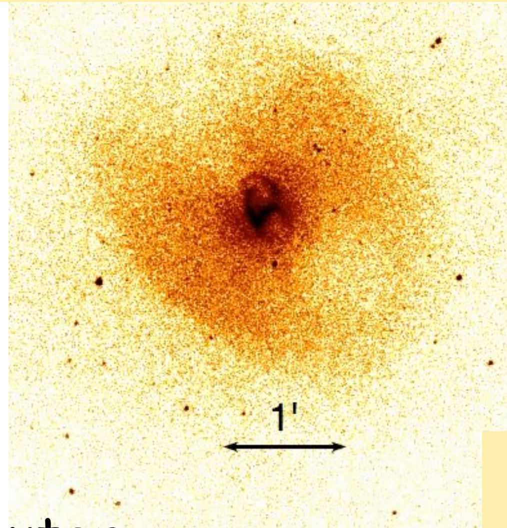
Feedback in Early-type Galaxies

Bill Forman

- Solve Cooling flow "problem"
- Why are early type galaxies "red and dead"
- Understand low accretion rate AGN (P_{mech}/P_{rad} ~1000) aka "radio mode"
- How does energy transfer from SMBH outbursts to hot gas
  - Shocks? Relativistic plasma?
  - What are typical characteristics of SMBH outbursts

A "typical" galaxy in a Chandra Survey

NGC5813 - multiple outbursts



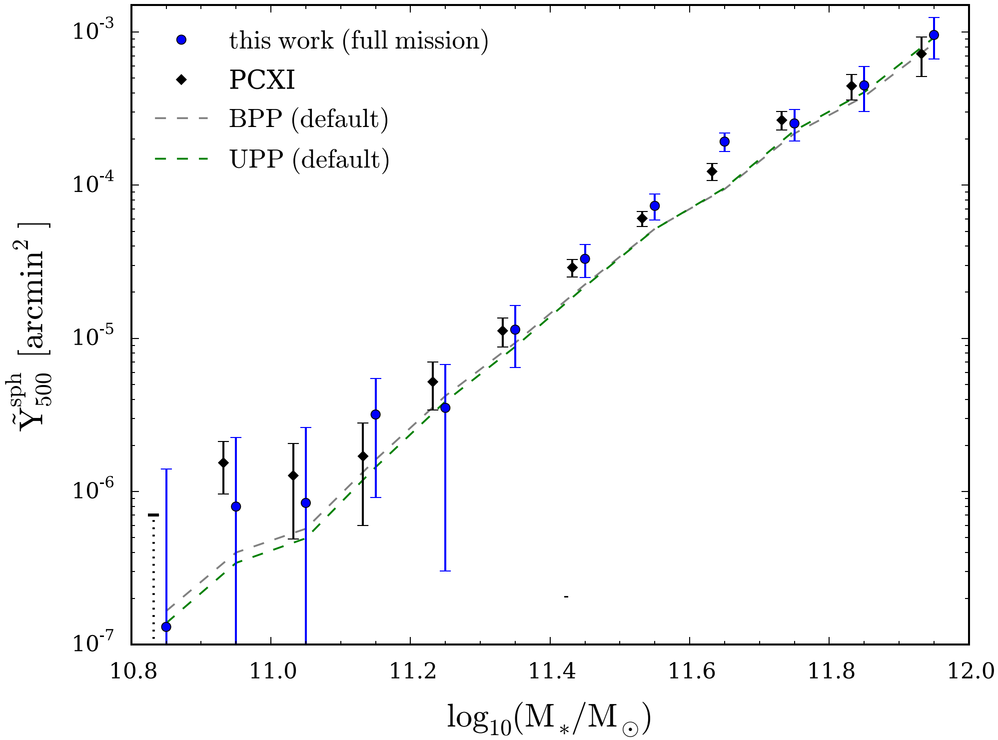
Scott Randall+15

	inner	middle	outer	
Ages	0.6	3	10	$\times 10^{7}$ yrs
Energies	1	21	20	$\times 10^{56}$ ergs

L_{nuc} ~ few x 10^{39} erg/s

- Cavities - Common (30% of galaxies; lower limit)
- Measure SMBH energy output
- Active nuclei - 70% seen as radio sources and 80% as X-ray sources

  $L_X \sim 10^{38} - 10^{42}$ erg s^{-1} Low Eddington ratios $\sim 10^{-5}$
- Radiatively weak - radiated power < 10^{-3} mechanical power
- Measure power from cavity and shocks - can overcome cooling



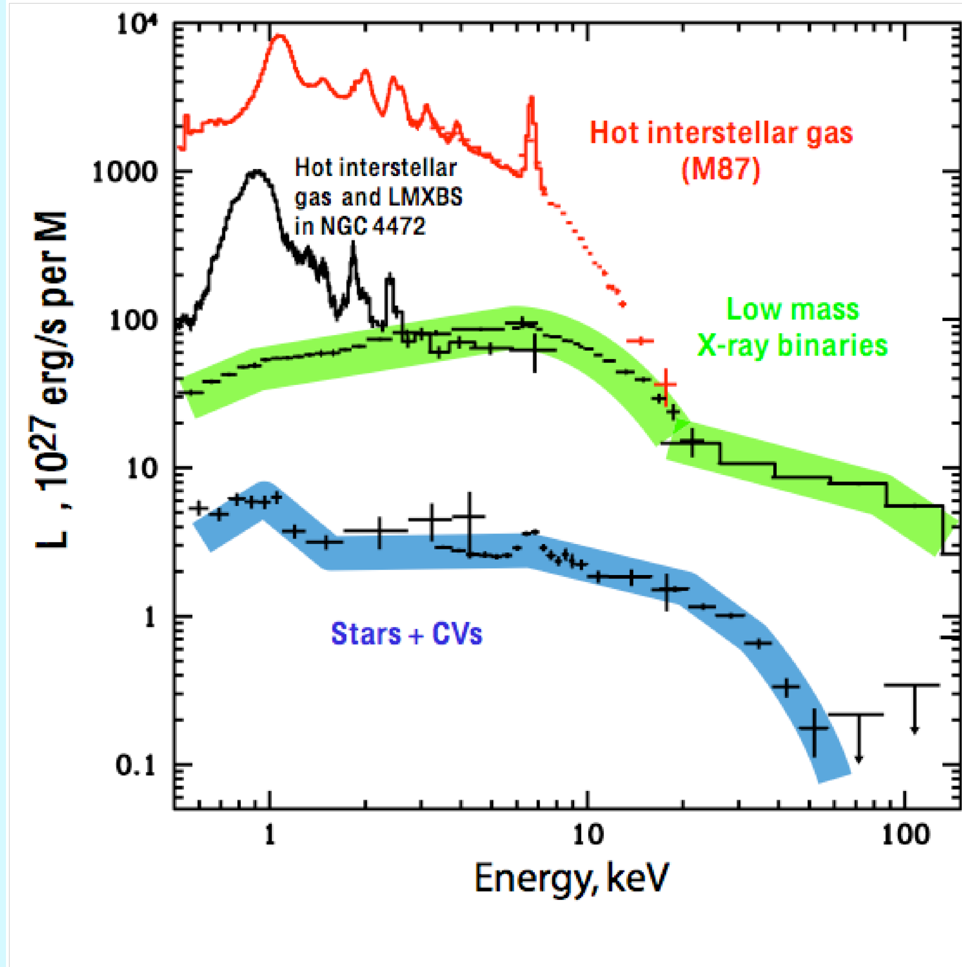
Greco 2015+ ApJ, 808, 151; account for dust contribution

Planck intermediate results. XI 2013, A&A, 557, 52

- Planck detects early type/BCG galaxy/group coronae in SZ stacks (to a few times 10^{11} M_{sun})
- 188,000/260,000 locally brightest galaxies from SDSS
- Probing wide range of halo mass to M_{500}~$2x10^{13}$ M_{sun}
- **Great promise with higher angular resolution (SPT/ACT)**
- **Will/ hot corona vanish at low mass (onset of winds)? Is there a qualitative change in radio jet/lobe properties vs. stellar/halo mass as hot coronae vanish?**

X-ray emission from Early Type Galaxies

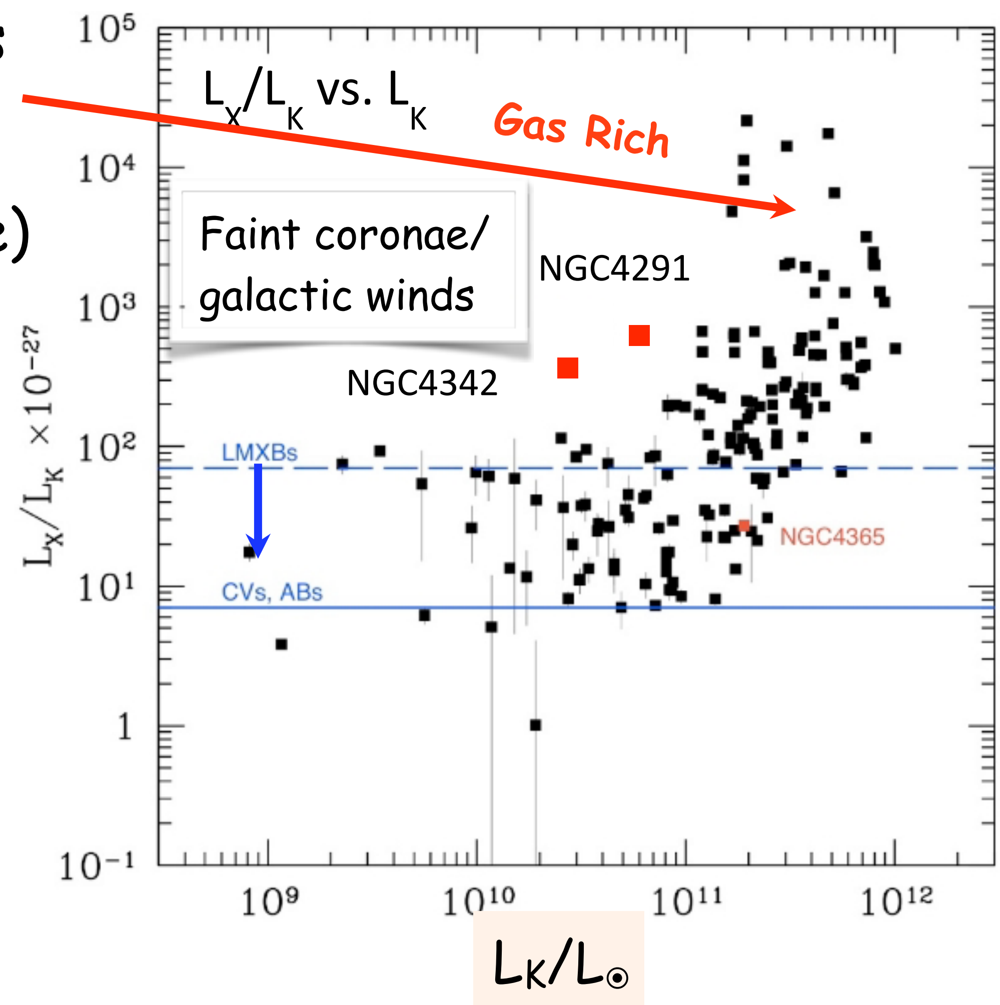
- Massive/luminous early type galaxies ($L_K > 10^{11}\ L_{sun}$) - gas rich
  - M_{gas} up to $10^{10}\ M_{sun}$
  - $kT_{gas} \sim 10^7$ K
- X-ray binaries & globular clusters
- Stars +CV's (multi-component spectrum)
  - Detected in fainter, nearby galaxies
  - Resolved in the Milky Way Galactic Ridge (Revnivtsev+08).
- Low luminosity AGN



- **Mergers are not "dry"**

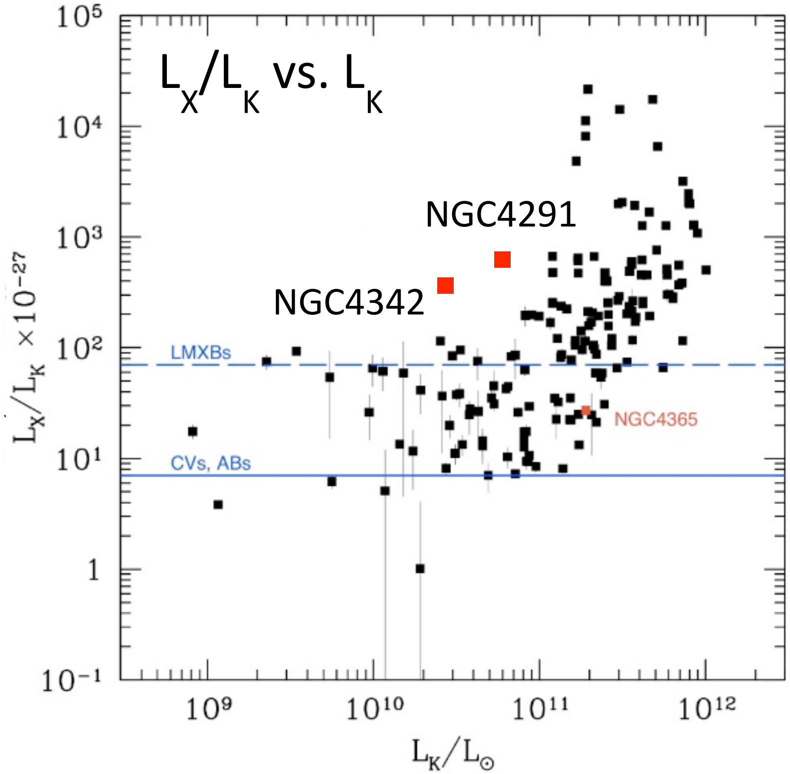
X-ray Emission in Early Type Galaxies

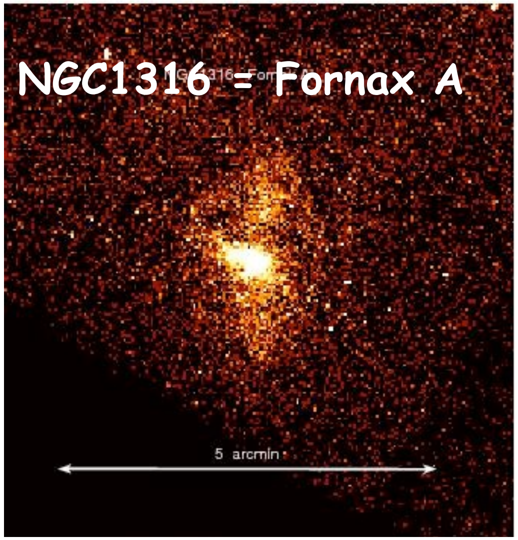
- Luminous early type galaxies have hot gaseous coronae (BCGs excluded from sample)
  - Result from Einstein (see Forman, Jones, Tucker 1985
- LMXBs - partially removed
- CVs, ABs (X-ray bright stellar systems) — always present

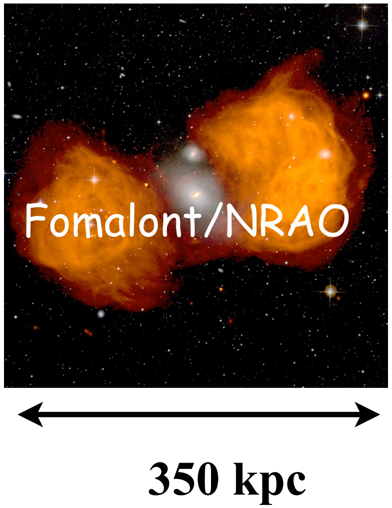


Anderson, Jones, Forman, Churazov

Massive SMBH, with enough fuel can disrupt galaxy atmospheres - e.g., Fornax A = NGC1316



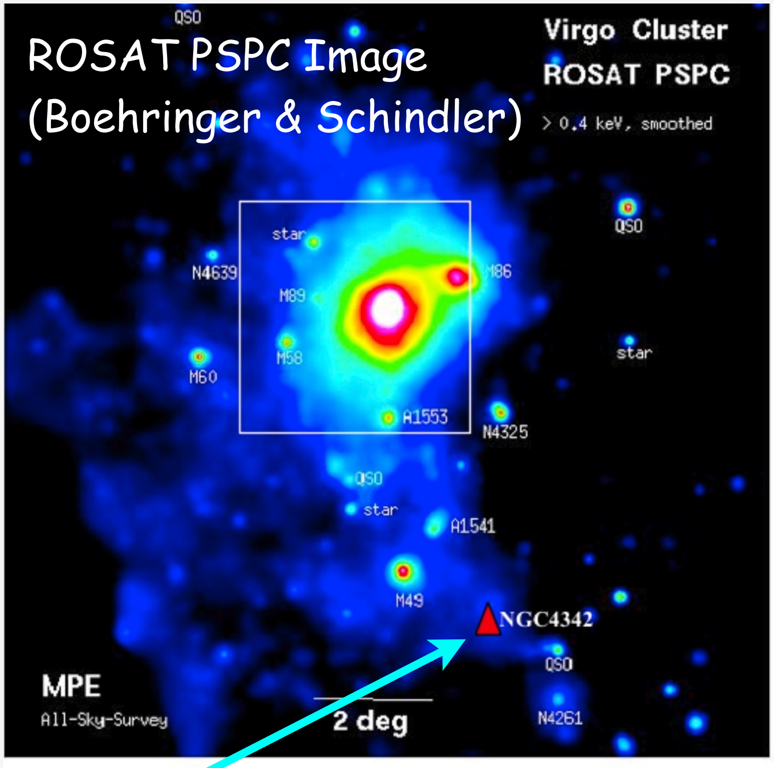




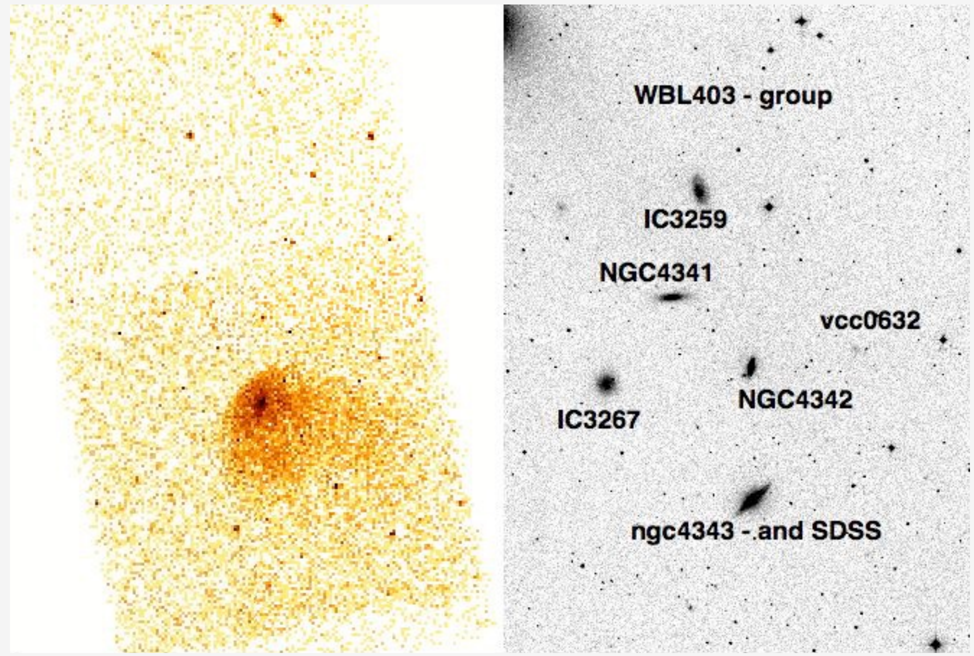
Scatter in L_X-opt mag relation is partly due to gas removal and partly due to environment (galaxies in the centers of "groups")

- Outskirts of Fornax cluster (>1.4 Mpc from NGC1399)
- L_{nuc}~2×10^{42} erg/s
- likely merger driven outburst
- Massive SMBH is willing and able to disrupt atmosphere given sufficient fuel; outburst power ~ 5×10^{58} ergs (Lanz+10)
- Such outbursts at early epochs could disrupt star formation

Optically faint, gas rich galaxies - NGC4342

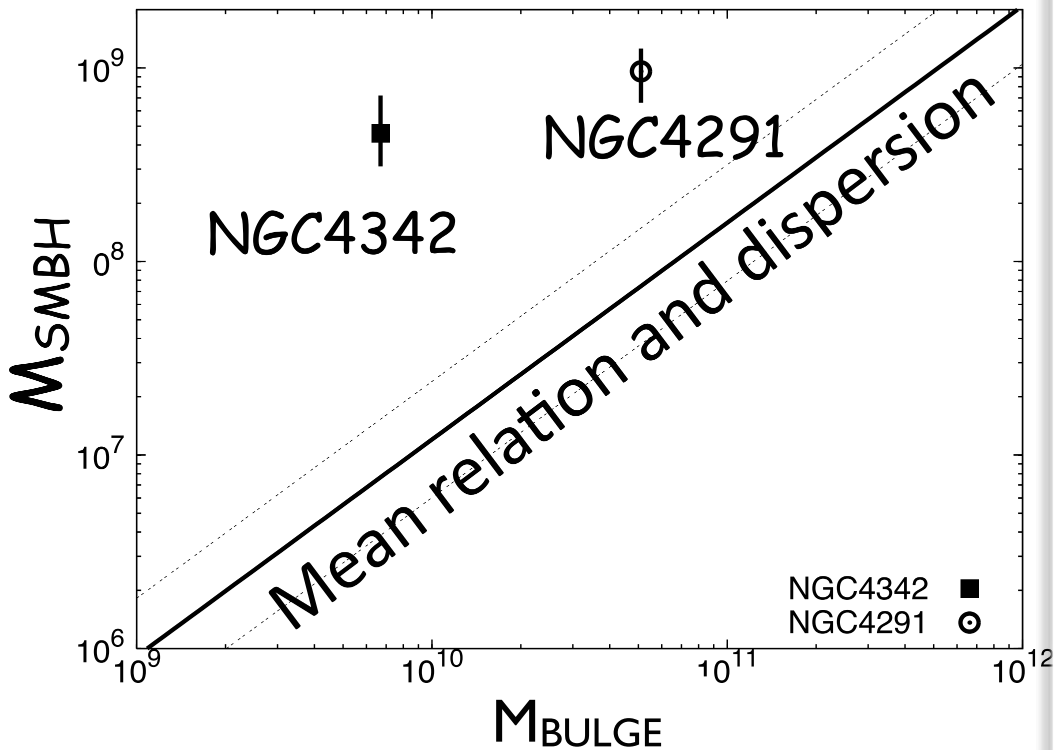


NGC4342 beyond r_{200} from M87
Only ~0.5 Mpc from NGC4472 (M49)
Virgo gas distribution - elongated N-S



Gaseous filament in Virgo outskirts
NGC4342 encounters external gas for the first time?
Ram pressure stripping underway?

Massive Black Holes (Bogdan et al. 2012) - two outliers

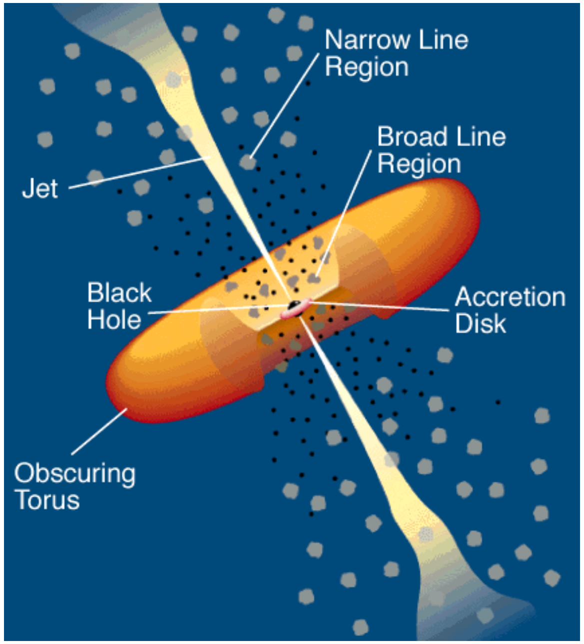


- Evolutionary scenario for NGC4342 and NGC4291
- Star formation suppressed by powerful SMBH outburst (e.g., like Fornax A at early epochs BEFORE all stars formed
- SMBH growth precedes stellar component?
- **eRosita will inventory dark matter halos**

- NGC4342 and NGC4291 host massive dark matter halos sufficient to bind hot coronae
  - measured via hydrostatic equilibrium
- **Black holes are too massive for their bulges (60x and 13x larger than "predicted")**

Feedback in Hot Atmospheres

- Too much feedback - NGC4342/NGC4391 - star formation likely terminated at early epochs by overly active SMBH (a la Fornax A)
- Too little feedback - Phoenix Cluster (see McDonald+13) with 740 M_{sun}/yr of star formation
- most/many SMBH's are getting it "just right" (over some duty cycle) but there are very interesting "failures" in both directions
- Current surveys are too small solid angle or lack sensitivity
- eRosita - will provide wealth of new data
  - find optically faint & X-ray bright (hot coronae) galaxies
    - galaxies where AGN has suppressed star formation at early times



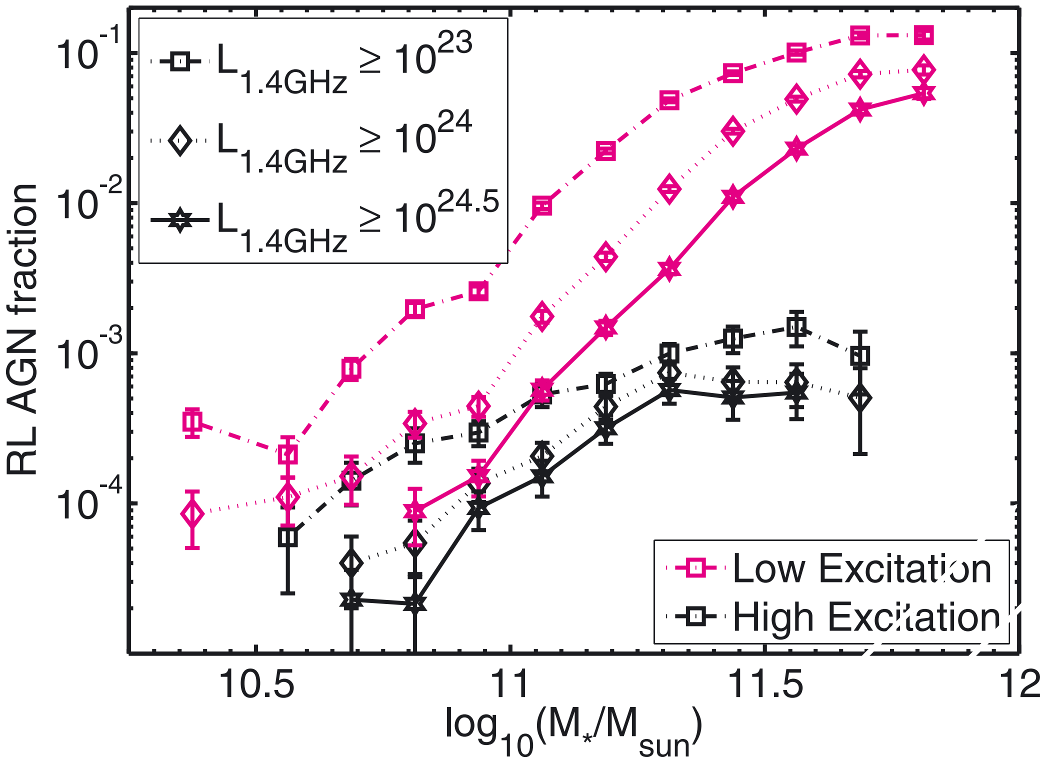
Two Types of AGN accretion modes

Croton +06
Churazov +05
Merloni & Heinz 08
Best +05, +06, +07, +12
...

