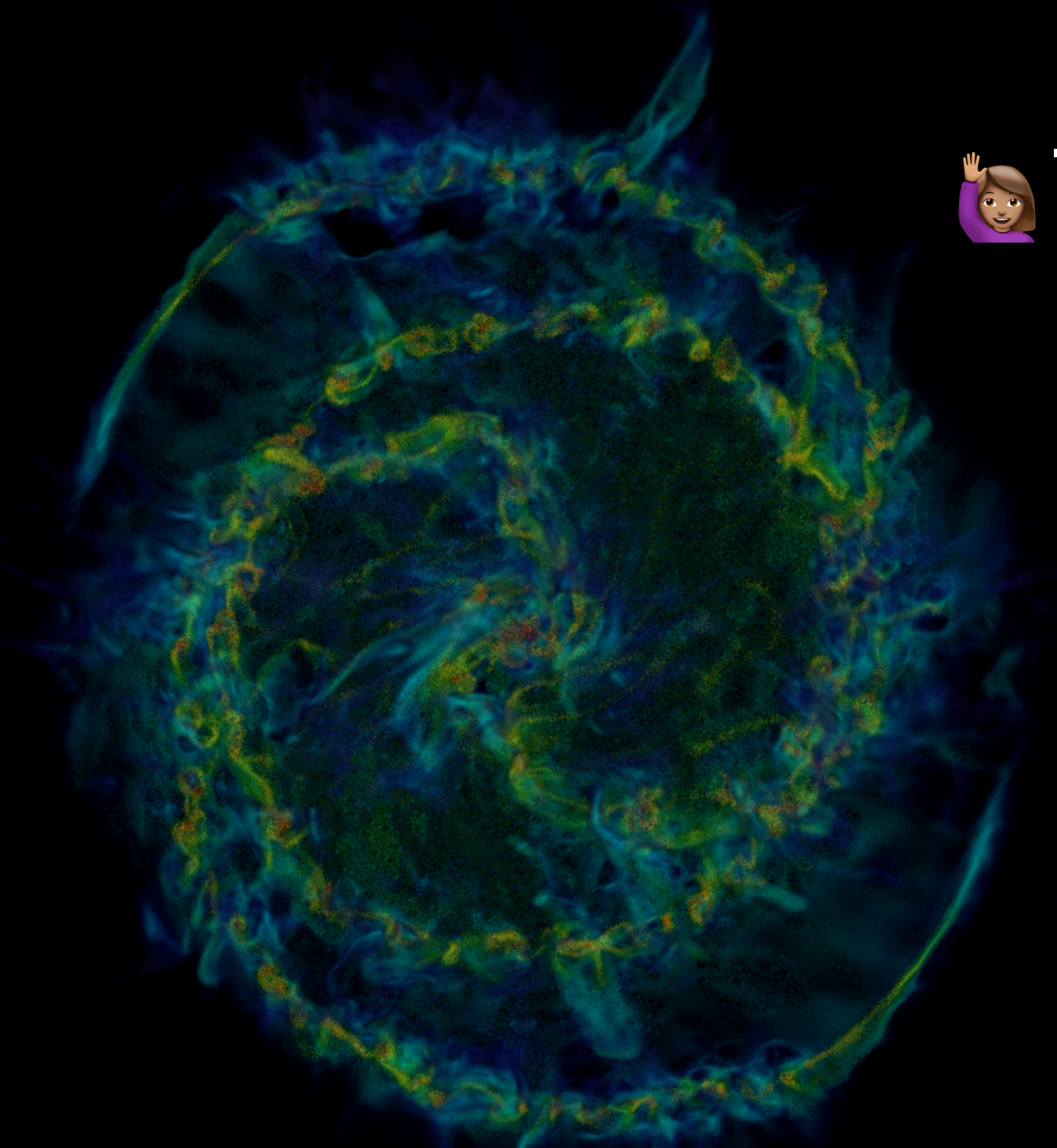
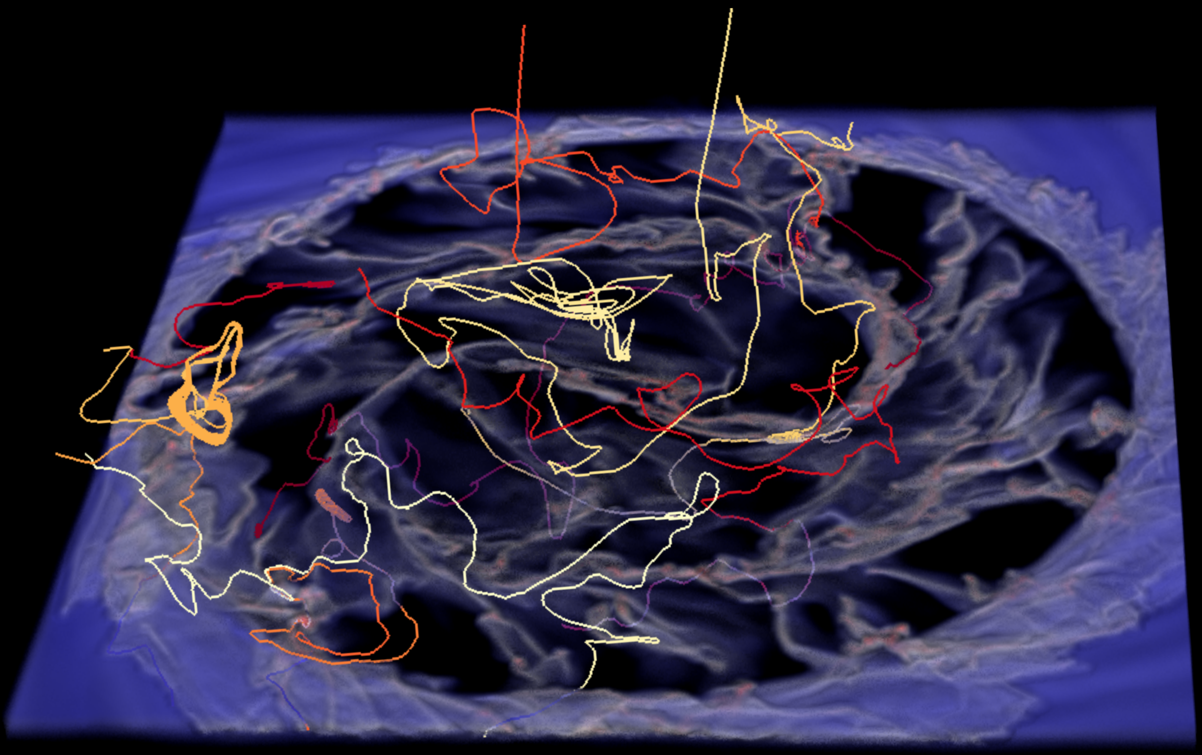
Eva Ntormousi

SCUOLA
NORMALE
SUPERIORE

How can we characterise magnetised turbulence in (and around) galaxies?

🙋🏽‍♀️ -and why should we?



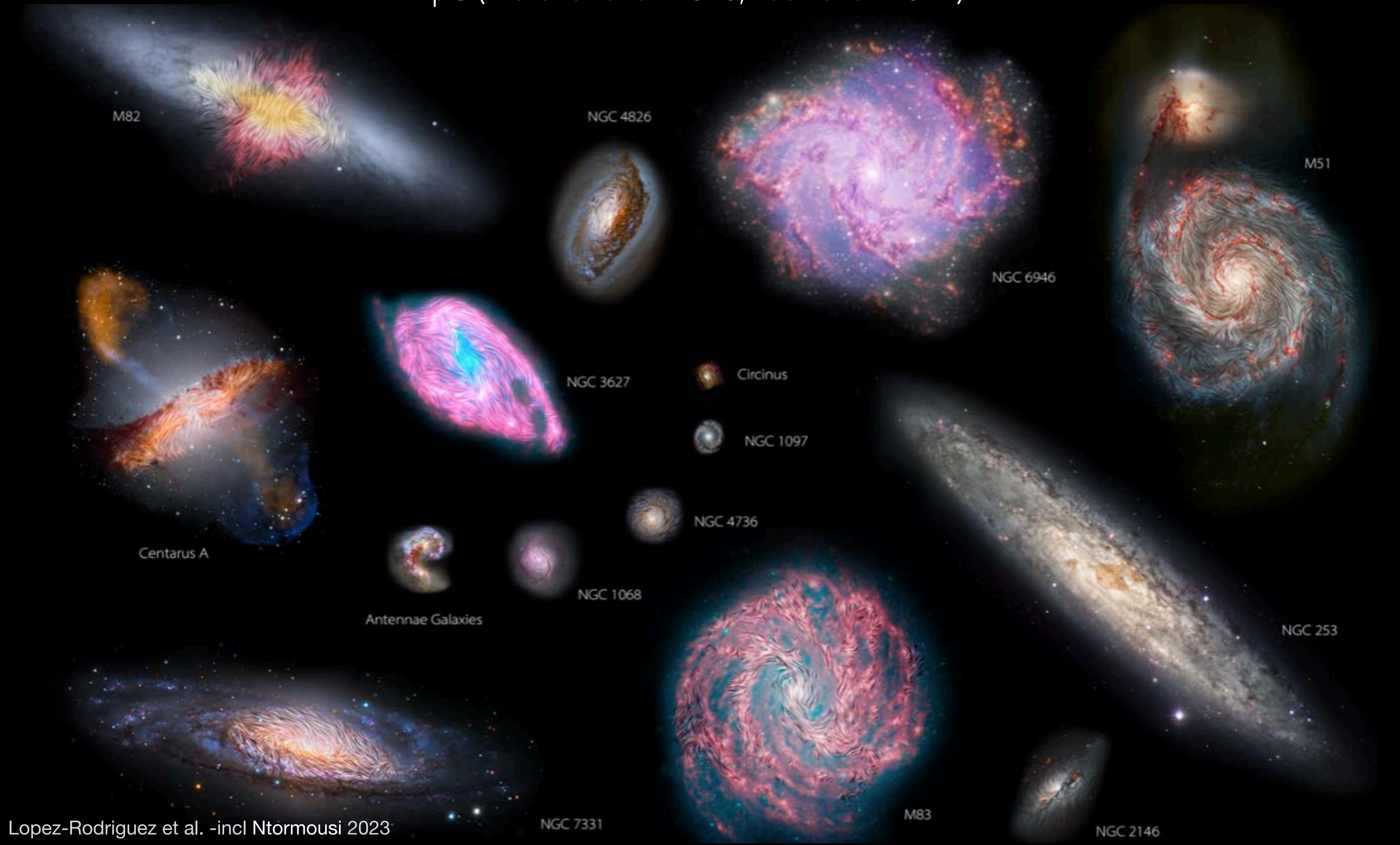


IGMF Focus meeting Trieste
February 13th, 202

My topic:

MHD turbulence in the ISM

Present-day spirals host large-scale coherent magnetic fields with a typical strength of a few μG (Fletcher et al. 2016,Beck et al. 2019)

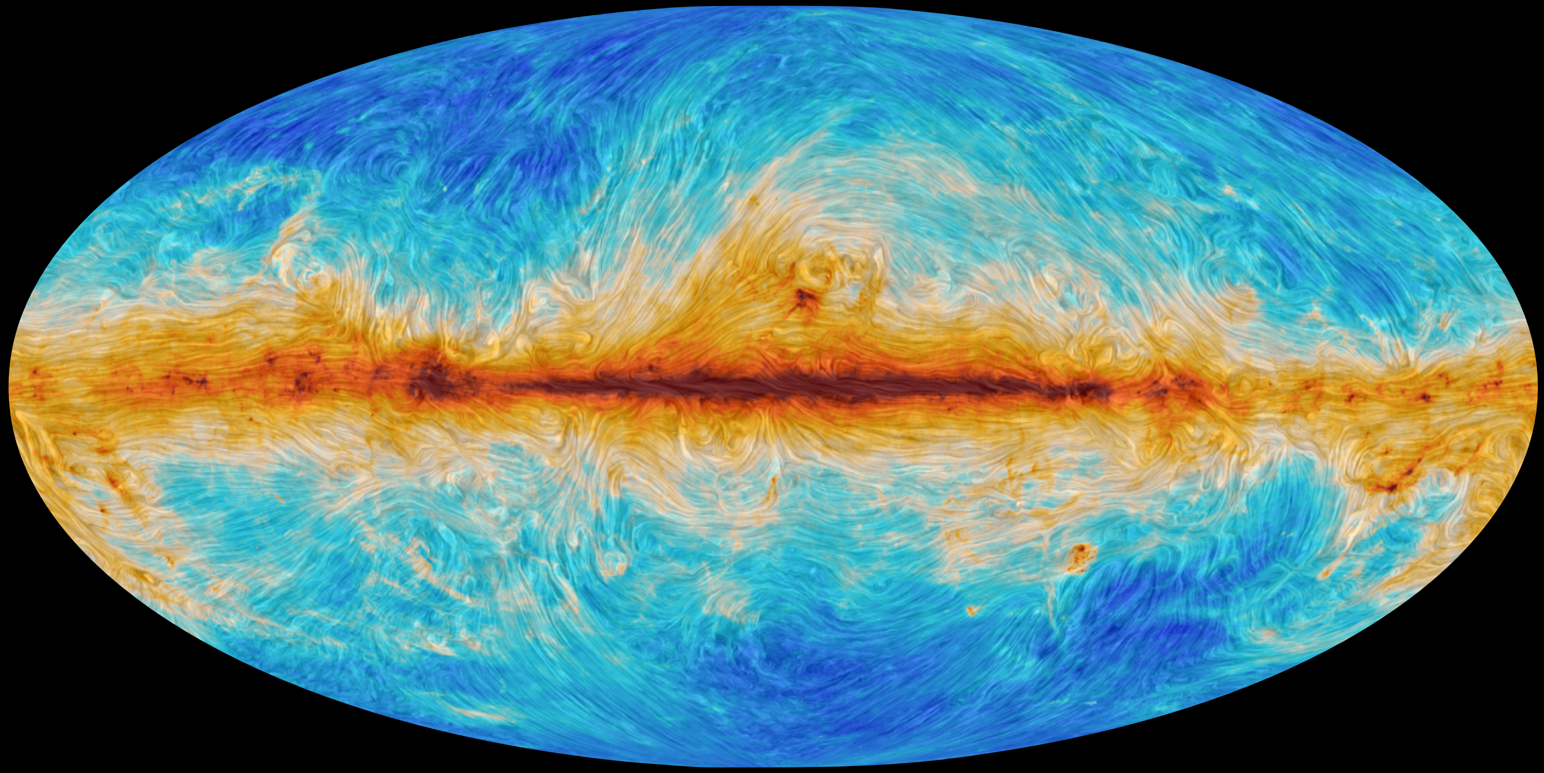


Lopez-Rodriguez et al. -incl Ntormousi 2023

The first estimates for redshifts z>1 yield fields of the order of μG already at these epochs! (Bernet et al. 2008, Mao et al. 2017,Geach et al. 2023,Chen et al.2024)

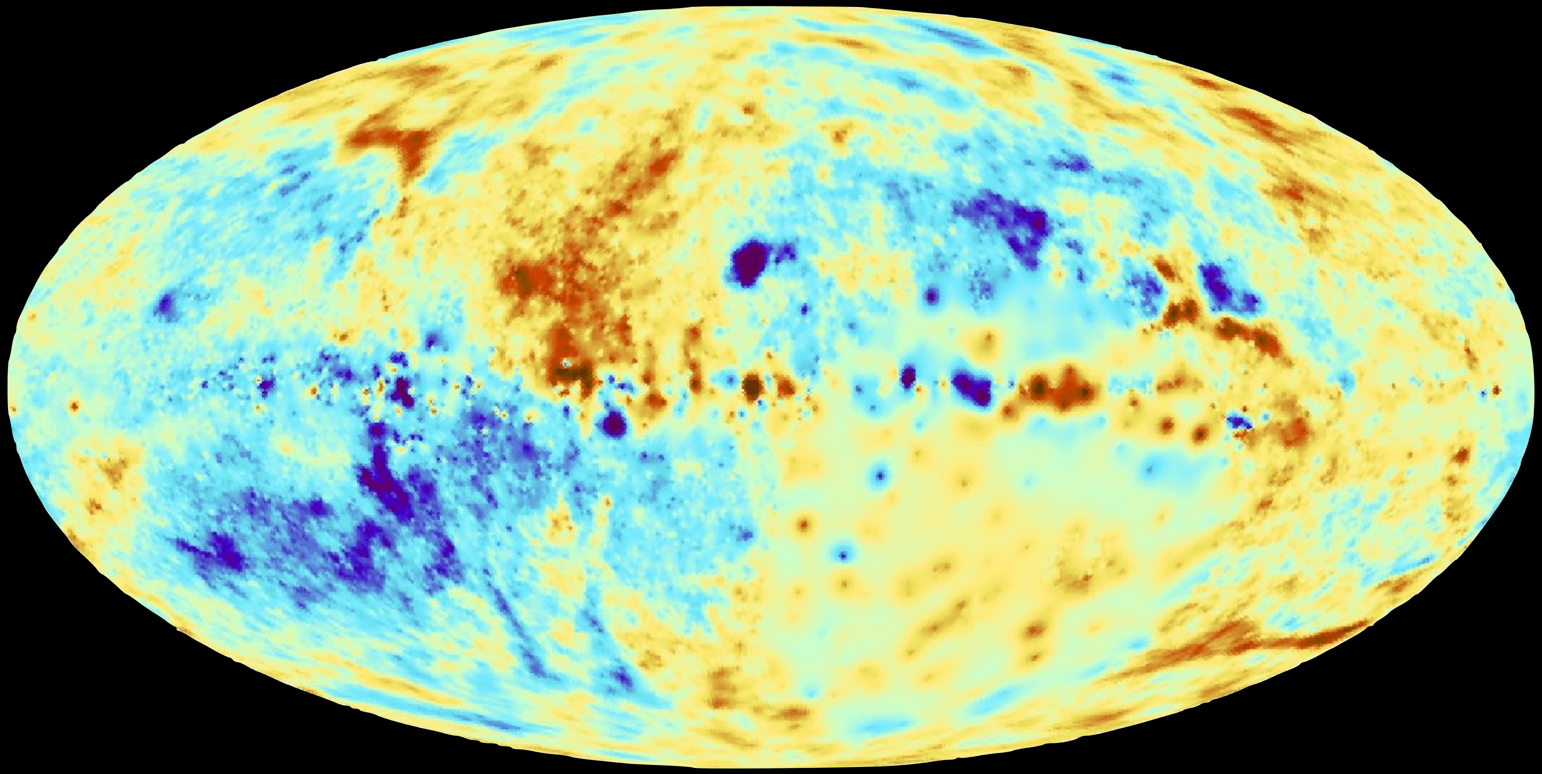
THE MAGNETIC FIELD OF THE MILKY WAY

Points to the field being dynamically important (e.g. Planck XXXII, 2014)



PLANCK DUST POLARIZATION MAP
FROM HTTPS://WWW.IAS.U-PSUD.FR/SOLER/PLANCKHIGHLIGHTS.HTML

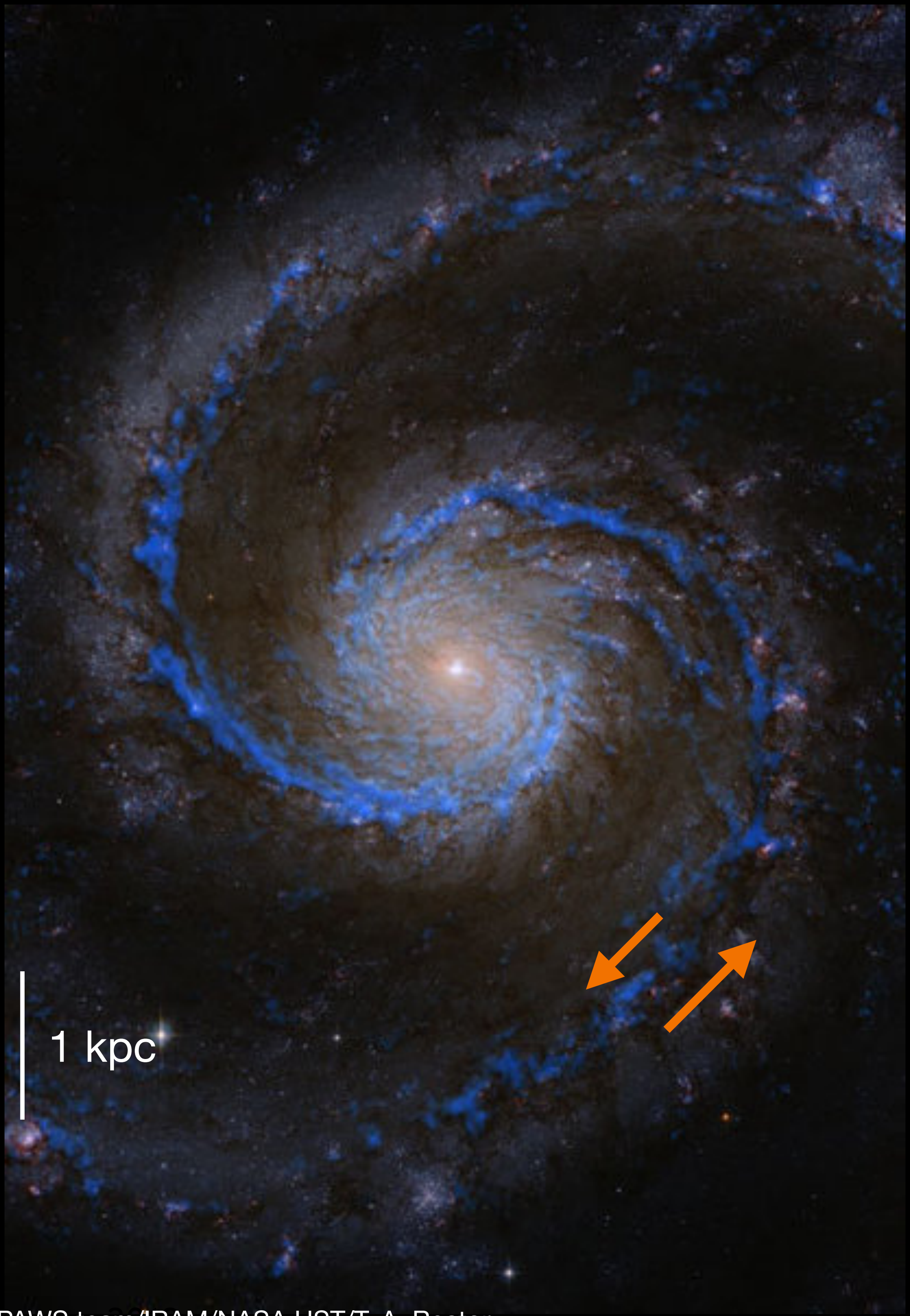
Shows a quadrupole in high latitudes and a coherent azimuthal field in the disk



