PRELIMINARY

Investigating the numerical dependencies of the galactic dynamo

Mark I.G. Ugalino (ugalino@umd.edu)

with Benedikt Diemer (UMD, ART), Vadim Semenov (Harvard CfA, ART),
Romain Teyssier (Princeton, RAMSES), Oliver Zier (Harvard CfA, AREPO),
Federico Marinacci (UBologna, AREPO), Matthieu Schaller, Nikyta Shchutskyi (Leiden, SWIFT)
and Jin Young Kim (UNC Chapel Hill)

RAMSES User Meeting 2026

UNIVERSITY OF MARYLAND

Investigating the numerical dependencies of the galactic dynamo

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3rd year PhD candidate, University of Maryland

Broadly interested in: Numerical methods (topic of this talk), Bridging galaxy scales and star formation + magnetic fields (with RAMSES) etc**

RAMSES User Meeting 2026

UNIVERSITY OF MARYLAND

What about magnetic fields?

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RAMSES User Meeting 2026

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What about magnetic field simulations should we worry about?

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RAMSES User Meeting 2026

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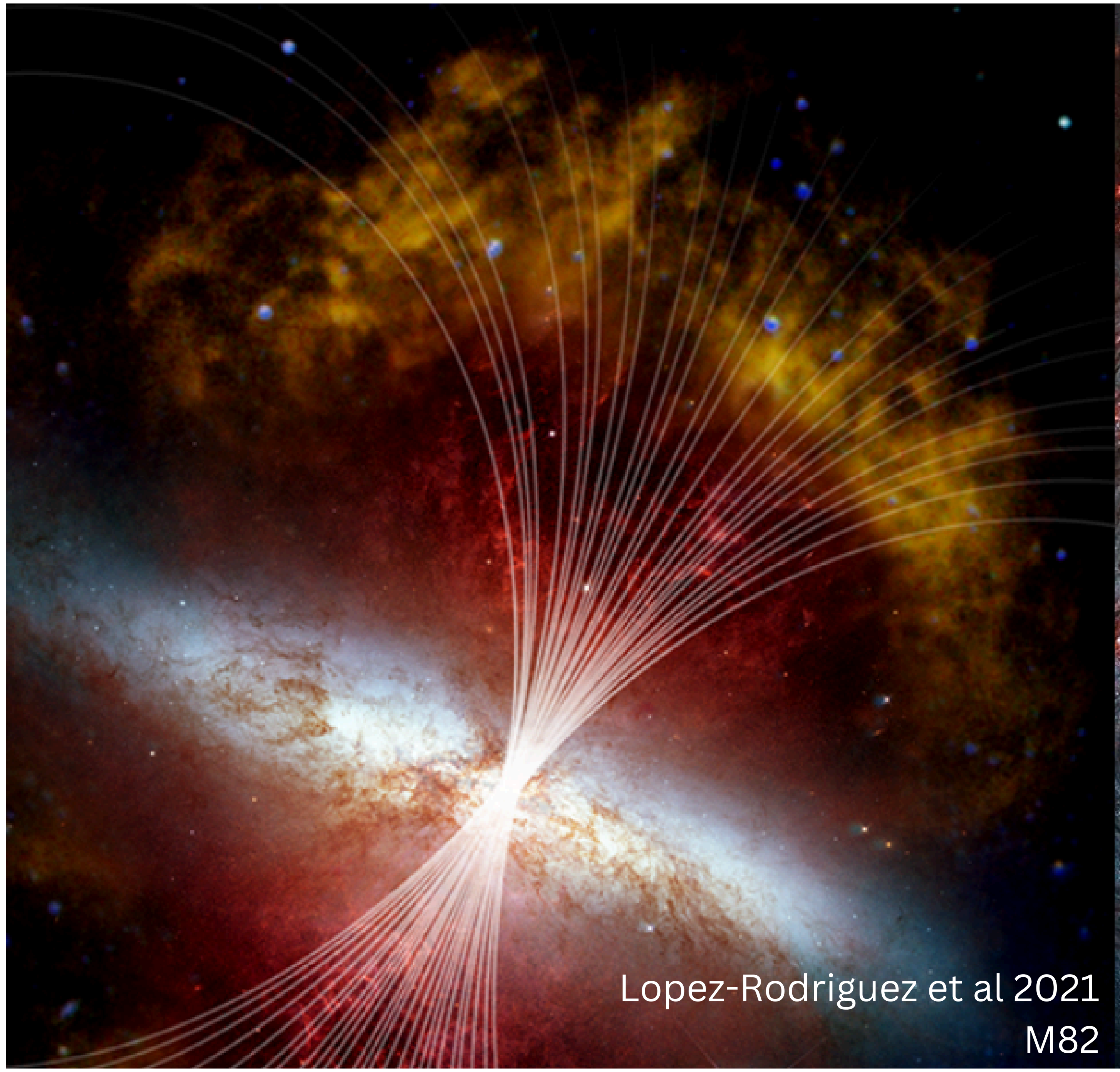
What have we learned so far about galactic $\vec{B}$?



Lopez-Rodriguez et al 2021
M82

NASA, the SOFIA science team, A. Borlaff; NASA, ESA, S. Beckwith (STScI), M51

(Graphics and content inspired by James R. Beattie's talk slides)

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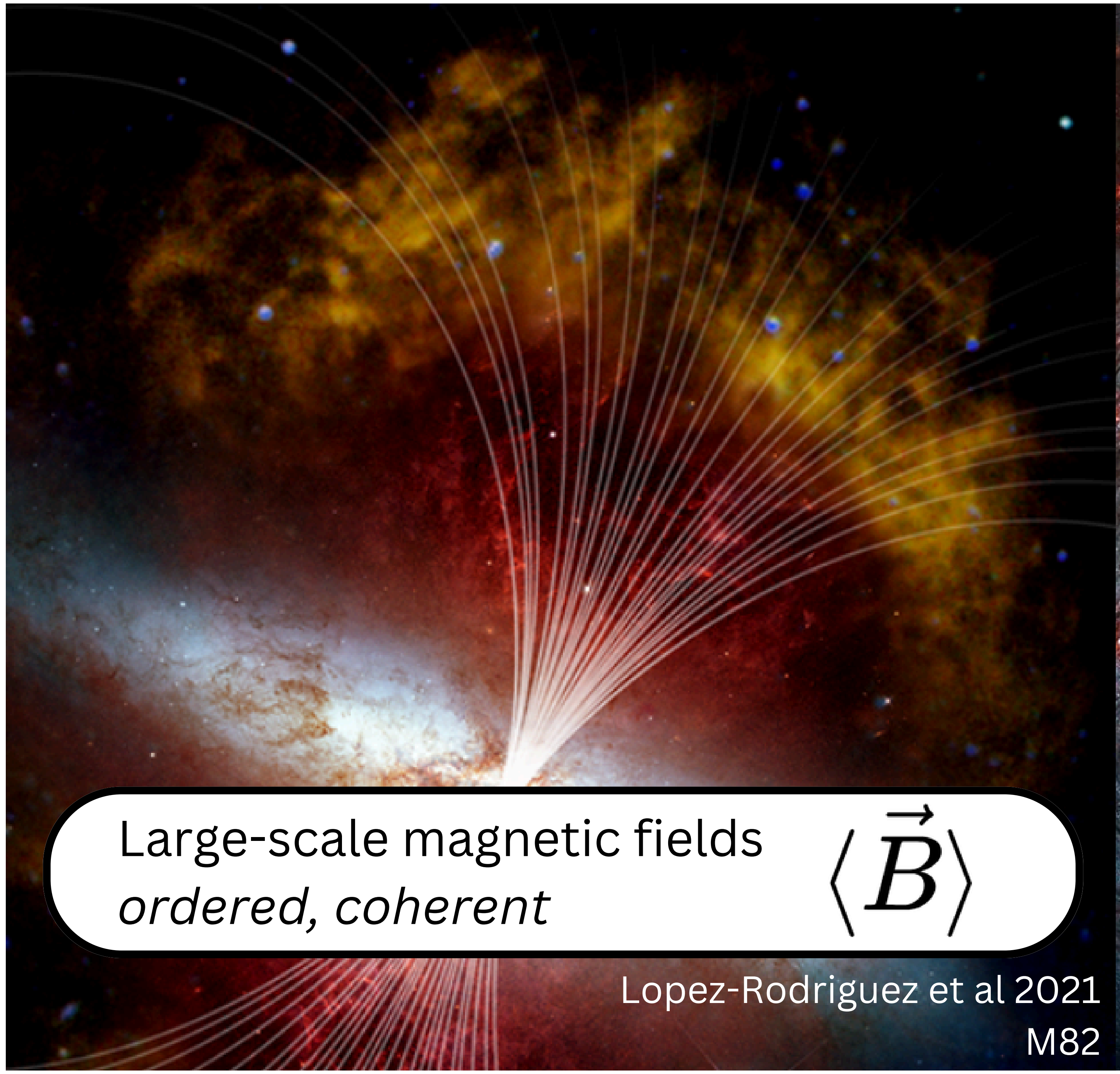

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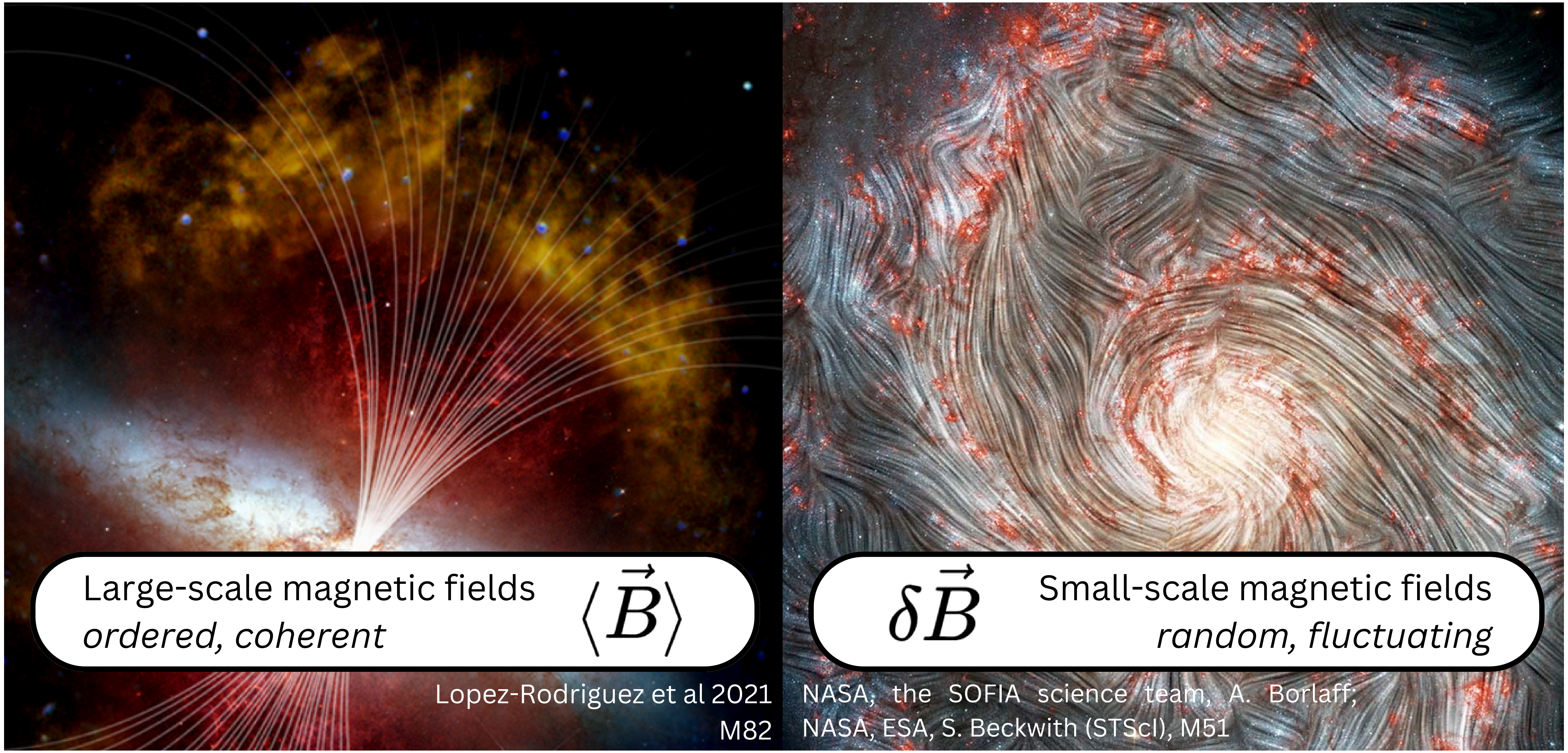

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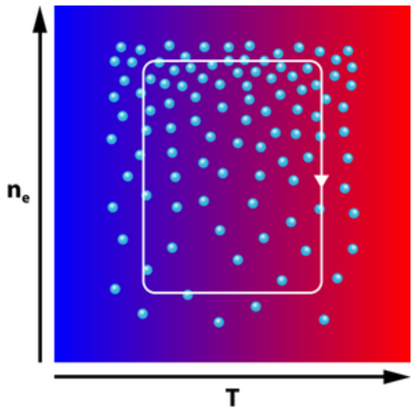
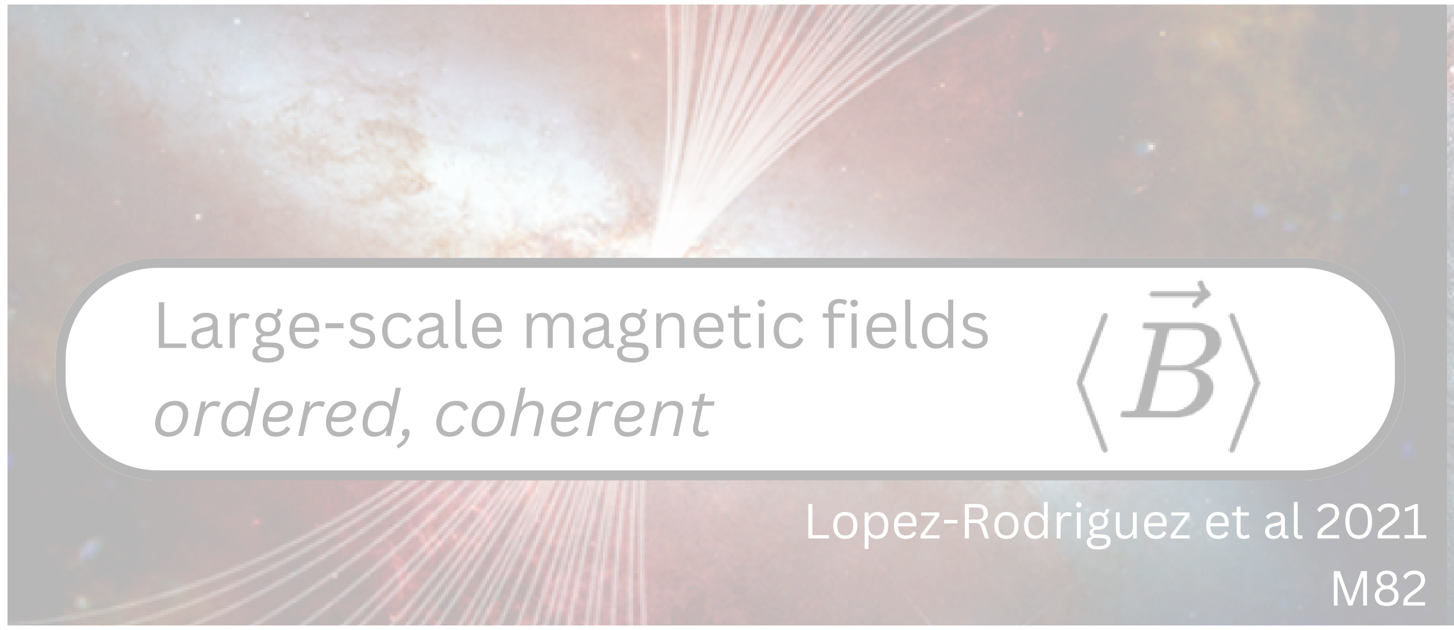
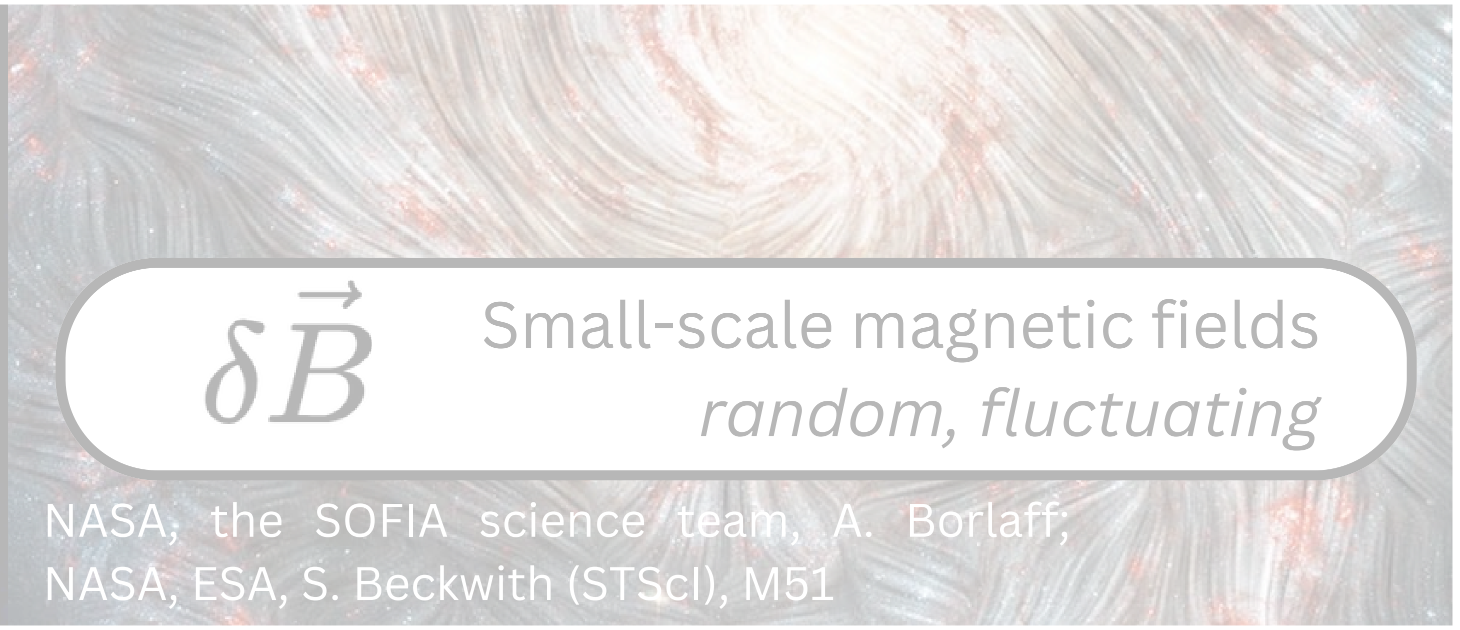


