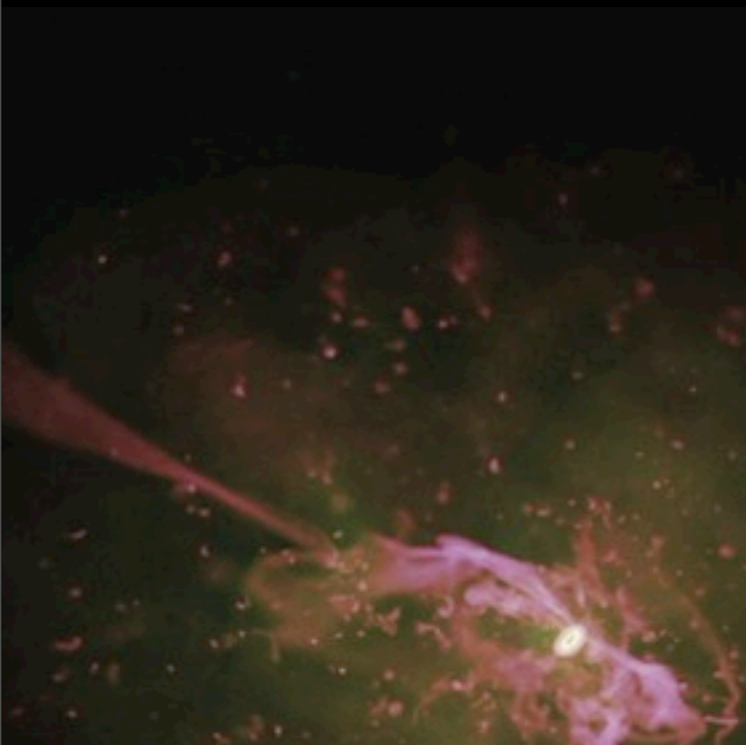
Galaxy Mergers: A Factory for Quasars, Feedback, Ellipticals, and even Disks?



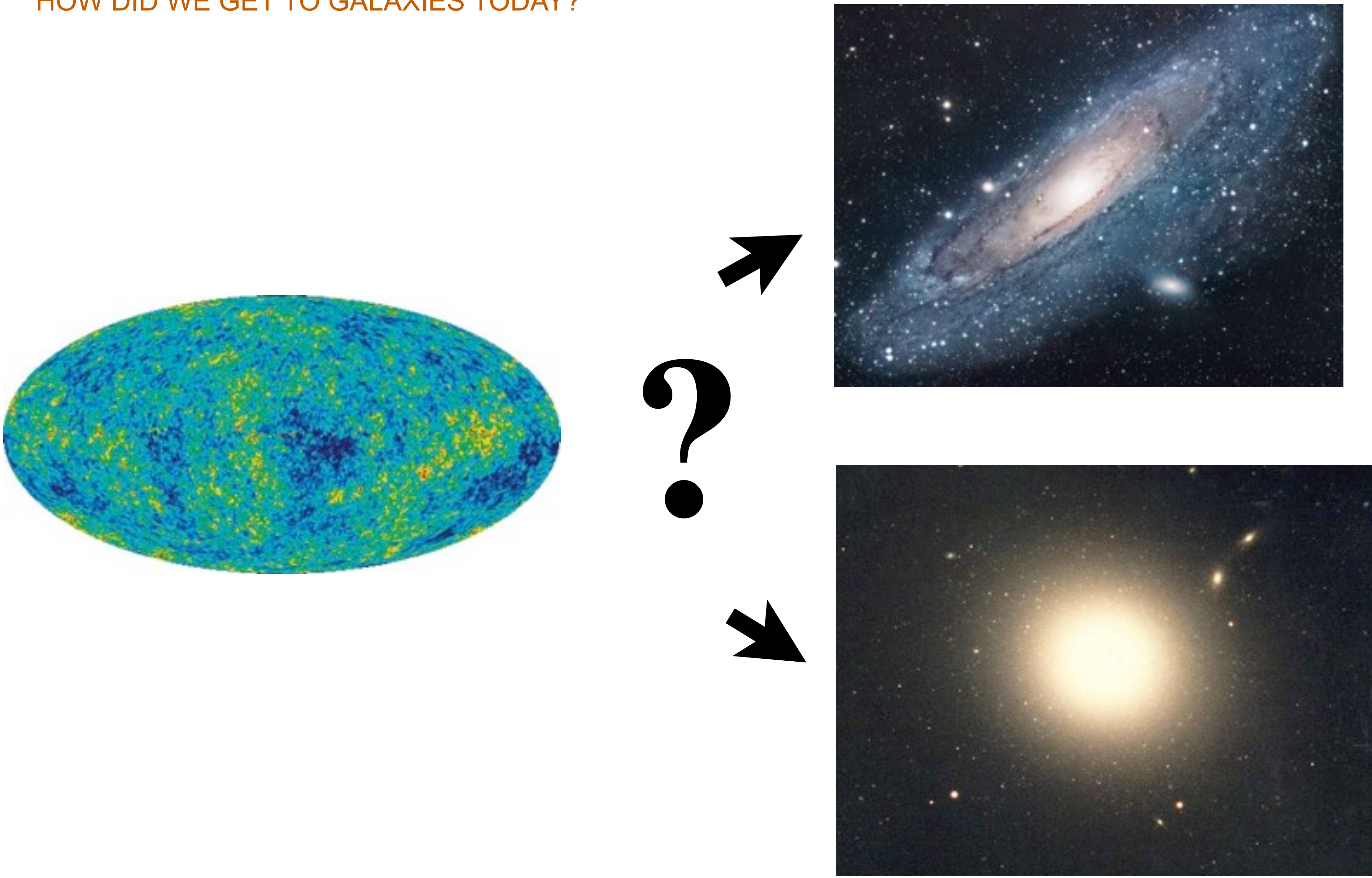
Philip Hopkins

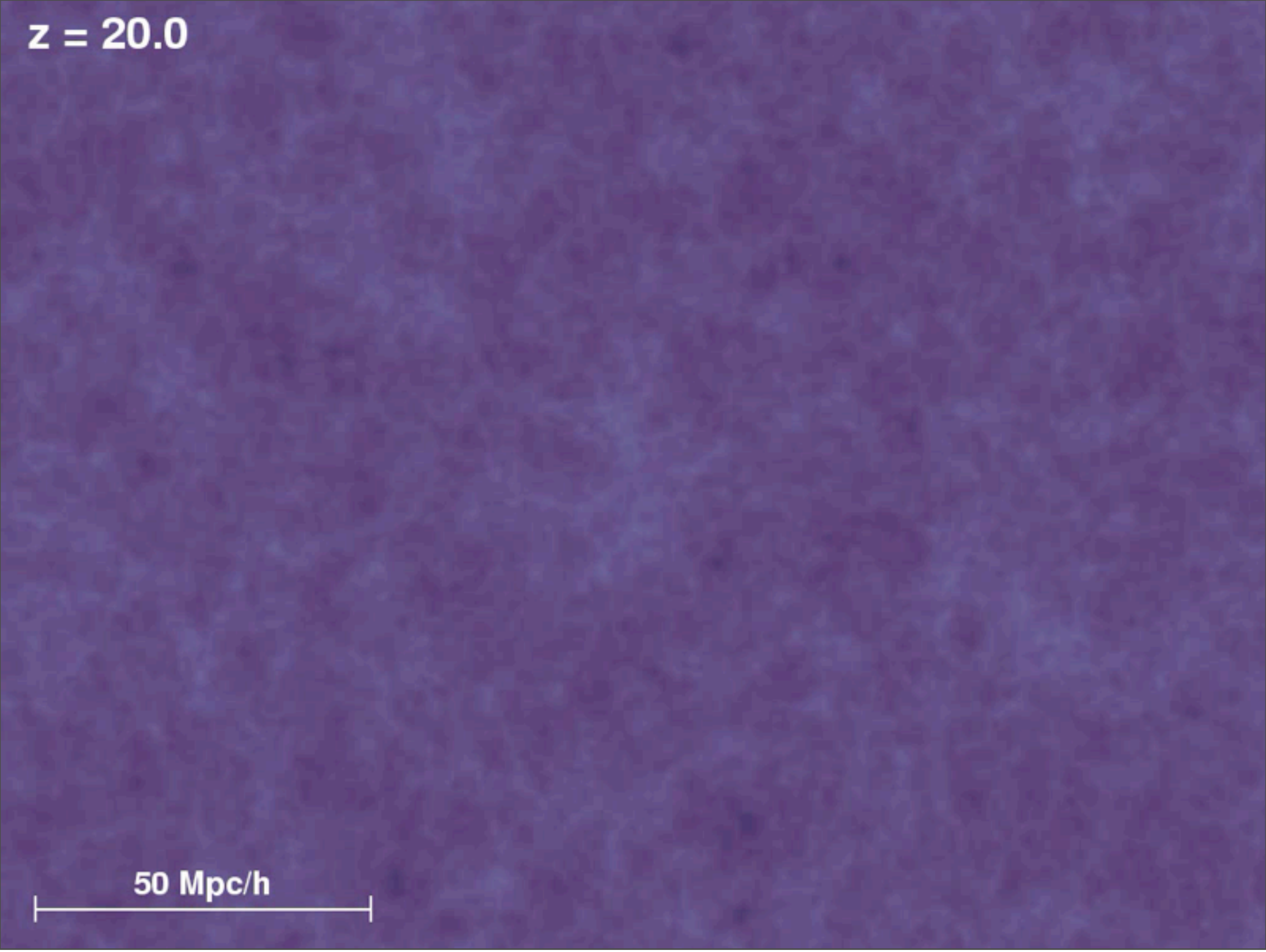
12/04/08

Lars Hernquist, T. J. Cox, Dusan Keres, Josh Younger, Volker Springel, Brant Robertson, John Kormendy, Tod Lauer, Adam Lidz, Tiziana Di Matteo, Yuexing Li, Gordon Richards, Alison Coil, Adam Myers, and many more

Motivation

HOW DID WE GET TO GALAXIES TODAY?




z = 20.0
50 Mpc/h

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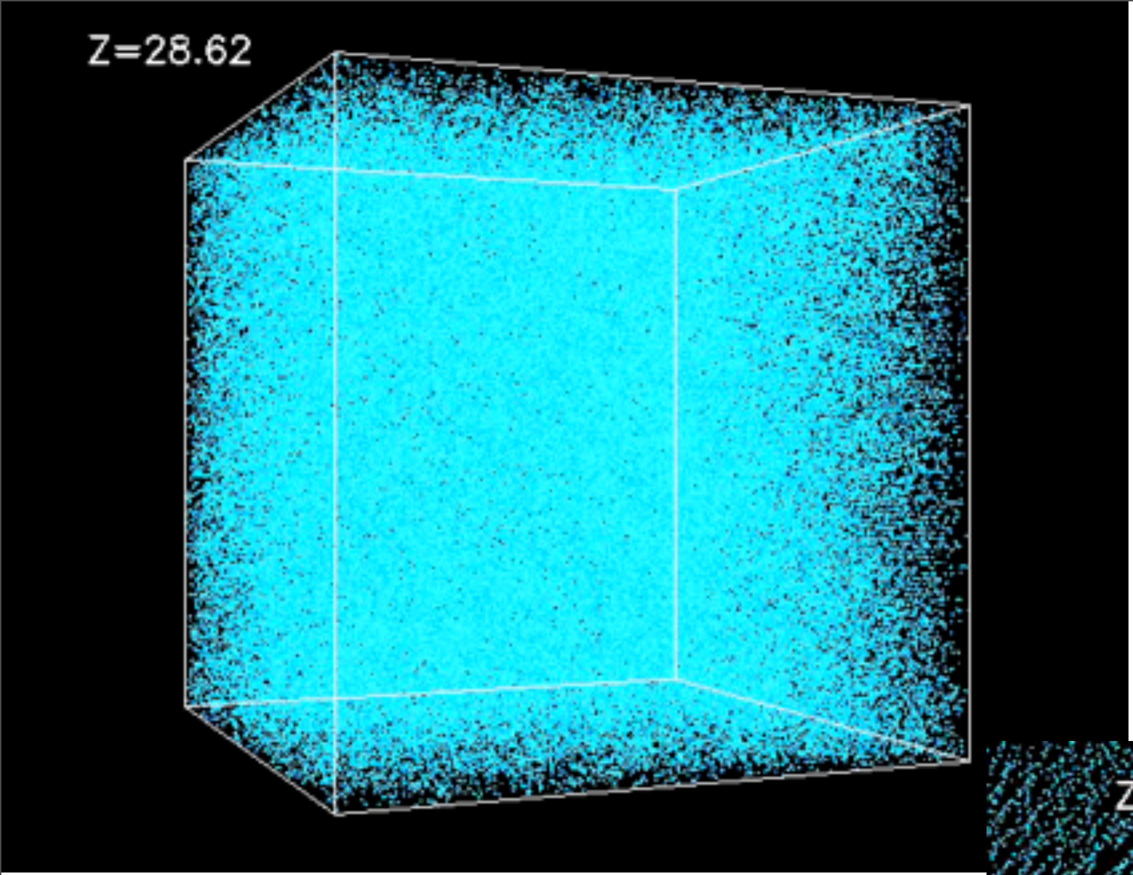
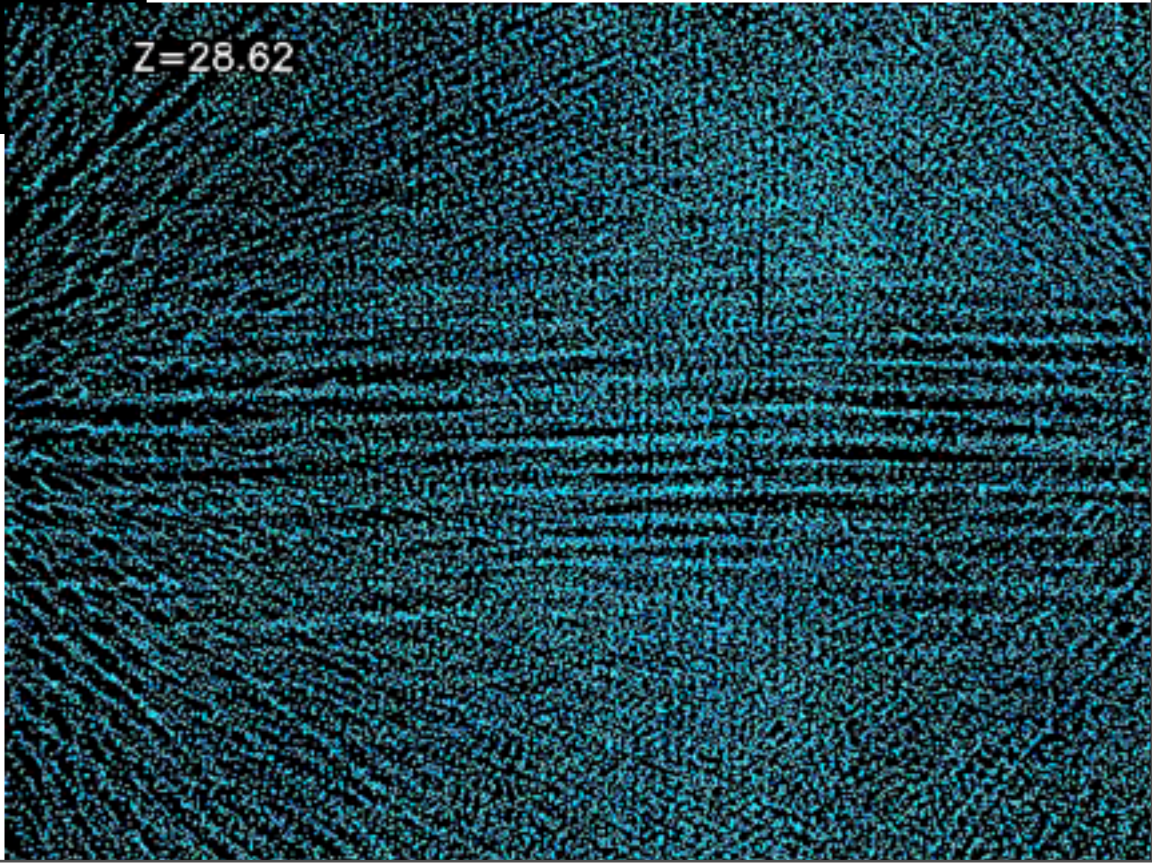


Kravtsov et al.

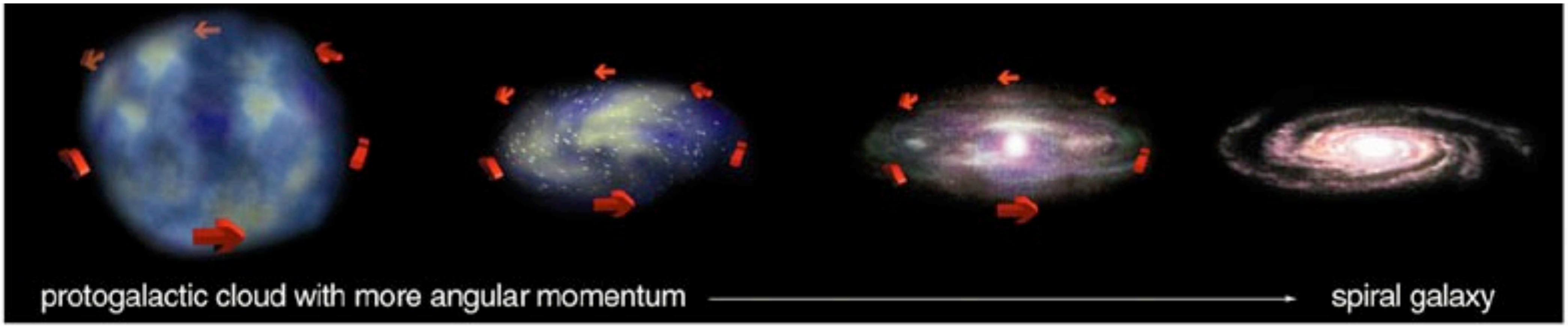


- Structure grows hierarchically: *must* understand mergers

Motivation

HOW DID WE GET TO GALAXIES TODAY?

- Dark matter halos collapse: gas cools into a disk



- What happens when that starts colliding into other galaxies?

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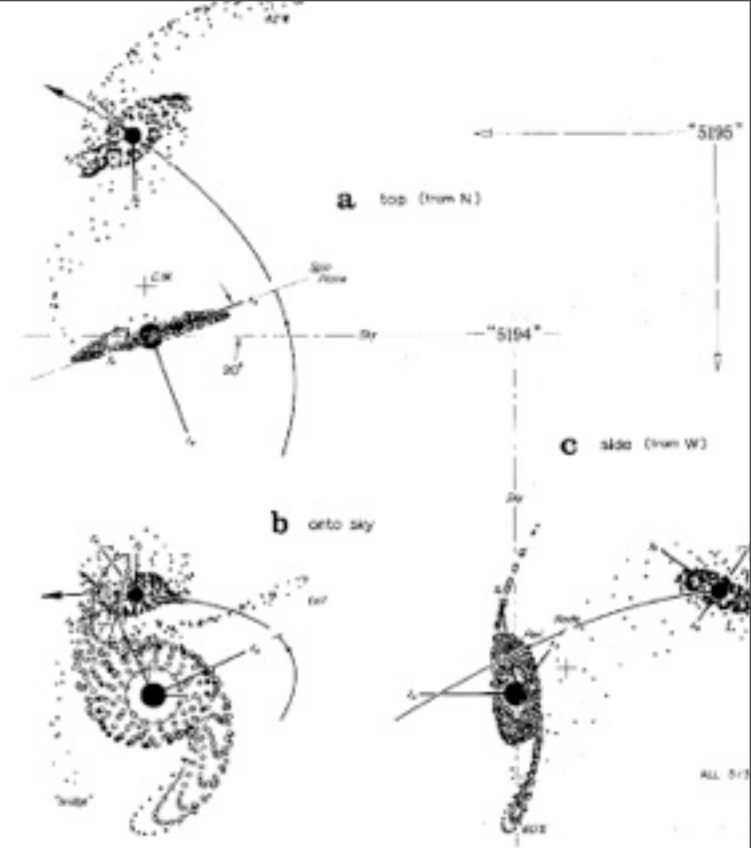
HOW DID WE GET TO GALAXIES TODAY?

- Toomre & Toomre (1972) : the "merger hypothesis"
  - Ellipticals are made by merger of spirals



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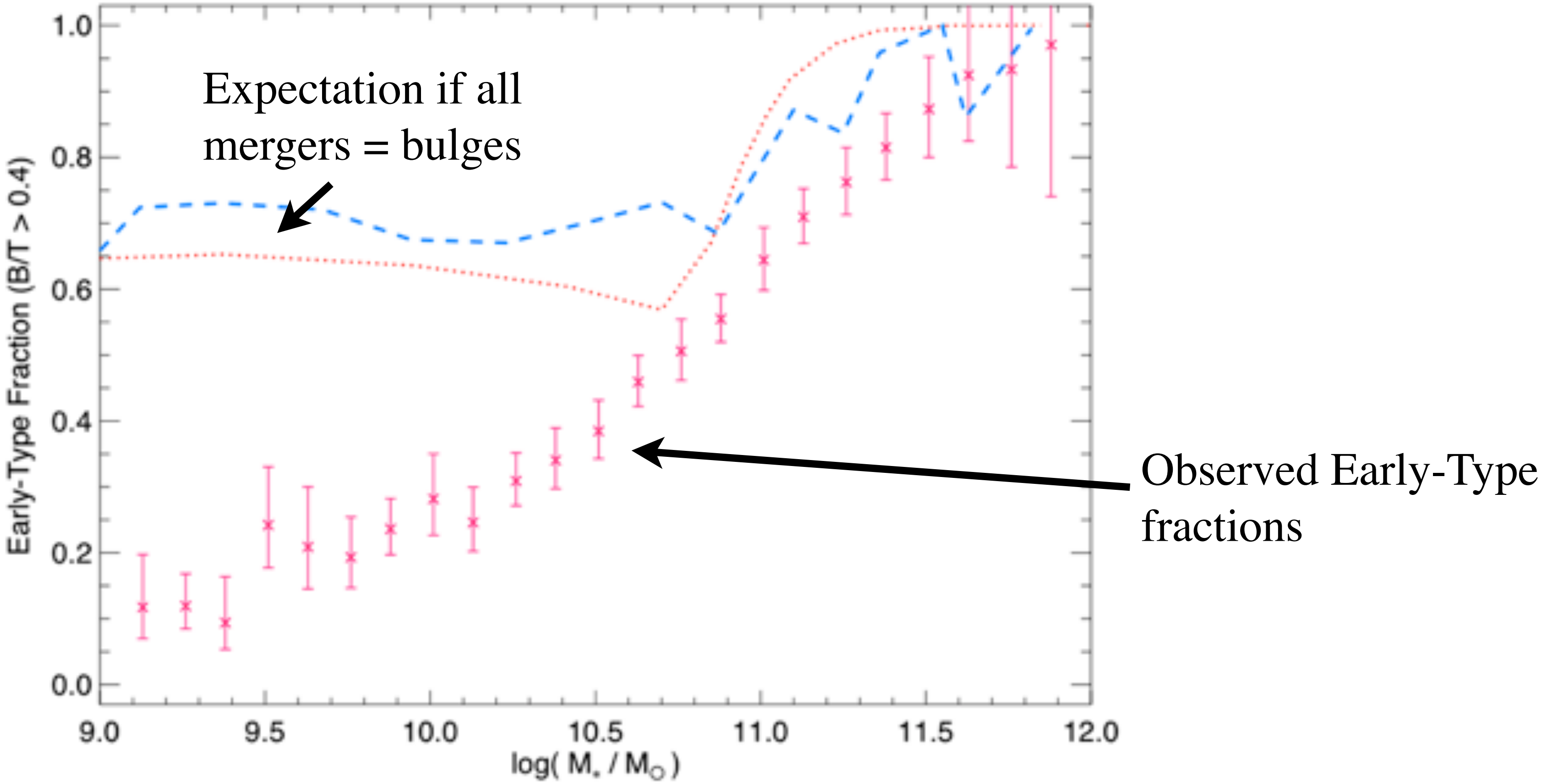
(1) Every merger -> elliptical leaves no disks!



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Two Problems:

(1) Every merger -> elliptical leaves no disks!

