TEONGRAV: HPC Simulations of Gravitational Wave Sources

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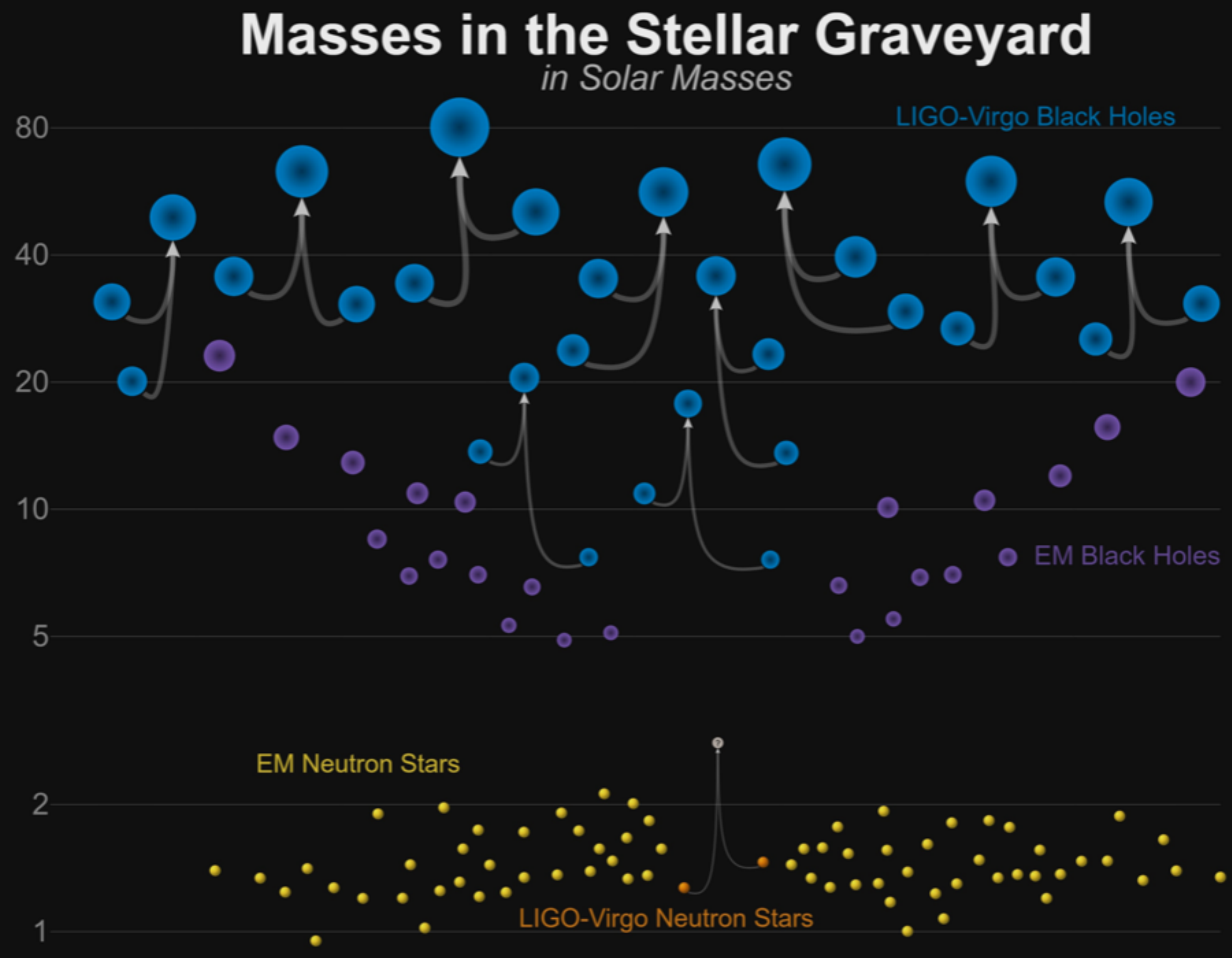
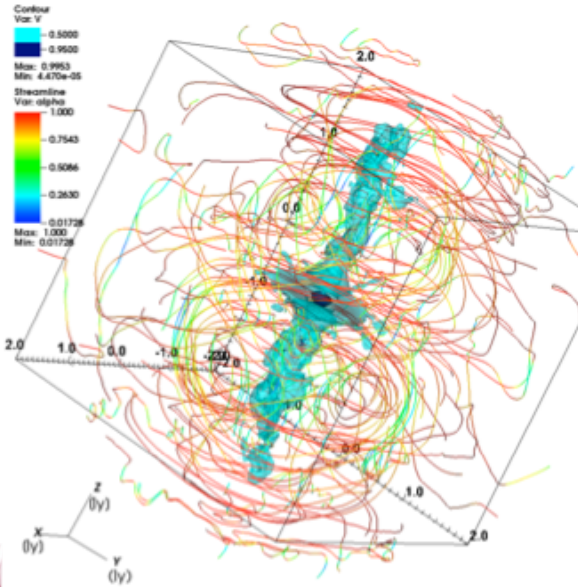