High excitation AGN
"standard" picture (called "quasar mode")

Low excitation AGN

- massive, red galaxies
- NO strong emission lines
- LACK accretion disk, broad line region, torus, ...
- Accrete (some) cooling hot gas?
- Advection-dominated accretion flows (ADAFs) - low Eddington ratio accretion
- show "radio-mode" feedback



Janssen et al. 2013

Nearly all massive/ bright low excitation are radio bright - **feedback**

Low excitation, massive, red galaxies

- have low Eddington accretion rates ($<10^{-5}$)
- show radio-mode feedback
  - $L_{radiated} \ll L_{total} \sim$ (up to a few percent of) $L_{Eddington}$
- Bondi accretion of hot gas? Fuel from hot gas?

Feedback (black holes + hot gas) and Baseball

Early type (bulge) galaxies (and massive spirals - see Akos Bogdan's papers)
- like a baseball team

Batter = SMBH - sometimes hits the ball (outbursts)
- infrequent
- exact trigger unknown
- different sizes (walks, singles, … home runs)

Pitcher = provides ball/fuel (cooling gas for accretion)

Hot X-ray emitting gas = fielders
- capture AGN output

Fielders are critical

No fielders (no gas)

==> No energy capture

No feedback

Unifies SMBH, AGN activity,
Galaxy properties (red/blue)
X-ray "cooling" flows

Gas Provides archive of AGN activity

Review: How Massive Black Holes Govern the Growth of Galaxies

Brian McNamara
University of Waterloo

Ringberg, December 2017

Outline:

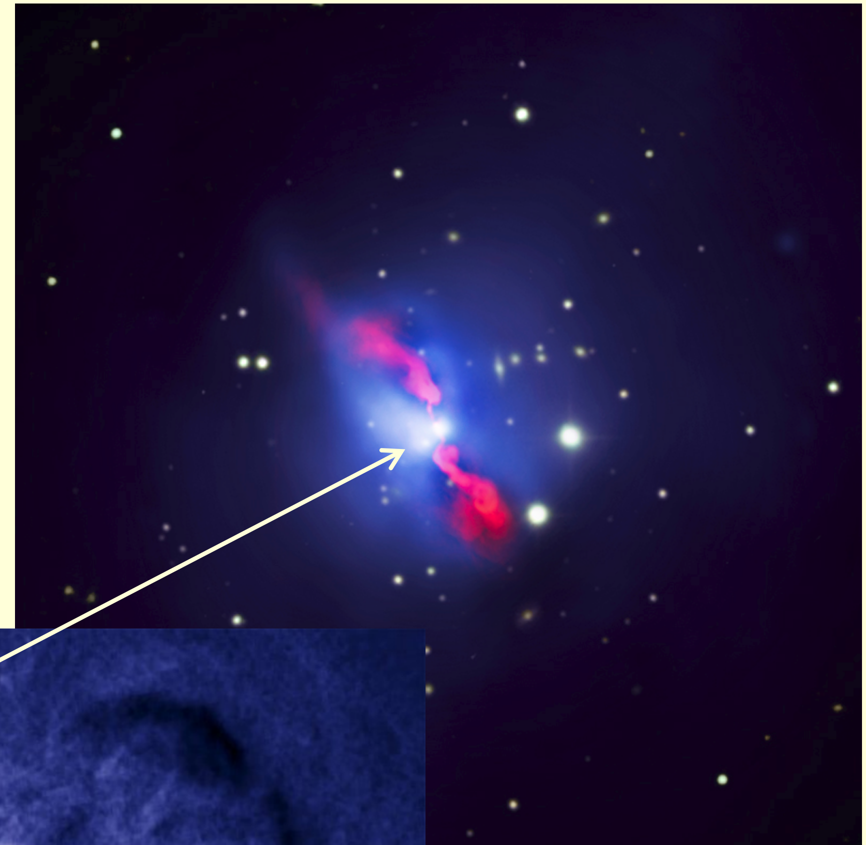
- Overview: quasar Mode & Radio mode feedback
- Consequences for galaxy formation & scaling

- Cold molecular flows in clusters – New ALMA results
- *Stimulated* Feedback & circulation flows

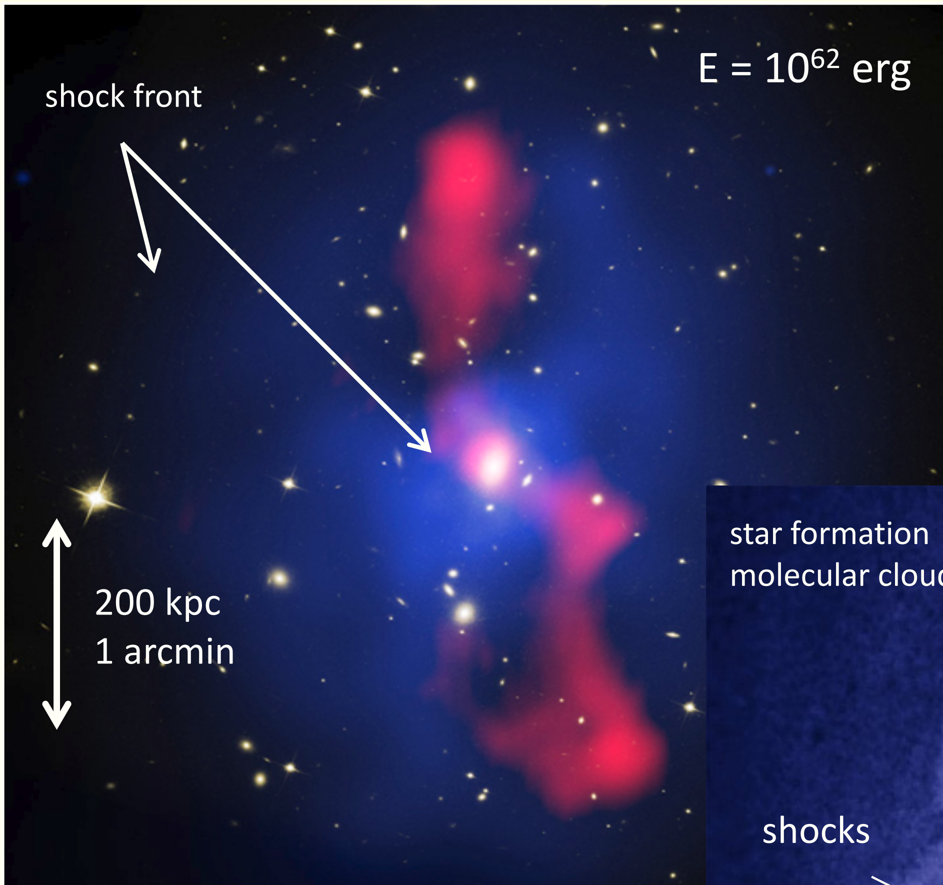
Radio/mechanical Feedback

X-ray + radio = mechanical feedback

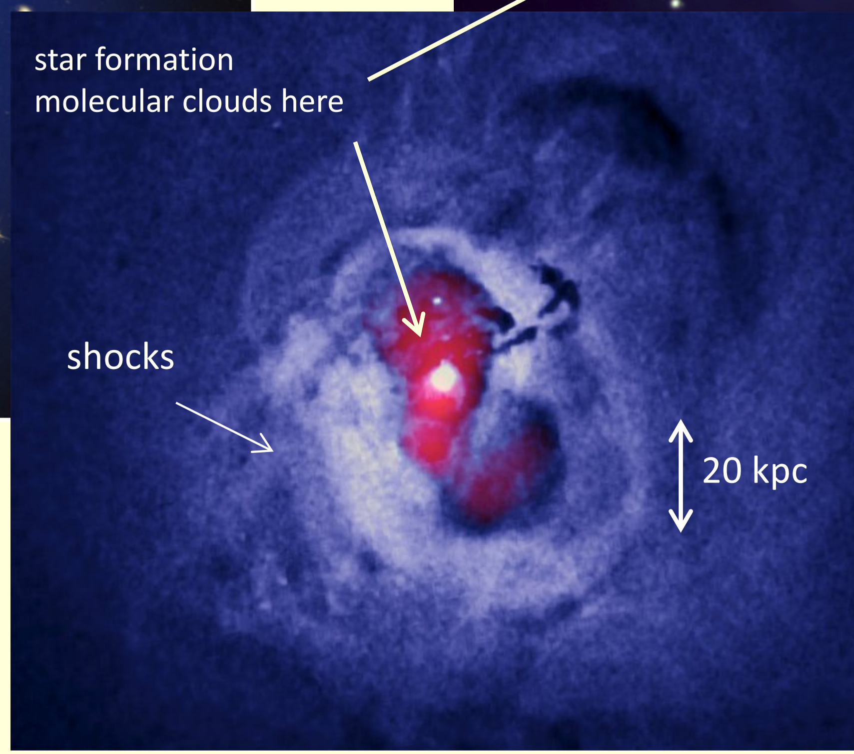
Hydra A Kirkpatrick+11



MS0735 McN + 05,09



Credit: H. Russell

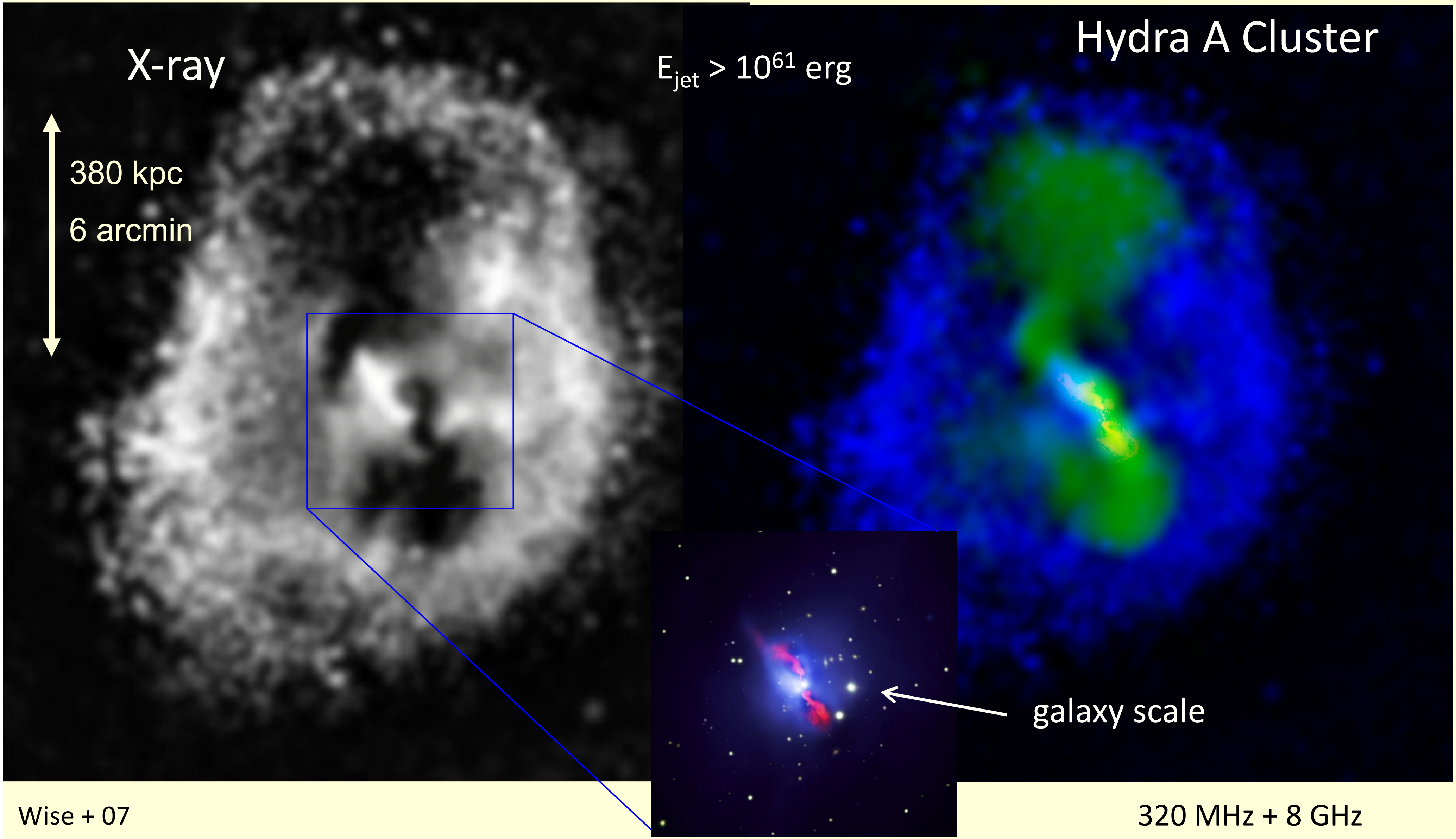


M87, Forman + 05, 07, 17

Perseus

Fabian + 00, 2008

AGN powered continually -- reach vast scales



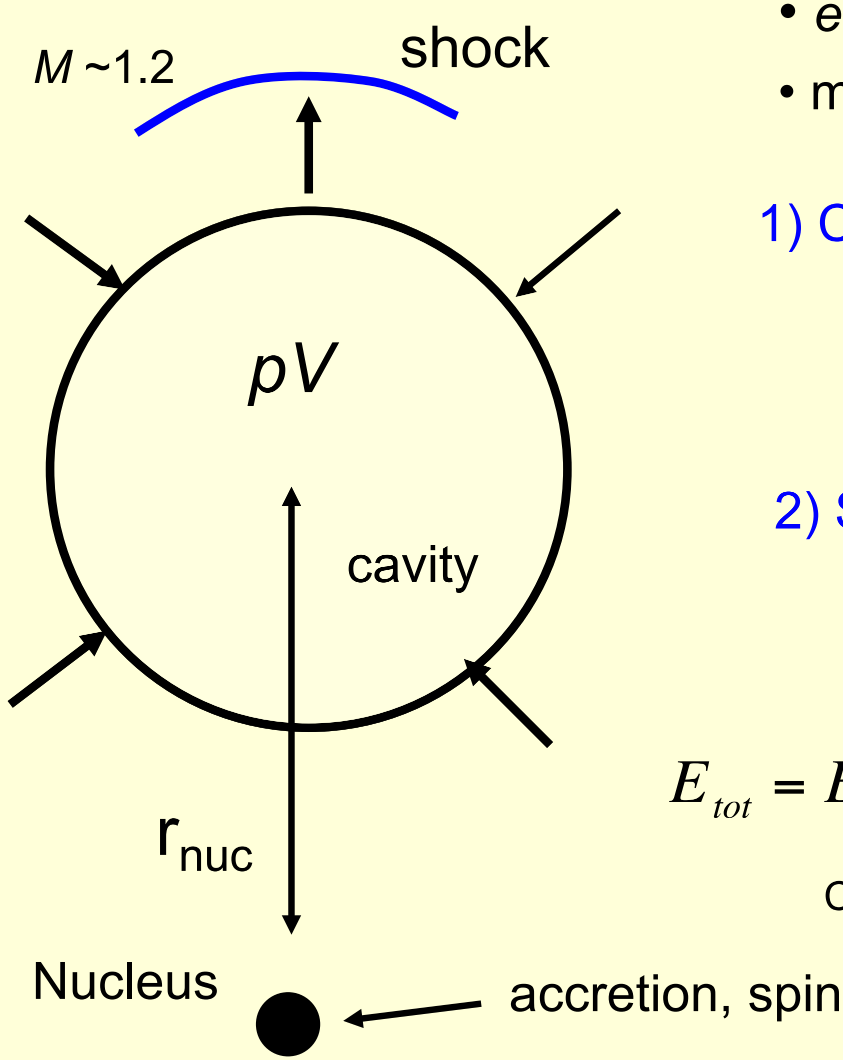
Wise + 07

Nulsen + 05

McN + 00

320 MHz + 8 GHz

Measuring Jet Power using X-ray Cavities



- *energy & age measured directly*
- measure mechanical (not synchrotron) power

1) Cavity enthalpy (pV work + internal energy)

$$E_{cav} = \frac{\gamma pV}{\gamma - 1} = 2.5\,pV - 4\,pV$$

$$t_{cav} = r_{nuc} / v_{buoy}$$

2) Shock energy

$$E_{shock} \approx \Delta pV \qquad t_{shock} \approx r_{shock} / c_s$$

$$E_{tot} = E_{cav} + E_{shock} + (E_{photon}) = 10^{55} - 10^{62}\,erg$$

Churazov 00,01, McNamara + 00,01 Fabian 00, Birzan + 04

Theory: Gull & Northover 1973, Scheuer 74, Churazov, Nulsen, Ruszkowski, Heinz, Bruggen, Begelman

slow gas motions < c_s, gentle heating

Hitomi 17

what consequences?

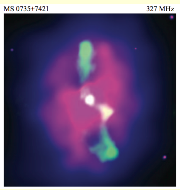
-- weak radio sources can be mechanically powerful

-- heating balances cooling on average in hot atmospheres

-- jet power scales with halo mass

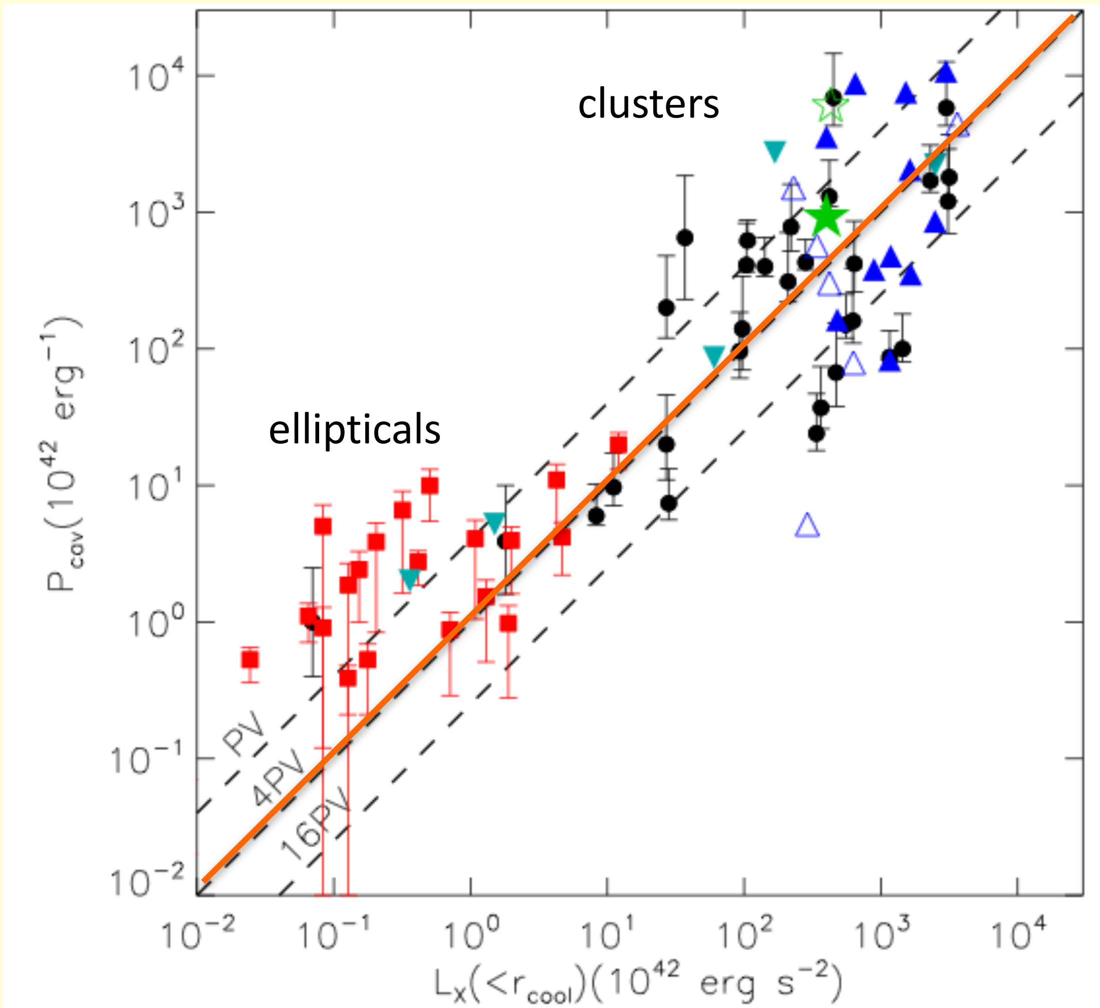
AGN heating balances cooling of X-ray atmospheres

mechanical power > 100 times synchrotron power



Birzan + 04 Dunn & Fabian 06 Nulsen + 08
Rafferty + 06 Hlavacek-Larrondo + 12

jet power



X-ray cooling luminosity

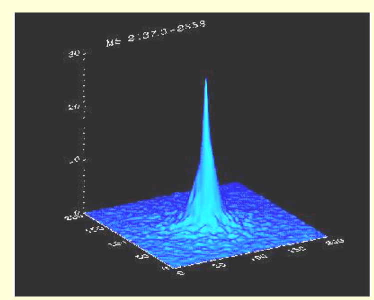
trend: cooling vs jet power

AGN knows how much enthalpy is needed to balance cooling

Local heating-- turbulent cascade
– Zhuravleva + 14

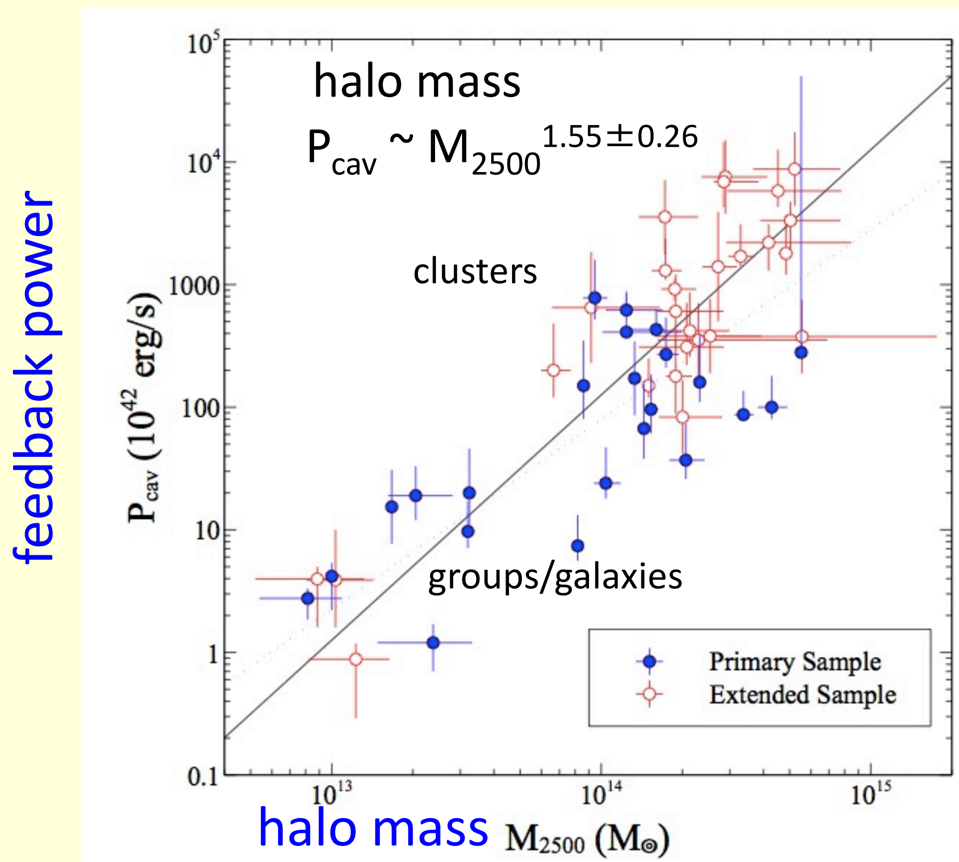
Reviews:

McNamara & Nulsen 07, ARAA
McNamara & Nulsen 12, NJP
Fabian 12, ARAA



Feedback Power scales with halo mass

... when the *central atmospheric cooling time is less than 1 Gyr*



Main + 17

-- Scaling is consistent with M-σ relation (Ferrarese & Merritt 00): $M \sim \sigma^5$

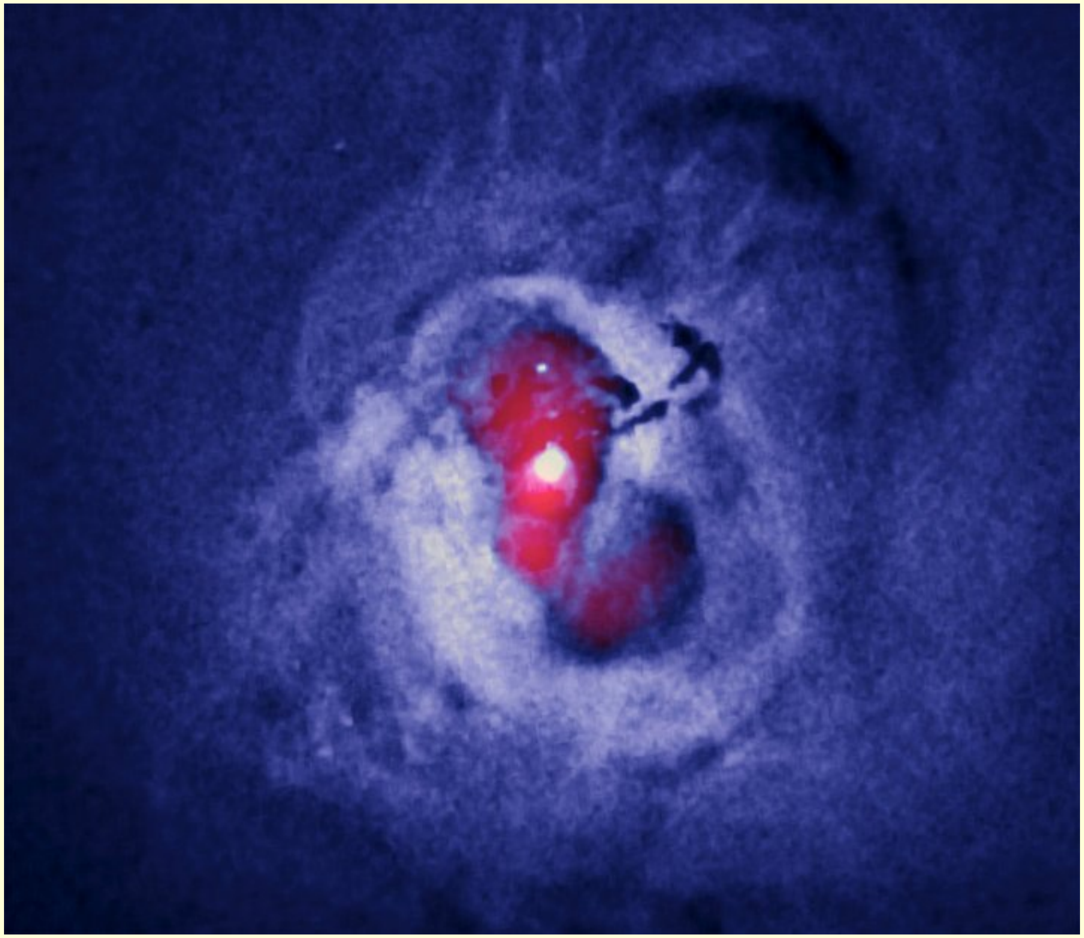
$P_{jet} \sim L_{cool} \sim M^{1.75}$, *assuming jets powered by feedback*

-- Trend vanishes in halos with central cooling times ≥ 1 Gyr

cooling time/entropy instability threshold– Cold Accretion

The energetics of AGN feedback are well understood

The cooling and accretion cycle that nurtures feedback is not



Perseus

Fabian + 00, 2008

Problem: AGN must be fueled promptly ~ t_{ff}

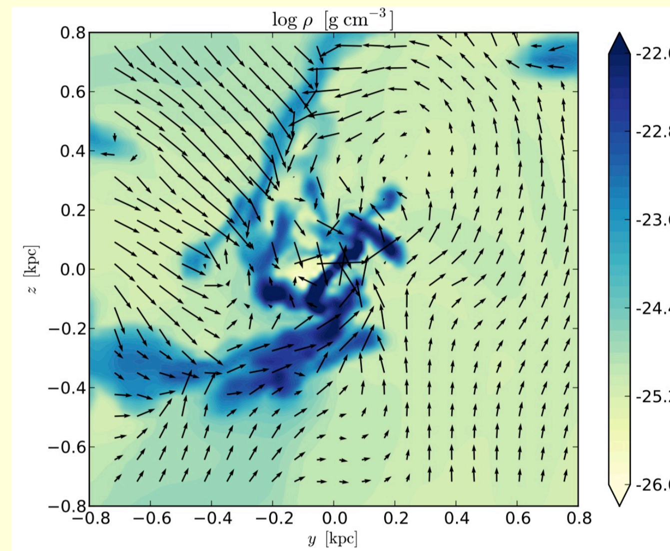
Angular momentum must be cancelled or transported away

When does molecular gas form?

-- $t_c < 10^9$ yr @10 kpc yields H_2, star formation

-- "precipitation" t_c/t_{ff} <10 ?

-- The physical canon: t_c/t_{ff} <1



Models positing t_c/t_{ff} drives cooling are problematical

t_c/t_{ff} always exceeds 10 (Hogan 17a, b, Pulido 17, arXiv)

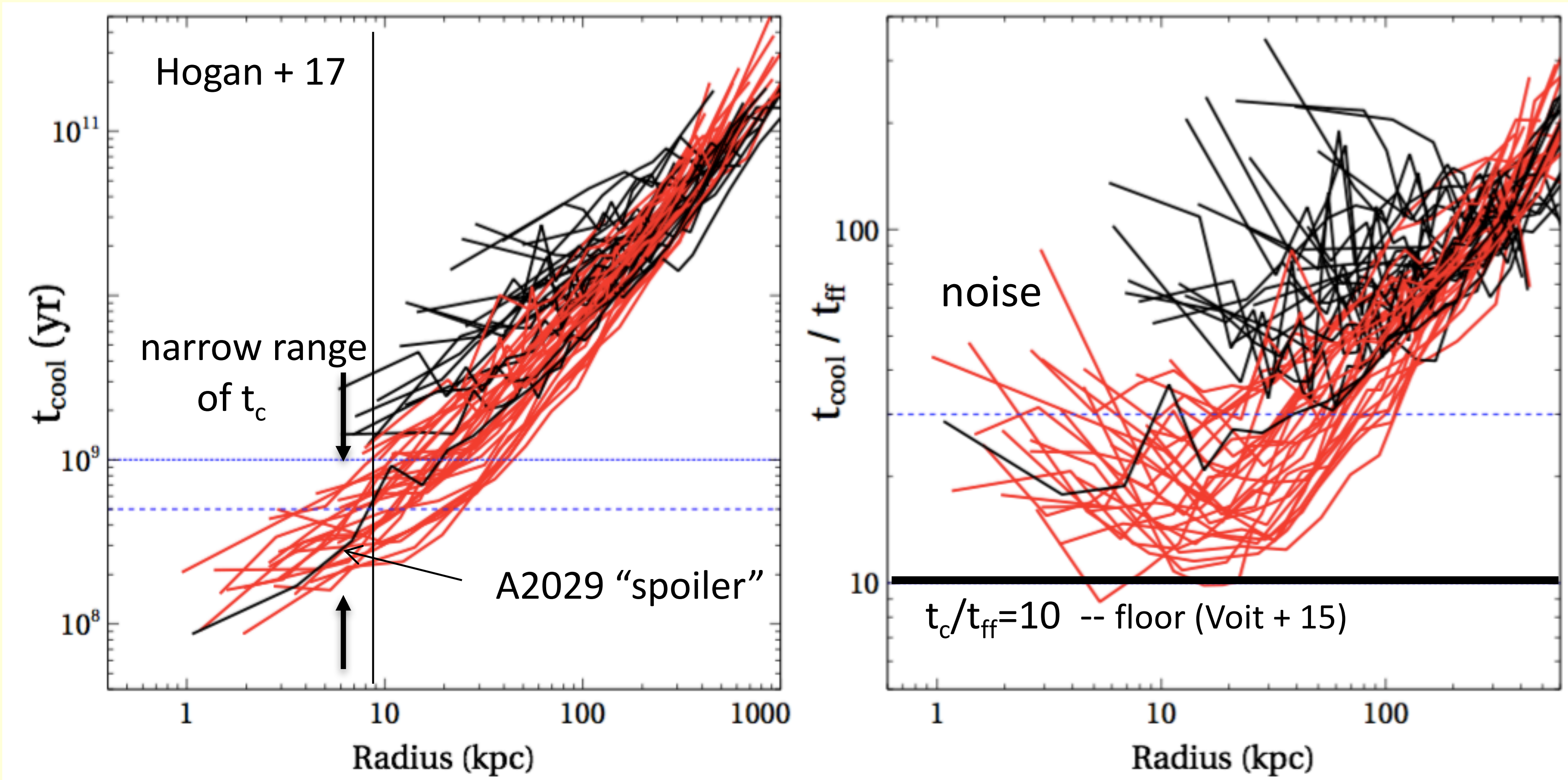
No direct indication that t_{ff} plays a significant role

Gaspari + 13
McCourt +11
Voit + 15
Li + 15

but read Pizzolato & Soker 05
Nulsen 86

Precipitation: Is t_c/t_{ff} a better probe of molecular gas than t_c alone?

apparently not --- free fall time adds noise



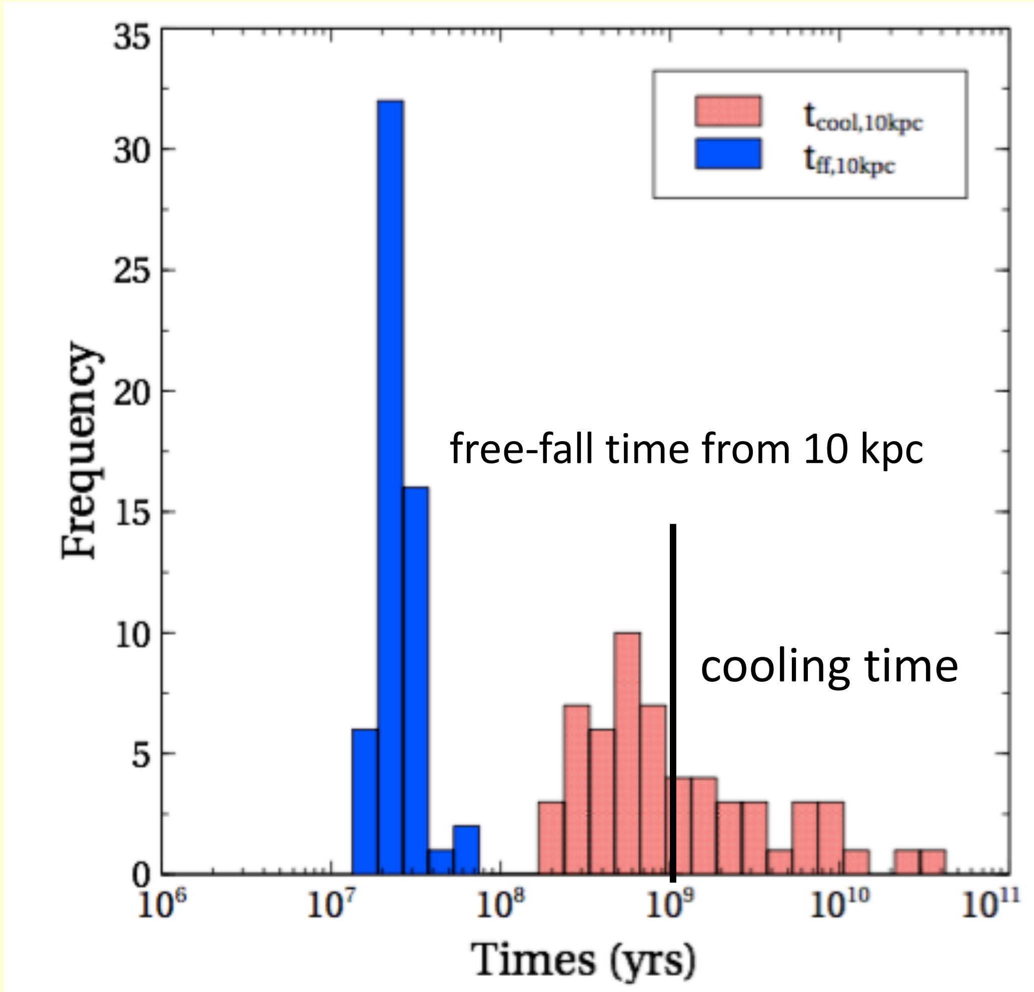
star formation + Hα   absent line emission, star formation

Low t_c/t_{ff} driven primarily by cooling time, not free-fall time

t_c/t_{ff} rarely falls below 10 -- inconsistent with "precipitation" growing from low amplitude linear density perturbations (Hogan 17a,b, Pulido +17)

McCourt +11, Sharma+11, Voit & Donahue 15, Li +15

Cooling time drives the t_c/t_{ff} ratio



Based on accurate halo mass profiles to within 10 kpc in clusters Hogan +17,a,b
proper accounting for central resolution effects

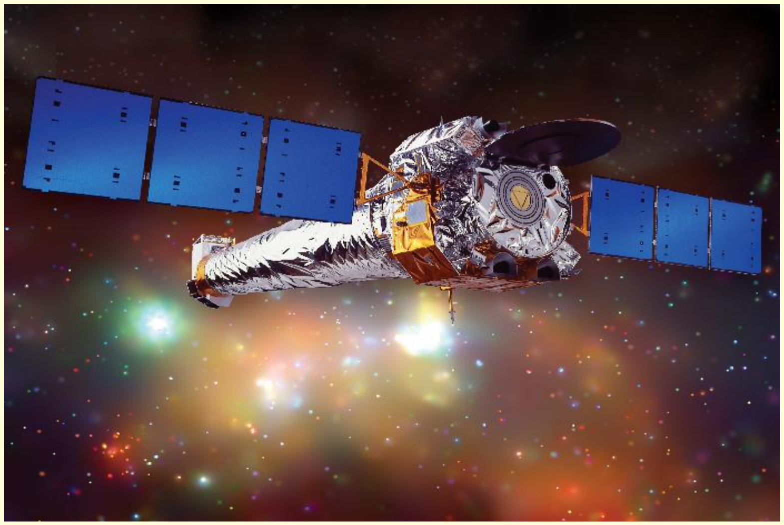
I will present evidence on Friday for a relationship with *infall* time of cooling blobs

ALMA: What role molecular gas in feedback?

-- central galaxies in cooling cluster cores rich in molecular hydrogen gas

Edge 2001, Salomé & Combes 2003

-- molecular gas at T~30 K, ρ ~ 10^5 cm^{-3} immersed in 10^8 K plasma



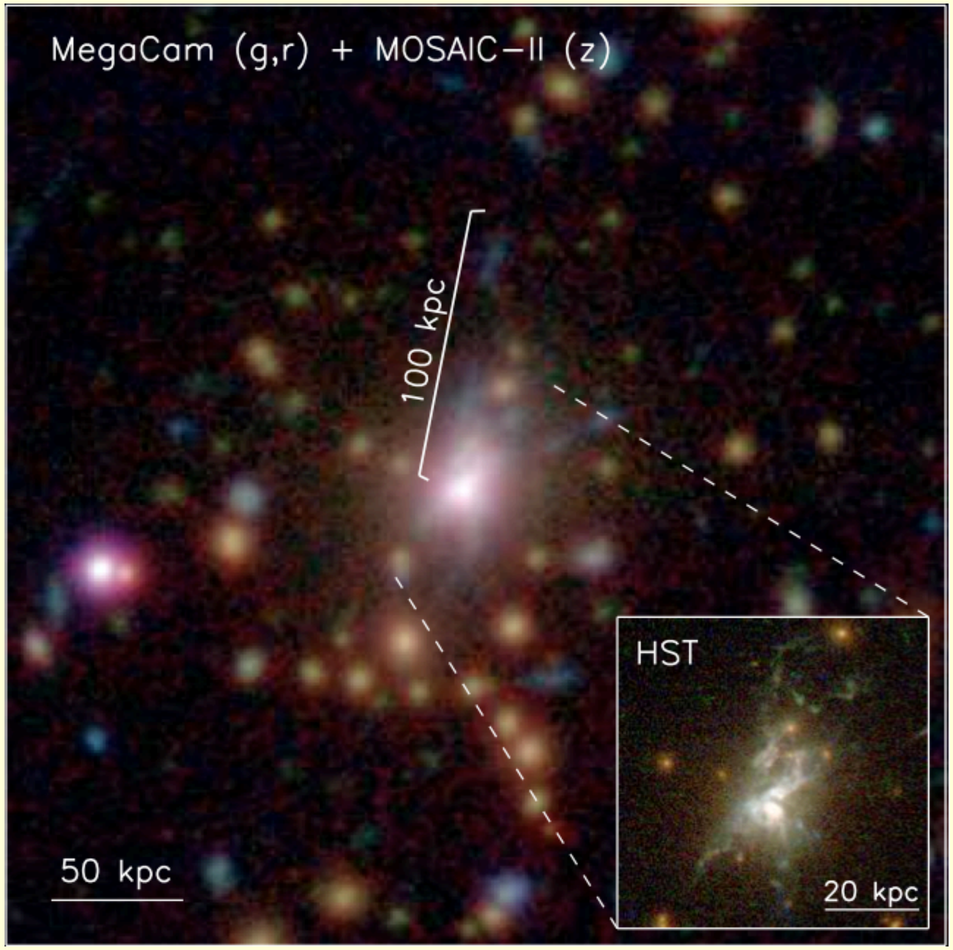
Chandra: energy output → ALMA: fuel input

- Origin of the 10^9- 10^{11} M_o molecular gas in central galaxies?
- Is molecular gas fuelling AGN feedback?
- Does radio-mechanical power effect molecular clouds?

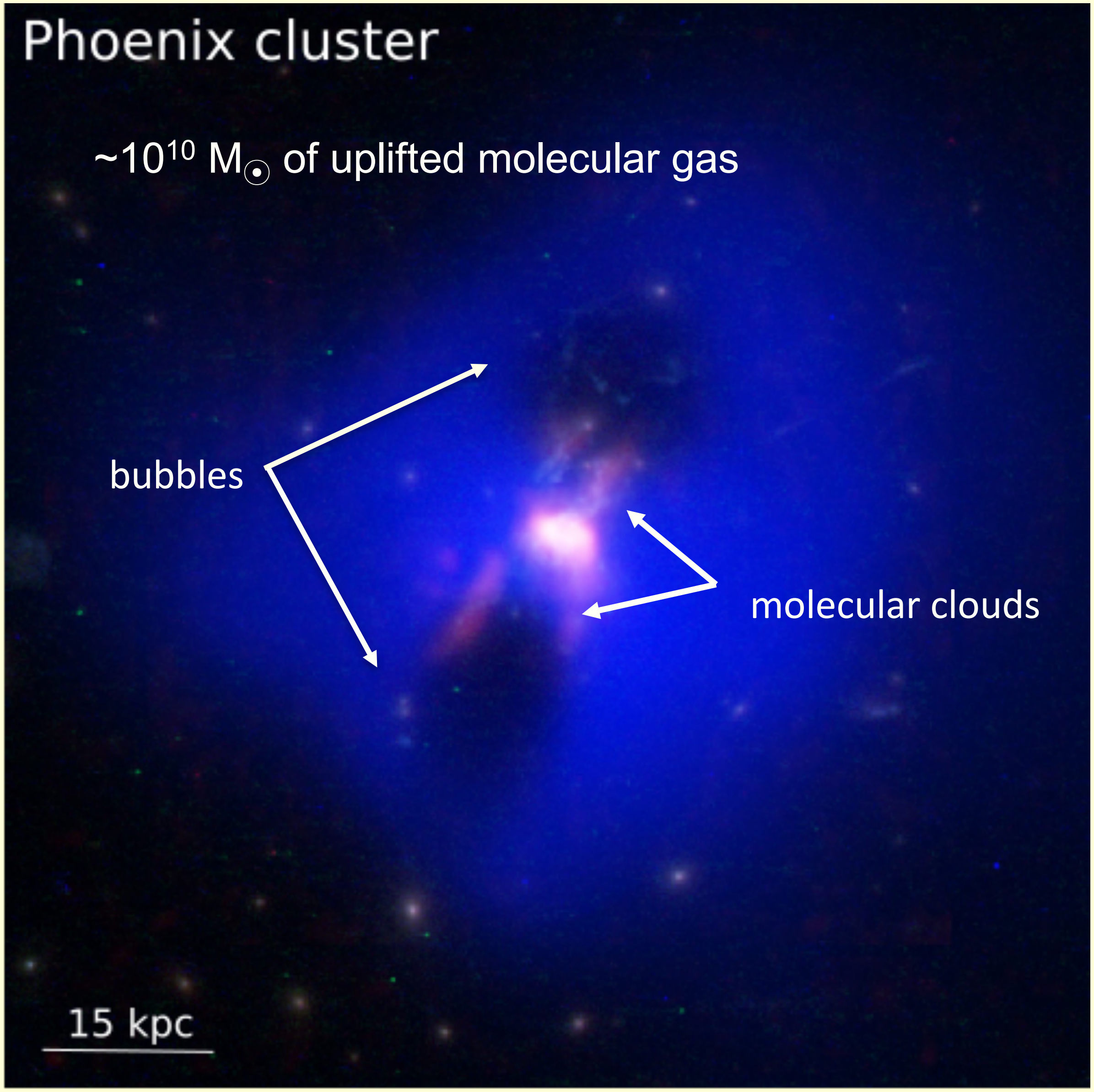
Russell+14,16,17a,b, McNamara+ 14, David + 14,17, Tremblay+16, Vantyghem+17...

