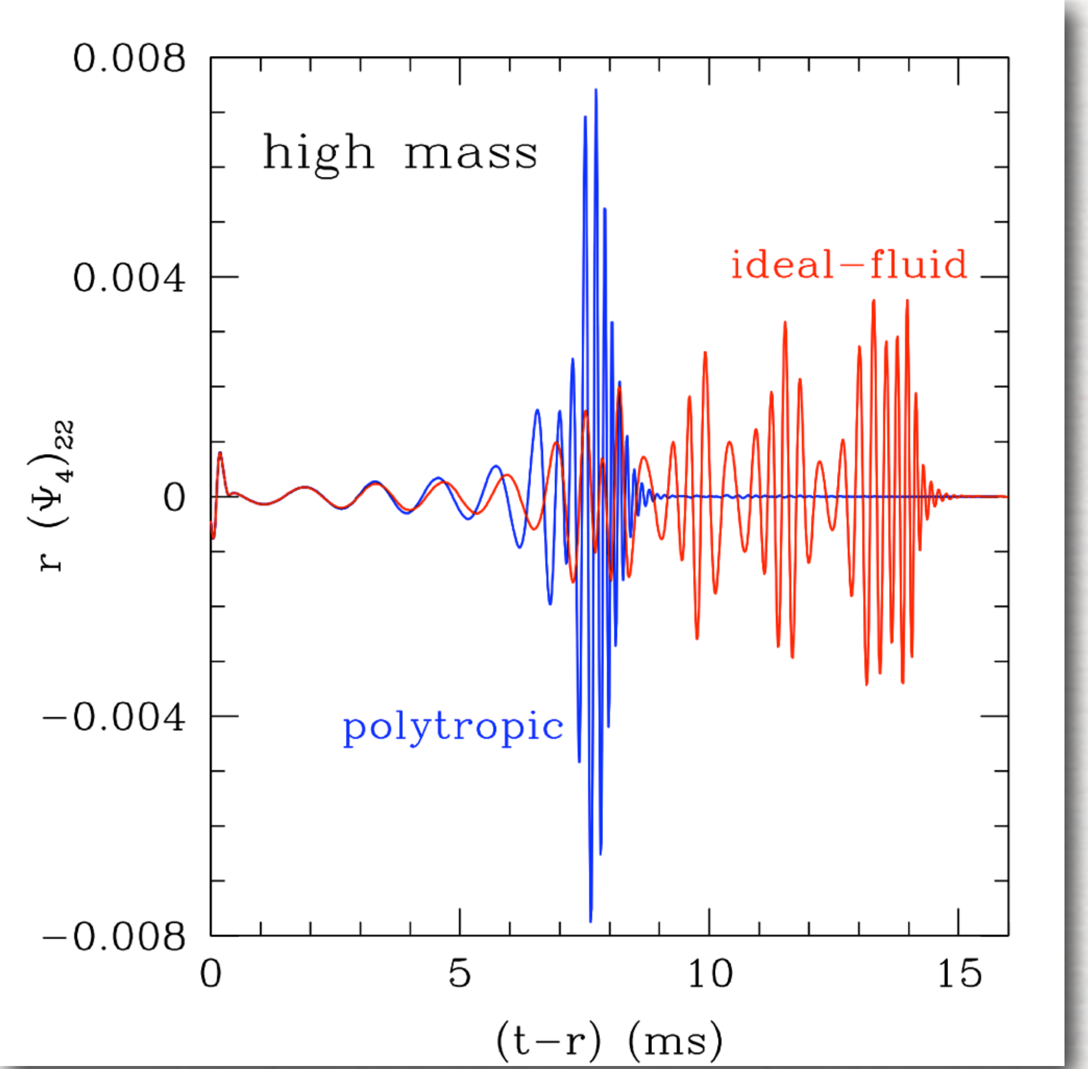