See https://gracedb.ligo.org/ for current status

LIGO-Virgo | Frank Elavsky | Northwestern

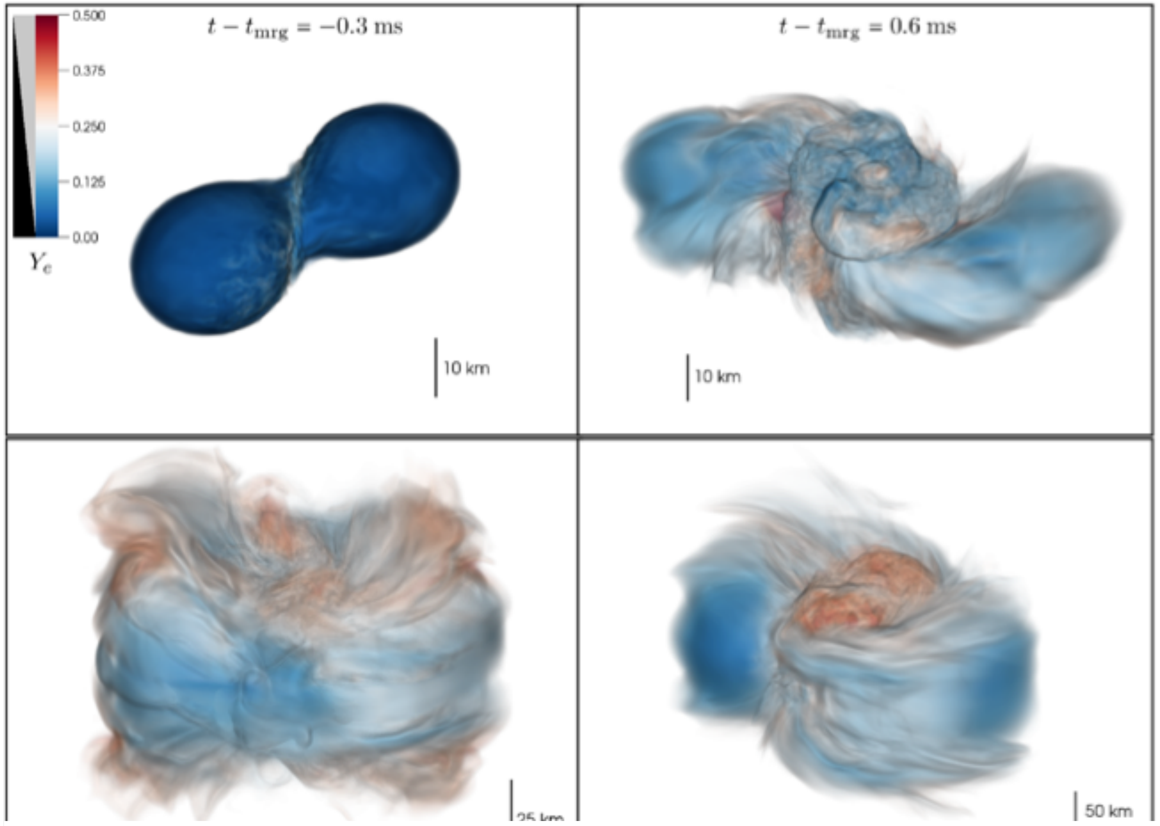
General Relativistic Simulations of Neutron Stars and Black Holes

GRMHD simulations of Pulsar Wind Nebulae, isolated neutron stars, and accreting black holes.

