Magnetar *formation* : observations and theory

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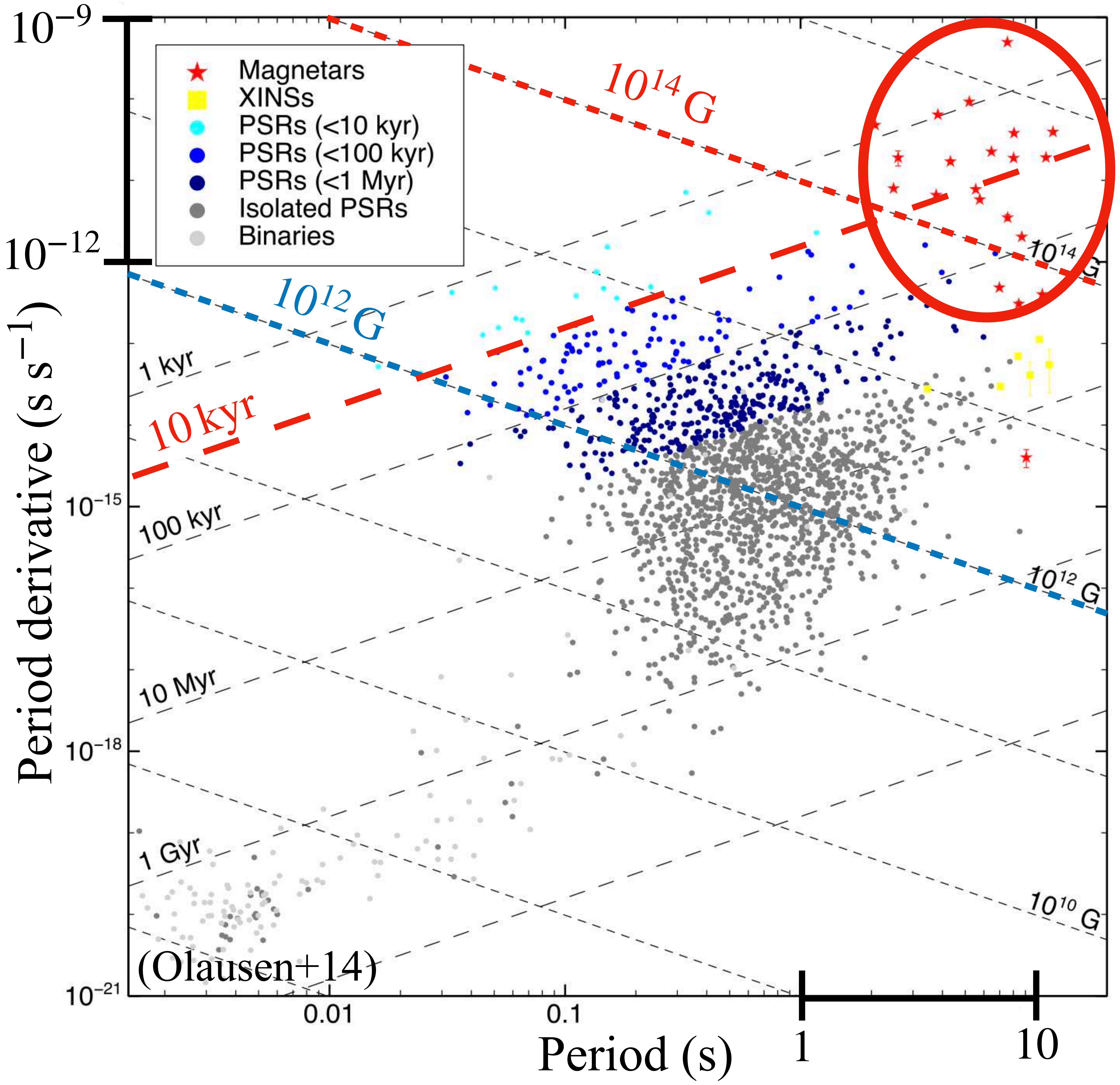
Journées PNHE

Institut d'Astrophysique de Paris, 6-8/09/2023



$$B_{\rm dip} \propto \sqrt{P\dot{P}} \sim 10^{14} - 10^{15}\,{\rm G}$$

- 30 Galactic, isolated X-ray sources (outbursts, giant flares) magnetically powered (Kaspi+17, Ajello+21)

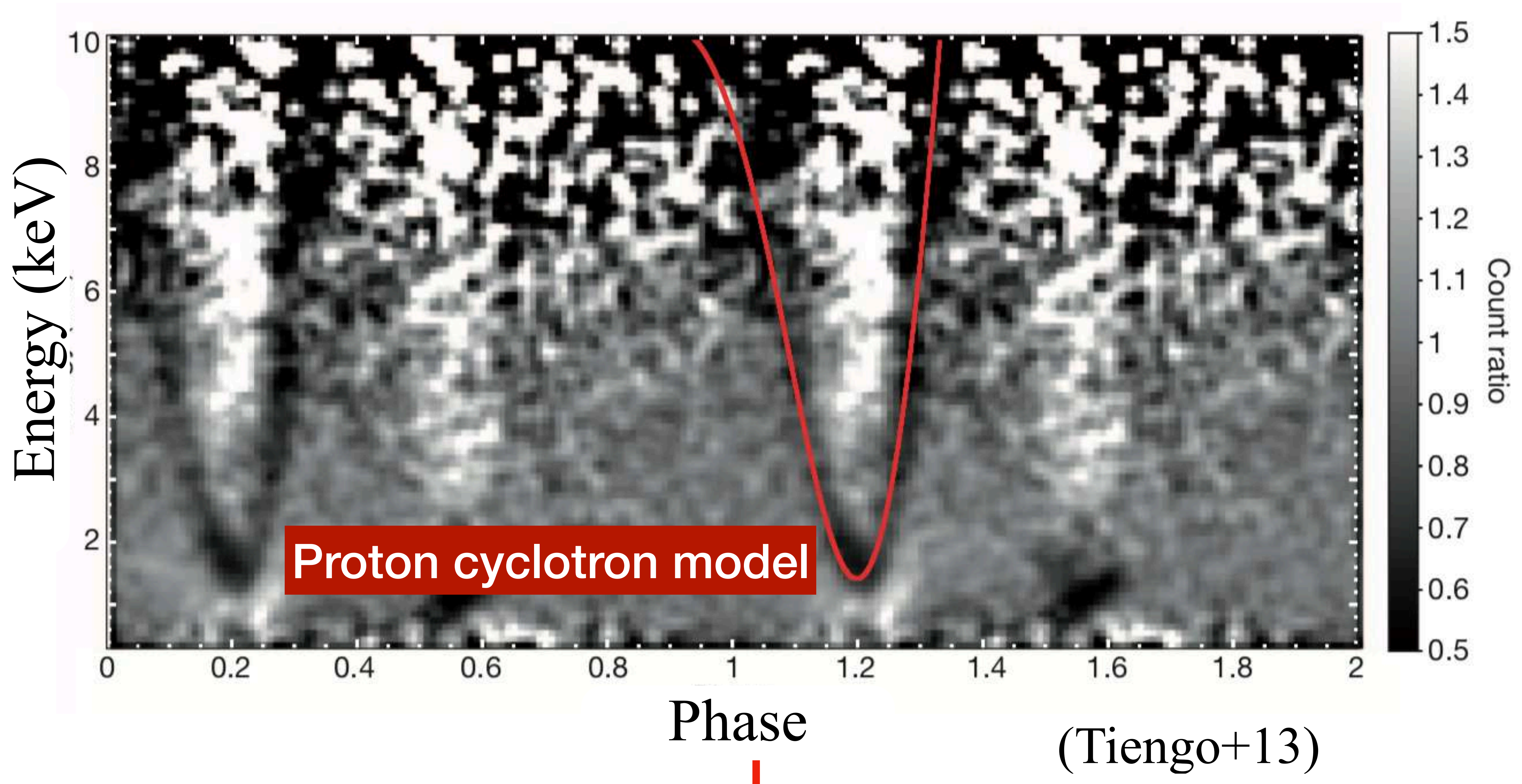
- 10 associated with core-collapse supernovae
  "Typical" remnants : $E_{kin} \sim 10^{51}$ erg $\Longrightarrow$
  constraints the initial period $P_0 > 5$ ms (Vink+06)

- Population: up to 40% of newborn neutron star (Kouveliotou+94, Beniamini+19)

- One source of Fast Radio Bursts (among others ?) (CHIME/FRB+20, Bochenek+20)
  $\Longrightarrow$ *see afternoon talks (Cherry Ng / G. Voisin)*

Beyond the dipole, some observational constraints

Variable absorption feature in X-ray burst/outburst spectrum

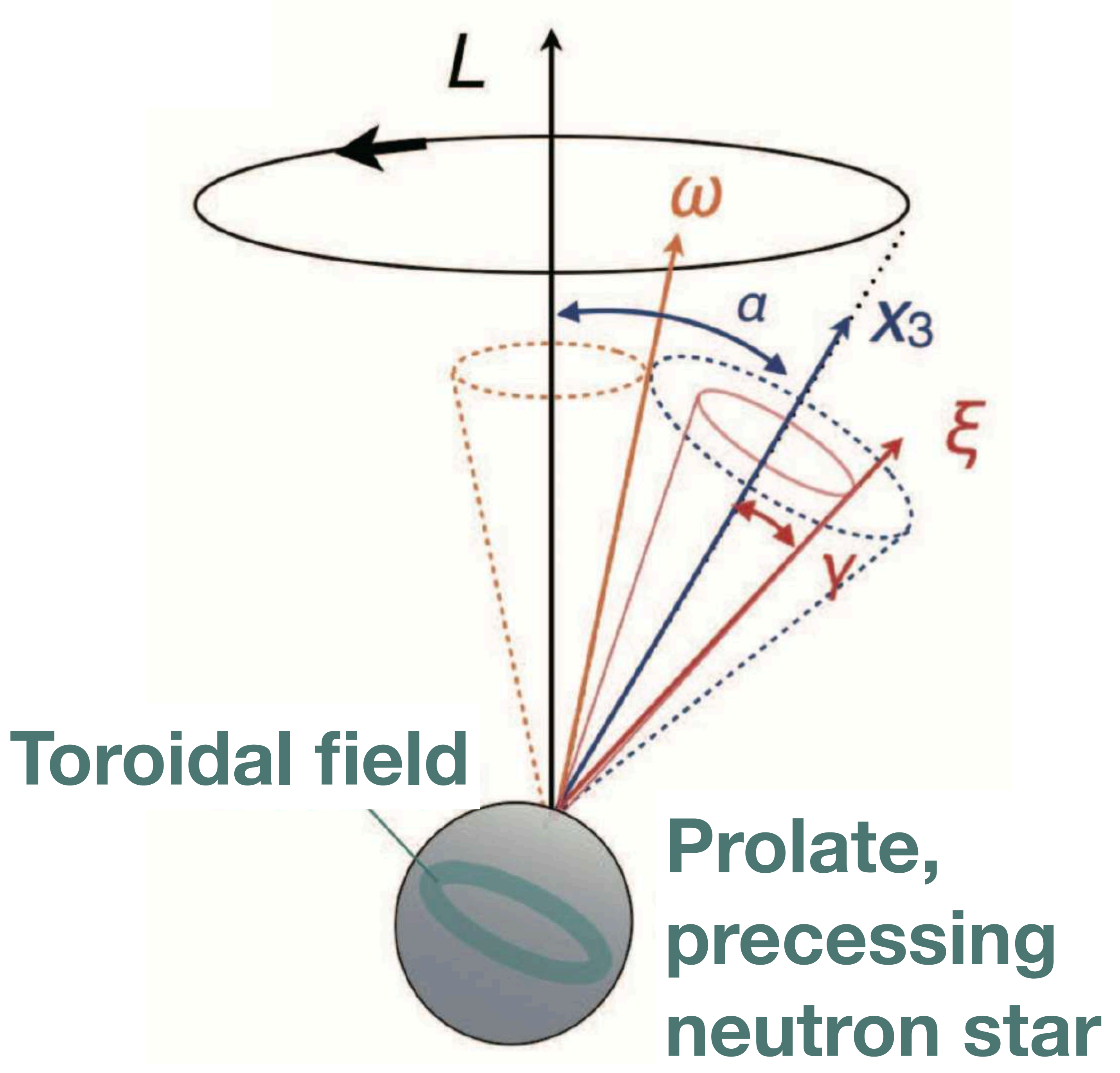


(Tiengo+13)

$$B_{\rm non-dip} \sim \text{few} \times 10^{14} - \text{few} \times 10^{15}\,\text{G}$$

(Tiengo+13, Rodríguez Castillo+16)

Phase modulation of X-ray pulsations



$$B_{\rm tor} \sim 10^{16}\,\text{G}$$

(Makishima+14, 16, 19, 21)

Millisecond magnetars: a central engine for extreme explosions

Central engine idea

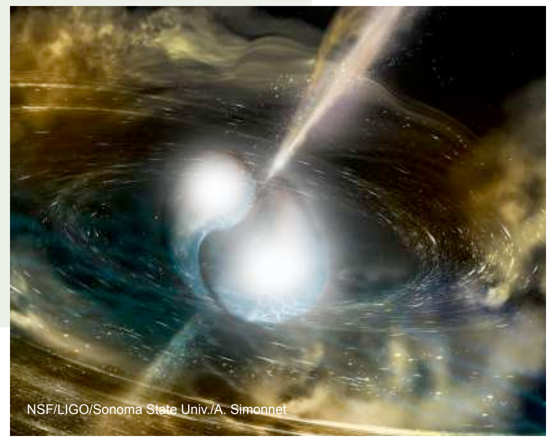
Delayed energy injection due to the spindown of a millisecond magnetar (Zhang+01)