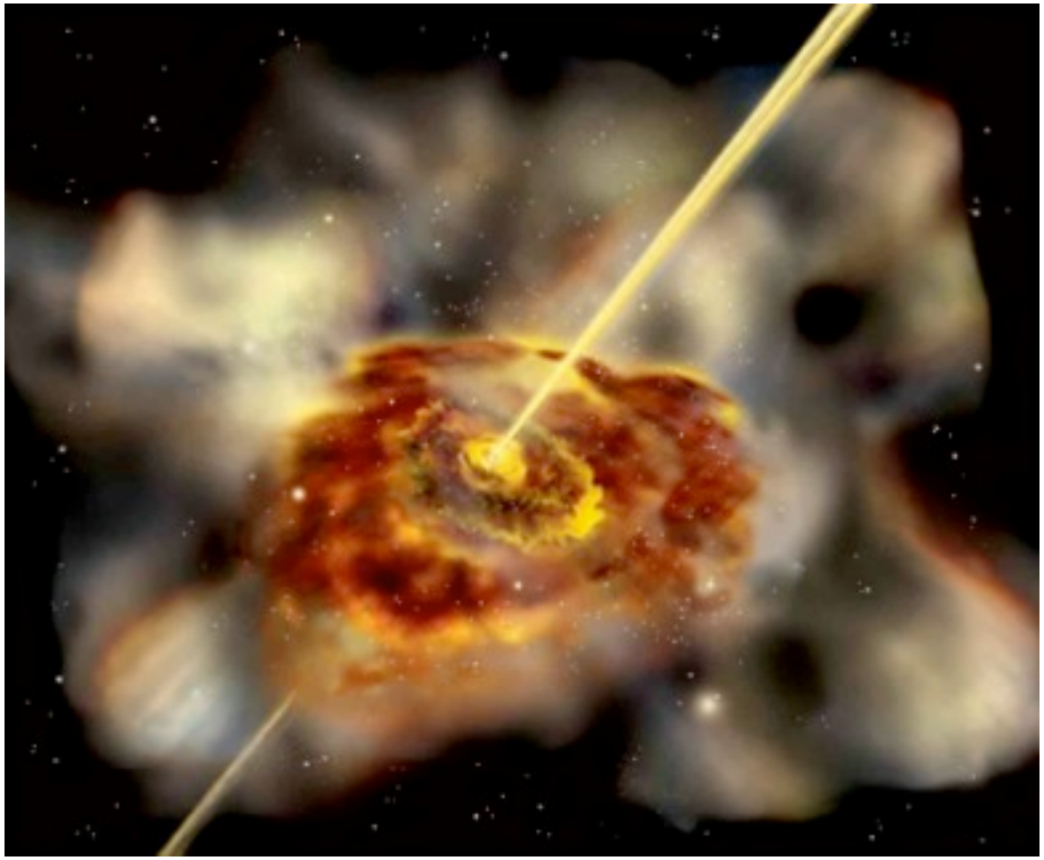
(2) Stellar disk-disk merger remnants look like...
nothing in the real Universe

-- sizes too large
-- profiles too flat
-- shapes too flattened

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- Every massive galaxy hosts a supermassive black hole

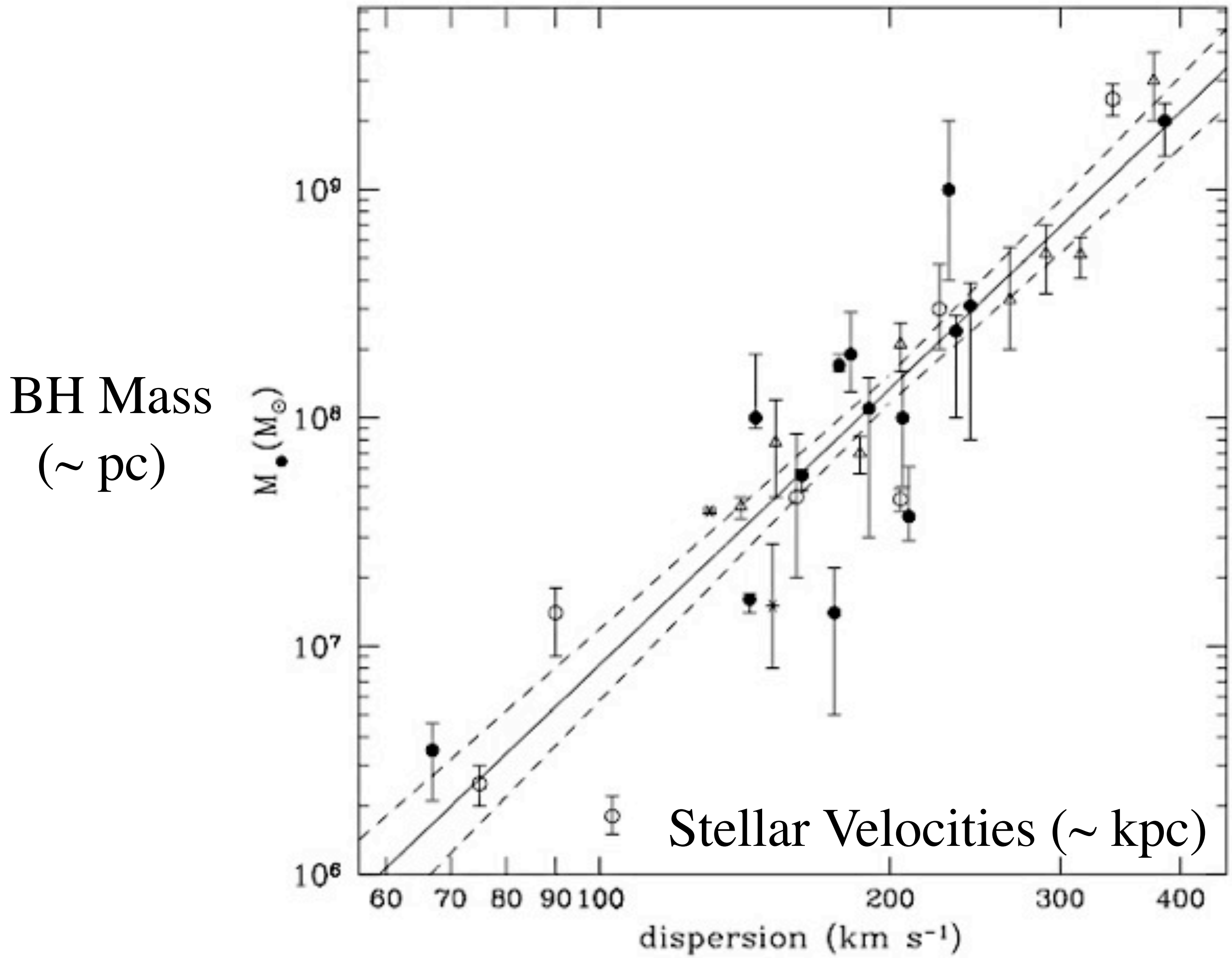


- These BHs accreted most of their mass in bright, short lived quasar accretion episodes: the “fossil” quasars

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

- Black holes are somehow sensitive to their host galaxies (bulges):



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

Motivation

HOW DID WE GET TO GALAXIES TODAY?

But a number of unsolved problems have tormented (excited?) theorists & observers for ~30 years:

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  How do we make a *real* elliptical?

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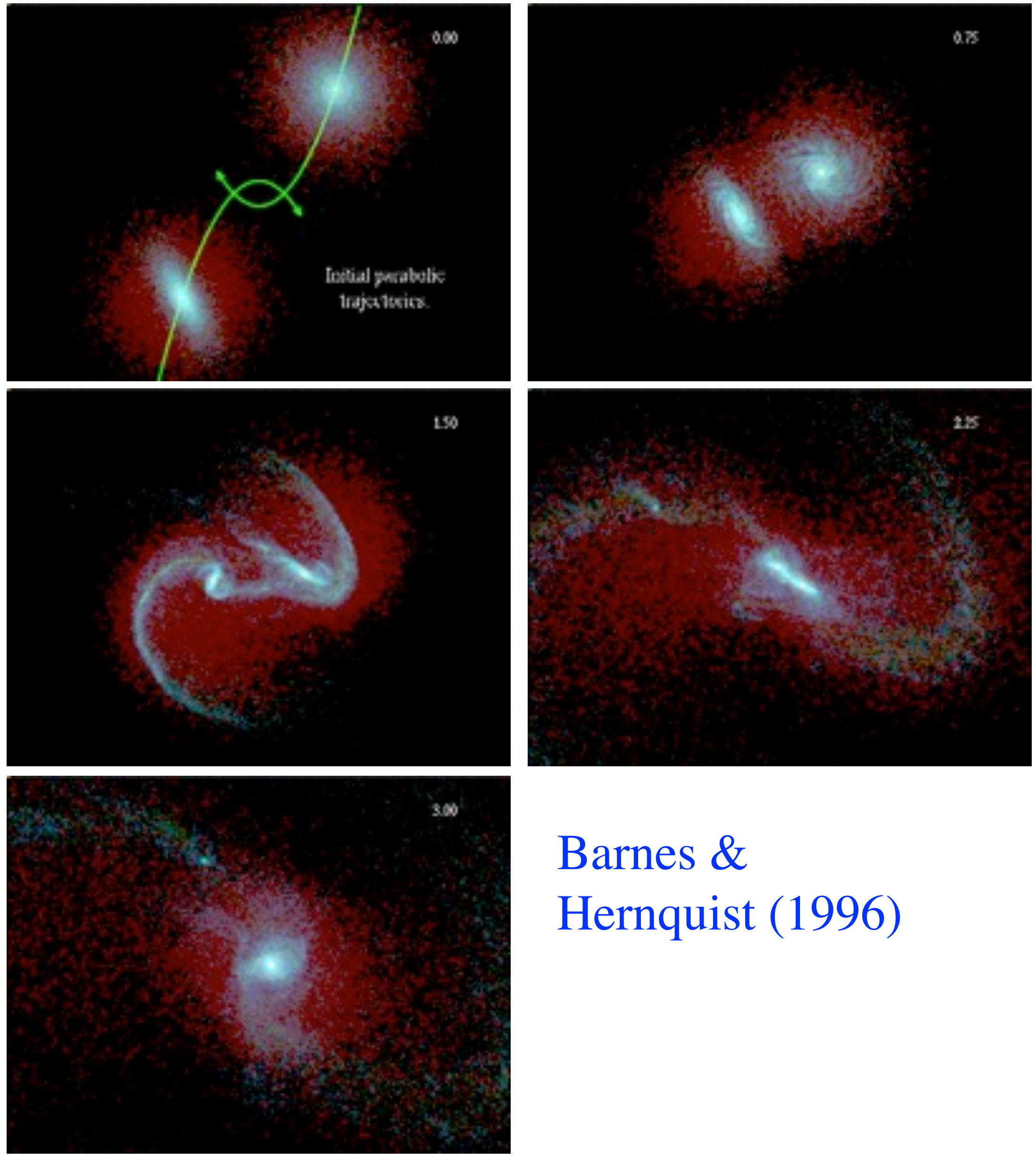
- Ellipticals are *smaller* than spirals!
  How do we make a *real* elliptical?
- How do galaxies *stop* growing?
- Where did these black holes come from!?

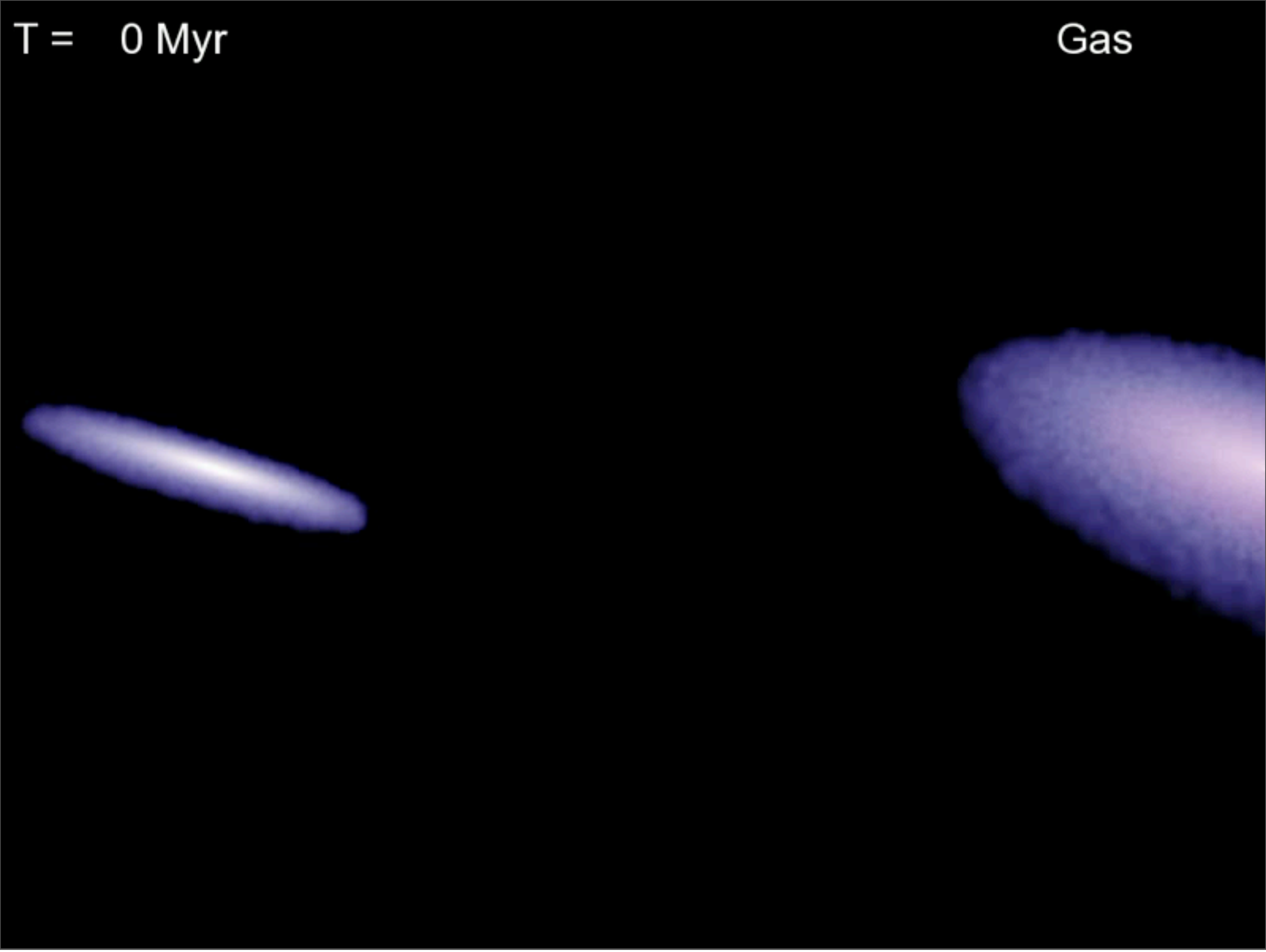
The Unsolved Questions

WHAT ACTUALLY HAPPENS IN A MERGER?

- Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)
- Triggers starburst (e.g. Mihos & Hernquist 1996)
- Feeds BH growth (e.g. Di Matteo et al. 2005)
- Merging stellar disks grow spheroid

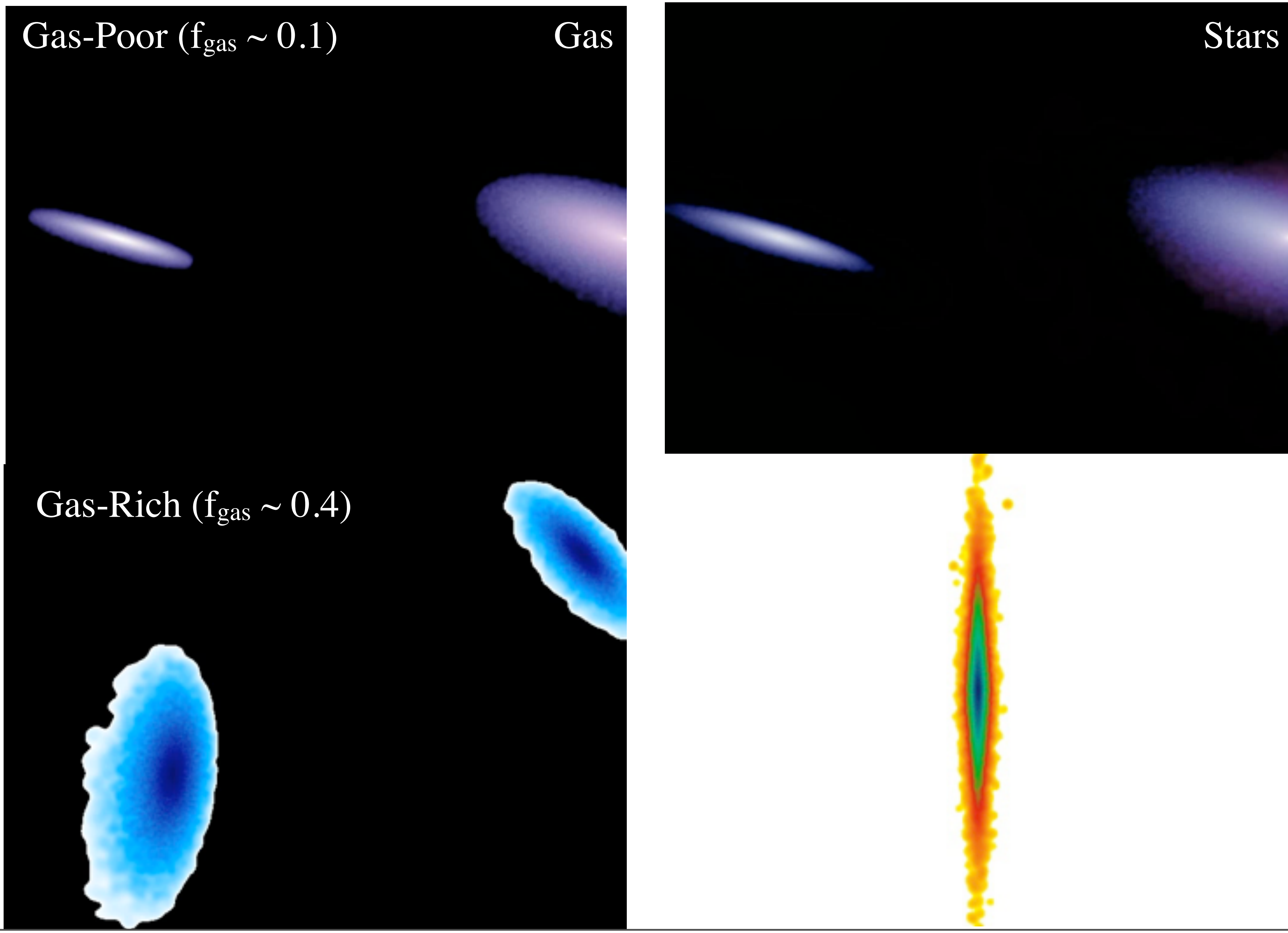


Barnes & Hernquist (1996)


T = 0 Myr
Gas

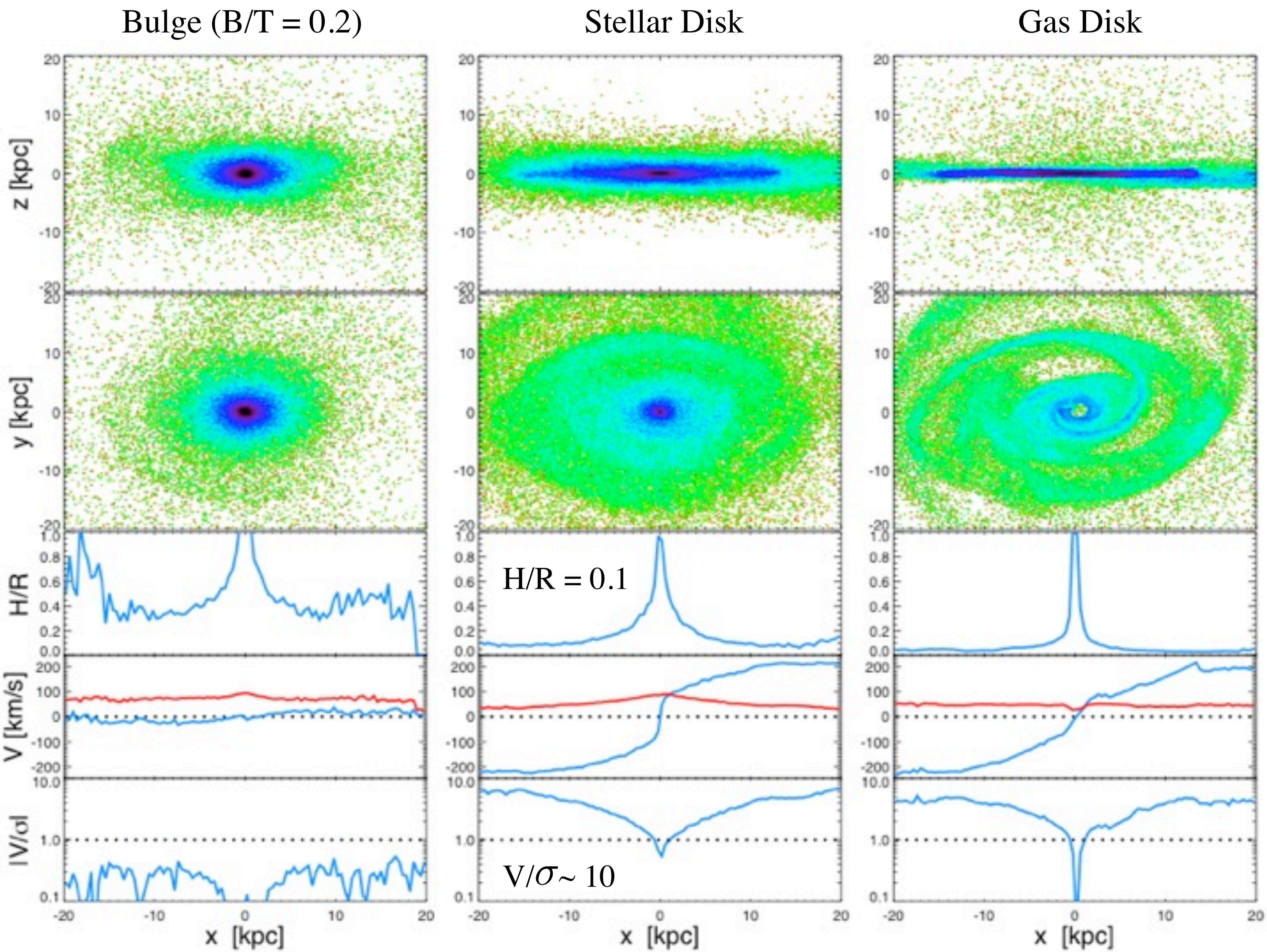
Galaxy Mergers

HOW GOOD IS OUR CONVENTIONAL WISDOM?



Major Merger Remnants

DO MERGERS DESTROY DISKS?



The Unsolved Questions

HOW CAN A DISK SURVIVE?

- Stellar disks are collisionless: they violently relax when they collide

+

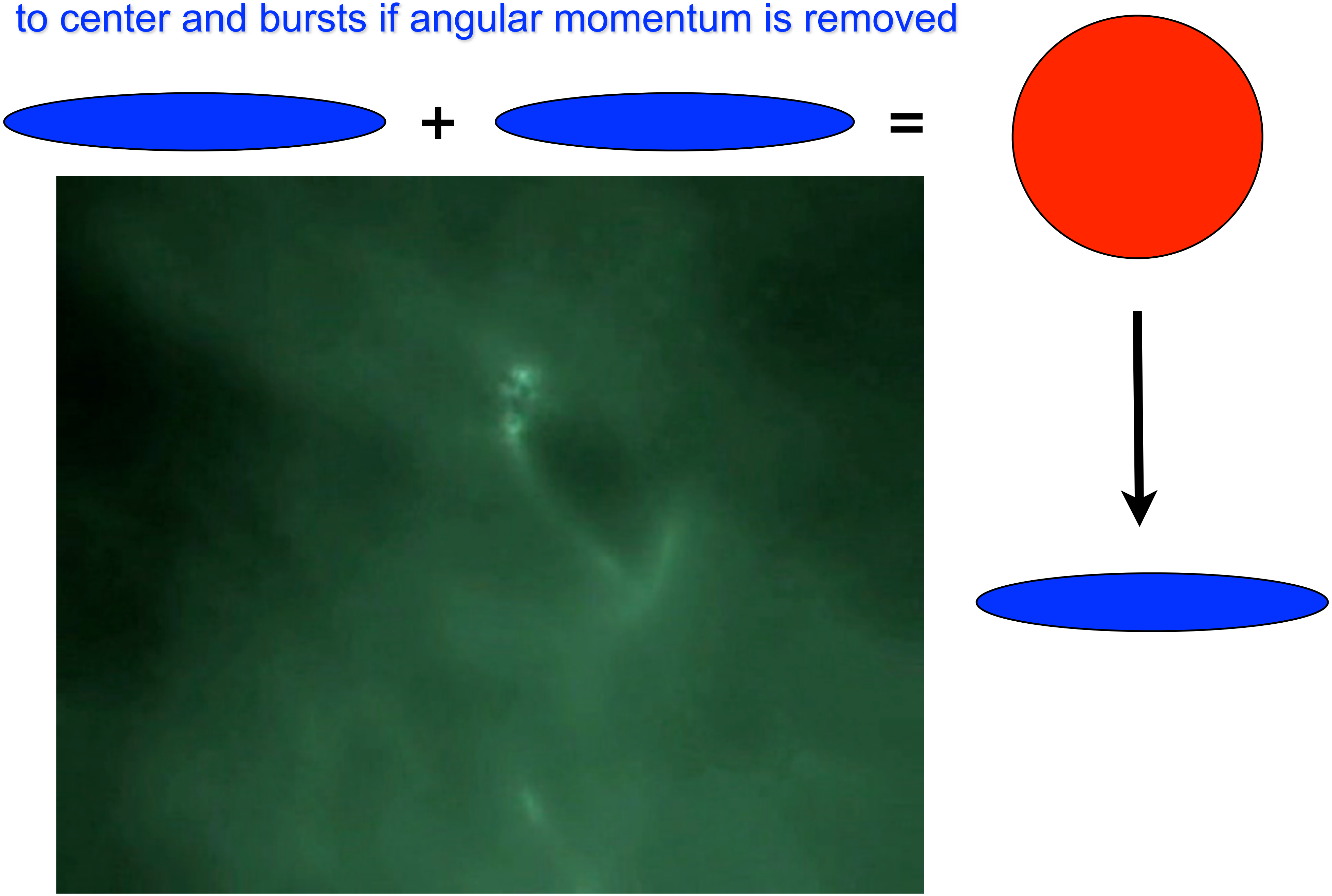
=

- Can’t “cool” into a new disk

The Unsolved Questions

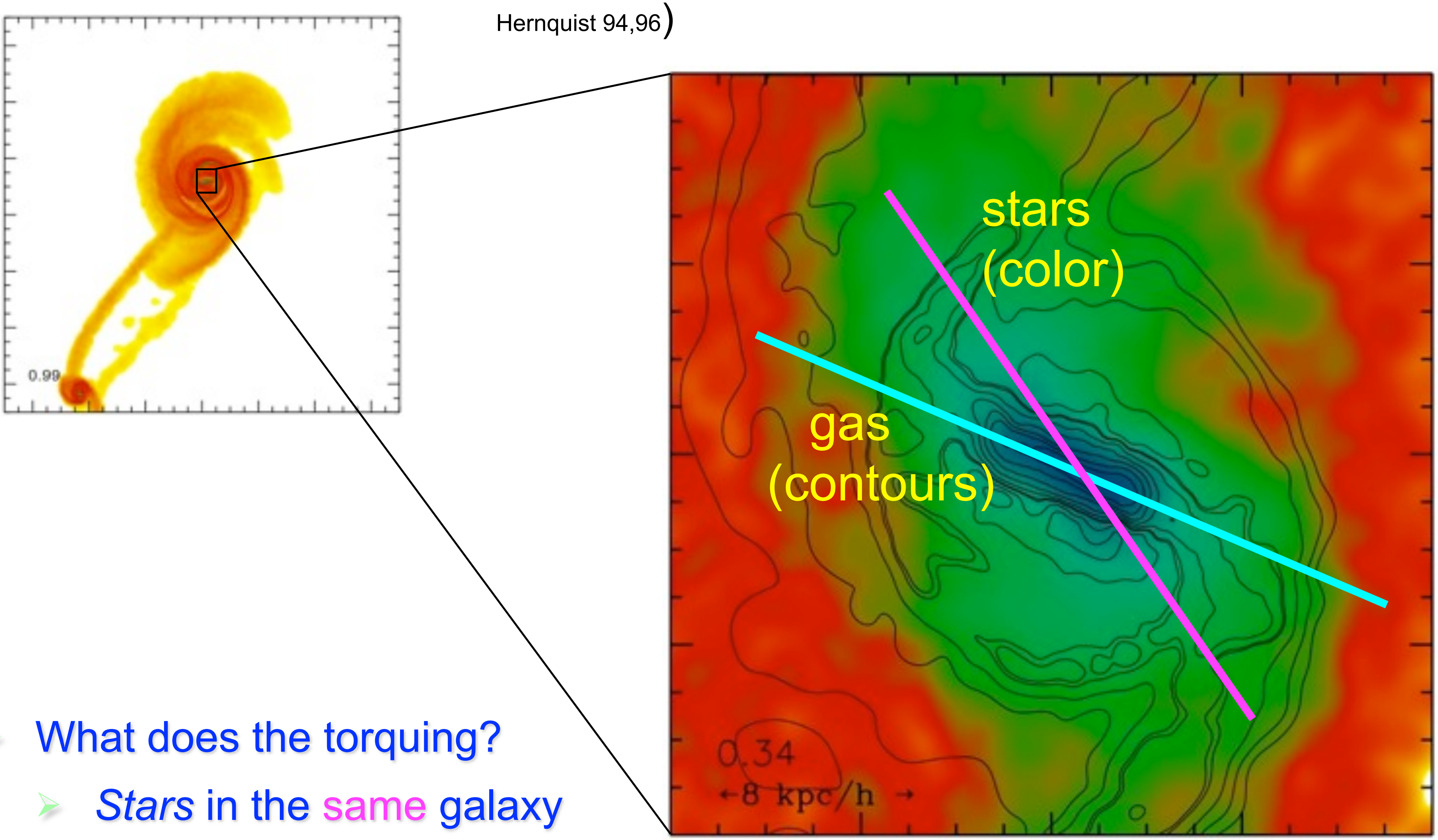
HOW CAN A DISK SURVIVE?

