General Relativistic MHD Simulations of Neutron Star Mergers

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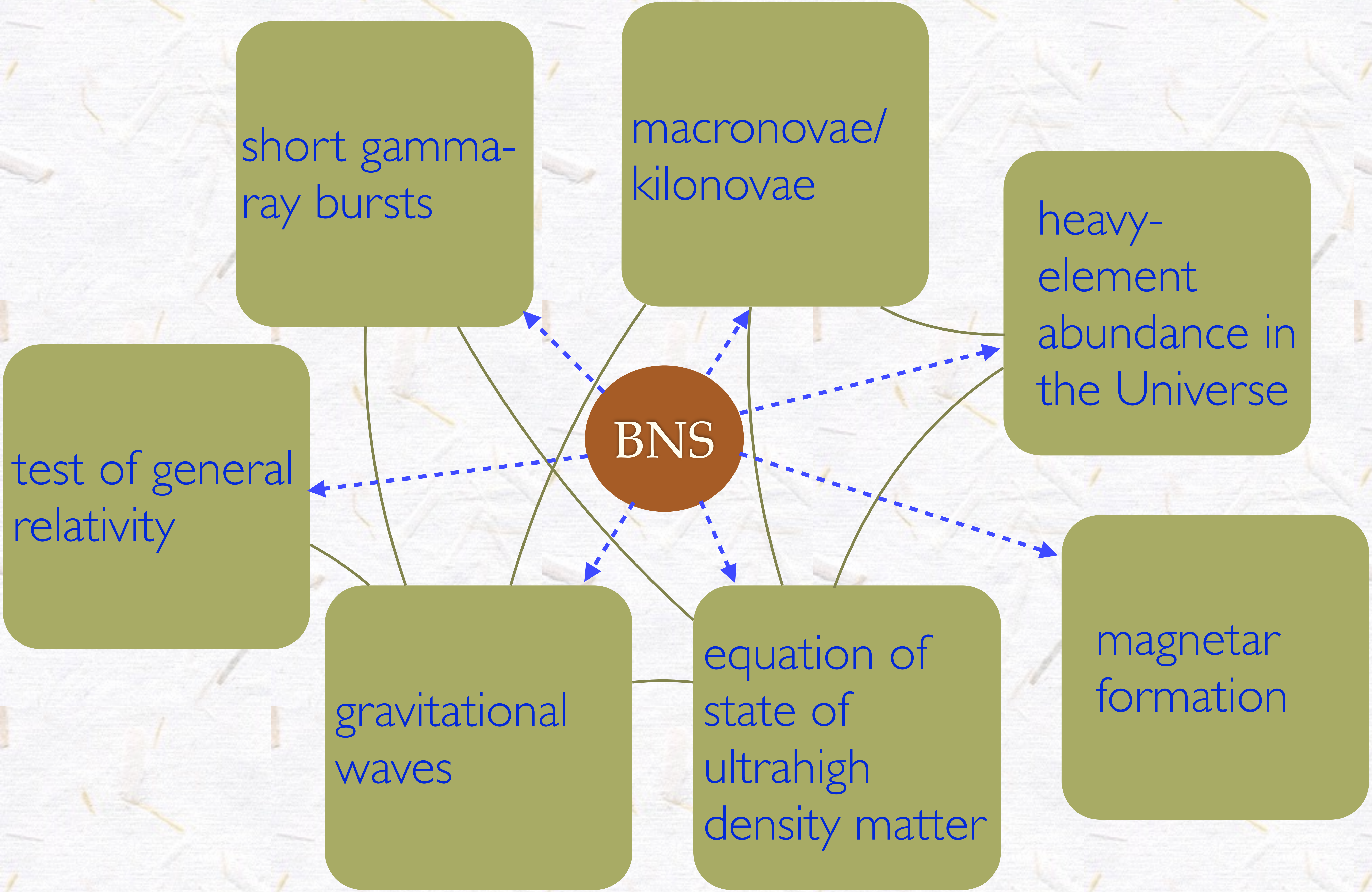
Plan of the talk

- Brief overview of the status of BNS simulations
- Magnetic fields in BNS mergers
- Compact-star equation of state from gravitational-wave signals

Interest in binary neutron stars



short gamma-ray bursts

macronovae/kilonovae

heavy-element abundance in the Universe

test of general relativity

BNS

gravitational waves

equation of state of ultrahigh density matter

magnetar formation

Gravitational-wave detectors in the World

Interferometric gravitational-wave detectors are now in operation in several places

KAGRA
(KAmioka GRAvity)

Large-scale
Cryogenic
Gravitational-wave
Telescope

Goal of modeling and simulations of BNS

- Several groups are working on BNS simulations with their own independent codes

The final goal is maybe a simulation that includes

- Einstein equations and relativistic hydrodynamic equations
- (resistive) magnetohydrodynamics (MHD)
- equations of state based on microphysical calculations
- neutrino and photon radiation transport
- nuclear-reaction networks
- high-order, high-accuracy numerical methods
- ...

and is fast enough to allow parameter-space exploration!

Status of modeling and simulations of BNS

The big picture on the state of the art is:

★ **robustly computed** by all groups (but improvements are being constantly made):

  ★ matter and spacetime dynamics (including long-term evolutions of the formed BHs and accretion discs)

  ★ gravitational-wave signal

★ intense **ongoing work** on:

  ★ linking future GW observations to physical properties of the emitting system (e.g. relating the main frequency of postmerger oscillations to the NS masses)

  ★ heavy-element production and macronovae / kilonovae (already satisfactory results)

  ★ improved initial data (spins)

★open issues:

  ★ magnetic fields after the merger [and before the merger if resistive MHD (pre-merger e.m. emission)]

  ★ effects of neutrino and photon radiation transport

Status of modeling and simulations of BNS: macronovae/kilonovae and heavy-element abundance

Core-collapse **supernovae** are the textbook **r-process sources** but have been found to be seriously **challenged in providing the physical conditions** (high entropy, low electron fraction, rapid expansion) **that are required to produce the heavy (A > 90) r-process elements.**

An **alternative** r-process nucleosynthesis mechanism comes from **compact binary mergers** which release neutron-rich matter in at least three ways:

- matter that is ejected dynamically via gravitational torques
- a contribution due to neutrino-driven winds
- ejections from the late-time dissolution of accretion discs.

The starting point is the same (cold NS matter in β equilibrium), but the three channels differ in the amounts of released matter, in their entropies, expansion time-scales and electron fractions. Therefore they might possibly produce different nucleosynthetic signatures.

The ejecta are responsible for **two types of electromagnetic transients**:

- Dissipation of the kinetic energy of the ejecta in the ambient medium (radio flares that arise from the interaction of sub- to mildly relativistic outflows with the surrounding matter).
- Radioactive decays of the decompressed NS matter. This is expected to produce an optical display similar to a SN, but much shorter, referred to as **'macronova' or 'kilonova'**, which has been shown to produce detectable short-lived infrared (IR) to ultraviolet (UV) signals powered by the same radioactive decay on a time-scale of a day.

Status of modeling and simulations of BNS: short gamma-ray burst engines, jet formation

There are mainly four processes for magnetic-field amplification in binary neutron star mergers:

- the Kelvin Helmholtz (KH) instability developed in the shear layer when the two stars come into contact
- the magneto rotational instability (MRI) inside the remnant neutron star formed after the merger and/or the massive disks formed after a black hole formation (simulations with resolution high enough to resolve MRI are unfeasible with current computational resources)
- compression
- magnetic winding

More later in the talk.

The fundamental equations

We solve the following equations:

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

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

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

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

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

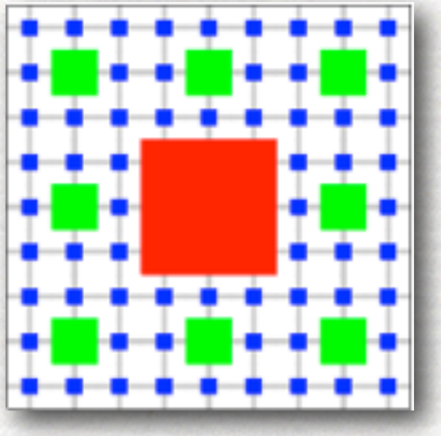
The complete set of equations is solved with the codes:

`Cactus/Carpet/Whisky`.

