Galaxy cluster simulations

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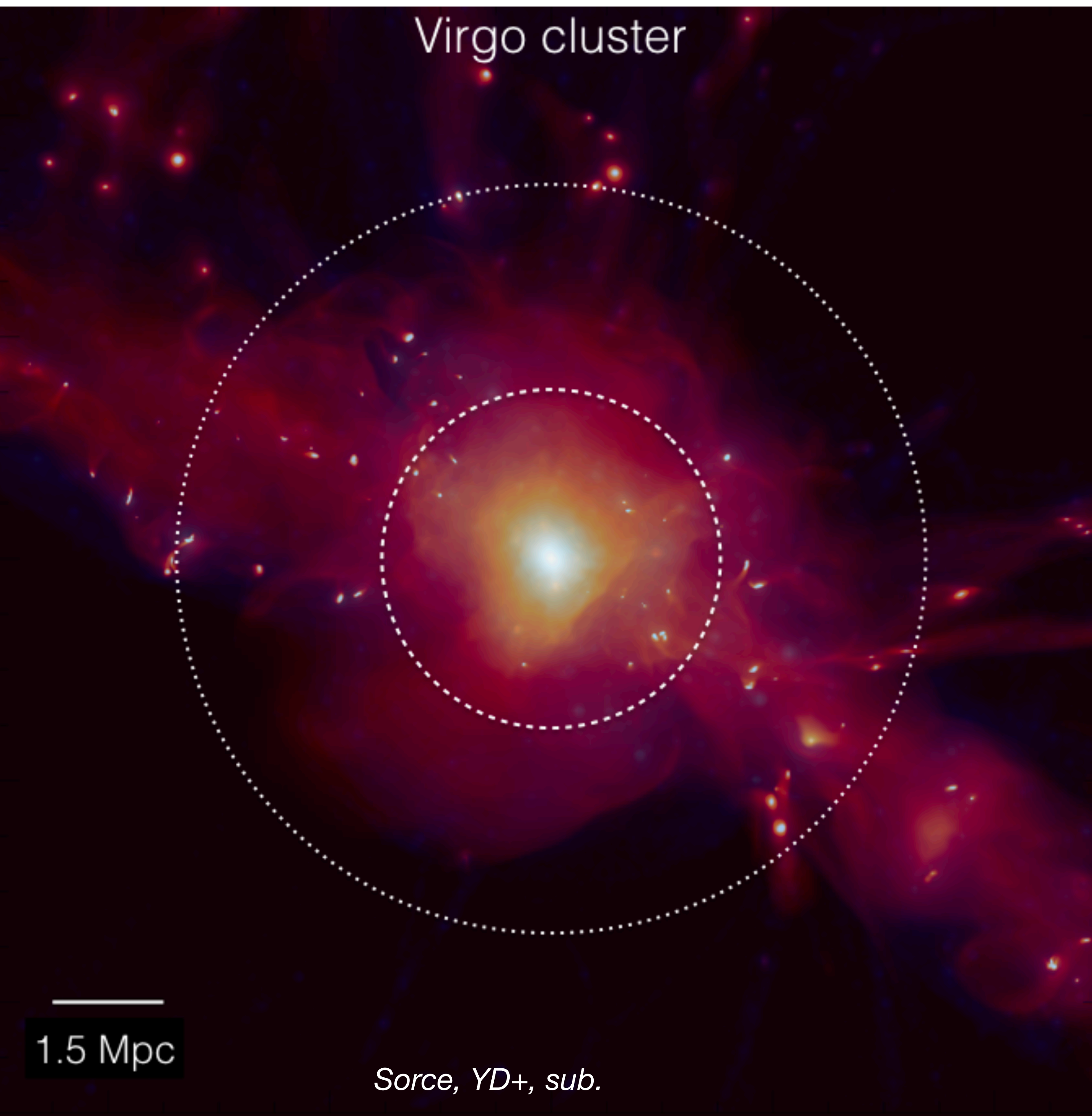
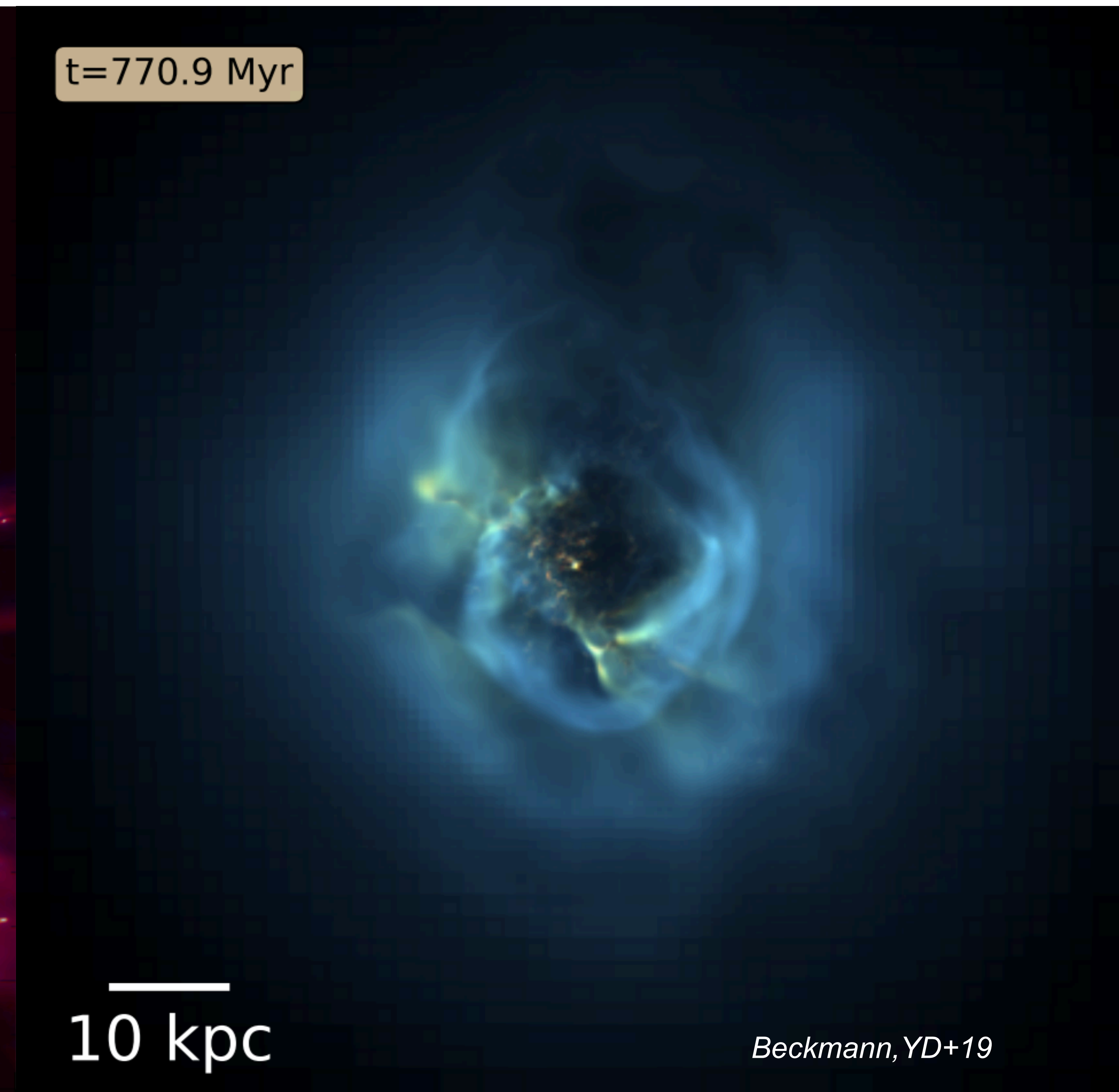


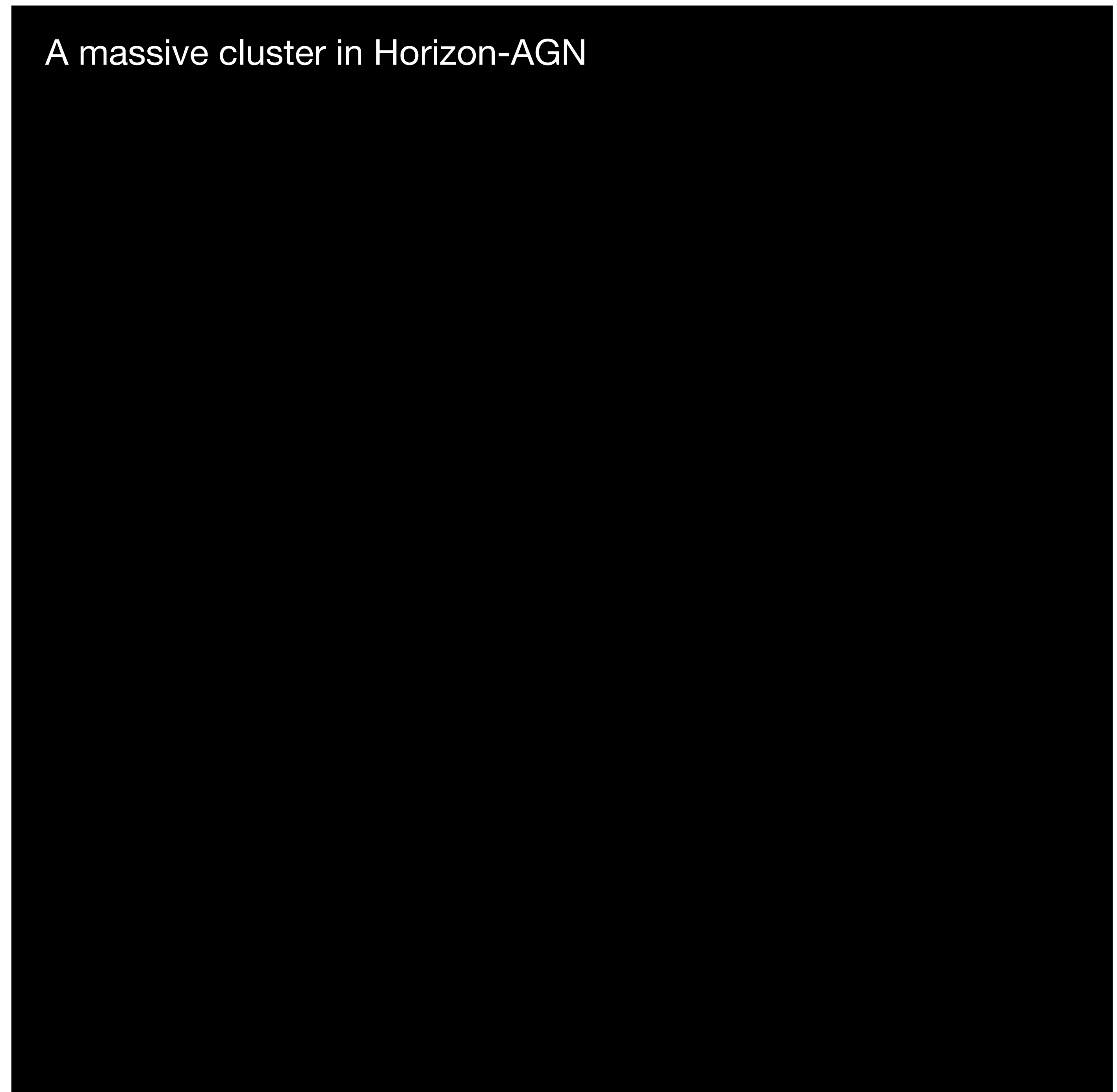


State-of-the-art* of cosmological simulations of galaxy clusters

- Hydrodynamics (AMR or SPH)
- ~kpc resolution
- Gas radiative cooling
- Star formation + stellar feedback
- **Supermassive black holes and Active Galactic Nuclei**

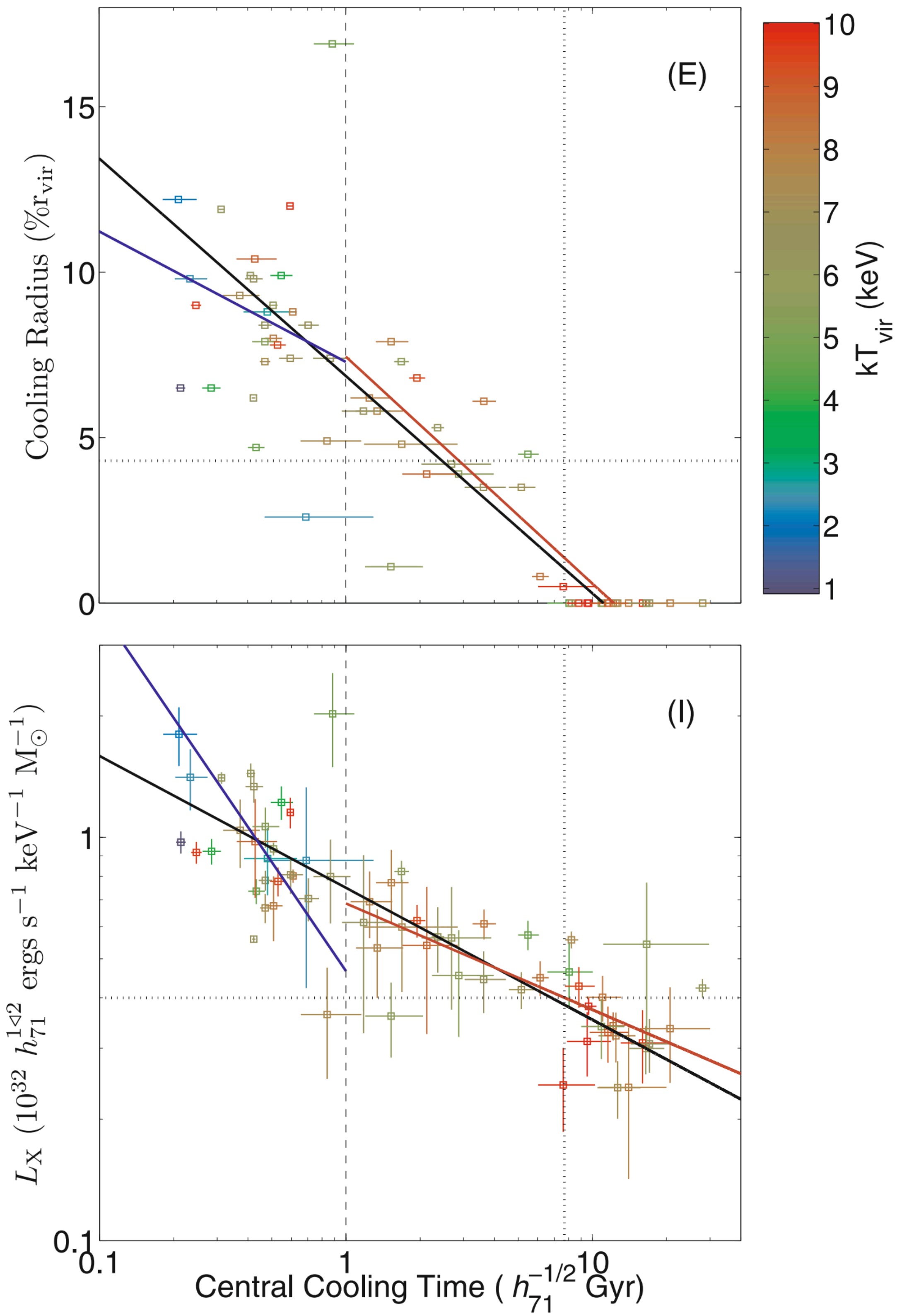
- OWLS(Schaye+10) / COSMO-OWLS(LeBrun+14) / BAHAMAS(McCarthy+17)
- Horizon-AGN(Dubois+14) / Horizon-Run5(Lee+20) / Extreme-Horizon (Chabanier+20)
- Eagle(Schaye+15) / C-Eagle(Barnes+17) / Hydrangea(Bahé+17)
- Illustris(Vogelsberger+14) / Illustris-TNG(Pillepich+18)
- Magneticum(Dolag+16)
- Rhapsody-G(Hahn+17)
- YZiCS(Kim+20)
- …

Temperature map



* Simulations with a sample (>10) of groups/ clusters

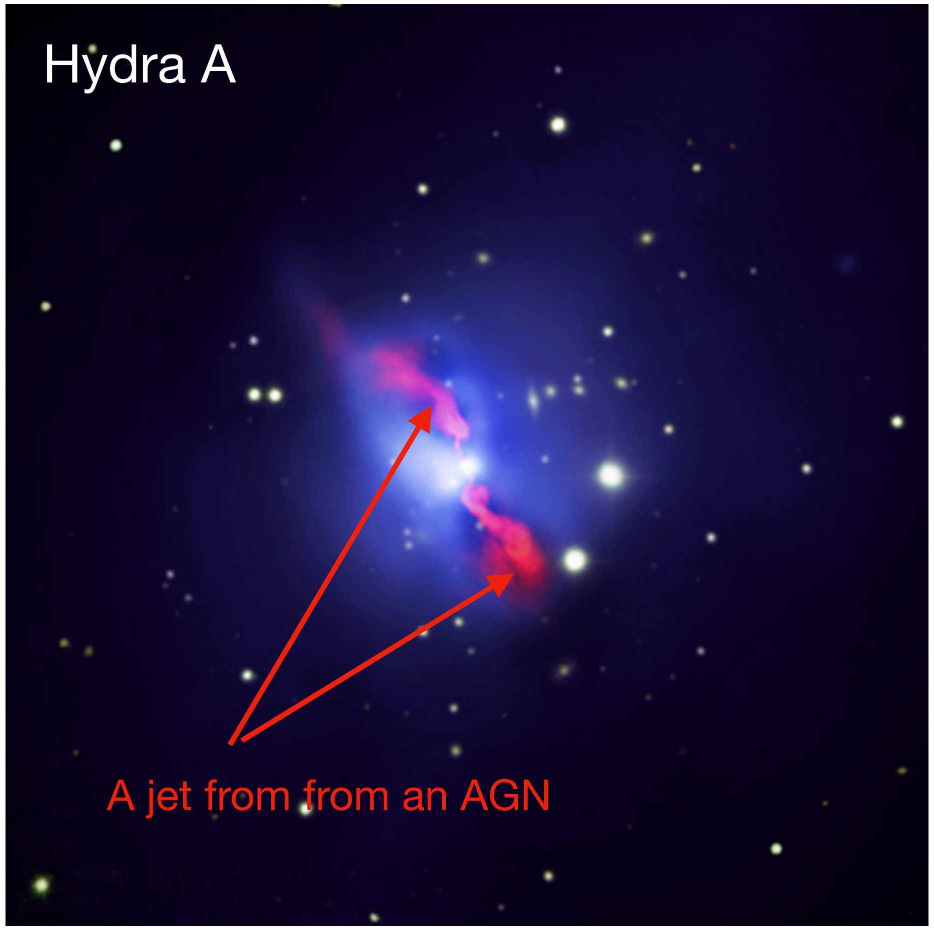
Why are AGN so important in clusters?



