Binary neutron stars to explore nuclear physics and astrophysics

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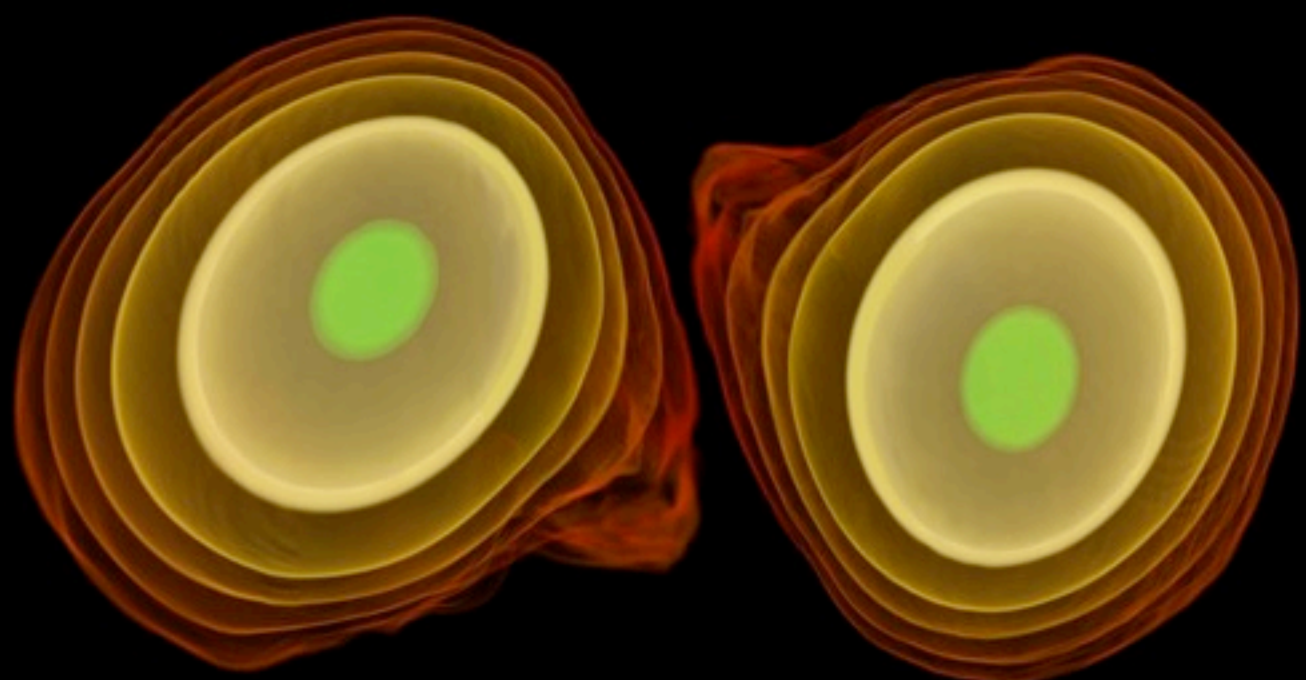


Recent developments in astronuclear and astroparlicle physics,
Trieste, 21/11/12

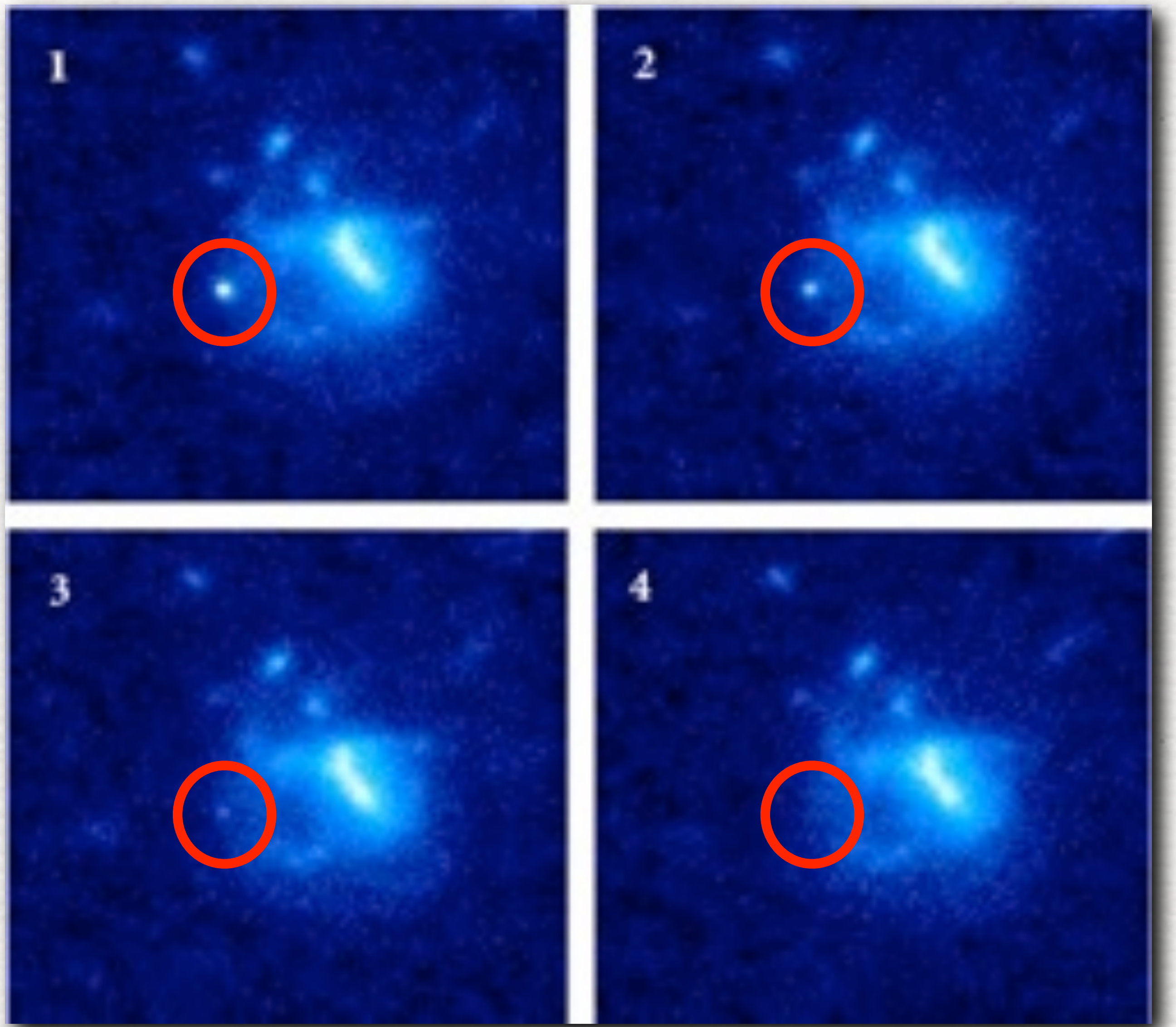
Plan of the talk

- Binary neutron stars in full GR:
  - ✴ probes of fundamental physics
  - ✴ probes of high-energy astrophysics

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

Why investigate binary neutron stars?

- We know they exist as opposed to binary BHs, whose existence is expected but never observed.
- Excellent sources of gravitational waves (GWs) and are expected to be most common source for advanced detectors



- We expect them related to SGRBs: energies released ~ $10^{48\text{-}50}$ erg.
- Despite decades of observations no self-consistent model has yet been produced to explain them

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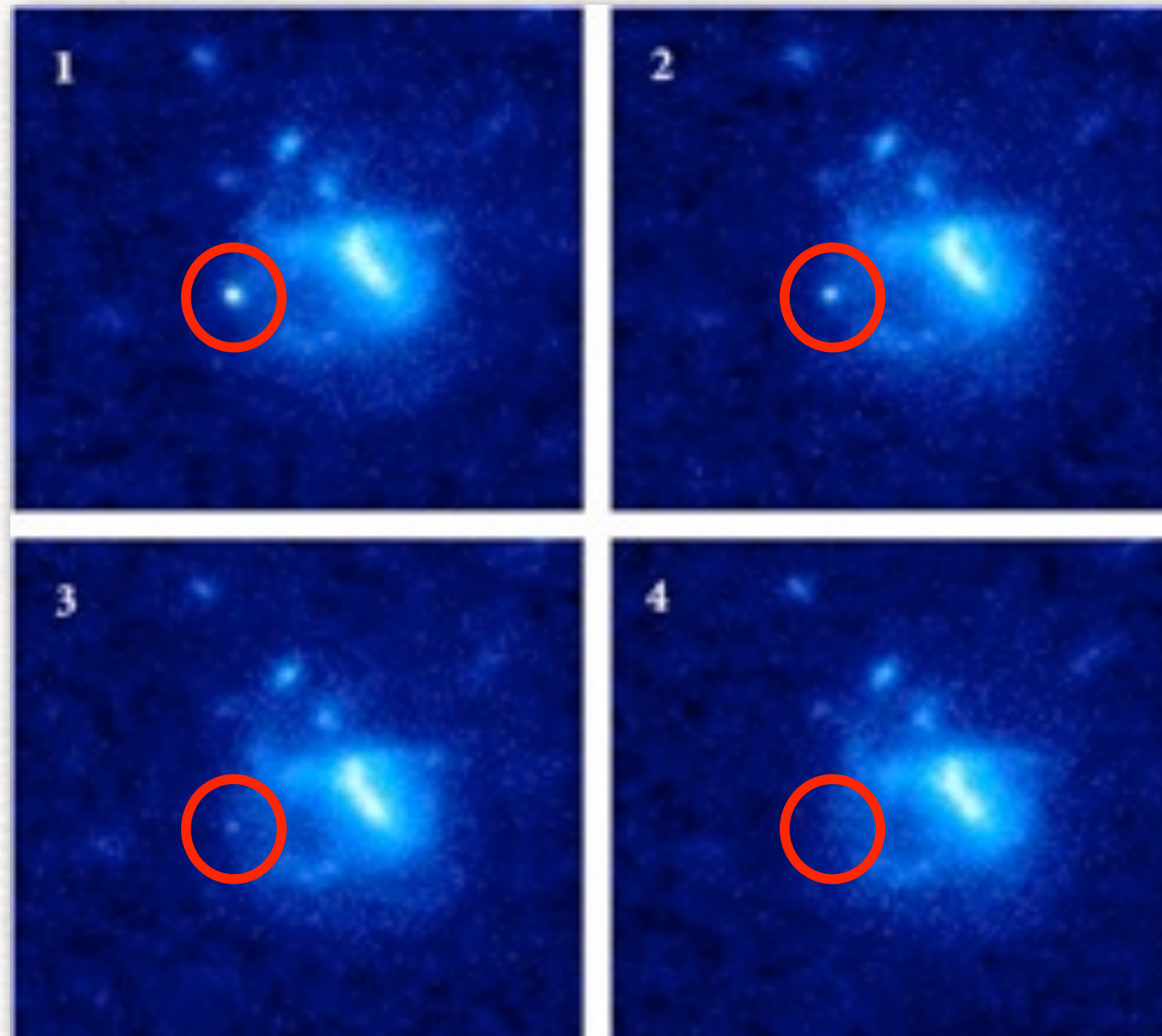
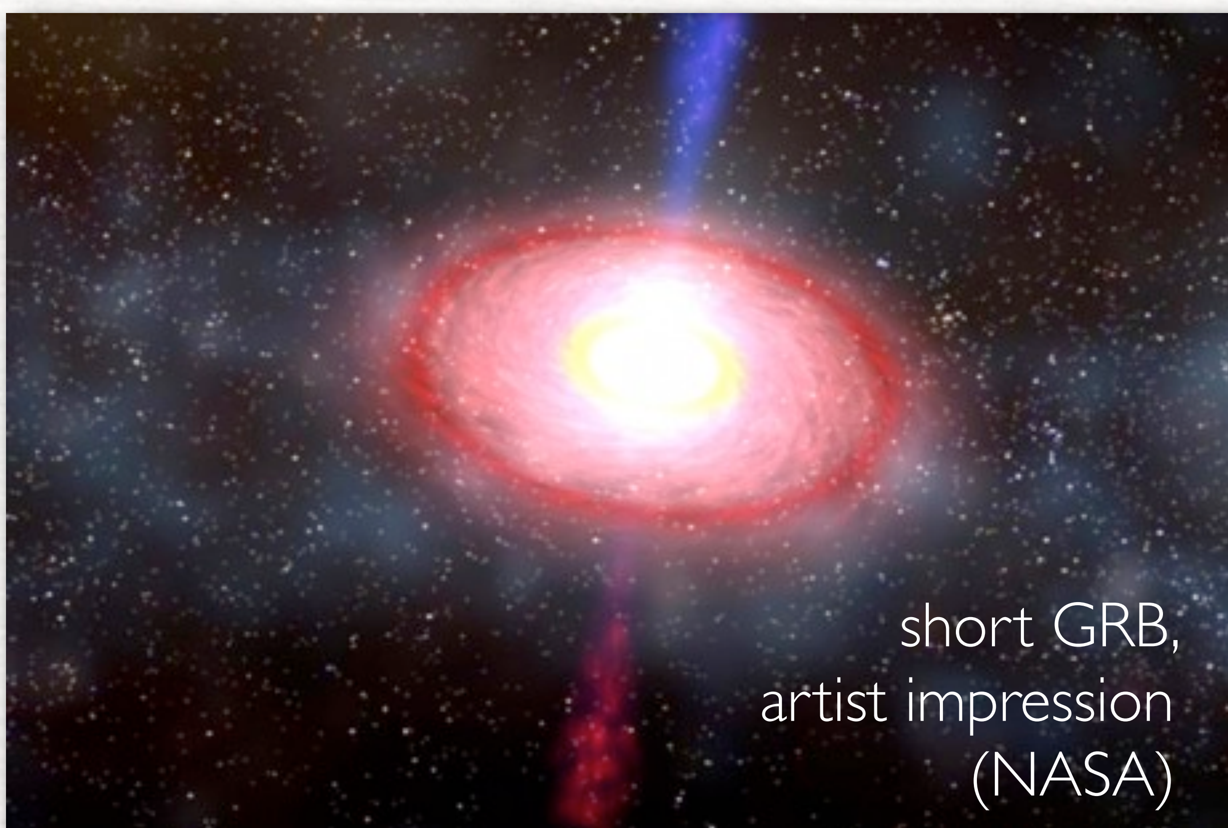




short GRB,
artist impression
(NASA)

- We expect them related to SGRBs: energies released ~ $10^{48\text{-}50}$ erg.
- Despite decades of observations no self-consistent model has yet been produced to explain them

Mathematical framework

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**".

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

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

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

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

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

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

It's our approximation to *"reality"* and it can be continuously improved: microphysics, magnetic fields, viscosity, radiation transport, resistive effects, ...

The two-body problem in GR

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

BH + BH → 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 → HMNS + **... ?** → BH + torus + **... ?** → BH

All complications are in the intermediate stages; the rewards high:

- studying the HMNS will show strong and precise imprint on the EOS
- studying the BH+torus will tell us on the central engine of GRBs

NOTE: with advanced detectors we expect to have a **realistic** rate of ~**40 BNSs** inspirals a year, ie ~ 1 a week (Abadie+ 2010) *“merger → HMNS → BH + torus”*

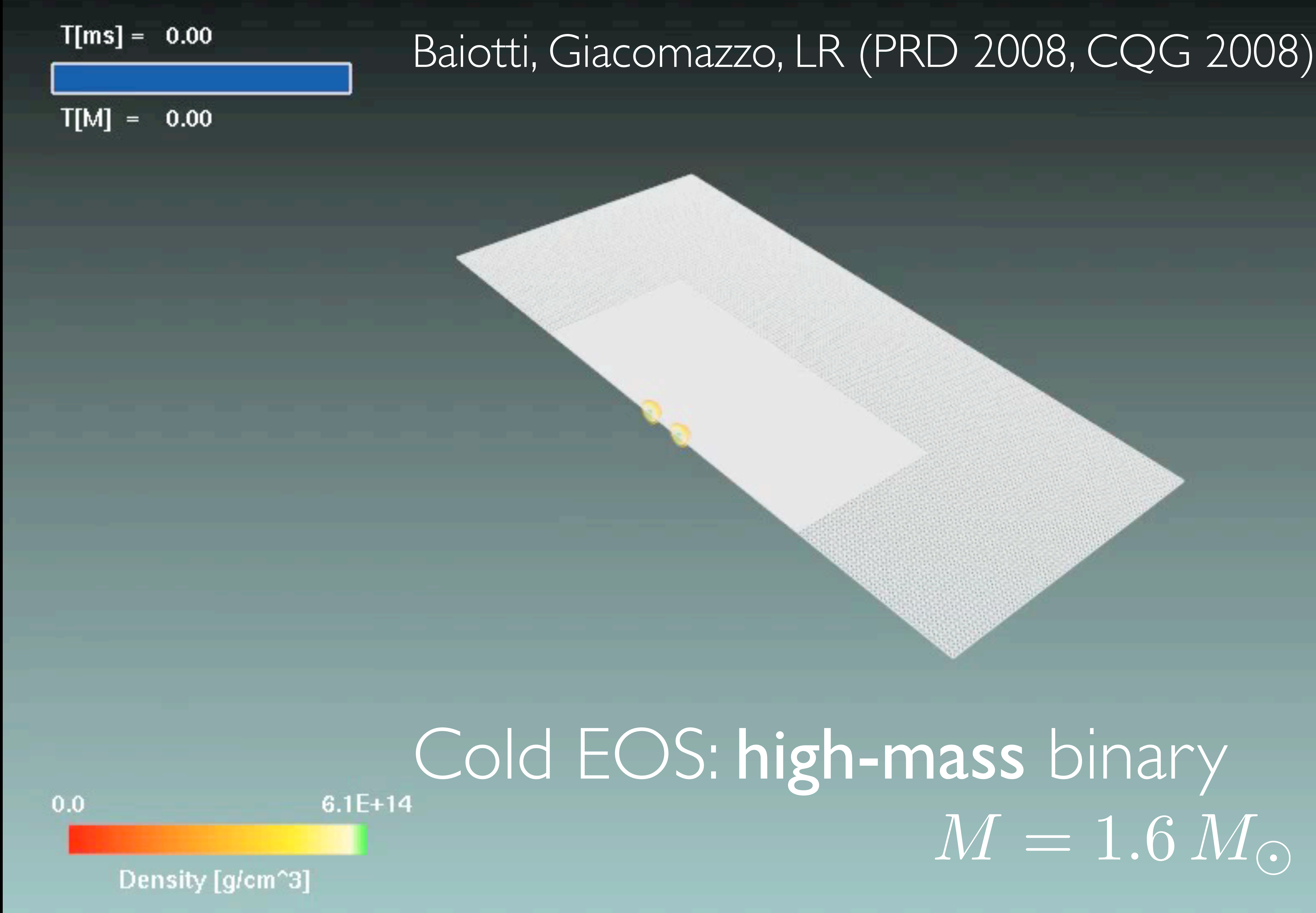
Quantitative differences are produced by:

