Black holes, neutron stars and gravitational waves: exploring Einstein universe with supercomputers

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5th International Conference on New Frontiers in Physics
Kolymbari 07 July 2016

Plan of the talk

* goals of numerical relativity
* two-body problem: black holes and neutron stars
* theoretical physics meets astrophysics
* do black hole really exist?

The goals of numerical relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} = 8\pi T_{\mu\nu}$$

Einstein's theory is as **beautiful** as **intractable** analytically

Numerical relativity solves Einstein/HD/MHD eqs. in regimes in which no approximation is expected to hold.

The equations of numerical relativity

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} \,, \qquad \text{(field equations)}$$

$$\nabla_\mu T^{\mu\nu} = 0 \,, \qquad \text{(cons. energy/momentum)}$$

$$\nabla_\mu (\rho u^\mu) = 0 \,, \qquad \text{(cons. rest mass)}$$

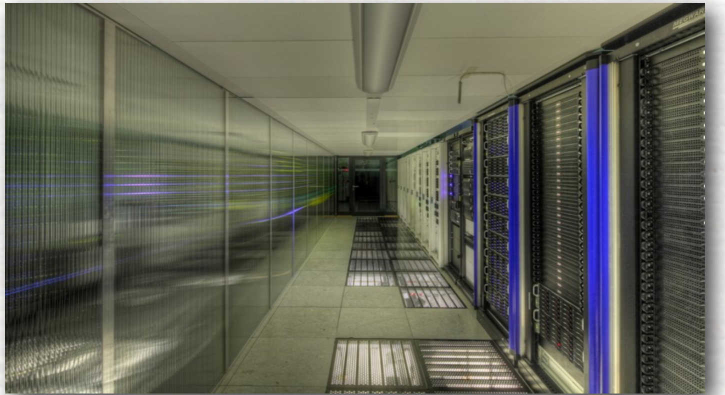
$$p = p(\rho, \epsilon, Y_e, \ldots) \,, \qquad \text{(equation of state)}$$

$$\nabla_\nu F^{\mu\nu} = I^\mu \,, \quad \nabla_\nu^* F^{\mu\nu} = 0 \,, \qquad \text{(Maxwell equations)}$$

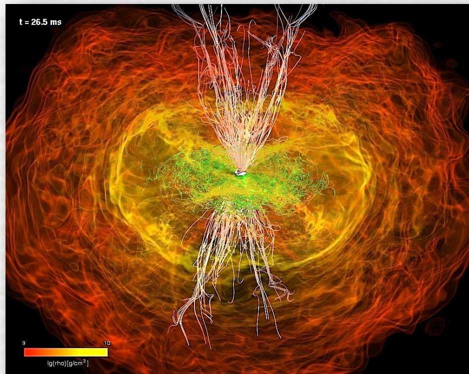
$$T_{\mu\nu} = T^{\text{fluid}}_{\mu\nu} + T^{\text{EM}}_{\mu\nu} + \ldots \qquad \text{(energy} - \text{momentum tensor)}$$

To solve these equations we build codes:
our **”theoretical laboratories”.**

Theoretical laboratory

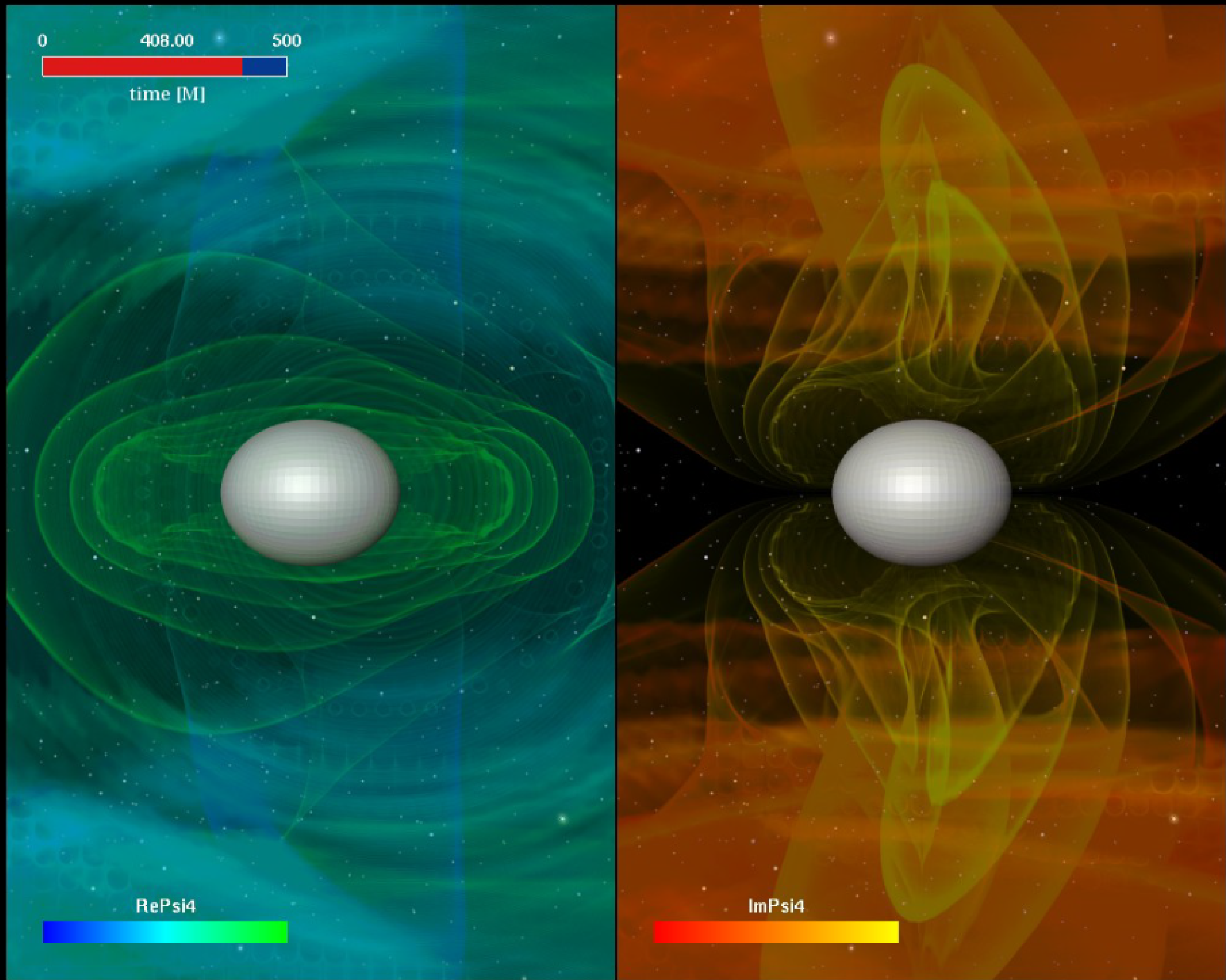


$$G_{\mu\nu} = 8\pi G T_{\mu\nu},$$
$$\nabla_\mu T^{\mu\nu} = 0$$



Think of them as a "*factory*" of "gedanken experiments"

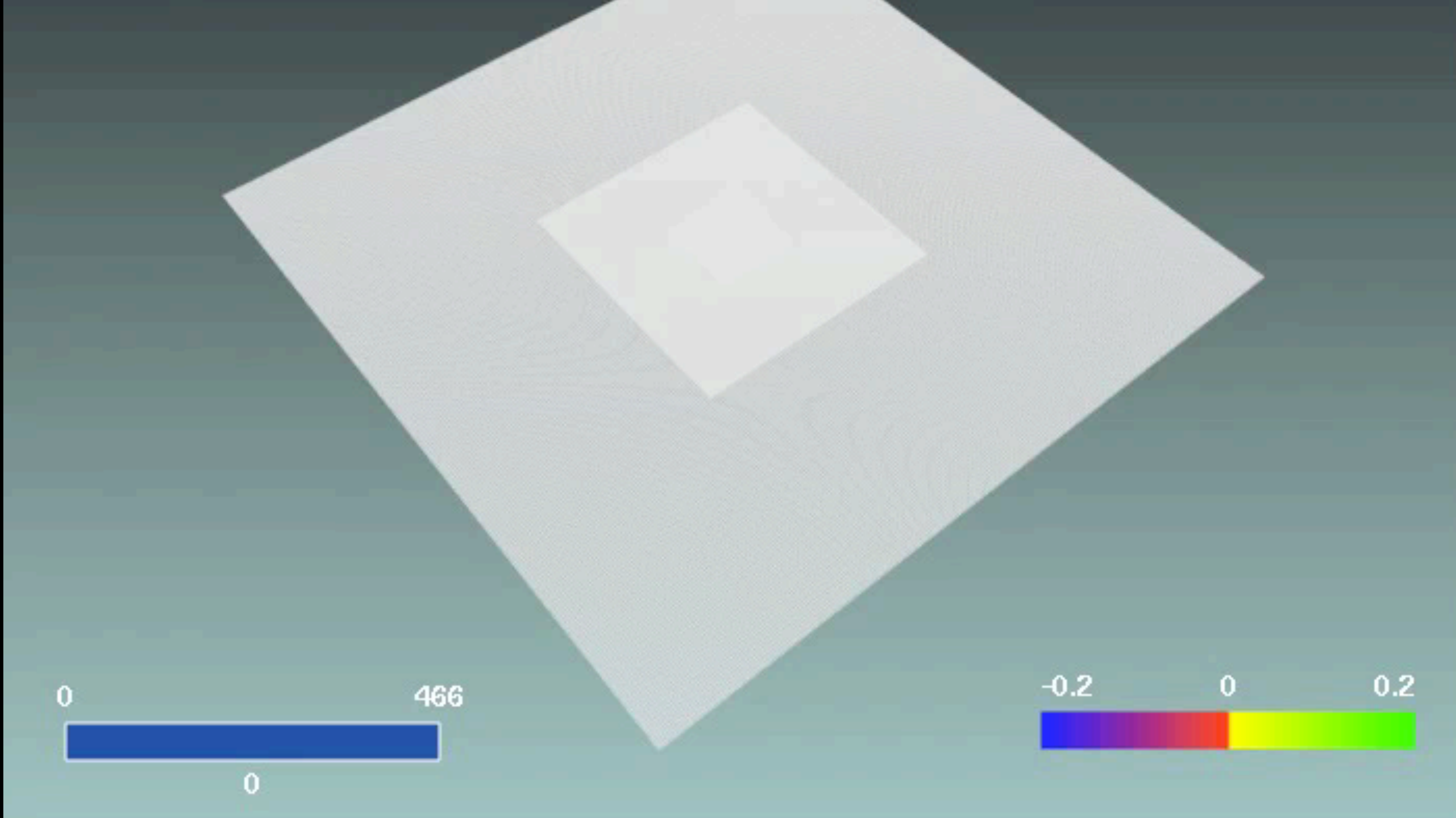
Black-hole binaries



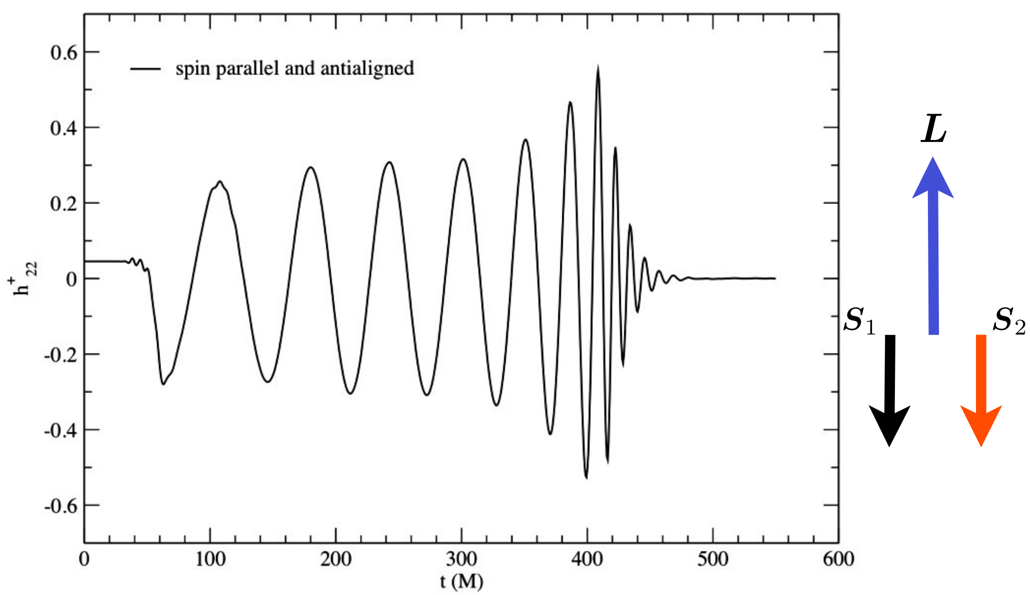
In vacuum the Einstein equations reduce to

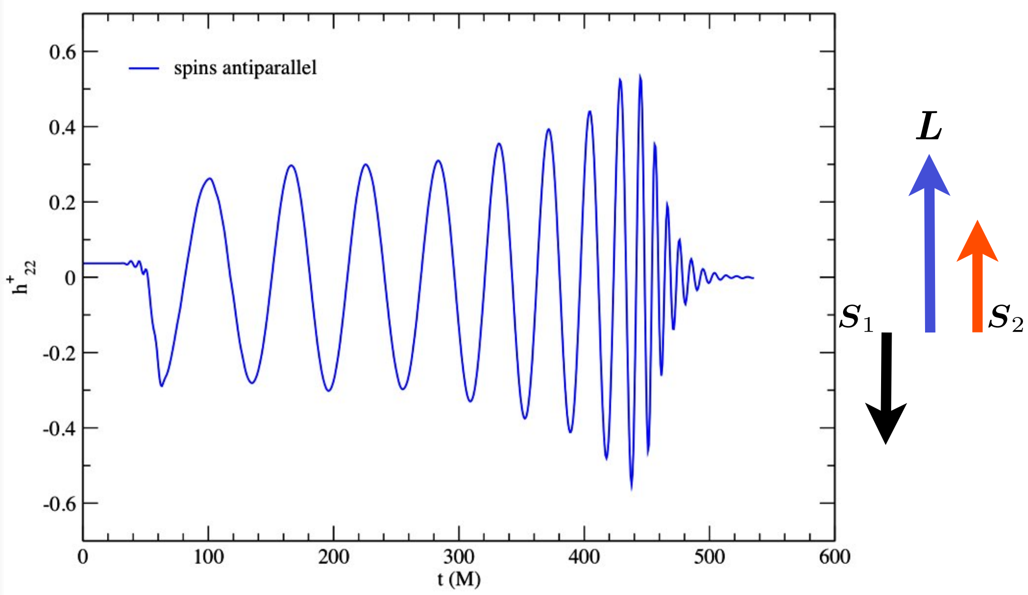
$$R_{\mu\nu} = 0$$

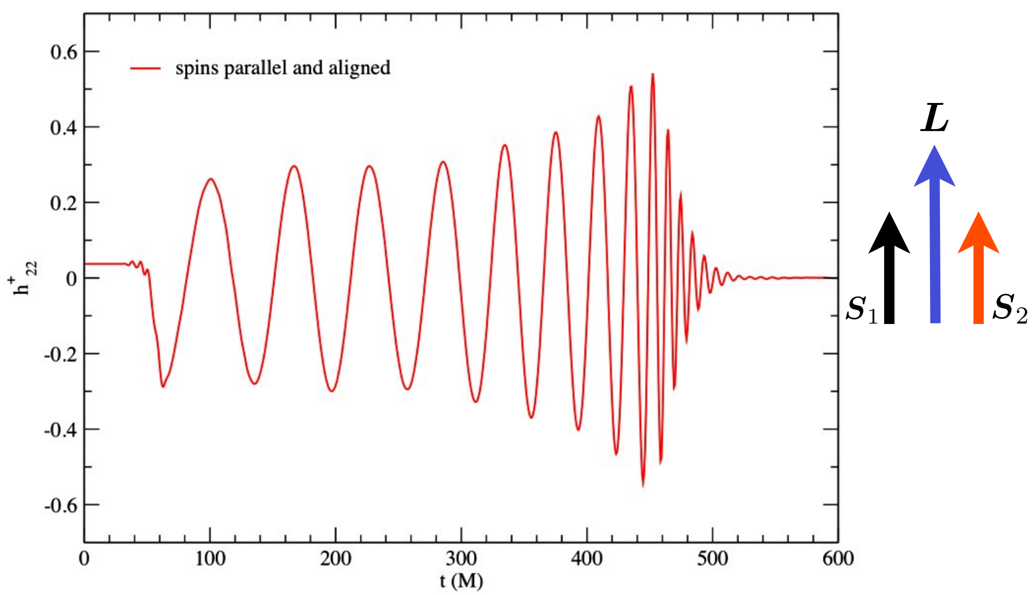
How difficult can that be?



