Leibniz-Institut für Astrophysik Potsdam

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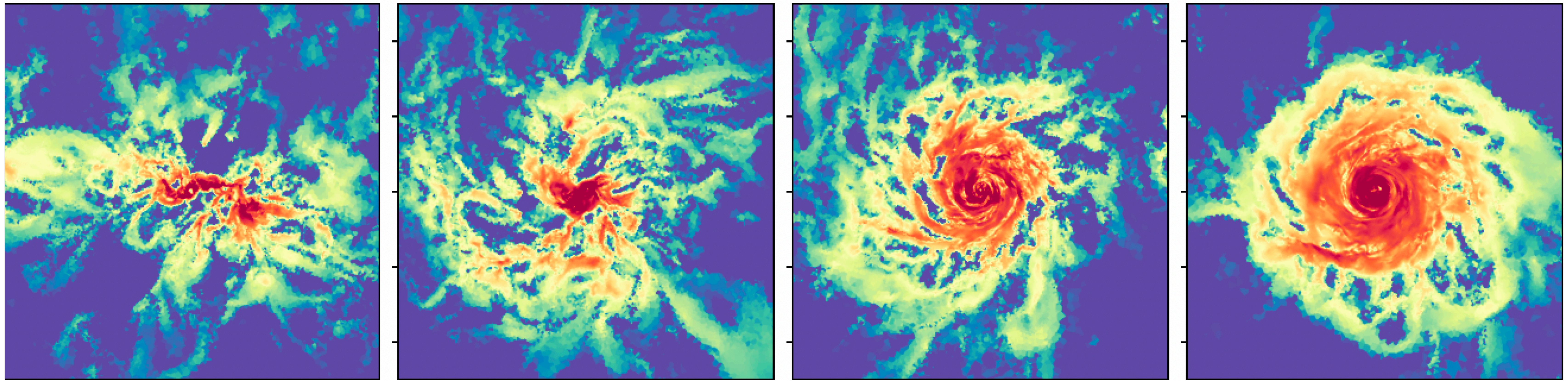
The impact of magnetic fields on cosmological galaxy mergers

Joseph Whittingham

Martin Sparre (UoP), Christoph Pfrommer (AIP), Rüdiger Pakmor (MPA)



Motivation

Disc galaxies in the local Universe have magnetic fields on order of μG

→ dynamically important at the current epoch!

...what about galaxy evolution as a whole?

Component	$u(\mathrm{eV\,cm^{-3}})$	Note
Cosmic microwave background ($T_{\mathrm{CMB}} = 2.725\,\mathrm{K}$)	0.265	a
Far-infrared radiation from dust	0.31	b
Starlight ($h\nu < 13.6\,\mathrm{eV}$)	0.54	c
Thermal kinetic energy $(3/2)nkT$	0.49	d
Turbulent kinetic energy $(1/2)\rho v^2$	0.22	e
Magnetic energy $B^2/8\pi$	0.89	f
Cosmic rays	1.39	g

Energy densities in the local ISM

Credit: Physics of the Interstellar and Intergalactic Medium, Princeton University Press

a Fixsen & Mather (2002).
b Chapter 12.
c Chapter 12.
d For $nT = 3800\,\mathrm{cm^{-3}}\,\mathrm{K}$ (see §17.7).
e For $n_{\mathrm{H}} = 30\,\mathrm{cm^{-3}}$, $v = 1\,\mathrm{km\,s^{-1}}$, or $\langle n_{\mathrm{H}}\rangle = 1\,\mathrm{cm^{-3}}$, $\langle v^2\rangle^{1/2} = 5.5\,\mathrm{km\,s^{-1}}$.
f For median $B_{\mathrm{tot}} \approx 6.0\,\mu\mathrm{G}$ (Heiles & Crutcher 2005).
g For cosmic ray spectrum X3 in Fig. 13.5.

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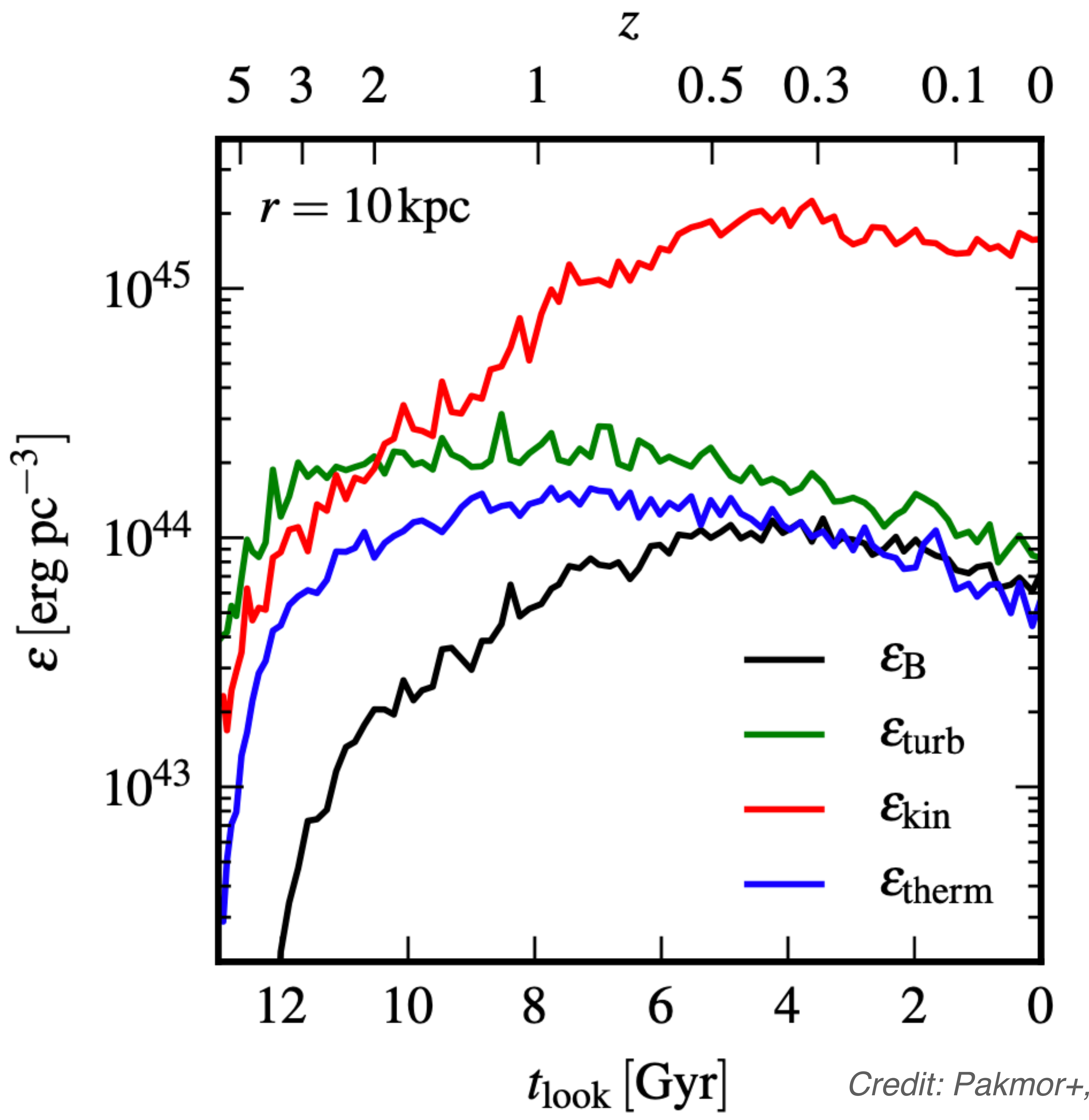

Credit: Pakmor+, 2017

Energy densities over time in a cosmological disc

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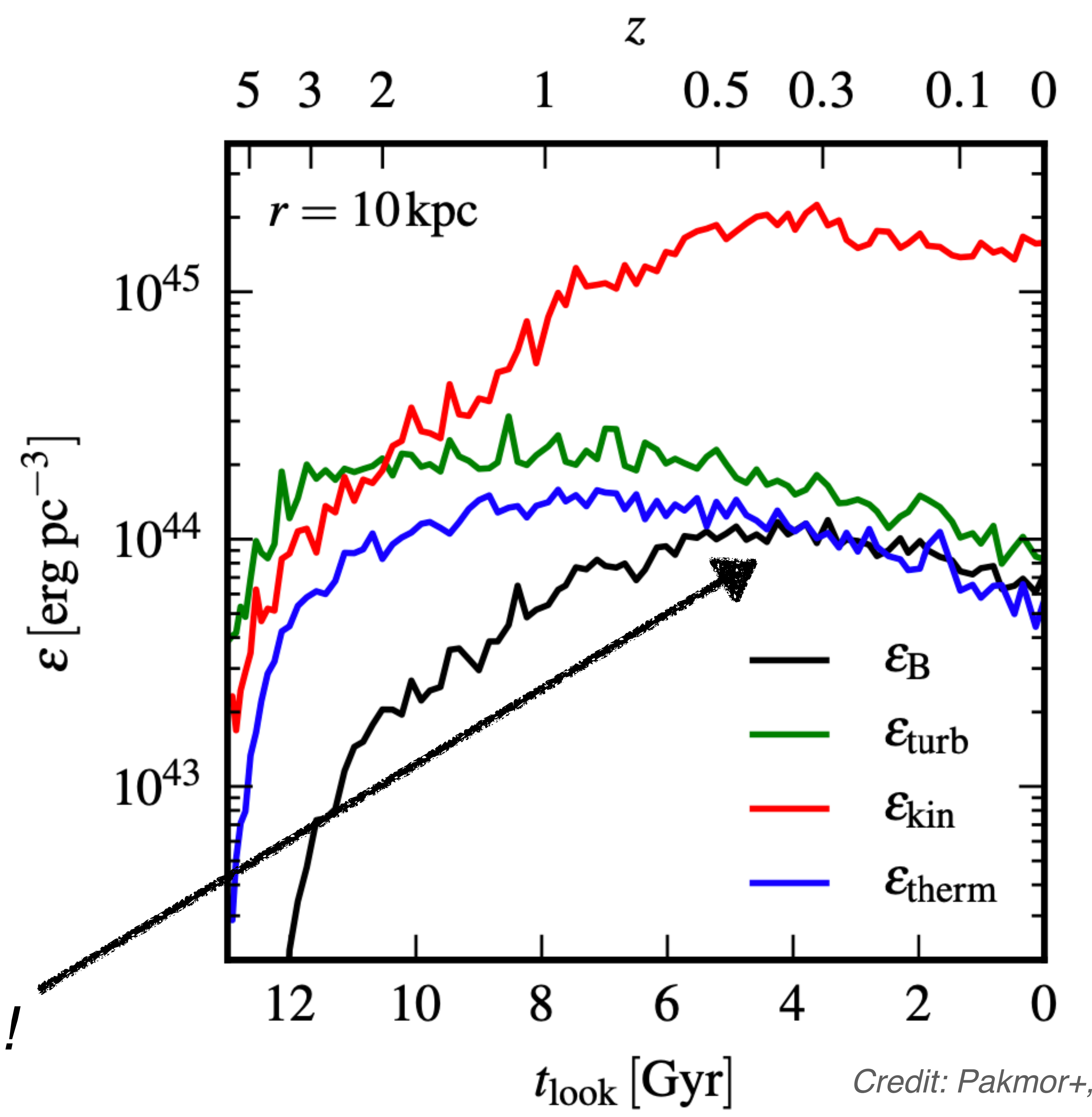

Too late!

Credit: Pakmor+, 2017

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Simulations were of "isolated" galaxies, but structure forms hierarchically

...what about mergers?

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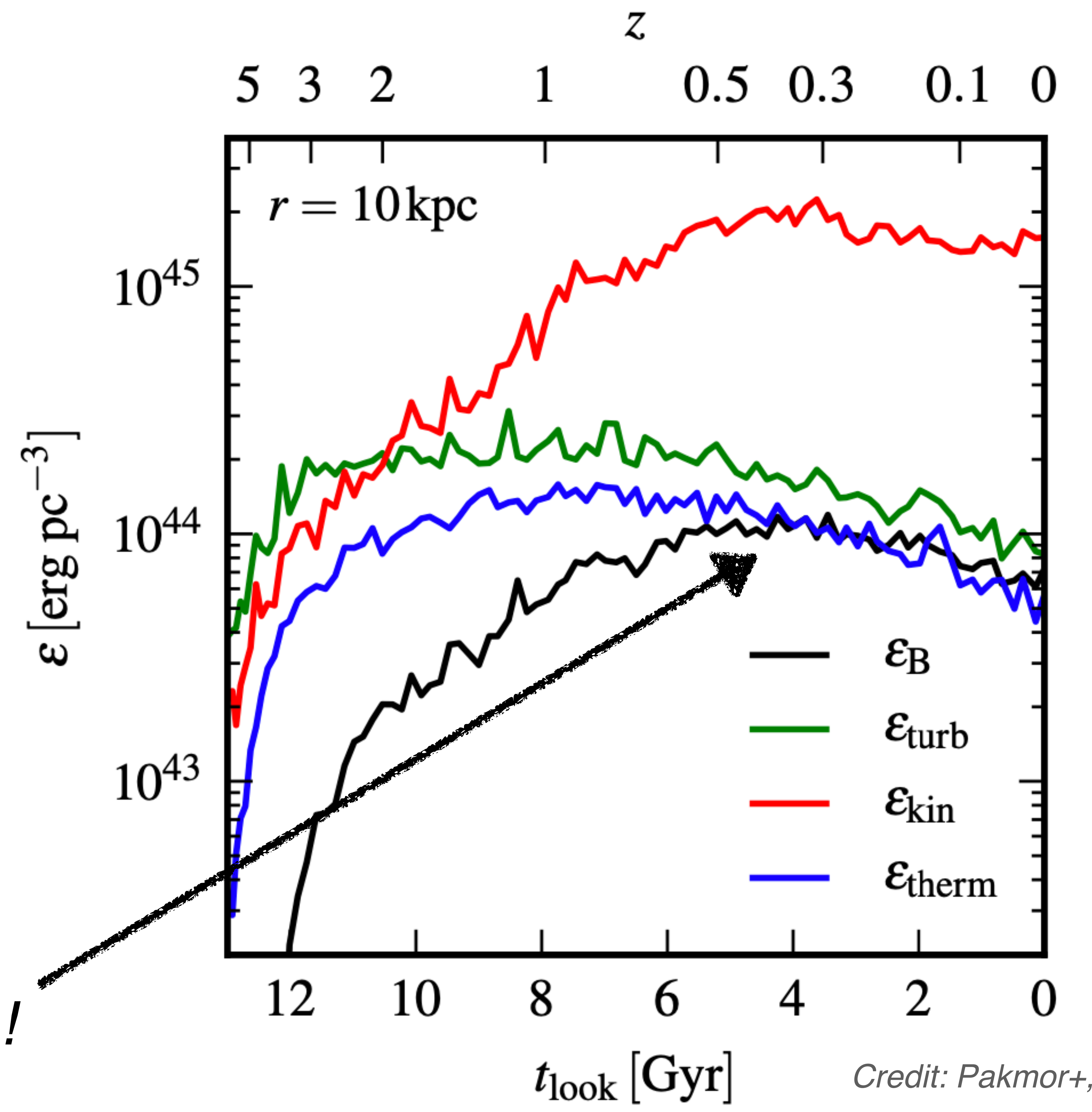

