3D MHD core-collapse progenitors:

Rotation, magnetic-field amplification, and magnetic topology.

Adam Griffiths

In colloboration with

Miguel Ángel Aloy Torás   Martin Obergaulinger

Keele collaborators: Raphael Hirschi , Vishnu Varma , Em Whitehead , Kate Goodman

Keele UNIVERSITY

VNIVERSITAT DE VALÈNCIA

MINISTERIO DE CIENCIA E INNOVACIÓN

Financiado por la Unión Europea

Plan de Recuperación, Transformación y Resiliencia

AGENCIA ESTATAL DE

Motivation for 3D MHD supernova progentiors

Setup of simulations performed

Key takeaways for magnetic fields

All Results from: (In peer review)

Griffiths et al. 2026a

Griffiths et al. 2026b

Motivation: Core collapse supernova

Massive stars:
$M_{\mathrm{ZAMS}} \gtrsim 8M_{\odot}$

Nuclear fusion:
$\mathrm{H} \rightarrow \mathrm{Fe}$

Core unstable: Gravitational collapse

Supernova explosion: $10^{51-52}\,\mathrm{erg}$

Leftovers: Supernova remnant + compact object (BH/NS)

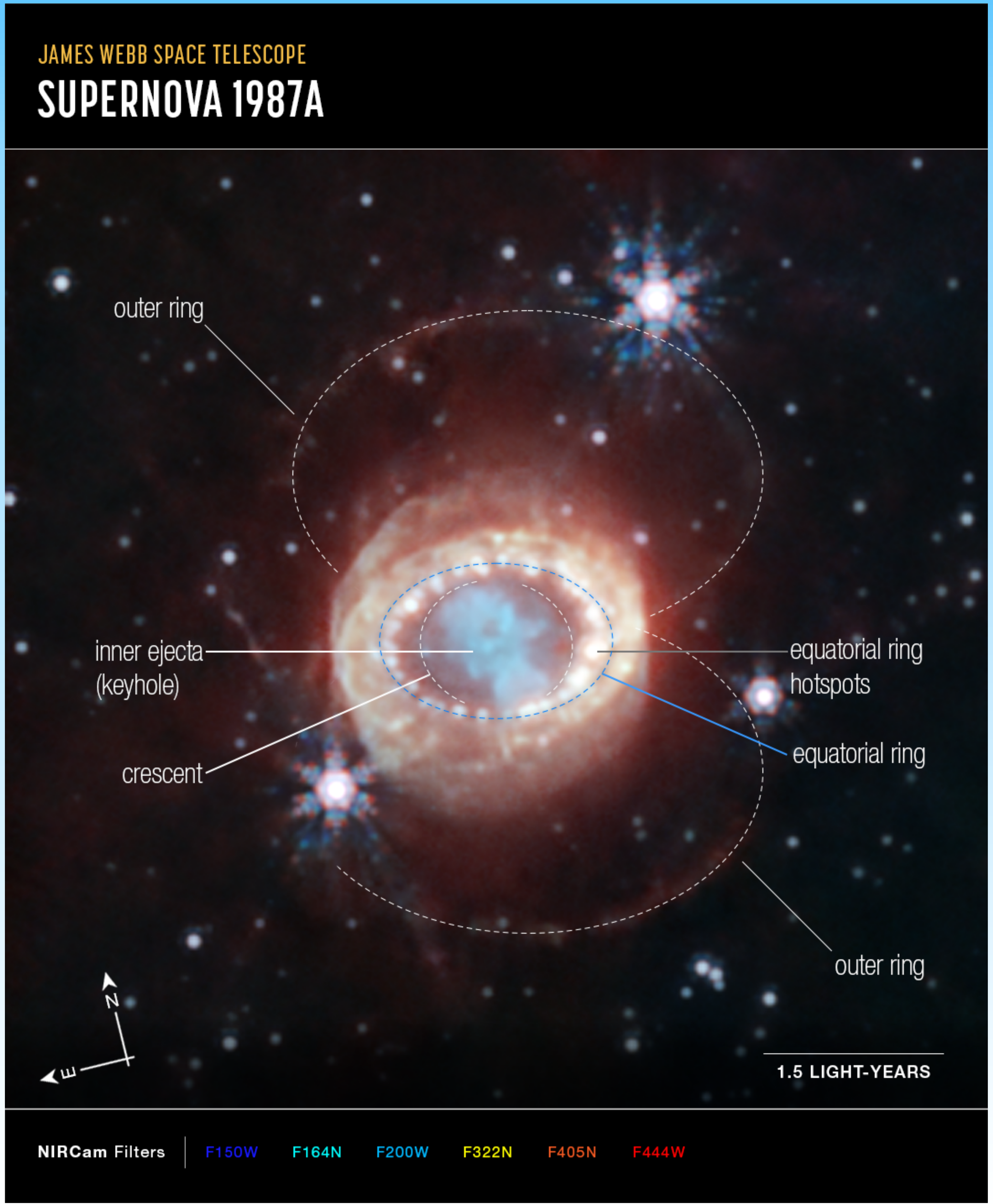
BINARY progenitors!

1D Stellar evolution codes (Spherical symmetry)

GENEC and MESA in this work

Many free parameters + unknowns

Credit: NIRCam 2022



Motivation: The pre-collapse magnetic field

Stellar evolution modelling is a 1D & approximate game!

Supernova explosion dynamics/ mechansim sensitive to magnetic field assumptions at collapse.

See Obergaulinger and Aloy III. 2021

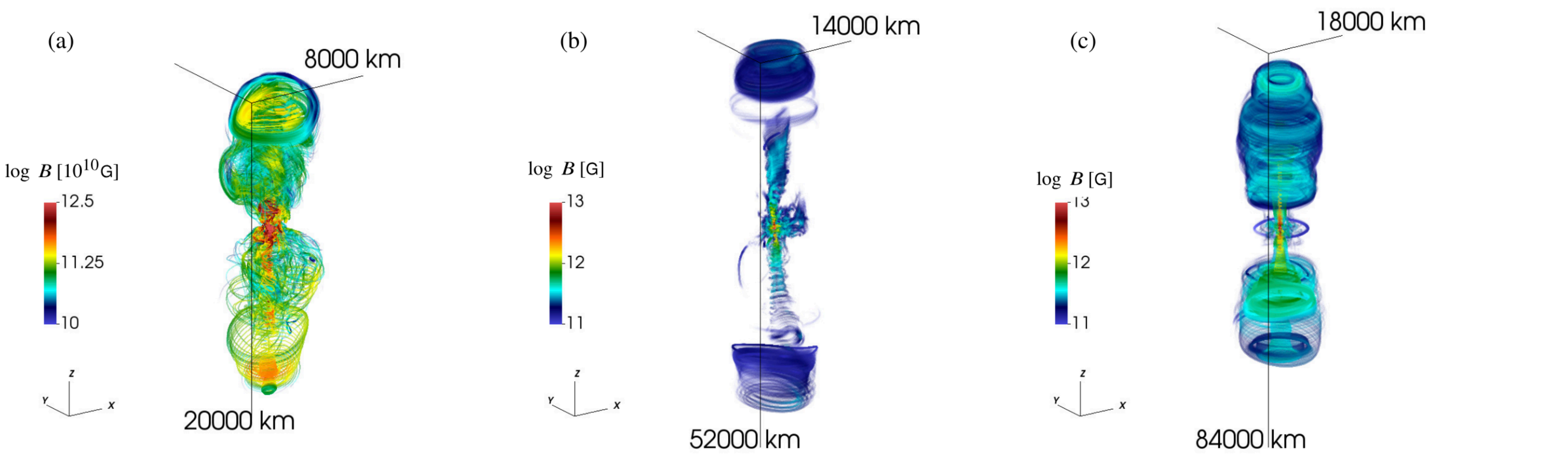


Figure 22. Field lines in the jets of models O, P, and S (left to right) at the end of the simulations with the colour indicating the field strength.

The field geometry chosen also impacts explosions mechanisms and nucleosynthesis.

