Magnetic Field Effects in the Post-Merger Phase of Binary Neutron Stars

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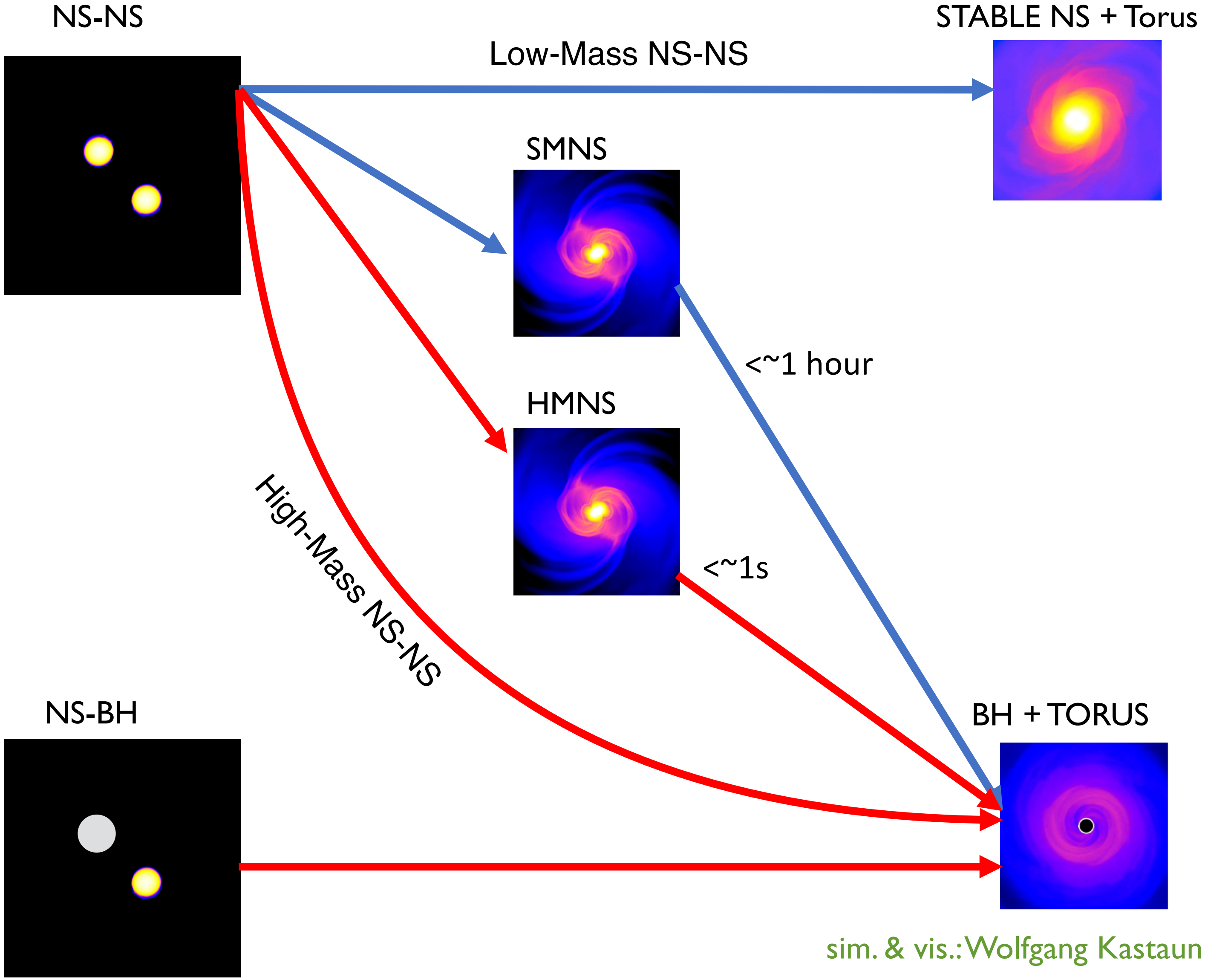
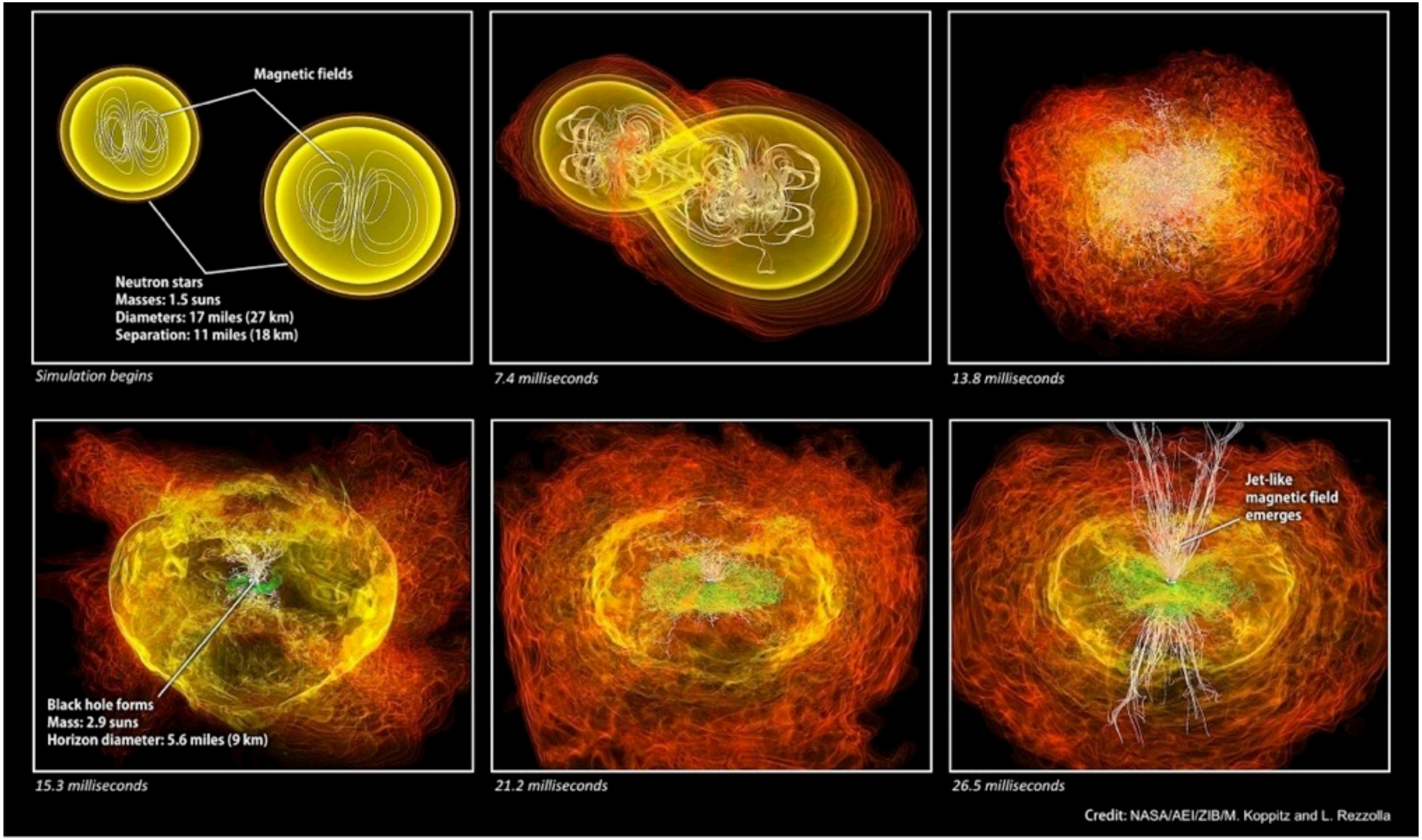
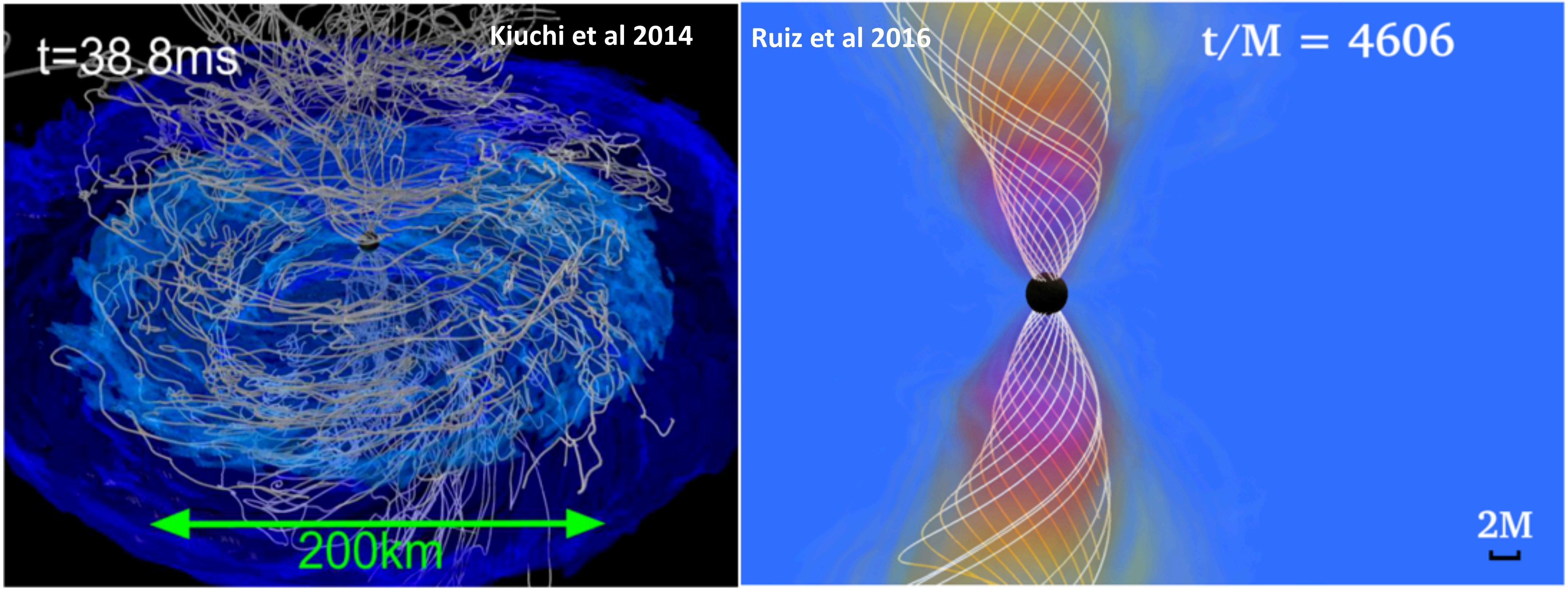
BNS MERGER OUTCOME



JETS FROM BNS MERGERS?



Jet or no Jet?



Missing Link (Rezzolla et al 2011): showed formation of strongly collimated magnetic fields after collapse to BH.

Kiuchi et al 2014: reported no ordered structure in the magnetic field.

Ruiz et al 2016: mildly relativistic collimated outflow

BNS Mergers and Short GRBs: Effects of Magnetic Field Orientation, Equation of State, and Mass Ratio

Kawamura, **Giacomazzo**, Kastaun, Ciolfi, Endrizzi, Baiotti, Perna 2016, PRD 94, 064012

New set of GRMHD simulations of 6 "high-mass" BNSs by the **Trento NumRel group**:

- Ideal-Fluid EOS:
  - Equal-Mass (1.5-1.5) with field alignment UU, UD, DD
  - Unequal-Mass (1.4-1.7)
- H4 EOS:
  - Equal-Mass (1.4-1.4)
  - Unequal-Mass (1.3-1.5)

All models start with an initial magnetic field of ~10^{12} G (vs ~10^{16} G of Ruiz et al 2016).