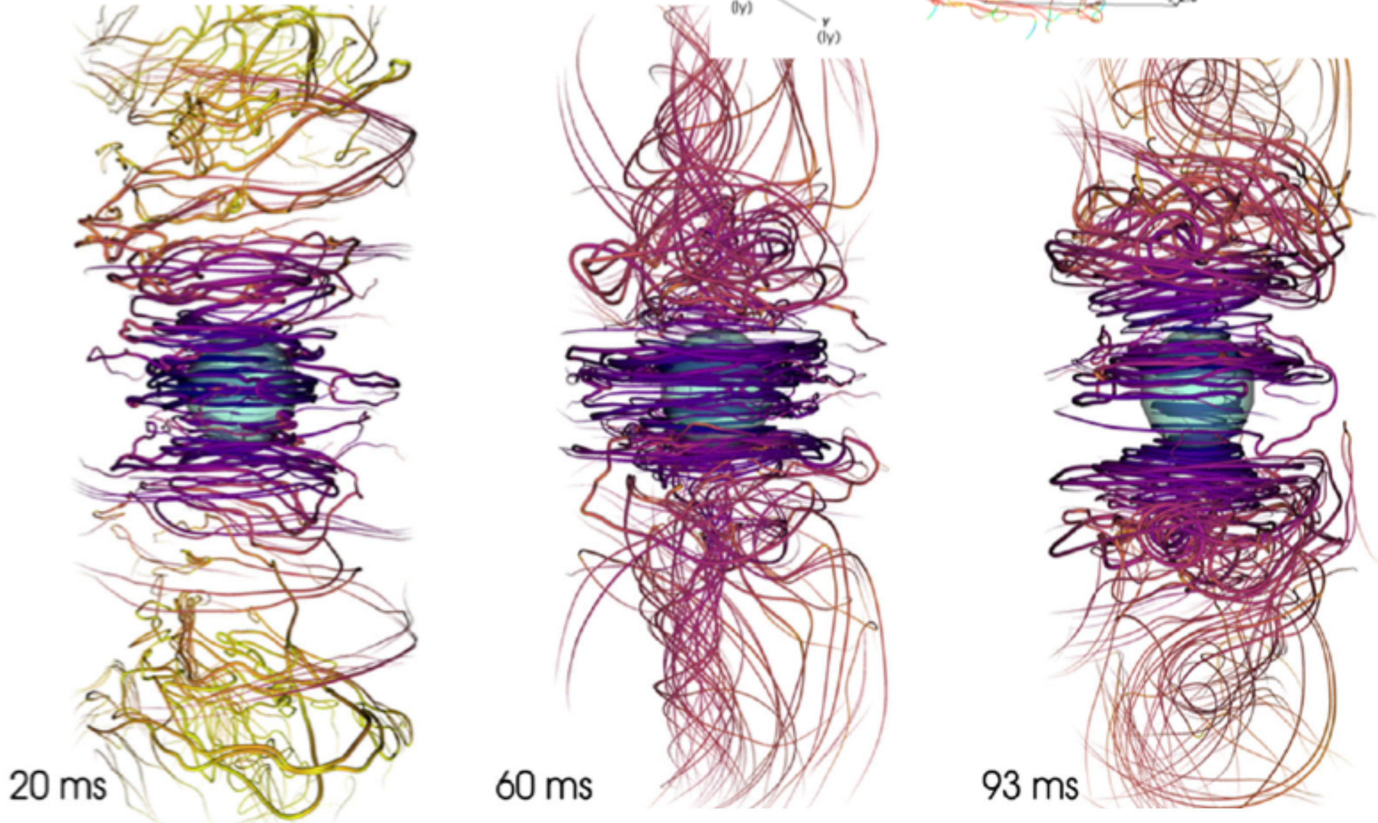


Del Zanna et al 2018

Systematic studies of NS-NS mergers including accurate modelling of nuclear equations of state and neutrino emission.
GRMHD simulations of NS-NS mergers and study of their post-merger EM and GW emission.

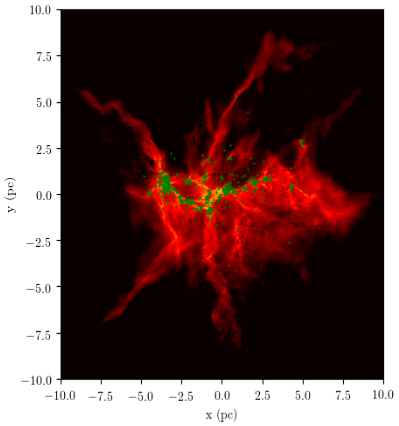


Radice, Perego, Hotokezafa, Fromm, Bernuzzi, Roberts ApJ 2018



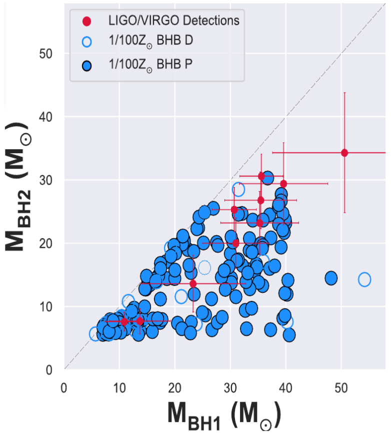
Ciolfi, Kastaun, Kalinani, Giacomazzo PRD 2019

Black Hole Demographics for Virgo, LIGO, and LISA Observatories



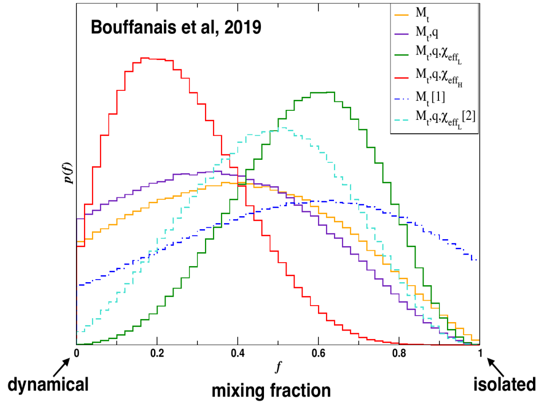
10 **hydrosimulations** to study star formation in giant molecular clouds, to get more **realistic initial conditions for N-body** simulations, to study the **demographics of binary compact objects**

(Ballone et al., in prep.)



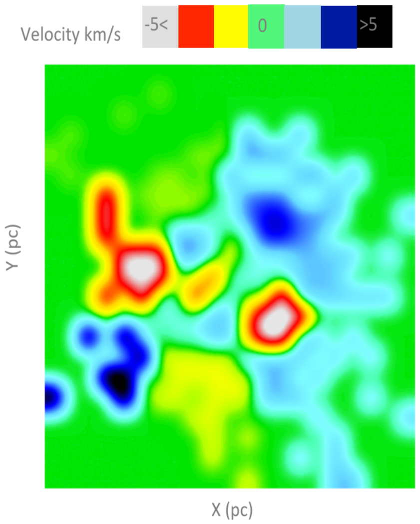
> 80000 **N-body simulations** to study the **interplay between dynamics and binary stellar evolution** in the formation of black hole binaries

(Di Carlo et al., 2019; Rastello et al., in prep.)



