Galactic Dynamo II

Feedback, Scaling Relations, and Observational Prospects

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DoA Student Seminar

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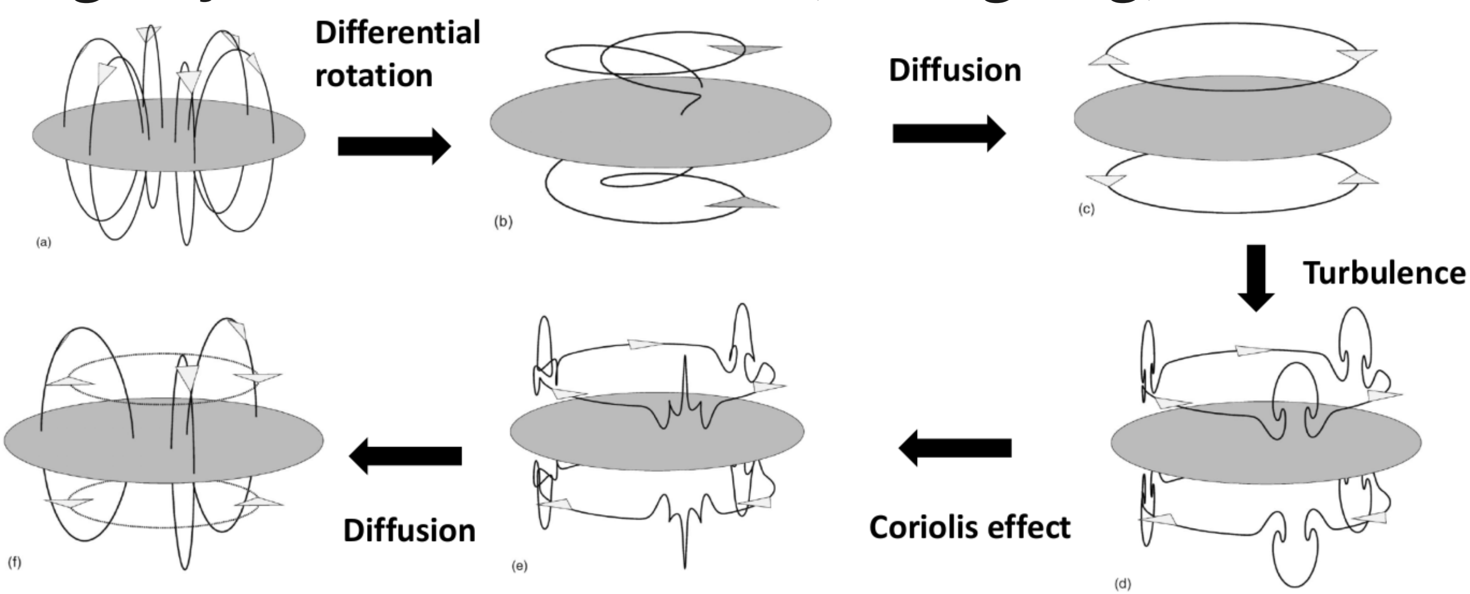
Outline

- Dwarf and MW halo simulation with feedback
- Cosmo Zoom-in Simulation
- Cosmo MHD Simulation: IllustrisTNG
- Scaling relations
- Prospects of Radio Halo observations

Retrospect

- Primordial B fields could be generated by mechanisms like the Biermann Battery (Dr. Zhou)
- Cowling's theorem demands broken axisymmetry for galactic dynamos to work (Jiacheng)
- Alpha-Omega Dynamo viable for GF (Changxing)



Sequence of events illustrating galactic dynamo(Widrow,et al,2002)

- **Galactic dynamo is an effective way to maintain the galactic magnetic field!**

Single halo simulation setup

Ideal MHD

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0 \quad (1)$$

$$\partial_t (\rho \boldsymbol{u}) + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}^T - \boldsymbol{B}\boldsymbol{B}^T + P_{\rm tot}) = 0 \quad (2)$$

$$\partial_t E + \nabla \cdot [(E + P_{\rm tot})\boldsymbol{u} - (\boldsymbol{u} \cdot \boldsymbol{B})\boldsymbol{B}] = 0 \quad (3)$$

$$\partial_t \boldsymbol{B} - \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) = 0 \quad (4)$$

Solonoidal constraint by Constrained Transport

$$\nabla \cdot \boldsymbol{B} = 0.$$

Gas metal cooling and Star formation

$$\dot{\rho}_* = \epsilon_* \frac{\rho_{\rm gas}}{t_{\rm ff}}$$

SN feedback+Radiation feedback (in MW only)

$$\rho \frac{D\epsilon_{\rm turb}}{Dt} = \dot{E}_{\rm inj} - \frac{\rho \epsilon_{\rm turb}}{t_{\rm diss}} \qquad \dot{E}_{\rm inj} = \dot{\rho}_* \eta_{\rm SN} \cdot 10^{50}\,{\rm erg/M_\odot}$$

$$E_{\rm UV} = E_{\rm rad}\left[1 - \exp(-\kappa_{\rm UV}\rho_{\rm dust}\Delta x)\right] \qquad E_{\rm IR} = E_{\rm UV}\left[1 - \exp(-\kappa_{\rm IR}\rho_{\rm dust}\Delta x)\right]$$

Initial conditions

NFW halo+Gas

Initial spin param: 0.04

Biermann battery initial

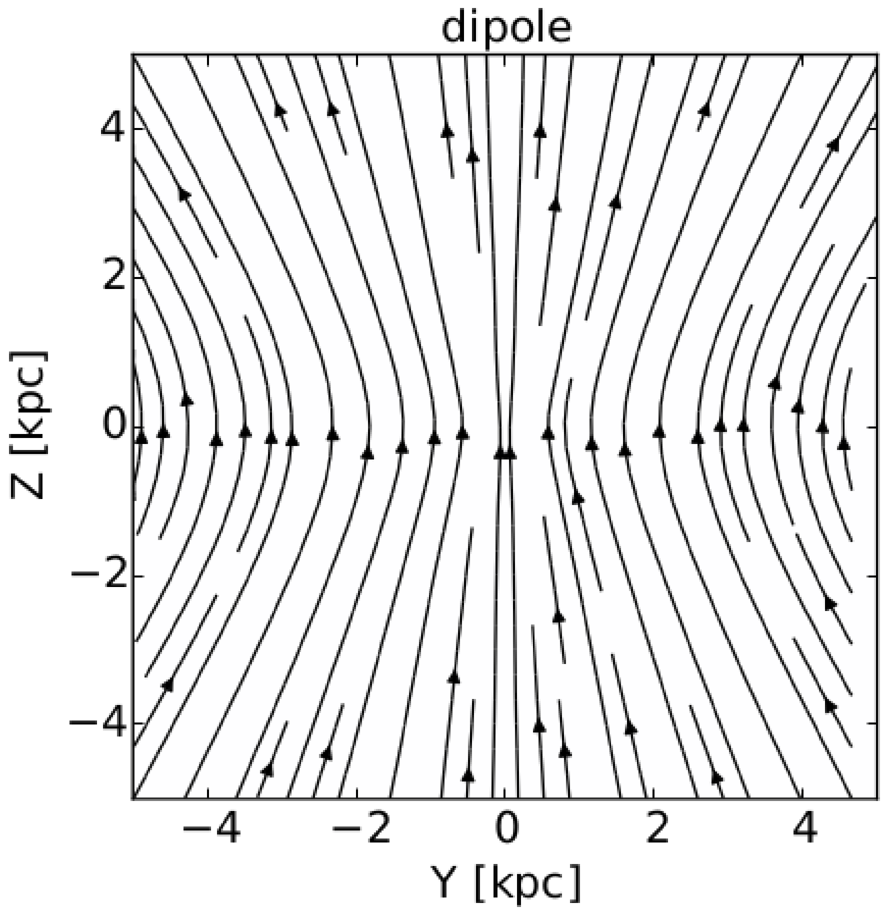
B-field: 1e-20 G $\|\boldsymbol{B}\| \propto \rho^{2/3}$

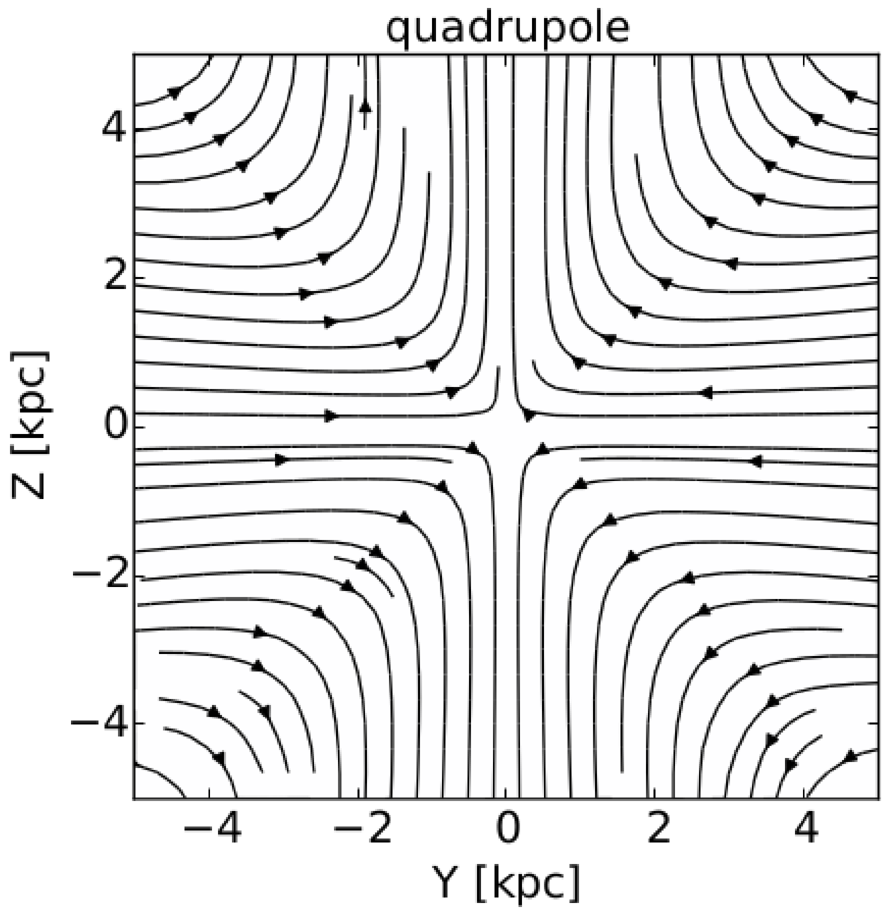
Dipole and Quadruple intial setups for different field parity

parameter	Dwarf	Milky-Way	units
R_{200}	50	230	kpc
V_{200}	35	160	km/s
M_{200}	1.4×10^{10}	1.3×10^{12}	$M_\odot$
Δx	18	84	pc
m_{res}	1.5×10^3	1.5×10^5	$M_\odot$
m_*	2.0×10^3	5.9×10^4	$M_\odot$
T_*	100	2000	K
n_*	14	4	H/cc
ϵ_*	1	1	%
η_{SN}	10	10	%
Z_{ini}	0.05	0.05	$Z_\odot$
met. yield	10	10	%

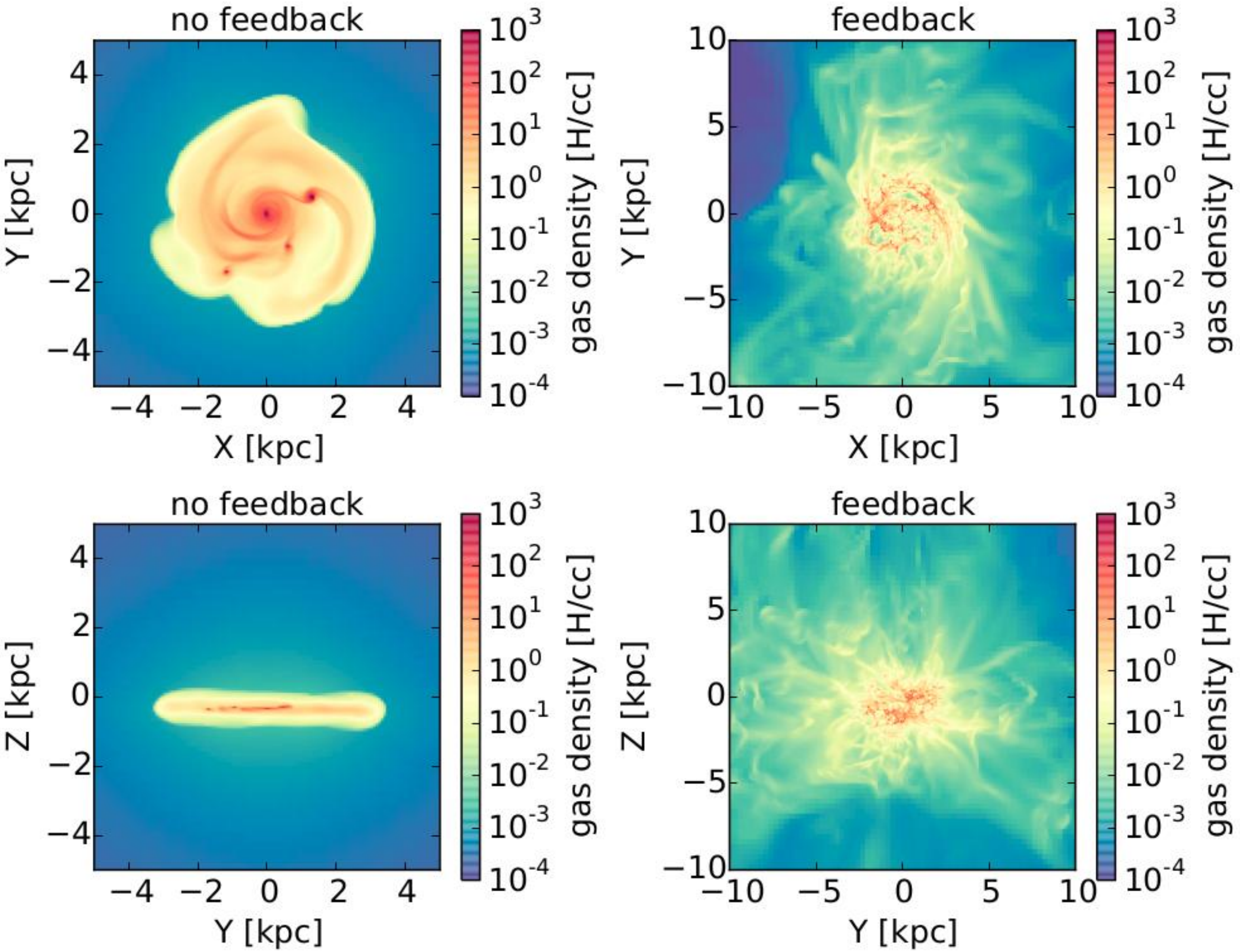
$$\boldsymbol{B}_{\text{initial}} = \nabla \times \boldsymbol{A} \qquad \boldsymbol{A}_{\text{D}} = B_0 \left[\frac{\rho(r,z)}{\rho_0}\right]^{2/3} r\,\boldsymbol{e}_\phi \qquad \boldsymbol{A}_{\text{Q}} = B_0 \left[\frac{\rho(r,z)}{\rho_0}\right]^{2/3} z\,\boldsymbol{e}_\phi$$

