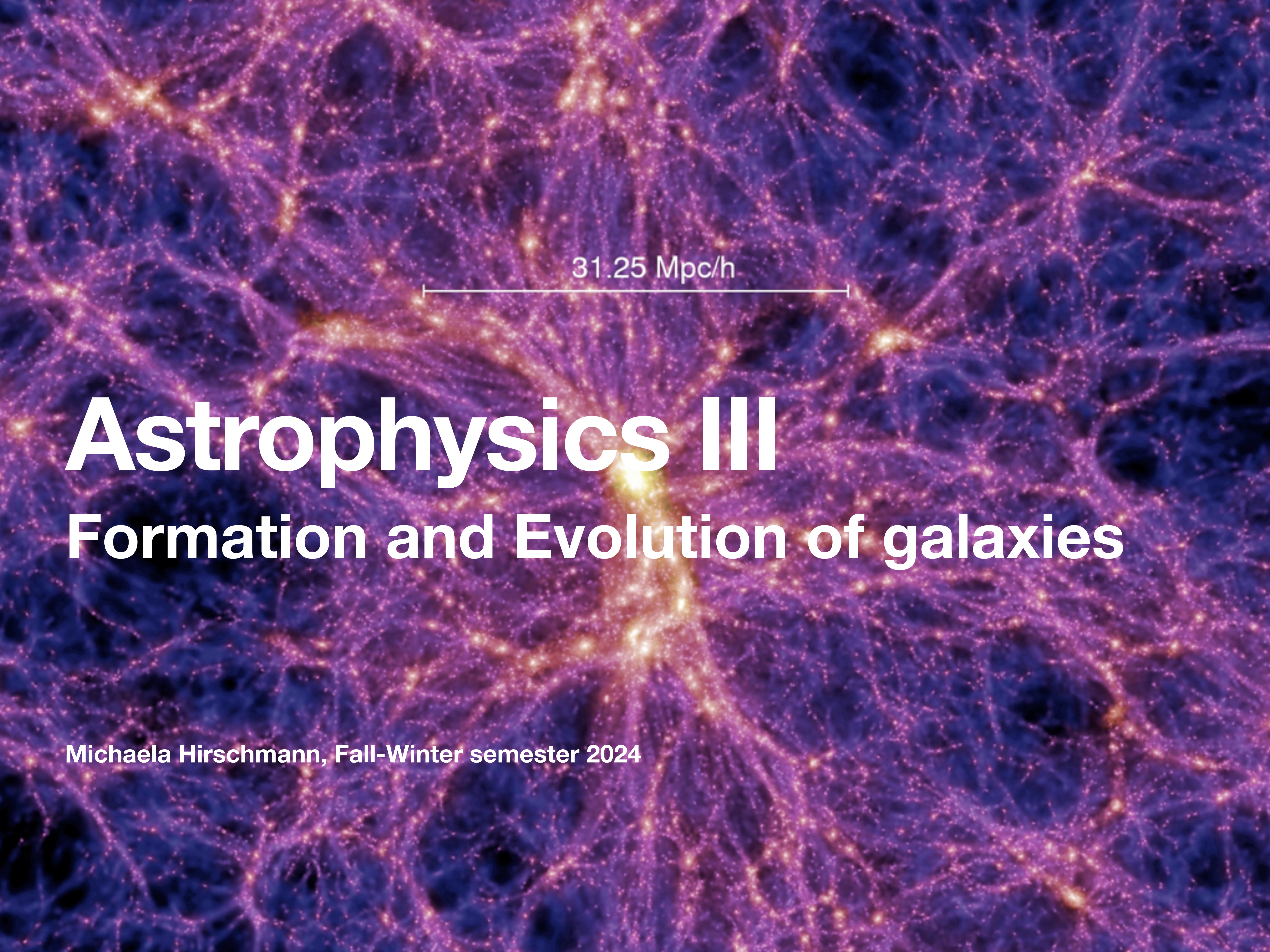

Astrophysics III

Formation and Evolution of galaxies

Michaela Hirschmann, Fall-Winter semester 2024

Lecture content and schedule

- *Chapter 1*: Introduction (galaxy definition, astronomical scales, observable quantities — repetition of Astro-I)
- *Chapter 2:* Brief review on stars
- *Chapter 3*: Radiation processes in galaxies and telescopes;
- *Chapter 4:* The Milky Way
- *Chapter 5*: The world of galaxies I
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- *Chapter 7:* Black holes and active galactic nuclei
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- *Chapter 10*:
    - Cosmology in a nutshell; Linear structure formation in the early Universe
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- *Chapter 17*: Modern simulations & future prospects

Part I: Observational basics & facts of galaxies first 7 lectures

Part II: Theory & models of galaxy evolution processes second 7 lectures

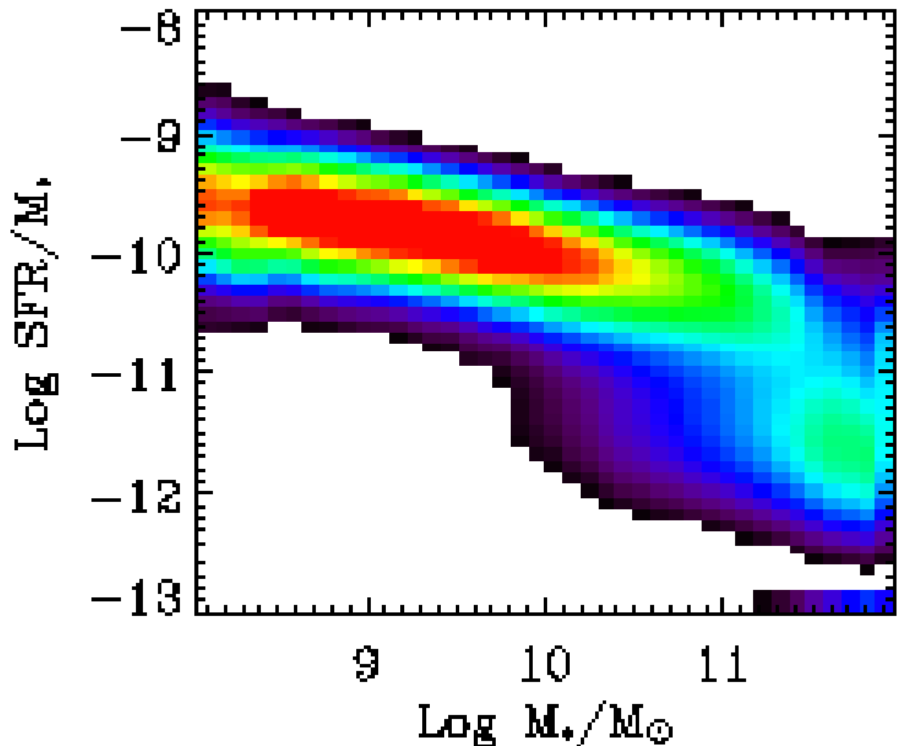
Outline of Chapter 16

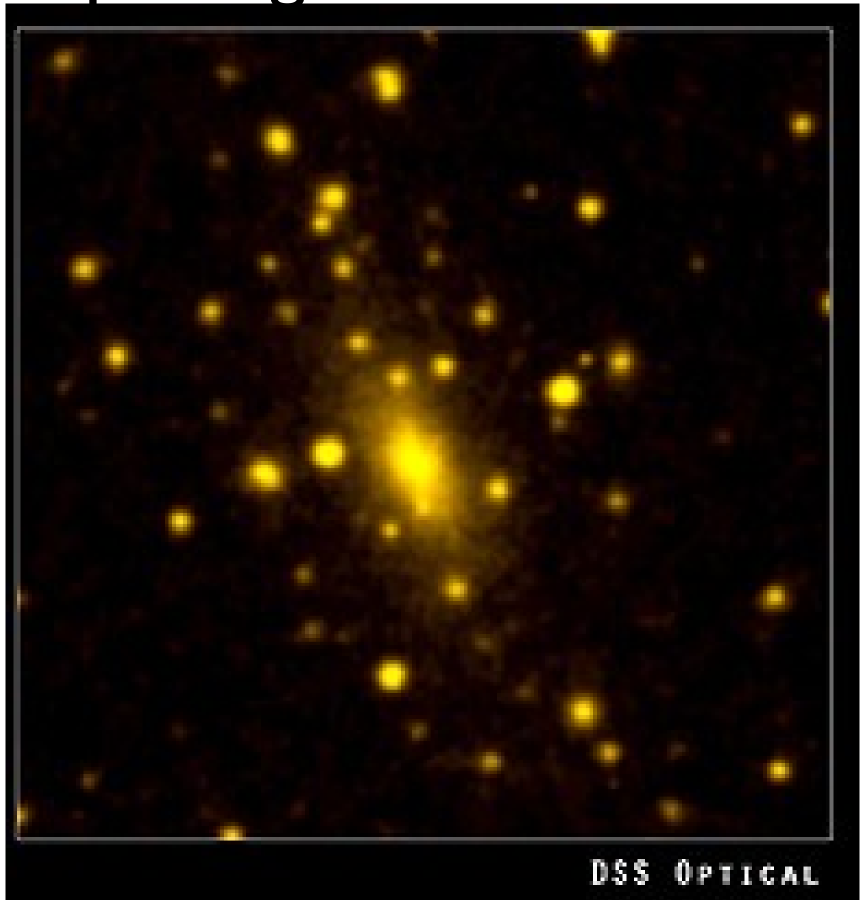
- Motivation for feedback from accreting BHs
- Small-scale physical processes of BH accretion and AGN feedback
- Different models for BH accretion and AGN feedback in cosmological simulations
- AGN feedback and galaxy properties in cosmological simulations

Persisting problems with massive galaxies

- Massive galaxies: stellar fb can be efficient at high z progenitors, but towards lower redshifts, not enough energy to eject material out of the galaxy resulting in
  - Over-cooling problem: too many too massive galaxies
  - Massive galaxies have too high SFRs at late times
  - Massive galaxies have too young and blue stellar populations (no color bi-modality)
  - Massive galaxies have too small sizes/ too compact
  - Massive galaxies often have more disk-like morphologies
  - Cooling flow problem in galaxy clusters