Seeded by fields produced by particle-level mechanisms like the **Biermann battery** that produce

$$B \sim 10^{-20} - 10^{-17} \mu\text{G}$$





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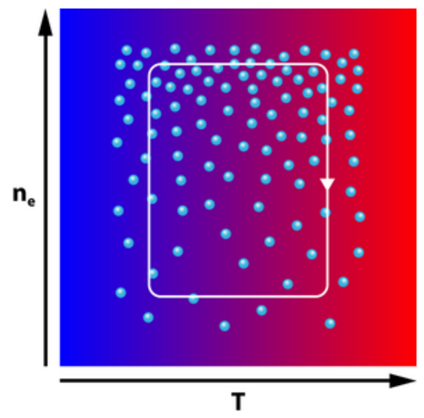

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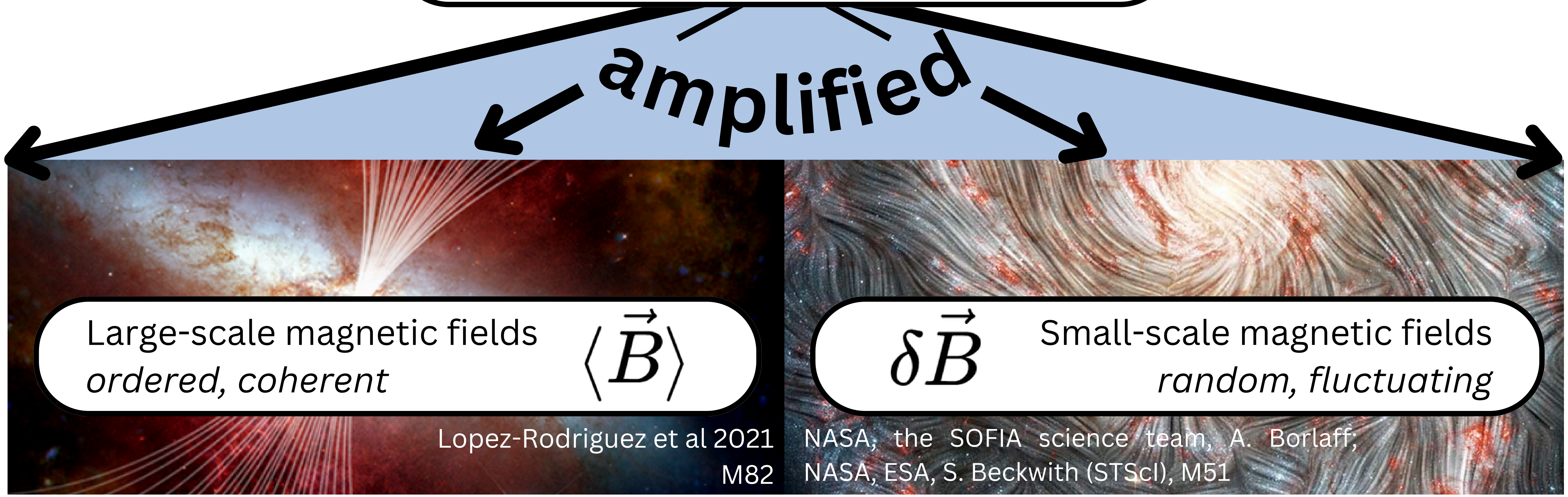

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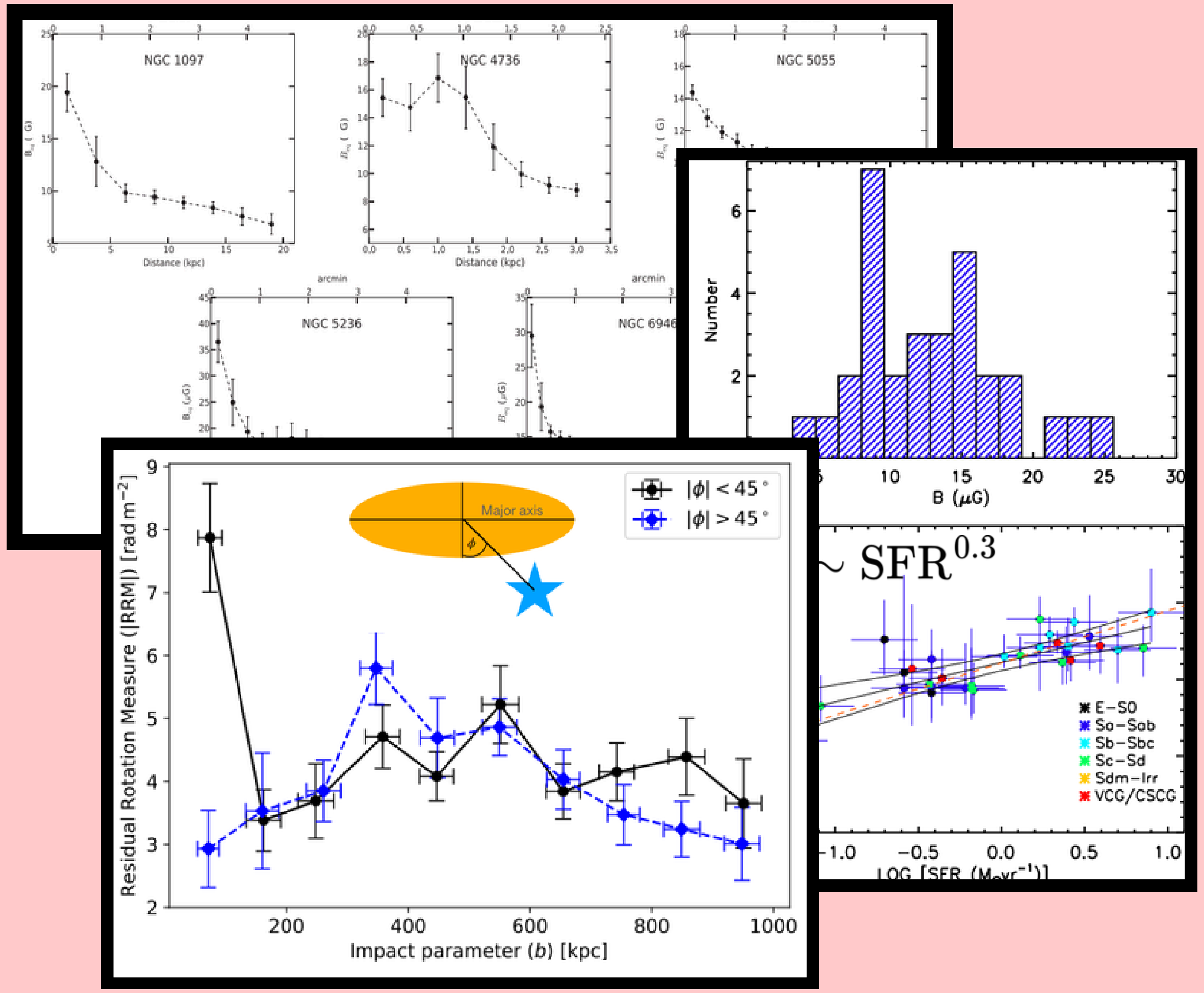

and many others...

Observations of nearby spiral galaxies indicate that...

- Average field strengths:

$$B \sim 1 - 10 \mu G$$

- Magnetic field strengths decrease gradually and is dynamically important within the circumgalactic medium (CGM) [r < 100 kpc]

(Tabatabaei et al 2017, Schleicher and Beck 2013, Basu and Roy 2013, Heesen et al 2023)

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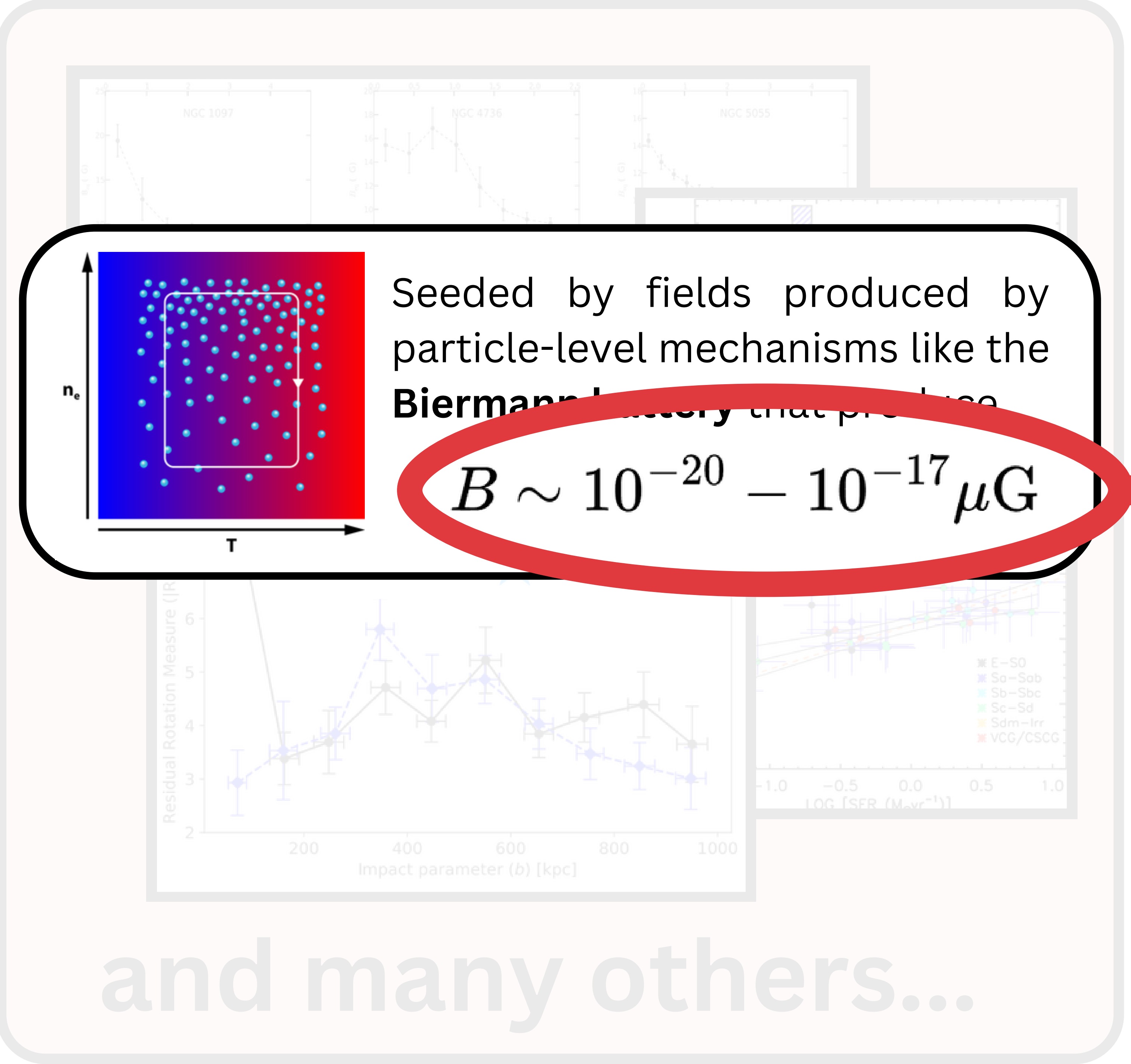

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Main science question:

How do galactic magnetic fields grow to observed μG strengths from minute seed fields?

How do magnetic fields grow (in theory)?

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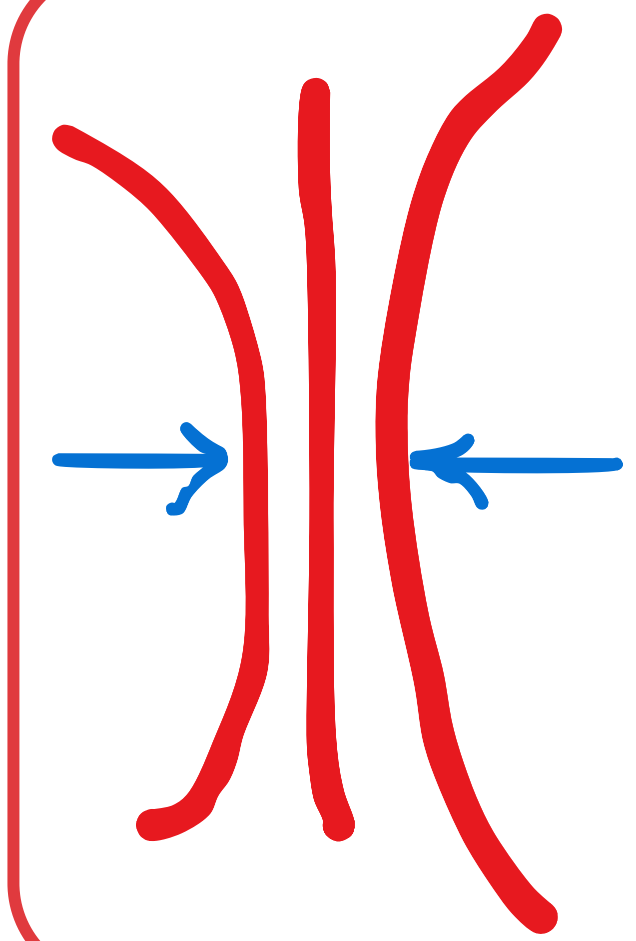
GRAVITY



Gas undergoes spherical collapse and field grows as

$$B \propto \rho^{2/3}$$

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GRAVITY

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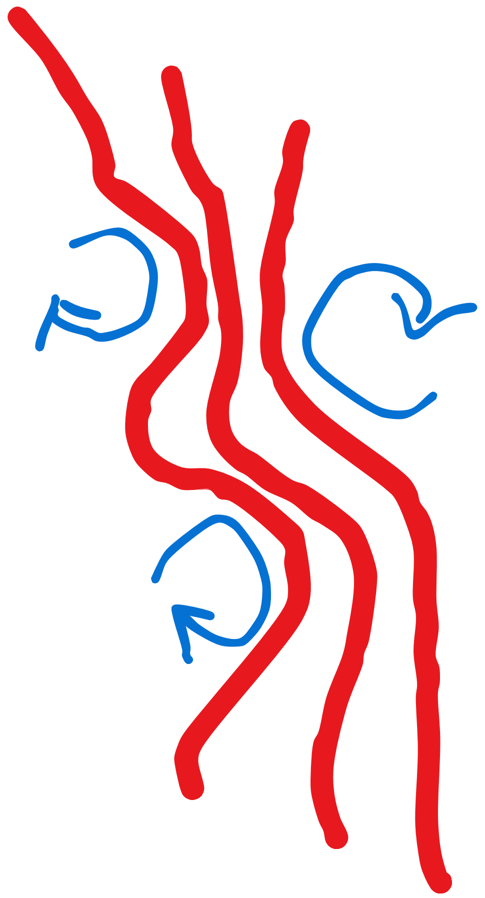
TURBULENCE / SHEAR



