

Binary Neutron Star Mergers

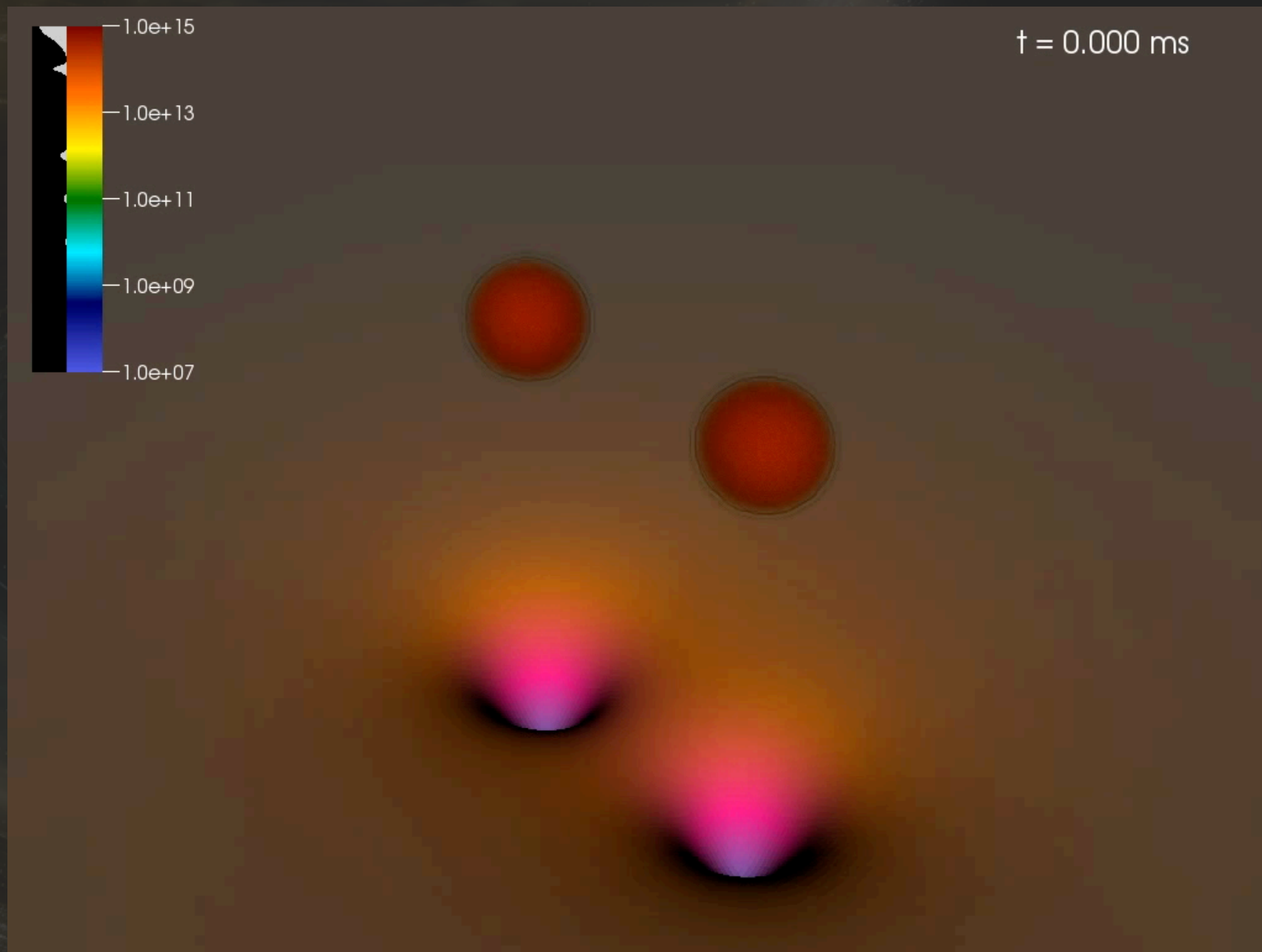
Eduardo M. Gutiérrez

Postdoctoral Scholar
Penn State University
(From October: AEI)

17th July 2026
AthenaK Summer School



PennState
Eberly College of Science



Courtesy of D. Radice

Open questions on Binary Neutron Star Mergers?

- What is the equation of state of dense nuclear matter?
- How are magnetic fields amplified and sustained?
- What determines the fate of the merger remnant?
- How are relativistic jets launched? Can both NS and BH power short GRBs?
- How are the heaviest elements synthesized?
- How different are GW signals from different NS mergers?
- What multi messenger counterparts are produced in BNS mergers?

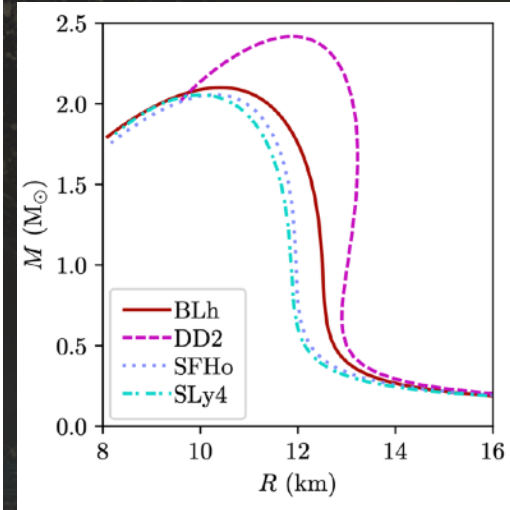
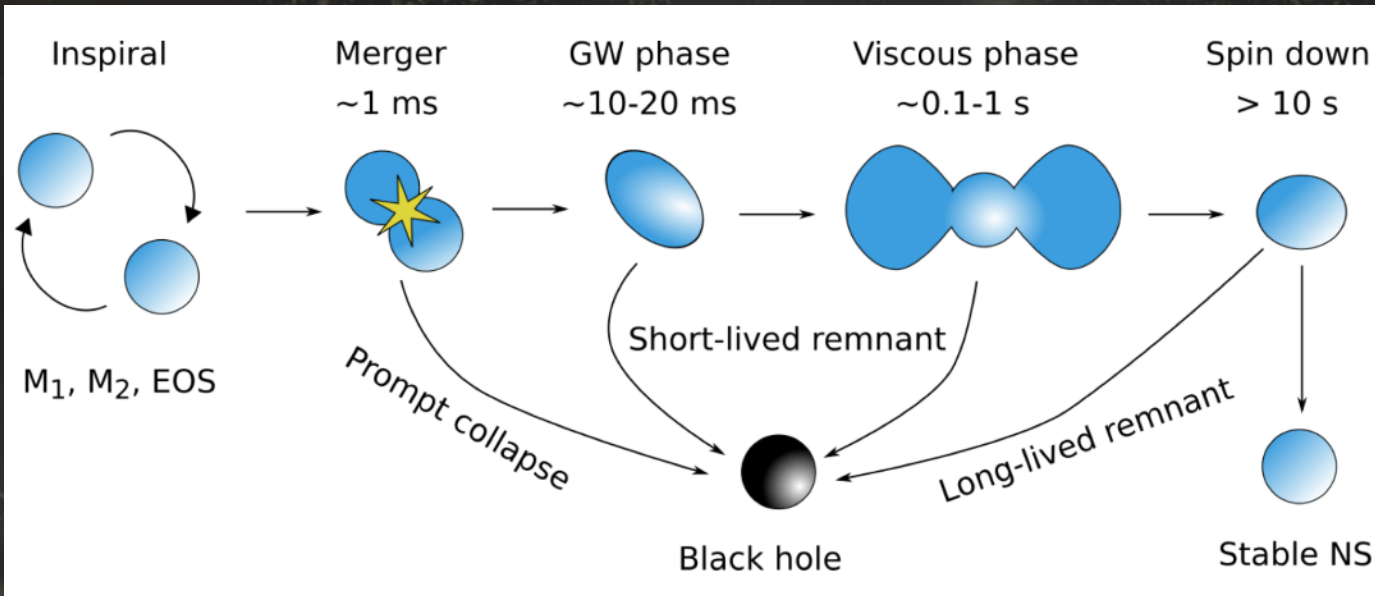
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Physical Ingredients for Realistic Binary Neutron Star Merger Simulations:

- Dynamical spacetime: Full Numerical Relativity
 - Nuclear Equation of State (EOS): many proposals; largely unknown
 - Relativistic Hydrodynamics and shocks
 - Magnetic fields: instabilities and growth
 - Neutrinos driving outflows and changing matter composition
- **You want:** highest resolutions, best radiation treatment, realistic initial conditions, longest possible simulation, largest possible set of simulations

The merger of two neutron stars may leave different types of remnants

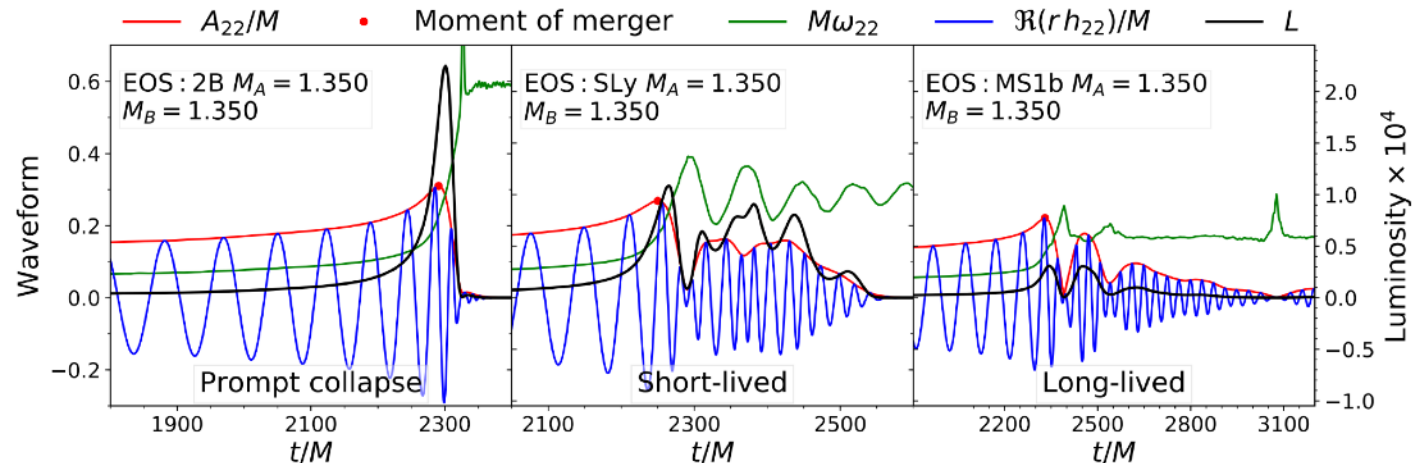
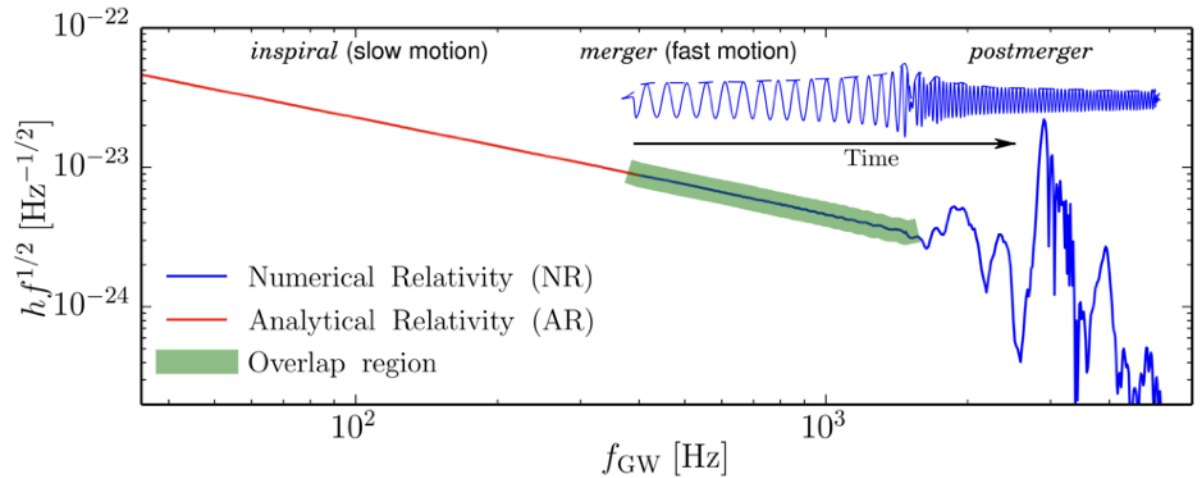


Espino++, arXiv:2311.12923 (2023)

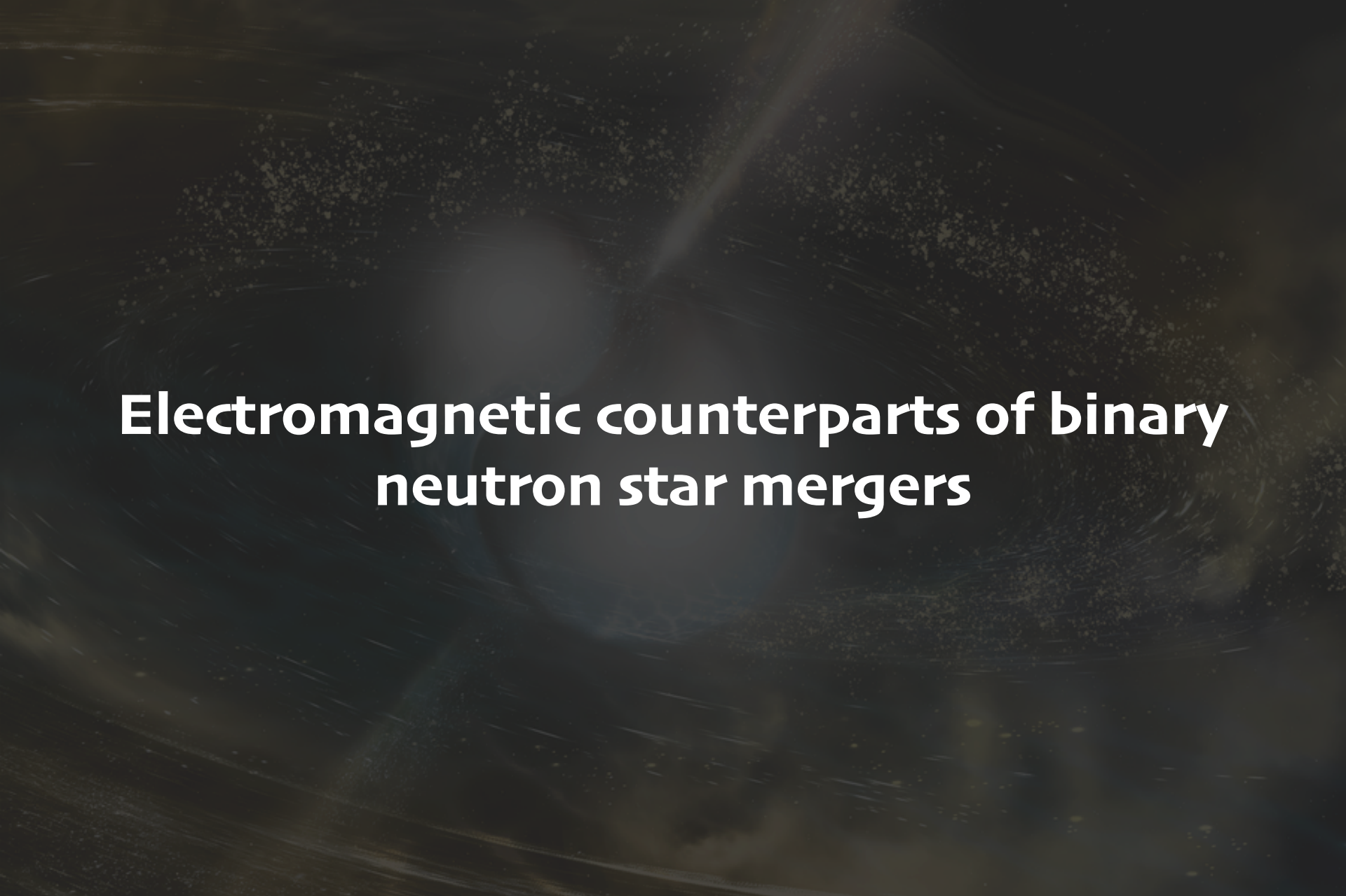
From Radice+, Ann. Rev. Nucl. Part. Sci (2020)

Gravitational Wave signal from BNS mergers

Radice+,
ARNPS (2020)

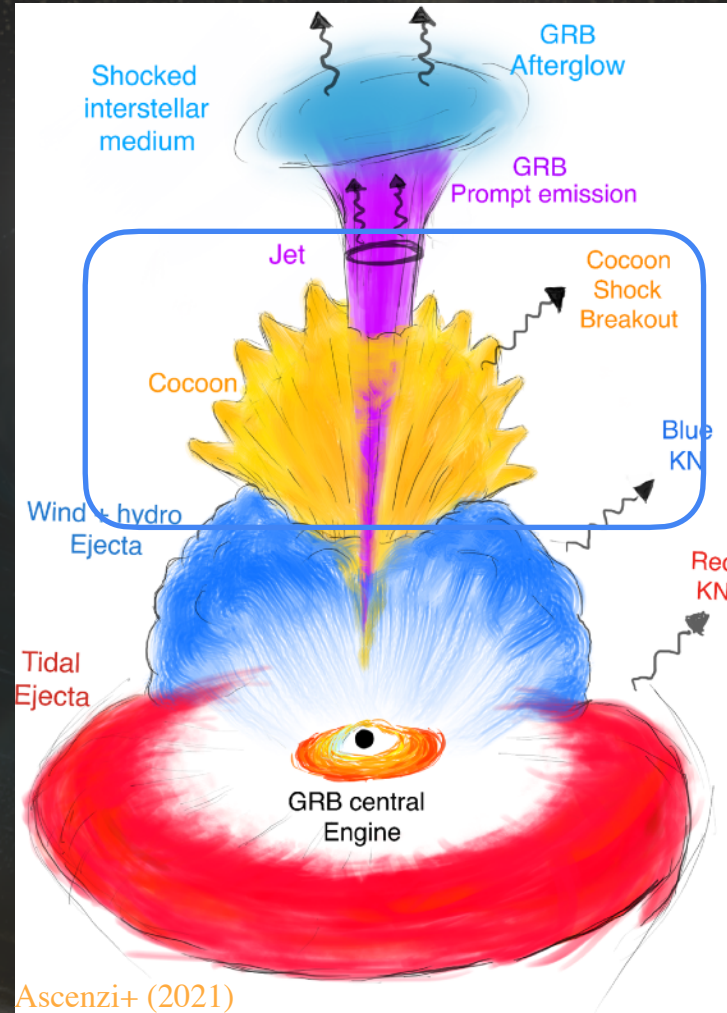


From Bernuzzi,
GReGr (2020)

The background of the slide is a dark, cosmic scene. It features a dense field of stars, many of which are blurred into long, curved streaks, suggesting a long-exposure photograph of the night sky. A prominent, bright, and colorful nebula is visible in the upper right quadrant, displaying shades of blue, purple, and white. The overall atmosphere is mysterious and scientific.

