The impact of magnetic fields on cosmological galaxy mergers

A tale of magnetohydrodynamics and galactic dynamics

Based on work by
Joe Whittingham, Martin Sparre, Christoph Pfrommer, Rüdiger Pakmor (2021, 2023)

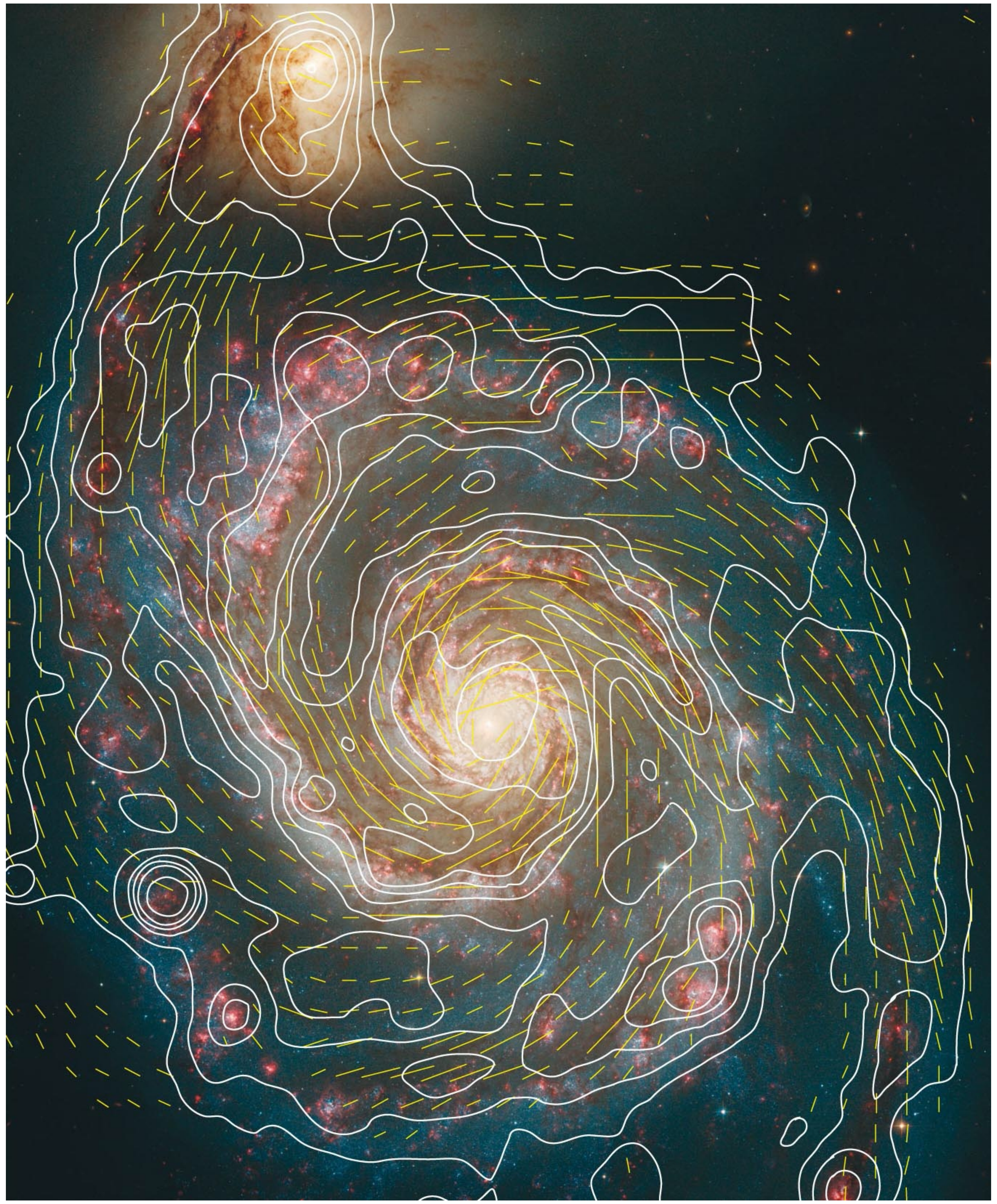
Christoph Pfrommer / IAS Astro Coffee / Feb 22, 2023

Motivation for this work

Magnetic fields exist on all scales (incl. galactic!)

Know this from:

- Zeemann splitting
- Stellar light /dust polarisation
- Faraday rotation
- Synchrotron radiation
  (needed for FIR-radio correlation!)



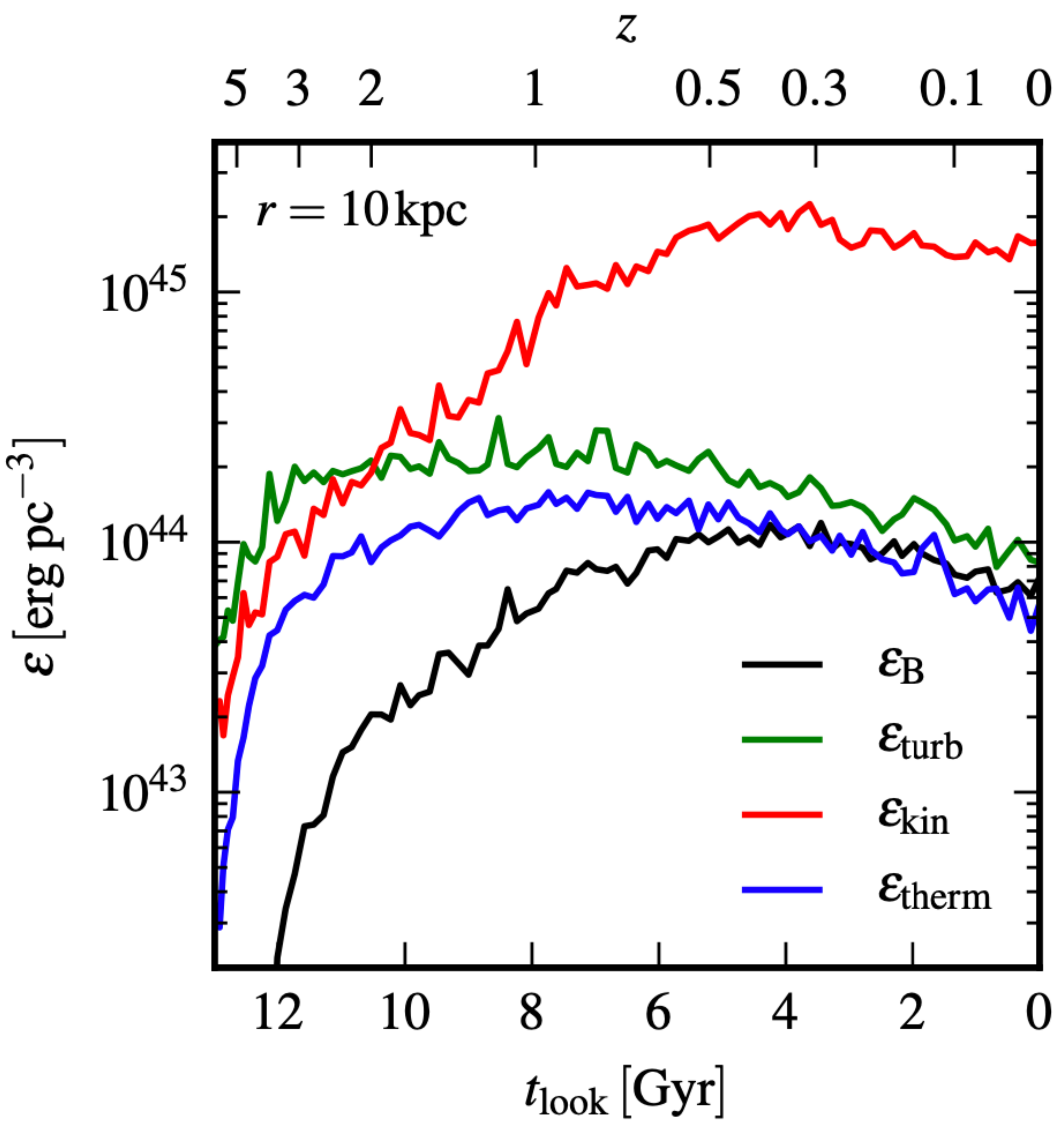
Synchrotron emission in M51 *Credit: Fletcher and Beck*

Are magnetic fields important for galaxy evolution?

Magnetic fields appear to be important in disc galaxies today:

$$p = p_{\mathrm{th}} + \underbrace{(p_{\mathrm{turb}} + p_{\mathrm{mag}} + p_{\mathrm{CR}} + p_{\mathrm{dyn}})}_{\text{approximately in equipartition}}$$

Are they important for galaxy *evolution*?

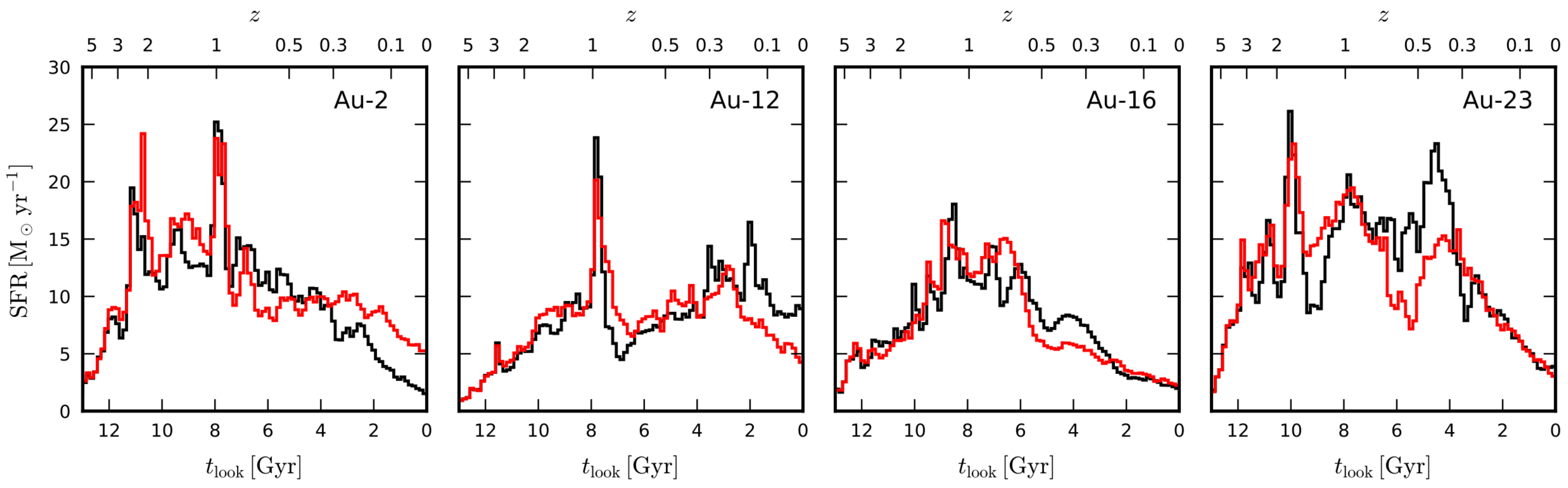


Credit: Pakmor+, 2017

Are magnetic fields important for galaxy evolution?