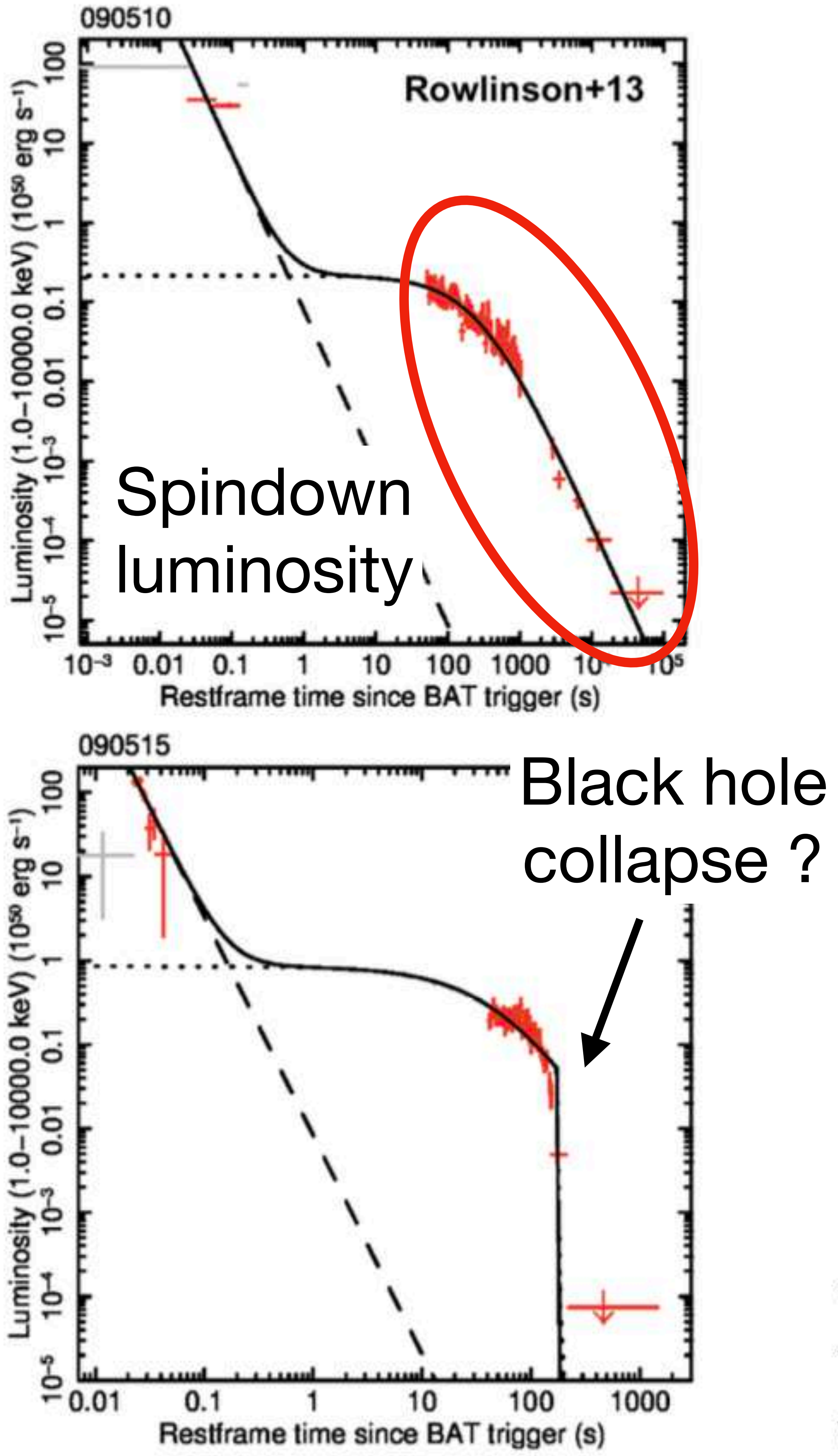
$\Longrightarrow$ Light curve fits give $\{P_{\rm rot}, B_{\rm dip}\}$

Capable of powering

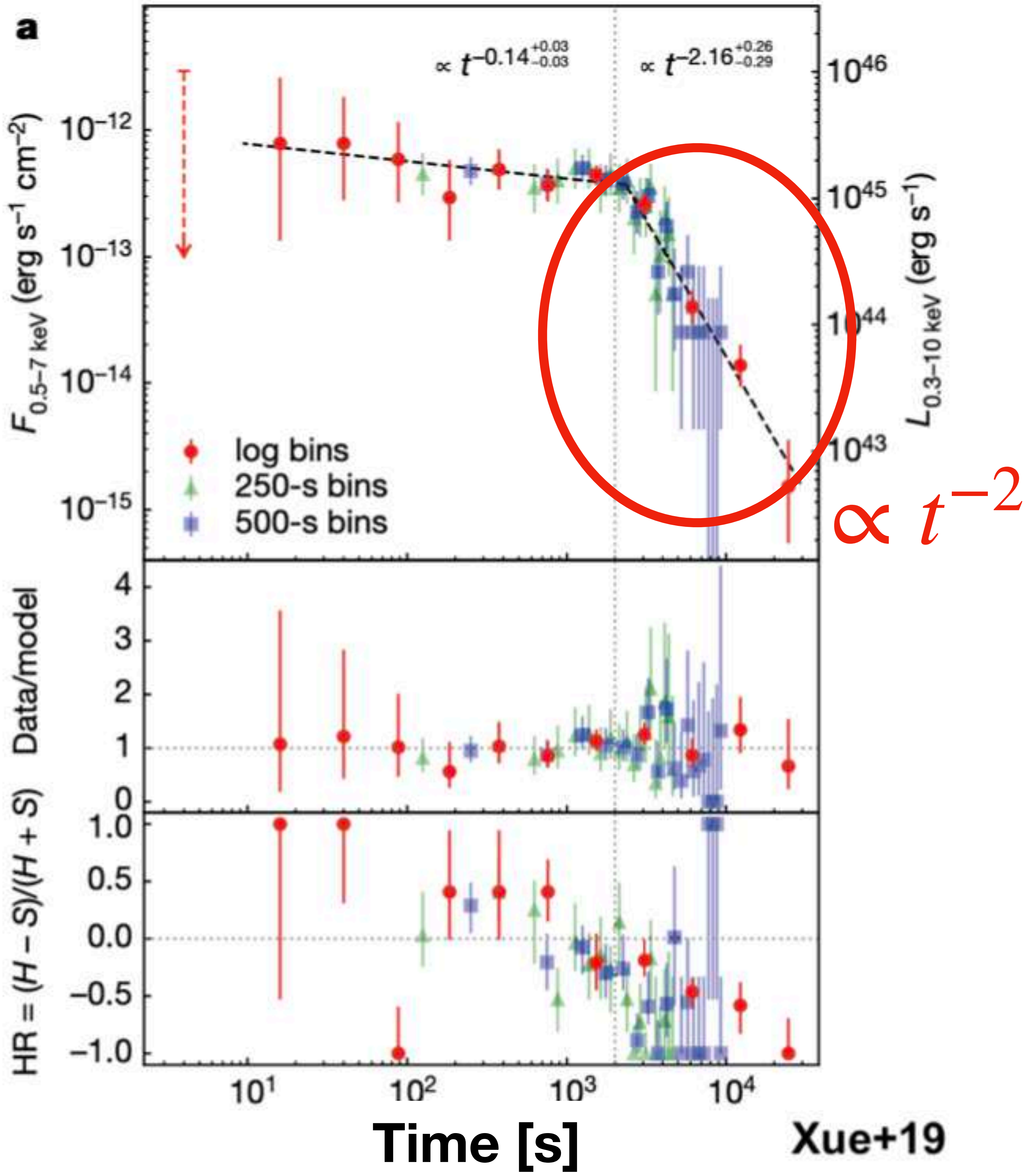
- **Superluminous supernovae**
  ($L \sim 100 \times 10^{49}$ erg) (Inserra+13, Mösta+15)
- **Hypernovae and long GRBs**
  ($E_{kin} \sim 10 \times 10^{51}$ erg)
  $\Longrightarrow$ magneto-rotational explosions
  (Greiner+15, Bugli+23,22,21)
- **X-ray plateaux of GRBs**

Gompertz+11, Rea+15, Dall'Osso+23



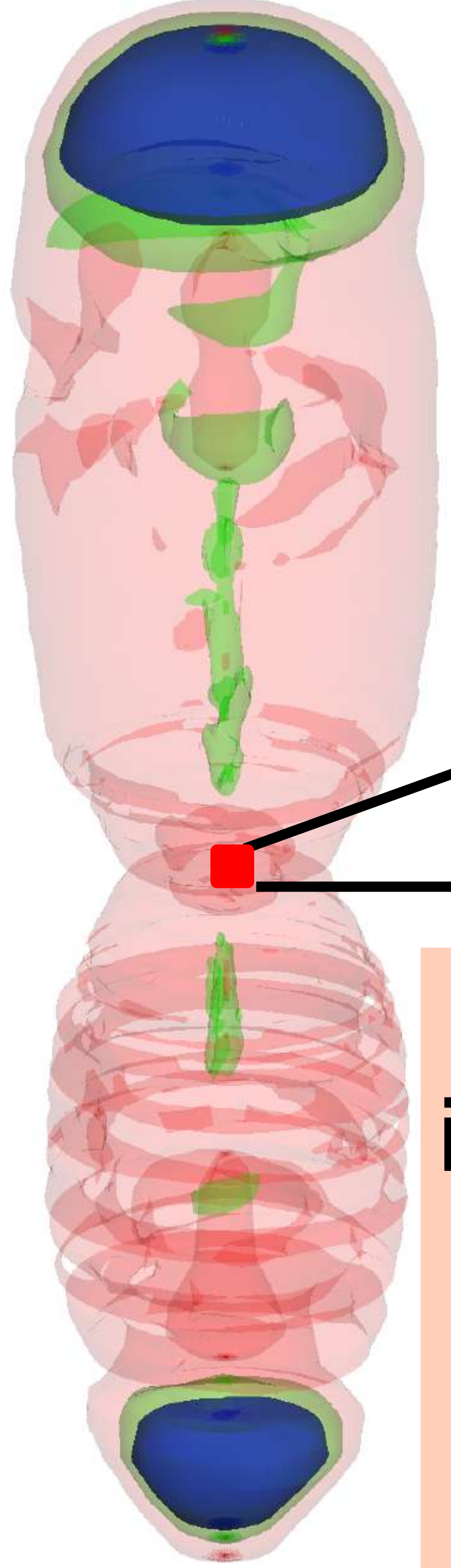


sGRB light curves



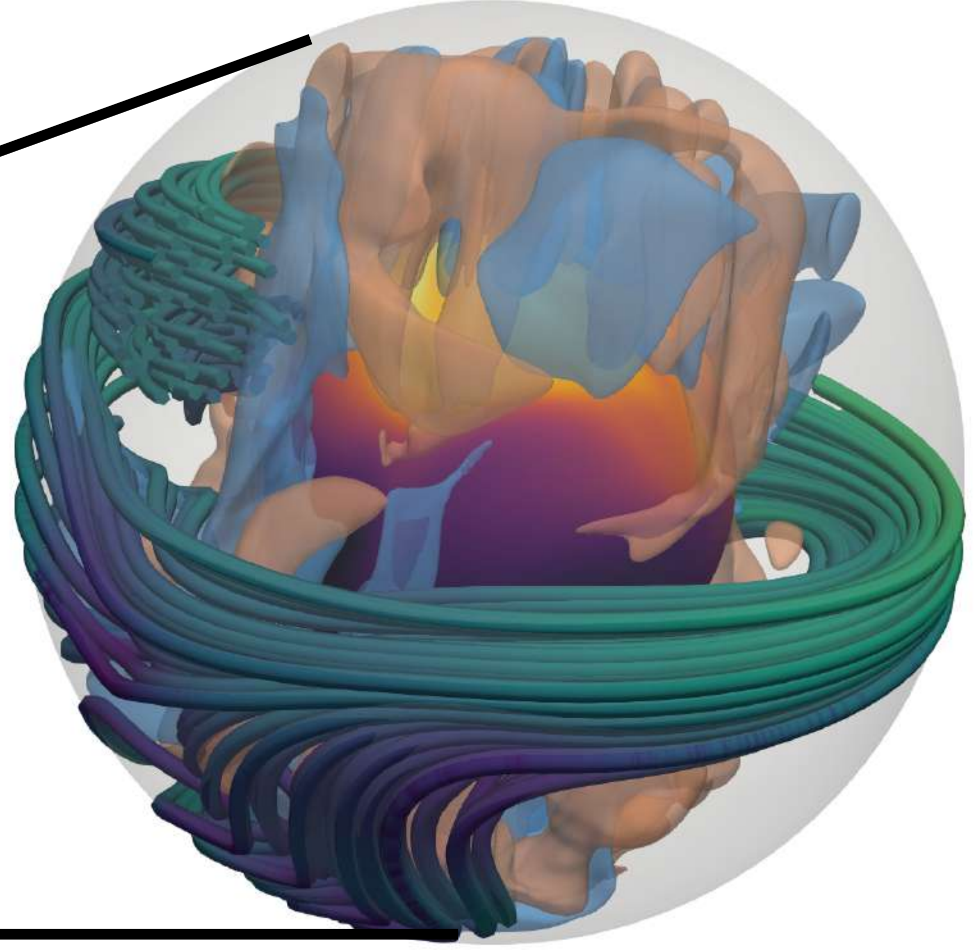
X-ray transient consistent with magnetar central engine

Numerical modelling: a challenging multi-scale problem



10^4 km

10 km



Core-collapse simulations

including

Neutrino transport

Special relativity

Neutron star equation of state

- Magnetic field impact on the explosion
- Prediction of multi-messenger observables

~ 1 Mh CPU/run

Bugli+23, 21, 20

Proto-neutron star simulations

- Idealized model
- Dynamo processes
    - field strength
    - field topology
- Derivation of physical scaling laws via extensive parameter studies

~ 0,1 Mh CPU/run

Jean Zay @ IDRIS

HPC RESSOURCES

~ 10 Mh CPU/yr

Formation scenarios

Fossil field

- Amplification factor

$$\left(\frac{r_{core} \sim 10^3 \text{ km}}{r_{NS} \sim 10 \text{ km}}\right)^2 \sim 10^4$$

$$\implies B_{core} \sim 10^{11} \text{ G}$$

- magnetic massive stars, stellar mergers ? (Schneider+19)