Tools: Cactus/Carpet/Whisky

Whisky (www.whiskycode.org) is a code for the solution of the relativistic hydrodynamics and magnetohydrodynamics equations in arbitrarily curved spacetimes. It is developed at Osaka University, Albert-Einstein-Institut, Frankfurt University, University of Trento, ...

Cactus (www.cactuscode.org) is a computational "toolkit" developed at the AEI/LSU and provides a general infrastructure for the solution in 3D and on parallel computers of PDEs (e.g. Einstein equations).



Carpet (www.carpetcode.org) provides box-in-box adaptive mesh refinement with vertex-centred grids.

einstein toolkit

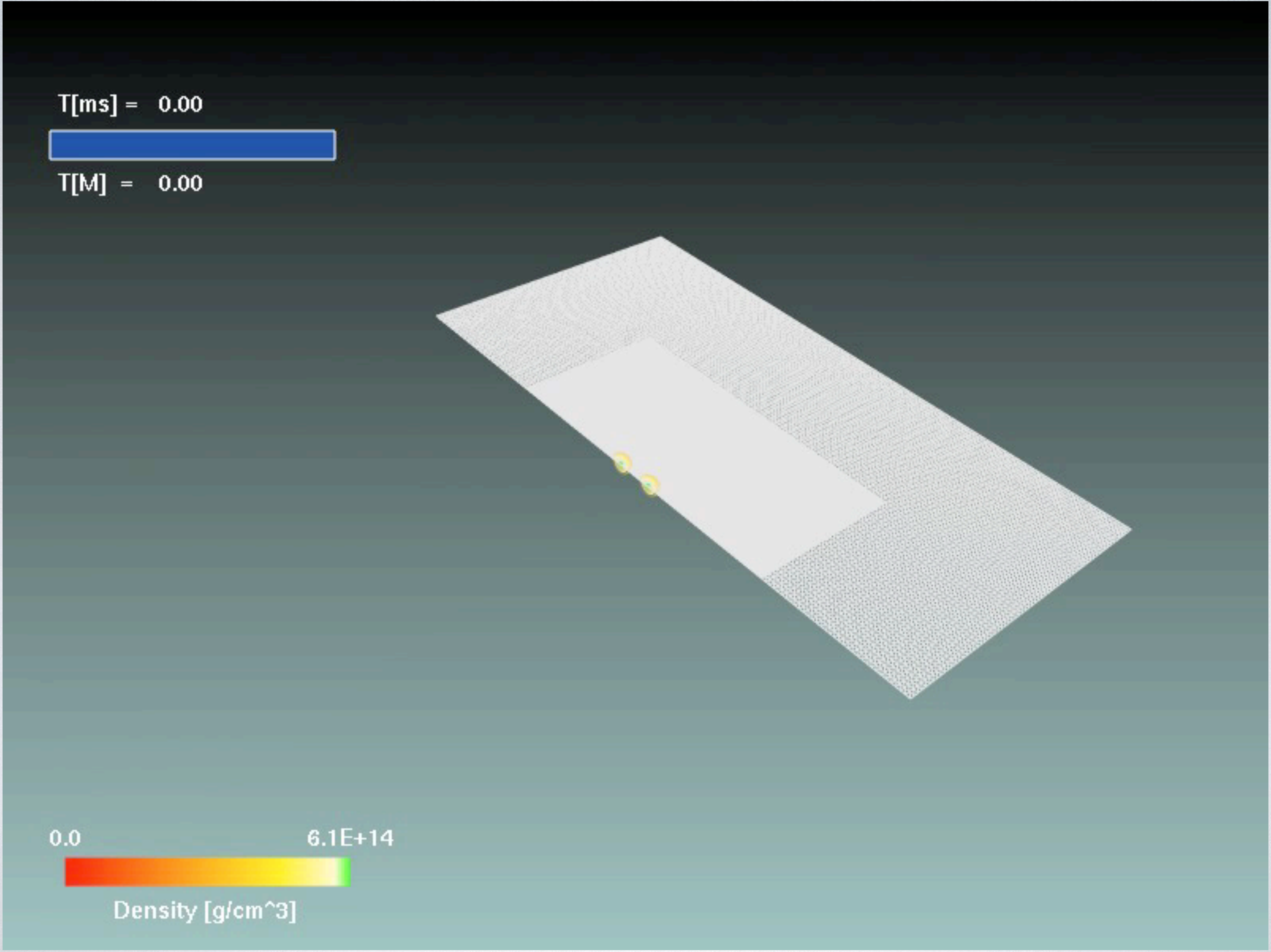
http://einsteintoolkit.org/

- The Einstein Toolkit is a **state-of-the-art** set of tools for **basic numerical relativity** (initial data, evolution, analysis, simulation management, …)
- Open and free source
- Community-driven software development

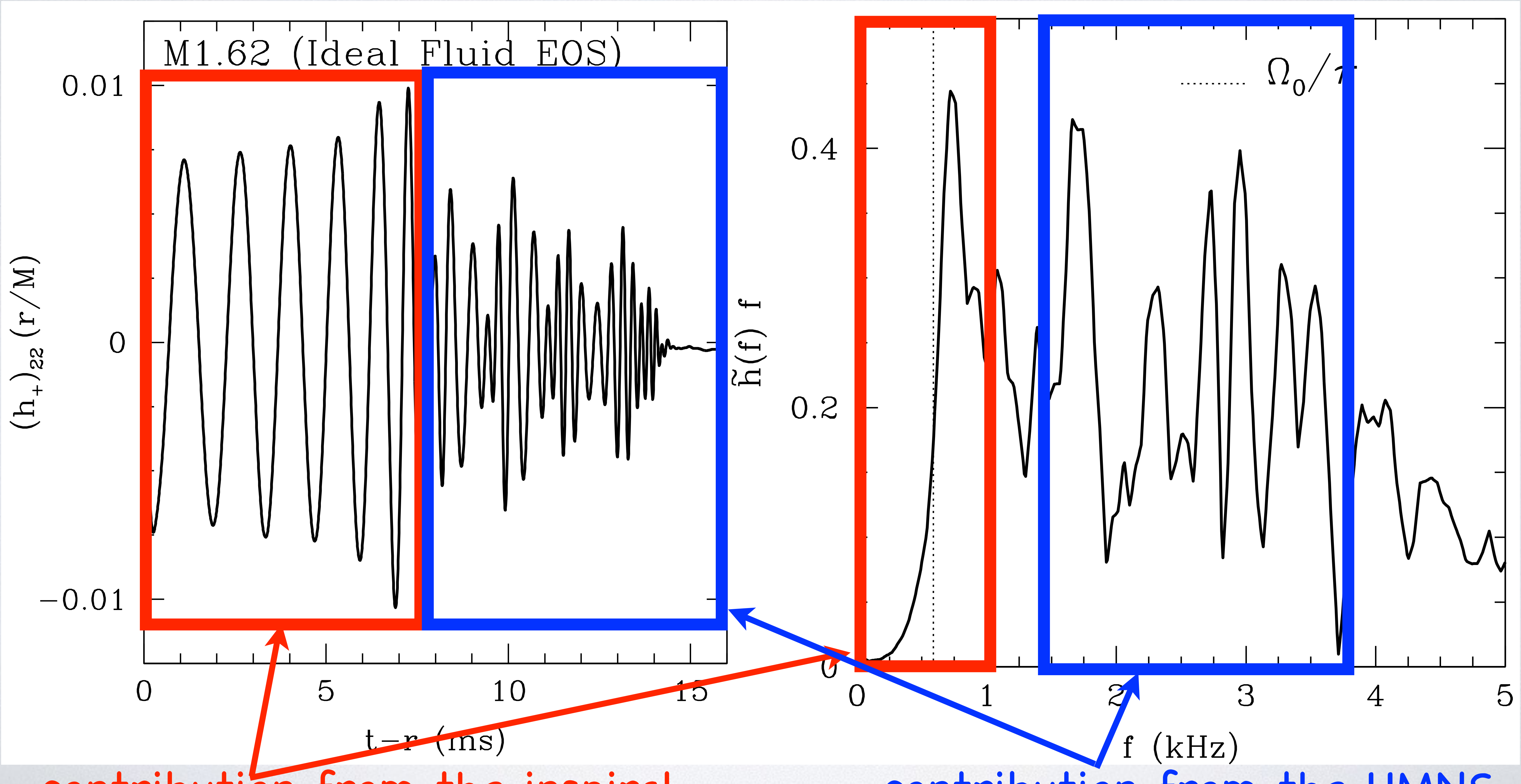
INITIAL MODELS

All the initial models are computed using the **Lorene code** for unmagnetized binary NSs (Bonazzola et al. 1999). A **poloidal magnetic field** is added by hand to the initial data.

