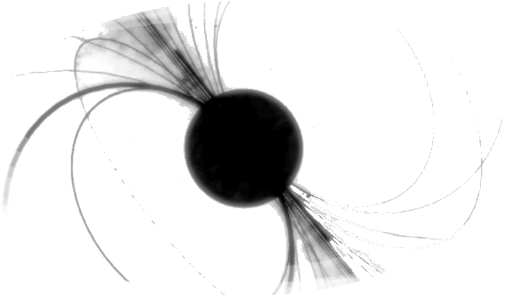
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

MAGNETIC FIELDS IN GRMHD SIMULATIONS OF BNS MERGERS

May 2022



Pedro Espino

Penn State

INTRODUCTION

INTRODUCTION

- GW170817 + associated EM counterparts have proven crucial for understanding many phenomena including:
  - BNS mergers as sites of short gamma-ray bursts (sGRBs)
  - important constraints on the nuclear EOS

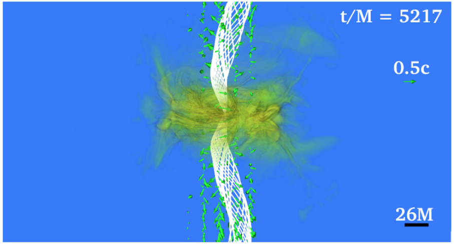
- presently, the best methods for understanding the most extreme parts of the merger (the merger itself and the post-merger environment) reside within numerical relativity

- the effect of magnetic fields during the different stages of the merger remain poorly understood, with only a handful of studies having been carried out

OPEN QUESTIONS: JET FORMATION AND SGRBS

What was the GRB central engine?

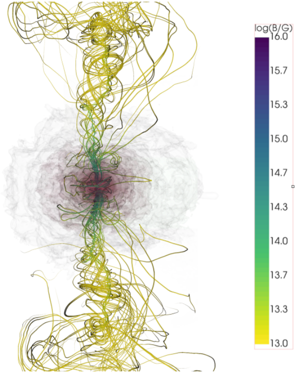
BH central engine



[1]

Ruiz et al., Astrophys.J.Lett. 824 (2016) 1, L6
Paschalidis et al., Astrophys.J.Lett. 806 (2015) 1, L14

Magnetar central engine



[2]

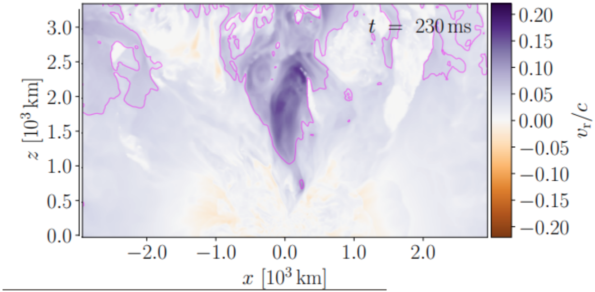
see also: Mosta et al., Astrophys.J.Lett. 901 (2020) L37

---

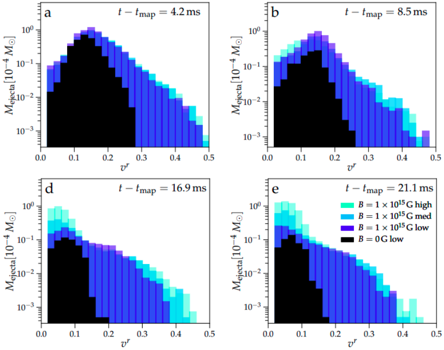
[1] Ruiz et al., Phys.Rev.D 104 (2021) 12, 124049
[2] Ciolfi et al., Mon.Not.Roy.Astron.Soc. 495 (2020) 1, L66-L70

OPEN QUESTIONS: EJECTA AND KN

- → For the typical post-merger magnetic energies, up to 0.1 $M_\odot$ of mass outflow at $\sim 300km$ (even if only a small fraction of this unbound, it can make up the majority of the ejecta)
- → With magnetic fields, ejecta is more collimated (mostly around half-opening angle of $\theta \sim 30^o$, and can be boosted to velocities of up to 0.2c



3



4

---

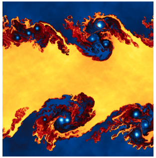
[3] Ciolfi et al., Astrophys.J.Lett. 900 (2020) 2, L35