FARADAY ROTATION SKY FROM OPPERMANN ET AL. 2012

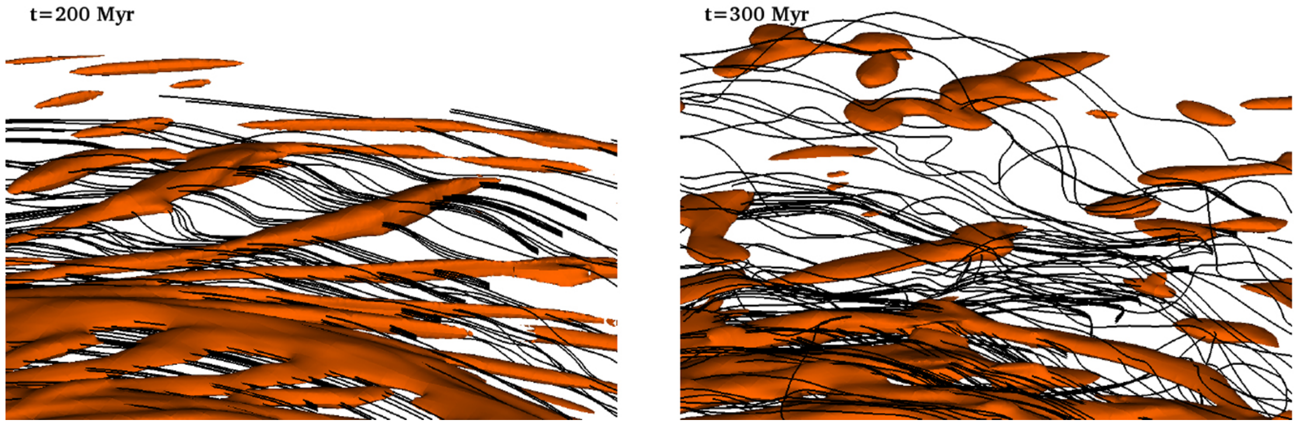
MHD turbulence in the interstellar medium

Generated by large-scale instabilities, shear from differential rotation, feedback

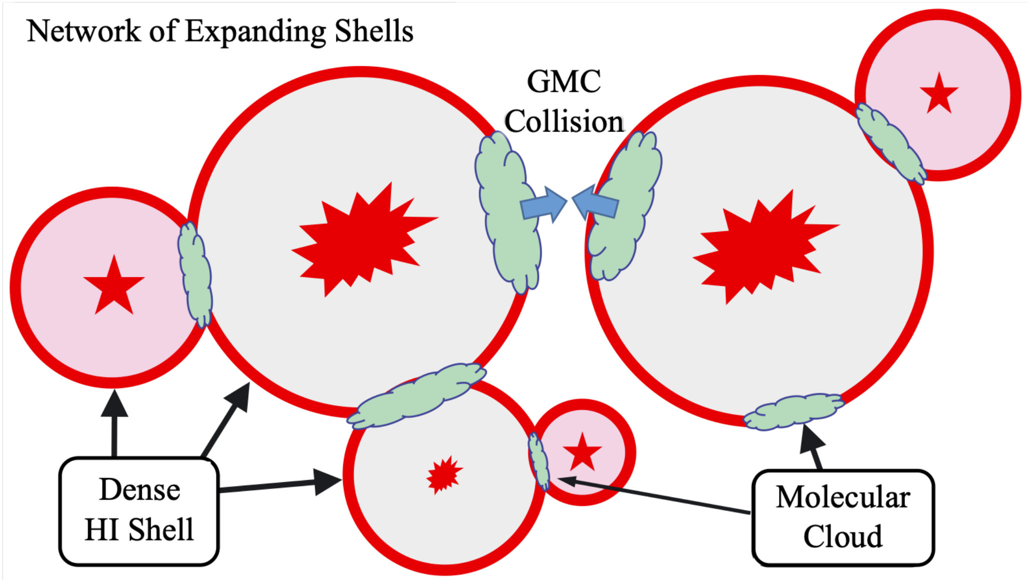


PAWS team/IRAM/NASA HST/T. A. Rector

c. Parker instability in global disk simulations (Körtgen et al. 2018)



d. Multiple shell collisions (Inutsuka et al. 2015)



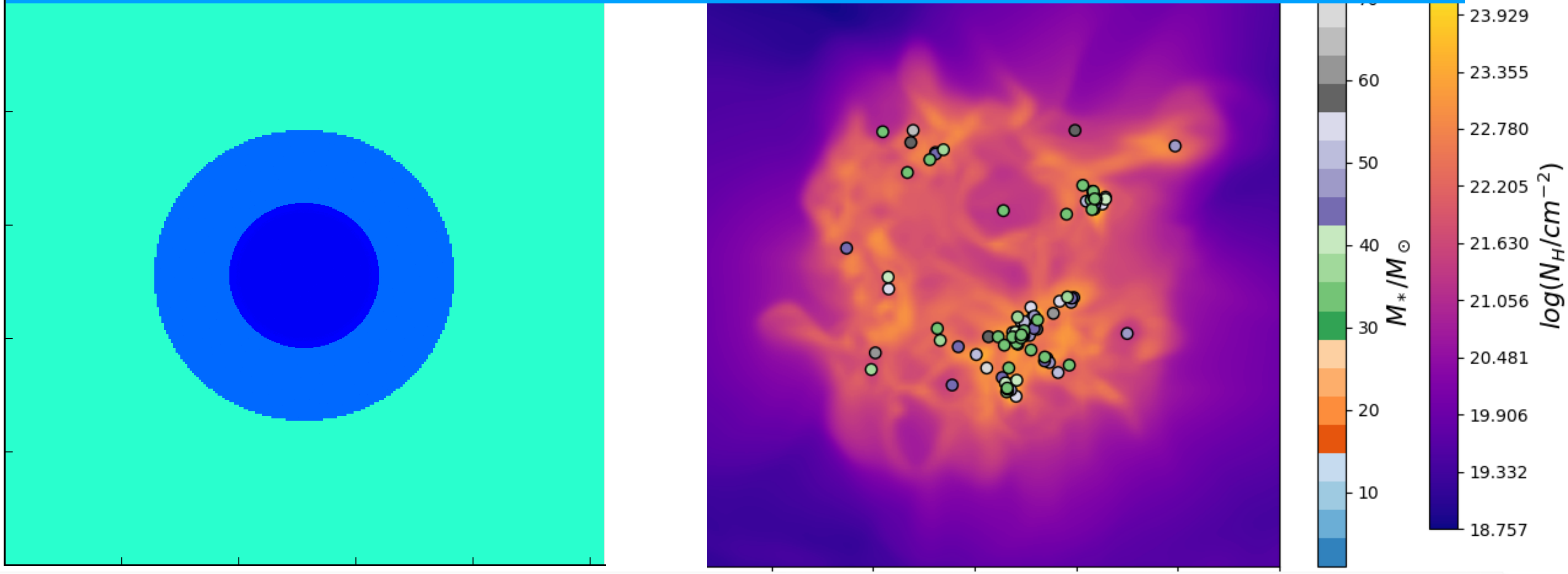
The coupling of these unstable modes can cause **rapid re-organization** of the magnetic field

ALMA (ESO/NAOJ/NRAO), J. Tobin; NRAO/AUI/NSF, S. Dagnello; Herschel/ESA

Impact of stellar feedback on the ISM

The energy and momentum injected by massive stars **shapes and dissipates** their parent clouds, but the details of this process are unclear.
The dissipation time of the cloud is crucial for establishing the efficiency with which galaxies form stars
The shape of molecular clouds decides the
ionising photons and metals that can escape to the ISM and the CGM

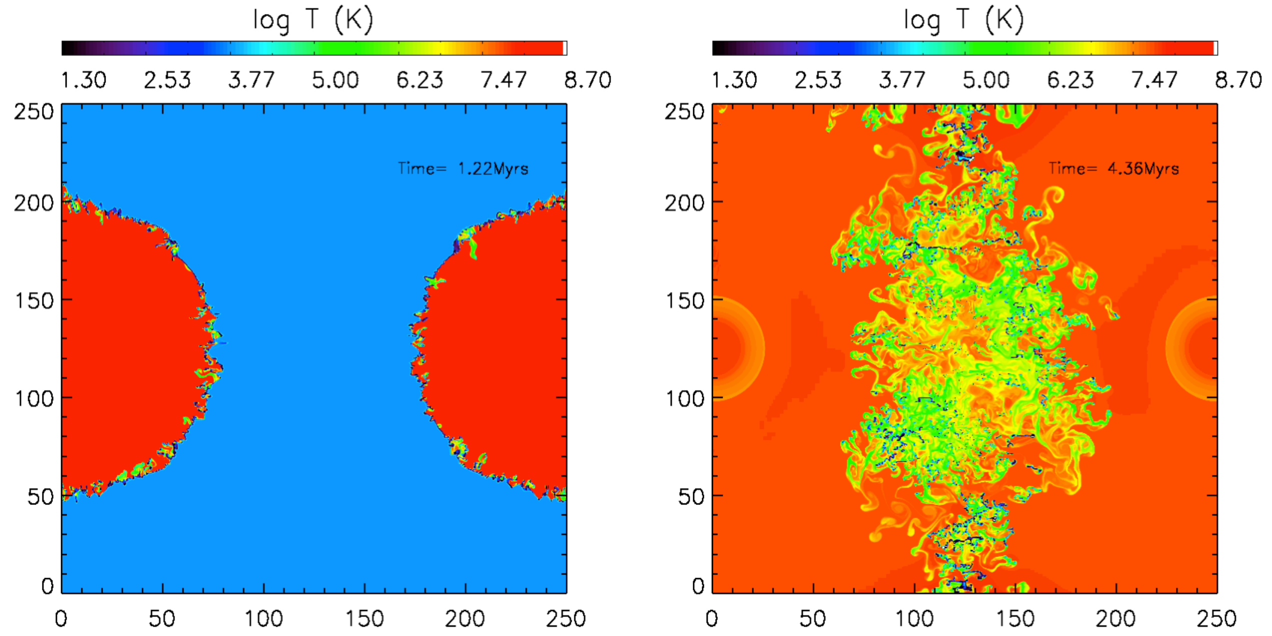
Simulations with RAMSES-RT+KROME+MHD+stellar particles:
All the relevant ingredients for massive star formation and feedback studies
Stellar feedback models from Starburst99, on the process of update



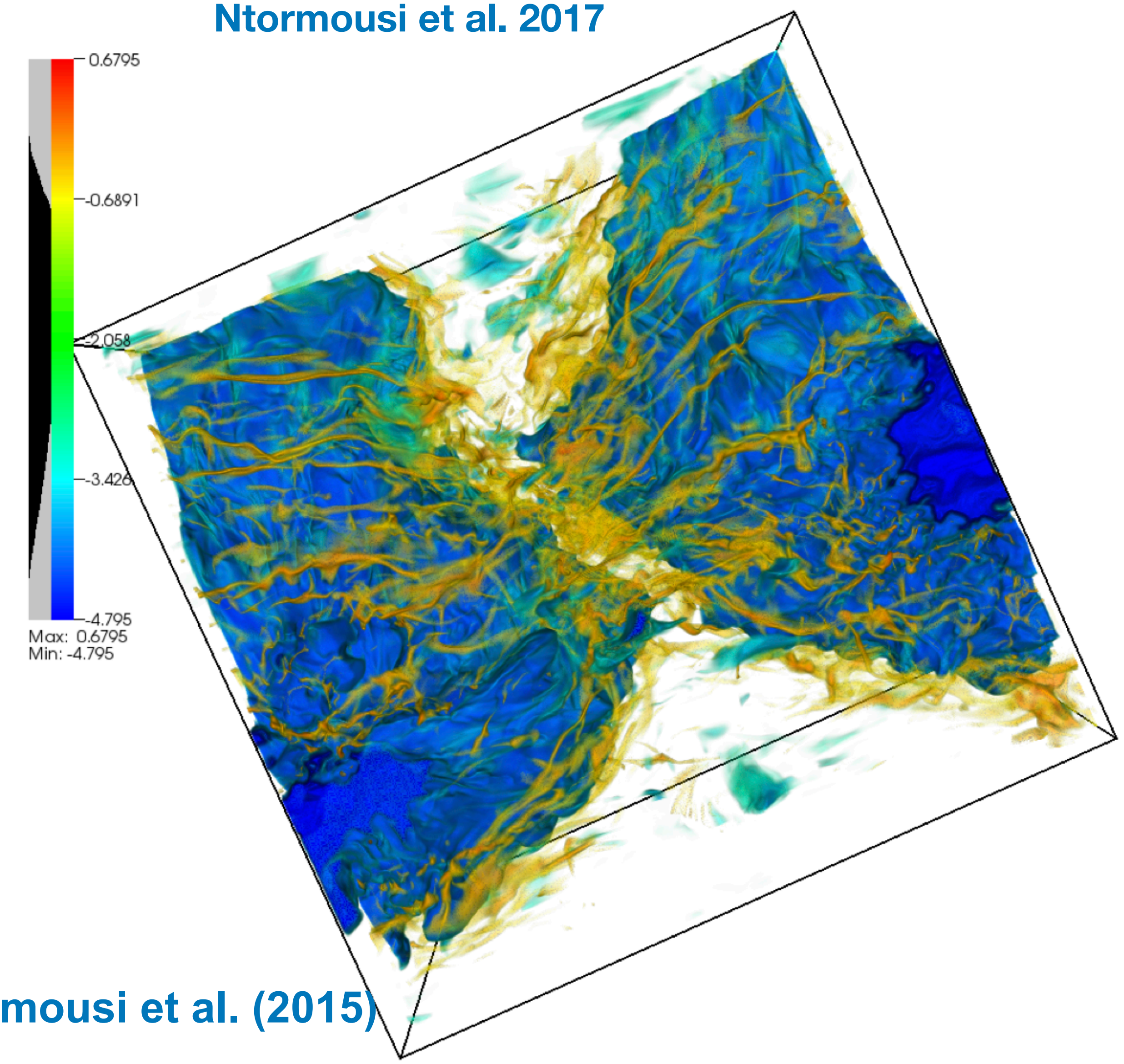
Massive stars are also a source of turbulence
as strong as the large-scale complexity of the galaxy!

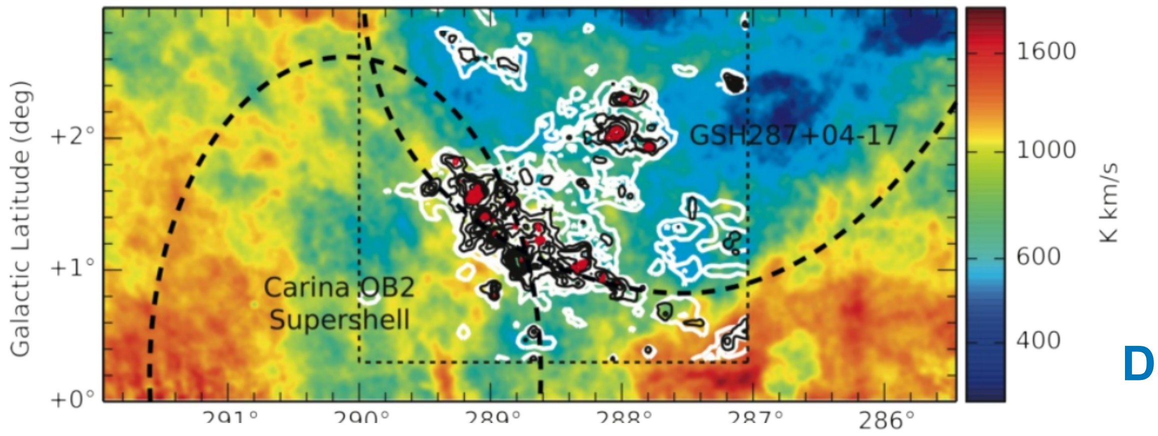
Massive stellar feedback and triggered cloud formation

Ntormousi et al. 2011

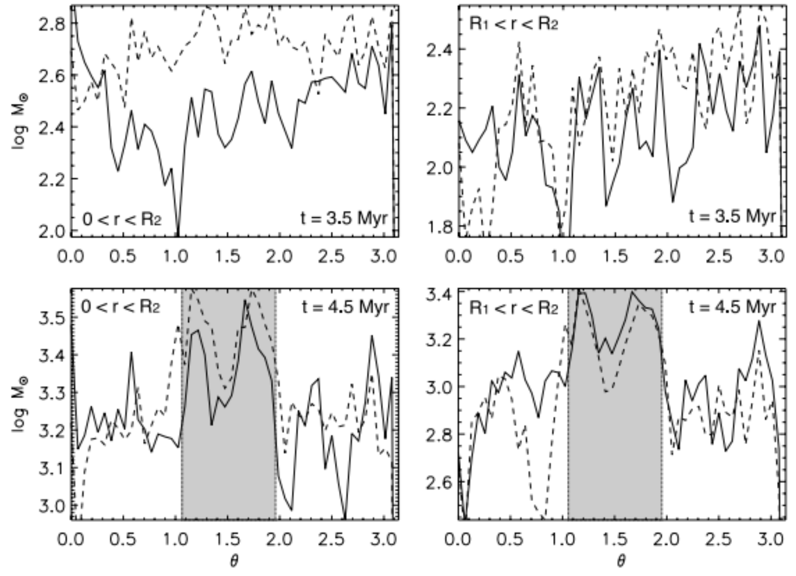


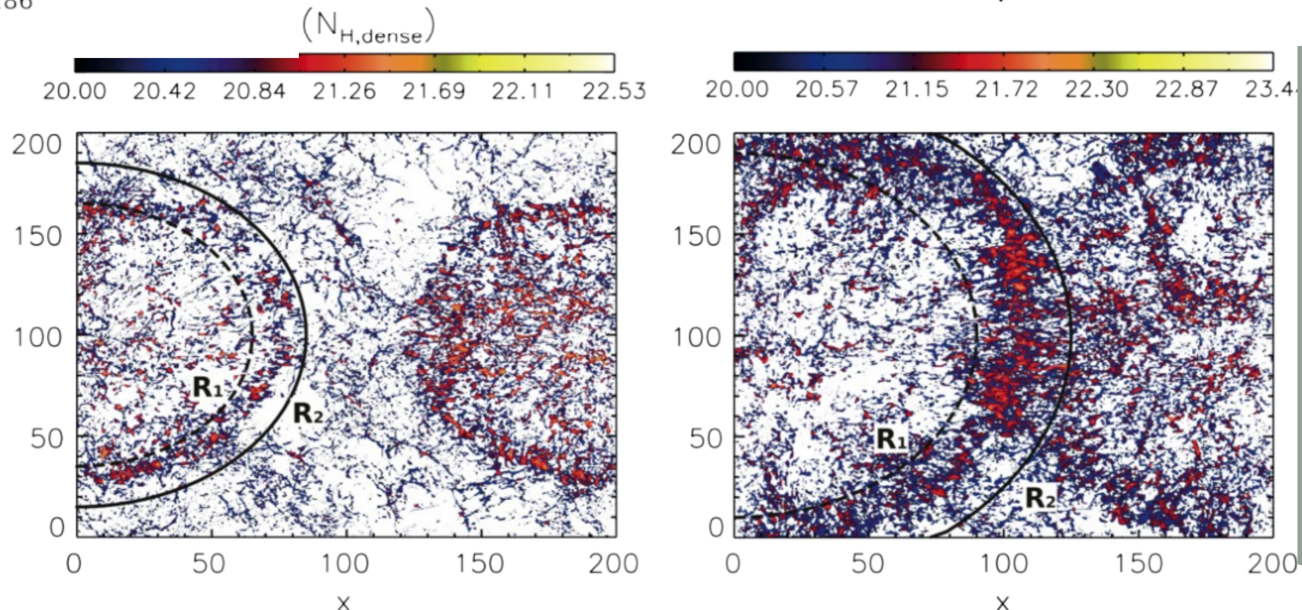
Ntormousi et al. 2017





Dawson, Ntormousi et al. (2015)





Comparison between hydro simulations and observations of a GMC between two Galactic supershells:

No additional dense gas due to the shell collision!

Massive stellar feedback and triggered cloud formation

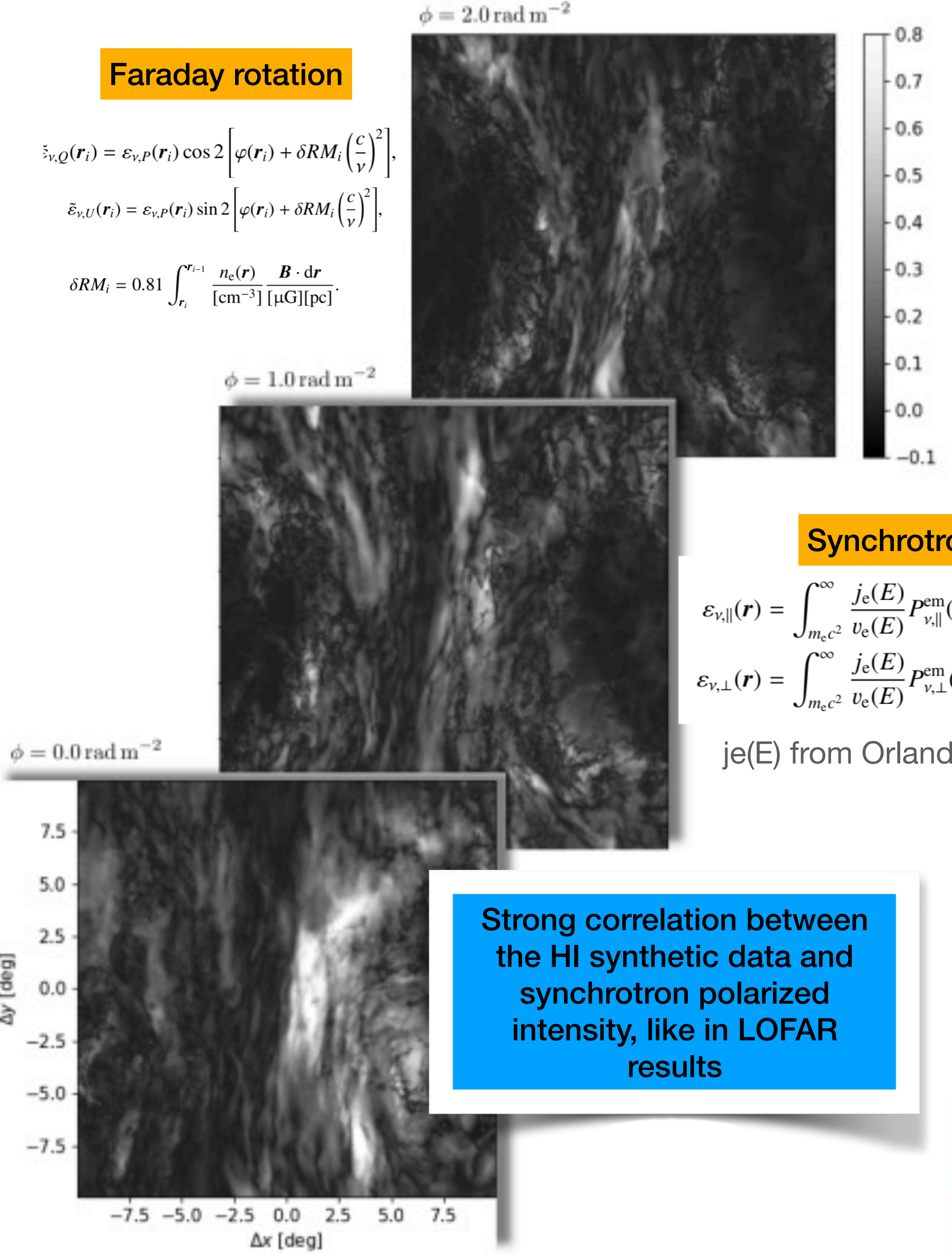
Bracco, Ntormousi et al. 2022

Faraday rotation

$$\varepsilon_{\nu,Q}(\boldsymbol{r}_i) = \varepsilon_{\nu,P}(\boldsymbol{r}_i)\cos 2\left[\varphi(\boldsymbol{r}_i) + \delta RM_i\left(\frac{c}{\nu}\right)^2\right],$$

$$\tilde{\varepsilon}_{\nu,U}(\boldsymbol{r}_i) = \varepsilon_{\nu,P}(\boldsymbol{r}_i)\sin 2\left[\varphi(\boldsymbol{r}_i) + \delta RM_i\left(\frac{c}{\nu}\right)^2\right],$$

$$\delta RM_i = 0.81\int_{r_i}^{r_{i-1}} \frac{n_e(\boldsymbol{r})}{[\mathrm{cm}^{-3}]}\,\frac{\boldsymbol{B}\cdot \mathrm{d}\boldsymbol{r}}{[\mu\mathrm{G}][\mathrm{pc}]}.$$



