Compact objects and gravitational waves

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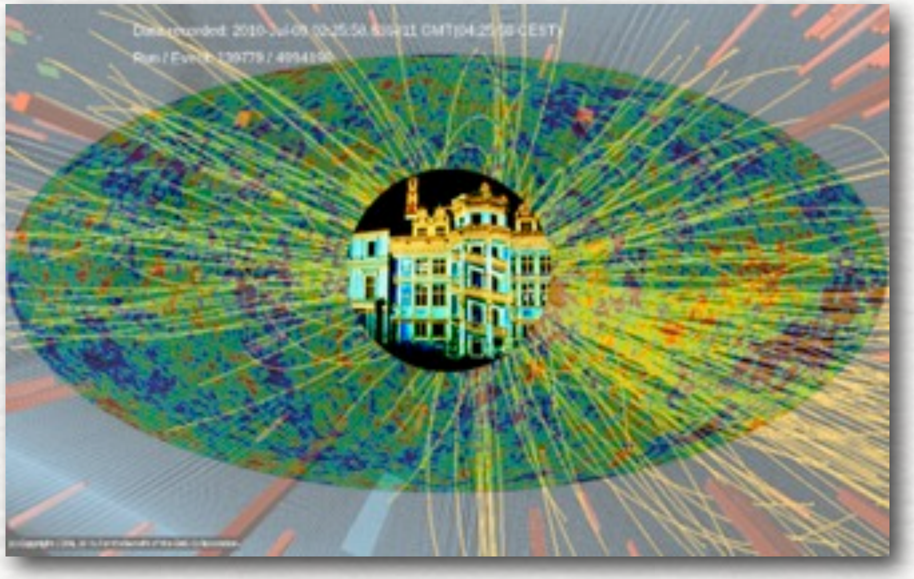
Blois,

03/06/11



Plan of the talk

- Gravitational waves from binary black holes
  - ✶kicks
  - ✶anti-kicks
- Gravitational waves from binary neutron stars
  - ✶equal-mass, different EOSs, no magnetic field
  - ✶equal-mass, magnetic field

NR: ie when everything else fails

Numerical relativity (NR) solves Einstein equations in those regimes in which no approximation holds: eg in the most nonlinear regimes of the theory. We build codes which we consider as "**theoretical laboratories**".

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} \qquad (\text{field eqs}: \ 6+6+3+1)$$

$$\nabla_\mu T^{\mu\nu} = 0 \ , \qquad (\text{cons. en./mom.}: \ 3+1)$$

$$\nabla_\mu (\rho u^\mu) = 0 \ , \qquad (\text{cons. of baryon no}: \ 1)$$

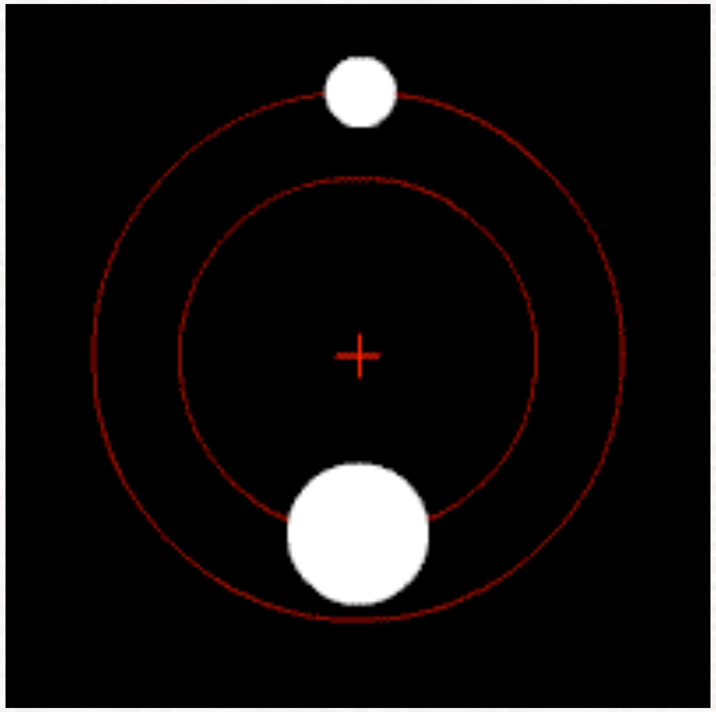
$$p = p(\rho, \epsilon, \ldots) \ . \qquad (\text{EoS}: \ 1 + \ldots)$$

$$\nabla^*_\nu F^{\mu\nu} = 0, \qquad (\text{Maxwell eqs.}: \ \text{induction, zero div.})$$

$$T_{\mu\nu} = T^{\text{fluid}}_{\mu\nu} + T^{\text{em}}_{\mu\nu} + \ldots$$

The two-body problem: Newtonian gravity

The solution to the problem in which two massive objects of mass m_1 and m_2 interacting only via the gravitational force they exert on each other is very simple:



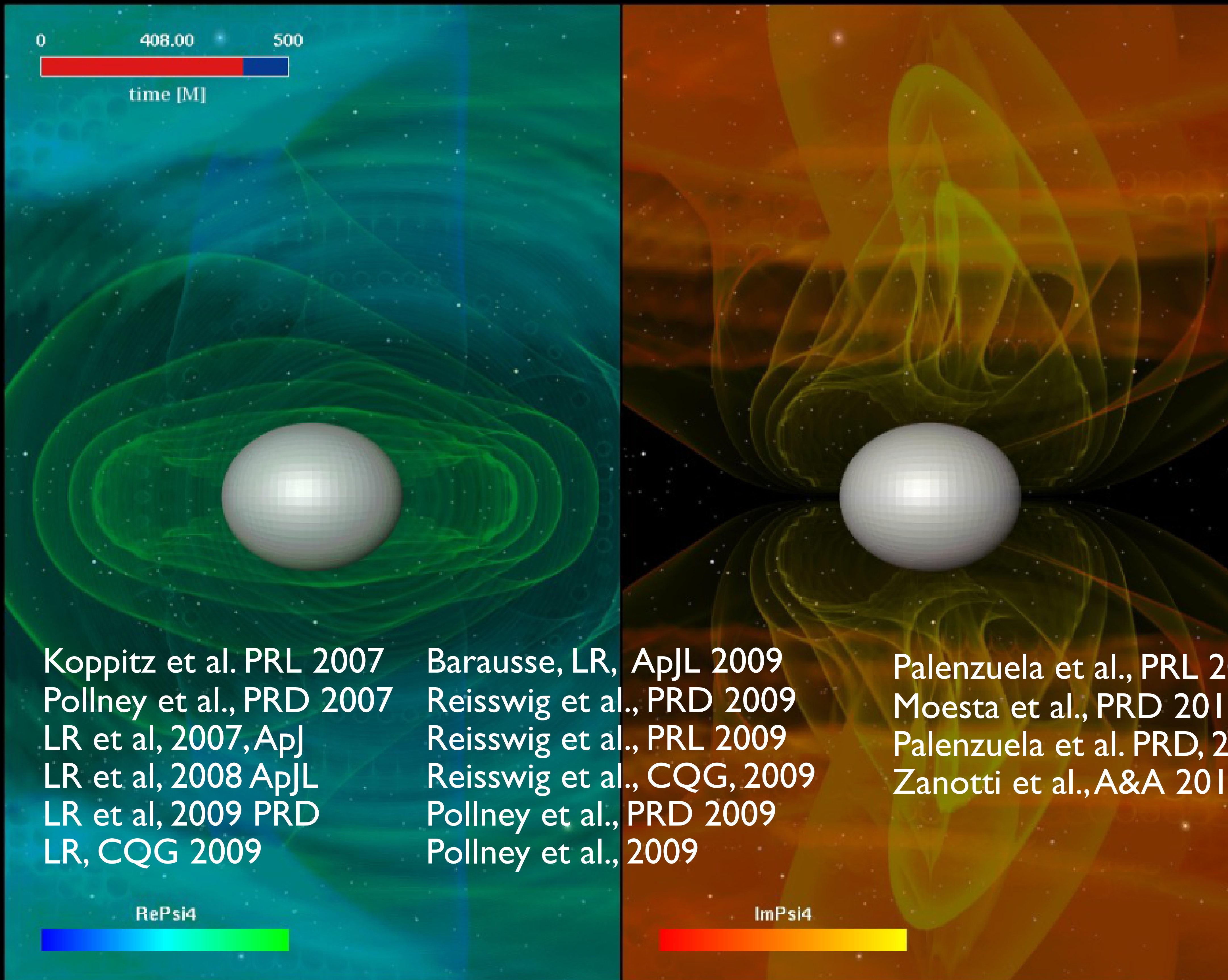
$$\ddot{\boldsymbol{r}} = -\frac{GM}{d_{12}^3}\boldsymbol{r}$$

where

$$M \equiv m_1 + m_2\,, \boldsymbol{r} \equiv \boldsymbol{r}_1 - \boldsymbol{r}_2\,, d_{12} \equiv |\boldsymbol{r}_1 - \boldsymbol{r}_2|\,.$$

The system admits closed orbits (circular/elliptic). At lowest order, this equation describes the motion of most astronomical objects (eg in our solar system).

Binary Black Holes



Koppitz et al. PRL 2007
Pollney et al., PRD 2007
LR et al, 2007, ApJ
LR et al, 2008 ApJL
LR et al, 2009 PRD
LR, CQG 2009

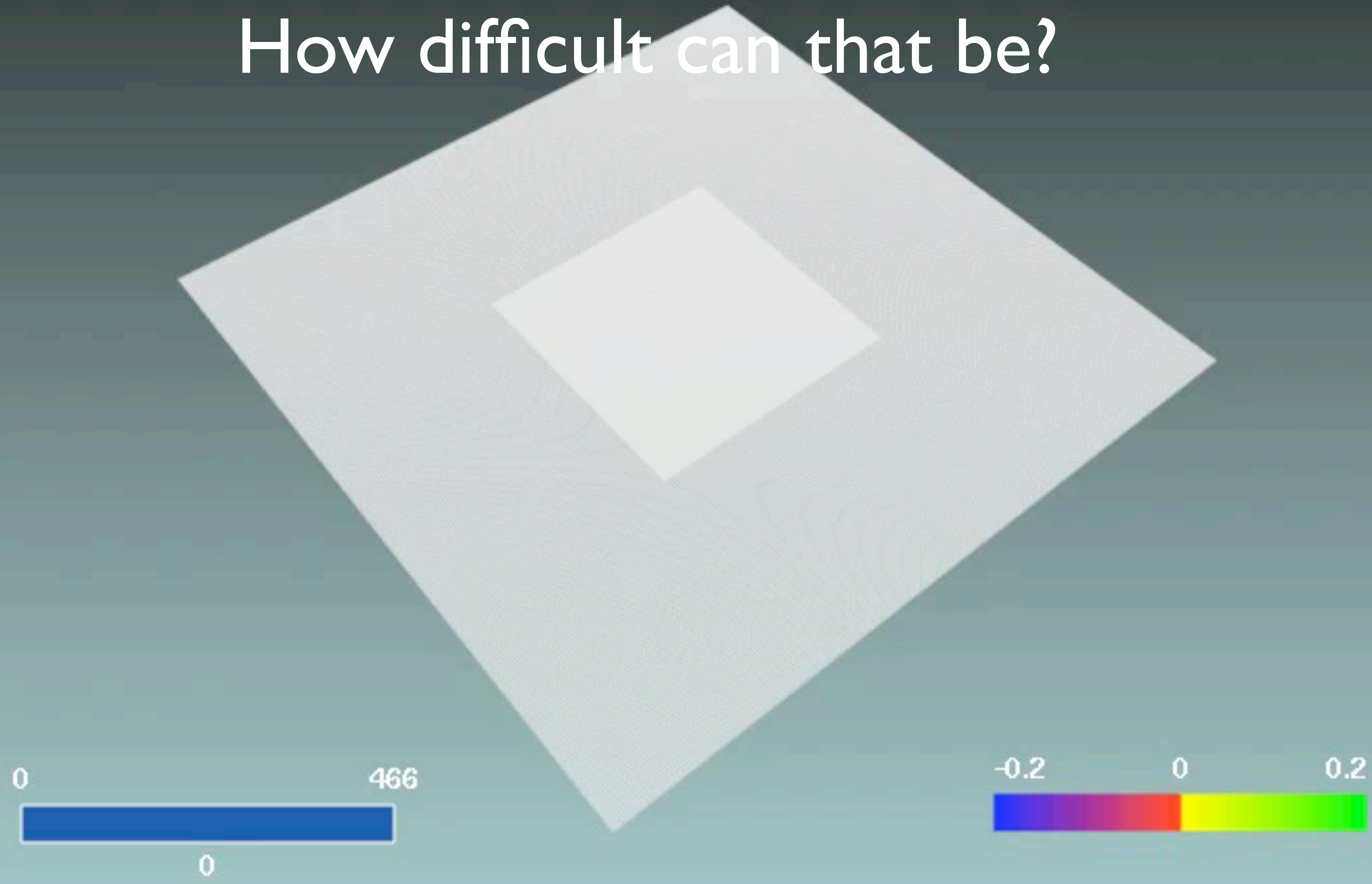
Barausse, LR, ApJL 2009
Reisswig et al., PRD 2009
Reisswig et al., PRL 2009
Reisswig et al., CQG, 2009
Pollney et al., PRD 2009
Pollney et al., 2009

Palenzuela et al., PRL 2009
Moesta et al., PRD 2010
Palenzuela et al. PRD, 2010
Zanotti et al., A&A 2010

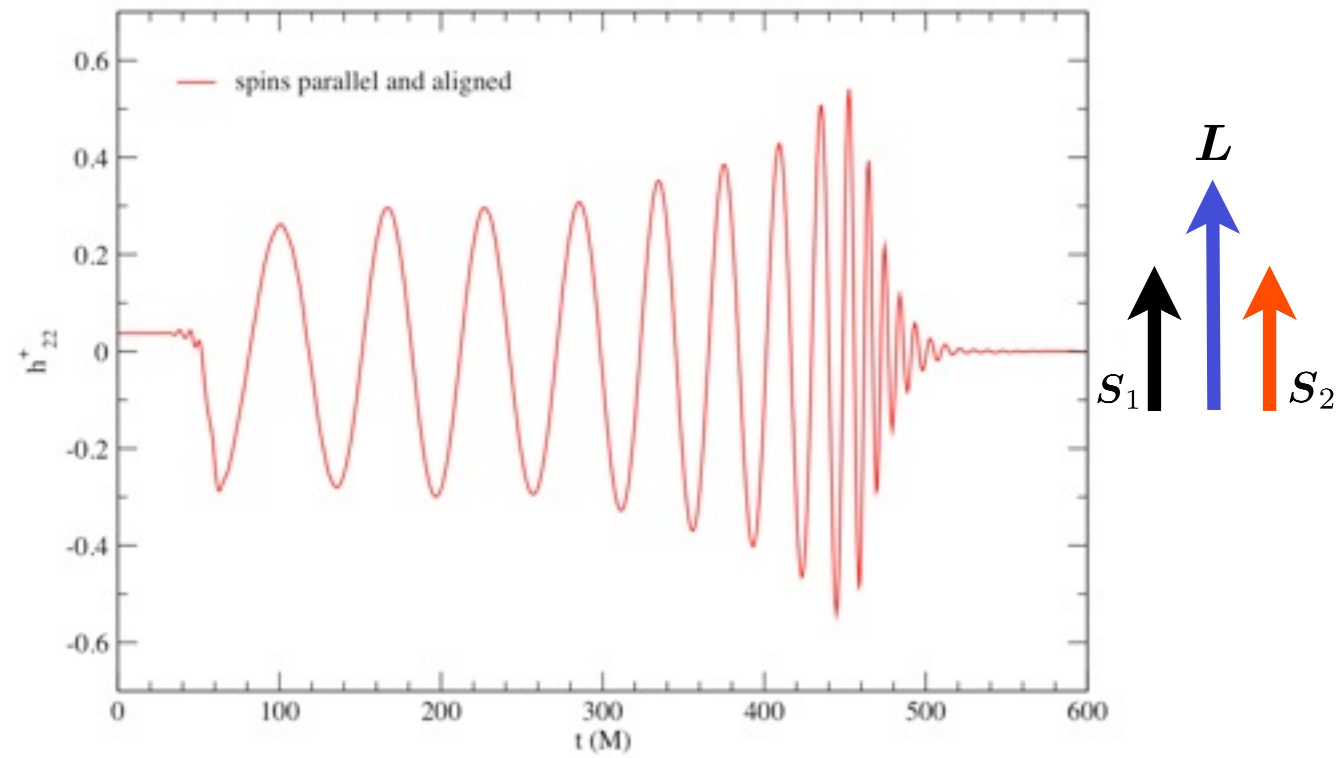
In vacuum the Einstein equations reduce to