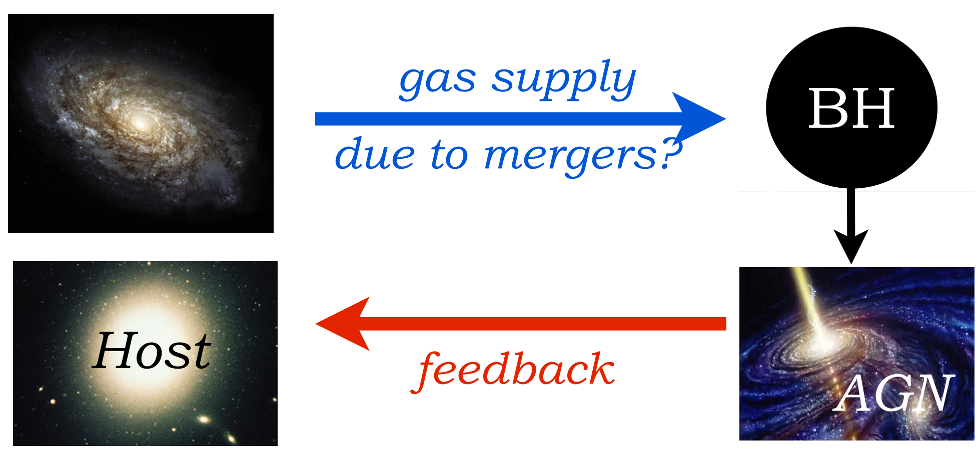
NEED FOR OTHER ENERGY SOURCES

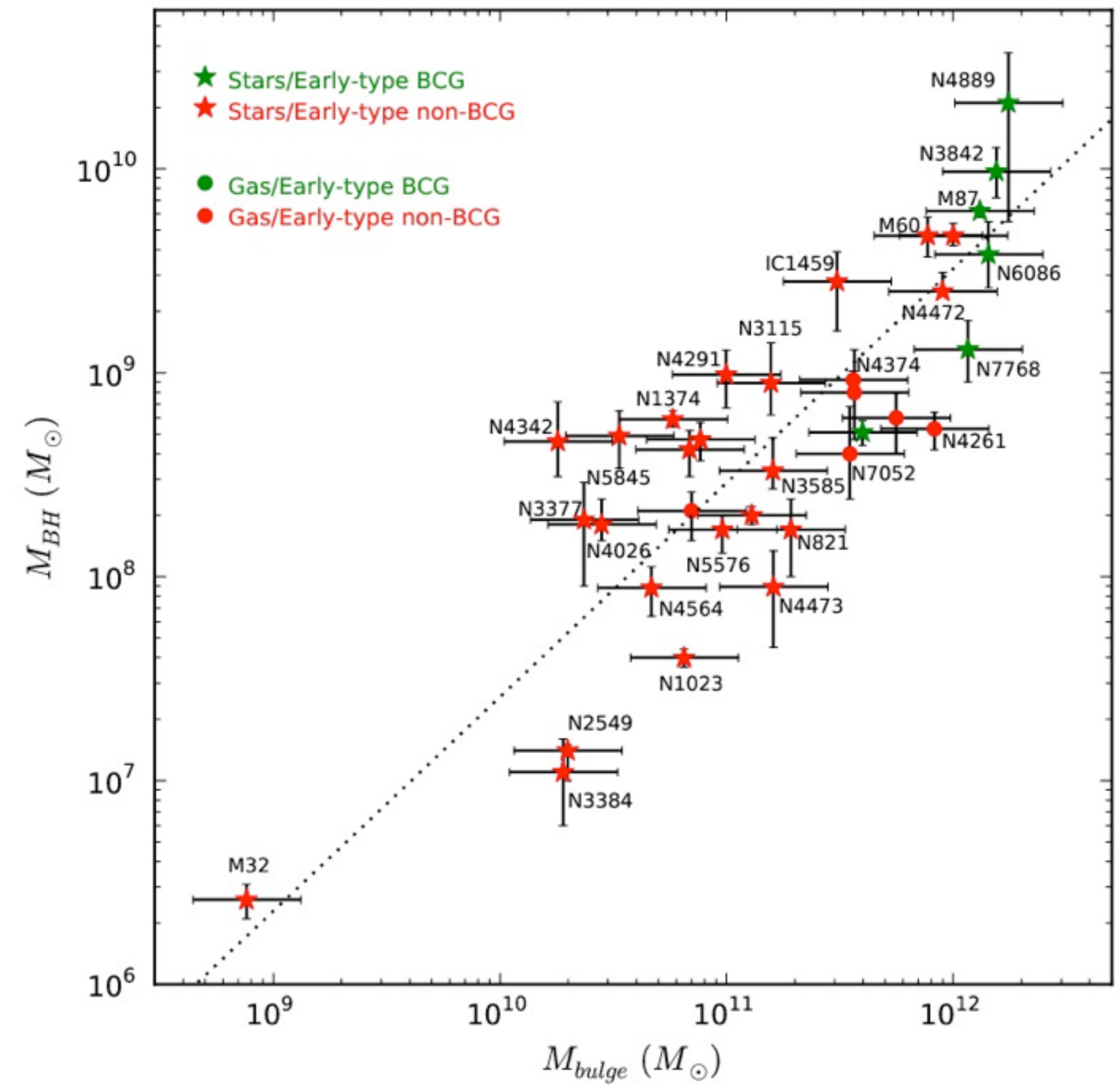




Supermassive BHs in galaxies

- Possible solution: AGN feedback
- Most if not all galaxies host a supermassive BH in their centre
- BH scaling relations suggest an evolutionary connection betweens BHs and their hosts





- Theorists "like" BHs as they are extremely efficient energy sources: 10% of rest mass converted into energy
  - Thermal binding energy of a $10^{13} M_\odot$ halo ... 10^{61} erg VS.
  - Accretion energy of a $10^{9} M_\odot$ BH …$2*10^{62}$ erg

➡Plausible that this energy affects the host…

Which observational evidence does exist for AGN feedback in galaxies?

- Quasar-driven winds in local & X-ray obscured AGN, out to z=6
  - Broad component of emission lines allows for for identification of gas outflows and quantification of outflow velocities
  - High gas accretion rates

- Observational evidence for hot X-ray cavities, so called radio-lobes
  - Radio lobes are fuelled by narrow core/BH powered relativistic jets (synchrotron emission)
  - Low gas accretion rates

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Small-scale physics: BH growth

AGN luminosity and BH accretion rate:

- With a radiative efficiency eps_r, a fraction of the rest mass energy of the accreting matter dM_{BH}/dt that is converted into observable electromagnetic radiation, $L_{AGN,bol}$

$$L_{\rm bol} = \epsilon_r \frac{dM_\bullet}{dt} c^2$$

- eps_r predicted by accretion disk simulations to range between 0.05 and 0.4 (depending on the spin), observations suggest 0.1-0.2

Upper limit for BH accretion from simple spherically symmetric model:

- Balance between outward directed radiation pressure force and inward directed gravitational force defines the maximum Eddington accretion rate/luminosity

$$F_{\rm rad} = \sigma_T \frac{L}{4\pi r^2 c} \qquad F_{\rm grav} = \frac{G M_\bullet m_p}{r^2} \qquad L_{\rm edd} = \frac{4\pi G M_\bullet m_p c}{\sigma_T} \approx 1.3 \times 10^{46} \left(\frac{M_\bullet}{10^8 M_\odot}\right) erg/s$$

Q: Do you think it is realistic to assume that in nature BHs can never accrete above the Eddington limit?

- Eddington ratio $f_{edd} := L/L_{edd}$ used to distinguish between radiatively efficient ($f_{edd}>0.1$) and inefficient ($f_{edd}<0.1$) BH accretion and AGN

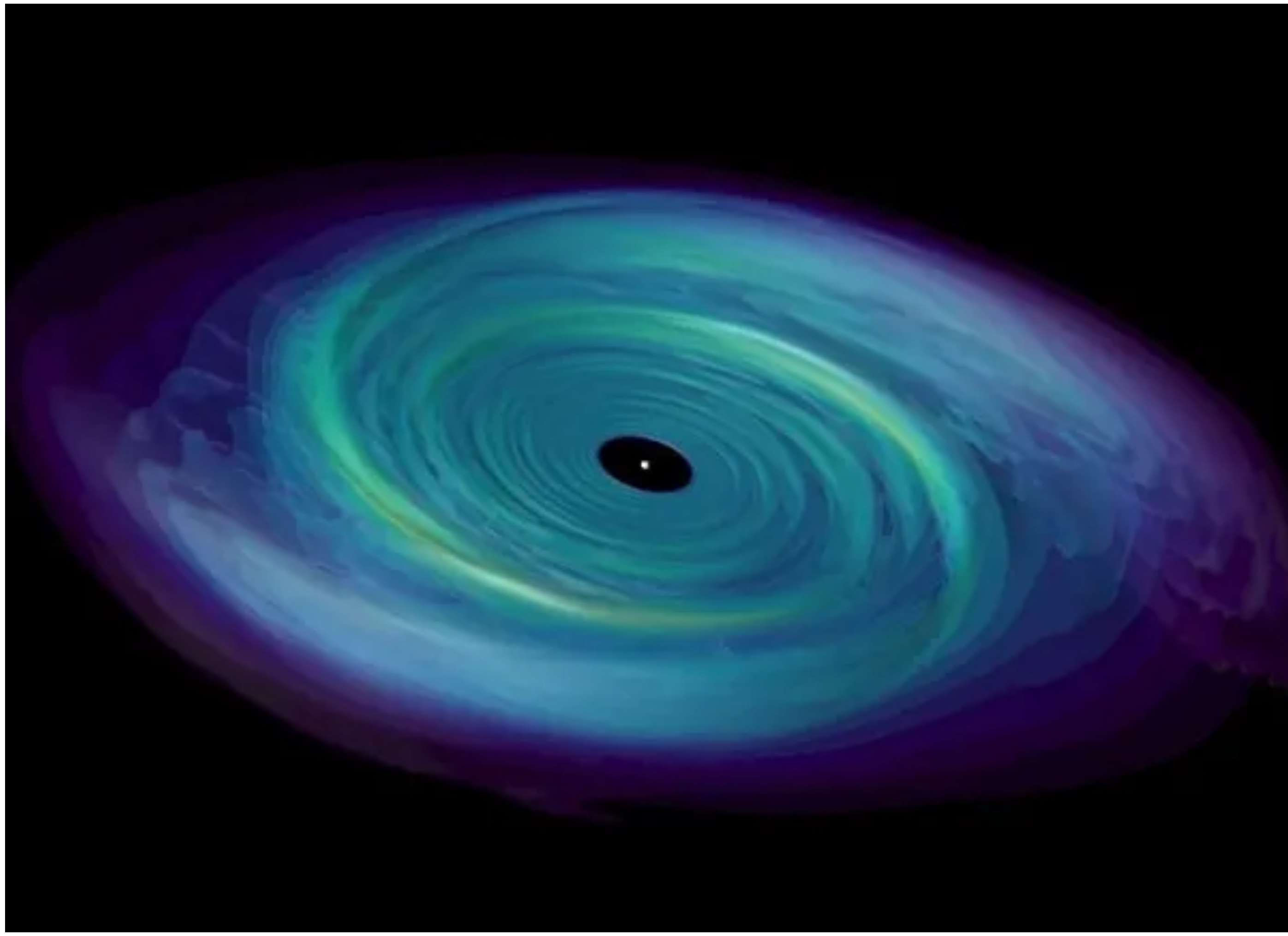
Small-scale physics: BH growth

But: f_{edd} changes with time depending on the gas supply!

Accretion in the radiatively efficient regime:

Geometrically thin (optically thick) accretion disks

- Since gas has angular momentum, accretion most likely through a Keplerian disk
- Gas must loose its angular momentum to accrete to set free gravitational energy
- Viscous processes (due to turbulence and magnetic stress) can transport angular momentum outwards
- Spinning BHs complicate the picture, can de/increase gas accretion