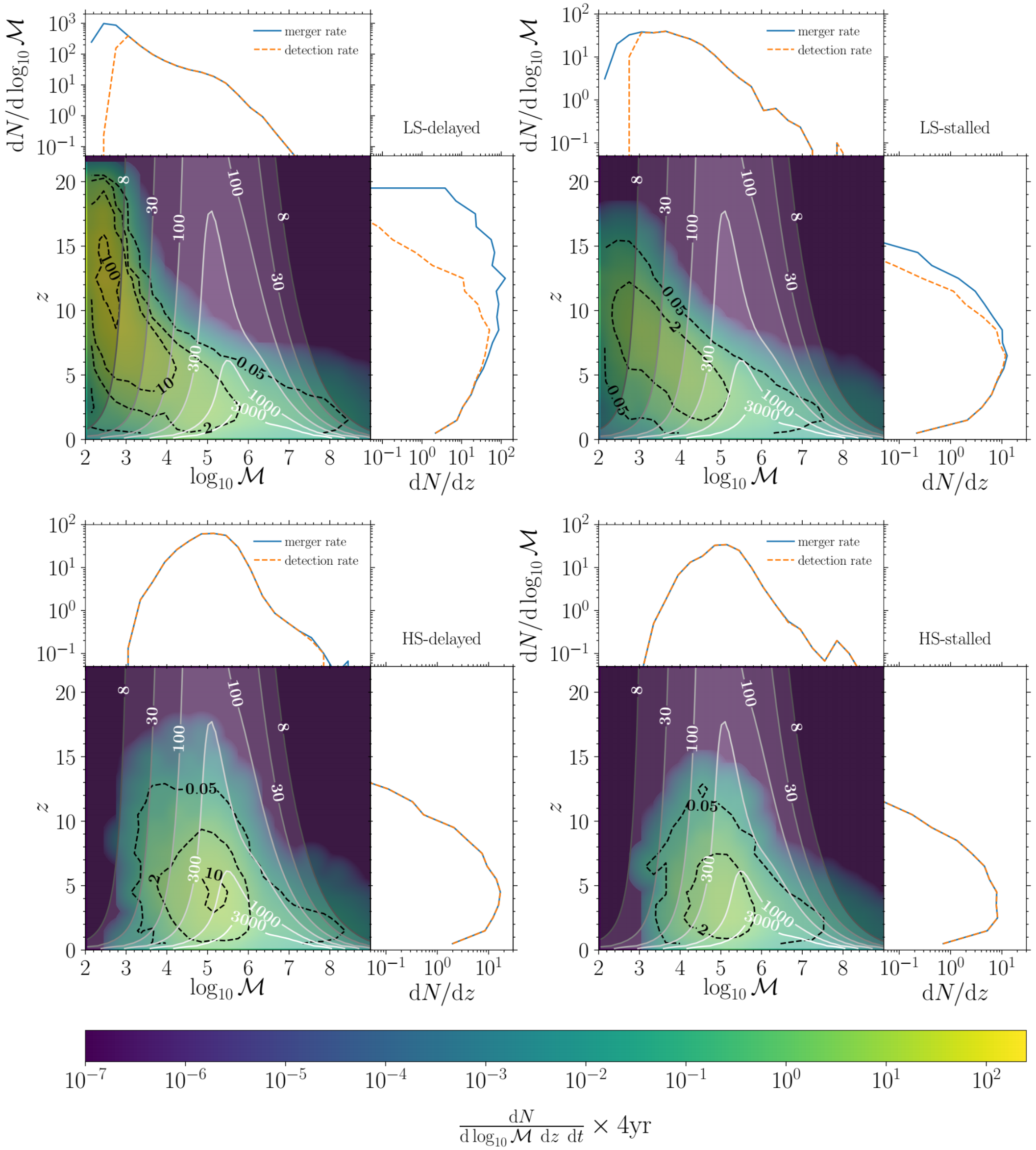
Use LIGO/Virgo data to assess the **fraction** of merging black hole binaries from **isolated and dynamical formation channels** through the use of **hierarchical Bayesian inference**

(Bouffanais et al., 2019)



Train a **neural network** to infer the **mass of IMBHs** from velocity map data in star clusters produced with N-body simulations

(Pasquato & Mastrobuono-Battisti, in prep.)



Bonetti et al. 2019, MNRAS 486 4044

Merger rate of massive black hole binaries in the context of LISA mission

HPC Usage

- In 2019 we used INFN CINECA resources on
  - Marconi A2 (KNL): 11,700,000 cpu hours
  - Marconi A3 (SKL): 12,850,000 cpu hours + 2,000,000 (for Virgo users)

- **> 20 M** cpu hours in the last two years with Iscra B and INAF proposals
- **> 90 M** cpu hous within PRACE calls in the last few years

INFN provides us a significant fraction of cpu hours that support in particular students and young researchers.

We thank Leonardo Cosmai for managing such resources!

