Turbulence and magnetic configurations in neutron star interiors

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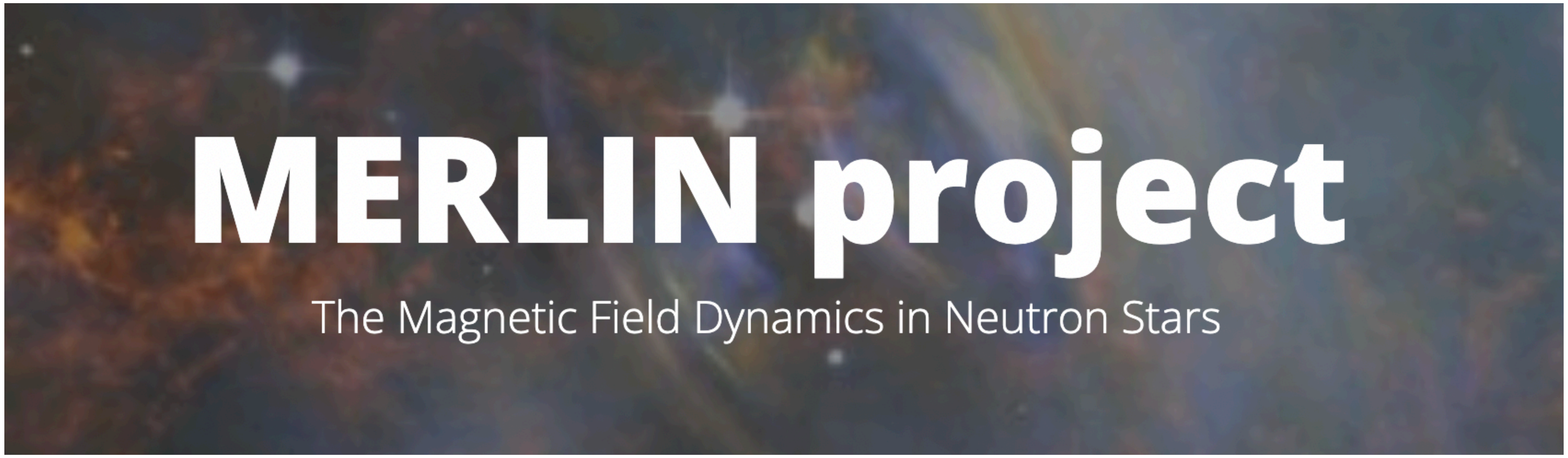

https://merlin-neutronstars.bitbucket.io/

OPUS-LAP

Joint NCN - DFG grant, CAMK and FSU Jena

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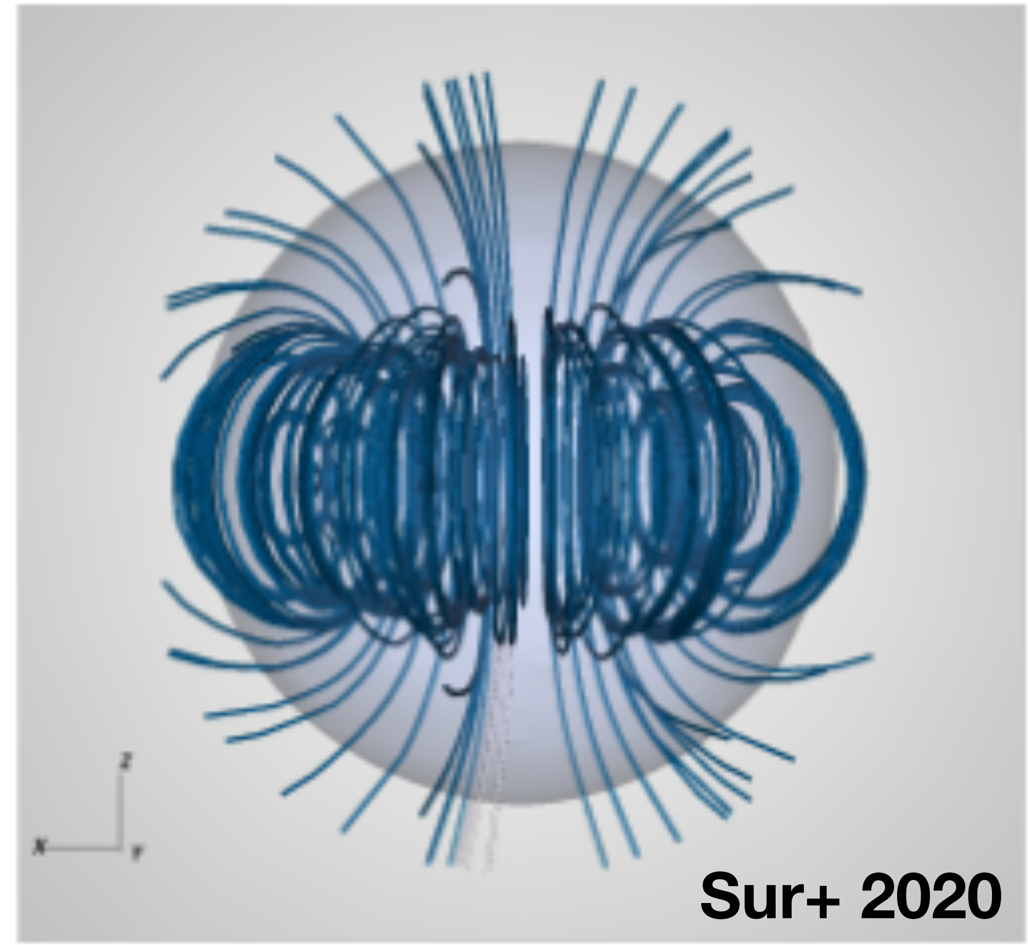
Physical problem

