Numerical Relativity Simulations of Gravitational Wave Sources

Bruno Giacomazzo
University of Milano-Bicocca
TEONGRAV, INFN Milano-Bicocca
www.brunogiacomazzo.org

UNIVERSITA' DEGLI STUDI DI MILANO
AUDENTES FORTUNA IUVAT
BICOCCA

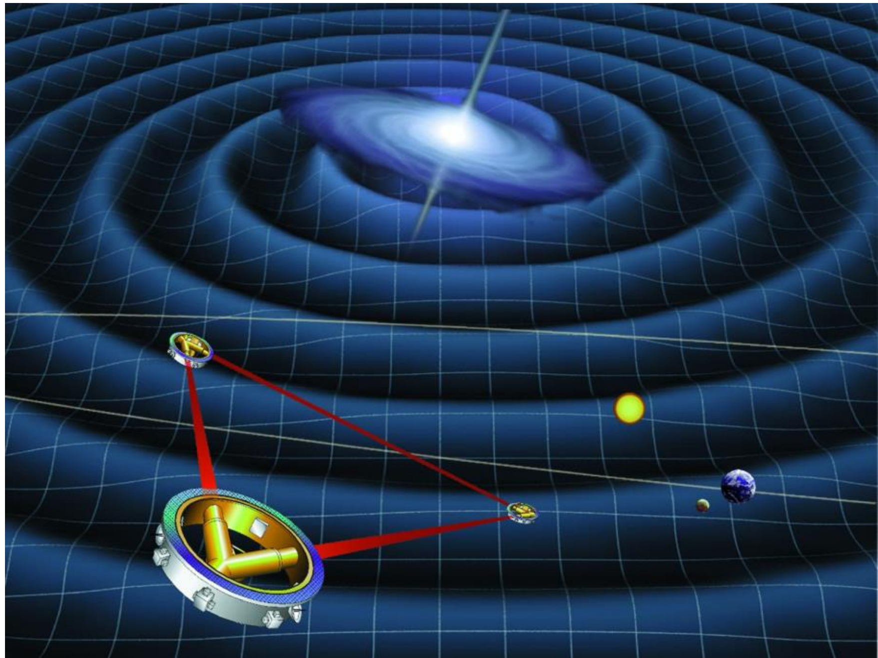
INFN
Istituto Nazionale di Fisica Nucleare

Gravitational Waves

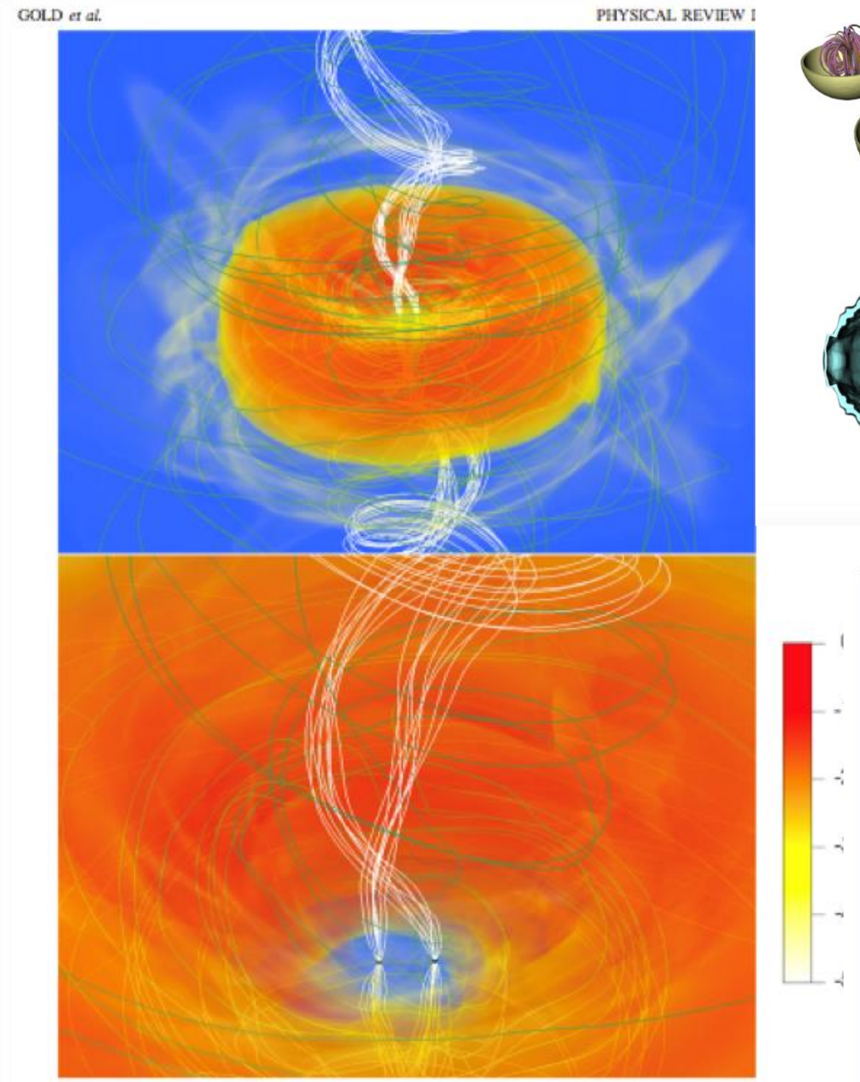
The Virgo detector is currently observing mergers of (stellar mass) black holes and neutron stars together with the two LIGO detectors in the USA.

LIGO and Virgo have observed more than 100 gravitational wave sources and led to a significant impact on the study of compact objects.

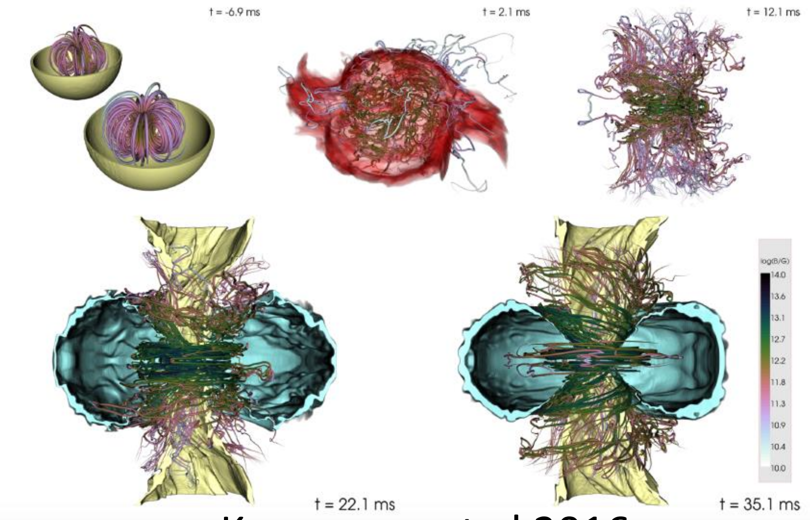
The LISA detector will be launched into space in 2035 and it will be able to see gravitational waves from supermassive black holes (such as those at the center of galaxies) and help us unveil the mechanism that forms them and study the history of the Universe.



