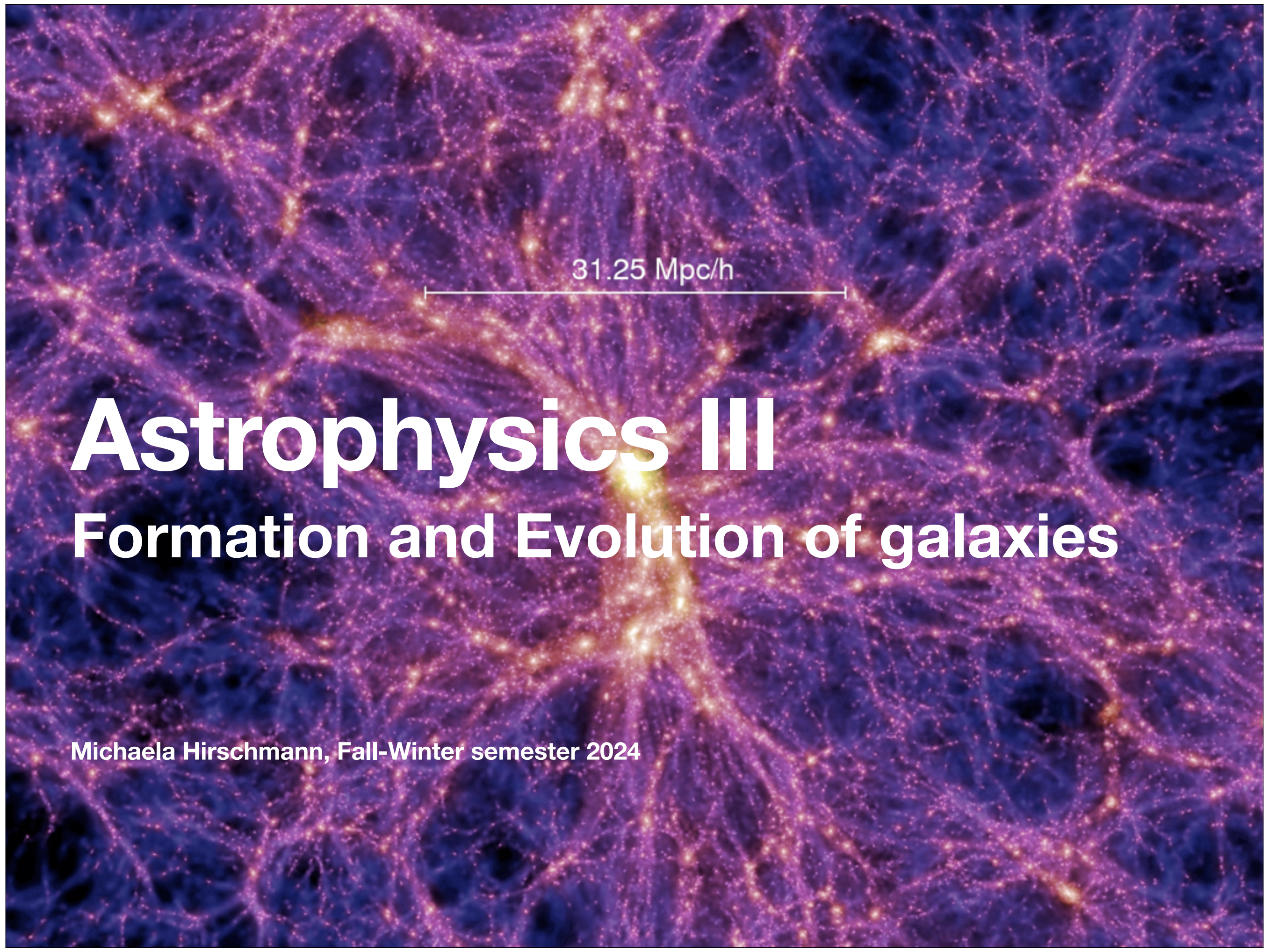


Astrophysics III

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
- *Chapter 6*: The world of galaxies II
- *Chapter 7:* Black holes and active galactic nuclei
- *Chapter 8:* Galaxies and their environment;
- *Chapter 9:* High-redshift galaxies

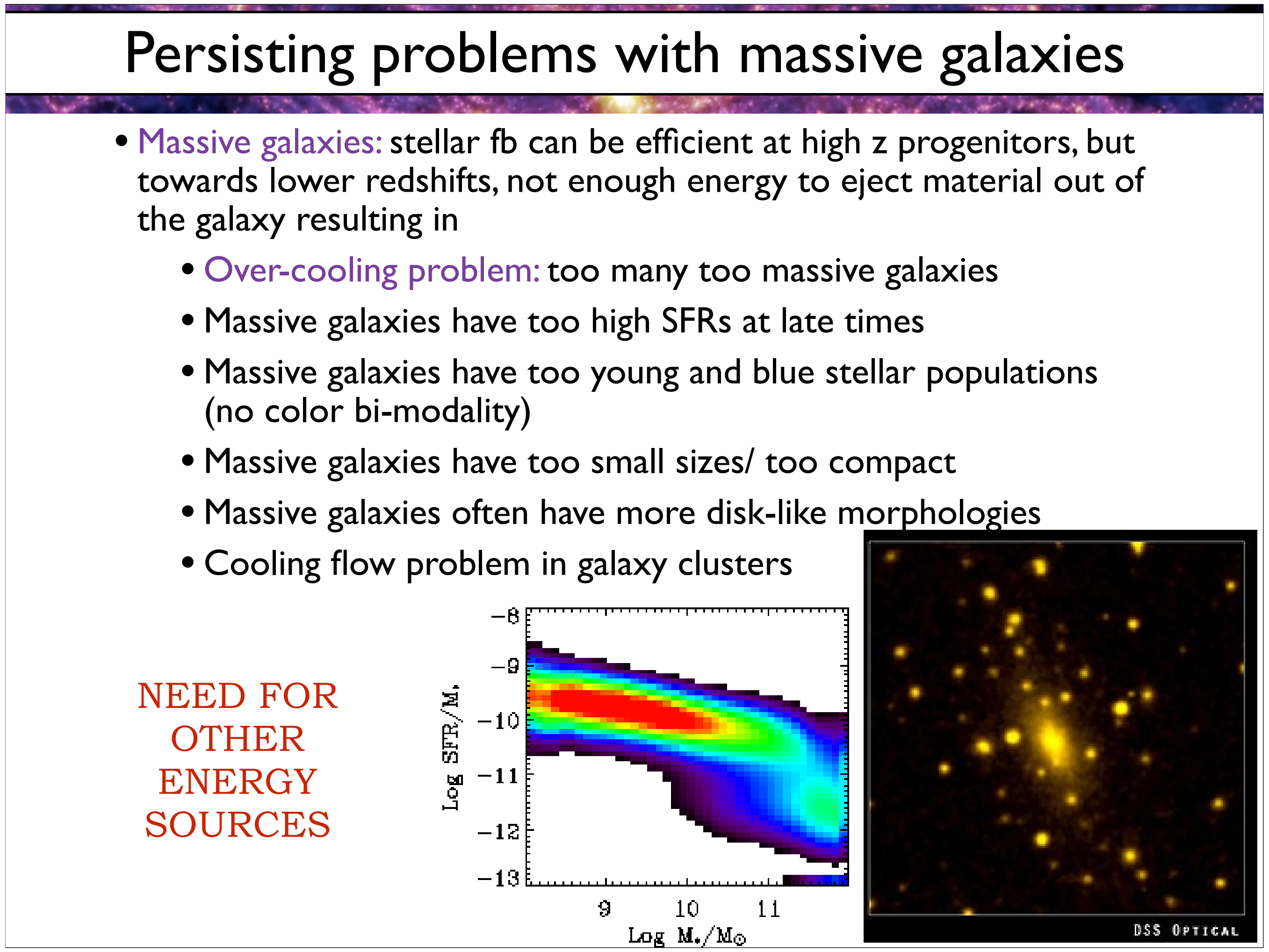
Part I:
Observational basics & facts of galaxies
first 7 lectures

- *Chapter 10*:
  - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11*:
  - Dark matter and the large-scale structure
  - Cosmological N-body simulations of dark matter
- *Chapter 12*: Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13:* Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14*: Gas cooling/heating and star formation
- *Chapter 15*: Stellar feedback processes
- *Chapter 16*: Black hole growth & AGN feedback processes
- *Chapter 17*: Modern simulations & future prospects

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



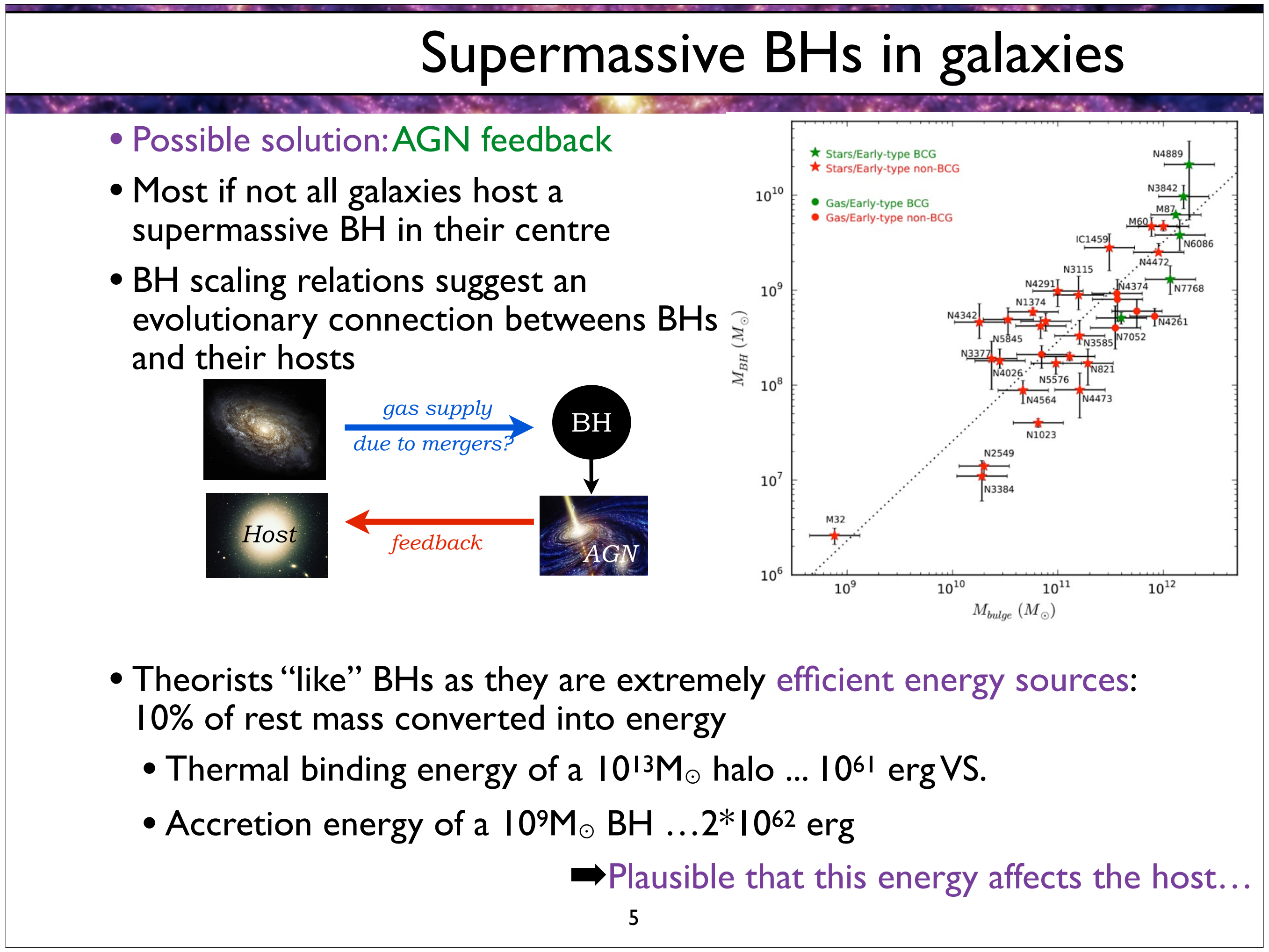
Persisting problems with massive galaxies

- 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

— The motivation for adding BH physical processes like AGN feedback in galaxy simulations is because massive galaxies (with stellar masses above ~3e10 Msun) were found to be unrealistic as described by the bullet points on the slide,

—> suggesting that another energy source in massive galaxies is needed.