- Gas, however, is collisional (will cool into new disk): only goes to center and bursts if angular momentum is removed



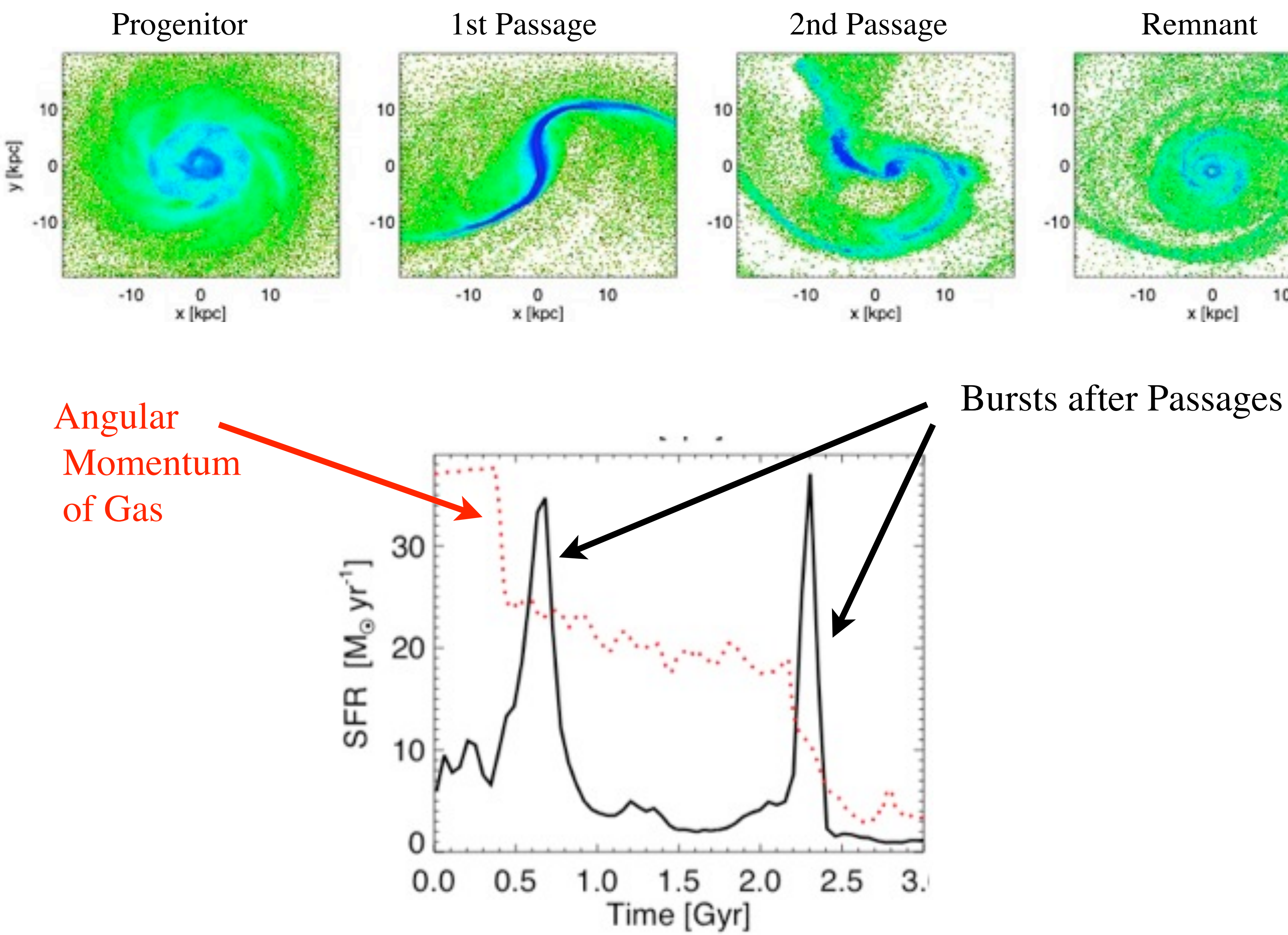
How Do Disks Survive Mergers?

companions -- bars -- gas/star offset -- torques -- gas inflow (see, e.g., Barnes 92, Barnes & Hernquist 96, Mihos & Hernquist 94,96)



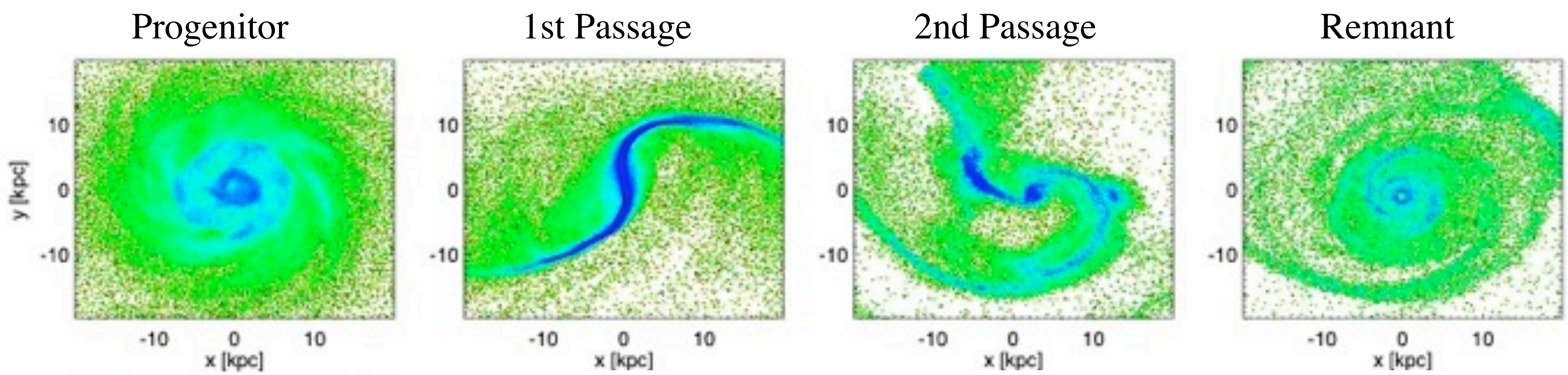
- What does the torquing?
  - *Stars* in the same galaxy

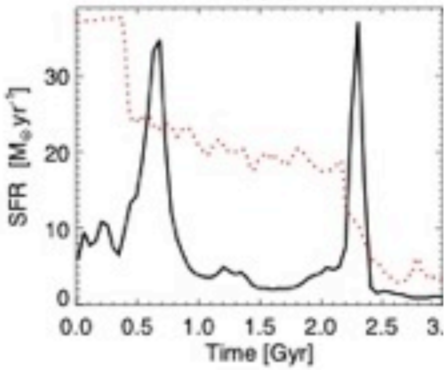
How Do Disks Survive Mergers?

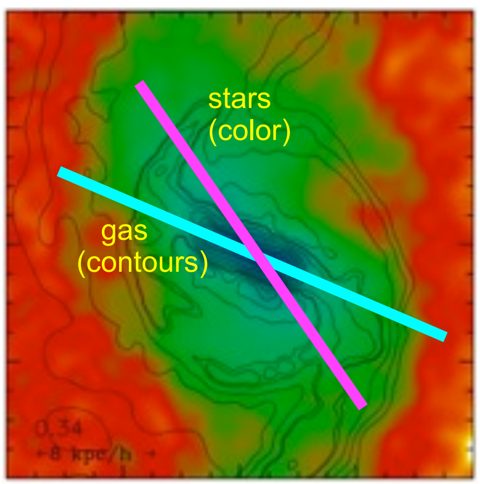


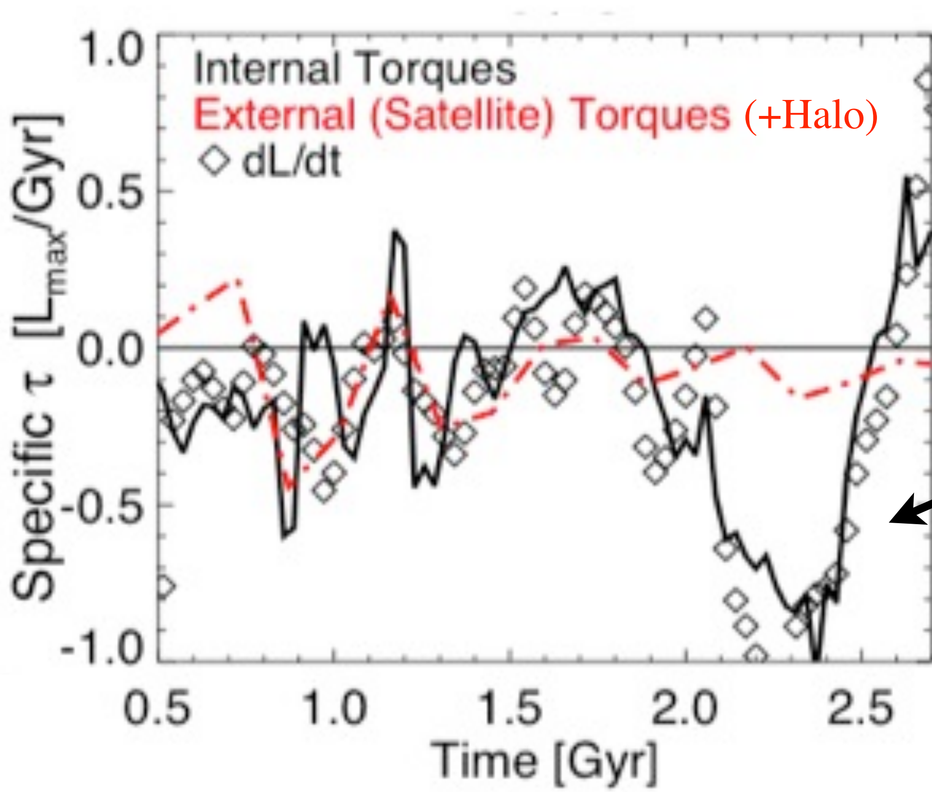
PFH et al. ‘08

How Do Disks Survive Mergers?





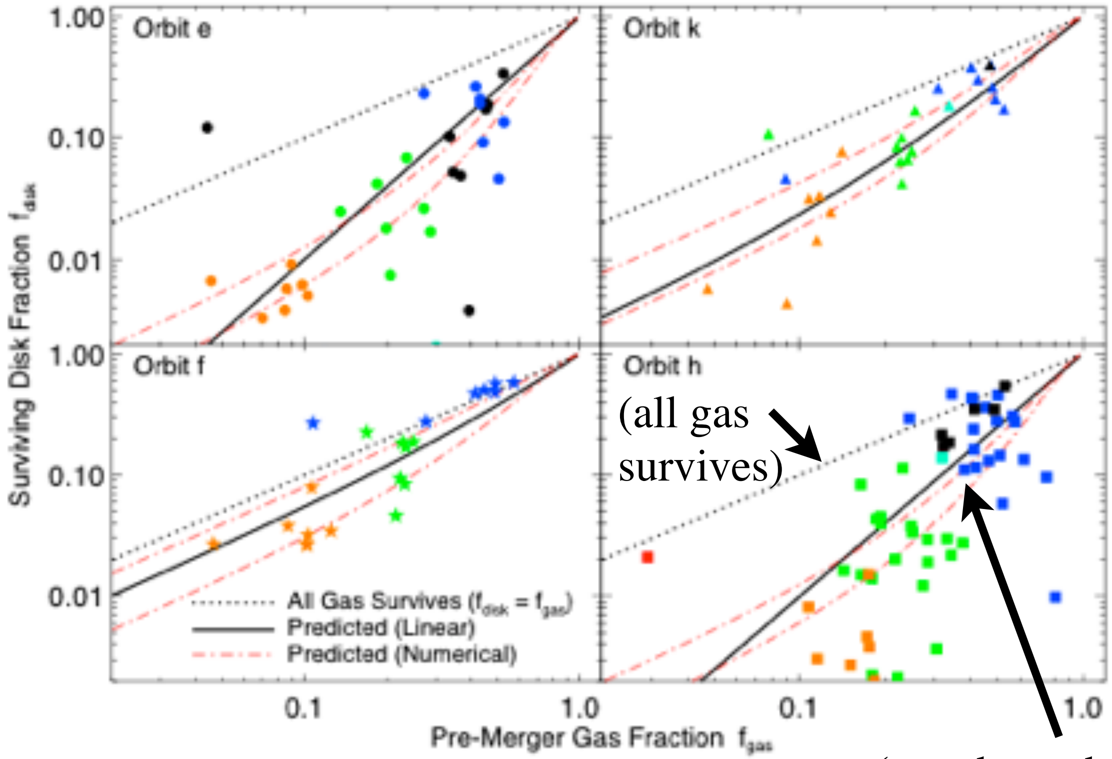




J_{gas} loss dominated by *stars* in the *same* disk

How Do Disks Survive Mergers?

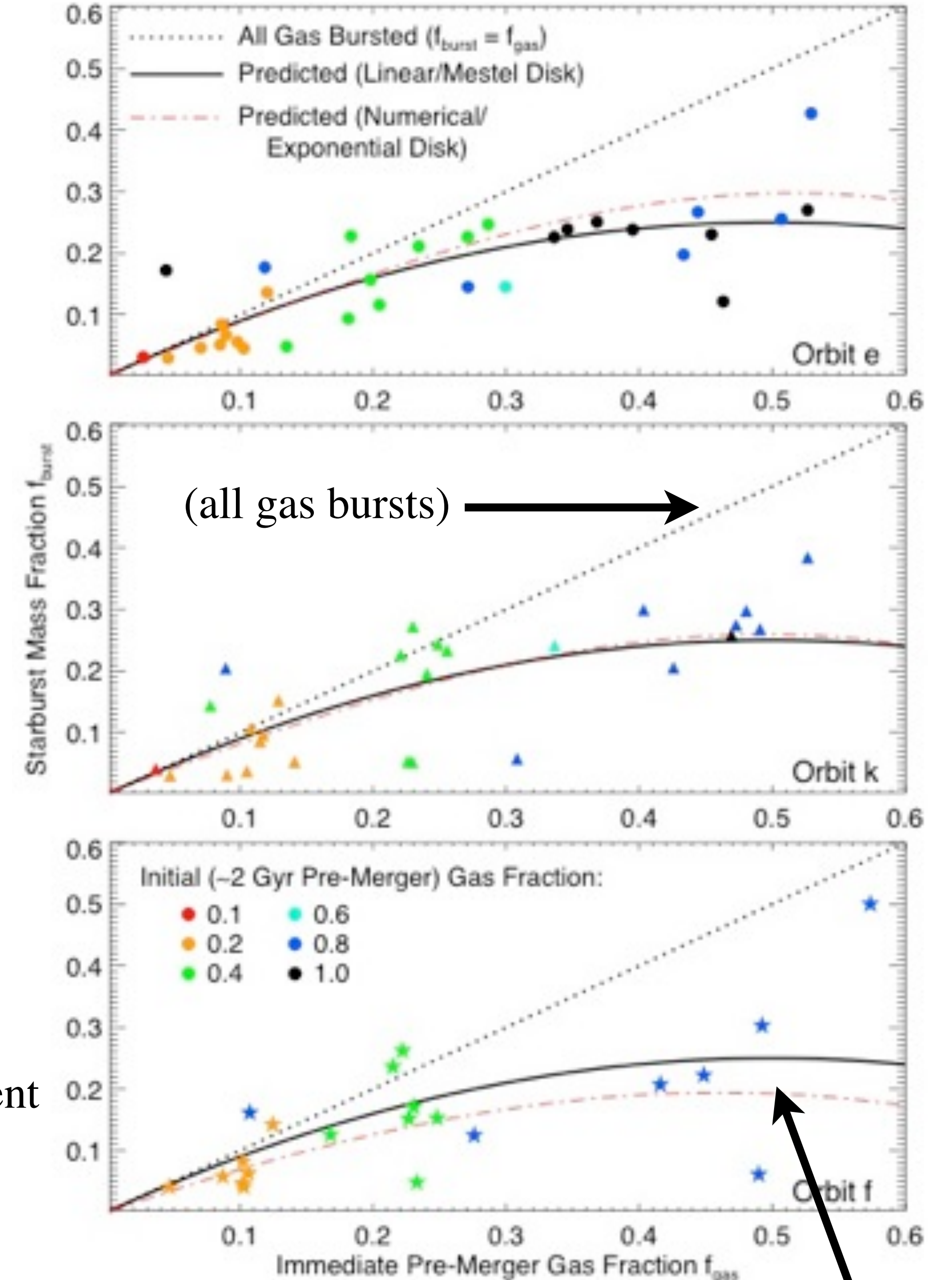
Surviving Gas Disk Mass vs. f_{gas}



(all gas survives)

(gas-dependent prediction)

Burst mass vs. f_{gas}



(all gas bursts)

(gas-dependent prediction)

Torque on gas:

$t \sim G\, M_{\text{stellar bar}} / dr$

for the same merger/perturbation,

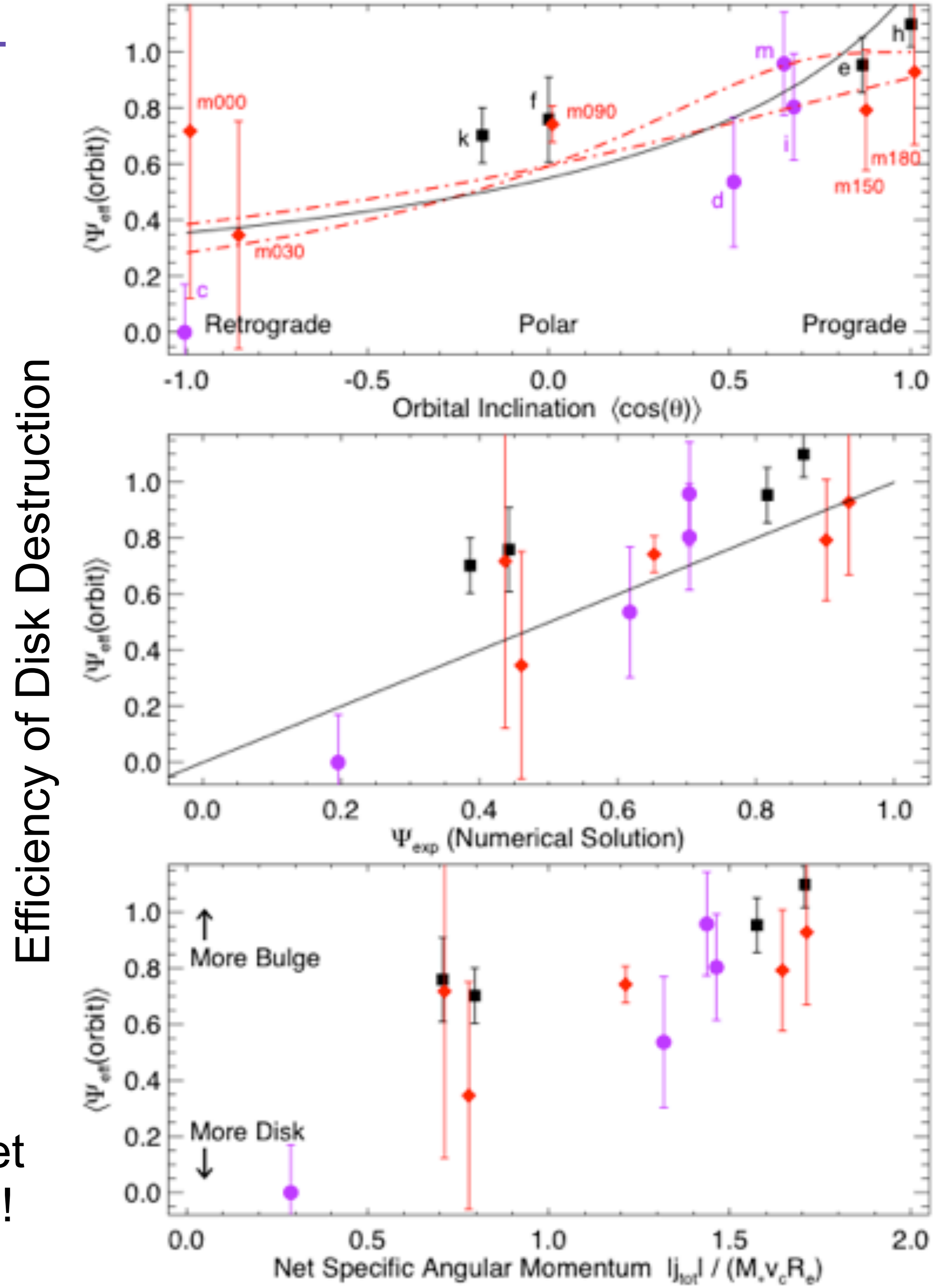
$M_{\text{stellar bar}} \propto M_{\text{stellar}} \propto (1 - f_{gas})$

How Do Disks Survive Mergers?

Can similarly calculate
dependence on orbital parameters

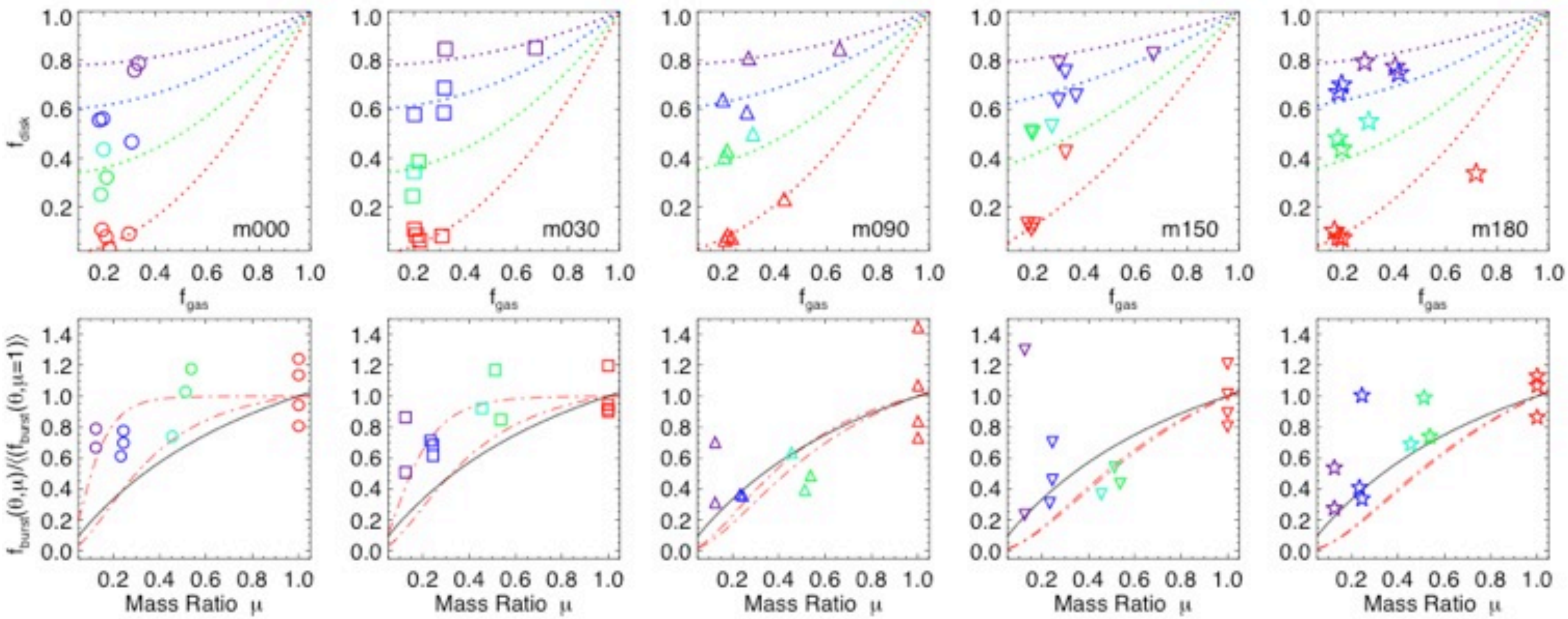
- A *driven* distortion:
  much simpler than secular

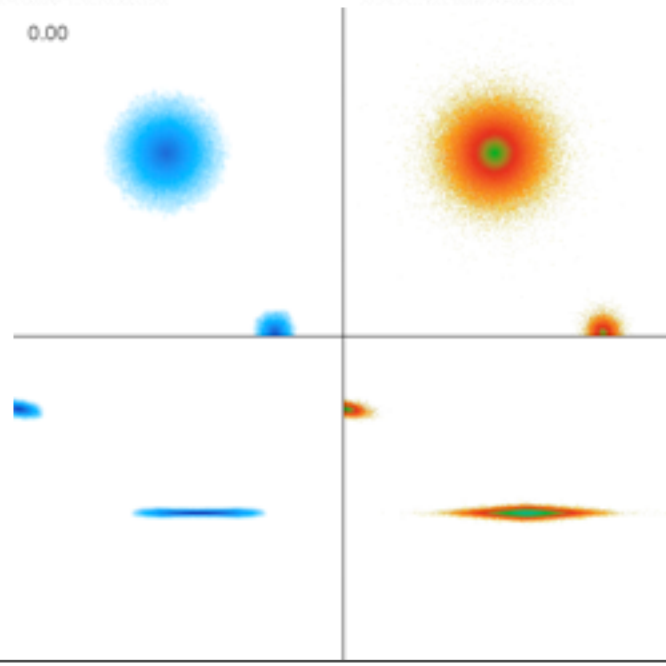
- Timescales are short:
  halo/secular exchange
  can be completely ignored



Nothing to do with net
angular momentum!

