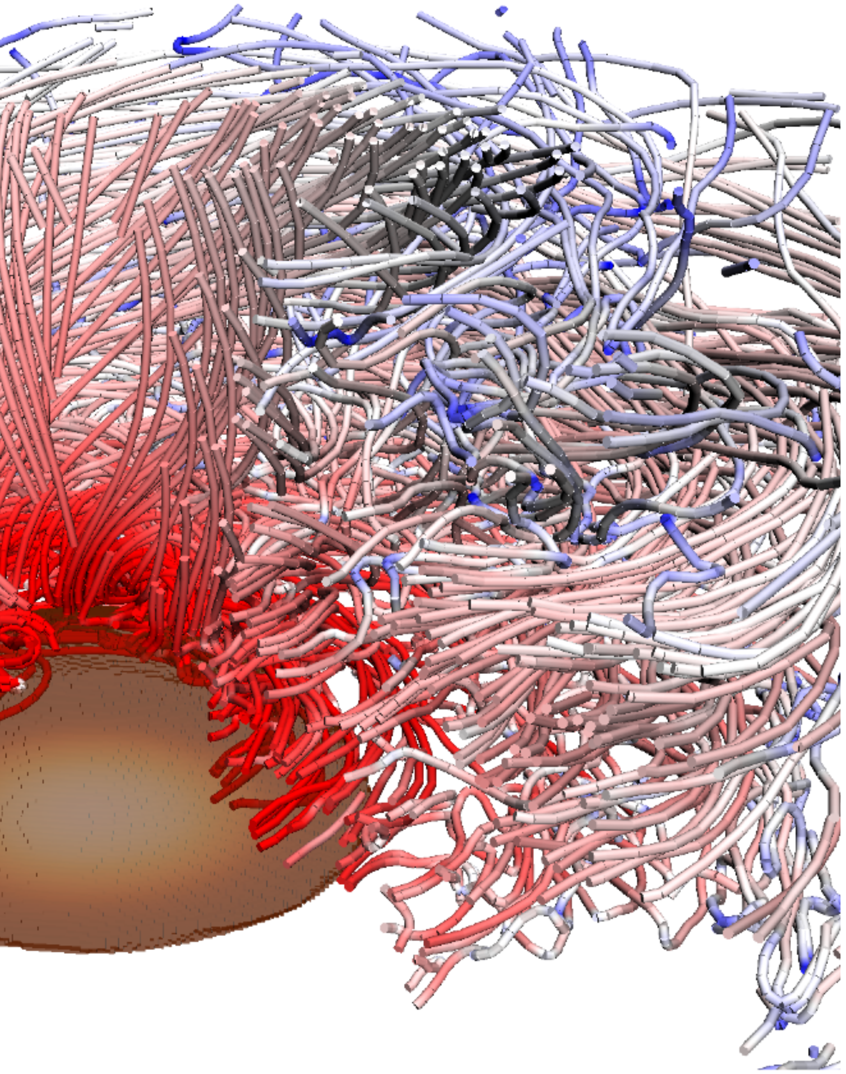


Dynamos in Neutron Star Remnants Implications for Multi-Messenger Observations

Alexis Reboul-Salze

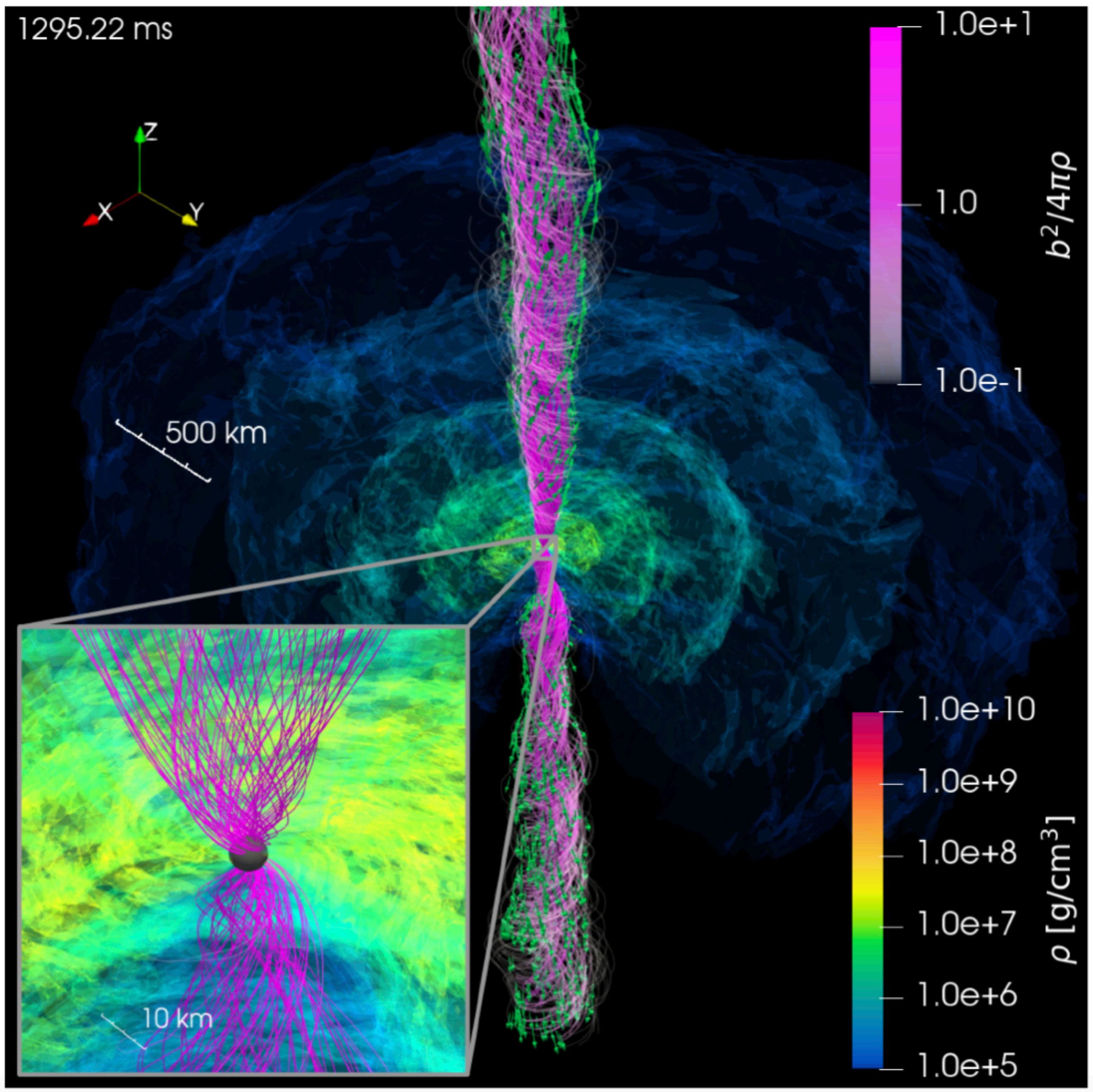
in collaboration with
Loren Held, Kenta Kiuchi, Masaru Shibata,
Jérome Guilet, Paul Barrere, Raphael Raynaud

Motivation for dynamos in NS remnants: GRB central engine

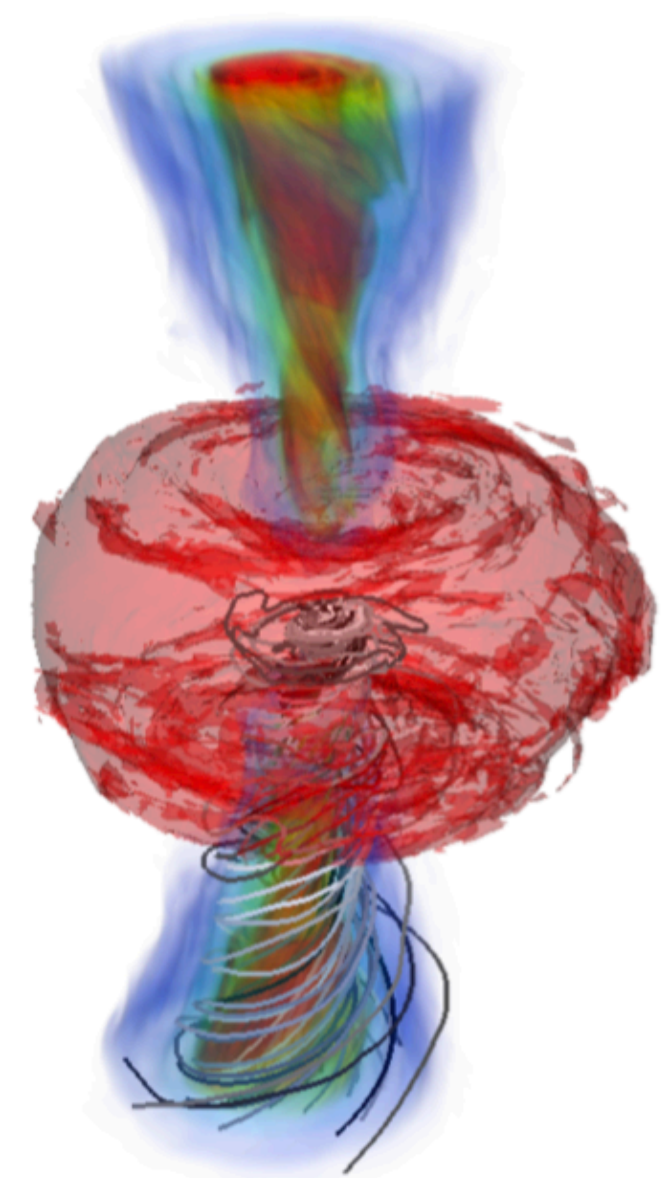
See talk by Maria Grazia Bernardini

Black Hole + disk systems

Hypermassive neutron star + disk systems



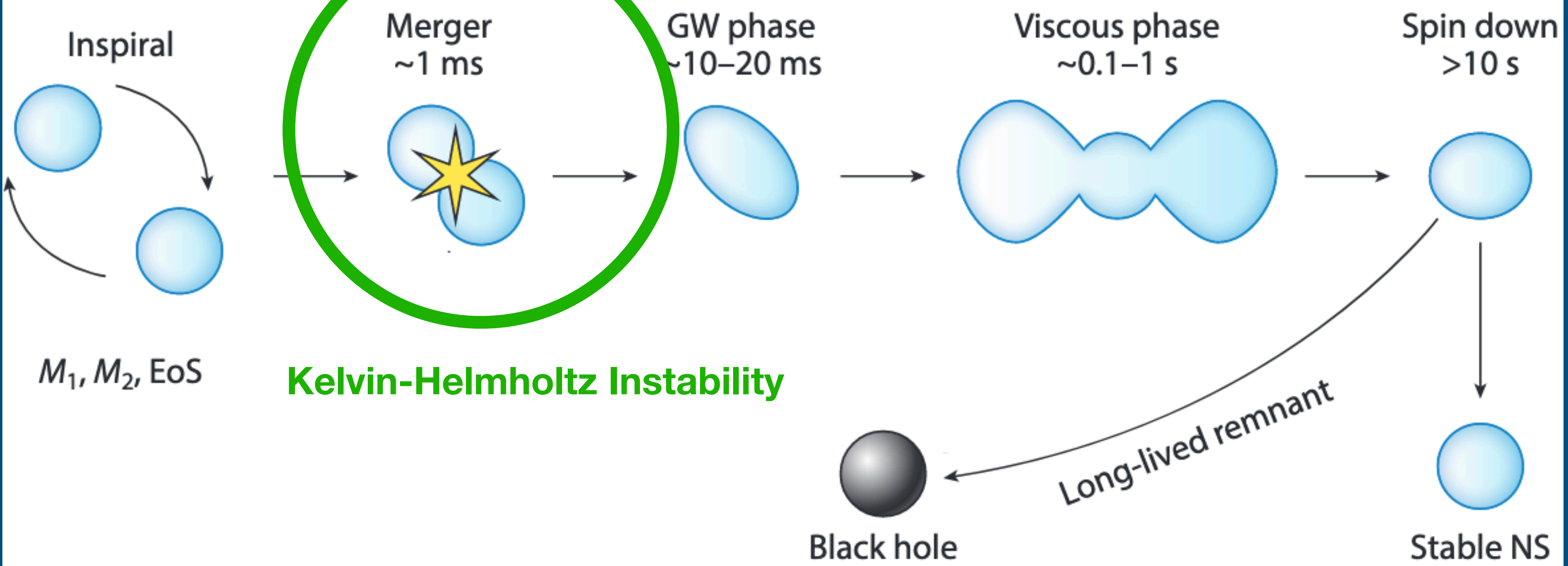
Hayashi+2024
(Ruiz+2021,Sun+2022)



Mosta et al 2020
(Combi+2022, Kiuchi, **ARS**+ 2024, Musolino+ 2024)