Feedback and rotation drives motions which stretch, twist and fold magnetic fields

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

which leads to amplification

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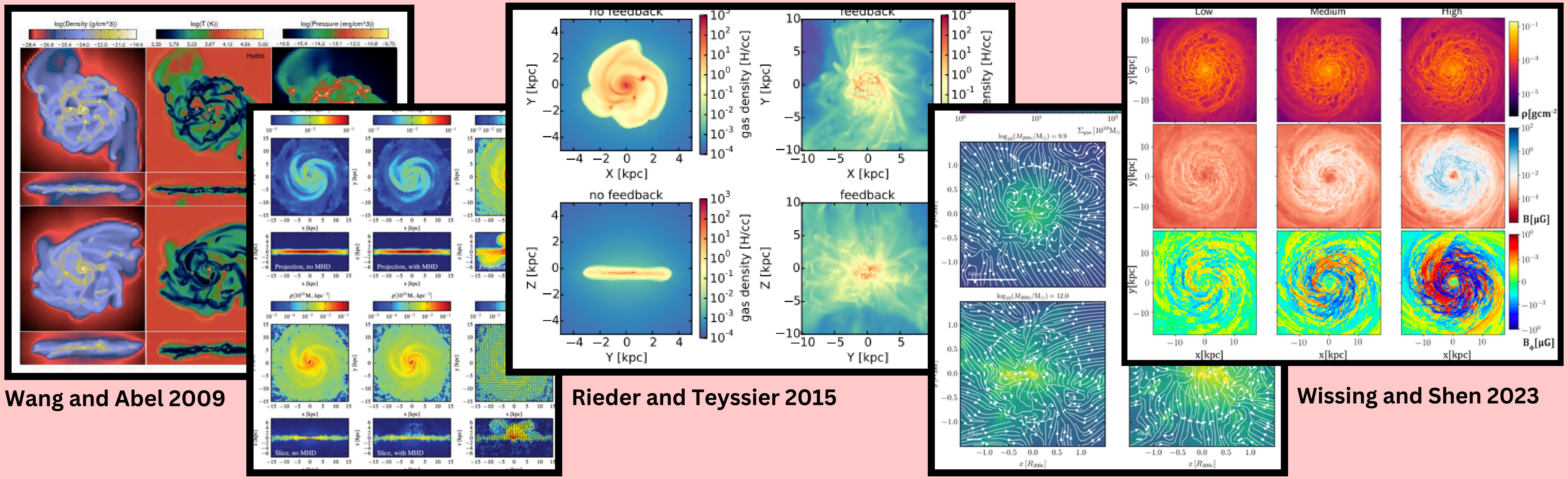
GRAVITY + TURBULENCE / SHEAR

Inherently complex and nonlinear process!

How do magnetic fields grow (in theory)?

GRAVITY ➕ TURBULENCE / SHEAR



Wang and Abel 2009

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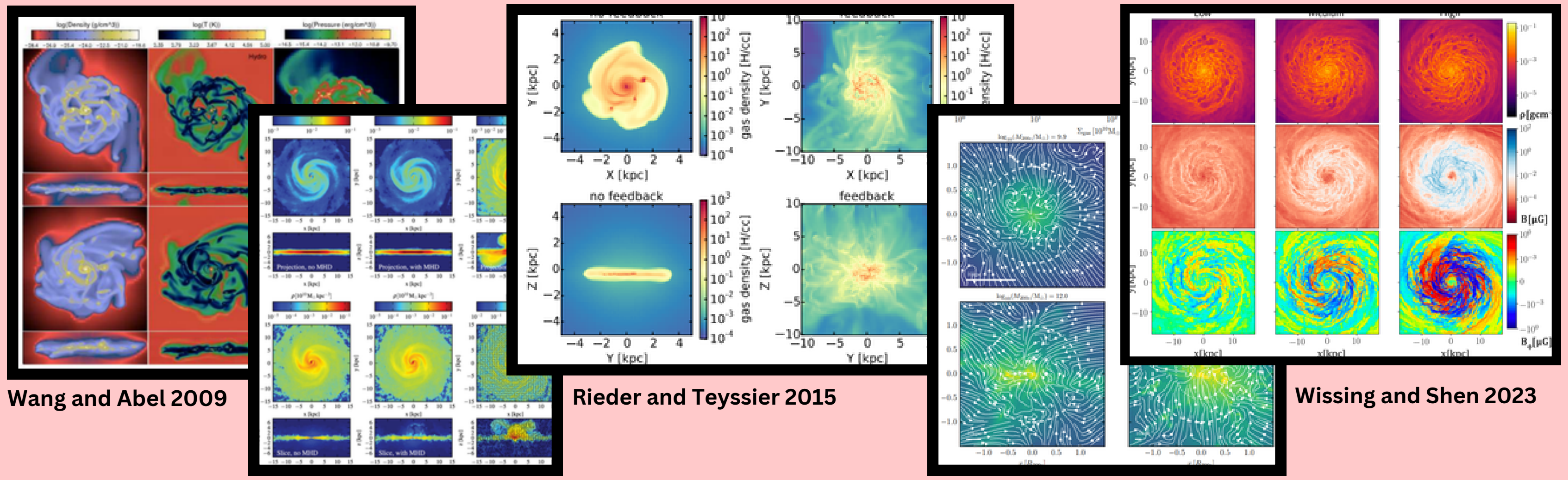
Key tool: magnetohydrodynamical simulations!

What causes simulation results to differ?



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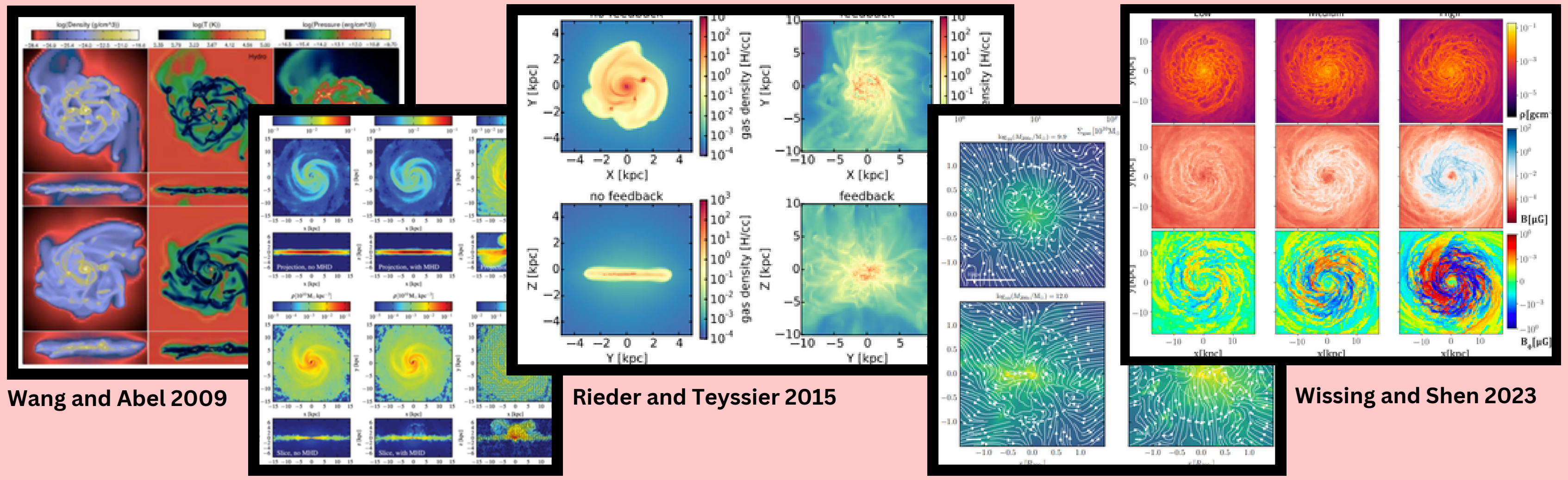
Zoo of codes with different schemes



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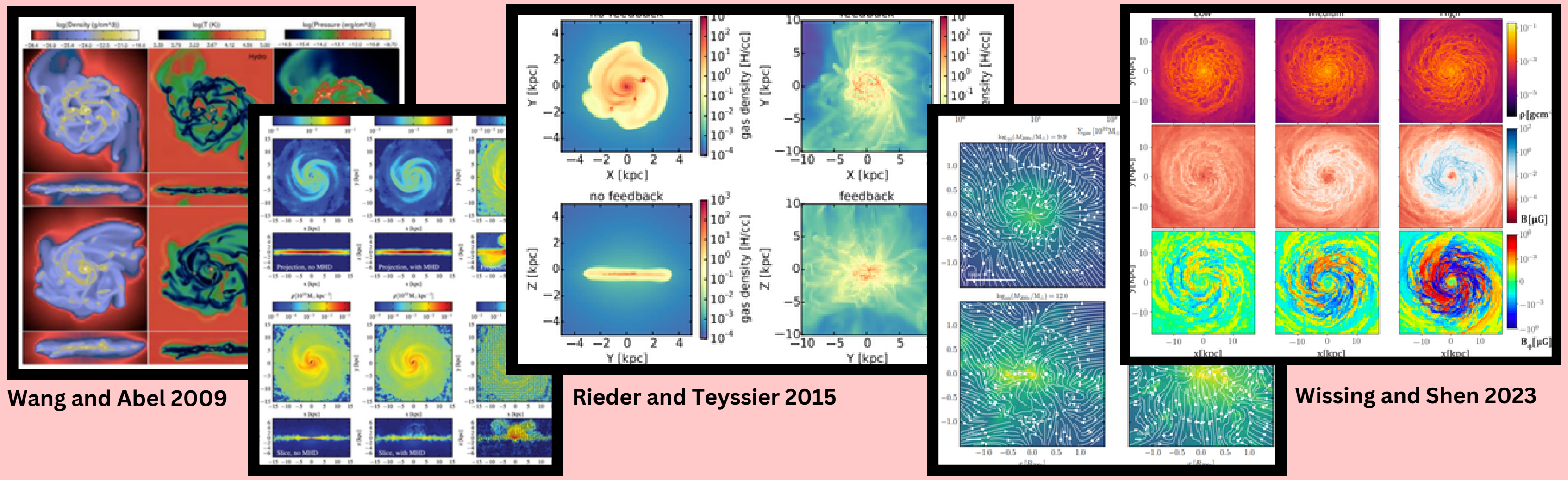

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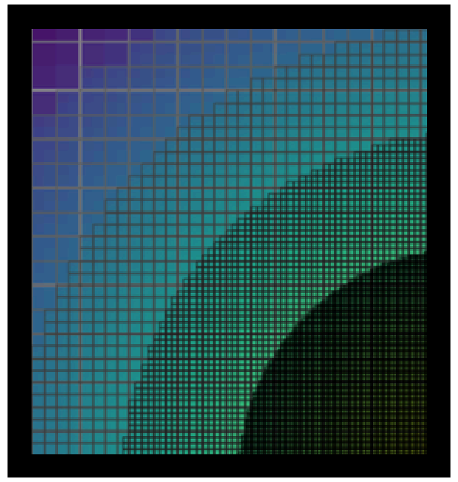
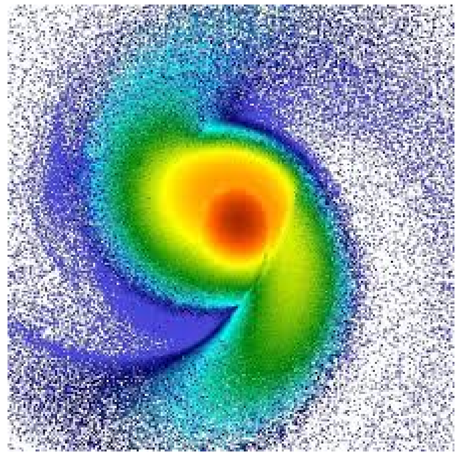


Solved in an adaptively refined mesh (Eulerian)



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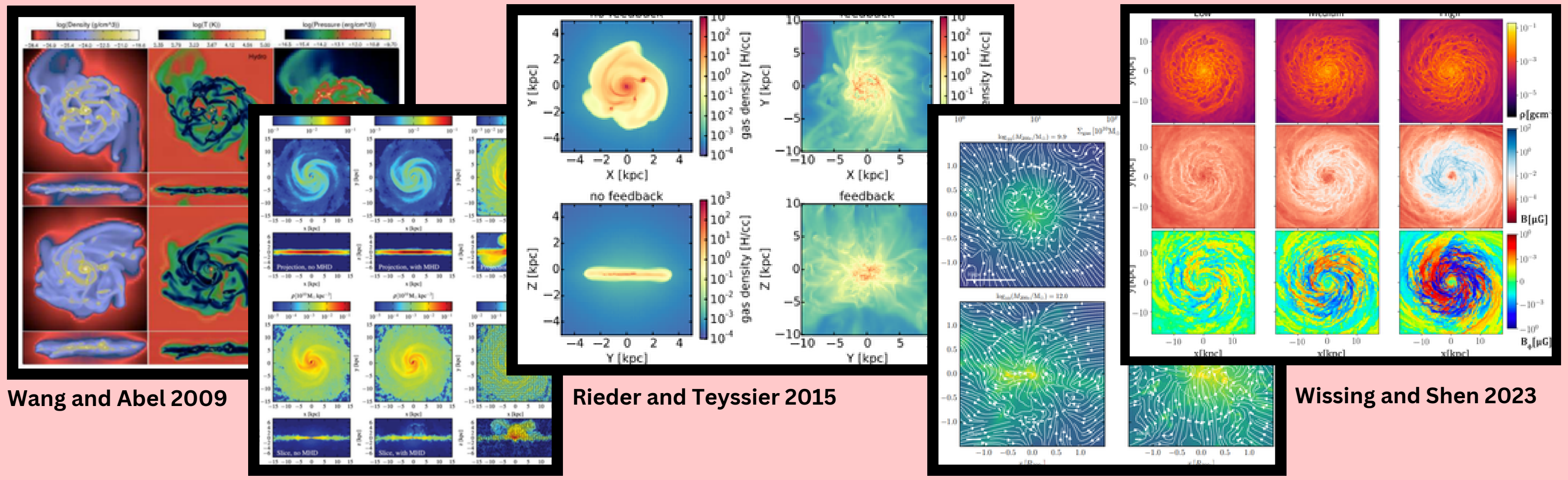

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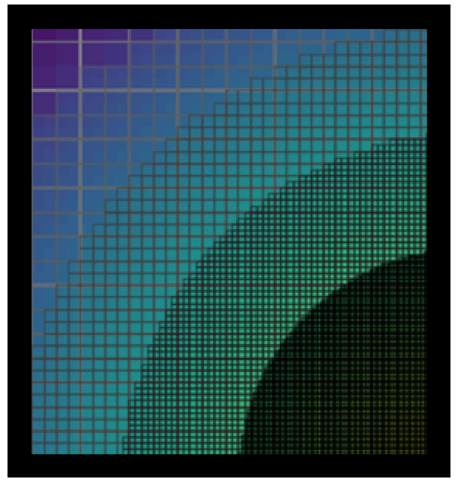

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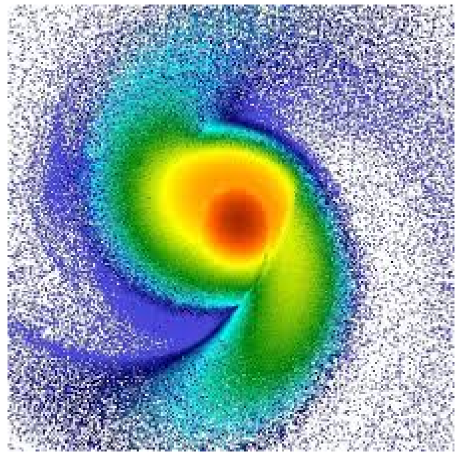