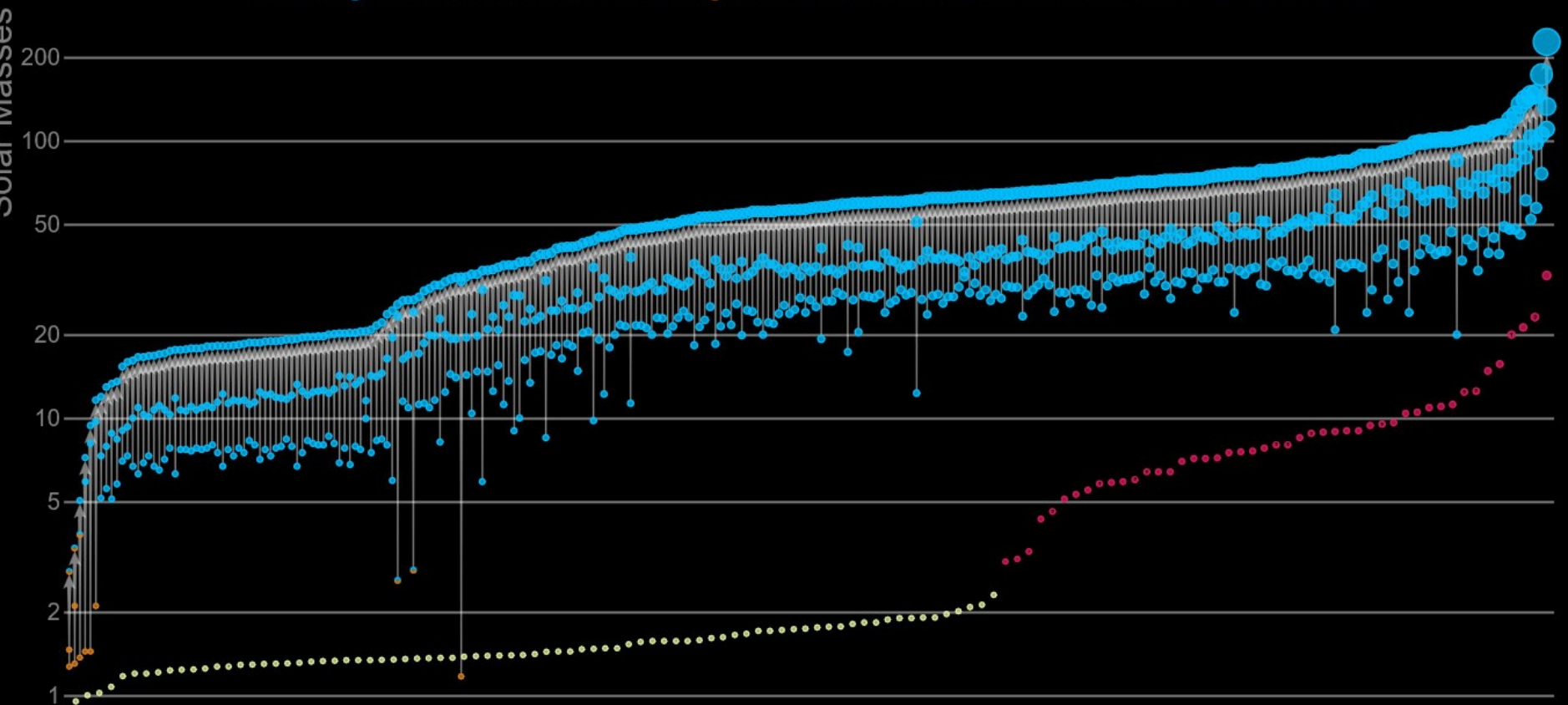
Electromagnetic counterparts of binary neutron star mergers

A 'Zoo' of Electromagnetic Counterparts from Binary Neutron Star Mergers



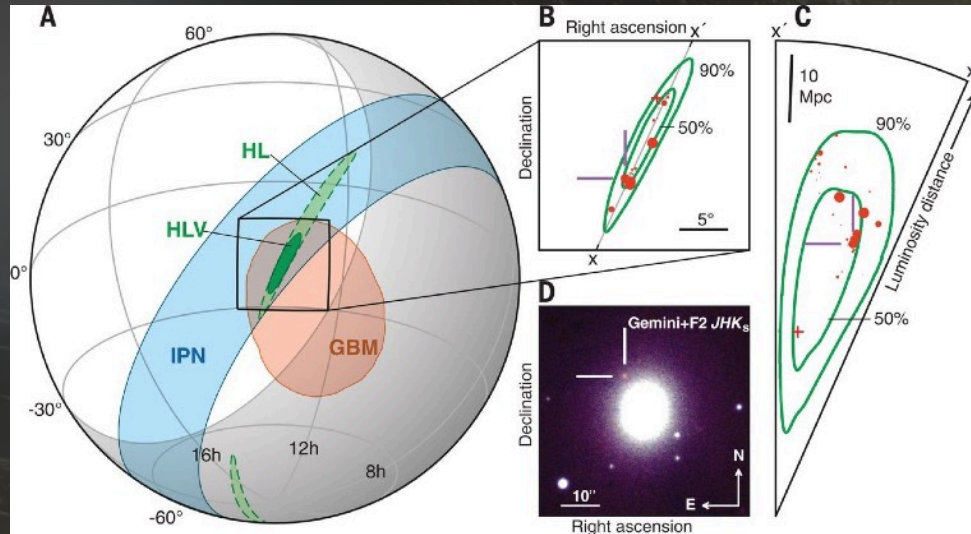
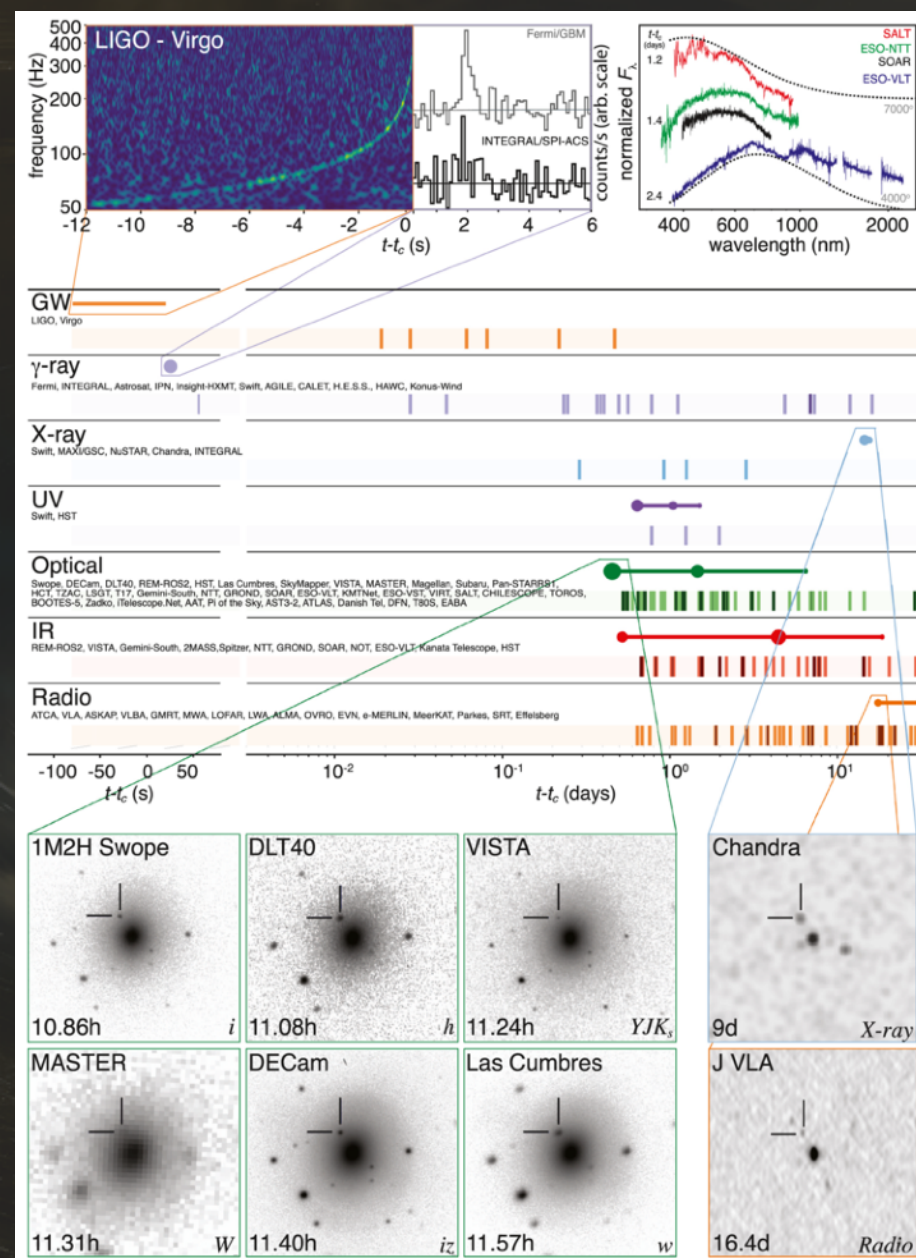
Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*



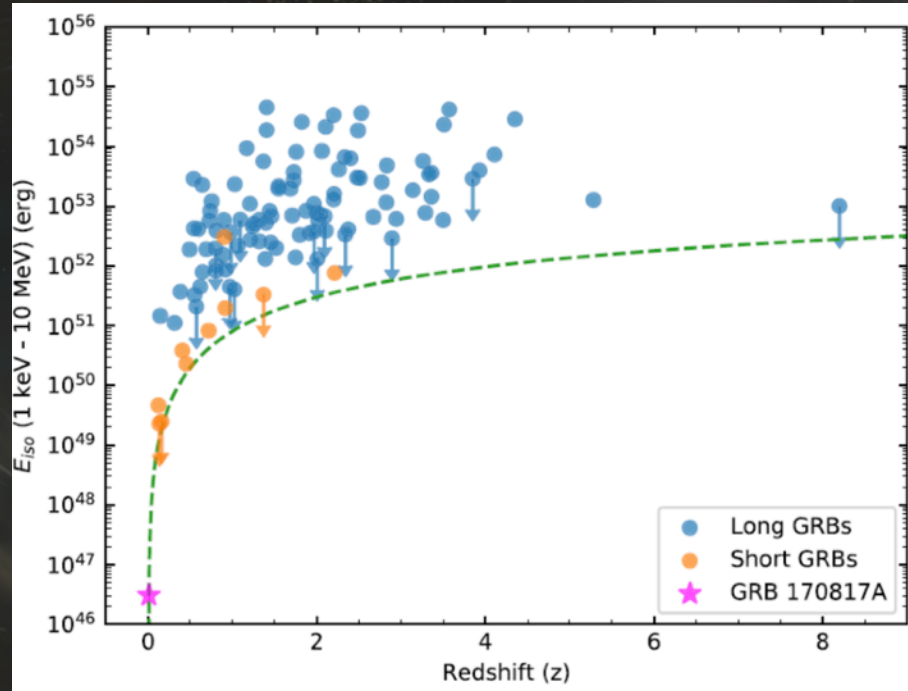
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW170817: First multimessenger event of GWs and EM radiation

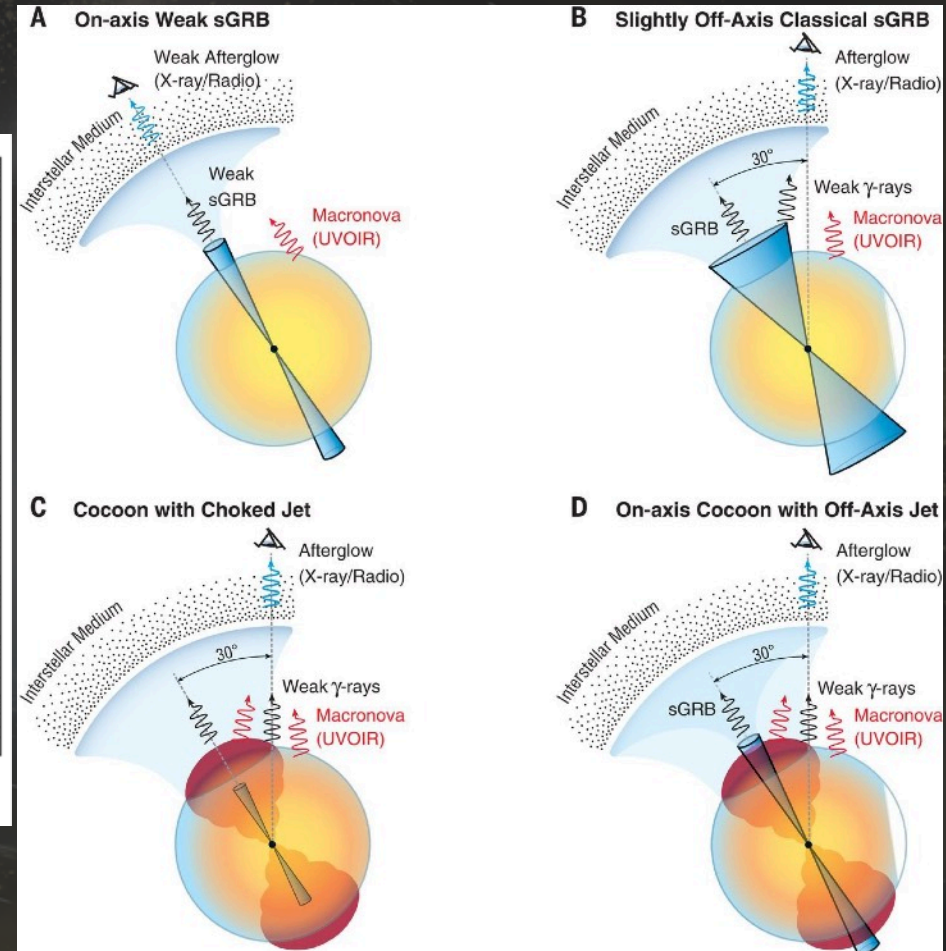


Abbot+ (2017)

GRB170817 had a very low-luminosity. Why?



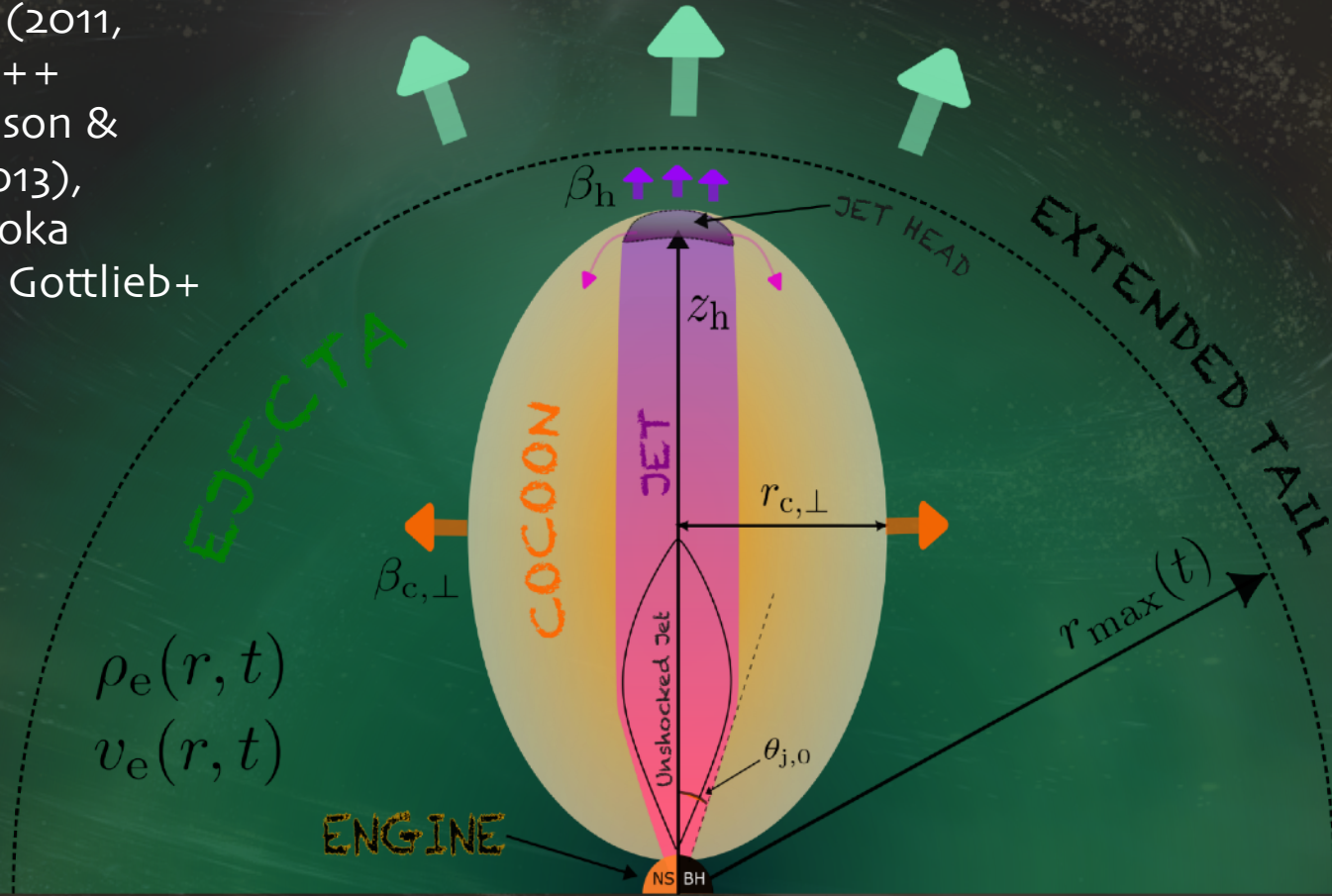
Abbott+, ApJL (2017)



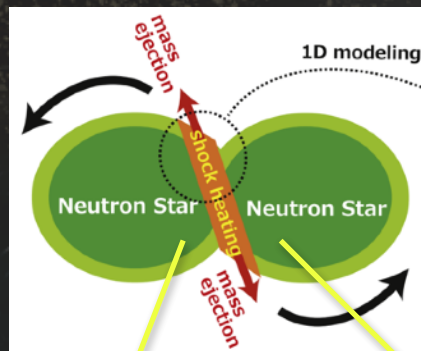
Kasliwal+, Science (2017)

MODEL: The **JET**, launched by the **ENGINE**, propagates through the merger **EJECTA**, and feeds the **COCOON** Gutierrez++, PRD (2025)

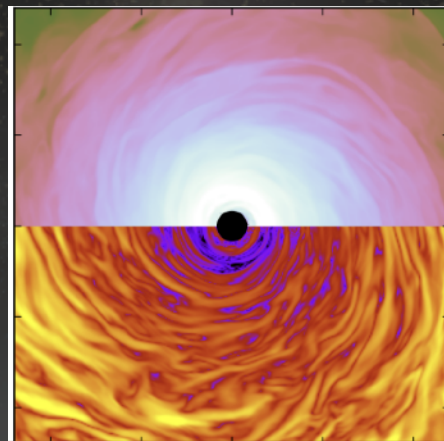
Bromberg++ (2011, 2014), Salafia++ (2020), Levinson & Begelman (2013), Hamidani & Ioka (2020, 2021), Gottlieb+ (2022),...