Previous work uncertain:

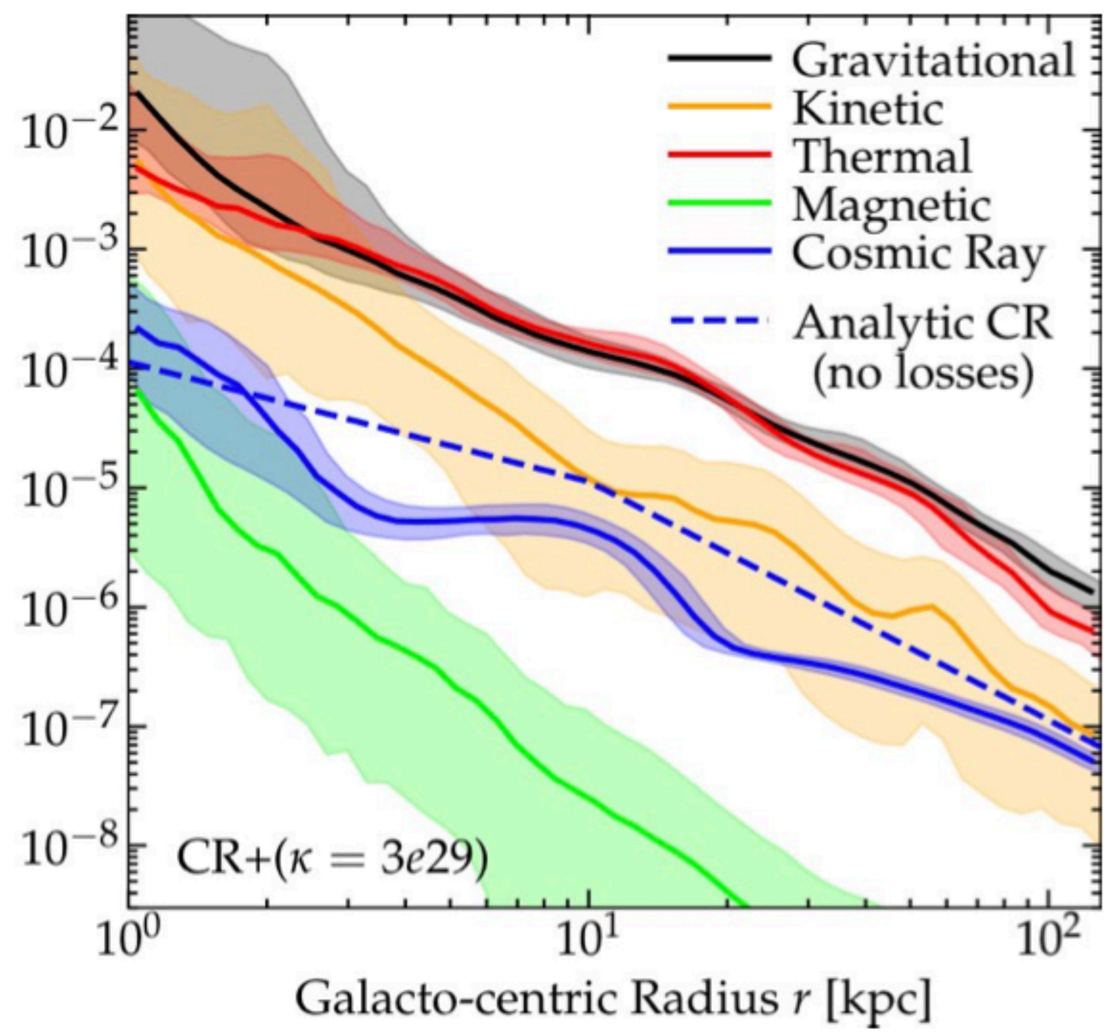
- Auriga: SFH unaffected
- FIRE: magnetic field doesn't reach equipartition



Credit: Pakmor+, 2017

… but if we increase the seed-field strength to (unphysically) large values

- suppress SFRs *(Marinacci & Vogelsberger, 2016)*
- reduce disc size *(Martin-Alvarez et al. 2020; Katz et al. 2021)*



Credit: Hopkins+, 2020

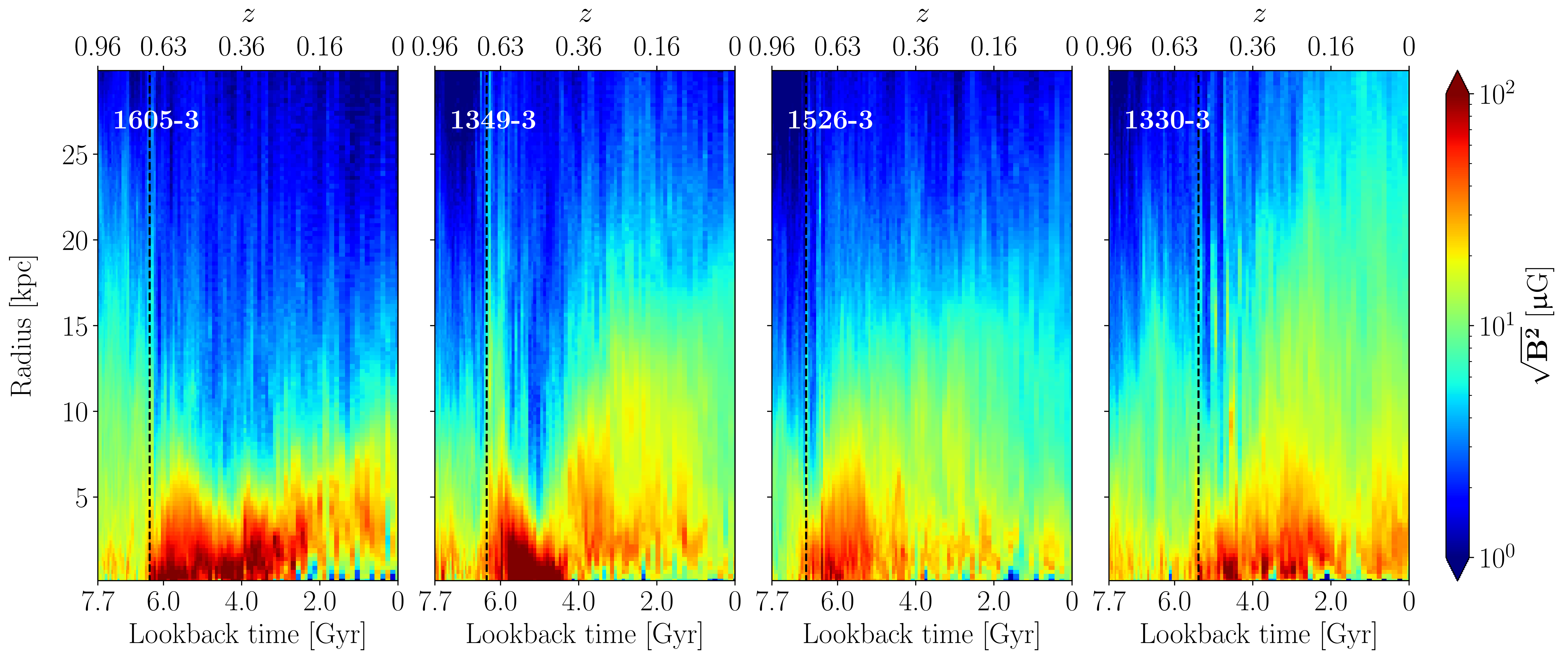
Set-up

Re-simulate mergers selected from Illustris with ***~38.5x*** better resolution

- Major mergers of disc galaxies at z~0.7
- Recover in relative isolation
- Auriga galaxy formation model *(Grand+, 2017)*
- Run with/without MHD from same initial conditions

Magnetic field amplification

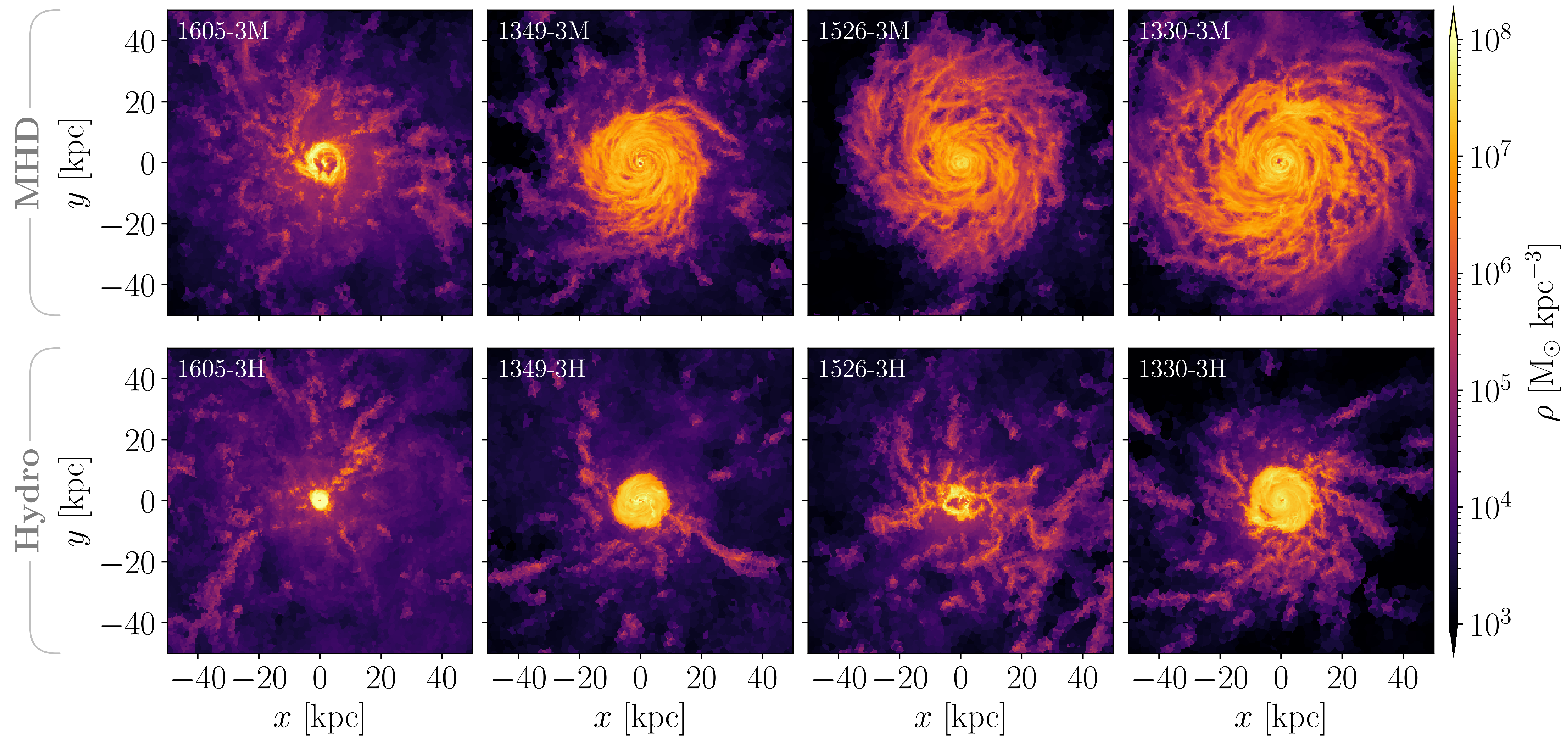
Mergers amplify the magnetic field rapidly



Magnetic field modifies gas disc

Mergers amplify the magnetic field rapidly

Lead to substantial change in morphological features at z=0



Slices through midplane; colours show gas density

Magnetic field modifies stellar disc

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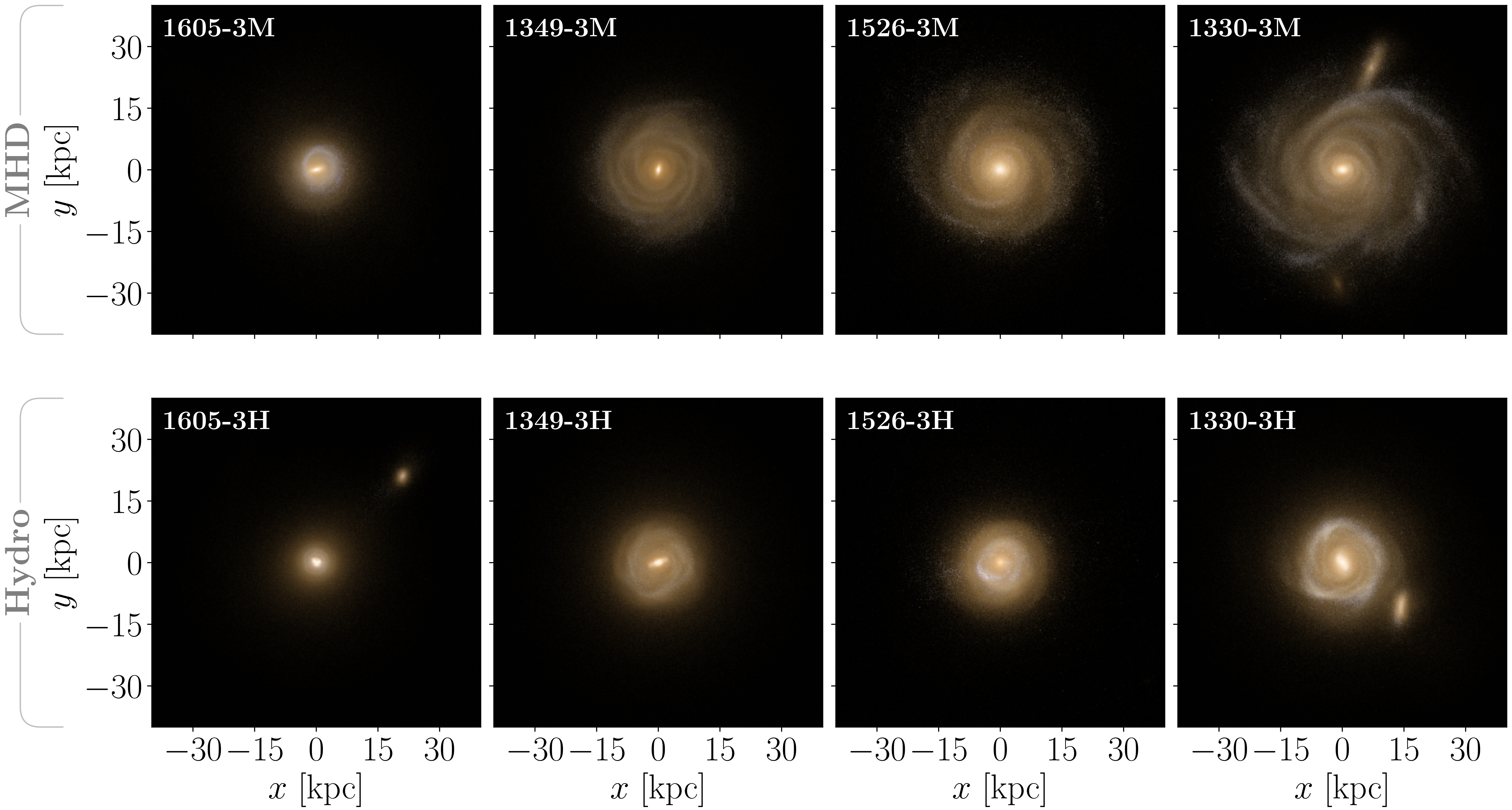
Lead to substantial change in morphological features at z=0