Supermassive BHs in galaxies

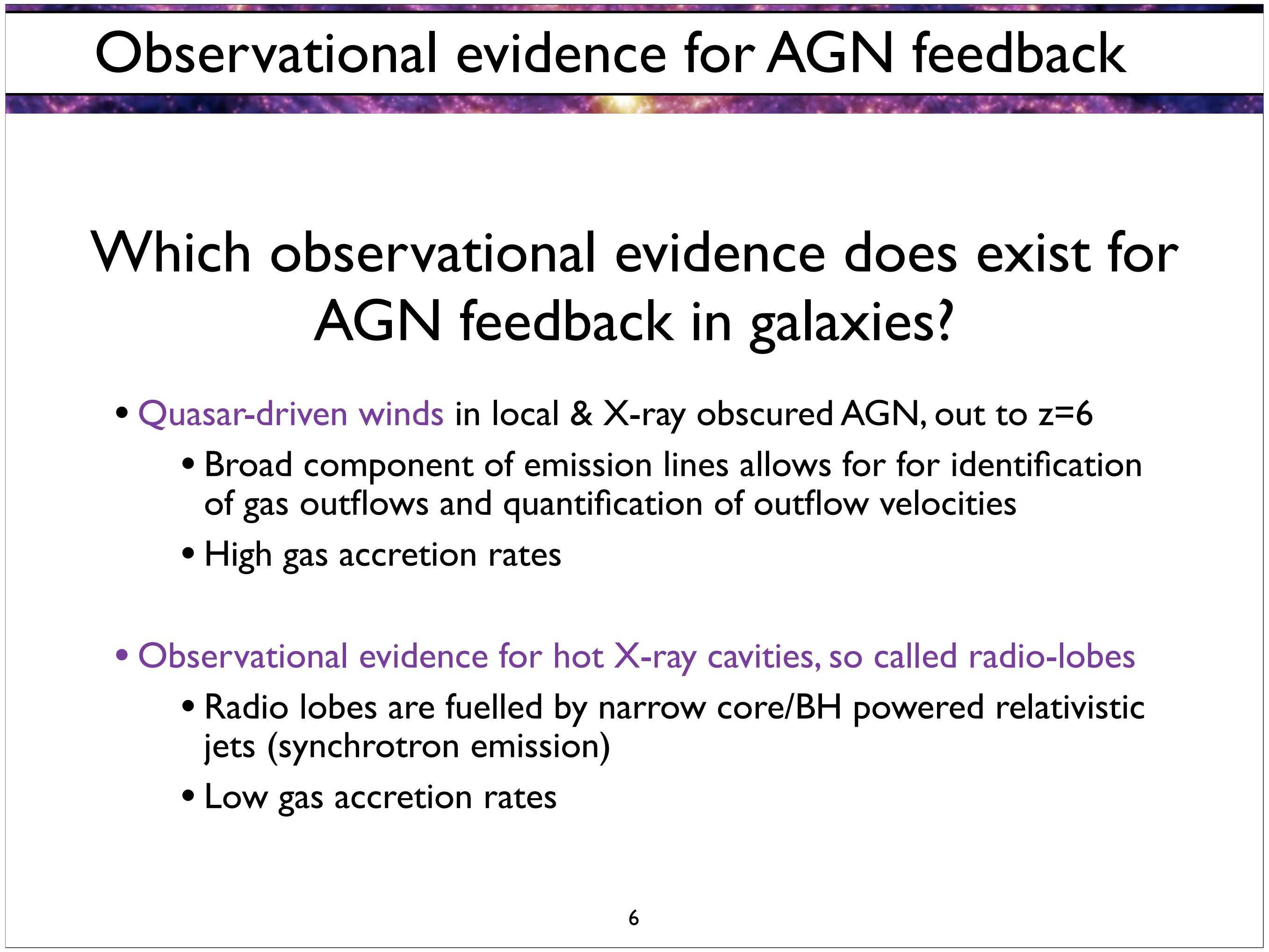
- Possible solution: AGN feedback
- Most if not all galaxies host a supermassive BH in their centre
- BH scaling relations suggest an evolutionary connection betweens BHs and their hosts

- 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…

— In this respect, as already discussed for SAMs, a possible solution might be provided by BHs and corresponding feedback from AGN,
—> because **BHs are extremely efficient energy sources**: 5-30% of their rest mass can be converted into energy.
—> Doing some simple energy calculations, we see that
—> for a 1e13 Msun halo, the thermal binding energy is ~1e61 erg,
—> but from a 1e9 Msun BH, an energy of 2e62 erg can be released!
—> Thus, it can be plausible that this **BH energy may affect the host galaxy,**
—> supported by the **observed BH scaling relations**, which also suggest that galaxy and BH growth may be causally coupled.

— THEORISTS LIKE BHS, SINCE HUGE AMOUNTS OF ENERGY CAN BE RELEASED DUE TO GAS ACCRETION ONTO THEM!



Observational evidence for AGN feedback

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

— Moreover, as we discussed in the first part of this course, **there is also plenty of direct observational evidence for AGN feedback** in form of quasar-driven winds and jets/hot X-ray cavities as outlined on the slide.

— But, as it was the case for stellar-driven galactic-scale outflows in the previous chapter,
—> **from observations alone it is hard to make any robust conclusions** on how these processes affect the evolution of galaxies, i.e., whether there is any causal connection.
—> To explore that, we need numerical galaxy simulations.

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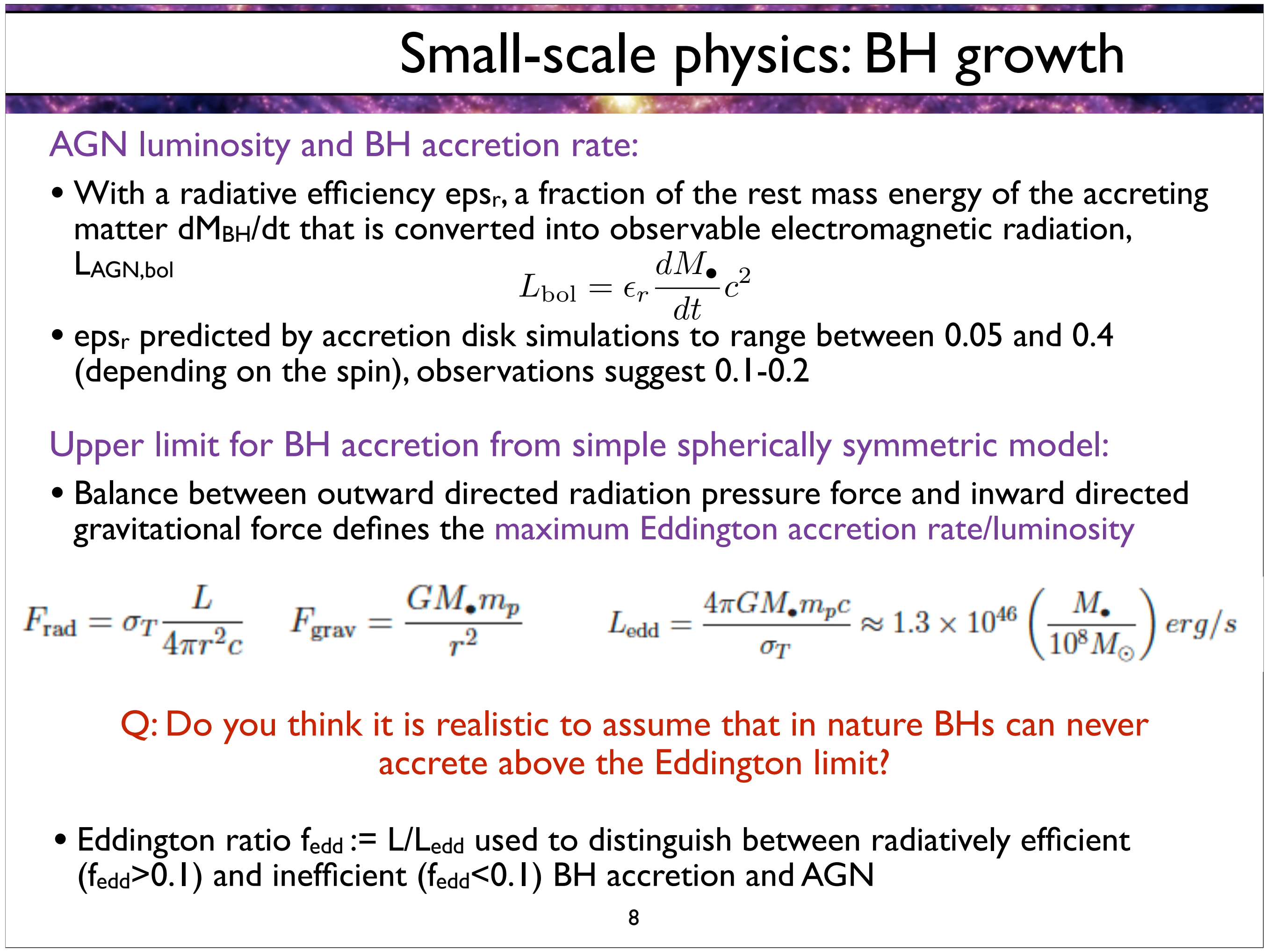


Small-scale physics: BH growth

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

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

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

— You may remember that we **compute the AGN luminosity L_bol**, the radiated energy from the BH accretion disk per unit time,

—> by assuming that a certain fraction of the rest-mass energy of the accreted matter is converted into electro-magnetic radiation.

—> L_bol is given by the first equation on the slide, with eps_r being the radiative efficiency, ranging between 0.05 and 0.4 based on accretion disk simulations, depending on the halo spin.

—> Observations suggest an eps_r of 10-20%.

—Then, **if we assume that we have spherically symmetric gas accretion onto the BH**,

—> we can derive an **upper limit for BH accretion** from the balance between the outward directed radiation pressure force F$_{rad}$ and the inward directed gravitational force F$_{grav}$ (see equations on the slide).

—> By setting these forces equal and solving for the Luminosity, we obtain the **maximum possible luminosity proportional to the BH mass, the so called "Eddington luminosity" L$_{edd}$, given by the bottom right equation on the slide.**

—> Is it realistic to assume that there is never any gas accretion above Eddington limit?

—> Not necessarily, because of:

- **Anisotropic Radiation**: Radiation pressure might not be the same in all directions, which may lead to accretion at rates higher than Eddington.
- **Highly Ionized Material**: If the accreting material is highly ionised, it may not interact efficiently with the radiation, reducing the effectiveness of radiation pressure in counteracting gravity.
- **Clumpy gas accretion:** Dense gas clumps are more resistant against radiation pressure so that effectively, more gas could be accreted.

— In this context let me also define the "Eddington ratio" f$_{edd}$ as the ratio of the actual AGN luminosity and the maximum Eddington luminosity of a BH:

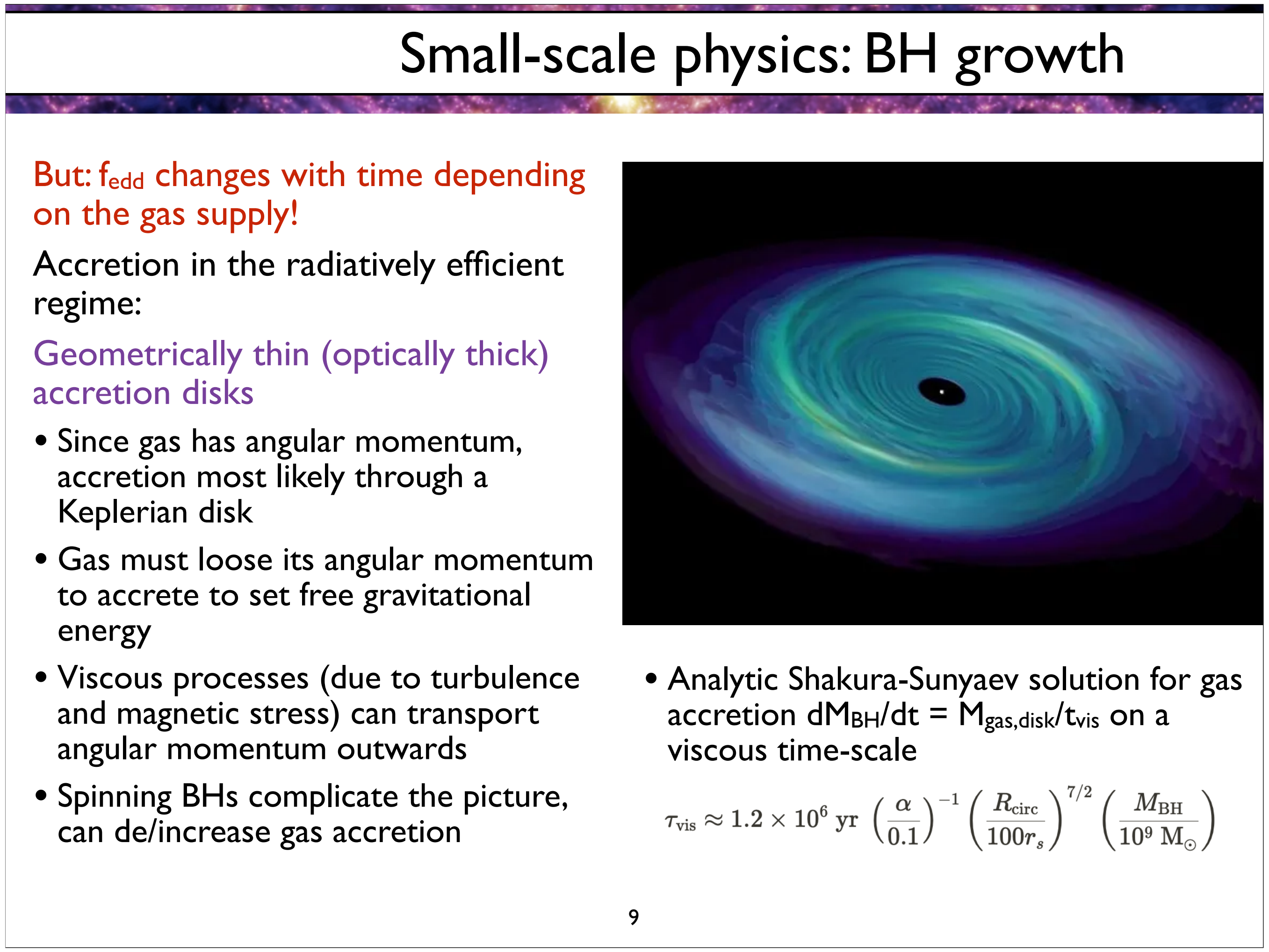
—> This ratios gives an idea of how efficiently a BH is accreting matter.

—> It allows us to distinguish between radiatively efficient and inefficient regimes, often simply via a cut in f_{edd} of 0.1

Additional information:

Why is eps_r larger for of more rapidly spinning BHs?

For a non-spinning (Schwarzschild) black hole, the innermost stable circular orbit (ISCO) is located at a radius of $3\ R_s$ (Schwarzschild radii). However, for a spinning black hole, the ISCO can be much closer to the event horizon. This is because the spin of the black hole drags space-time around with it (a phenomenon known as frame-dragging), effectively allowing material in the accretion disk to orbit stably at closer distances. The closer the material can get to the black hole before plunging in, the more gravitational potential energy can be converted into radiation, thereby increasing the radiative efficiency.



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

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

—It’s important to note that **Eddington ratio of a BH is not constant over time,** but can significantly change depending on the gas supply.

—To better understand how gas is being accreted on a BH, let’s look a bit more into **small-scale accretion-disk physics**:

—In the **radiatively efficient regime**, i.e. at high f_{edd}, the BH is typically surrounded by dense cold gas.

—> In that case, a **geometrically thin, optically thick gas accretion disk around the BH** emerges (studied analytically since a long time, so called Shakura-Sunyaev alpha-accretion disks).