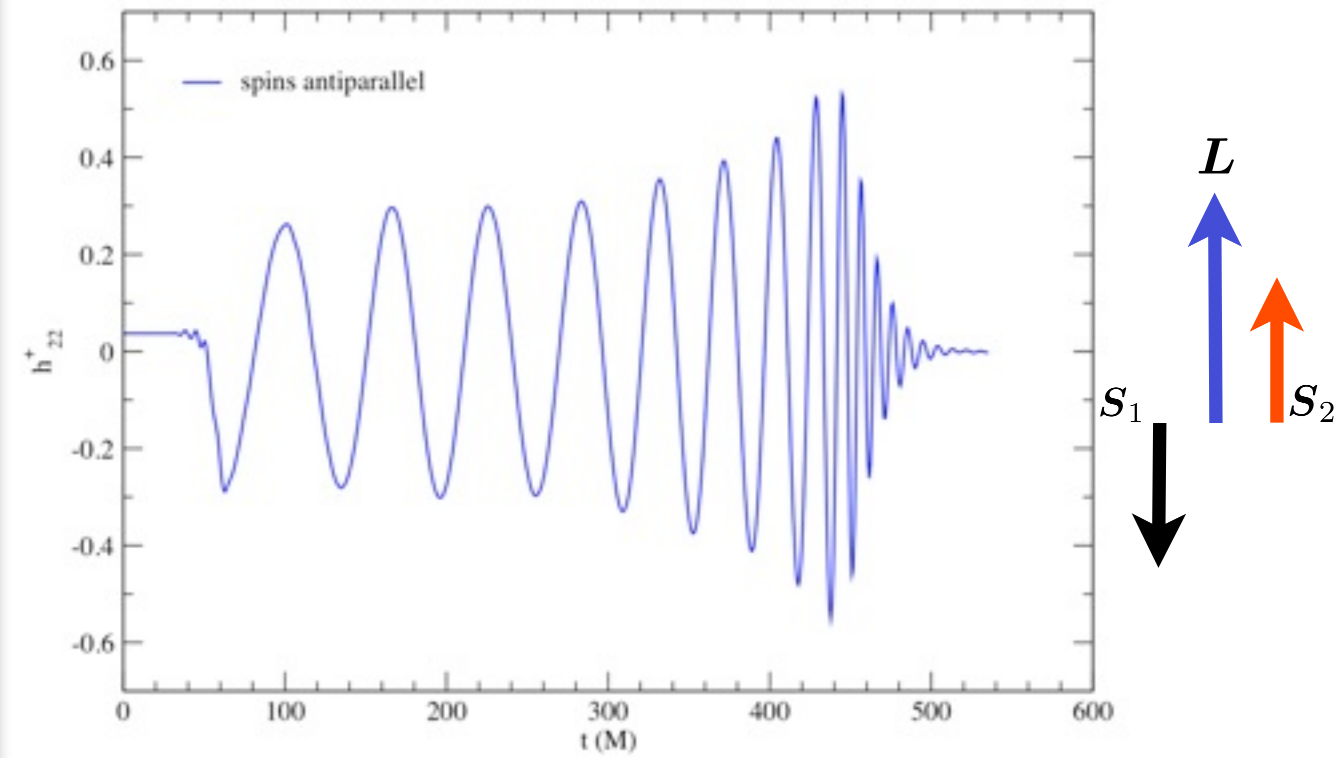
$$R_{\mu\nu} = 0$$

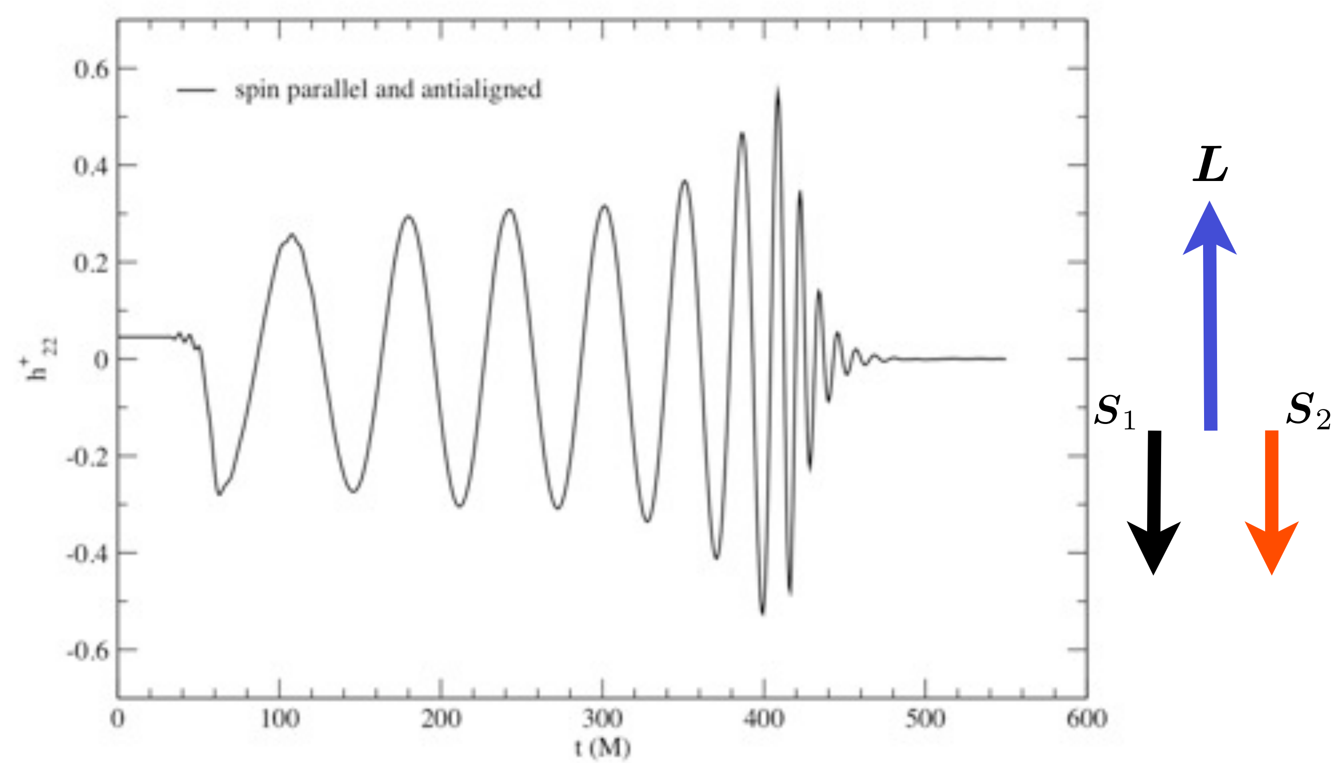
How difficult can that be?



Animation by Kaehler, Reisswig, LR







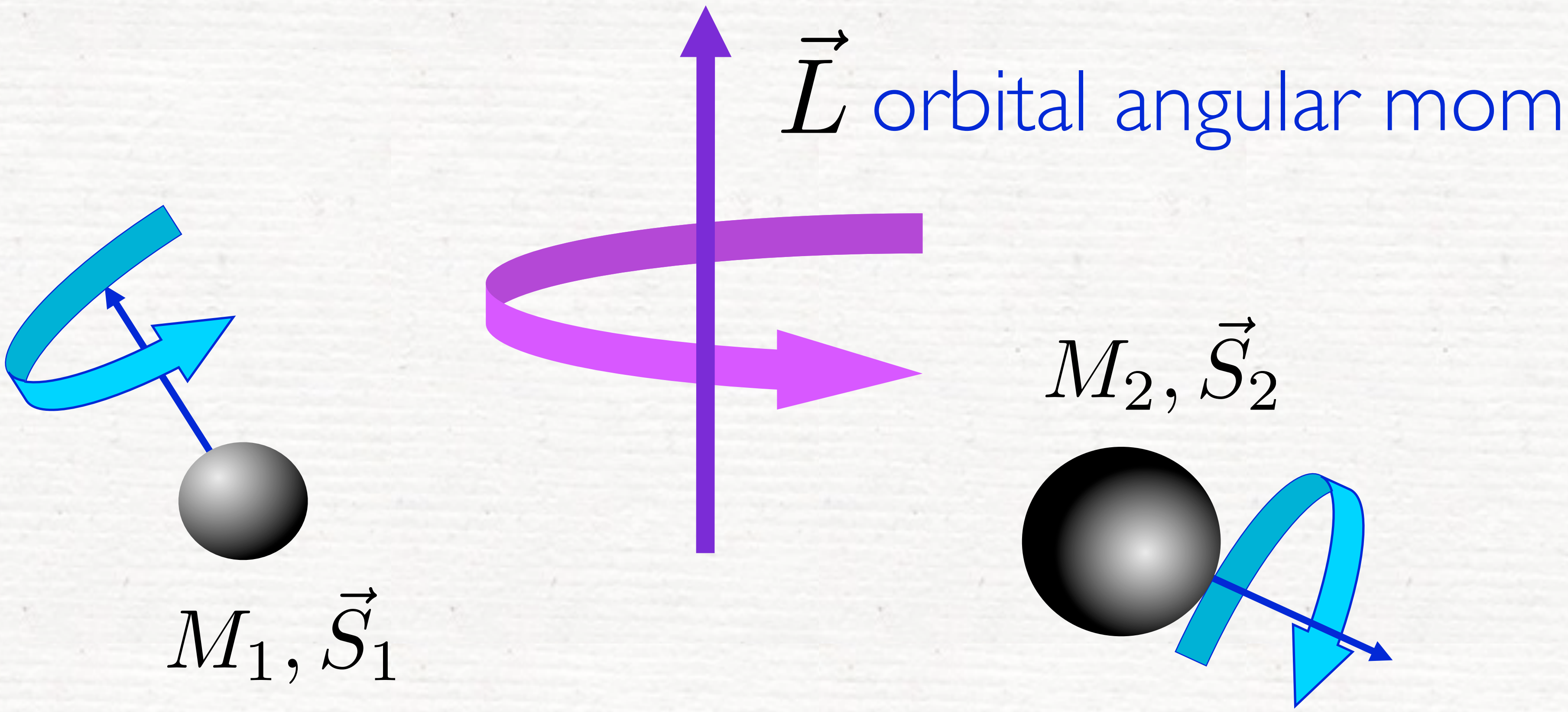
All the information is in the waveforms

- used in matched filtering techniques (data analysis)
- compute the physical/astrophysical properties of the merger (kick, final spin, etc.)

Modelling the final state

Consider BH binaries as "engines" producing a final single black hole from two distinct initial black holes

Before the merger...



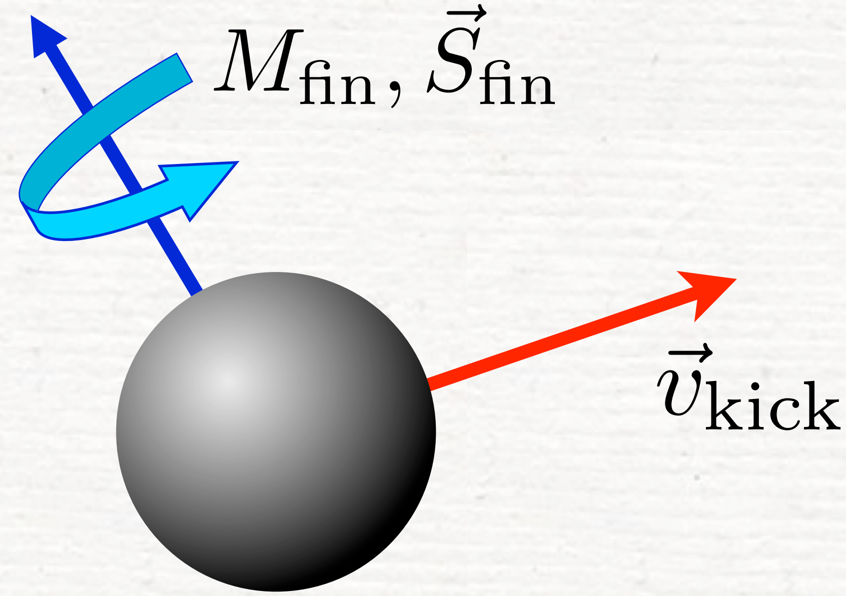
The space of parameters is 7-dimensional (2 spin vectors, mass ratio) and tiny when compared to that of NSs

Modelling the final state

Consider BH binaries as "engines" producing a final single black hole from two distinct initial black holes

After the merger...

LR et al, 2007
LR et al, 2008
LR et al, 2008
LR, 2009
Barausse, LR 2009



Buonanno et al. 2007
Boyle et al, 2007
Boyle et al, 2008
Tichy & Marronetti, 2008
Kesden, 2008
Lousto et al. 2009
van Meter et al. 2010
Kesden et al. 2010

The final BH has 3 specific properties: **mass, spin, recoil.**
Their knowledge is important for astrophysics and cosmology

Can predict with **% precision** the **magnitude** and **direction** of final **spin** and the **magnitude** of the **kick** for arbitrary binaries.

Understanding the recoil

At the end of the simulation and unless the spins are equal, the final black hole will acquire a recoil velocity: aka "kick".

The emission of GWs is beamed and thus asymmetrical: the linear momentum radiated at an angle will not be compensated by the momentum after one orbit.