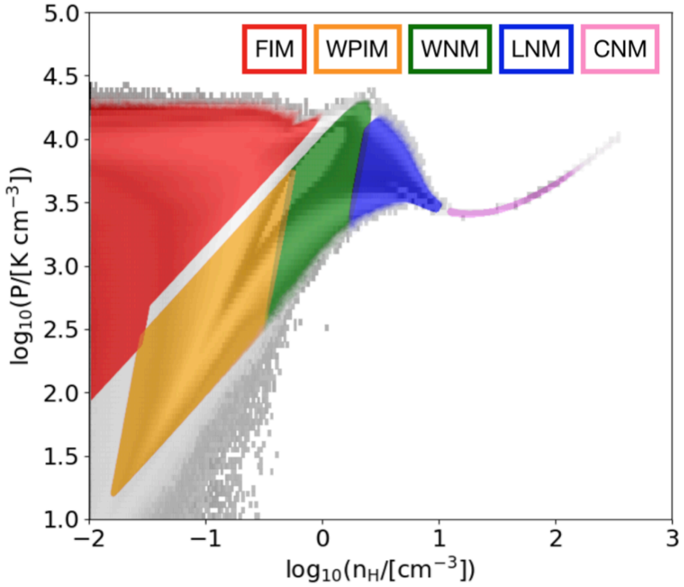
Strong correlation between the HI synthetic data and synchrotron polarized intensity, like in LOFAR results

Synchrotron

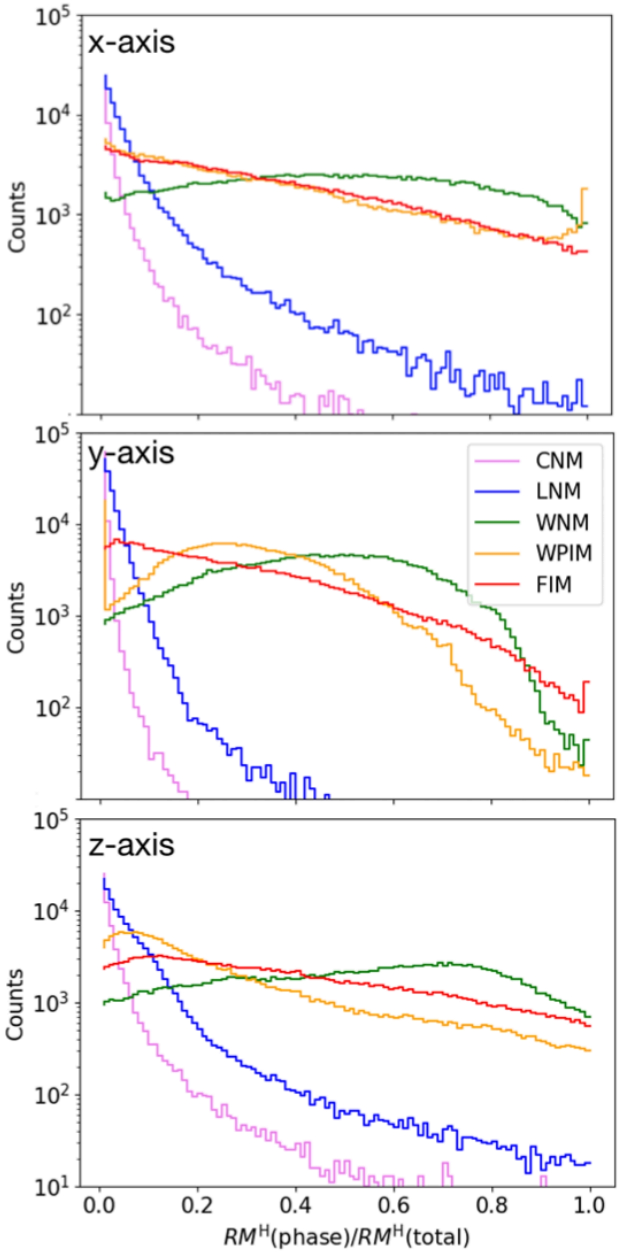
$$\varepsilon_{\nu,\parallel}(\boldsymbol{r}) = \int_{m_e c^2}^{\infty} \frac{j_e(E)}{v_e(E)} P^{\mathrm{em}}_{\nu,\parallel}(E, B_\perp(\boldsymbol{r}))\,\mathrm{d}E,$$

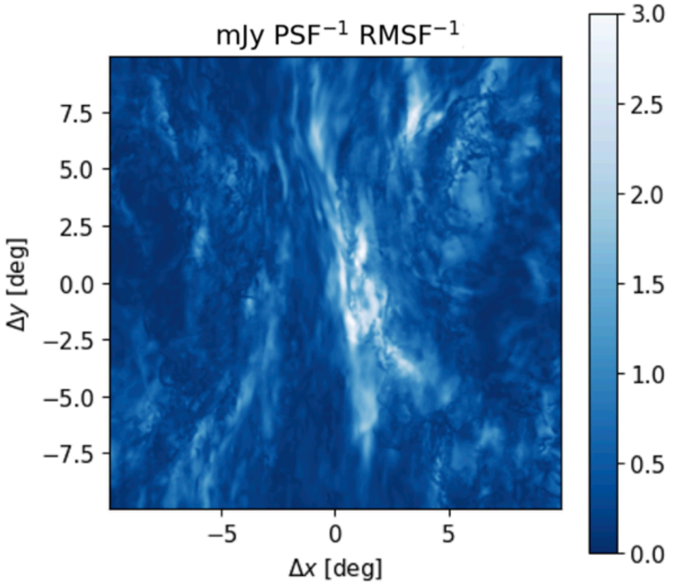
$$\varepsilon_{\nu,\perp}(\boldsymbol{r}) = \int_{m_e c^2}^{\infty} \frac{j_e(E)}{v_e(E)} P^{\mathrm{em}}_{\nu,\perp}(E, B_\perp(\boldsymbol{r}))\,\mathrm{d}E.$$

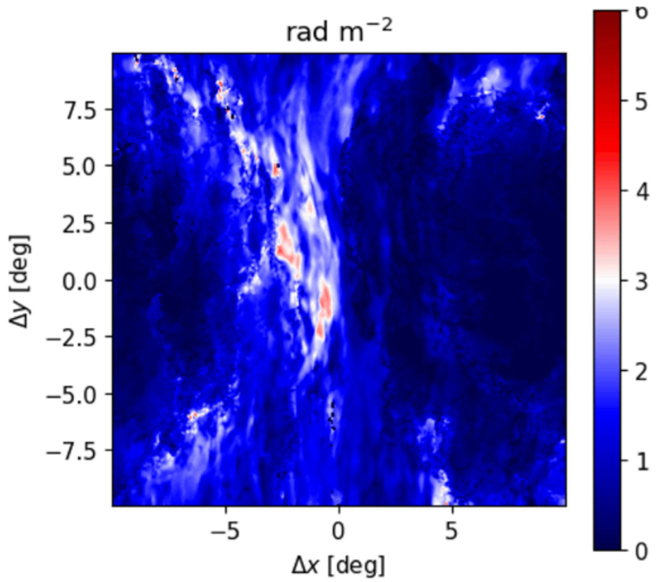
je(E) from Orlando (2018)



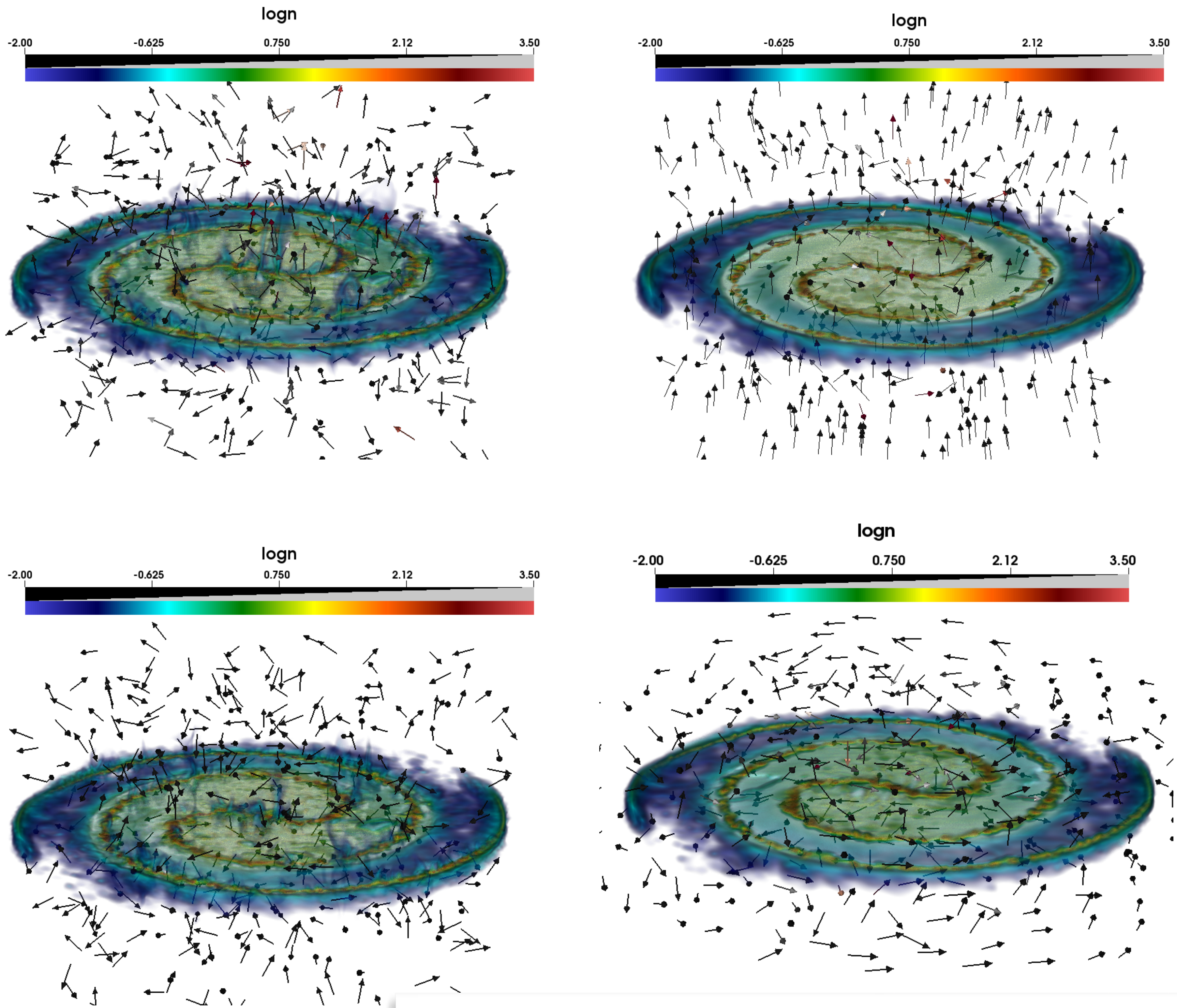
Dominant contribution to the RM comes fro the WIM and WPIM BUT Simulations contain very little CNM



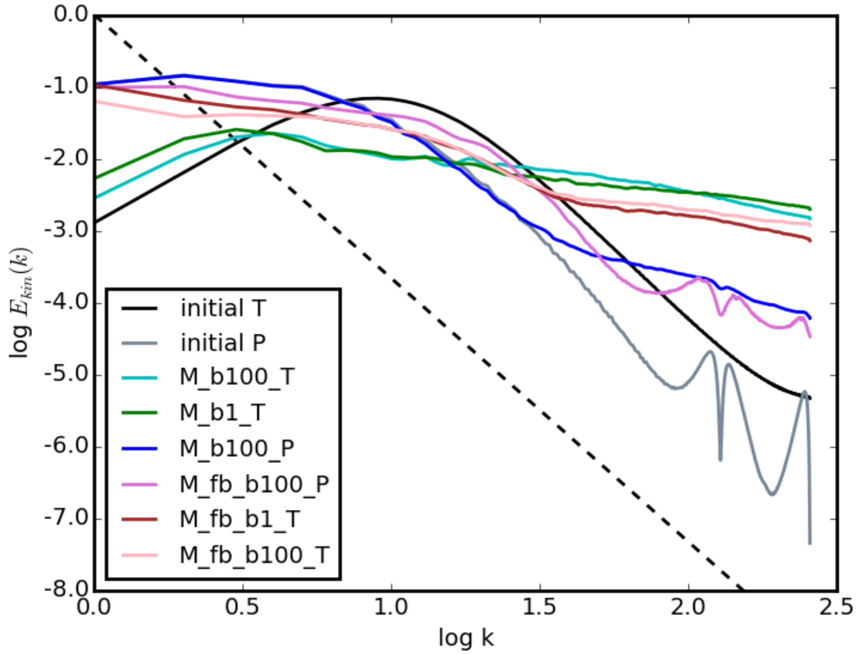


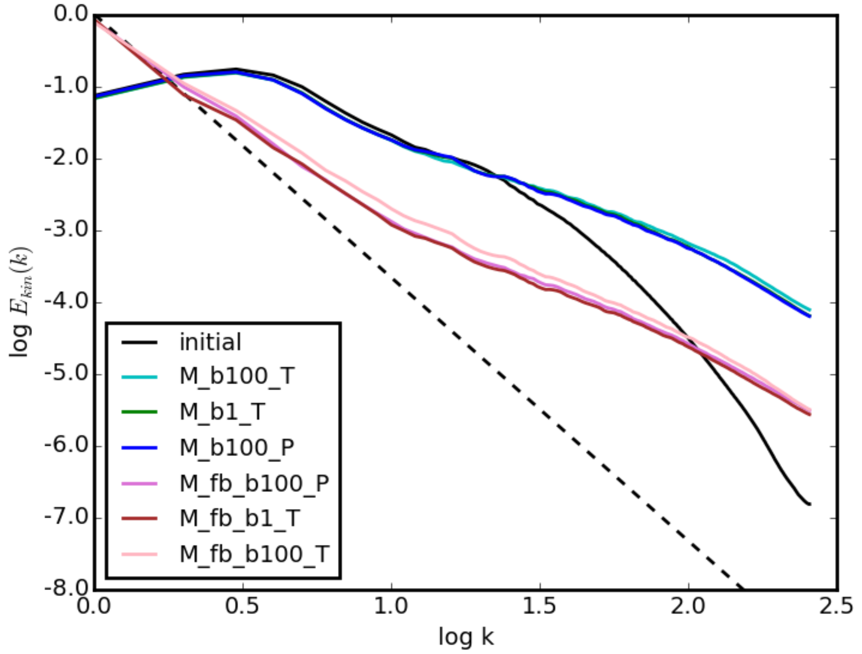


Effects of massive stellar feedback on galaxy scales



Magnetic energy



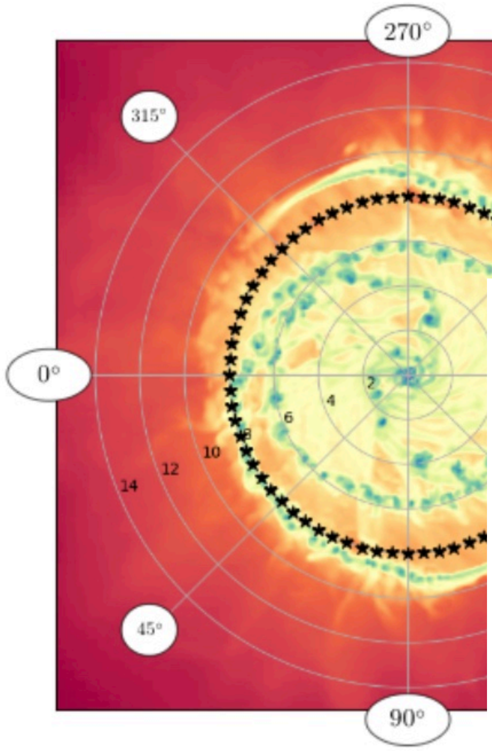


Kinetic energy

Feedback from massive stars drives turbulence out to several kpcs above/below the disk

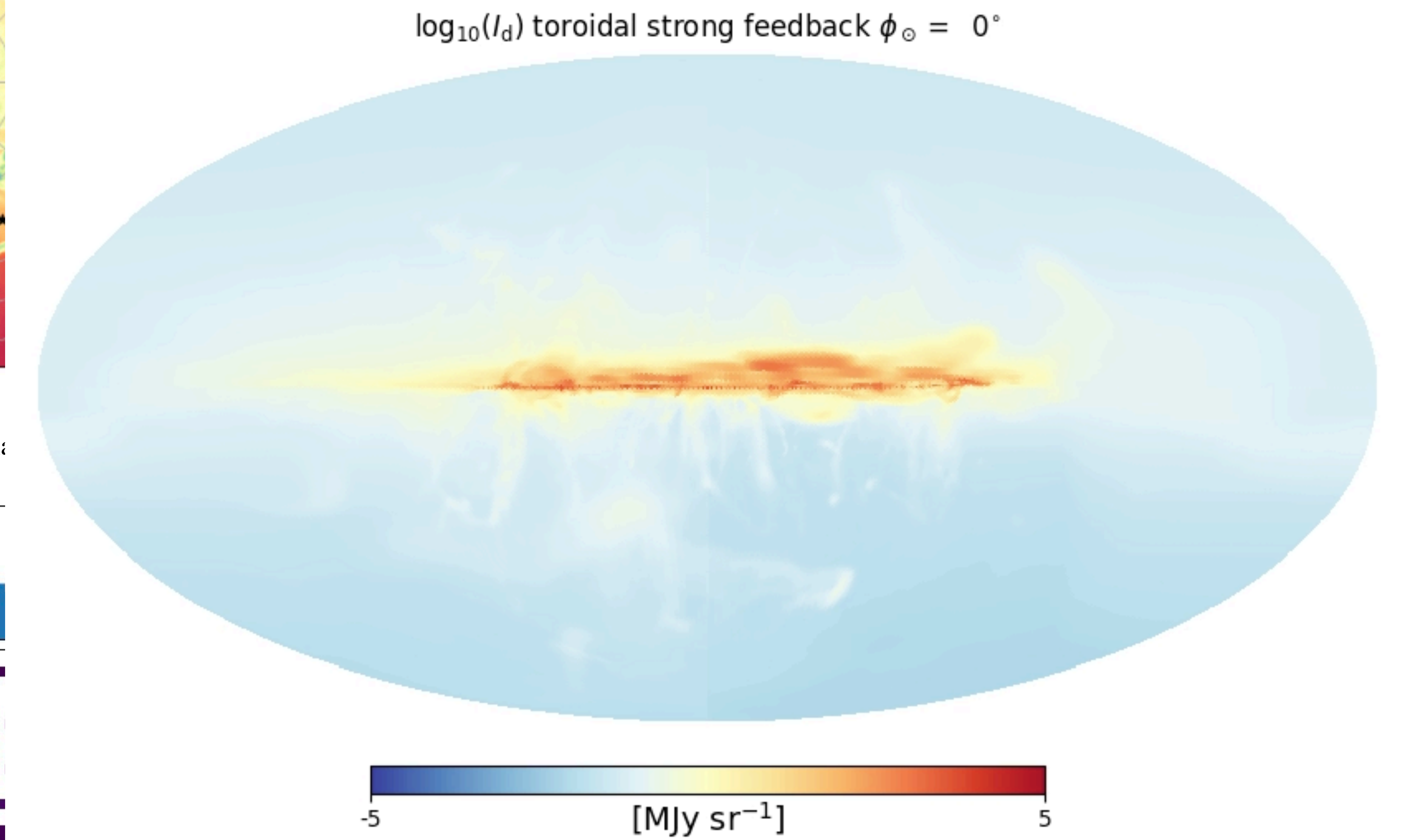
Ntormousi (2018)

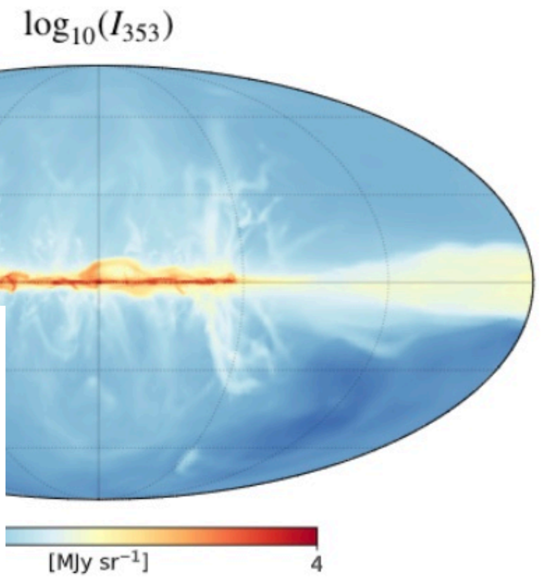
Synthetic polarisation maps, TE correlation and EE/BB asymmetry