How Do Disks Survive Mergers?





Likewise, versus mass ratio μ

- To lowest order, magnitude of everything (fraction of disk destroyed) $\propto \mu$

How Do Disks Survive Mergers?

THE PUNCHLINE

Derive:

Gas angular momentum loss/starburst mass
Surviving gas disk fraction
Violently relaxed fraction of stellar disk

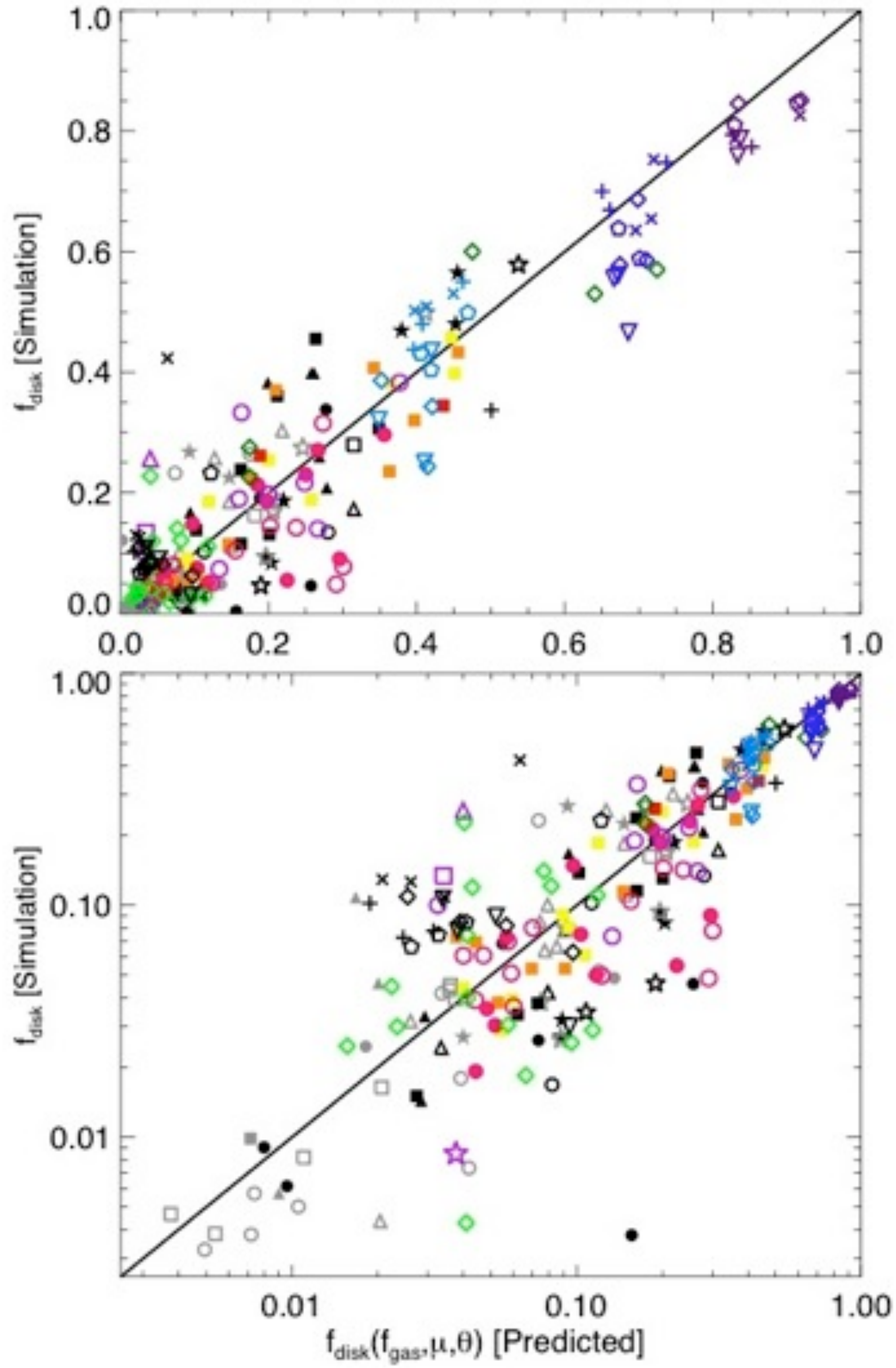
$$= F(f_{gas}, \mu, \theta_{orbit})$$

Works varying:

Baryonic/halo mass
Redshift
BH properties (presence, mass, feedback)
Galaxy concentrations/initial B-T/sizes
Mass ratio, orbital parameters, gas fraction
Stellar feedback

Purely gravitational process:

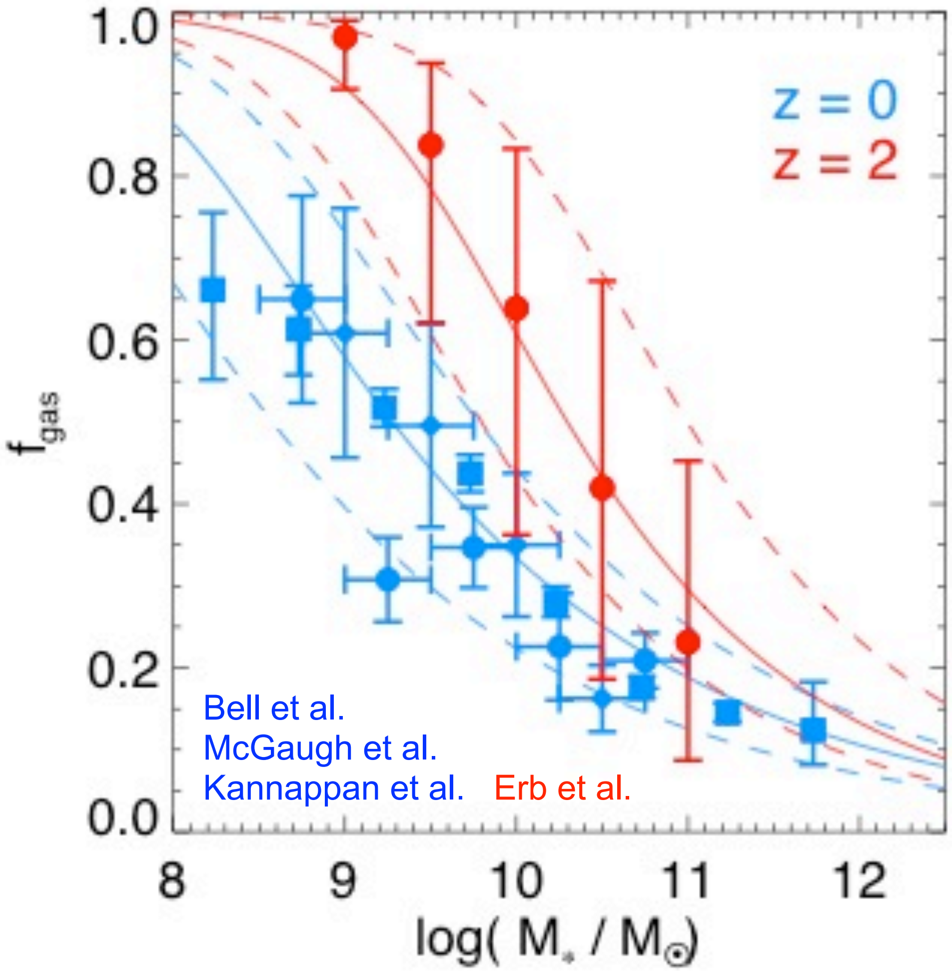
Independent of feedback
Must happen

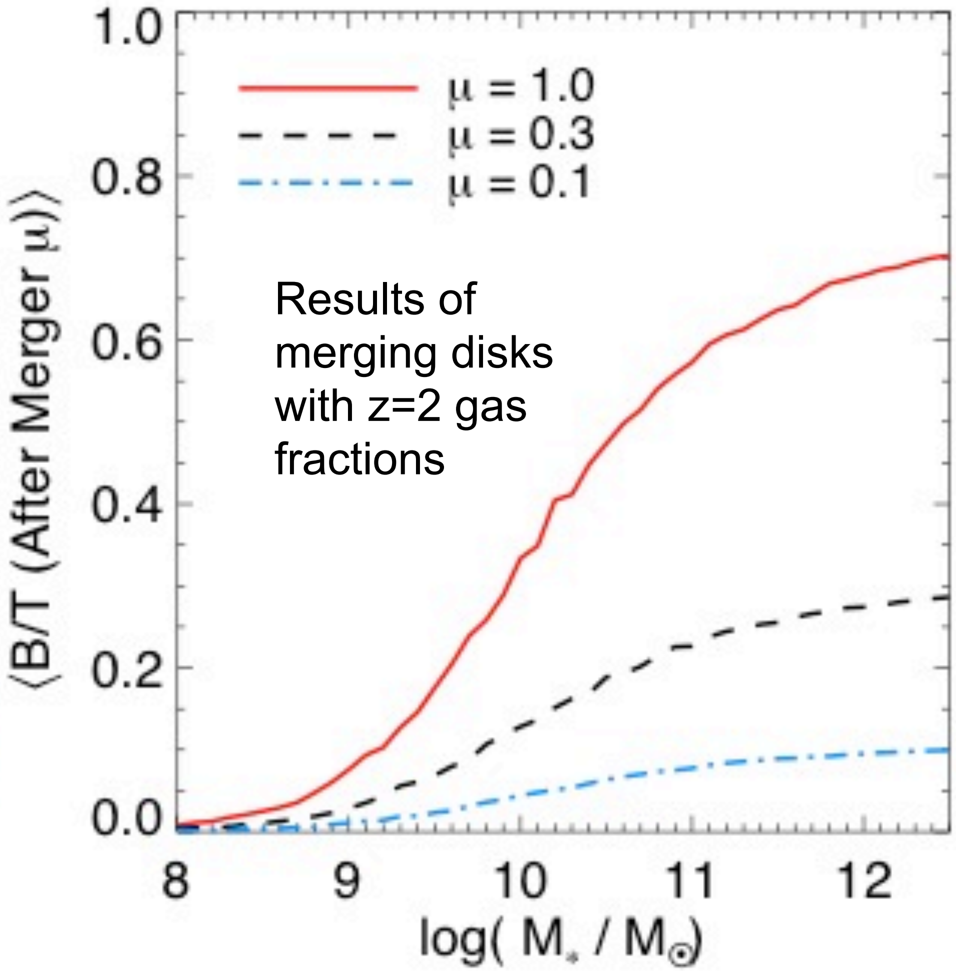


Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

- Fold this into a cosmological model: why do we care?





- Low-mass galaxies have high gas fractions: less B/T for the same mergers

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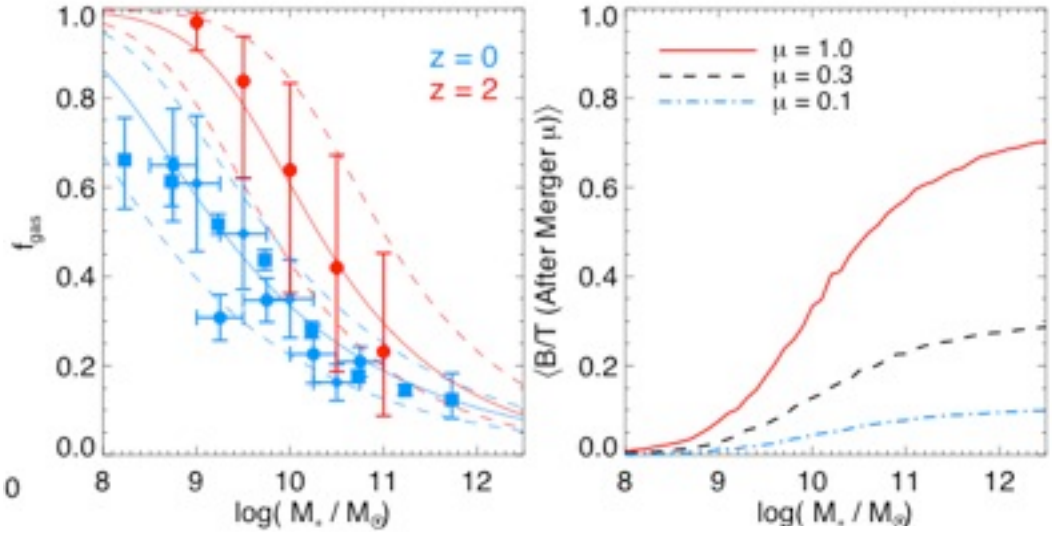

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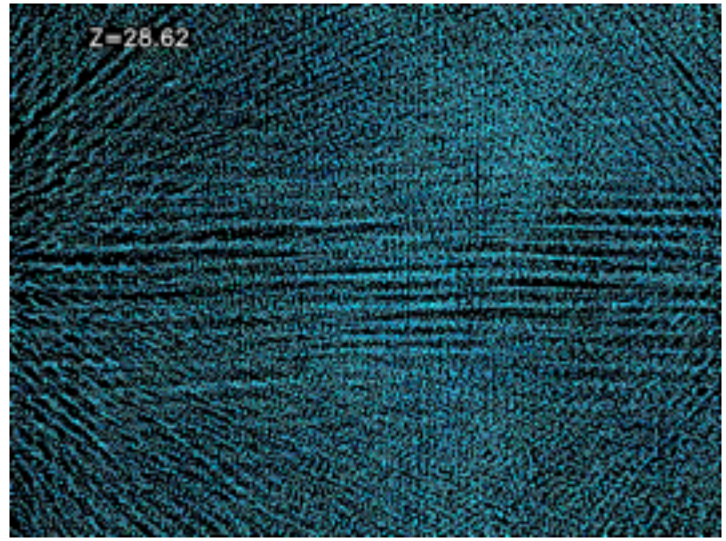

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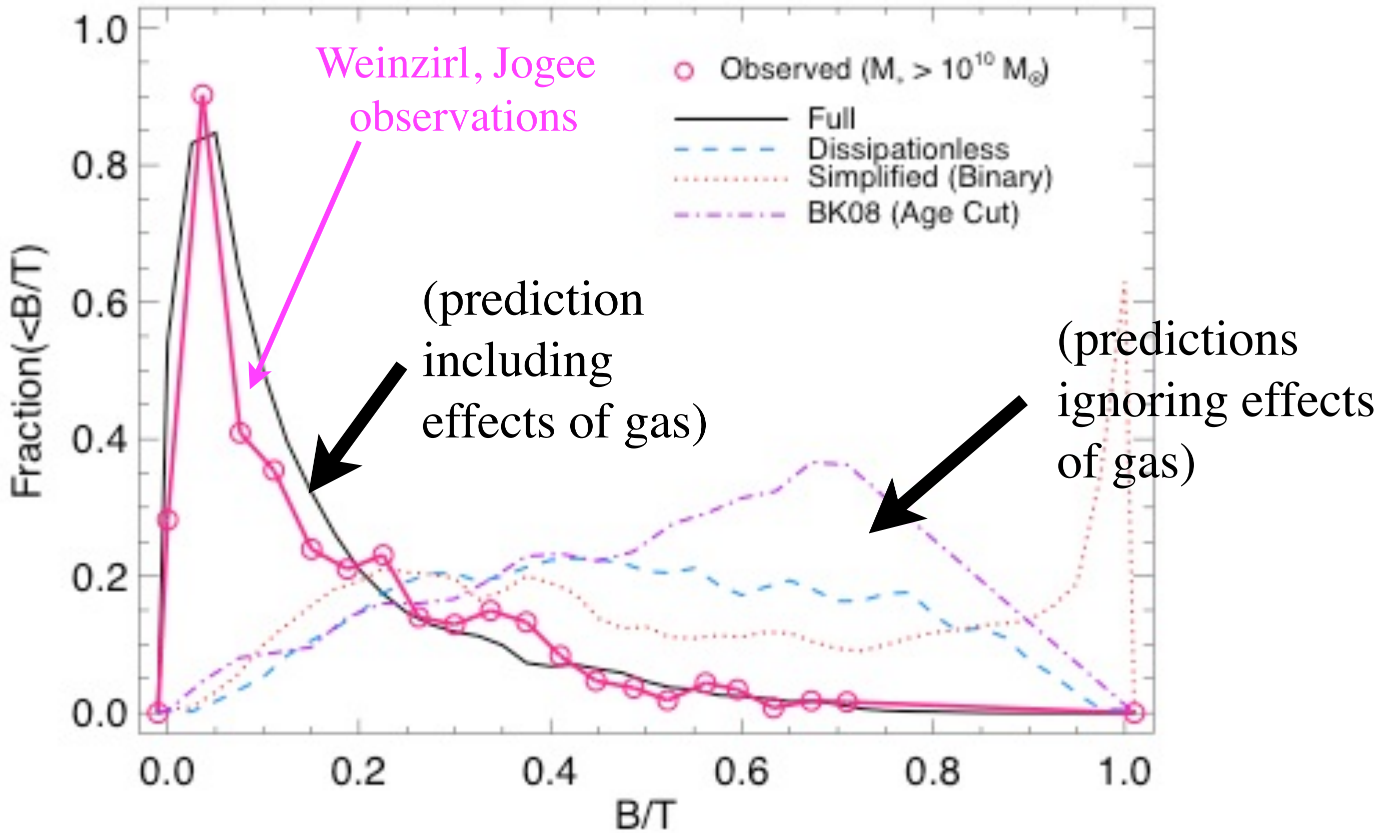

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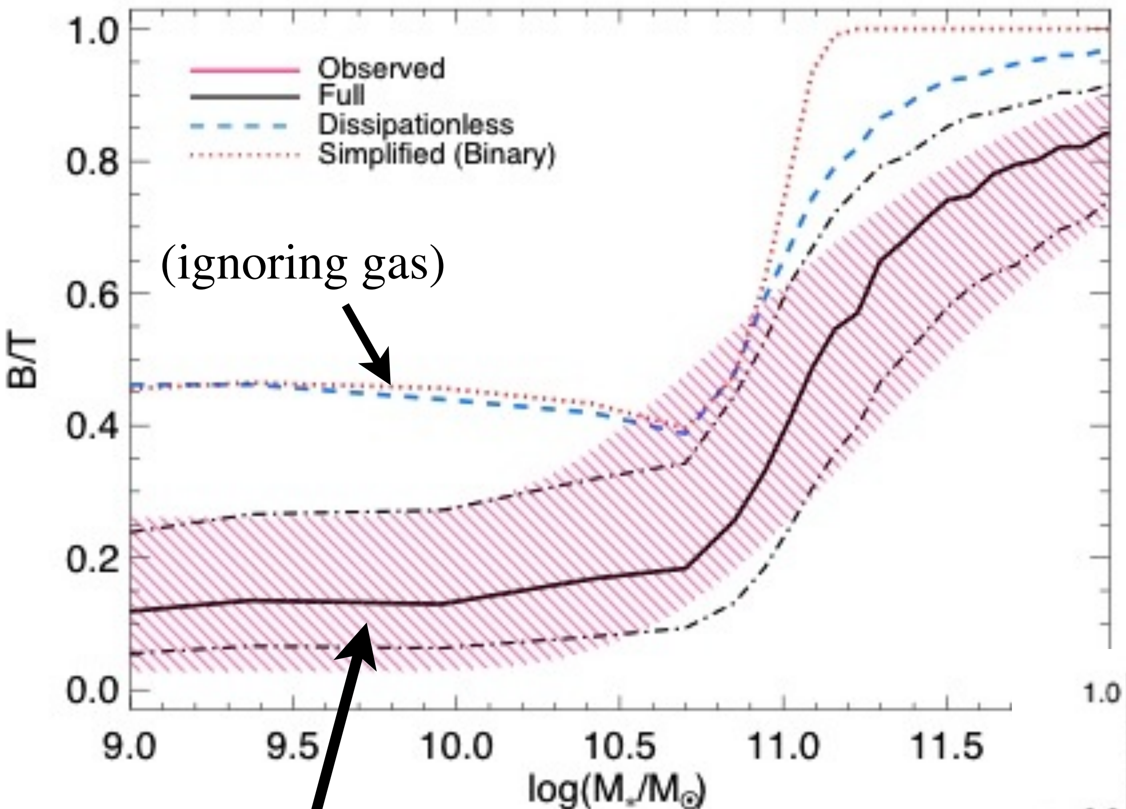
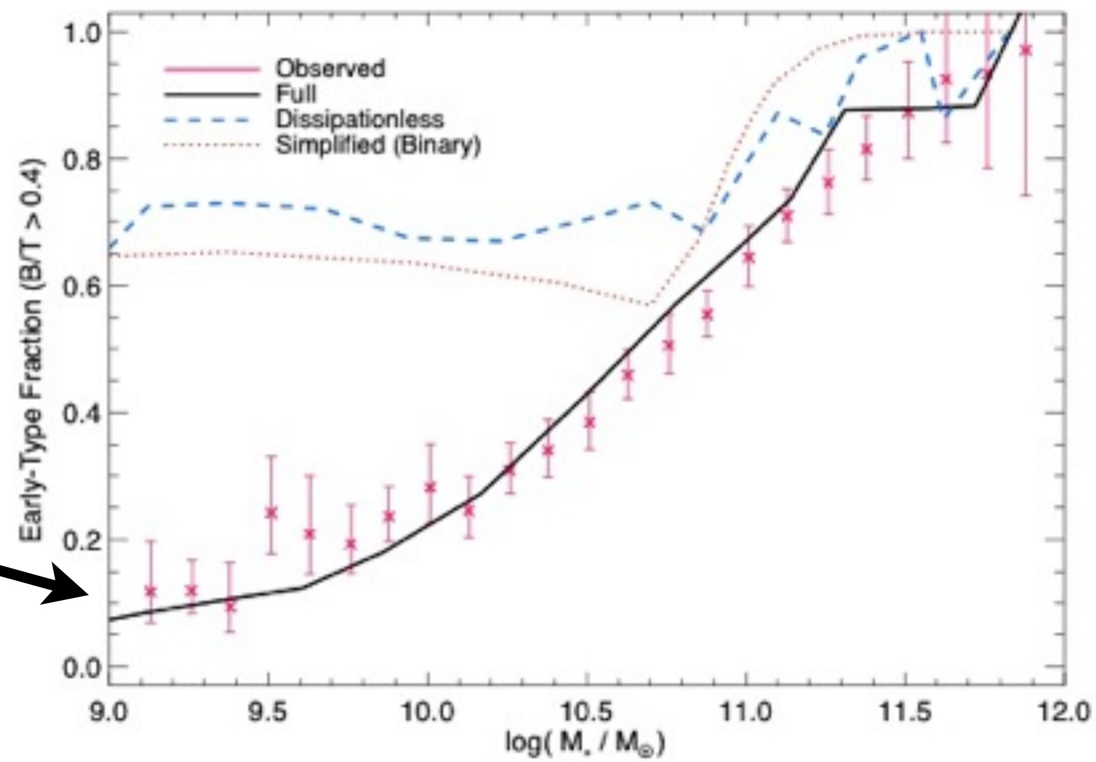


(ignoring gas)

(including effects of gas)

- Morphology-mass relation:
  - NOT possible to obtain with just dependence of merger history on mass/environment
    - (Stewart, Khochfar et al)
  - Natural consequence of f_{gas}-mass

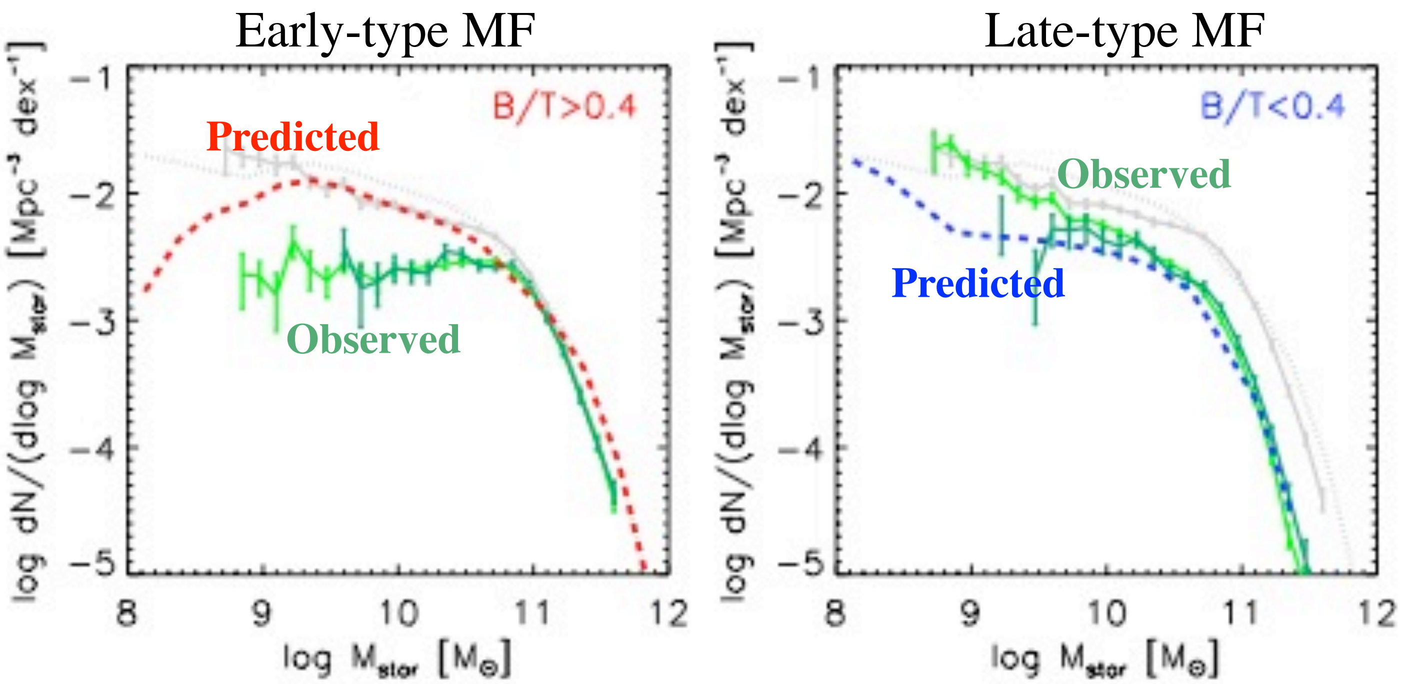


(Discrepancy between gas-blind models and observations grows at z=1, as merger rates rise)