—> Such an (Keplerian) accretion disk emerges because the gas has some angular momentum,

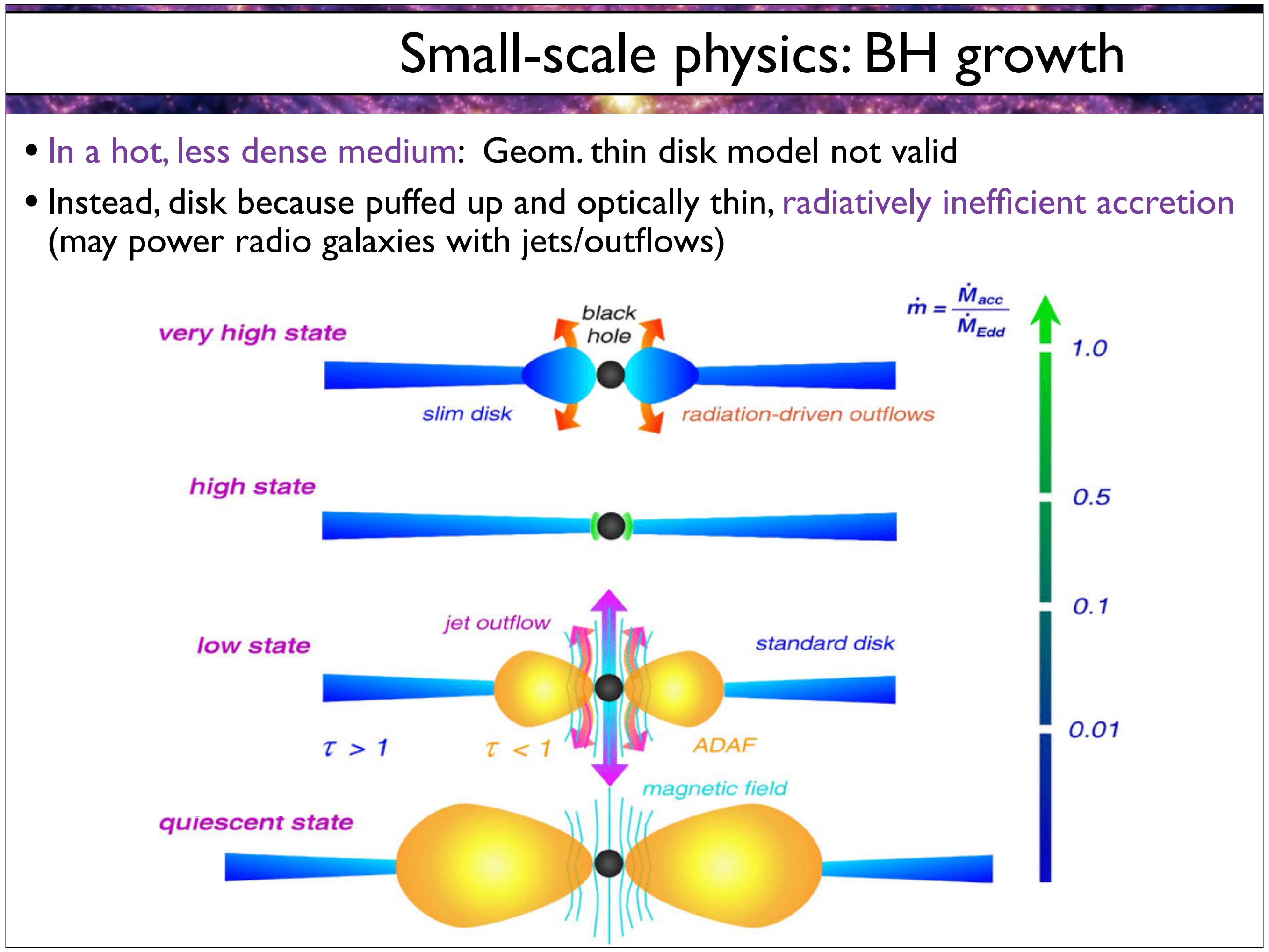
—> i.e. to be accreted onto the BH, the gas must **loose its angular momentum.**

—> This can happen via viscous processes and/or magneto-rotational instabilities (details not yet fully understand), which help to transport the angular momentum outwards and the matter/the gas inwards.

—> Such gas accretion disks can be best studied via **3D GR-MHD simulations (e.g. fully general-relativistic magnetohydrodynamical simulations).**

—> But for a “simple” thin accretion disk, an a**nalytic model has been developed in the 70s by Shakura and Sunyaev:**

- The gas in the vicinity of the BH is assumed to be accreted over a **viscous time scale,** dependent on circularisation radius R_{circ} (extent of accretion disk) and BH mass, as given by the formula shown on the slide.
- The **alpha parameter** encapsulates effects of viscosity and turbulent stresses in the disk.



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)

—This picture of a **thin accretion disk is only valid for radiatively efficient gas accretion onto BHs**,
—> which is typically the case when there is lots of cold gas available.

—Otherwise, **at low Eddington ratios f_{edd}, the disk gets more and more puffed up**,
—> i.e. it becomes geometrically thick and optically thin, as you can see here in this cartoon,
—> violating the assumptions of an alpha accretion disk model.

—Also, **at low Eddington ratios, the efficiency of radiative cooling decreases**.
—>The disk may not be able to cool effectively, leading to a inflow of gas that is advection-dominated (i.e., the heat is carried along with the flow rather than radiated away).
—>This situation is not well-described by the alpha disk model, which assumes **efficient radiative cooling**.
—> **Specific advection-dominated accretion flow (ADAF) models** have been developed to describe a thickened disk —> very complex, and also here GR-MHD accretion-disk are best to study this.

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!

— Another simplified way to **mimic accretion in the radiatively inefficient regime at low f_{edd}, i.e. when lots of hot gas is around, is via the Bondi-Hoyle** accretion scheme (developed in the 50s by Bondi and extended later-on by Fred Hoyle)

—> In this model, we assume again **spherically symmetric accretion**, and
—> we further assume **hot gas to be ideal, to be in hydrostatic equilibrium and without any angular momentum.**
—> Then gas is assumed to be accreted when the gravitational force on the gas overcomes the thermal pressure of the gas.
—> This is when the sound speed of the gas c_s is roughly the square root of $2GM_{BH}/R$, with R being the distance of the gas to the BH.
—> Then we **solve this for the radius**, which is the "Bondi" radius, i.e. the radius, at which the sound speed of gas equals the escape velocity,
—> implying that in this simple model, **all gas within the Bondi radius can be accreted onto the BH.**

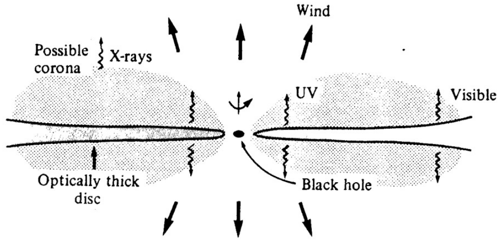
— The **Bondi accretion rate** can then be derived by evaluating the mass flow rate at the critical/Bondi radius as shown by the bottom equation.

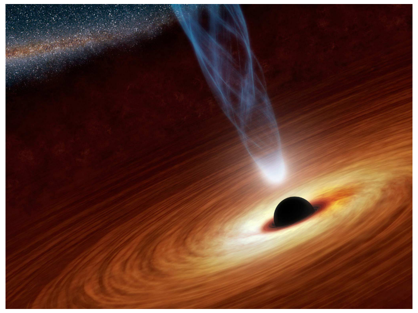
—This is certainly a rather **simplified model**: in reality, there is no spherically symmetry, not only gas pressure acting against gravity etc.

—> More accurate estimations for BH accretion can be done via **GRMHD simulations,**
—> to get an idea how different gas accretion is in the radiatively inefficient regime compared to the radiatively efficient regime.

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

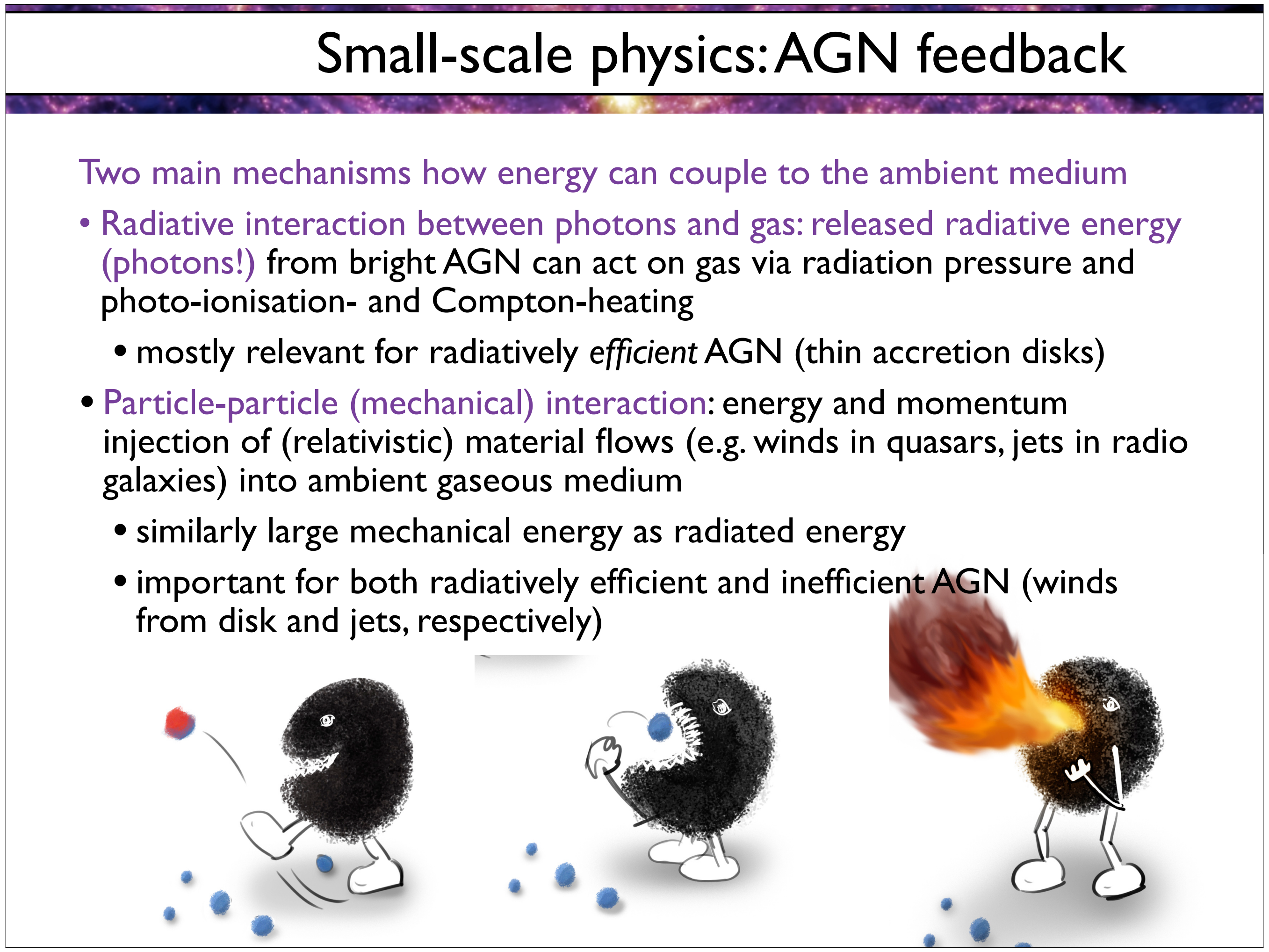




— When gas is accreted onto BHs, **significant amounts of energy can be released.**

— We can distinguish **two main modes of energy production**:
—> Via an **accretion disk** where viscous processes and magneto-rotational instabilities can produce **energetic photons and fast relativistic particles leading to fast particle winds.**
—> Via **relativistic jets**, where the interaction of magnetic field lines (in magnetically arrested disk) with the spin of the BH lead to collimated, highly relativistic particle streams, so called jets, perpendicular to the disk.

Additional information on magnetically arrested accretion disks:
A Magnetically Arrested Accretion Disk (MAD) is a specific type of accretion disk, typically found around black holes, where the accretion process is strongly influenced, or even dominated, by powerful magnetic fields. In this scenario, the magnetic fields are so intense that they can significantly affect the dynamics of the accreting material, potentially leading to unique and extreme behaviors.



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)

— Irrespective of the energy source, we can distinguish **two main mechanisms how energy from the BH can couple to the ambient gaseous medium:**

—> radiative processes as explained in detail on the slide, and

—> mechanical processes as also explained on the slide.

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)

Outline of this lecture

- Motivation for feedback from accreting BHs
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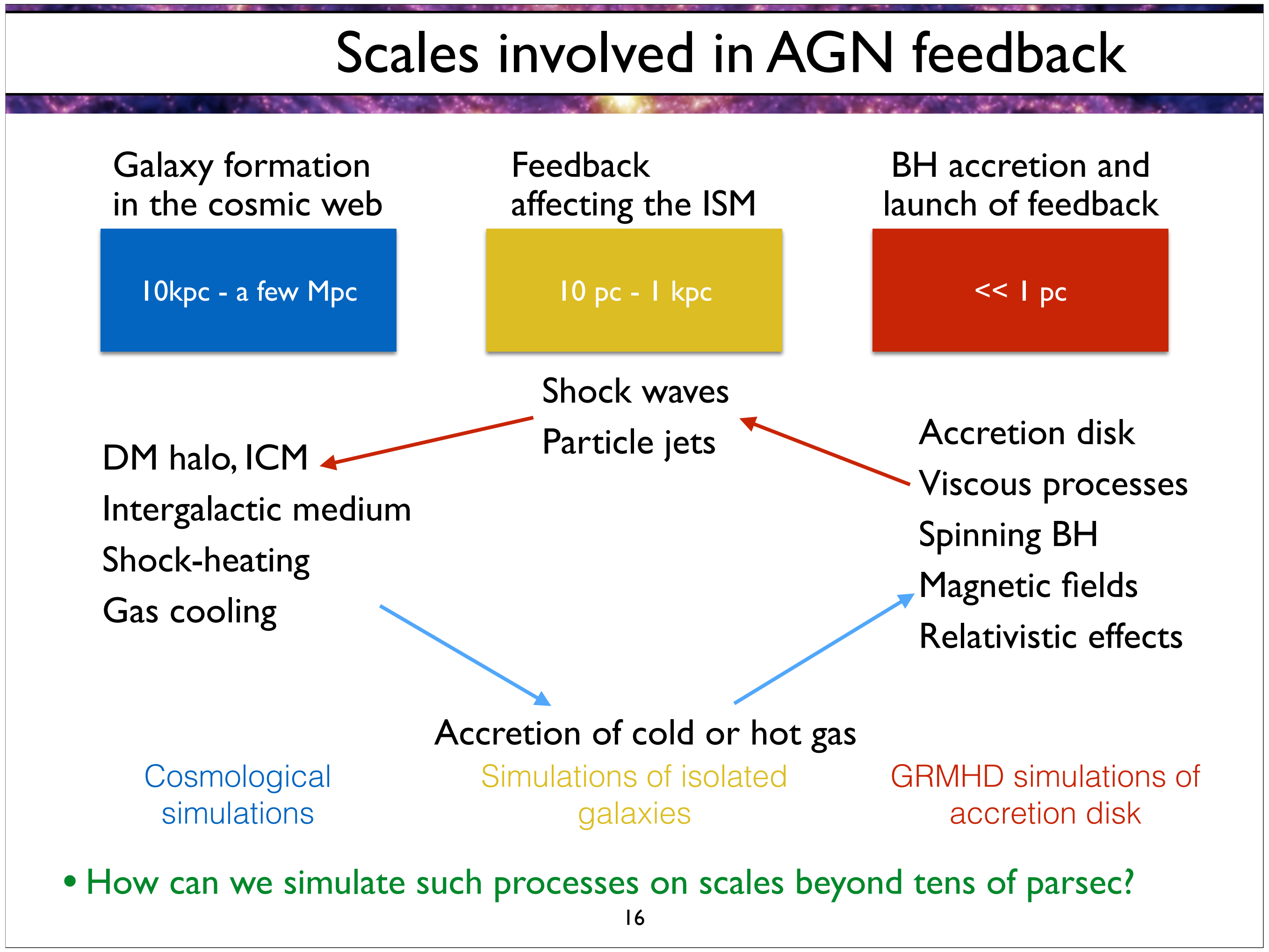


