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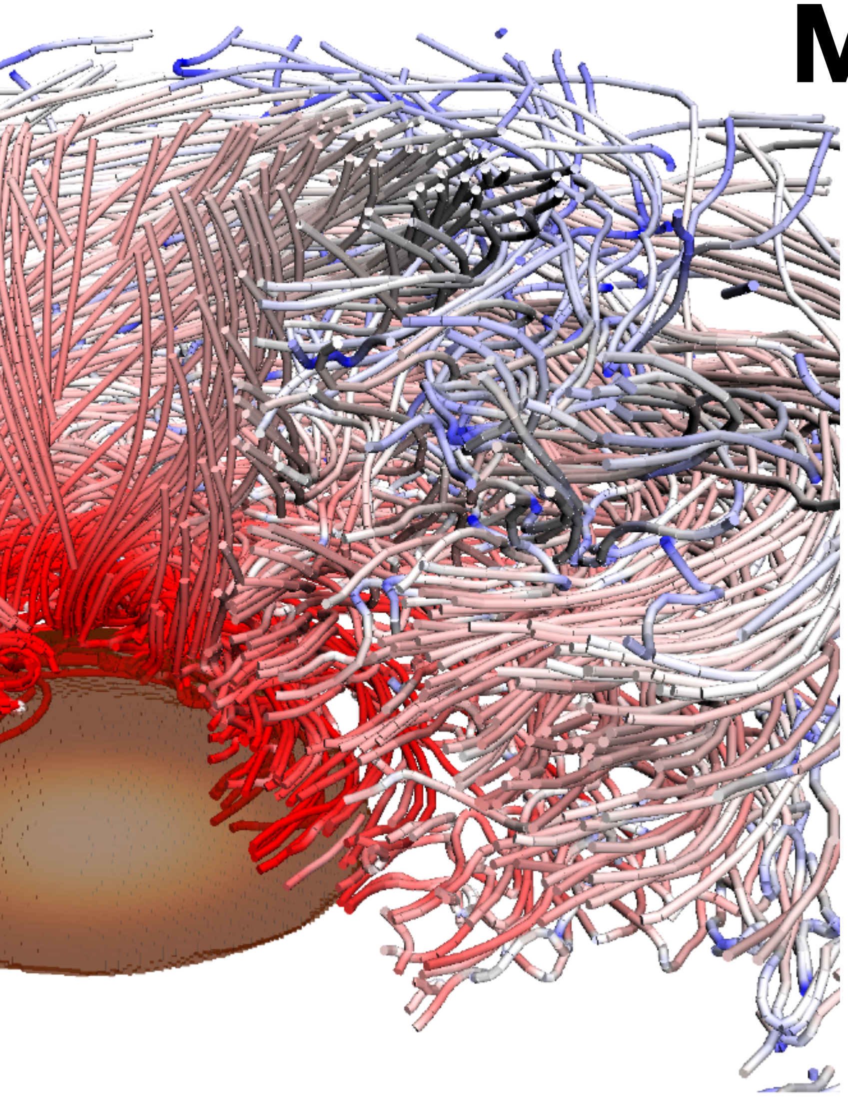

Magnetized turbulence and dynamos in compact objects

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in collaboration with
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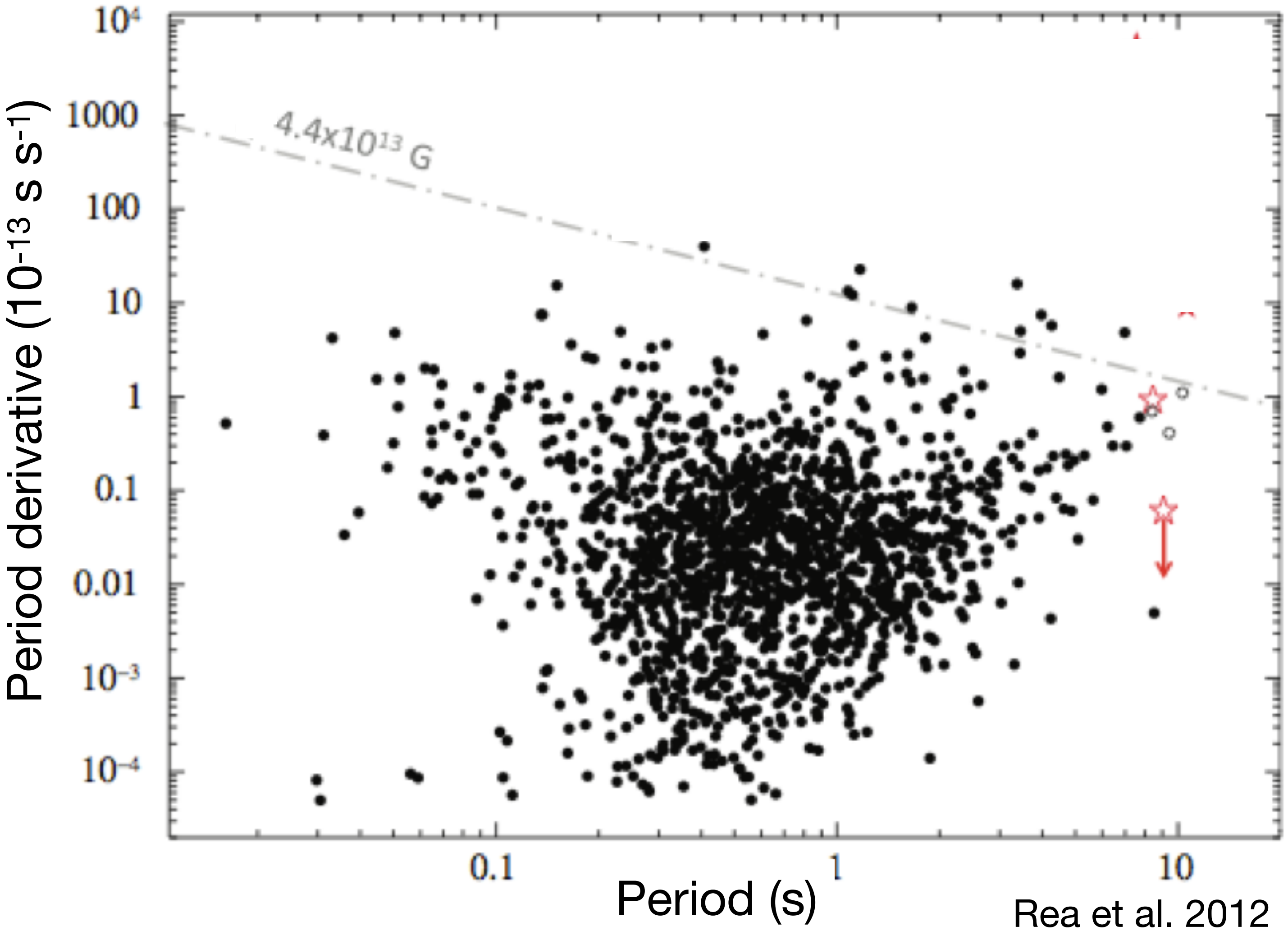
[3]DAMTP, Cambridge
[4]Département d'Astronomie, Université de GenèveGenève

Isolated neutron stars

$P - \dot{P}$ diagram



Rea et al. 2012

Pulsars

- Regular radio pulse by a neutron star modulated its spin
- Spin and spin-down measurement
- **Dipolar** magnetic field :

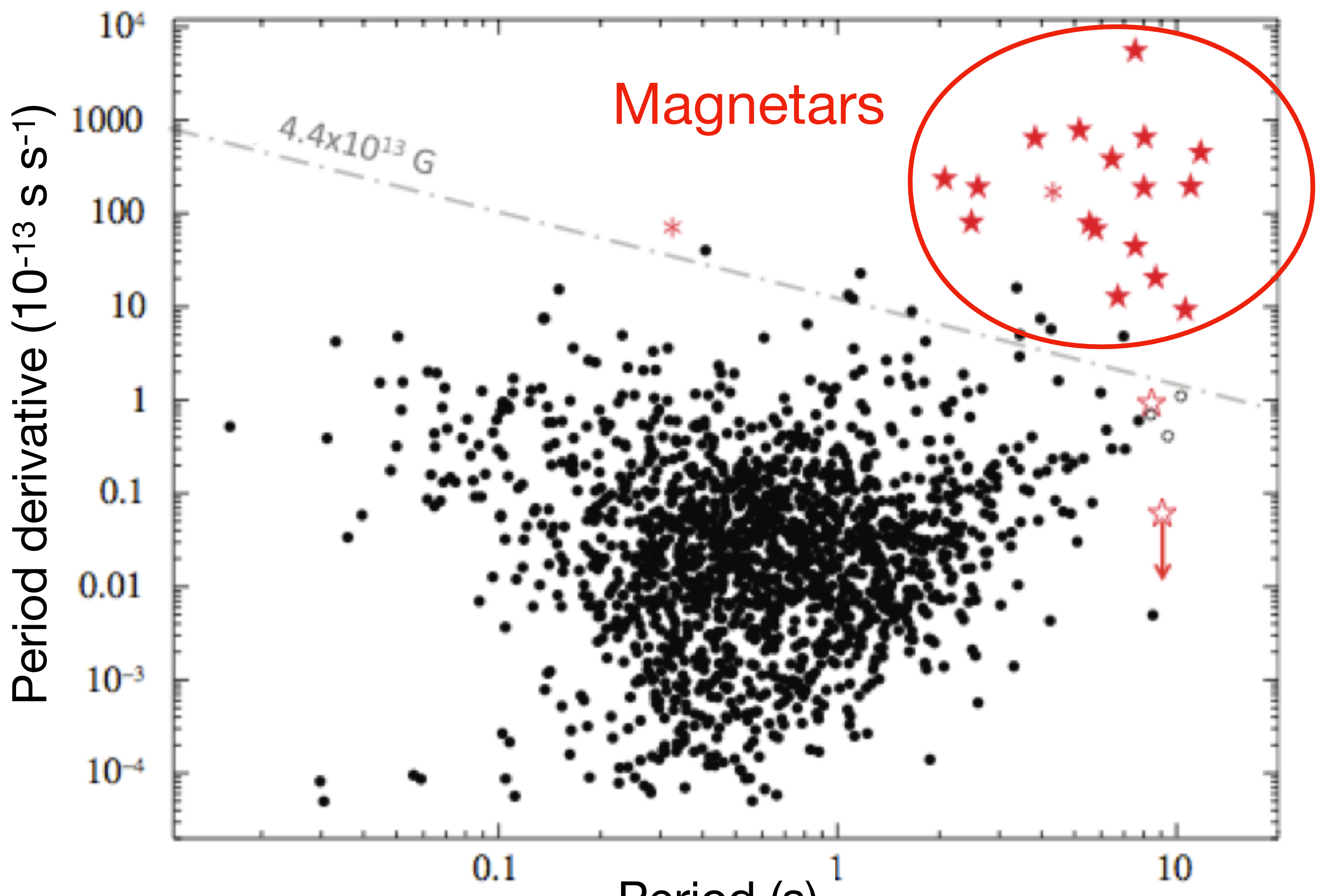
$$B_{\rm dip} \propto \sqrt{P\dot{P}}$$

$$B_{pulsar} \approx 10^9 - 10^{12}\ \mathrm{G}$$

Pulsar wind nebulae

Isolated neutron stars

$P - \dot{P}$ diagram



Rea et al. 2012

~10-40% of neutron star birth

- Gamma ray observations
  ⟶ Soft Gamma Repeaters (SGR)
- X-ray observations of pulsations
  ⟶ Anomalous X-Ray Pulsar (AXP)
- Spin and spin-down measurement
- **Dipolar** magnetic field :

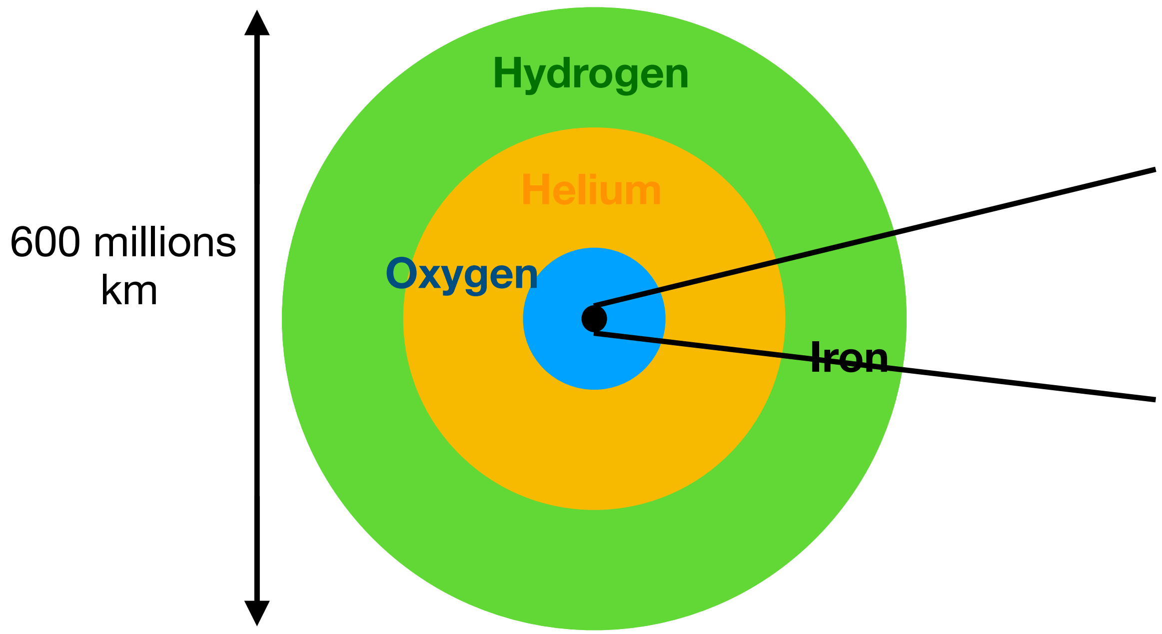
$$B_{\mathrm{dip}} \propto \sqrt{P\dot{P}}$$

$$B_{magnetar} \approx 10^{14} - 10^{15} G$$

Emission powered by magnetic dissipation
Giant flares, outbursts, etc.

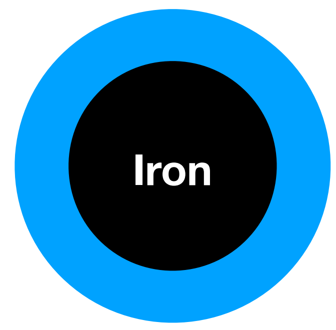
Core-collapse supernovae

Massive stars:

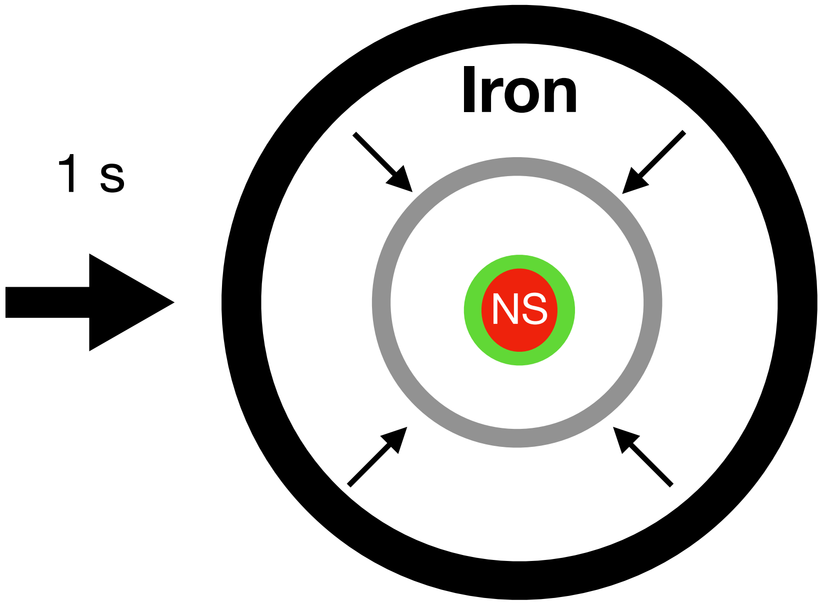


$M_{Fer} \approx 1.4 M_{\odot}$

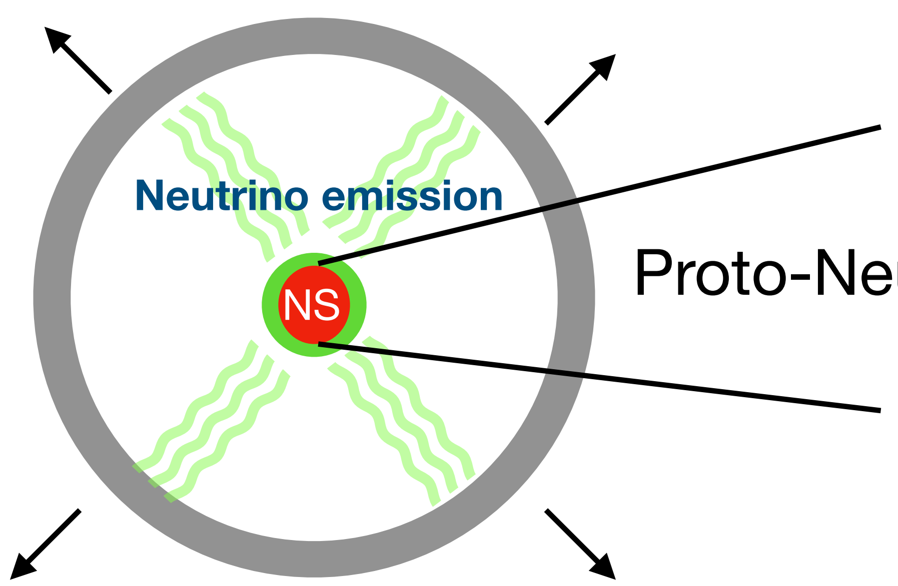
2000 km



Rebound and stalling shock



Revived shock and explosion



Proto-Neutron Star (PNS)

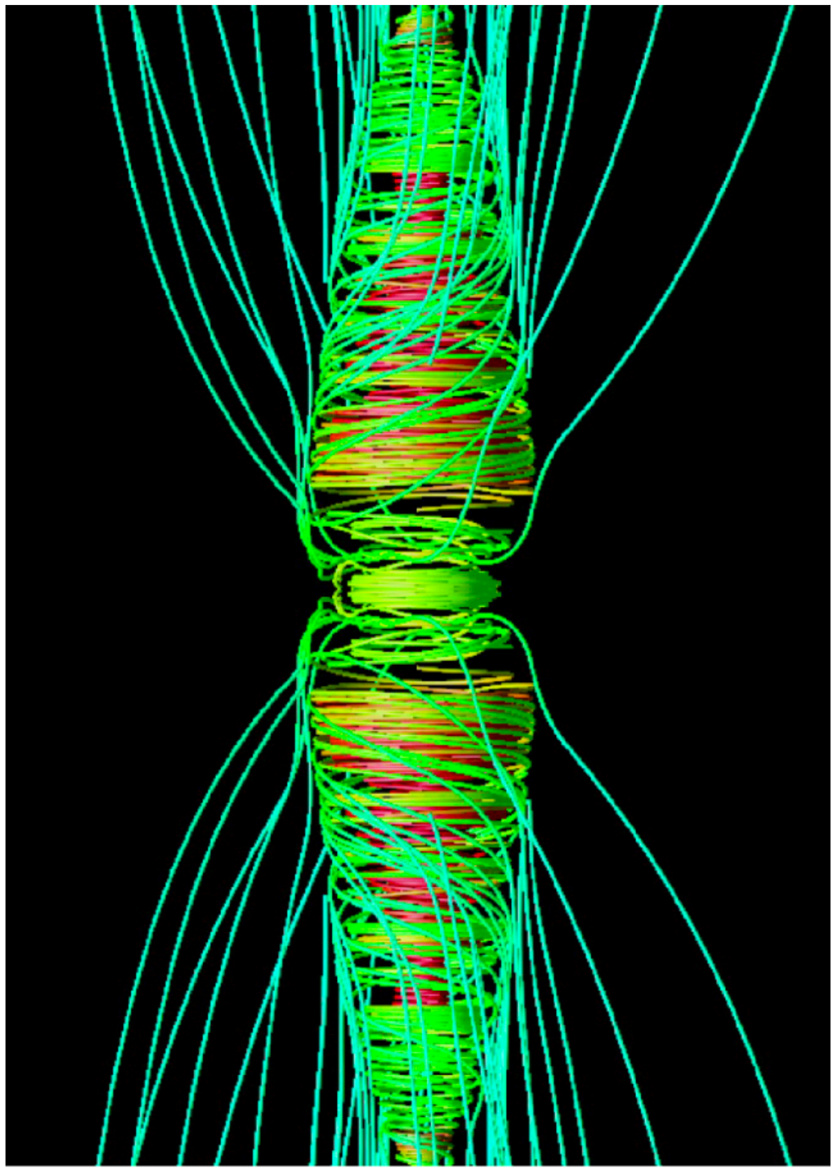
Kinetic energy of the explosion
→ Classic Supernova 10^{51} erg
→ Hypernova (~1 %) 10^{52} erg

Long GRBs are associated with Supernovae type Ic-BL (Hypernovae)

→Need an other explosion mechanism

Central engines of hypernovae

Millisecond magnetar



Credit: Burrows+07

- → Rotation period $P = 1\mathrm{ms}$
- → Magnetic field $B > 10^{15}\mathrm{G}$

Collapsar

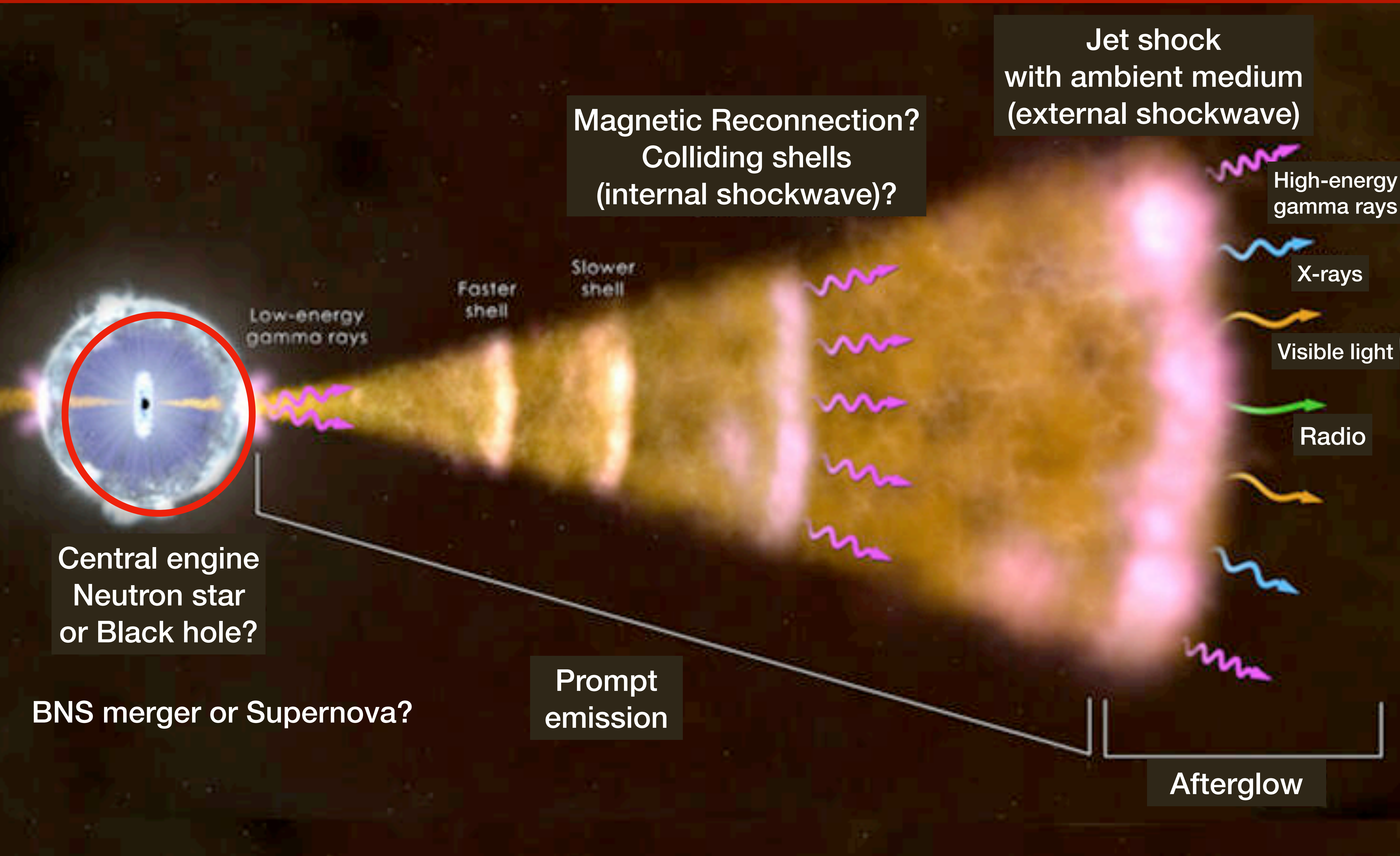
Gottlieb et al 2023

Angular momentum of infalling stellar material
-> formation of accretion disk around the BH

Accrete enough magnetic flux in the BH

$$B_h > 10^{15}\ \mathrm{G}$$

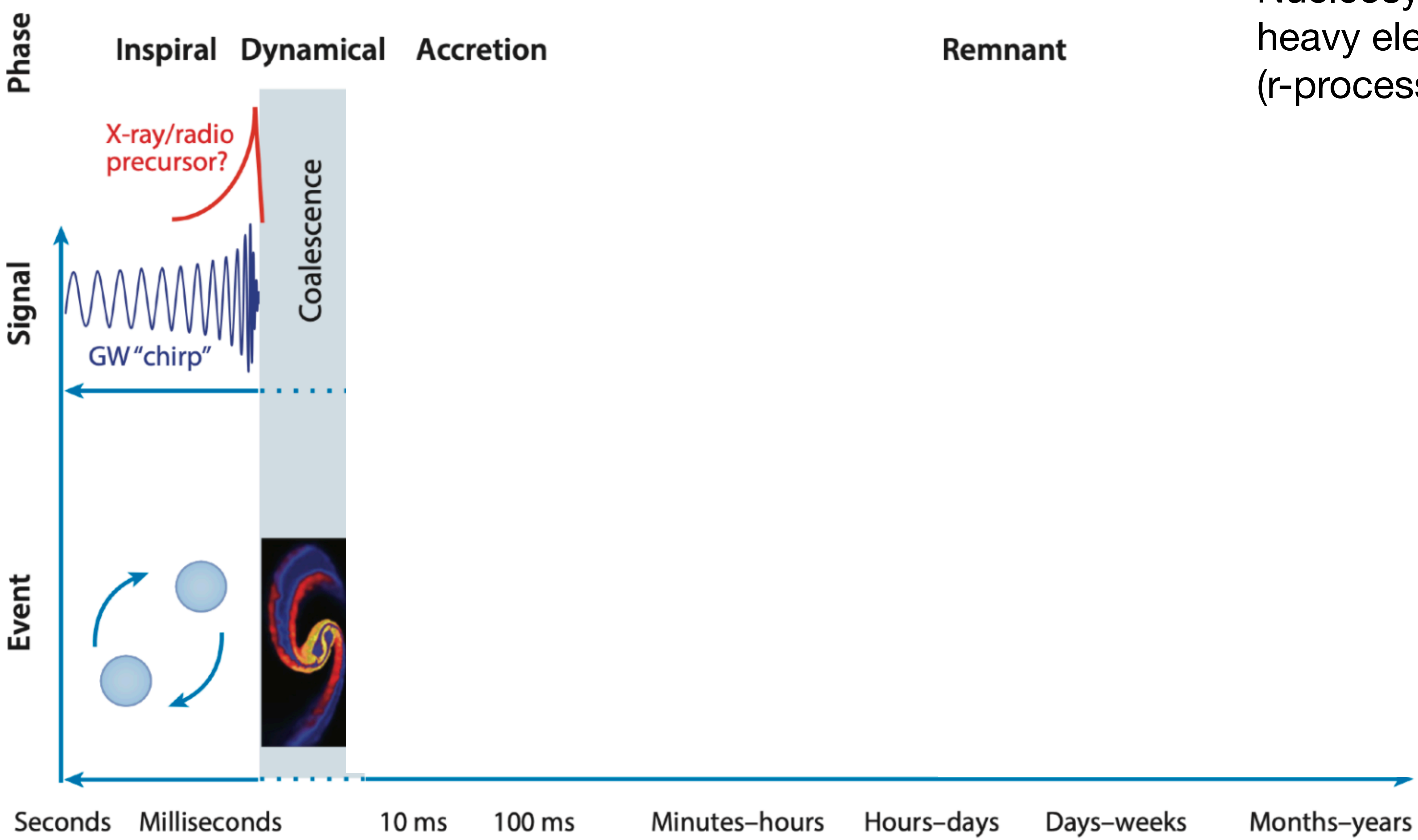
Gamma-ray bursts



BNS merger or Supernova?

Binary neutron star mergers

Nucleosynthesis of heavy elements (r-process)

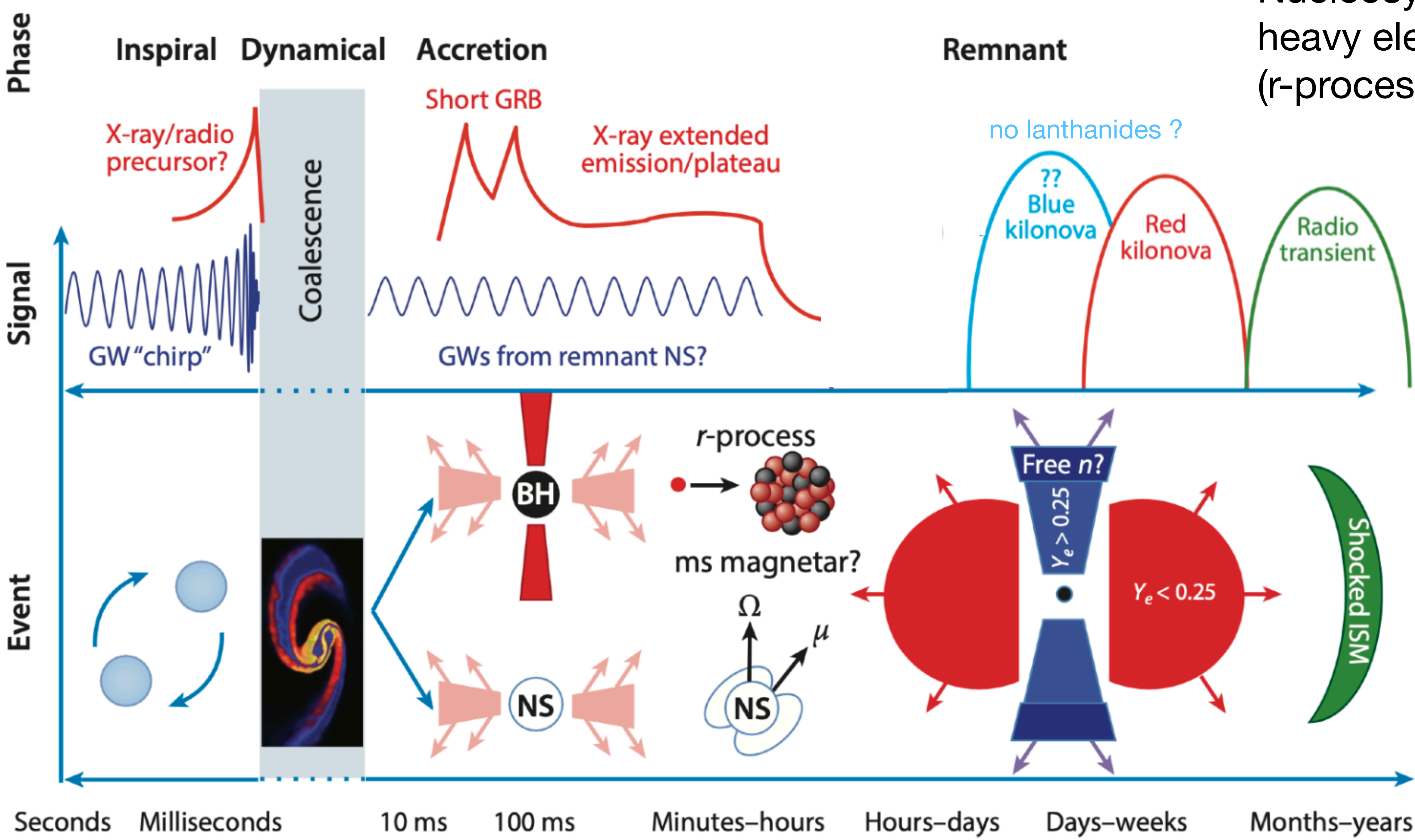


Fernandez & Metzger 2016

Magnetic Reconnection in inspiral?
See Skiathar+2025 (Force-free simulations), Parssons+2026 (Kinetic simulations)

Binary neutron star mergers

Nucleosynthesis of heavy elements (r-process)



Fernandez & Metzger 2016

Magnetic Reconnection in inspiral?
See Skiathar+2025 (Force-free simulations), Parssons+2026 (Kinetic simulations)

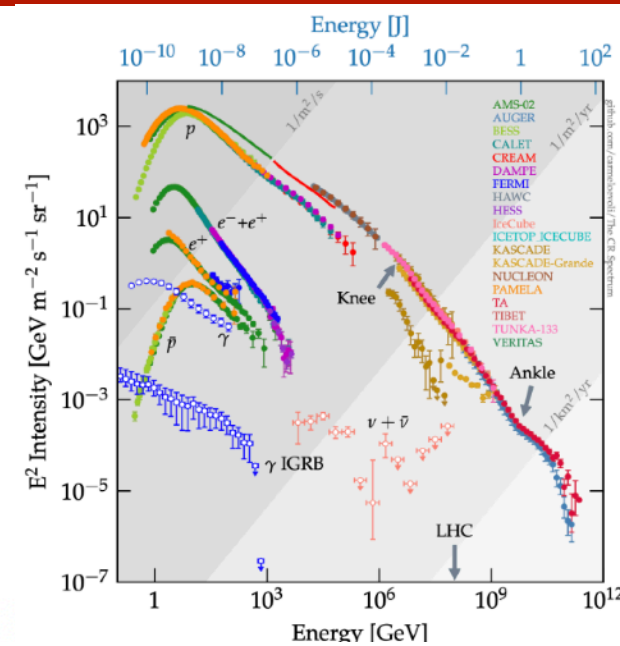
Site for particle acceleration? (Farrar 2025)

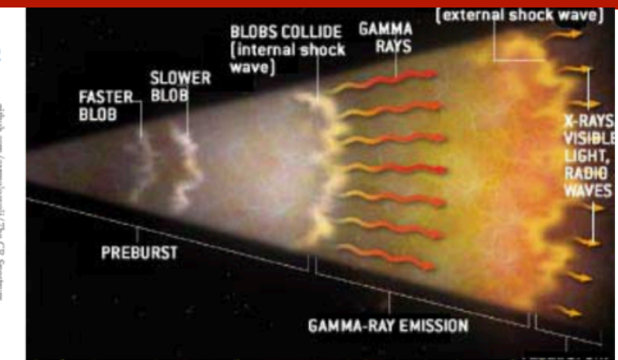
Motivation: Particle acceleration in extreme environments

Cosmic rays

- Highly energetic particles
- Sources of acceleration?