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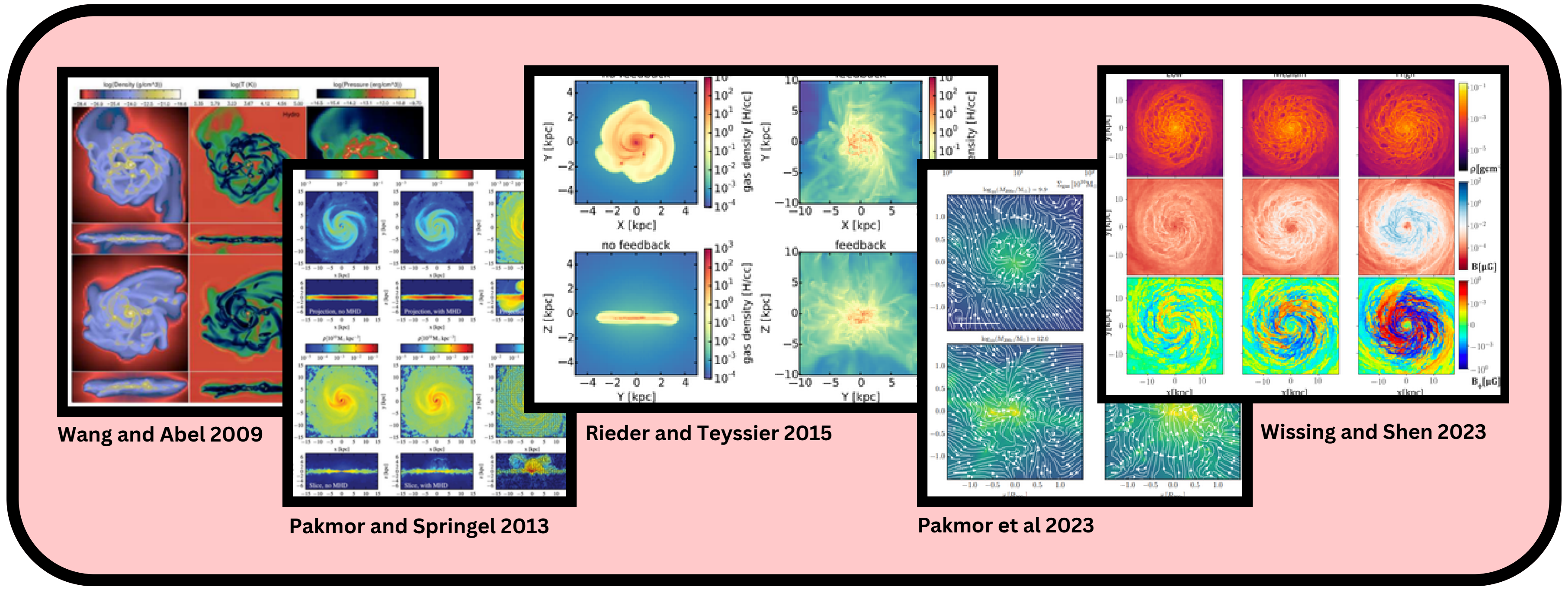

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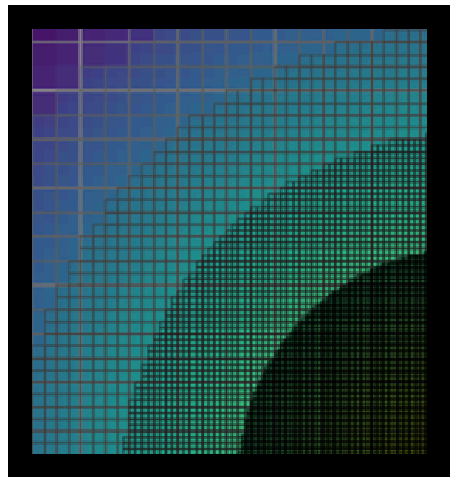

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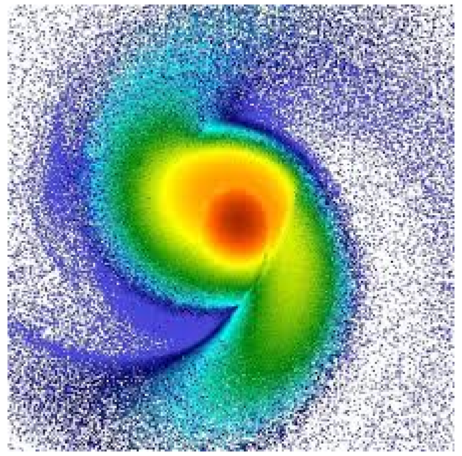

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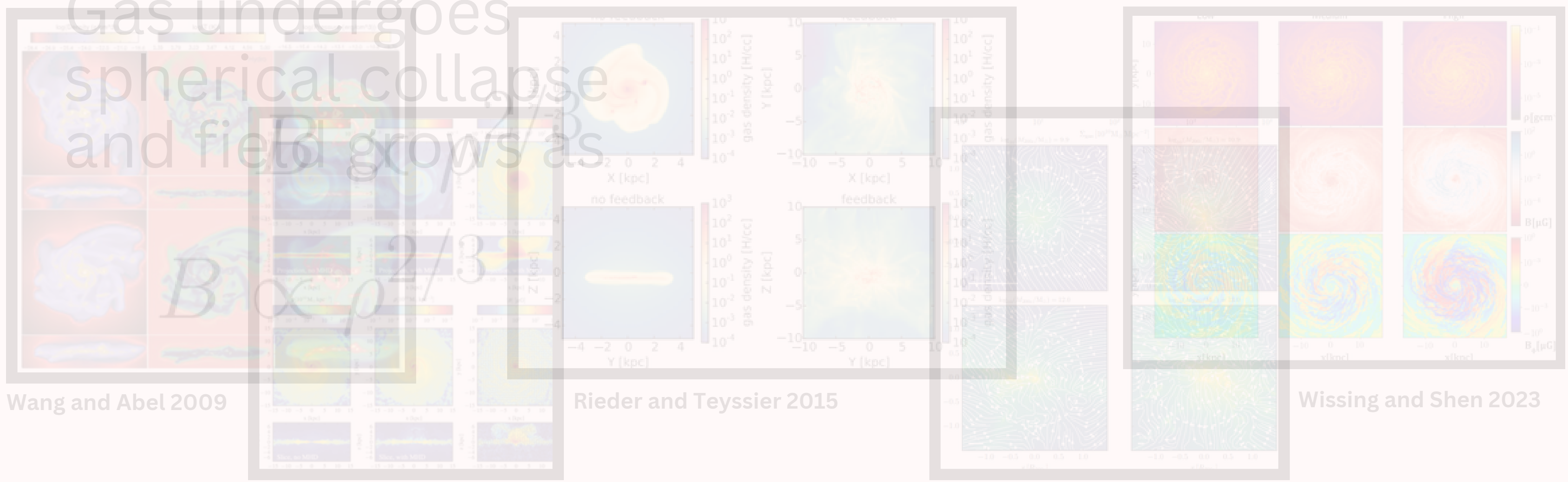

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Powell

(8-wave Method)

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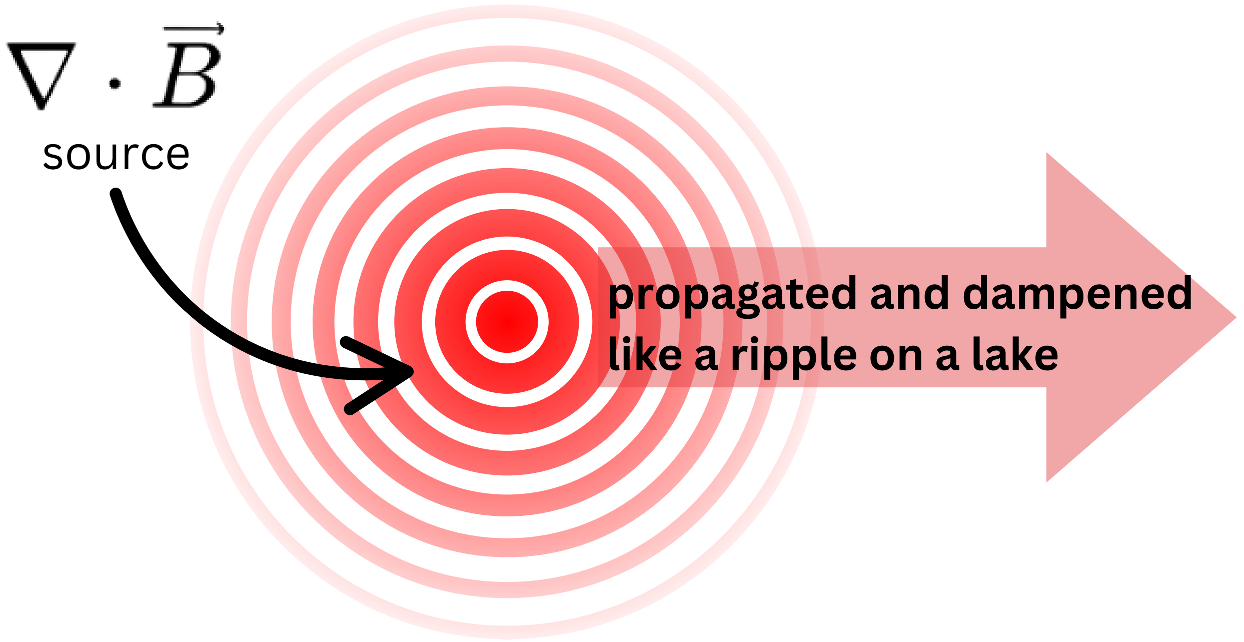

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Dedner
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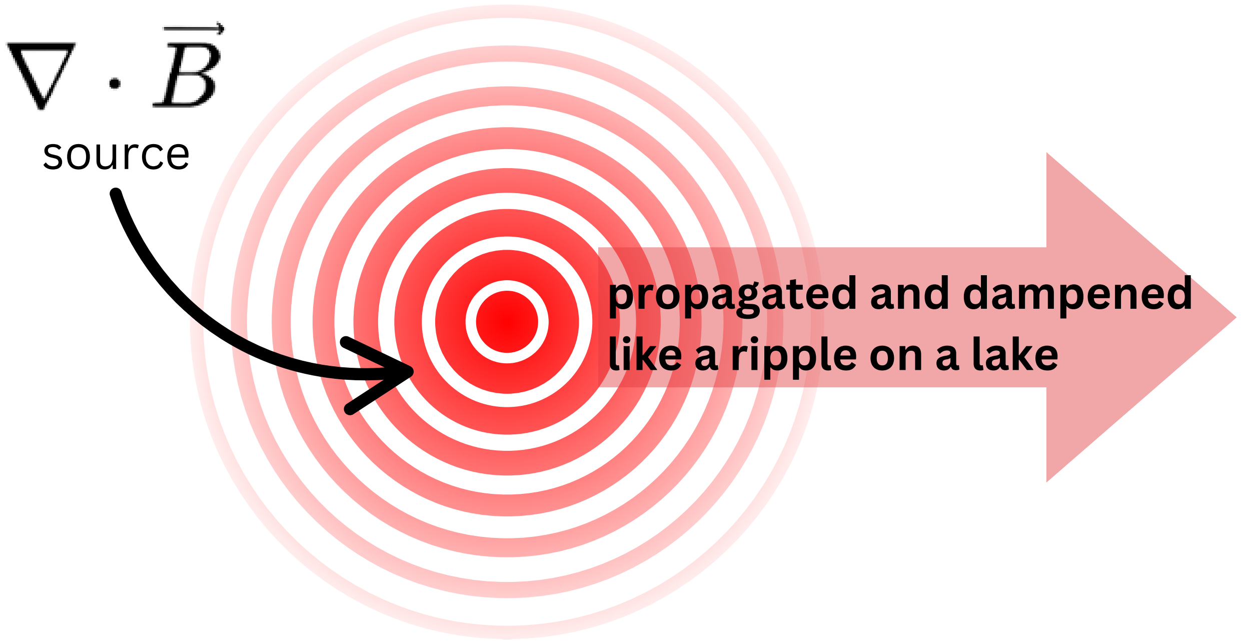

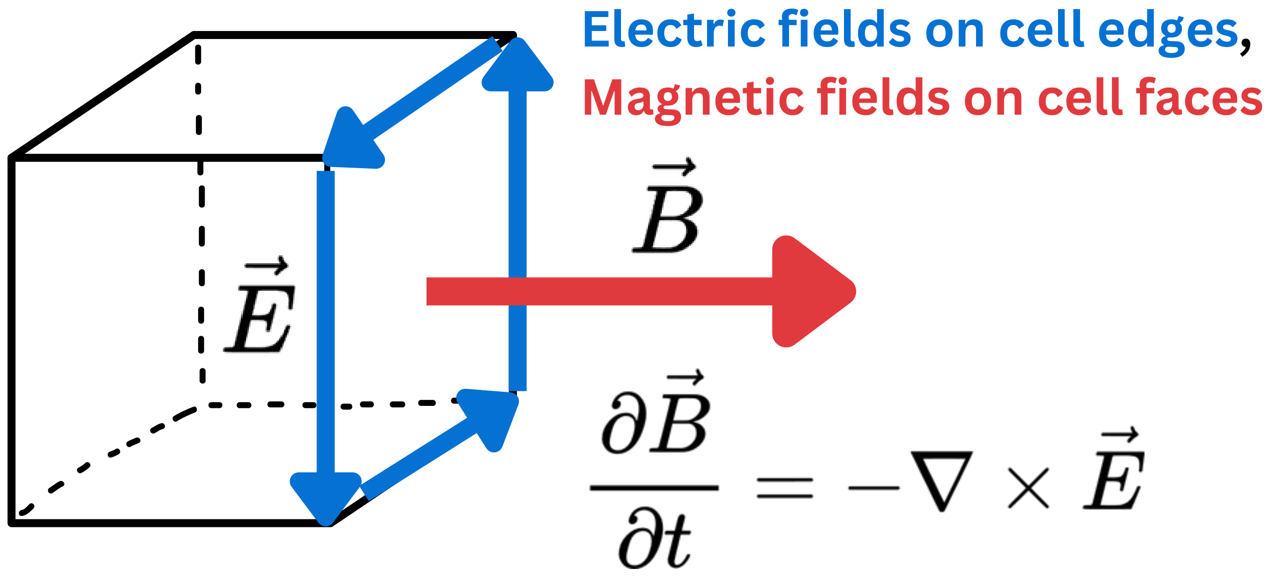

$\nabla \cdot \vec{B} = 0$ by construction

Powell
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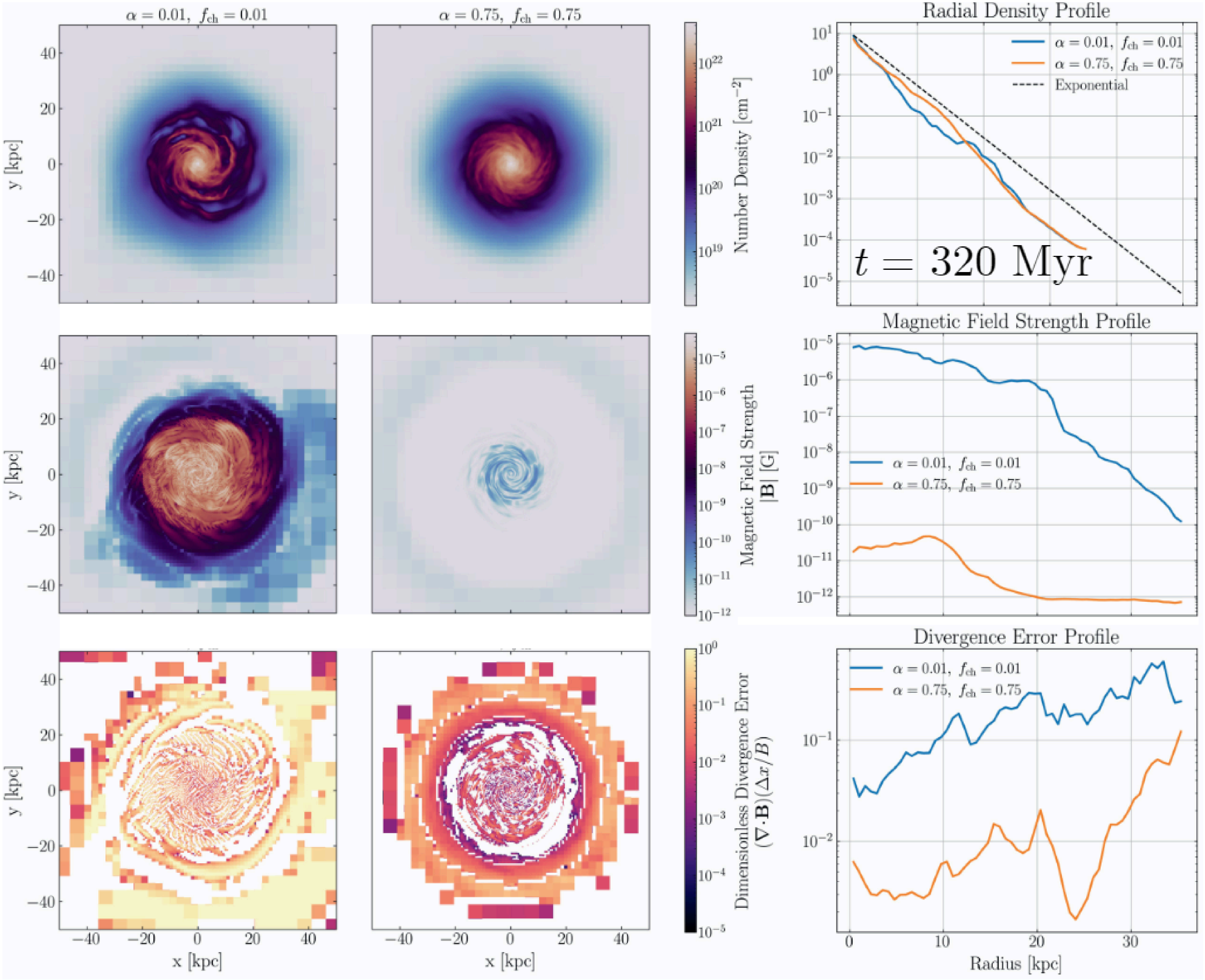
Dedner
(Generalized Lagrange Multiplier Method)

