

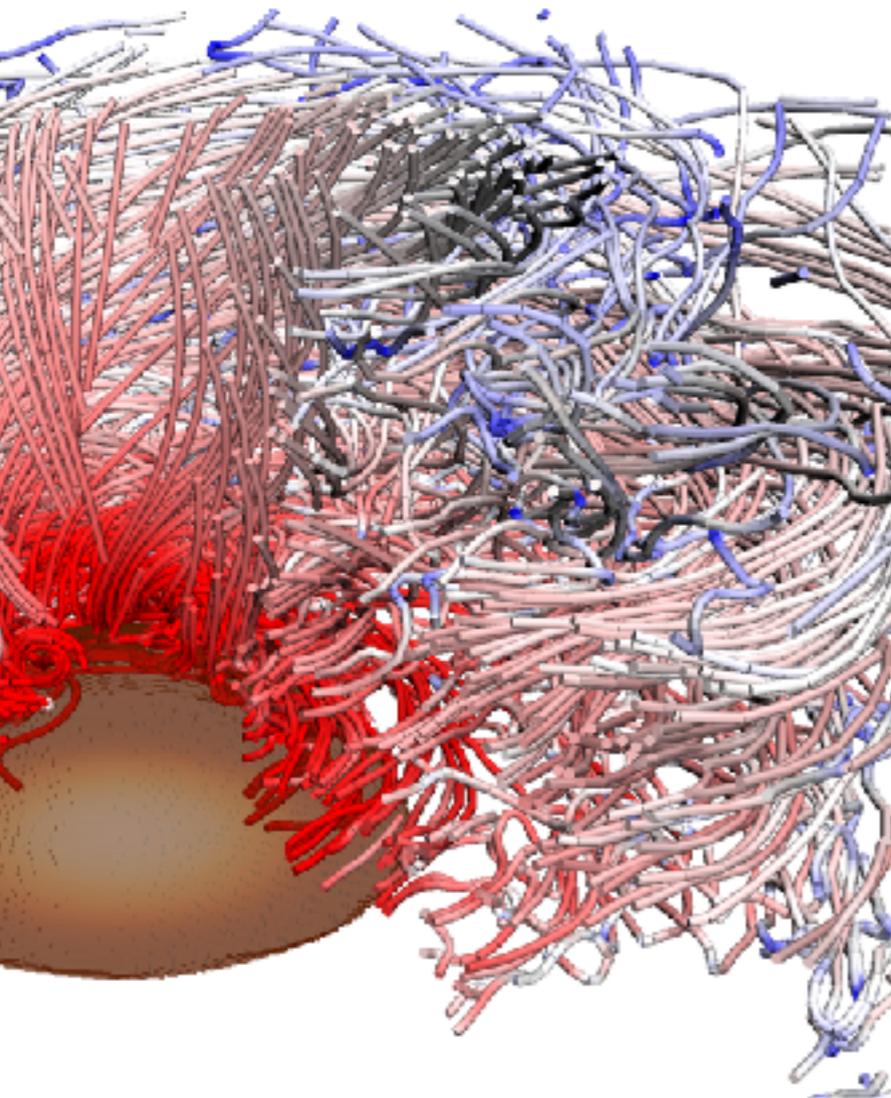
MRI-driven dynamo and jet launching in binary neutron star merger simulations

Alexis Reboul-Salze

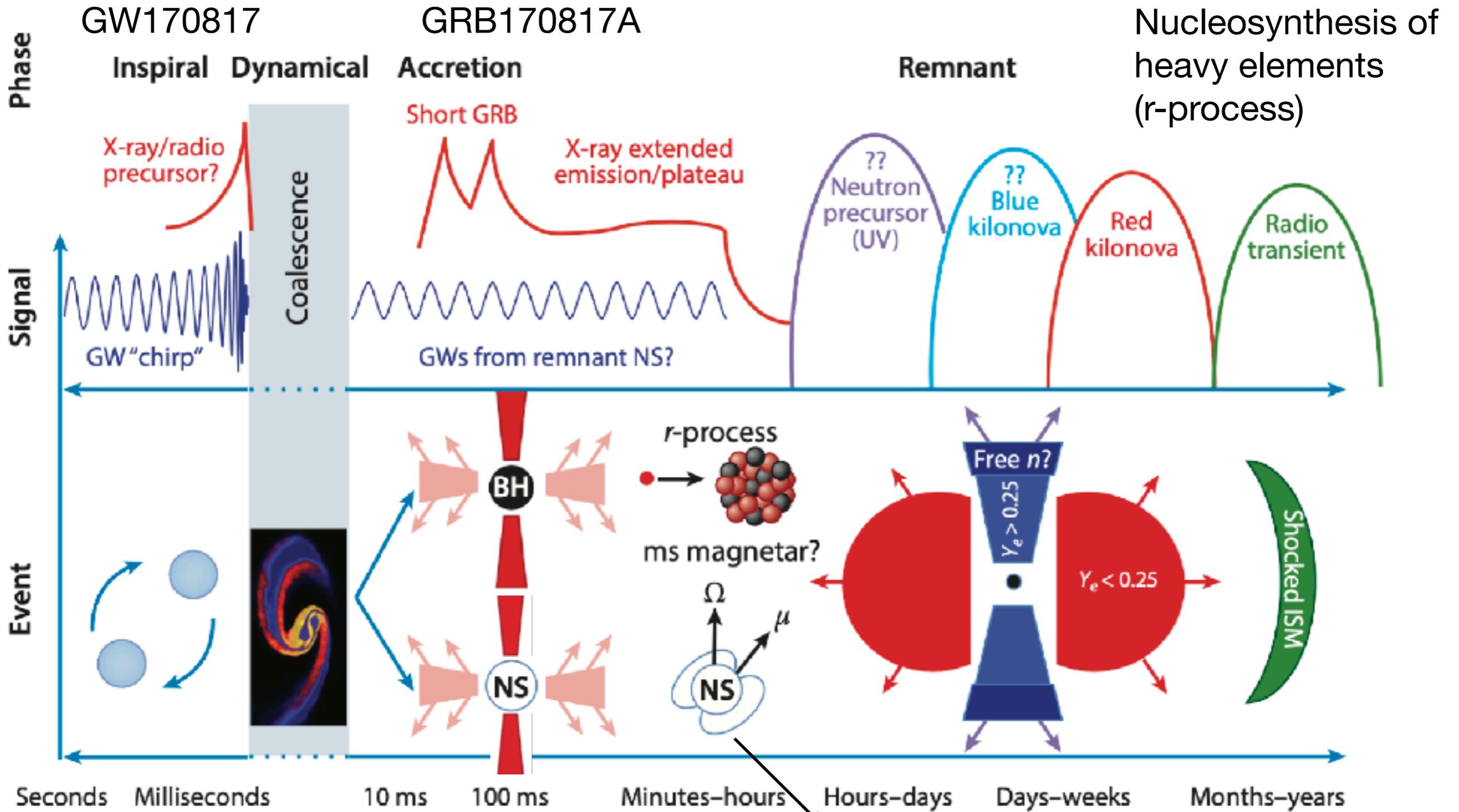
in collaboration with
Kenta Kiuchi¹, Loren Held^{1,2},
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²DAMTP, Cambridge



Binary neutron star mergers



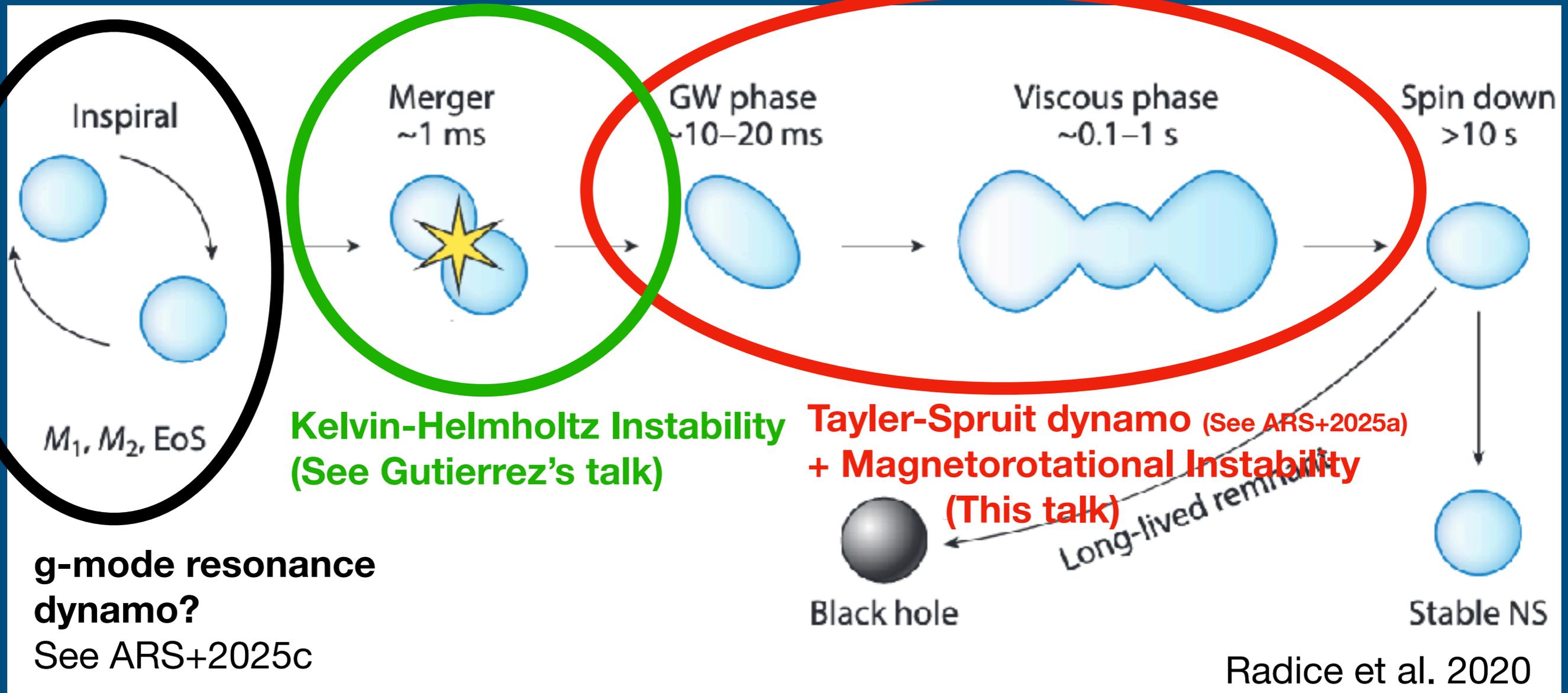
Mode resonances in GW?
See Kuan's and Yong's talk

Detectability of a magnetar?
See Piasse, ARS+, submitted

Fernandez & Metzger 2016

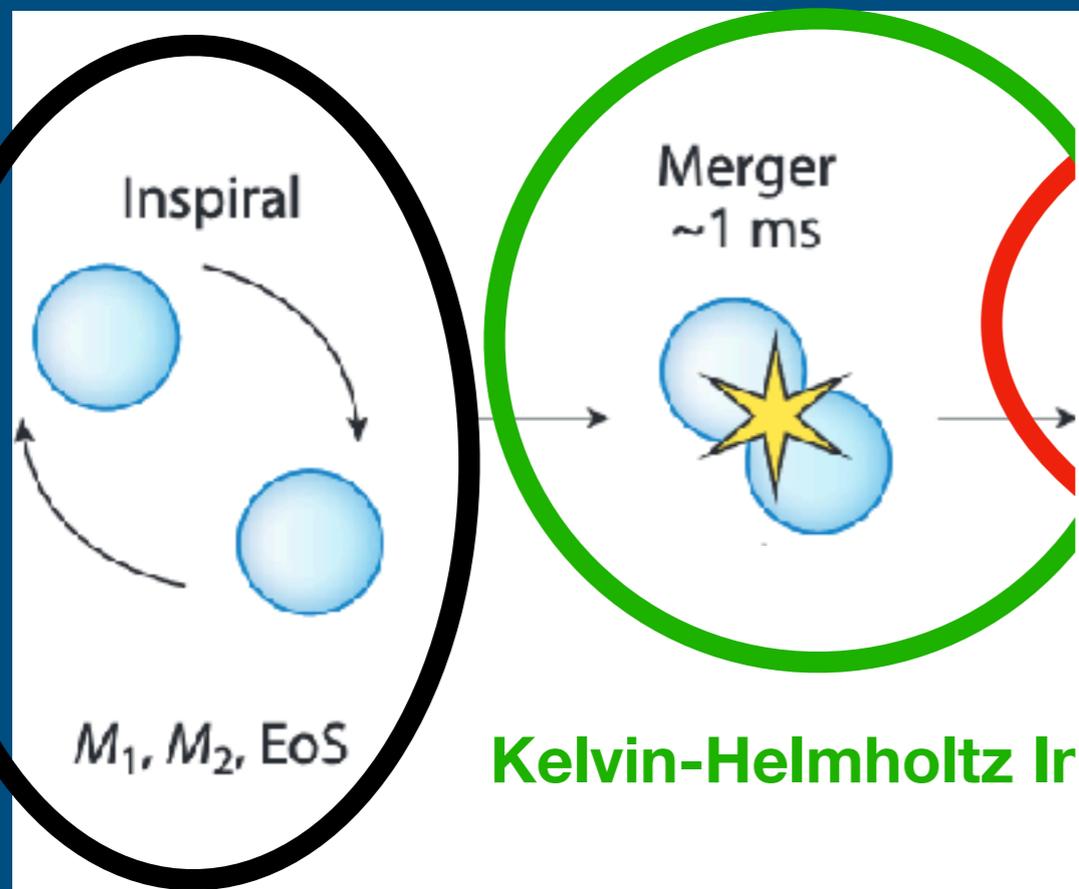
Amplification mechanisms in neutron star mergers