- Magnetic field configuration in NSs unknown
- Evidence for dipole far from the star, but NICER suggests more complicated structure

[Gendreau + 2016, Bilous + 2019, Sur + 2024]



Sur+ 2020

- Dipole is unstable and a toroidal component is needed to stabilise the field (how strong?)

[Tayler + 1957, 1973, Markey and Tayler 1973, 1974]
[Braithwaite+ 2006 2009, Ciolfi+ 2011, 2013, Lasky+ 2011]

- Turbulence plays a role in the evolution of the field

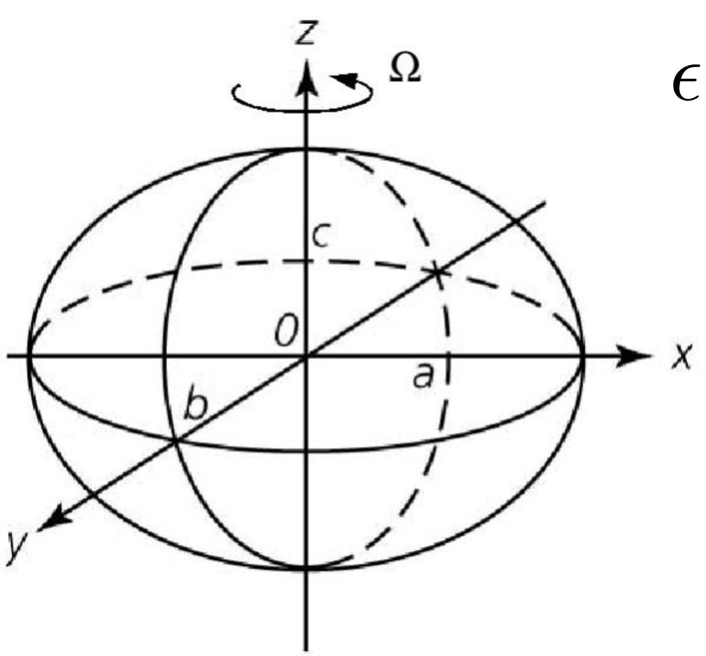
[Sur + 2020, 2021, Sarin+ 2023]

Minimum ellipticity

- **A magnetised NS (or a merger remnant) produces a 'continuous' GW signal**

  [Bonazzolla and Gourgoulhon 1996] $10^7\mathrm{G} \lesssim B \lesssim 10^{16}\mathrm{G}$

- Magnetic fields can support a quadrupole in the star



$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

- GW emission at $2\nu_{spin}$ and ν_{spin}

$$\epsilon \propto 10^{-11} \left(\frac{B}{10^{12}G}\right)^2$$

Magnetic deformation

$$\epsilon \propto 10^{-9} \left(\frac{B}{10^{12}G}\right) \left(\frac{H_c}{10^{14}G}\right)$$

