Modeling Magnetic Field Amplification in Neutron Star Mergers

Ben Goldman, Columbia University

Question

How do colliding neutron stars transform their kenetic energy into magnetic energy?

Background

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

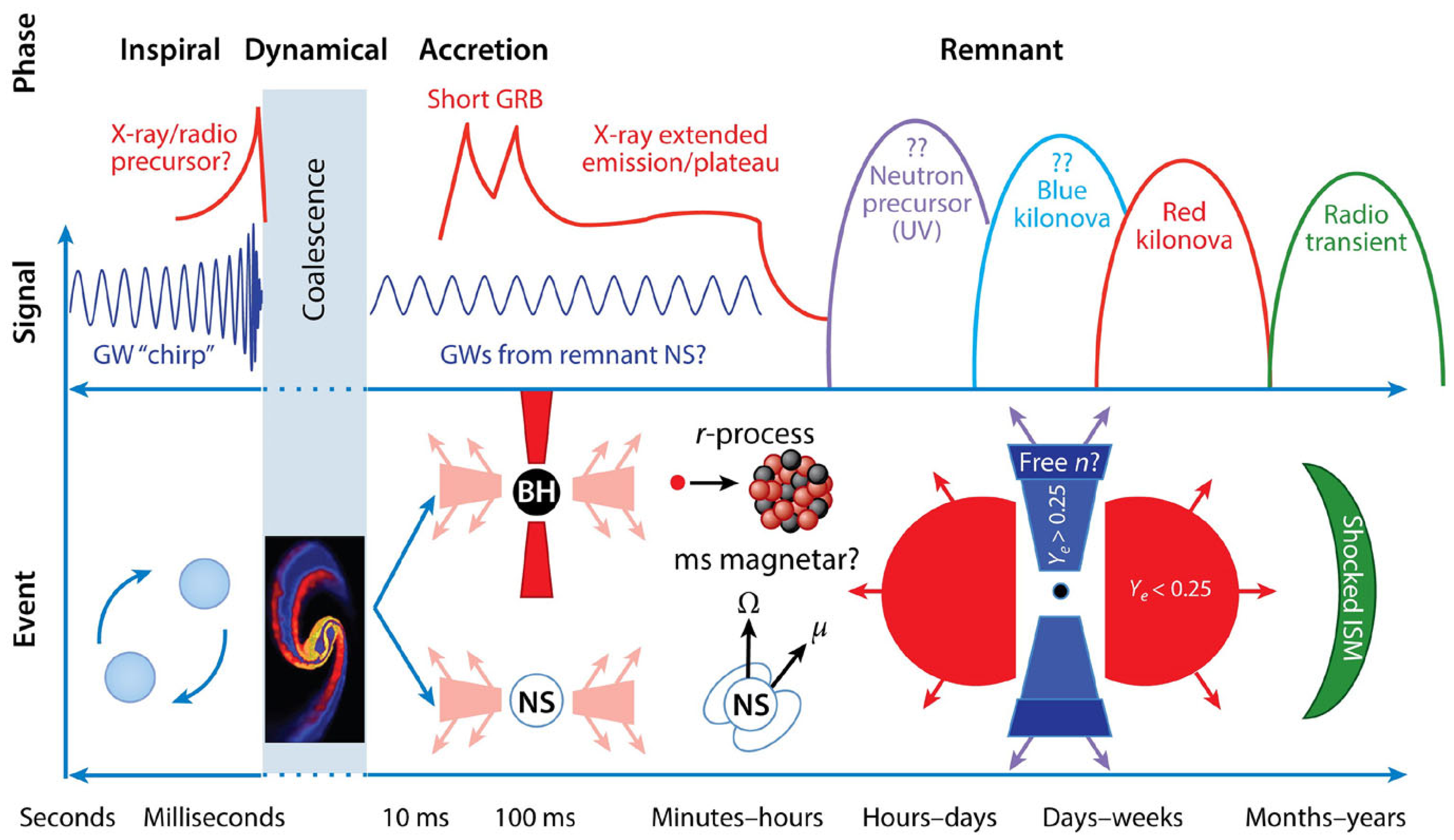
Instability: System in which perturbations grow exponentially

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

- Extremely strong magnetic field produces gamma-ray burst and particle jets.
- NSes merge **very** rapidly during coalescence.