Hudson+10

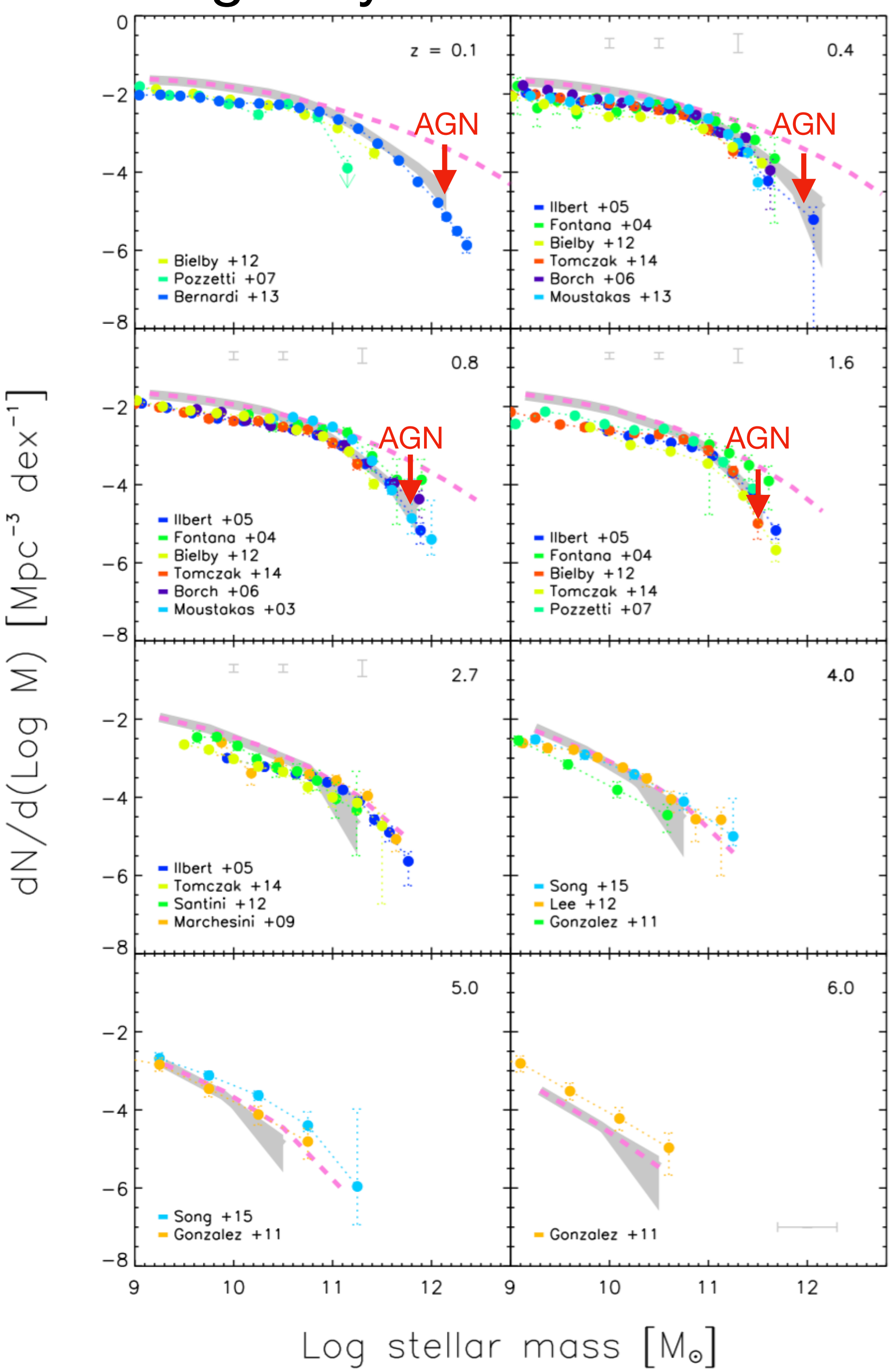
Cooling times < t_{Hubble} for cool-core clusters.

Cooling in halos is a runaway process (« cooling catastrophe ») that must be counter-balanced by a heating source of some sort.



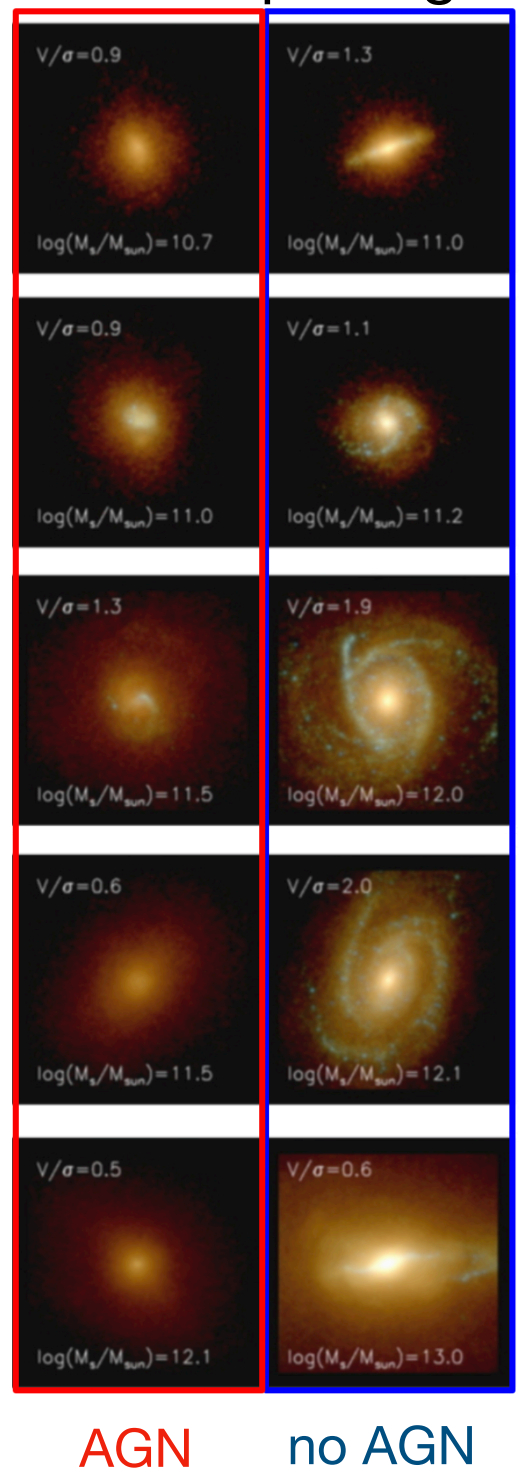
AGN is a solution for many galaxy/halo properties

galaxy mass functions



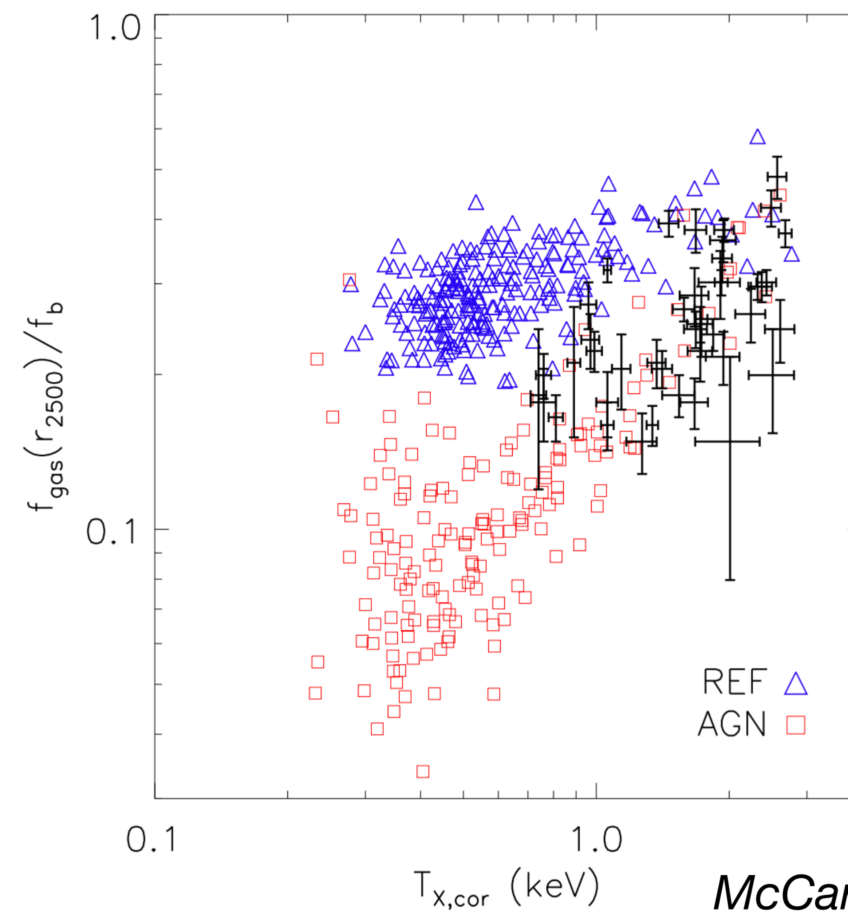
Kaviraj+17

BCG morphologies



Dubois+13,16

Cluster gas fractions

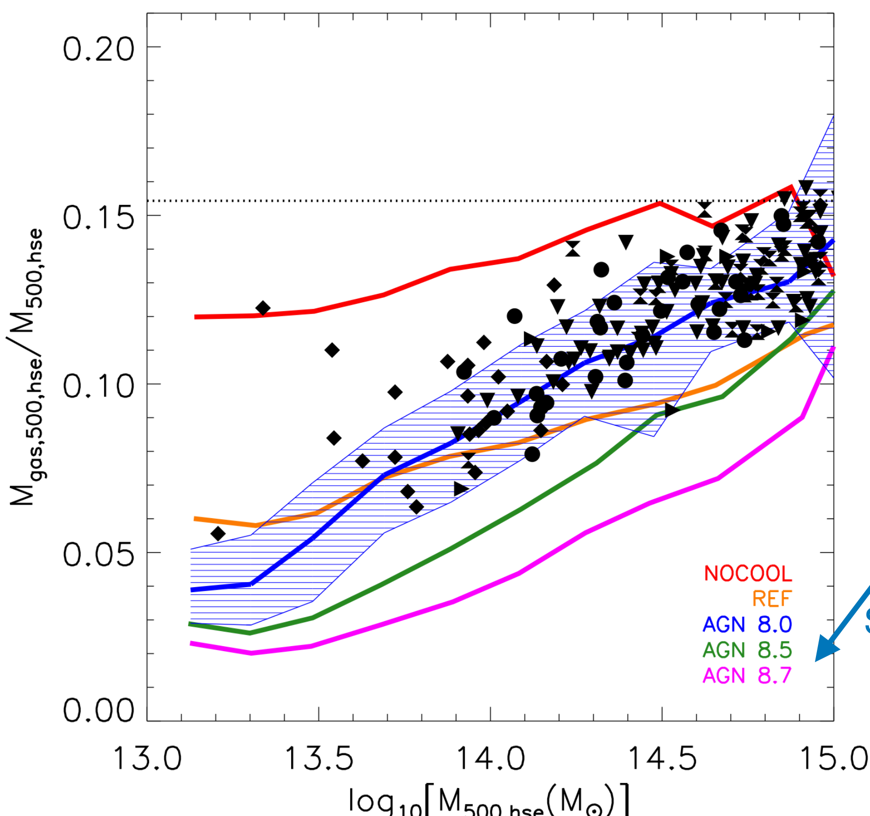


McCarthy+10

+ X-ray gas properties + dark matter cusp/core + galaxy sizes + metallicity

Some level of fine-tuning*

(old) Gadget SPH



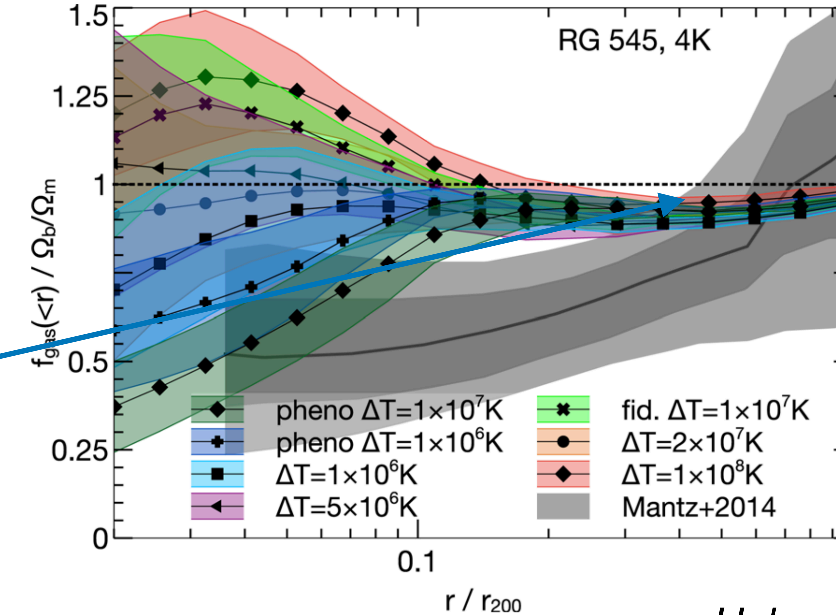
Le Brun+14

Accumulate energy before release until dT>10^8 K or…

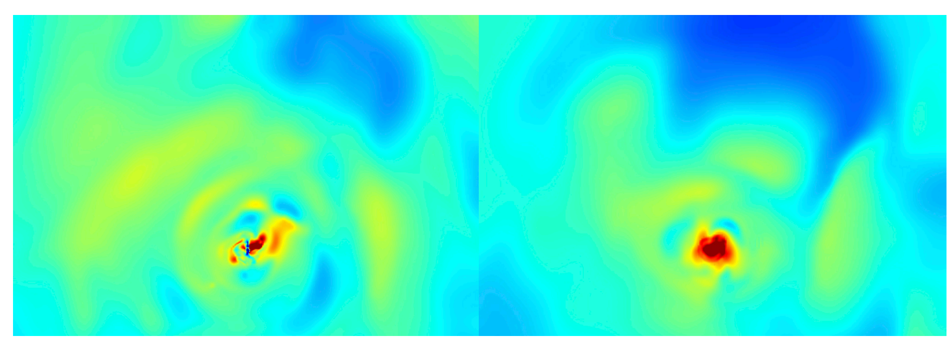
Mostly irrelevant effect there

Strong effect here

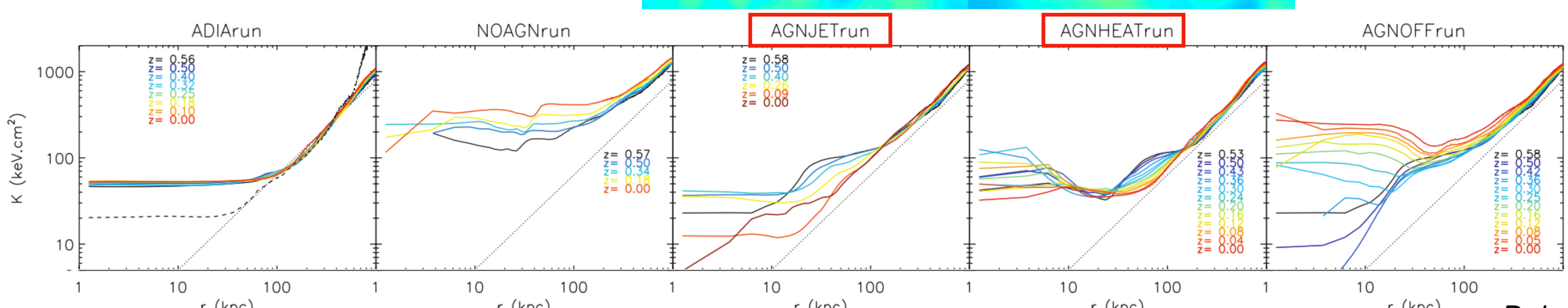
Ramses AMR



Hahn+17



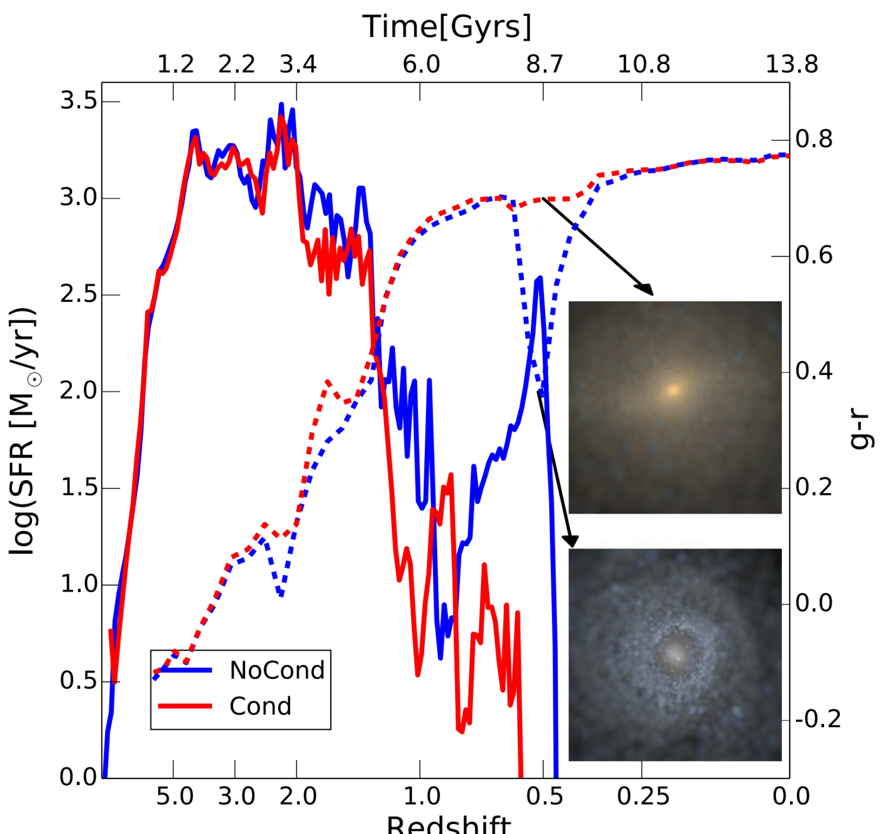
entropy



Dubois+11

*It is not just about how much energy is released but about how it is released (Dubois+11,12; Weinberger+17), how gas is accreted (Gaspari+,Angles-Alcazar+), how the BH moves, etc.
+ how the code handles shocks and instabilities, i.e. redistribute the feedback energy into the hot gas (Ogiya+18)

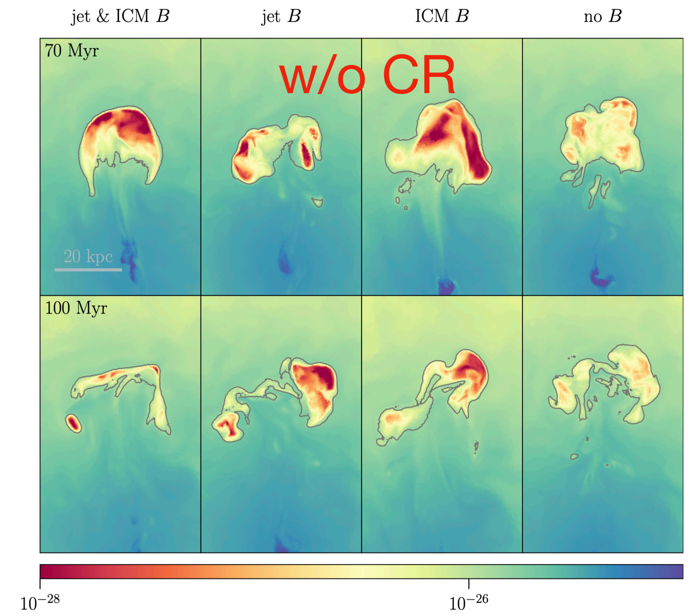
Beyond pure HD effects
(what about magnetic fields? conduction? cosmic rays?)