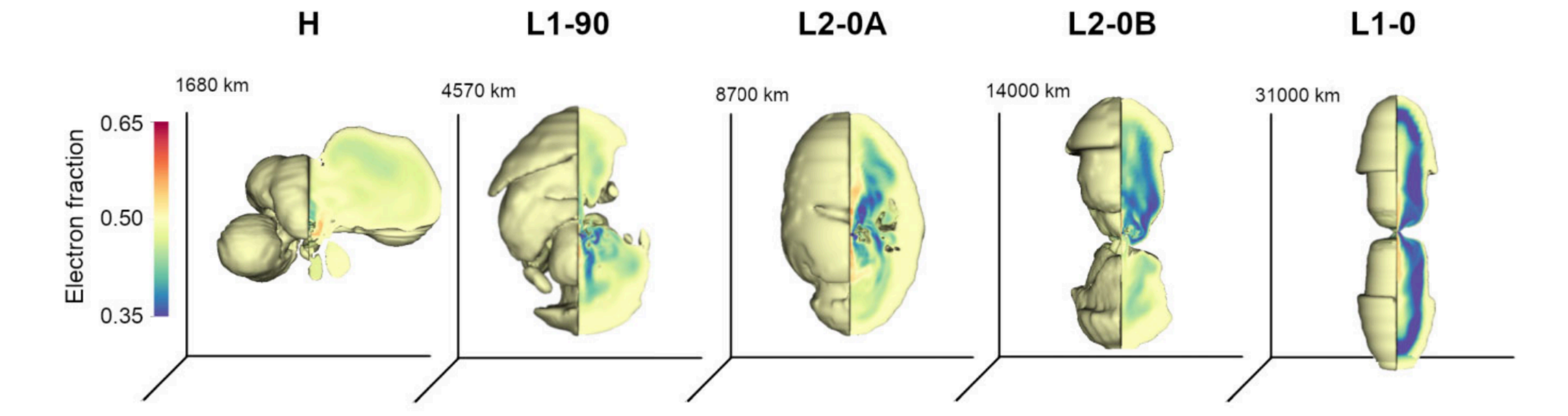


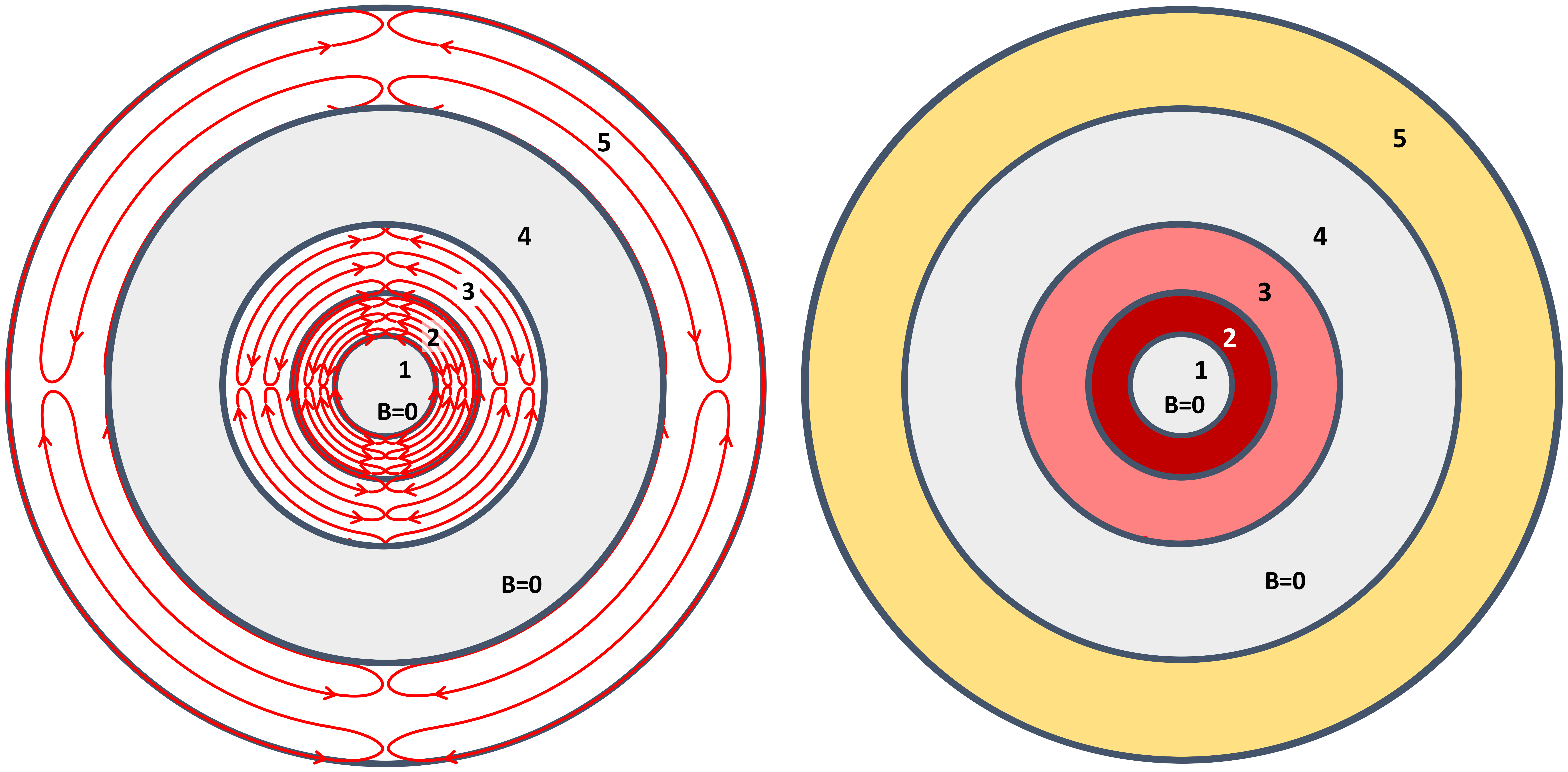
Figure 1. Electron fraction of the ejecta from the different models at the end of the simulation. The models are roughly ordered from least (left) to most (right) jet-like. This coincides with the neutron-richness of the model.

See Reichert et al. 2024 and Bugli et al. 2020

Which regions of the star are even magnetised ?

Radiative shells:
Assume devlopement of magnetic instabilities like MRI/TS dynamo

Convective regions:
Assume flux disipation/ explusion. Does it still hold at late times?



See Griffiths et al. 2022

Motivation: The need for 3D models

General Strategy: 321D

SE models initialises 3D simulation.

1D

How to do this with mangetic fields ?

3D

See for example velocity field initilisation:

Varma et al. 2025

See for example implementation of convective boundary mixing:

Whitehead et al. 2025

With 3D results we guide/correct the 1D assumptions to get better initial conditions