See the many talks during this workshop





SNR

Two broad categories of particle acceleration

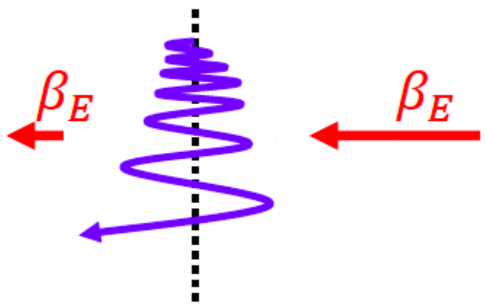
on large ("astrophysical") scales, $\mathbf{E} = -\beta_\mathbf{E} \times \mathbf{B}$ from the magnetised plasma flow

on small ("kinetic") scale, non-ideal fields, parallel to $\mathbf{B}$ or larger than $\mathbf{B}$

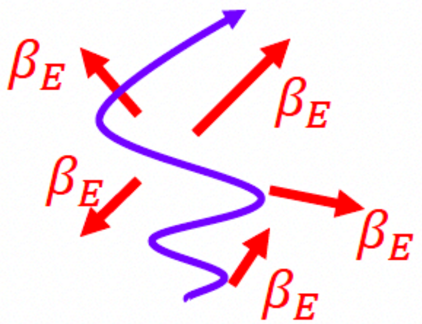
See talk by S. Aerdker

Fermi acceleration: $\mathbf{E} = -\beta_\mathbf{E} \times \mathbf{B}$, acceleration by varying fluid velocities

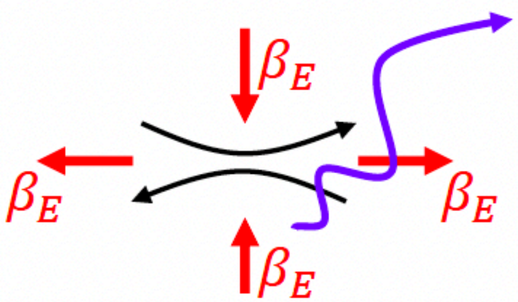
shock wave



turbulence



reconnection (outside X-point)

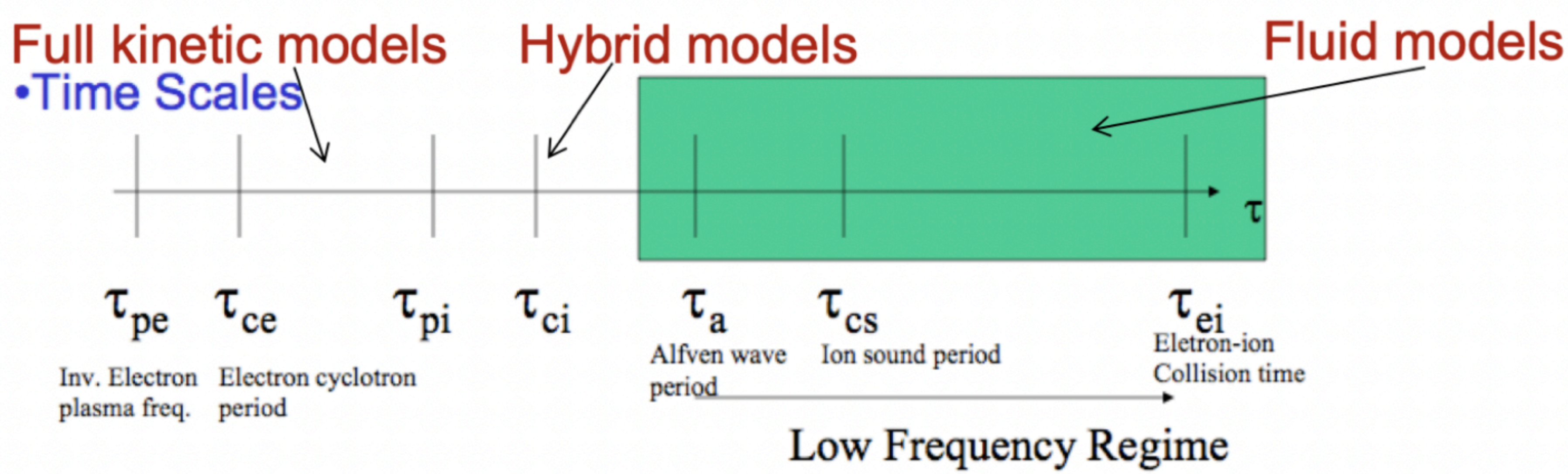


Credit: M. Lemoine

Characteristic time and length scales

$$\omega_p = \left(\frac{4\pi \, ne^2}{m}\right)^{1/2} \qquad \lambda_D = \frac{V_{thermal}}{\omega_p} \propto \left(\frac{T}{n}\right)^{1/2} \qquad \lambda_{skin} = c/\omega_p \qquad \omega_c = \frac{eB}{mc}$$

Plasma frequency — Debye length — skin depth — Larmor

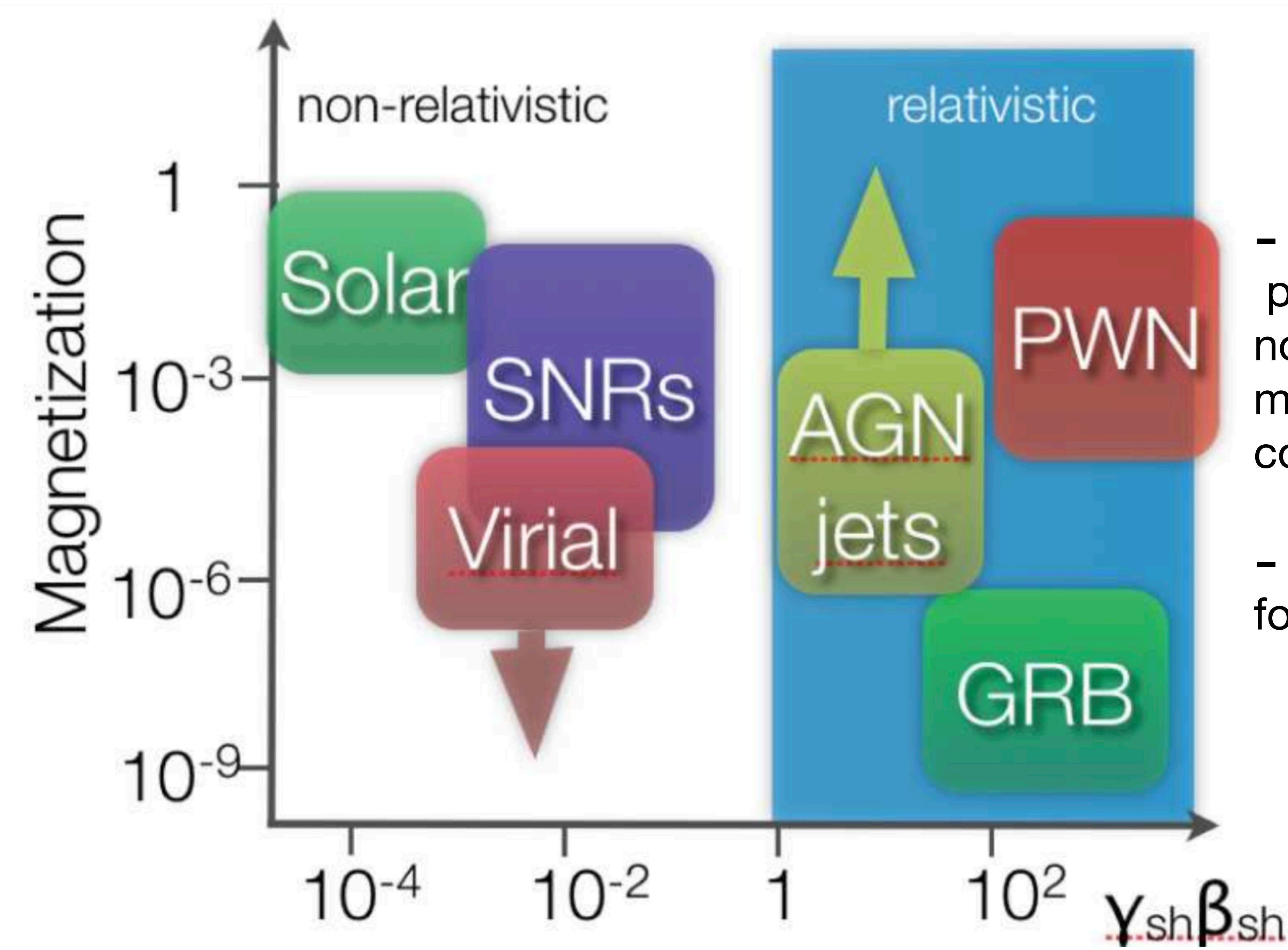


Credit: A. Spitkowsky

plasma length scales $r_{g,th}$, $c/\omega_{pi} \sim 10^7 n_0^{-1/2}$ cm << Fluid length scale

Inside a neutron star, $n_0 \approx 1.5$ baryon fm^{-3}, $B \approx 10^{10} - 10^{15}$G

Shocks



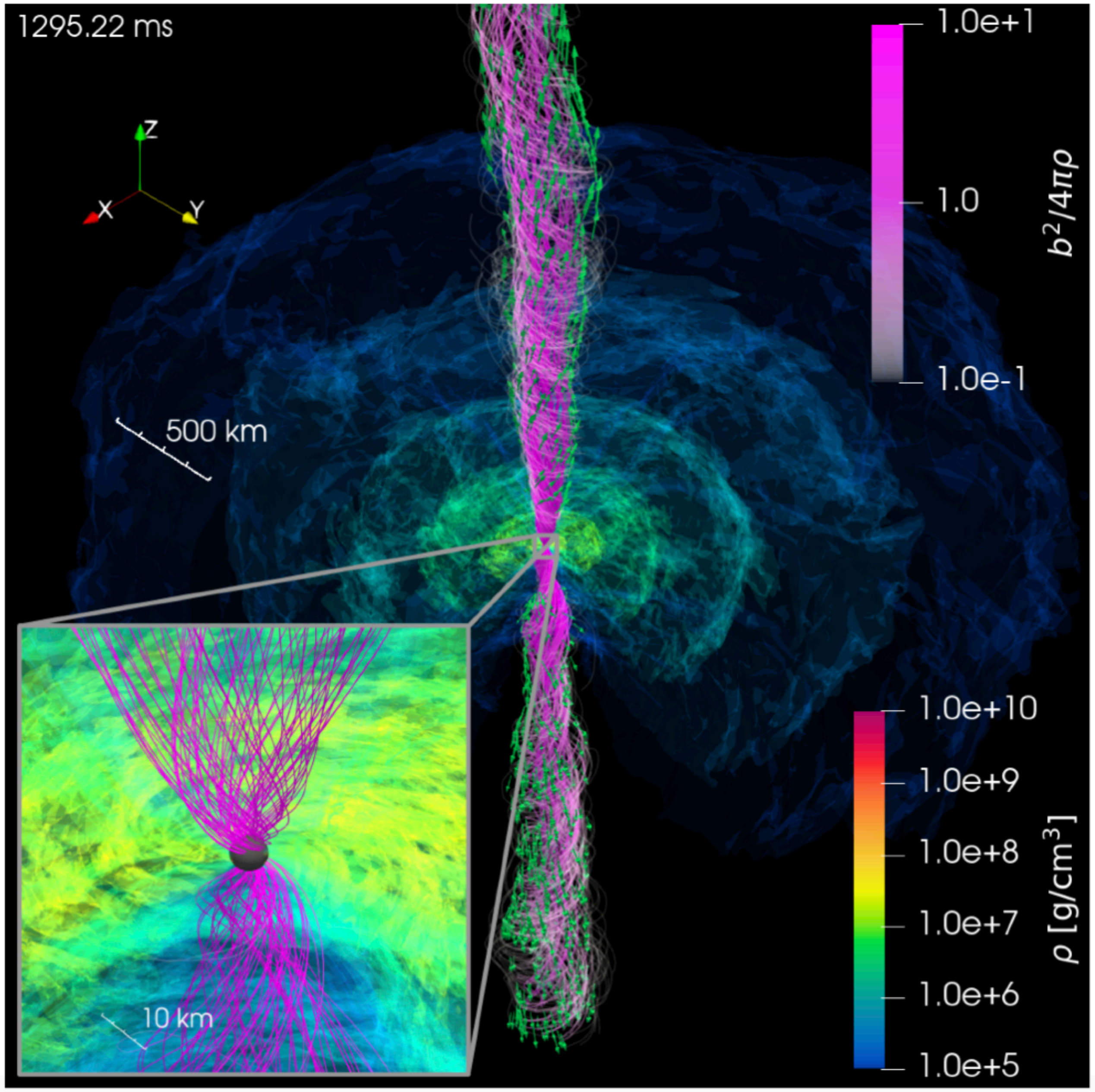
Credit: A. Spitkowsky

- Modelling kinetic effects, particle acceleration, non-ideal effects, magnetic reconnection, collision-less plasma, etc.

- Modelling the source for large-scale parameters

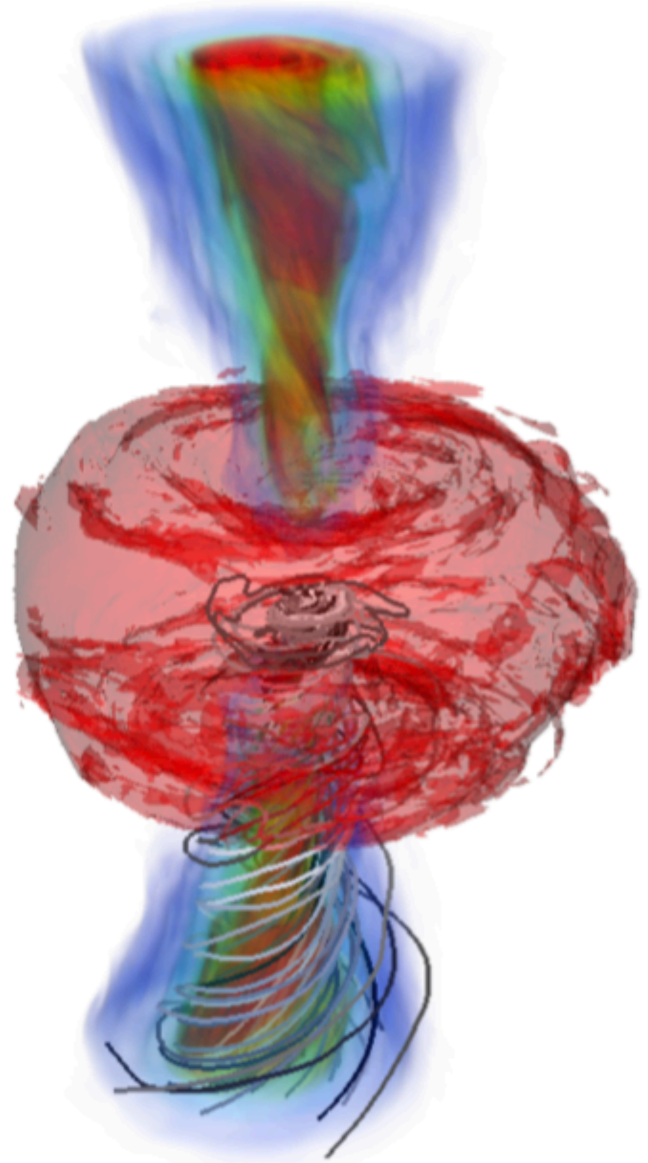
GRB central engines

Black Hole + disk systems



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

Fast-Rotating Neutron Star + disk systems



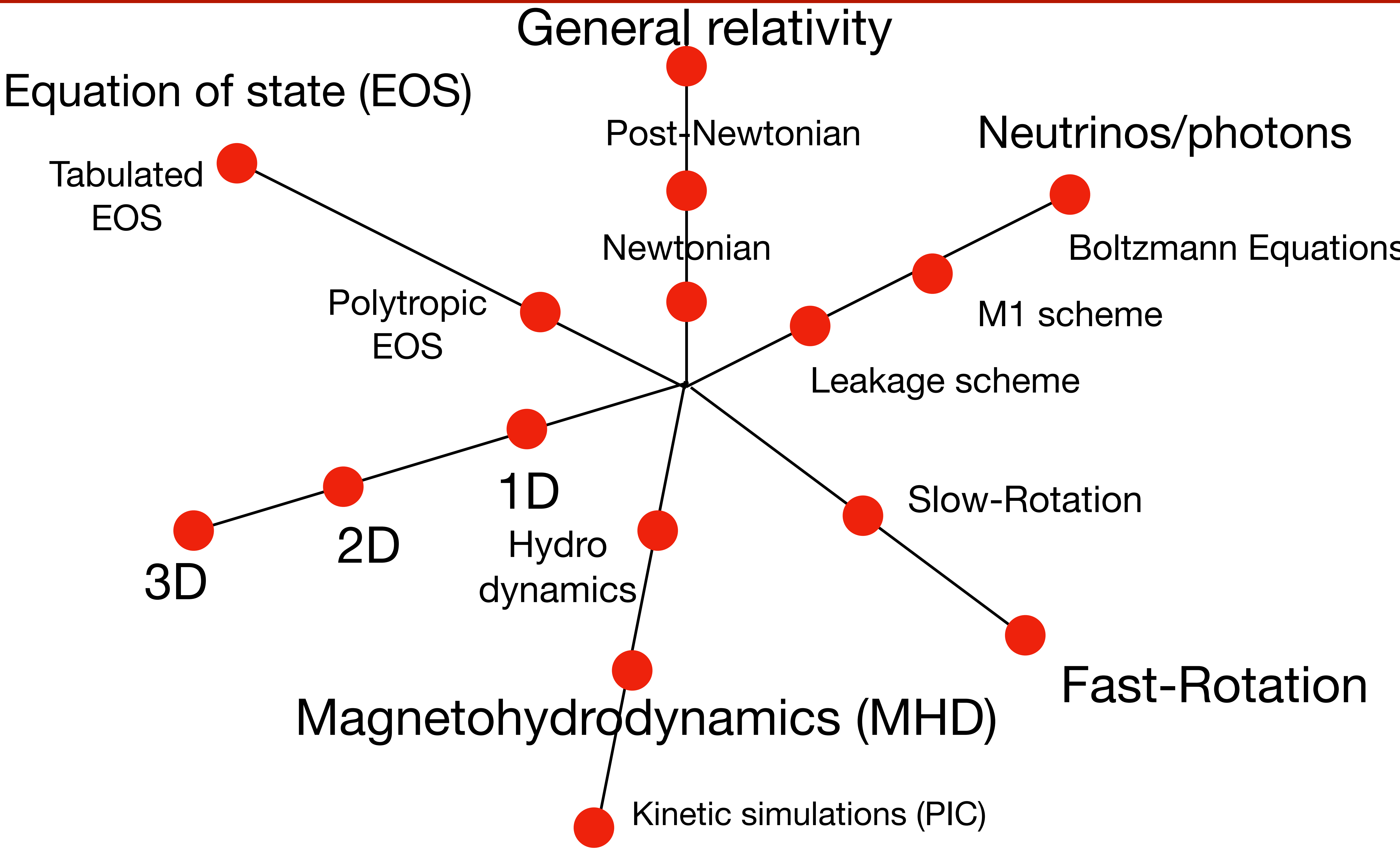
Mosta et al 2020

(Combi+2022 Kiuchi, **ARS**+ 2024 Musolino+ 2024)

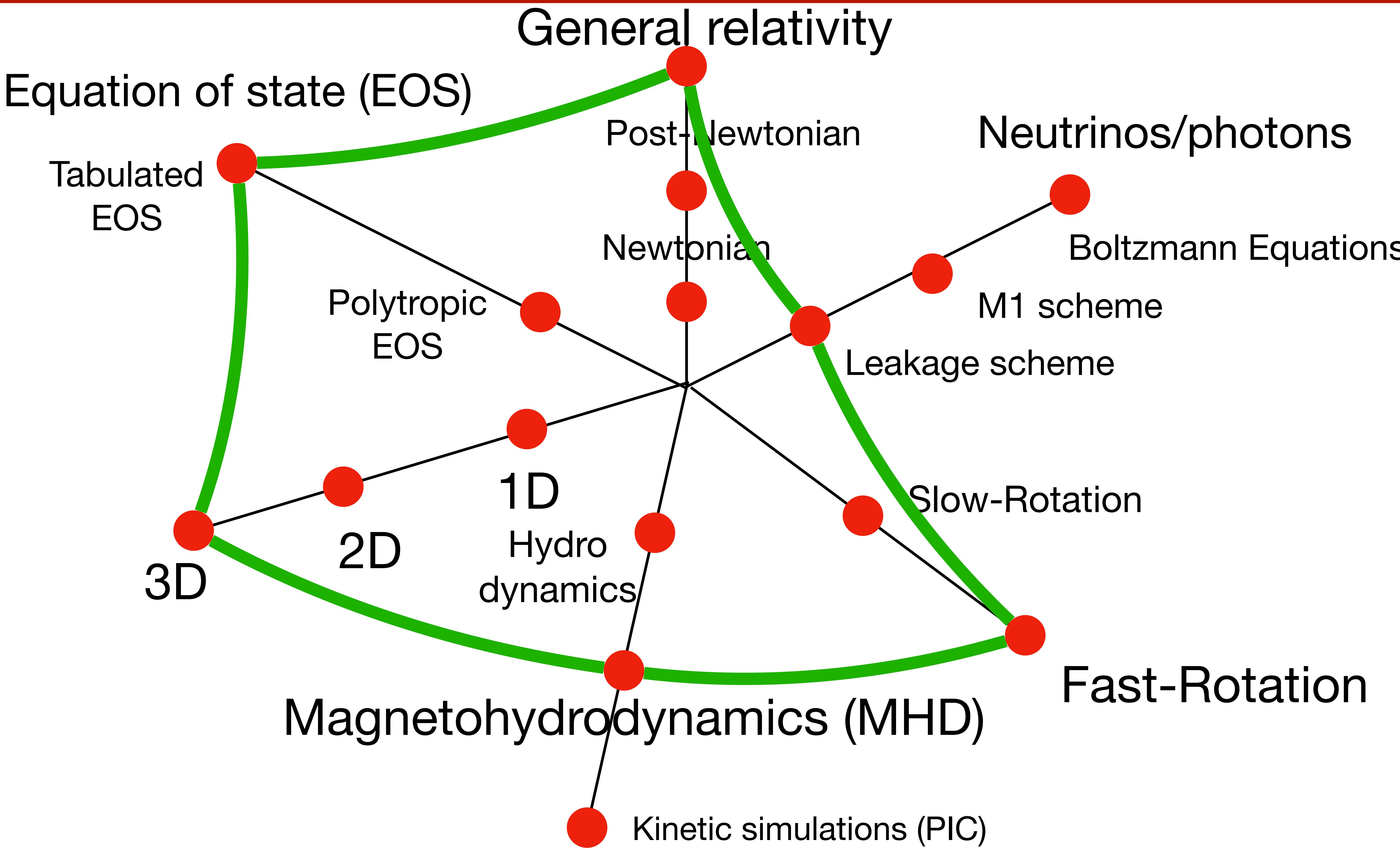
Blandford-Payne/Znajek effect
(in Active Galactic Nuclei, talk by Fichet de Clairfontaine)

Blandford-Payne effect

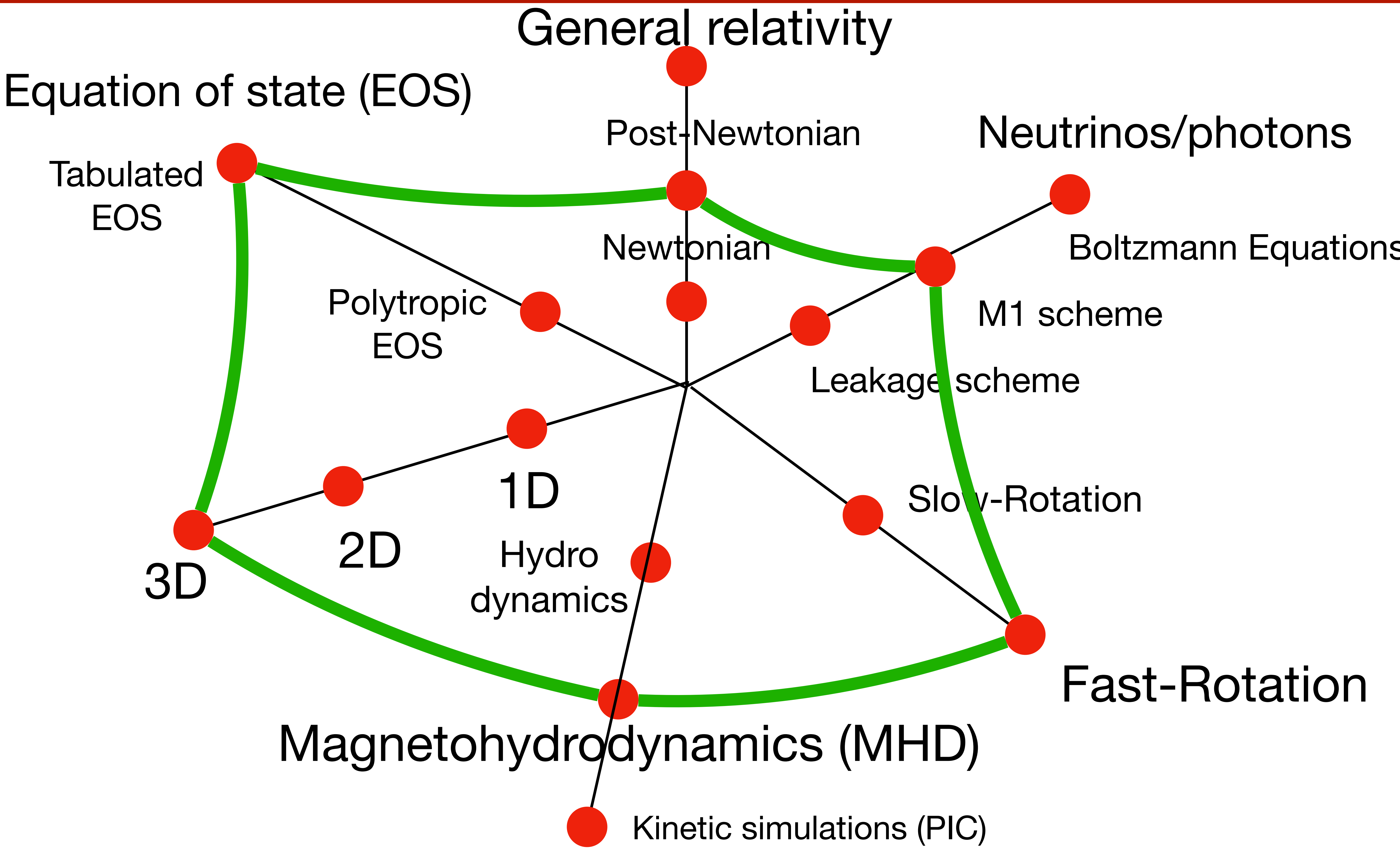
Modelling compact objects: Key physical ingredients



Highest resolution global BNS merger simulation

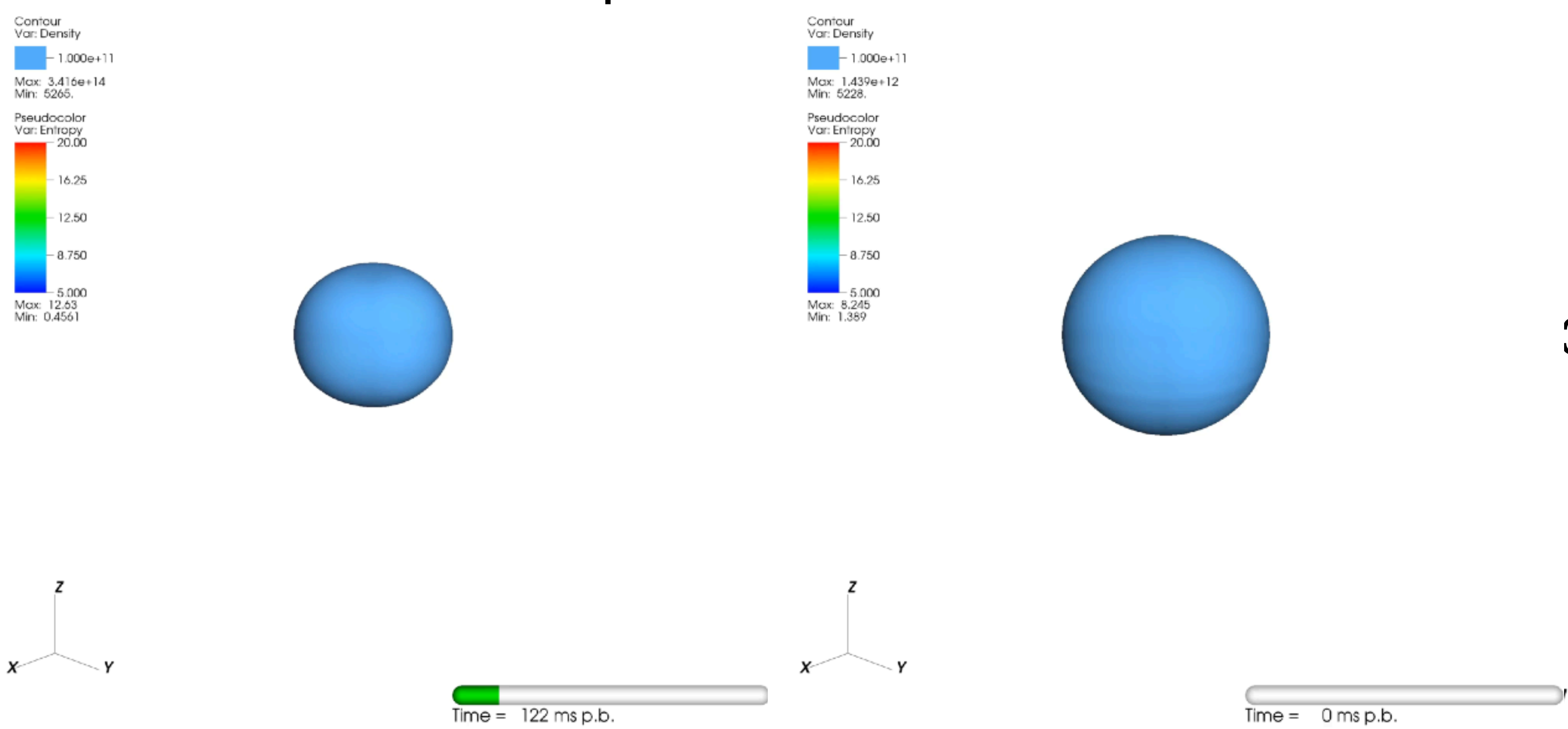


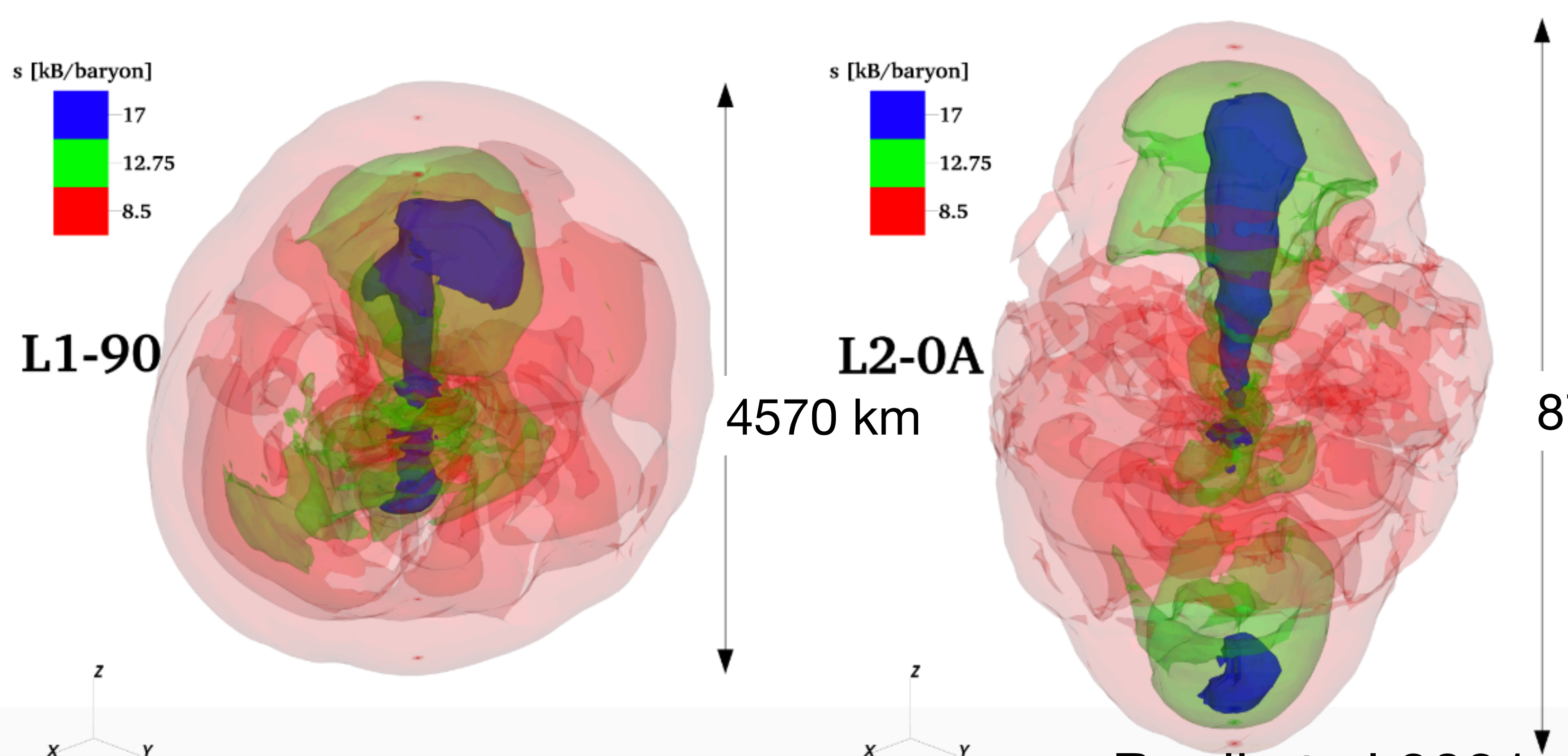
Example of millisecond magnetar simulations



What are the conditions for jet launching?