Initial B fields





First impression of feedback



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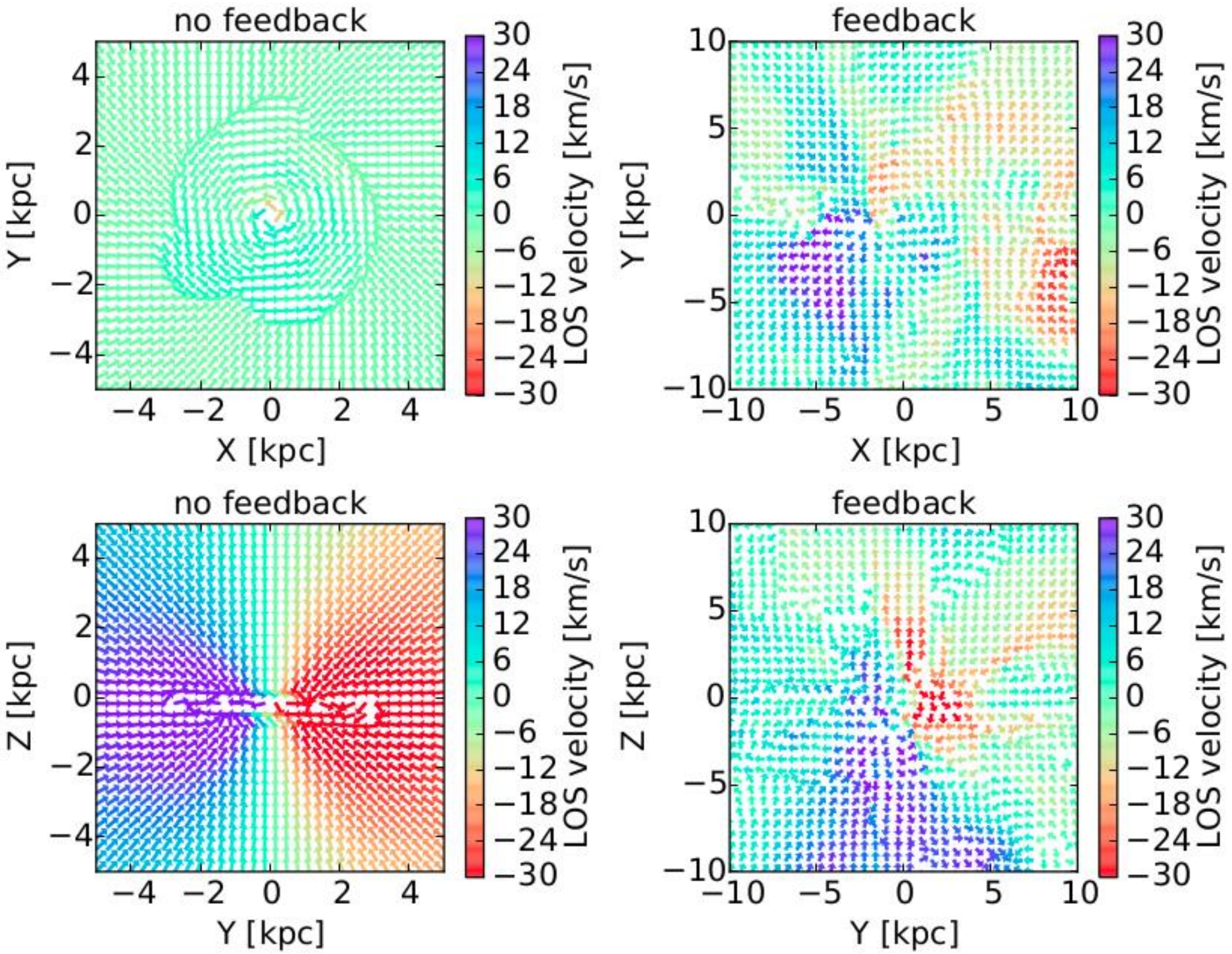
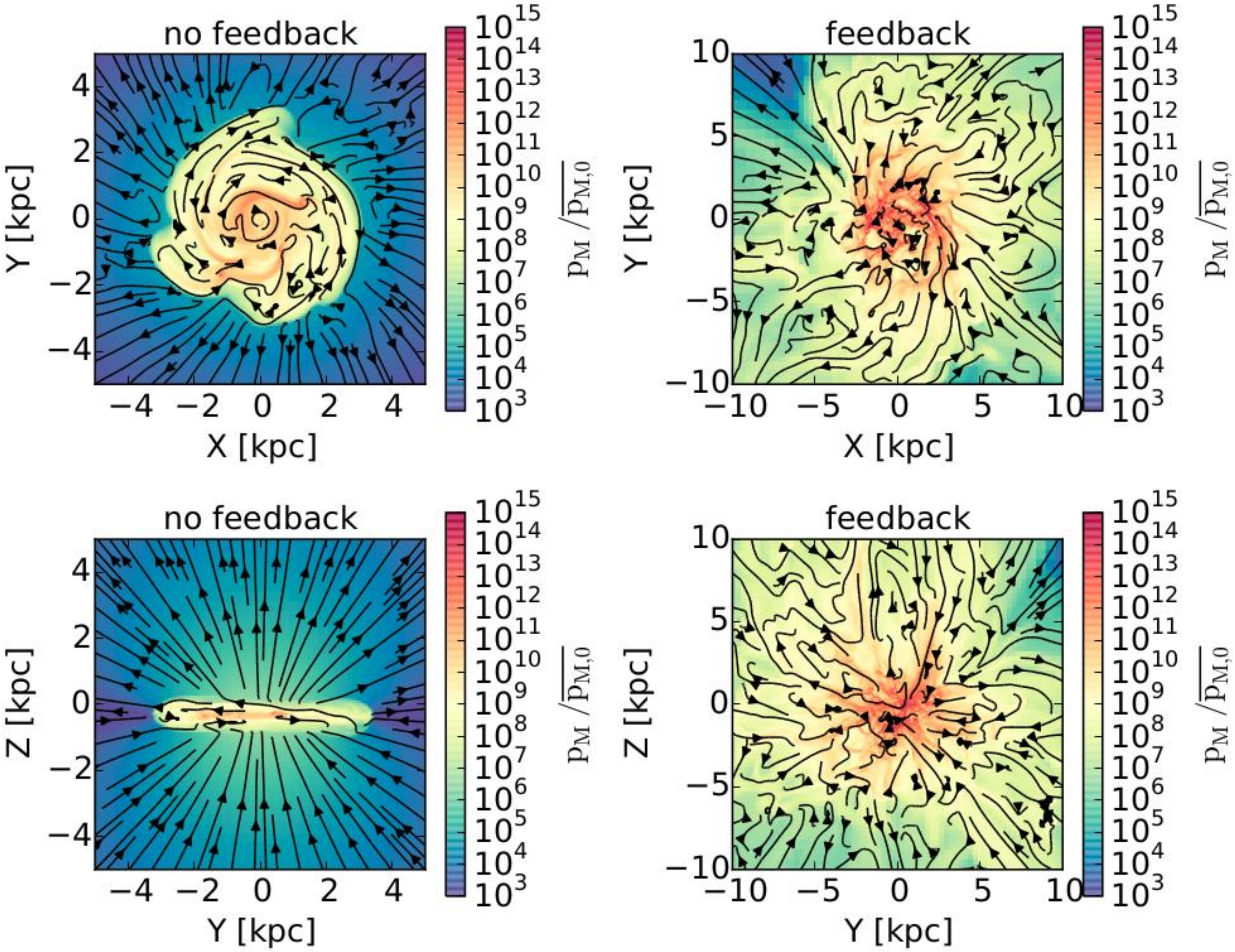


* Turbulence forcing scale (kinetic energy injection) ~ scale radius

First impression of feedback

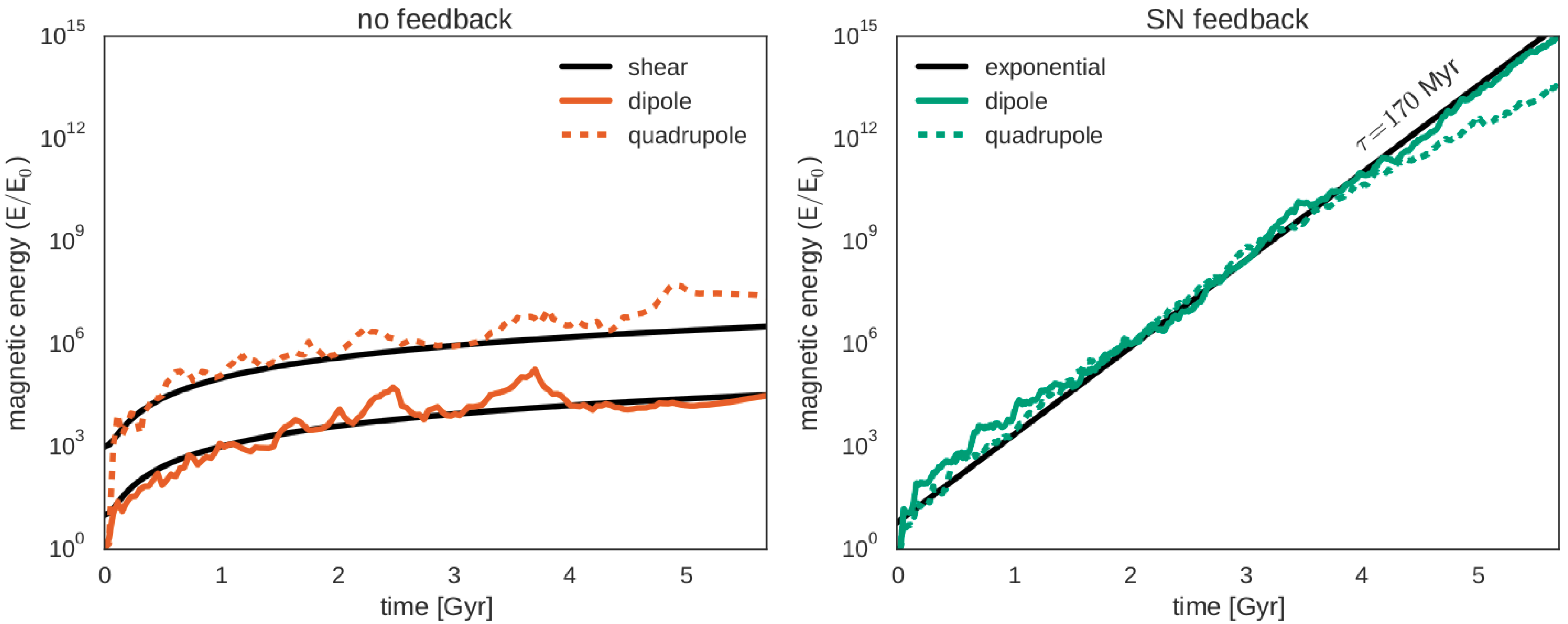


The effects of SN Feedback

$$\partial_t B_r \simeq 0 \quad \text{and} \quad \partial_t B_\theta \simeq r B_r \partial_r \Omega.$$

$$E_S = E_C \cdot \left(1 + (S \cdot t)^2\right) \qquad S = r \partial_r \Omega.$$