Past research

- Applied GRMHD (general relativity magnetohydrodynamics) to simulate coalescence phase of neutron star collision (Palenzuela et al., 2022).
- 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.

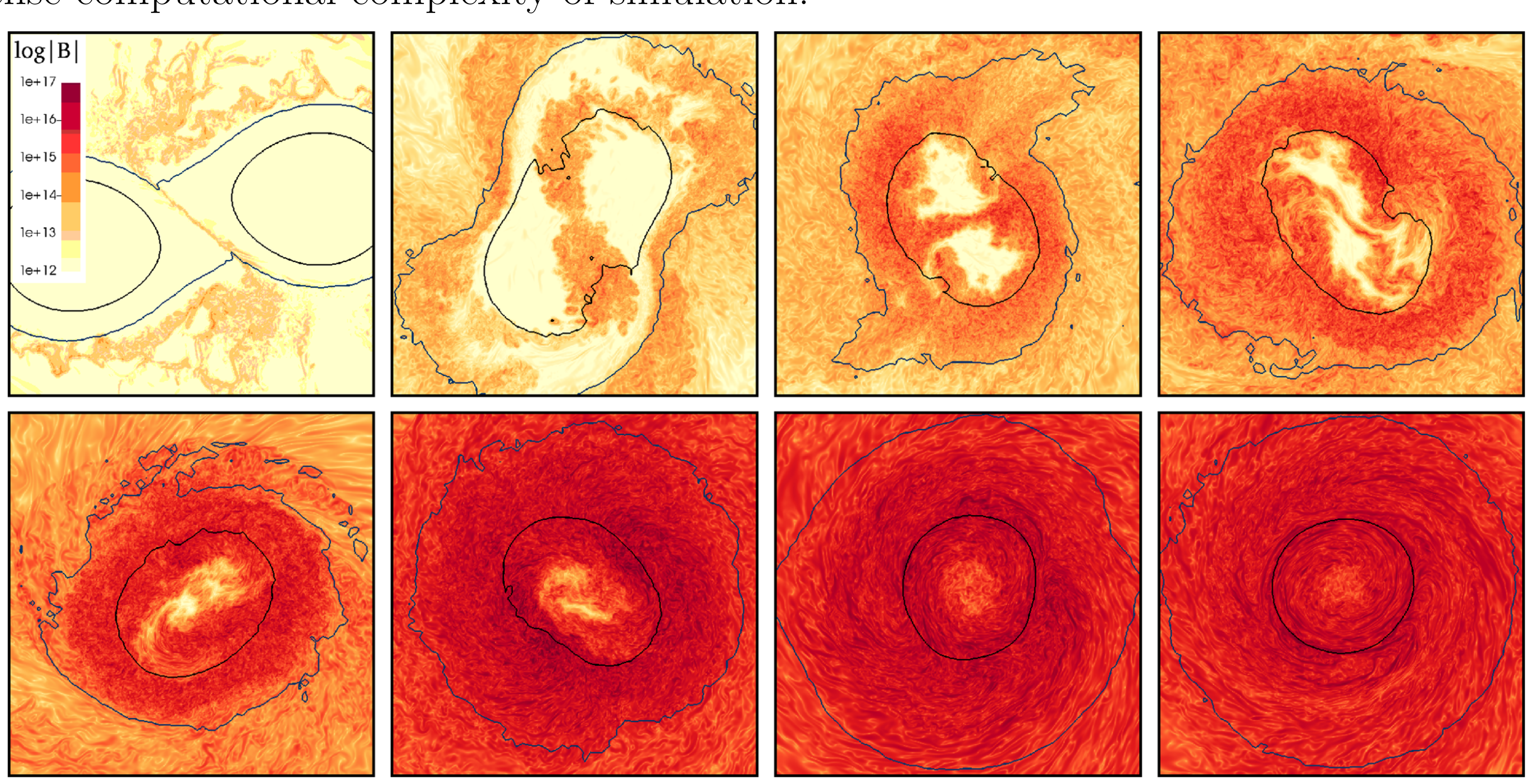