Core-Collapse simulations





Bugli et al 2021

In addition to **fast rotation**,
Jets requires **strong large-scale** magnetic fields in the polar region

Geometry of the magnetic field is also important

Magnetar with an Equatorial dipole
-> Superluminous supernovae
-> Extended emission deposited in the ejecta

How to generate a strong large-scale magnetic field?

How do we form magnetars?

Outline

Introduction

I-Dynamos in proto-neutron stars

II- Dynamos in BNS mergers

Magnetic field amplification in core-collapse supernova

Fossil field scenario:
Very magnetised stars on surface (B >1 kG)
During collapse of iron core, amplification by **$\sim 10^4$**
A **10^{10}-10^{11} G** field in the iron core ?
Slow rotators

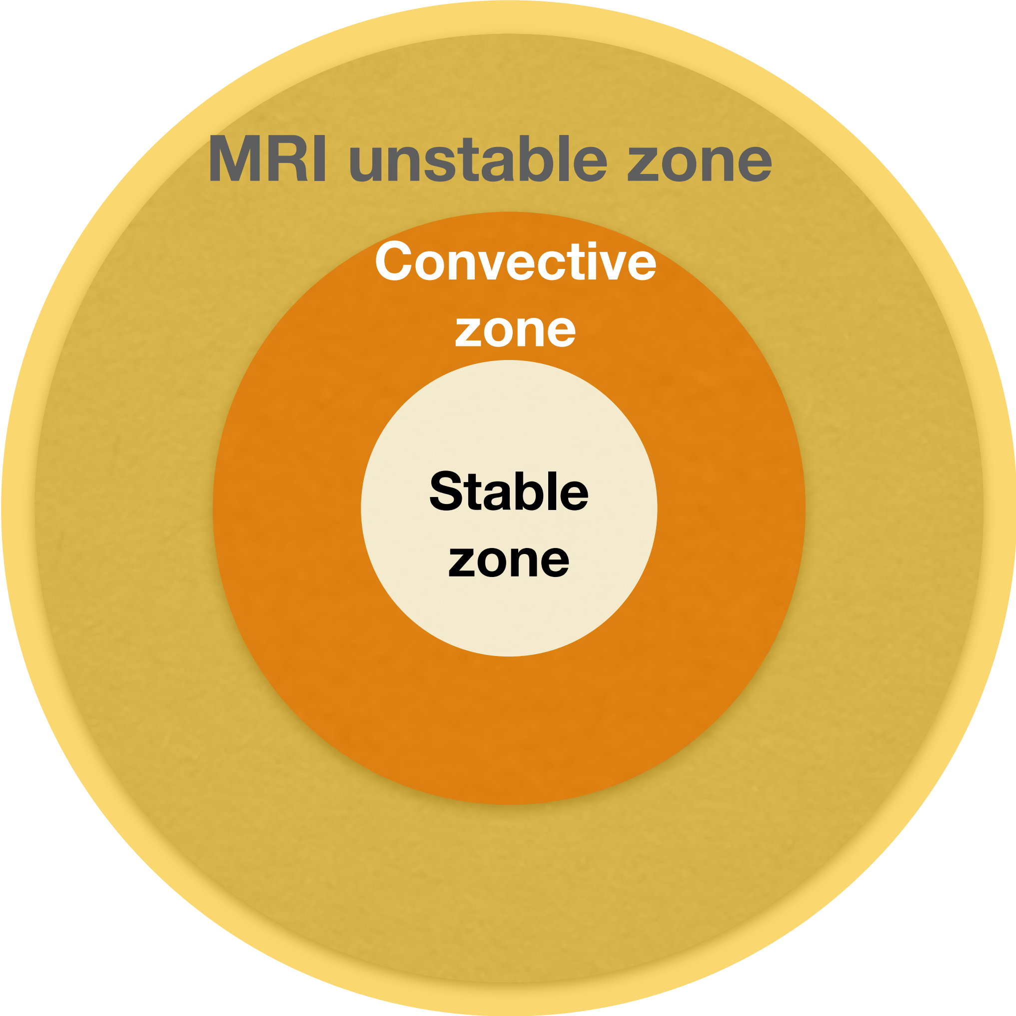
PNS dynamo scenario:

Convective dynamo
In Supernova (SN)
Similar to planetary & stellar dynamos
(Raynaud+2020,2021)

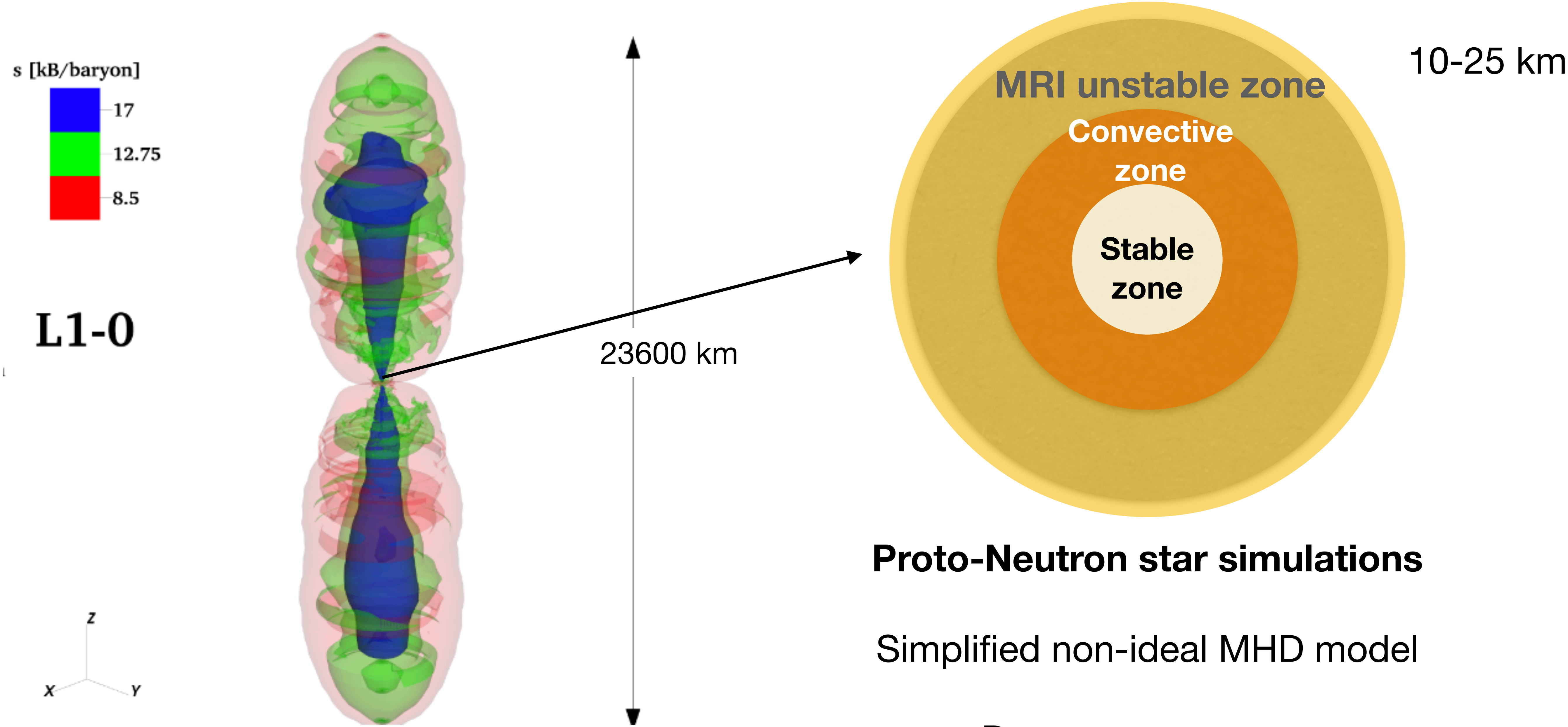
Magnetorotational instability
Both SN & NS mergers
Similar in accretion disks

Tayler-Spruit dynamo
SN with fallback (Barrere+2022,2024) or HMNS core
Similar to stellar radiative zones

t = 0.2 s



Modelling Proto-neutron star dynamos



Global core-collapse supernova

Proto-Neutron star simulations

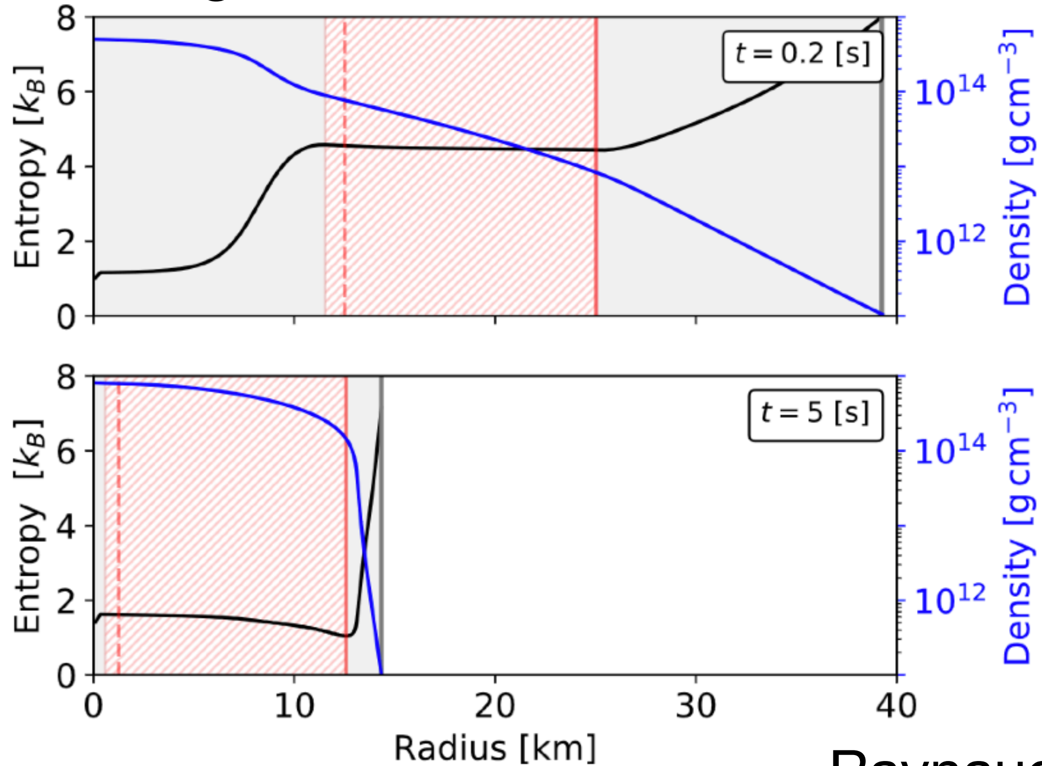
Simplified non-ideal MHD model

Dynamo processes:
B field strength and geometry

Derive physical scaling laws via parameter studies

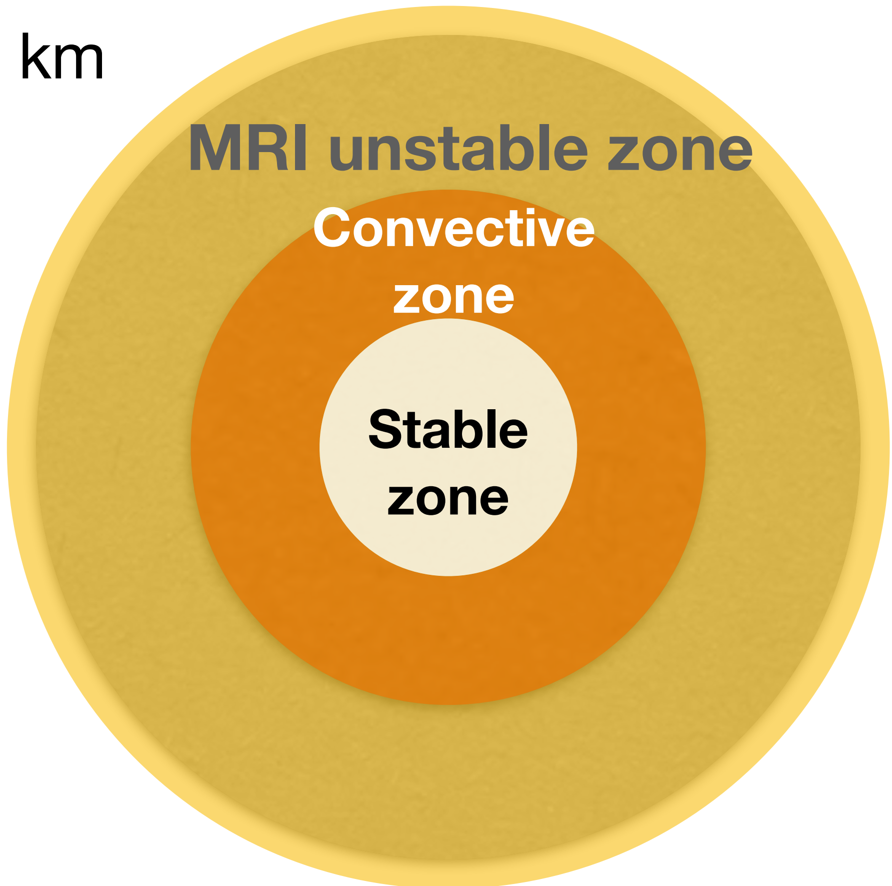
Modelling Proto-neutron star dynamos

Background from 1D simulations

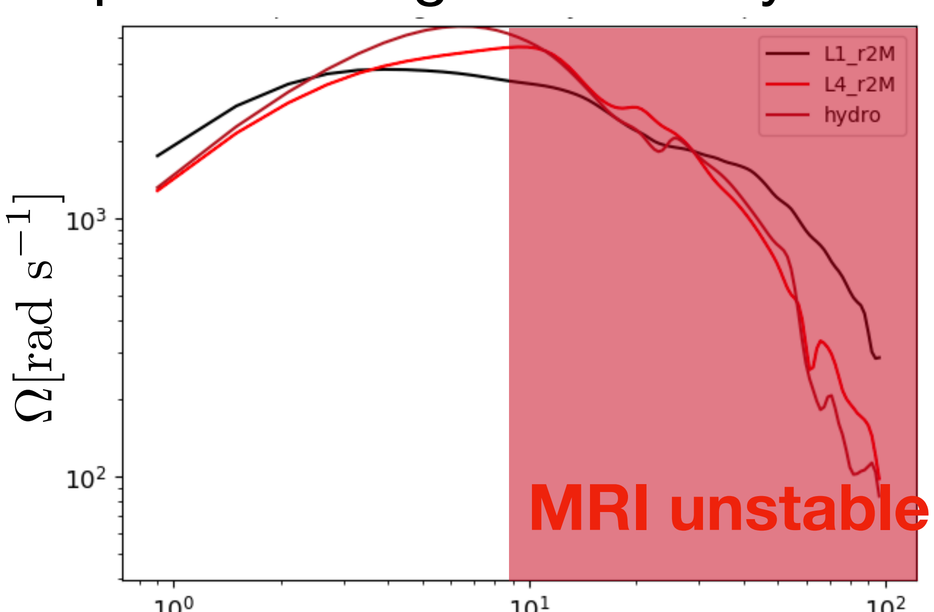


Raynaud et al 2022

10-25 km



Equatorial Angular velocity at t=0.4 s



Bugli et al 2021

Proto-Neutron star simulations

Simplified non-ideal MHD model

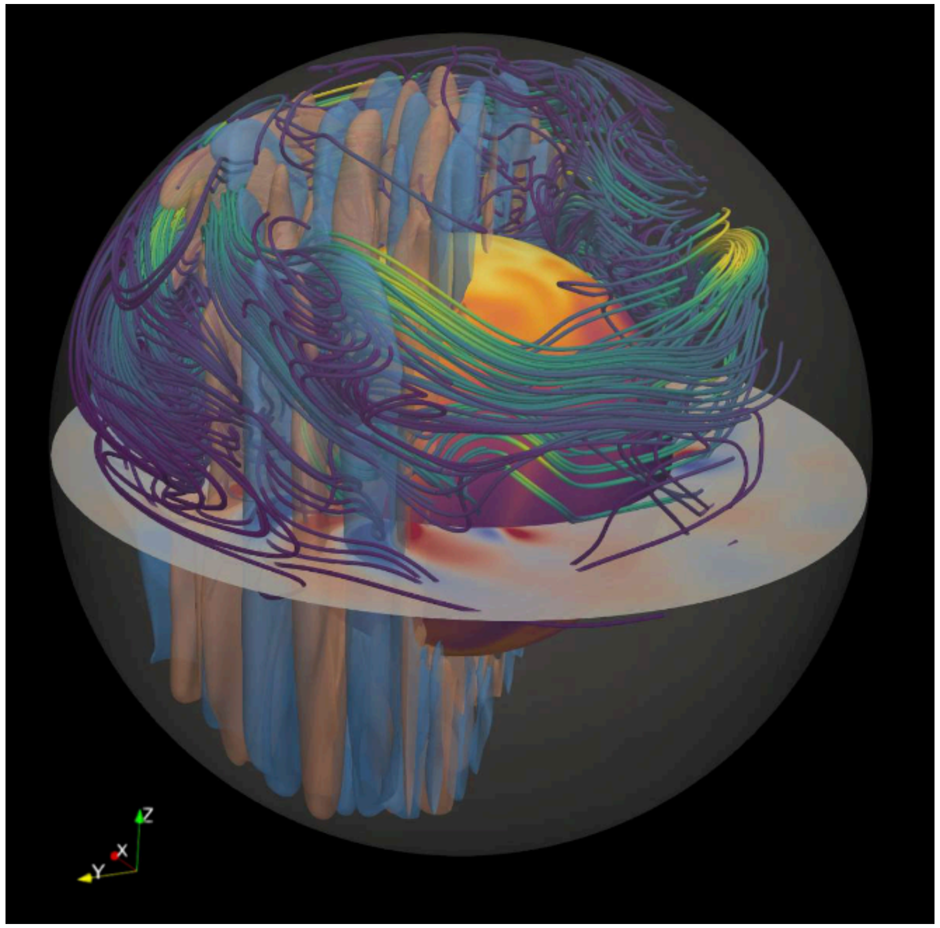
Dynamo processes:
B field strength and geometry

Derive physical scaling laws via parameter studies

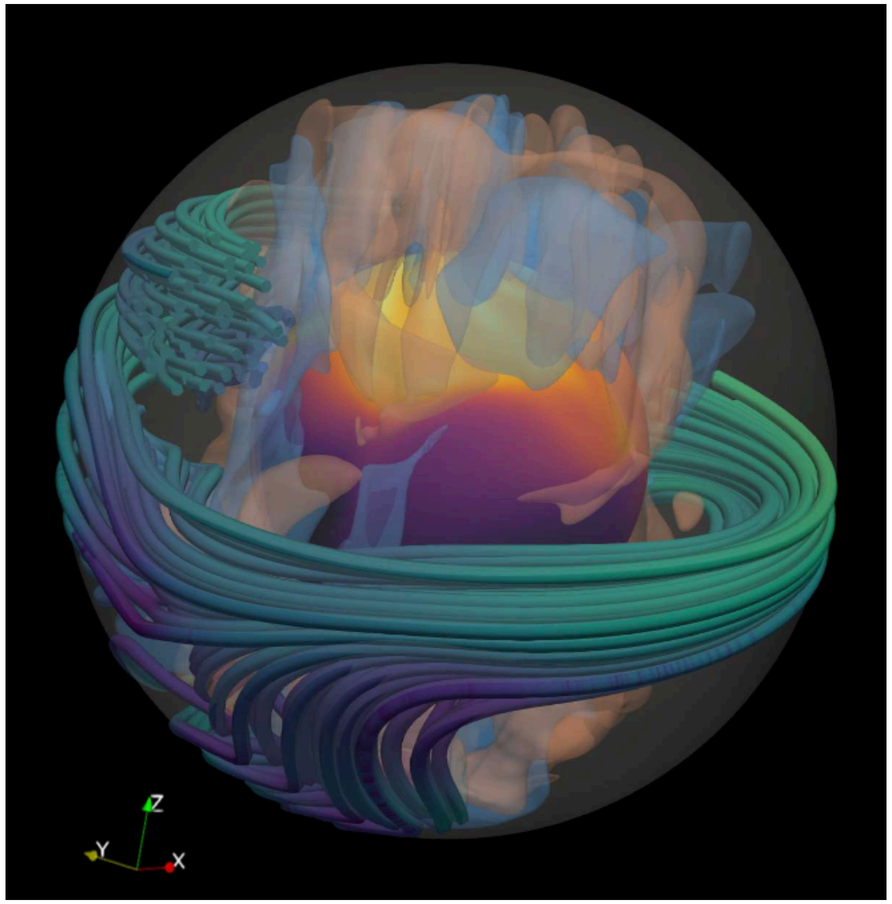
Magnetar formation through convective dynamo

Convection in the proto-neutron star until 10 s in core collapse supernova

First plateau of the dynamo



Saturated state of the dynamo

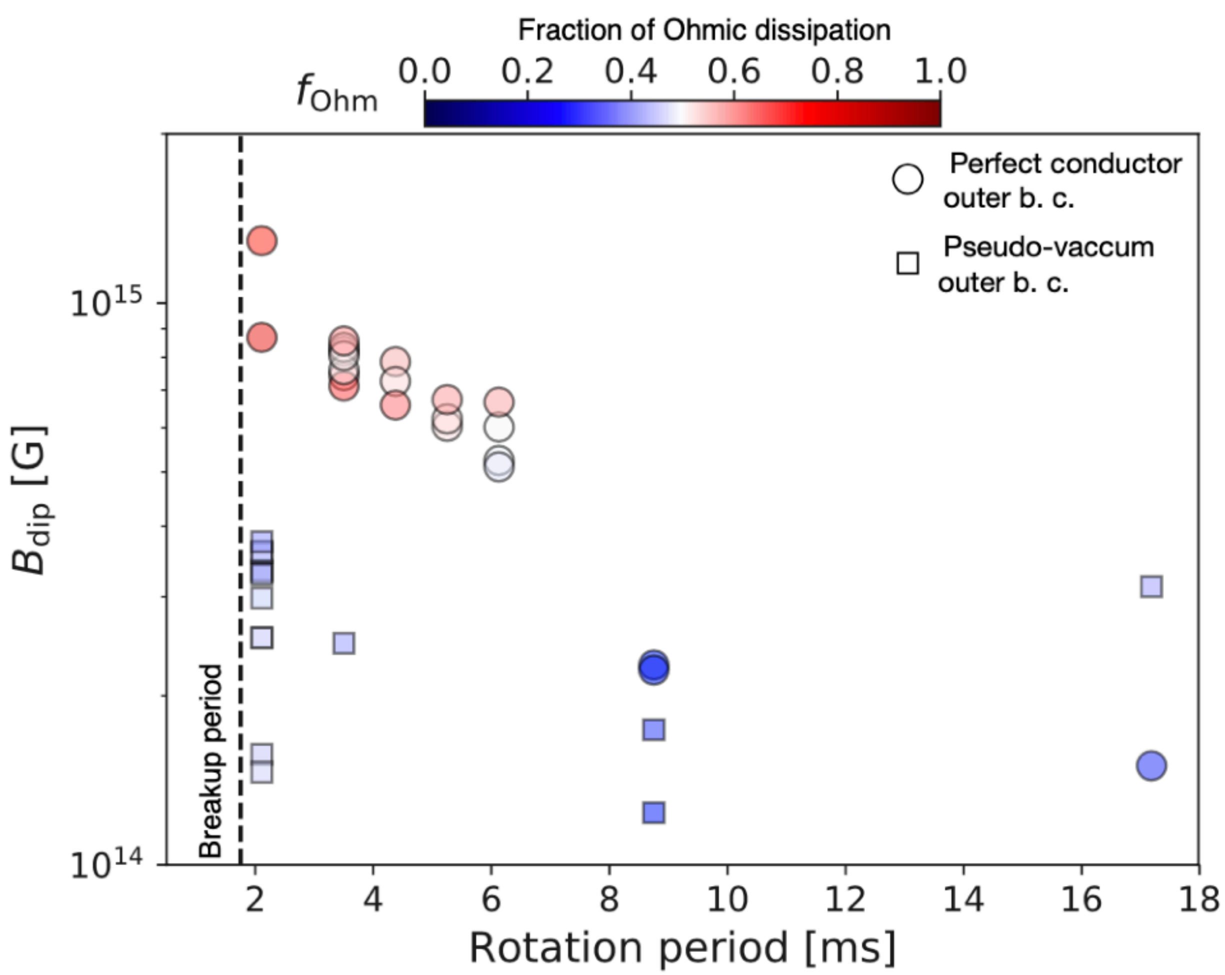


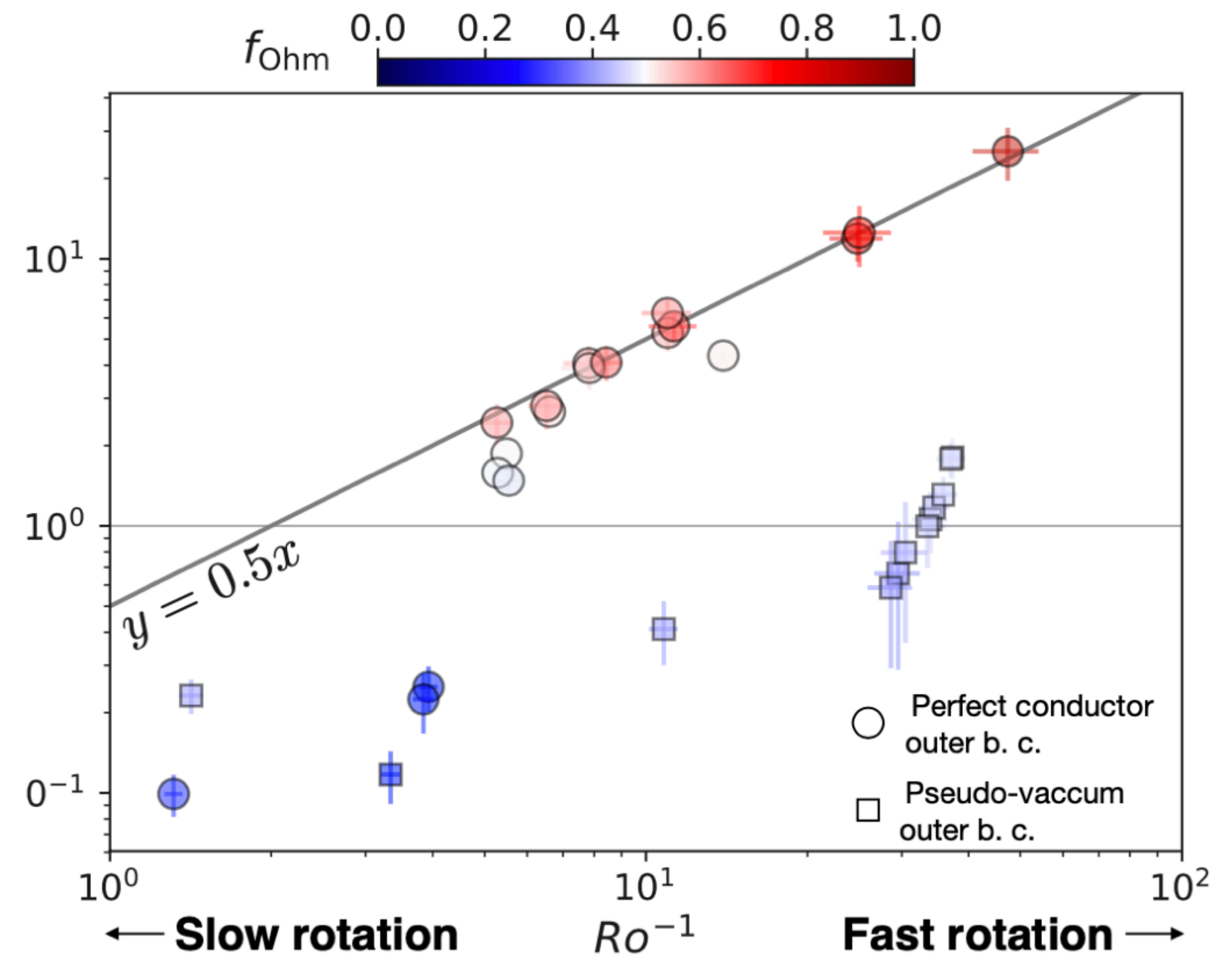
Raynaud+2020

- Strong toroidal field and magnetar like dipole for fast rotation

Magnetar formation through convective dynamo

Convection in the proto-neutron star until 10 s in core collapse supernova



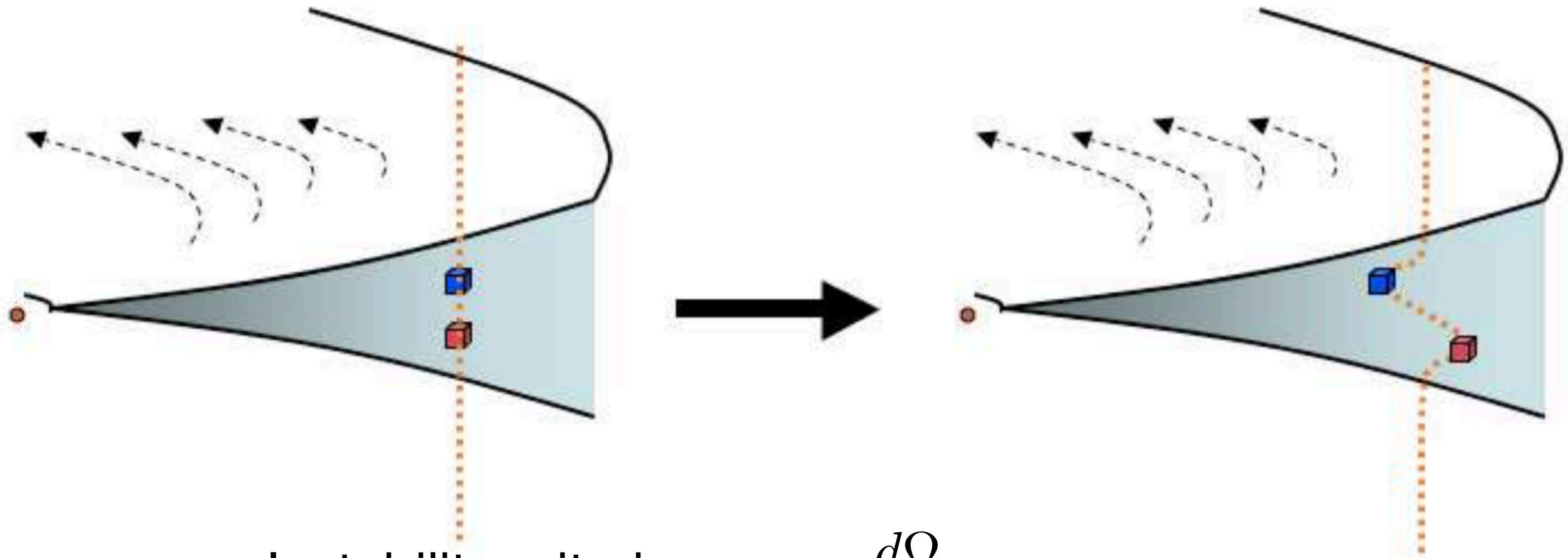


Raynaud+2020

- Strong toroidal field and magnetar like dipole for fast rotation
- Scaling laws from Coriolis and Lorentz force balance