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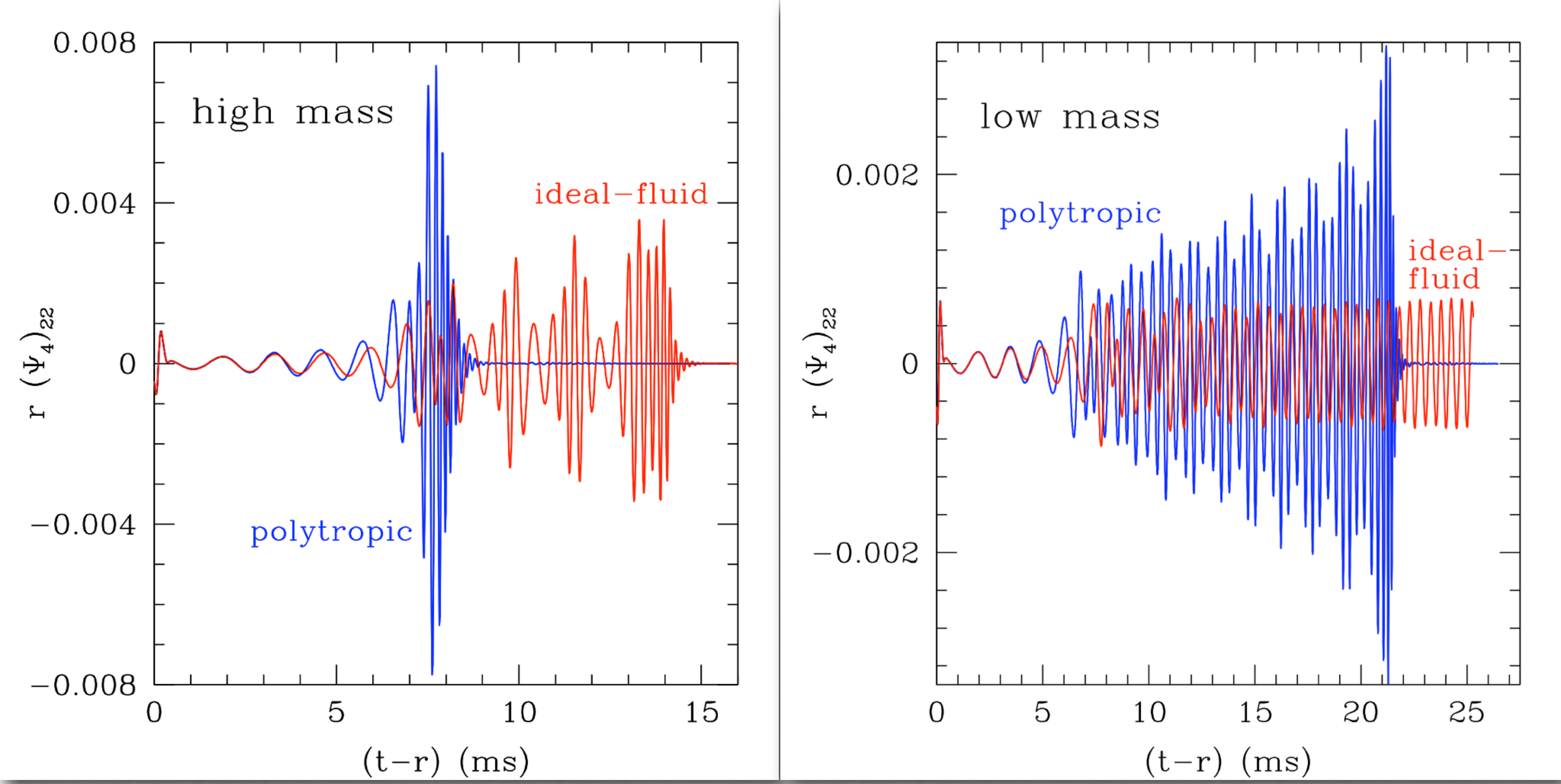