Figure: Magnetic field development in simulated neutron star collision (Palenzuela et al., 2022)

The Kelvin-Helmholtz instability

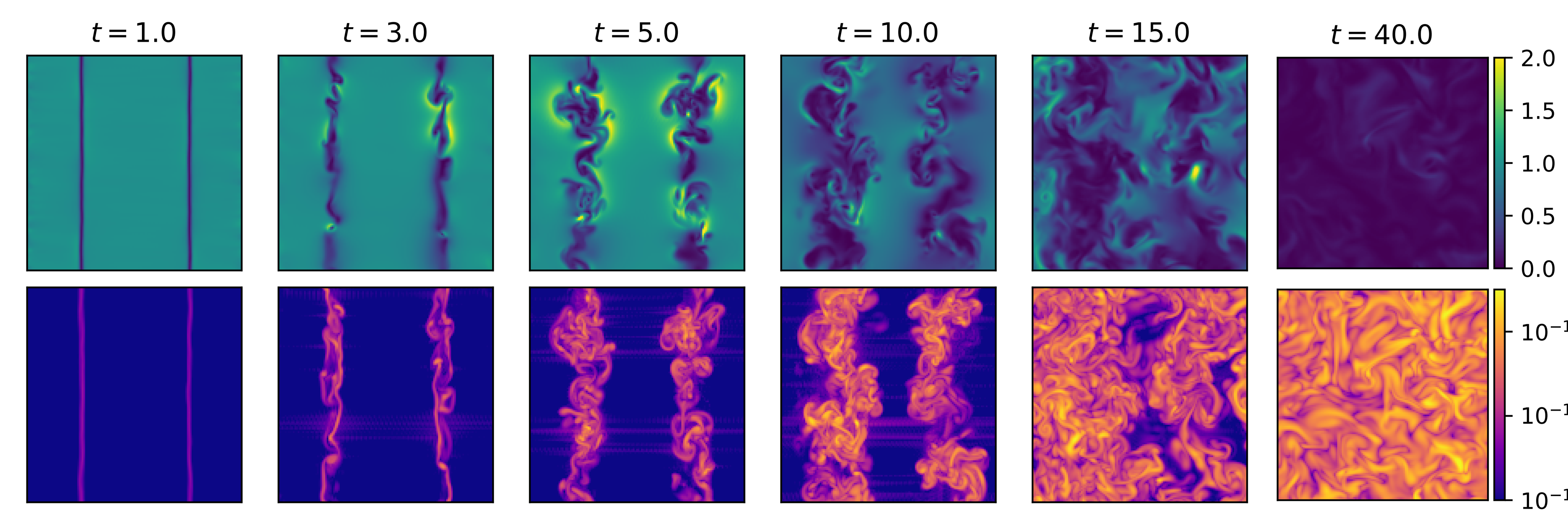
- Opposing fluid velocity layer produces unstable system.
- Initially when perturbed, wavelike "lumps" develop.
- Eventually becomes turbulent as waves grow and interact.

