Quasars, Feedback, and Galaxy Formation

01/28/09

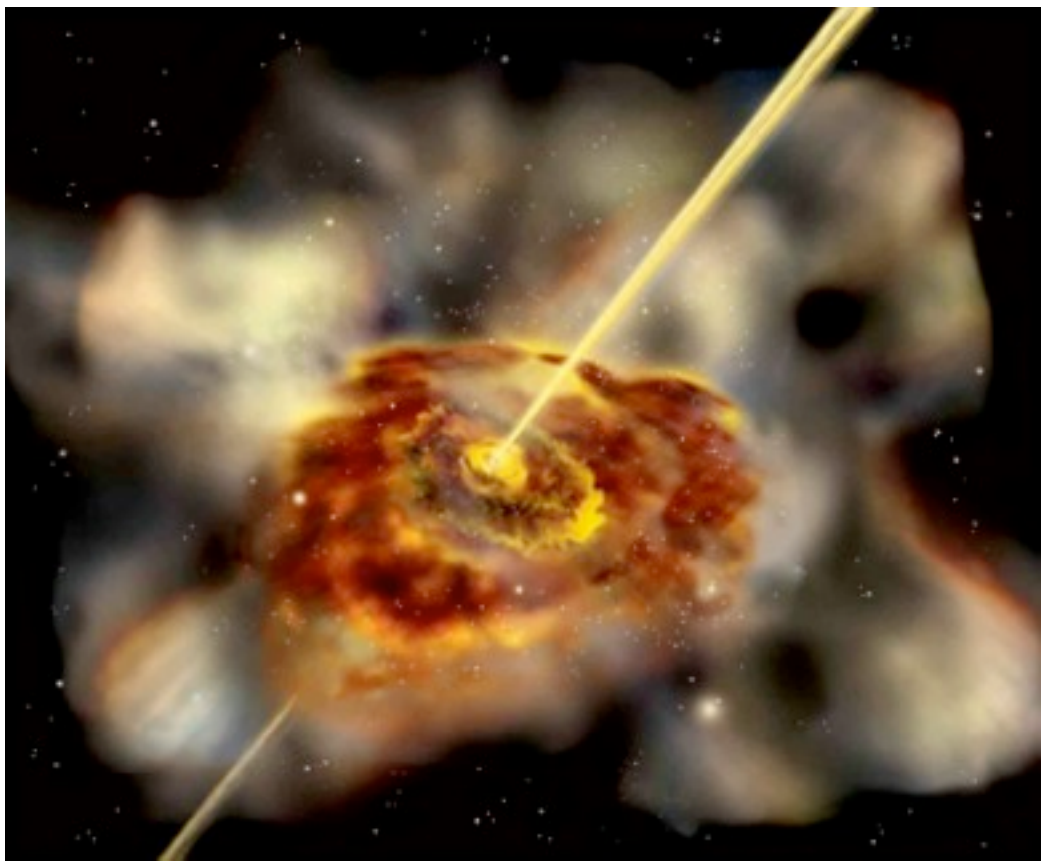
Philip Hopkins

Lars Hernquist, T. J. Cox, Eliot Quataert, Gordon Richards, Volker Springel, Dusan Keres, Brant Robertson, Kevin Bundy, Paul Martini, Adam Lidz, Tiziana Di Matteo, Yuexing Li, Josh Younger, Sukanya Chakrabarti, Alison Coil, Adam Myers, and many more

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- Every massive galaxy hosts a supermassive black hole



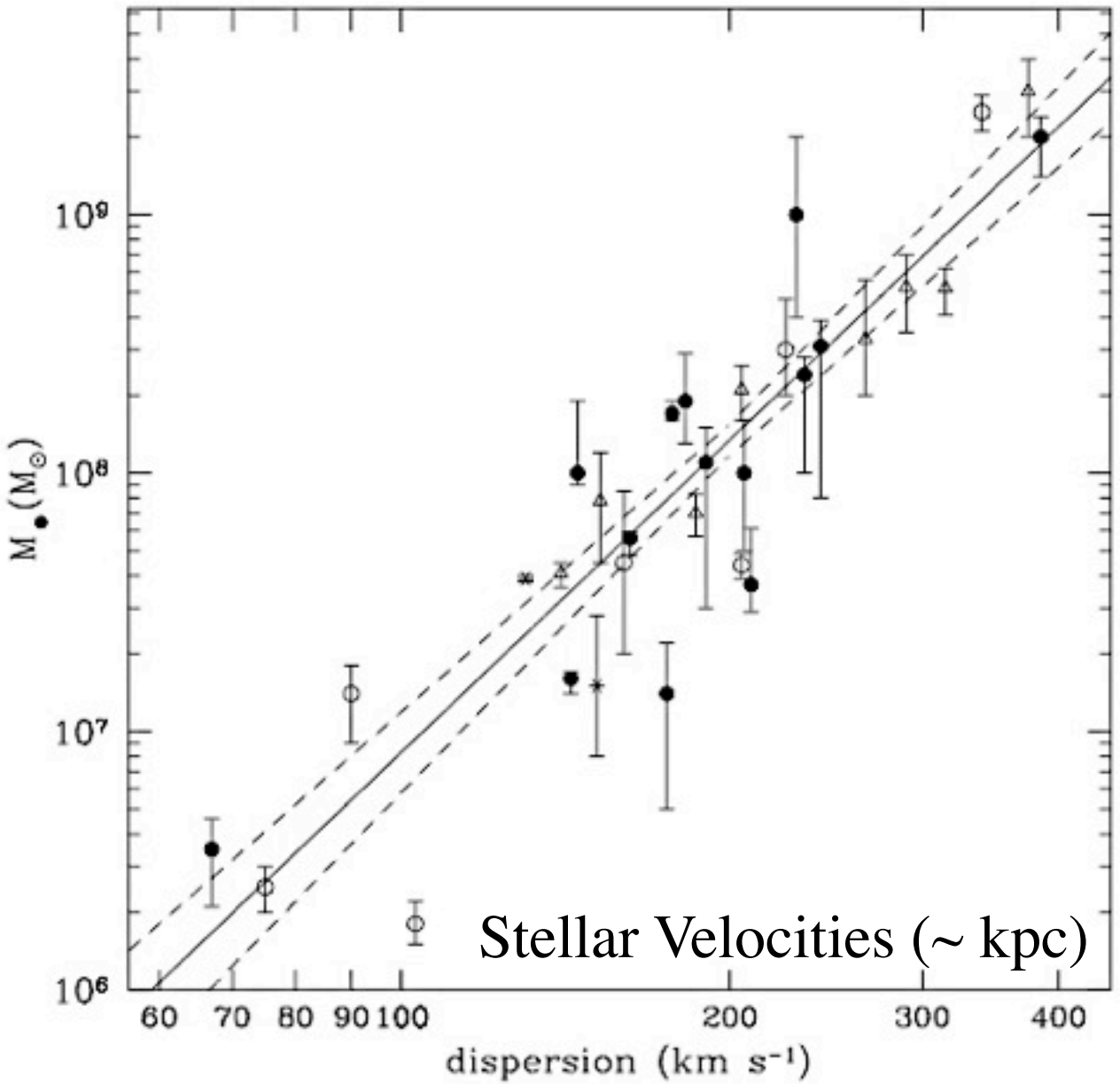
- These BHs accreted most of their mass in bright, short lived quasar accretion episodes: the “fossil” quasars

Motivation

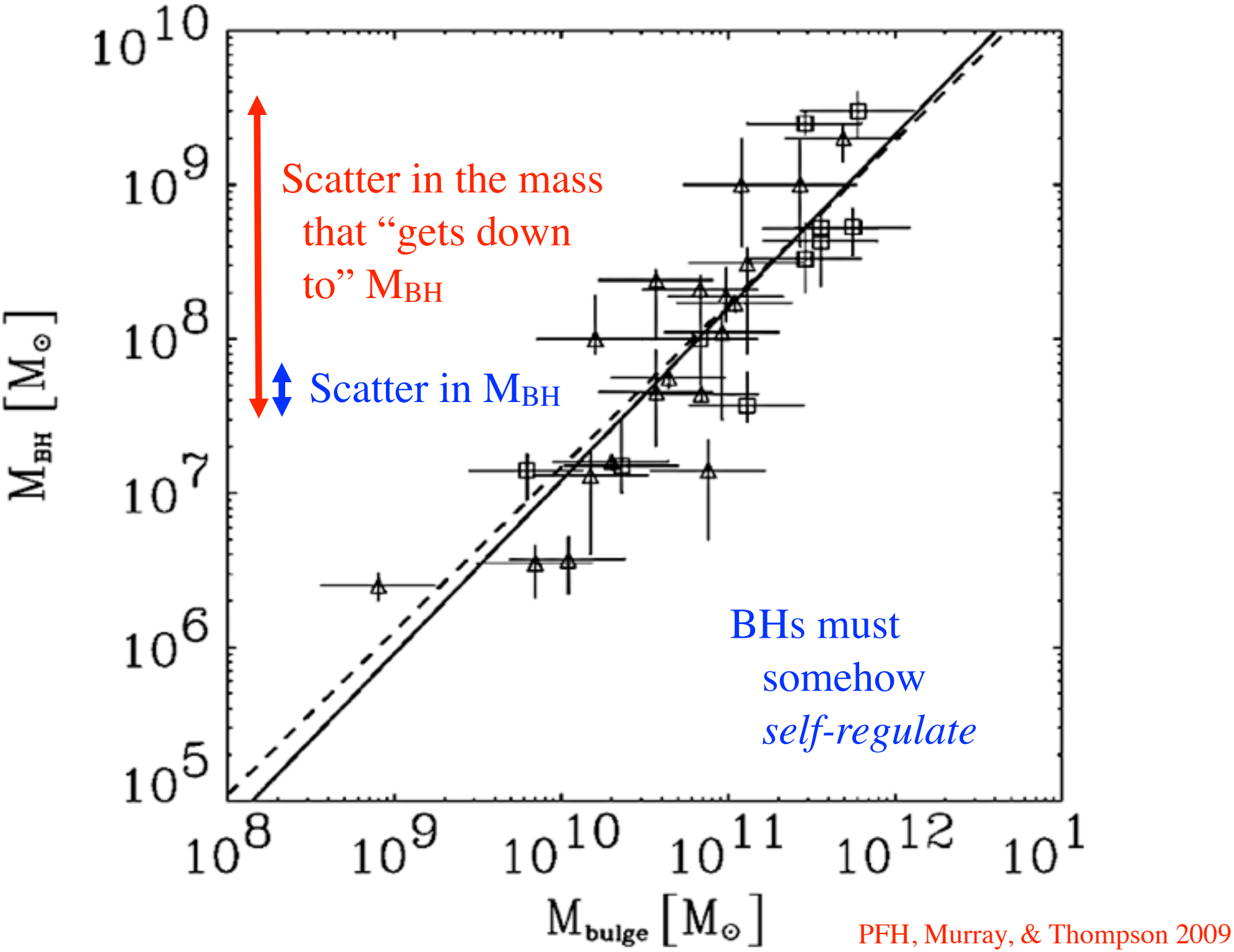
WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- Black holes are somehow sensitive to their host galaxies:

BH Mass
(~ pc!)



Ferrarese & Merritt '00,
Gebhardt+ '00
Tremaine et al. '02



PFH, Murray, & Thompson 2009

Simplest Idea:

FEEDBACK ENERGY BALANCE (SILK & REES '98)

- Luminous accretion disk near the Eddington limit radiates an energy:
  - $L = e_r \, (dM_{BH}/dt) \, c^2$ $(e_r \sim 0.1)$
- Total energy radiated:
  - $\sim 0.1 \, M_{BH} \, c^2 \sim 10^{61}$ ergs in a typical $\sim 10^8 \, M_{sun}$ system
- Compare this to the gravitational binding energy of the galaxy:
  - $\sim M_{gal} \, s^2 \sim (10^{11} \, M_{sun}) \, (200 \text{ km/s})^2 \sim 10^{59}$ erg!
- If only a few percent of the luminous energy coupled, it would unbind the baryons in the galaxy!
  - Turn this around: *if* some fraction h ~ 1-5% of the luminosity can couple, then accretion *must* stop (the gas will all be blown out the galaxy) when
    - $M_{BH} \sim (a/h e_r) \, M_{gal} \, (s/c)^2 \sim 0.002 \, M_{gal}$

Simplest Idea:

FEEDBACK ENERGY BALANCE (SILK & REES '98)

- Needs to come in *bright* stage (where most BH growth takes place)

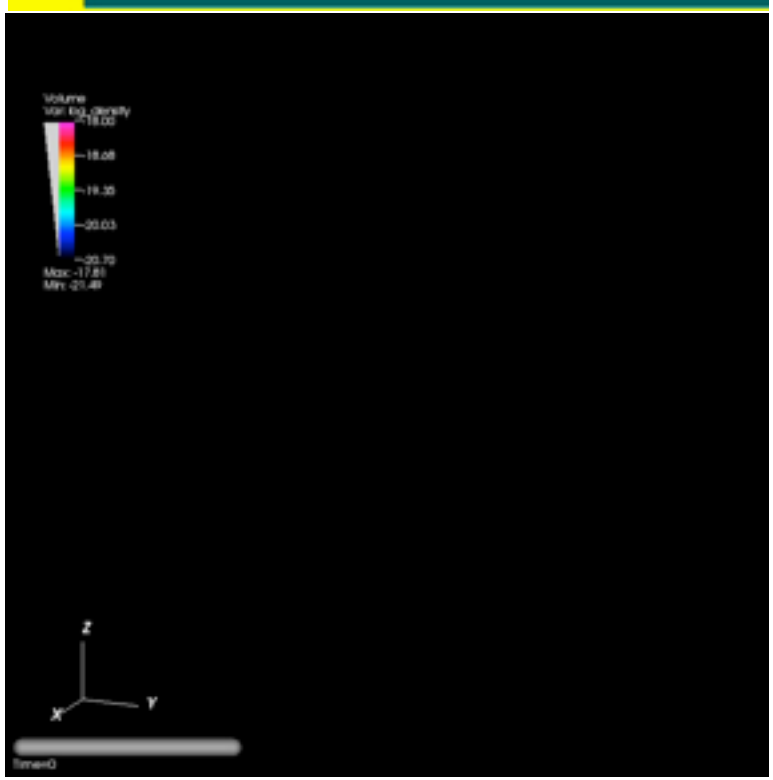
- ~5% of Energy or ~ L/c Momentum
  - Compton/Ionization heating (Sazonov et al.)
  - Dusty, momentum driven winds (Murray et al.)
  - Line-driven winds (Proga et al.)

- See this in observed systems:
  - BAL winds (Gabel,Arav,et al.)
  - Warm absorbers? (Krongold,McKernan)
  - High-z, radio-loud QSOs (Reuland,Nesvadba)

  - ~L/c at ~kpc scales (Tremonti, Hennawi):
    - Can this impact the galaxy?

Proga et al.

z



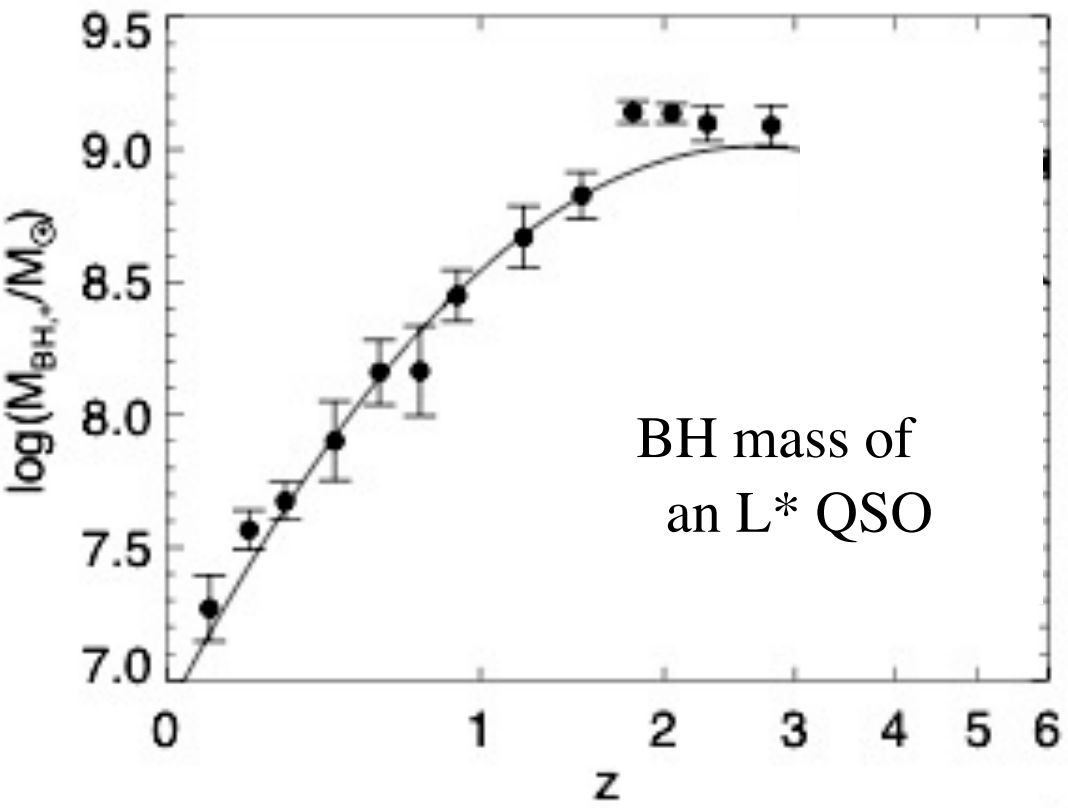
z

R

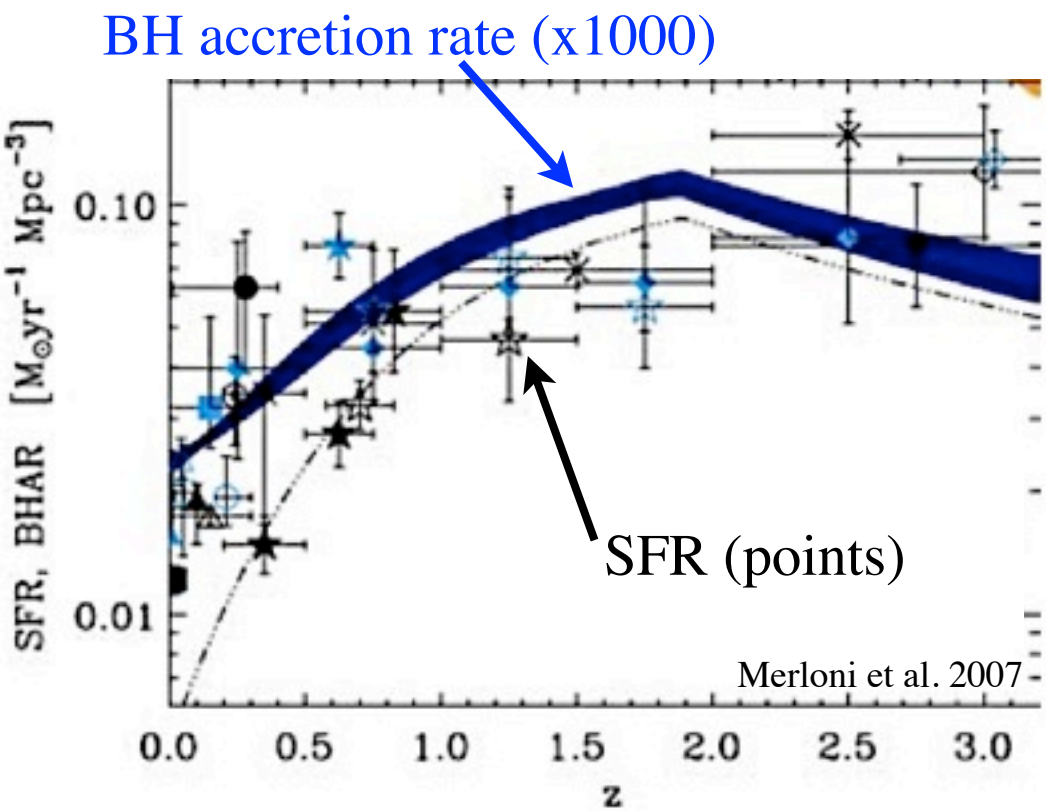
Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- BH "Downsizing":



- Traces SFR Evolution:

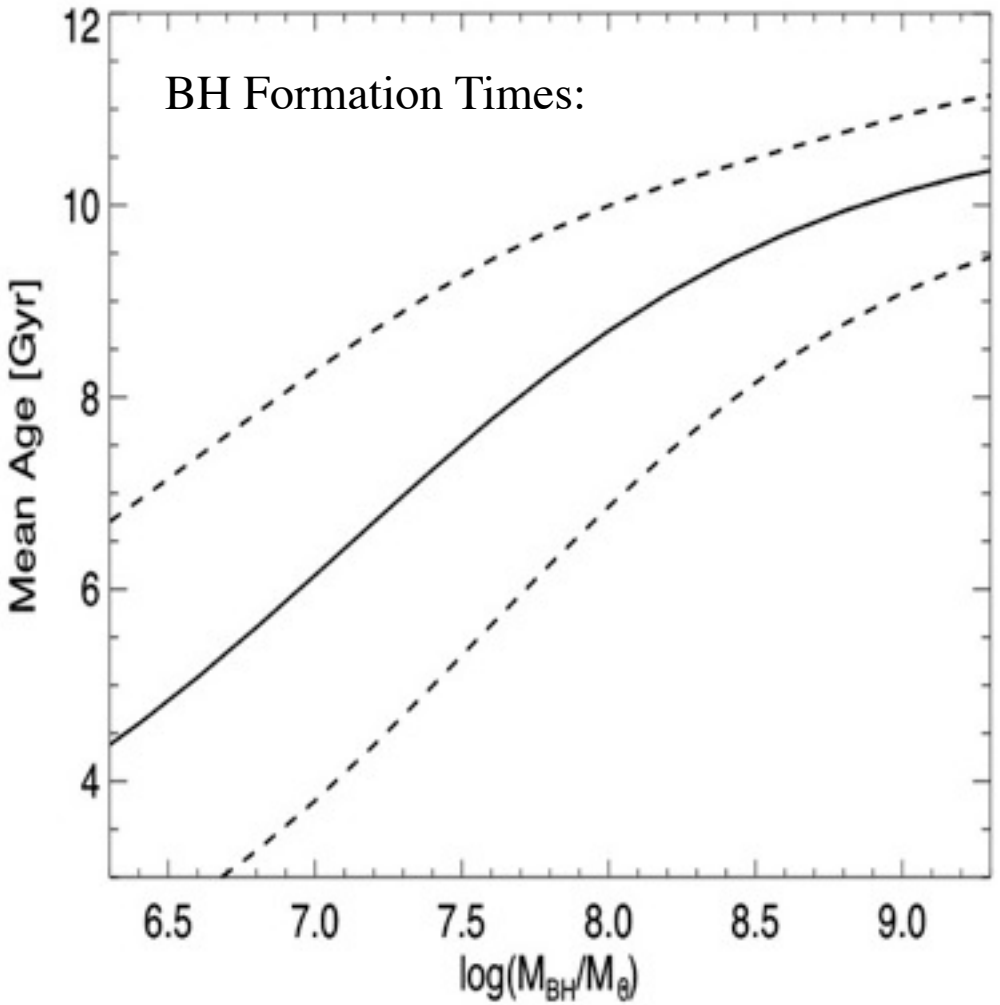


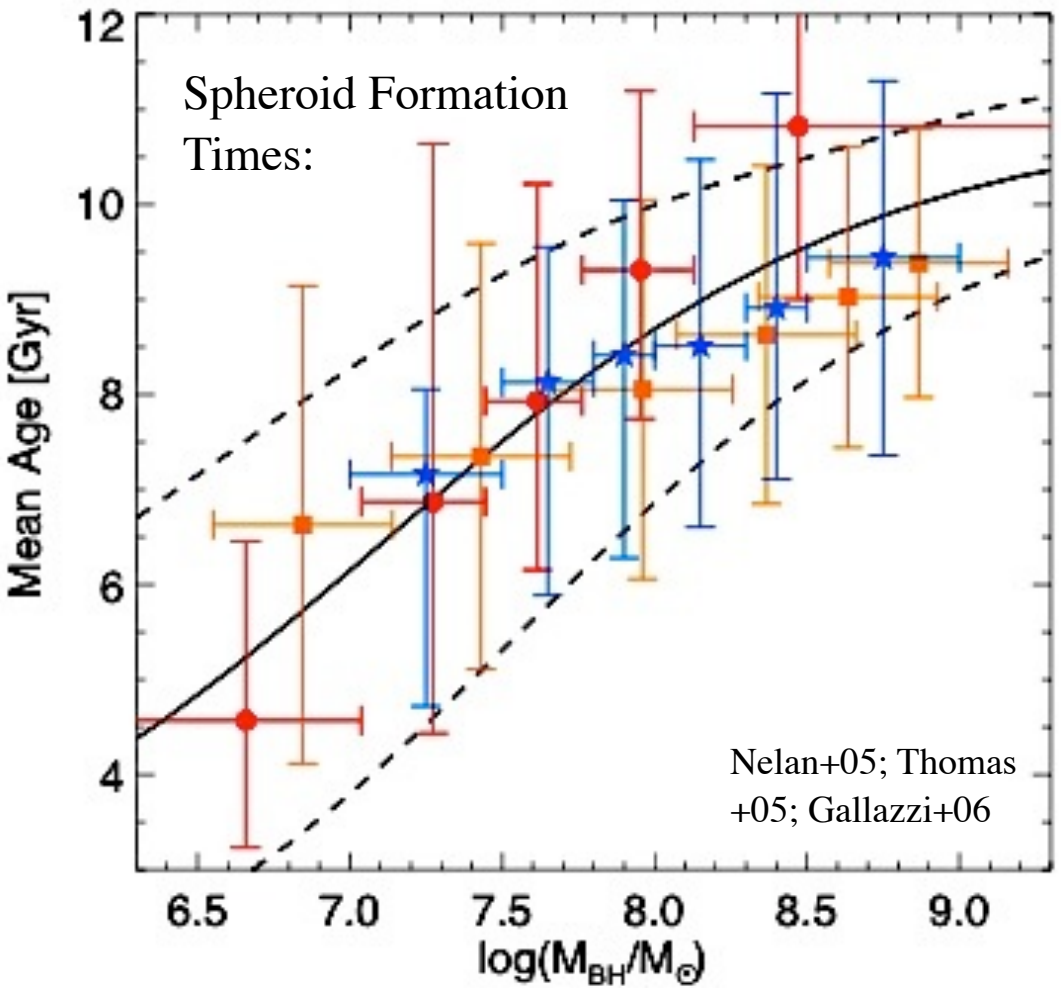
PFH, Richards, & Hernquist 2007

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- Quasars were active/BHs formed when SF shut down...

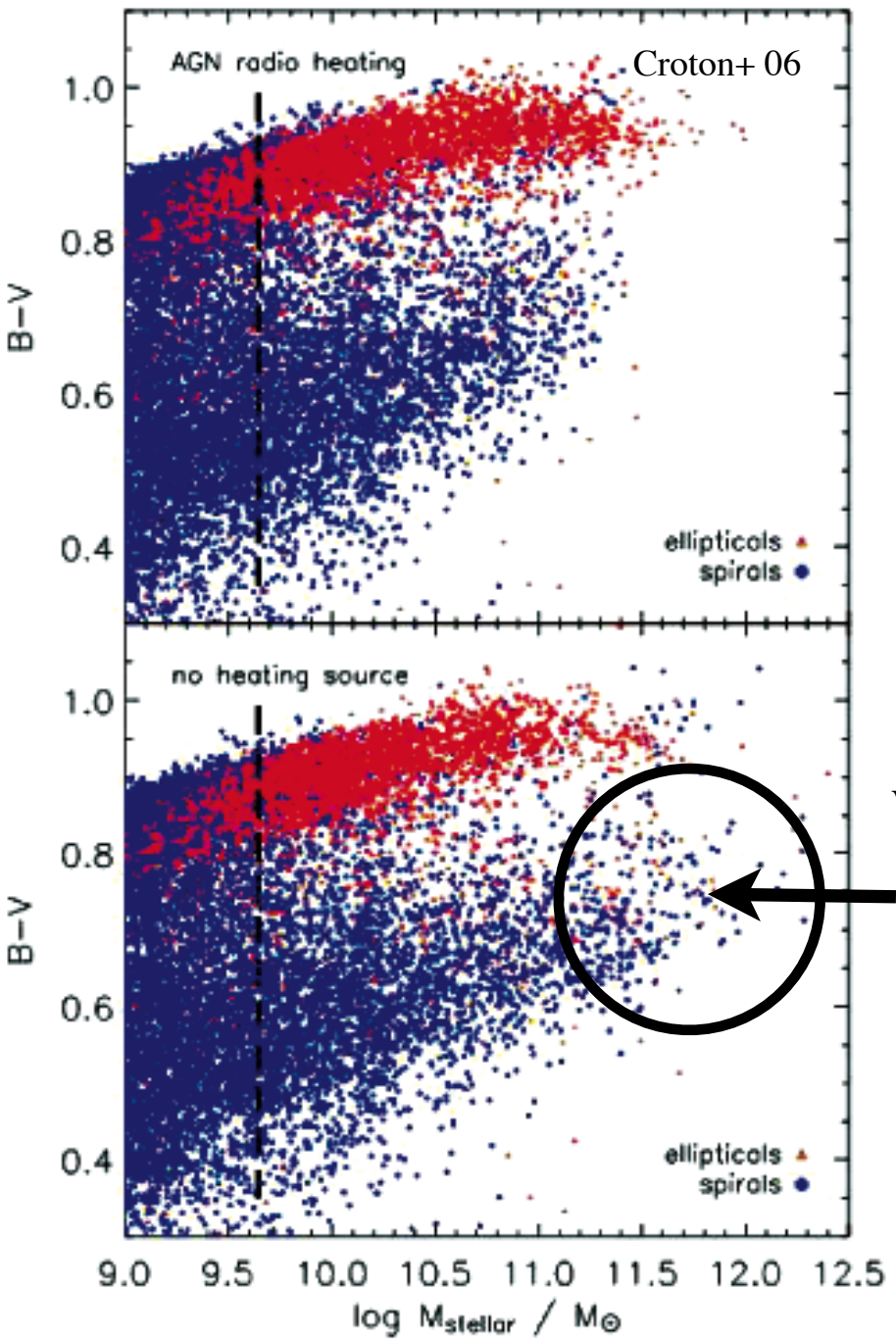




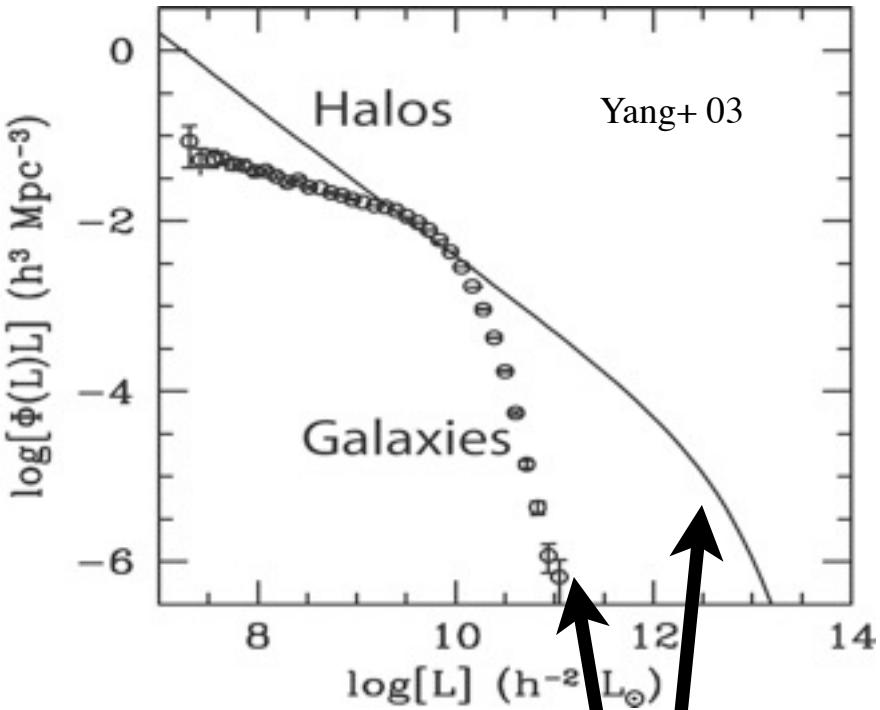
PFH, Lidz, Coil, Myers, et al. 2007

Motivation

MAYBE THIS CAN EXPLAIN OTHER, LONG-STANDING PROBLEMS?