Evolution of the merger

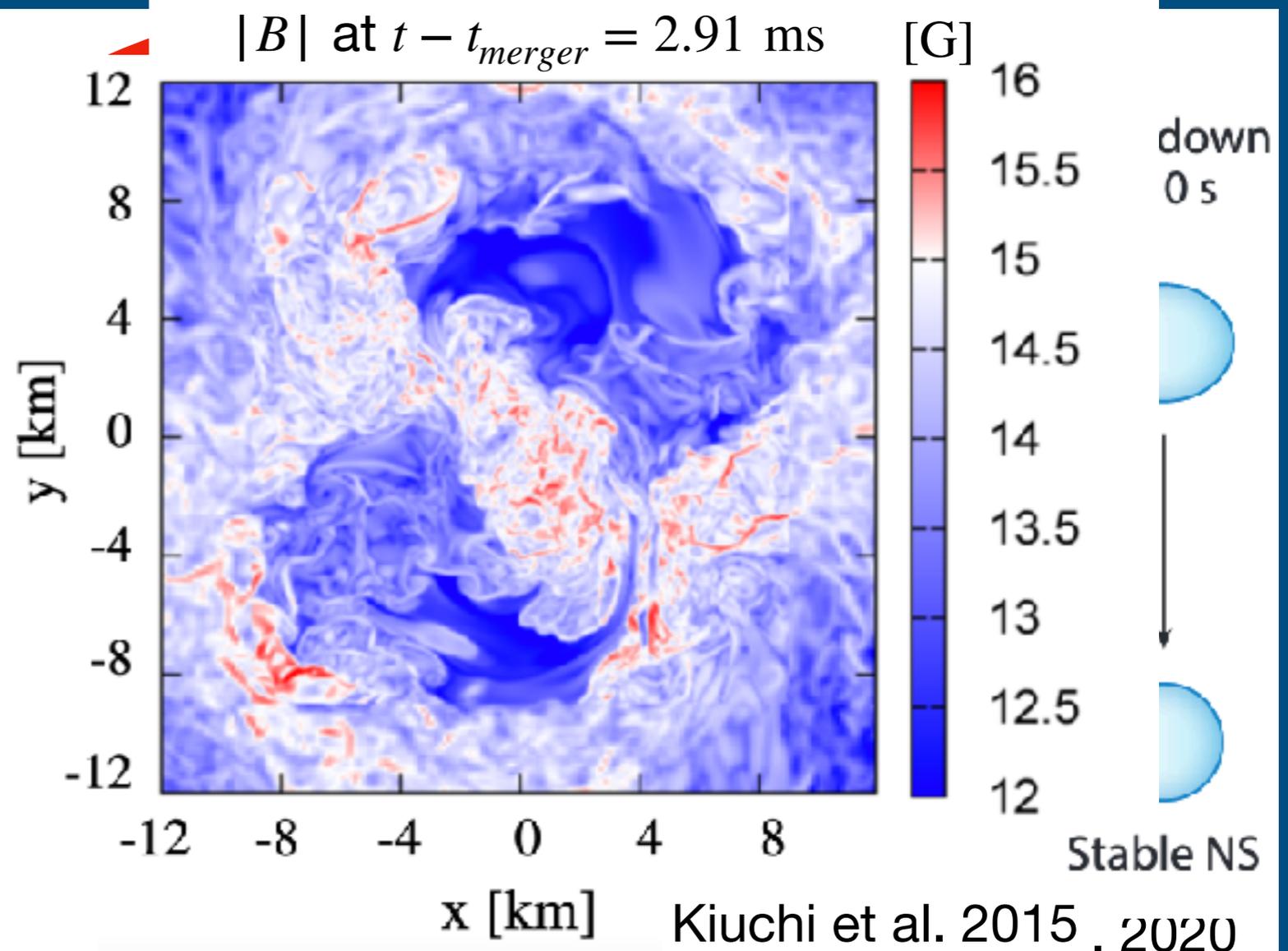


Amplification mechanisms in neutron star mergers

Evolution of the merger



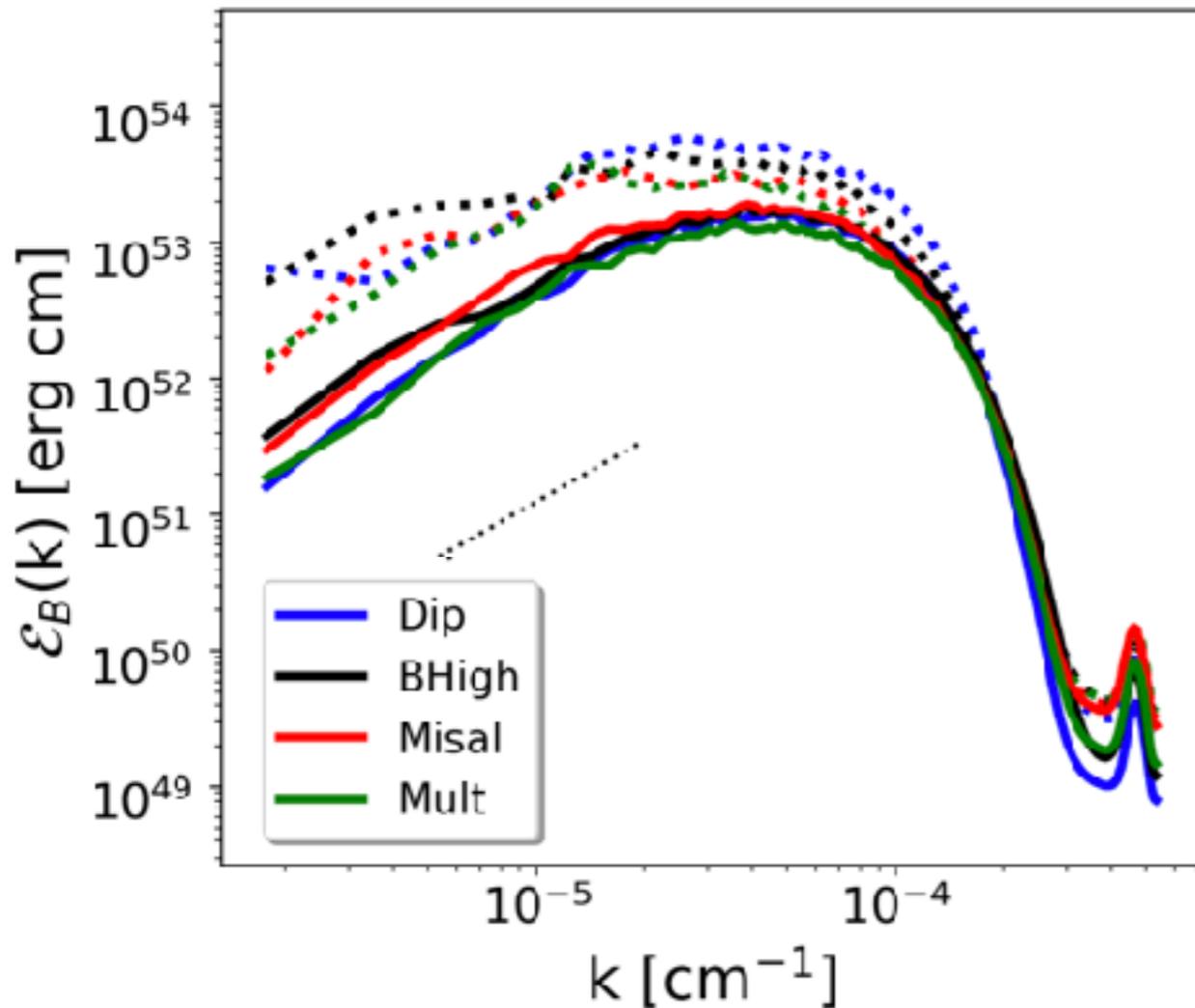
**g-mode resonance
dynamo?**
See ARS+2025c



Amplification from 10^{13} G to 10^{16} G on small scales
Energy saturation at \sim a few 10^{50} erg

