Simulating magnetic field amplification by the Kelvin-Helmholtz dynamo in neutron star mergers

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Background

Neutron Star (NS): Extremely dense core of collapsed massive stars

Instability: System in which perturbations grow exponentially

Turbulence: Disorderly fluid state characterized by vortex motion and energy dissipation

Dynamo: Self-sustaining process where turbulence within a conducting fluid amplifies an existing magnetic field

Neutron Star Mergers

- Gravitational waves emitted during inspiral as stars spiral in.
- **Short-lived coalescense phase in which stars merge.**
- Particles and gamma rays are emitted during accretion as energy is released.
- Lower-energy waves continue to be emitted from collision remnant.

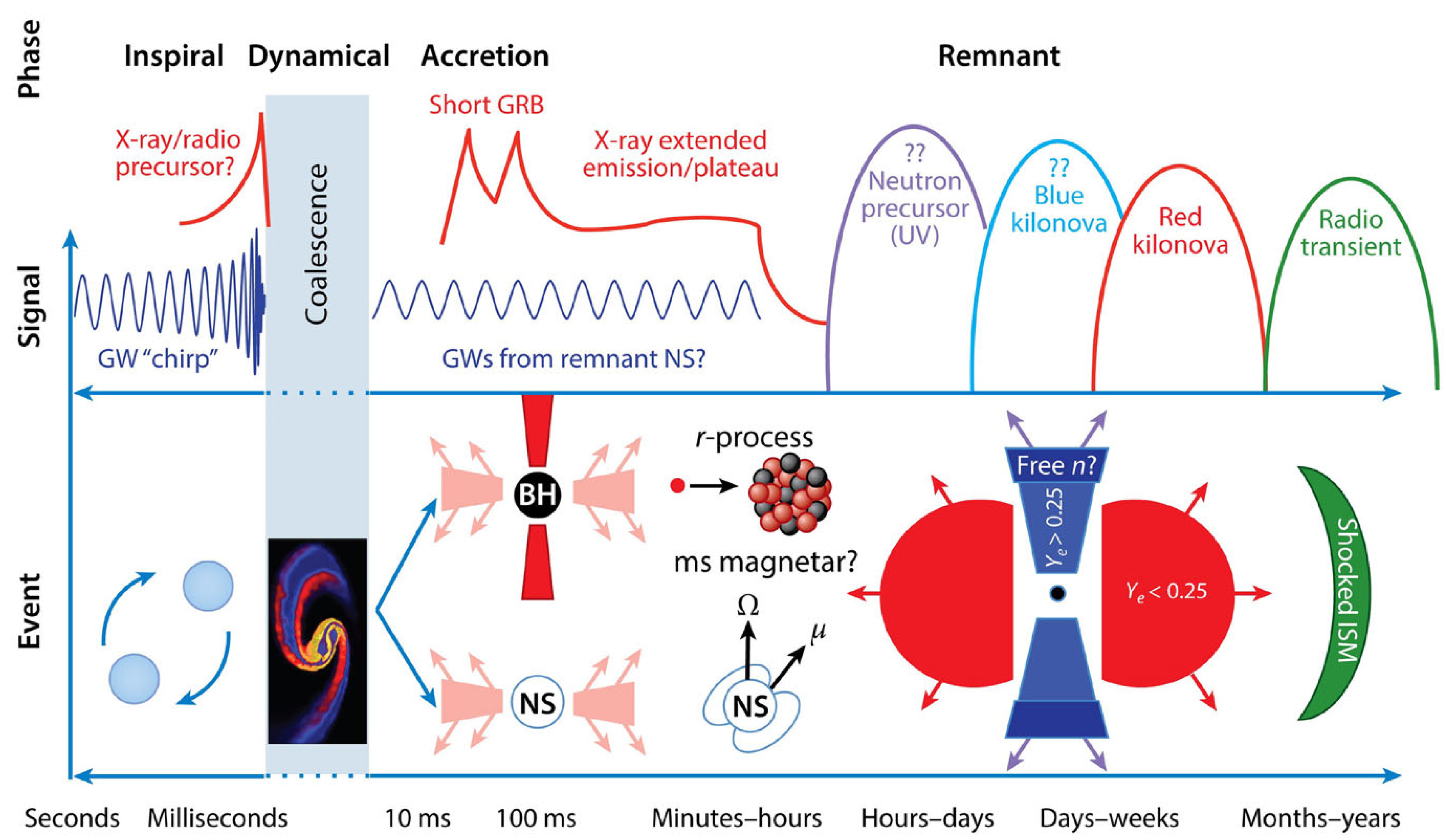

Figure 1. Summary of the phases of a neutron star collision (Burns, 2020)

Background research

- Palenzuela et al. (2022) applied GRMHD (general relativity magnetohydrodynamics) to simulate coalescence phase of neutron star collision.