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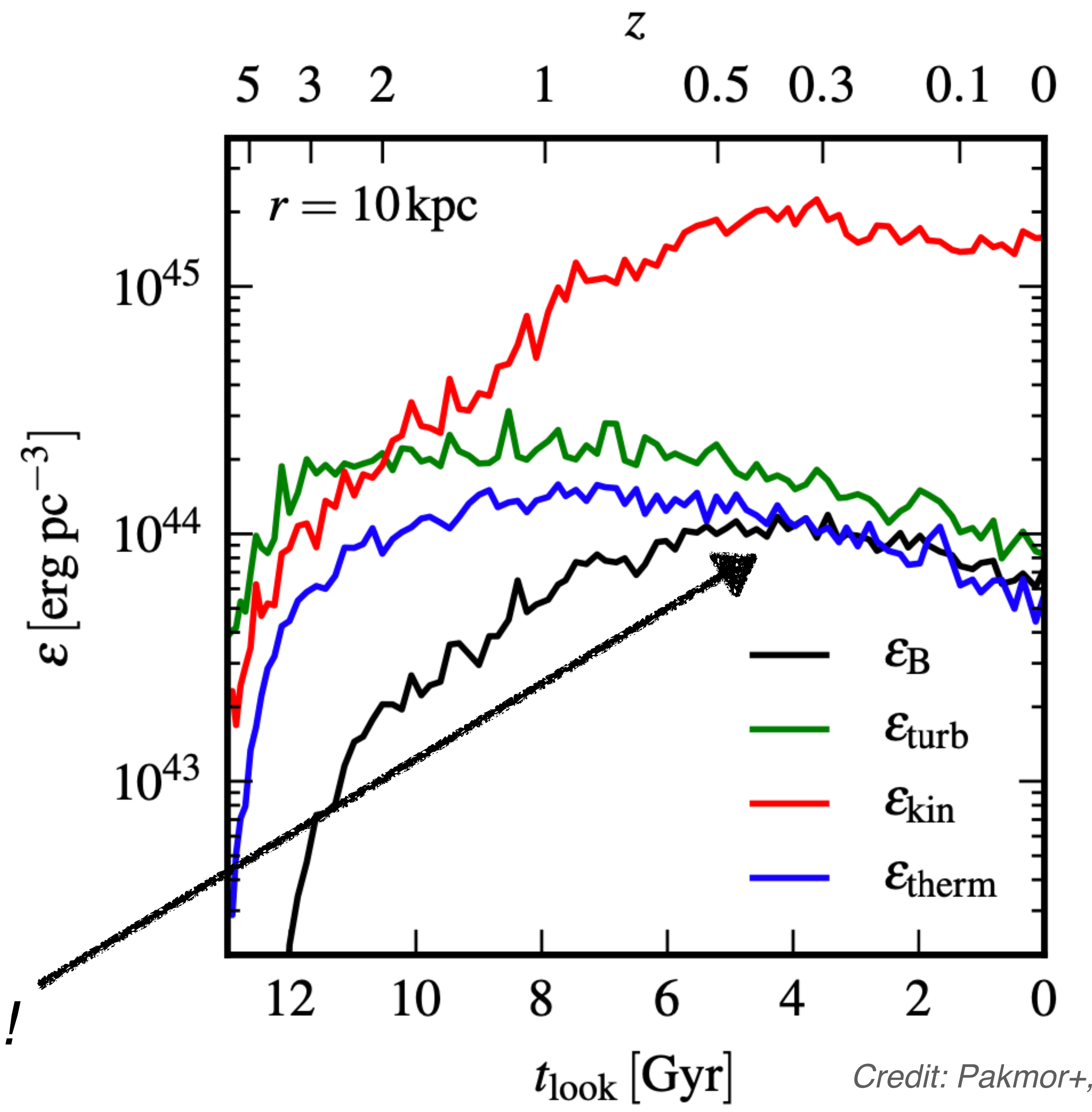
...what about mergers?

- Adiabatic compression
- Shearing
- Injection of turbulence → small-scale dynamo?

Too late!



Credit: Pakmor+, 2017

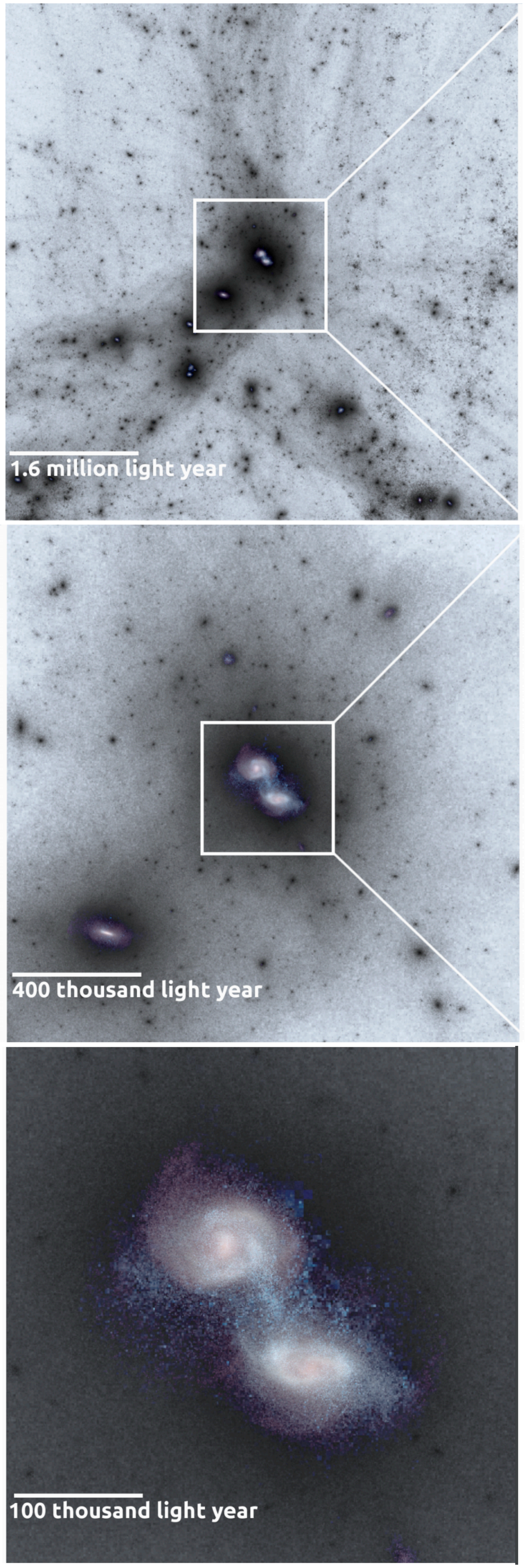
Energy densities over time in a cosmological disc

Set-up

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

- 4x2 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

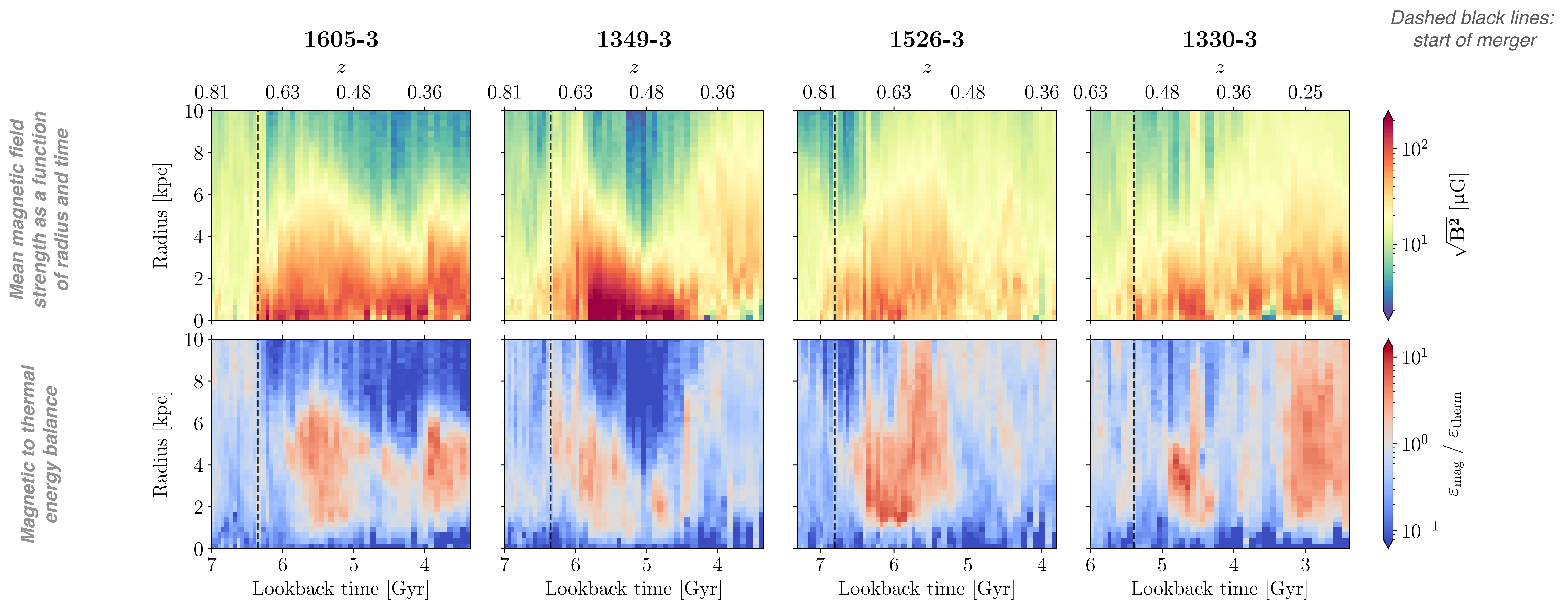
Simulations still fully cosmological
(reduce assumptions on merger parameters, initial field, etc)



Zoom-in on merging galaxies (stellar light on DM background)

Credit: Martin Sparre

Mergers strongly amplify magnetic fields!



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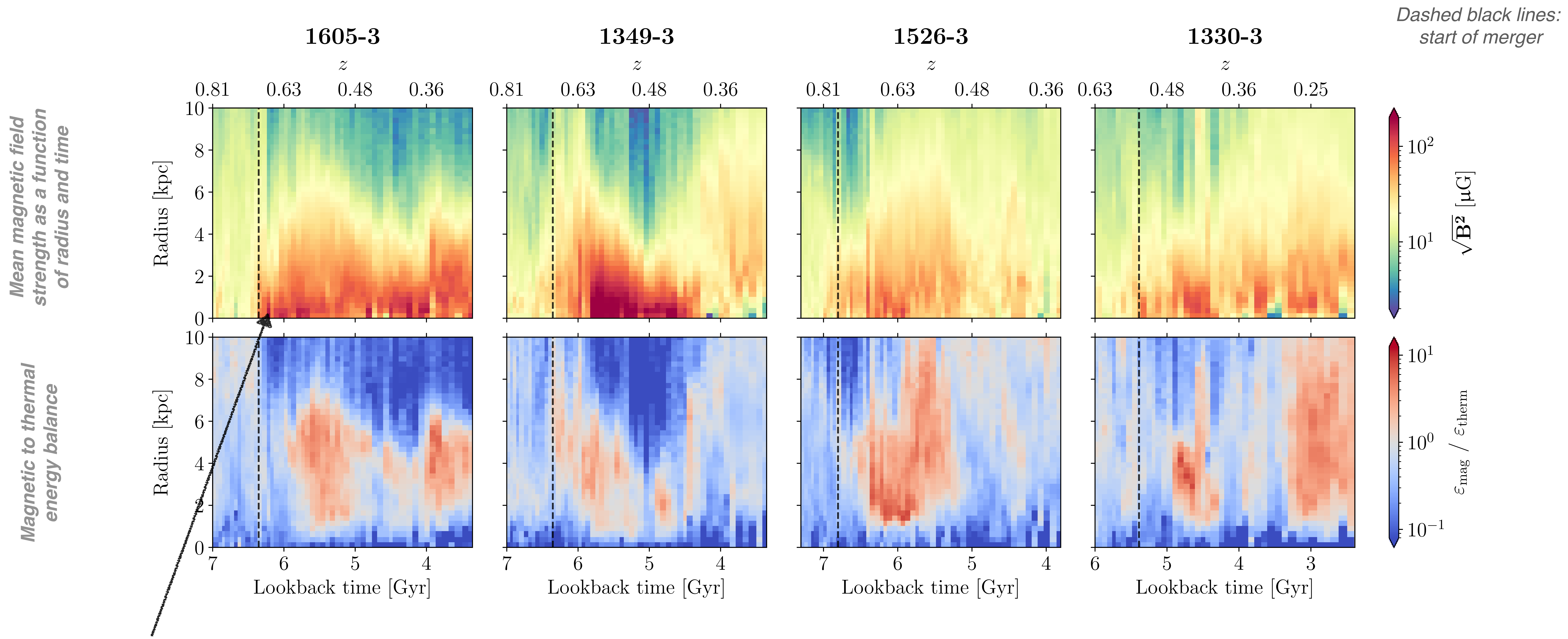

Sustained amplification by up to an order of magnitude for a few Gyr

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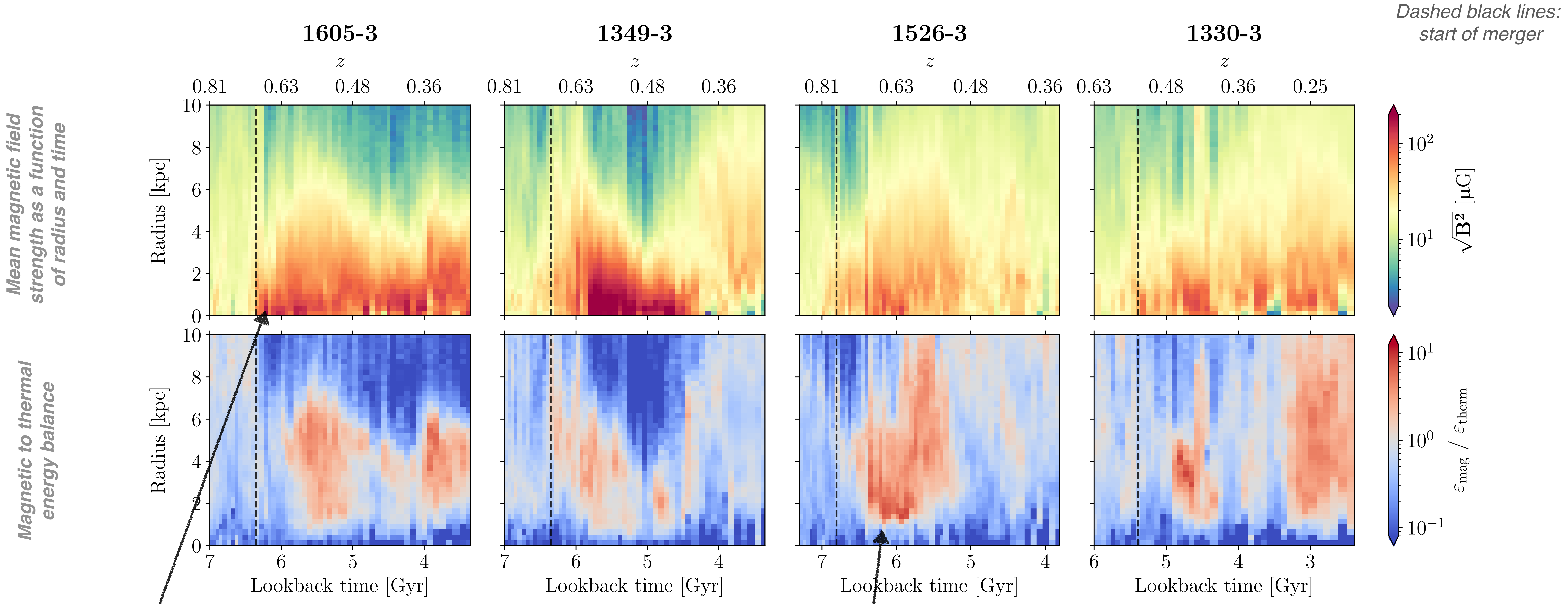