- Equal-mass binary
- Gravitational mass of the system ≈ 3 $M_\odot$ → prompt collapse
- Realistic initial magnetic fields: maximum strength B≈10^{12} G
- Initial distance 45 km
- Ideal-fluid EoS $P = \rho\epsilon(\Gamma - 1)$ or tabulated EoS


T[ms] = 0.00
T[M] = 0.00
0.0
6.1E+14
Density [g/cm^3]

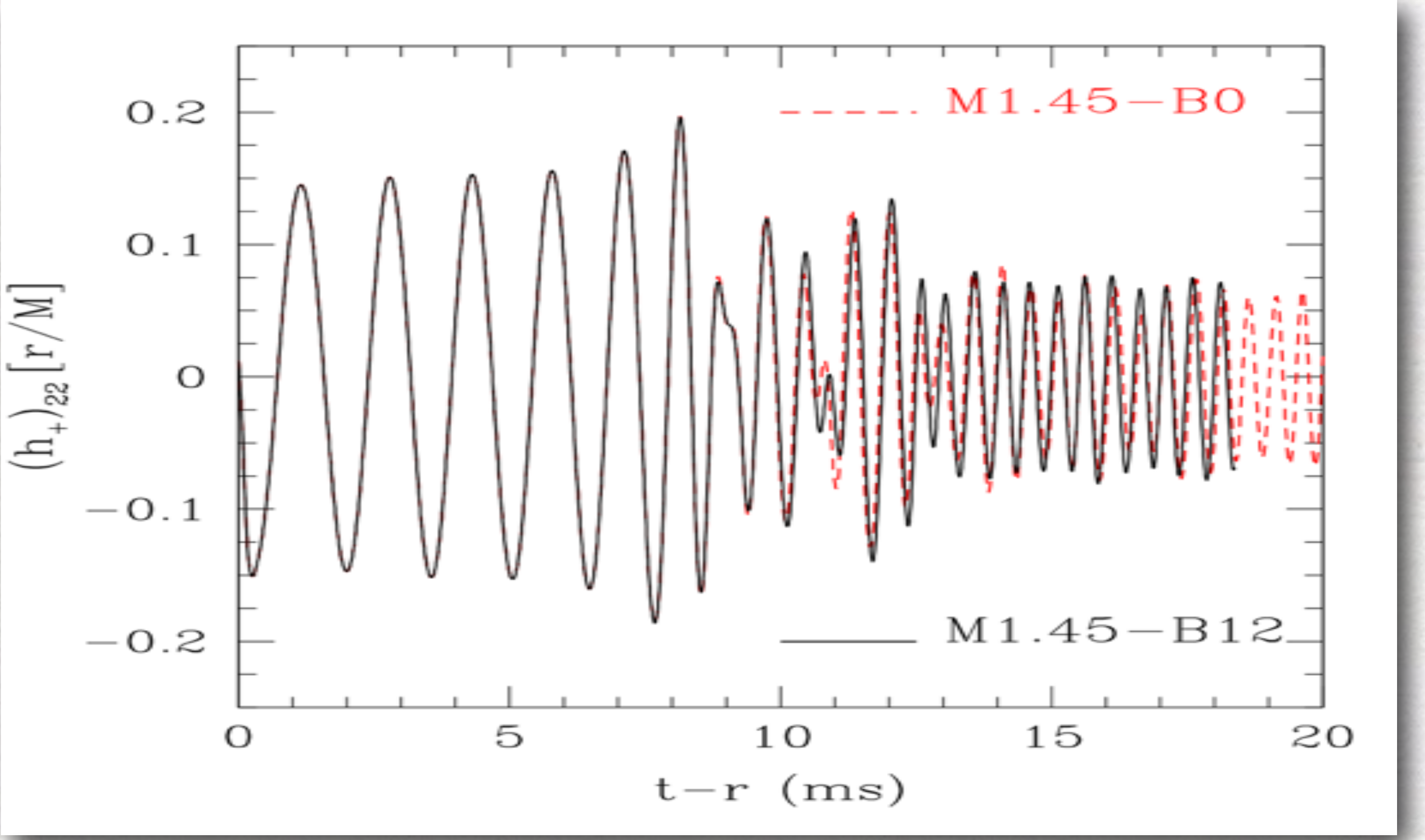
GRAVITATIONAL WAVES FROM BINARY NEUTRON STARS