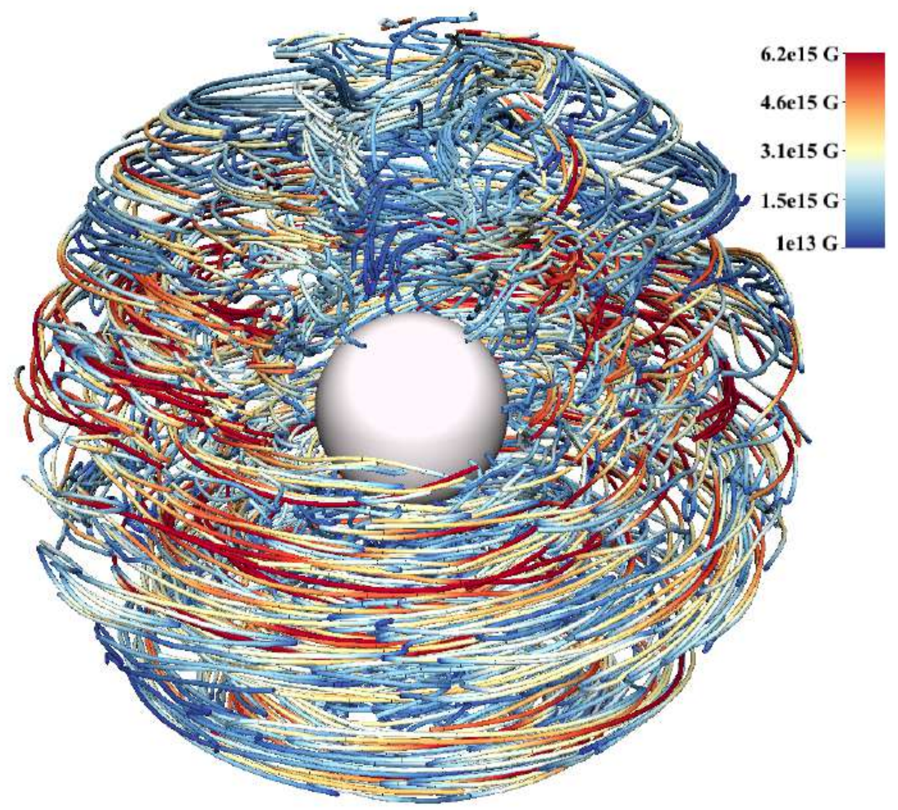
- Hardly compatible with the millisecond magnetar scenario

- Unlikely to simultaneously reproduce pulsar and magnetar populations (Makarenko+21)

Dynamo field: in *situ* amplification

Stably stratified zone & differential rotation

Magneto Rotational Instability

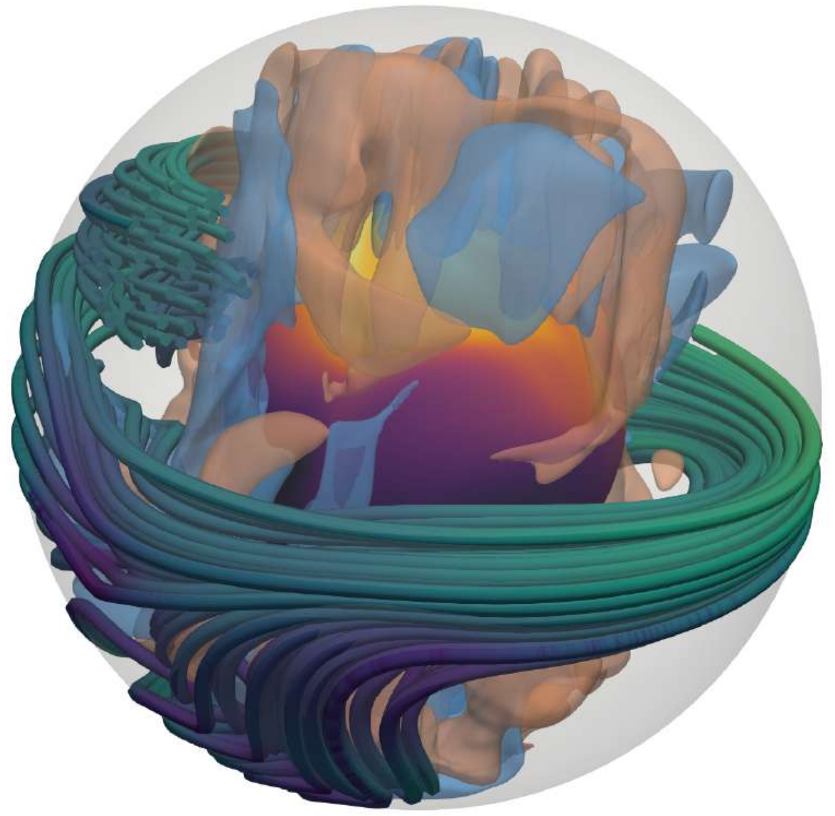


Reboul-Salze+21,22

- Equatorial dipole component

Convection lasting for ~10 s

Convective dynamo



Raynaud+20,22

- Strong toroidal magnetic field
- Magnetar-like dipole field for ~ millisecond rotation period

Formation scenarios

Fossil field

- Amplification factor

$$\left(\frac{r_{\rm core} \sim 10^3 \text{ km}}{r_{NS} \sim 10 \text{ km}}\right)^2 \sim 10^4$$

$$\Longrightarrow \quad B_{\rm core} \sim 10^{11} \text{ G}$$

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Dynamo field: *in situ* amplification

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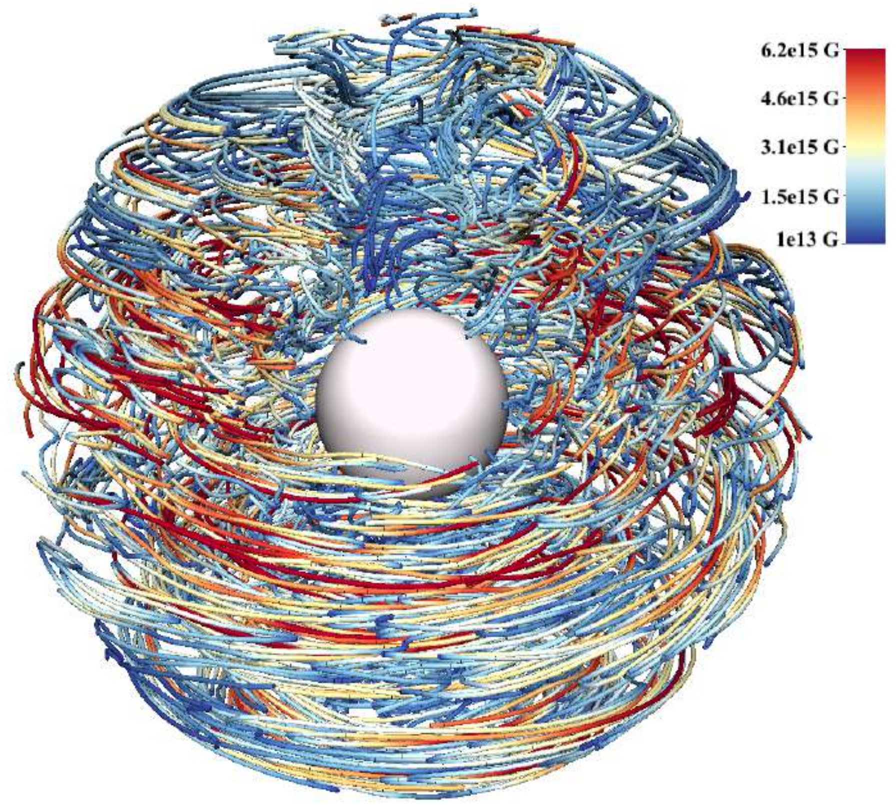

Reboul-Salze+21,22

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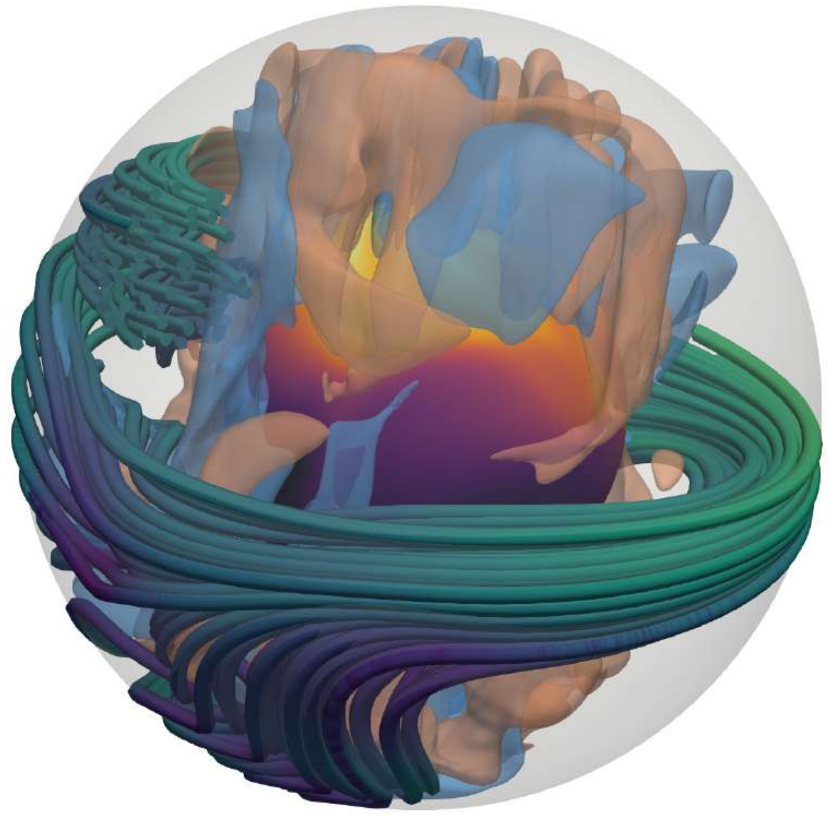
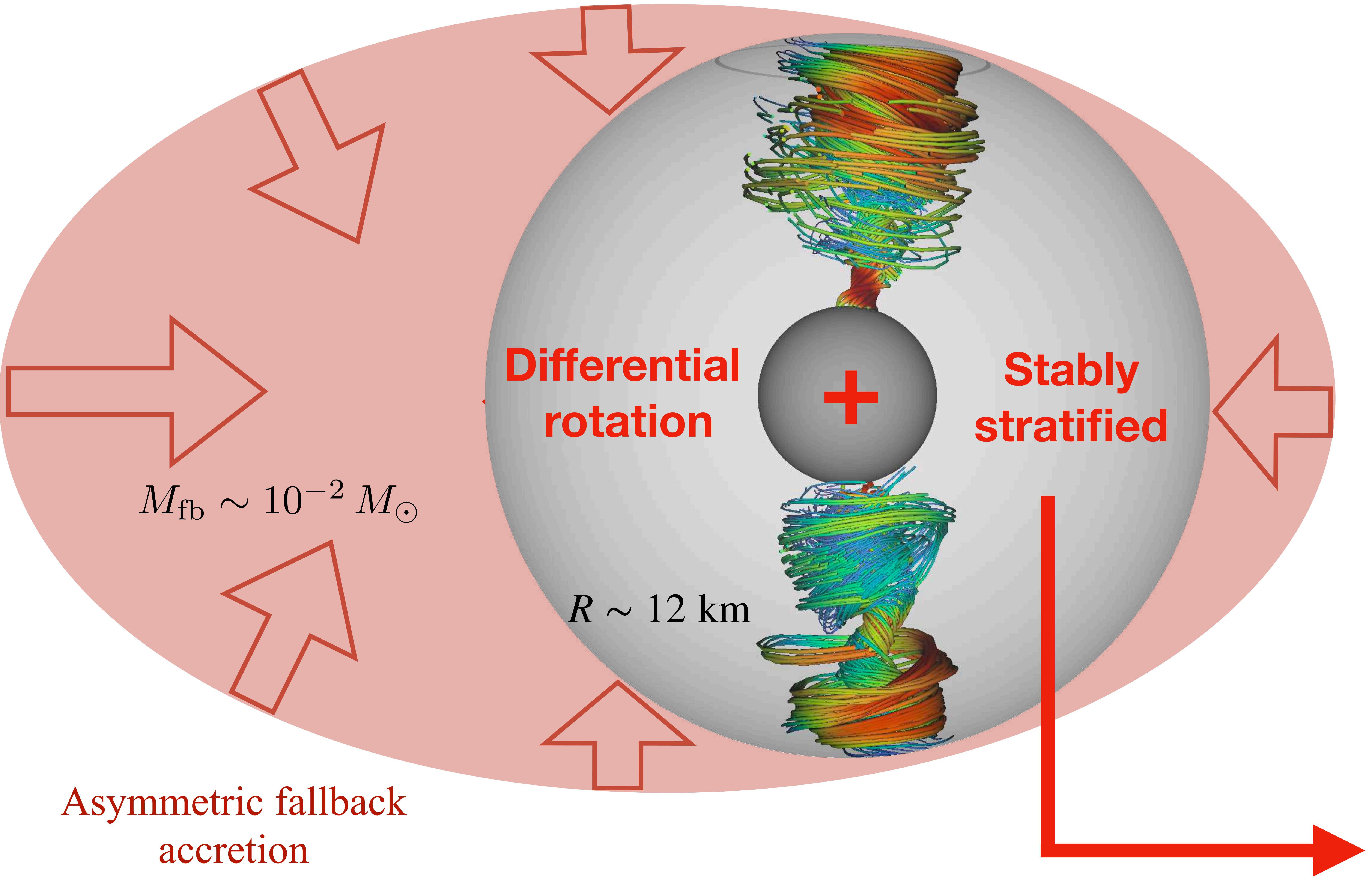


Raynaud+20,22

+ : fast rotation + strong field $\Longrightarrow$ magneto-rotational explosions

- : typical neutron star initial period ~ 0.1 s (Igoshev+22) $\Longrightarrow$ in general not fast enough, hard to explain Galactic magnetars