Kannan+17

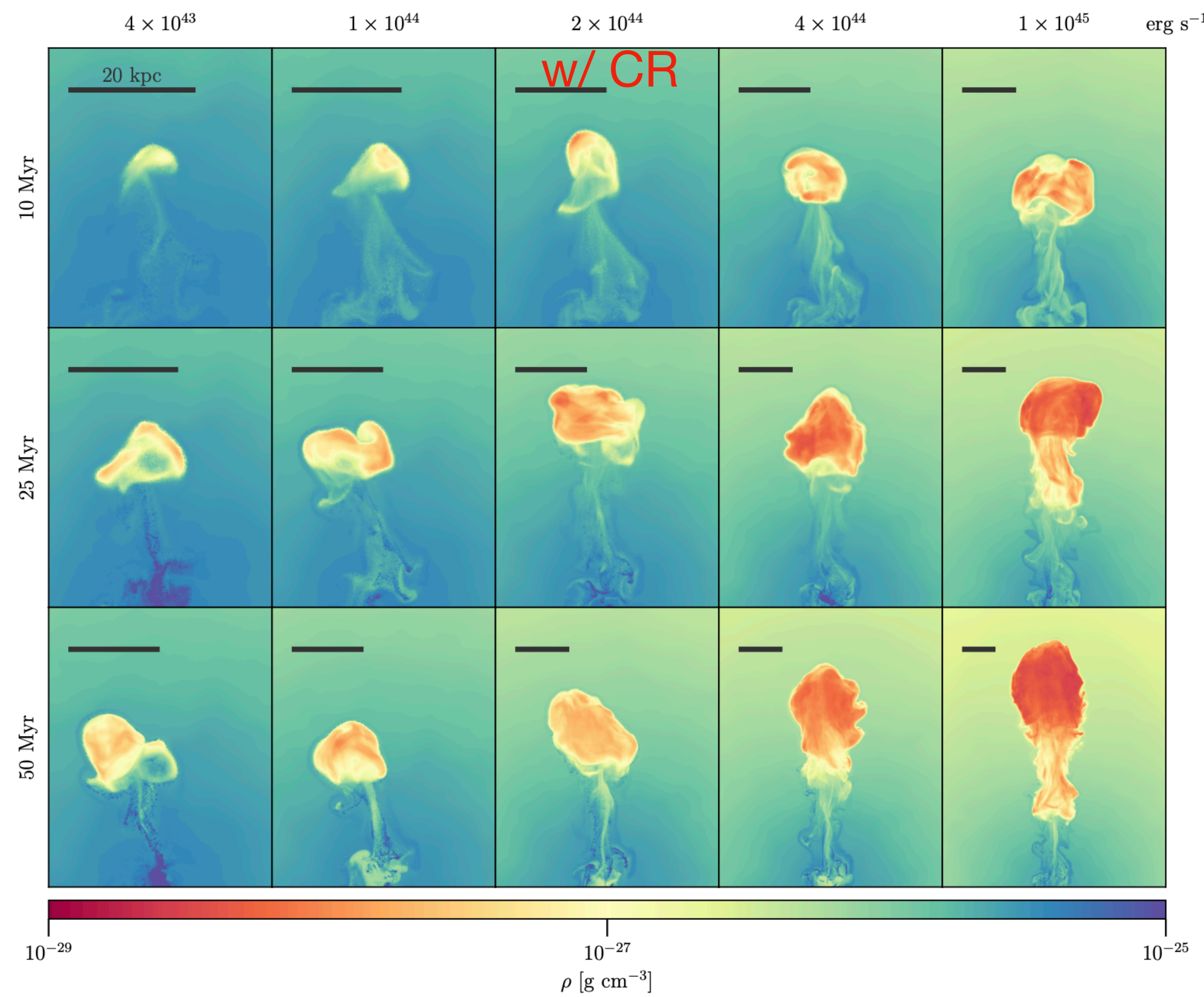
Conduction is not a game changer but it helps to enhance the impact of AGN (significant temperature effect since conductivity goes like $T^{2.5}$)

See also Parrish+10; Ruszkowski+11; Yang & Reynolds 16



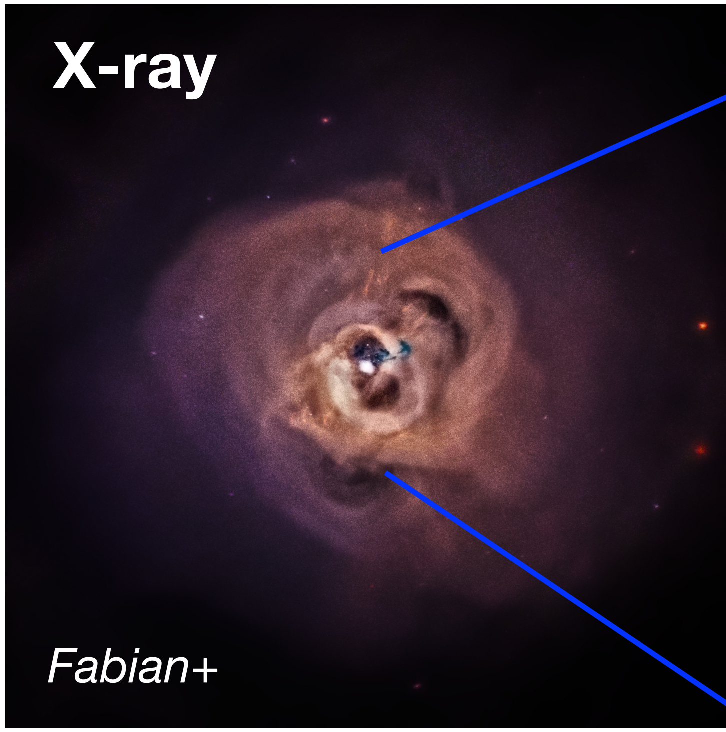
Cosmic rays (CR) together w/ magnetic draping of the bubble helps counter-acting the fragmentation of the bubble due to shear instabilities

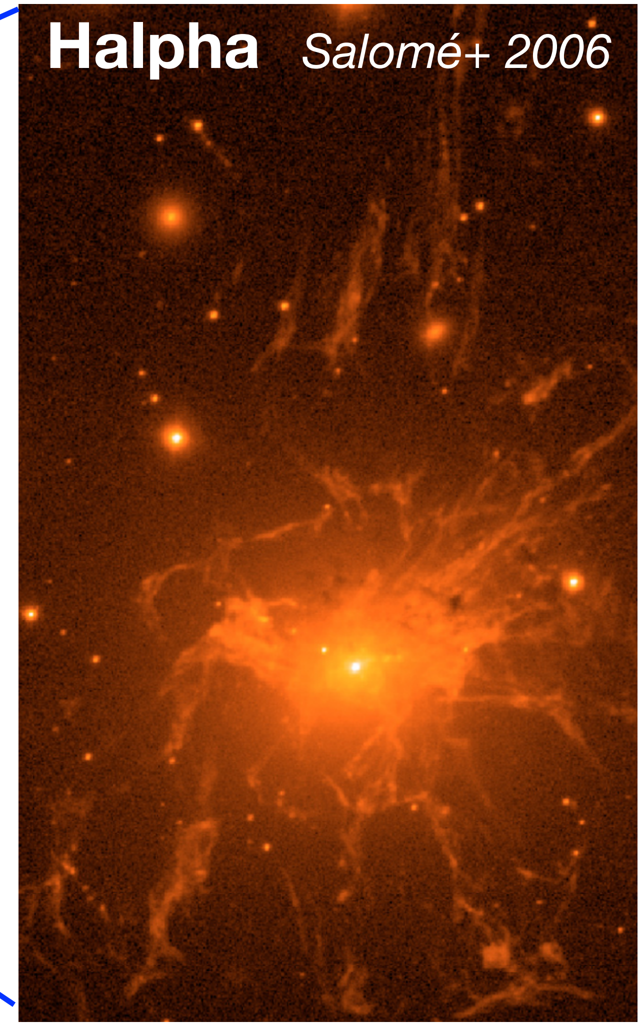
See also Sijacki+08; Guo & Matthews11; Ruszkowski+08, 17



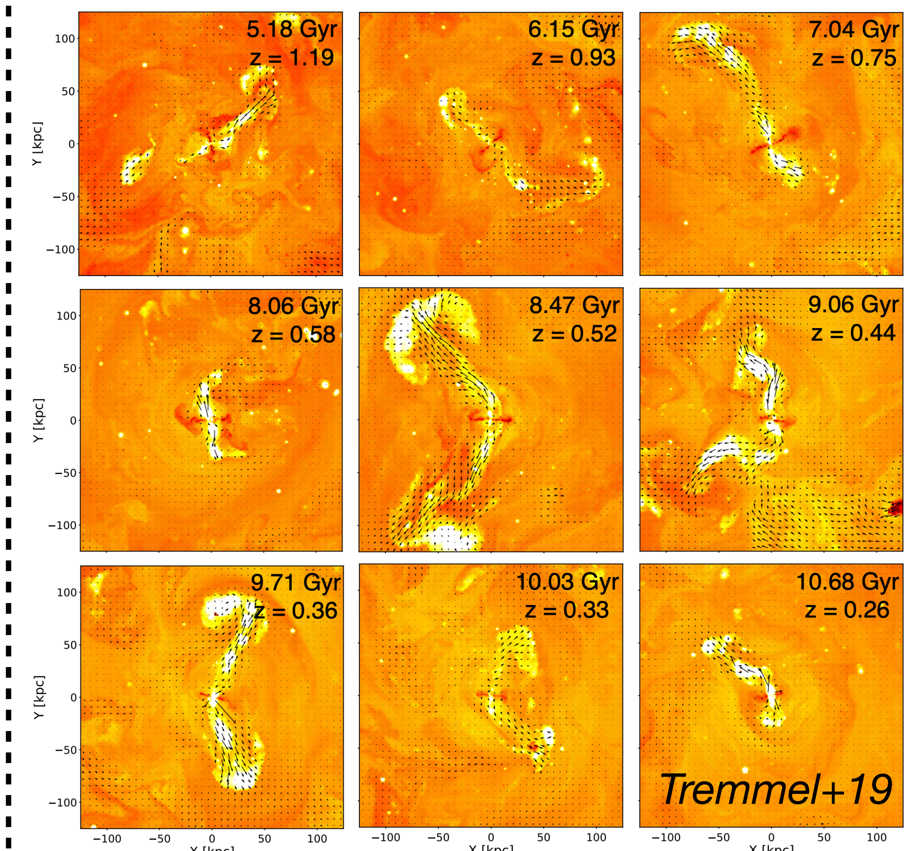
Ehlert+18

And the cold filamentary gas?

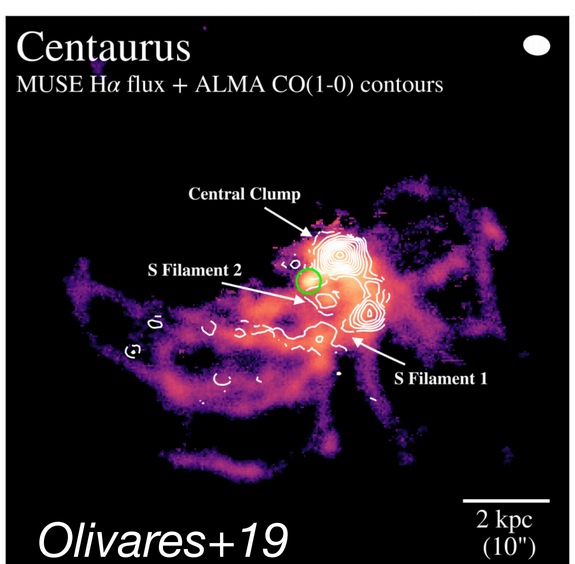


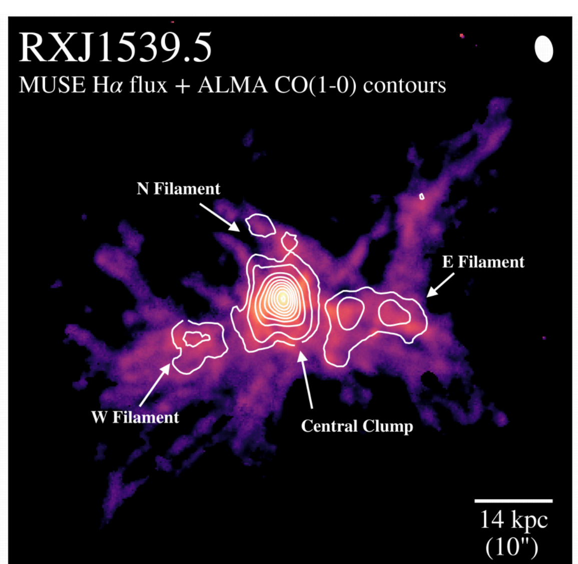


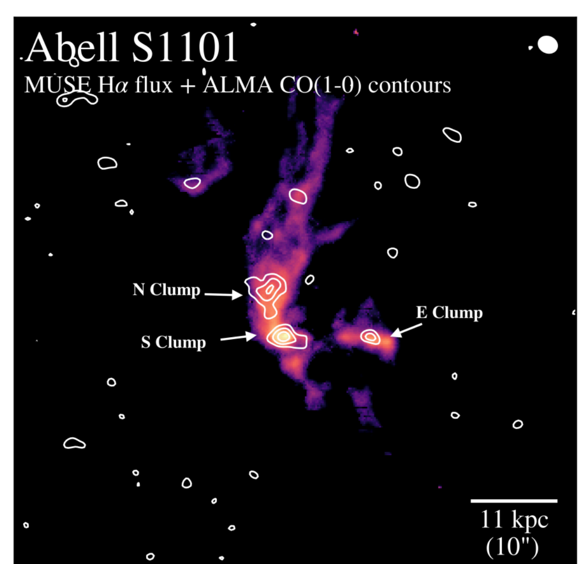
But nowhere seen in cosmological simulations even for those with the best-achieved resolution (here dx=0.25kpc)



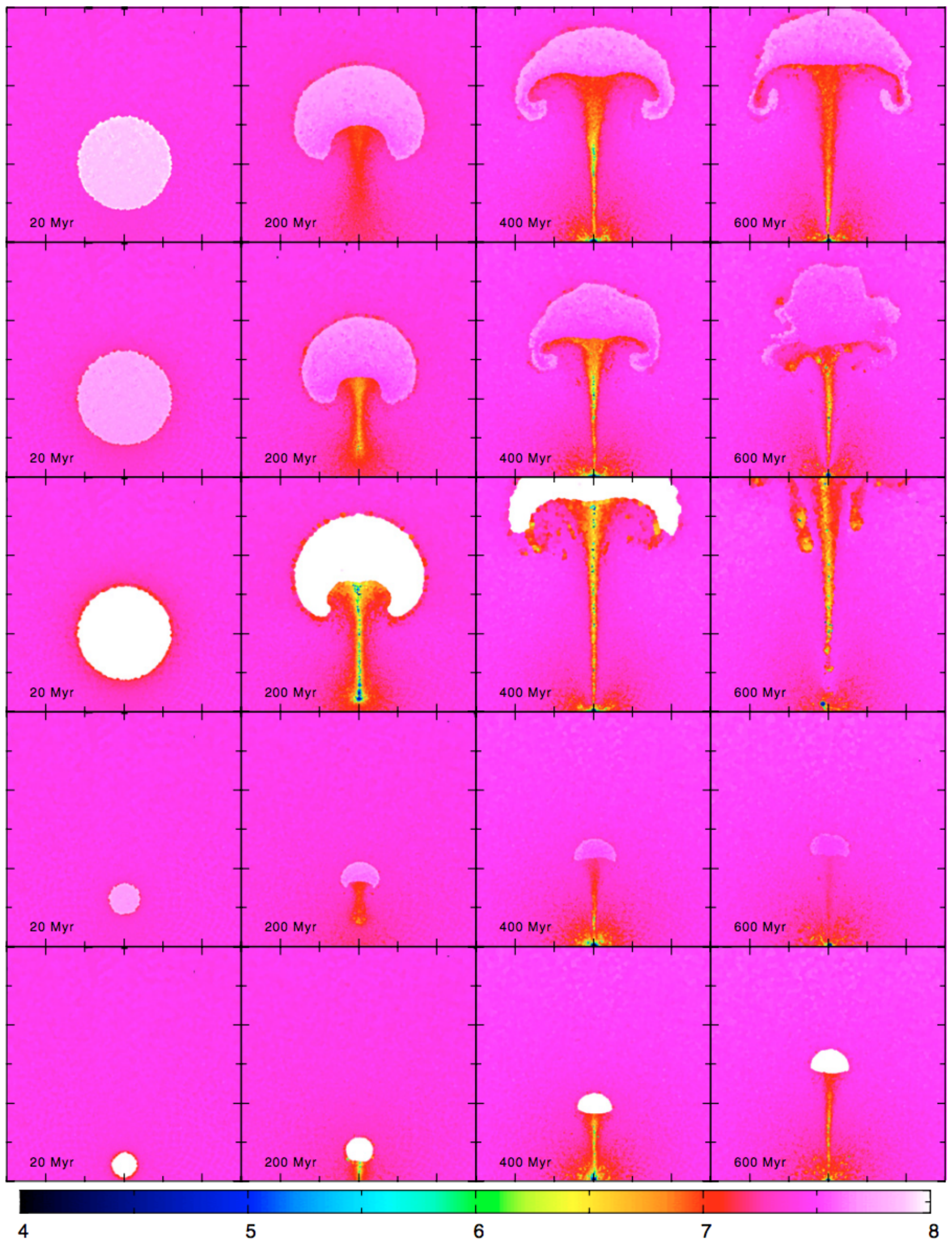
resolution effect?
physical effect?