[4] Mosta et al., Astrophys.J.Lett. 901 (2020) L37

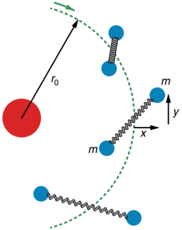
CHALLENGES

FIELD AMPLIFICATION

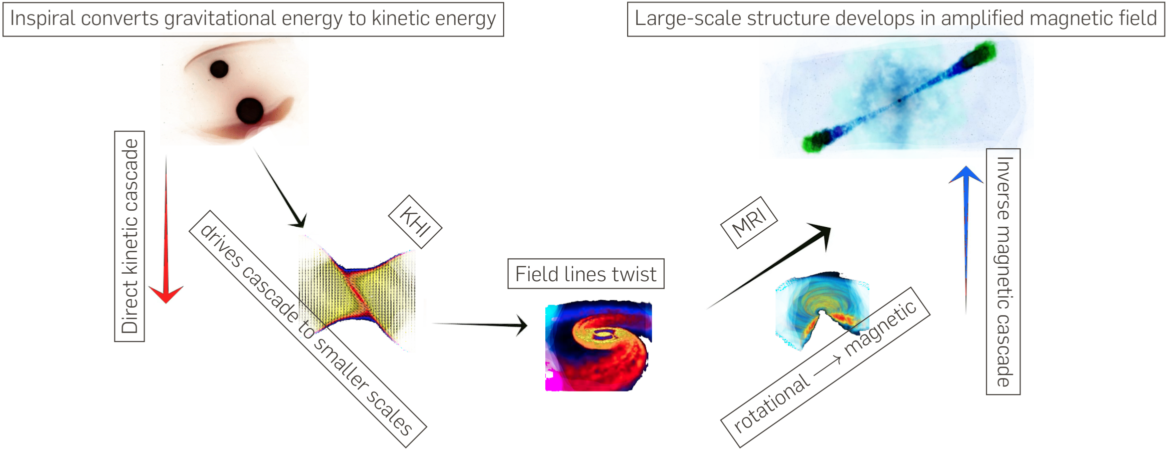
- Inspiral fields expected to be $\sim 10^{10} - 10^{12}\,G$
- Post-merger fields can be amplified as high as $10^{15} - 10^{17}\,G$
- Three relevant mechanisms for field amplification during and after merger include
  - Magnetic winding: Arises from differential rotation, leads to linear field growth. Most relevant at large scales.
  - Kelvin-Helmholtz instability (KHI) (exponential field growth): initial small scale amplification at shear layers



  - Magnetorotational instability (MRI) (exponential field growth): relevant for differentially rotating magnetized fluids. Results in large scale field structuring



BASIC PHYSICAL PICTURE: ENERGY CASCADE



Inspiral converts gravitational energy to kinetic energy

Direct kinetic cascade

KHI

drives cascade to smaller scales

Field lines twist

MRI

rotational ⟶ magnetic

Inverse magnetic cascade

Large-scale structure develops in amplified magnetic field

- → our simulations can capture only part of this cascade
  - → below the length scale set by the computational grid, we cannot resolve the relevant fluid dynamics

SOLUTIONS: USUAL APPROACHES

How do we get strong magnetic fields in the post-merger environment?

SOLUTIONS: USUAL APPROACHES

Approximate (most-common) solution

Superimpose unphysically large, simplified (dipole) magnetic fields on fluid during the inspiral

$$\lambda_{MRI} \approx \frac{2\pi B}{\Omega\sqrt{4\rho}} \tag{1}$$

How do we get strong magnetic fields in the post-merger environment?

SOLUTIONS: USUAL APPROACHES

Approximate (most-common) solution

Superimpose ur

the inspiral

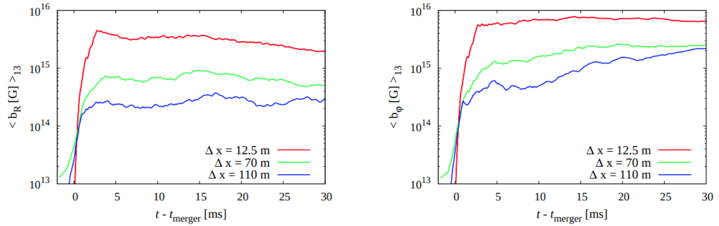
How do we

Improve accuracy of simulations

→ Use higher order schemes for fluid evolution

→ Increase grid resolution. Highest resolution sims to date carried out by Kiuchi and Shibata, with smallest grid spacing $\Delta x_{\rm grid} \sim 12.5m$

  → KHI was at least partially resolved in these sims
  → Unphysically large inspiral B-fields still required at this grid resolution ($10^{13} - 10^{15}\,G$)
  → Results do not converge!