Magneto-rotational instability (MRI)

MRI mechanism in a simple case:



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

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

→ Fast growth for fast rotation

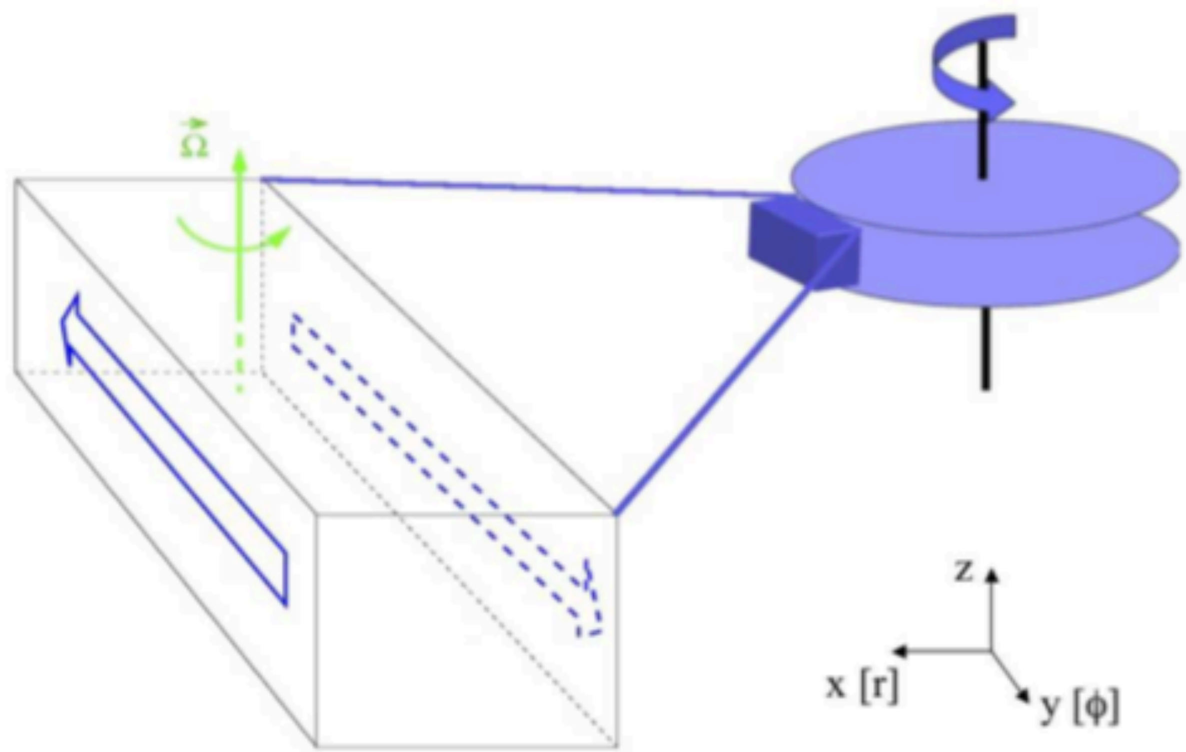
Wavelength: $\lambda_{MRI} \propto \frac{B}{\sqrt{\rho}\Omega}$

→ Short wavelength for weak magnetic fields

See Celora+2025, Jannaud+2025 for derivation in more complex setup

Local models of the MRI

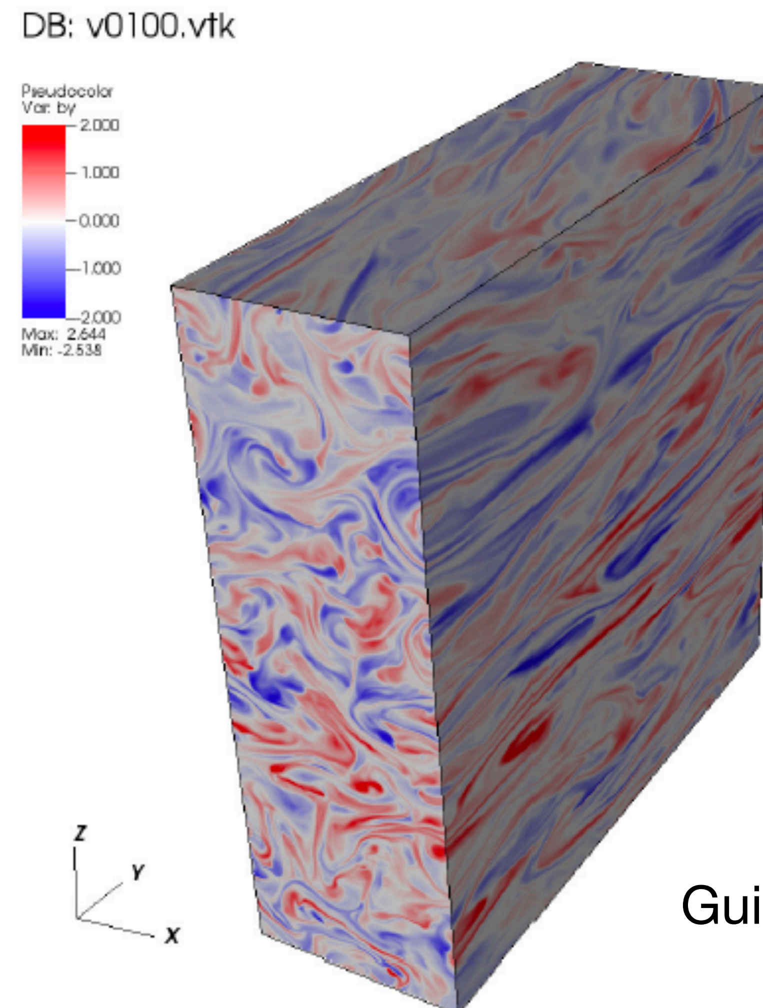
“Shearing box” models



Non-ideal MHD equations

Credit: G. Lesur

Turbulence MHD : toroidal field



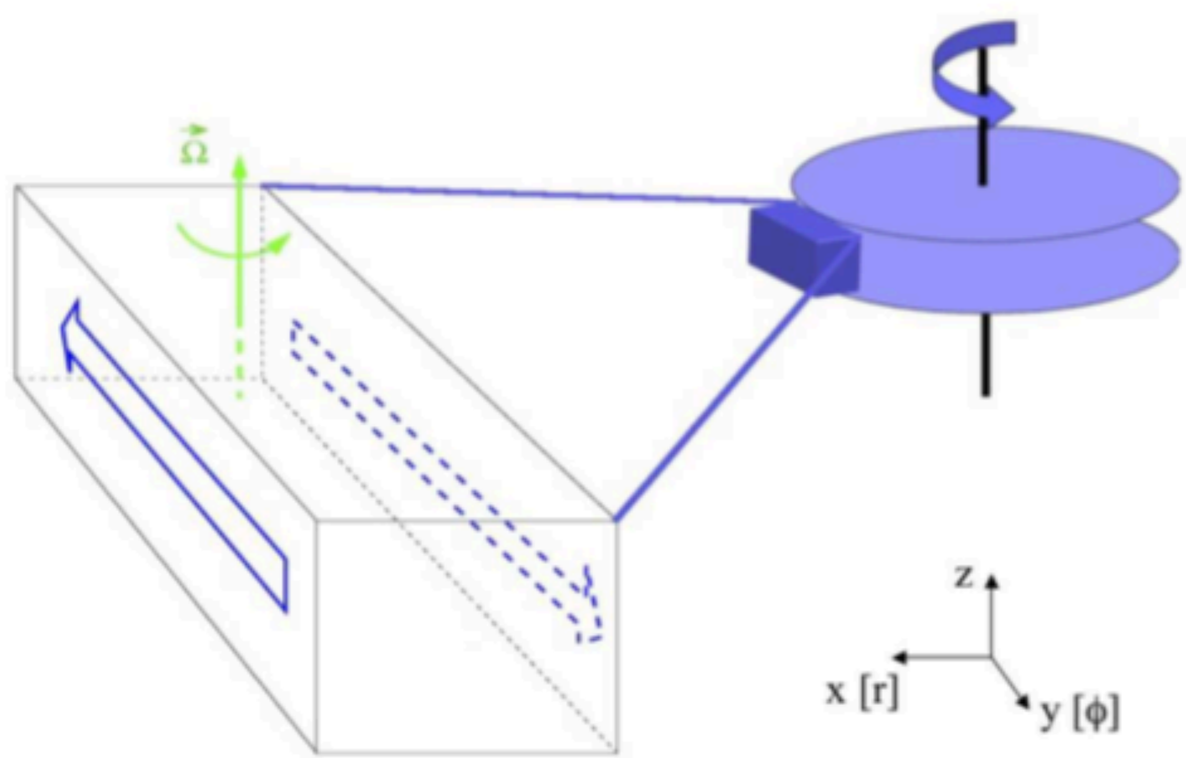
Guilet et al. 2022

Important parameters for the MRI in neutron stars

- Neutrino viscosity: Viscous impact on growth rate (Guilet+2015, 2017)
- Magnetic Prandtl number Pm = viscosity/resistivity (Guilet+2022, Held+2022,+2023)
- Buoyancy: Brunt-Vaisala Frequency N/Ω (Guilet+2015)

Local models of the MRI

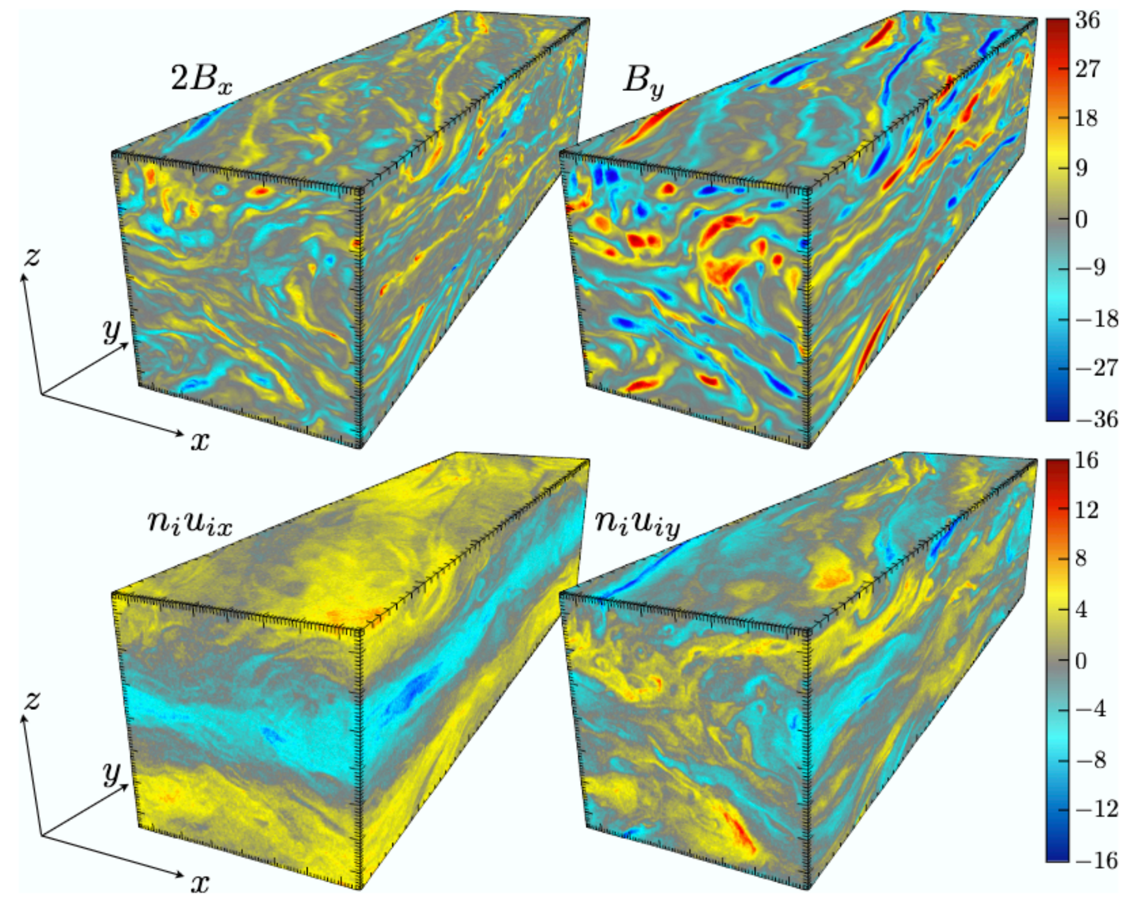
"Shearing box" models



Non-ideal MHD equations

Credit: G. Lesur

Collisionless MRI



Kunz+2016

Important parameters for the MRI in neutron stars

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- Magnetic Prandtl number Pm = viscosity/resistivity (Guilet+2022, Held+2022,+2023)
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Impact of MRI-driven turbulence on large scales

Angular momentum transport

Turbulent contribution to momentum equation

Maxwell tensor $M_{r\phi} = -\frac{B_r B_\phi}{4\pi}$

Reynolds tensor $R_{r\phi} = R_r R_\phi$

angular momentum transport parameter

$$\alpha \equiv \frac{\langle R_{r\phi} + M_{r\phi} \rangle}{\langle P \rangle}$$

(See also Miravet-Tenes+2025)

Model as viscous hydro simulations

$$\nu_{\mathrm{MRI}} = \alpha h_{\mathrm{t}}^2 \Omega q, \quad d\Omega/dr < 0$$

$$t_\nu = \frac{r^2}{\nu_{MRI}} = \frac{r^2}{\alpha H^2 \Omega q}$$

Mean-field dynamo

Mean field equations

$\vec{B} = \overline{\vec{B}} + \vec{b}$ and $\vec{U} = \overline{\vec{U}} + \vec{u}$

Induction equation for mean field

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

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

the electromotive force (EMF)

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

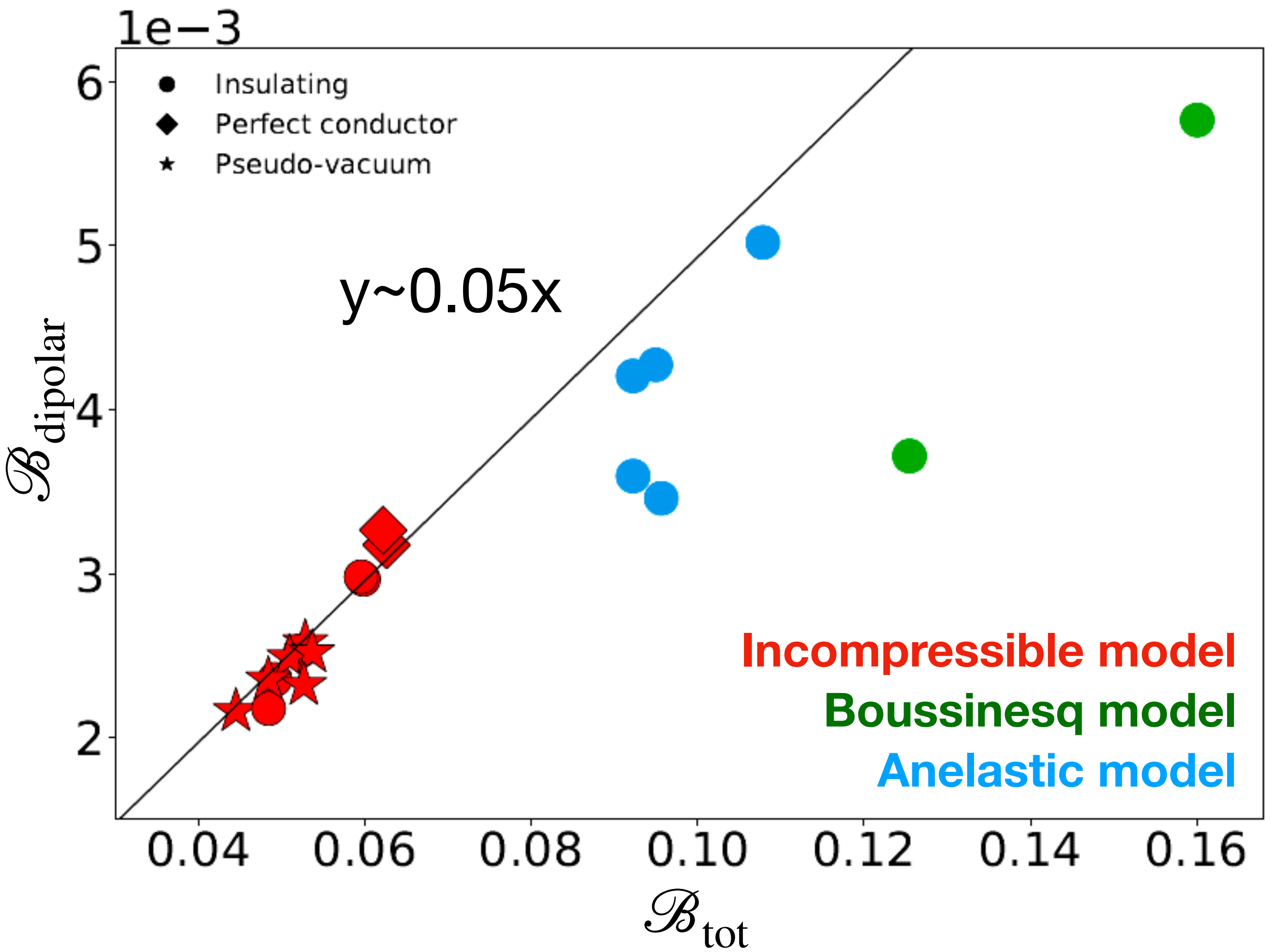
Alpha effect $\mathcal{E}_i = \alpha_{ij} \overline{B}_j$

Resistive effect $\mathcal{E}_i = \beta_{ij} \overline{B}_j$

Gressel+2015, ARS+ 2022, Dhang+2024

Large-scale magnetic generation by the MRI in PNS

Dipole generation in simplified models



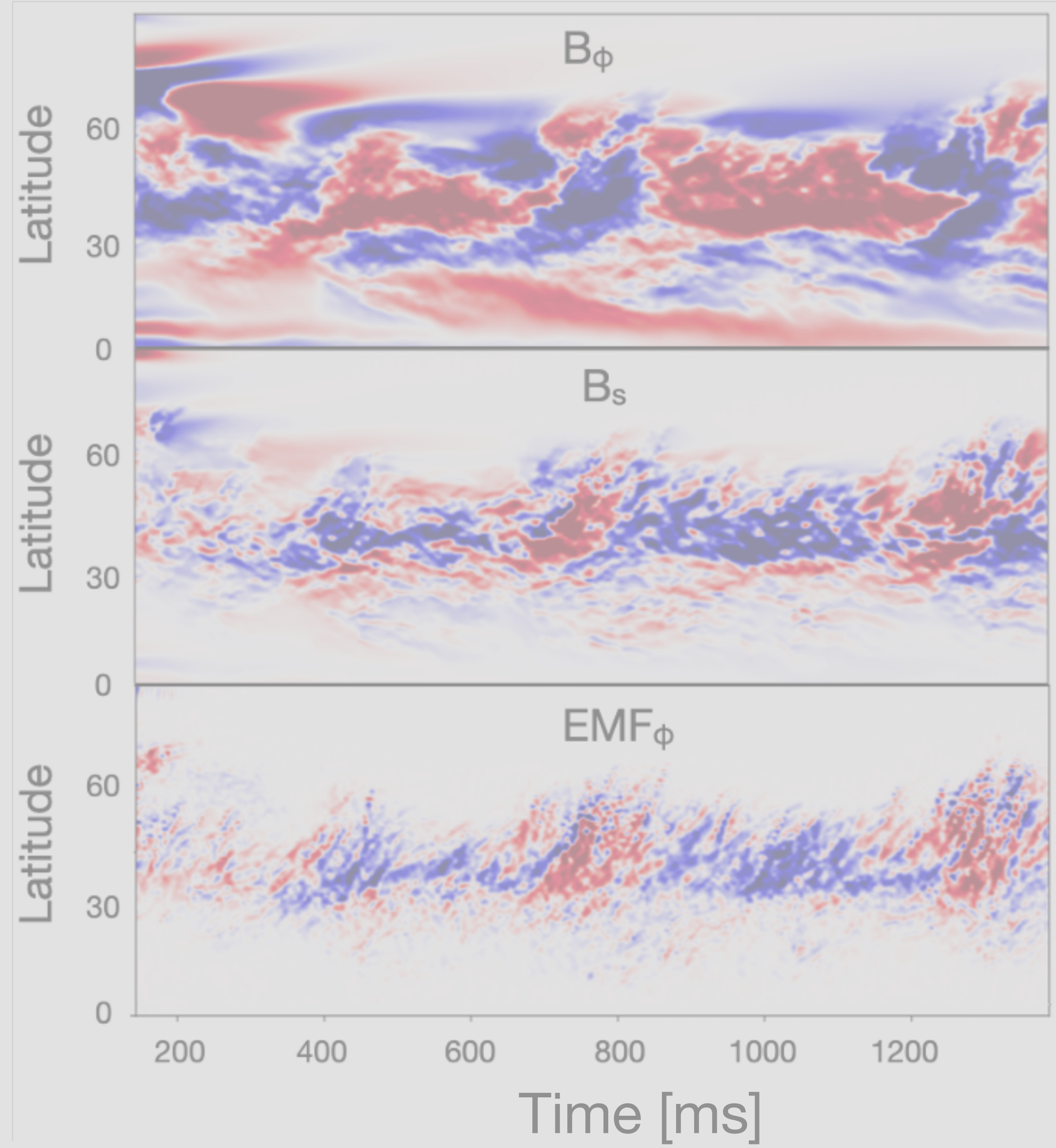
Normalization $\mathscr{B} = \dfrac{B}{\sqrt{\rho_0 \mu_0} D\Omega}$

$B_{dip} \sim 10^{14}$ G for a Neutron Star

But mainly equatorial dipole

Reboul-Salze+2021,2022

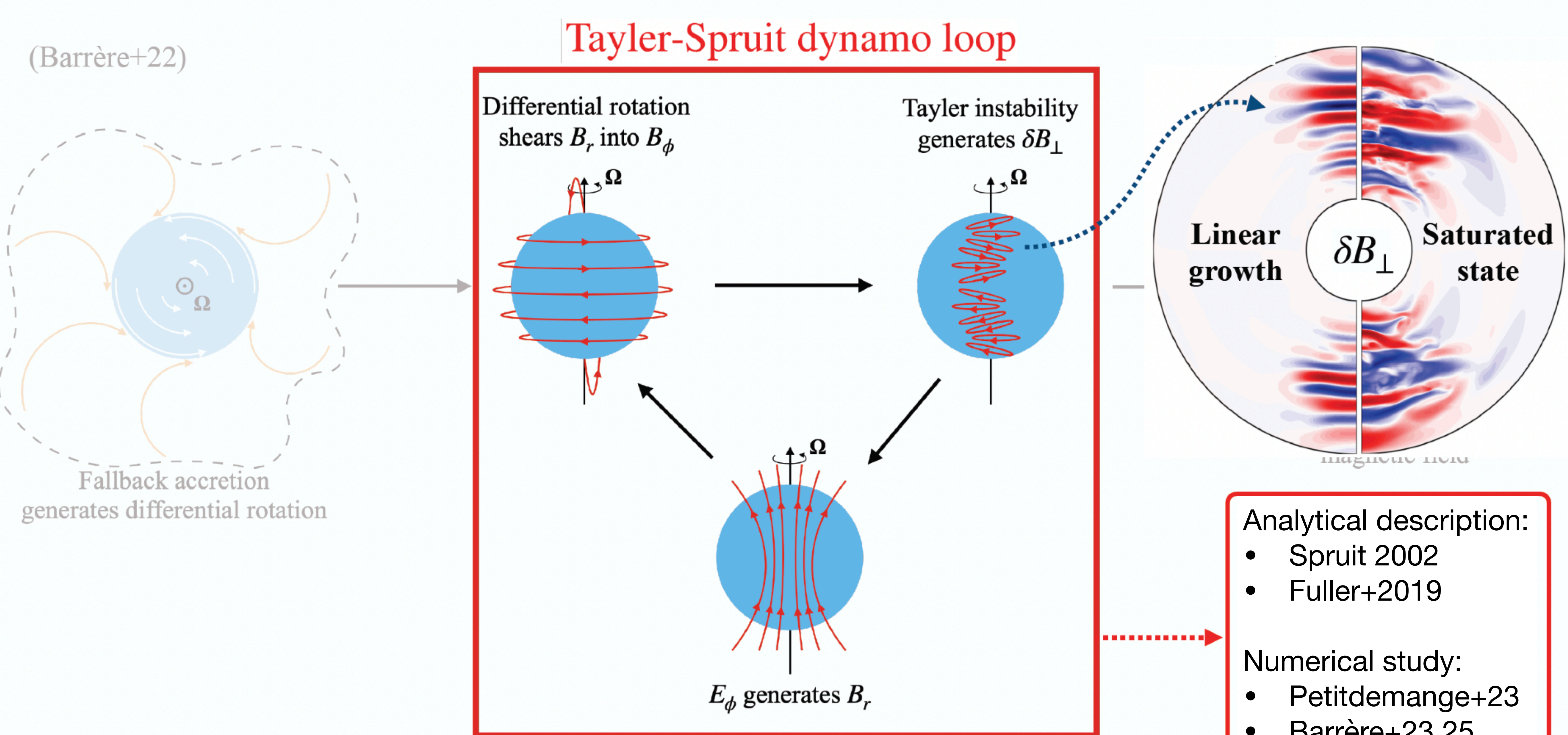
alpha-Omega dynamo in PNS



Reboul-Salze+2022

Tayler-Spruit dynamo

First considered for angular momentum transport in main-sequence stars (Spruit 2002)

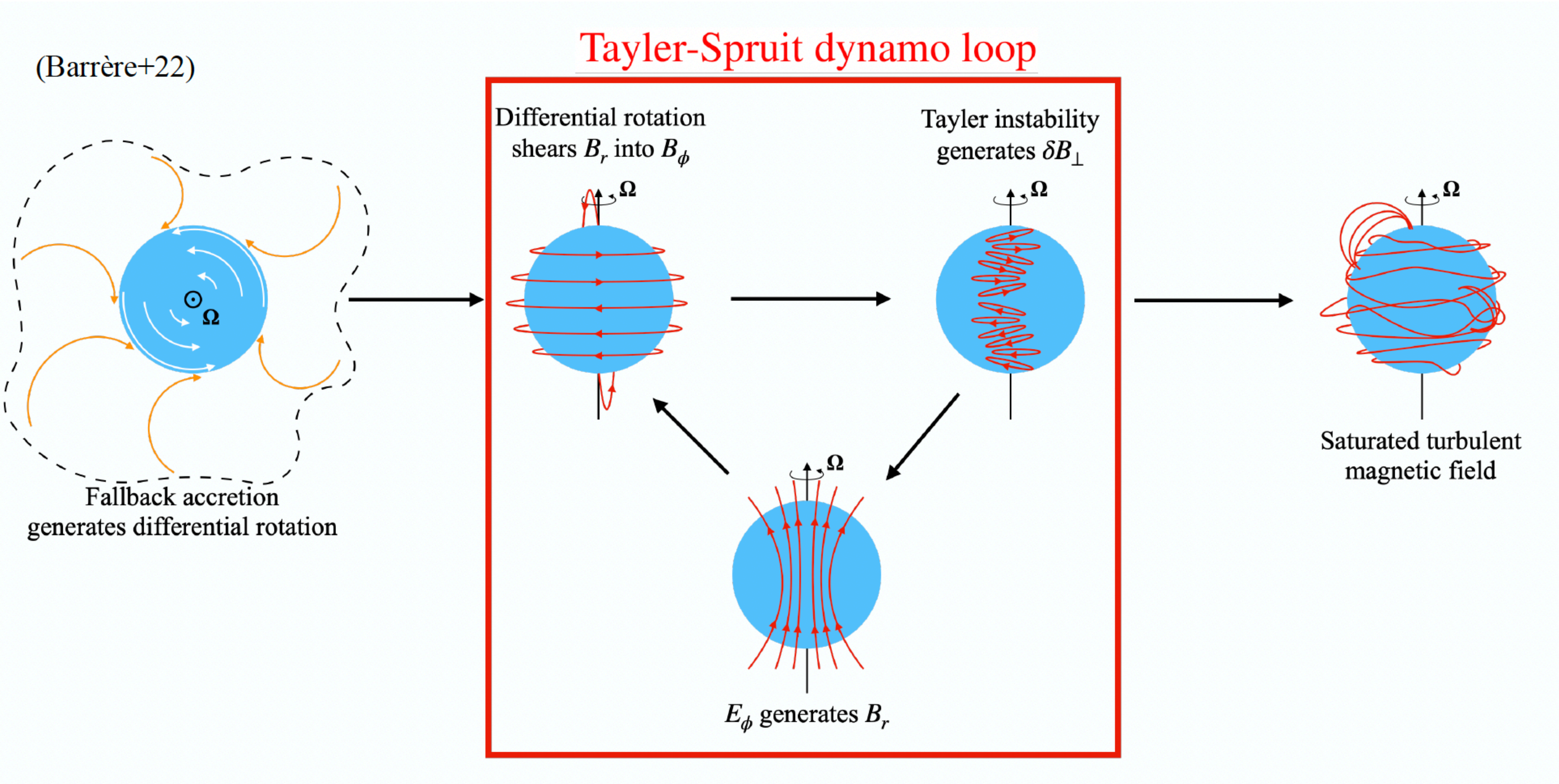


Analytical description:
- Spruit 2002
- Fuller+2019

Numerical study:
- Petitdemange+23
- Barrère+23,25

First numerical studies ~20 years after analytical studies

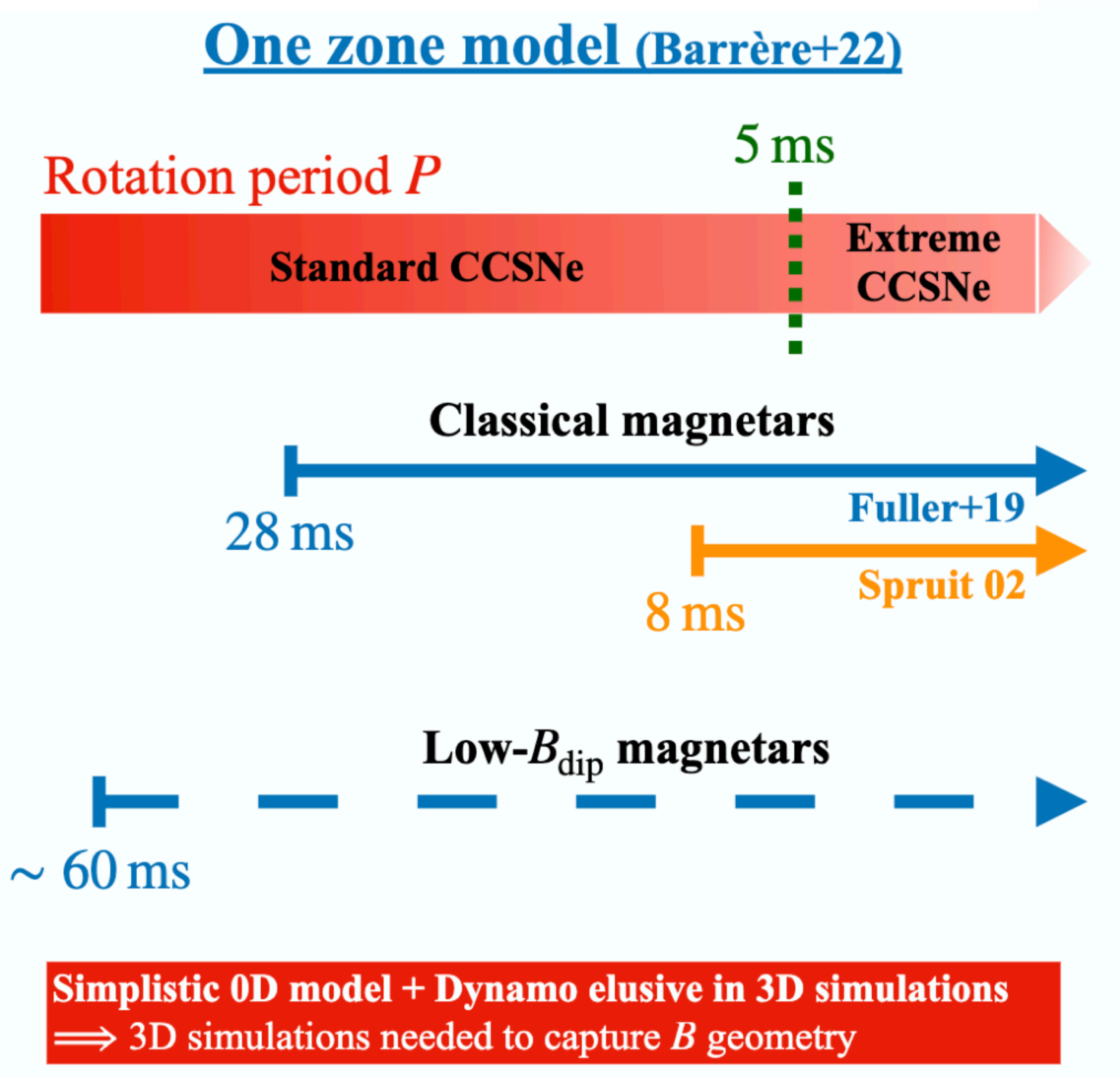
Tayler-Spruit dynamo as a magnetar formation scenario