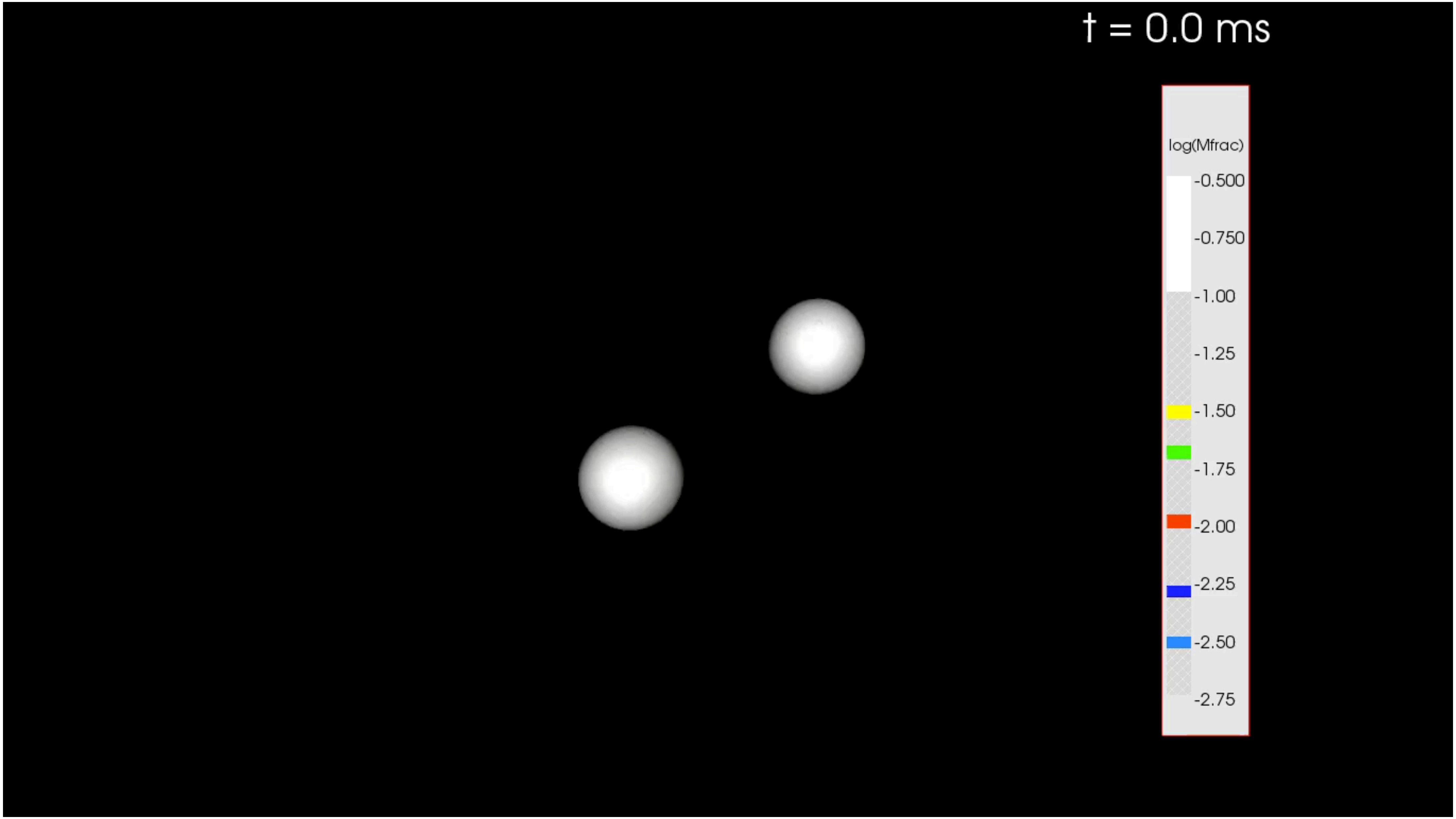
Unequal-mass models studied for the first time.

NUMERICAL CODES

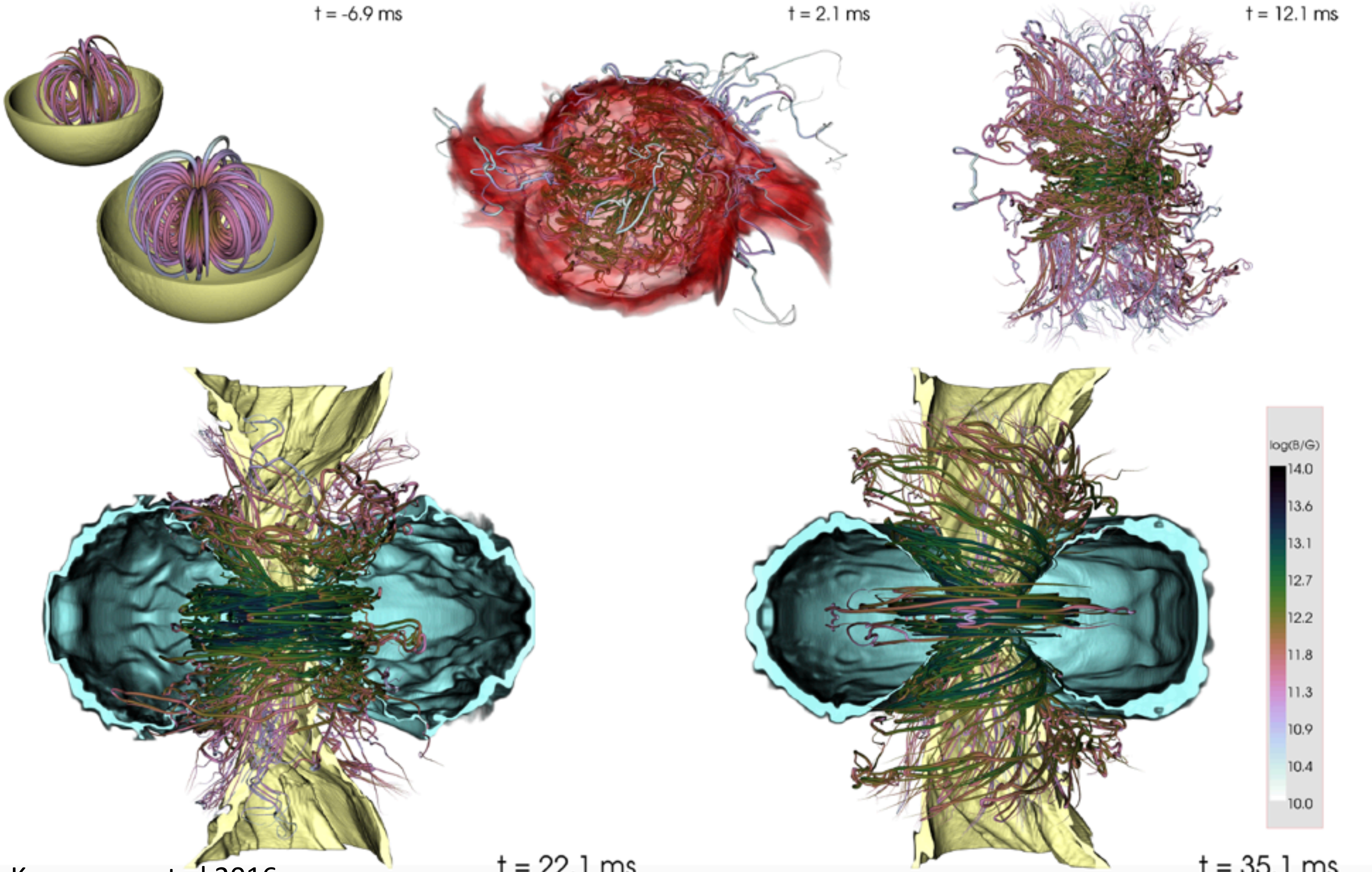
The **Einstein Toolkit** (einsteintoolkit.org) is a set of open source codes for computational relativity. It provides infrastructures for parallelization, I/O, AMR, space-time evolution routines,...

Whisky (www.whiskycode.org) is a numerical code, initially developed at the AEI and SISSA, for the solution of the general relativistic hydrodynamics and magnetohydrodynamics equations in arbitrary curved spacetimes.

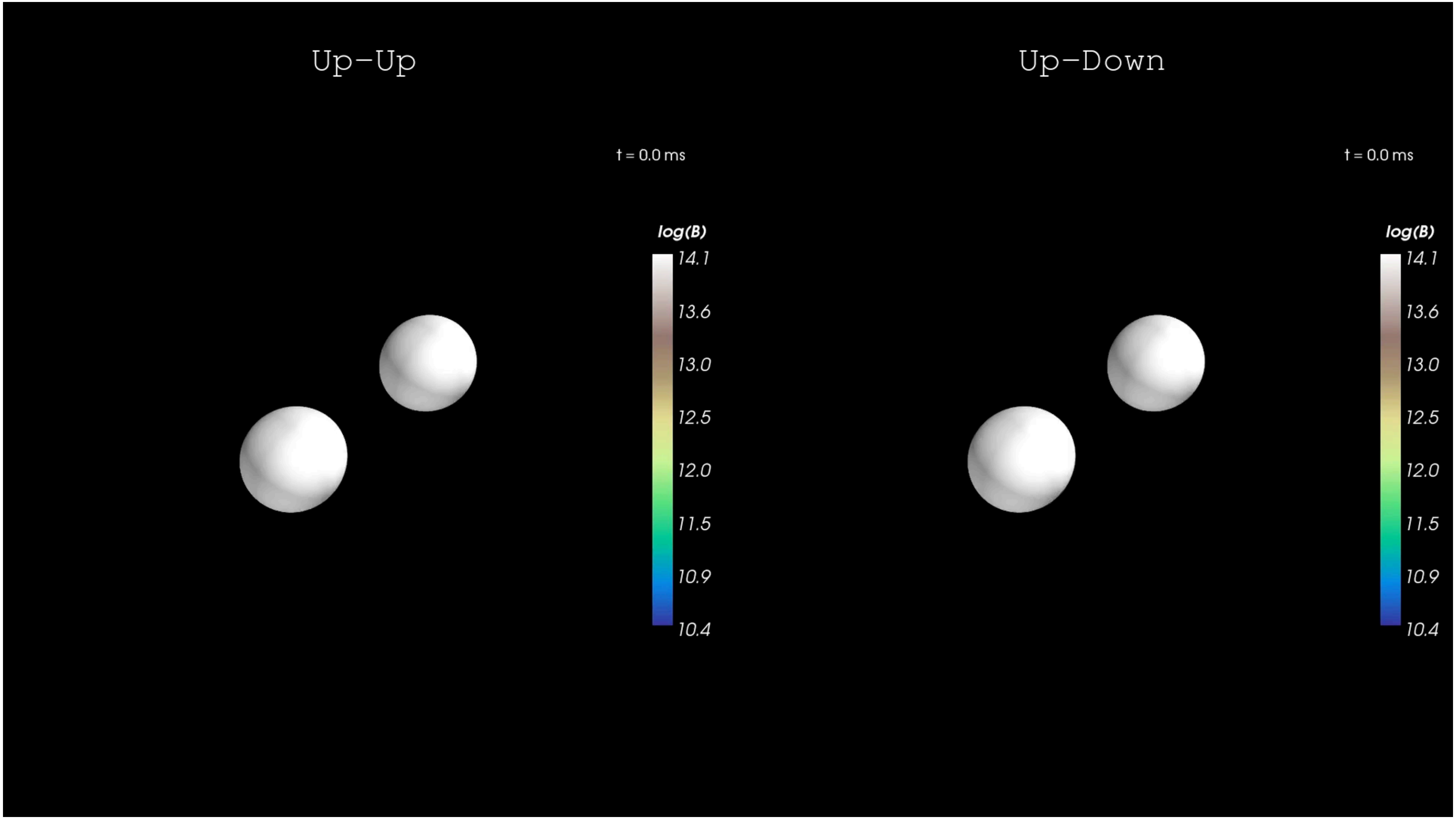
ET → $G_{\mu\nu} = 8\pi T_{\mu\nu}$ ← **Whisky**