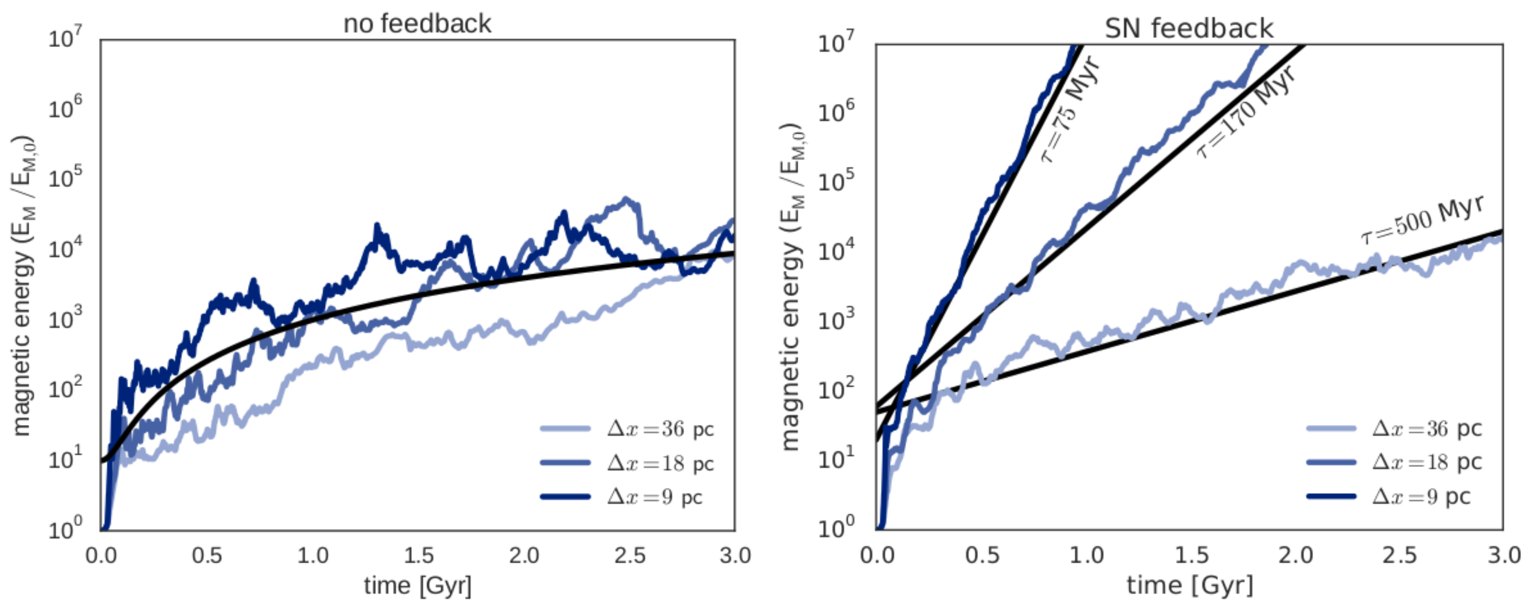
$$\Gamma \simeq \Omega.$$

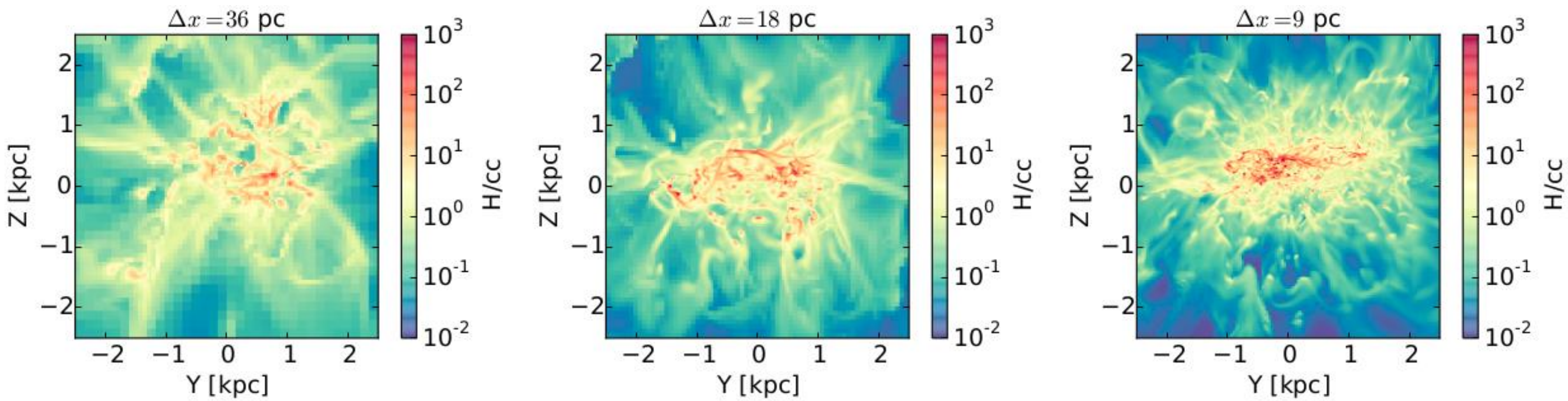


The effects of SN Feedback

Resolution correlated with dissipation timescale

* Weak field, pure kinematic regime, no back-reaction of Lorentz forces considered

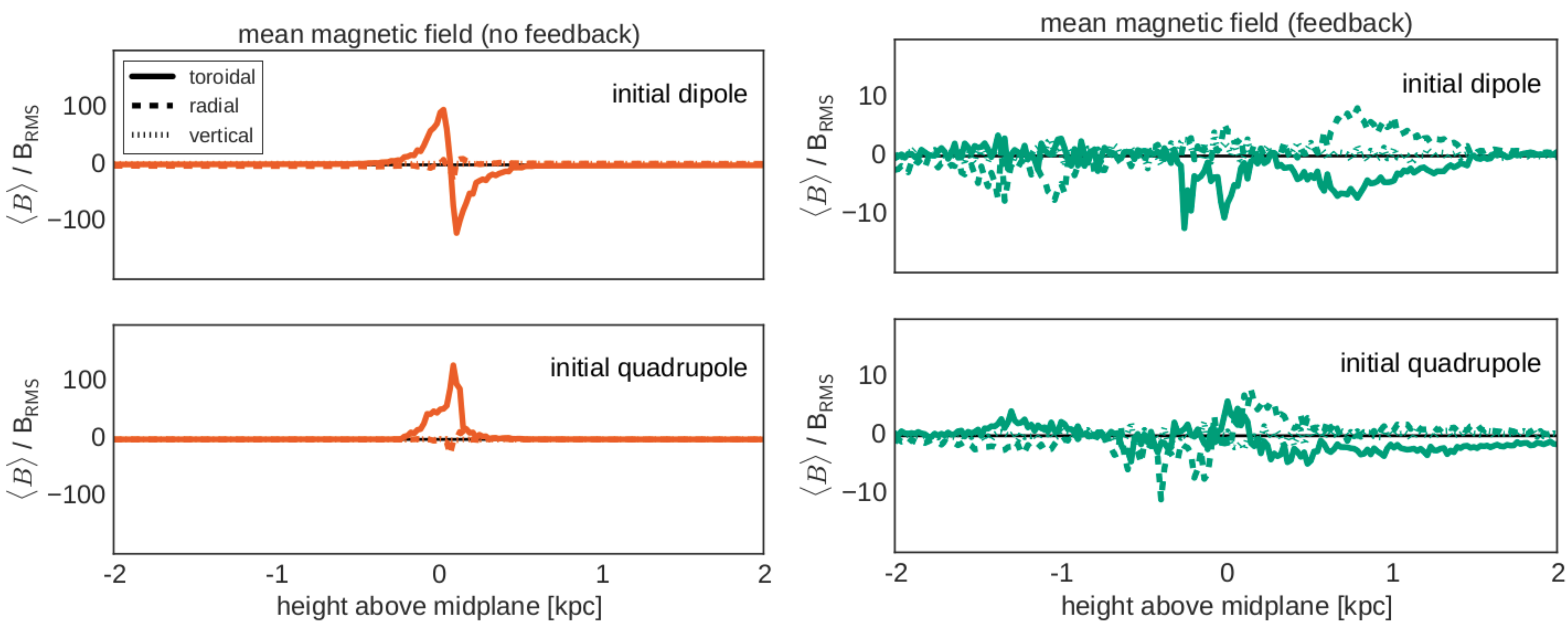




The effects of SN Feedback

Variation of field strength with disk height

Parity altered with feedback, all 3 components amplified

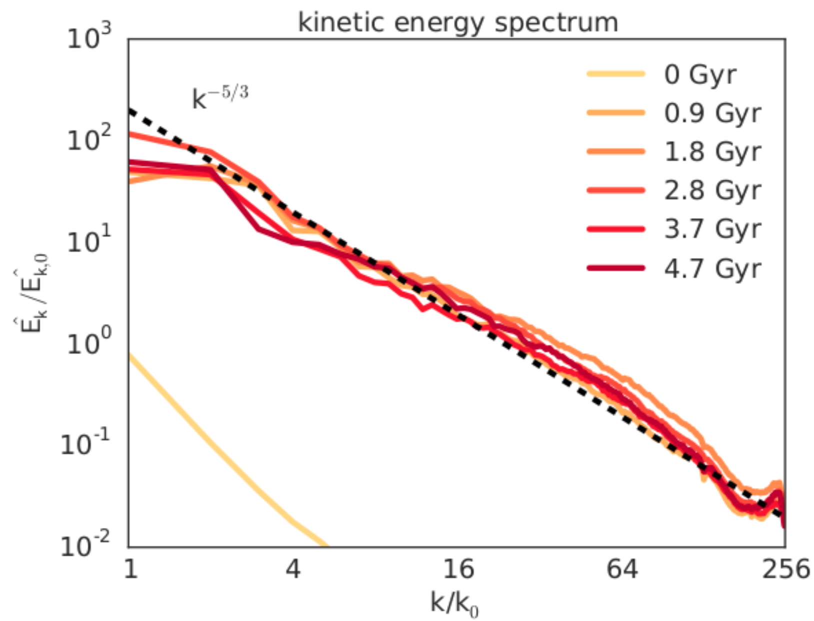


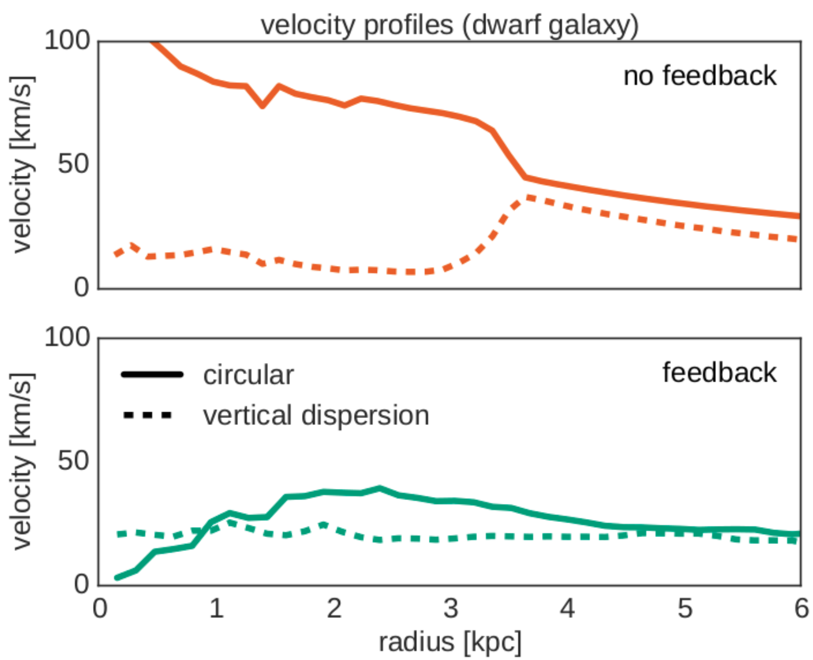
Power spectrum and kinematics

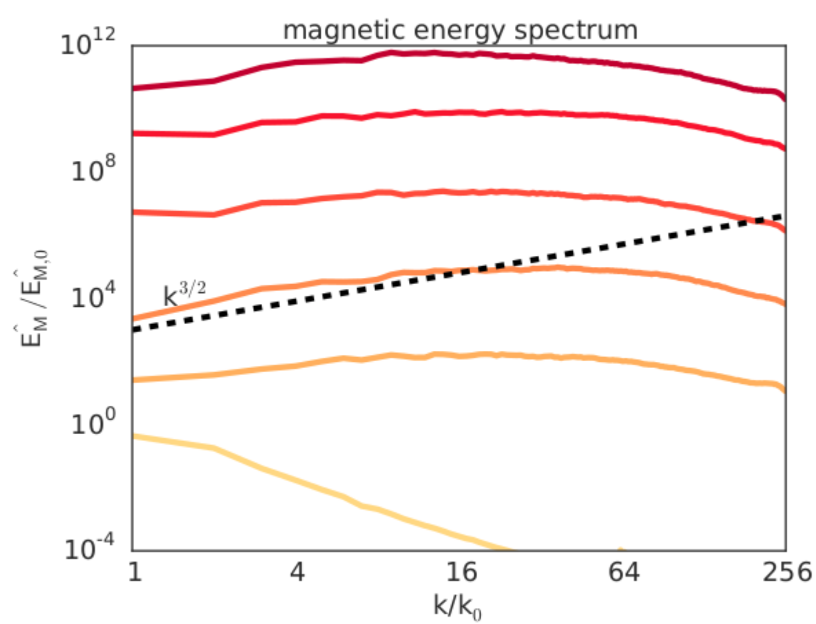
Significant dispersion with feedback

Kolmogorov turbulence(-5/3) + Kanzantsev dynamo(3/2) that inversely cascades to large scales

Small scale suppressed due to resolution (Nyquist frequency of grid cells)

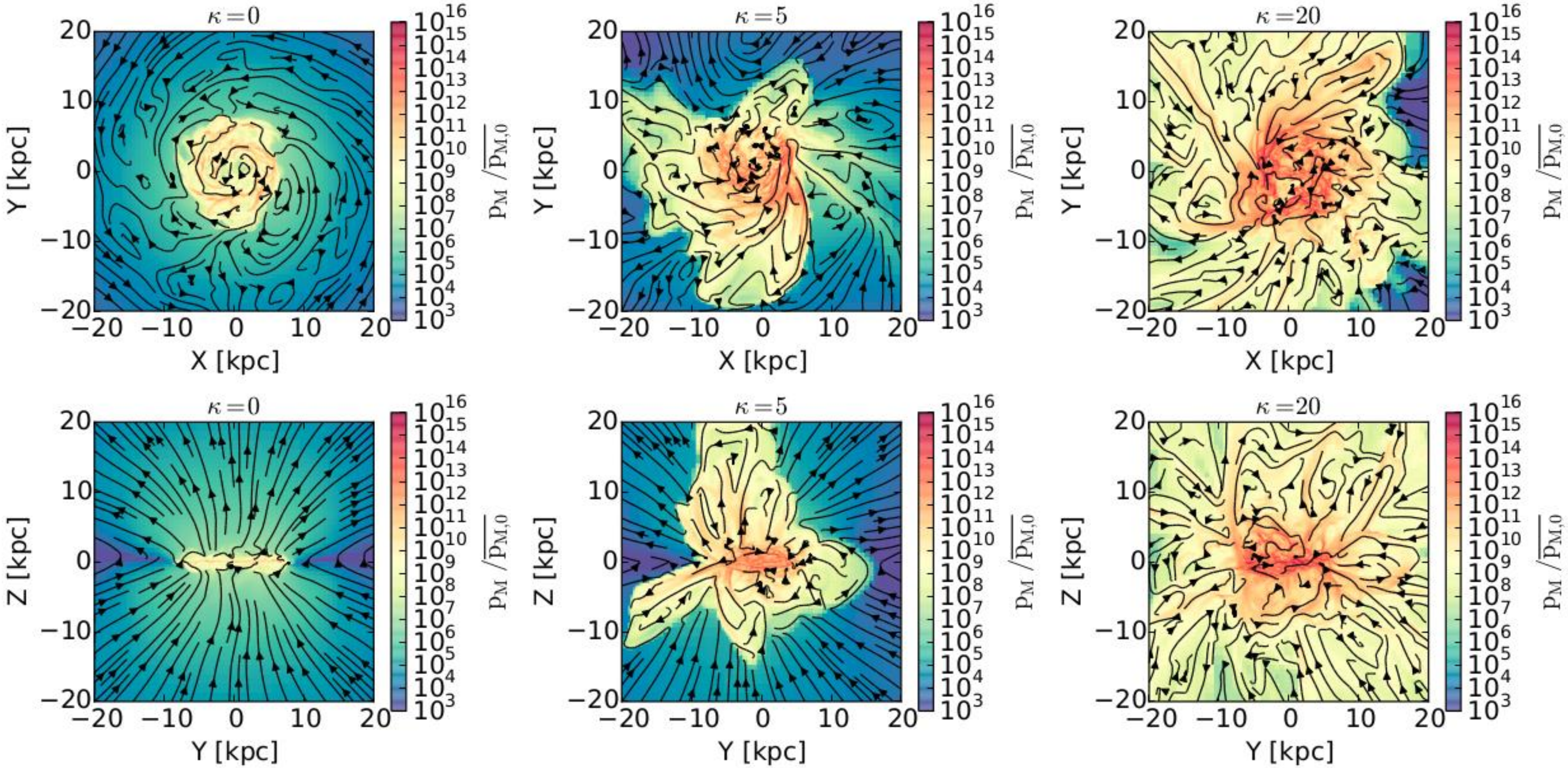






Radiation feedback (MW only)