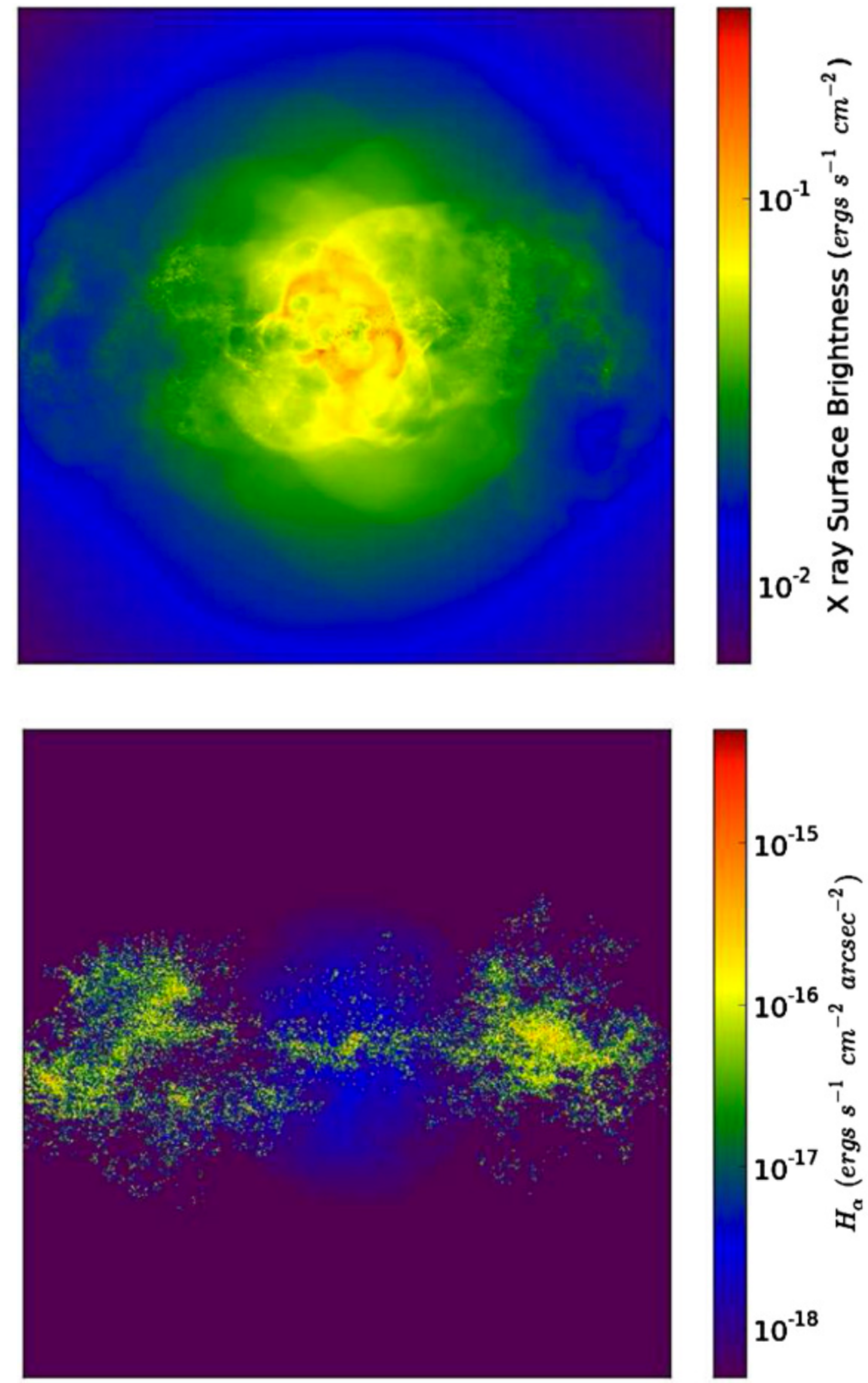




AGN and cold gas formation

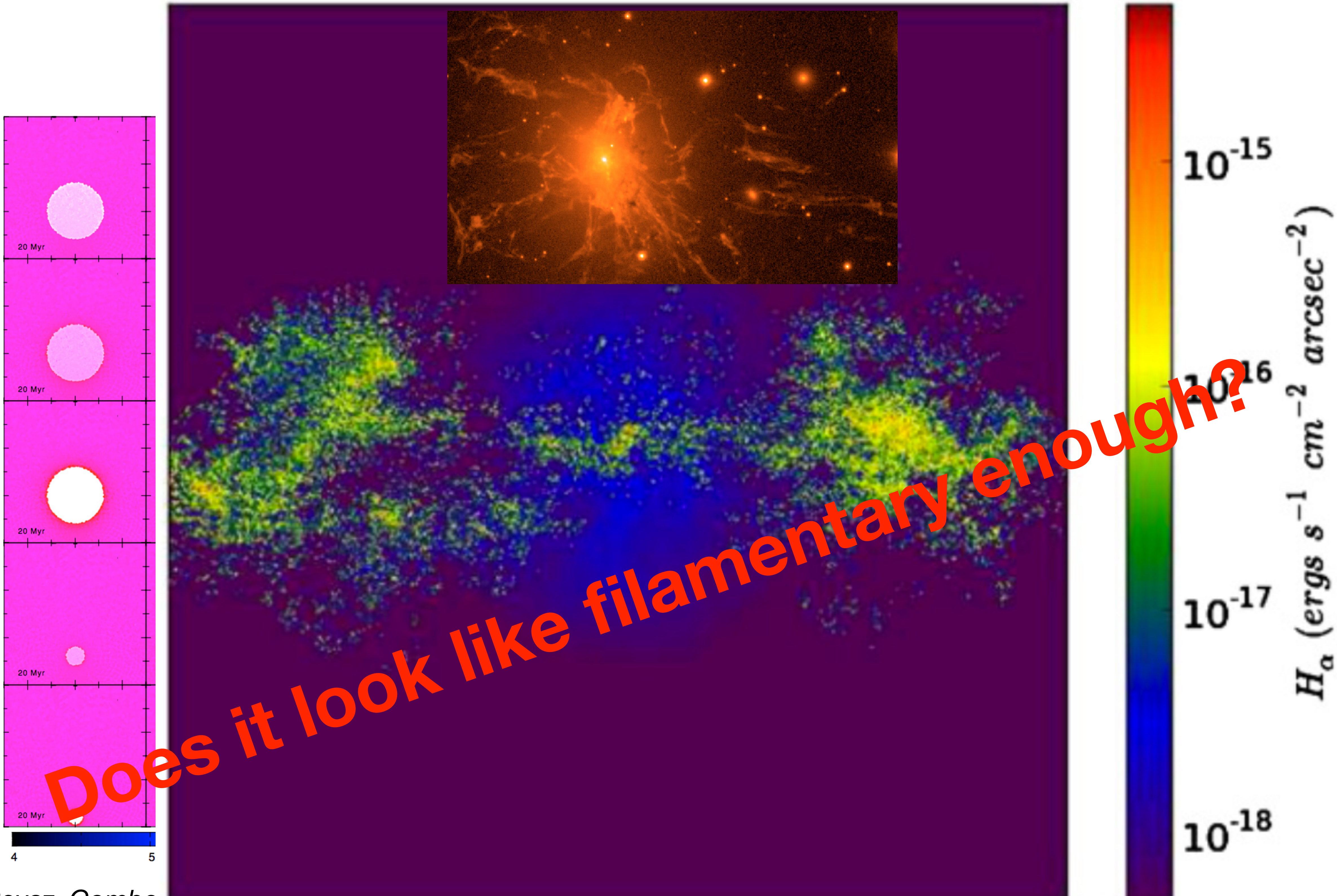


Revaz, Combes & Salomé 08



Li & Bryan 14

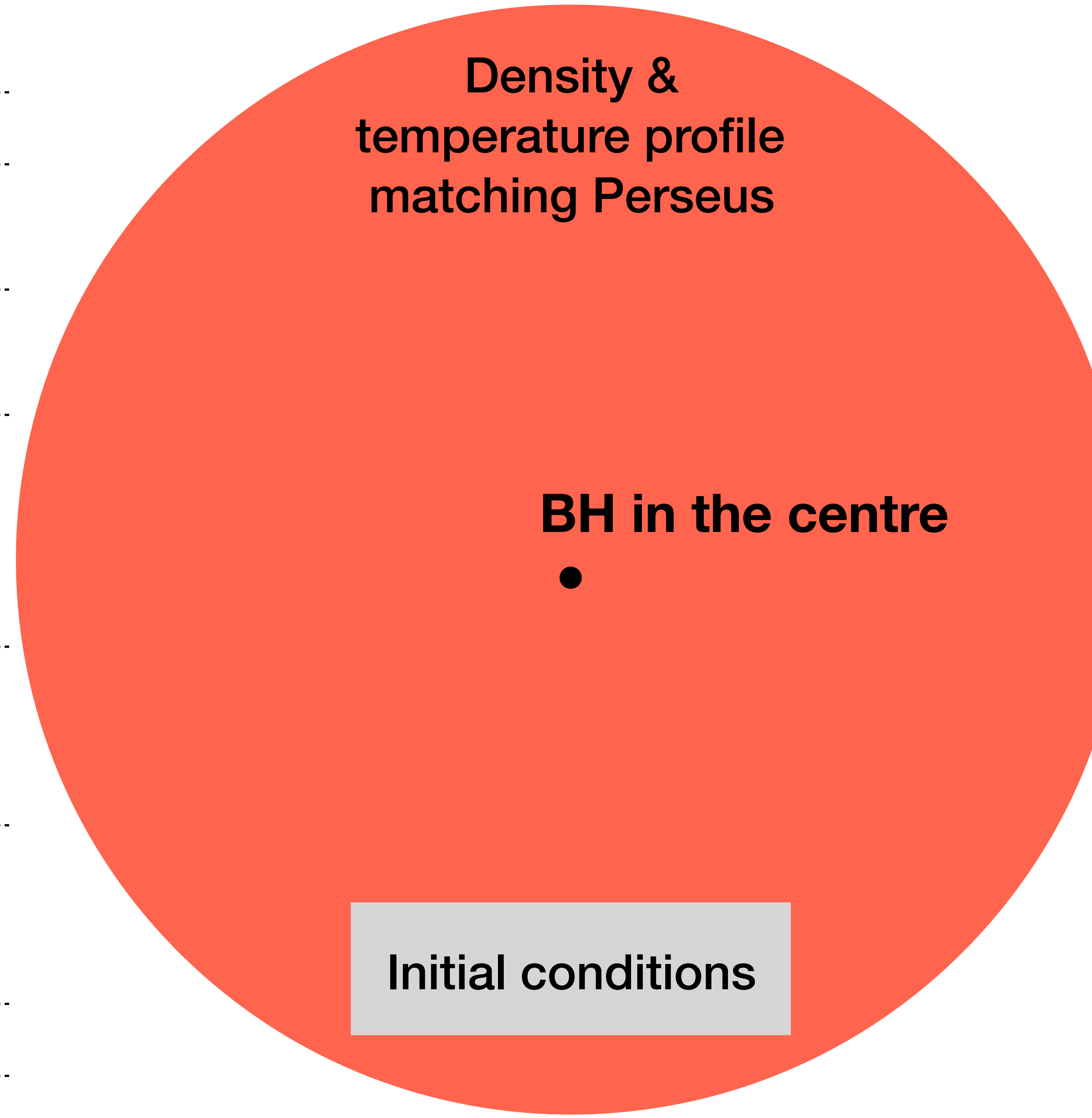
AGN and cold gas formation



Revaz, Combe

Simulating the cooling cycle in a Perseus-like Cluster

Halo mass	8.5x10^{14} Msun
Halo profile	NFW, with a core radius of 20 kpc
Temperature profile	Hydrostatic equilibrium, with a gas fraction of 15%
Black hole mass	4x10^{8} Msun
Black hole physics	• Black hole is free to move within the cluster • Spin-driven black hole jet • Bondi-Hoyle-Lyttleton accretion
Other physics	• Cooling • Star formation + stellar feedback • Metallicity and dust evolution
Other features	• Tracer particles • Use scalar tracer to selectively refine feedback bubbles
Runtime	1 Gyr
Resolution	120 pc (in dense gas and in the jet)



Beckmann, Dubois+19

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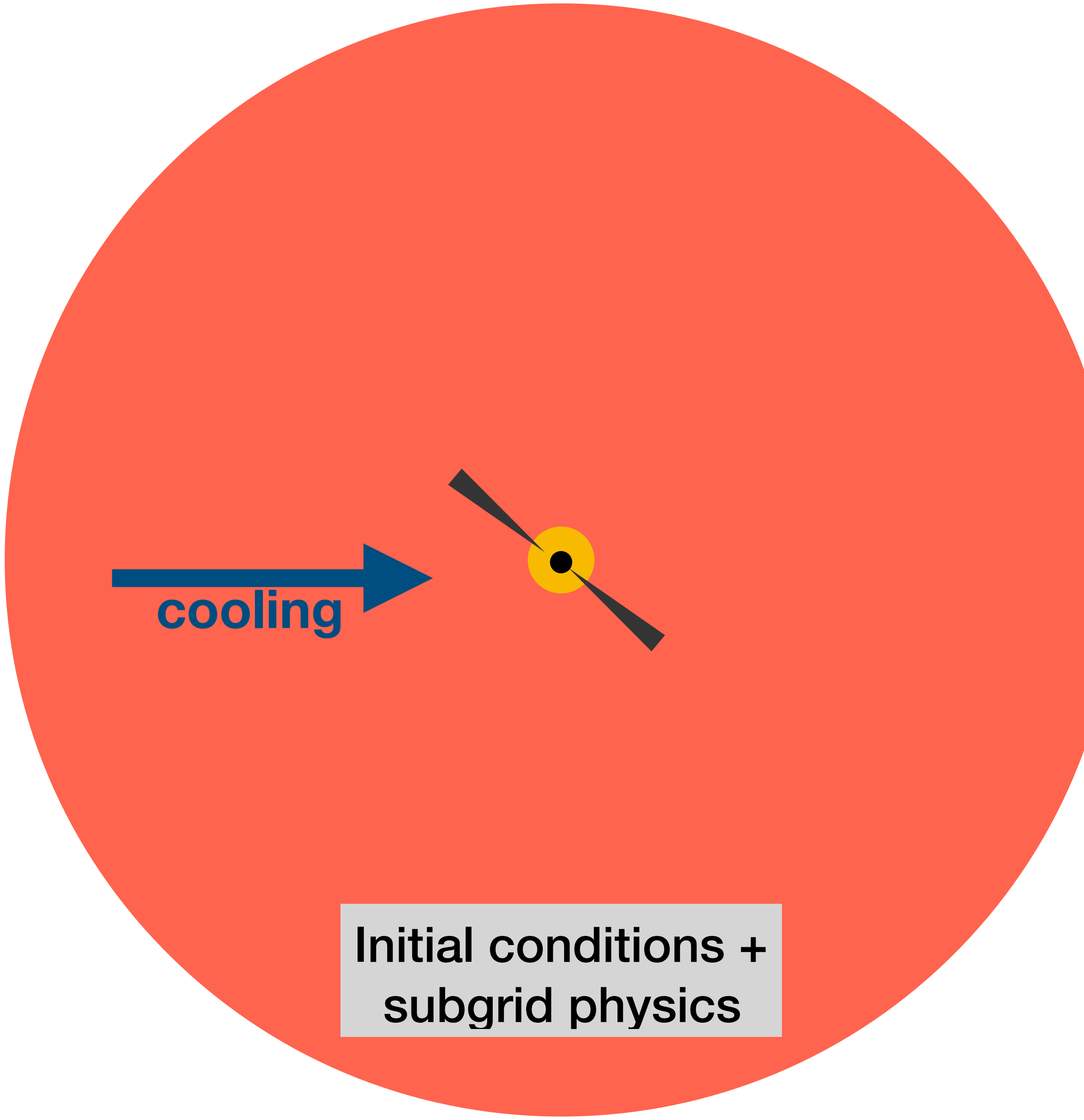

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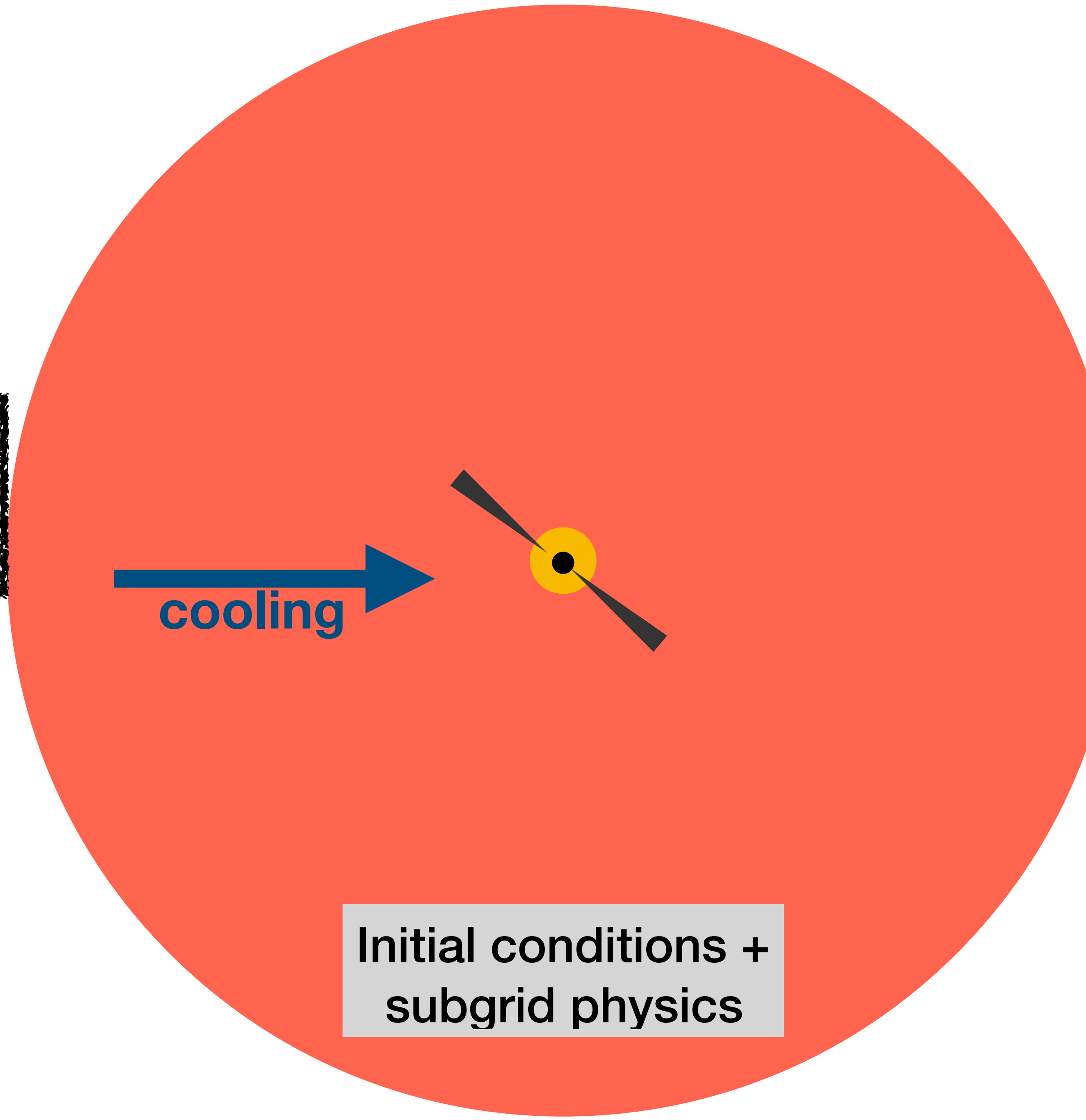
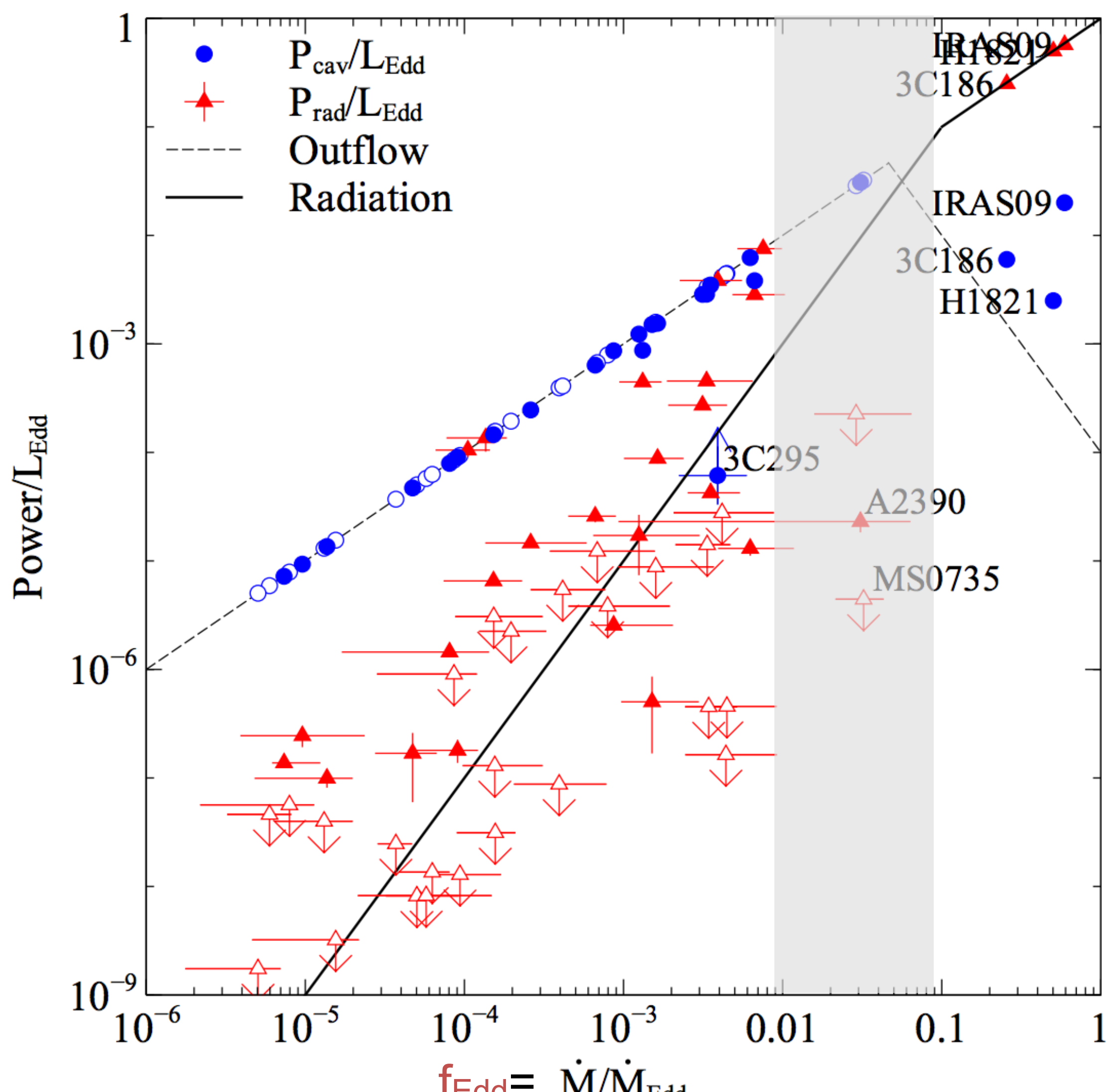


Beckmann, Dubois+19

AGN feedback

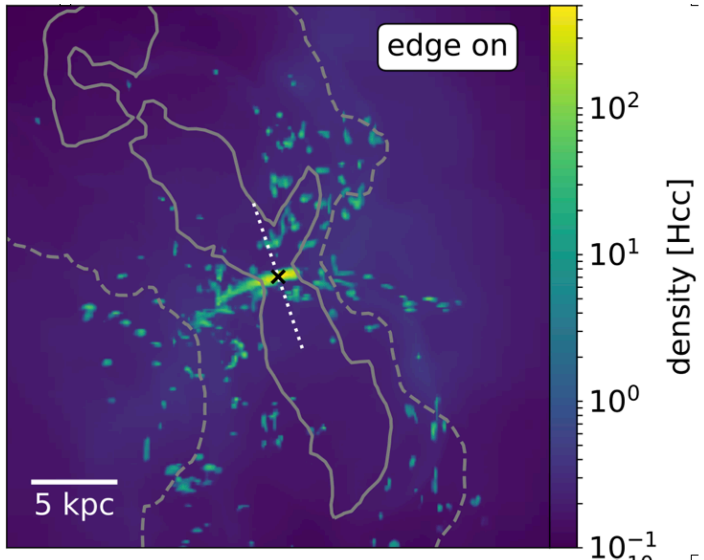
- BH grow by accretion and coalescence
- Accretion is Bondi-Hoyle-Littleton limited at Eddington
- Feedback proceeds by :
    - thermal winds at $f_{Edd}>0.01$ (Teyssier+ 2011)
    - radio jets at $f_{Edd}<0.01$ (Dubois+ 2010, 2011)