Scales involved in AGN feedback

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

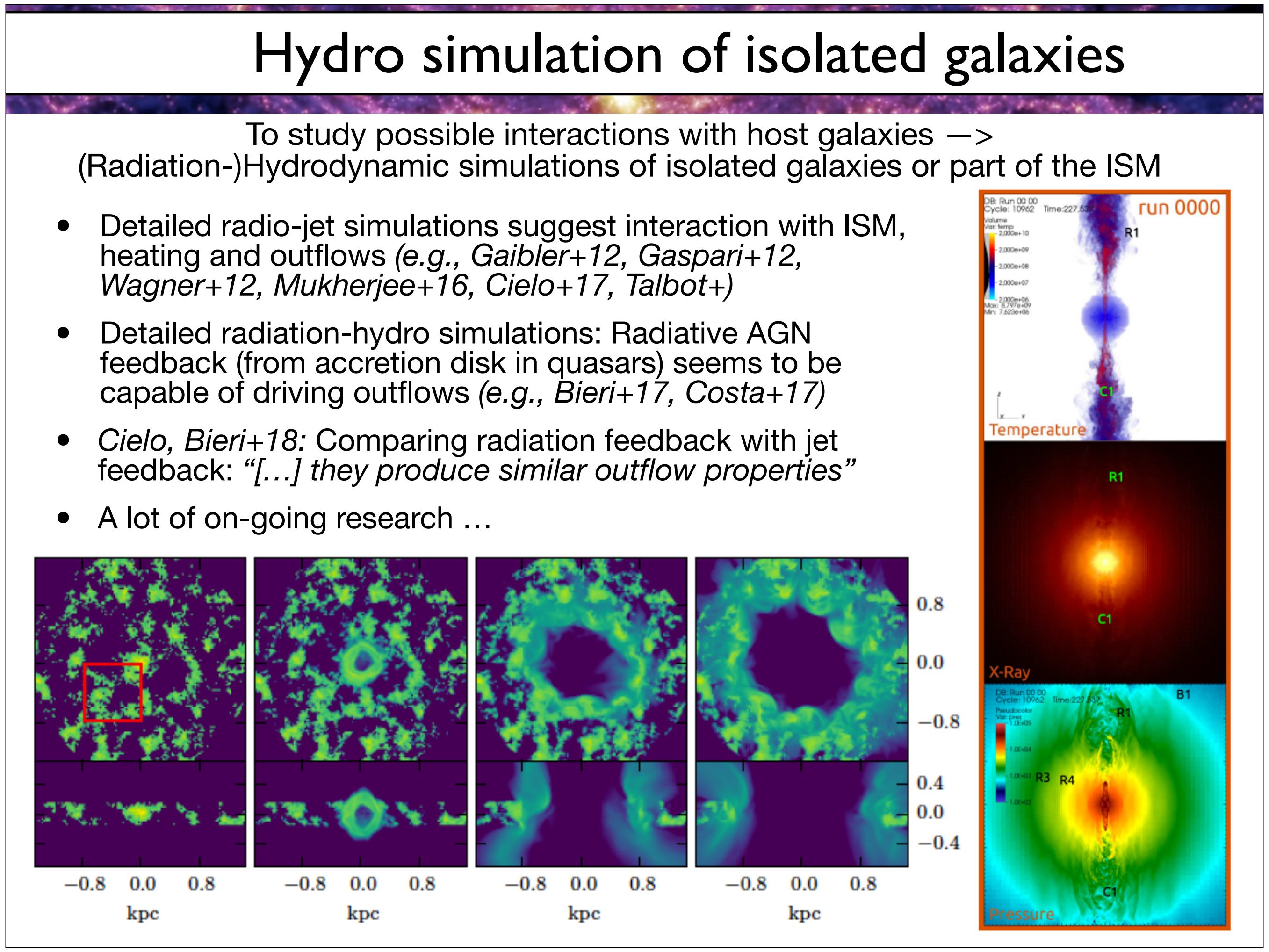
- How can we simulate such processes on scales beyond tens of parsec?

— As already for stellar feedback, but even more severely, a **large dynamic range of scales** is involved when describing BH accretion and feedback in a galaxy and cosmological context.

— The scale of accretion disks goes down to a few Schwarzschild radii, close to the event horizon, highly sub-parsec scales (e.g., 1e-4 pc for a 1e9 Msun BH, lower scales for less massive BHs).
—> On these small scales, various processes become important, such as relativistic effects, magnetic fields, the BH spin, the gas accretion disk etc.

— At the same time, **the produced outflows/particle jets can extent to the DM halo or even beyond,** i.e. out to even several tens of kpc.
—> Cosmological simulations can further extend to hundreds of Mpc,
—> encountering a huge dynamic range problem!

— **How can we simulate such BH processes on scales beyond tens of parsec, the maximum resolution for large cosmological simulations?**



Hydro simulation of isolated galaxies

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

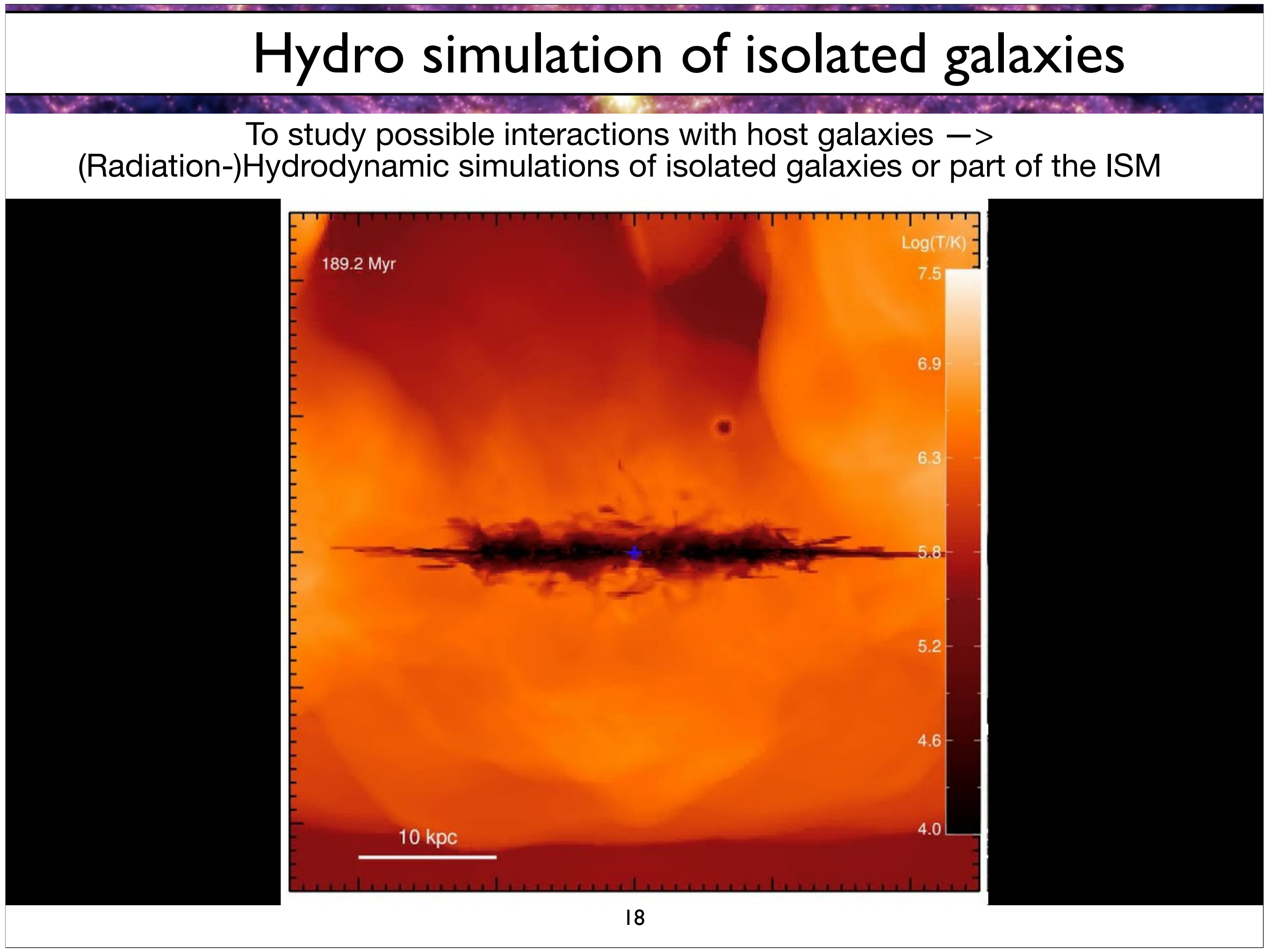
- Detailed radio-jet simulations suggest interaction with ISM, heating and outflows *(e.g., Gaibler+12, Gaspari+12, Wagner+12, Mukherjee+16, Cielo+17, Talbot+)*
- Detailed radiation-hydro simulations: Radiative AGN feedback (from accretion disk in quasars) seems to be capable of driving outflows *(e.g.,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

—First, it can be helpful **study in more detail in how energy/momentum release from radiation/jets** can be impacting the ISM:

—> we need again, as for stellar feedback, **idealised, detailed, very high-resolution simulations** of galaxies or just a part of a galaxy.

—> To explain: ***idealised*** **galaxy simulation** means we are not having a cosmological initial conditions, but we start with a particle distribution based on analytic profiles for DM, gas and stars (like NFW for DM).

— There is a lot of on-going research, as listed on the slide — still without a complete theory for how AGN winds/jets affect the ISM.



Hydro simulation of isolated galaxies

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

—Here you can see a nice example of an idealised galaxy simulation, where **AGN radiation is assumed to thermally couple to the ISM,**

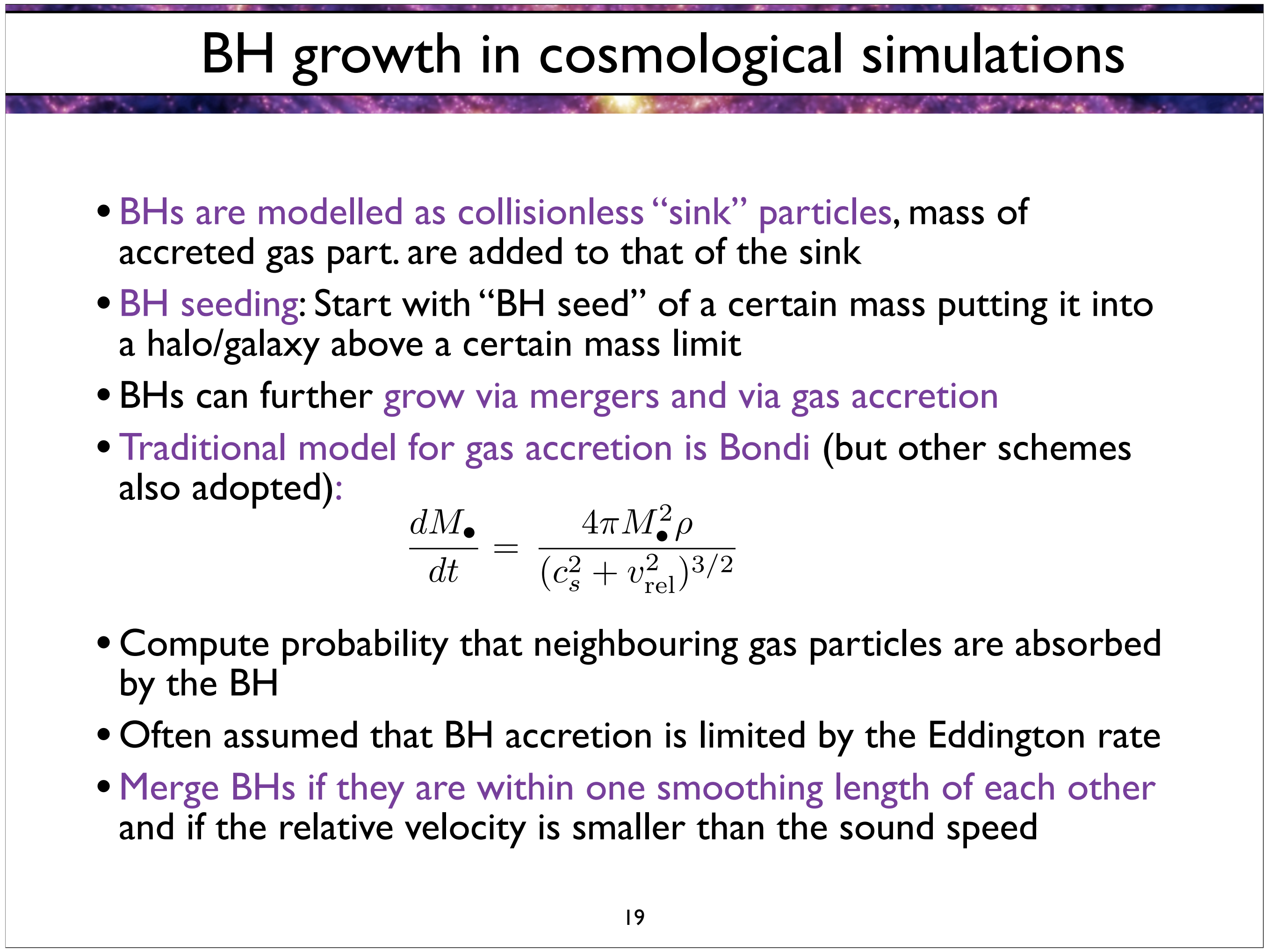
—>leading to these biconical, AGN-driven wind bubbles, which heat gas, and drive it out of the galaxy.

