Title: Magnetic field effects in binary neutron star mergers: insights from GRMHD simulations

Speakers: Eduardo Gutierrez

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

Date: March 27, 2025 - 10:15 AM

URL: https://pirsa.org/25030142

Abstract:

Magnetic fields play a key role in shaping the dynamics and observational phenomenology of binary neutron star (BNS) mergers. In this talk, I will present results from general relativistic magnetohydrodynamic (GRMHD) simulations performed with the code GR-Athena++, exploring how different initial magnetic field configurations affect the evolution of BNS mergers. We investigated magnetic field amplification, primarily driven by the Kelvin-Helmholtz instability, the post-merger remnant and disk structure, and the characteristics of the ejected material. I will discuss how these processes impact potential electromagnetic counterparts and their detectability. Finally, I will highlight recent advancements in our numerical methods that improve the modeling of magnetized neutron star mergers, paving the way for more accurate predictions of multimessenger signals from these extreme events.

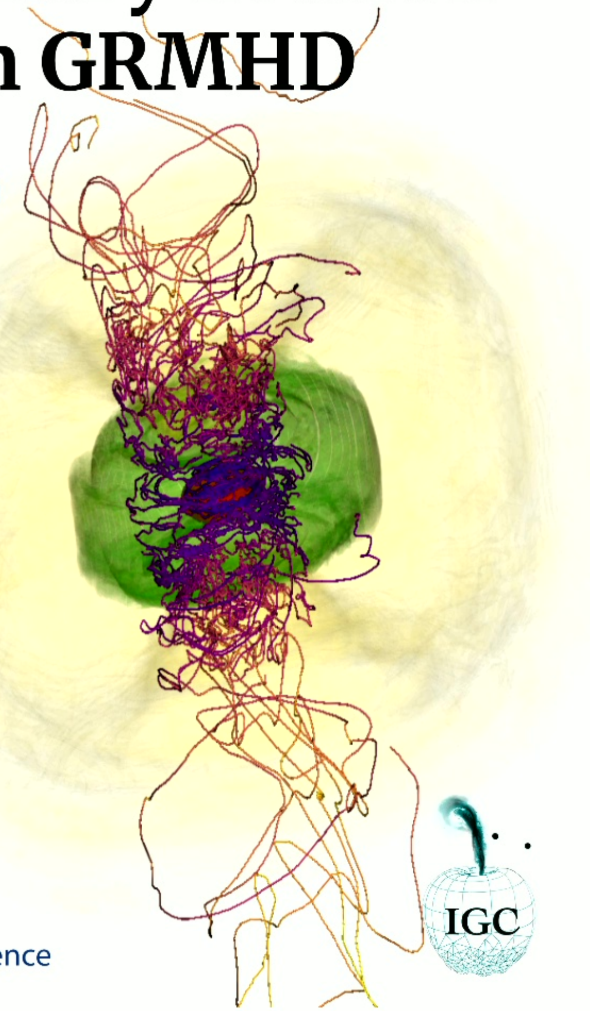
Magnetic field effects in binary neutron star mergers: insights from GRMHD simulations

- **EG**, WC++, in prep. (2025)
- WC, **EG**++, in prep. (2025)

Eduardo M. Gutiérrez
Postdoctoral Scholar
Penn State University

Collabs: W. Cook, D. Radice, S. Bernuzzi, B. Daszuta, J. Fields, H. Bandyopadhyay, P. Hammond, and NR group at PSU

27th March 2025
Magnetic fields around compact objects
Perimeter Institute



PennState
Eberly College of Science

IGC

Why do magnetic fields matter in BNS simulations?

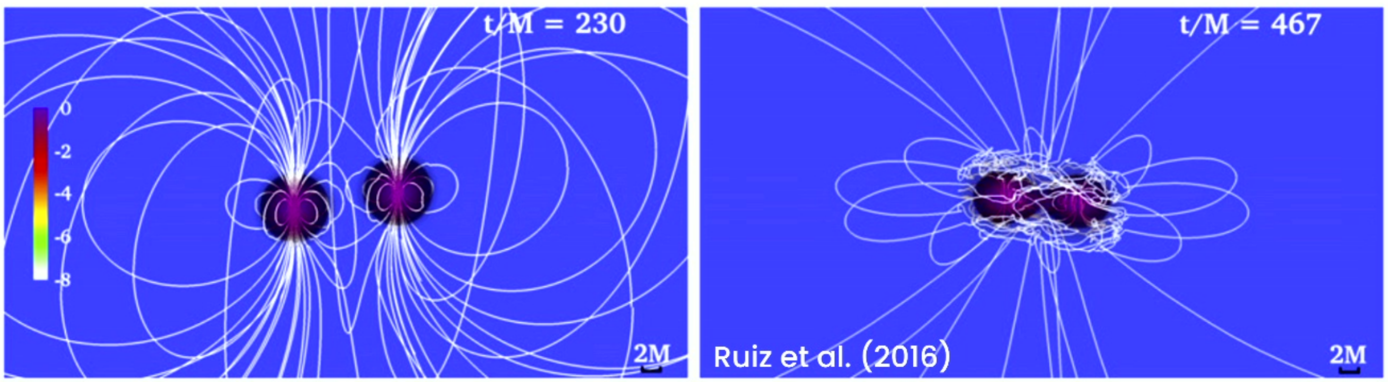
- Binary NSs: $\boxed{B_{\rm surf} \sim 10^{8} - 10^{12}\ \mathrm{G}}$

Lorimer (2008)

$$\left\{ \begin{array}{c} \boxed{E_B \sim 5 \times 10^{41} B_{12}\ \mathrm{erg}} \\ \ll \\ \boxed{E_{\rm k} \sim 10^{53}\ \mathrm{erg}} \end{array} \right.$$

- During and after the merger, instabilities may amplify the magnetic field by ~orders of magnitude.