Simulations performed

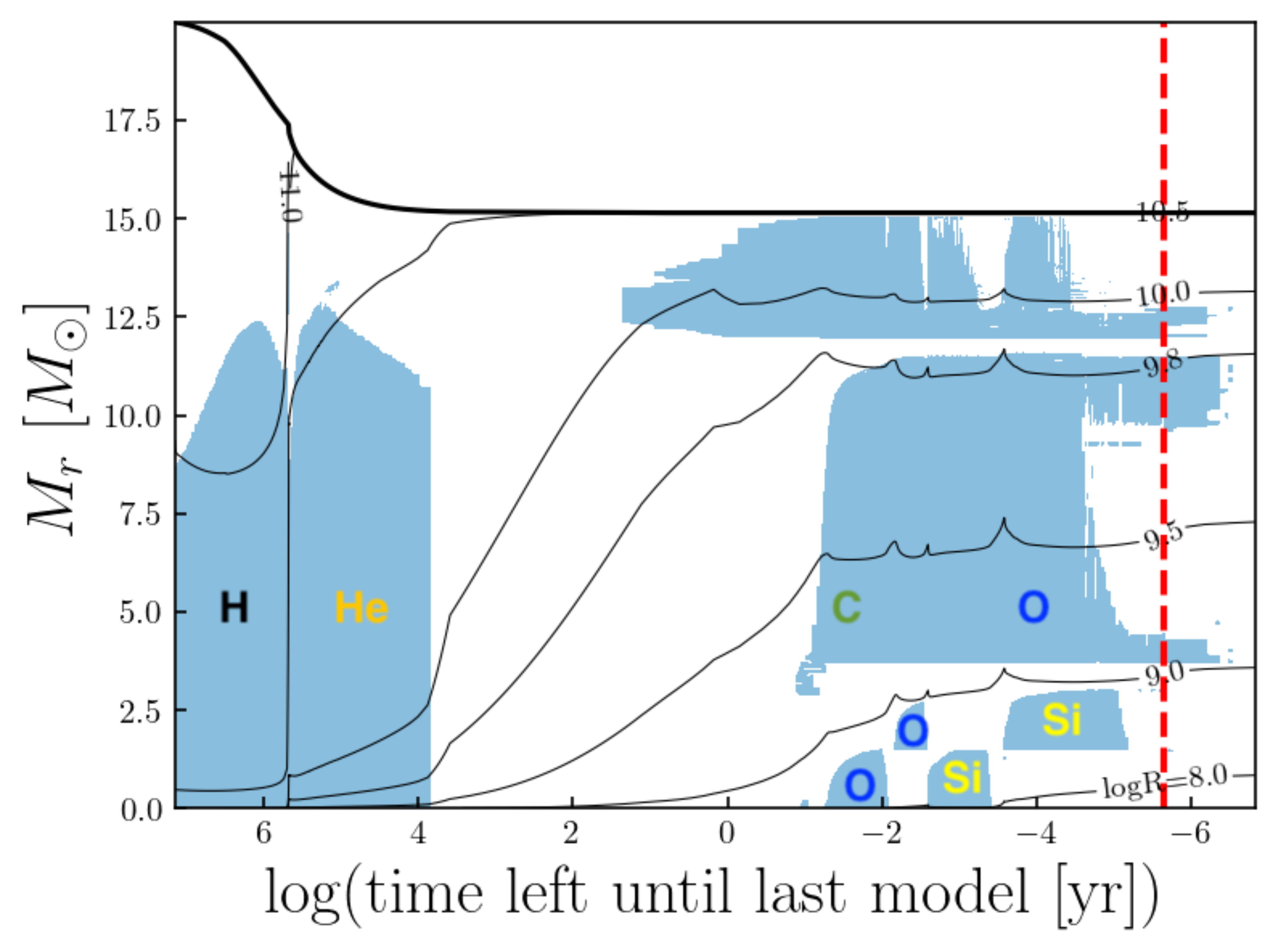
Initial conditions

GENEC model (G20)

$M_{\rm ini} = 20 M_\odot$ $Z_{\rm ini} = Z_\odot/10$ $v_{\rm ini} = 460 \text{ km s}^{-1}$

TS dynamo + MRI

(Eggenberger 2022) (Griffiths 2022)



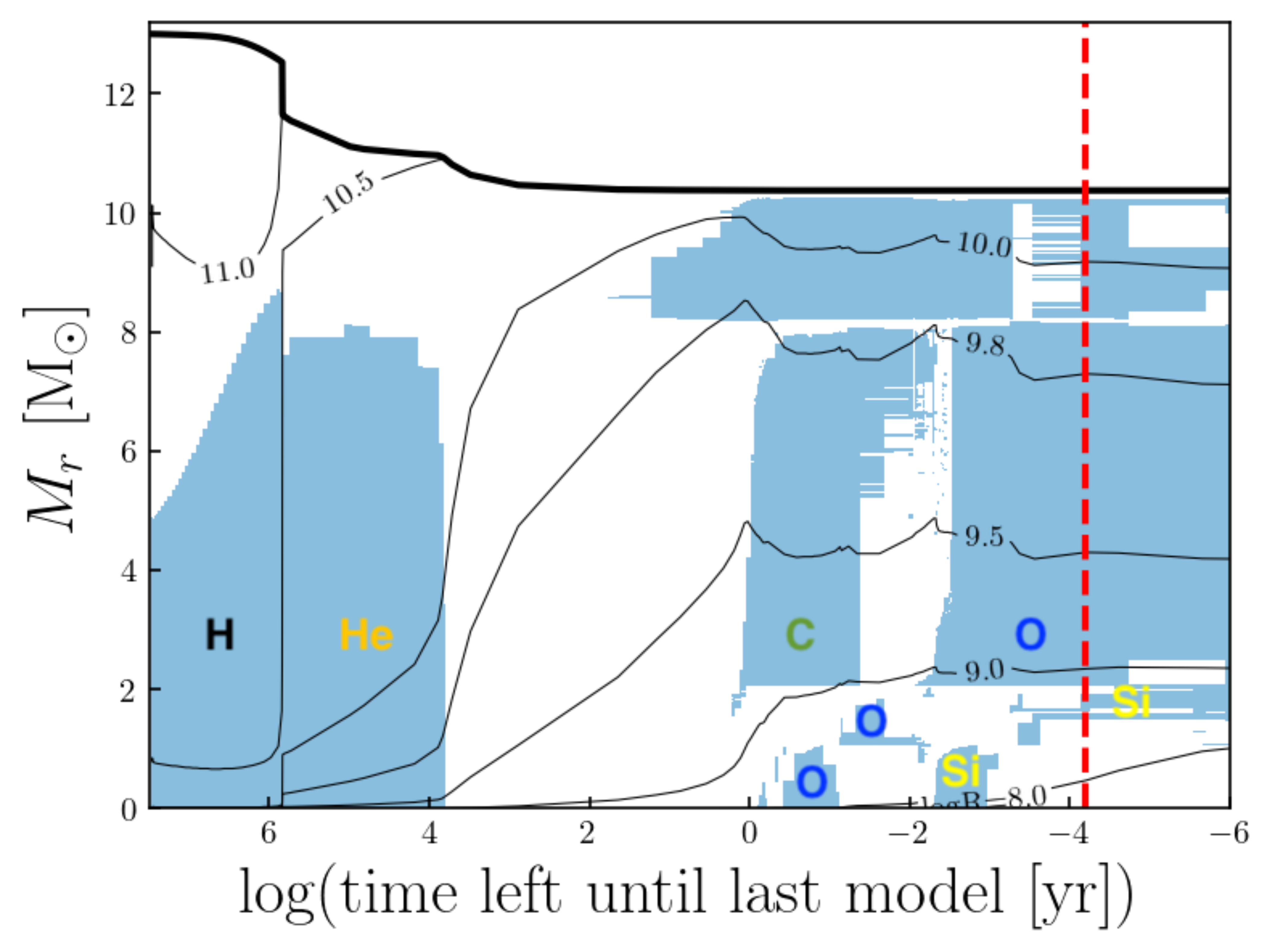
MESA model (M13)

(Aguilera Dena 2020)

$M_{\rm ini} = 13 M_\odot$ $Z_{\rm ini} = Z_\odot/50$ $v_{\rm ini} = 600 \text{ km s}^{-1}$

TS dynamo (Heger 2005)

Boosted chemical mixing



Simulations performed

Code used

3D MHD code: Aenus-Alcar

(Obergaulinger & Aloy 2020)

HLLC/MP5 with Low Mach fix up

(Chen 2019)

Reaction network: ReNet : 28 species ~ SE

(See Navo 2023)