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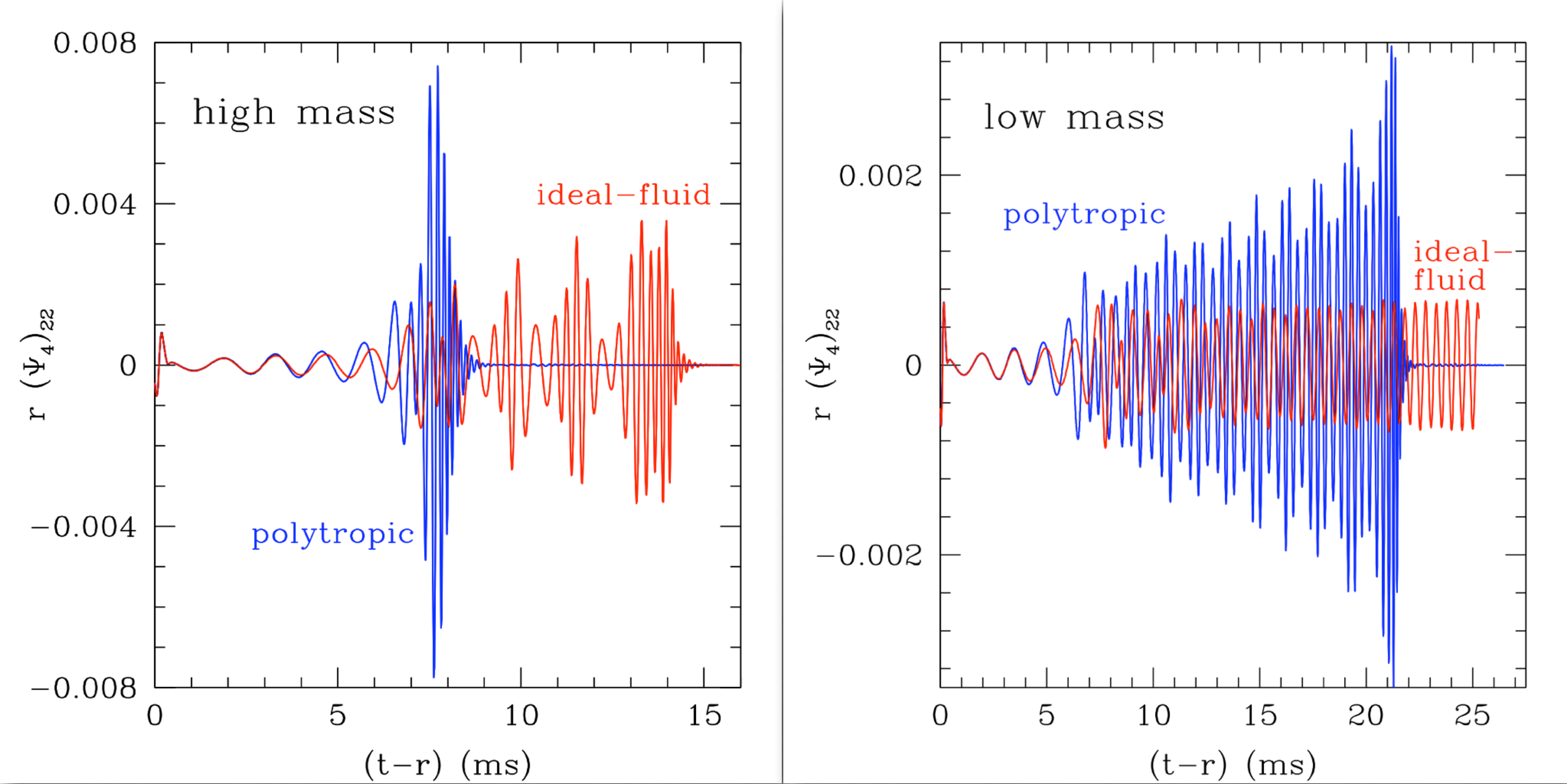

It is reasonable to expect that for any realistic EOS the waveforms will be in between these two extreme cases