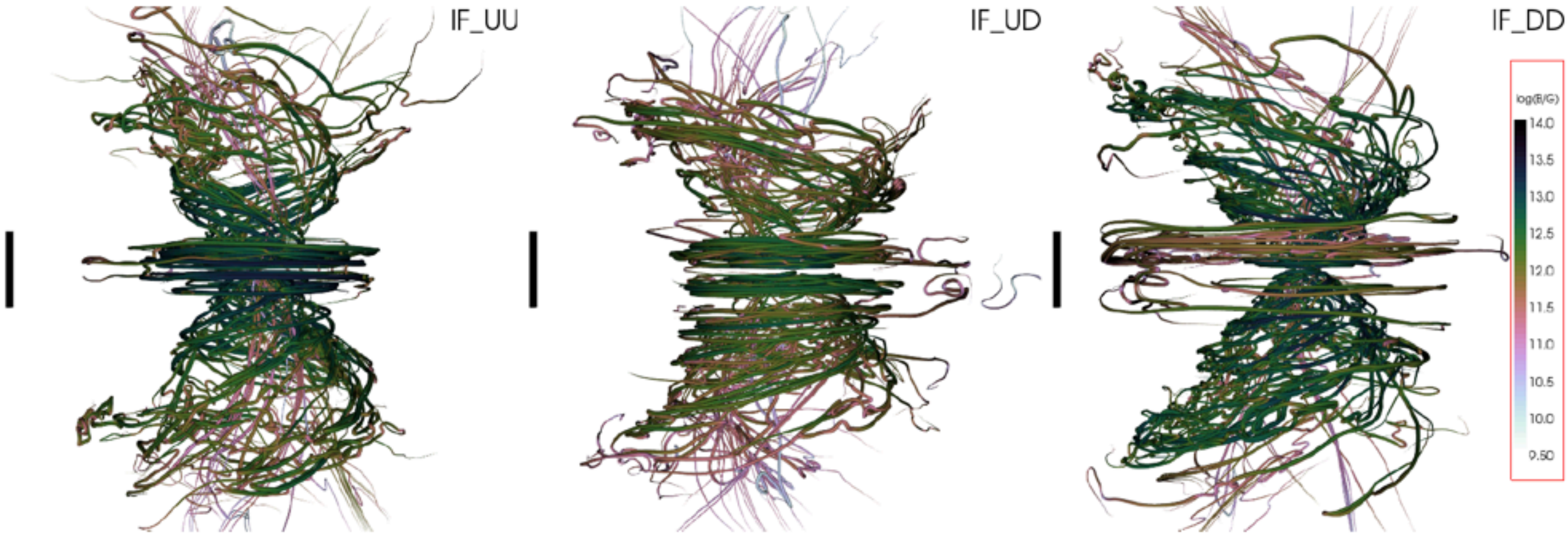

t = 0.0 ms
log(Mfrac)
-0.500
-0.750
-1.00
-1.25
-1.50
-1.75
-2.00
-2.25
-2.50
-2.75

Magnetic Field Structure Evolution

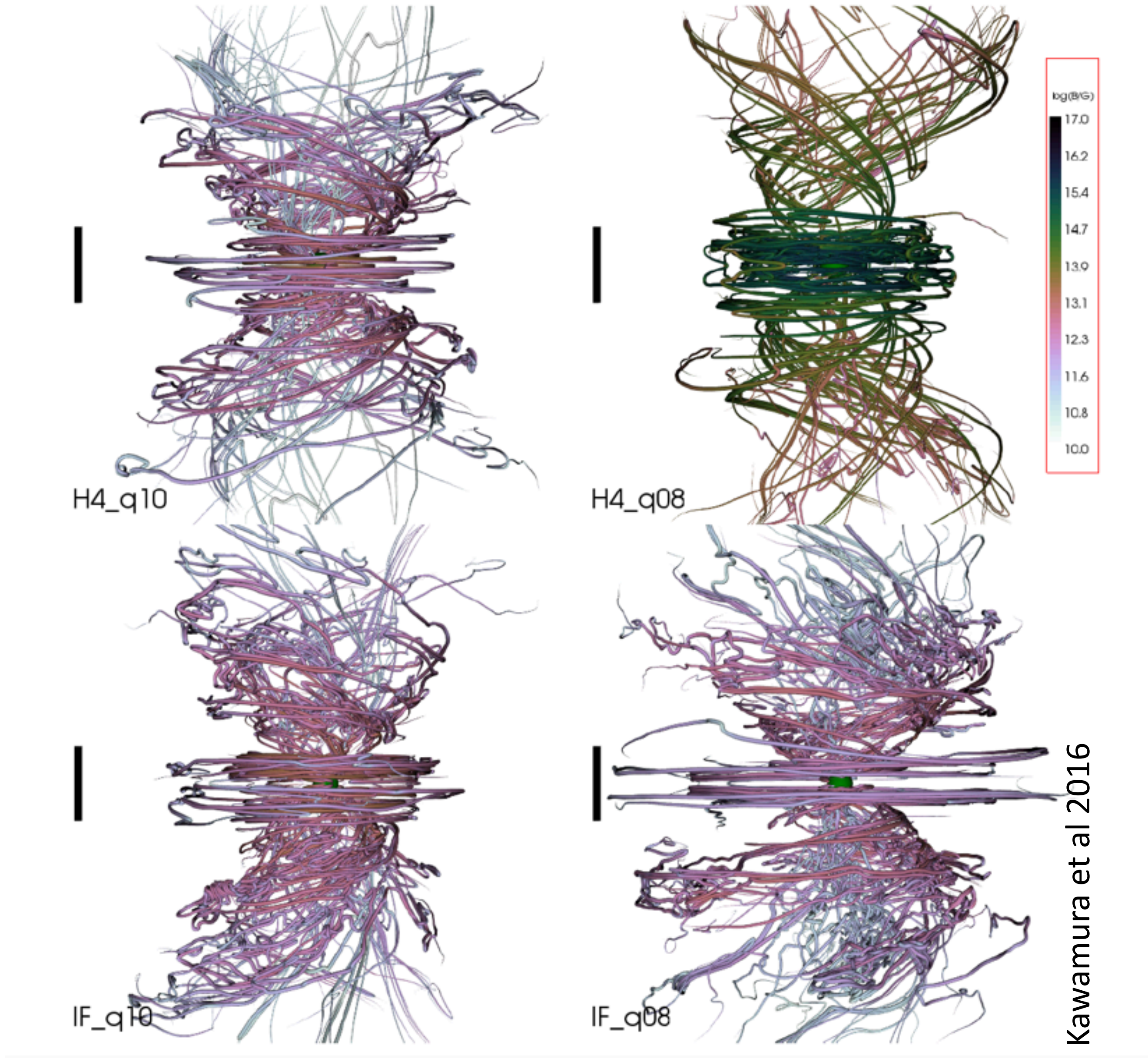


Kawamura et al 2016

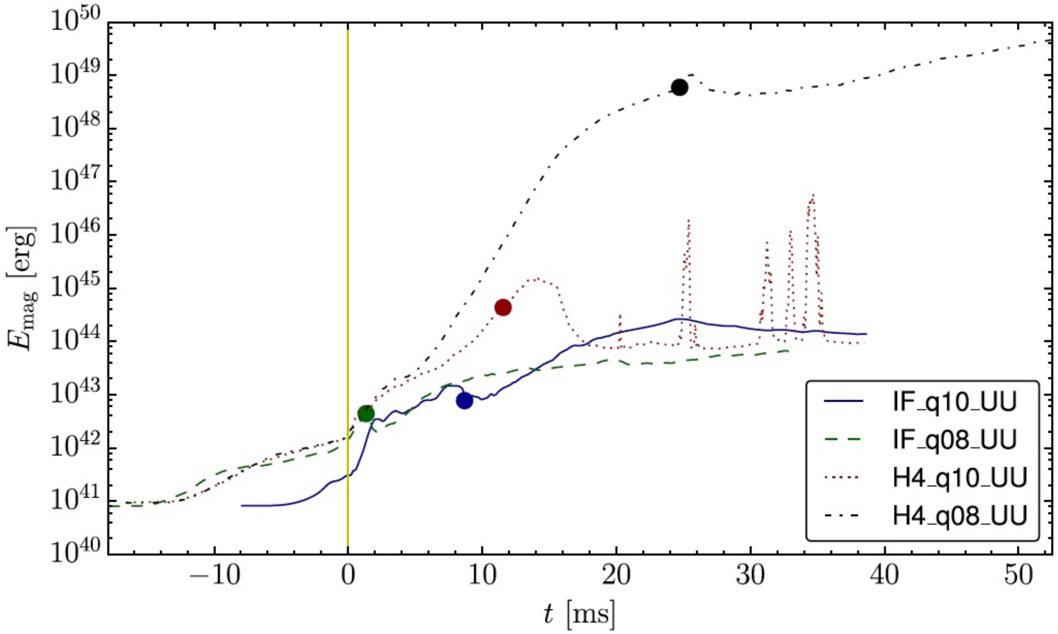

Up-Up
Up-Down
t = 0.0 ms
log(B)
14.1
13.6
13.0
12.5
12.0
11.5
10.9
10.4
t = 0.0 ms
log(B)
14.1
13.6
13.0
12.5
12.0
11.5
10.9
10.4



Kawamura et al 2016

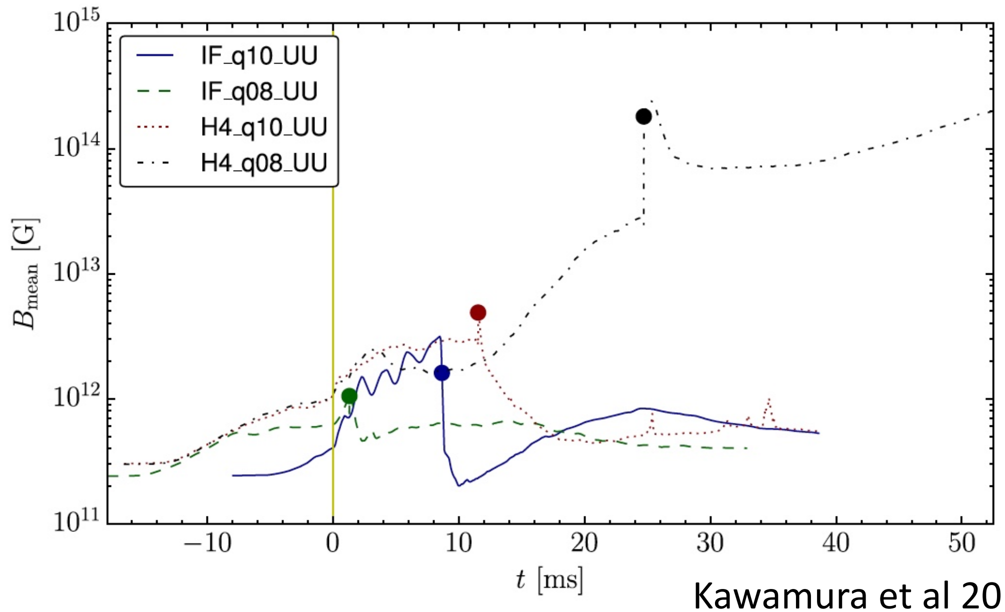


Role of **EOS** and **Mass Ratio**



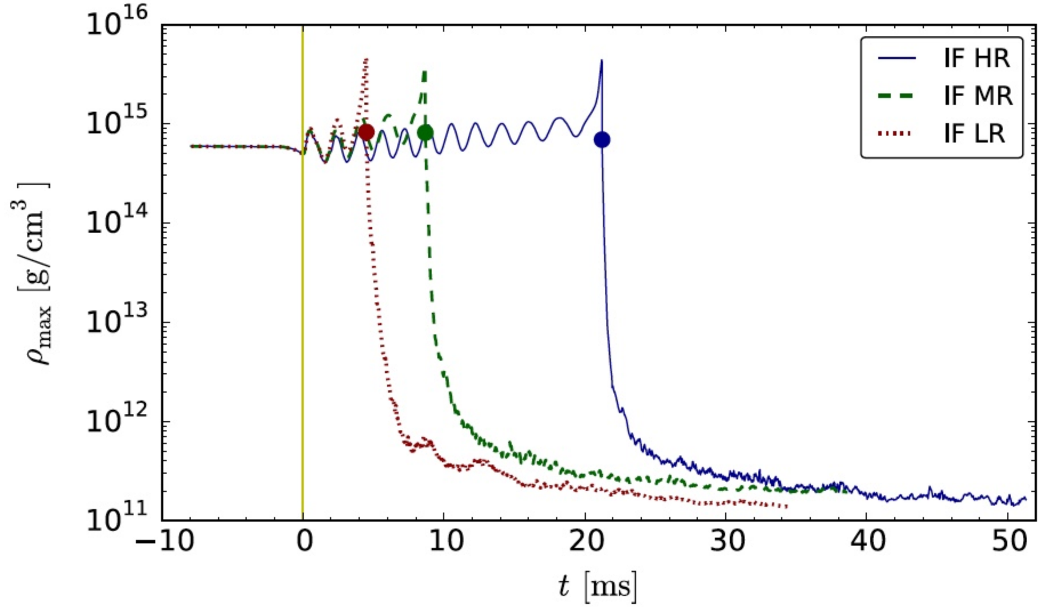
H4_q08 has the longest-living HMNS and shows largest magnetic field amplification.