GRMHD Simulations of Compact Binaries

- The simulations performed by the **Milano-Padova-Trento** group are based on the use of the **Einstein Toolkit** and of the GRMHD **WhiskyMHD** code
- Solve the full set of Einstein and ideal MHD equations
- Used for NS-NS, NS-BH, and BH-BH systems

- We also developed a new GRMHD code (**Spritz**) with full support for finite temperature EOS and neutrinos: https://arxiv.org/abs/1912.04794

Equations

Einstein Equations

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

Hydro Equations

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\nabla_\mu J^\mu = 0$$

$$P = P(\rho, \epsilon)$$

$$J^\mu = \rho u^\mu$$

$$T^{\mu\nu} = (\rho h + b^2) u^\mu u^\nu + \left(p + \frac{b^2}{2} \right) g^{\mu\nu} - b^\mu b^\nu$$

Maxwell Equations

$$\nabla_\nu {}^*F^{\mu\nu} = 0$$

GRMHD equations

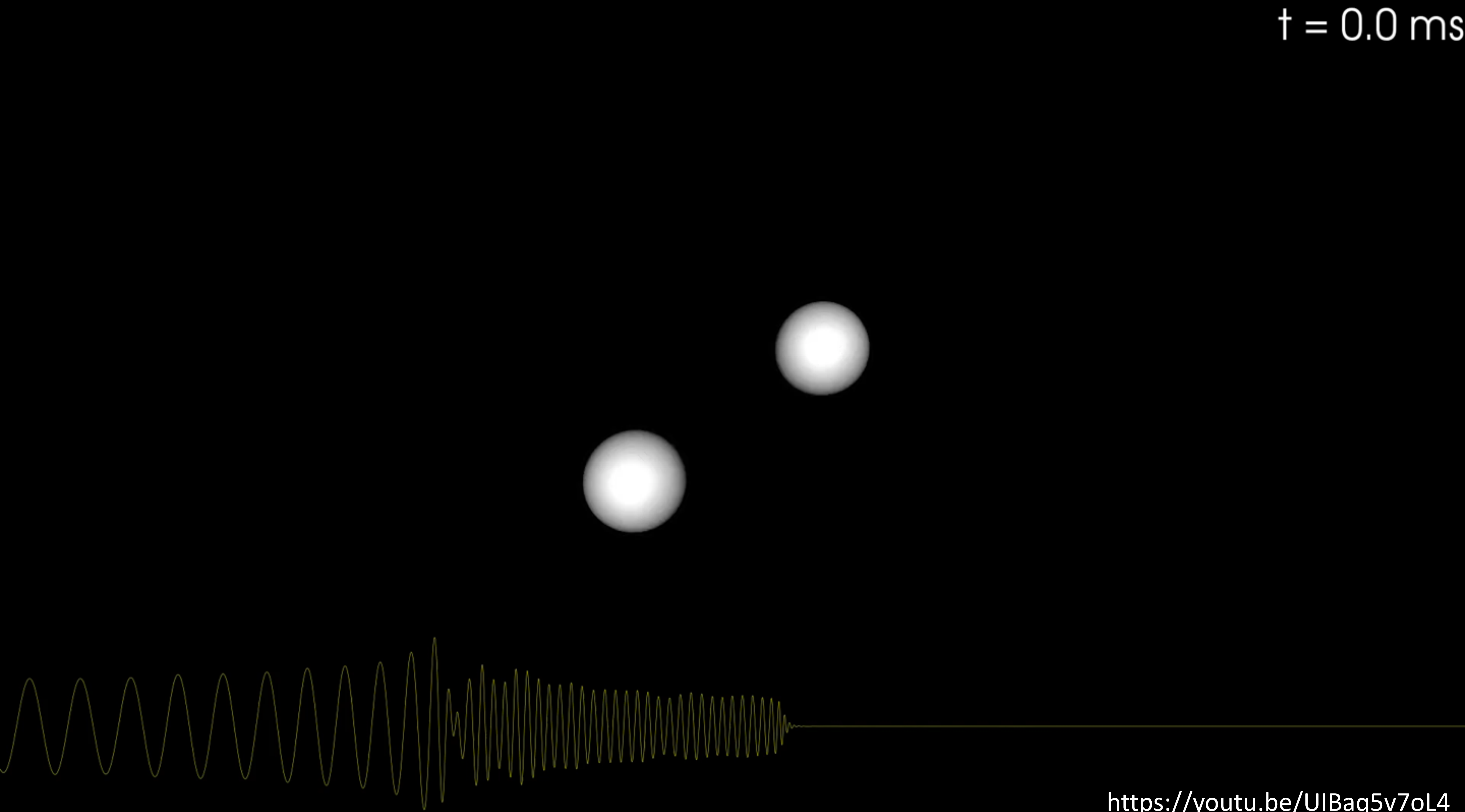
The system of equations is written in a conservative form (Valencia formulation, Anton et al 2006):

$$\left.\begin{array}{rcl}\nabla_\mu(\rho u^\mu) & = & 0\\ \nabla_\mu T^{\mu\nu} & = & 0\end{array}\right\} \Rightarrow \frac{1}{\sqrt{-g}}\left(\frac{\partial\sqrt{\gamma}\mathbf{U}}{\partial t} + \frac{\partial\sqrt{-g}\mathbf{F}^i}{\partial x^i}\right) = \mathbf{S}$$

where **U** is the vector of conserved variables, $\mathbf{F}^\mathbf{i}$ the fluxes, and **S** the source terms. They can then be solved using HRSC methods using approximate Riemann solvers. To these one has to add the equations for the evolution of the magnetic field:

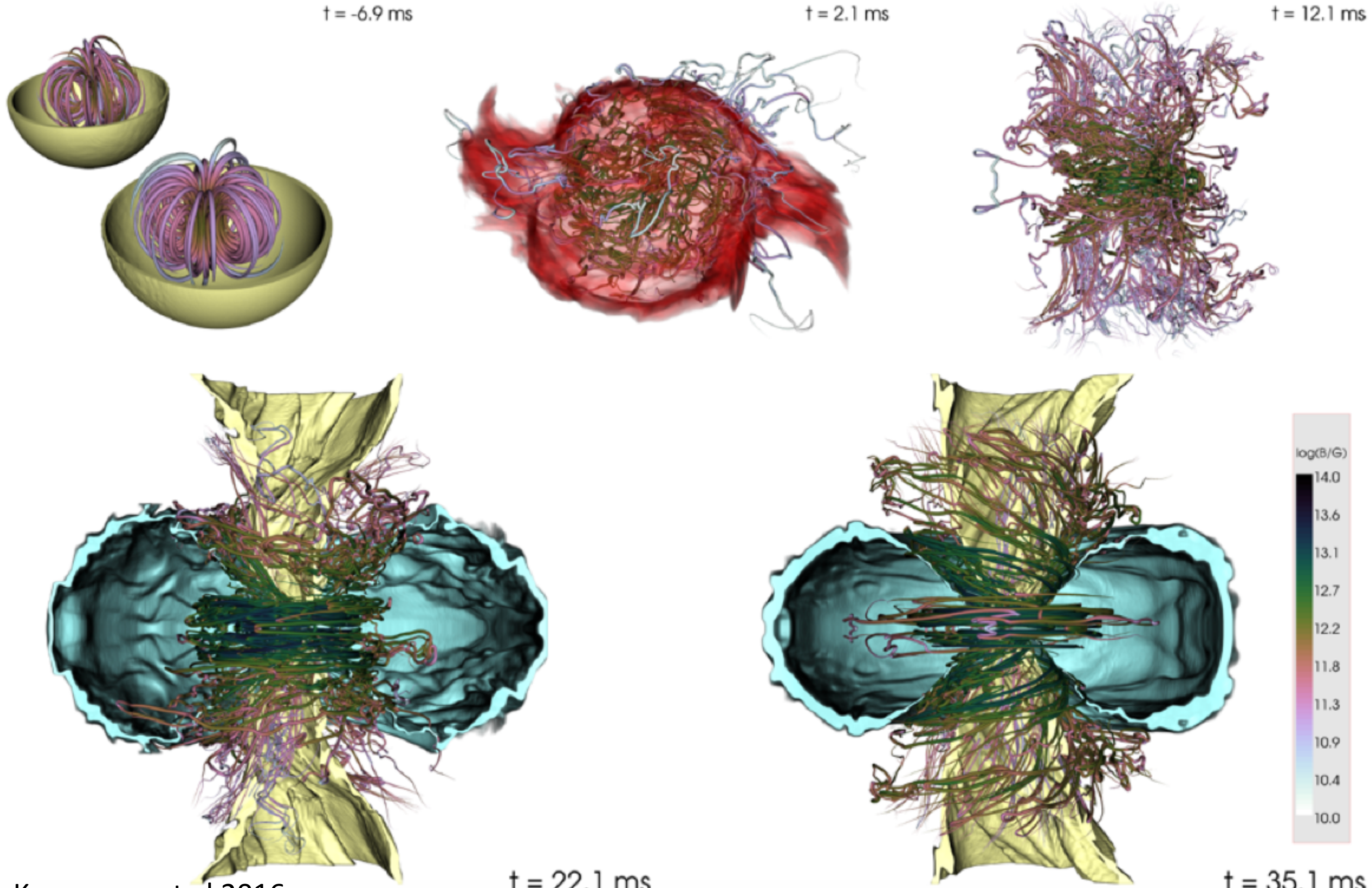
$$\frac{\partial}{\partial t}\left(\sqrt{\gamma}\vec{B}\right) = \nabla \times \left[\left(\alpha\vec{v} - \vec{\beta}\right) \times \left(\sqrt{\gamma}\vec{B}\right)\right]$$