Mock gri visual image from stellar light

Magnetic field modifies stellar disc (Auriga)

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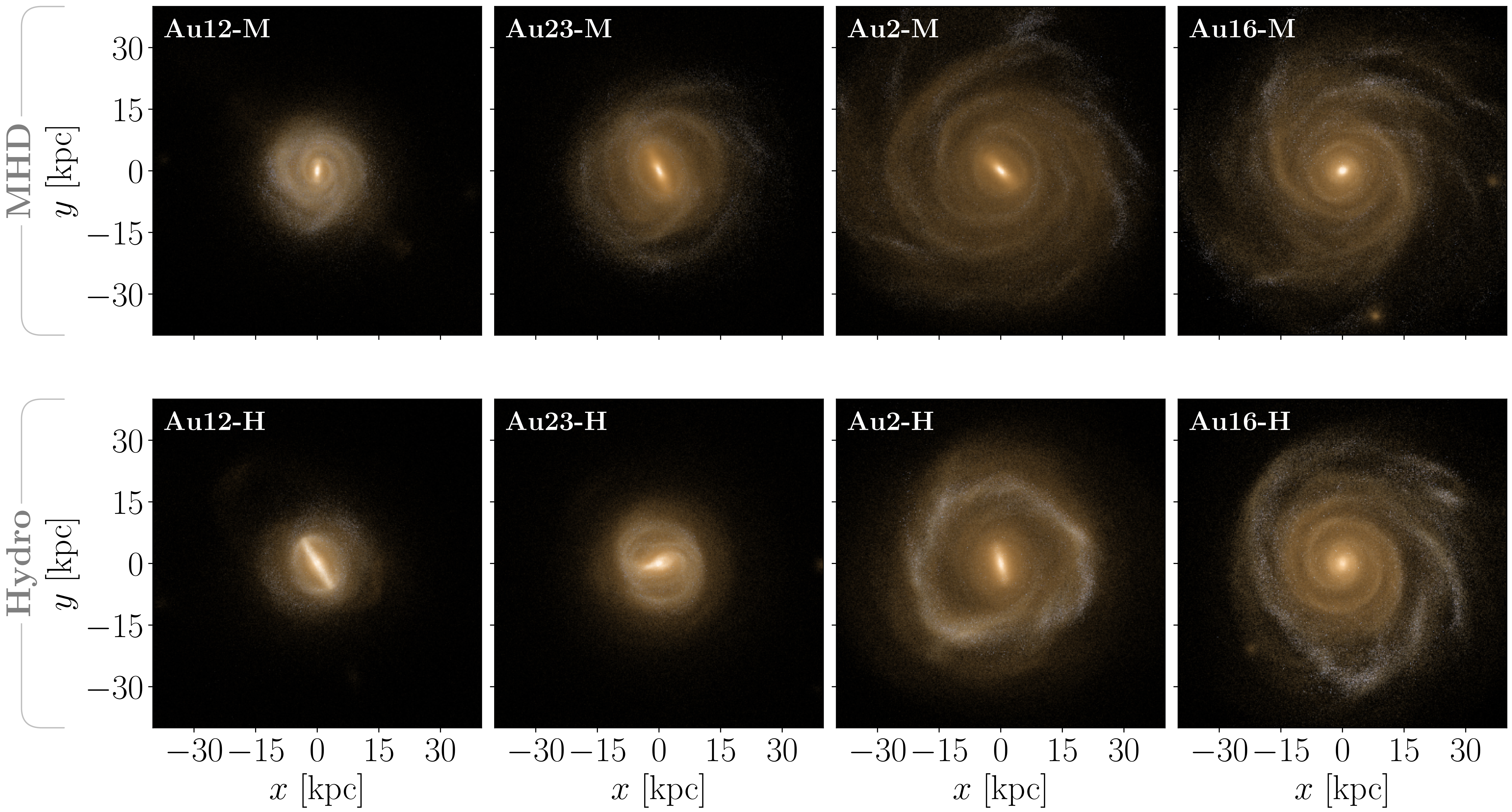
Lead to substantial change in morphological features at z=0

Even for more "isolated" (but still cosmological) galaxies



Mock gri visual image from stellar light

Sufficient resolution is key

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Lead to substantial change in morphological features at z=0

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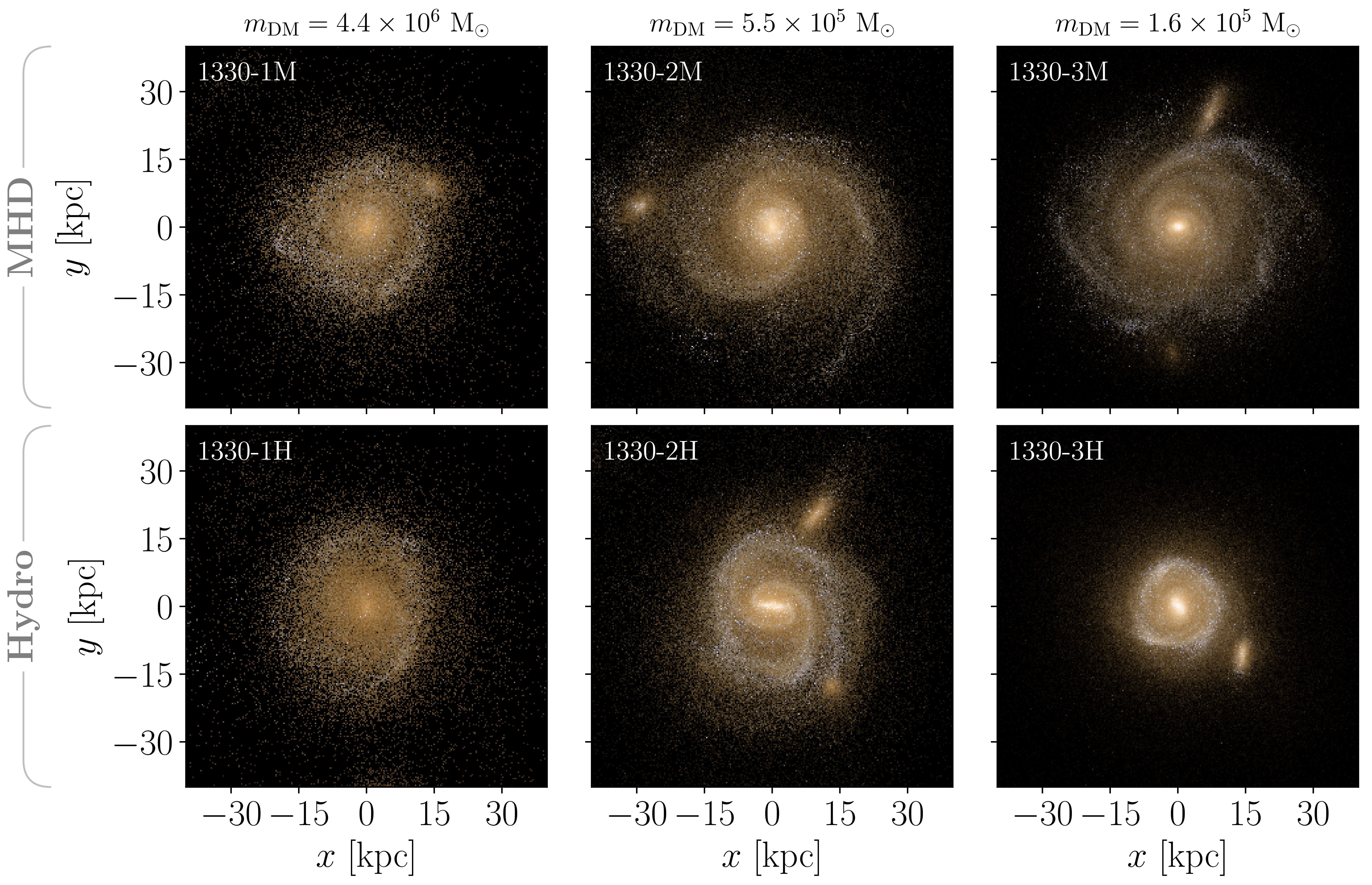
But sufficient resolution is required



Mock gri visual image from stellar light
(resolution becomes finer left to right)

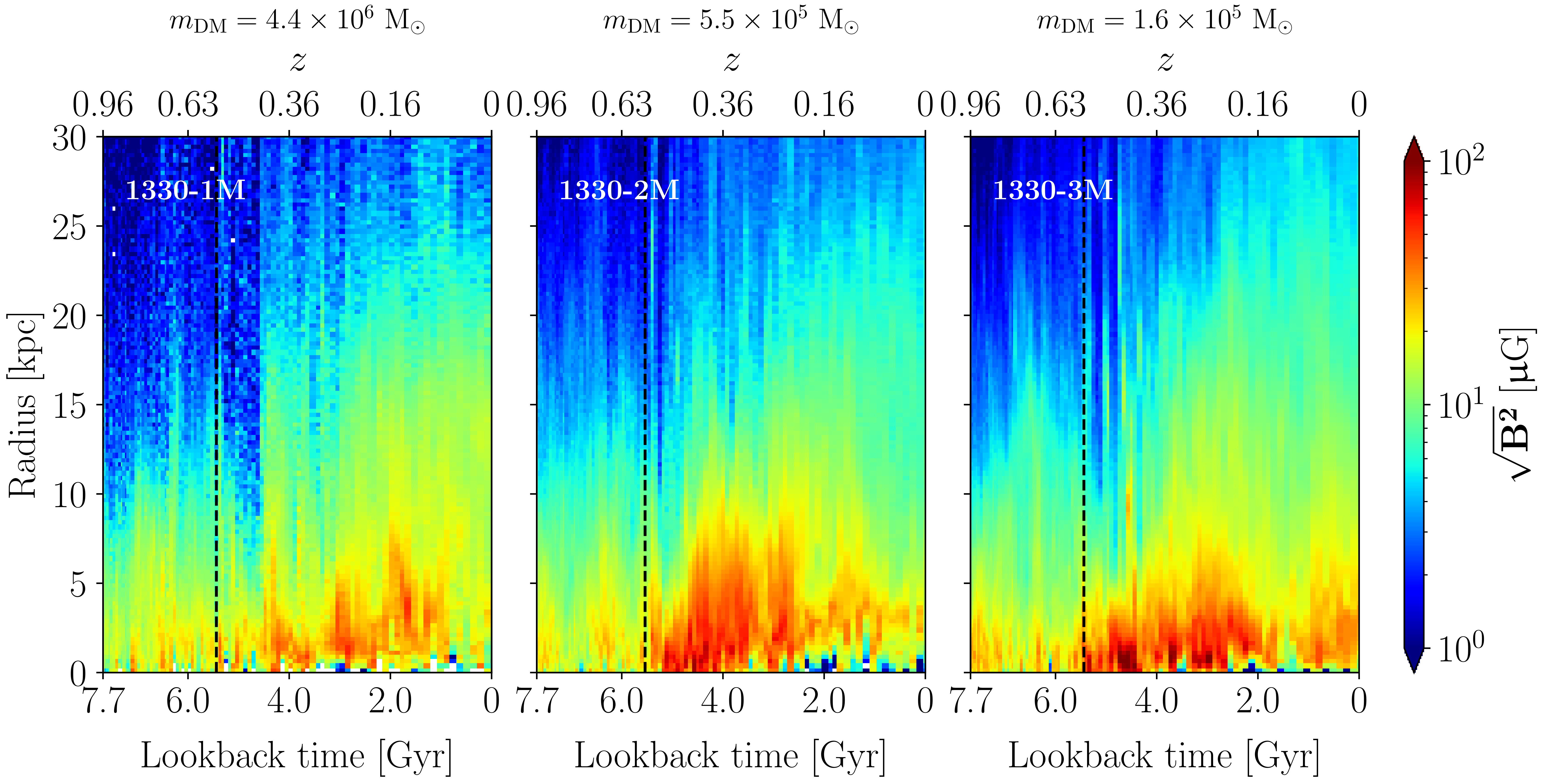
Sufficient resolution is key for magnetic dynamo

Mergers amplify the magnetic field rapidly

Lead to substantial change in morphological features at z=0

Even for more "isolated" (but still cosmological) galaxies

But sufficient resolution is required (must resolve small-scale dynamo!)