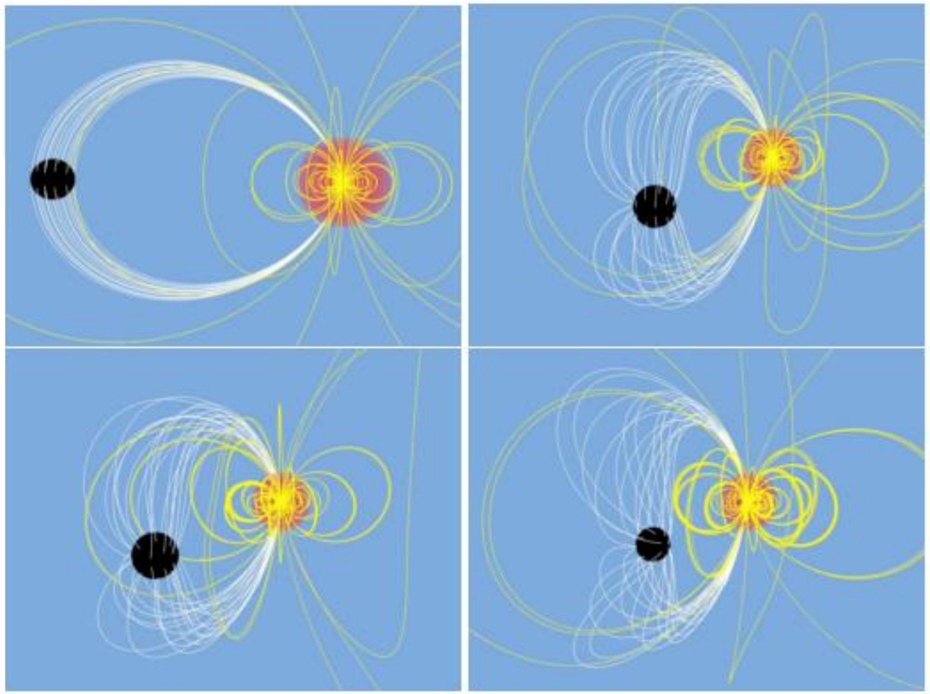
SIMULATIONS OF COMPACT OBJECTS



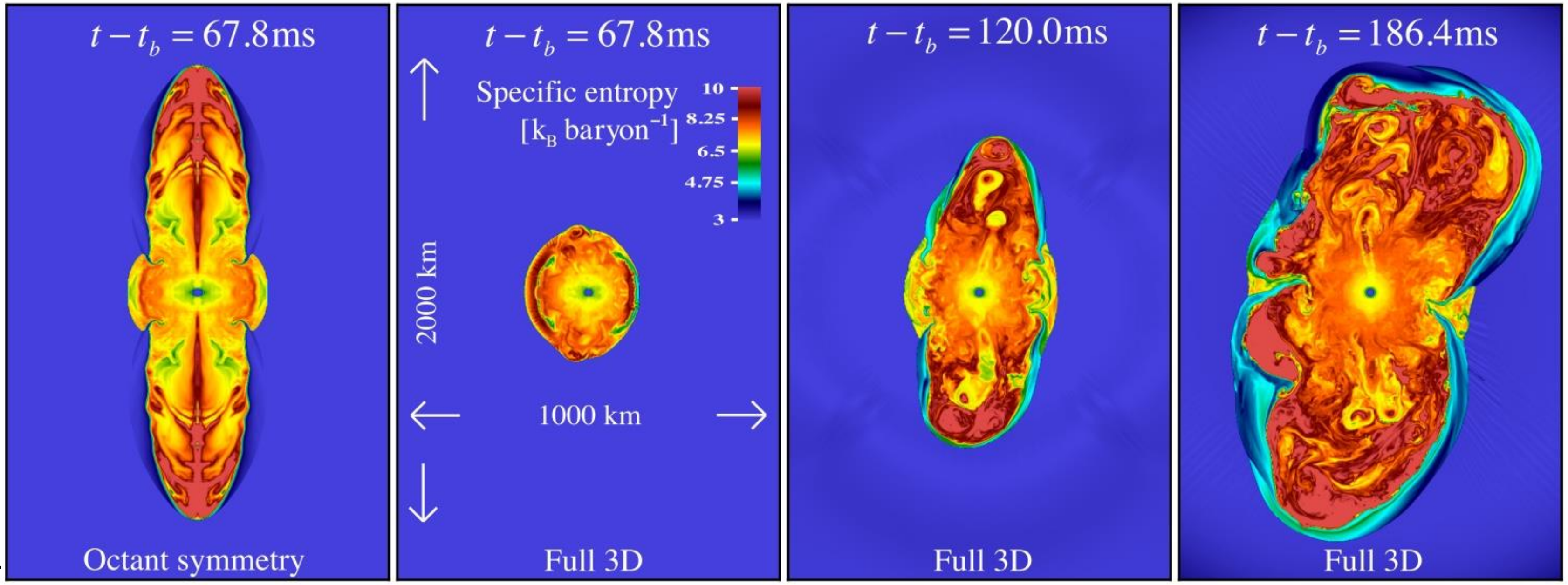
Gold et al 2014



Kawamura et al 2016



Paschalidis et al 2013



Moesta et al 2014

Equations

Einstein Equations

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

Hydro Equations

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

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

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

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

$h \equiv 1 + \epsilon + P/\rho$

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

Maxwell Equations

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

Einstein Toolkit

einsteintoolkit.org

- Set of publicly available tools for relativistic astrophysics
- Latest release on December 6 2023 (codename “Meitner”)
- More than 150 users on 6 continents
- Tested on several HPC infrastructures around the world
- Includes over 100 Cactus thorns, including:
  - McLachlan and Baikal (space-time evolution)
  - GRHydro and IllinoisGRMHD (GRMHD equations)
  - Several initial data and analysis routines
- Data can be read and visualized by open-source codes:
  - Visit https://visit-dav.github.io/visit-website
  - Kuibit https://sbozzolo.github.io/kuibit/
- Every year workshops and (sometimes) schools are organized in EU and USA:
  - EU – 8-12 July 2024 at the University of Amsterdam, Netherlands
  - USA – 3-7 June 2024 at the Louisiana State University, Baton Rouge, Louisiana (hybrid)

- Open-source framework
  - Decentralized code development
  - Active and friendly user community
  - Module-based approach

- Infrastructure modules
  - Parameter file handling
  - Parallelization (MPI + OpenMP)
  - Adaptive Mesh refinement (Carpet)
  - IO (ASCII and HDF5) + checkpointing
  - GPU support (via AMREX)
  - Scaling up to 10 000 cores on CPUs