A simple mechanic analogue is offered by a rotary sprinkler

Consider a sequence of spinning BHs in which one of the spins is held fixed and the other one is varied in amplitude

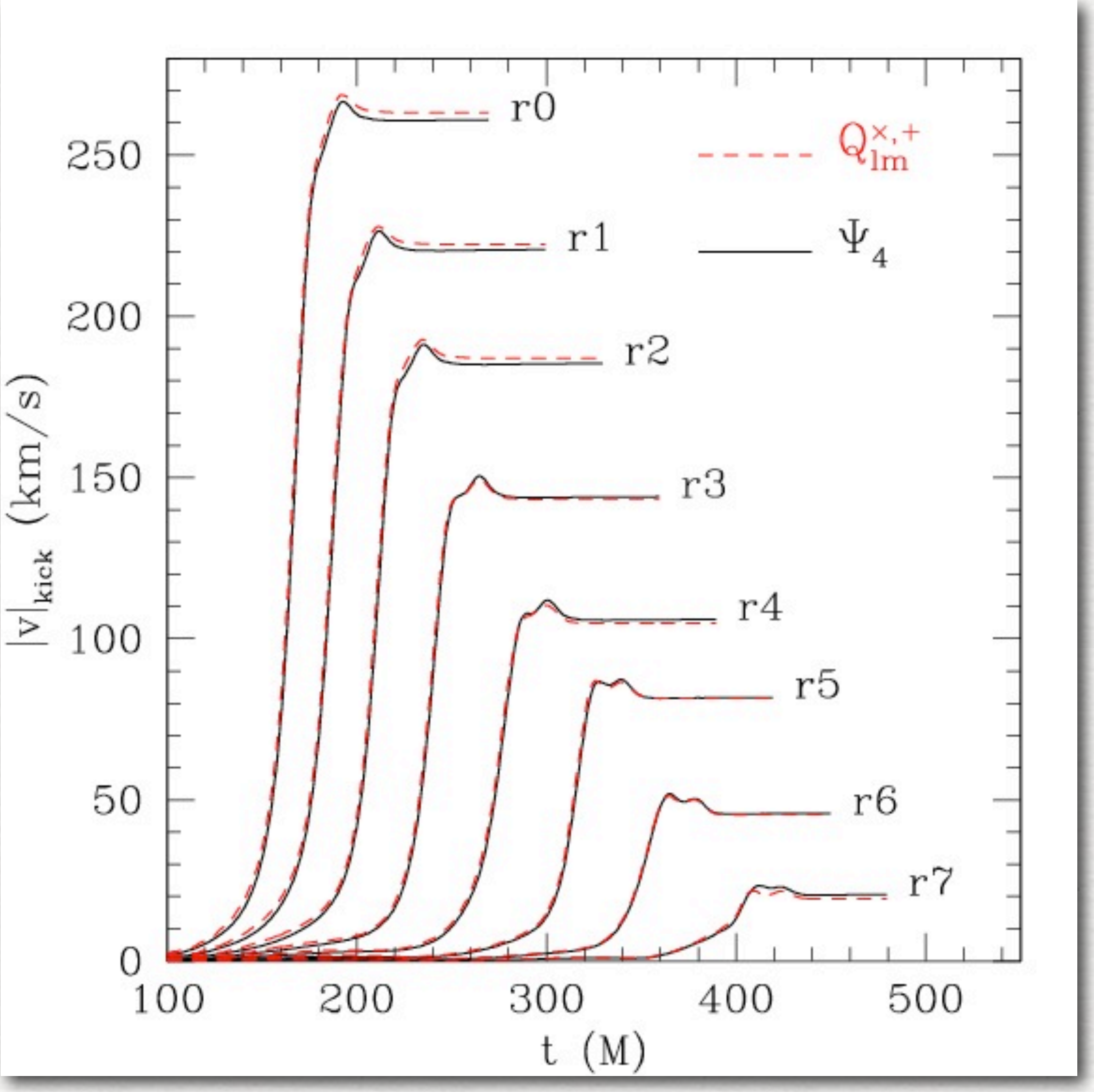
r0: ↑ ↓ $(a_1/a_2=-4/4)$

r2: ↑ ↓ $(a_1/a_2=-2/4)$

r4: ↑ . $(a_1/a_2=-0/4)$

r6: ↑ ↑ $(a_1/a_2=2/4)$

r8: ↑ ↑ $(a_1/a_2=4/4)$



What we know (now) of the kick

$$v_{\rm kick} = v_m \boldsymbol{e}_1 + v_\perp \left(\cos(\xi)\boldsymbol{e}_1 + \sin(\xi)\boldsymbol{e}_2\right) + v_\| \boldsymbol{e}_3$$

where

$$v_m \simeq A\nu^2\sqrt{1-4\nu}(1+B\nu)$$

$$v_\perp \simeq c_1 \frac{\nu^2}{(1+q)}\left(q a_1^\| - a_2^\|\right) + c_2\left(q^2 (a_1^\|)^2 - (a_2^\|)^2\right)$$

$$v_\| \simeq \frac{K_1\nu^2 + K_2\nu^3}{(1+q)}\left[q a_1^\perp \cos(\phi_1 - \Phi_1) - a_2^\perp \cos(\phi_2 - \Phi_2)\right]$$

mass asymmetry $\lesssim 150 \mathrm{km/s}$

spin asymmetry; contribution **off** the plane $\lesssim 450 \mathrm{km/s}$

spin asymmetry; contribution **in** the plane $\lesssim 3500 \mathrm{km/s}$

LR 2008 (review)
van Meter et al. 2010

However, there is more than just the final recoil velocity

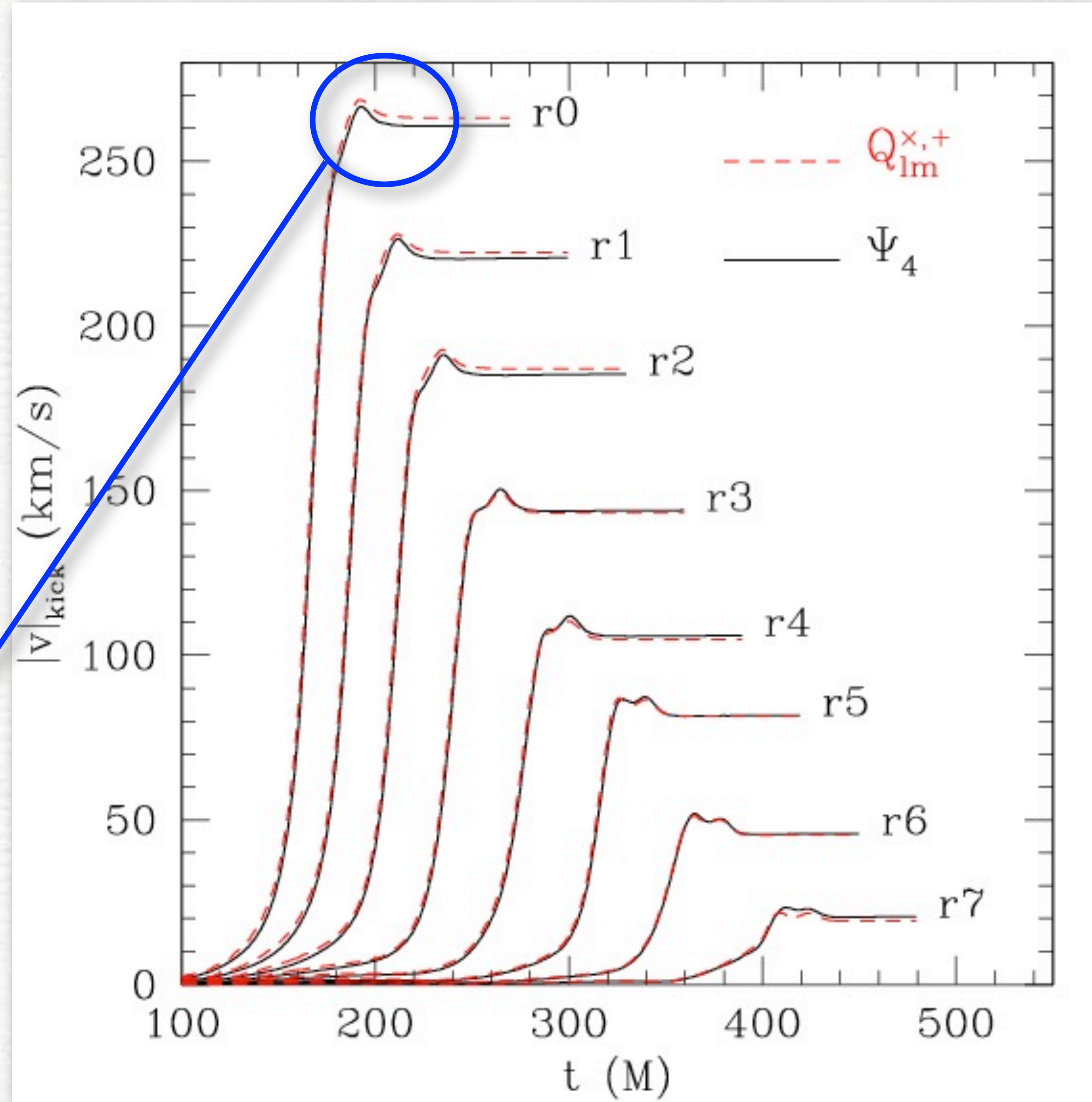
r0: ↑ ↓ (a_1/a_2=-4/4)

r2: ↑ ↓ (a_1/a_2=-2/4)

r4: ↑ . (a_1/a_2=-0/4)

r6: ↑ ↑ (a_1/a_2=2/4)

r8: ↑ ↑ (a_1/a_2=4/4)



why do BHs "anti-kick"?

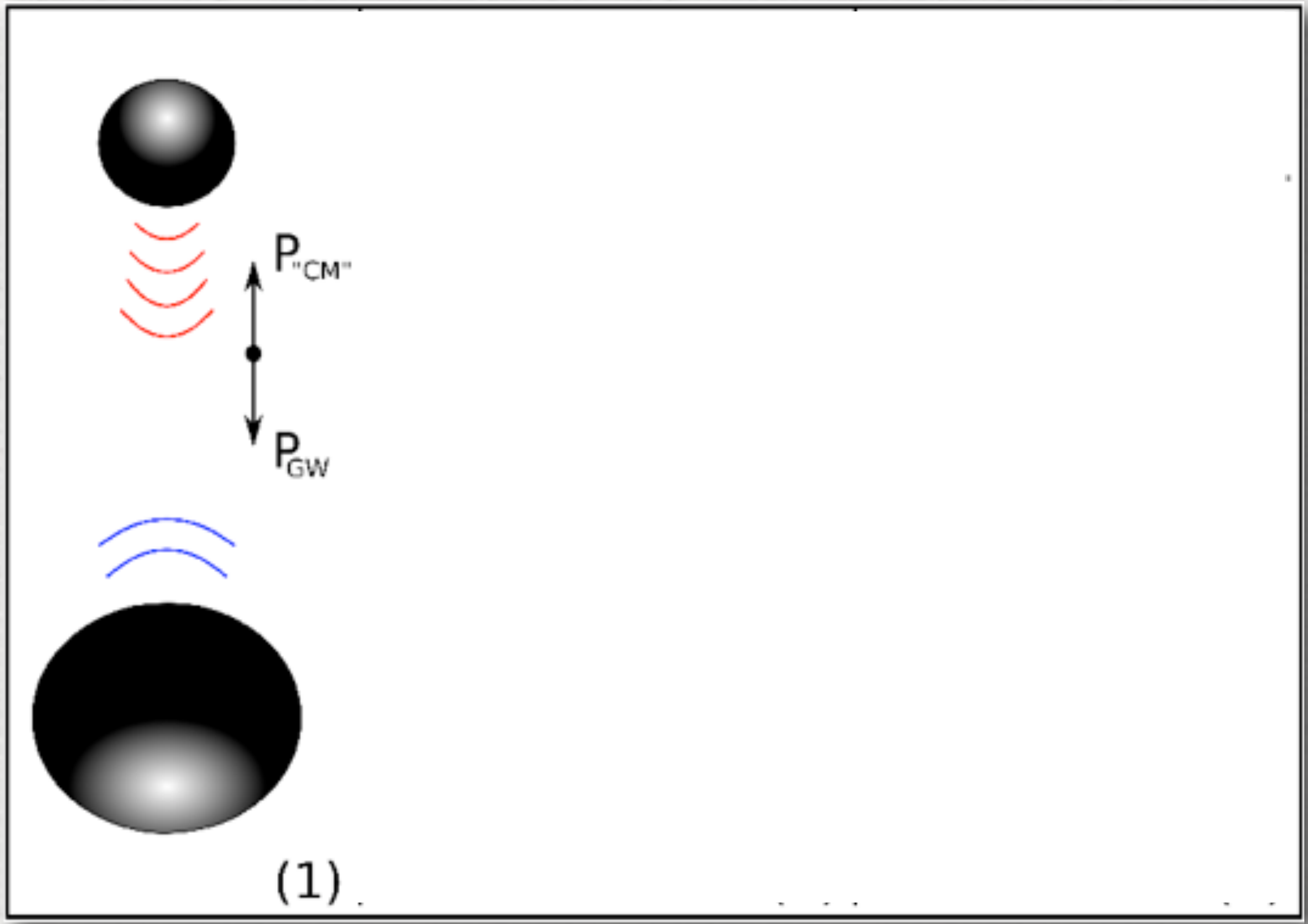
Understanding the anti-kick

LR, Macedo, Jaramillo, PRL 2010

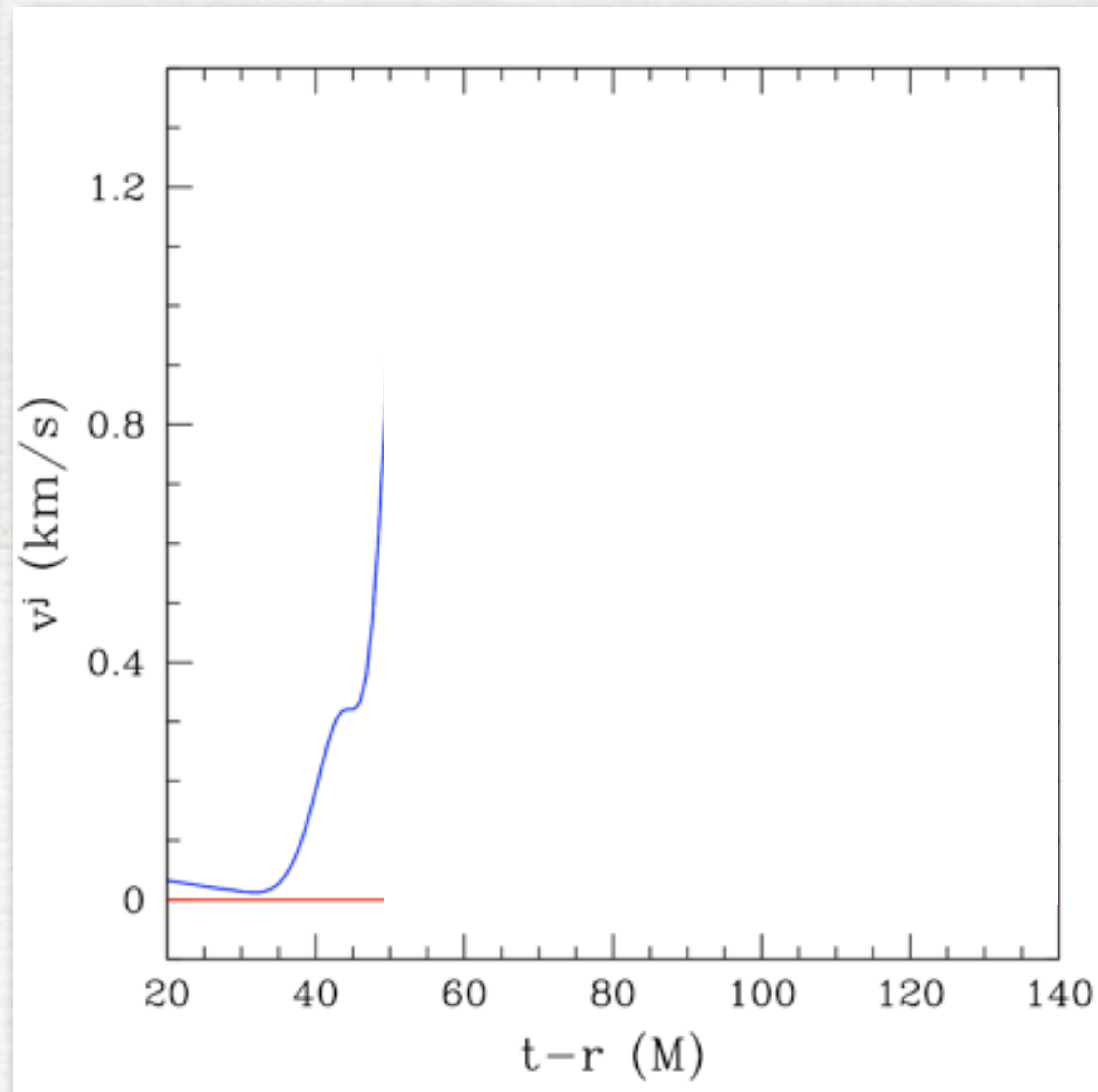
The basic idea:

- At coalescence a single deformed BH is formed, i.e. a BH with an anisotropic (i.e. non-axisymmetric) distribution of mean curvature.
- Asymptotically all of this curvature must be radiated to leave a Kerr (or Schwarzschild) BH
- The emission of the distorted BH will reflect the anisotropic distribution of the curvature and dictate the directionality of the recoil (holographic view).

