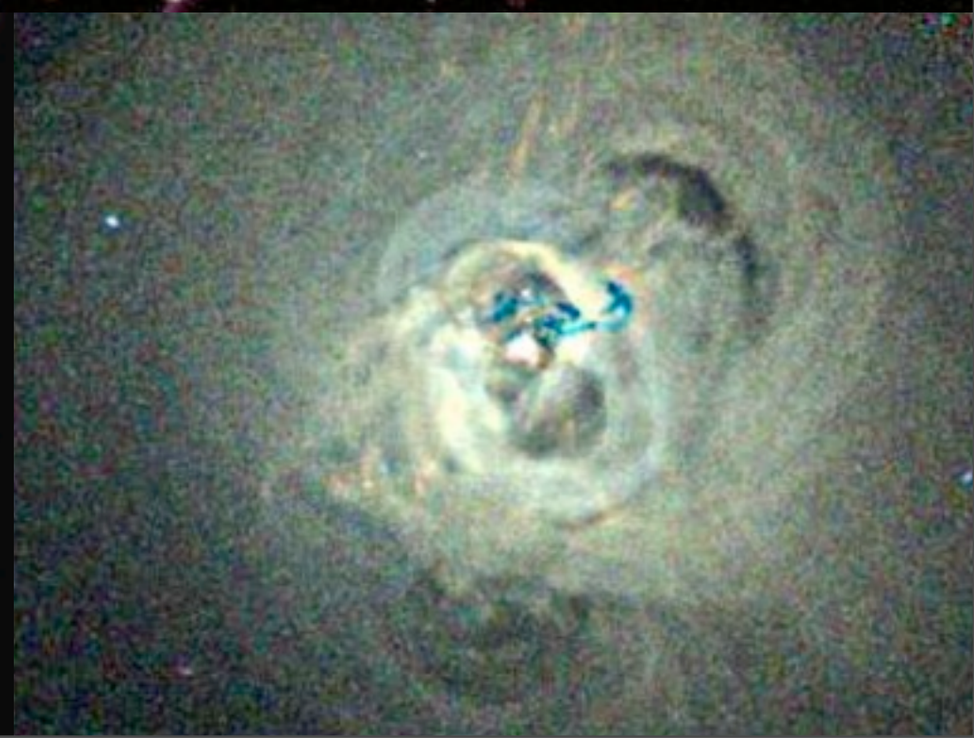
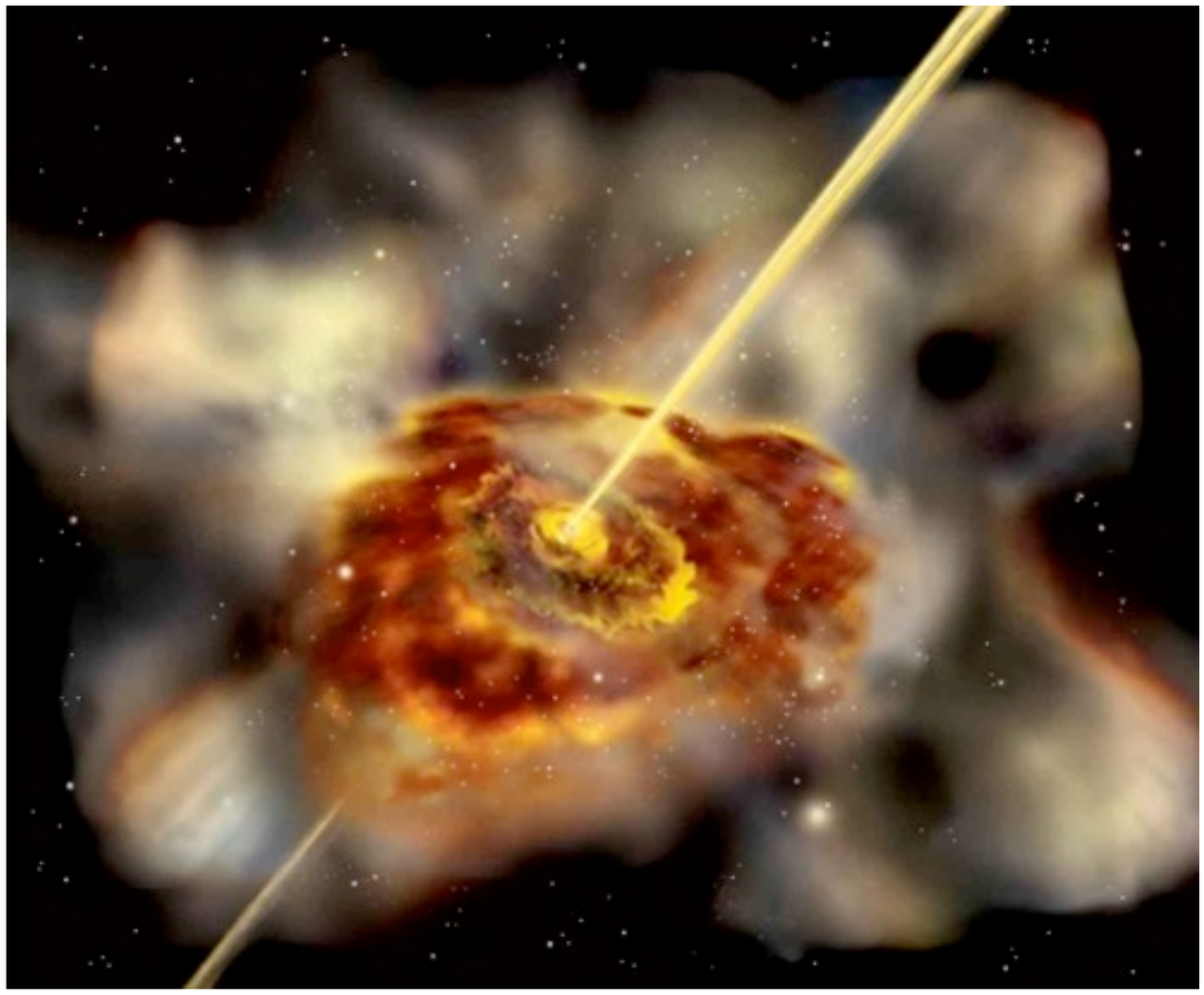
The Monster Roars:
AGN Feedback & Co-Evolution with Galaxies



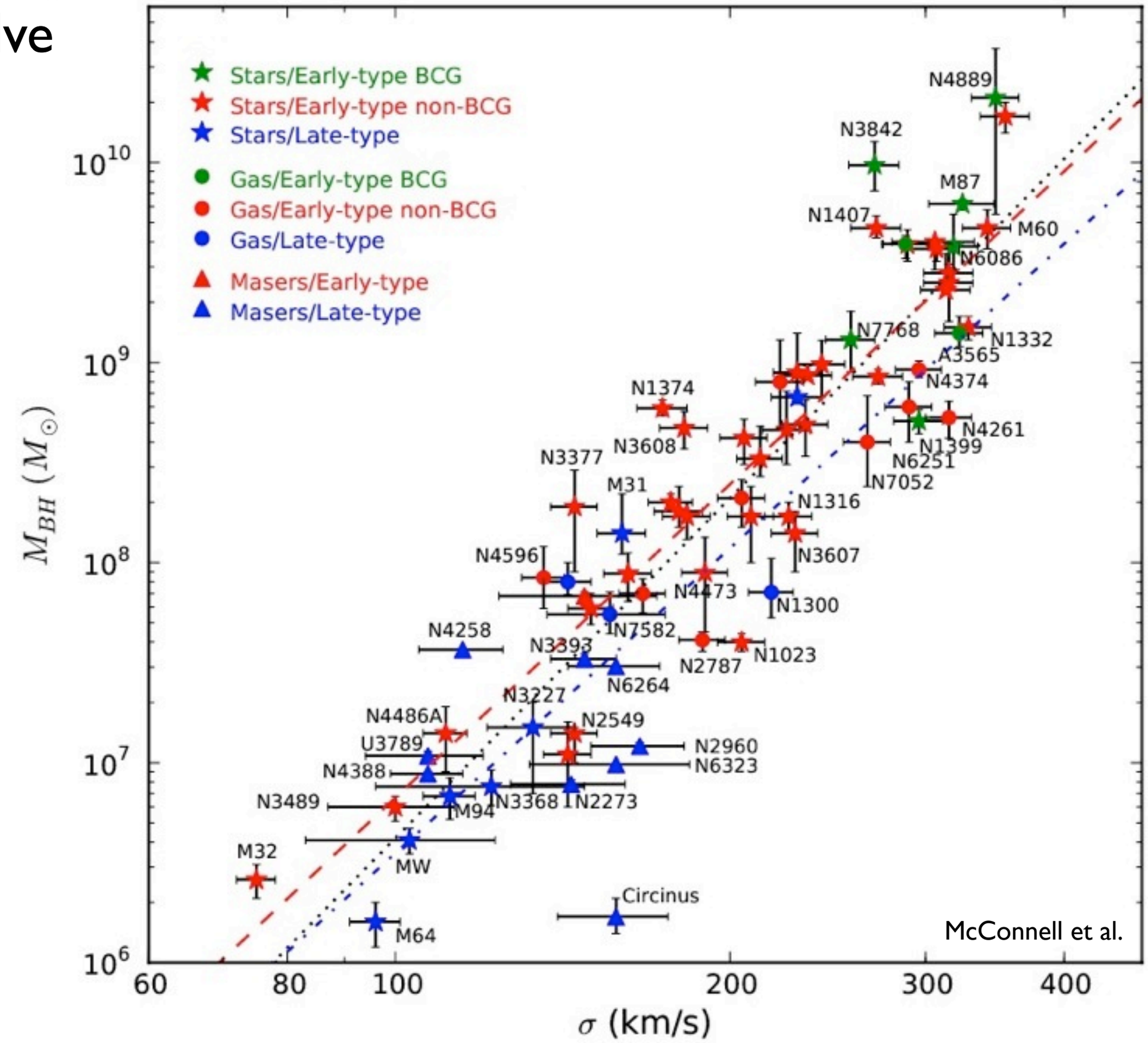
Philip Hopkins

- (Nearly?) Every massive galaxy hosts a supermassive black hole



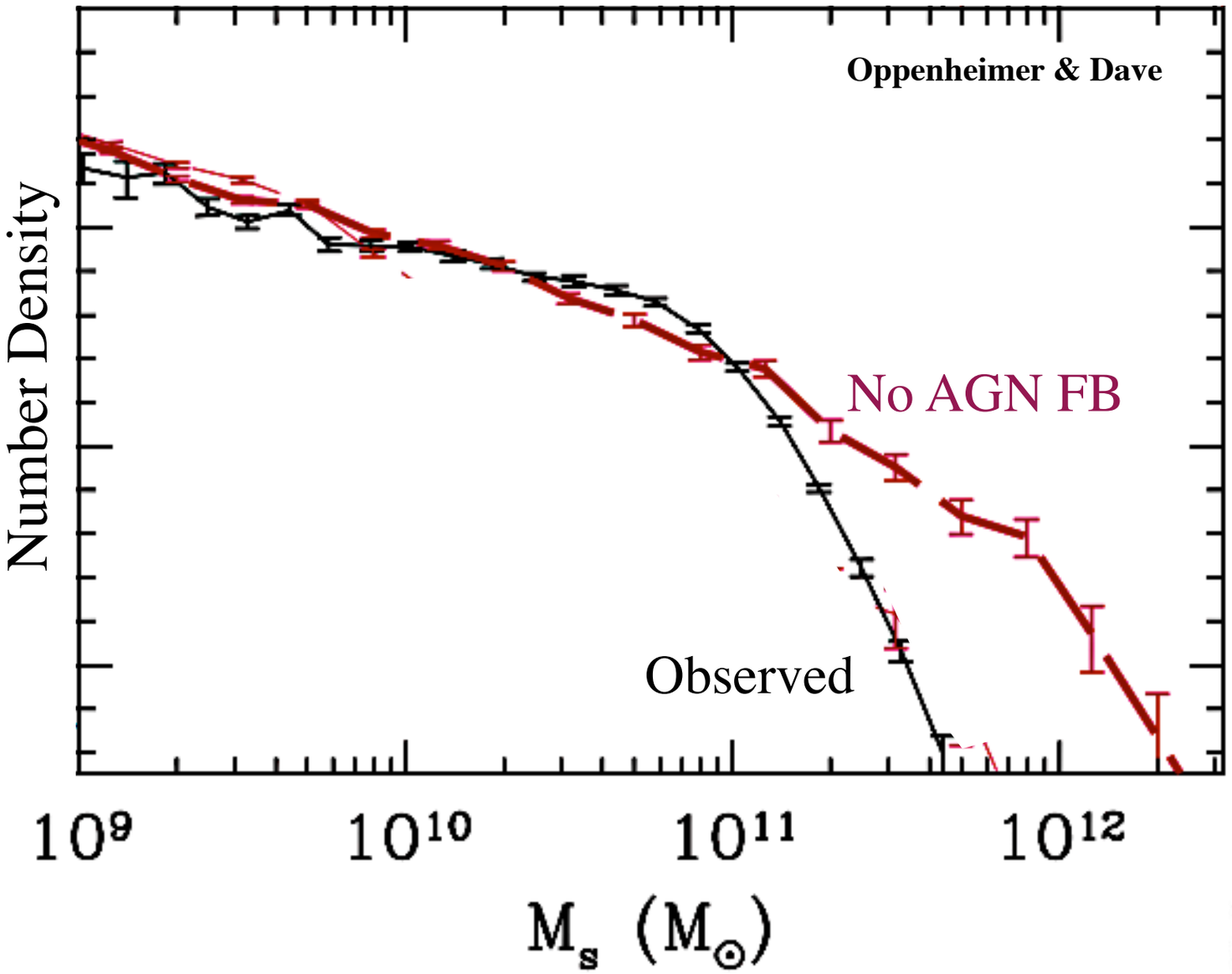
- Mass accreted in ~couple bright quasar phase(s)
  (Soltan, Salucci+, Tremaine+, Yu & Lu, PFH, Shankar, et al.)

BHs and Bulges Co-evolve



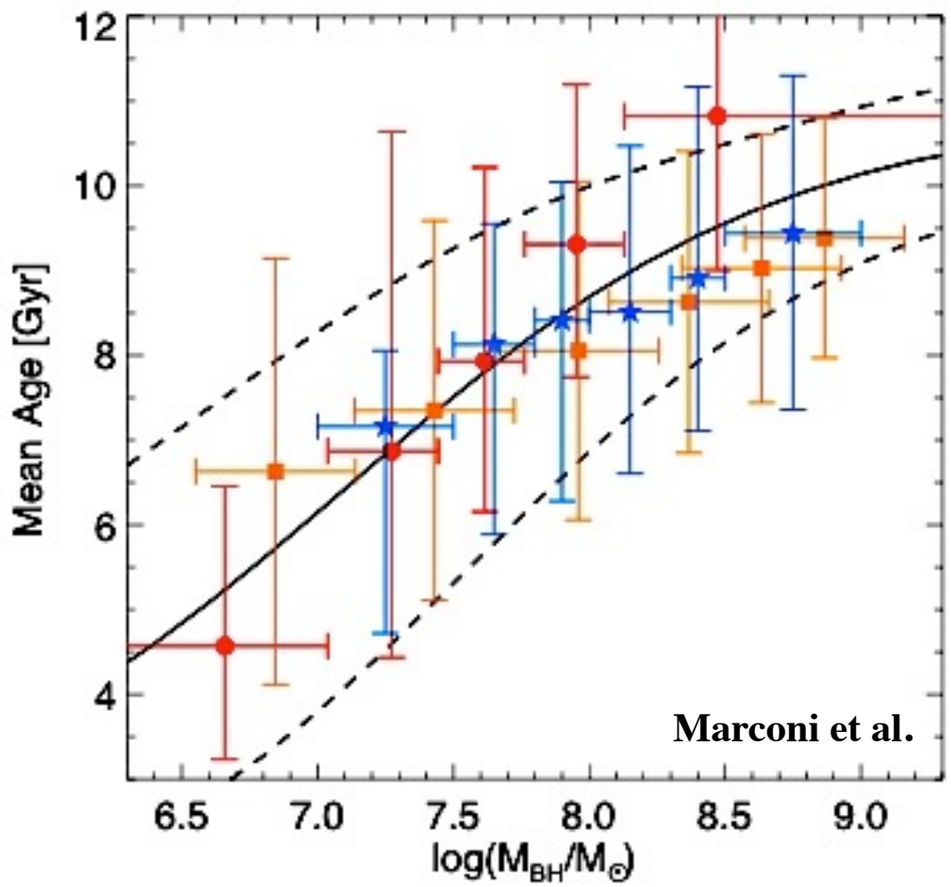
McConnell et al.

Problems?



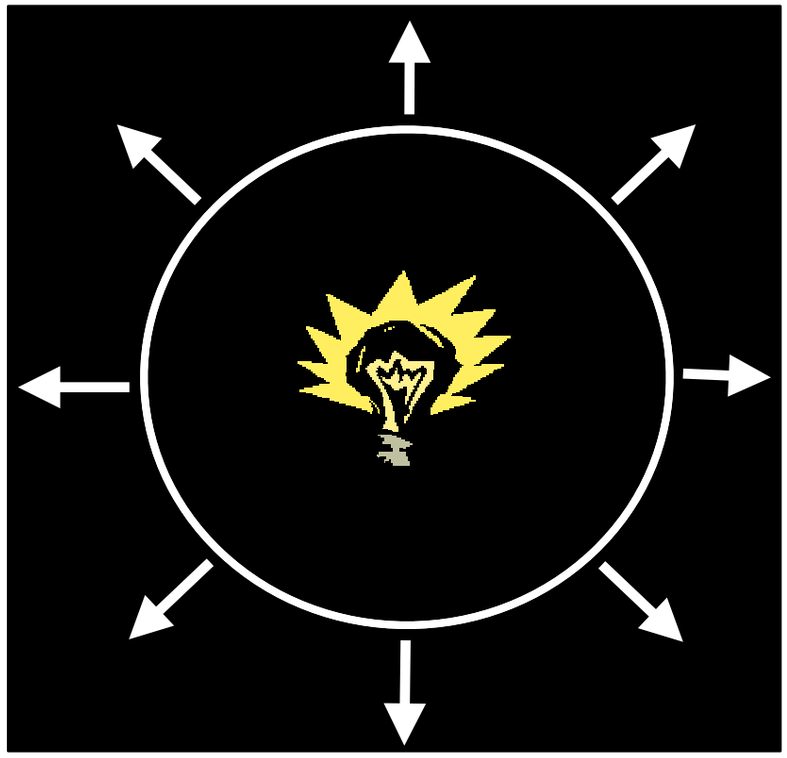
- Sharp color bimodality
- Lowering mass of >M* galaxies
- Removing/heating gas in groups

Spheroid & BH Formation Times:



Quasar Feedback as a Means to Regulate BHs

SANDERS 88, SILK & REES 98, MURRAY ET AL. 05, MANY MORE



Quasar Feedback as a Means to Regulate BHs

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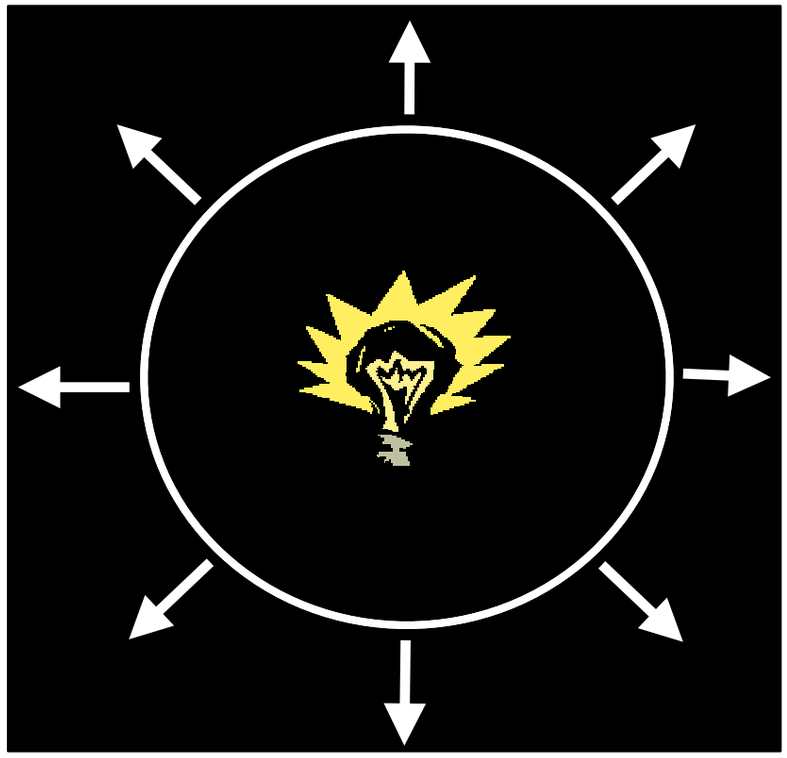
$$F_{\rm rad} \sim \frac{L}{c} \sim \frac{M_{\rm BH}\, c}{t_{\rm Salpeter}}$$



Quasar Feedback as a Means to Regulate BHs

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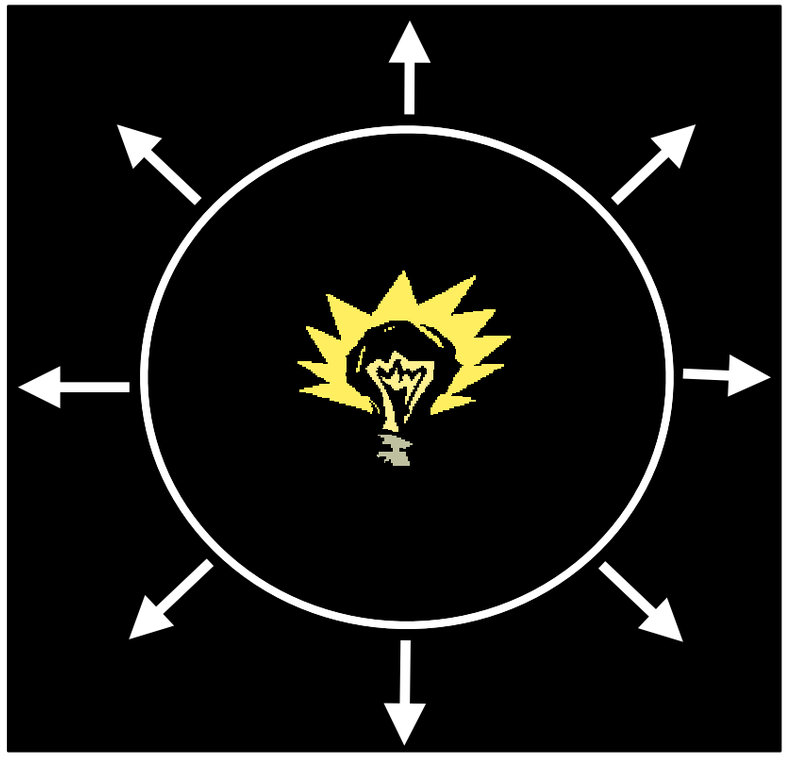
$$F_{\rm rad} \sim \frac{L}{c} \sim \frac{M_{\rm BH}\, c}{t_{\rm Salpeter}}$$

$$F_{\rm grav} \sim \frac{G\, M_{\rm gal}\, M_{\rm gas}}{R_{\rm gal}^2} \sim f_{\rm gas}\, \frac{\sigma^4}{G}$$



Quasar Feedback as a Means to Regulate BHs

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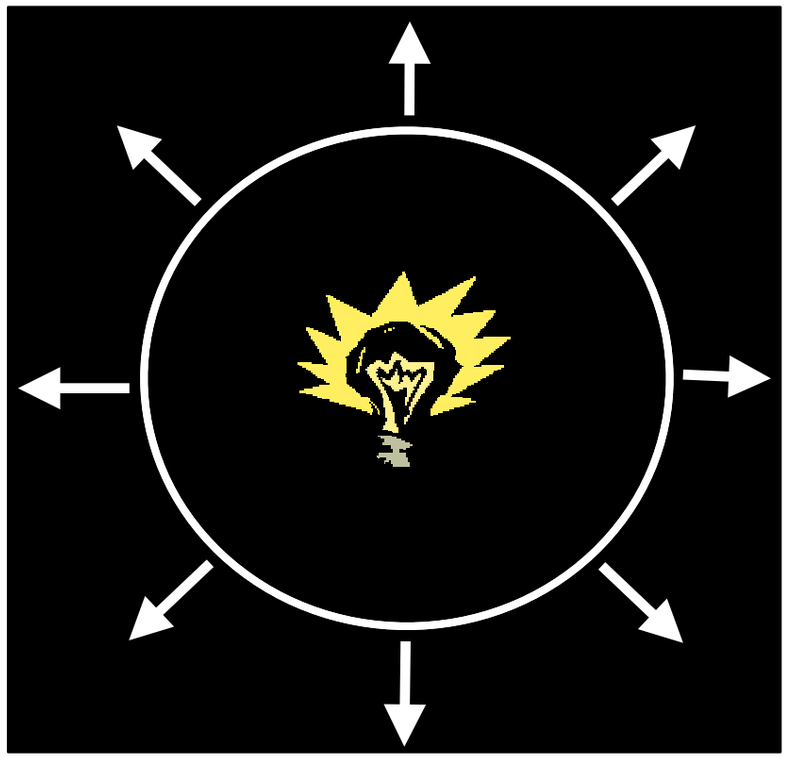