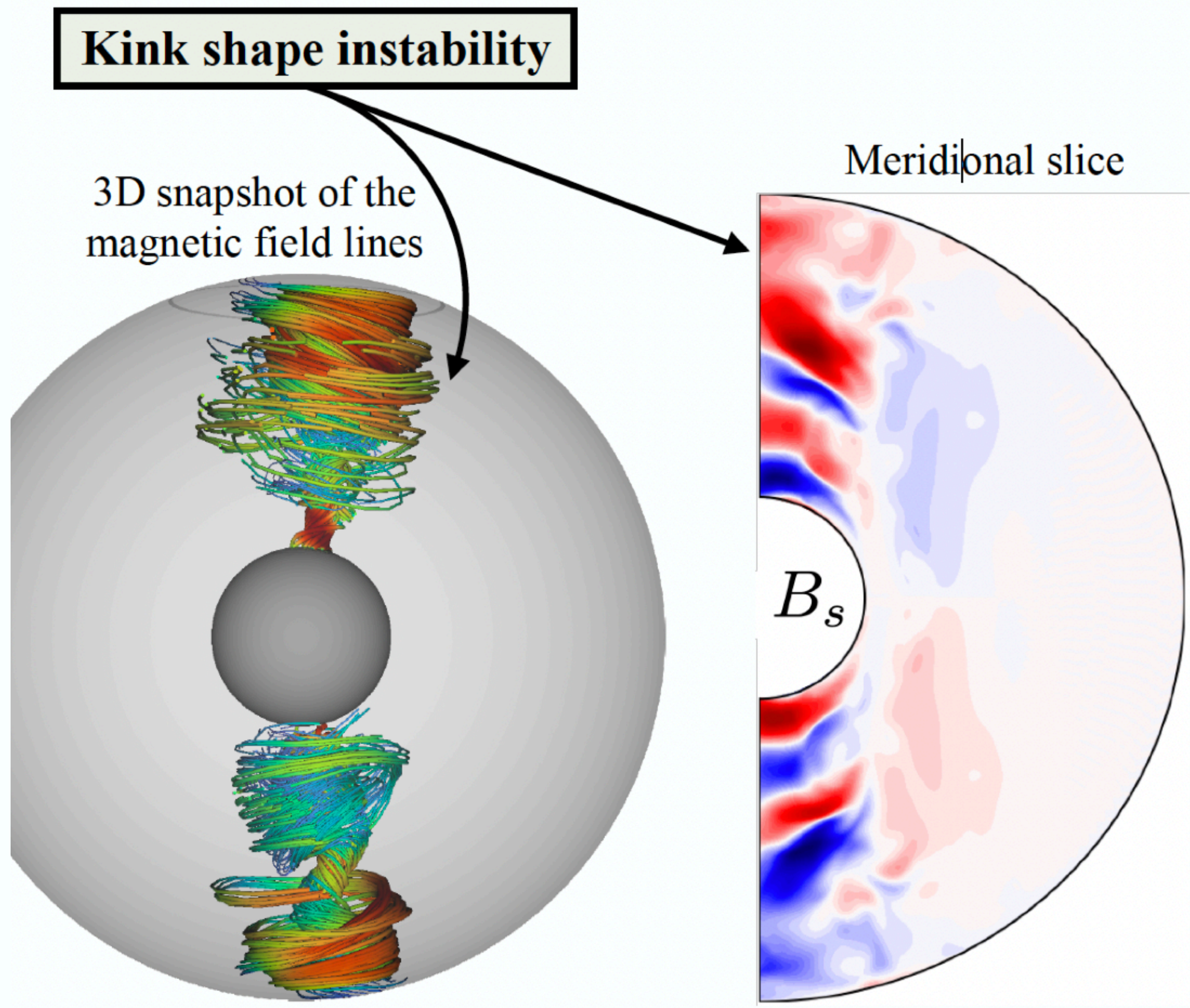


Need 10^{-2}-10^{-1} $M_\odot$ of fallback matter to form magnetars

Tayler-Spruit dynamo in core-collapse supernova

3D MHD simulations



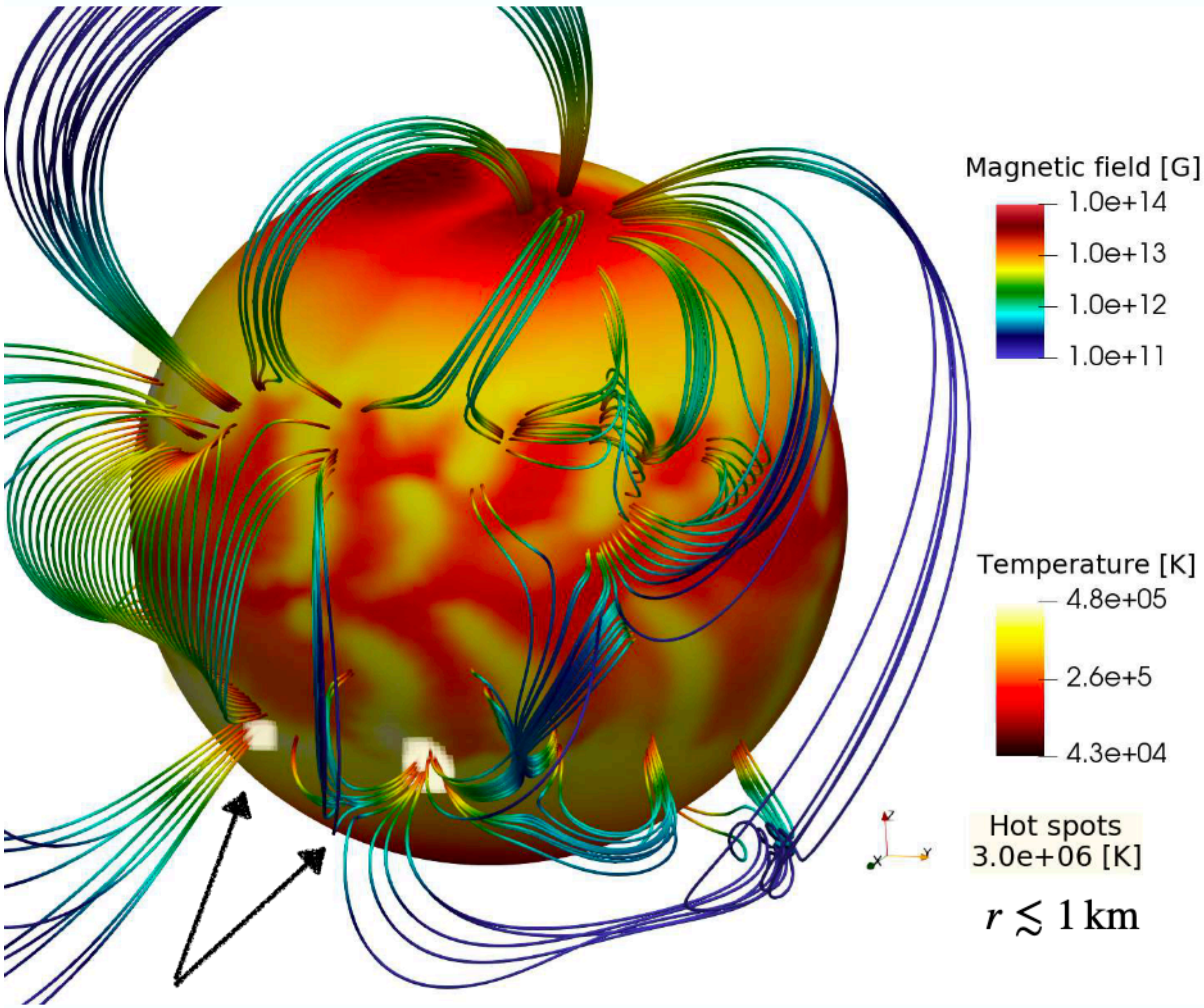


Credit: P. Barrère

Barrère+2023, 2025

Relaxation of the turbulent magnetic field

External magnetic field at 200 kyr



- B field creates large T variations
- Footpoints with $B_r > 10^{13}$ G could produce hot spots heated by magnetospheric currents
  => X-ray light curve modulation

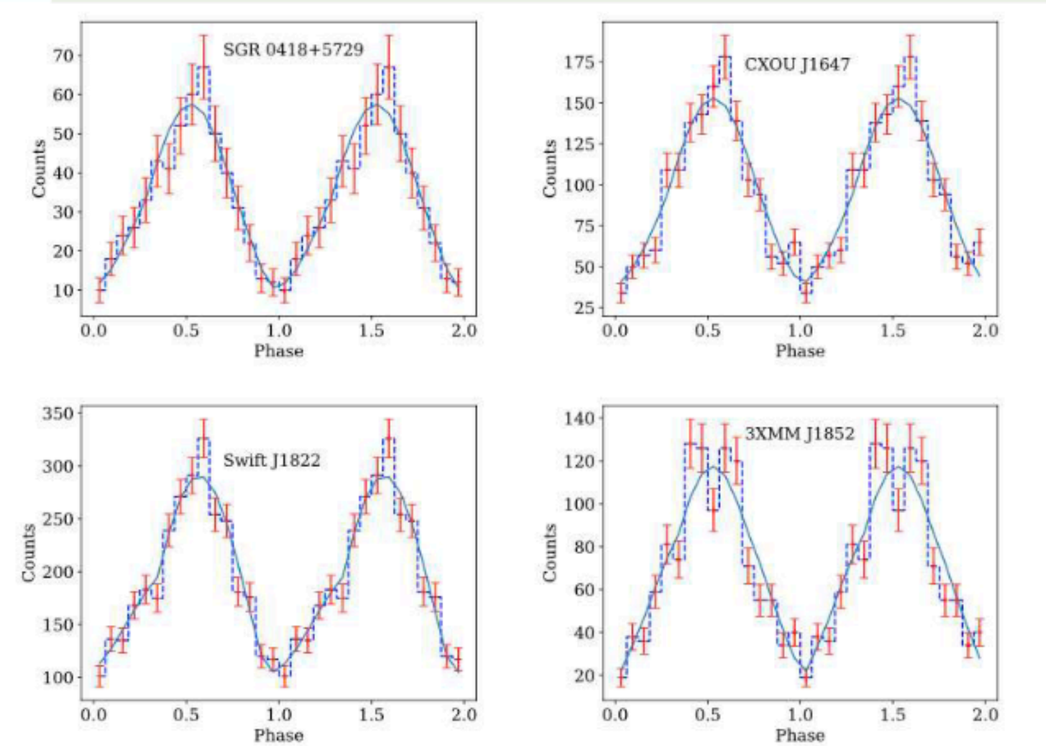


Figure 10: Observed soft X-ray lightcurves in the range of 0.3-2 keV for low-field magnetars i the quiescent state and the best fits (solid blue line). It is assumed that emission is produced b hot spots formed at the places with radial magnetic field exceeding 7×10^{13} G.

Igoshev, Barrere+2024

Outline

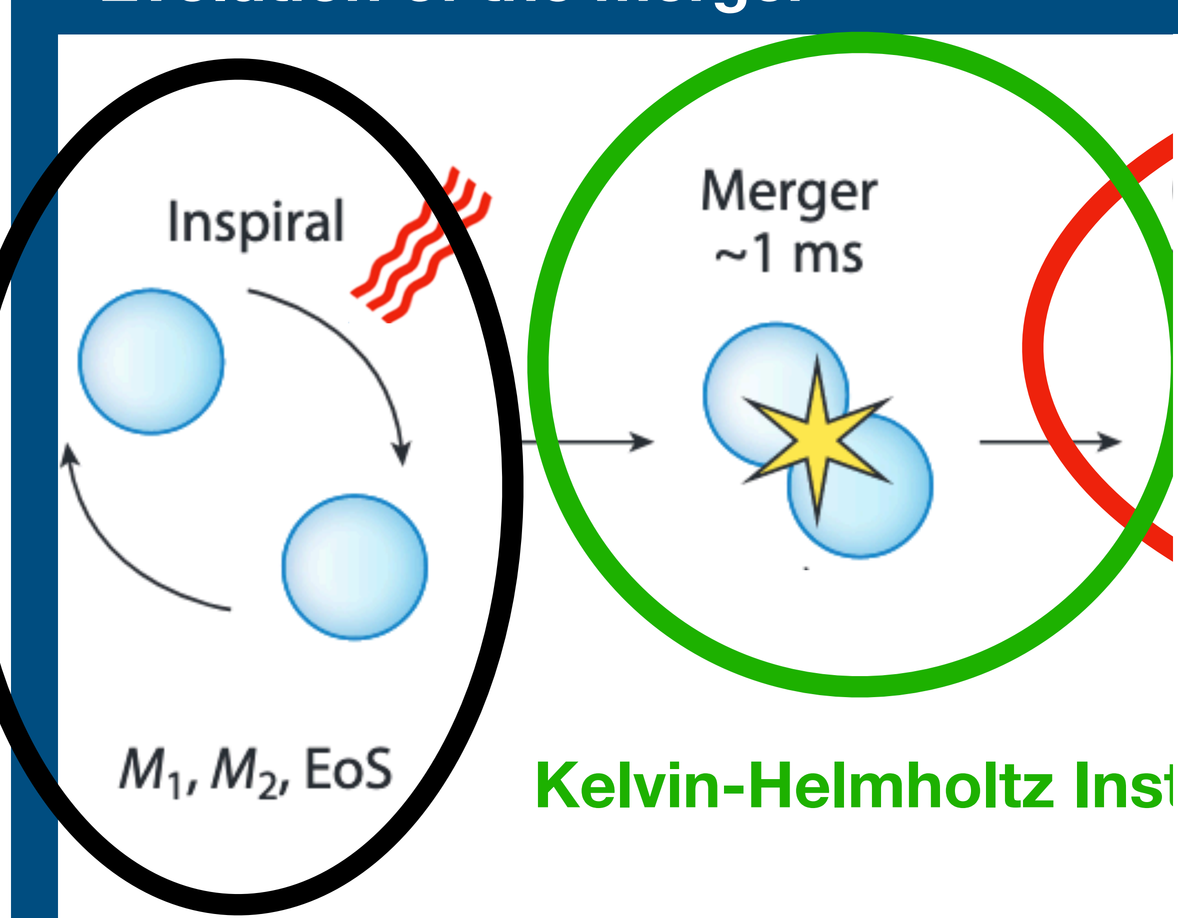
Introduction

I-Dynamos in proto-neutron stars

II- Dynamos in binary neutron star mergers

Amplification mechanisms in neutron star mergers

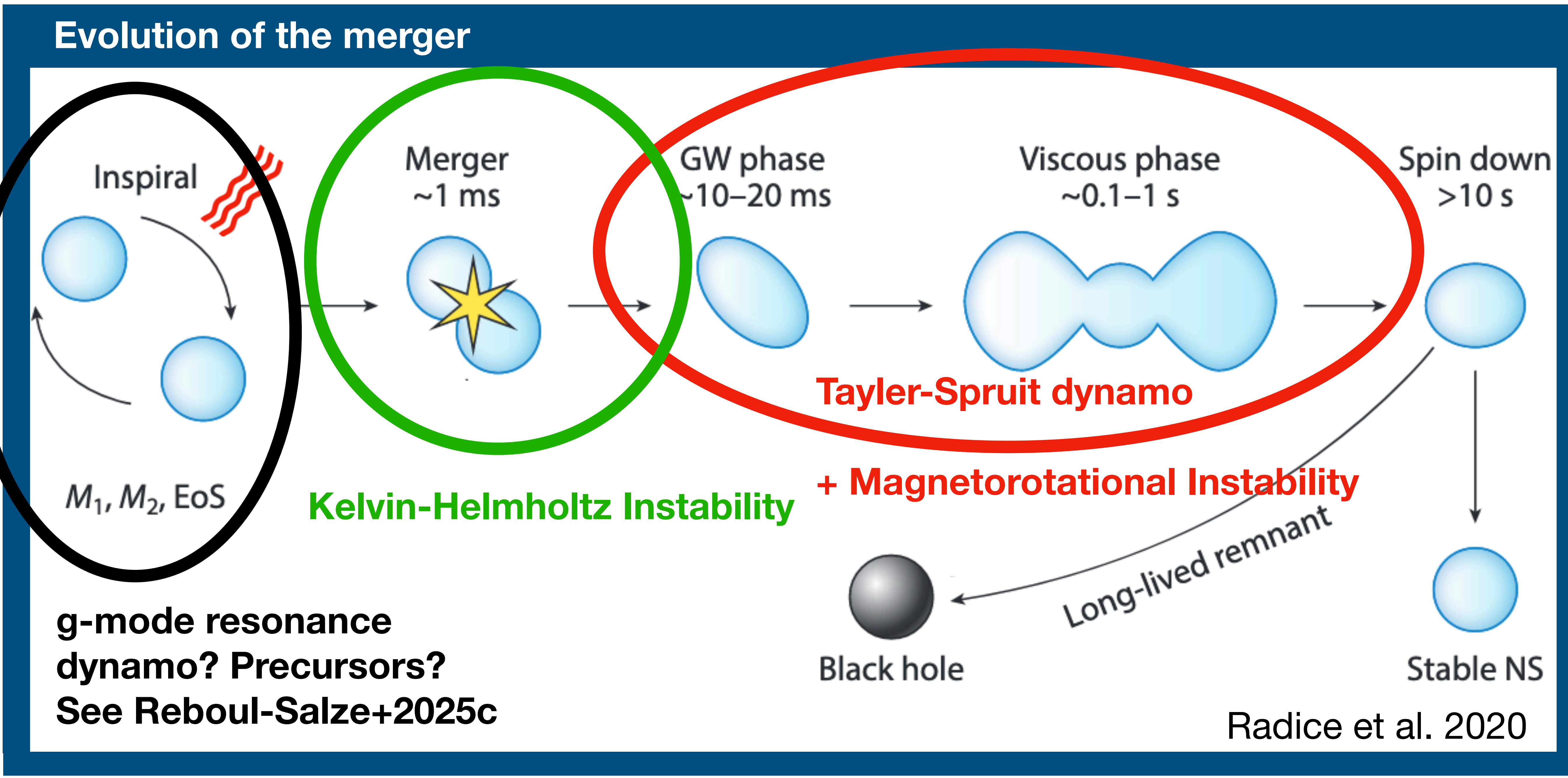
Evolution of the merger



g-mode resonance
dynamo? Precursors?
See Reboul-Salze+2025c

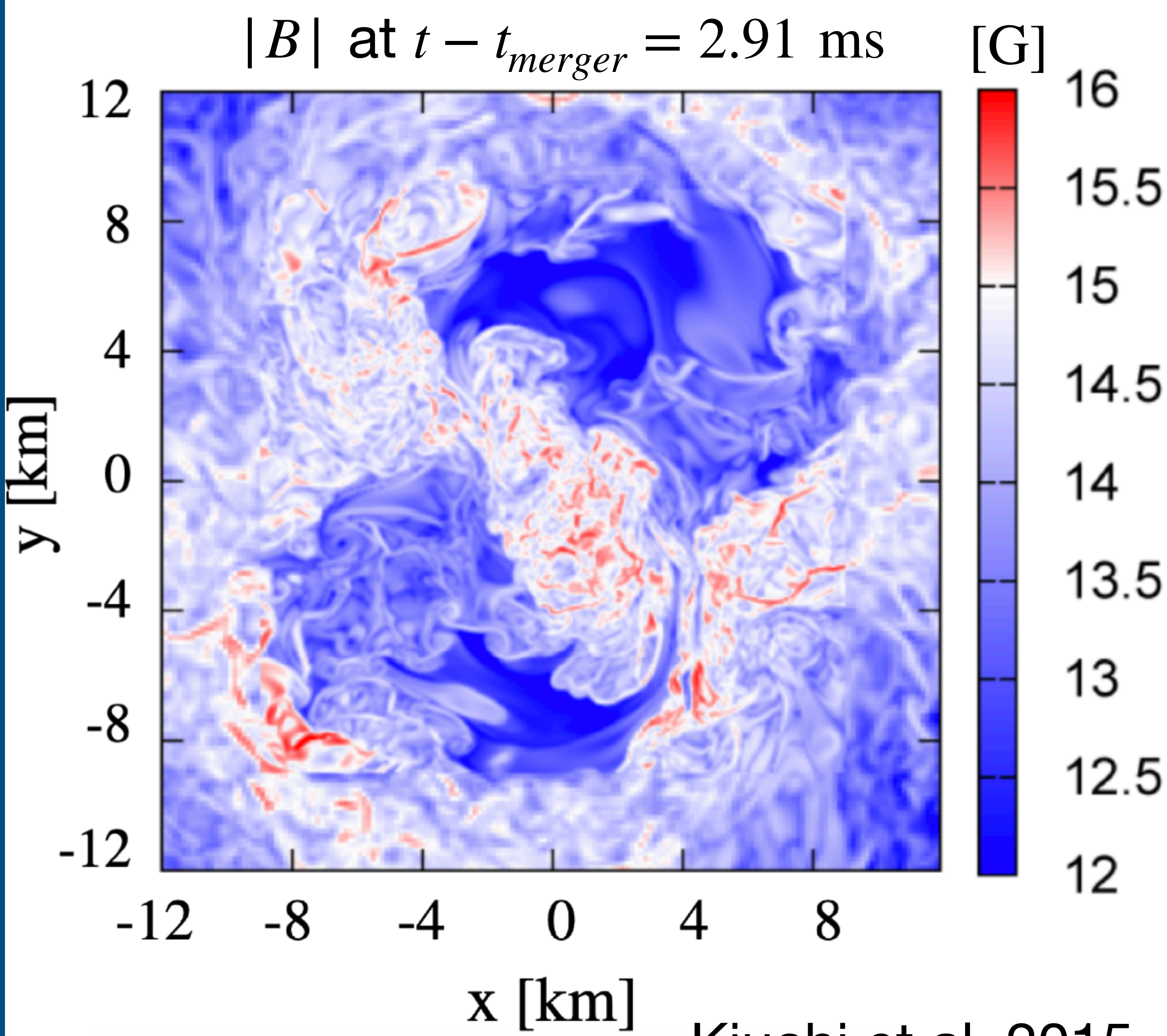
Radice et al. 2020

Amplification mechanisms in neutron star mergers



Amplification by the Kelvin-Helmholtz instability

Kelvin-Helmholtz in NS mergers



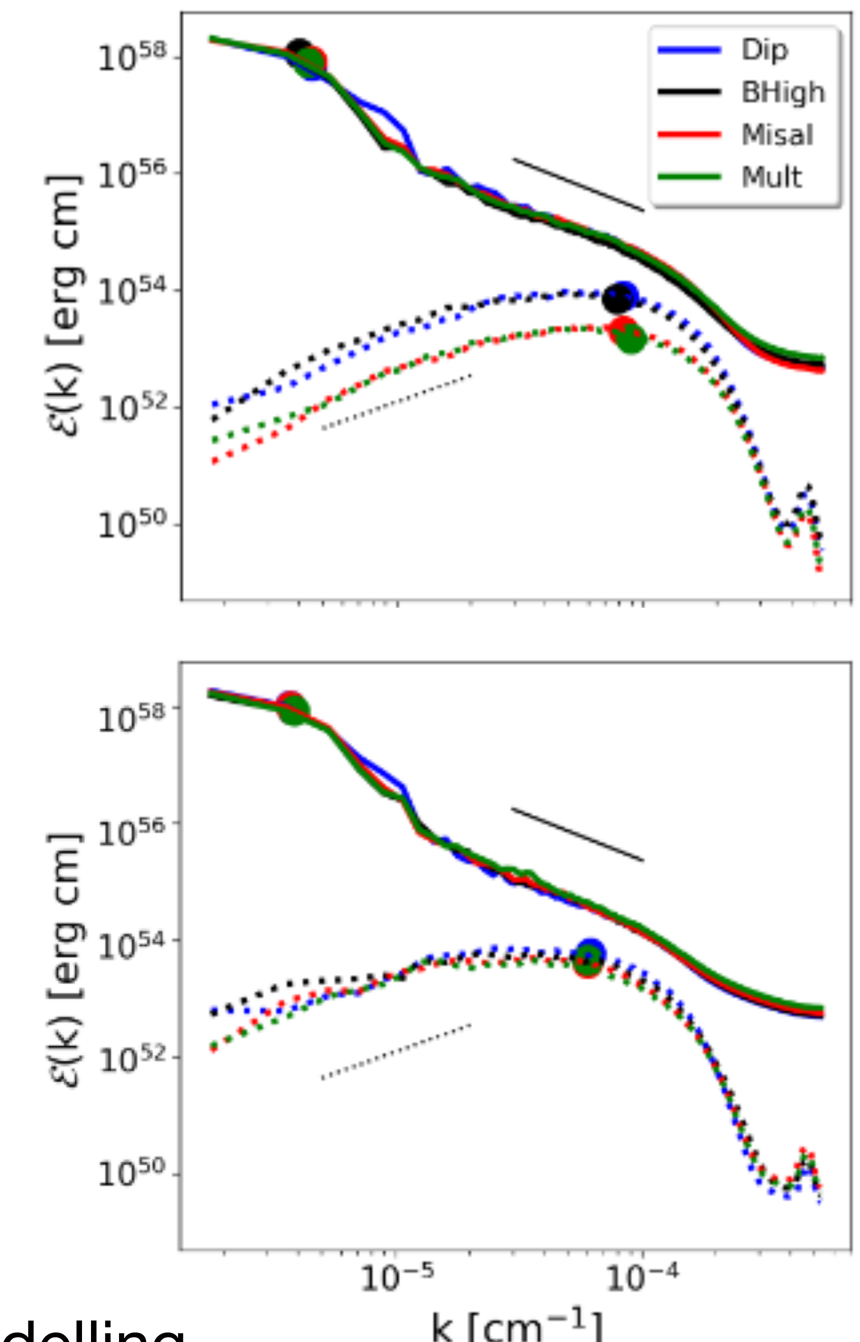
Kiuchi et al. 2015

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

A universal magnetic spectra?