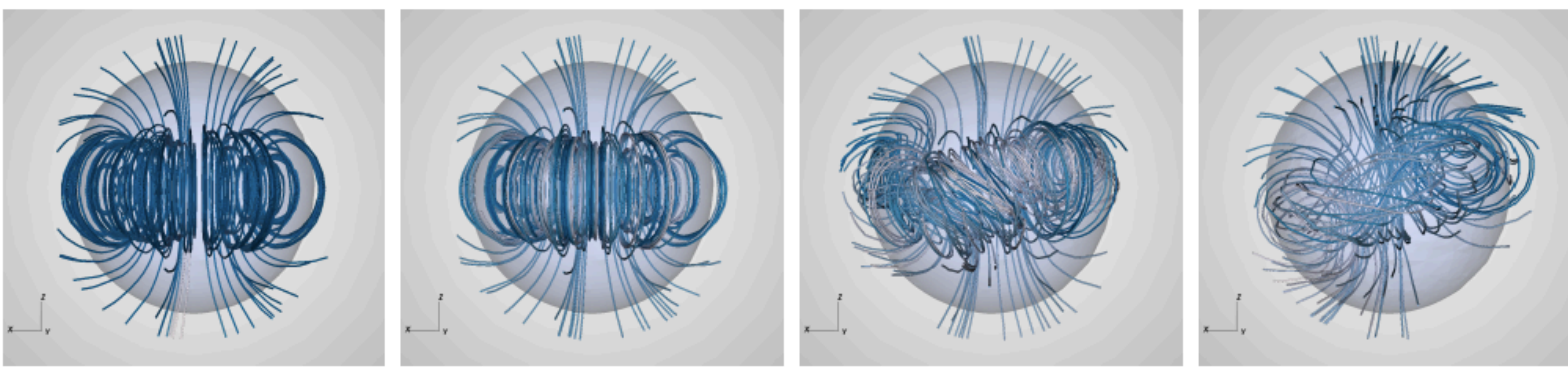
- Evidence for residual deformation in the radio pulsar population

  [Woan+ 2018]

Project objectives

- Perform long-term high resolution simulations of isolated NS to investigate magnetic configurations
- Tool of choice AthenaK **[Stone et al. 2024, Zhu+ 2024, Fields+ 2025]**
- Investigate turbulent cascades in magnetised stars **[Sur et al. 2021]**
- Use insight to investigate GW emission and simulate mergers of magnetised BNS

Sur+ 2020



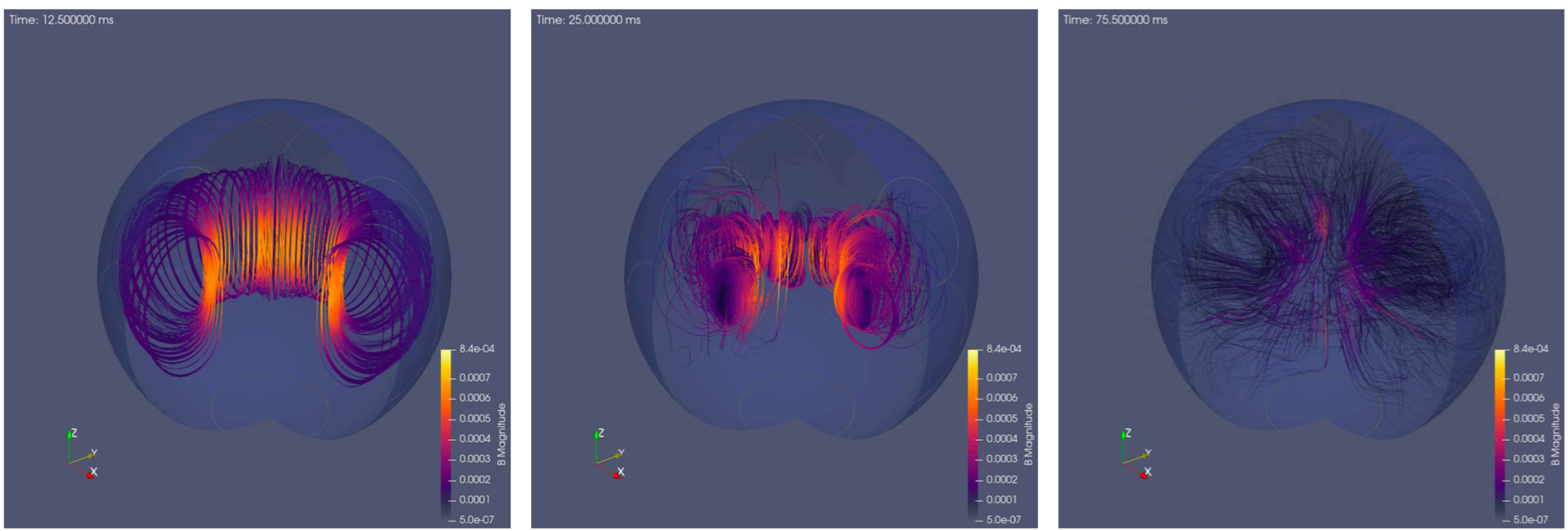
Problem setup

- Setup TOV star with Gamma law EoS and Poloidal field (average $B = 1.23 \times 10^{16}$ G)