Radio/mechanical feedback regulates, it may not quench

Phoenix Cluster SFR ~ 500 $M_\odot$ yr^{-1}

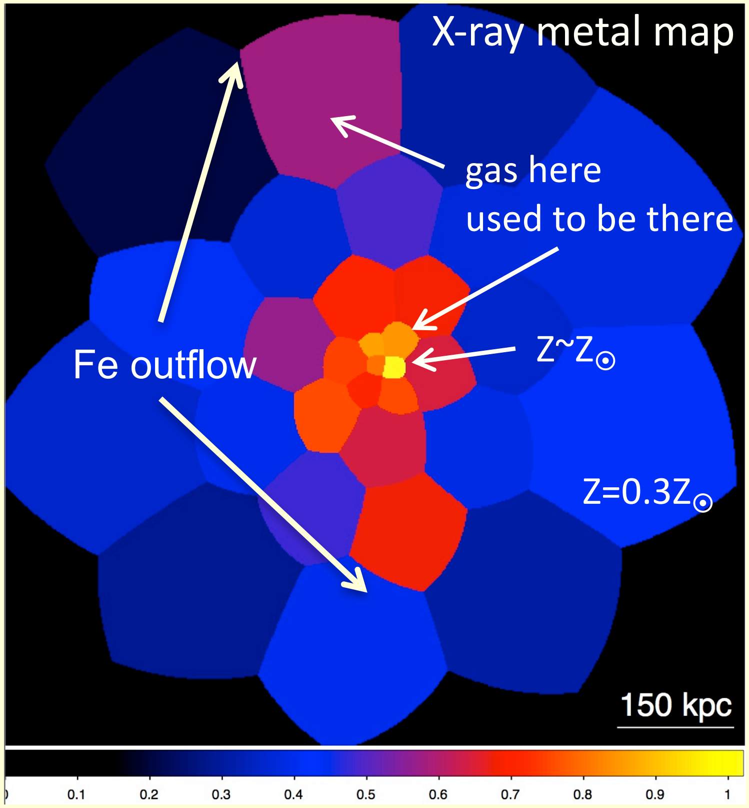


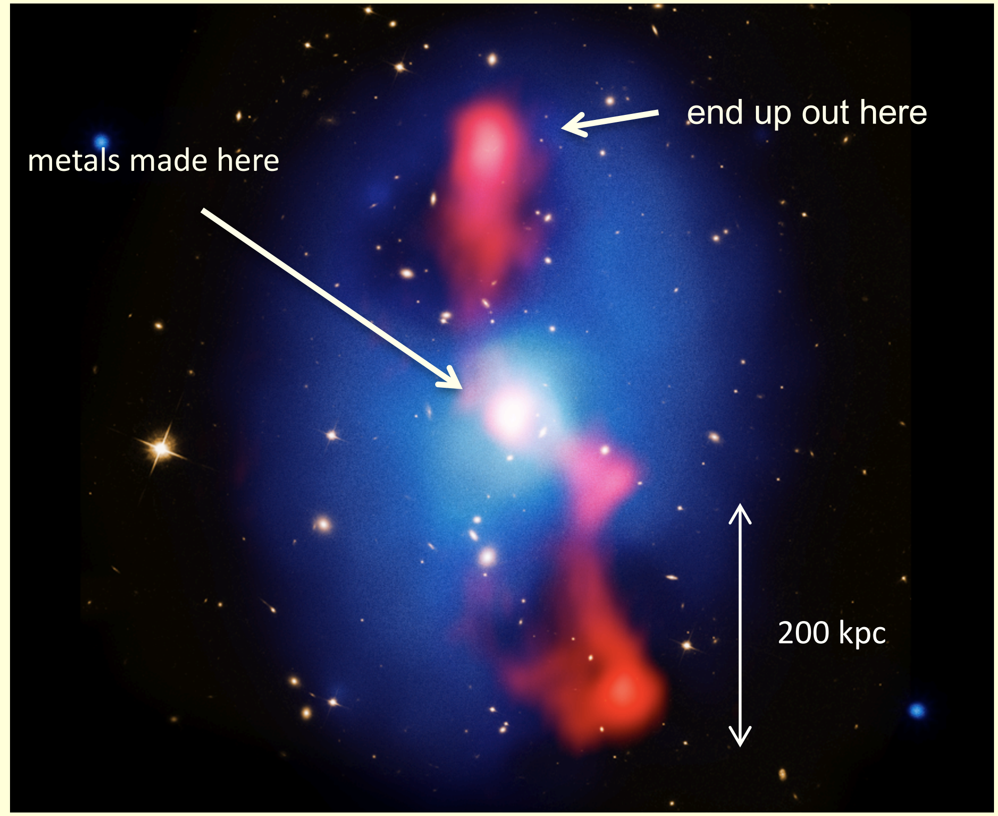
McDonald + 15


Phoenix cluster
~10^10 M☉ of uplifted molecular gas
bubbles
molecular clouds
15 kpc

Russell + 17

X-ray bubbles drag-up cool, low-entropy plasma





500 ks Chandra image
VLA, HST

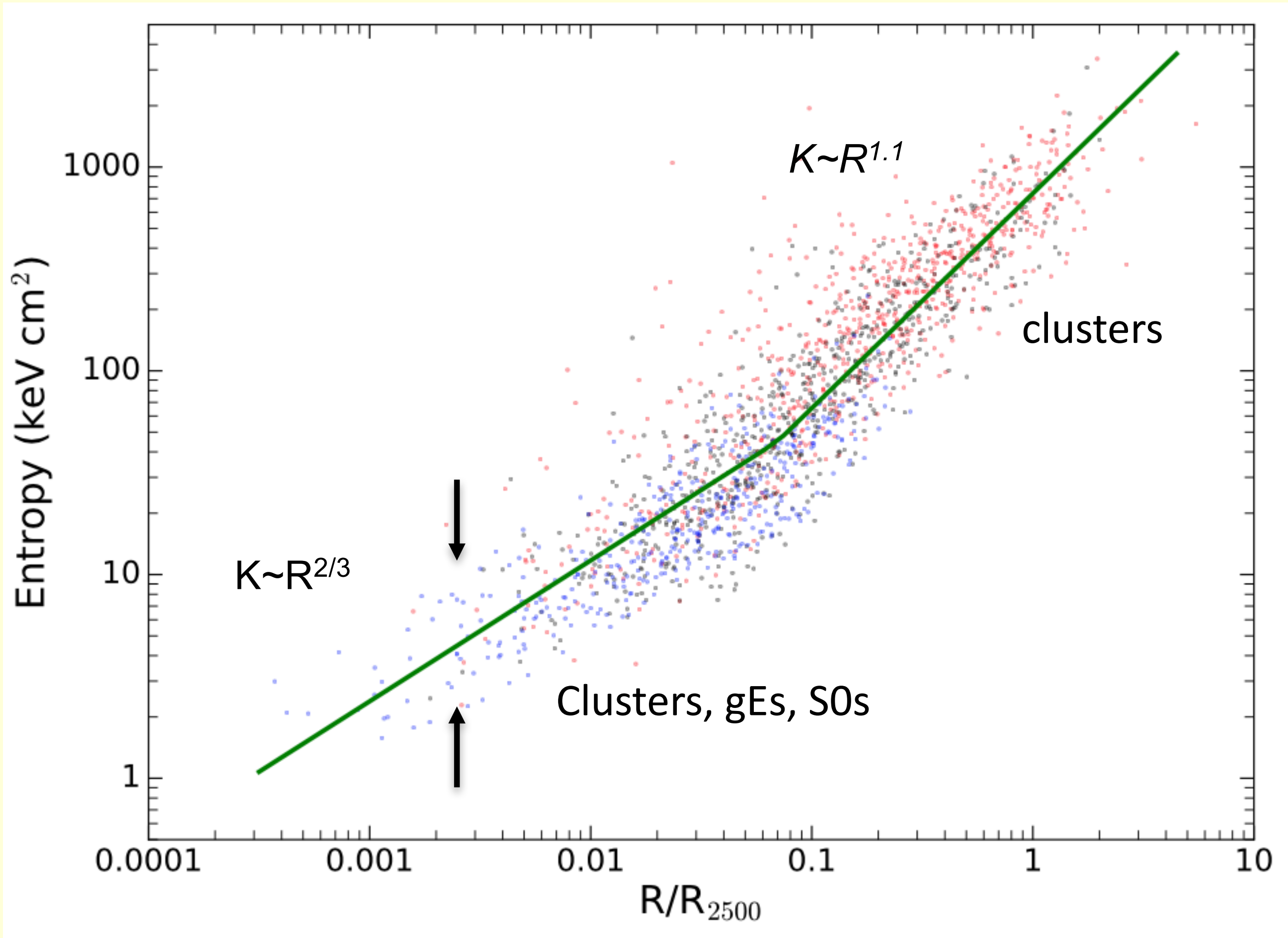
Powerful thrust: P_{jet}~ 3x10^{46} erg s^{-1} E_{jet} ~ 10^{62} erg

Lifted/displaced mass ~ 10^{10} $M_\odot$ ~100 $M_\odot yr^{-1}$ R_{Fe}~300 kpc

Simionescu + 08, Werner 09, Forman + 06, Kirkpatrick 09,11,14

Stable Entropy Profile for Hot Atmospheres: *Gentle Feedback*

4.5 decades in jet power, 4 decades in halo mass



$K\sim R^{1.1}$ $R > 0.1R_{2500}$

$K\sim R^{2/3}$ $R < 0.1R_{2500}$

Babyk + 2017, submitted

-- Thermally unstable cooling in $K\sim R^{2/3}$ region

Calibration standard for simulations

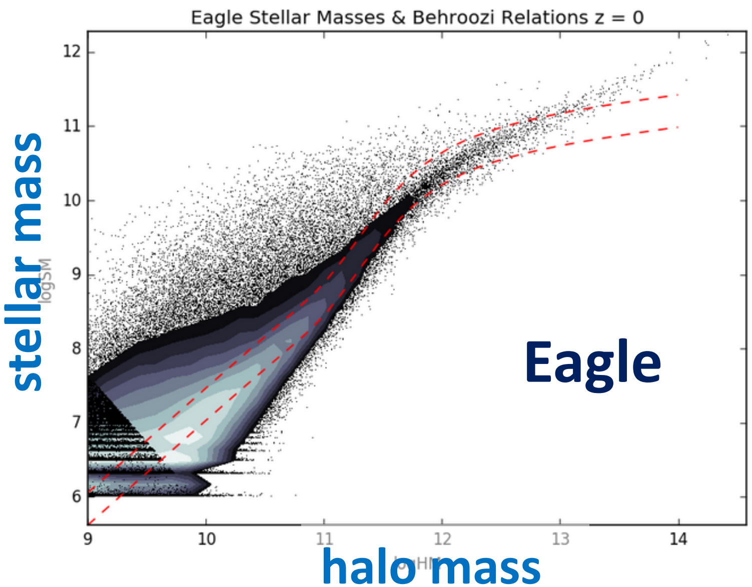
Thanks !

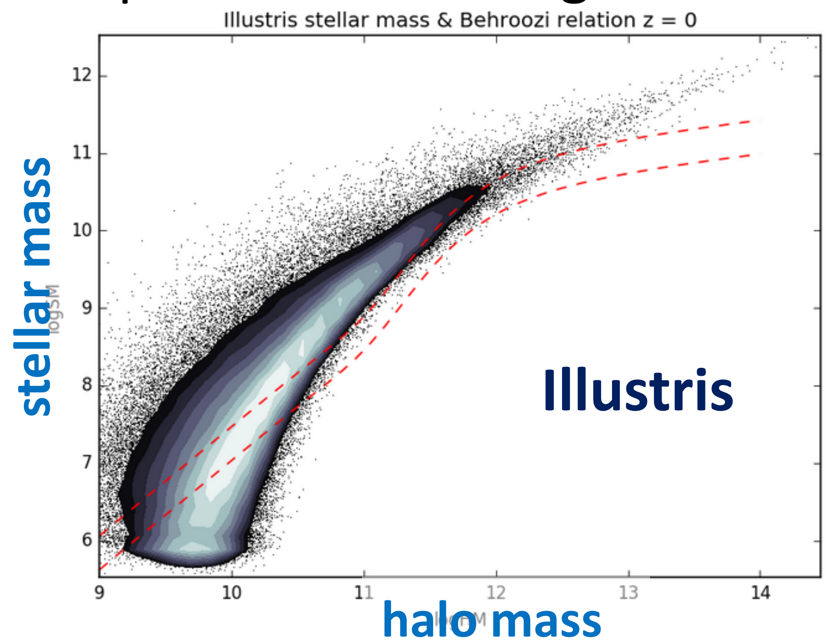
Stellar Feedback

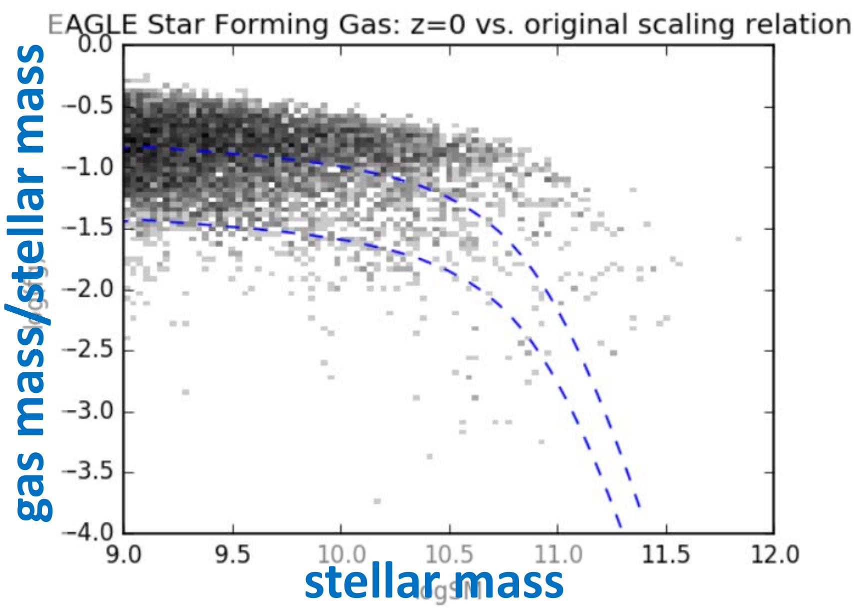
- Young stars inject energy, momentum, and metals released during thermonuclear burning back to the interstellar medium
- They ionize and push out dense gas around them, and thus regulate formation of future stars
- Multiple supernovae from star clusters propagate more efficiently than isolated SNe (Gentry+17)
- Momentum and energy feedback depend on SFR:

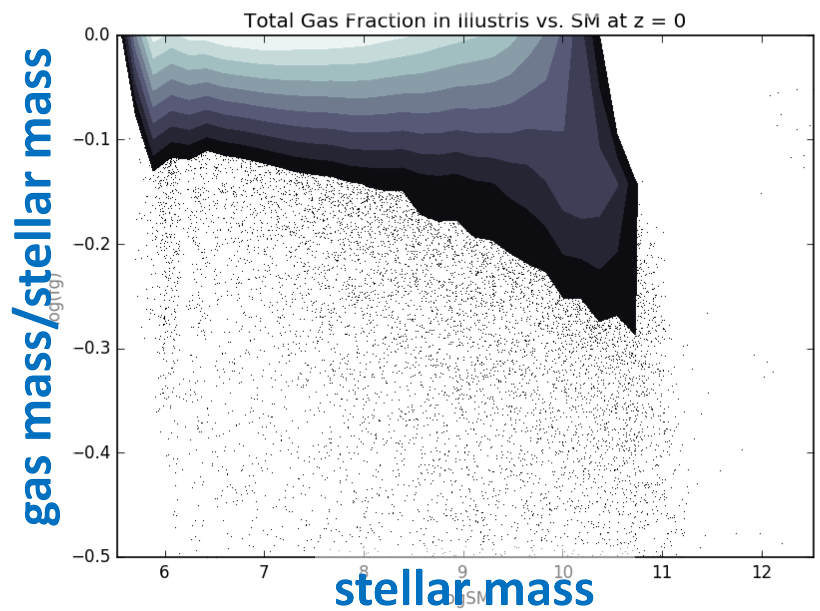
Star formation and feedback are tightly coupled and cannot be treated independently

Feedback prescription matters: Eagle and Illustris reproduce the stellar mass – halo mass relation, but predict different gas content



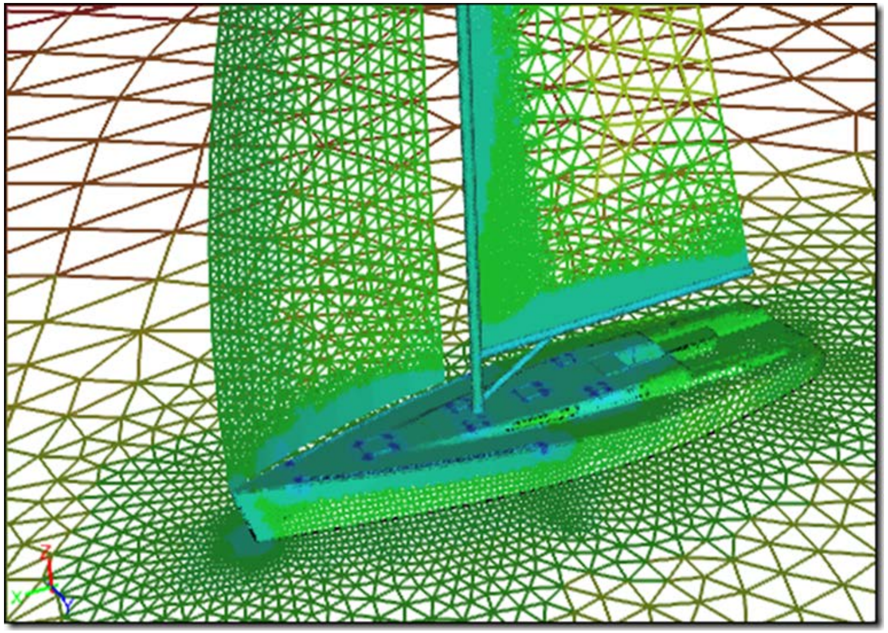






Cosmological simulations with run-time treatment of H_2 chemistry, stellar feedback, radiative transfer, and subgrid-scale turbulence

- Adaptive Mesh Refinement ART code
- star formation in molecular gas, supernova feedback and metal enrichment, stellar mass loss
- radiative cooling and heating: Compton, UV background, with density and metallicity dependent rates
- 3D radiative transfer
- H2 formation on dust grains/destruction by UV, with self-shielding and shielding by dust (N. Gnedin & Kravtsov 2011)
- Novel treatment of subgrid-scale turbulence (Semenov et al. 2016)
- Enhanced momentum feedback from SN remnants (Gentry et al. 2017, Martizzi et al. 2015)



$$\frac{\partial n_j}{\partial t} + 3Hn_j + \frac{1}{a}\mathrm{div}_x(n_j \vec{v}) = \dot{\mathcal{I}}_j + \dot{\mathcal{M}}_j + \dot{\mathcal{D}}_j,$$

Ionization by cosmic and local interstellar UV flux

atomic and molecular chemistry

dust chemistry

Star Formation in Cosmological Simulations

$$\rho_{\rm gas,SF} = \rho_{\rm gas} > \rho_{\rm SFthreshold}$$

$$\tau_{\rm SF} = \sqrt{\frac{3\pi}{32G\rho}}$$

the local SF rate → $$\dot{\rho}_* = \varepsilon_{\rm SF} \frac{\rho_{\rm gas,SF}}{\tau_{\rm SF}}$$

used to "spawn" a star particle of mass → $$m_* = \dot{\rho}_* \Delta t$$

In standard implementation of star formation, star particles are created *instantaneously* and affect only the formation of *future* particles (through their effect on the surrounding gas)

At the spatial resolution of ~10 parsec, solving gas dynamics PDE require time steps of < 10^3 yr. Real stars take 10^5 – 10^6 yr to form, so creating them instantaneously is *inconsistent*.

New algorithm for the formation of star cluster particles

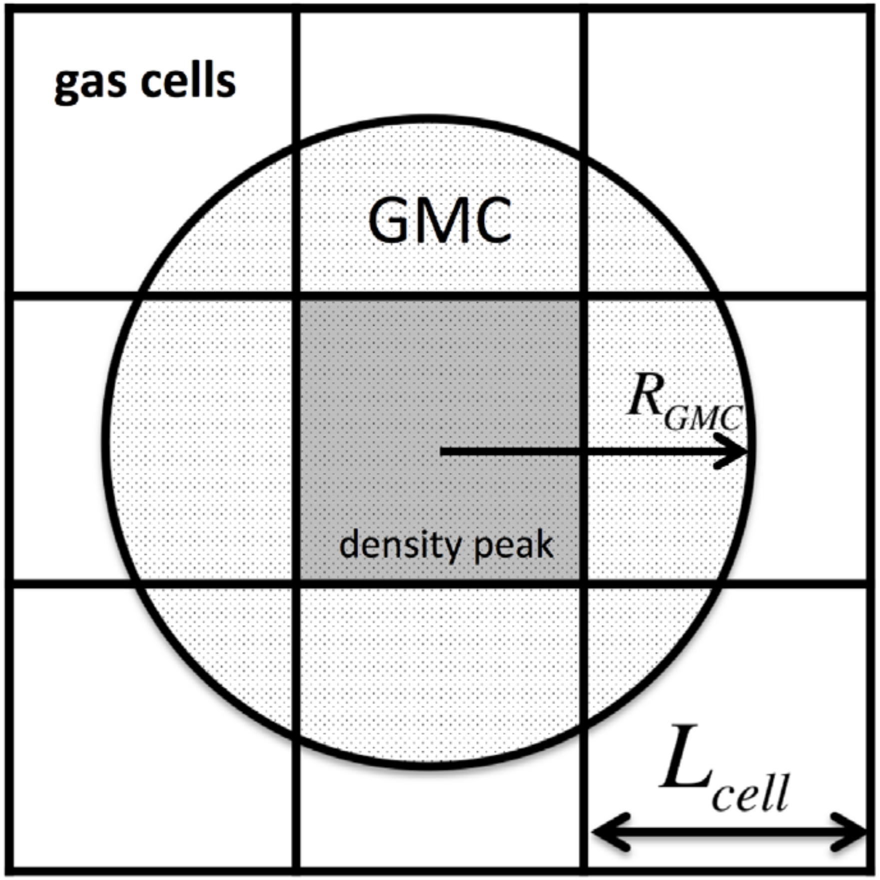
Seed — local density peak

↓

Grow — $\rho_{\mathrm{SFR}} = \epsilon_{\mathrm{ff}} \frac{f_{\mathrm{H_2}} \rho_{\mathrm{gas}}}{\tau_{\mathrm{ff}}}$

↓

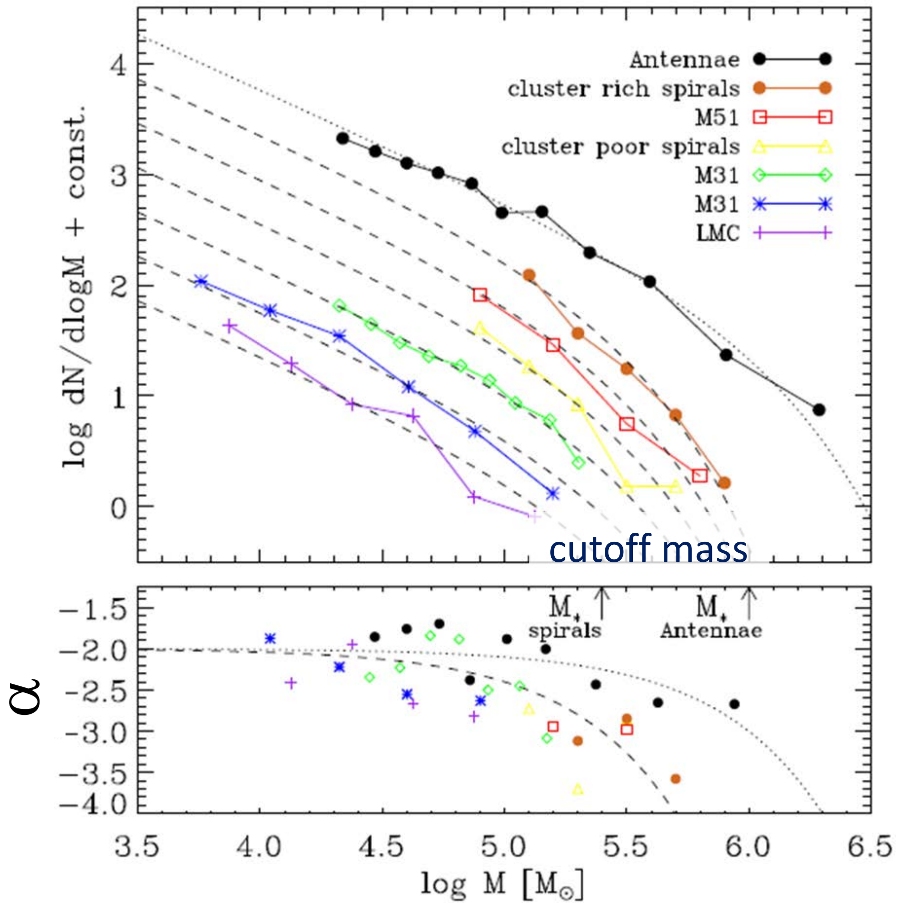
Terminate — feedback of own stars

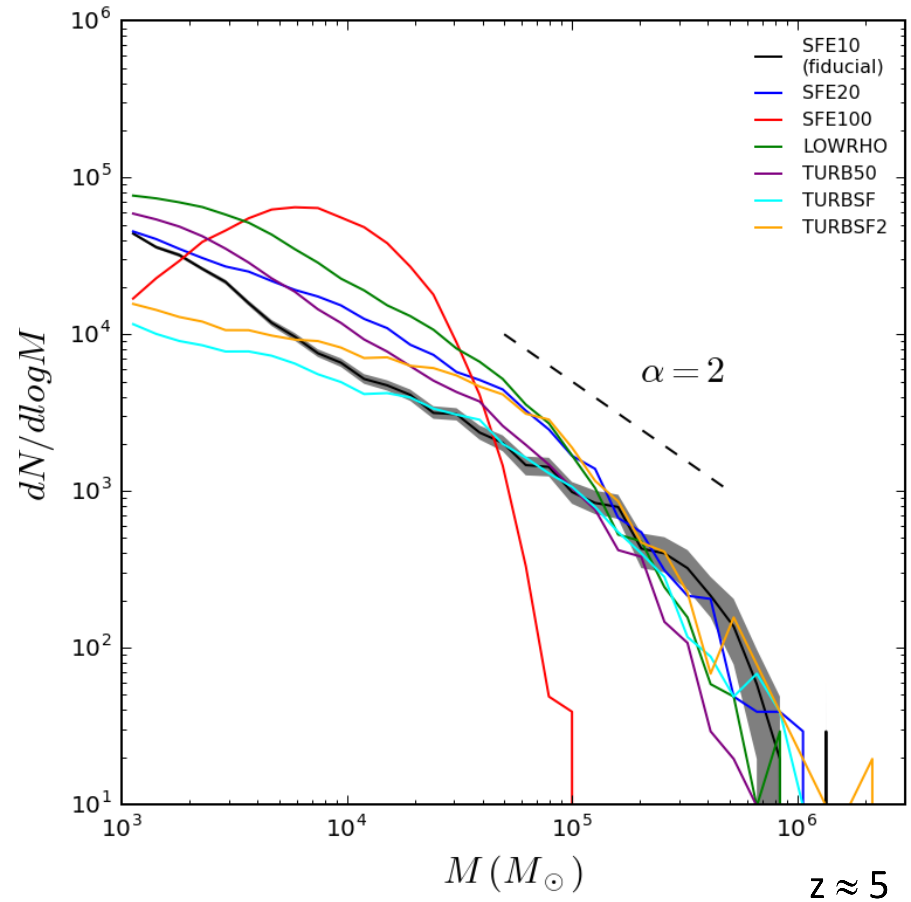


R_{GMC} = 5 pc (not comoving) L_{cell} = 3-6 pc

- Growth of individual star clusters is resolved in time, with local time steps ~ 100 years. *Thousands of time steps per cluster formation*.
- Mass growth of a given cluster is terminated by *its own feedback*.
- Final mass is then obtained *self-consistently* and represents the actual mass of a newly formed star cluster within the GMC.