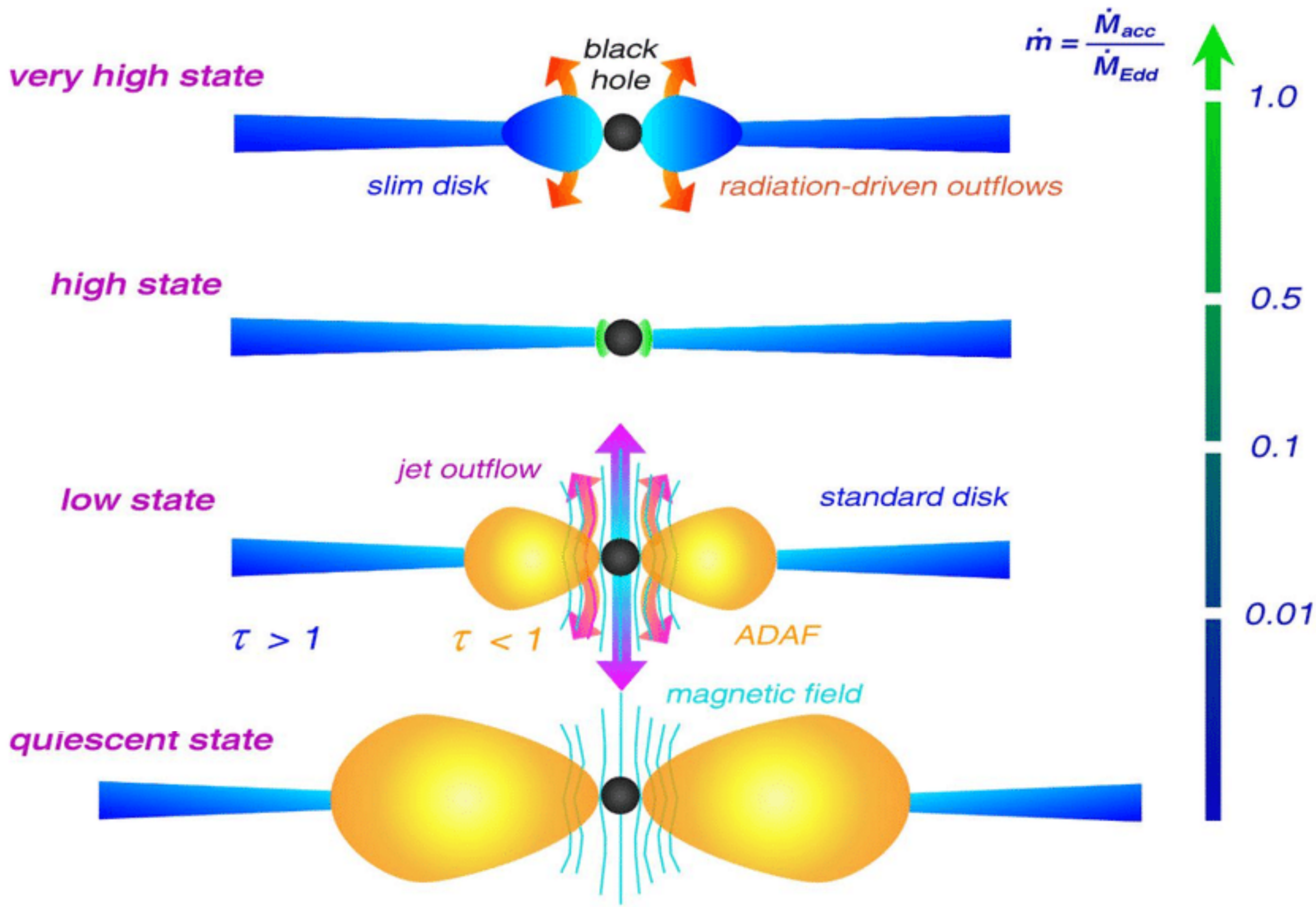


- Analytic Shakura-Sunyaev solution for gas accretion $dM_{BH}/dt = M_{gas,disk}/t_{vis}$ on a viscous time-scale

$$\tau_{\rm vis} \approx 1.2 \times 10^6 \text{ yr} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_{\rm circ}}{100 r_s}\right)^{7/2} \left(\frac{M_{\rm BH}}{10^9 \text{ M}_\odot}\right)$$

Small-scale physics: BH growth

- In a hot, less dense medium: Geom. thin disk model not valid
- Instead, disk because puffed up and optically thin, radiatively inefficient accretion (may power radio galaxies with jets/outflows)



Small-scale physics: BH growth

- Instead, disk because puffed up and optically thin, radiatively inefficient accretion (may power radio galaxies with jets/outflows)
- BH may rather accrete hot gas via Bondi-Hoyle accretion scheme
  - Spherically symmetric accretion (from a hydrostatic hot, ideal gas around BH with no angular mom.), when gravitational potential energy of BH overcomes the thermal energy of the gas

$$\sqrt{\frac{2GM}{R}} \simeq c_s \, ,$$

  - This defines the accretion ("Bondi") radius i.e. radius at which sound speed of gas equals the escape velocity

$$R \simeq \frac{2GM}{c_s^2}$$

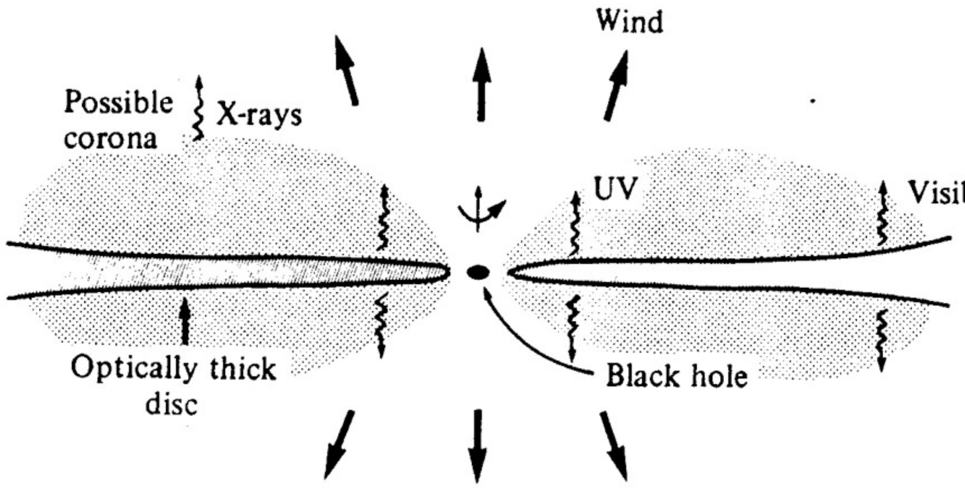
  - Accretion rate is roughly

$$\dot{M} \simeq \frac{4\pi\rho G^2 M^2}{c_s^3}$$

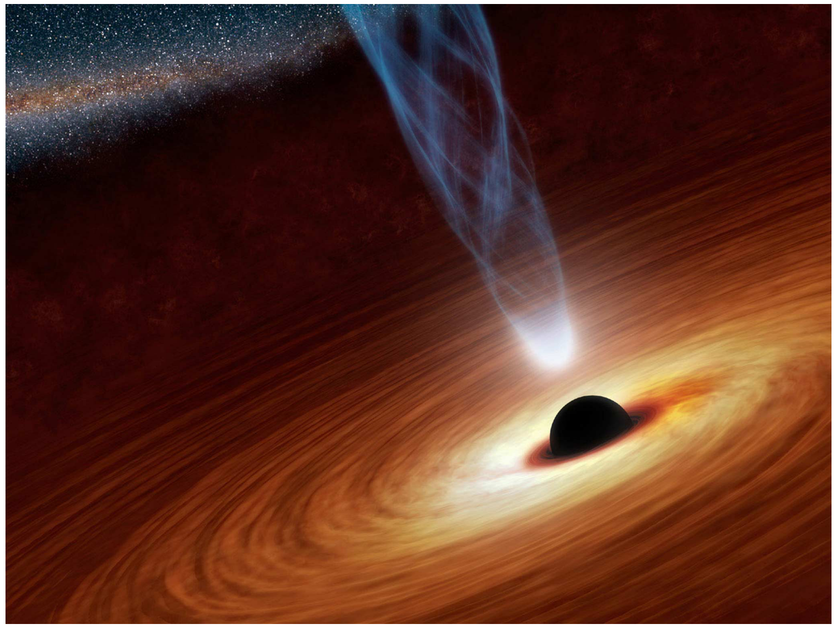
  - More accurate estimations come from GRMHD simulations of gas accretion disk around BHs —> high complexity!

Small-scale physics: AGN feedback

- Gas accretion onto BHs can lead to significant amounts of energy release (radiative and mechanical form)
- Two main modes of energy production:
  - Thin accretion disk: Loss of angular mom. in a Keplerian accretion disk (via viscosity, magneto-rotational instability) —-> radiation + fast particle winds



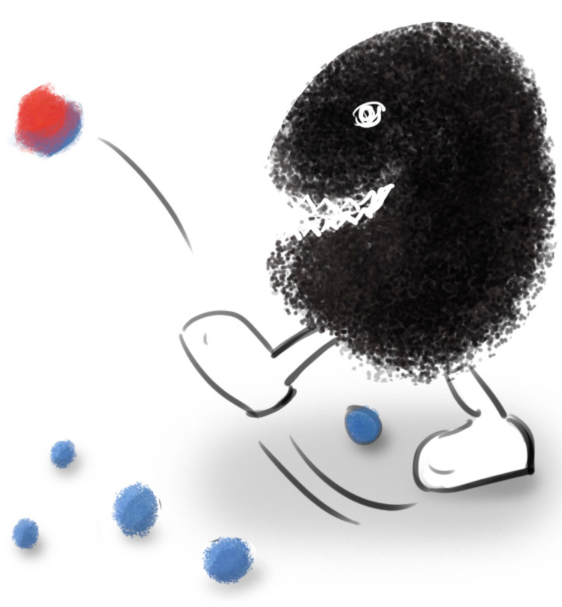
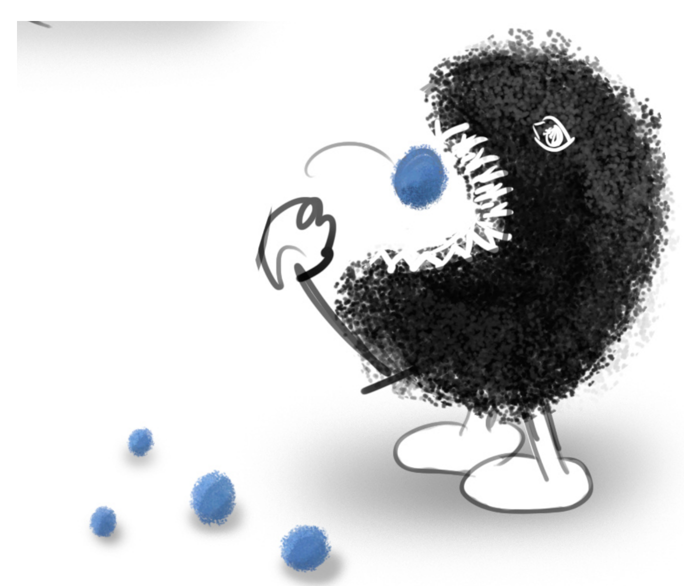
  - Relativistic jets: Magneto-hydrodynamic processes in form of magnetically arrested disks together with the spin of the BH lead to relativistic particle streams/ jets perpendicular to the disk



Small-scale physics: AGN feedback

Two main mechanisms how energy can couple to the ambient medium

- Radiative interaction between photons and gas: released radiative energy (photons!) from bright AGN can act on gas via radiation pressure and photo-ionisation- and Compton-heating
  - mostly relevant for radiatively *efficient* AGN (thin accretion disks)
- Particle-particle (mechanical) interaction: energy and momentum injection of (relativistic) material flows (e.g. winds in quasars, jets in radio galaxies) into ambient gaseous medium
  - similarly large mechanical energy as radiated energy
  - important for both radiatively efficient and inefficient AGN (winds from disk and jets, respectively)


Small-scale physics: summary

- Simple model of spherical gas accretion onto BHs:
  - maximum accretion at the Eddington limit (balance between gravity and radiation pressure)
  - but may be "violated" in reality under certain conditions (e.g., when we have lots of cold, turbulent around)
- BH accretion physics complex, can be studied with GRMHD simulations
  - Cold accretion via thin, optically thick accretion disk — radiatively efficient, high f_{edd}
  - Hot accretion via puffed-up disk, radiatively inefficient, low f_{edd}, (Bondi approach might be a good approximation)
- BH most efficient energy sources in our Universe
  - Between 10 and 20% of a BH's rest mass can be converted into energy, e-m radiation
  - Radiation and winds from gas accretion from gas accretion disk (radiative and mechanical processes)
  - Fast relativistic particle jets (mechanical)

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Scales involved in AGN feedback

Galaxy formation in the cosmic web	Feedback affecting the ISM	BH accretion and launch of feedback
10kpc - a few Mpc	10 pc - 1 kpc	<< 1 pc