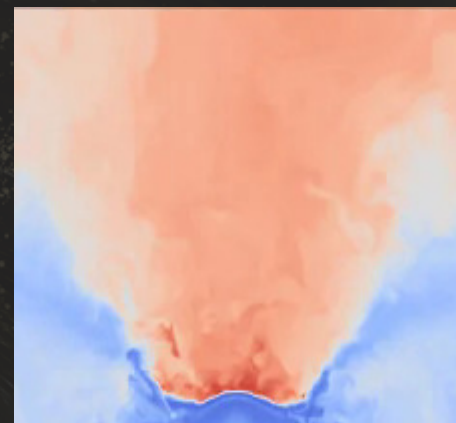
Dynamical ejecta + Neutrino-driven winds



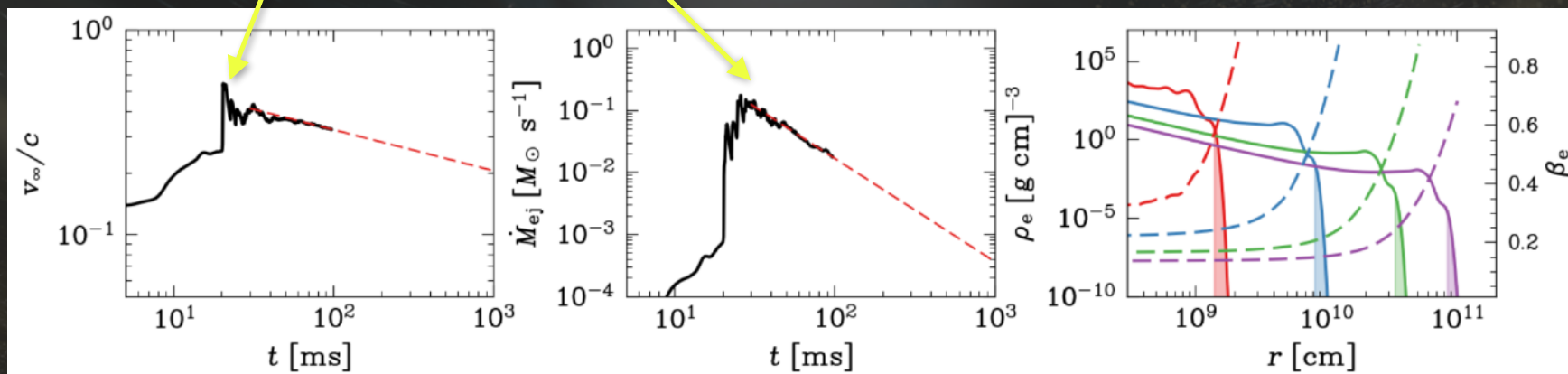
From Ishi++2018



Siegel&Metzger 2017

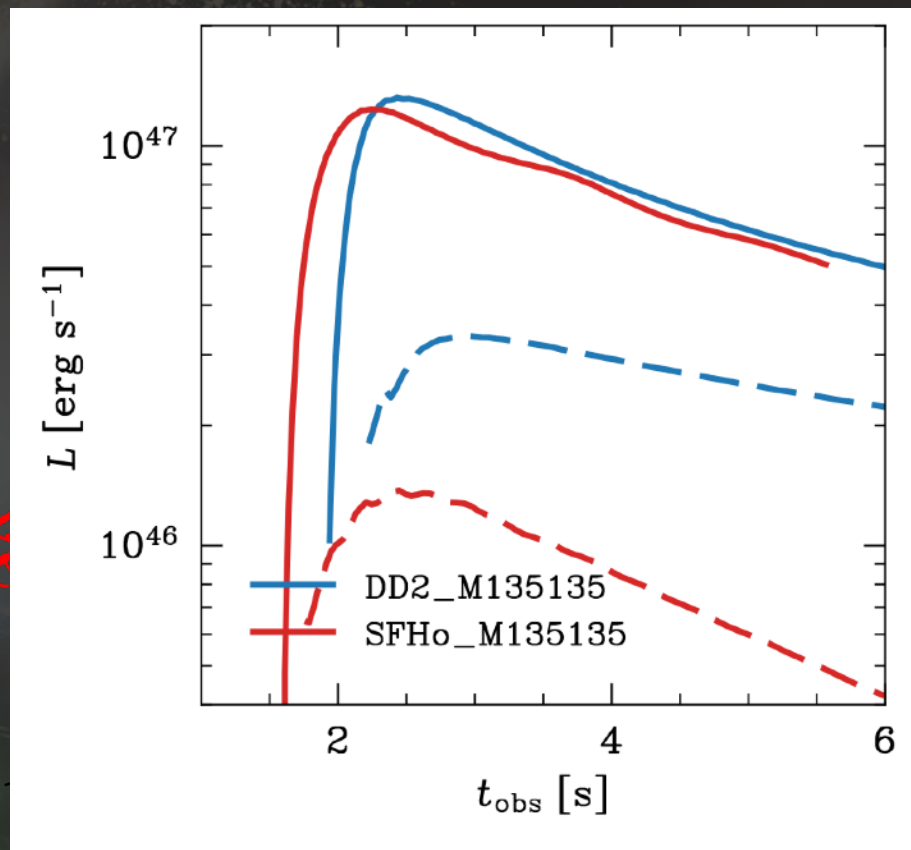
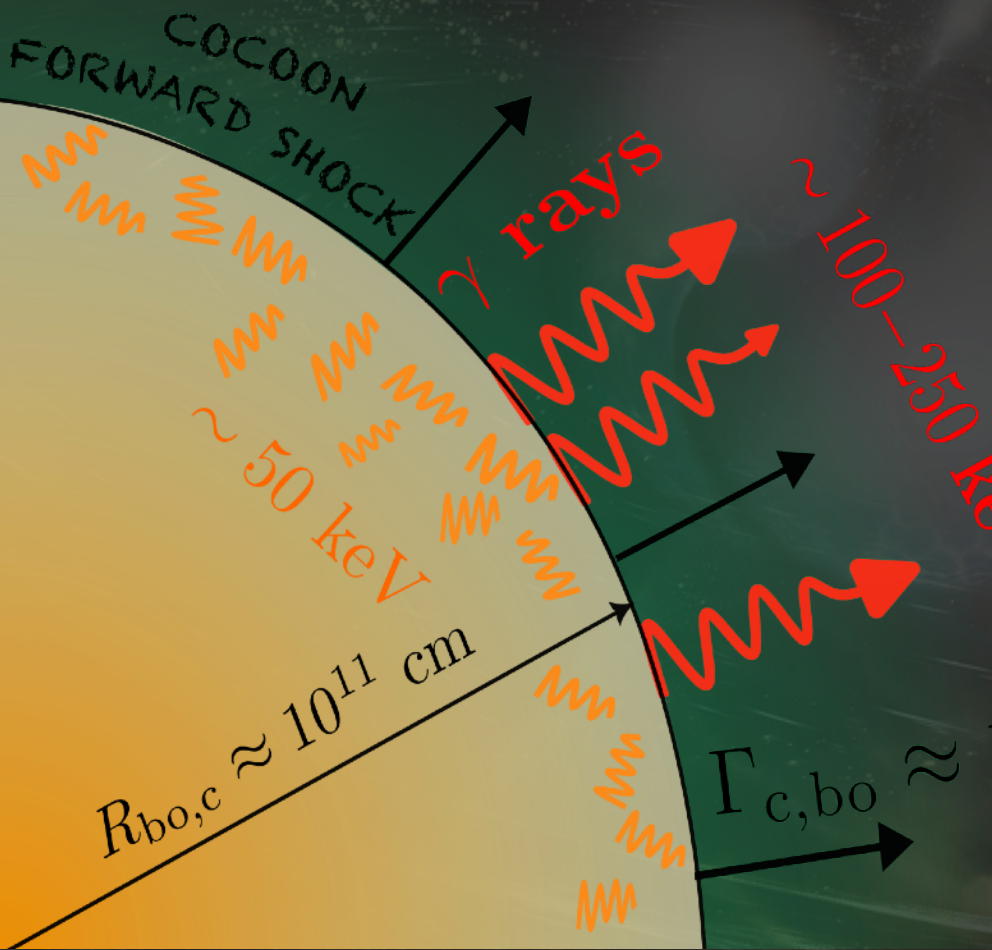


(Nedora+19)



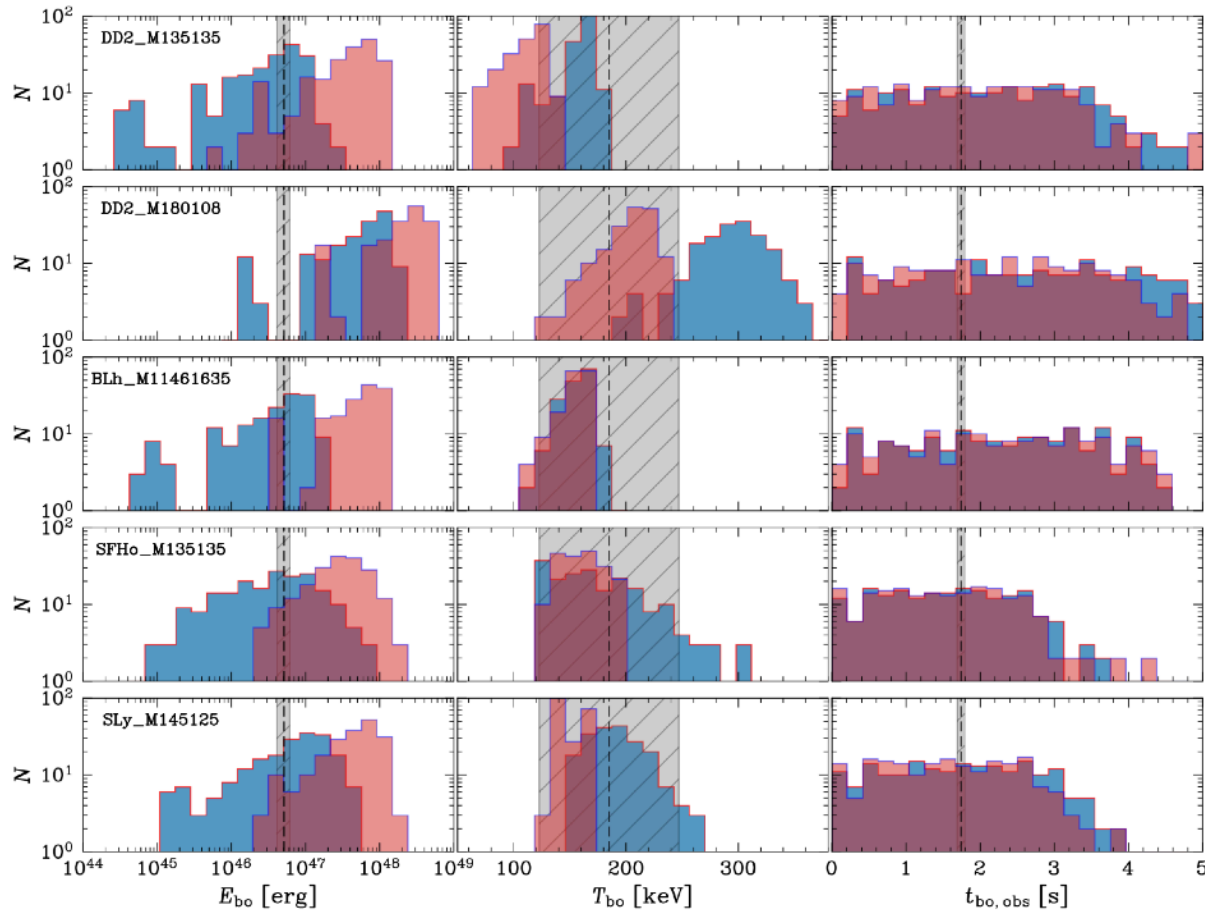
Gutierrez++, PRD (2025)

Cocoon shock breakout emission



Gutierrez++, PRD (2025)

Set of simulations with different engine parameters

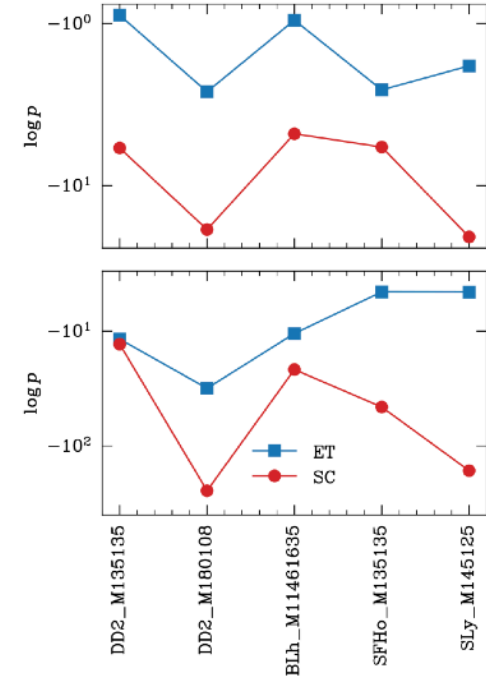
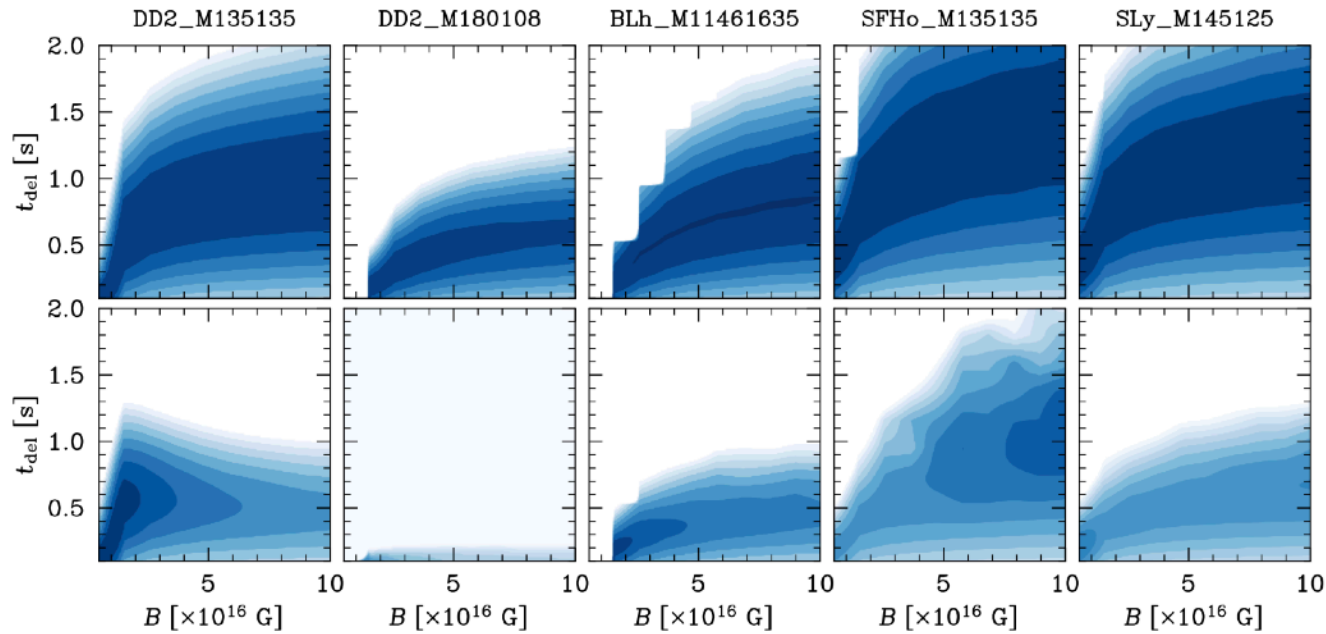