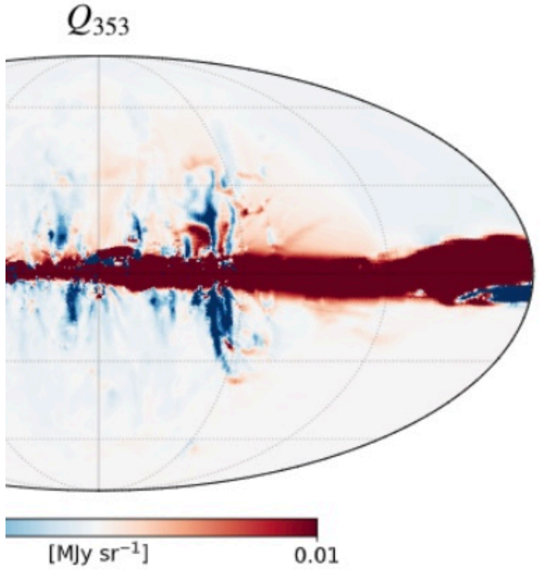


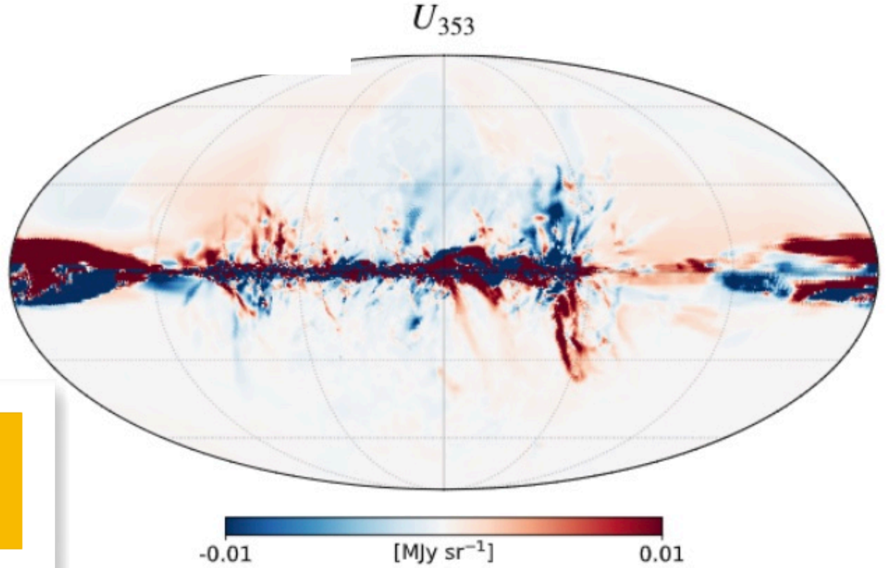
(red point from Planck Colla

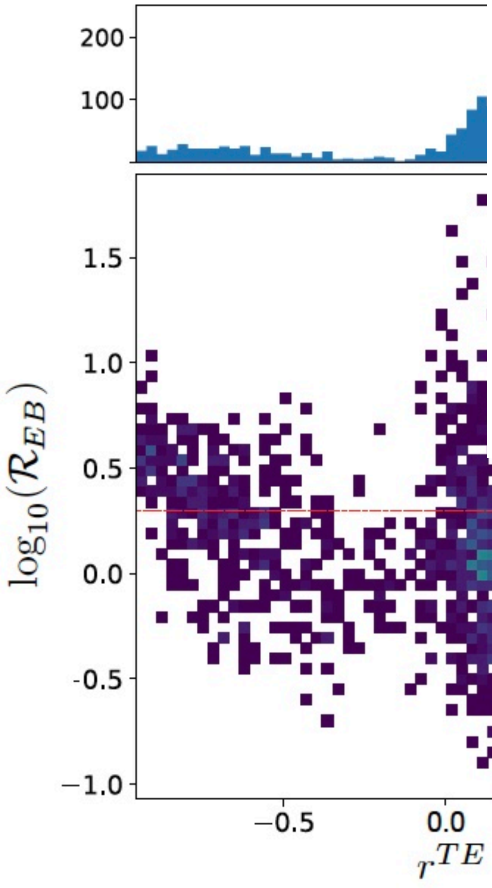
$$I^i_{\mathbf{e}_r} = \lambda^i_{\mathbf{e}_r}\, n^i_{\mathrm{d}} \left(1 - p_0 \left(\frac{B_\theta^{i\,2} + B_\phi^{i\,2}}{|\mathbf{B}^i|^2} - 2/3\right)\right)$$











$$\sqrt{C_\ell^{XX}\, C_\ell^{YY}}$$

r_l^{XY}=1 –> perfect correlation

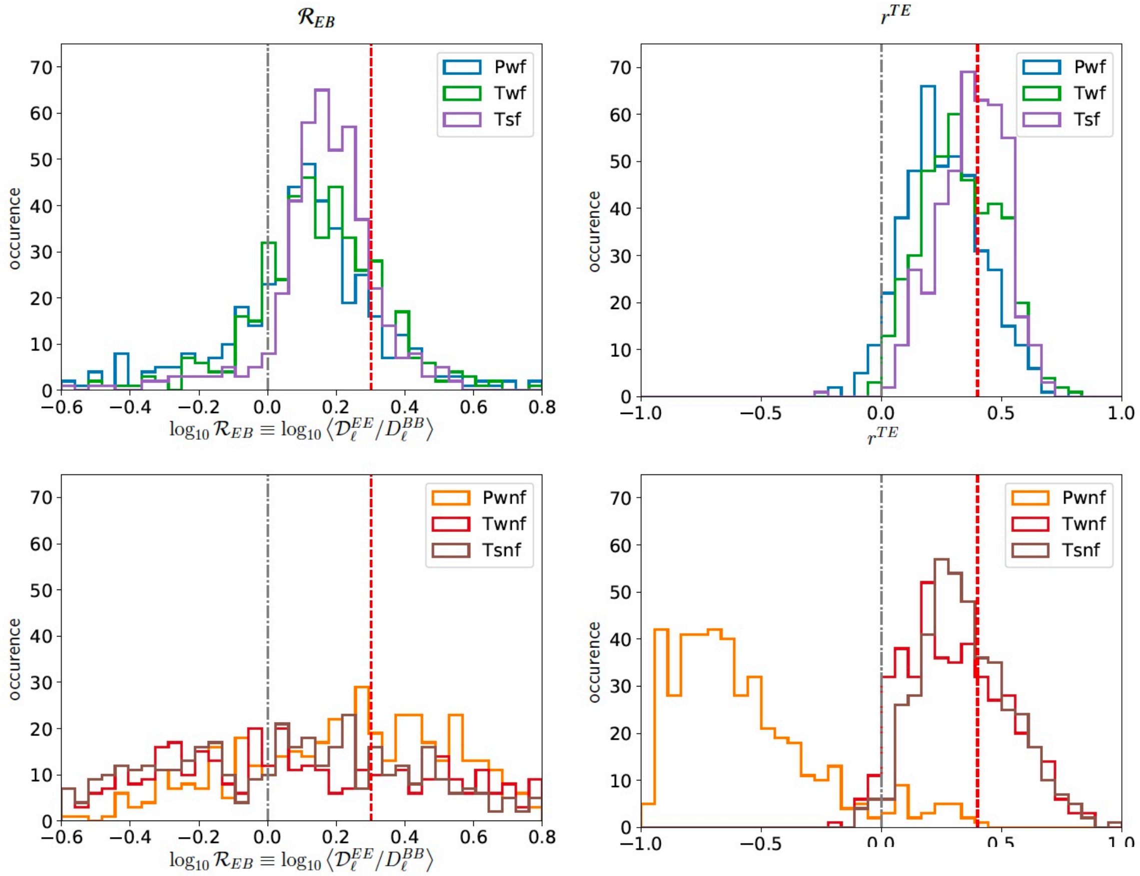
r_l^{XY}=-1 –> perfect anti=correlation

r_l^{XY}=0 –> no correlation

Small systematic increase of R_{EB} and r^{TE} with f_{sky}

Pelgrims, Ntormousi + Tassis (2022)

Synthetic polarisation maps, TE correlation and EE/BB asymmetry

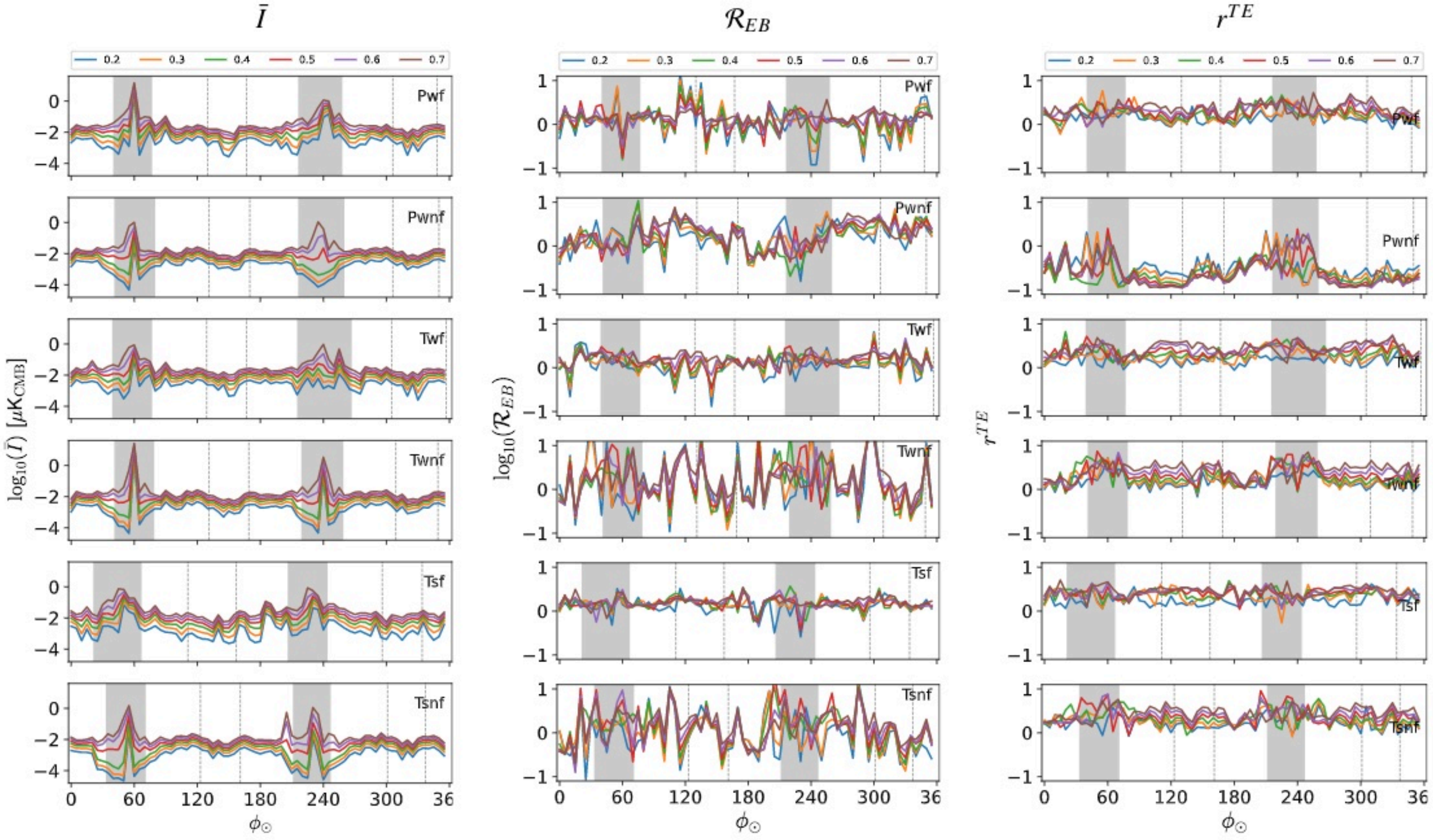


Models with SN feedback

Feedback has the effect of narrowing down the range of R_{EB} and r^{TE}

A toroidal magnetic field topology leads to positive TE correlations. A stronger magnetic field strengthens the correlation.

Models without feedback



Observers in the spiral arms are a peculiar sample.

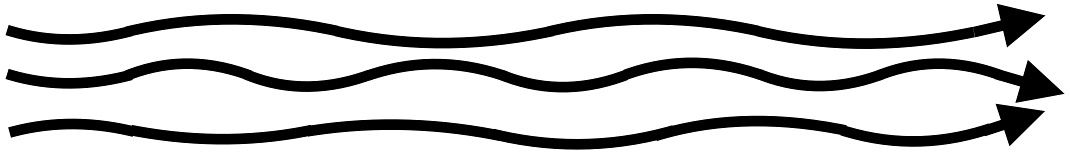
The same is true of observers inside superbubbles.

Pelgrims, Ntormousi + Tassis (2022)

Current question:

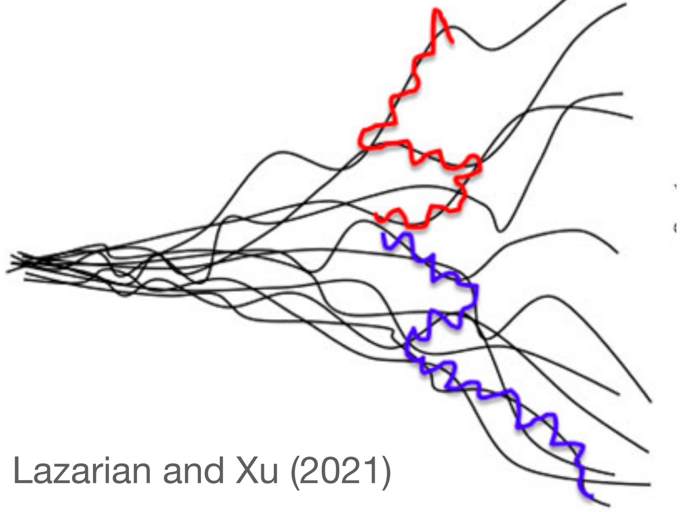
Characterising turbulence in the ISM

Weak turbulence: $\delta \mathbf{B} < \mathbf{B}_0$



Magnetic fluctuations are described as a superposition of weakly non-linear modes

The spectral transfer of energy happens through resonant three wave interaction (Vedenov 1963; Galtier 2009)



Lazarian and Xu (2021)

For CR propagation this means we can take the small-angle scattering approximation and describe the propagation as a diffusion process (the only existing approach in on-the-fly simulations)

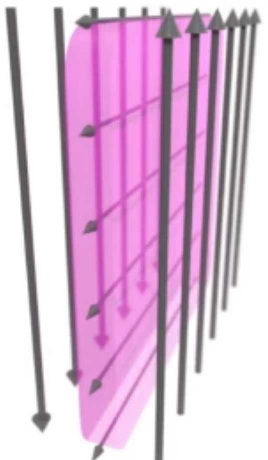
Predicts scattering rates orders of magnitude different between models, and wrong scaling between residence time and CR rigidity $\mathrm{R} = \frac{\mathrm{pc}}{\mathrm{Ze}}$

(e.g. Hopkins et al. 2021c, see also Butsky et al. 2024)

Strong turbulence: $\delta \mathbf{B} \geq \mathbf{B}_0$

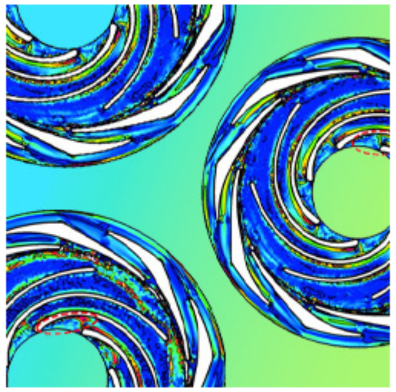
Intermittent appearance of Magnetic Coherent structures (MCoSs)

Current sheets



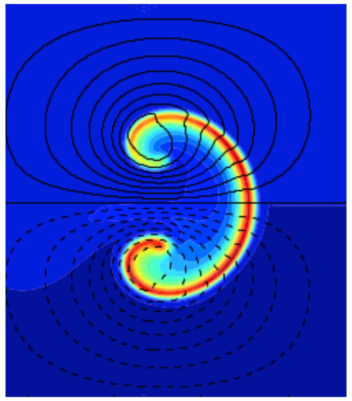
Yoon, Wendel & Yun 2023

Magnetic vortices



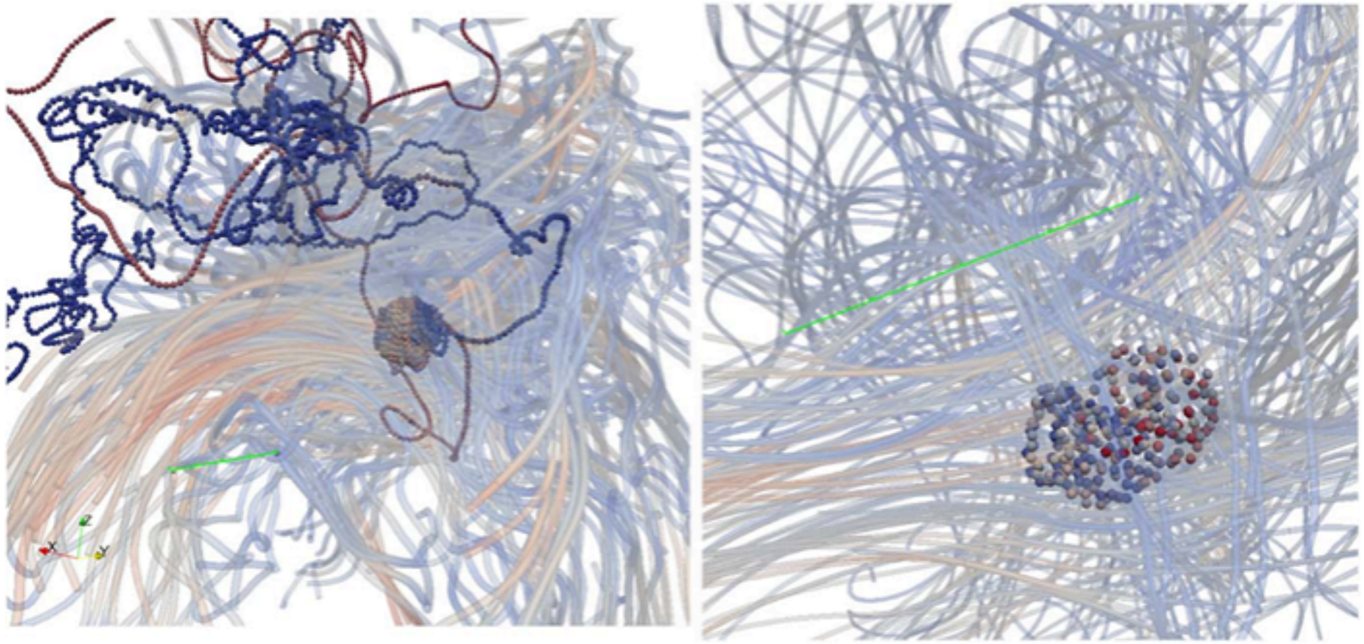
Phys. Of Fluids AIP

Magnetic filaments



Dudson et al. 2009

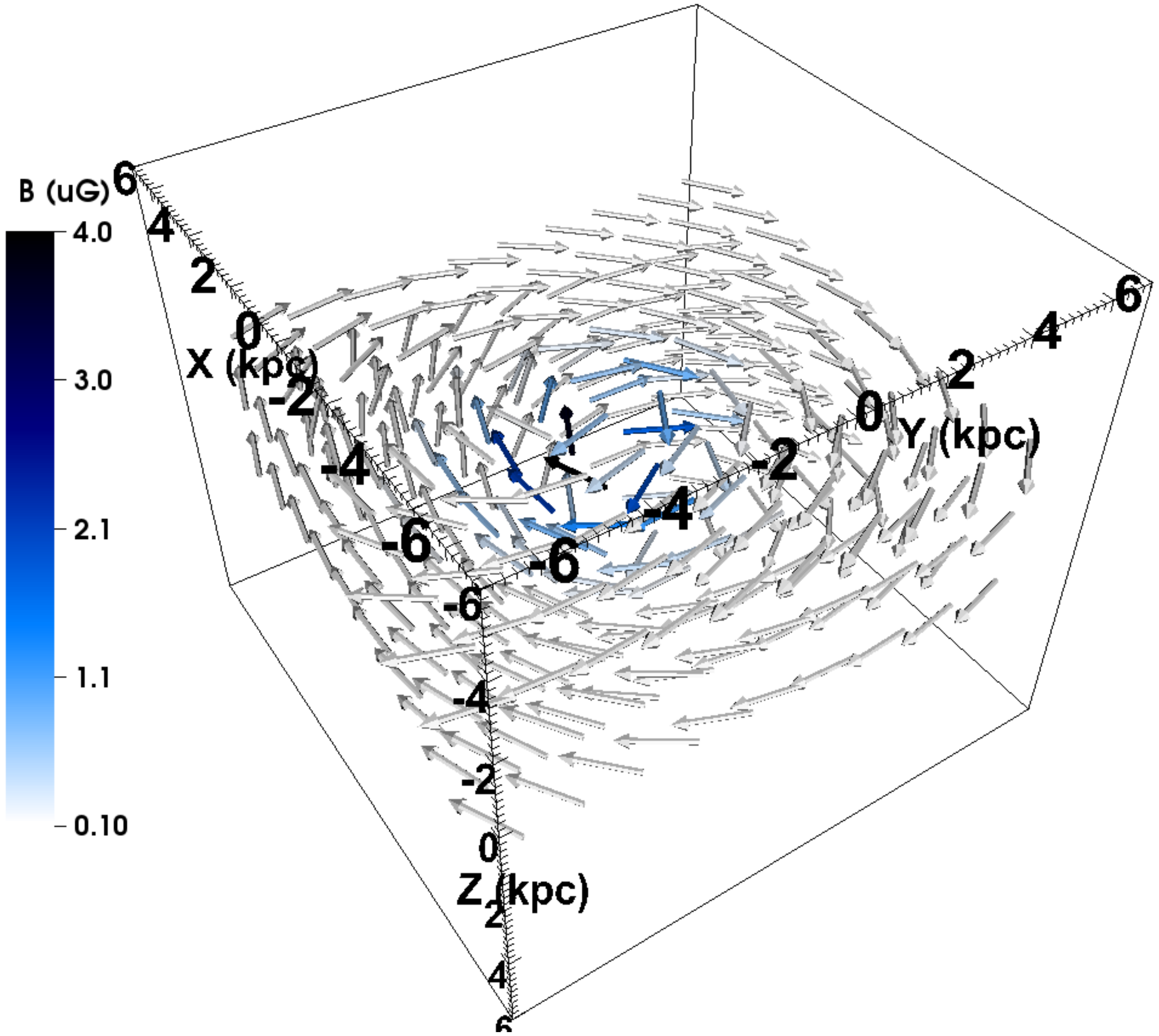
Particles suffer large deflections, trapping, heating/acceleration in MCoSs

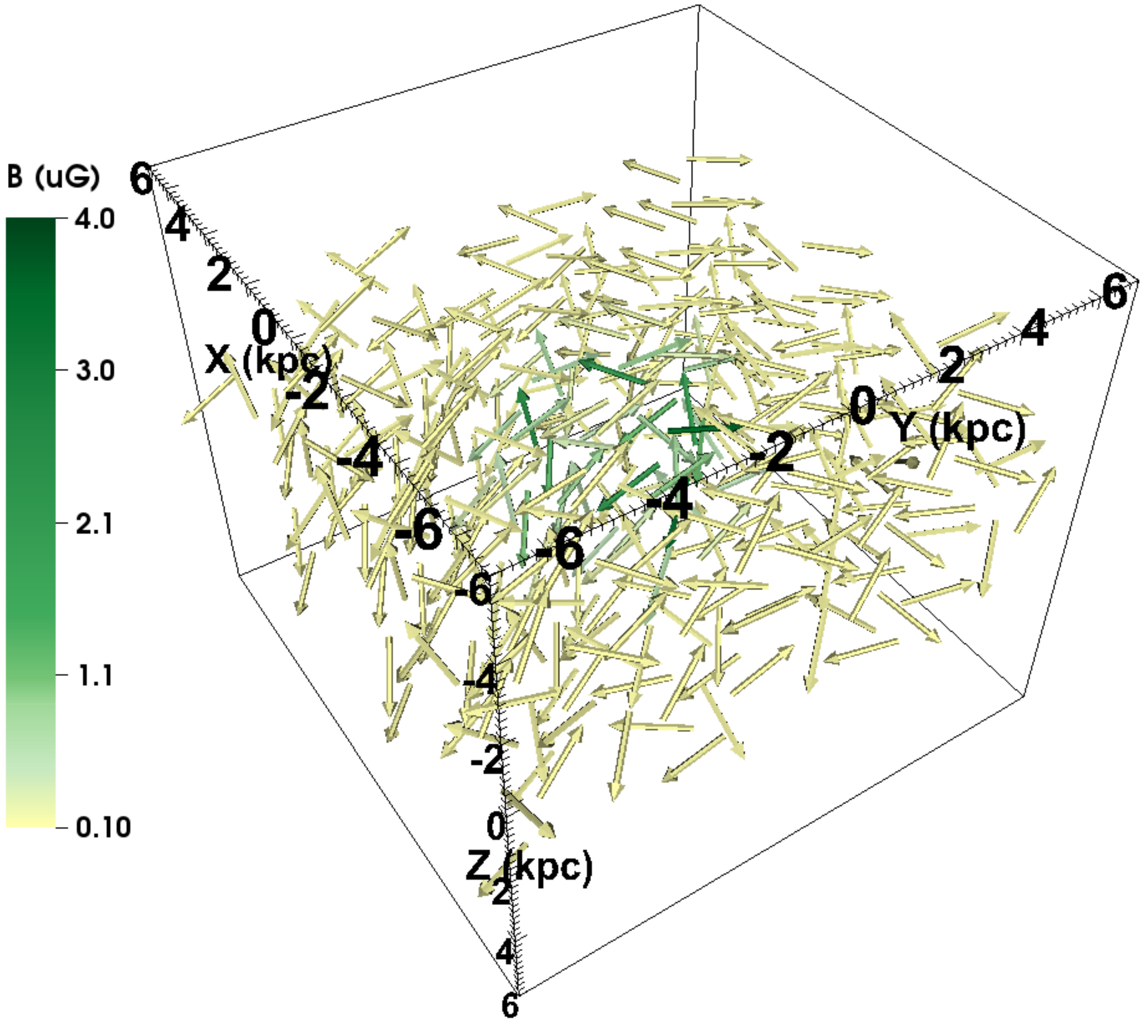


Pezzi, Blasi & Matthaeus 2022

The simulations

(A. Konstantinou, E. Ntormousi, K. Tassis & A. Pallottini A&A 2024)