$$A^{\phi} = A_b \max(p, p - 0.04 p_{\max})$$

- Evolve (Cowling approximation) up to 1200 ms with (230, 114, 57) m resolutions

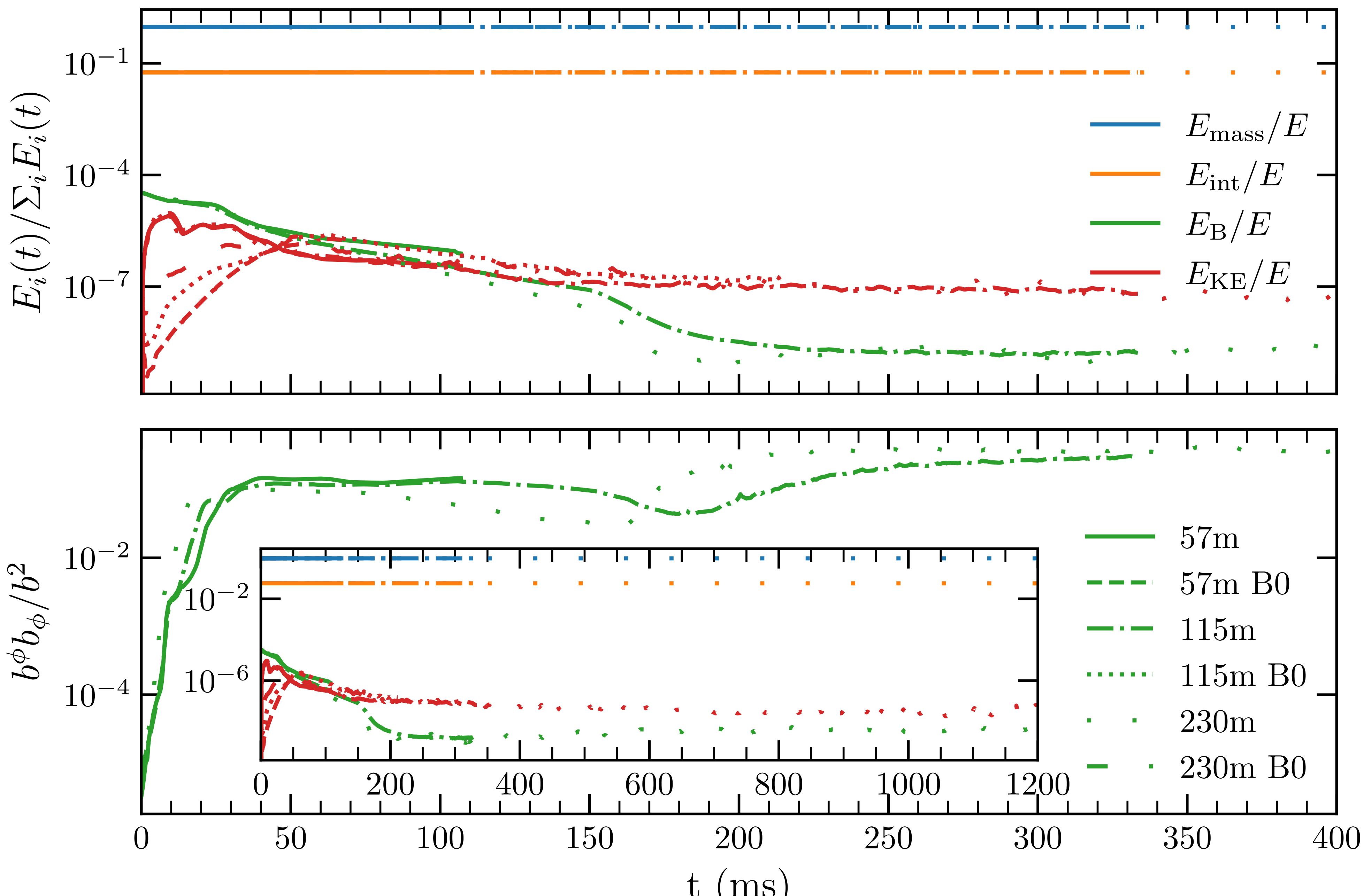
- Study relaxation after initial instability of the poloidal field



(a) $t = 12.5$ms (b) $t = 25$ms (c) $t = 75$ms

B field evolution

- Magnetic energy decays
- Toroidal component of ~15% of total consistently develops