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

Gas-blind models:



Somerville, Croton, Bower+ SAMs; alternative HOD models:

Hundreds/thousands of model runs with ~10-20 free parameters each: always overproduce low-mass bulge-dominated population

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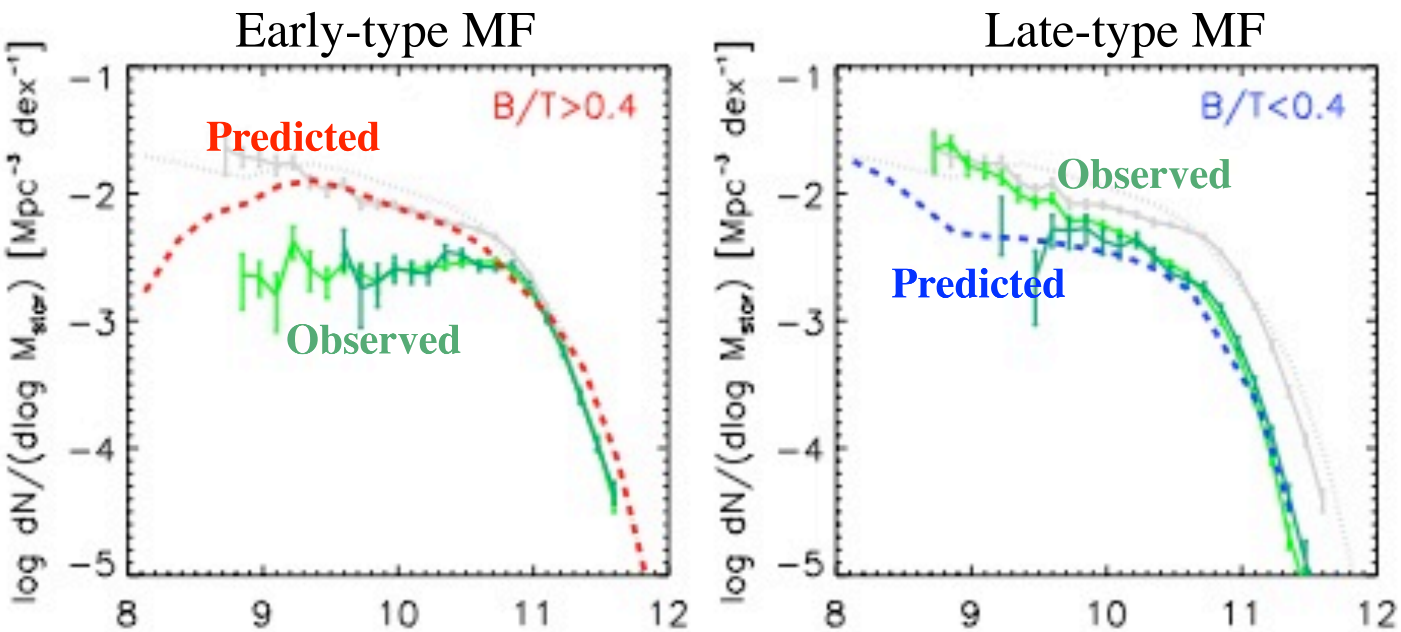
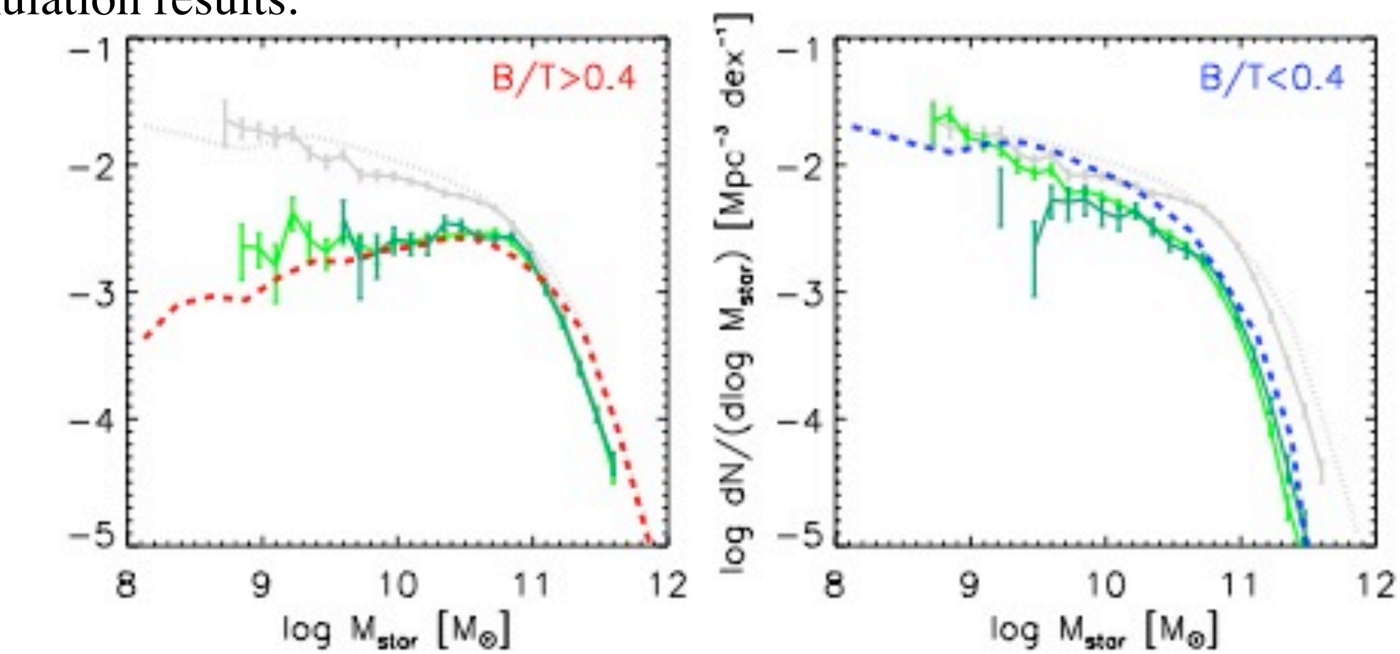


Exact same model, adding f_{gas}-dependent simulation results:



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HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

Weak evolution:

Makes existence of high-z disks much easier

Disks could form (at least some mass) earlier than z=1

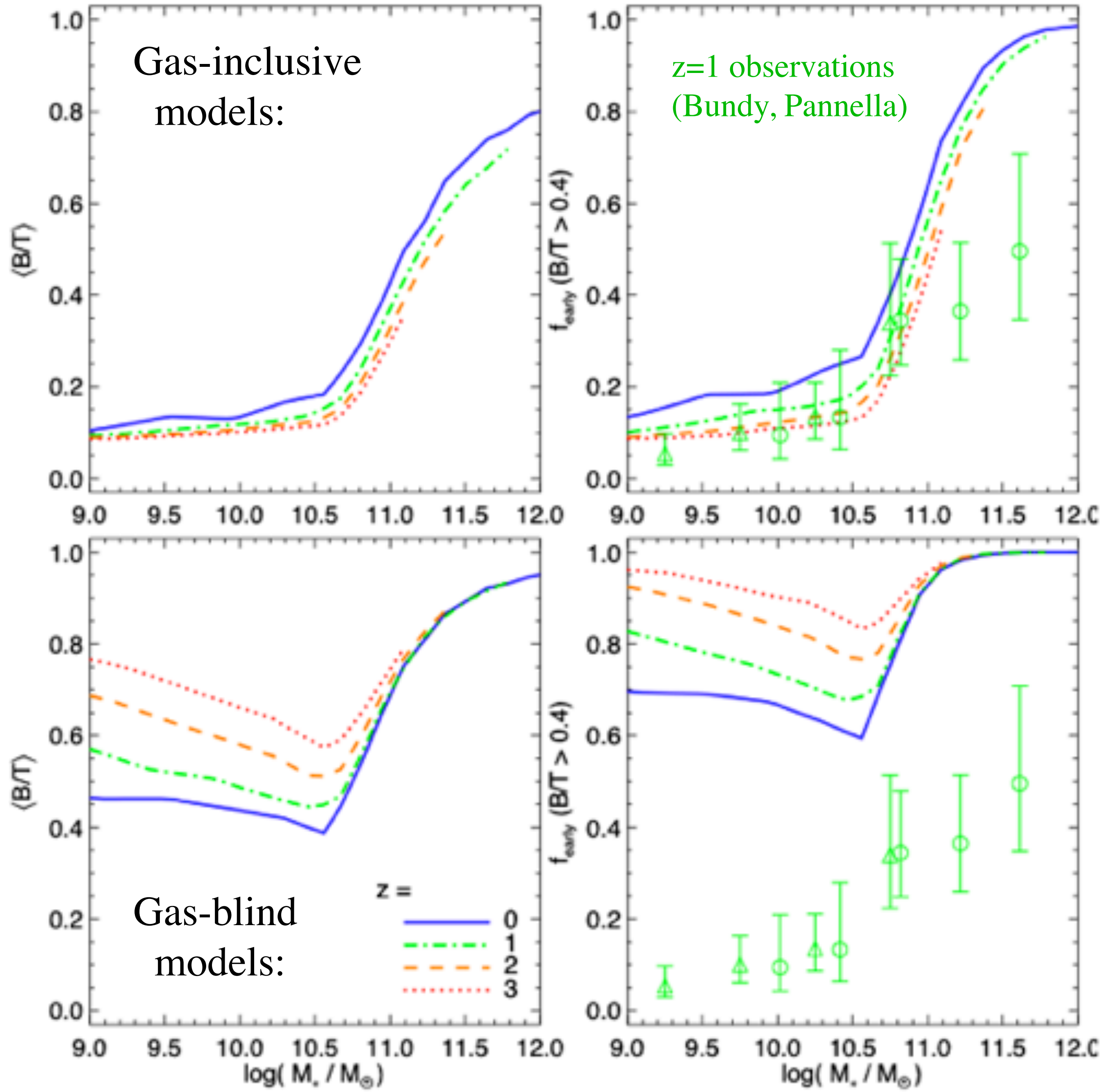
May be seeing this at high redshift:

Hammer et al.

Robertson & Bullock ’08

Shapiro et al.

(turbulent, low V/σ disks)



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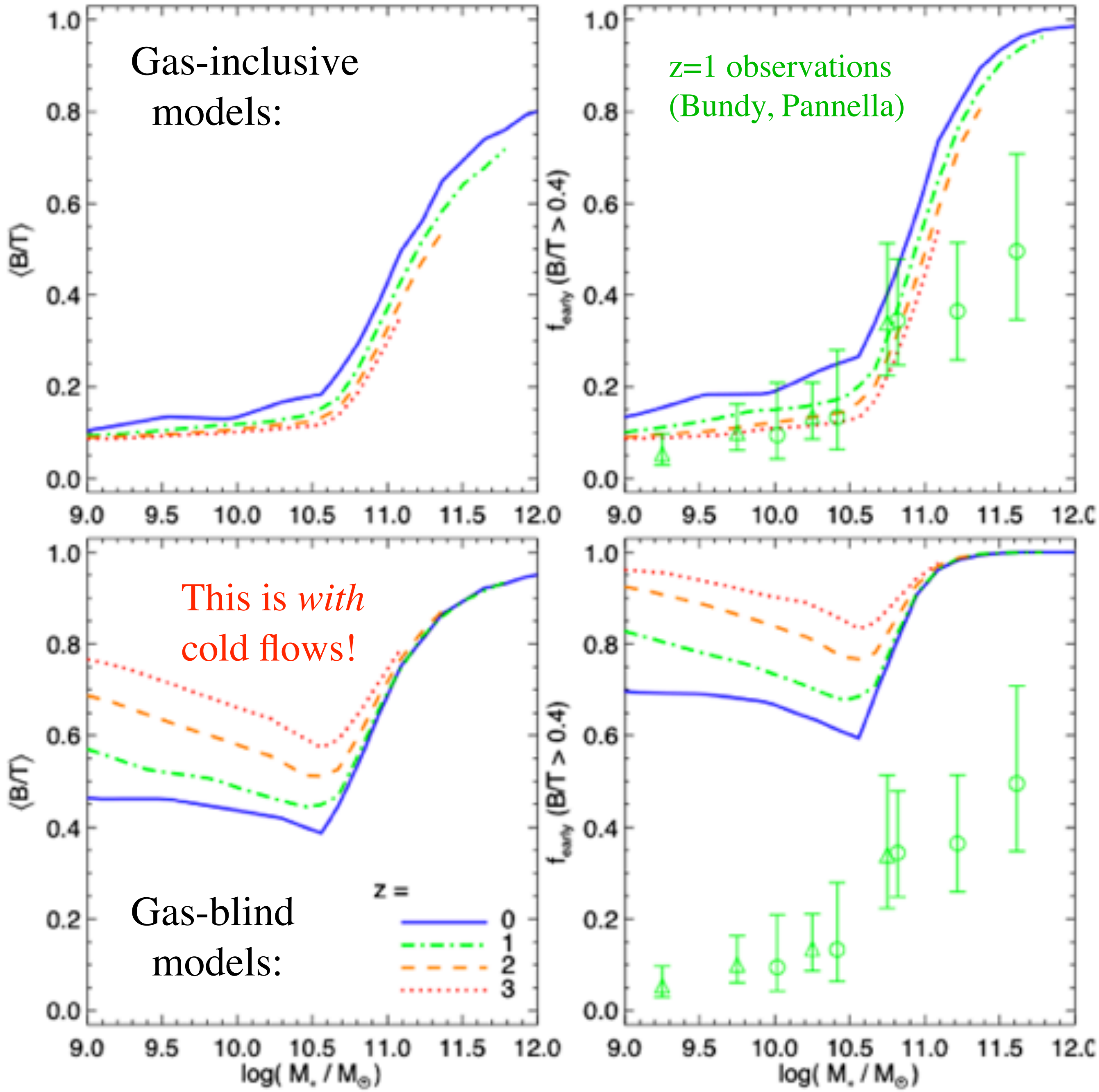

Disk Survival In Mergers

HOW CAN A DISK SURVIVE?

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      - This *will* happen

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- If gas fractions are anything close to what observers tell us...

Disk Survival In Mergers

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  - This is a purely gravitational process:
    - If gas is collisional
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    - And we understand gravity
      - This *will* happen
- If gas fractions are anything close to what observers tell us...
  - This *is* very important for bulge formation

What about the gas that *does* lose angular momentum?

What About the Gas that Does Lose Angular Momentum?

CAN WE MAKE A REAL ELLIPTICAL?

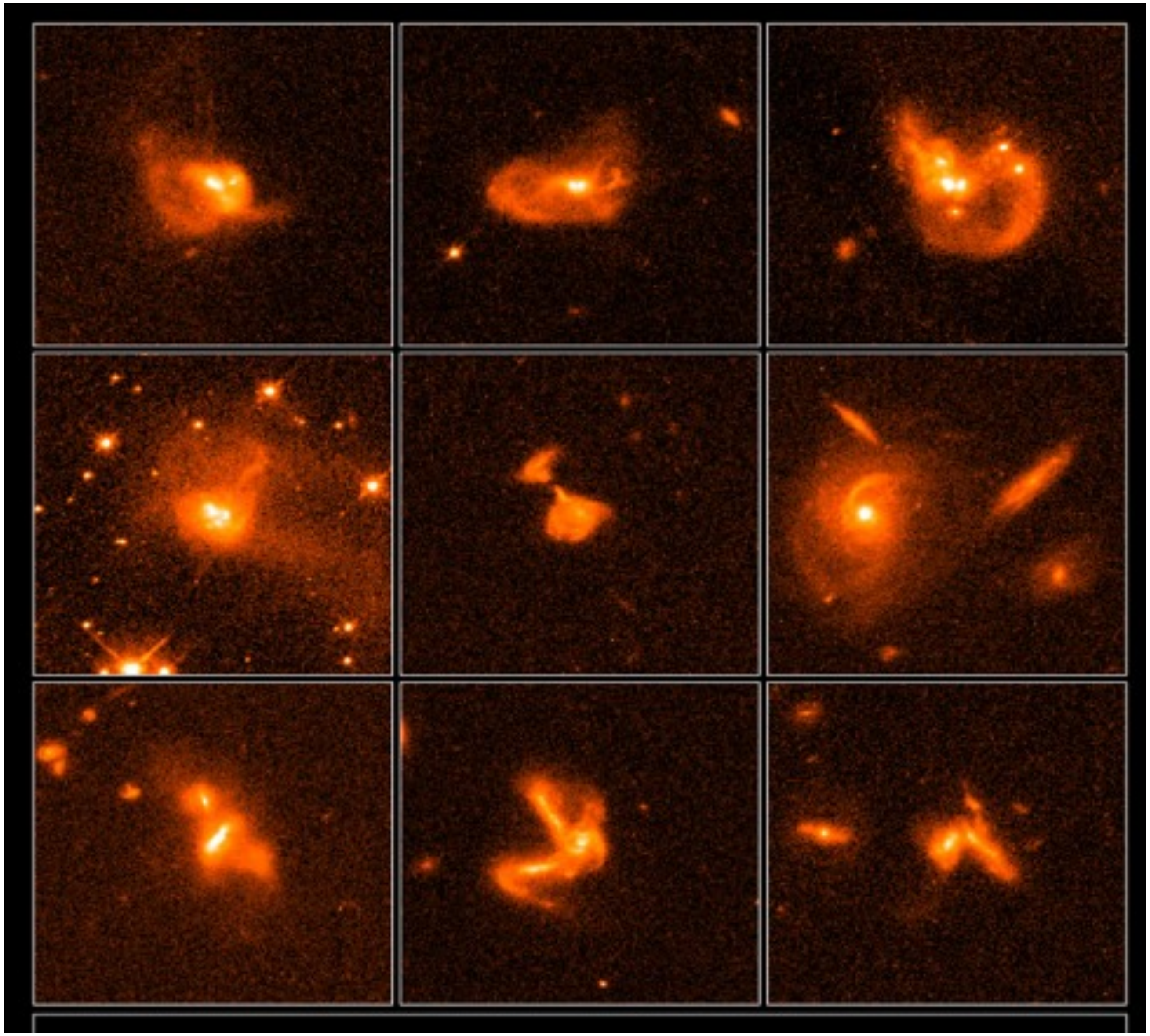
Borne et al., 2000

Funneled to the center
-> massive starbursts

Look at late-stage
merger remnants

Bright ULIRGs make
stars at a rate of
$>100\ M_{sun}$/yr.

Compact (<kpc scales)



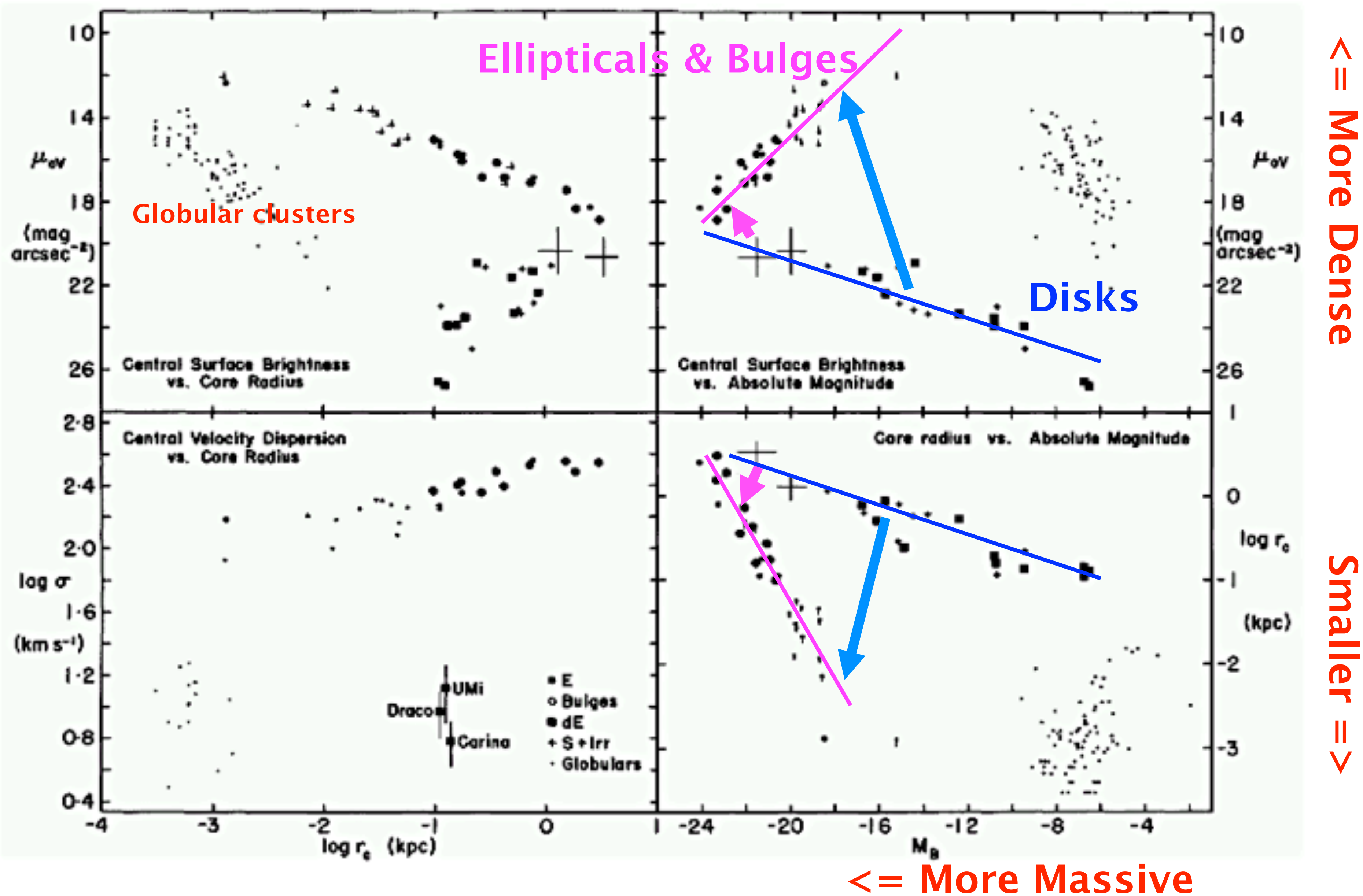
Most luminous starbursts in the Universe:
are they the progenitors of ellipticals?