Constrained Transport



$\nabla \cdot \mathbf{B} = 0$

catastrophe in action (e.g. Dedner in ART)

Left - slow propagation, weak damping (blue curve)

Right - fast propagation, fast damping (orange curve)

Diemer, Semenov, Ugalino et al (*in prep*)

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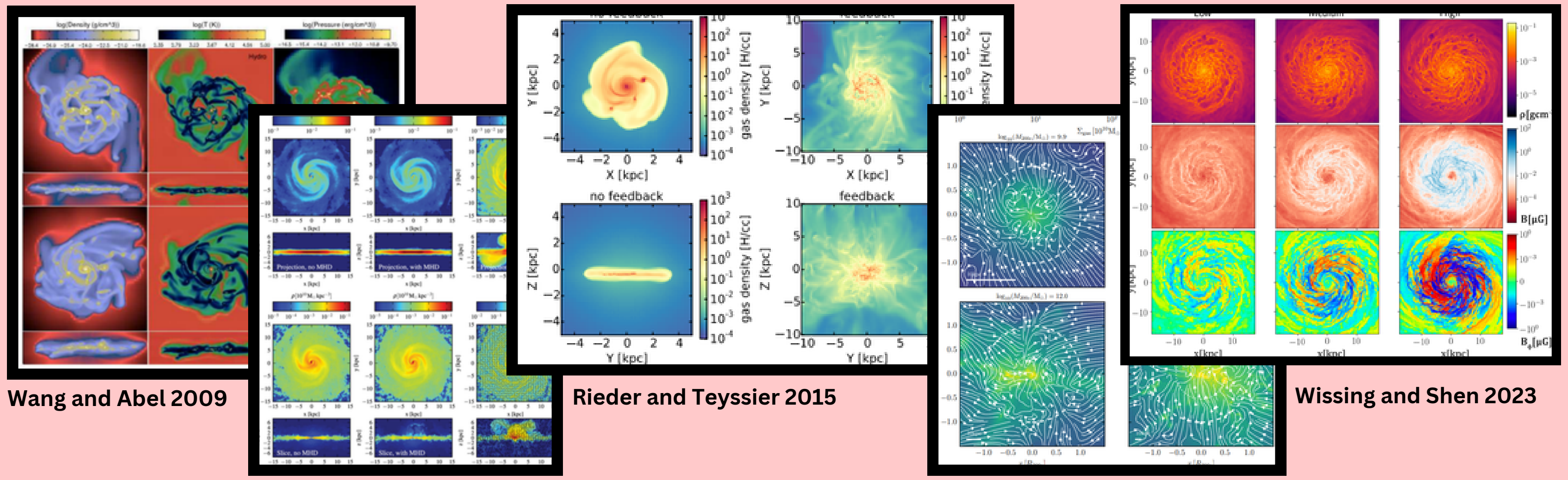

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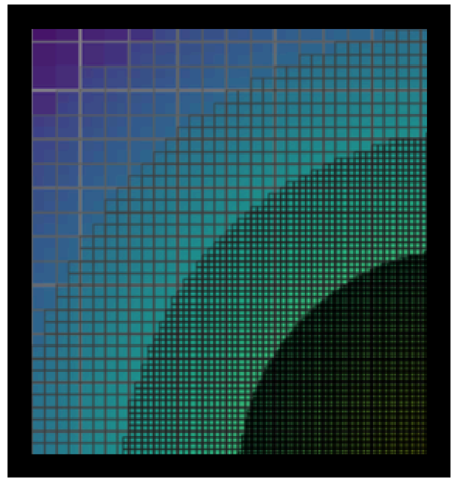

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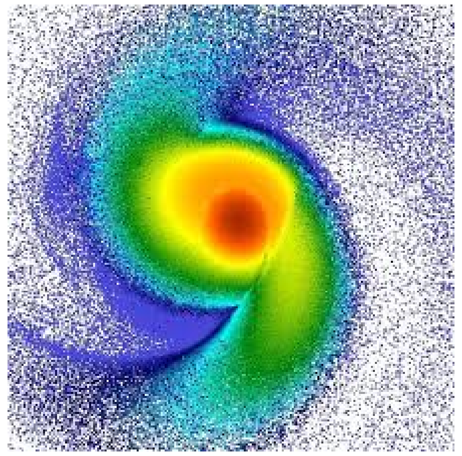


or with particles or a moving mesh (Lagrangian)

+ $\nabla \cdot \mathbf{B} = 0$

+ different initial conditions

What causes simulation results to differ?

Methods question:

Zoo of codes with different schemes

Solved in an adaptively

an)

moving

$+ \nabla \cdot \mathbf{B} = 0$

\+ different initial conditions

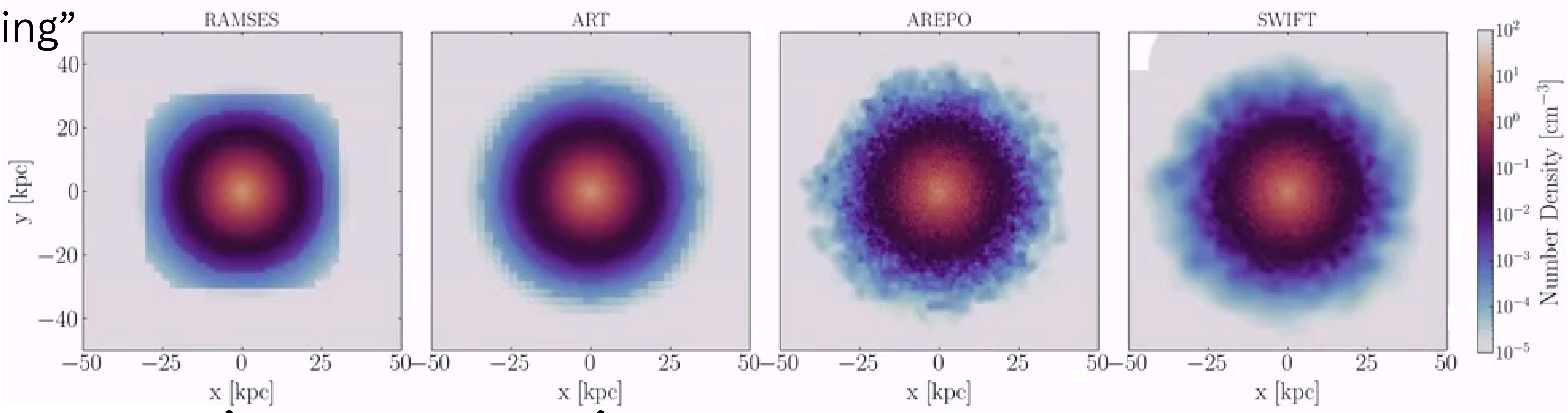
Wang

How sensitive is the magnetic field amplification to the choice of numerical scheme? 🤔

Towards reliable simulations of galactic B-fields

We compare simulation results obtained using **four (4) cosmological simulation codes** with **common initial conditions (Milky Way-like galaxy)**:

Divergence "cleaning" — **CT** — **GLM/Dedner** — **Powell** — **GLM/Dedner**



Discretization — **Grid-based codes** (RAMSES, ART) — **Moving mesh** — **Particle code**

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ART
RAMSES
AREPO
SWIFT

Common ICs

Gas and
AGORA
"Old" stars
Dark matter
Uniform *B*

→

AGORA-like comparison

Simulations without magnetic fields, with/out star formation and feedback

(HD control)

Dynamo comparison 1

Simulations with magnetic fields but without star formation and feedback

(MHD control)

Dynamo comparison 2

Simulations with full physics

(SF+FB suite)

+ comparable cooling, same SF
+ similar supernova feedback presc.

at different effective resolutions of up to ~20 pc scales...

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- **In the kinematic phase (linear regime), magnetic energy growth is quadratic in time (Dubois & Teyssier 2010)**

$$\tau = (q\Omega)^{-1}$$

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- **AGORA LOW ($dx = 80$ pc)**

AGORA-like comparison

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Note:

- **No feedback, driven by shear/MRI,** $\tau = (q\Omega)^{-1}$
- **AGORA LOW (**$dx = 80$ pc**)**
- **Similar cooling prescriptions across all codes + pressure floor to support disk in the absence of feedback**

Dynamo comparison 1

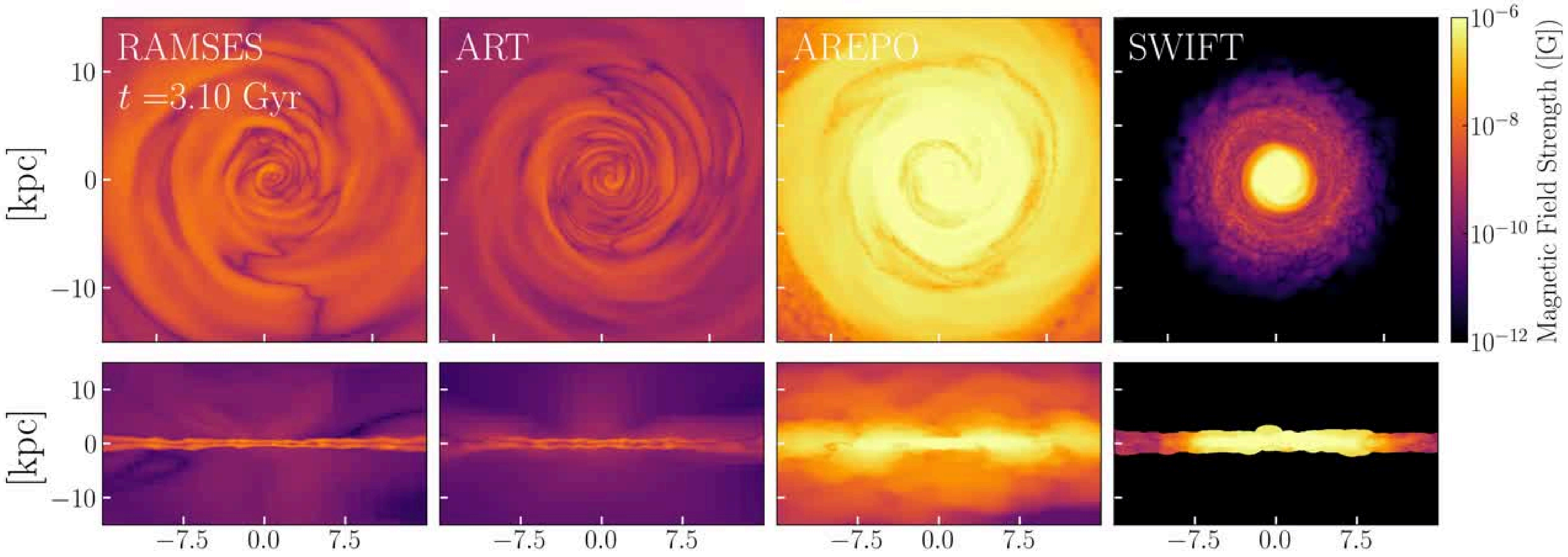
Simulations with magnetic fields but without star formation and feedback

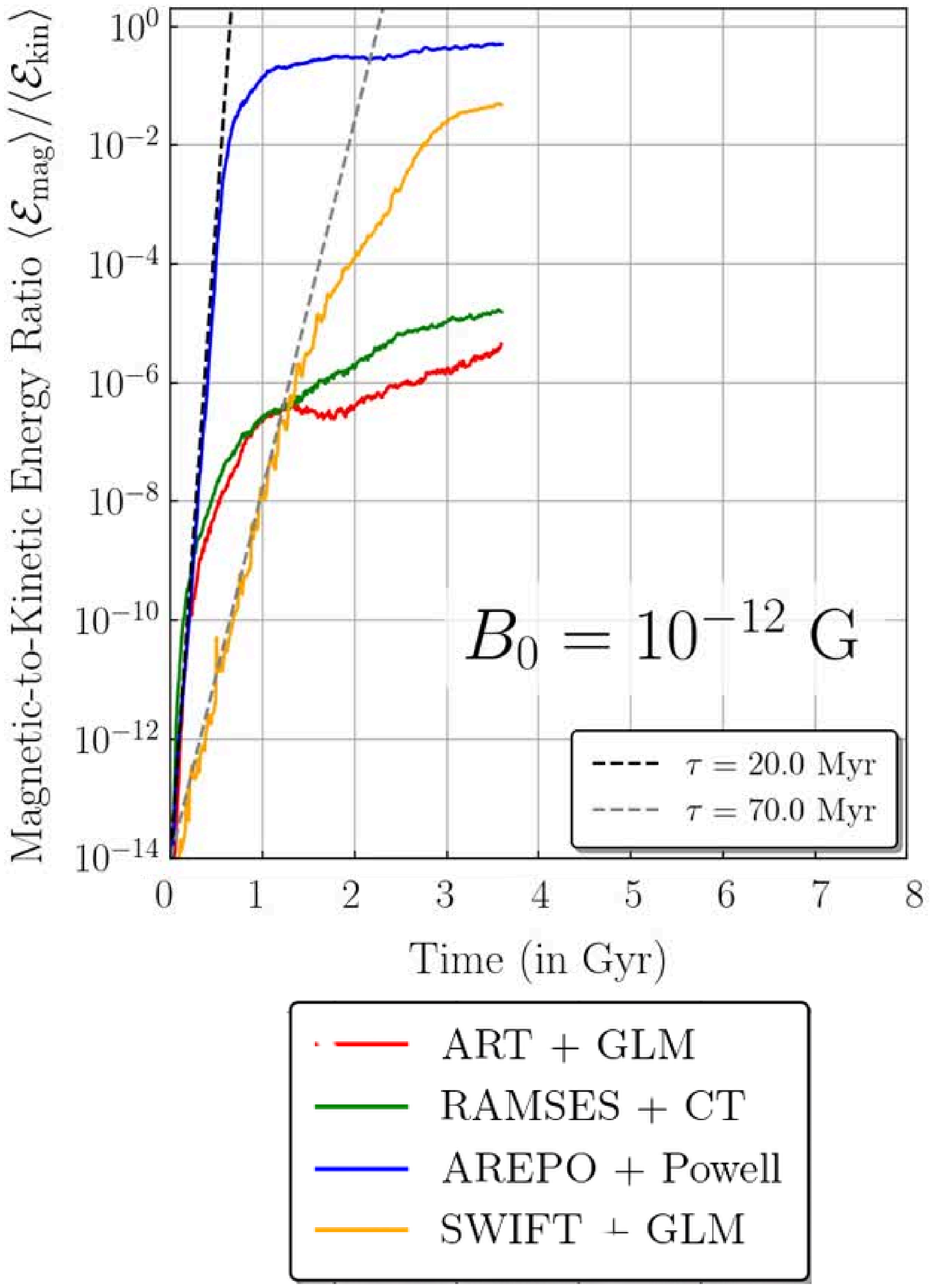
(MHD control)

Results: Midplane slices, equipartition

PRELIMINARY

Ugalino et al (*in prep*)