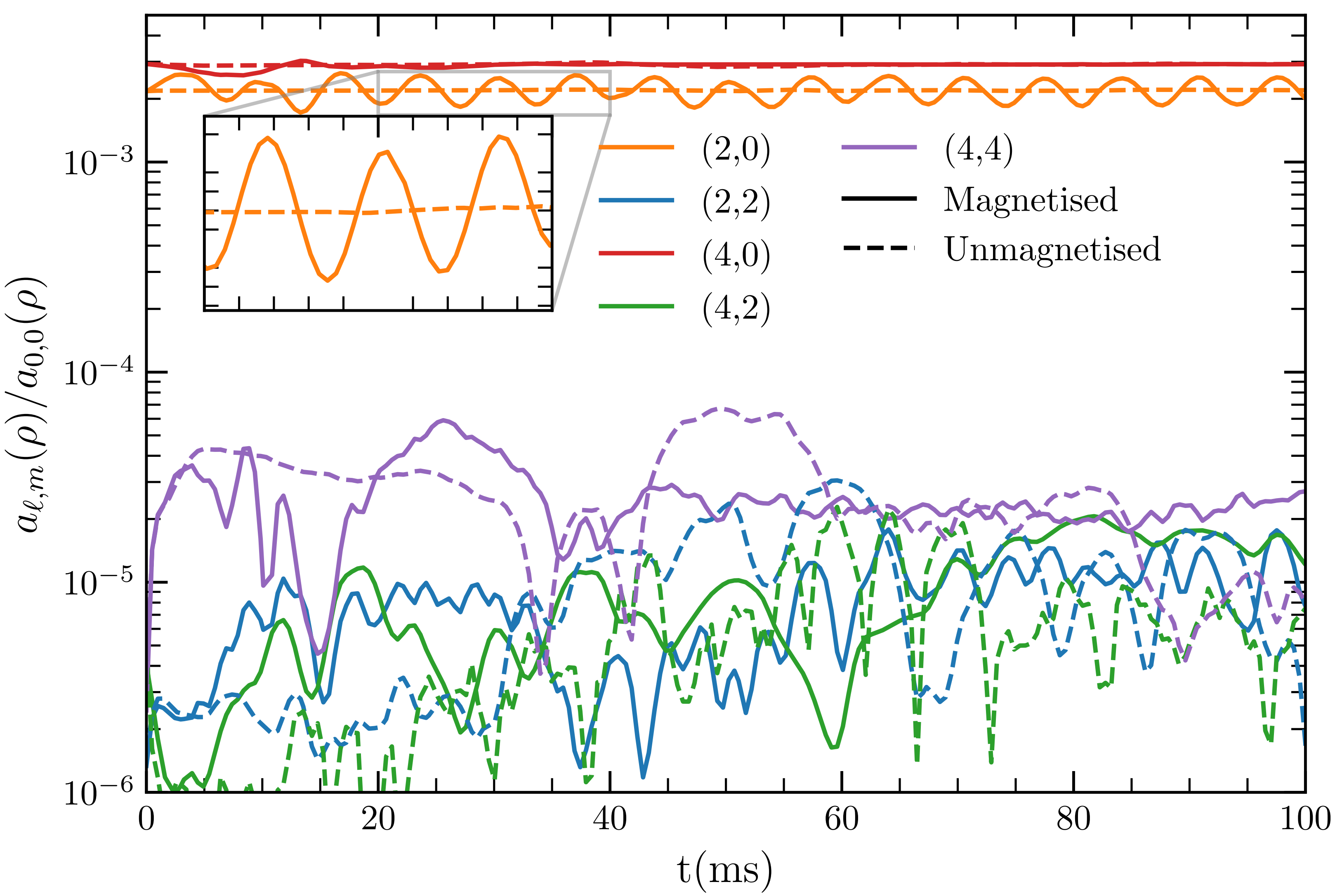


Oscillations

- l=2,m=0 oscillation (absent in pure hydro) appears at 145 Hz

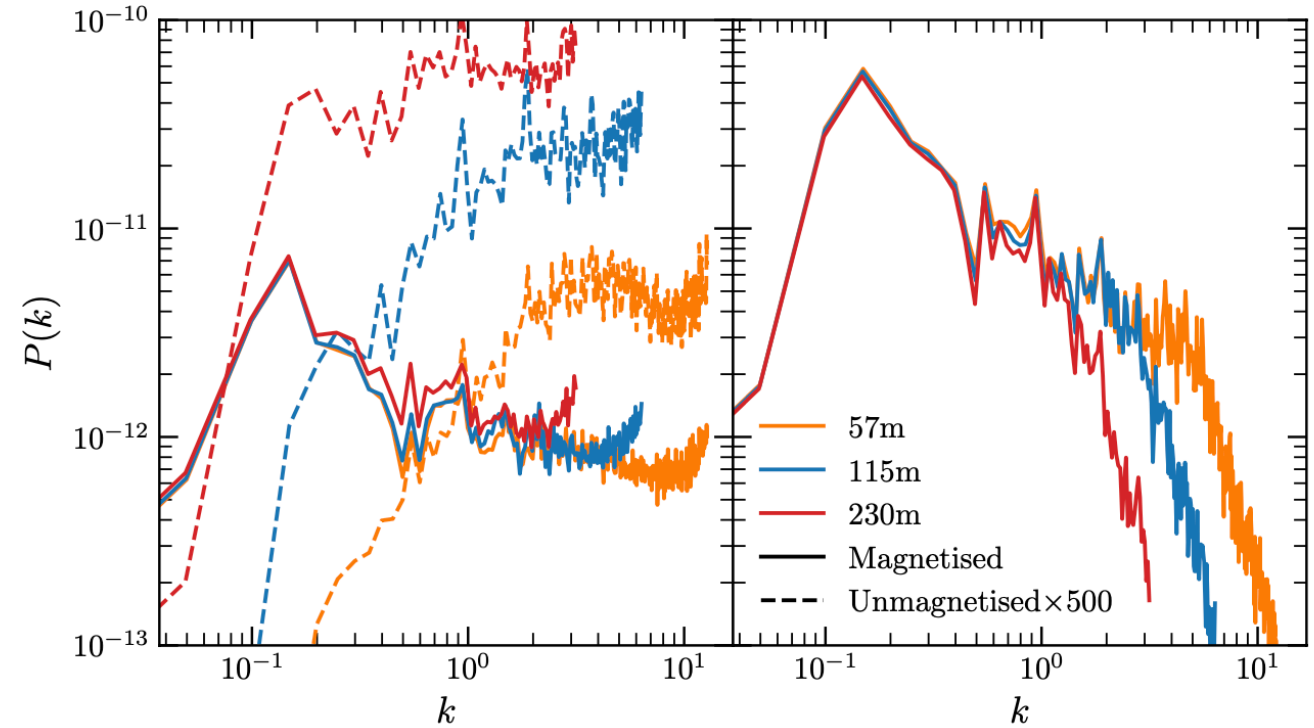
- Sotani+ 08 find Alfven modes at similar frequencies.

  Link to QPOs in magnetars [Israel+05]