—>In this simulation, there is, however, limited impact on the SFR of the host galaxy.

—But: This galaxy has been simulated **only simulated for a few hundred Myr** without any cosmological context (no gas accretion from the cosmic web, no mergers etc.),

—> i.e., not allowing any meaningful comparison with observations.

—> For that, we need to go to cosmological simulations after all.



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):

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

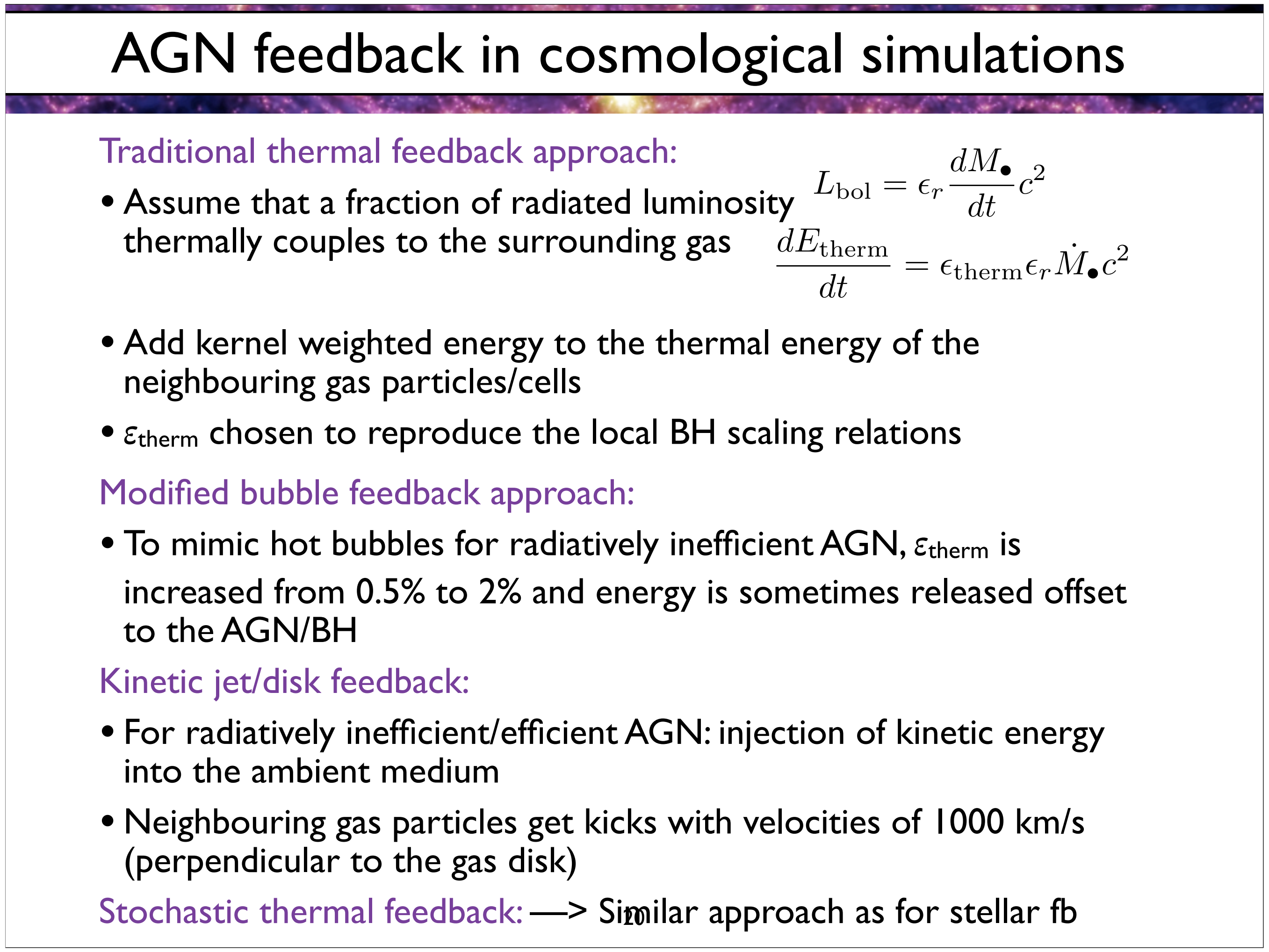
- Compute probability that neighbouring gas particles are absorbed by the BH
- Often assumed that BH accretion is limited by the Eddington rate
- Merge BHs if they are within one smoothing length of each other and if the relative velocity is smaller than the sound speed

— **For cosmological simulations**, BH growth and related feedback can be only modelled in a rather approximate way, i.e. by smoothing over the small-scale complexity (because **no full theory** has been developed from small-scale simulations).

—Specifically, BHs are modelled as collisionless "sink" particles, where the mass of accreted gas particles is added to that of the sink.
—> To explain, **sink particles** represent self-gravitating objects consisting of many SPH gas particles, which can be replaced (during a calculation) by a single, massive, "sink" particle, only interacting via gravity.

—Then in different cosmological simulations, **a BH is seeded** with a certain mass into a halo above a certain halo or stellar mass limit (not resolving any physical BH seeding mechanism).

—Gas accretion onto BHs is in most cosmological simulations still modelled following the Bondi-Hoyle approach (using the equation shown on the slide, rho being the gas density, c_s the sound speed of the gas, v_{rel} the relative velocity of the gas to the BH).
—> This means that **the larger the BH mass, the higher the density and the lower the T (scaling with the sound speed of the gas), the larger is the gas accretion rate.**
—> With that equation, we compute gas accretion rate, and stochastically select gas particles within the accretion region which are accreted onto the BH sink particle.
—> Often additional simplifying assumptions are made:
- Gas accretion capped at the Eddington limit.
- Close BHs are merged if they are within one smoothing length of each other and if the relative velocity is smaller than the sound speed (i.e. the actual BH merger happening on sub-parsec is not resolved, which may lead to "over-merging", i.e. too fast BH merging compared to reality).



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

— Now let’s turn to **how to model feedback from accretion BH** in a cosmological context:

— The **simplest implementation is the traditional thermal feedback approach**,
—> in which we assume that a fraction of radiated luminosity $L_{\rm bol}$ thermally couples to the surrounding gas, as shown by the equations on the slide, with eps_therm being a free parameter (typically matched to reproduce the local BH scaling relations).

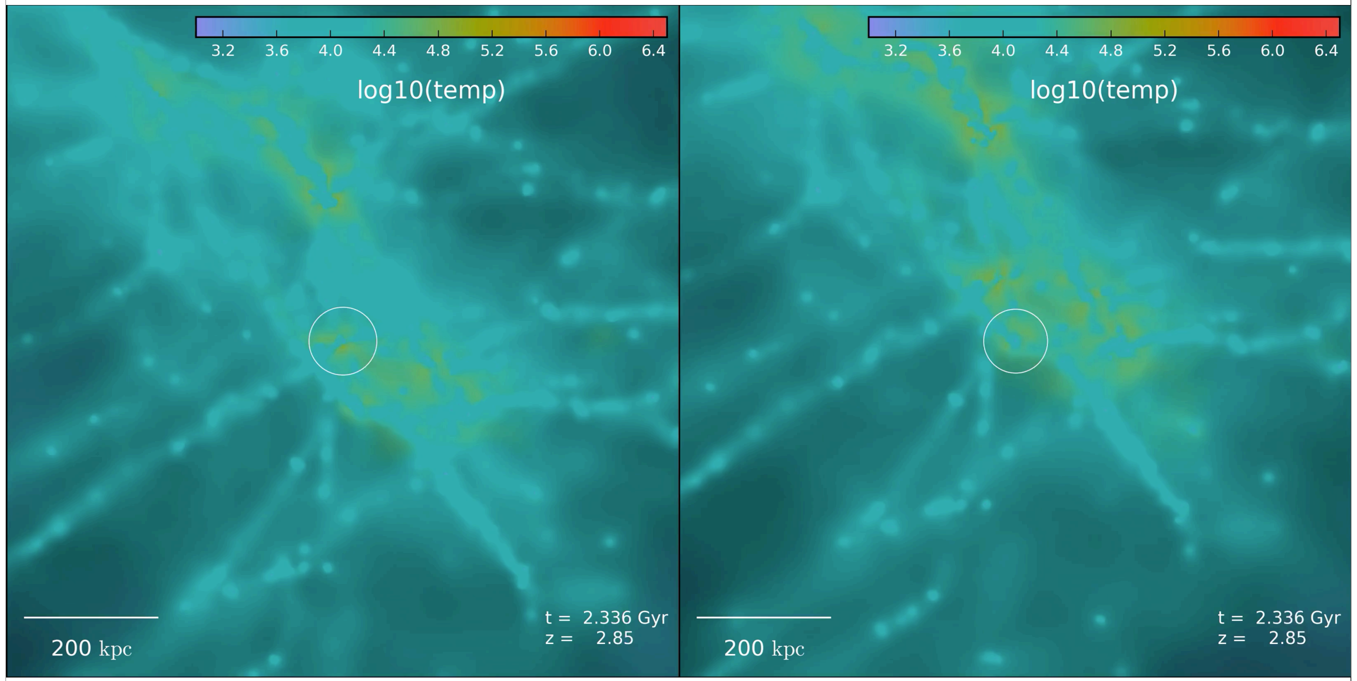
— But it has been shown repeatedly, that thermal feedback is **not fully sufficient to efficiently suppress star formation** in massive galaxies/halos at low redshift.

— Thus, **other AGN feedback schemes** have been developed and tested as well:
—> “**Bubble**” feedback: Increase of eps_therm in the radiatively inefficient regime; sometimes the thermal energy is released at a certain distance to the BH to mimic the hot-gas cavities due to jets as observed.
—> “**Kinetic**” feedback: Injection of kinetic energy/momentum into neighbouring gas elements; numerical implementations can still greatly differ among different codes.
—> “**Stochastic**” thermal feedback: similar as for stellar feedback (distribution of thermal energy over smaller amount of neighbours, increasing their T, reducing their cooling, making thermal energy injecting more efficient in driving a wind).

Outline of this lecture

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

Visualization of a zoom-in simulation…

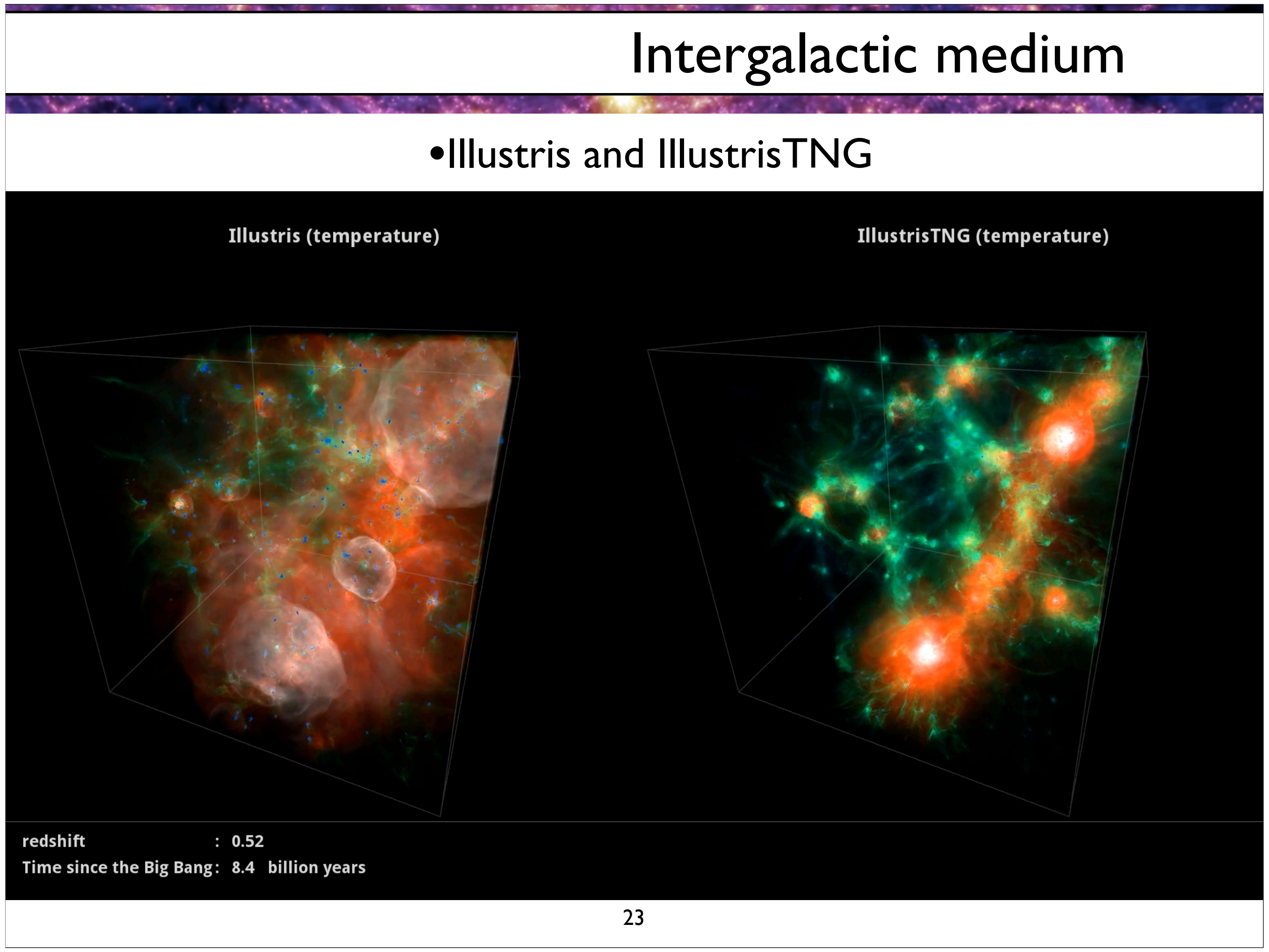


- …of a massive DM halo with and without kinetic AGN feedback as described in Choi+17/Hirschmann+17
- Similar implementations: e.g., Weinberger+18 (IllustrisTNG), Dave+19 (Simba simulation)

— Here you saw a movie from one of our cosmological zoom simulations of a massive galaxy, ran with thermal AGN feedback and with AGN-wind feedback schemes (the latter being a kinetic AGN feedback model).