RAMSES (Teyssier 2002, Fromang et al 2006) with KROME chemical network for H_2 formation, following H, H^+, e^-, He, He^+, He^{++}, H_2, H_2^+ for a constant UV background (G_0=1)

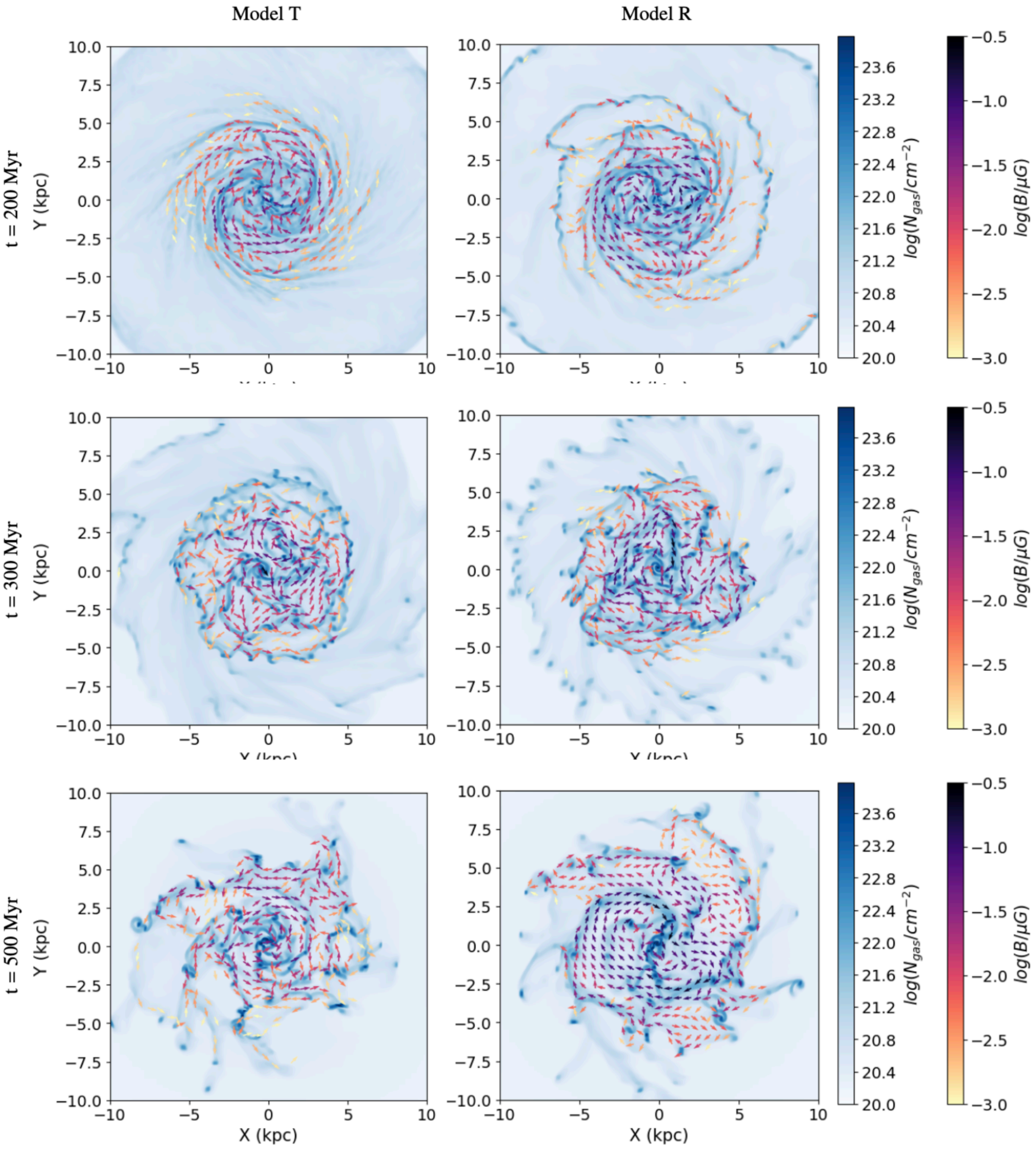
Metal cooling also from KROME assuming solar metallicity

Star formation follows the Schmidt-Kennicutt relation (Schmidt 1959, Kennicutt 1998) based on H_2 content (Pallottini et al. 2017) with an efficiency ε=1%.

Supernova feedback from 20% of the stellar mass given as thermal energy to the neighbouring 27 cells

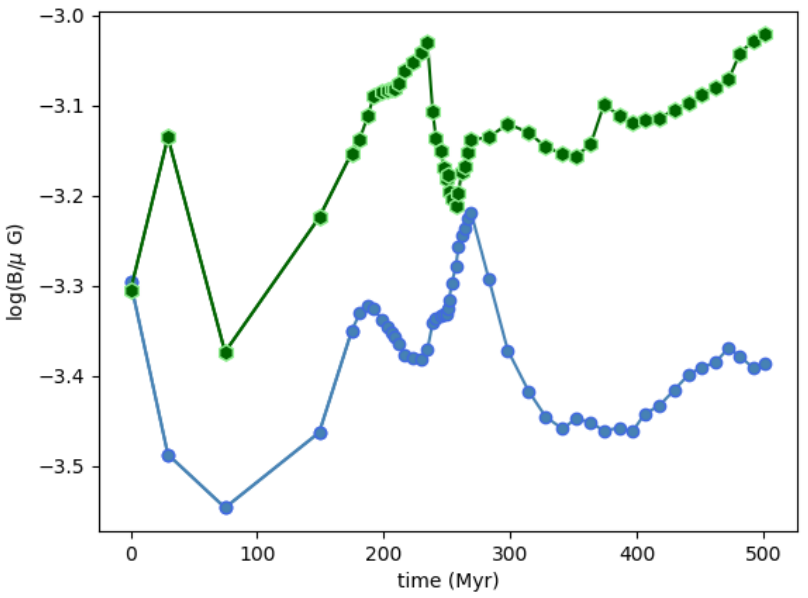
100 kpc box, coarse grid 128^3, 5 levels of AMR

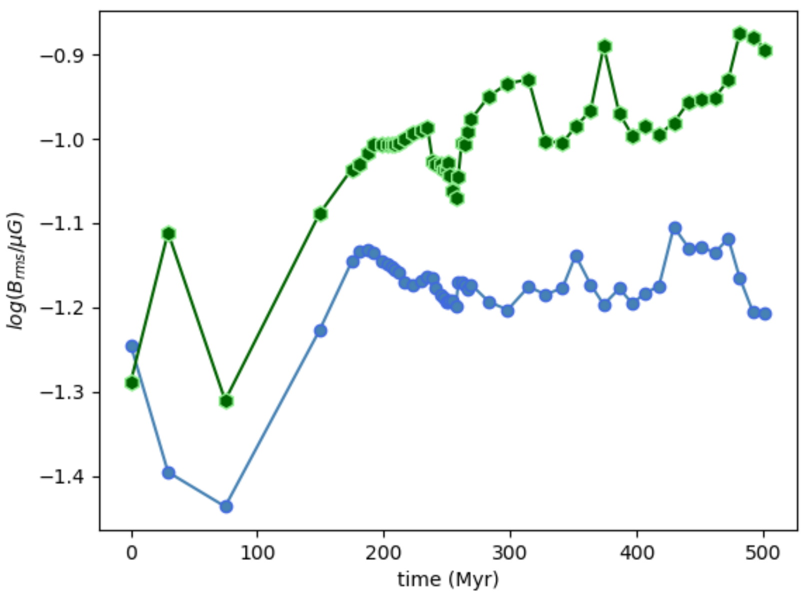
Subtle differences in the model evolution:



Model R is slightly larger in the radial direction

Model R's magnetic field is stronger over a wider radial range



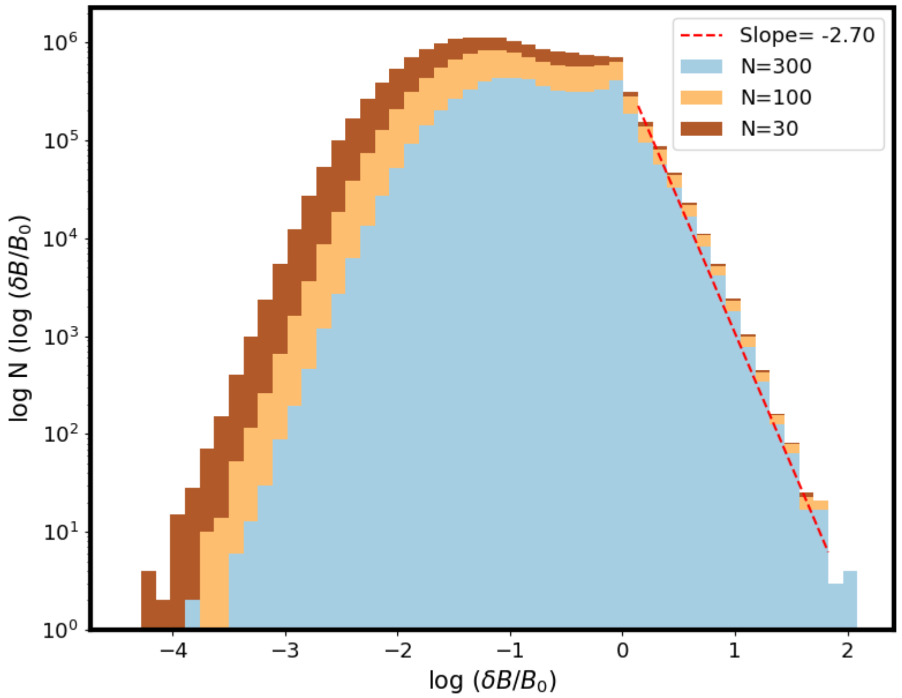


A. Konstantinou, E. Ntormousi, K. Tassis & A. Pallottini A&A 2024

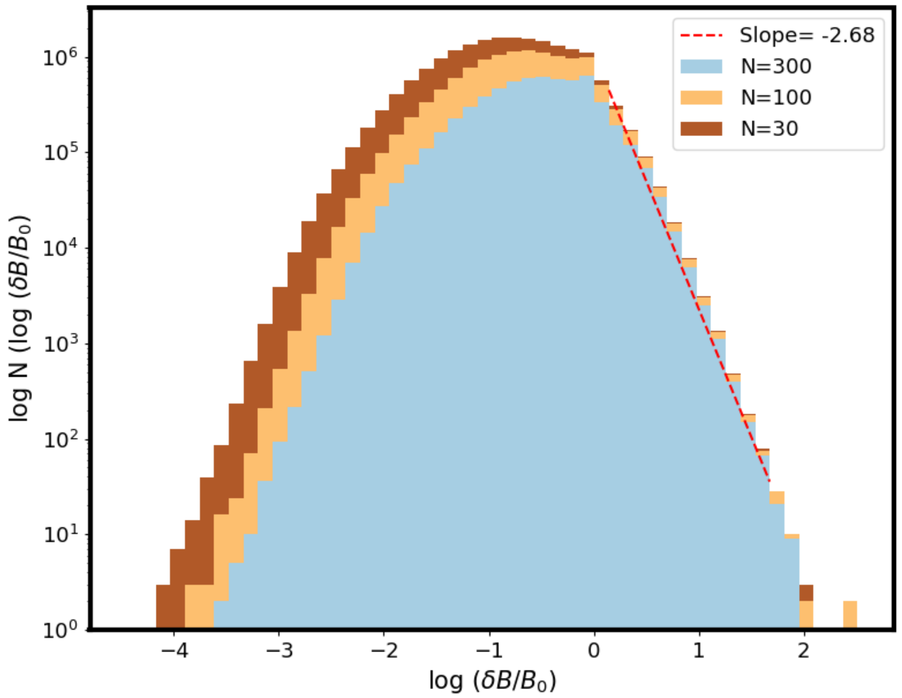
δB/B0 and J/Jrms PDFs

To calculate δ**B**:
For each AMR cell we find the N closest neighbors using a KDTree and take the mean **B₀** from these locations.
The residual is δ**B**.

Model T



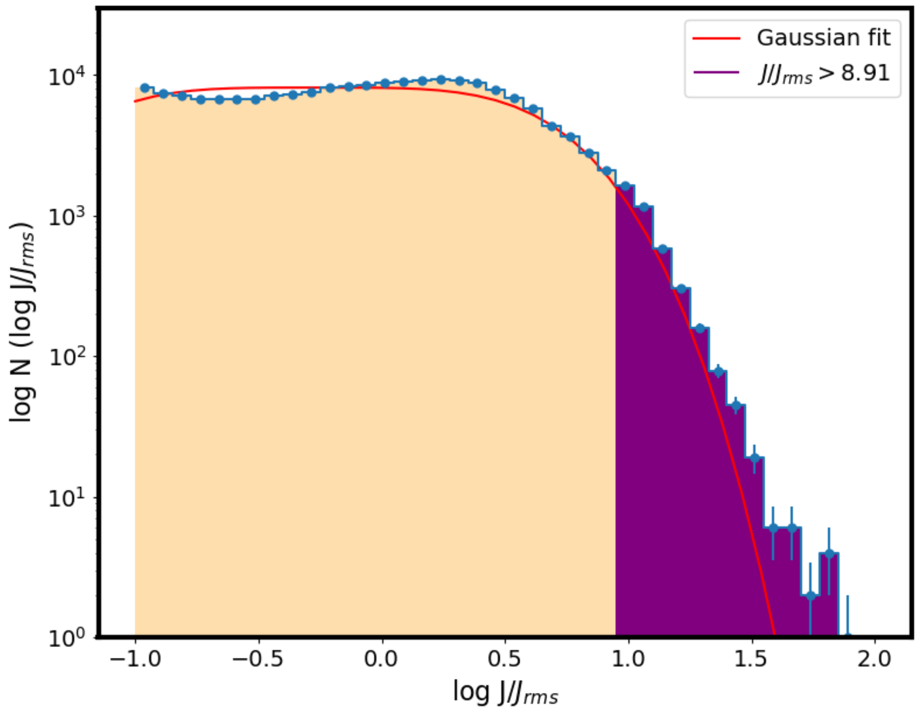
Model R



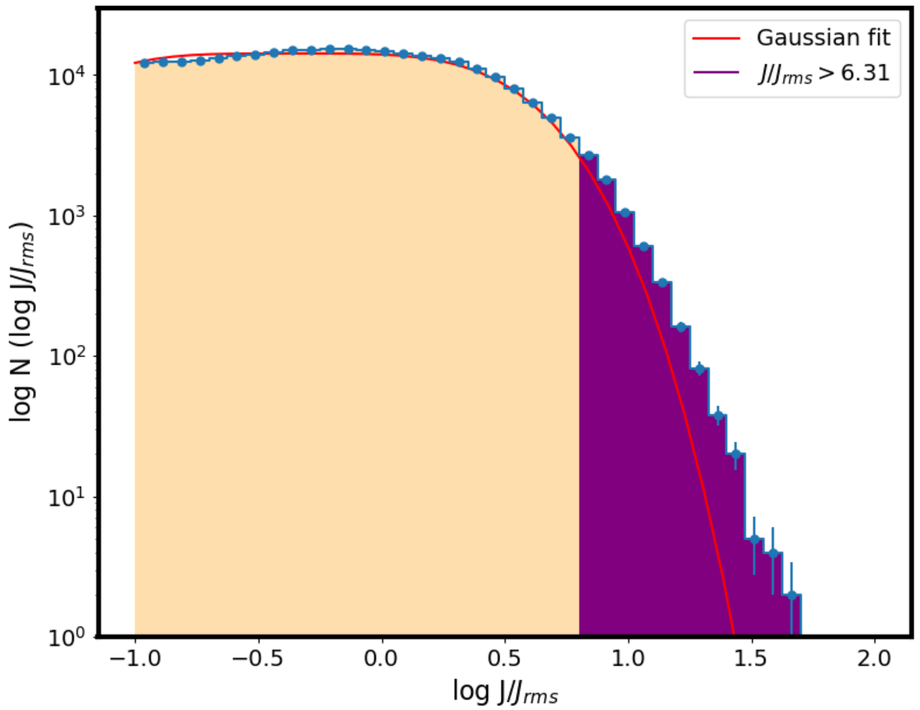
The point $\left(J/J_{\mathrm{rms}}\right)_c$ where the distributions start deviating from a log-normal defines the threshold for a MCoS

The currents are calculated as $\nabla \times \mathbf{B}$ at each location using the octree for the derivatives. The log-normal is fit only to the part of the distribution plotted.

Model T



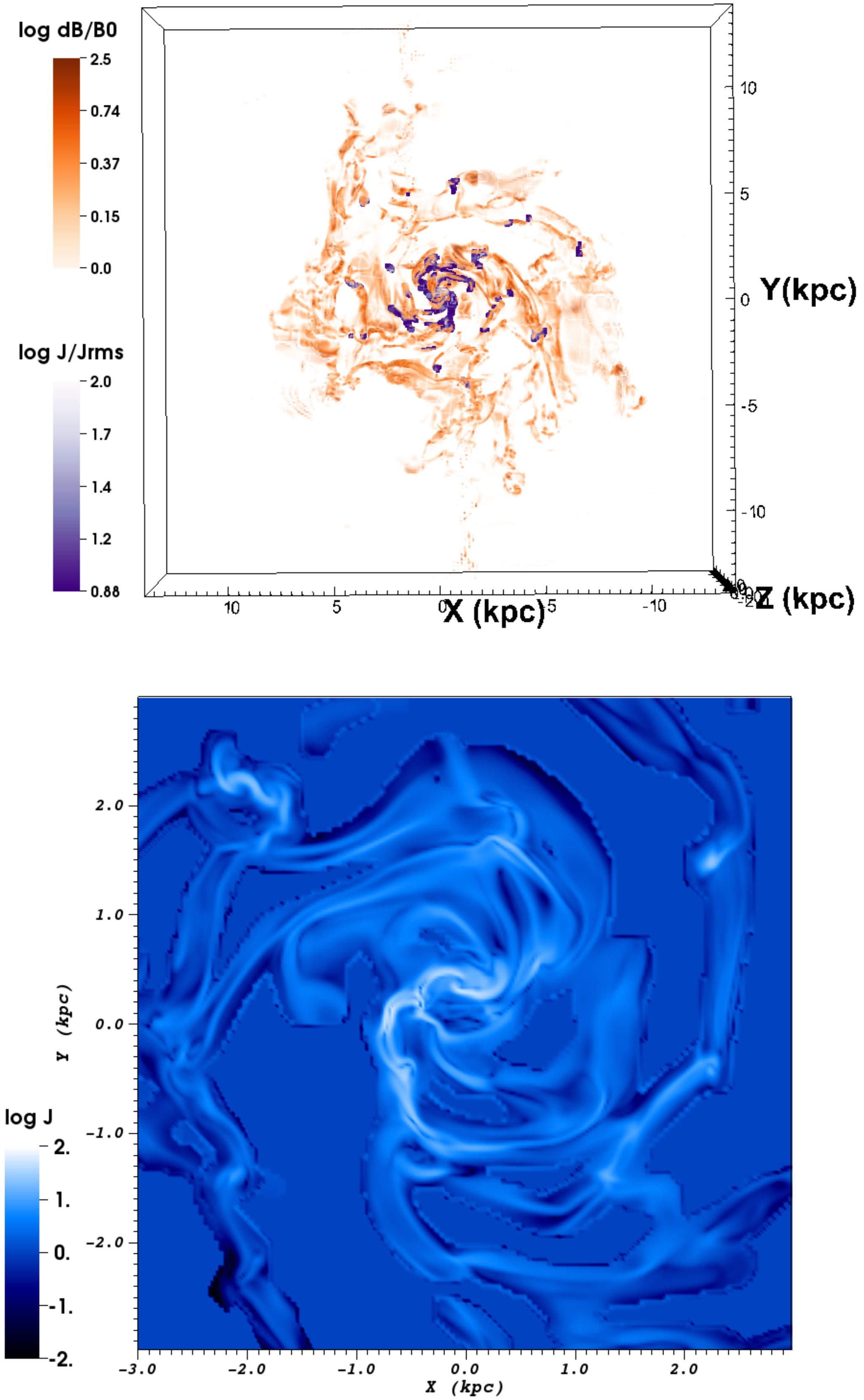
Model R



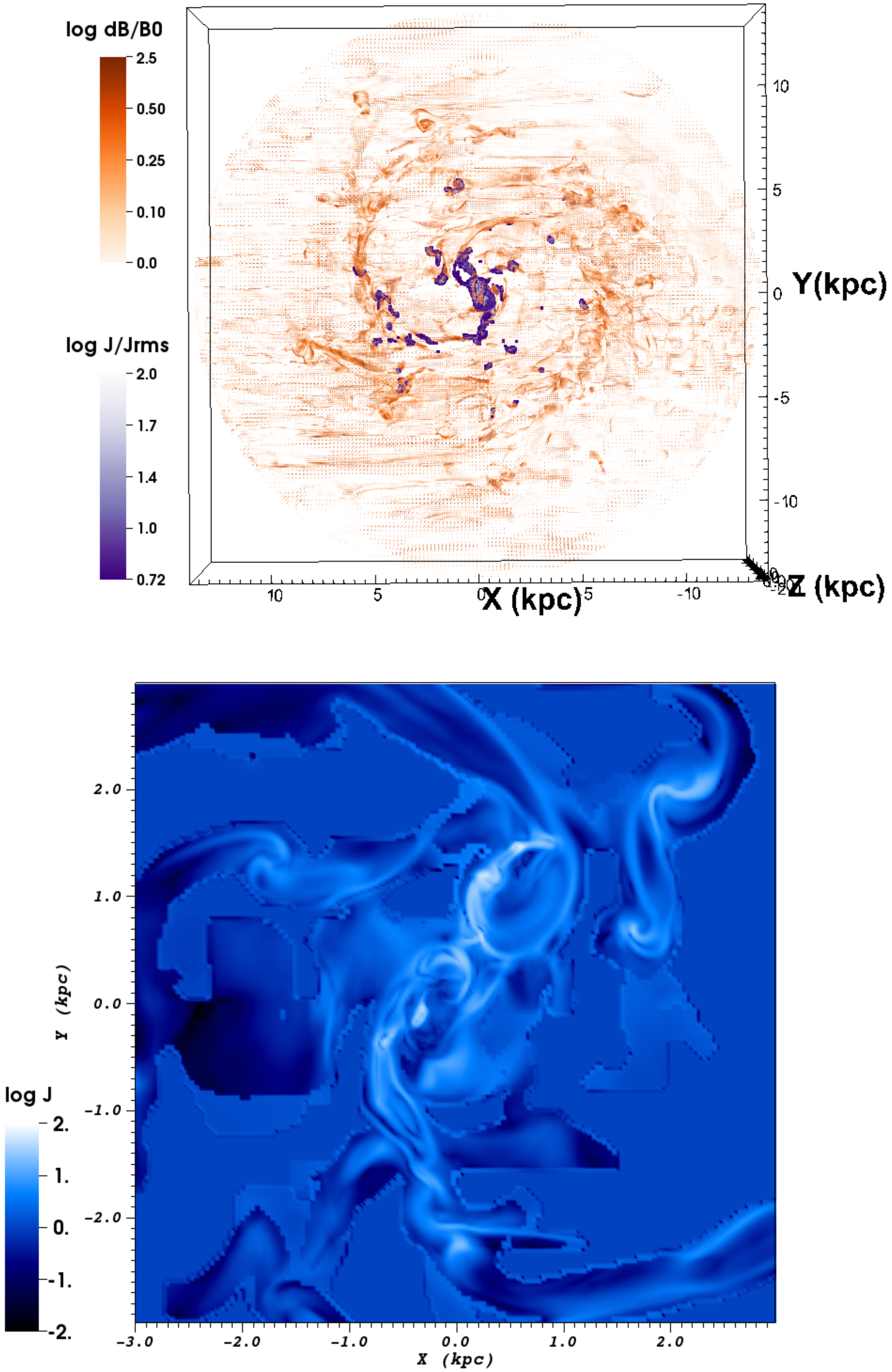
(E. Ntormousi, L. Vlahos, A. Konstantinou,& H. Isliker A&A 2024)