Shock waves

Particle jets

DM halo, ICM

Intergalactic medium

Shock-heating

Gas cooling

Accretion disk

Viscous processes

Spinning BH

Magnetic fields

Relativistic effects

Accretion of cold or hot gas

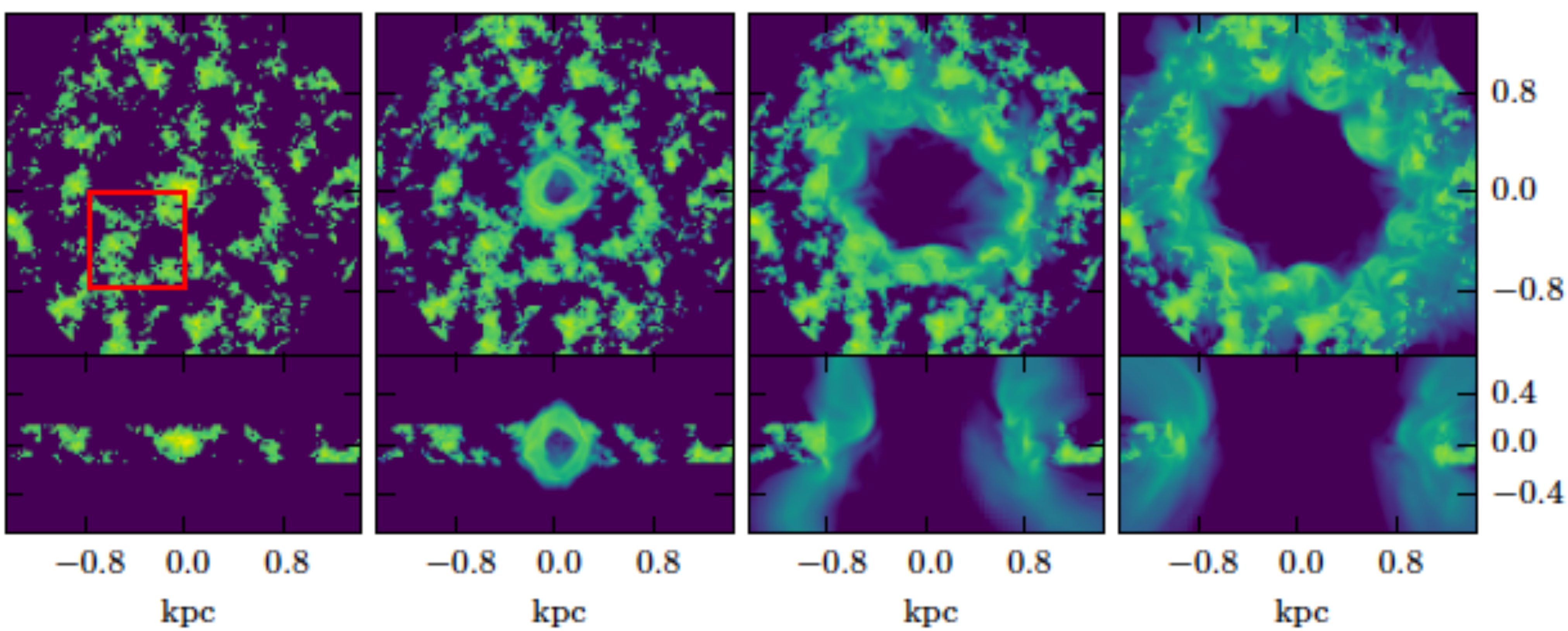
Cosmological simulations	Simulations of isolated galaxies	GRMHD simulations of accretion disk

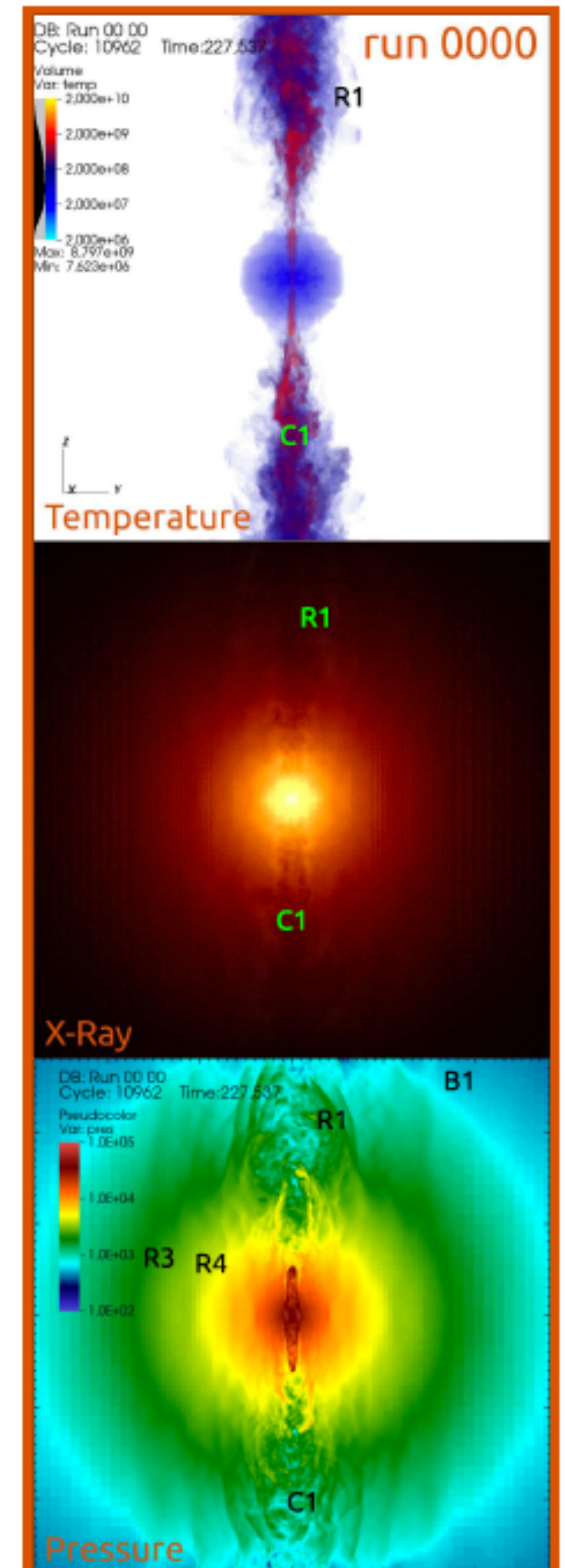
- How can we simulate such processes on scales beyond tens of parsec?

Hydro simulation of isolated galaxies

To study possible interactions with host galaxies —>
(Radiation-)Hydrodynamic simulations of isolated galaxies or part of the ISM

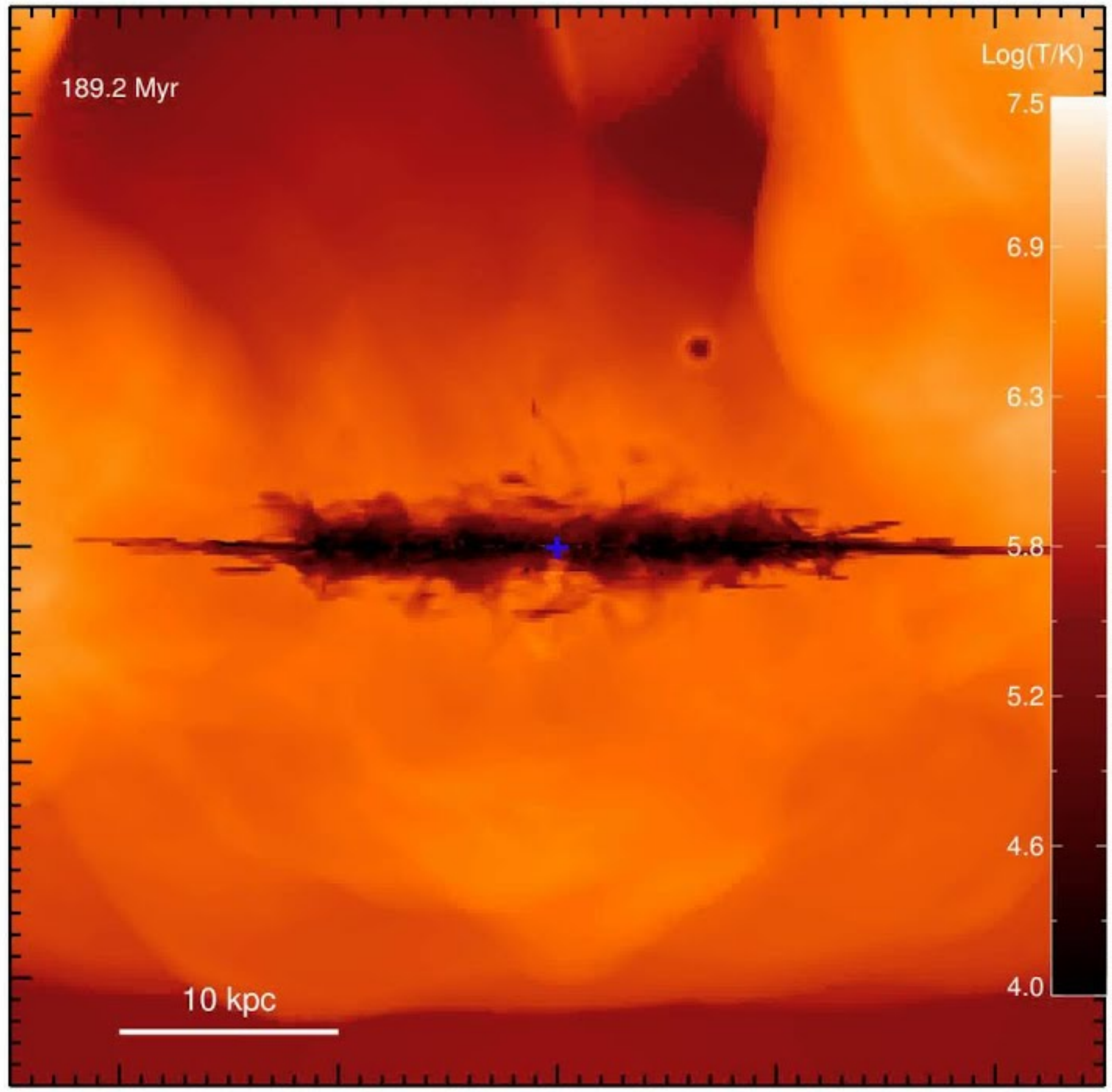
- Detailed radio-jet simulations suggest interaction with ISM, heating and outflows *(e.g., Gaibler+12, Gaspari+12, Wagner+12, Mukherjee+16, Cielo+17, Talbot+)*
- Detailed radiation-hydro simulations: Radiative AGN feedback (from accretion disk in quasars) seems to be capable of driving outflows *(e.g., Bieri+17, Costa+17)*
- *Cielo, Bieri+18:* Comparing radiation feedback with jet feedback: *"[…] they produce similar outflow properties"*
- A lot of on-going research …





Hydro simulation of isolated galaxies

To study possible interactions with host galaxies —>
(Radiation-)Hydrodynamic simulations of isolated galaxies or part of the ISM



BH growth in cosmological simulations

- BHs are modelled as collisionless "sink" particles, mass of accreted gas part. are added to that of the sink
- BH seeding: Start with "BH seed" of a certain mass putting it into a halo/galaxy above a certain mass limit
- BHs can further grow via mergers and via gas accretion
- Traditional model for gas accretion is Bondi (but other schemes also adopted):

$$\frac{dM_\bullet}{dt} = \frac{4\pi M_\bullet^2 \rho}{(c_s^2 + v_{\rm rel}^2)^{3/2}}$$

- Compute probability that neighbouring gas particles are absorbed by the BH
- Often assumed that BH accretion is limited by the Eddington rate
- Merge BHs if they are within one smoothing length of each other and if the relative velocity is smaller than the sound speed

AGN feedback in cosmological simulations

Traditional thermal feedback approach:

- Assume that a fraction of radiated luminosity thermally couples to the surrounding gas

$$L_{\rm bol} = \epsilon_r \frac{dM_\bullet}{dt} c^2$$

$$\frac{dE_{\rm therm}}{dt} = \epsilon_{\rm therm} \epsilon_r \dot{M}_\bullet c^2$$

- Add kernel weighted energy to the thermal energy of the neighbouring gas particles/cells
- $\varepsilon_{\rm therm}$ chosen to reproduce the local BH scaling relations

Modified bubble feedback approach:

- To mimic hot bubbles for radiatively inefficient AGN, $\varepsilon_{\rm therm}$ is increased from 0.5% to 2% and energy is sometimes released offset to the AGN/BH

Kinetic jet/disk feedback:

- For radiatively inefficient/efficient AGN: injection of kinetic energy into the ambient medium
- Neighbouring gas particles get kicks with velocities of 1000 km/s (perpendicular to the gas disk)