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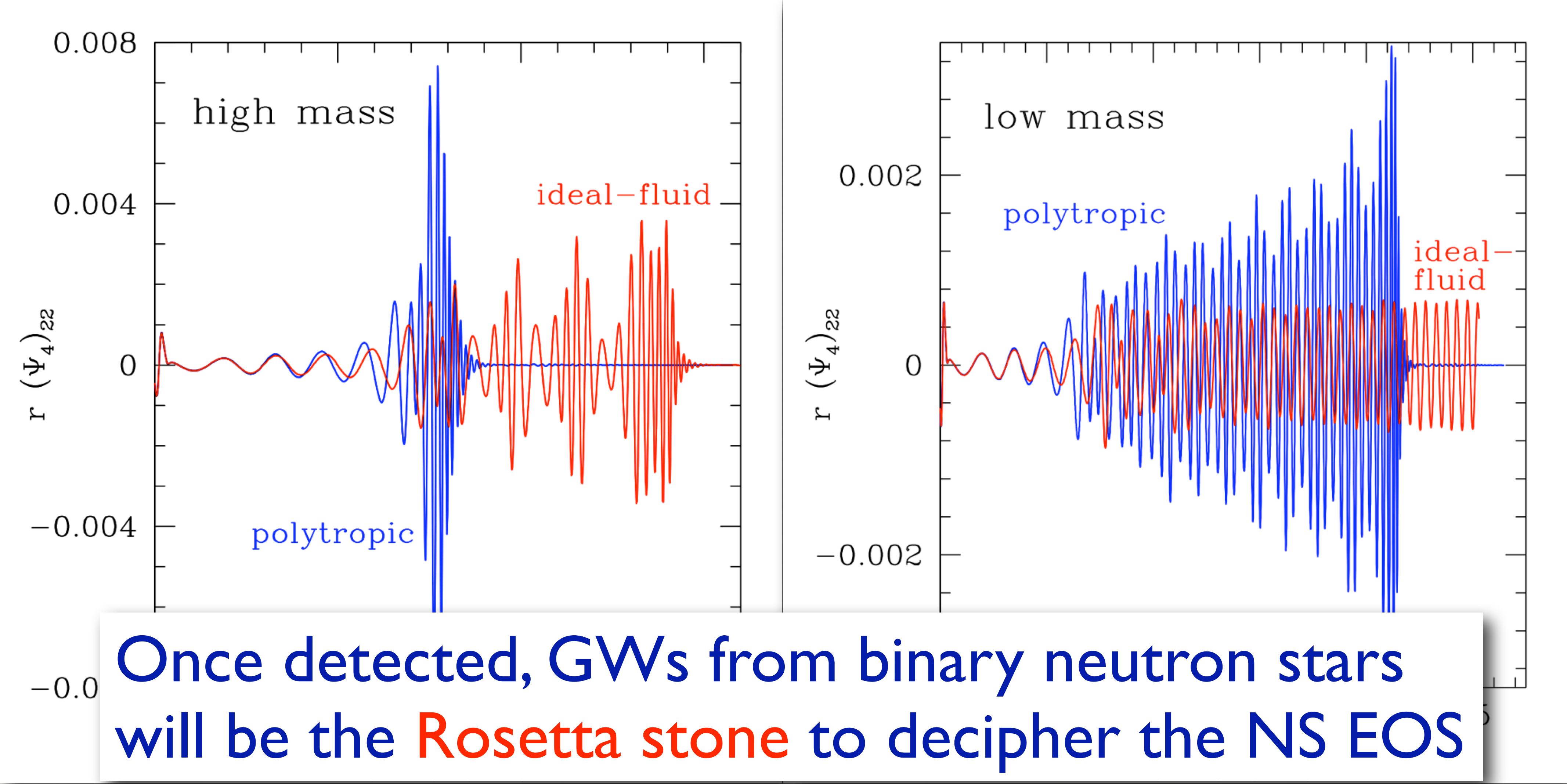

Once detected, GWs from binary neutron stars will be the Rosetta stone to decipher the NS EOS