New scenario: proto-neutron star spun up by supernova fallback



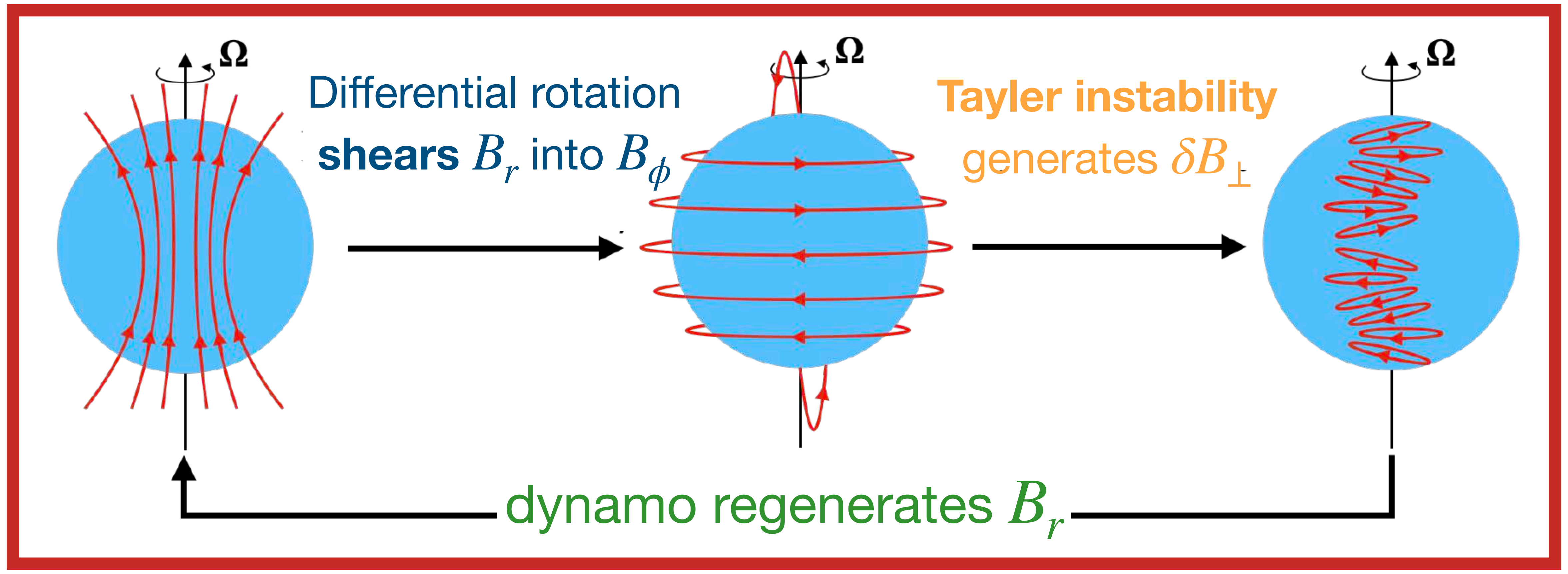
= **"Tayler-Spruit" dynamo ?**

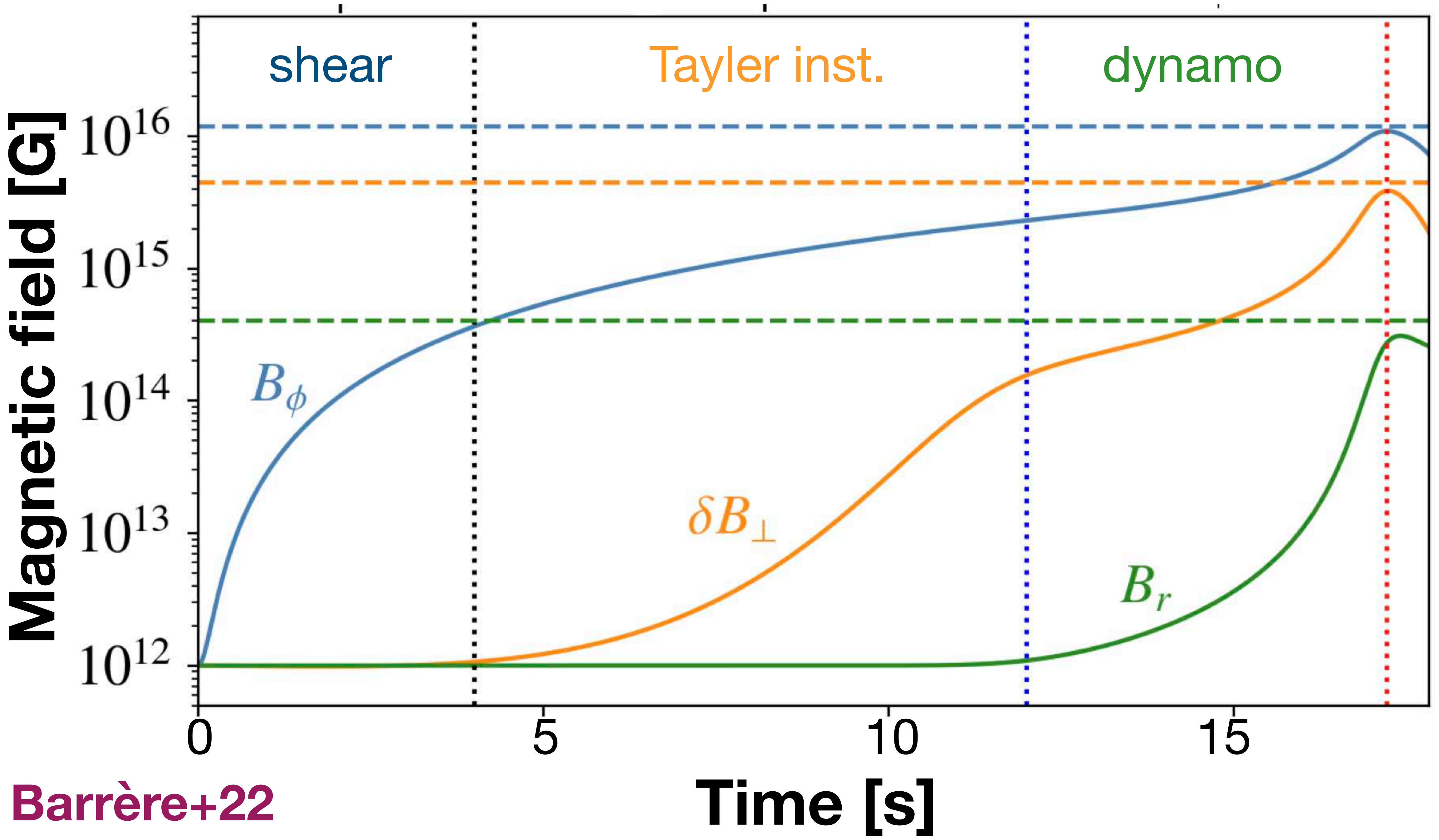
Fallback in 3D CCSN simulations

- *Fallback* = matter that remains gravitationally bound
- starts **~10 s** after the core bounce
- $M_{\text{fallback}} \in [10^{-4}, 10^{-1}]\, M_\odot$
- lasts from minutes to hours
- Potential to spin up the proto-neutron star up to break up

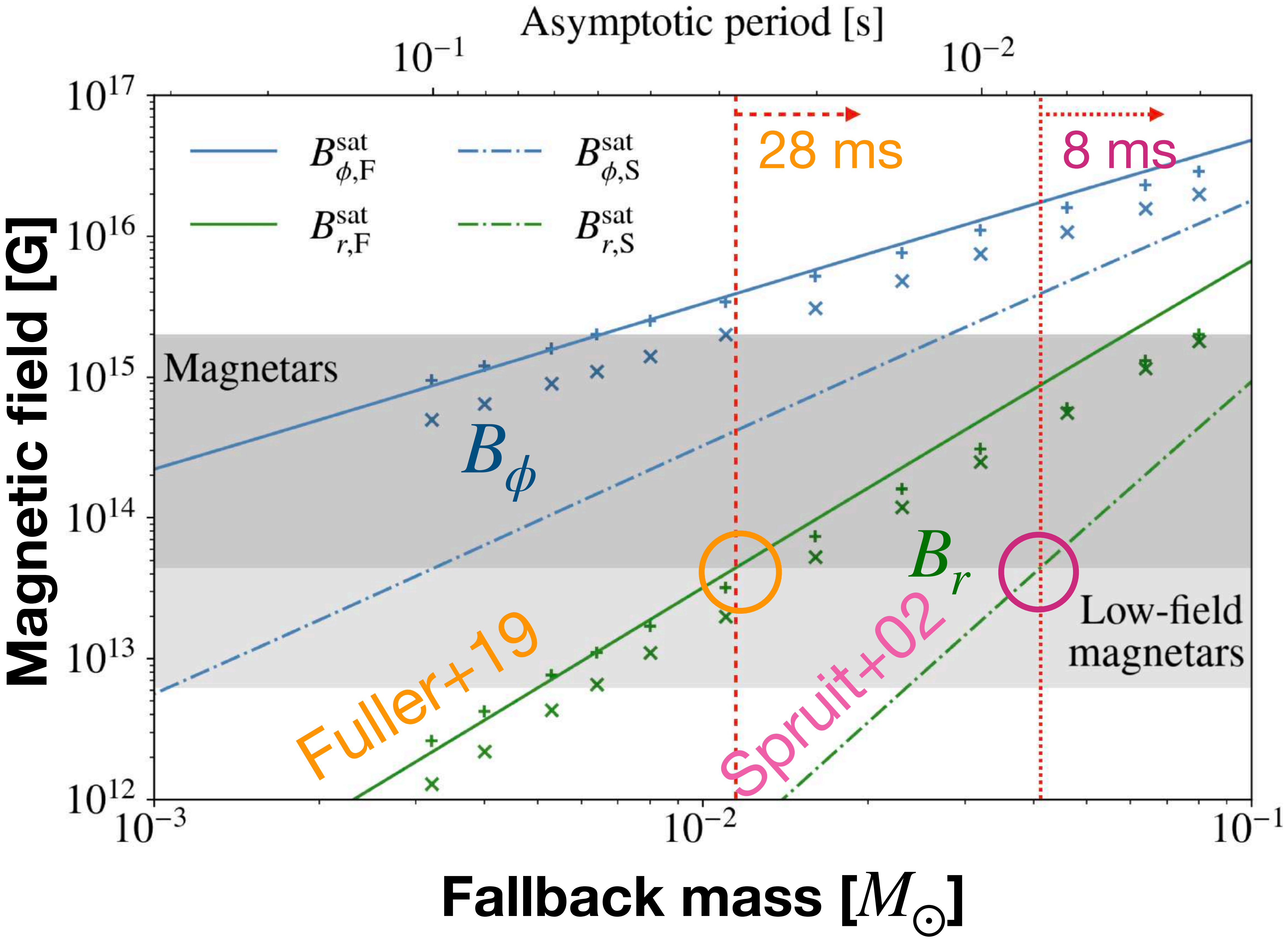
(Chan+20, Janka+22)

Tayler-Spruit dynamo loop (Spruit+02, Fuller+19)





Barrère+22



- $B_\phi \gg B_r > 4.4 \times 10^{13}$ G
  $\Longrightarrow M_{\text{fallback}} \geq [1.1 - 4] \times 10^{-2} M_\odot$
- $15 \text{ s} < \tau_{\text{sat}} < 30 \text{ s}$

3D modelling: the setup

- **Neutron star** ~ 7 s **post-bounce**
  $M \sim 1.4\ \mathrm{M}_\odot$
  $r_o = 12$ km, $P_o = 10$ ms

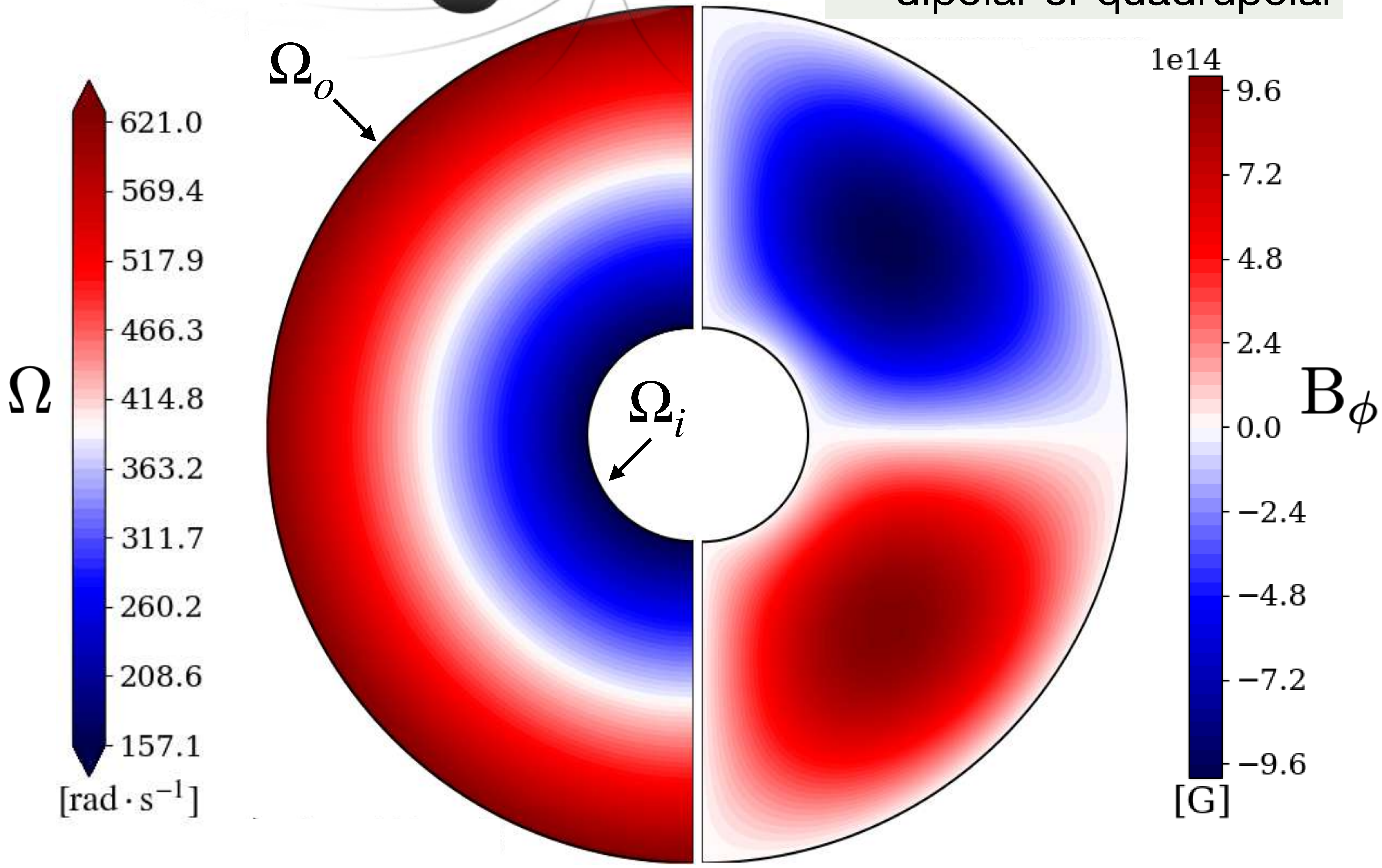
- **Boussinesq** fluid
  $Pr = \nu/\kappa = 0.1$
  $Pm = \nu/\eta = 1$