Initial Mass Function of young clusters is almost invariant





$z \approx 5$

$$\frac{dN}{dM} \propto M^{-\alpha} \exp(-M/M_{\rm cut})$$

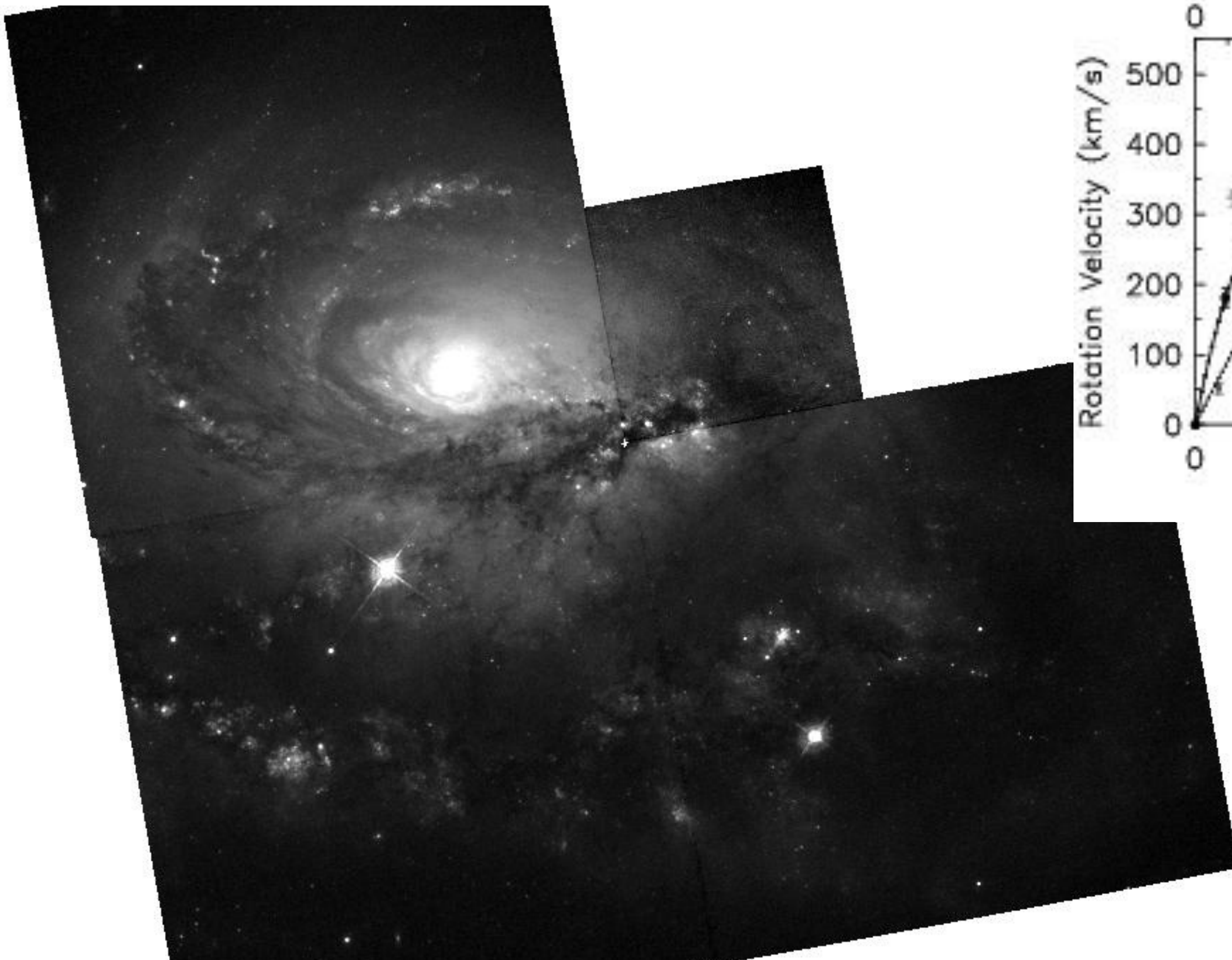
slope $\alpha \approx 2$

Cosmological simulation of a Milky Way sized-galaxy (Li, OG et al. 2017, 2018):

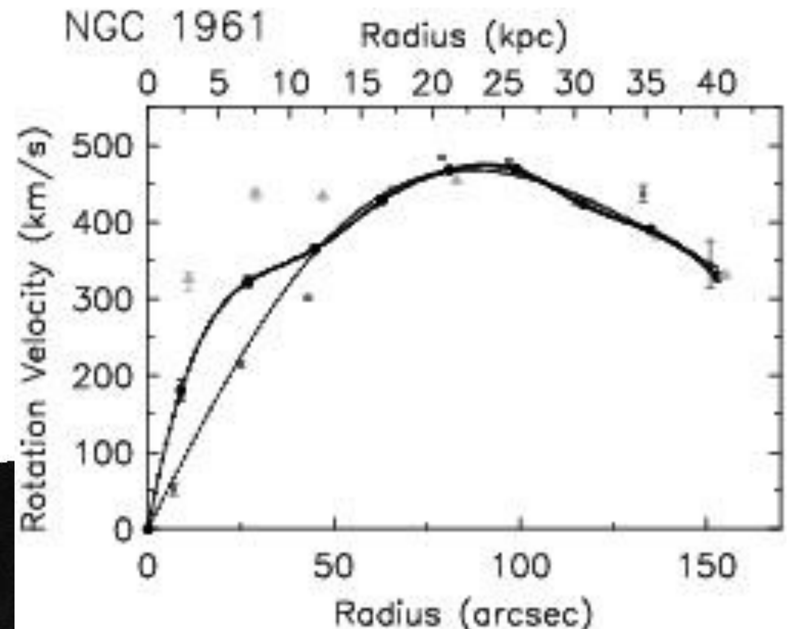
- MF is a power law as observed for young star clusters
- Depends on local star formation efficency

Hot Halos Around Spiral Galaxies

- Spiral galaxies have hot halos too!



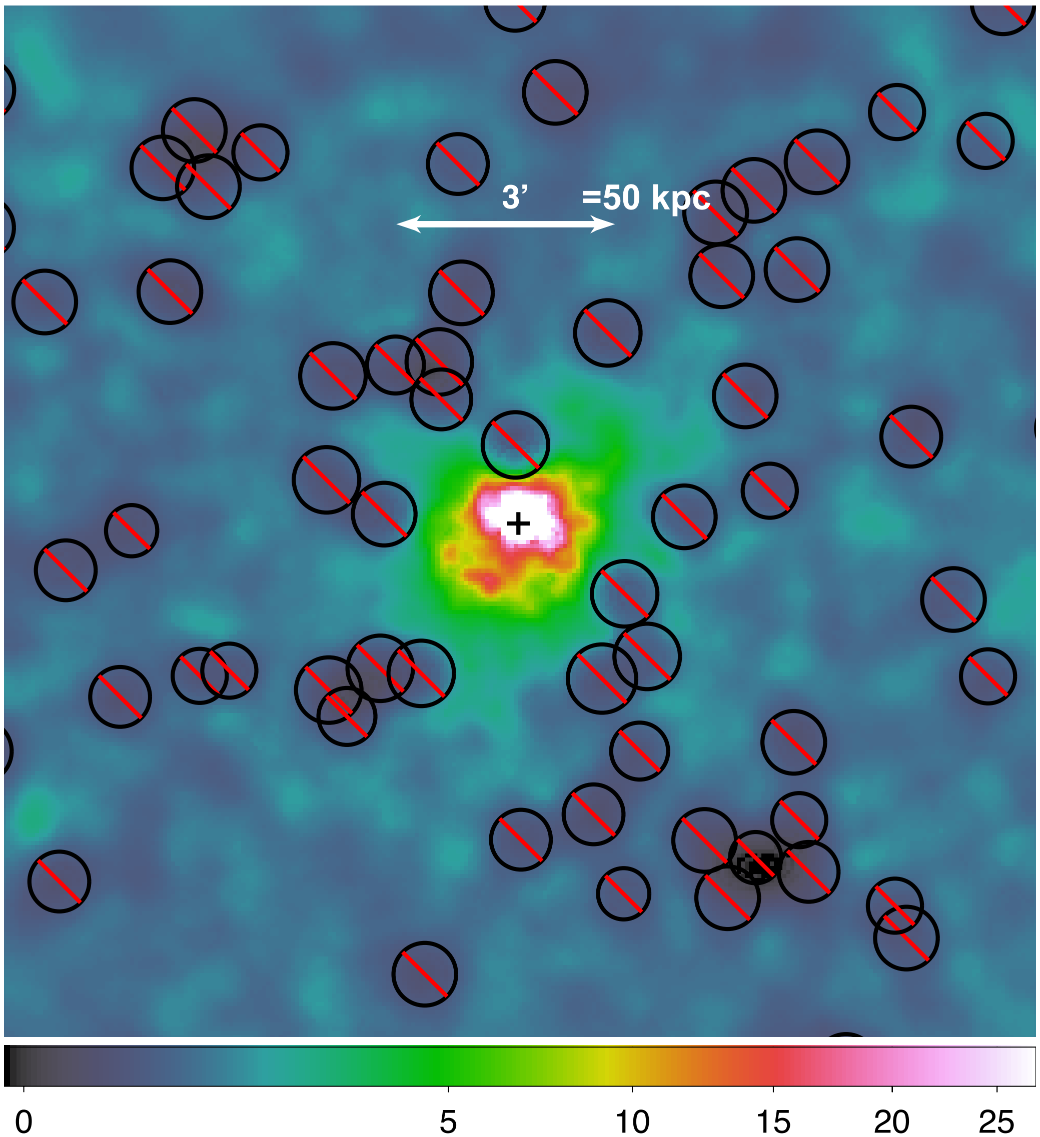
HST/WFPC2 F547M



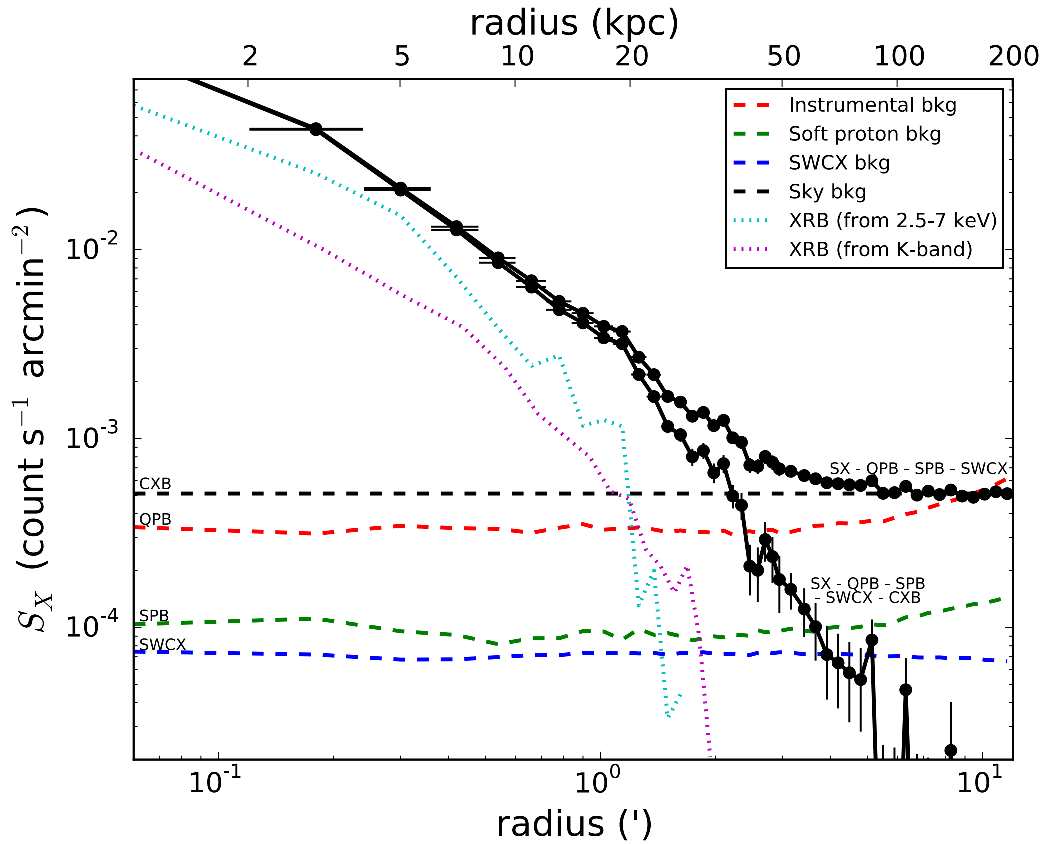
d = 58 Mpc
M* = 3e11 Msun
SFR = 15 Msun/yr

Hot Halos Around Spiral Galaxies

- Spiral galaxies have hot halos too!



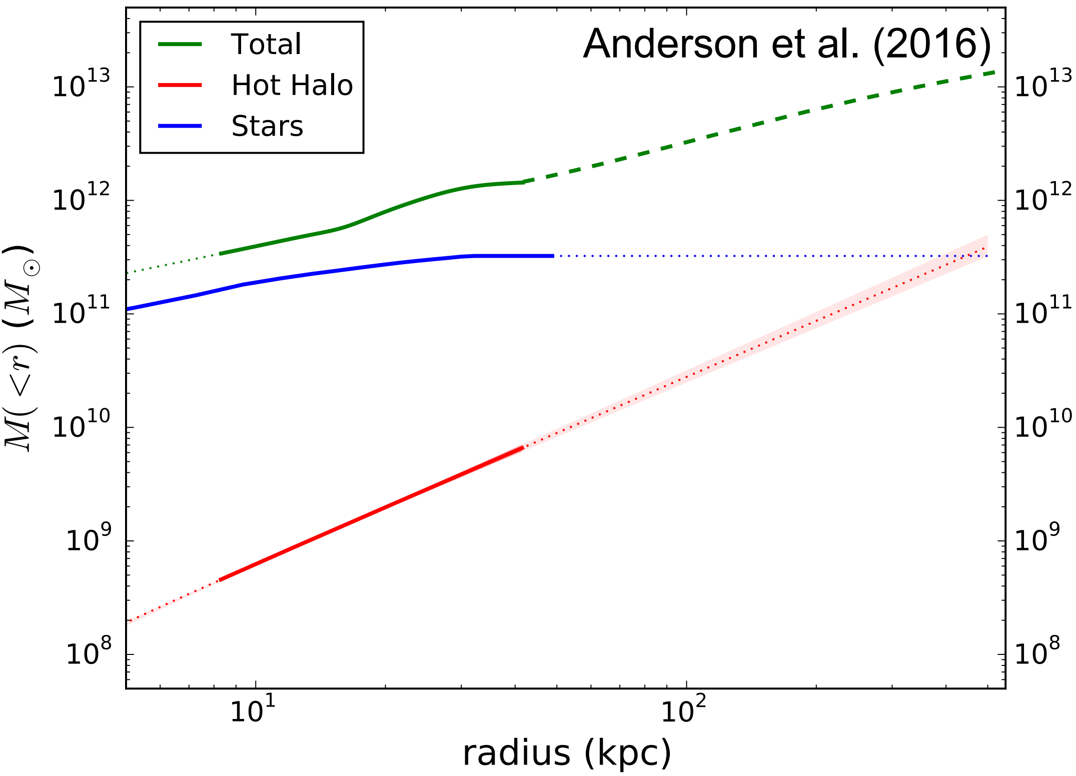
Anderson et al. (2016)



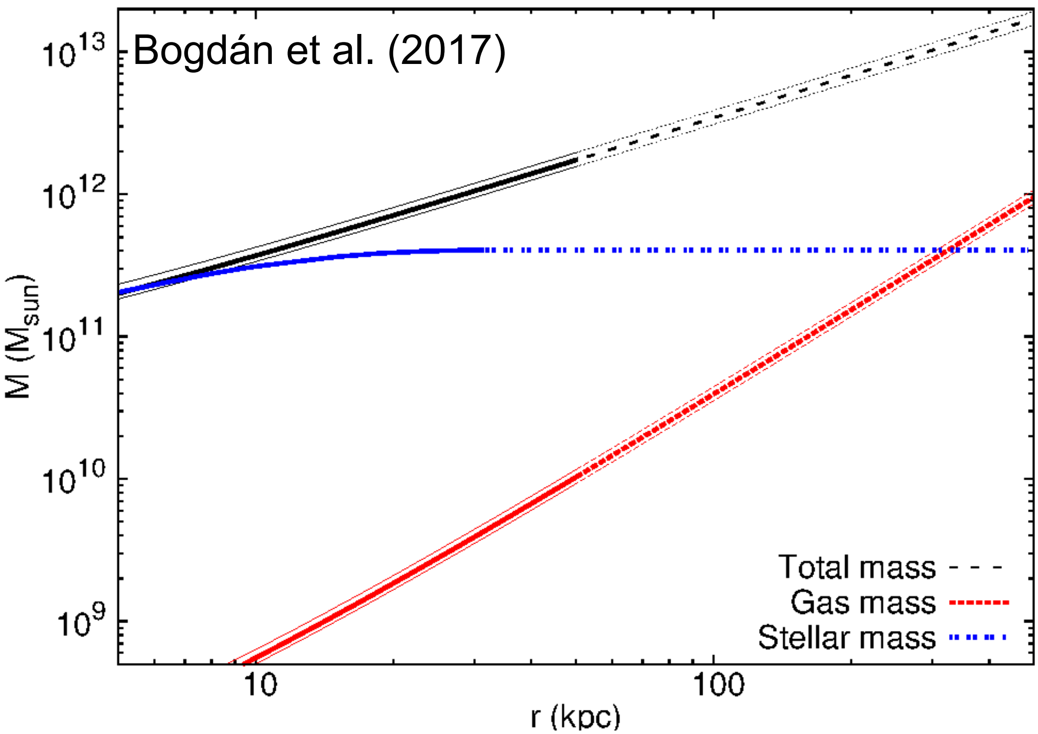
Hot Halos Around Spiral Galaxies

- Spiral galaxies have hot halos too!

NGC 1961

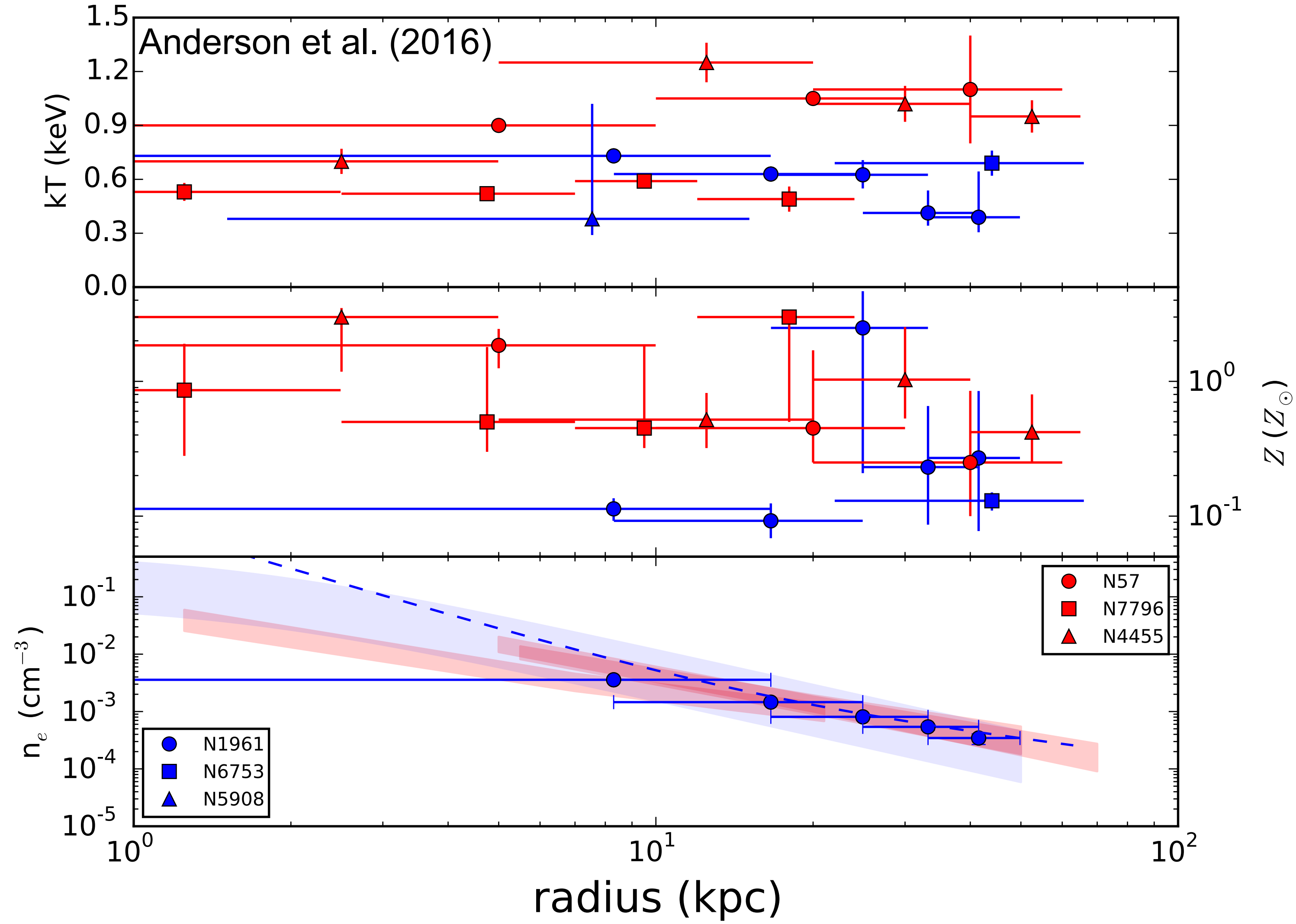


NGC 6753



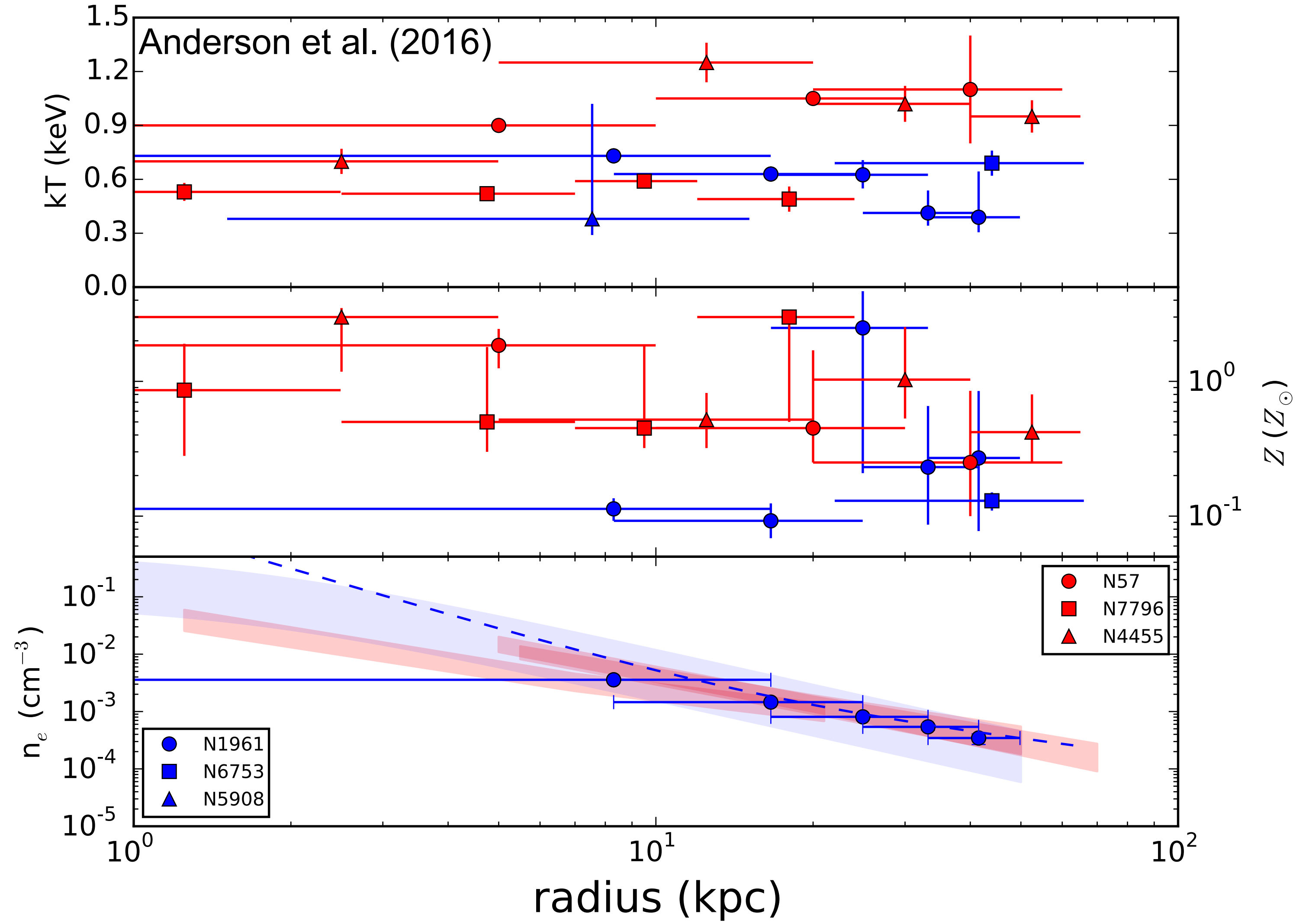
Hot Halos Around Spiral Galaxies

- Hot halos have similar **temperature** and **density** profiles in isolated spiral and in elliptical galaxies