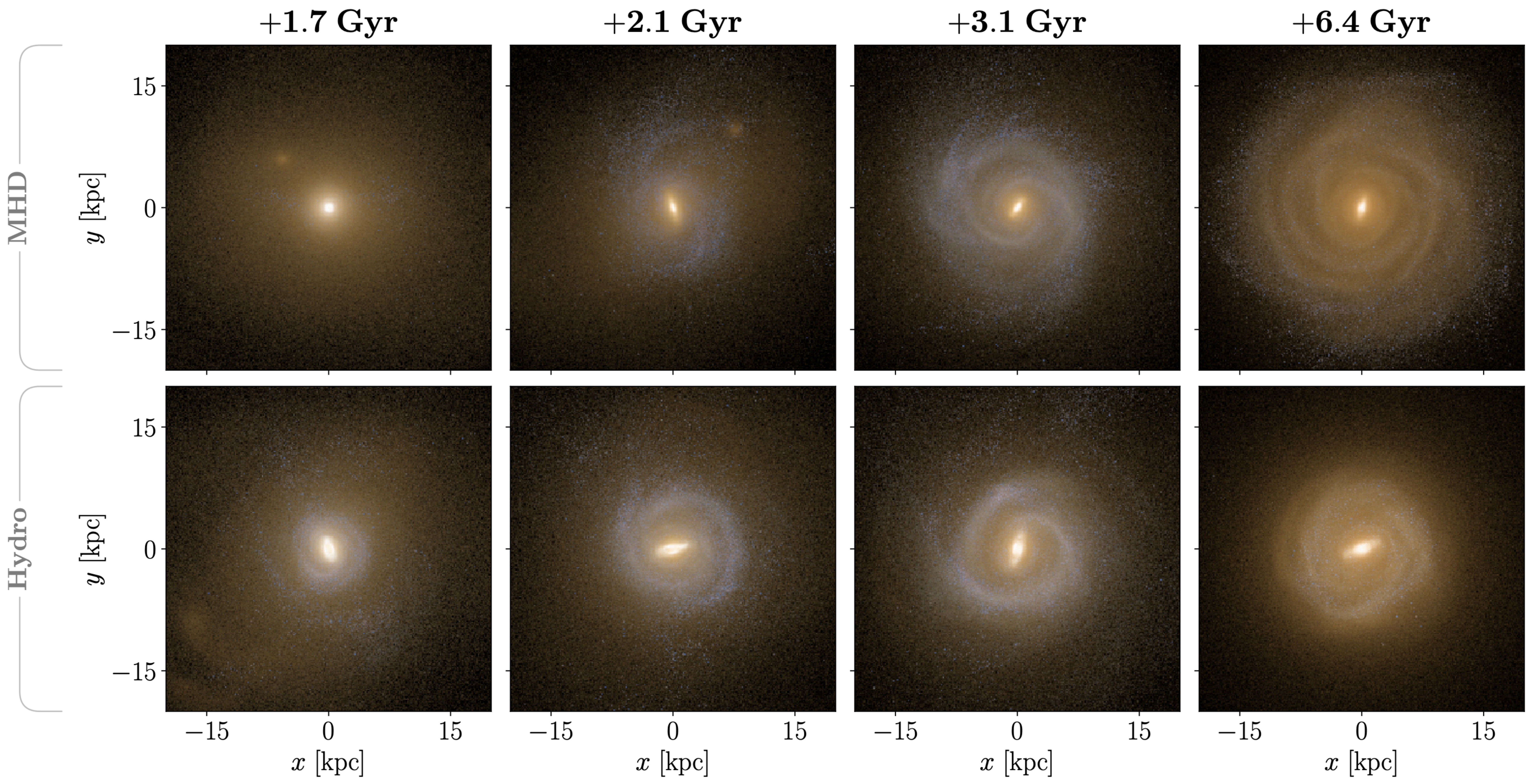


Ok, but *how* do magnetic fields affect the merger?

Case study

Things to notice:

- Stellar distribution initially more compact in MHD
- Hydro produces bar and ring morphology whilst MHD produces spiral arms
- MHD remnant ultimately becomes much larger



Mock gri visual image from stellar light for 1349-3M and 1349-3H

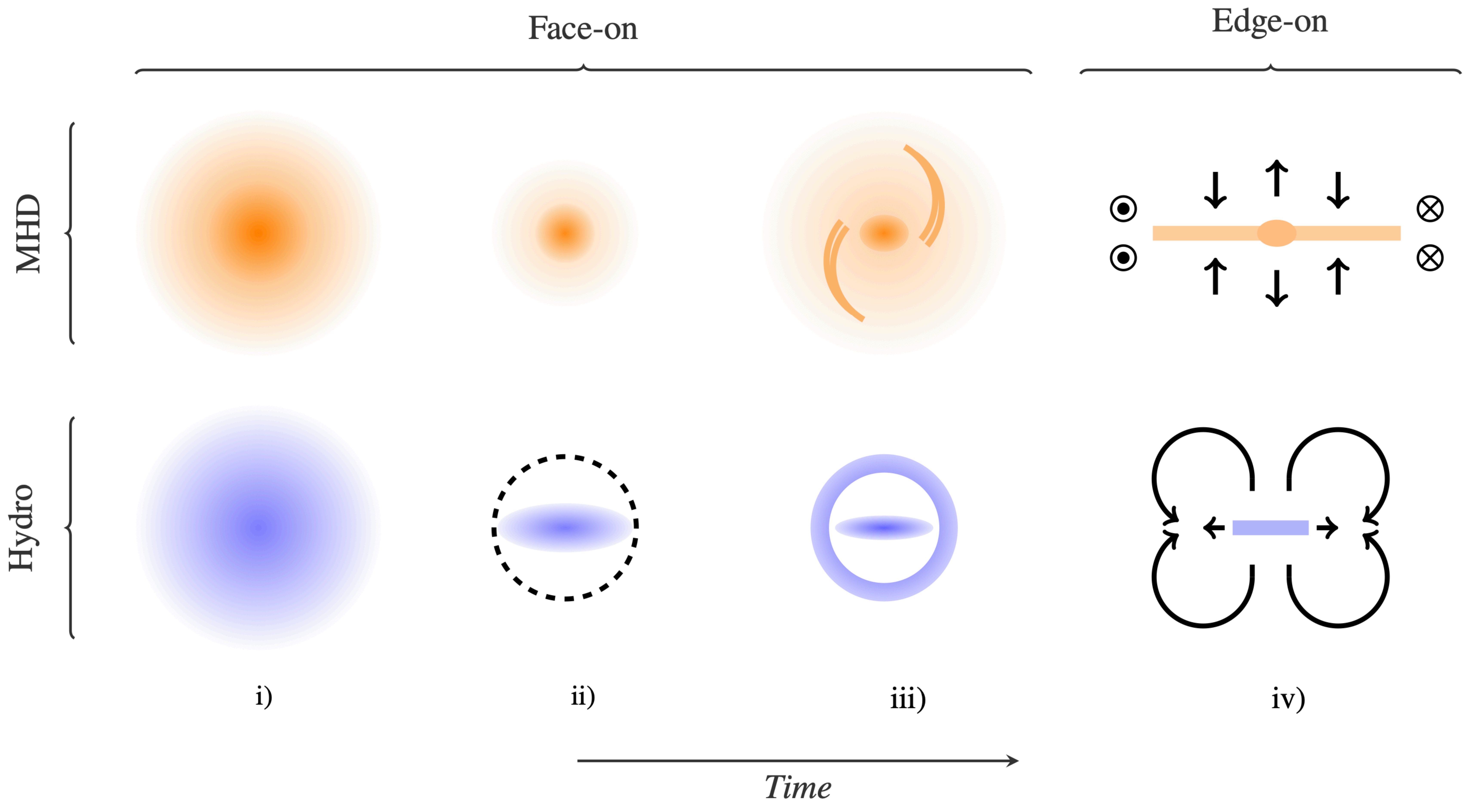
Model

i) Magnetic field changes angular momentum transport *(usually increases baryonic concentration)*

ii) This suppresses a bar instability in MHD case

iii) Bar in hydro case forms rapidly, produces ring structure

iv) More compact star formation in hydro case leads to strong stellar wind (disrupts CGM)

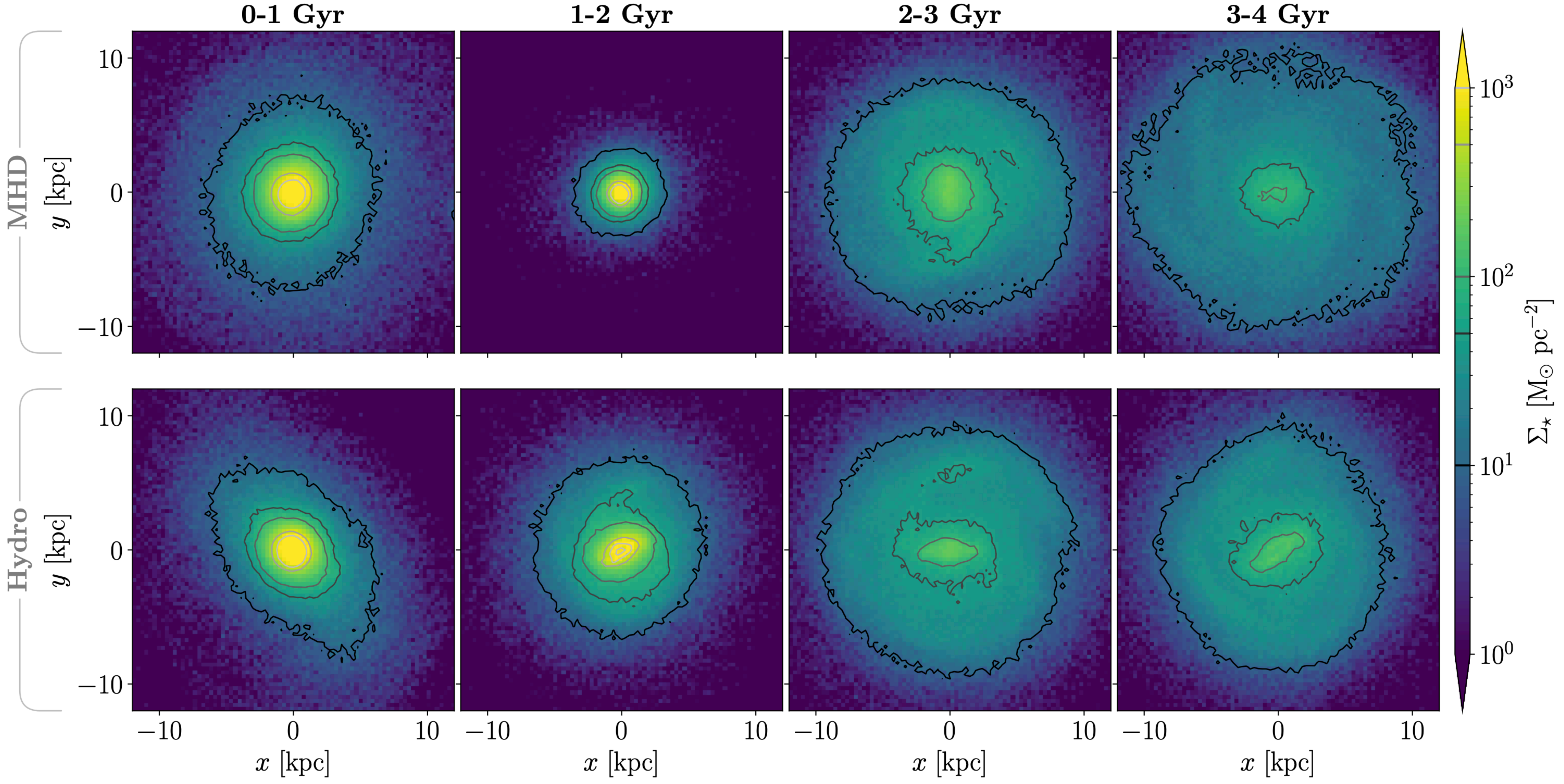


Comparing to simulations

Major evolutionary stage within 2 Gyr (*starburst within this time*)