Stochastic thermal feedback: —> Similar approach as for stellar fb

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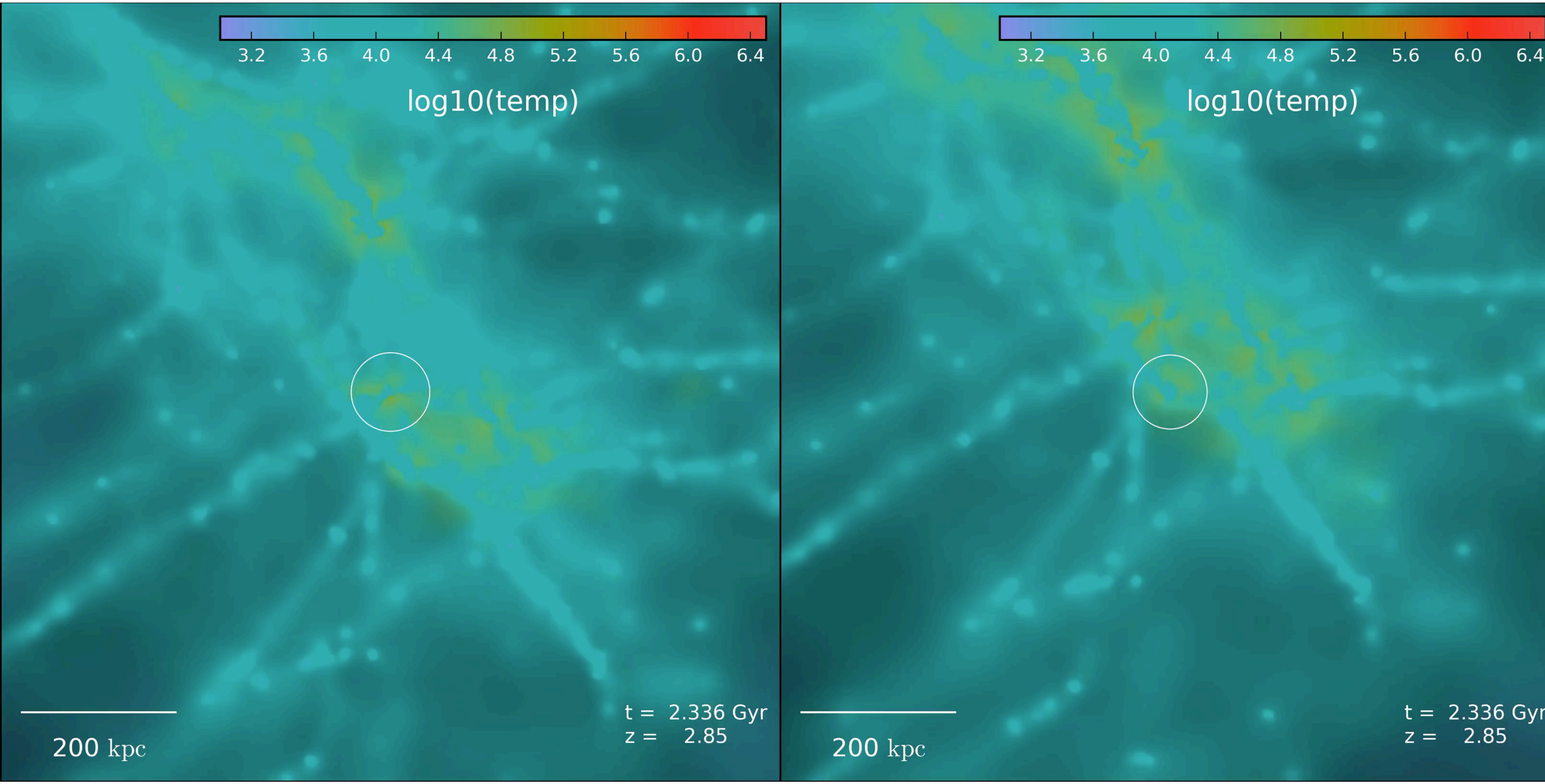
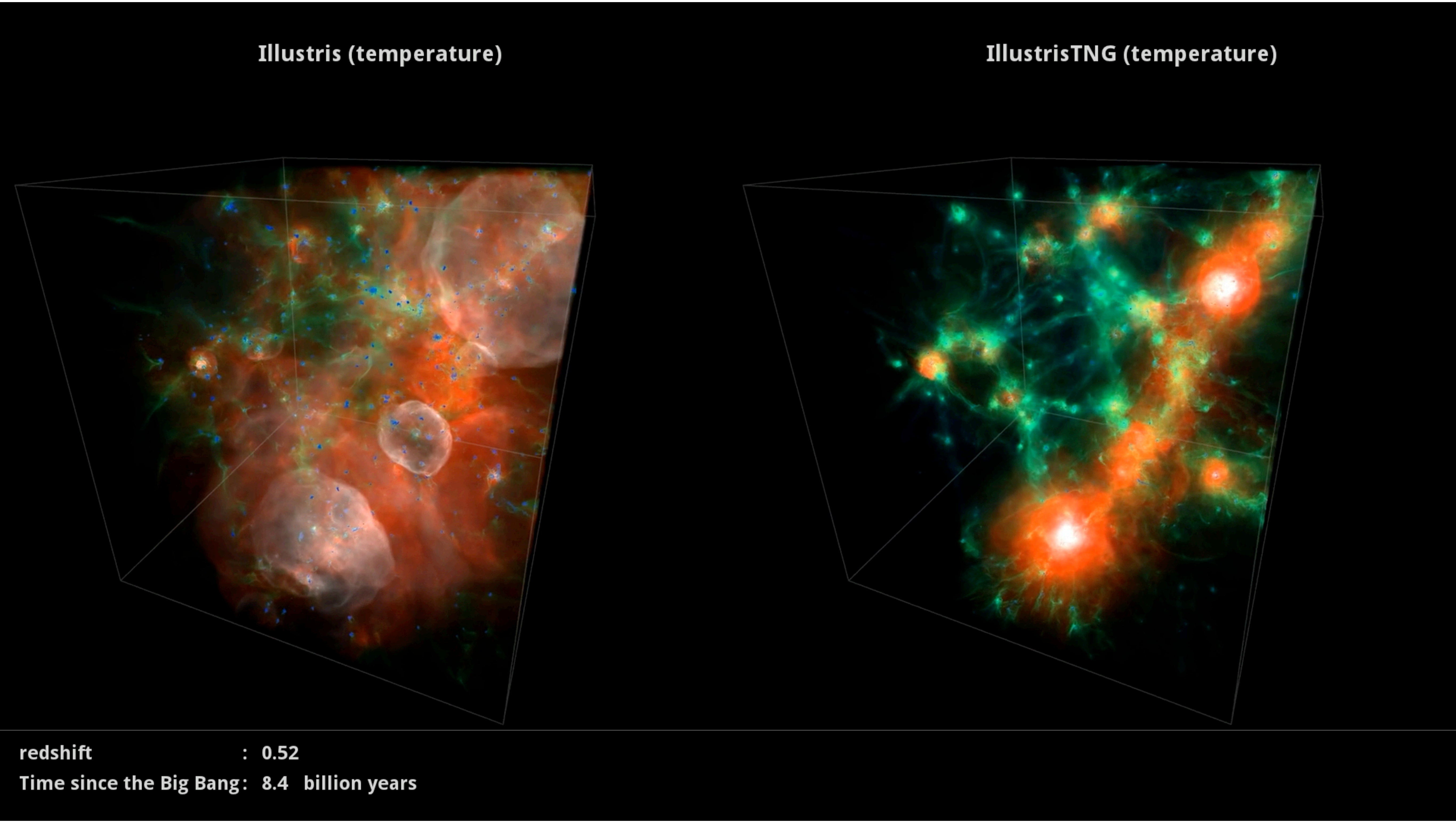
Visualization of a zoom-in simulation…



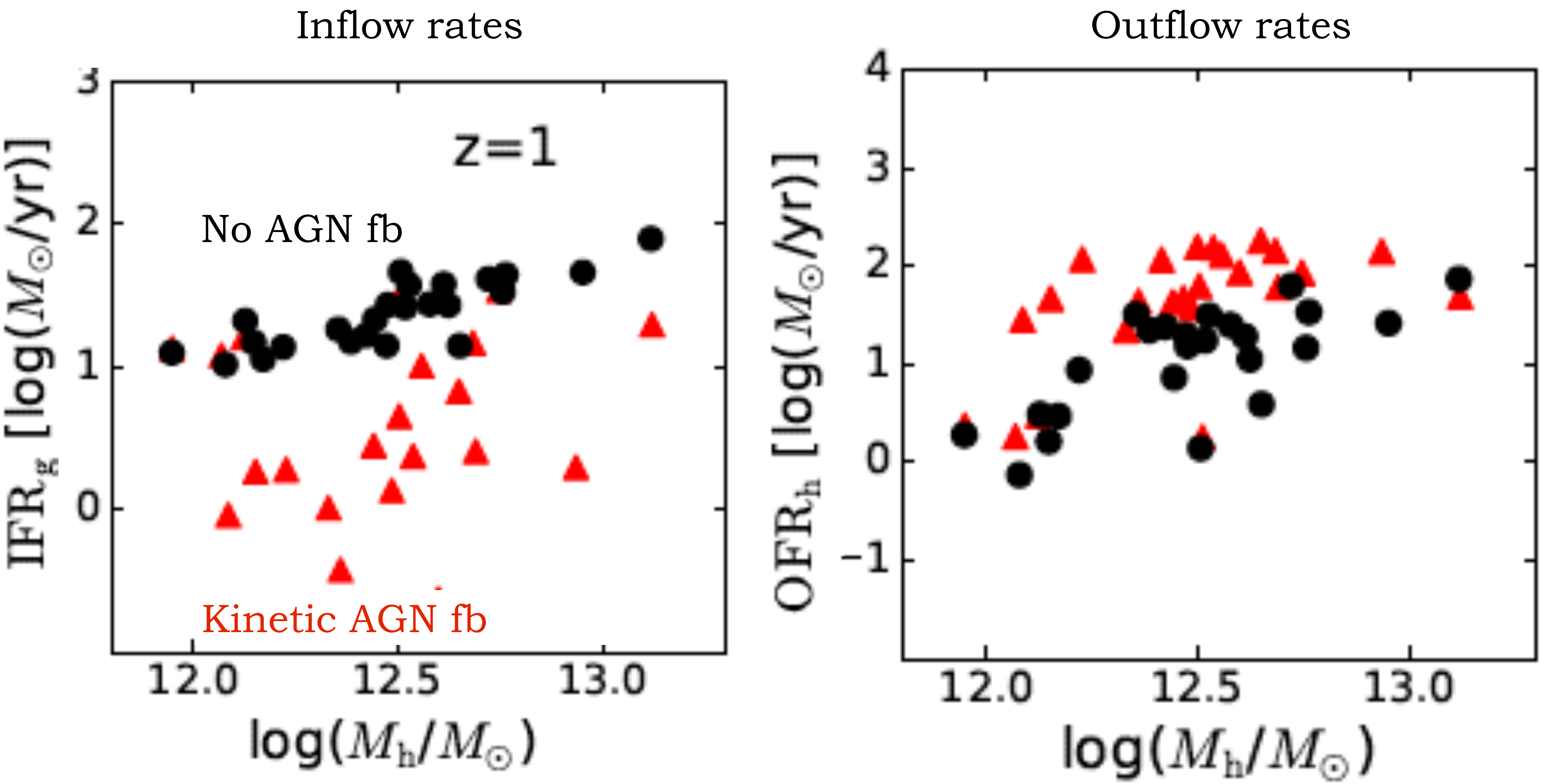
- …with and without kinetic AGN feedback as described in Choi+17/ Hirschmann+17
- Similar implementations: e.g., Weinberger+18 (IllustrisTNG), Dave+19 (Simba simulation)