Feedback efficiency correlated with dust opacity



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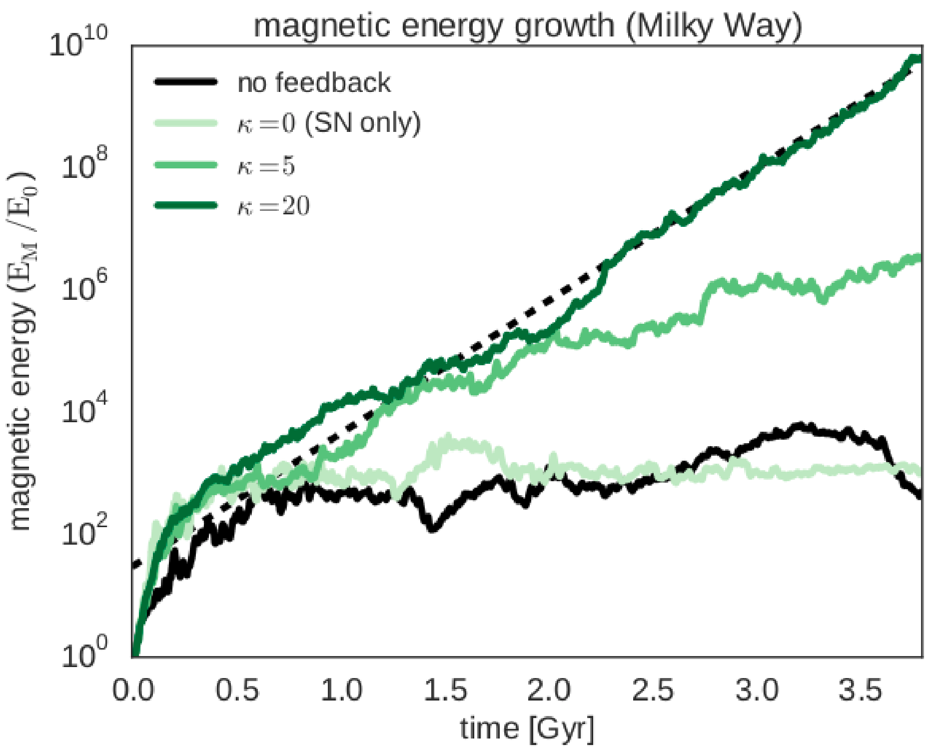
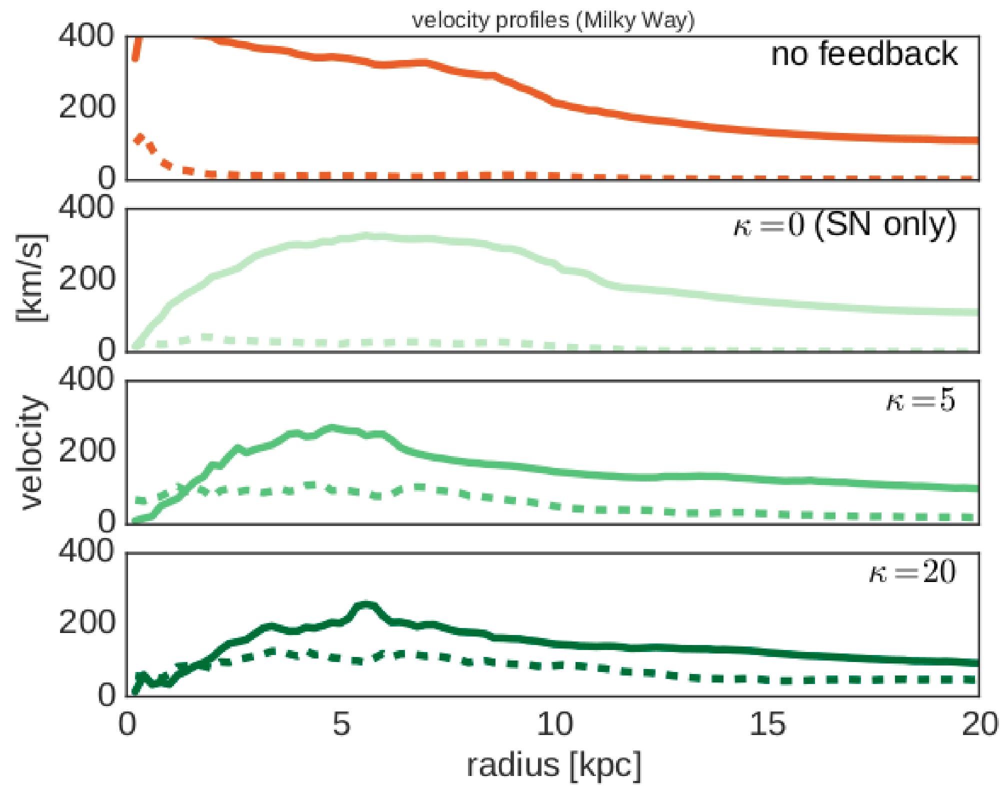
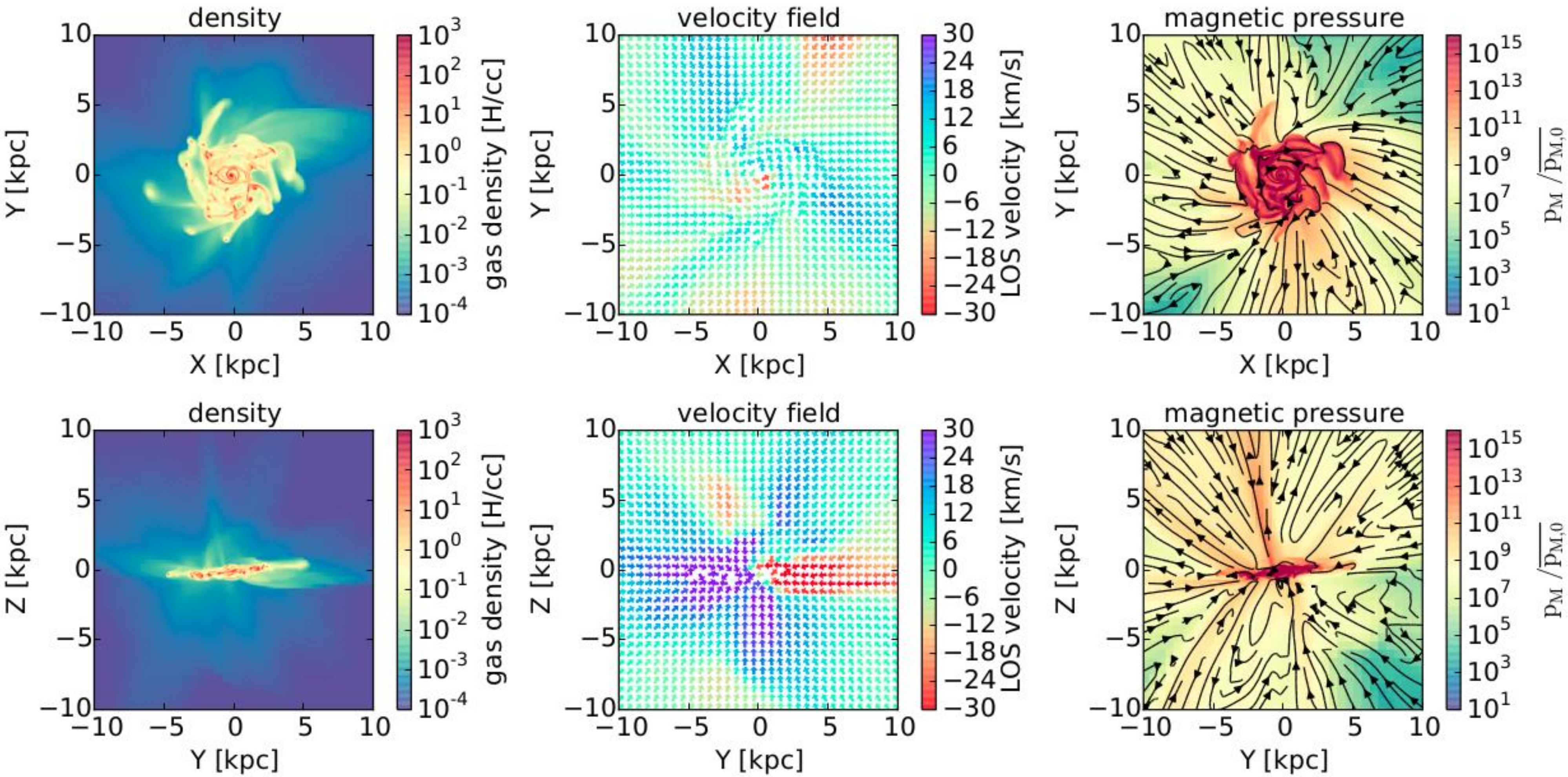




Turning feedback off after a while

Gas settles to an order-rotation dominated thin disk



Turning feedback off after a while

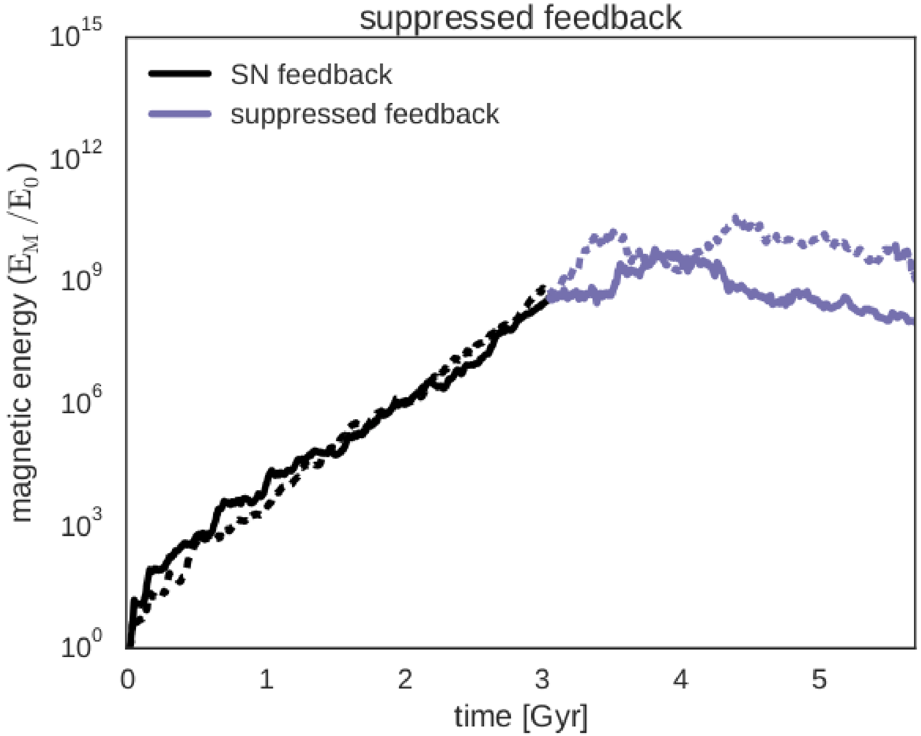
Large scale collapse amplification with compression