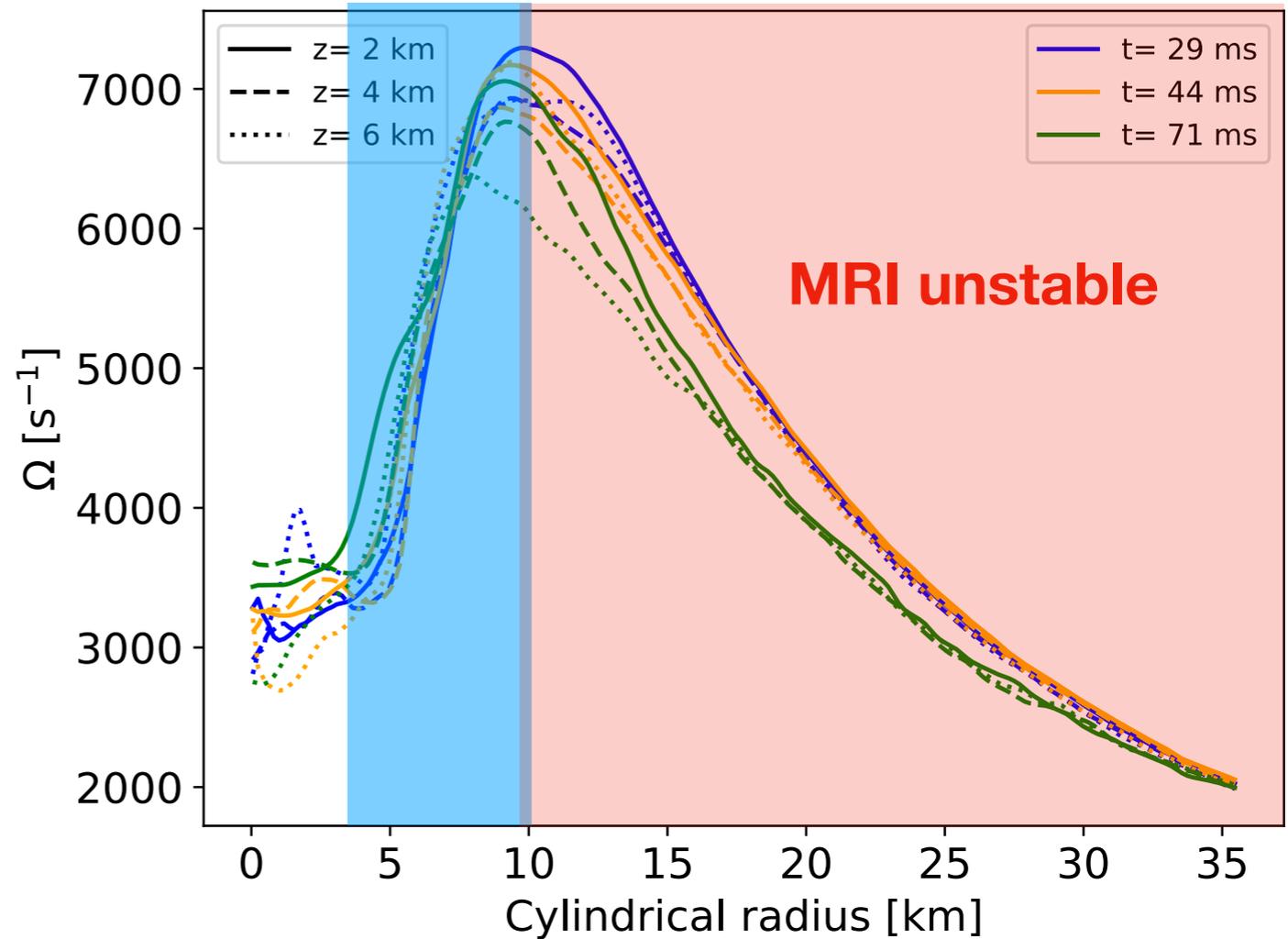
Initial conditions right after mergers

Converged magnetic field spectrum
at $t=10$ ms



Aguilera-Miret et al. 2022

Taylor-Spruit dynamo



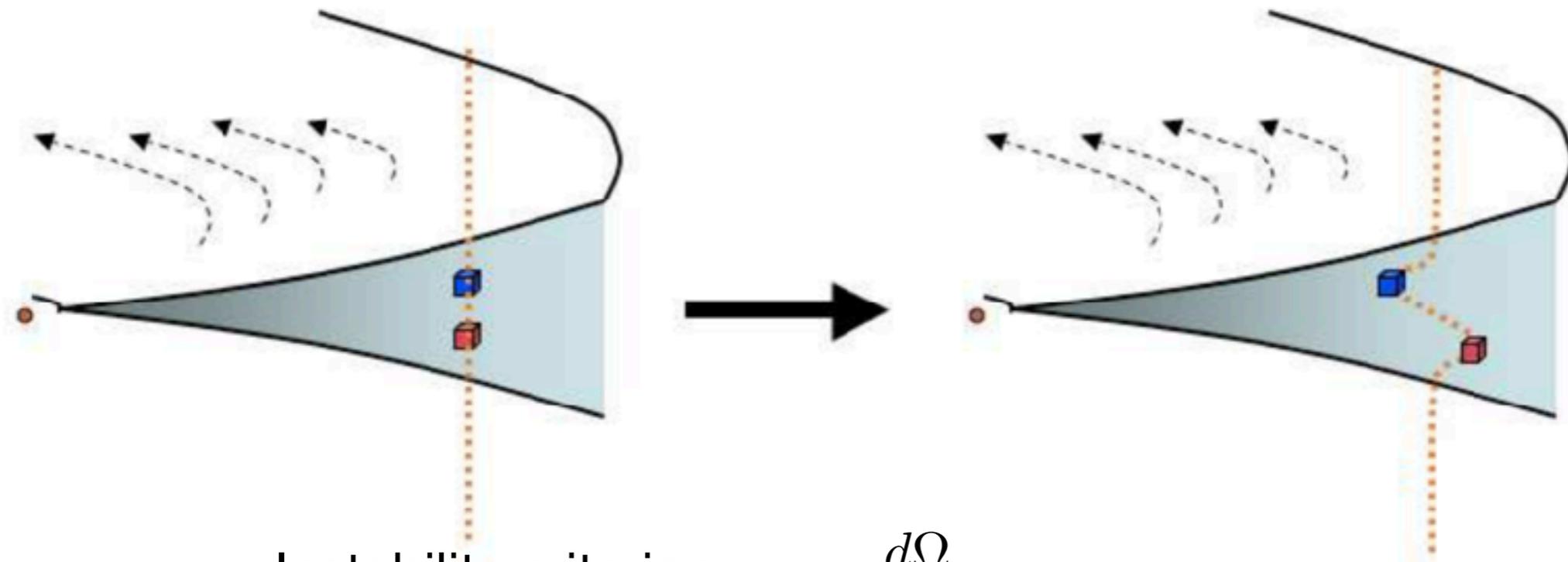
TS dynamo: ARS et al. 2025a

See also Gutierrez's talk

Magneto-rotational instability (MRI)

MRI mechanism in a simple case:

see Miravet-Tenes' talk



Instability criterion:

$$\frac{d\Omega}{dr} < 0$$

Growth rate:

$$\sigma = \frac{q\Omega}{2} \text{ with } \Omega \propto r^{-q}$$

→ Fast growth for fast rotation

Wavelength:

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

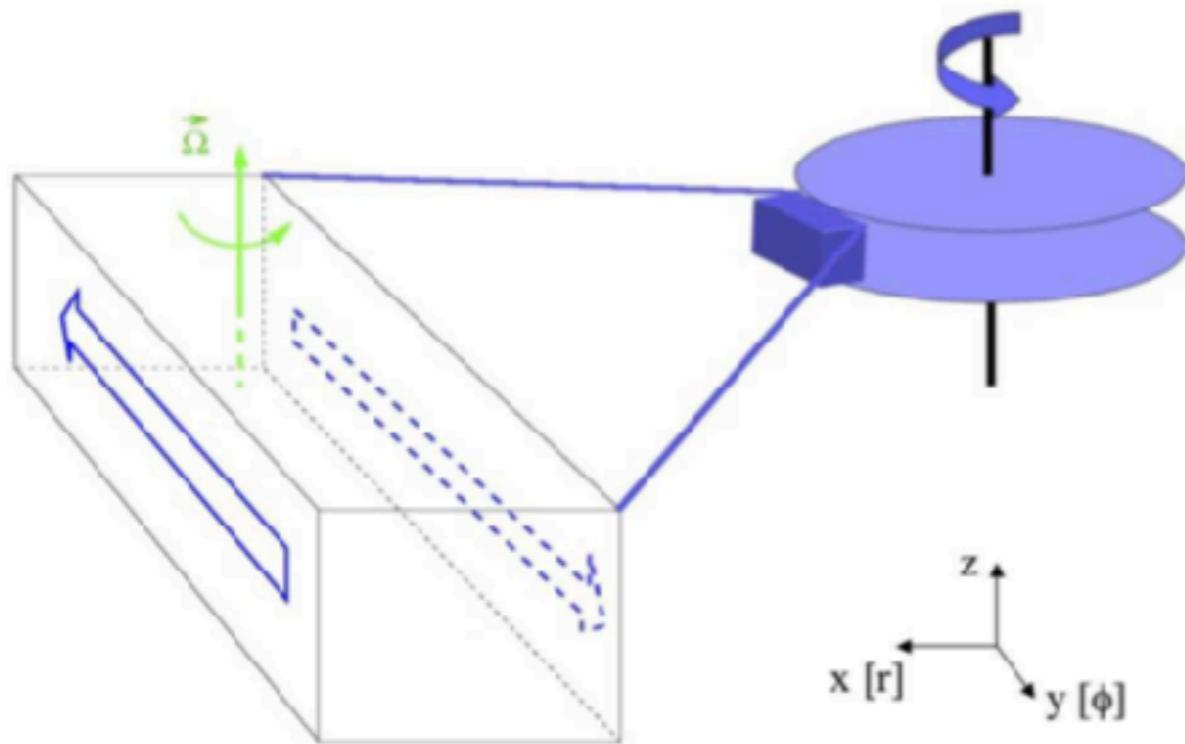
→ Short wavelength for weak magnetic fields

See Jannaud+2025 for derivation in zero-net flux setups

Credit : Fromang

Local models of the MRI

“Shearing box” models



Ideal/non-ideal MHD equations

Credit: G. Lesur

MHD turbulence: toroidal field

DB: v01C0.vtk

Flux density
Var. by
7 mm
1.000
0.000
-1.000
-2.000
Max: 2.342
Min: -2.333



Guilet et al. 2022

user: jguilet
Thu Oct 31 11:35:52 2019

Important parameters for HMNS (and PNS)

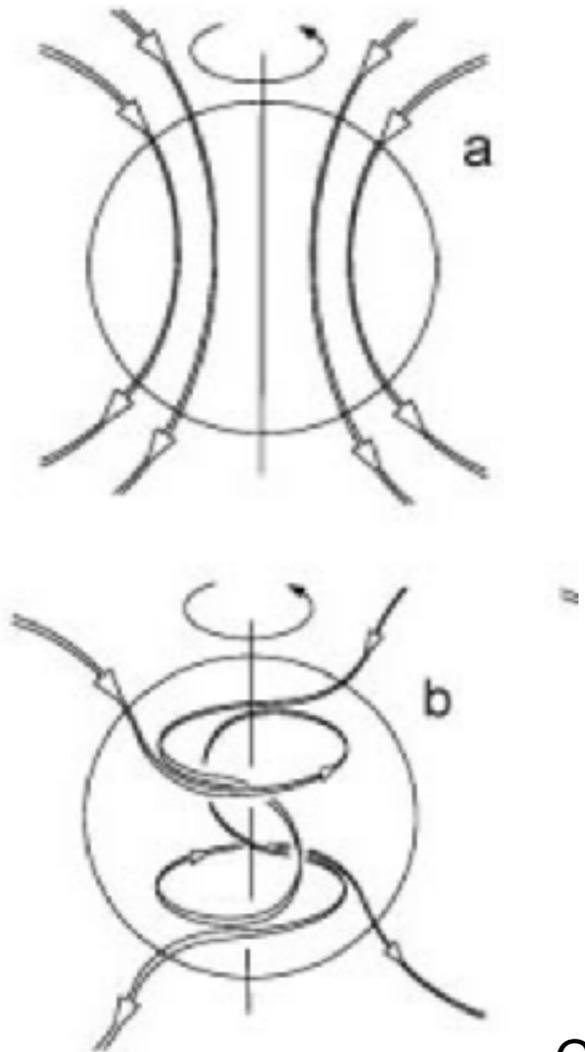
- Neutrino viscosity: Viscous impact on growth rate (Guilet+2015, 2017)
- High Magnetic Prandtl number $P_m = \text{viscosity}/\text{resistivity}$ (Guilet+2022, Held+2022,+2024)
- Buoyancy: Brunt-Vaisala Frequency N/Ω (Guilet+2015)