Why are there no massive, bulge-dominated star forming (blue) galaxies?



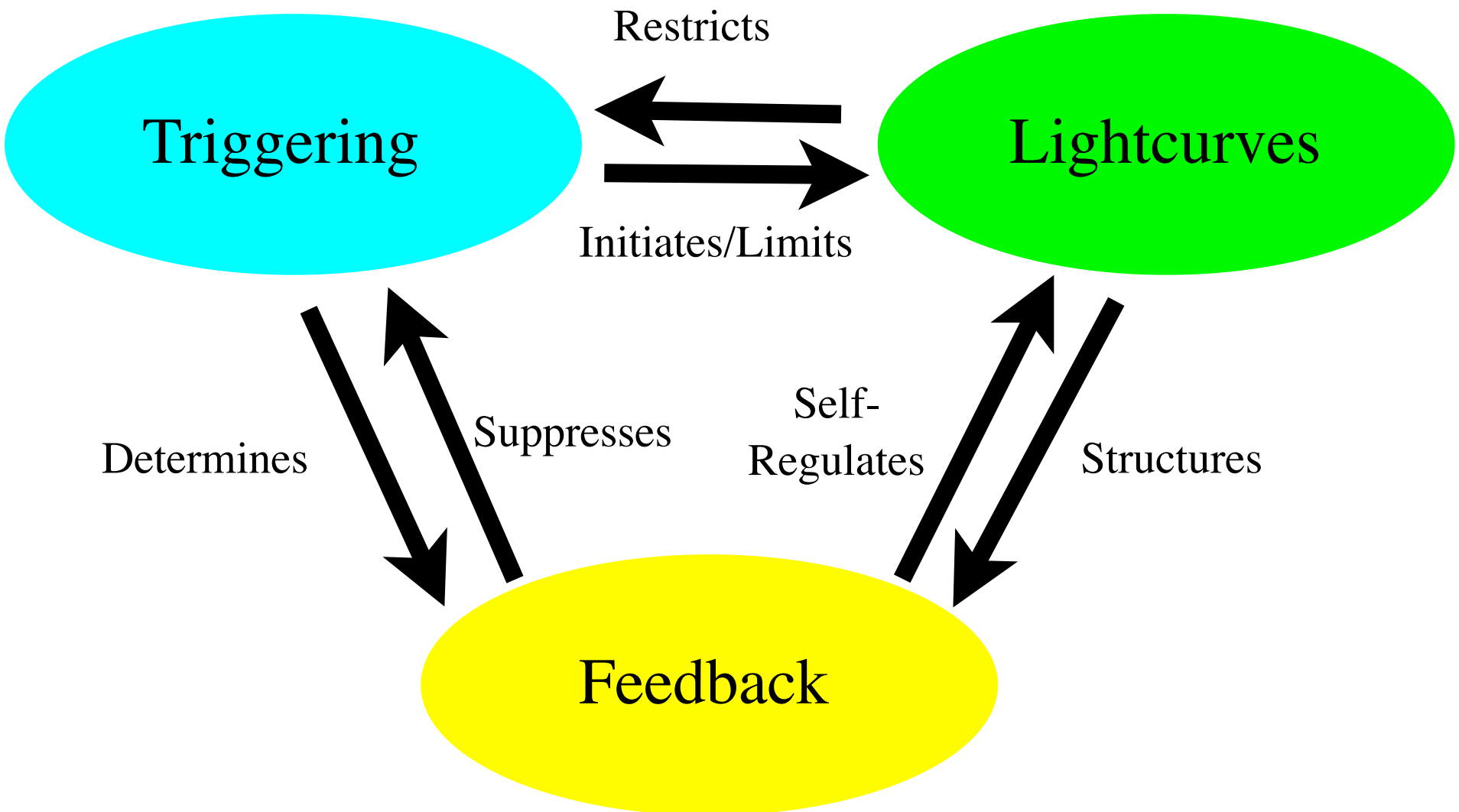
Why do massive galaxies *stop* growing while their host halos keep growing?

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- BH and Galaxy Formation is a coupled problem:
  - BH-BH merger rates? Kicks?
    - Need to know galaxy-galaxy mergers
    - Spin alignment from accretion disks
  - BH Spins? Jet Physics?
    - Triggering mechanisms/feedback/momentum of accreted material
  - Seed BHs?
    - Where do galaxies “take over”? Low-M occupation fraction?
  - Clusters for cosmology?
    - Feedback effects on X-ray gas, halo occupation, M_{gal}-M_{halo}
  - IGM temperature distributions? Metal?, Lya?
    - AGN “preheating” & entropy injection
    - Comparable metal/mass ejection to stars

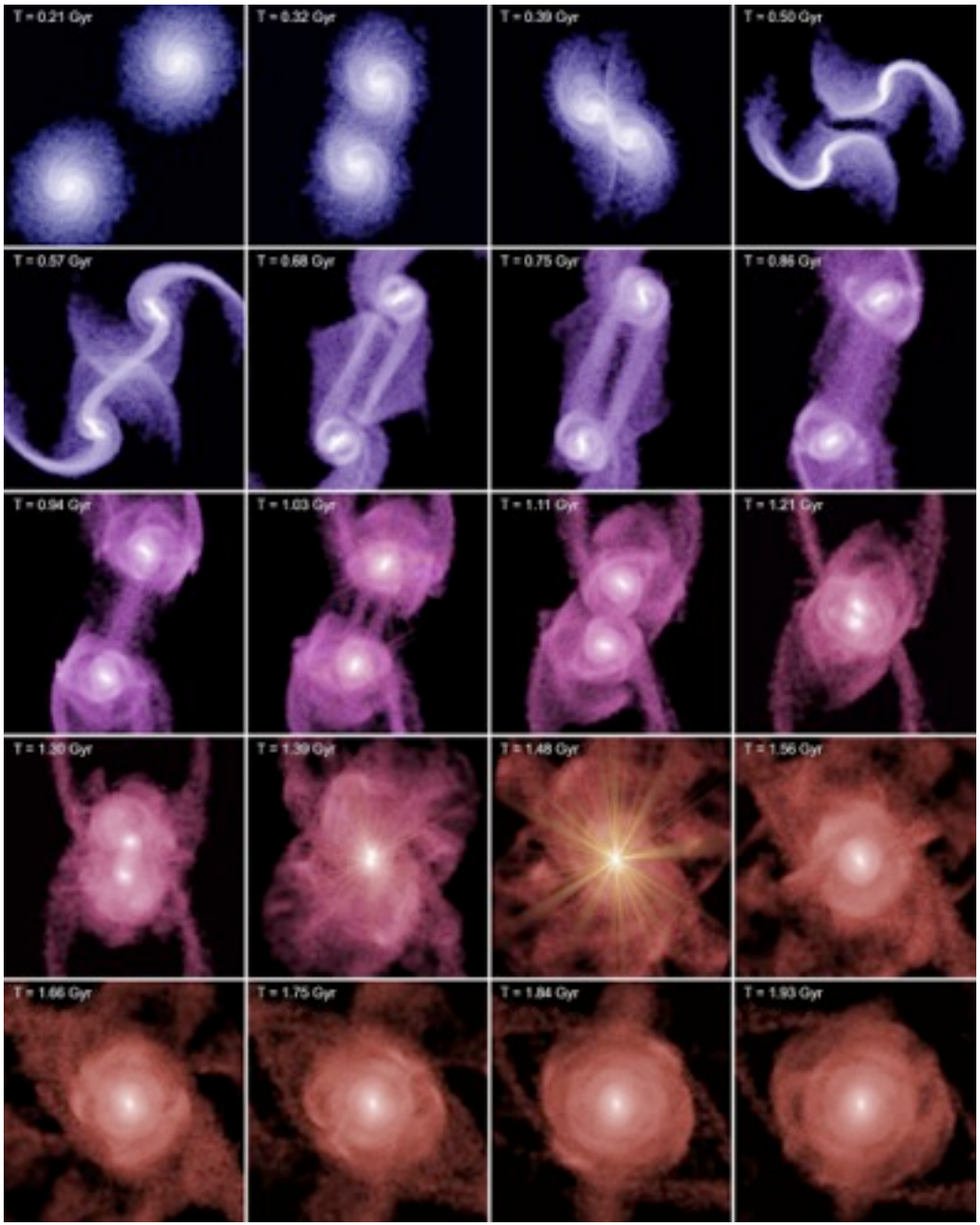
Three Outstanding (Inseparable?) Questions:



"Feeding the Monster"

WHY ARE WE INTERESTED IN MERGERS?

PFH et al. 2005



Mergers a long-time candidate for BH fueling:

- Fast, violent:

  Soltan (1982): growth in short-lived QSOs

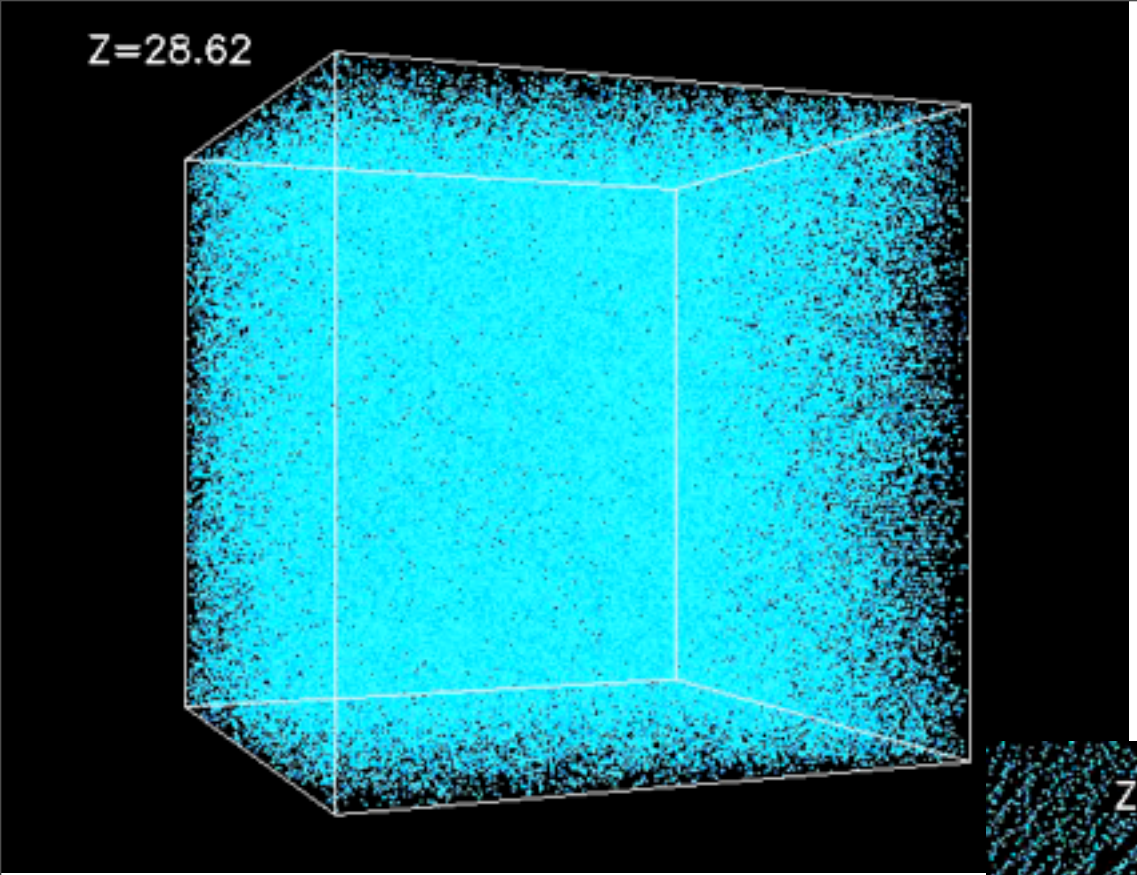
  → gas dynamics; rapid (~ few 10^7 years)

  Angular momentum problem: perturbed at all radii

- Blend of gas & stellar dynamics:

  Lynden-Bell (1967): orbits redistributed by large, rapid potential fluctuations

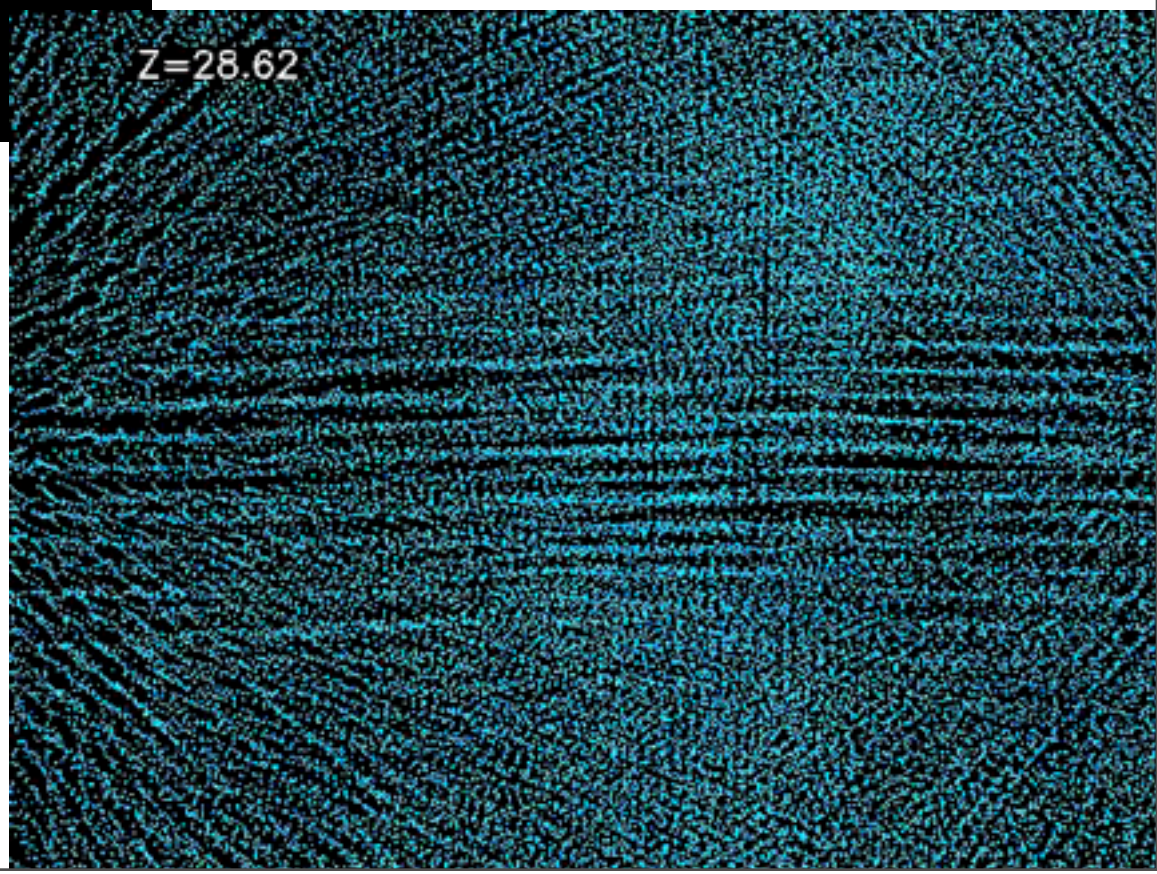
  → stellar dynamics; freefall timescale



“Feeding the Monster”

WHY ARE WE INTERESTED IN MERGERS?

Kravtsov et al.

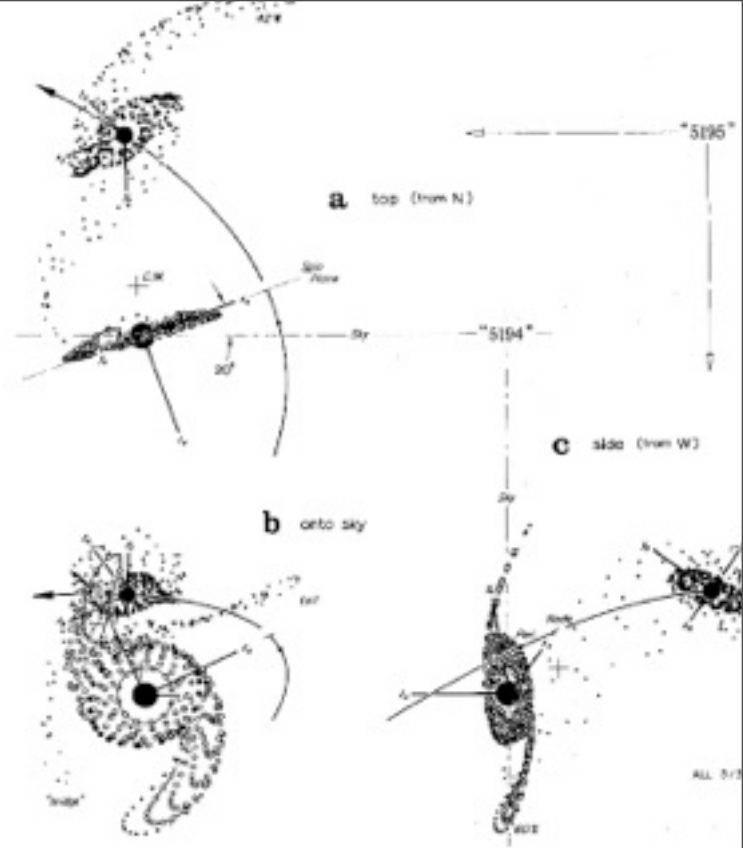


- Structure grows hierarchically: must understand mergers

“Feeding the Monster”

WHY ARE WE INTERESTED IN MERGERS?

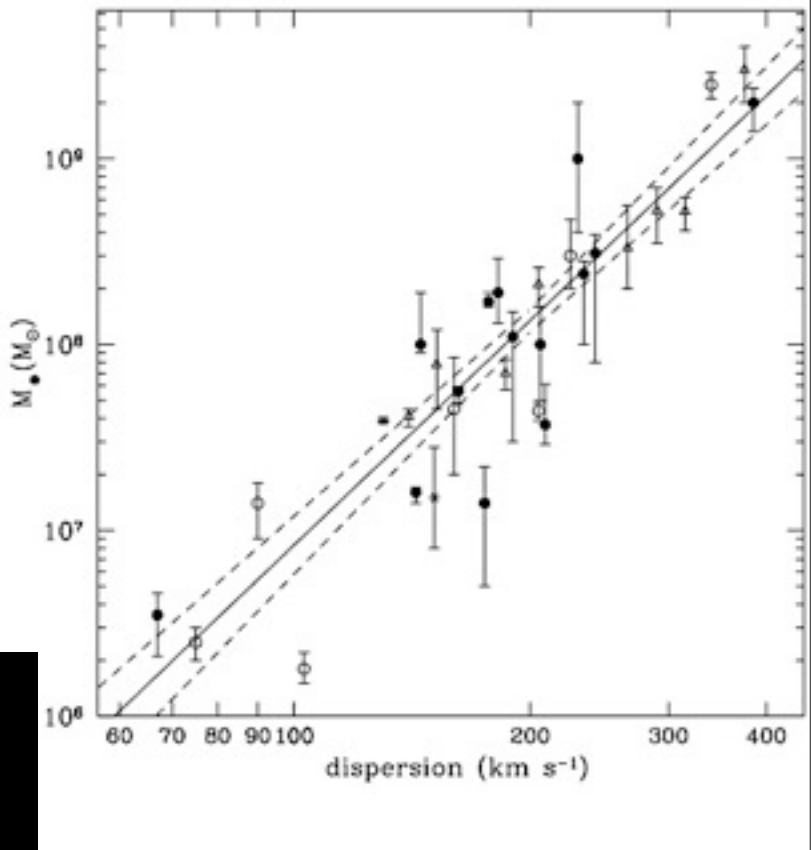
- Toomre & Toomre (1972) : the “merger hypothesis”
  - Spheroids are made by merger of spirals



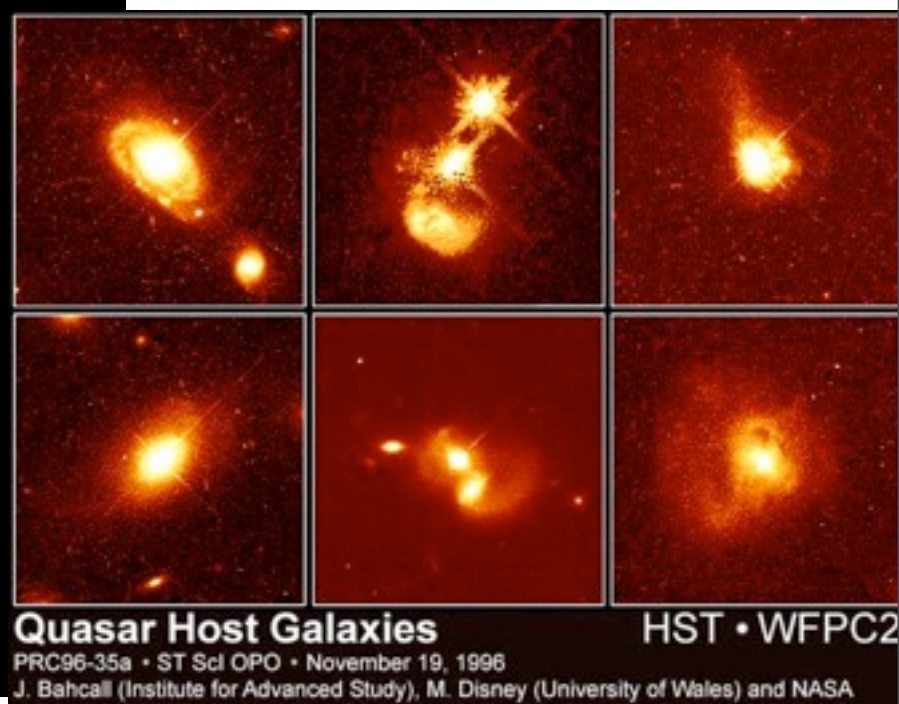
“Feeding the Monster”

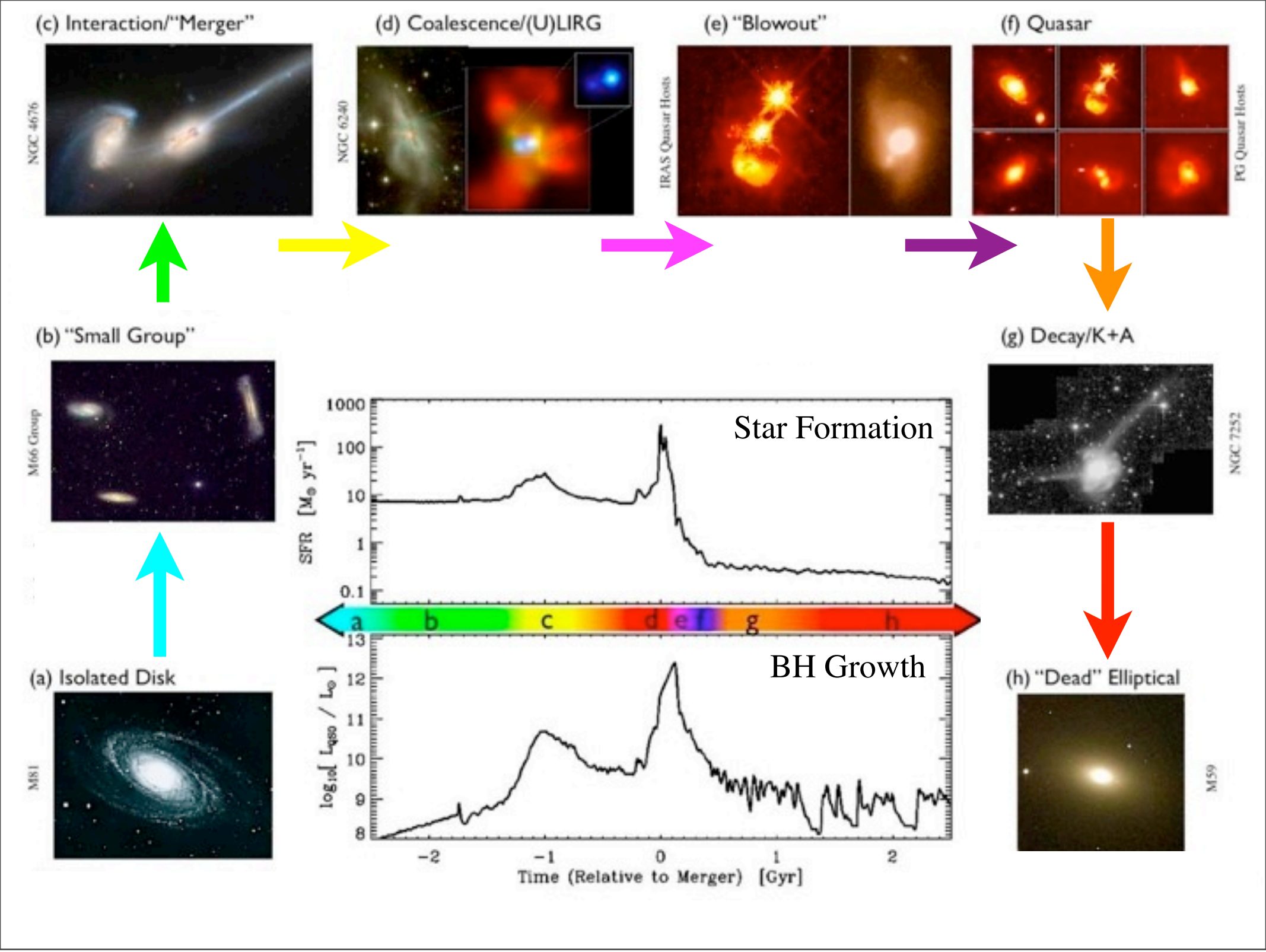
WHY ARE WE INTERESTED IN MERGERS?

- If BHs trace spheroids, then *most* growth from mergers



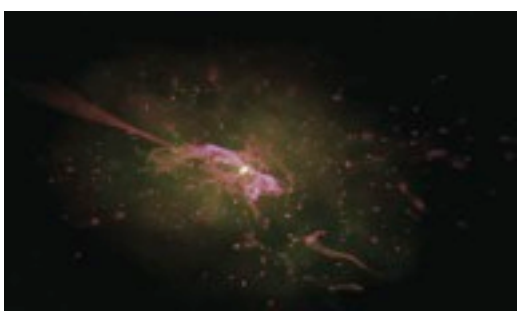
Komossa et al.