Sustained amplification by up to an order of magnitude for a few Gyr

Magnetic energy can dominate over thermal energy

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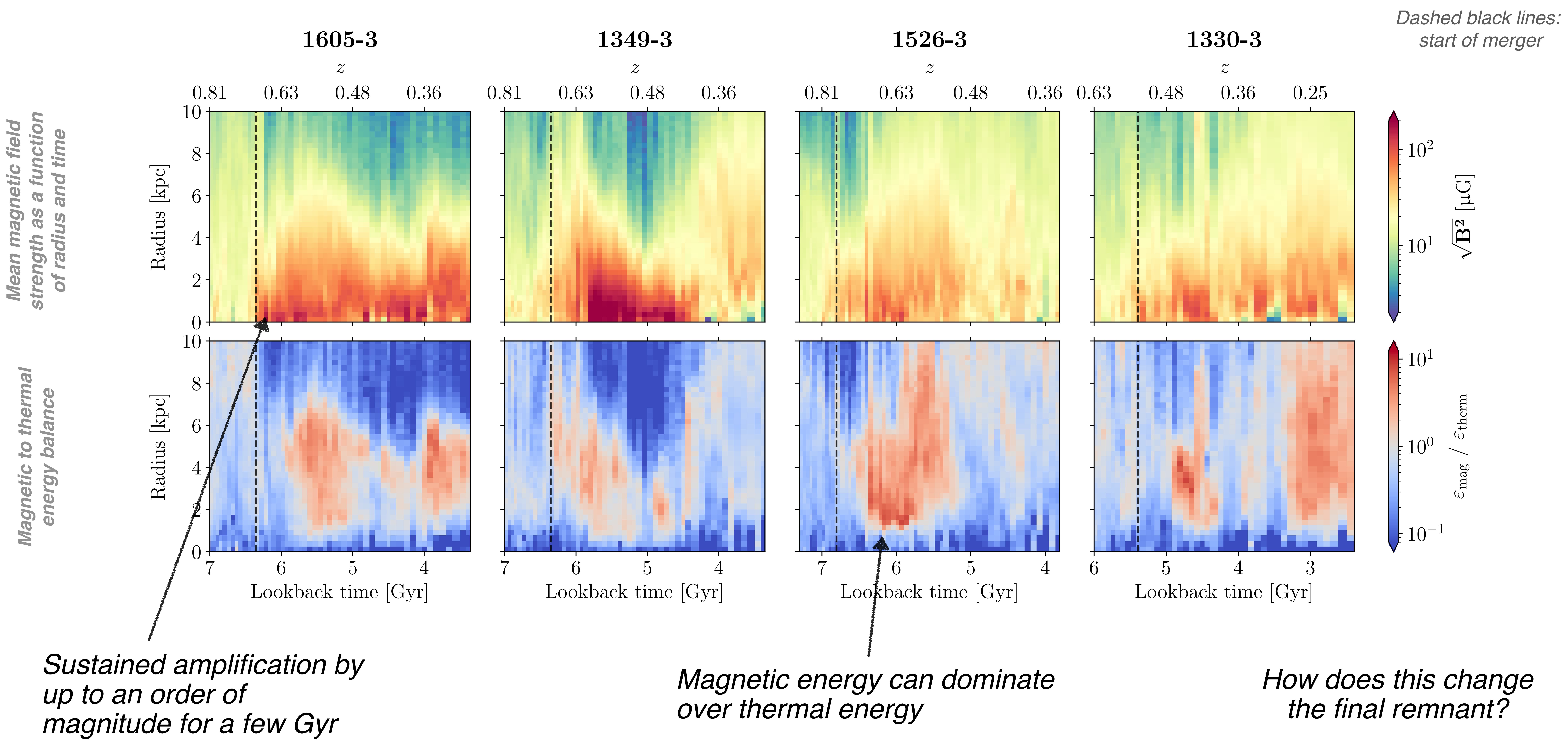
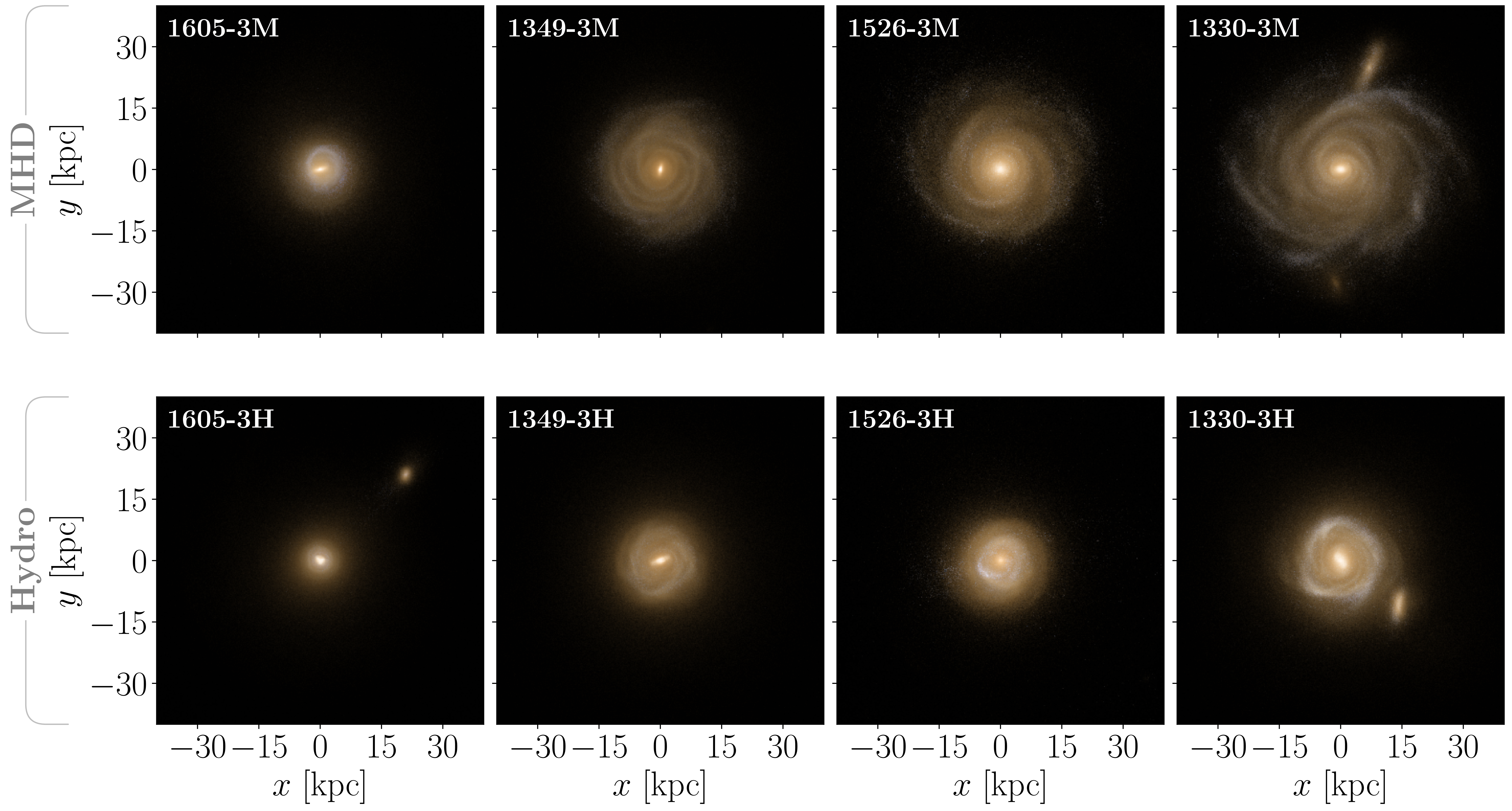


How does this change the final remnant?

Magnetic fields strongly affect the outcome of a merger



Mock gri visual image from stellar light at z=0

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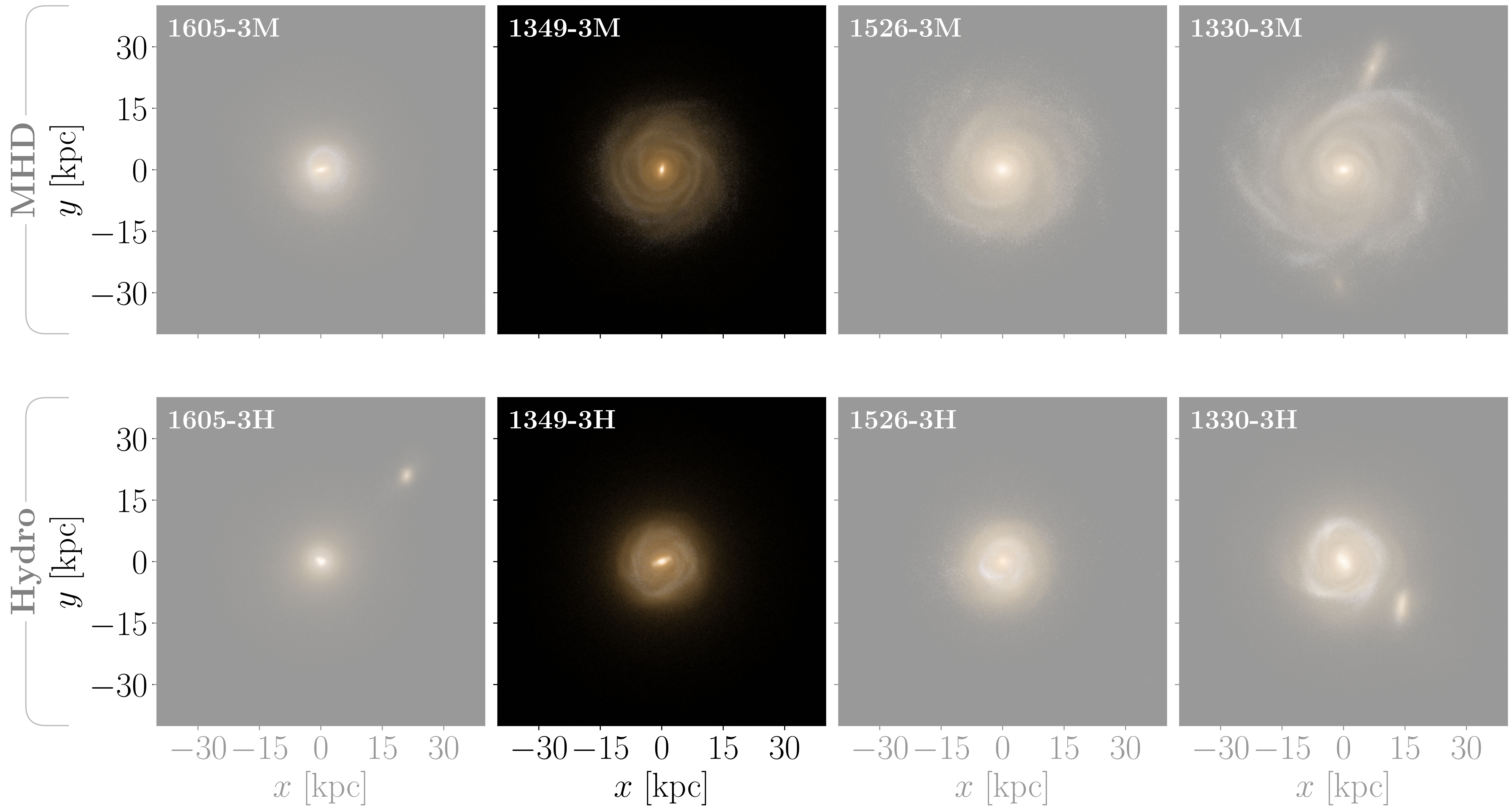
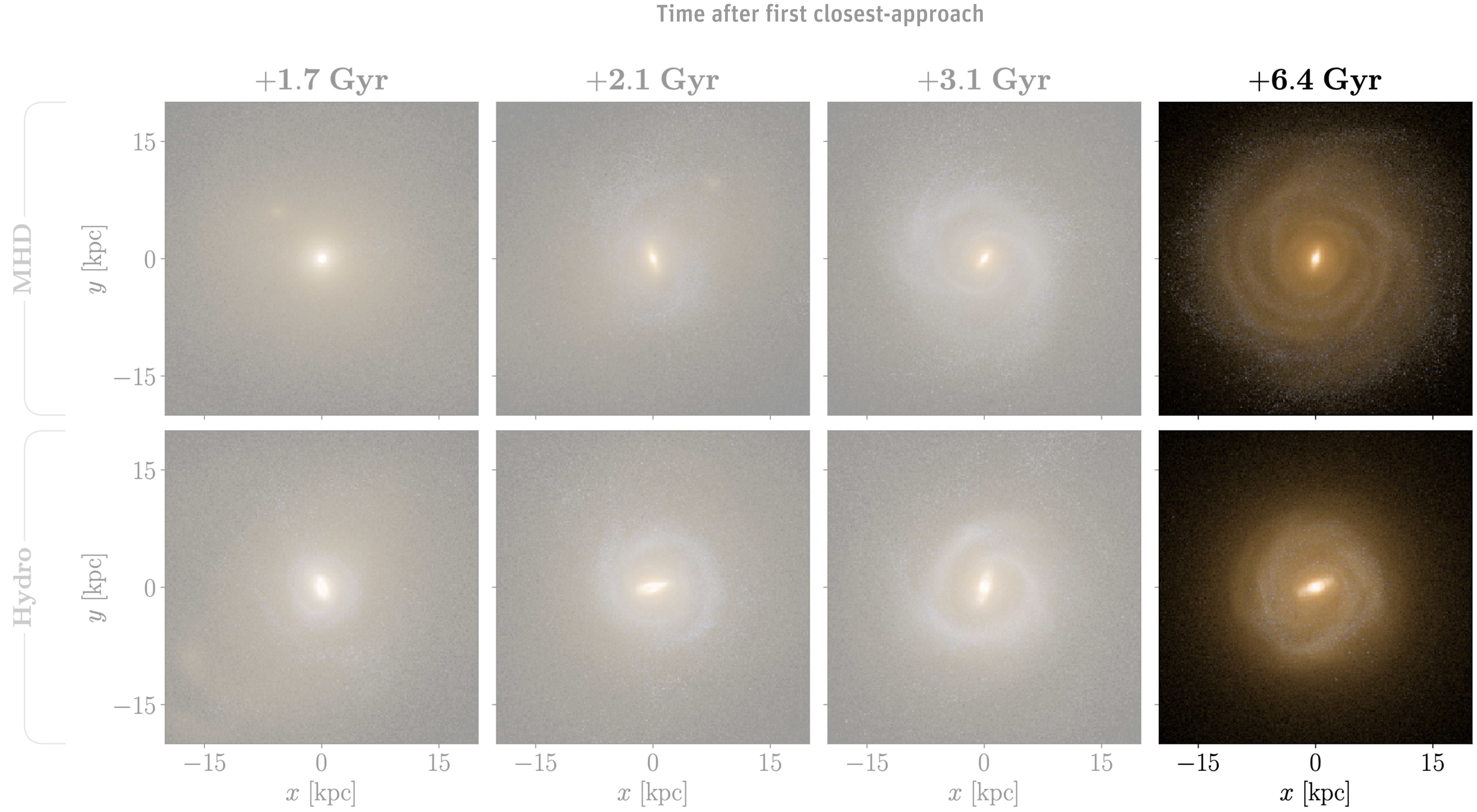