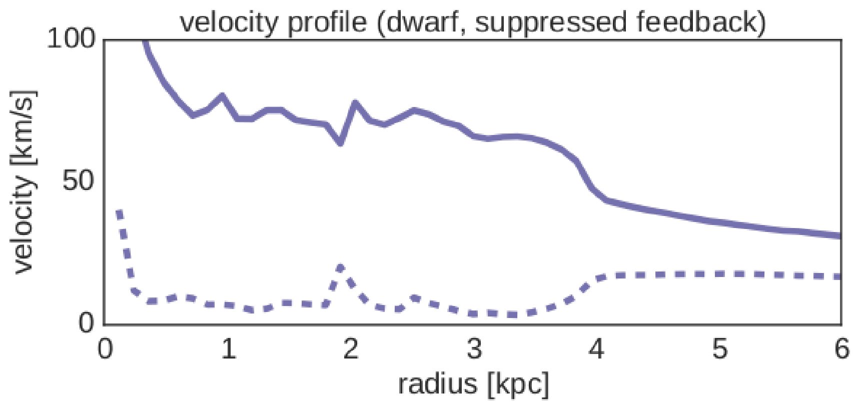
Small scale reconnection suppression

Two cancels out, non-trivial

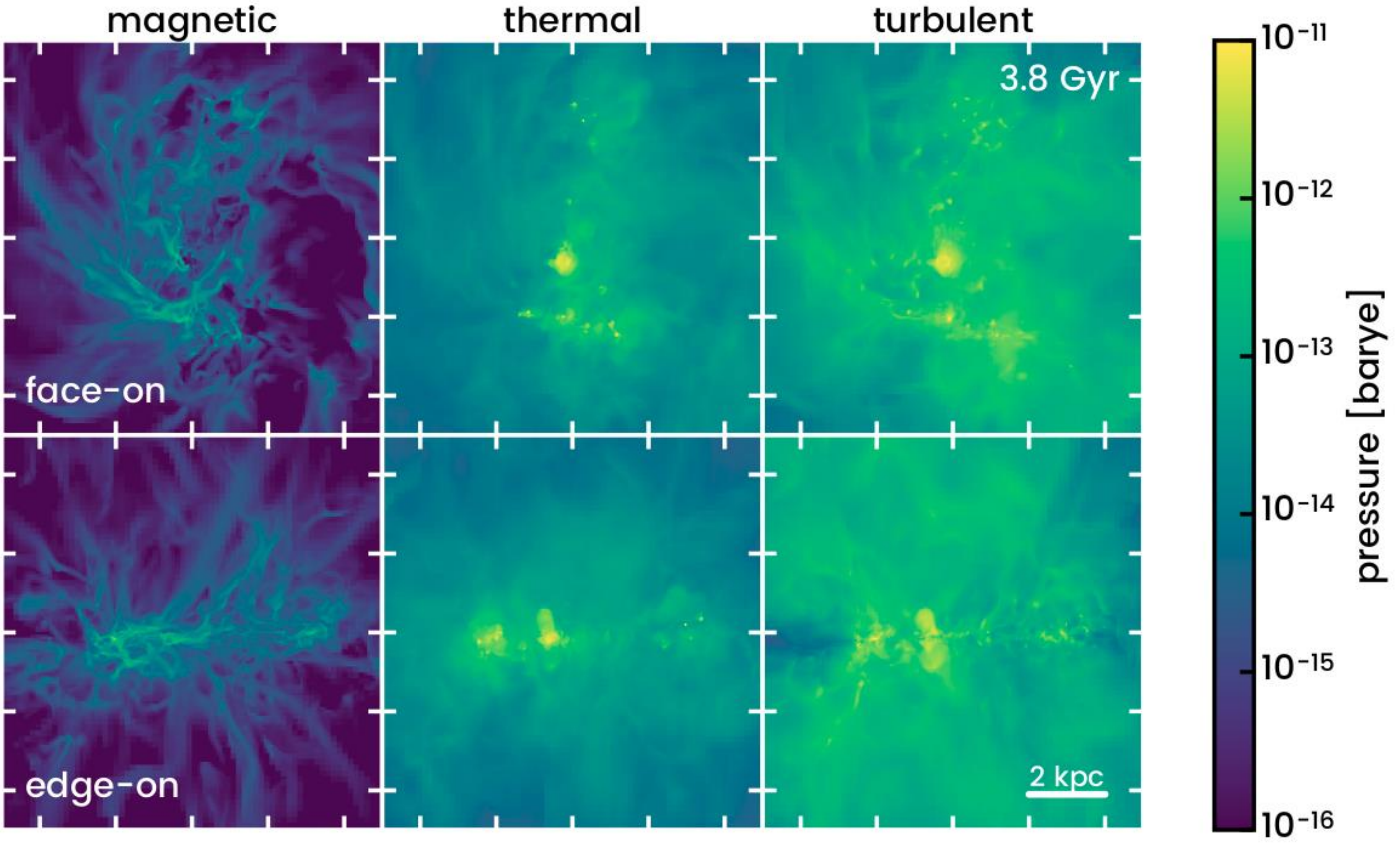
Inverse cascade upwards to turbulance forcing scale stored enough magnetic energy to balance out reconnection, large scale fields preserved

Dispersion suppressed, ordered rotation restores





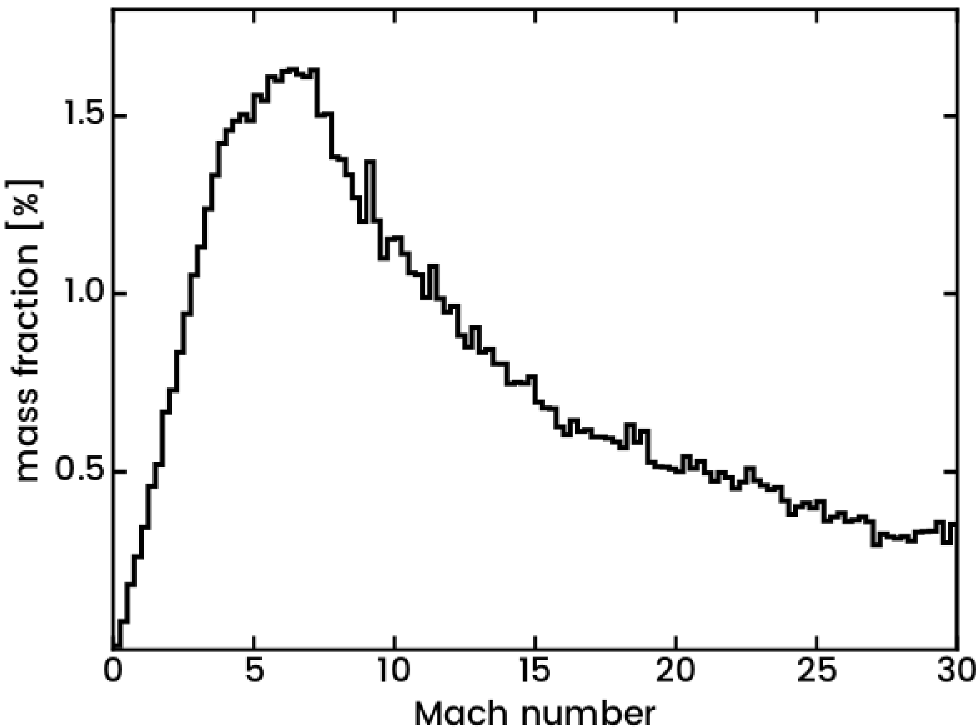
What happens when we consider field saturation due to Lorentz force back reaction?

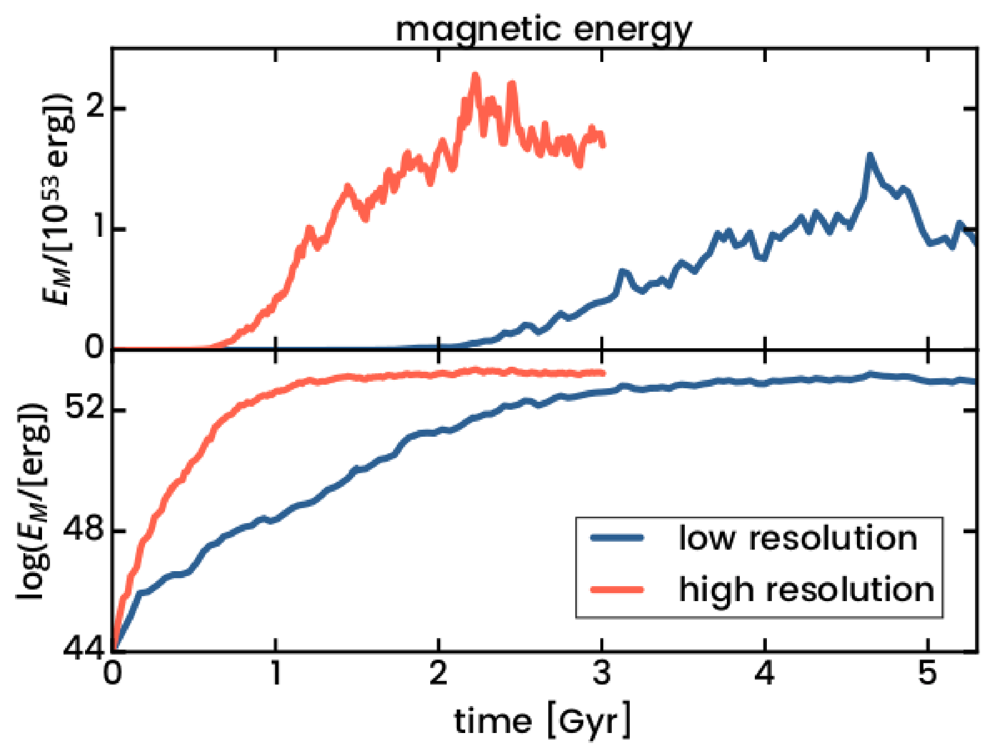


Turbulance and magnetic saturation

Supersonic Mach number, shock dominated turbulance

Higher resolution s $P_{\rm turb} \sim \frac{1}{2}\rho u_z^2$ aster with higher magnetic energy

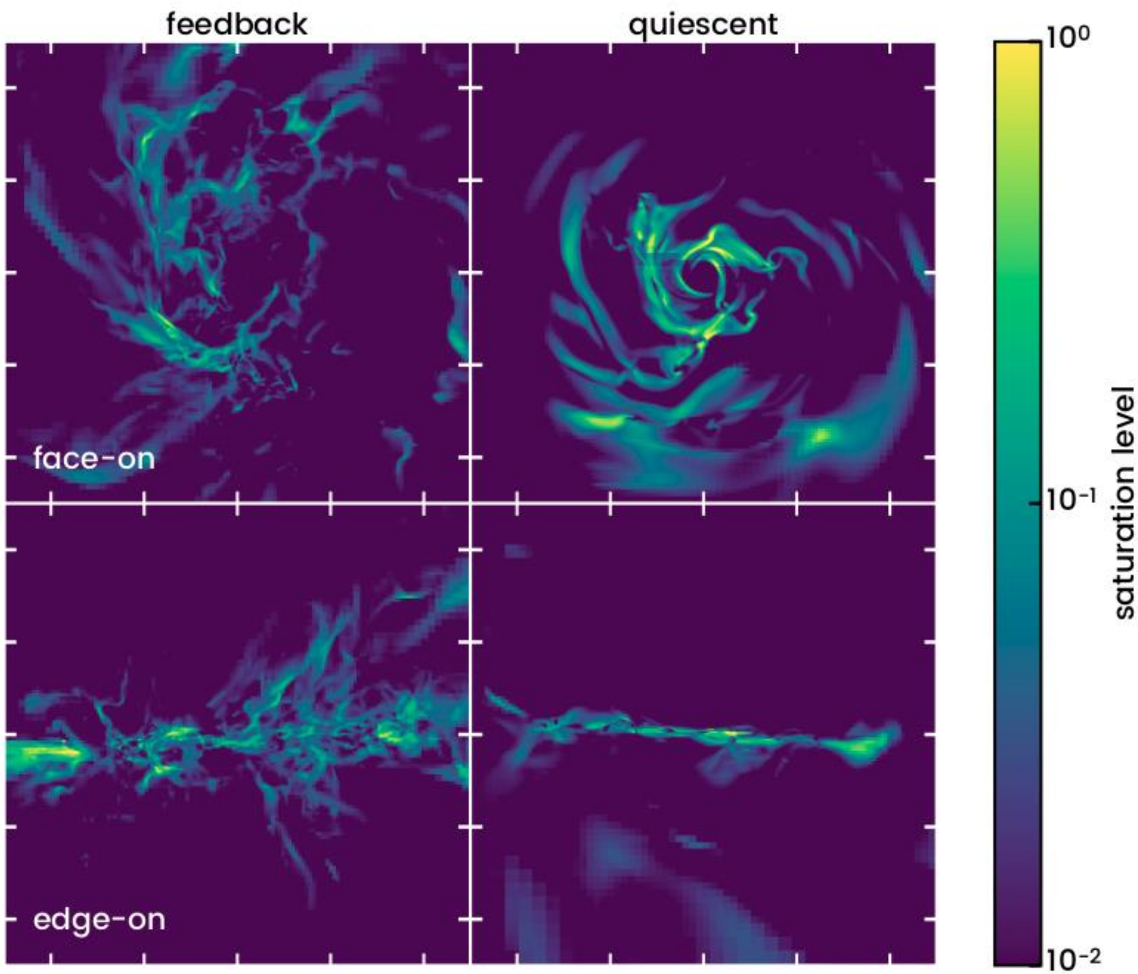




Equipartition?

Sub-equipartition of turbulance and magnetic energy in the non-linear phase(slow growth due to backreaction)

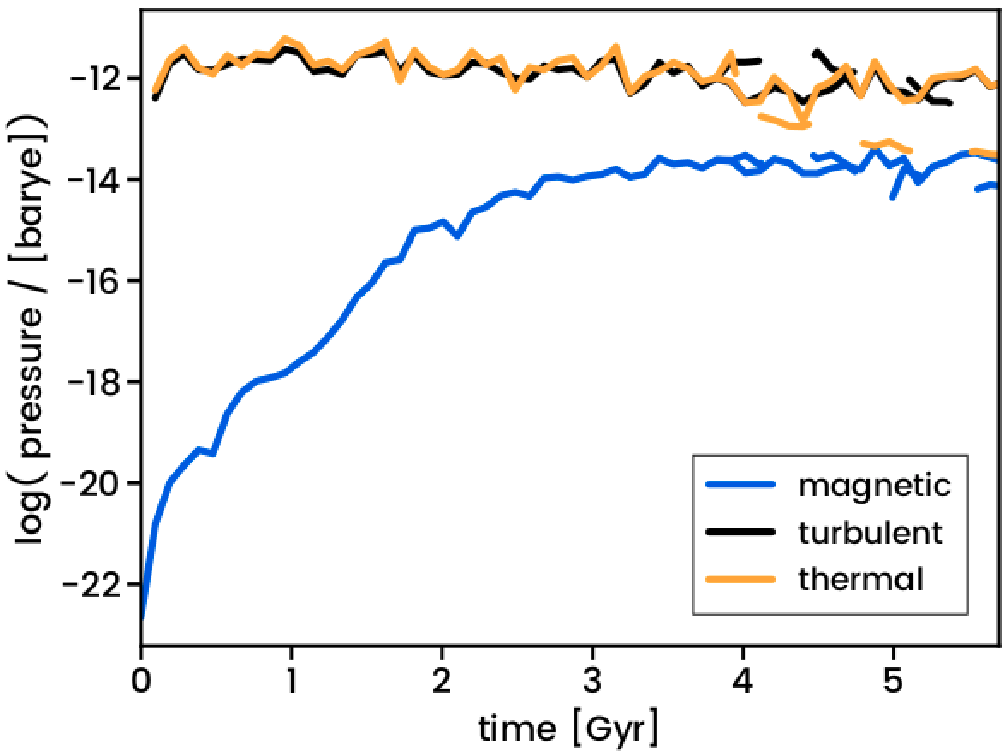
Equipartition reached after saturation in the quiescent phase (feedback turned off)