Animation by Kaehler, Reisswig, LR



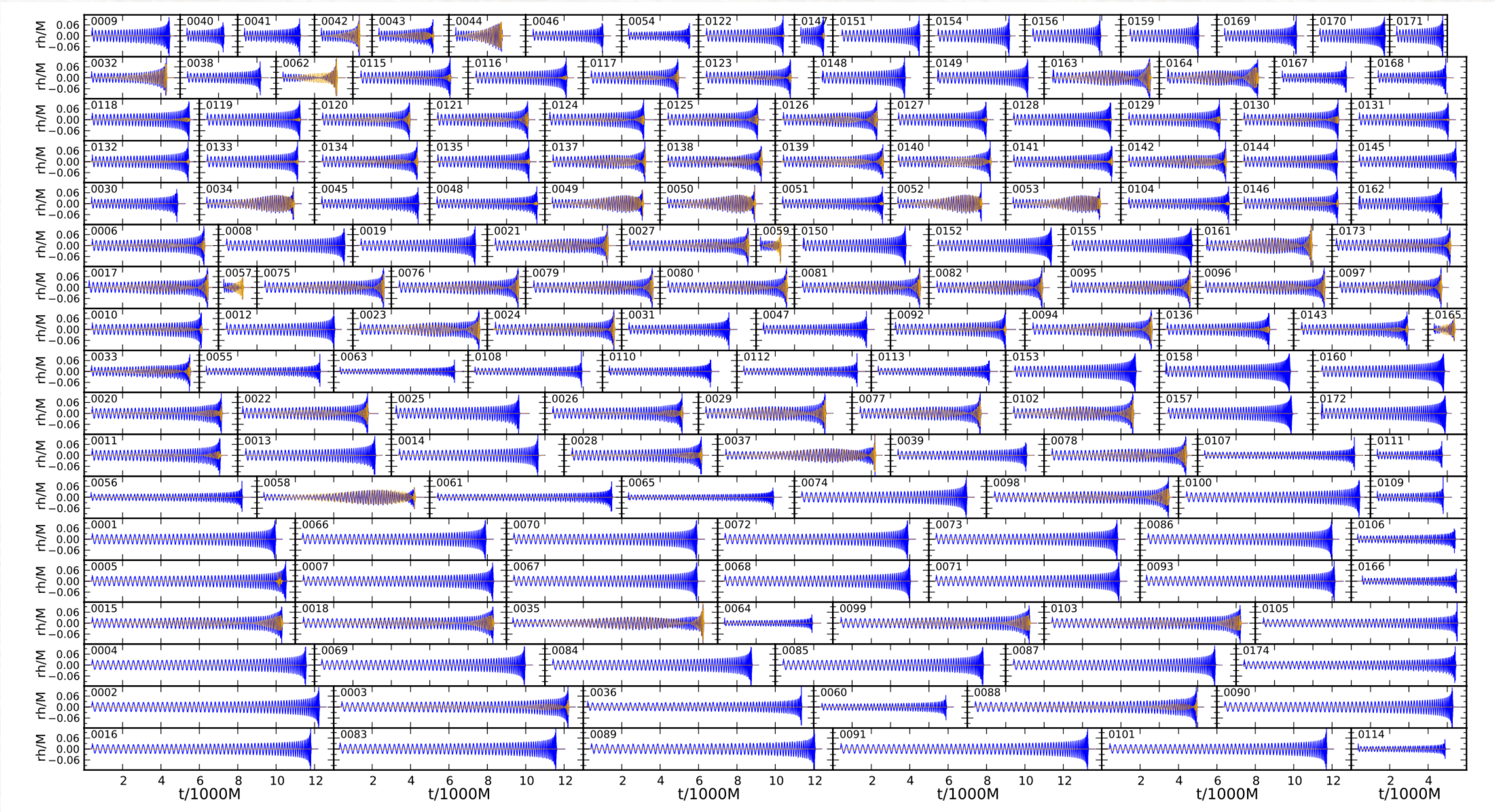




As the **total** angular momentum is increased, so is the time to merger: more orbits spent to lose **orbital** angular momentum

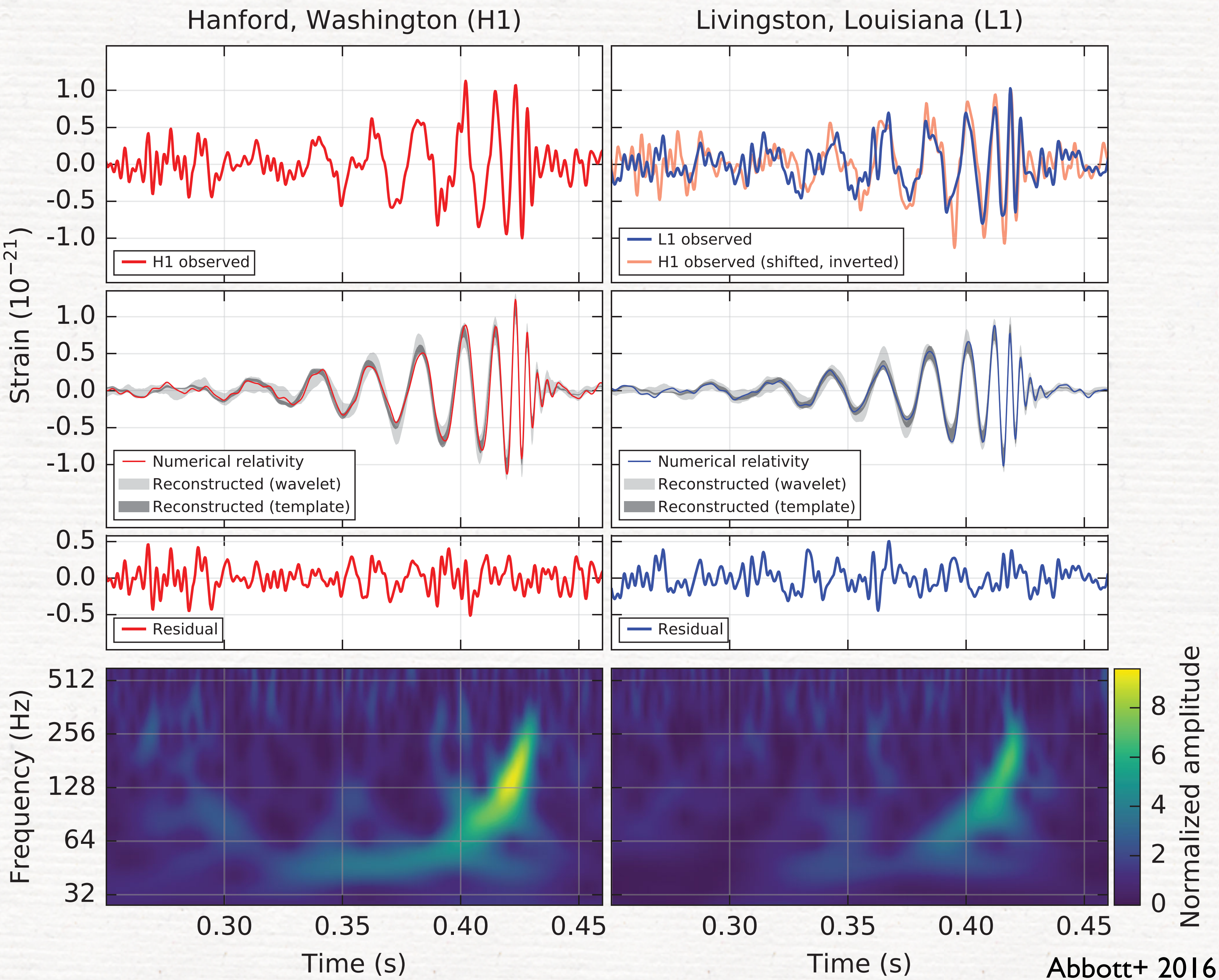
Going industrial…

The numerical-relativity community has now explored a good portion of space of parameter, producing accurate and long waveforms matched to post-Newtonian expressions.



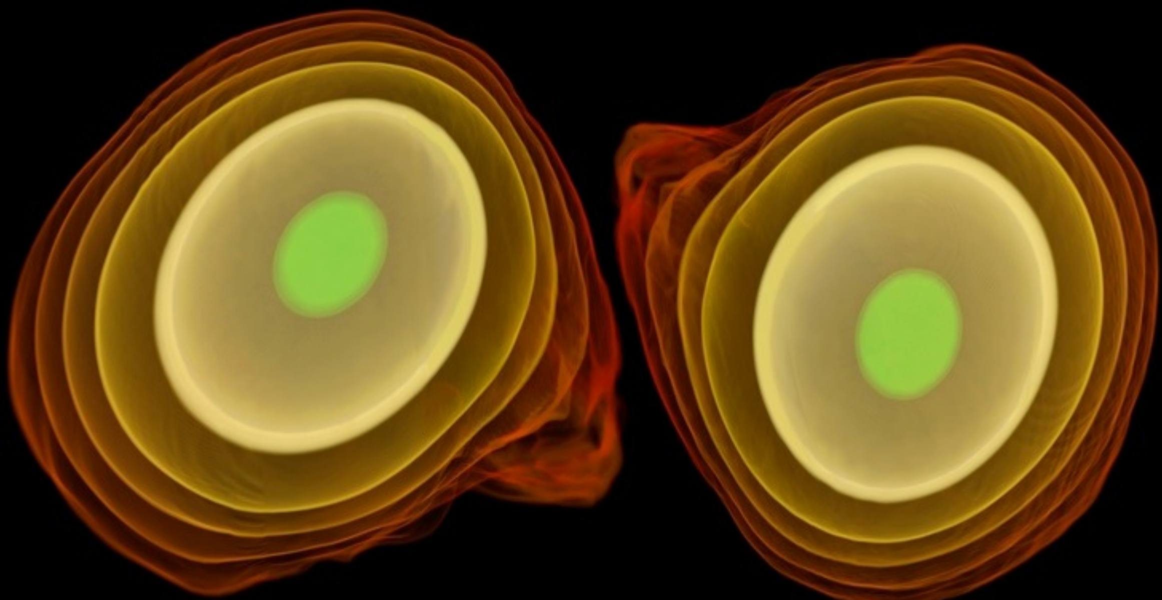
Mroue+ 2013

GW150914: the birth of GW astronomy



Abbott+ 2016

Neutron-star binaries



The two-body problem in GR

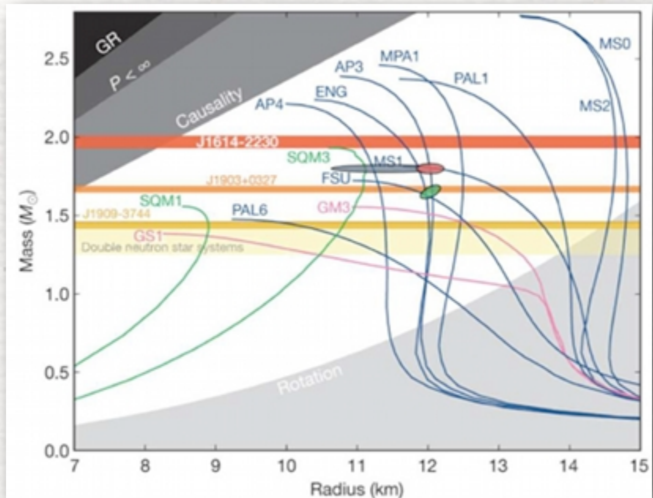
- For BHs we know what to **expect**:

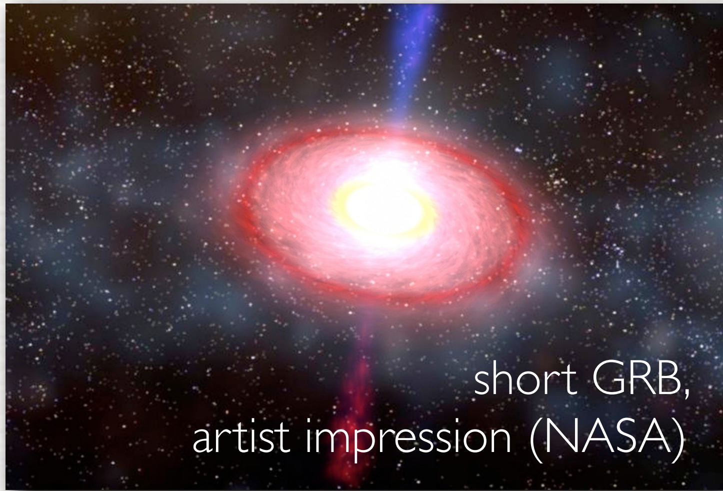
BH + BH ⟶ BH + GWs

- 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

- **HMNS** phase can provide clear information on **EOS**





- **BH+torus** system may tell us on the central engine of **GRBs**

Animations: Breu, Radice, LR

$$M = 2 \times 1.35\, M_\odot$$

LS220 EOS

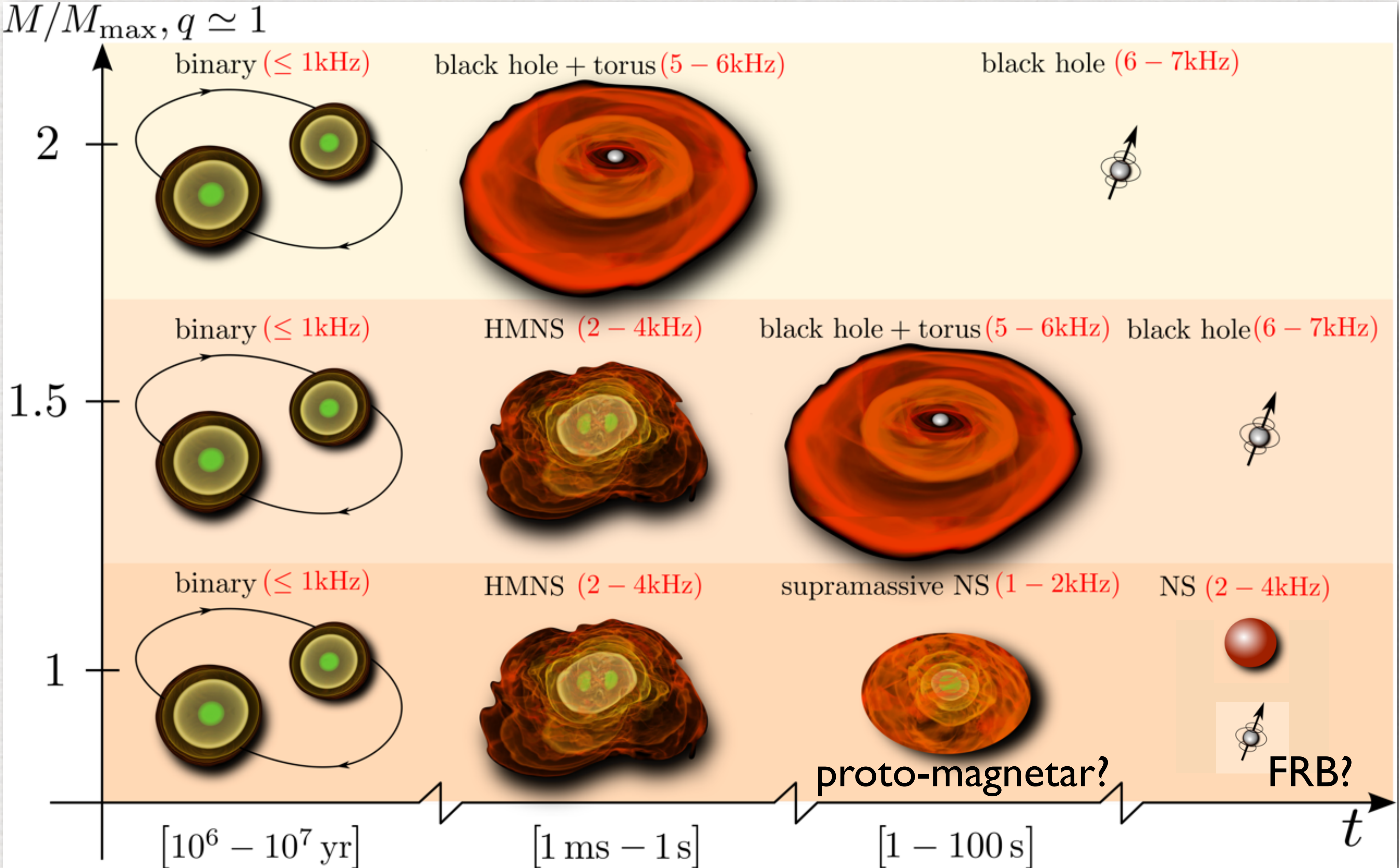
"merger → HMNS → BH + torus"

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

Broadbrush picture



"merger → HMNS → BH + torus"

Quantitative differences are produced by:

- **differences induced by the gravitational MASS:**
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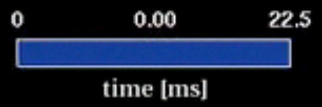
- **differences induced by MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH



Animations: Giacomazzo, Koppitz, LR

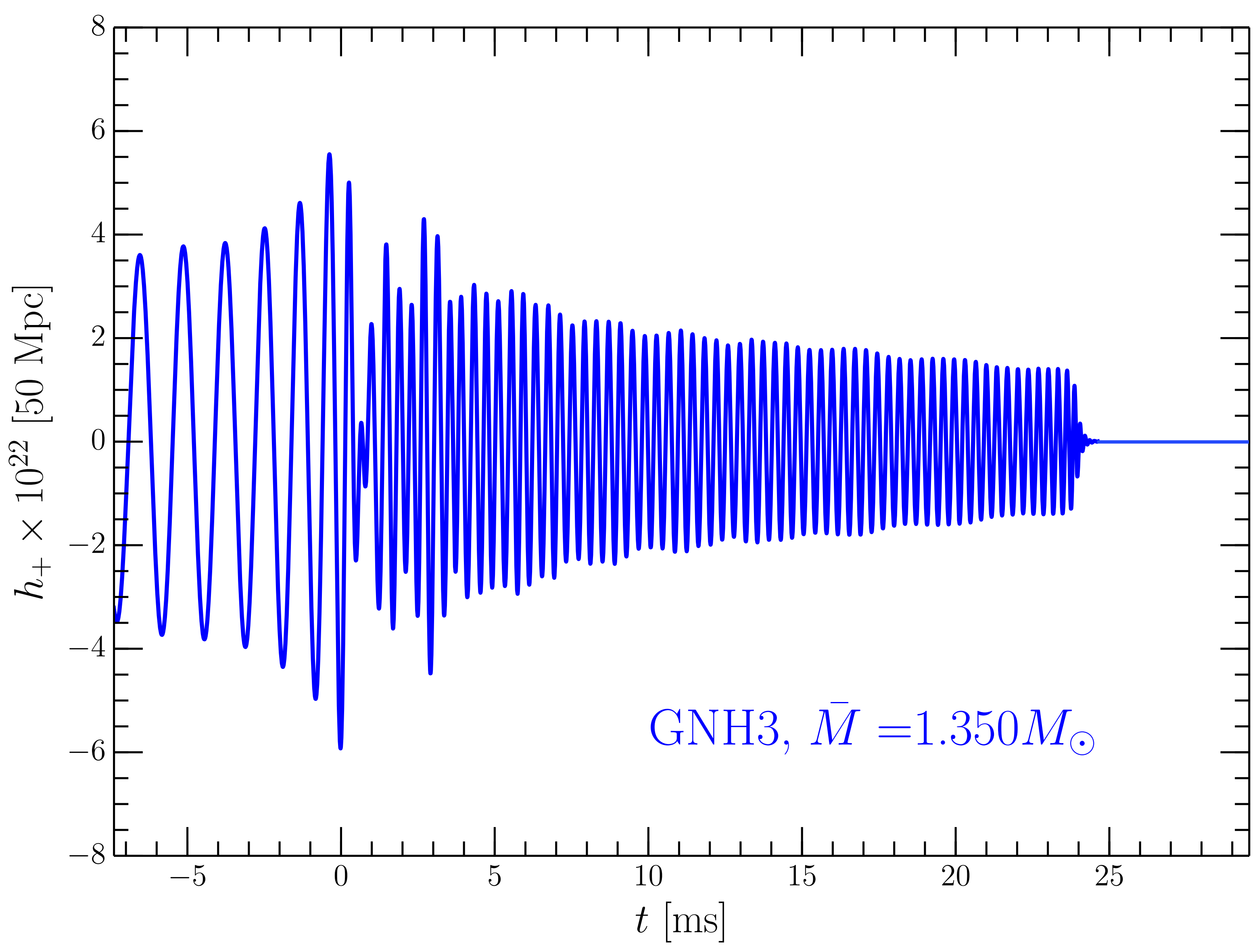
$$\text{Total mass : } 3.37\, M_{\odot}; \quad \text{mass ratio :} 0.80;$$

"merger → HMNS → BH + torus"

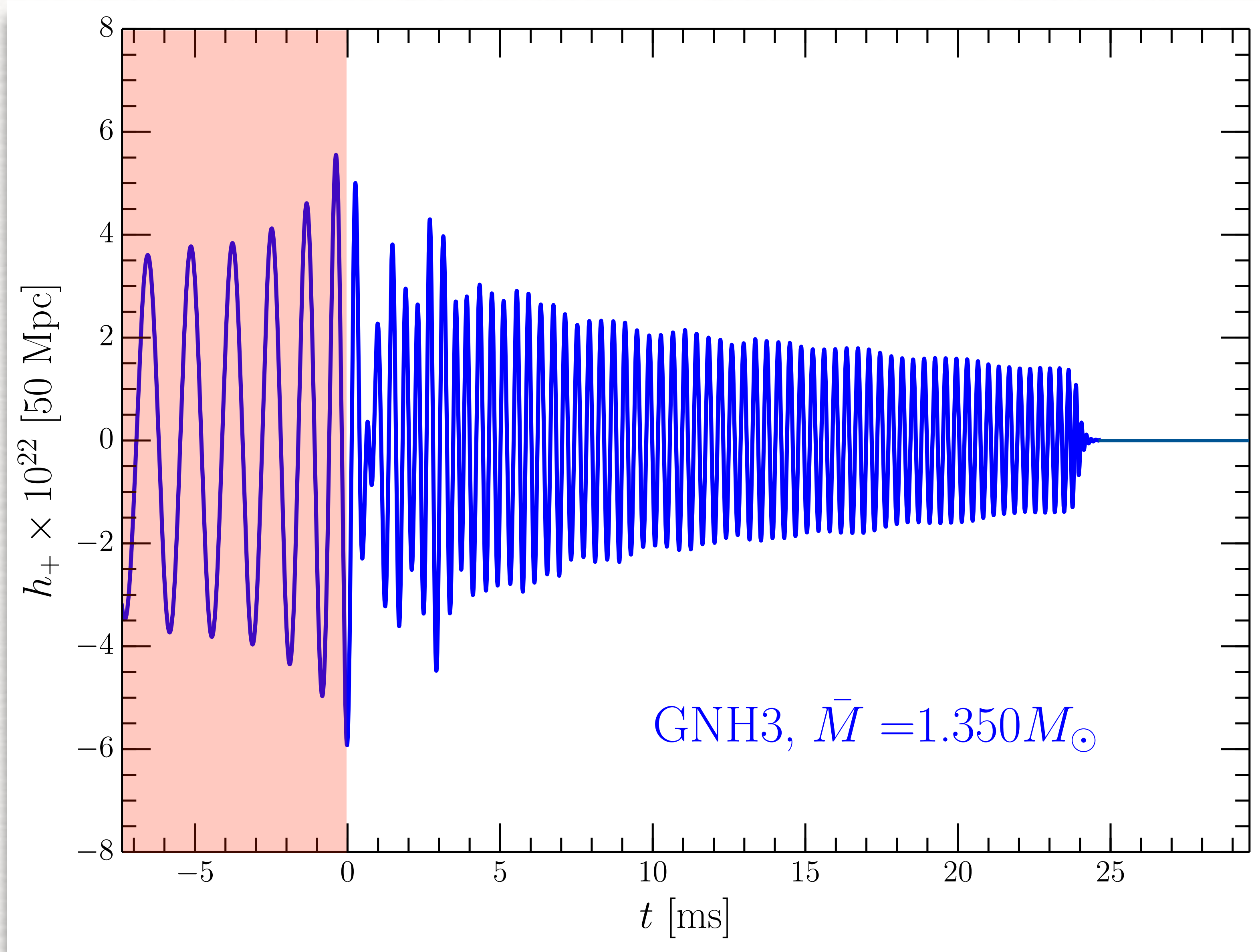
Quantitative differences are produced by:

- **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 MASS ASYMMETRIES:**
  tidal disruption before merger; may lead to prompt BH
- **differences induced by the EOS:**
  stiff/soft OESs will have different compressibility and deformability, imprinting on the GW signal
- **differences induced by MAGNETIC FIELDS:**
  the angular momentum redistribution via magnetic braking or MRI can increase/decrease time to collapse; EM counterparts!
- **differences induced by RADIATIVE PROCESSES:**
  radiative losses will alter the equilibrium of the HMNS