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

Ellipticals are much more dense than spirals of the same mass:

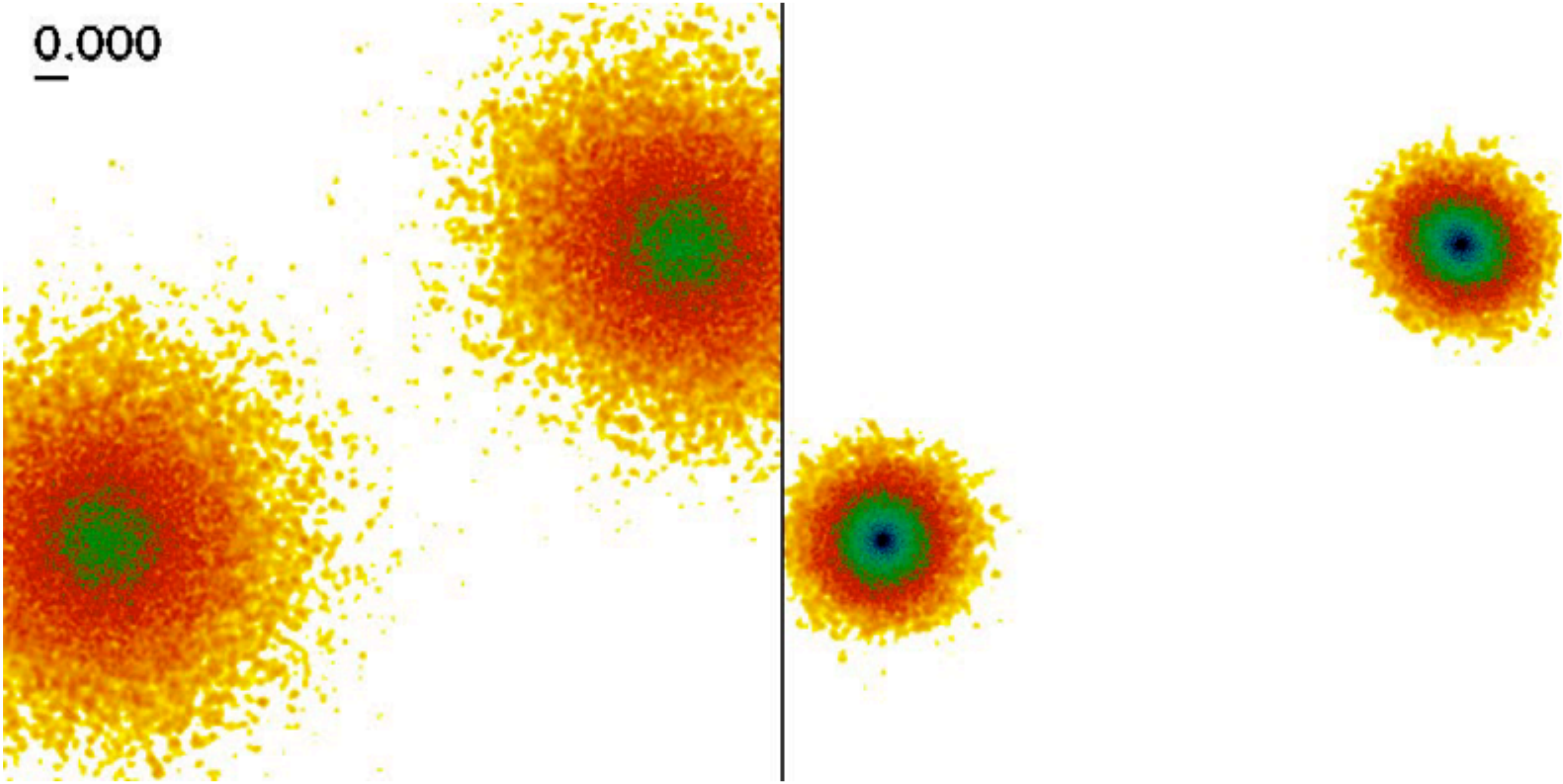
Kormendy (1985)



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

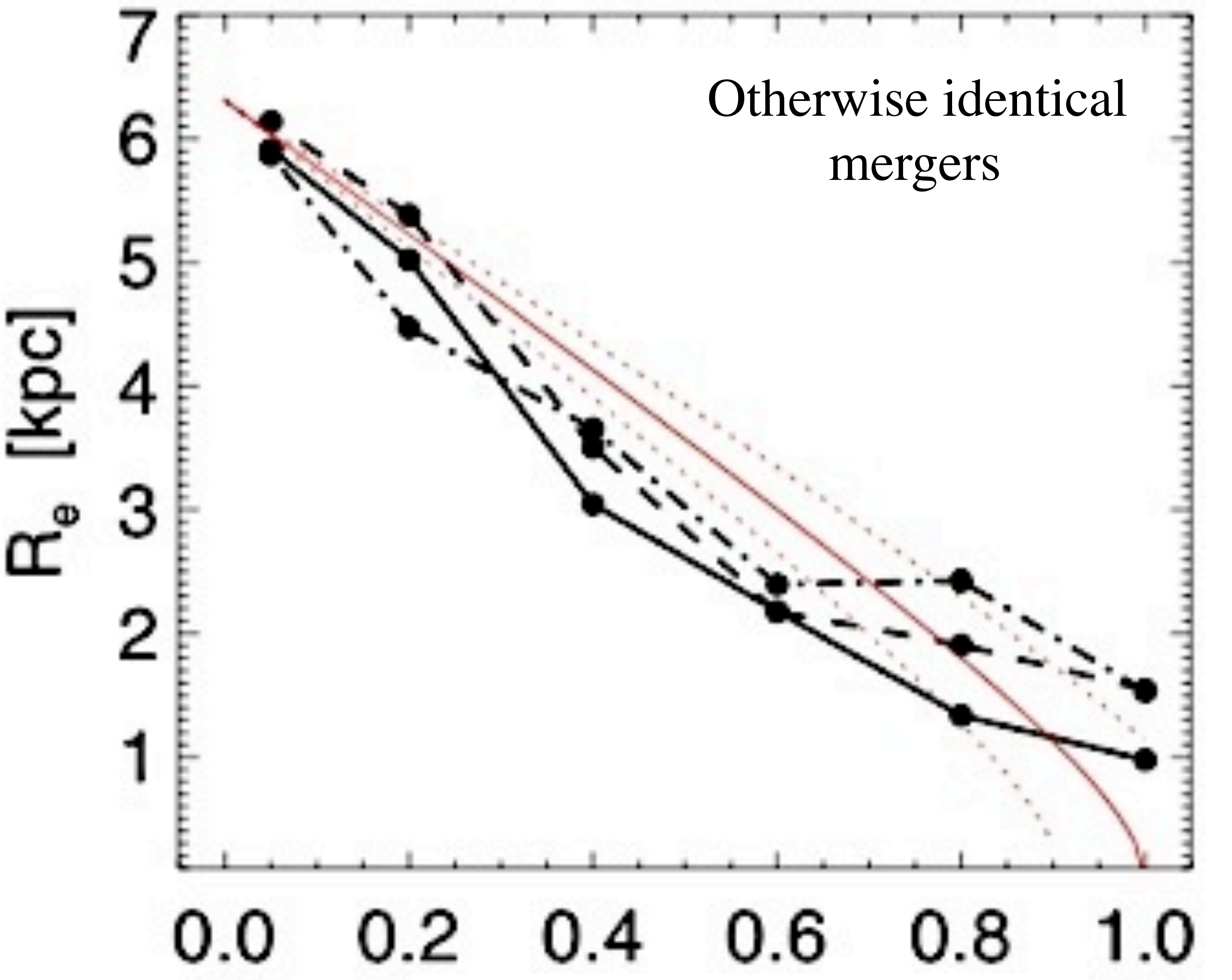
- Why are ellipticals so much smaller than disks?
  Gas dissipation allows them to collapse to small scales!



The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

- Increased dissipation→smaller, more compact remnants (Cox; Robertson; Khochfar; Naab)

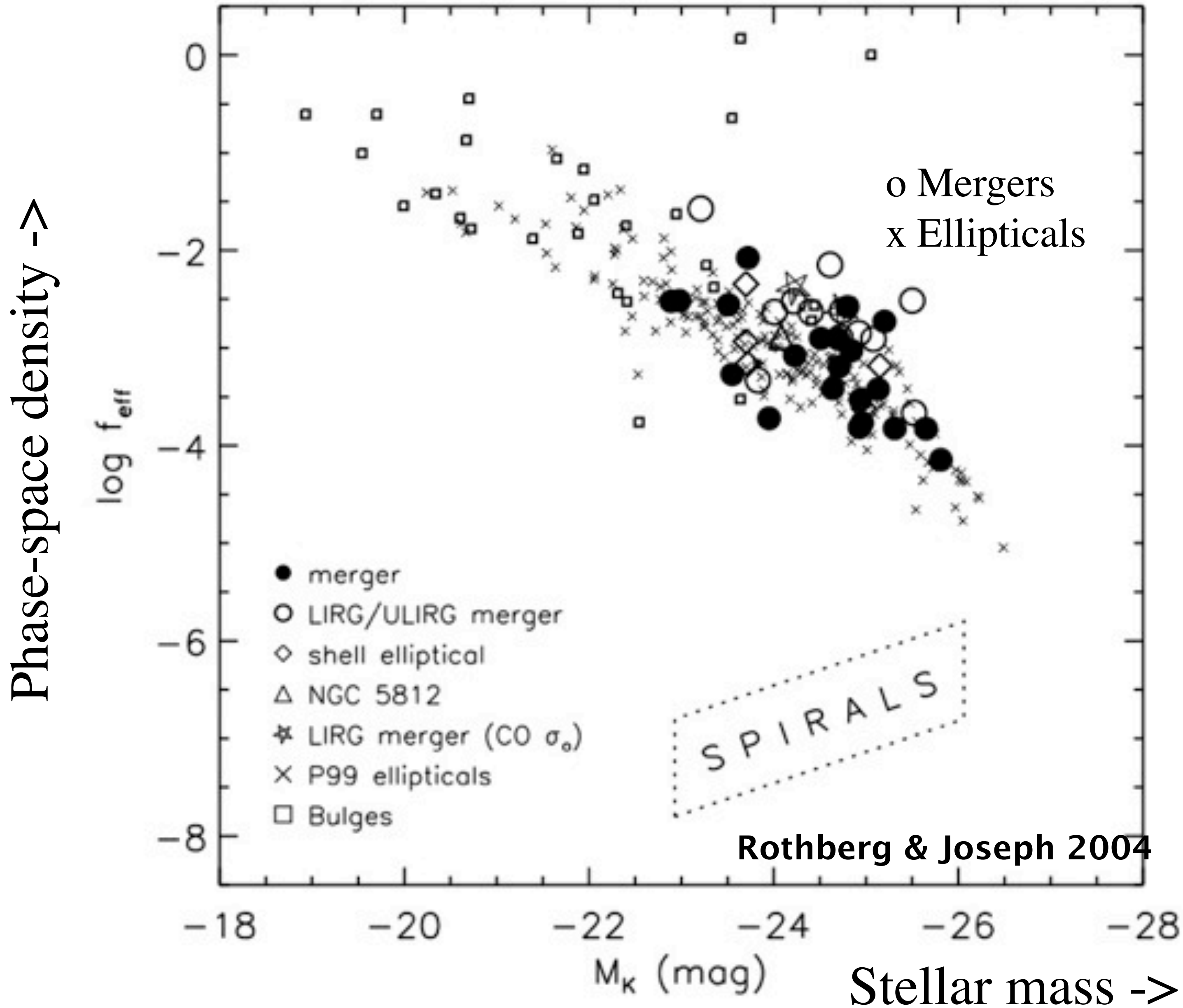


Bulge mass fraction formed in bursts (versus violently relaxed from disks)

The Solution: Gas Dissipation?

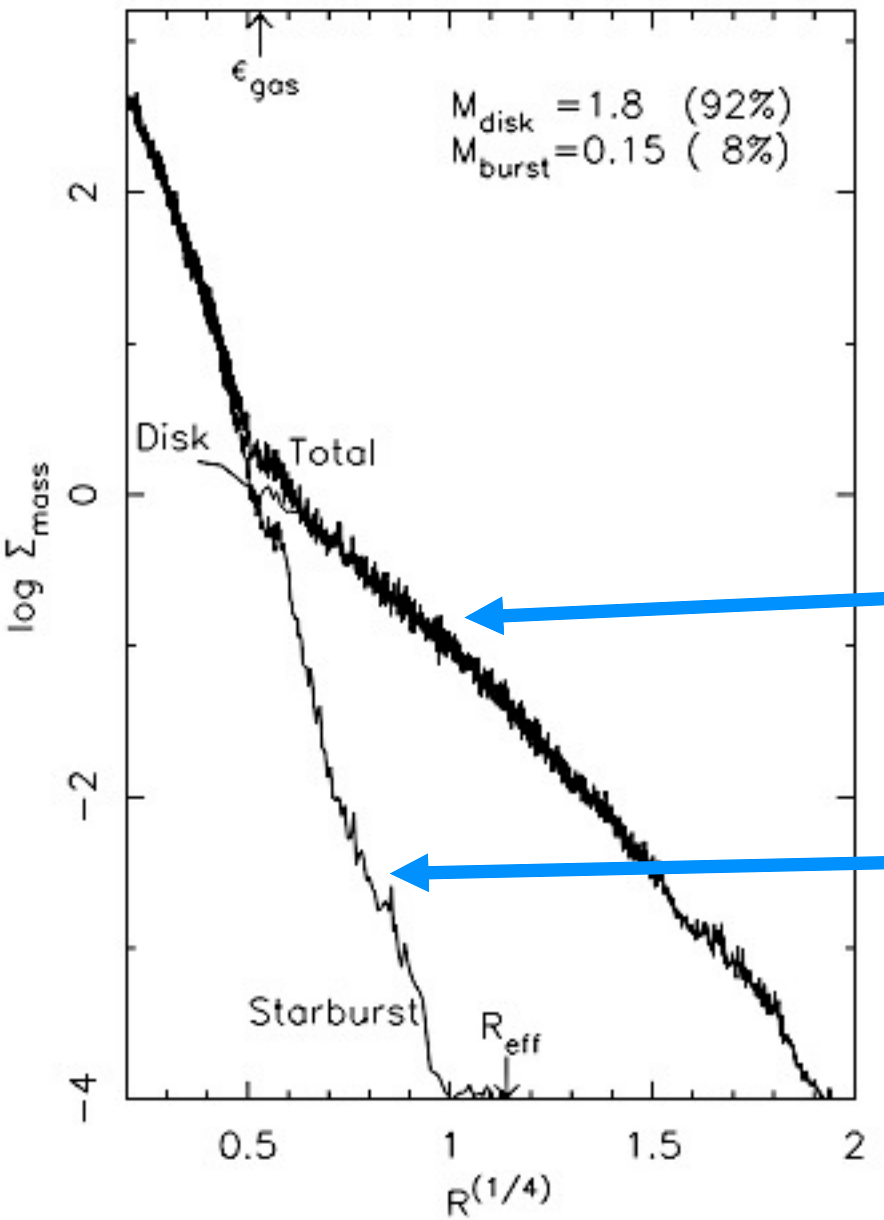
COMPARE WITH OBSERVED RECENT GAS-RICH MERGER REMNANTS

- Mergers *have* solved this problem: we just need to understand it



Starburst Stars in Simulations Leave an "Imprint" on the Profile

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS



Mihos & Hernquist 1994:

Merger remnant elliptical profiles should be fundamentally two-component:

Pre-starburst/Disk (dissipationless, violently relaxed)

Starburst (dissipational, no strong violent relaxation)

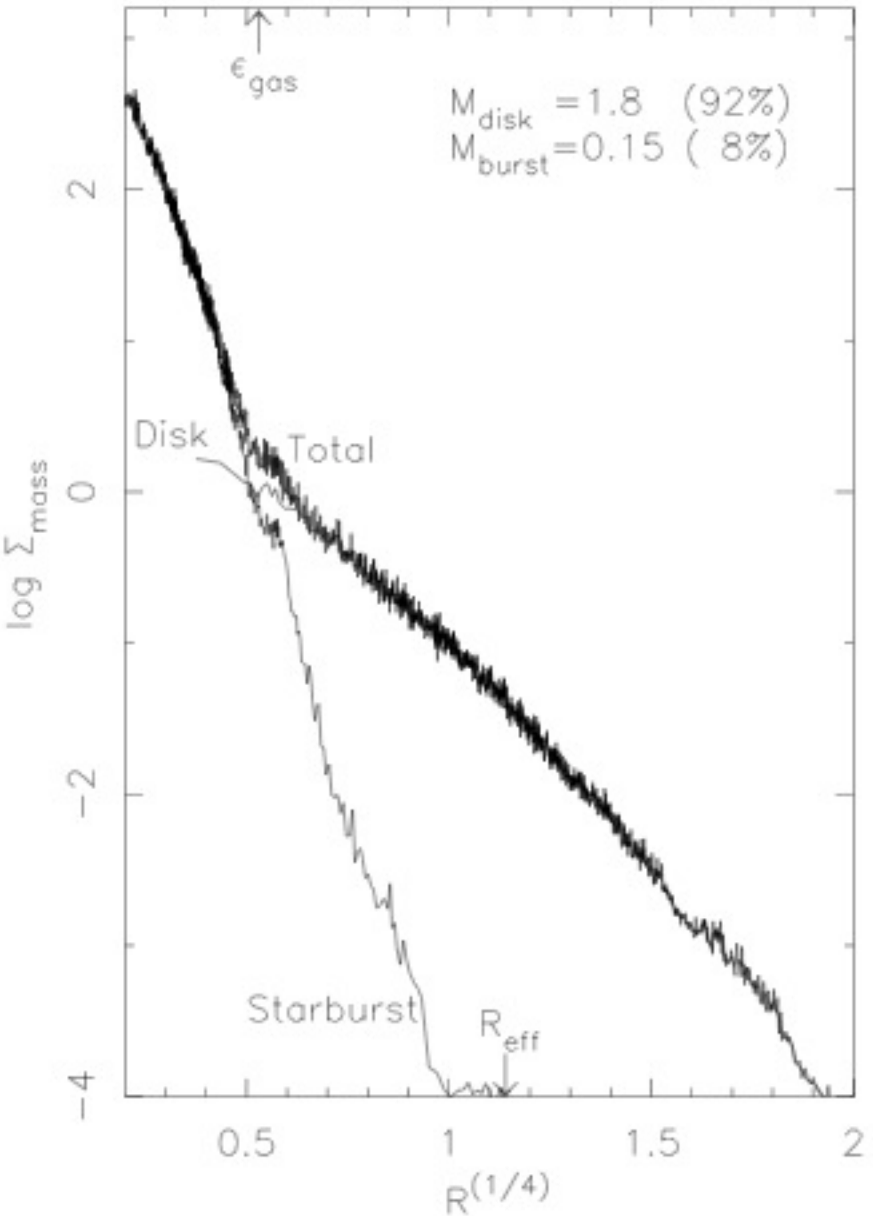
Not observed at the time:

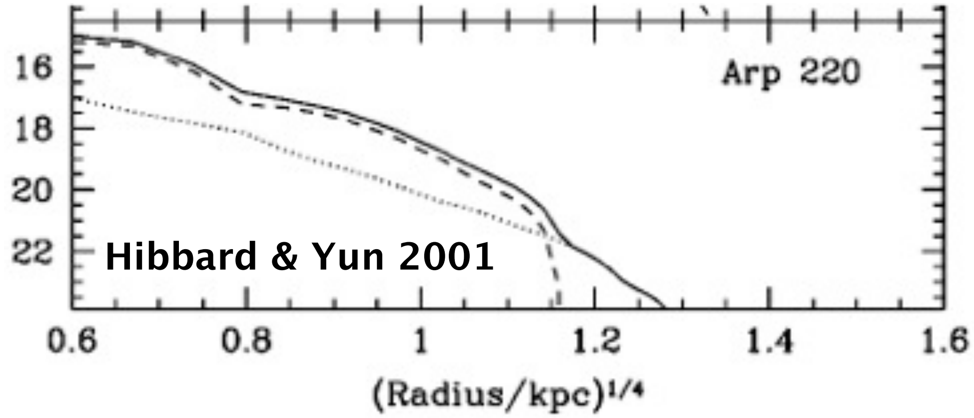
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

Starburst Stars in Simulations Leave an “Imprint” on the Profile

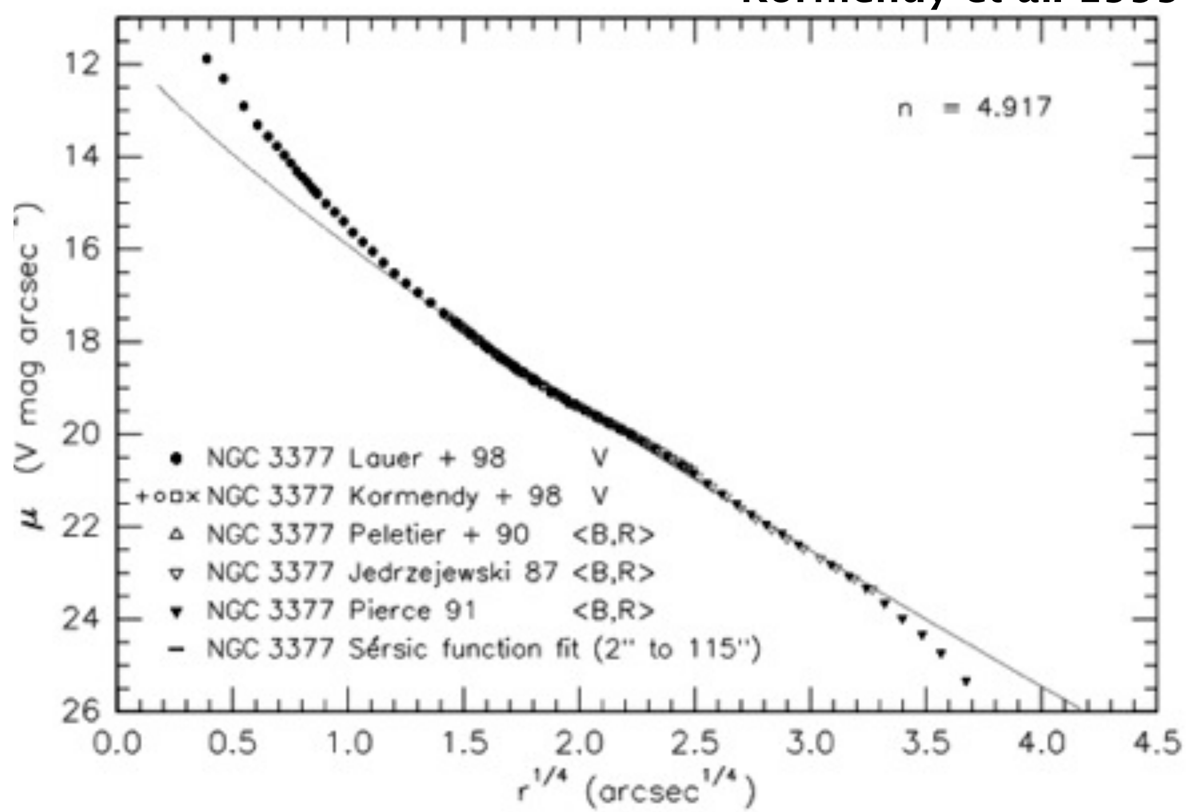
RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

- Since then...





Kormendy et al. 1999

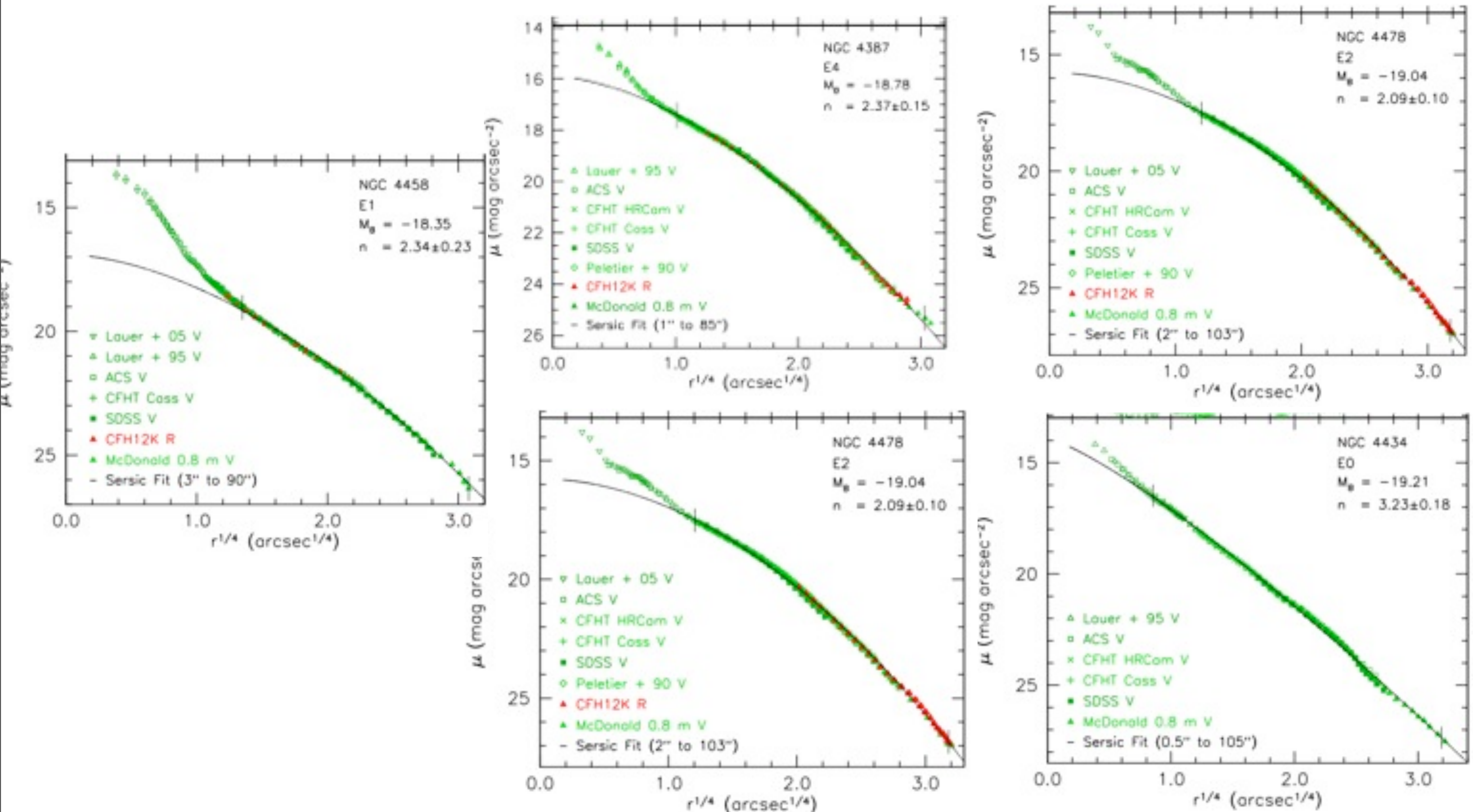


Starburst Stars in Simulations Leave an "Imprint" on the Profile

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

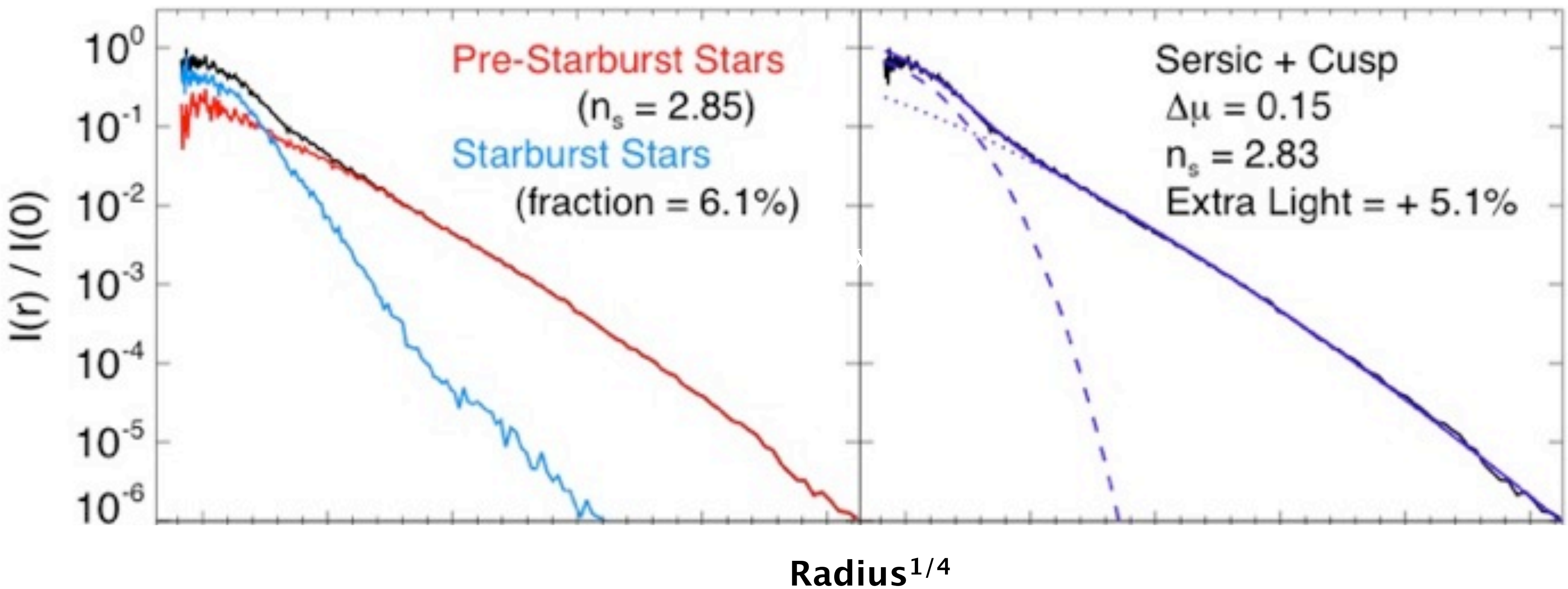
- Since then...