— In this AGN wind **model**, we assume that not all of the infalling gas is actually accreted onto the BH, but a certain fraction is expelled again.
    —> In practice, gas particles in the close vicinity of the BH can get a velocity kick/momentum input perpendicular to the gas disk —
    —> motivated by observed broad absorption line winds of quasars.
    —> This model was originally implemented in a SPH code (Gadget-3), but a PostDoc in my group ported it to the AREPO code.
    —> Currently testing this feedback model in quenching SF in high-redshift massive galaxies!

— What you could see in this movie is that only with AGN winds, significant gas outflows are driven out of the galaxy and out of the DM halo (halo virial radius is illustrated by the white circle). Instead without winds, the hot halo gas is remaining inside the DM halos



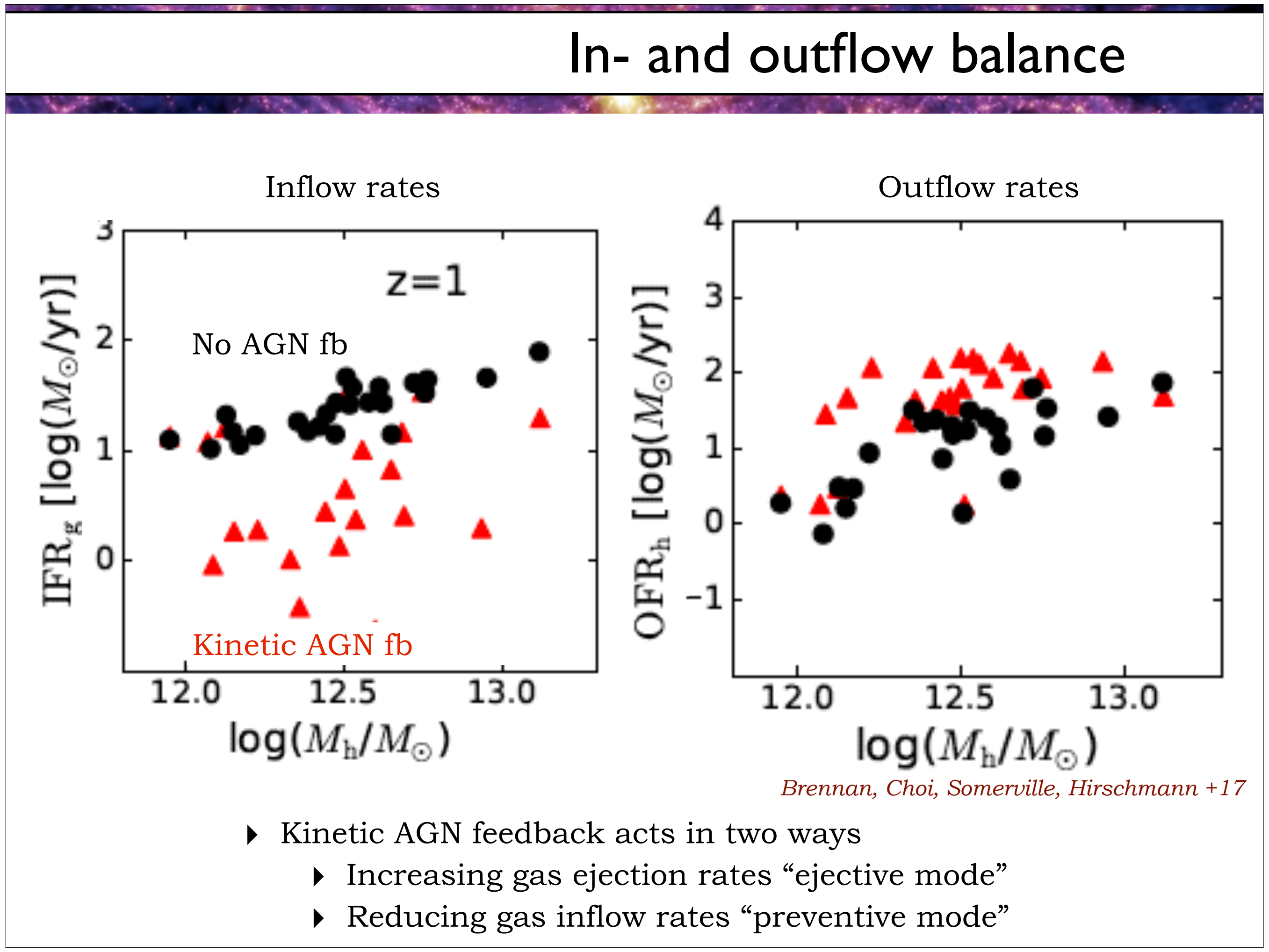
Intergalactic medium

- Illustris and IllustrisTNG

—But **how exactly AGN feedback heats the gas and drives it out** of galaxies depends strongly the exact implementation of AGN feedback!

—Here you saw the evolution of the gas content (color-coded by T) in the older **Illustris** (left, bubble feedback) **and the newer IllustrisTNG simulation** (right, kinetic feedback in the radiatively inefficient regime).
—> You can see how differently gas outflows are driven, and thus, how different the intergalactic medium (IGM) looks like at late times.
—> With bubble feedback more hot gas expelled into IGM, but less star formation suppressed within the galaxy compared to the kinetic feedback.

— **How can we decide which of these simulations is the more realistic one?**
—> To understand how realistic AGN feedback is modelled, it is useful to analyse outflows and inflows,
—> in particular, use observational constraints for the hot halo gas, i.e. X-ray luminosities of galaxy groups and clusters, as well as also many other galaxy properties (see next slides).



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”

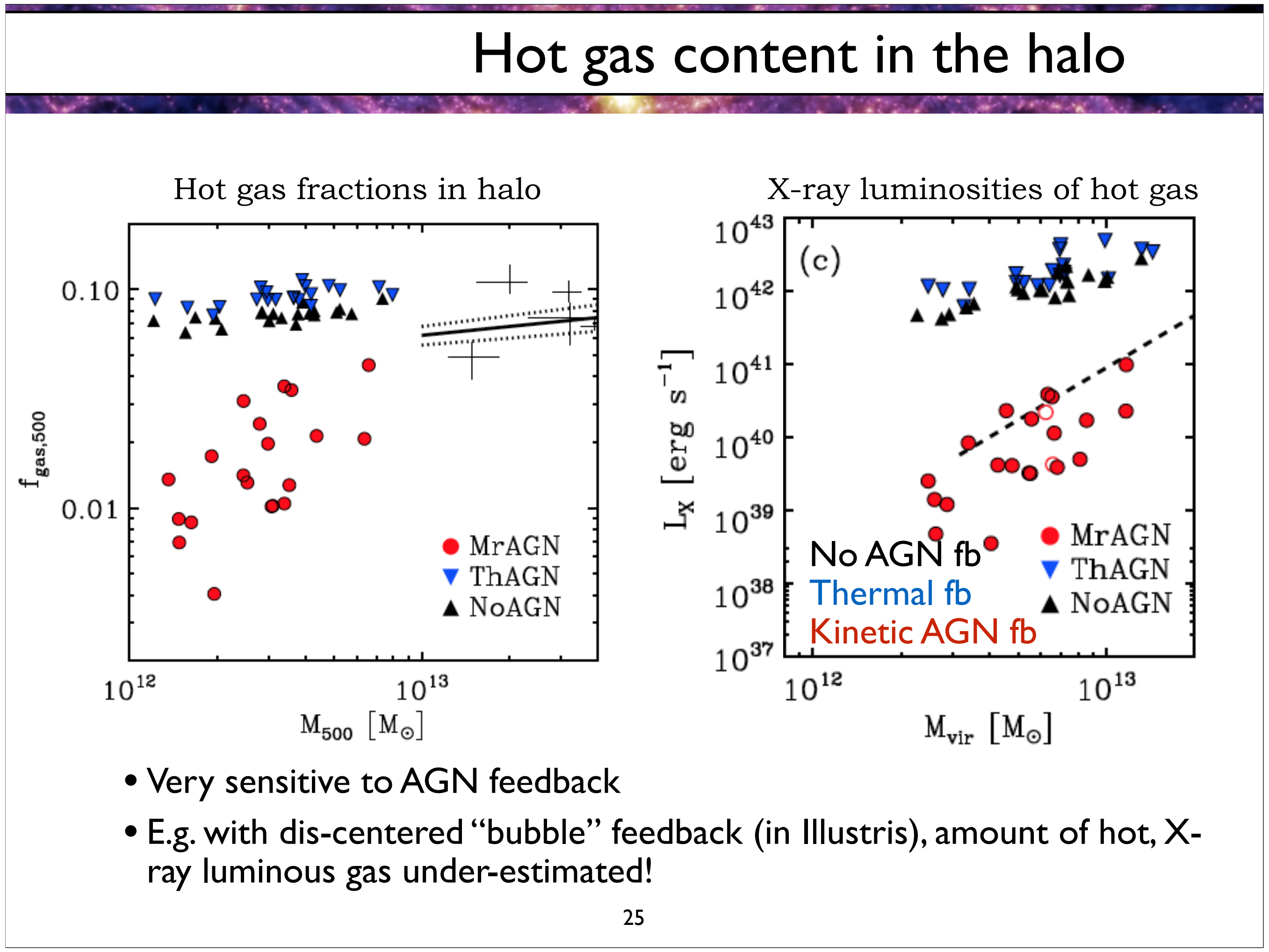
— When analysing outflow and inflow rates in our simulations or also in other simulations like IllustrisTNG,

—> as shown in figures above, we found that the outflow rates (out of the halo, right panel) at a given halo mass are increased with kinetic AGN feedback (red symbols), but also that inflow rates (back onto the galaxy, left panel) at a given halo mass are reduced with kinetic feedback (red symbols).

—> **This is because outflowing gas particles in the kinetic AGN feedback run can travel further away from the galaxy/halo and are less likely to be re-accreted back onto the halo and thus, onto the galaxy.**

—> This illustrates AGN feedback can **act simultaneously in two ways**: increase gas ejection rate and at the same time reduce gas inflow rate.

—> Similar results have been found for other simulations, such as IllustrisTNG.



Hot gas content in the halo

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

— Since such kinetic AGN feedback models produce these higher gas outflow rates from the halo with reduced gas inflow rates — compared to no AGN feedback or only thermal AGN feedback,

—> the **hot gas content in the halo is strongly affected**, namely significantly reduced as shown in the panel on the left (illustrating the fraction of hot gas versus DM halo mass).

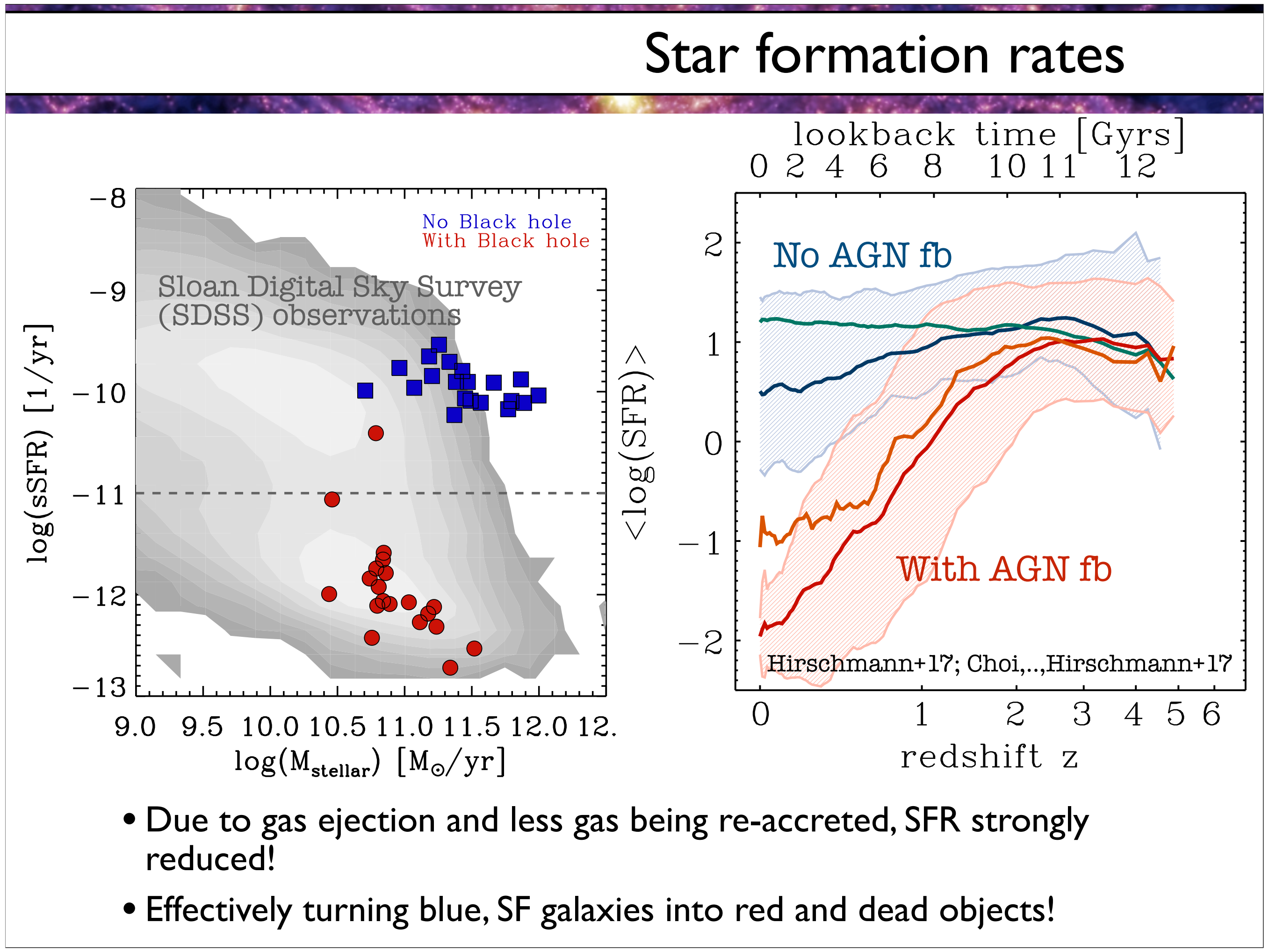
—> Such a reduced amount of hot gas at a given halo mass leads to **lower X-ray luminosities** of halo gas more consistent with observations, which is shown in the right panel (X-ray luminosity of the hot gas versus virial DM halo mass).