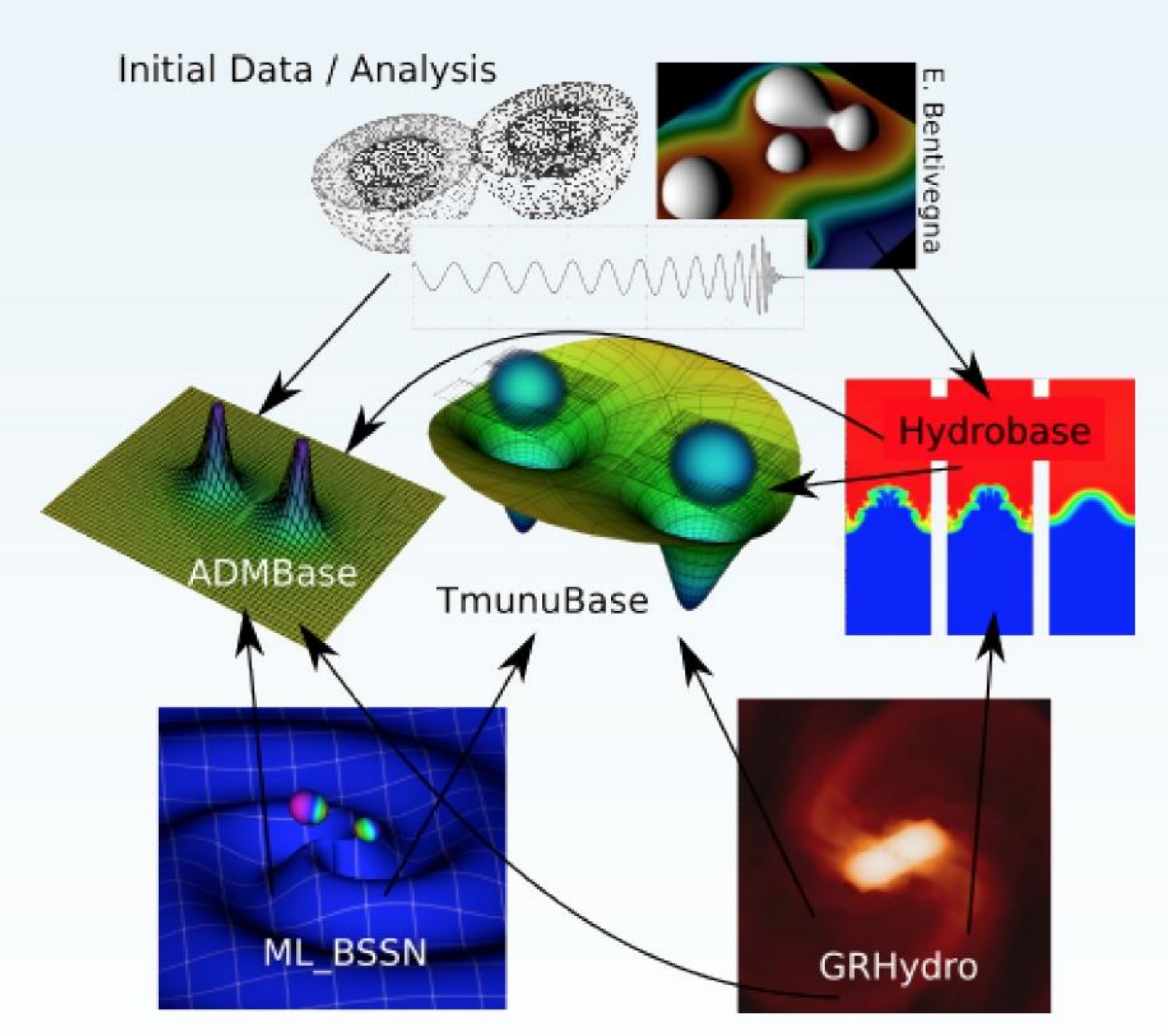
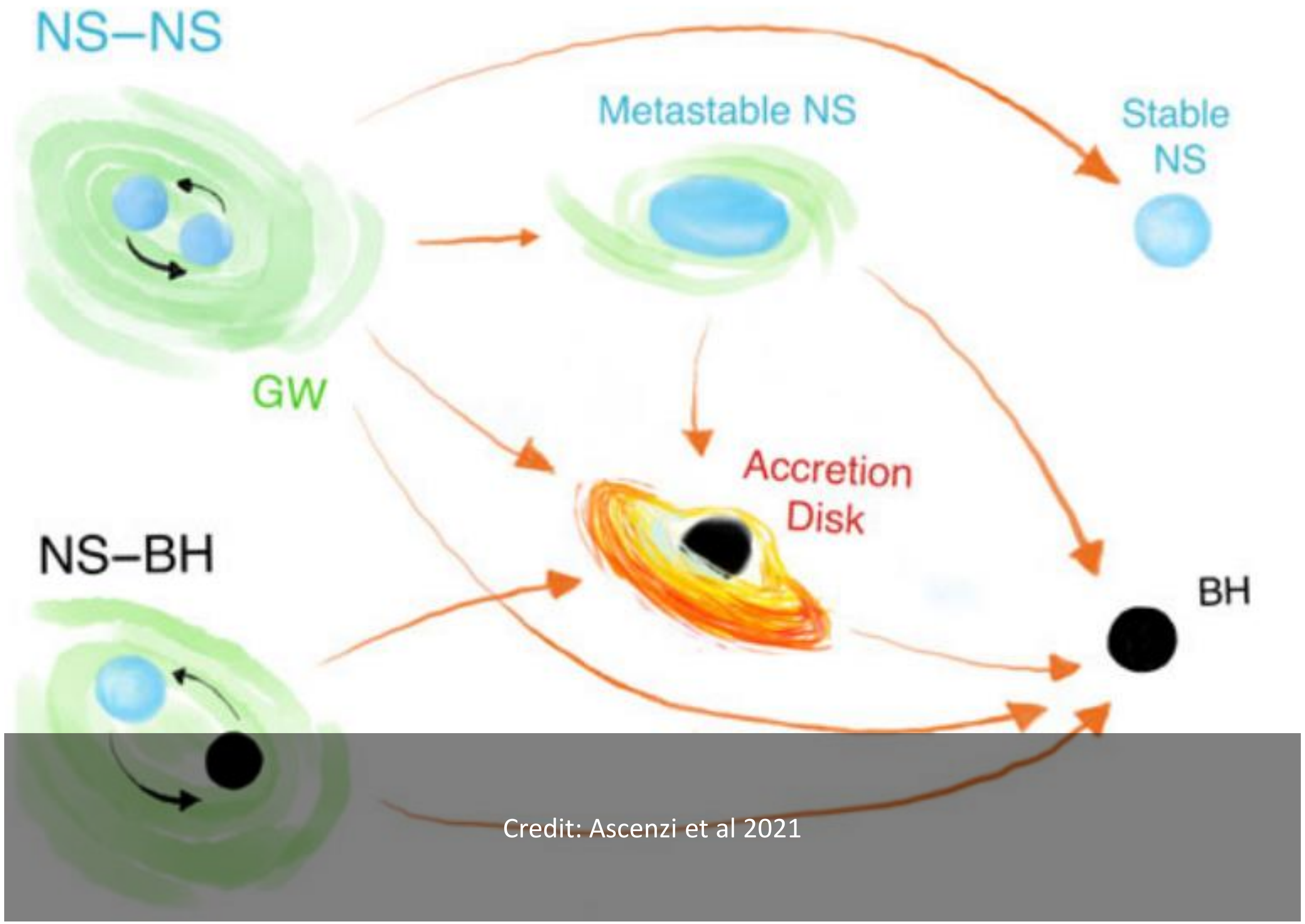


Figure by R. Haas



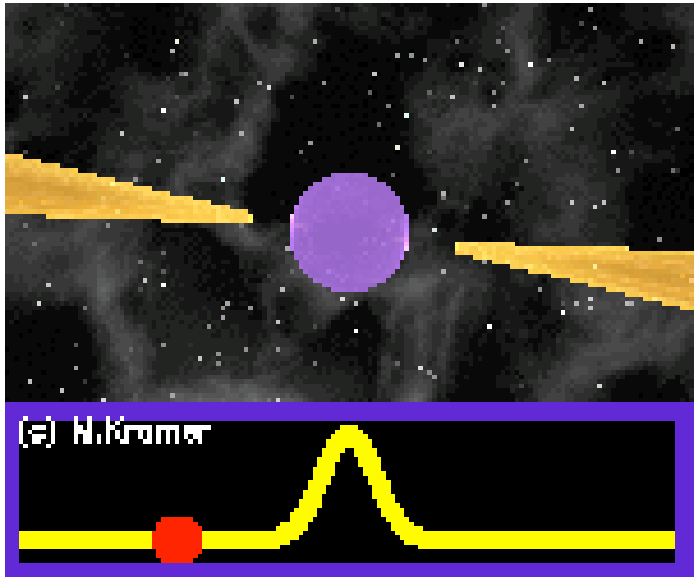
Credit: Ascenzi et al 2021

Binary Neutron Star Mergers

NS: DISCOVERY

First NS discovered as a "pulsar" (radio frequencies) in 1967 by PhD student Jocelyn Bell and her supervisor Antony Hewish.