- Magnetic field amplified in Kelvin-Helmholtz instability in core of merging system.
- Required to mathematically approximate dynamo, rather than simulate turbulent flow due to immense computational complexity of simulation.

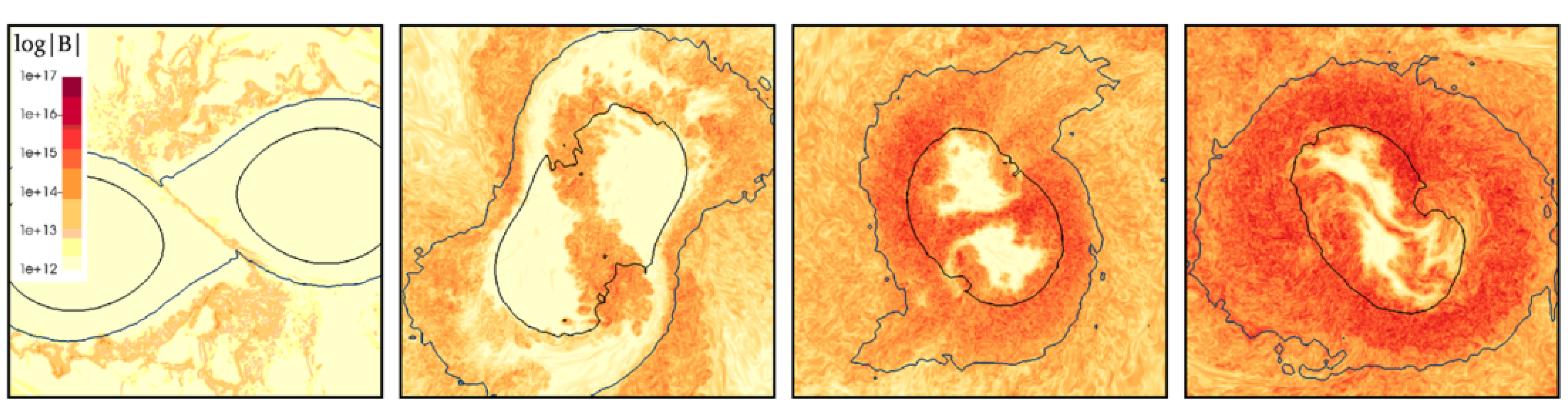

Figure 2. Magnetic field development in GRMHD neutron star merger simulation (Palenzuela et al., 2022)

The Kelvin-Helmholtz instability

- Opposing fluid velocity layer produces unstable system.
- Initially when perturbed, wavelike "lumps" develop.
- Eventually becomes turbulent as waves grow and interact.

Figure 3. Clouds formed by the Kelvin-Helmholtz instability in the Earth's atmosphere (Rachel Gordon/BBC)

Methods

- Used spectral MHD solver SpectralDNS (Mortensen and Langtangen, 2016) to simulate the Kelvin Helmholtz insatability on Columbia Ginsburg cluster.
- Initialized model with weak magnetic field and small velocity perturbations.
- Ran simulation until magnetic field stabilized.
- Recorded magnetic energy spectrum and growth rate.