t=5 ms

t=10 ms



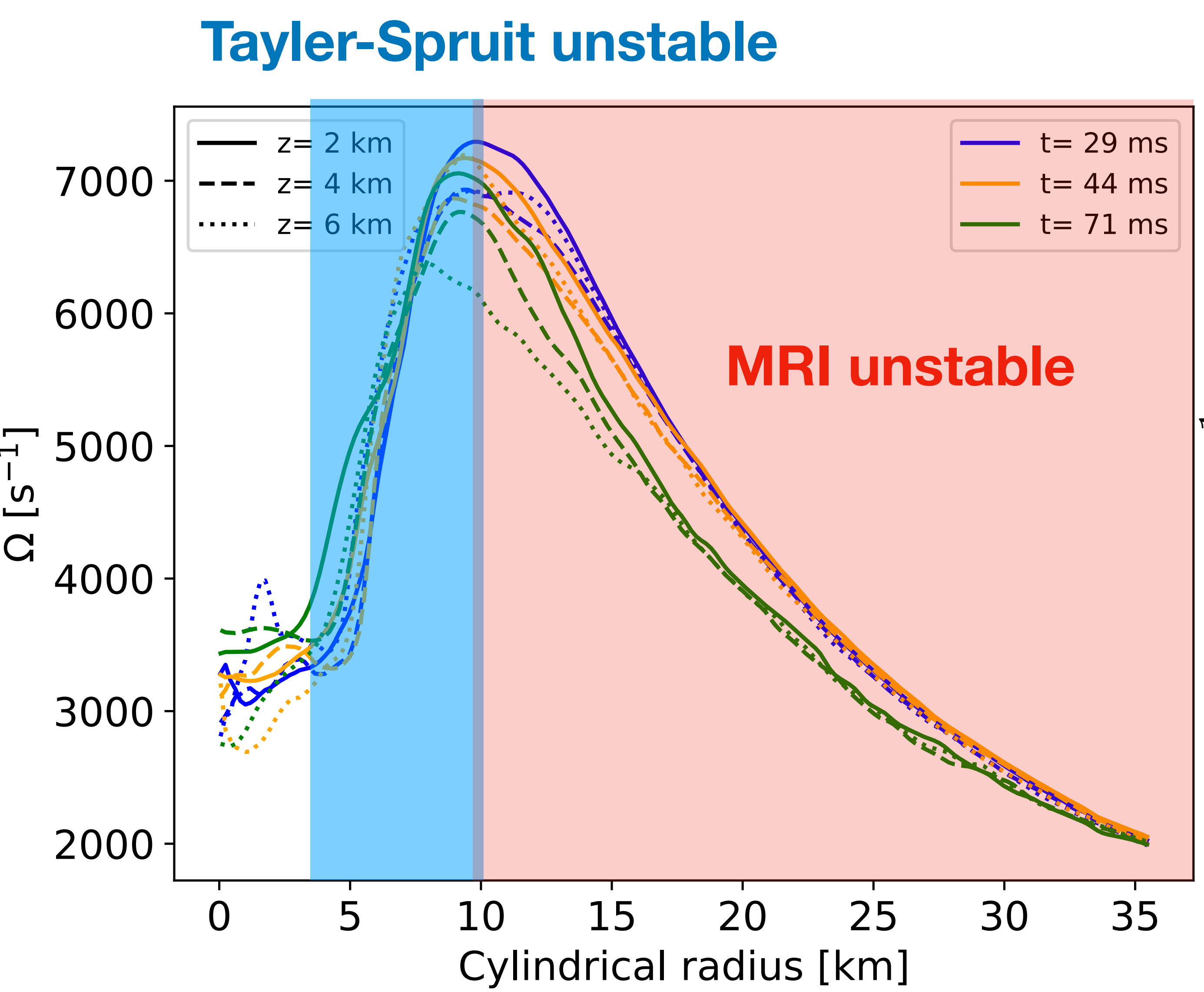
Subgrid modelling

Aguilera-Miret+2022

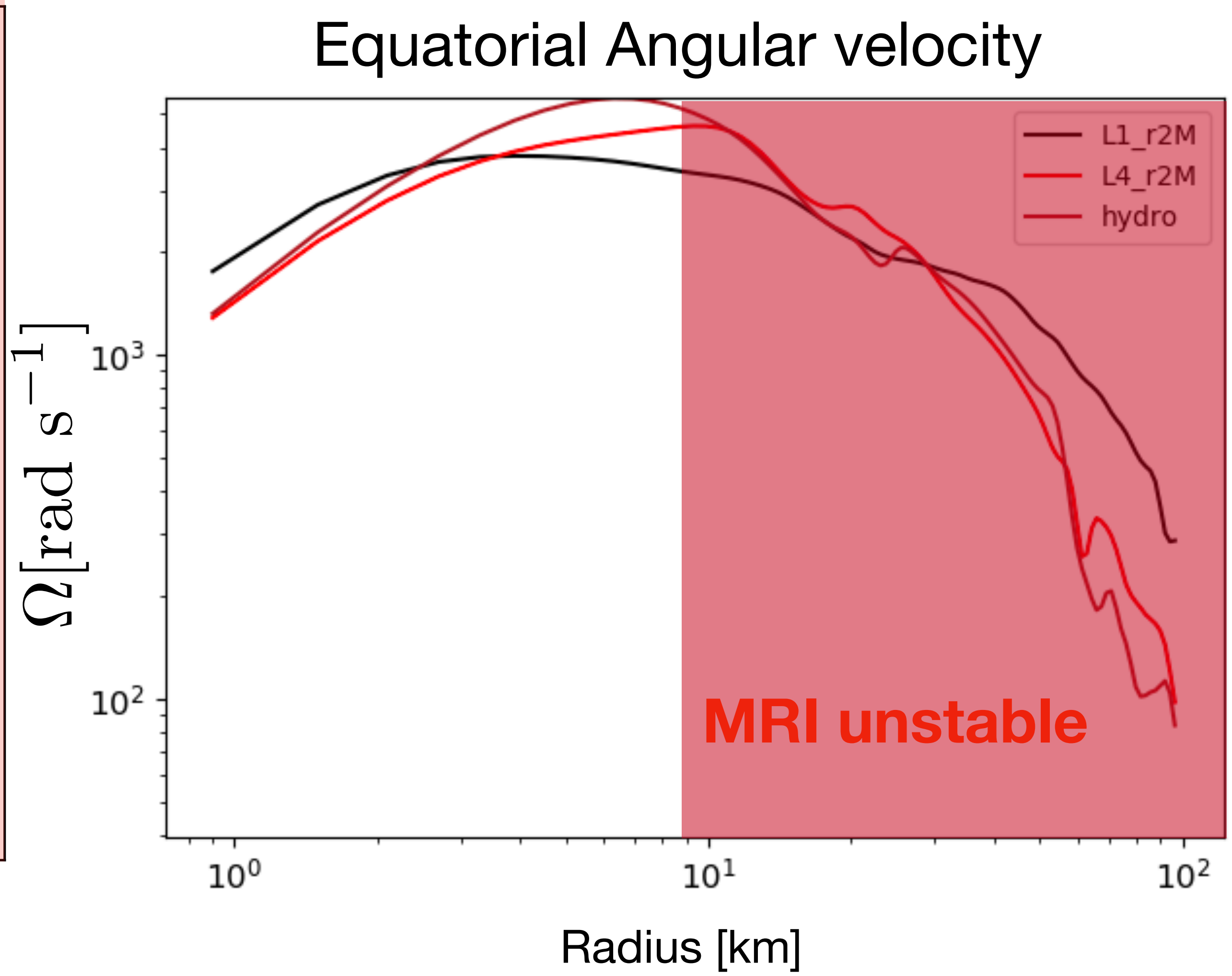
Initial rotation profile

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

Post-Newtonian CCSN simulation with
a 30 $M_\odot$ fast rotating progenitor



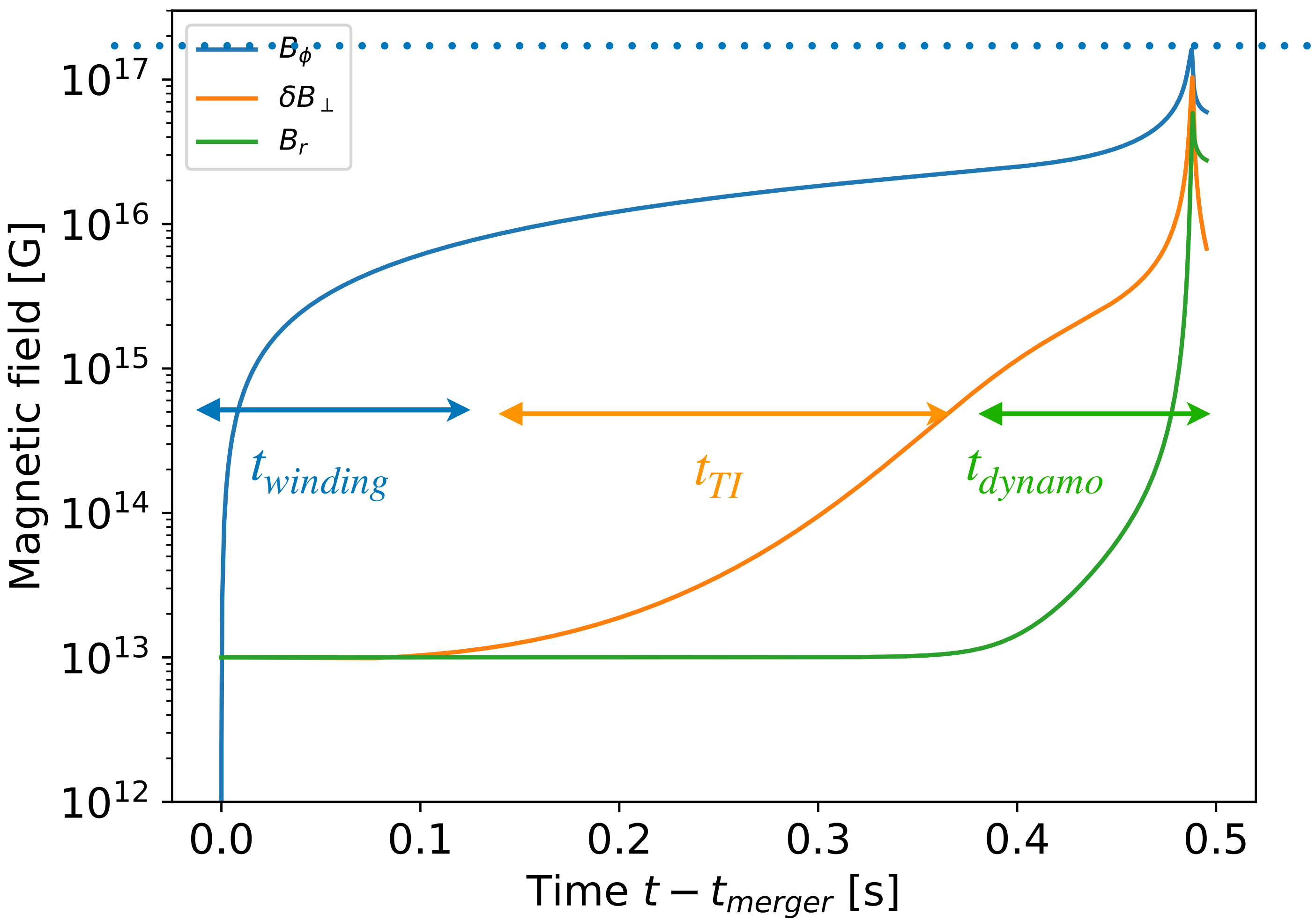
TS dynamo: **Reboul-Salze** et al. 2025a



Bugli et al 2021

Tayler-Spruit dynamo in binary neutron stars

Magnetic field evolution



Dynamo stops when there is no more rotation

⟶ could lead to faster collapse to a BH

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

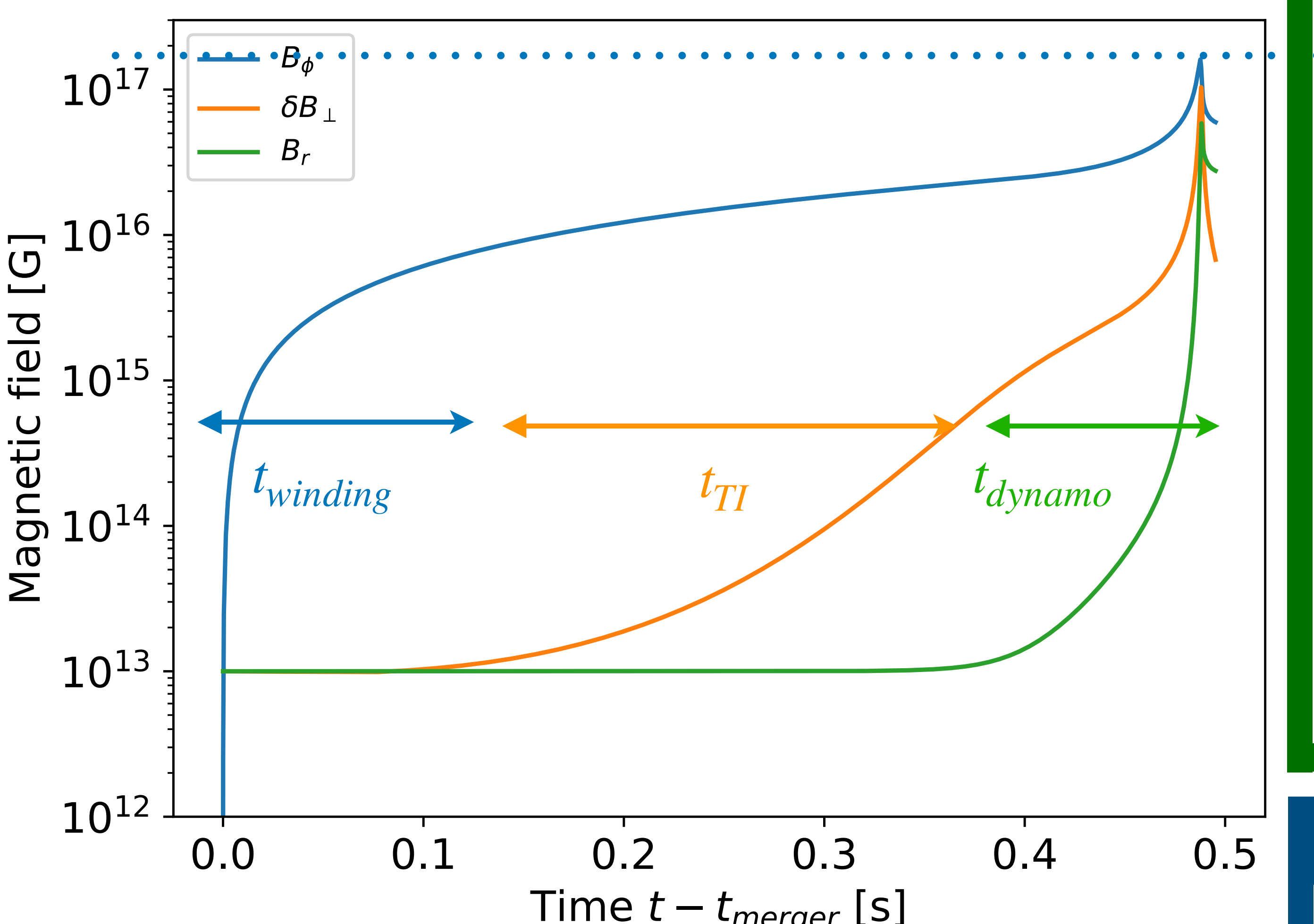
$$B_{R,sat} = 6.0 \times 10^{16} \mathrm{G}$$

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

ARS et al, 2025a

One-zone model for HMNS

Magnetic field evolution



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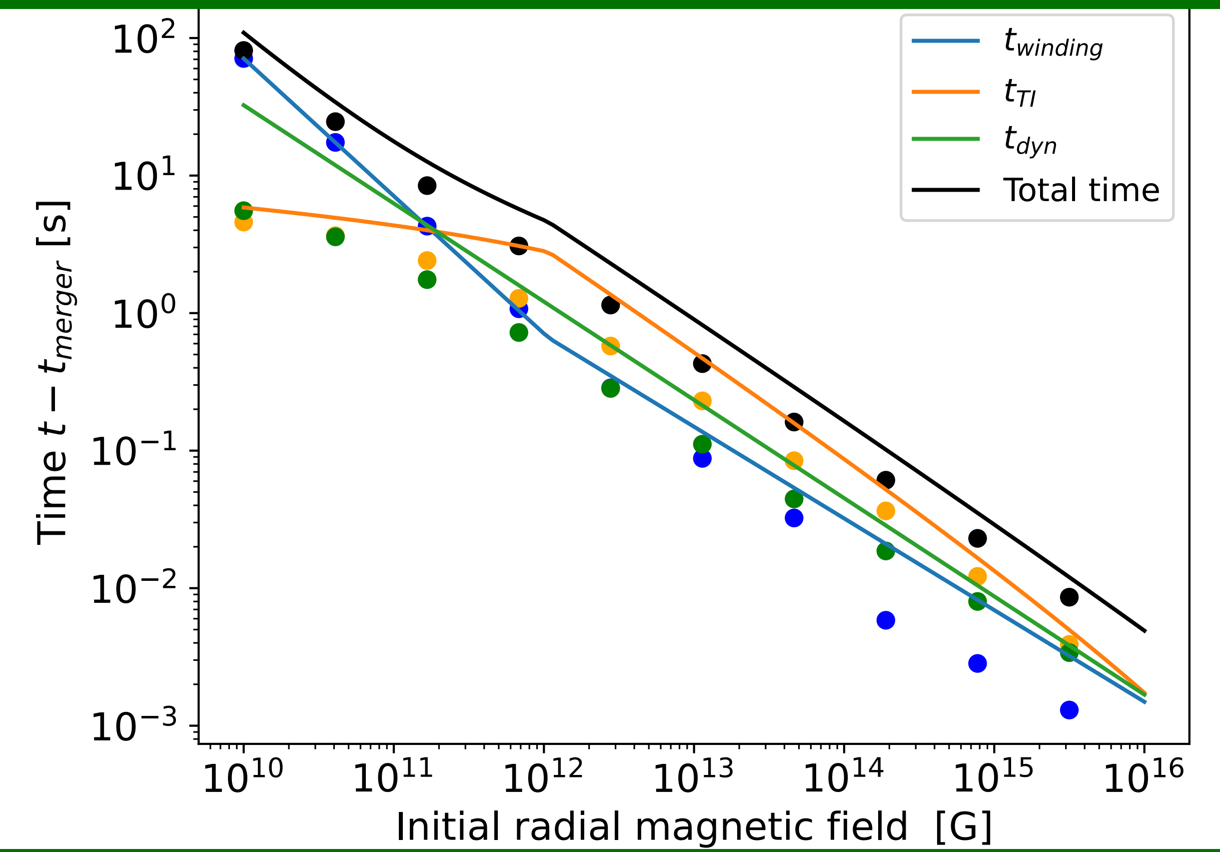
ARS et al, 2025a

Initial Magnetic field dependence



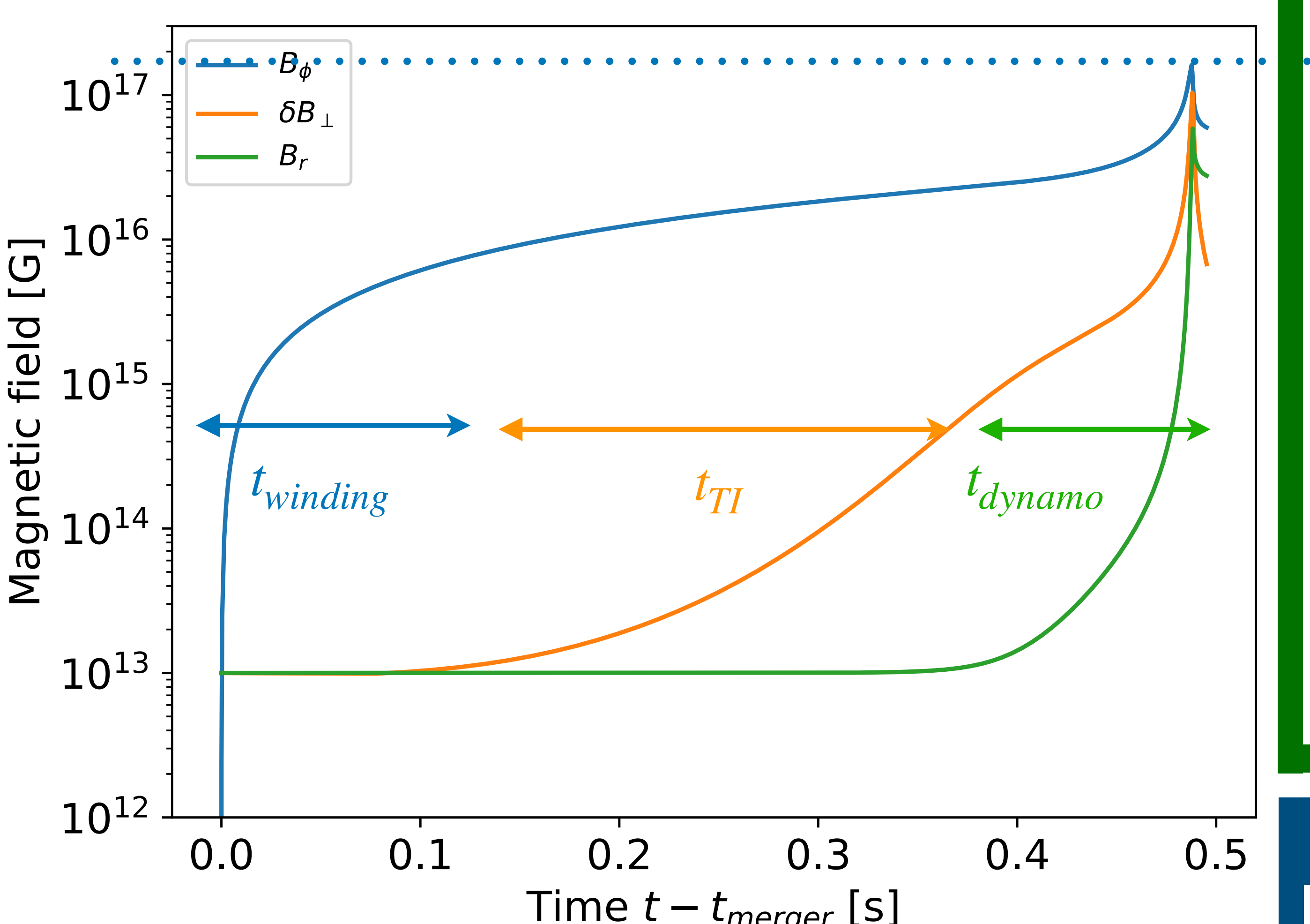
Caveats

Comparison to Barrere's simulations $B^{m=0}_{\rm tor} \approx 10^{16}$ G $B^{m=0}_{\rm pol} \approx 10^{15}$ G
(Barrere et al. 2023 and 2025)

⟶ Need to explore simulations for HMNS

One-zone model for HMNS

Magnetic field evolution



Dynamo stops when there is no more rotation

→ could lead to faster collapse to a BH

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

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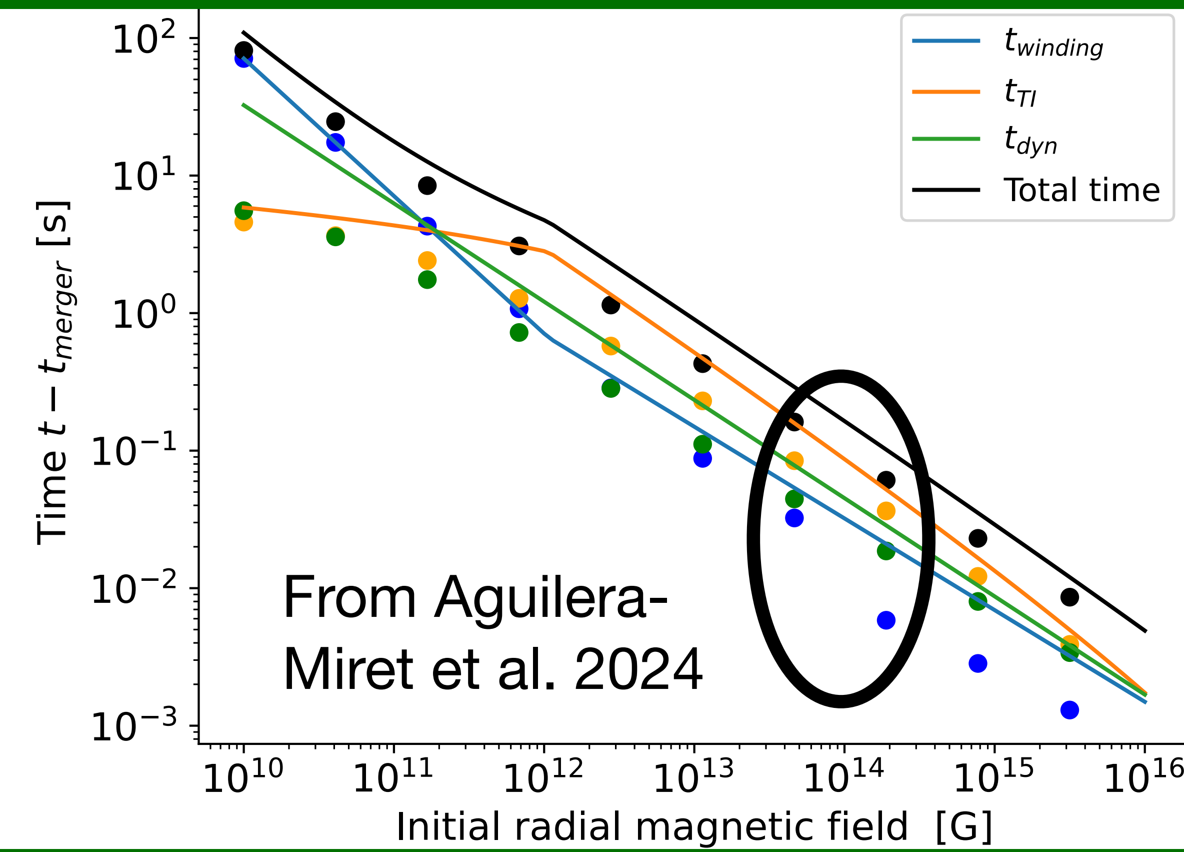
ARS et al, 2025a

Initial Magnetic field dependence



Caveats

Comparison to Barrere's simulations $B_{\mathrm{tor}}^{m=0} \approx 10^{16}$ G, $B_{\mathrm{pol}}^{m=0} \approx 10^{15}$ G

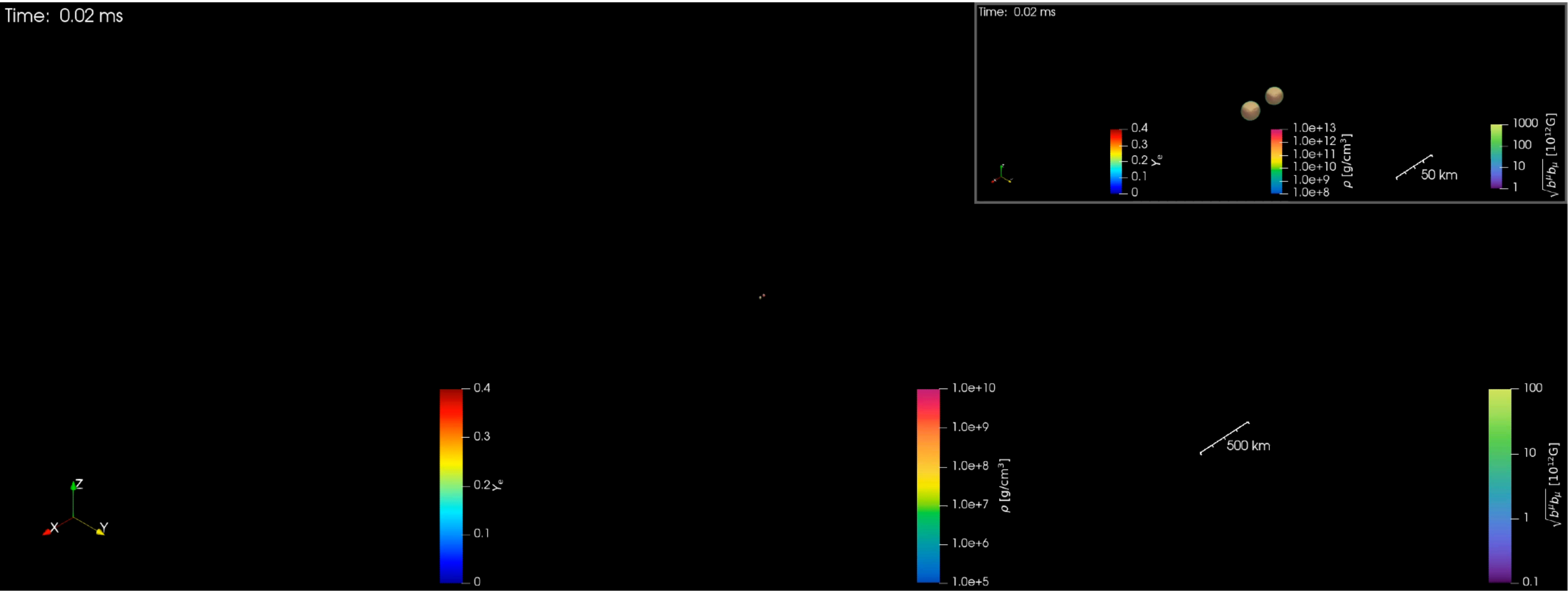
(Barrere et al. 2023 and 2025)

→ Need to explore simulations for HMNS

GRMHD BNS merger simulation: long-lived remnant

DD2 equation of state, 1.35-1.35 $M_\odot$ binary, finest resolution $\Delta x = 12.5$ m, $B_0 = 3 \times 10^{15}$ G

Fixed mesh refinement with 16 levels, with equatorial symmetry, **~60 M CPU hours**

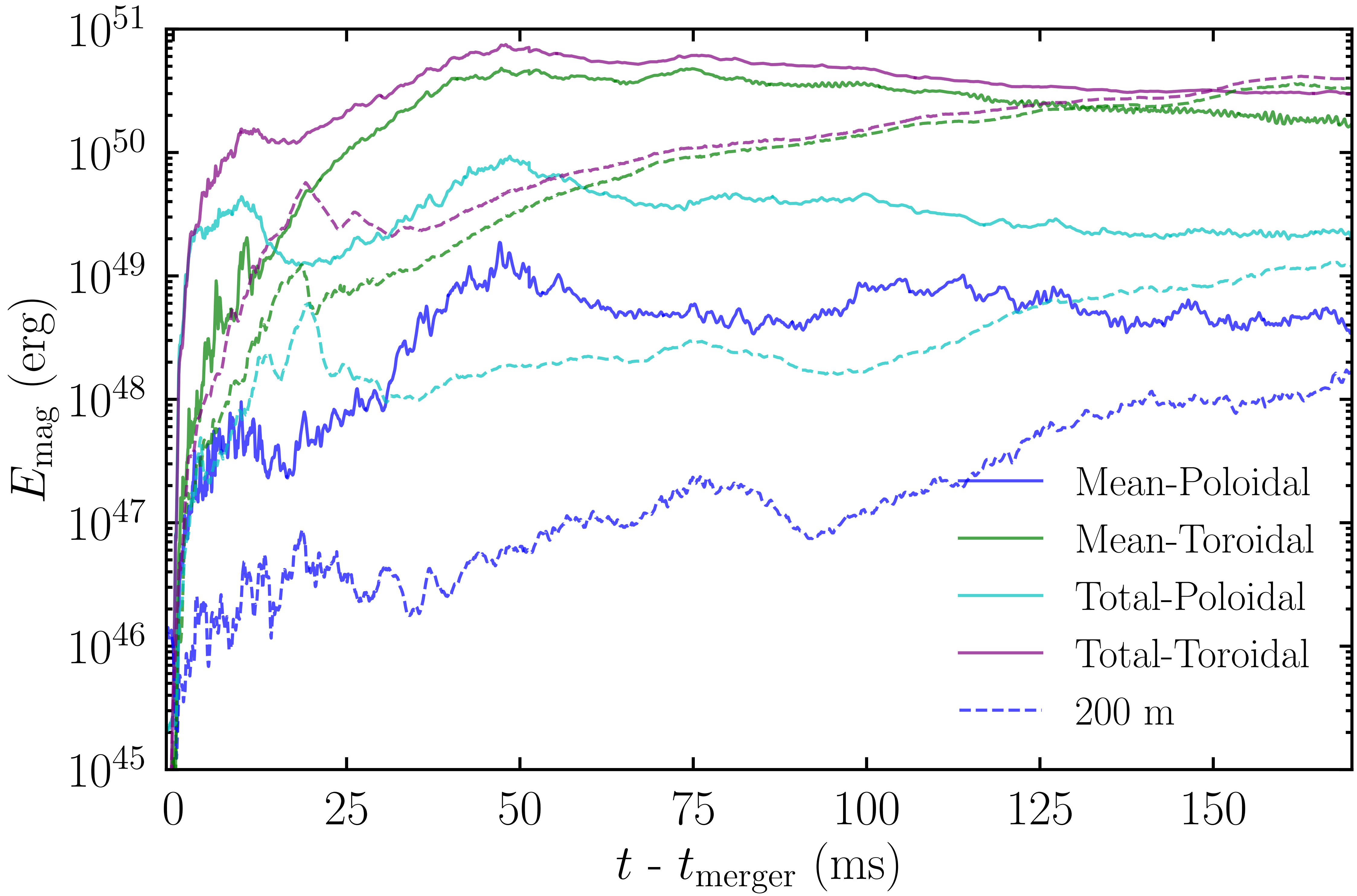


Jet launched at $t - t_{merger} \approx 50$ ms

Kiuchi, **Reboul-Salze** et al. 2024

Time evolution of the MRI-unstable zone

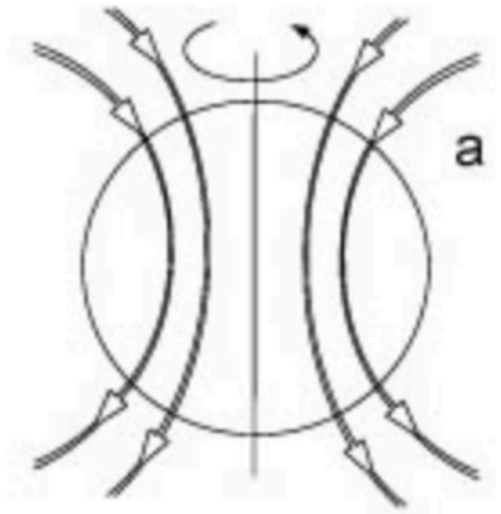
Energy evolution when $\rho < 10^{14.5}$ g cm^{-3}

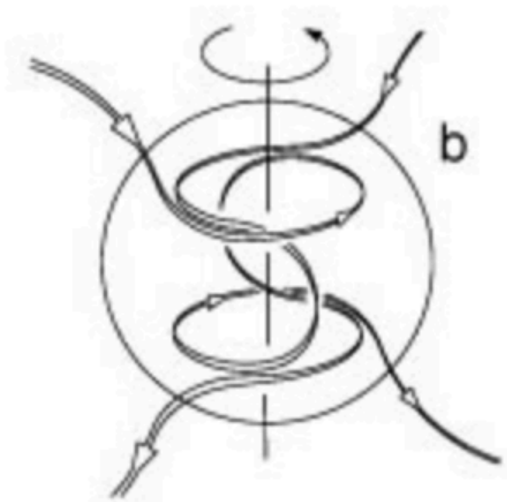


MRI-driven alpha-Omega dynamo in ideal GRMHD simulations

$$\frac{\partial \overline{\vec{B}}}{\partial t} = \vec{\nabla} \times \left(\overline{\vec{U}} \times \overline{\vec{B}} + \vec{\mathcal{E}} - \eta \vec{\nabla} \times \overline{\vec{B}} \right)$$ where $$\vec{\mathcal{E}} = \overline{\vec{u} \times \vec{b}}$$ $$\mathcal{E}_i = \alpha_{ij} \overline{B}_j + \beta_{ij} \left(\vec{\nabla} \times \overline{\vec{B}} \right)_j + \ldots$$