Shut down accretion when: $F_{\rm rad} \gtrsim F_{\rm grav}$

Quasar Feedback as a Means to Regulate BHs

SANDERS 88, SILK & REES 98, MURRAY ET AL. 05, MANY MORE

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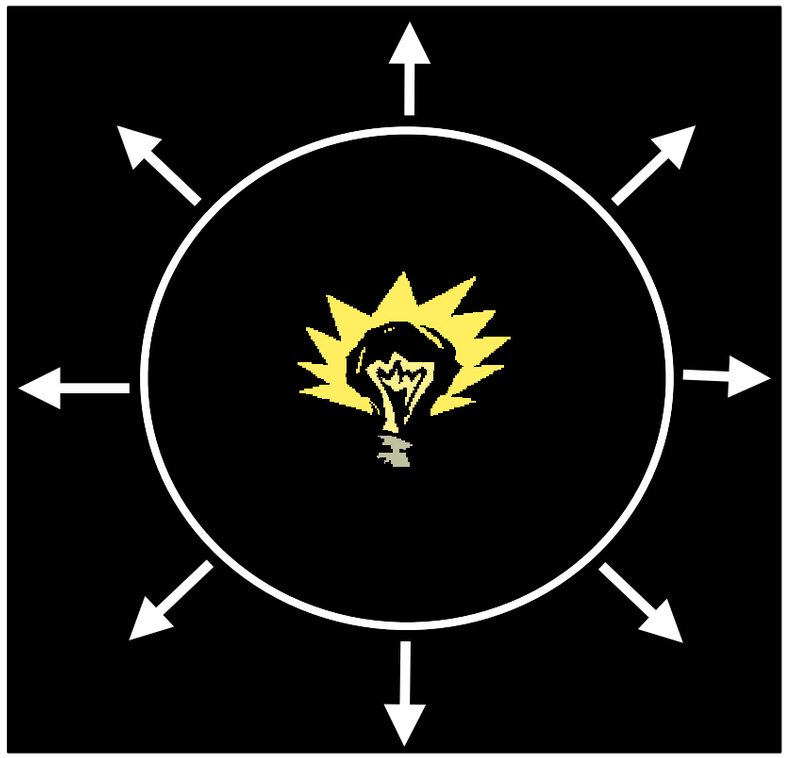
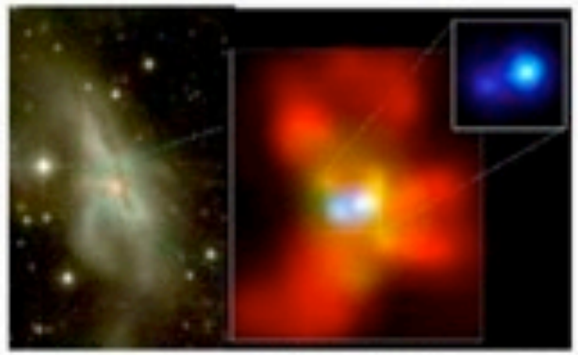


Shut down accretion when: $F_{\rm rad} \gtrsim F_{\rm grav}$

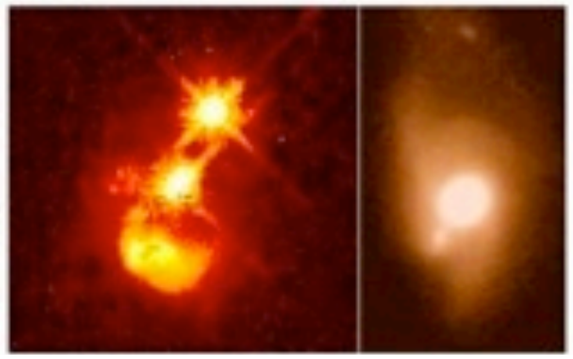
$$M_{\rm BH} \sim \frac{f_{\rm gas}\, t_{\rm S}}{G\, c}\, \sigma^4 \sim 10^8\, M_\odot \left(\frac{\sigma}{200\,{\rm km\,s^{-1}}}\right)^4$$

(c) Interaction/"Merger"

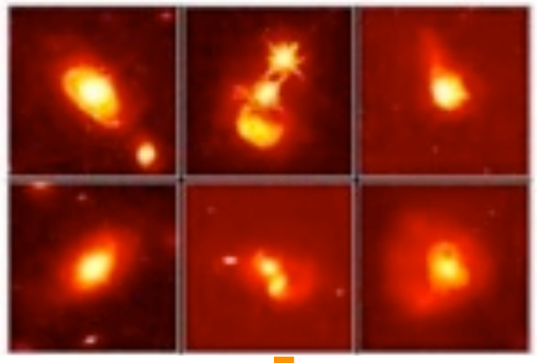
(d) Coalescence/(U)LIRG



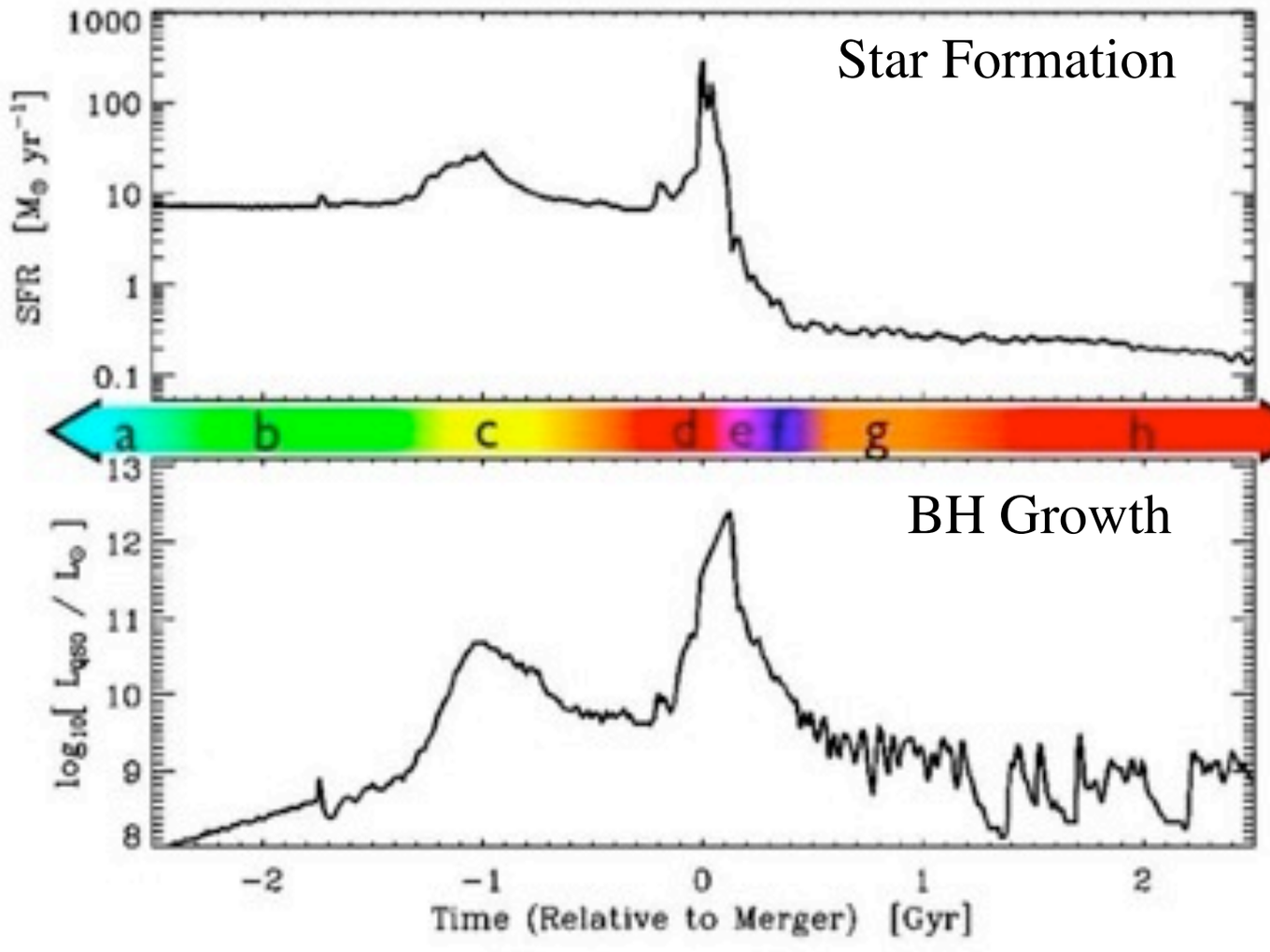
(e) "Blowout"



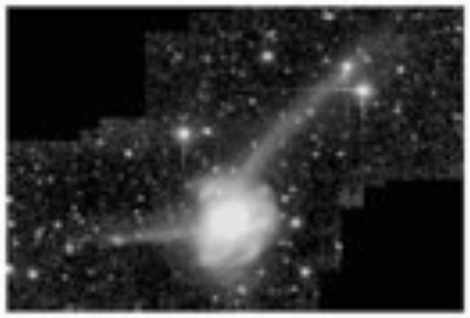
(f) Quasar



(b) "Small Group"



(g) Decay/K+A



(a) Isolated Disk

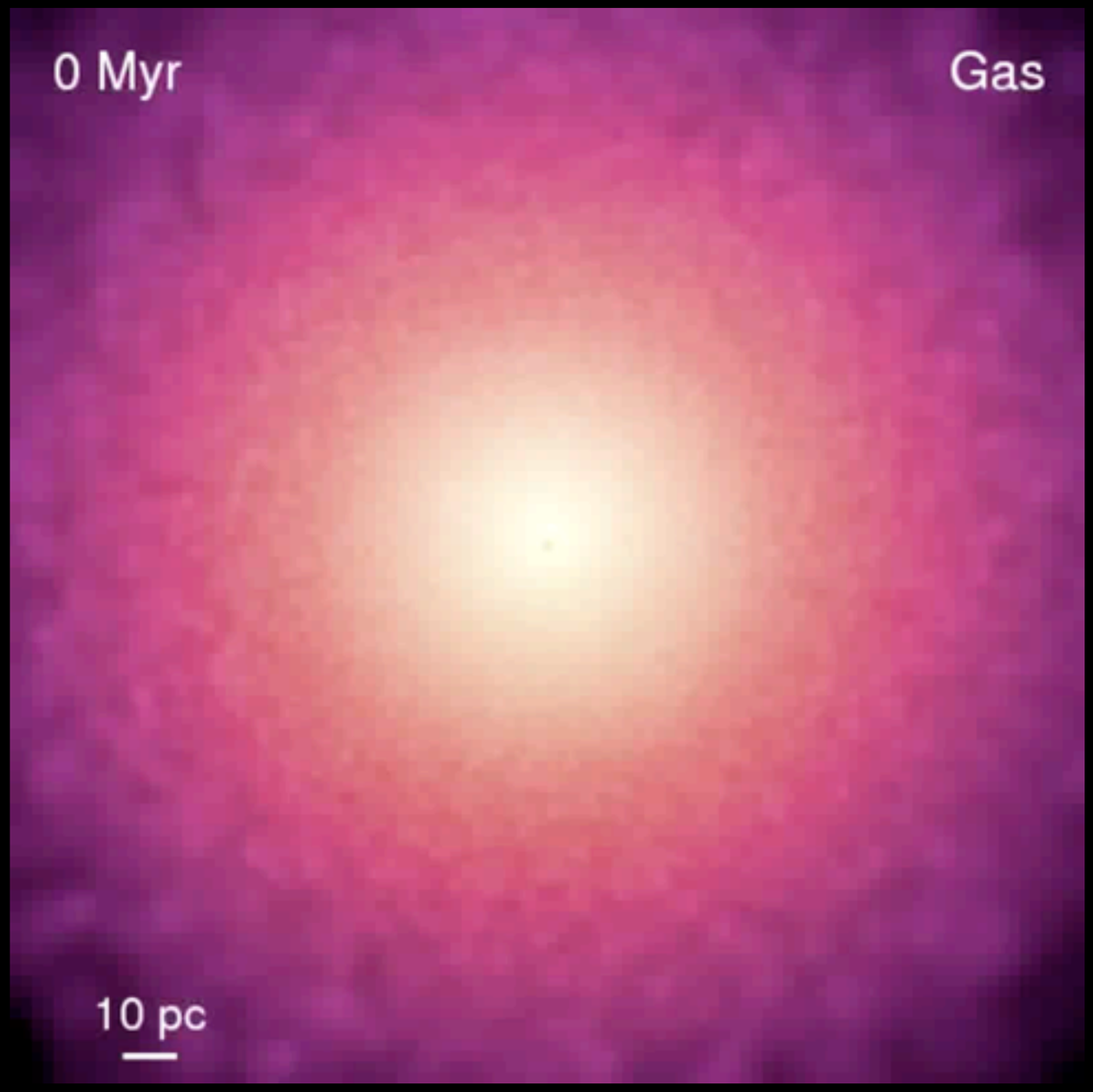
(h) "Dead" Elliptical


T = 0 Myr
Gas

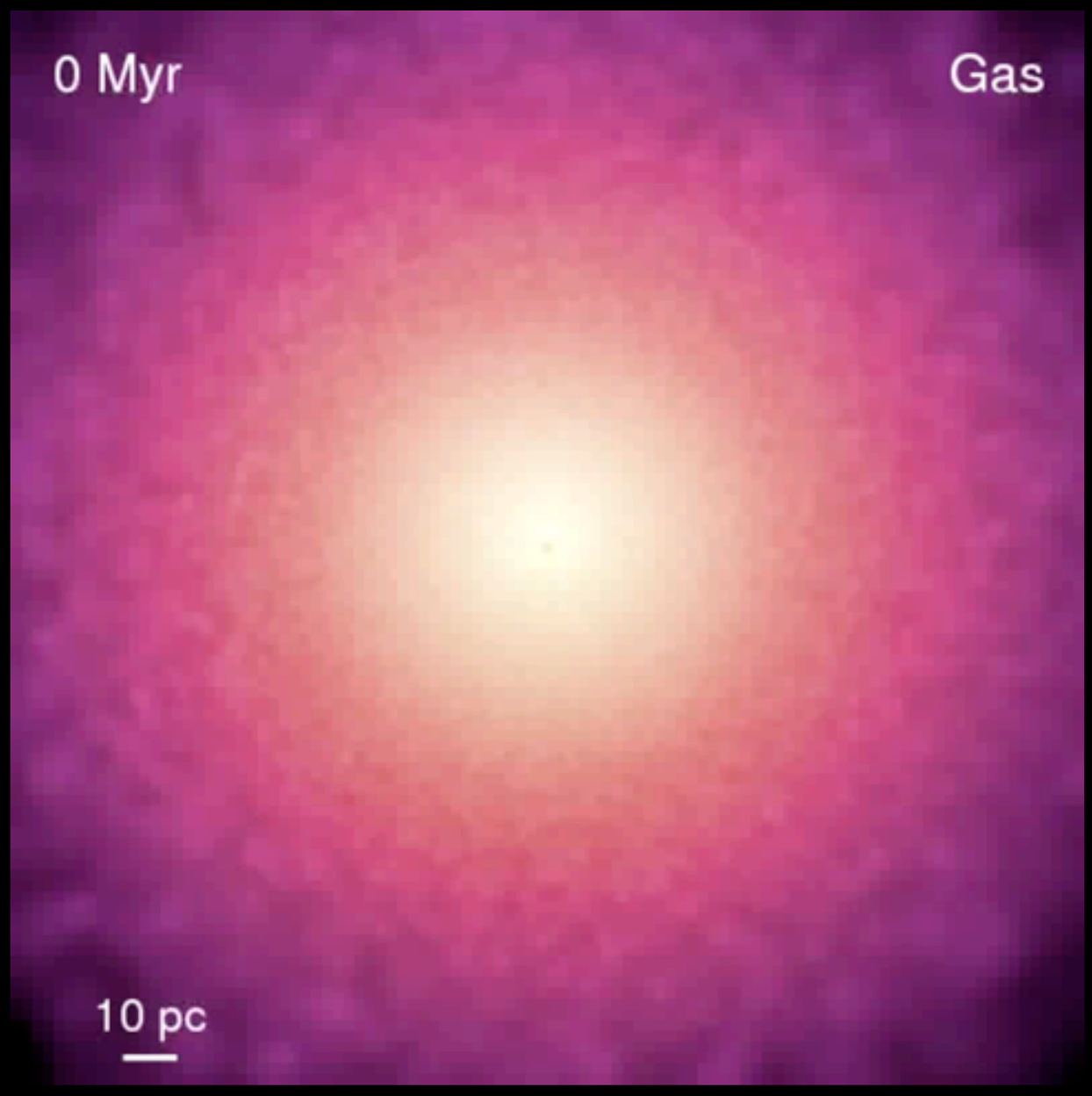
BAL Winds on ~1pc - 1kpc scales:

Wada et al.

No BAL Winds



With BAL Winds

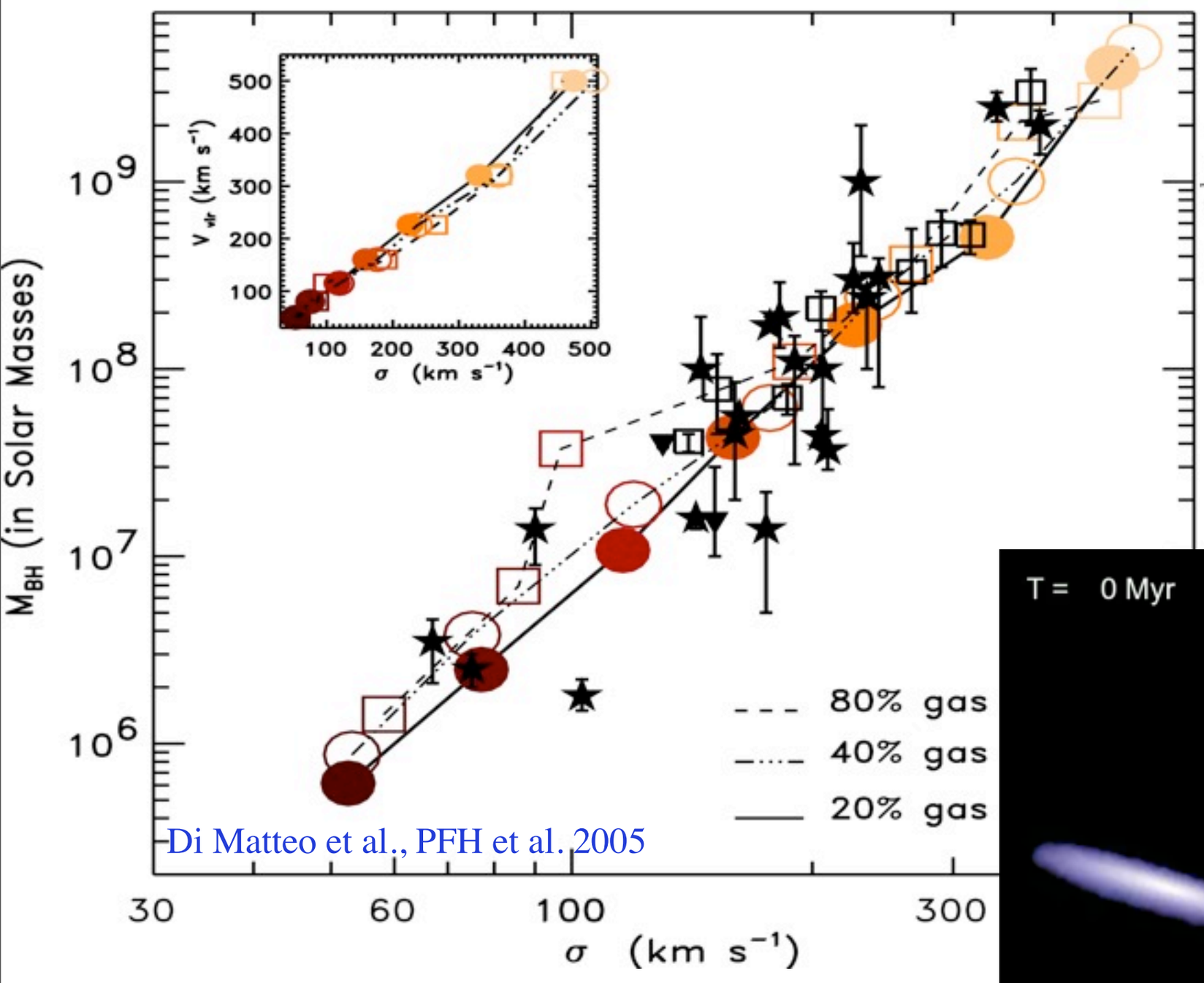


$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

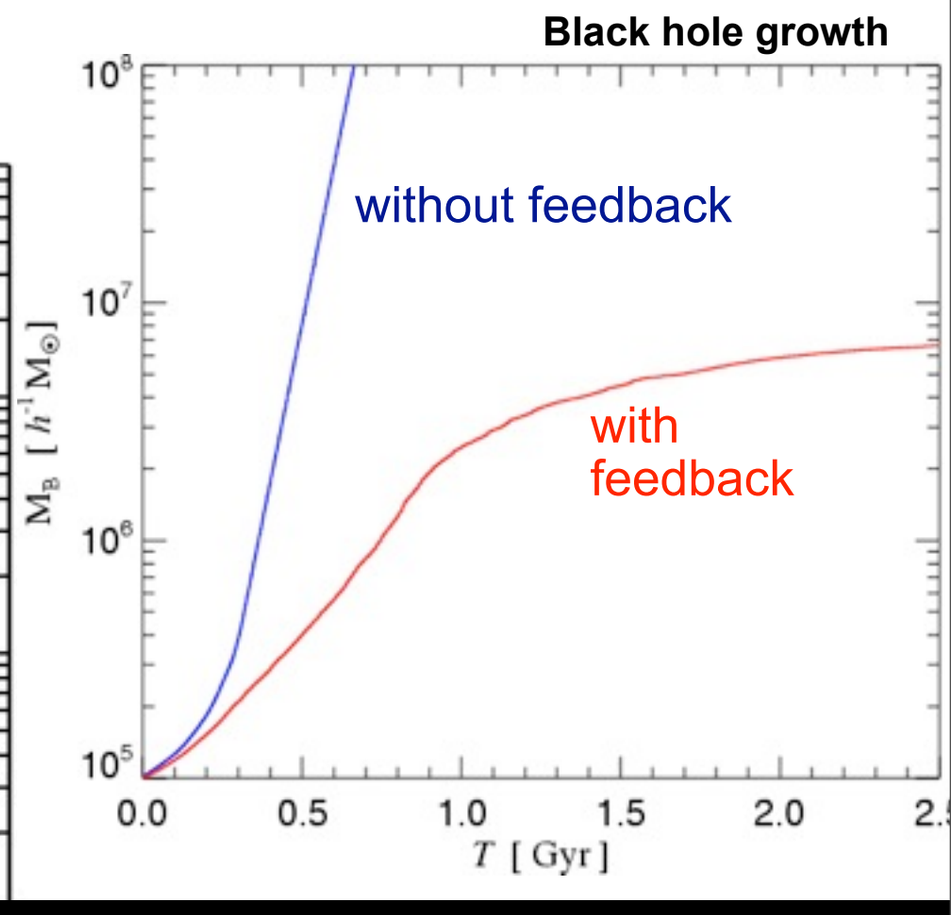
$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$

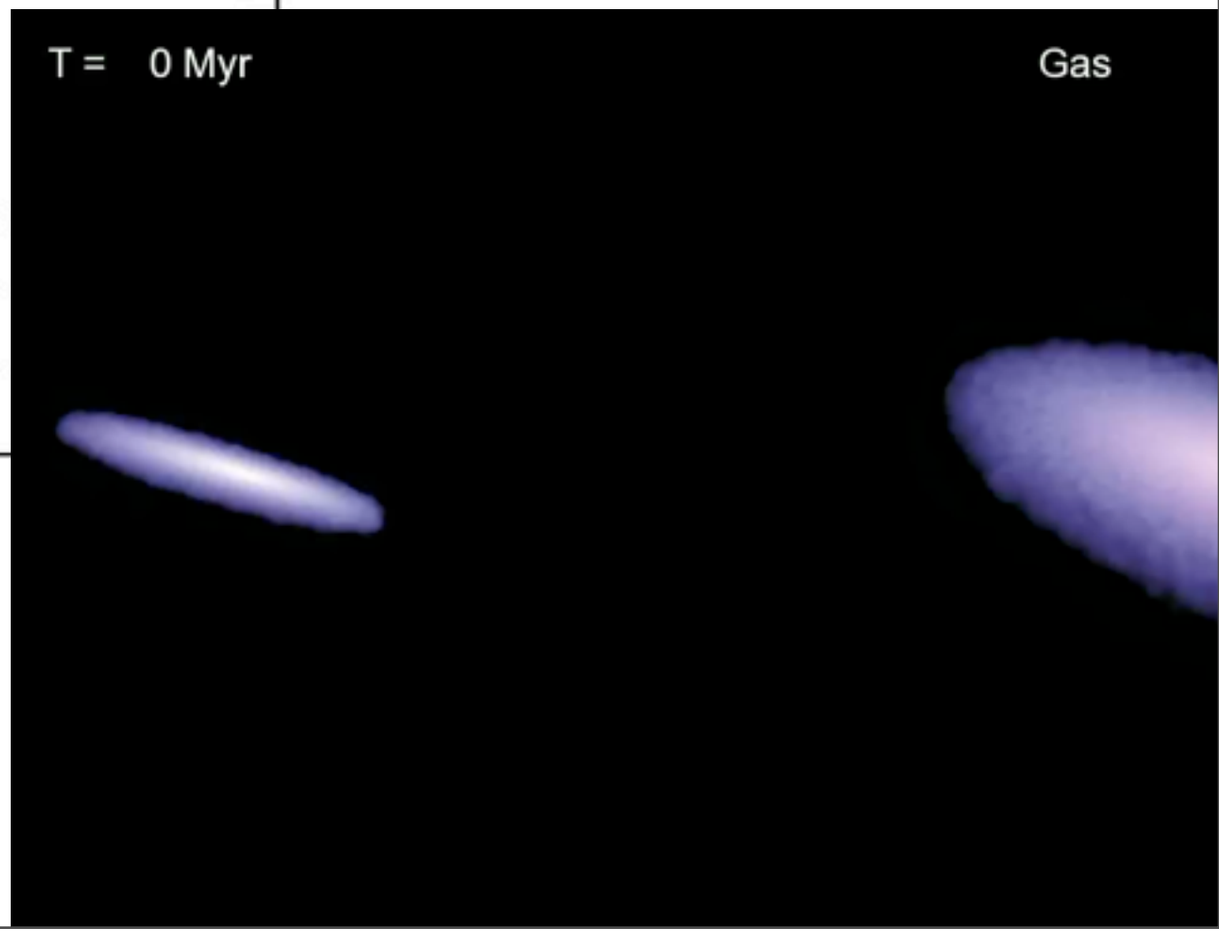
M-sigma Suggests *Self-Regulated* BH Growth