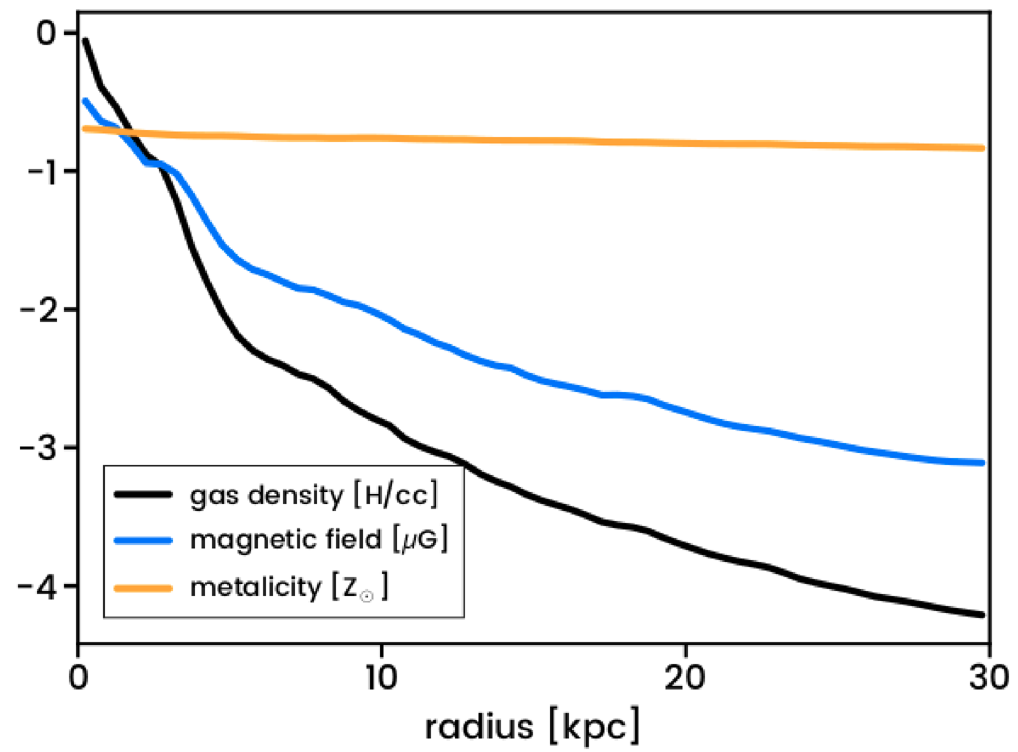


B field and Metals carried by winds

Turbulent energy dominates throughout galaxy evolution

Metals and B-field distributed to large radii



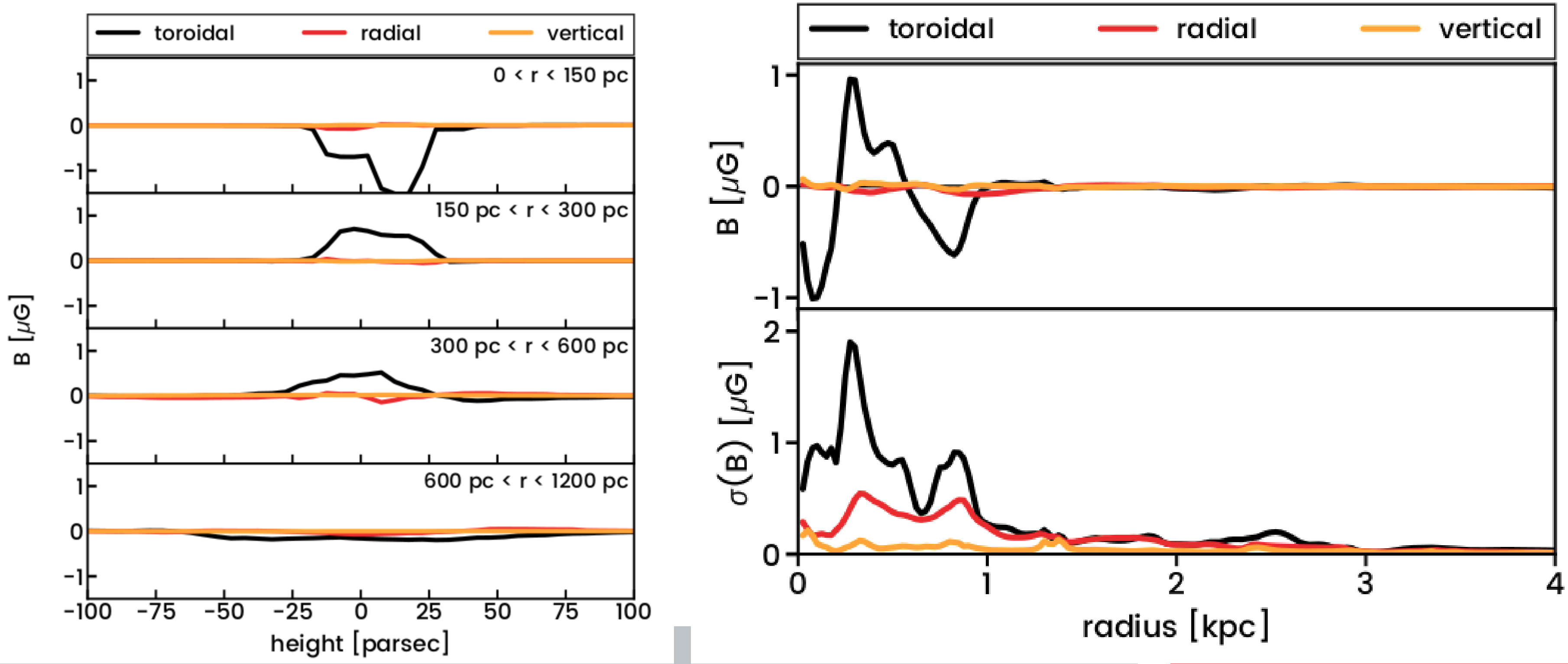


B-field radial profile

Toroidal component dominates

~1 micro Gauss field intensity

Sign reversals in radial profile (SSD relics, spiral structure)



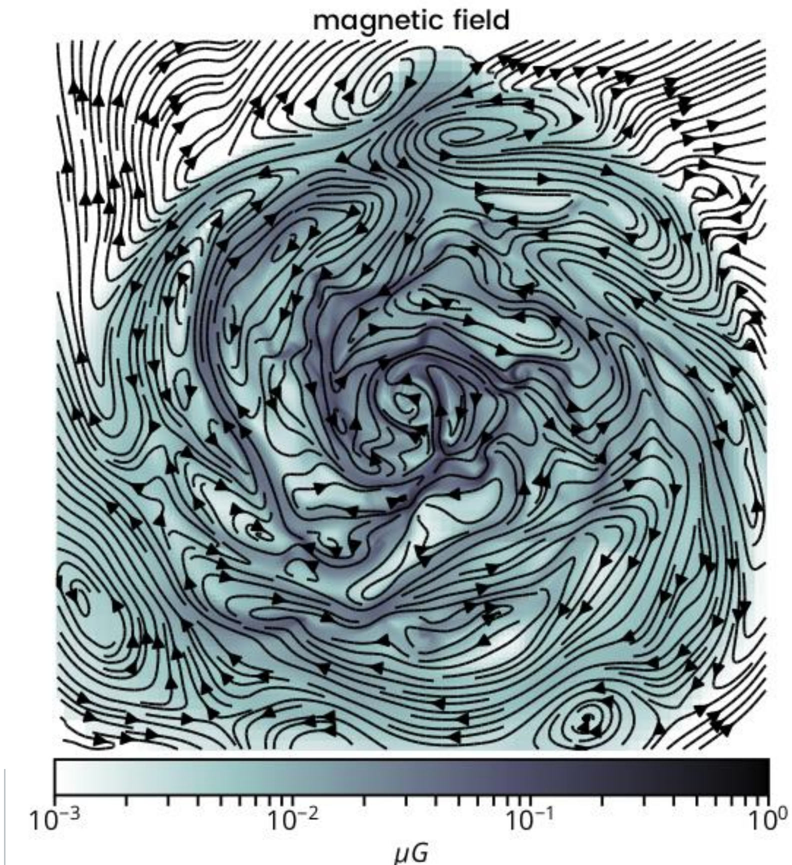
B-field pitch angle

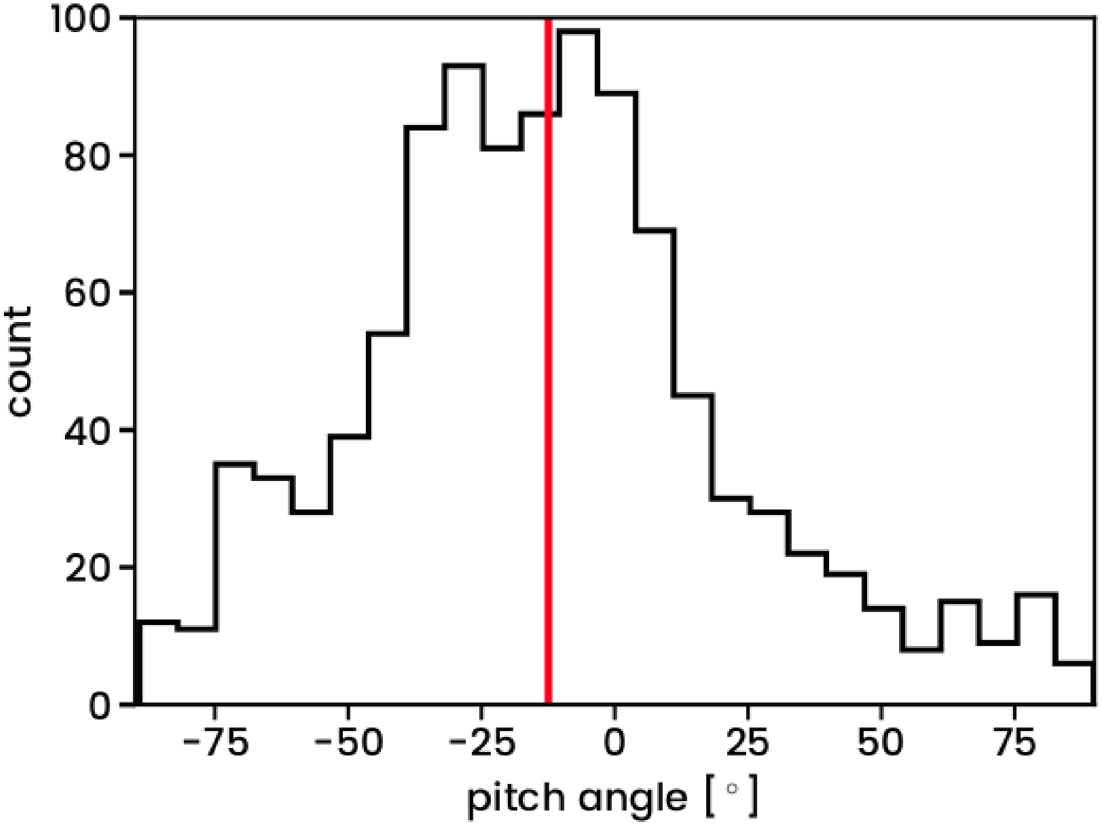
Widely measured in observations

$$p_B = \arctan \frac{B_r}{B_t}.$$

Negative B-field pitch angle connected to spiral structure

$$\langle p_{\rm B} \rangle = -12.4\,^{\circ}$$





Criticism and resolve

- Amplification timescale much longer than eddy diffusion timescale: continuous energy injection by violent feedback at high redshift, phase 1
- Lorentz forces on small scale suppress dynamo: field saturation, phase 2, terminates exponential amplification
- Reynolds number too big in present-day galaxies for significant trubulance: quiescent phase 3, turbulance and B-field settles down to equipartition, large B-field already in place at high redshift

$$\alpha \sim \alpha_T / [1 + (\bar{B}/B_{eq})^2 R_M^p]$$

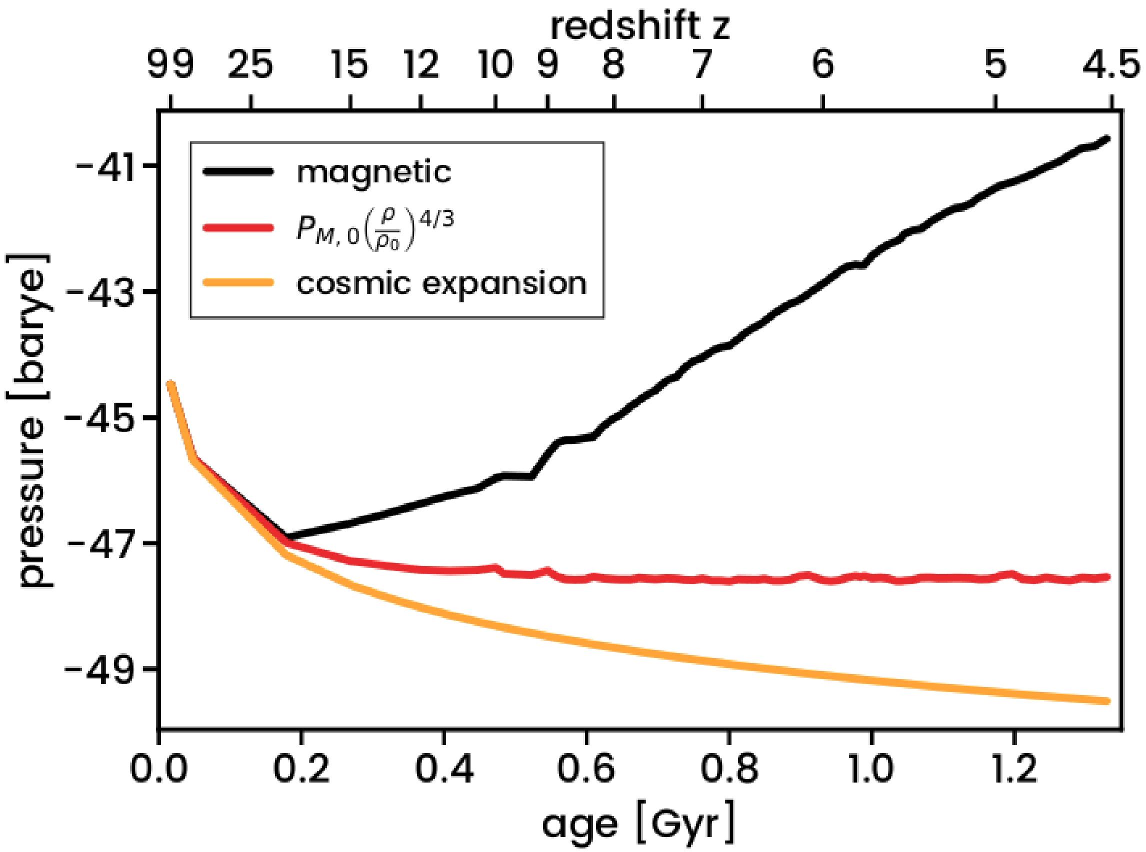
(i) exponential growth (kinematic phase)
(ii) constant growth (non-linear phase)
(iii) zero growth (saturation)