(c) Interaction/"Merger"
(d) Coalescence/(U)LIRG
(e) "Blowout"
(f) Quasar
NGC 4676
NGC 6240
IRAS Quasar Hosts
PG Quasar Hosts
(b) "Small Group"
M66 Group
(g) Decay/K+A
NGC 7252
Star Formation
SFR [M⊙ yr⁻¹]
1000
100
10
1
0.1
a
b
c
d
e
f
g
h
BH Growth
log[M_BH / M⊙]
13
12
11
10
9
8
−2
−1
0
1
2
Time (Relative to Merger) [Gyr]
(a) Isolated Disk
M81
(h) "Dead" Elliptical
M59

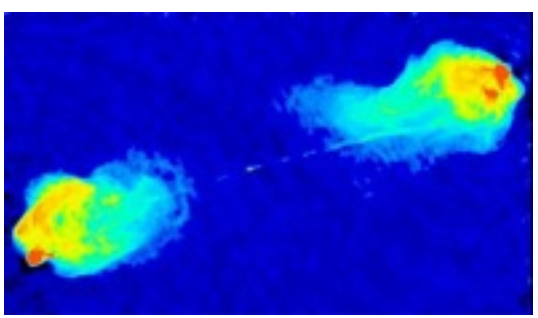
"Transition" vs. "Maintenance"

- Move mass from Blue to Red
- Rapid
- Small scales
- "Quasar" mode (high mdot)
- Morphological Transformation
- Gas-rich/Dissipational Mergers



- Regulates *Black Hole* Mass

- Keep it Red
- Long-lived (~Hubble time)
- Large (~halo) scales
- "Radio" mode (low mdot)
- Subtle morphological change
- Hot Halos & Dry Mergers



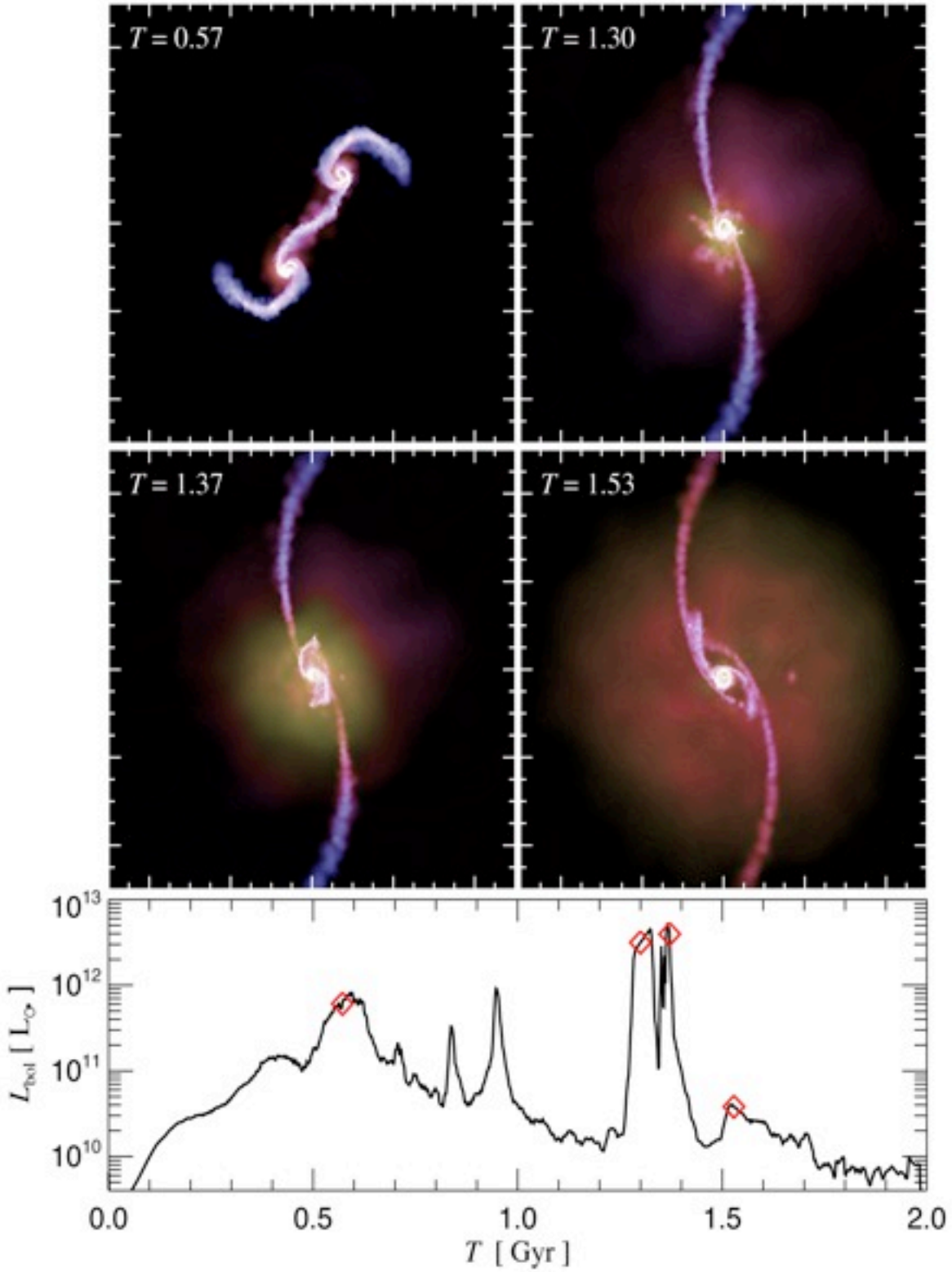
- Regulates *Galaxy* Mass

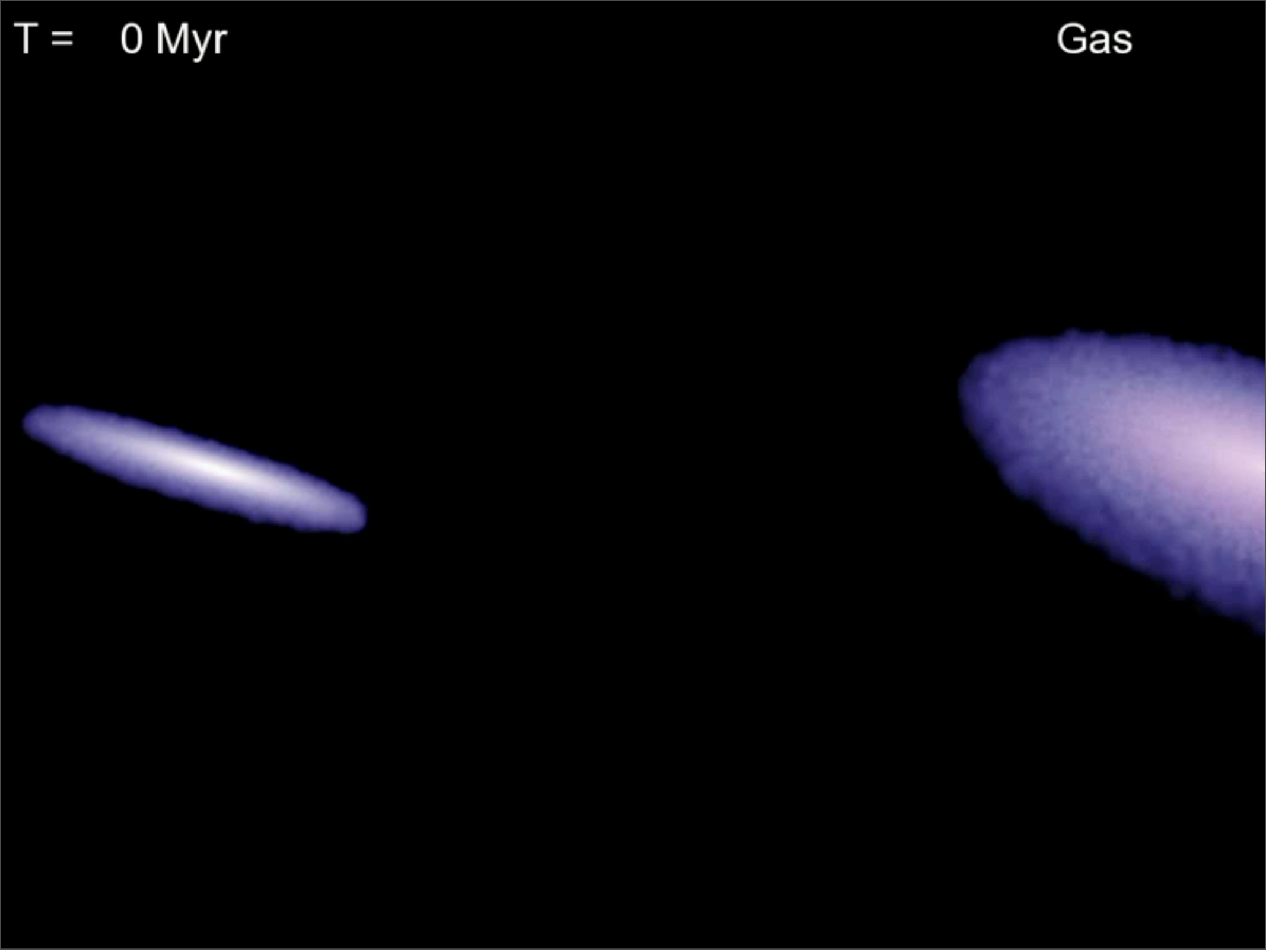
Simplest Experiment:

- R_{sch} ~ few AU ~ 10^{-6} x our resolution

- BUT, we can get to the BH radius of influence, and R_{Bondi} ~ 10 pc (typical)
  - Accrete from nearby gas
  - ~0.1 radiative efficiency
  - ~5% couples to local gas

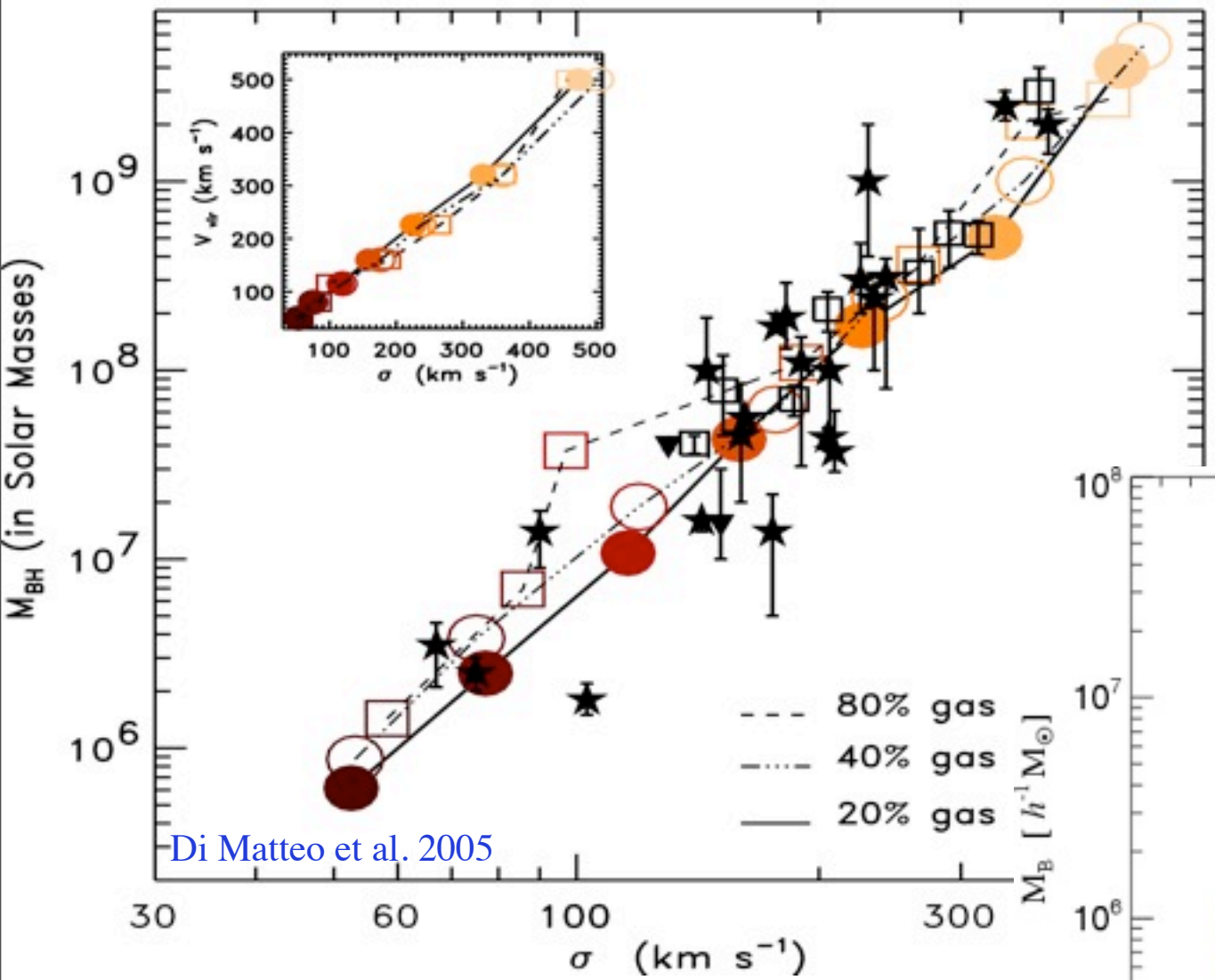
- Let's see if it works!



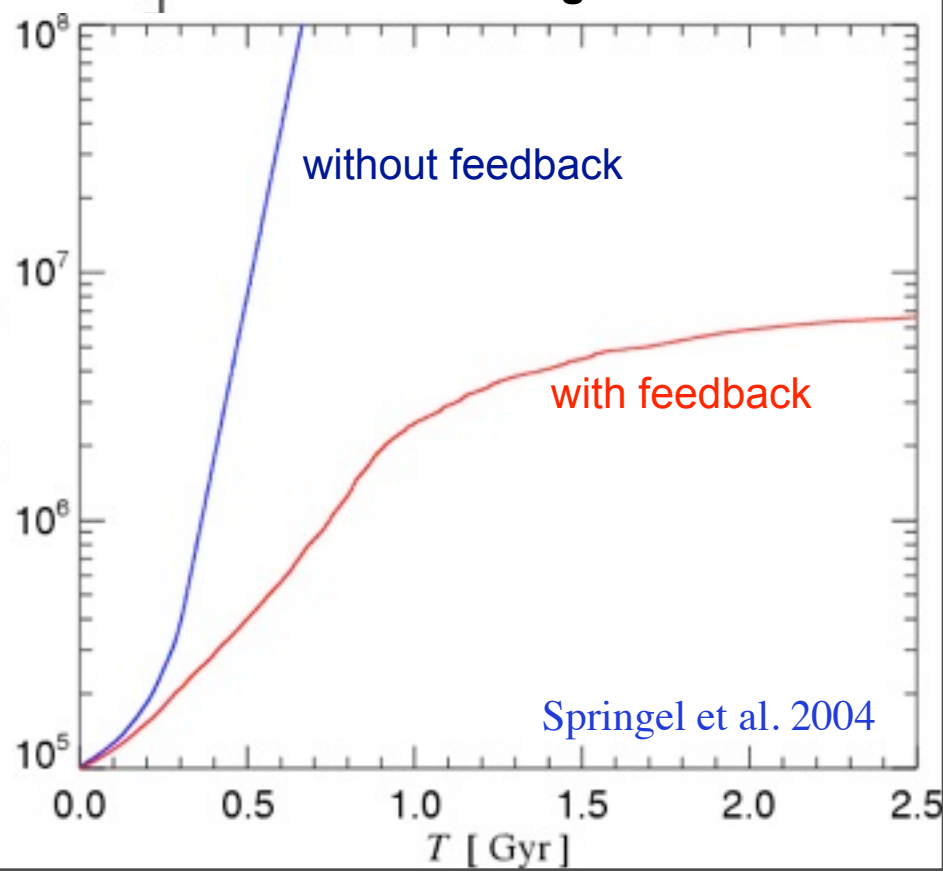

T = 0 Myr
Gas

M-sigma Relation Suggests *Self-Regulated* BH Growth

PREVENTS RUNAWAY BLACK HOLE GROWTH



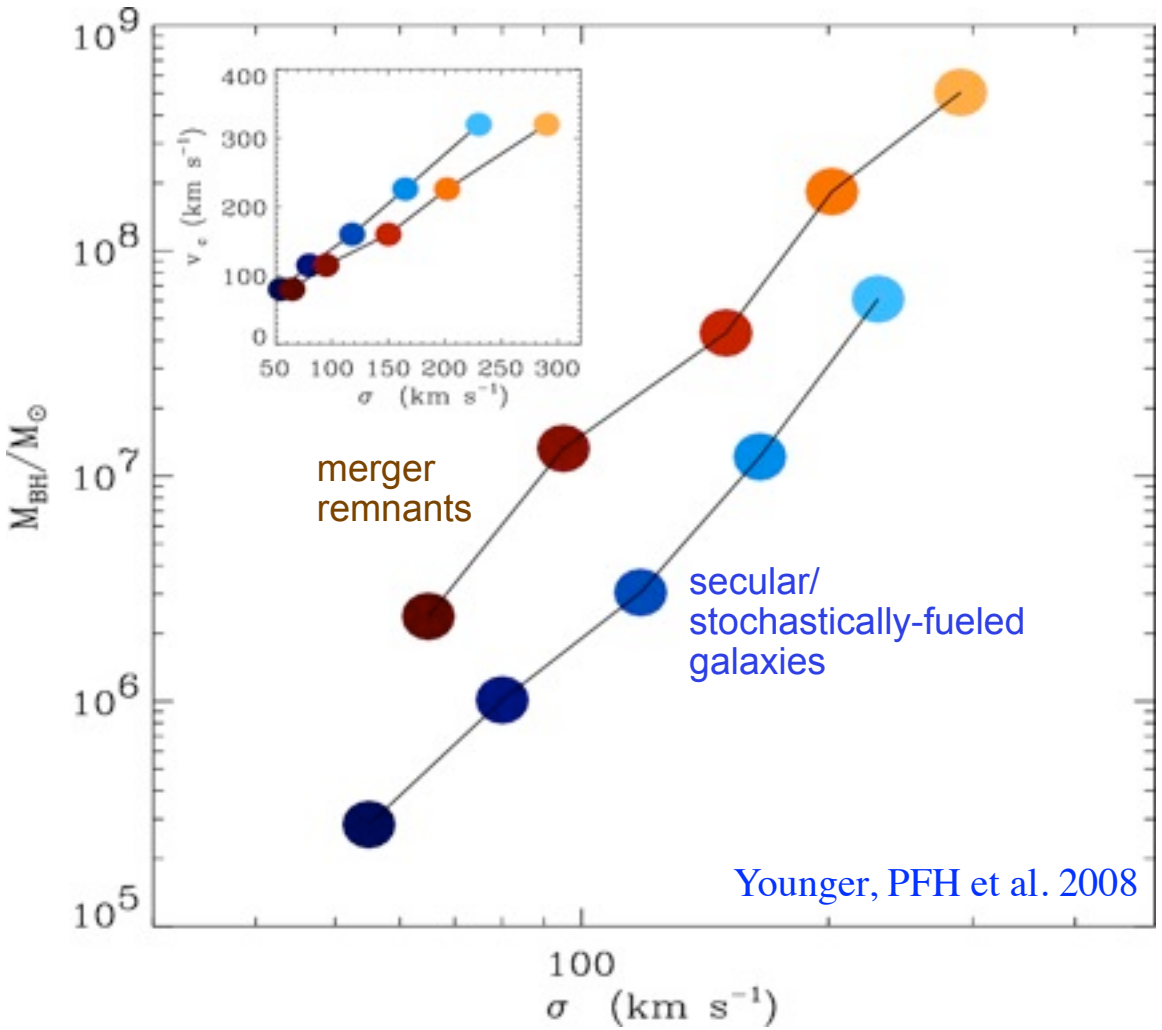
Black hole growth:



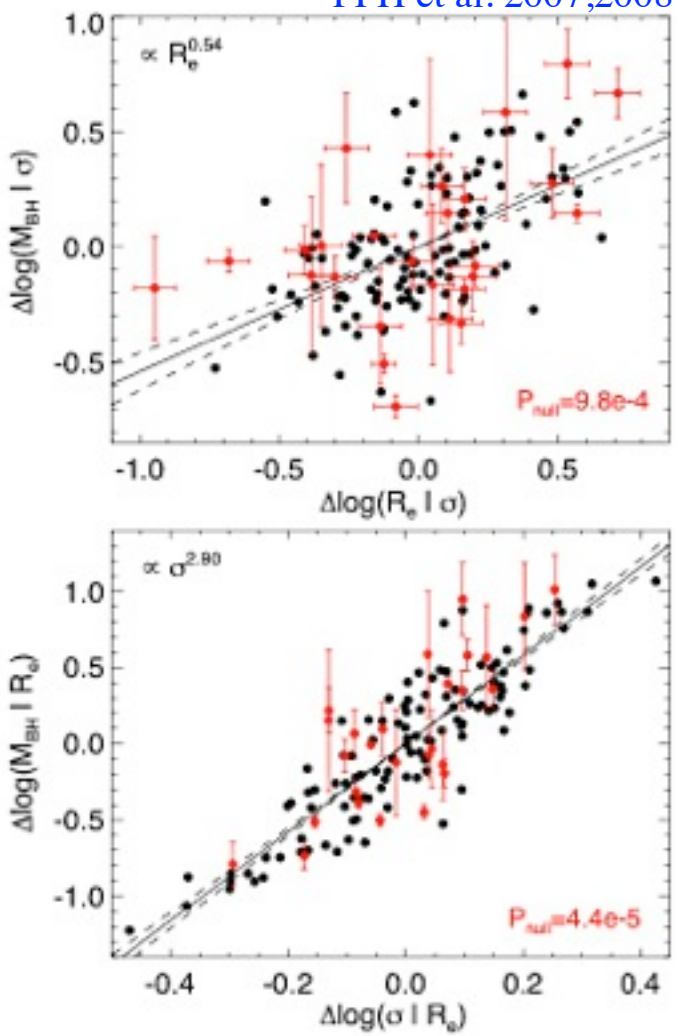
Observations & Simulations Suggest this Simple Picture Works

MAKES UNIQUE PREDICTIONS:

- What is the "fundamental" correlation? Not M_{BH}-s, but M_{BH}-$E_{binding}$ (PFH et al.)
- Different correlation for "classical" and "pseudobulges"
  - Both tentatively observed (PFH et al.; Aller; Greene et al.; Hu)



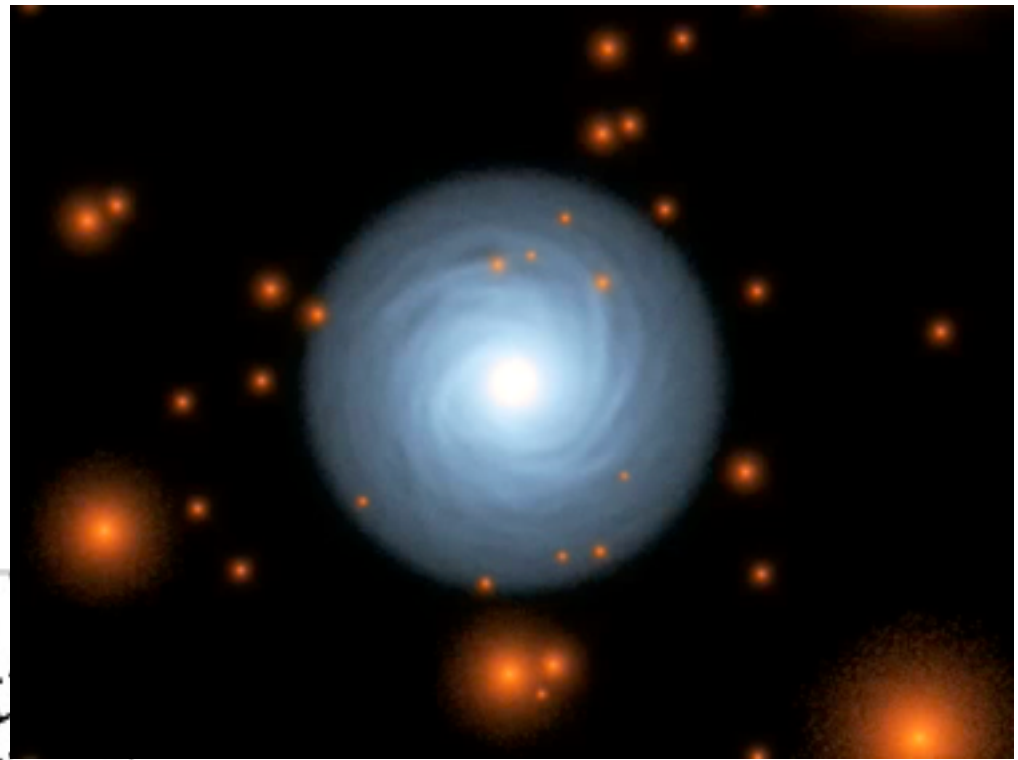
PFH et al. 2007,2008

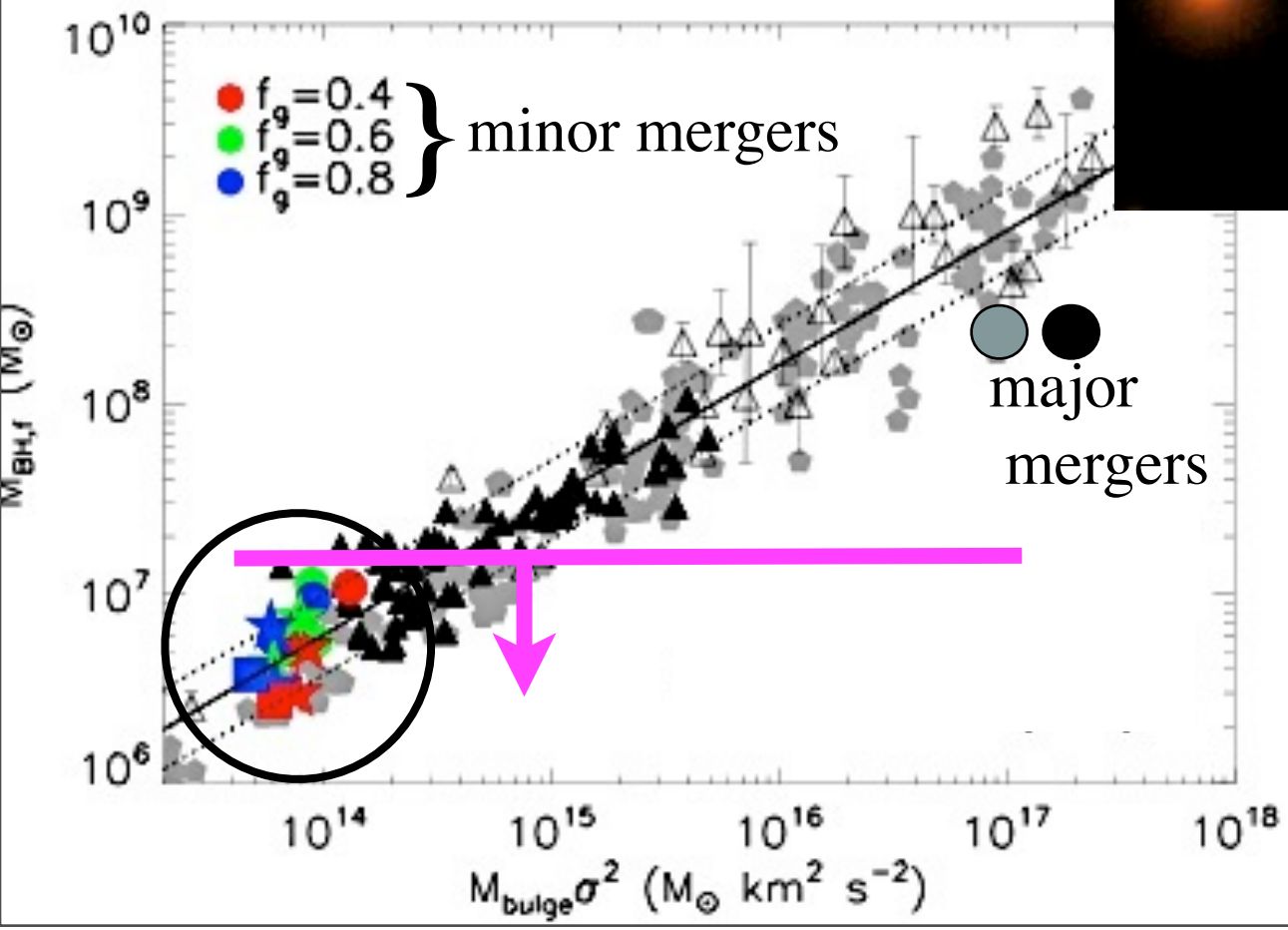


Of Course, Not *Every* AGN Needs a Merger

MORE QUIESCENT GROWTH MODES?

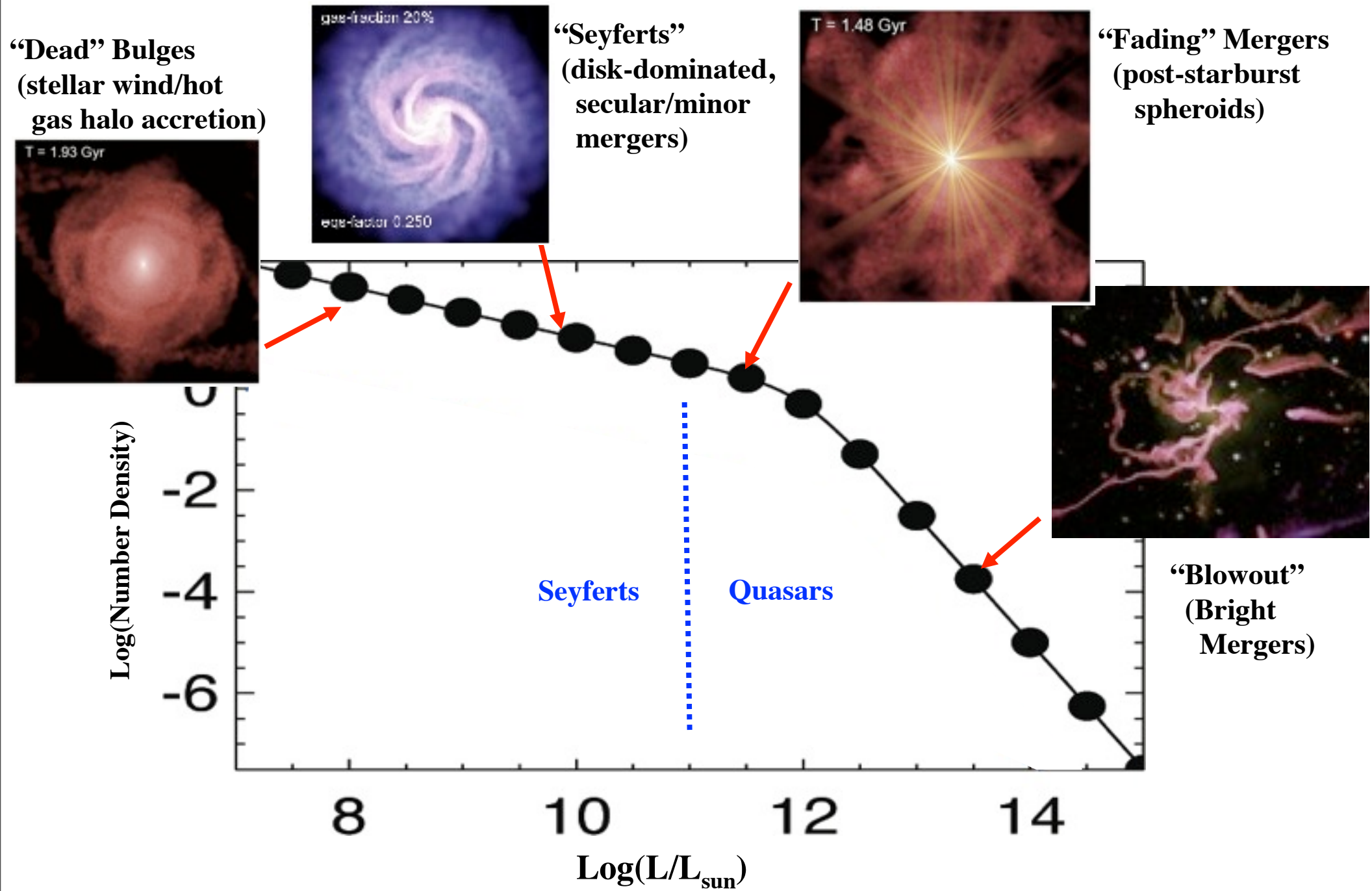
- z~2 QSO: 10^{11} M_{sun} in <10pc in ~t_{dyn}
- Seyfert: only $10^{7\text{-}8}$ M_{sun} ~ GMC
  - Minor mergers?
  - Secular instabilities/bars?