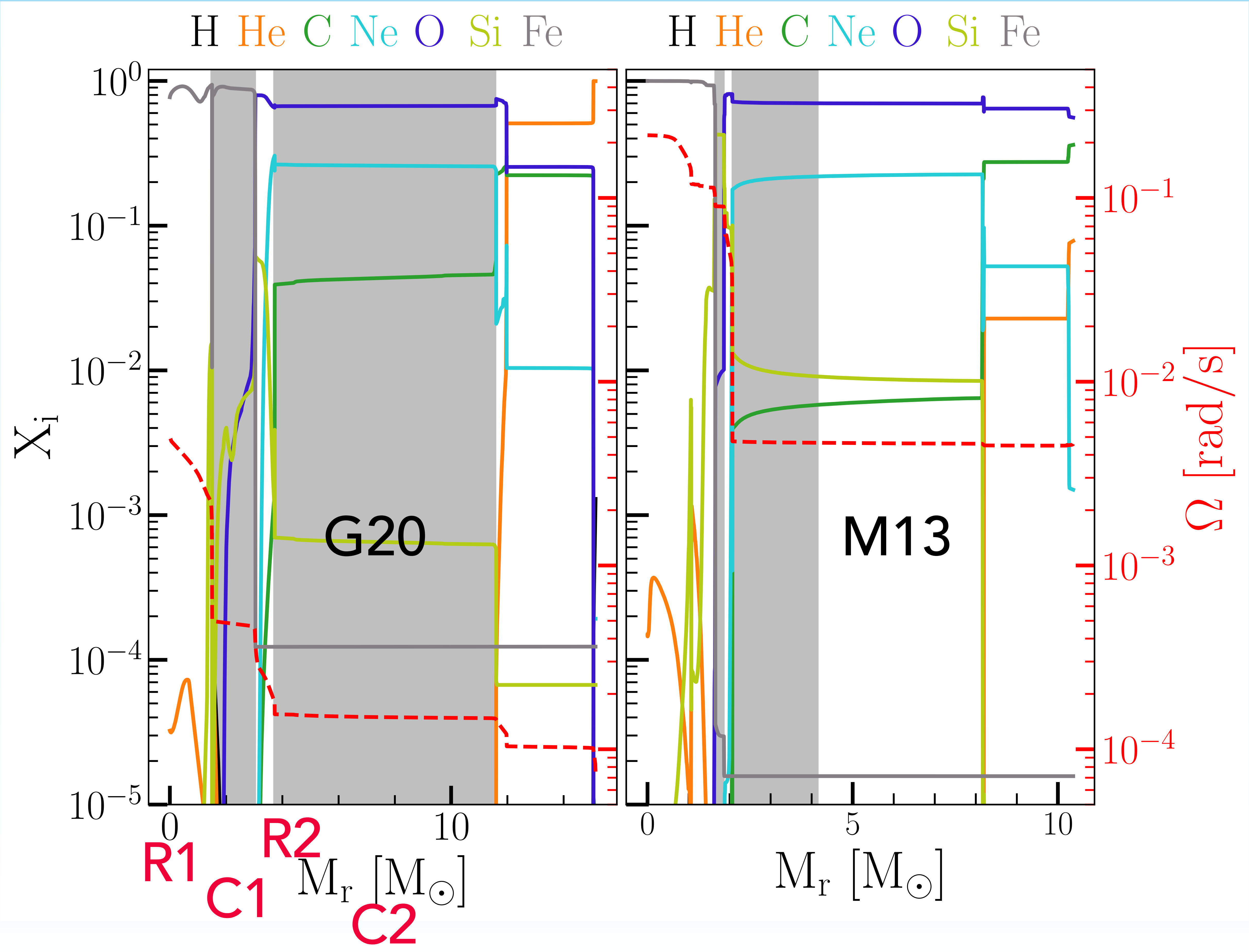
Numerical setup

$(n_r, n_\theta, n_\phi) = (640, 128, 256)$ $\quad r_{\min} = 7.5\,\mathrm{km}$

$\Delta t_{ini} \approx 1.4\,\mathrm{ms}$ $\quad \Delta t_{fin} \approx 0.9\,\mathrm{ms}$

Total simulation time: G20 3mins & M13 5mins

Structure at Mapping



Magnetic fields

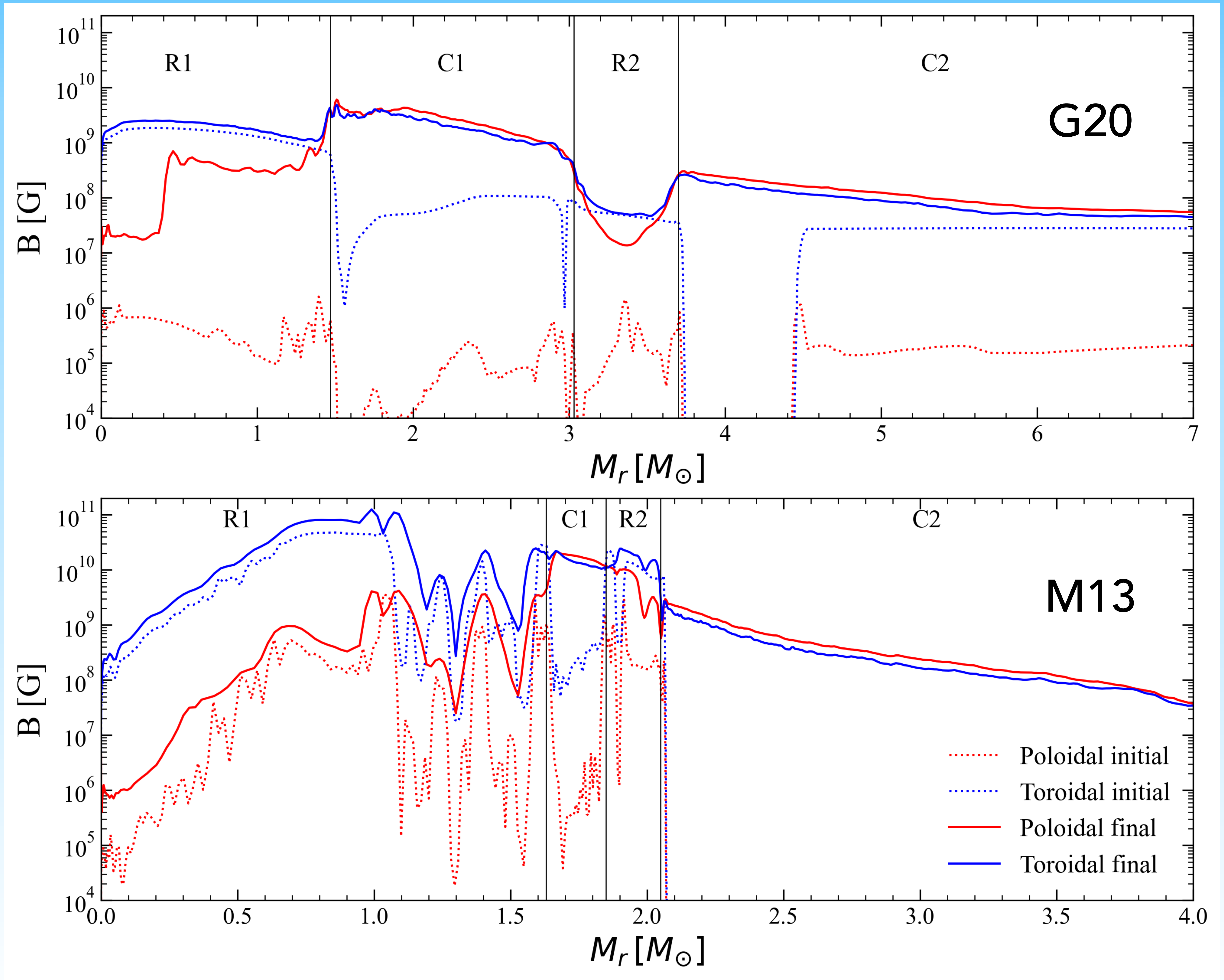
Convective regions rapidly magnetised

Saturation of shear type instability:

$$B_{\rm sat}^2 \sim \rho r^2 \Omega^2 \left| \frac{d \ln \Omega}{d \ln r} \right|$$

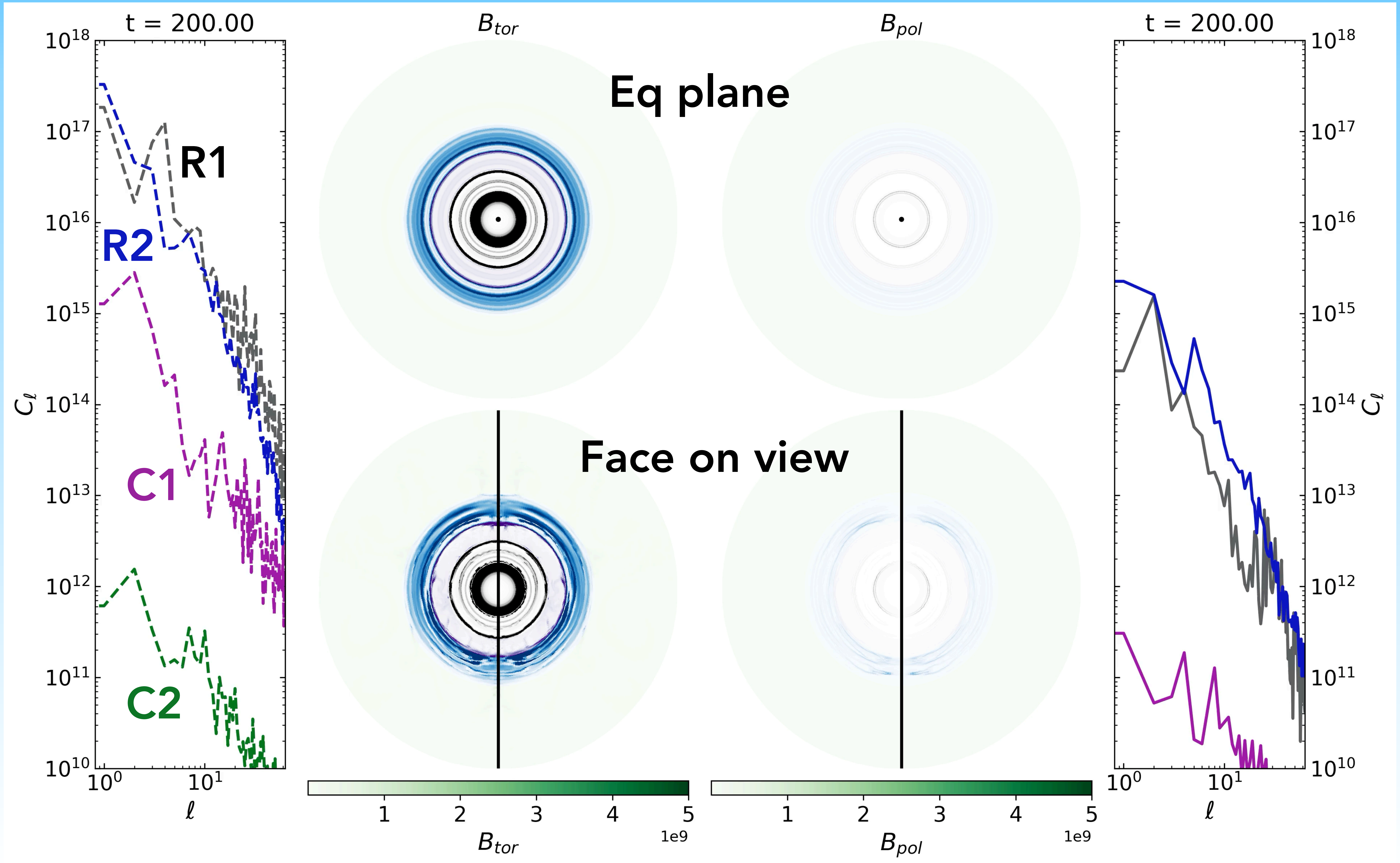
Poloidal dominates toroidal (R_{of} dependance)