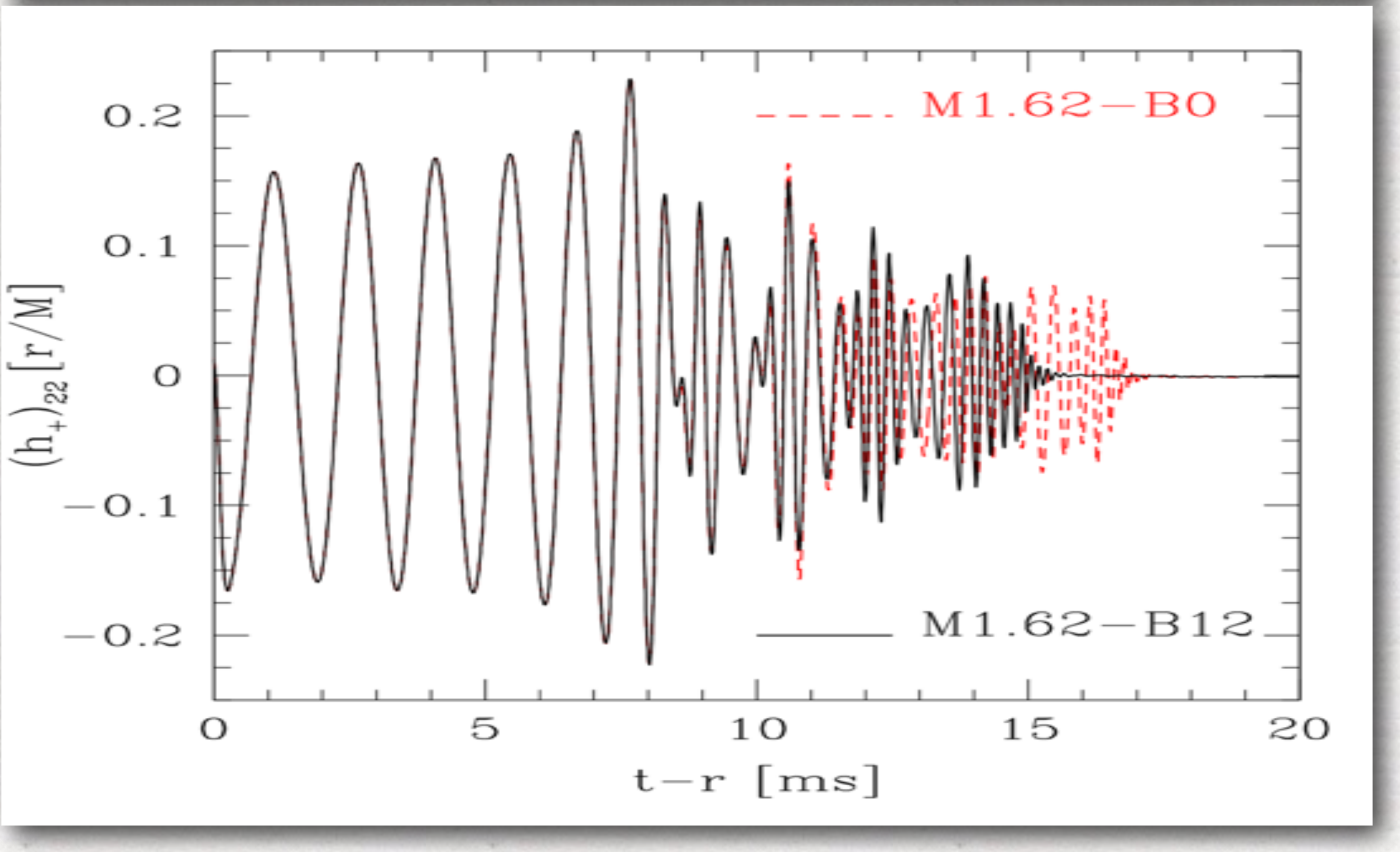


contribution from the inspiral

contribution from the HMNS

Waveforms: comparing against magnetic fields



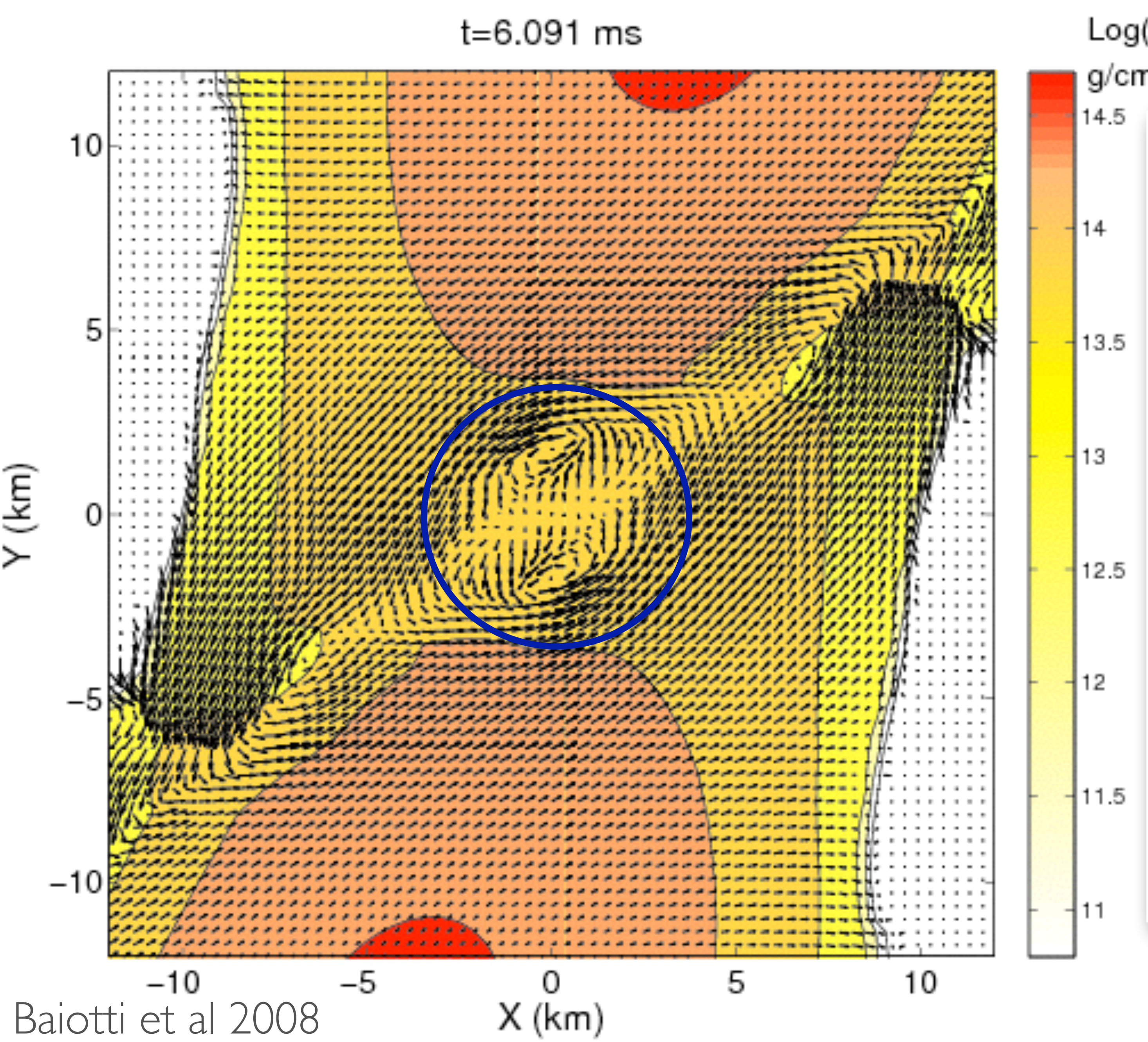


Comparison of GW waveforms of simulations with/without magnetic field:

- Differences in the **inspiral** are not significant for realistic fields.
- The **post-merger** evolution may be very different