FEEDBACK PREVENTS RUNAWAY BLACK HOLE GROWTH



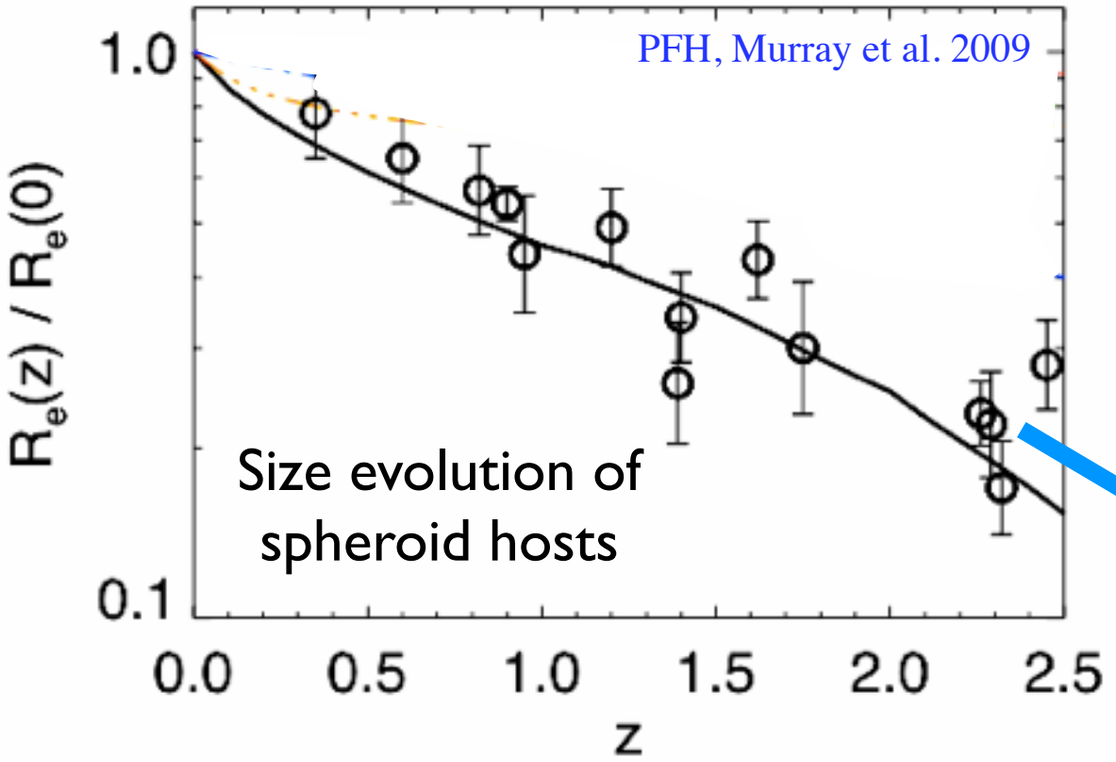
Di Matteo et al., PFH et al. 2005

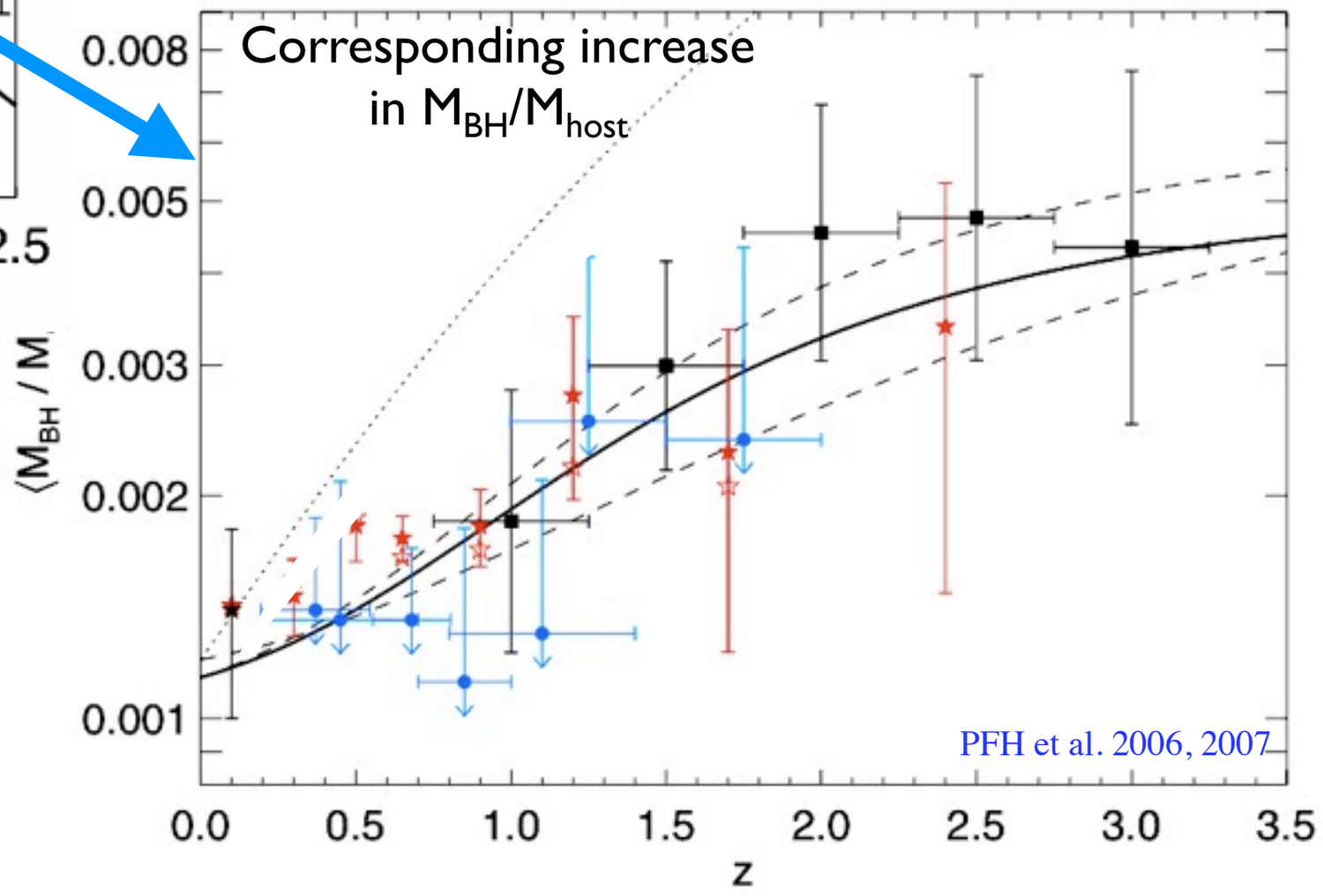




Predictions?

- M_{BH}-σ evolution:
  - Hosts more gas rich/compact at high-z → more "work" for the BH before self-regulation

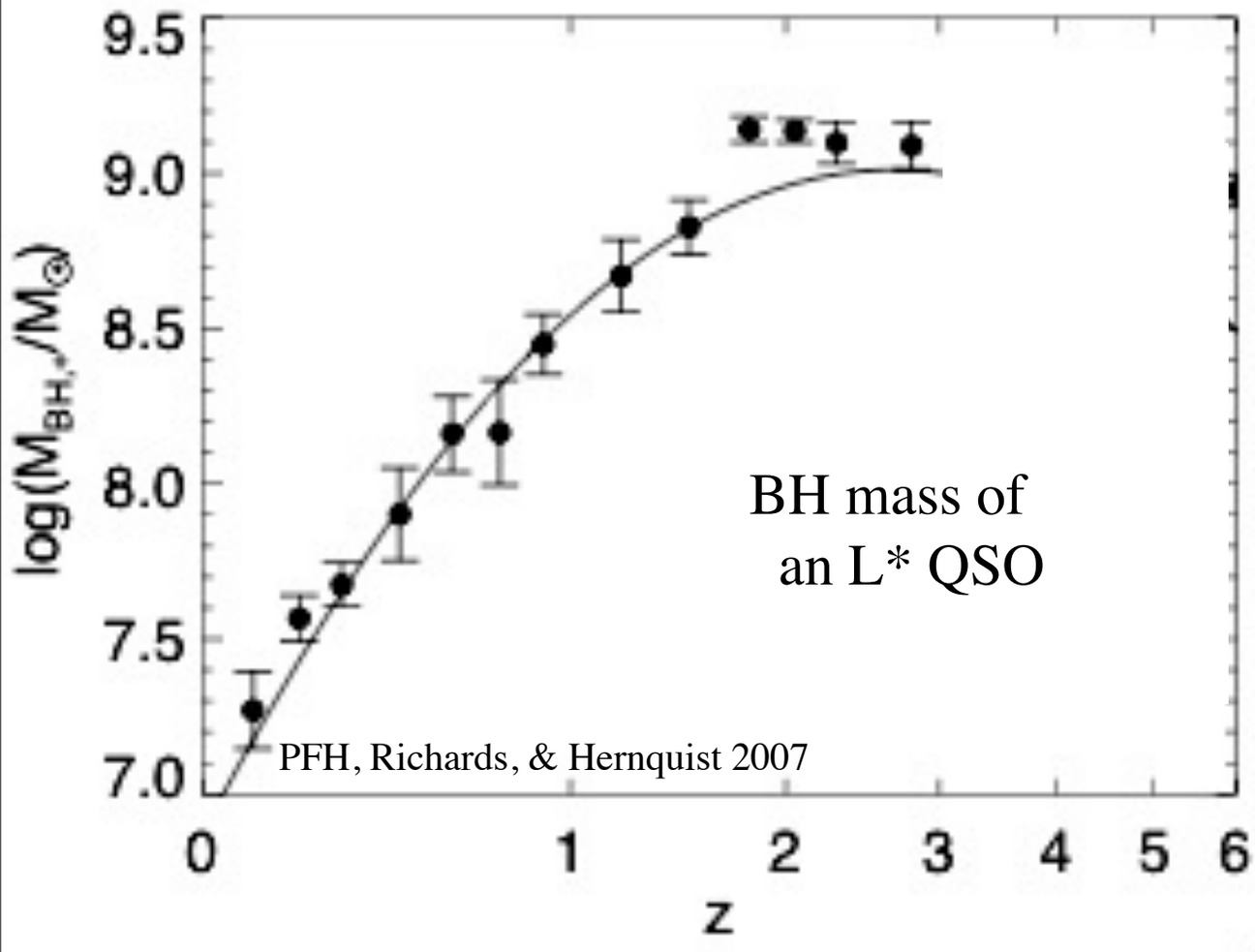


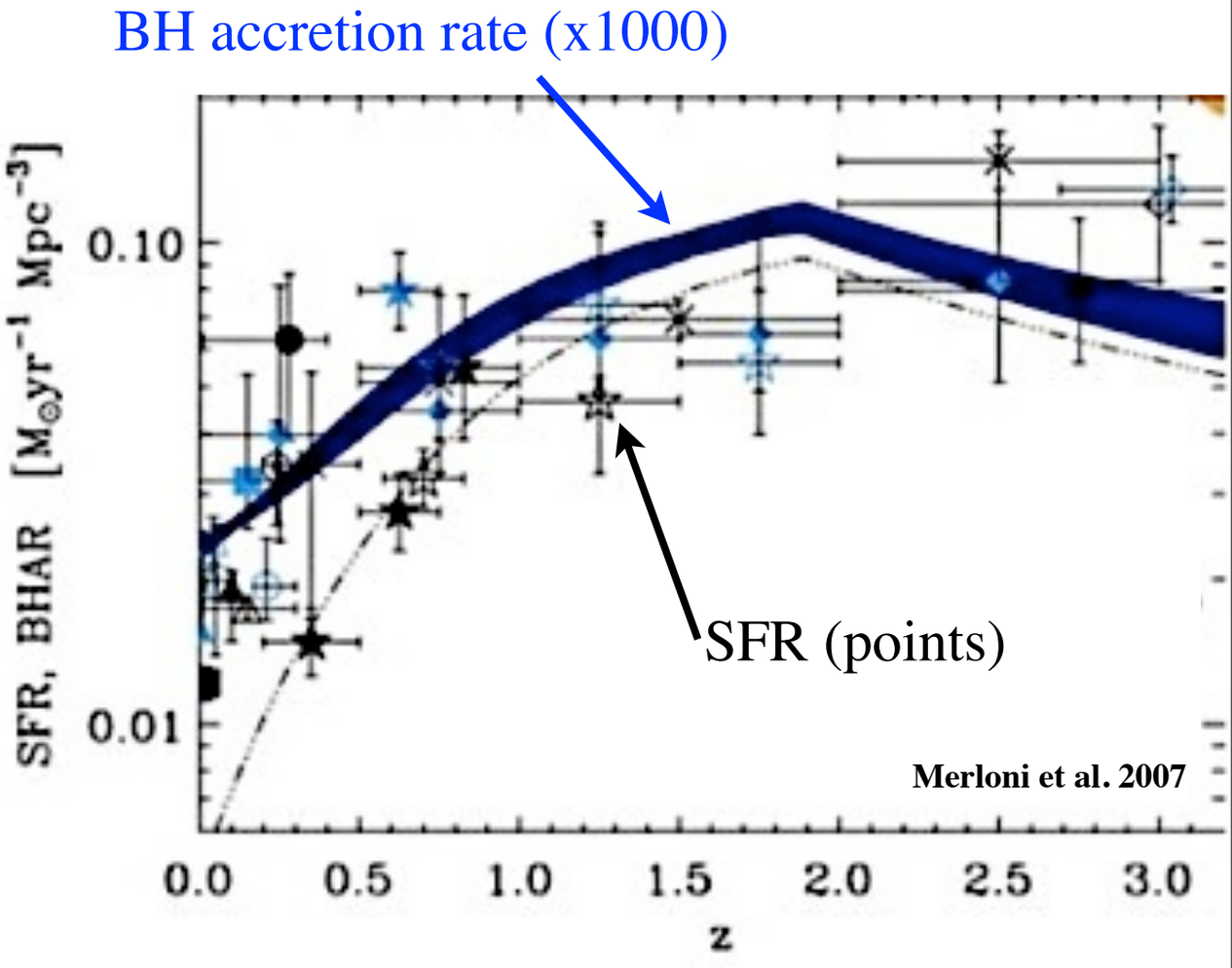


- Doesn't mean that BHs grew "before" their hosts

Co-Evolution falls out naturally:

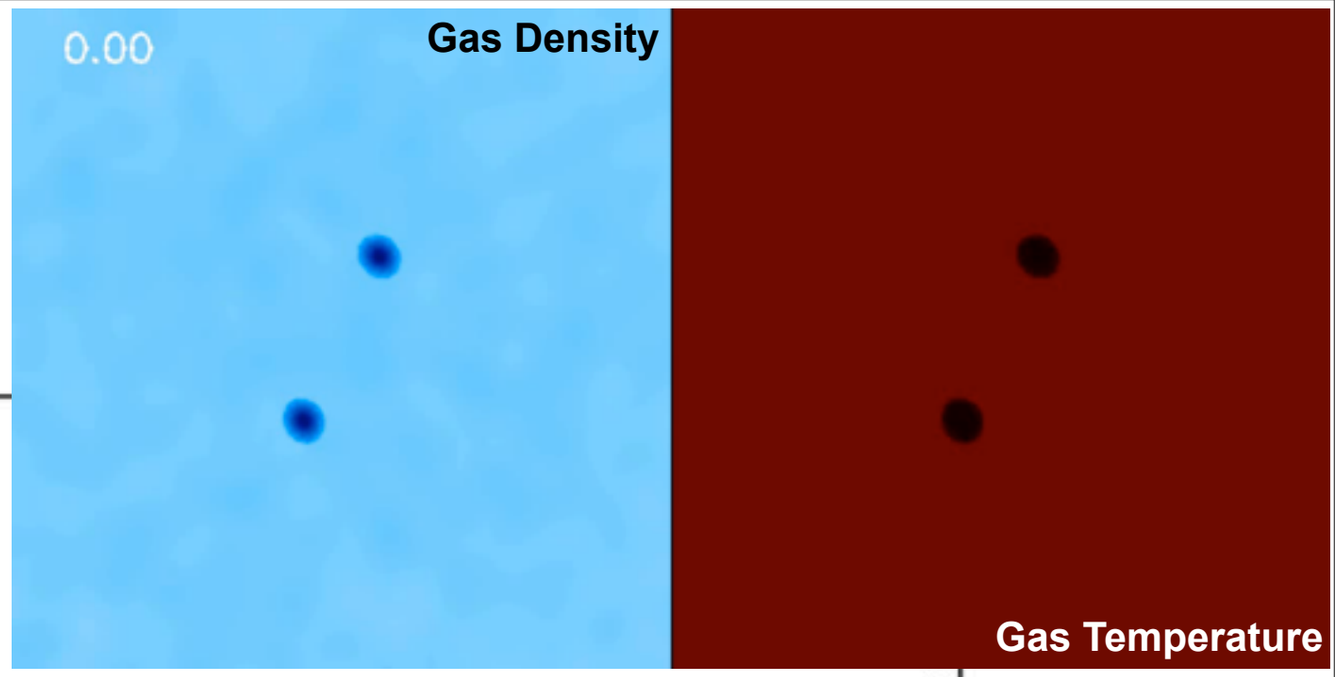
"Downsizing" in BHs and Galaxies is the same:



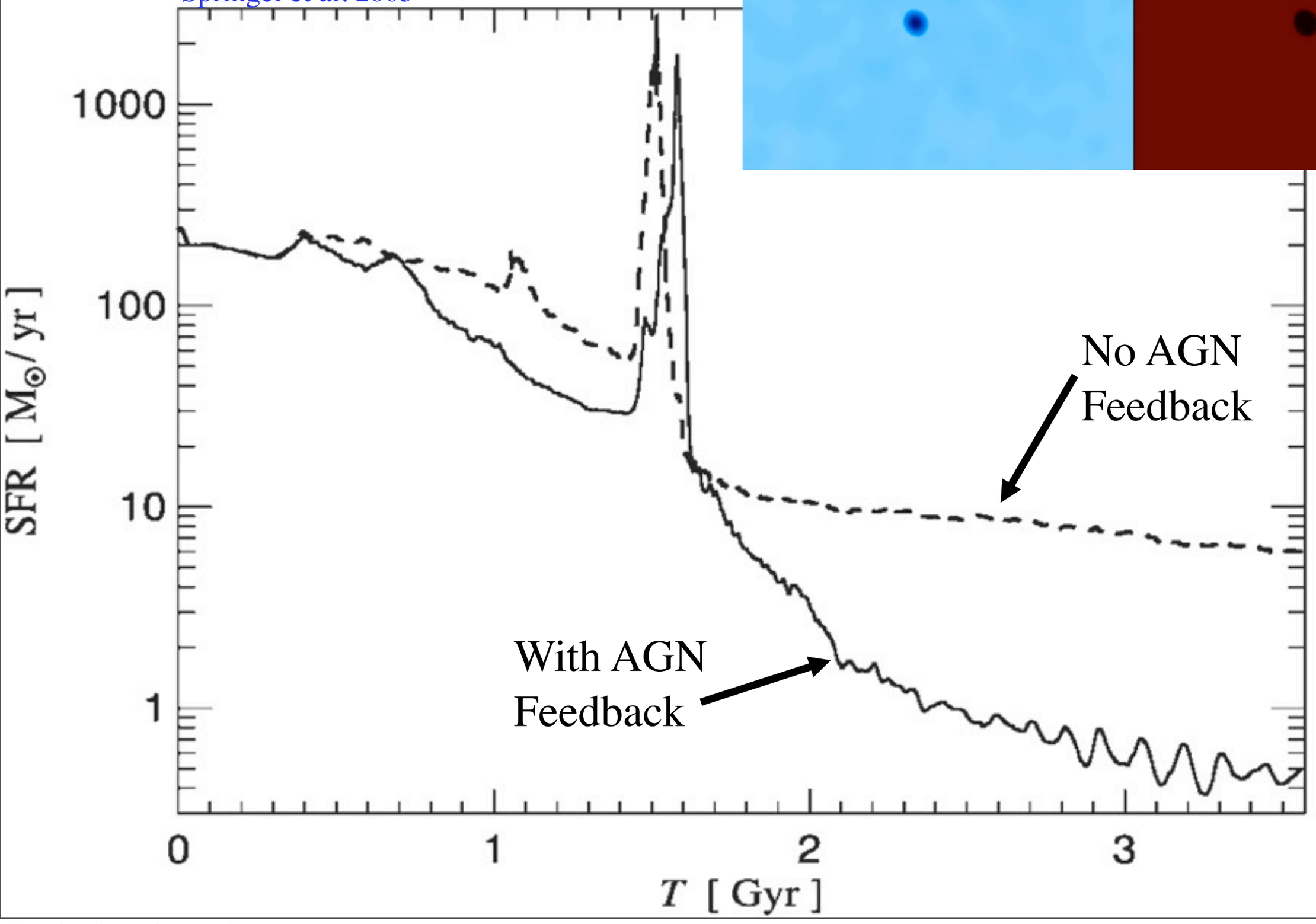


- Provided *self-regulation* exists, average correlations are *independent* of fueling

Helps Ensure Ellipticals are "Red and Dead"