Radiative core only amplified by contraction



Magnetic field geometry

M13



What we learnt about magnetic fields

Magnetic fields in convective regions, amplified via magneto-convection

Predominantly small scale fields —> major difference to radiative zones

Strength of field in convective regions dependant on the local Rossby number

Pathway for 321D feedback to build initial magnetic fields

Progenitor interiors may be fully connected magnetically

Implications for core-collapse explosions results (cf motivations)

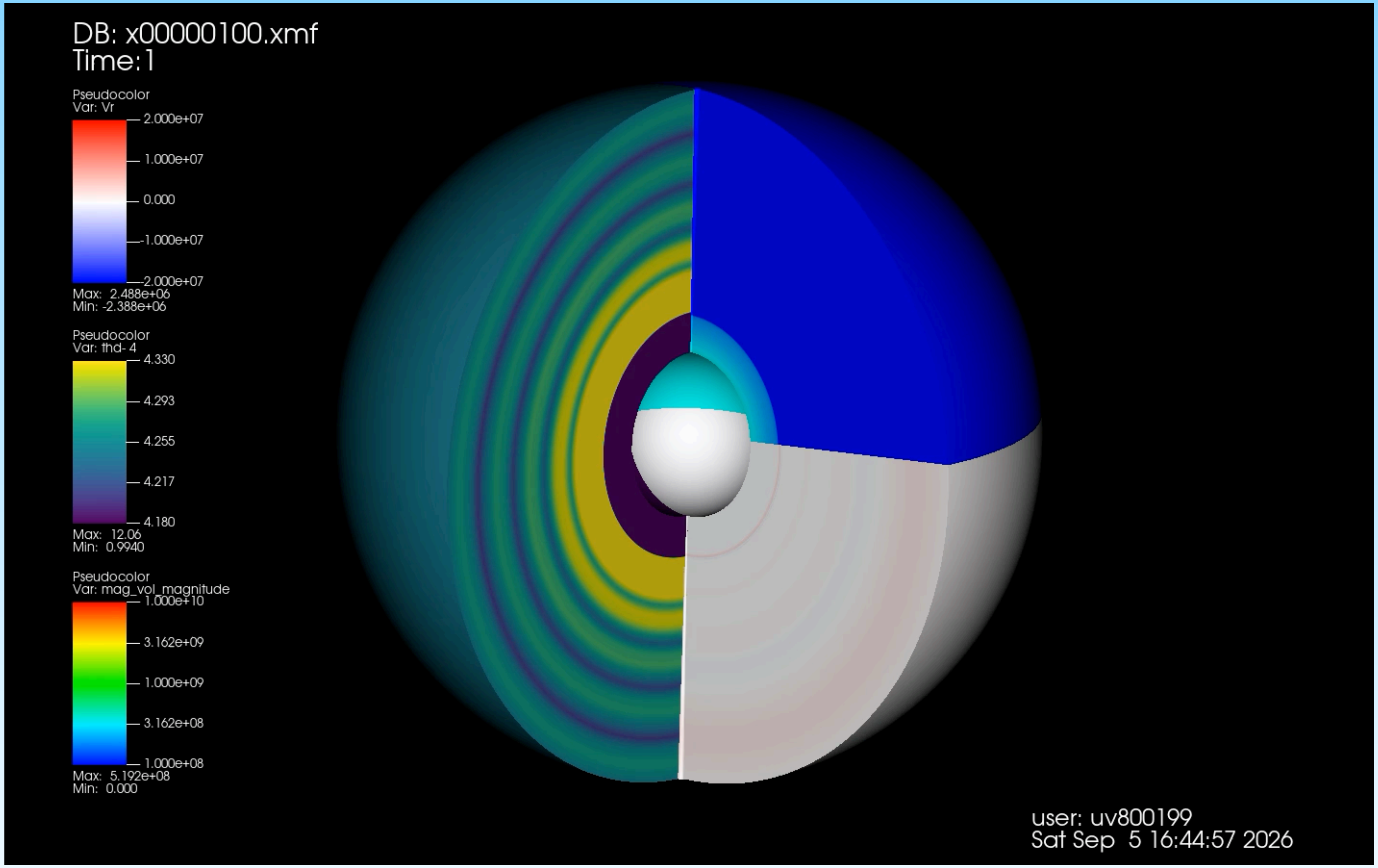
Future work

Explode models and determine impact of 3D progenitor field