Anatomy of the GW signal

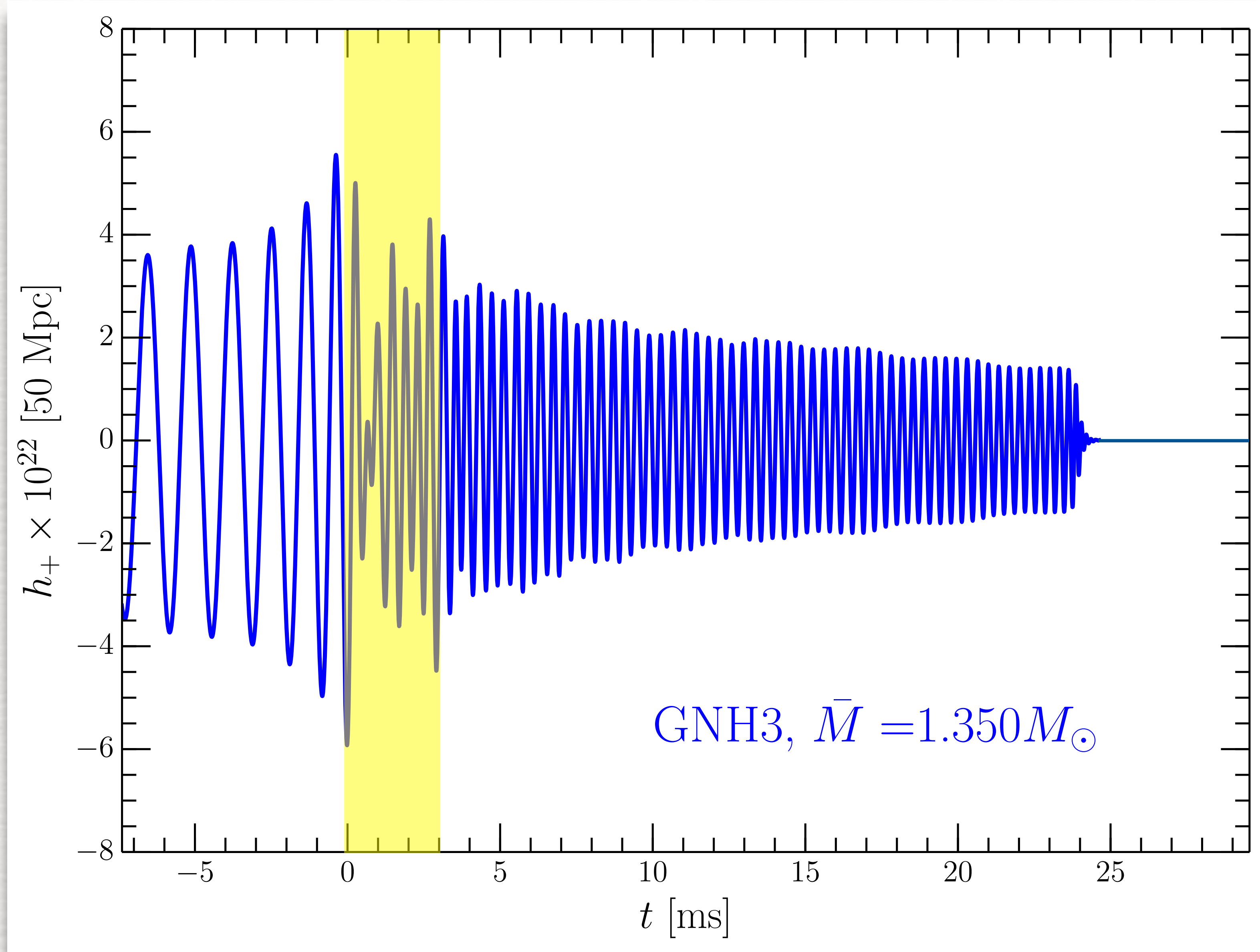


Anatomy of the GW signal



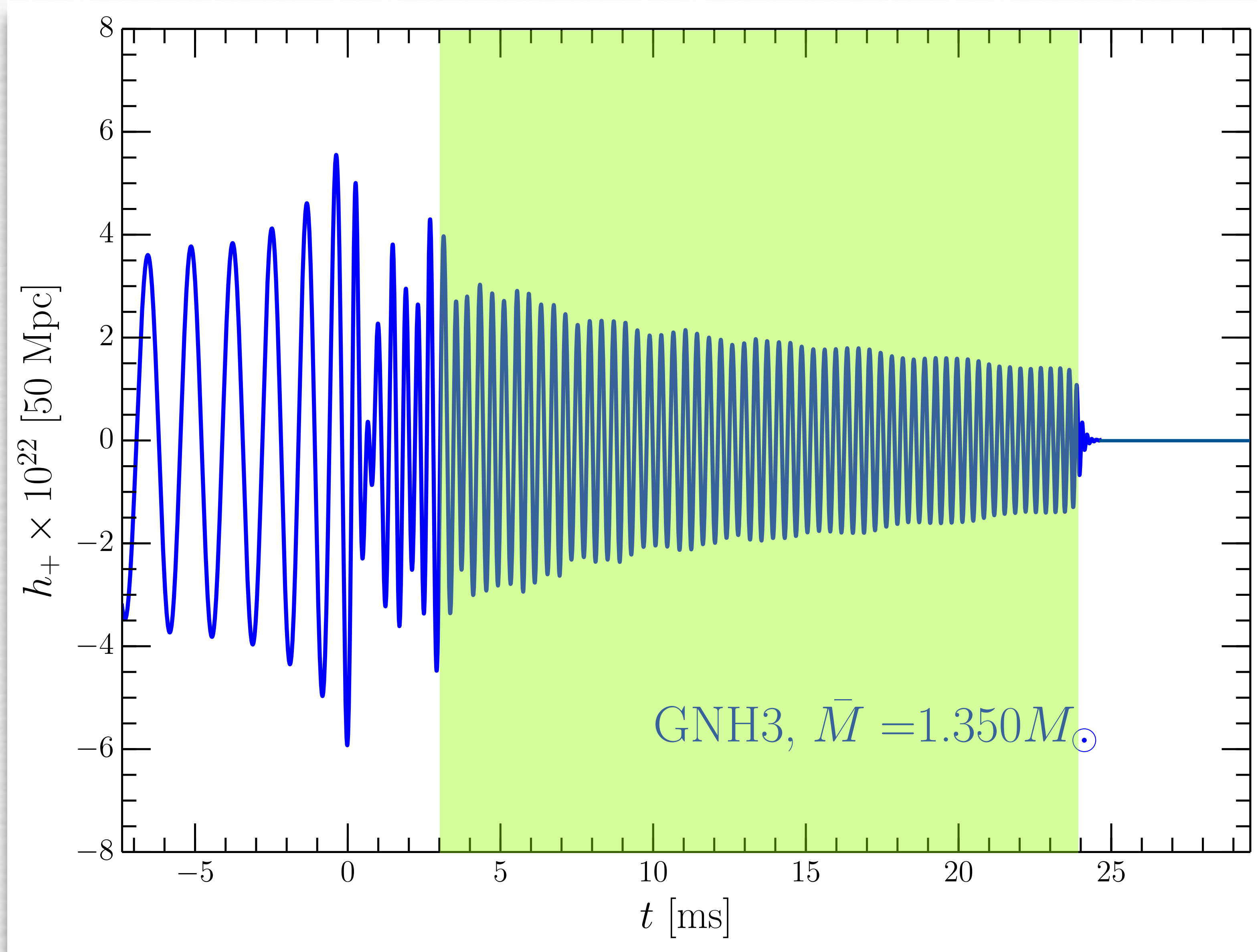
Inspiral: well approximated by PN/EOB; tidal effects important

Anatomy of the GW signal



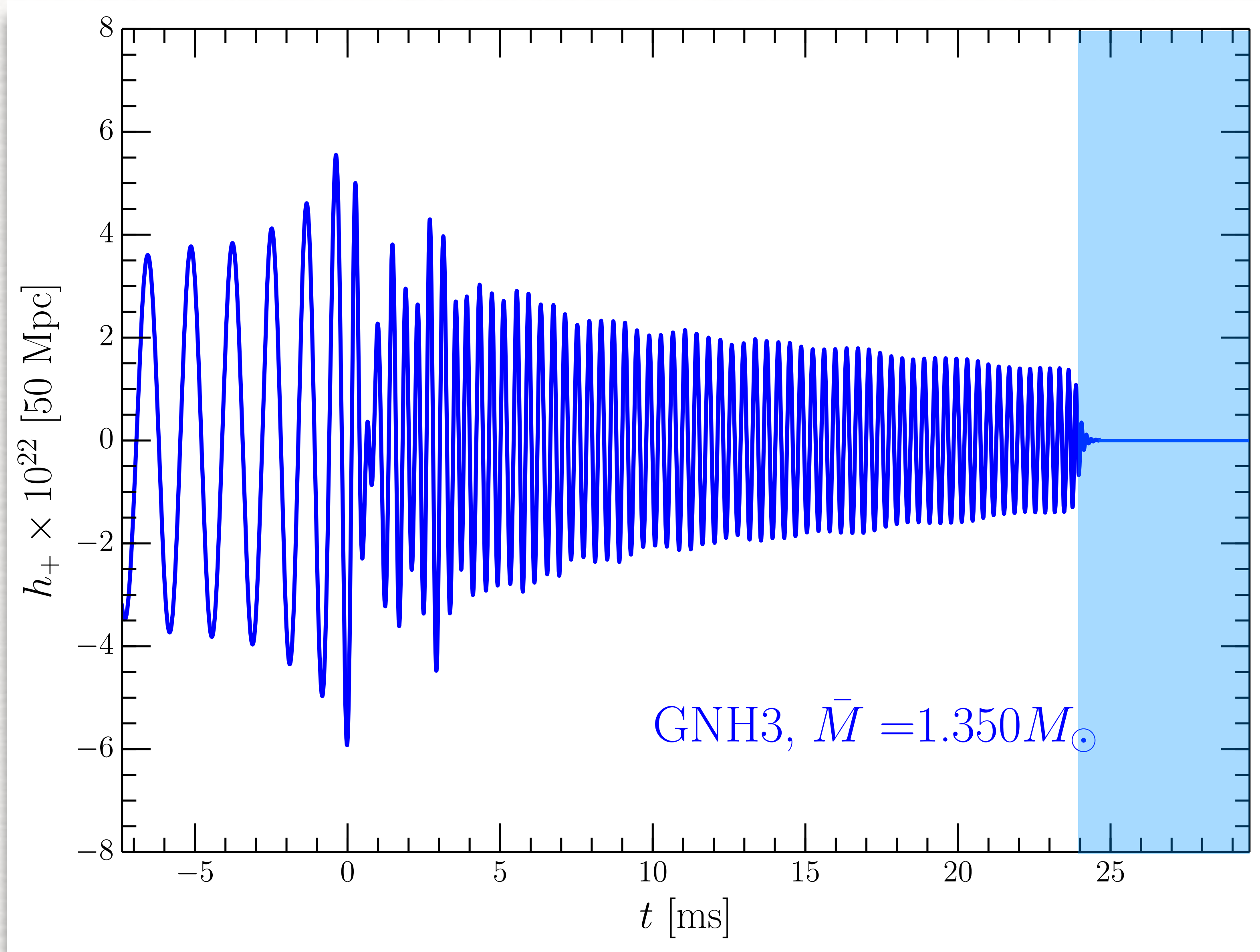
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



post-merger: quasi-periodic emission of bar-deformed HMNS

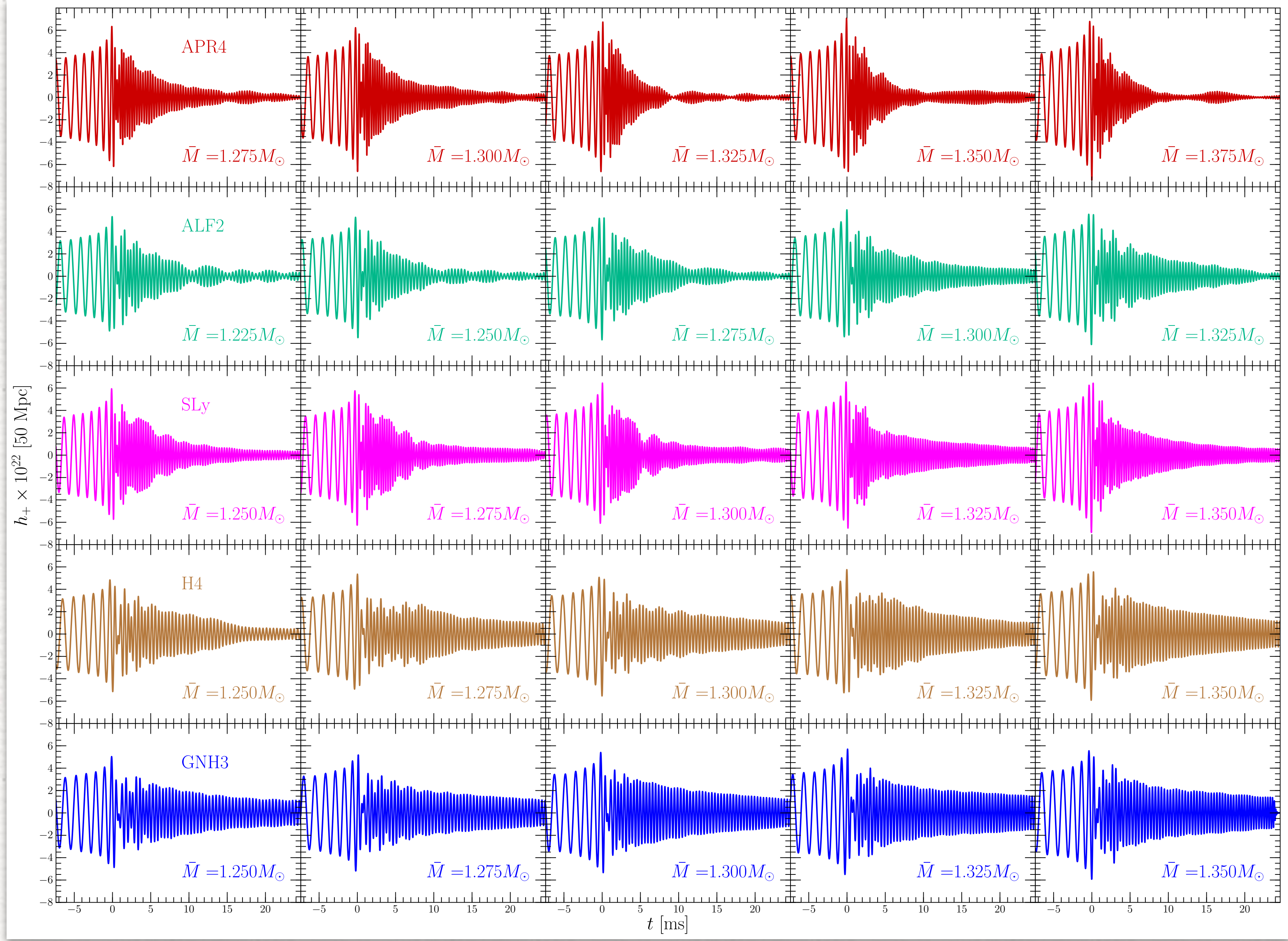
Anatomy of the GW signal



Collapse-ringdown: signal essentially shuts off.

Extracting information from the EOS

Takami, LR, Baiotti (2014, 2015), LR+ (2016)



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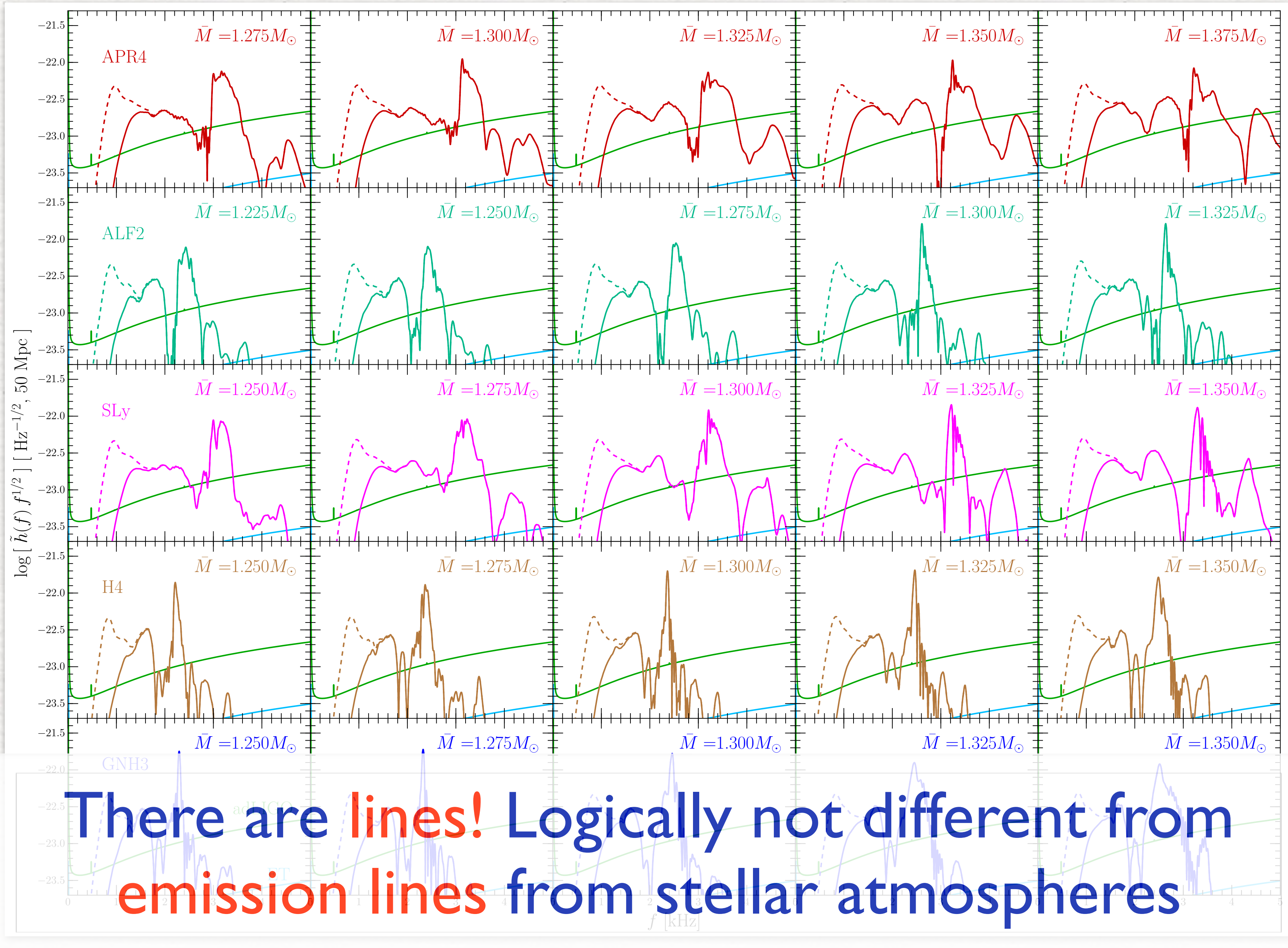
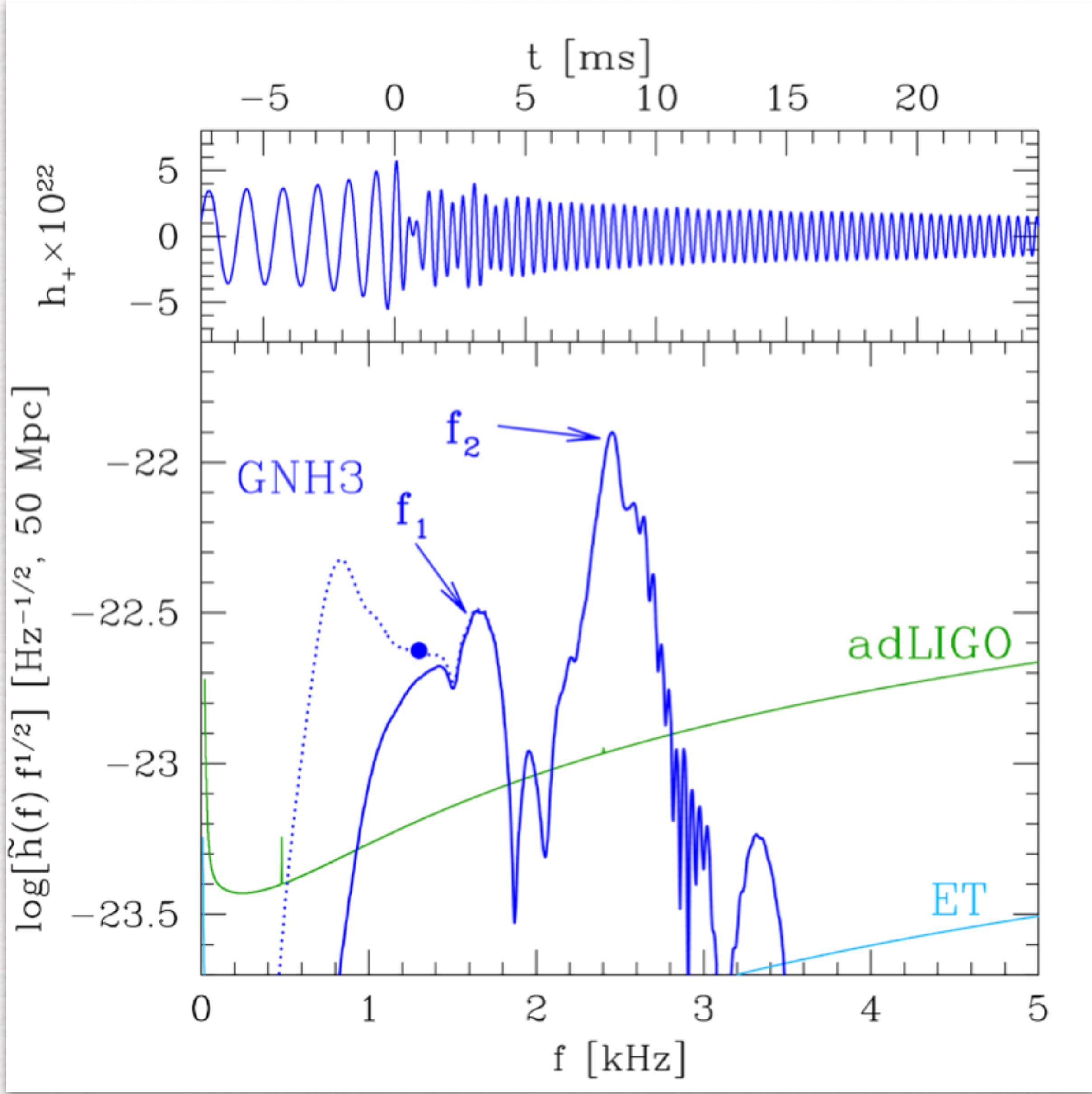