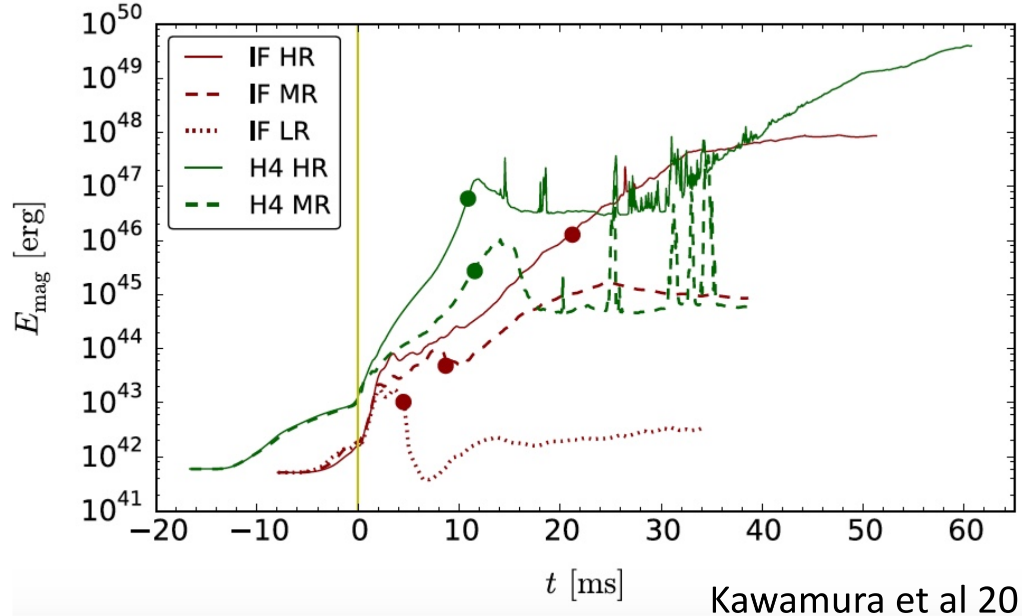
Large magnetic field survives also after BH collapse.
Possible to resolve MRI in this case.



Kawamura et al 2016

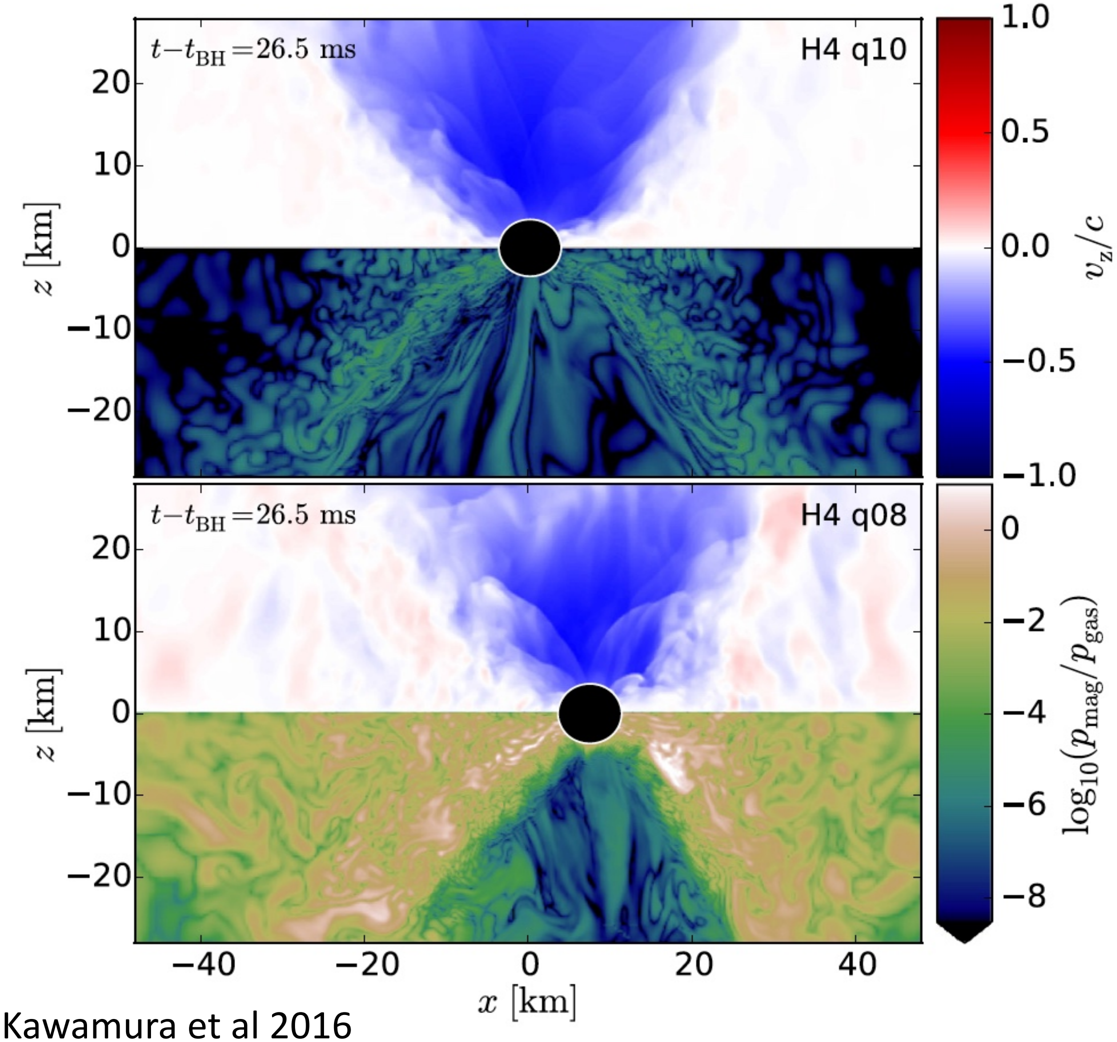
Resolution Effects





Kawamura et al 2016

HMNS lifetime longer with higher resolution.
As expected higher resolutions produce stronger magnetic fields.



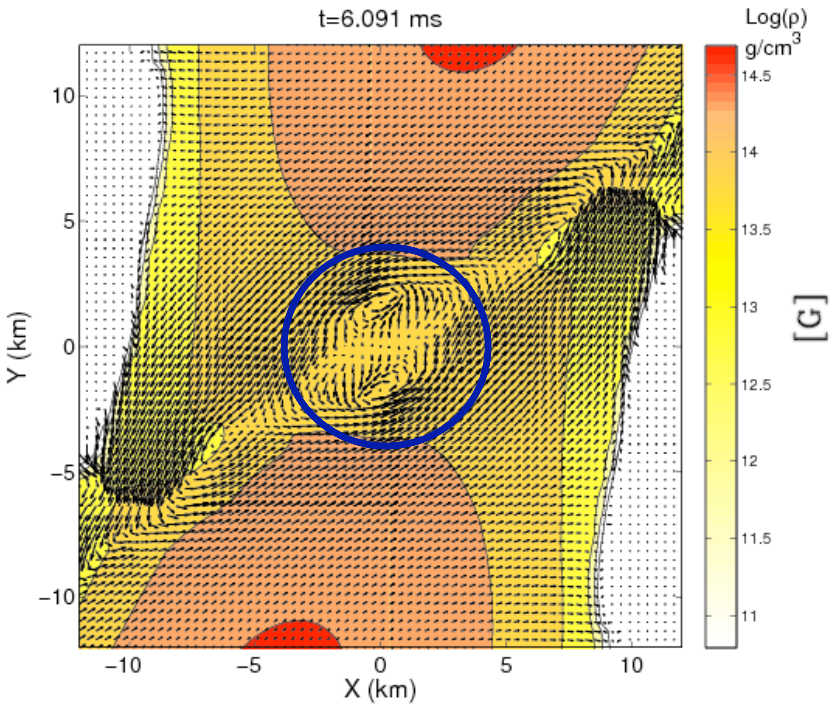
Kawamura et al 2016

No Jet observed, but it may change with longer evolutions and (much) higher resolutions.

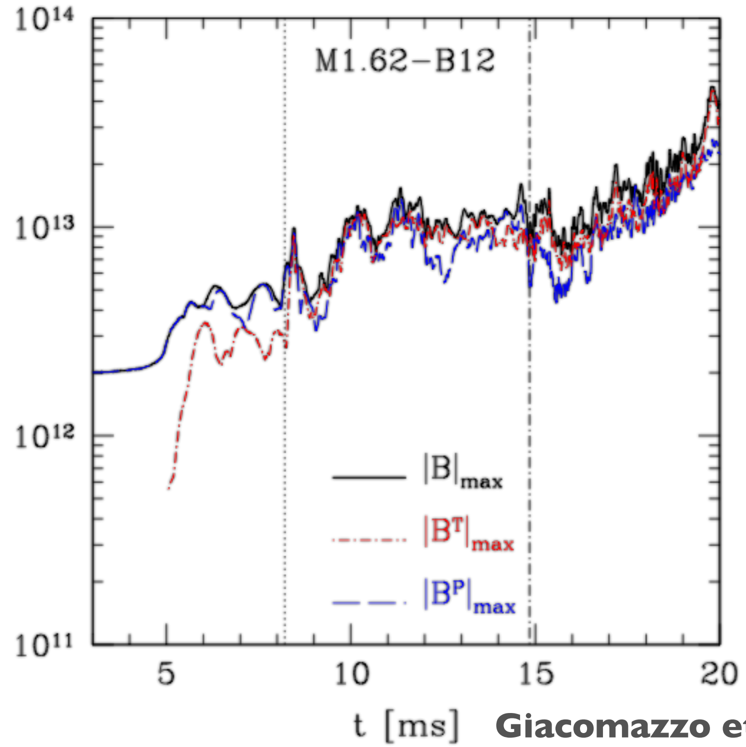
Necessary to have a magnetically dominated funnel to launch a jet

KH INSTABILITY AND MAGNETIC FIELDS

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



Baiotti et al 2008

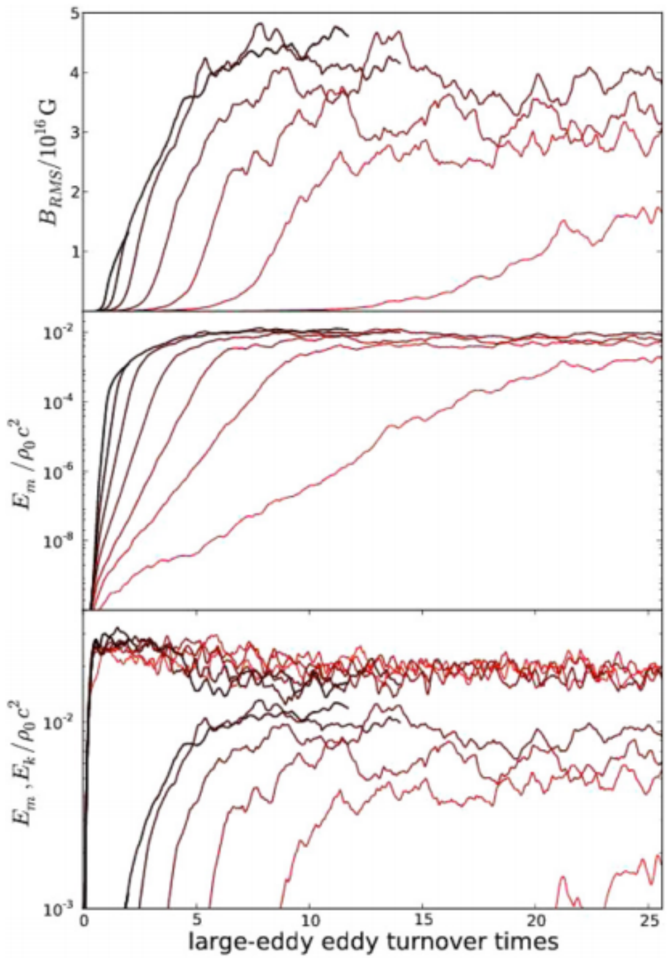


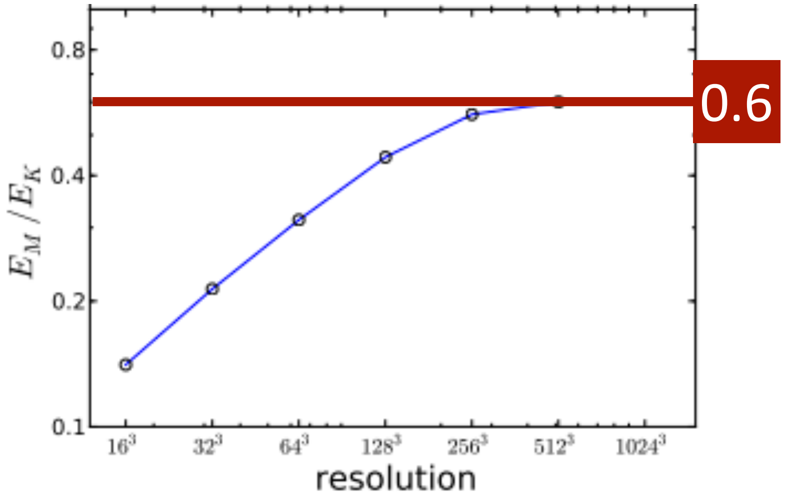
Giacomazzo et al 2011

After merger the magnetic field grows of only ~1 order of magnitude (because of resolution). So magnetic field effects were not too strong in the post-merger phase.