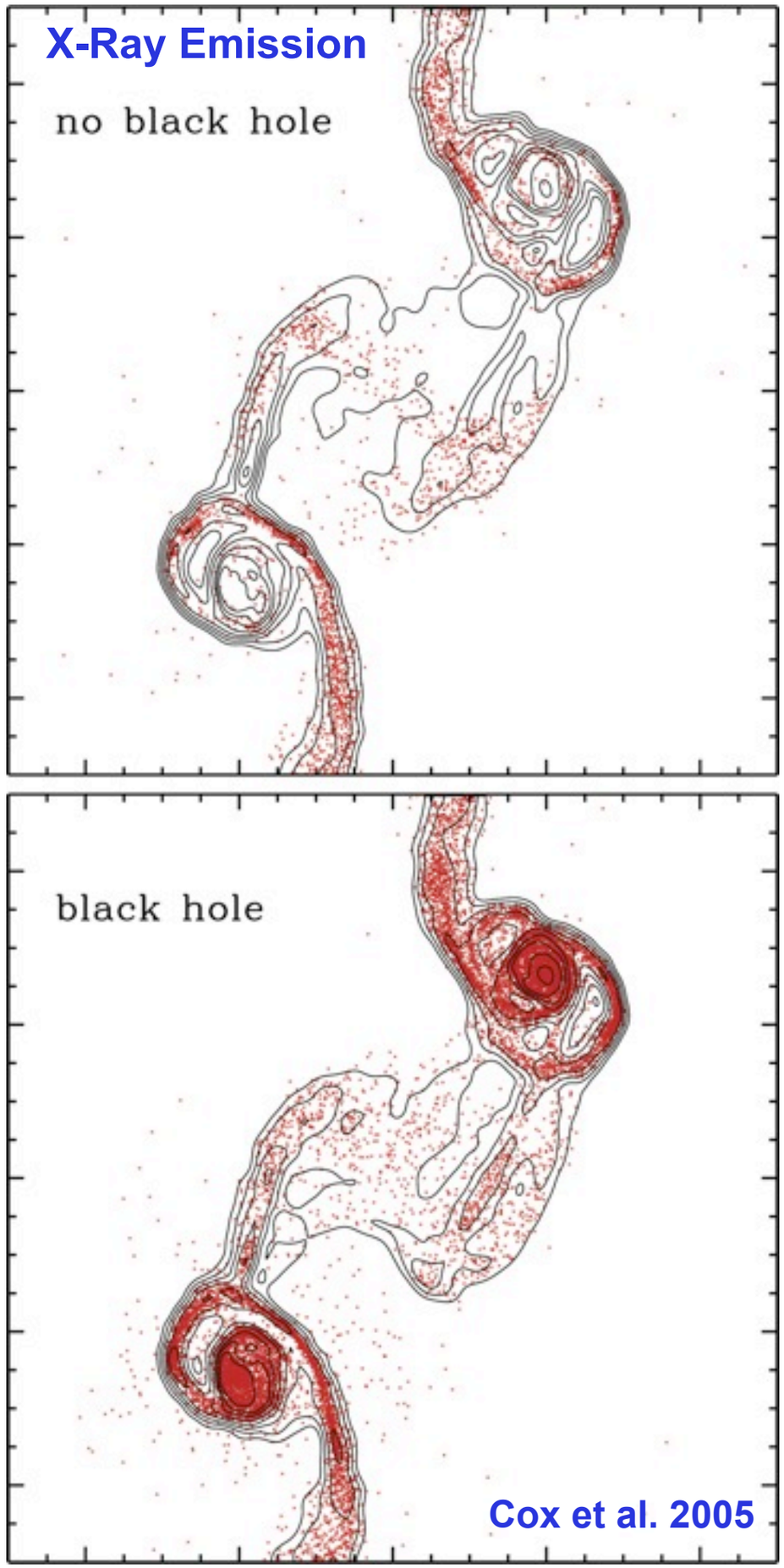


Springel et al. 2005



Feedback-Driven Winds

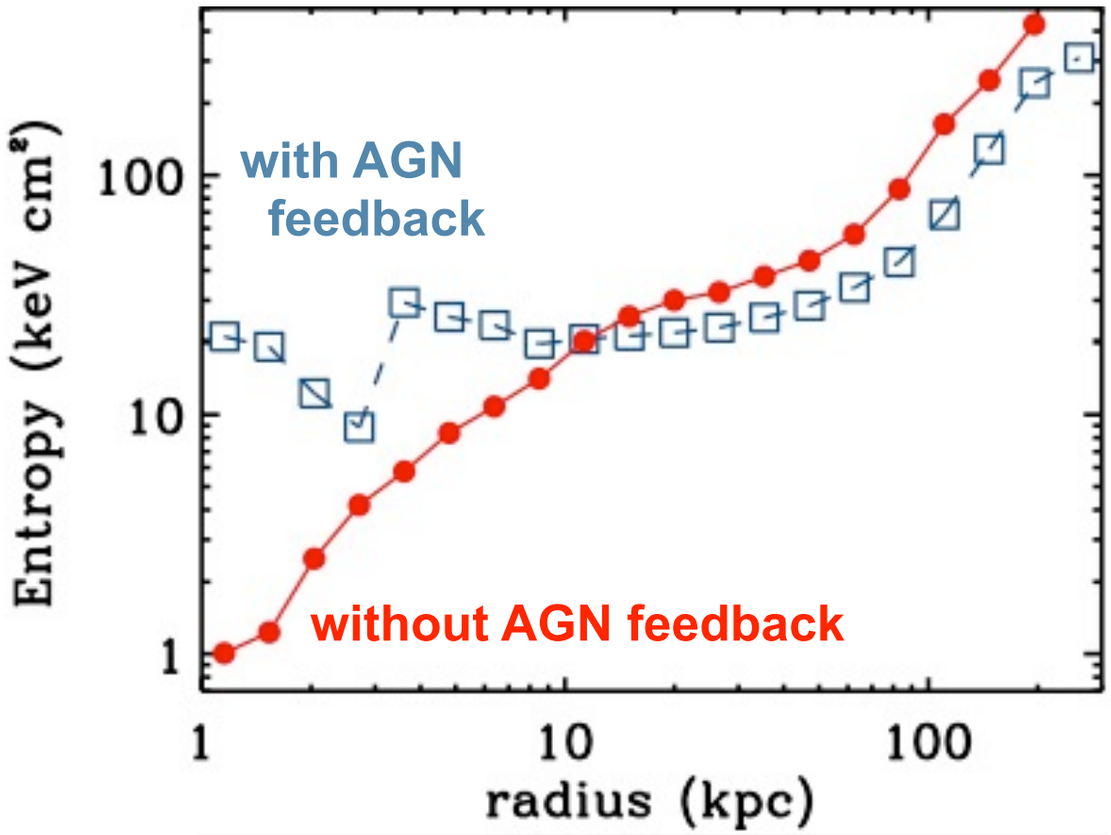
METAL ENRICHMENT & BUILDING THE X-RAY HALO

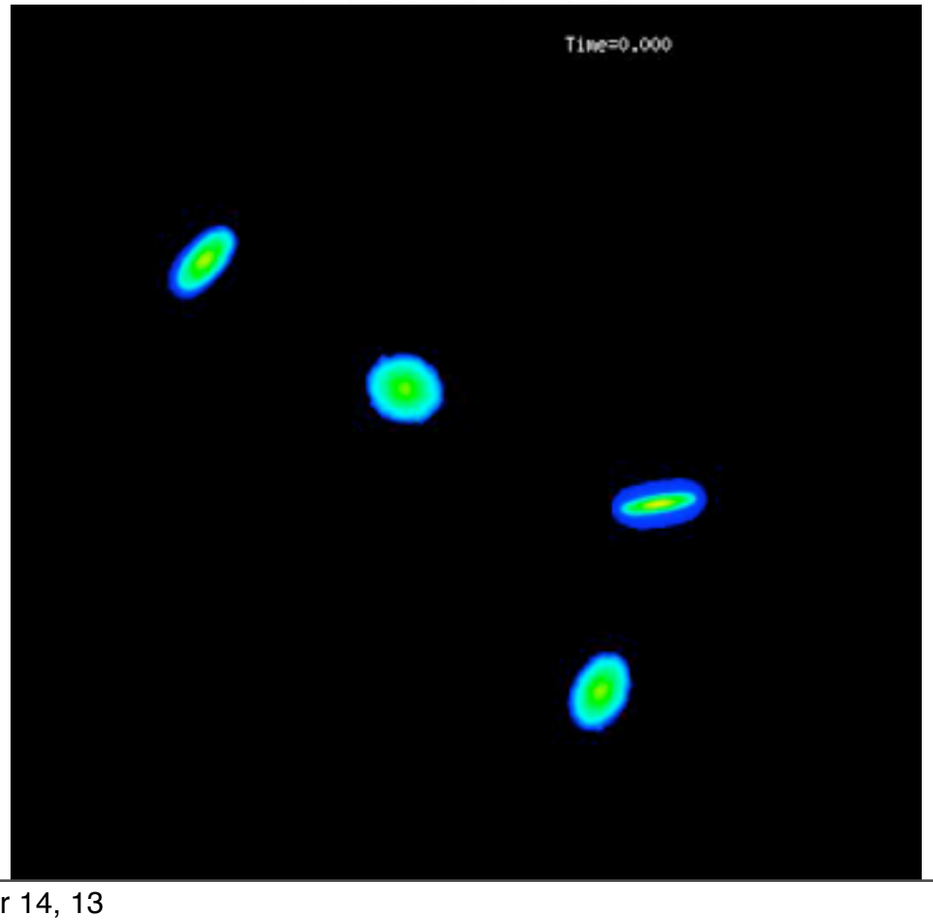


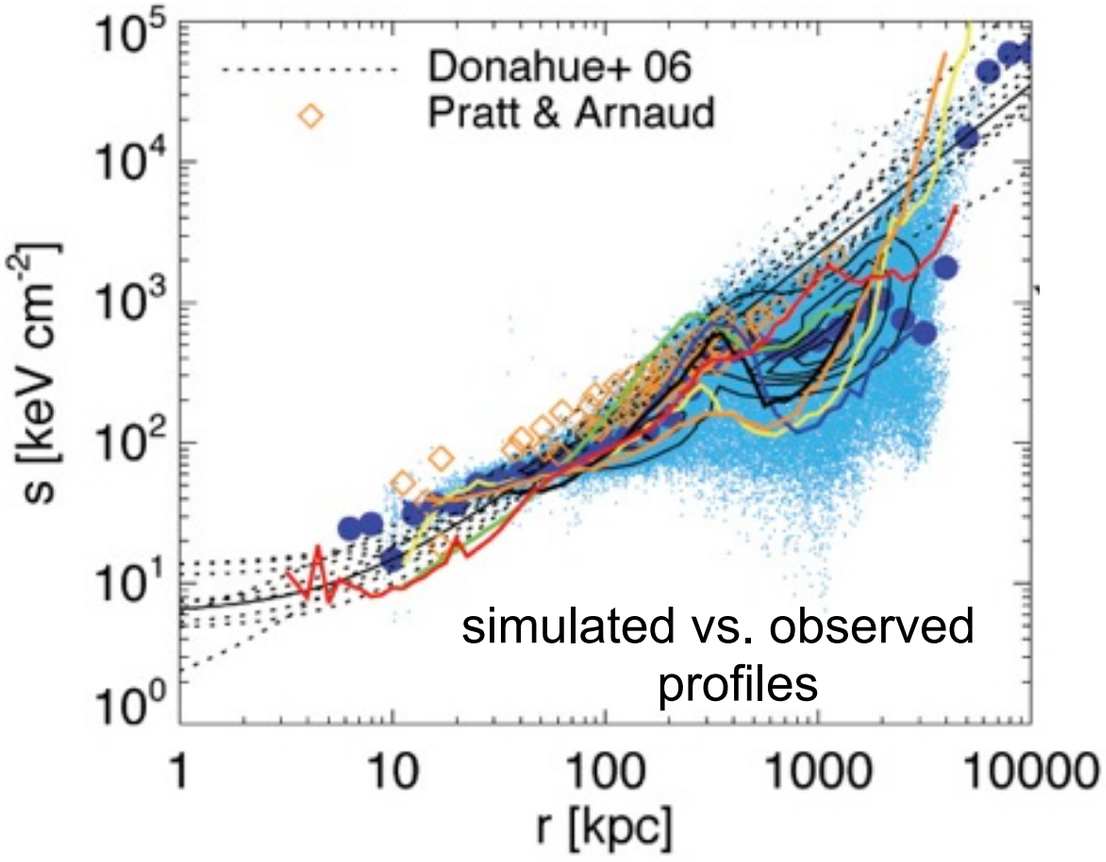
Quasar Outflows May Be Significant for the ICM & IGM

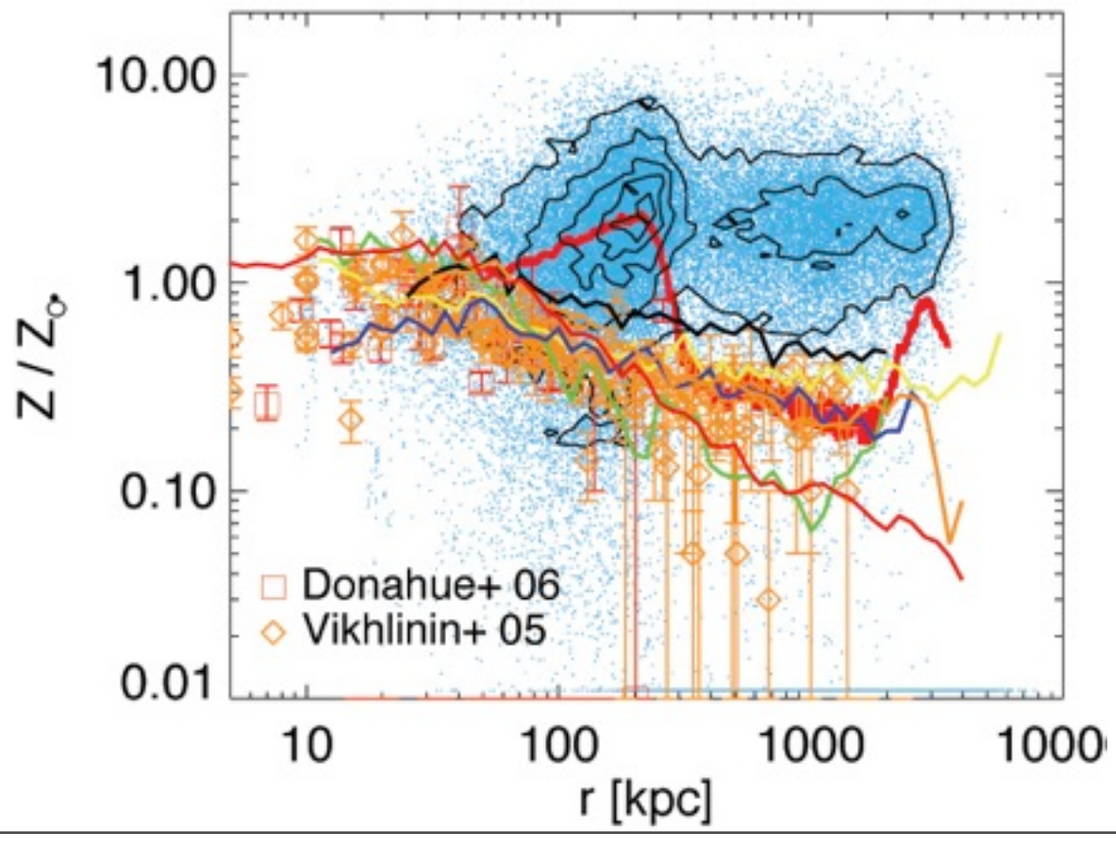
McCarthy et al., Schaye et al. 2011

SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?



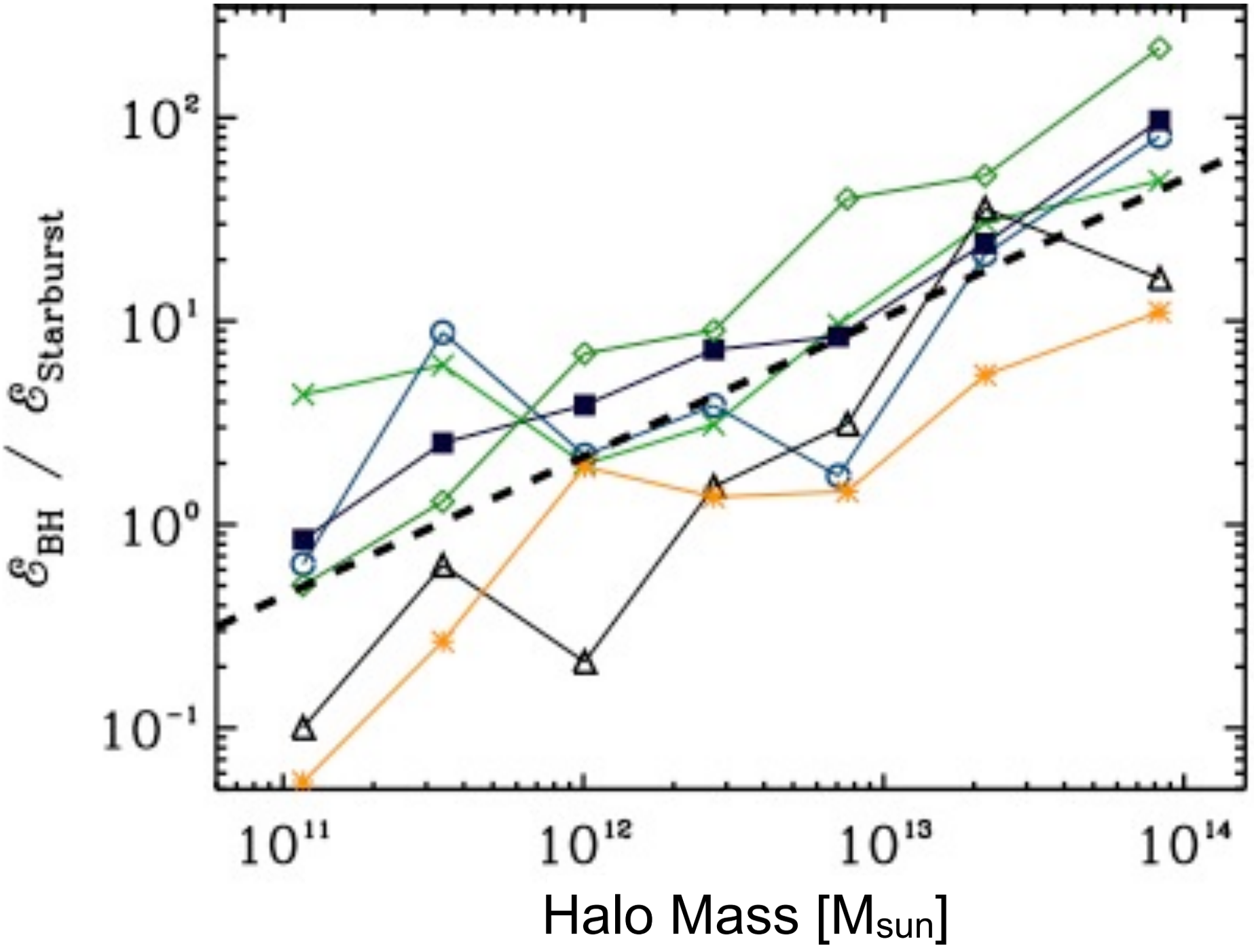






AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?

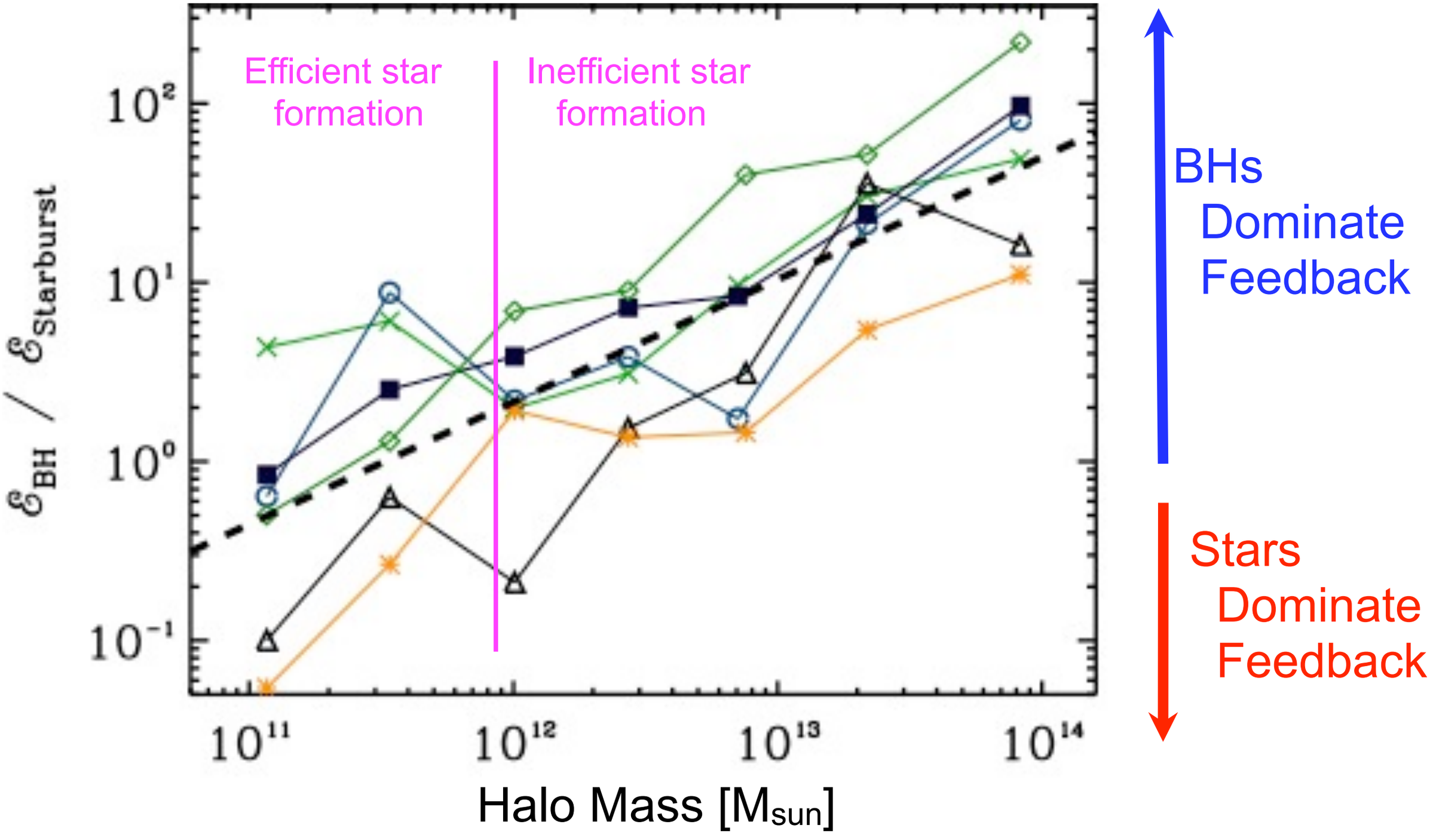


BHs Dominate Feedback

Stars Dominate Feedback

AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?



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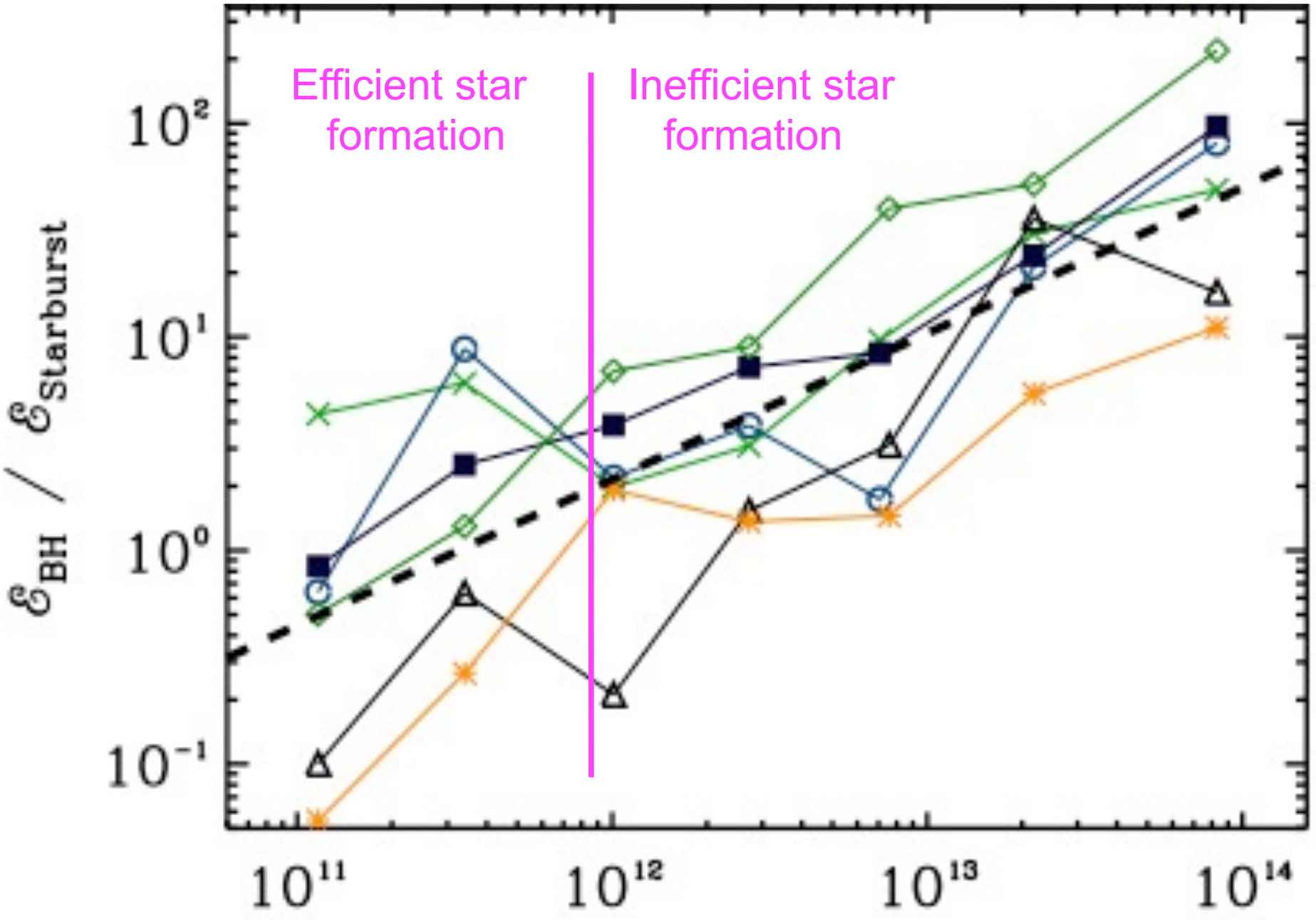


BHs Dominate Feedback

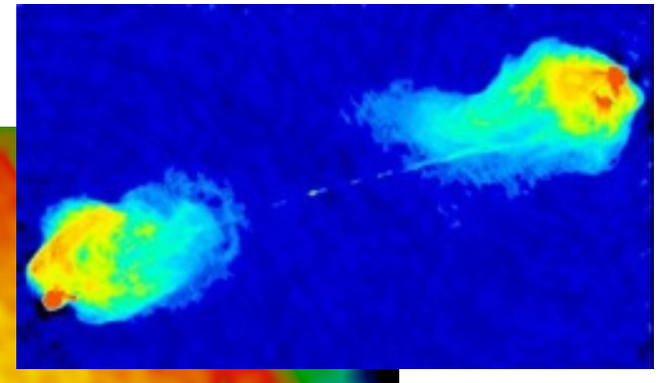
Stars Dominate Feedback

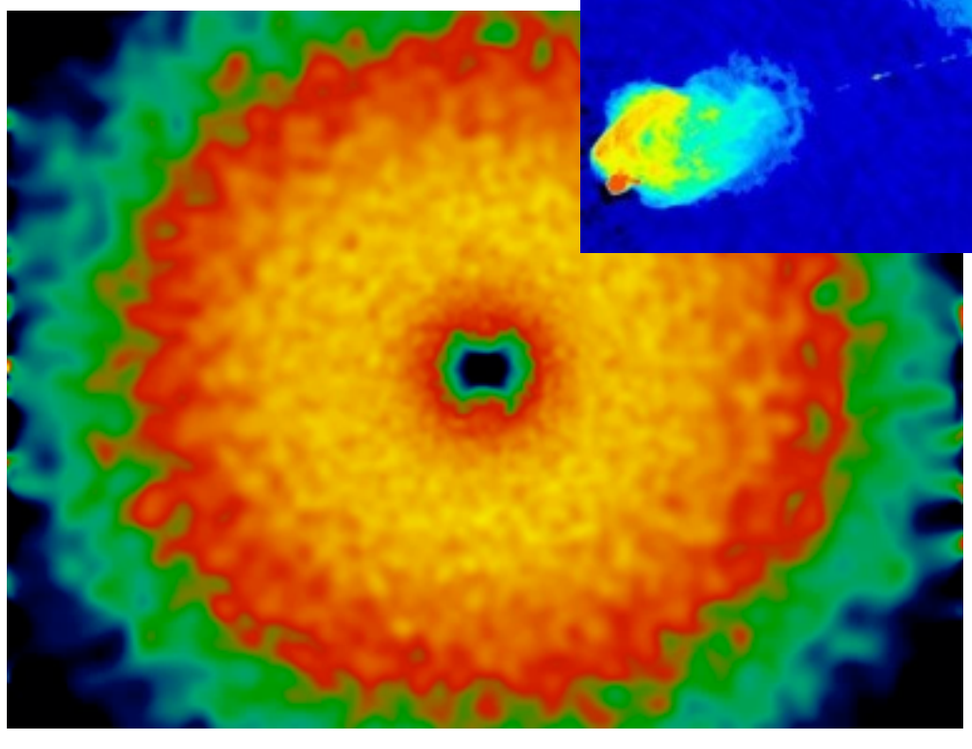
How is this inefficient star formation *maintained*?