Intergalactic medium

- Illustris and IllustrisTNG



In- and outflow balance

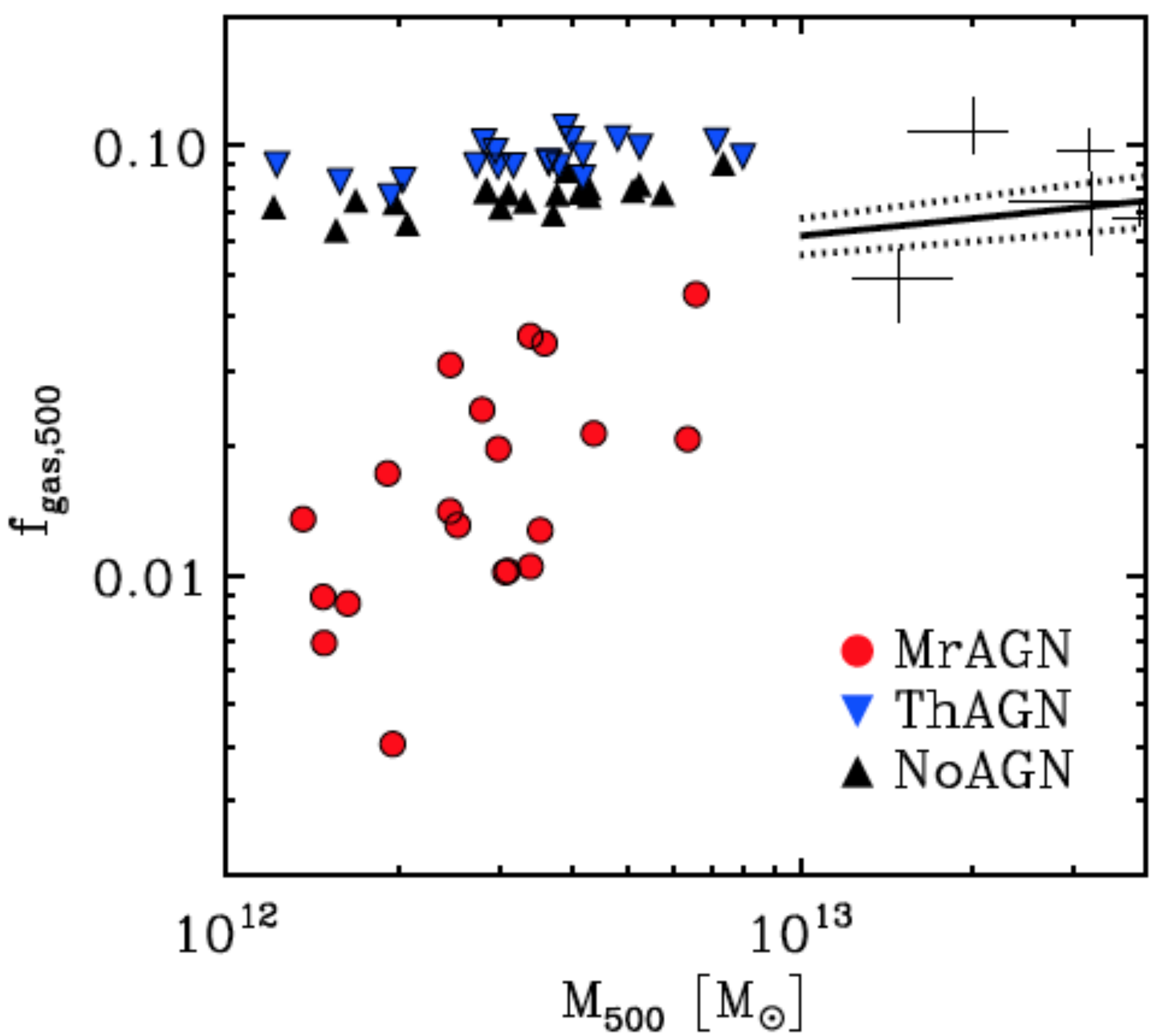


Brennan, Choi, Somerville, Hirschmann +17

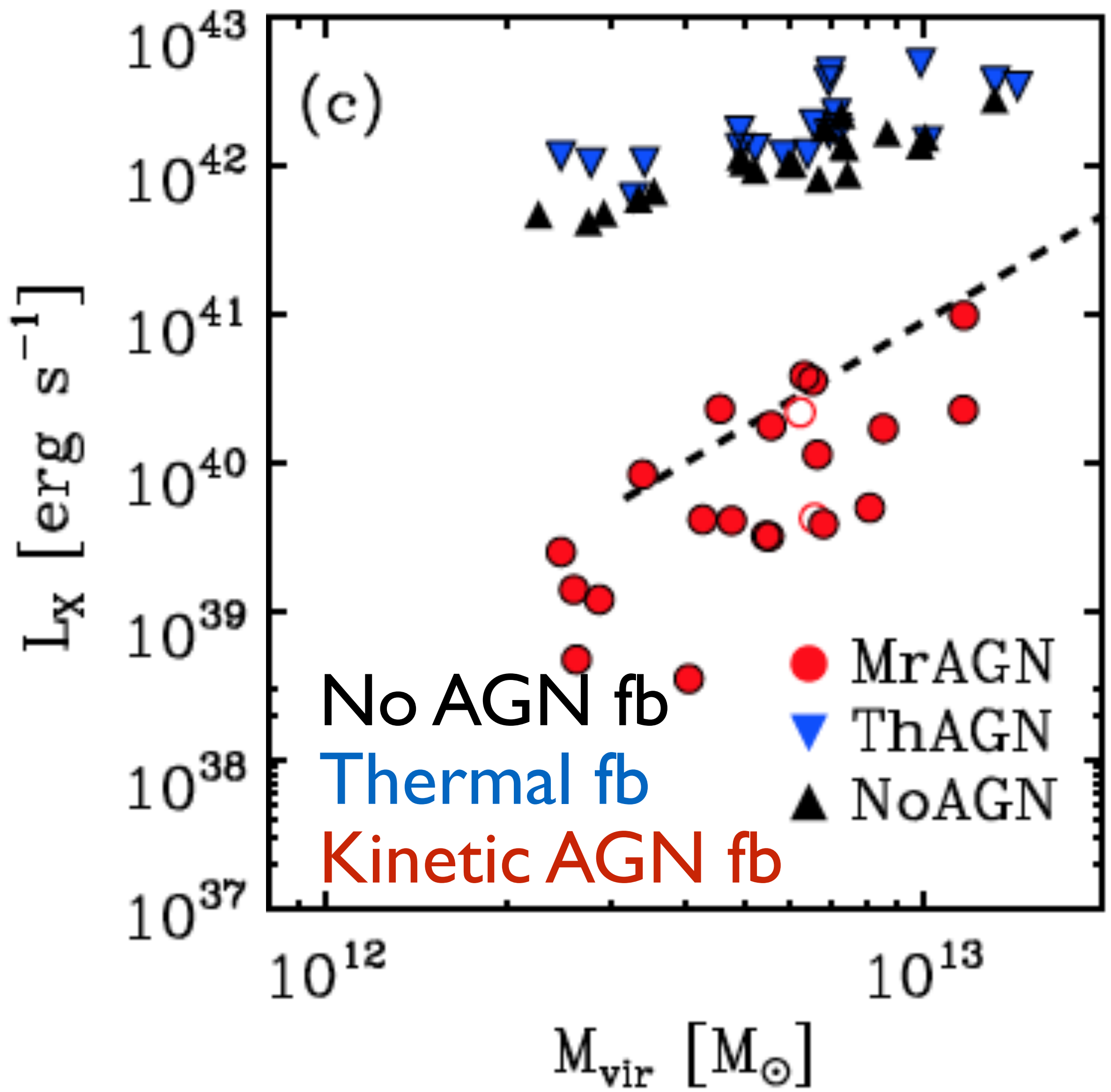
- Kinetic AGN feedback acts in two ways
  - Increasing gas ejection rates "ejective mode"
  - Reducing gas inflow rates "preventive mode"