Spatial distribution of δB/B0 and MCoSs

Model T

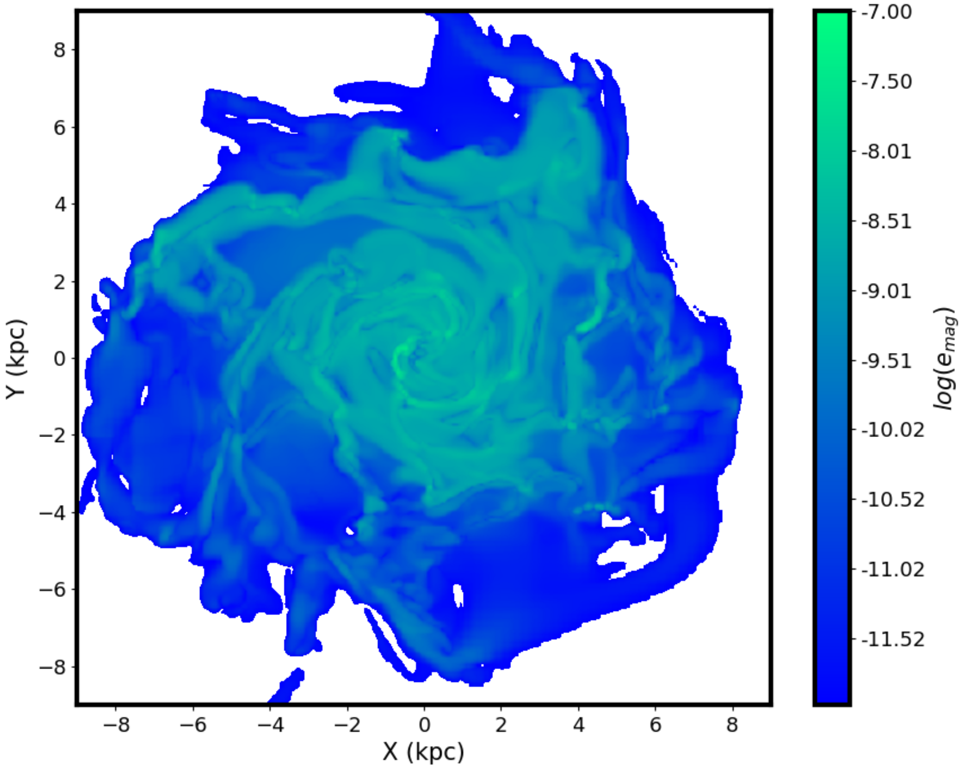


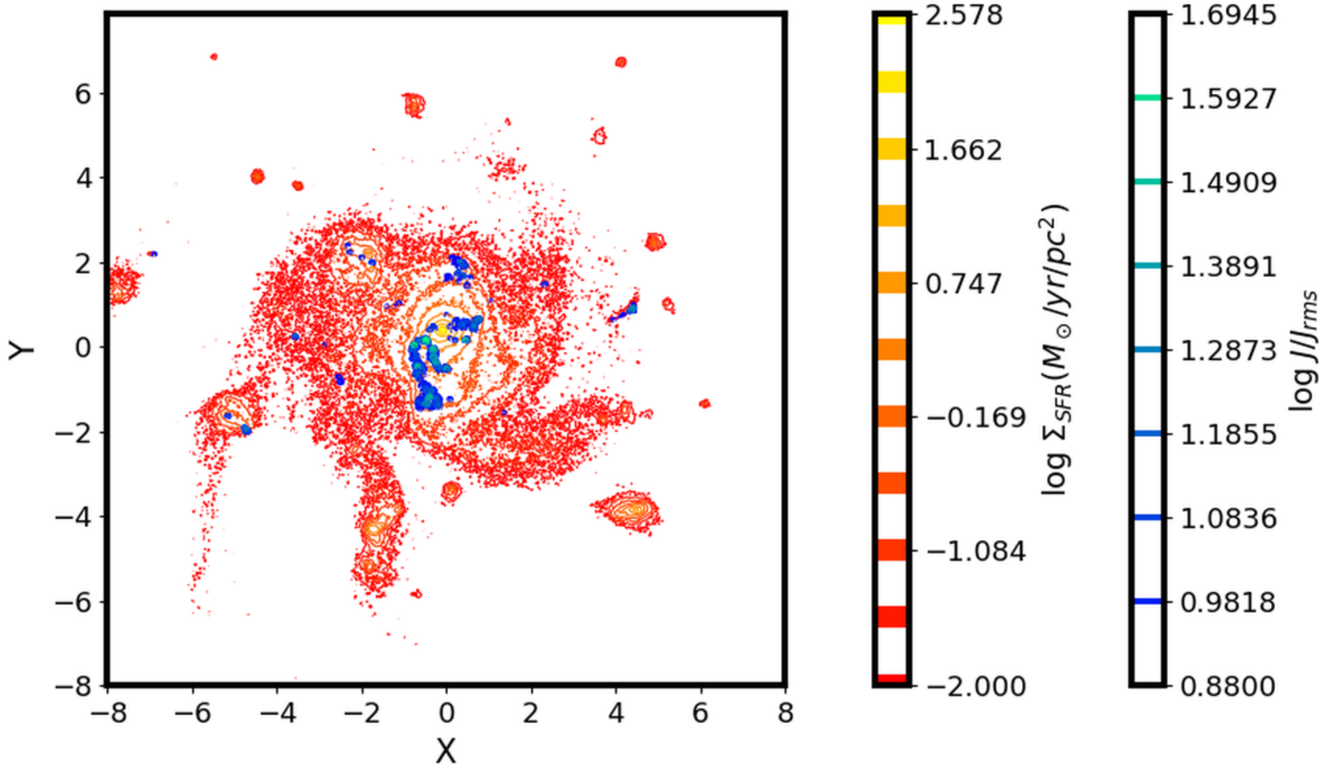
Model R



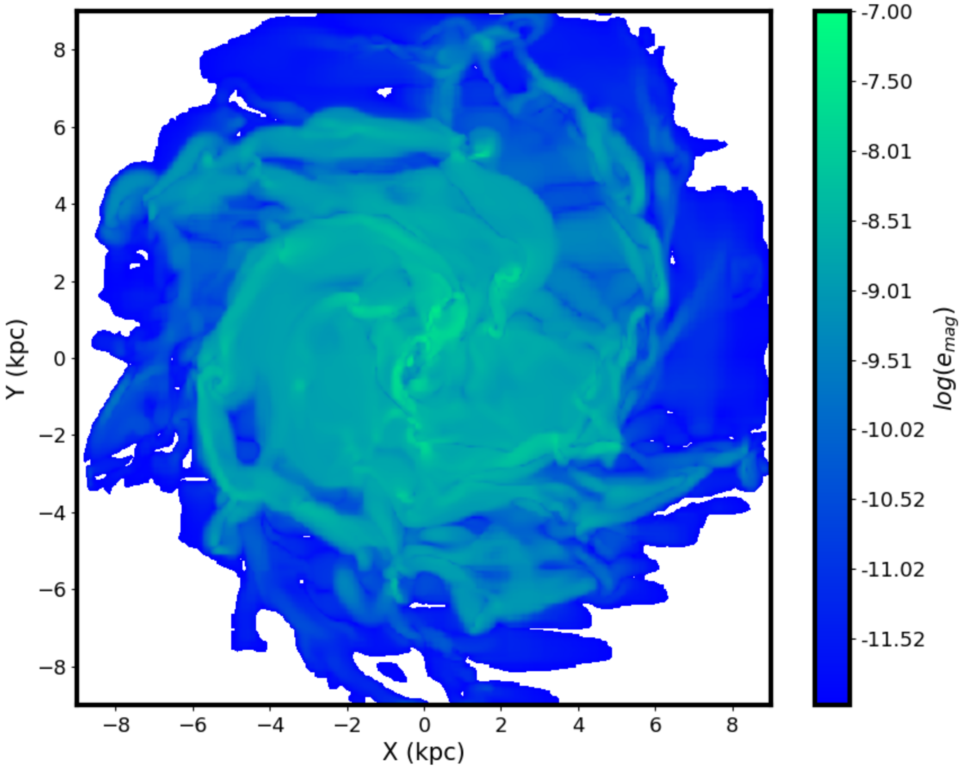
Magnetic energy and MCoSs

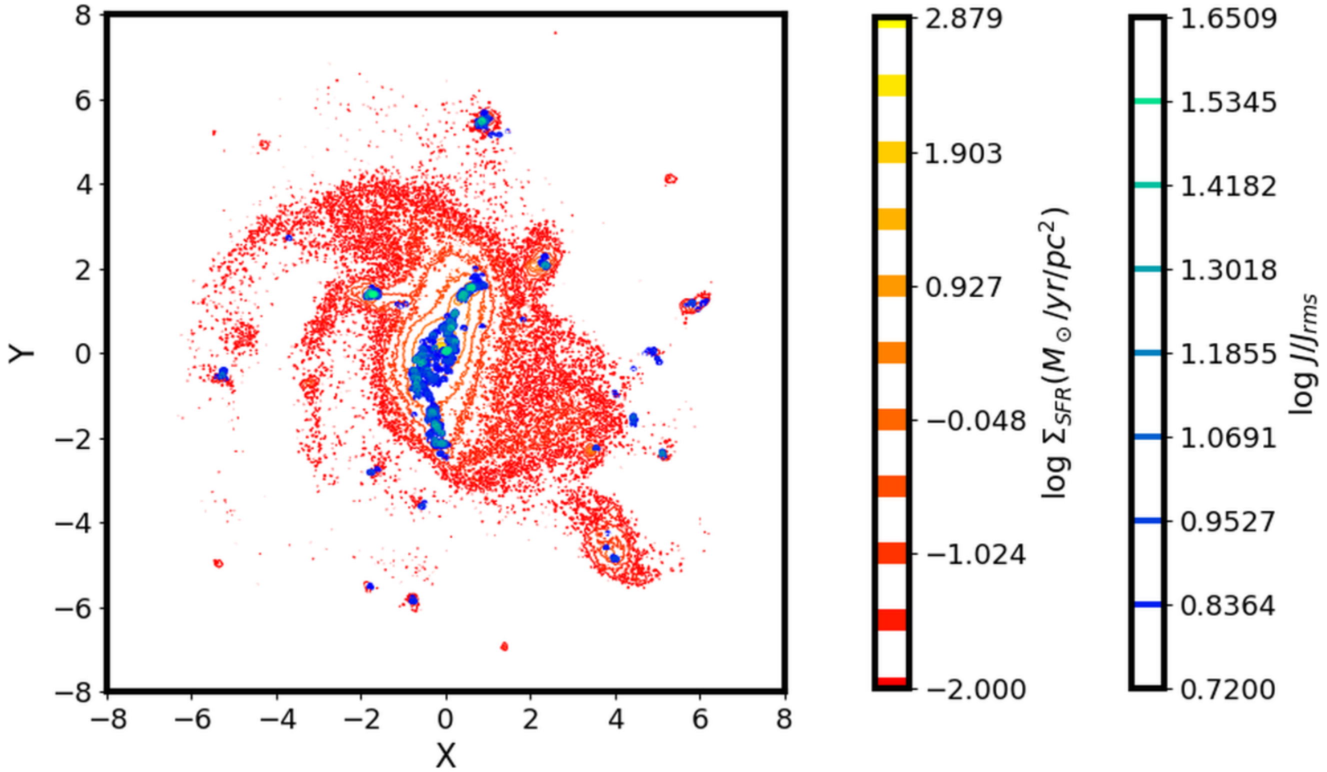
Model T



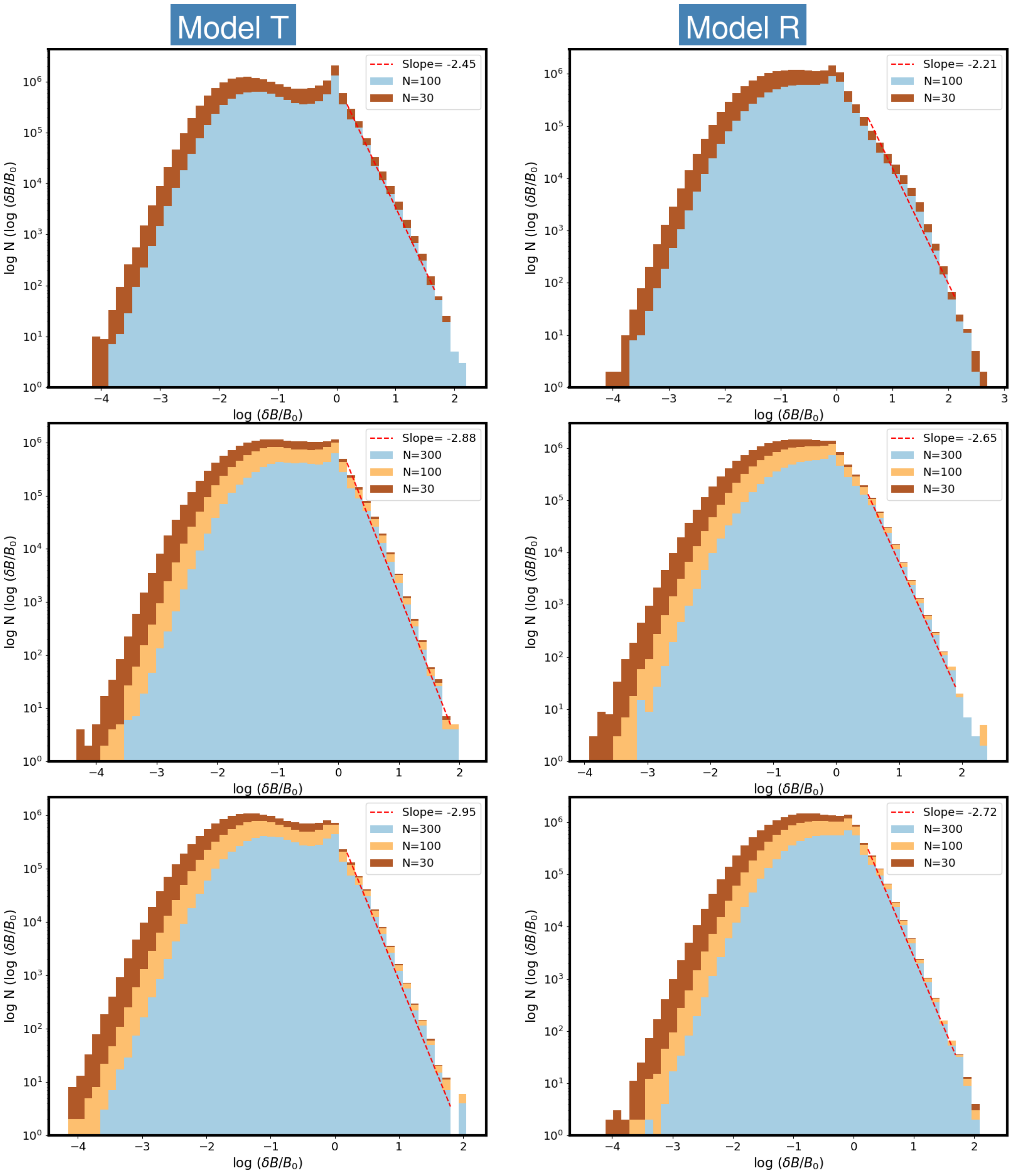


Model R





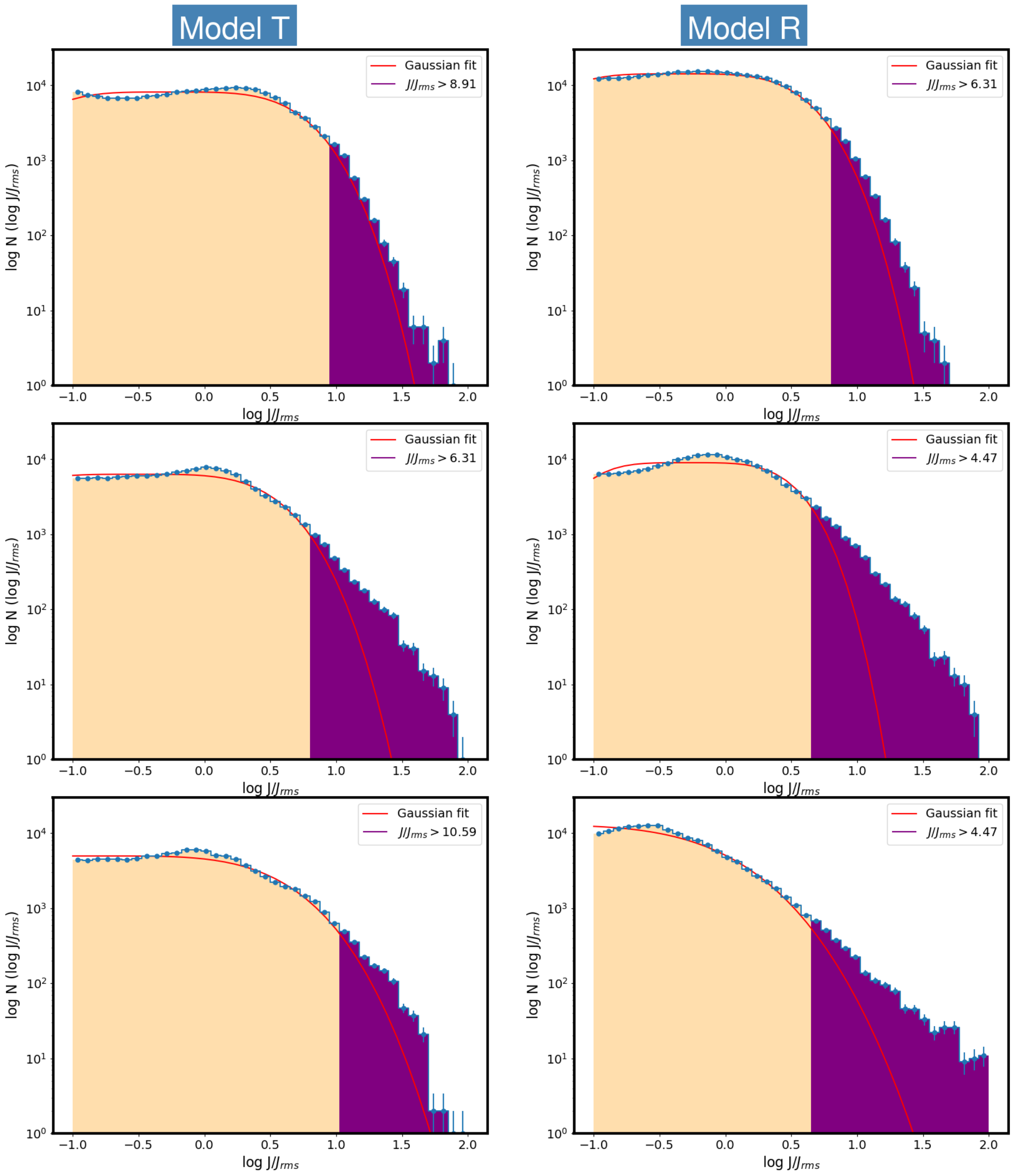
δB/B0 and J/Jrms PDFs over time



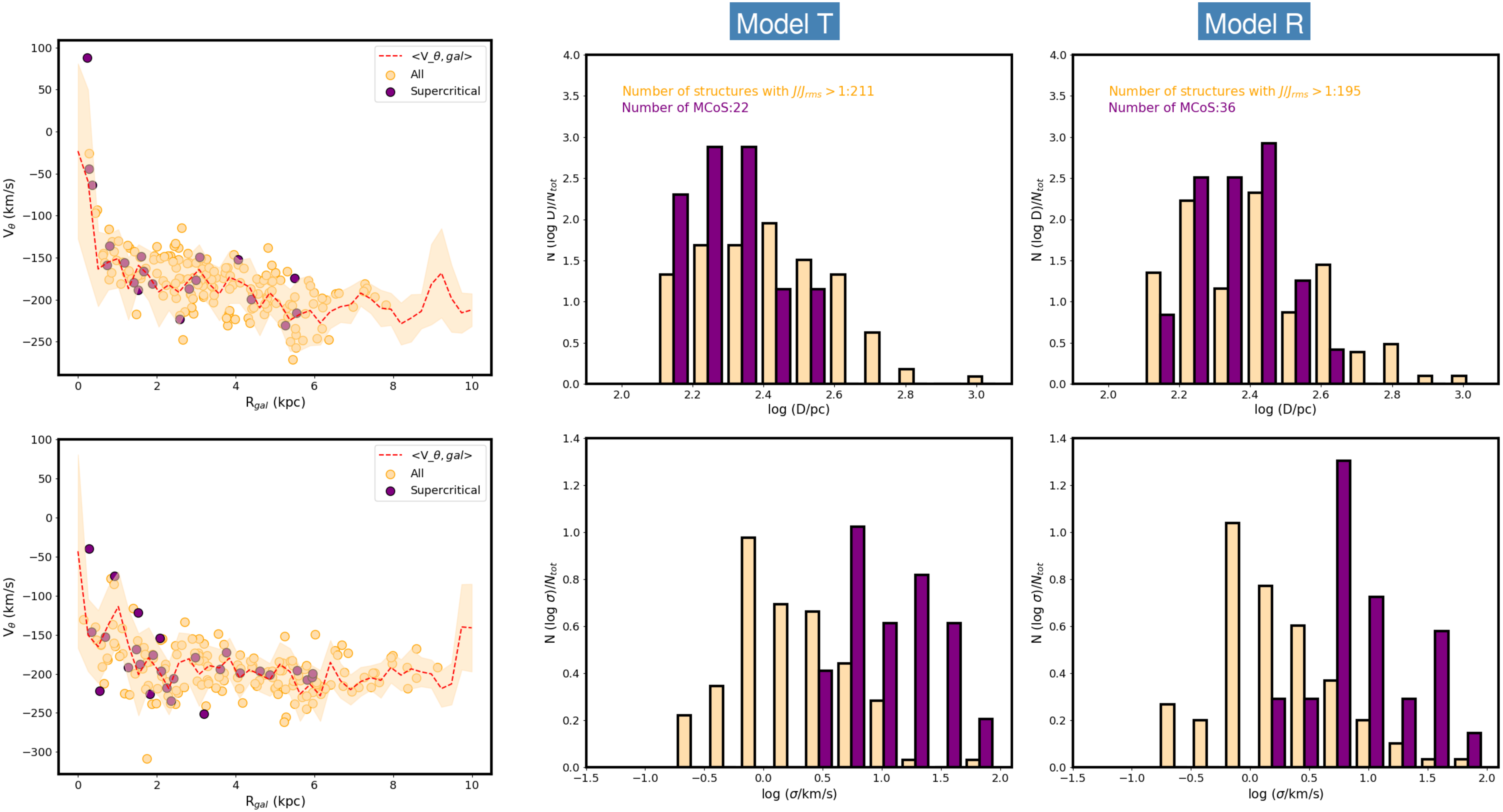
200 Myrs

300 Myrs

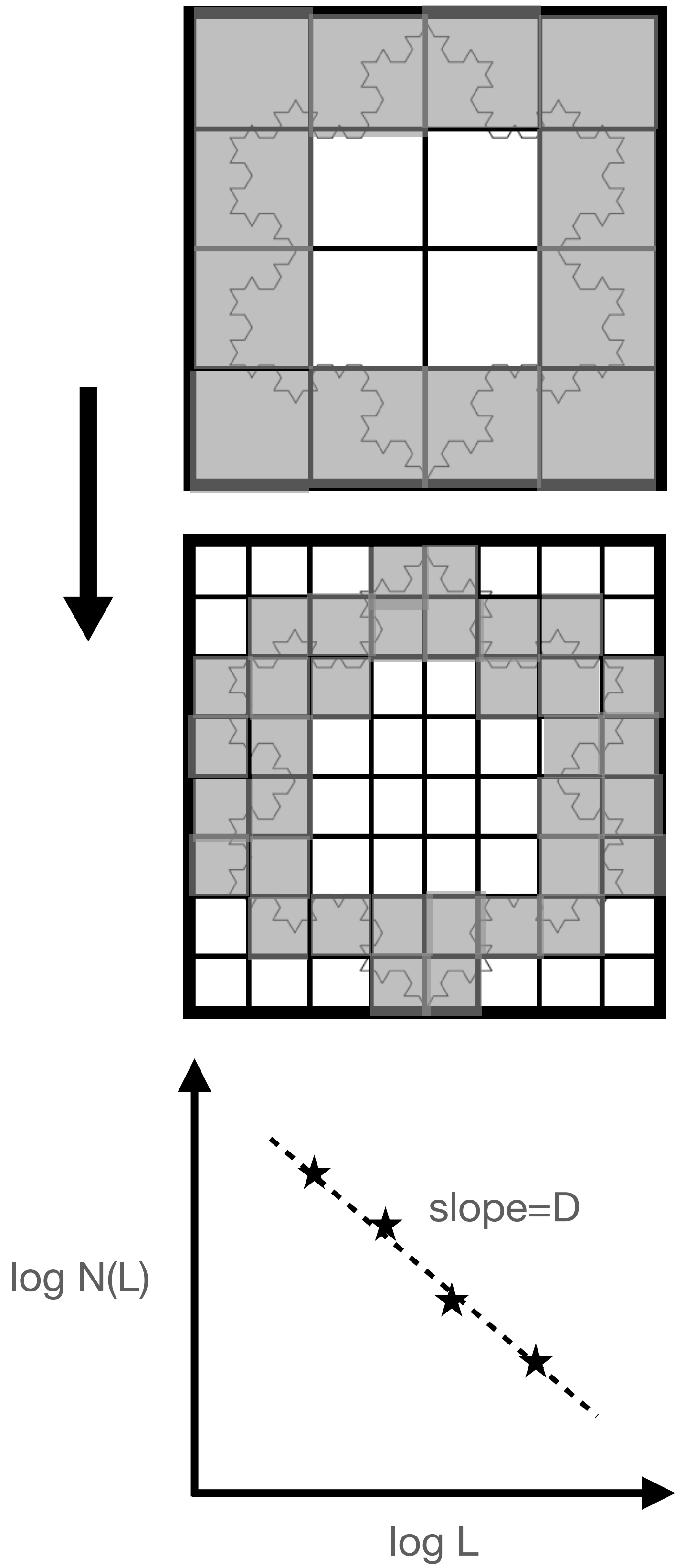
400 Myrs



MCoSs: Sizes, velocities and velocity dispersions



MCoSs: fractal dimension

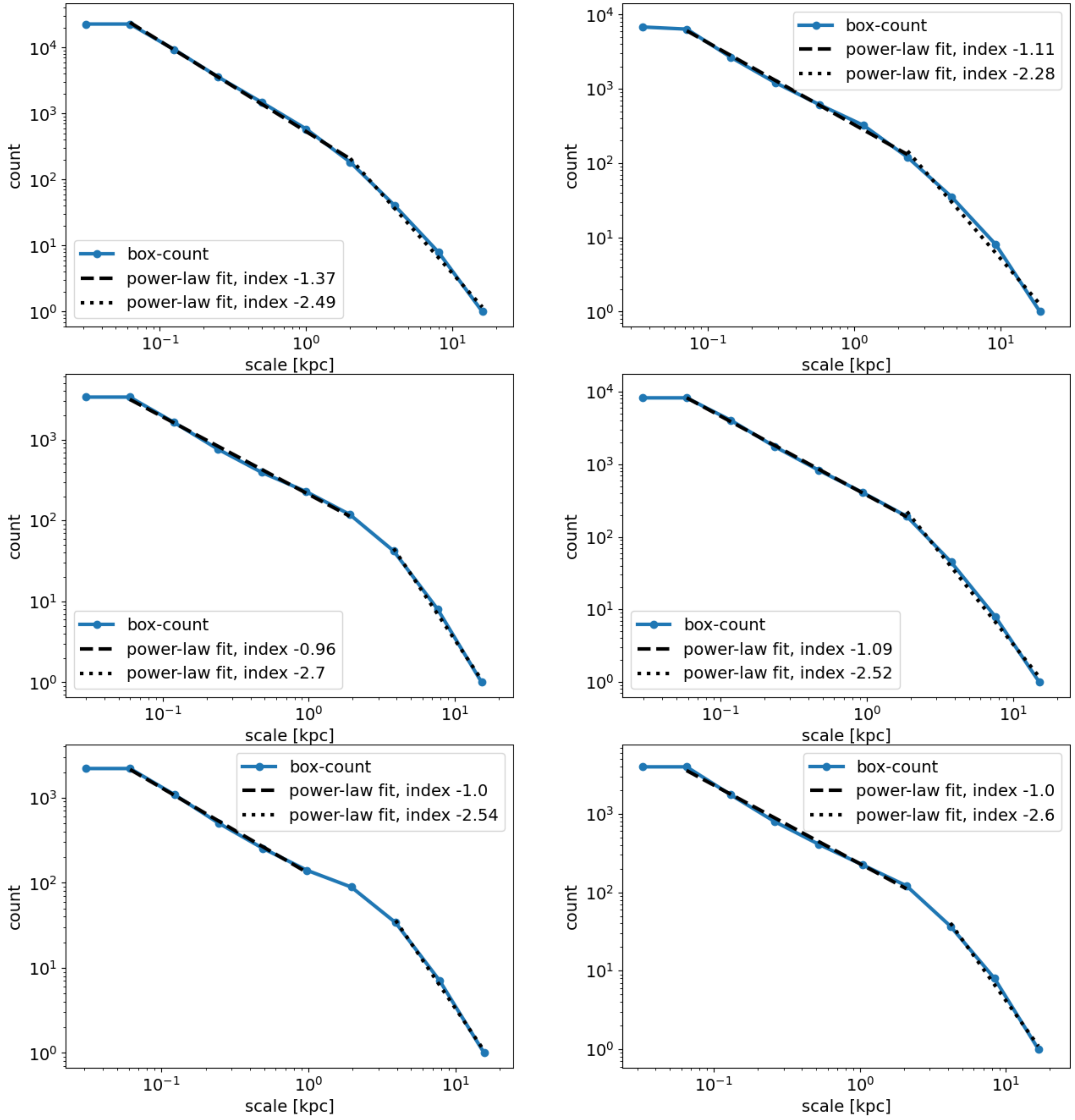


Model T **Model R**

200 Myrs

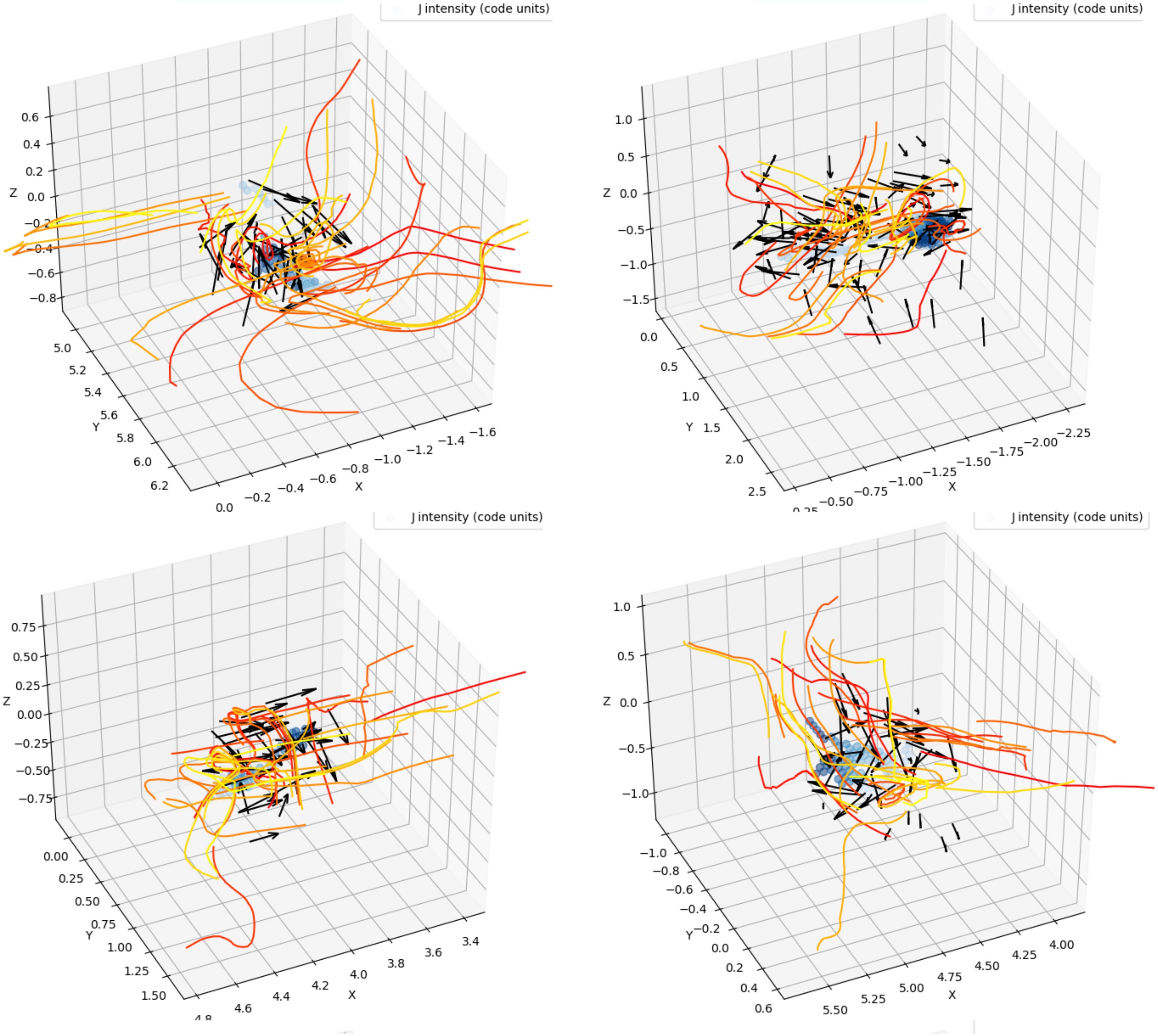
300 Myrs

500 Myrs