“Transition” vs. “Maintenance”

- “**Quasar**” mode (high mdot)
- Move mass from Blue to Red?
- Rapid (~10^7 yr)
- Small(er) scales (~pc-kpc)
- Gas-rich/Dissipational Mergers?
- Regulates *Black Hole* Mass

- “**Radio**” mode (low mdot)
- Keep it Red
- Long-lived (~Hubble time)
- Large (~halo) scales
- Hot Halos & Dry Mergers
- Regulates *Galaxy* Mass

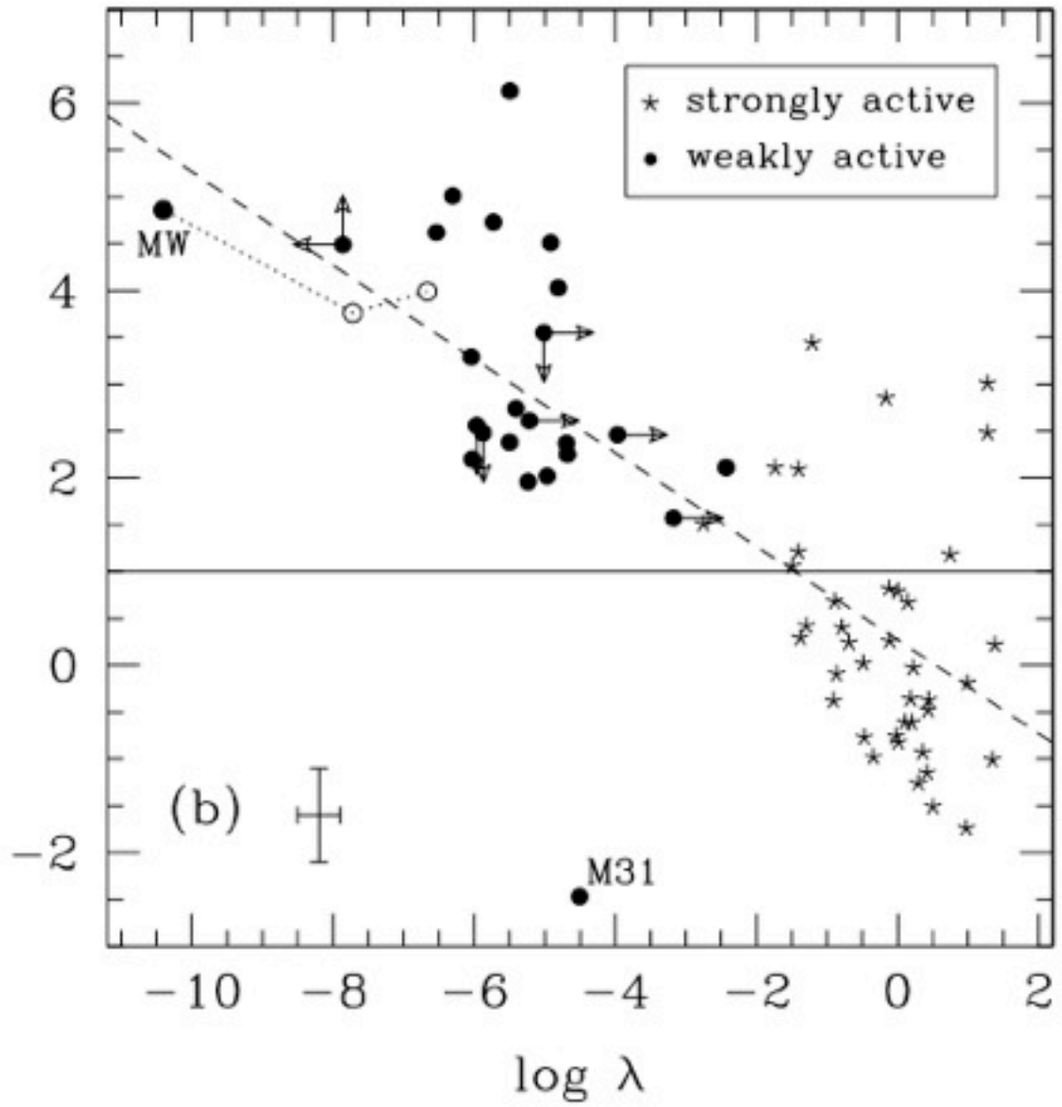




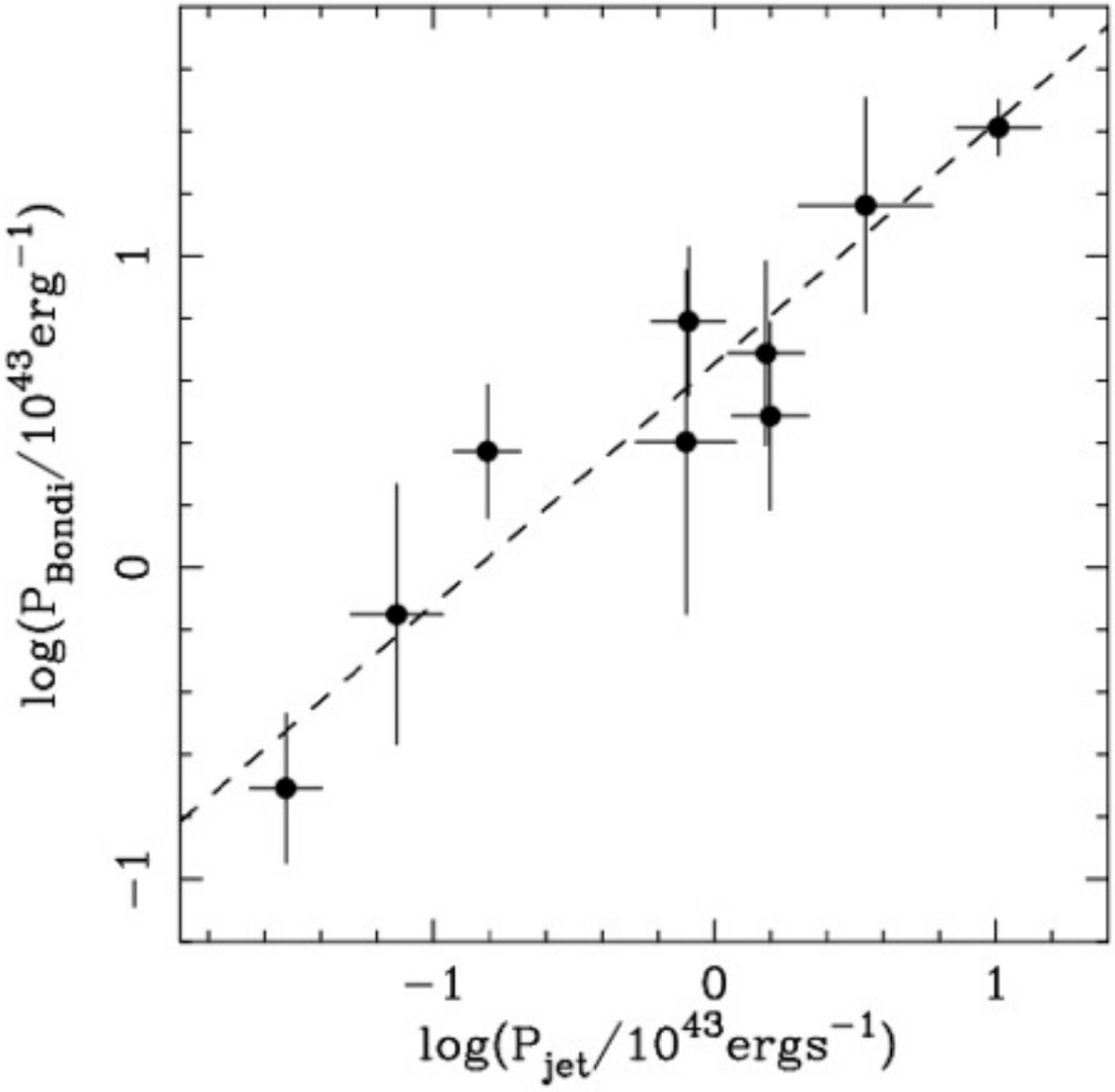
Maintenance Mode

IS IT ALSO "RADIO"-MODE?

Ho: P(radio) versus Eddington ratio:



Allen: P(jet) versus P(accretion):

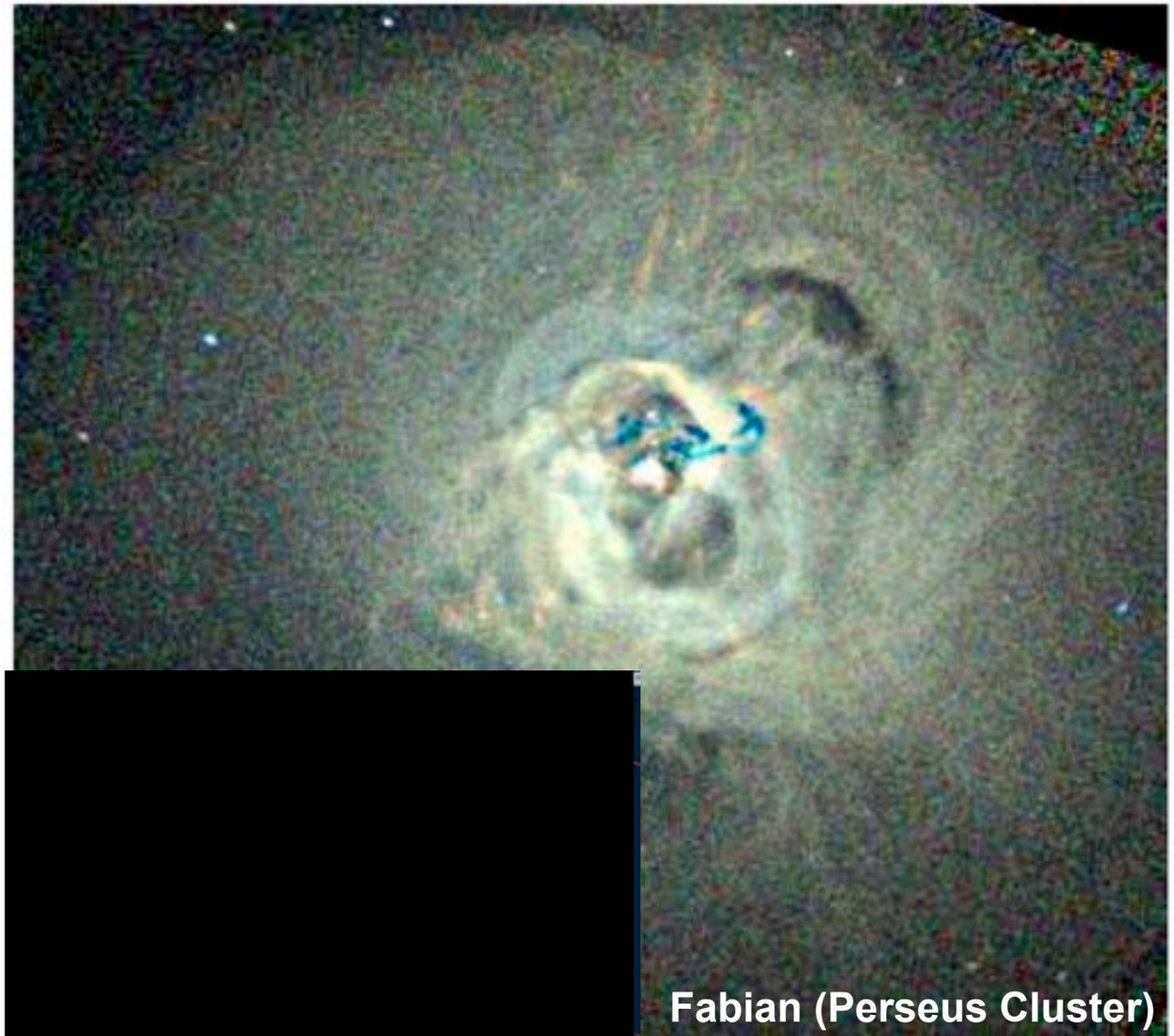


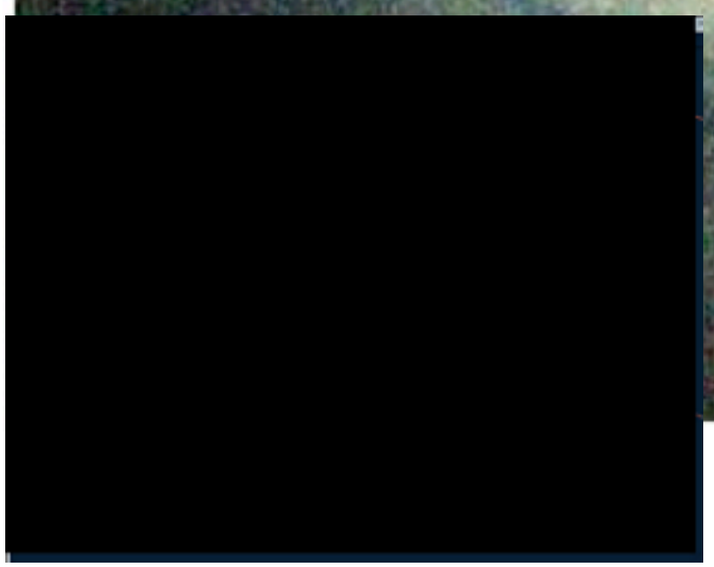
- Observational constraints on the power involved are leading the way

Maintenance Mode

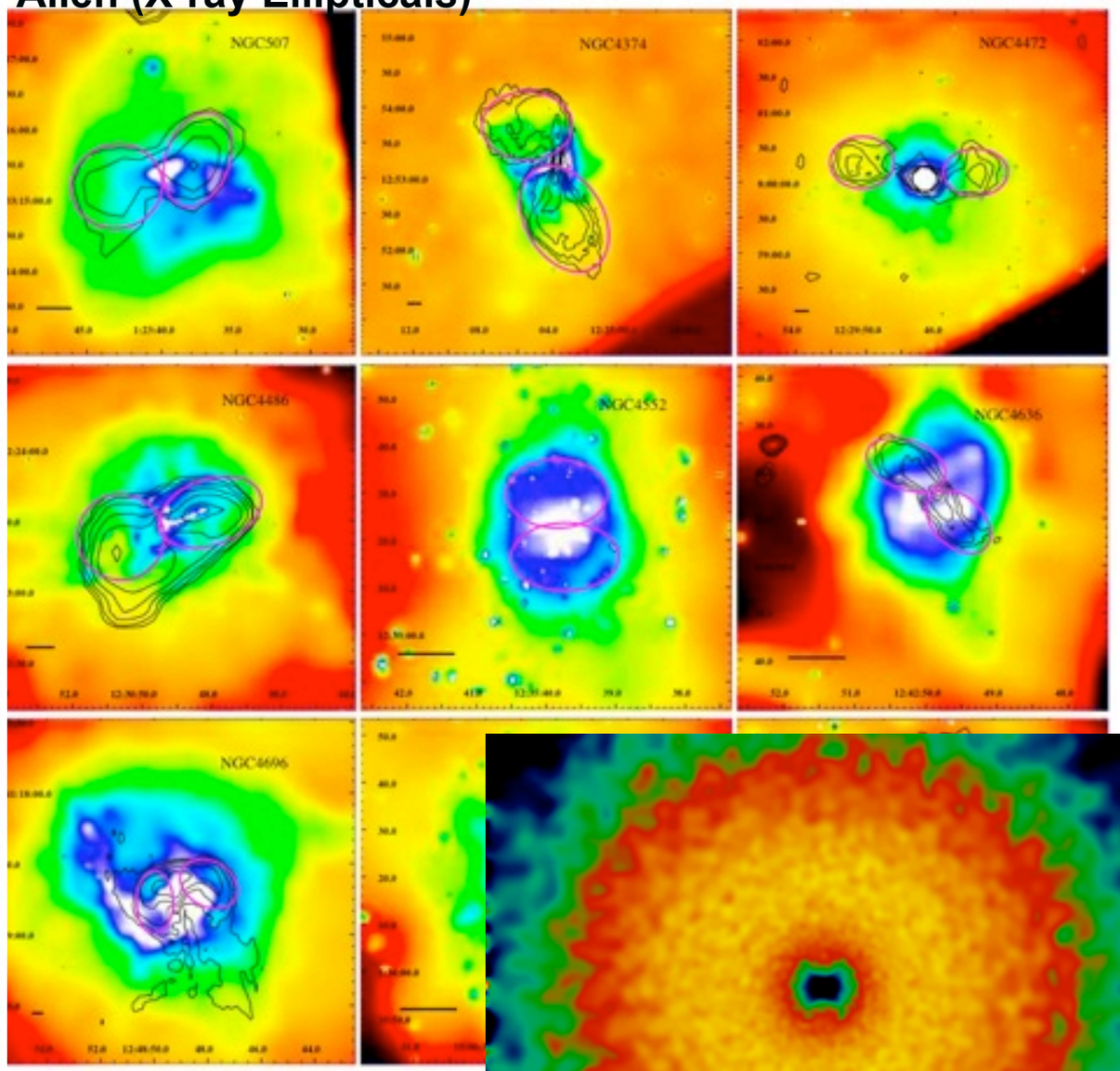
IS IT ALSO "RADIO"-MODE?

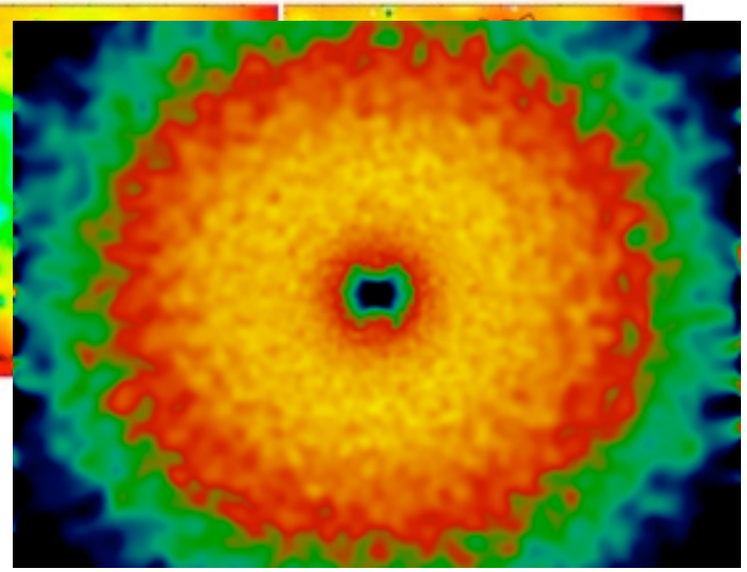
- Know that (non-cooling flow) clusters do look "pre-heated"...
  but we also *see* radio jets doing work:
- What is "typical"?

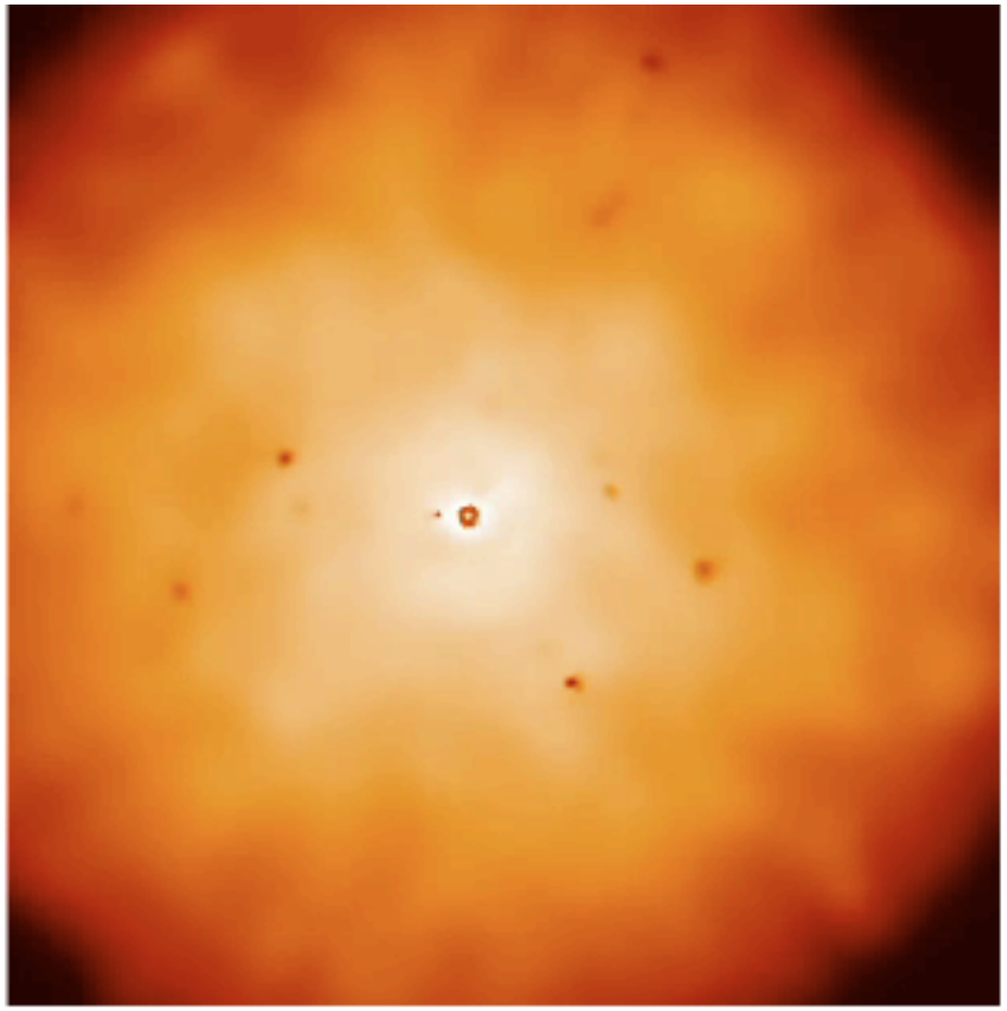


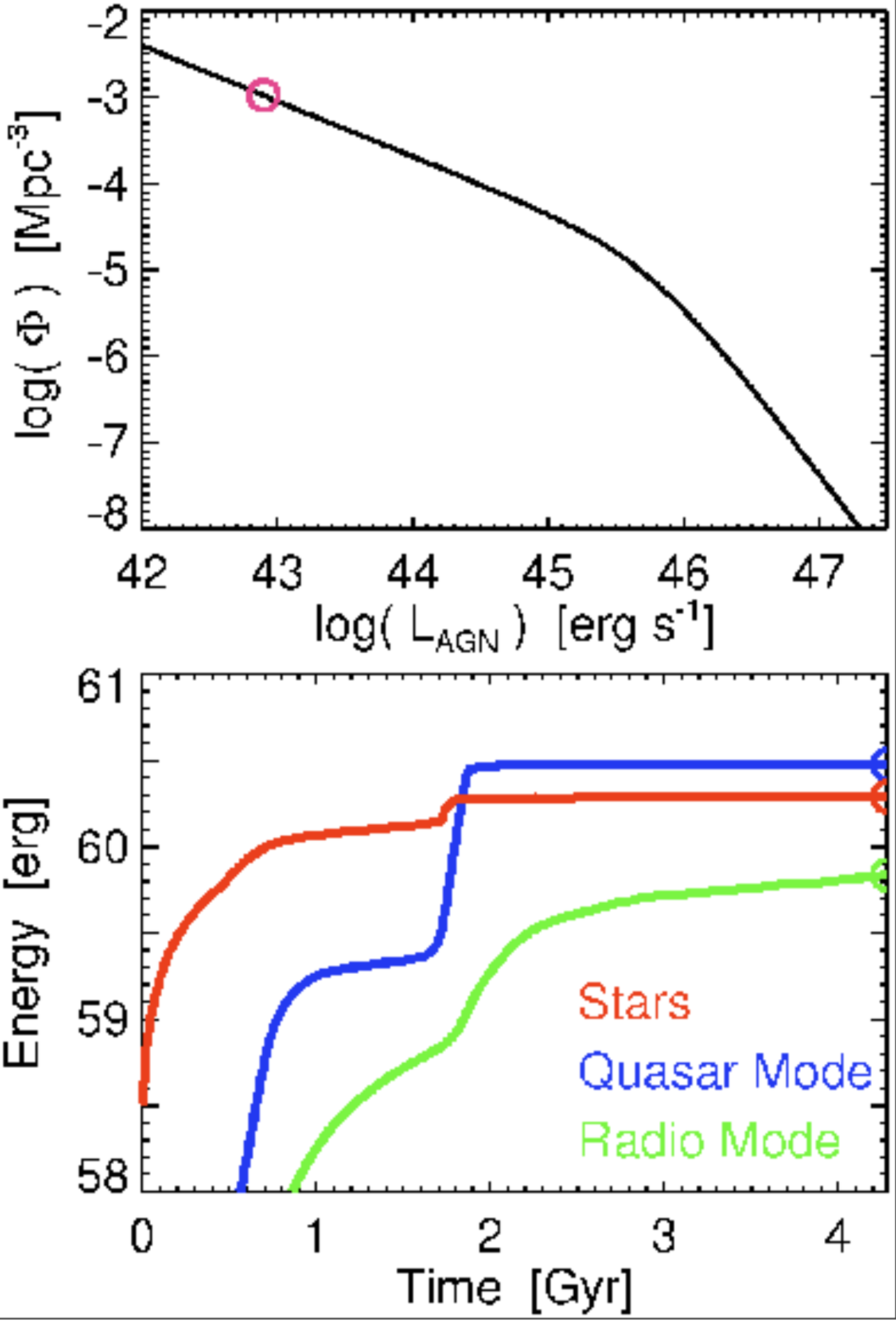


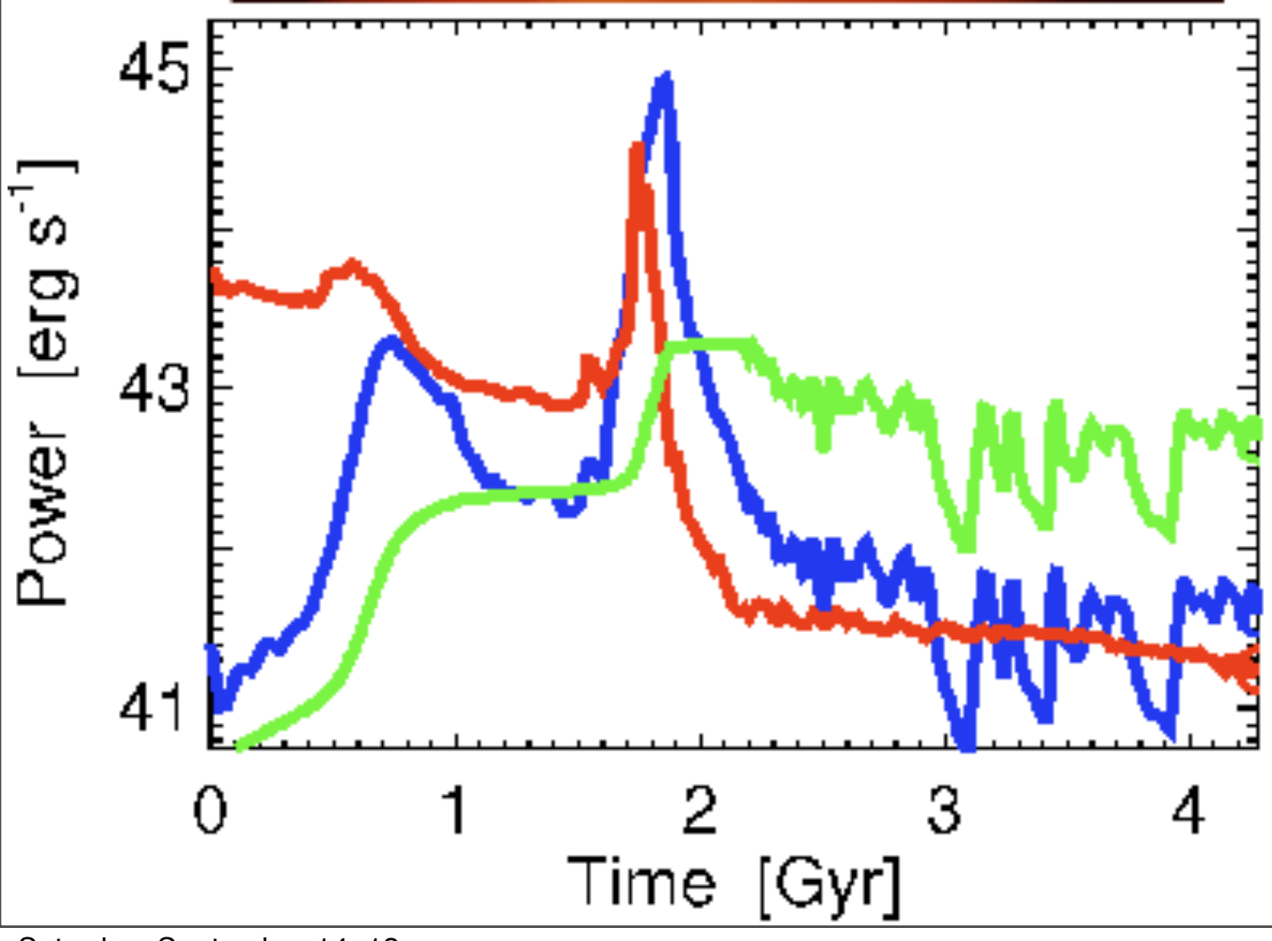
Allen (X-ray Ellipticals)