Omega effect

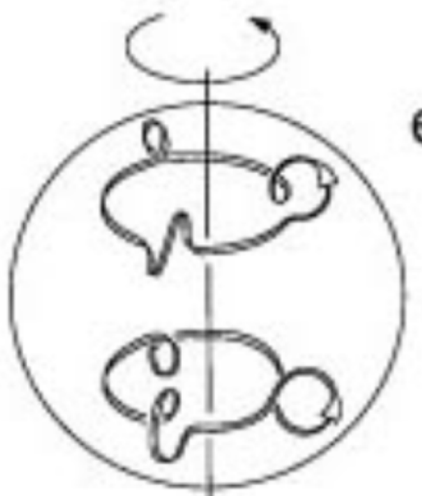


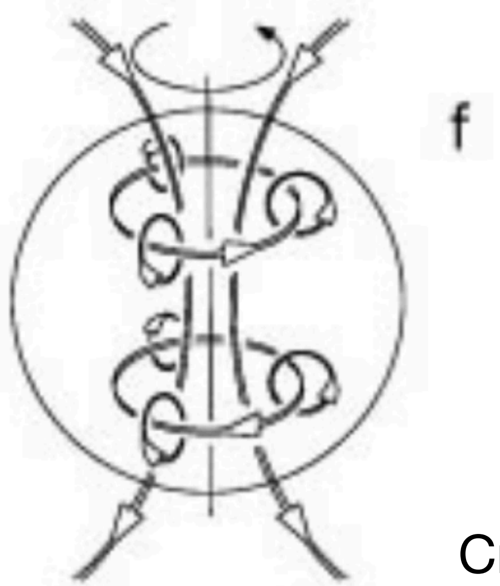


Credit: Love 99

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

alpha effect





Credit: Love 99

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

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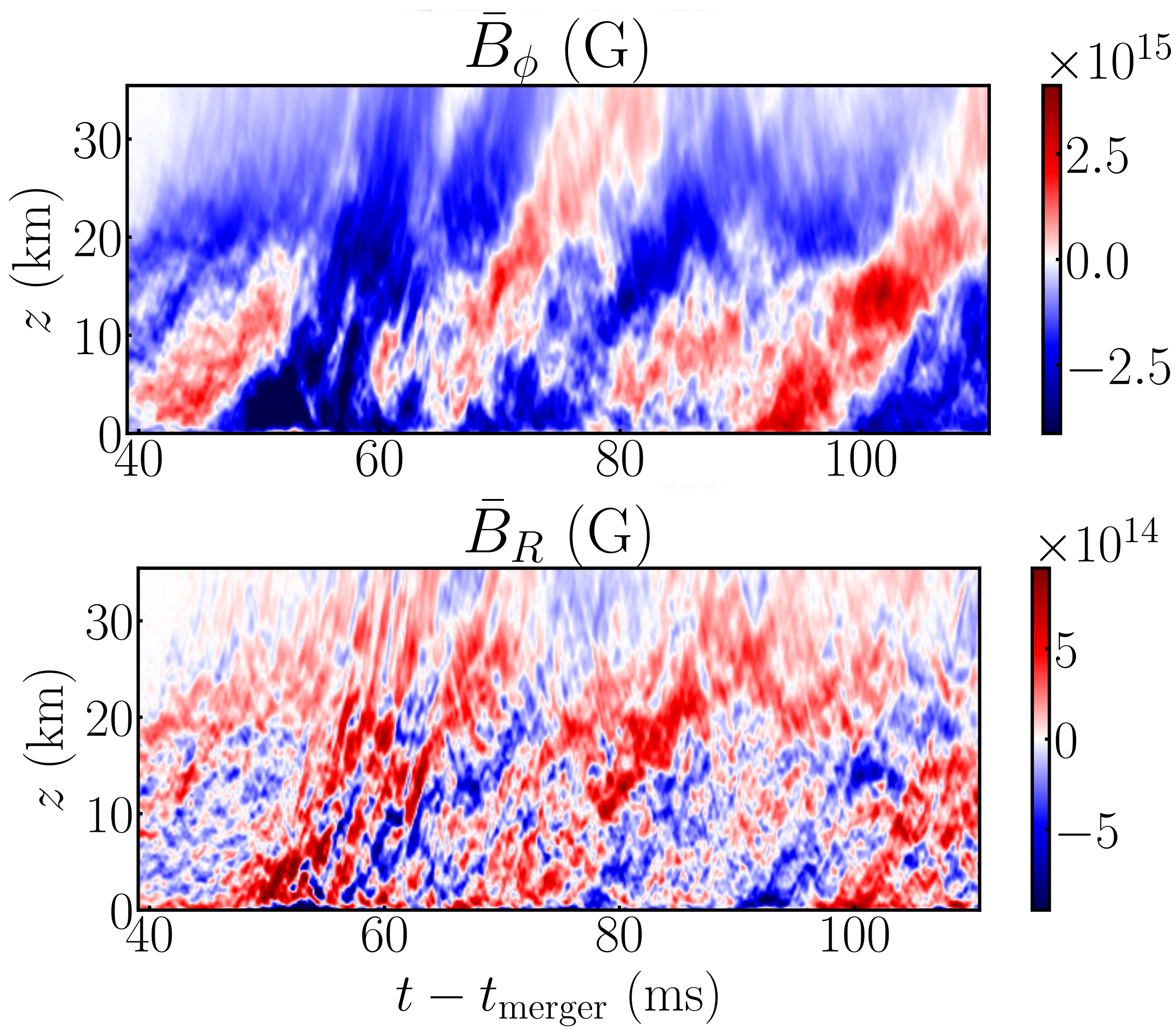
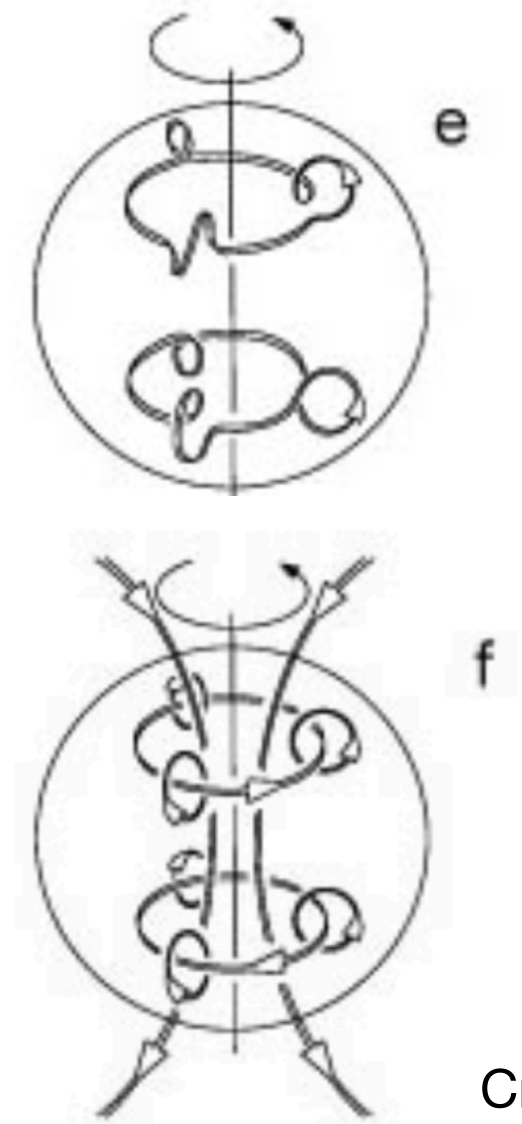
Omega effect at R = 30 km



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

alpha effect



Credit: Love 99

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MRI-driven alpha-Omega dynamo in ideal GRMHD simulations

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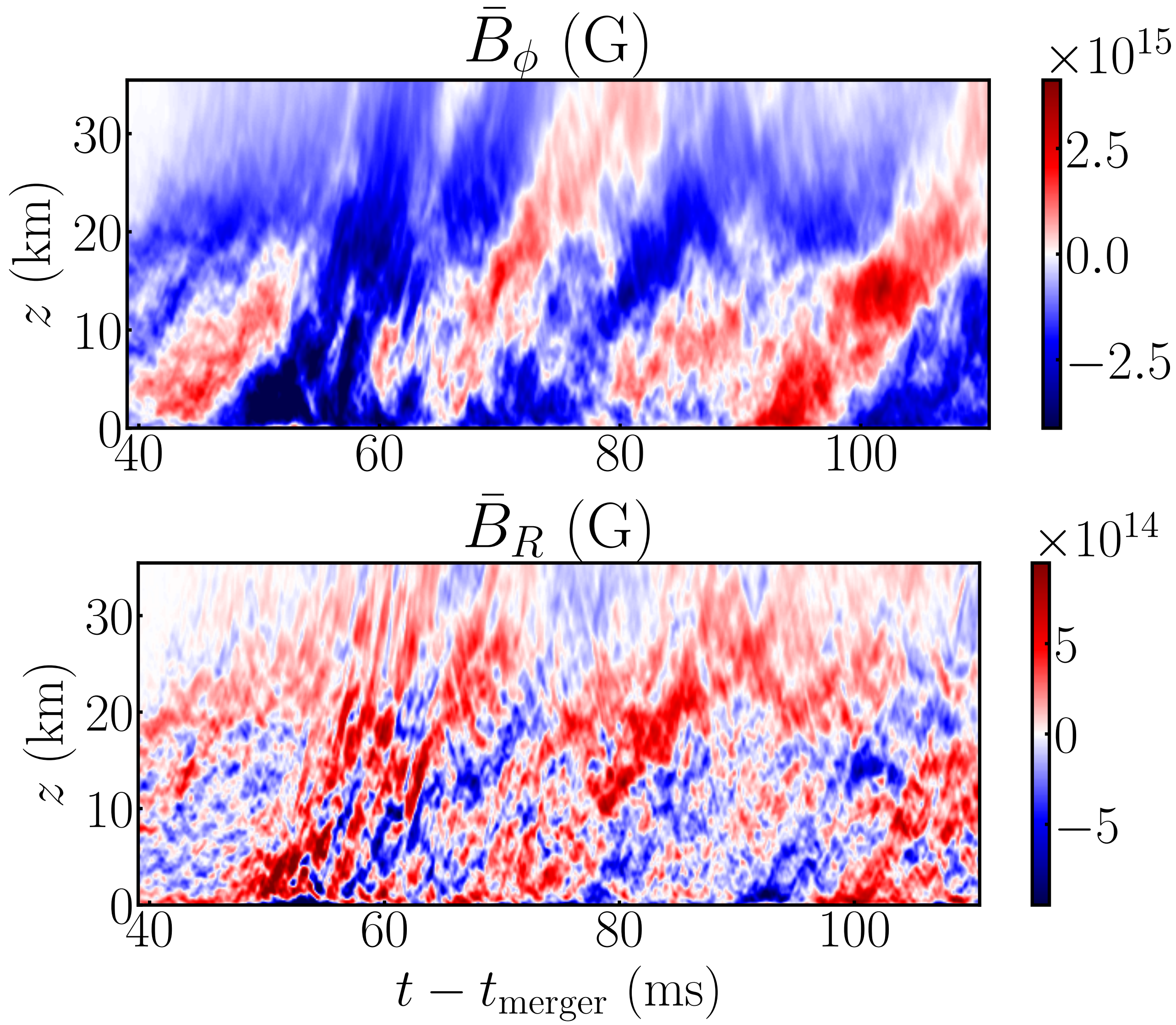
where

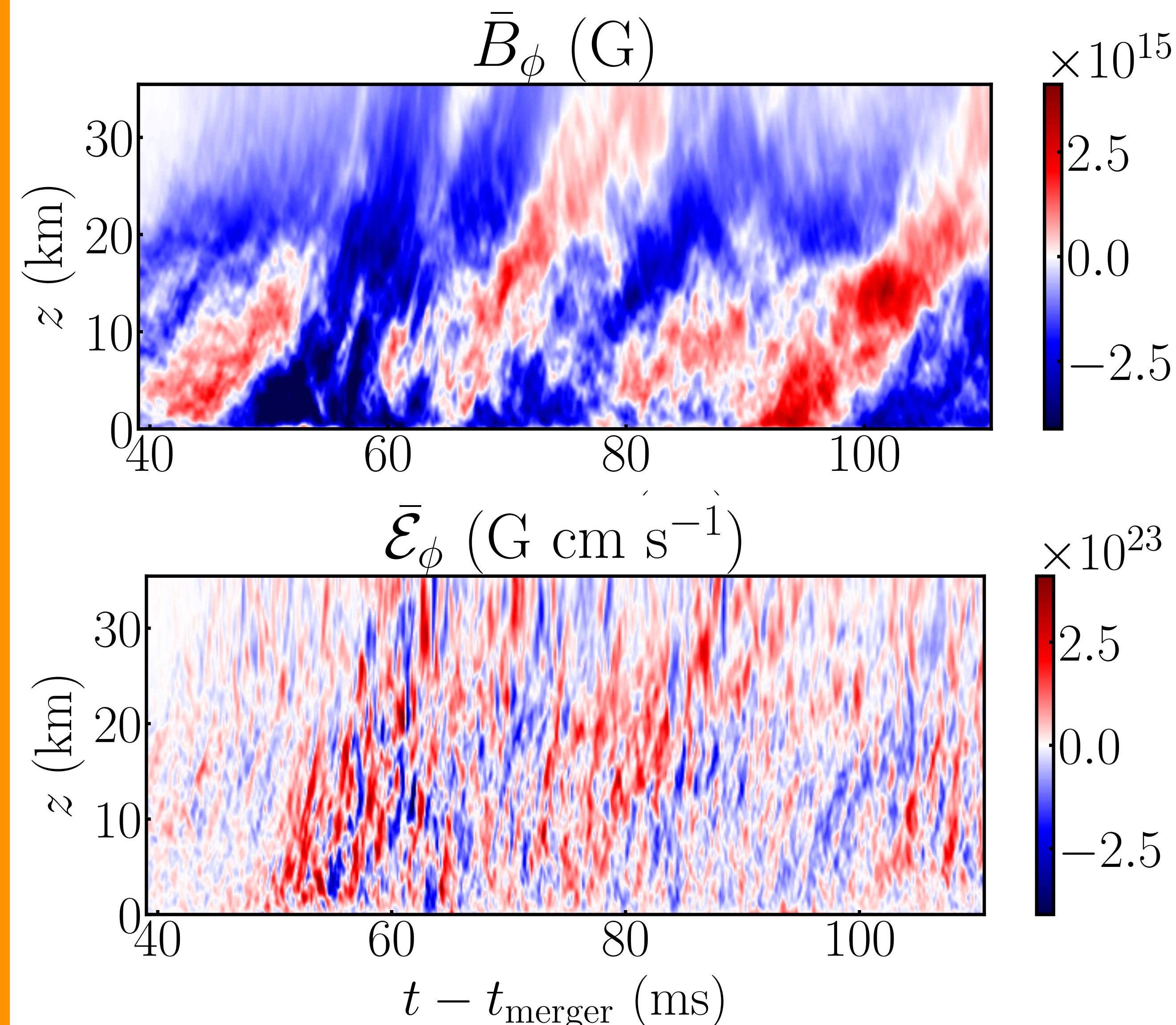
$$\vec{\mathcal{E}} = \overline{\vec{u} \times \vec{b}}$$
$$\mathcal{E}_i = \alpha_{ij} \overline{B}_j + \beta_{ij} \left(\vec{\nabla} \times \overline{\vec{B}} \right)_j + \ldots$$

Omega effect at R = 30 km



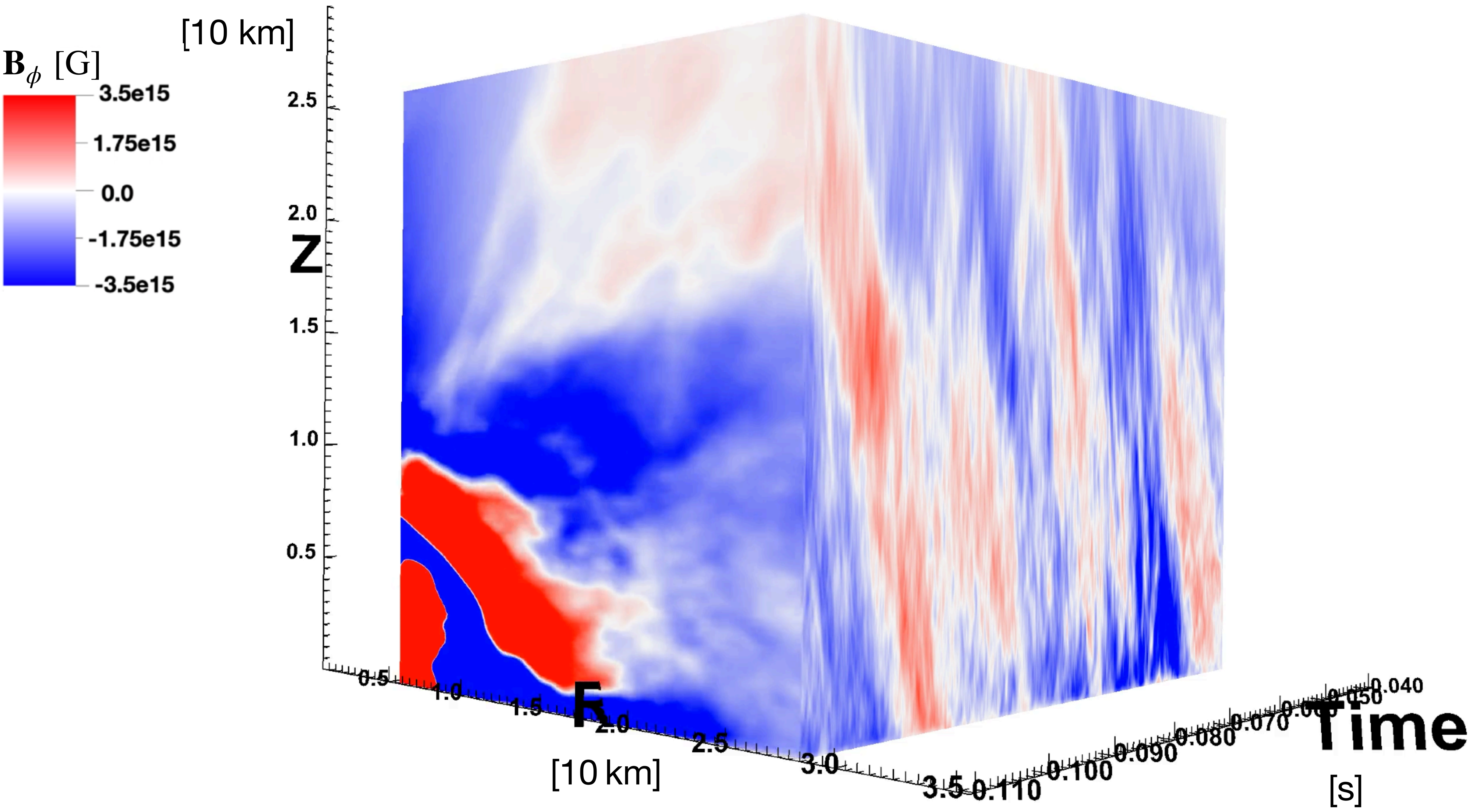
$$\frac{\partial \overline{B}_\phi}{\partial t} = \mathrm{R}\, \overline{B}_\mathrm{R} \frac{d\Omega}{ds}$$

alpha-effect at R = 30 km

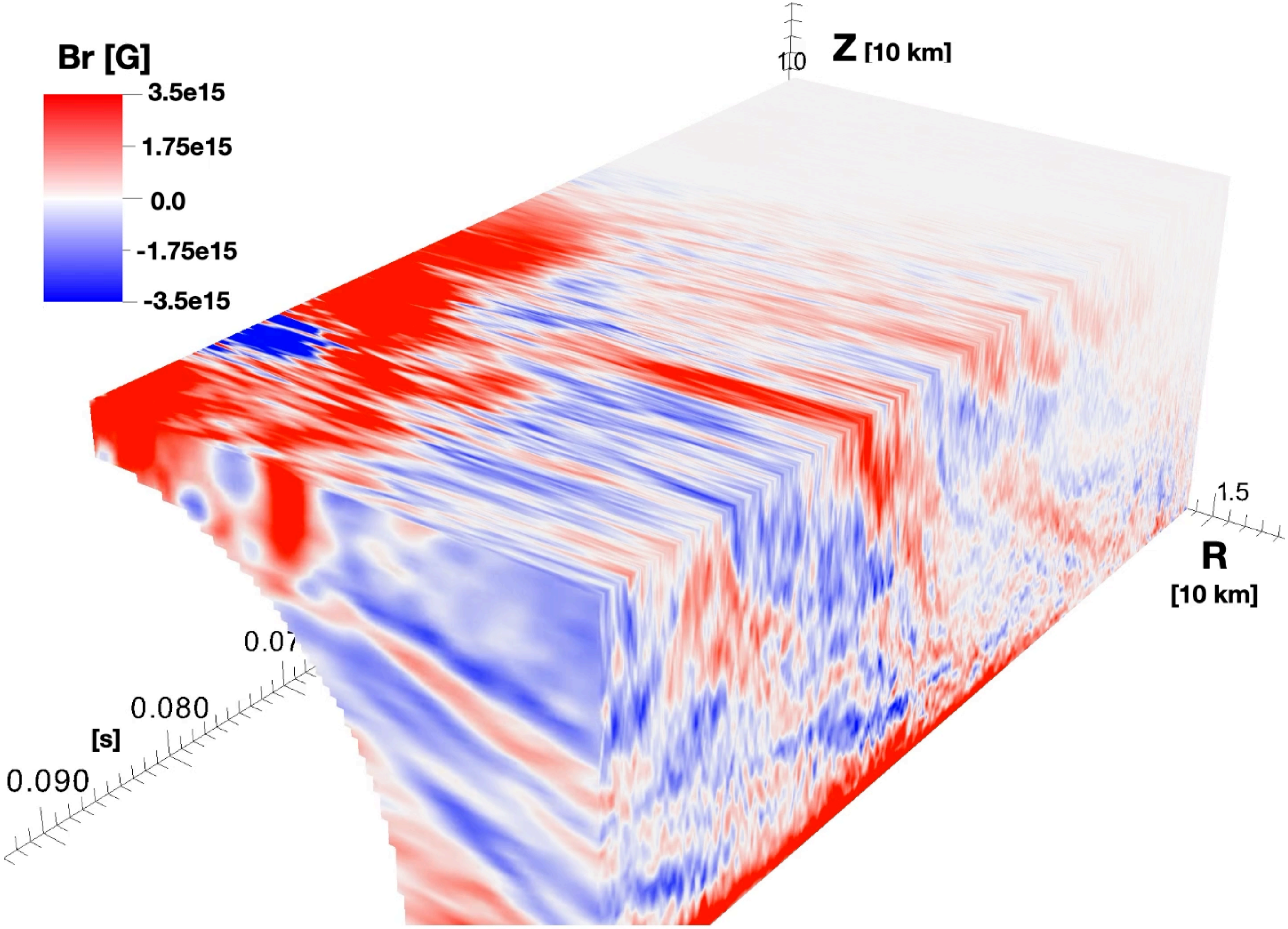


$$\mathcal{E}_\phi = \alpha_{\phi\phi} \bar{B}_\phi$$

Dynamo wave propagation



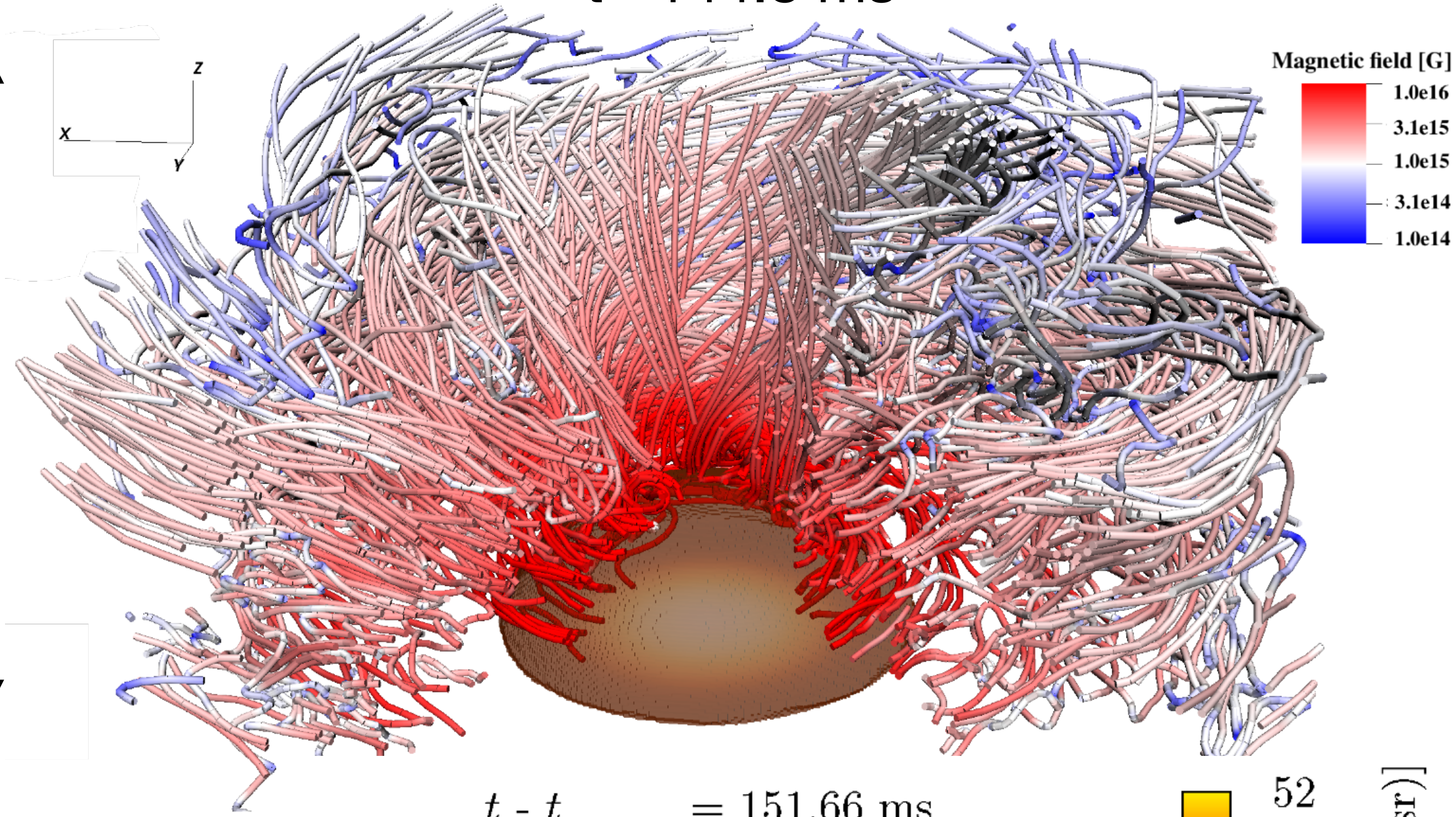
Link between polar outflow and alpha-Omega dynamo



Magnetic field lines and jet

t= 144.8 ms

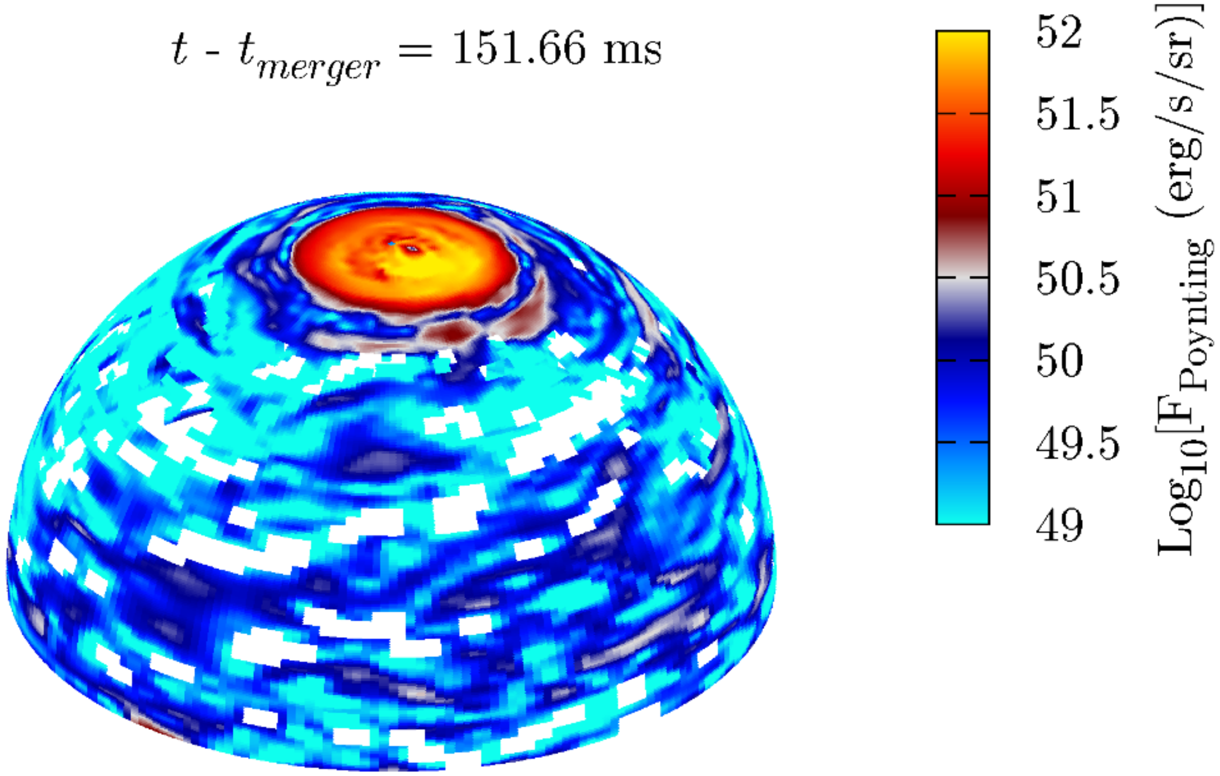
35 km



Turbulence dominated by the toroidal field

Jet starts from ~10 km

500 km



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

Jet angle $\theta < 12°$

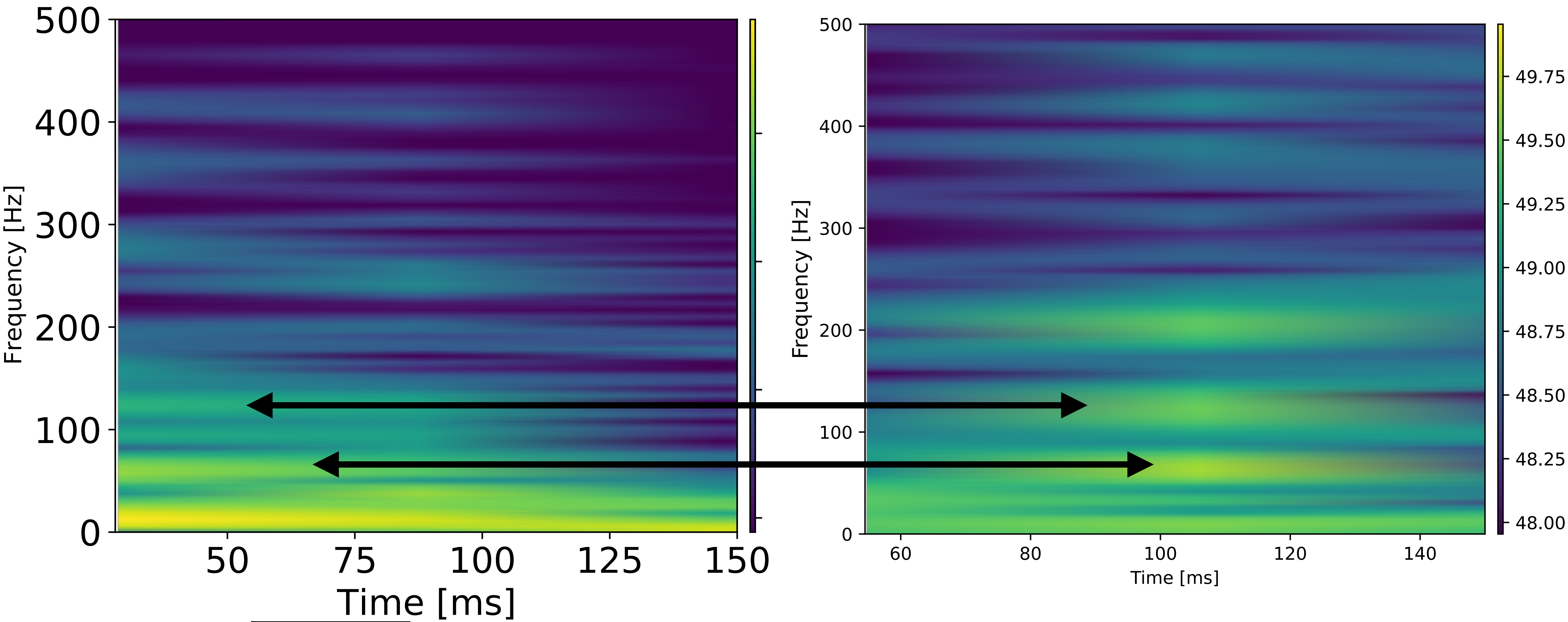
Magnetisation parameter

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

Jet+winds:
Post-merger ejecta Mass
~ $0.1 M_\odot$

Impact on the GRB luminosity?