MHD case shows compaction stage - density much higher

Hydro case starts forming a bar at 1-2 Gyr



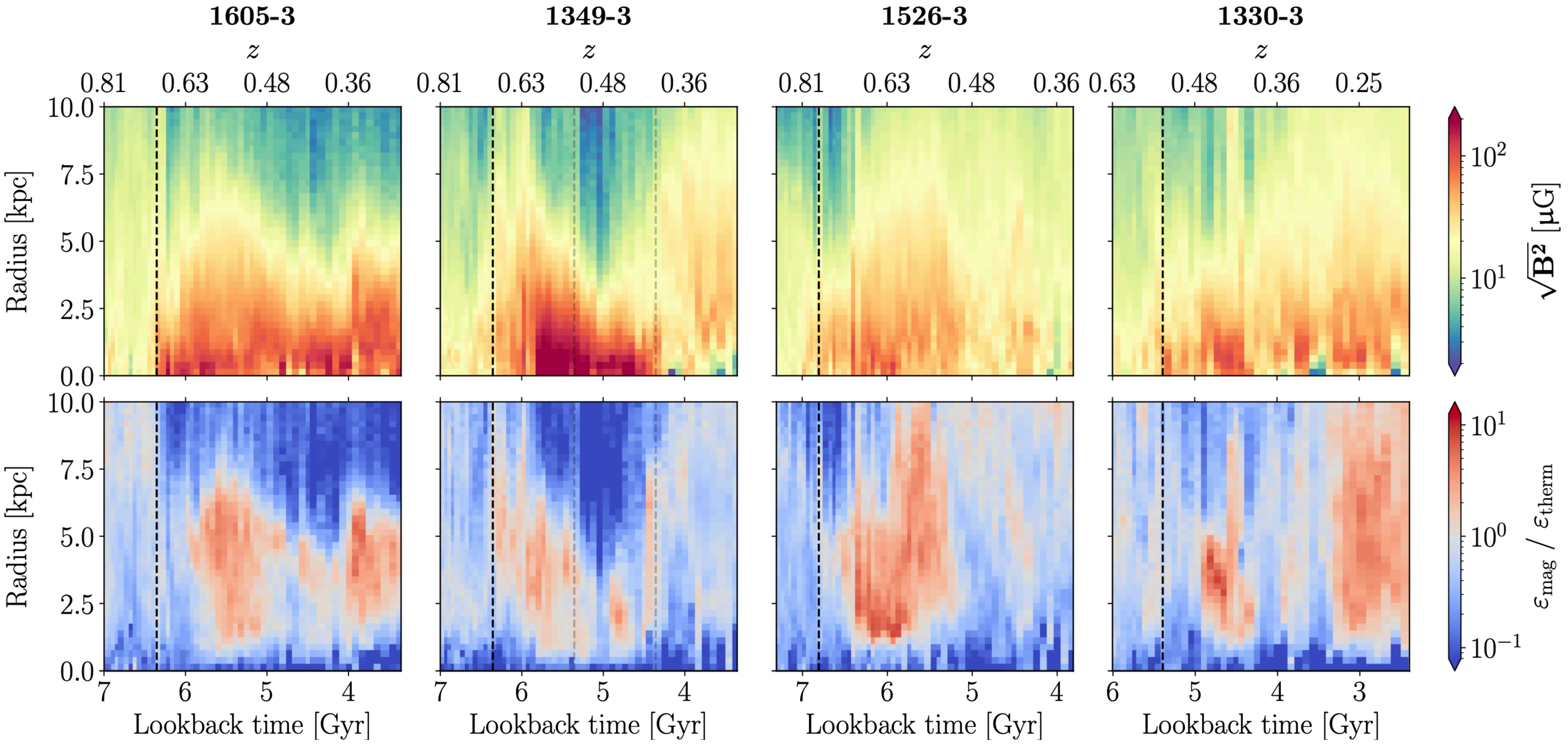
Stellar surface density maps for 1349-3M and 1349-3H (+/-5 kpc projection)

Is magnetic field strong enough?

Yes!

(although technically could be important even at lower strengths; cf. MRI)

NB: can also see signature of decreasing disc size for 3/4 cases



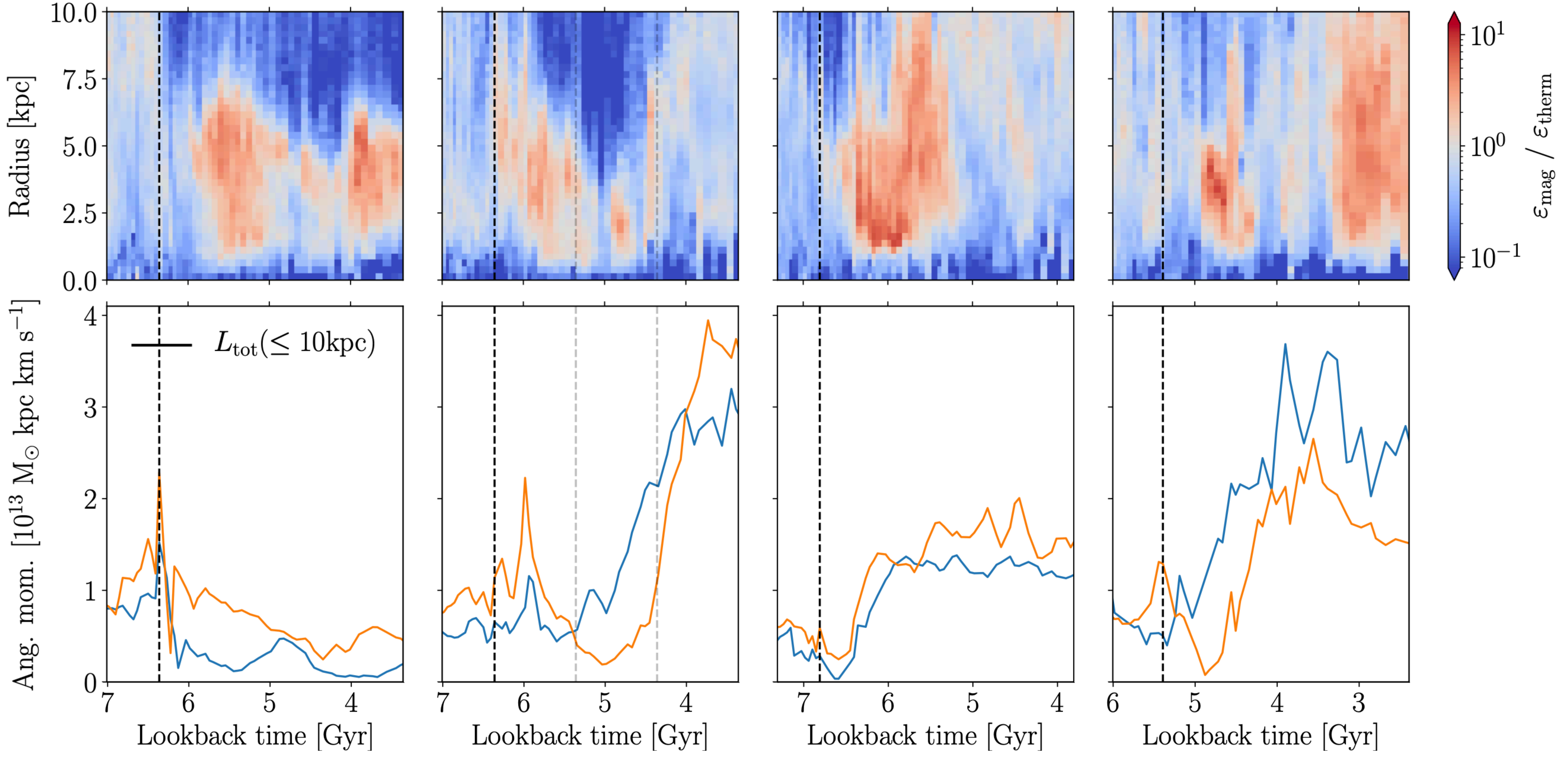
Impact on angular momentum

Reflected in evolution of gas angular momentum within 10 kpc of remnant

Evolution is fundamentally different in 3/4 cases:

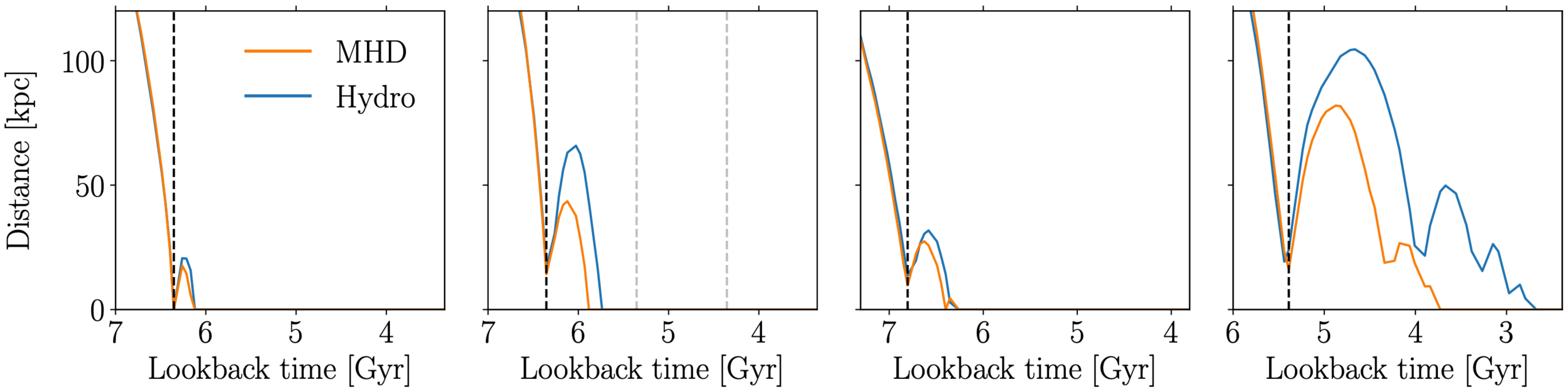
- *Peaks higher in MHD (indicative of more coherent flows; magnetic draping)*

- *3/4 cases show reduction*



→ *magnetic field more effective at redistributing angular momentum*

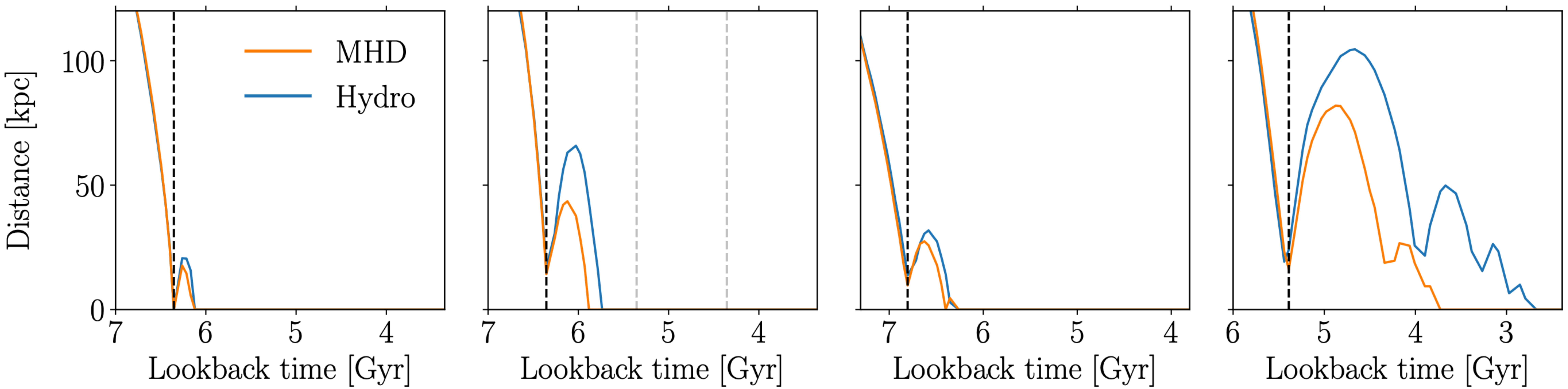
Impact on angular momentum



Angular momentum transfer speeds up merger

(most effective for most "in-spiralling" merger)