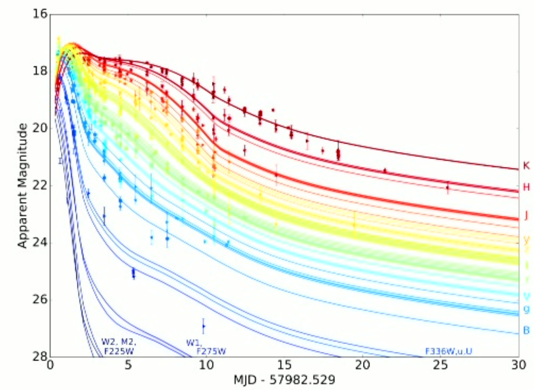
$$\boxed{\begin{array}{l} E_B \sim 10^{50} - 10^{51}\ \mathrm{erg}, \\ B \sim 10^{16}\ \mathrm{G} \end{array}}$$



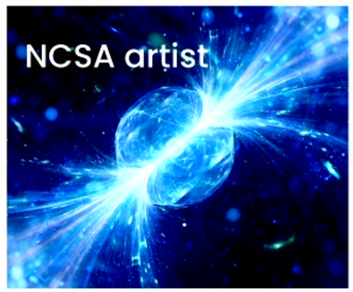
Ruiz et al. (2016)

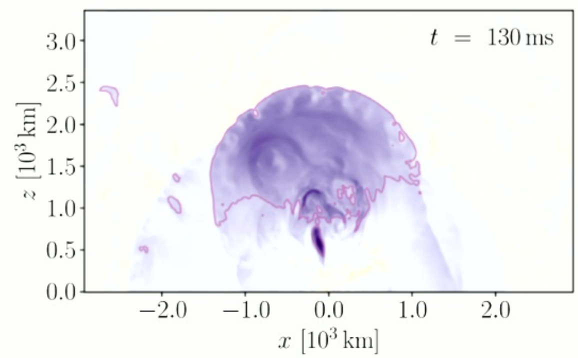
Why do magnetic fields matter in BNS simulations?

- Key role in the launching of **MHD winds, relativistic jets, sGRBs, precursors or delayed emission, kilonova**

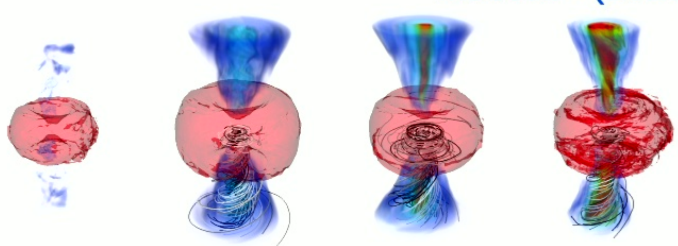


Ashley Villar+ (2017)





Moesta+ (2020)



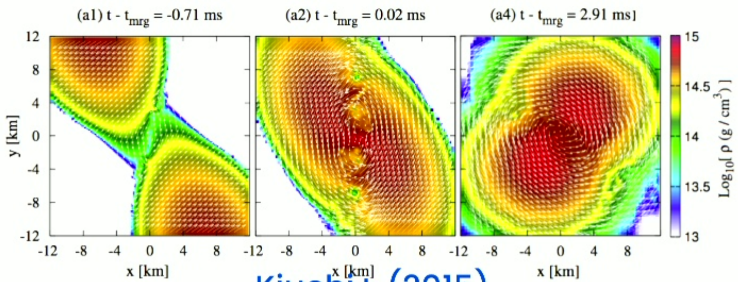
Ciolfi+ (2020)

The challenge of small-scale amplification

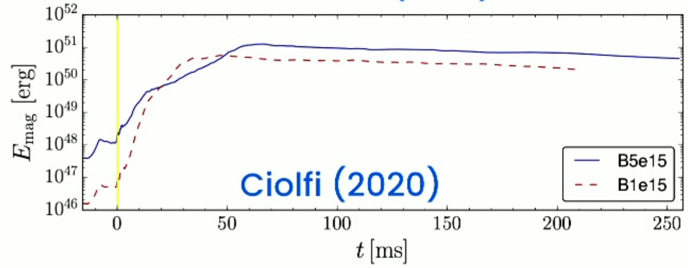
- KH instability: $t_{\rm KH}^{-1} \propto k$

- MRI: $\lambda_{\rm MRI} \sim \frac{B}{\sqrt{4\pi\rho}} \frac{2\pi}{\Omega}$

$$Q_{\rm MRI} = \frac{\lambda_{\rm MRI}}{\Delta x} \sim 8 - 10$$



Kiuchi+ (2015)



Ciolfi (2020)

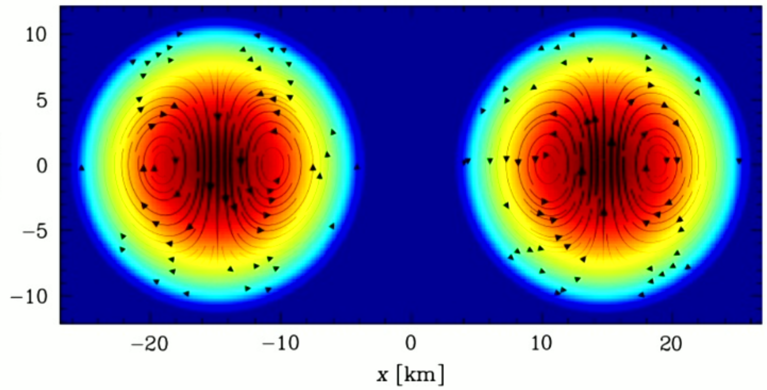
How to get a large magnetic field after merger?