Hot gas content in the halo

Hot gas fractions in halo

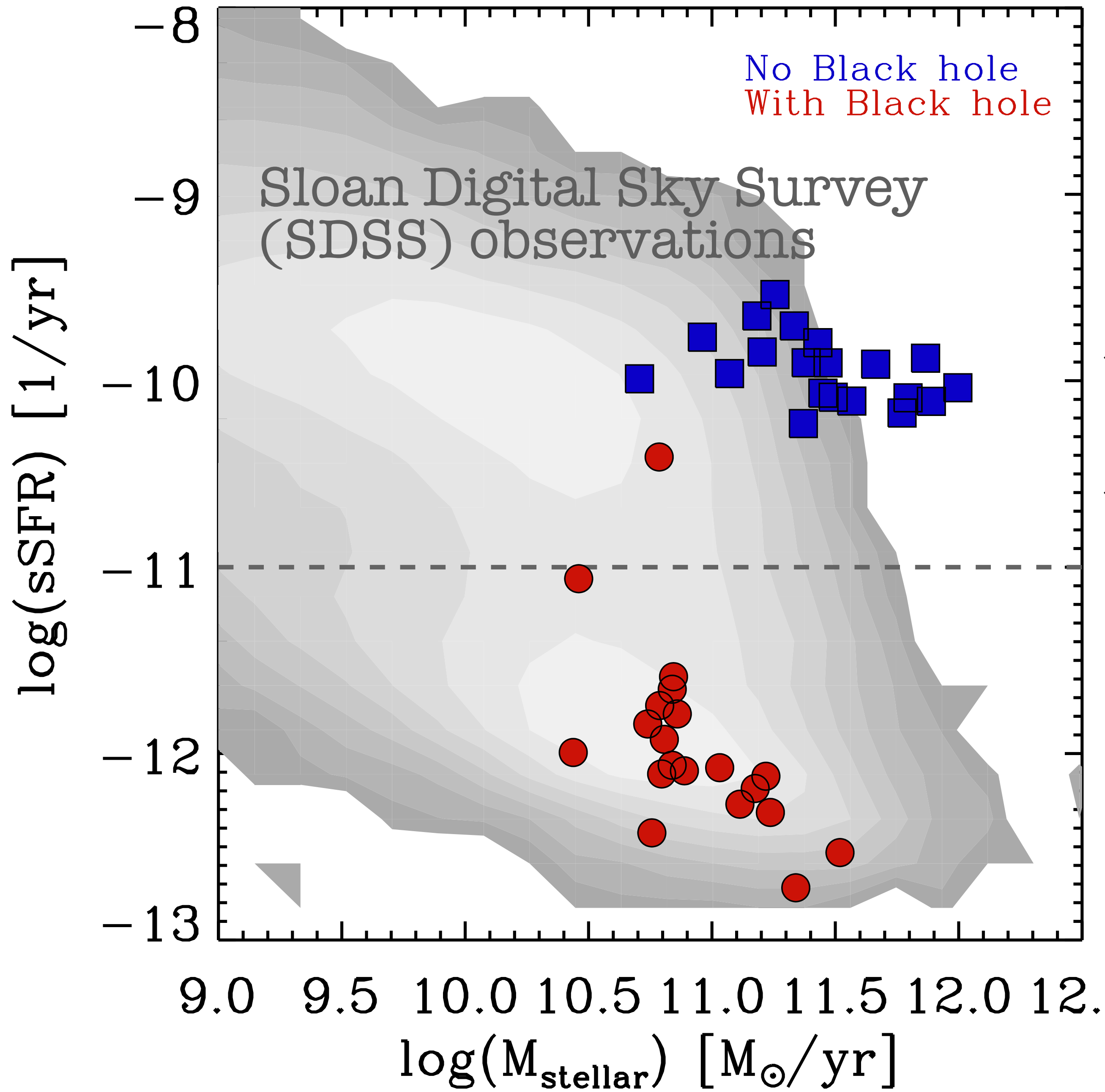


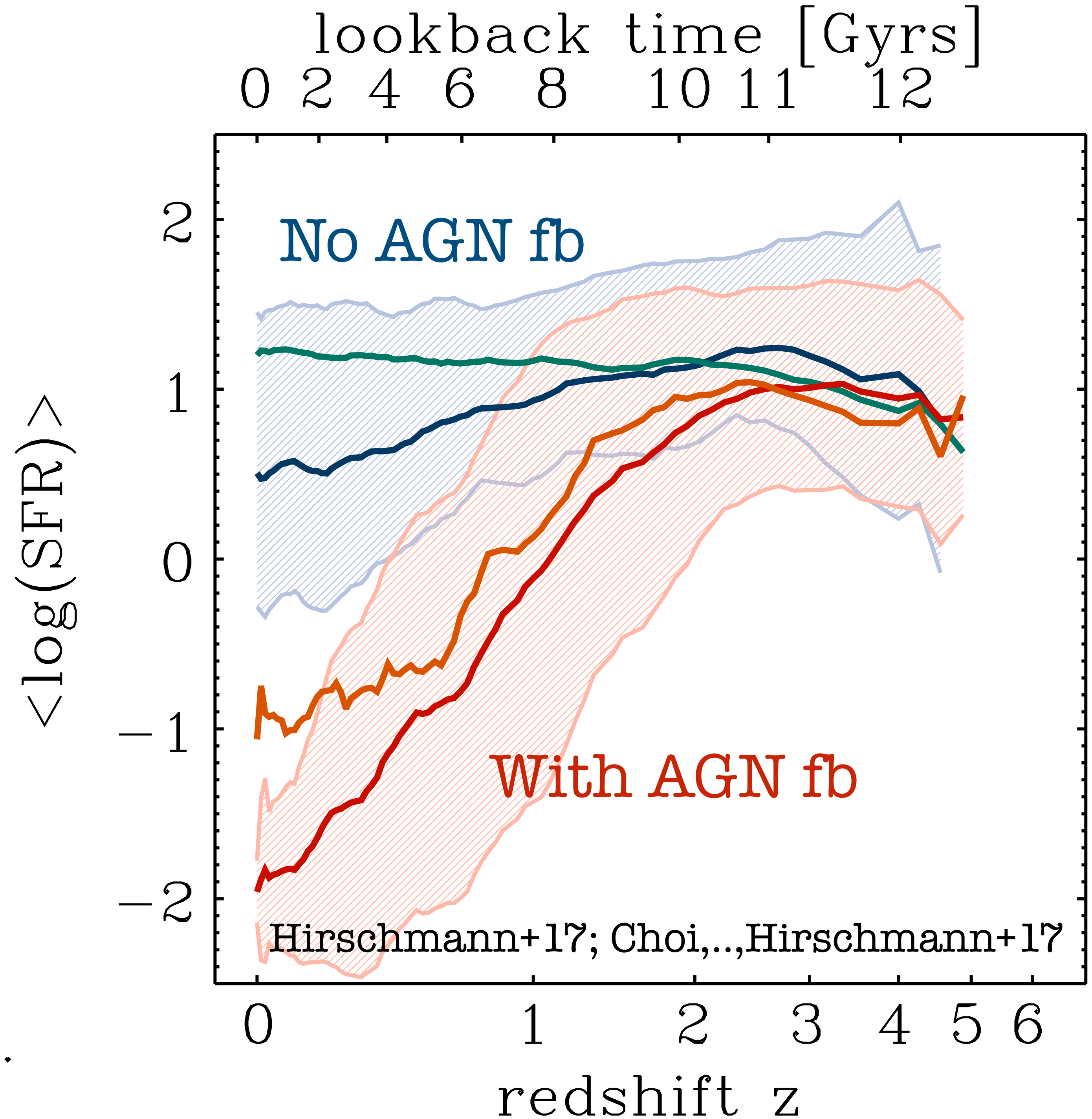
X-ray luminosities of hot gas



- Very sensitive to AGN feedback
- E.g. with dis-centered "bubble" feedback (in Illustris), amount of hot, X-ray luminous gas under-estimated!

Star formation rates



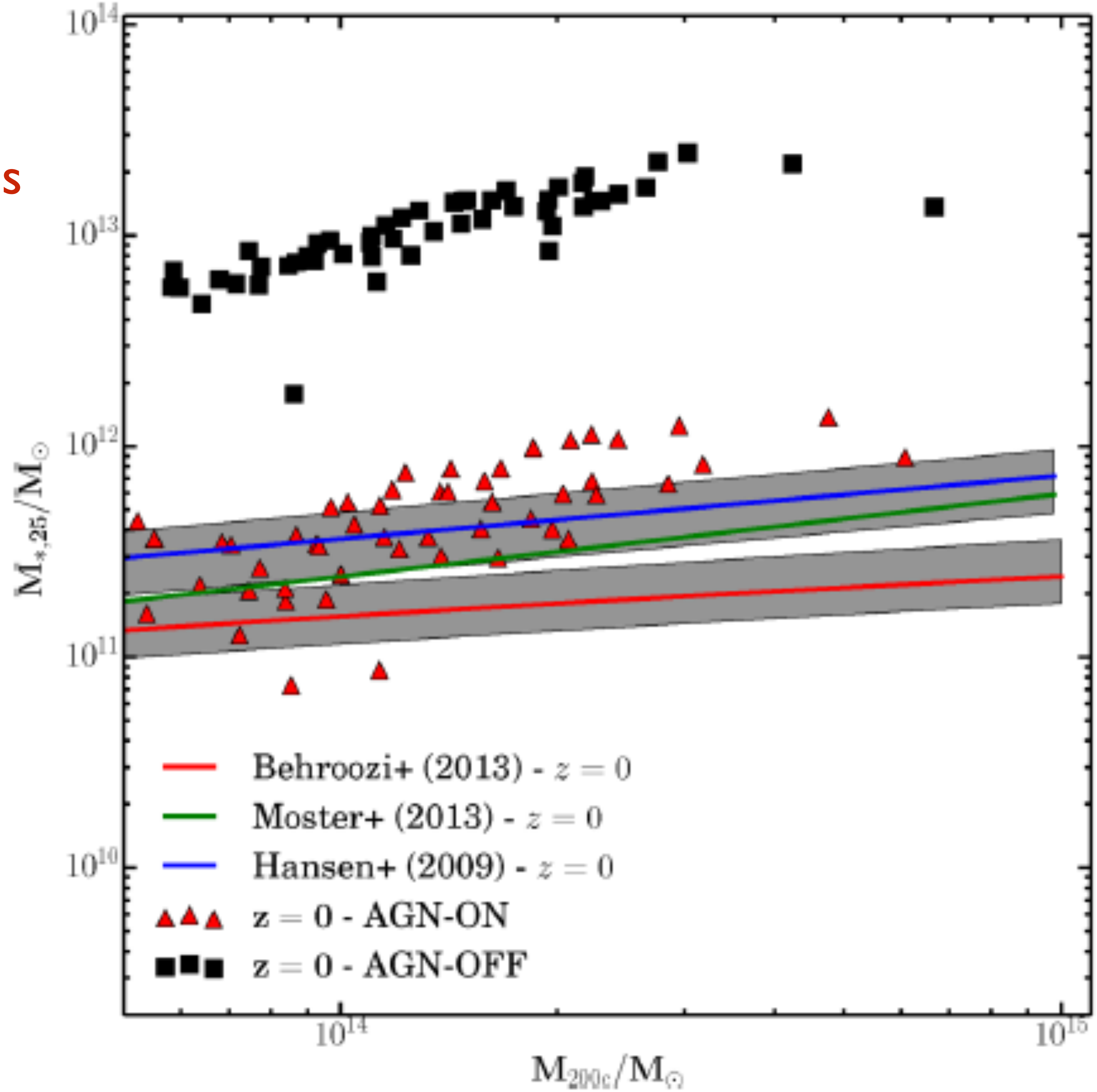


- Due to gas ejection and less gas being re-accreted, SFR strongly reduced!
- Effectively turning blue, SF galaxies into red and dead objects!