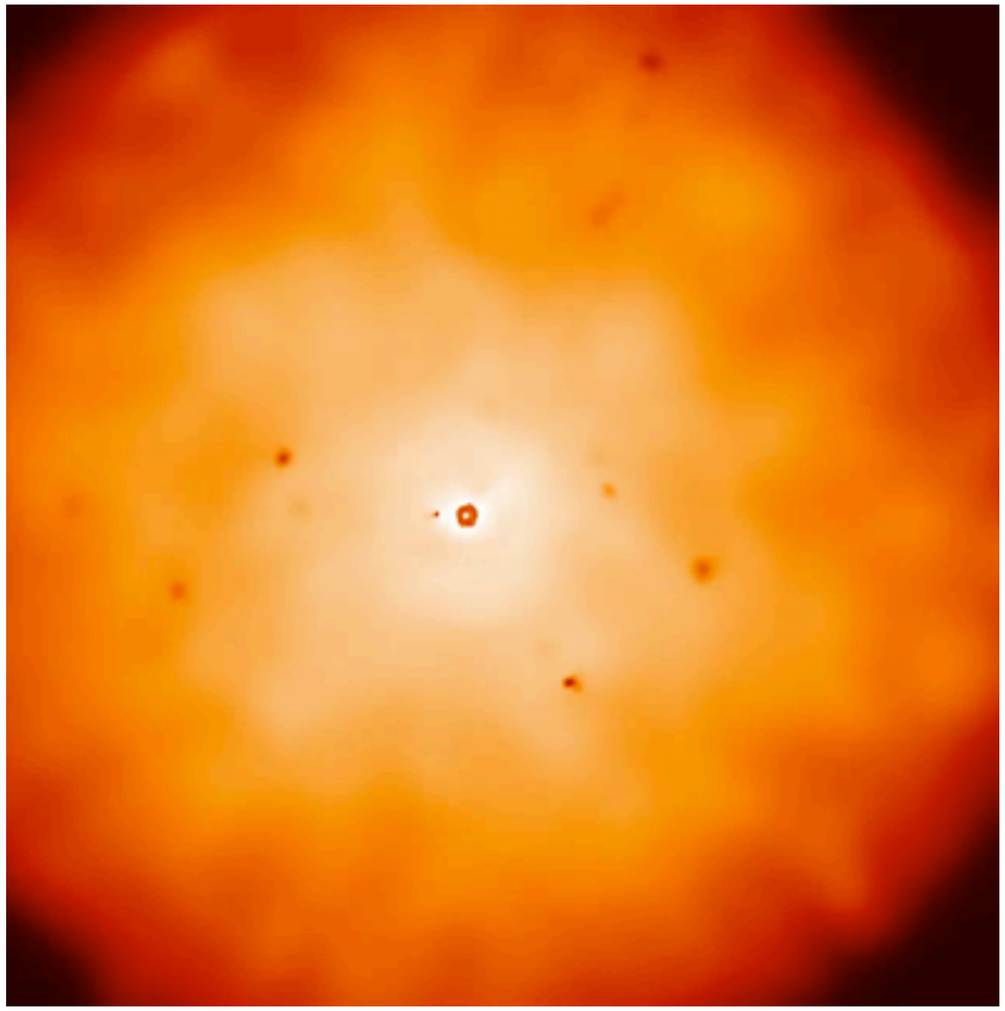


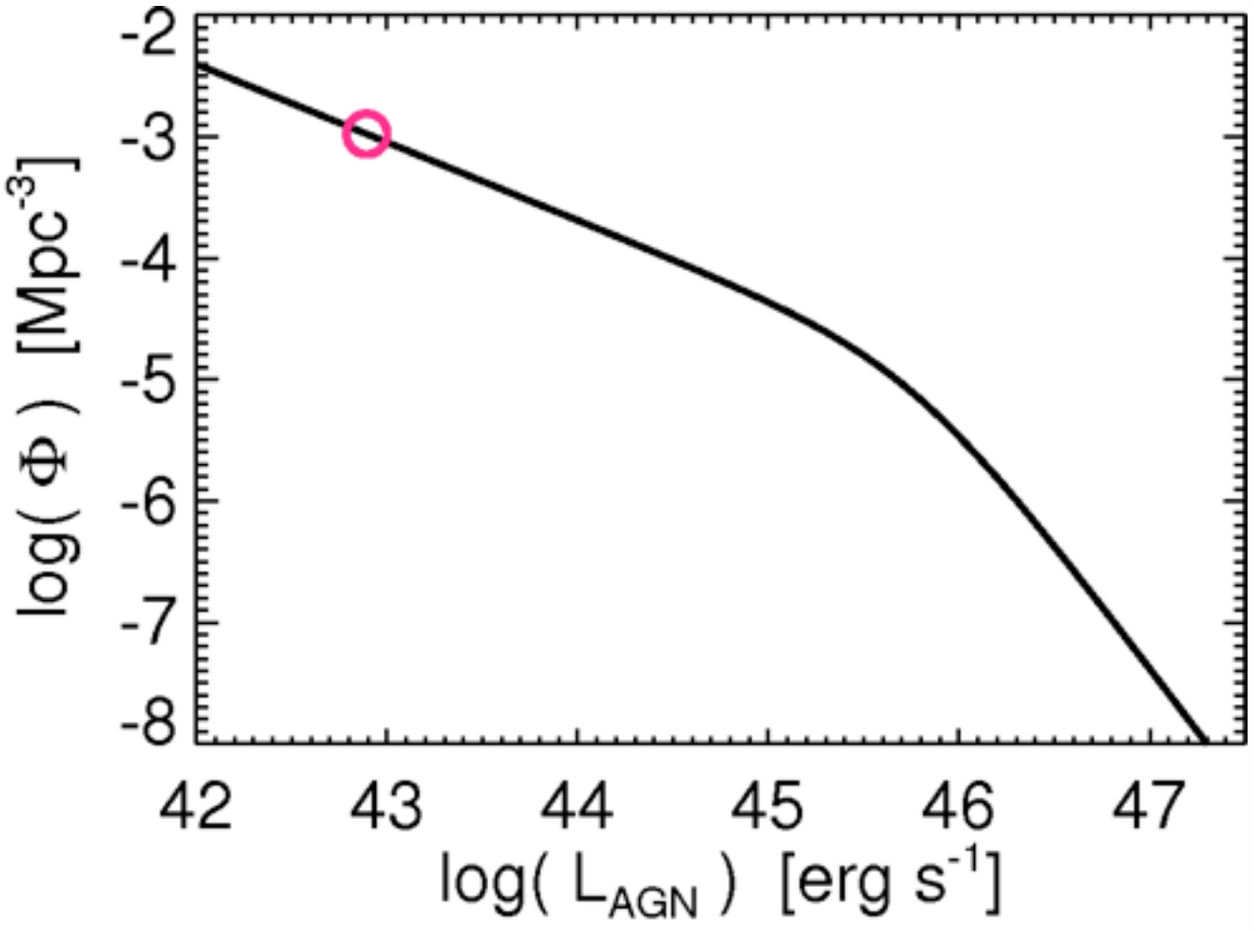


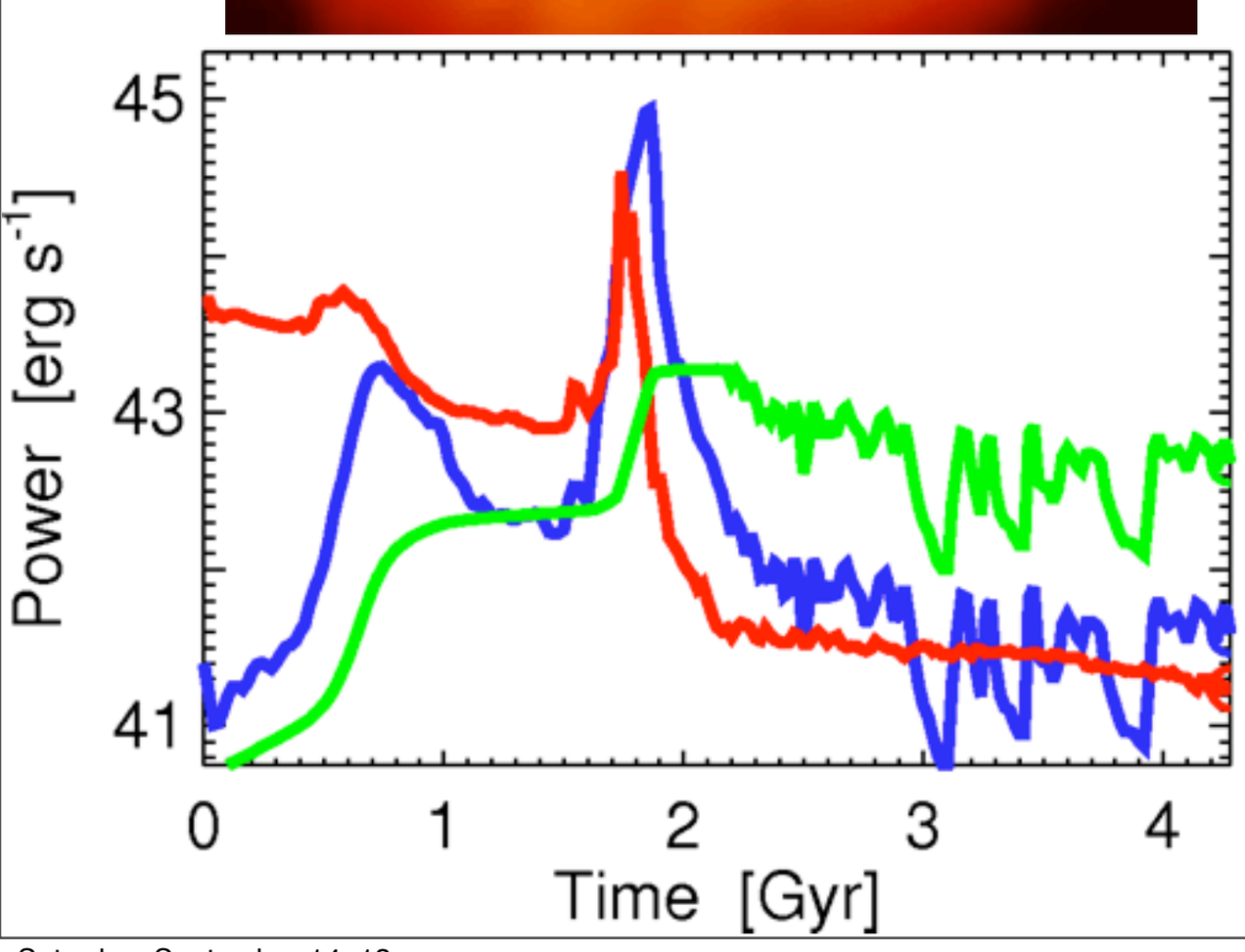


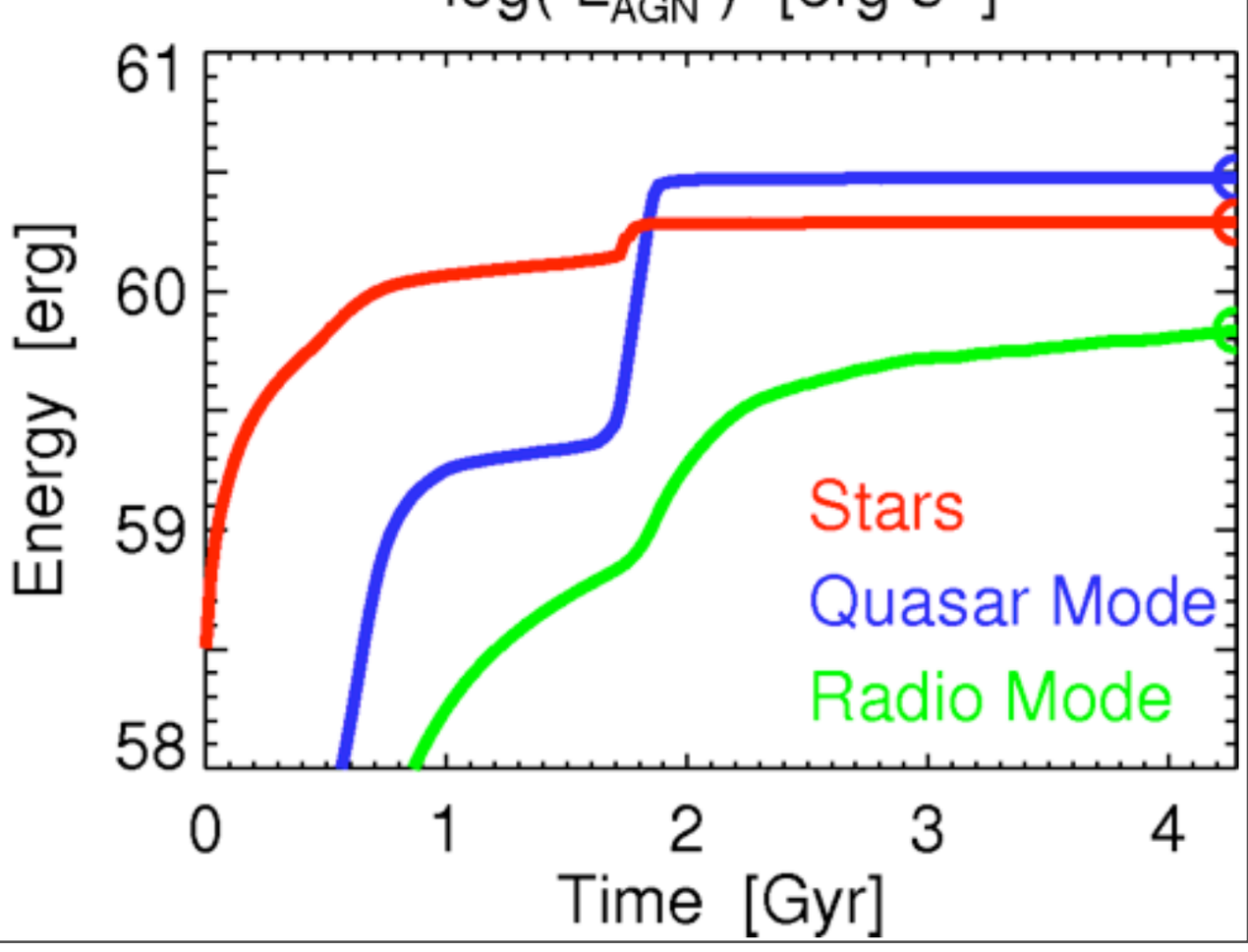

log(Φ) [Mpc^{-3}]
-2
-3
-4
-5
-6
-7
-8
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]
61
60
59
58
Energy [erg]
Stars
Quasar Mode
Radio Mode
0
1
2
3
4
Time [Gyr]


45
43
41
Power [erg s^{-1}]
0
1
2
3
4
Time [Gyr]

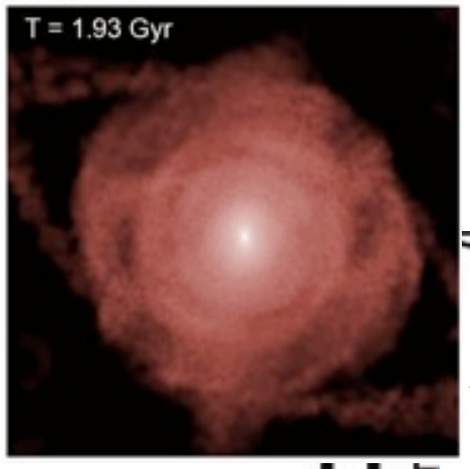


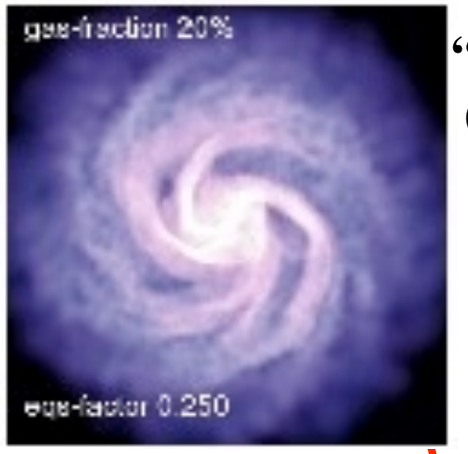

-2
-3
-4
-5
-6
-7
-8
log(Φ) [Mpc^{-3}]
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]


45
43
41
Power [erg s^{-1}]
0
1
2
3
4
Time [Gyr]

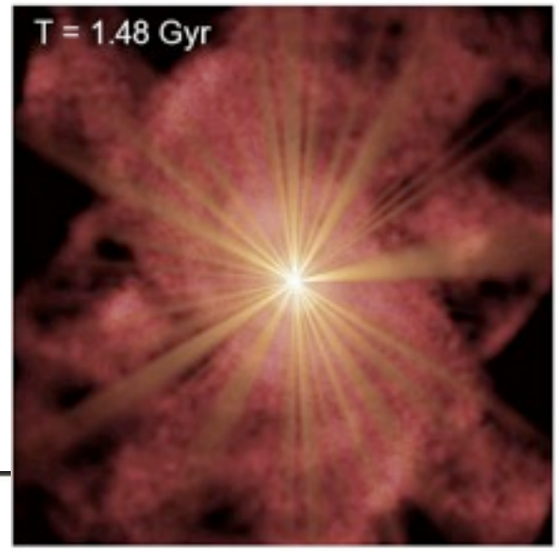

61
60
59
58
Energy [erg]
Stars
Quasar Mode
Radio Mode
0
1
2
3
4
Time [Gyr]

"Dead" Bulges (stellar wind/hot gas halo accretion)

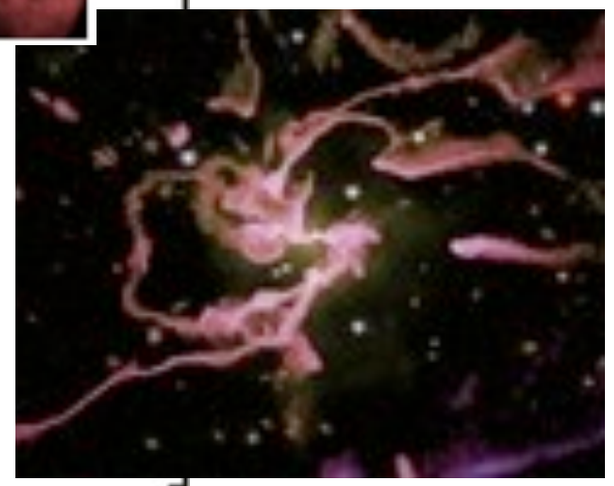




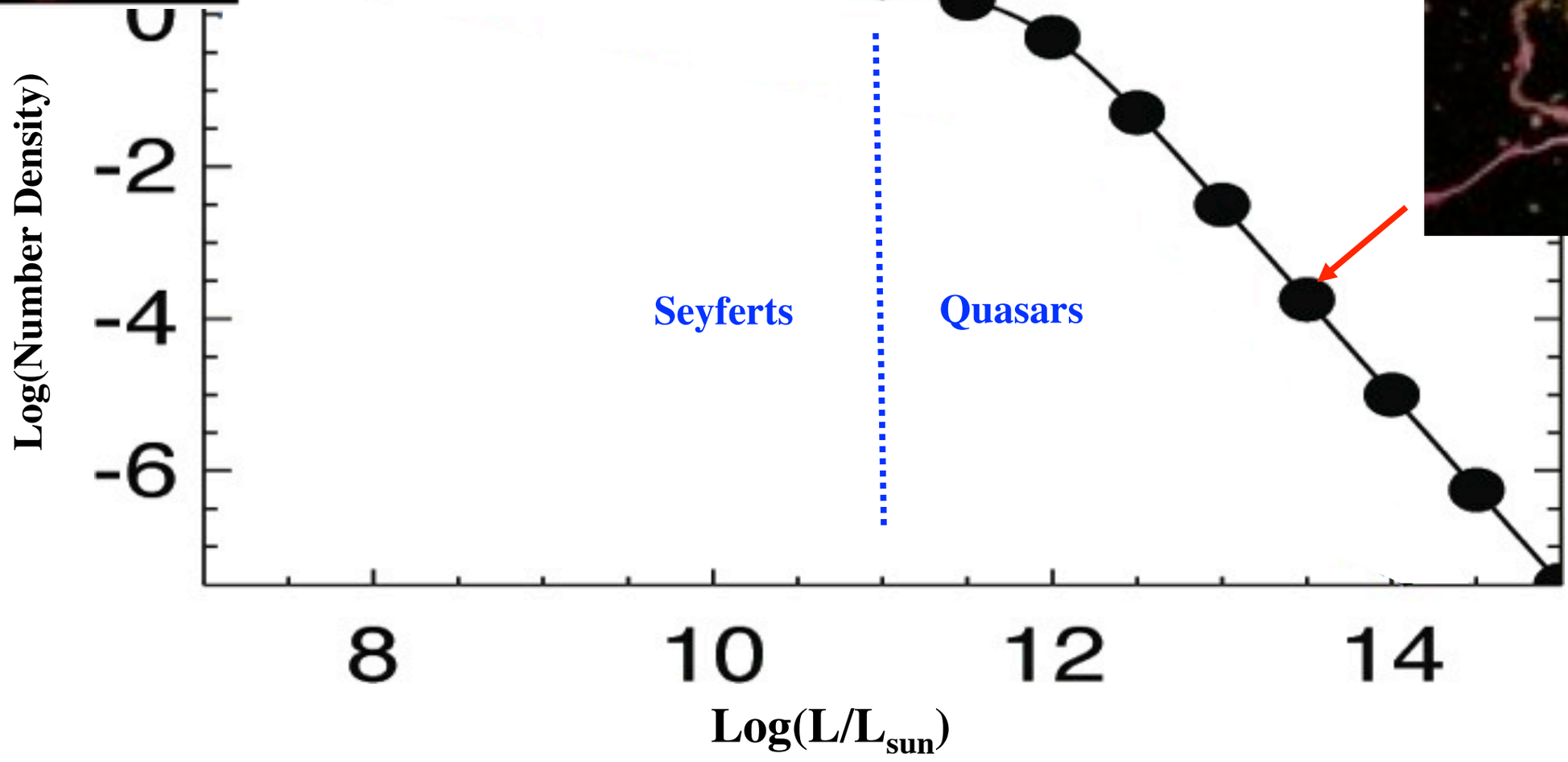
"Seyferts" (disk-dominated, secular/minor mergers)