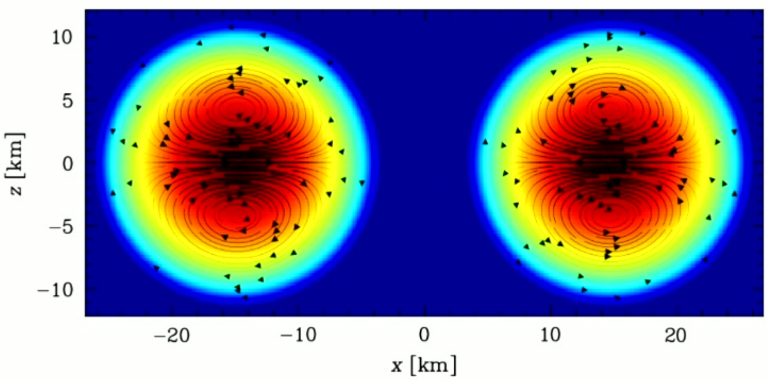
- Very-high resolution (unachievable yet)
- Sub-grid modeling
- **Initialize artificially large magnetic fields**

Kiuchi+ (2014, 2015, 2023, 2024), Ciolfi+ (2019, 2020), Palenzuela+ (2022), Aguilera-Miret+ (2022, 2023), Chabanov+ (2023), Combi & Siegel (2023), Ruiz+ (2011, 2016, 2020, 2021), Kawamura+ (2016)

This work: explore the effect of different initial conditions for the magnetic field on its evolution

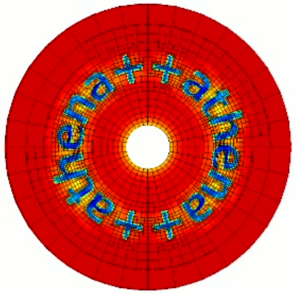
- $\uparrow\uparrow$, $\uparrow\downarrow$, Tilted $\rightleftharpoons$, Tor, Mixed, no B, bitant sym.
- **SFHo** (soft), **DD2** (stiff) EOS
- $\Delta x_{\min} \sim 180$ m
- $t_{\rm end} - t_{\rm mrg} \sim 17 - 35$ ms
- $m_1/m_2 = 1, 1.2$
- $B_{\max} \sim 10^{15}$ G

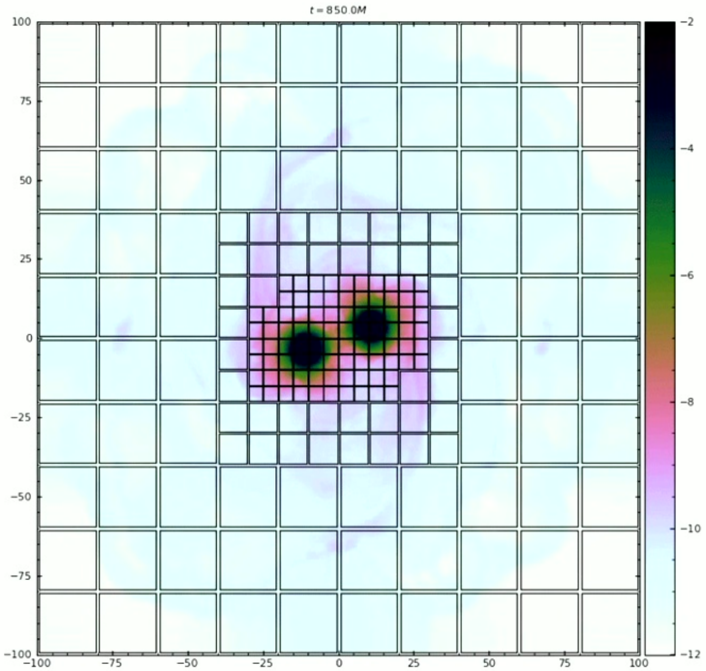




GR-Athena++

Stone+ (2020)
Daszuta+ (2021)
Cook+ (2025)