MRI-driven alpha-Omega dynamo in ideal GRMHD simulations

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

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

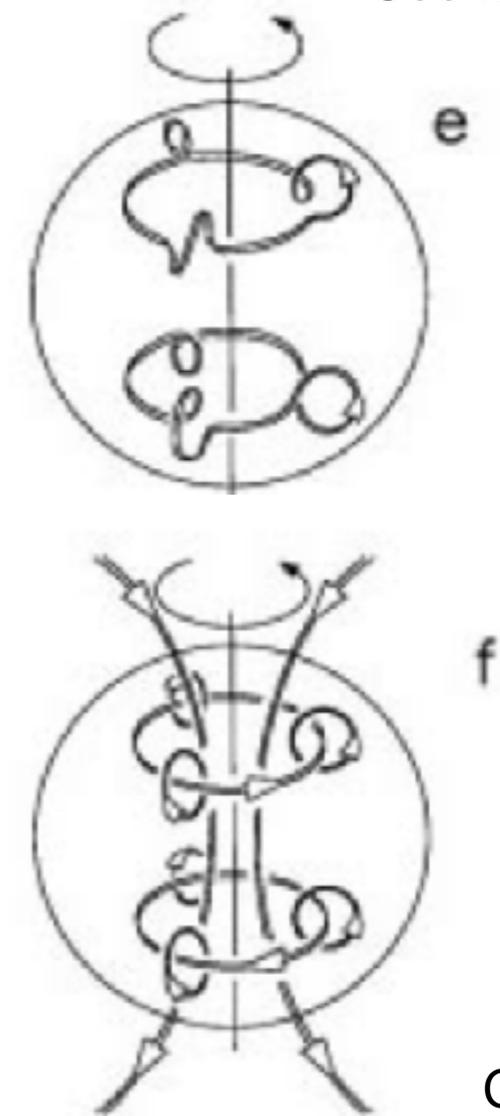
Omega effect



Credit: Love 99

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

alpha effect



Credit: Love 99

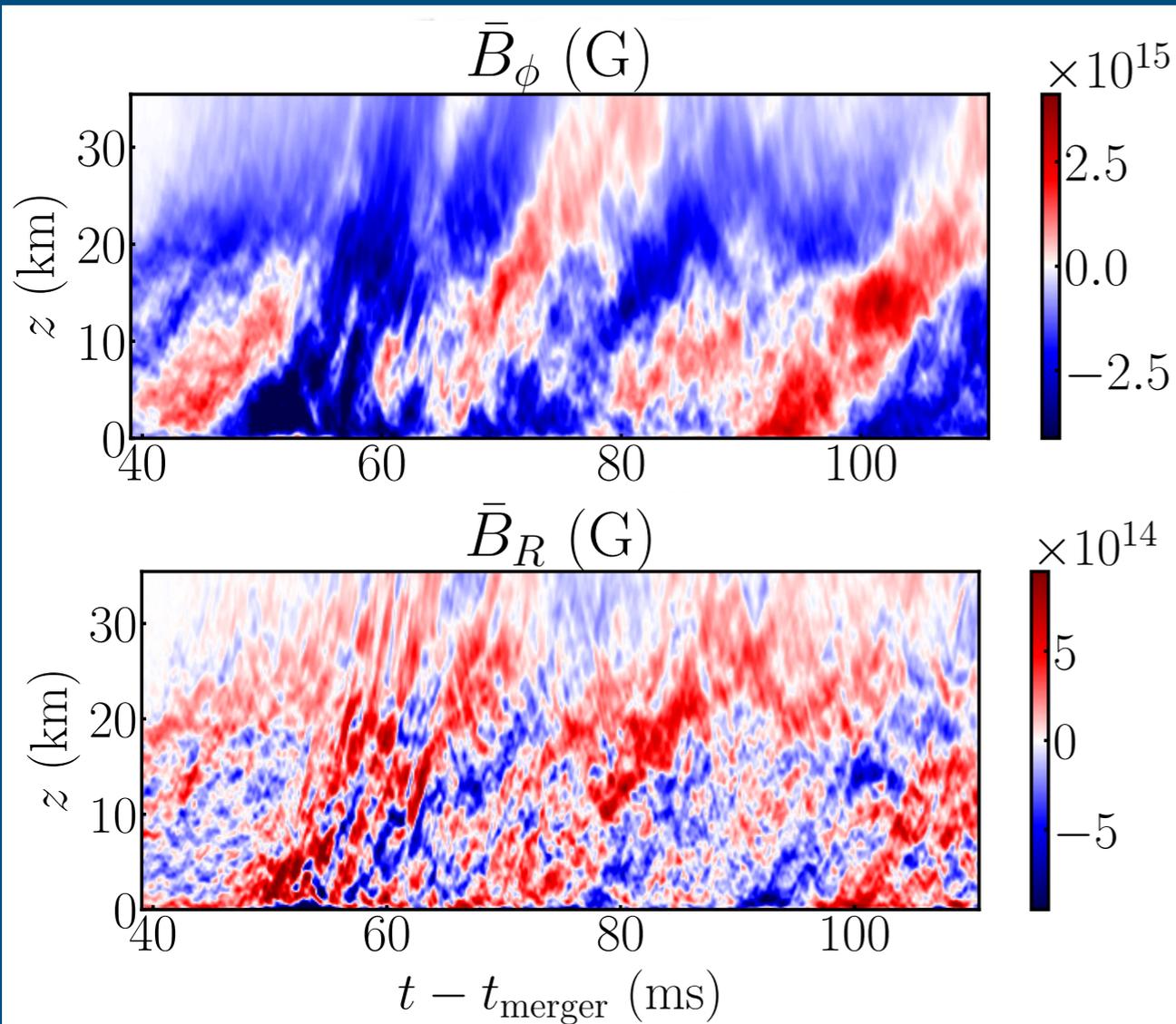
$$\mathcal{E}_\phi = \alpha_{\phi\phi} B_\phi$$

MRI-driven alpha-Omega dynamos in ideal GRMHD simulations

$$\frac{\partial \bar{\mathbf{B}}}{\partial t} = \bar{\nabla} \times \left(\bar{\mathbf{U}} \times \bar{\mathbf{B}} + \bar{\mathcal{E}} - \eta \bar{\nabla} \times \bar{\mathbf{B}} \right) \quad \text{where} \quad \bar{\mathcal{E}} = \bar{\mathbf{u}} \times \bar{\mathbf{b}}$$

$$\mathcal{E}_i = \alpha_{ij} \bar{B}_j + \beta_{ij} \left(\bar{\nabla} \times \bar{\mathbf{B}} \right)_j + \dots$$