Look at long lived magneto-convection behaviour earlier in evolution

Links to material

Griffiths et al. 2026a



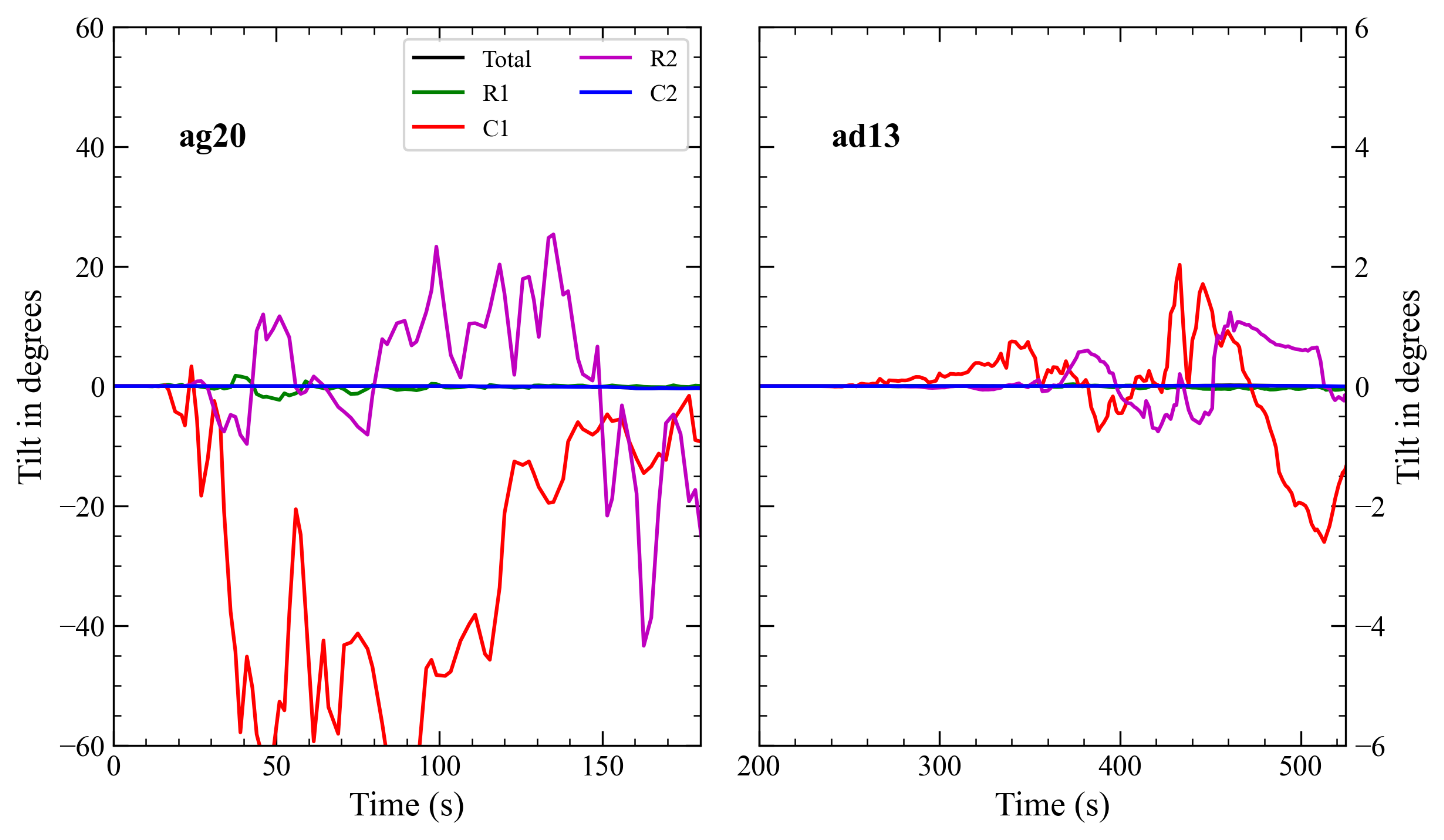
Movies

Griffiths et al. 2026b

Additional Information

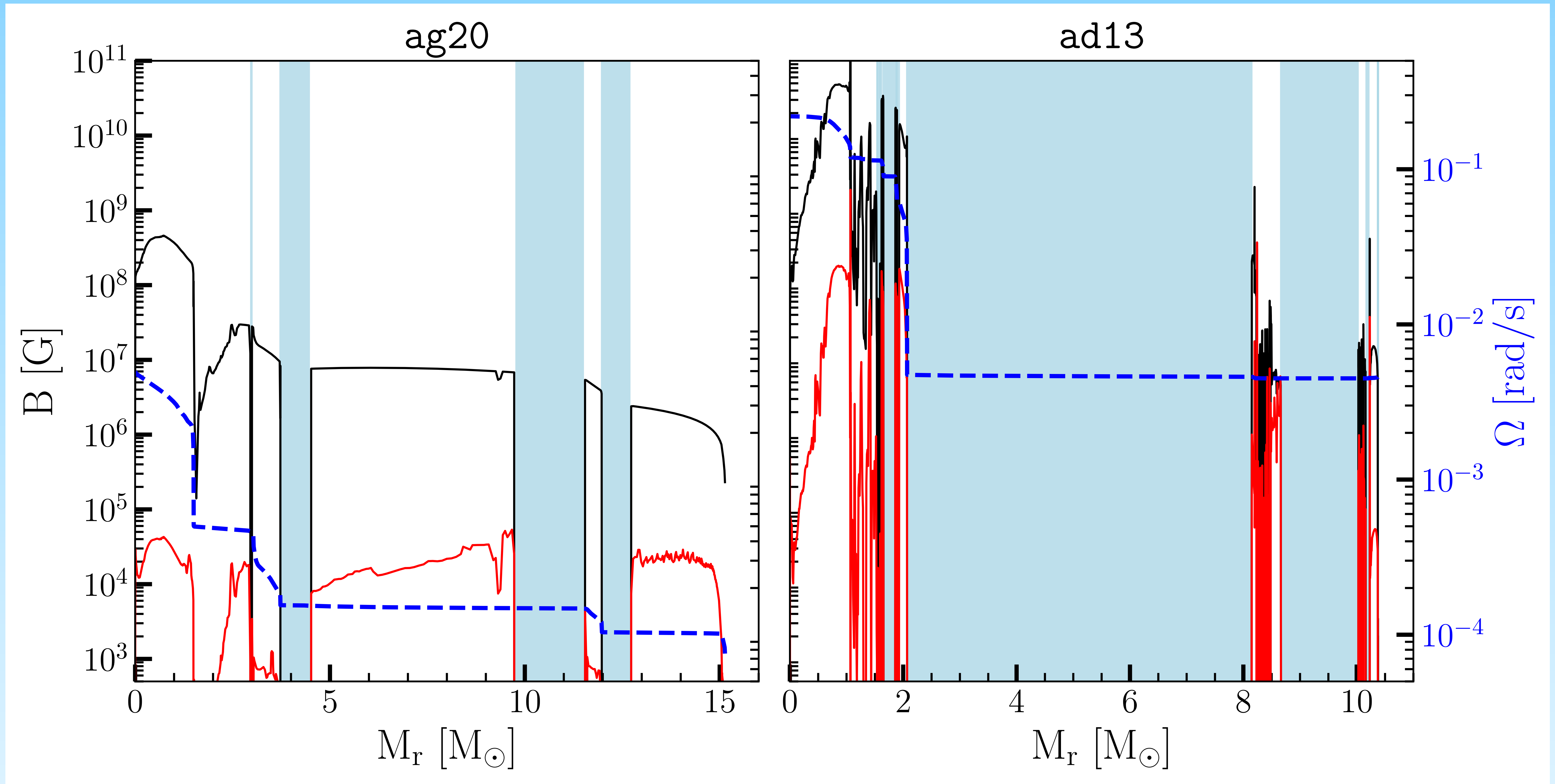
Rotational alignement

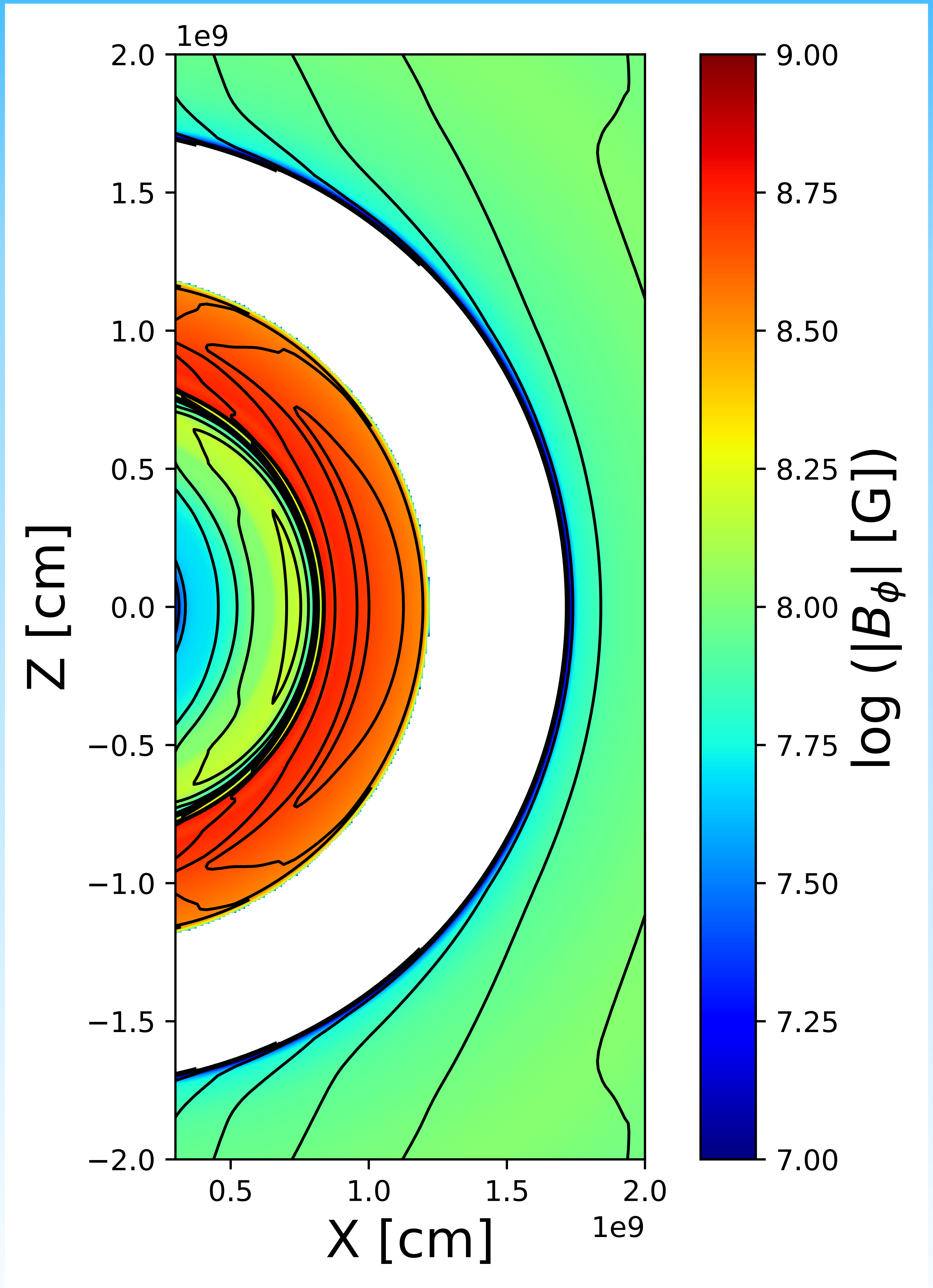
G20 M13



Magnetic field setup