Results

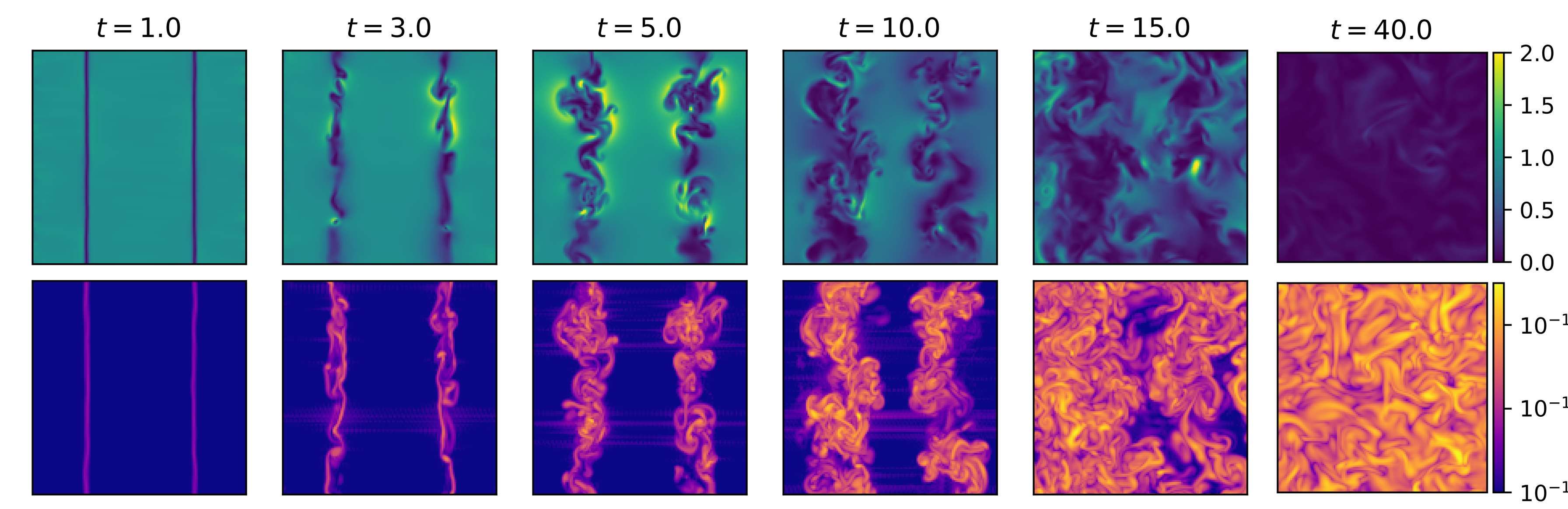

Figure 4. Kinetic (top) and magnetic (bottom) field strength at selected timesteps.

- 3-dimensional waves and eddies develop before turbulence onset.
- Magnetic field grows first during wavelike KH growth phase and then again during early development of turbulence.
- Kinetic energy dissipates during turbulence while magnetic field stays stable.
- Dynamo efficiency dependent on fluid velocity, i.e., dies down as turbulence dissipates.