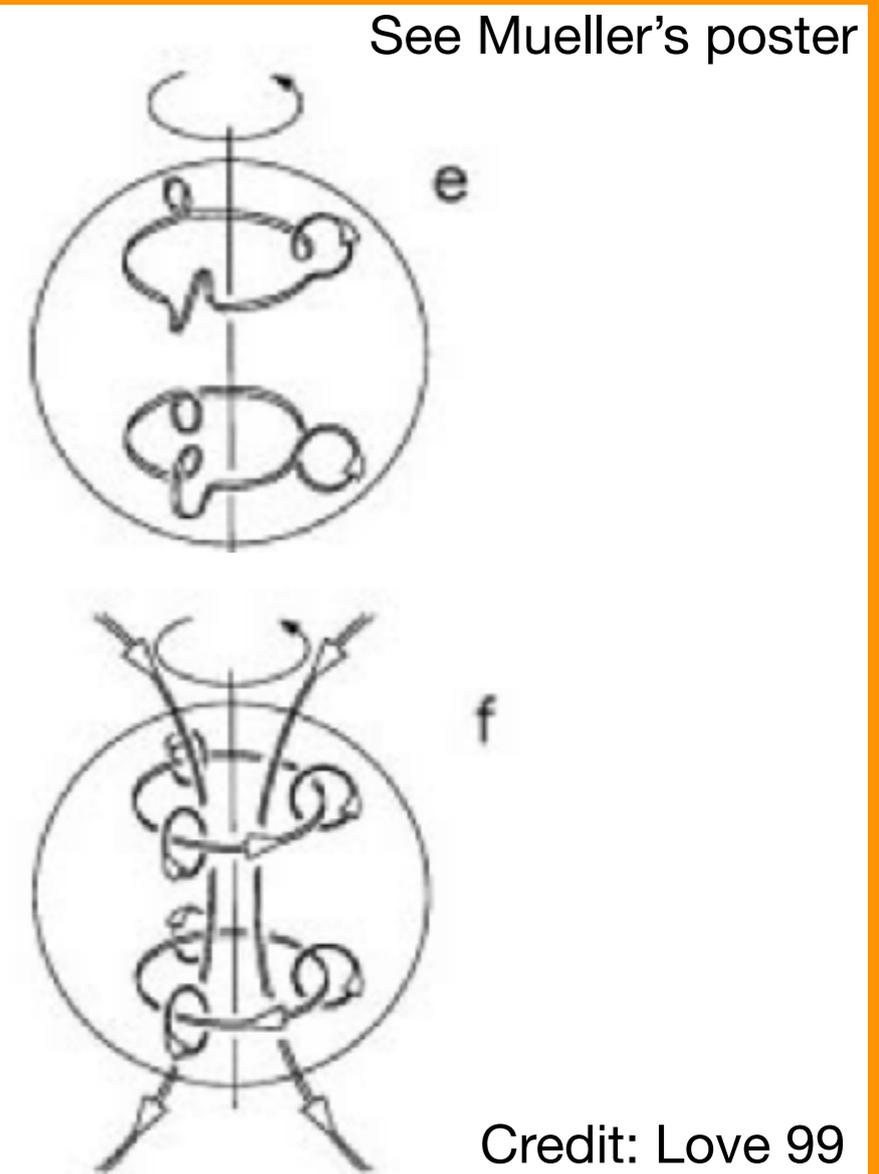
Omega effect at R = 30 km



$$\frac{\partial \bar{B}_\phi}{\partial t} = R \bar{B}_R \frac{d\Omega}{ds}$$

Kiuchi, ARS+ 2024

alpha effect

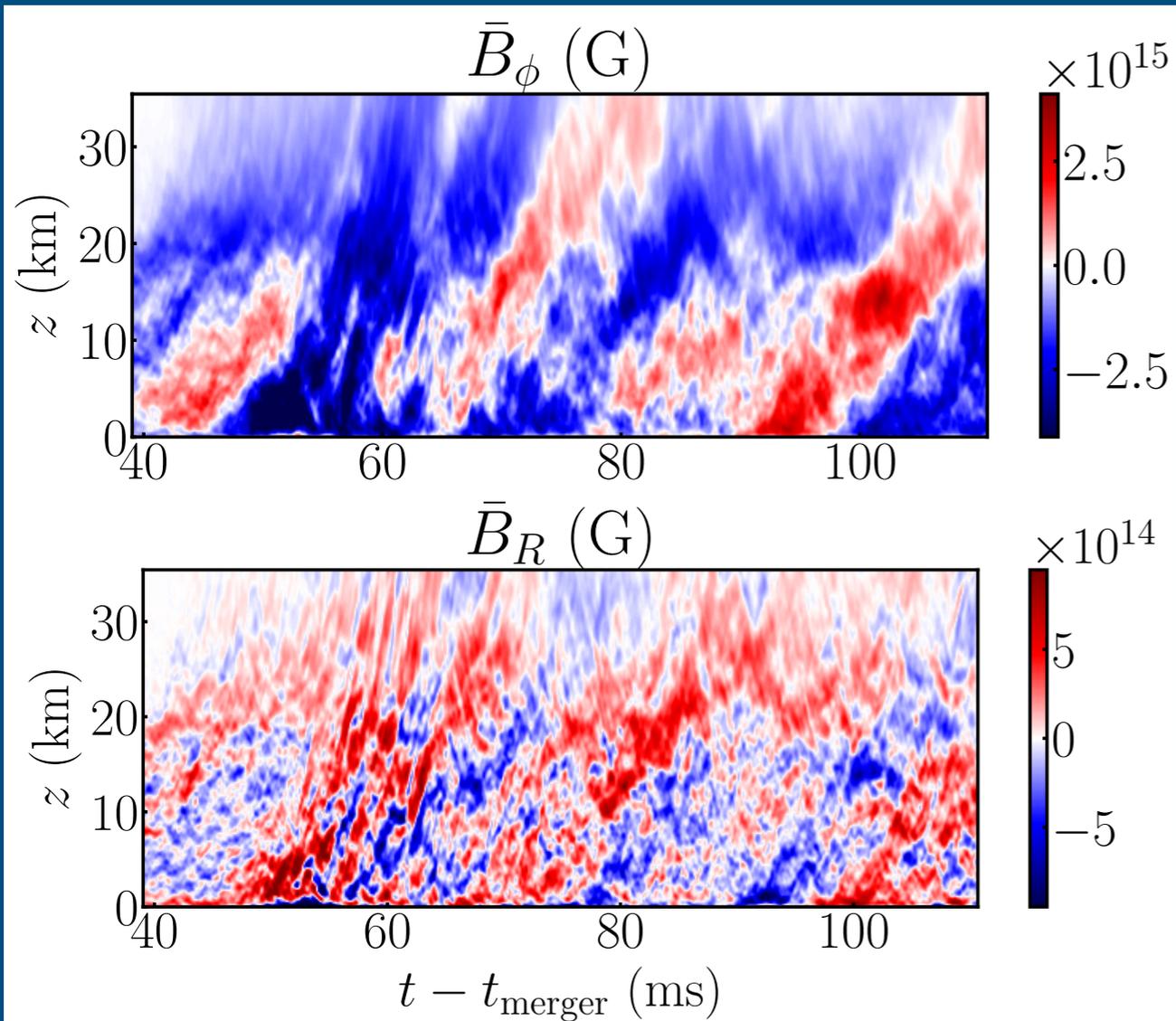


$$\mathcal{E}_\phi = \alpha_{\phi\phi} B_\phi$$

MRI-driven alpha-Omega dynamos in ideal GRMHD simulations

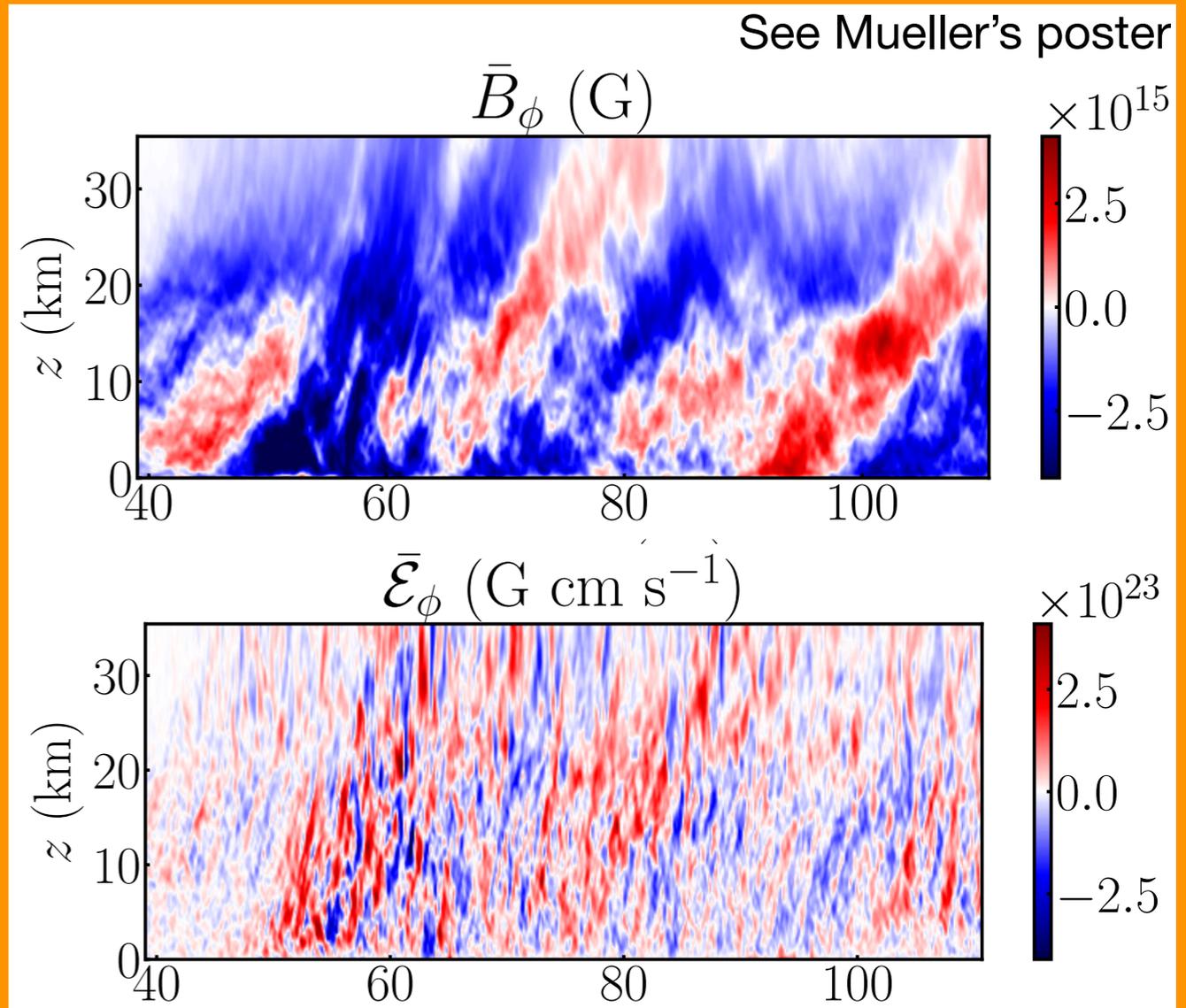
$$\frac{\partial \bar{\mathbf{B}}}{\partial t} = \bar{\nabla} \times \left(\bar{\mathbf{U}} \times \bar{\mathbf{B}} + \bar{\mathcal{E}} - \eta \bar{\nabla} \times \bar{\mathbf{B}} \right) \quad \text{where} \quad \begin{aligned} \bar{\mathcal{E}} &= \bar{\mathbf{u}} \times \bar{\mathbf{b}} \\ \mathcal{E}_i &= \alpha_{ij} \bar{B}_j + \beta_{ij} \left(\bar{\nabla} \times \bar{\mathbf{B}} \right)_j + \dots \end{aligned}$$

Omega effect at R = 30 km



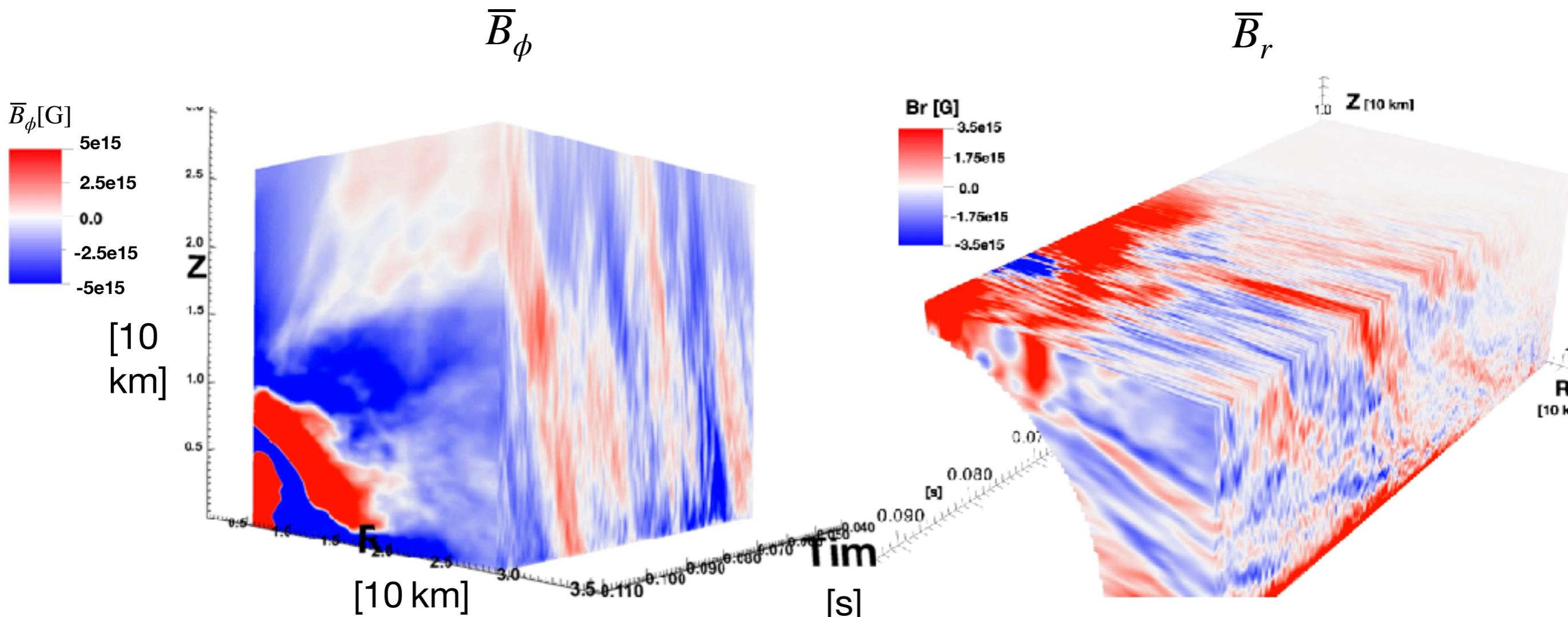
$$\frac{\partial \bar{B}_\phi}{\partial t} = R \bar{B}_R \frac{d\Omega}{ds} \quad \text{Kiuchi, ARS+ 2024}$$

alpha-effect at R = 30 km



$$\mathcal{E}_\phi = \alpha_{\phi\phi} \bar{B}_\phi \quad \text{Kiuchi, ARS+ 2024}$$

Large-scale dynamo and jet launching

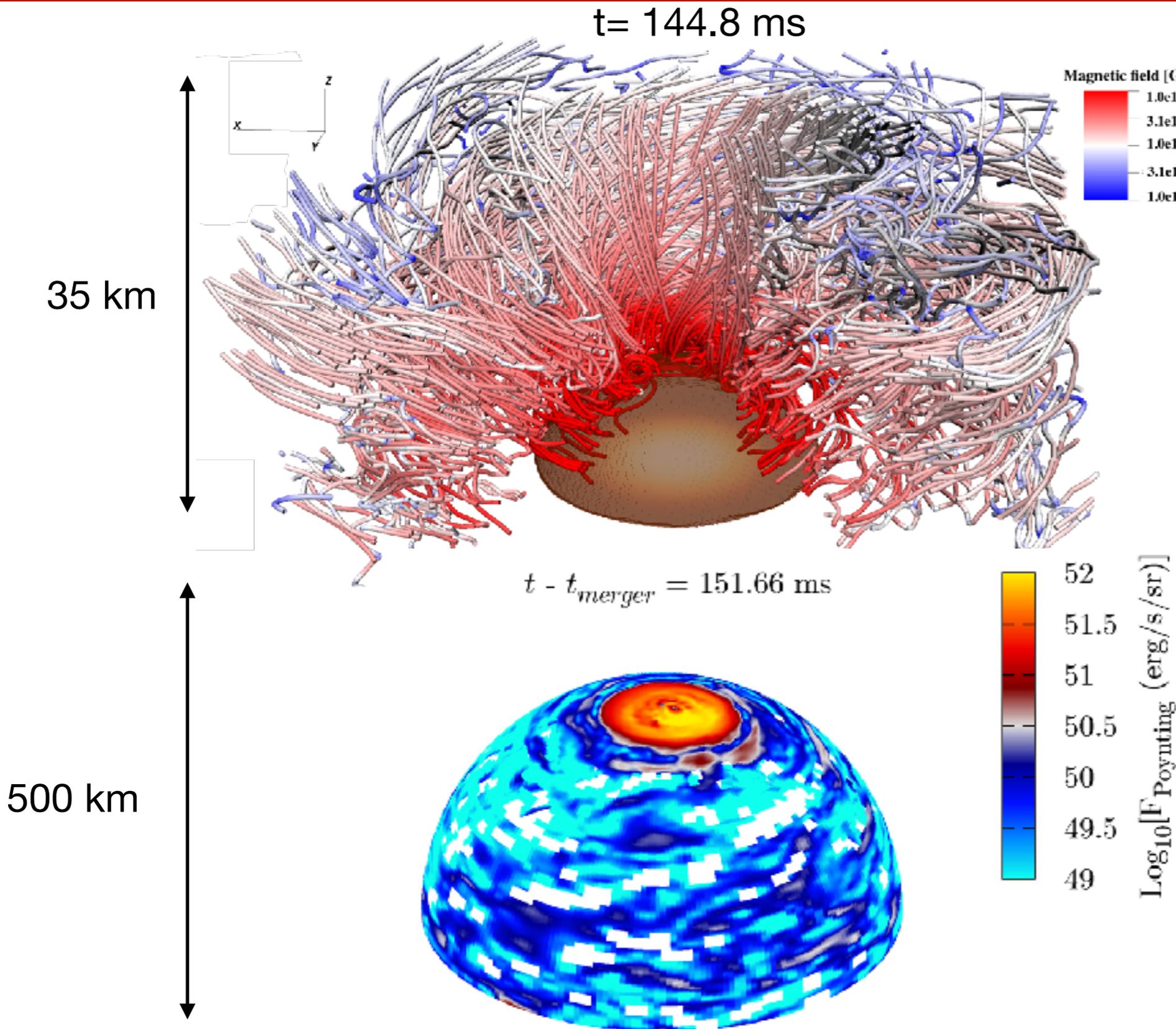


$$t_{\alpha\Omega} = \frac{2\pi}{\sqrt{\alpha_{\phi\phi}\pi q\Omega/H}} \sim 20 \text{ ms}$$