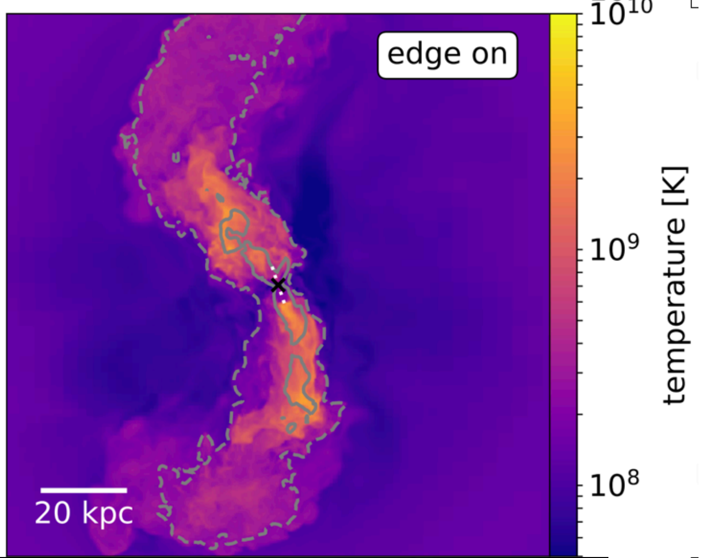


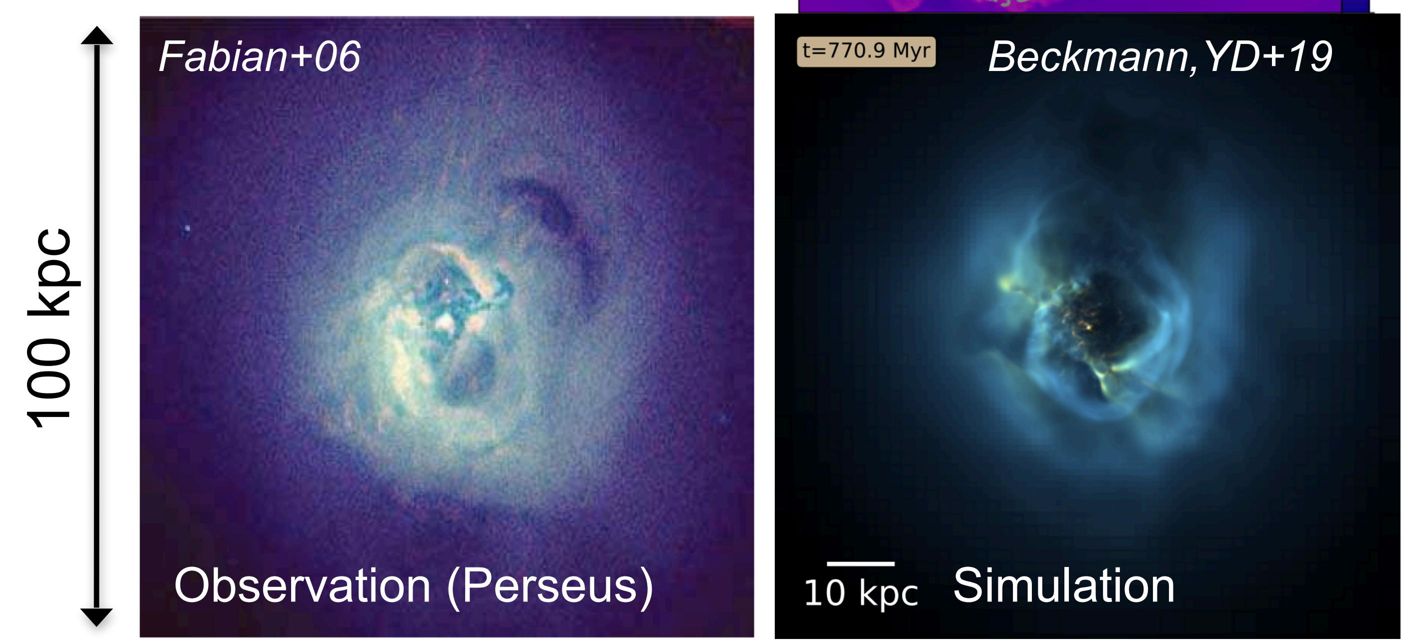
Russel+13

$$\dot{M} = \frac{4\pi\rho_{\rm gas}G^2M^2}{(c_{\rm sound}^2 + u_{\rm rel}^2)^{3/2}}$$

$$\dot{E}_{\rm AGN} = \epsilon \dot{M} c_{\rm light}^2$$







X-ray (3 bands)

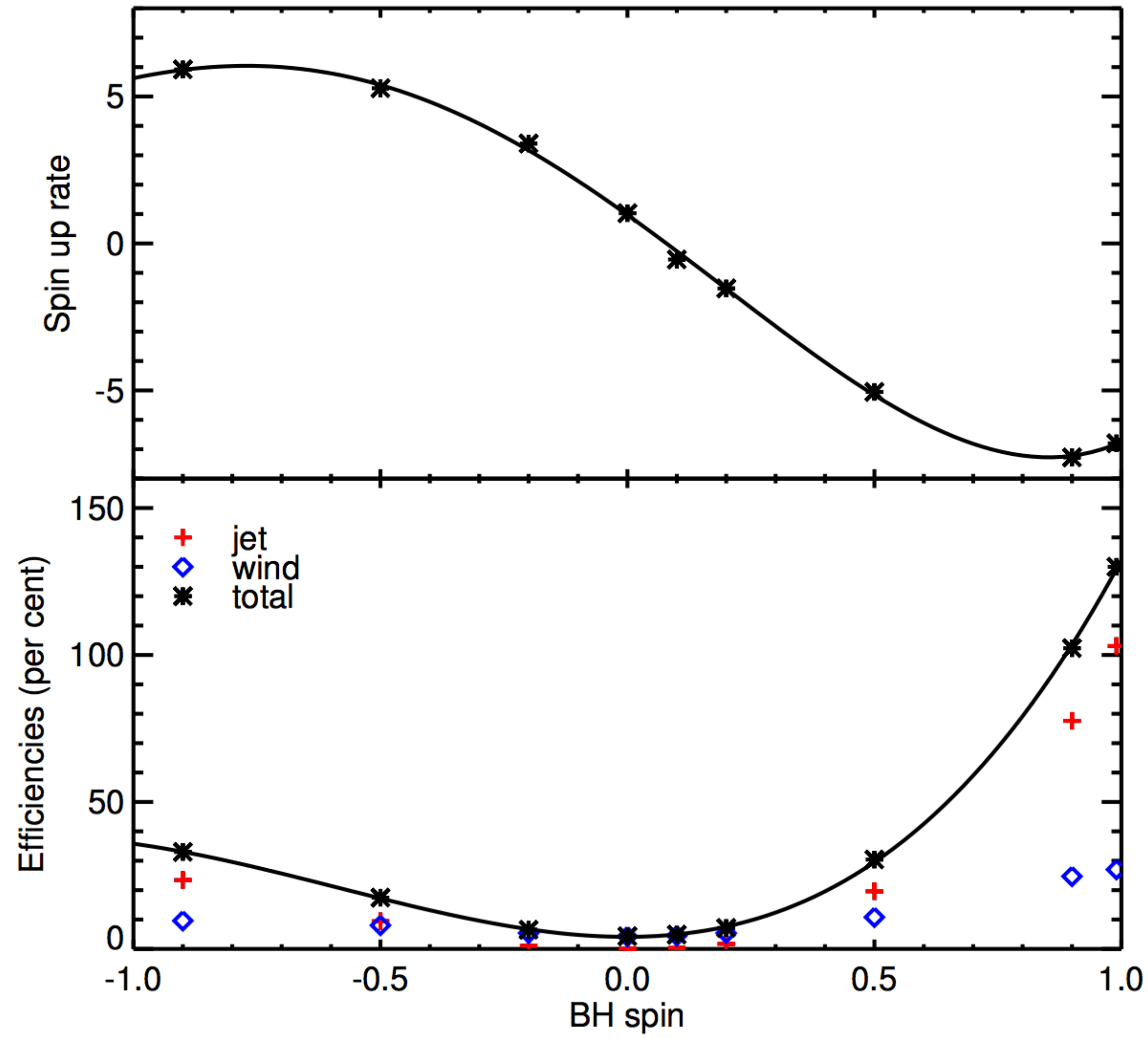
New spin-altered BH/AGN model

BHs can be completely described by their mass, spin and ~~charge~~ (no hair theorem)

Why are BH spins of any interest for galaxy formation problems???

MAD model

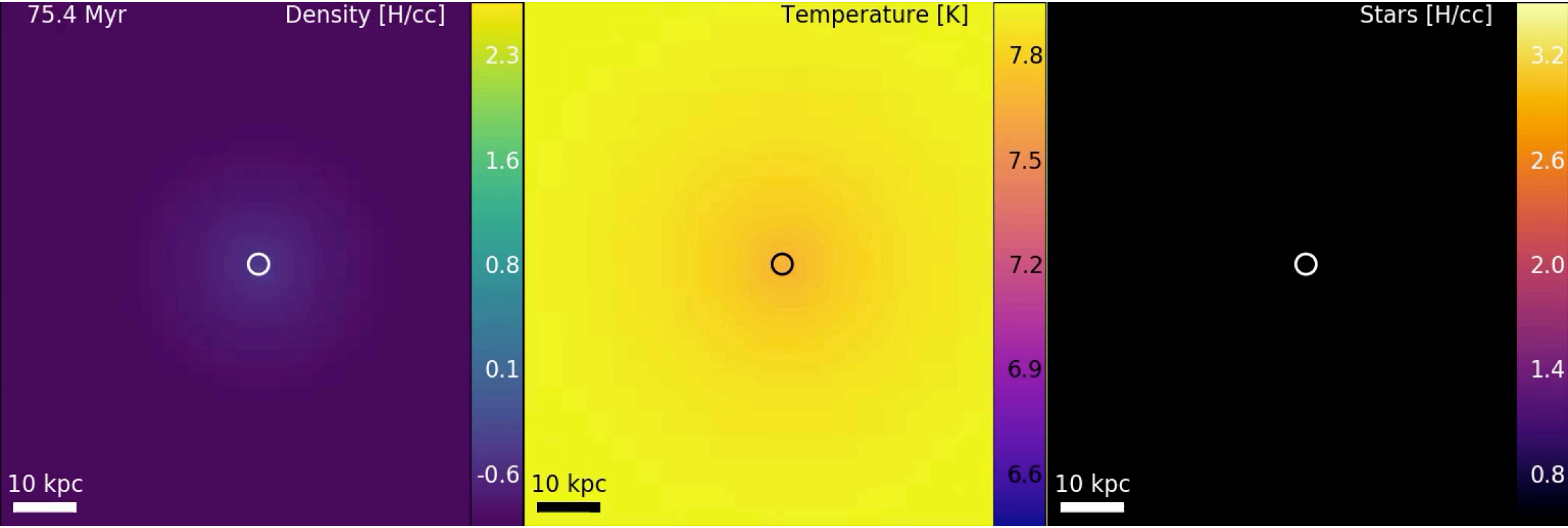
▪**Spins** set the **radiative efficiency** of the accretion disc through the size of its innermost stable circular orbit (ISCO).
▪**Radiative efficiency** sets the **Eddington rate** of accretion.
▪**Spins** set the **jet mode efficiency** of AGN feedback through magnetically arrested disc (MAD) solutions (McKinney+12; Tchekovskoy+12).
▪**Spins** set the AGN **jet orientation.**



Dubois+20

Thus, spins change both the intrinsic BH accretion rates and the AGN feedback energy deposit

Evolution of the simulated high-resolution idealised cluster



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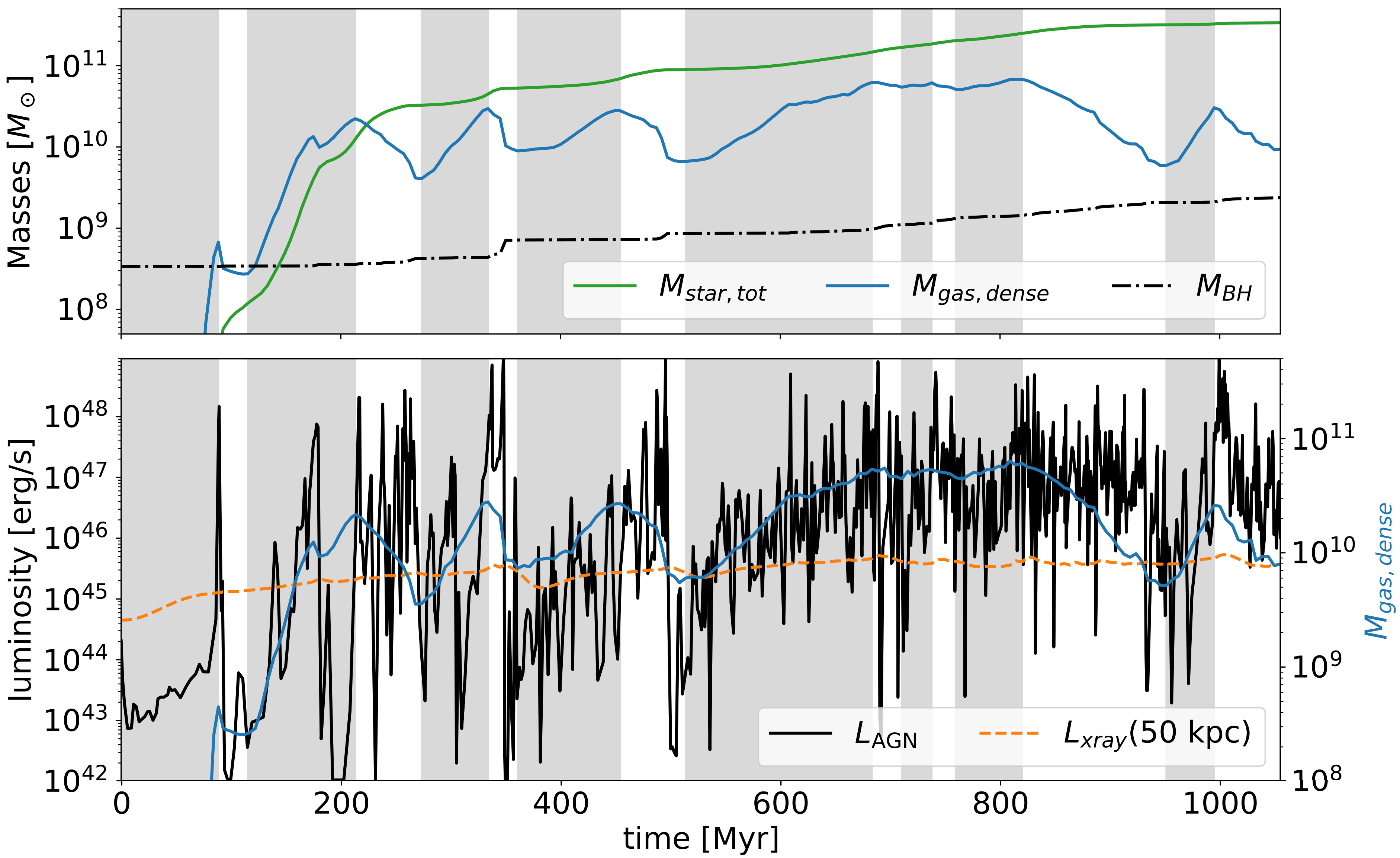
Co-evolution of the cold gas and AGN activity



Both the AGN and the total cold gas mass undergo a closely linked, cyclic evolution.

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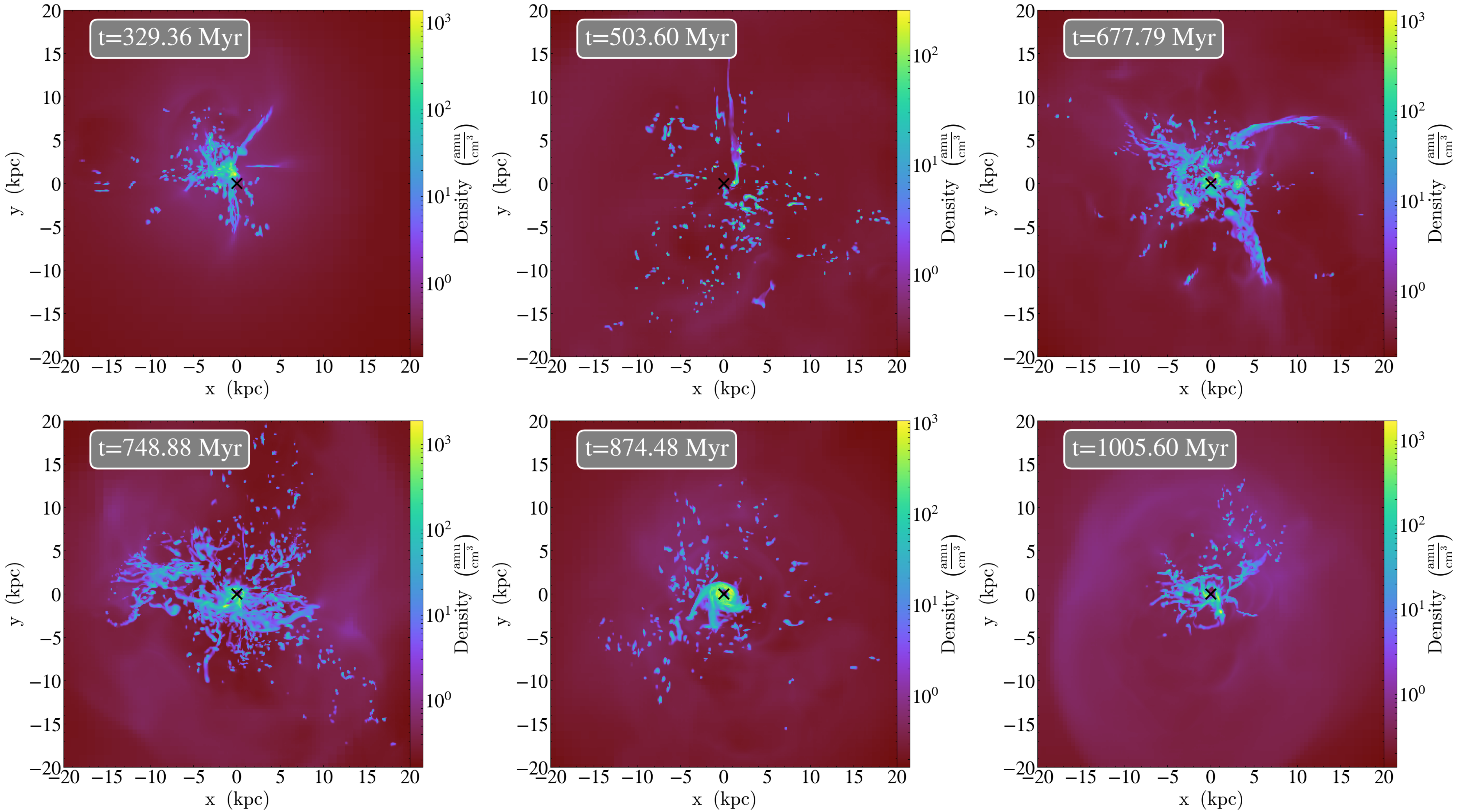