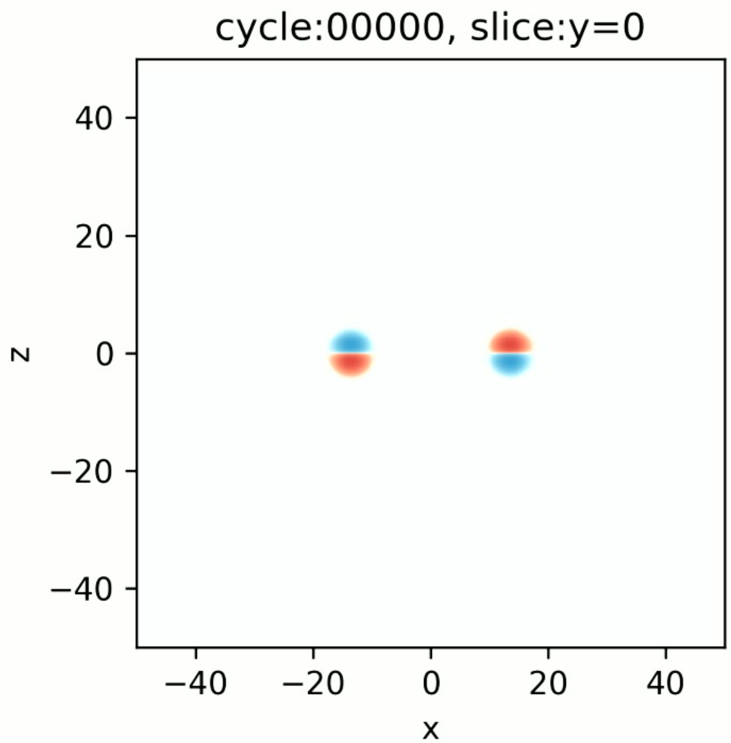




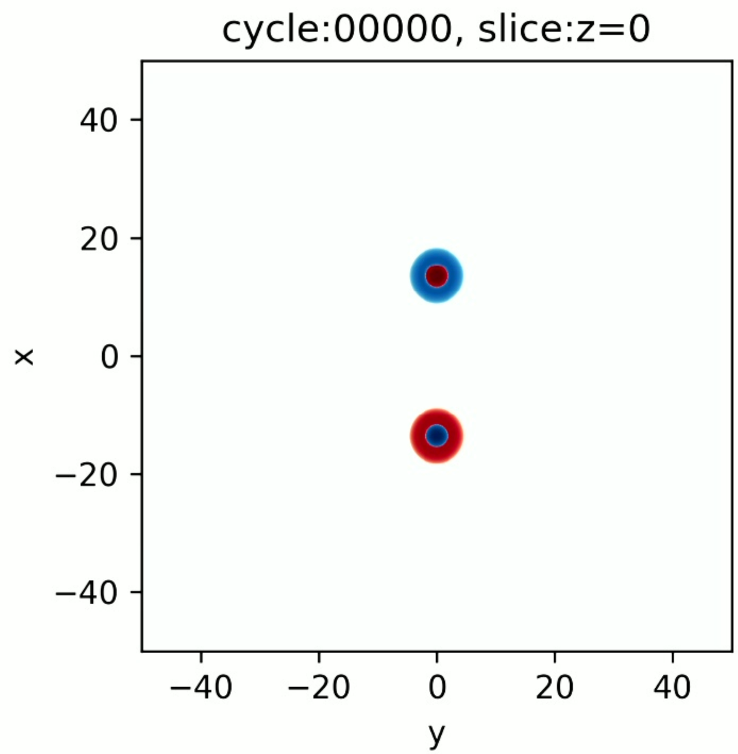
Video from M. Jacobi

- Extension of Athena++ to dynamical spacetimes (Z4c evolution, VC)
- Block-based AMR, CT
- Valencia formulation of MHD
- Tabulated Nuclear EOS
- M1 neutrino transport