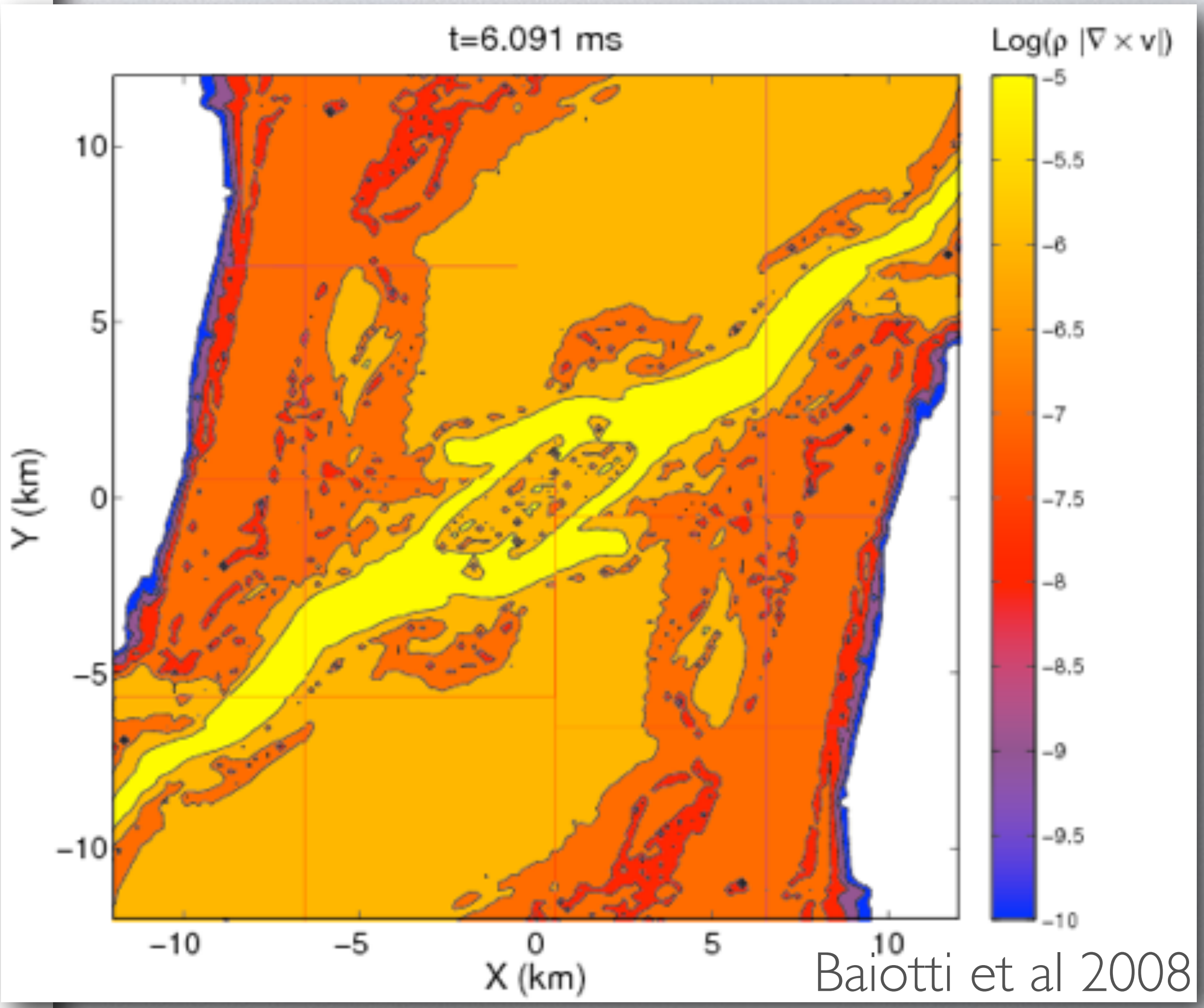
KELVIN-HELMHOLTZ INSTABILITY AND MAGNETIC FIELDS

During the merger a shear interface forms and Kelvin-Helmholtz instability develops, which produces a series of vortices.