$$\nabla \cdot \left(\sqrt{\gamma}\vec{B}\right) = 0$$



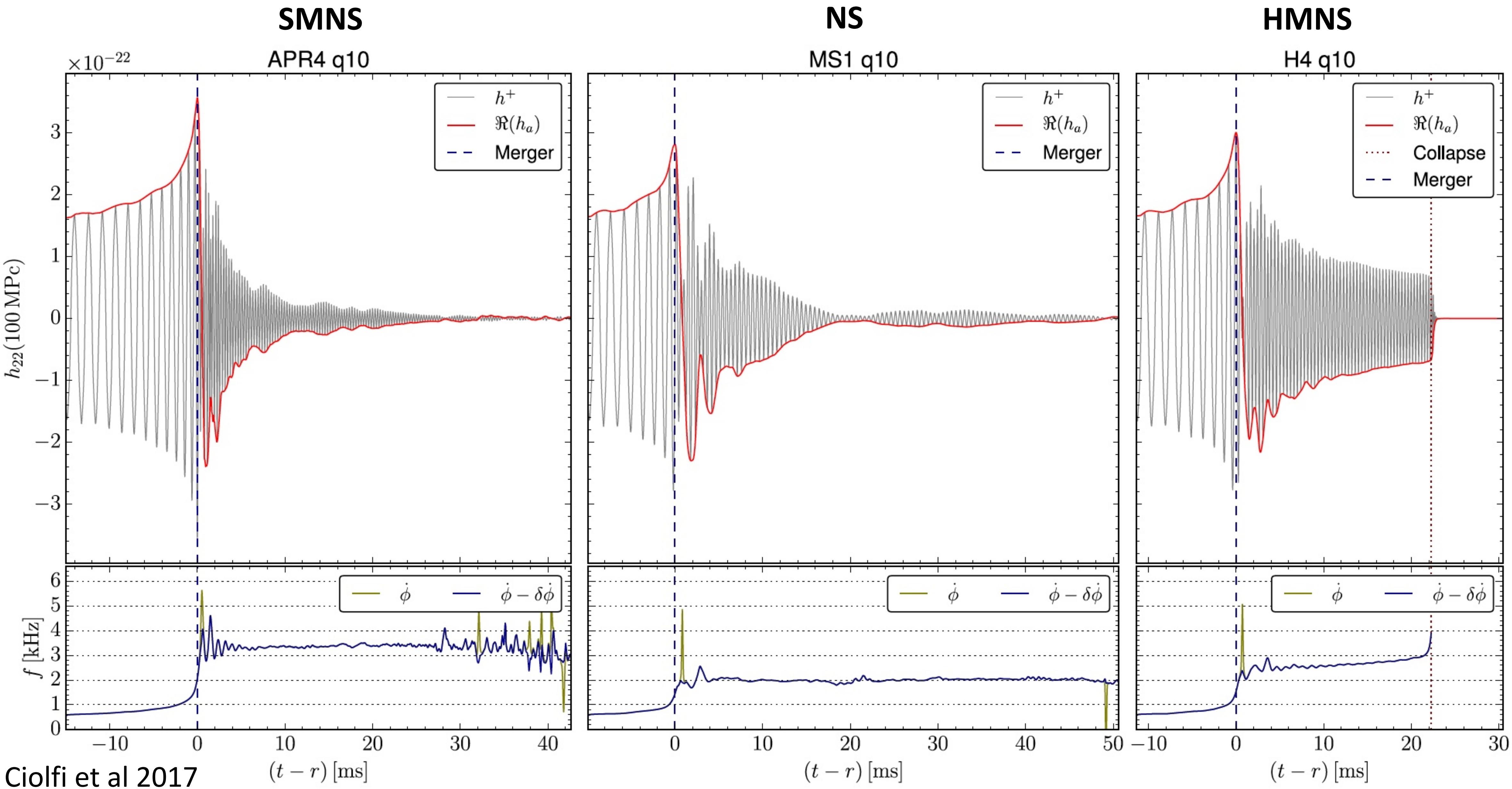
https://youtu.be/UIBaq5v7oL4

Magnetic Field Structure Evolution



Kawamura et al 2016

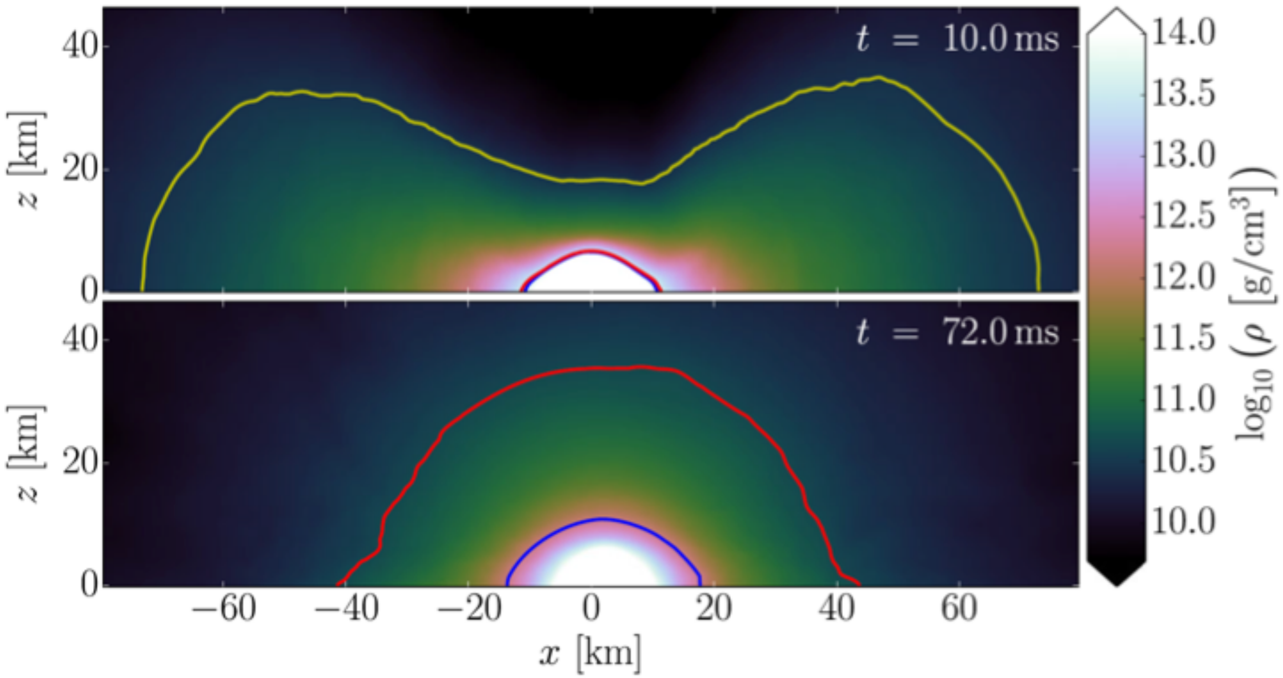
GRAVITATIONAL WAVES



Ciolfi et al 2017

First 100 ms of a long-lived magnetized neutron star formed in a binary neutron star merger

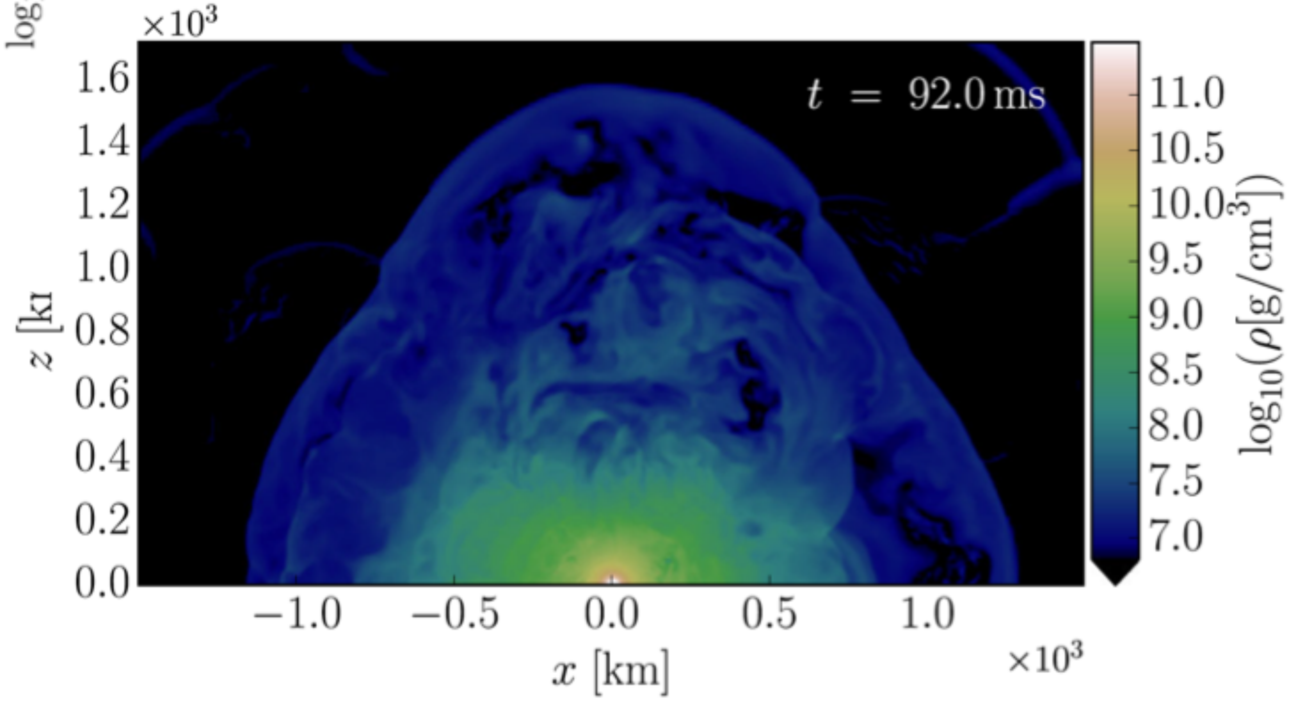
R. Ciolfi, W. Kastaun, J. Kalinani, B. Giacomazzo 2019, PRD 100, 023005



Longest GRMHD simulation to date of a post-merger remnant

Magnetic field energy saturates at ~10^{51} erg

No sign of jet formation



Followed ejected matter on a scale of almost 2000 km

Only eventual later collapse to black hole may drive torus and jet formation

Conclusions

- HPC allows us to model gravitational wave sources at different scales
- Models can be compared with observation to help us learn more about gamma-ray bursts, nuclear physics, stellar evolution, cosmology, etc…
- Binary neutron star simulations can follow all phases of inspiral, merger and post-merger evolution (but quite a lot of physics is still not properly accounted for)
- The Milano-Padova group performed the longest GRMHD study of a post-merger remnant and its connection with SGRB engine
- Publicly available tools (such as the Einstein Toolkit) play a very crucial role

For more movies see www.brunogiacomazzo.org