"Fading" Mergers (post-starburst spheroids)



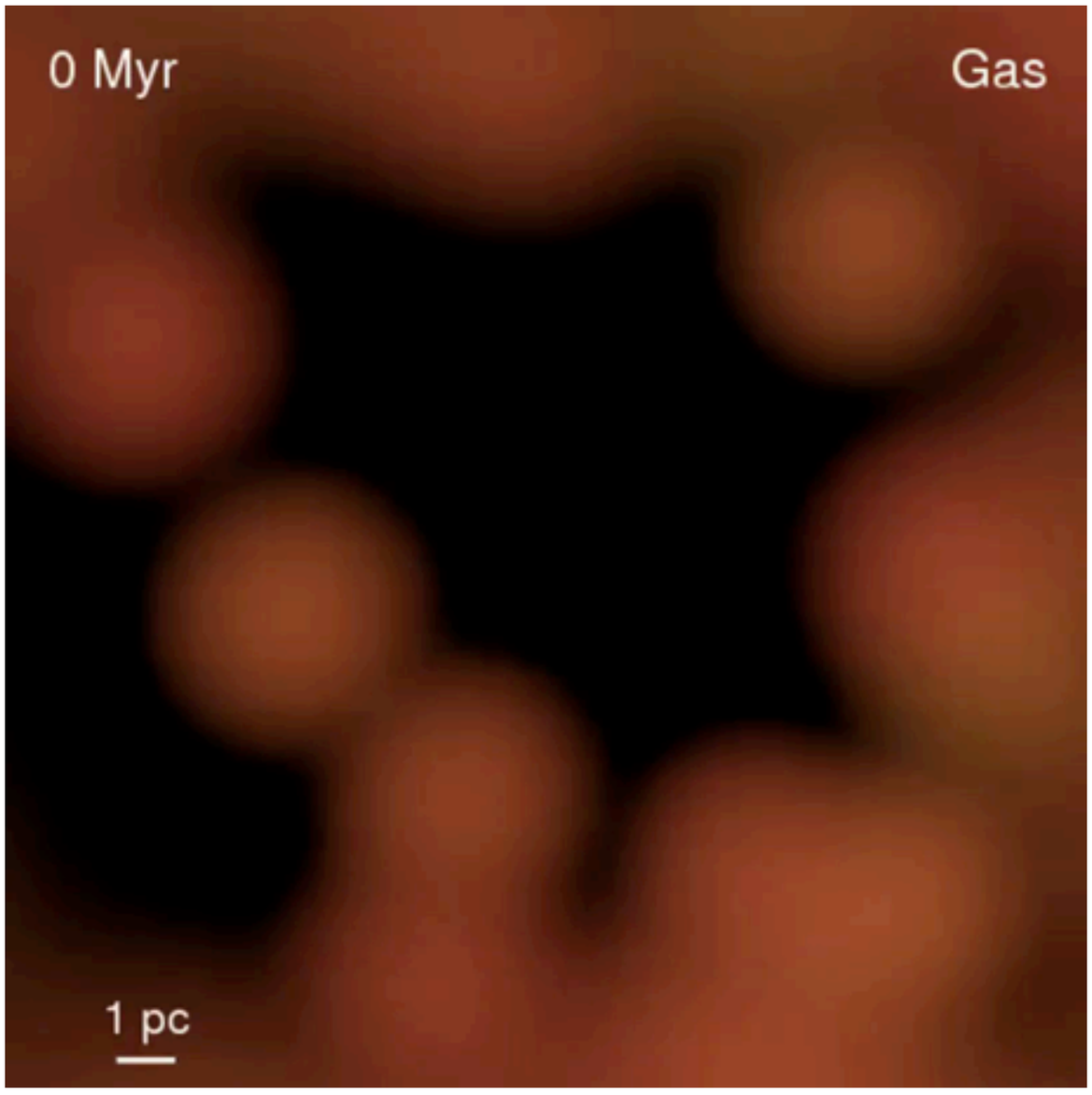
"Blowout" (Bright Mergers)



- Observed luminosity function: populations at different *evolutionary* stages

Where to From Here?

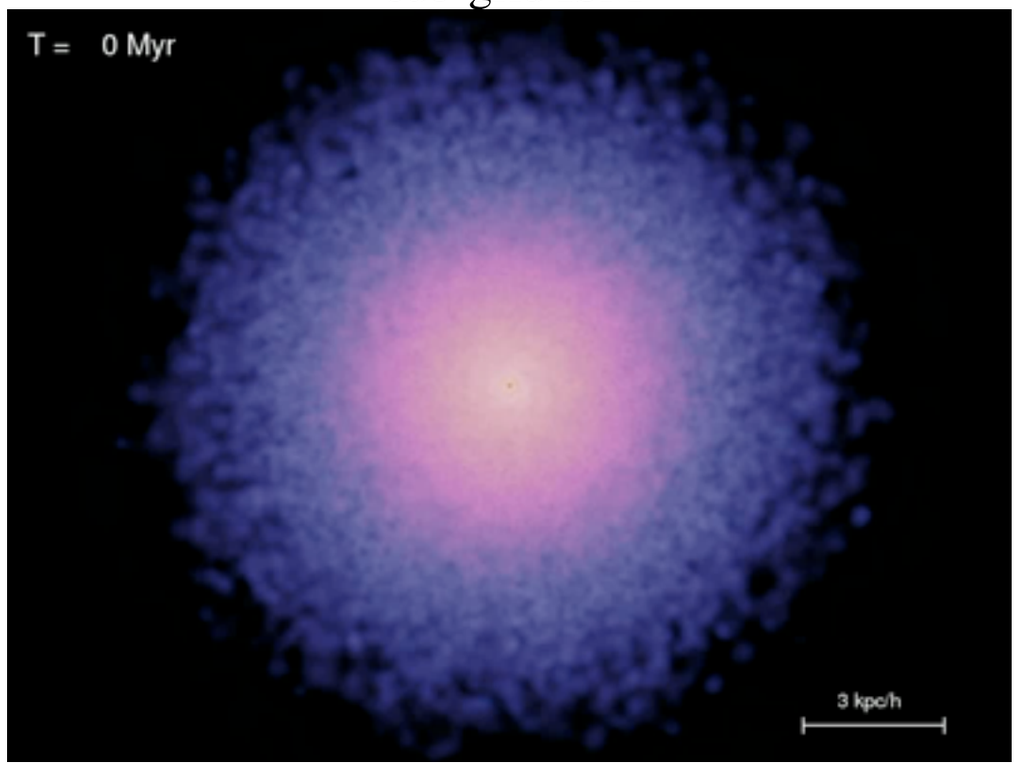
Step 1: *Stellar* Feedback & the ISM



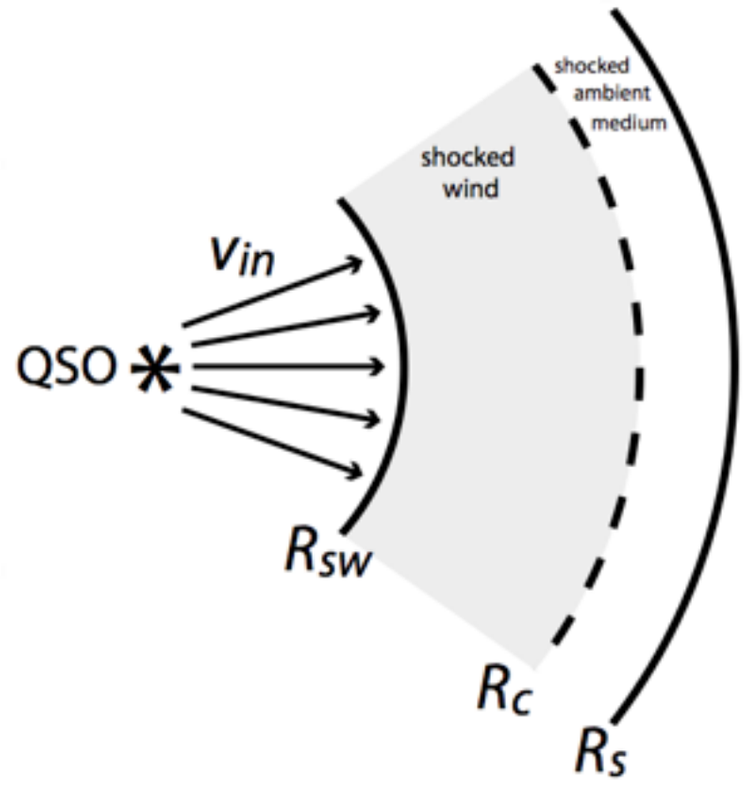
multi-phase ISM with outflows

≠

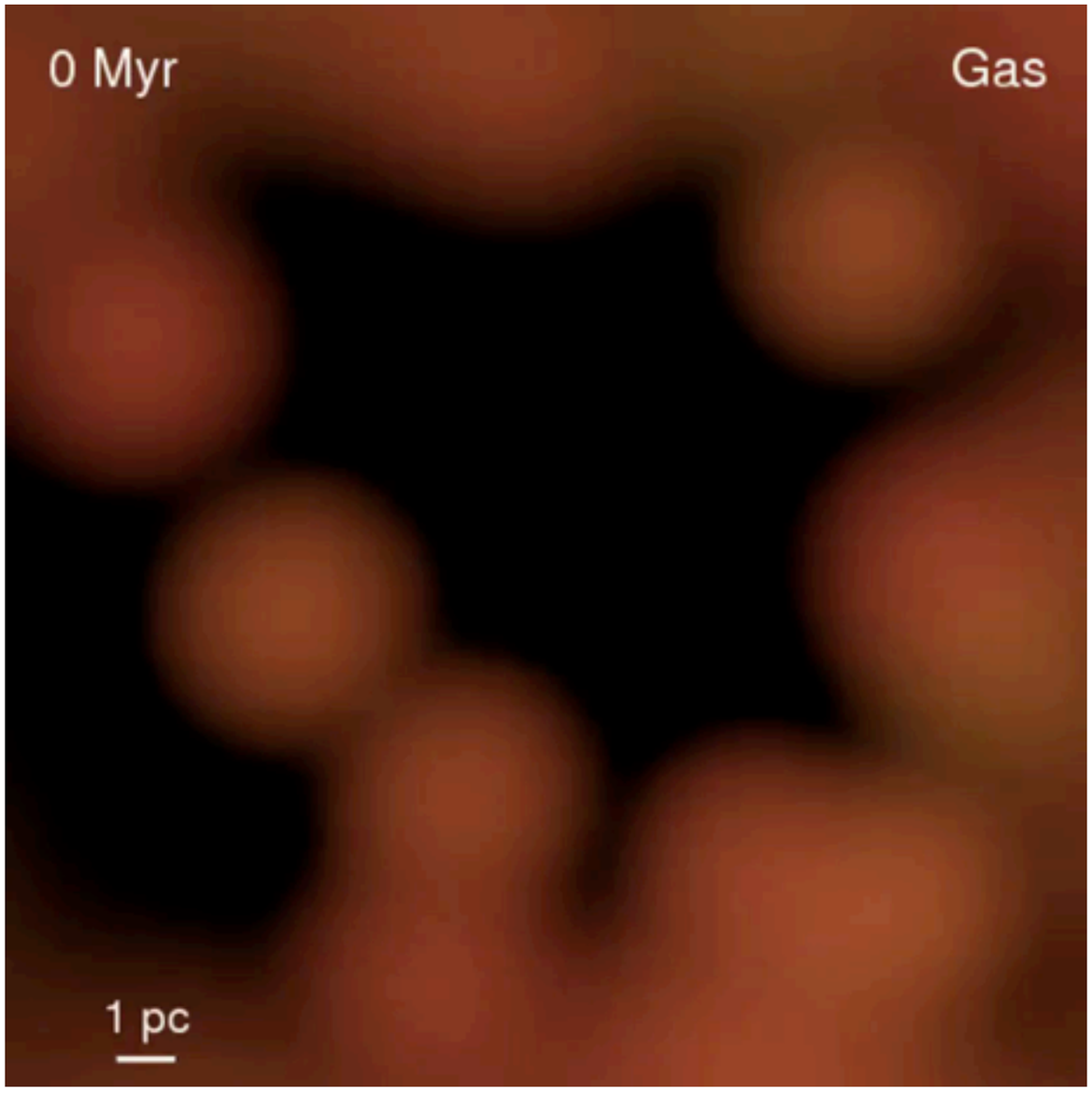
sub-grid ISM



cutting-edge analytic models



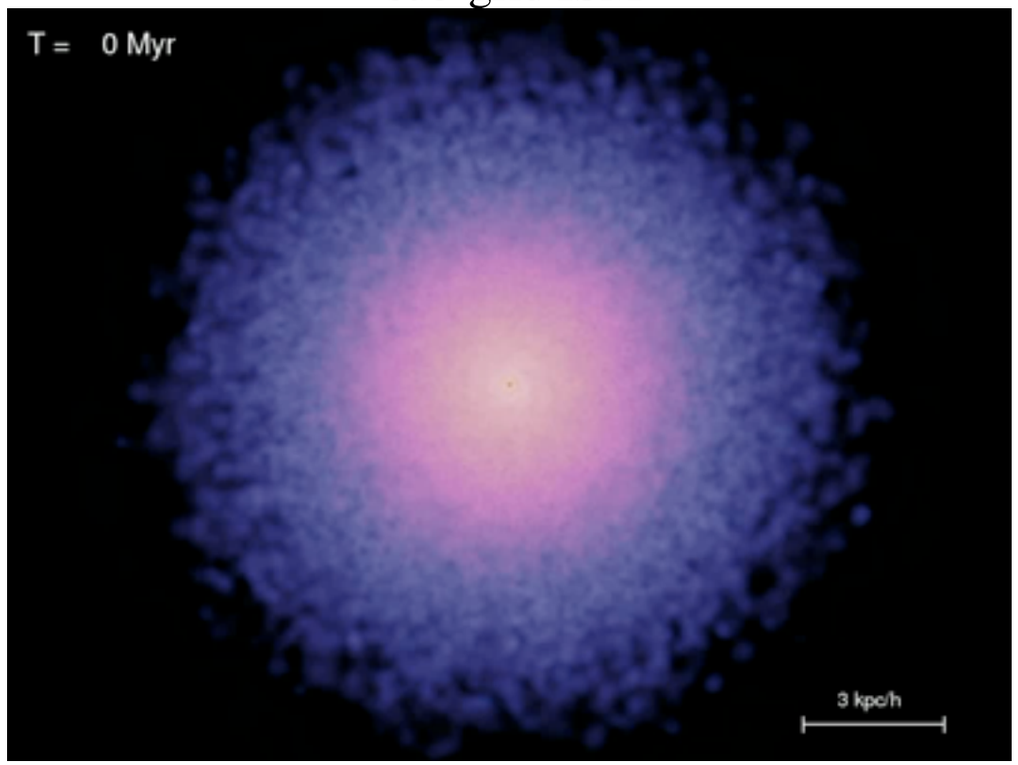
Step 1: *Stellar* Feedback & the ISM



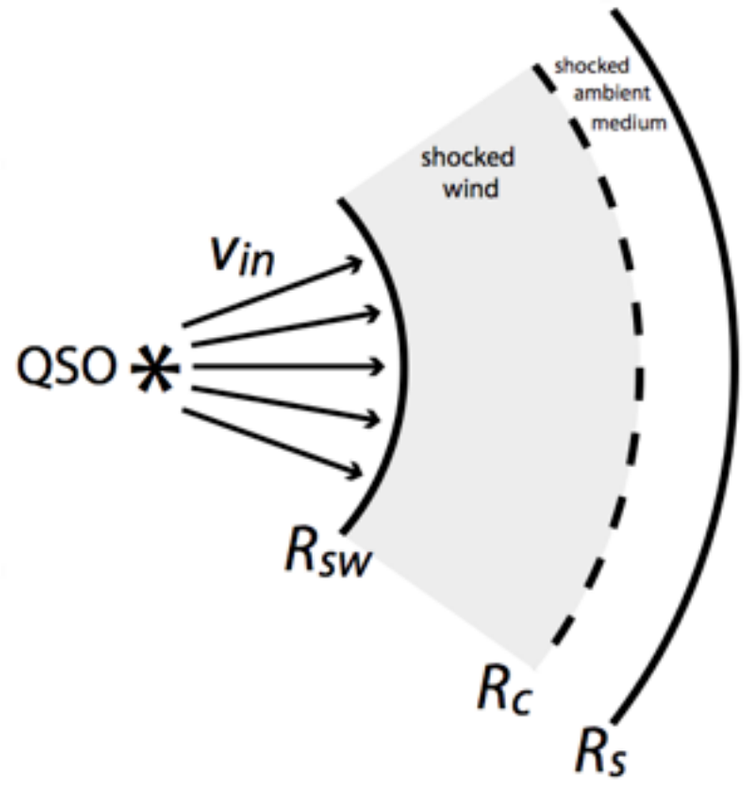
multi-phase ISM with outflows

≠

sub-grid ISM



cutting-edge analytic models

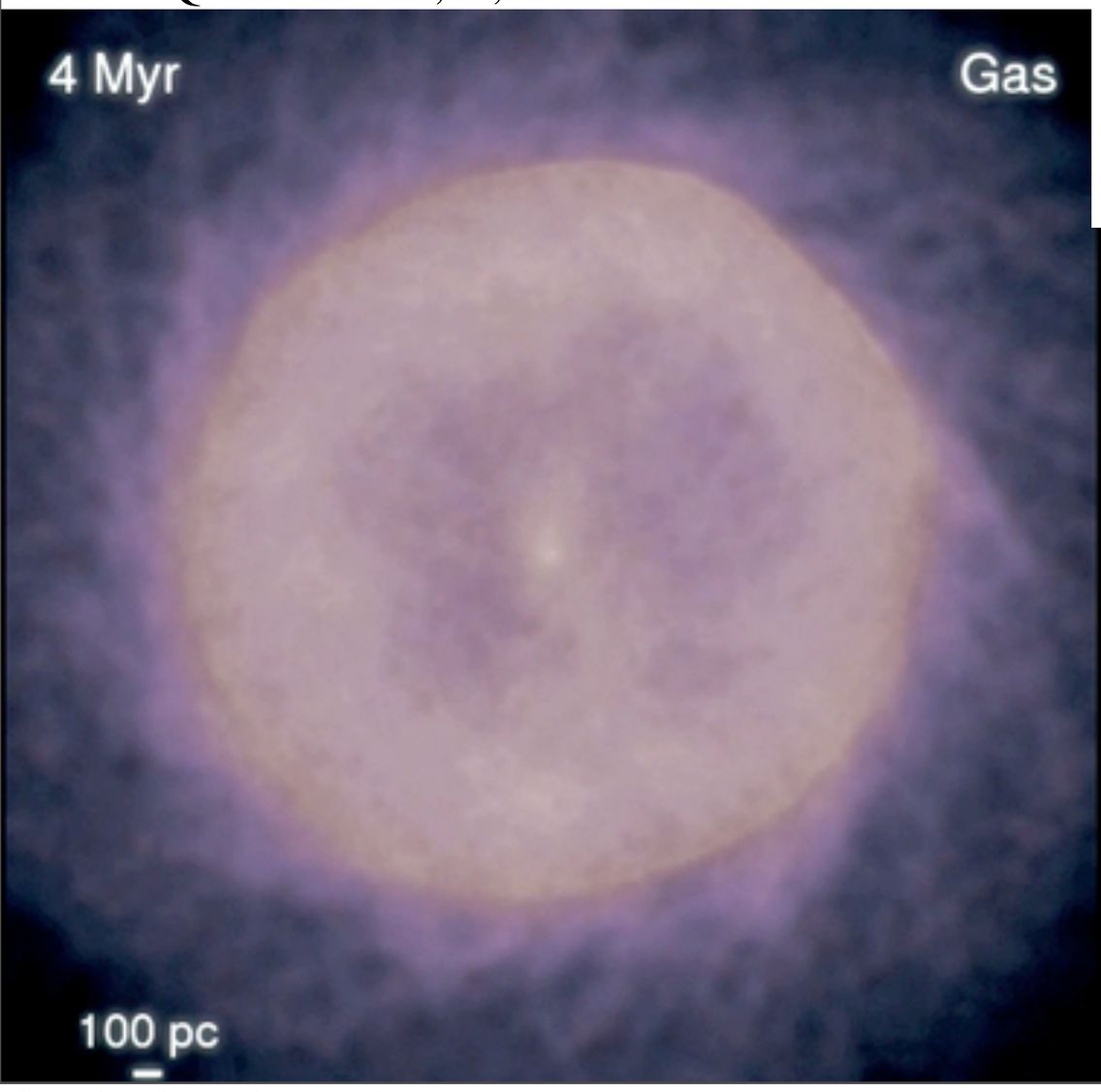


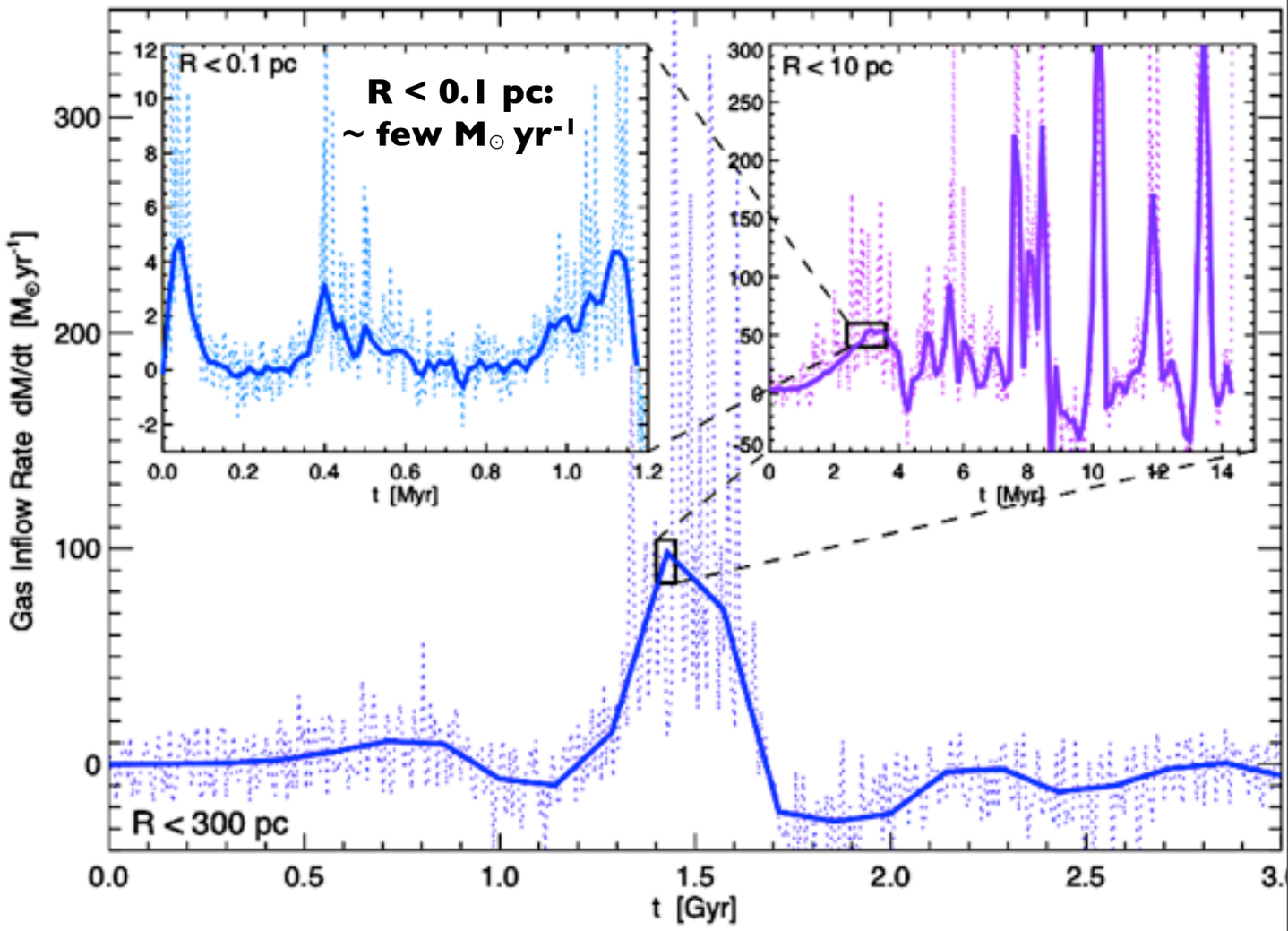
- Non-linear QSO-Stellar feedback interactions *matter*