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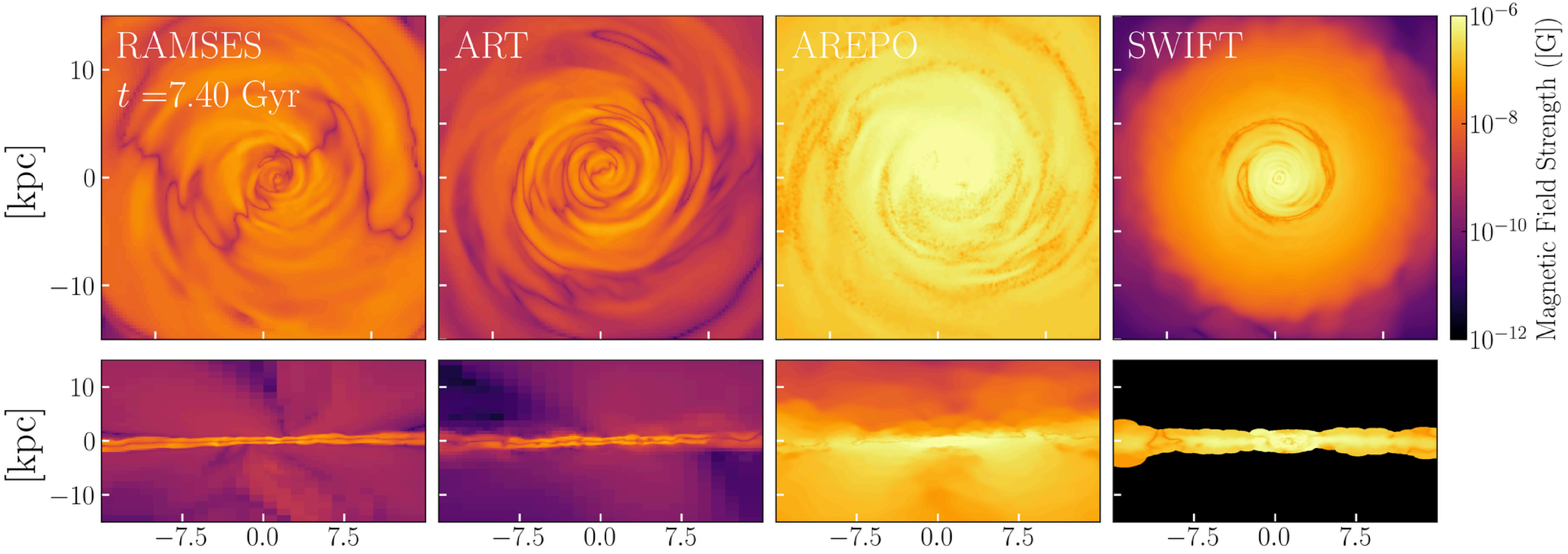
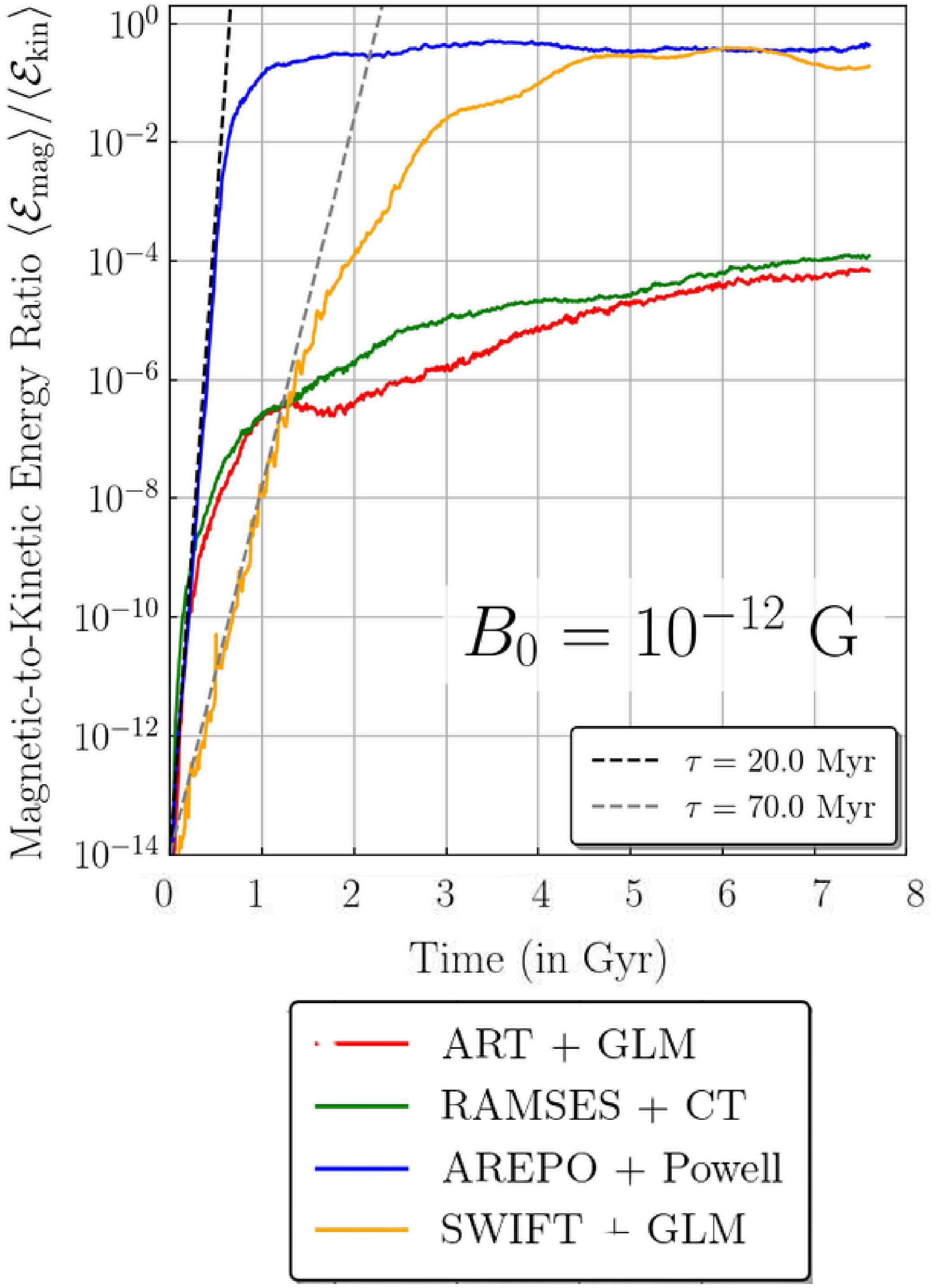
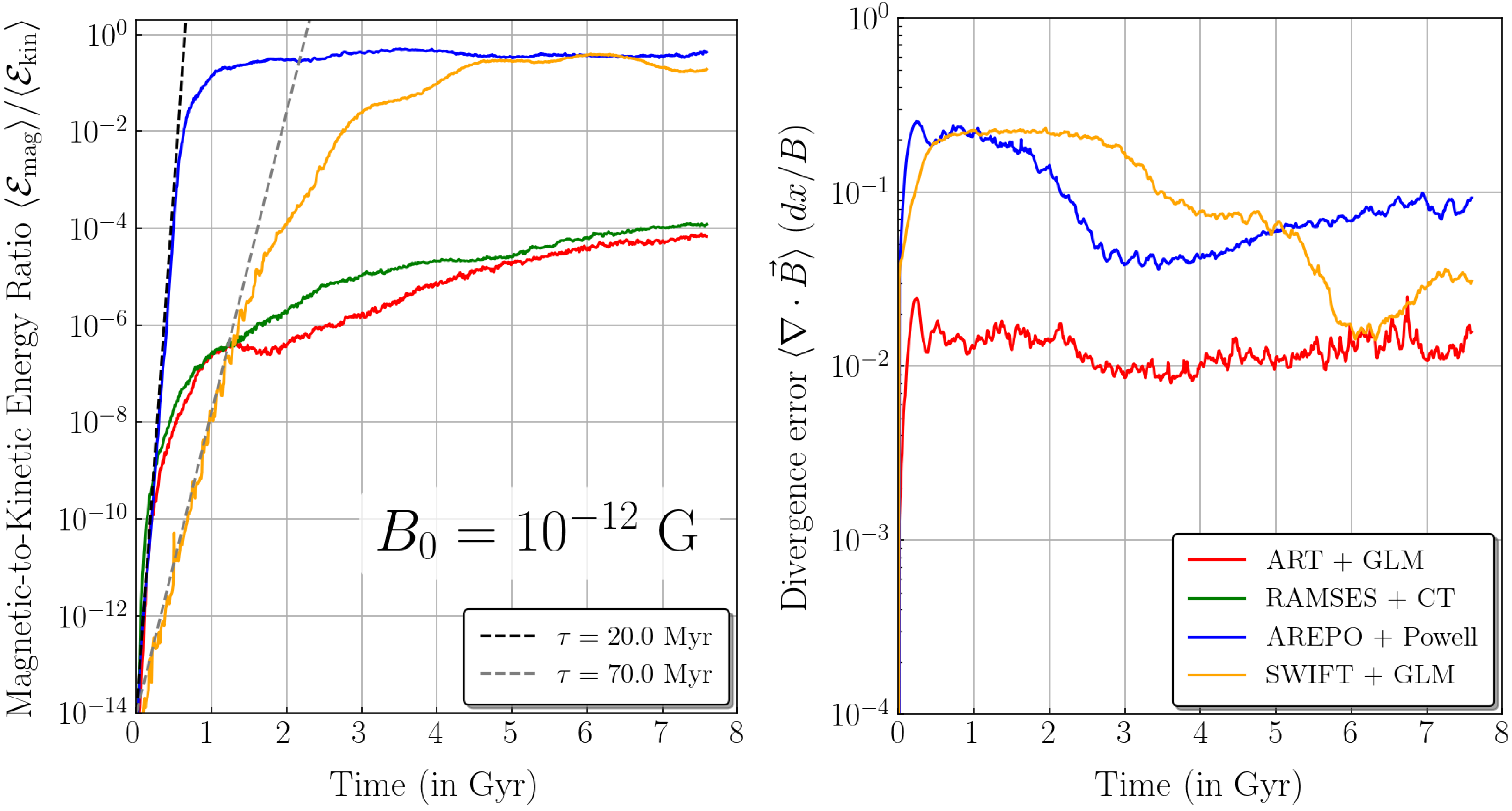




Additional notes from Mark: All of these simulations are of isolated disks with initial conditions similar to AGORA. Magnetic fields are initially uniform and is pointing along the z-direction. Hence, seeds for magnetic field growth along radial and azimuthal directions are generated a few timesteps into the simulations.

PRELIMINARY

Results: Evolution of volume-averaged B energy and div(B)



Ugalino et al (*in prep*)

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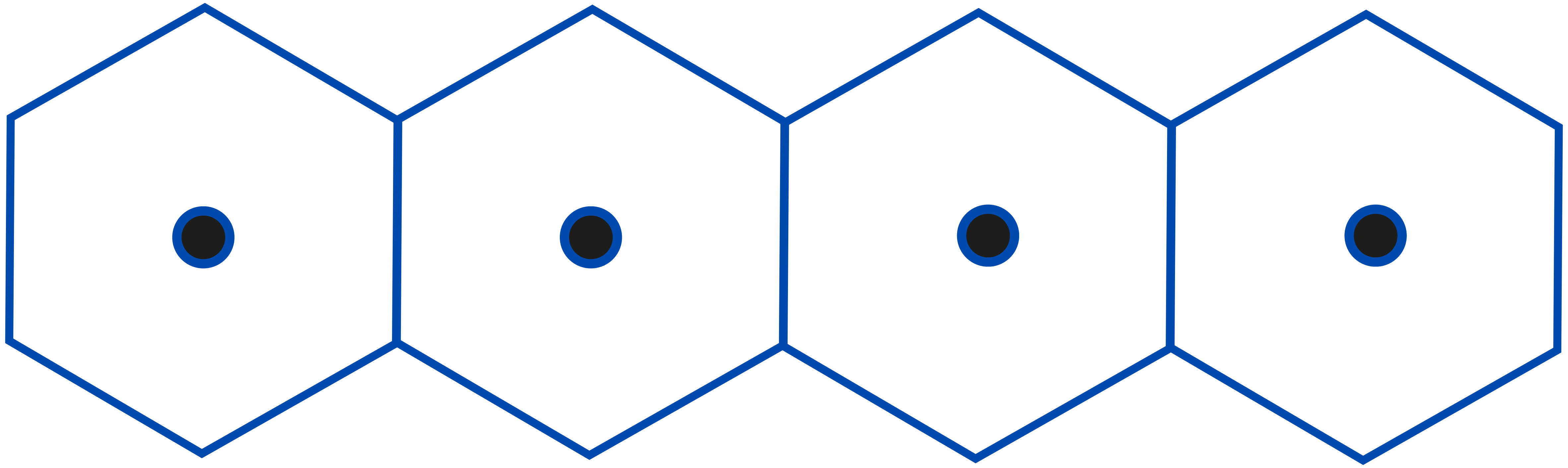

$$u_{\mathrm{mesh}} = u_{\mathrm{gas}}$$

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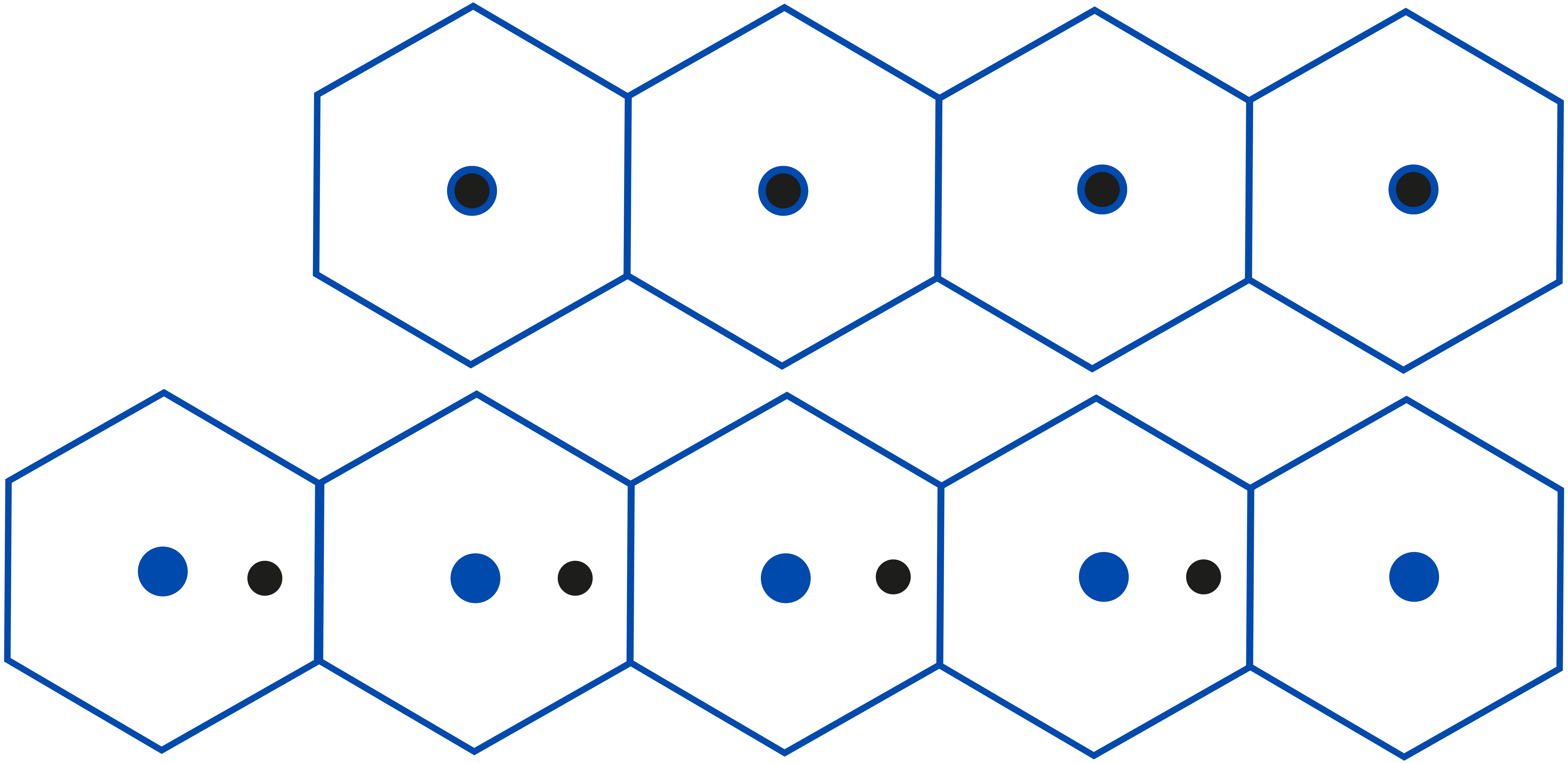

$$u_{\mathrm{mesh}} = u_{\mathrm{gas}}$$

$$u_{\mathrm{mesh}} = \alpha u_{\mathrm{gas}}$$
$$(\alpha < 1)$$

Results: What if we slow down the Arepo mesh?