There are lines! Logically not different from emission lines from stellar atmospheres

A new approach to constrain the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, LR+2016…



A new approach to constrain the EOS

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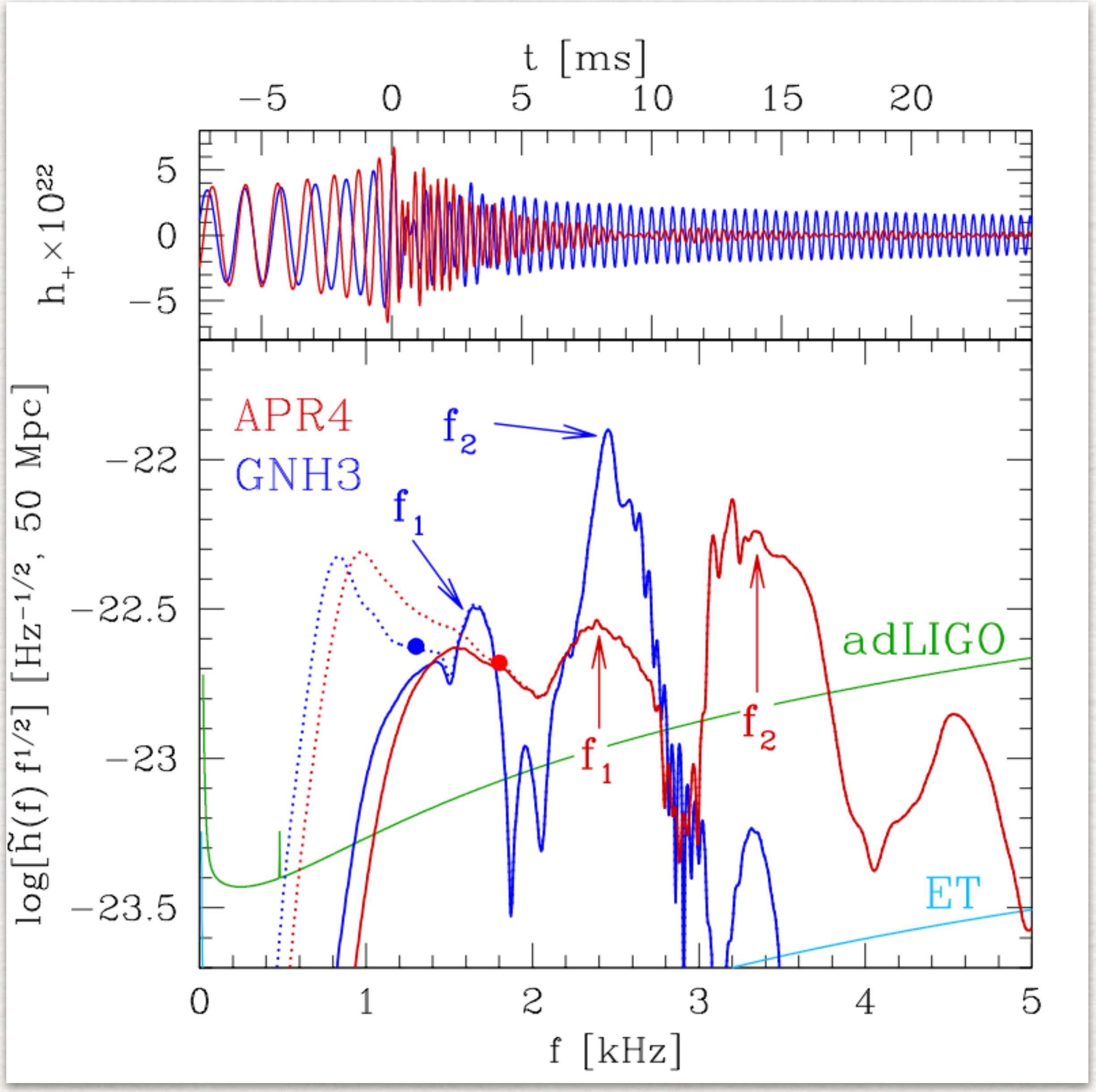
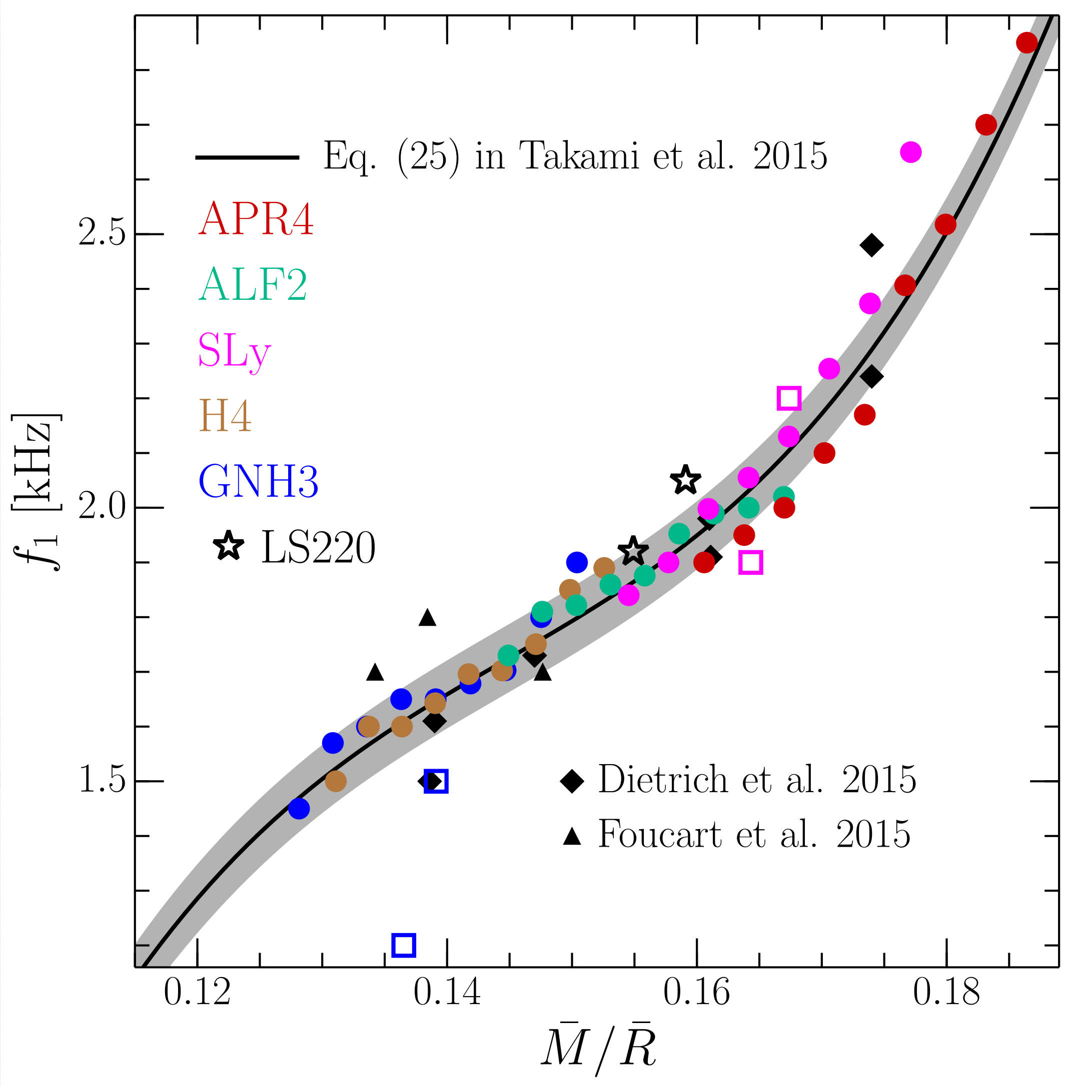


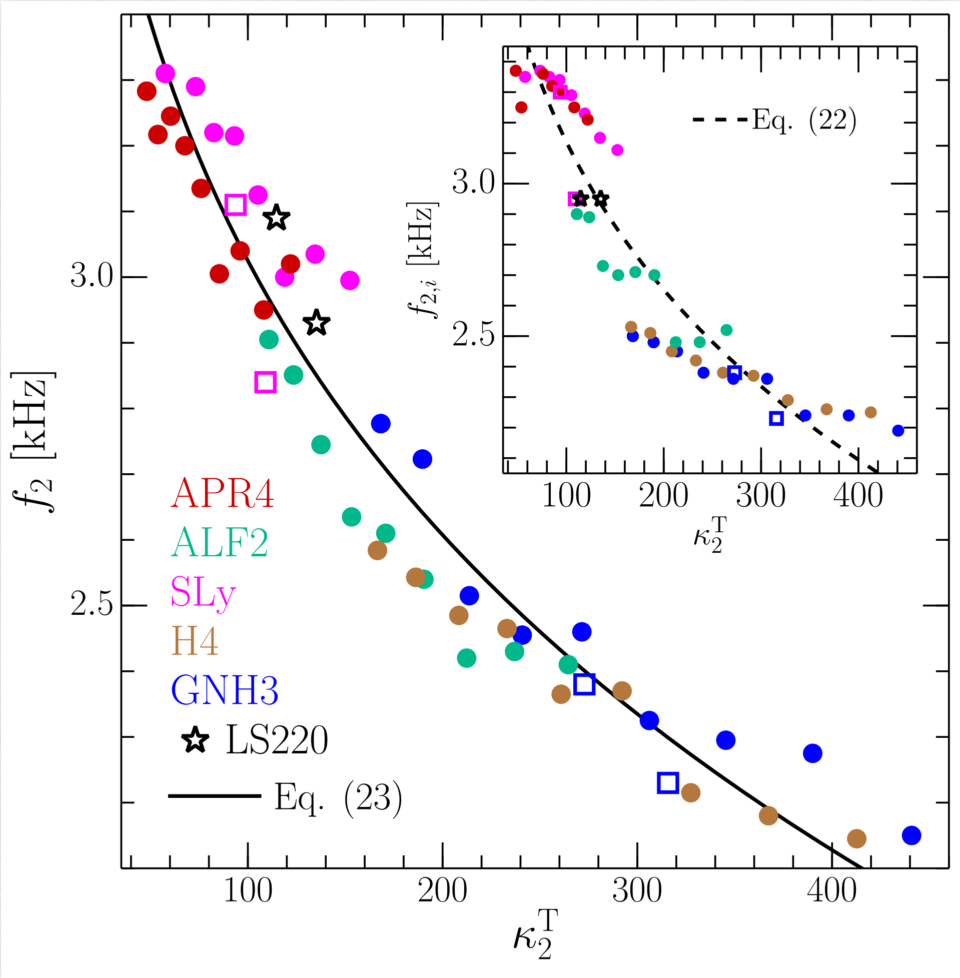
Quasi-universal behaviour



We have found **quasi-universal behaviour**: the properties of the spectra are only weakly dependent on the EOS.

This has profound implications for the analytical modelling of the GW emission: what we do for one EOS can be extended to all EOSs.