Mature Kelvin Helmholtz instability in the Earth's atmosphere (Rachel Gordon/BBC)

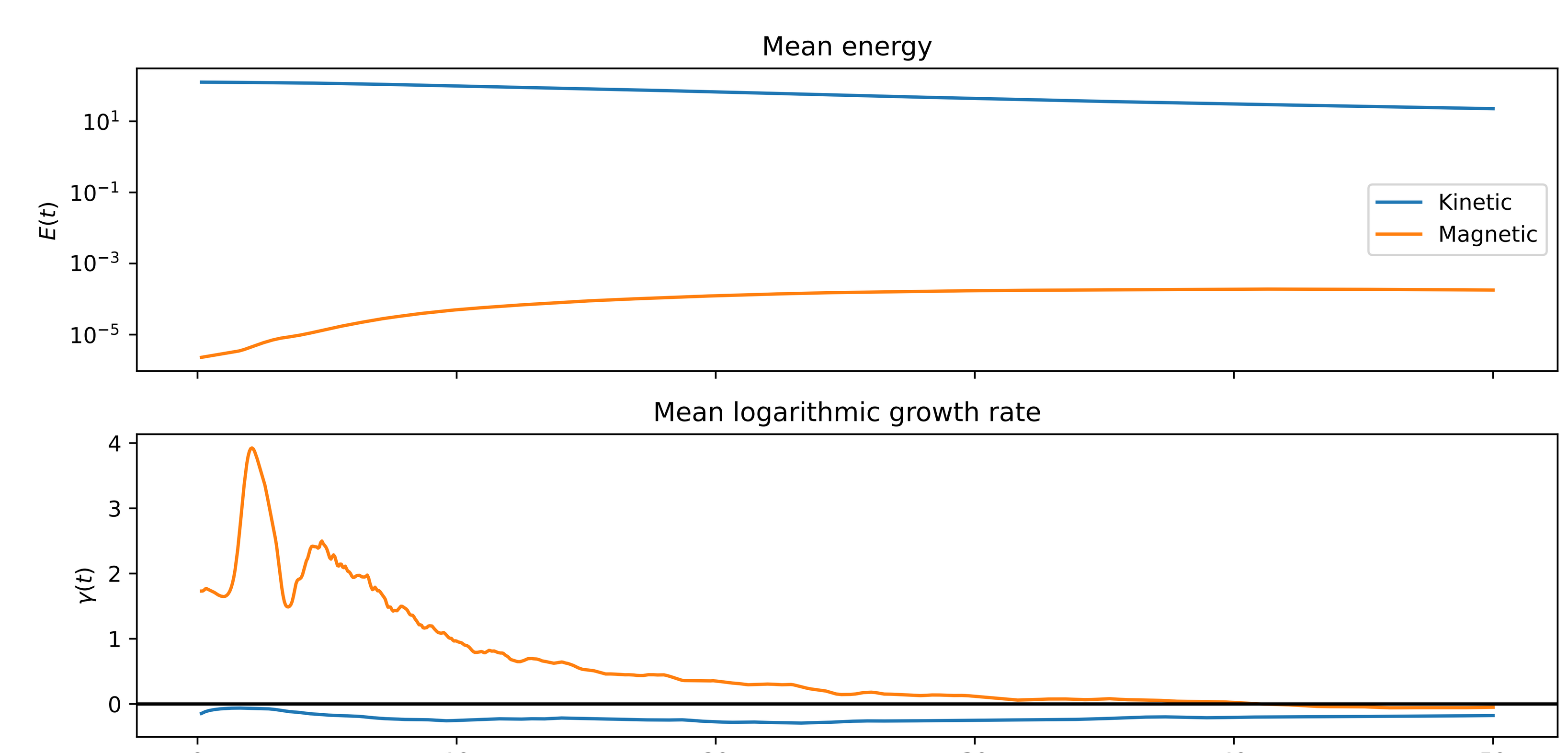
Methods

- 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



- 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.



Conclusions

- 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.
- Introduce angular momentum of neutron stars.

References

Burns, E. (2020). Neutron star mergers and how to study them. *Living Reviews in Relativity*, 23(1):4.

Mortensen, M. and Langtangen, H. P. (2016). High performance Python for direct numerical simulations of turbulent flows. *Computer Physics Communications*, 203:53–65.

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.