- **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)

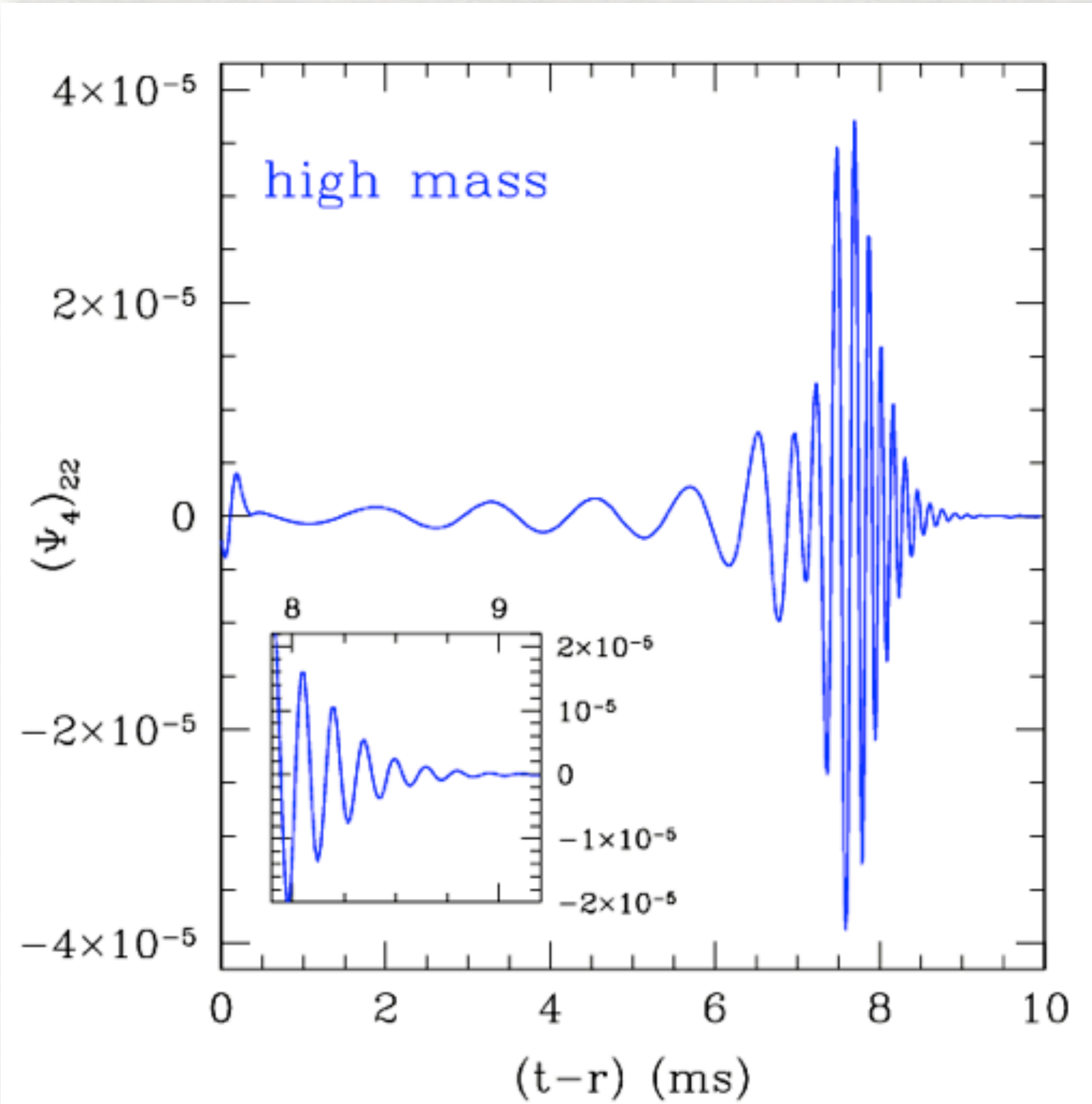


Cold EOS: **high-mass** binary

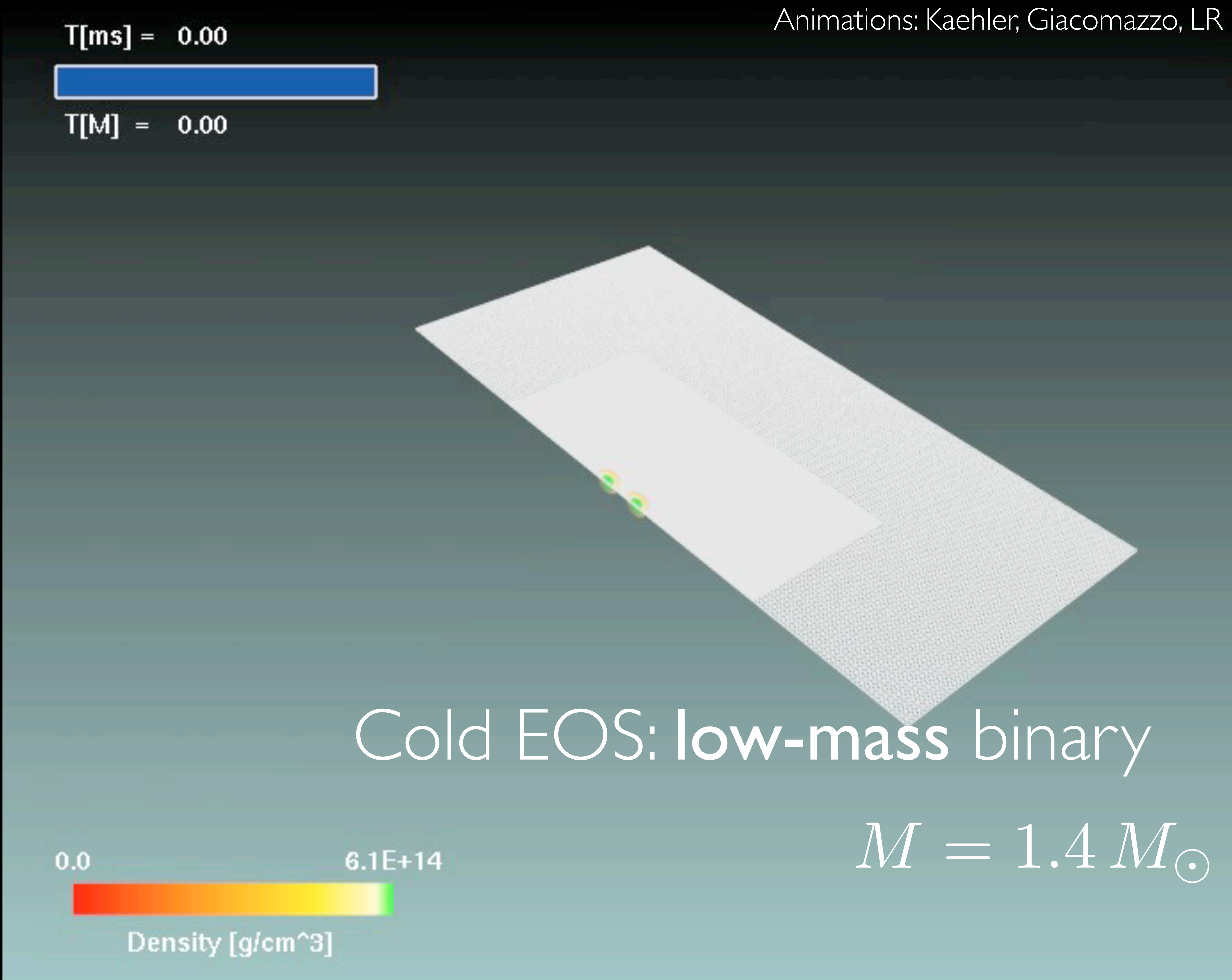
$$M = 1.6\, M_{\odot}$$

Waveforms: cold EOS

high-mass binary



Animations: Kaehler, Giacomazzo, LR

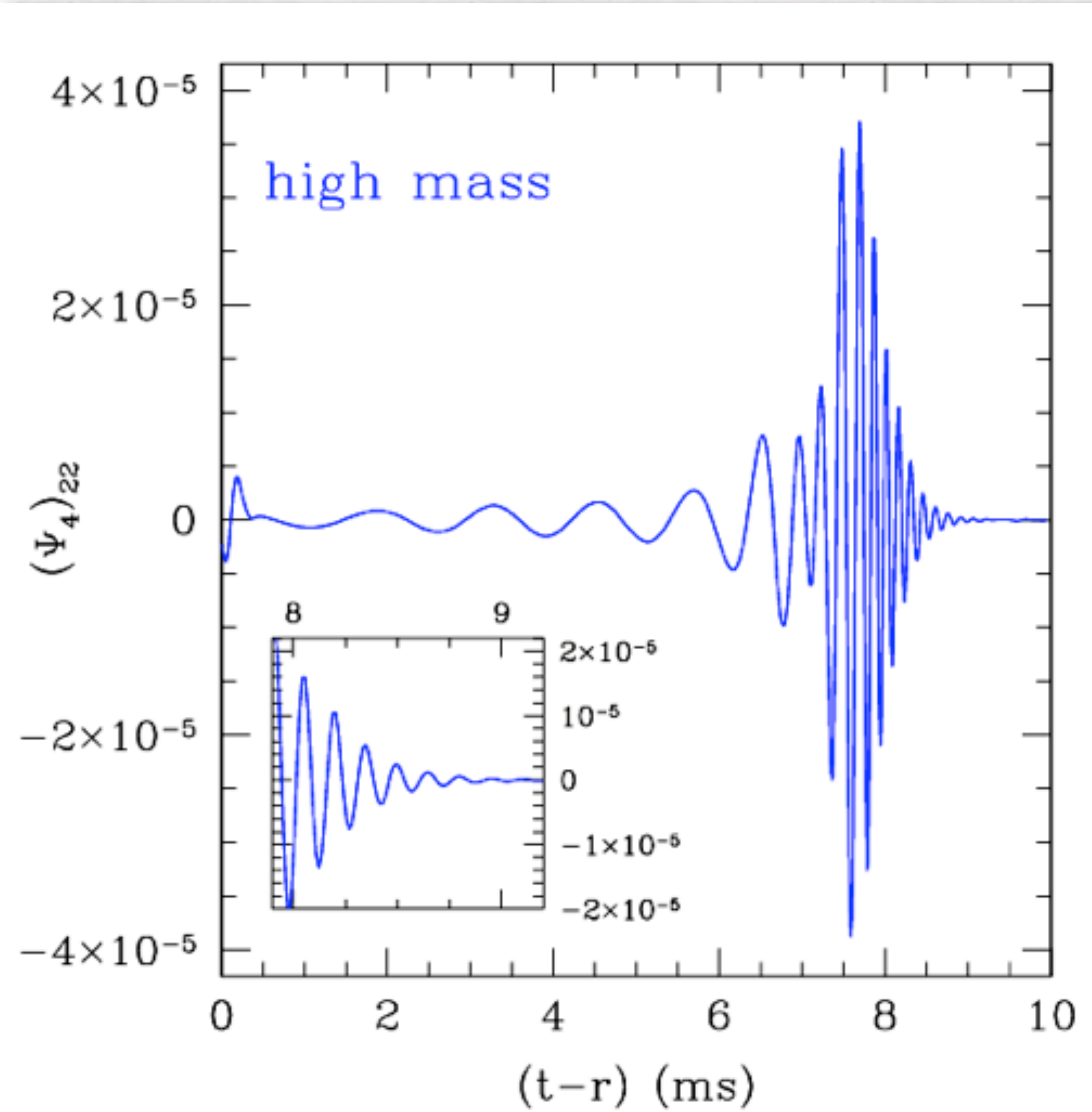


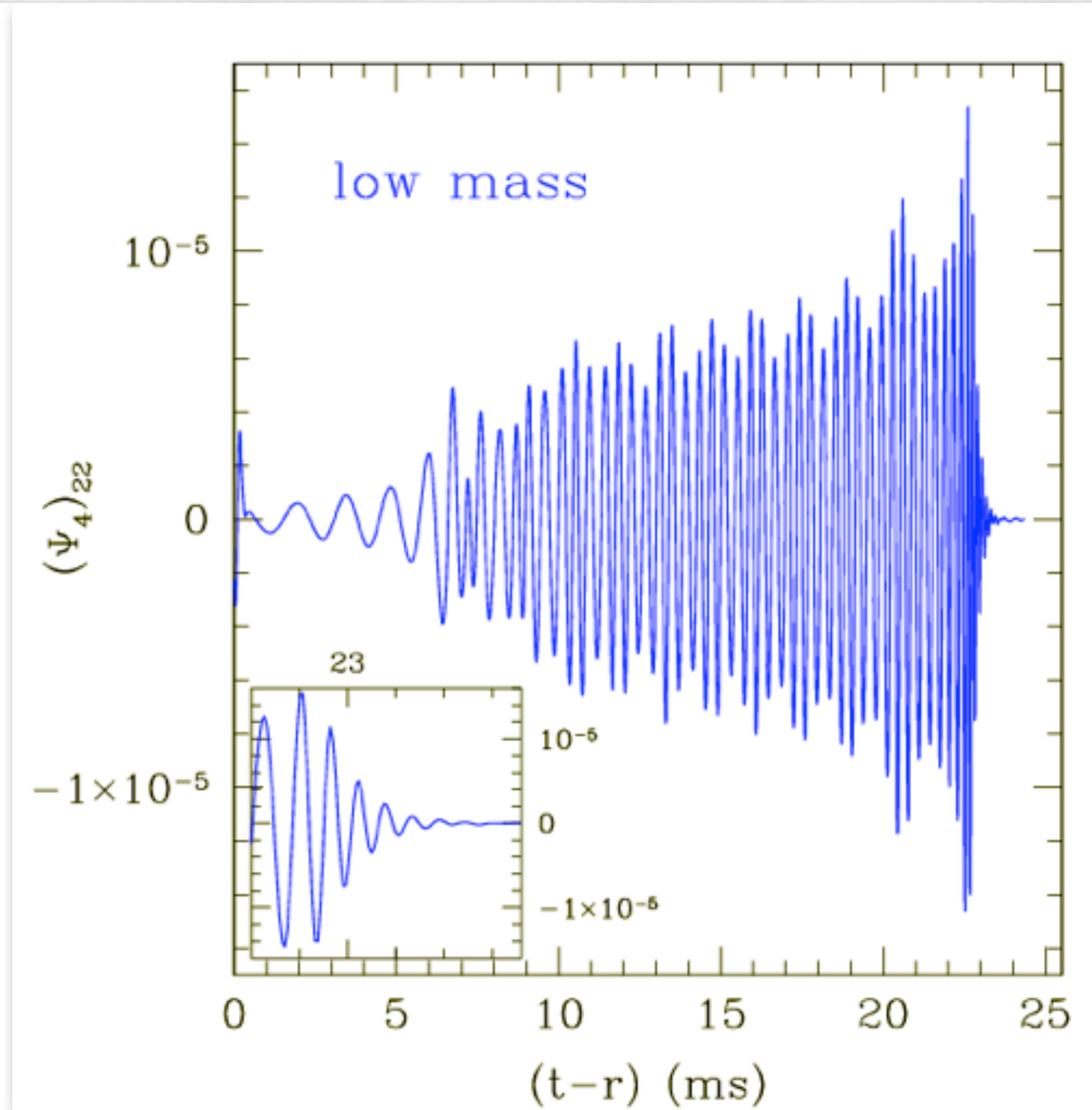
Cold EOS: **low-mass** binary

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

Waveforms: cold EOS

high-mass binary　　　　low-mass binary





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

development of a bar-deformed NS leads to a long gw signal *"merger → HMNS → BH + torus"*

Quantitative differences are produced 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

- **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

Here:

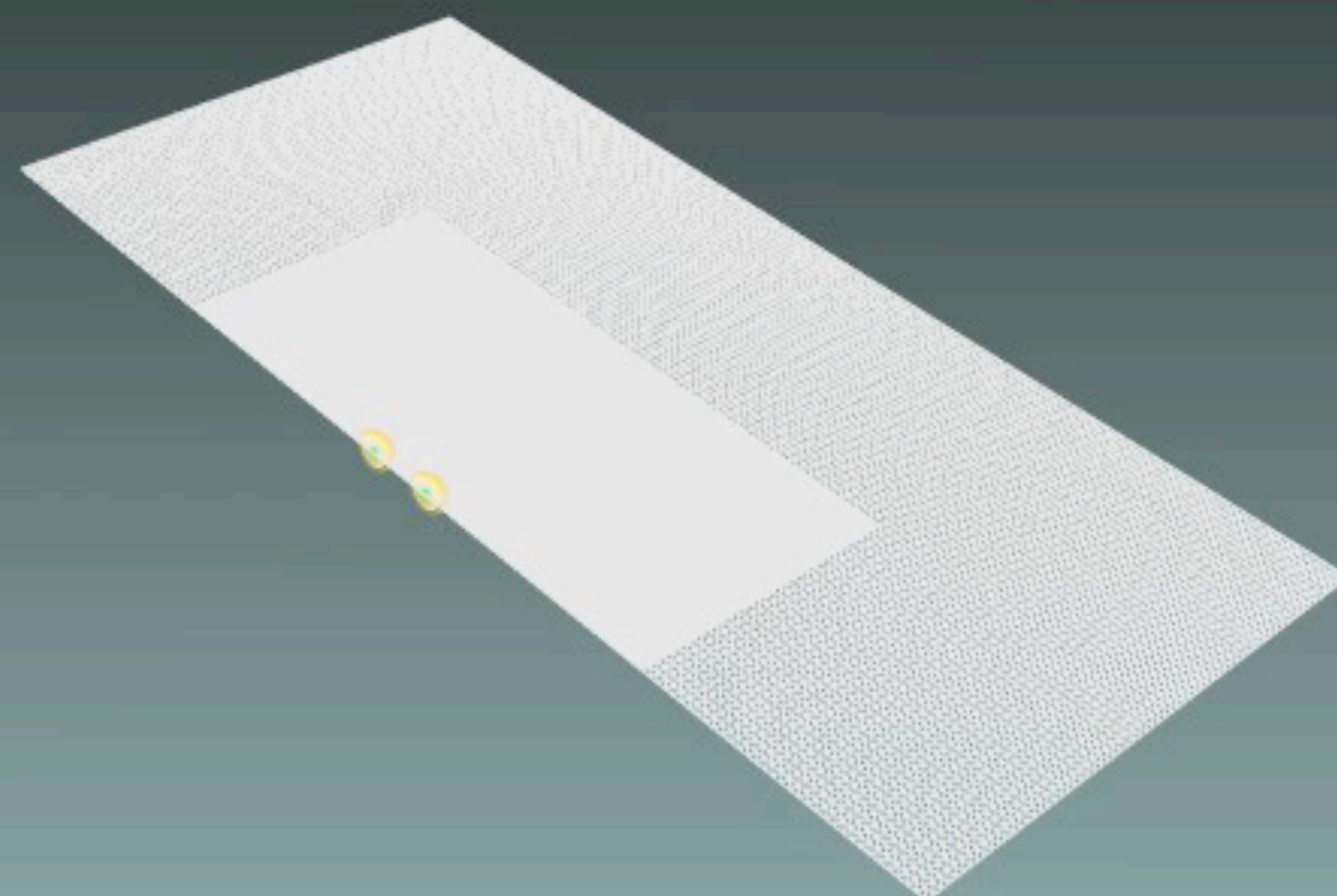
"cold" is a polytropic EOS: $p = K\rho^{\Gamma}$

"hot" is an ideal-fluid EOS: $p = \rho\epsilon(\Gamma - 1)$

Animations: Kaehler, Giacomazzo, Rezzolla

T[ms] = 0.00

T[M] = 0.00



Hot EOS: **high-mass** binary

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

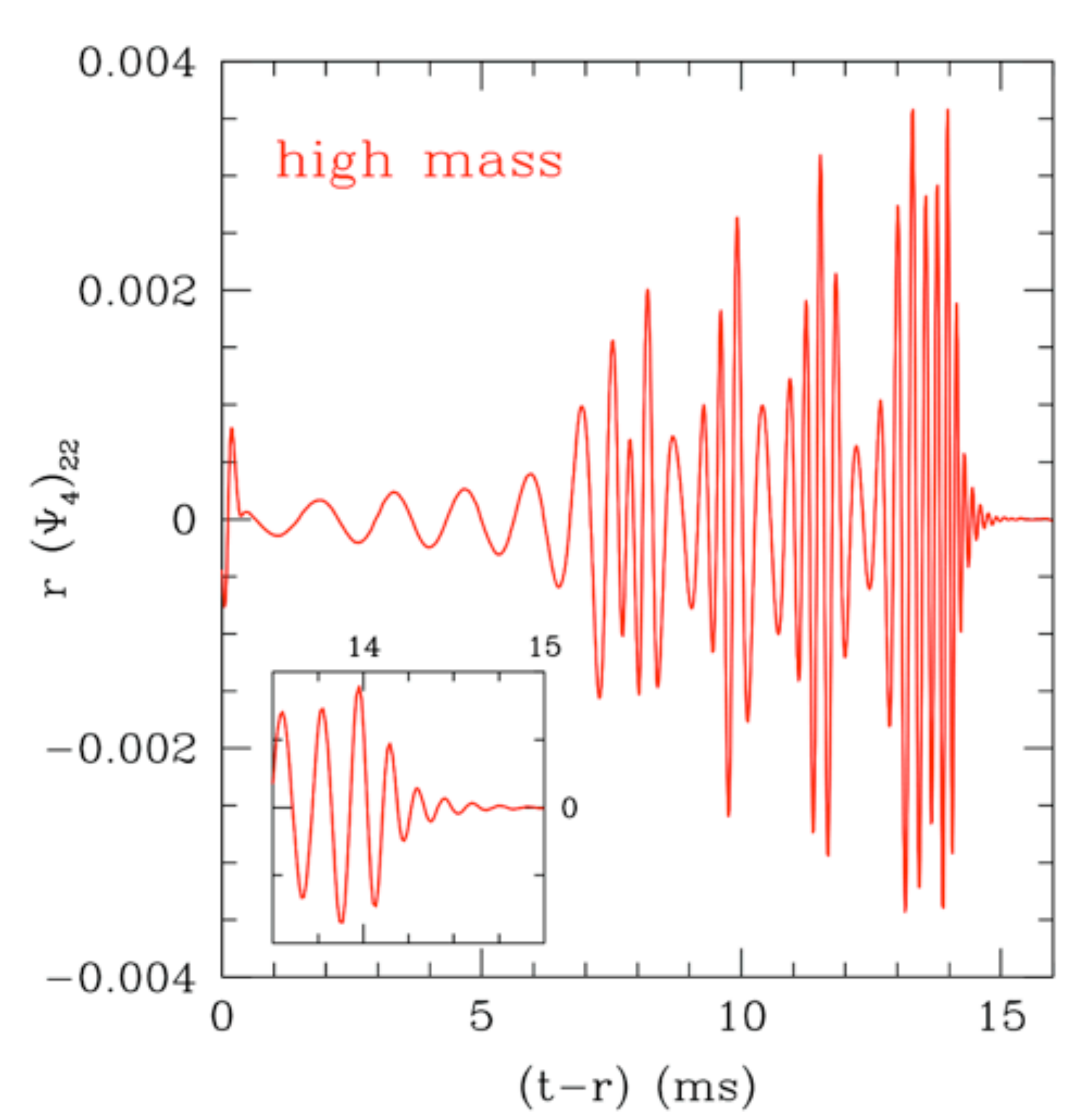
0.0 6.1E+14

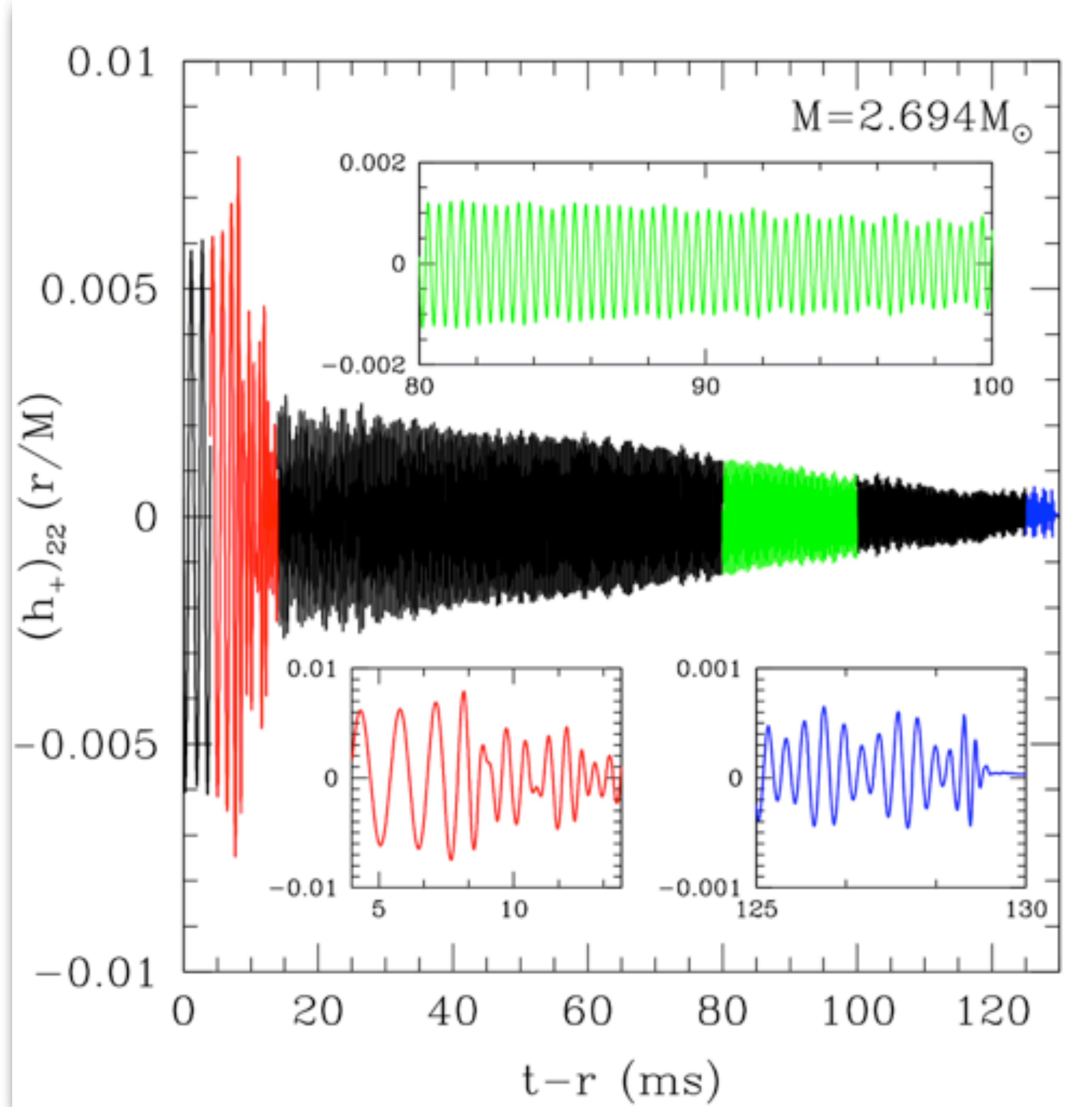
Density [g/cm^3]