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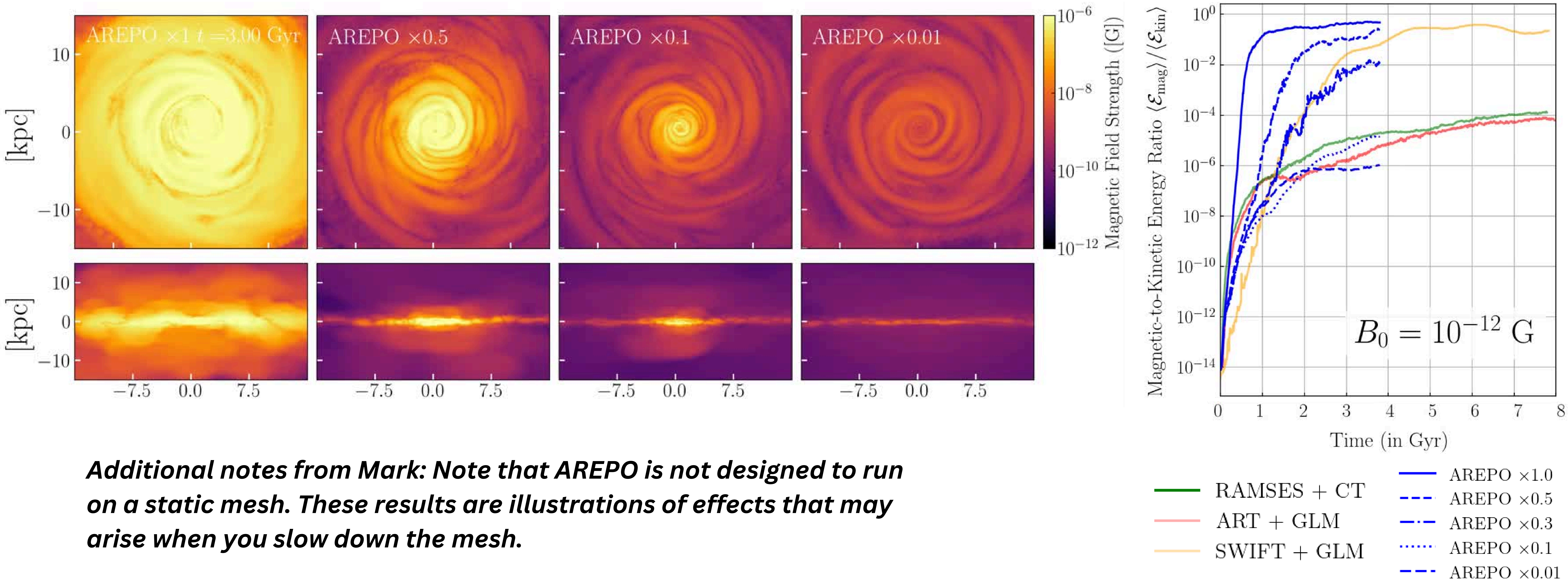
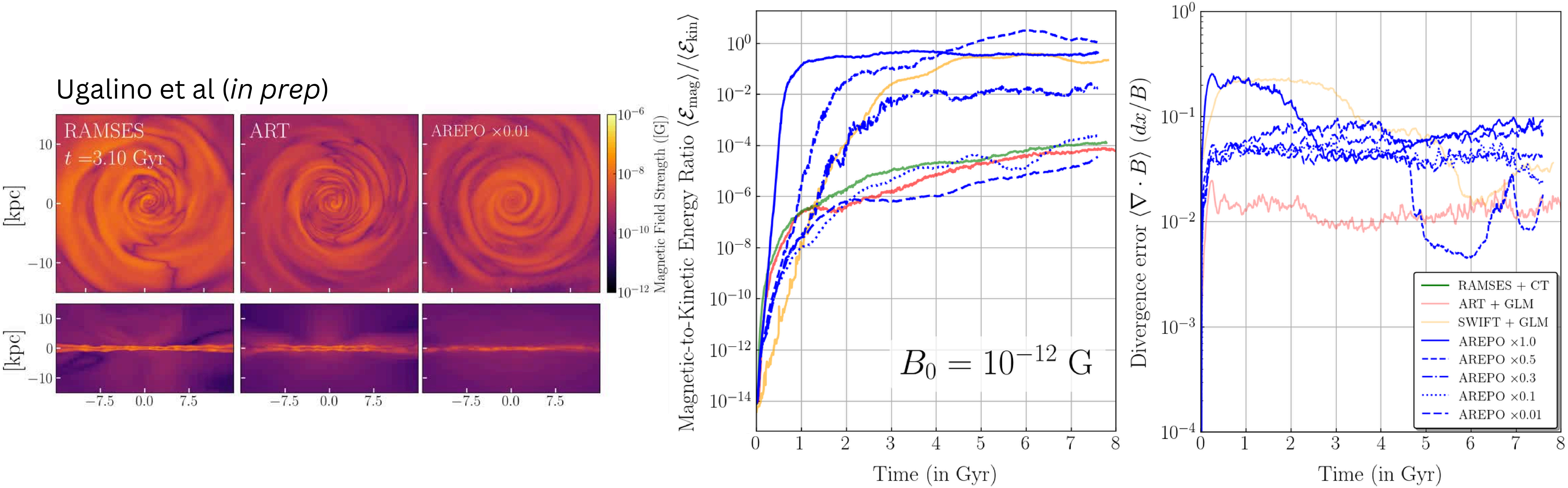


Additional notes from Mark: Note that AREPO is not designed to run on a static mesh. These results are illustrations of effects that may arise when you slow down the mesh.

Results: What if we slow down the Arepo mesh?

Ugalino et al (*in prep*)



Additional notes from Mark: Note that AREPO is not designed to run on a static mesh. These results are illustrations of effects that may arise when you slow down the mesh.

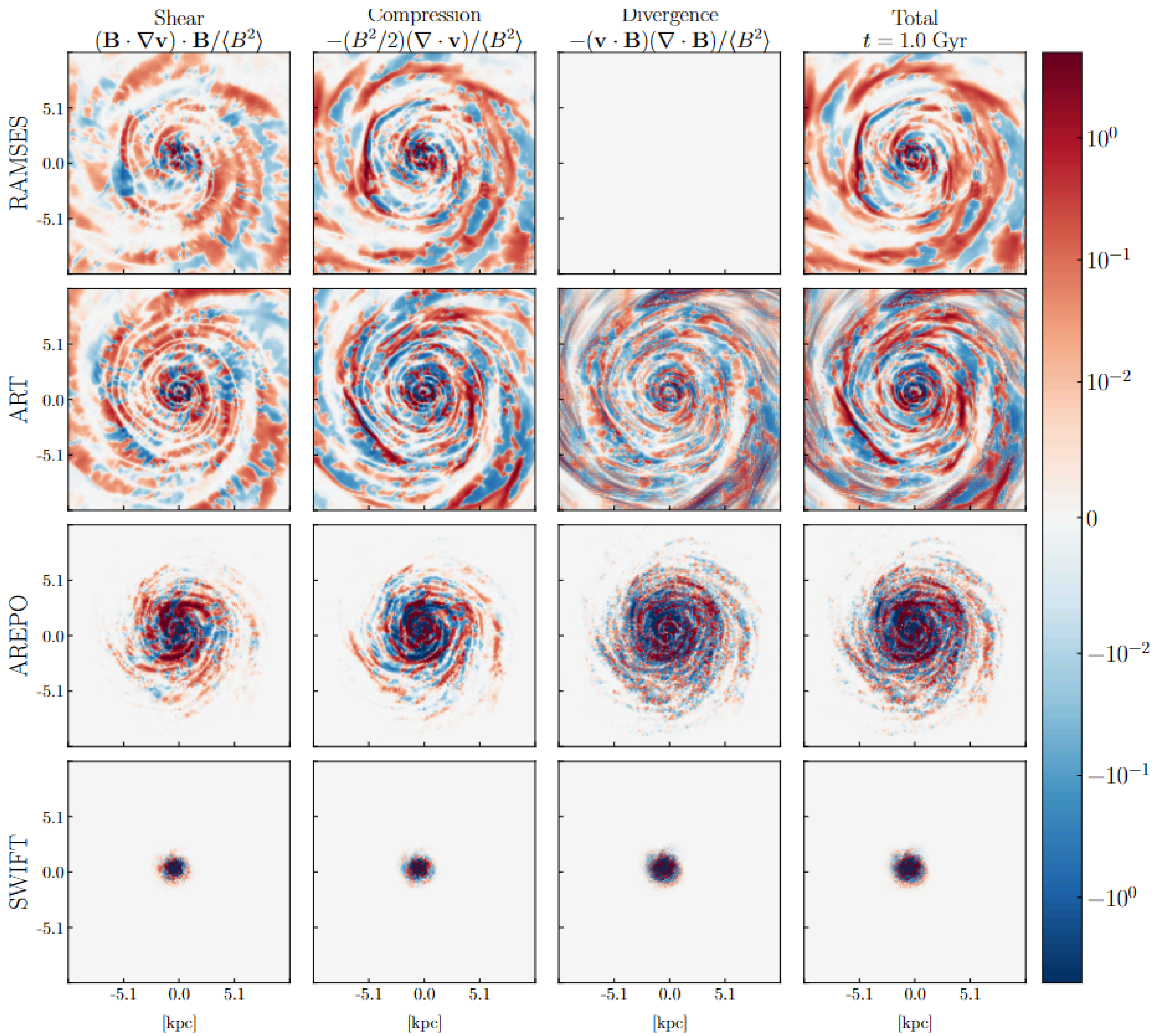
Results: What's causing the growth?

$$\frac{\mathrm{D}}{\mathrm{D}t}\left(\frac{B^2}{2}\right) = \underbrace{-\frac{B^2}{2}(\nabla \cdot \mathbf{u})}_{\text{compression}} + \underbrace{\mathbf{B} \cdot (\mathbf{B} \cdot \nabla \mathbf{u})}_{\text{shear}} \underbrace{-(\mathbf{u} \cdot \mathbf{B})(\nabla \cdot \mathbf{B})}_{\text{spurious divergence}}$$

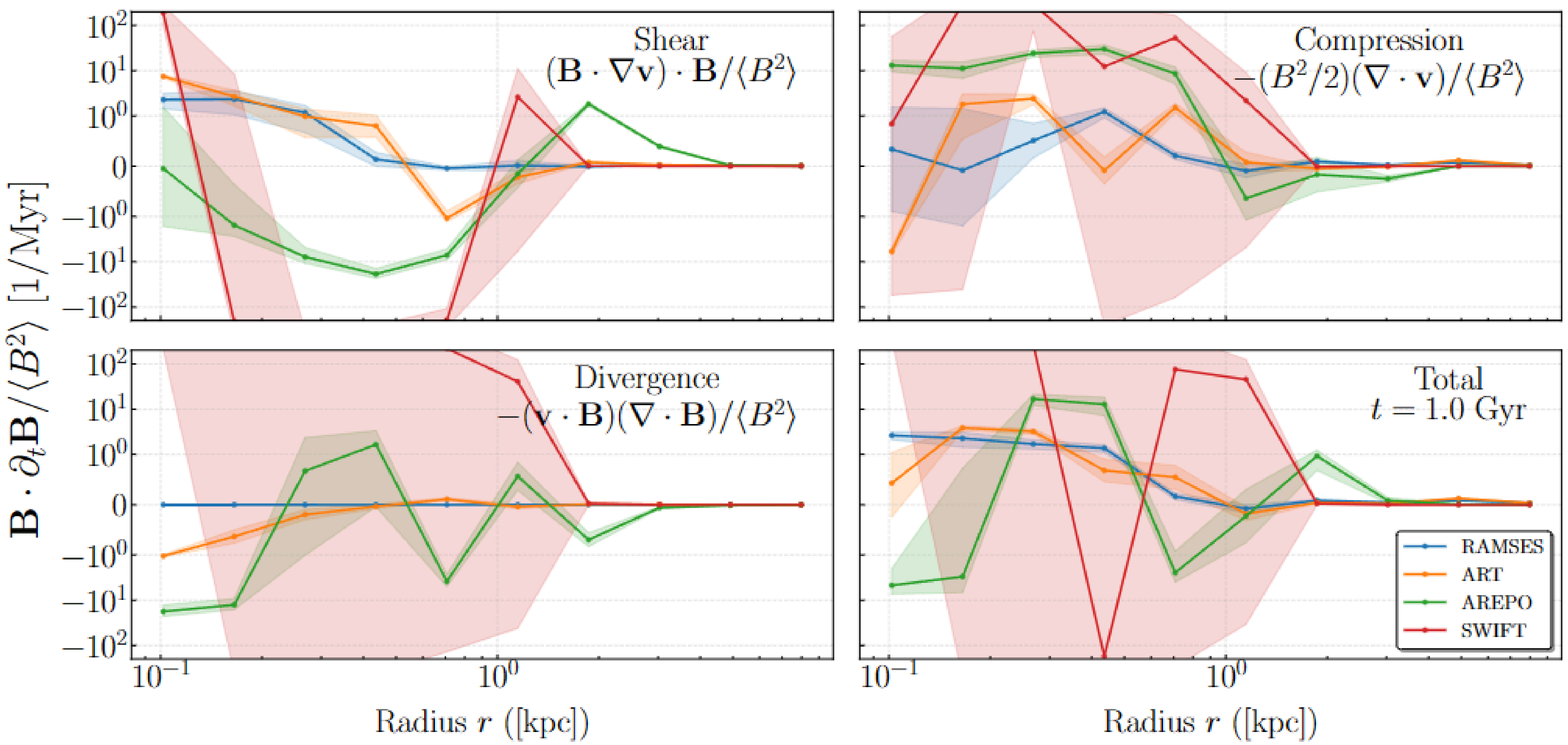
Additional notes from Mark: While it is a great metric, dimensionless divergence errors alone do not provide the entire picture for field growth. One should compare the divergence term above to physical drivers of growth like compression and shear!

PRELIMINARY

Results: What's causing the growth?