Amplification mechanisms in hypermassive neutron stars

Evolution of the merger

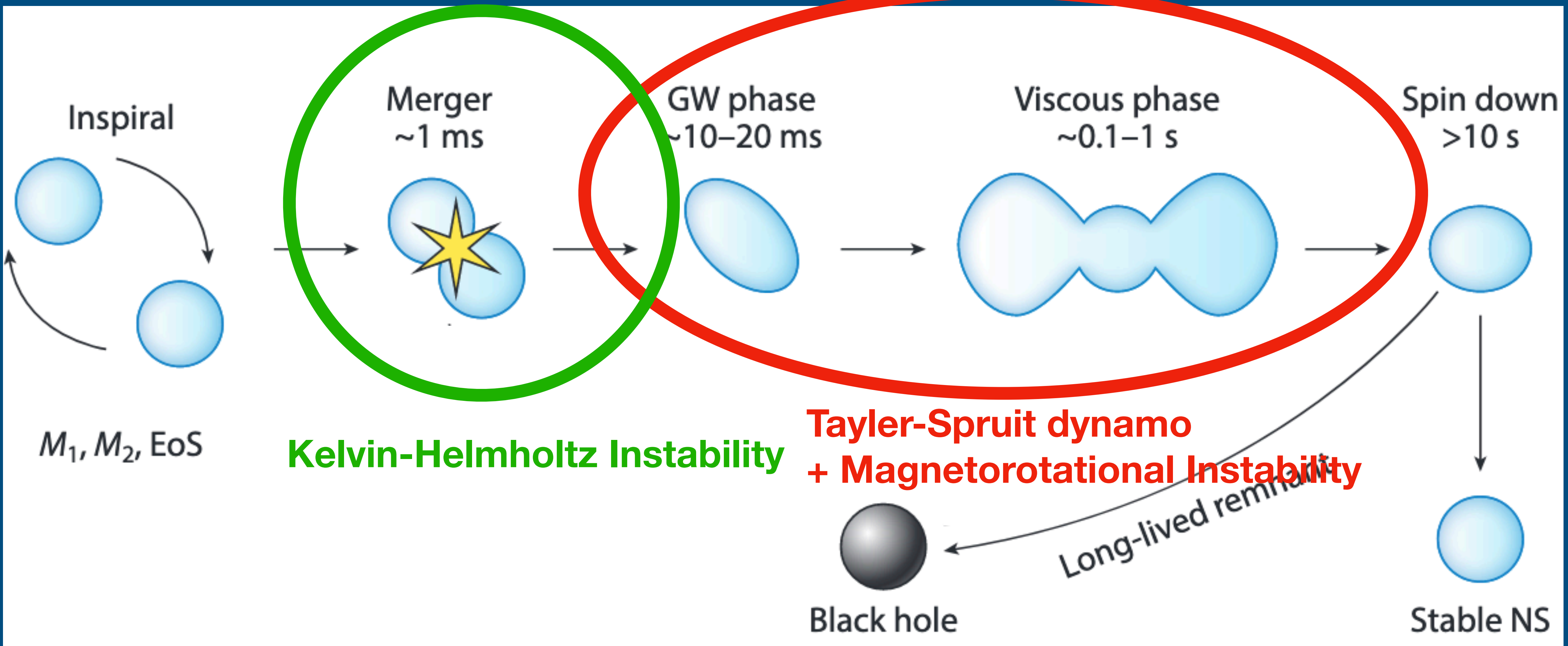


Kelvin-Helmholtz Instability

Radice et al. 2020

Amplification mechanisms in hypermassive neutron stars

Evolution of the merger



Radice et al. 2020

Amplification mechanisms in hypermassive neutron stars

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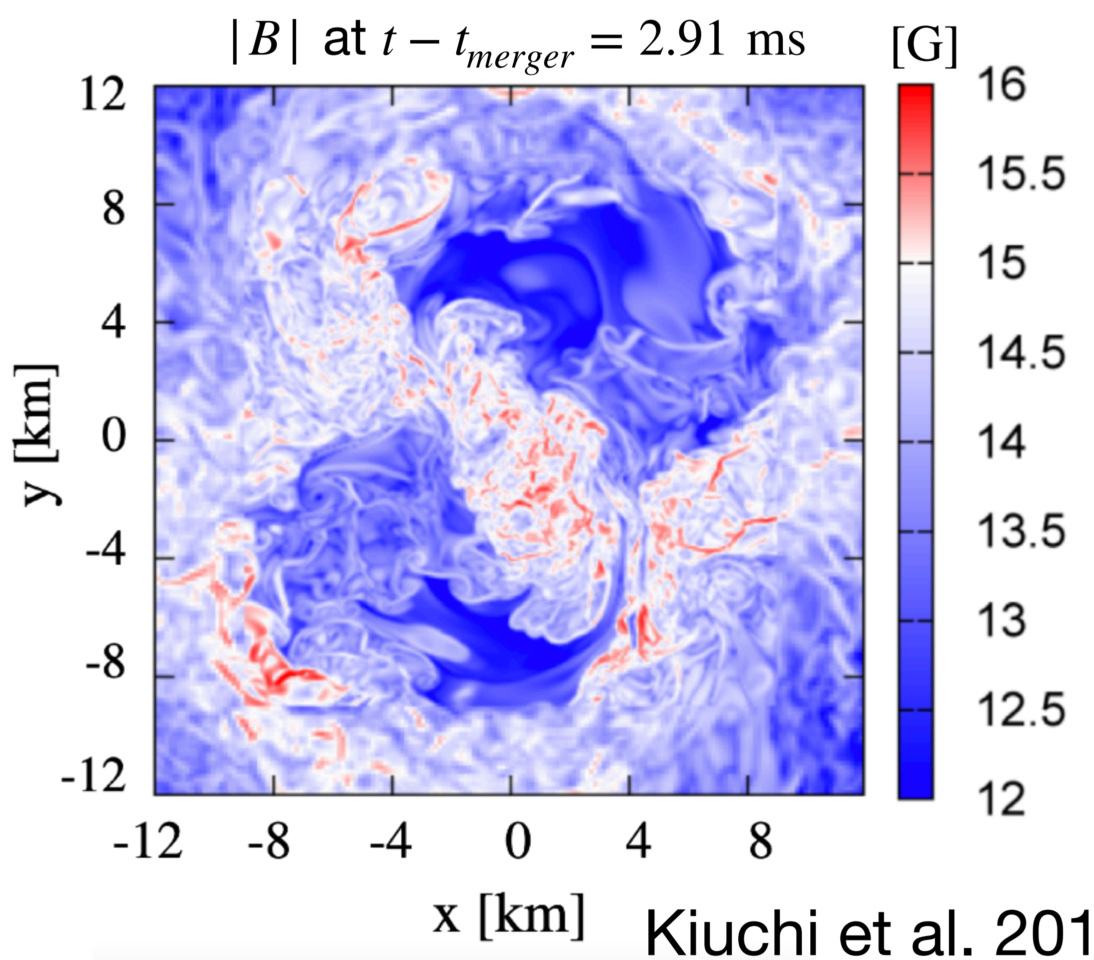
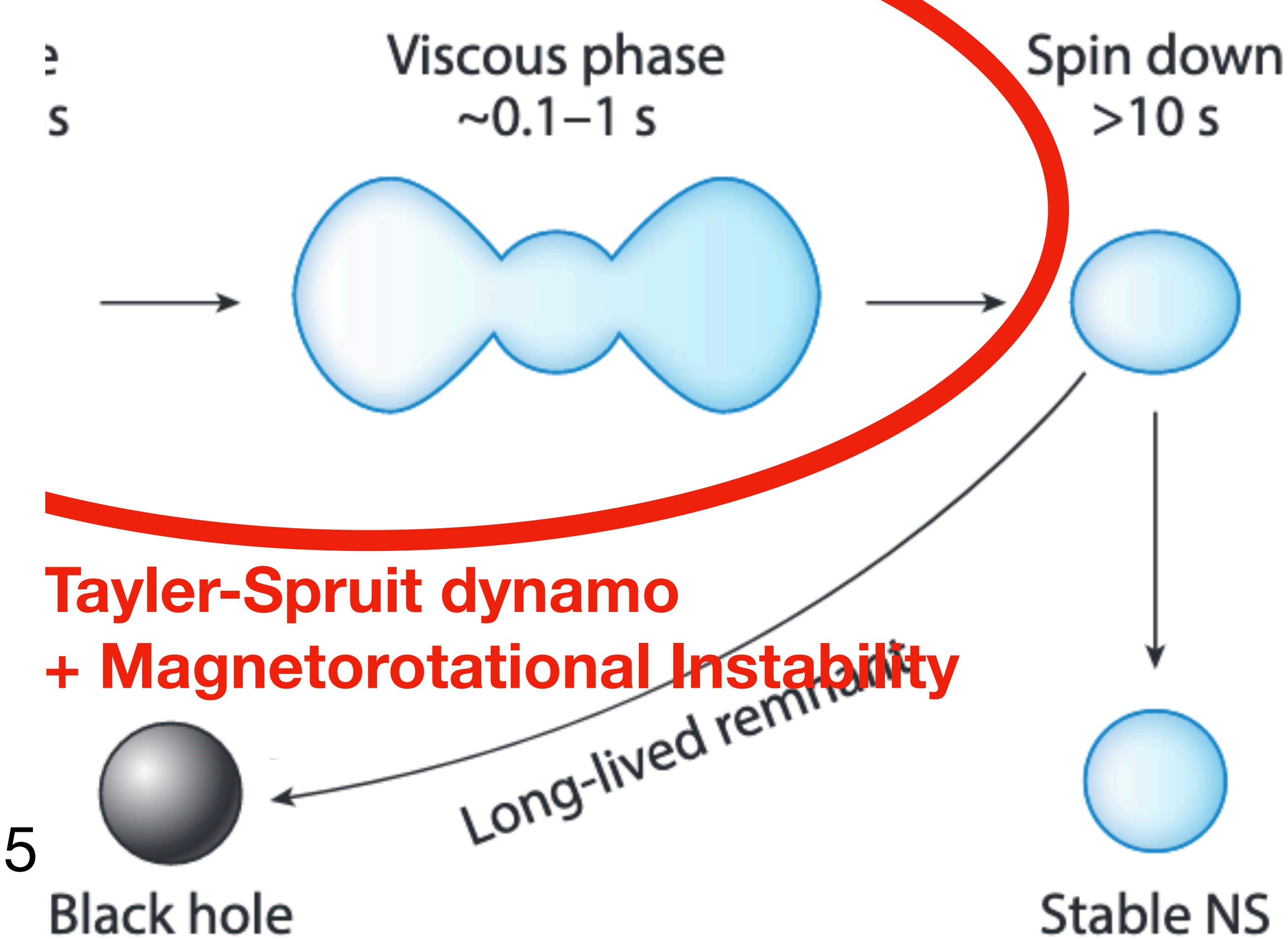


Kiuchi et al. 2015



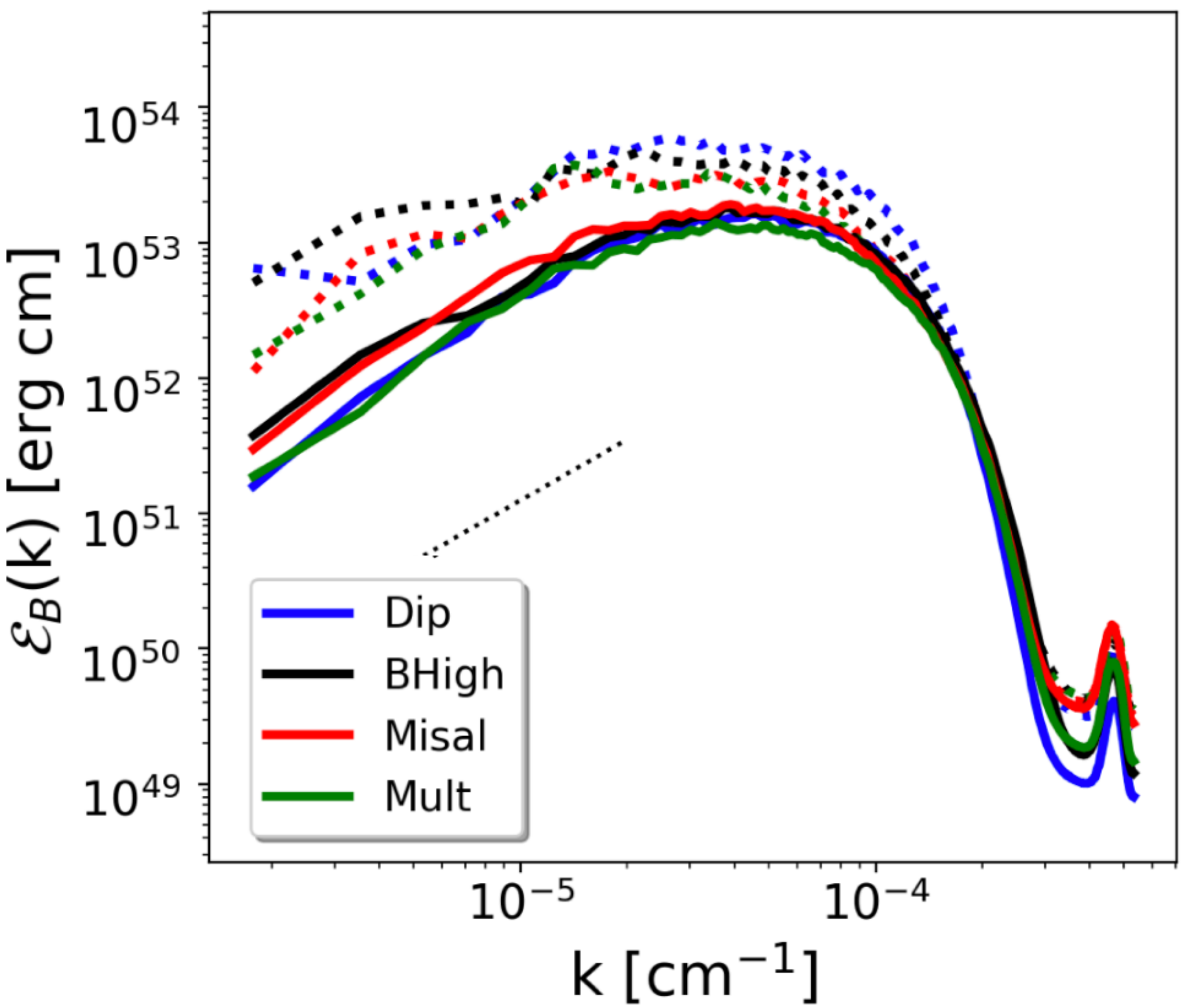
Tayler-Spruit dynamo
+ Magnetorotational Instability

Radice et al. 2020

Initial condtitions right after mergers

GMHD simulation with subgrid model

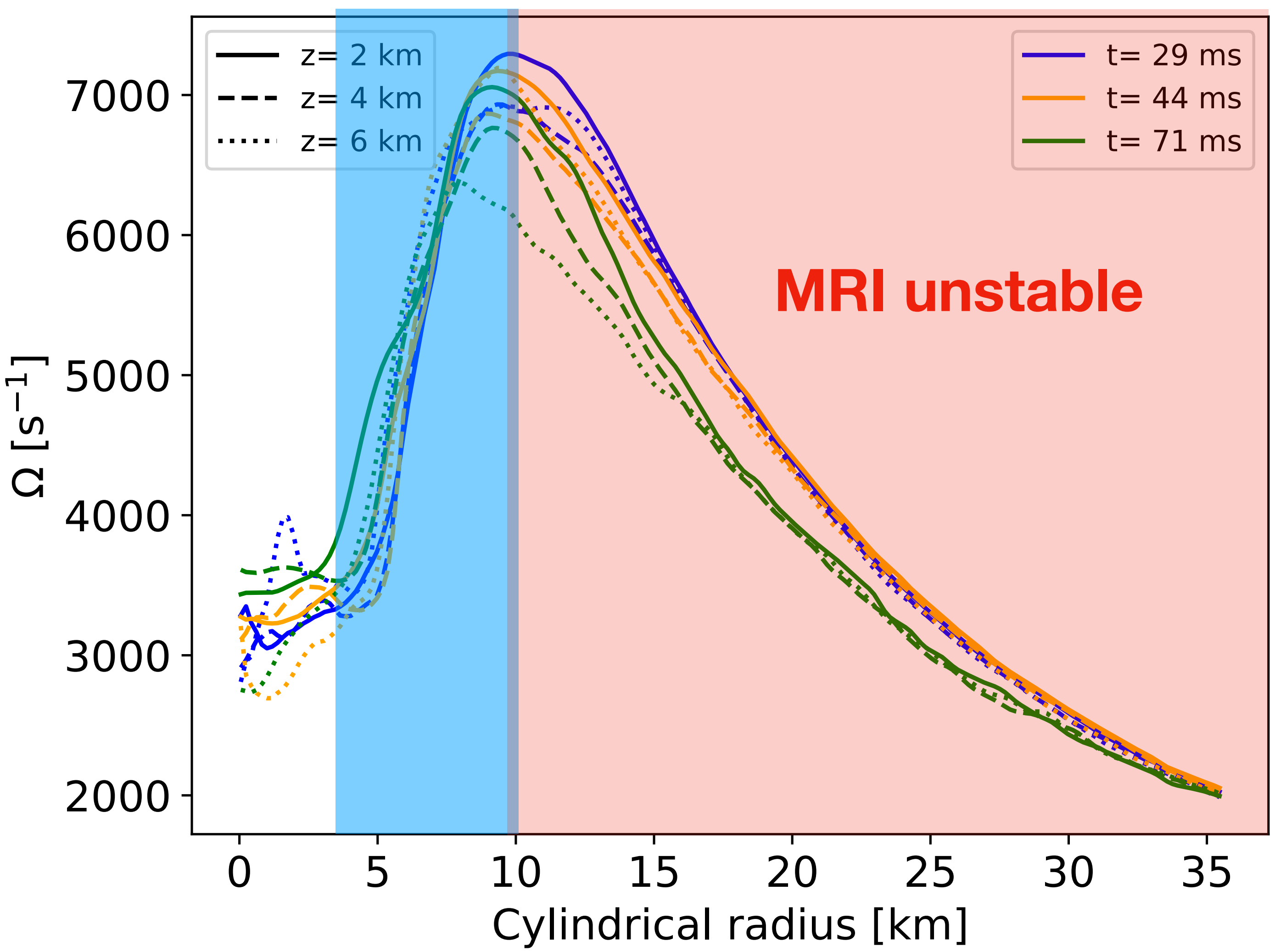
Magnetic field spectrum at t=10 ms



Aguilera-Miret et al. 2022

GRMHD simulation with
DD2 EOS, 1.35-1.35 $M_\odot$ BNS merger

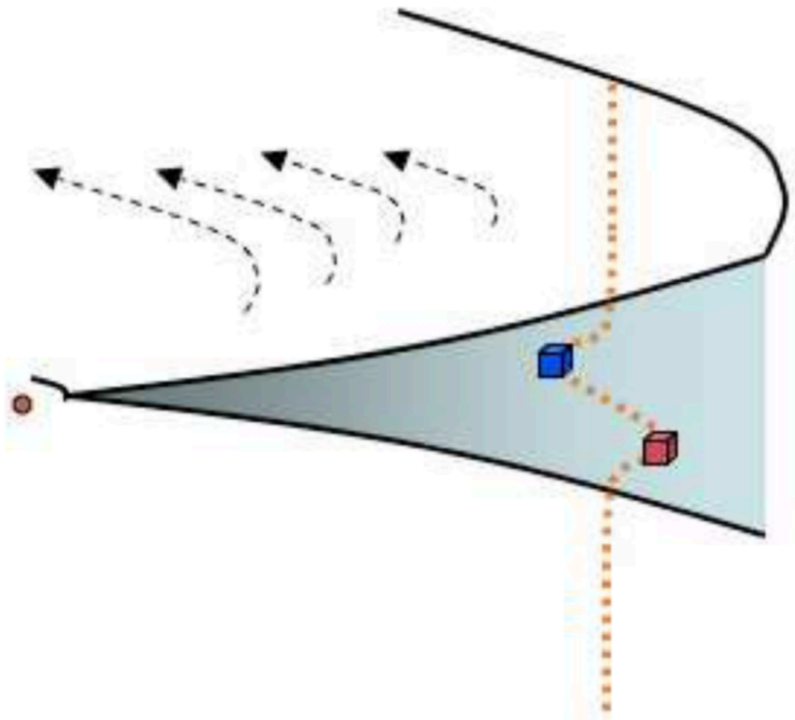
Tayler-Spruit unstable



MRI-driven dynamo: Kiuchi, ARS et al. 2024
TS dynamo: ARS et al. 2025

Amplification mechanism: magneto-rotational instability (MRI)