Waveforms: hot EOS

high-mass binary

low-mass binary

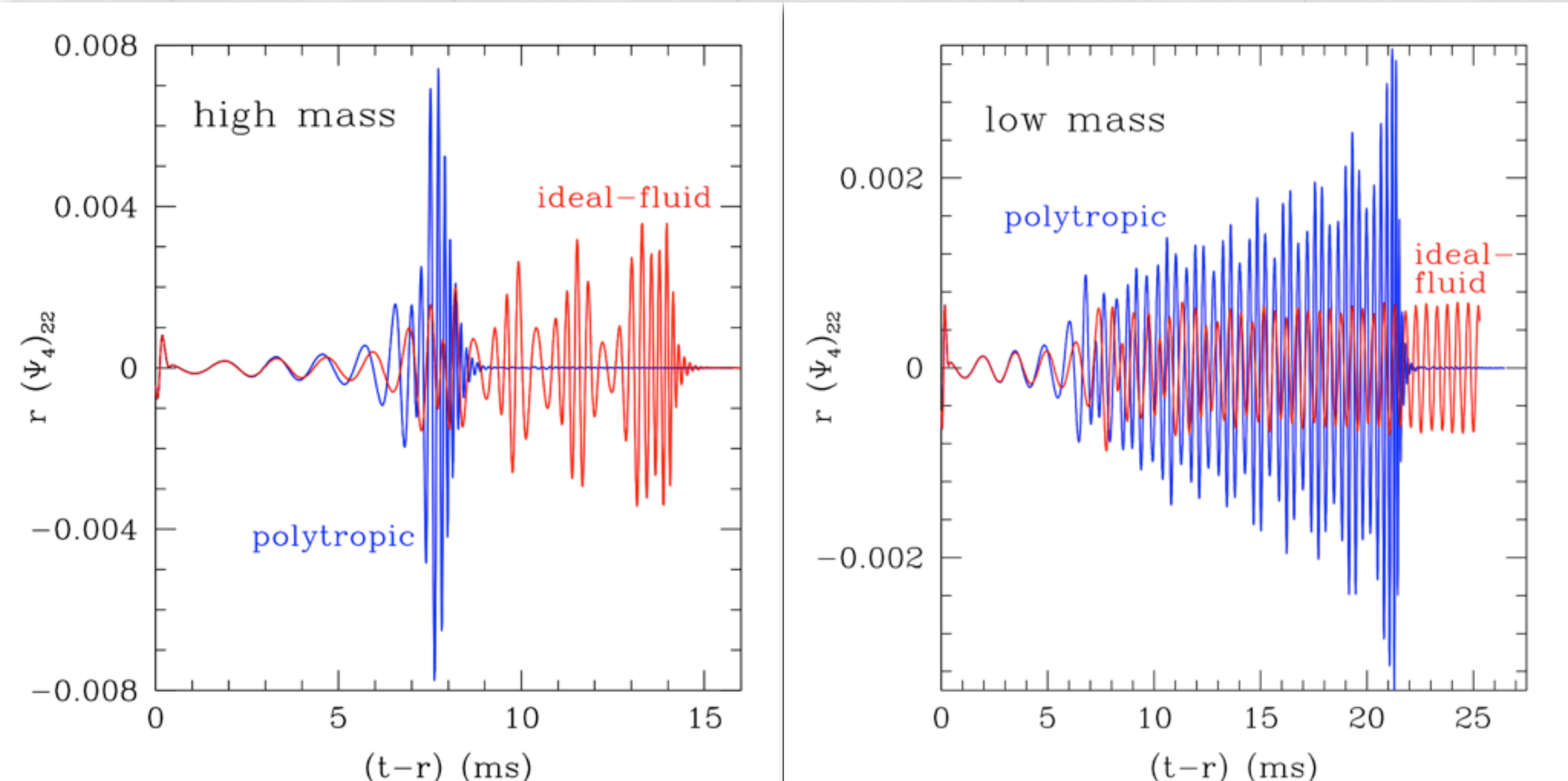




the high internal energy (temperature) of the HMNS prevents a prompt collapse

the HMNS evolves on longer (radiation-reaction) timescale

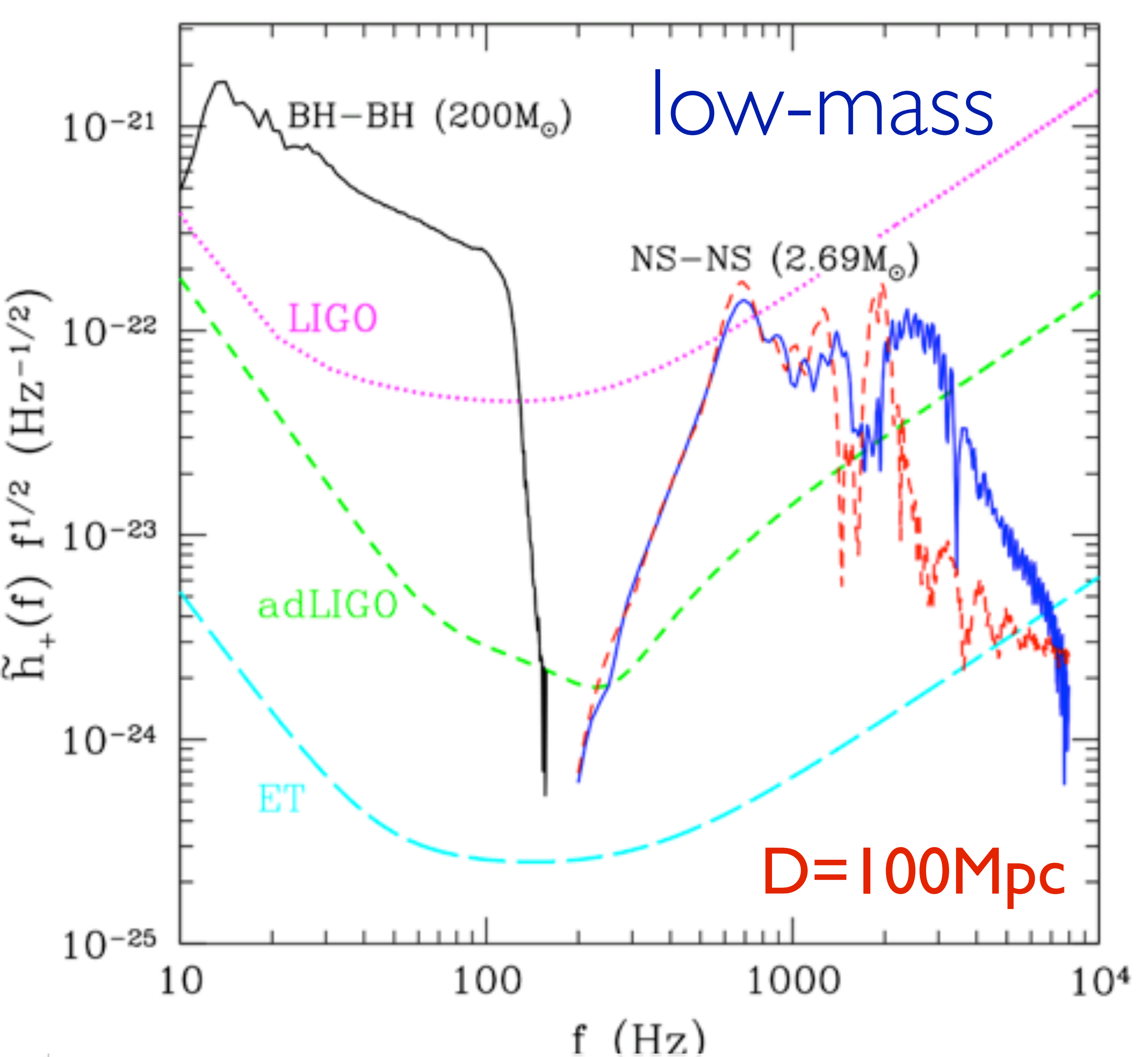
Imprint of the EOS: **hot** vs **cold**

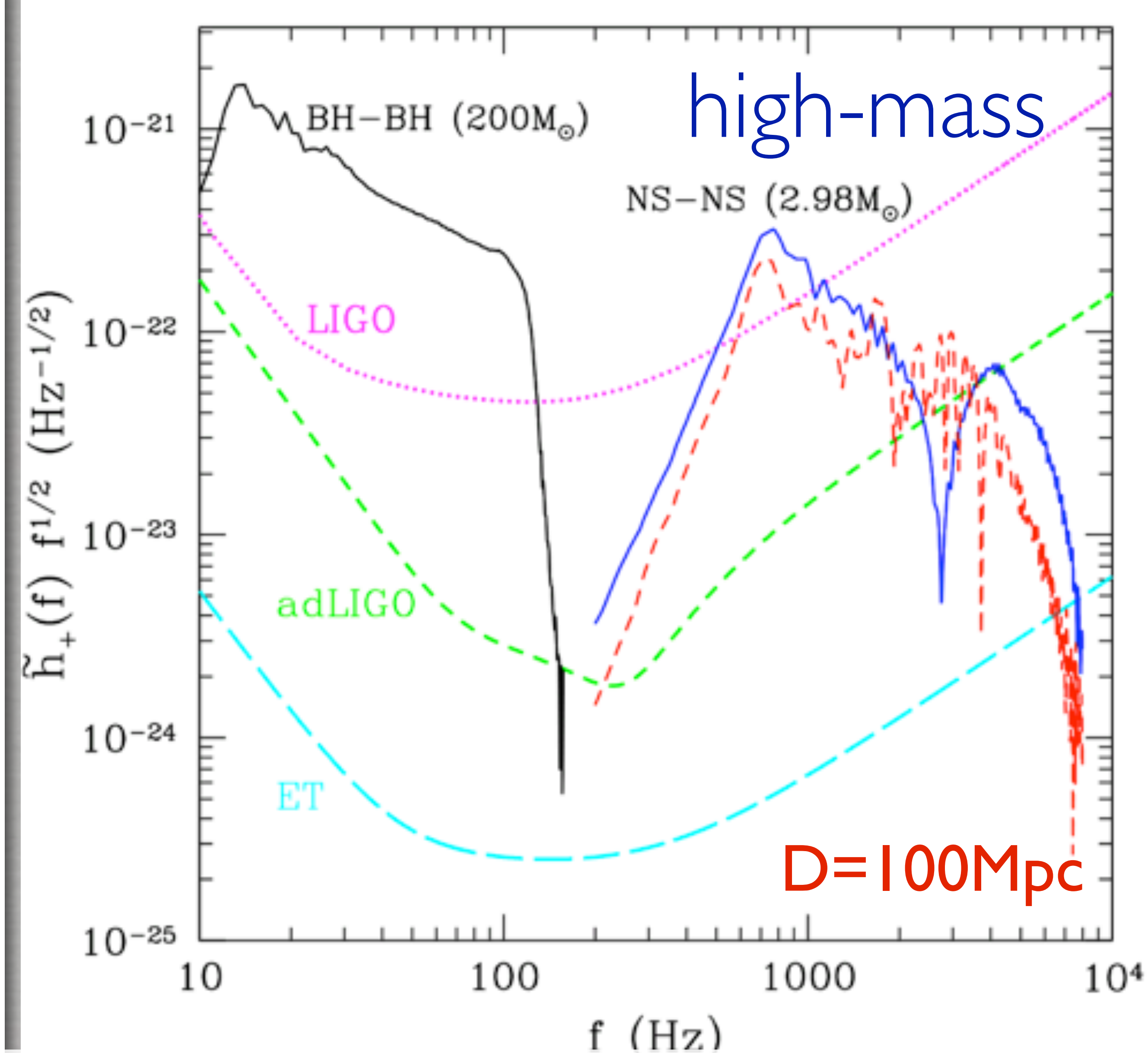


There are clear differences for the **same mass** and for the **same EOS**: multidimensional parameter space

Imprint of the EOS: frequency domain

Andersson et al. (GRG 2009)





With sufficiently sensitive detectors, GWs will work as the Rosetta stone to decipher the NS interior *"merger → HMNS → BH + torus"*

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- **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

- **mass asymmetries:**
  tidal disruption before merger; may lead to prompt BH

- **radiative processes:**
  radiative losses will alter the equilibrium of the HMNS

- **magnetic fields:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse

0 0.00 22.5
time [ms]

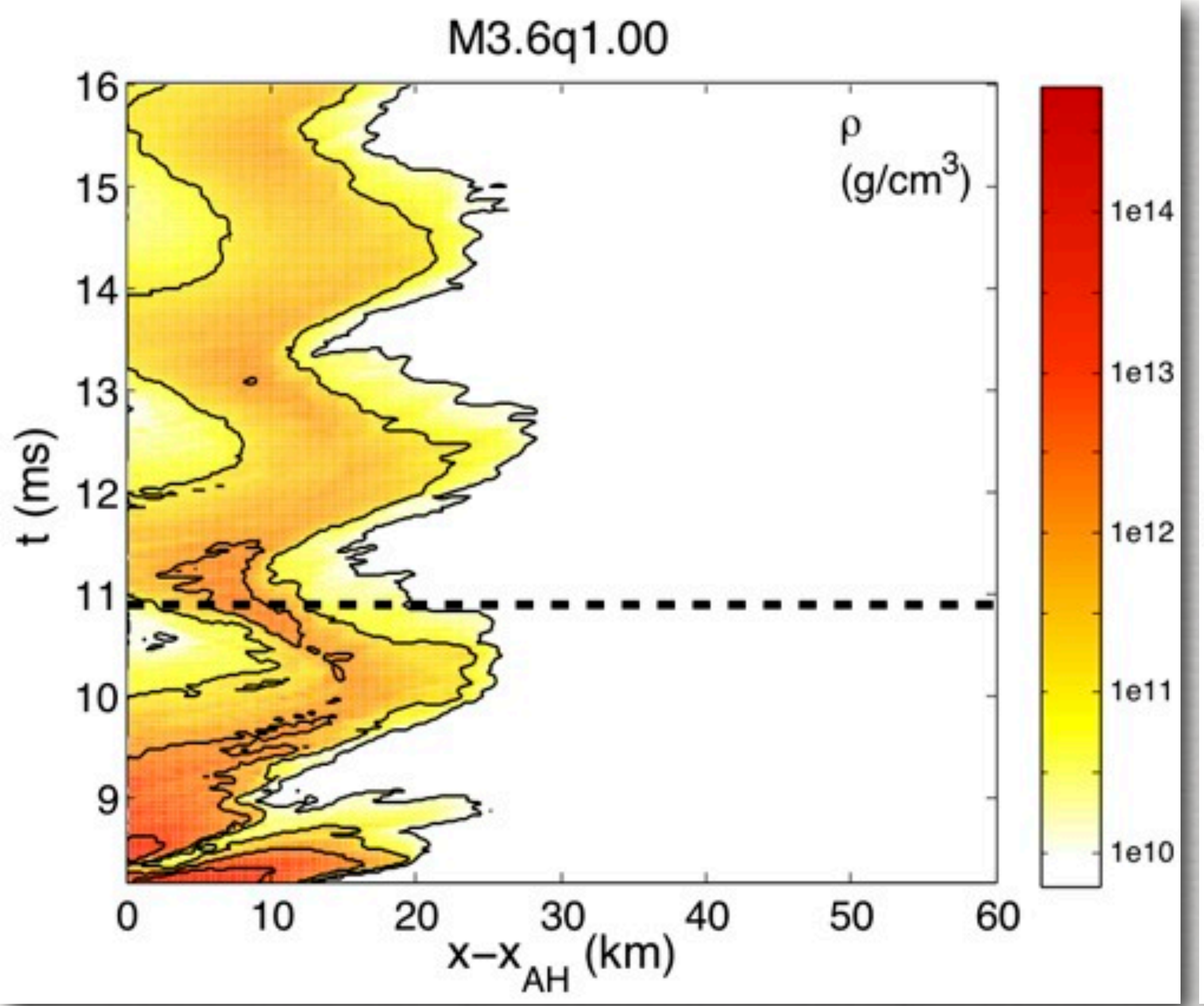
Animations: Giacomazzo, Koppitz, LR

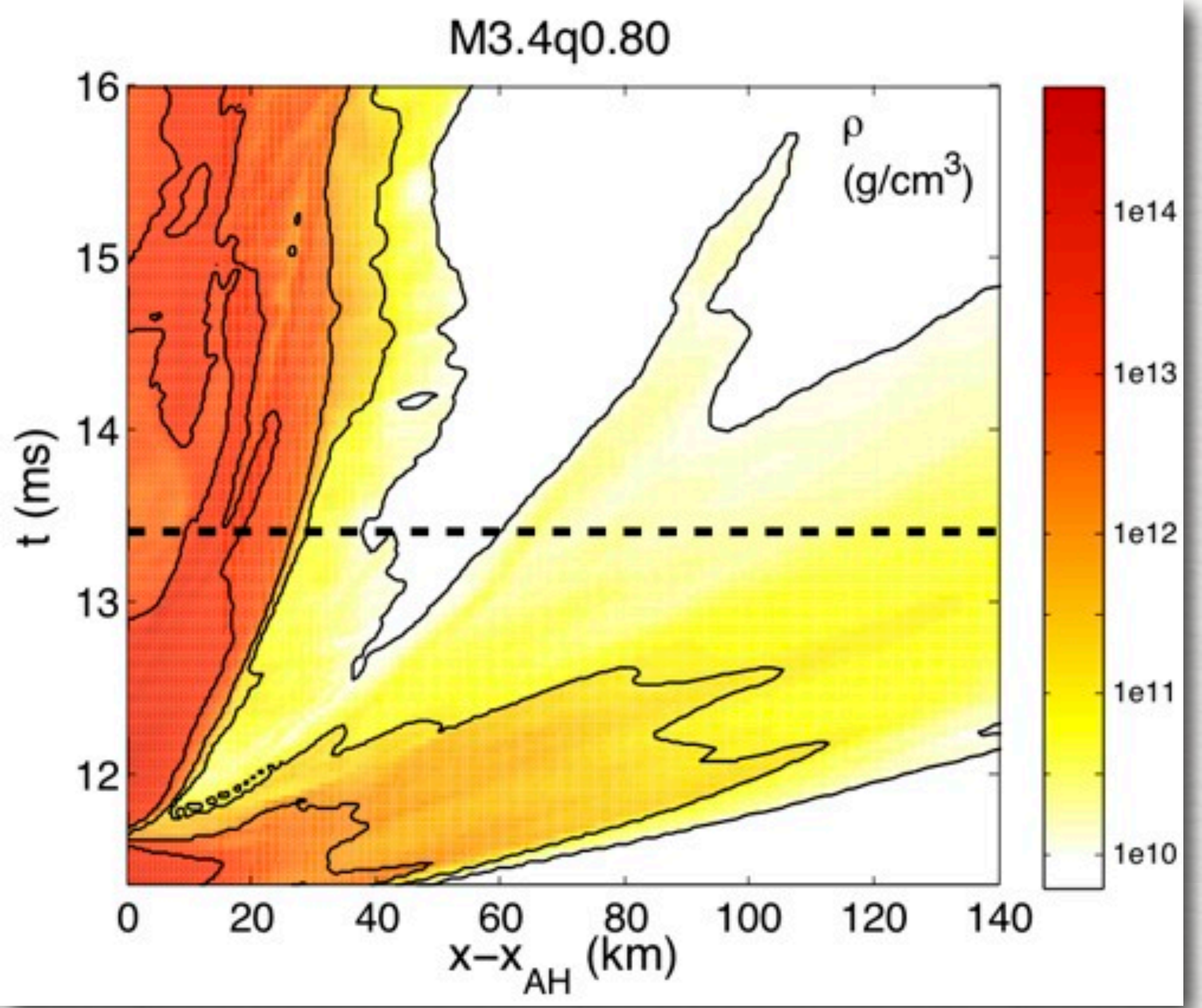
$$\text{Total mass} : 3.37\, M_{\odot}; \qquad \text{mass ratio} : 0.80;$$

- the torii are generically more massive
- the torii are generically more extended
- the torii tend to stable quasi-Keplerian configurations
- overall unequal-mass systems have all the ingredients needed to create a GRB

Torus properties: density

spacetime diagram of rest-mass density along x-direction



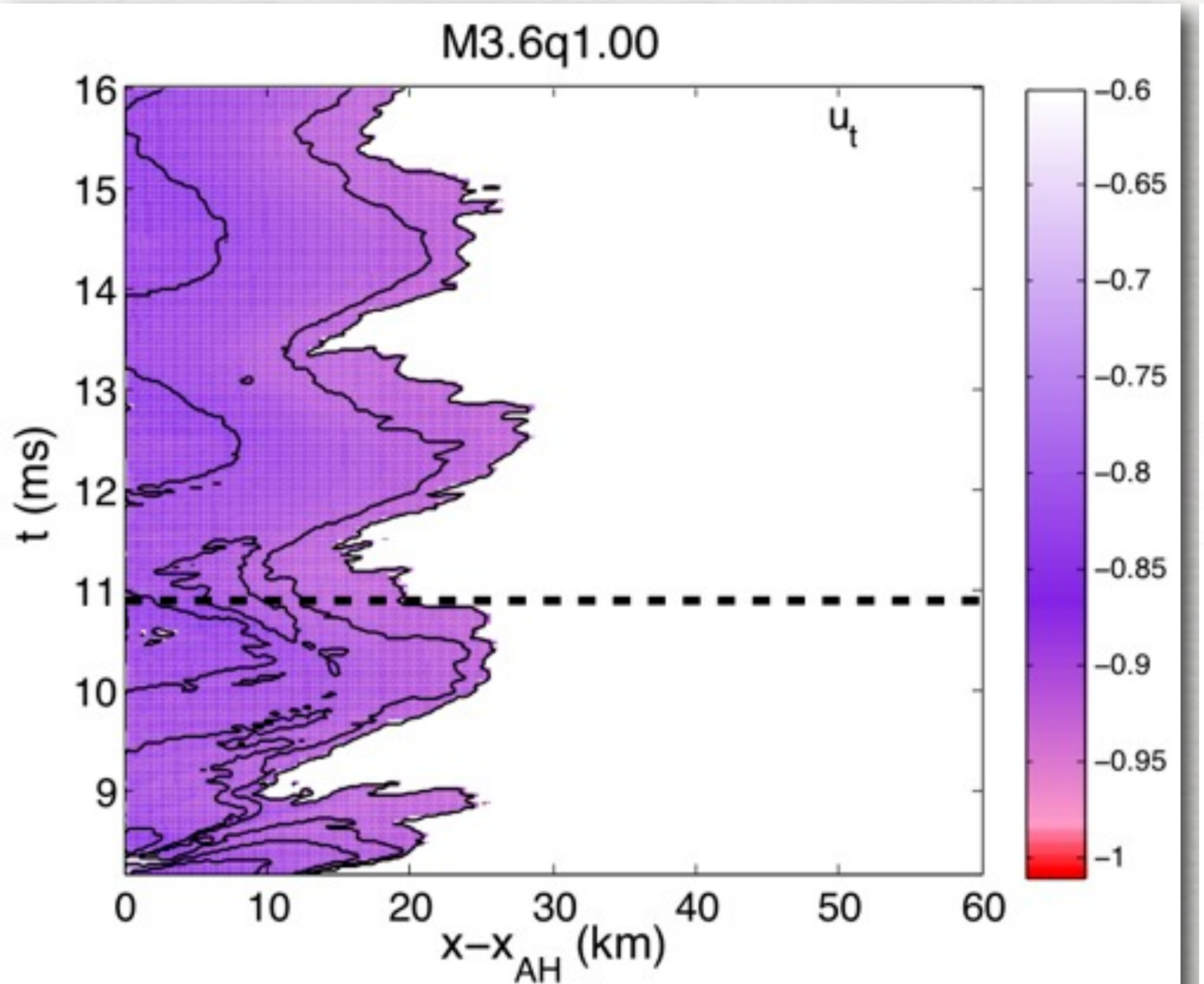


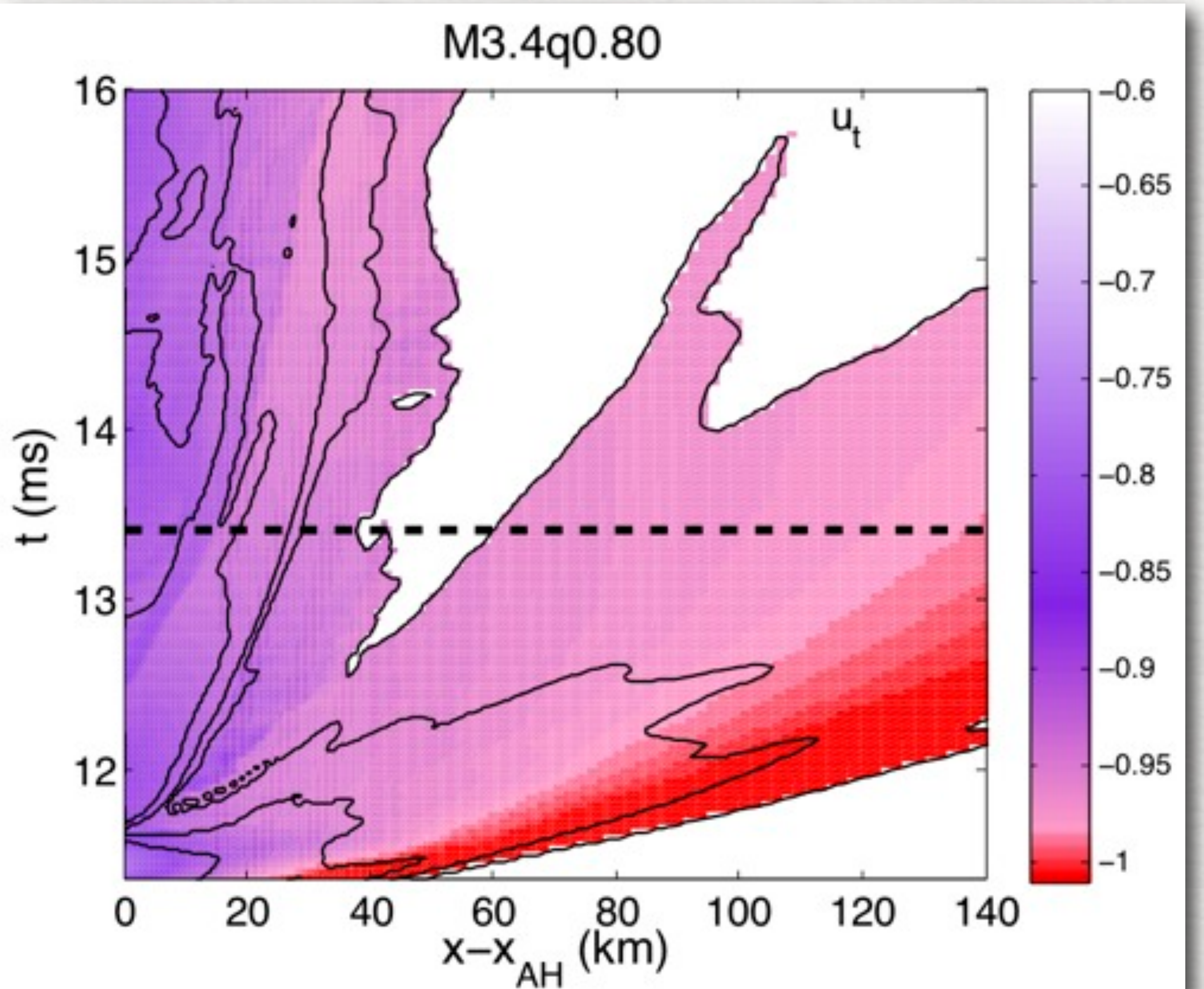
equal mass binary: note the periodic accretion and the compact size; densities are not very high

unequal mass binary: note the continuous accretion and the very large size and densities (temperatures)