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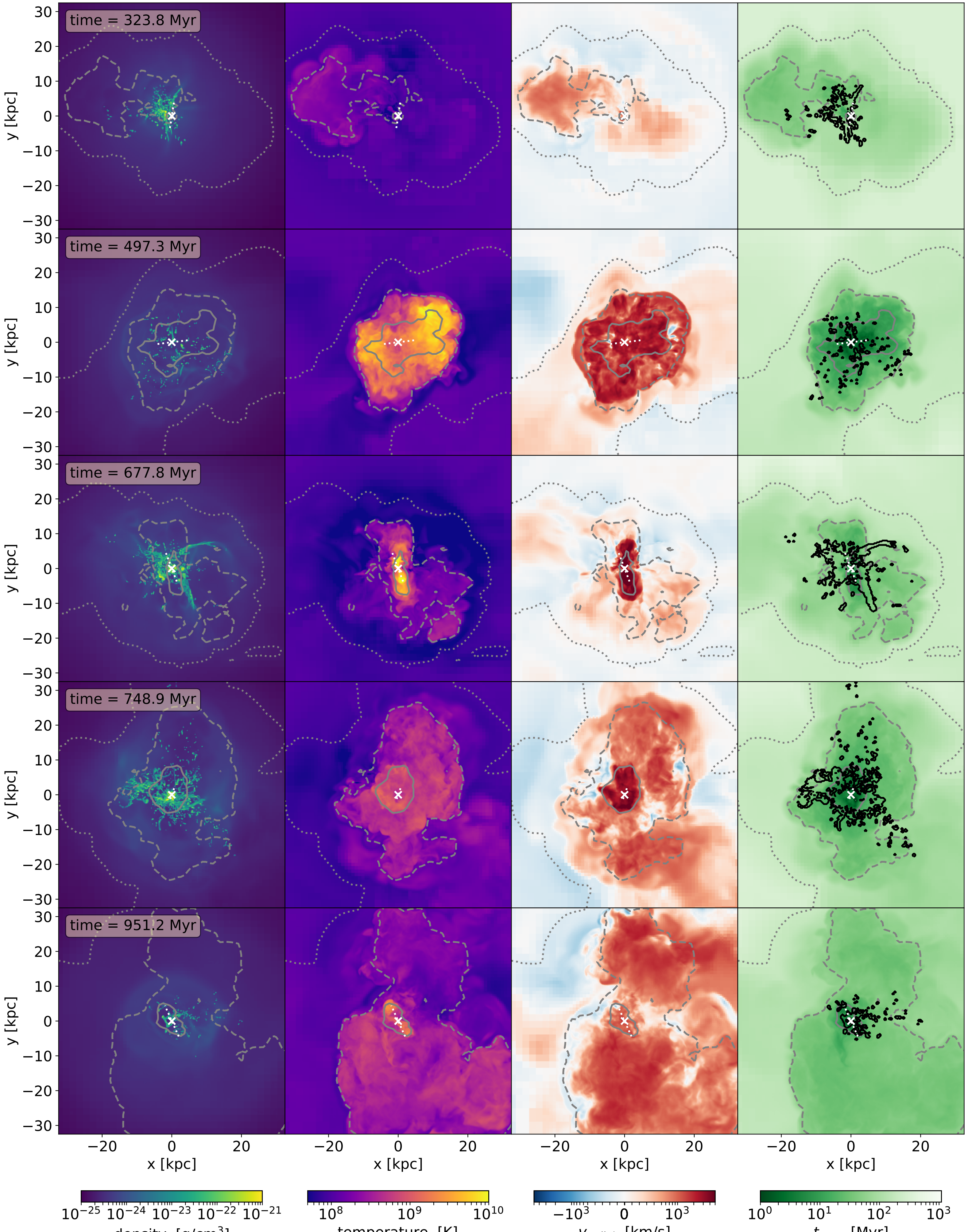

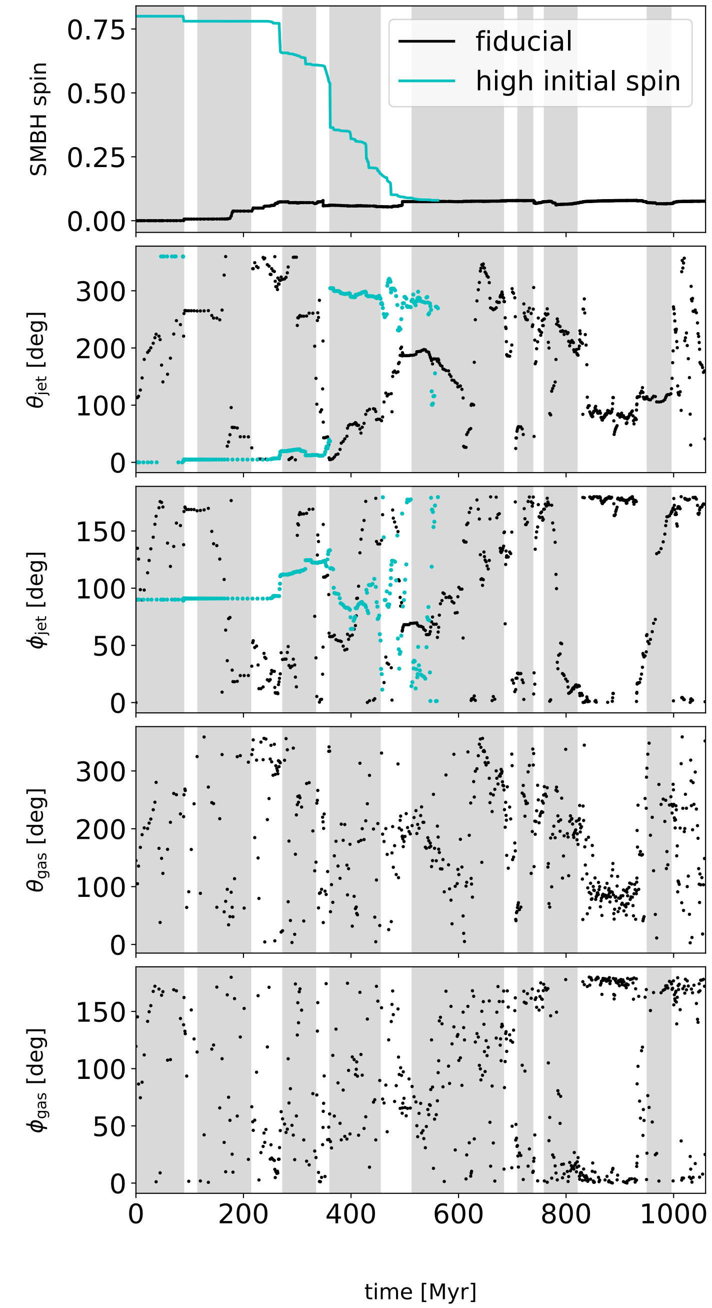

A rapid reorientation of jets is required for an efficient energy redistribution (Gaspari+13)

chaotic cold accretion + BH spin

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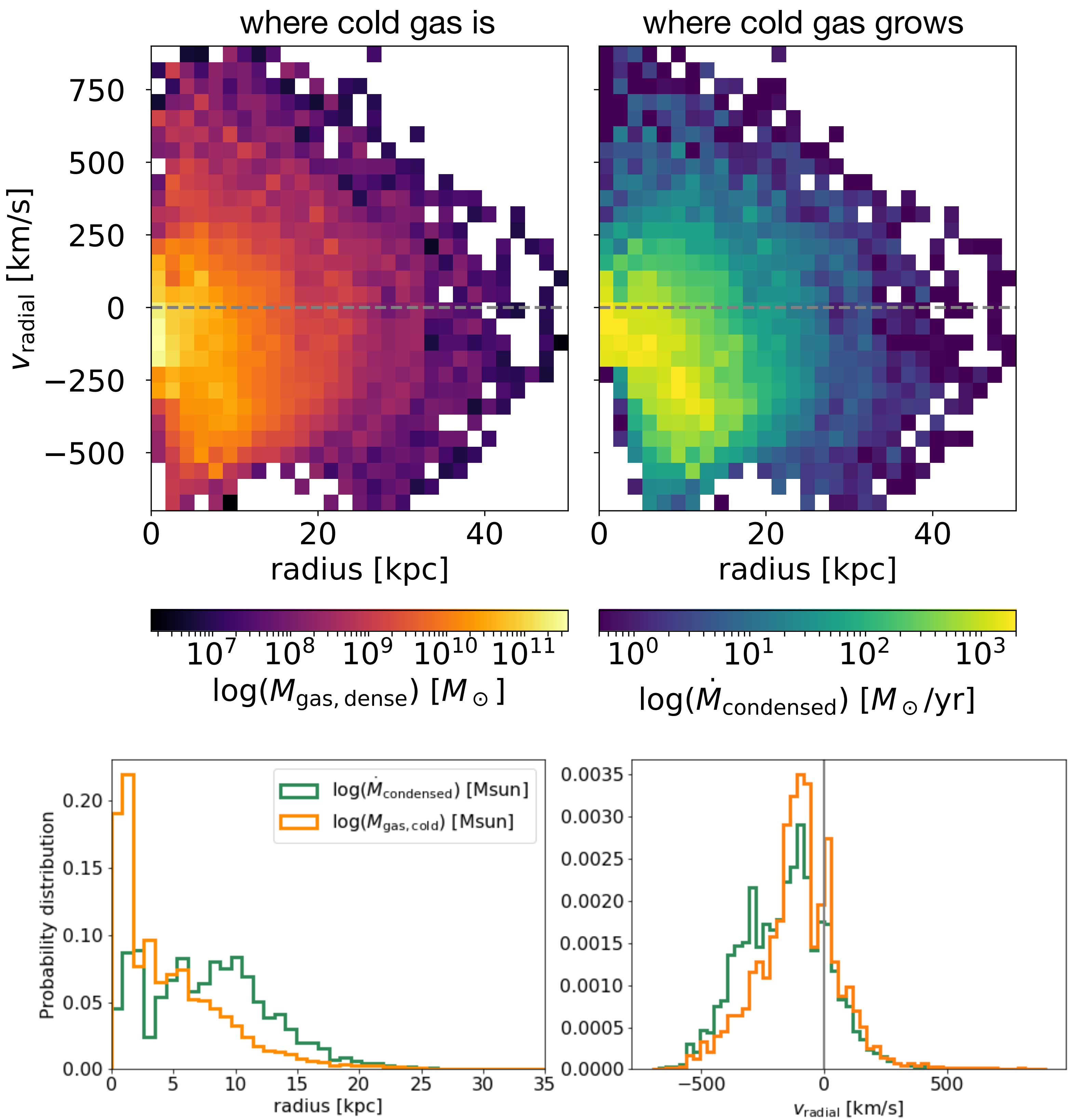
Where and when does the dense gas form?



Gas is

- Preferentially infalling
- Can be found as far as 50 kpc from the center, but the bulk is found at much smaller radii
- Has velocities +/- 700 km/s

Condensation

- Happens at larger radii than where gas is preferentially found
- Typically happens on infall, but can also happen on outflow

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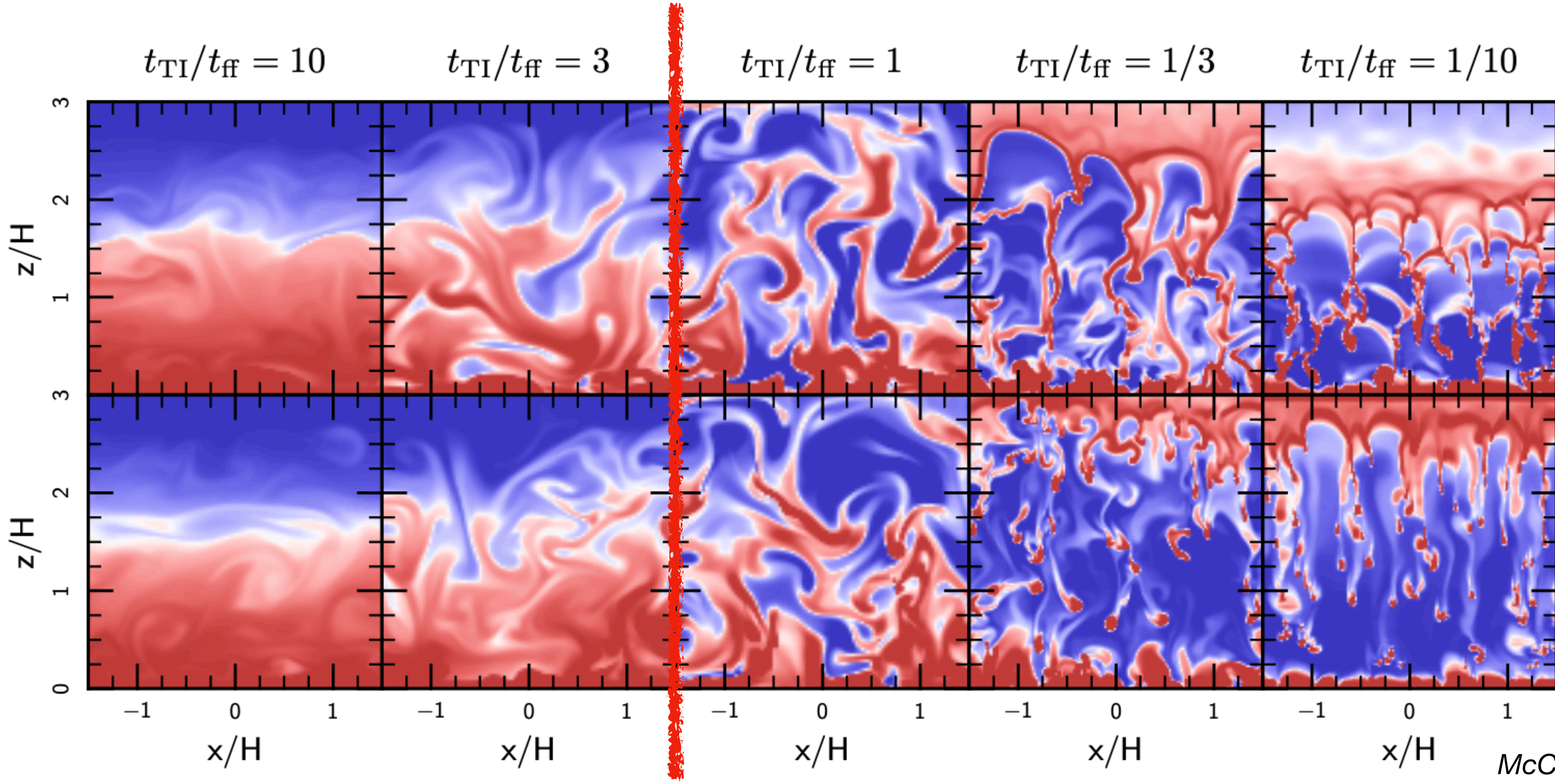
Local thermal instability in galaxy clusters



Even for a globally thermally stable hot halo, gas can condense out of the hot phase locally when the local cooling timescale is sufficiently low compared to the free-fall time.

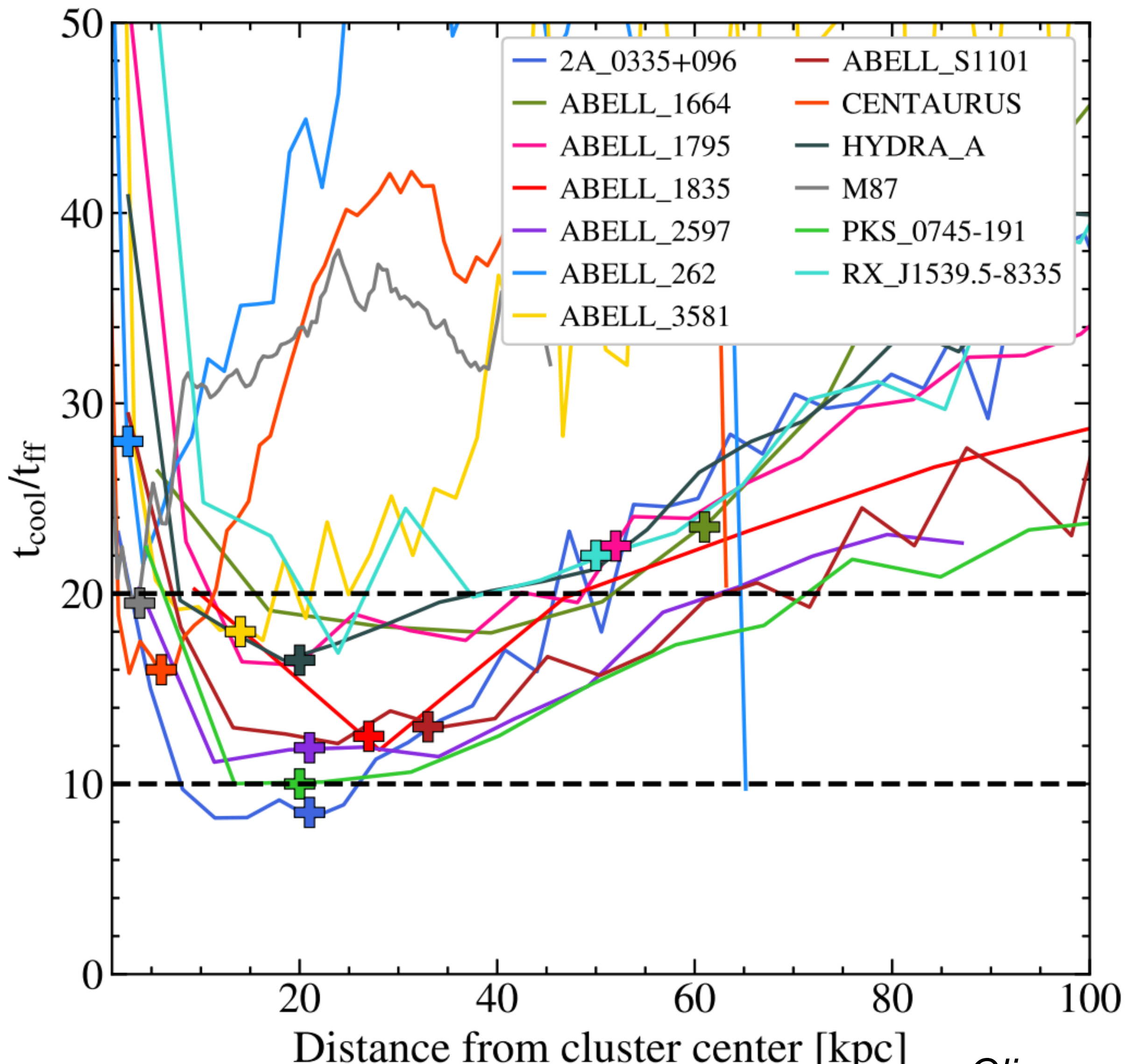
In spherical geometry, this criterion becomes $t_{\rm TI}/t_{\rm ff}<10$ (Sharma+12)

$$t_{\rm ff} = \left(\frac{2z}{g_0}\right)^{1/2}$$

$$t_{\rm TI} \simeq t_{\rm cool} = \frac{3}{2}\frac{T^{1/2}}{n\Lambda_{\rm cool}}$$

The influence of t_{cool}/t_{ff} on cold gas

Observation

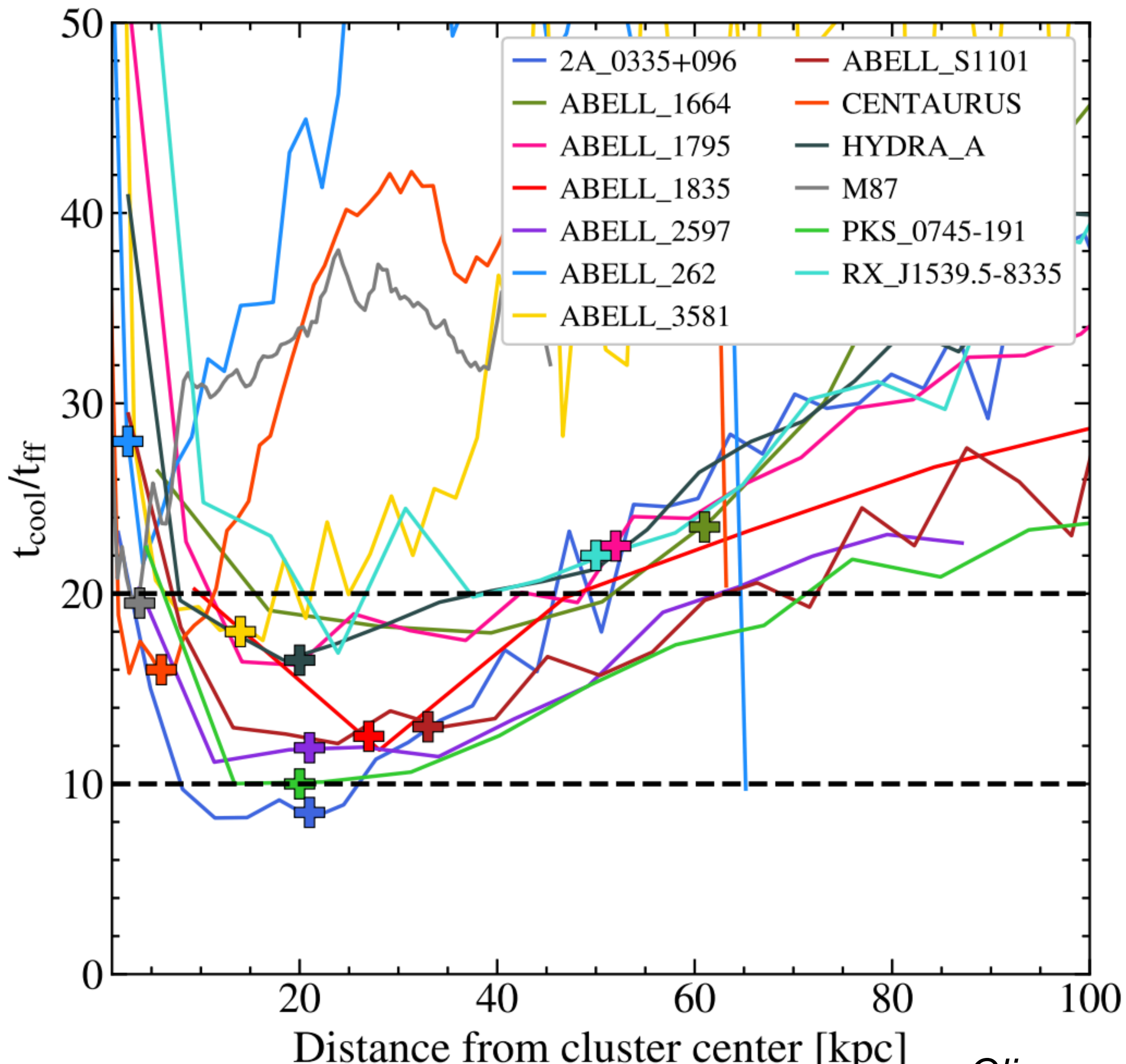


Olivares+19

Observationally, cold gas in galaxy clusters is often found near the bottom of the t_{cool}/t_{ff} profile but not always.