— In fact, the amount of hot gas, and thus of X-ray luminosities, in a DM halo are very sensitive to different AGN feedback models.

—> It is not shown here, but for the **bubble** feedback, adopted for example in the Illustris simulation, **X-ray luminosities are too low** compared to observed ones, because too much gas is blown out from the DM halo.

—> Instead for thermal AGN feedback (blue points in the panels above), the hot gas fractions and related X-ray luminosities are too high (i.e. this model is not efficient enough in removing hot gas from the halo).

—> Most realistic AGN feedback models in cosmological simulations seem to be kinetic AGN feedback schemes, with an explicit momentum injection in gas elements close to the BH.



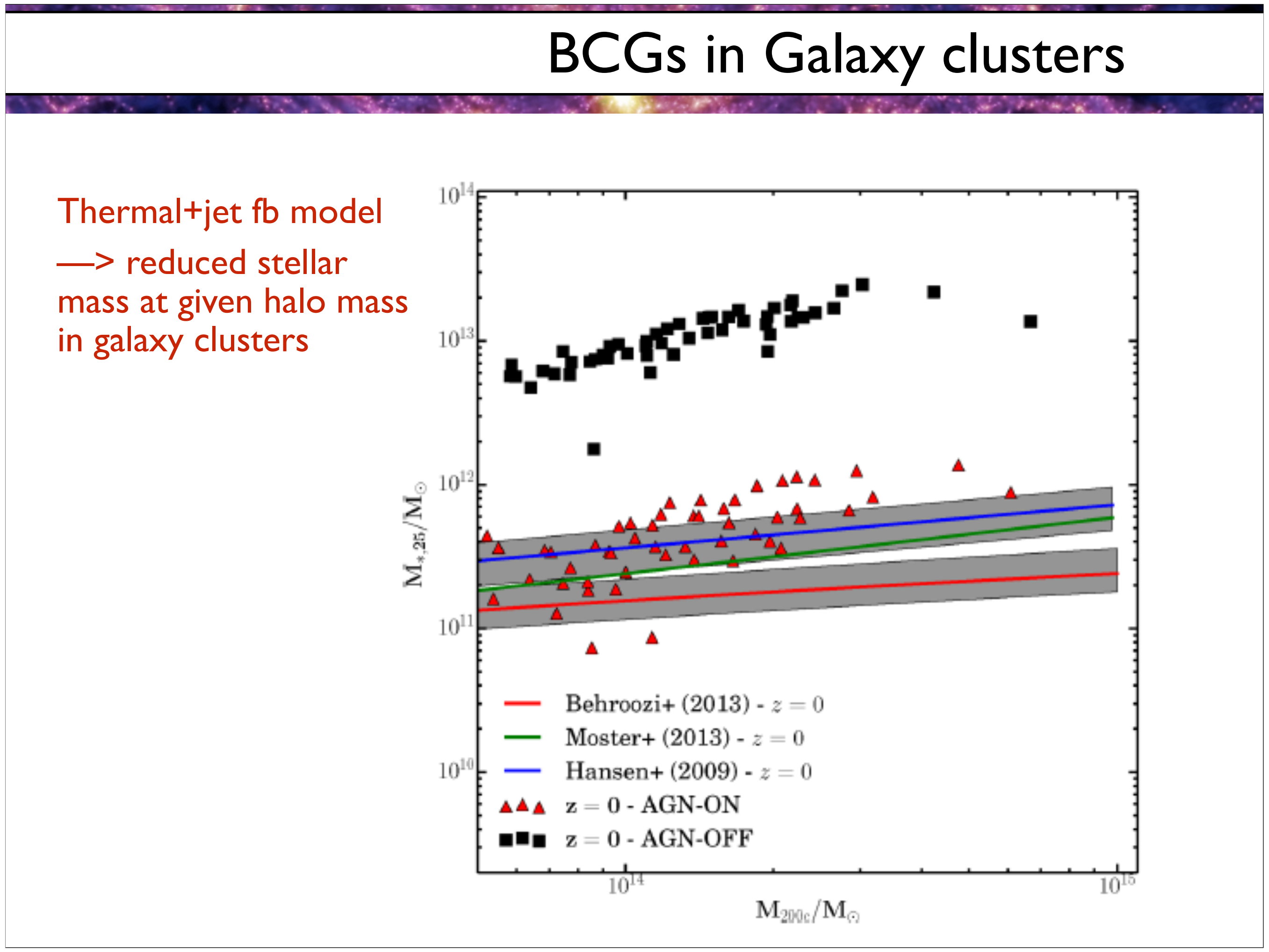
Star formation rates

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

— Different cosmological simulations also agree that AGN feedback is needed to strongly **reduce SF in massive galaxies**, as we already saw for semi-analytic models, shown the right panel (average SFR versus redshift with and without AGN feedback).

—> Thus, AGN feedback is crucial to **produce a population of quiescent, massive galaxies** as observed in SDSS as illustrated in the left panel (Shown is the specific SFR versus stellar mass, the grey area illustrates observed SDSS galaxies. Only AGN feedback, red symbols, can quench galaxies producing low specific SFR. Without AGN feedback, massive galaxies are too SF — inconsistent with SDSS data).

—> In other words, AGN feedback has been repeatedly shown to be crucial for turning blue, star-forming galaxies into red and quiescent (“dead”) galaxies.



BCGs in Galaxy clusters

Thermal+jet fb model

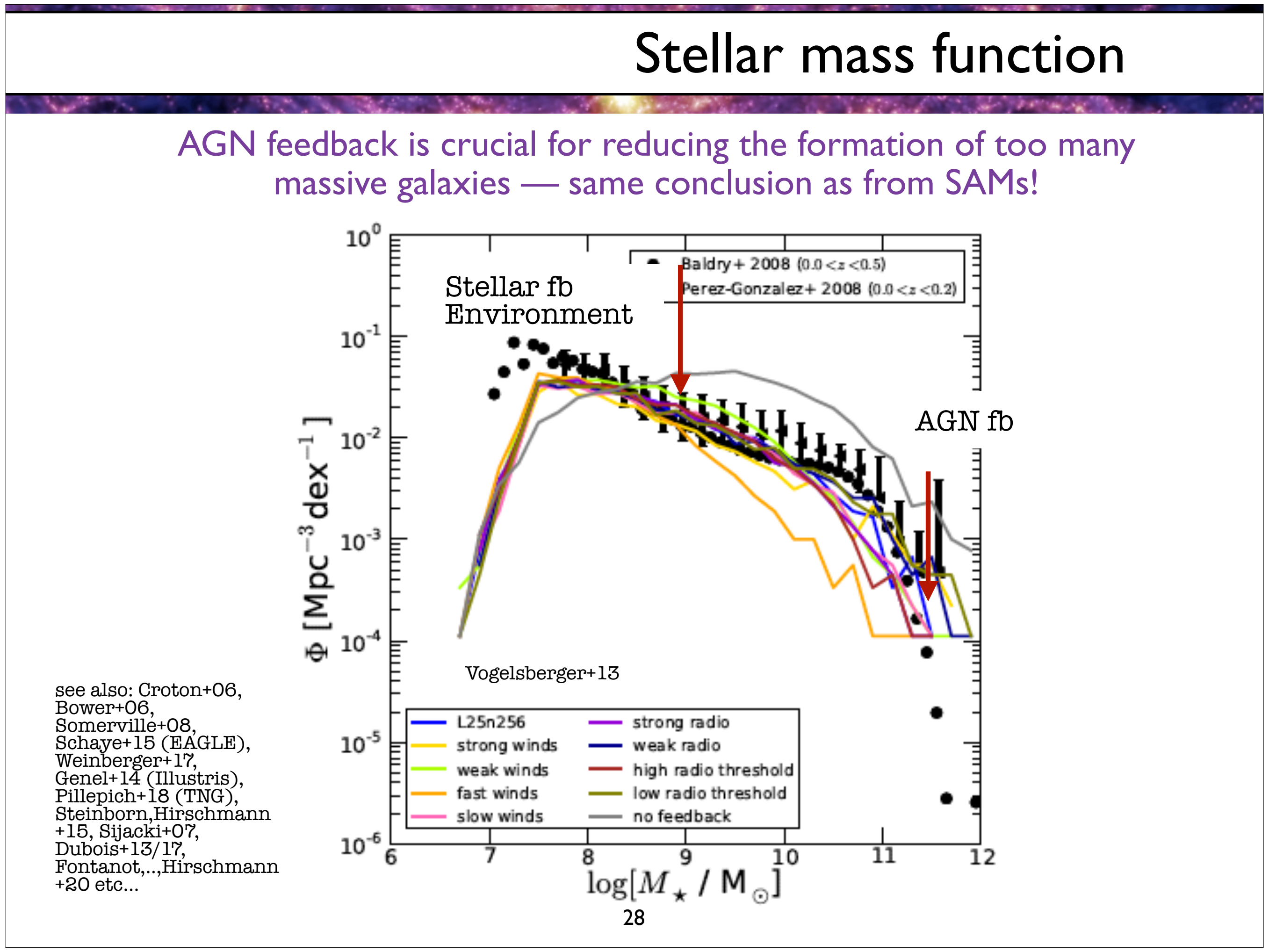
—> reduced stellar mass at given halo mass in galaxy clusters

— A further consequence of reduced SFRs is that

—> the **stellar mass for a given halo mass is efficiently reduced by AGN feedback (shown for cluster DM halo masses > a few 1e13 Msun at z=0 in the panel above).**

—> Such lower stellar masses are more consistent with observations/abundance matching predictions as shown by the different coloured lines in the figure.

—> Note that black symbols illustrate cosmological zoom simulations without AGN feedback, red symbols correspond to those (based on the same initial conditions) including BHs and AGN feedback.



Stellar mass function

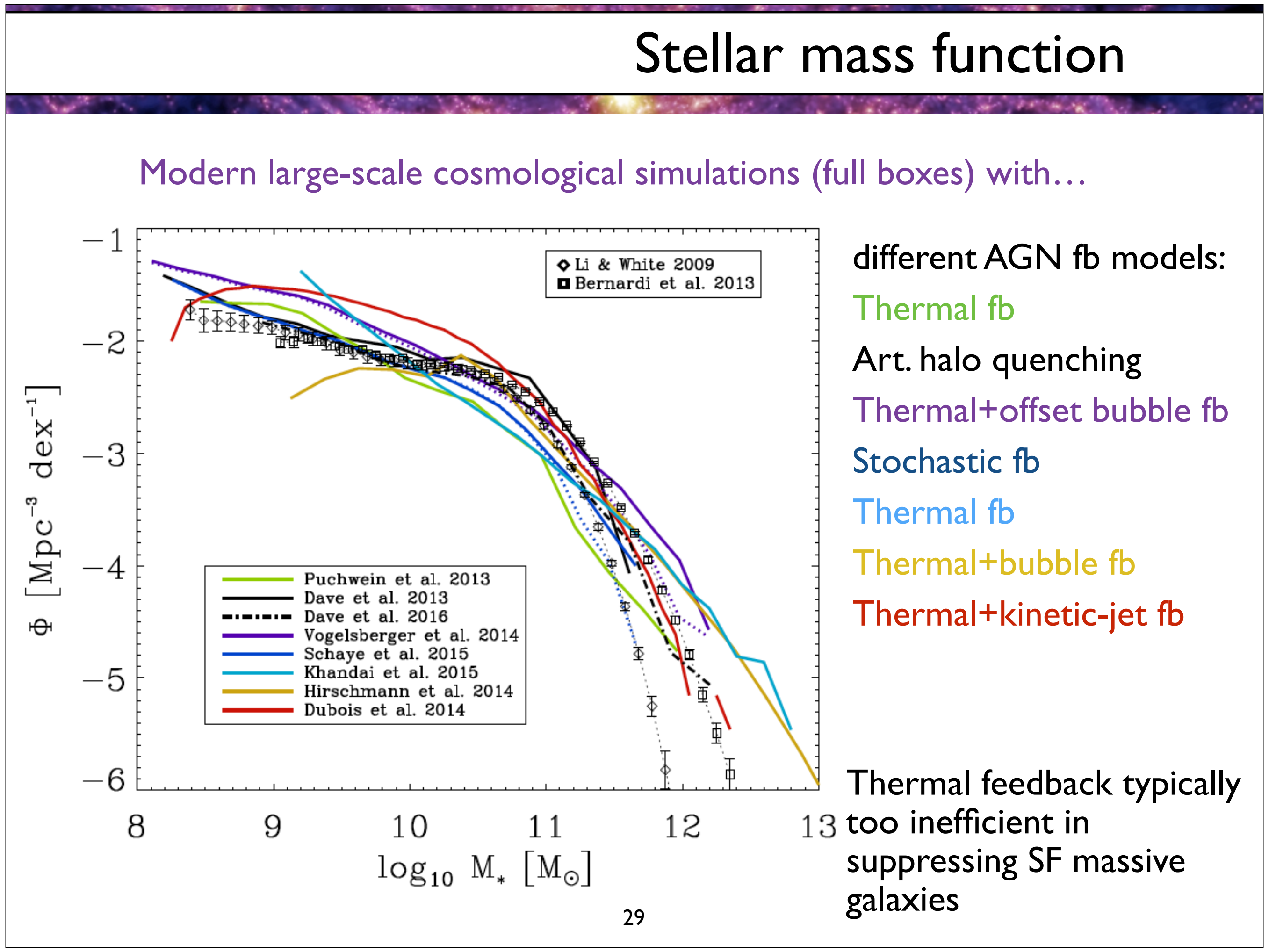
AGN feedback is crucial for reducing the formation of too many massive galaxies — same conclusion as from SAMs!

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…

— As we already saw for SAM, a direct consequence of such less massive galaxies is that **the massive end of the galaxy stellar mass function at low redshift** is reduced,

—> in agreement with observations, as shown in the panel (lines correspond to different simulation predictions, black symbols show observations).