Mock gri visual image from stellar light at z=0

Case study

- 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

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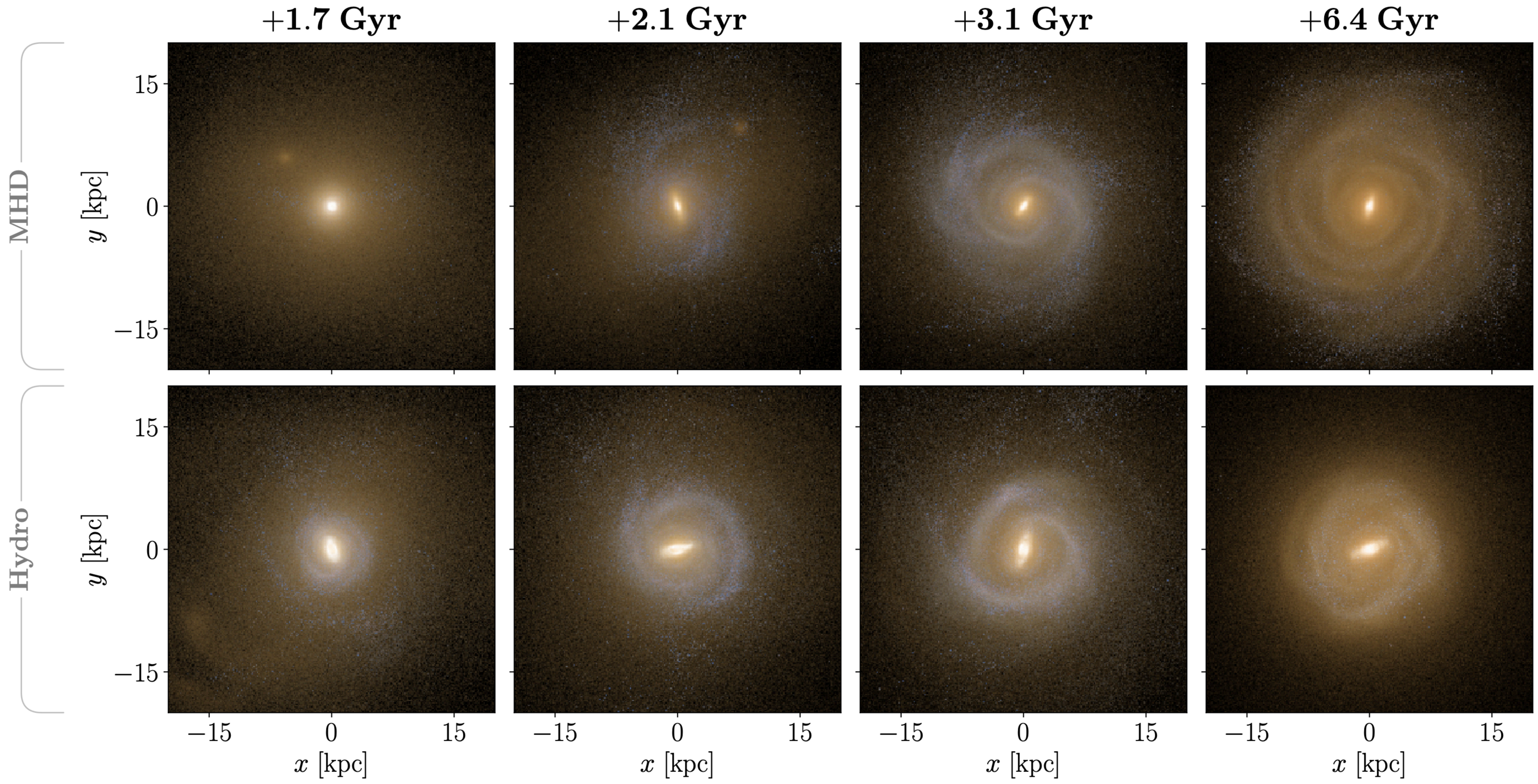
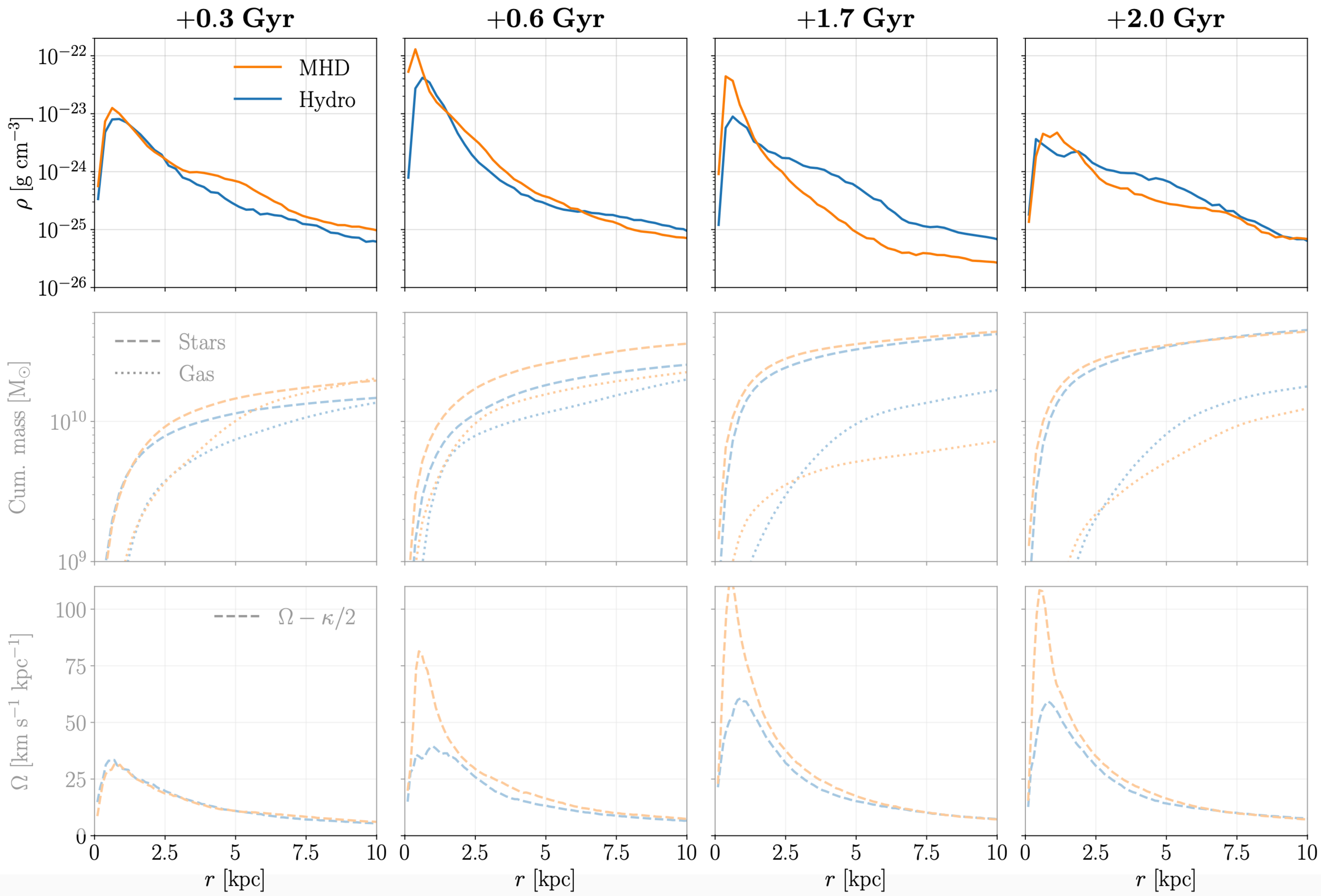
Time after first closest-approach



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

Why the MHD remnants start smaller

Magnetic fields cause a more effective transfer of angular momentum --> increases the gas concentration



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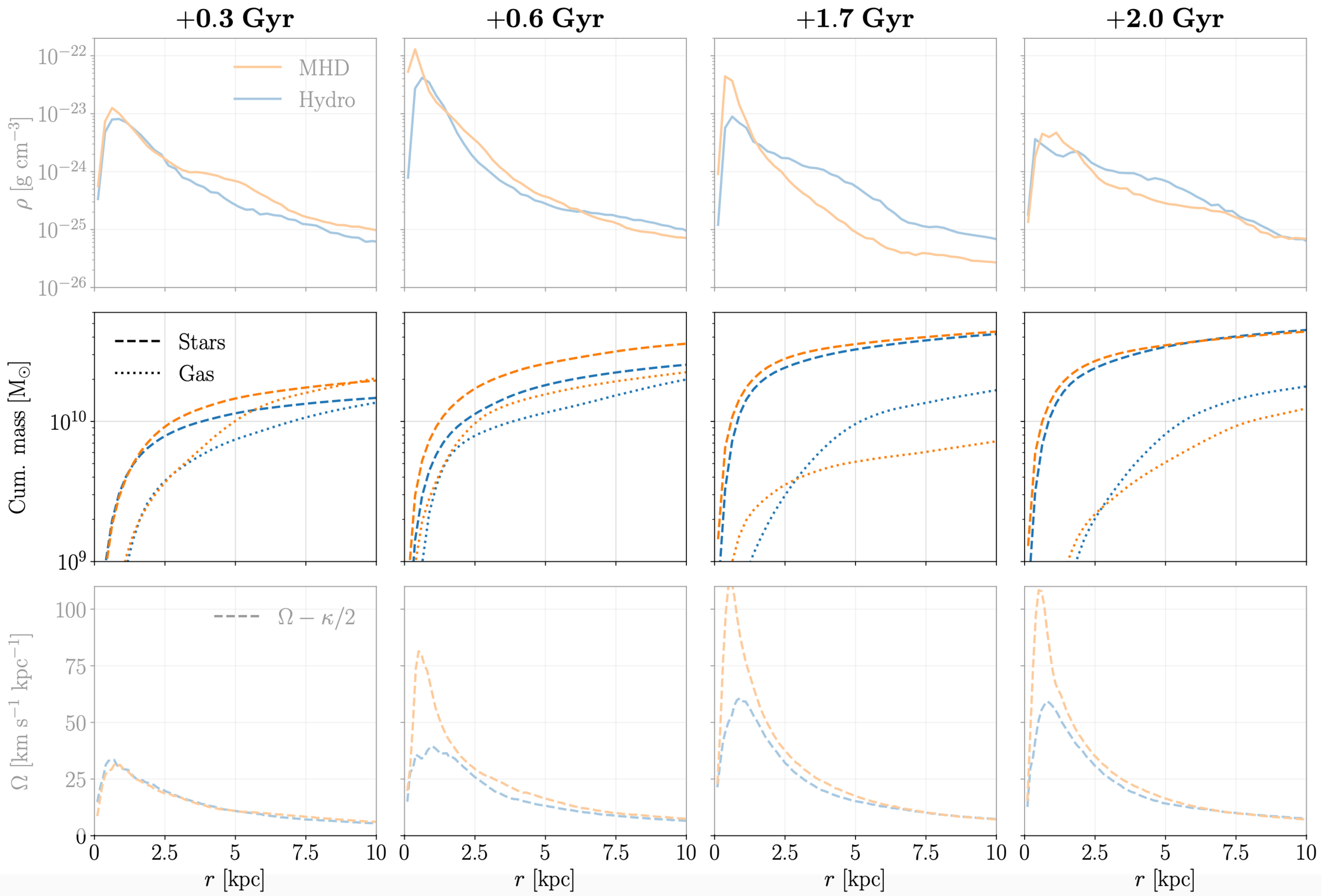

Why a bar forms in hydro runs and not in MHD ones

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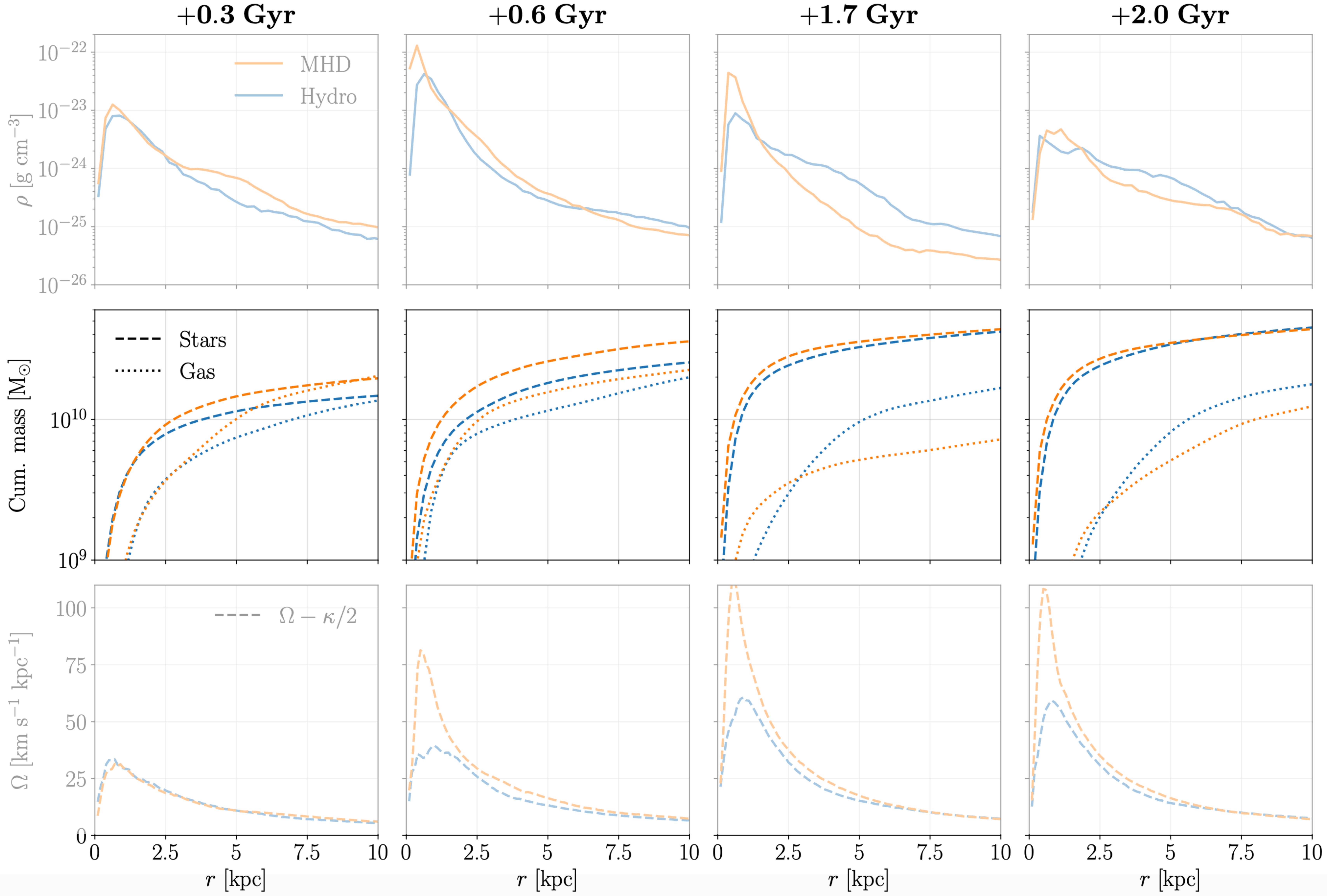

Why a bar forms in hydro runs and not in MHD ones

Magnetic fields cause a more effective transfer of angular momentum --> increases the gas concentration