Example MCoS

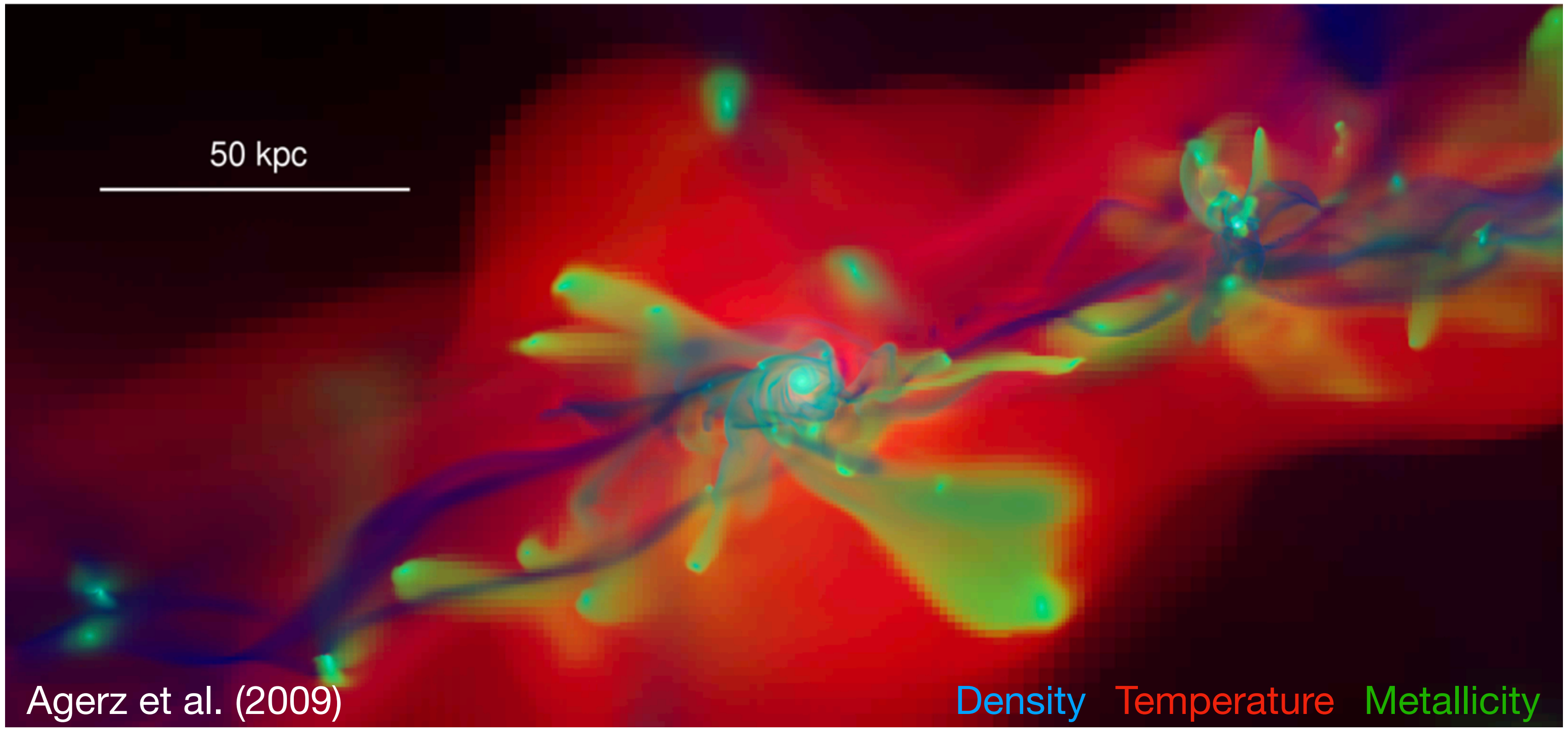
Model T **Model R**



Bonus topic for discussion: Galactic magnetic fields from cold inflows

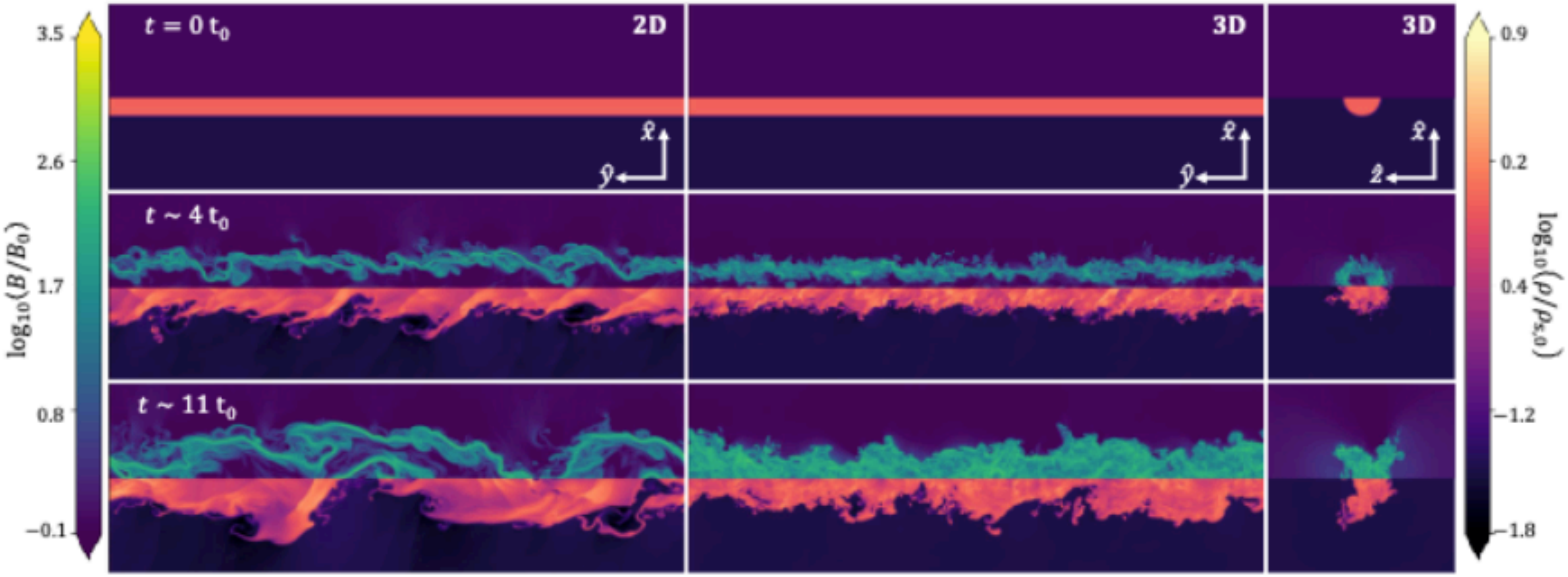
N. Ledos, E. Ntormousi, S. Takasao, K. Nagamine A&AL 2024

Filamentary accretion onto galaxies



Agerz et al. (2009)

Numerical simulations of cosmic structure formation predict that massive galaxies are fed by filamentary cold accretion (Fardal et al. 2001; Kereš et al. 2005; Dekel & Birnboim 2006; Dekel et al. 2009, Agerz et al. 2009)

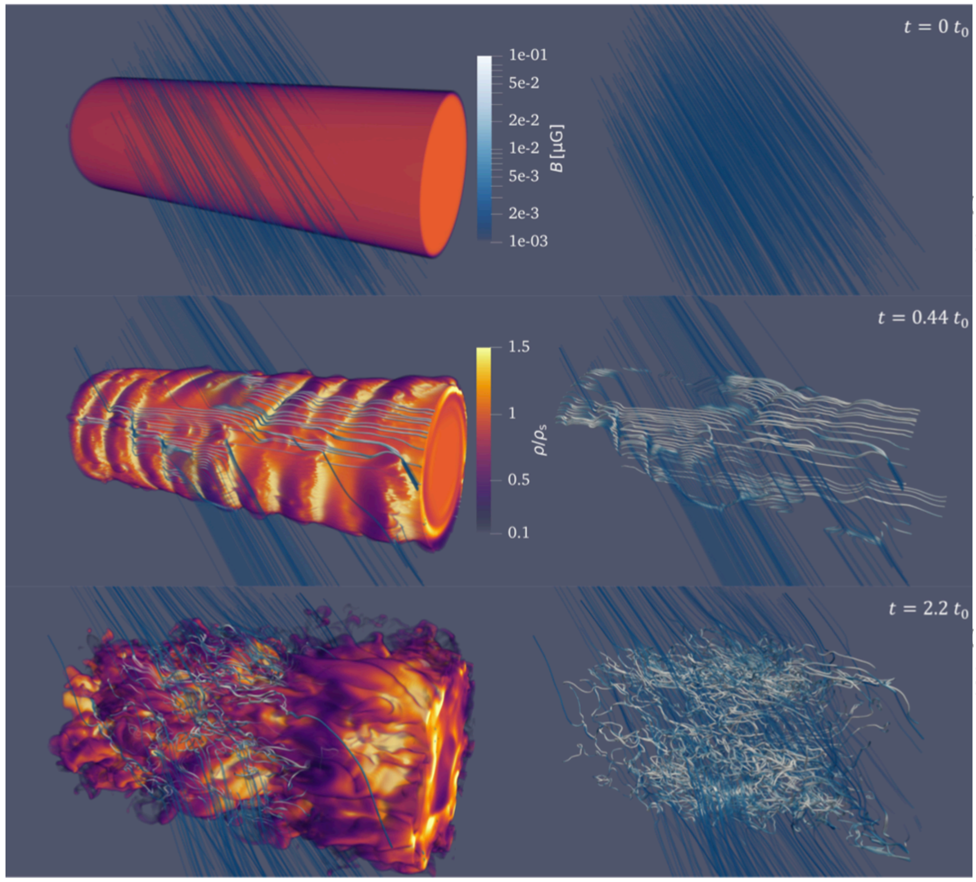


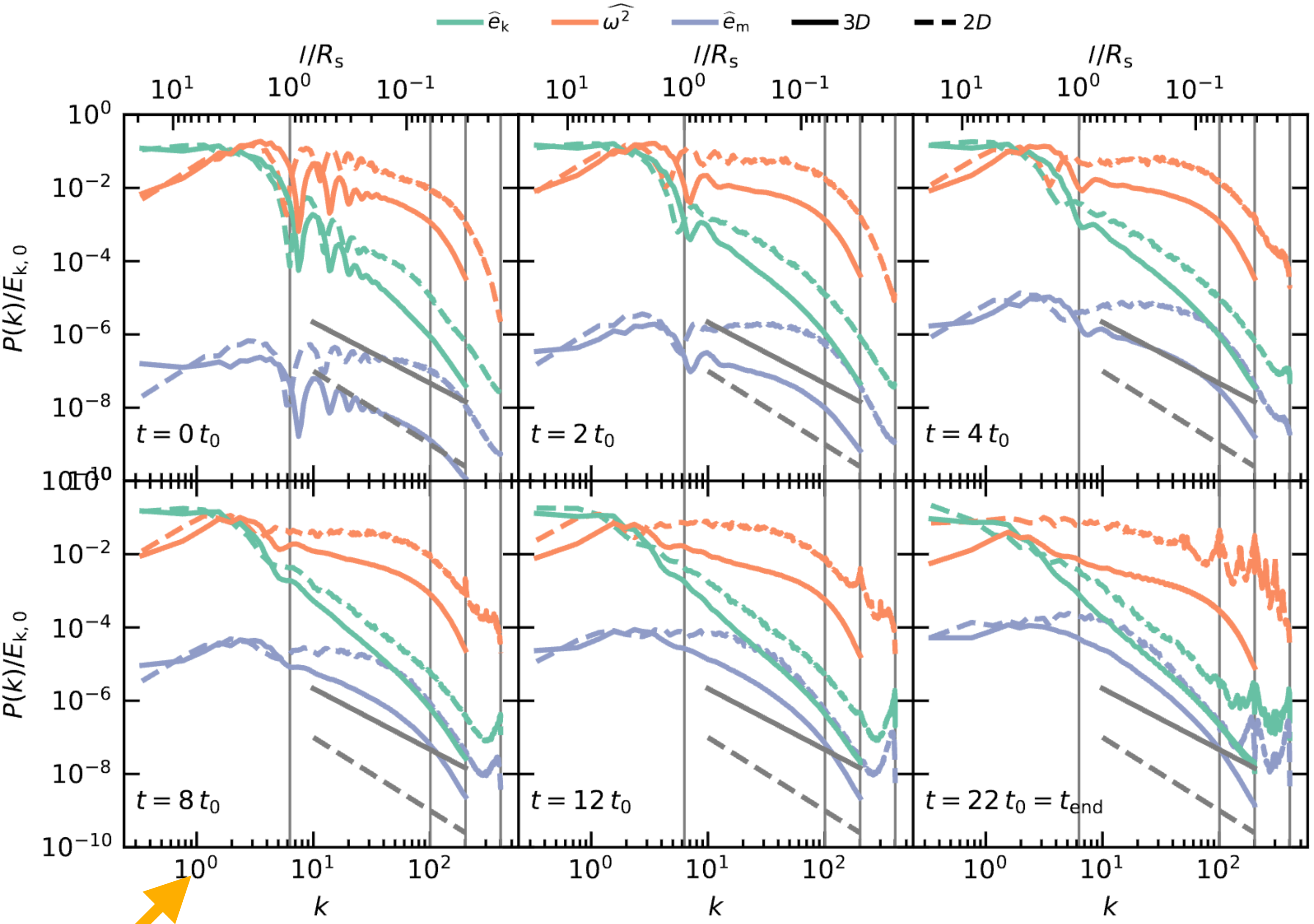
These strongly sheared regions are KH unstable and the vortical motions can tangle the magnetic field