MRI mechanism in a simple case:



Credit : Fromang 2013

Instability criterion: $\frac{d\Omega}{dr} < 0$

Growth rate: $\sigma = \frac{q\Omega}{2}$ with $\Omega \propto r^{-q}$

-> Fast growth for fast rotation

Wavelength: $\lambda_{MRI} \propto \frac{B}{\sqrt{\rho}\Omega}$

-> Short wavelength for weak magnetic fields

Impact of MRI-driven turbulence

angular momentum transport

$$\alpha \equiv \frac{\langle \rho v_r v_\phi - B_r B_\phi / 4\pi \rangle}{\langle P \rangle}$$

MRI-driven $\alpha\Omega$ dynamo

$$\frac{\partial \overline{\vec{B}}}{\partial t} = \vec{\nabla} \times \left(\overline{\vec{U}} \times \overline{\vec{B}} + \vec{\mathcal{E}} - \eta \vec{\nabla} \times \overline{\vec{B}} \right)$$

with $\vec{\mathcal{E}} = \overline{\vec{u} \times \vec{b}}$

the electromotive force (EMF)

$$\mathcal{E}_i = \alpha_{ij} \overline{B}_j + \beta_{ij} \left(\vec{\nabla} \times \overline{\vec{B}} \right)_j + \ldots$$

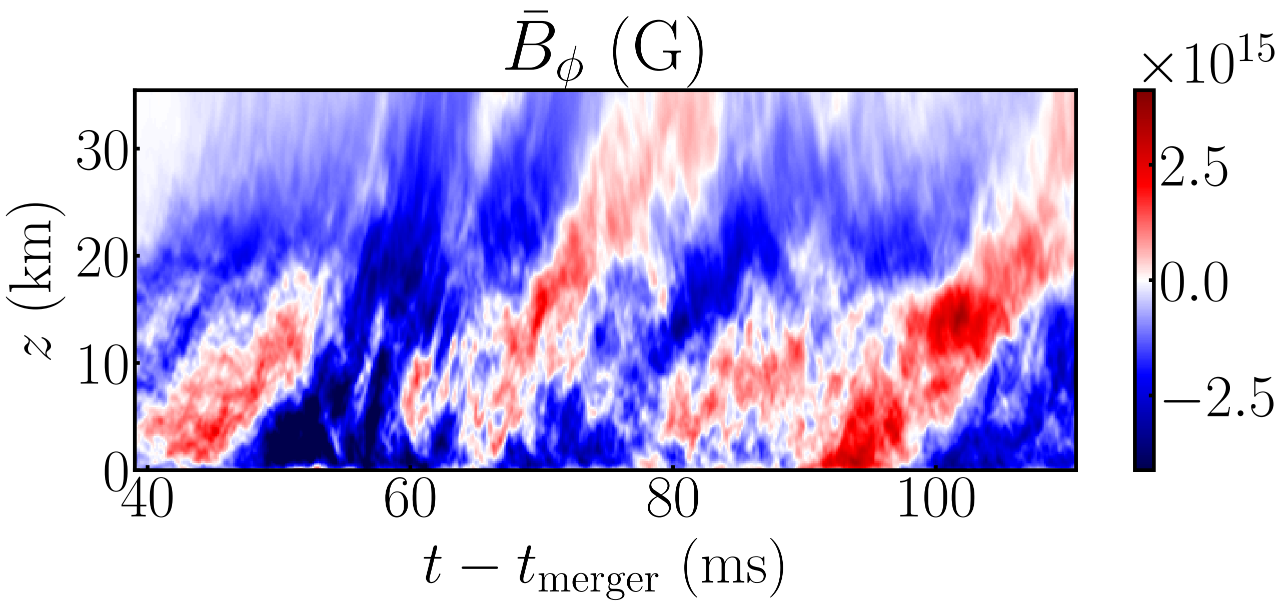
Alpha effect $\mathcal{E}_i = \alpha_{ij} \overline{B}_j$

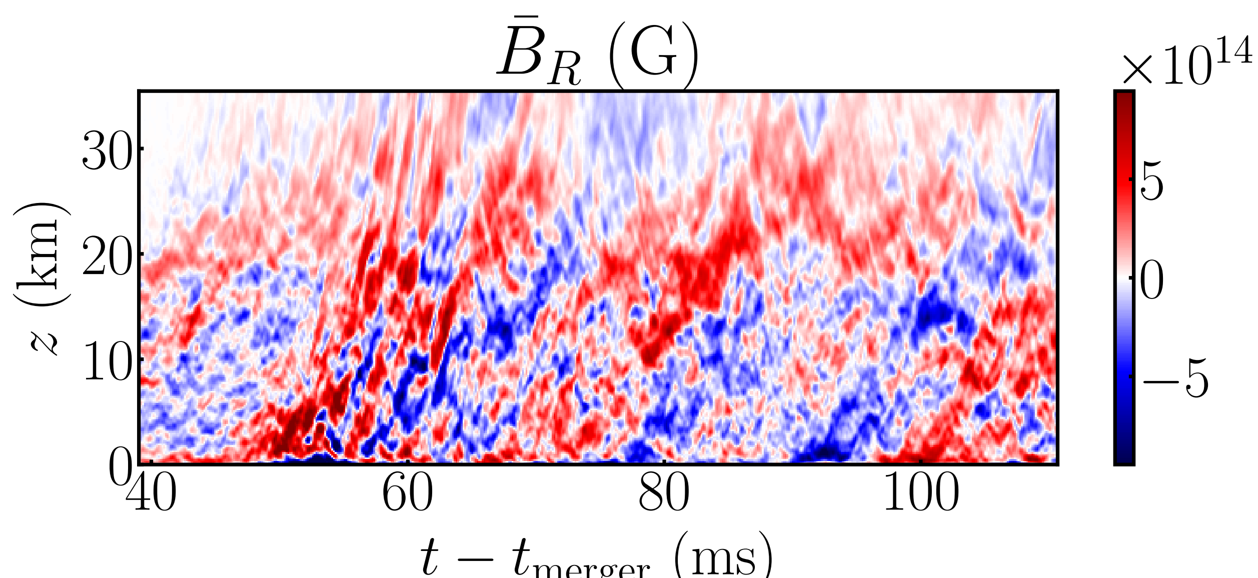
$$t_{\alpha\Omega} = \frac{2\pi}{\sqrt{\alpha_{\phi\phi} \pi q \Omega / H}}$$

Gressel+2015, ARS+ 2022, Dhang+2024

MRI-driven alpha-Omega dynamos in GRMHD simulations

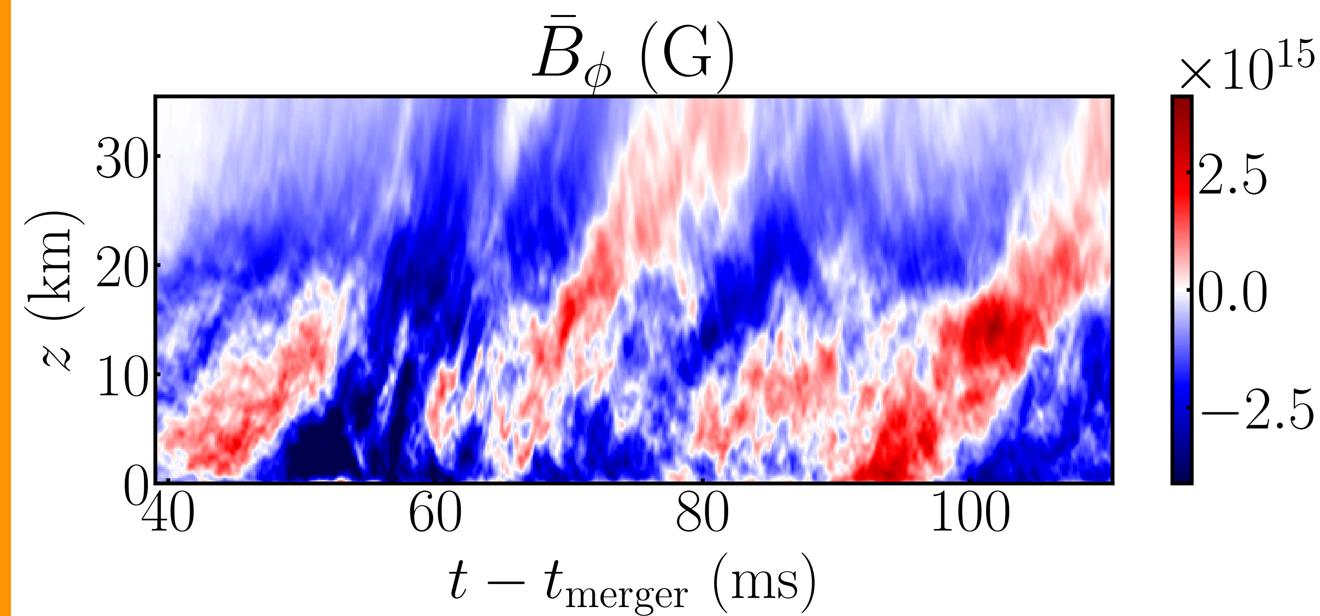
Omega effect



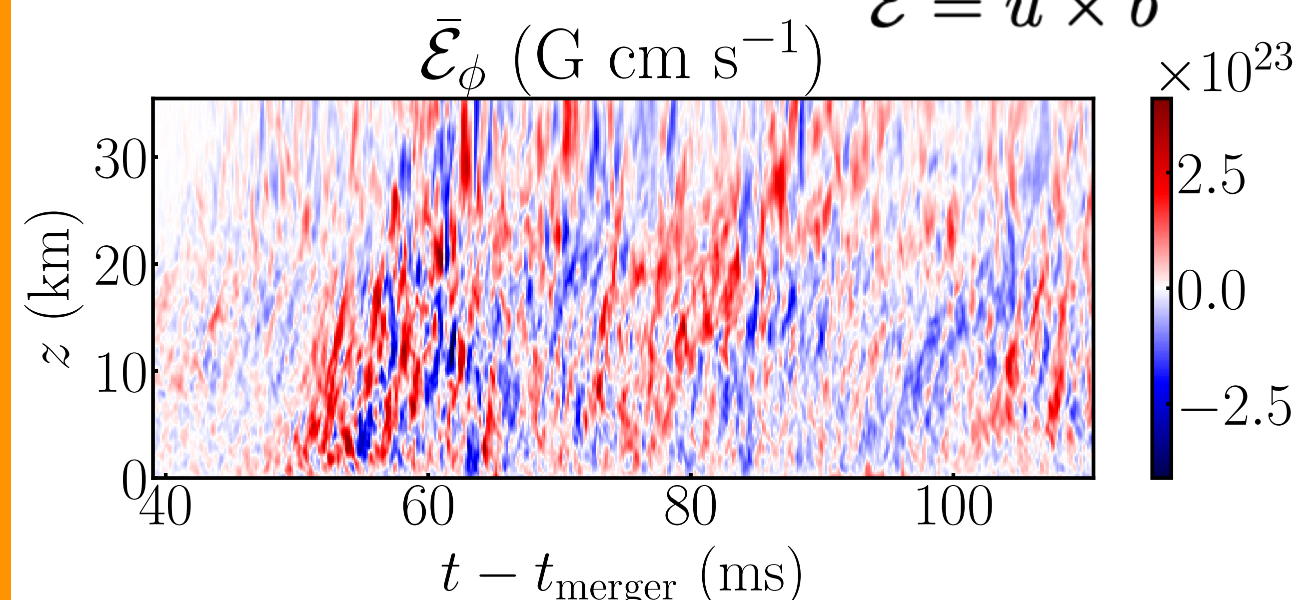


$$\frac{\partial \overline{B}_\phi}{\partial t} = \mathrm{R}\,\overline{B}_{\mathrm{R}} \frac{d\Omega}{ds}$$