$$B_p \in [5 \times 10^{14}, 10^{16}] \text{ G}$$

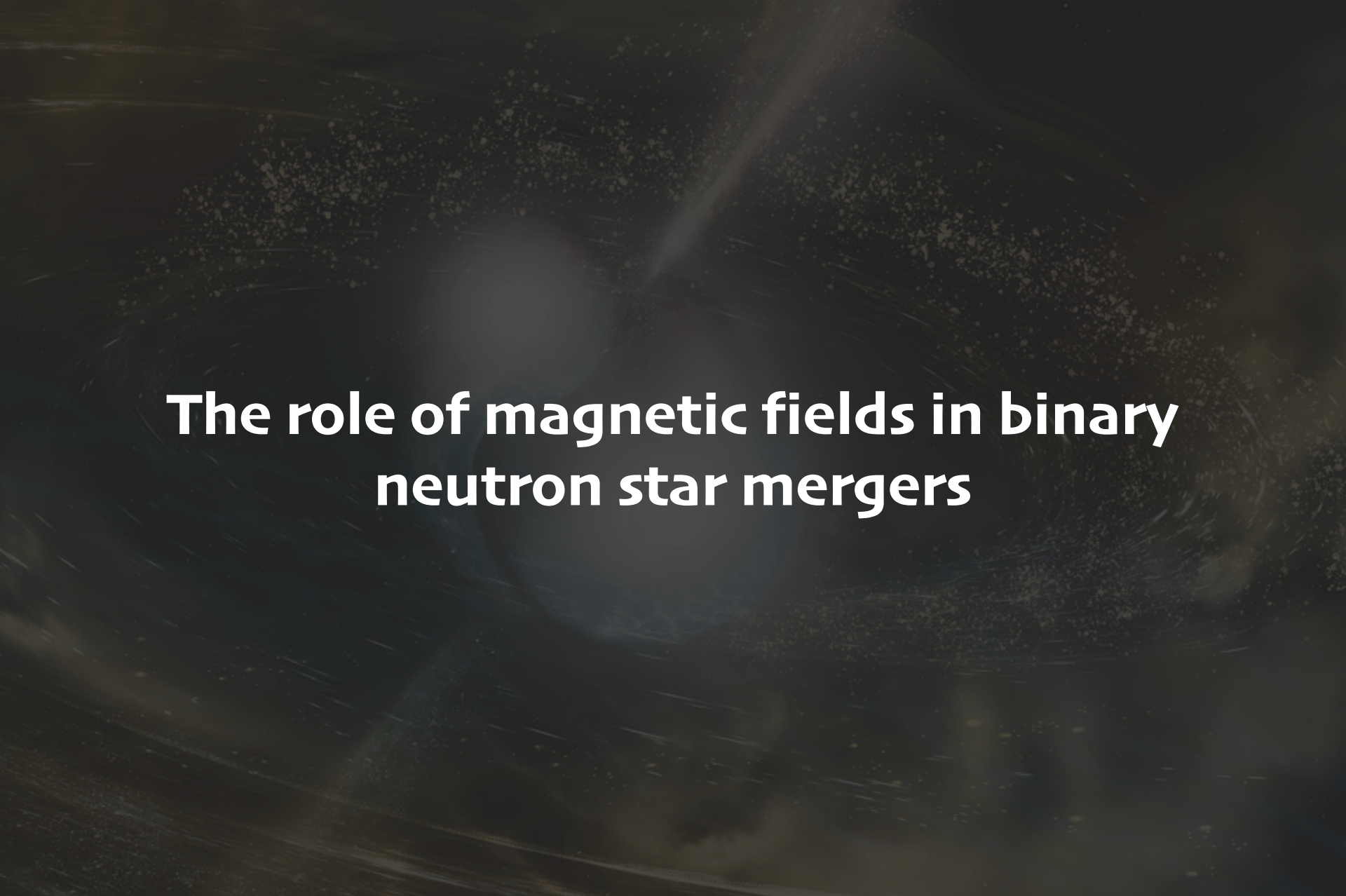
$$t_{\text{del}} \in [0.1, 2] \text{ s}$$

$$\theta_{0,j} = 8^\circ, 16^\circ$$

Most likely BNS ejecta scenario and engine parameters?



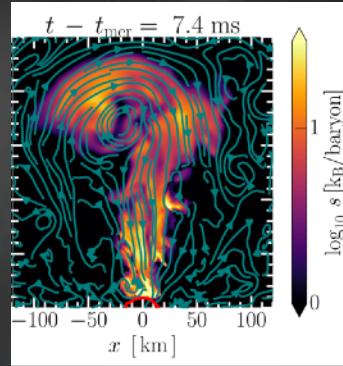
Gutierrez++, *PRD*, 111, 6 (2025)



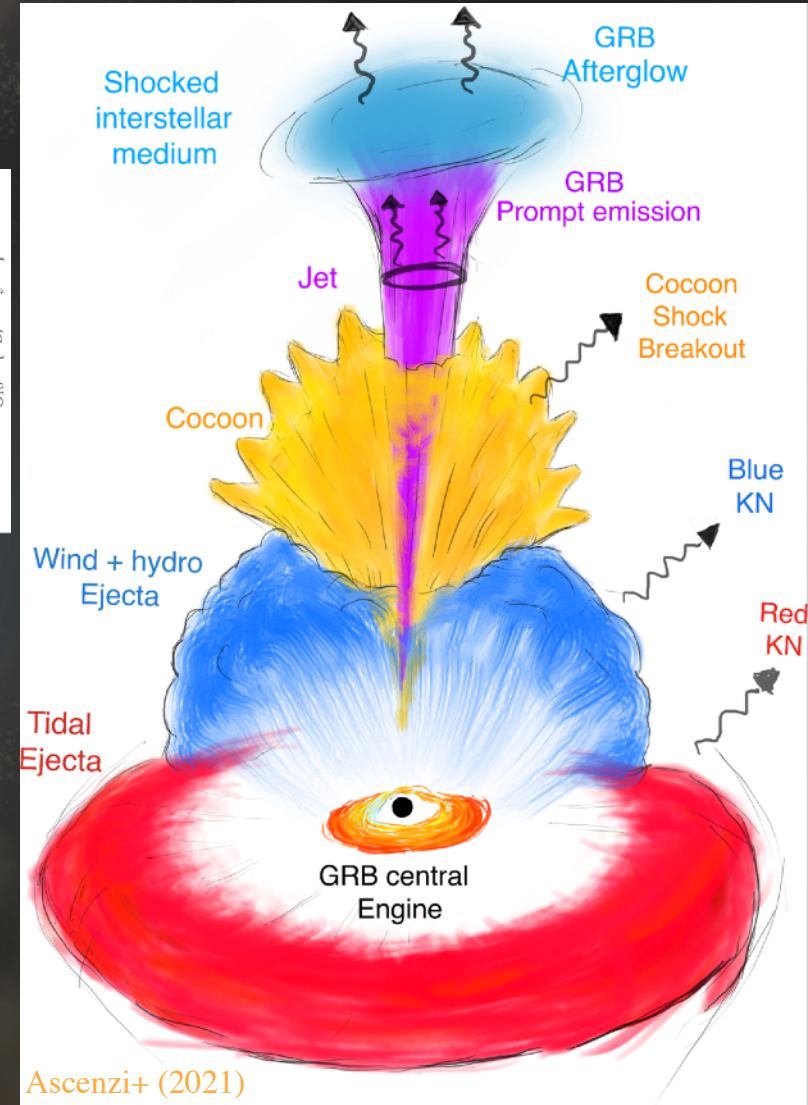
The role of magnetic fields in binary neutron star mergers

Why do magnetic fields matter in binary neutron star mergers?

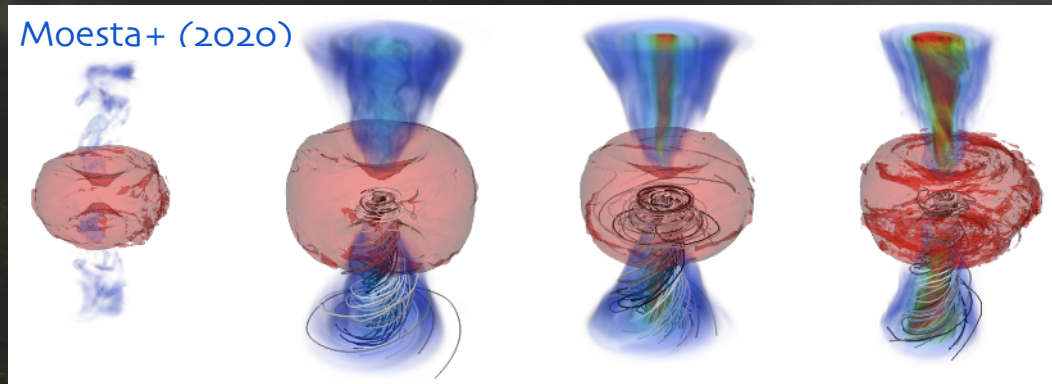
- Key role in the launching of **MHD winds**, **relativistic jets**, **sGRBs**, **precursors** or **delayed emission**, **kilonova**



Most & Quataert (2023)



Ascenzi+ (2021)



Moesta+ (2020)

Why do magnetic fields matter in binary neutron star mergers?

- Binary NSs:

$$B_{\text{surf}} \sim 10^8 - 10^{12} \text{ G}$$

Lorimer (2008)

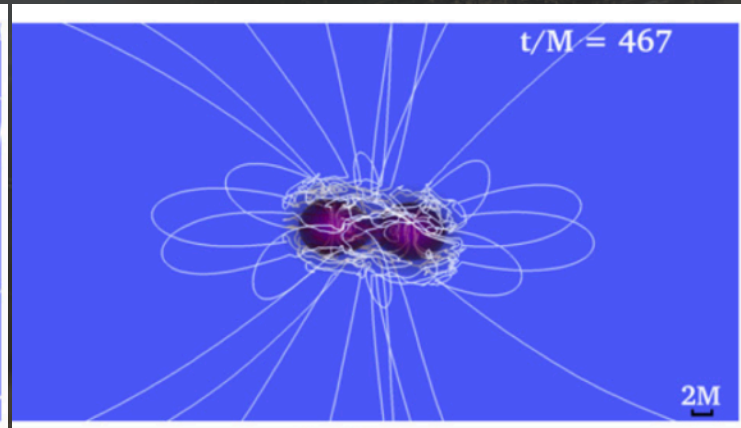
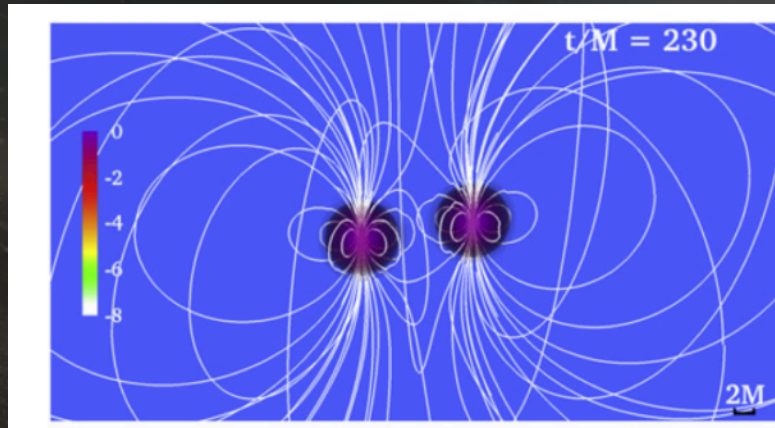
- During and after the merger, **instabilities can amplify the magnetic field** by ~orders of magnitude.

$$E_B \sim 5 \times 10^{41} B_{12} \text{ erg}$$

$$\ll E_k \sim 10^{53} \text{ erg}$$

$$E_B \sim 10^{51} \text{ erg}$$

$$B \gtrsim 10^{16} \text{ G}$$



Instabilities drive dynamo processes that amplify the magnetic field

- ◆ Kelvin-Helmholtz Instability (KHI)

Price & Rosswog (2006); Obergaulinger+2010; Zrake & MacFadyen (2013); Giacomazzo+2015; Kiuchi+2014,2015,2026

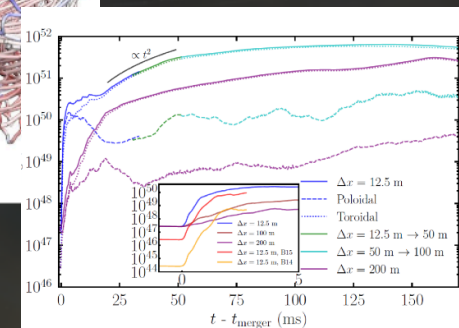
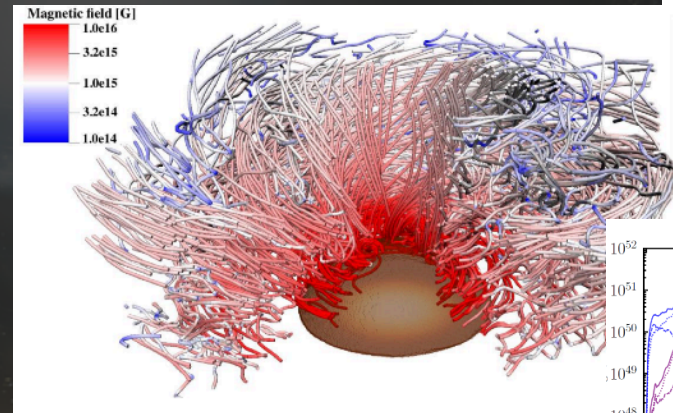
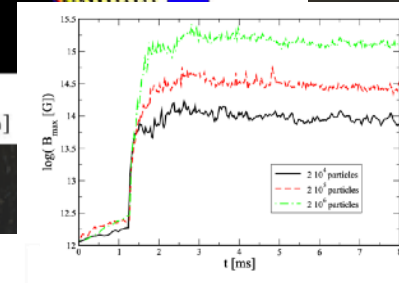
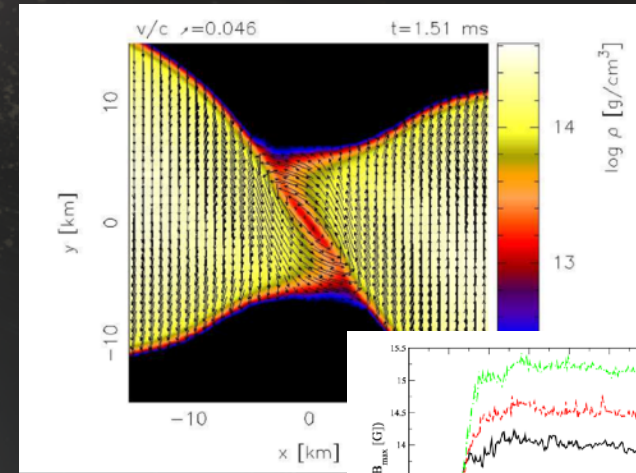
- ◆ MRI-driven dynamo, winding

Siegel+2013; Kiuchi+2024; Most (2023); Reboul-Salze+2025; Aguilera-Miret+2025;...

- ◆ Tayler-Spruit dynamo

Reboul-Salze+2024

- ◆ ...