- **Stably stratified**
  $N/\Omega_o = 0.1$

- **Spherical Couette** flow
  Rossby number $Ro = \Delta\Omega/\Omega_o$
  Positive shear $\Delta\Omega = \Omega_o - \Omega_i > 0$

- **Parameter study**
  $Ro \in [0.125,\ 1.2]$

Initial magnetic field
- weak or strong
- dipolar or quadrupolar

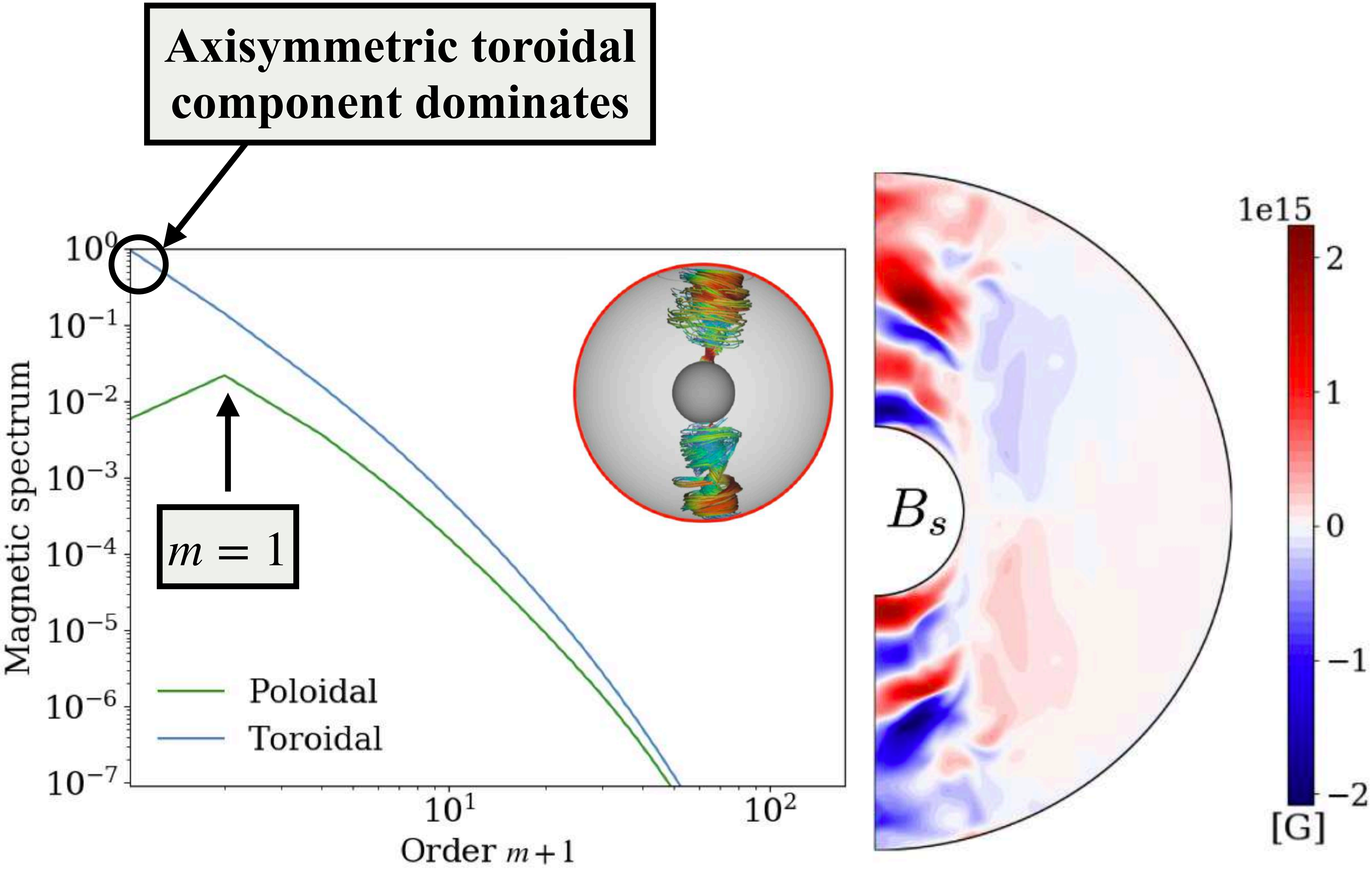


Bifurcation diagram + magnetic field topology

$\Lambda = B_{\rm rms}^2/(4\pi\rho\eta\Omega_o)$

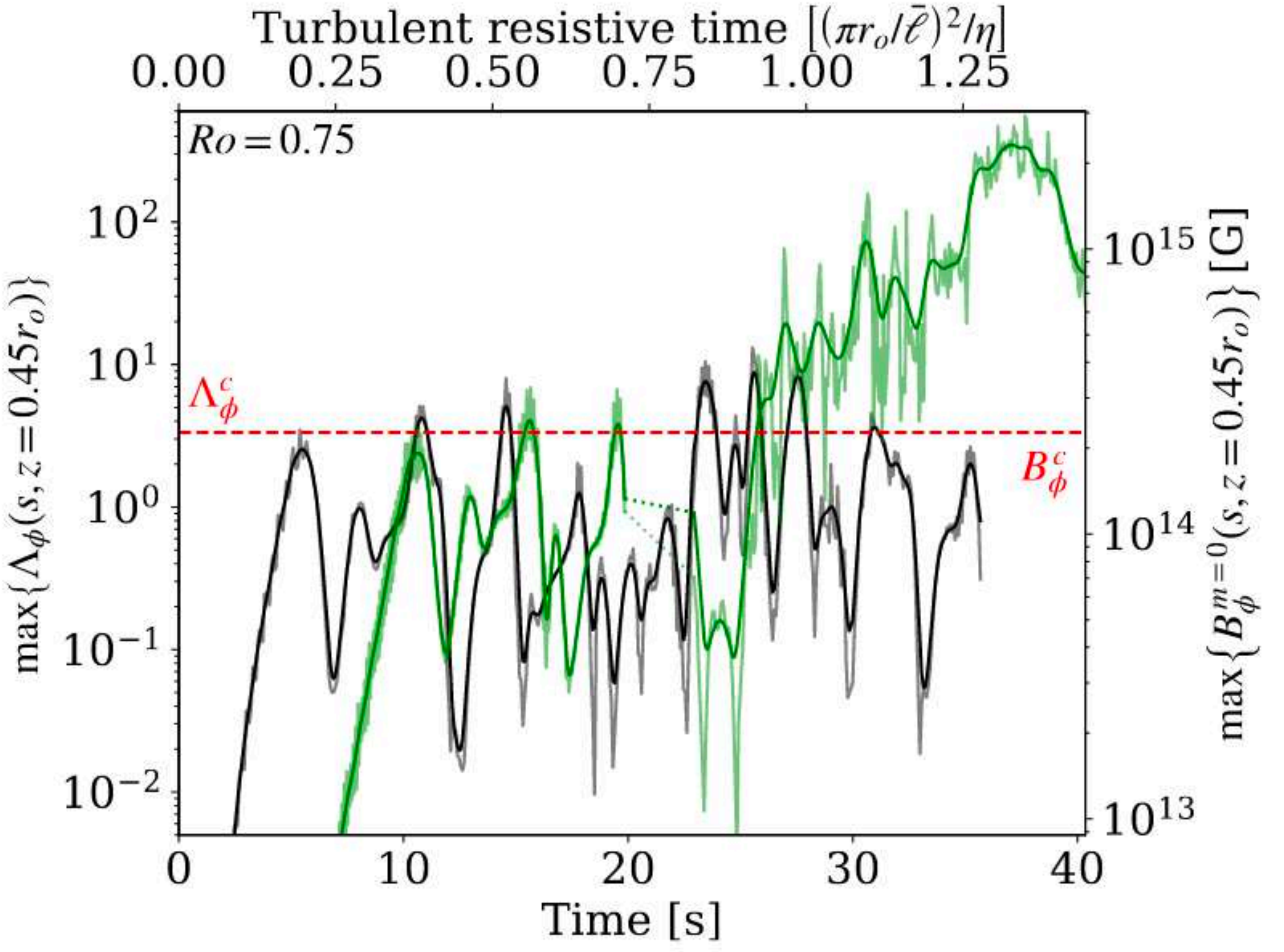
Tayler-instability driven dynamos

Field structure

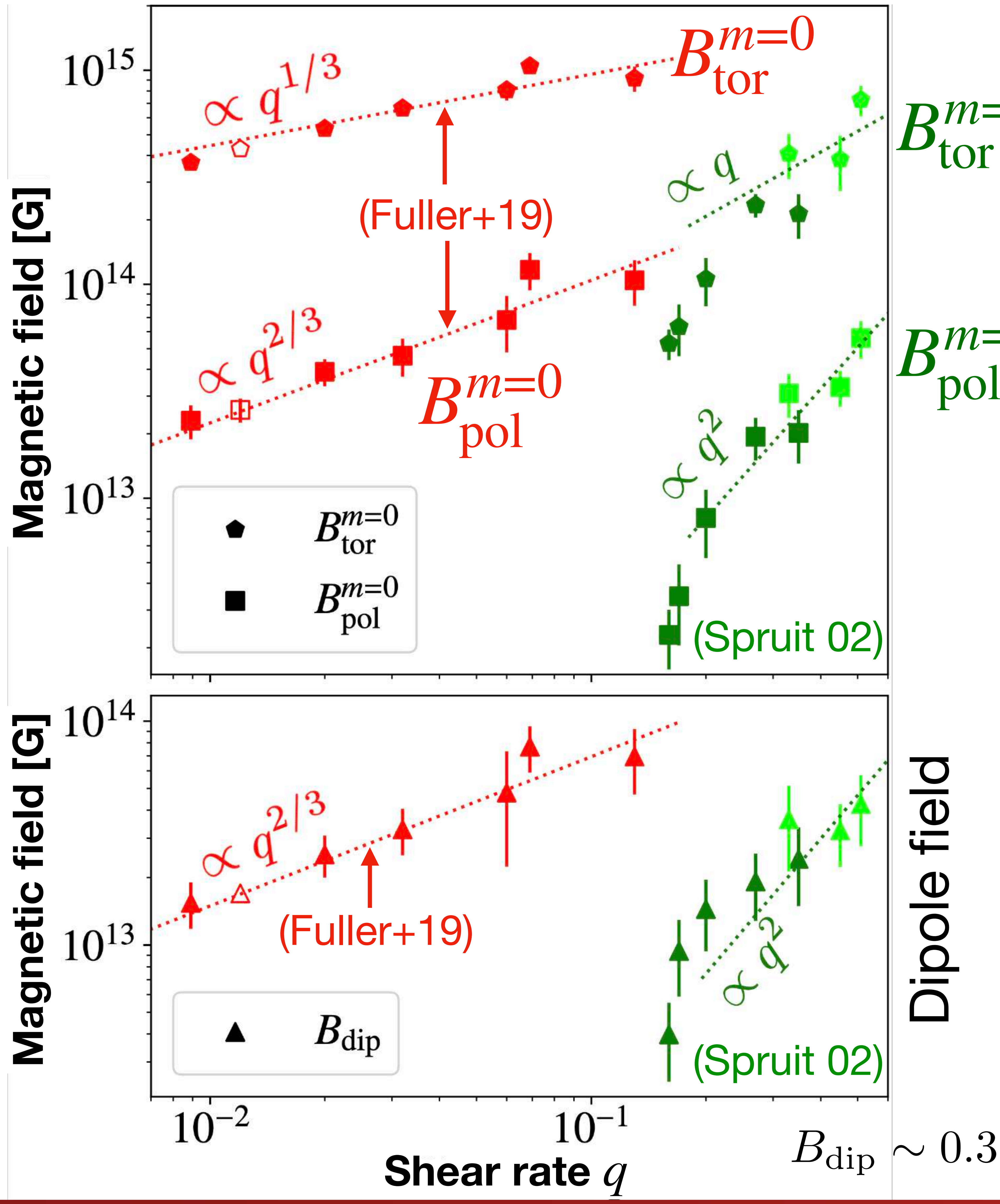


Tayler instability threshold

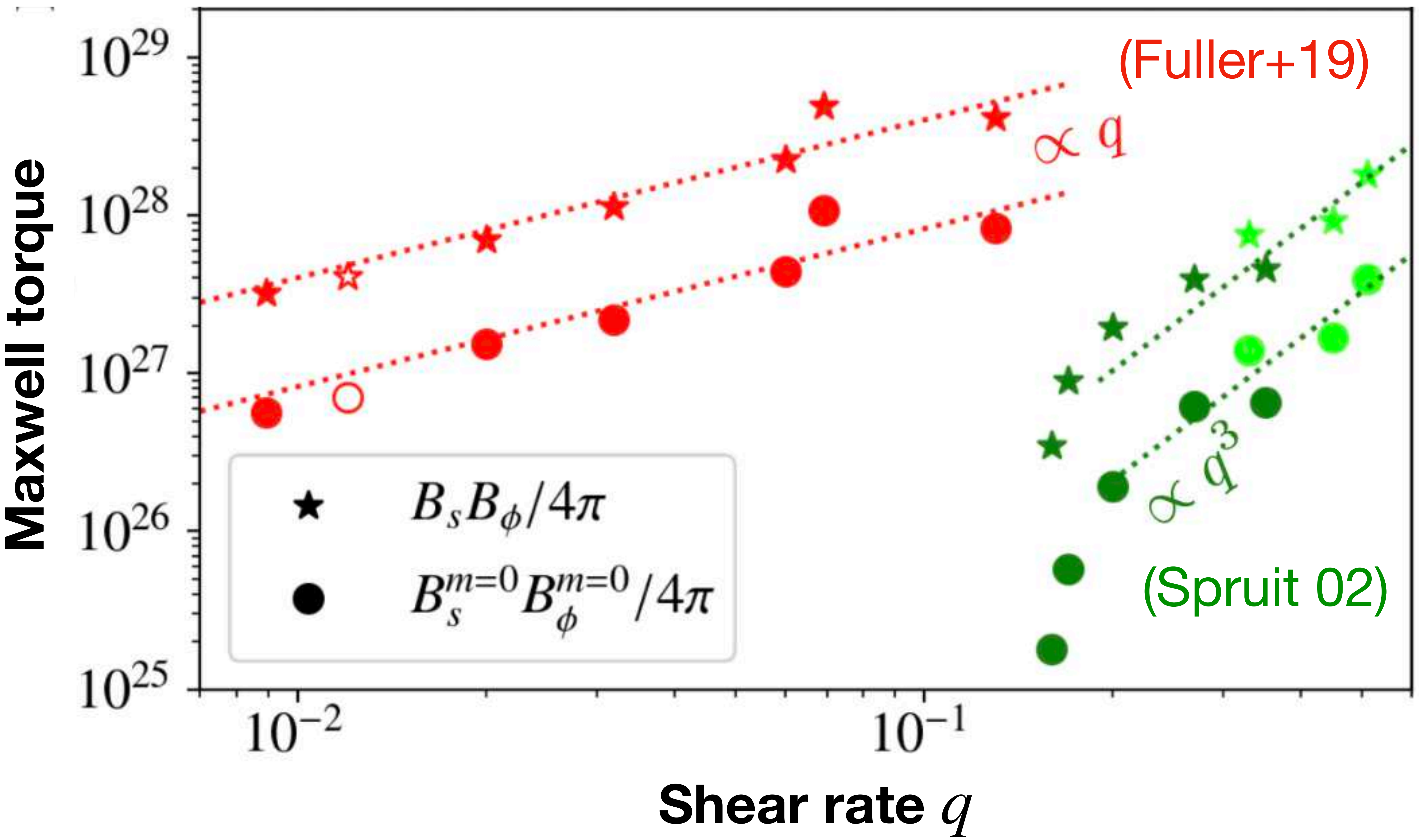
Local maximum of $E_{\mathrm{tor}}^{m=0}(z = 0.45 r_o)$



Scalings: axisymmetric magnetic field and Maxwell torque



$B_{\rm dip} \sim 0.33 B_{\rm pol}^{m=0}$



Theory

$\omega_A \ll \Omega \ll N$

Simulations

$\frac{\omega_A}{\Omega} \lesssim 0.02$ **but** $\frac{N}{\Omega} = 0.1$

Conclusions

- Proto-neutron star interiors are “dynamo friendly”, via different MHD instabilities

- Constraints to disentangle formation channels
  - Direct / indirect observations on the B field
  - Environment (e.g. magnetar - SNR association)