alpha-effect

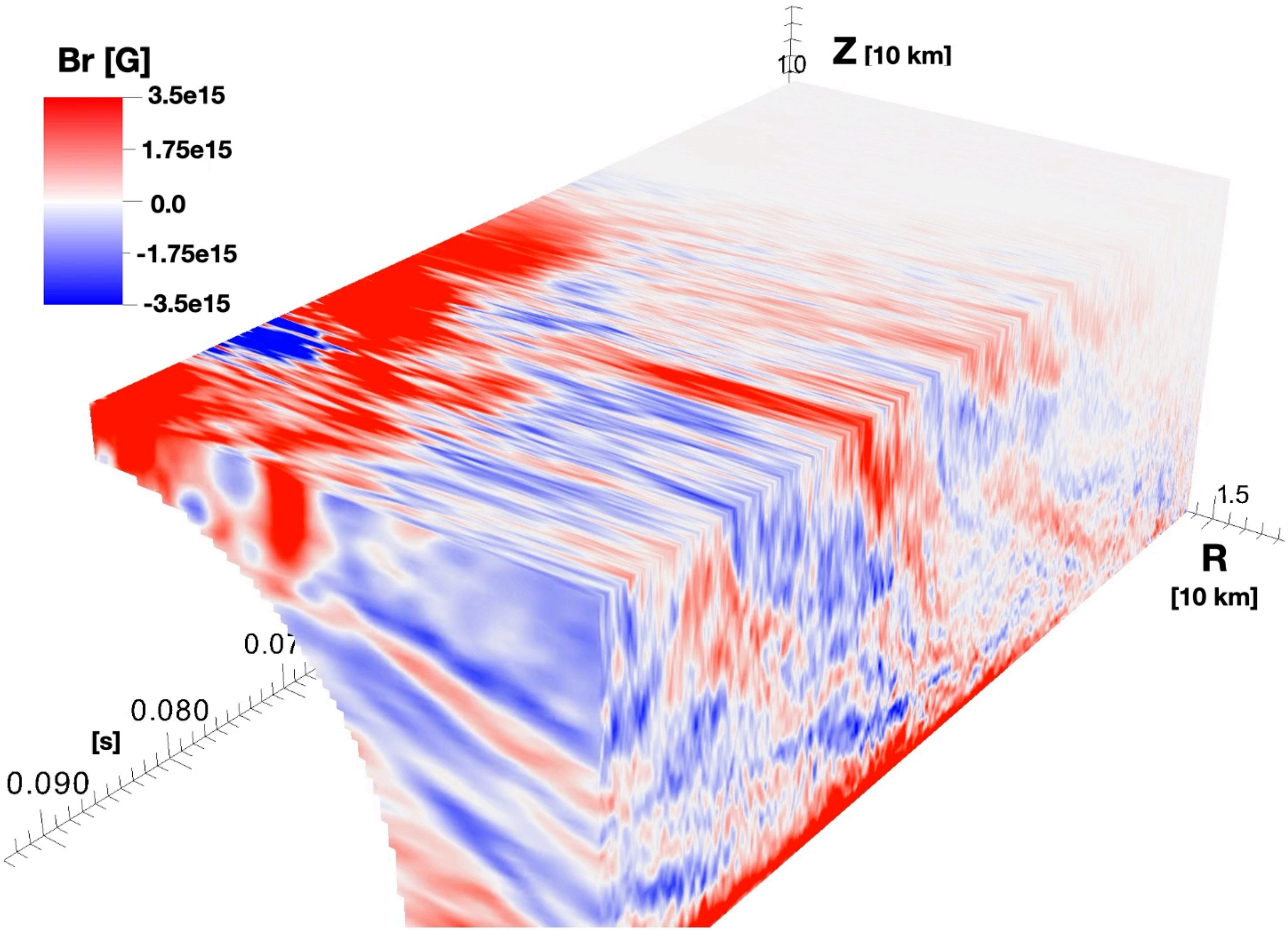


$$\vec{\mathcal{E}} = \overline{\vec{u} \times \vec{b}}$$



$$\mathcal{E}_\phi = \alpha_{\phi\phi} \bar{B}_\phi$$

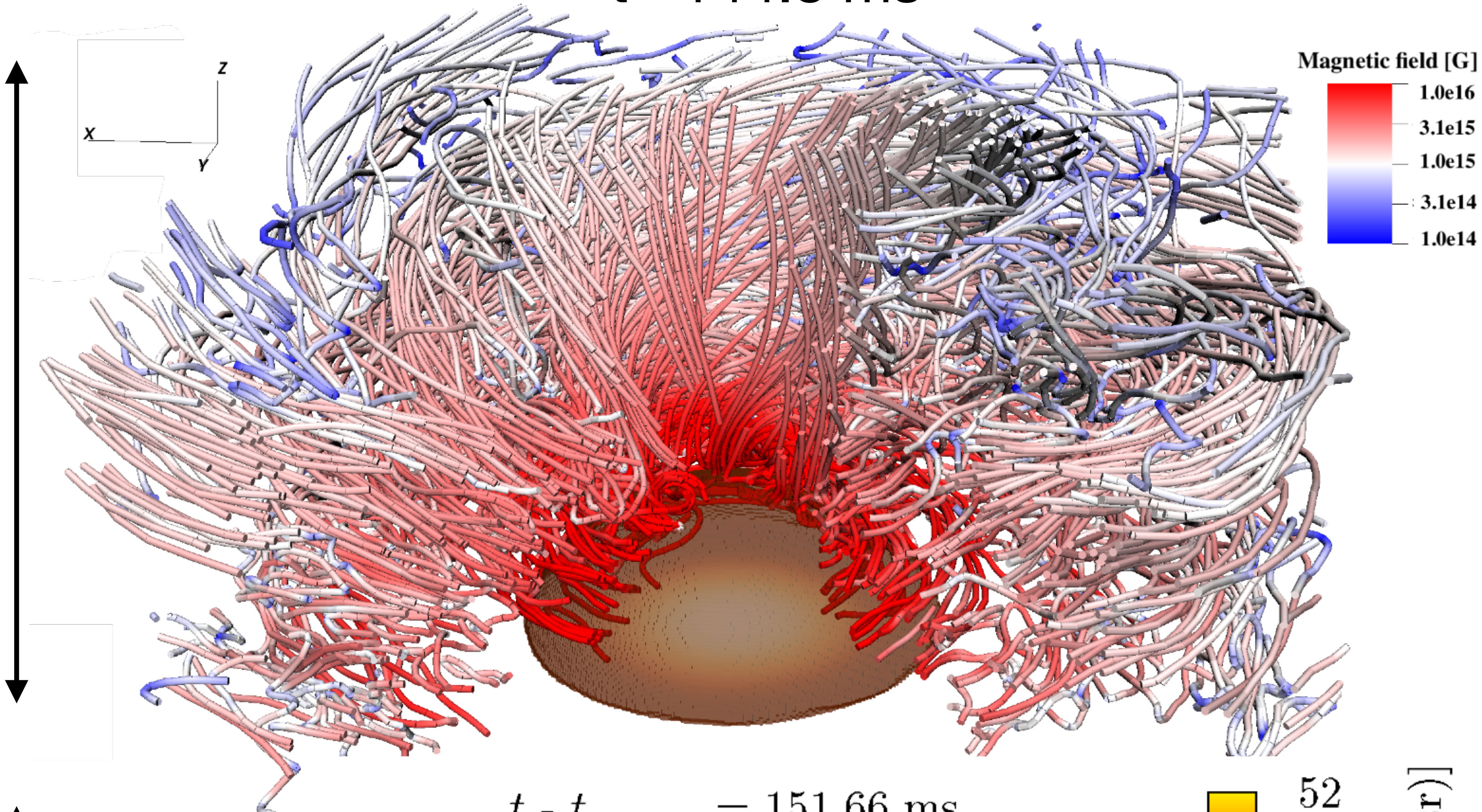
Link between polar outflow and alpha-Omega dynamo



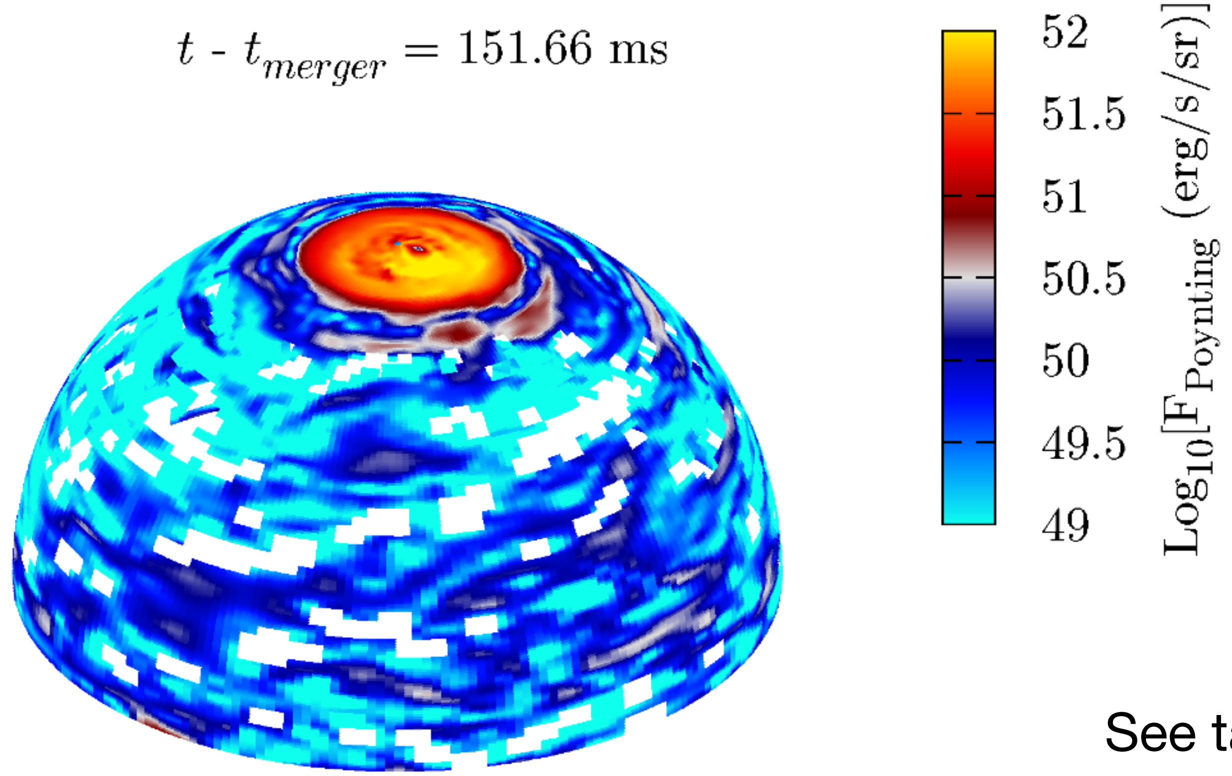
Magnetic field lines and jet

t= 144.8 ms

35 km



500 km



Turbulence dominated by the toroidal field

Jet starts from ~10 km

Pointing-flux isotropic luminosity ~ 10^{52} erg/s

Jet angle $\theta < 12^\circ$

Magnetisation parameter

$$\sigma_{LC} \equiv \frac{b^2}{4\pi\rho c^2} = 10 - 20$$

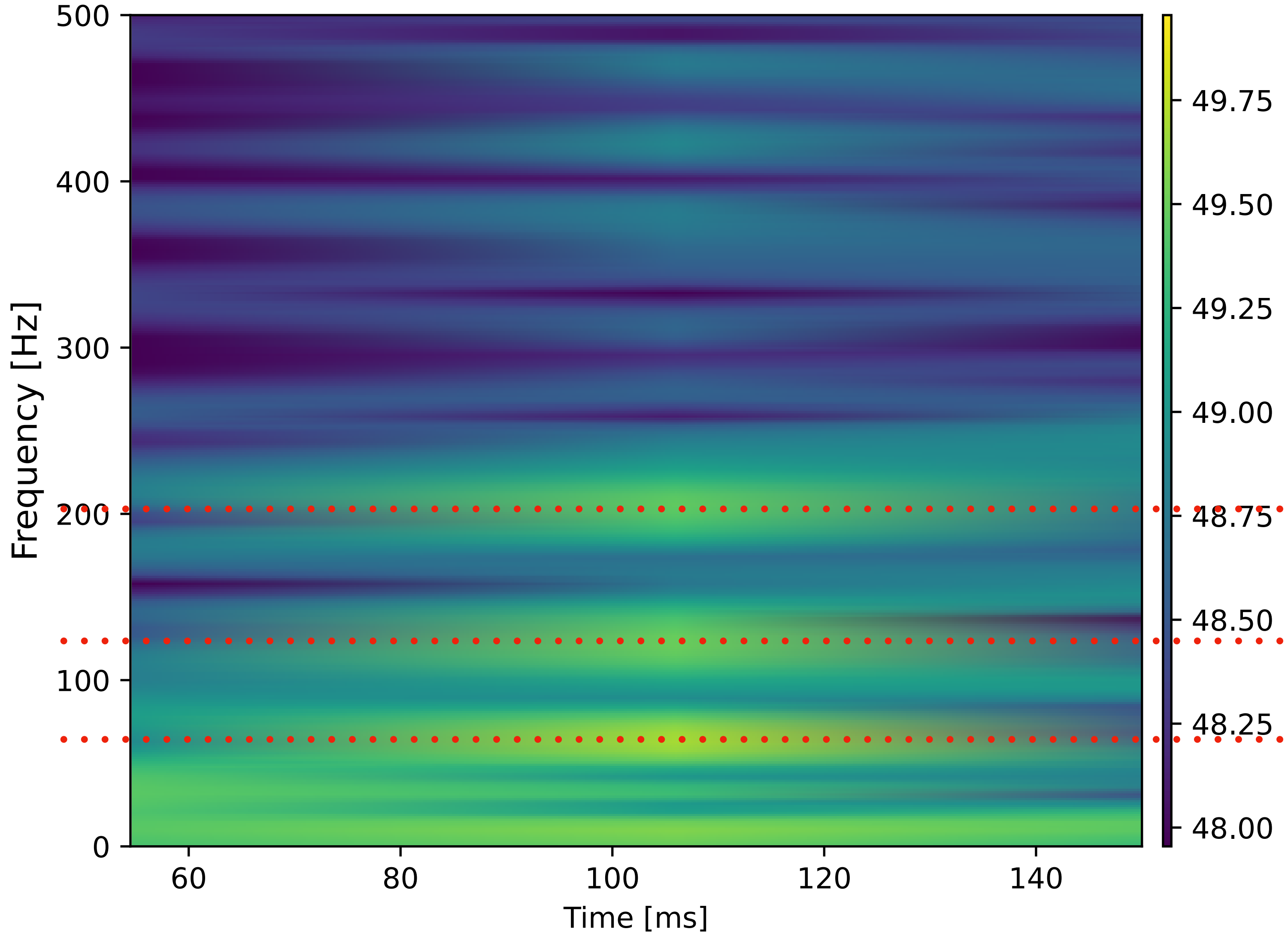
Jet+winds:
Post-merger ejecta Mass

$$\sim 0.1 M_\odot$$

See talk by Daniel Siegel for kilonova

A link to low-frequency QPOs?

Spectrogramm of Poynting-Flux luminosity at 500 km



$\sim 3.3 f_{\alpha\Omega}$

$2 f_{\alpha\Omega}$

$f_{\alpha\Omega} \sim 60$ Hz at r=12-13 km

Reboul-Salze et al, in prep

Dynamo frequency in BHNS/BNS (Hayashi+2022, 2024):

25 Hz for ~6.25 $M_{\odot}$ BH with ~0.2 $M_{\odot}$ disk at 10 ms

33 Hz for ~2.8 $M_{\odot}$ BH with ~0.1 $M_{\odot}$ at 10 ms

$$\omega_{\alpha\Omega} \propto \sqrt{q c_s \frac{c^5}{(GM_{CC})^2}} \propto \frac{\sqrt{q c_s}}{M_{CC}}$$

How does this variability evolves with the jet propagation? See talks by Marina Masson/Clément Pellouin

Magnetic Prandtl number dependency

Pm regime in PNS and BNS merger

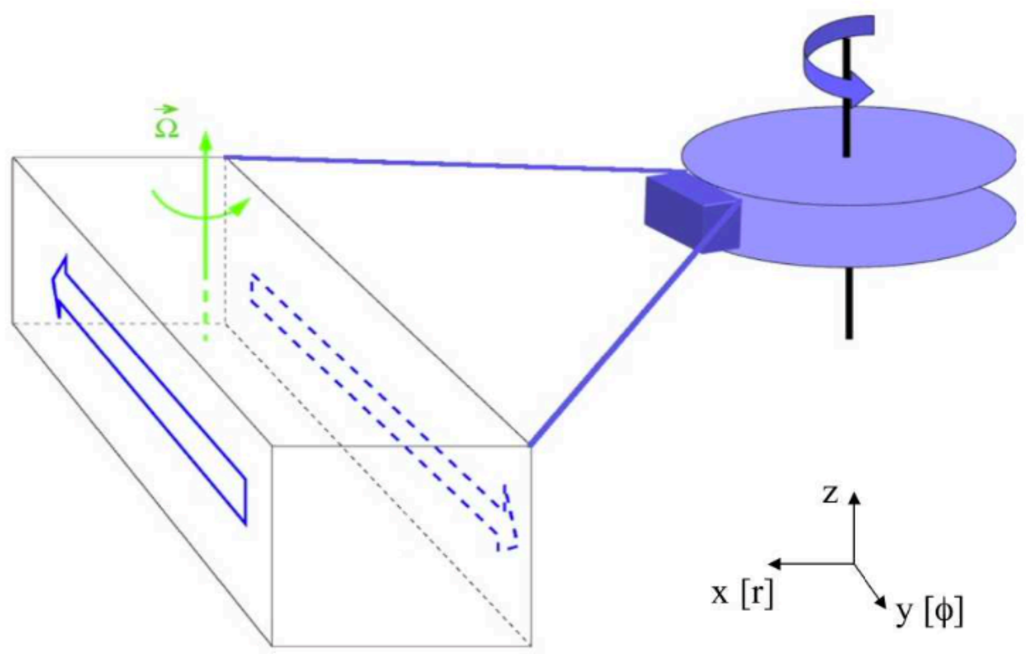
Magnetic Prandtl number: $Pm = \frac{\nu}{\eta}$