Hot Halos Around Spiral Galaxies

- …but they seem to have lower **metallicity** in spirals

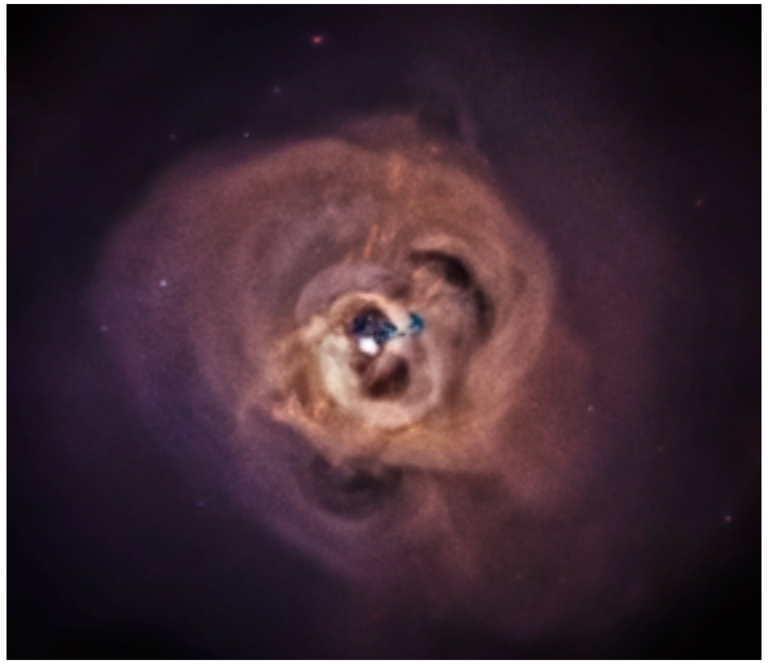


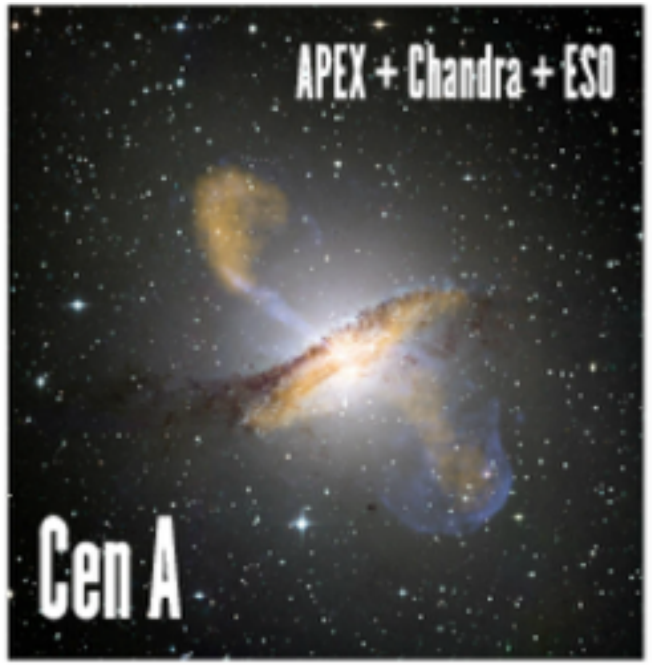
Implementation of Feedback
in Cosmological Simulations

BH Feedback: Subgrid Implementation

Goal: to exchange energy and/or momentum from the central BH to the surrounding medium

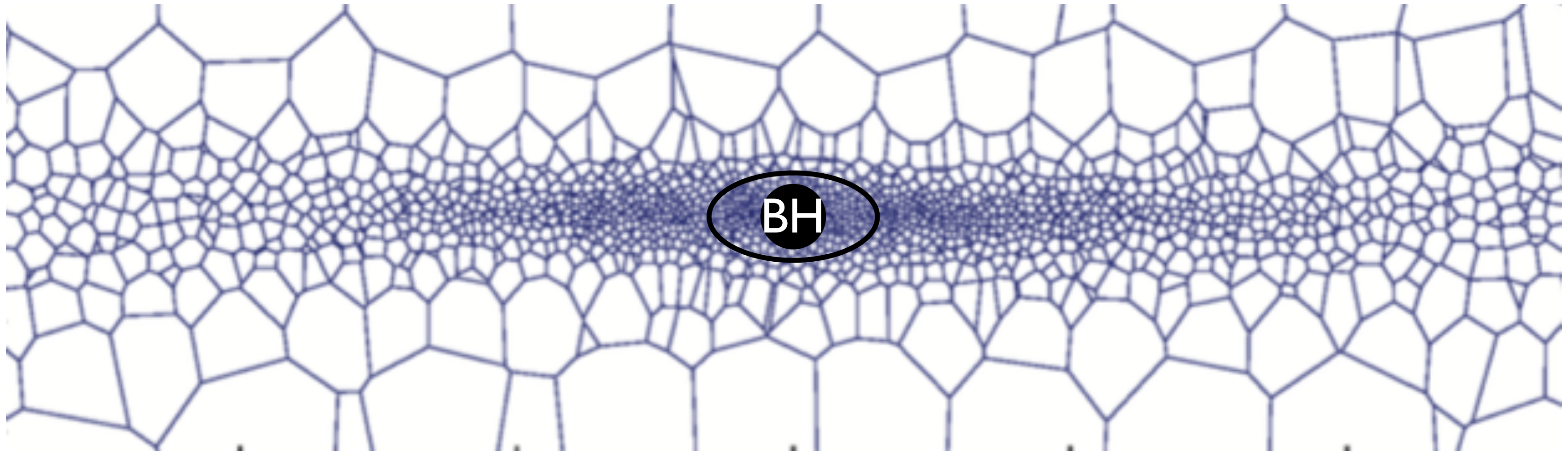
Possibly, with outcomes that resemble what we think we see in reality





BH Feedback: BH seeding and accretion

BHs are usually placed by hand as “sink particles”:
they can grow in mass by `accreting` material from the surroundings



Mesh in a disk (V. Springel)

ILLUSTRIS

BH Seed Mass
FoF Halo Mass for BH seeding
BH Accretion
BH Accretion
BH Positioning

TNG

BH Feedback: BH seeding and accretion

BHs are usually placed by hand as “sink particles”:
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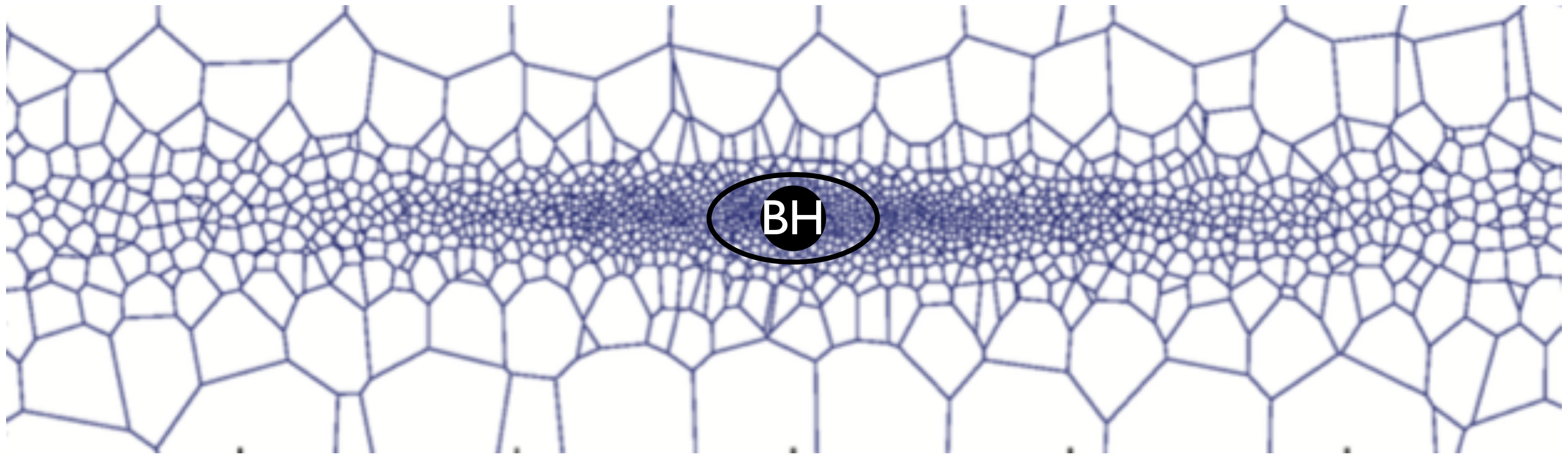


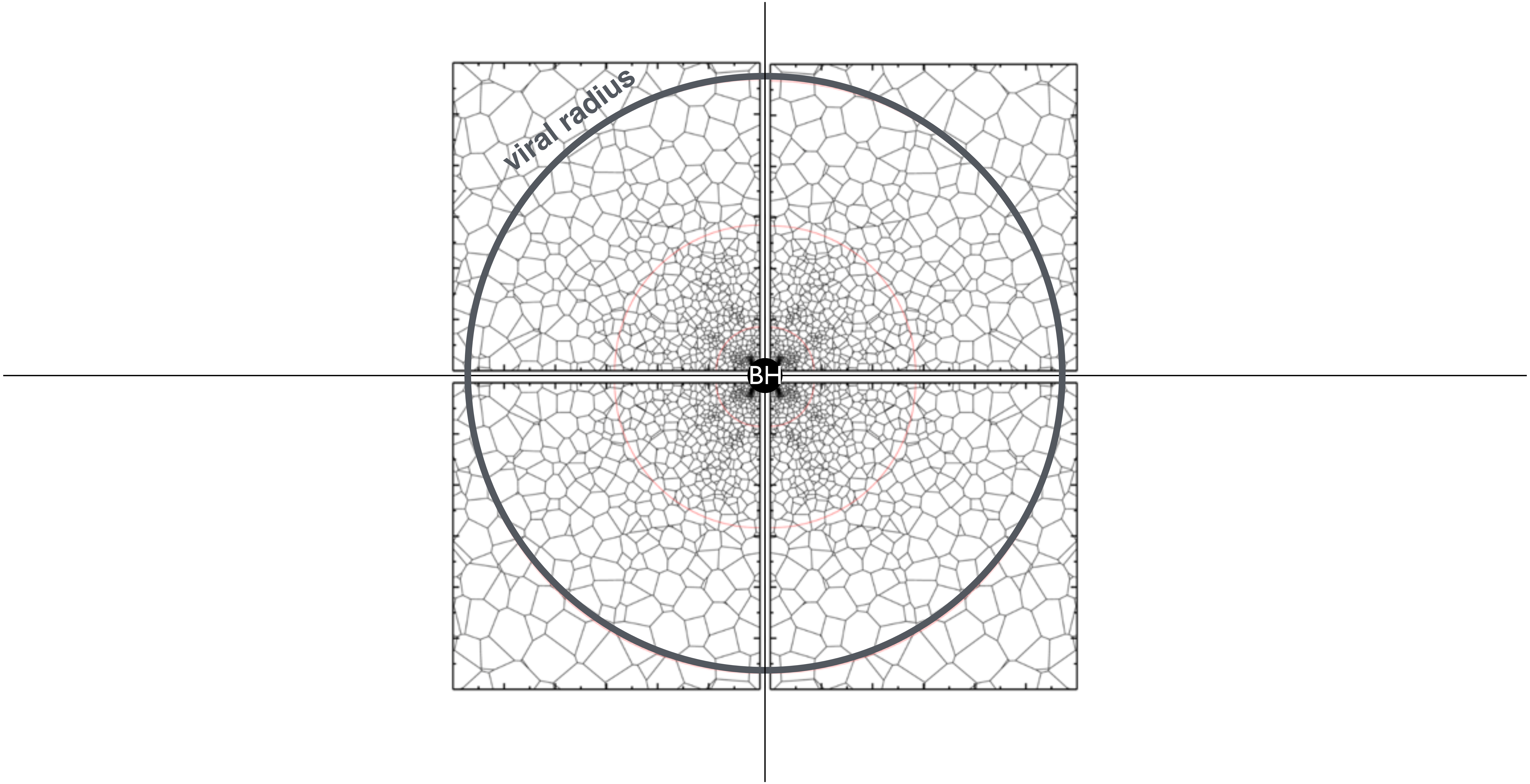
Mesh in a disk (V. Springel)

$$\dot{M}_{\rm BH} = \frac{4\pi\alpha G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}$$

ILLUSTRIS		TNG
$1 \times 10^5 h^{-1} \mathrm{M}_\odot$	BH Seed Mass	$8 \times 10^5 h^{-1} \mathrm{M}_\odot$
$5 \times 10^{10} h^{-1} \mathrm{M}_\odot$	FoF Halo Mass for BH seeding	$5 \times 10^{10} h^{-1} \mathrm{M}_\odot$
$\alpha = 100$ Boosted Bondi-Hoyle	BH Accretion	Un-boosted Bondi-Hoyle (w/ v_A)
parent gas cell, Eddington limited	BH Accretion	nearby cells, Eddington limited
fixed to halo potential minimum	BH Positioning	fixed to halo potential minimum

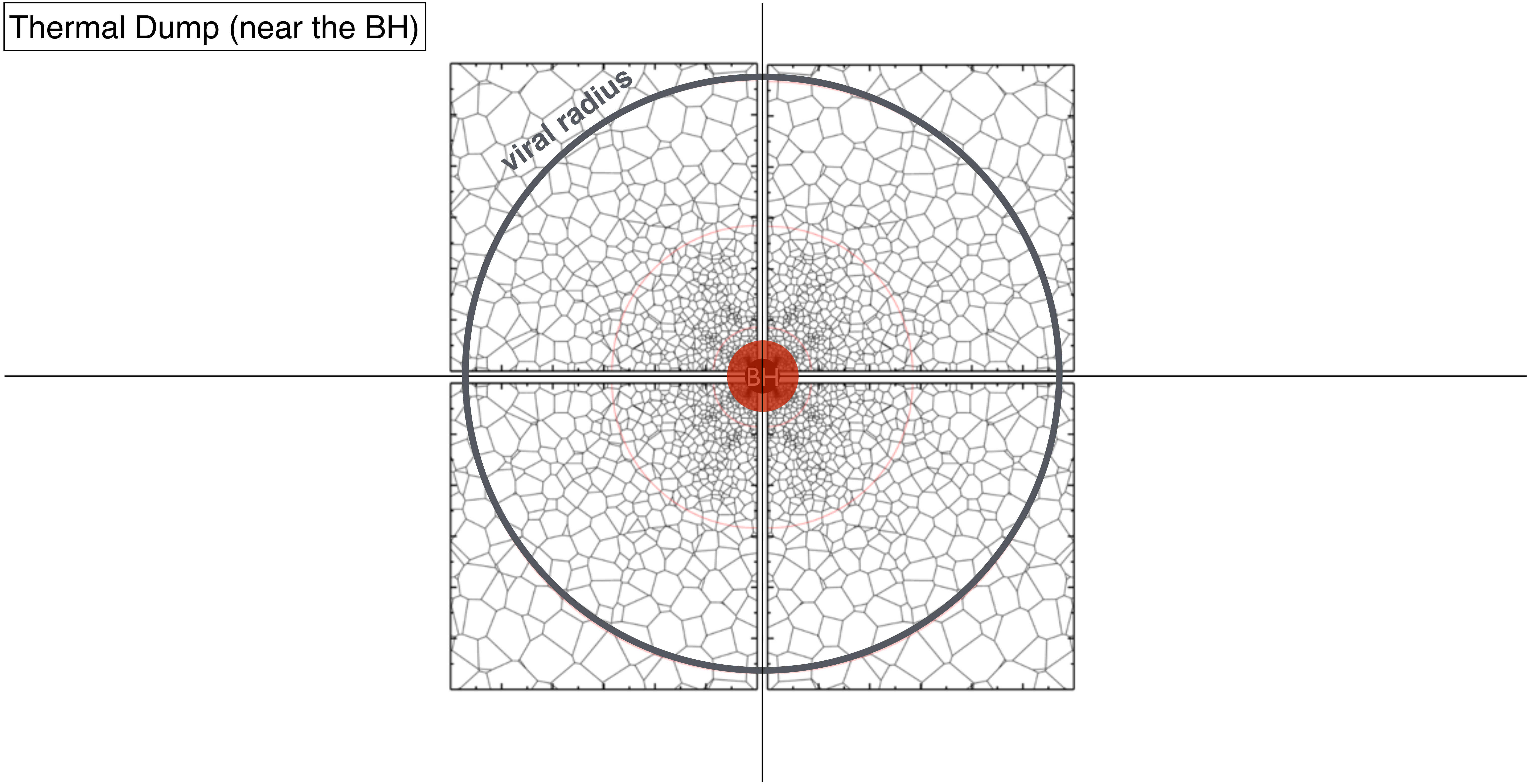
$$\dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_p}{\epsilon_r \sigma_T c}$$

BH Feedback: Subgrid Implementation



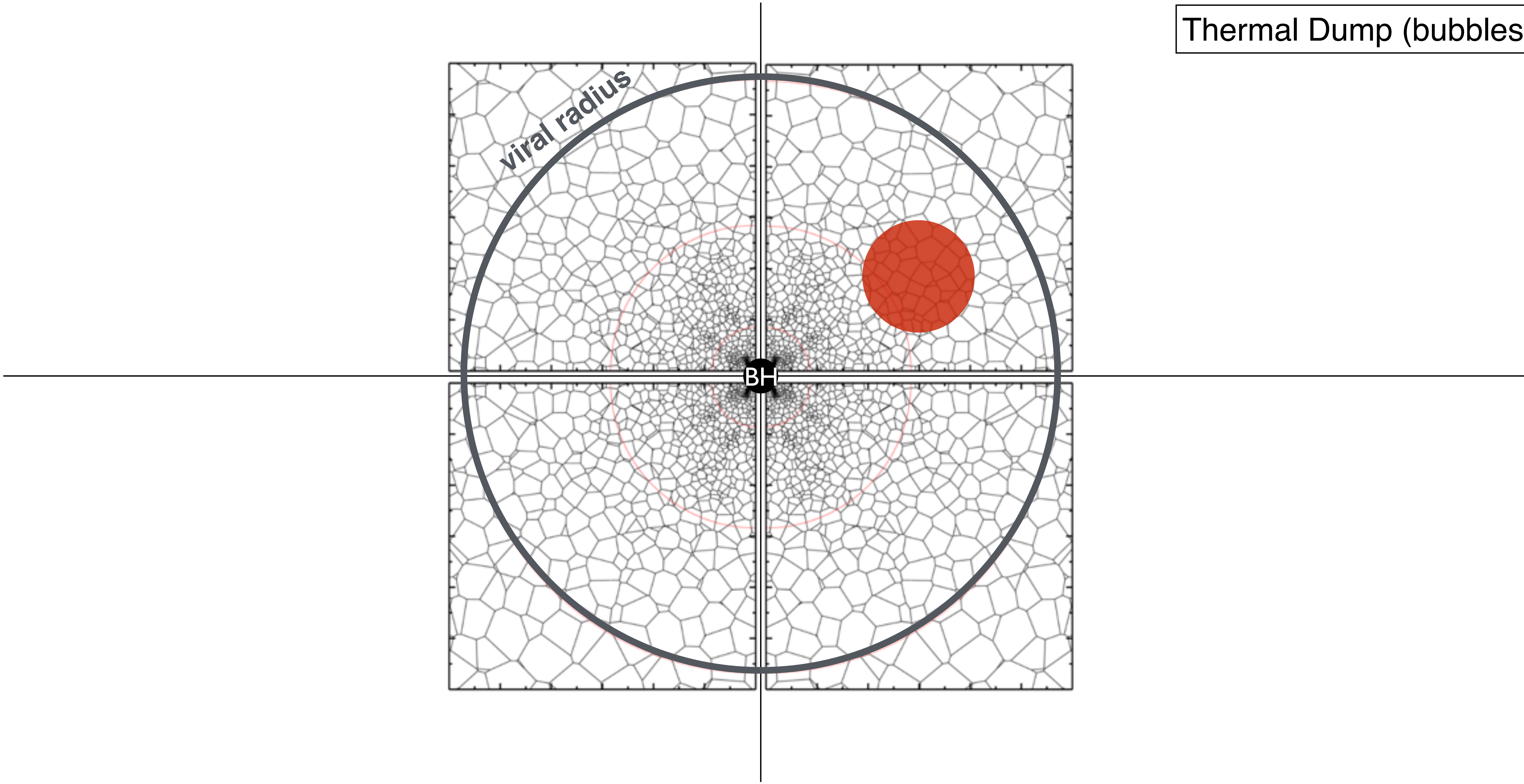
BH Feedback: Subgrid Implementation

Thermal Dump (near the BH)



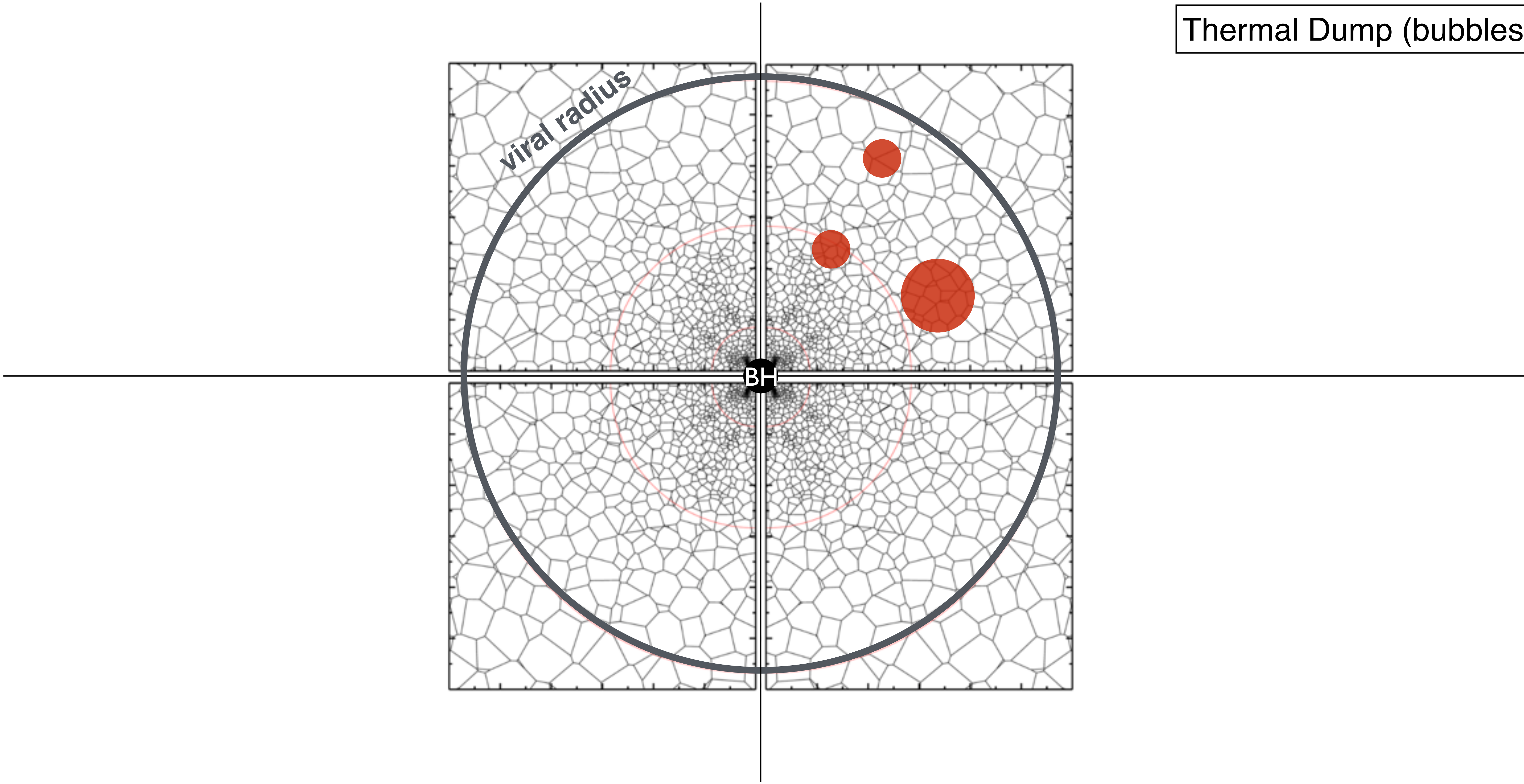
BH Feedback: Subgrid Implementation

Thermal Dump (bubbles)

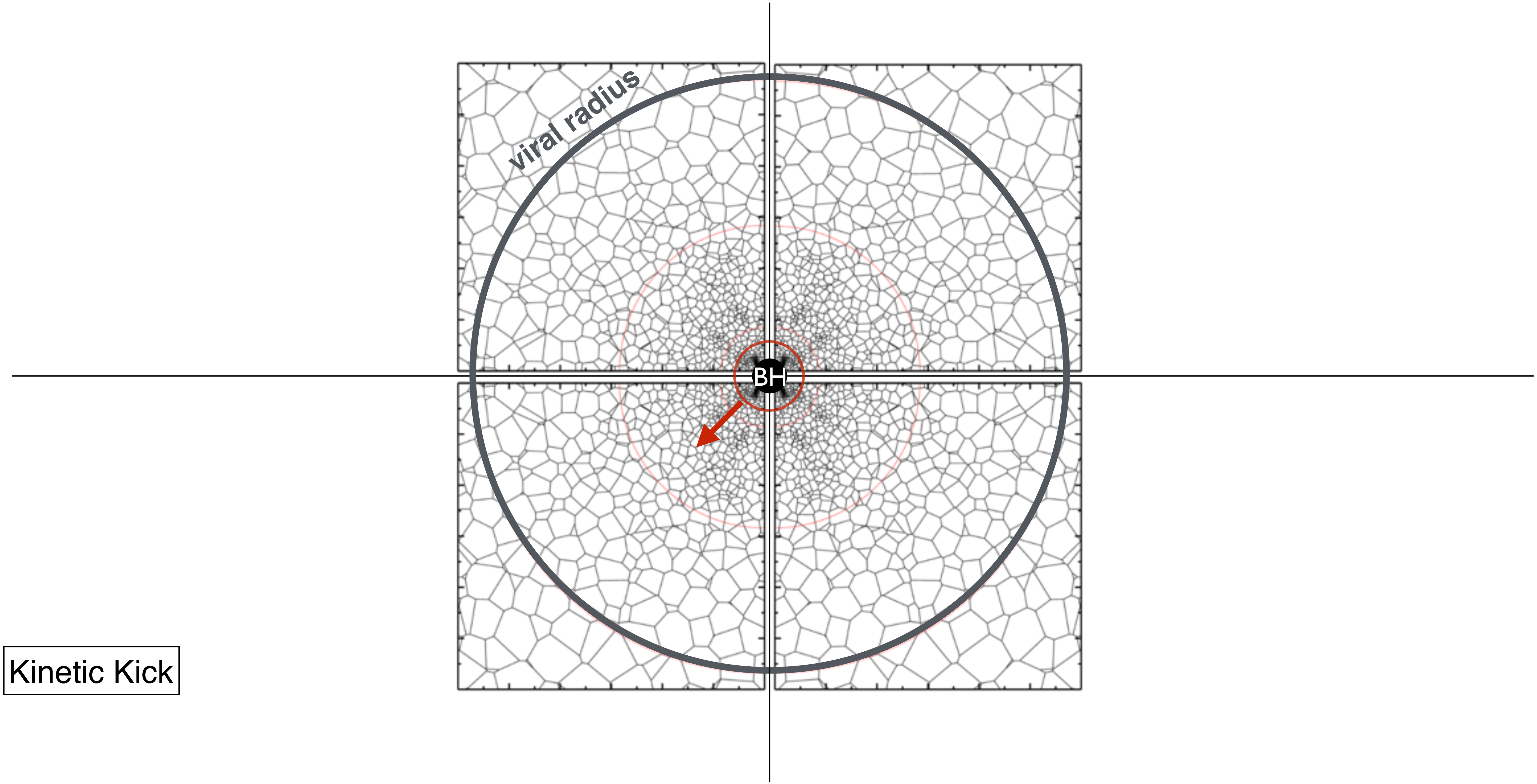


BH Feedback: Subgrid Implementation

Thermal Dump (bubbles)