A useful example: head-on collision of unequal-mass nonspinning BHs

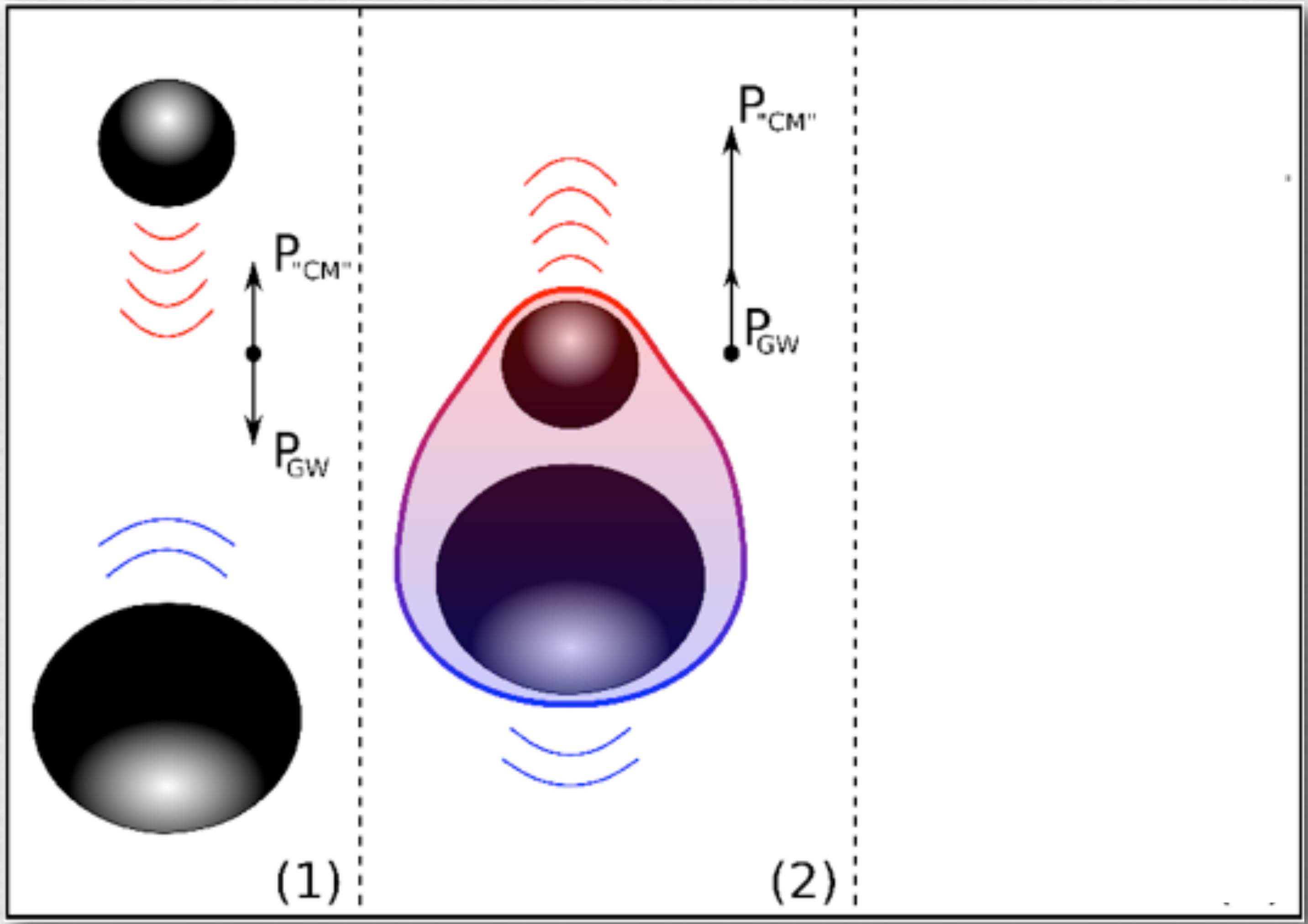


Consider two unequal-mass nonspinning BHs moving along the z-axis



The computed BH recoil is shown in the right panel and indicates a positive acceleration and then a negative one

A useful example: head-on collision of unequal-mass nonspinning BHs



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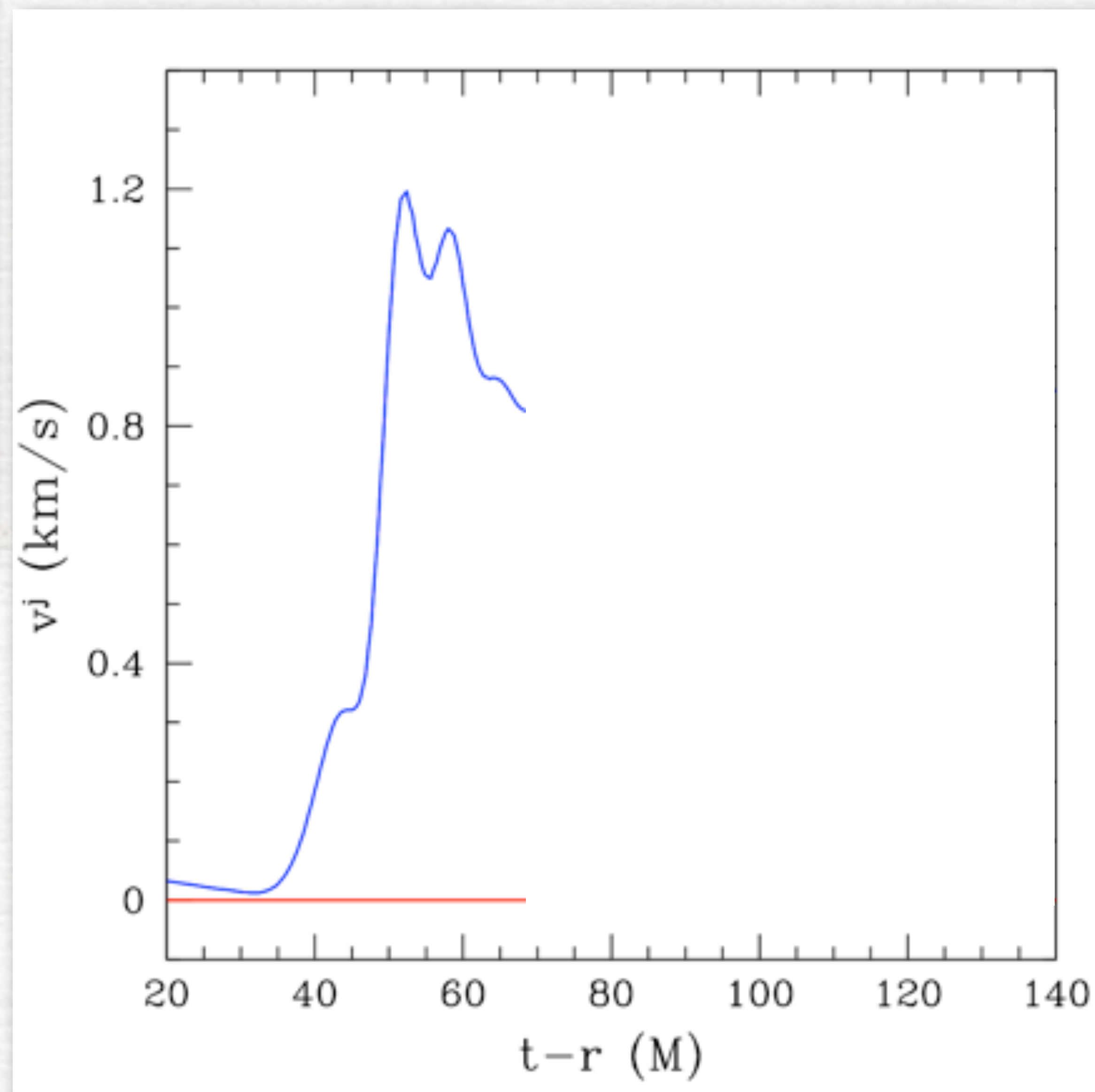

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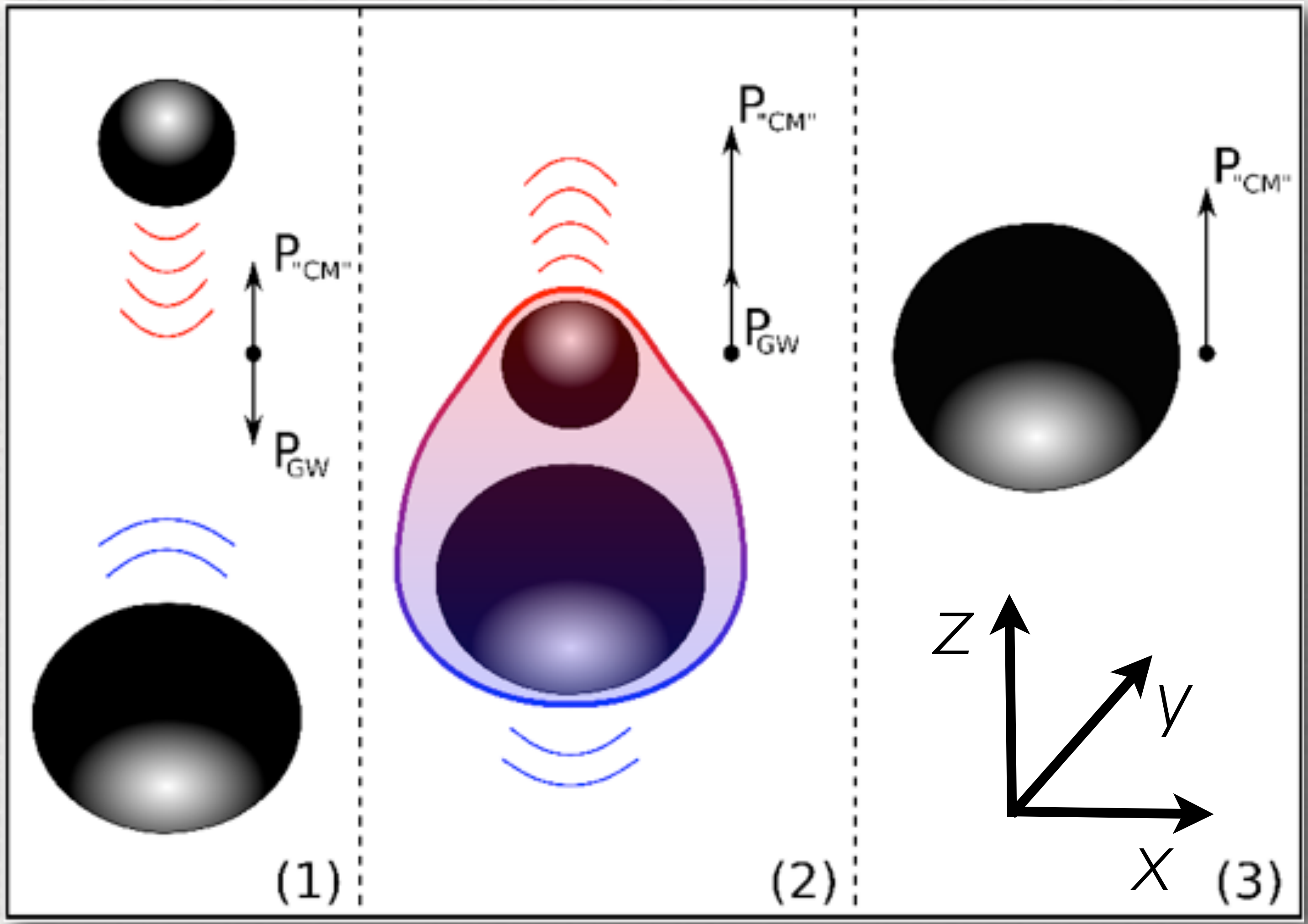

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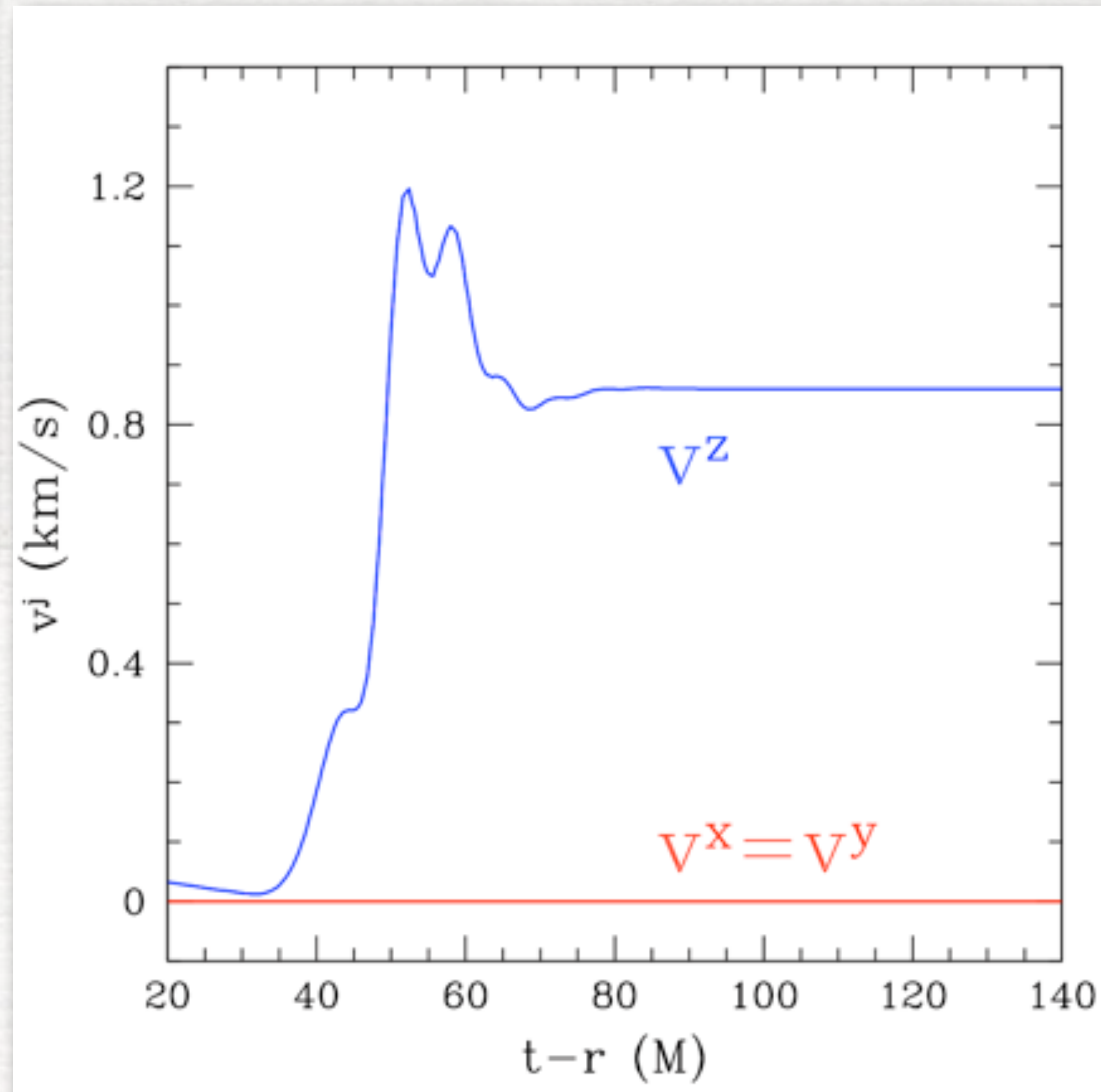
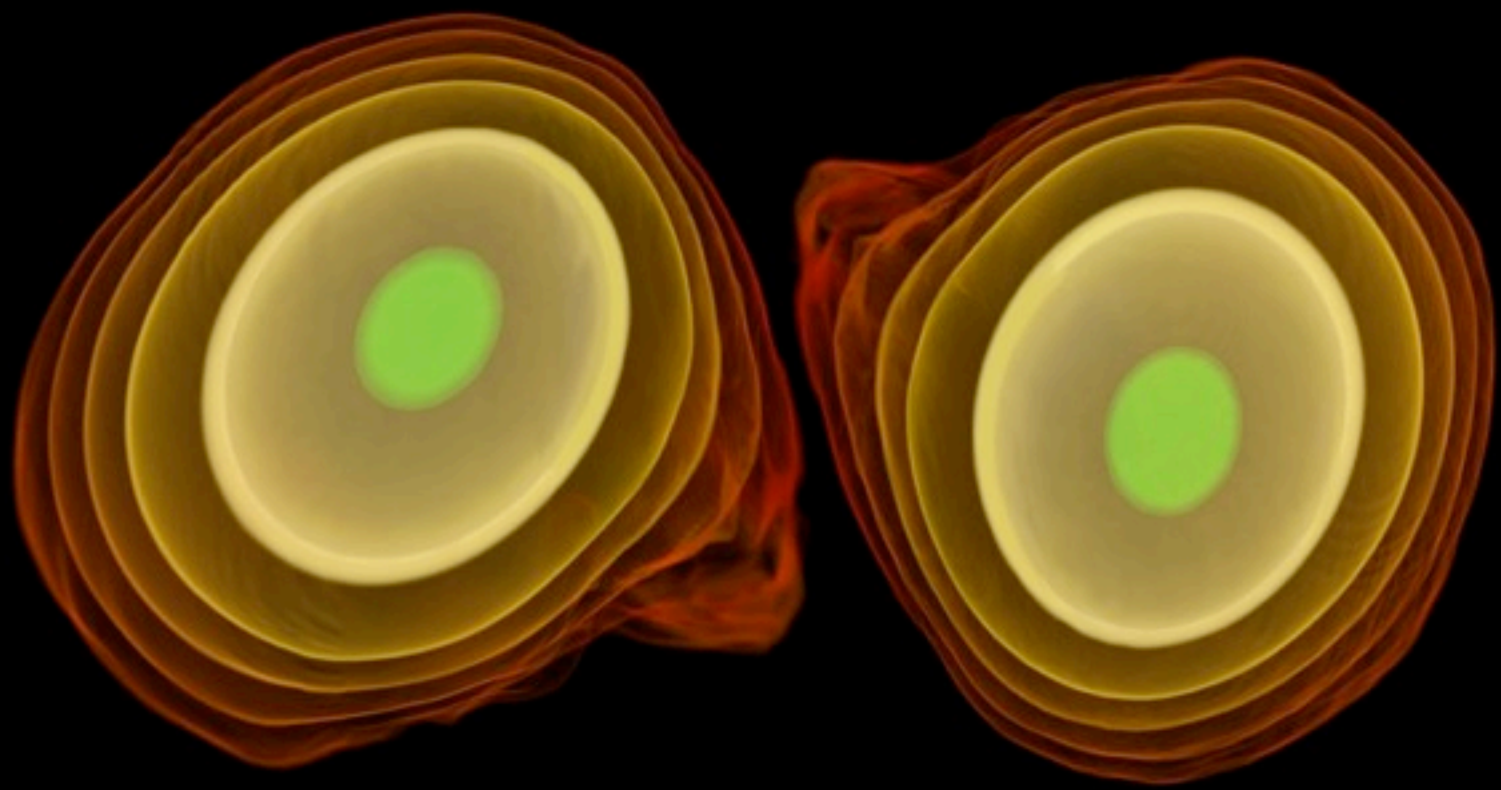