Diffusive approximation for neutrinos

Weak resistivity due to degenerate relativistic electrons

$Pm \sim 10^{13}$ $(Pm \sim 10^3 - 10^4)$

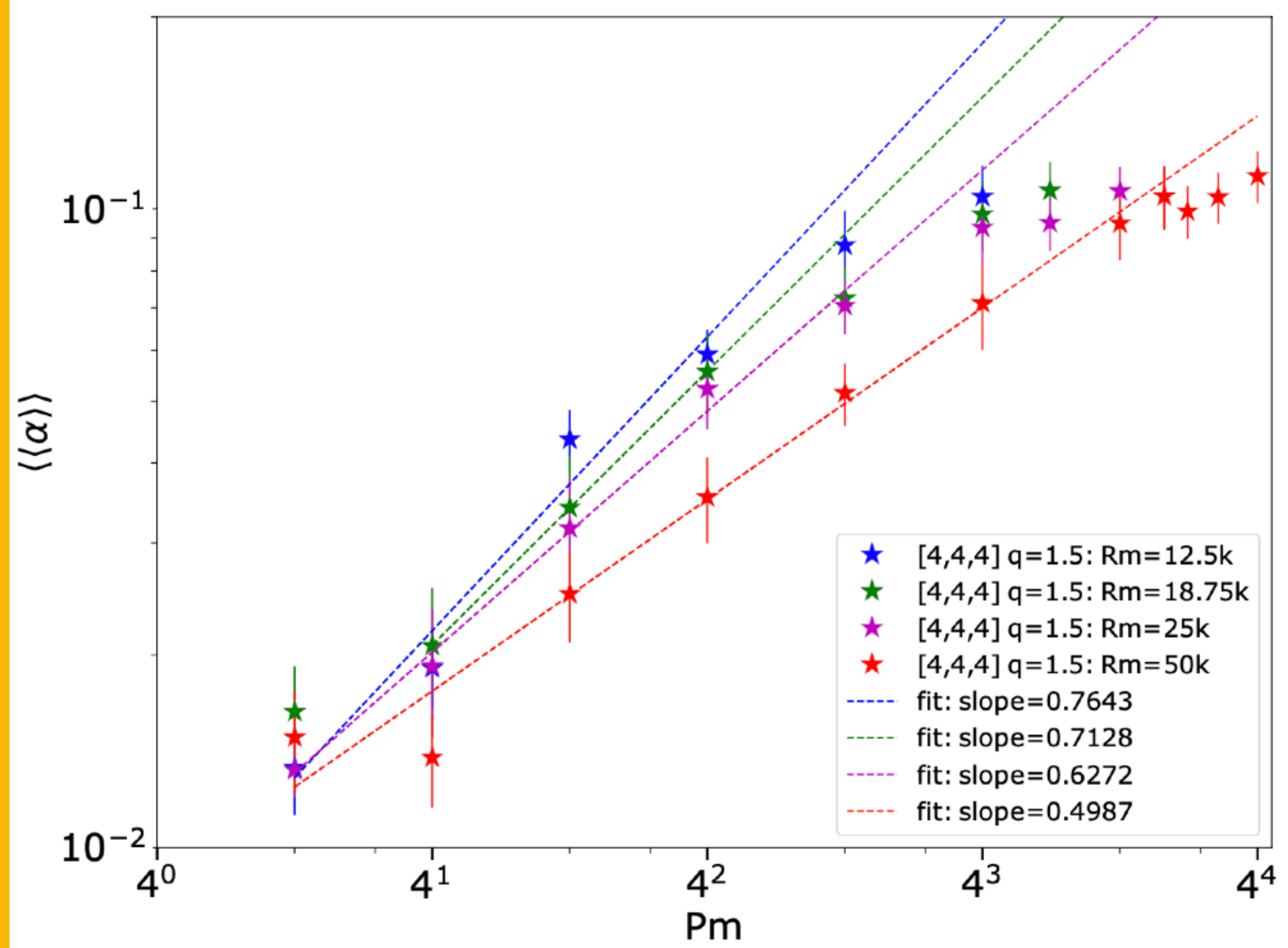
Local simulations



Fromang 2013

Held et al., 2024

Stratified case with increasing viscosity



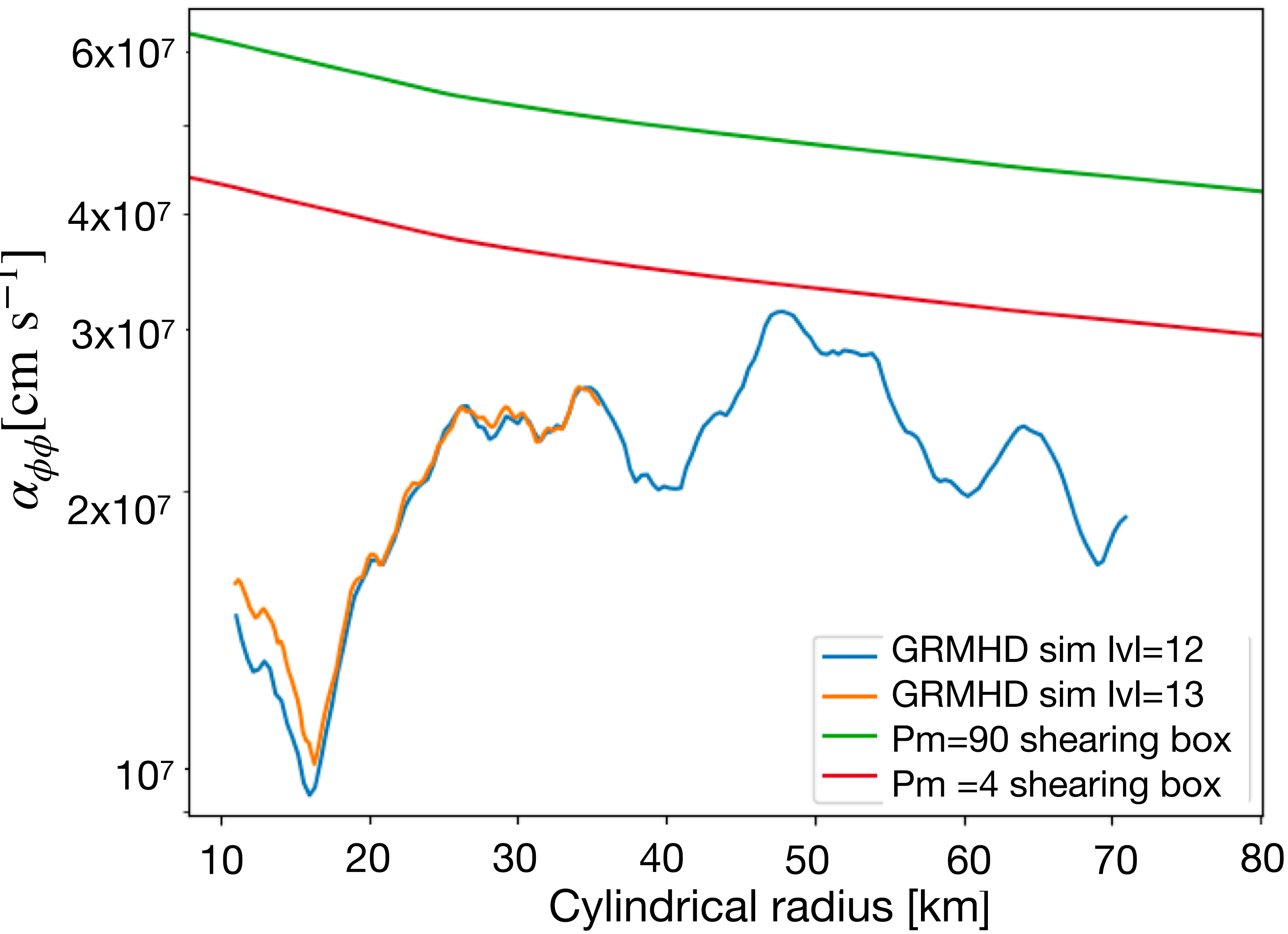
In the mid plane (|z|<2 H): MRI-driven dynamo dynamics

In the "atmosphere" (|z|>2 H): magnetic buoyancy instabilities

$H = \frac{c_s}{\Omega}$

Magnetic field amplification modelling: global vs local

Peak alpha value



ARS et al, 2025

Similar results to GRMHD simulation in the HMNS case but weaker alpha

-> Faster growth rate and period

$$P = 2\pi \left(\frac{1}{2} \alpha_{\phi\phi} \frac{d\Omega}{d \ln s} k_z \right)^{-1/2}$$

~ 14-18 ms instead of 20-25 ms

Magnetic field would be > 3 times higher than GRMHD simulation

-> magnetisation could become

$$\sigma_{LC} \sim 100$$

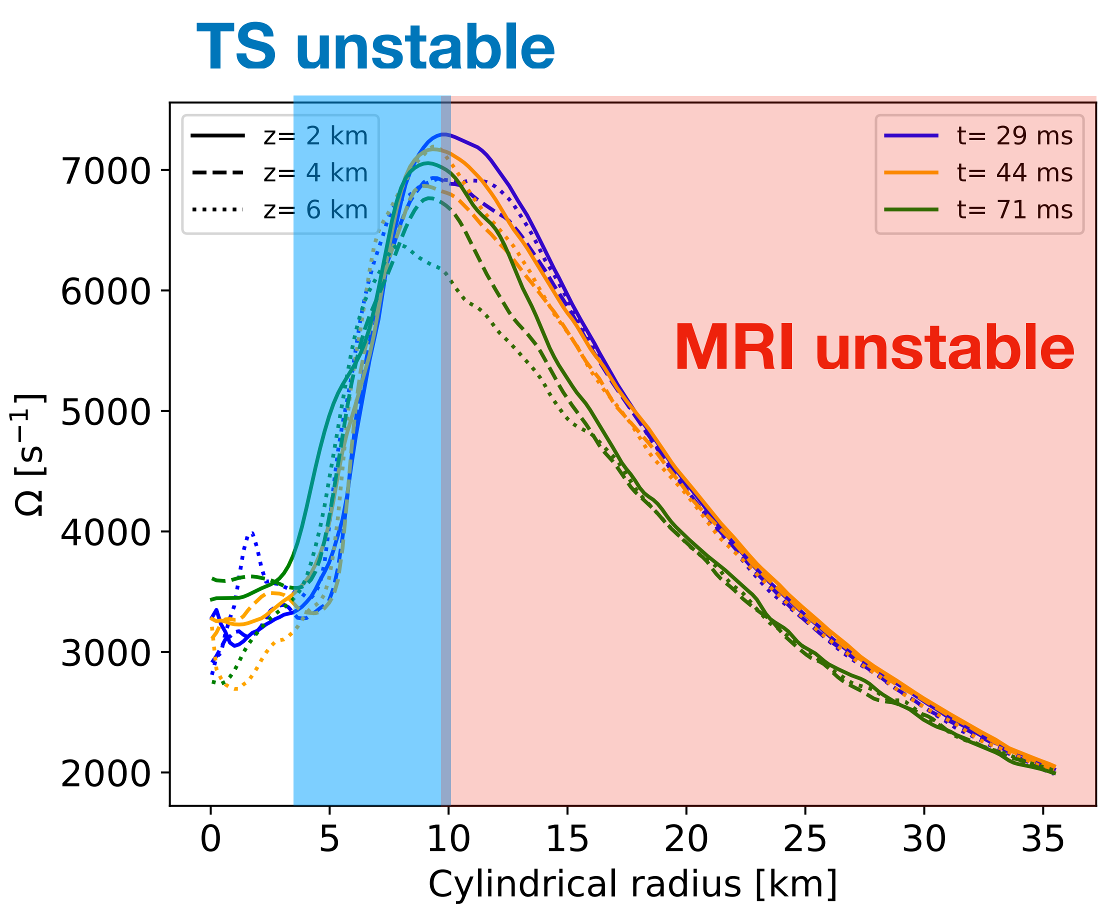
Isotropic luminosity could reach 10^{53} erg s^{-1}

Outline

Introduction

I-MRI-driven αΩ dynamos in BNS mergers

II- Taylor-Spruit dynamo in BNS mergers



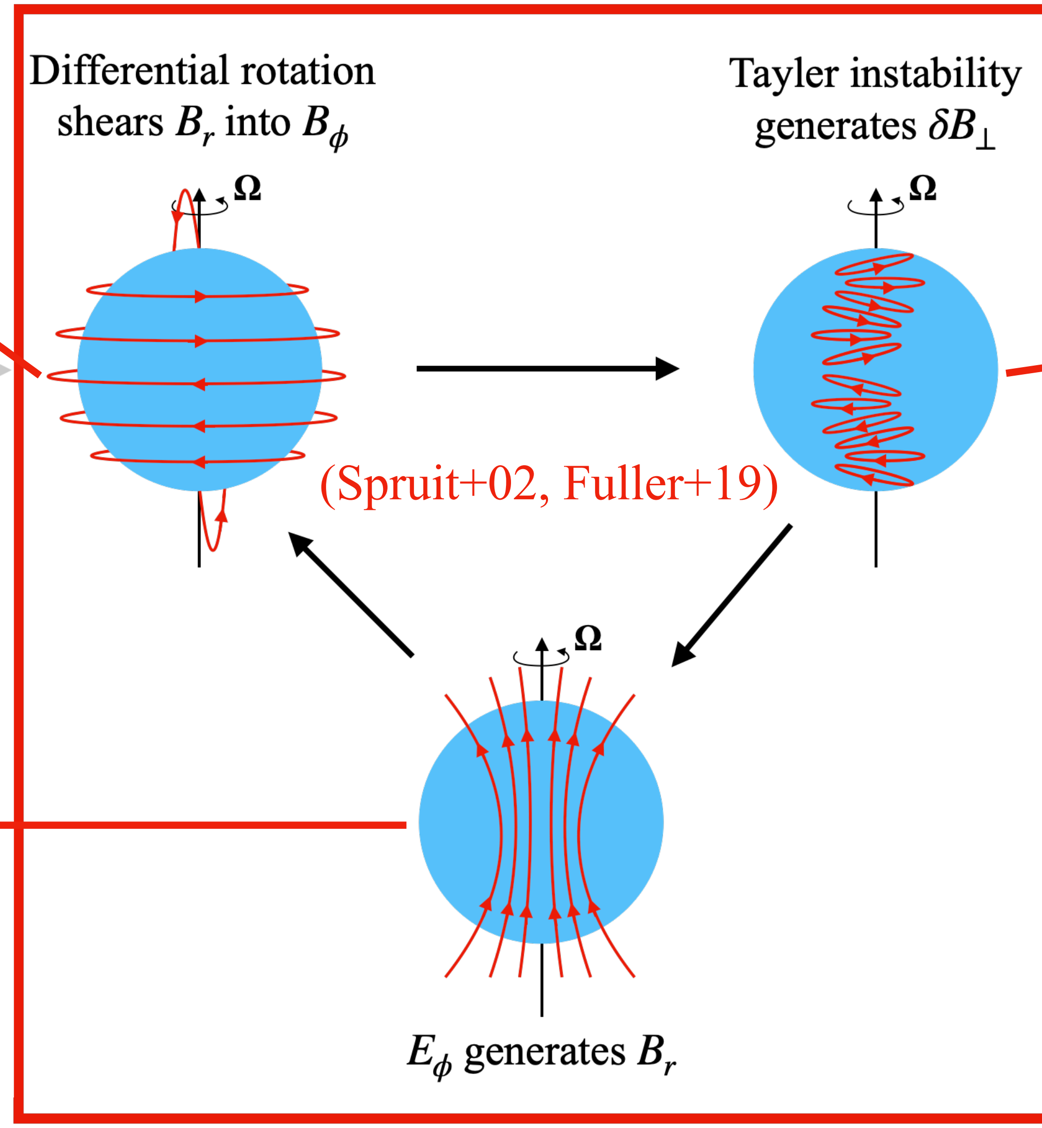
TS dynamo for hypermassive neutron star

Shearing

- Radial-dependent differential rotation (*shellular* rotation)
- Adimensional shear rate q

$\Longrightarrow$ Growth rate $\sigma_{\rm shear}$ of the toroidal magnetic field B_ϕ

Tayler-Spruit dynamo loop



Tayler instability (Tayler+73)

- B_ϕ is the main background field
- Alfvén frequency: $\omega_{\rm A} \equiv \dfrac{B_\phi}{\sqrt{4\pi\rho r^2}}$
- $N \sim \Omega \gg \omega_{\rm A}$

$\Longrightarrow$ Growth rate $\sigma_{\rm TI}$ of the perturbed magnetic field $\delta B_\perp$

Saturated turbulent magnetic field

Non-linear induction

- Mean-field theory
- Azimuthal electromotive force:

$$E_\phi \equiv \left\langle \delta\vec{v} \wedge \delta\vec{B} \right\rangle_\phi$$

$$E_\phi \sim \left\langle \delta v_r \delta B_\theta - \delta v_\theta \delta B_r \right\rangle \sim \delta v_r \delta B_\perp$$

$\Longrightarrow$ Growth rate $\sigma_{\rm NL}$ of the radial magnetic field B_r

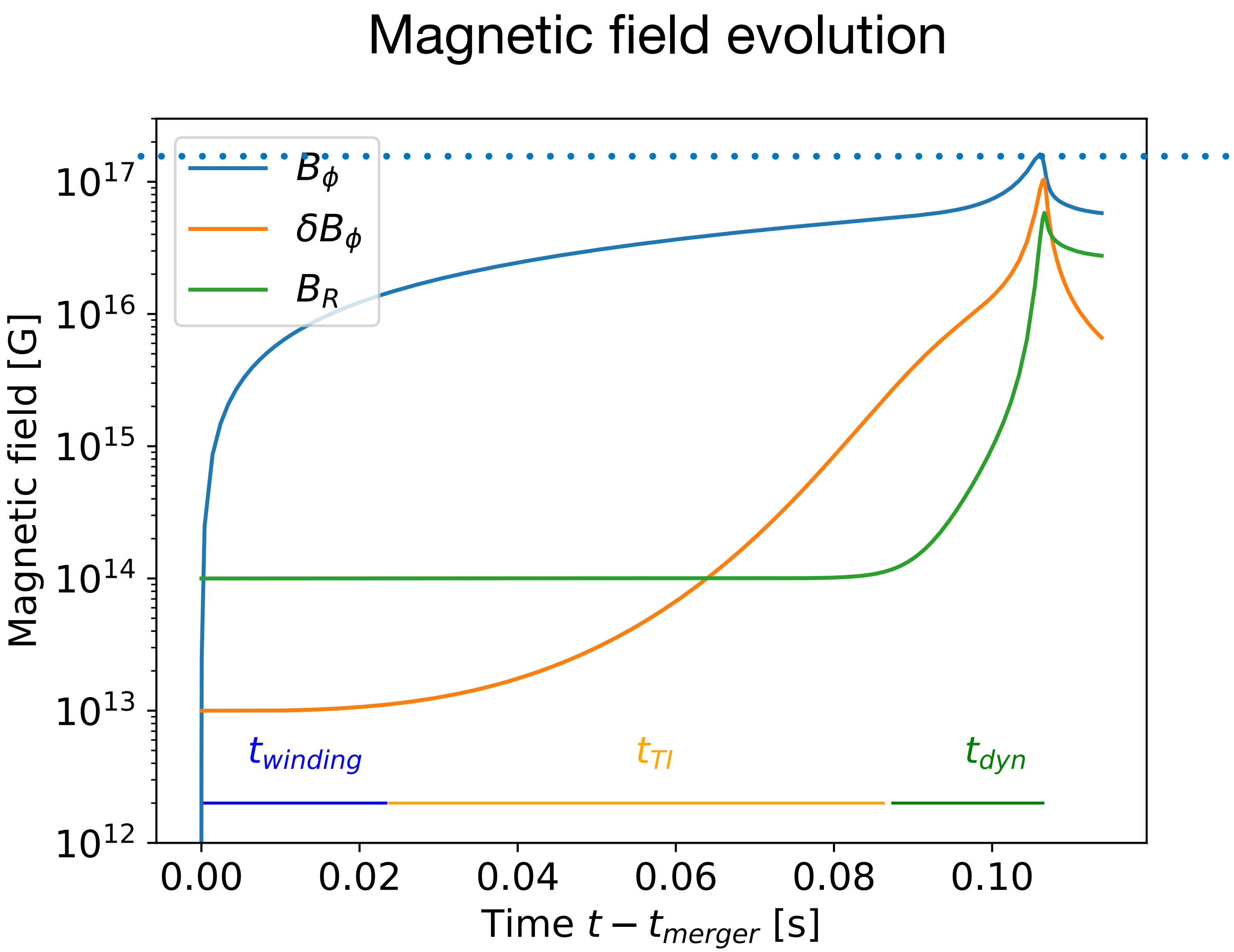
Brunt-Vaisala frequency in GR (static BG):

$$N^2 \equiv -c^2 \frac{\alpha C_{\rm L}}{\rho h \phi^4} \frac{\partial \alpha}{\partial r}$$