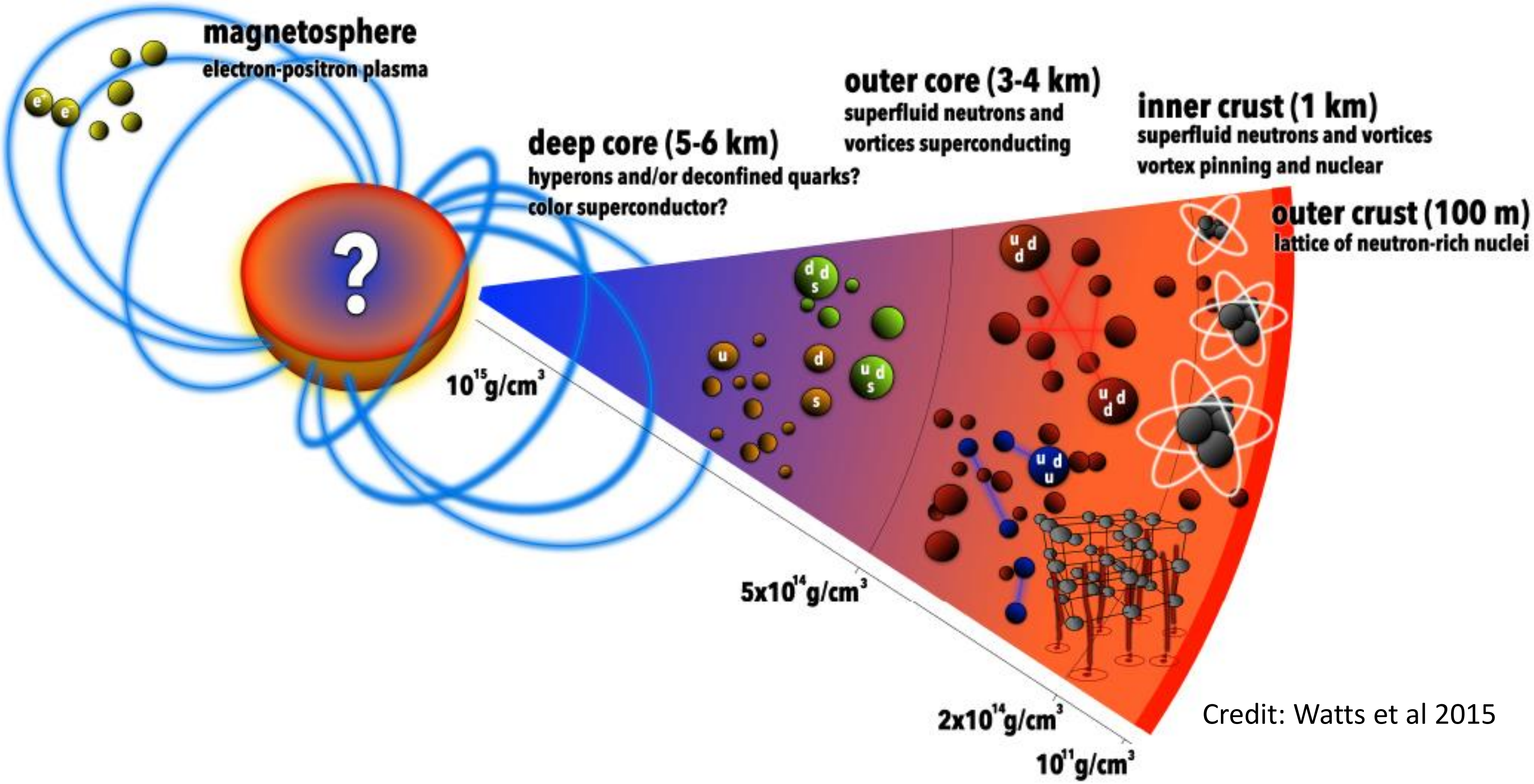
Photo by Daily Herald Archive/SSPL/Getty Images (23/02/1968)