LOCAL SIMULATIONS

(Zrake and MacFadyen 2013)





Performed local very high resolution relativistic MHD simulations of turbulent flows.

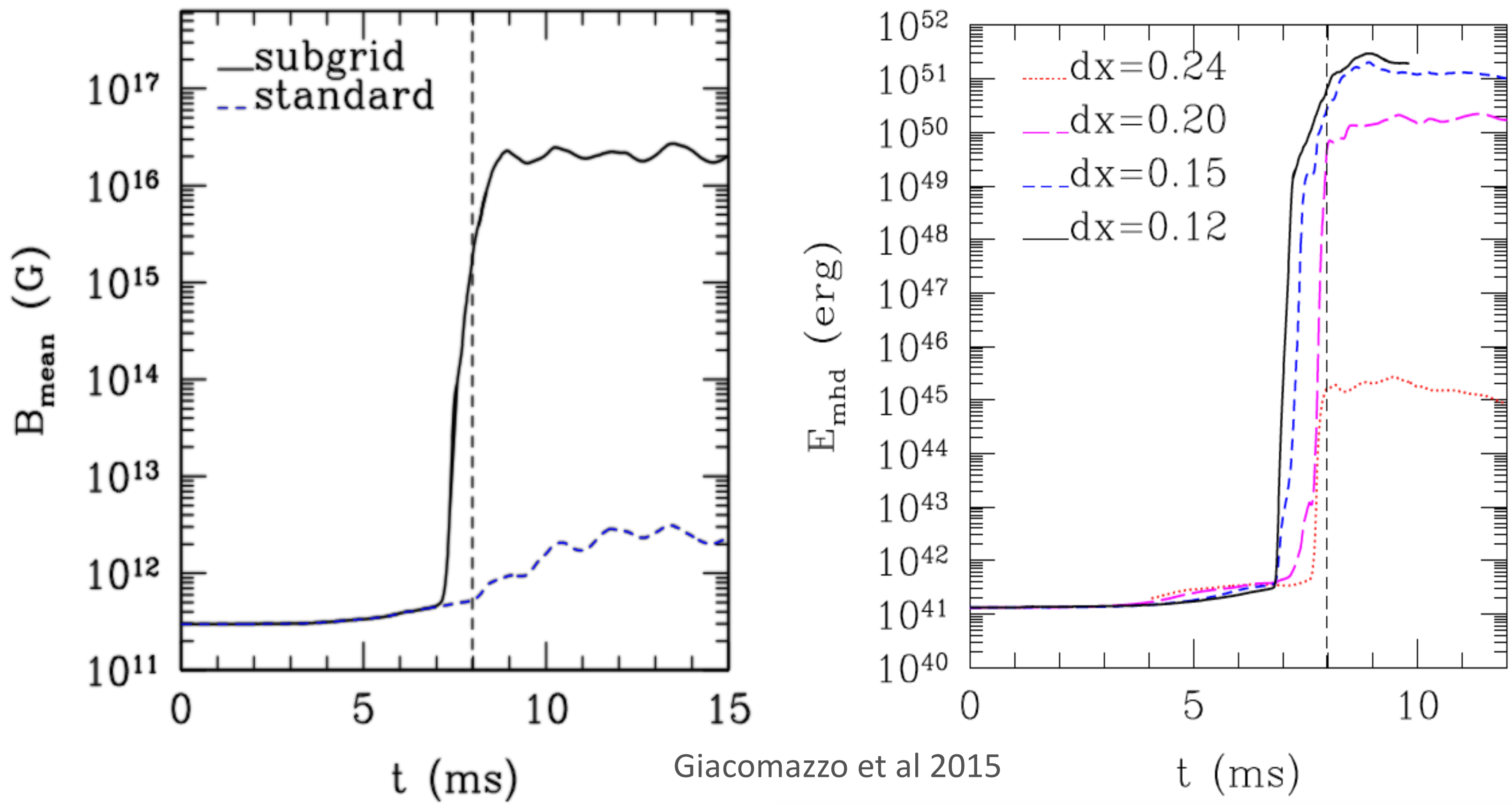
Magnetic energy reaches equipartition with kinetic energy.

Similar results (in Newtonian MHD) were obtained by Obergaulinger et al 2010.

MAGNETIC FIELD AMPLIFICATION AT MERGER

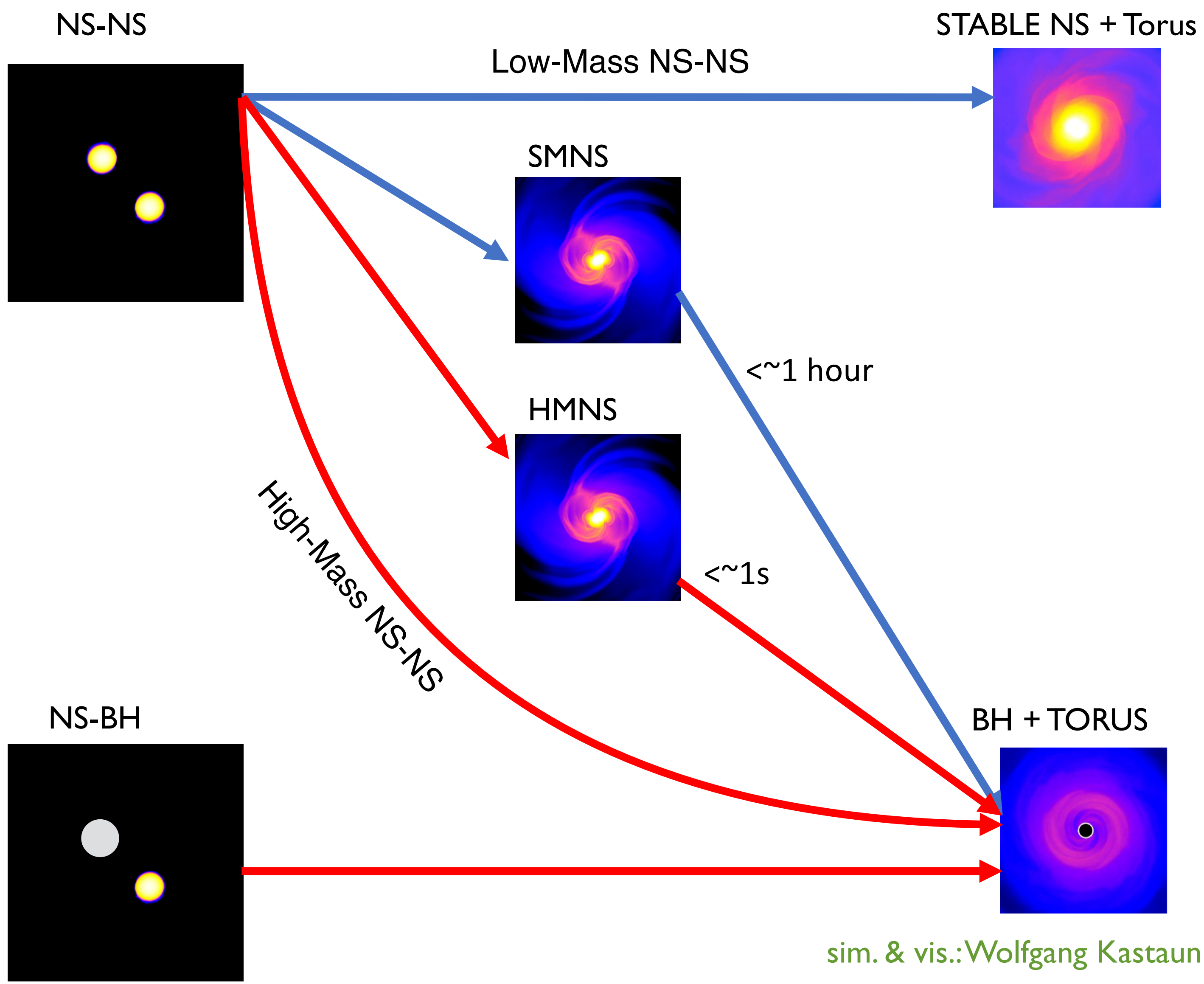
Giacomazzo, Zrake, Duffell, MacFadyen, Perna 2015, ApJ, 809, 39

We implemented a sub-grid model in our GRMHD code and run a set of NS-NS simulations.