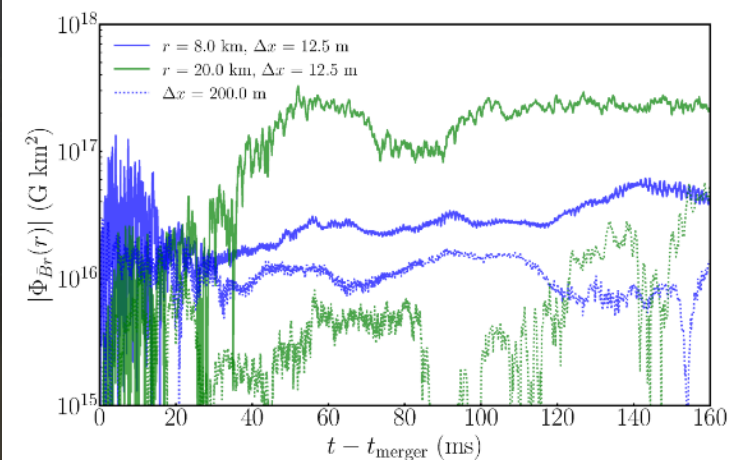
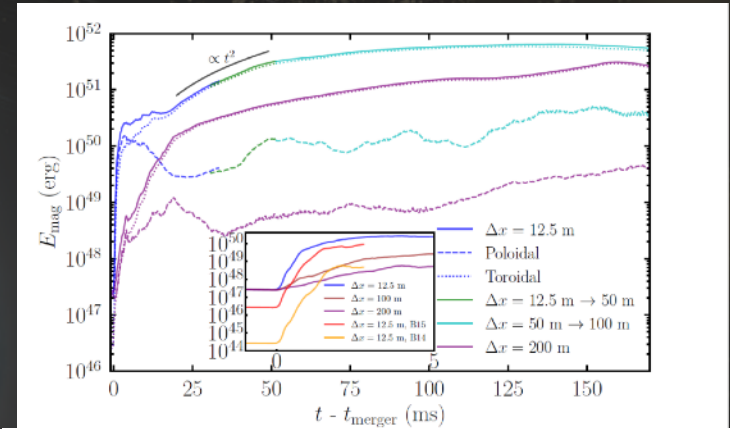
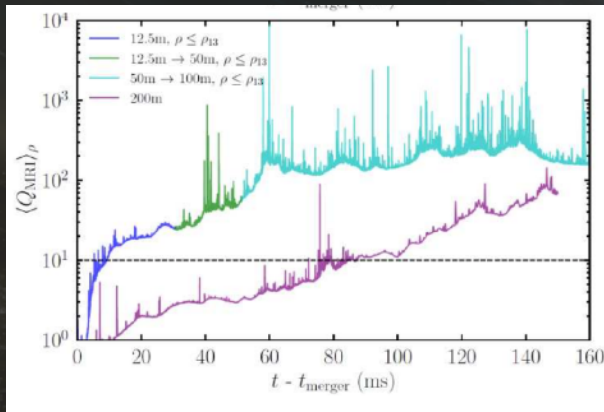


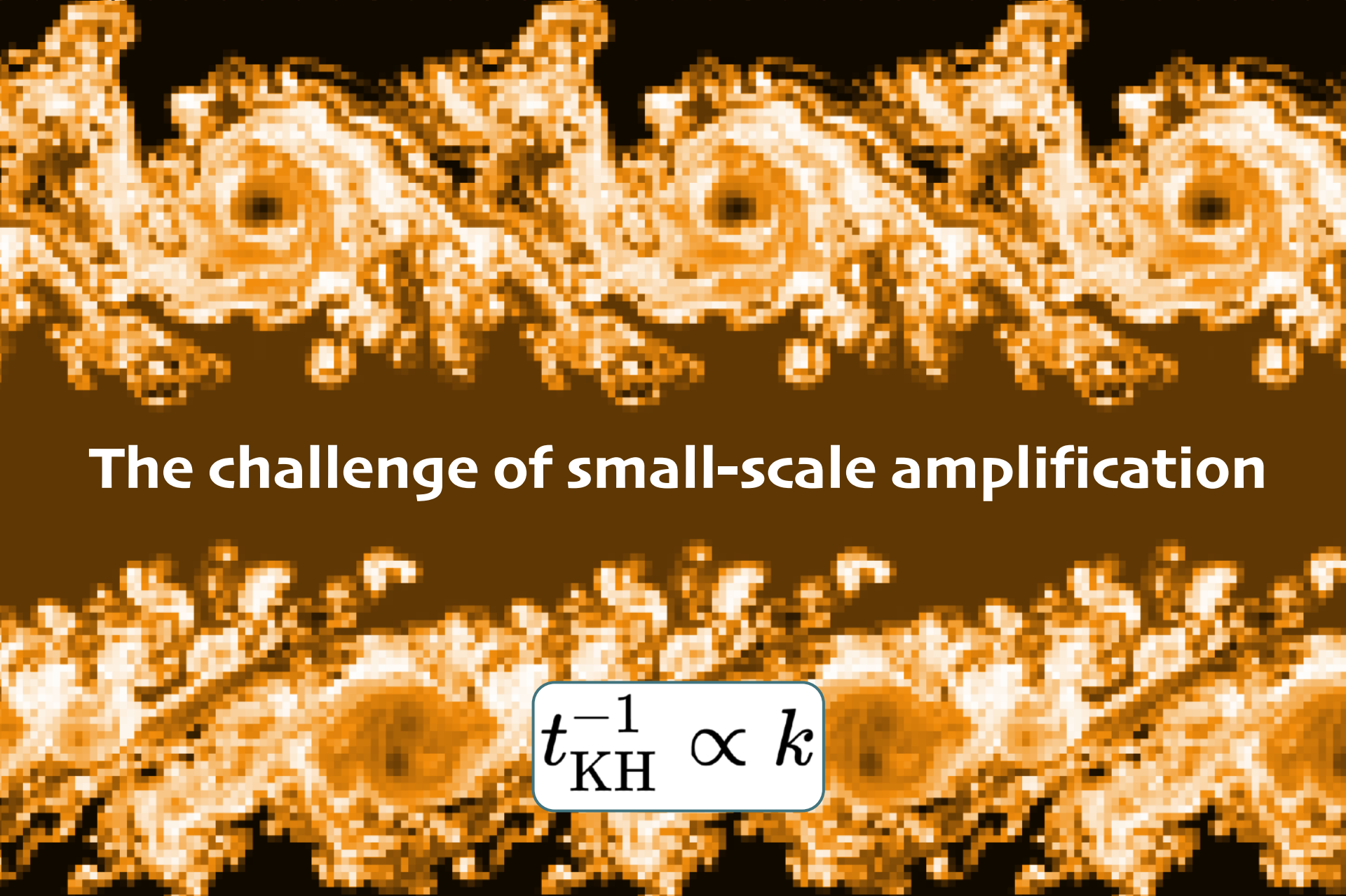
An $\alpha\Omega$ -dynamo has been shown to operate to generate large-scale magnetic fields: MRI and winding

Kiuchi+ (2024) $\Delta x \sim 12$ m

$$\lambda_{\text{MRI}} \sim \frac{B}{\sqrt{4\pi\rho}} \frac{2\pi}{\Omega}$$

$$Q_{\text{MRI}} \equiv \frac{\lambda_{\text{MRI}}}{\Delta x} \sim 10$$





The challenge of small-scale amplification

$$t_{\text{KH}}^{-1} \propto k$$

How to capture the large magnetic field amplification after merger in numerical simulations?

- High resolution
- 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);...

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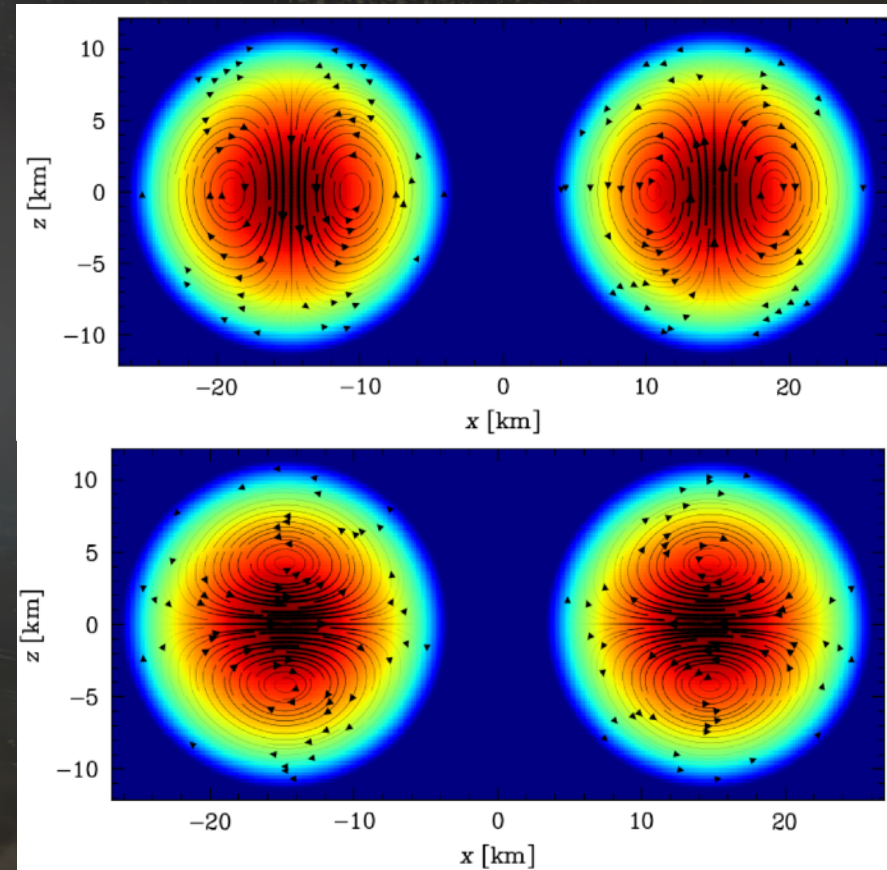
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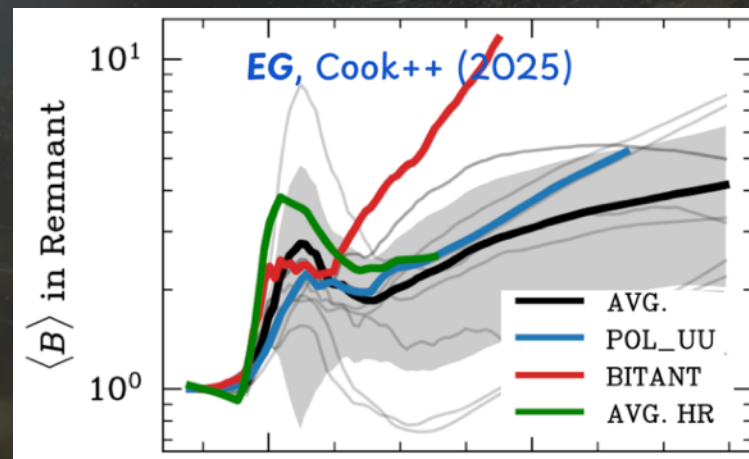
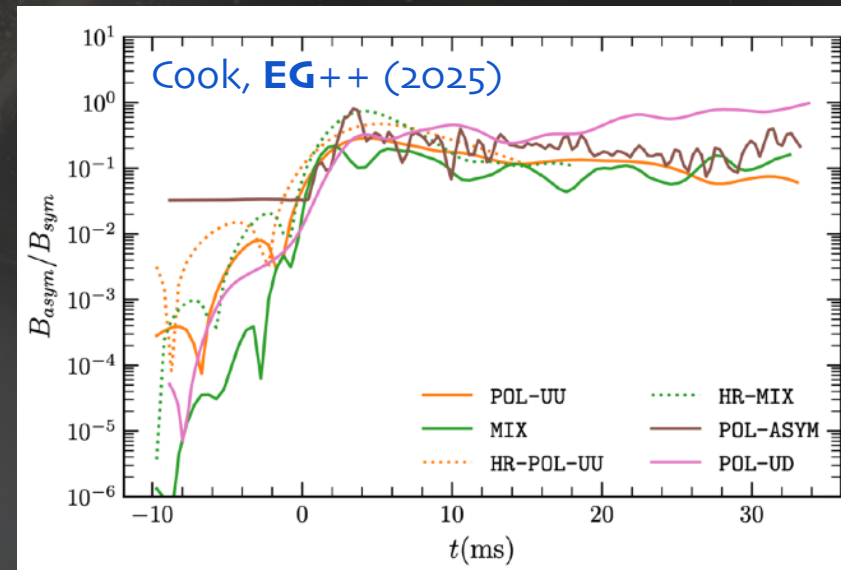
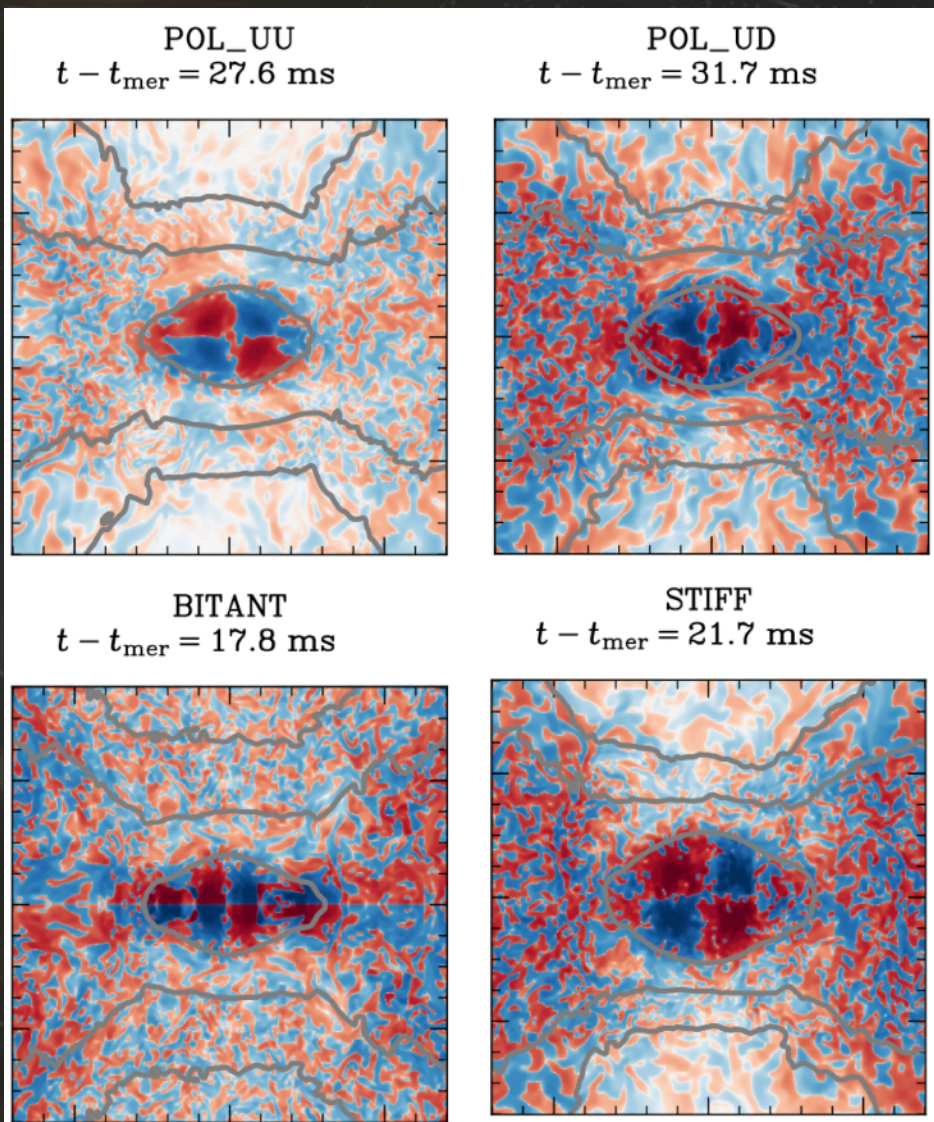
How reliable is to assume artificially large magnetic fields in our simulations?

We planned a set of binary setups to investigate this question

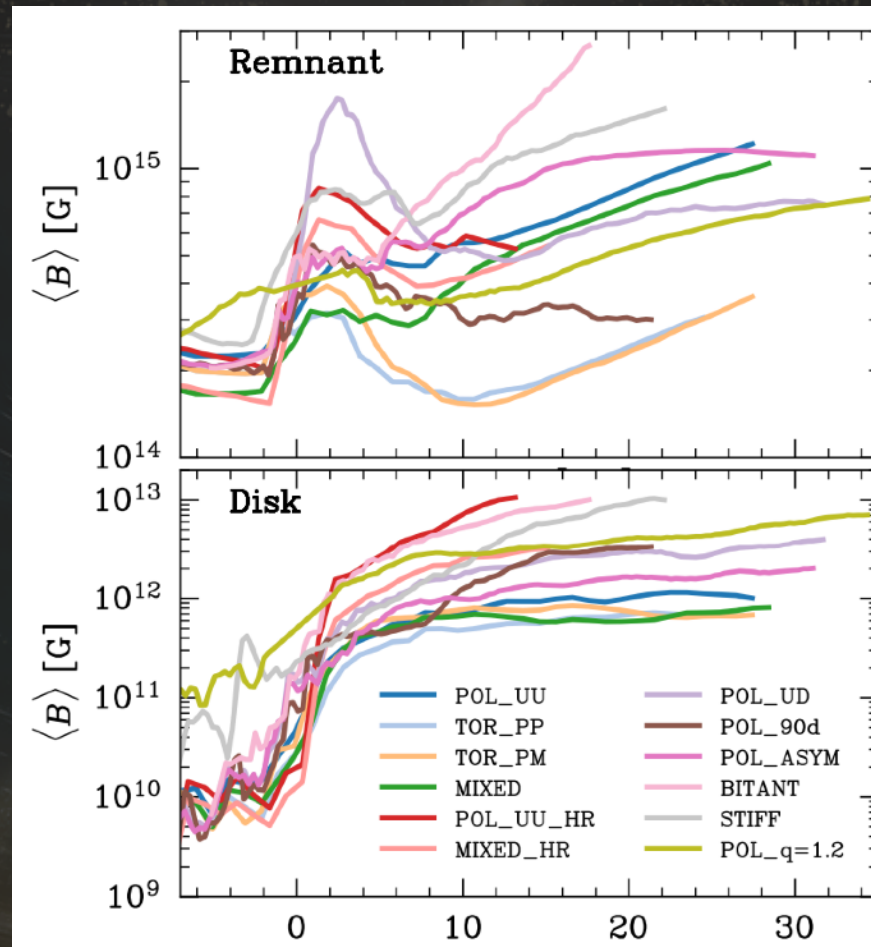
- $\uparrow\uparrow$, $\uparrow\downarrow$, Tilted $\rightleftharpoons$, Toroidal, Mixed, Hydro, **BITANT** symmetry
- Soft (SFHo) and stiff (DD2) EOS
- $m_1/m_2 = 1, 1.2$



Symmetry breaking across the $z=0$ plane



Magnetic field amplification is affected by the initial topology of the field



How to capture the large magnetic field amplification after merger in numerical simulations?

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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);...