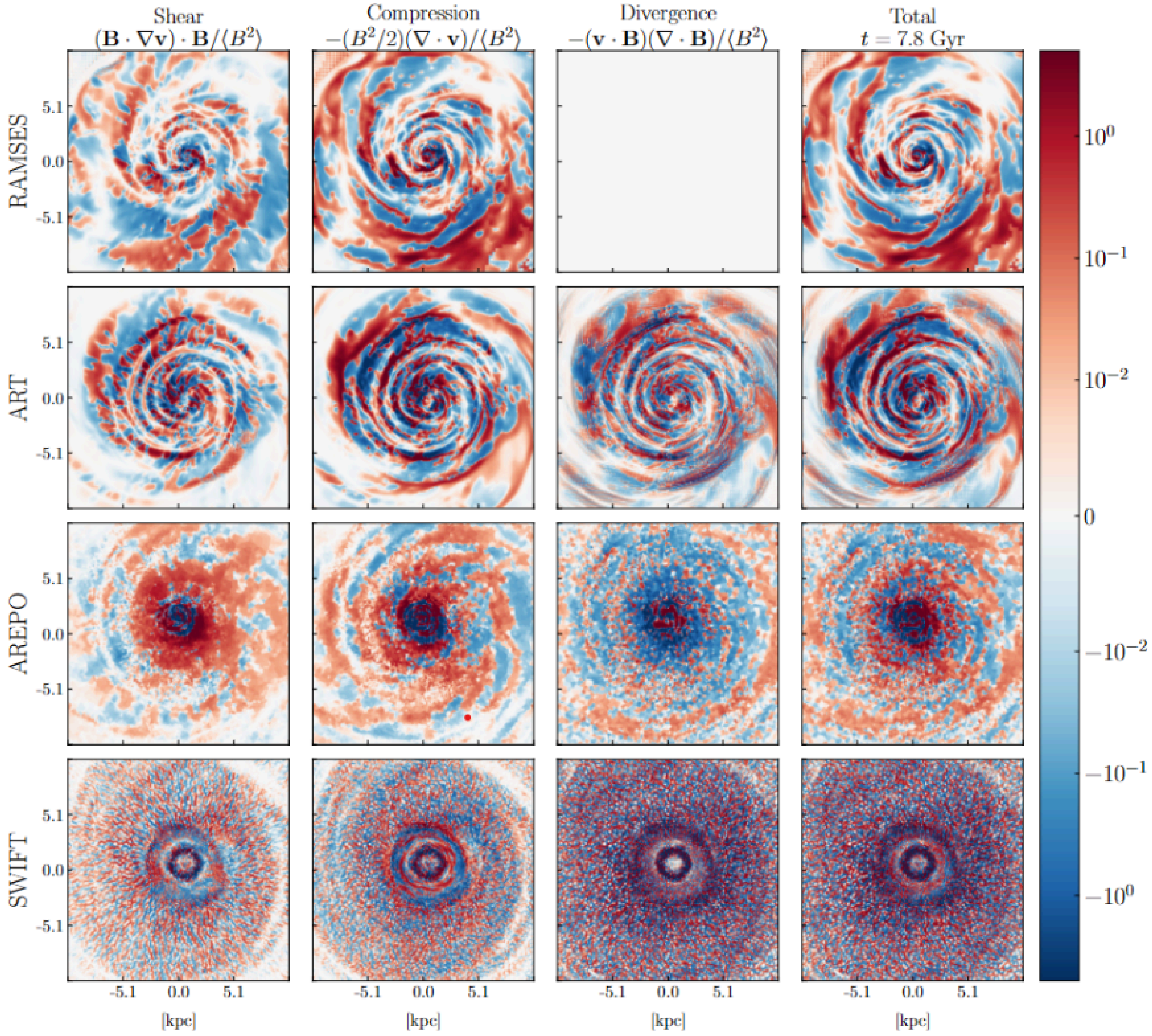
Energy growth rate at $t = 1.0$ Gyr



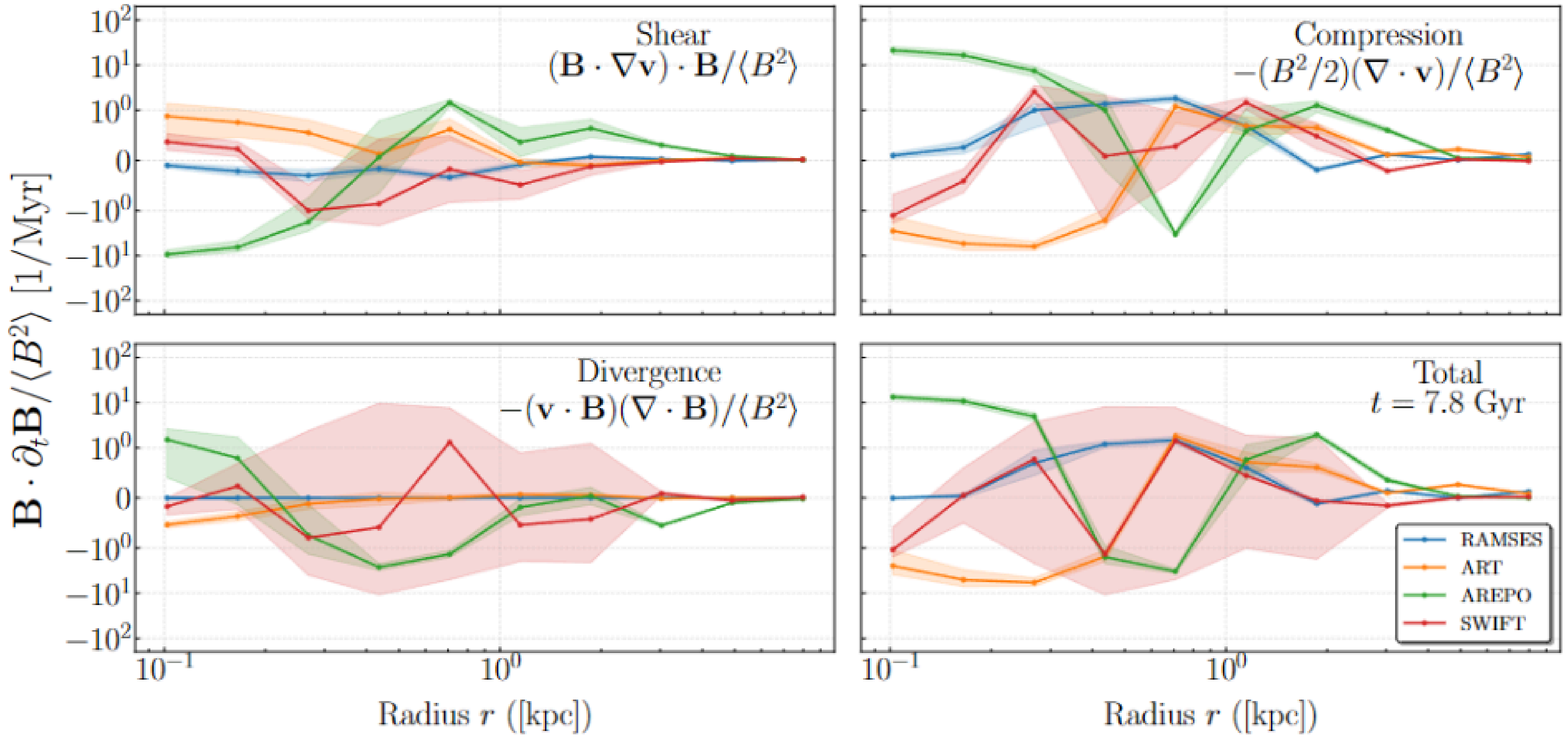
Red curves show a very noisy measurement due to the fact that we are computing gradients on a uniform grid for SPH data (currently working on a fix)

PRELIMINARY

Results: What's causing the growth?



Energy growth rate at $t = 7.8\ \mathrm{Gyr}$



Red curves show a very noisy measurement due to the fact that we are computing gradients on a uniform grid for SPH data (currently working on a fix)

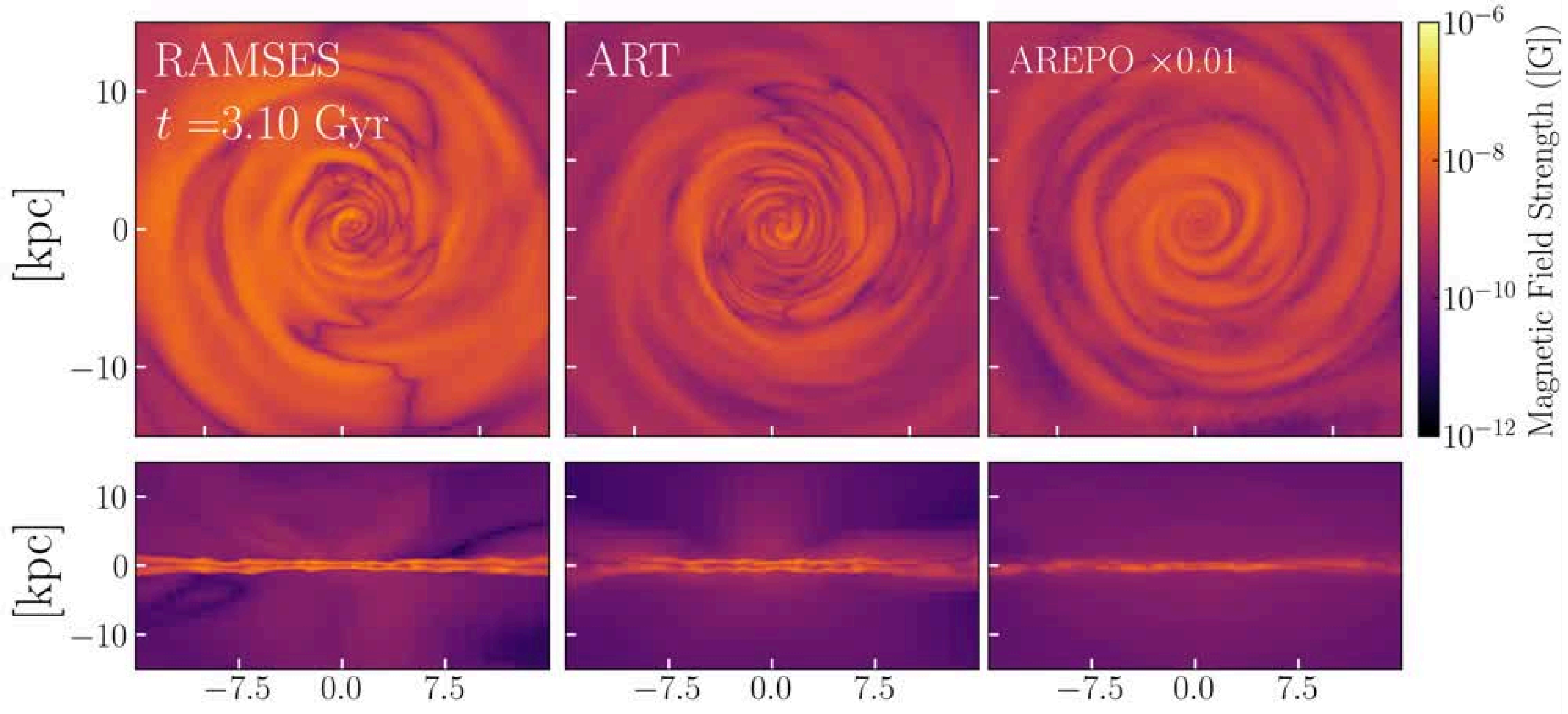
PRELIMINARY

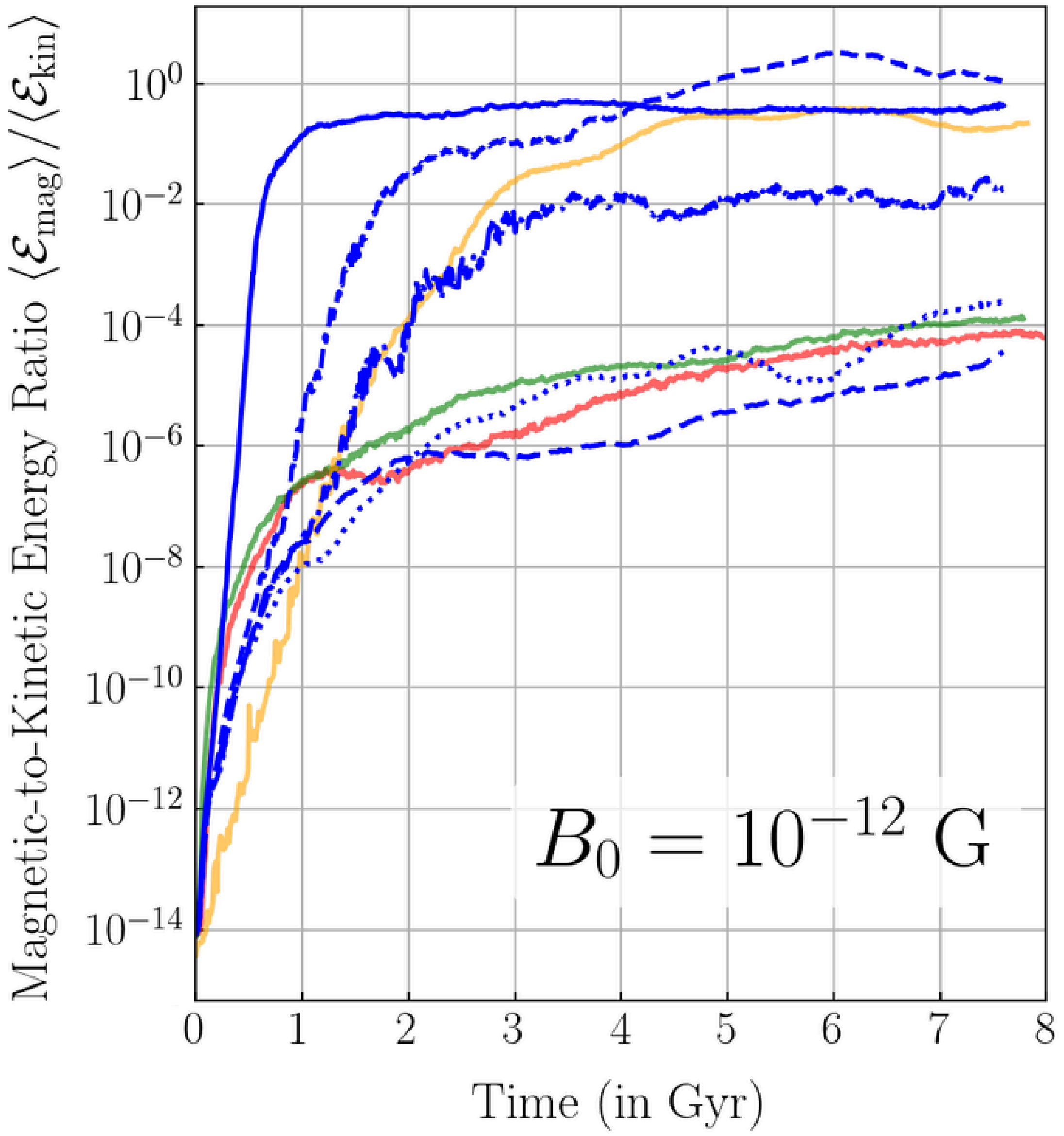
Investigating the numerical dependencies of the galactic dynamo

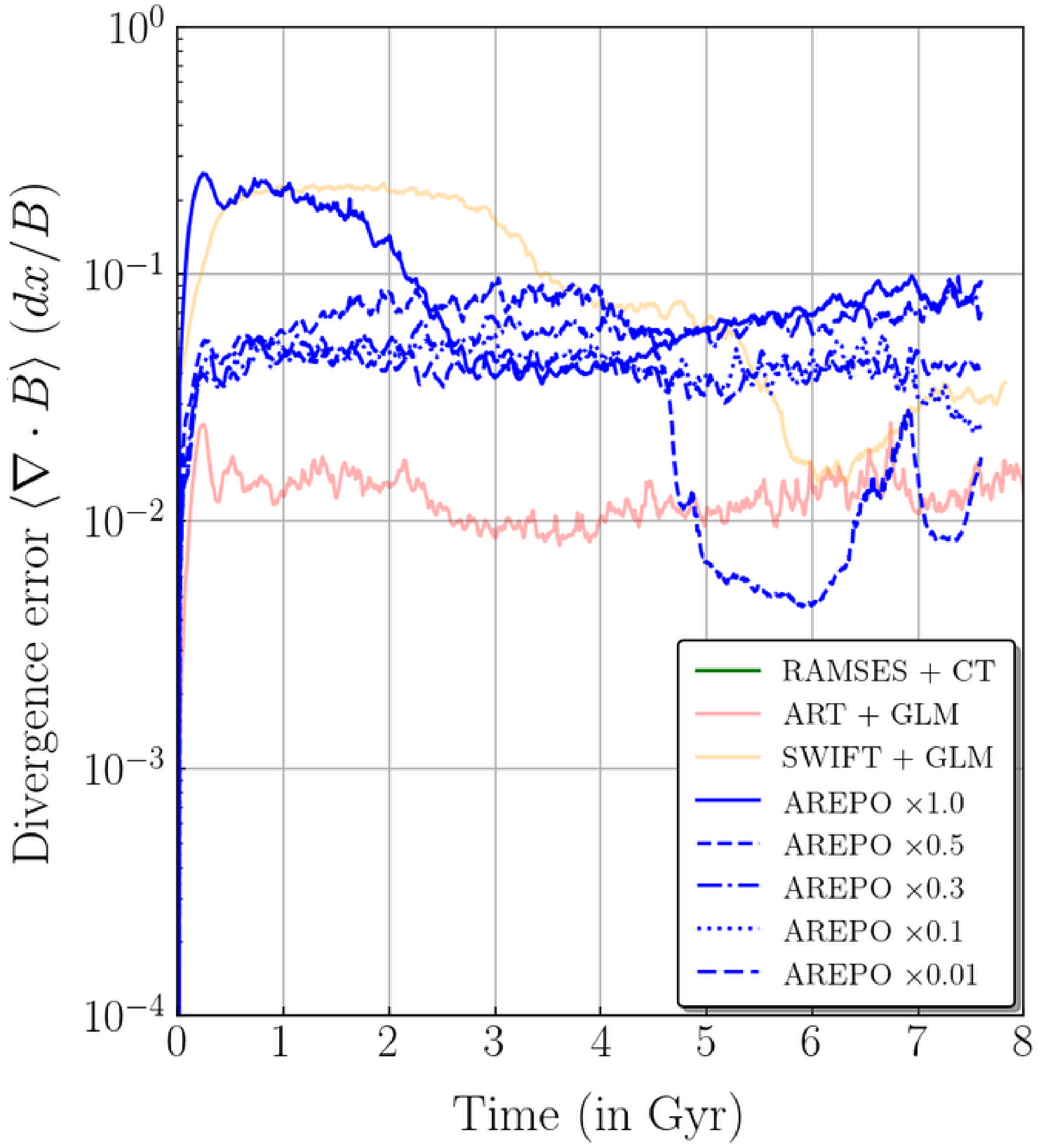
Mark I.G. Ugalino (ugalino@umd.edu)

RAMSES User Meeting 2026

Ugalino et al (*in prep*)







Watch out for our paper Summer or Fall 2026!