Impact on angular momentum



Angular momentum transfer speeds up merger

(most effective for most "in-spiralling" merger)

i) Magnetic field changes angular momentum transport *(usually increases baryonic concentration)* ✓

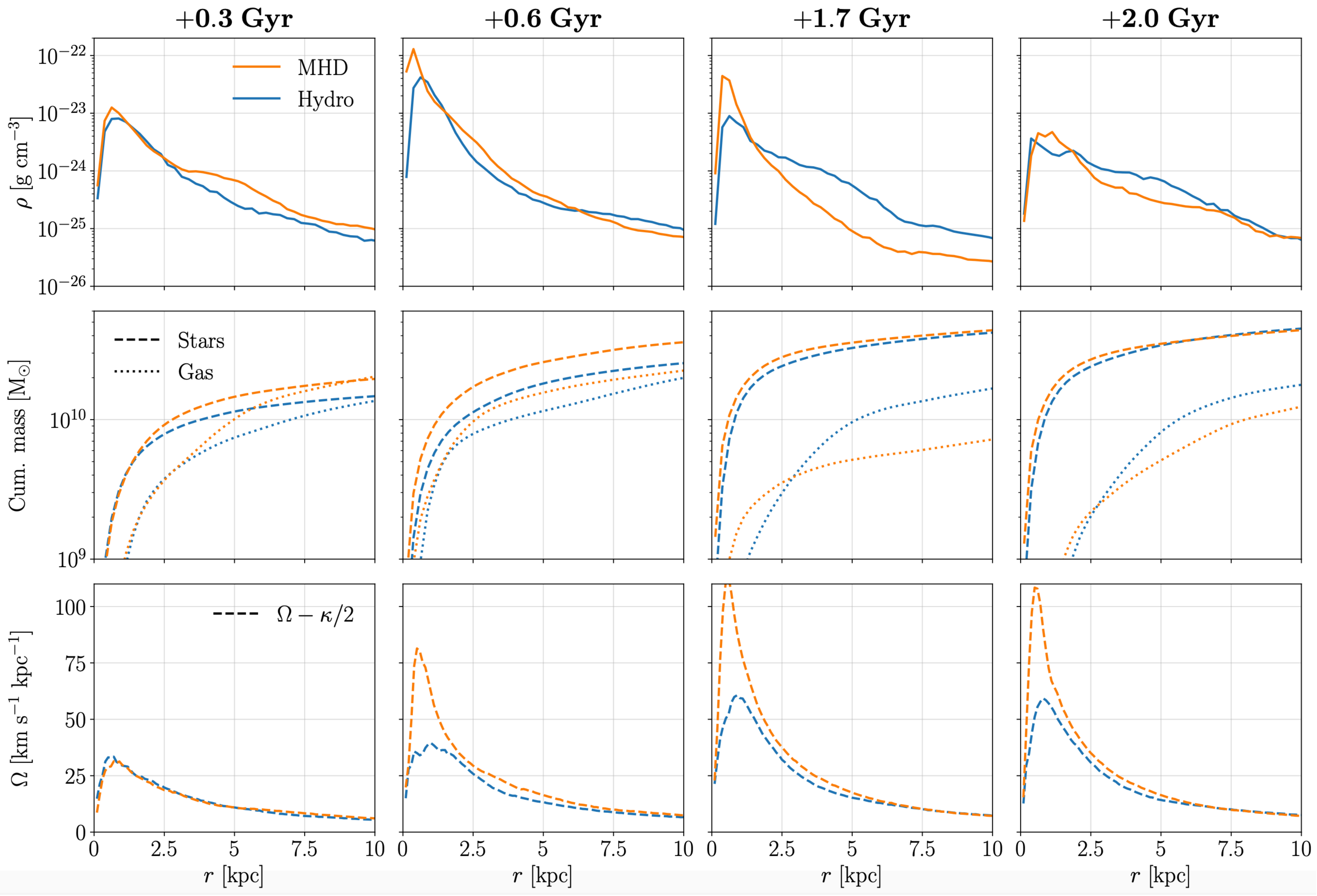
Why a bar forms in hydro runs and not in MHD ones

Loss of angular momentum increases gas concentration

This increases the subsequent stellar concentration

The effect appears small, but has a major impact on the formation of the inner Lindblad resonance (ILR)

A large ILR is a barrier to bar formation - *"x_2" orbits exist within ILR and are aligned orthogonally to bar, acting against it*



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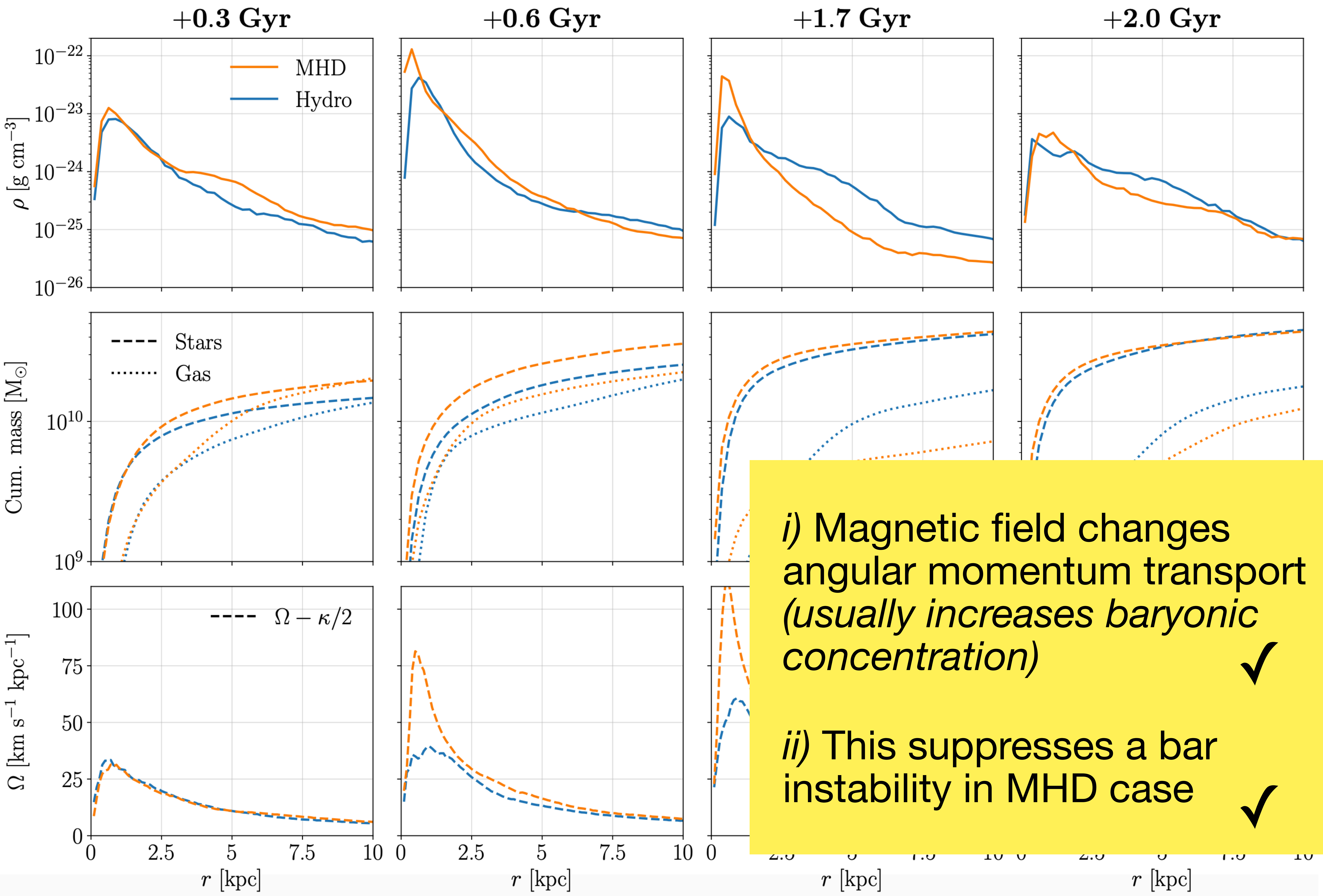

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ii) This suppresses a bar instability in MHD case ✓

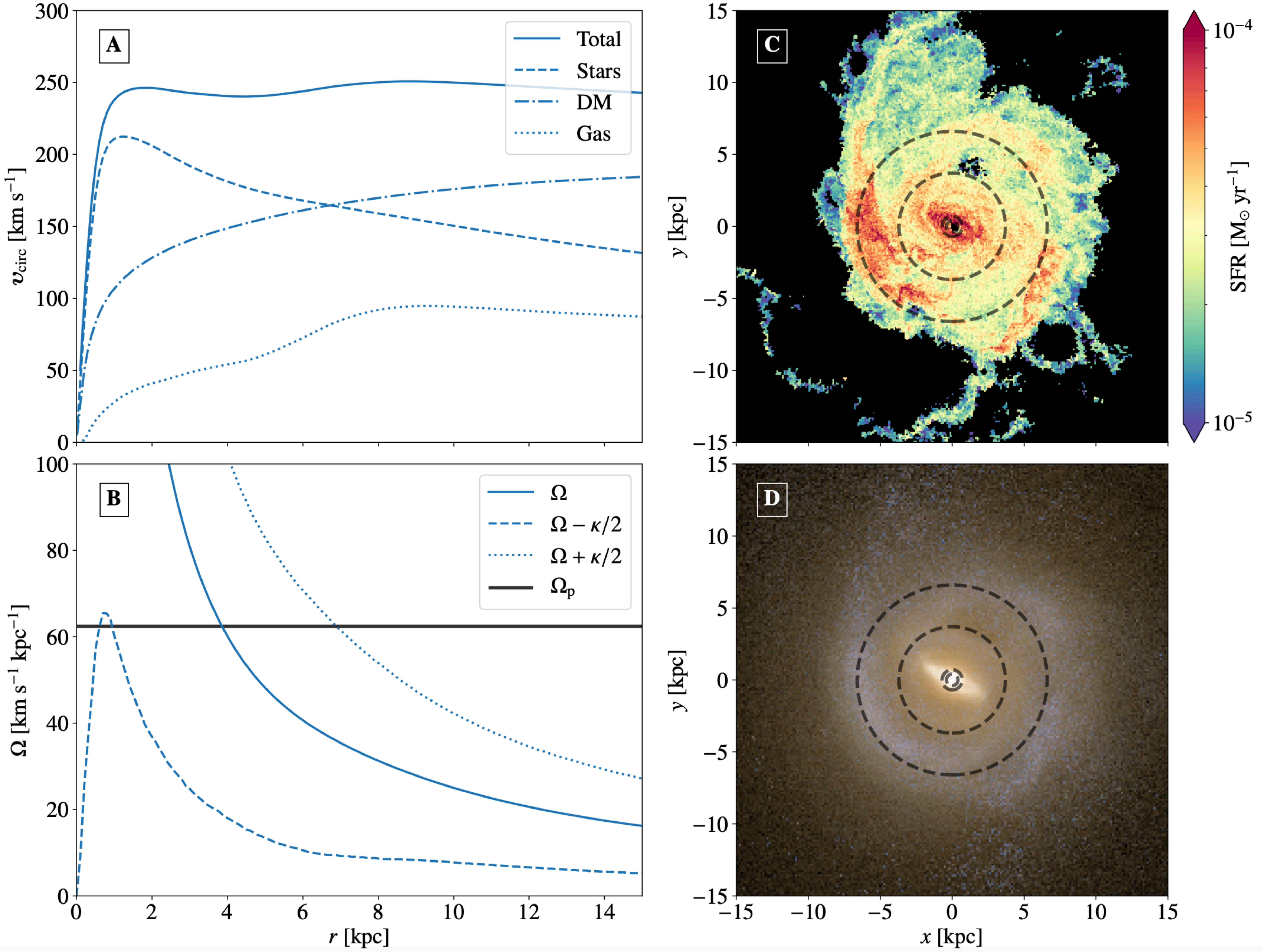
How the bar affects hydro sims

Two other important resonances: co-rotation, and outer Lindblad (OLR)