The computed BH recoil is shown in the right panel and indicates a positive acceleration and then a negative one

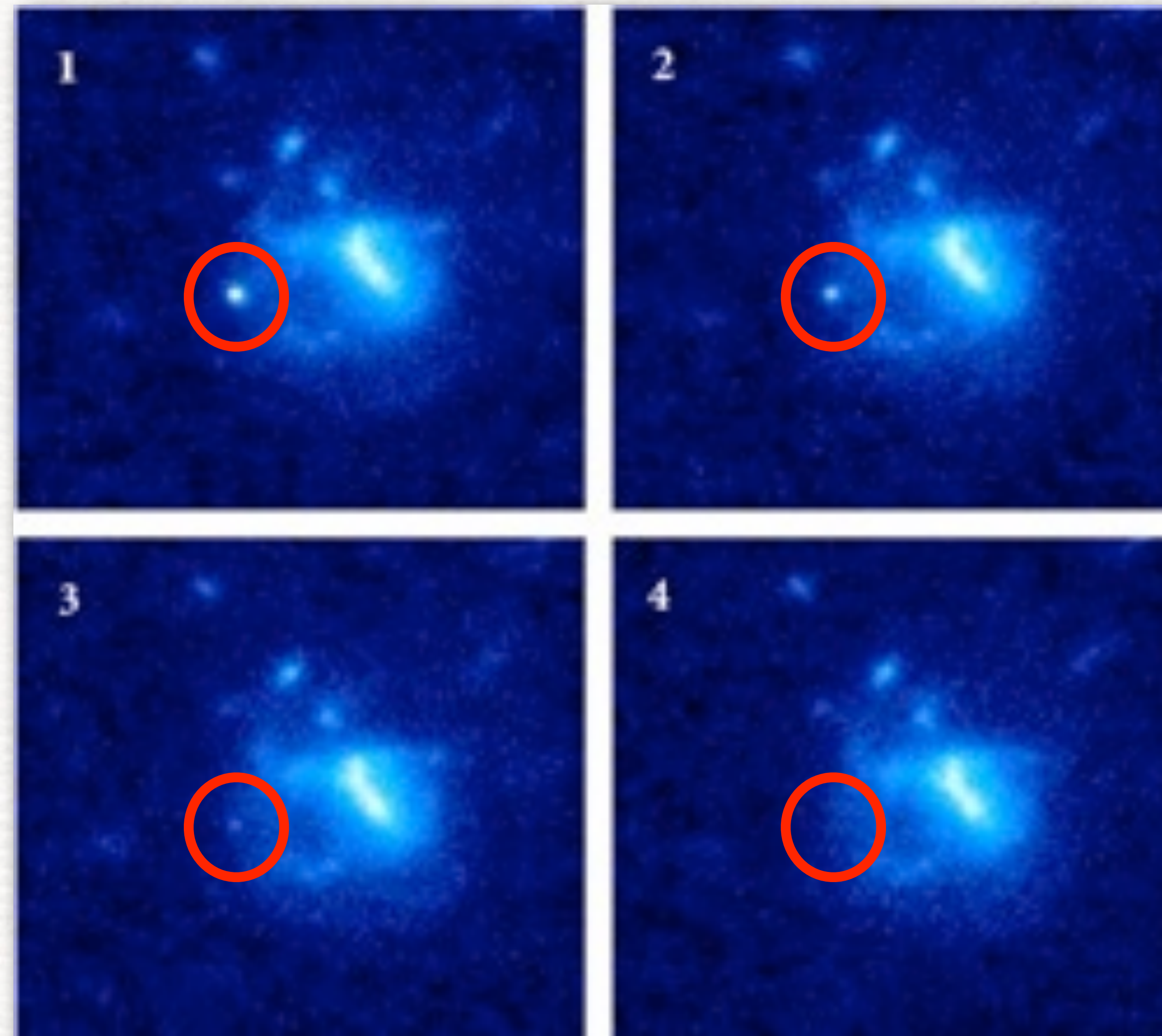
Binary Neutron Stars



Baiotti, Giacomazzo, LR, PRD (2008); Baiotti, Giacomazzo, LR, CQG (2009); Giacomazzo, LR, Baiotti, MNRAS (2009); LR, et al CQG 2010); Giacomazzo, LR, Baiotti, PRD (2011); Baiotti et al, PRL (2010); LR et al (ApJL 2011)

Why investigate binary neutron stars?

- We know they exist (as opposed to binary BHs) and are among the strongest sources of GWs
- We expect them related to SGRBs: energies released are huge: $10^{48\text{-}50}$ erg. Equivalent to what released by the whole Galaxy over ~ 1year:



short GRB, artist impression (NASA)

- Despite decades of observations no self-consistent model has yet been produced to explain them.
- go from an artist impression to a scientist impression

The two-body problem: GR

Any two-body system inspirals and will eventually merge. Binary black holes (BHs) and binary neutron stars (BNSs) behave differently and not only because the equations are different.

- For BHs we know what to **expect**:

BH + BH $\longrightarrow$ BH + gravitational waves (GWs)

- For NSs the question is more **subtle:** the merger leads to an hyper-massive neutron star (HMNS), ie a metastable equilibrium:

NS + NS $\longrightarrow$ HMNS + **... ?** $\longrightarrow$ BH + torus + **... ?** $\longrightarrow$ BH

All the physics and complications are in the intermediate stages; the rewards are however high (EOS,GRBs, nuclear physics, etc).

"merger → HMNS → BH + torus"

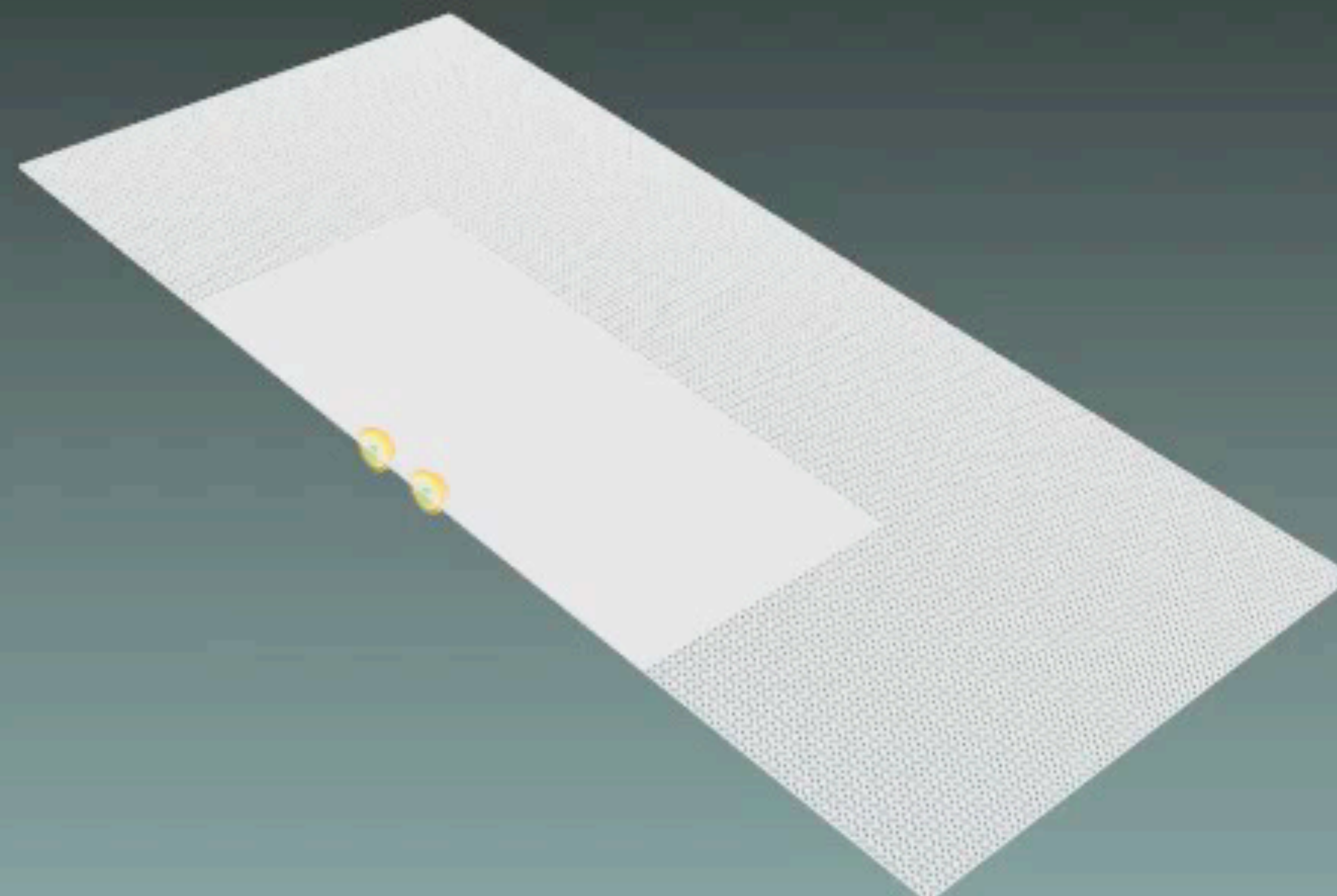
Quantitative differences are produced by:

- **differences induced by the gravitational MASS:**

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

Animations: Kaehler, Giacomazzo, LR

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

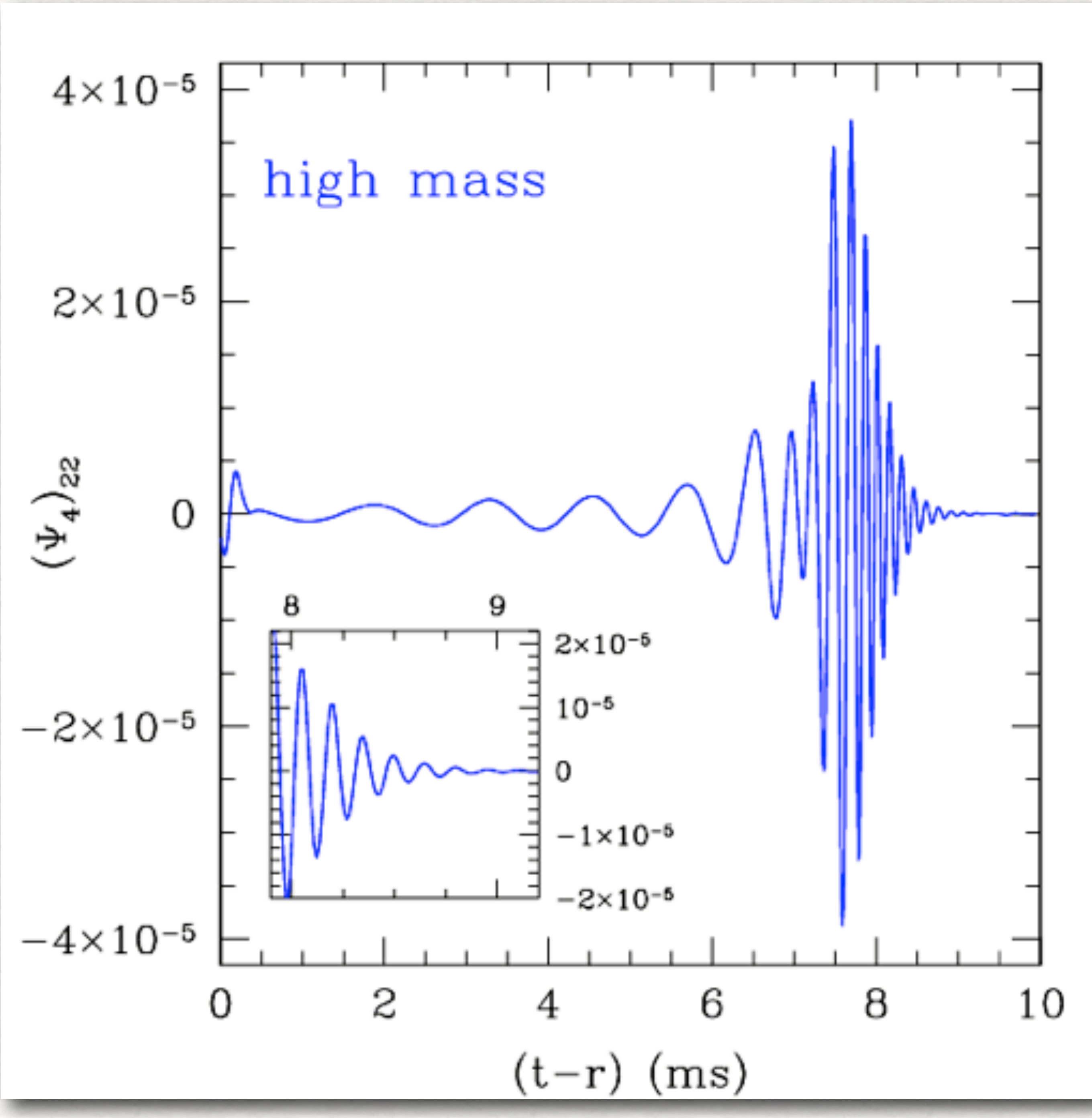


Cold EOS: **high-mass** binary

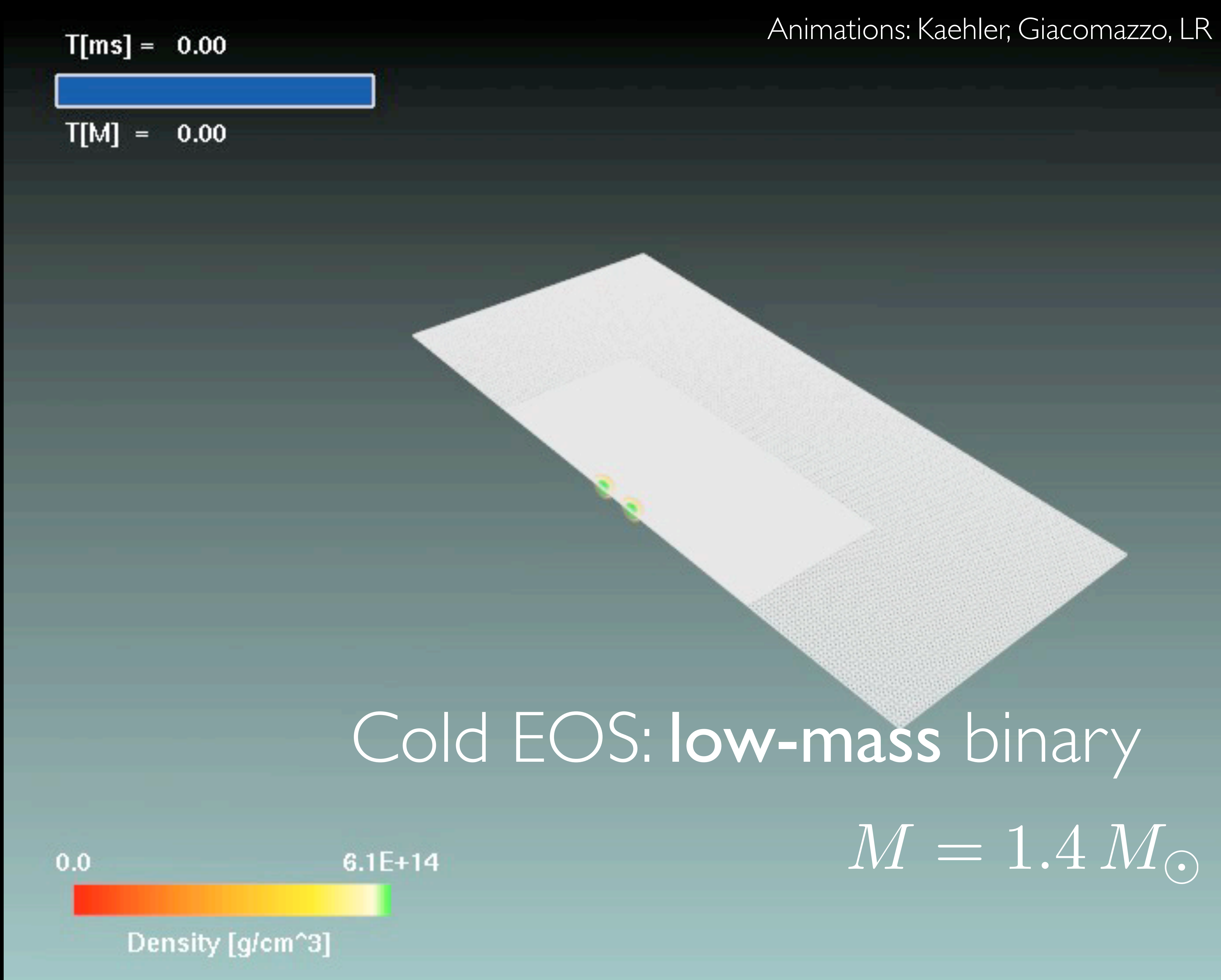
$$M = 1.6\, M_{\odot}$$

Waveforms: cold EOS

high-mass binary



Animations: Kaehler, Giacomazzo, LR

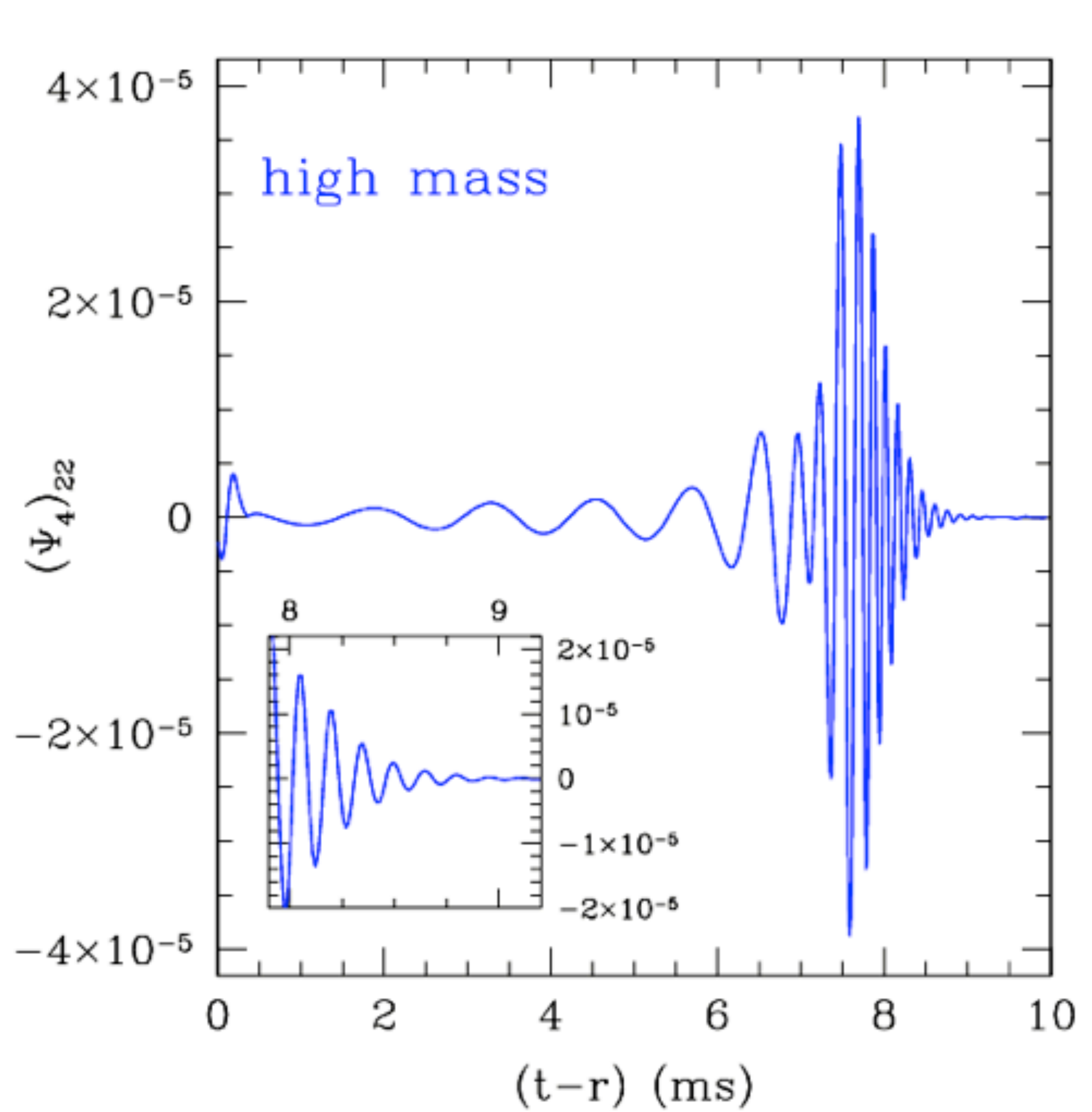


Cold EOS: **low-mass** binary

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

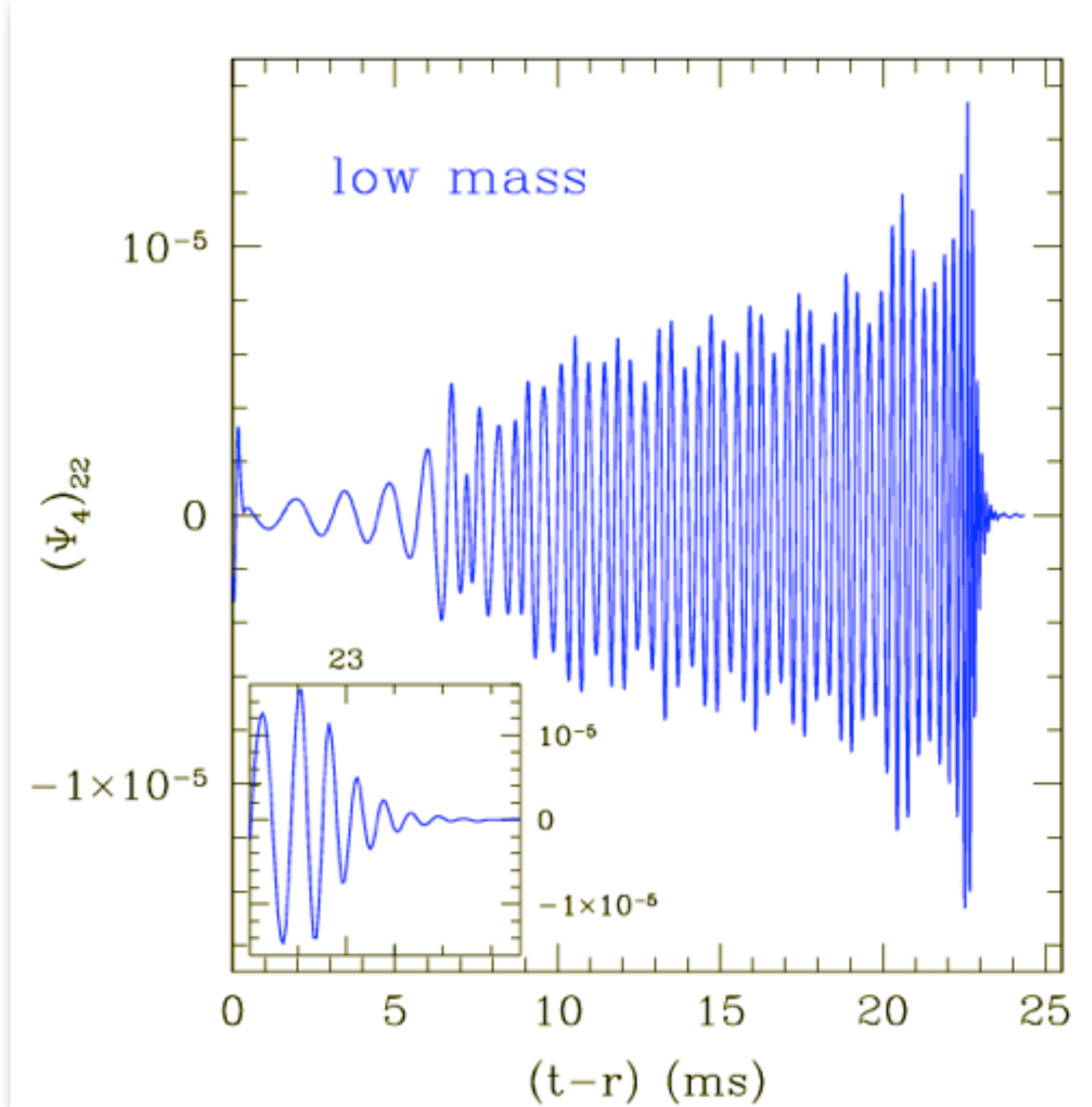
Waveforms: cold EOS

high-mass binary



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

"merger → HMNS → BH + torus"

Quantitative differences are produced by:

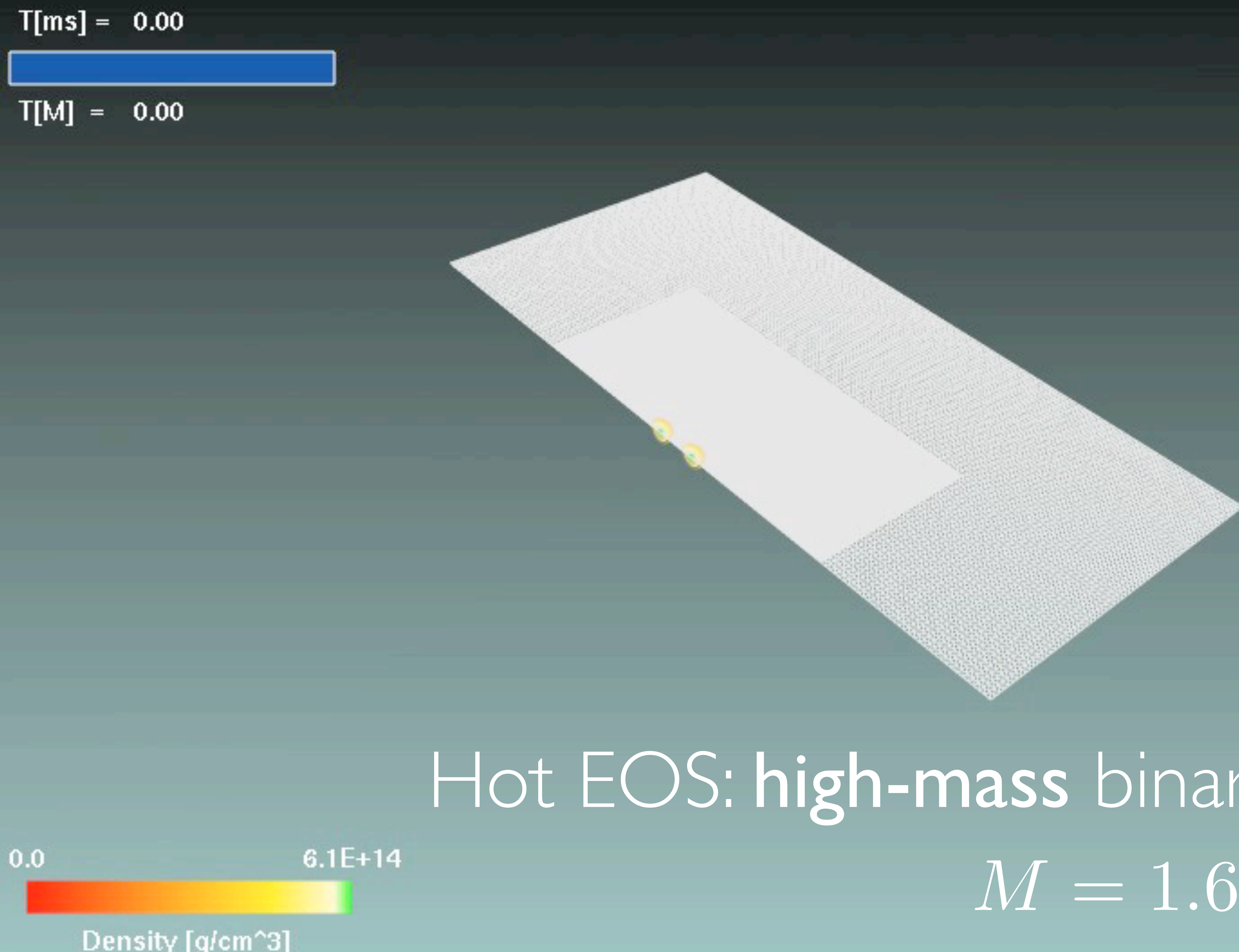
- **differences induced by the gravitational MASS:**

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

- **differences induced by the EOS ("cold" or "hot"):**

  a binary with an EOS with large thermal capacity (ie hotter after merger) will have more pressure support and collapse later