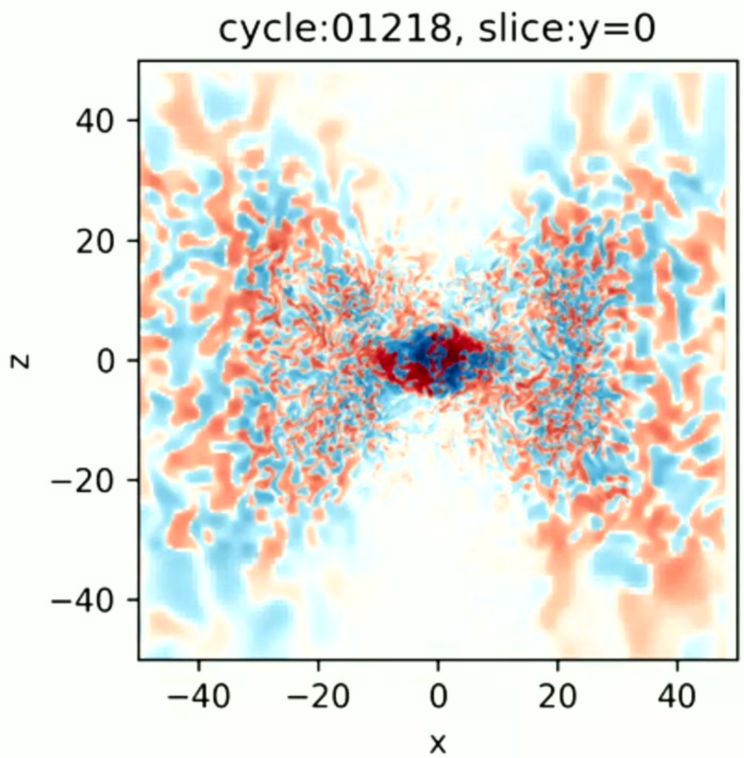
Toroidal



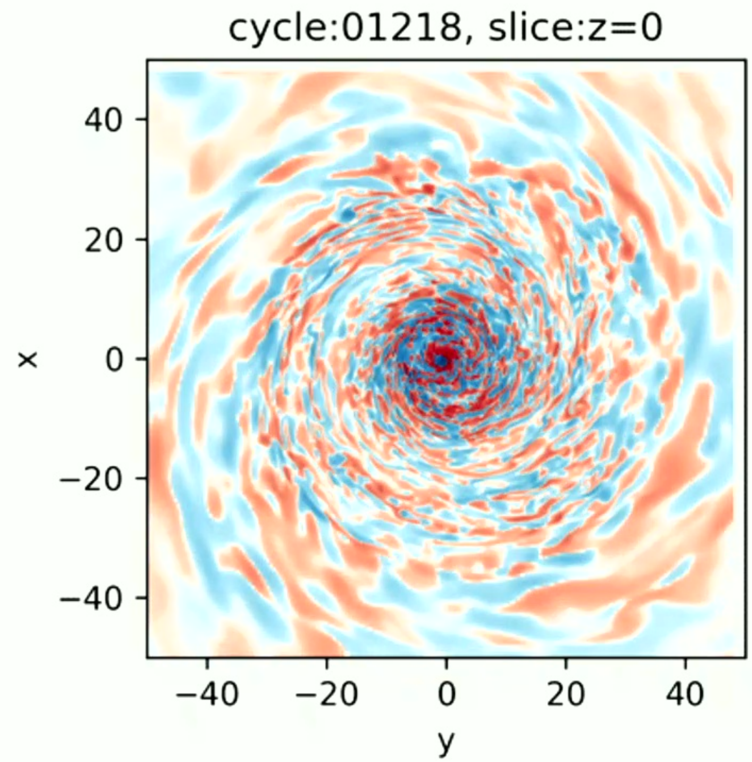
Poloidal



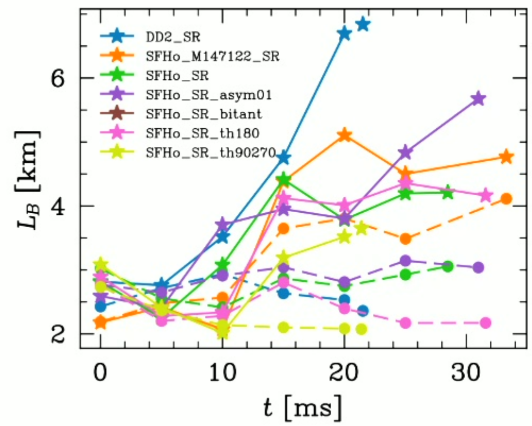
Toroidal

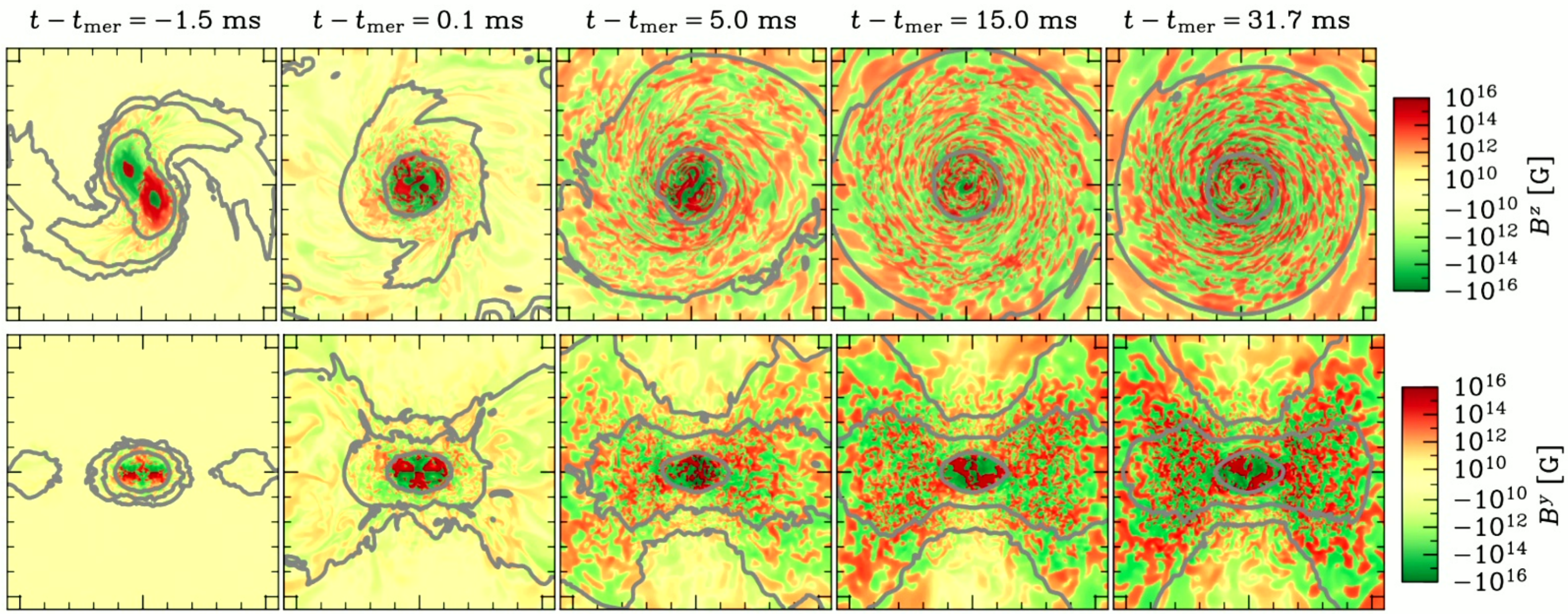