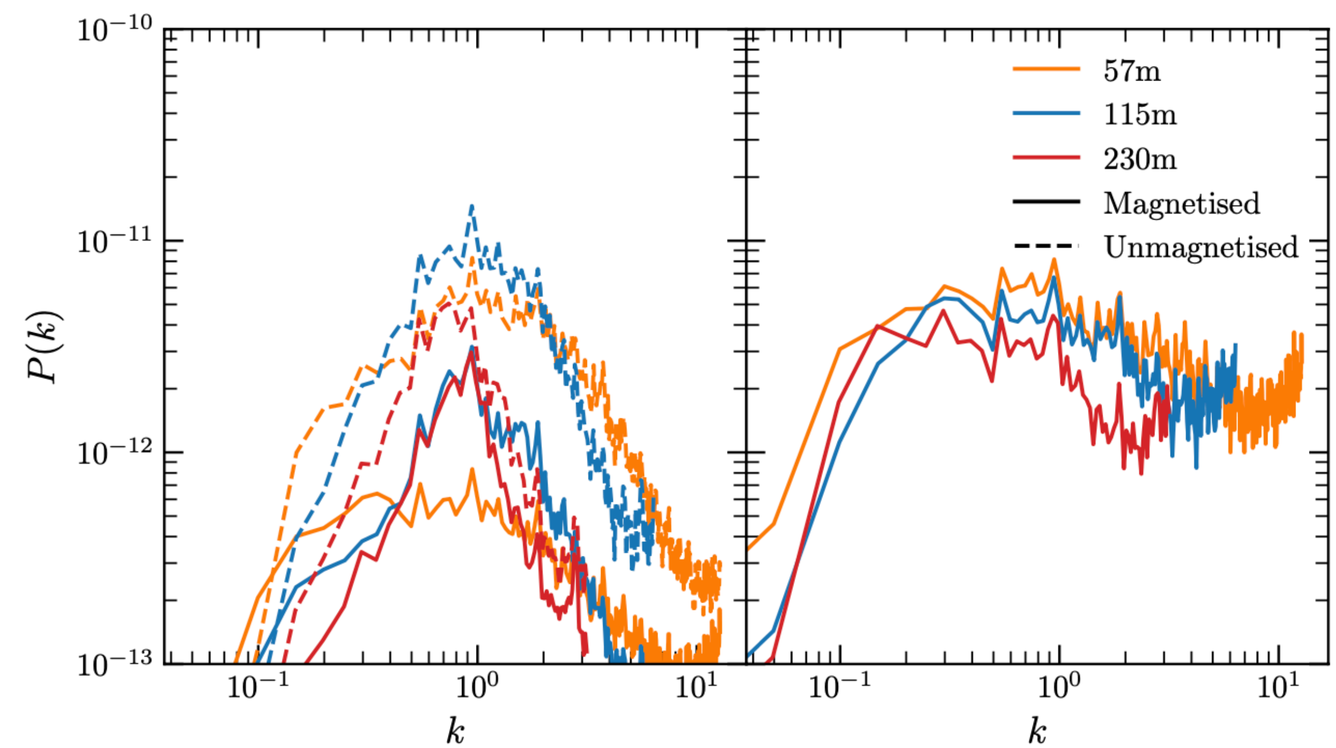


Turbulence

- Sur+ 2021 found a turbulent cascade - indistinguishable between HD and MHD
- We find clear evidence for a cascade (scaling ~ Kolmogorov), clear difference in high res B runs.
- After accounting for overall decay, spectral density remains constant