Pulsars are highly-magnetized rotating neutron stars with spins up to ms

Source: https://link.springer.com/article/10.12942/lrr-2008-8

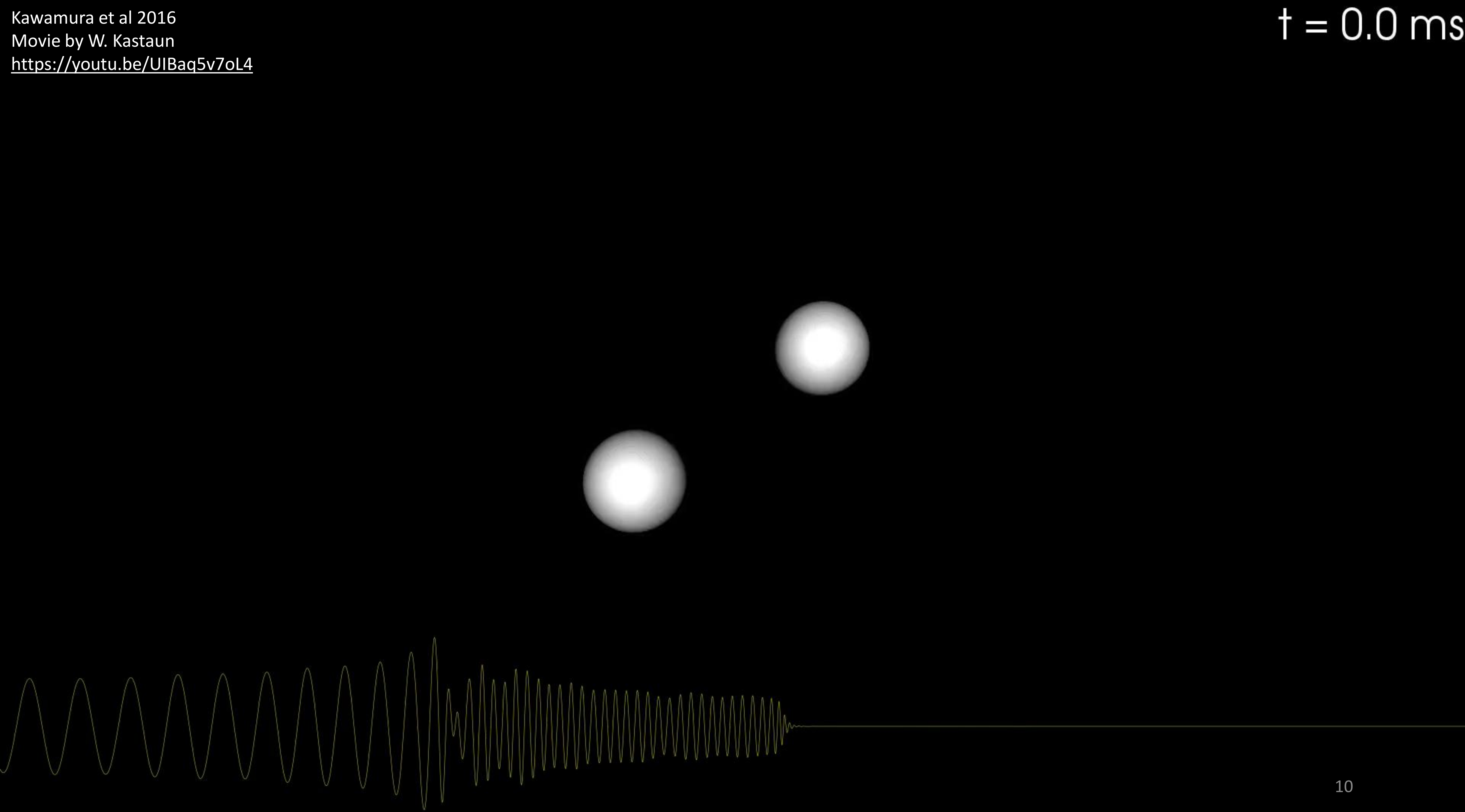
Neutron Star Structure



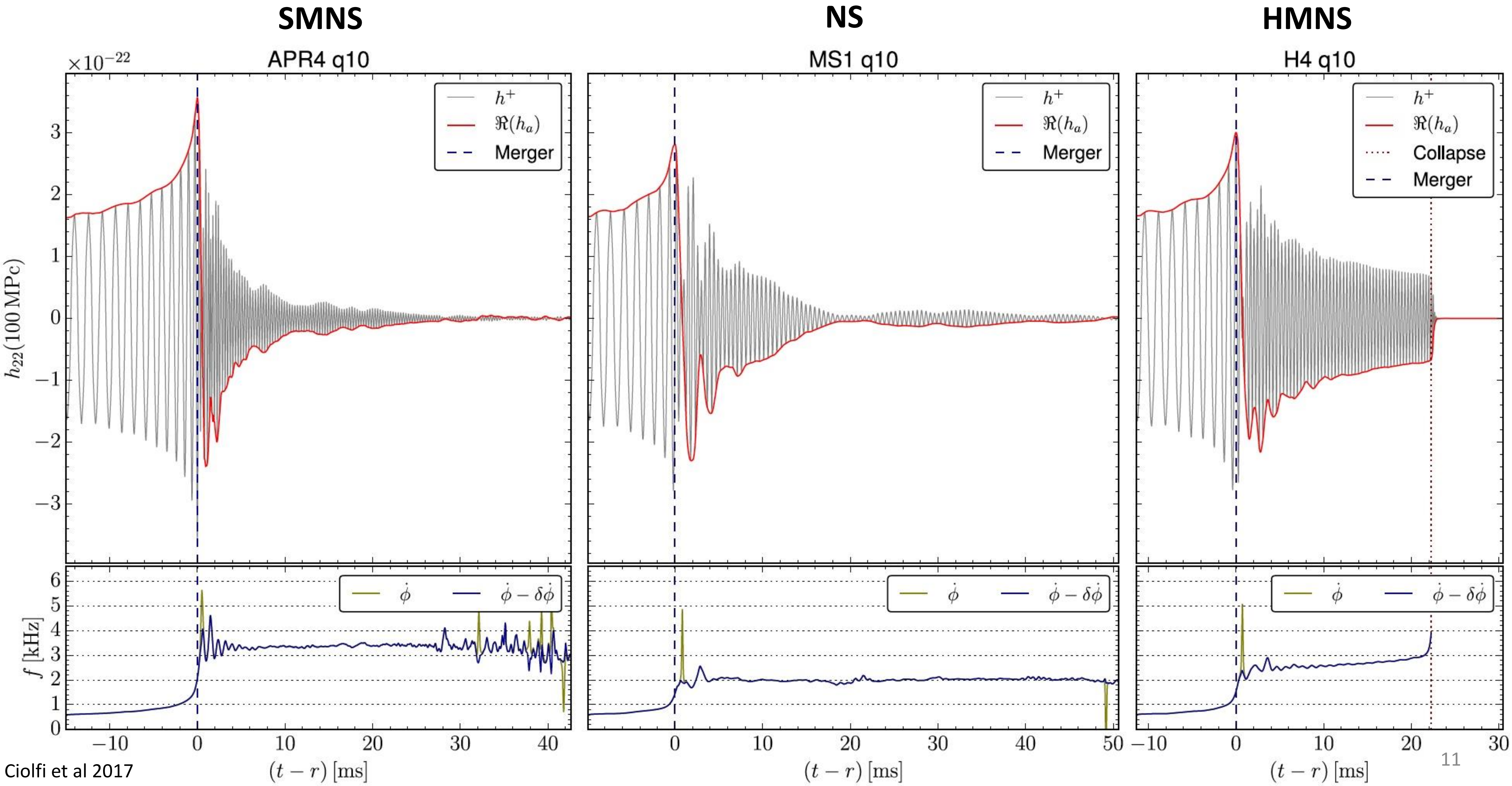
Credit: Watts et al 2015

Internal structure of NSs is still unknown (how does matter behave at $\sim 10^{15}$ g cm^{-3}?). GWs can help to unveil their structure, but theoretical models are necessary to analyze data.