Poloidal

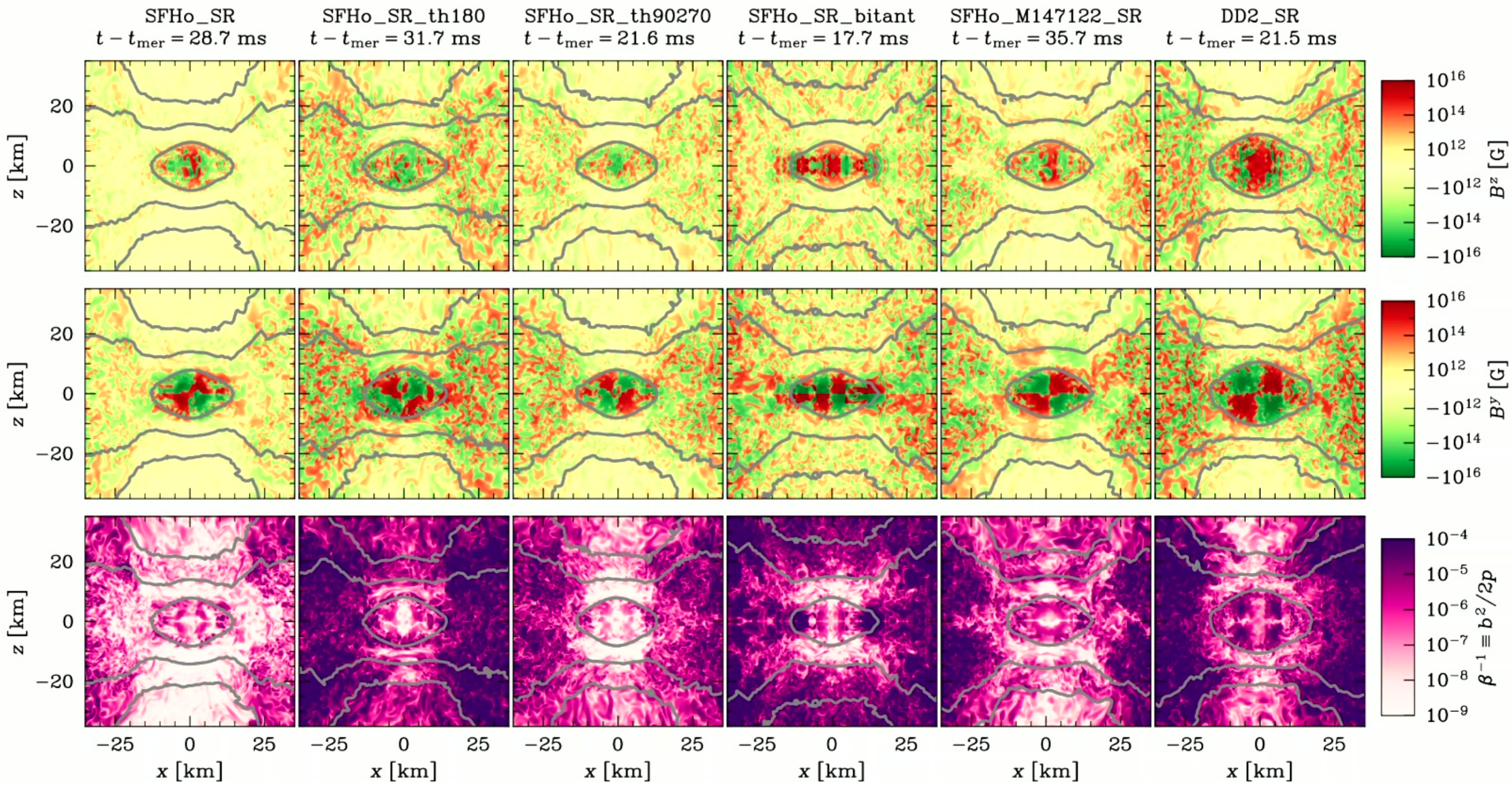


Toroidal field starts turbulent and slowly becomes more coherent

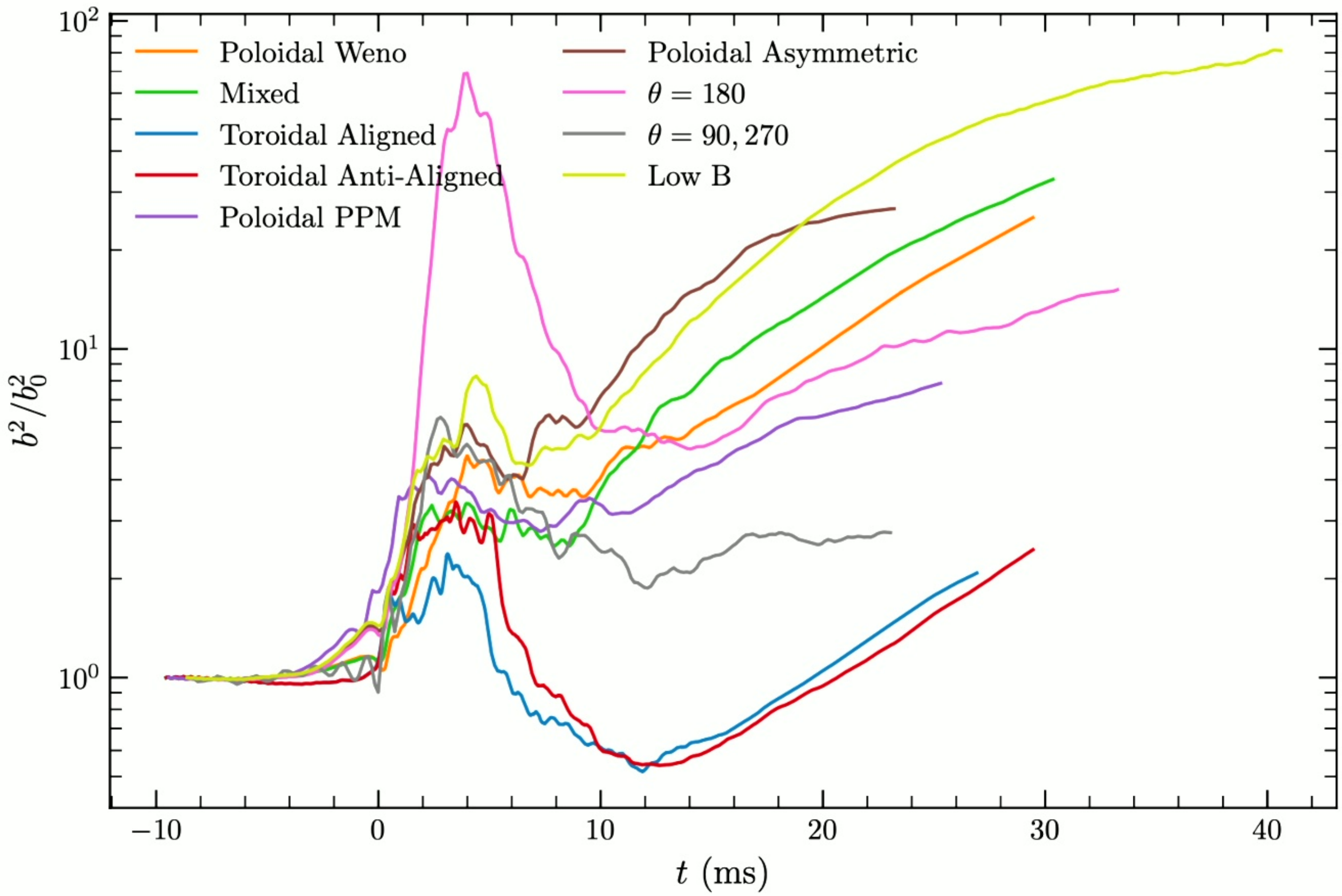