Bar acts to drive gas away from co-rotation resonance and towards ILR and OLR

Results in high gas density
high star formation rate

→ This causes the blue stellar ring



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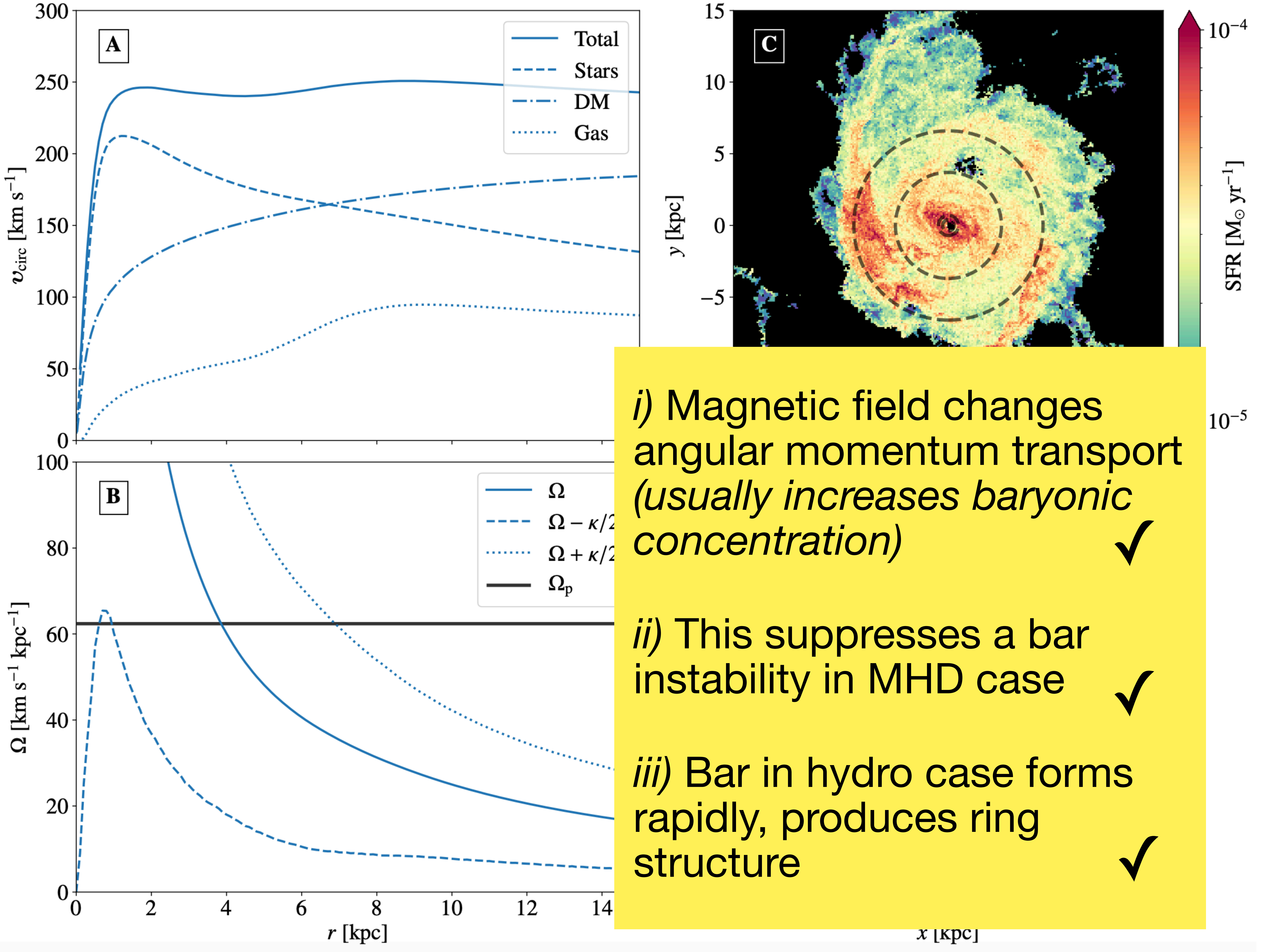

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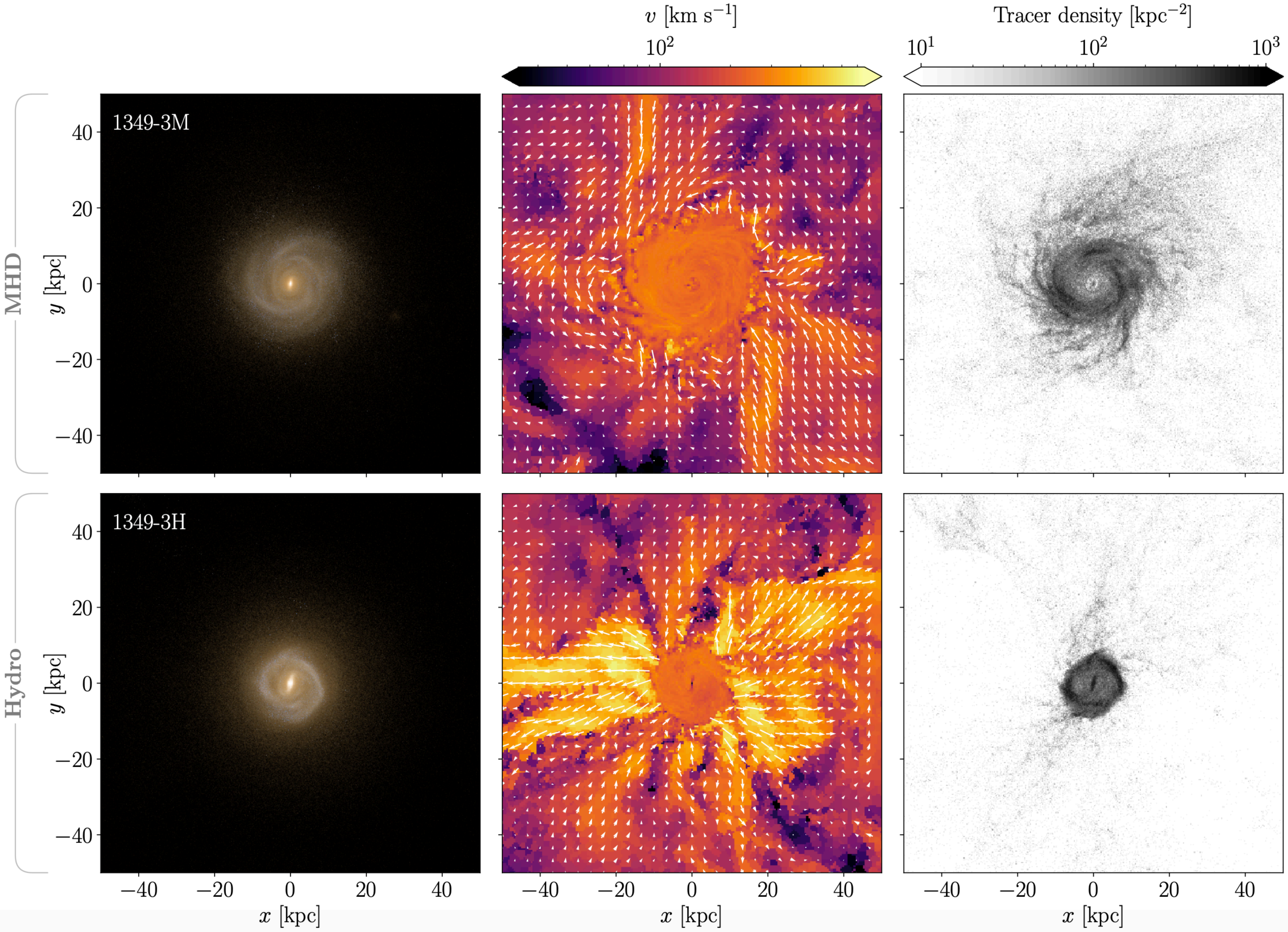
The impact of winds on accretion

Stellar ring in hydro simulation severely disrupts the local CGM; *as a result, accreting gas must have a strong radial component*

Star formation is more distributed in MHD simulations; *stellar wind is weaker, gas at the outskirts retains its angular momentum*

Tracer analysis shows gas joining remnant in MHD simulation is typically closer; *this allows rapid (radial) growth*



(5 Gyr post-merger, lookback time of ~ 1.4 Gyr)

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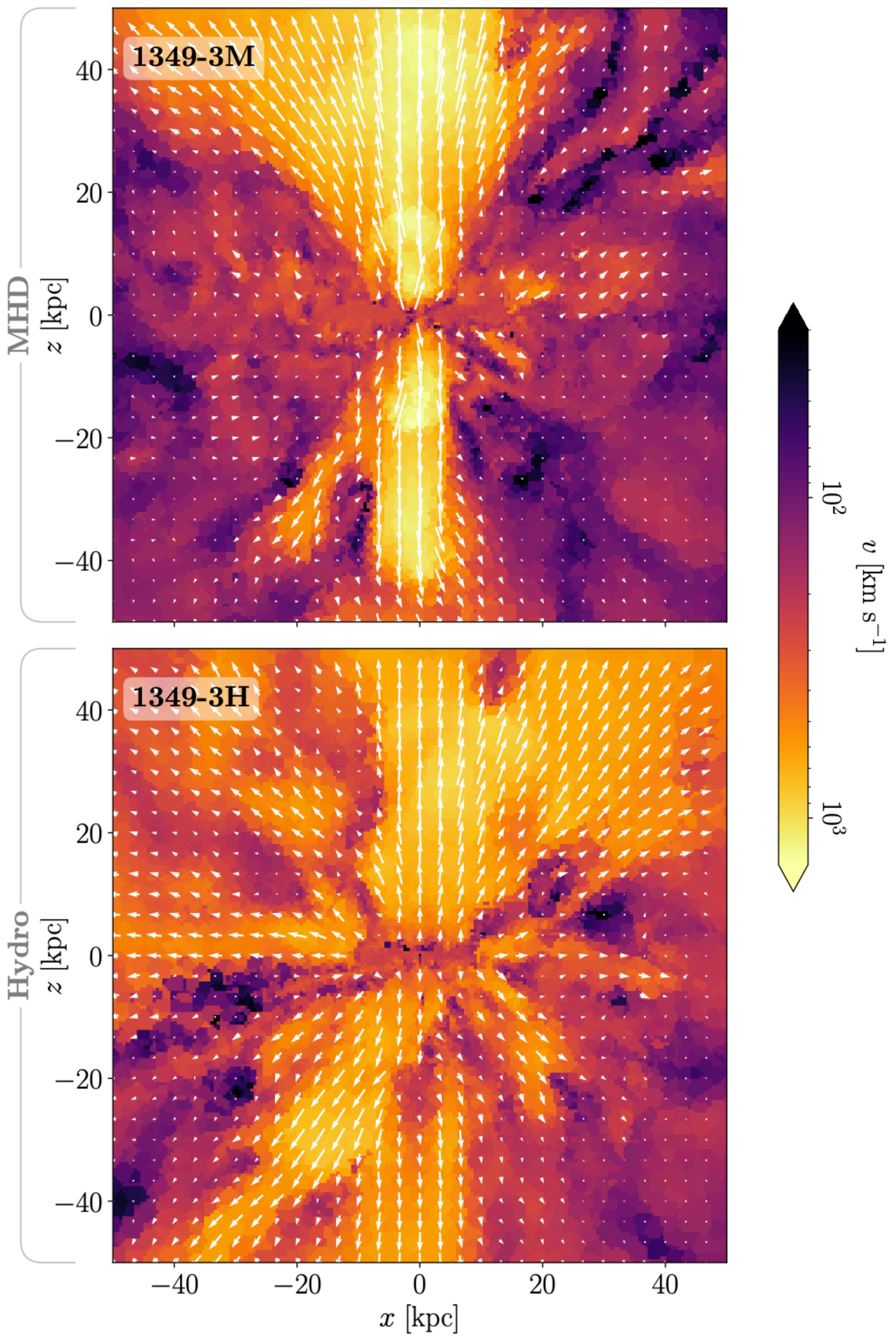