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We investigate the **KHI amplification** by means of a “**zoom-in**” simulation approach

FIRST: We run a global simulation of BNS merger

using **AthenaK**: <https://github.com/IAS-Astrophysics/athenak>

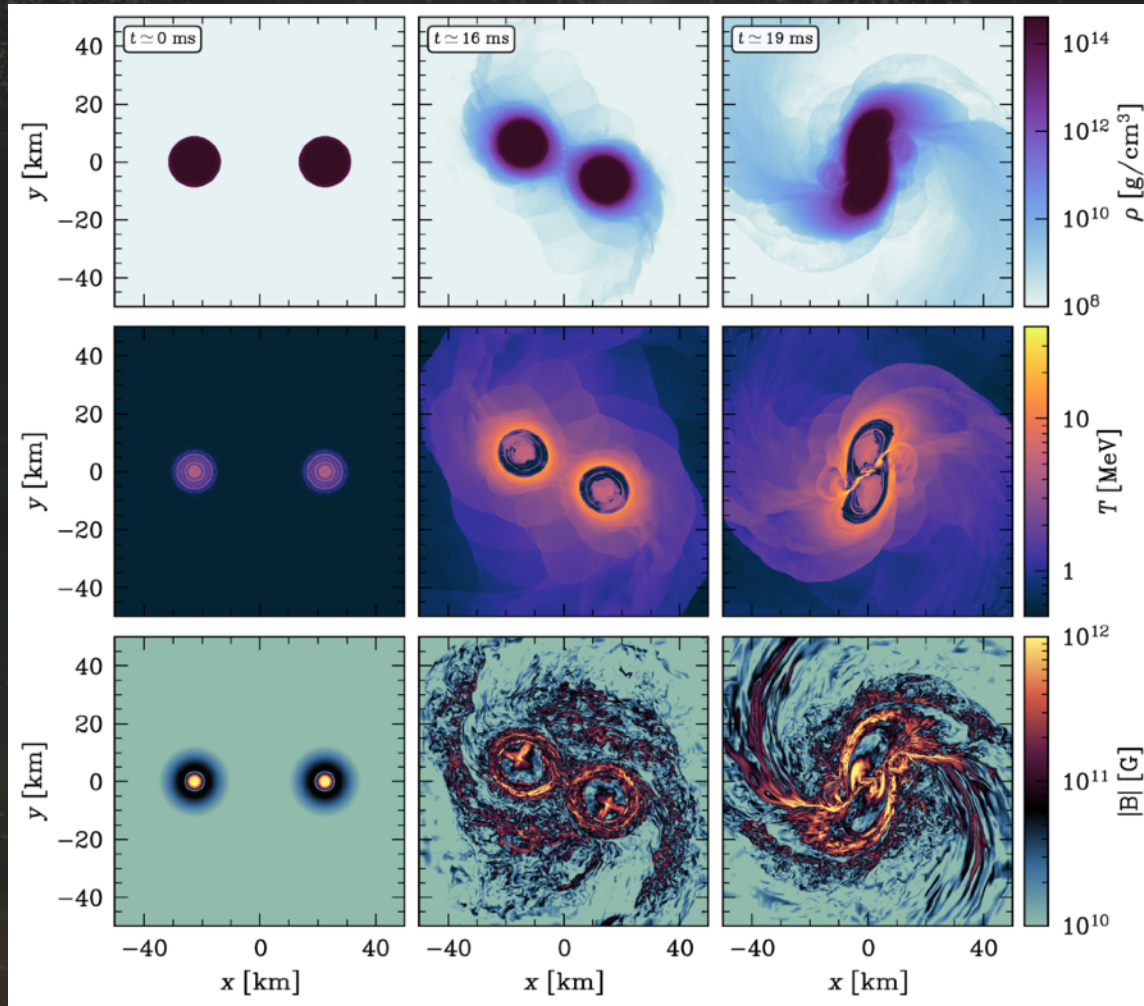
Stone+ (2026)
Zhu+ (2025)
Fields+ (2025)

- SFHo EOS (w/ trapped ν)
- $M_1 = M_2 = 1.3M_\odot$
- $B_{\text{surf}} \sim 10^{10}$ G
- $\Delta x \approx 92$ m

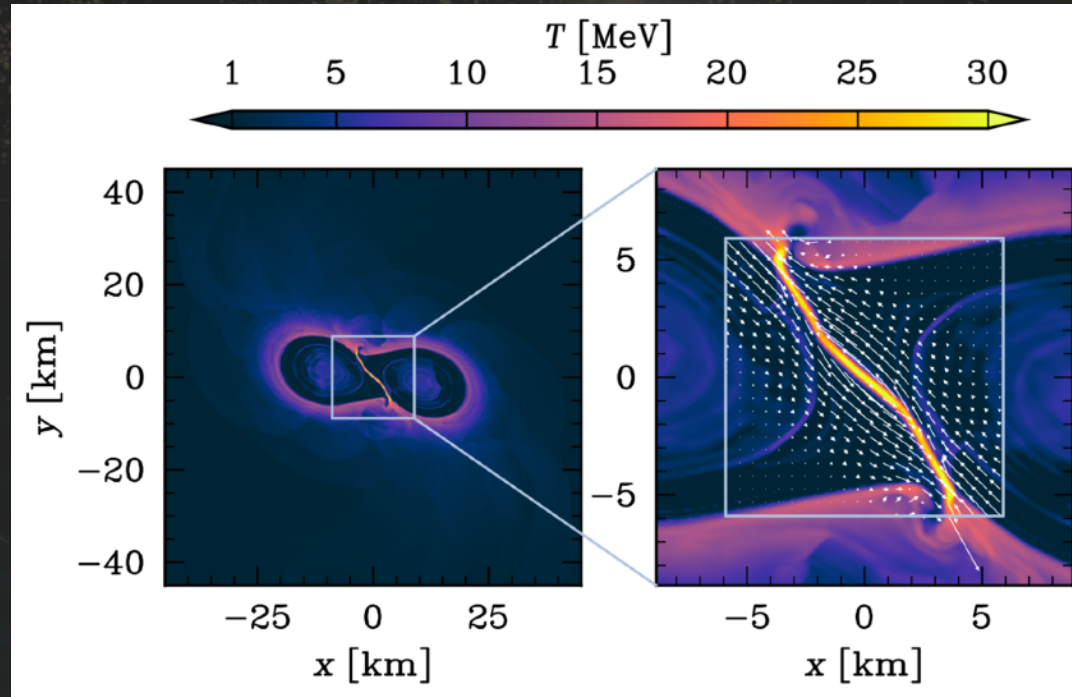
- $$\mathcal{A}_\phi = \frac{\pi r_0^2 I_0 \varpi^2}{(r_0^2 + r^2)^{3/2}} \left[1 + \frac{15 r_0^2 (r_0^2 + \varpi^2)}{8 (r_0^2 + r^2)^2} \right]$$



Global simulation evolved up to a few milliseconds after the merger. We record high-frequency data in the inner regions

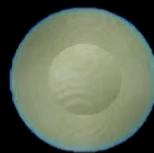


THEN: when the stars make contact, we map the region containing the hot shear-layer to a new “zoom-in” grid

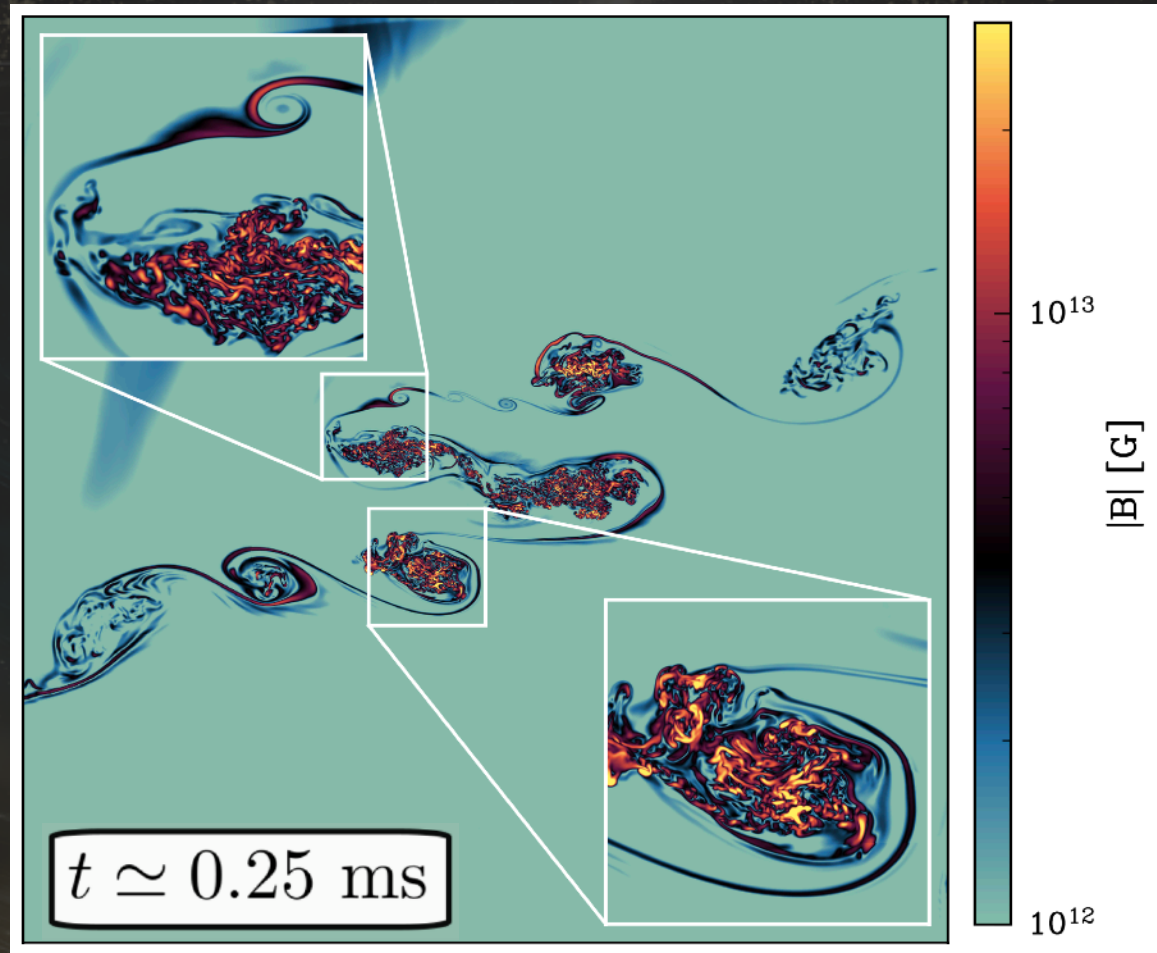


- We run a set of “**zoom-in**” simulations with resolutions: $\approx 92\text{m}$, 46m , 23m , 12.5m , 5.8m , 2.9m

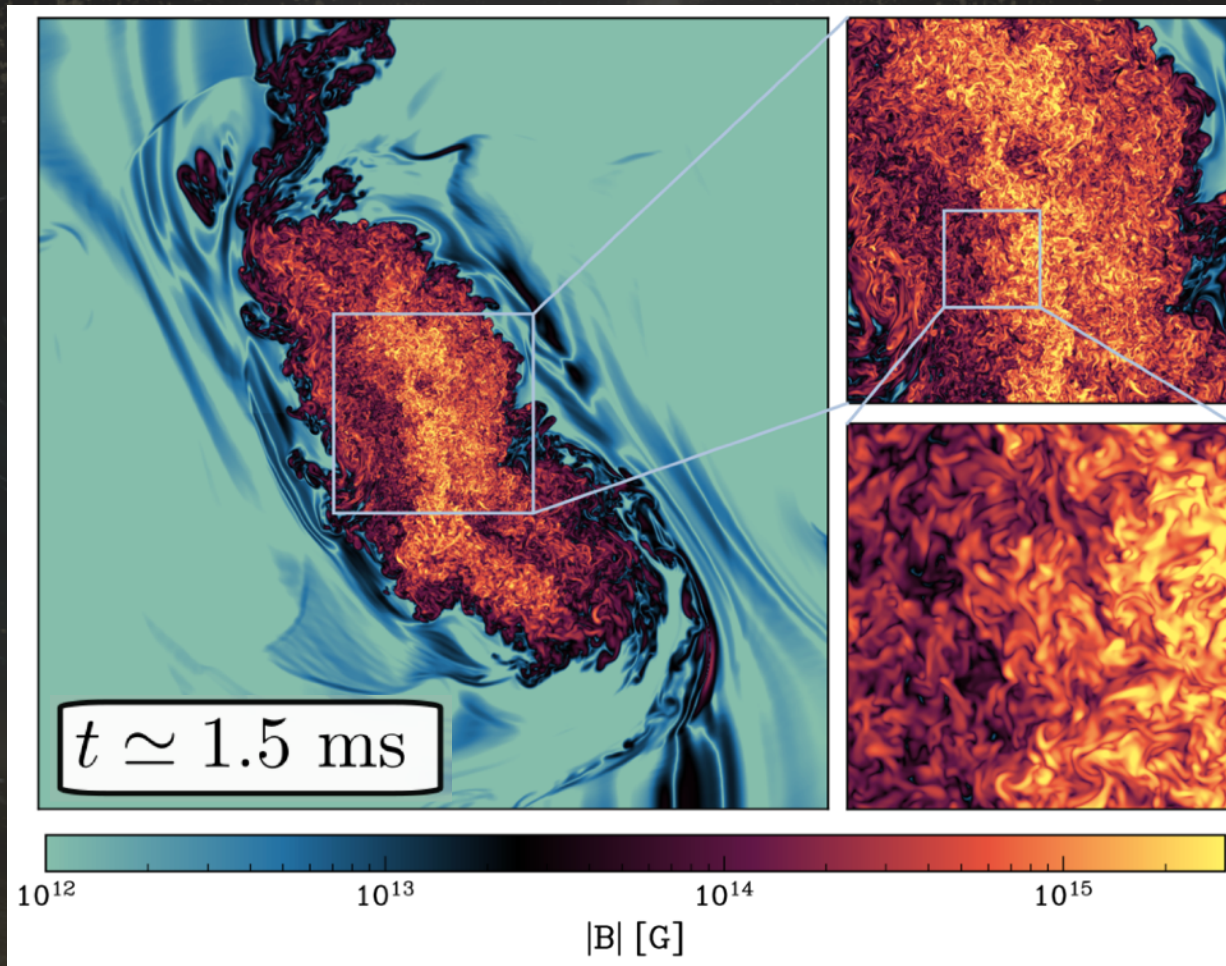
$t = 0.00 \text{ ms}$



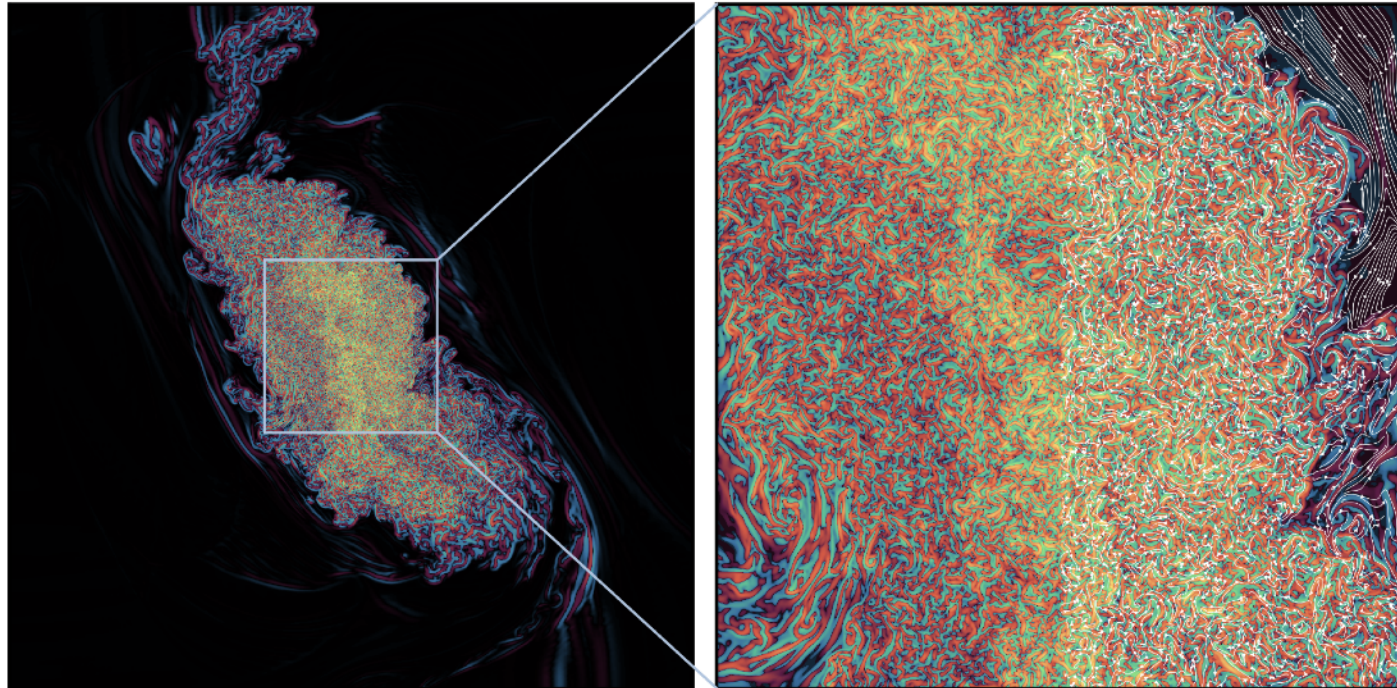
The shear layer rapidly becomes KHI-unstable and generates vortical structures where the field undergoes exponential amplification.



As vortices become themselves KHI-unstable, the shear layer grows in size, merge, and fill a large fraction of the volume with turbulent structures.