  - Statistical constraints on magnetar birth rates
  - Central engines of extreme explosions (SVOM is coming)

- Various models point towards extreme conditions (concerning progenitor magnetisation / rotation)

- In tension with actual (high) rate of magnetar formation

- **Promising new scenario:** proto-neutron star spun by CCSN fallback

- $B_{\rm dip} \sim 3 \times 10^{14}$ G and $B_{\rm tor} \sim 2 \times 10^{15}$ G

- Confirmation of a 20 years old dynamo mechanism with state-of-the art 3D MHD simulations
  - Stellar physics: Petitdemange+23a,b (with a *negative* shear)
  - In proto-neutron stars: Barrère+23 (with a *positive* shear)

2 dynamo branches:
- dipolar vs hemispherical symmetry
- different theoretical scalings Fuller+19 vs Spruit 02

References

magnetar formation…

Tayler-Spruit dynamo

1. Barrère+23, MNRAS, (2306.12296)
2. Barrère+22, A&A, (2206.01269)

MRI and convective dynamo

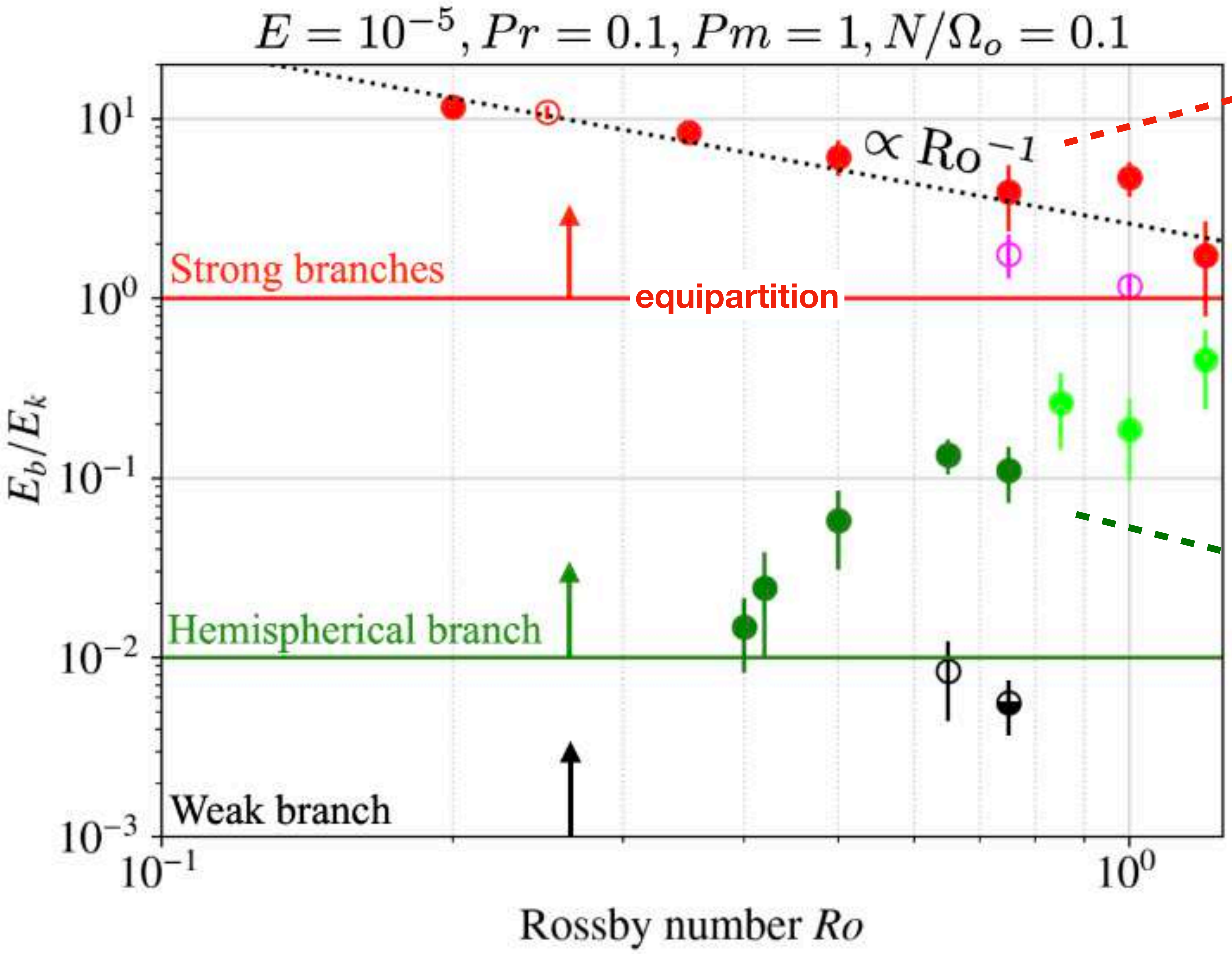
1. Kiuchi, Reboul-Salze+22, (2306.15721)
2. Reboul-Salze+22, MNRAS, (2111.02148)
3. Reboul-Salze+21, A&A, (2005.03567)
4. Raynaud+22, MNRAS, (2103.12445)
5. Raynaud+20, Sci. Adv., (2003.06662)