Kawamura et al 2016
Movie by W. Kastaun
https://youtu.be/UIBaq5v7oL4

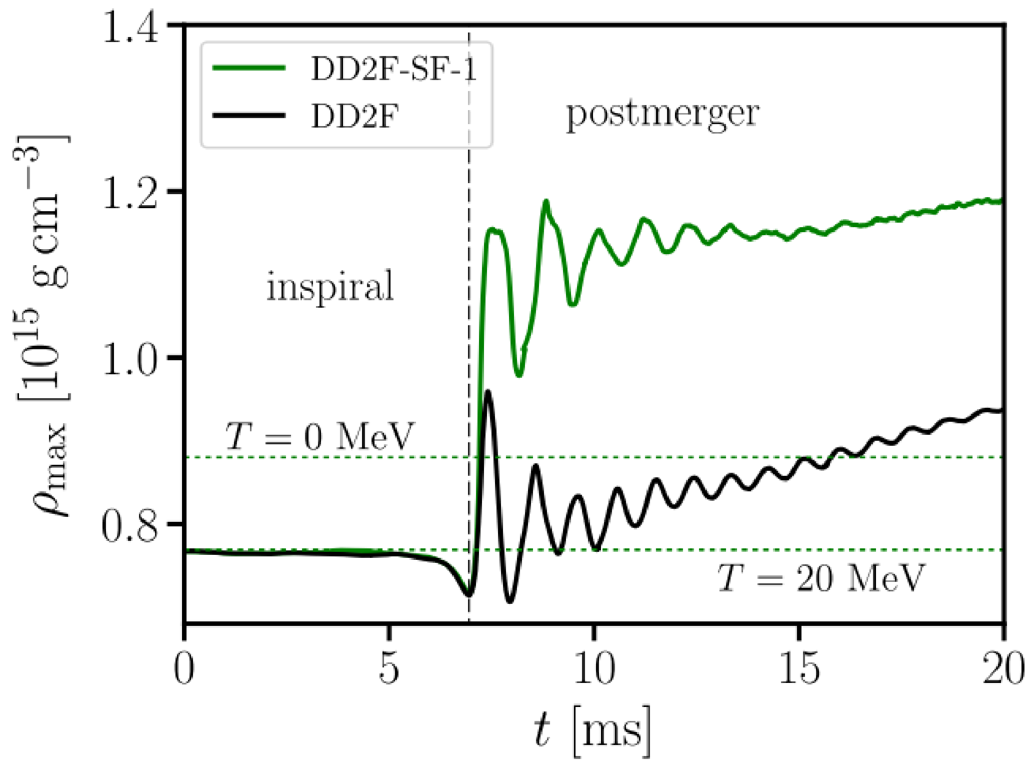


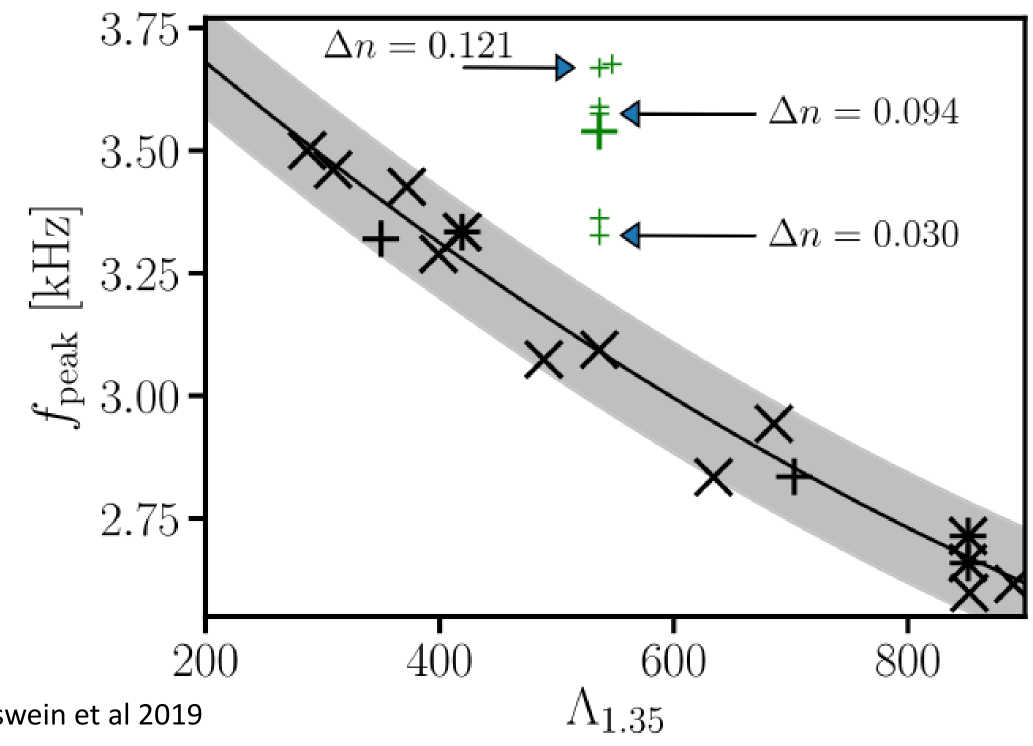
Gravitational Waves



Ciolfi et al 2017

Phase transitions in the post-merger

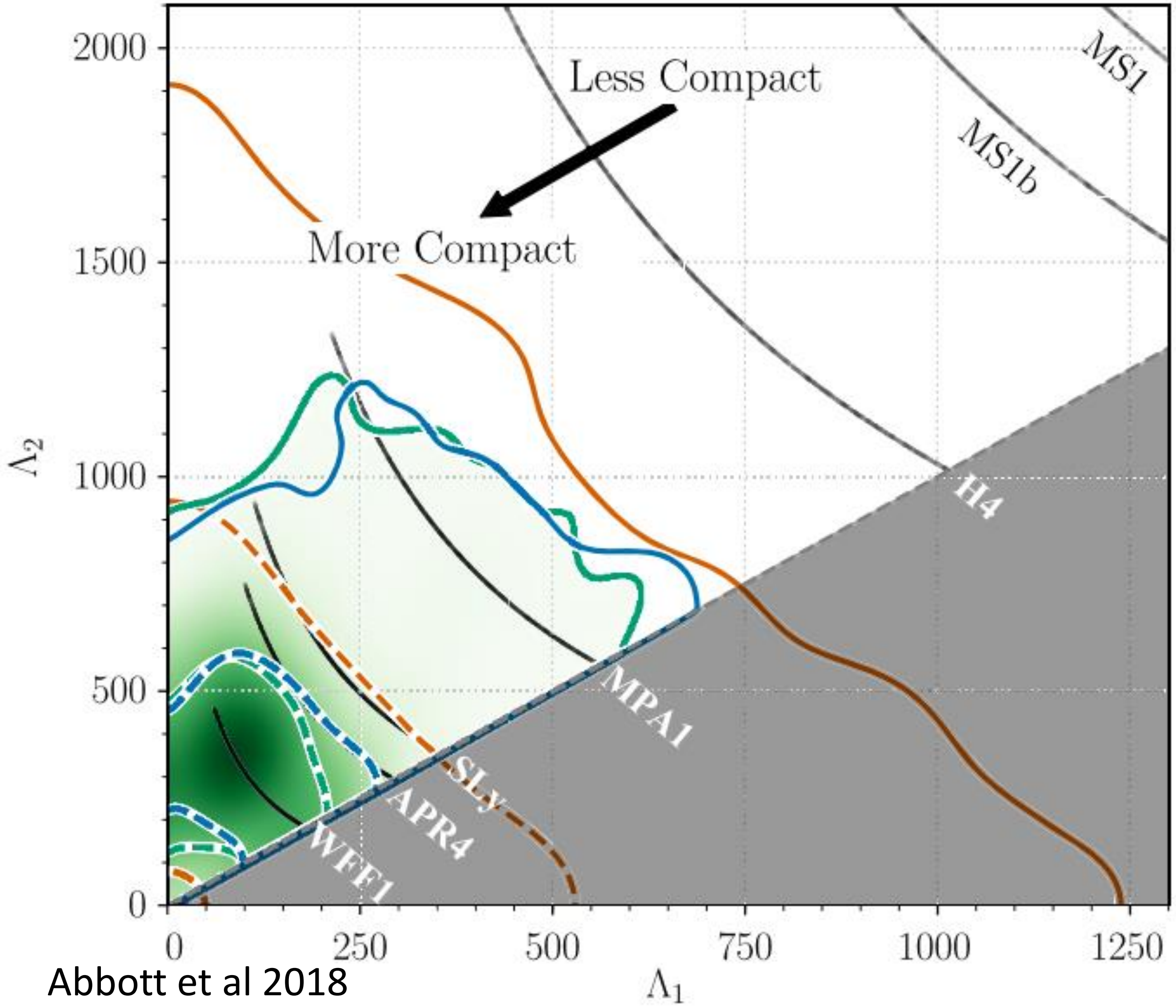


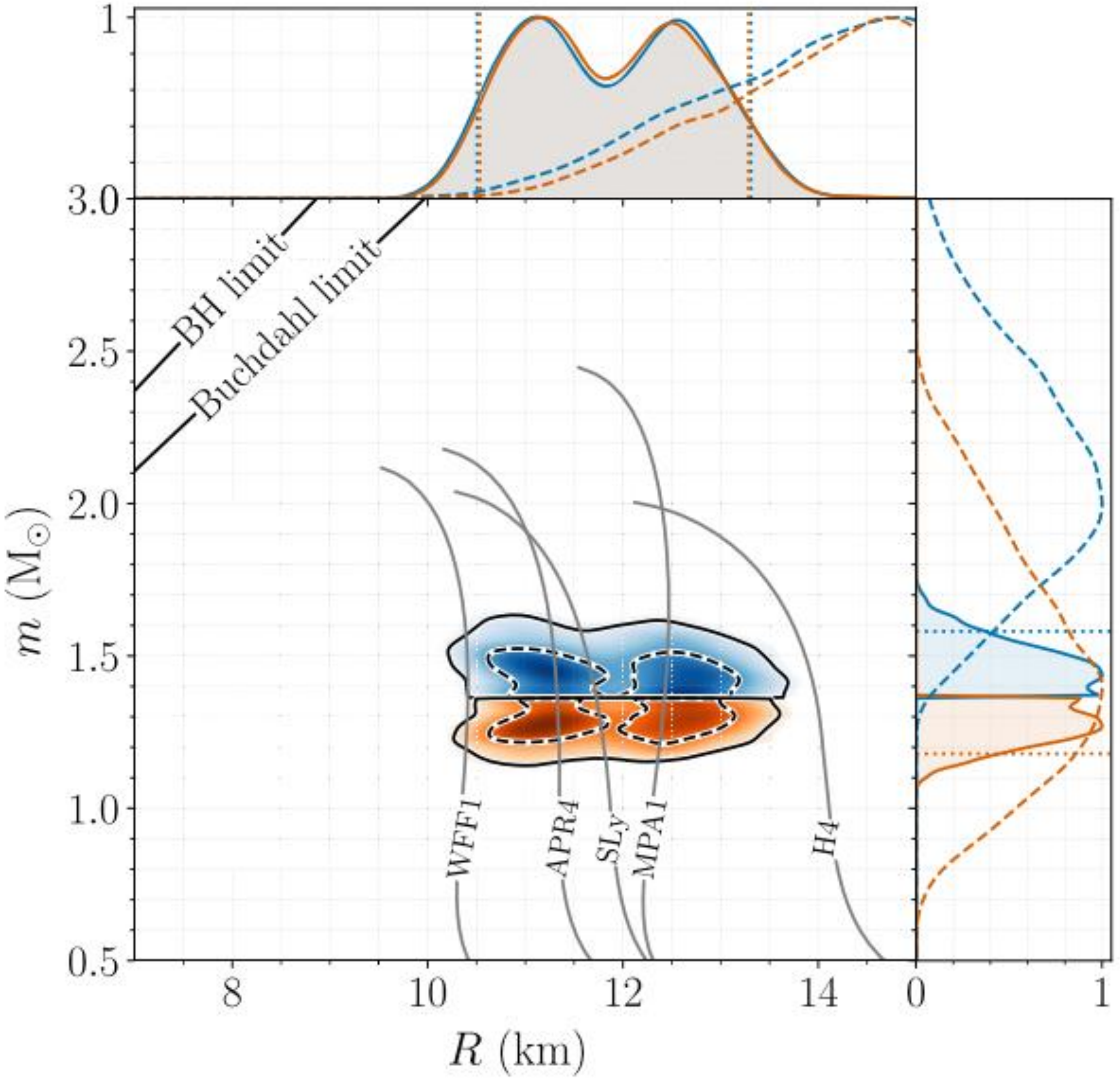


Bauswein et al 2019

A phase transition to a deconfined-quark-matter core significantly affects the GW signal.