Animations: Kaehler, Giacomazzo, Rezzolla



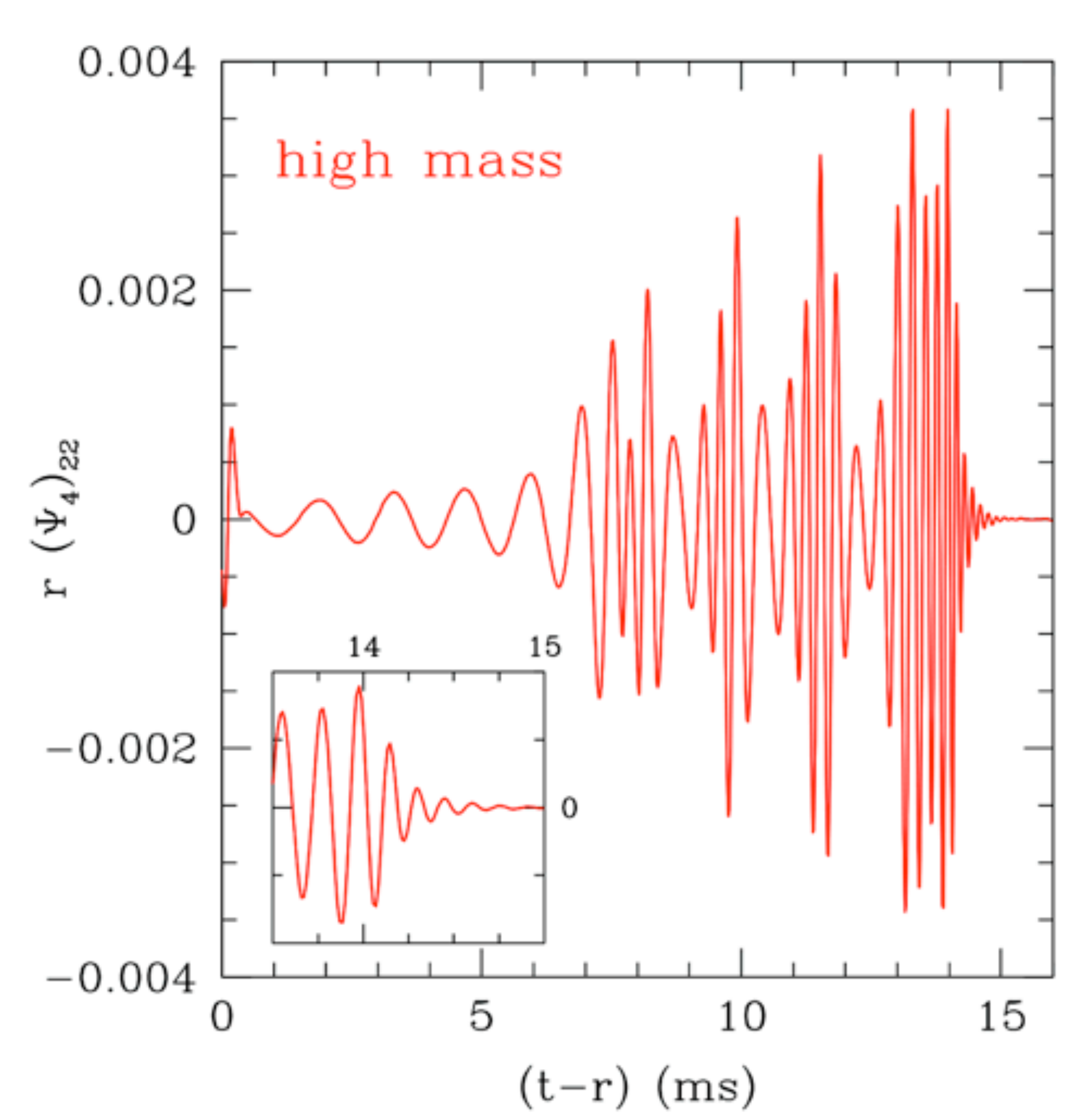
Hot EOS: **high-mass** binary

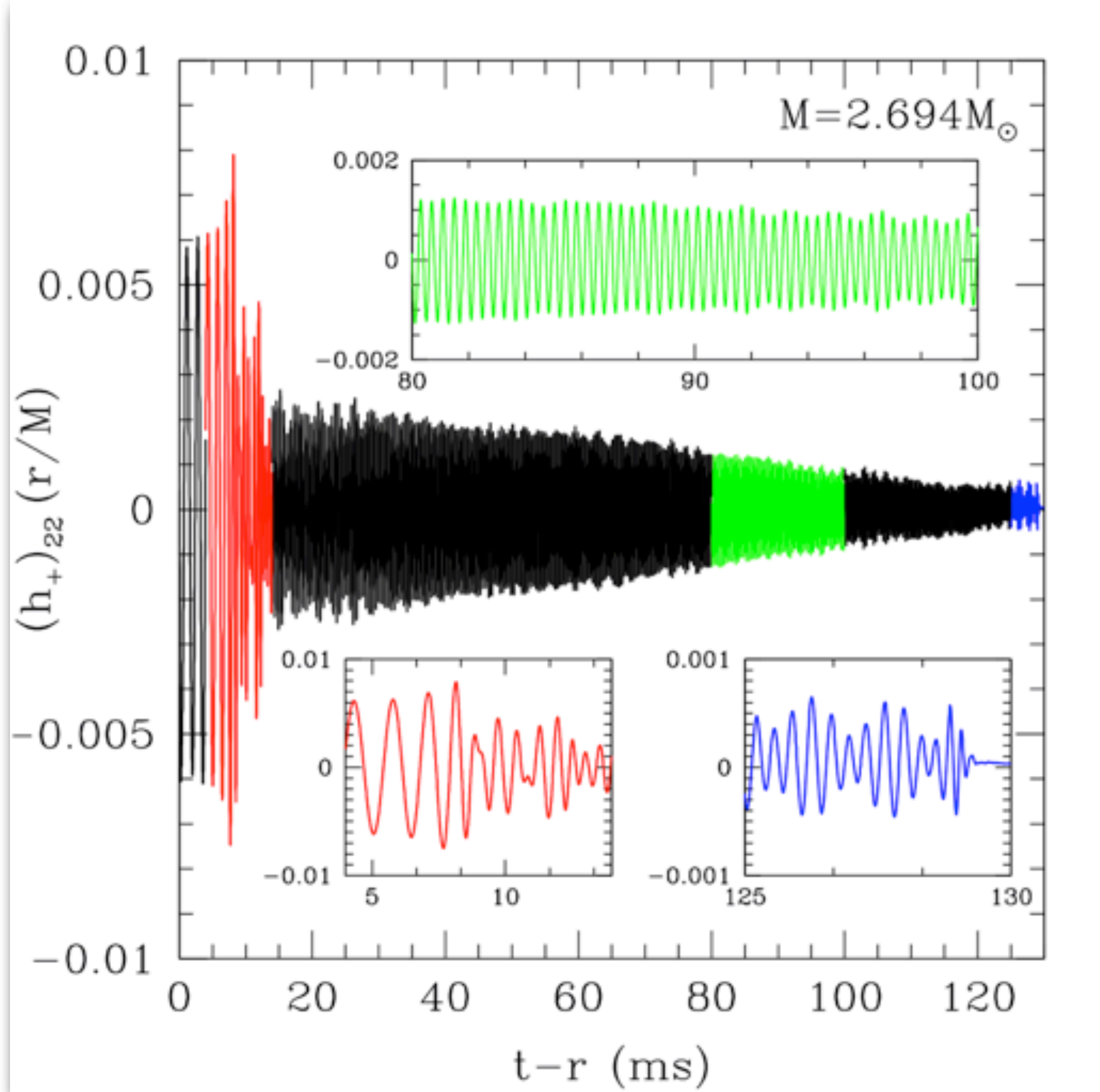
$M = 1.6\, M_\odot$

Waveforms: hot EOS

high-mass binary

low-mass binary

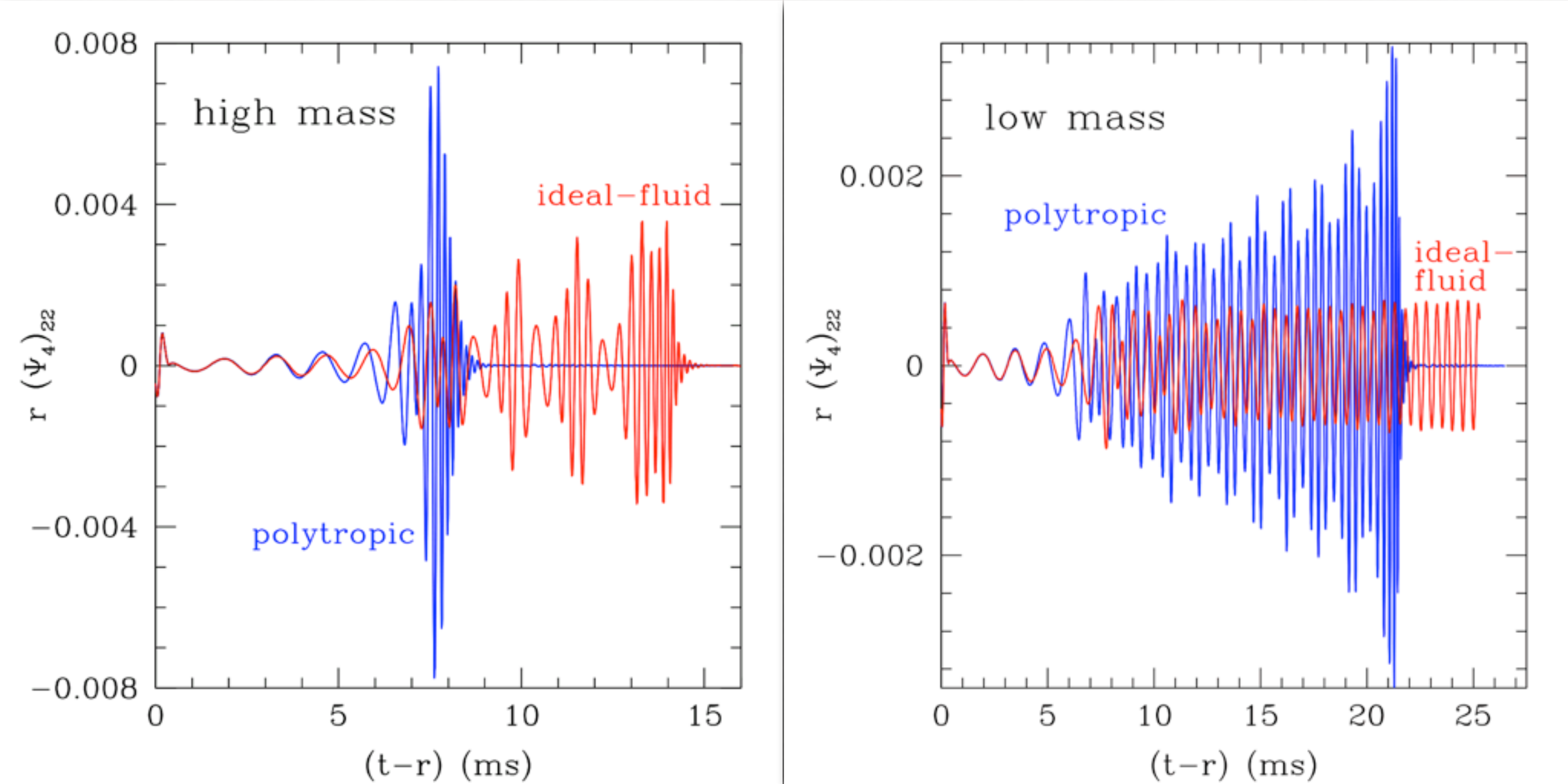




the high internal energy (temperature) of the HMNS prevents a prompt collapse

the HMNS evolves on longer (radiation-reaction) timescale

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



With sufficiently sensitive detectors, GWs will work as the Rosetta stone to decipher the NS interior

"merger → HMNS → 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 and will collapse at a later time
- **differences induced by the EOS ("cold" or "hot"):**
  a binary with an EOS with large thermal capacity (ie hotter after merger) will have more pressure support and collapse later
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH
- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse
- **differences induced by RADIATIVE PROCESSES:**
  radiative losses will alter the equilibrium of the HMNS

Extending the work to MHD

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.

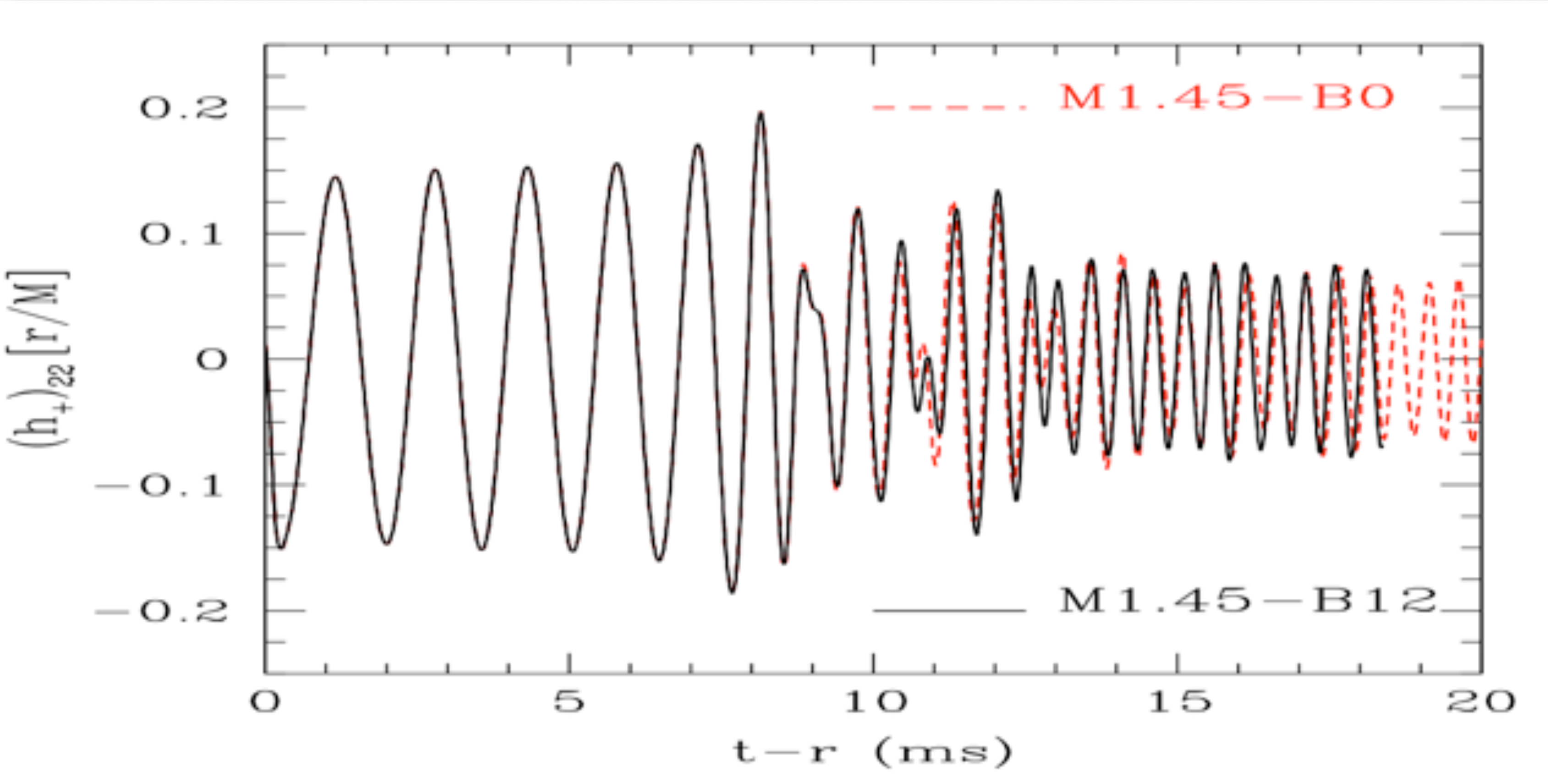
▸ We have considered 12 binaries (low/high mass) with MFs:

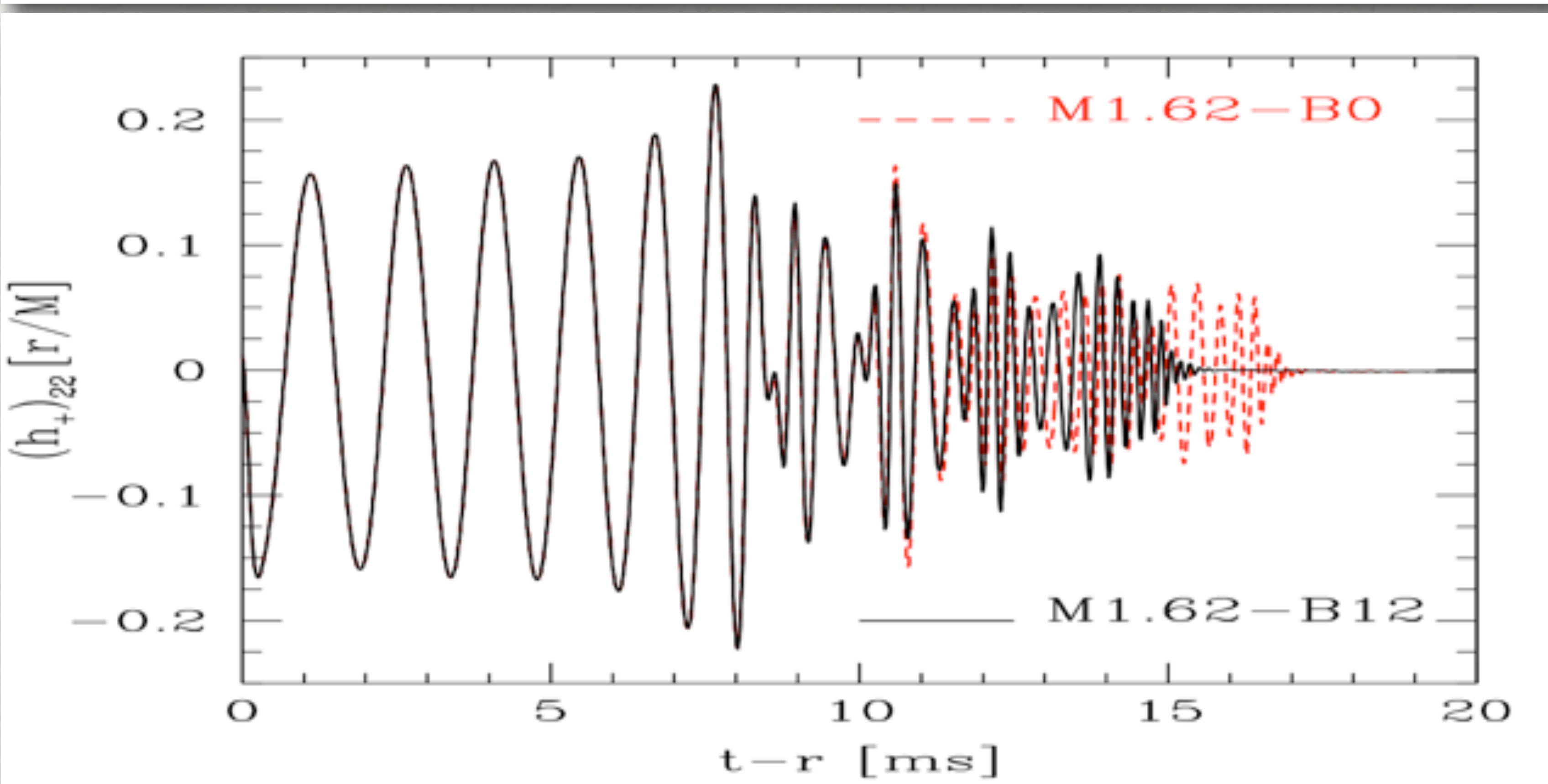
$$B = 0,\ 10^8,\ 10^{10},\ 10^{12},\ 10^{14},\ 10^{17}\ \mathrm{G}$$

Animations:, LR, Koppitz

Typical evolution for a magnetized binary (hot EOS) $M = 1.5\,M_\odot, B_0 = 10^{12}\,\mathrm{G}$

Waveforms: comparing against magnetic fields





Compare B/no-B field:

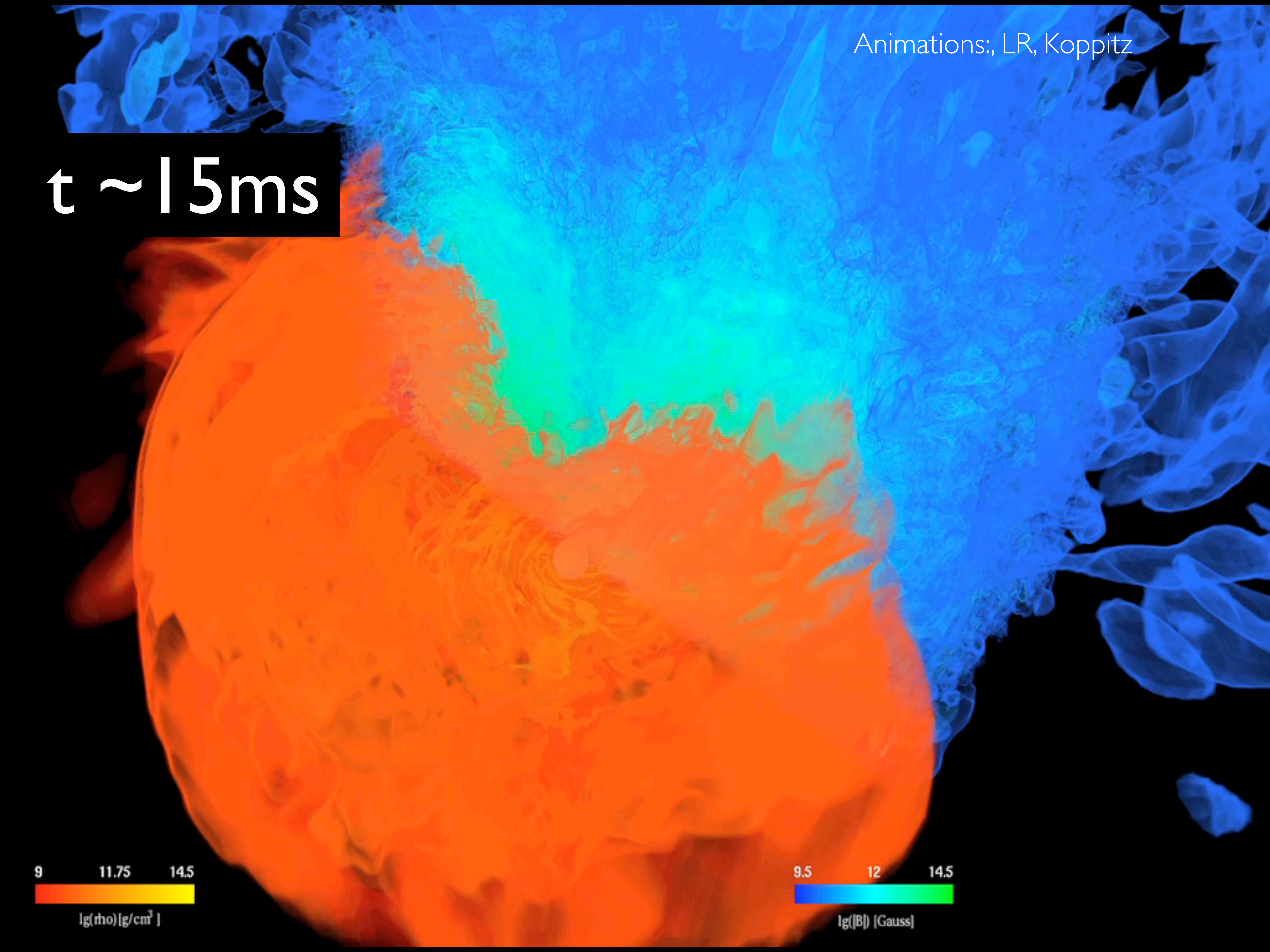
- the evolution in the **inspiral** is different but only for ultra large B-fields ($B \sim 10^{17}$ G)
- the **post-merger** evolution is different for all masses; strong B-fields delay the collapse to BH

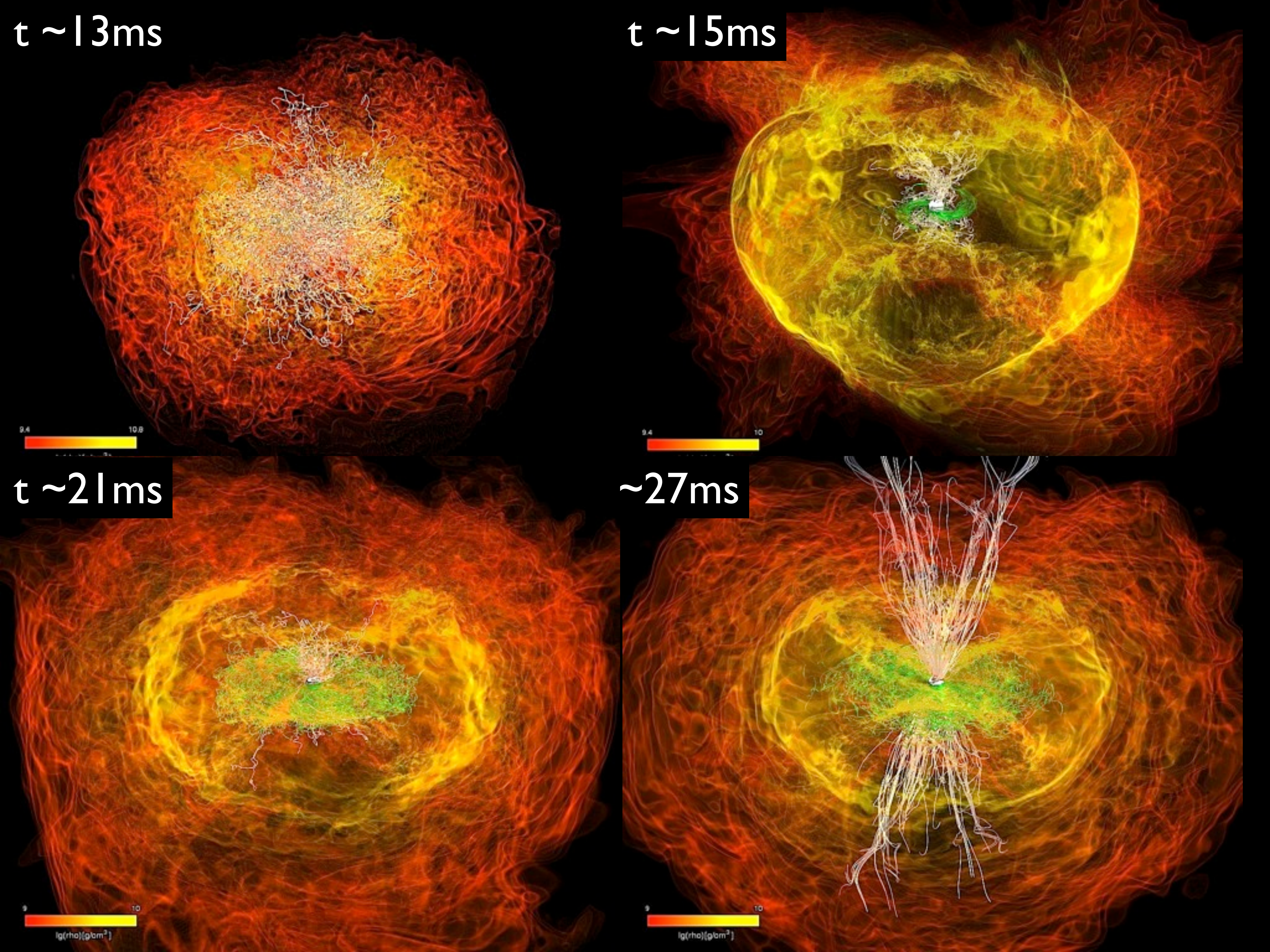
However, mismatch is too small for present detectors: influence of B-fields on the inspiral is **cannot be detected!**

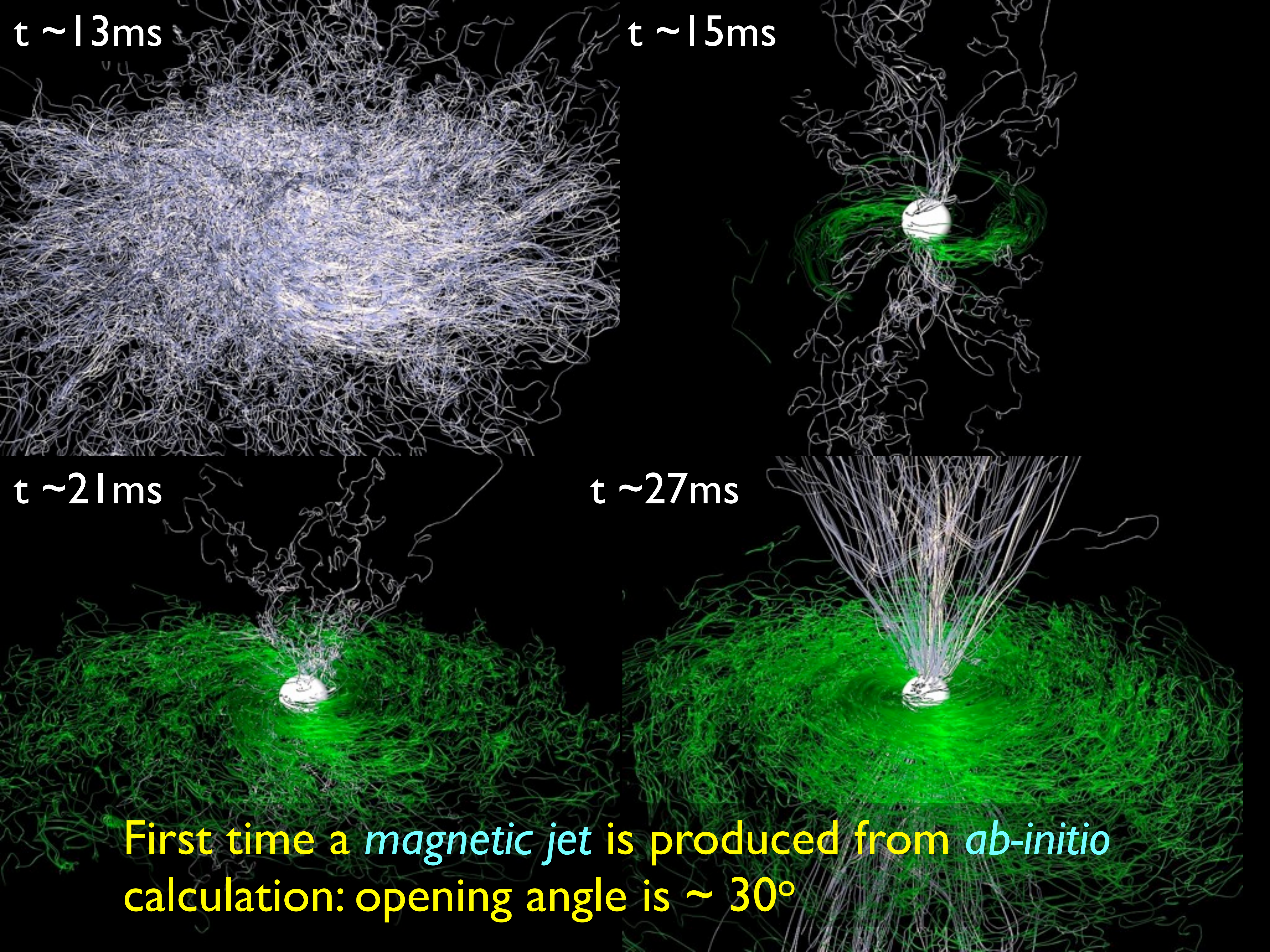
Going beyond BH formation

From a gravitational-wave point of view, the binary becomes silent after BH formation and ringdown.

Is that really the end of the story?


Animations:, LR, Koppitz
t ~15ms
9
11.75
14.5
lg(rho) [g/cm³]
9.5
12
14.5
lg(|B|) [Gauss]


t ~13ms
9.4
10.8
t ~15ms
9.4
10
t ~21ms
9
10
lg(rho)[g/cm^3]
~27ms
9
10
lg(rho)[g/cm^3]



First time a *magnetic jet* is produced from *ab-initio* calculation: opening angle is ~ 30°

Conclusions

✴Evolution of BBHs is under control and accurate waveforms are possible in large space of parameters. Small mass ratios and a better understanding of the nonlinear dynamics are the frontier.

✴With simple EOSs have reached possibly the most complete description of BNSs from the inspiral, merger, collapse to BH. Can draw this picture with/without B-fields, equal and unequal masses.

✴GWs from BNSs are much complex/richer than from BBHs: can be the Rosetta stone to decipher the NS interior.

✴Magnetic fields unlikely to be detected during the inspiral but important after the merger (amplified by dynamos/instabilities)

✴**Numerical relativity is a very versatile tool to explore new aspects of fundamental physics and astrophysics**