Credit: P. Barrere et al 2022

- Angular momentum transport in stellar evolution (Spruit 2002, Fuller et al 2019)
- Formation of magnetar through fallback in CCSN (Barrere et al. 2022,2023,2025)

One-zone model for HMNS



Dynamo stops when there is no more rotation

⟶ could lead to faster collapse to a BH

$$B_{\phi,sat} = 1.6 \times 10^{17}\mathrm{G}$$

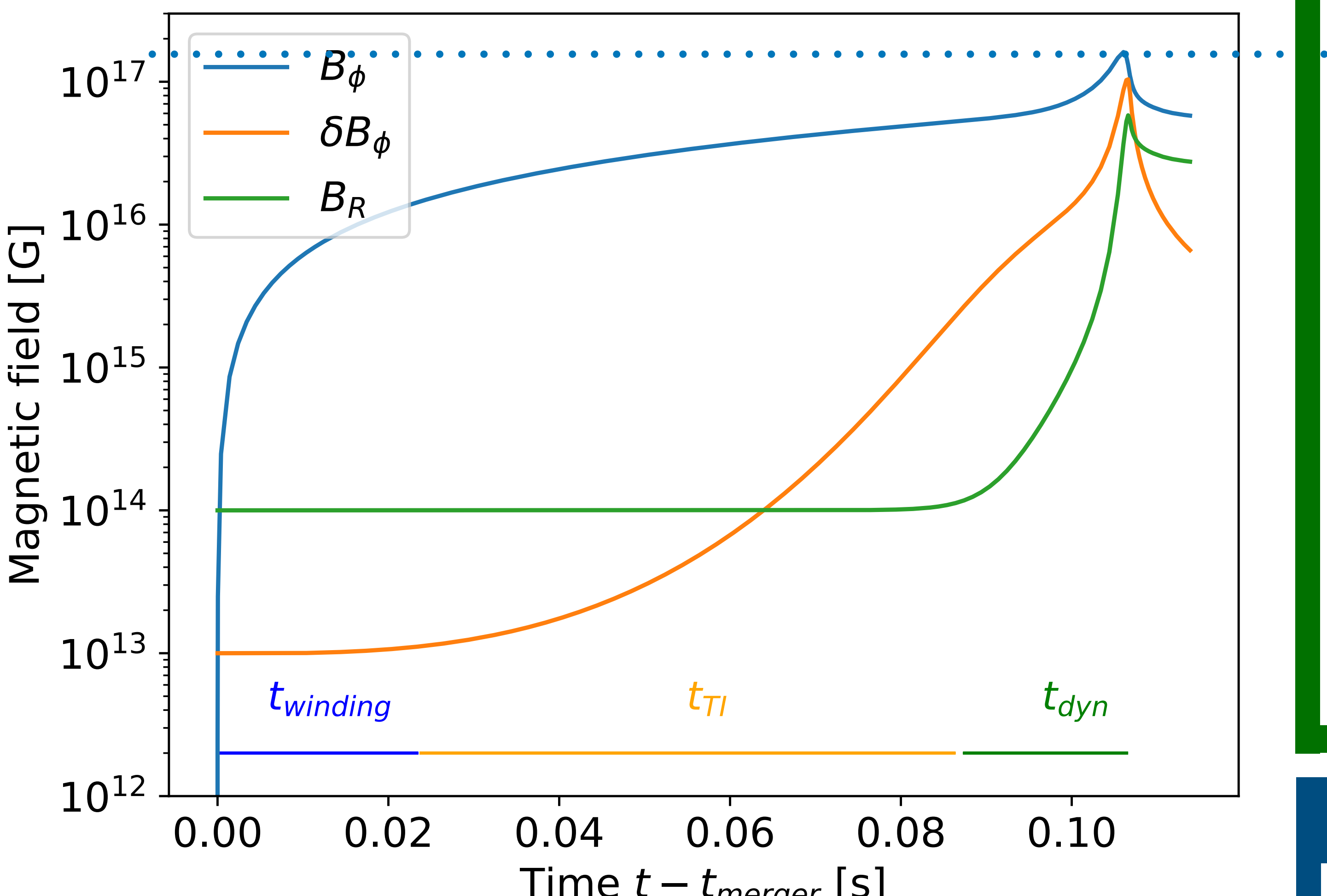
$$B_{R,sat} = 6.0 \times 10^{16}\mathrm{G}$$

$$\delta B_{\phi,sat} = 1.0 \times 10^{17}\mathrm{G}$$

ARS et al, 2025

One-zone model for HMNS

Magnetic field evolution



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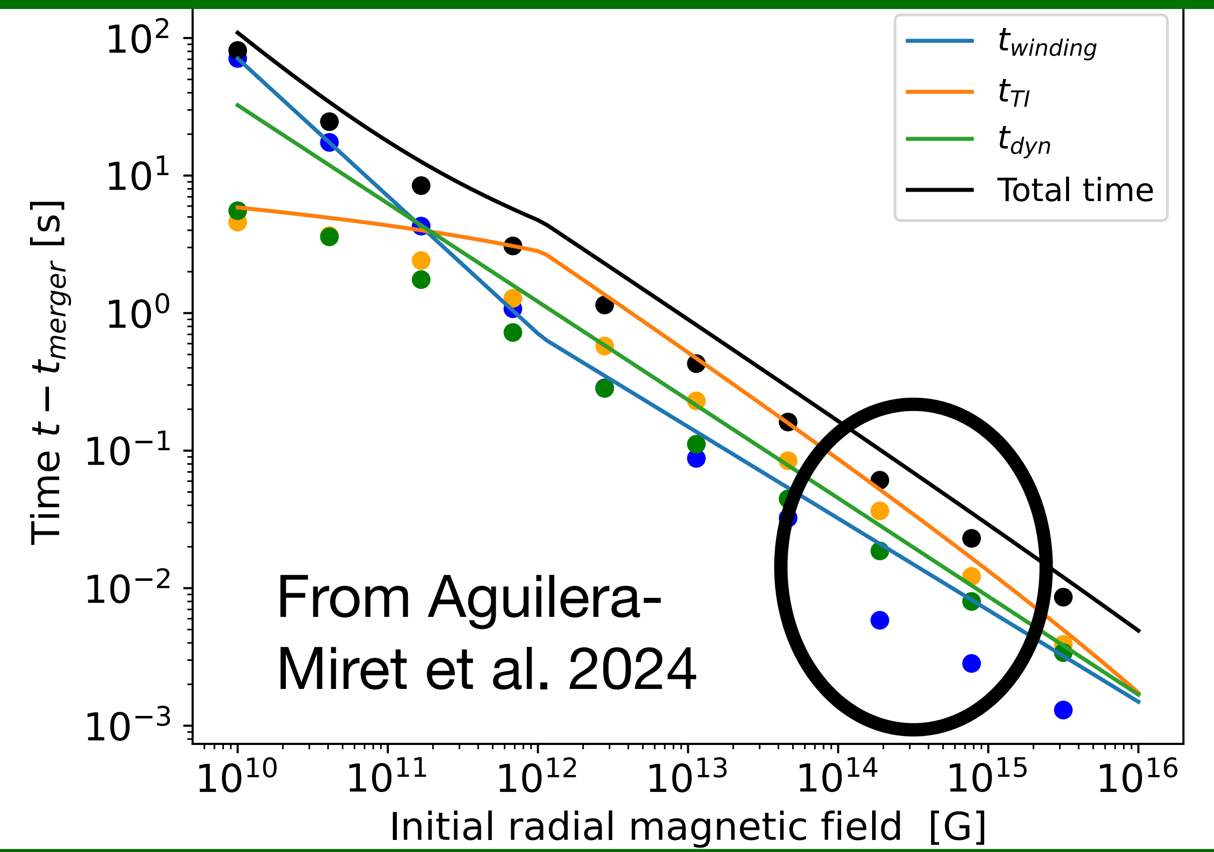
ARS et al, 2025

Initial Magnetic field dependence



Caveats

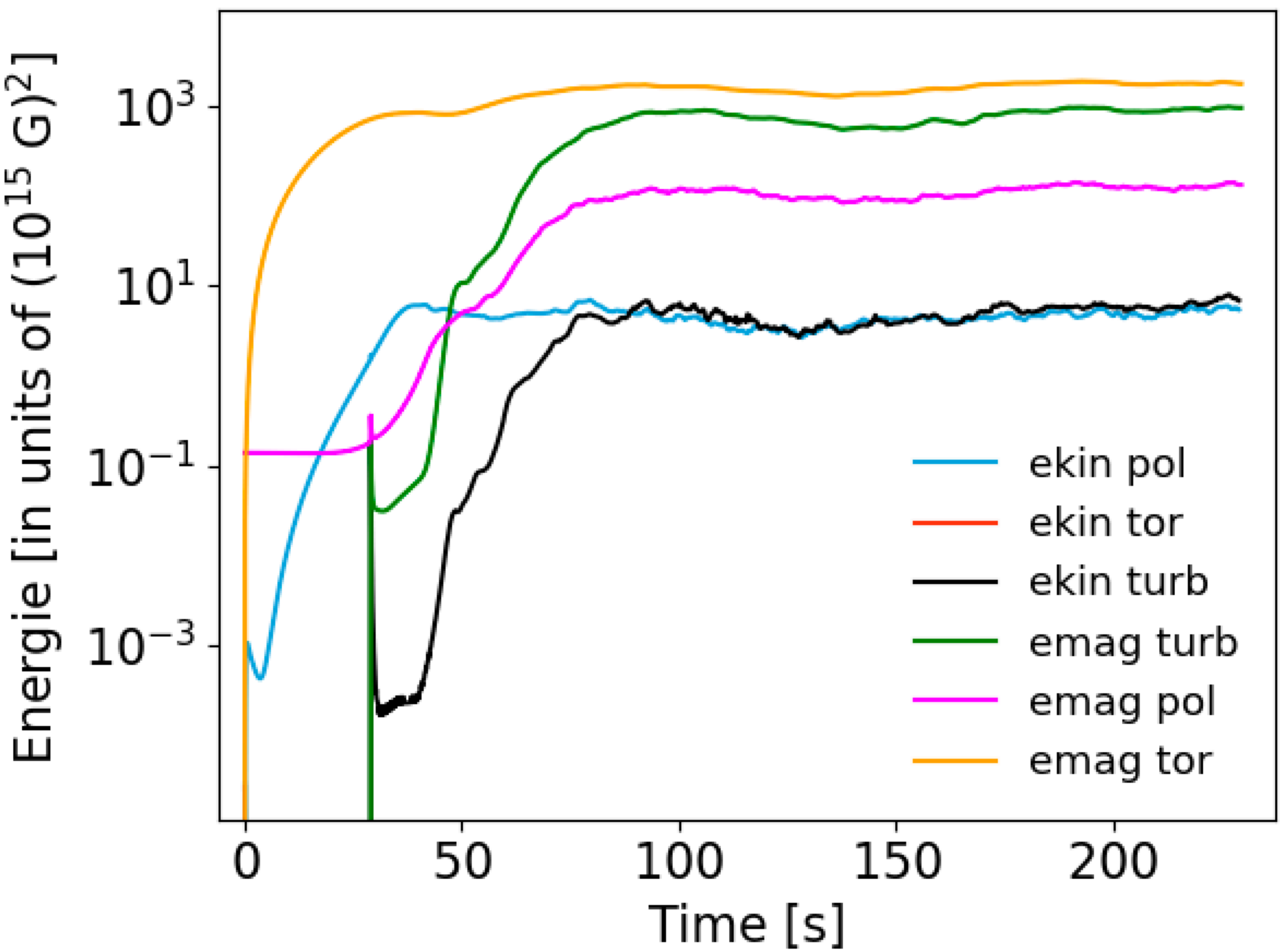
Comparison to current simulations (Barrere et al. 2023, 2025)

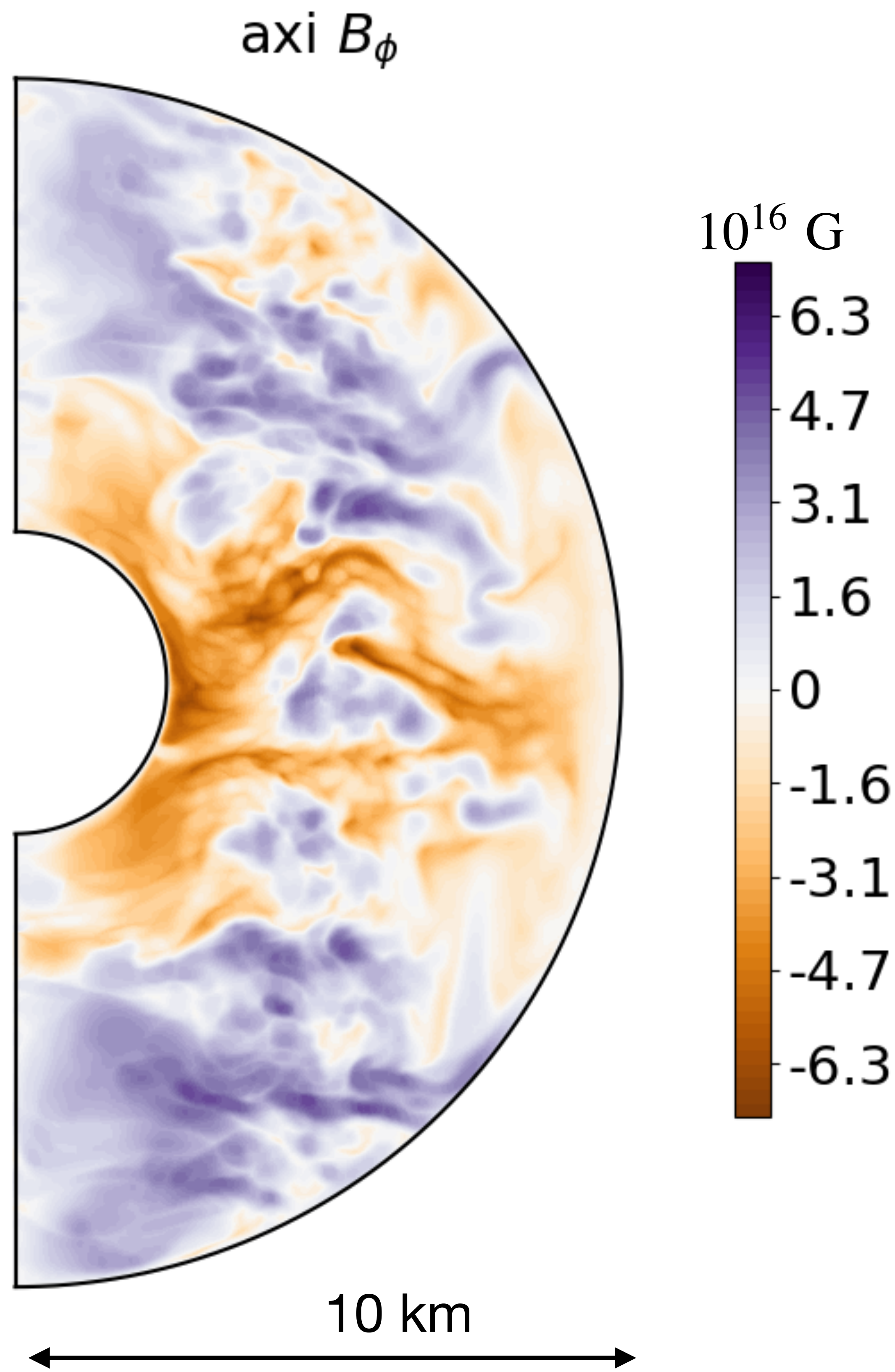
$$B_{\rm tor}^{m=0} \approx 10^{16} \ \mathrm{G}$$