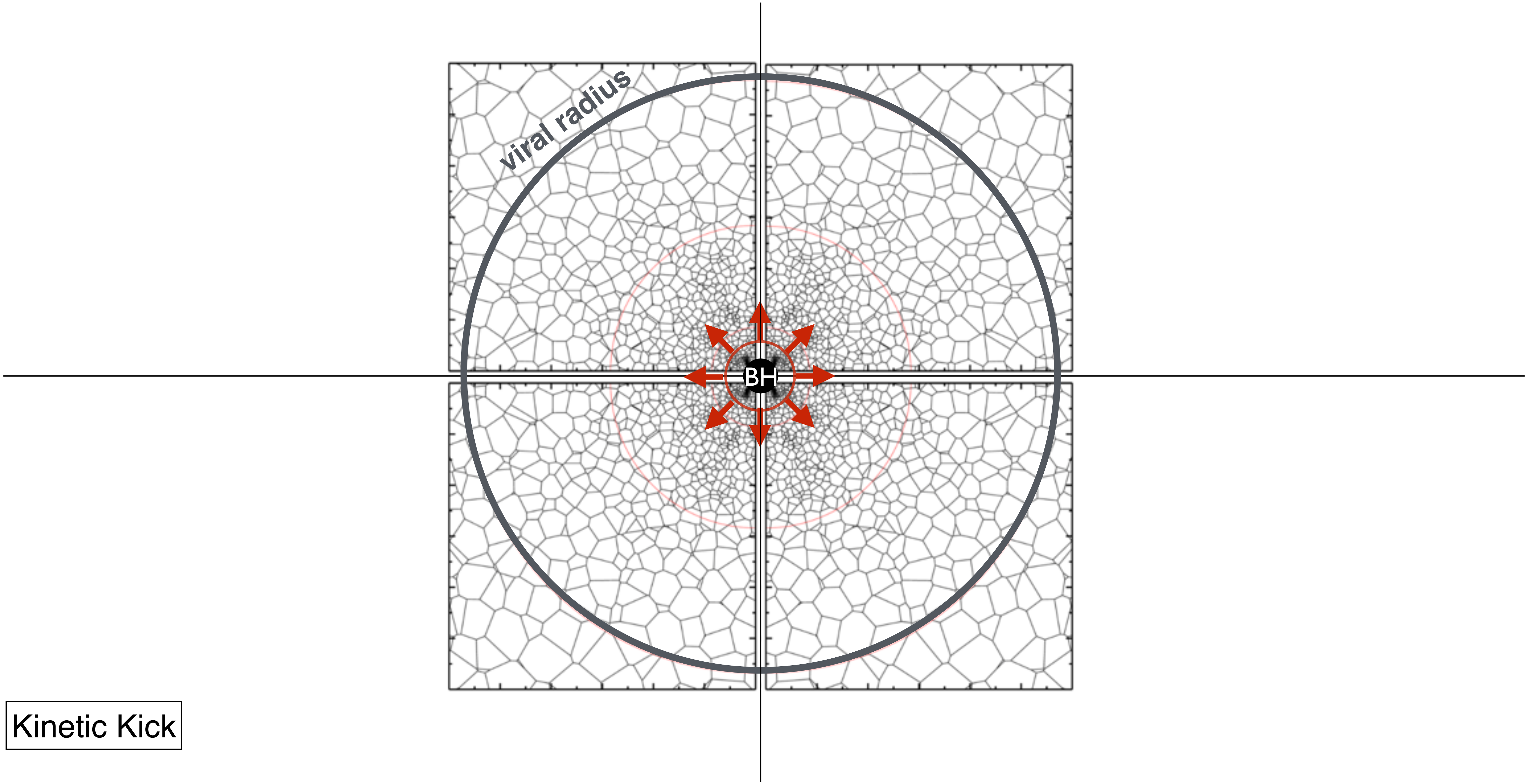


BH Feedback: Subgrid Implementation



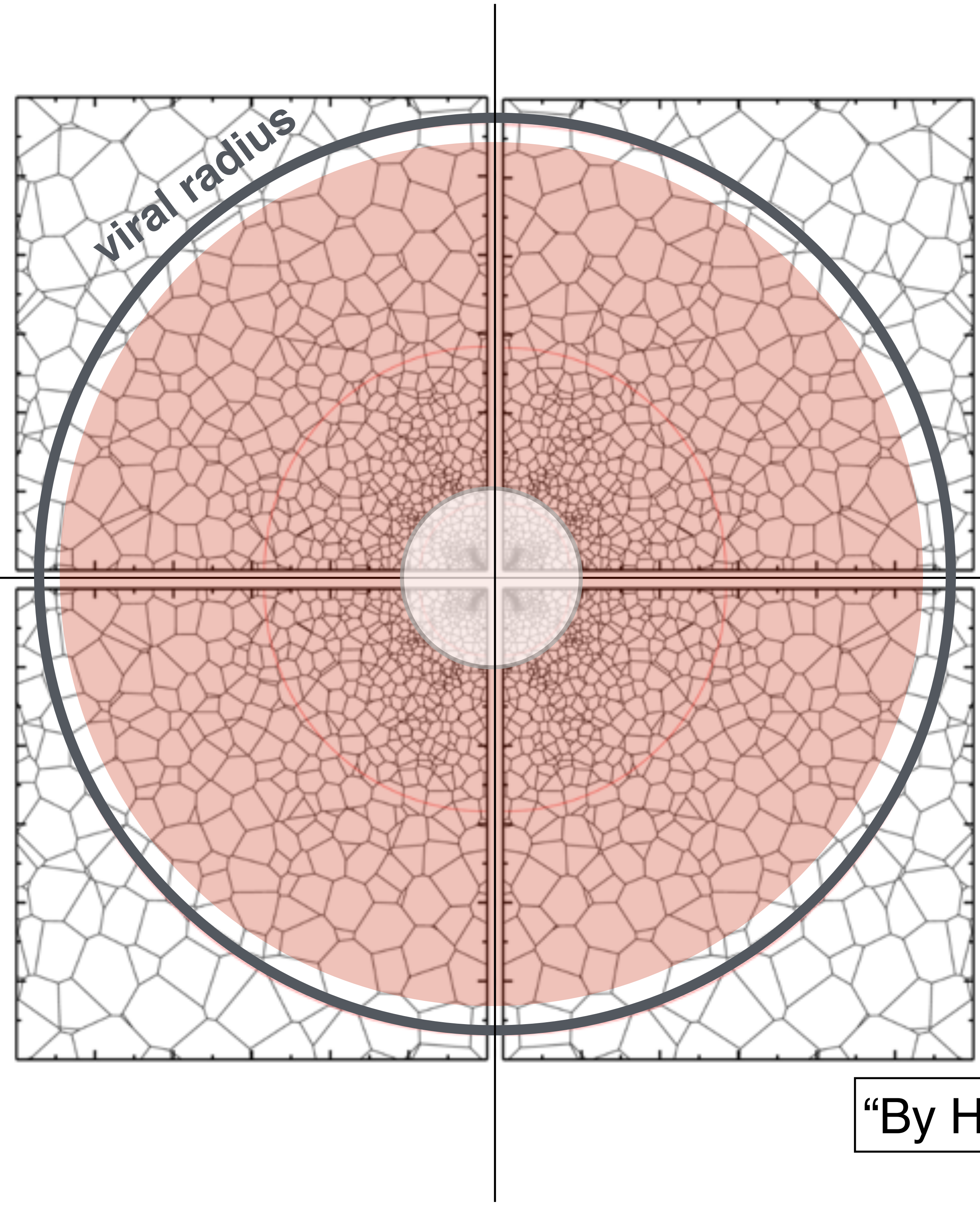
Kinetic Kick

BH Feedback: Subgrid Implementation



Kinetic Kick

BH Feedback: Subgrid Implementation



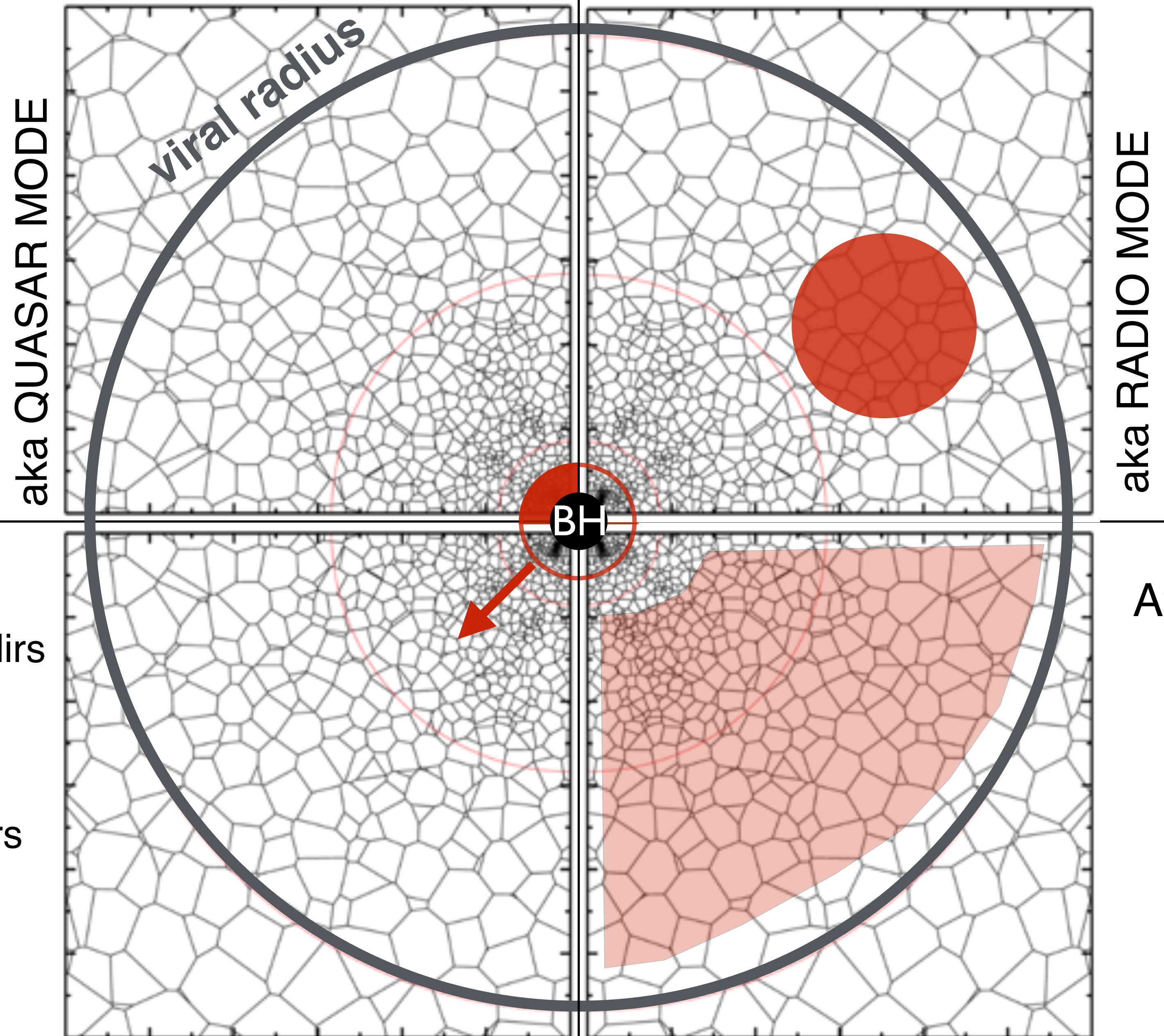
"By Hand" heating of the gaseous halo

BH Feedback: Subgrid Implementation

Thermal Dump (near the BH)

Continuous?
- yes e.g. Illustris, HorizonAGN
- no e.g. Eagle

Only at high accretion rates?
- yes e.g. Illustris
- no e.g. Eagle (all the time)



Thermal Dump (bubbles)

Very sporadic, energetic bubbles: Illustris
More frequent, "smaller bubbles": Auriga

Only at low accretion rates?
- yes e.g. Illustris
- no e.g. Auriga (all the time)

Isotropic?
- no e.g. TNG, each time in different dirs
- no: bipolar e.g. HorizonAGN

Continuous?
- ~ e.g. TNG, each time in different dirs

Only at low accretion rates?
- yes e.g. TNG, HorizonAGN

Kinetic Kick

See also Choi et al. 2012, 2014, 2015; Dubois et al. 2010, 2012; Weinberger et al 2017

Affecting only non-self shielded gas e.g. Mufasa, NIHAO variations

"By Hand" heating of the gaseous halo

BH Feedback: Subgrid Implementation in TNG

Weinberger, Springel, Hernquist, et al. 2016

ILLUSTRIS | | TNG

Two: "Quasar/Radio"	BH Feedback Modes	Two: "High/Low Accretion State"
Thermal Injection around BHs	High-Accr-Rate Feedback	Thermal Injection around BHs
Thermal 'Bubbles' in the ICM	Low-Accr-Rate Feedback	BH-driven kinetic wind
constant: 0.05	Low/High Accretion Transition: χ	BH-mass dependent, $\leqslant 0.1$
0.2	Radiative efficiency: ϵ_r	0.2
$\epsilon_f \epsilon_r$, with $\epsilon_f = 0.05$	High-Accr-Rate Feedback Factor	$\epsilon_f \epsilon_r$, with $\epsilon_f = 0.1$
$\epsilon_m \epsilon_r$, with $\epsilon_m = 0.35$	Low-Accr-Rate Feedback Factor	$\epsilon_{f,kin} \leqslant 0.2$
yes	Radiative BH Feedback	yes

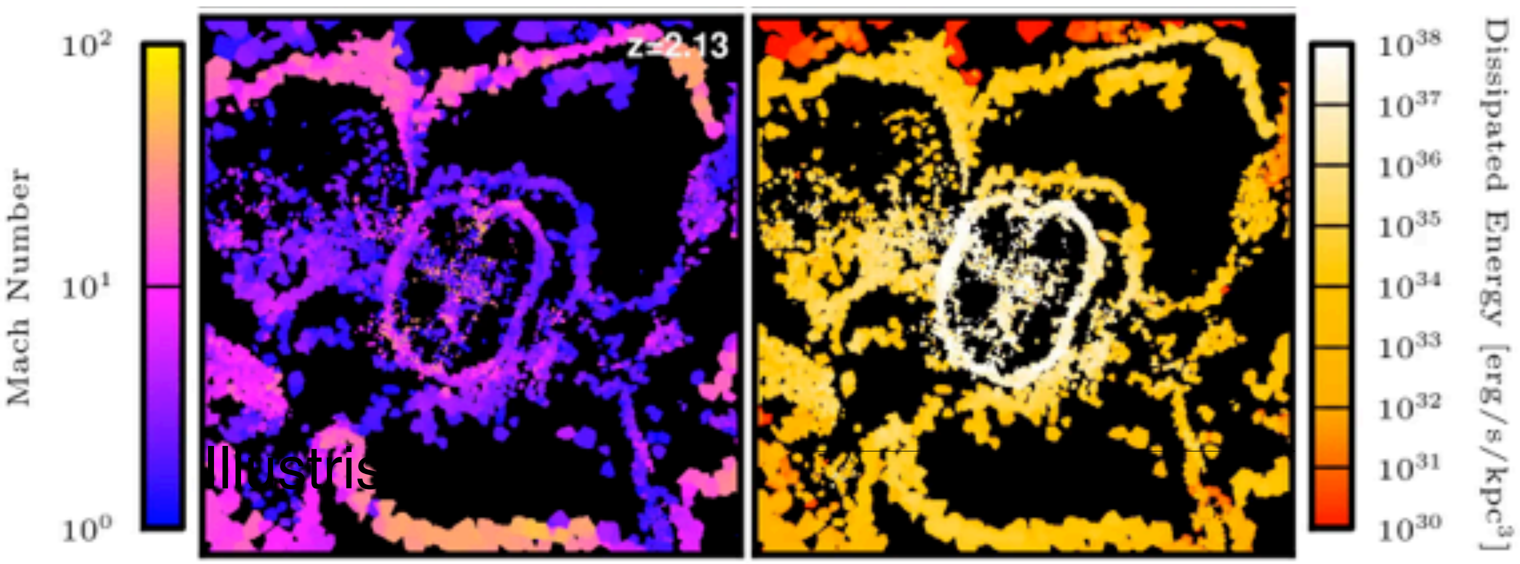
$$\Delta \dot{E}_{\rm high} = \epsilon_{\rm f,high} \epsilon_{\rm r} \dot{M}_{\rm BH} c^2,$$

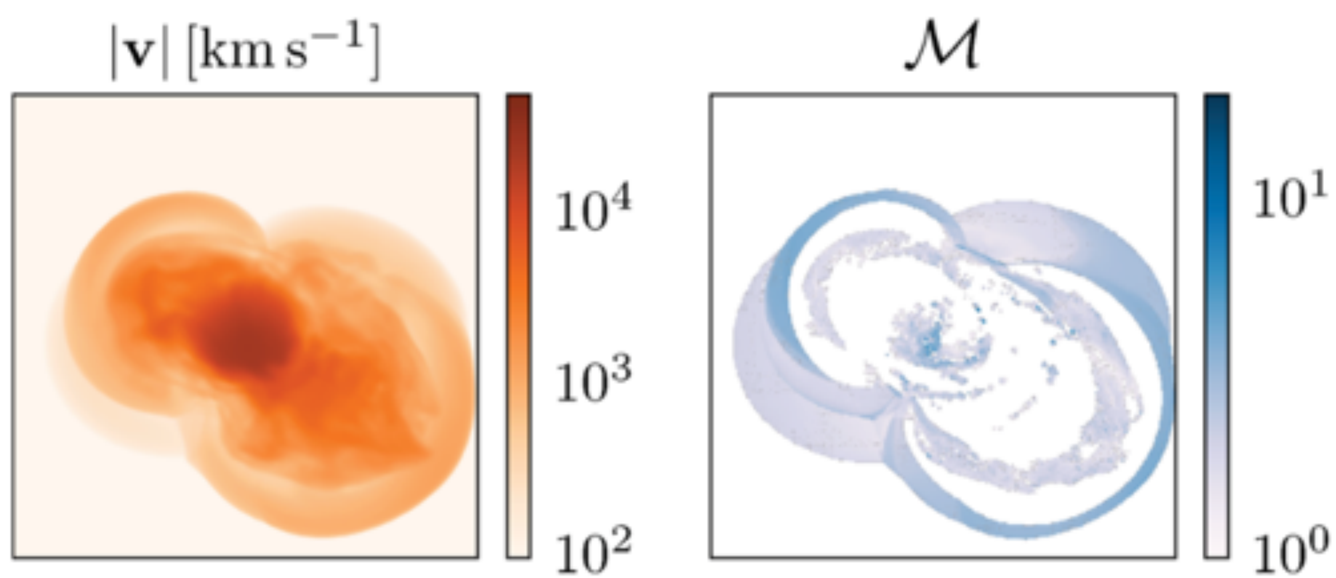
$$\Delta \dot{E}_{\rm low} = \epsilon_{\rm f,kin} \dot{M}_{\rm BH} c^2$$

$$\chi = \min \left[\chi_0 \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot} \right)^{\beta}, 0.1 \right]$$

Phenomenology of the Illustris issues: Illustris BH feedback is too violent, removes all the gas from the halo and yet does not quench the central galaxies

Schaal, Springel et al. 2016





Weinberger, Springel, et al. 2016 (idealised setup, n~0.1 cm^-3)

BH Feedback: Subgrid Implementation in TNG

Weinberger, Springel, Hernquist, et al. 2016

ILLUSTRIS

ILLUSTRIS		TNG
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yes	Radiative BH Feedback	yes

$$\Delta \dot{E}_{\mathrm{high}} = \epsilon_{\mathrm{f,high}} \epsilon_r \dot{M}_{\mathrm{BH}} c^2,$$

$$\Delta \dot{E}_{\mathrm{low}} = \epsilon_{\mathrm{f,kin}} \dot{M}_{\mathrm{BH}} c^2$$

$$\chi = \min \left[\chi_0 \left(\frac{M_{\mathrm{BH}}}{10^8\,\mathrm{M}_\odot} \right)^\beta, 0.1 \right]$$

TNG

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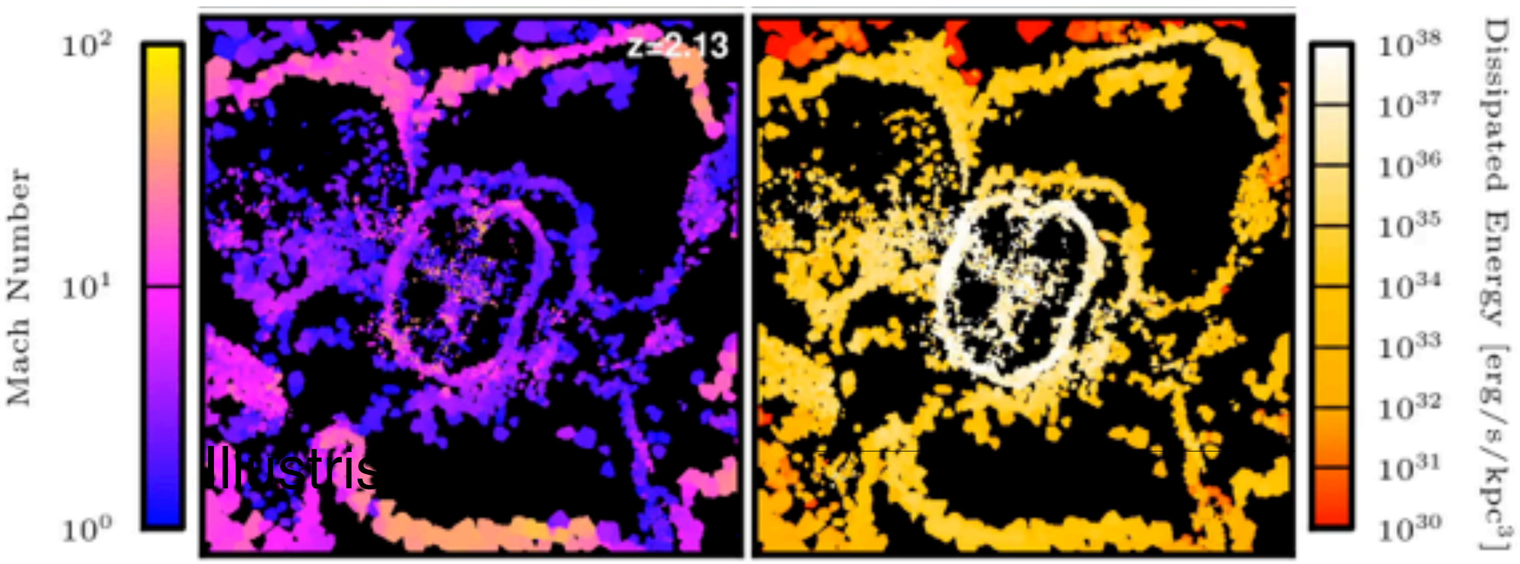
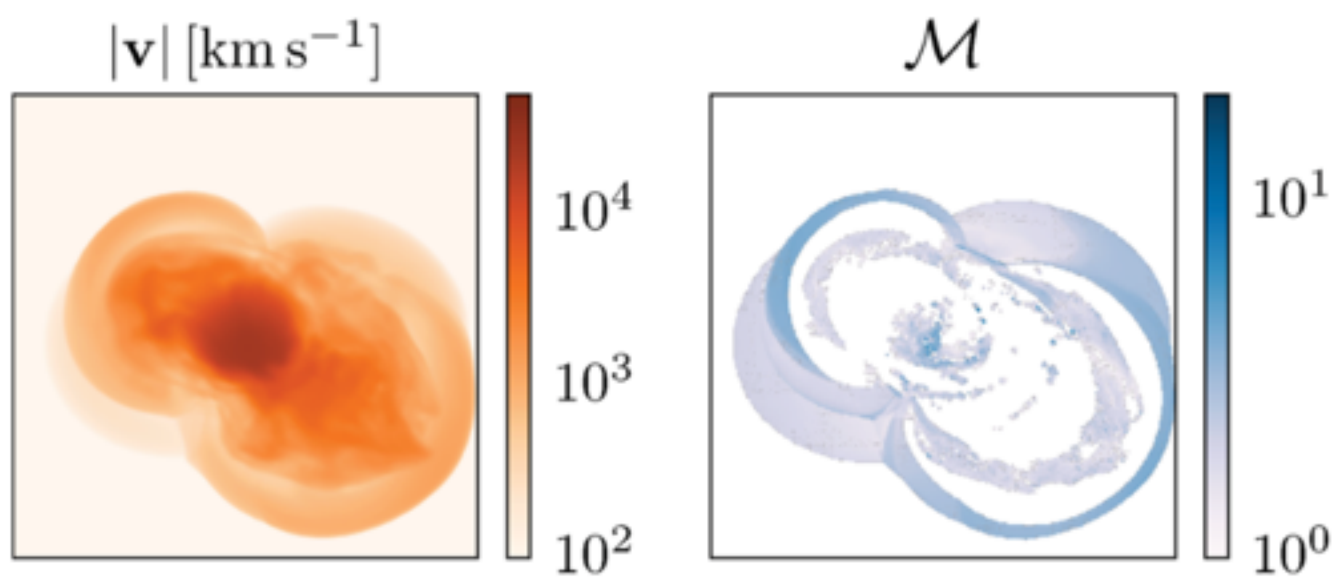
Schaal, Springel et al. 2016