Baiotti et al 2008

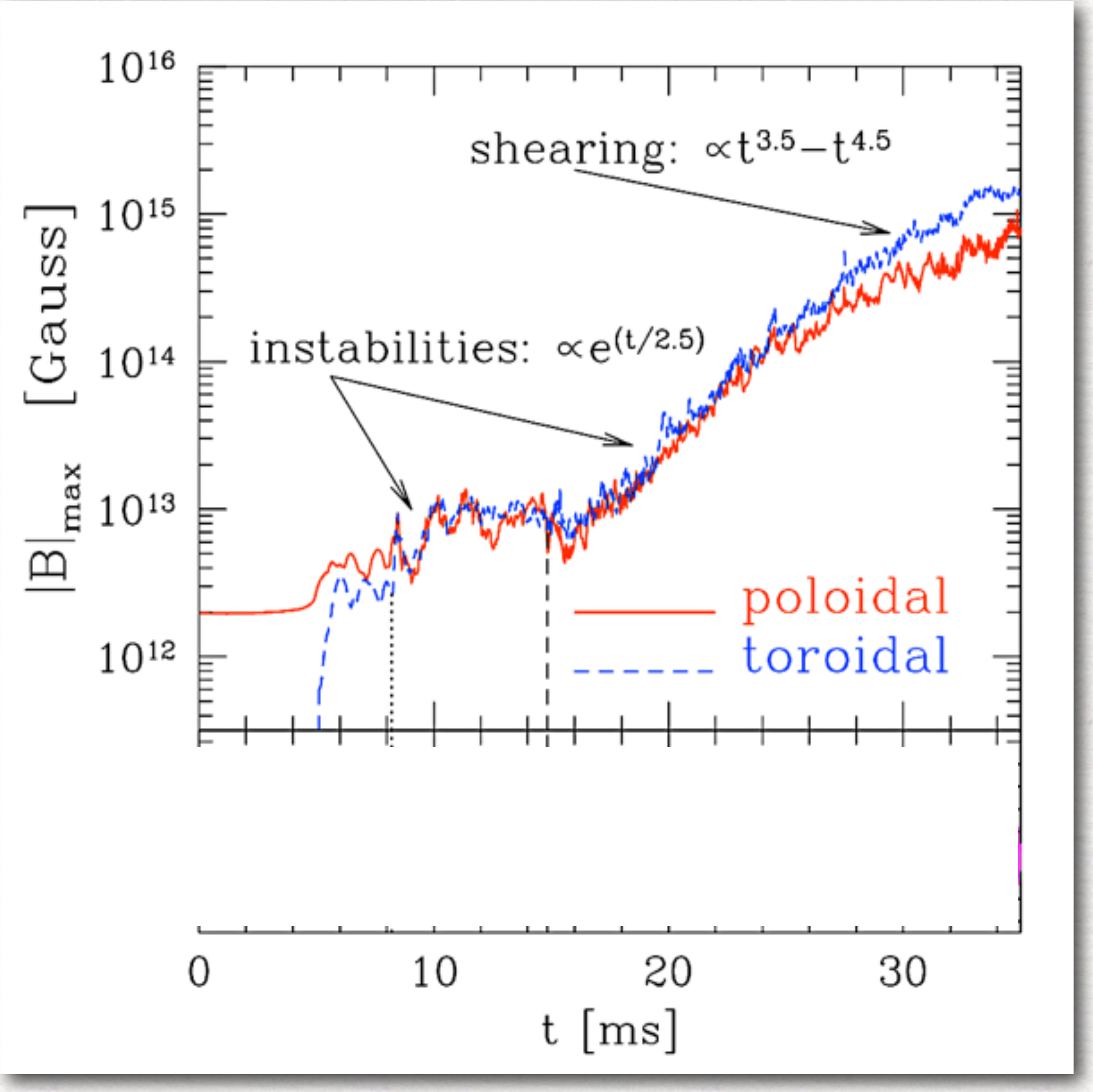
(v^x, v^y) in "corotating" frame



Baiotti et al 2008

$$\rho|\nabla \times v|^z$$

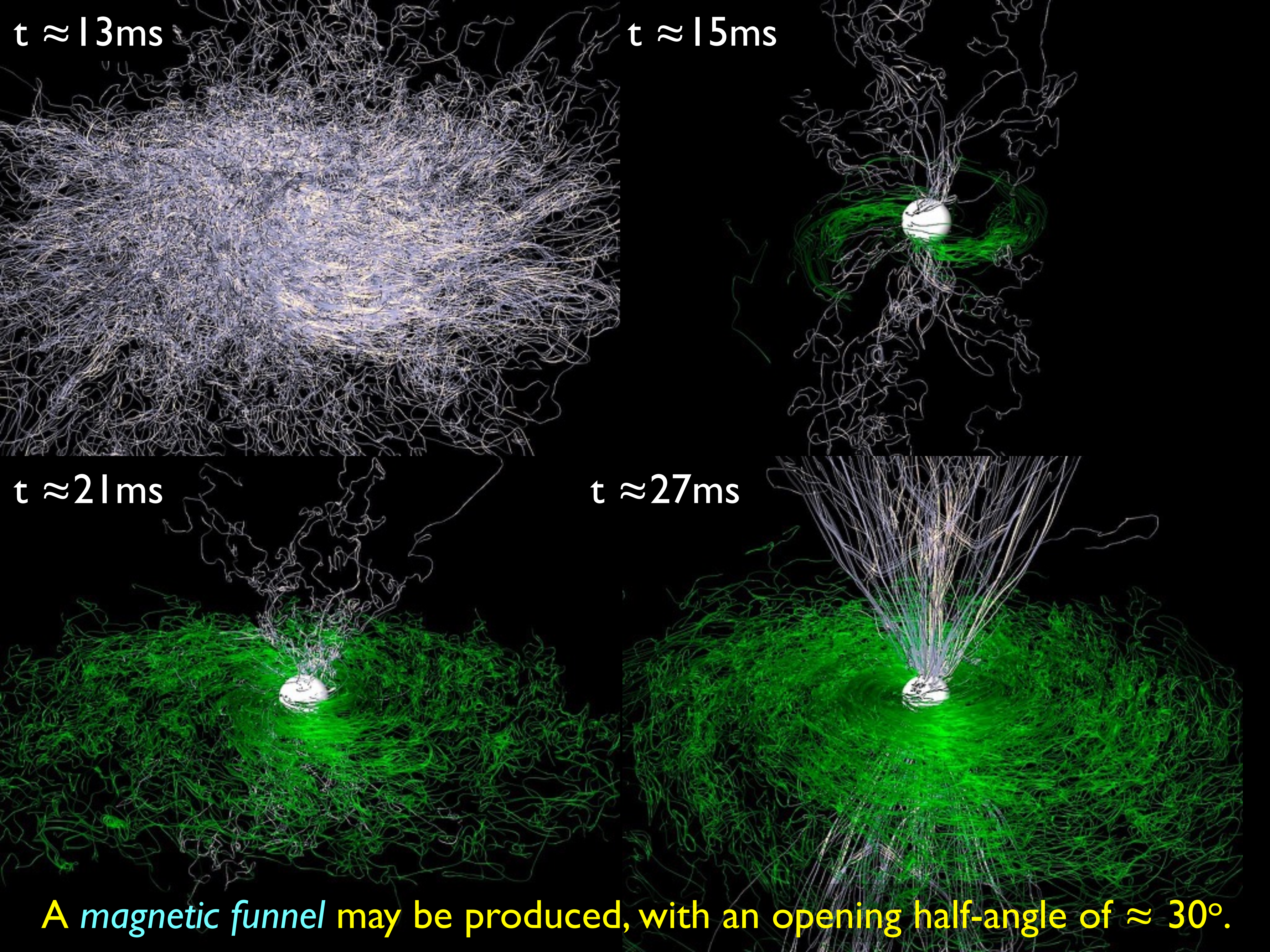
Amplification of magnetic fields



- ✳The B-field grows exponentially first because of instabilities

- ✳Later on the growth is only a power law as the B-field reaches equipartition

- ✳The B-field is mostly toroidal in the torus and ~10^{15} G.
- ✳A poloidal component may dominate along the BH spin axis.