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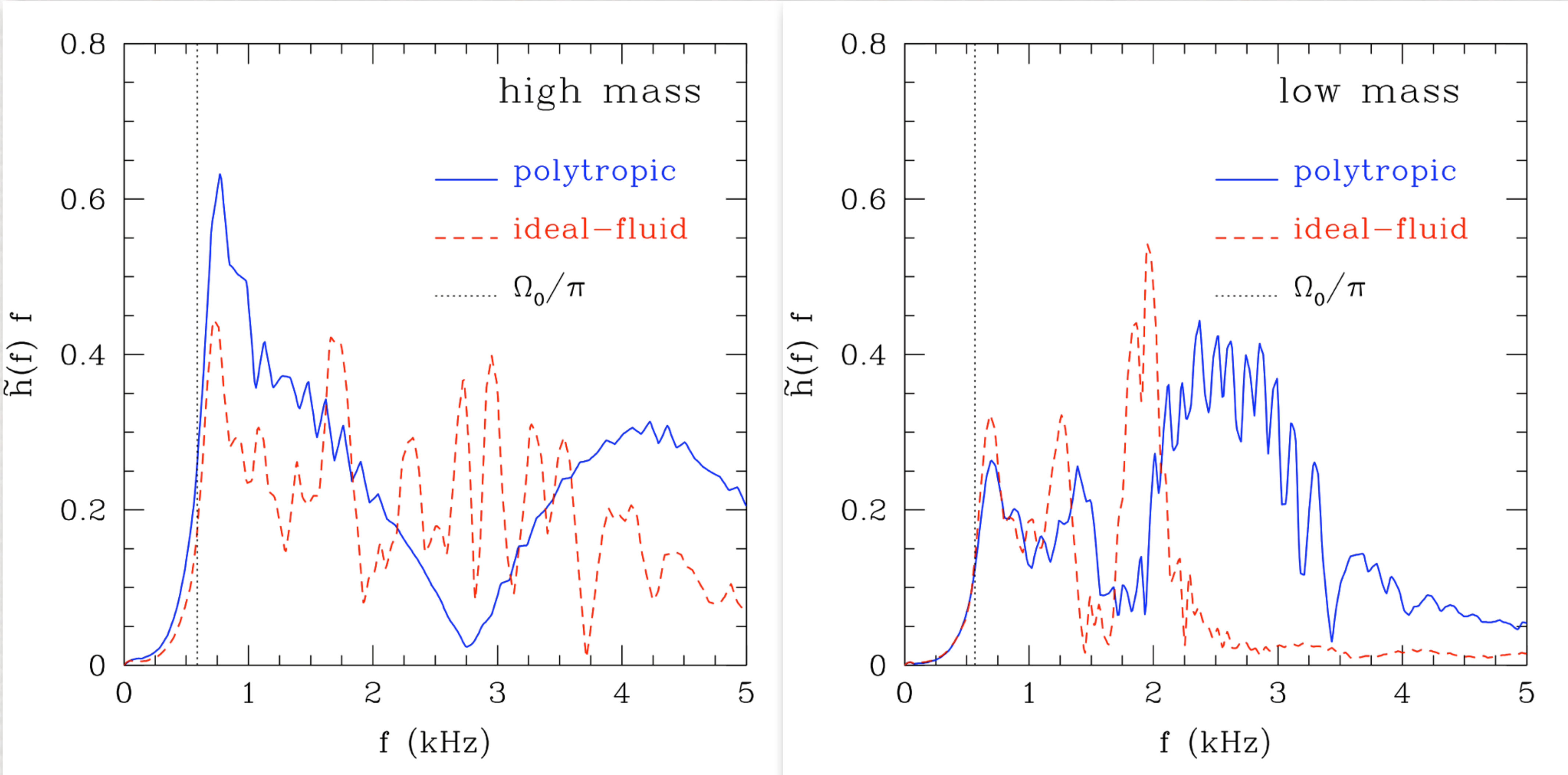
Conclusions and prospects

- ✶ With improved numerical techniques and increased computational power, NR is passing from being a "tool-to-be-developed" to a "tool-to-be-used".
- ✶ NR can act as a bridge between GR and other research areas: astrophysics (GRBs), cosmology (BBHs), GWDA (templates).
- ✶ The work at the AEI is aligned with this philosophy and often leading the way
- ✶ In summary: there is a lot that NR can do for ET and a lot that ET can do for NR/GR!