Torus properties: bound matter

spacetime diagram of local fluid energy: u_t





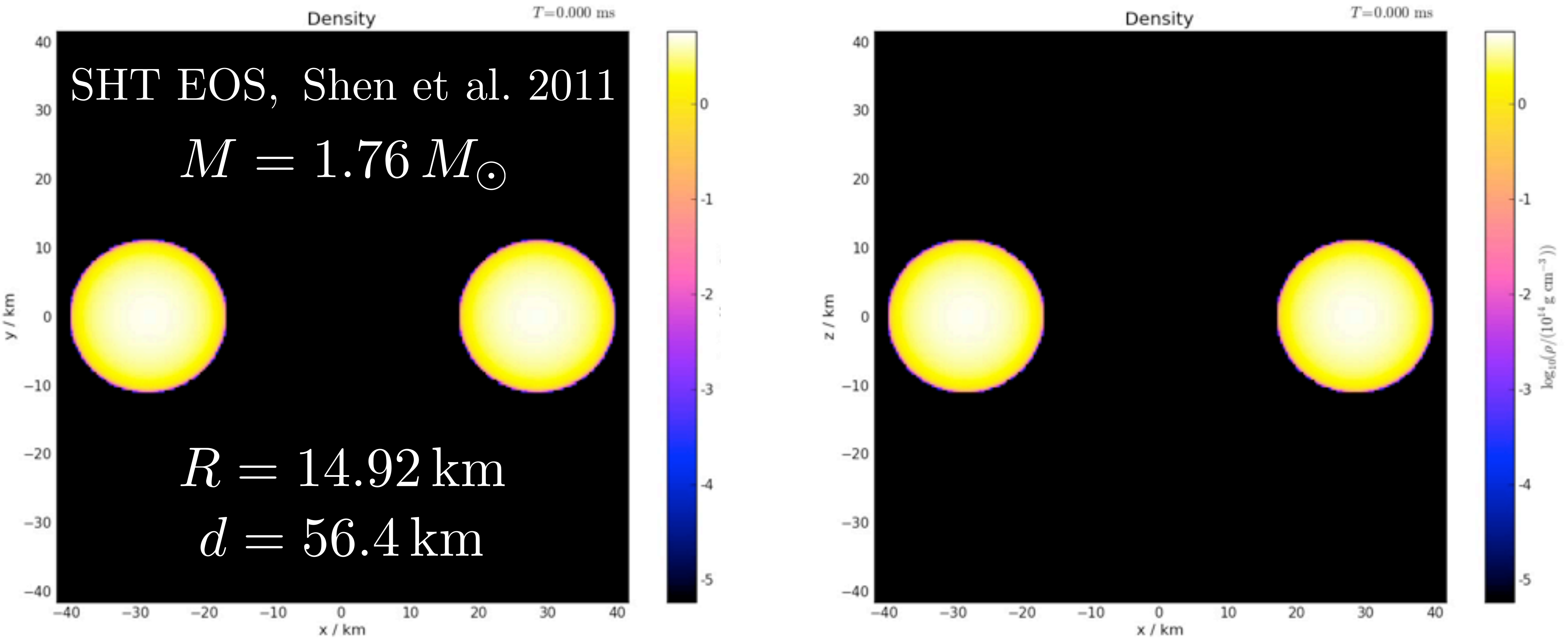
equal mass : all matter is clearly bound, i.e. $u_t < -1$
Note the accretion is quasi-periodic

unequal mass: some matter is unbound while other is ejected at large distances (cf. scale). In these regions r-processes can take place

Extending the work to hot realistic EOSs

Galeazzi, Kastaun, LR

We are now able to perform simulations also with realistic hot EOSs (Lattimer-Swesty, Shen-et-al, Shen-Horowitz-Teige, etc.) and taking first steps towards modelling **radiative losses** (via "leakage" approach) and **r-process nucleosynthesis**.

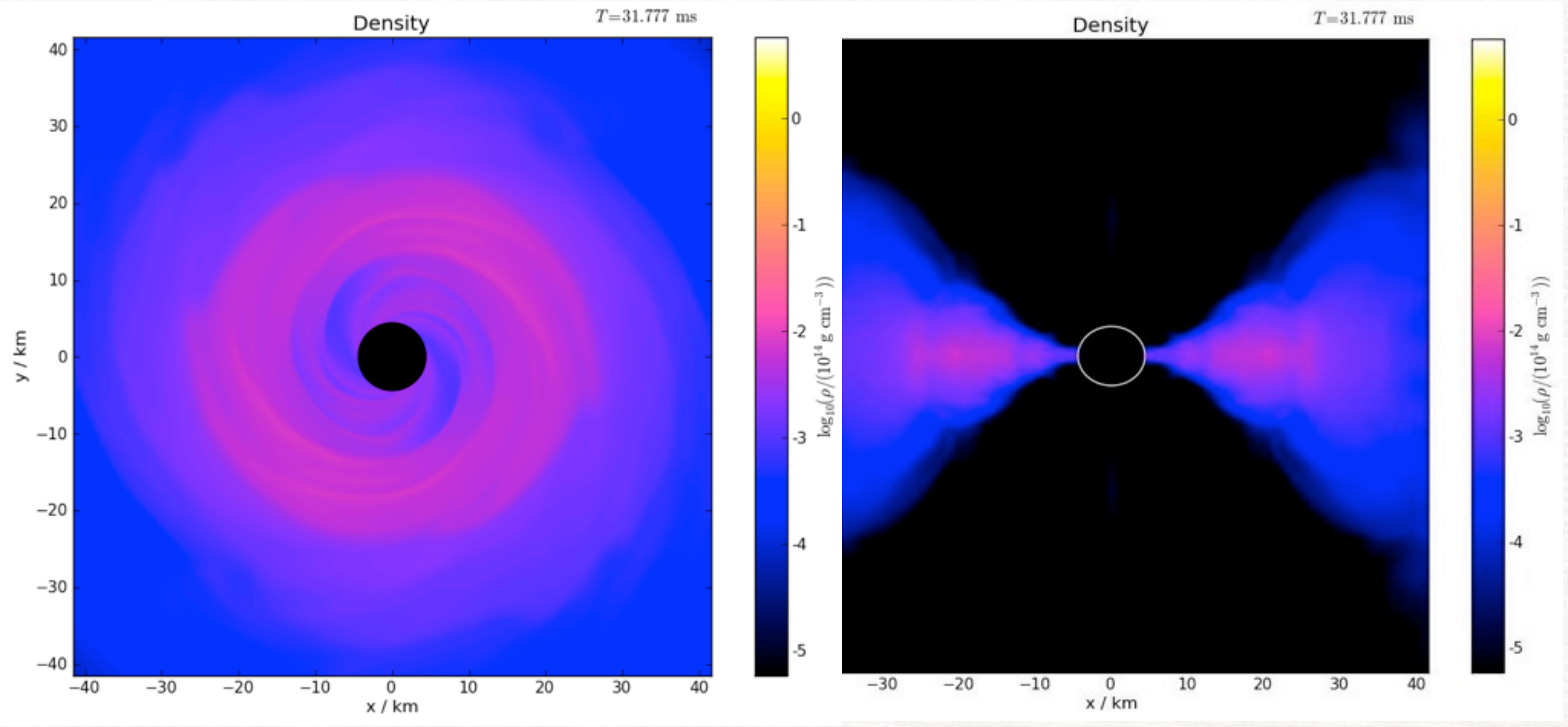


Extending the work to hot realistic EOSs

As expected, many of the **qualitative** features of analytic EOSs (ideal-fluid) are present also when considering realistic EOSs:

merger → HMNS → BH+torus: $M_{\rm torus} \simeq 0.024 M_{\odot} = 0.6\% M_0$

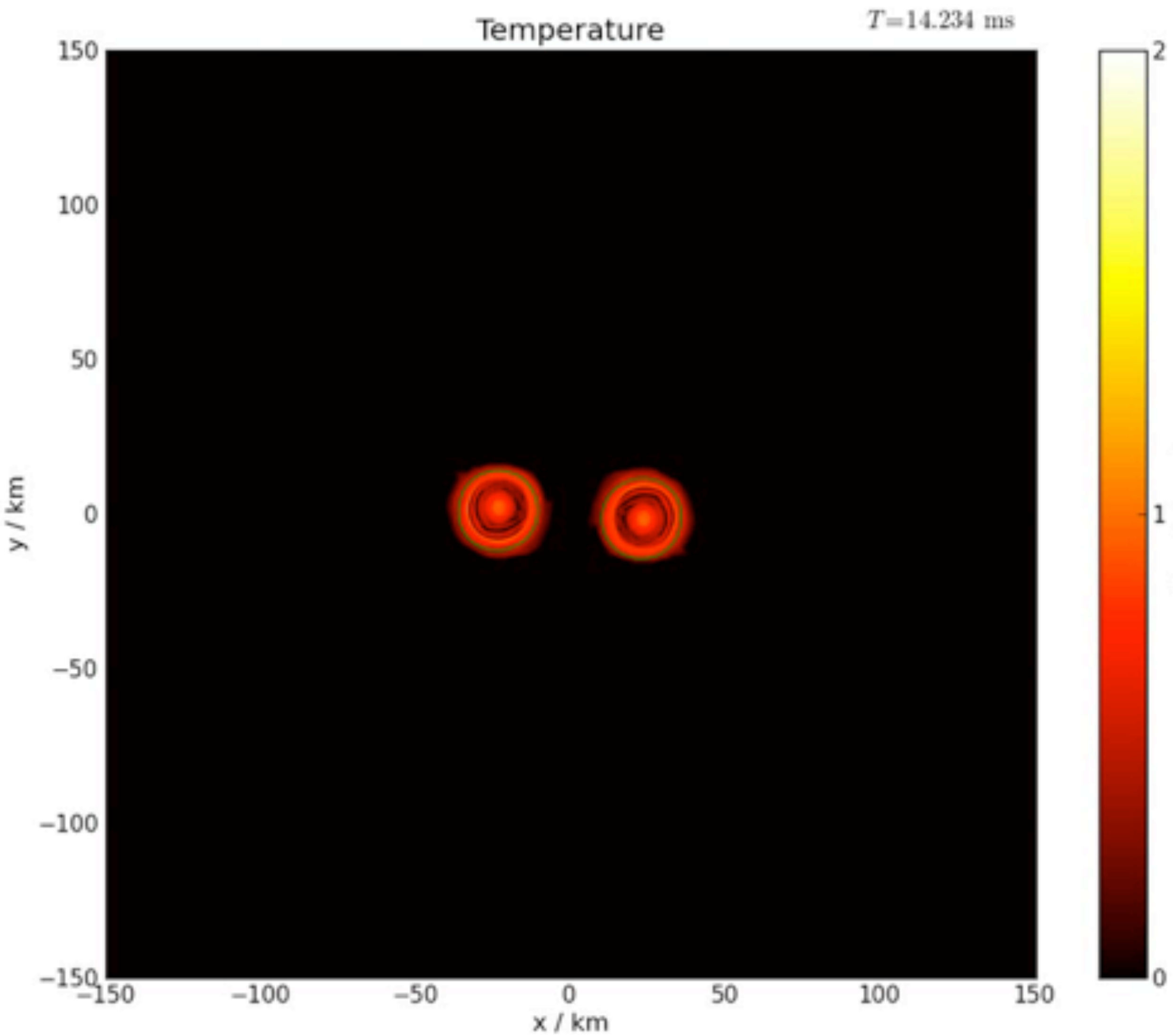
small but expected for equal-mass binaries

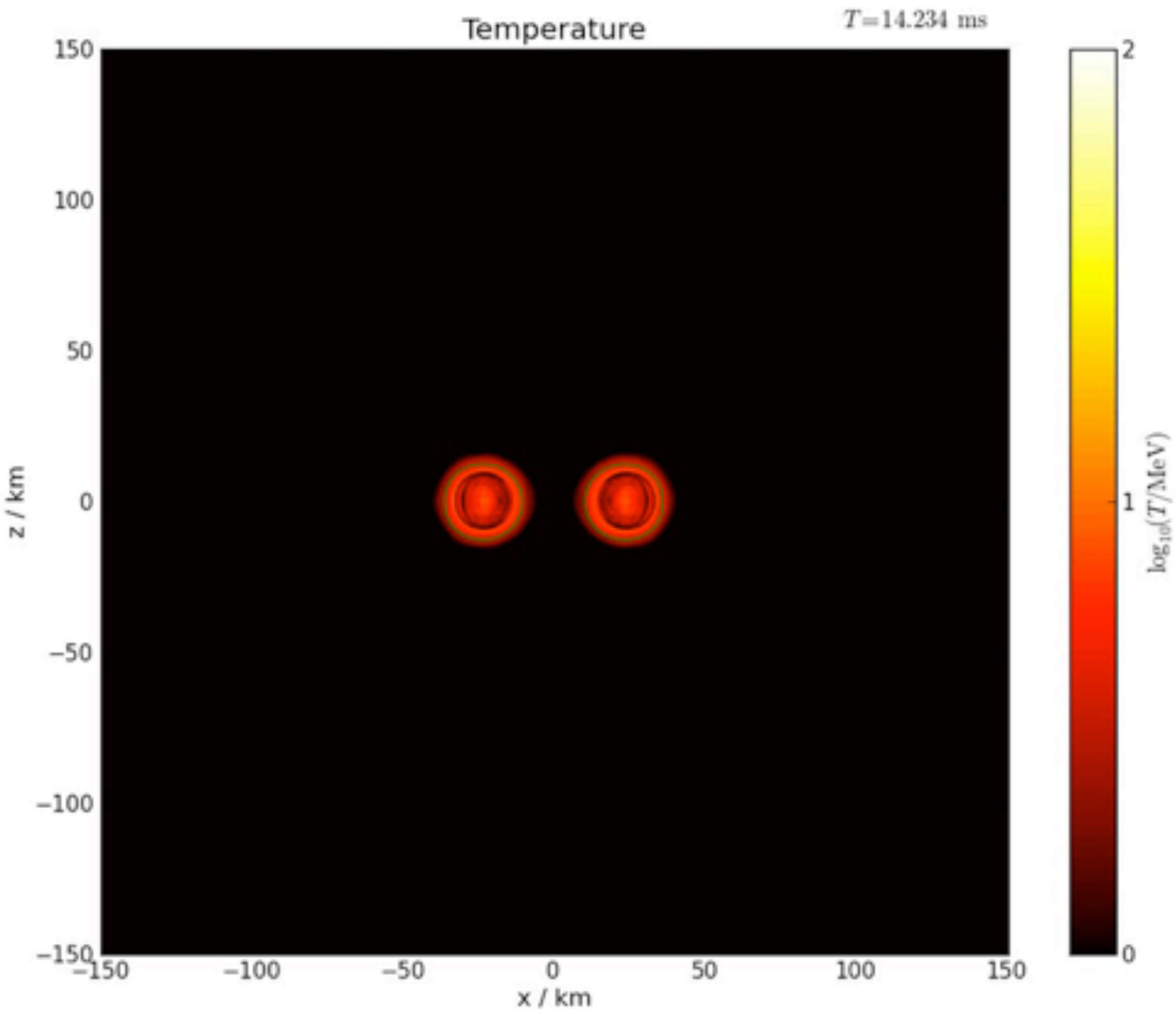


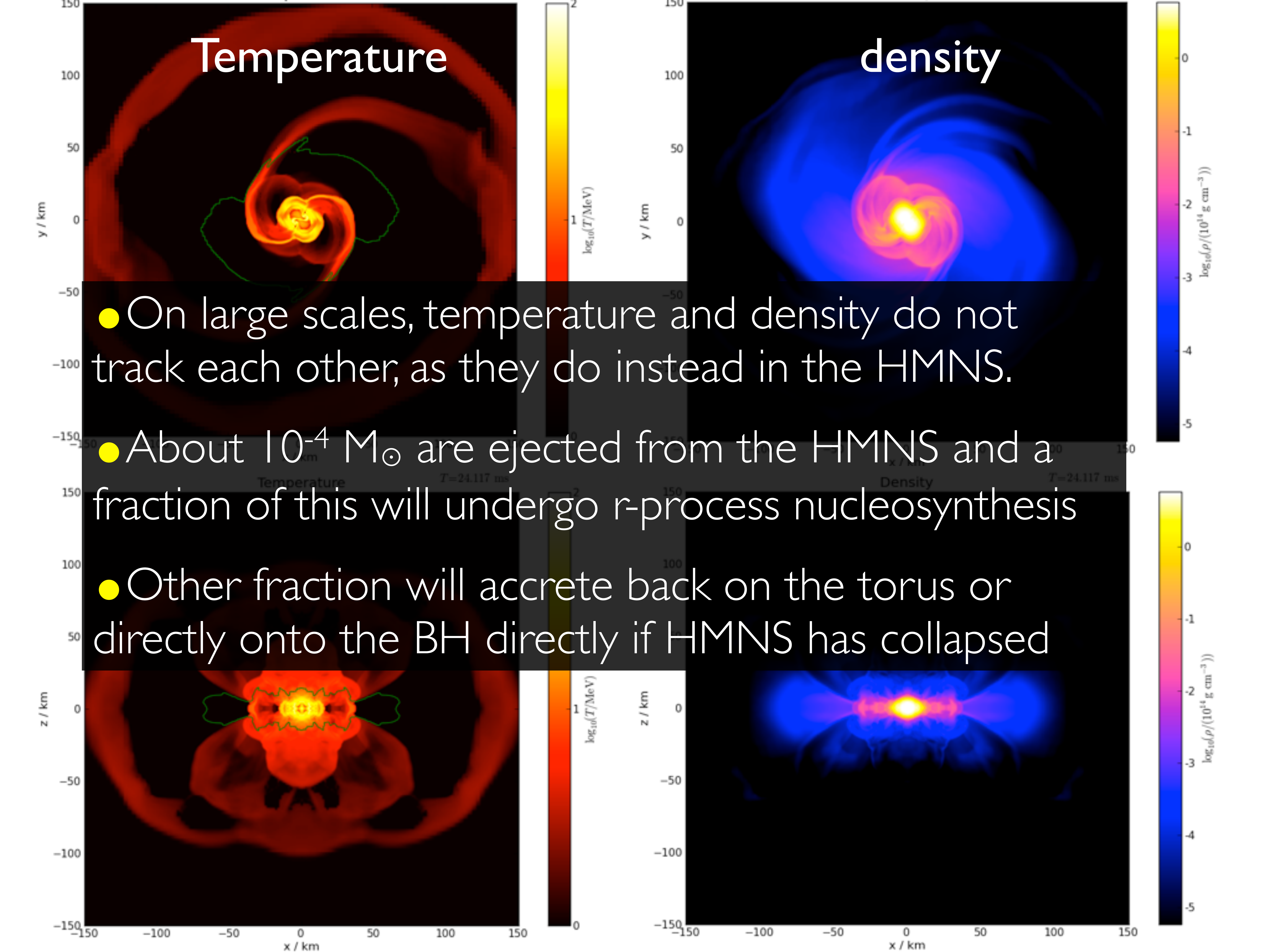
Extending the work to hot realistic EOSs