t ≈13ms

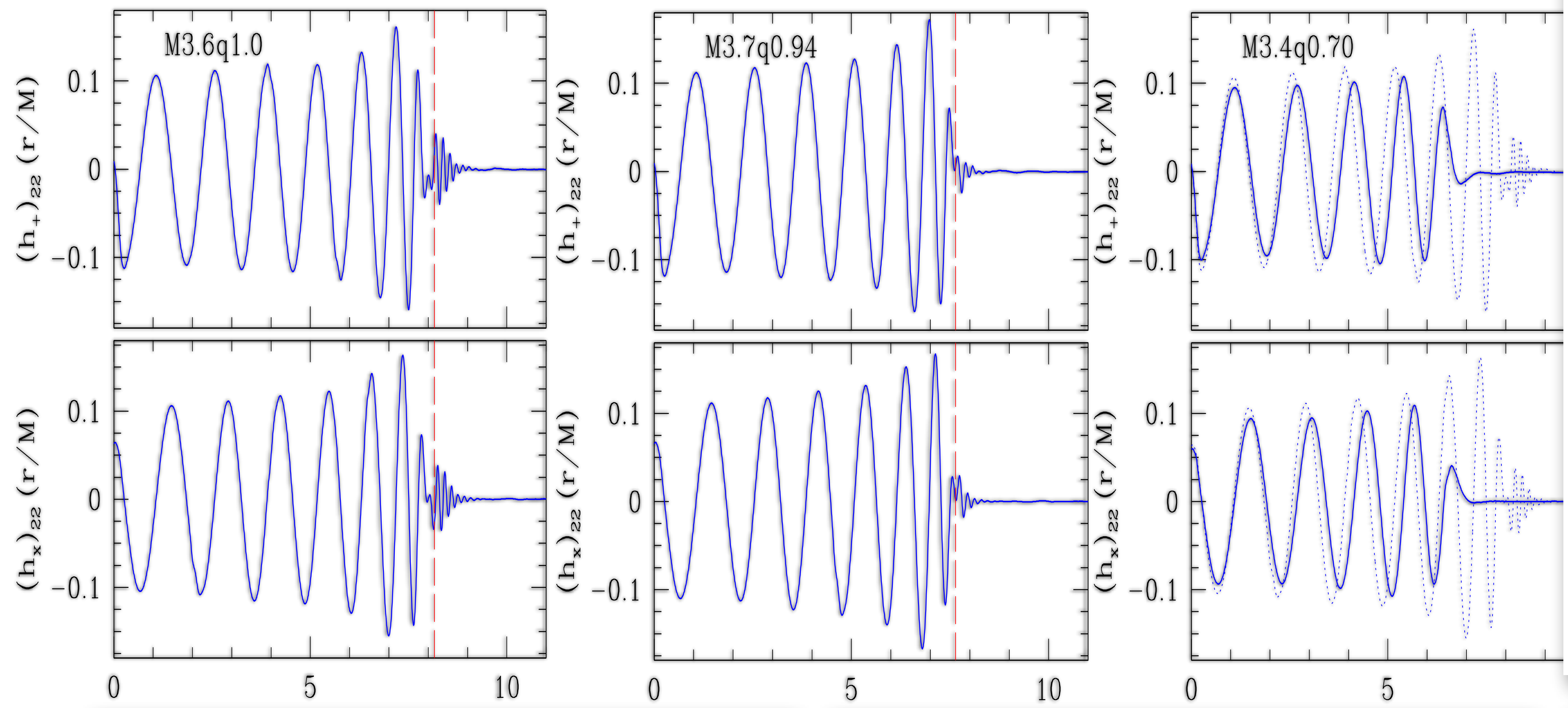
t ≈15ms

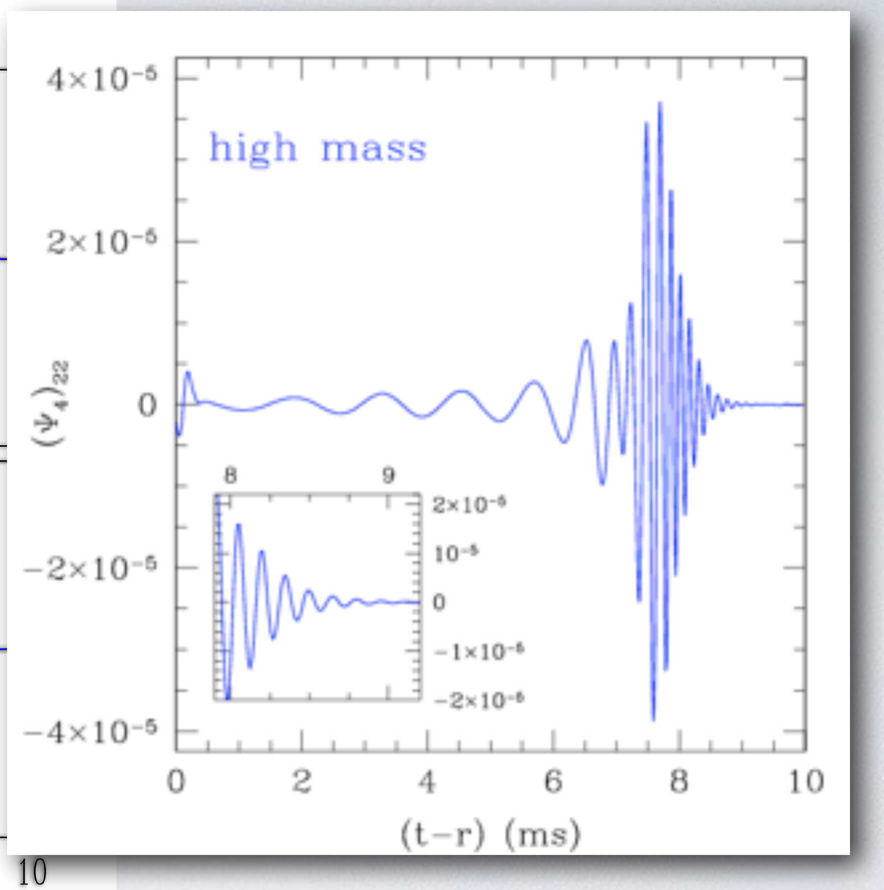
t ≈21ms

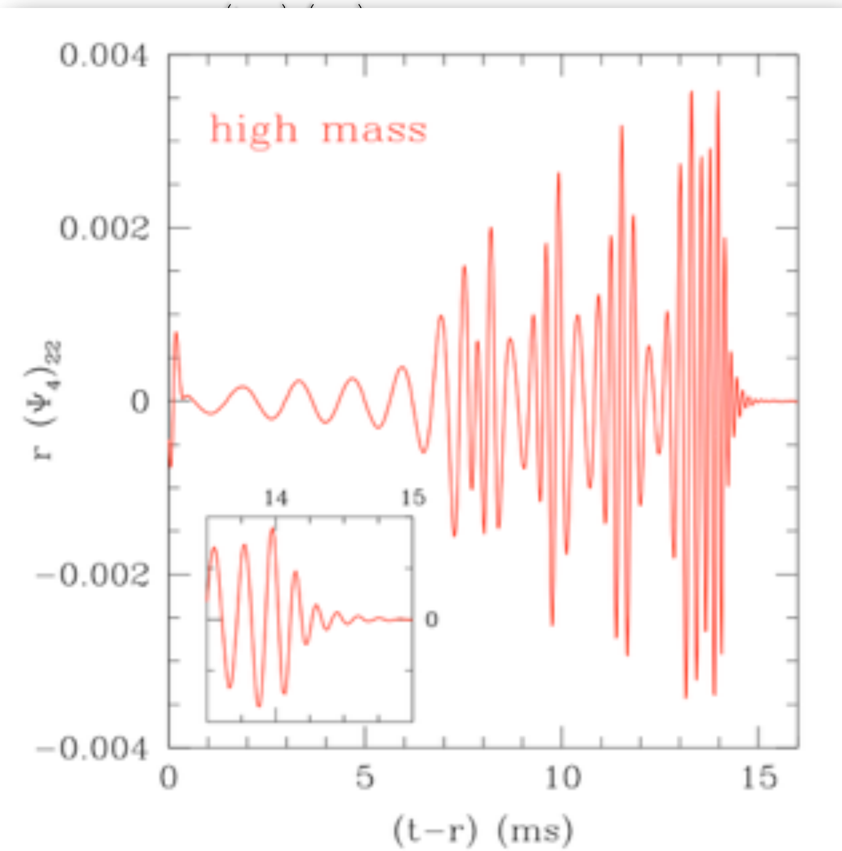
t ≈27ms

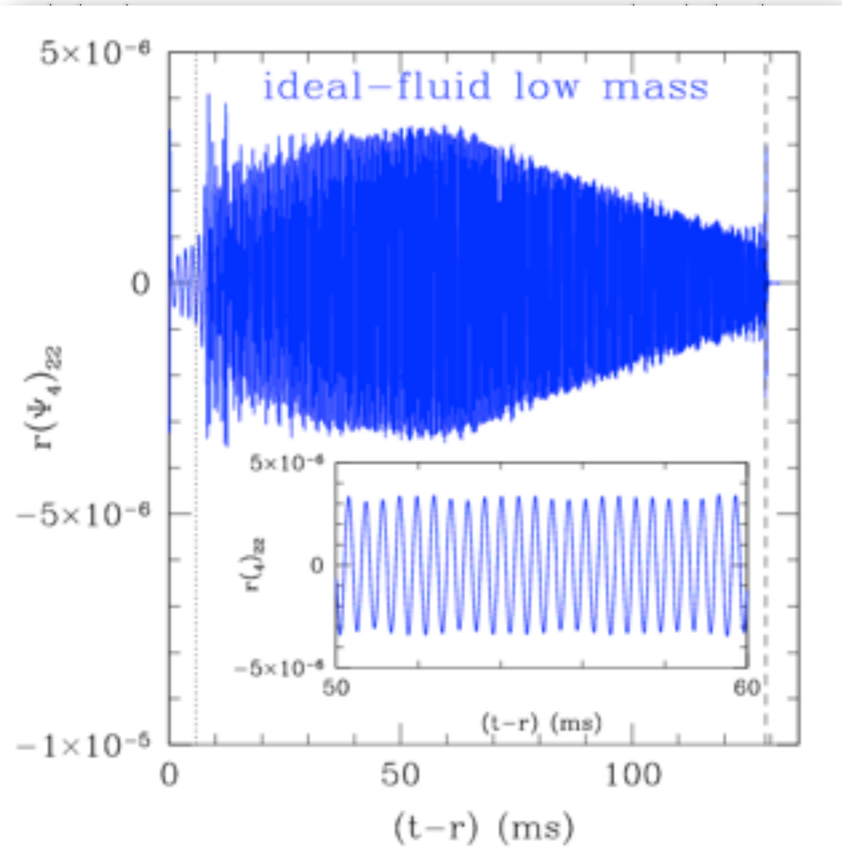
A *magnetic funnel* may be produced, with an opening half-angle of ≈ 30°.