BCGs in Galaxy clusters

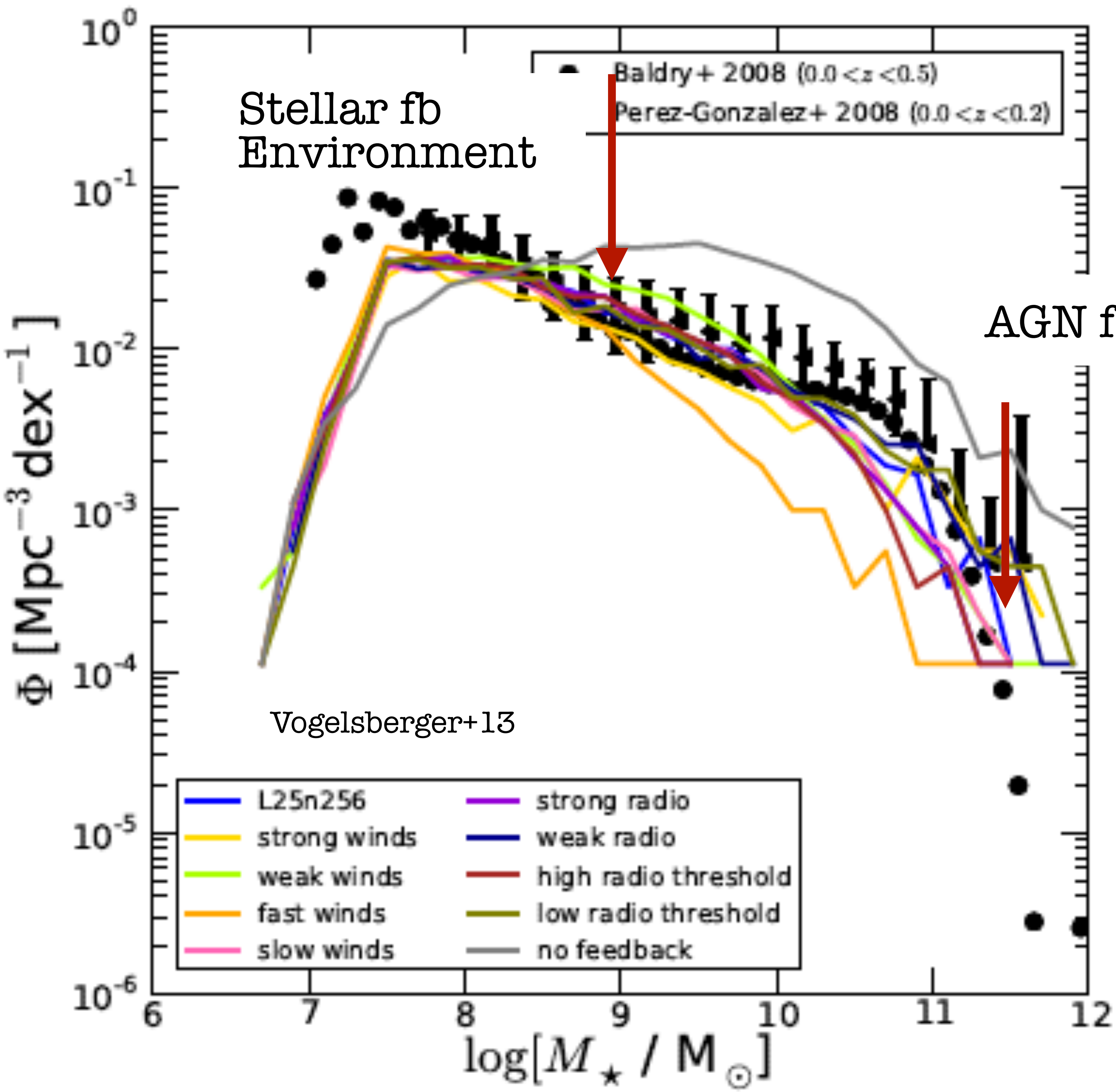
Thermal+jet fb model

—> reduced stellar mass at given halo mass in galaxy clusters



Stellar mass function

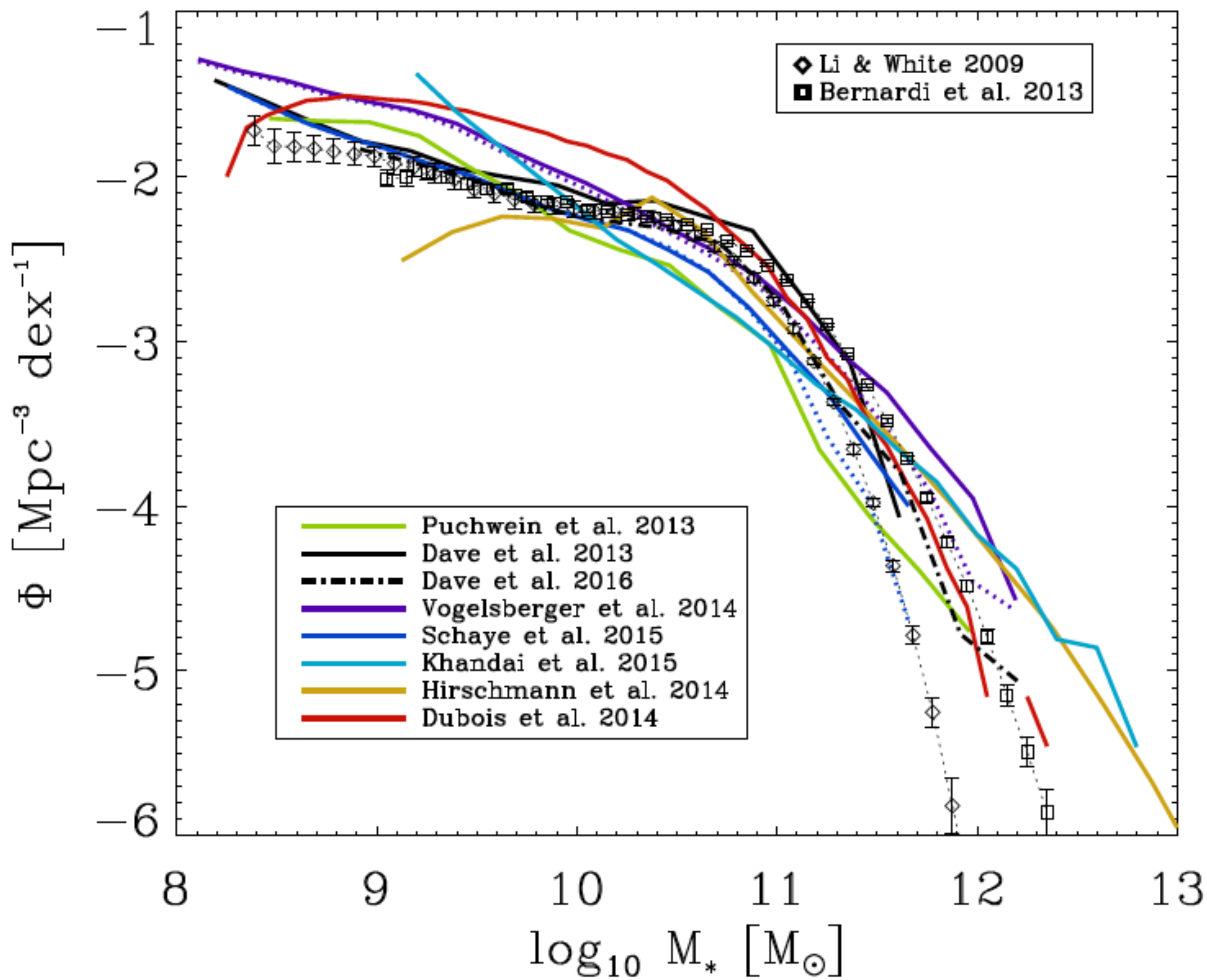
AGN feedback is crucial for reducing the formation of too many massive galaxies — same conclusion as from SAMs!



see also: Croton+06, Bower+06, Somerville+08, Schaye+15 (EAGLE), Weinberger+17, Genel+14 (Illustris), Pillepich+18 (TNG), Steinborn,Hirschmann +15, Sijacki+07, Dubois+13/17, Fontanot,..,Hirschmann +20 etc…

Stellar mass function

Modern large-scale cosmological simulations (full boxes) with…



different AGN fb models:

Thermal fb

Art. halo quenching

Thermal+offset bubble fb

Stochastic fb

Thermal fb

Thermal+bubble fb

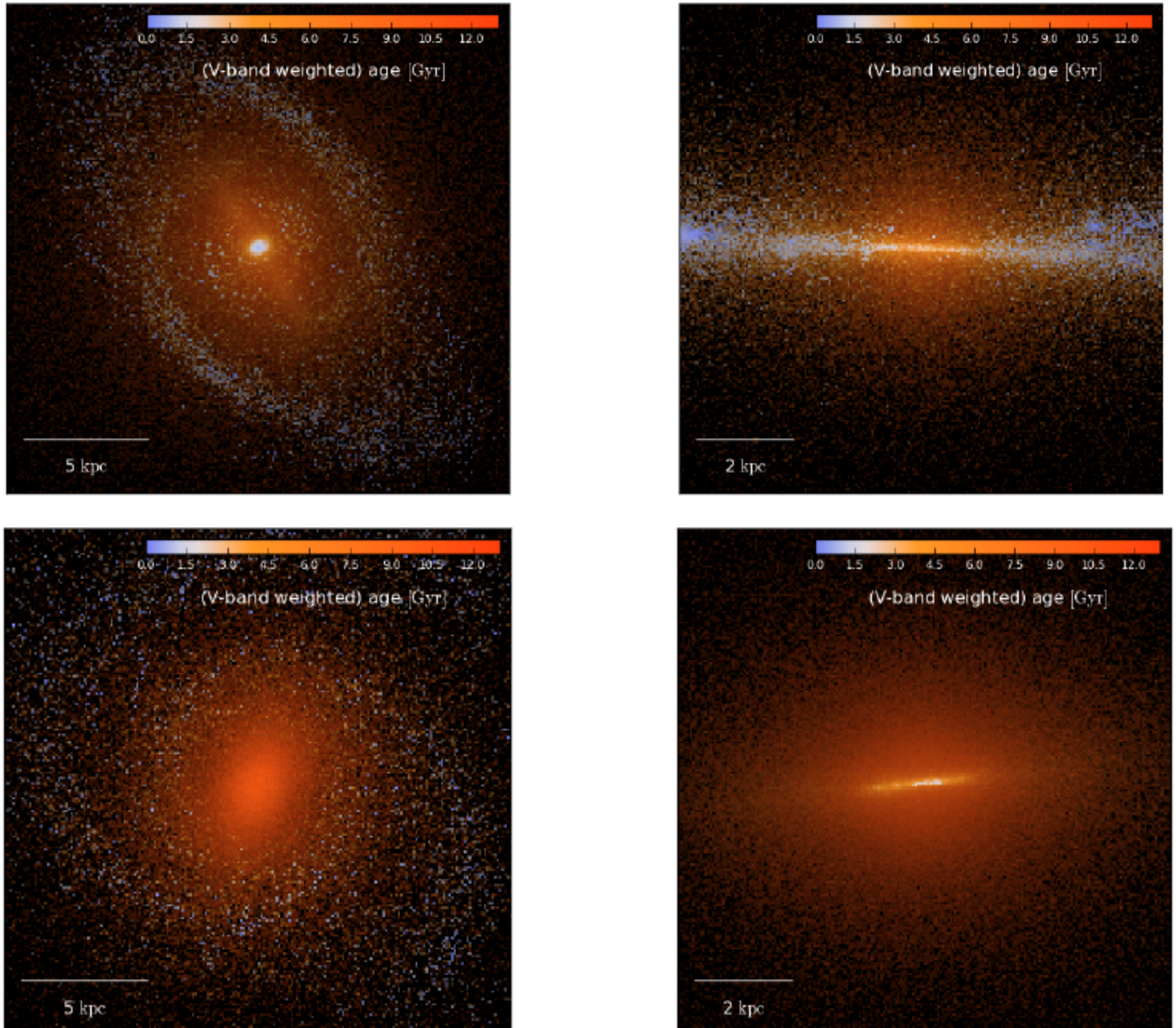
Thermal+kinetic-jet fb

Thermal feedback typically too inefficient in suppressing SF massive galaxies

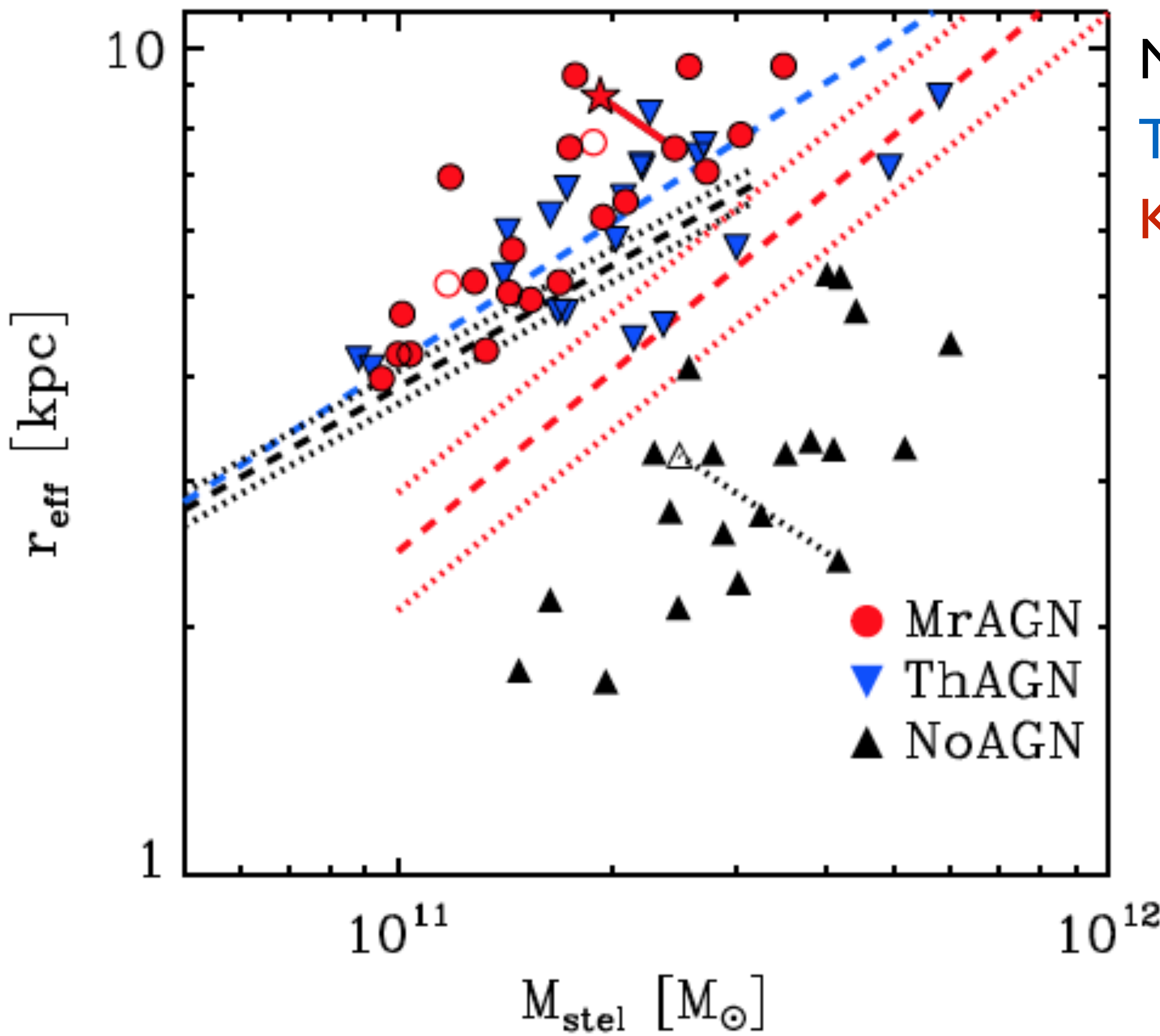
Galaxy morphology

No AGN fb

Kinetic AGN fb



Galaxy sizes



No AGN fb

Thermal fb

Kinetic AGN fb

- Increased sizes for a given galaxy stellar mass with efficient AGN fb due to
  - Less dissipative processes —> adiabatic expansion
  - Larger fractions of accreted stellar systems, see *Choi+18*

AGN in cosmological sims — Summary

- BH physical processes are complex and not yet fully understand
  - Gas is accreted onto BHs via thin accretion disks & via ADAFs
  - Energy can be released from accretion disks (radiation processes and fast particles) and from collimated jets (relativistic particles)
- In cosmological simulations, sub-grid recipes for BH seeding, growth and feedback have to be adopted
- AGN fb primarily affects massive galaxies
  - acts in both an ejective and preventive way
  - lower hot gas content in halo
  - lower/suppressed SF, older stellar ages
  - Elliptical-like shapes and larger sizes
- What are the caveats of BH/AGN models in cosmological simulations?

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