- If you don't build massive bulges, doesn't matter if you can get the gas in!

Younger, PFH et al. 2008

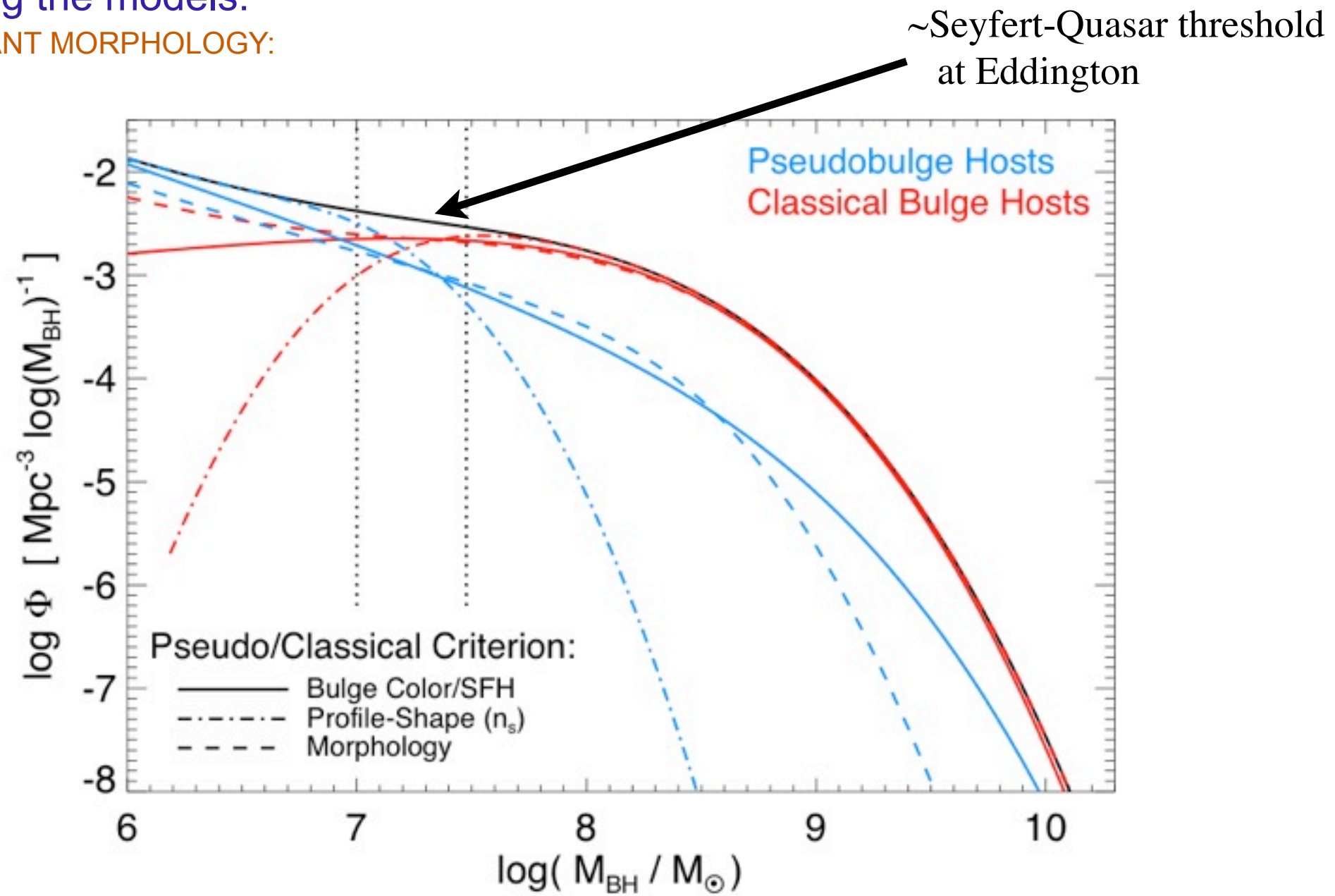


- Observed luminosity function: populations at different *evolutionary* stages

PFH & Hernquist 2006, 2008

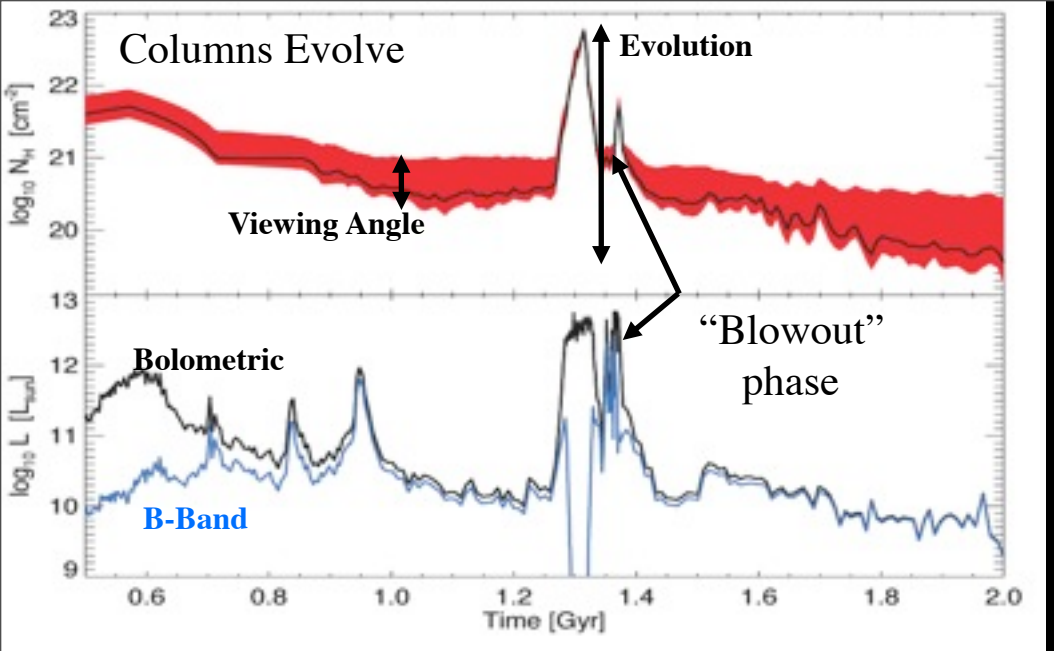
Testing the models:

REMNANT MORPHOLOGY:



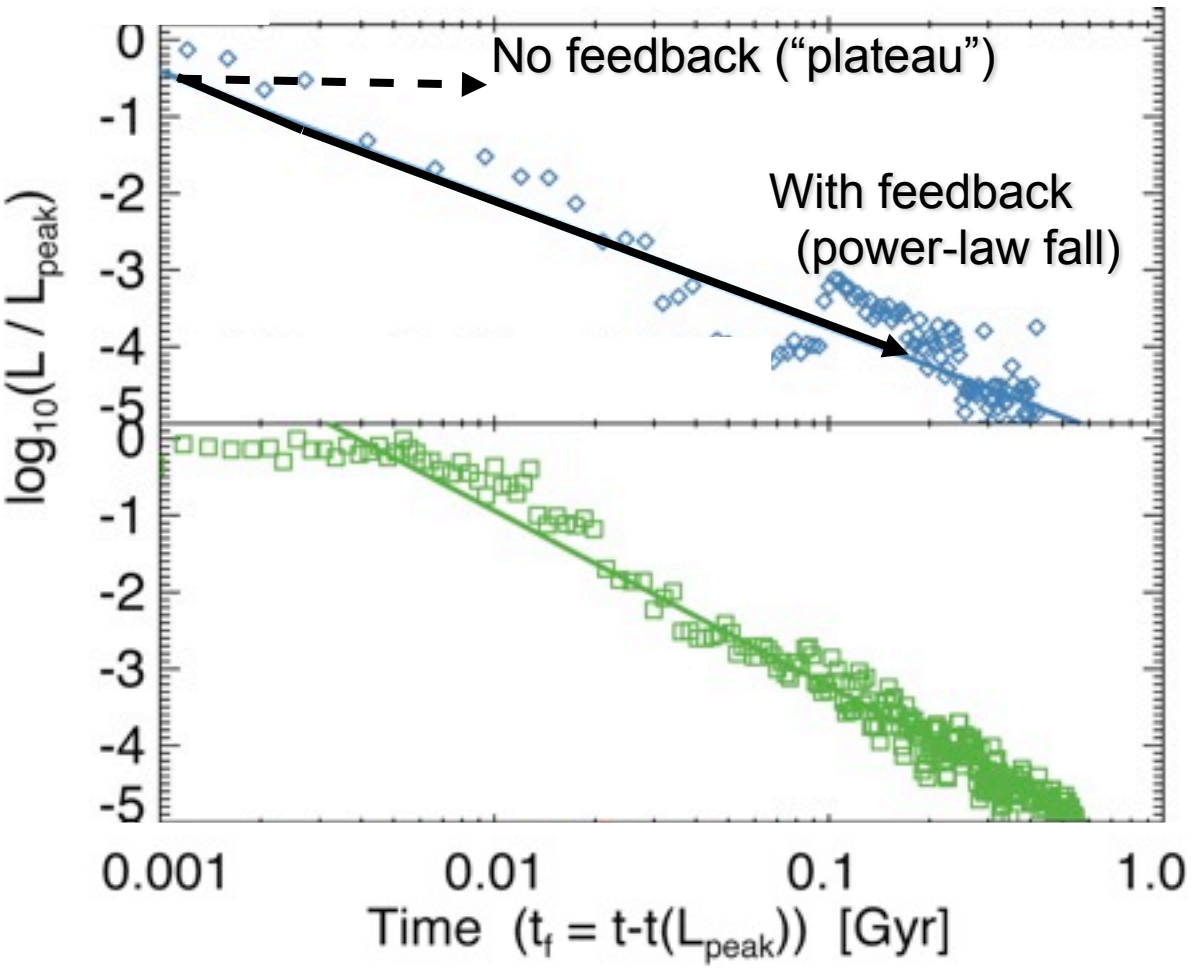
- Most mass in "classical" bulges, not "pseudobulges
  - But, *are* important below <~ Sa-types

PFH & Hernquist 2008


Columns Evolve
Evolution
Viewing Angle
"Blowout" phase
Bolometric
B-Band
log10 NH [cm-2]
log10 L [Lsun]
Time [Gyr]
23
22
21
20
13
12
11
10
9
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Quasar Lightcurves and Lifetimes

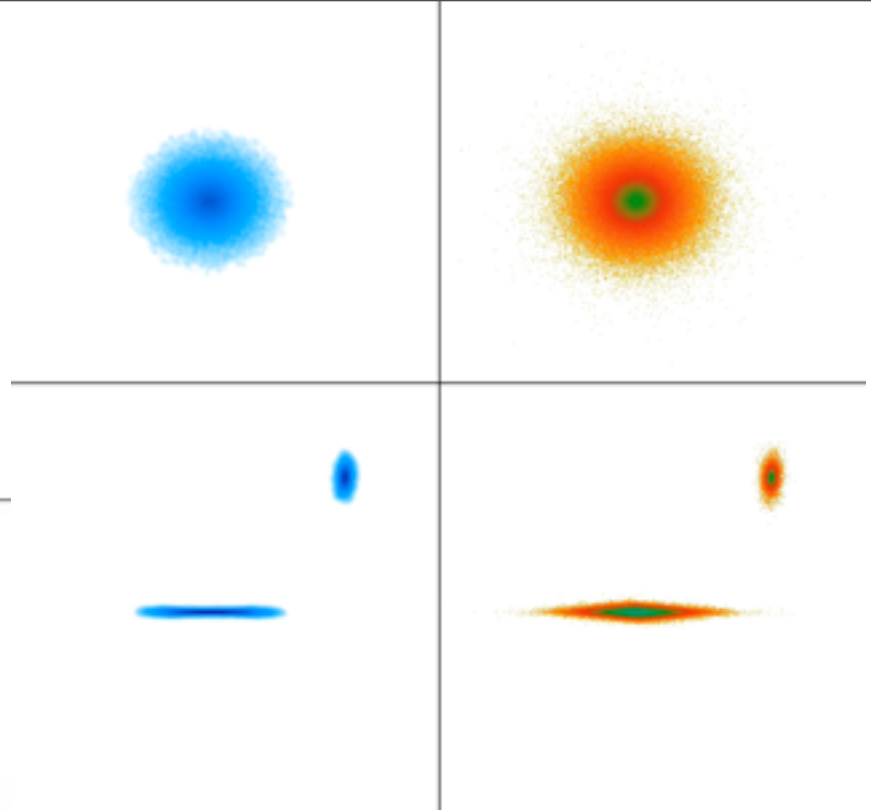
- Feedback determines the decay of the quasar light curve:



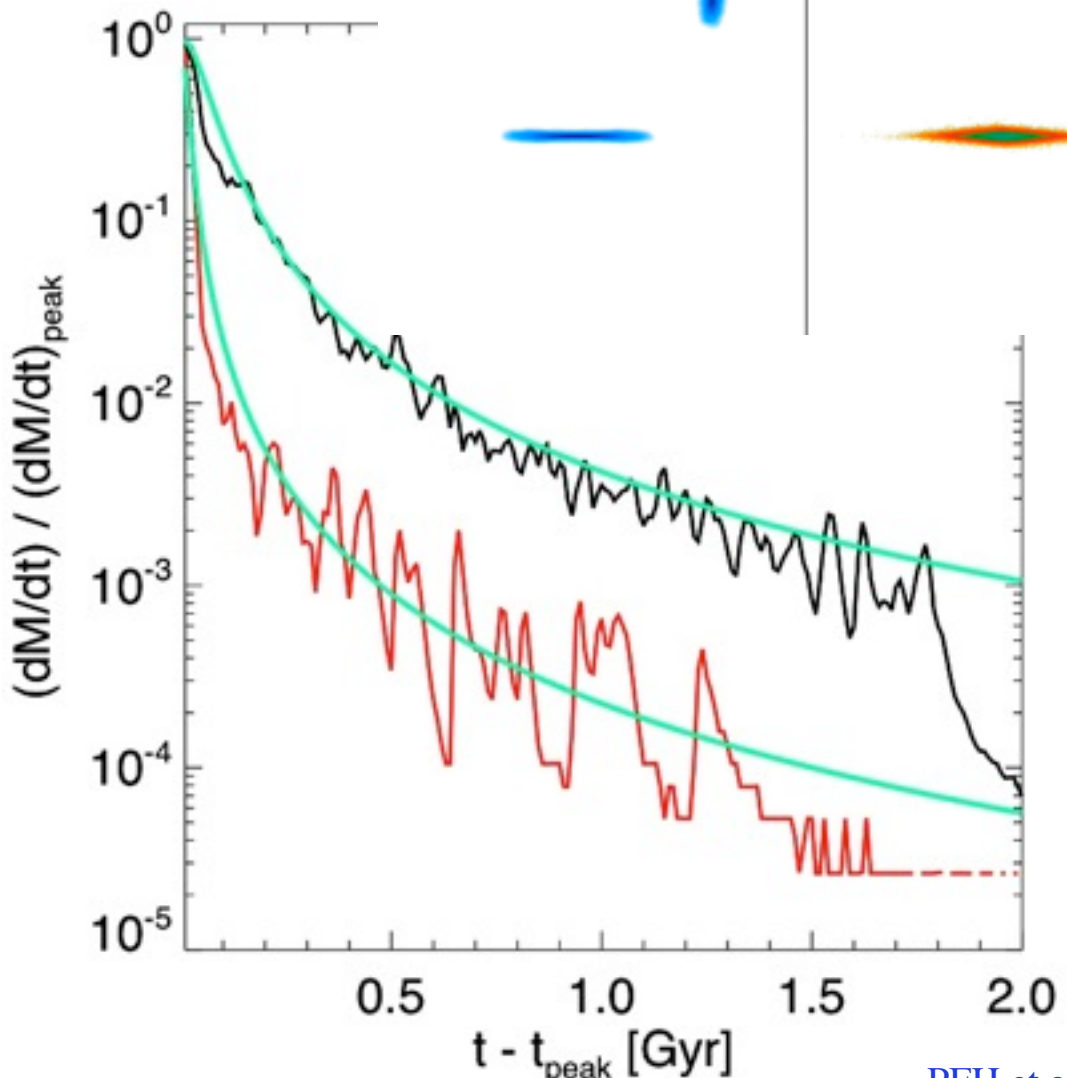
- Explosive blowout drives power-law decay in L
- No Feedback:
  - Runaway growth (exponential light curve)
  - “Plateau” as run out of gas but can’t expel it (extended step function)

PFH et al. 2006a

This is Very General:
(EVEN THOUGH NOT ALL AGN ARE MERGER-DRIVEN)

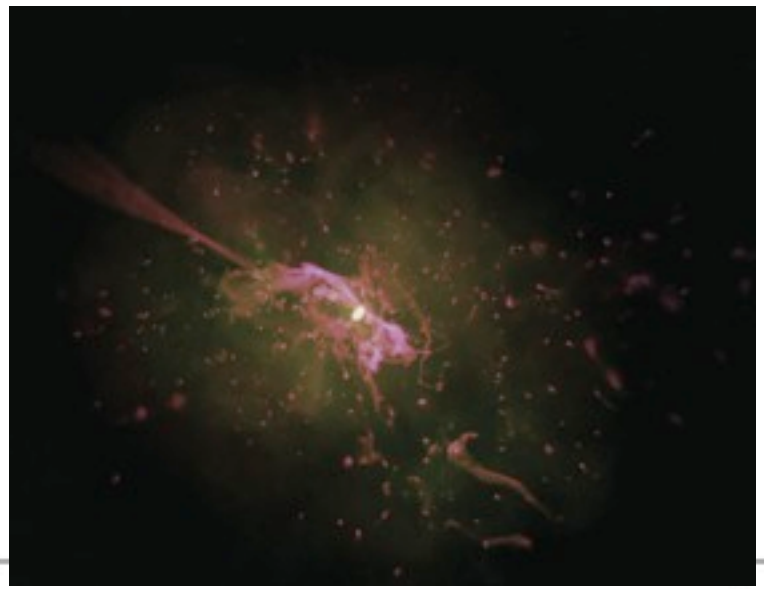


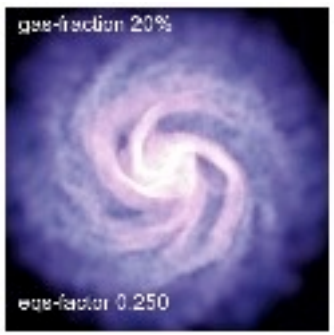
- Almost any (ex. radio) AGN feedback will share key properties:
  - Point-like
  - Short input (~ $t_{Salpeter}$)
  - E~$E_{binding}$
- Simple, analytic solutions:
  - $L \sim (t / t_Q)^{-1.7(ish)}$
  - Agrees well with simulations!
- Generalize to "Seyferts"
  - Disk-dominated galaxies with bars
  - Minor mergers

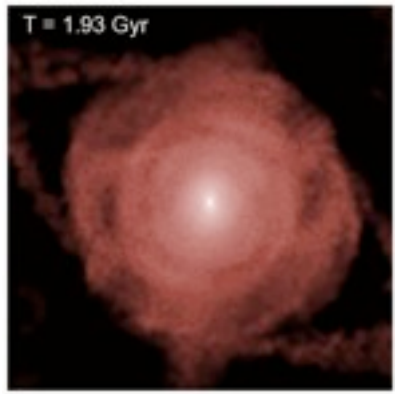


PFH et al. 2006b,c

So What Is the “Quasar Lifetime”?

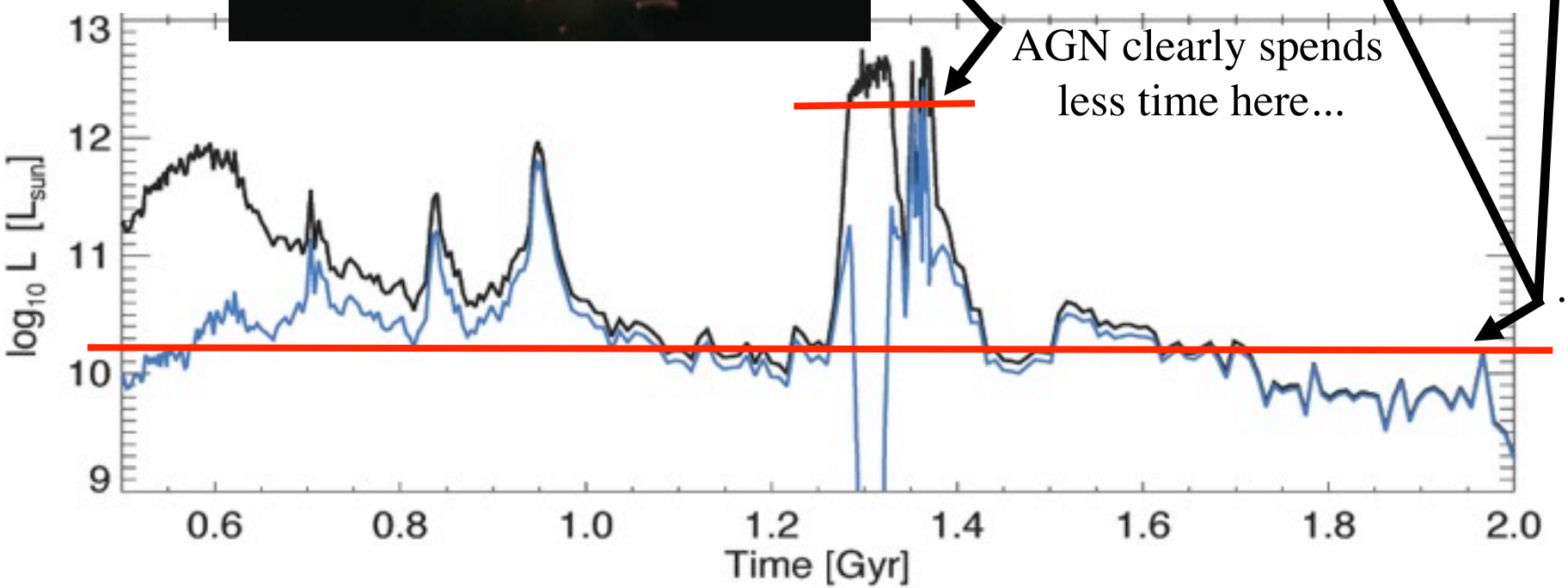






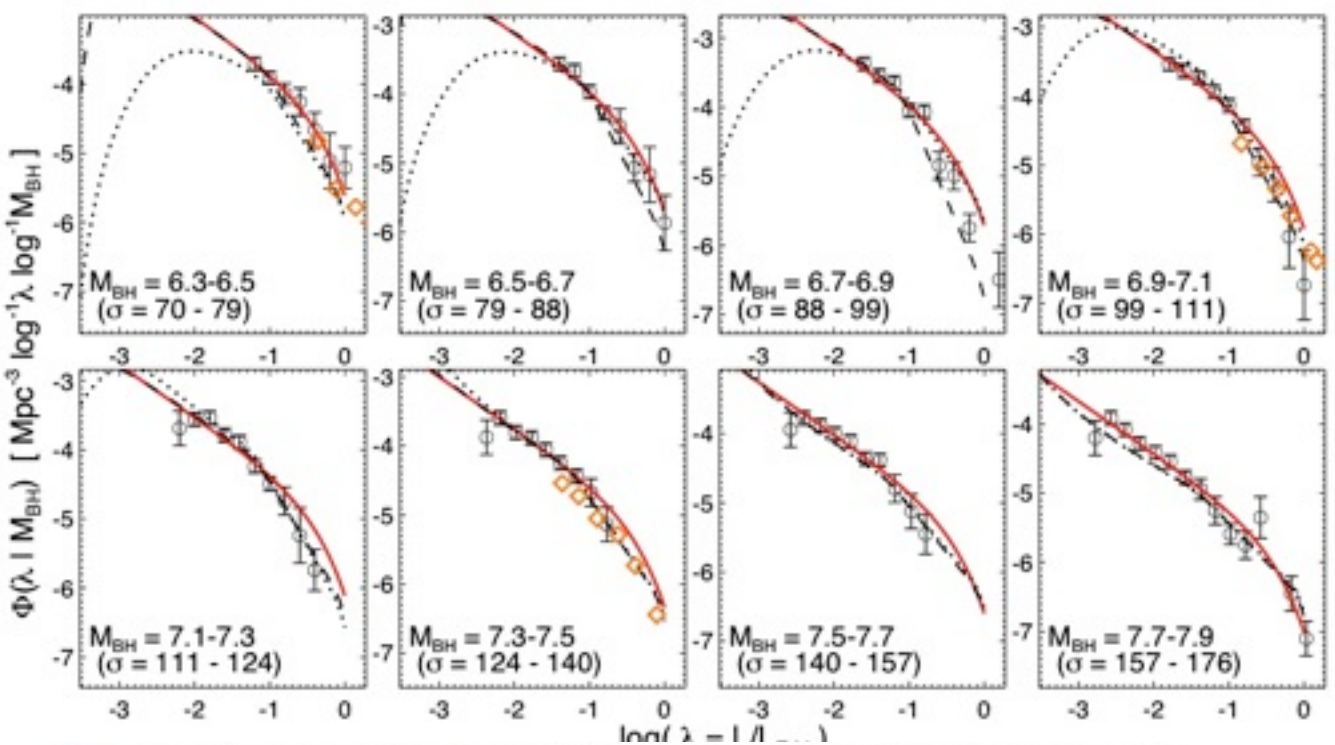
AGN clearly spends less time here...