$$B_{\rm pol}^{m=0} \approx 10^{15} \ \mathrm{G}$$

→ Need to explore simulations for HMNS

An MHD toy model of the TS dynamo



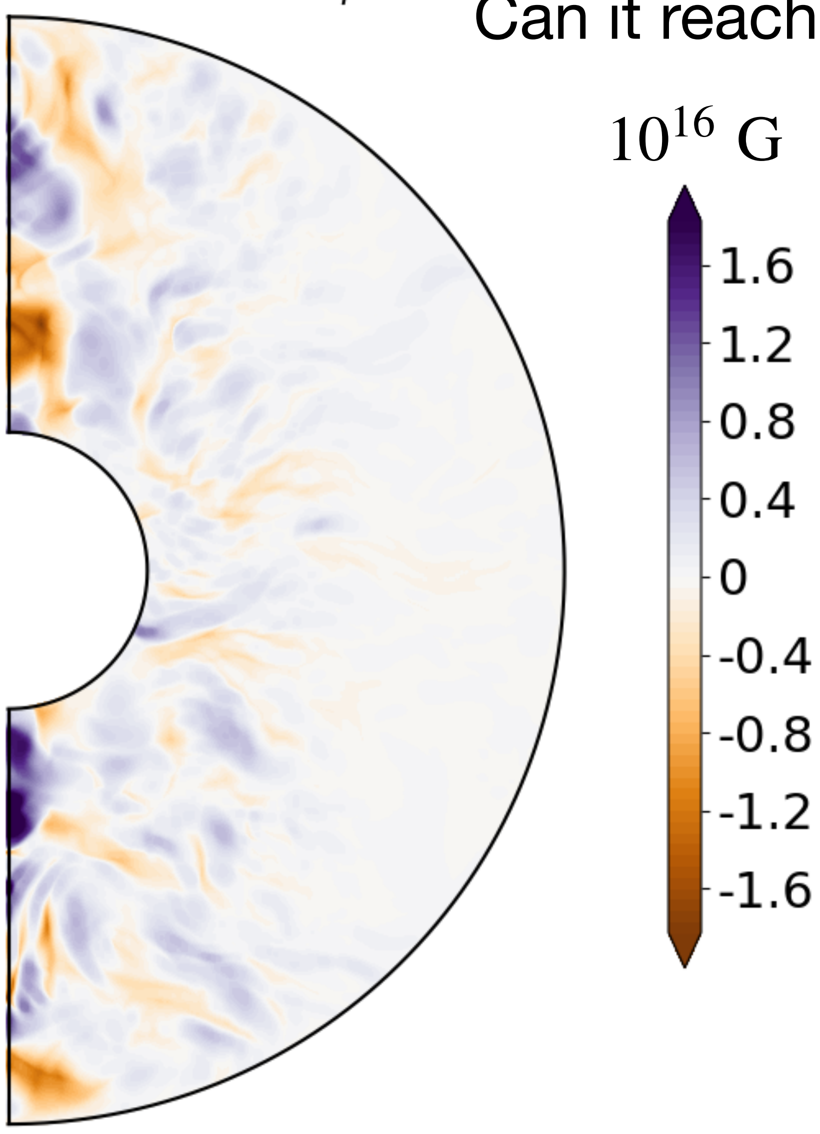


Astrophysical consequences

Large-scale poloidal field

axi B_r

Can it reach the surface?



Transport angular momentum in ~110 ms

⟶ Supermassive NS with strong dipole

See Clara Piasse's talk for evolution of NS

Impact GW

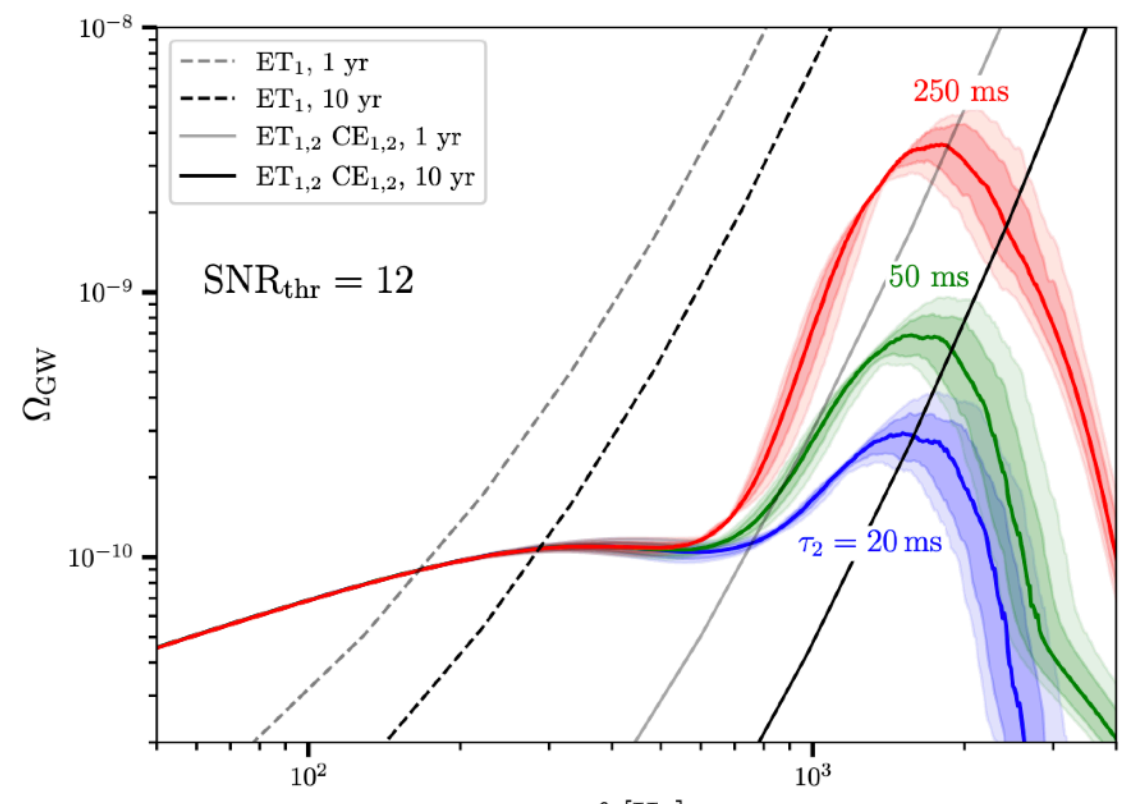
Turbulence in the highest density region

⟶ Excitation of modes and emit GW?

⟶ B field impact on post-merger signal?

Ex: convective dynamos in supernova (Raynaud et al. 2022)

stochastic GW background



Impact of the decay time of f mode and remnant life time (Lehoucq+2025)

Summary and Perspectives

- MRI-driven alpha-Omega dynamo

→ 20 ms period dynamo
→ Produce luminous and magnetised jets
→ A link between dynamo frequency and low-frequency QPOs?
→ If GW and QPO detection -> remnant and disk masses?

- MRI-driven alpha-Omega dynamo at high-Pm

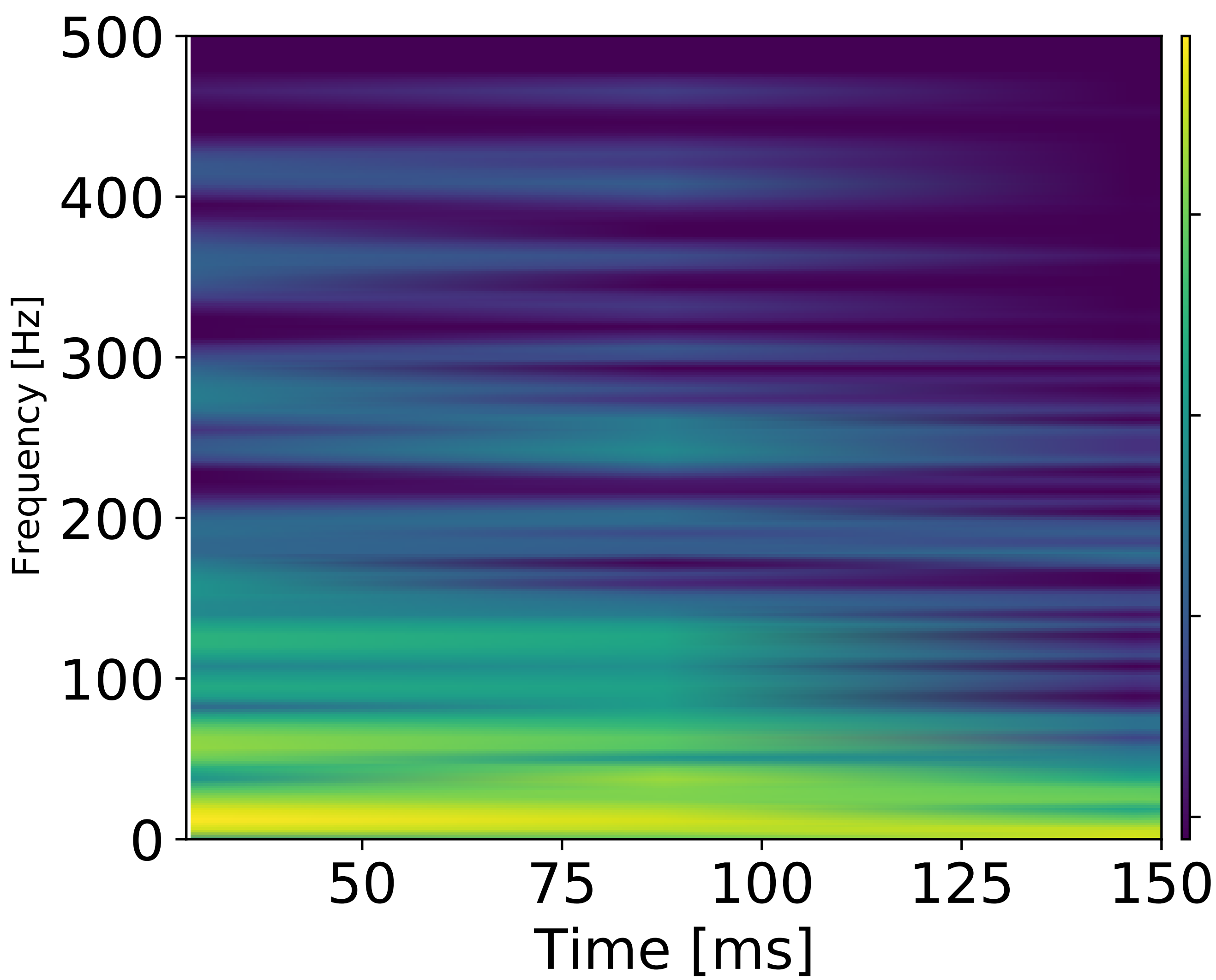
→ Increased dynamo strength at high-Pm
→ Stronger magnetic fields and variability
→ **Explore this regime with 2D axisymmetric simulations?**

- Tayler-Spruit dynamo

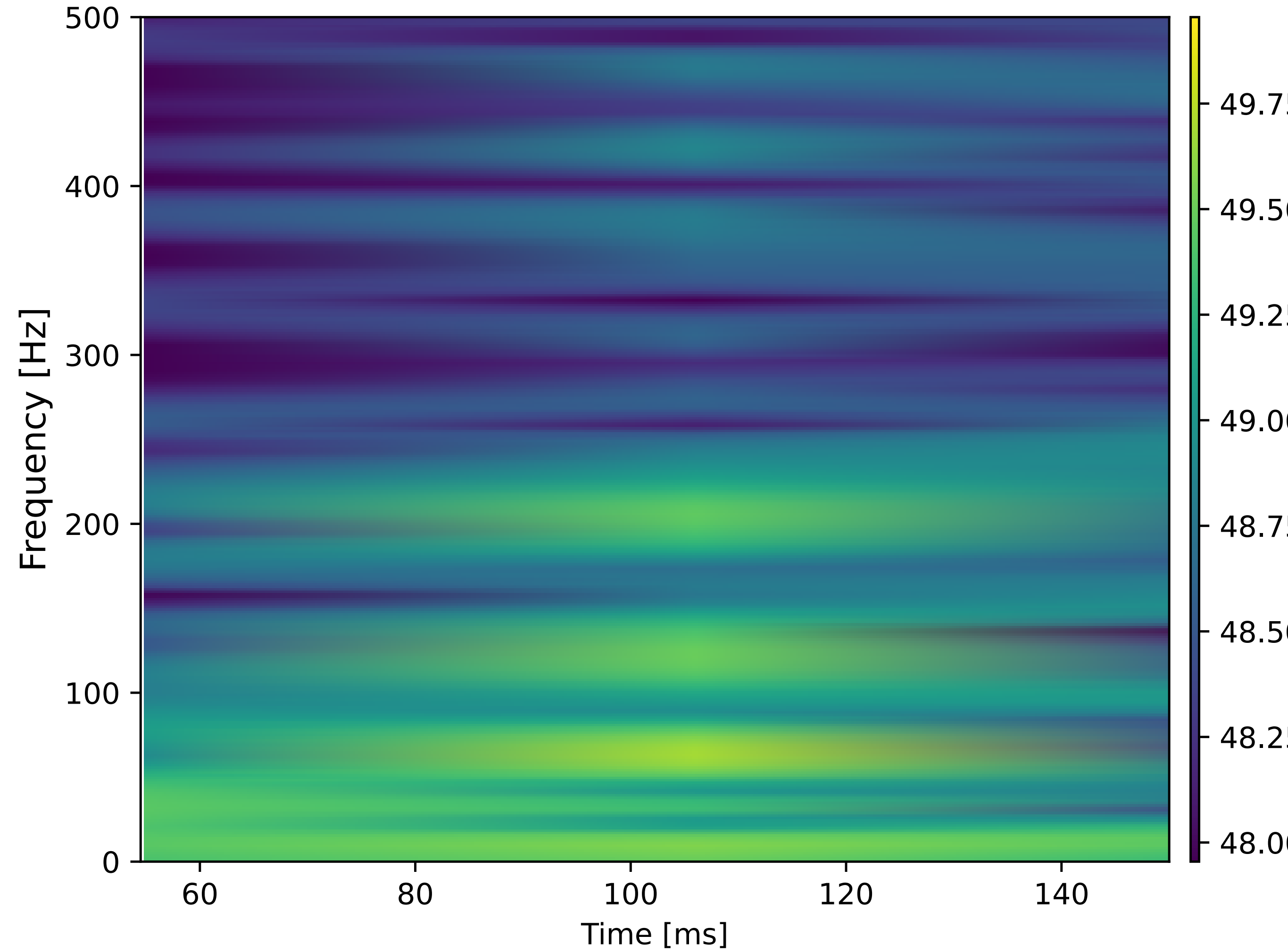
→ Dynamo amplify the magnetic field in the core to $B_\phi > 5 \times 10^{16} - 10^{17}$G and $B_R > 10^{16}$ G, in less than 0.1 seconds.
→ It transports angular momentum efficiently and reduce the remnant lifetime.
→ Does B_R field stay confined in the remnant or can lead to EM emission?
→ Multimessenger Observations: Emission of GW?

A link to low-frequency QPOs?