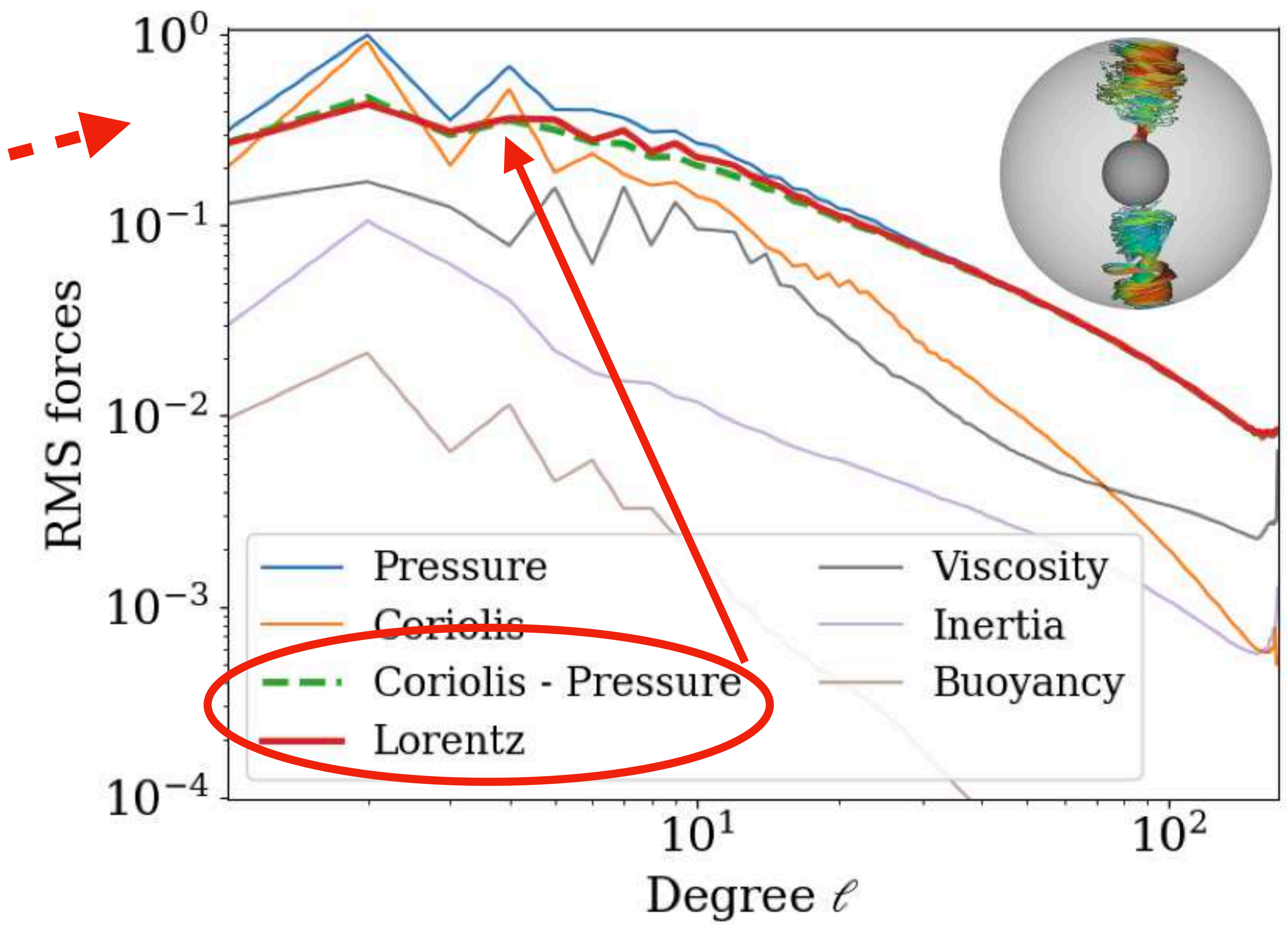
… and more…

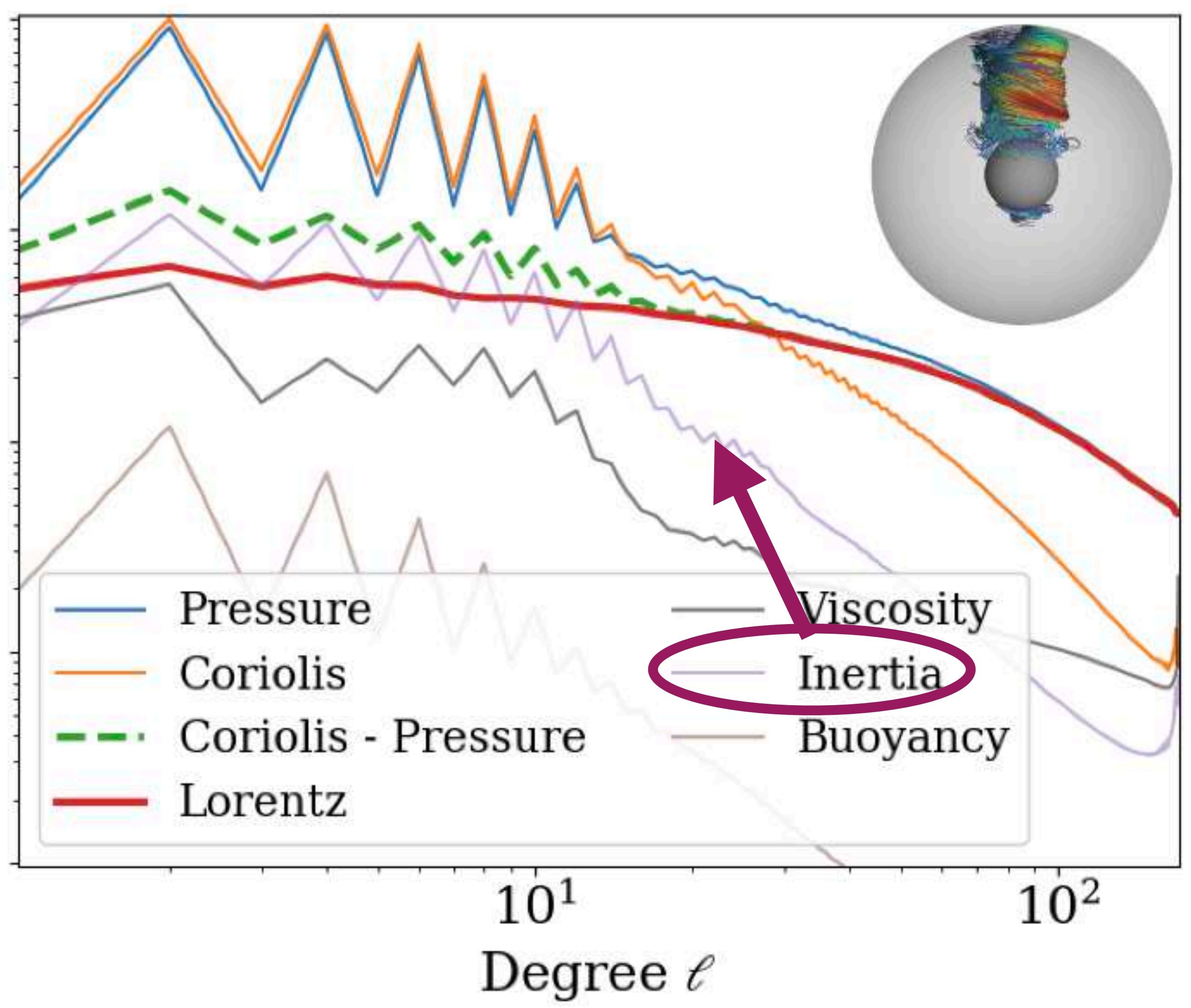
Magneto-rotational explosions

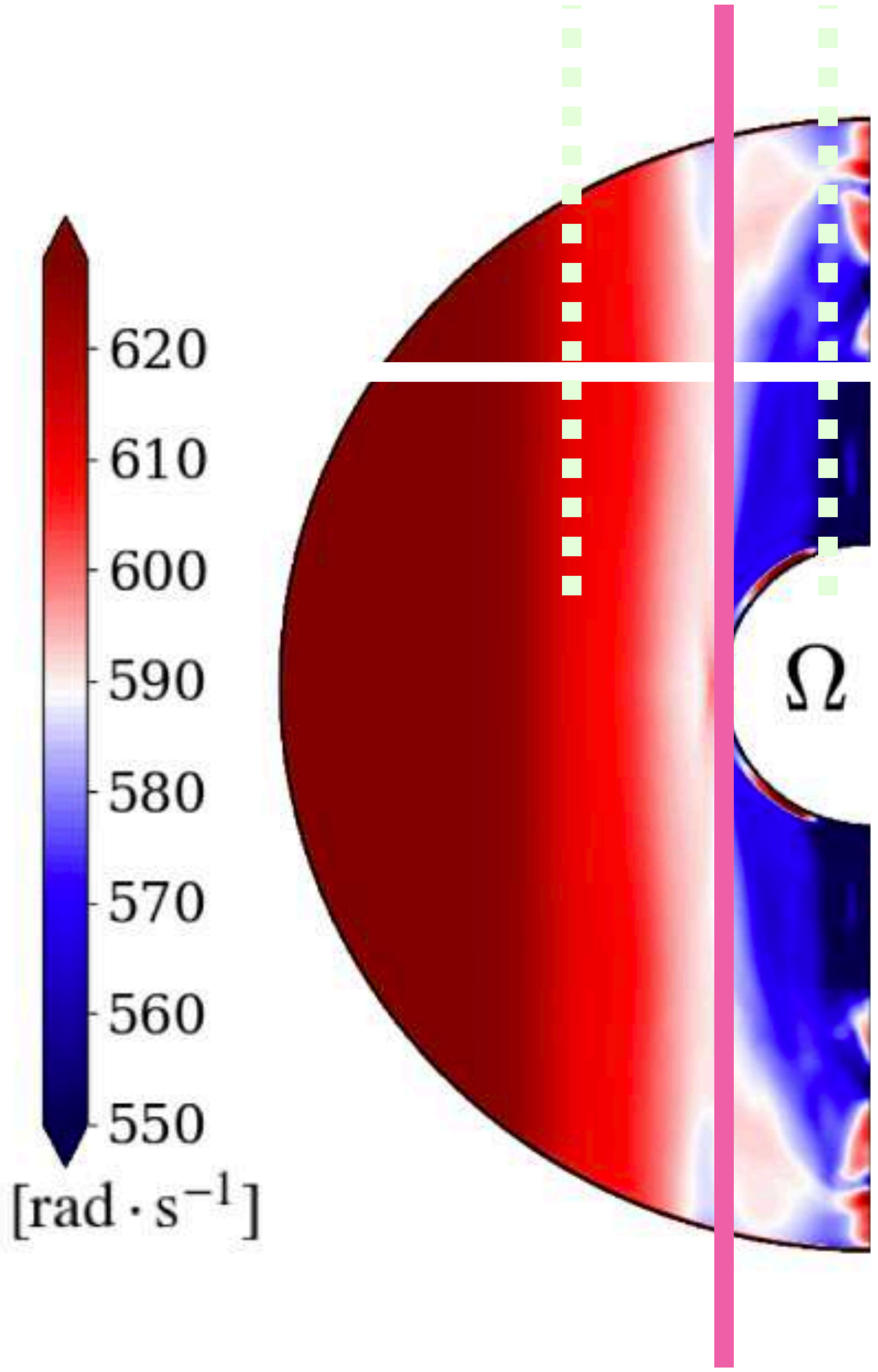
1. Bugli+23, MNRAS, (2210.05012)
2. Bugli+21, MNRAS, (2105.00665)
3. Bugli+20, MNRAS, (1909.02824)

Appendix: force balance

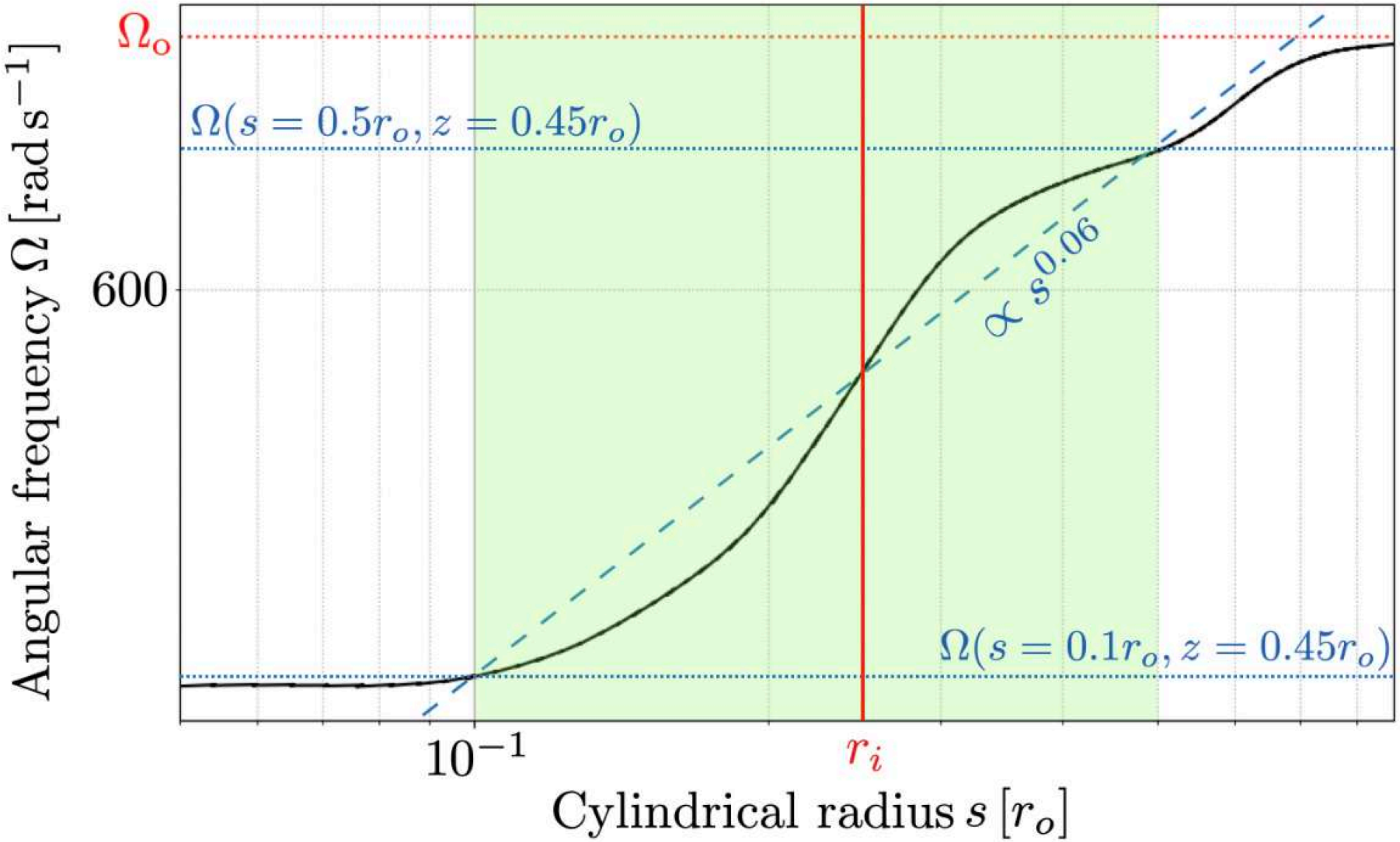






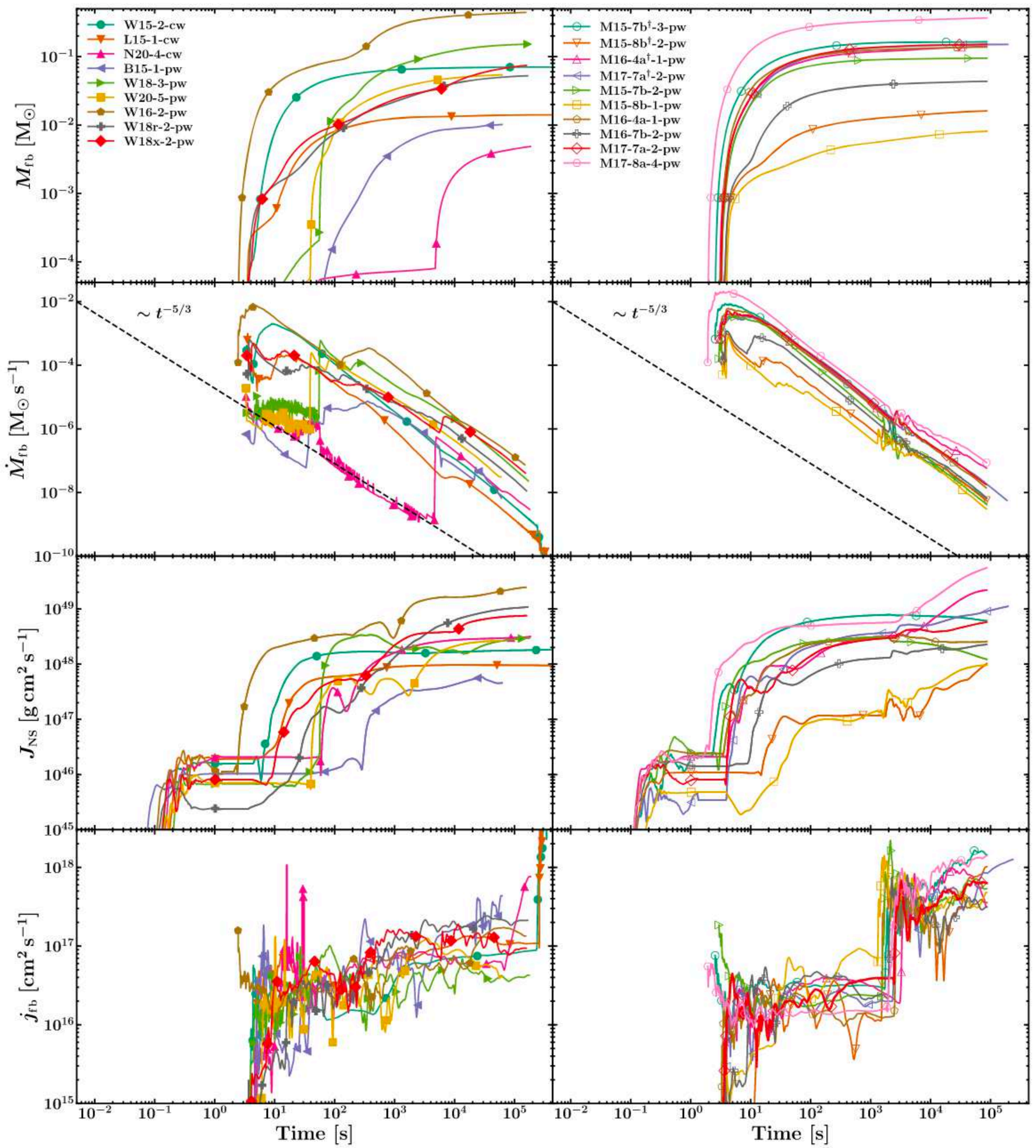


Time-averaged rotation profile at $z = 0.45 r_o$



Appendix: fallback properties

THE ASTROPHYSICAL JOURNAL, 926:9 (30pp), 2022 February 10 Janka, Wongwathanarat, & Kramer