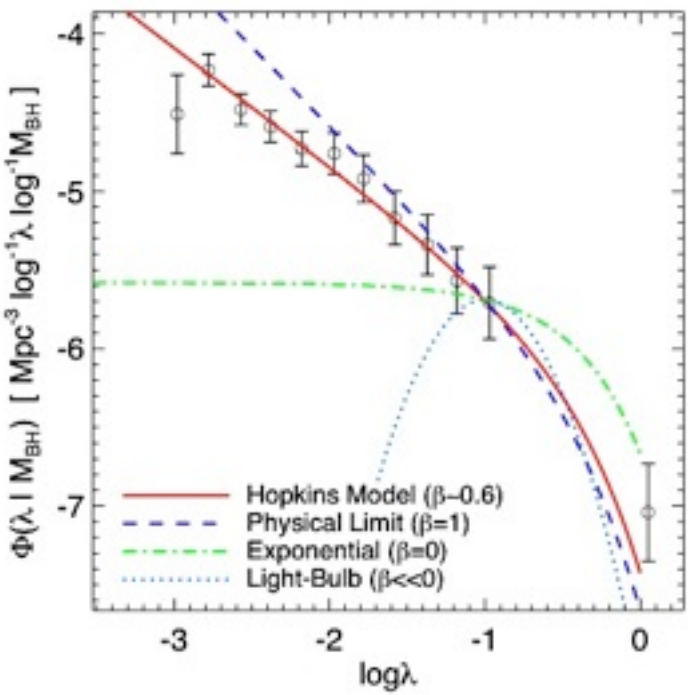
... than here

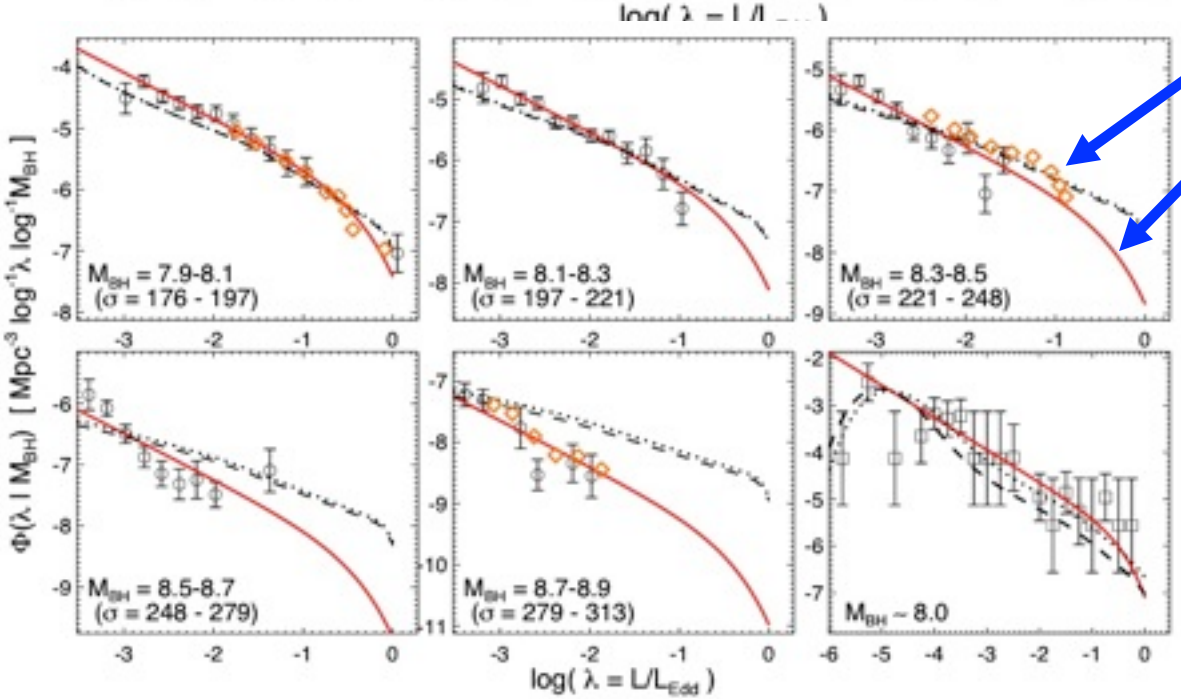


- “Quasar Lifetime”: a conditional, *luminosity-dependent* distribution

Directly Apparent in the Observed Eddington Ratio Distribution







Observed

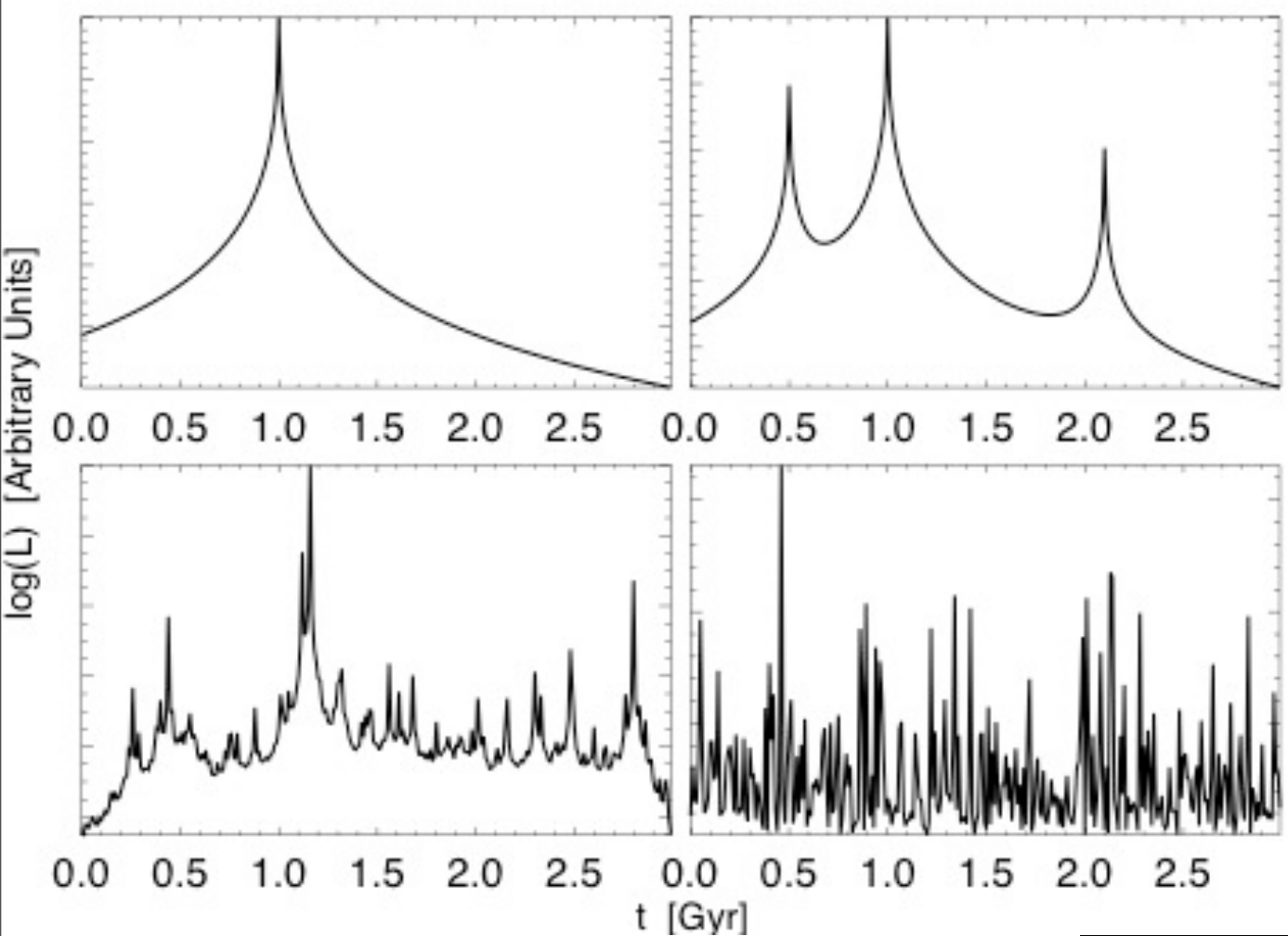
Predicted

$$\frac{dt}{d\log L} = t_0 \left(\frac{L}{L_{peak}}\right)^{-\beta} \exp\left(-L/L_{peak}\right)$$

$$L \propto (t/t_Q)^{-(1.5-2.0)}$$

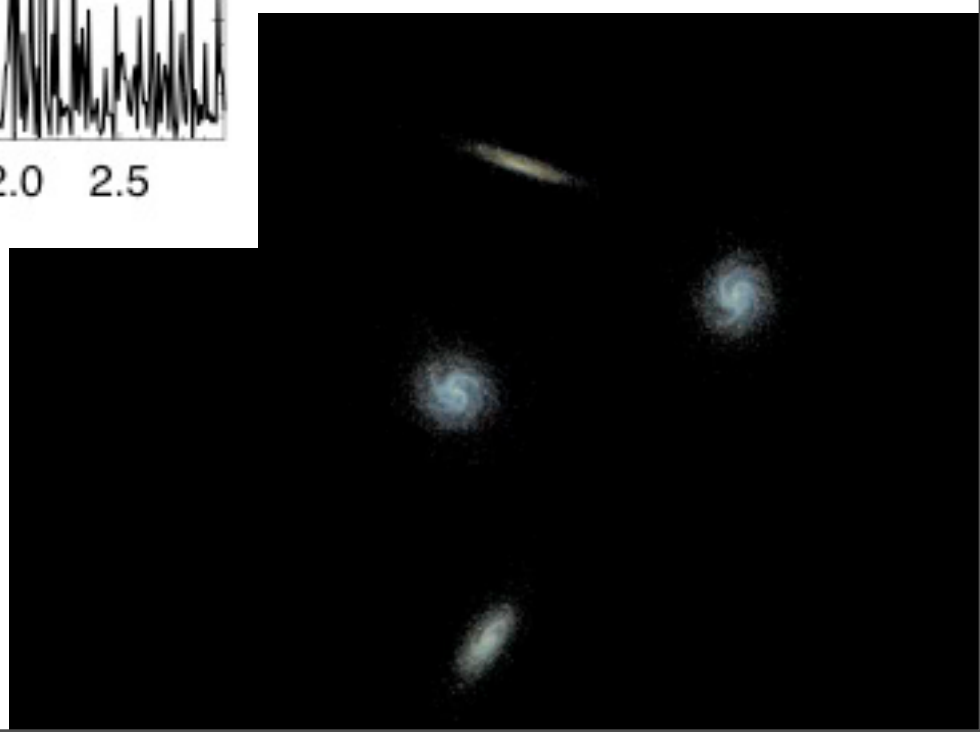
PFH et al. 2009

Directly Apparent in the Observed Eddington Ratio Distribution



May be multiple "events," but AGN decay/regulation is self-similar!

- BH, not galaxy, determines lightcurve evolution



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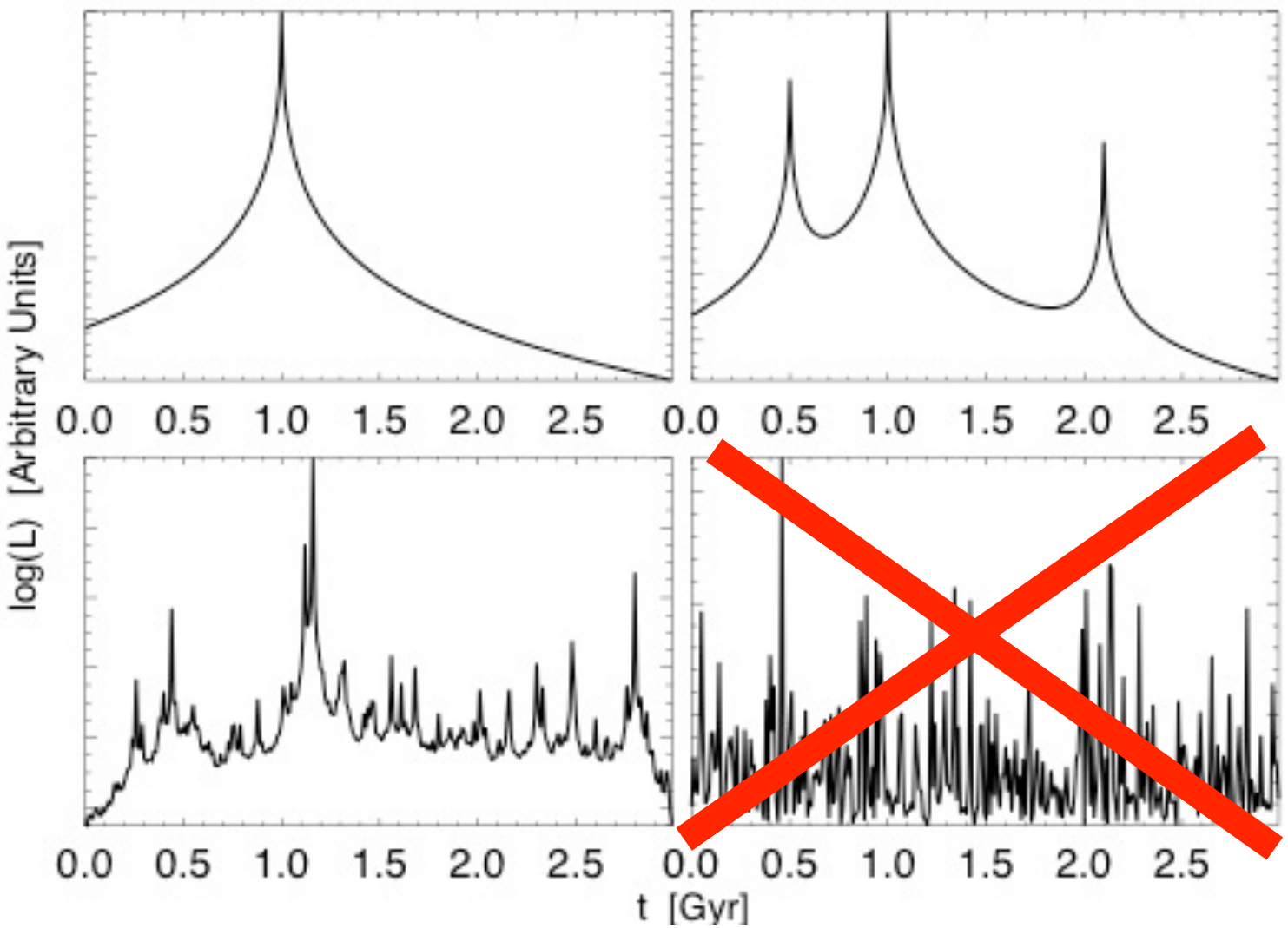


Ruled out by transverse proximity effect

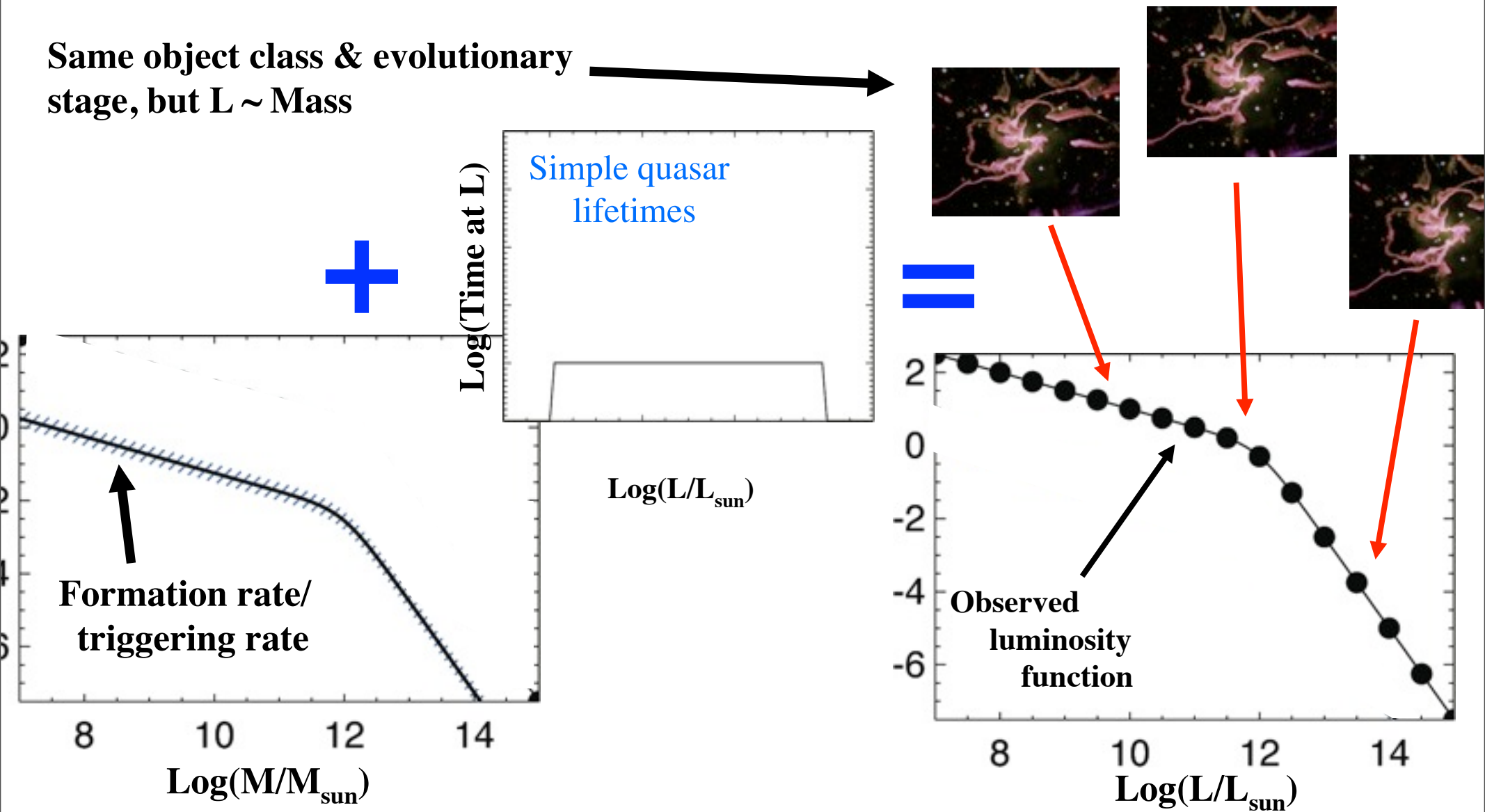
$t_{episodic} \sim t_{total}$

- Complimentary constraints from clustering (Meyers, Croom, Porciani, da Angela)
  - BHs grew in <~ a couple events

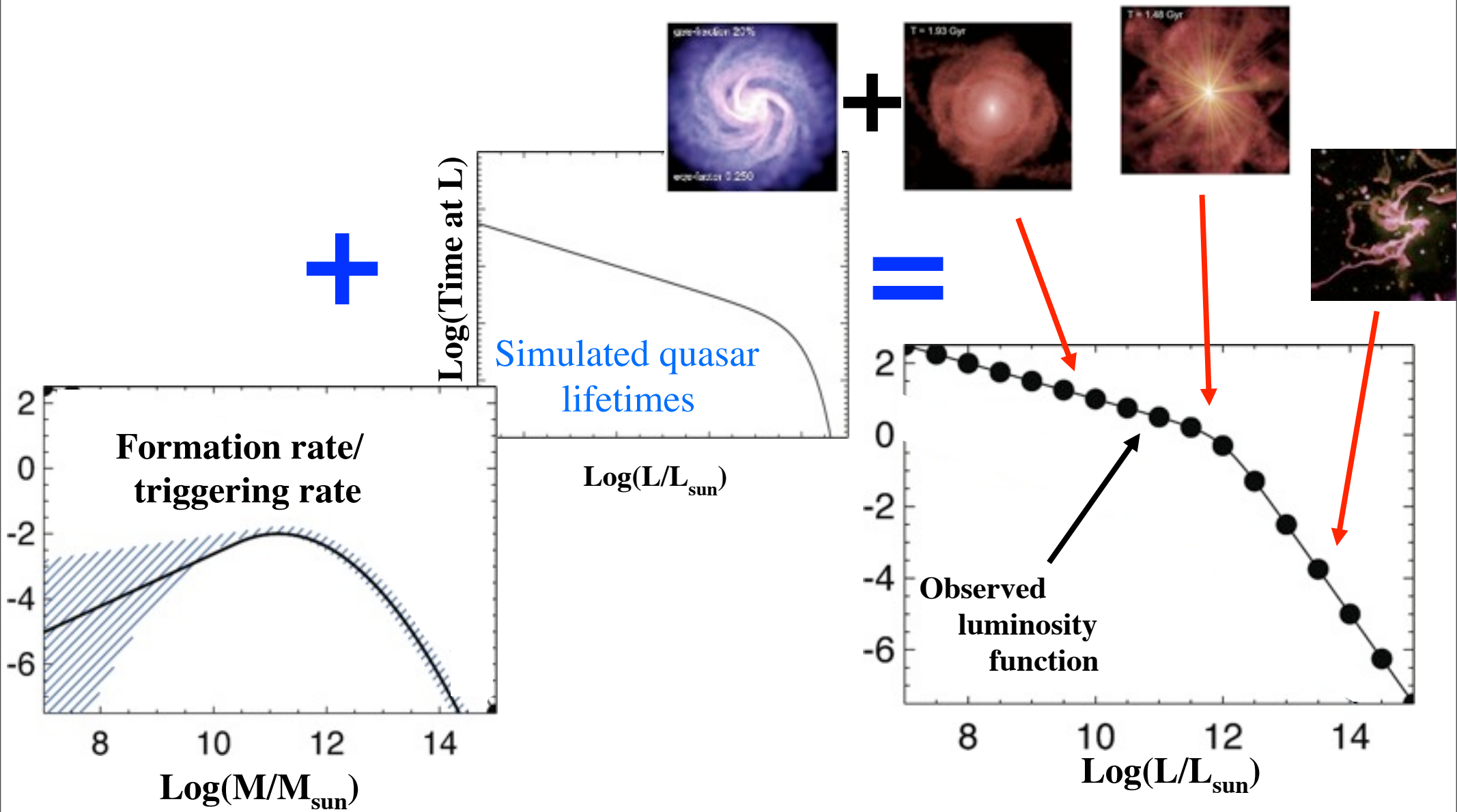
Given the Conditional Quasar Lifetime, De-Convolve the QLF

QUANTIFIED IN THIS MANNER, UNIQUELY DETERMINES THE RATE OF "TRIGGERING"

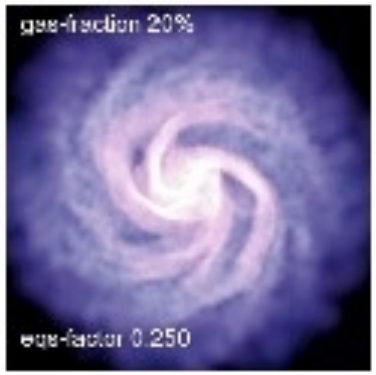
Same object class & evolutionary stage, but L ~ Mass



- If every quasar is at the same fraction of Eddington, the active BHMF (and host MF) is a trivial rescaling of the observed QLF

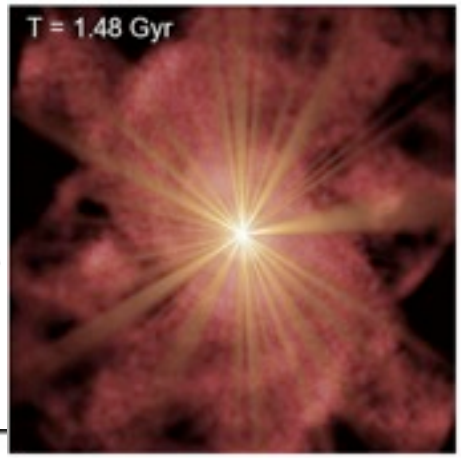


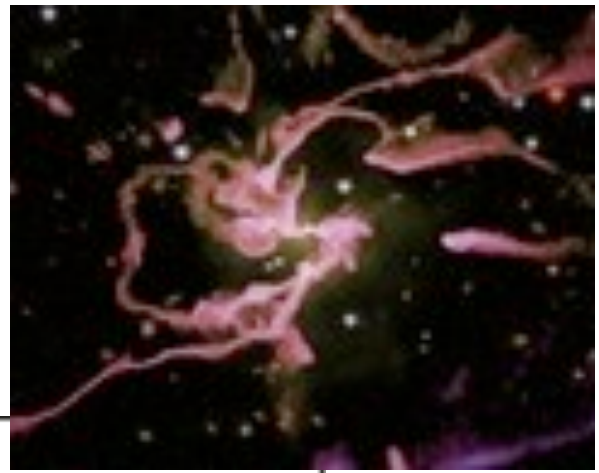
- *Different* shapes
- Much stronger turnover in formation/merger rate
- Large “faint” population of decaying systems: optically dim? (PFH, Hickox, Quataert ‘09)



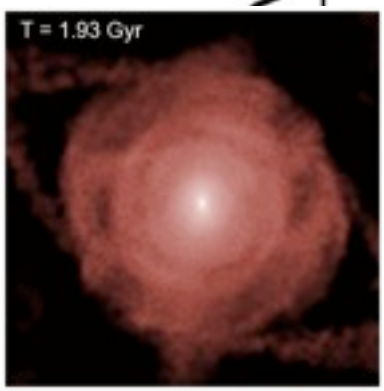
Disks & "Dead" Ellipticals

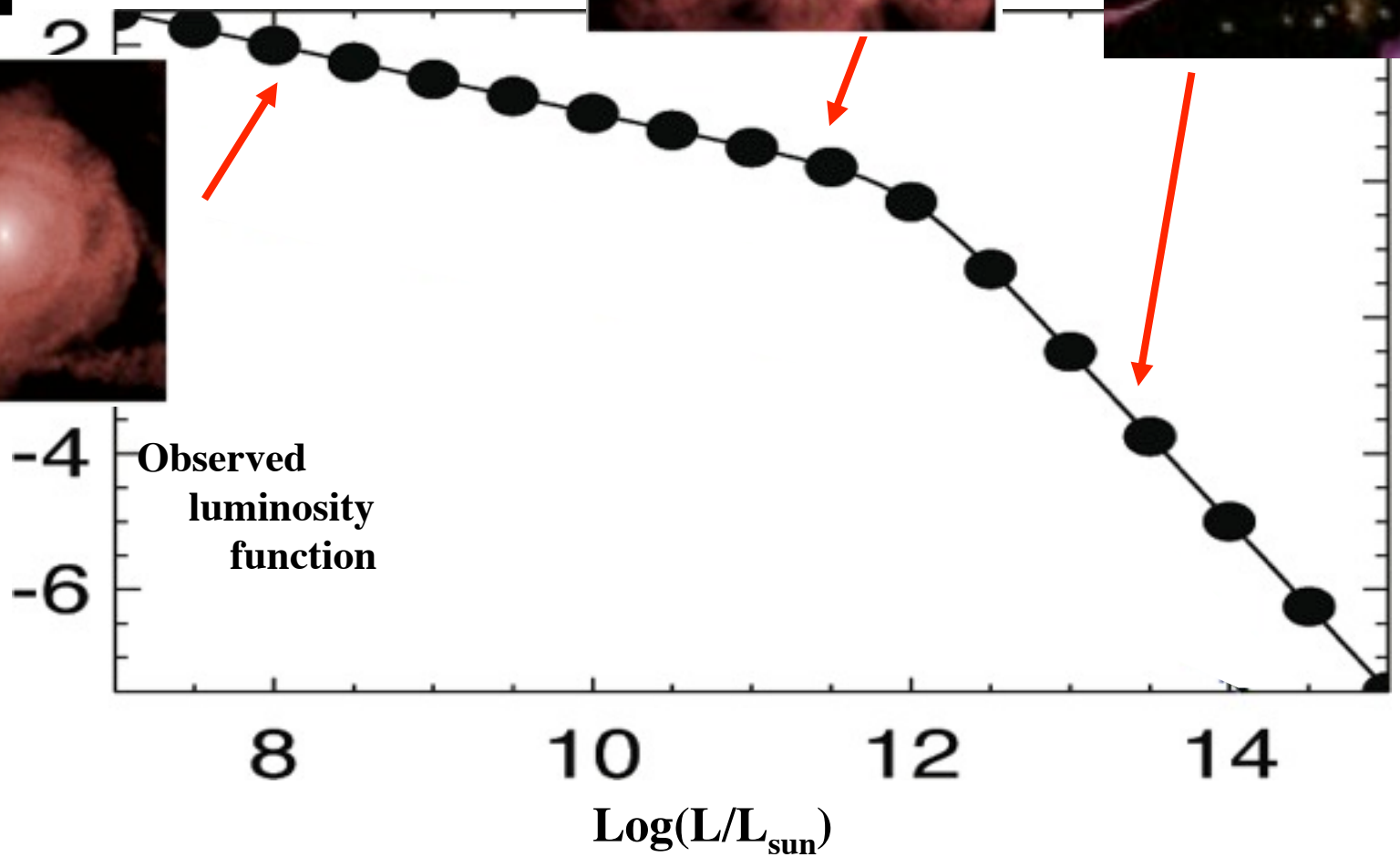
"Fading" Mergers (young ellipticals)





Peak Mergers



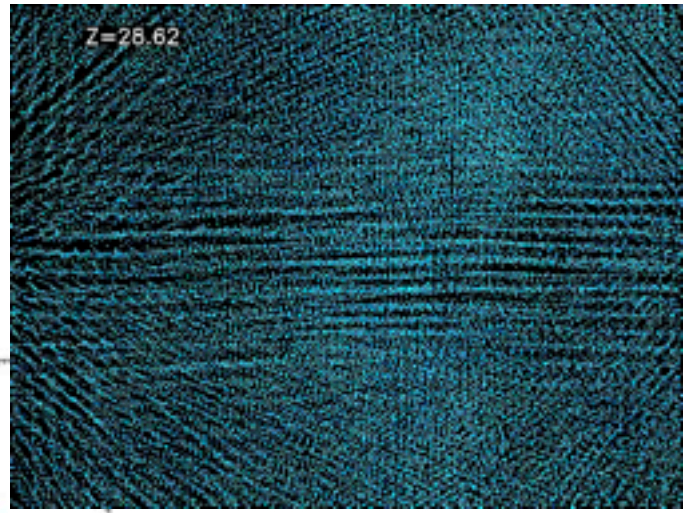


- Return to this picture:
  QLF reflects populations at different *evolutionary* stages

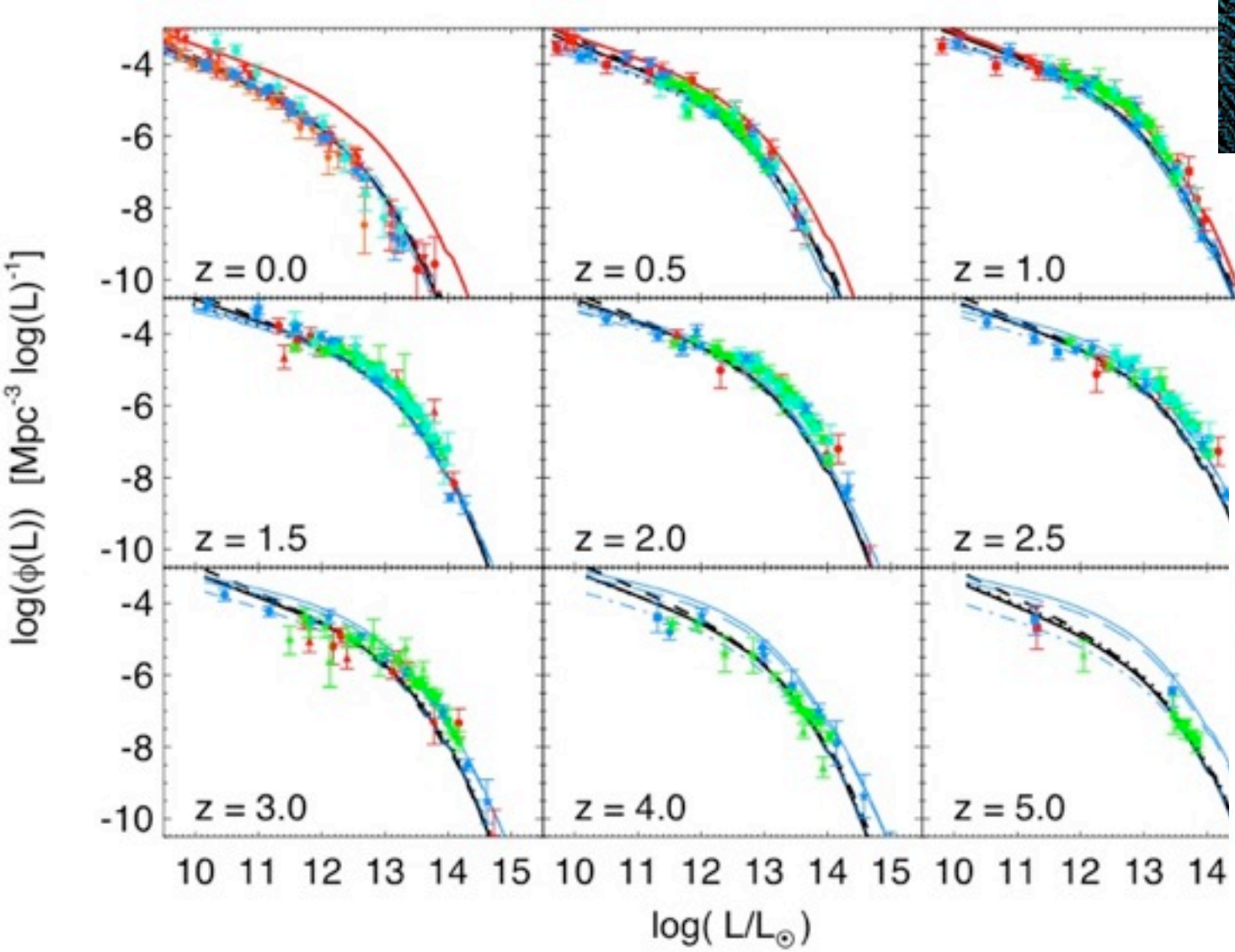
Testing the models:

NECESSARY CHECKS:

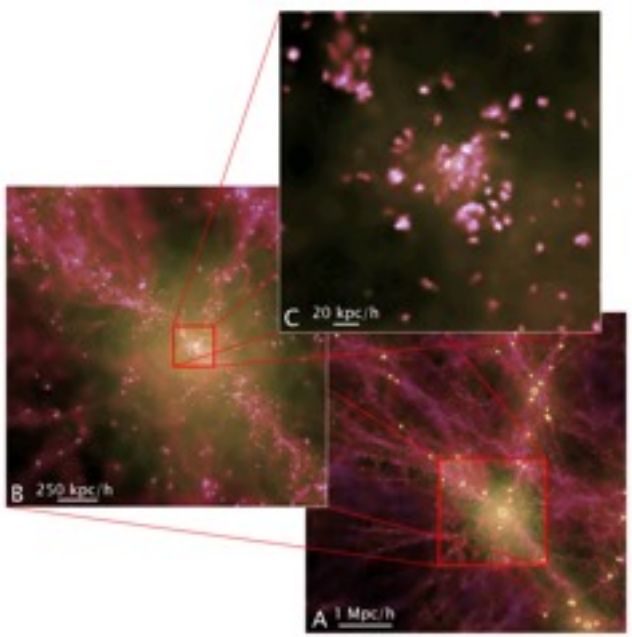
- Predict QLF; clustering; obscuration; scaling laws



PFH08



Di Matteo et al. 08

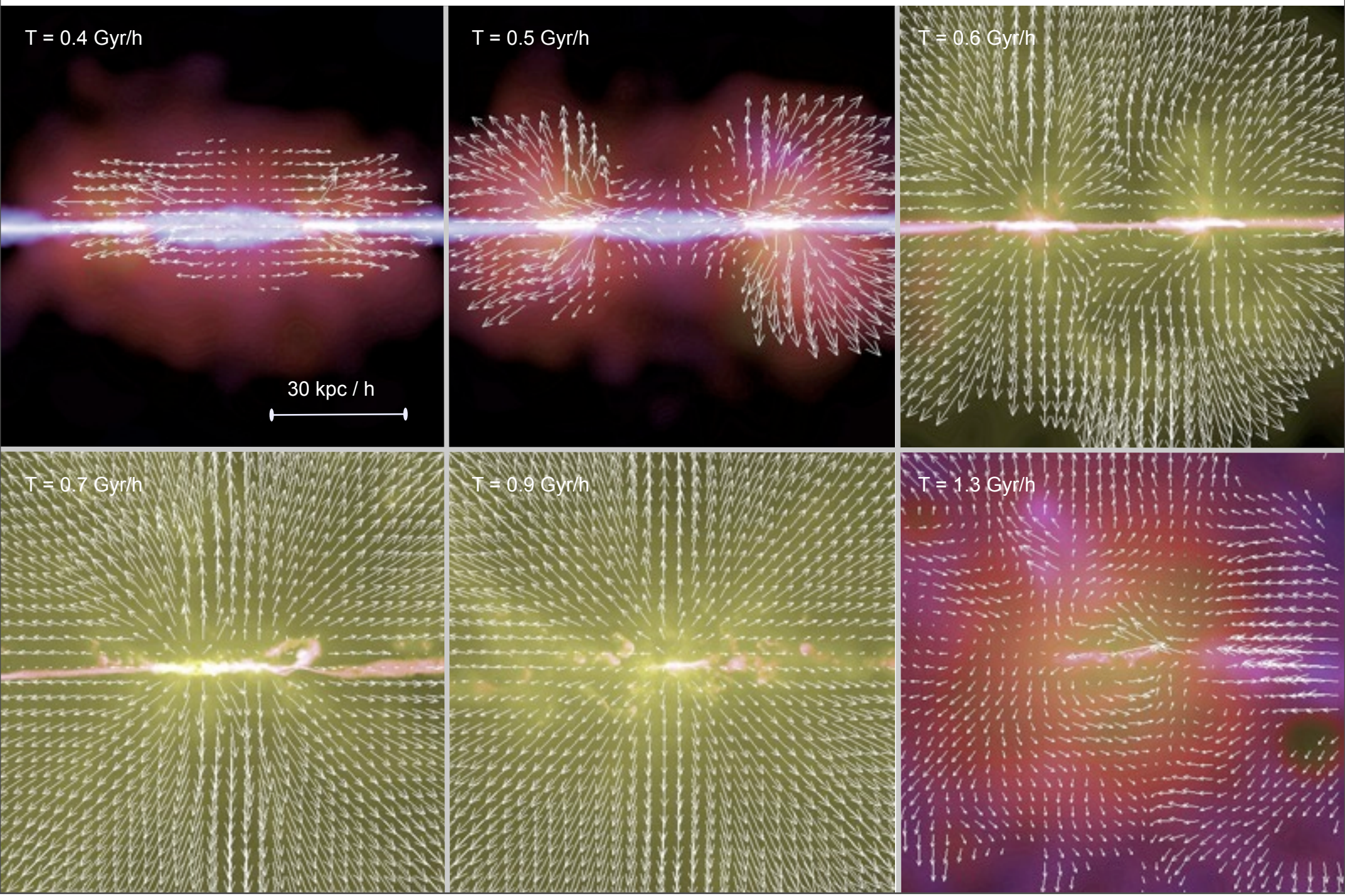


- There are “enough” mergers: hierarchical growth can account for todays BHs

Where Does the Energy/Momentum Go?

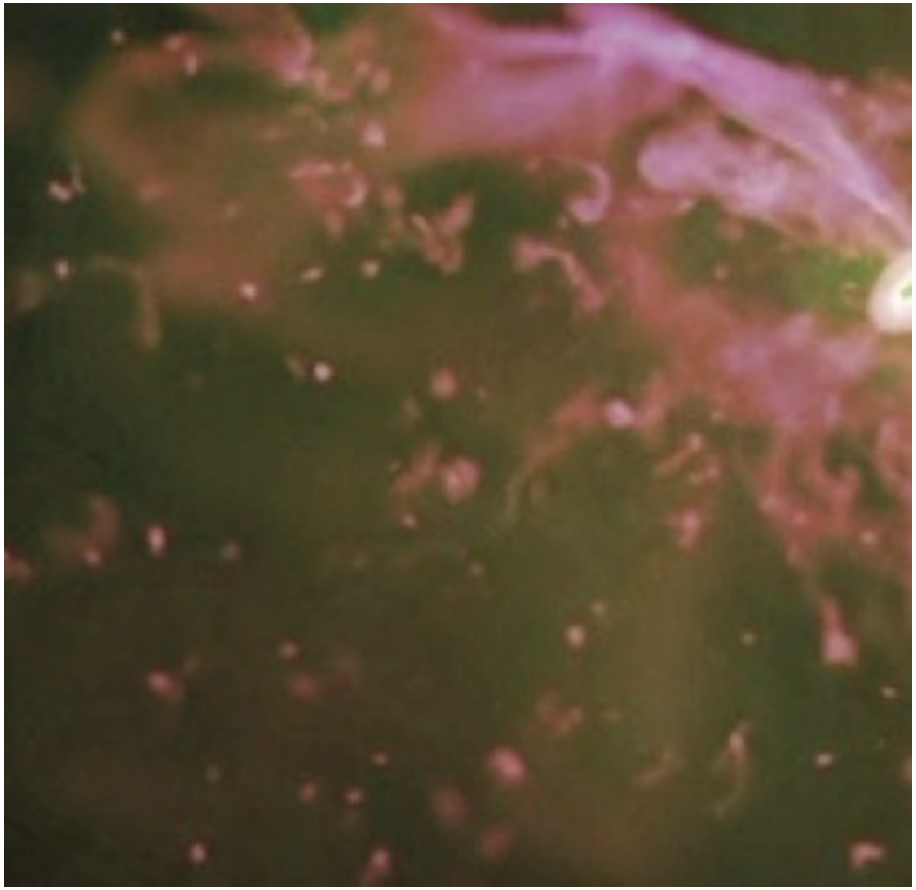
QUASAR-DRIVEN OUTFLOWS?

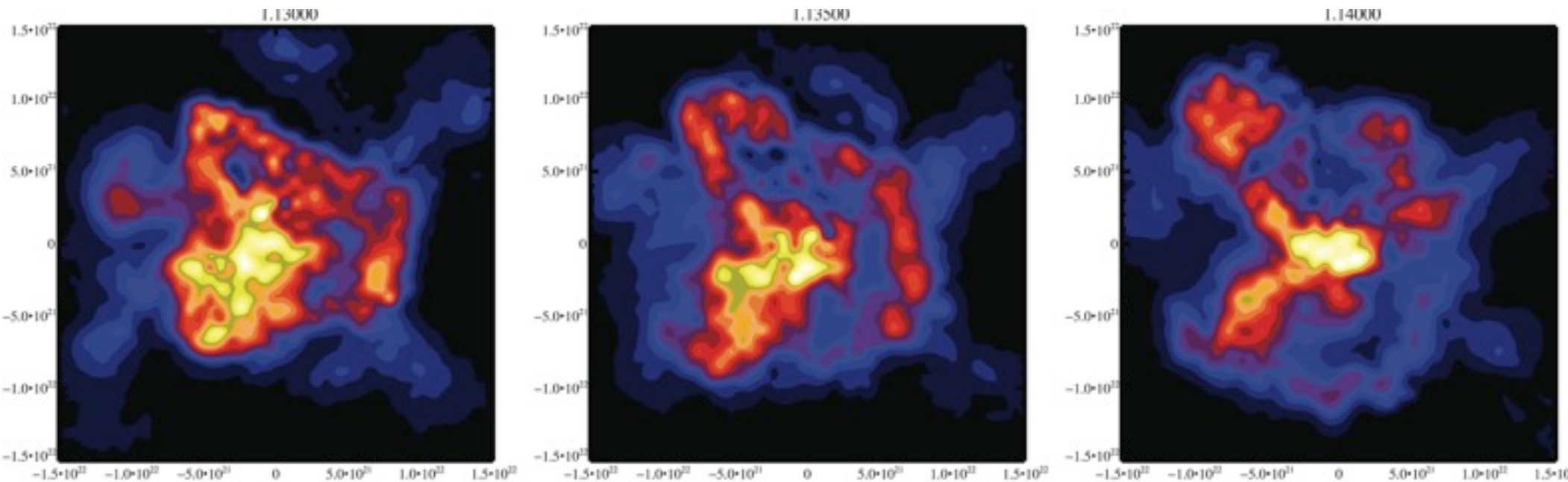
(outflow reaches speeds of up to ~1800 km/sec)



Outflows are Explosive and Clumpy

- Rapid BH growth => point-like injection
  - “Explosion-like”, independent of coupling
- Clumpy
  - ULIRG cold/warm transition (S. Chakrabarti)
  - CO outflows (D. Narayanan)
- Cold shell (through galaxy)

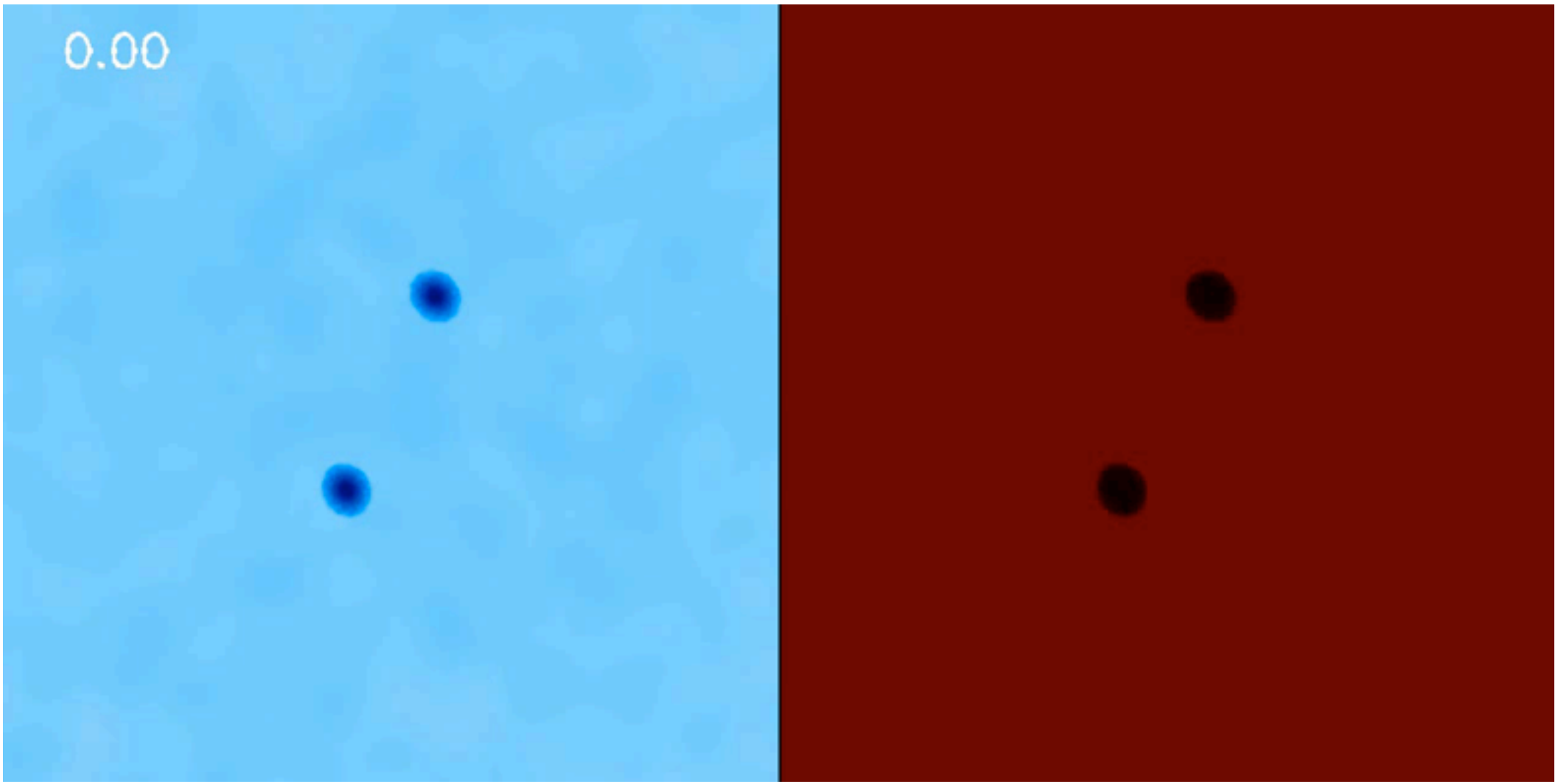




Quasar Outflows May Be Significant for the ICM & IGM

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

Gas Density | **Gas Temperature**



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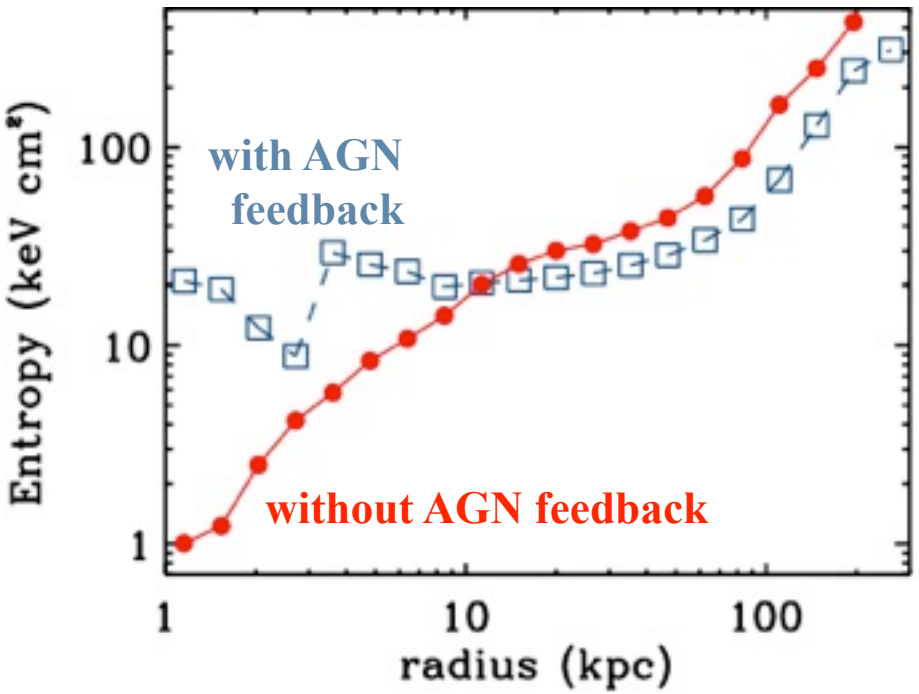
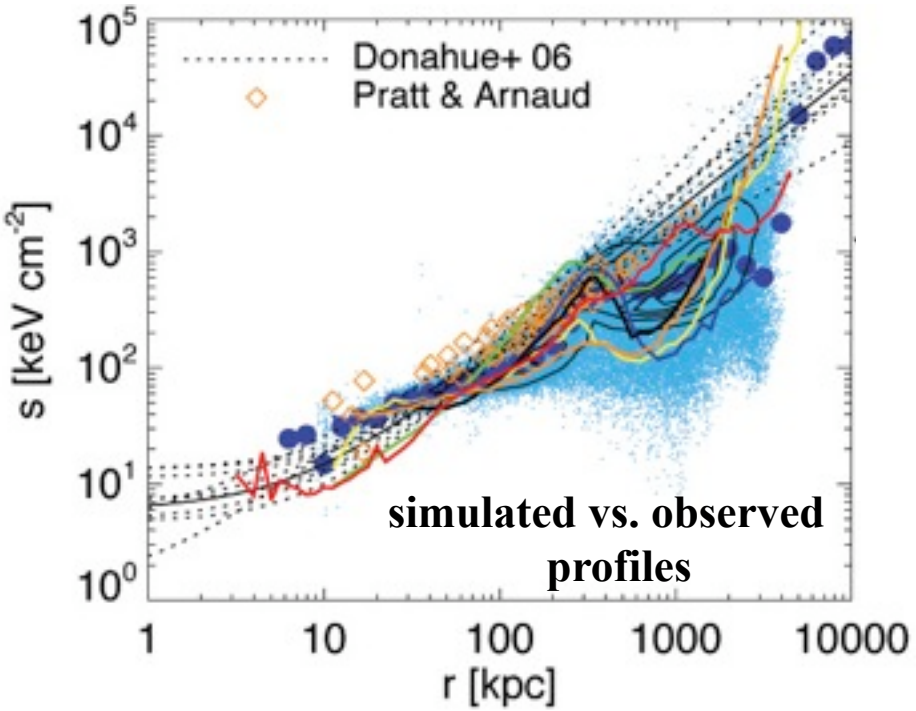
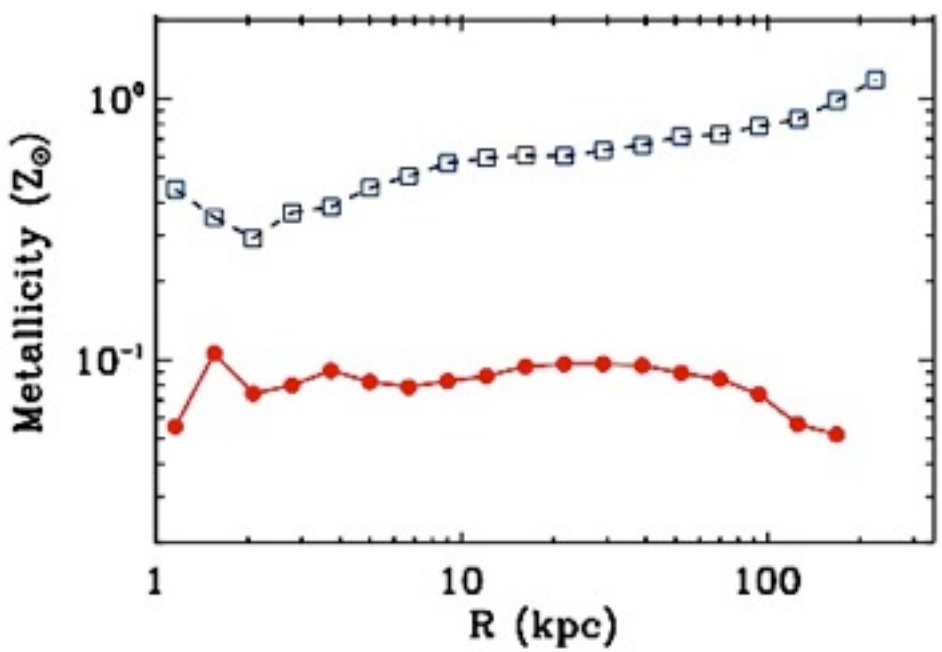
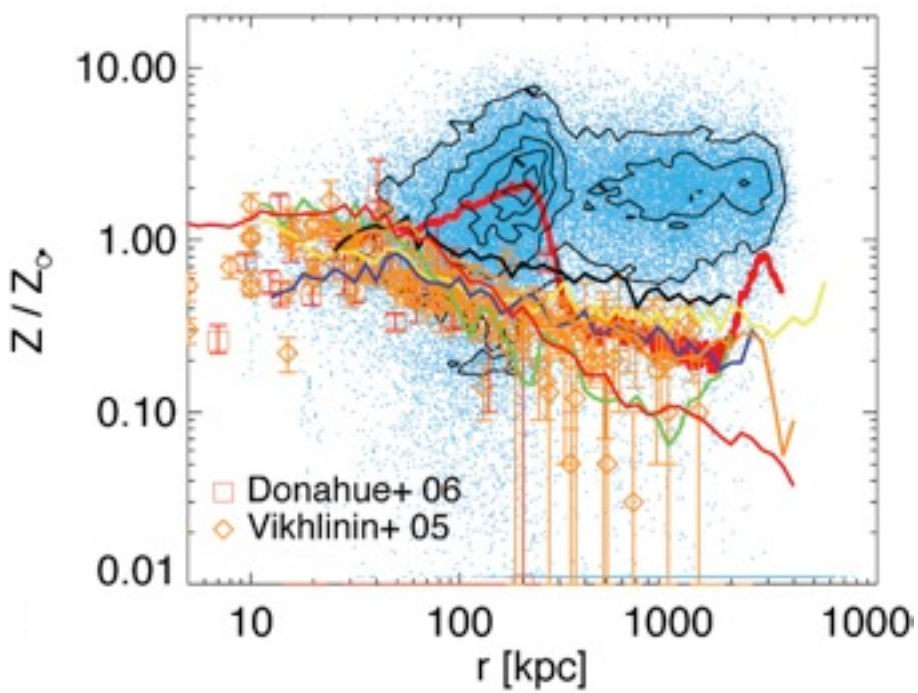


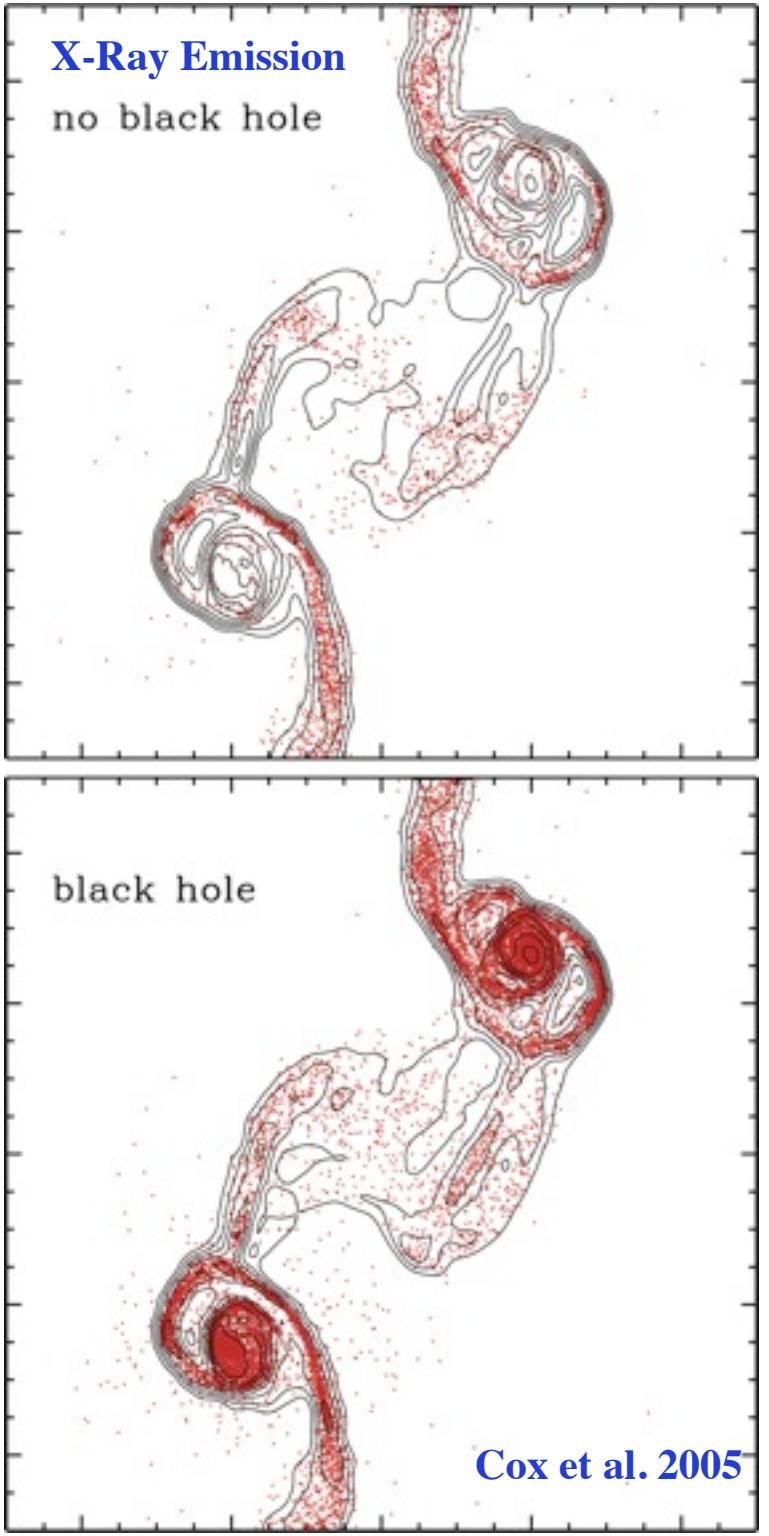






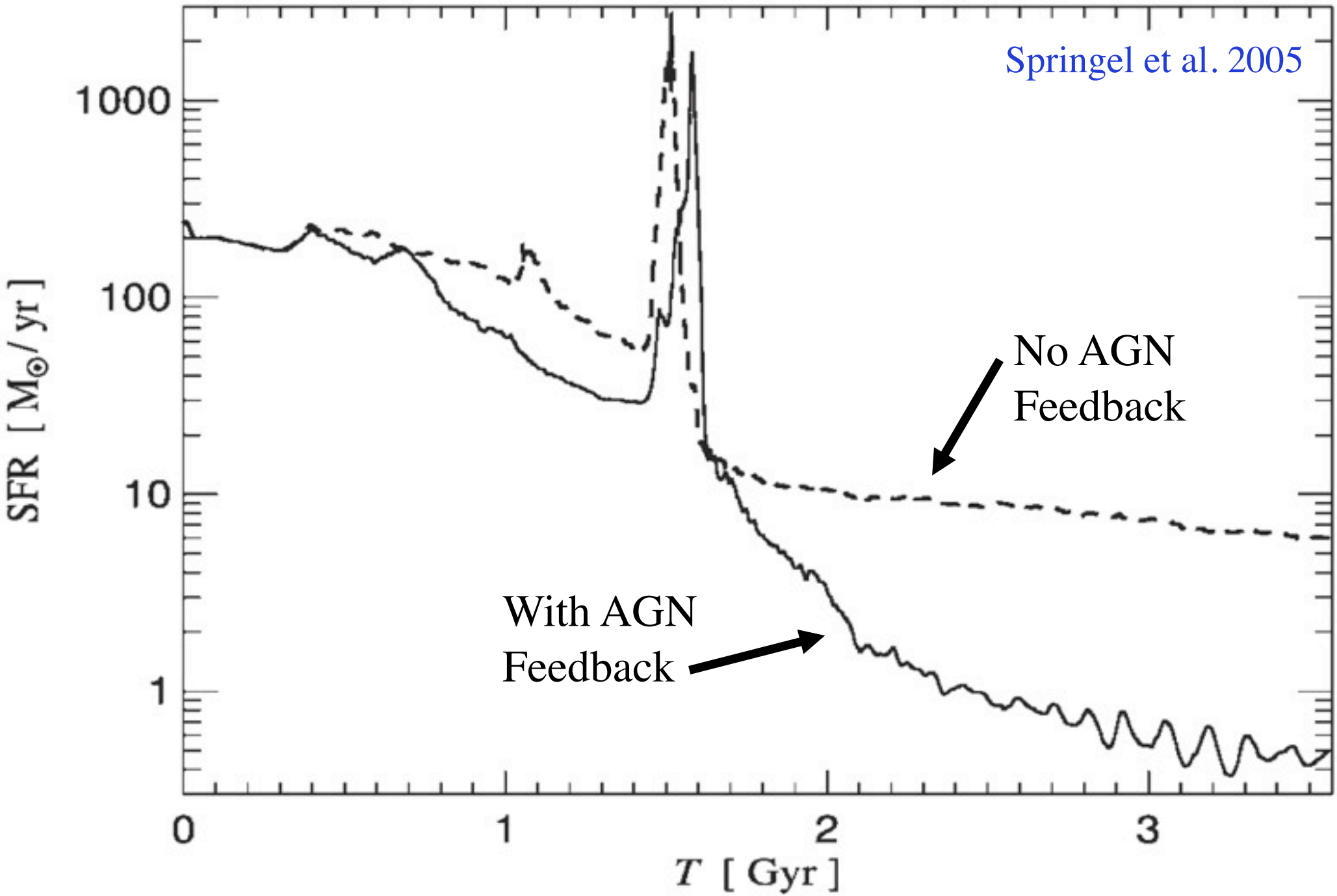
Feedback-Driven Winds

METAL ENRICHMENT & BUILDING THE X-RAY HALO



Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?