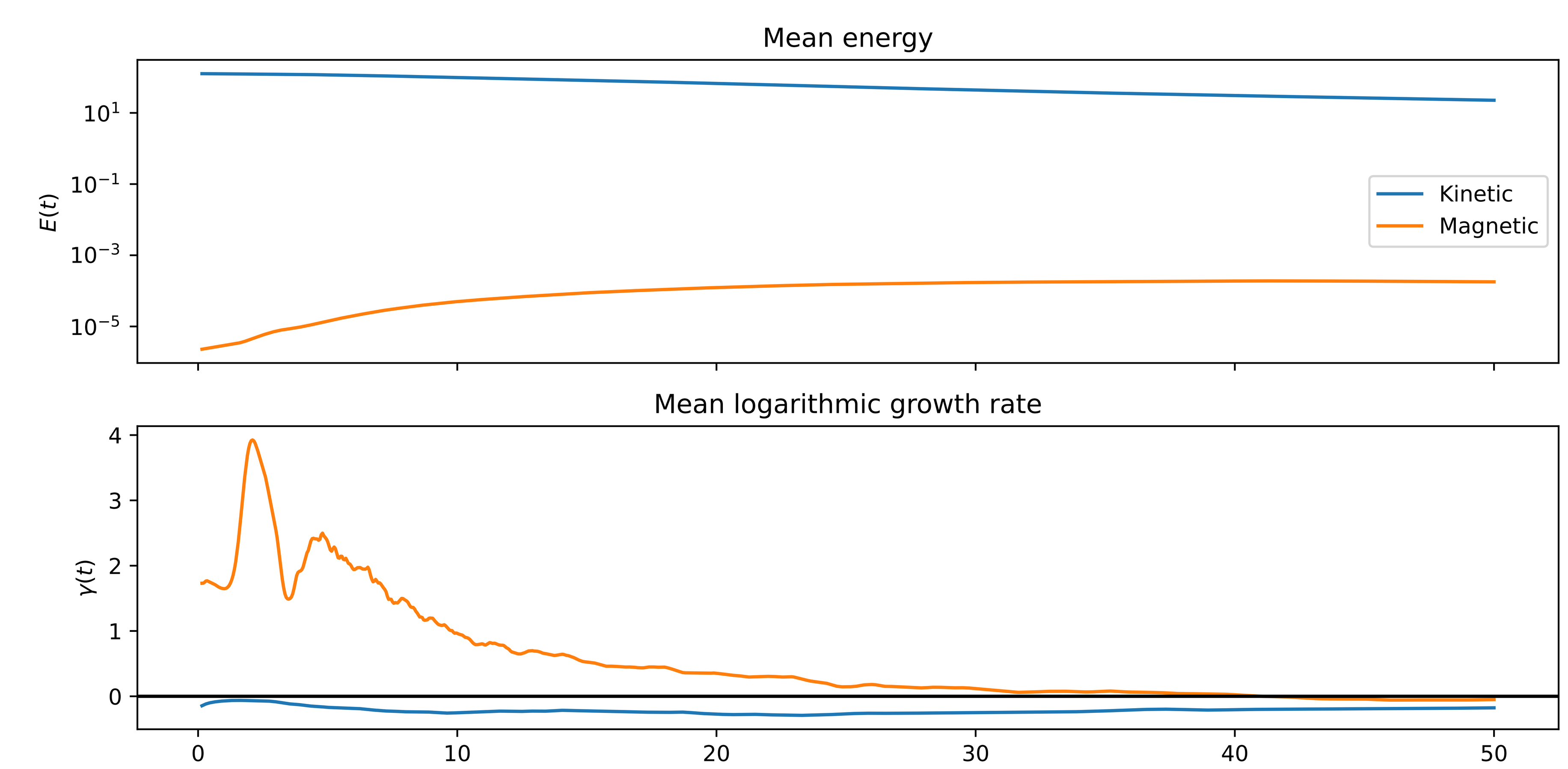

Figure 5. Kinetic and magnetic mean energy and logarithmic field growth rate.

Conclusions

- Successfully simulated MHD system with realistic initial conditions.
- The Kelvin Helmholtz instability can produce an efficient dynamo.
- Magnetic field is amplified mostly during early coalescence.

Next steps

- Rerun simulations under different choices of Reynolds number/viscosity
- Introduce angular momentum of neutron stars.
- Calculate relationship between maximum dynamo growth rate and Reynolds number to produce theoretical model.
- Combine results with large-scale understanding towards a theory of GRB origin.

References

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Palenzuela, C., Aguilera-Miret, R., Carrasco, F., Ciolfi, R., Kalinani, J. V., Kastaun, W., Miñano, B., and Viganò, D. (2022). Turbulent magnetic field amplification in binary neutron star mergers. *Physical Review D*, 106(2):023013.

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