Particularly interesting are the evolutions of the **temperature** and of the **electron fraction**

Color range in between 1 and ~200 MeV







- On large scales, temperature and density do not track each other, as they do instead in the HMNS.
- About $10^{-4}\,M_\odot$ are ejected from the HMNS and a fraction of this will undergo r-process nucleosynthesis
- Other fraction will accrete back on the torus or directly onto the BH directly if HMNS has collapsed

Extending the work to ideal MHD

NSs have large magnetic fields and it is natural to ask:

- can B-fields be detected during the inspiral?
  - ✳**NO**: present and future GW detectors will not be sensitive enough to measure the small differences

Giacomazzo, LR, Baiotti (2009)

- can B-fields be detected in the HMNS?
  - ✳**YES** (in principle): different B-fields change the survival time of the HMNS (effect may be degenerate)

Giacomazzo, LR, Baiotti (2010)

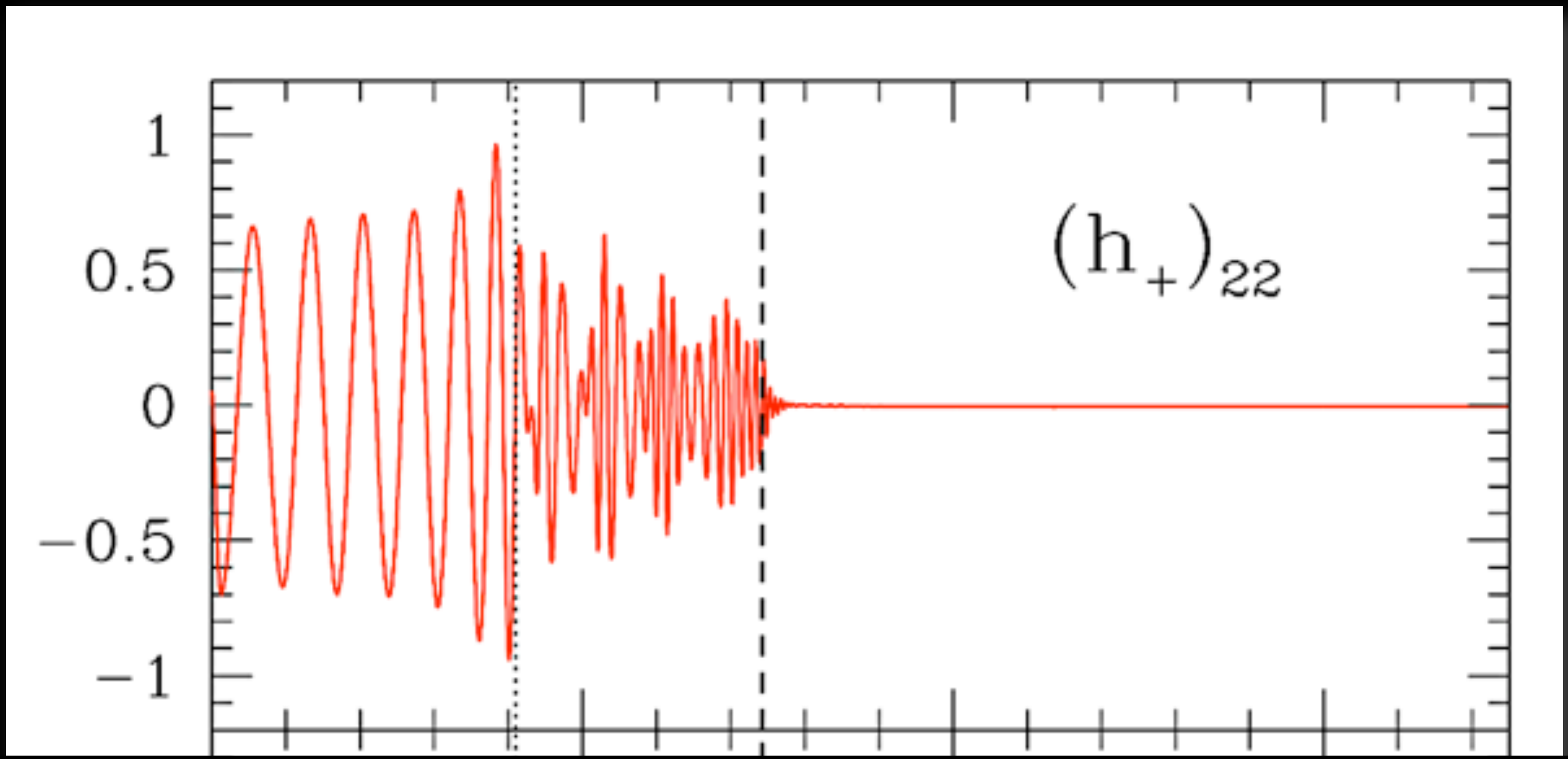
- can B-fields grow after BH formation?
  - ✳**YES**: B-fields are subject to instabilities and rotation of the BH introduces preferred direction for field geometry

LR, Giacomazzo, Baiotti, + (2011)

Animations:, LR, Koppitz

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

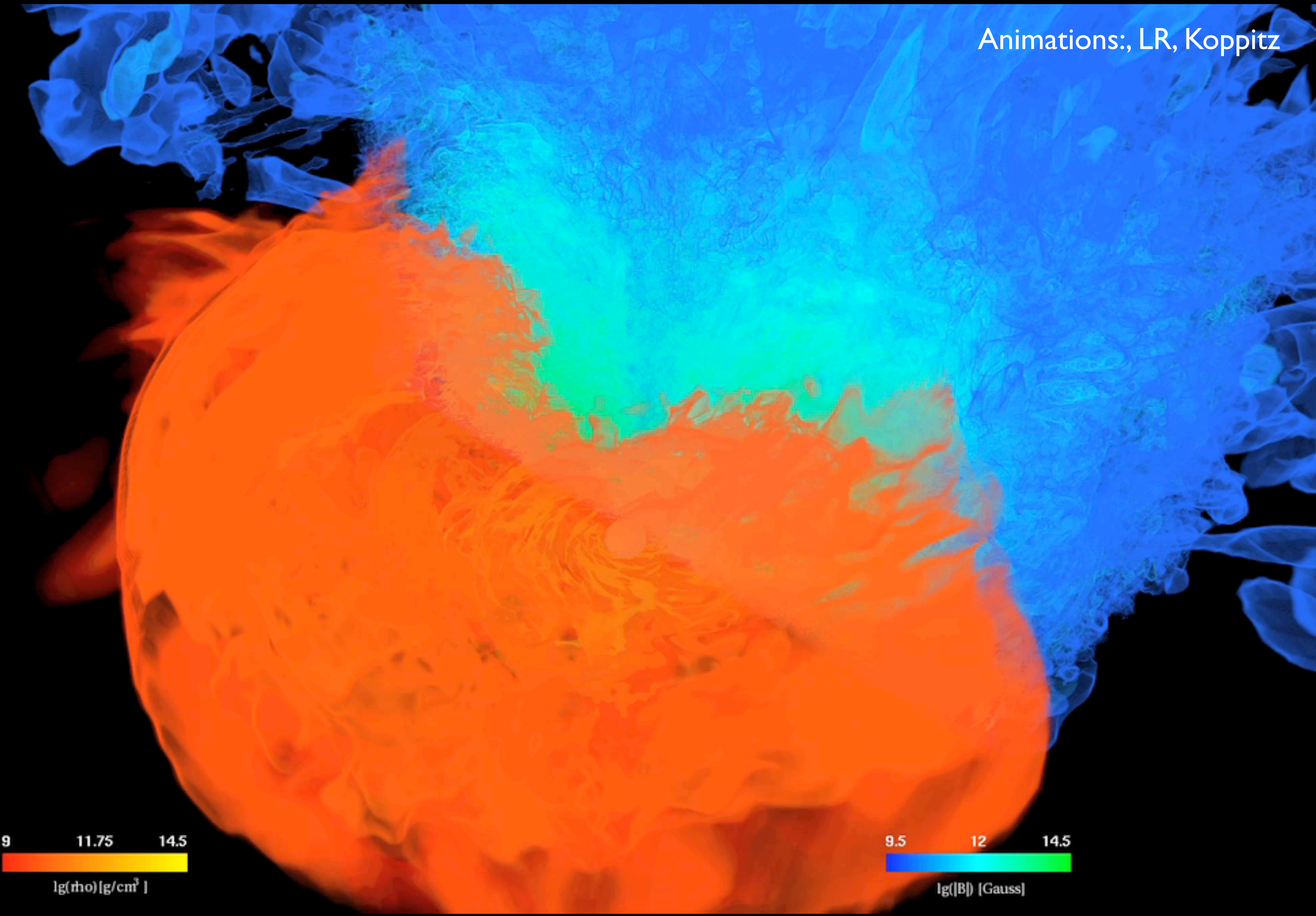
Going beyond BH formation

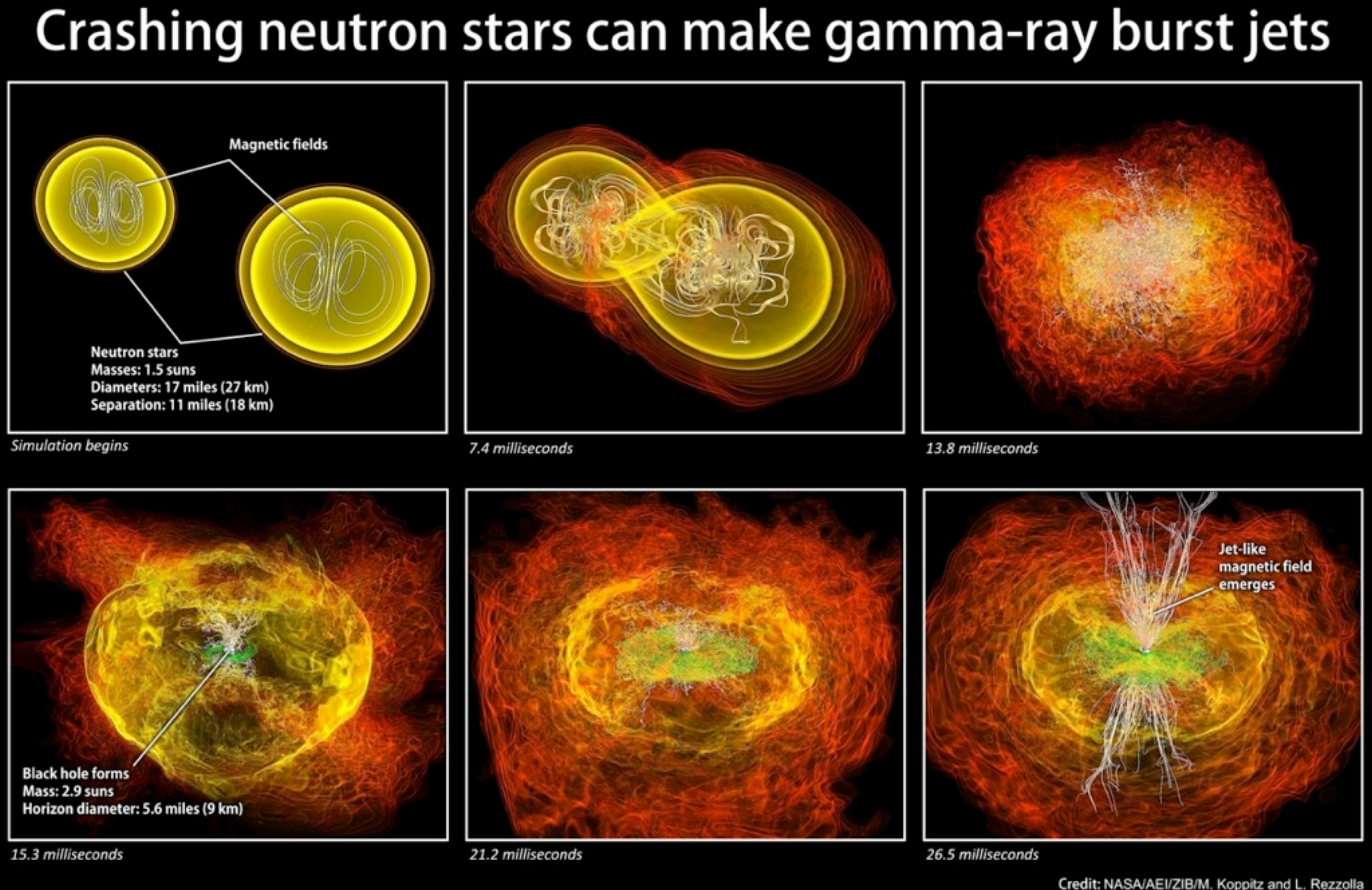


From a GW point of view, the binary becomes silent after BH formation and ringdown.

Is this really the end of the story?