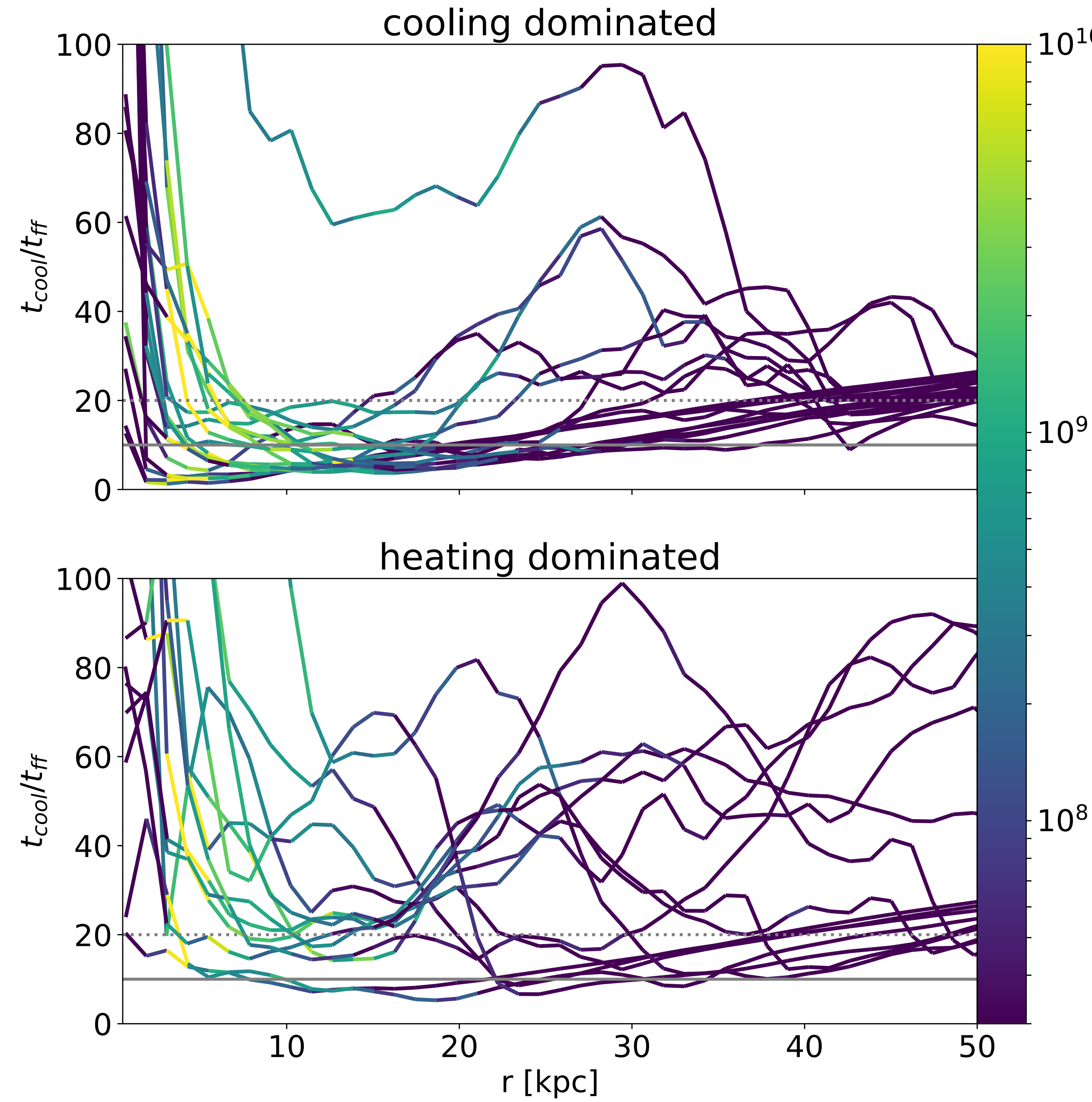
The influence of t_{cool}/t_{ff} on cold gas

Observation



Olivares+19

Simulation



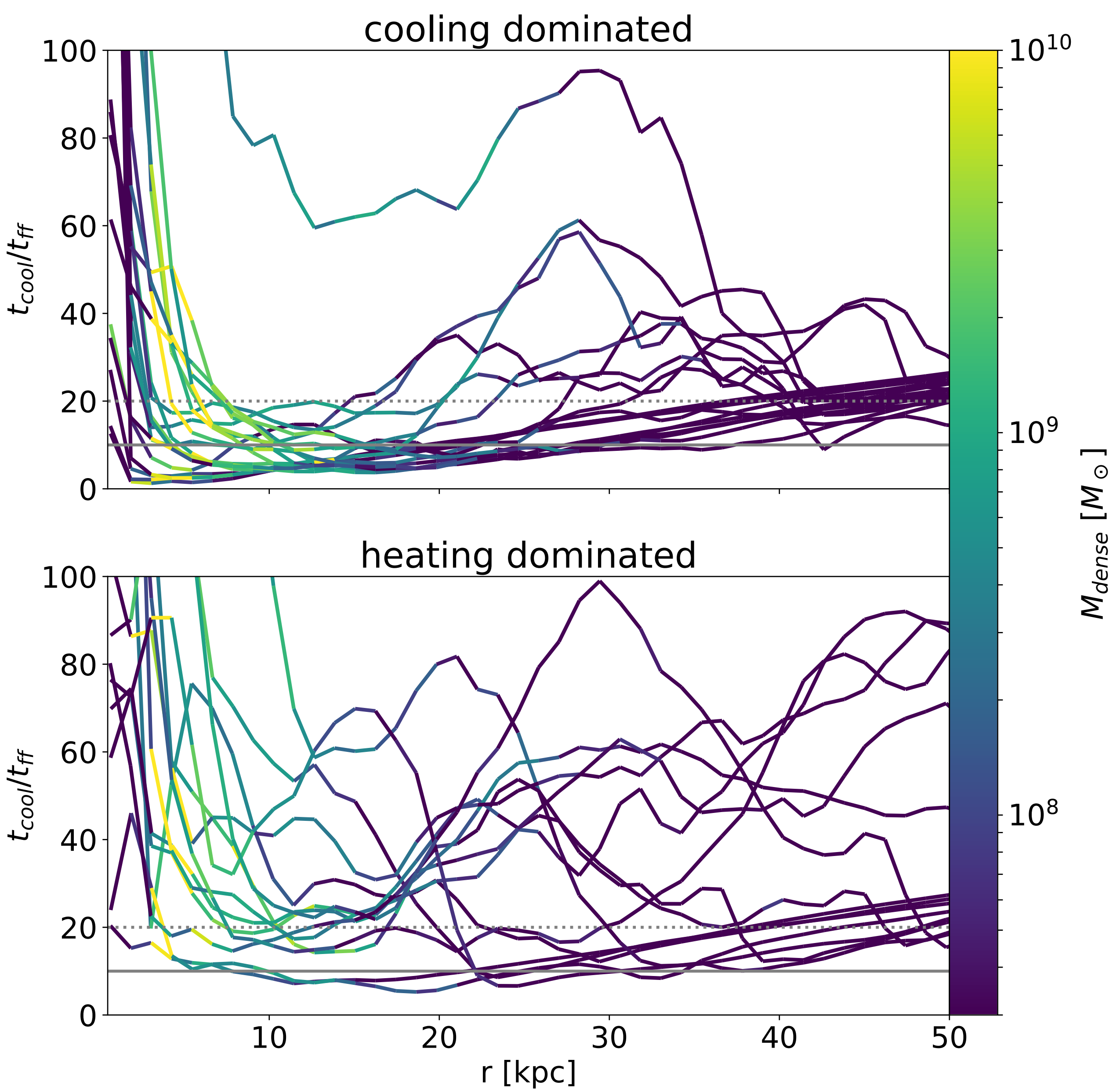
Observationally, cold gas in galaxy clusters is often found near the bottom of the t_{cool}/t_{ff} profile but not always.

The same holds in our simulations

Beckmann, Dubois+19

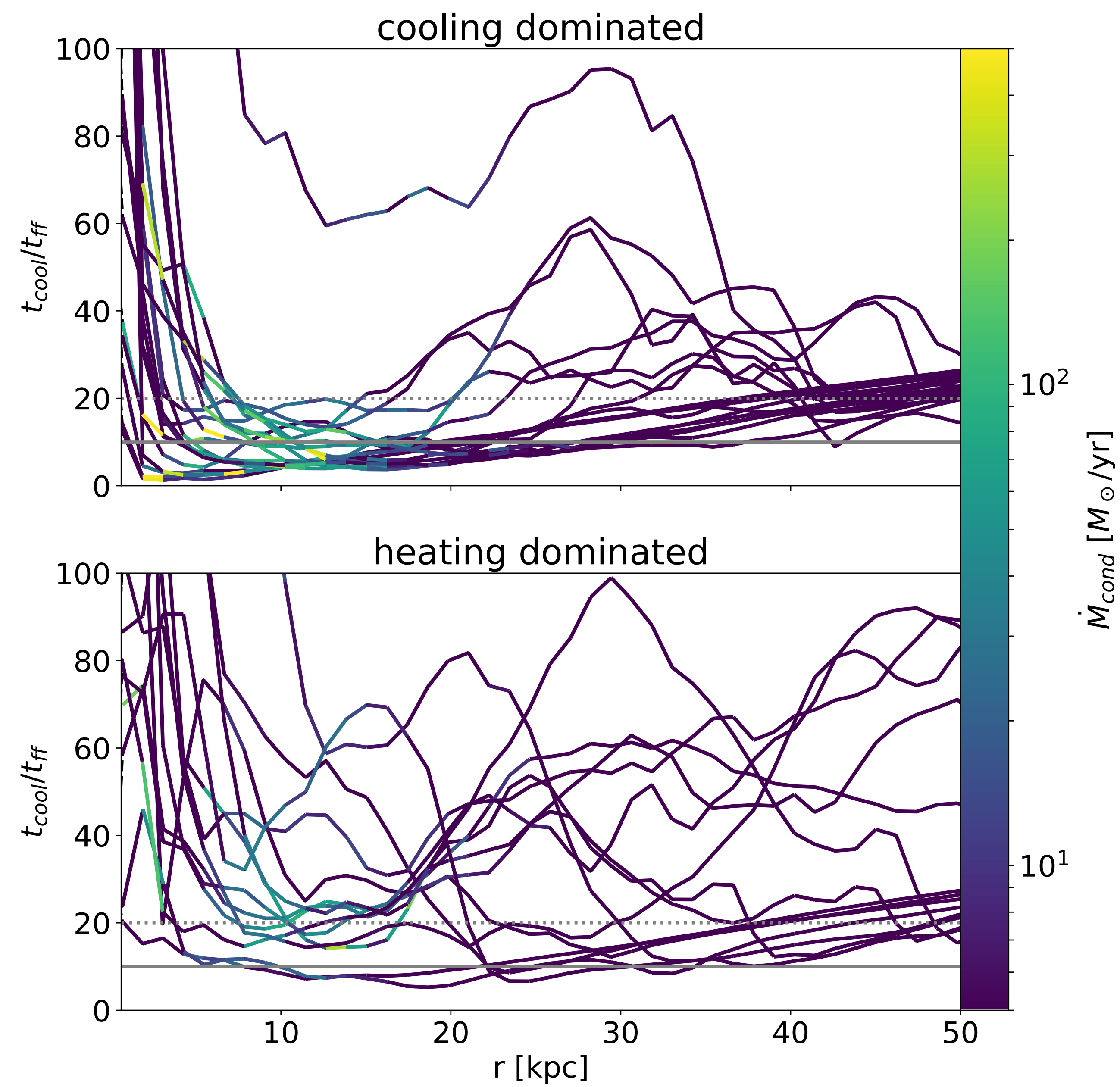
The influence of t_{cool}/t_{ff} on cold gas

Colour-coded by gas mass



Cold gas is also seen during AGN active phases, and at high local values of t_{cool}/t_{ff}.

Colour-coded by condensation rate



Condensation is only seen during AGN quiet times, when t_{cool}/t_{ff} < 20.

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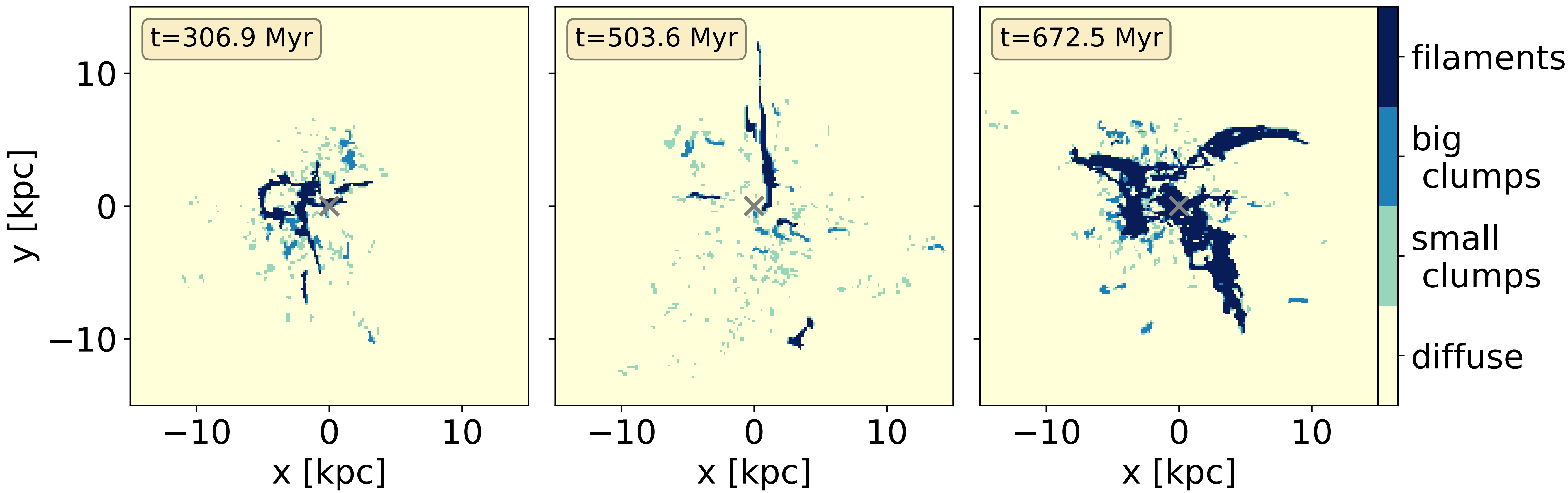
Classifying gas morphology

Depending on their axis ratios, clumps are categorized into **small clumps, big clumps and filaments.**



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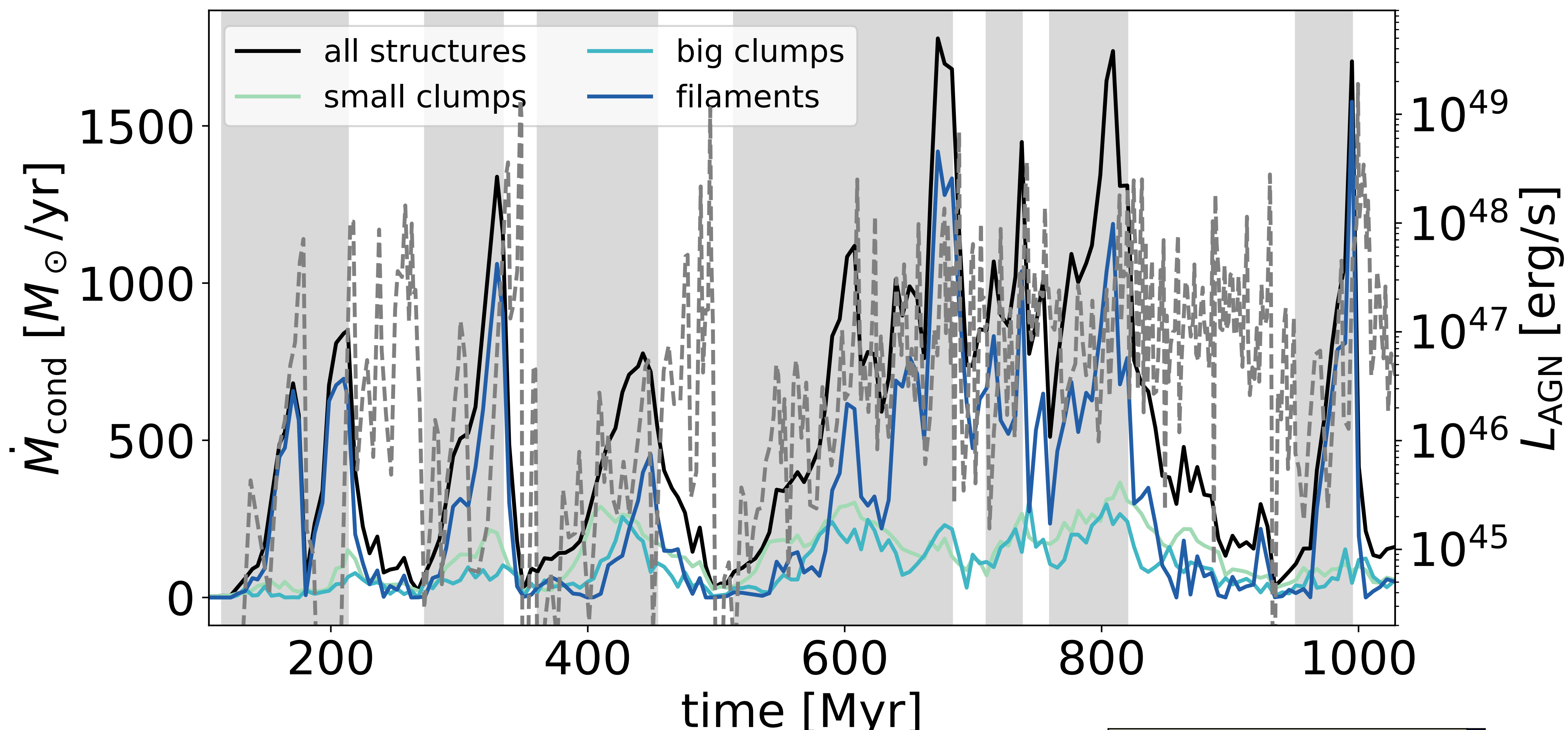
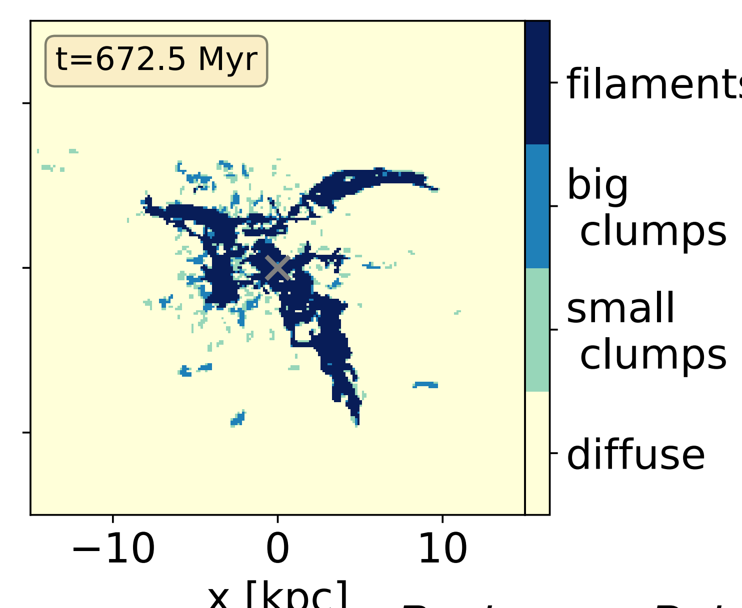
What drives the dense gas morphology?