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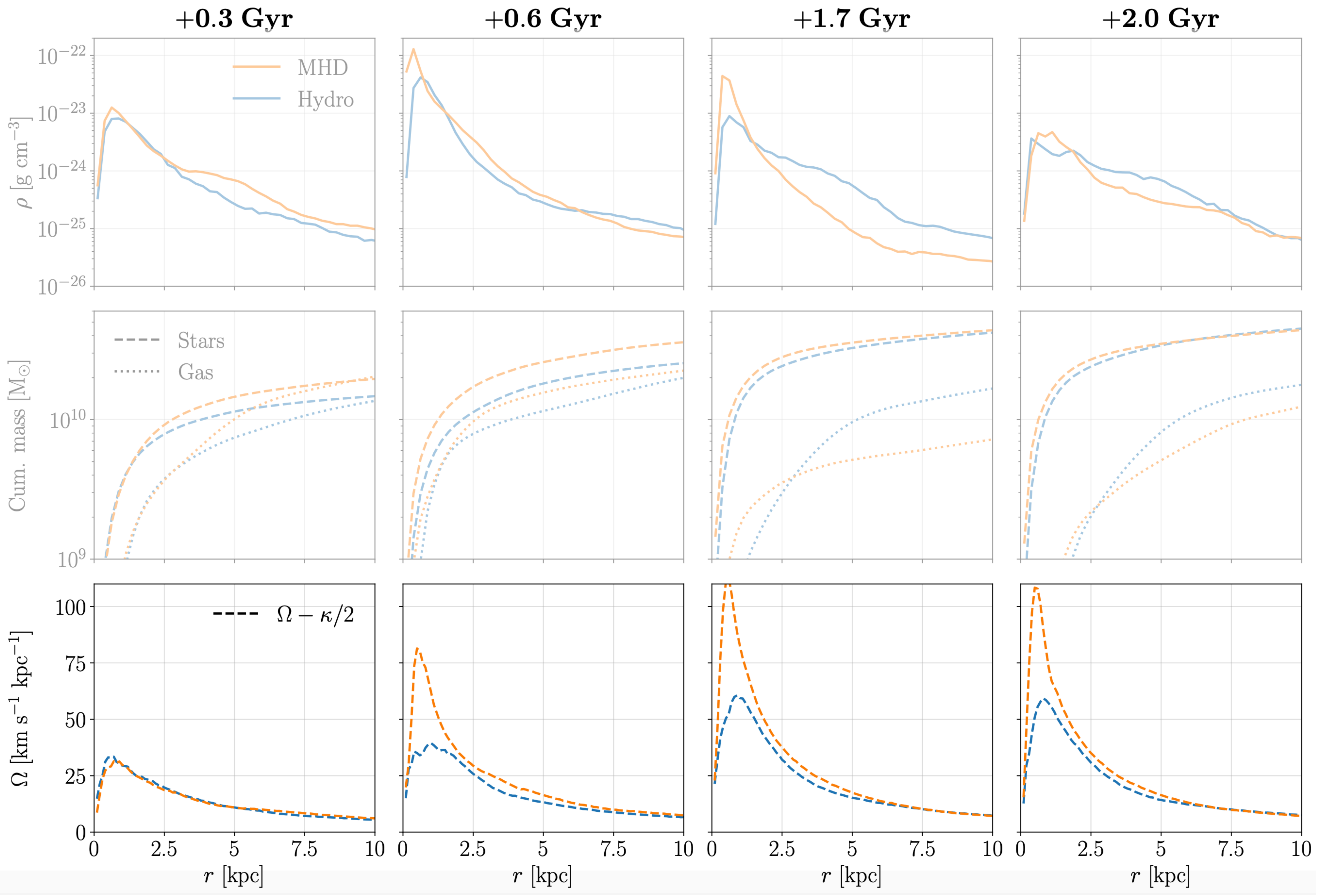
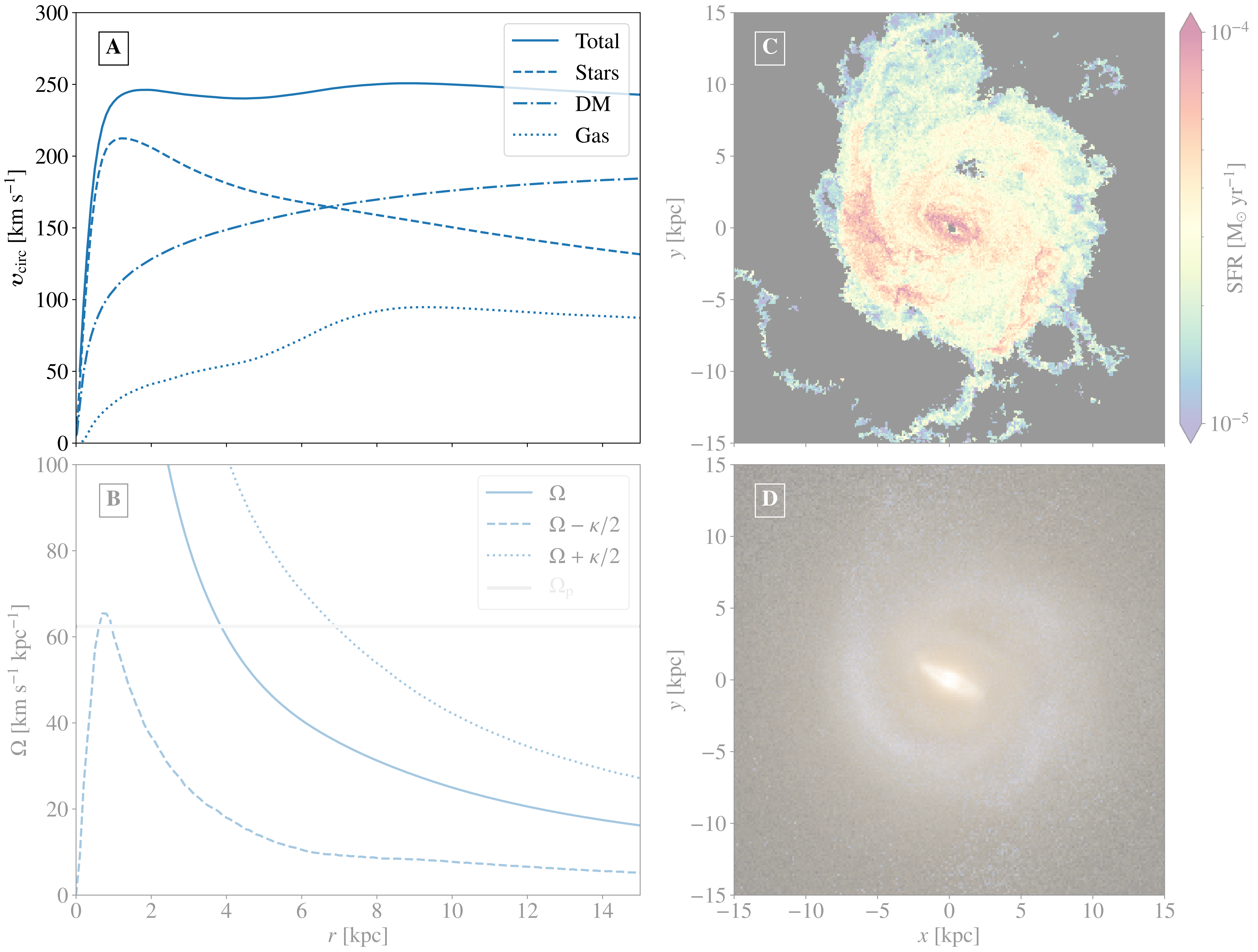
The increased concentration has a major impact on the formation of the inner Lindblad resonance (ILR)

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



Why a ring forms in hydro sims

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



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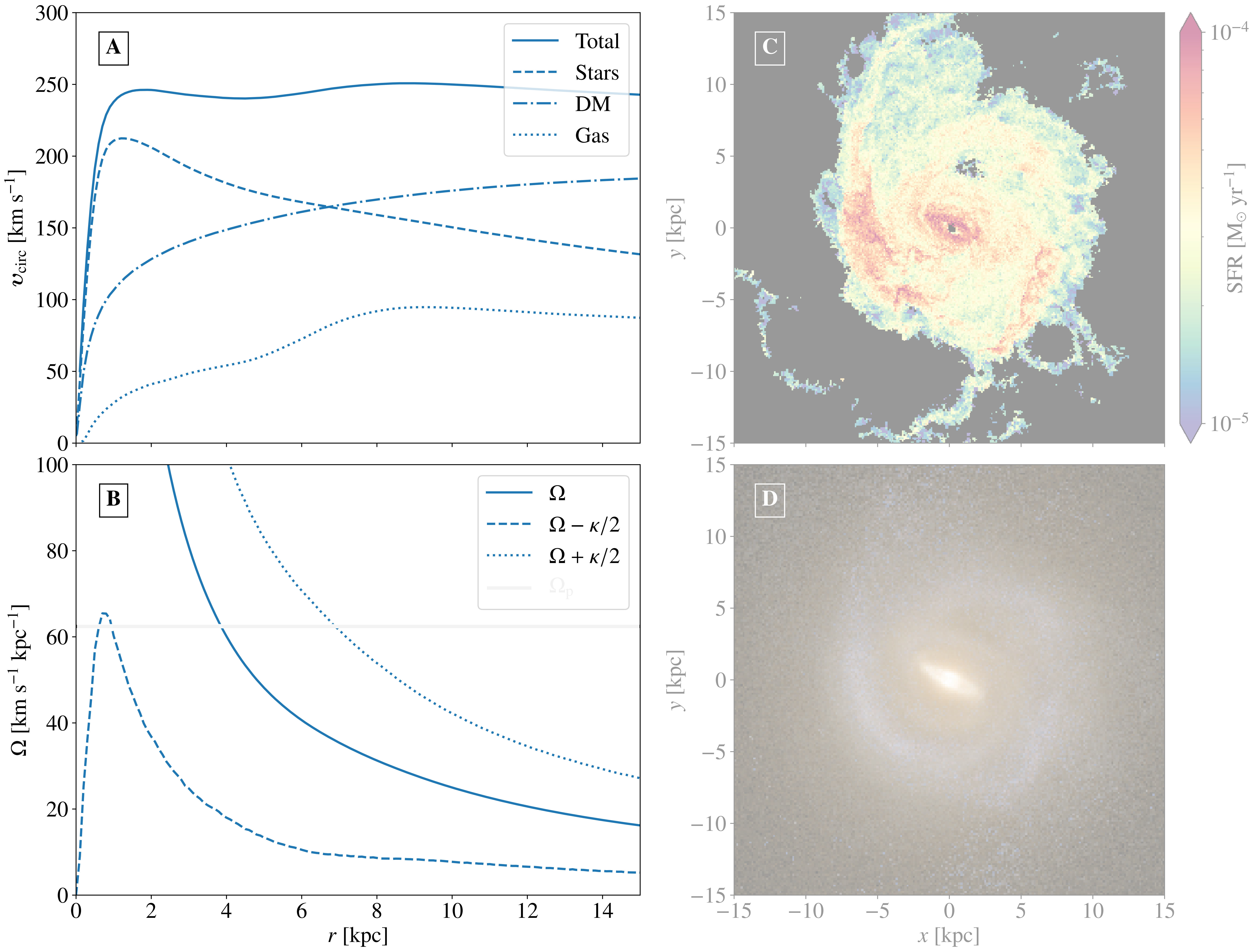
Key formula:

$$\Omega = v_{\rm circ}/r$$

$$\kappa^2 = 2\Omega\left(\Omega + \frac{dv_{\rm circ}}{dr}\right)$$



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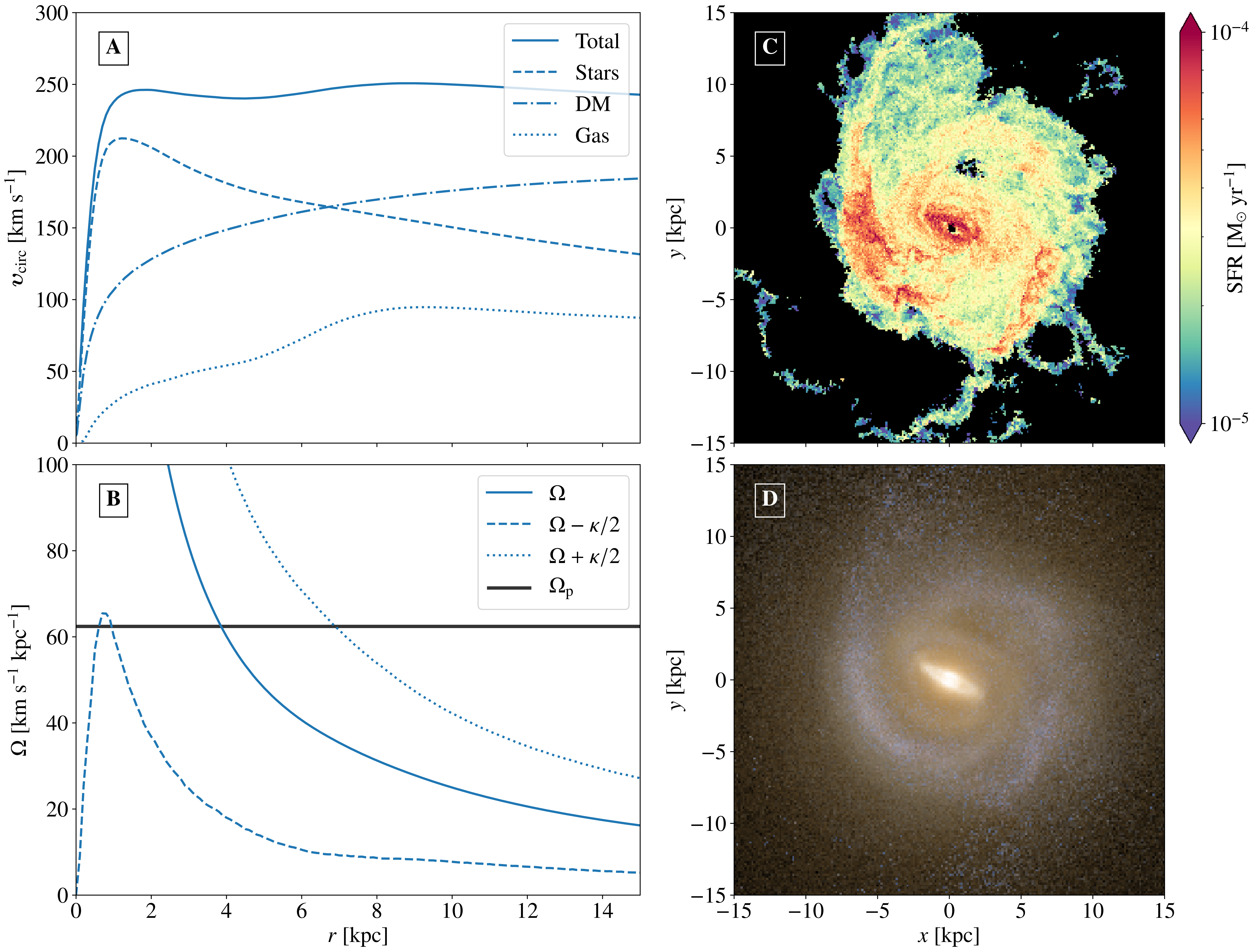
Intersection of bar pattern frequency and resonant profiles gives (radial) position of resonances



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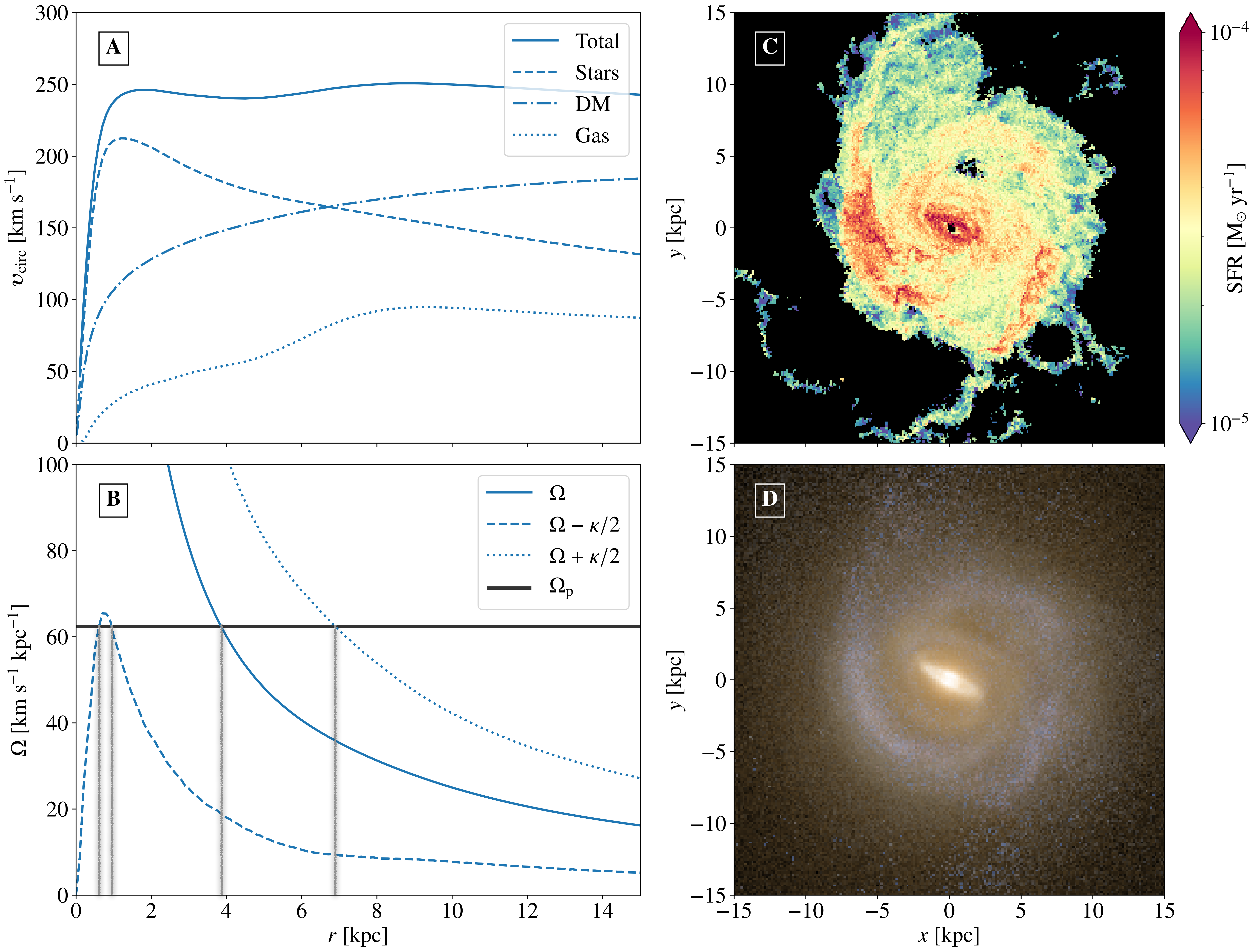