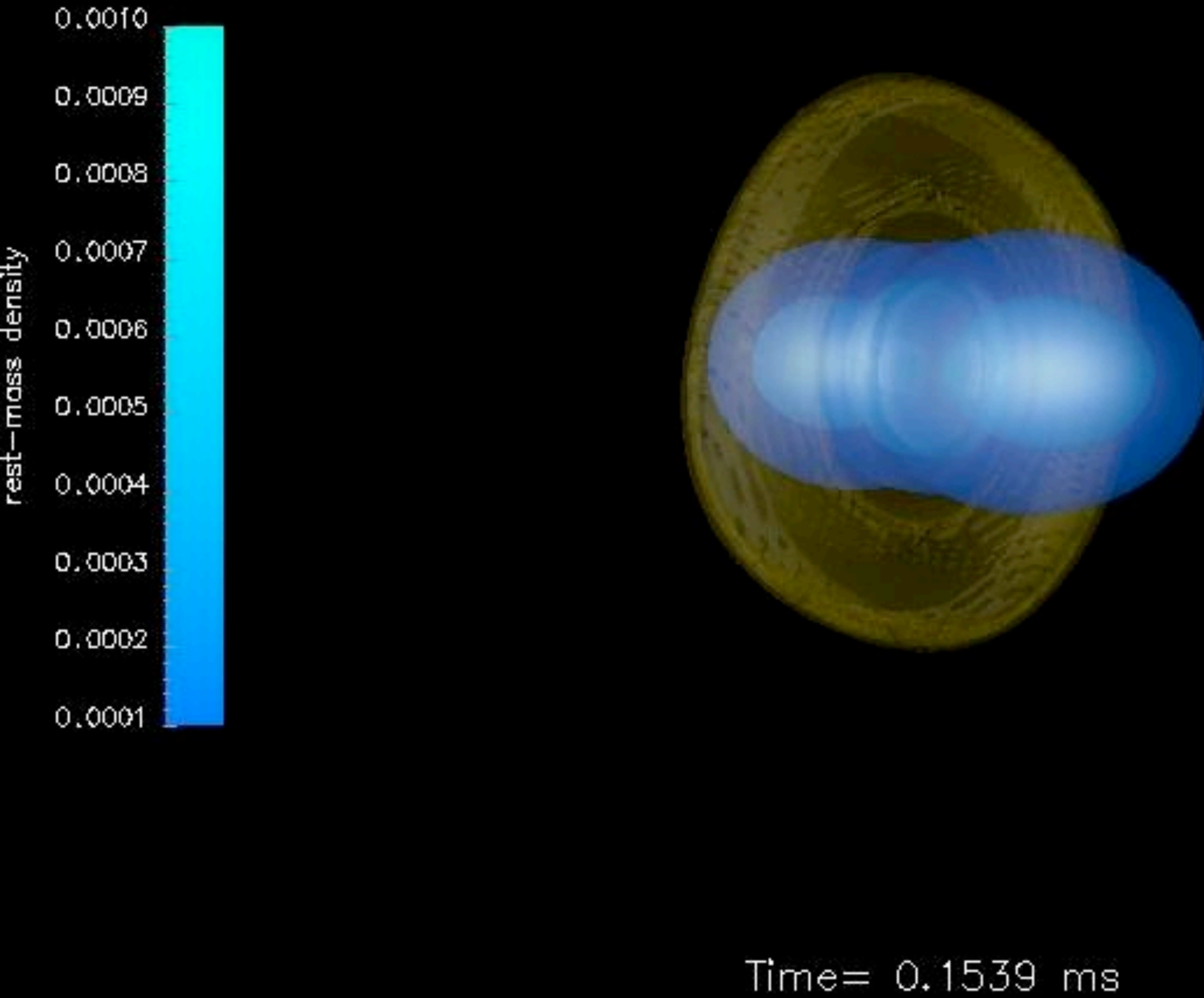
Animations:, LR, Koppitz





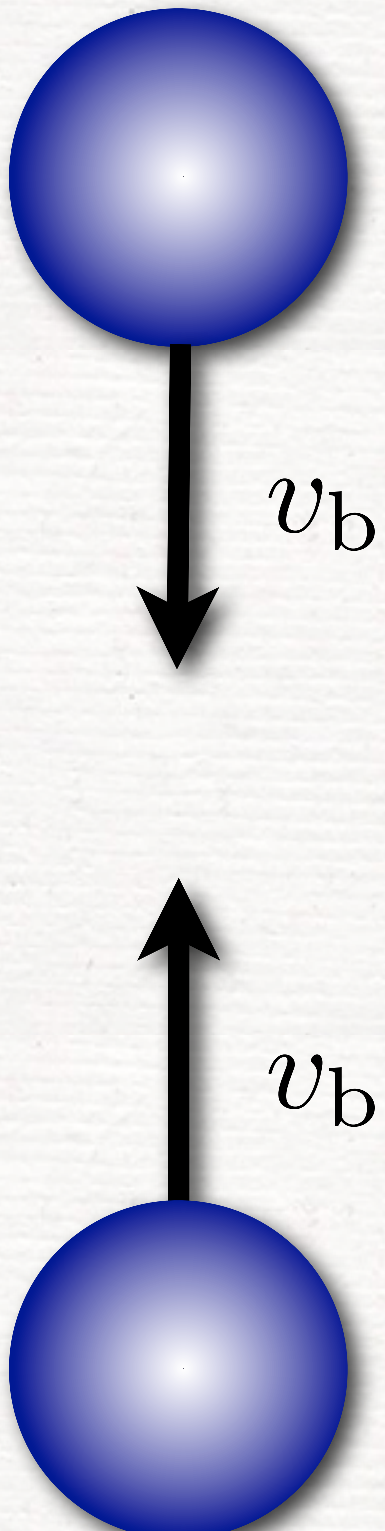
$J/M^2 = 0.83$ $\qquad$ $\mathrm{M_{tor}} = 0.063 M_\odot$ $\qquad$ $\mathrm{t_{accr}} \simeq M_{\rm tor}/\dot{M} \simeq 0.3\ \mathrm{s}$

From star collisions to particle collisions



LR, K. Takami, 2012

The process in a cartoon



The question is very simple:
what are the conditions under which a black hole can be formed from the collision of two self-gravitating objects?

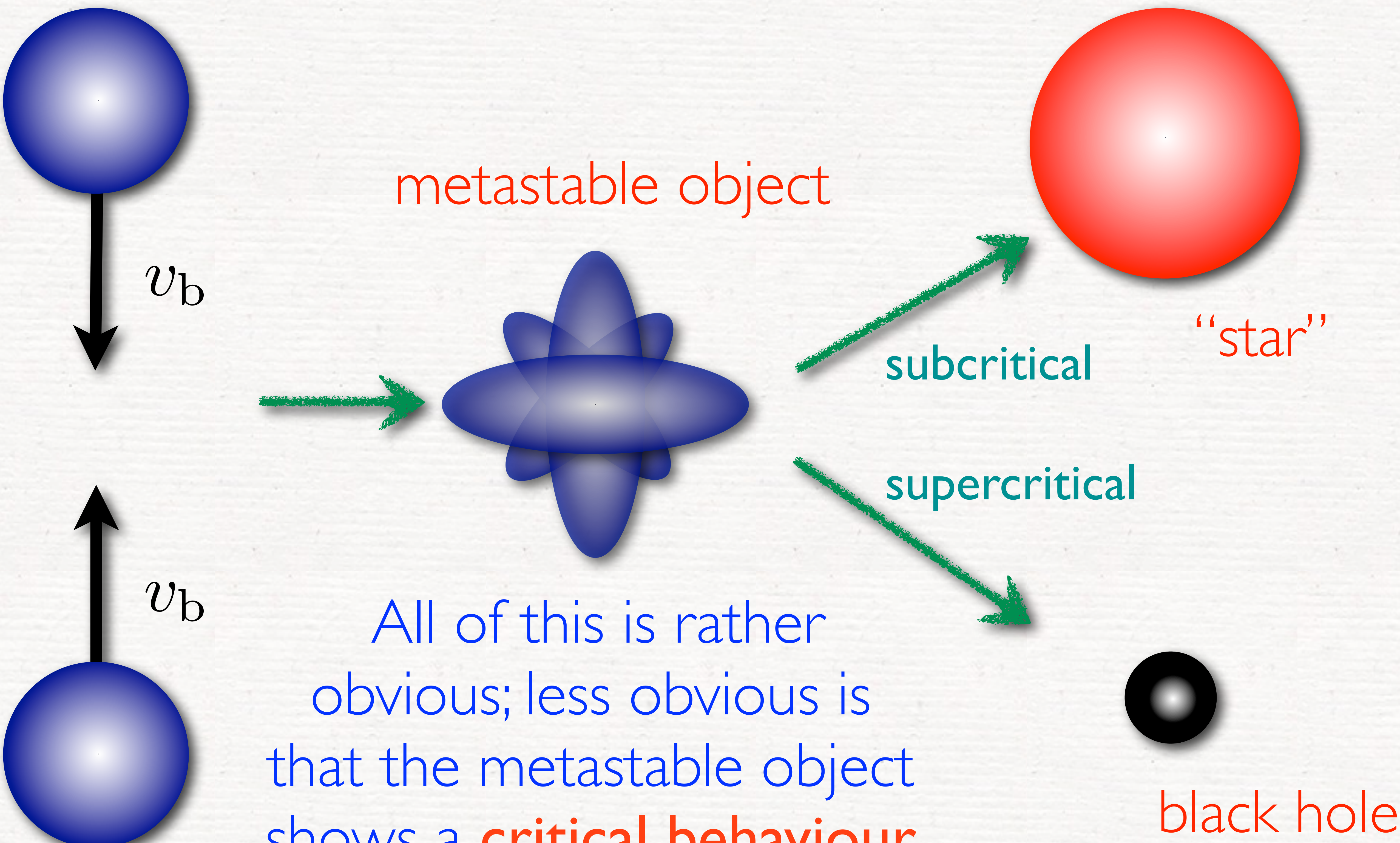
The answer does not exist yet:
no sufficient/necessary conditions are known. Some guidance is offered by Thorne's ***hoop conjecture***

$$R_\mathrm{hoop} \leq R_S = 2MG/c^2$$

Not a rigorous condition! (difficult to measure energy in a volume in GR)

Numerical-relativity simulations can provide clues

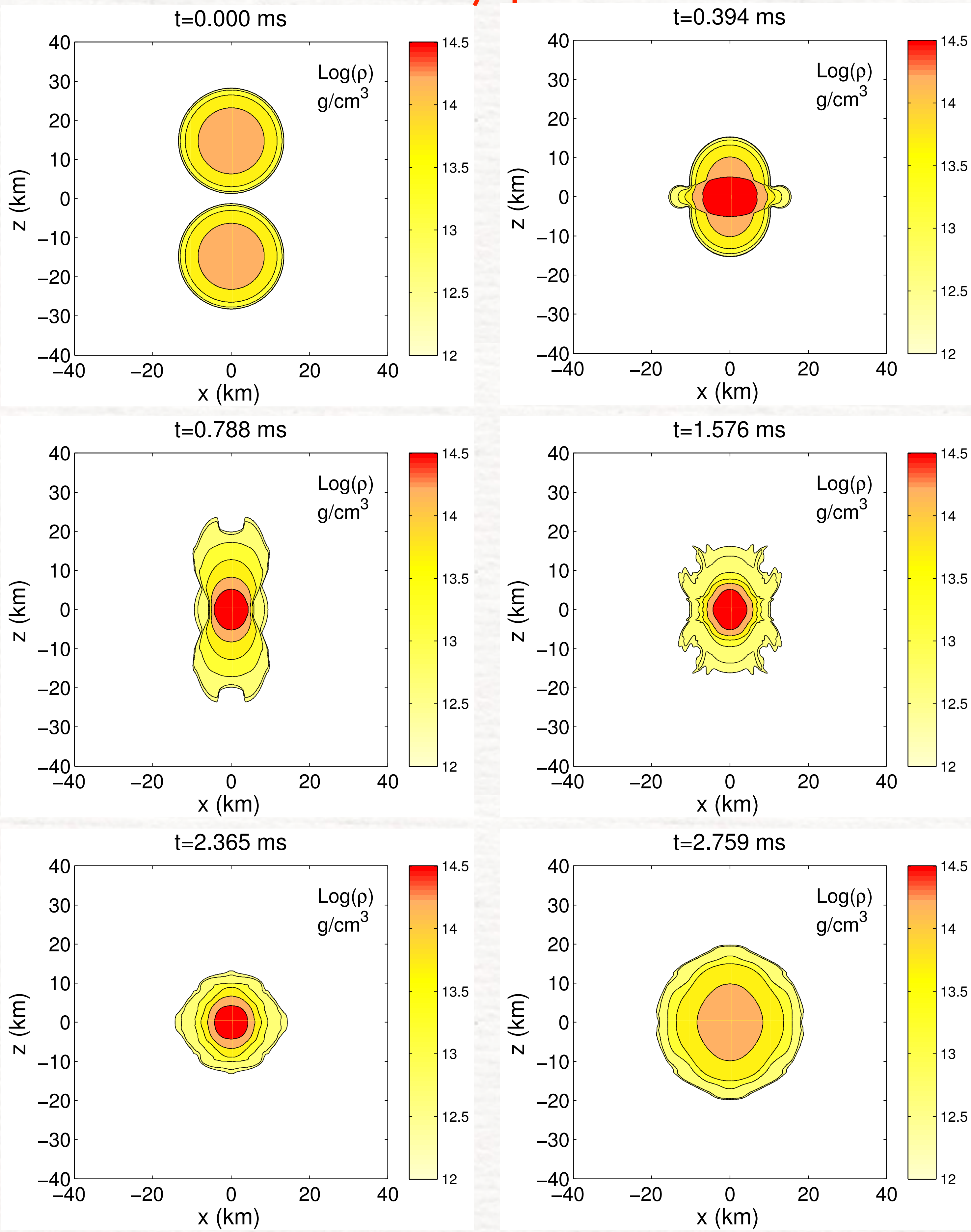
The process in a cartoon



All of this is rather obvious; less obvious is that the metastable object shows a **critical behaviour**

(Jin et al 2007, Kellermann, LR et al 2010)

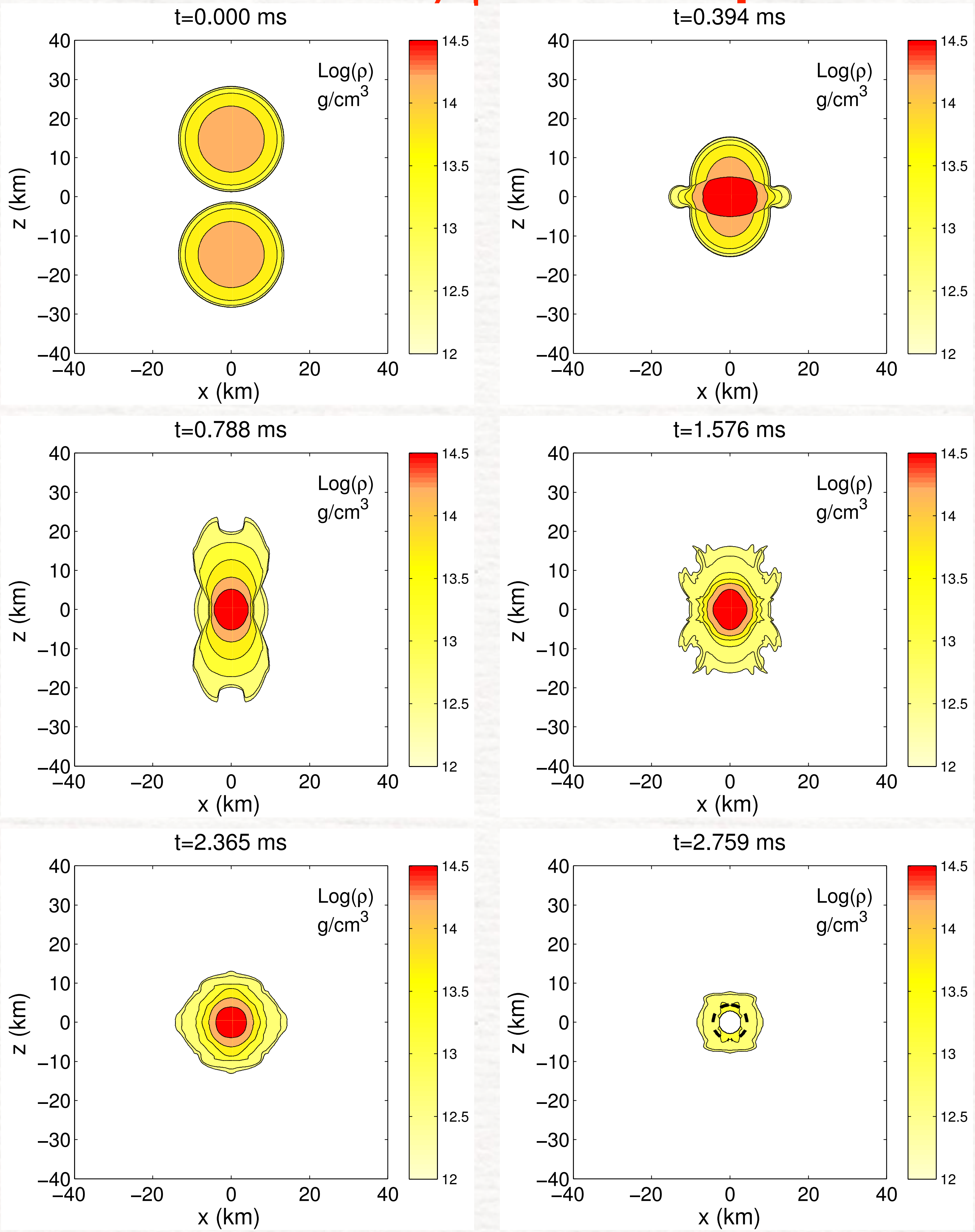
Typical **subcritical** collision



The different panels show snapshots of the rest-mass density at representative times for a **subcritical** binary.

Note the metastable object in panels 2-5.

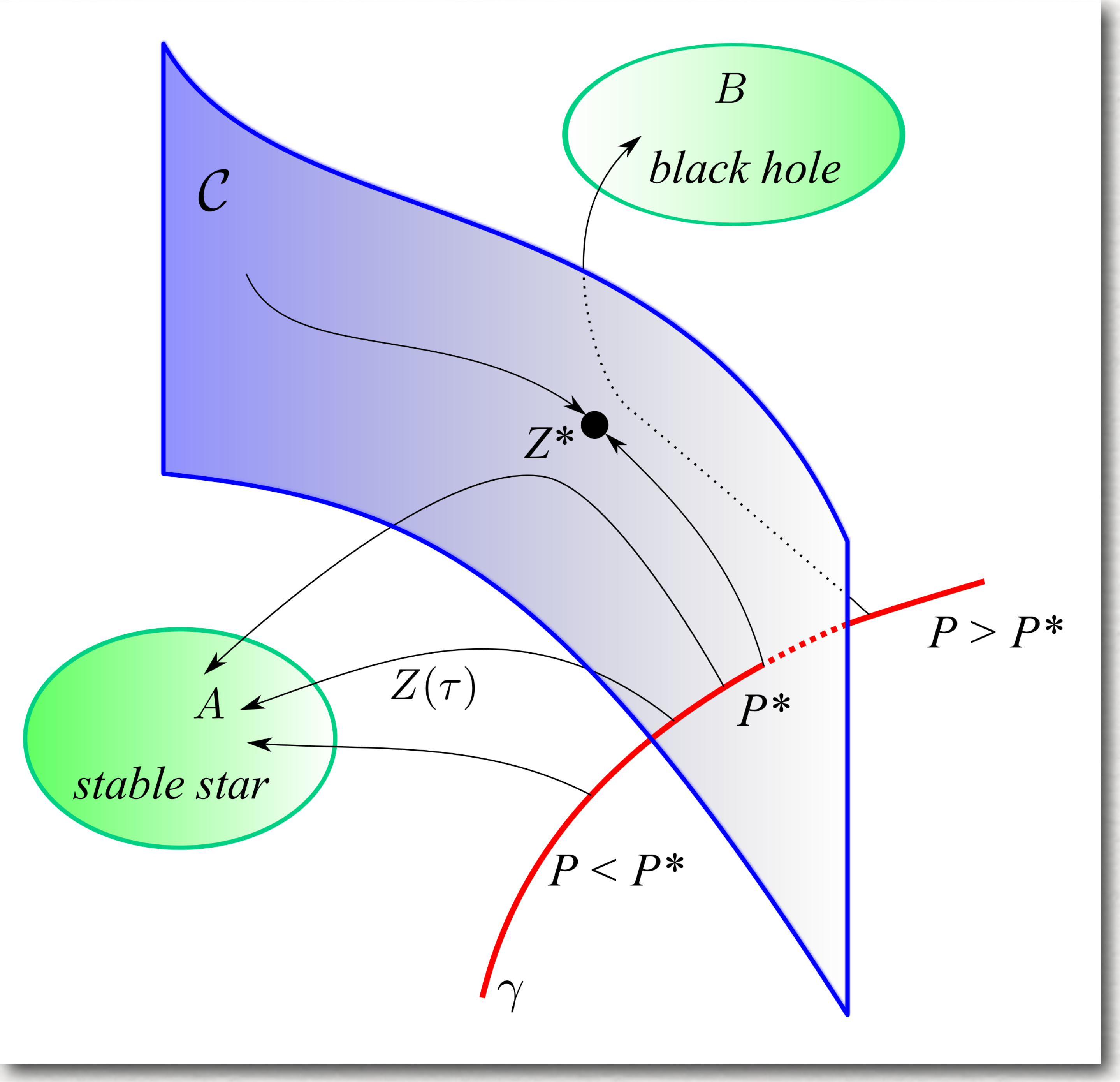
Typical **supercritical** collision



The different panels show snapshots of the rest-mass density at representative times for a **supercritical** binary.