The bulk of condensation occurs onto filaments, but structures of all shapes do experience condensation.



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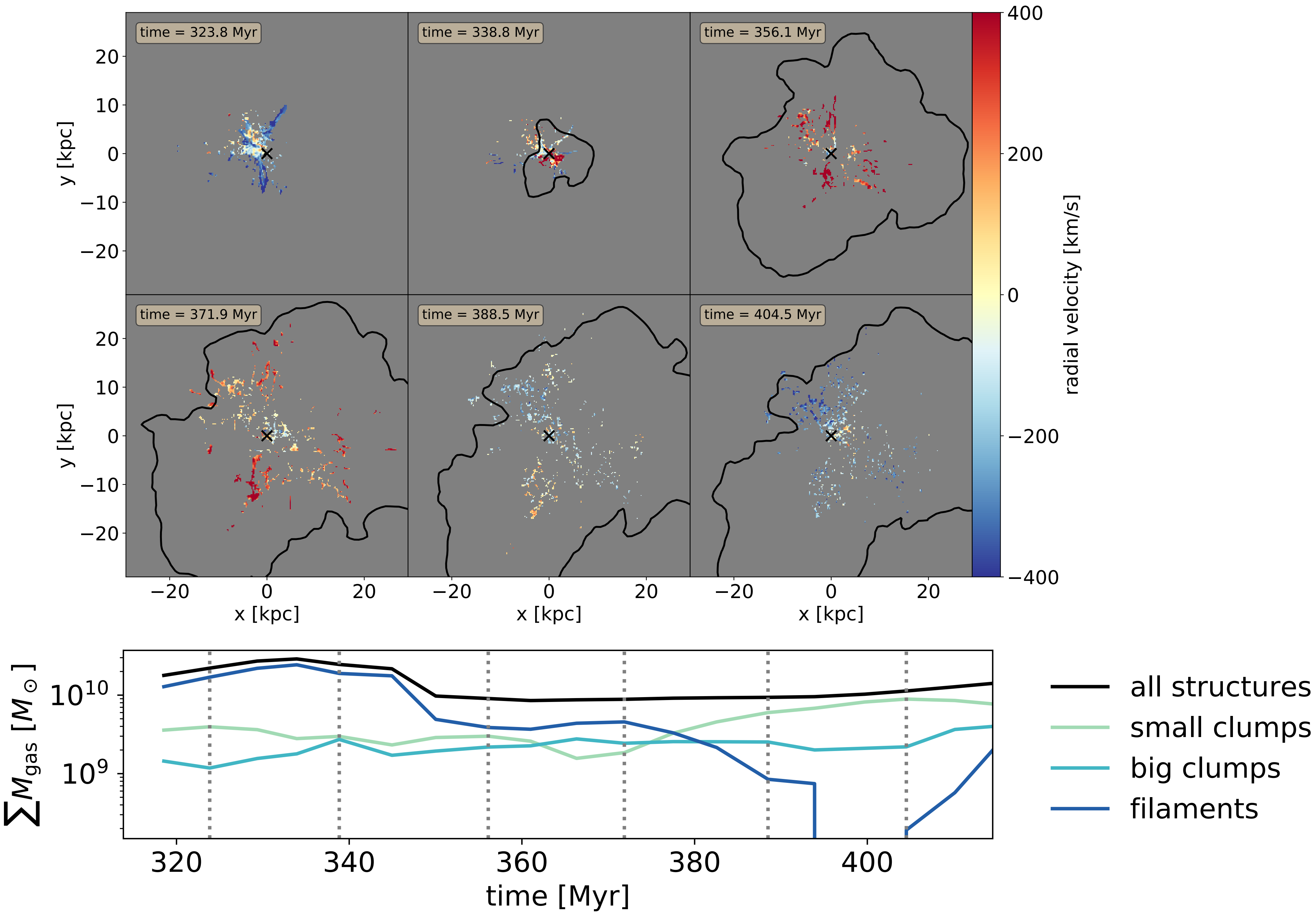

Cold gas gets uplifted by the AGN. During uplifting, cold gas gets destroyed, and big, filamentary structures are shattered into small clumps

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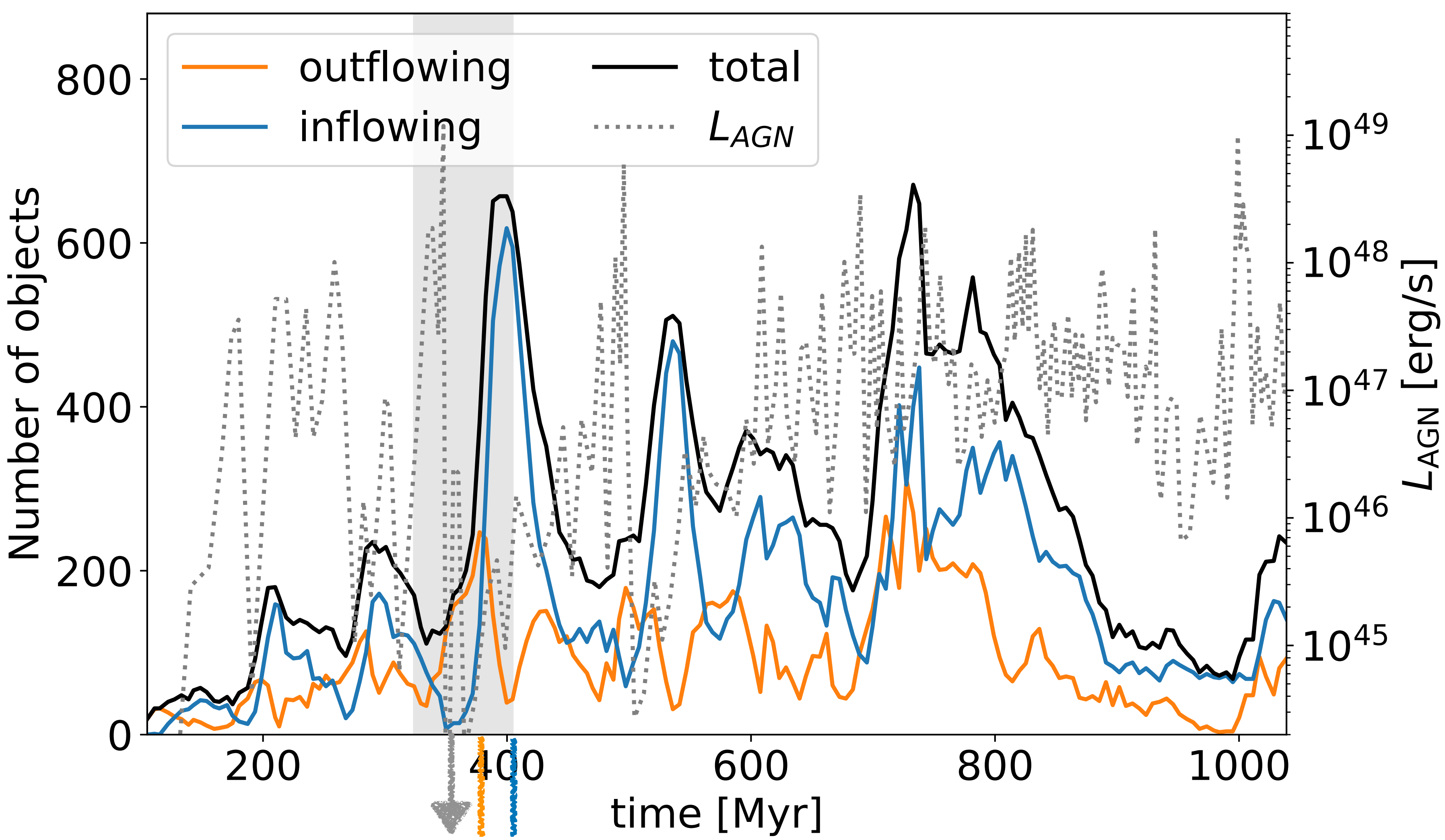
What drives the dense gas kinematics?

Time evolution of the number of inflowing and outflowing clumps



Spike in AGN feedback

Number of clumps increases, mostly outflowing

Peak of number of individual clumps, mostly inflowing

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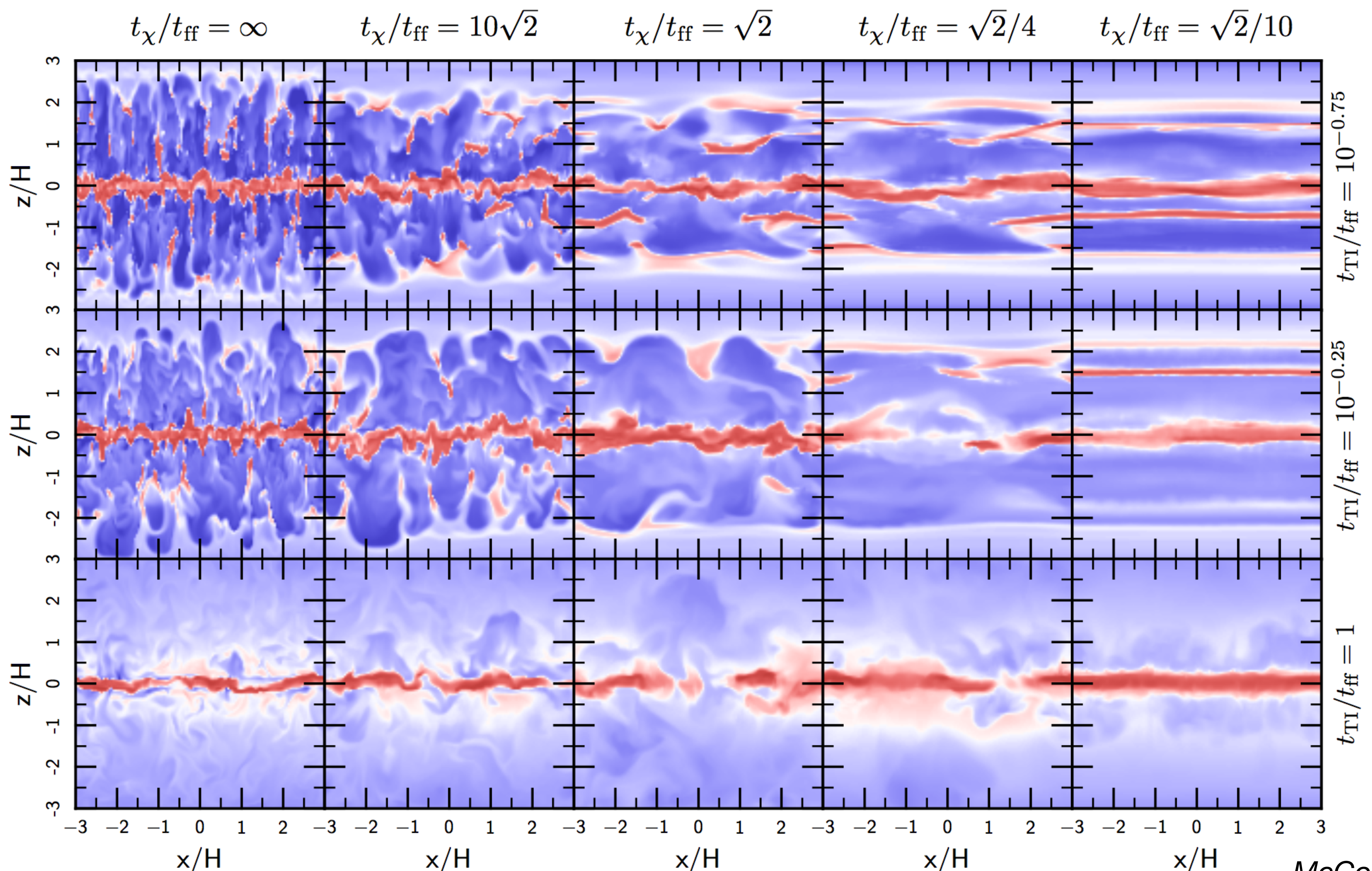
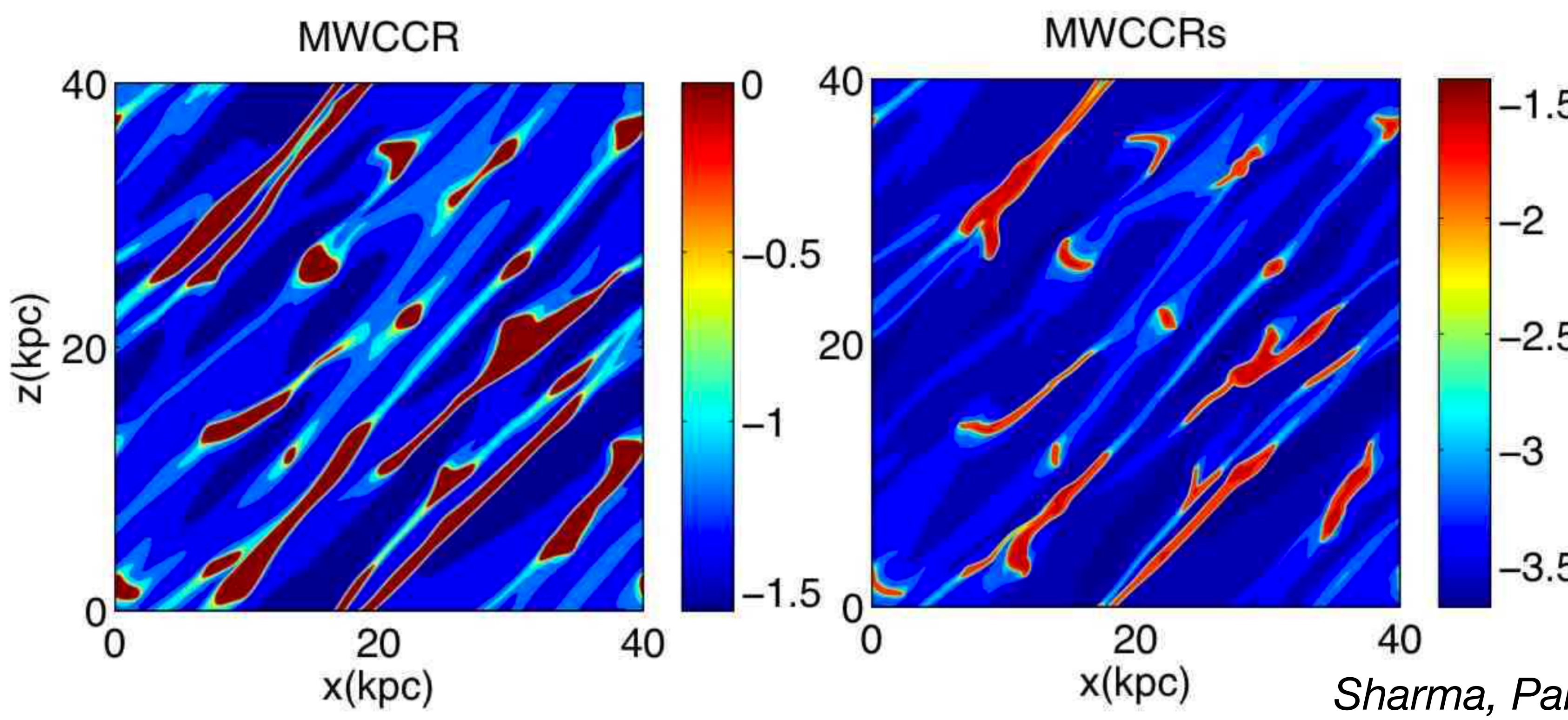
The formation of cold gas:
effect of thermal conduction



McCourt+12

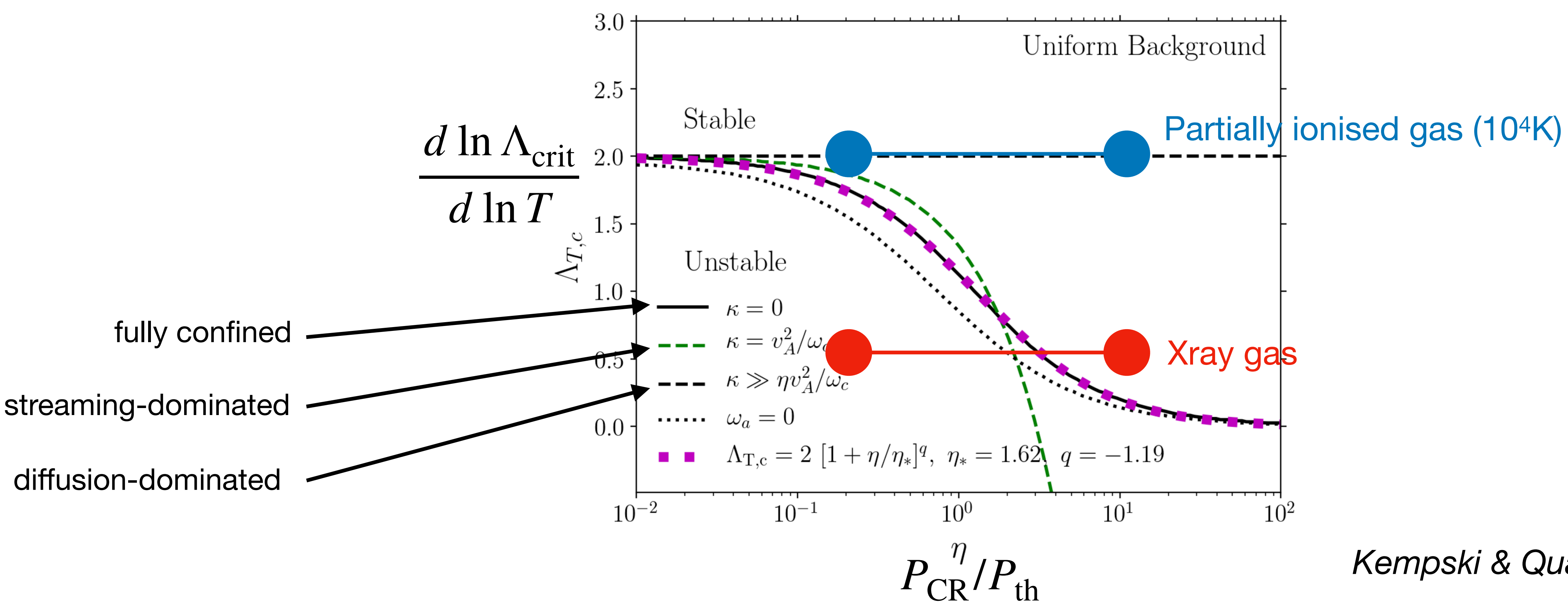
The formation of cold gas:
effect of CR pressure support

initial CR-to-total pressure ratio = 10^{-1} initial CR-to-total pressure ratio = 10^{-3}



Log CR-to-total pressure ratio

Sharma, Parrish & Quataert 10



Kempski & Quataert 20