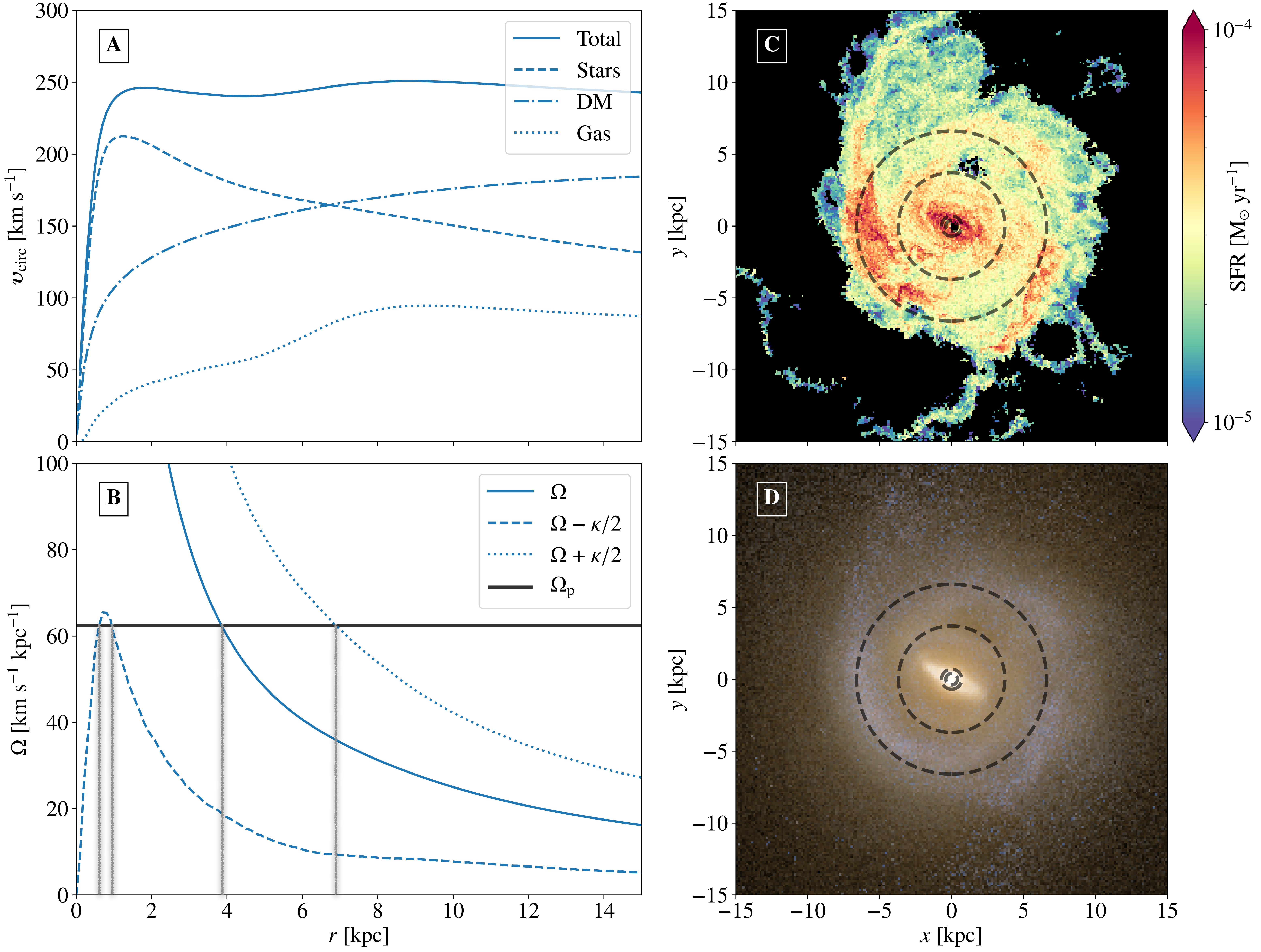
Why a ring forms in hydro sims

Bar acts to drive gas away from co-rotation resonance and towards ILR and OLR (as expected from theory!)

Results in high gas density

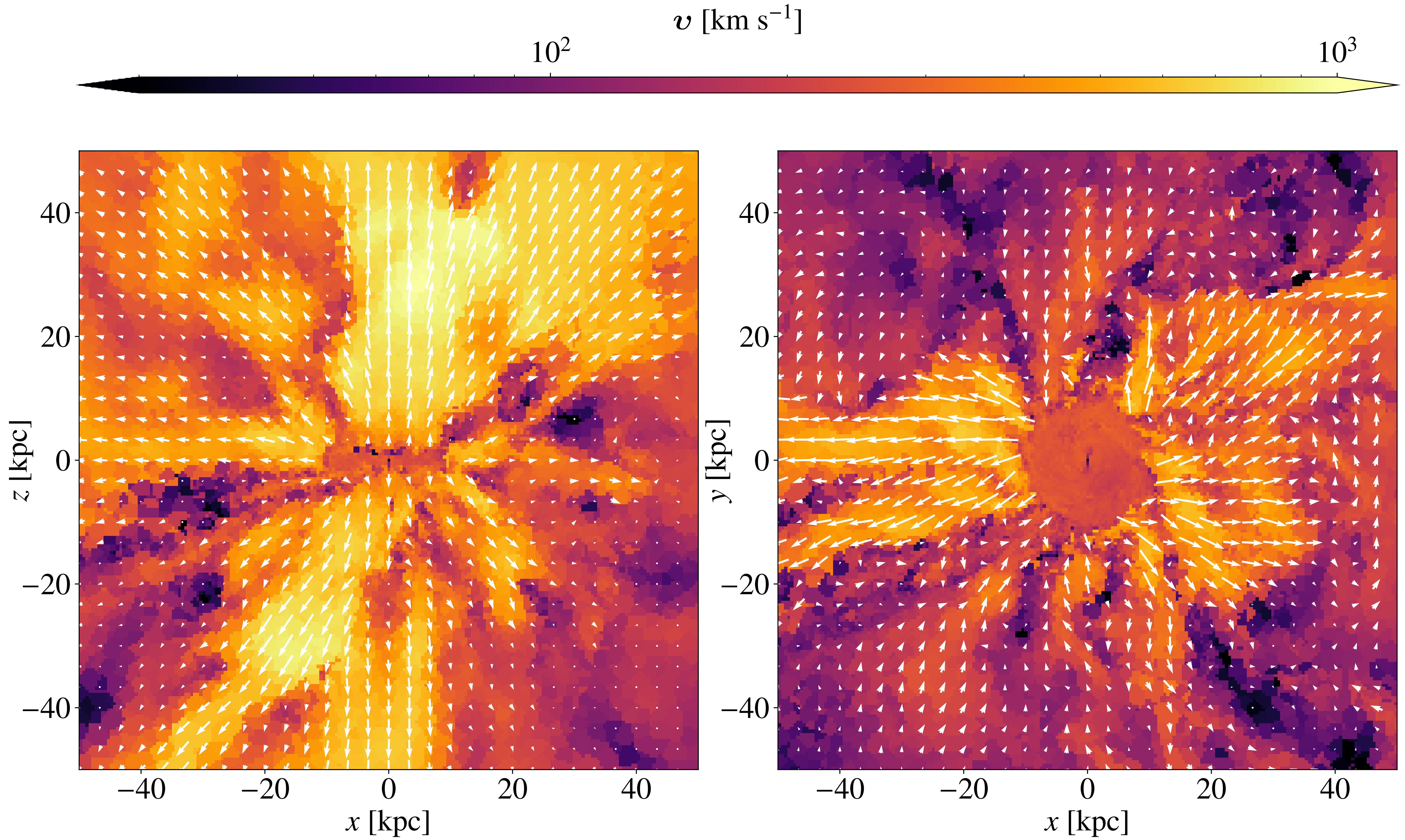
→ high star formation rate!

This causes the blue stellar ring



Why the hydro remnant stops growing

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



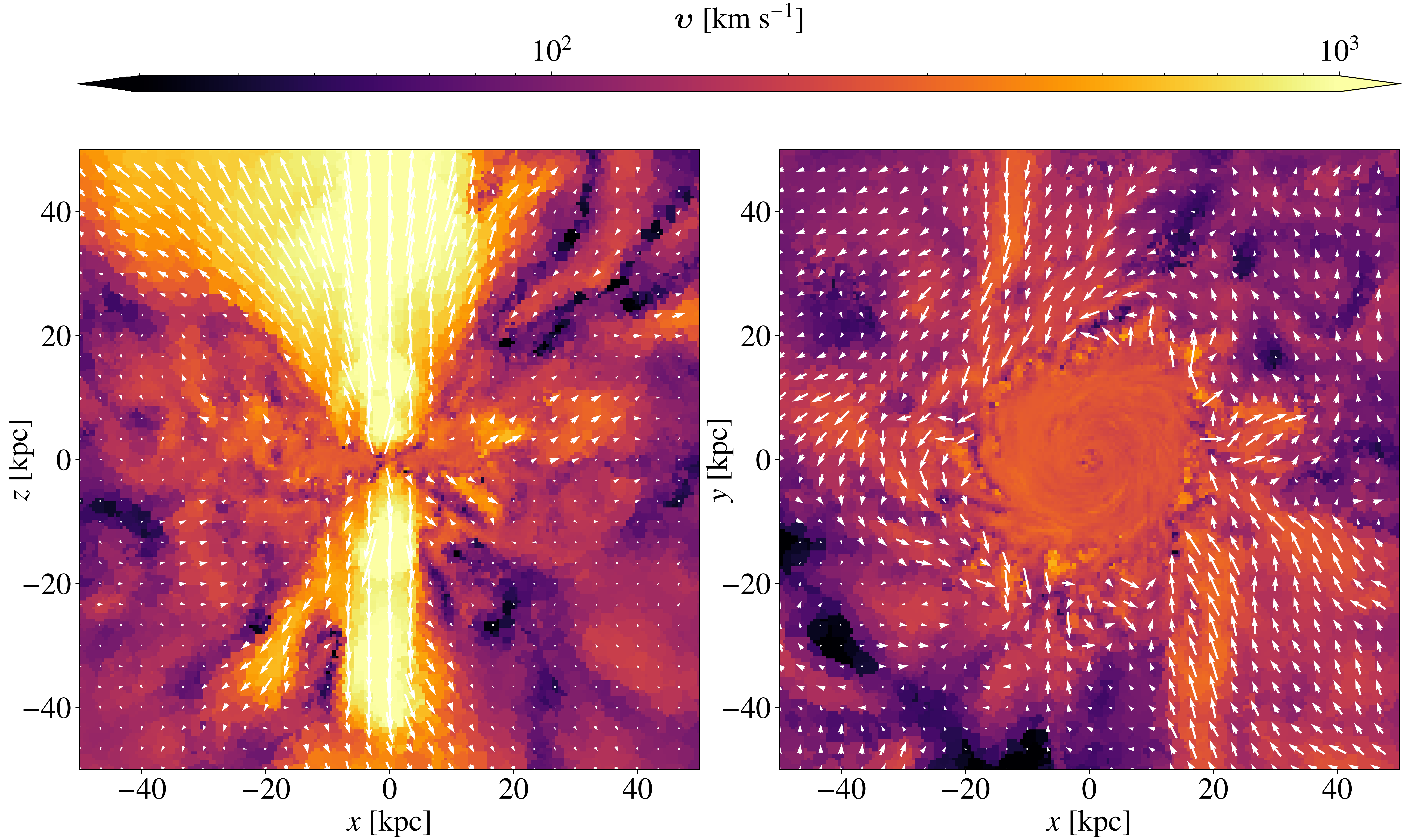
Edge-on slice showing gas velocity

Face-on slice showing gas velocity

Why the MHD remnant grows larger

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

Star formation is more distributed in MHD sims; stellar wind is weaker, gas at the outskirts retains its ang. mom.



Edge-on slice showing gas velocity

Face-on slice showing gas velocity

Magnetic fields have a significant impact on mergers!