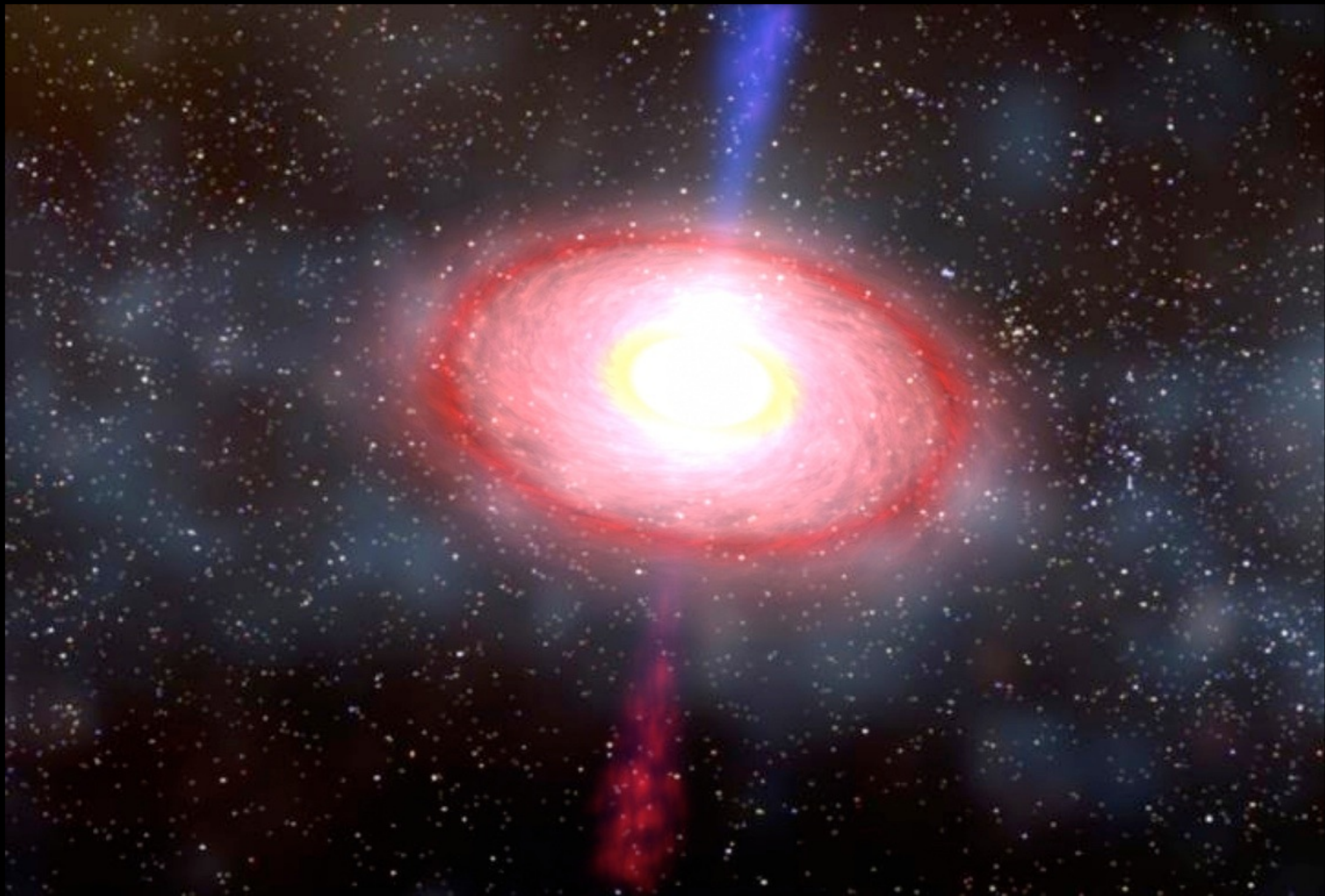
Quasi-universal behaviour



Correlations with stellar properties (Love number) have been found also for f_2 and $f_{2\text{-}0}$ peak (Takami+ 2015, Bernuzzi+ 2015, LR+2016)

These correlations are weaker but equally important. Despite its complexity, a complete **analytical** description of pre- and post-merger signal is **possible.**

Theoretical physics meets astrophysics



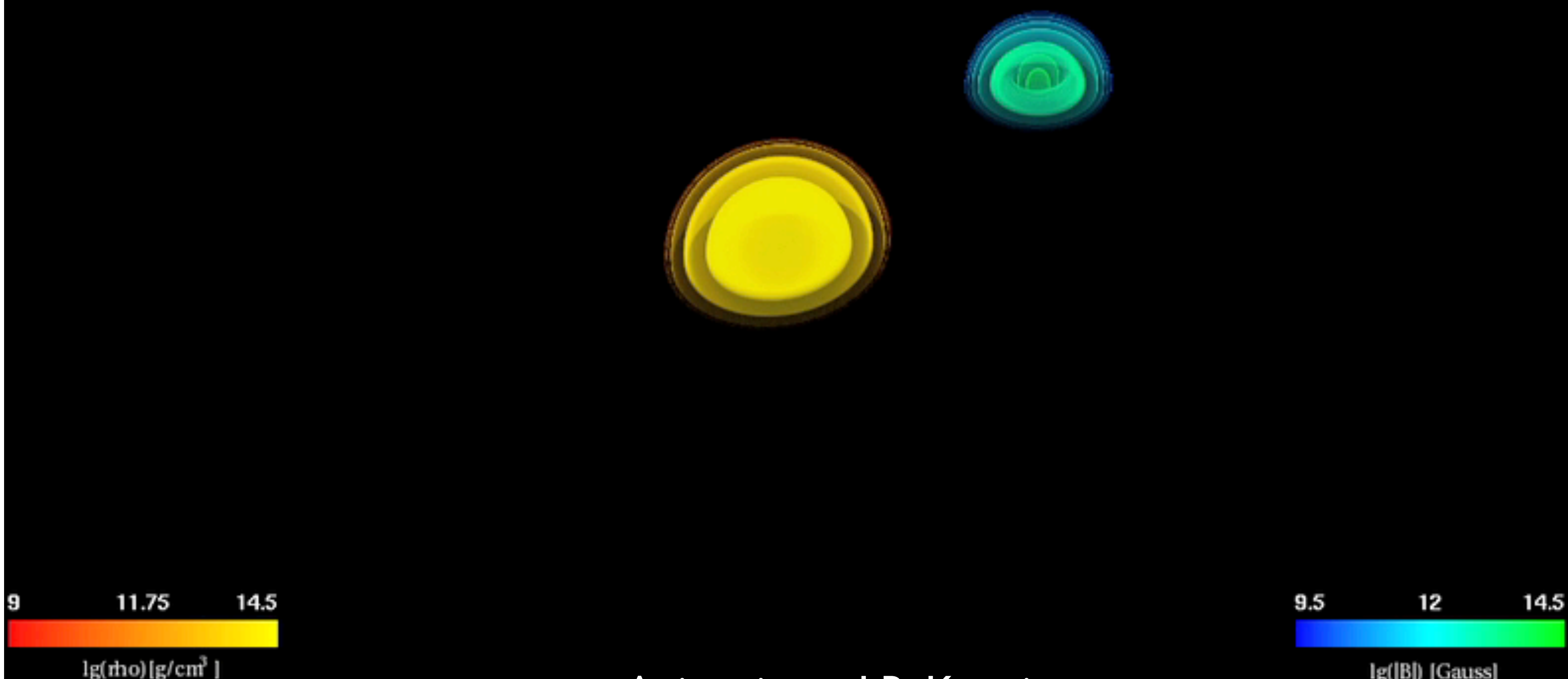
short GRB,
artist impression (NASA)

Gamma-ray bursts (GRBs)

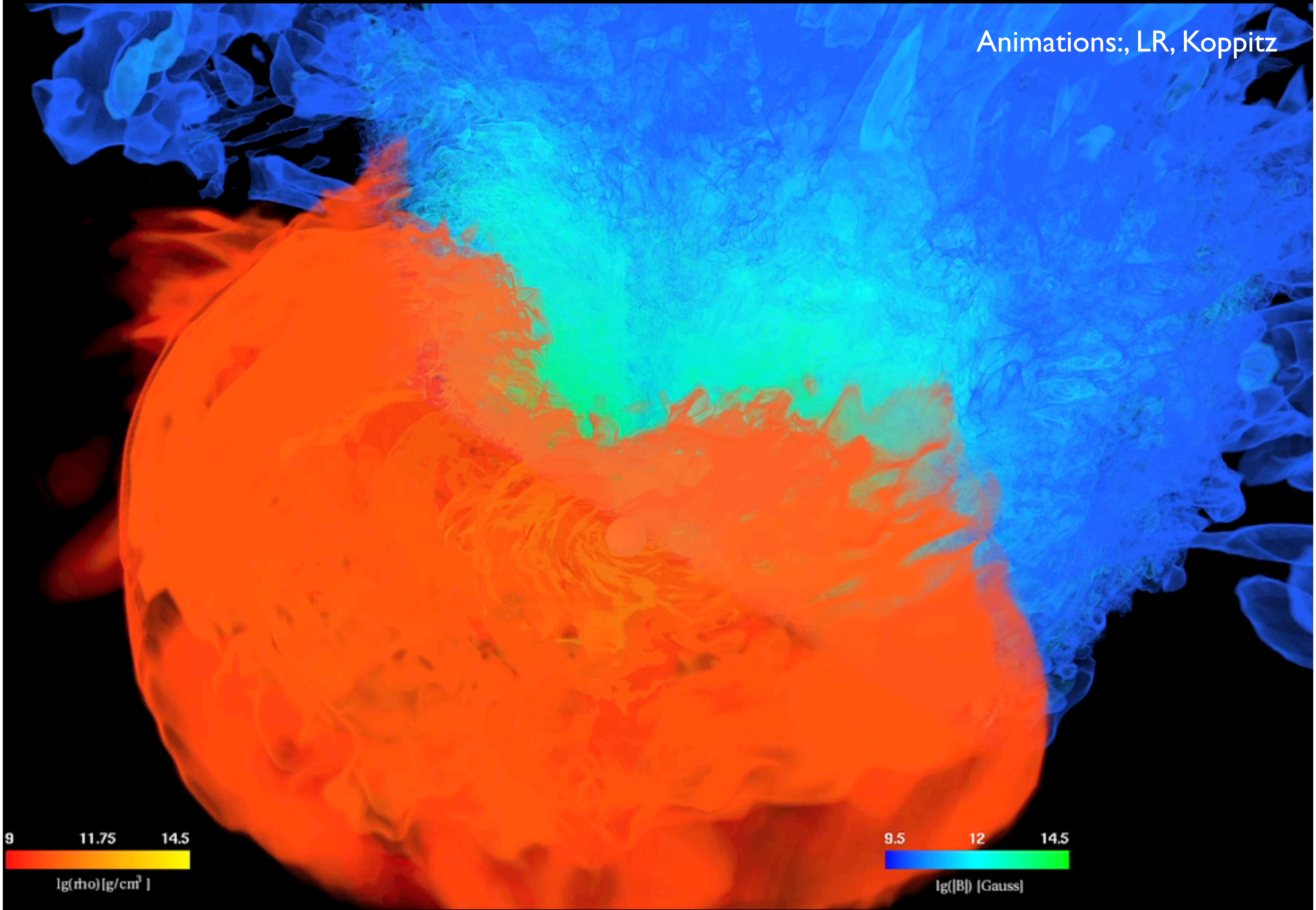
- Everyday we observe GRBs: the most catastrophic events in the universe, with huge energies released: $10^{48\text{-}50}$ erg.
- Despite decades of observations we don't know what produces them and in particular the jet emission.
- Merger of binary system of neutron stars could provide the required energy and is favoured model.
- How can we be sure that neutron stars are behind GRBs?
- Are there other observables? (Nuclear reactions!)
- However, how is a jet produced?

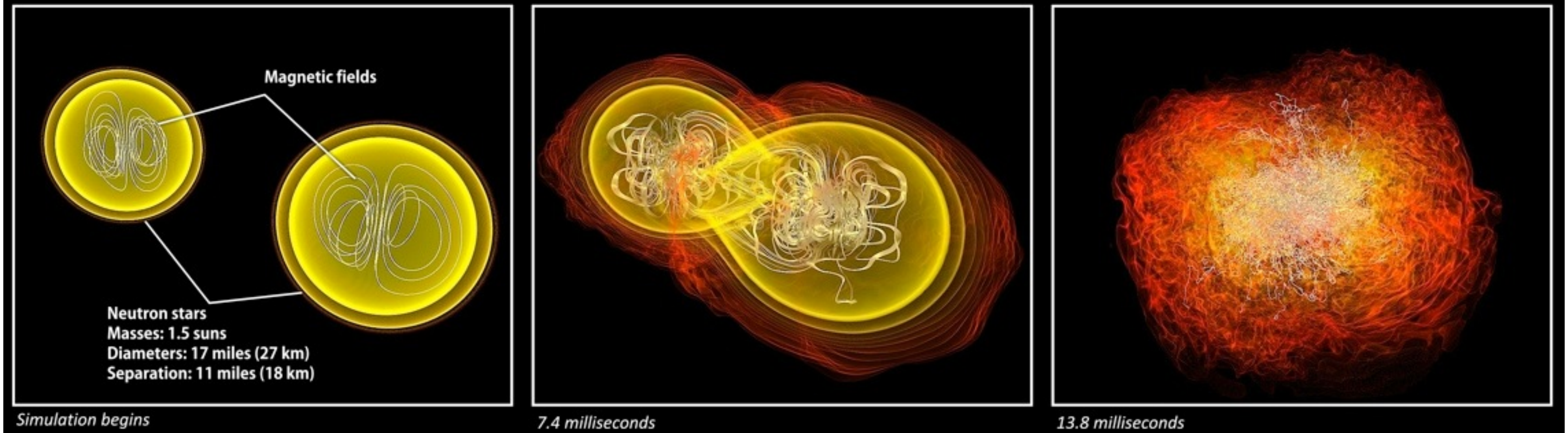
B-fields during inspiral phase

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



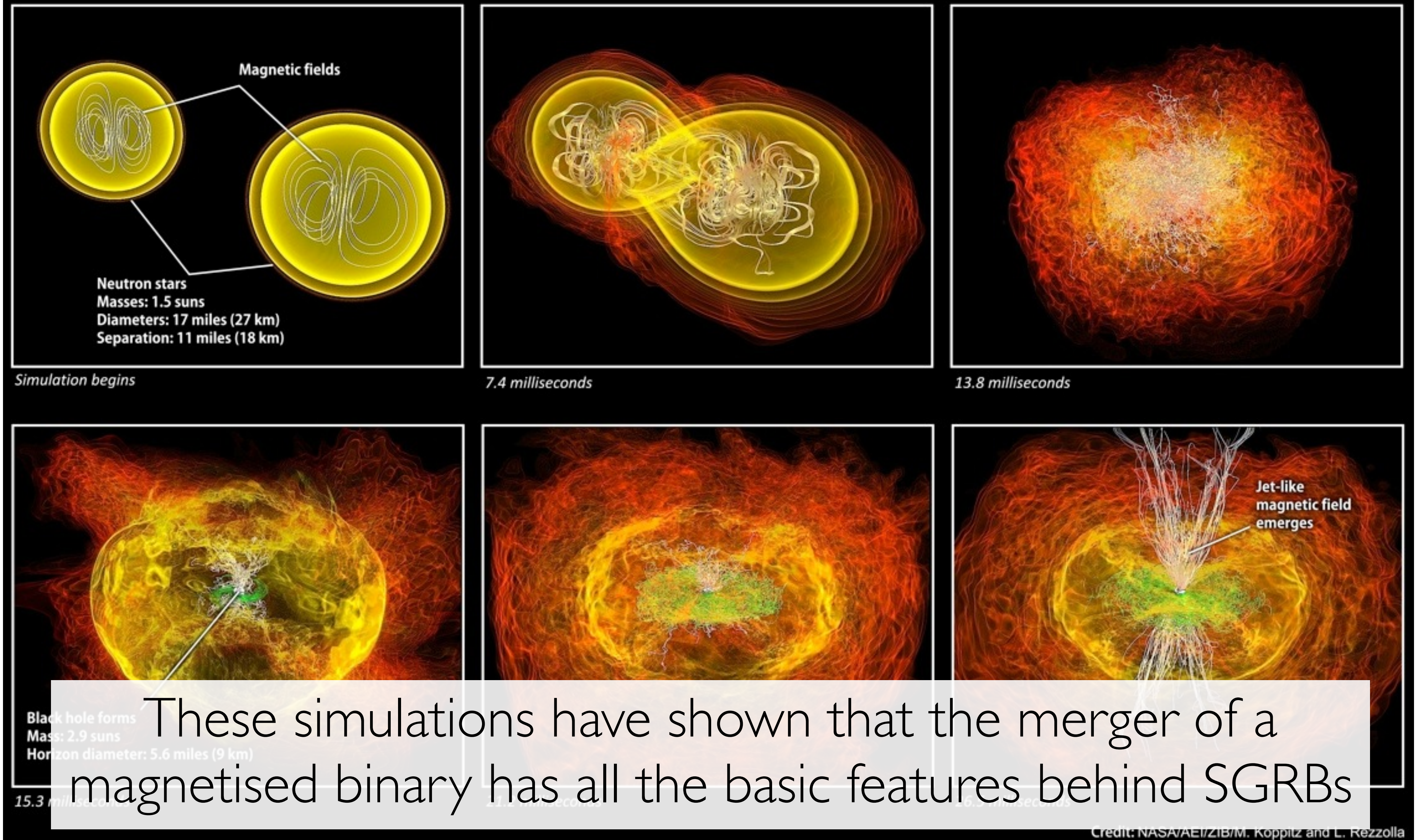
Animations:, LR, Koppitz


Animations:, LR, Koppitz
9
11.75
14.5
lg(rho) [g/cm^3]
9.5
12
14.5
lg(|B|) [Gauss]



Magnetic fields in the HMNS have complex topology: dipolar fields are destroyed.