Kormendy et al. 2008

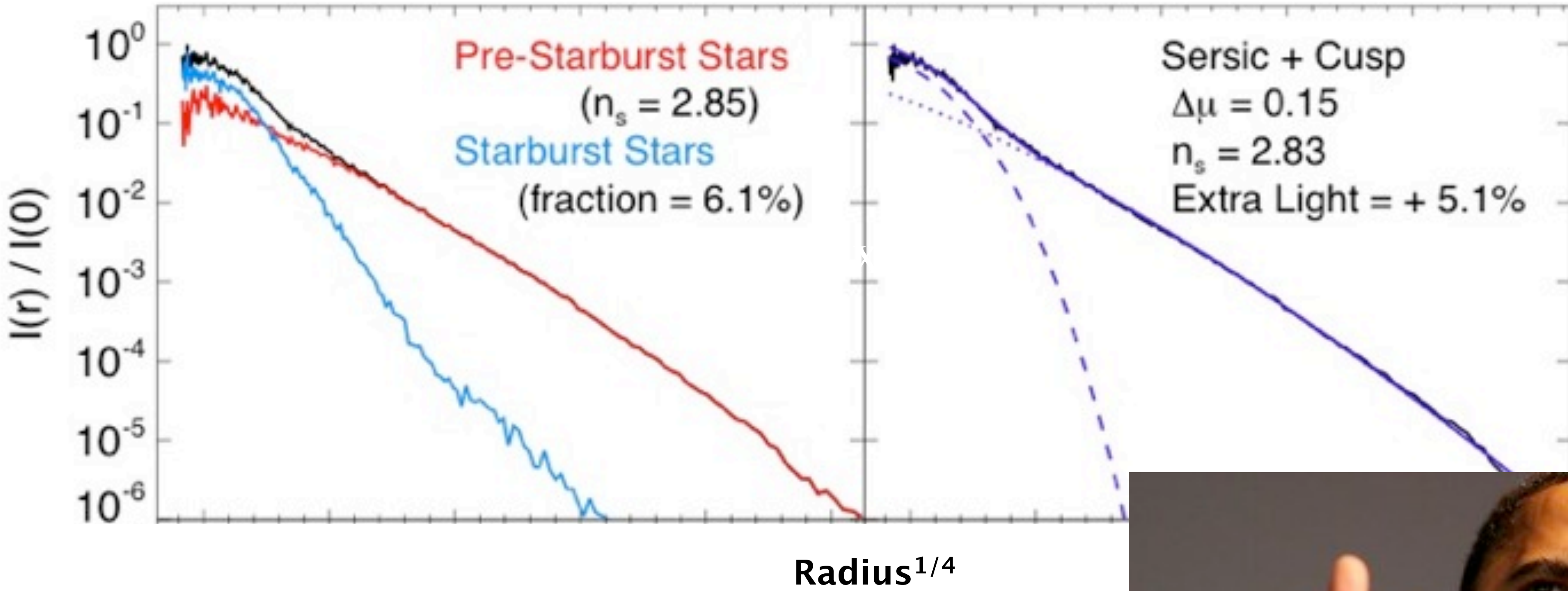


"Normal and low-luminosity ellipticals... in fact, have *extra*, not missing light at at small radii with respect to the inward extrapolation of their outer Sersic profiles."

Q: Can we design a decomposition that separates disk/starburst stars in the final profile?



Q: Can we design a decomposition that separates disk/starburst stars in the final profile?



A: Yes we can

(Kormendy et al.; Balcells et al.)

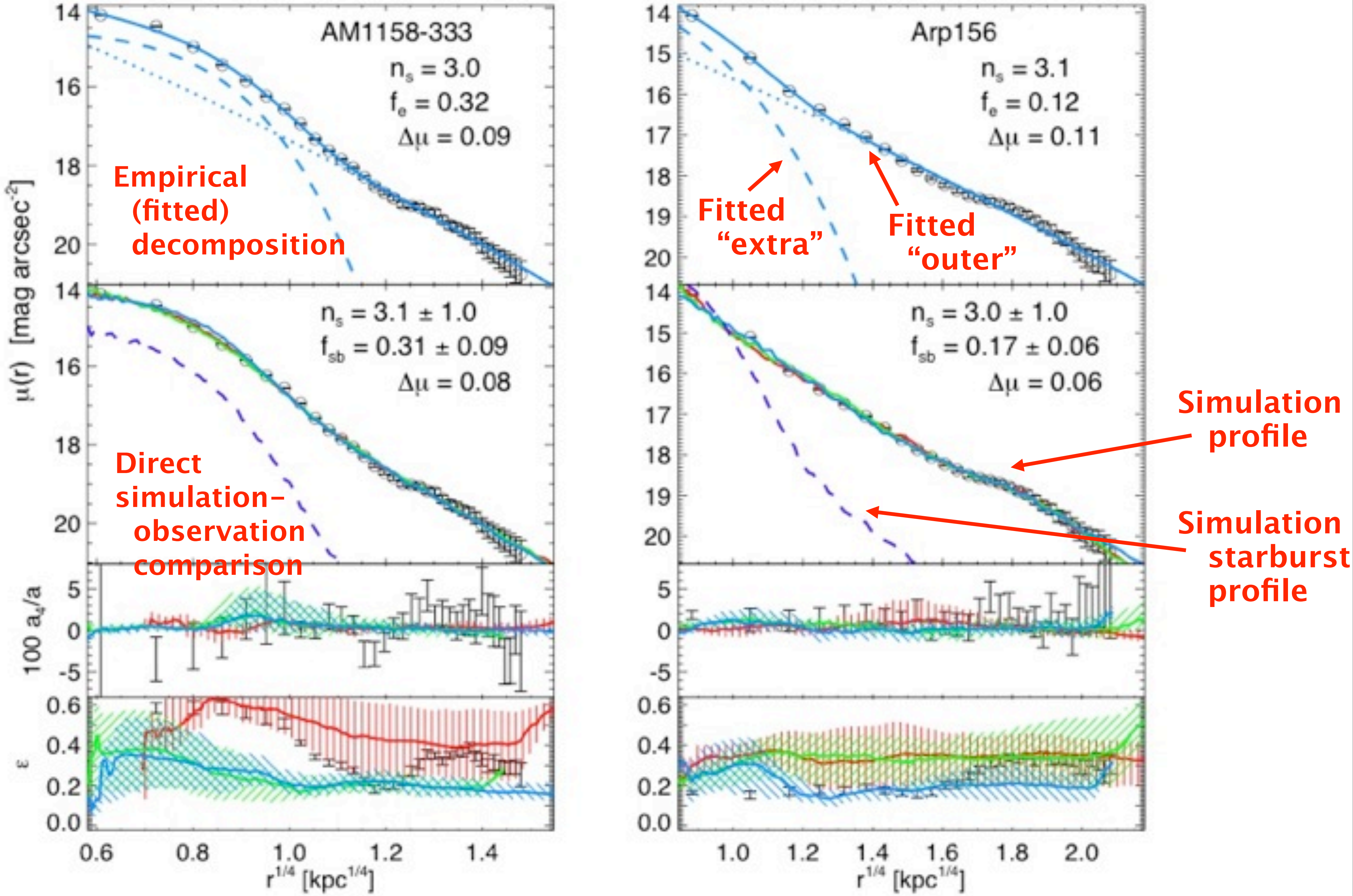
Application: Merger Remnants

RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008

- Apply this to a well-studied sample of local merger remnants & ellipticals:



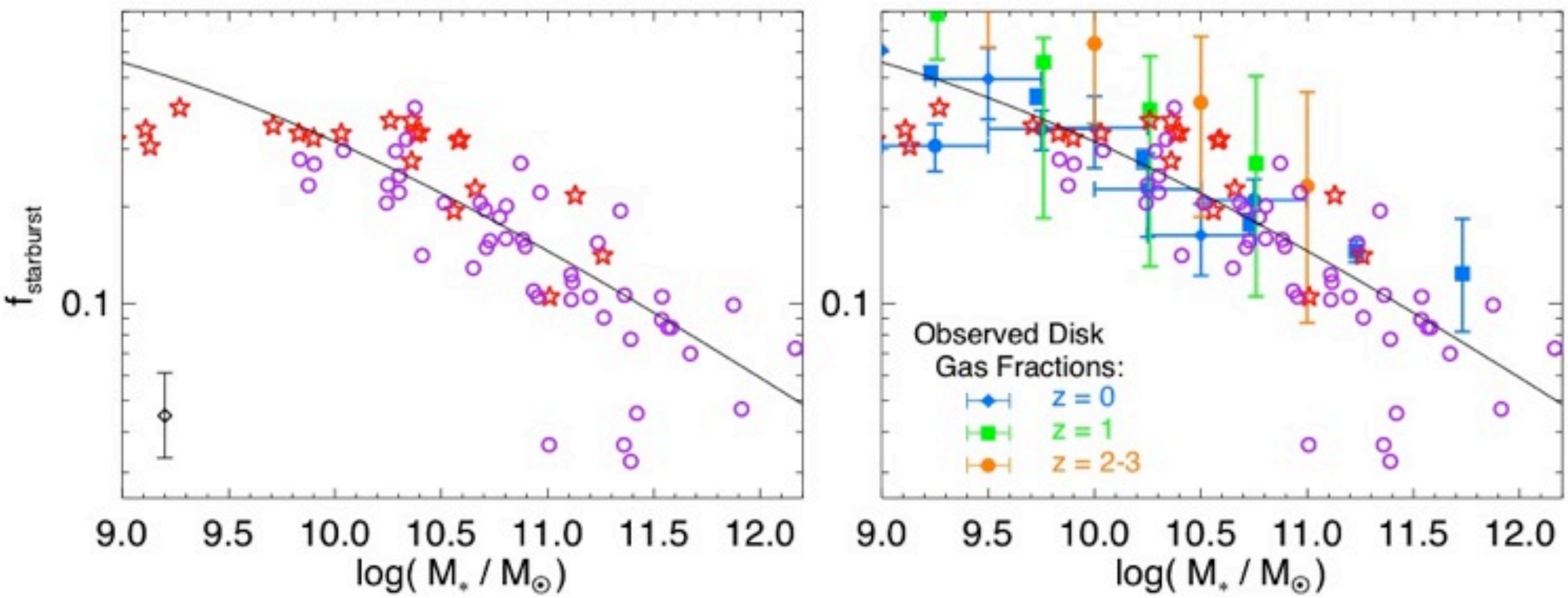
Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008

Starburst gas mass needed to match observed profile (or fitted to profile shape):

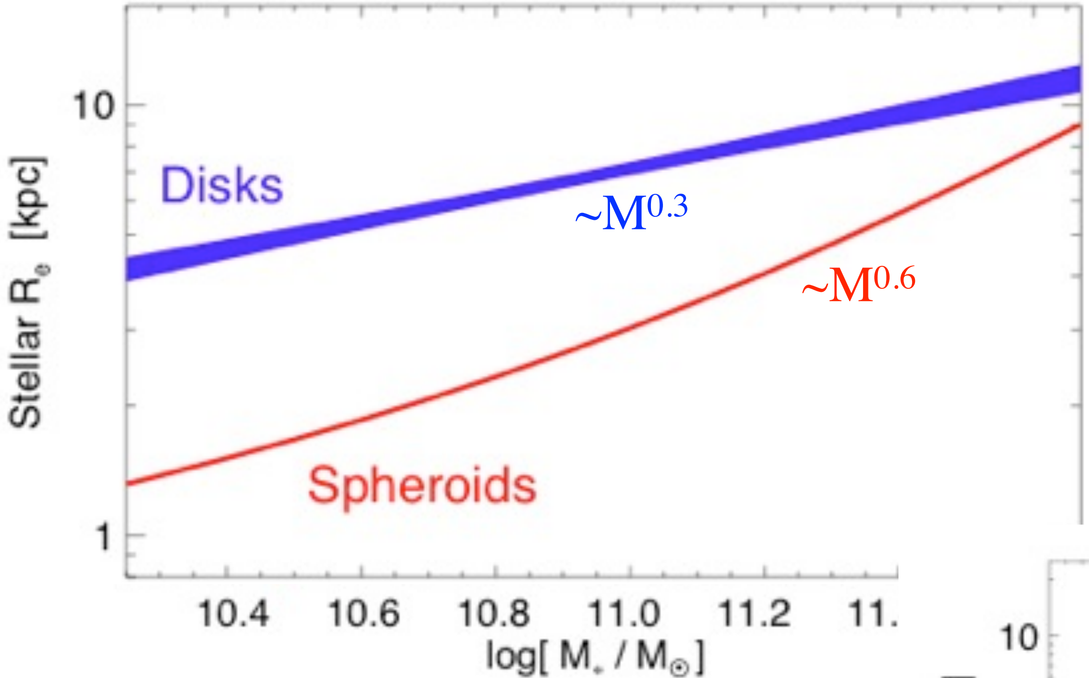


- You can and *do* get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns (e.g. Graves talk)

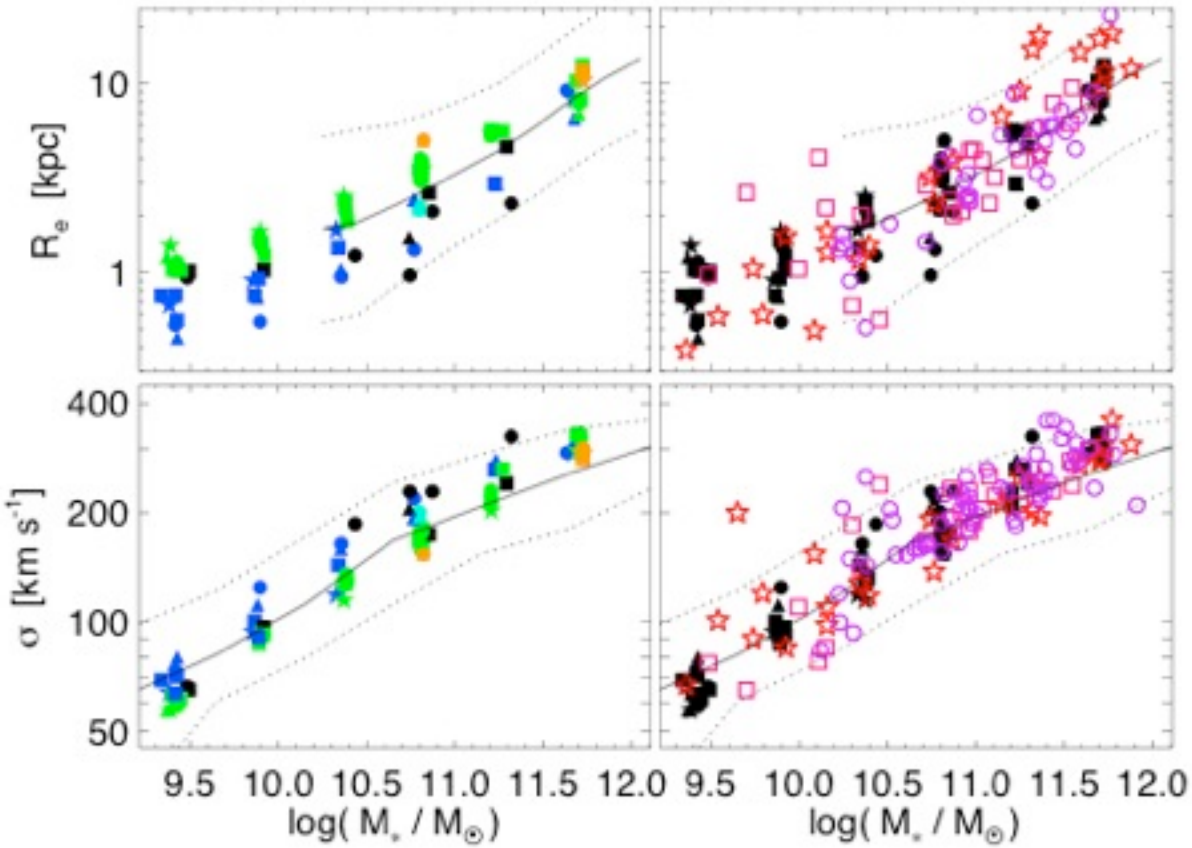
Structure in Elliptical Light Profiles

PFH, Cox, & Hernquist 2008

THE ROLE OF GAS IN THE SIZE-MASS RELATION



- Recall, low-M ellipticals are more compact than disks of similar mass

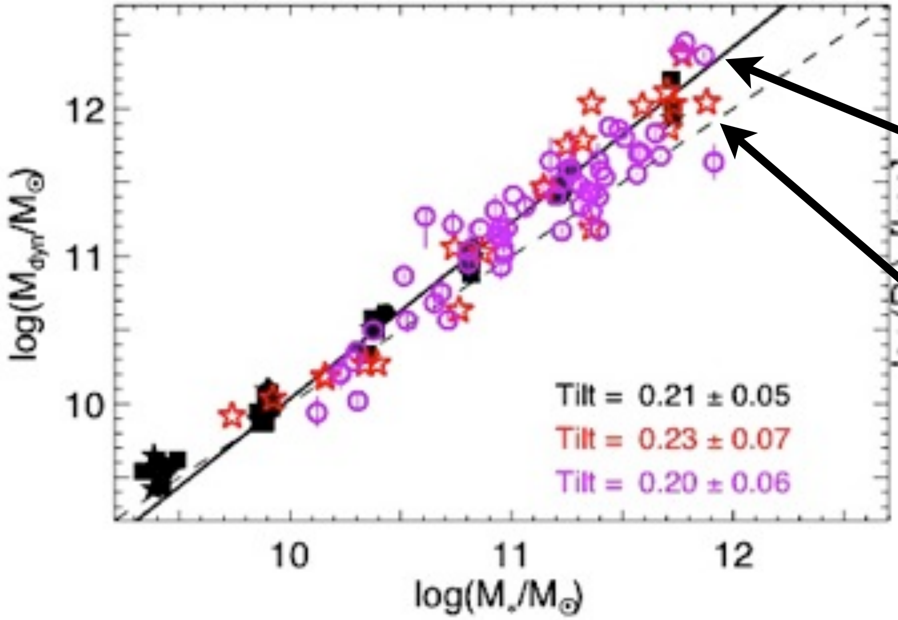


- Include effects of gas: reproduce fundamental plane, sizes, etc. of ellipticals

Fundamental Plane Tilt

WHERE DOES IT COME FROM?

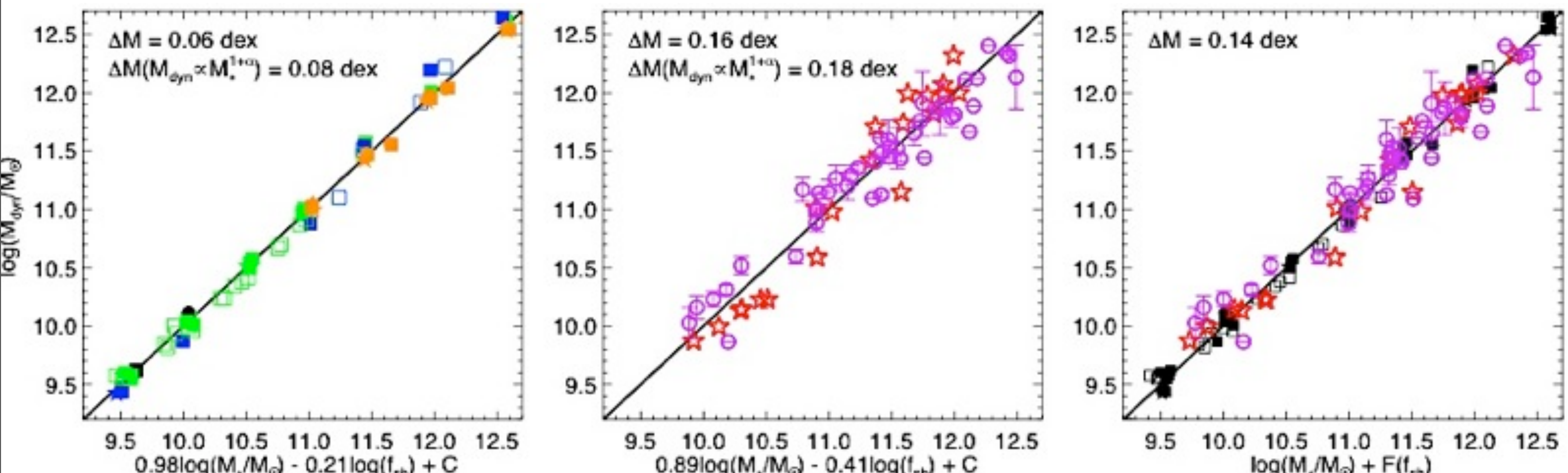
- Simulate just galaxies on observed f_{gas}-$M_{stellar}$ relation:
    - Observed FP!



Observed FP:
$M_{dyn} / M_{stellar} \sim M^{0.2}$

Relation without gas:
$M_{dyn} / M_{stellar} = \text{constant}$

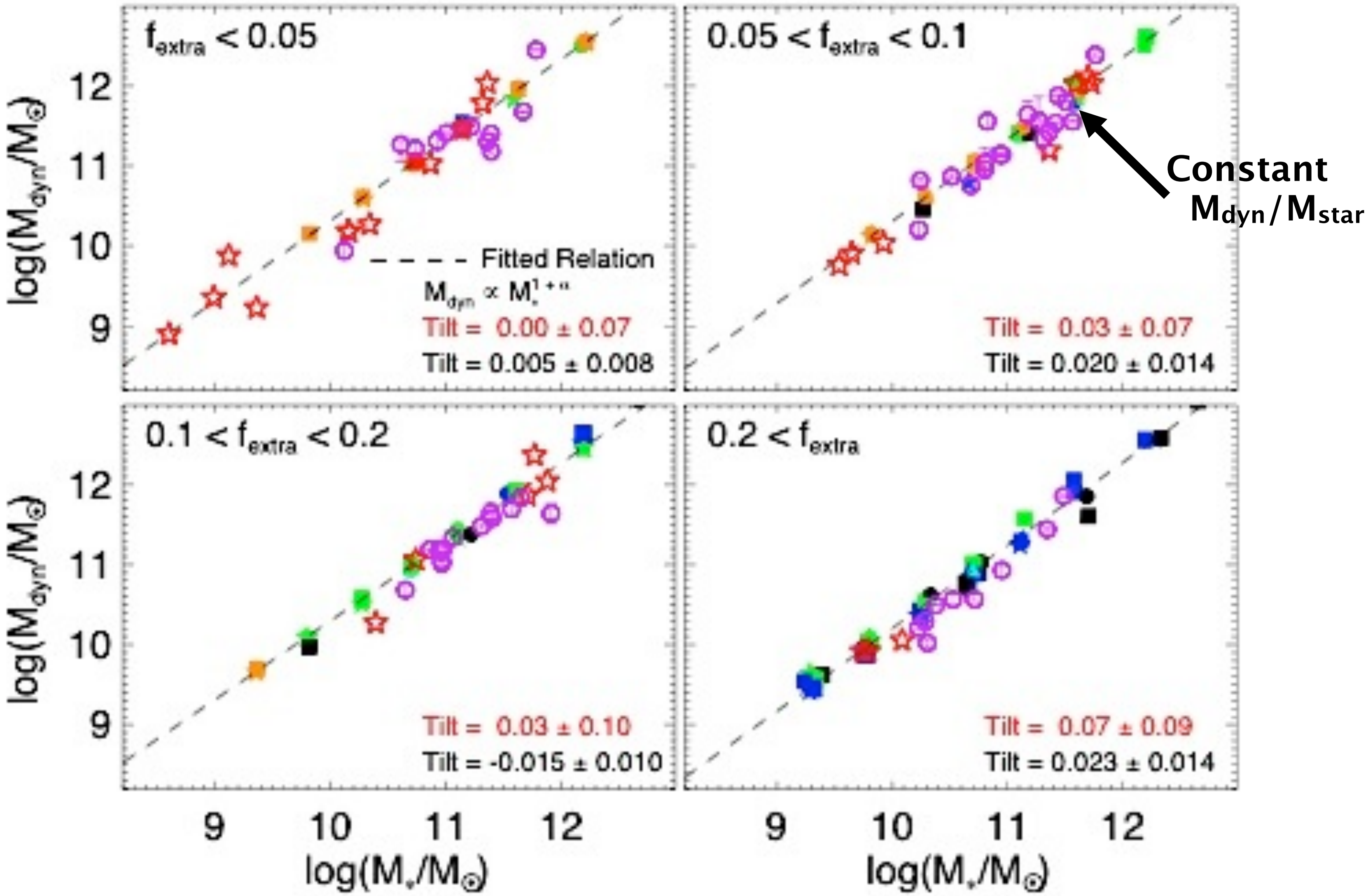
- Having some f_starburst for each observed system, can we factor it out?
  Yes: FP can be physically restated as $M_{dyn} \sim M_{stellar} \times F(f_{dissipational})$



Fundamental Plane Tilt

WHERE DOES IT COME FROM?

- Go further: is there any FP 'tilt' left if we just consider systems with the same amount of dissipation?