[a] [b]

---

[a] Kiuchi et al., Phys.Rev.D 92 (2015) 6, 064034

[b] Kiuchi et al., Phys.Rev.D 97 (2018) 12, 124039

SOLUTIONS: USUAL APPROACHES

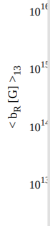
Approximate (most-common) solution

Superimpose ur
the inspiral

How do we

Improve accuracy of simulations

- → Use higher
- → Increase gr
  with small
  - → KHI wa
  - → Unphys
  - → Results



---

[a] Kiuchi et al., Phy

[b] Kiuchi et al., Phy

Sub-grid modeling: large-eddy simulations (LES)

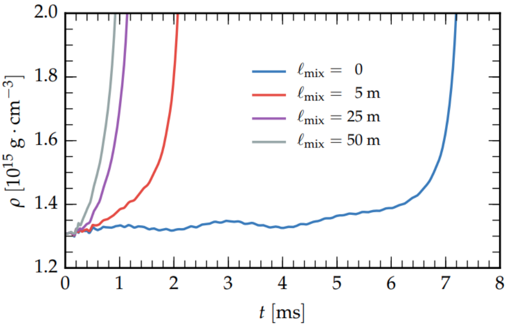


Figure 1. Maximum density in the collapse of a differentially rotating equilibrium configuration. Turbulent transport of angular momentum leads to an accelerated collapse. [a]

---

[a] Radice, Astrophys.J.Lett. 838 (2017) 1, L2

SOLUTIONS: USUAL APPROACHES

Approximate (most-common) solution

Superimpose ur
the inspiral

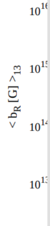
How do we

Improve accuracy of simulations

→ Use higher

→ Increase gr
with small

- → KHI wa
- → Unphys
- → Results

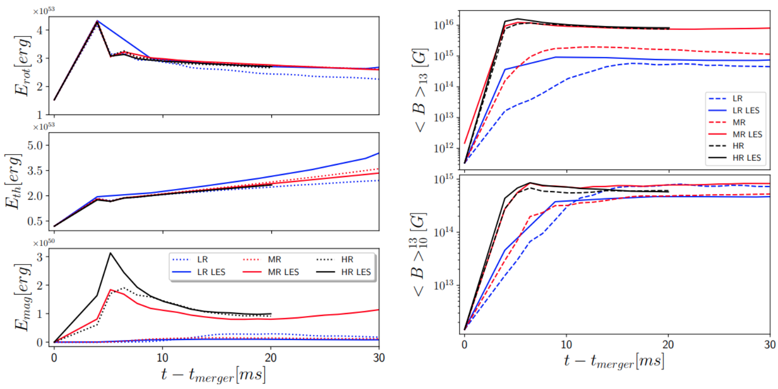


---

[a] Kiuchi et al., Phy

[b] Kiuchi et al., Phy

Sub-grid modeling: large-eddy simulations (LES)



a

---

[a] Palenzuela et al., arxiv: 2112.08413 (2021)

RECENT RESULTS

→ We simulate BNS mergers with strong magnetic fields and finite- temperature equations of state.

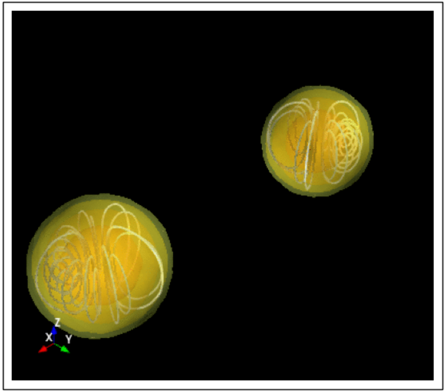
EOS	$M_{\rm tot}$ ($M_\odot$)	$R_{\rm NS}$ (km)	$B_{\rm max}(0)$ (G)	$M_{\rm supra}$ ($M_\odot$)	h_c
LS220	2.7	10.02	4.70×10^{15} G	2.42	0.2025
DD2	2.7	10.50	3.96×10^{15} G	2.92	0.1861

→ Numerical grids identical during inspiral, resolve stars with 64 gridpoints/$R_{\rm NS}$.

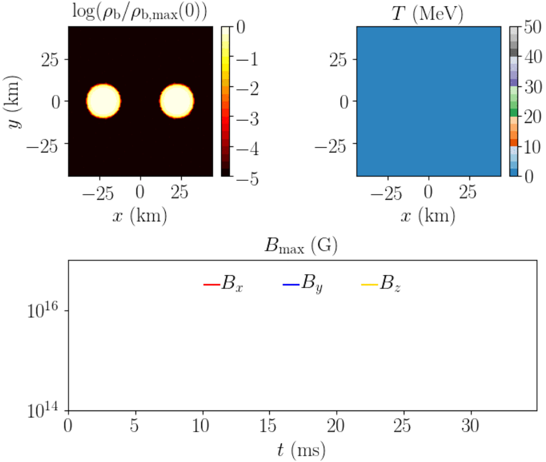
→ At a time close to and before merger, we dynamically activate refined grids near the origin, where merger happens.