FFT of toroidal field at 12 km in the HMNS   Poynting Flux luminosity at 500 km



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

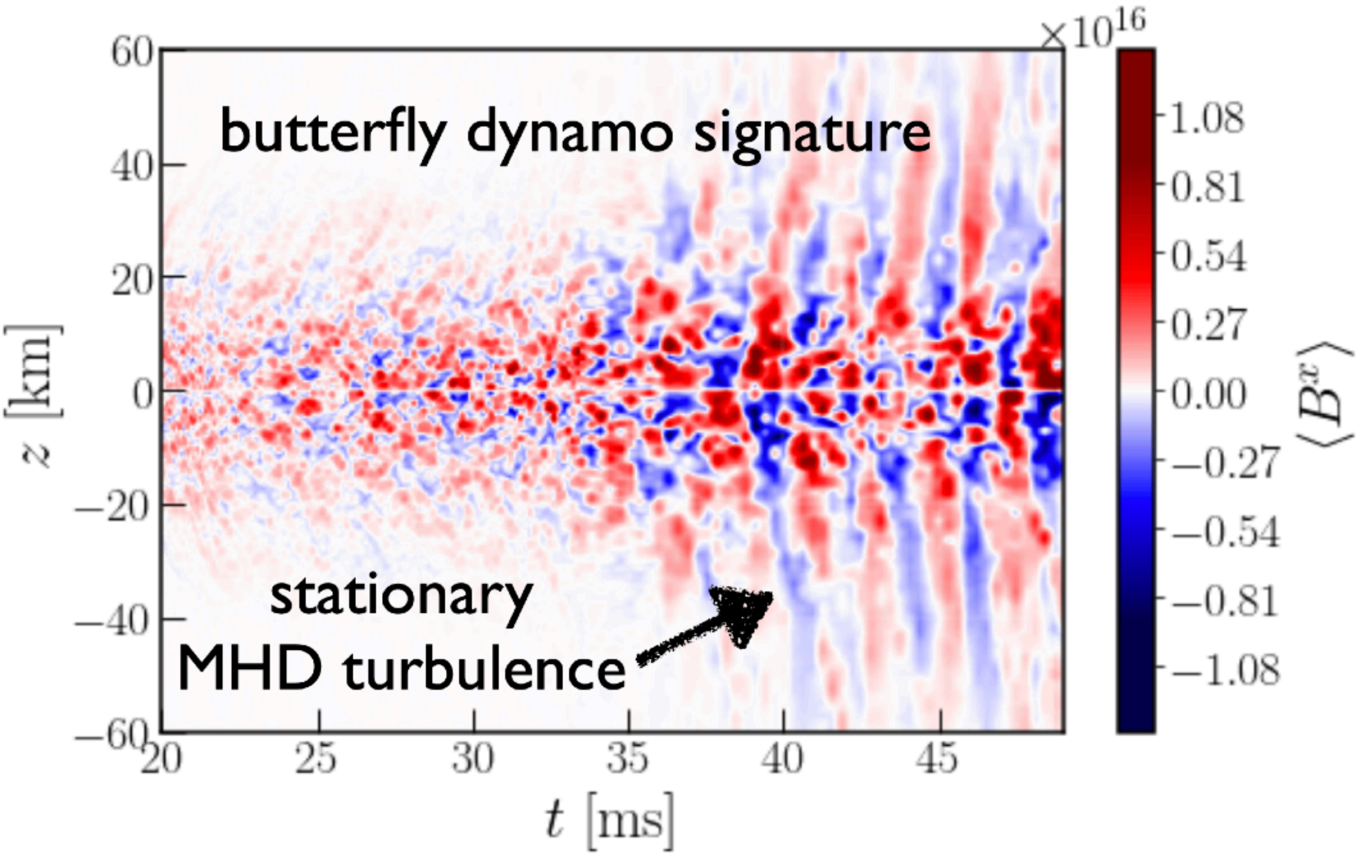
Reboul-Salze et al, in prep

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

How does this variability evolves with jet propagation? Magnetic reconnection in the jet?

Can this variability be detected in short GRBs?

Comparison with other GRMHD models



APR EOS and different code

Combi & Siegel 2022

no jet found

BNS merger with subgrid model, realistic B_0

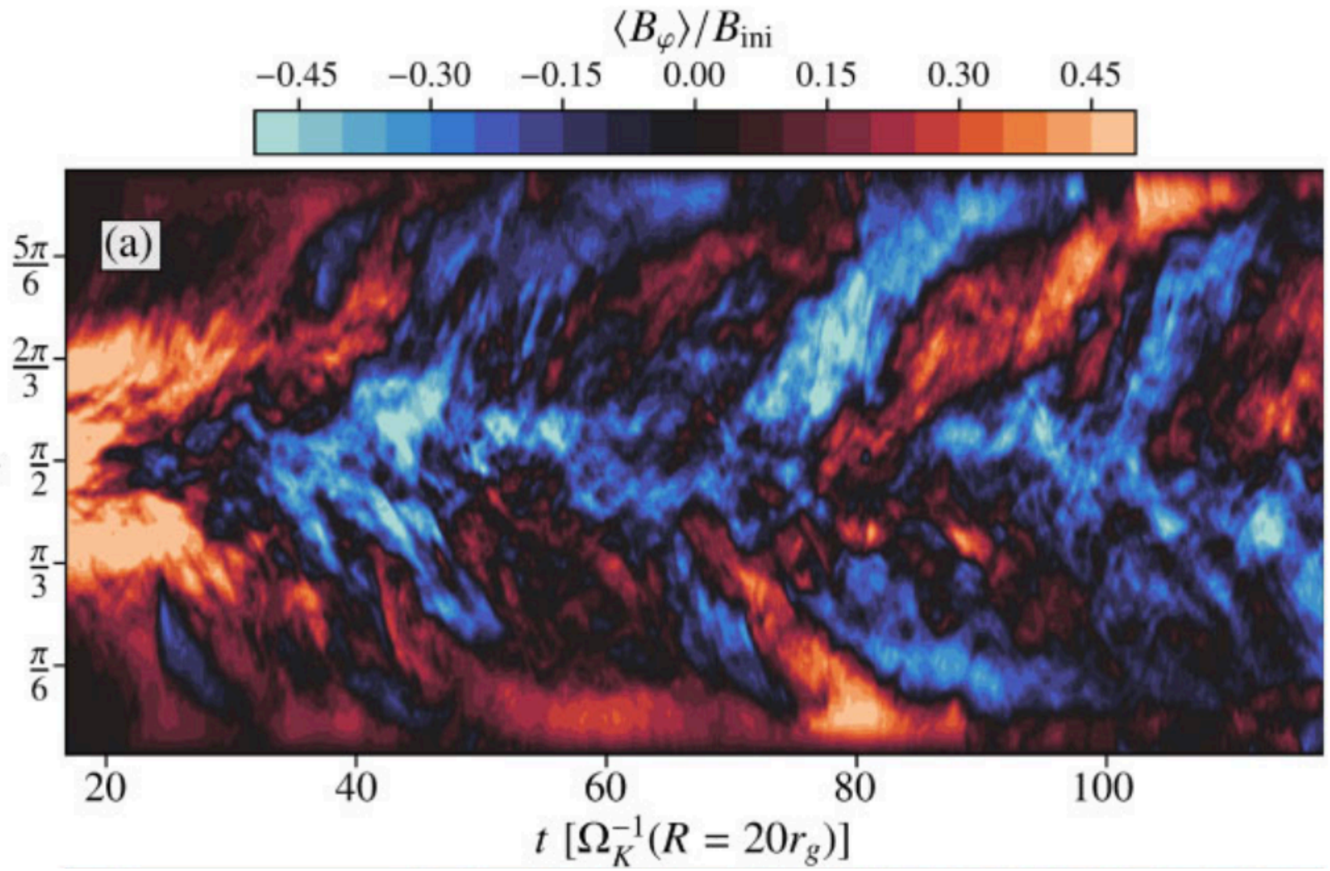
Aguilera-Miret et al 2023,2024

Neutrinos help to launch the jet and winds (Musolino et al. 2025)

Similar mechanism in BH+disks systems

Comparison with BH disk systems

BH + thick disk systems:

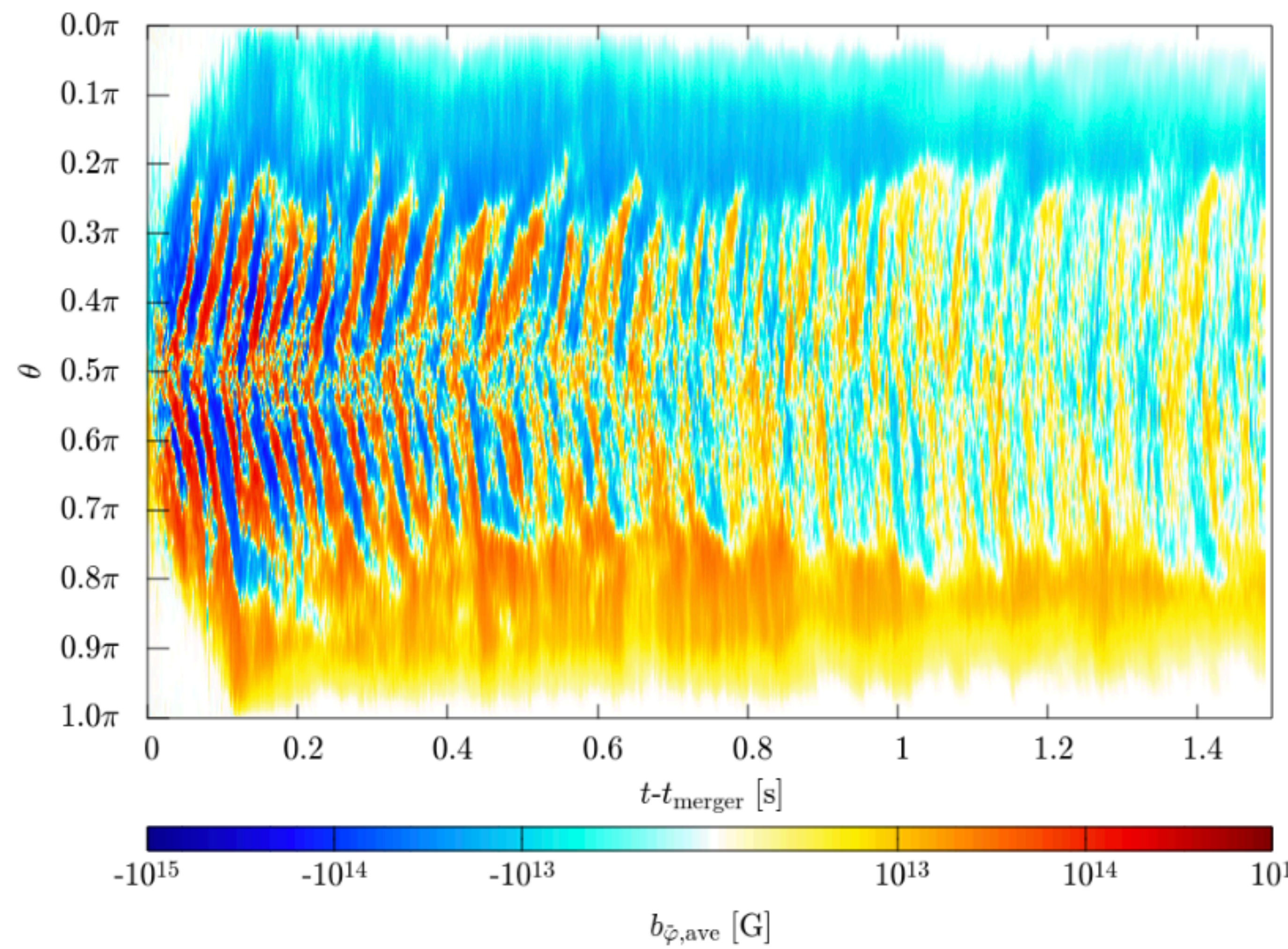


Jacquemin-Ide+2024, 2025

$t_{gen} \approx 10\Omega_K^{-1}$ and $t_{adv} \approx 60\Omega_K^{-1}$

Disk dynamo for **MAD disks (AGN/X-ray binaries)**

BNS short-lived systems:



Hayashi et al. 2025 in **BH-NS** mergers

Setup Uncertainties: Numerical techniques, initial magnetic field, resolution

Physical Differences: disk thickness, equation of state, neutrinos, resistivity, radiation, etc.

Microphysics: magnetic Prandtl number dependency

Pm regime in PNS and BNS merger

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

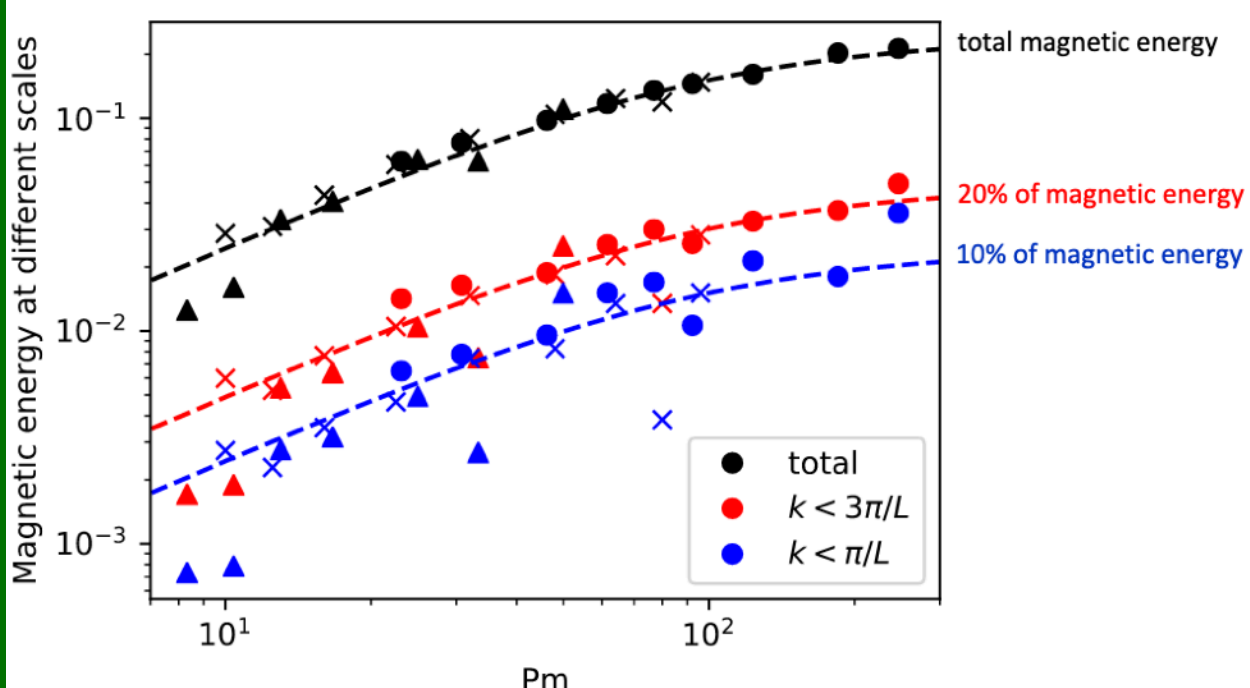
Diffusive approximation for neutrinos

Weak resistivity due to degenerate relativistic electrons

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

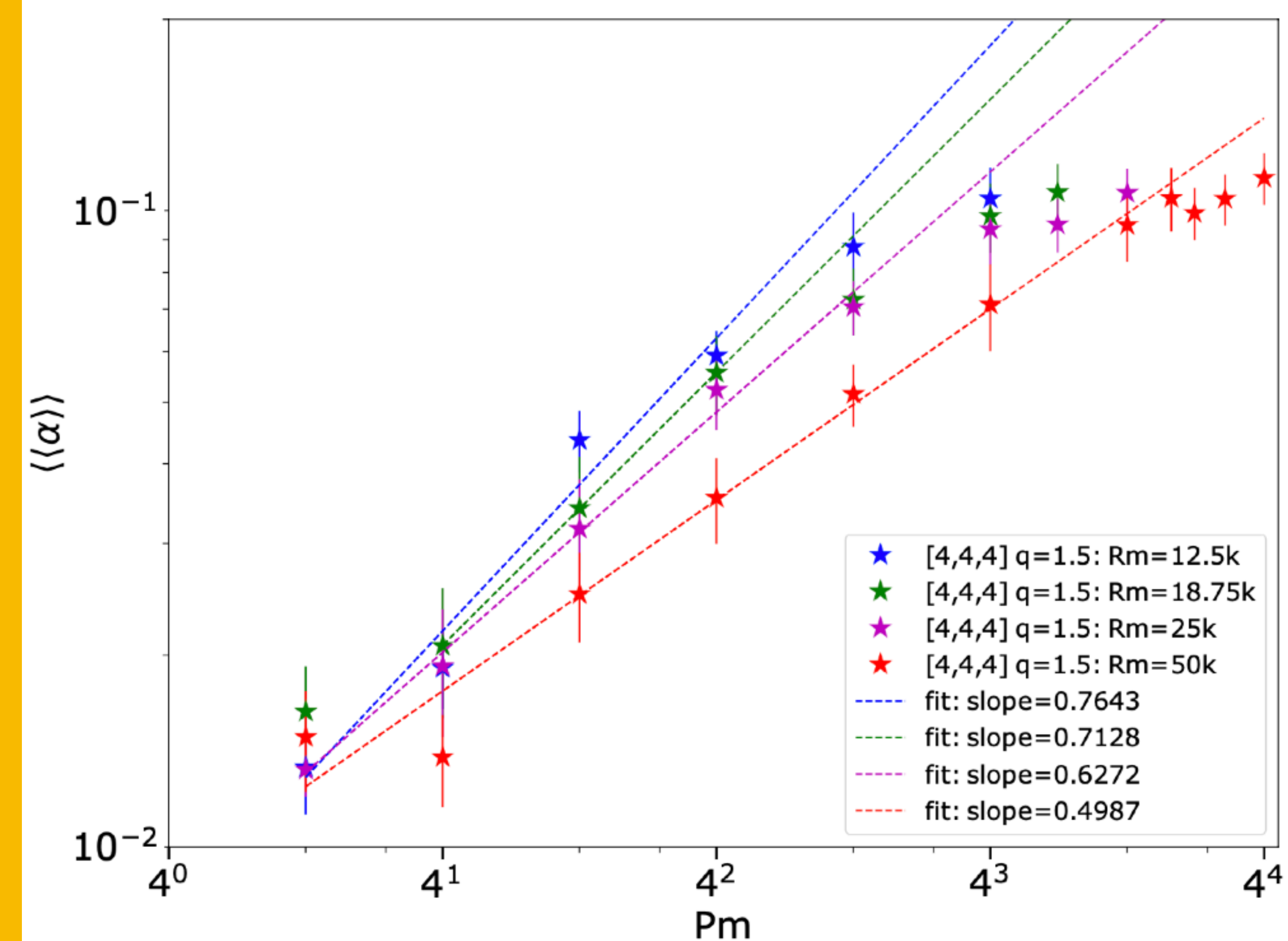
Guilet, Reboul-Salze et al., 2022

Unstratified shearing box studies



Held et al., 2024

Stratified case with increasing viscosity



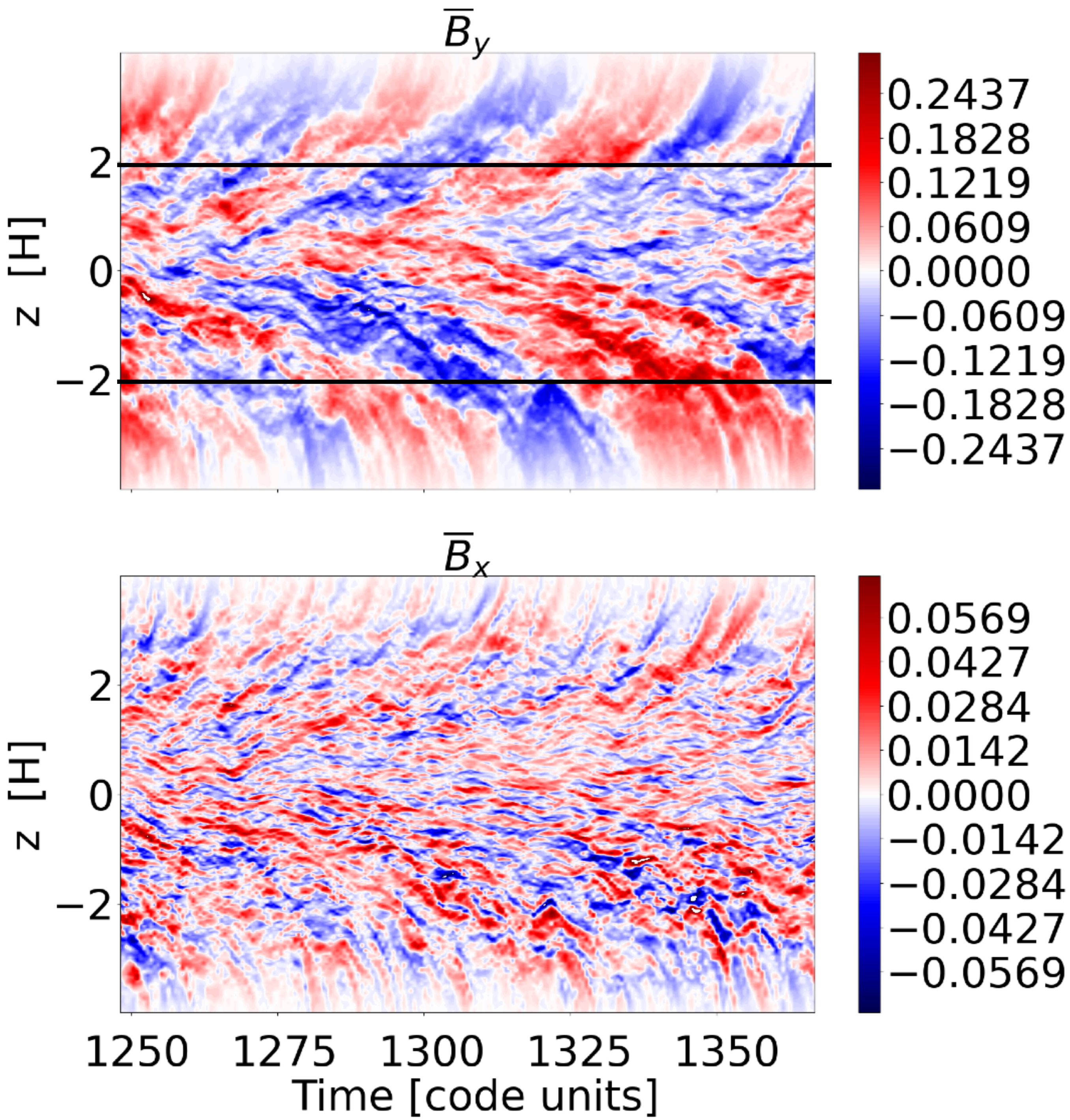
In the mid plane (|z|<2 H): MRI-driven dynamo dynamics

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

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

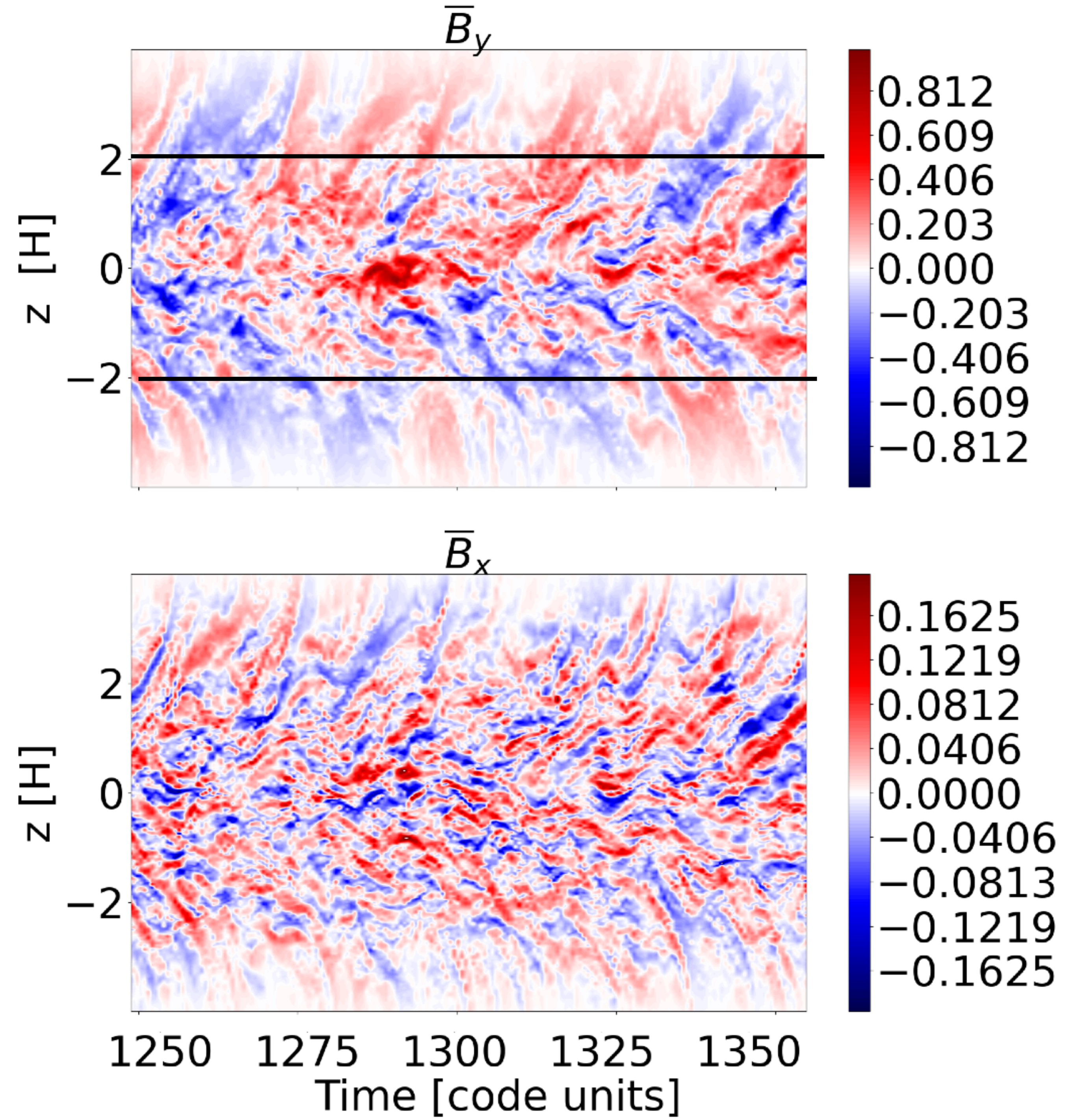
Azimutal averaged magnetic field comparison

Pm=4



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

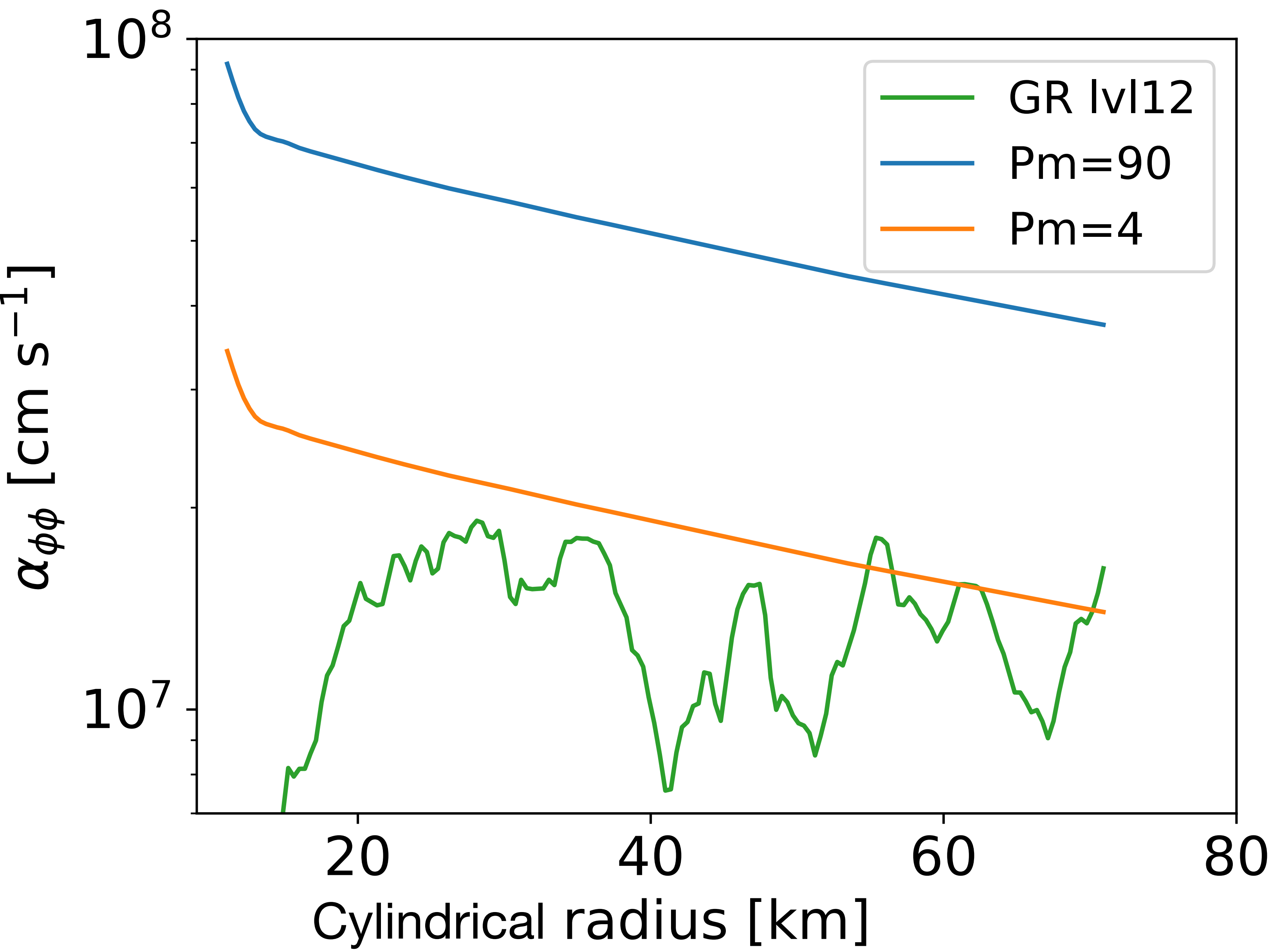
Pm=90



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

Large-scale magnetic field amplification: global vs local

Peak alpha strength



- 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

Reboul-Salze et al, 2025b

Similar behaviour in collisionless plasma as high Pm in local sims (Kunz et al. 2016)

Summary and Perspectives

- Magnetised turbulence and dynamo in compact objects
  ⟶ Magnetar formation: Generation of large-scale fields with fast rotation and local strong turbulence
  ⟶ Launch of (mildly-)relativistic outflows with high luminosity
  ⟶ Dynamo period impacts the variability in the jet luminosity
  ⟶ Non-ideal effects: Faster growth rate, variability and propagation

- Key challenges
  ⟶ Scale separation: saturation of dynamos depends on resistivity
  ⟶ Effective resistivity based on PIC (Bugli+2025), subgrid models?
  ⟶ Particle acceleration and its impact on the turbulence
  ⟶ Understanding different BH+disks systems, AGN, X-ray binaries, etc.

  ⟶ GRB observations: jet propagation, shocks, magnetic reconnection and particle acceleration in the jet
  ⟶ Pulsar/magnetar observations: magnetic field evolution and magnetosphere modelisation

- Common mechanisms with other stellar/planetary systems