Propagation of magnetic field to the poles

1.35 – 1.35 M_{\odot} NS binary with DD2 EOS

Magnetic field lines and jet



Turbulence dominated by the toroidal field

Jet starts from $\sim 10 \text{ km}$

Pointing-flux isotropic luminosity

$\sim 10^{52} \text{ erg/s}$

Jet angle $\theta < 12^\circ$

Magnetisation parameter

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

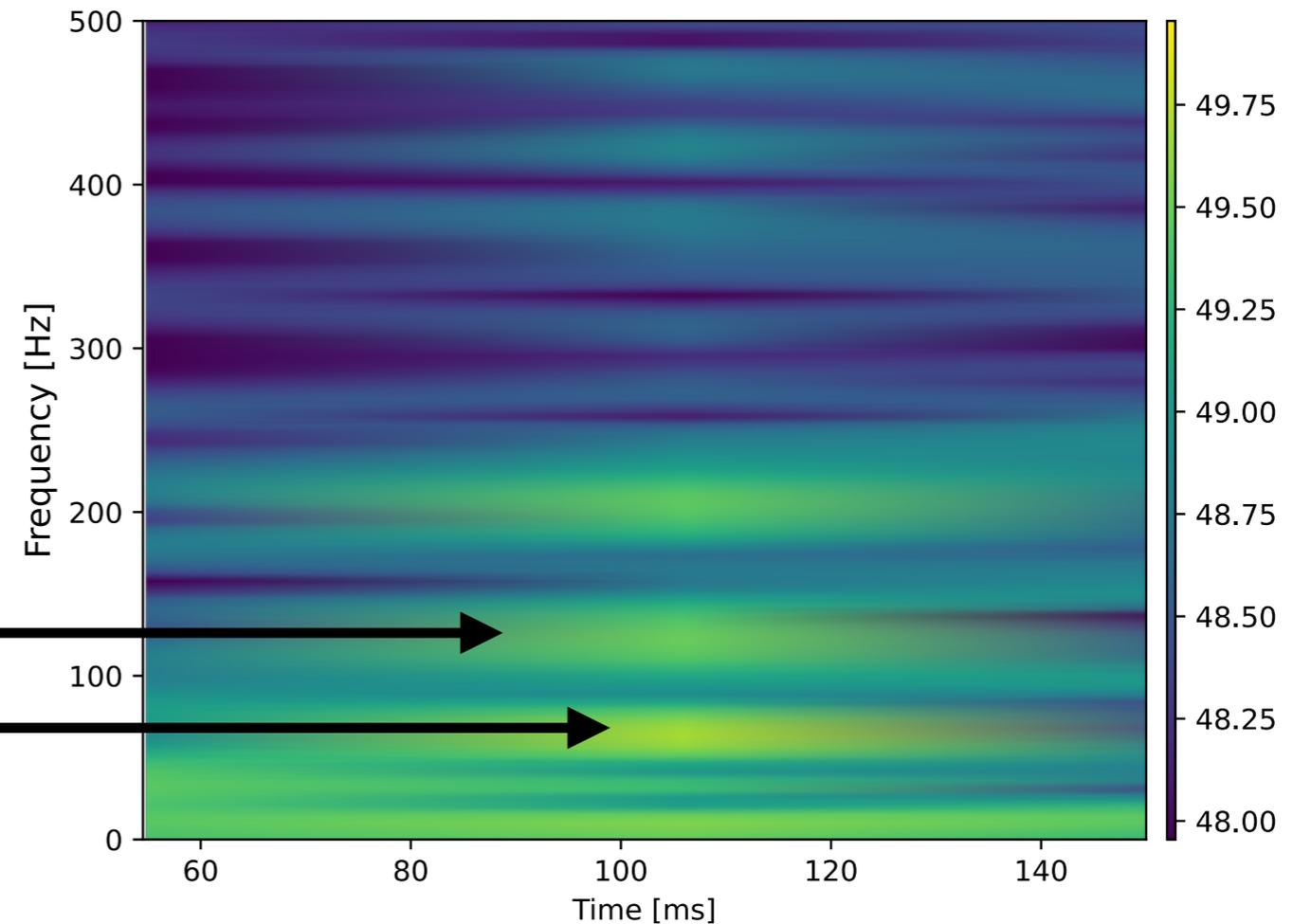
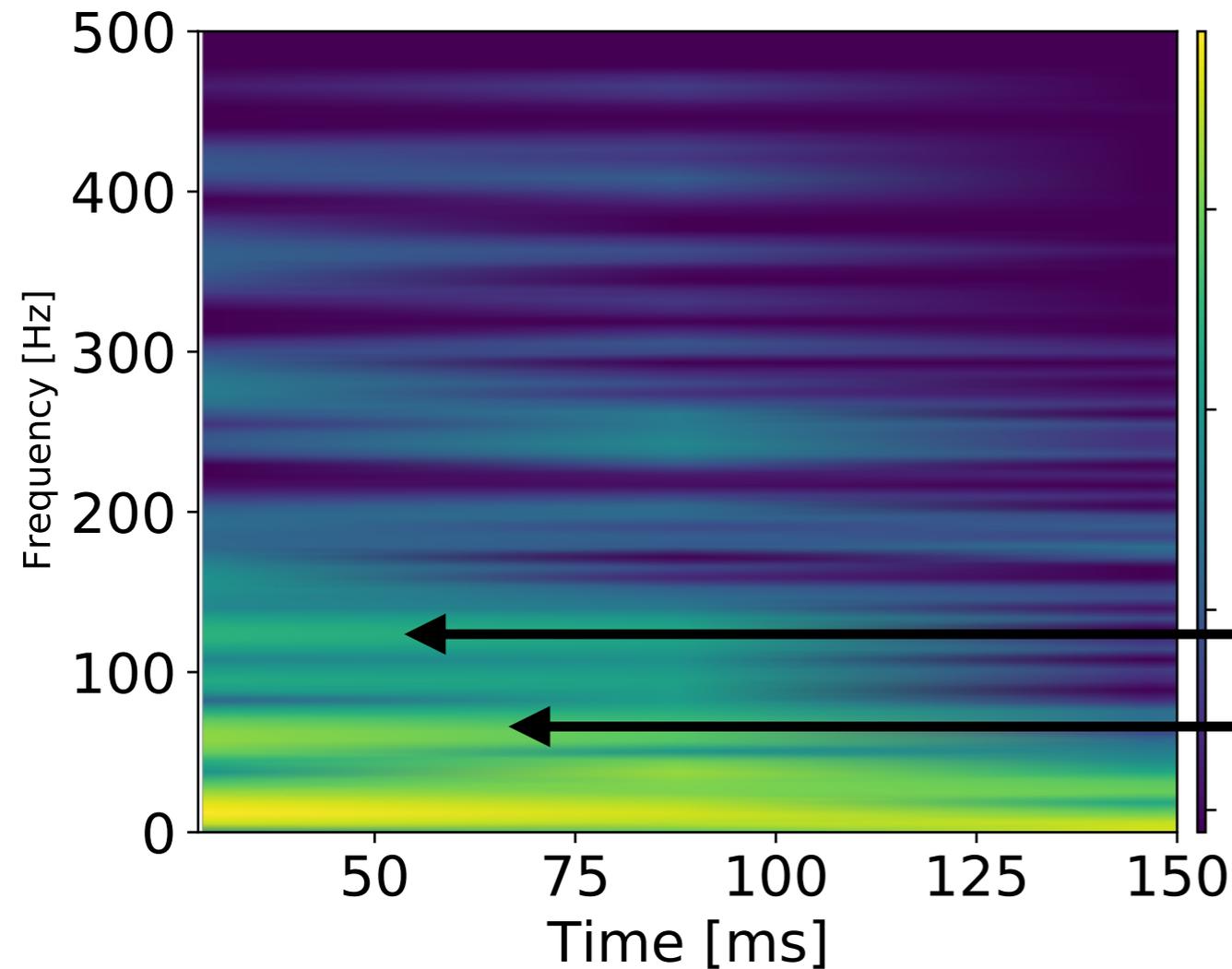
Jet+winds:

Post-merger ejecta Mass $\sim 0.1 M_\odot$

Impact on the GRB luminosity?

FFT of toroidal field at 12 km in the HMNS

Poynting Flux luminosity at 500 km



$$\omega_{\alpha\Omega} = \sqrt{\frac{1}{2}\alpha_{\phi\phi}q\Omega k_z} \text{ where } k_z \sim \frac{2\pi}{H}$$

ARS+, in prep

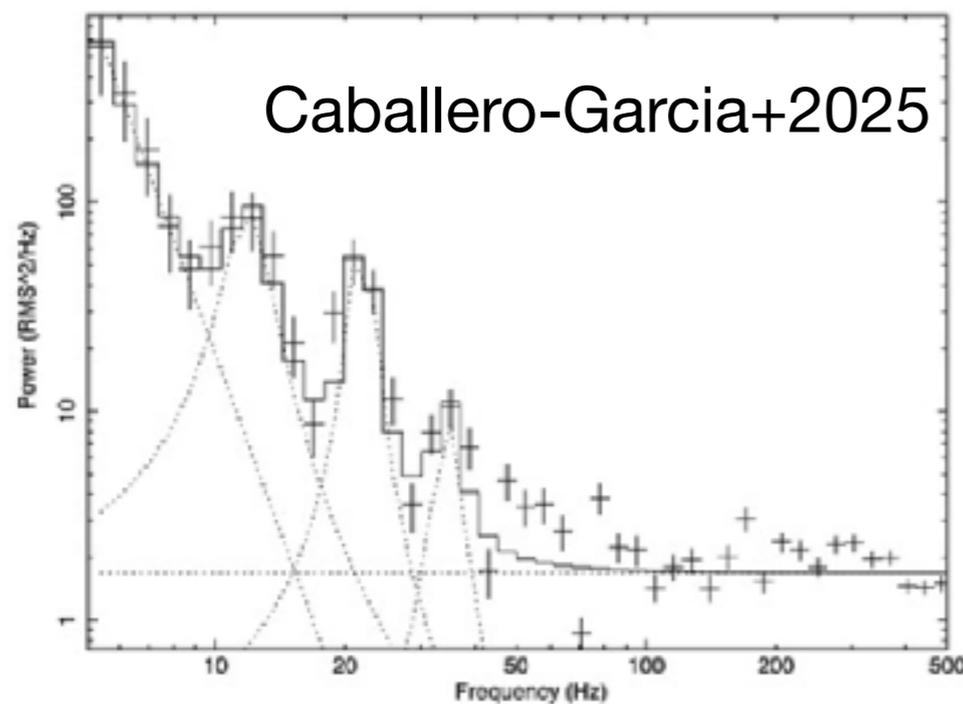
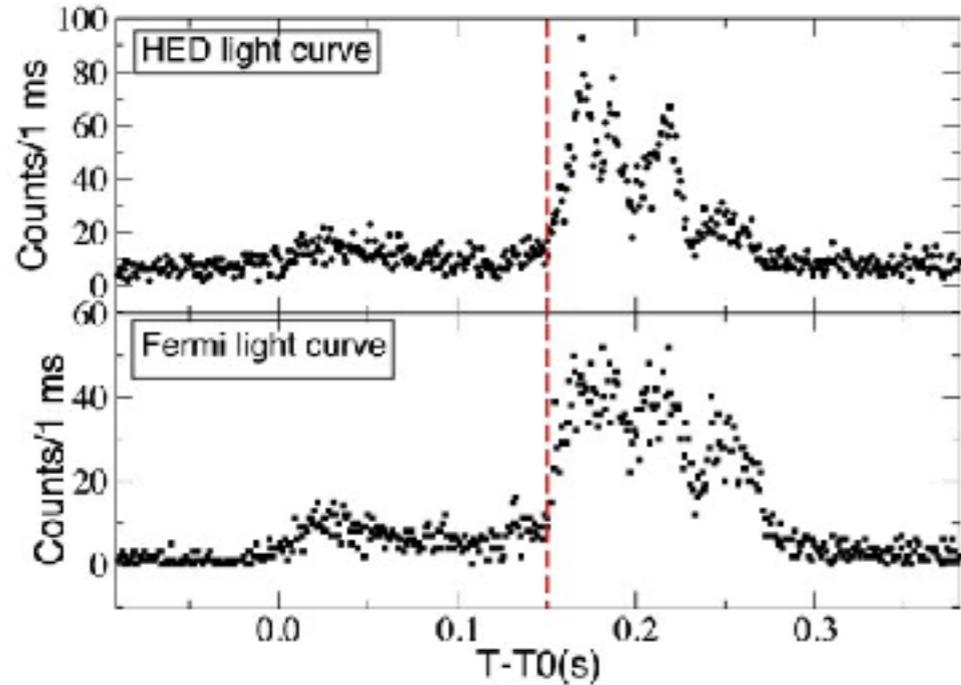
How does the dynamo frequency changes with initial conditions, EOS and microphysics?

How does this variability evolves with the jet propagation?

Can this variability be detected in short GRBs?

Quasi-periodic oscillations in GRBs associated with mergers?