Crashing neutron stars can make gamma-ray burst jets

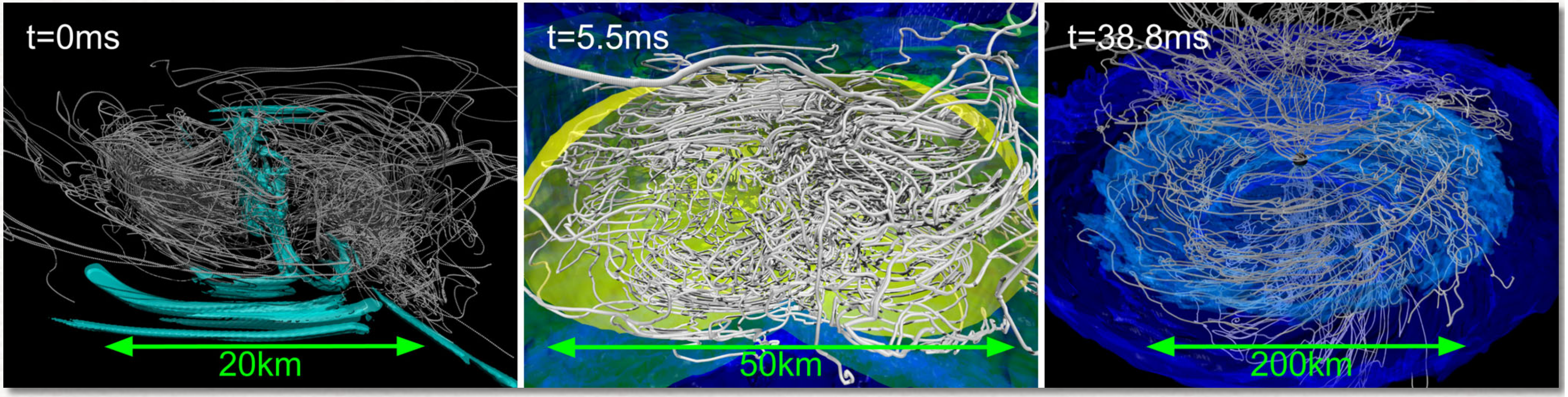


These simulations have shown that the merger of a magnetised binary has all the basic features behind SGRBs

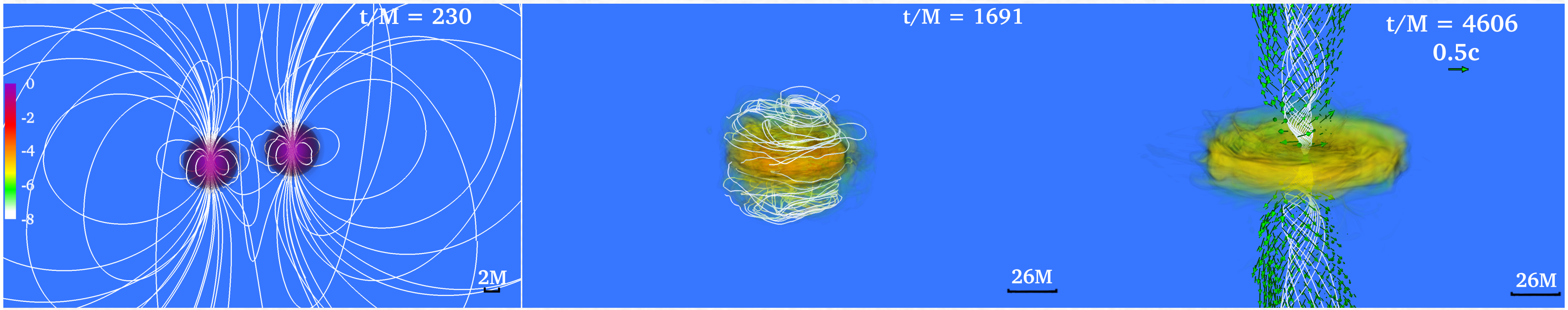
$J/M^2 = 0.83$ $\quad$ $\mathrm{M}_{\rm tor} = 0.063 M_\odot$ $\quad$ $\mathrm{t}_{\rm accr} \simeq M_{\rm tor}/\dot{M} \simeq 0.3\ \mathrm{s}$

Results from other groups (IMHD only)

With due differences, other groups confirm this picture.

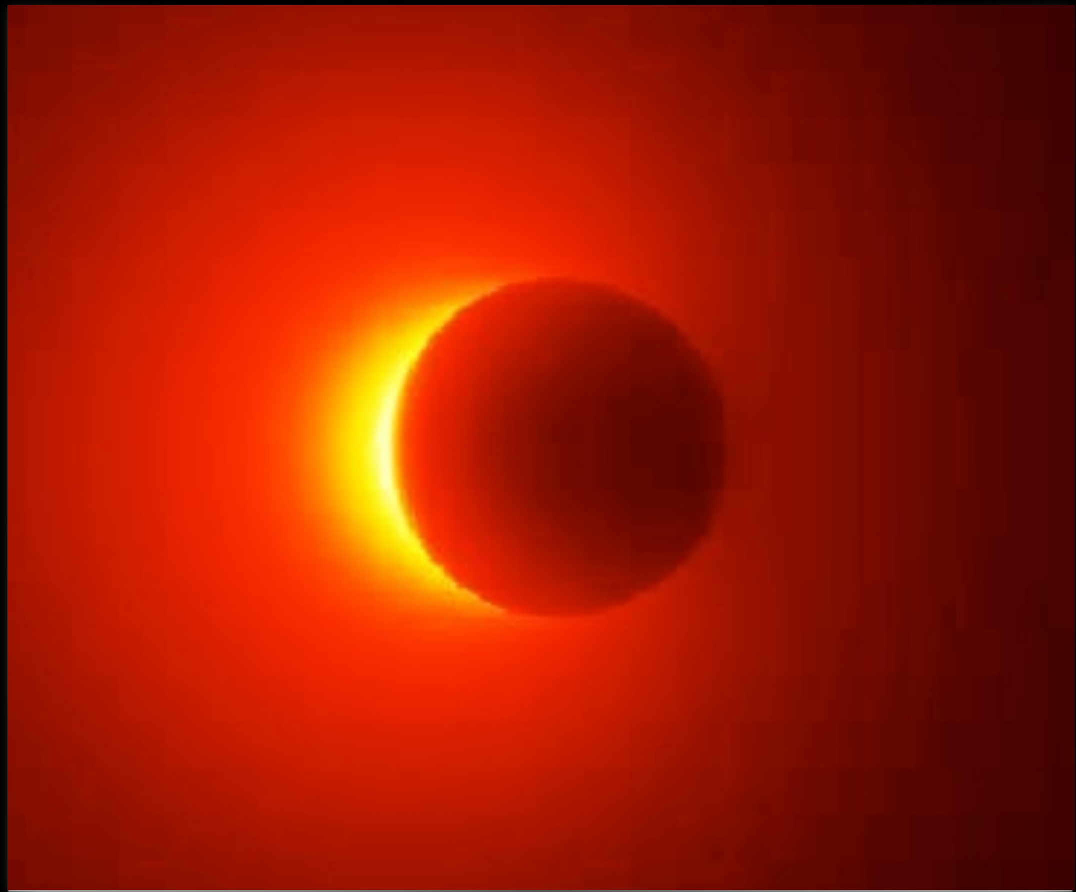


Kiuchi+ 2014



Ruiz+ 2016

Do black holes really exist?…



GW150914: what we know

$$\mathrm{S/N} = 24$$

$$M_1 = 36^{+5}_{-4}\, M_\odot$$

$$M_2 = 29^{+5}_{-4}\, M_\odot$$

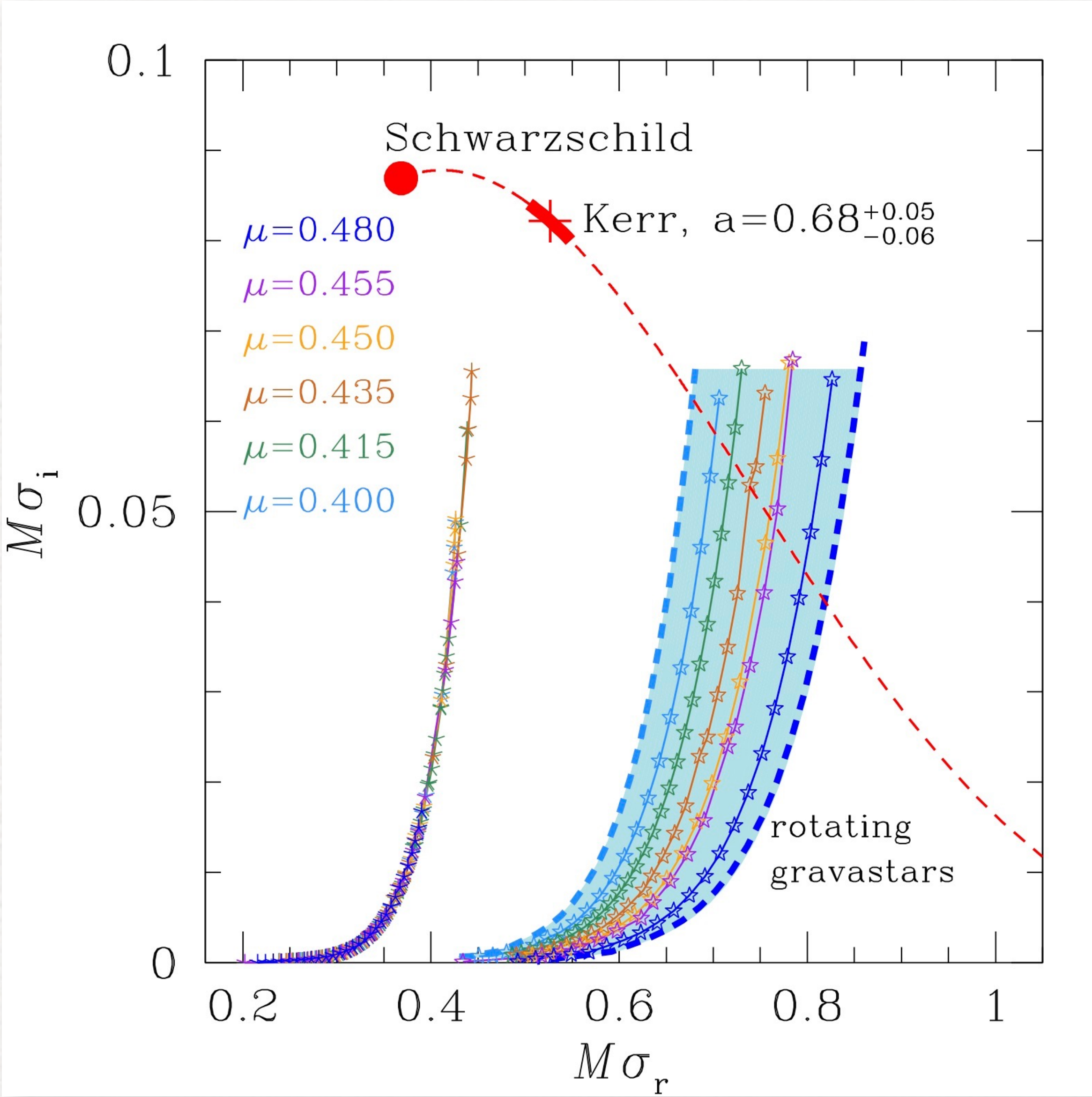
$$M_{\rm fin} = 62^{+4}_{-4}\, M_\odot$$

$$a_{\rm fin} = 0.67^{+0.05}_{-0.07}$$

$$d = 410^{+160}_{-180}\,\mathrm{Mpc}$$

- Could this be a **gravastar**?
  unlikely
- Does this rule out alternative theories?