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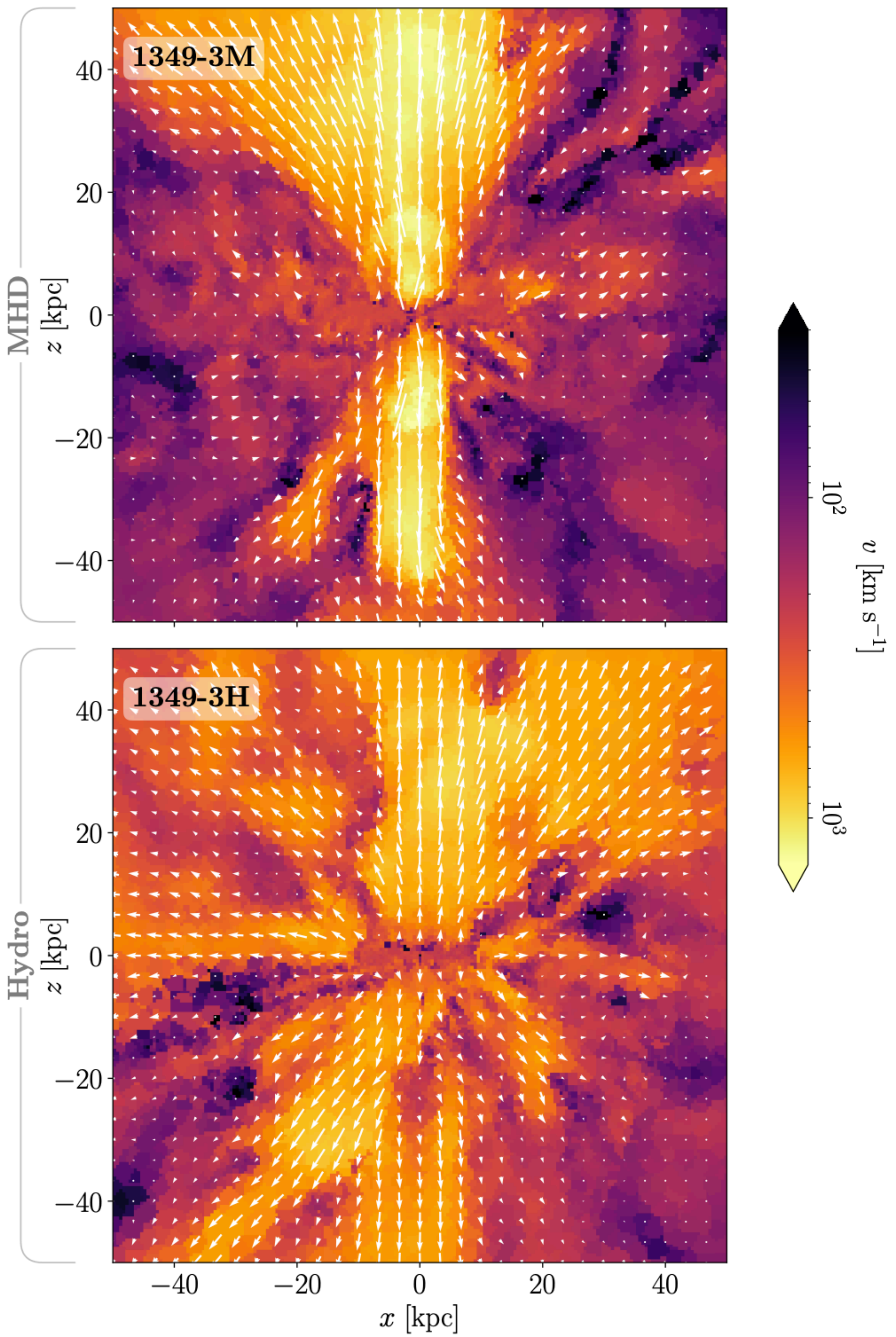

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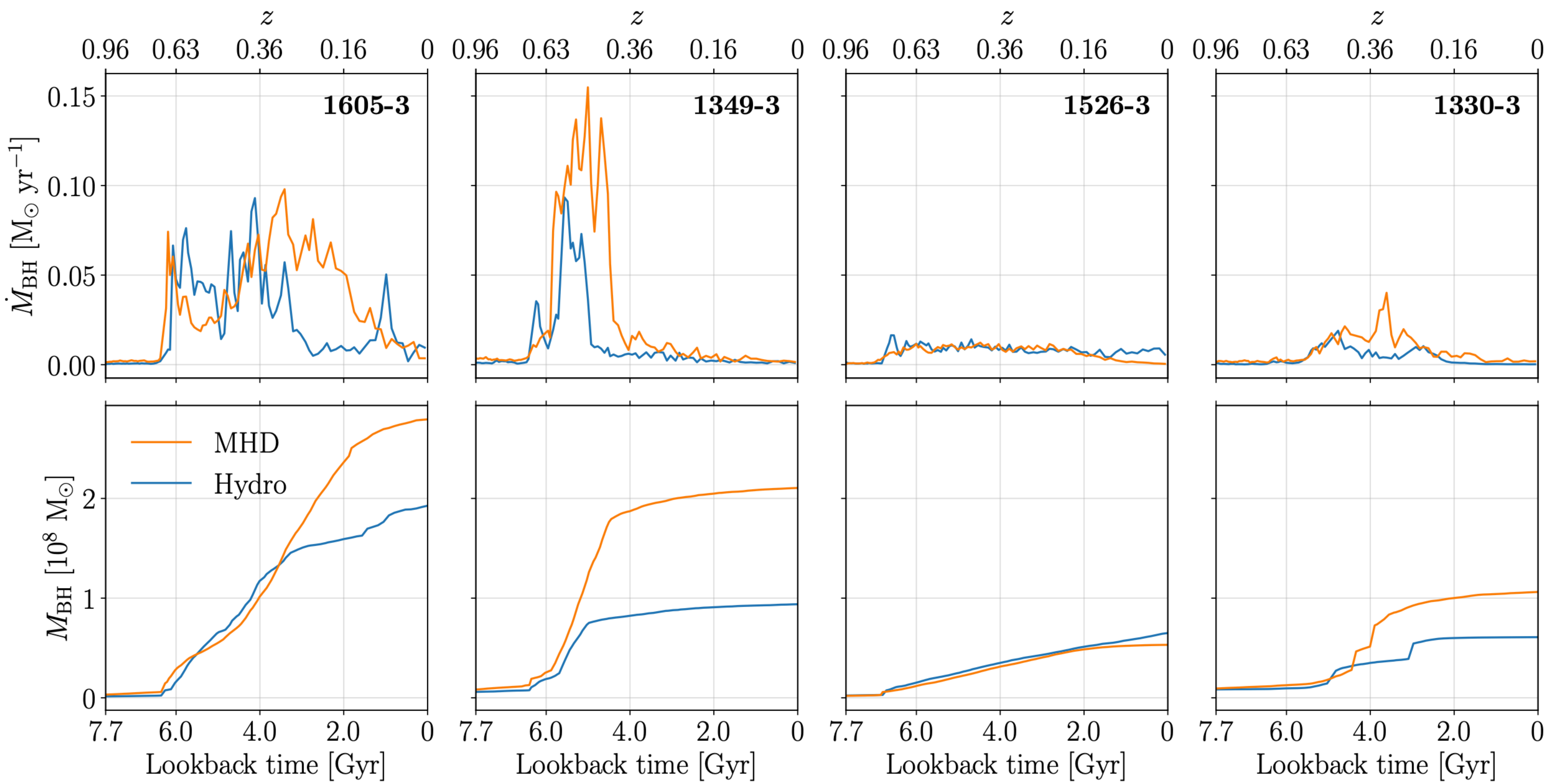
The impact *on* the supermassive black hole

If the gas concentration increases in the MHD case, we should expect the black hole accretion rate should go up

→ indeed, black holes can grow twice as large in MHD simulations!
(but this is still within errors of observed BH-stellar mass relation)

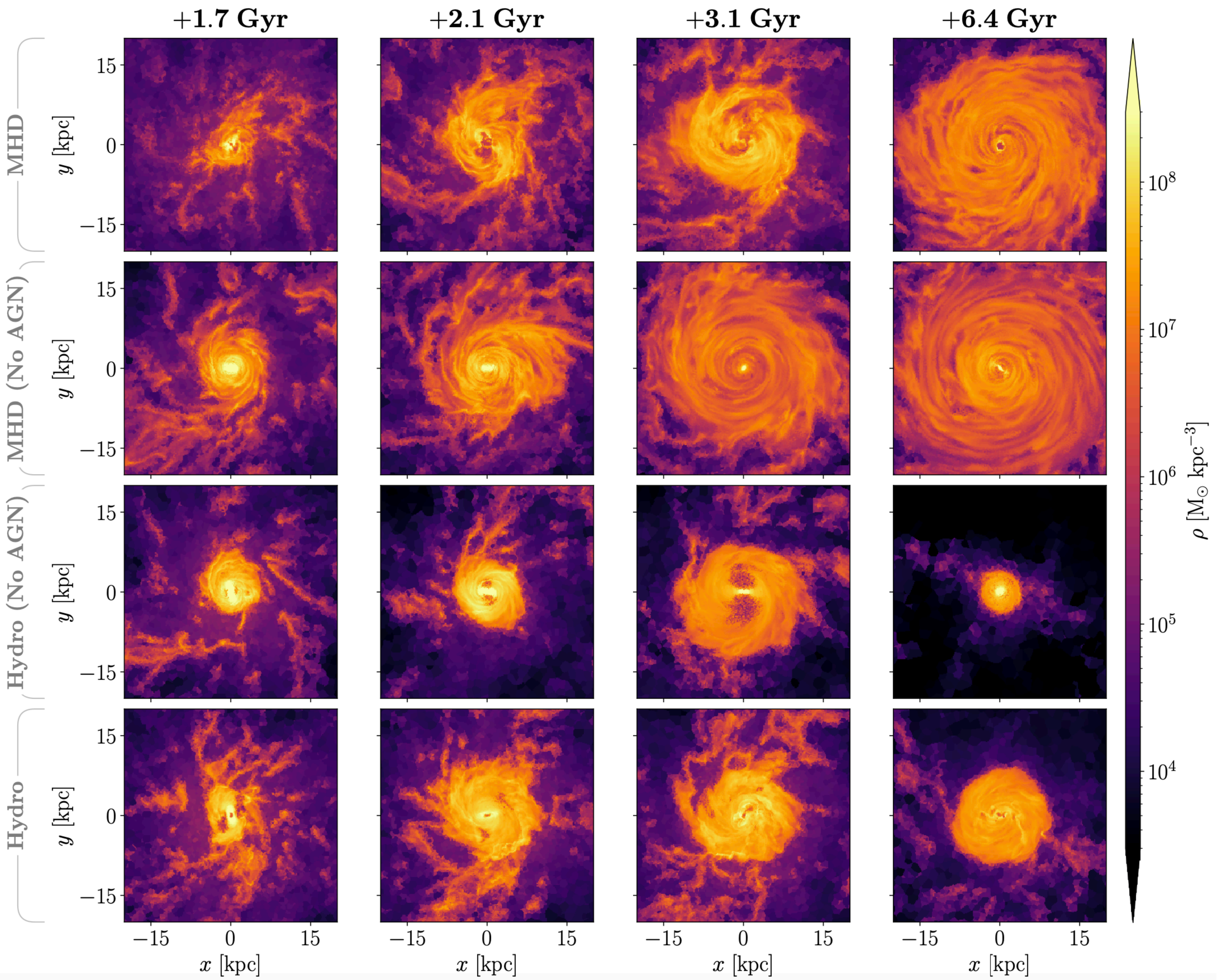


The impact *of* the SMBH *(is surprisingly weak!)*

Ran two extra simulations with quasar feedback turned off at start of merger

See same morphological changes anyway; in fact, differences are bigger without AGN feedback!

AGN appears to suppress effect rather than cause it



Summary

Magnetic field becomes dominant in first 100 Myr

- *Non-azimuthal field redistributes angular momentum between accreting gas and gas in disc; shrinks disc*

- Increased concentration produces inner Lindblad resonance, which suppresses bar instability *(azimuthally-orientated field provides support against collapse)*

- Bar in hydro run produces strong star-forming ring at outer Lindblad resonance *(lack thereof allows spiral arm features to form in MHD case)*

- High SFR density in ring launches strong stellar wind, which disrupts CGM; keeps disc small.
  In contrast, winds are less effective in MHD case; gas retains angular momentum, disc grows quickly and becomes larger

Summary

Side remarks:

- *Mergers are quicker in MHD case*
- *BHs grow up to 2x larger*

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