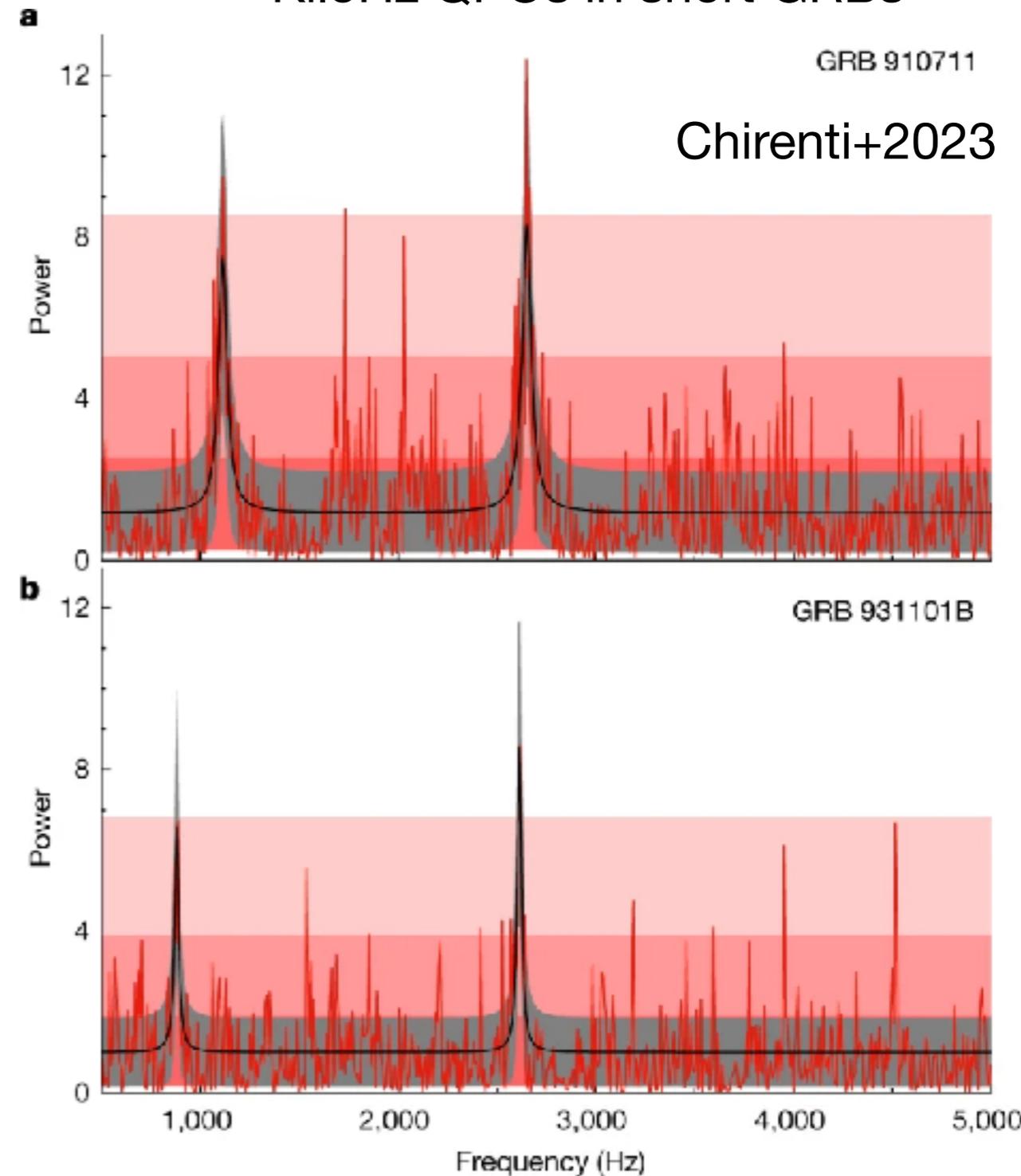
Low-frequency QPOs in GRB 181222B



Caballero-Garcia+2025

QPO of 19.5 Hz in GRB 211211A (Chirenti+2024)

KiloHz QPOs in short GRBs



Chirenti+2023

Also in GRB 230307A (Chen+2024)

Magnetic Prandtl number dependency in local models

Pm regime in PNS and BNS merger

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

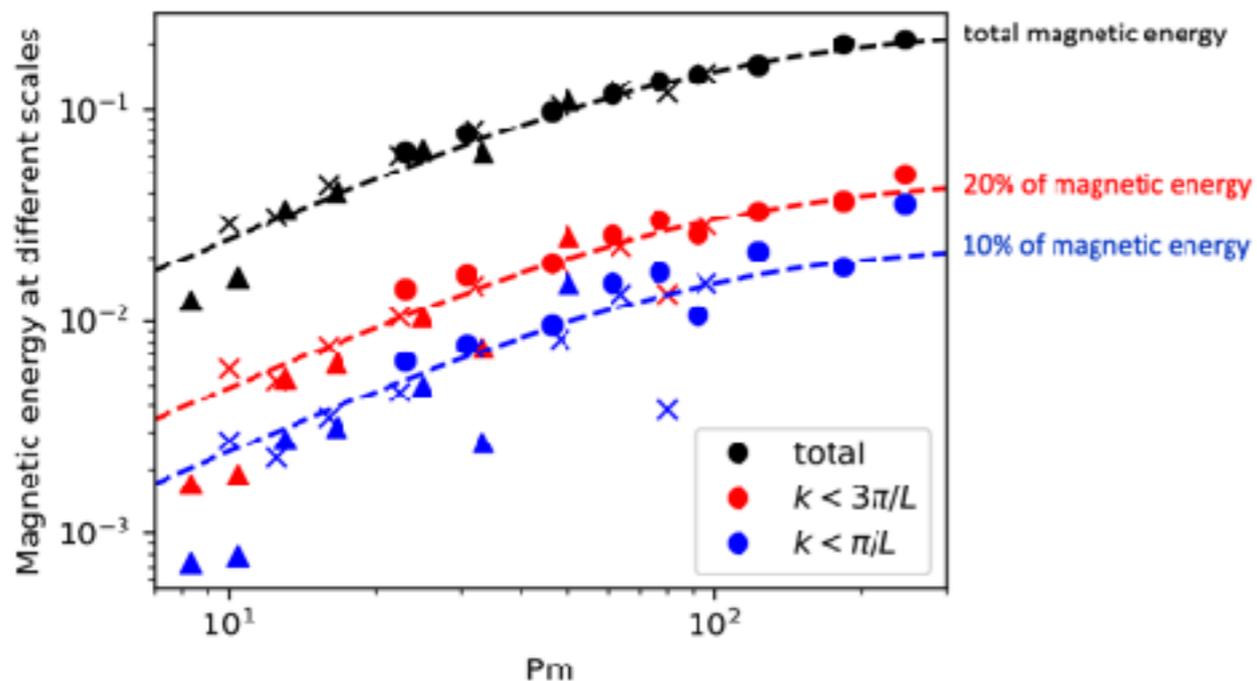
Diffusive approximation for neutrinos

Weak resistivity due to degenerate relativistic electrons

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

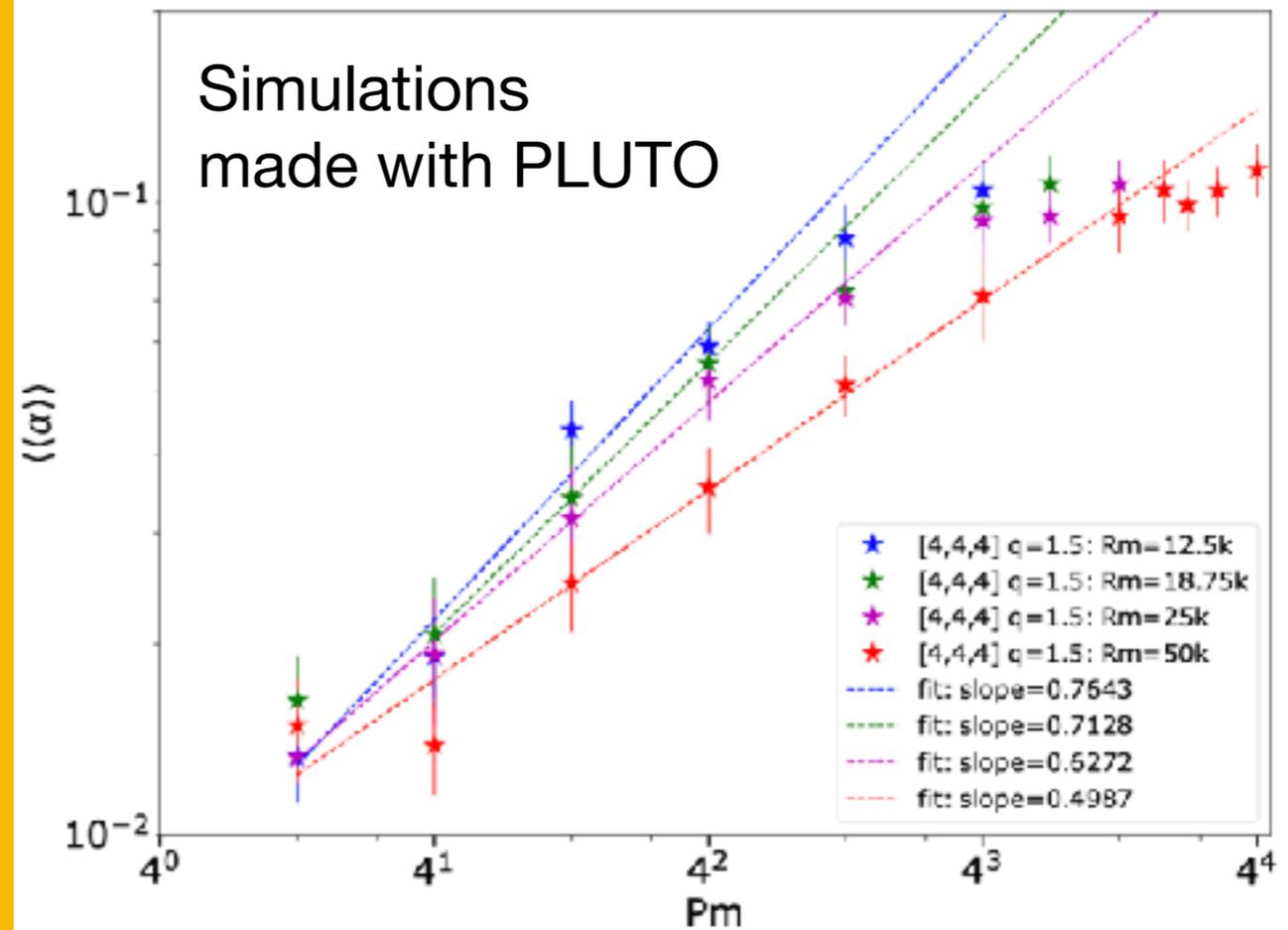
Guilet, ARS et al., 2022

Unstratified shearing box study with Snoopy



Held et al., 2024

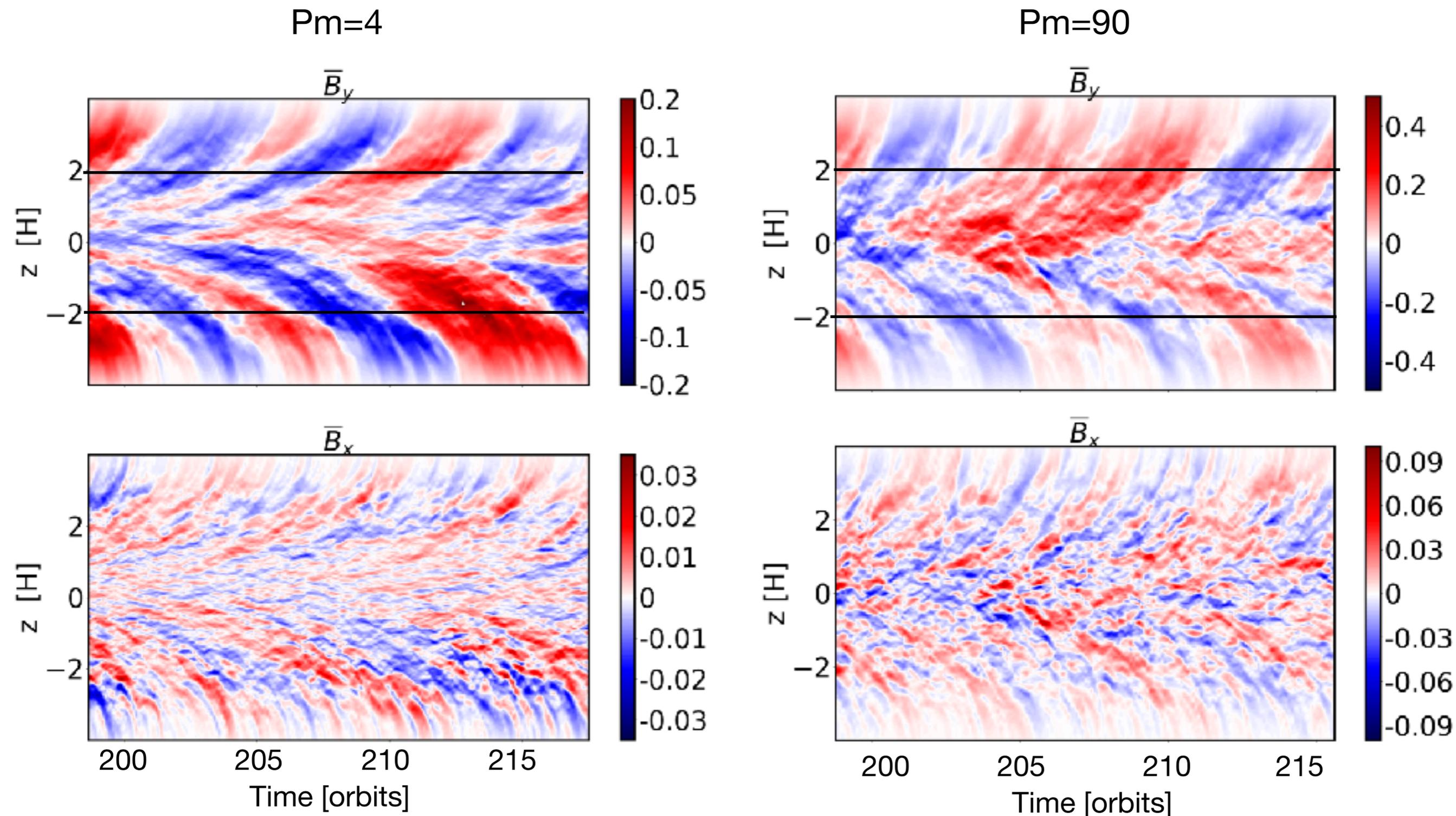
Stratified case with increasing viscosity