Accounting for cosmo-evolution

Expansion and hierarchical merging

$$\widetilde{\boldsymbol{B}} = a^{5/2} \frac{\boldsymbol{B}}{B_*}$$

$$\frac{\partial}{\partial \widetilde{t}} \widetilde{\boldsymbol{B}} = \widetilde{\nabla} \times \left(\widetilde{\boldsymbol{v}} \times \widetilde{\boldsymbol{B}} \right) + \frac{1}{2a} \frac{\mathrm{d}a}{d\widetilde{t}} \widetilde{\boldsymbol{B}}$$



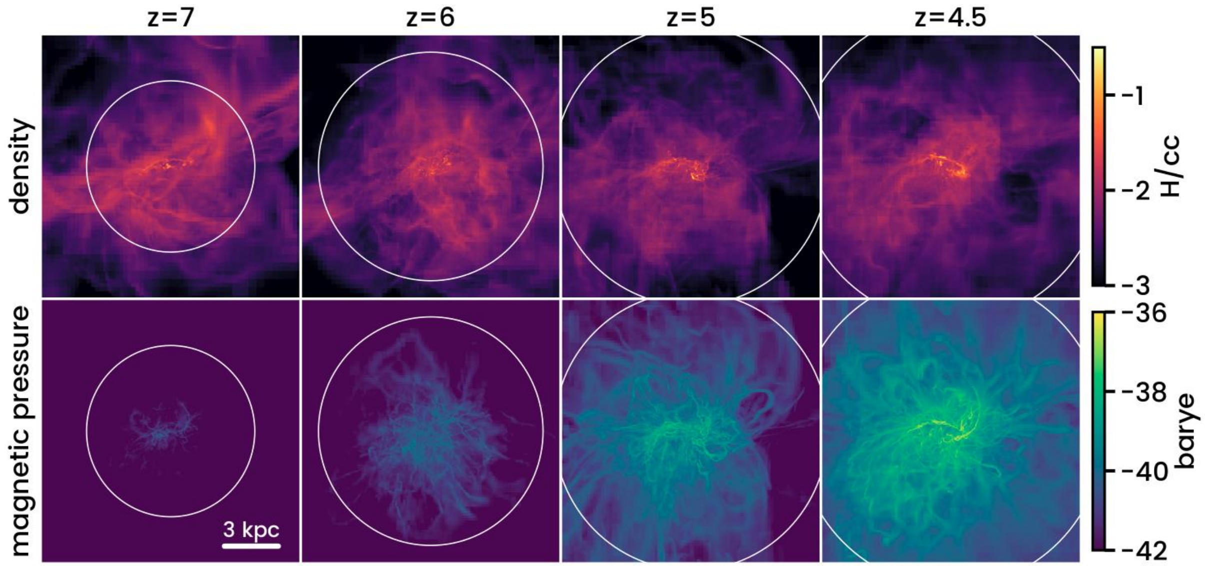
Expansion dominates above z=20

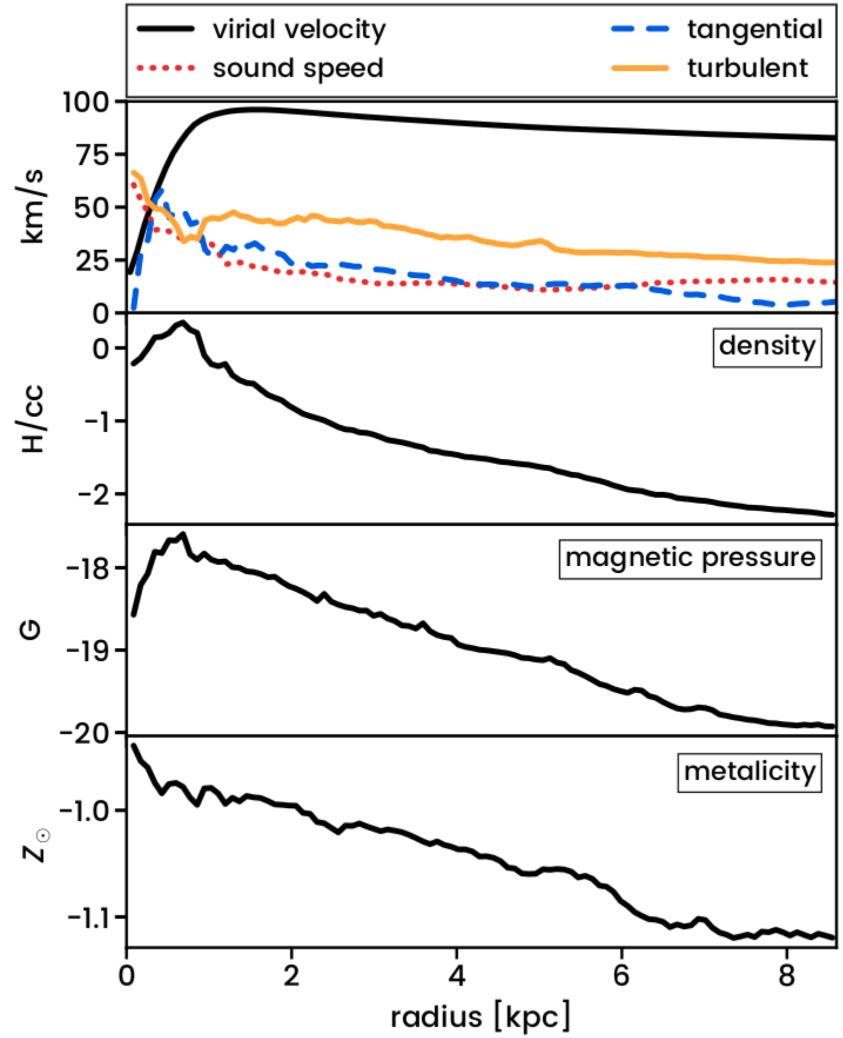
Later on structure formation dominates

B-field formation scenario preserves

Despite cosmo-expansion and hierarchical merging,

SSD scenario and turbulance driven build-up of B-field still viable in cosmological context