Note the metastable object in panels 2-5.

A brief introduction to critical behaviour



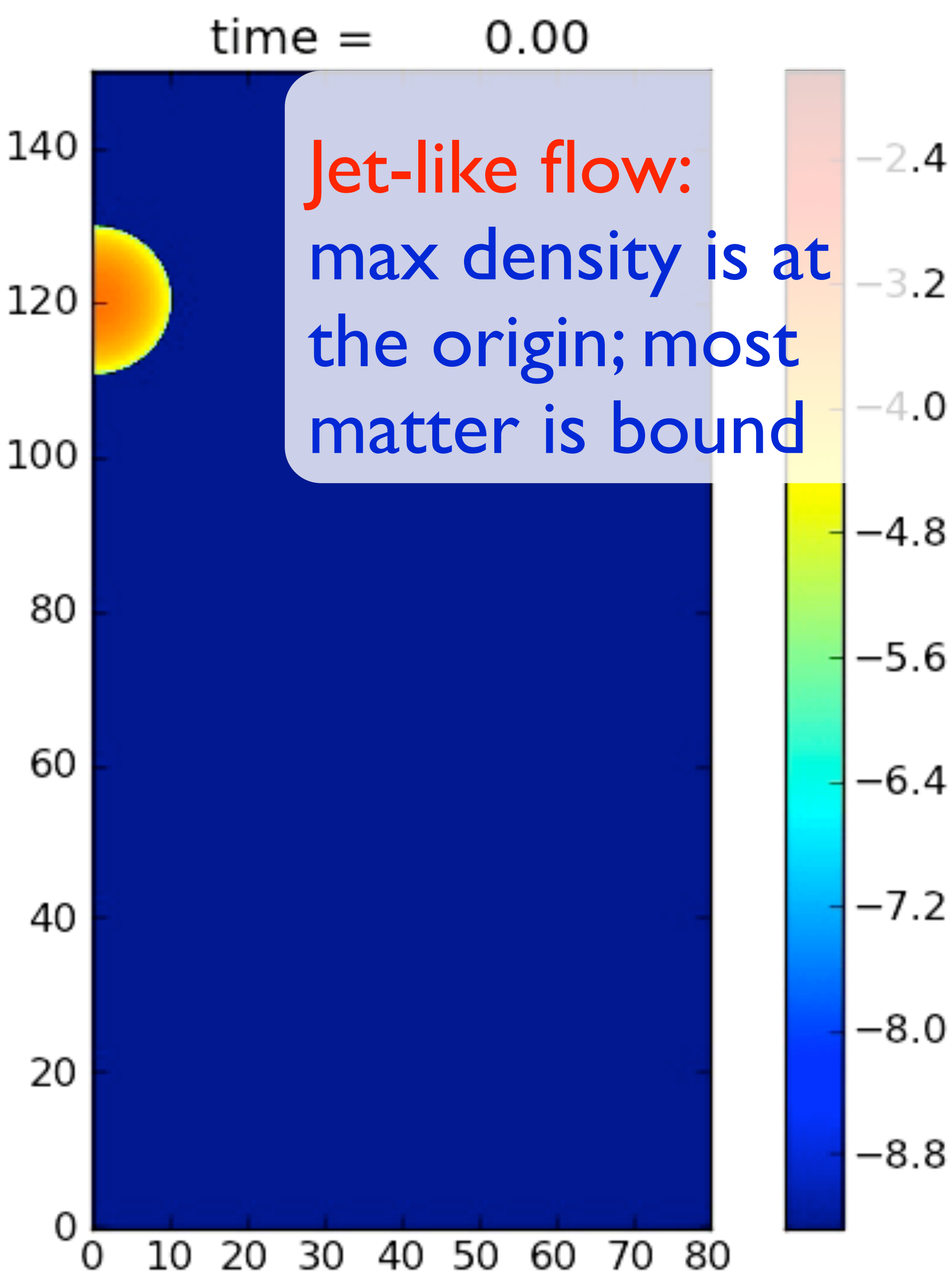
Given a series of initial data parametrized by a scalar quantity P, the critical solution at P^* will separate two basins of attracting solutions.

Solutions near the critical one will survive on the critical manifold for a certain time before evolving towards the corresponding basin

The critical solution is attractive on the critical manifold C, ie all but one mode converge towards Z^*

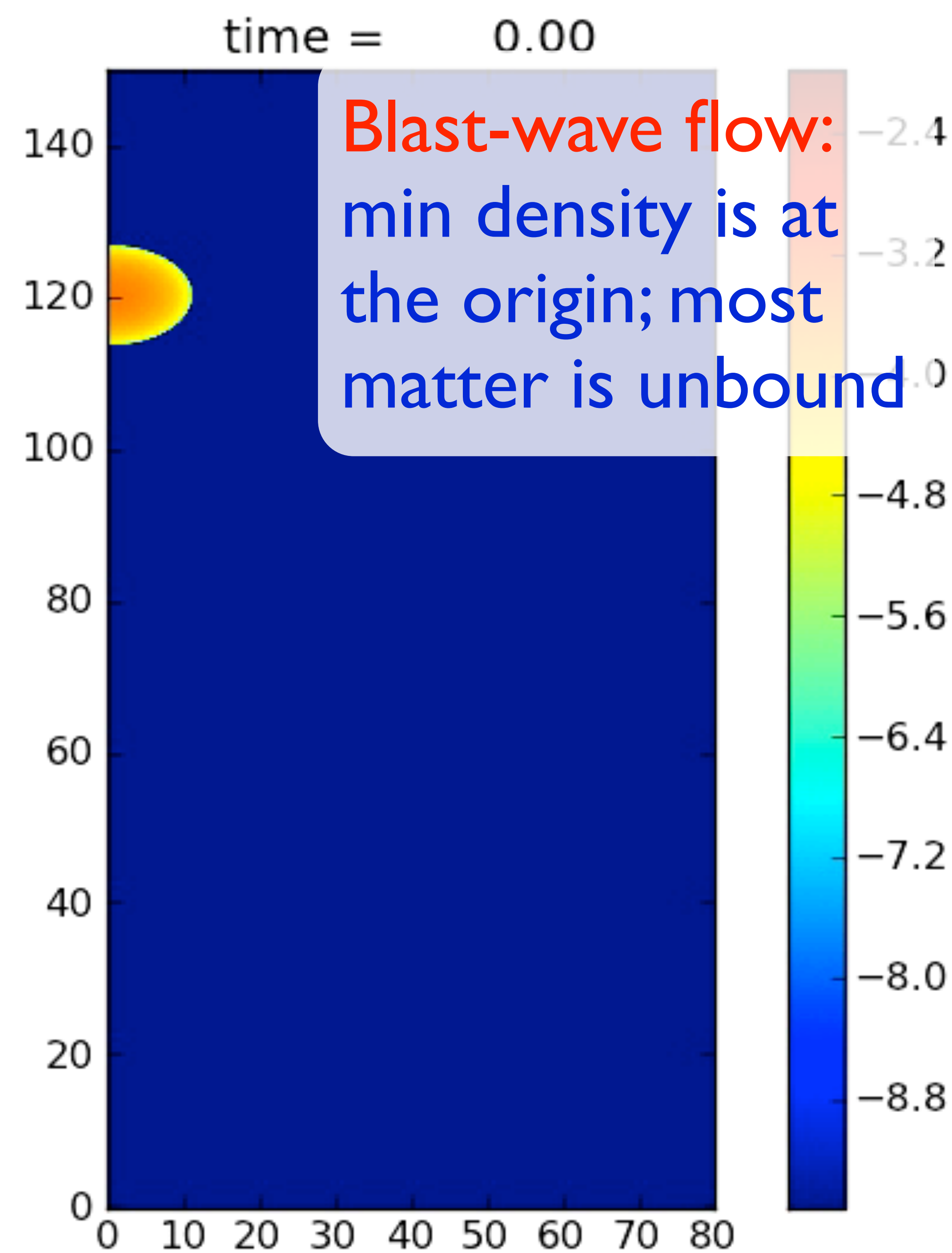
Different dynamics for different boosts

$v_{\rm b}/c = 0.3$



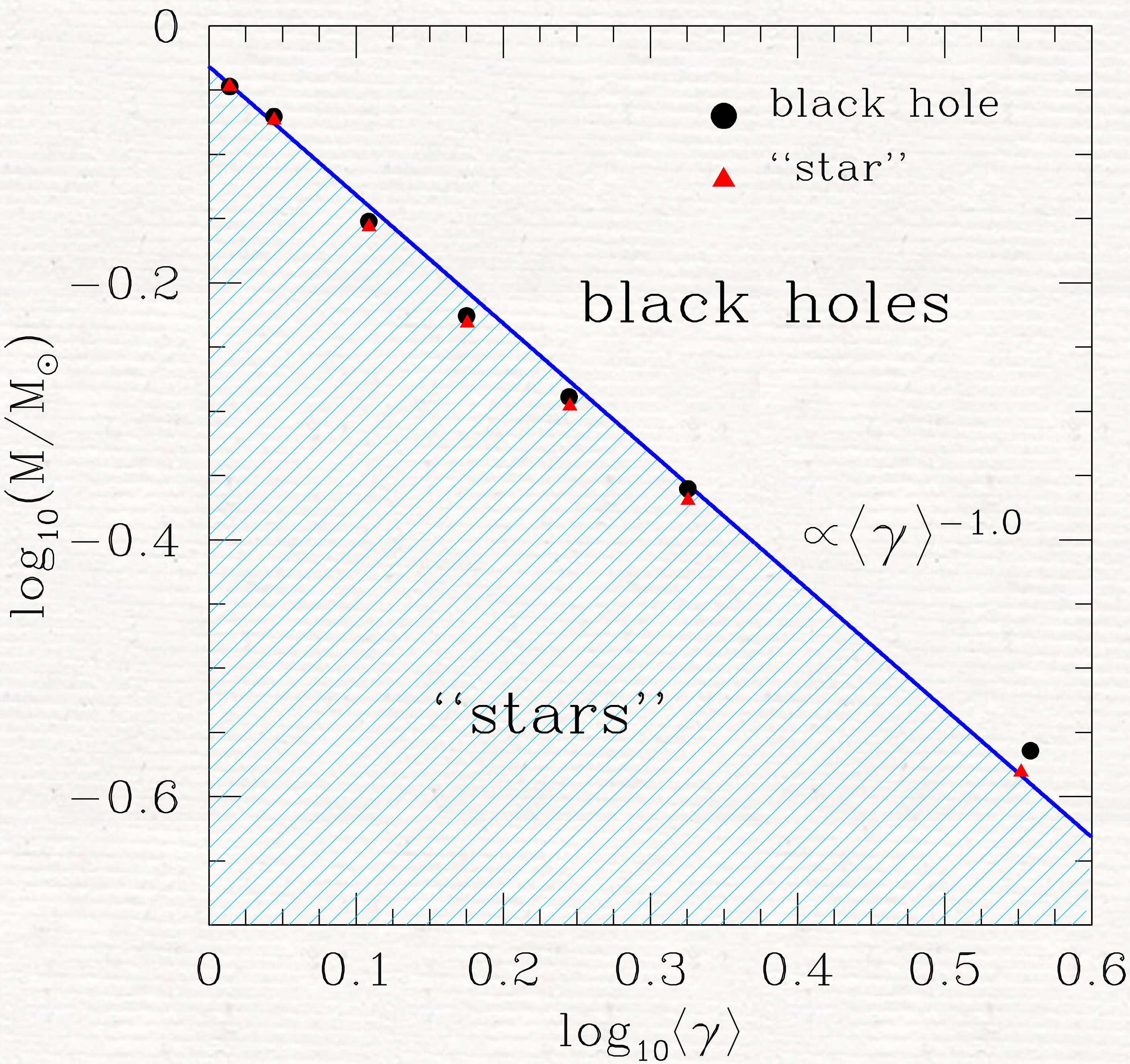
Jet-like flow:
max density is at the origin; most matter is bound

$v_{\rm b}/c = 0.8$



Blast-wave flow:
min density is at the origin; most matter is unbound

A simple scaling behaviour



For any value of the boost we can compute the threshold between BHs and NSs and find this follows a simple scaling law

$$\frac{M_c}{M_\odot} = K\ \langle\gamma\rangle^{-n} \approx 0.92\ \langle\gamma\rangle^{-1.03}$$

$$\langle\gamma\rangle \equiv \frac{\int dV\, T_{\mu\nu}n^\mu n^\nu}{(\int dV T_{\mu\nu}n^\mu n^\nu)_0}$$

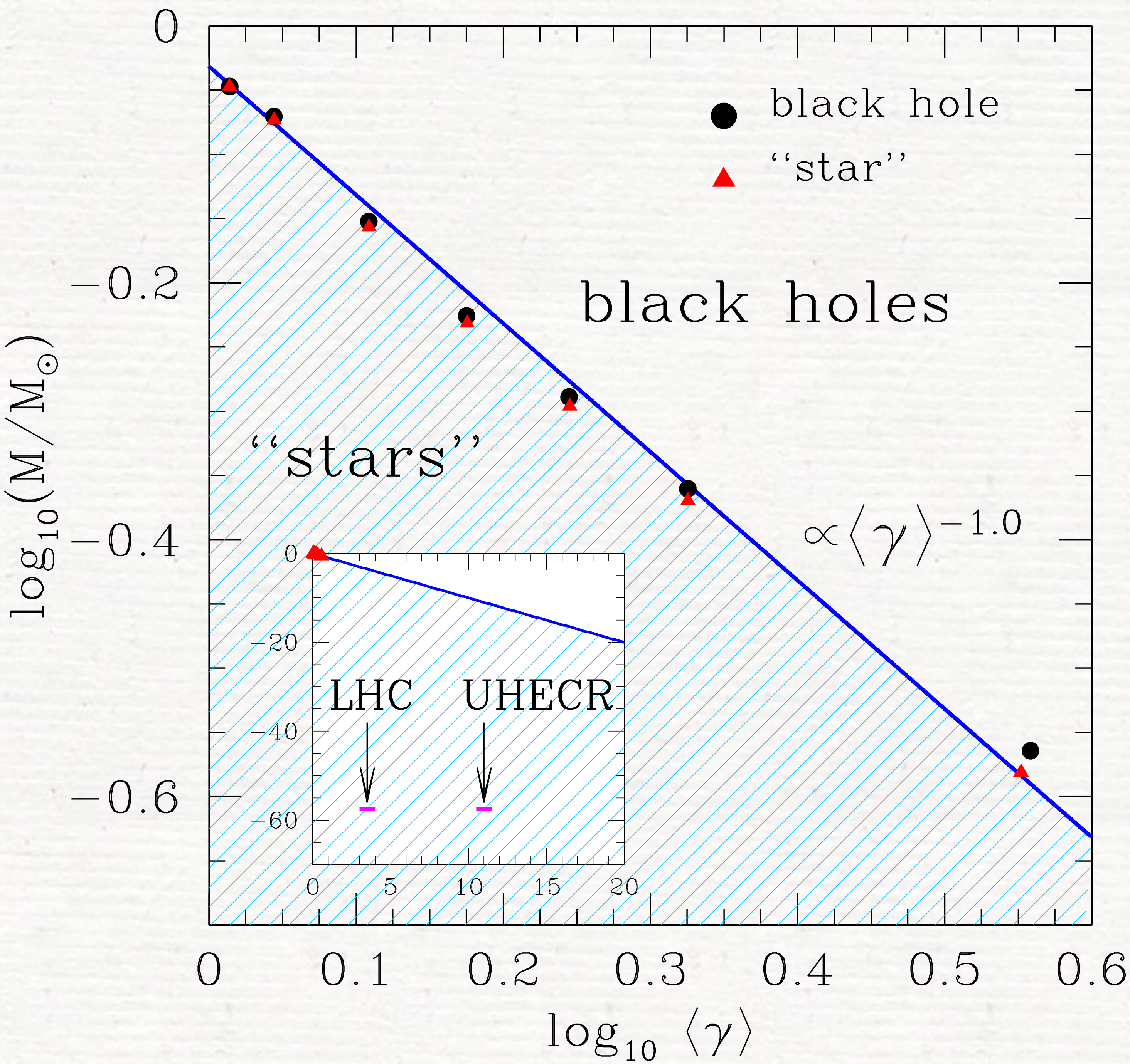
Relevant limits:

$$\langle\gamma\rangle \to 1 : \quad M_c \to 0.92\, M_\odot$$

$$\langle\gamma\rangle \to \infty : \quad M_c \to 0$$

For divergent kinetic energies, the critical BH has infinitesimal mass

A simple scaling behaviour



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Conclusions

✴ Modelling of binary neutron stars is now **mature**. All aspects can be followed accurately: inspiral, merger, collapse to BH+torus.

✴ GWs from BNSs are much more complex/rich than those 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).

✴Collisions of selfgravitating fluids show simple **scaling** behaviour and extrapolation to LHC scales suggests BHs are unlikely.

✴Binary neutron stars are **formidable laboratories** we are starting to explore. There is still a lot more to do: radiative transfer, resistive effects, nucleosynthesis, etc. Stay tuned!