Giacomazzo et al 2015

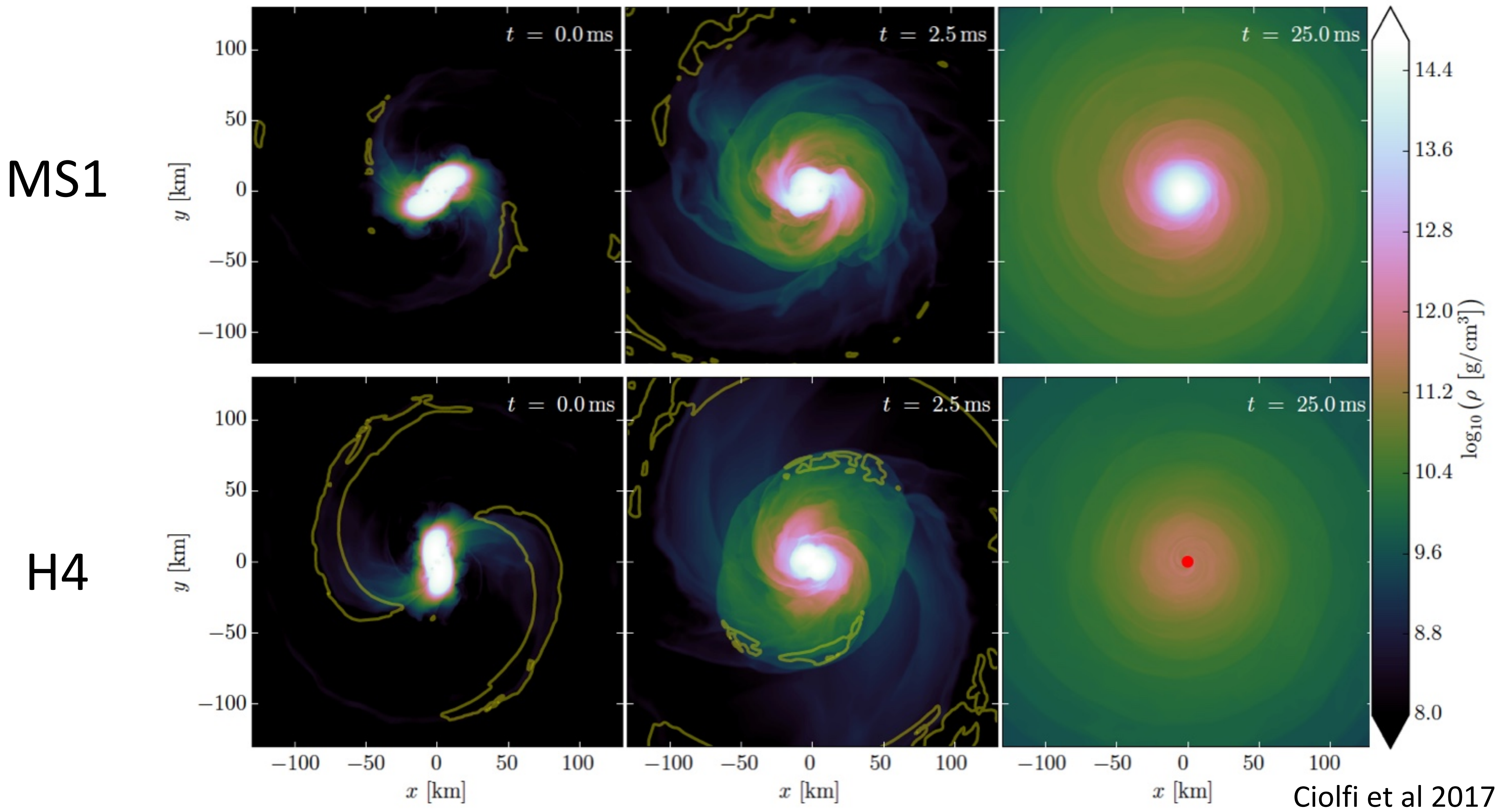
BNS MERGER OUTCOME



GRMHD Simulations of BNS Mergers Forming a Long-lived Neutron Star

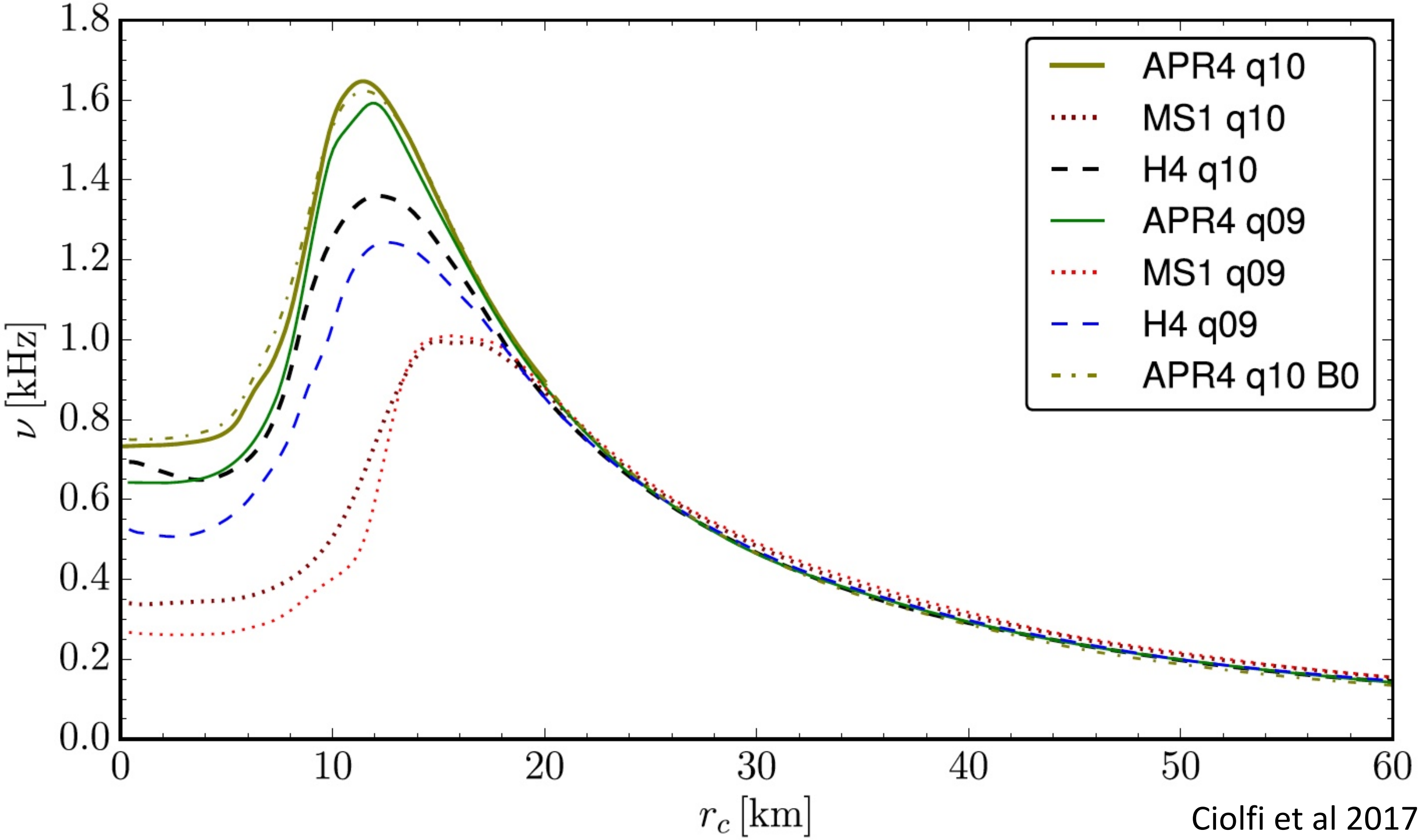
R. Ciolfi, W. Kastaun, **B. Giacomazzo**, A. Endrizzi, D. M. Siegel, R. Perna 2017, PRD 95, 063016

- New Set of Simulations by the **Trento NumRel group** investigating "Low-Mass" BNSs
- Considered 6 BNS systems:
  - 2 different mass ratios
  - 3 equations of state (APR4, MS1, H4) with a thermal component (1.8 gamma law)
- All models have the same total gravitational mass at infinity (2.7 $M_{\odot}$) and the same magnetic energy (initial magnetic field ~10^{15}G)
- 4 models produce a long lived NS and 2 a HMNS that collapses to BH



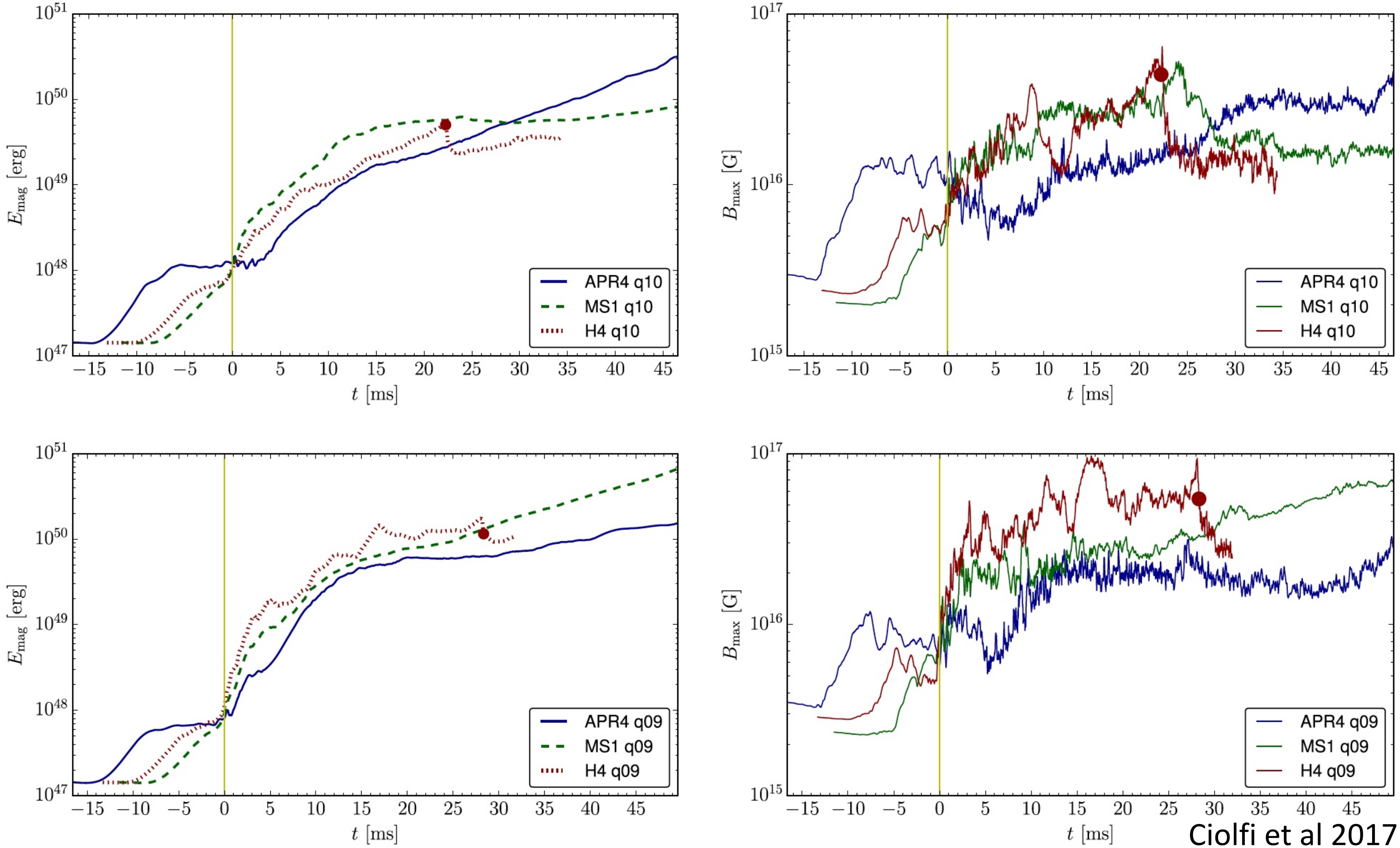
Final remnant (BH or NS) surrounded by an accretion of disk of ~0.1 (H4) to ~0.4 (MS1) $M_\odot$.
Unequal-mass models produce ~25% (~60%) larger disks when the remnant is a NS (BH).