Kinetic (a) $t = 2.995$ms **Magnetic**

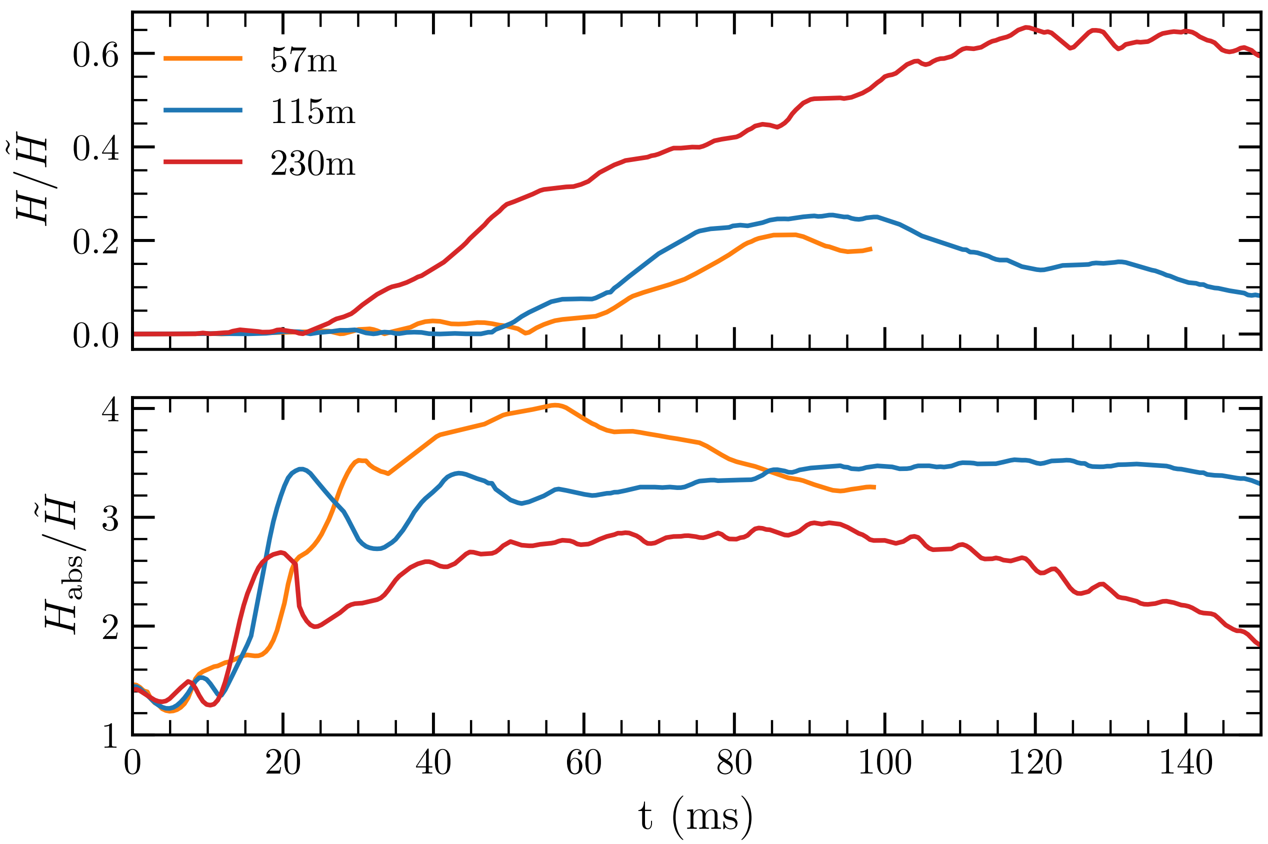


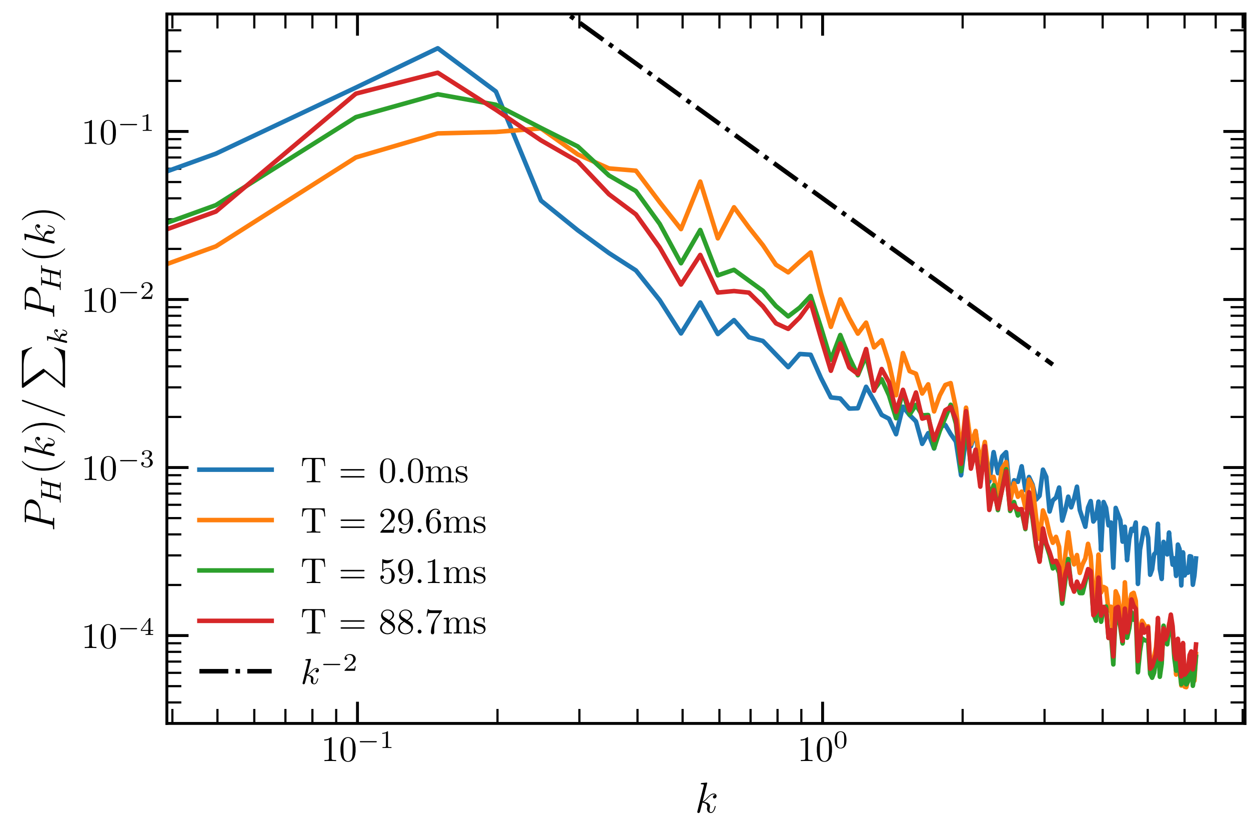
(c) $t = 60.091$ms

Helicity

- Helicity not conserves as energy falls off the grid due to turbulent cascade

- Inverse cascade develops large scale toroidal component





$$H = \int_V A \cdot B \; dV$$

$$H_{\rm abs} = \int_V |A \cdot B| \; dV$$

Conclusions

- High res simulations reveal magnetically driven turbulence and inverse cascade
- Poloidal unstable - toroidal component of approx. 15% total energy develops
- Alfven oscillations excited
- More realistic configurations (initial B field, exterior field, rotation) needed
- Applications to BNS simulations, and GW emission from isolated NSs