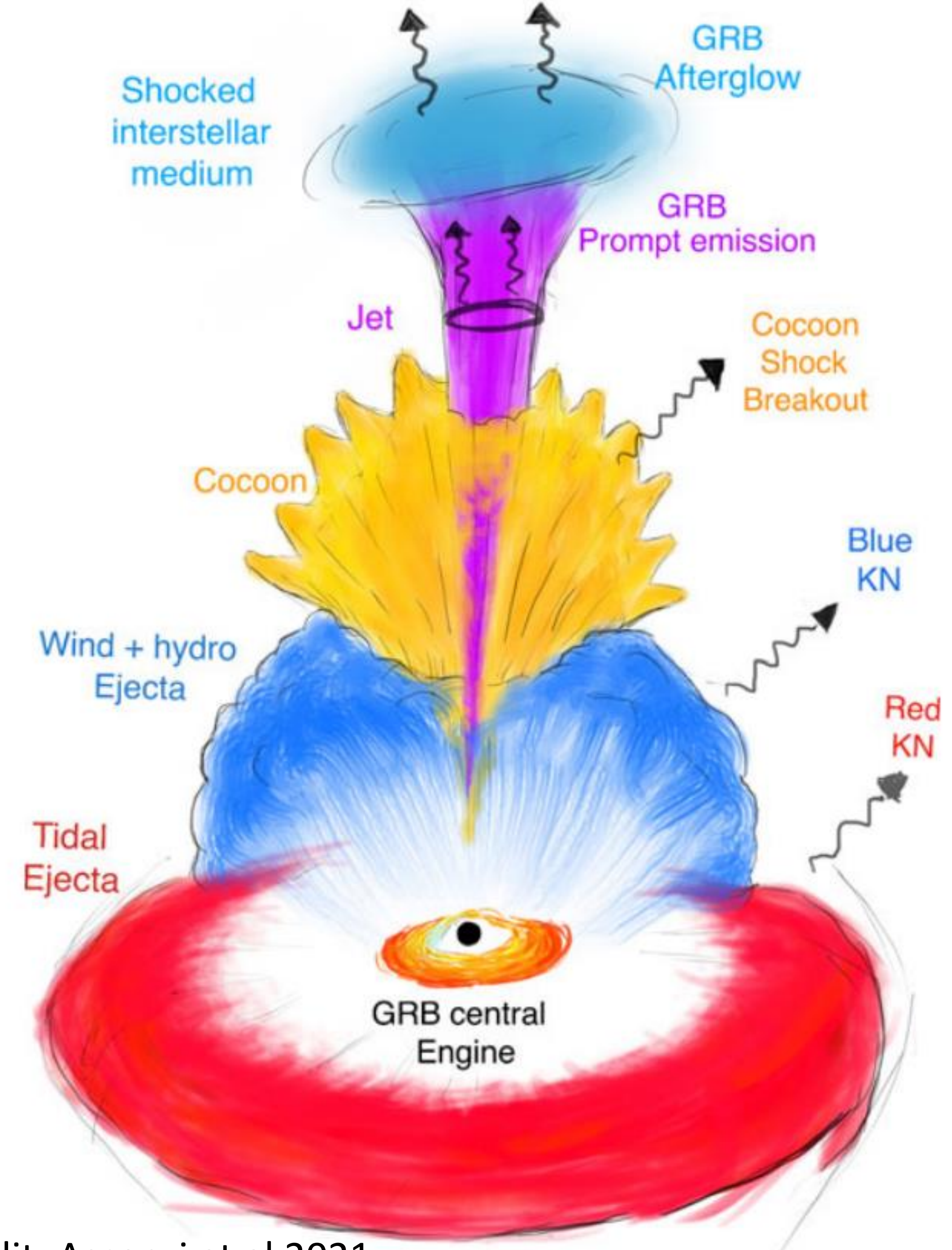
GW170817: EOS constraints





Abbott et al 2018

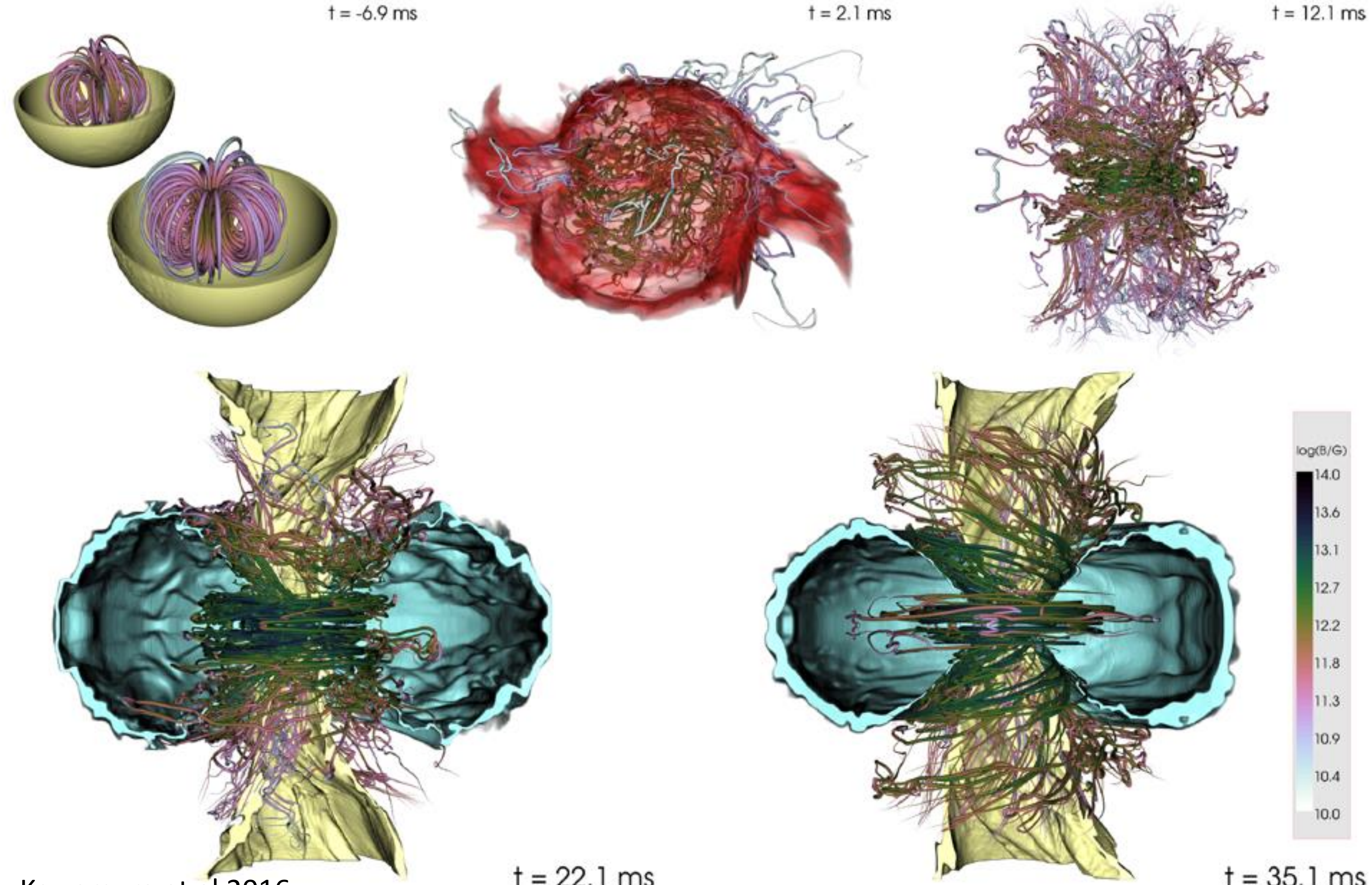
First constraints on NS equation of state, some EOSs now excluded, but still a lot of uncertainty.