G20 M13



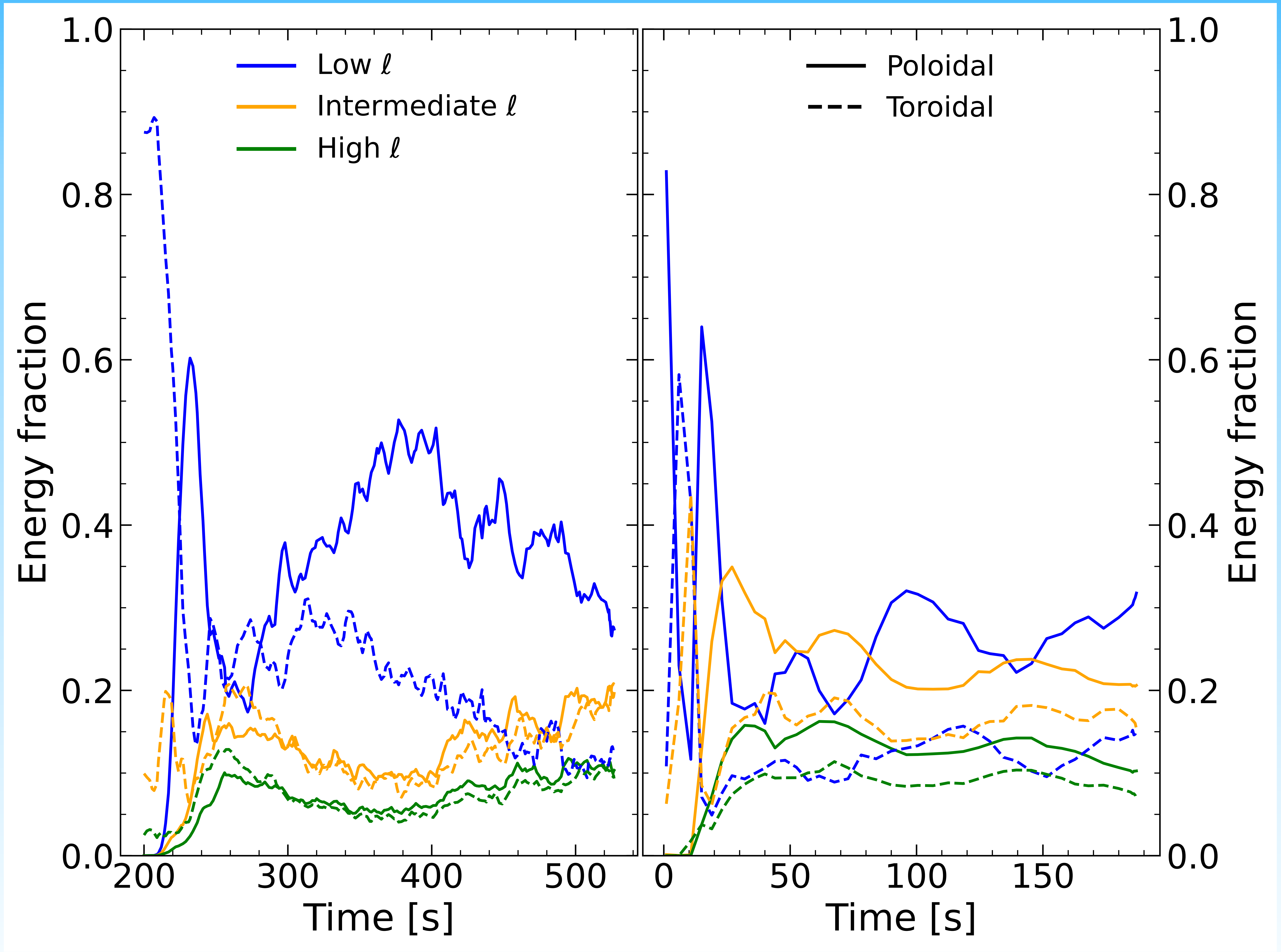


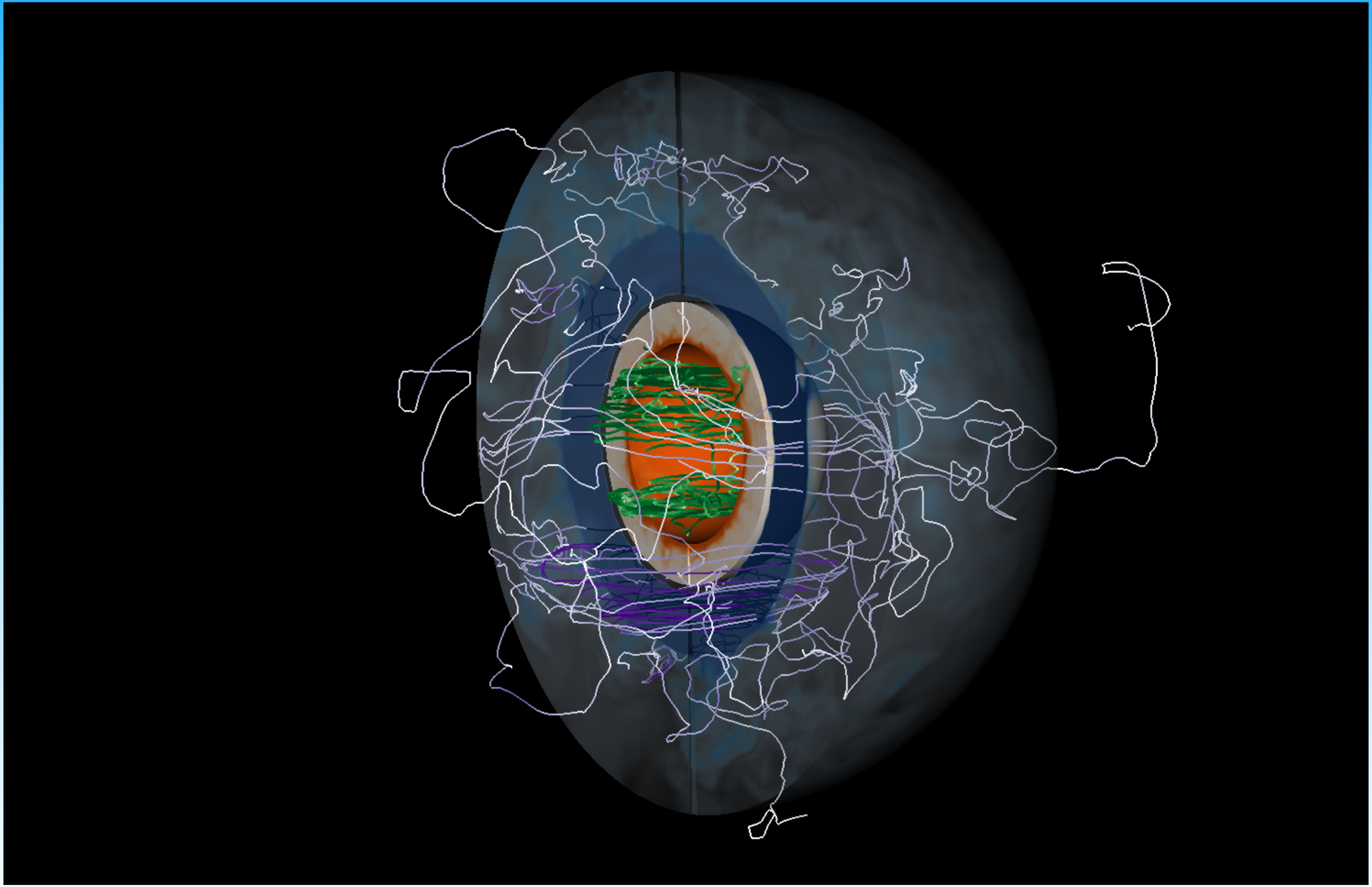
Power distribution

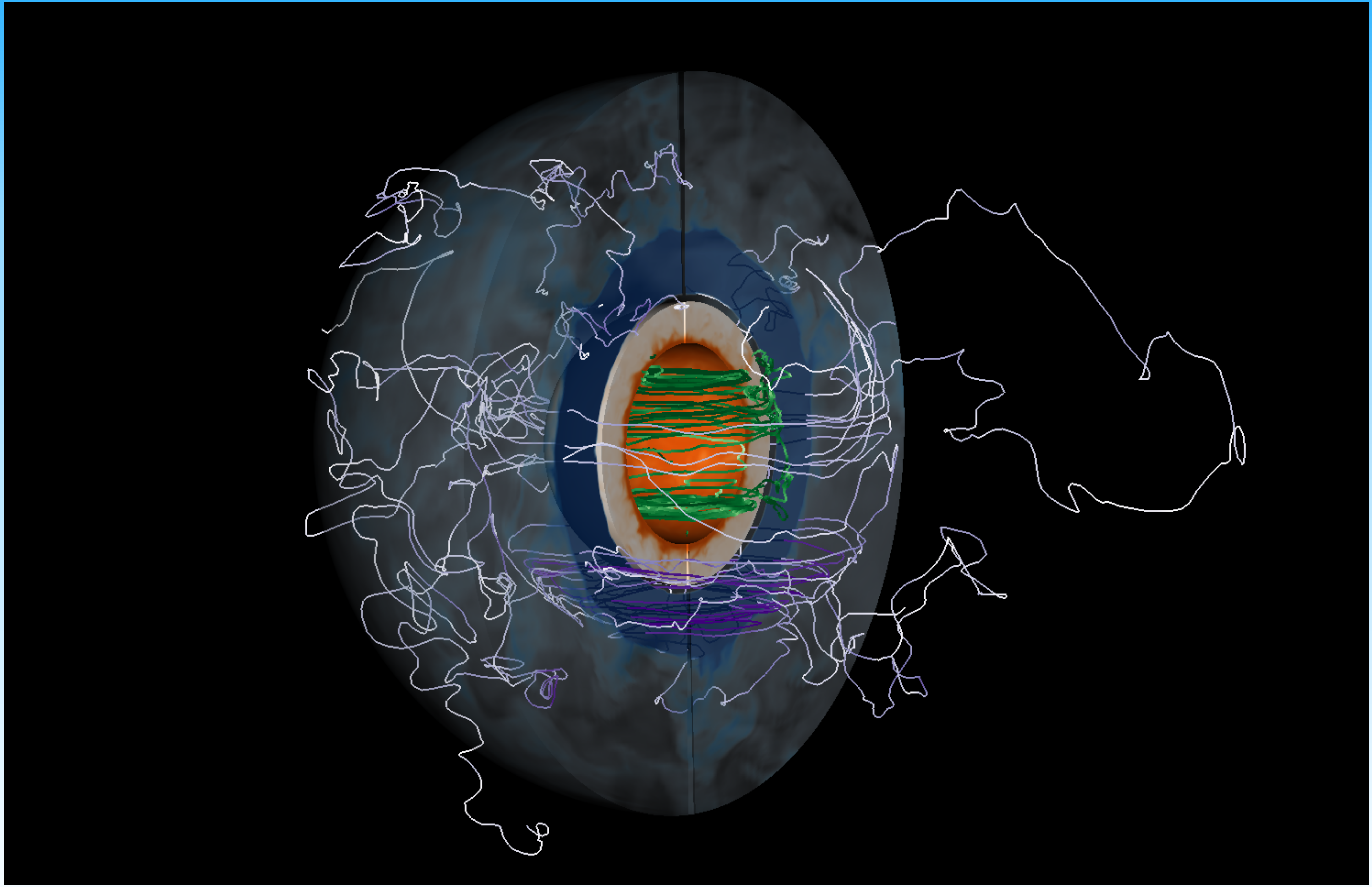
Low ℓ : [1 ; 5]

Intermediate ℓ : [5 ; 25]

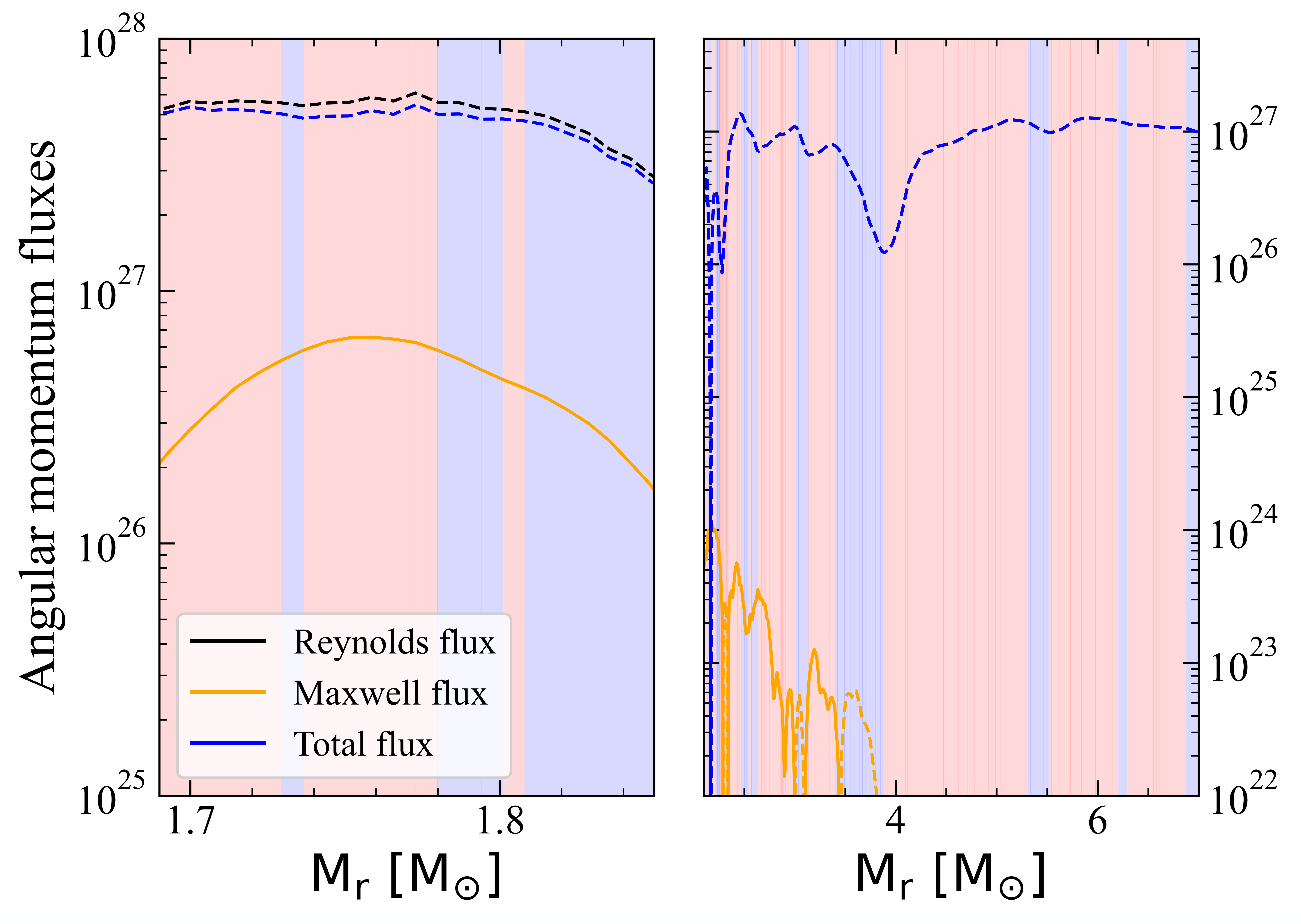
High ℓ : [25 ; 64]







Maxwell stress role on AM transport



MRI resolution study