ROTATION RATES



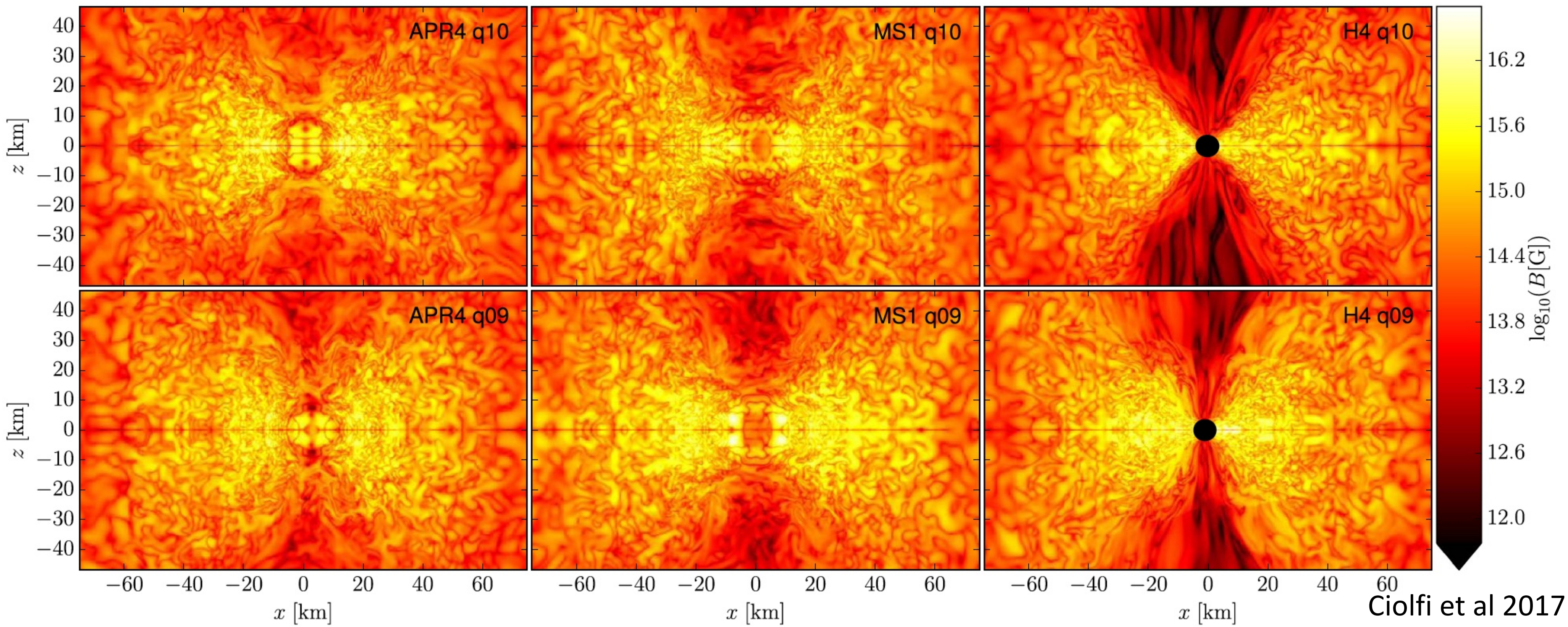
Ciolfi et al 2017

MAGNETIC FIELD EVOLUTION



Ciolfi et al 2017

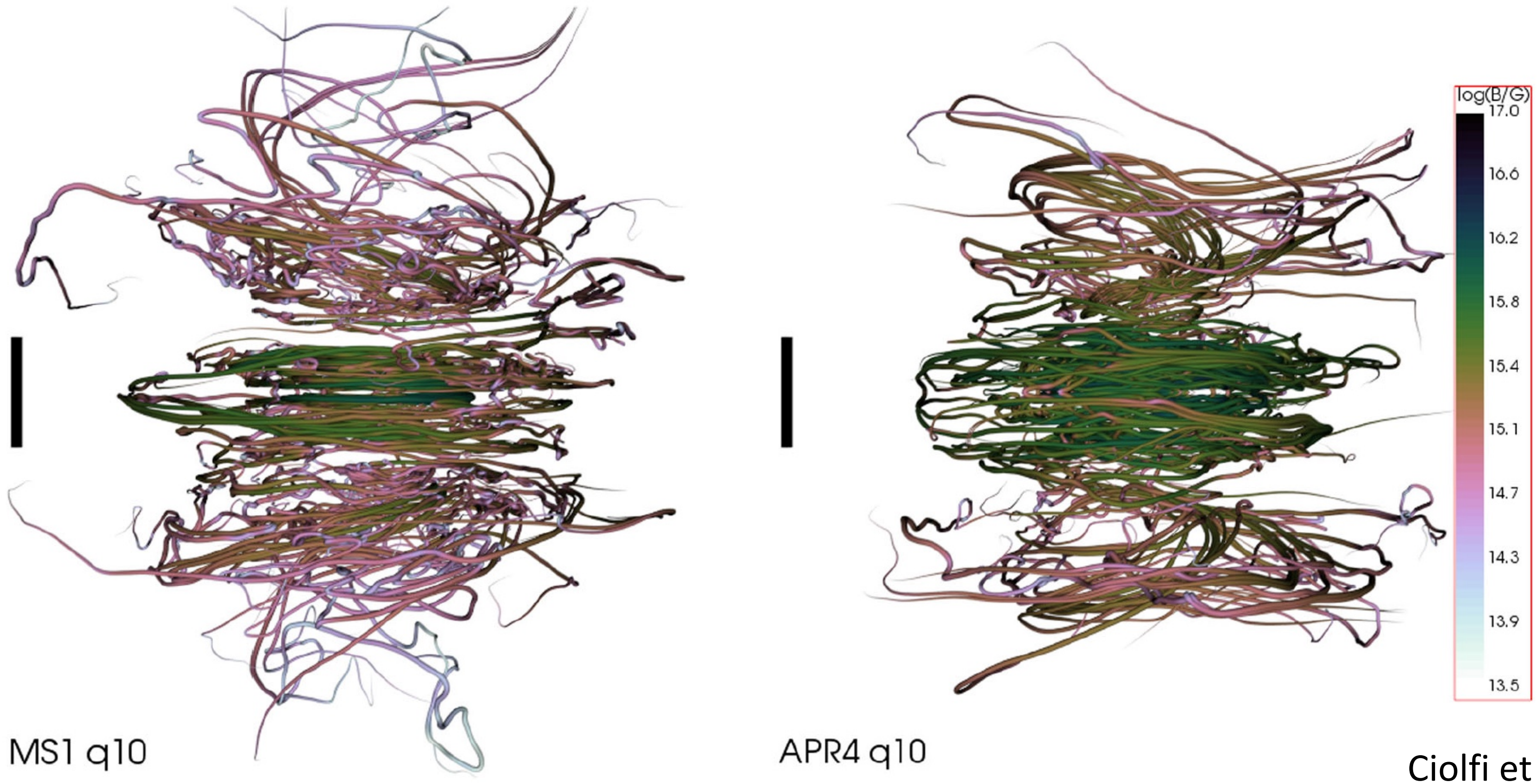
MAGNETIC FIELD STRENGTH



Ciolfi et al 2017

NS **NS** **BH**

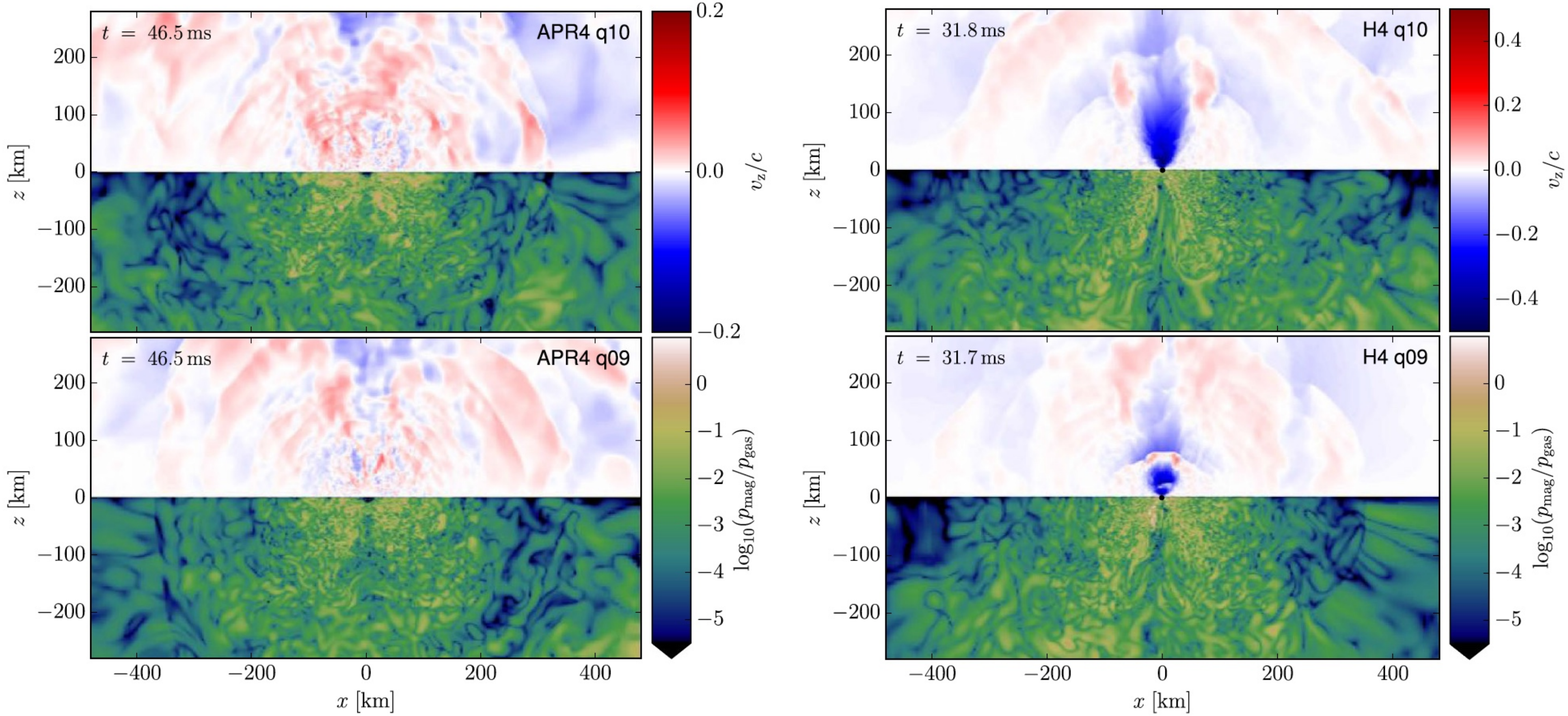
MAGNETIC FIELD STRUCTURE



Ciolfi et al 2017

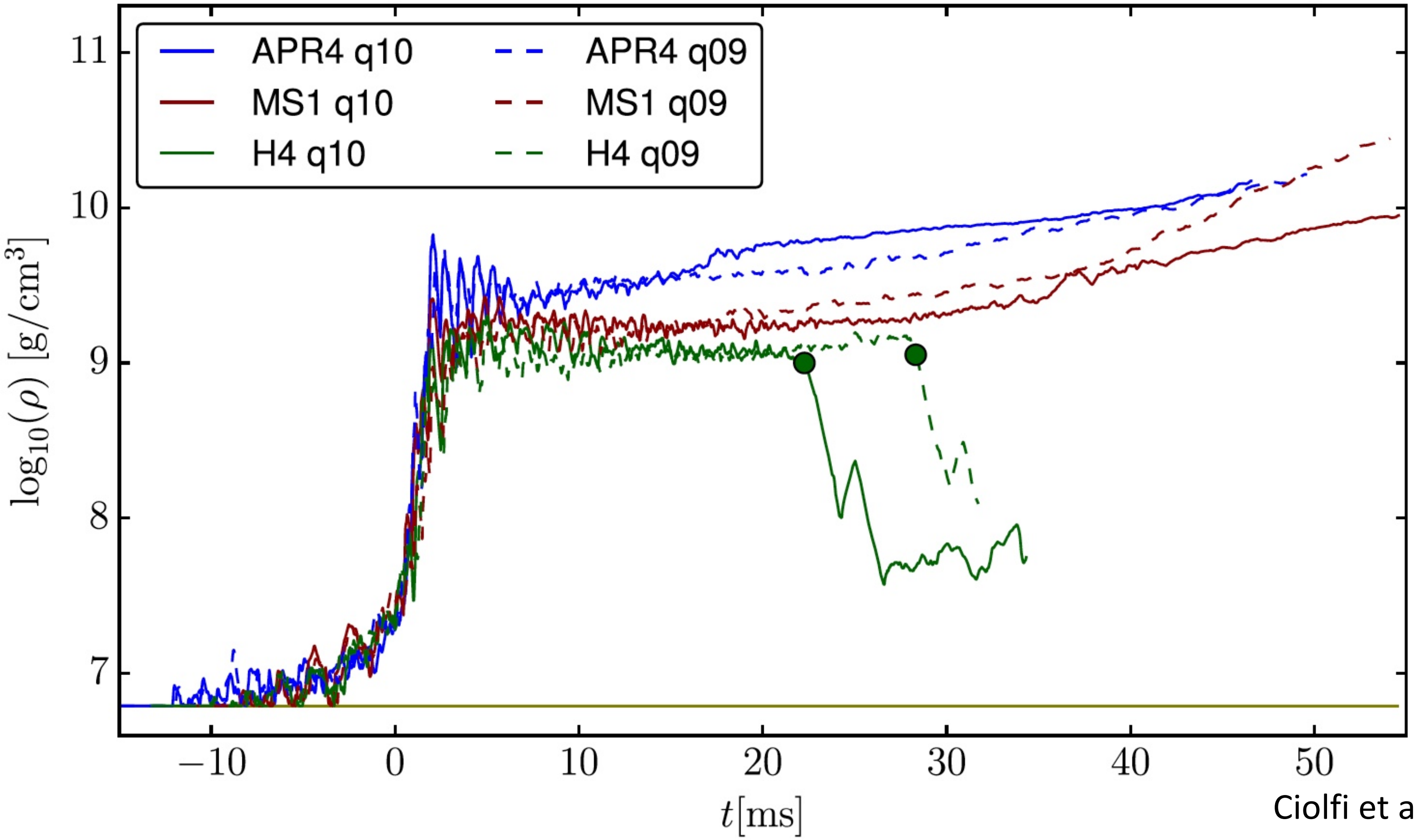
Twisted magnetic field structure formed in all cases.
Strong toroidal component on the equatorial plane and weak helical structure along spin axis.

SHORT GRB CONNECTION



In both NS and BH cases no magnetically dominated funnel.