→ Focus:

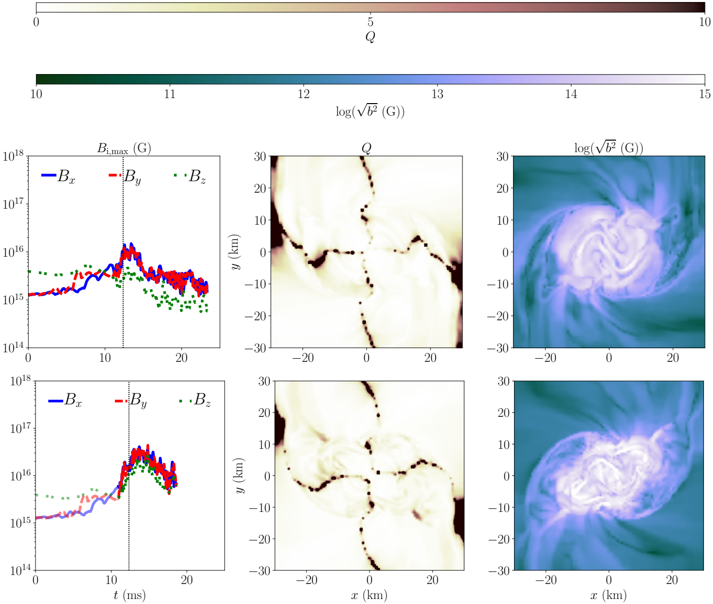
1. Field amplification
2. Effects of amplified fields on merger ejecta



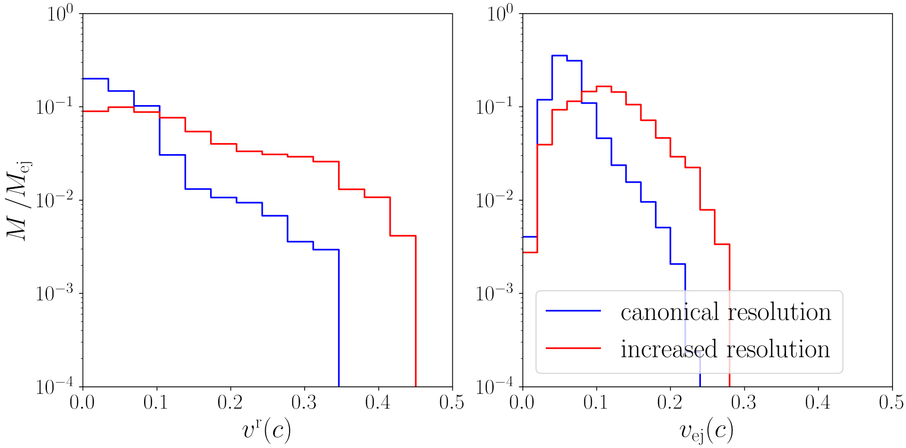
Pedro Espino, 2021



PLE, Paschalidis (in prep., 2022)


0
5
10
Q
10
11
12
13
14
15
$\log(\sqrt{b^2}\ (\mathrm{G}))$
$B_{\mathrm{i,max}}$ (G)
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
B_x
B_y
B_z
0
10
20
t (ms)
Q
$\log(\sqrt{b^2}\ (\mathrm{G}))$
30
20
10
0
−10
−20
−30
y (km)
−20
0
20
x (km)

EFFECT OF AMPLIFIED MAGNETIC FIELDS ON DYNAMICAL EJECTA



PLE, Paschalidis (in prep., 2022)

CONCLUSIONS

CONCLUSIONS

- Magnetic fields are expected to play a role in both the total amount of ejecta and in changing relevant ejecta properties
- Dynamically refining simulation grids allows for a ***direct comparison*** of ejecta properties due to stronger field amplification ***during the merger***. Specifically:
  - outflow is resolved with same resolution in all cases
  - magnetic fields are identical leading up to merger
- Ongoing work:
  - allow MRI to develop (long-term simulations) and consider secular outflow
  - consider convergence of magnetic field amplification with larger grid-refinement areas
  - consider refining larger areas to better resolve KHI (during merger) and MRI (after merger)
  - consider wider diversity of EOS models