Credit: Ascenzi et al 2021

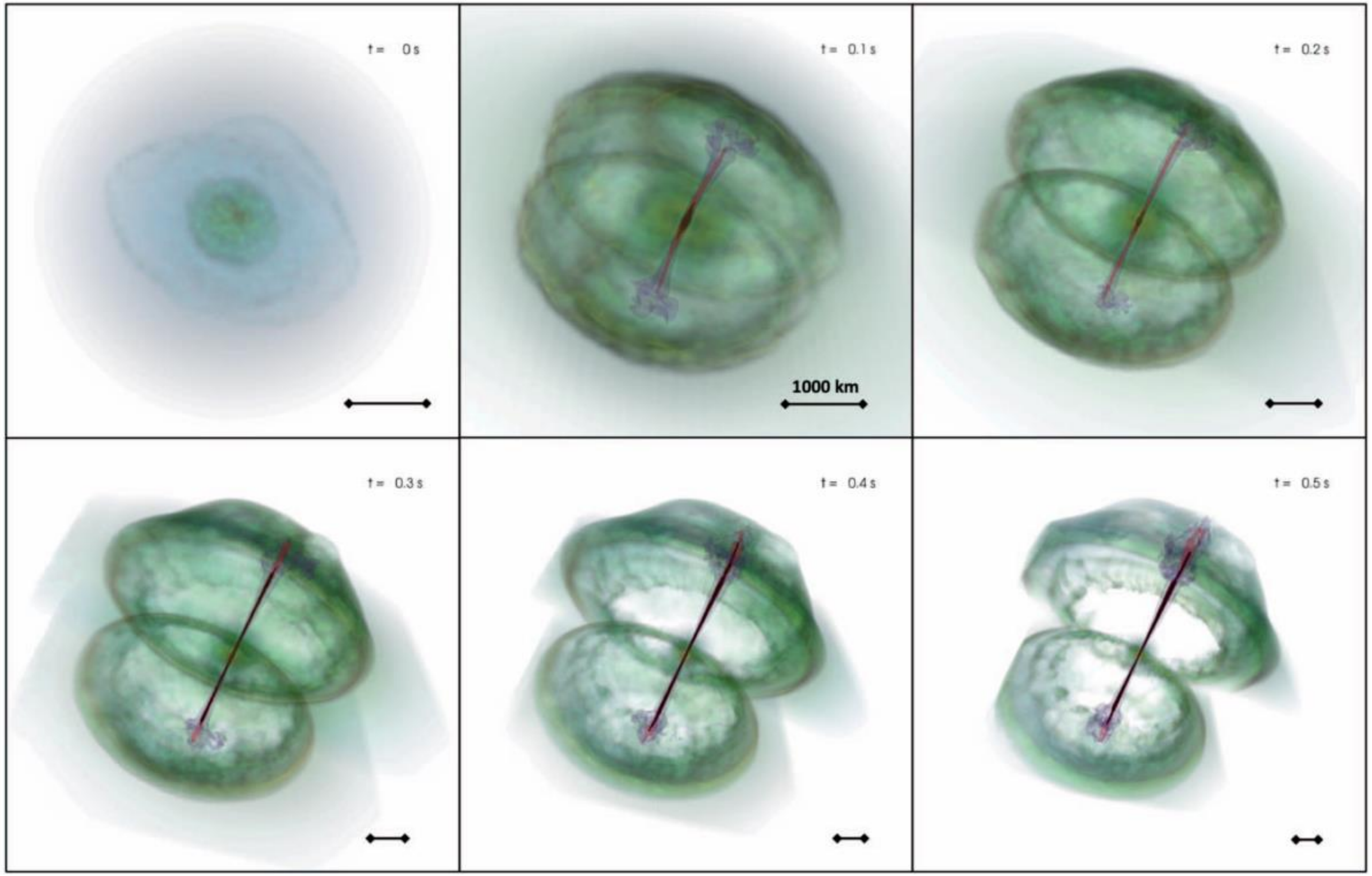
Electromagnetic Emission

Magnetic Field Structure Evolution



Kawamura et al 2016

Jet Propagation in BNS Merger Ejecta (Lazzati et al 2021)



Once a jet is produced, we need to follow its propagation on a long-time scale

This is not feasible in full GR and most works considered analytical setup for the ejecta.

We imported the outcome of a GRMHD simulation into a special relativistic hydrodynamic code. The breakout time is found to be ~0.6 s (see also Pavan et al 2021, Nathanail et al 2021).

The Spritz Code

https://zenodo.org/record/4350072

Cipolletta, Kalinani, **Giacomazzo***, Ciolfi 2020, CQG 37, 135010
Cipolletta, Kalinani, Giangrandi, **Giacomazzo***, Ciolfi, Sala, Giudici 2021, CQG 38, 085021
Kalinani, Ciolfi, Kastaun, **Giacomazzo**, Cipolletta, Ennoggi 2022, PRD 105, 103031

BNS sims require to account for magnetic fields, but also for EOS and neutrino emission. No public code was available that included all these effects.

We therefore developed a new General Relativistic MHD code named Spritz:

- Publicly available on Zenodo
- Based on the Einstein Toolkit Infrastructure (http://einsteintoolkit.org)
- GRMHD Valencia formulation
- Staggered vector potential formulation to evolve the magnetic field
- Support for finite-temperature tabulated Equations Of State
- Neutrino transport via a leakage scheme with a grey approximation (https://stellarcollapse.org/Zelmani) and 3 neutrino species ($\nu_e, \overline{\nu_e}, \nu_x$)
- 5-th order WENO-Z scheme for hydro
- Currently used for NS-NS simulations with jet formation

AsterX
https://github.com/jaykalinani/AsterX

(Kalinani, Armengol, Brandt, Campanelli, Ciolfi, Ennoggi, Giacomazzo, Haas, Ji, Schnetter, Tsao, Zlochower)

- GPU-accelerated GRMHD code for dynamical spacetimes, written in C++
- Built upon the CarpetX driver (scalable up to Exascale)
- CarpetX is based on AMReX, a software framework for block-structured AMR
- Heavily derived from the GRMHD code Spritz
- Solves the GRMHD equations in 3D Cartesian coordinates and on dynamical spacetimes using high-resolution shock-capturing (HRSC) schemes
- Based on the flux-conservative Valencia formulation

Conclusions

- Gravitational Waves from NS-NS mergers provide information on matter at nuclear densities and above
- HPC numerical relativity simulations of NS-NS mergers are needed to infer physical parameters from GW observations
- We can also estimate EM counterparts (SGRB and Kilonova emission)
- We are developing new publicly available HPC codes (CPU and GPU) to better model compact object mergers
- The Einstein Telescope detector will require more accurate (more computationally expensive) numerical relativity simulations