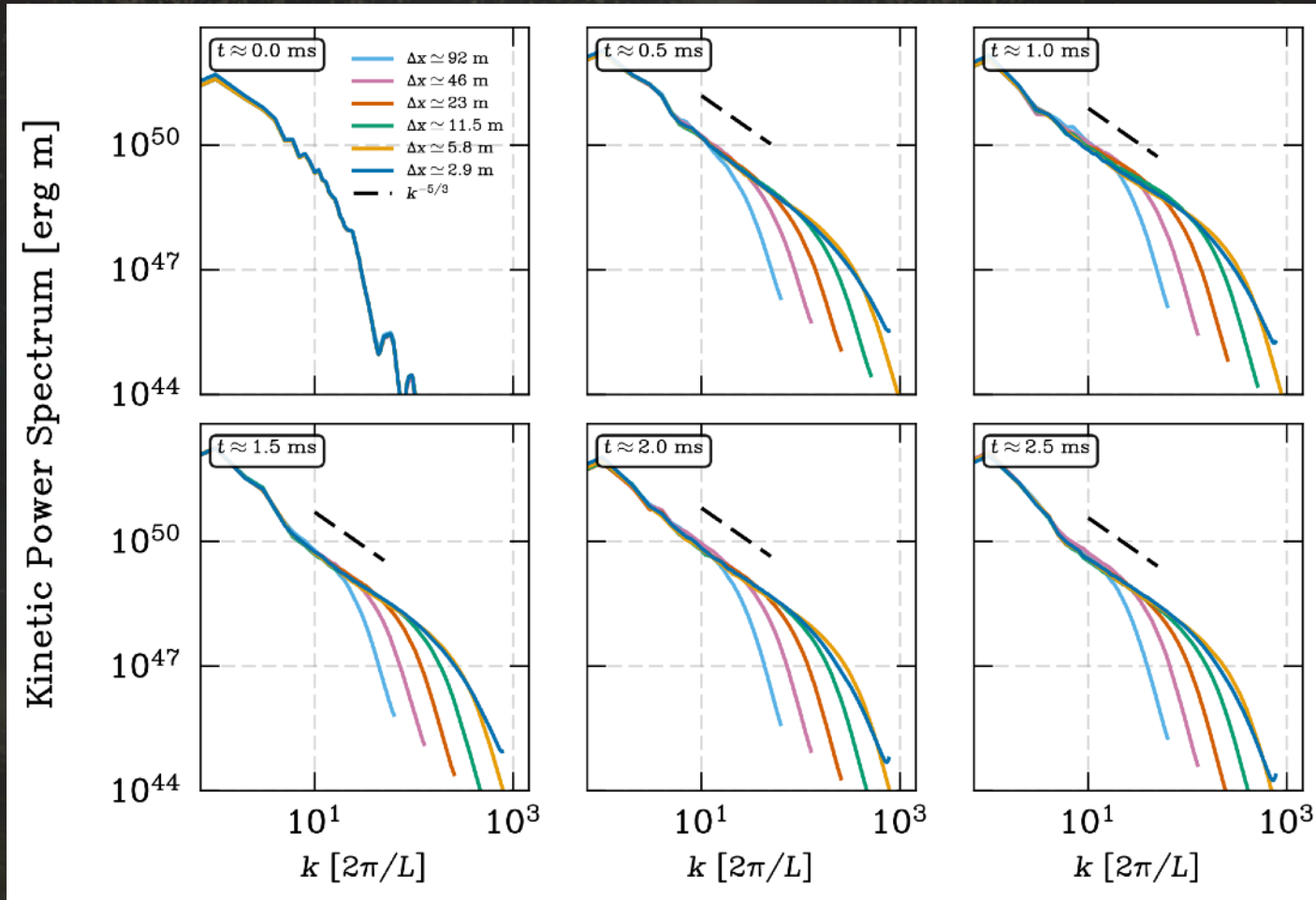


Small, intermittent current sheets form. The current density traces B field gradients, showing where the field is stretched, twisted, and folded

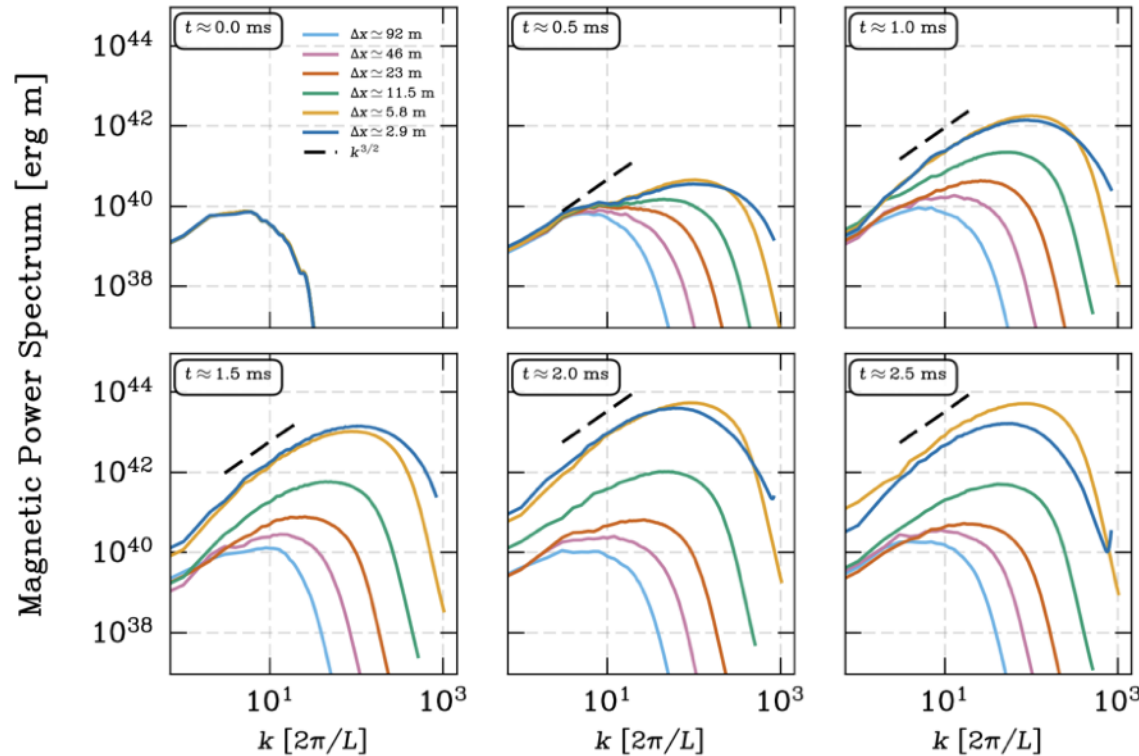


$$(\vec{J})_z \approx \frac{c}{4\pi} (\nabla \times \vec{B})_z \text{ [G/s]}$$

The velocity power spectrum rapidly develops a Kolmogorov power spectrum

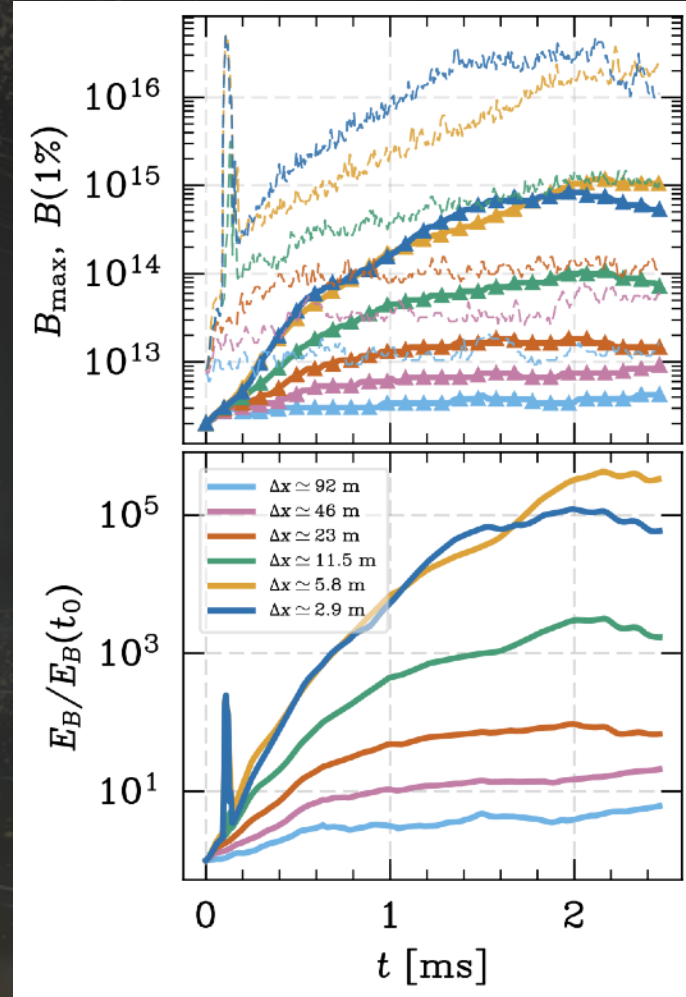


Magnetic spectrum suffers small-scale amplification; develops a Kazantsev power spectrum. At later times, magnetic field begins to grow at all wavelengths

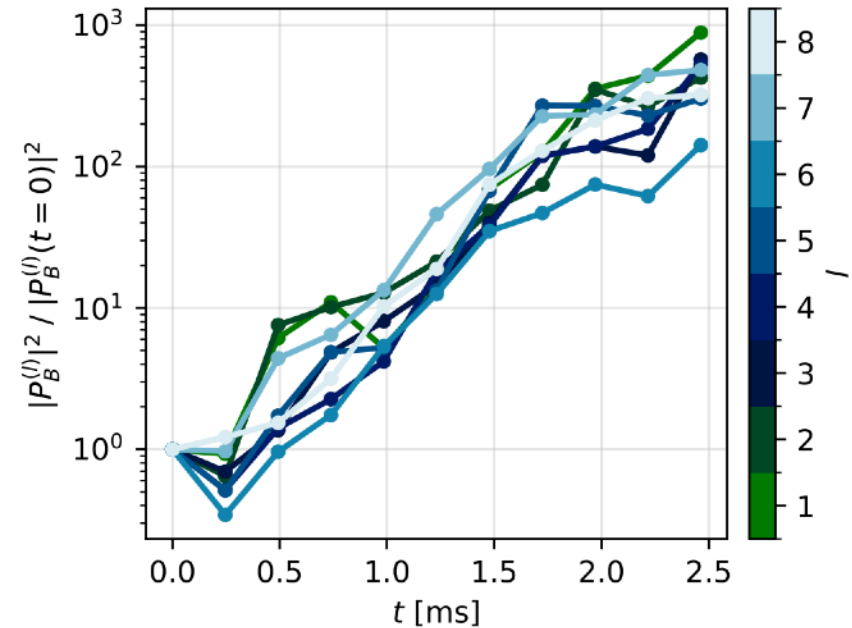
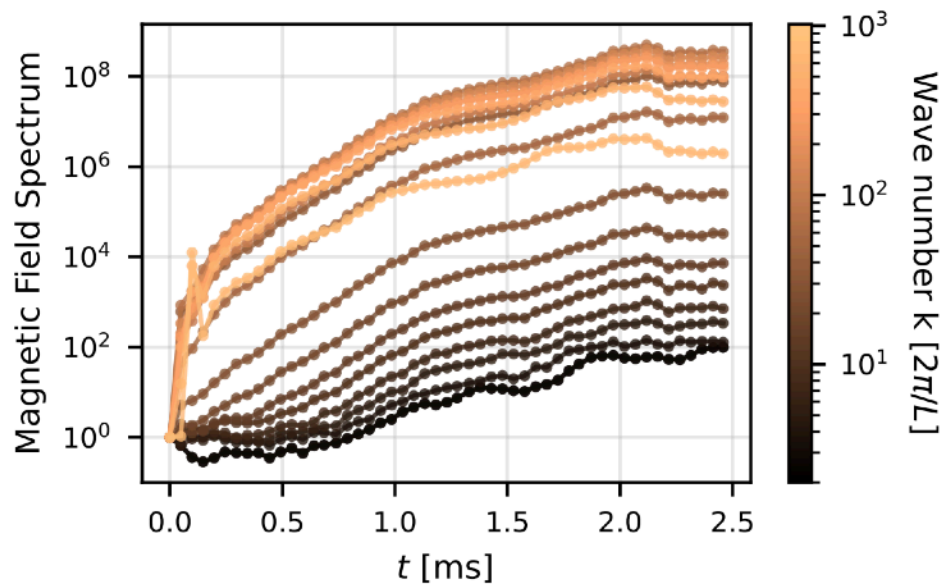


Similar results in global high-resolution BNS simulations

Kiuchi++ (2026)



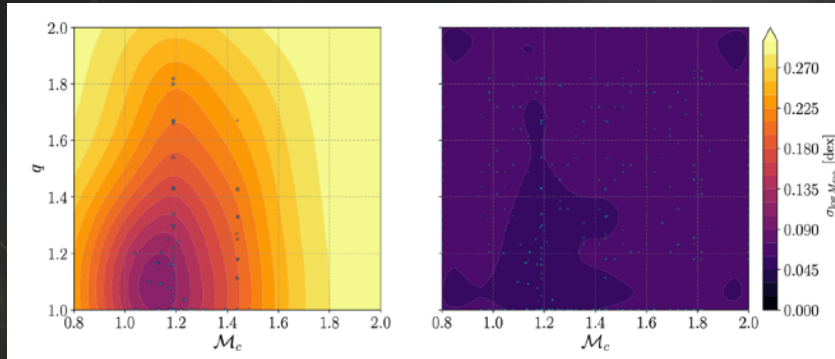
Magnetic power grows at all lengthscales once the small-scale field has reached sufficiently large amplitudes



Current/Future steps:

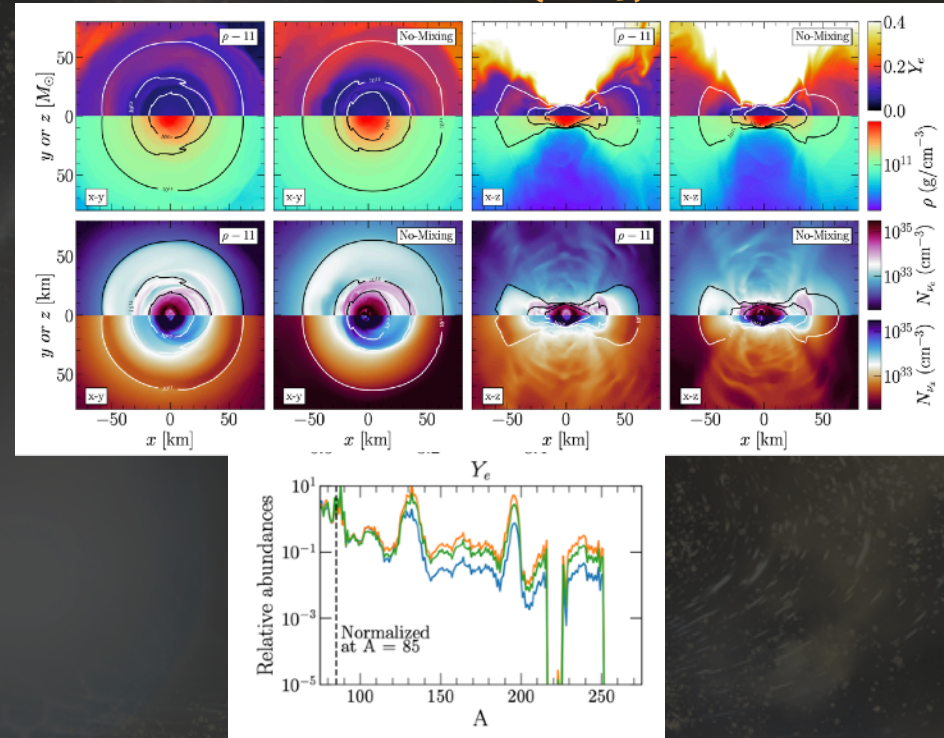
Train models to predict ejecta and disk masses from BNS systems: large number of simulations

Khadkikar+ (in prep.), Zhai++ (in prep.)



• Neutrino oscillations

Qiu++, PRL (2025)



• End-to-end BNS simulation: connect various simulation setups to follow BNS from merger to months/years after.

Smith Clark++ (in prep.)

Longo-Micchi++ (in prep.)

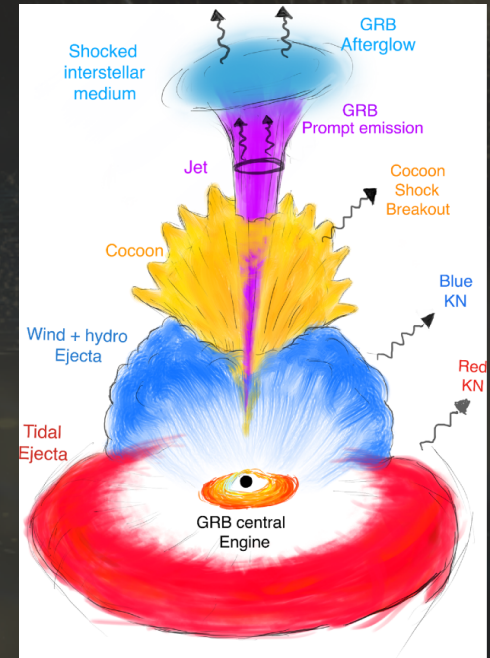
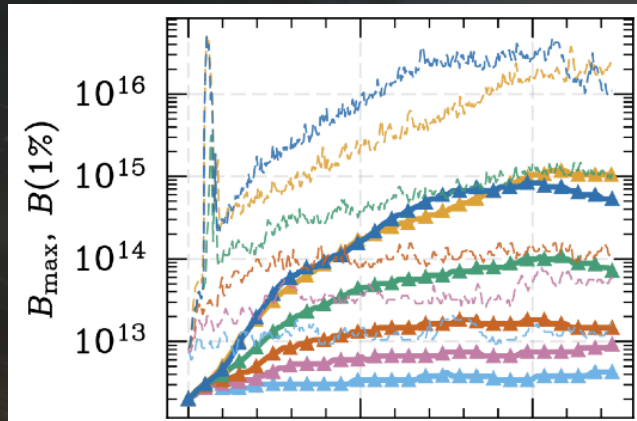
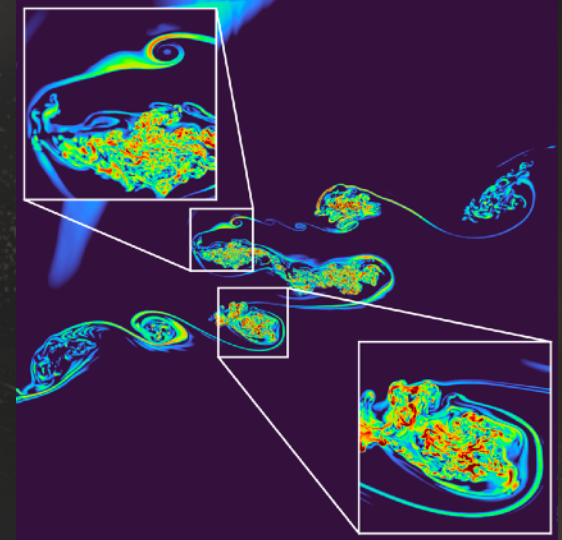
• Improve neutrino radiation transport:

• Full Boltzmann multi energy

Gutierrez++ (in prep.)