Imprint of the EOS: frequency domain



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

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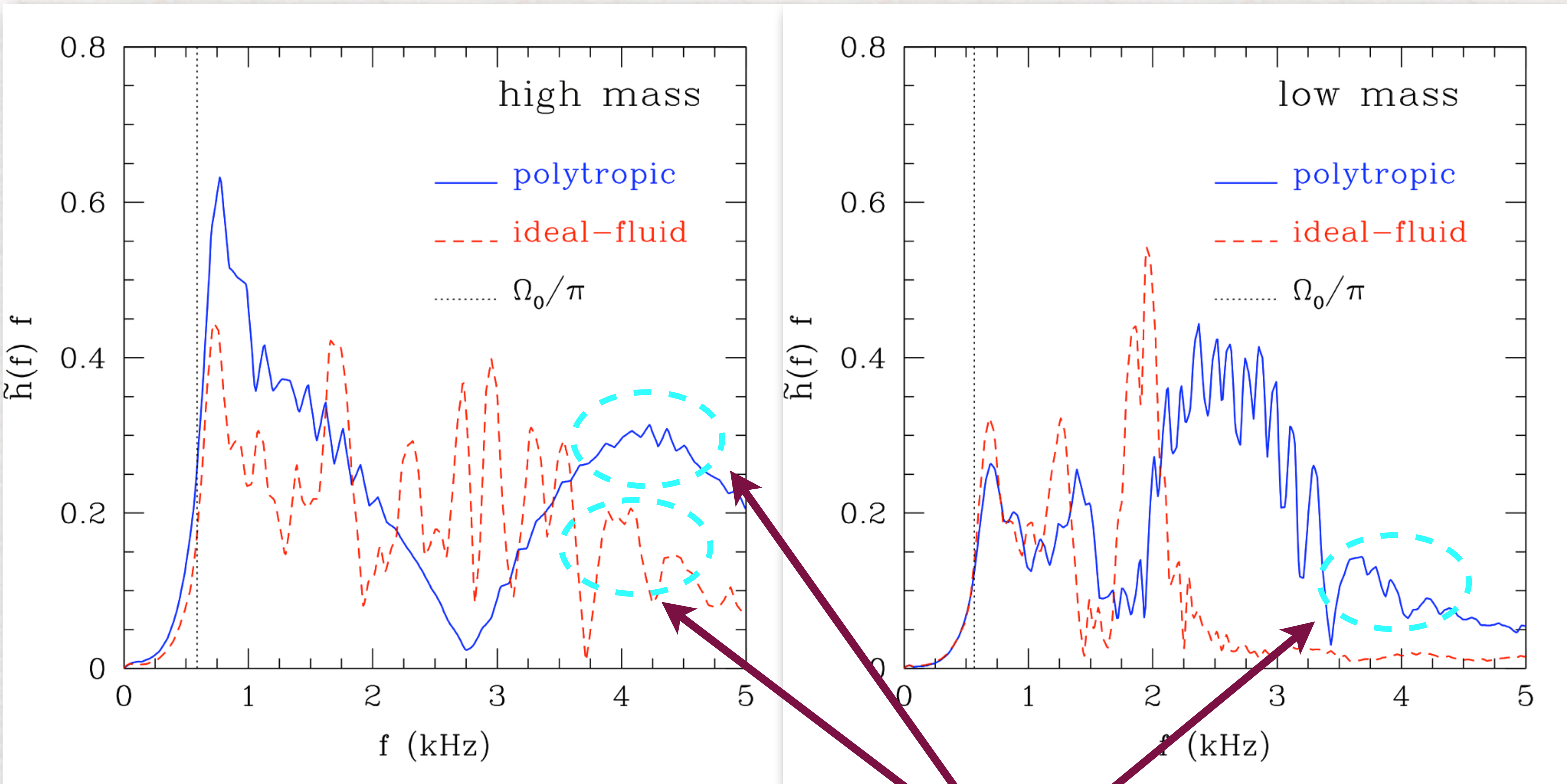