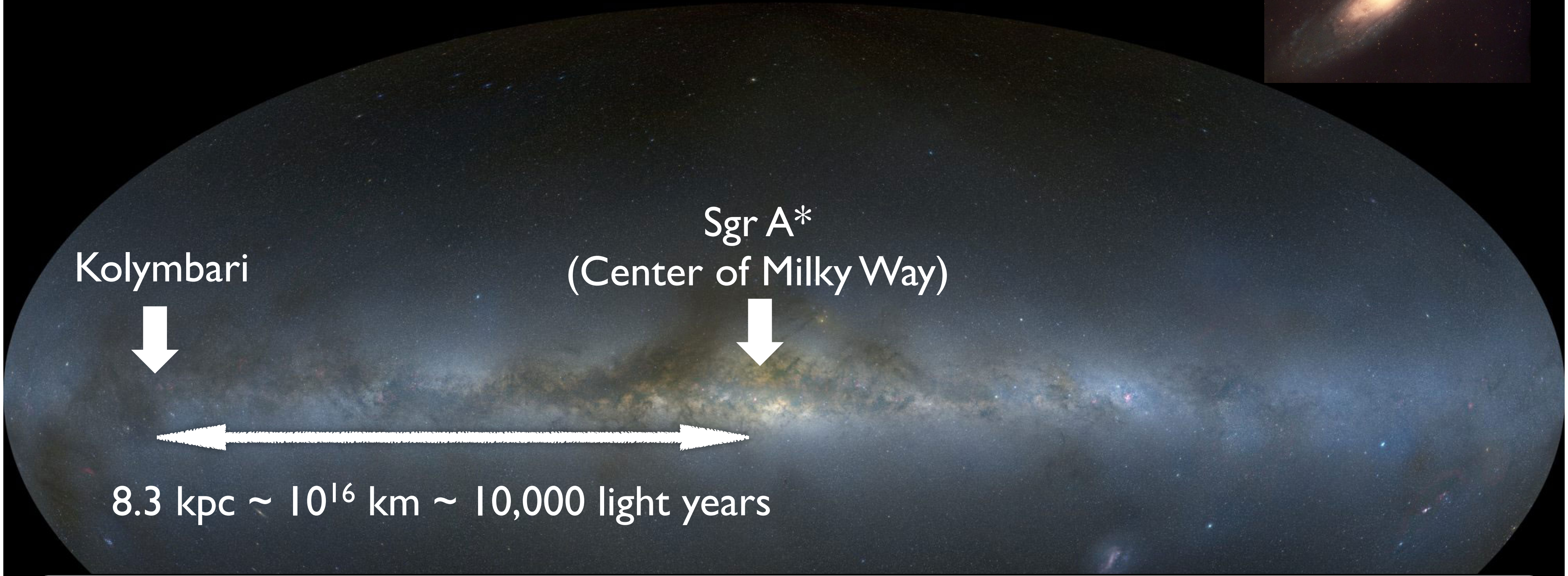
not really; still a lot of room



Chirenti & LR 2016

The Milky Way

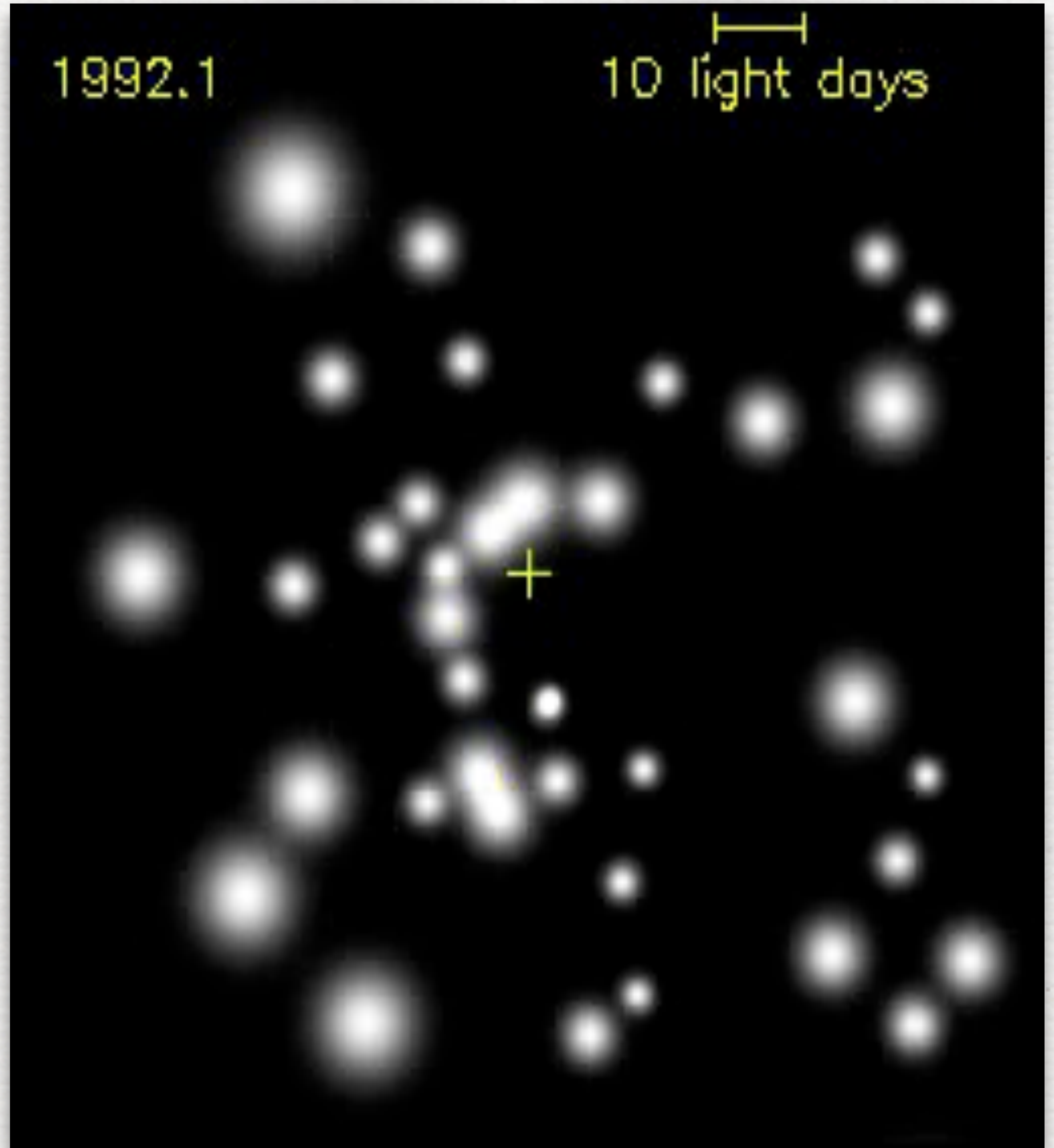
View of the full sky (north and south) in the optical.



- Black hole size is proportional to its mass: $R_S = 2GM/c^2$
- Biggest and largest BHs are at centers of galaxies
- The BH with largest diameter is at center of Milky Way

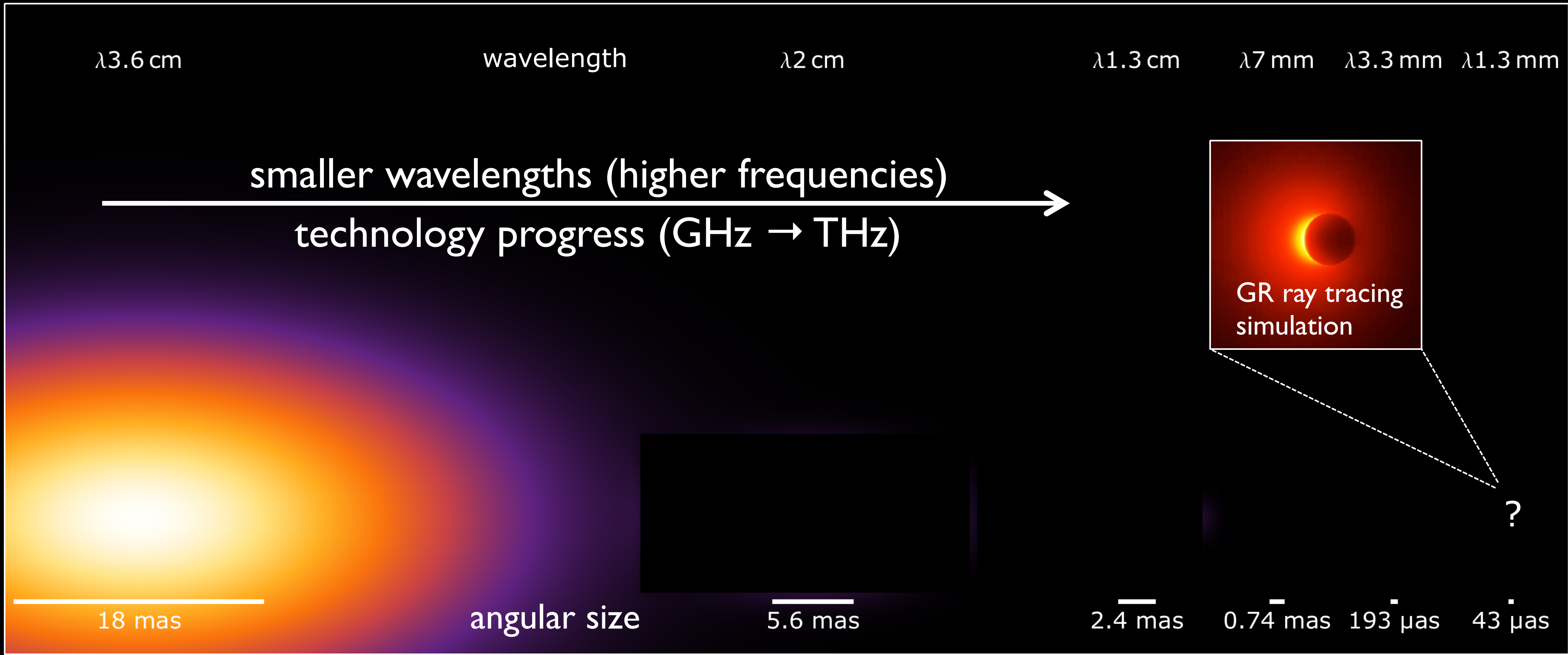
Sgr A*: the "dark object" in the Galactic Center

- Near-infrared telescopes (ESO) have measured orbits of individual stars.
- The stars orbit a dark object: the compact radio source Sgr A*.
- Study of orbits reveals a mass of 4.3 million times the mass of the Sun.



Gillessen/Eisenhauer/Genzel (MPE Garching)

Images of the radio source

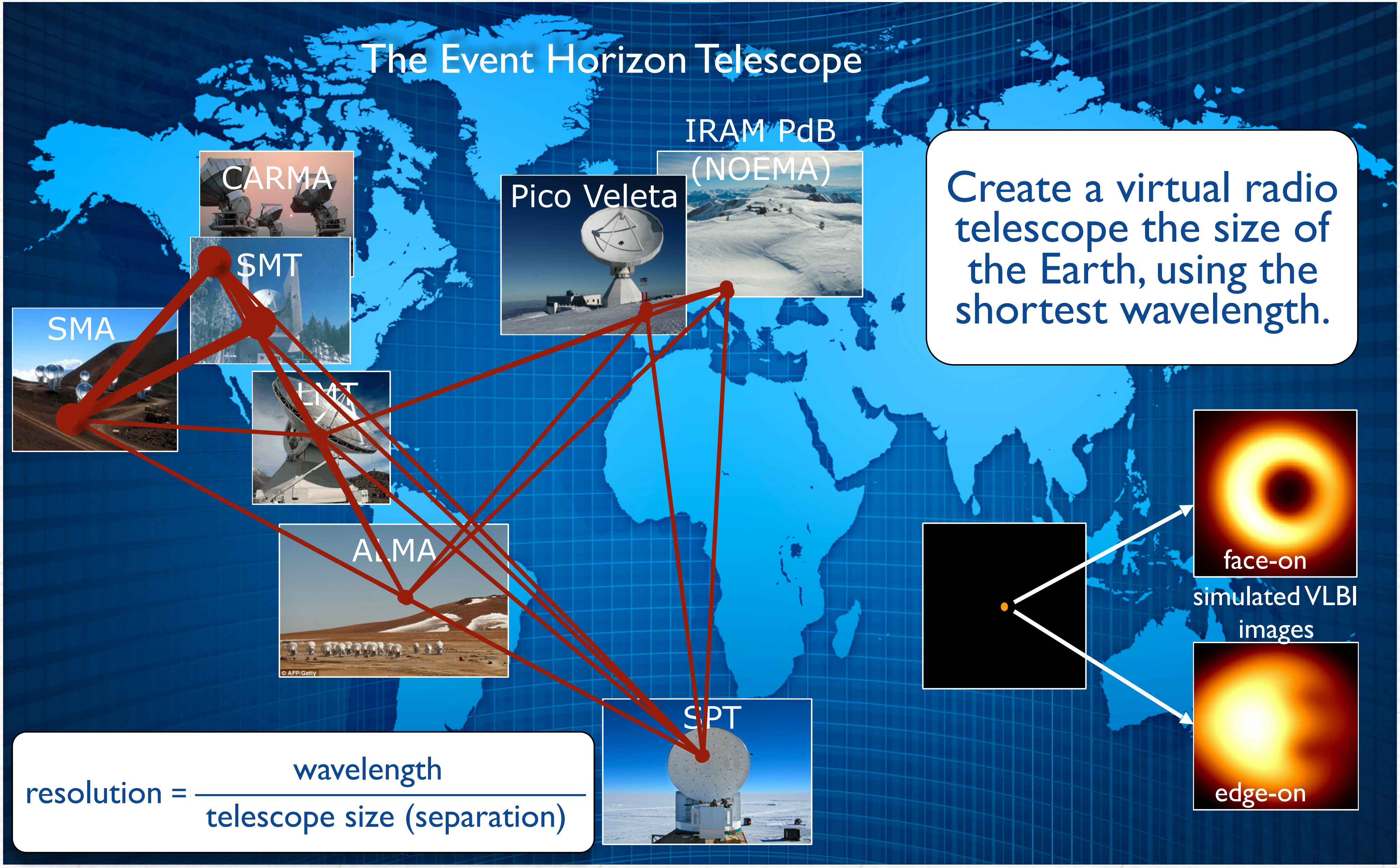


- The shorter the wavelength, the smaller the radio source.
- At λ=1.3 mm the radio source becomes the size of the event horizon.

mas = milli-arcsecond = 5×10^{-9} rad

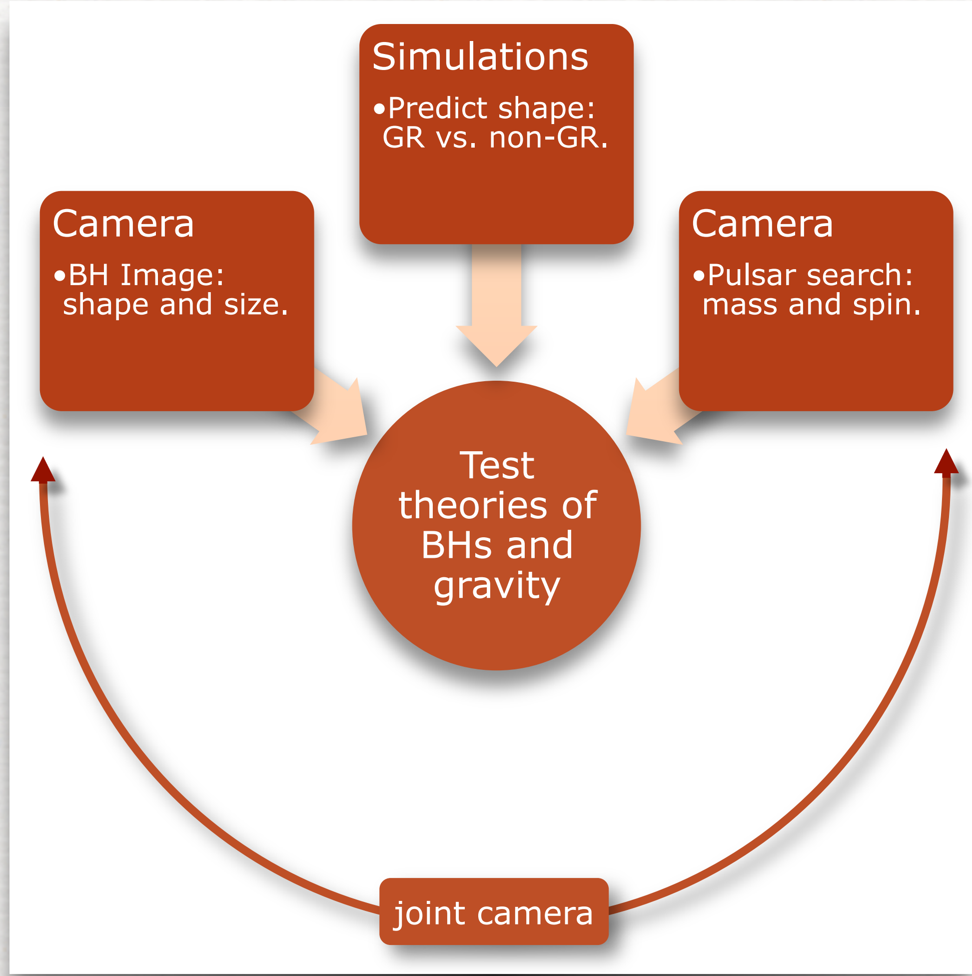
μas = micro-arcsecond = 5×10^{-12} rad

Very Long Baseline Interferometry (VLBI)



Take a picture: **BlackHoleCam** project!

- **Build a joint black hole camera**
  - ✳ image event horizon to the best of present VLBI technology
- **Hunt for pulsars near Sag-A***
  - ✳ detection of pulsars will provide unprecedented accuracy
- **Make theoretical predictions/ interpretations**
  - ✳ use numerical simulations to produce synthetic images
  - ✳ interpret observations to constrain theories of gravity



Not easy, but another milestone of modern physics

Conclusions

✴Modelling of binaries in full GR is **mature**: GWs from binary black holes and neutron stars with high precision.

✴Neutron stars are far more complex but also richer.

✴If observed, post-merger signal will set tight constraints on EOS

✴ We will soon be able to set constraints on the black hole at the center of the Galaxy

✴ Numerical relativity is an incredible tool to explore new physics and astrophysics

EXTRAS