Summary

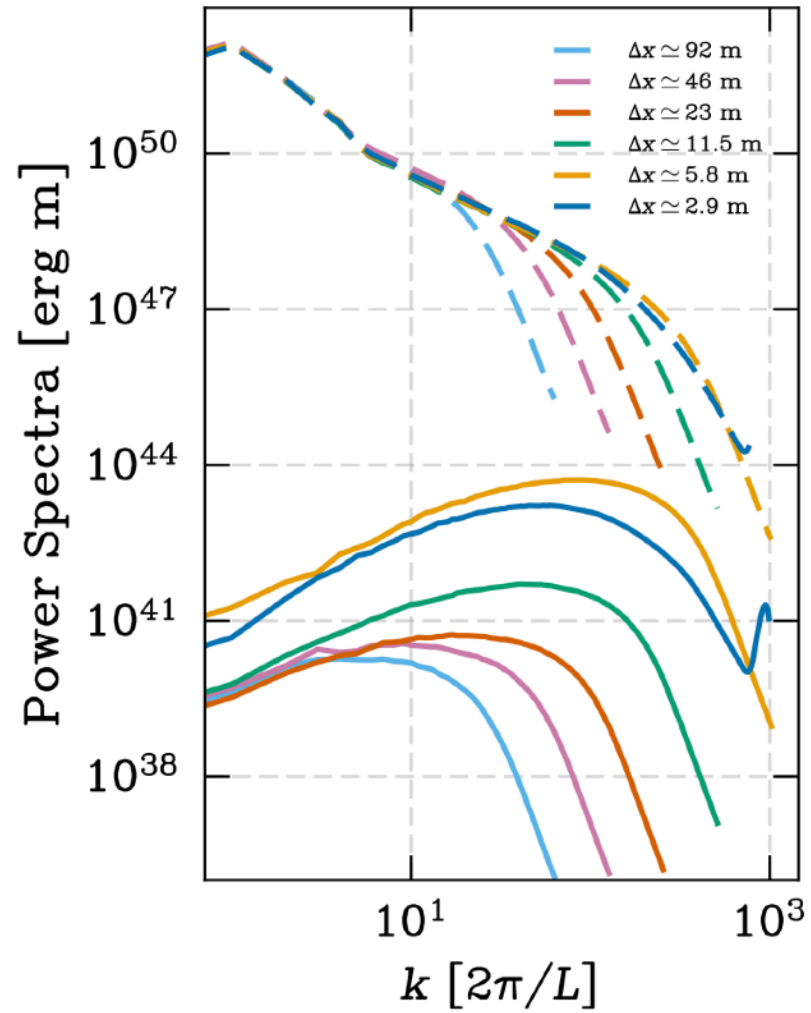
- Binary neutron star mergers are extreme events that both pose and help answer some of the biggest open questions in astrophysics.
- Huge 'zoo' of electromagnetic counterparts from different outflows.
- Magnetic fields play an essential role; difficult to track its evolution in simulations.





Backup slides

$t \approx 2.5 \text{ ms}$



During the global simulation, we record simulation data in a cube of side length $2L$, $L = 4.5 \text{ } GM_{\odot}/c^2 \simeq 6.65 \text{ km}$ centered about the origin. This data is used to provide initial data, boundary conditions, and background metric for the zoom-in simulations. To avoid possible boundary effects, the domain of the zoom-in simulations is restricted to a smaller cube with side length $2L'$, $L' = 4 \text{ } GM_{\odot}/c^2 \simeq 5.91 \text{ km}$. The data is stored on a Chebyshev endpoint grid with $N = 64$ points in each direction and sampled with a frequency of $\Delta t = 0.09375 \text{ } GM_{\odot}/c^3 \simeq 0.46 \text{ } \mu\text{s}$. In particular, we store and interpolate the fluid baryon number density n_b , the Lorentz-factor-weighted three velocity $\tilde{v}^i = Wv^i$, W being the Lorentz factor, the pressure p , and the proton fraction Y_e of the plasma. The spacetime geometry is encoded in the lapse and shift vectors α and β^i , respectively, the three metric γ_{ik} , and the extrinsic curvature, K_{ik} . See, e.g., Ref. [53] for a definition of these

We interpolate all fields, except for the magnetic field (which is described in detail below), using 6th order Lagrange interpolation on the Chebyshev grid. This results in a speedup of a factor $\sim (N/5)^3 \simeq 2 \times 10^3$ compared to the direct evaluation of the Chebyshev collocation basis, which would have been prohibitively expensive, as we need to interpolate spacetime data and boundary conditions at each timestep of the zoom-in simulation. We have verified that the error introduced by this truncation of the interpolation stencil is negligible, as

Still, unphysical artifacts can be expected if the initial magnetic field is not solenoidal. As a first step, we reconstruct the vector potential using the identity [55]

$$\mathcal{A}_i(x) = \int_0^1 \epsilon_{ijk} \mathcal{B}^j(\lambda x) x^k \lambda \mathrm{d}\lambda, \quad (2)$$

where ϵ_{ijk} is the antisymmetric symbol with $\epsilon_{123} = 1$. The integral in Eq. (2) is computed in pre-processing for each grid point using a Gaussian quadrature with 12 points. To this aim, the $\mathcal{B}$ field data is interpolated to the quadrature points using a 10th order accurate Lagrange interpolation.

Next, we interpolate the vector potential $\mathcal{A}_i$ at the cell edges of the zoom-in grid, using the same 6th order interpolation approach as for the other variables, and evaluate

$$\mathcal{B}^i = \epsilon^{ijk} \partial_j \mathcal{A}_k \quad (3)$$

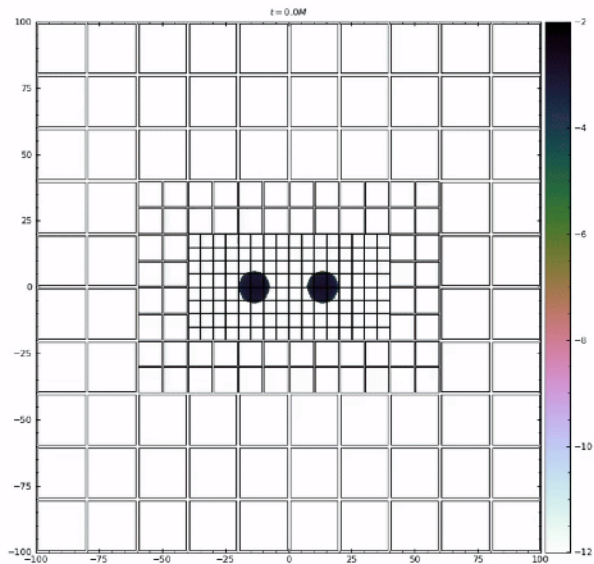
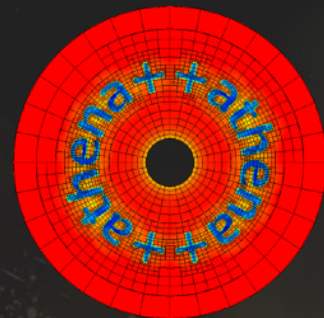
using the discrete curl operator consistent with the constrained-transport of AthenaK, e.g.,

$$\mathcal{B}_{k,j,i+1/2}^1 = \frac{(\mathcal{A}_3)_{k,j+1/2,i+1/2} - (\mathcal{A}_3)_{k,j-1/2,i+1/2}}{\Delta x^2} - \frac{(\mathcal{A}_2)_{k+1/2,j,i+1/2} - (\mathcal{A}_2)_{k-1/2,j,i+1/2}}{\Delta x^3}, \quad (4)$$

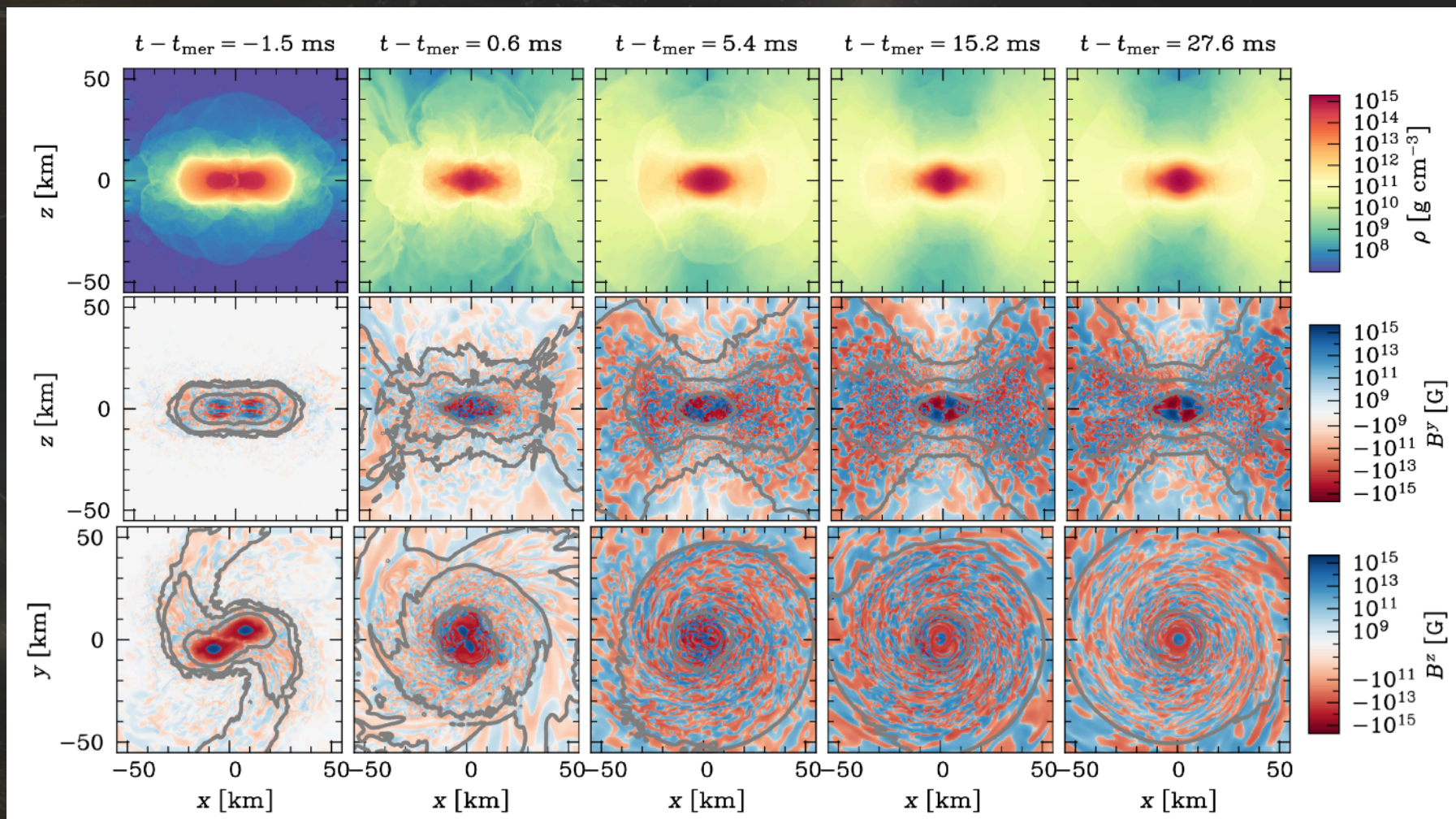
GR-Athena++

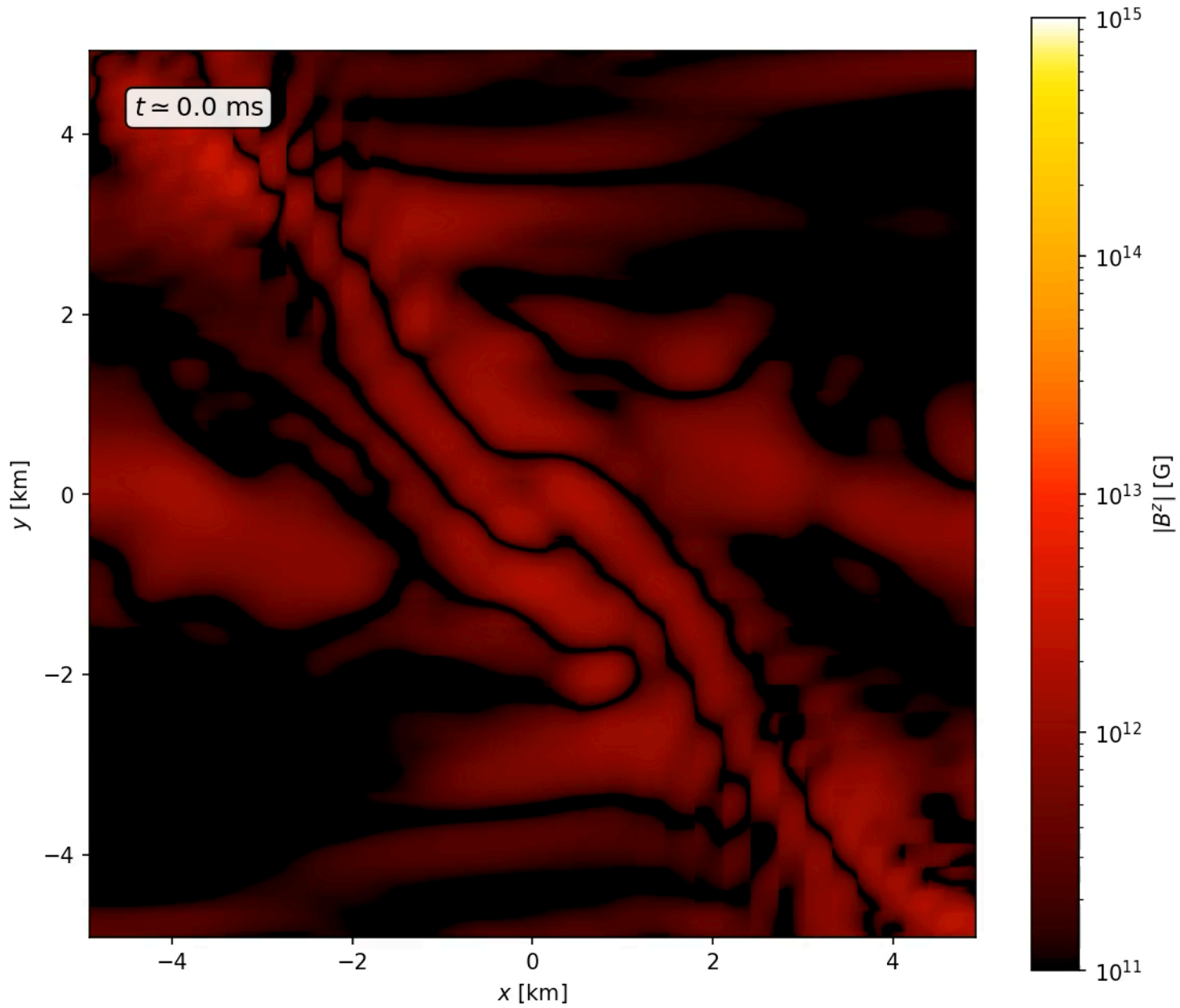
<https://github.com/computationalrelativity/gr-athena>

- Stone+ (2020)
- Daszuta+ (2021)
- Cook+ (2025)
- Daszuta+ (2026)

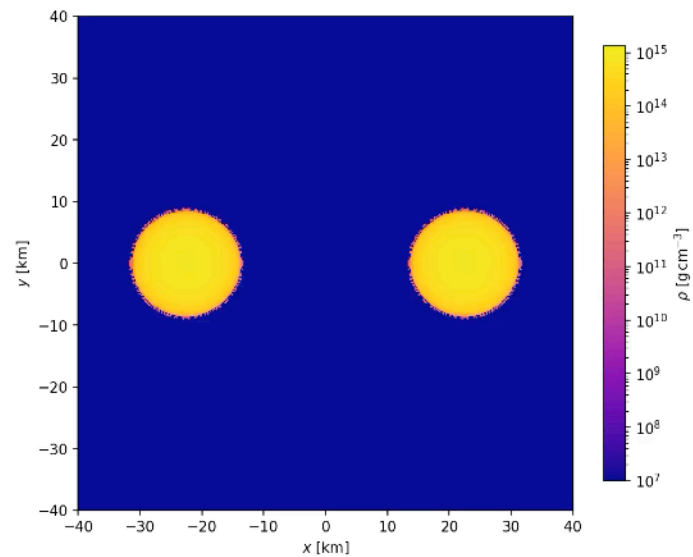
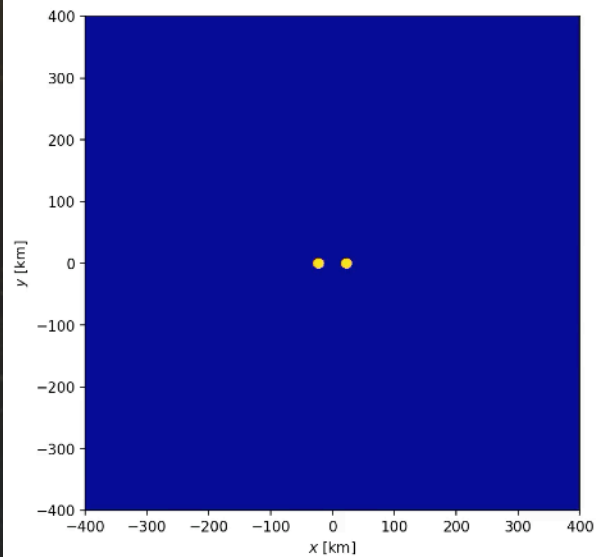


- ◆ **Extension of Athena++ to dynamical spacetimes (Z4c evolution)**
- ◆ **Block-based AMR, CT**
- ◆ **Valencia formulation of MHD**
- ◆ **Tabulated Nuclear EOS**
- ◆ **M1 neutrino transport**





hydro.prim.rho (snap 00000)



field.aux.B2 (snap 00000)