FFT of toroidal field at 12 km in the HMNS



Poynting Flux luminosity at 500 km



Reboul-Salze et al, in prep

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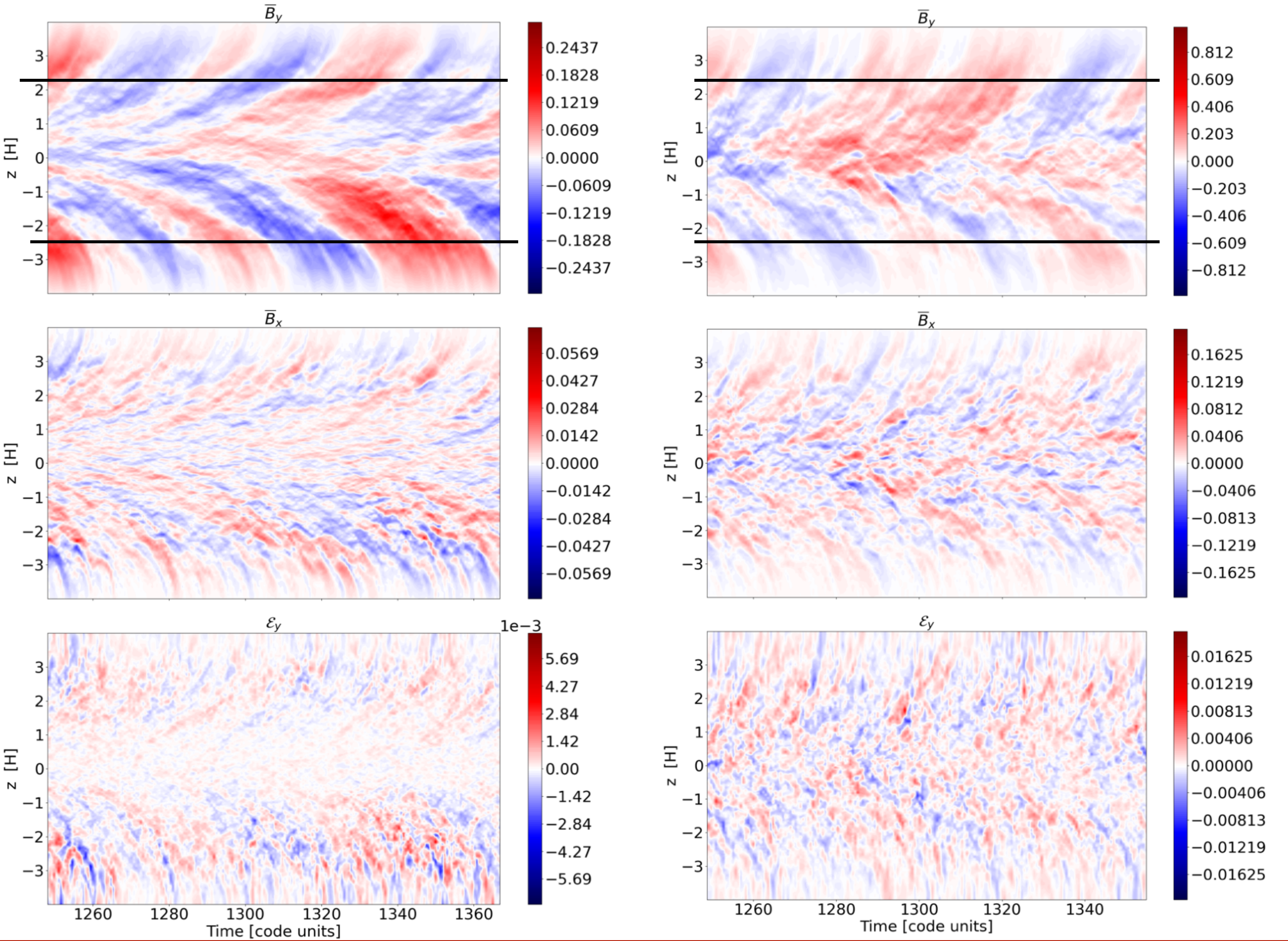
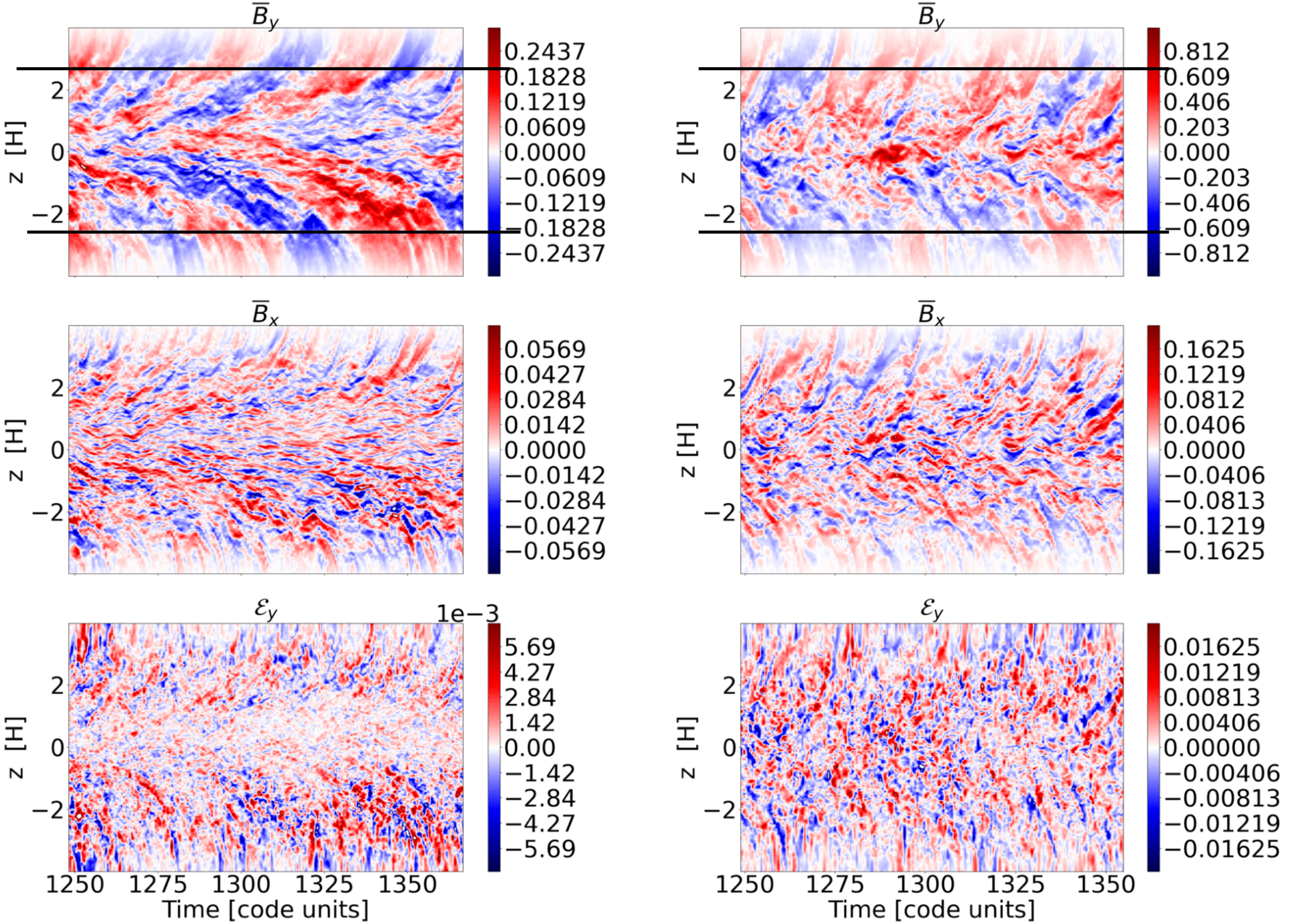
$$\omega_{\alpha\Omega} \propto \sqrt{q c_s \frac{c^5}{(G M_{CC})^2}} \propto \frac{\sqrt{q c_s}}{M_{CC}}$$

How does this variability evolves with the jet propagation?

Butterfly diagrams comparison



Butterfly diagrams comparison



Equations of the HMNS model

Rotation profile

$$\begin{cases} \dot{\Omega} = \dfrac{R_{\rm TI}^3 T_{R\phi}^{MAX}}{I} = -\dfrac{R_{\rm TI}^3 B_R B_\phi}{I}, \\ \dot{q} \; = \; -\gamma_{\rm AM} q = -\dfrac{B_r B_\phi}{4\pi\rho\Omega r^2} \end{cases}$$

Hypermassive NS properties

$$R_{TI} = 7\text{km}$$
$$\Omega = 5500\text{s}^{-1}$$
$$q = 1.1$$
$$\rho = 3.7 \times 10^{14}\text{g cm}^{-3}$$
$$N = 3700\text{s}^{-1}$$
$$I = 1.7 \times 10^{45}\text{g cm}^2$$

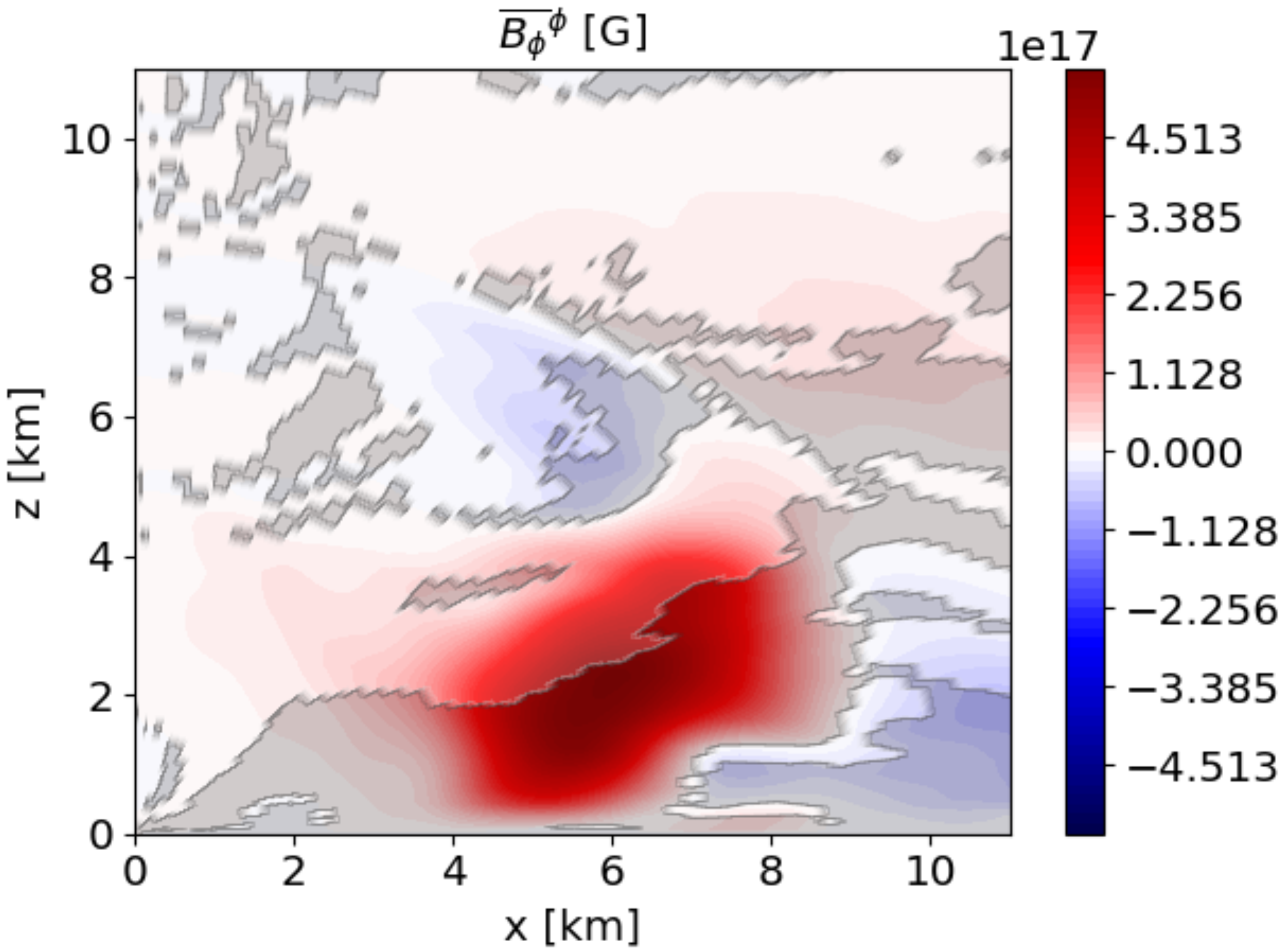
Magnetic field

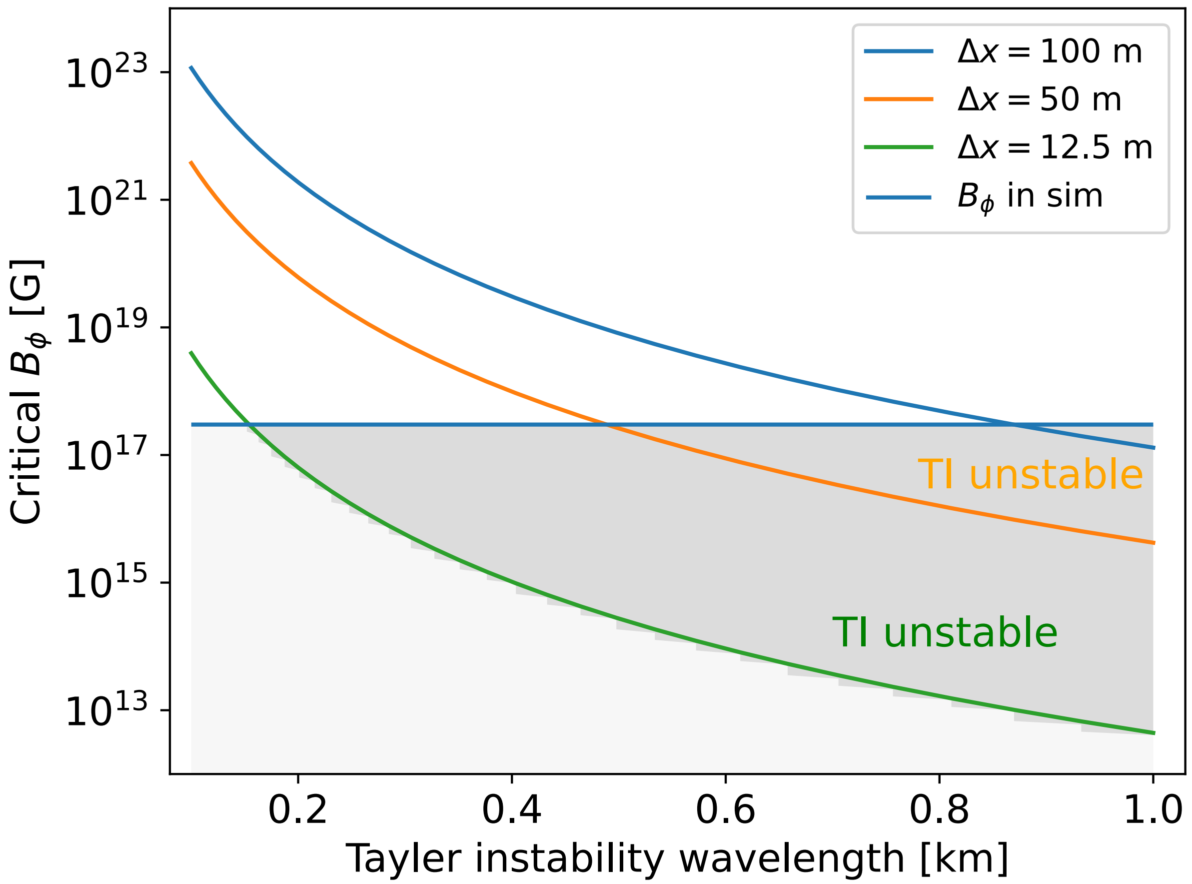
$$\begin{cases} \partial_t B_\phi = (\sigma_{\rm shear} - \gamma_{\rm diss}) B_\phi = q\Omega B_r - \dfrac{\omega_A^2}{\Omega}\dfrac{\delta B_\perp^2}{B_\phi} \\ \partial_t \delta B_\perp = (\sigma_{\rm TI} - \gamma_{\rm cas}) \delta B_\perp = \dfrac{\omega_A^2}{\Omega}\delta B_\perp - \dfrac{\delta v_A}{r}\delta B_\perp \\ \partial_t B_r = (\sigma_{\rm NL} - \gamma_{\rm diss}) B_r = \dfrac{\omega_A^2 \delta v_A}{N\Omega r}\delta B_\perp - \dfrac{\omega_A^2}{\Omega}\left(\dfrac{\delta B_\perp}{B_\phi}\right)^2 B_r \end{cases}$$

Credit: P. Barrere et al 2022

Can we resolve the TS dynamo in GRMHD simulations?

at t = 60 ms





Small unstable region ->
Numerical diffusion too strong

Required resolution would be around
$\Delta x = 12.5 - 25\text{m}$