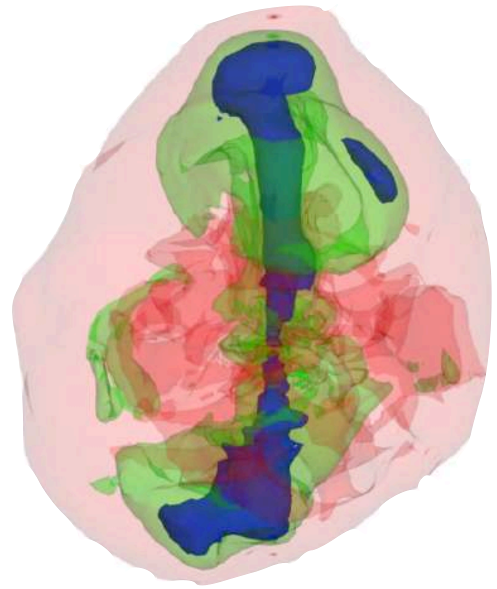


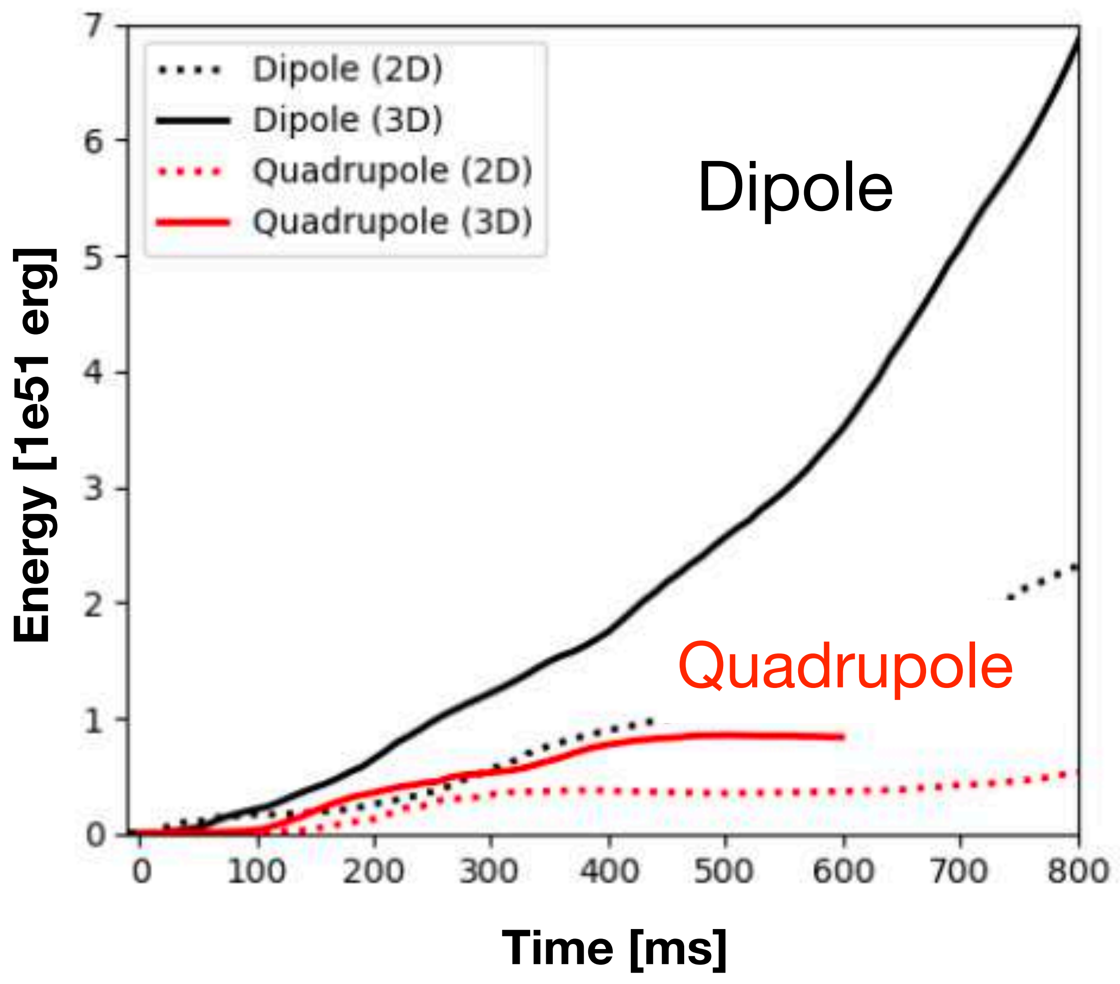
Appendix: magneto-rotational explosions

Impact of the magnetic field geometry

Axial dipole

Equatorial dipole

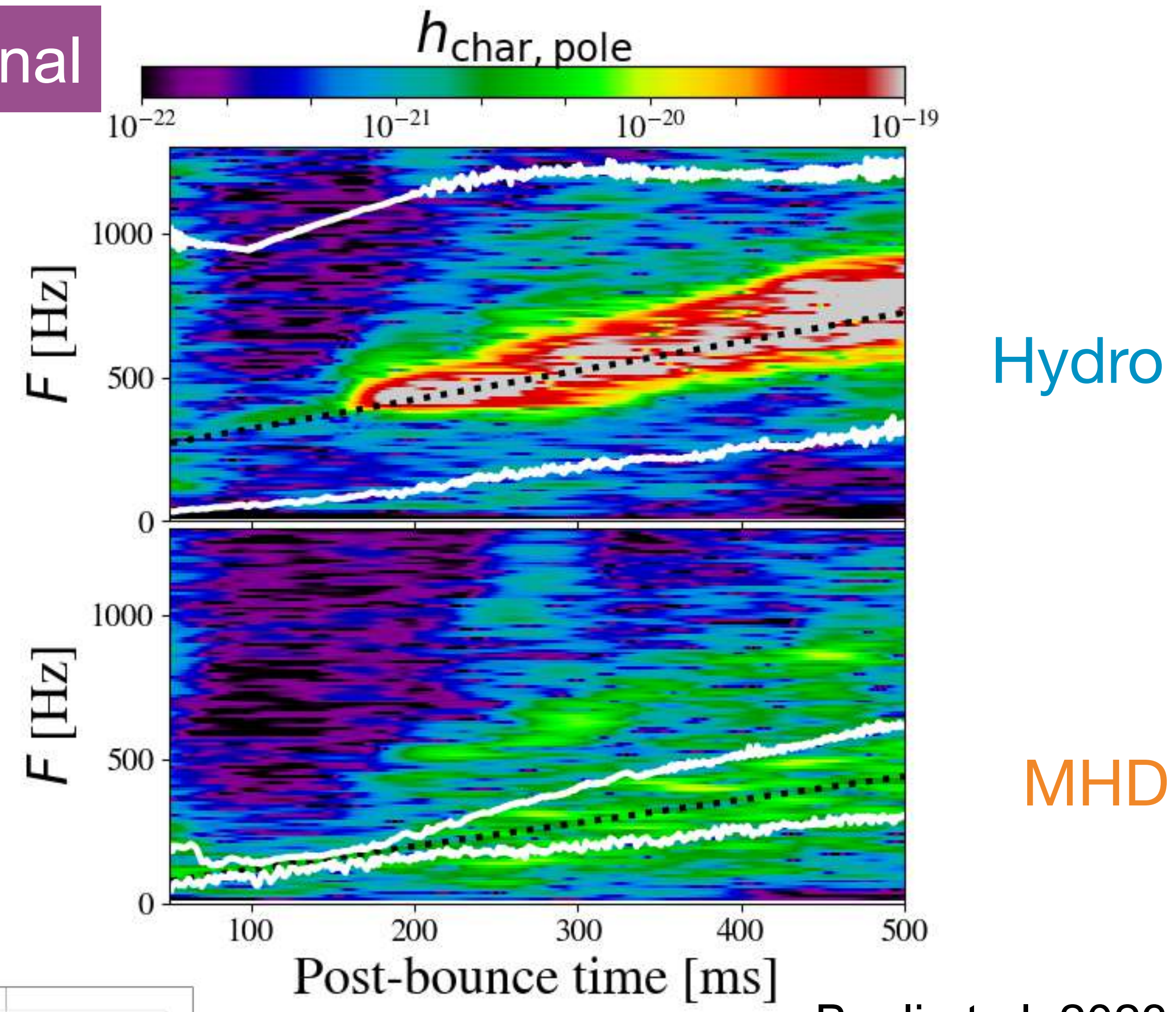




Bugli et al. 2020, 2021

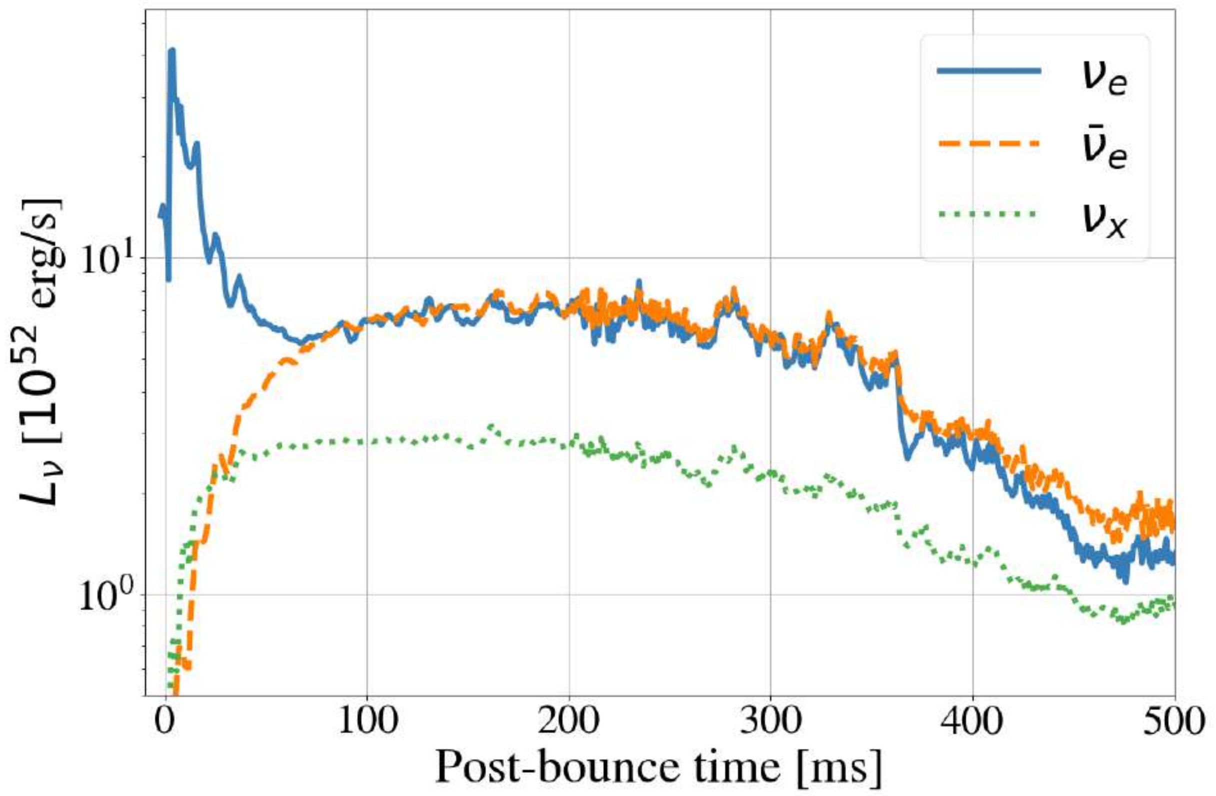
Multi-messenger signature

GW signal

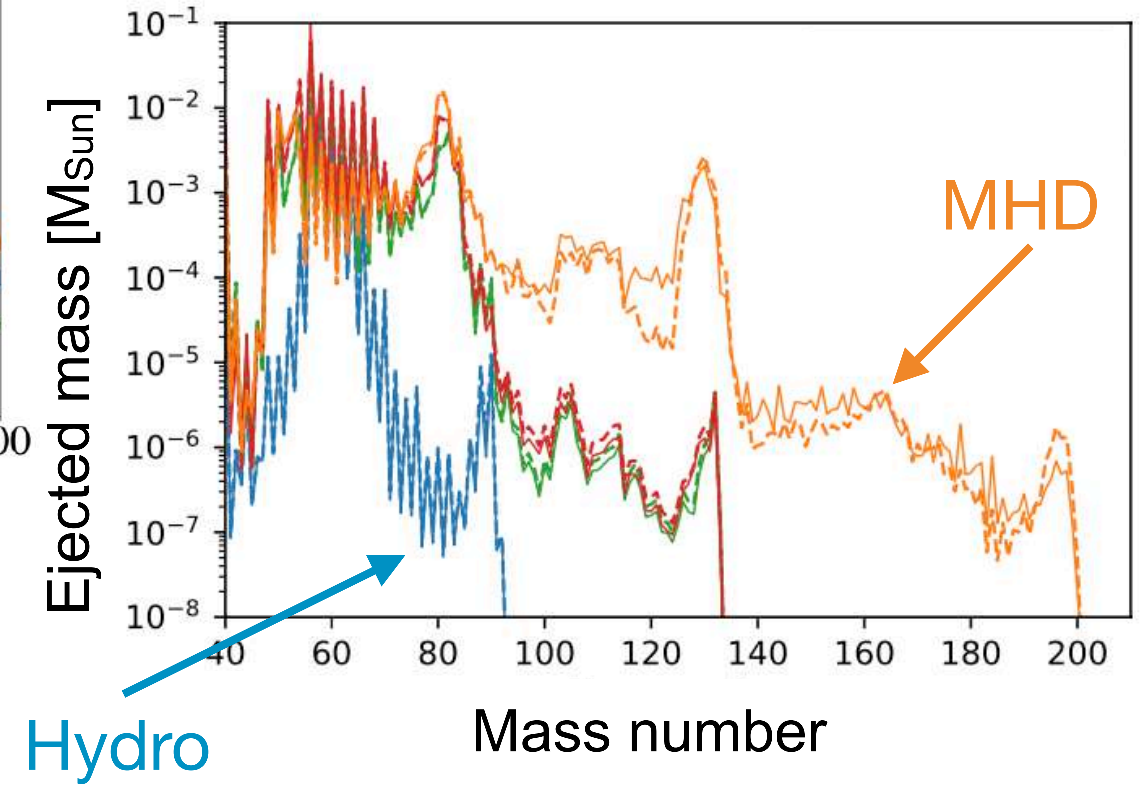


Bugli et al. 2023

Neutrino signal



Nucleosynthesis



Reichert, Bugli et al. 2023