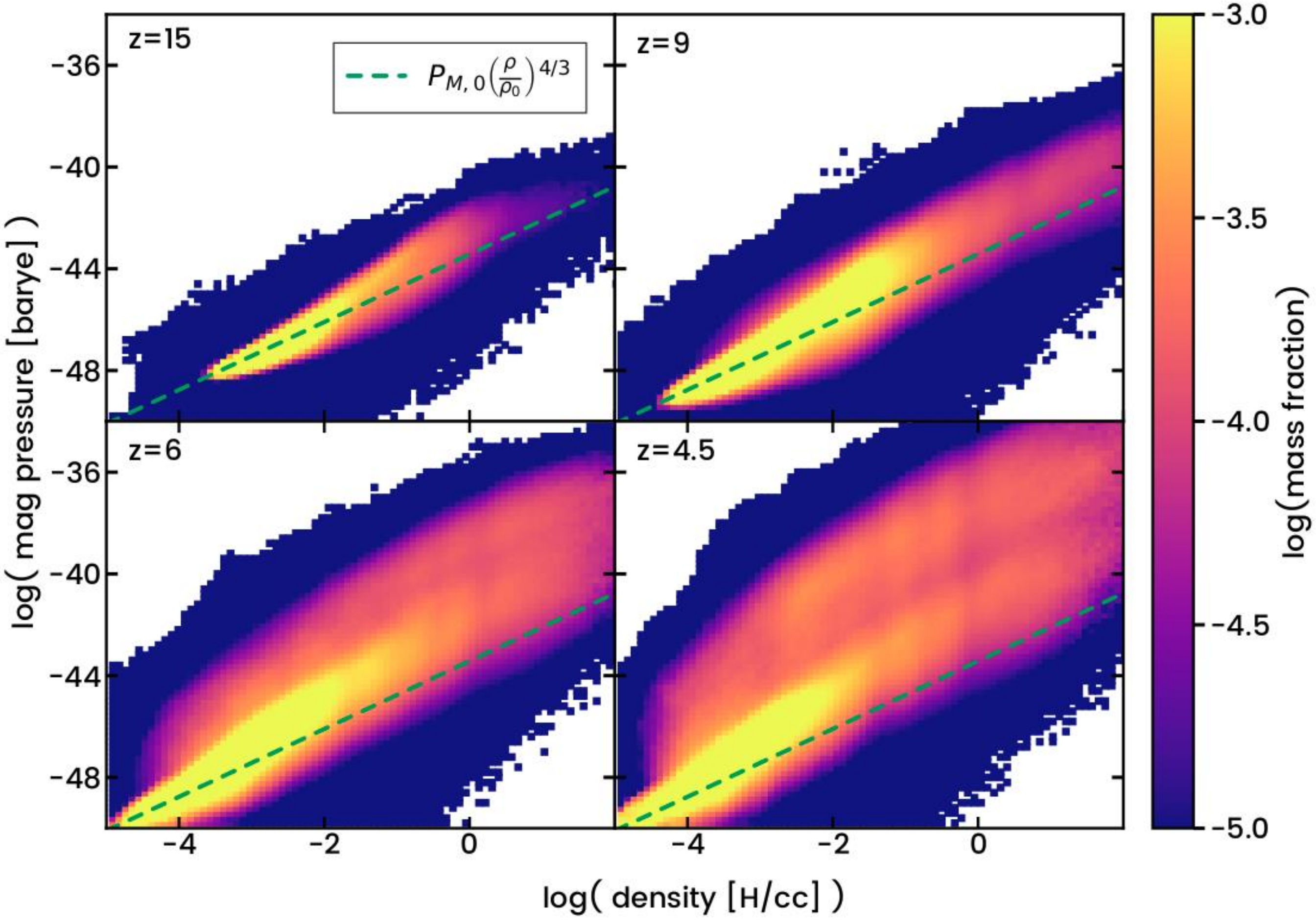


Magnetic Amplification

Most significant in high density regions

Corresponds to small scale galaxy central regions

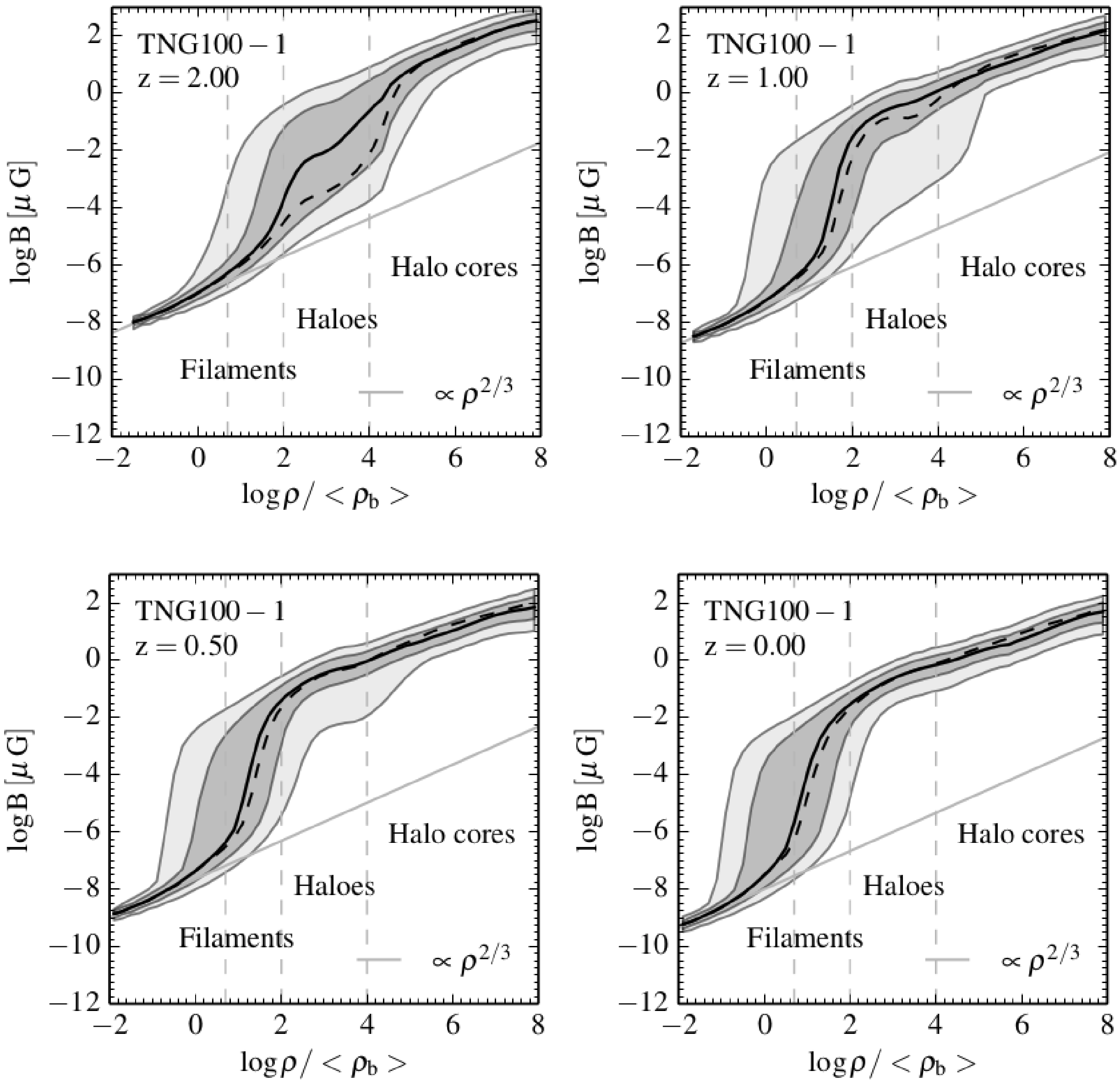
Usually hubs the strongest feedback



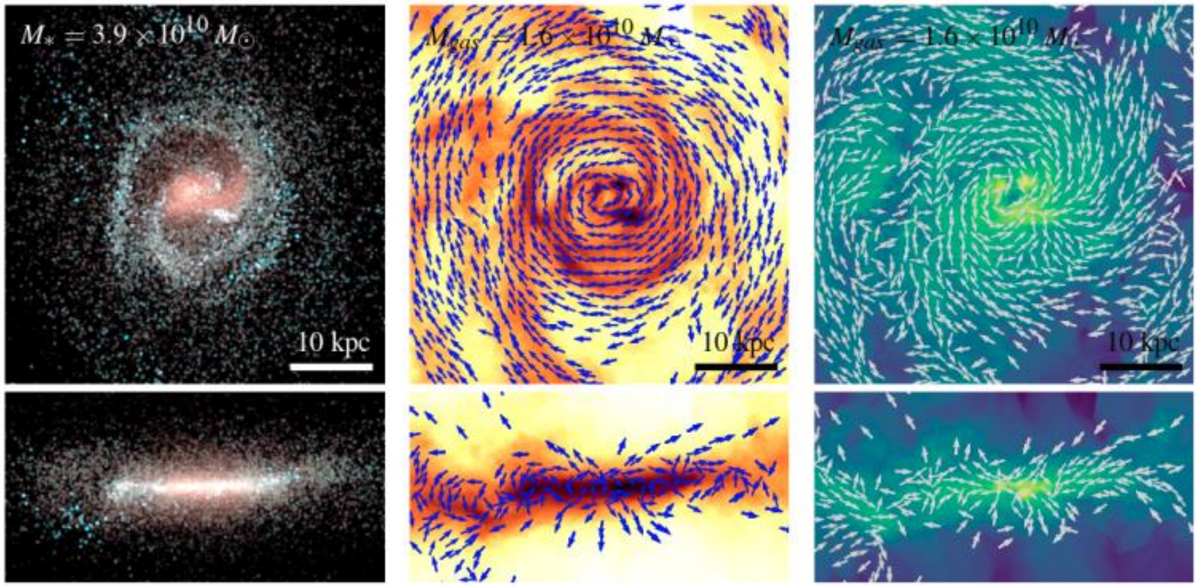
Similar amplification in IllustrisTNG

Self-consistent physical models with cosmological evolution

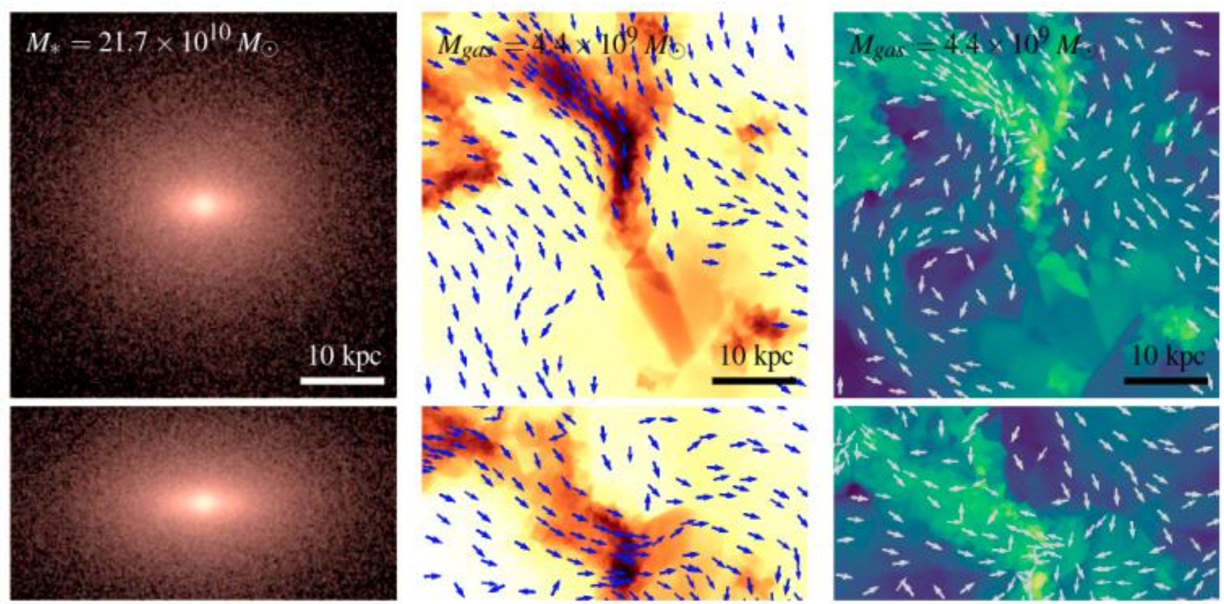
Amplification stronger with higher resolution, indirect justification for SSD (resolution much coarser)



Late VS Early type galaxies



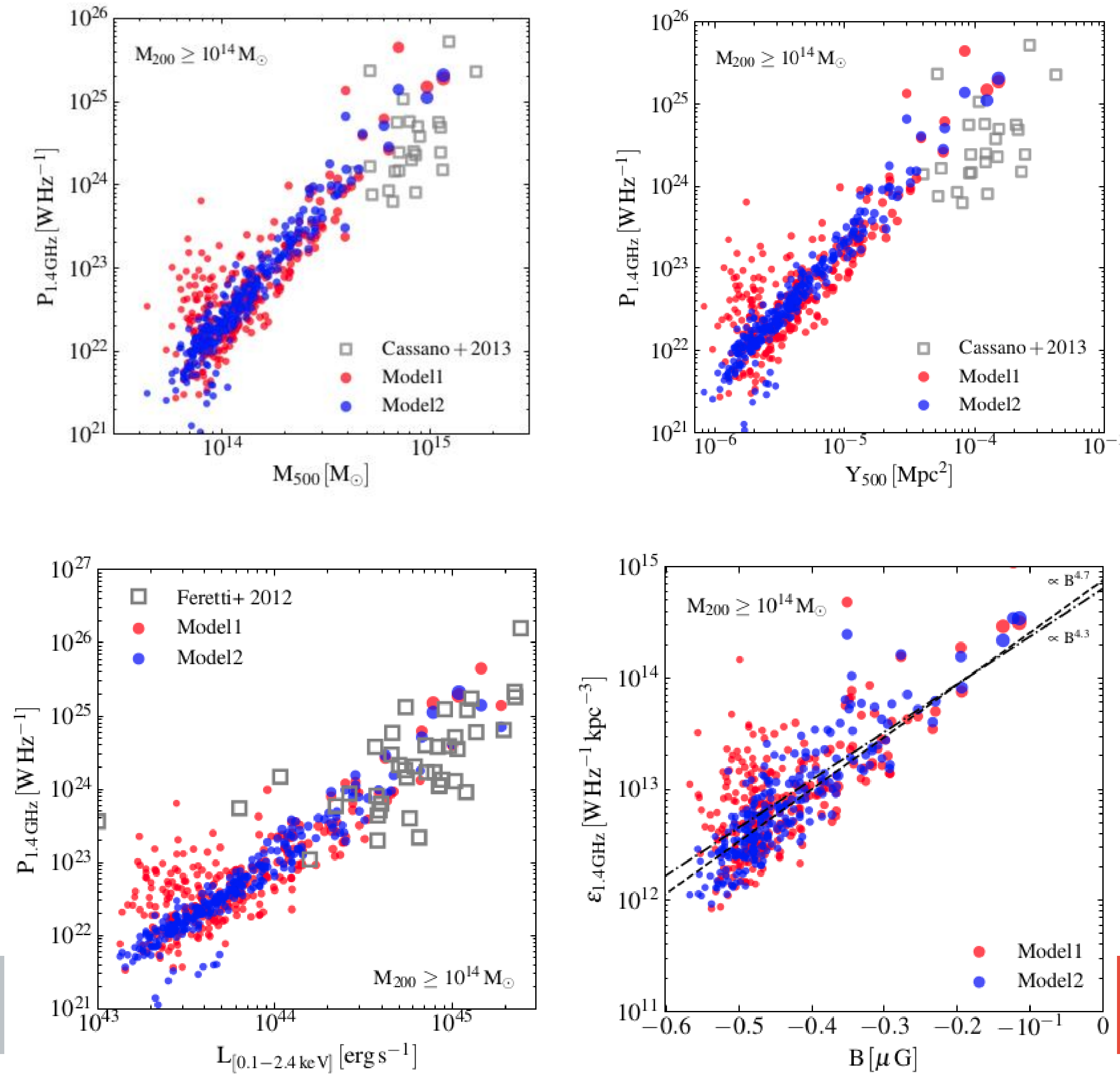
Shear supported large-scale fields decay with galaxy type-transition



Scaling relations

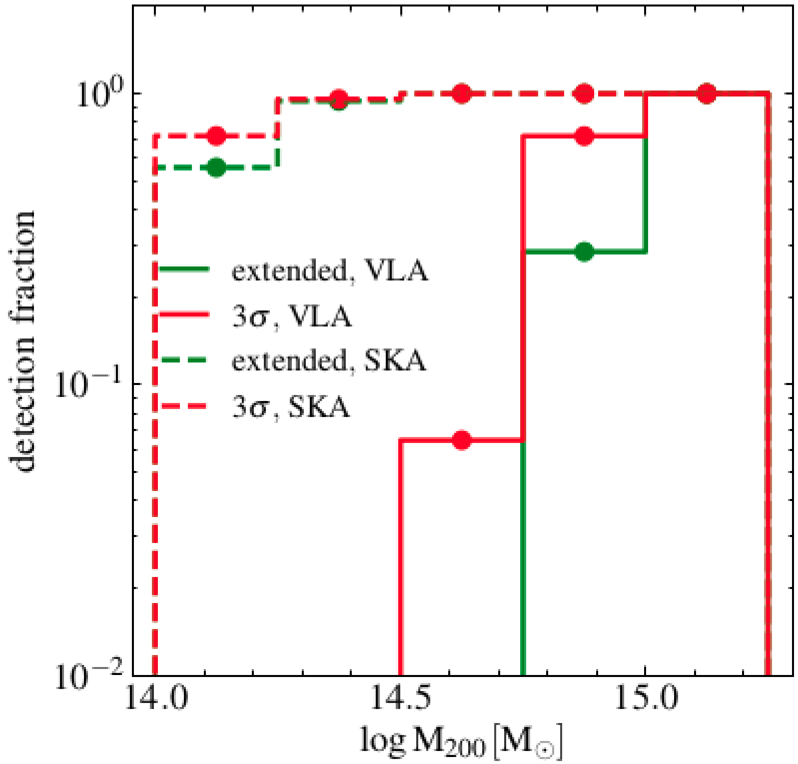
Despite simplistic treatment of relativistic particles responsible for synchrotron radiation

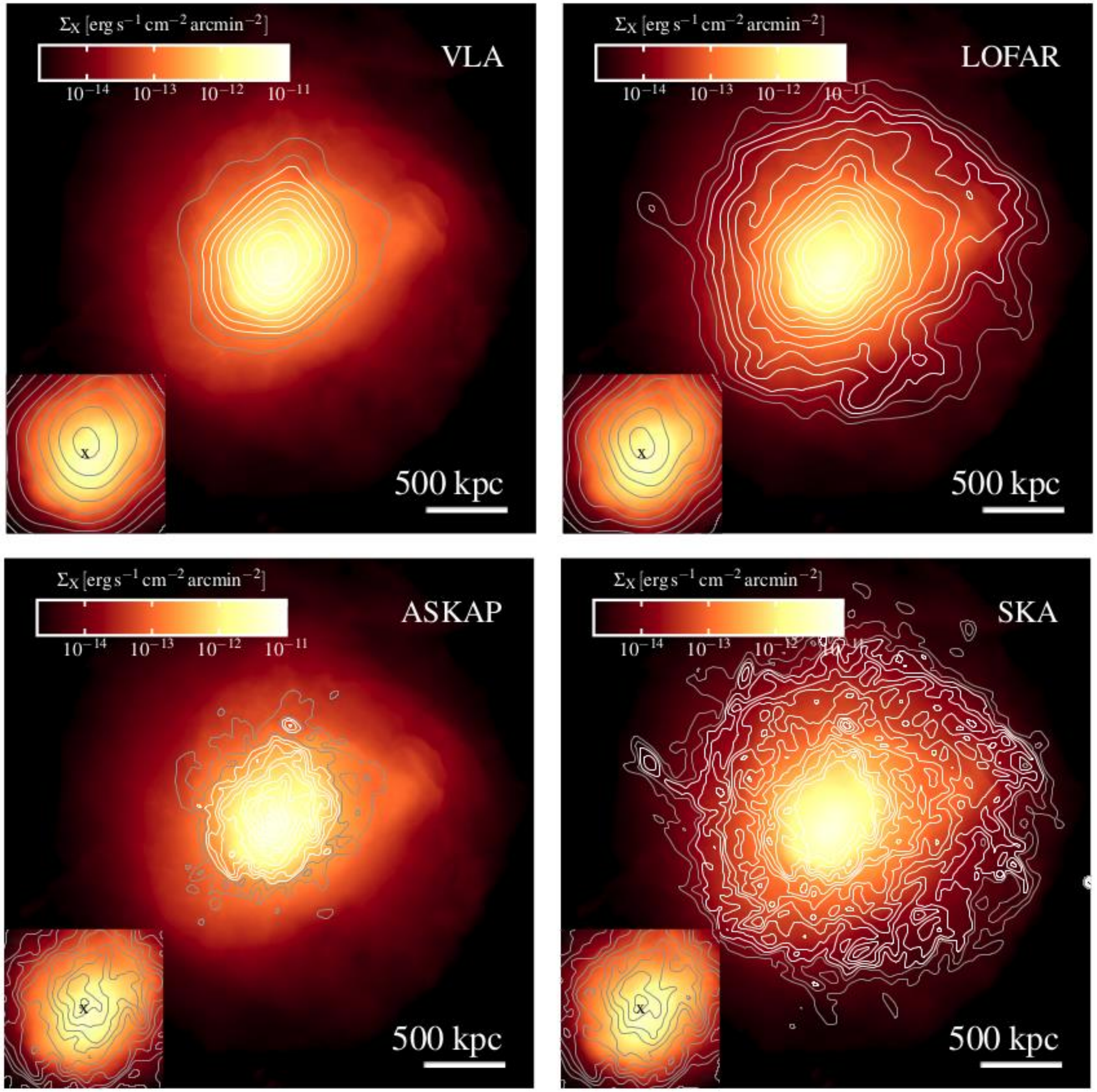
TNG matches observed radio halo scaling relation broadly



Observational prospects of radio halos

Finer radio maps + higher sensitivity to low mass halos with SKA





Take home message

Small-scale Dynamo viable for amplifying and sustaining B-field

Typical 3 phase evolution scenario addresses major concerns of the mean-field-theory

Compatible with zoom-in and full cosmological setups

B-field and scaling relations of IllustrisTNG galaxies/cluster confirms B-field amplification

Synchrotron radiation radio halos observations with SKA promising for constraining SSD theory

References

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