Step 2: Inflow

- Beginning to directly follow inflow to sub-pc scales

Mayer, Callegari, 09,10
Levine, Gnedin, Kravtsov 09,10
PFH & Quataert 2009,10,11





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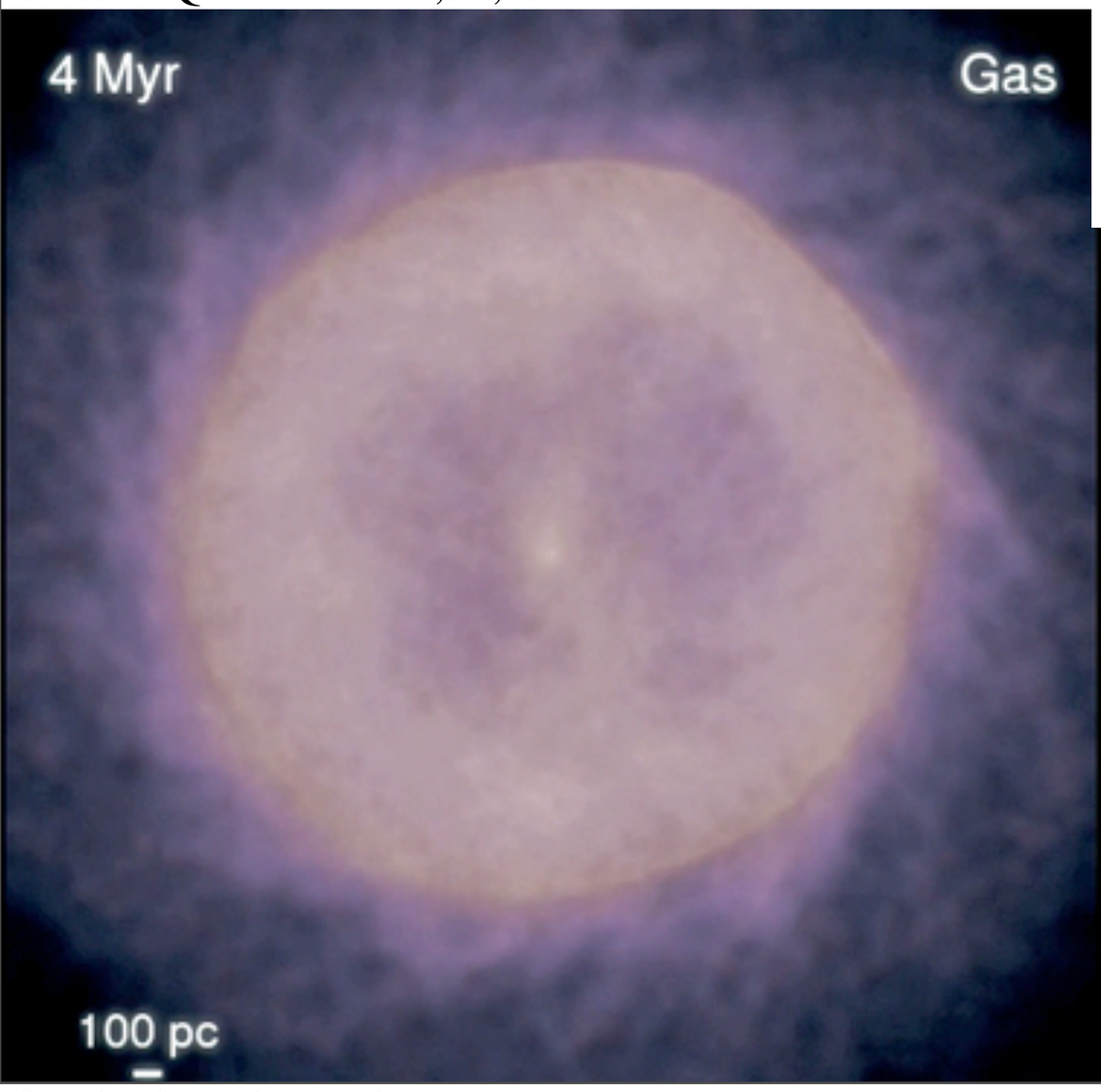
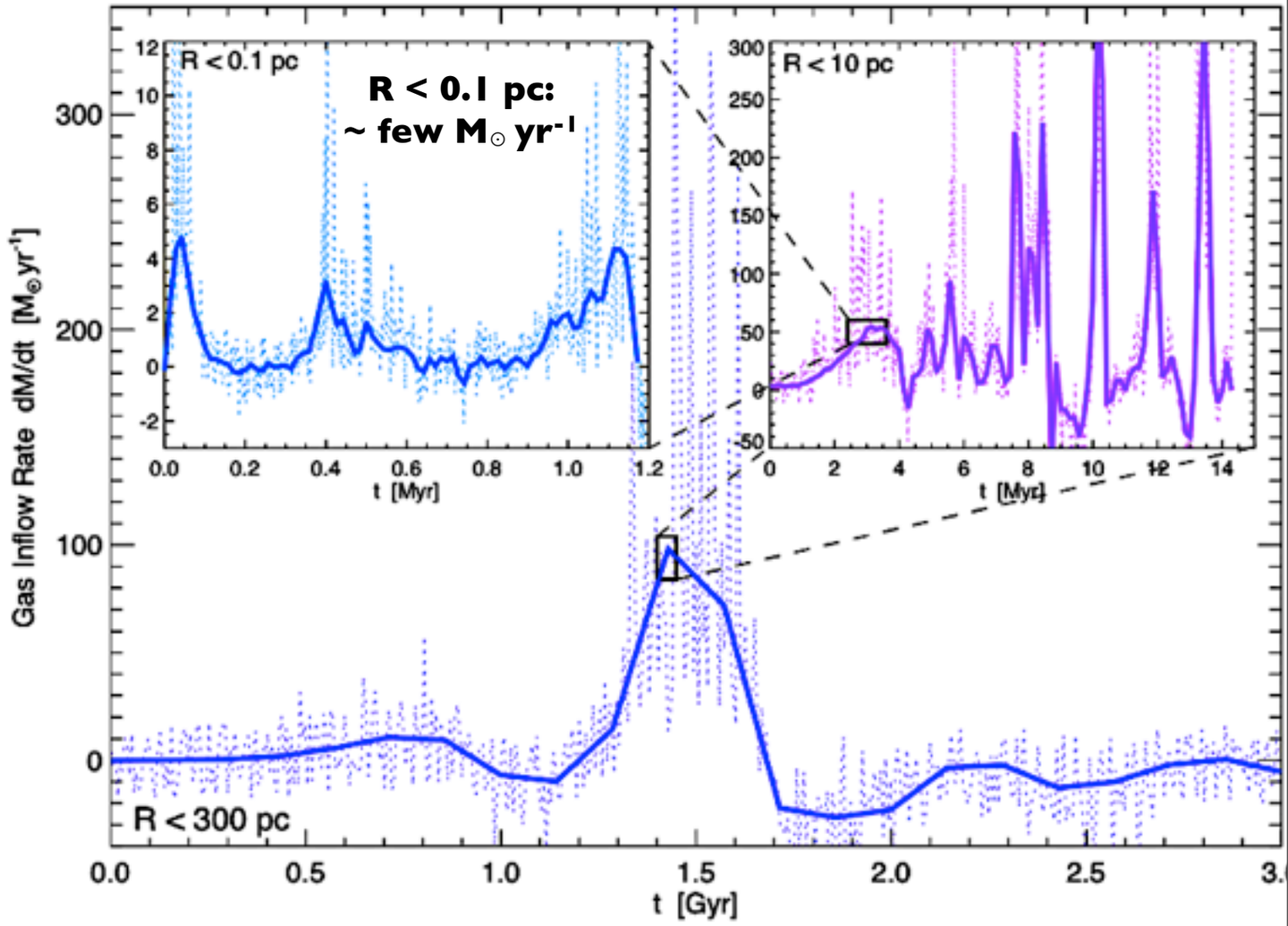




- *NOT:*
  - Bondi-Hoyle
  - Viscous (α-Disk)

(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

"It's Bars all the Way Down ..."

(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

"It's Bars all the Way Down ..."

More accurately ...

"It's Non-axisymmetric Features all the Way Down ..."

(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

"It's Bars all the Way Down ..."

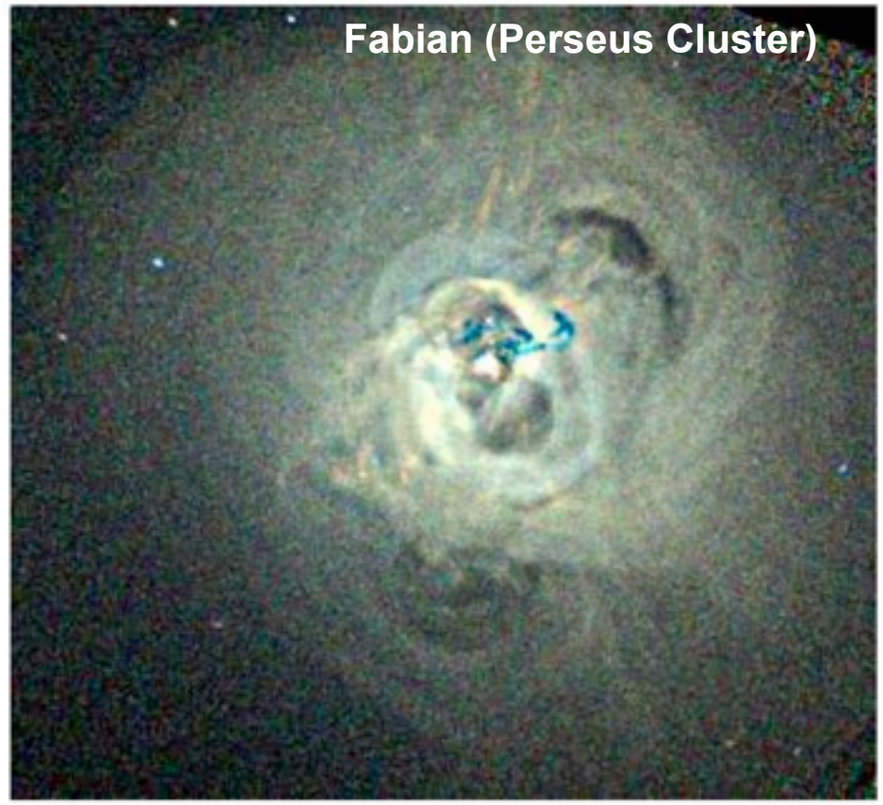
More accurately ...

"It's Non-axisymmetric Features all the Way Down ..."

$$\dot{M} \approx 10\, M_\odot\, \mathrm{yr}^{-1} \left(\frac{\mathrm{Disk}}{\mathrm{Total}}\right)^{5/2} M_{\mathrm{BH},\,8}^{-1/6}\, M_{\mathrm{gas},\,9}\, R_{0,100}^{-3/2}$$

Step 3: Observed Sources of AGN Feedback

- Jets
  - heat IGM/ICM (low-density), but not dense ISM?



Step 3: Observed Sources of AGN Feedback

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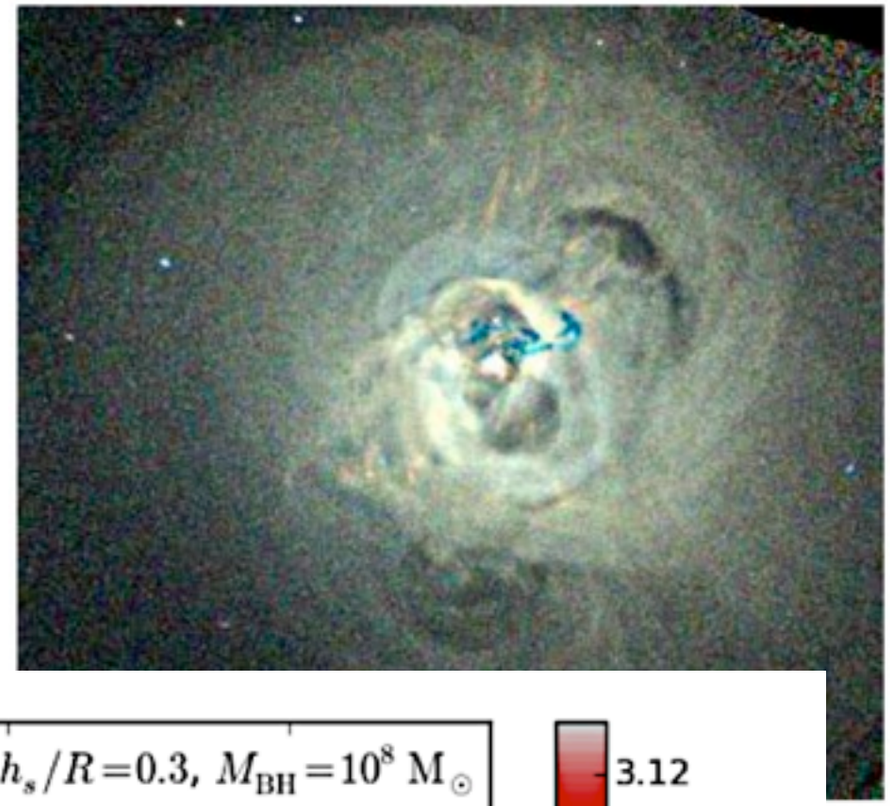
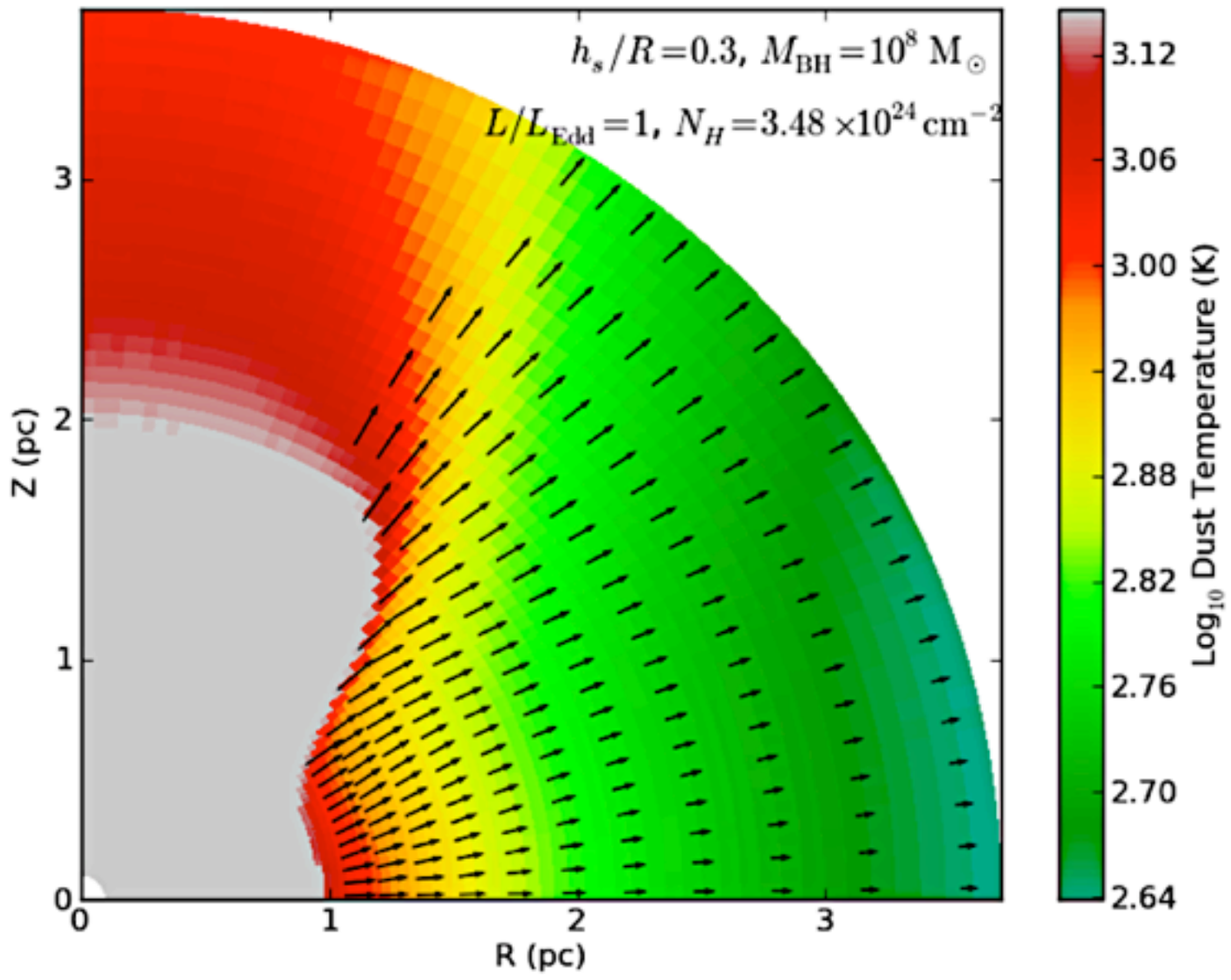
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$





Roth, Kasen, Quataert, PFH 2012 + in prep

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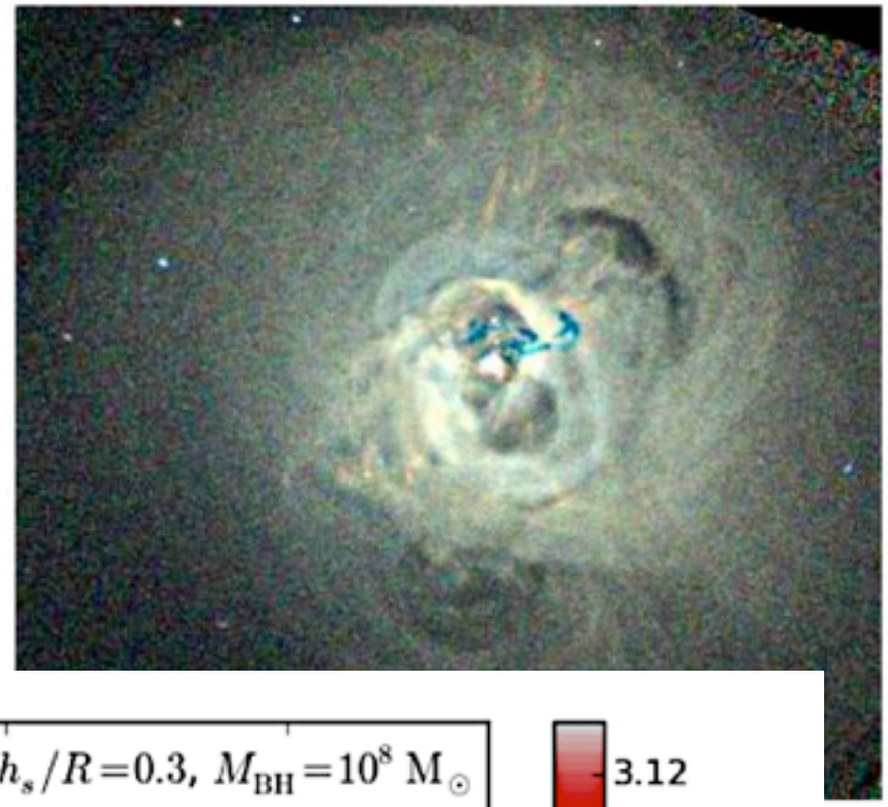
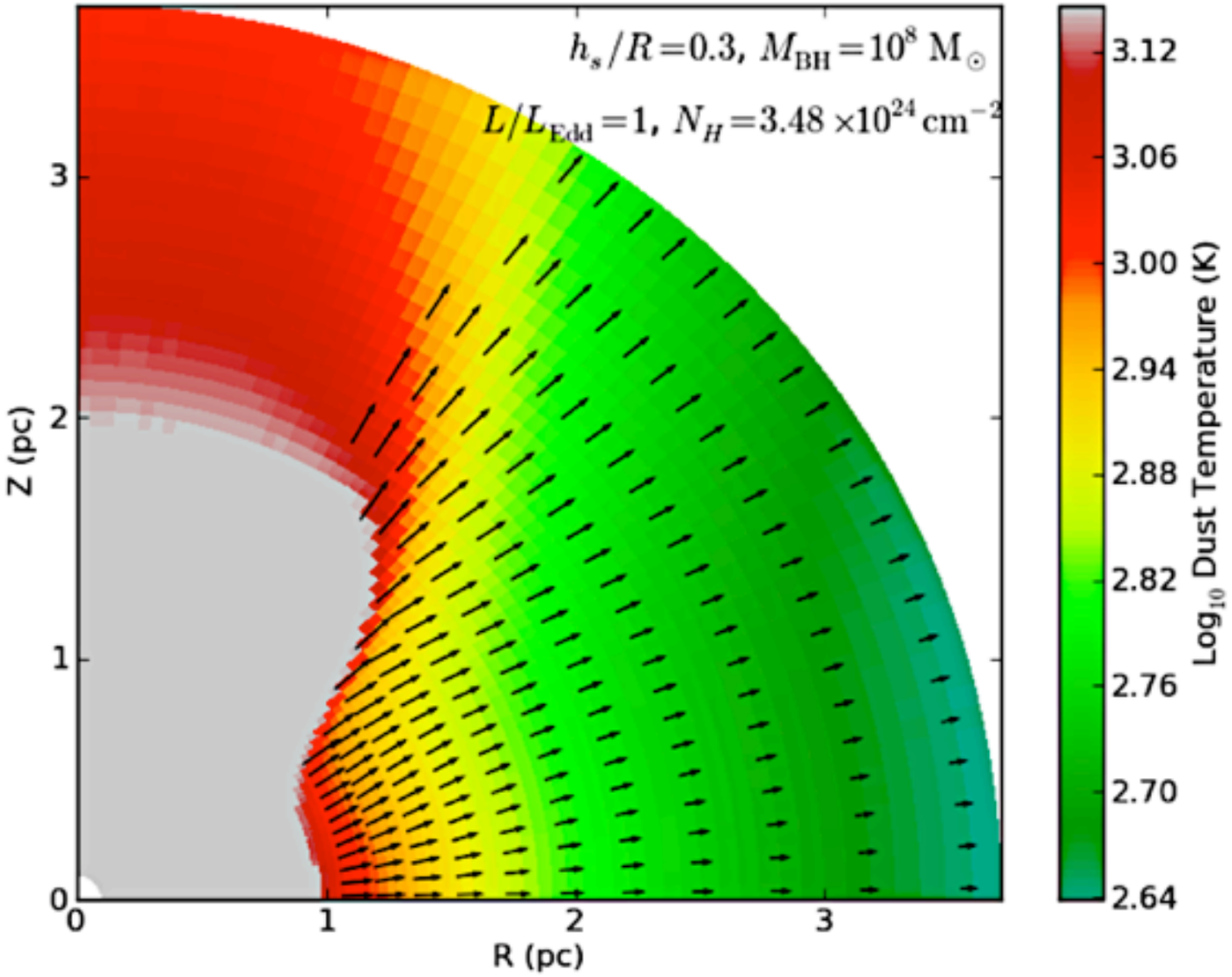


- Radiation Pressure
  - $L_{AGN} >> L_{stars}$

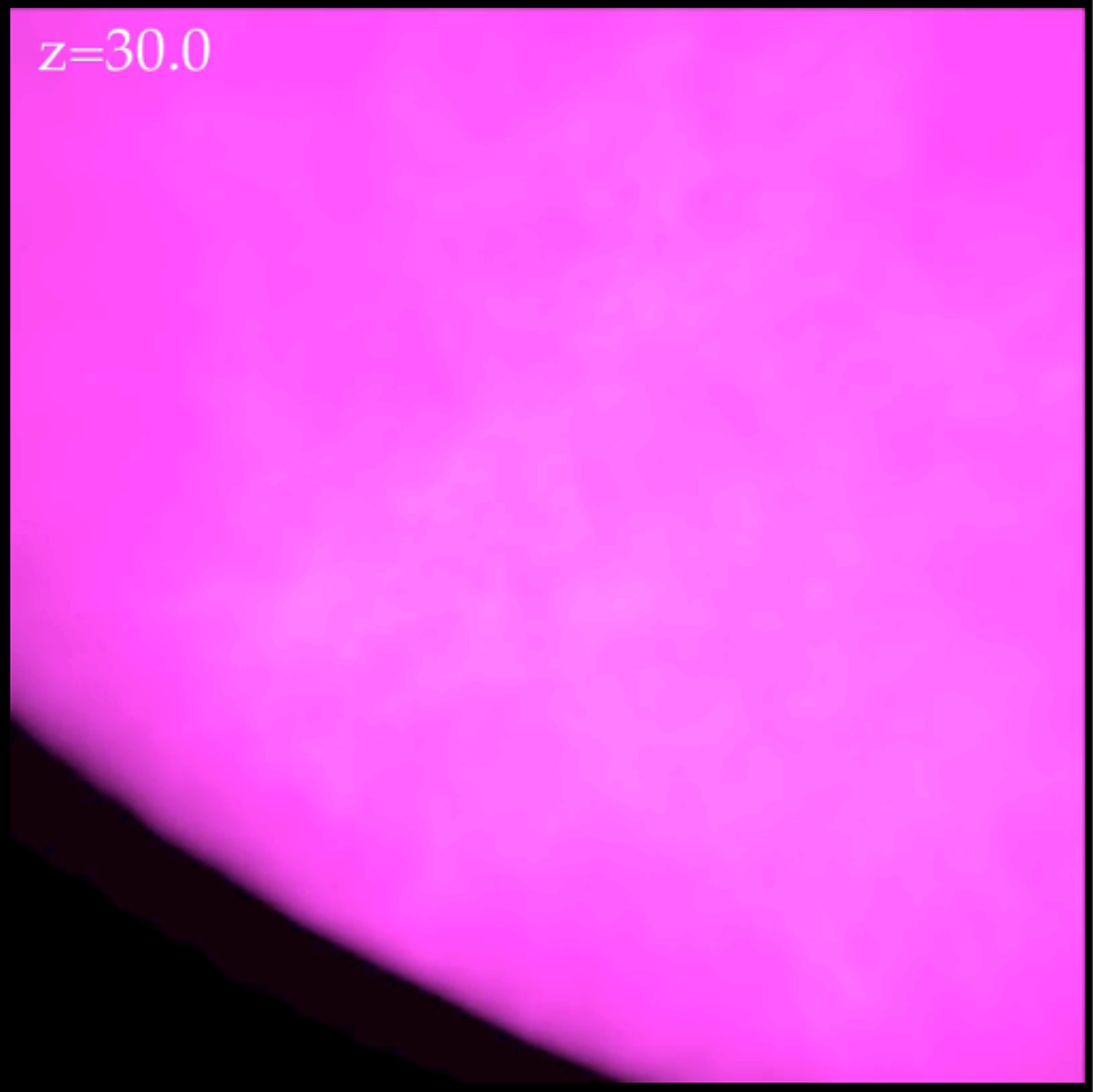
- Accretion Disk Winds
  - Broad Absorption Line Winds

Proga et al., Novak et al.



Roth, Kasen, Quataert, PFH 2012 + in prep

z=30.0



Put all of this into a cosmological simulation, and.... (?)

z=30.0