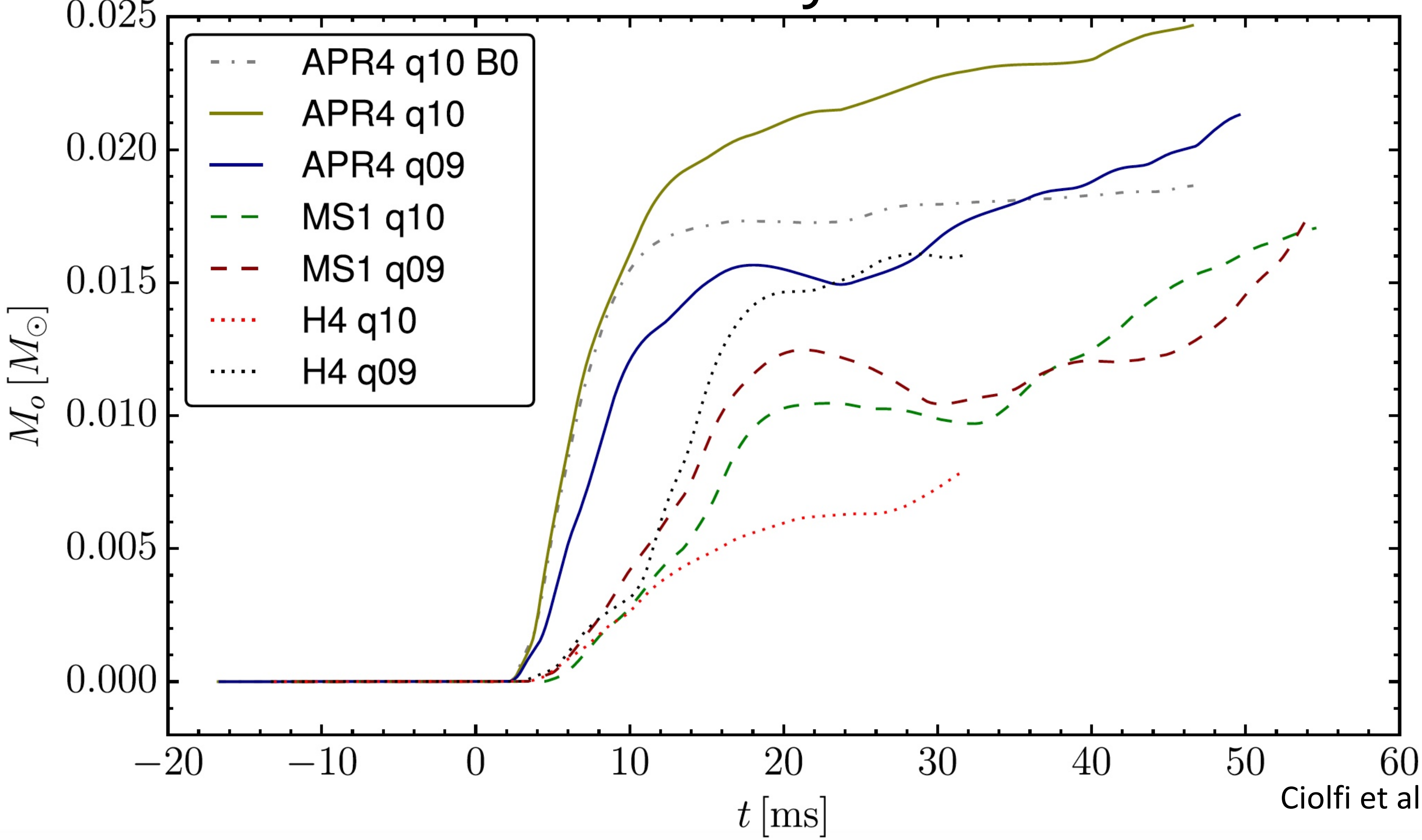
BARYON POLLUTION PROBLEM



Ciolfi et al 2017

Strong baryon pollution in the NS case. Difficult to launch a jet until after BH formation (e.g., Ciolfi & Siegel 2015).

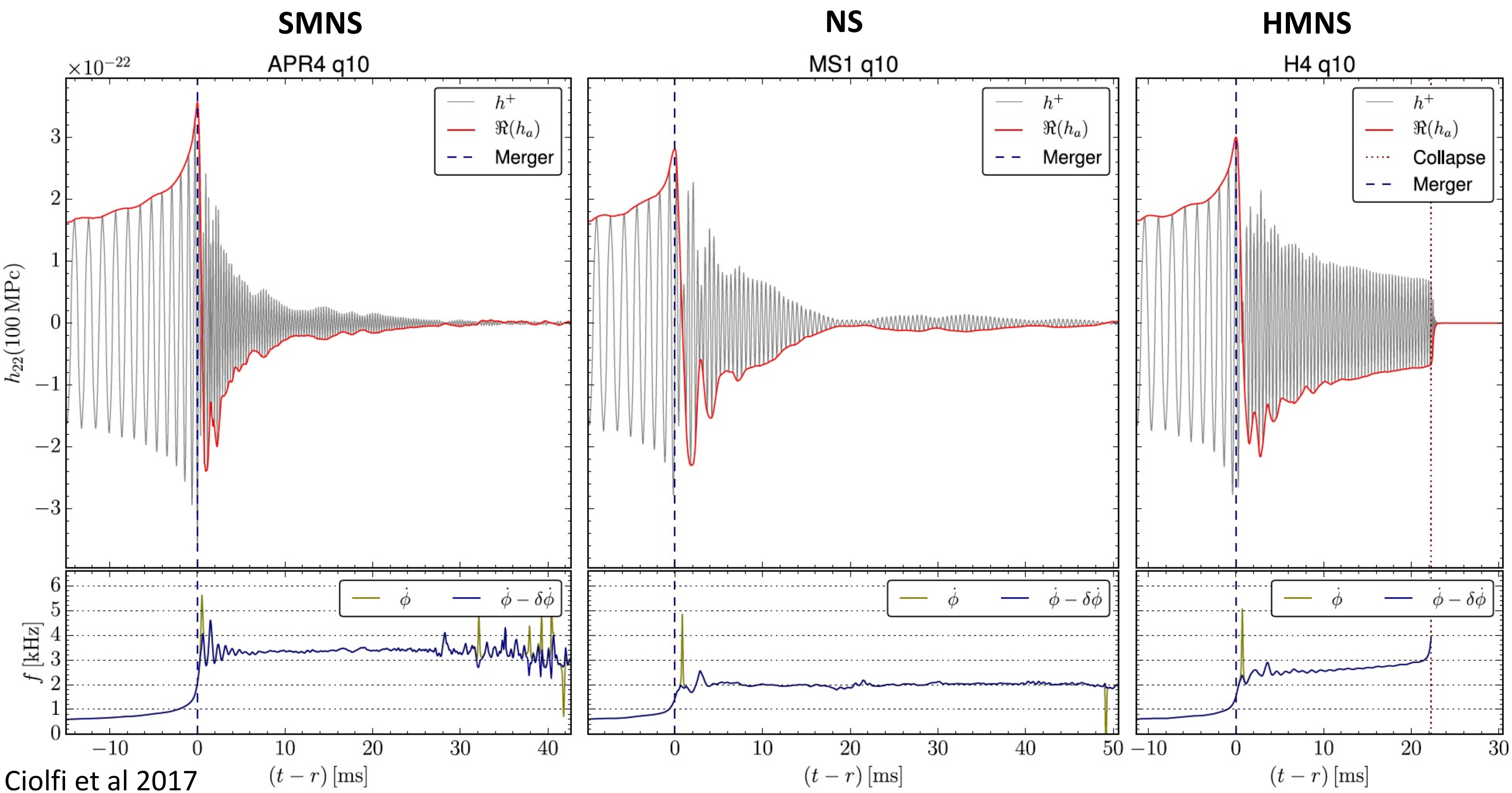
TOTAL EJECTA



Ciolfi et al 2017

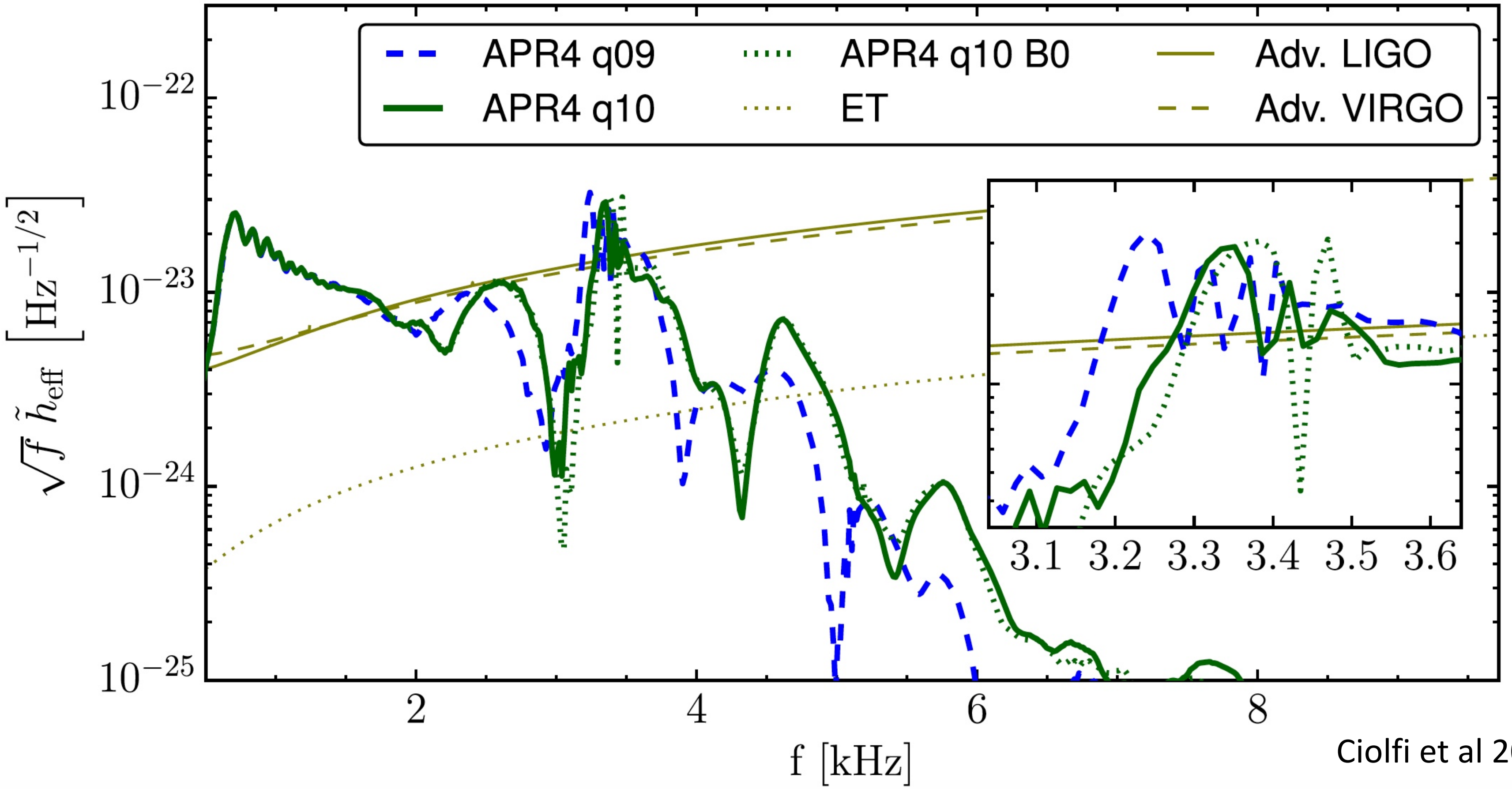
Magnetically-driven baryon-loaded winds provide the main contribution to the steady matter outflows observed towards the end of our simulations (t > 20 ms).

GRAVITATIONAL WAVES



Ciolfi et al 2017

Magnetic Field Effects on Post-Merger GW Emission



Ciolfi et al 2017

Evolved "low-mass" BNS with high magnetic fields (~10^{15} G during inspiral, ~10^{16} G after merger). Difference in the post-merger peak of less than ~100 Hz.

CONCLUSIONS

- Studied Magnetic field effects both in “high” and “low”-mass BNS scenarios

- “High-Mass” BNSs (Kawamura et al 2016)
  - Collimated emission seems possible (SGRB)
  - Still no jet, but much larger magnetic fields are required (~10^{16}G, Ruiz et al 2016)
  - Fundamental to resolve magnetic field amplification (very high res or subgrid sims)

- “Low-Mass” BNSs (Ciolfi et al 2017)
  - Baryon pollution problem (“time-reversal” scenario?)
  - Large Magnetic Fields seems to have limited impact of GW emission

Gravitational Waves, Initial Data, and Movies available as Supplemental Material