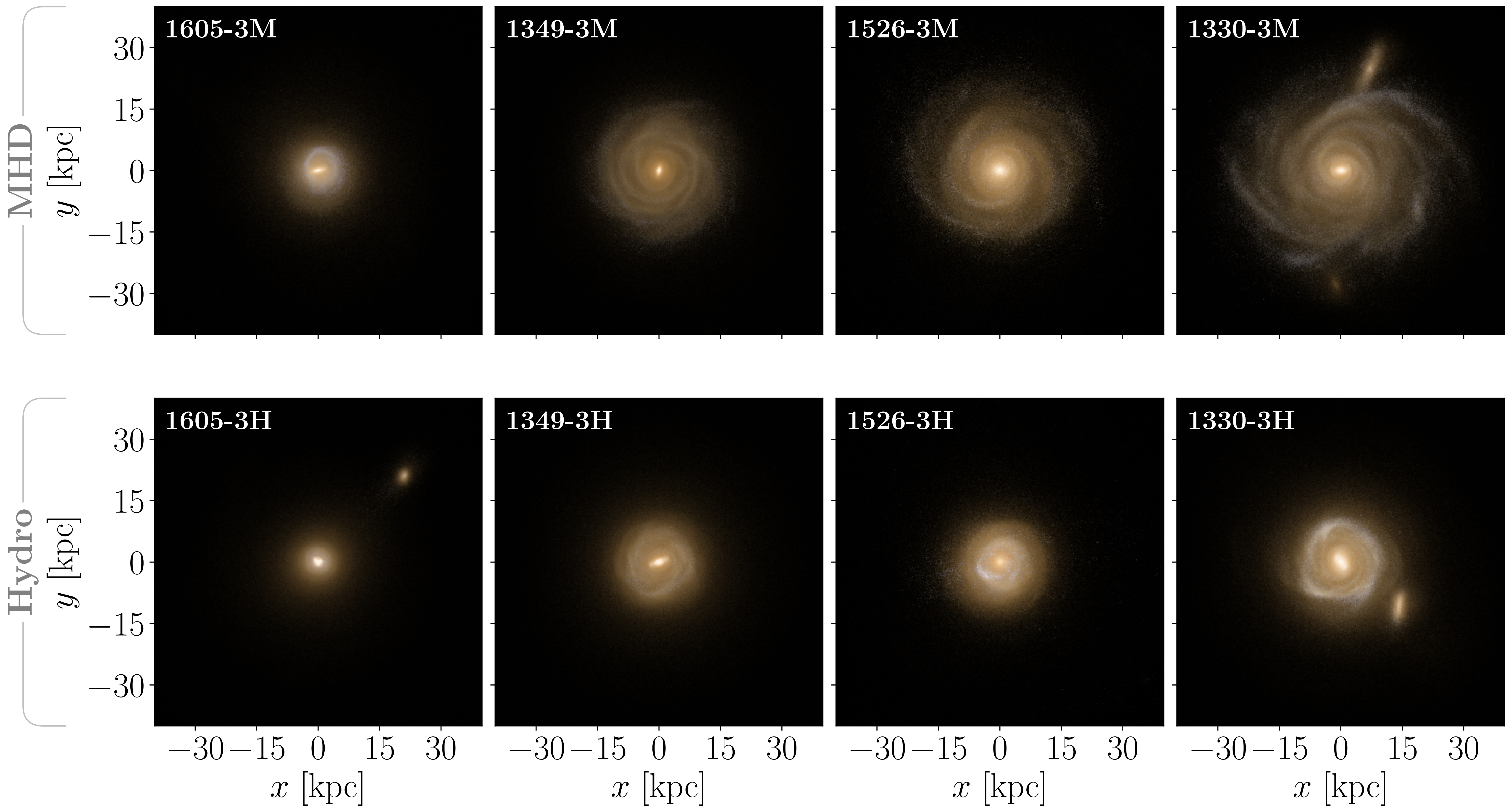
Summary

i) Magnetic field alters ang. mom. transport (typically makes initial remnant smaller)

ii) This suppresses a bar instability in MHD case

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

iv) More compact star formation leads to strong stellar wind (disrupts CGM) (and therefore growth of remnant)



Mock gri visual image of merger remnants from stellar light properties

Summary

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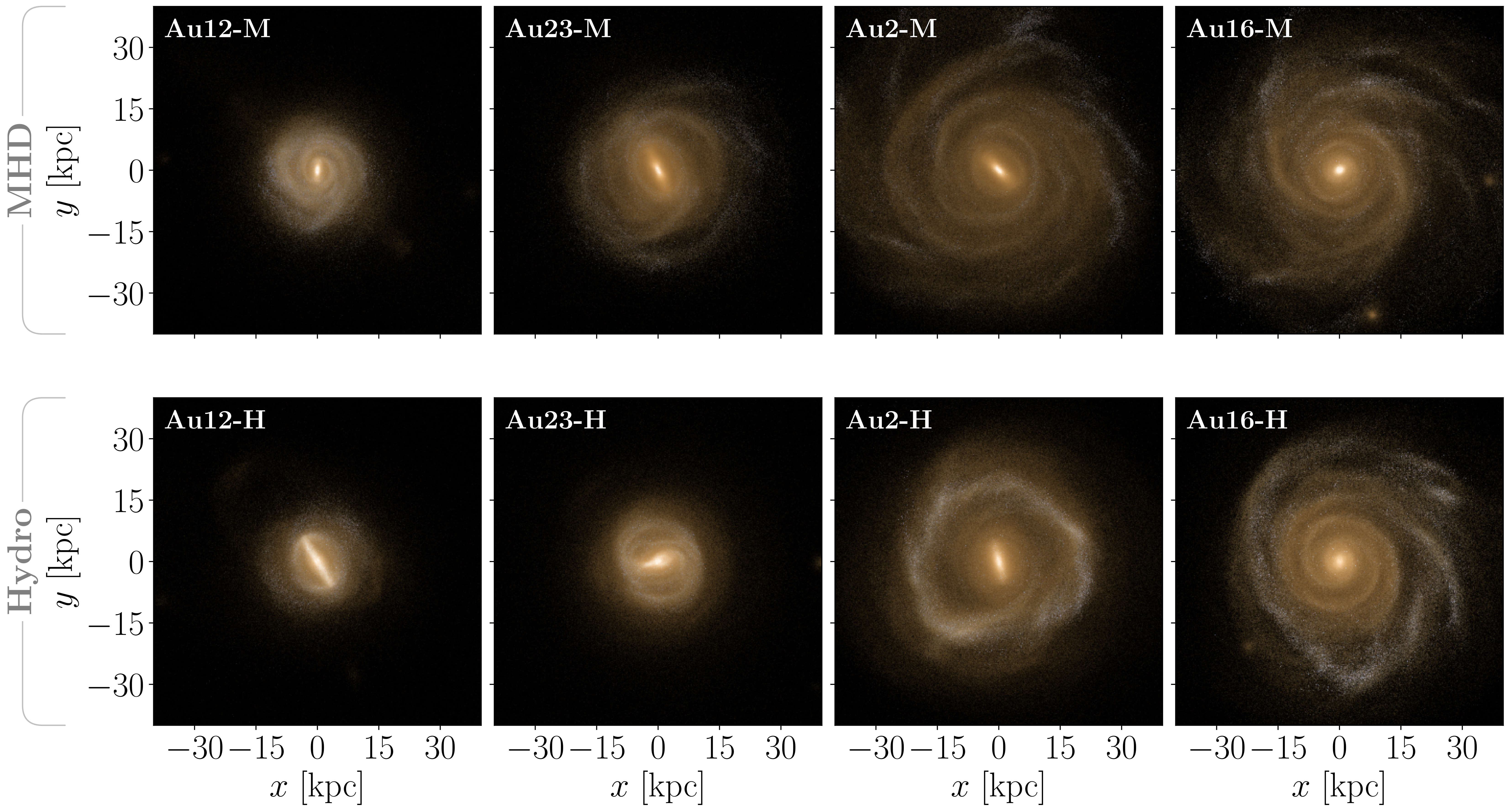
Magnetic fields have a significant impact on *disc galaxy evolution as a whole!*



Mock gri visual image of more isolated (but still cosmological galaxies) from stellar light properties

DFG
Deutsche Forschungsgemeinschaft

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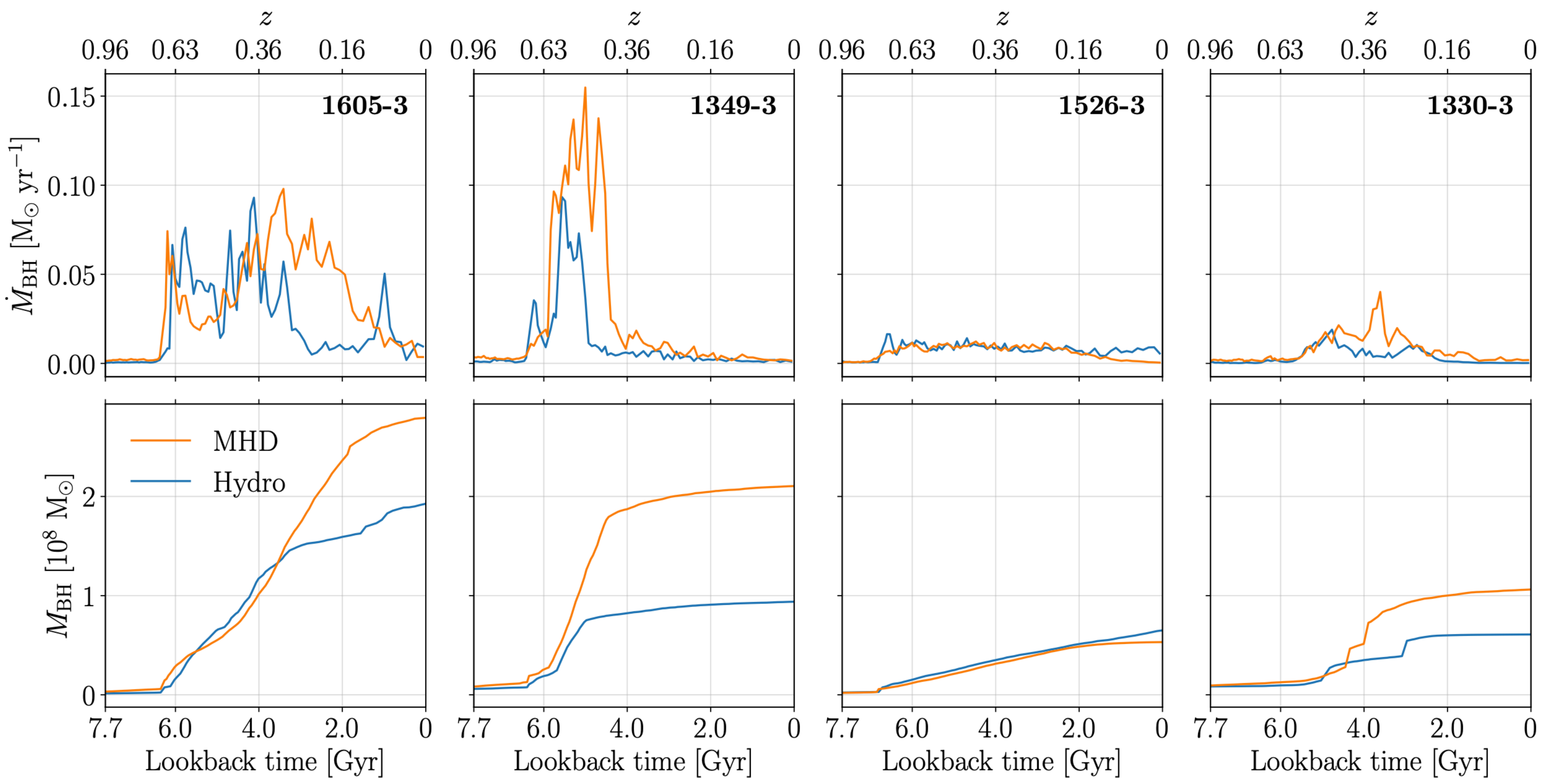
and German Science Foundation (DFG) under grant 444932369.

The impact on the SMBH

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

→ indeed, black holes can grow twice as large in MHD sims!

(but final mass still within errors of observed BH-stellar mass relation)



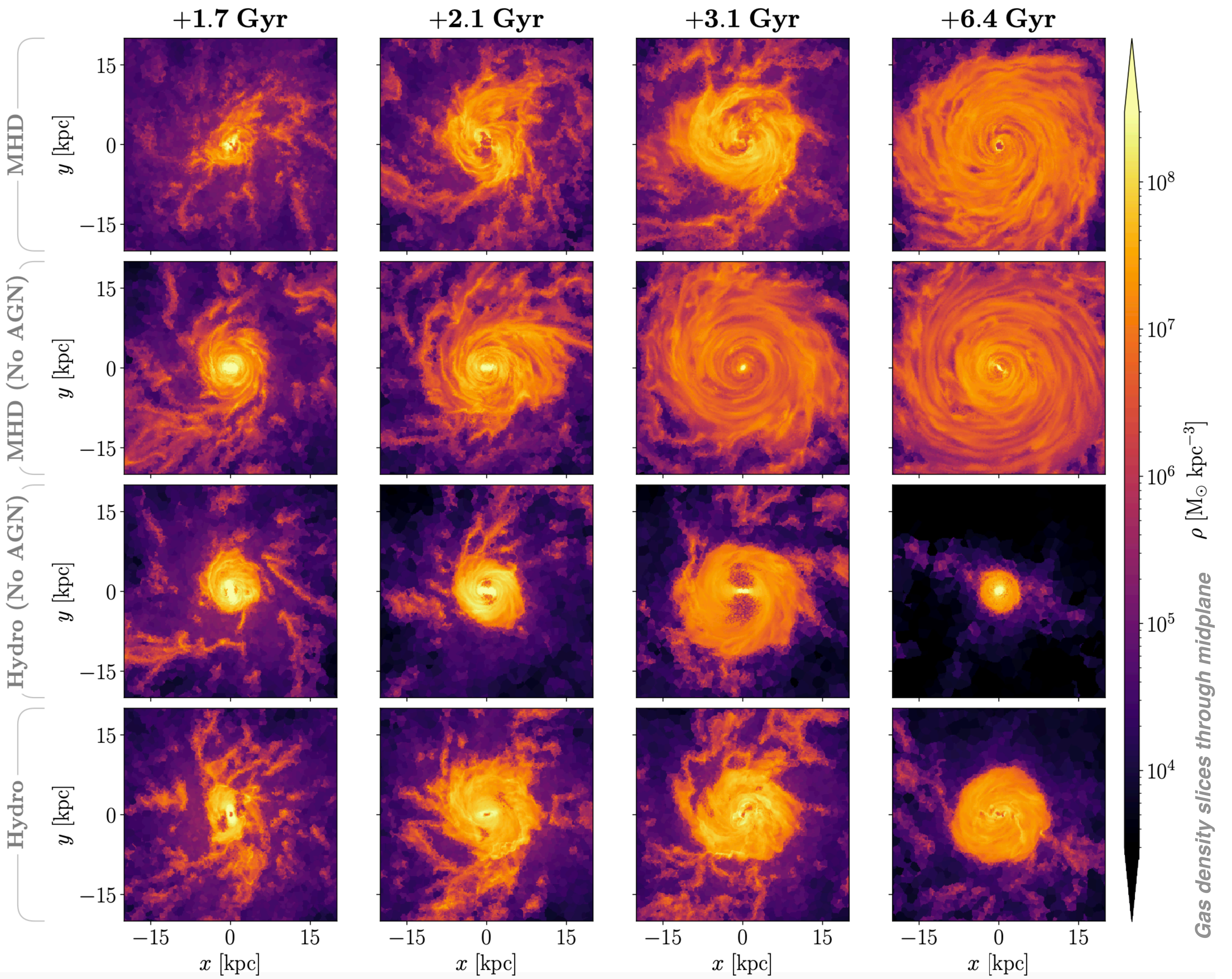
Black hole accretion rate and mass over time

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.



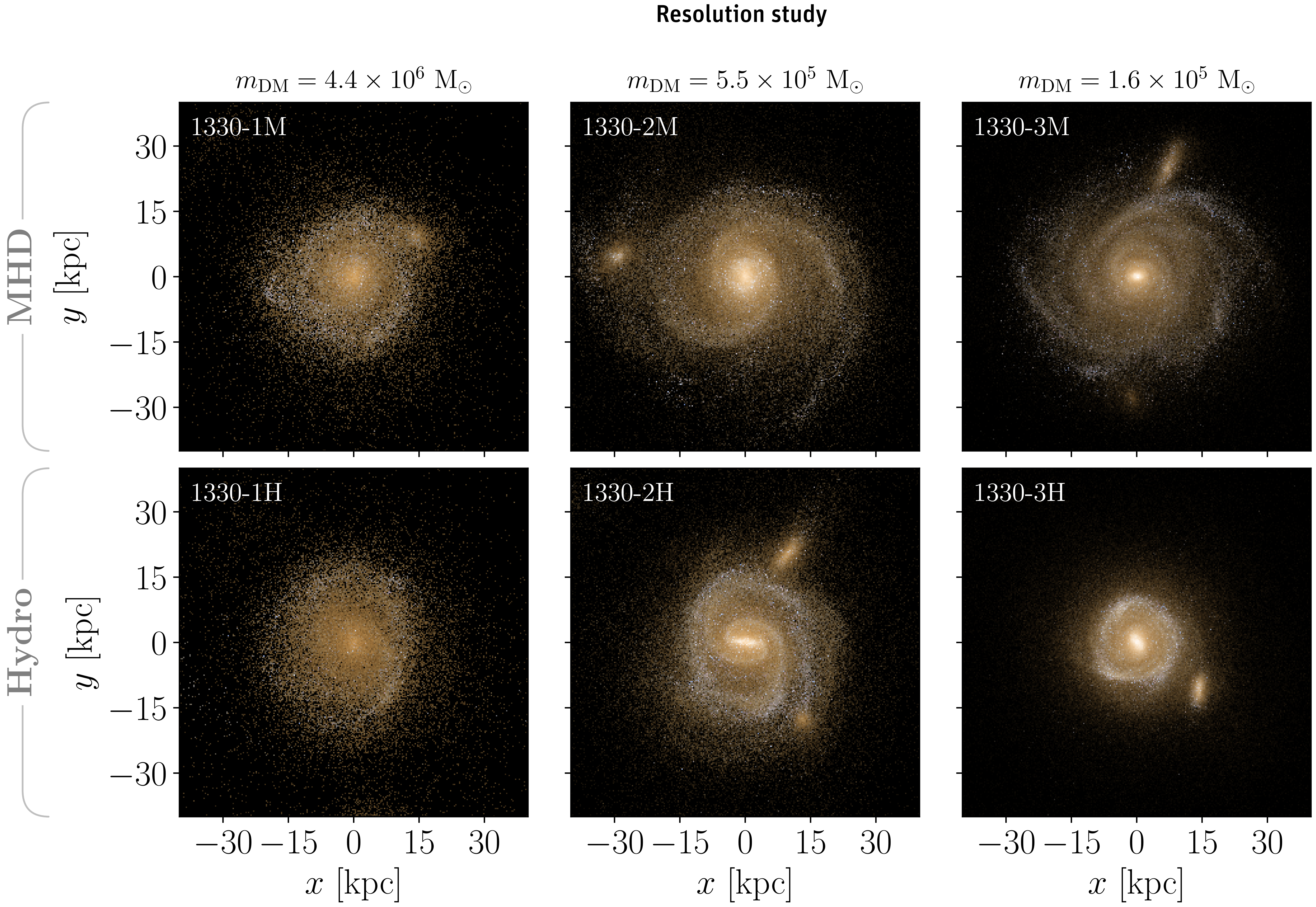
Bonus slide

The impact of resolution

Sufficient resolution is required to realise the effect

This originates from the need to resolve sufficiently small-scale eddies

(i.e. to realise a small-scale dynamo!)