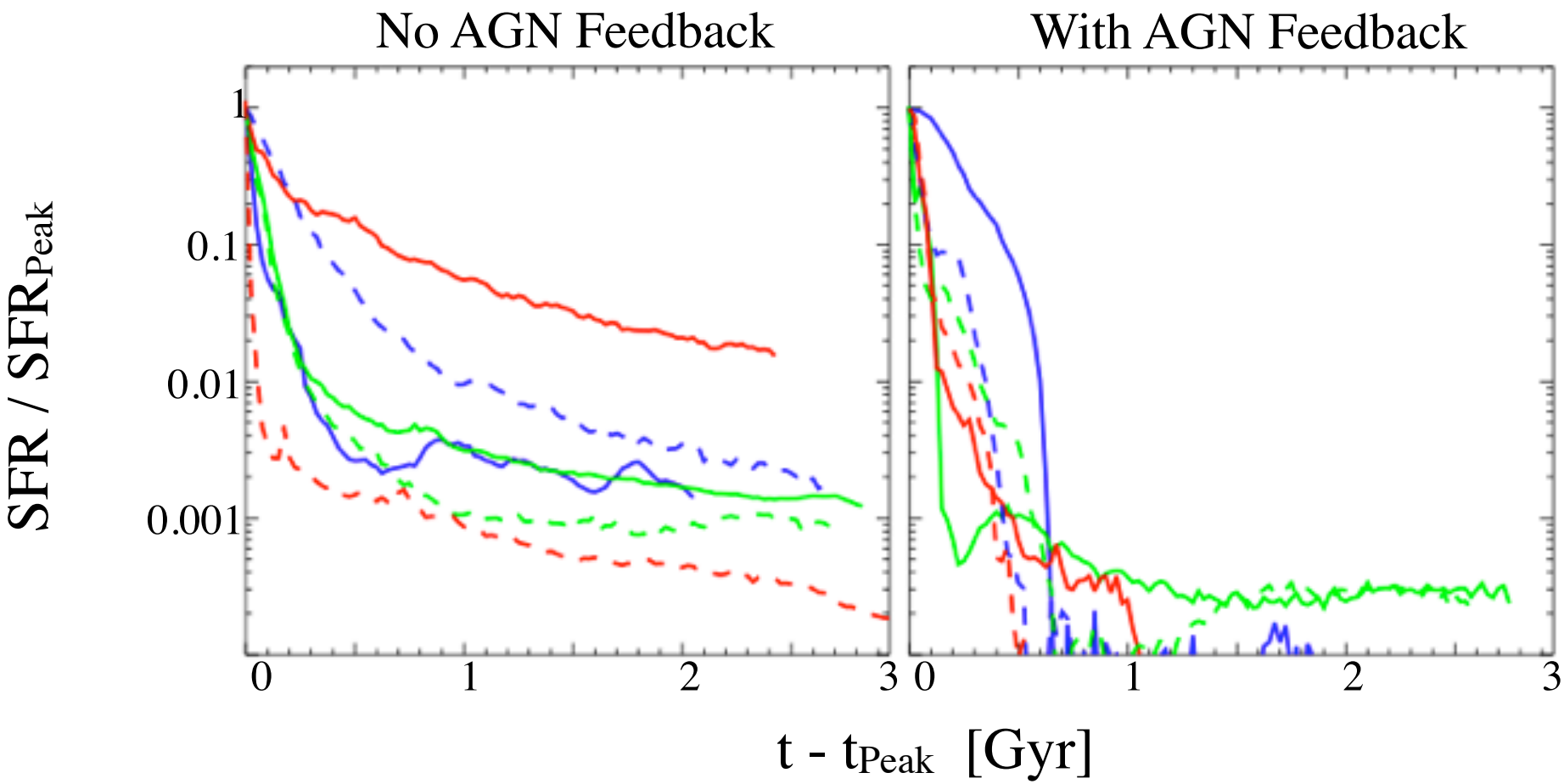


Expulsion of Gas Turns off Star Formation

PFH, Keres et al. 2008

ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?

... but ...

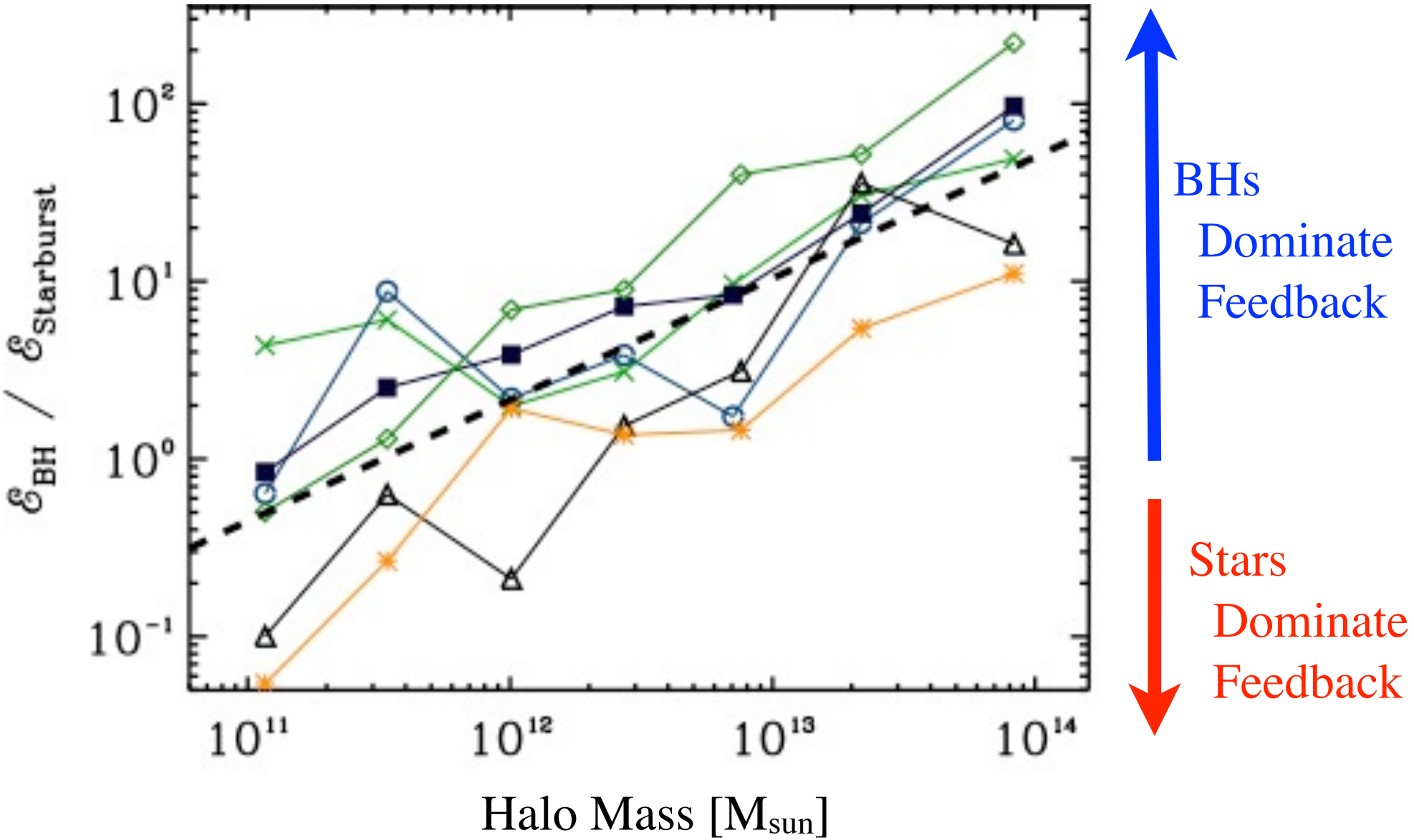


... MOST of the gas is still exhausted by star formation/stellar feedback

AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?

PFH, Cox et al. 2007



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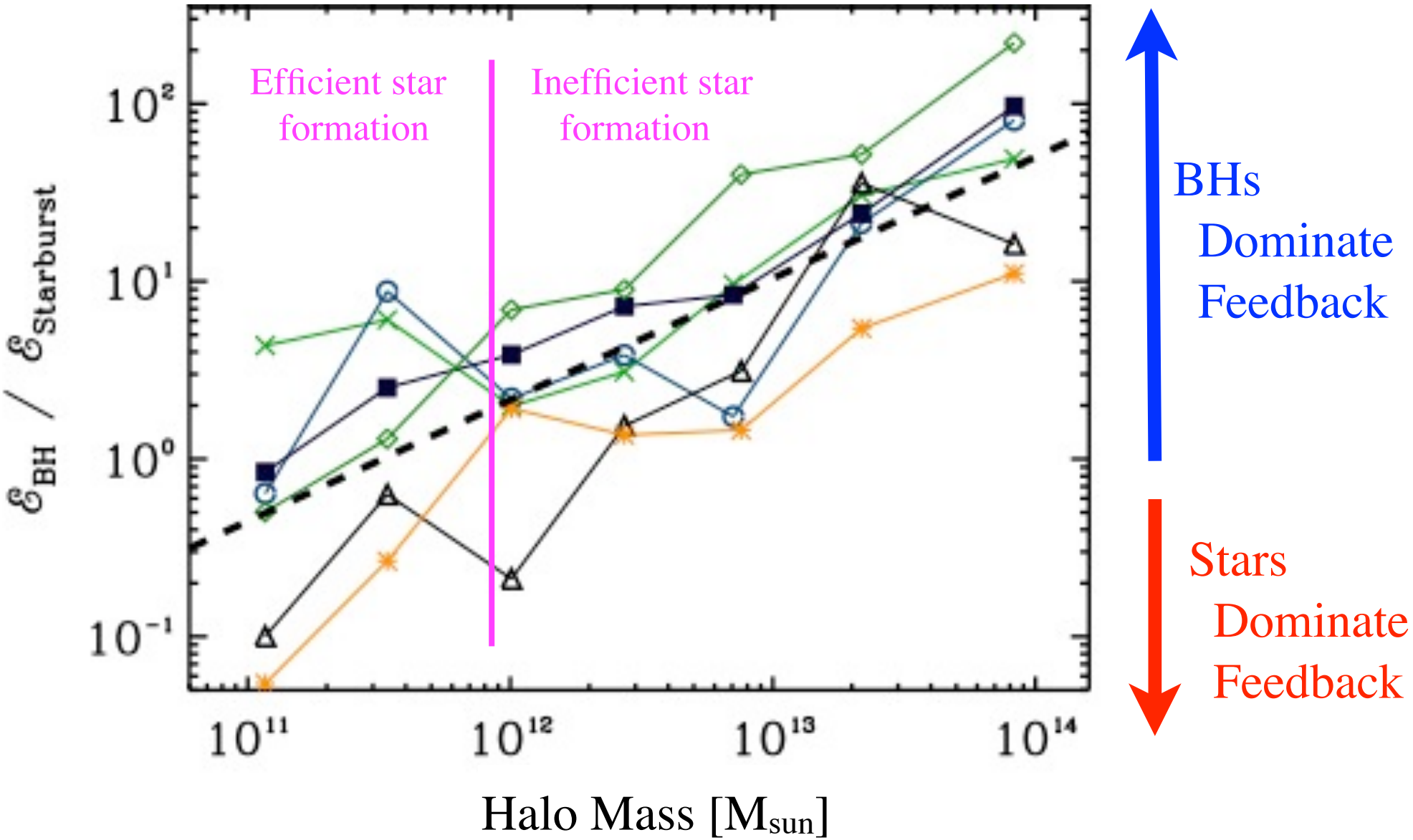
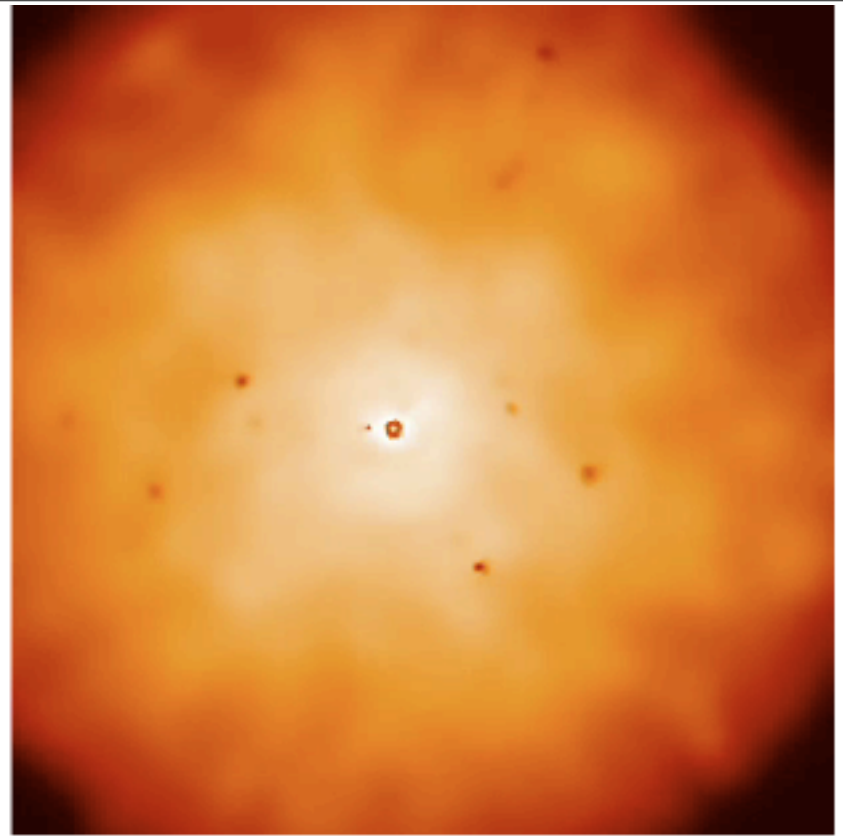
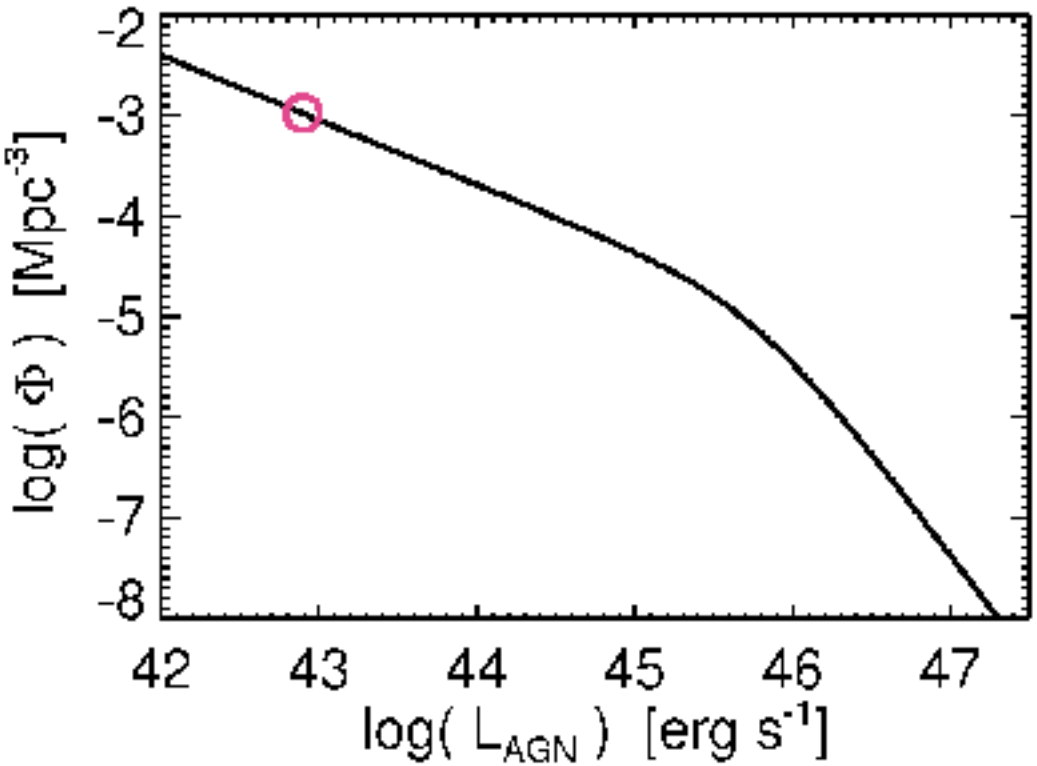
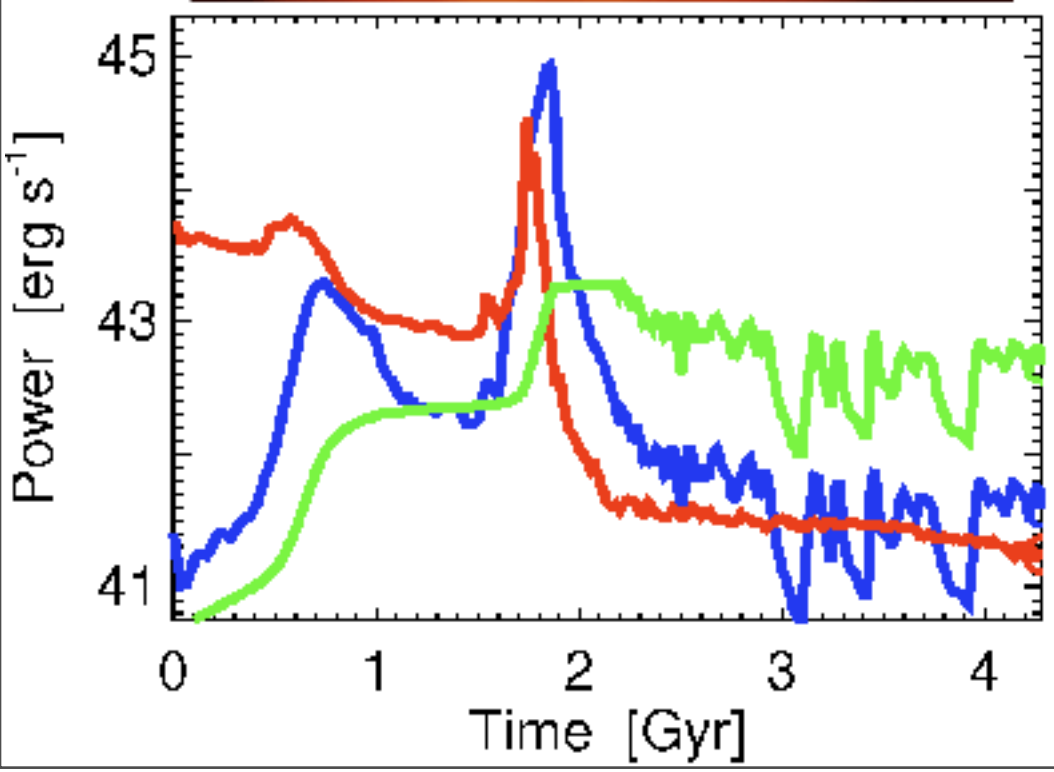
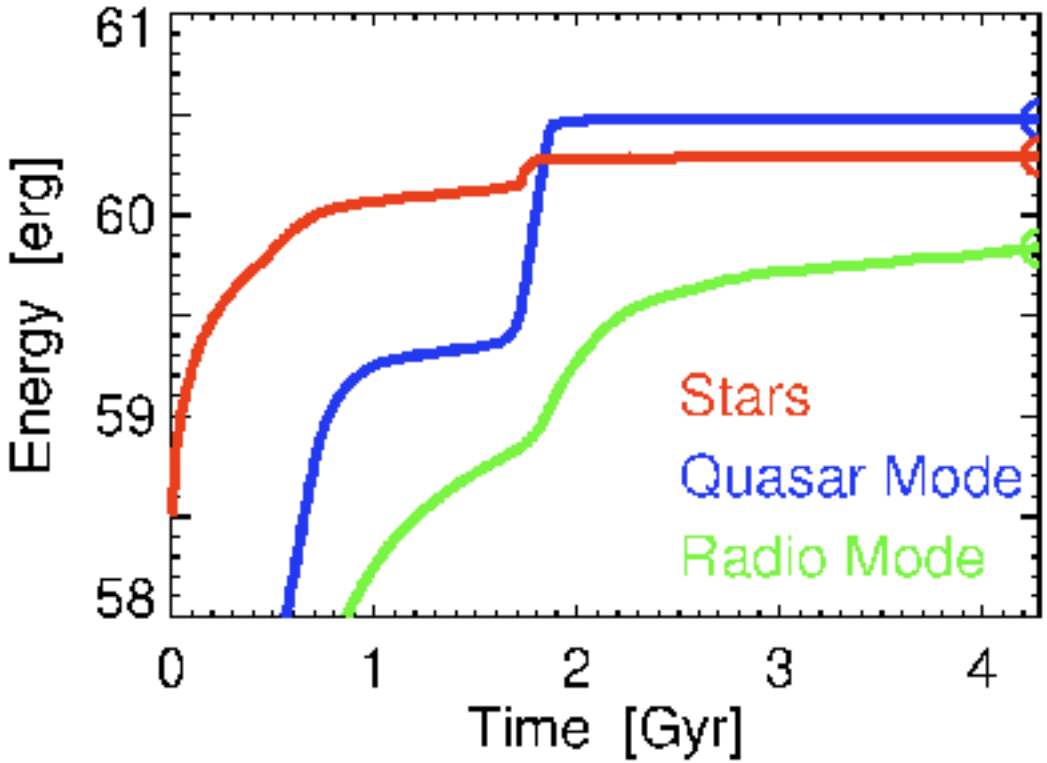
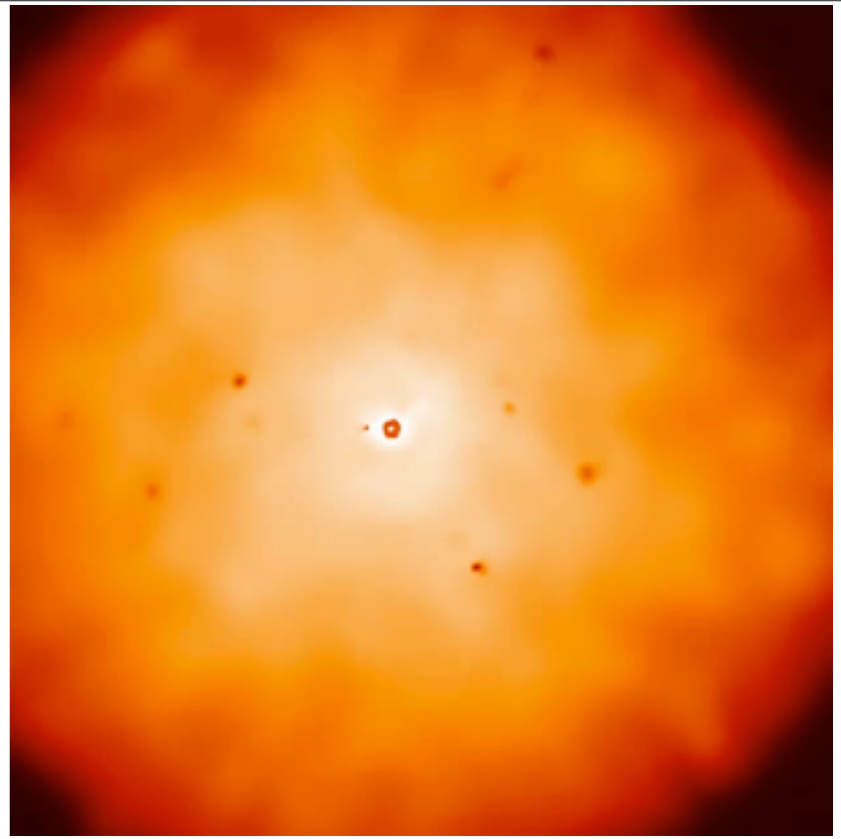


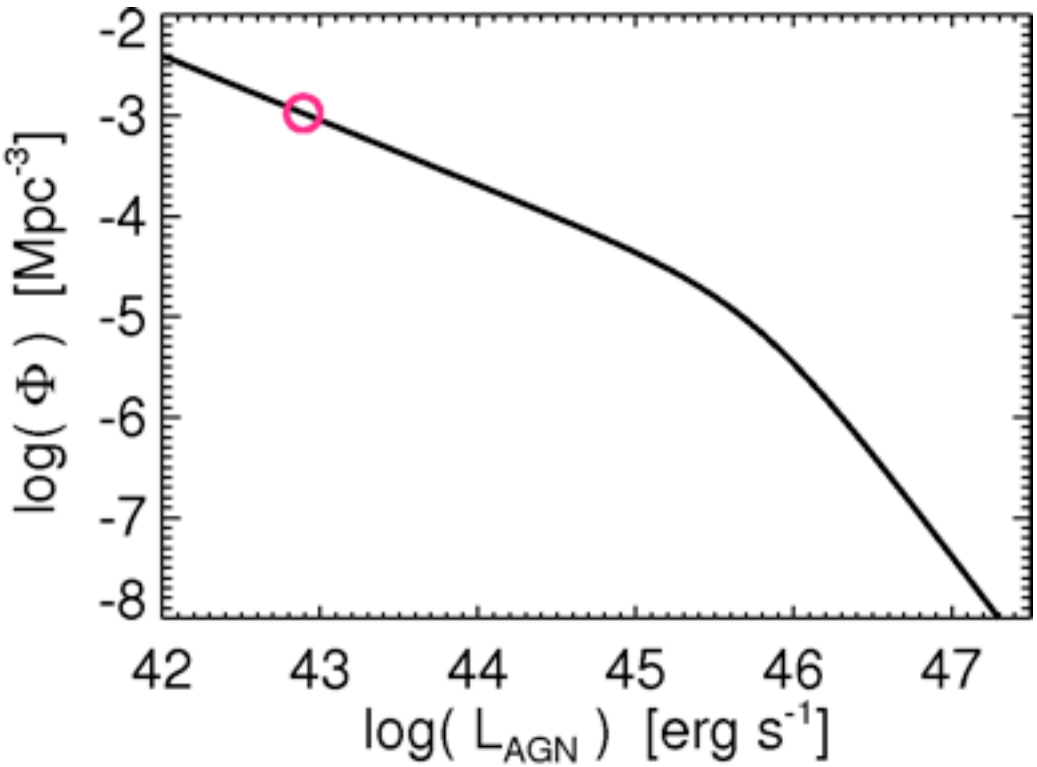



log(Φ) [Mpc^{-3}]
-2
-3
-4
-5
-6
-7
-8
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]


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


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

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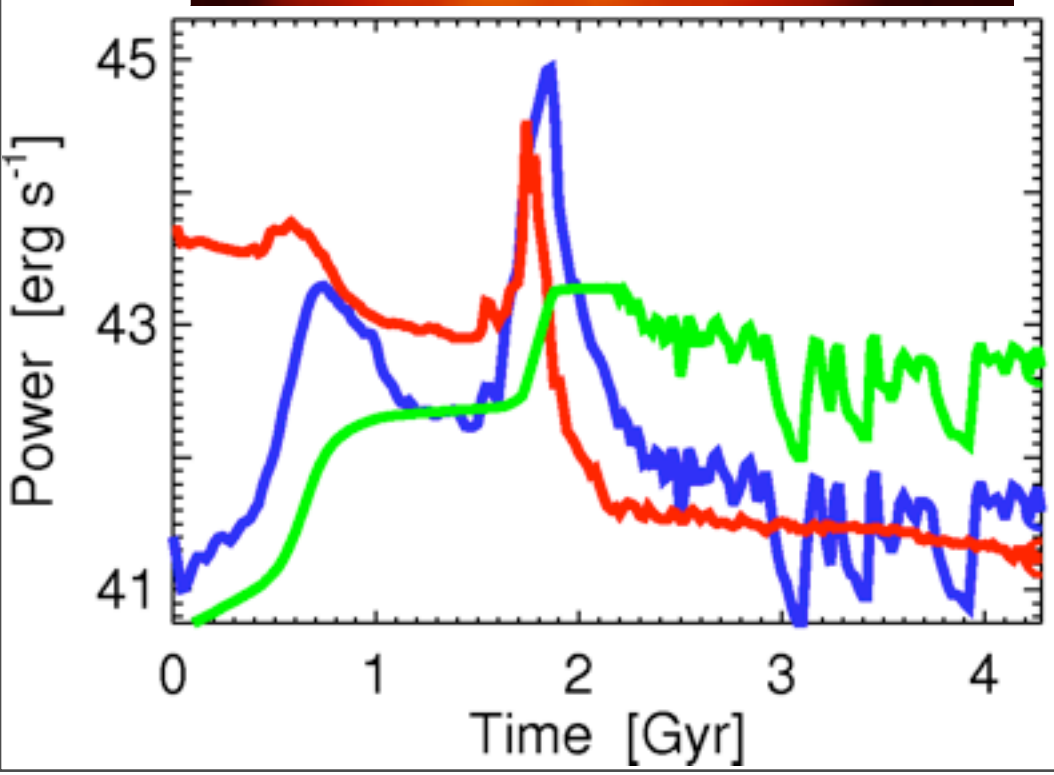
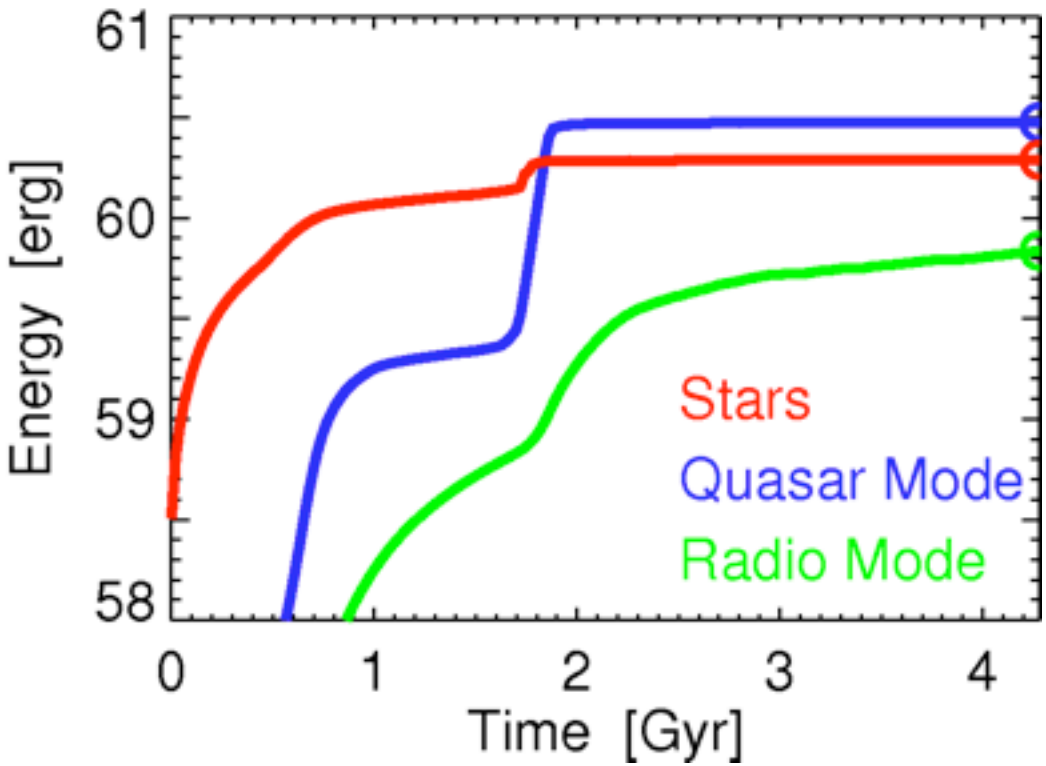