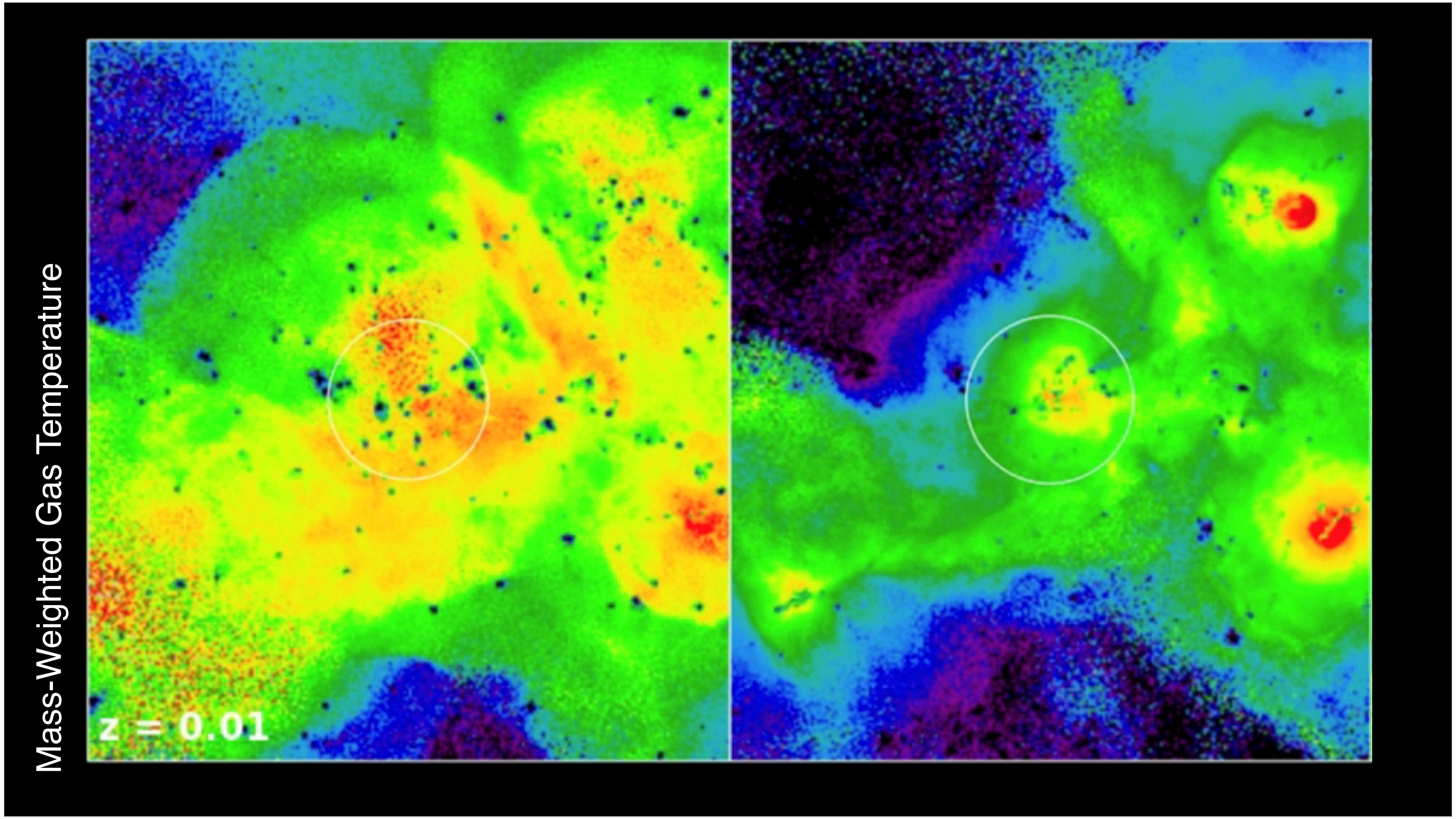


Weinberger, Springel, et al. 2016 (idealised setup, n~0.1 cm^-3)

BH Feedback: Effects

Zoom Cluster 2: 4×10^{13} Msun

Illustris	TNG
Thermal feedback inflates one large, hot bubbles every time δM_{BH} is above a threshold	Kinetic feedback kicks in random directions to neighboring gas cells

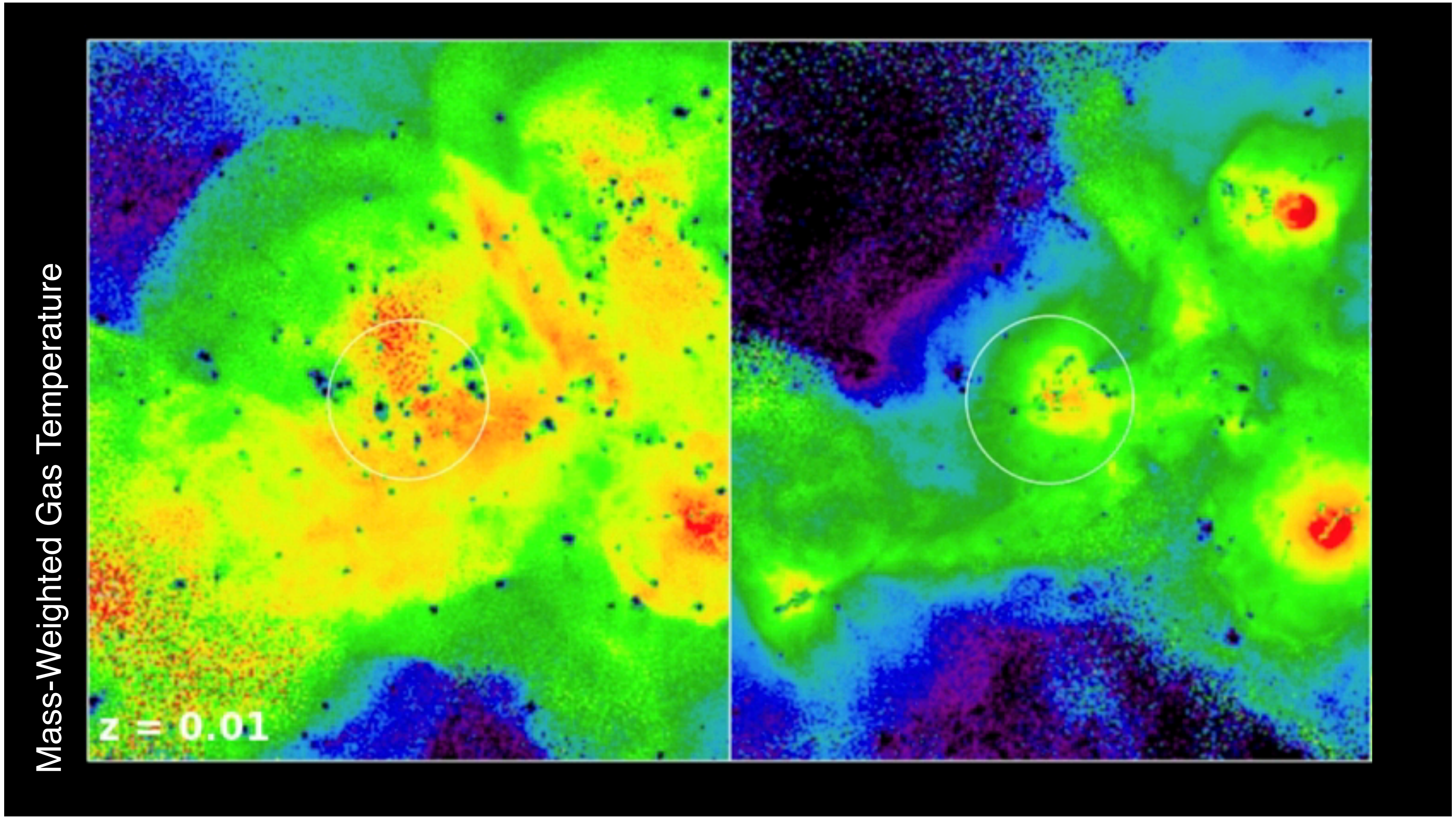


Credits C. Popa

BH Feedback: Effects

Zoom Cluster 2: 4×10^{13} Msun

Illustris	TNG
Thermal feedback inflates one large, hot bubbles every time δM_{BH} is above a threshold	Kinetic feedback kicks in random directions to neighboring gas cells



Credits C. Popa

BH Feedback: Effects

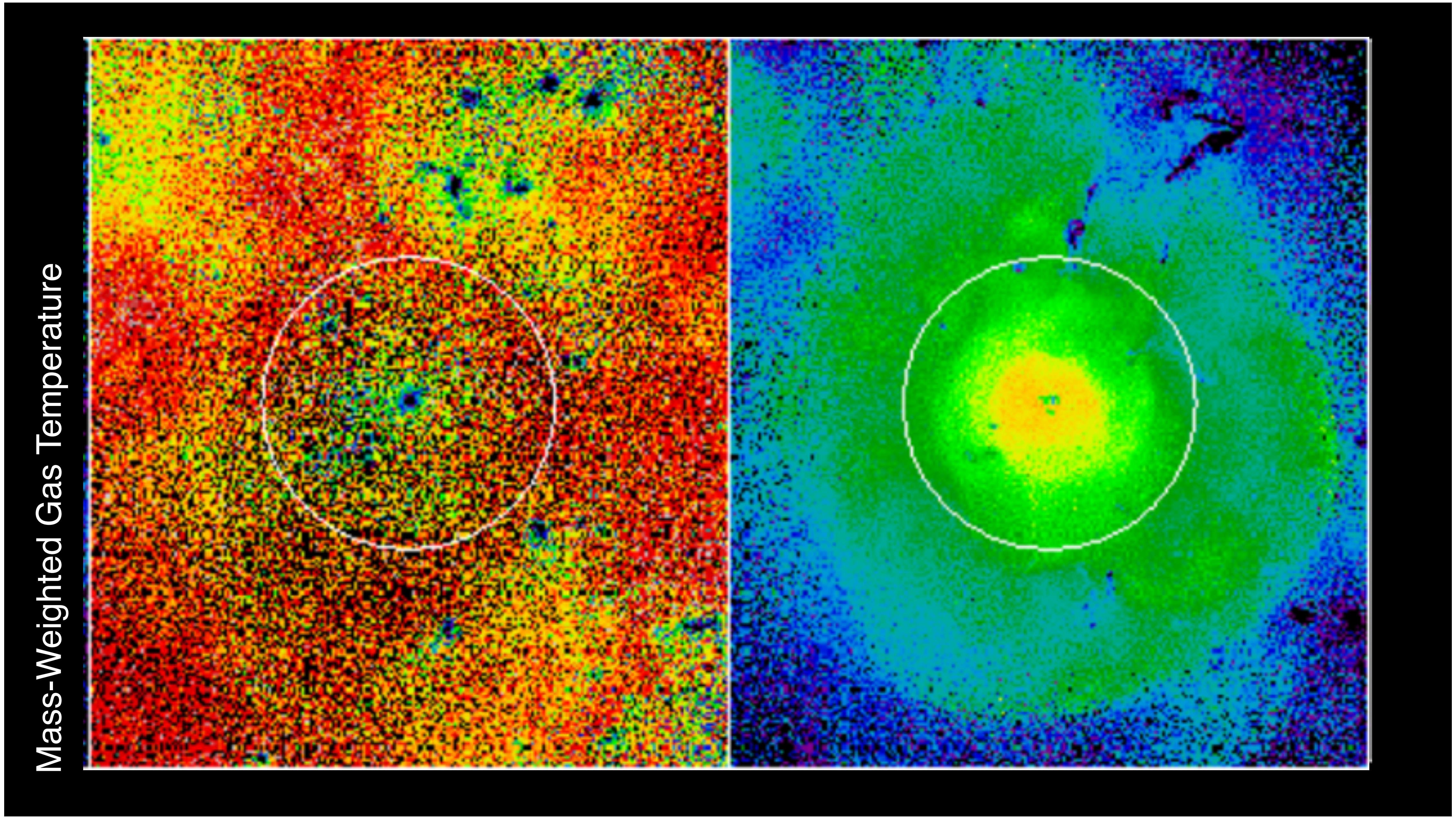
Zoom Cluster 1: 2x10^{13} Msun

Illustris

Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

TNG

Kinetic feedback
kicks in random directions to neighboring gas cells



Credits C. Popa

BH Feedback: Effects

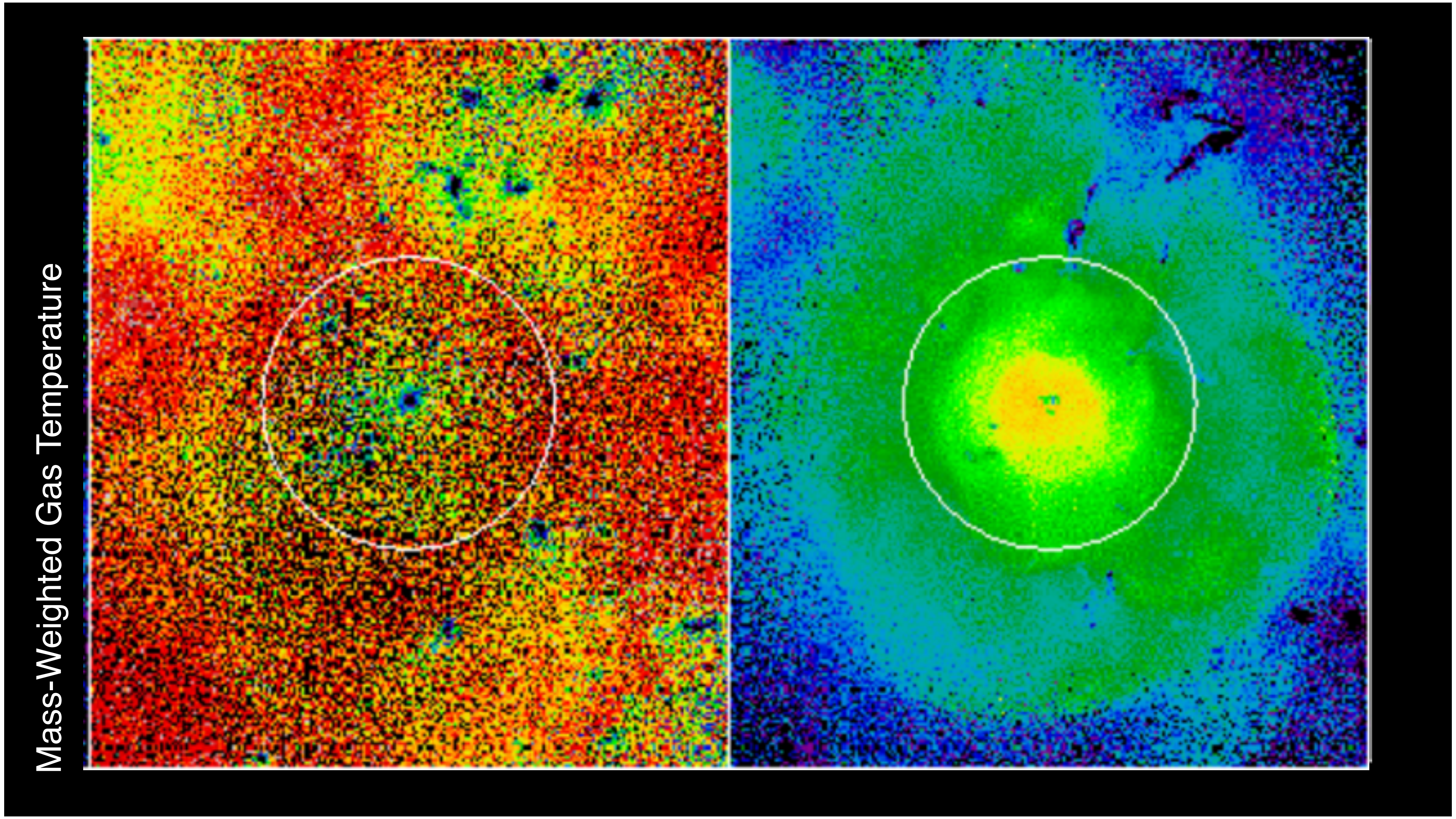
Zoom Cluster 1: $2x10^{13}$ Msun

Illustris

Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

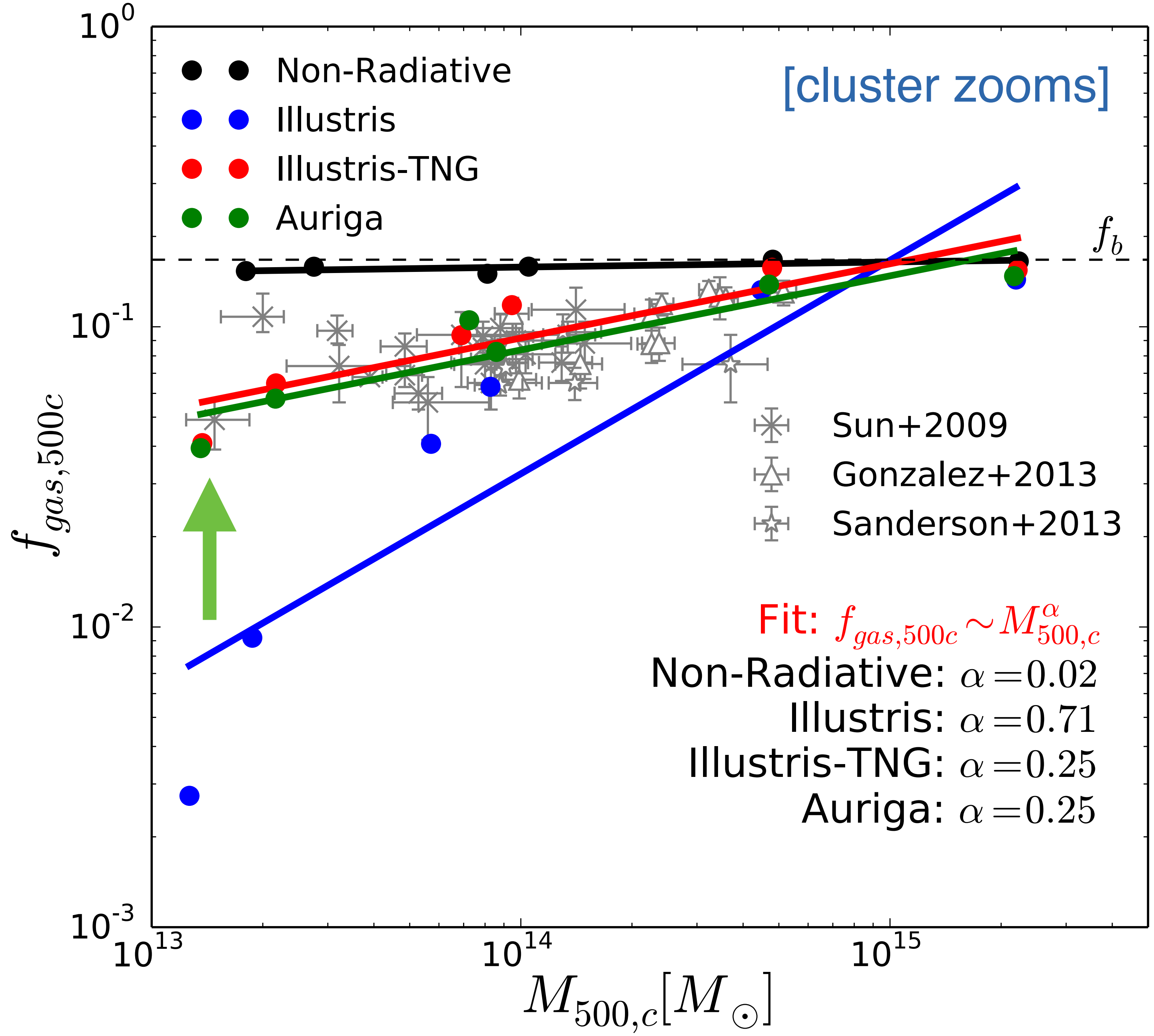
TNG

Kinetic feedback
kicks in random directions to neighboring gas cells



Credits C. Popa

BH Feedback: Effects on the ICM



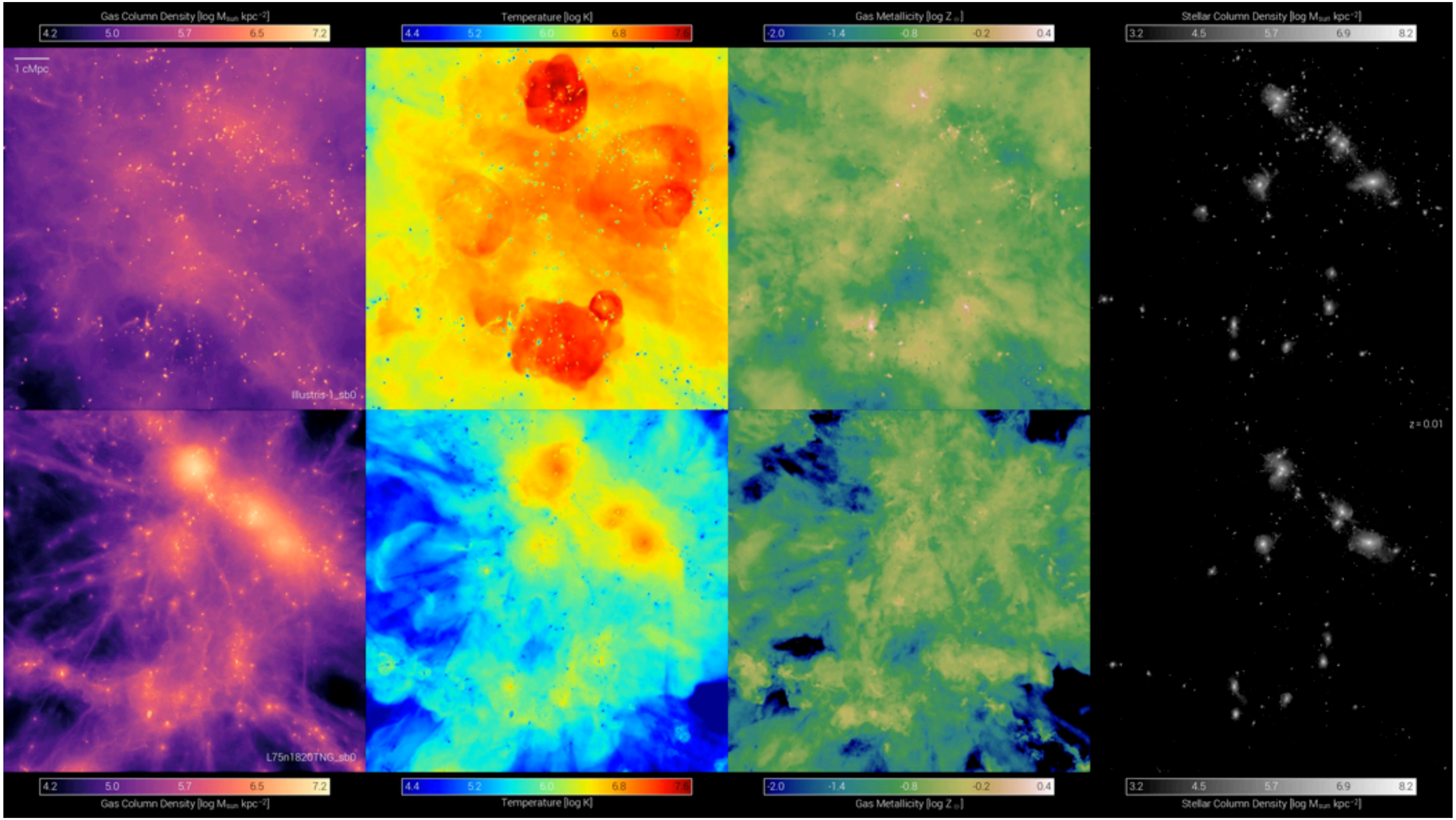
Different AGN feedback modes affect differently the state of the ICM

(but more so at group-mass scales)

Feedback: Effects beyond the galaxies

Illustris Model

TNG Model



Credits: Dylan Nelson (MPA) & IllustrisTNG Team

Feedback: Effects beyond the galaxies