In the mid plane ($|z| < 2 H$):
MRI-driven dynamo dynamics
In the “atmosphere” ($|z| > 2 H$):
magnetic buoyancy instabilities

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

Azimuthal averaged magnetic field comparison



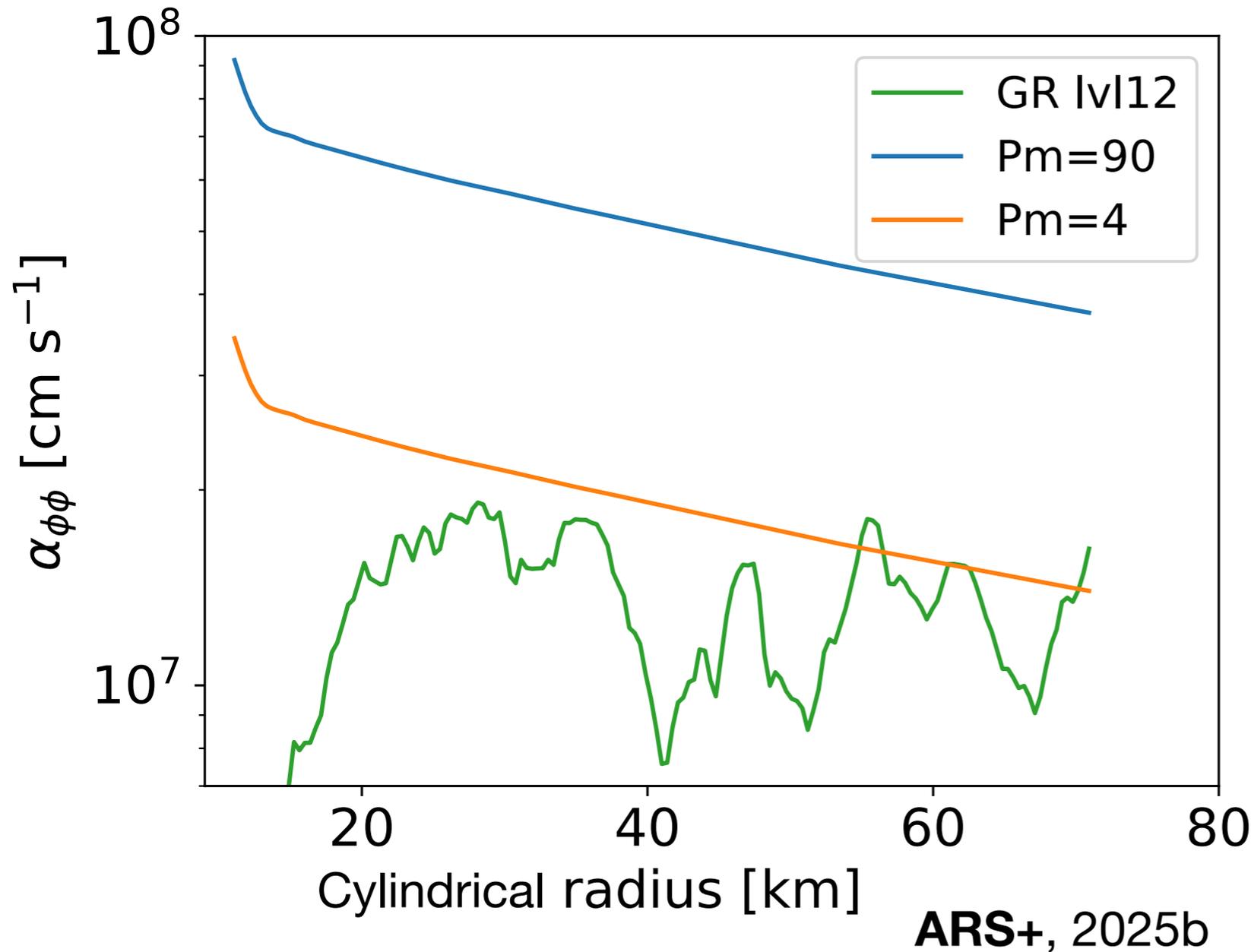
$P_{\alpha\Omega} \sim 10 - 11$ orbits

ARS+, 2025b

$P_{\alpha\Omega} \sim 7 - 8$ orbits

alpha effect and Dynamo frequency: global vs local

Peak alpha strength



ARS+, 2025b

Comparison with GRMHD simulation (Kiuchi et al. 2024)

- 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 > 3-5 times higher than GRMHD simulation

- Faster Propagation (off-diagonal alpha component)

- Stronger winds + more luminous jets compared to GRMHD simulations

Preliminary: Extrapolation and other simulations

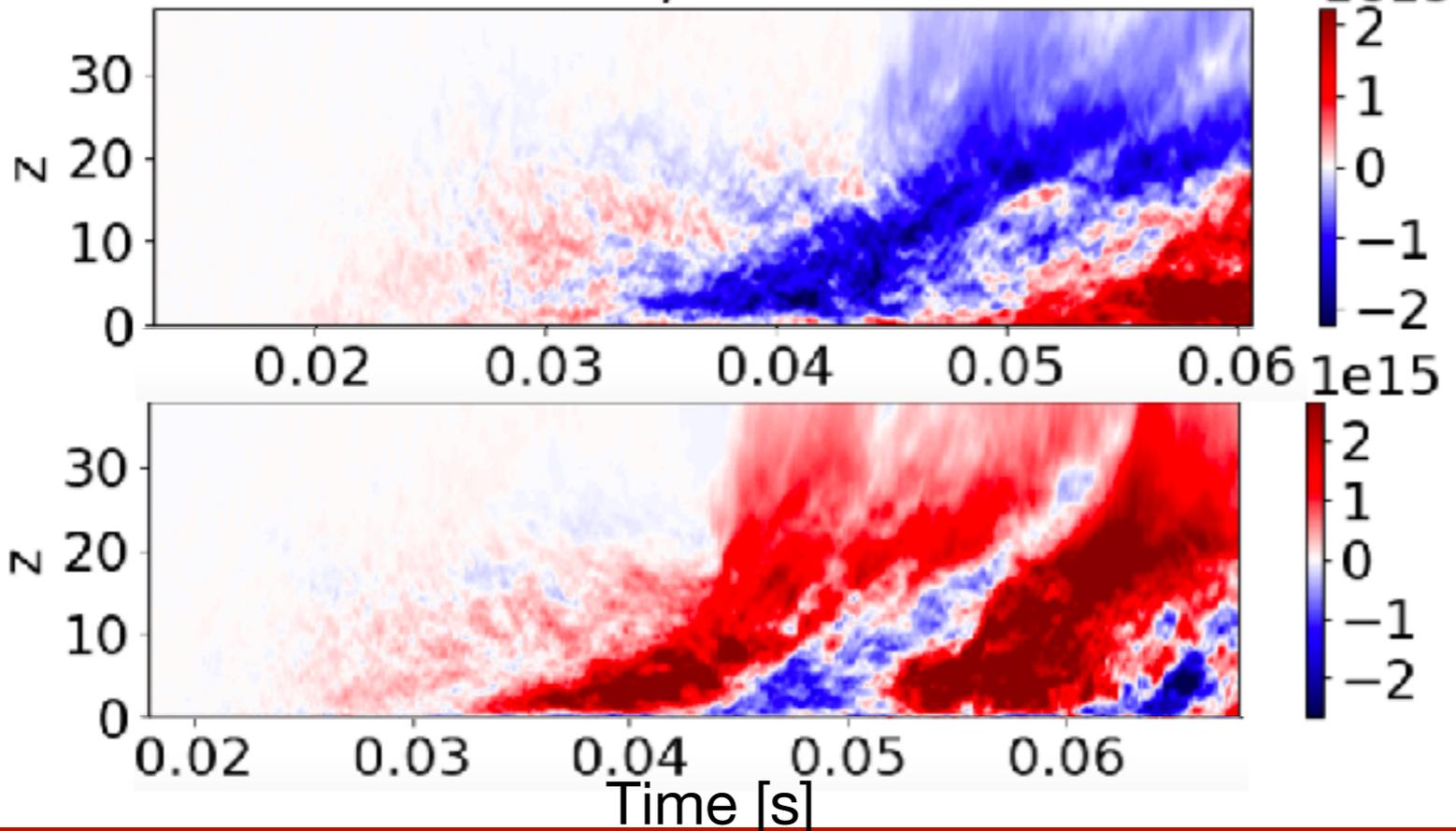
Extrapolation from local models

$$\omega_{\alpha\Omega} = \sqrt{\frac{1}{2}\alpha_{\phi\phi}q\Omega k_z}$$

$$\alpha_{\phi\phi} \approx 10^{-2}\Omega H \text{ and } k_z \approx \frac{2\pi}{H}$$

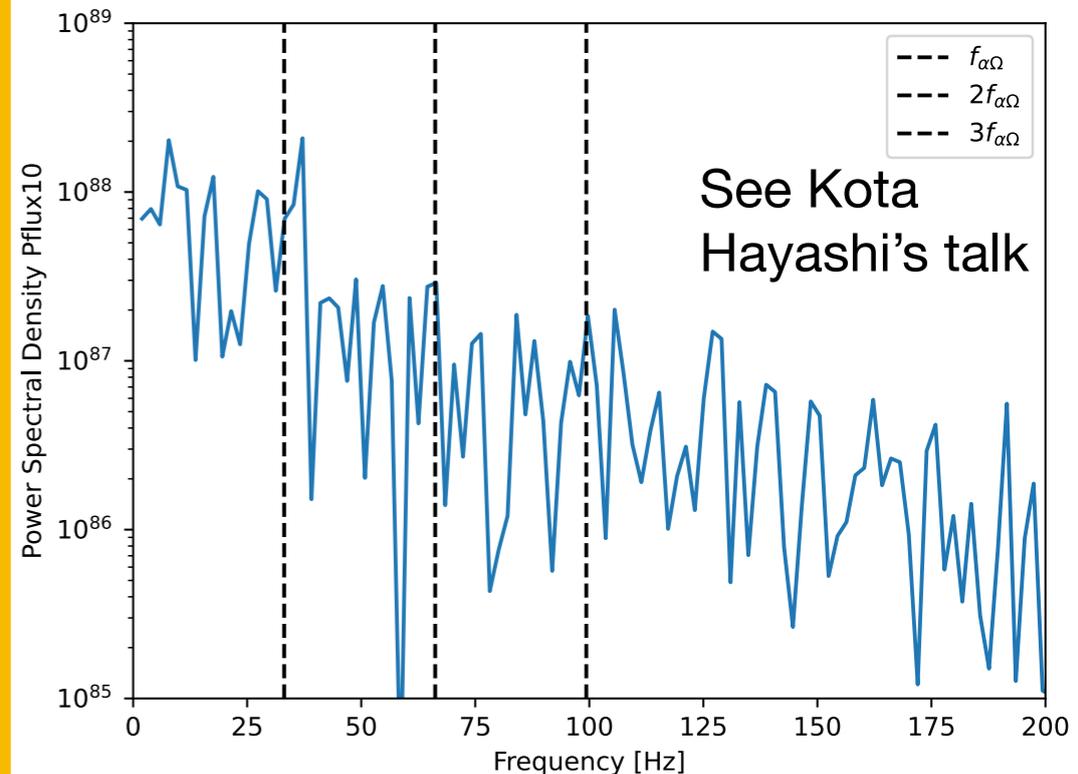
$$\omega_{\alpha\Omega} \approx \Omega/10 \propto \frac{1}{P_{NS}} \text{ or } \frac{1}{M_{BH}}$$

Intermediate-lived case (EOS BHB Λ_ϕ)
 \bar{B}_ϕ [G]



Short-lived case

Poynting Flux luminosity at 500 km



1.375 – 1.375 M_\odot NS binary
 ~ 33 Hz frequency

1.3625 – 1.3625 M_\odot NS binary
 ~ 60 Hz frequency

See Kenta Kiuchi's talk next week

Summary and Perspectives

- **MRI-driven alpha-Omega dynamo in BNS mergers**
 - Self-consistent MRI-driven alpha-Omega dynamo for different BNS mergers with frequencies 33-60 Hz
 - Dynamo period impacts the variability in the jet luminosity
 - Influence of initial conditions, EOS, NS masses, equatorial symmetry, resolution on dynamo period?
 - Evolution of the variability in jets?
- **High- P_m regime: higher dynamo efficiency**
 - Faster growth rate, variability and propagation
 - More luminous and magnetised jets
 - Stronger winds of the HMNS and disks
 - Explore this regime with 2D axisymmetric simulations with dynamo terms/ subgrid modelling?