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

Bonus slide

Evidence for a small-scale dynamo

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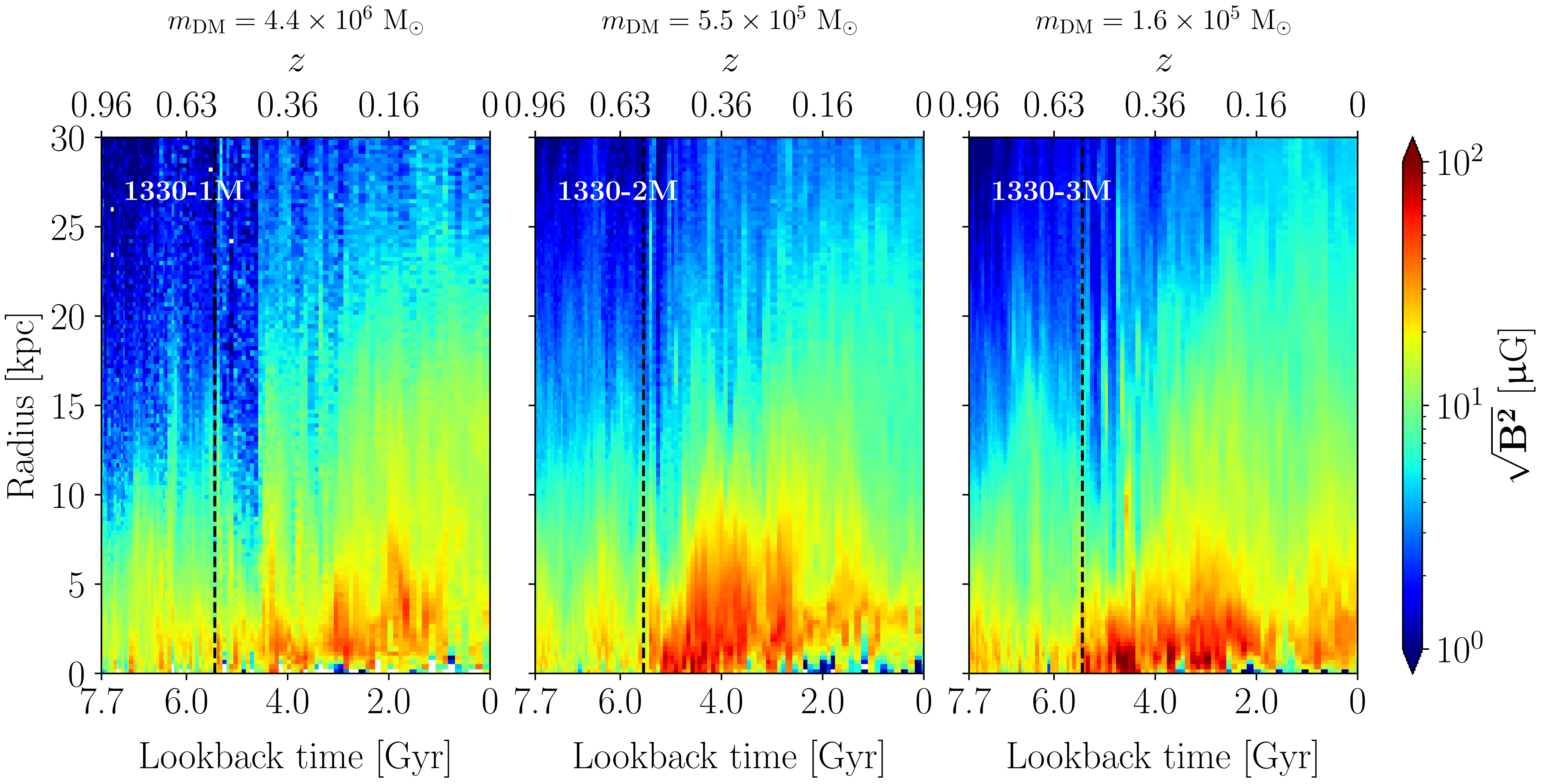
Resolution study



Mean radial magnetic field strength in the disc as a function of time
(Resolution becomes finer left to right)

Bonus slide

Evidence for a small-scale dynamo

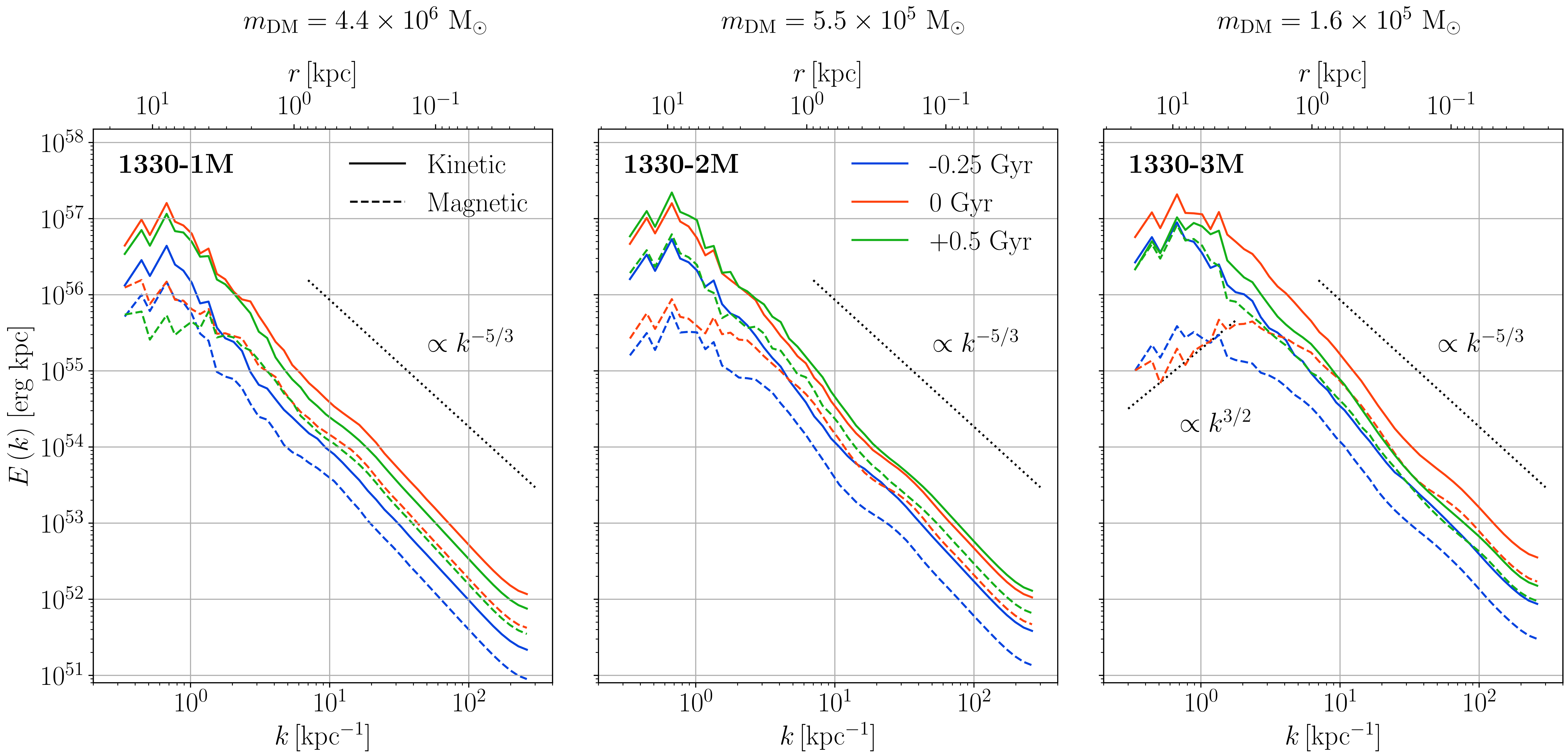
Almost identical initial increase in kinetic energy (solid)

Inverse cascade in magnetic energy (dotted)

Higher resolution → smaller eddies → quicker turnover time

More quickly onto non-linear phase of dynamo; respond on larger scales

Resolution study



Kinetic and magnetic power spectra
(Resolution becomes finer left to right)

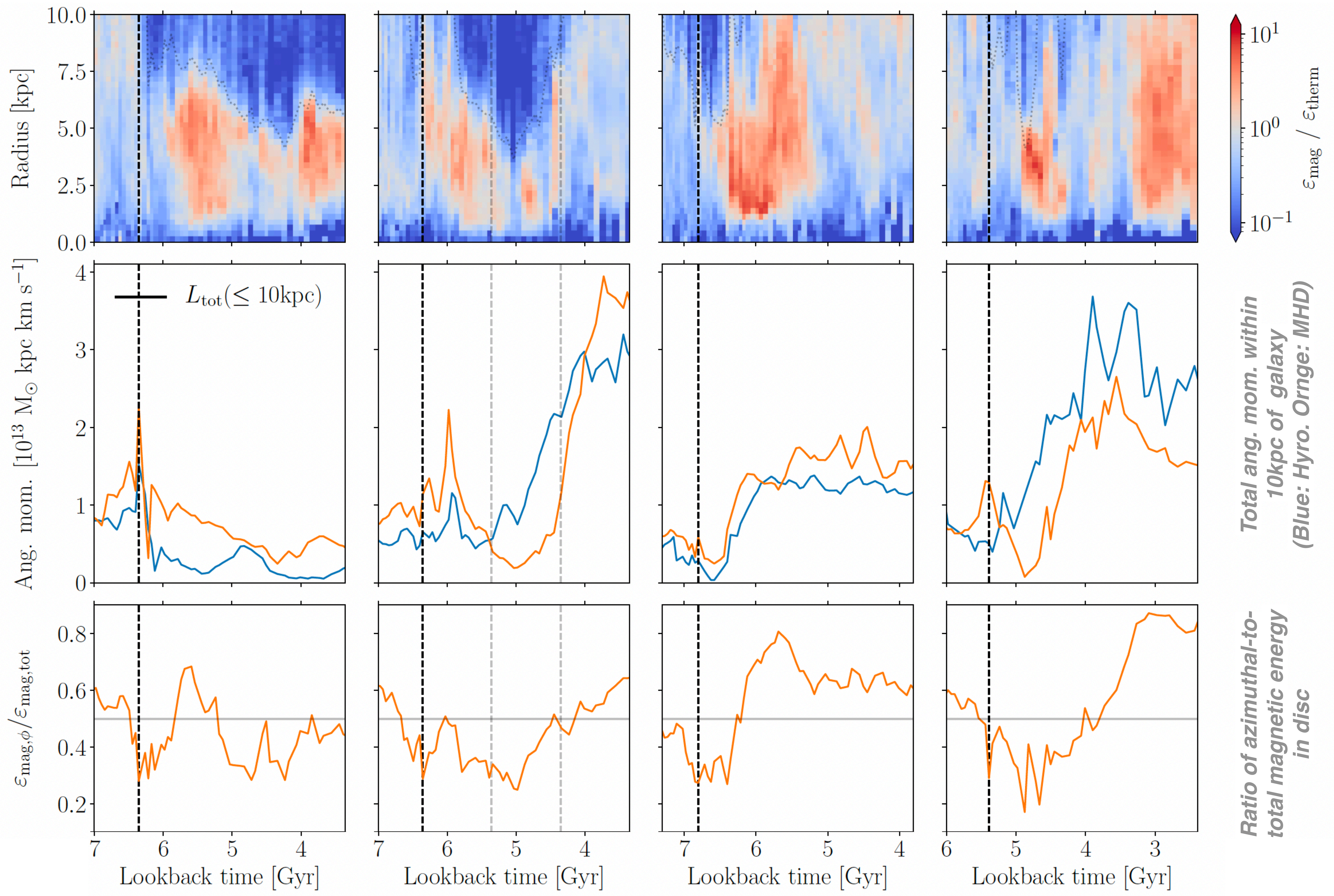
Bonus slide

Impact of magnetic field orientation

Magnetic field typically predominantly non-azimuthal when amplified

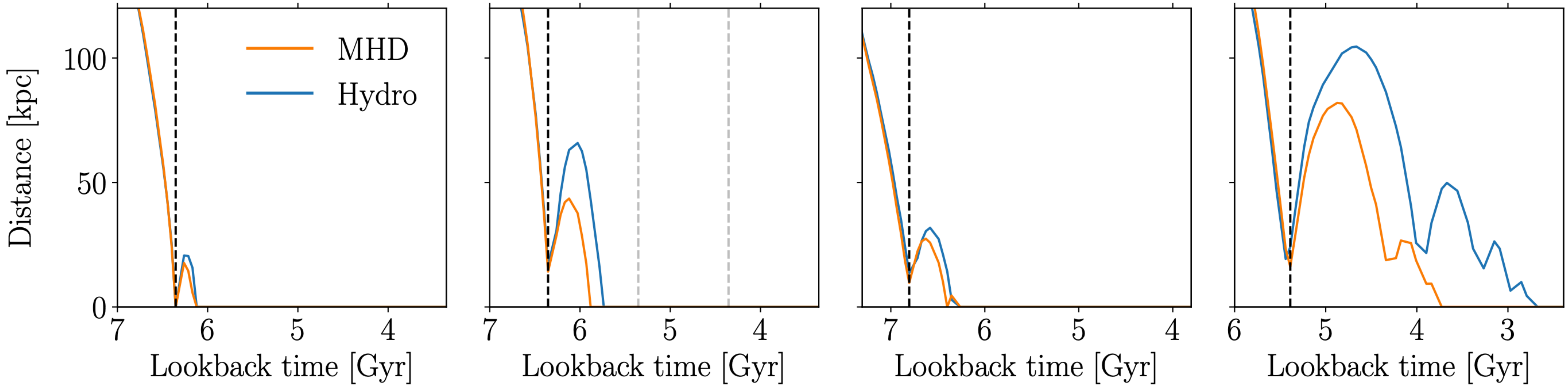
→ leads to efficient ang. mom. transfer

Not seen in one scenario, where the ang. mom. of the progenitors align well pre-merger



Bonus slide

Impact on angular momentum



Distance between the two merger progenitors over time

Angular momentum transfer speeds up merger

(most effective when merger is "in-spiralling")