45
43
41
Power [erg s^{-1}]
0
1
2
3
4
Time [Gyr]

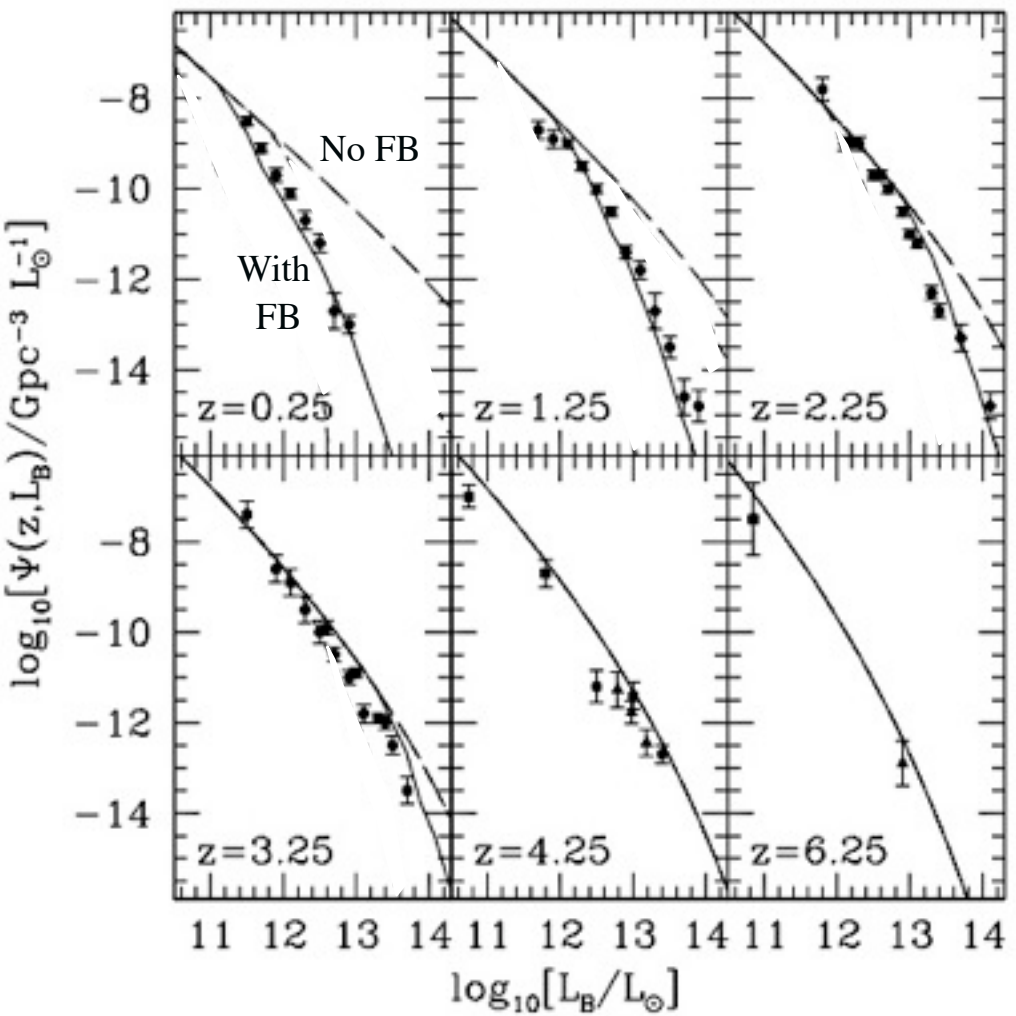

61
60
59
58
Energy [erg]
0
1
2
3
4
Time [Gyr]
Stars
Quasar Mode
Radio Mode

Maintenance Mode

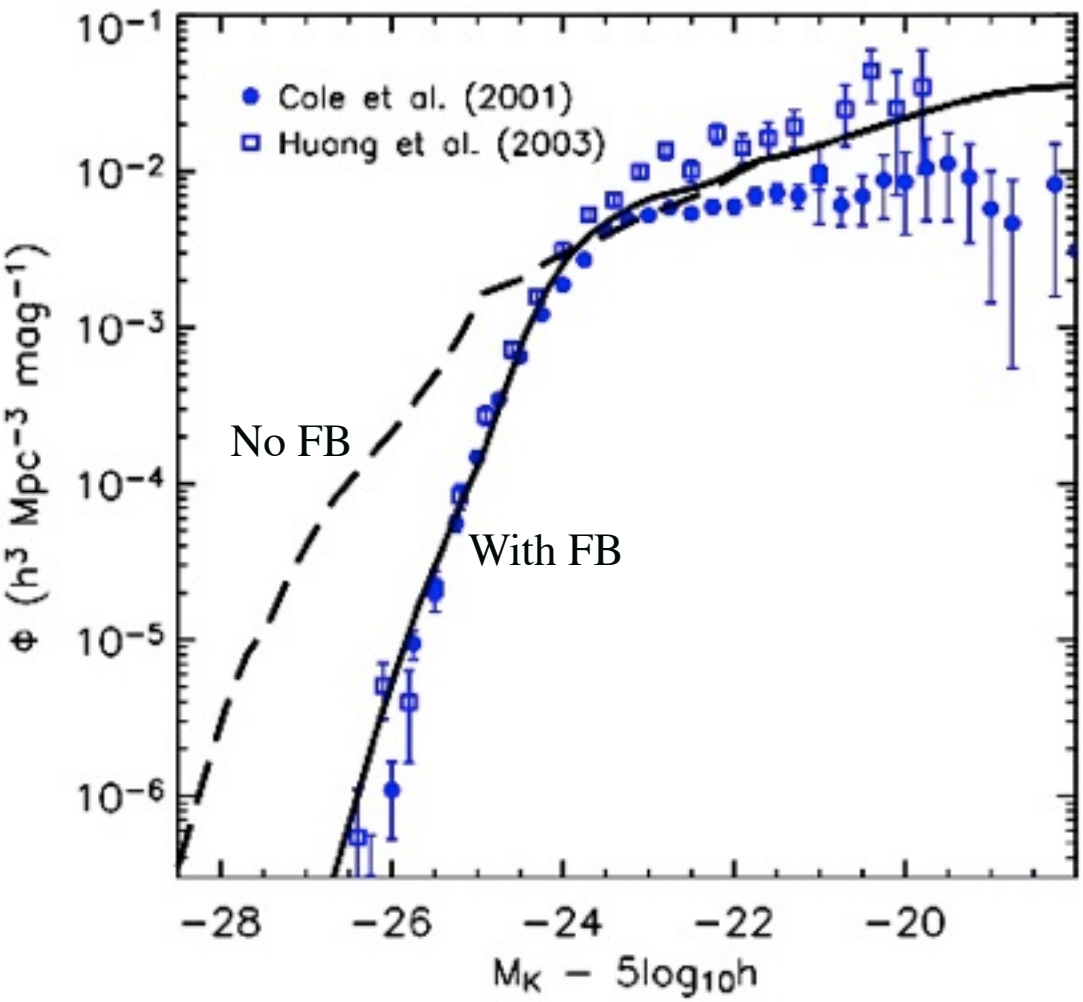
IS IT ALSO “RADIO”-MODE?

- How important is the “radio” or “maintance” mode?

Scannapieco & Oh ’04:
All “Quasar Mode” Feedback



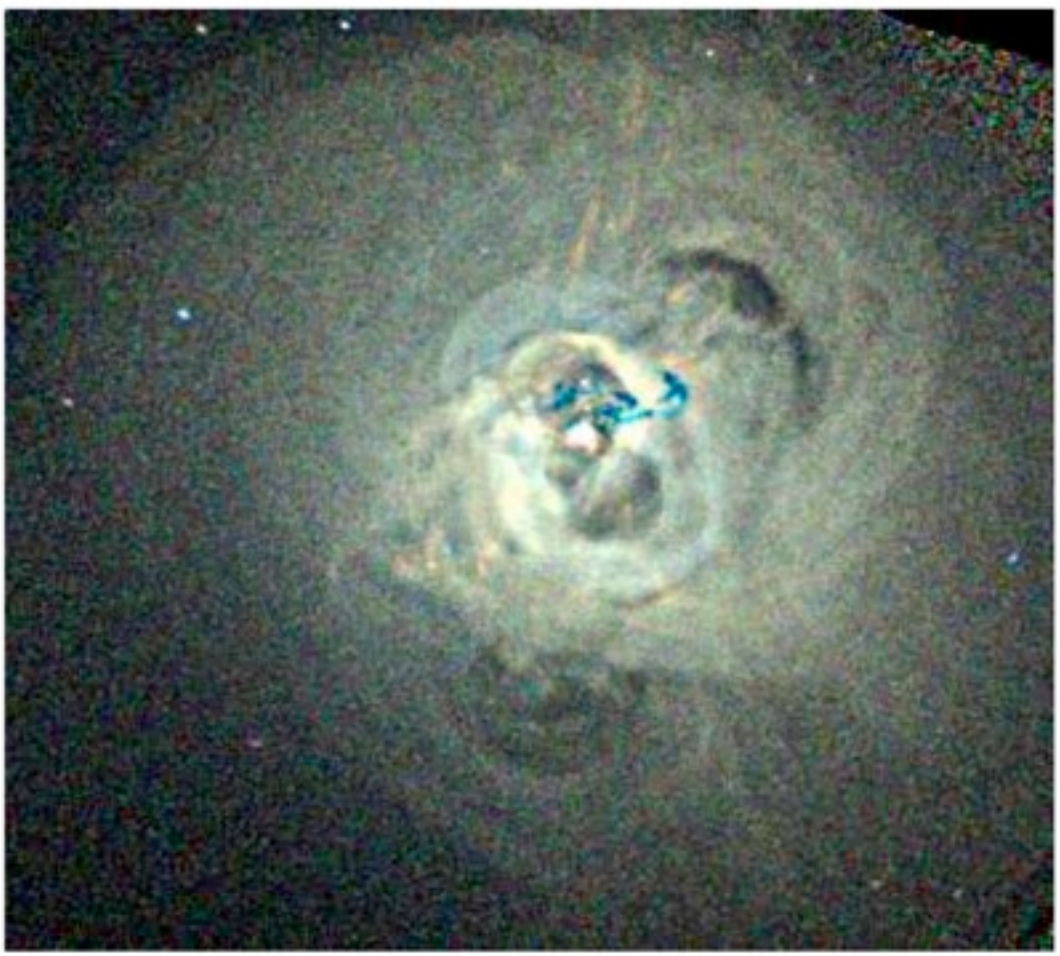
Croton et al. ’06:
All “Radio Mode” Feedback



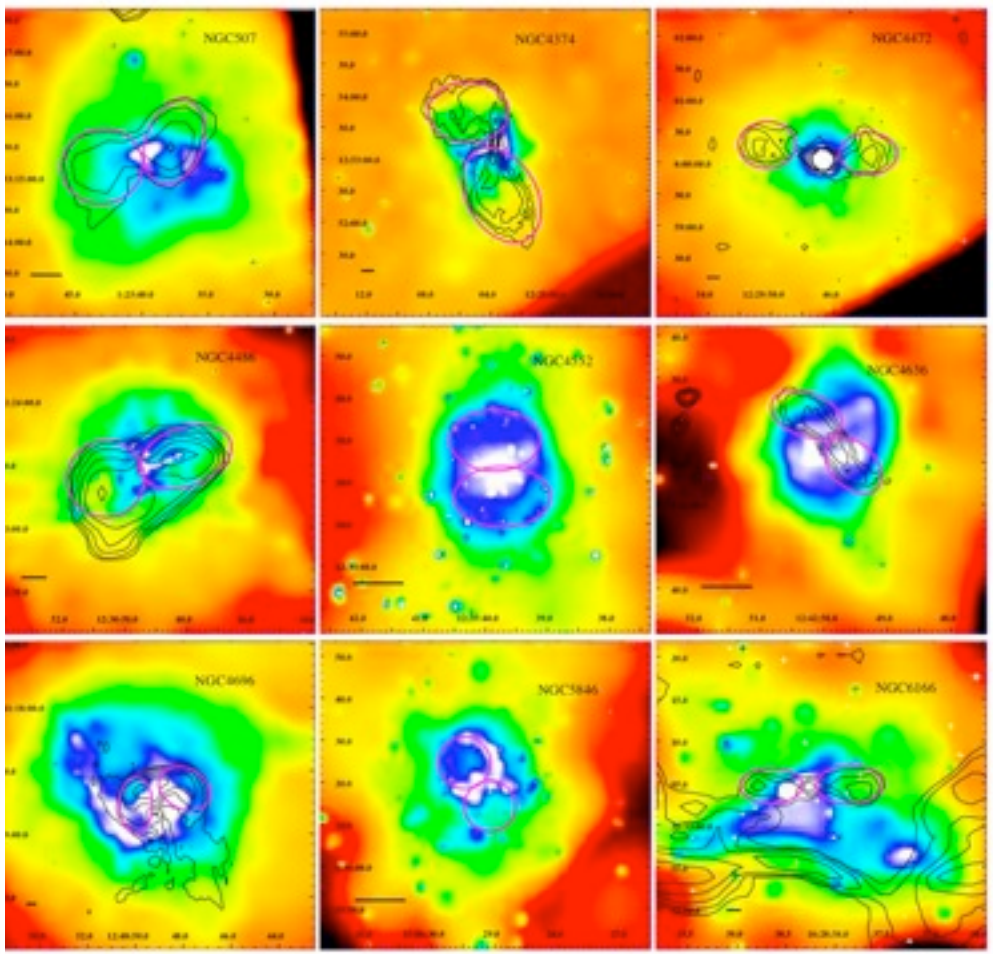
Maintenance Mode

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”?



Fabian (Perseus Cluster)



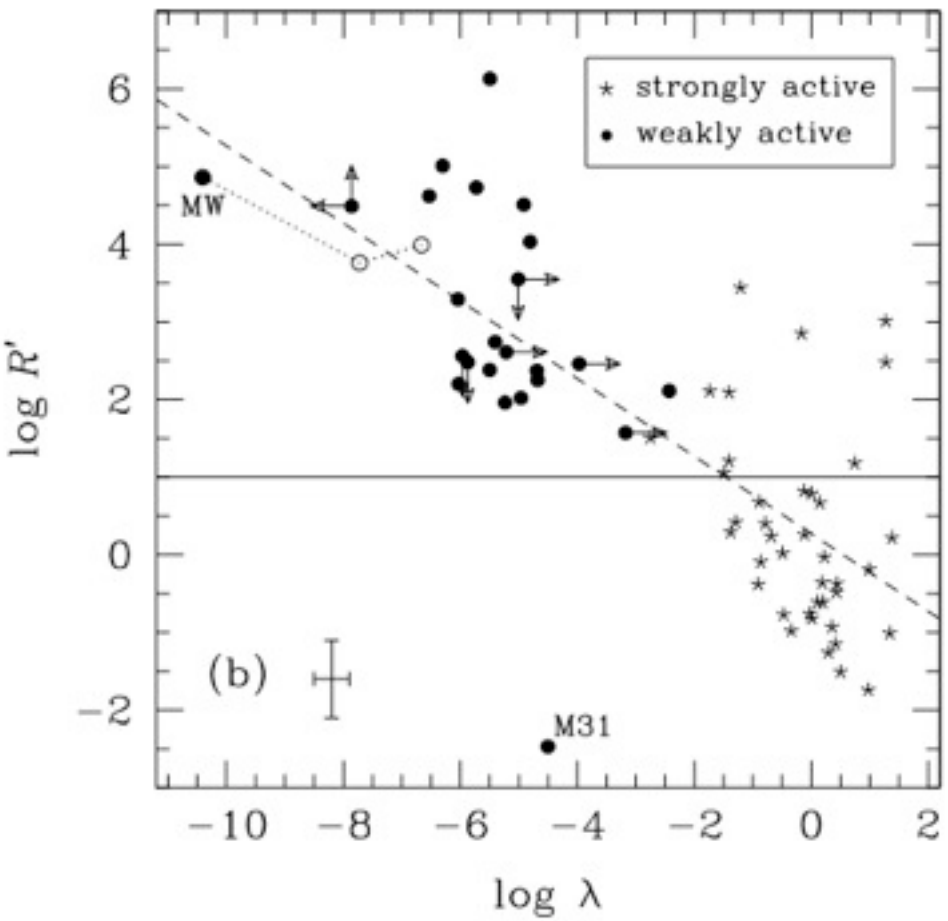
Allen (X-ray Ellipticals)

Maintenance Mode

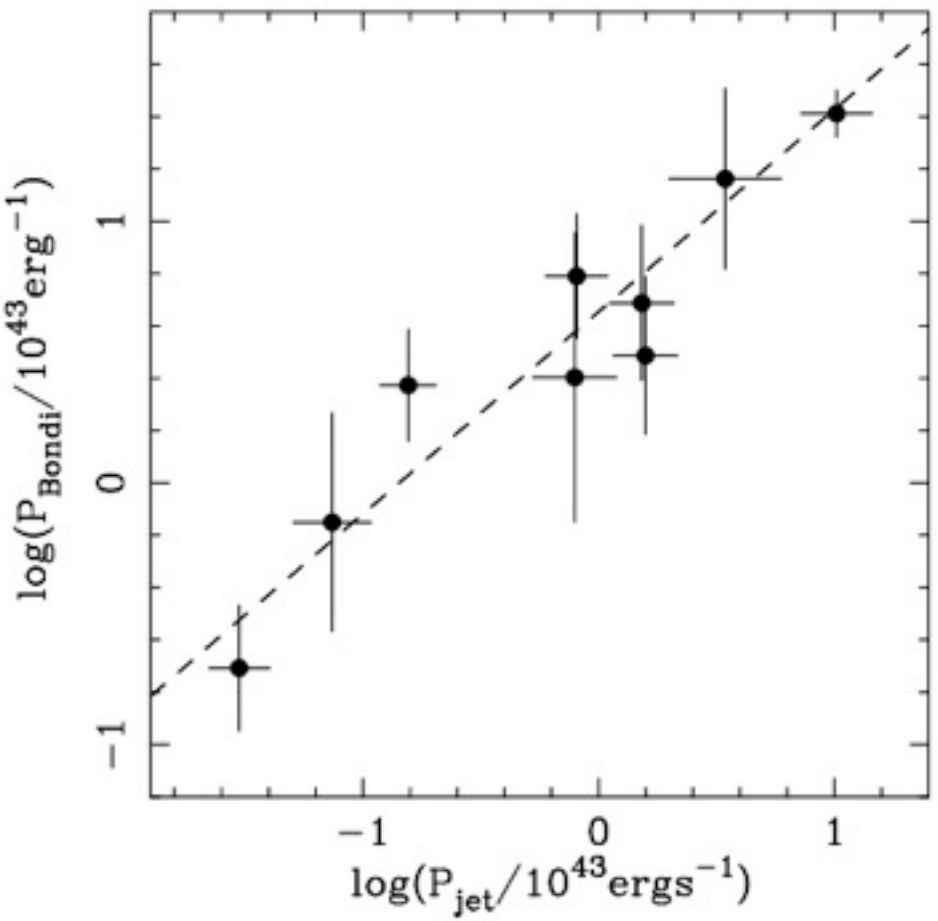
IS IT ALSO “RADIO”-MODE?

- Know that (non-cooling flow) clusters do look “pre-heated”...
  but we also *see* radio jets doing work:

Ho: P(radio) versus Eddington ratio:



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



- Observational constraints on the power involved are leading the way

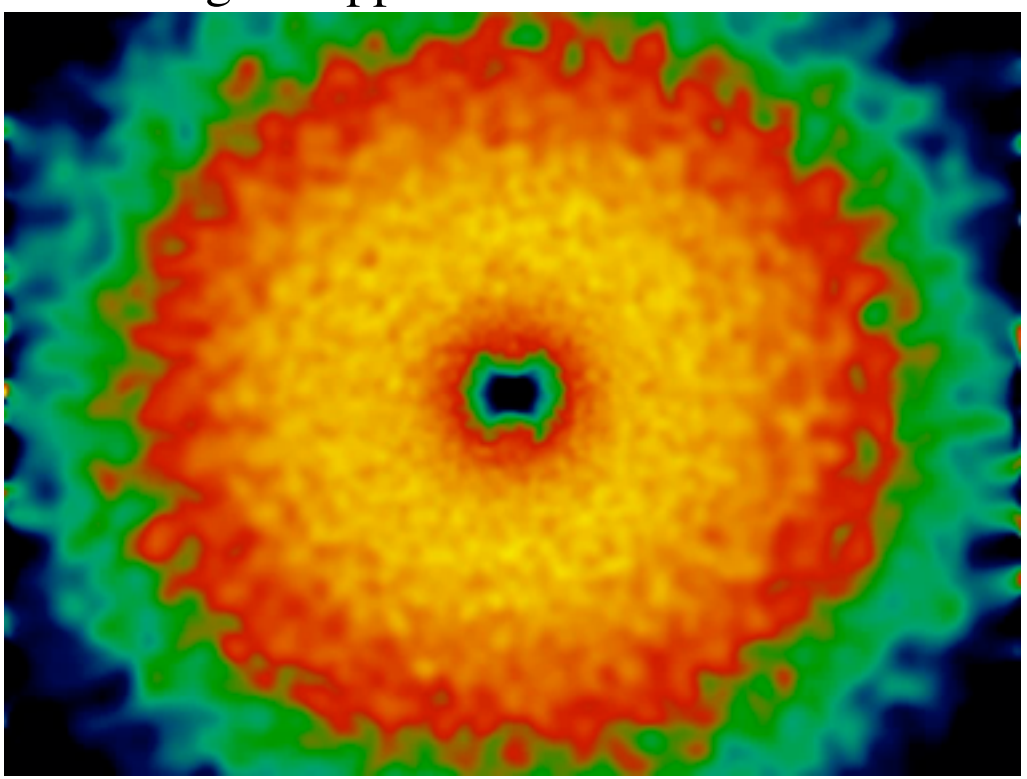
Maintenance Mode

IS IT ALSO “RADIO”-MODE?

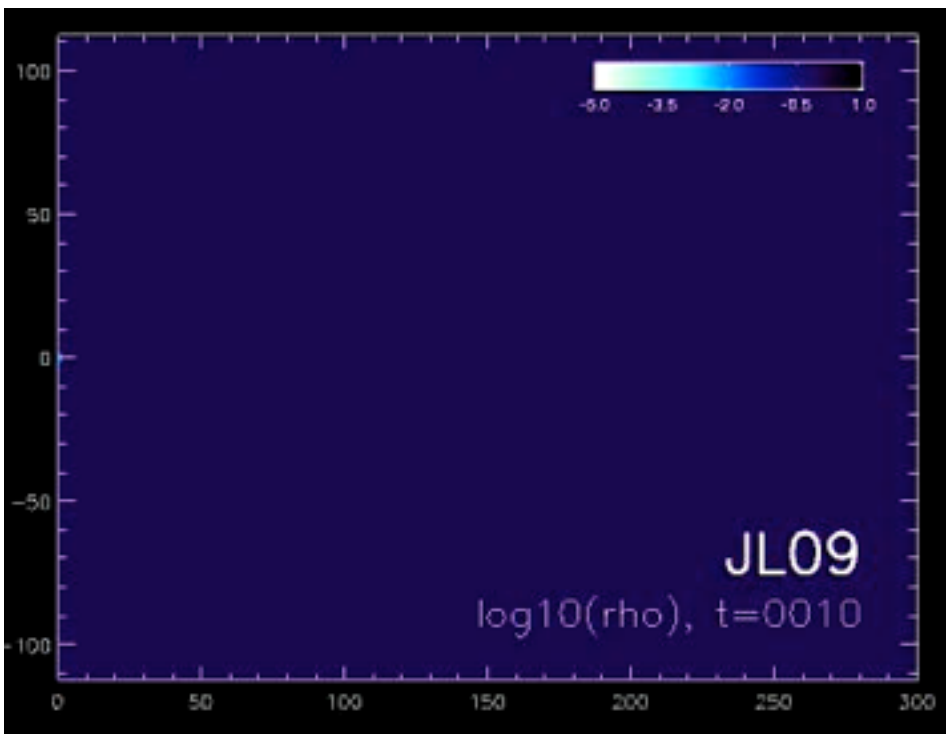
- Breakthroughs being made on the simulation side as well:

Sijacki et al.

Cosmological approximations:



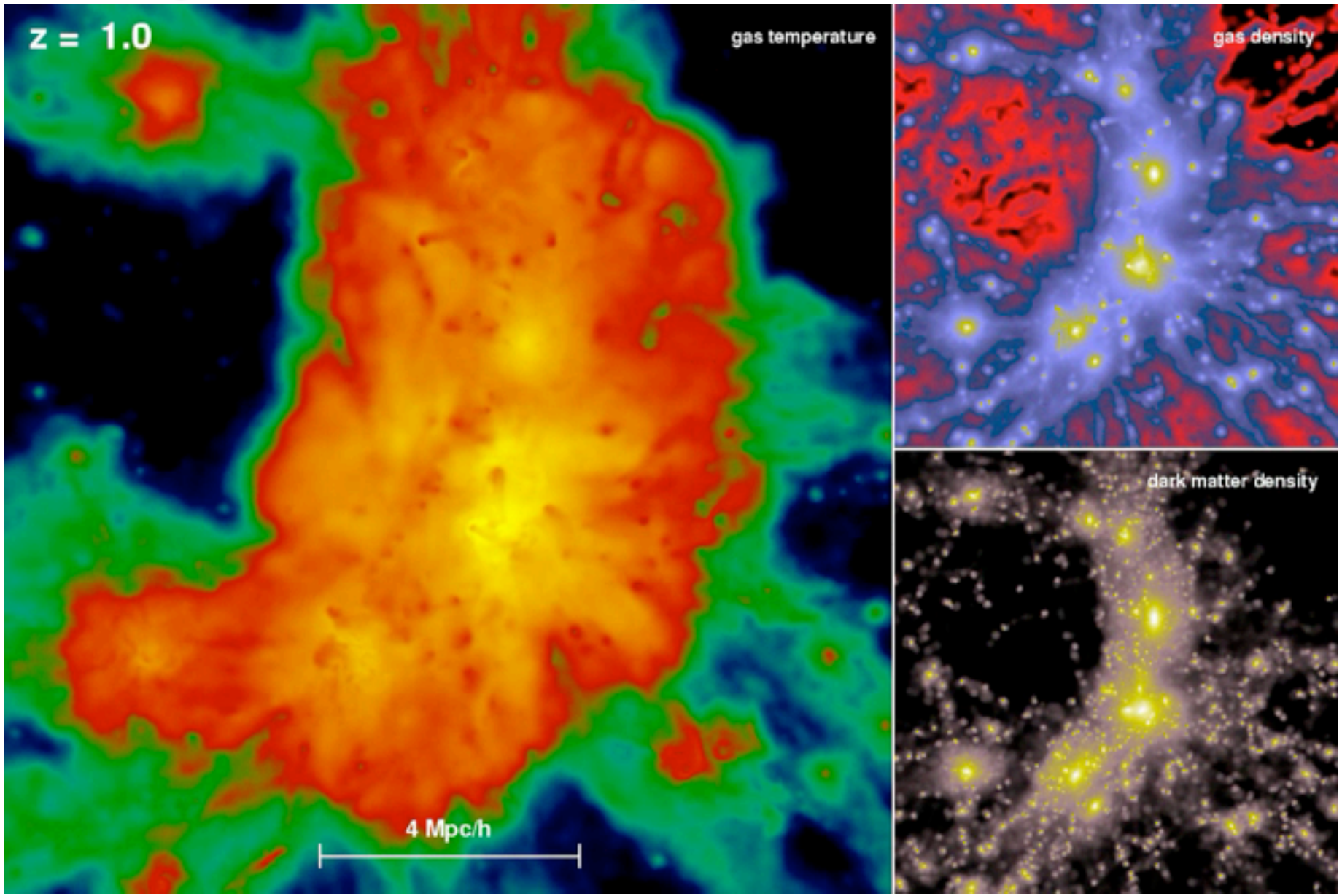
Idealized jets (even MHD ones!):



Maintenance Mode

IS IT ALSO “RADIO”-MODE?

- Lest we forget, real clusters are messy...



- Gravitational heating, distributed AGN heating, may be important as well

Summary

- M_{BH} traces spheroid $E_{binding}$
  - Suggests *self-regulated* BH growth
    - Which mechanisms dominate BH feedback? When/where?

- If self-regulated, this feedback is potentially radically important:
  - Heating gas, ejecting metals, shutting down SF
  - Self-regulated decay of QSO luminosity:
    - Why are quasar lifetimes generically self-similar?
  - Where/what is the transition/maintenance mode role?
    - Function of Eddington ratio?

- Most BH growth should come in mergers... but "are AGN mergers?" is the wrong question: we should ask:
  - "Where (as a function of L, z, d) do mergers vs. secular processes dominate the AGN population?"
    - Clustering vs. scale
    - Host galaxy colors/SFH
    - Host morphology/kinematics

Shameless Plug:

Lots of galaxy-side physics that I didn't get to talk about:
come find me if you want to hear more!

- How Do Disks Survive Mergers?
  - (PFH et al. 2008;
    PFH, Somerville et al. 2009 [today])
- How Do You Make A (Real) Elliptical?
  - (PFH, Rothberg et al. 2008;
    PFH, Kormendy, Lauer et al. 2008a-c;
    PFH, Cox, & Hernquist et al. 2008)
- How Do You Make A Compact, High-Redshift Elliptical?
  (And How Do You Make It Into A Normal Elliptical Today?)
  - (PFH, Keres, Cox, Wuyts et al. 2008;
    PFH, Quataert et al. 2009;
    PFH, Bundy et al. 2009)

Thanks!