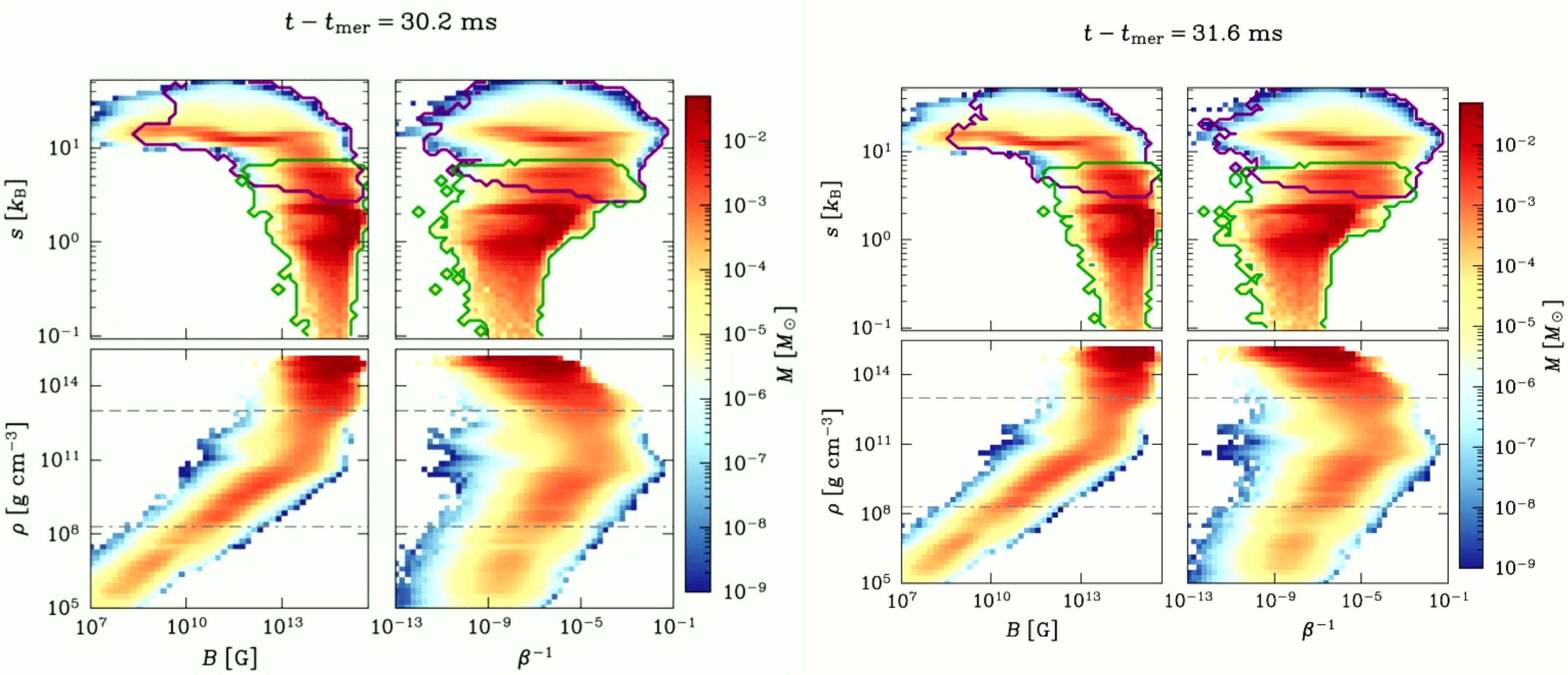
- Bitant symmetry decreases turbulence and rapidly gives rise to more coherent fields.
- Initial magnetic field affects the polarity of the toroidal field