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Contributions from the collapse to BH

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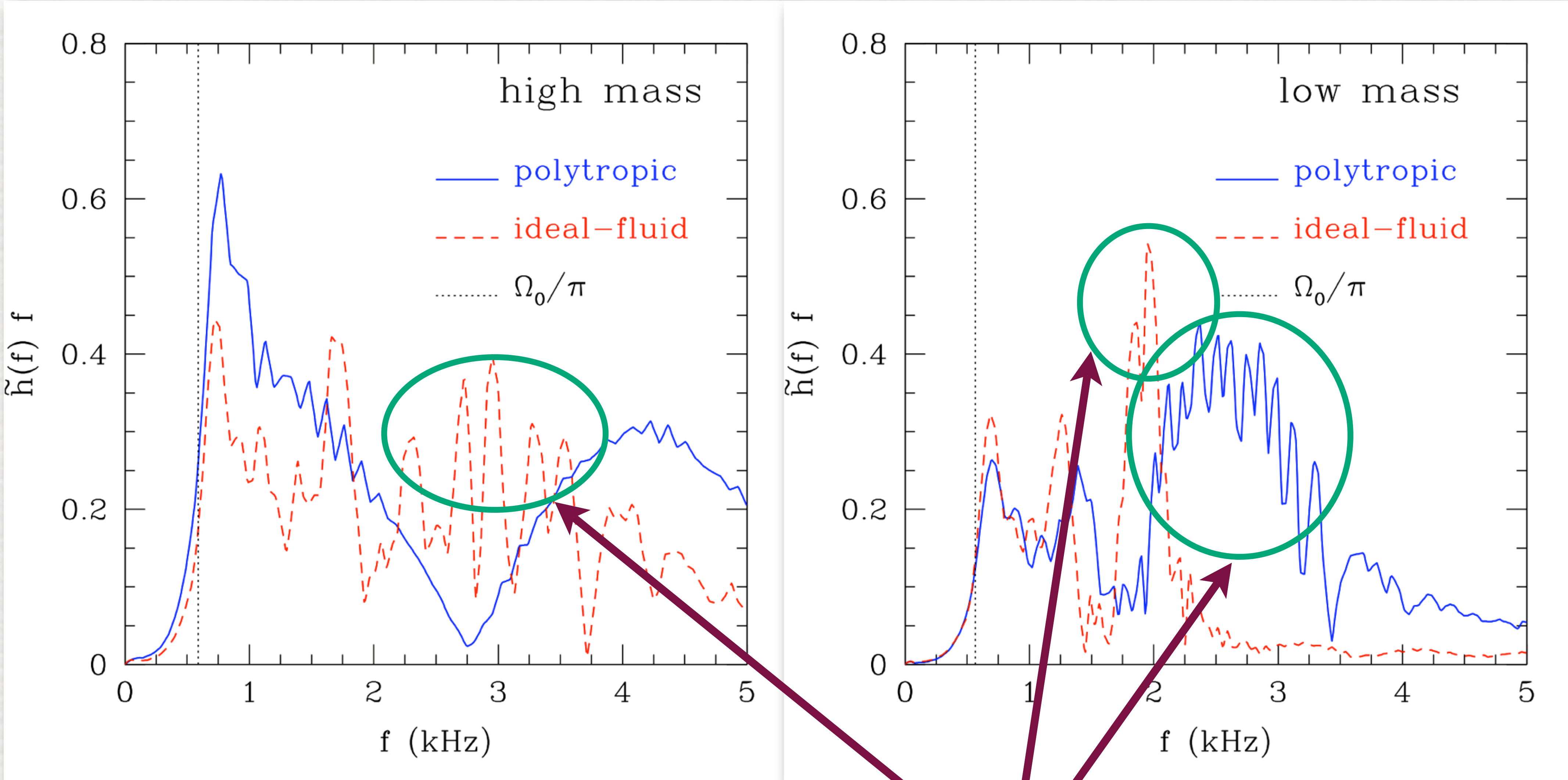

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Contributions from the bar-deformed HMNS