Ledos et al. 2023, Ledos, Ntormousi, Takasao, & Nagamine 2024

B-field amplification in sheared flow

If cooling dominates, the CGM gas in the mixing layer condenses onto the stream and the stream becomes more massive

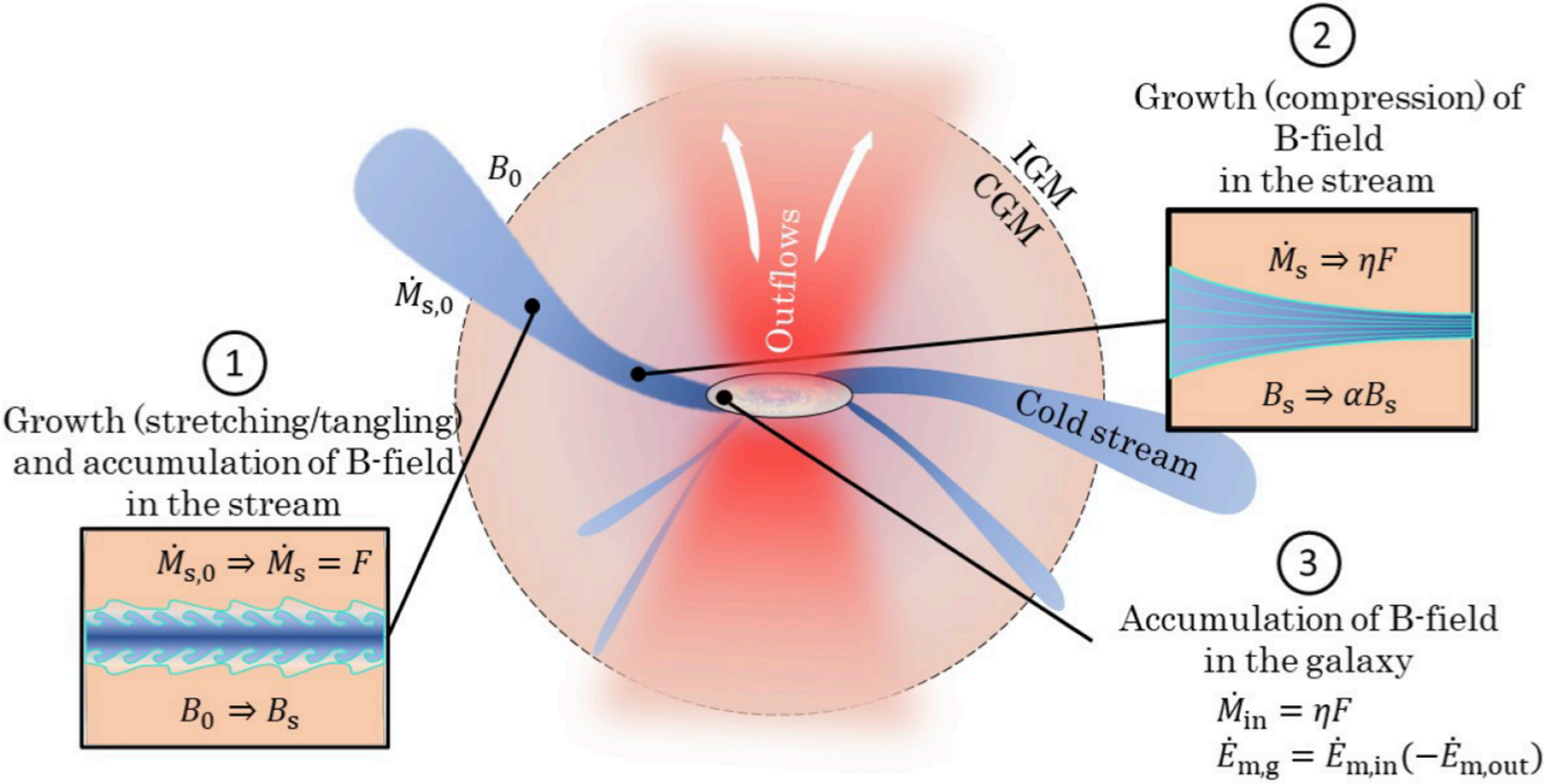




Scaled

The magnetic energy power spectrum has the same for as that of vorticity at earlier times
At later times it is closer to that of kinetic energy

Can magnetised inflows provide enough magnetic energy to the central galaxy?



① Growth (stretching/tangling) and accumulation of B-field in the stream

$\dot{M}_{s,0} \Rightarrow \dot{M}_s = F$

$B_0 \Rightarrow B_s$

② Growth (compression) of B-field in the stream

$\dot{M}_s \Rightarrow \eta F$

$B_s \Rightarrow \alpha B_s$

③ Accumulation of B-field in the galaxy

$\dot{M}_{in} = \eta F$

$\dot{E}_{m,g} = \dot{E}_{m,in} (-\dot{E}_{m,out})$

B-field in an accreting galaxy

$$\frac{\mathrm{d}E_{\mathrm{m,in}}}{\mathrm{d}t} = \frac{\mathrm{d}E_{\mathrm{m,in}}}{\mathrm{d}M_{\mathrm{in}}}\frac{\mathrm{d}M_{\mathrm{in}}}{\mathrm{d}t}$$

$$E_{\mathrm{m,in}} = \frac{B_{\mathrm{in}}^2}{8\pi}\times V_{\mathrm{in}} = \frac{B_{\mathrm{in}}^2}{8\pi}\times\frac{M_{\mathrm{in}}}{\rho_{\mathrm{in}}},$$

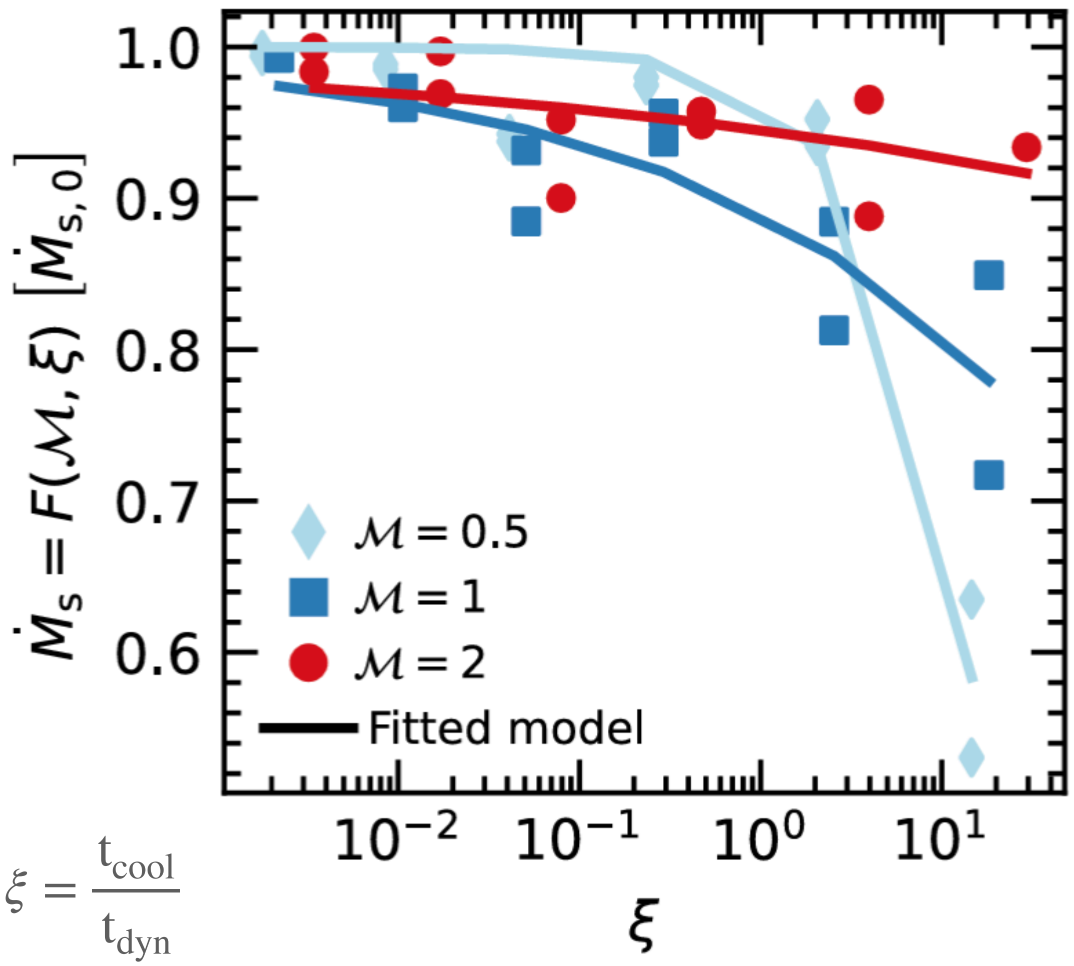
$$\frac{\mathrm{d}E_{\mathrm{m,g}}}{\mathrm{d}t} = \frac{B_{\mathrm{in}}^2}{8\pi\rho_{\mathrm{in}}}\frac{\mathrm{d}M_{\mathrm{in}}}{\mathrm{d}t}$$

$$B_{\mathrm{g}}(t) = \left(\frac{\alpha B_{\mathrm{s}}^2}{V_{\mathrm{g}}\rho_{\mathrm{s}}}\eta F\times t + B_{\mathrm{g},0}\right)^{1/2}$$

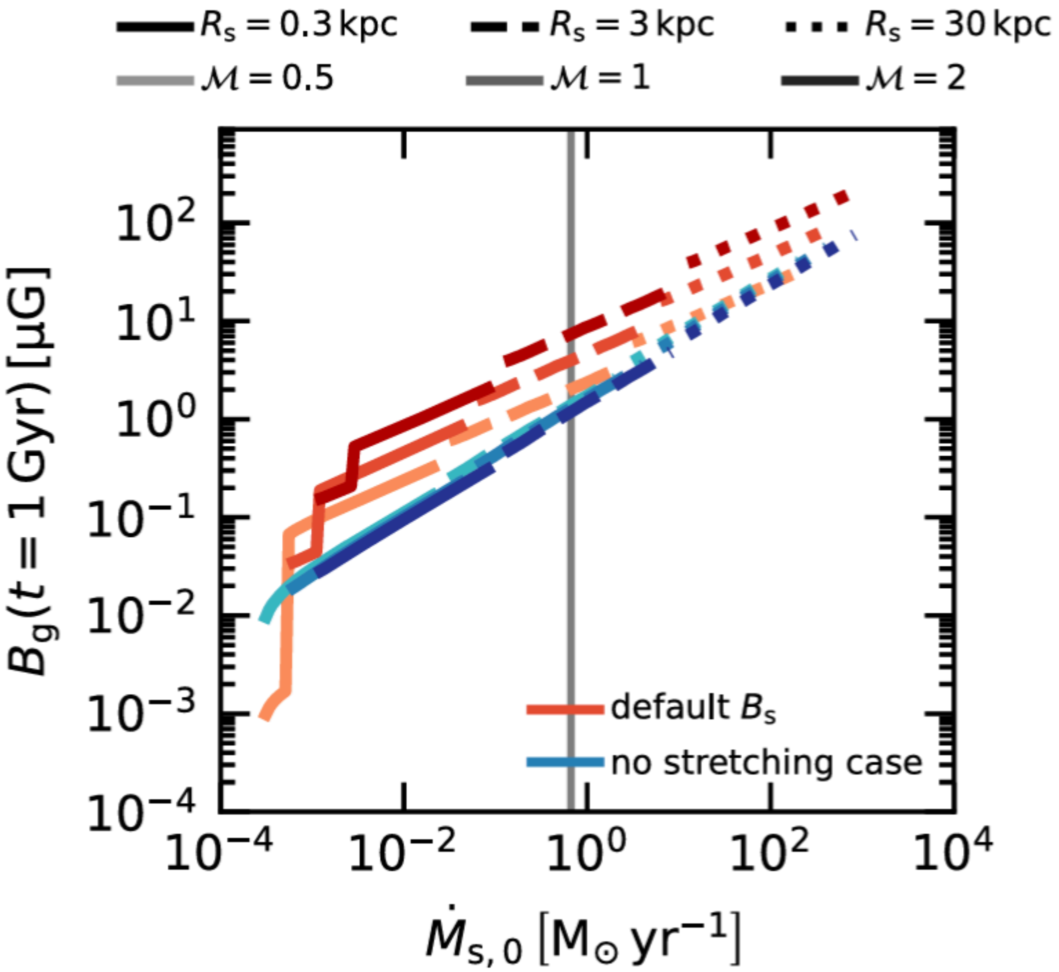
$$\frac{\mathrm{d}M_{\mathrm{in}}}{\mathrm{d}t} = \eta F\left(\mathbf{X}\right)$$

$$B_{\mathrm{in}} = \alpha B_s\left(\mathbf{X}\right)$$

From the simulations, where $0 \le \alpha \le 1, 0 \le \eta \le 1$

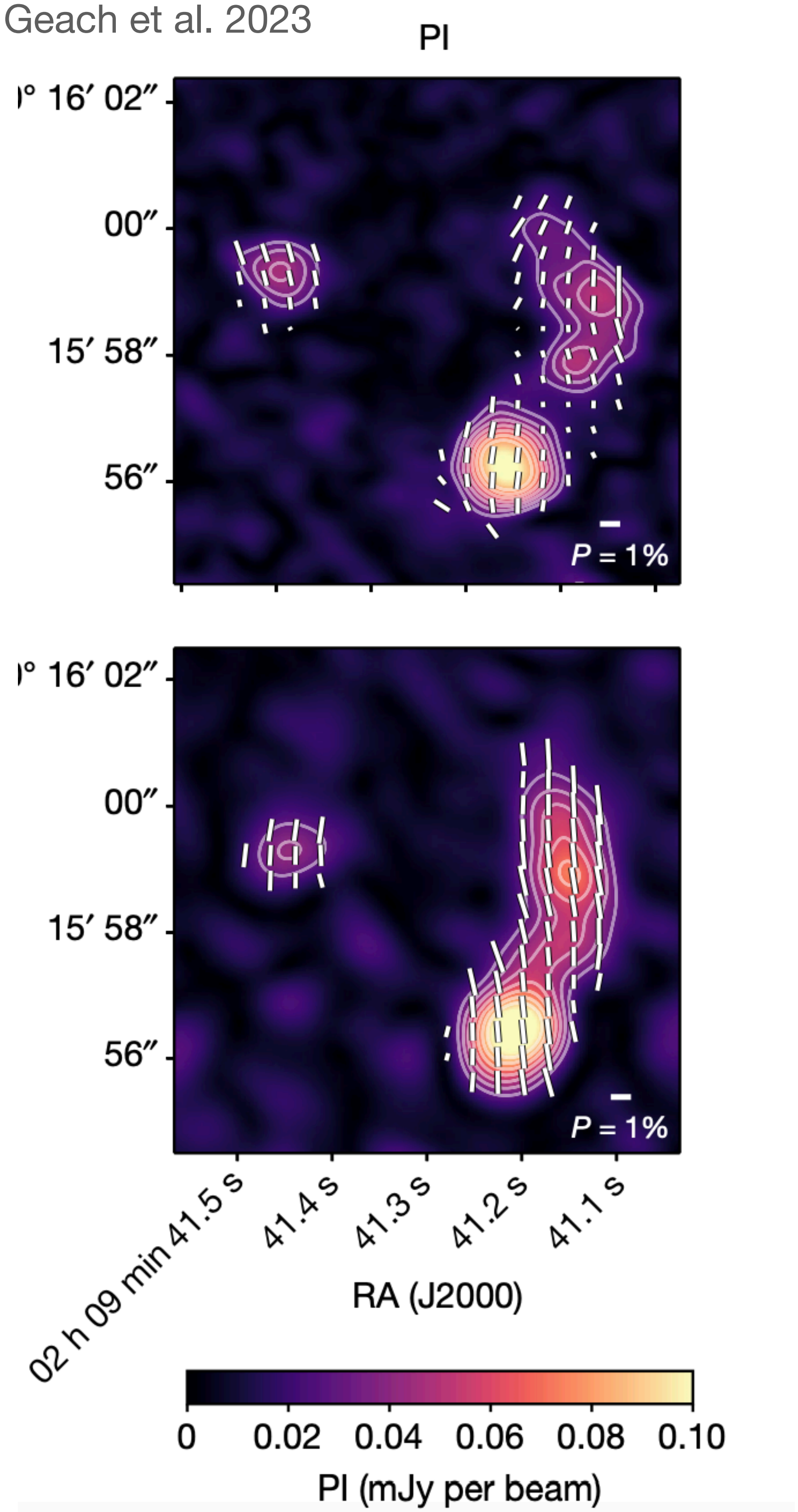


$$\xi = \frac{\mathrm{t_{cool}}}{\mathrm{t_{dyn}}}$$

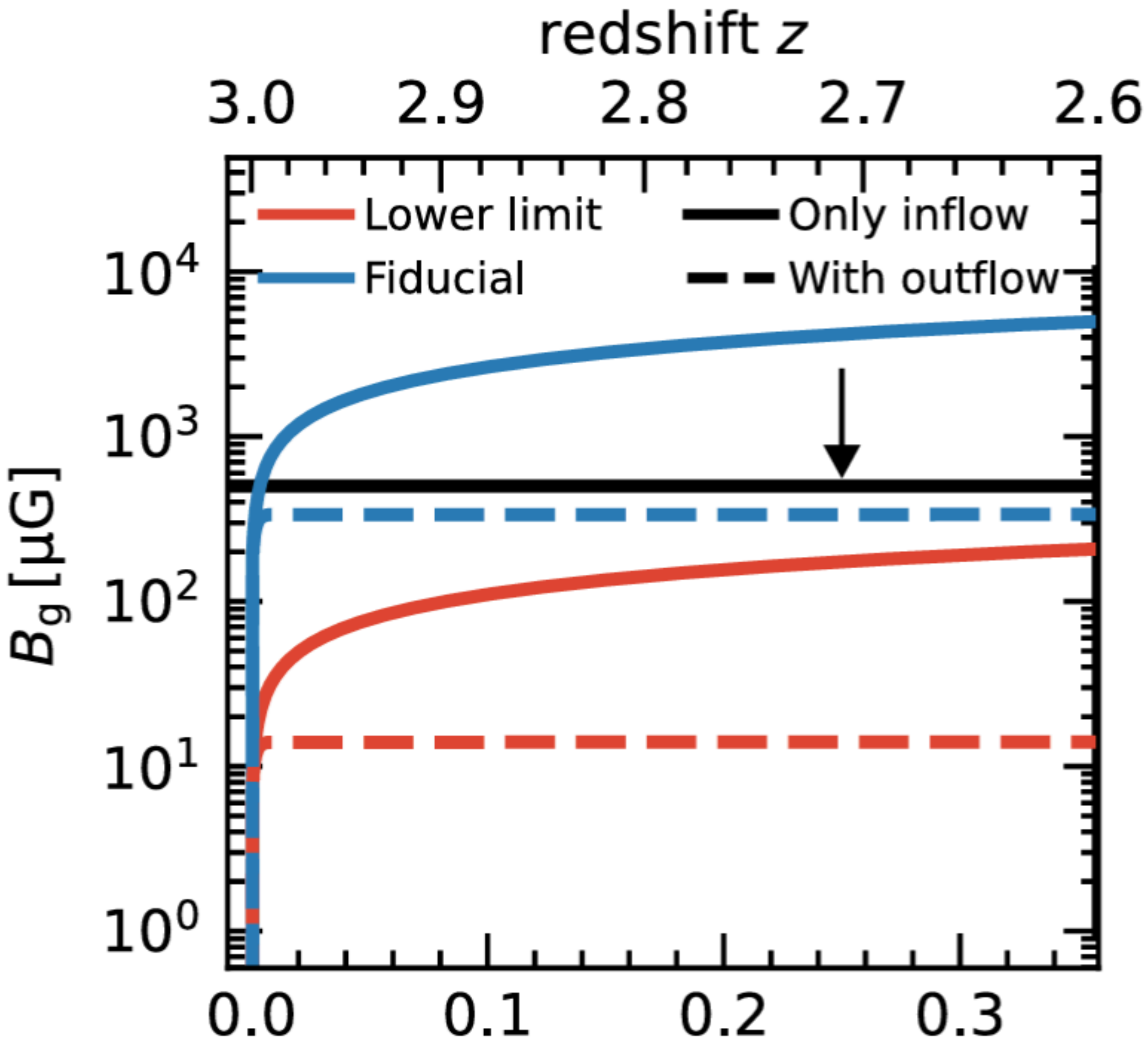


High galactic magnetization at high redshift (?)

Geach et al. 2023



Can magnetised inflows provide enough magnetic energy to the central galaxy?



BUT:
Simplified outflow model, no diffusion,
not self-consistent with galaxy evolution models

Conclusions and next steps

- Simple “bathtub” model predicts high magnetisation for typical inflow rates
- BUT: we need to properly model the time evolution of the flows and their interaction with the galaxy
- ALSO: We haven’t modelled diffusive properties, could this play a role?
- The future: can we model cosmic ray “trapping” in and around these flows? Would such a process have an observational signature?