— **Thus, the results of SAMs on the impact of AGN feedback on galaxy properties has been nicely confirmed by later, more precise cosmological hydrodynamic simulations.**



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

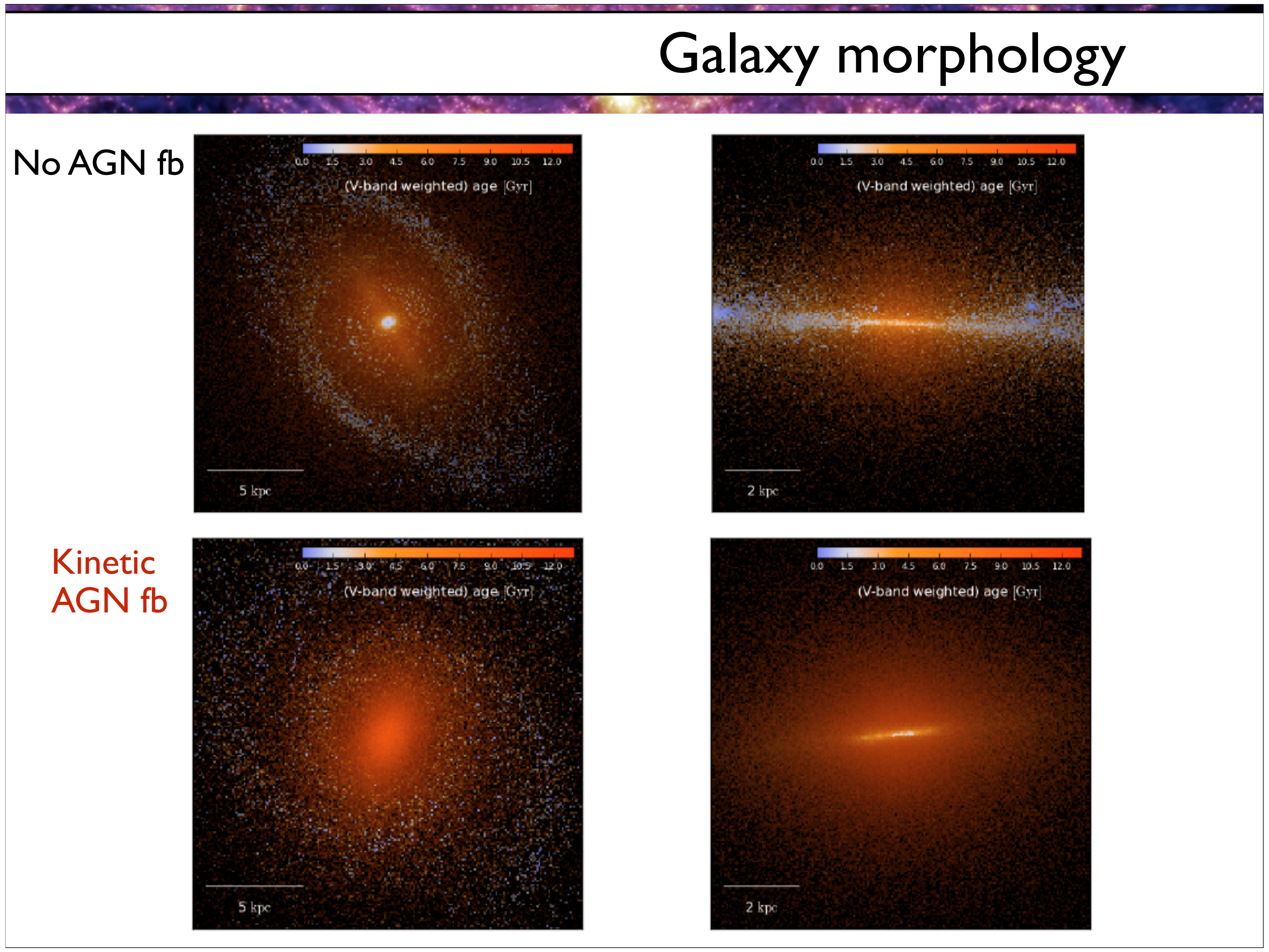
Thermal+kinetic-jet fb

Thermal feedback typically too inefficient in suppressing SF massive galaxies

— Nowadays, most state-of-the-art cosmological simulations (more or less) match the massive end of the galaxy stellar mass function as you can see here (coloured lines are simulations, grey symbols observations).

—>But with only thermal feedback (lila, yellow and blue lines), there are still a bit too many massive galaxies

—>only with more effective AGN feedback (like kinetic feedback) the massive end is perfectly matched (e.g. red line).



Galaxy morphology

No AGN fb

Kinetic AGN fb

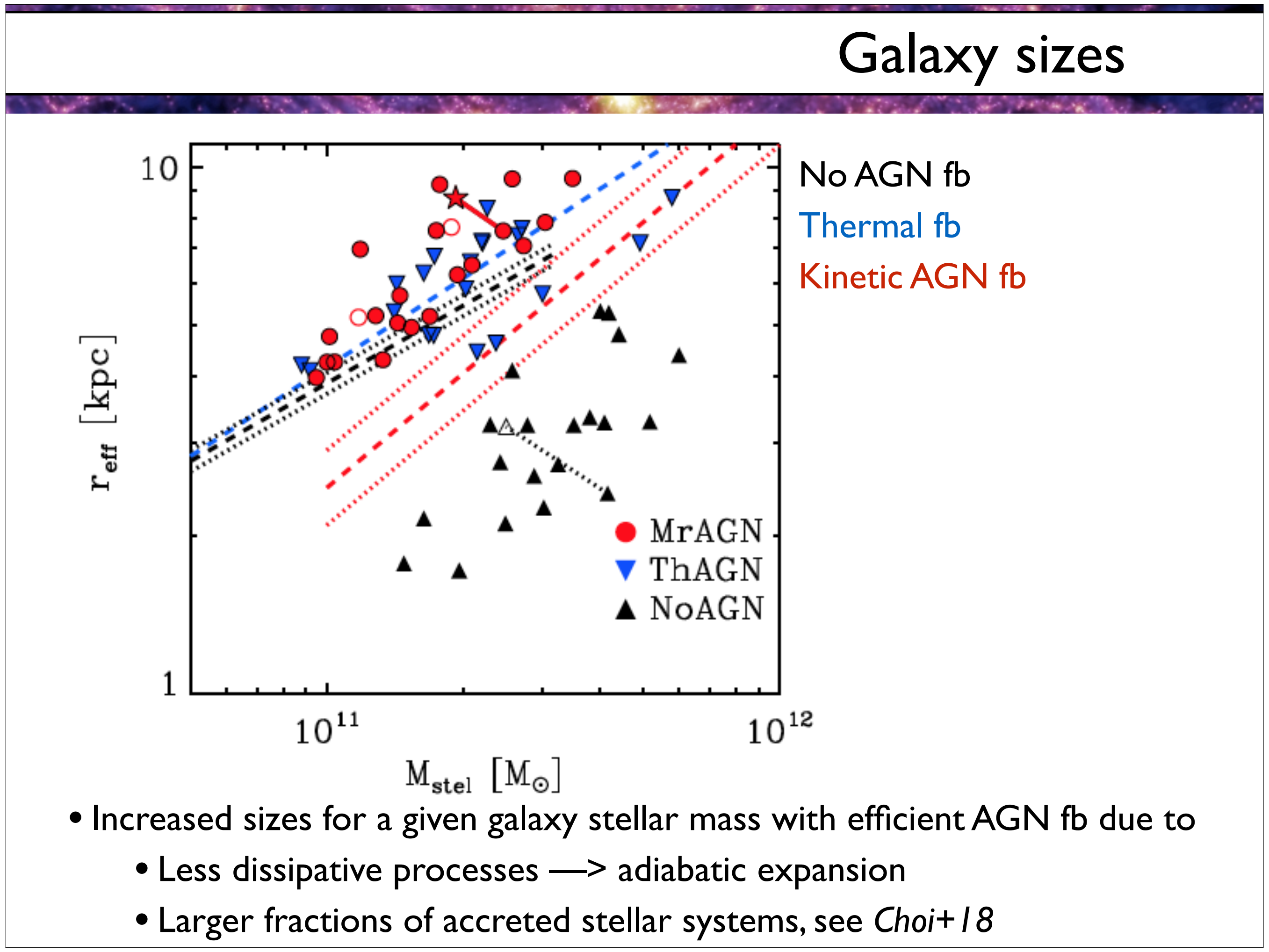
—But **in contrast to SAMs**, cosmological hydrodynamic simulations allow us to assess the **impact of AGN feedback on internal/structural galaxy properties**, like morphologies.

—> In this context, simulations have repeatedly shown that **AGN feedback can also strongly affect the morphology of galaxies.**

—>In fact, this process is needed to produce **massive galaxies with a realistic elliptical-like shape.**

—>This is because AGN feedback prevents late-accretion of high-angular momentum gas onto galaxies and, and thus, the late formation of disk/spiral structure (promoted by stellar feedback).

— Indeed, it has been explicitly shown that **with efficient stellar feedback but without any AGN feedback, cosmological boxes predict too many massive galaxies with disk-like structure and hardly any ellipticals — inconsistent with observations.**



Galaxy sizes

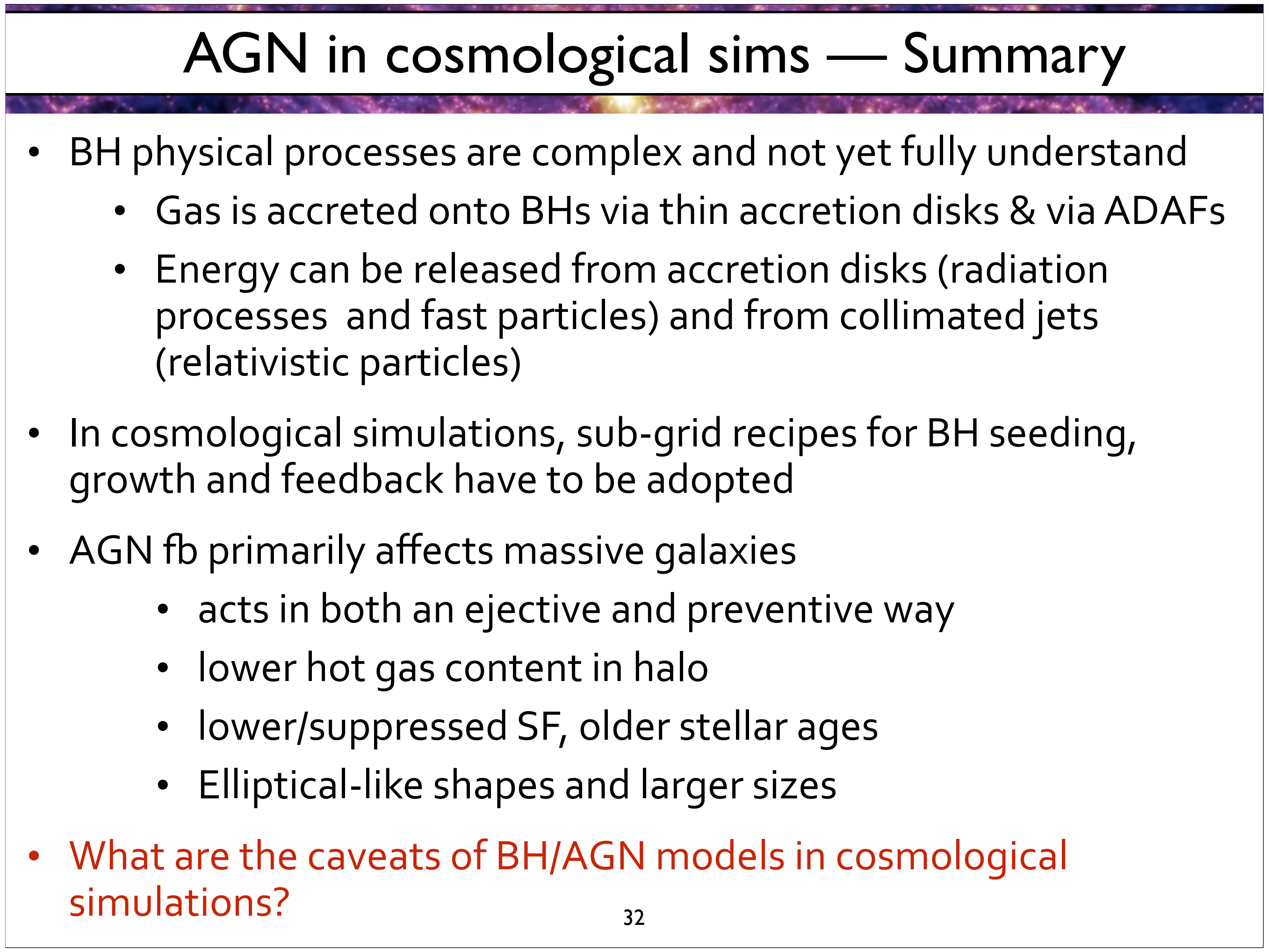
- Increased sizes for a given galaxy stellar mass with efficient AGN fb due to
  - Less dissipative processes —> adiabatic expansion
  - Larger fractions of accreted stellar systems, see *Choi+18*

— At the same time, with AGN feedback, we obtained **larger sizes for a given galaxy stellar mass**,

—> as shown in this panel (effective radius versus galaxy stellar mass) for runs with AGN feedback (blue and red points) and without AGN feedback (black points).

—> The reason for this size increase is linked

- to less dissipative processes as gas cooling and SF is suppressed resulting in adiabatic expansion,
- and to larger fractions of accreted stellar material brought in by minor mergers.



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?

— What are the **Caveats of such BH/AGN models in cosmological simulations?**

—> From such cosmological simulations, we cannot robustly conclude, which AGN feedback process is mainly responsible for star-formation quenching, gas heating and outflows.

—> This means it remains unclear whether it is mainly due to accretion-disk feedback or jet-mode feedback, radiation or mechanical feedback.

—> From different simulations, there seems to be some tentative consensus that at low-redshift, likely mechanical, jet-mode feedback might be the dominant mechanism.

—> But in general, dominant AGN feedback mechanisms cannot be robustly addressed in cosmological simulations as it strongly depends on the numerical implementation and because the small-scales are unresolved.

Up next…

- *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
- *Chapter 6*: The world of galaxies II
- *Chapter 7:* Black holes and active galactic nuclei
- *Chapter 8:* Galaxies and their environment;
- *Chapter 9:* High-redshift galaxies
- *Chapter 10*:
    - Cosmology in a nutshell; Linear structure formation in the early Universe
- *Chapter 11*:
    - Dark matter and the large-scale structure
    - Cosmological N-body simulations of dark matter
- *Chapter 12*: Populating dark matter halos with baryons: Semi-empirical & semi-analytical models
- *Chapter 13:* Modelling the evolution of gas in galaxies: Hydrodynamics
- *Chapter 14*: Gas cooling/heating and star formation
- *Chapter 15*: Stellar feedback processes
- *Chapter 16*: Black hole growth & AGN feedback processes
- *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