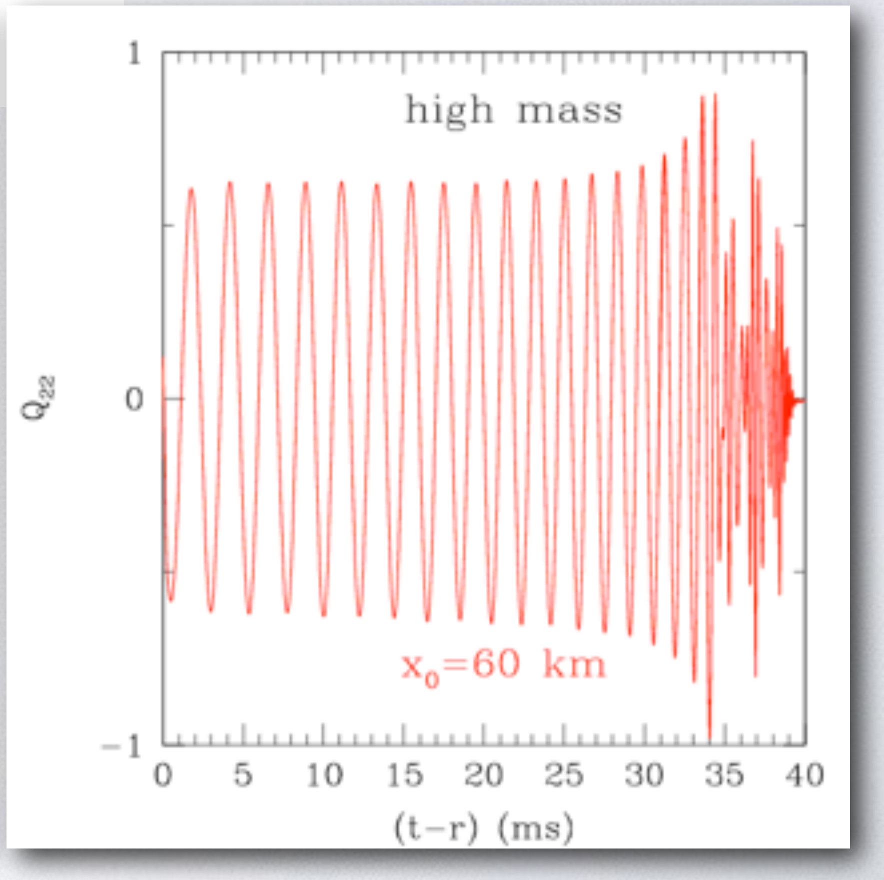
A variety of waveforms



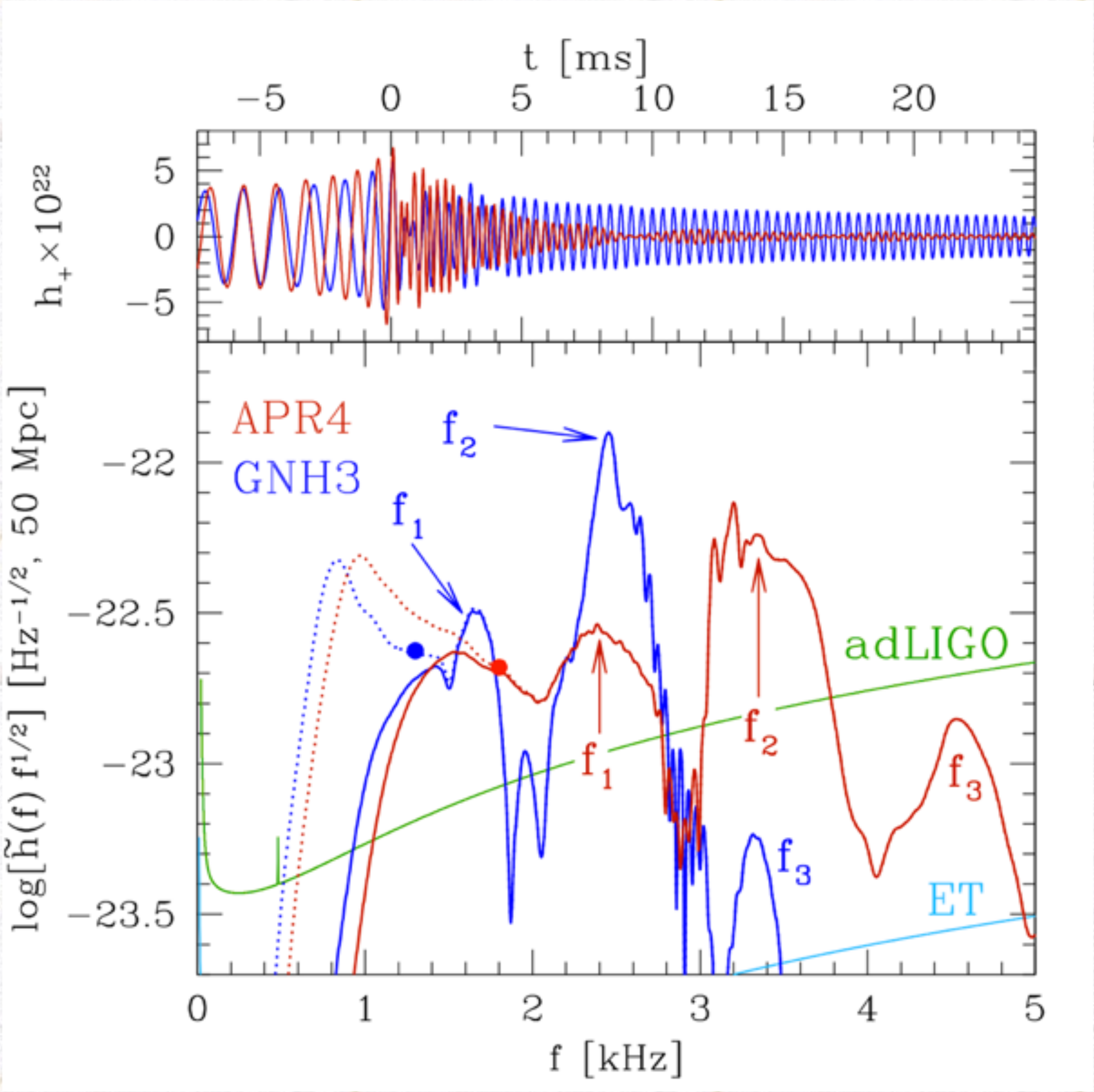






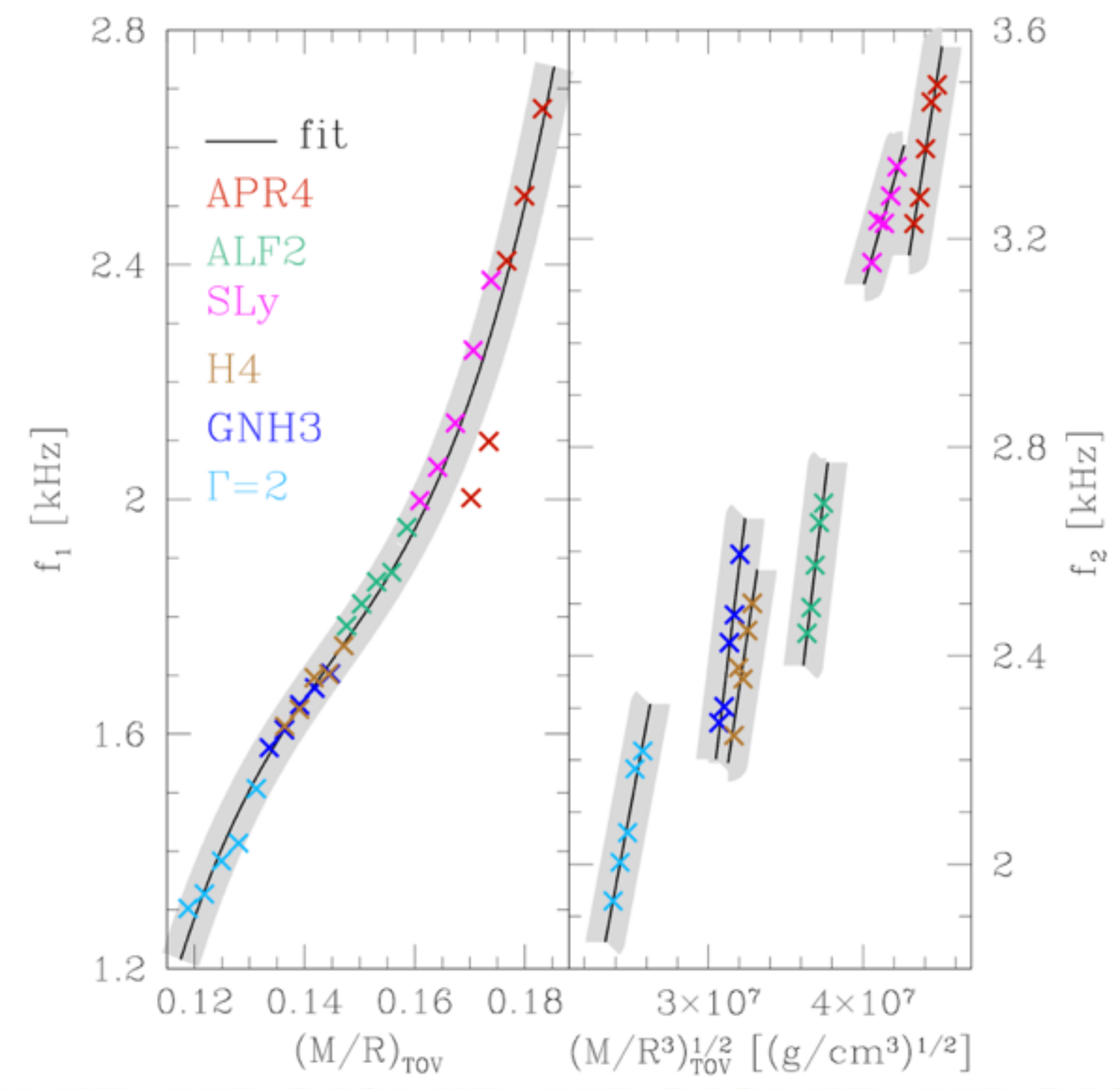


Peaks in the merger and post-merger spectra



- Peaks are clearly identifiable in the spectra for each EOS.
- f_1 is related to the merger.
- f_2 is related to the oscillations of the HMNS.
- f_3 has not been well interpreted yet.

Correlations between peaks and initial stellar properties



- We found correlations between several quantities, the most important of which is the correlation

  f_1 - compactness

- because it seems universal, namely data for all EoSs are well fitted by a single polynomial (cubic).

- This gives a relation:

$M=M(f_1, R)$

- f_2 seems not universal: a good fit for each EoS separately only.

- This gives relations

$M=M(f_2, R, EoS)$

Summary

- We study **binary neutron star systems** as sources of **gravitational waves** and engines of **gamma-ray bursts**.

- We witnessed the **growth** of seed **magnetic fields** during the BNS merger and the formation of a **funnel-like structure** that may hint at GRBs.

- We found relations for two **post-merger peak frequencies** and showed how to use them to **identify the EoS**.