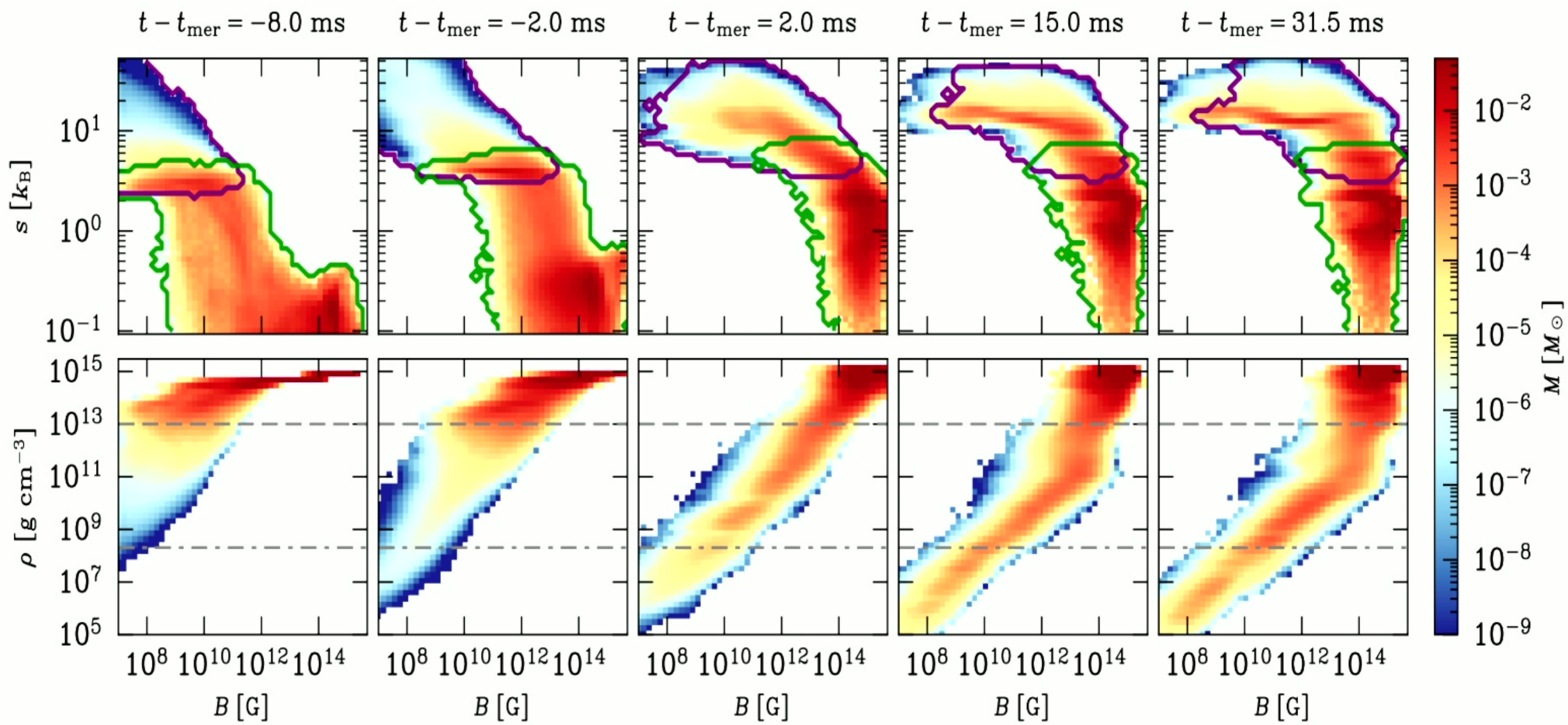
Magnetic field energy amplification



Magneto-thermodynamic evolution of the post-merger remnant and disk

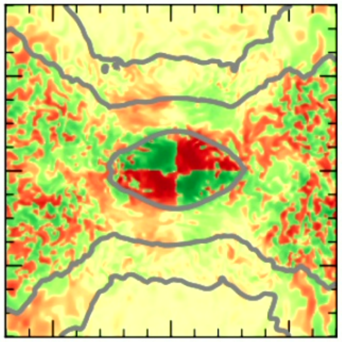


Magneto-thermodynamic evolution of the post-merger remnant and disk

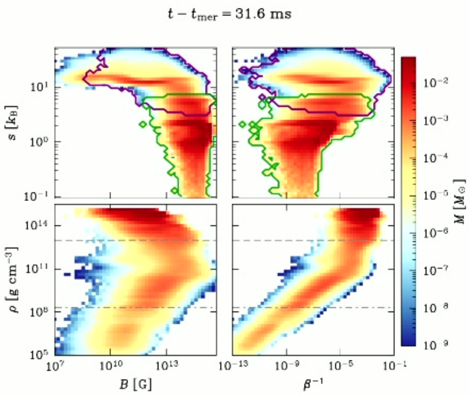


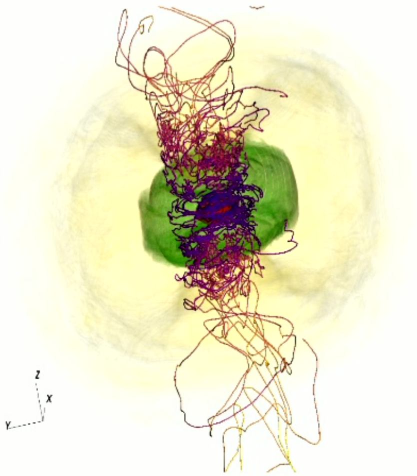
Take aways and future work

- Bitant symmetry gives rise to a larger amplification, lower turbulence close to the equatorial plane
- Initial B topology may affect amplification, post-merger topology



- **EG**, WC++, in prep. (2025)
- WC, **EG**++, in prep. (2025)





Caveats:

- Finite resolution
- Finite duration
- No neutrino transport

Magnetic field energy amplification