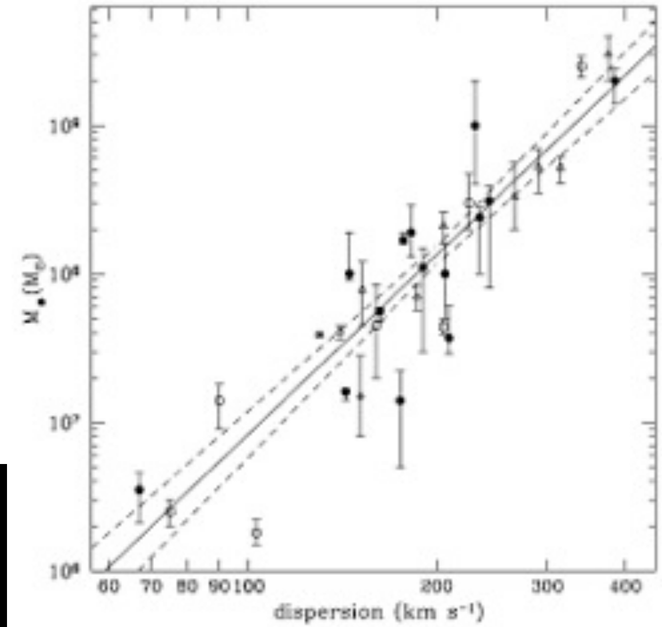
- At FIXED $f_{dissipational}$, there is NO TILT: look just like disks on these correlations!
  - Same for size-mass and other bulge correlations: without dissipation, follow disks

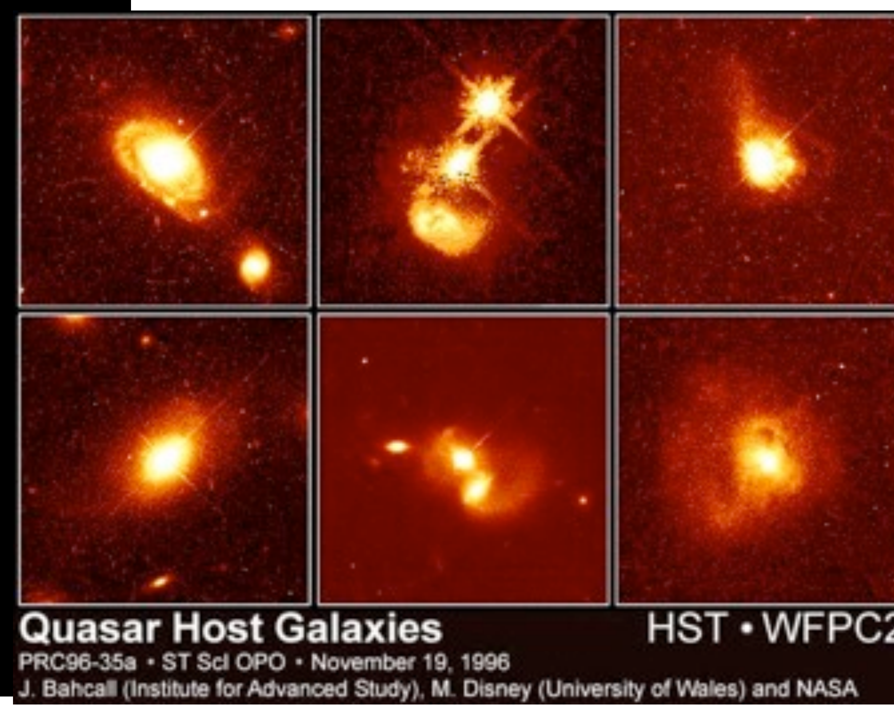
With all this gas getting to the center of the galaxy, what is the black hole doing?

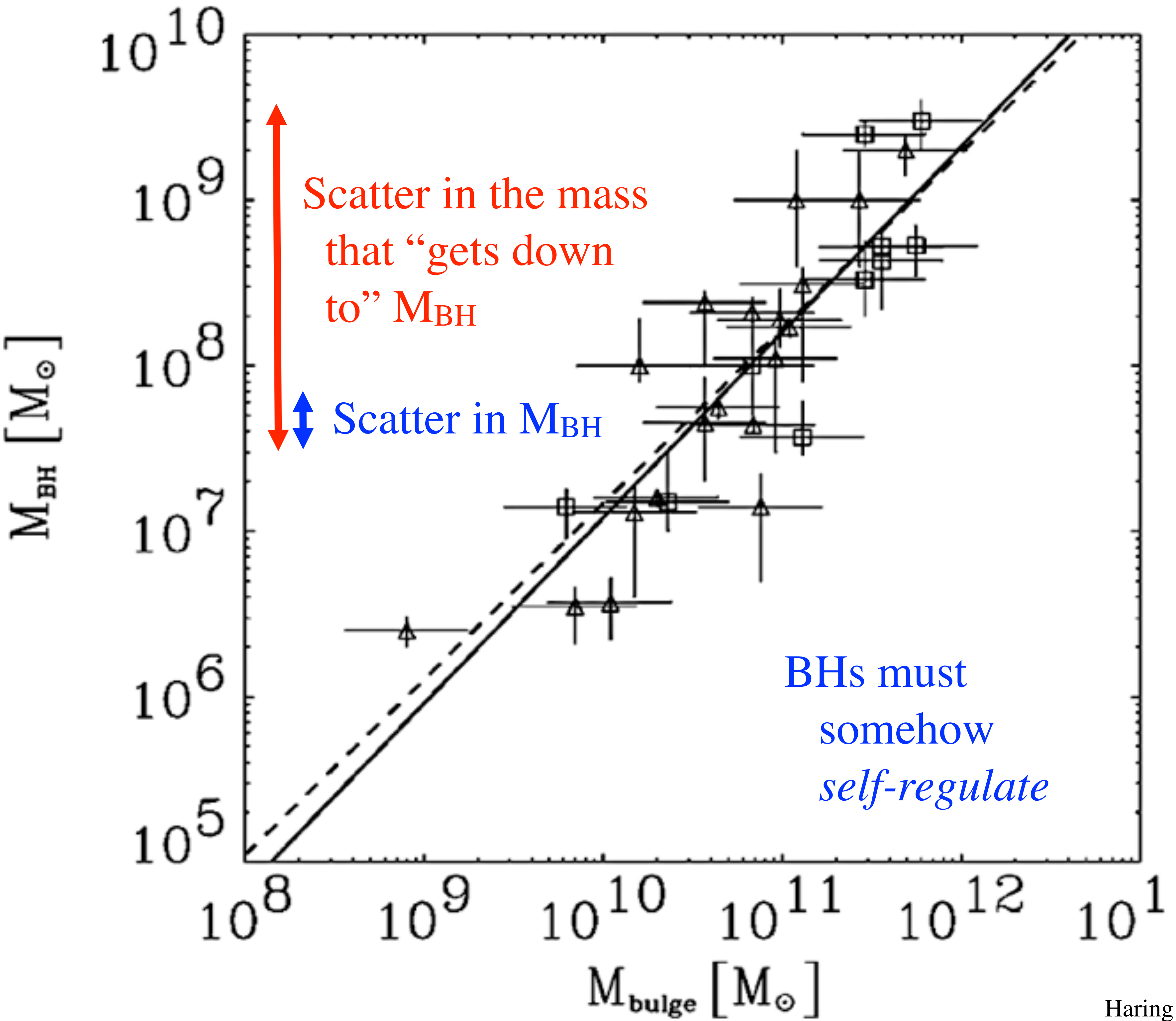
Triggering & Fueling: “Feeding the Monster”

WHAT CAN BREAK DEGENERACIES IN DIFFERENT FUELING MODELS?

- If BHs trace spheroids, then
  most mass added in mergers







Haring & Rix '04

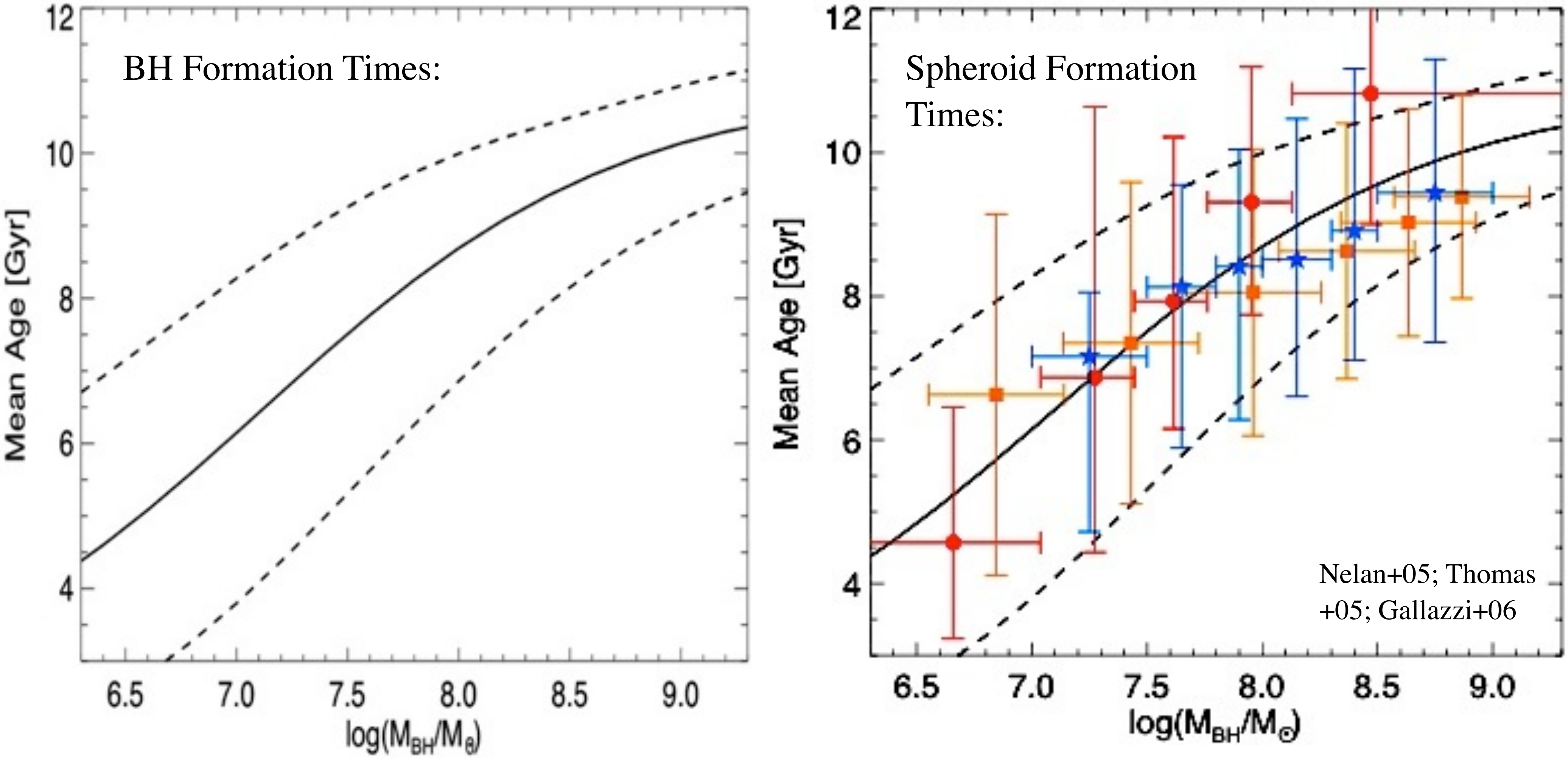
Simplest Idea:

FEEDBACK ENERGY BALANCE (SILK & REES '98)

- Luminous accretion disk near the Eddington limit radiates an energy:
  - $L = e_r\ (dM_{BH}/dt)\ c^2 \quad (e_r \sim 0.1)$
- 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:
  - $\sim M_{gal}\ s^2 \sim (10^{11}\ \mathrm{Msun})\ (200\ \mathrm{km/s})^2 \sim 10^{59}$ 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
    - $MBH \sim (a/he_r)\ M_{gal}\ (s/c)^2 \sim 0.002\ M_{gal}$

Feedback, you say? What can it do for me?

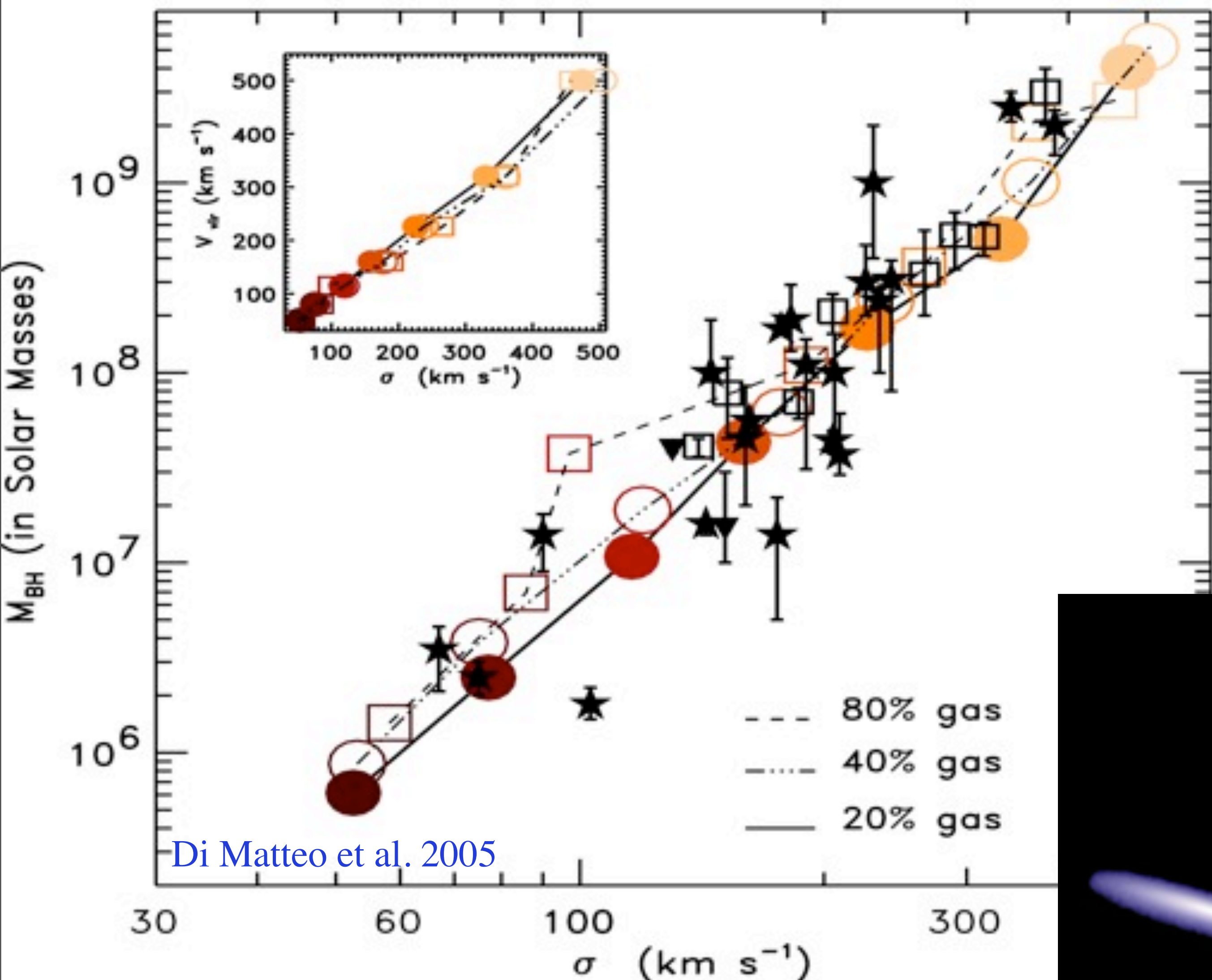
- Quasars were active/BHs formed when SF shut down...

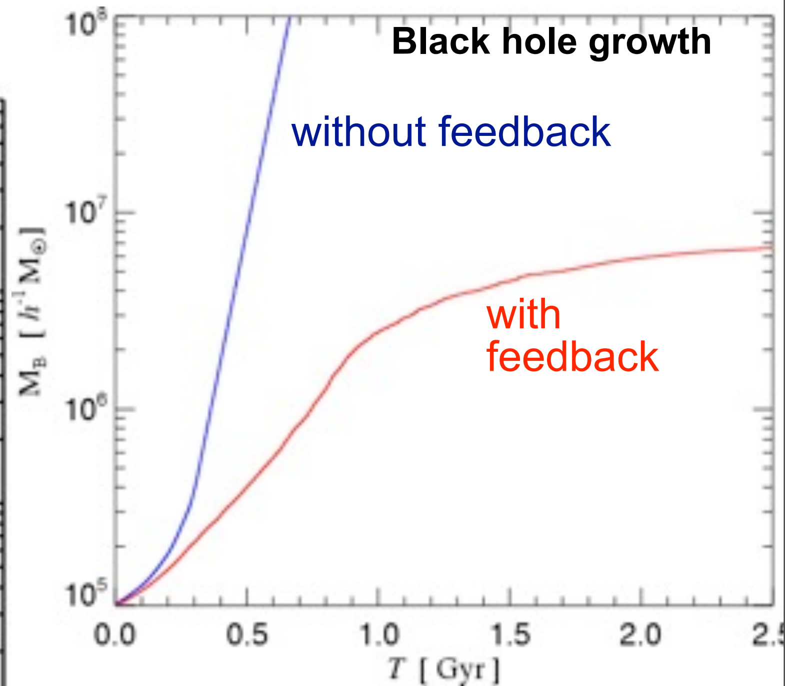


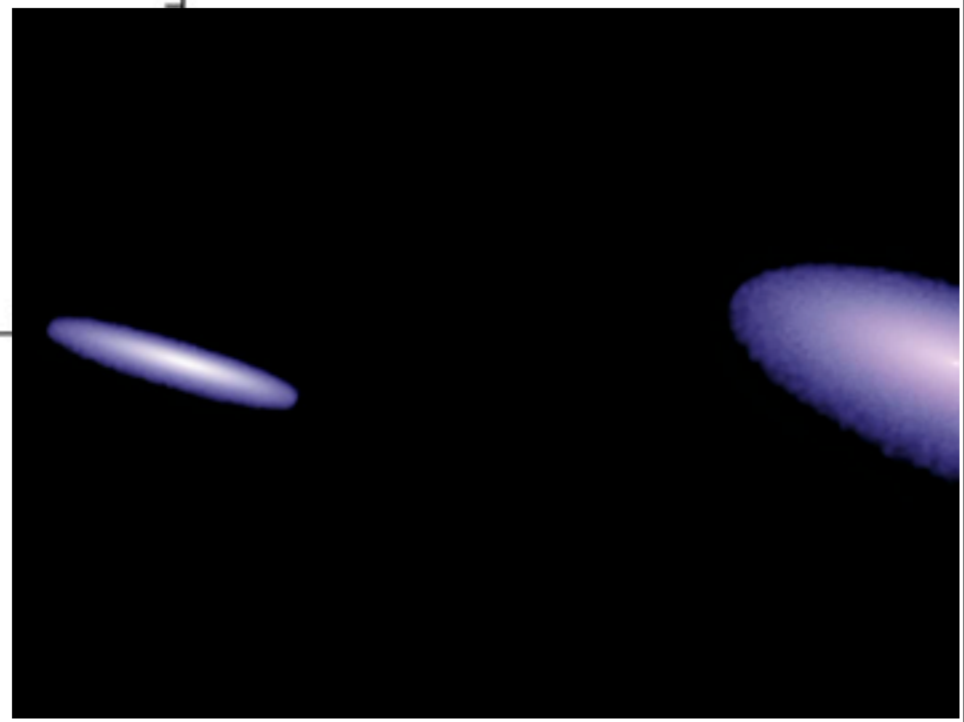
PFH, Lidz, Coil, Myers, et al. 2007

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

PREVENTS RUNAWAY BLACK HOLE GROWTH



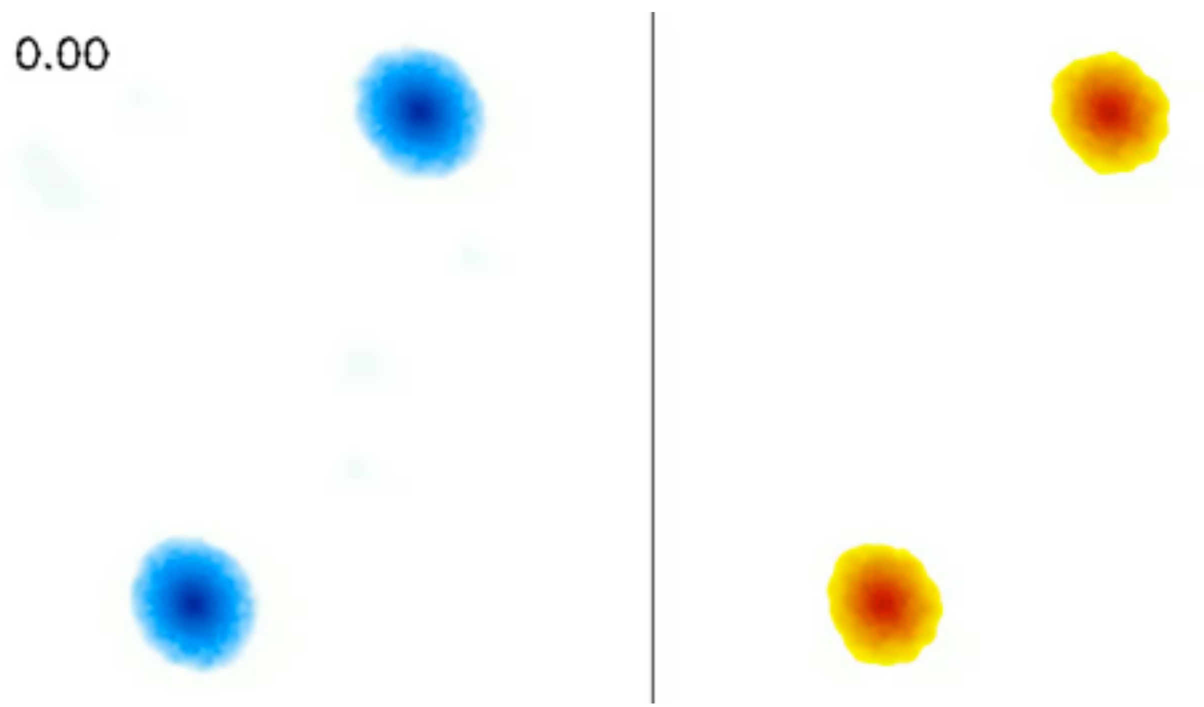


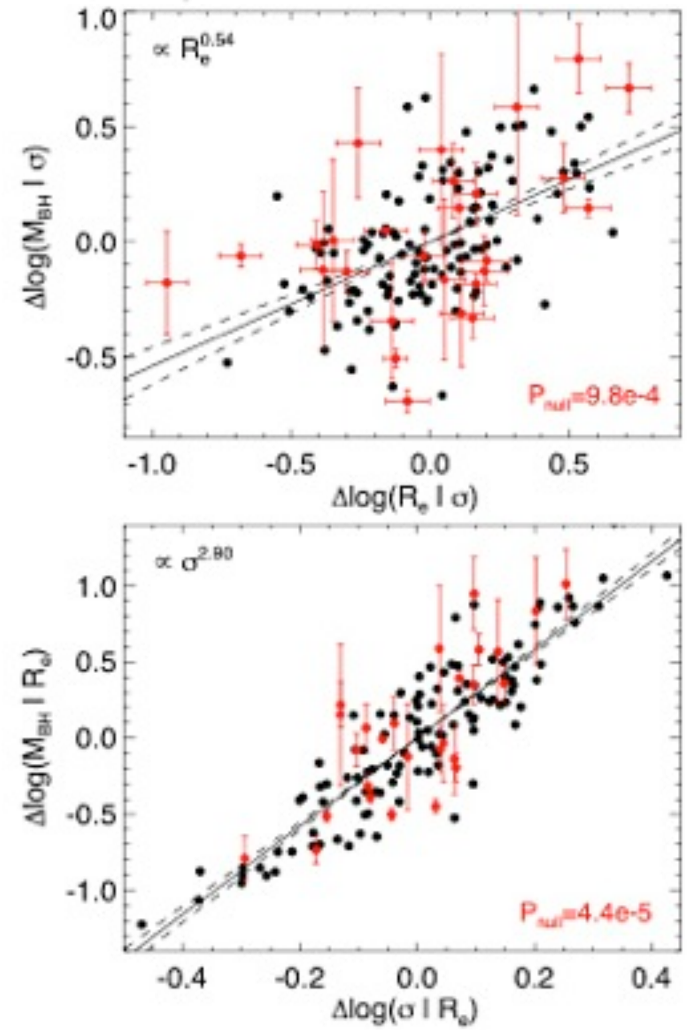


Observations & Simulations Suggest this Simple Picture Works

MAKES UNIQUE PREDICTIONS:

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



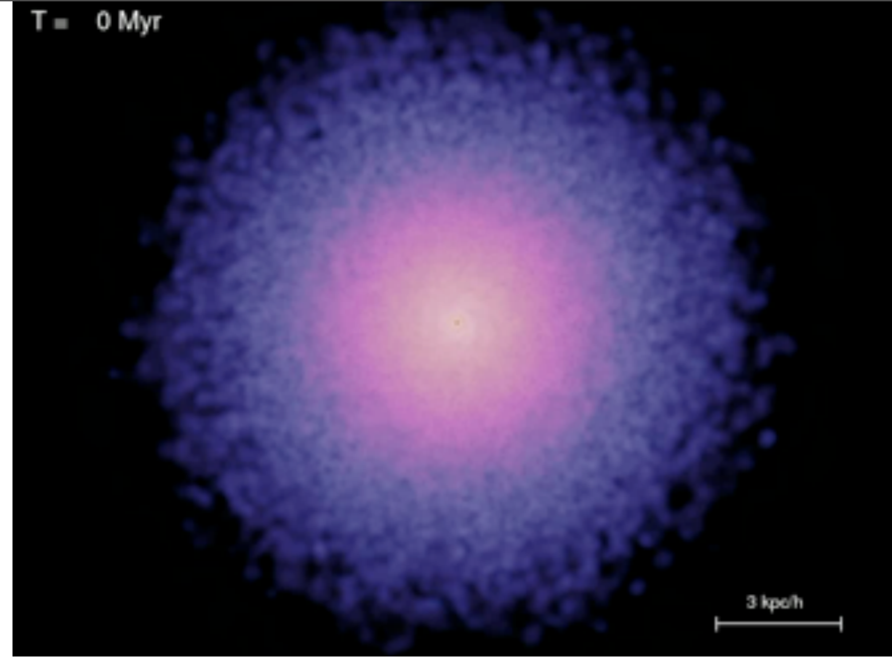


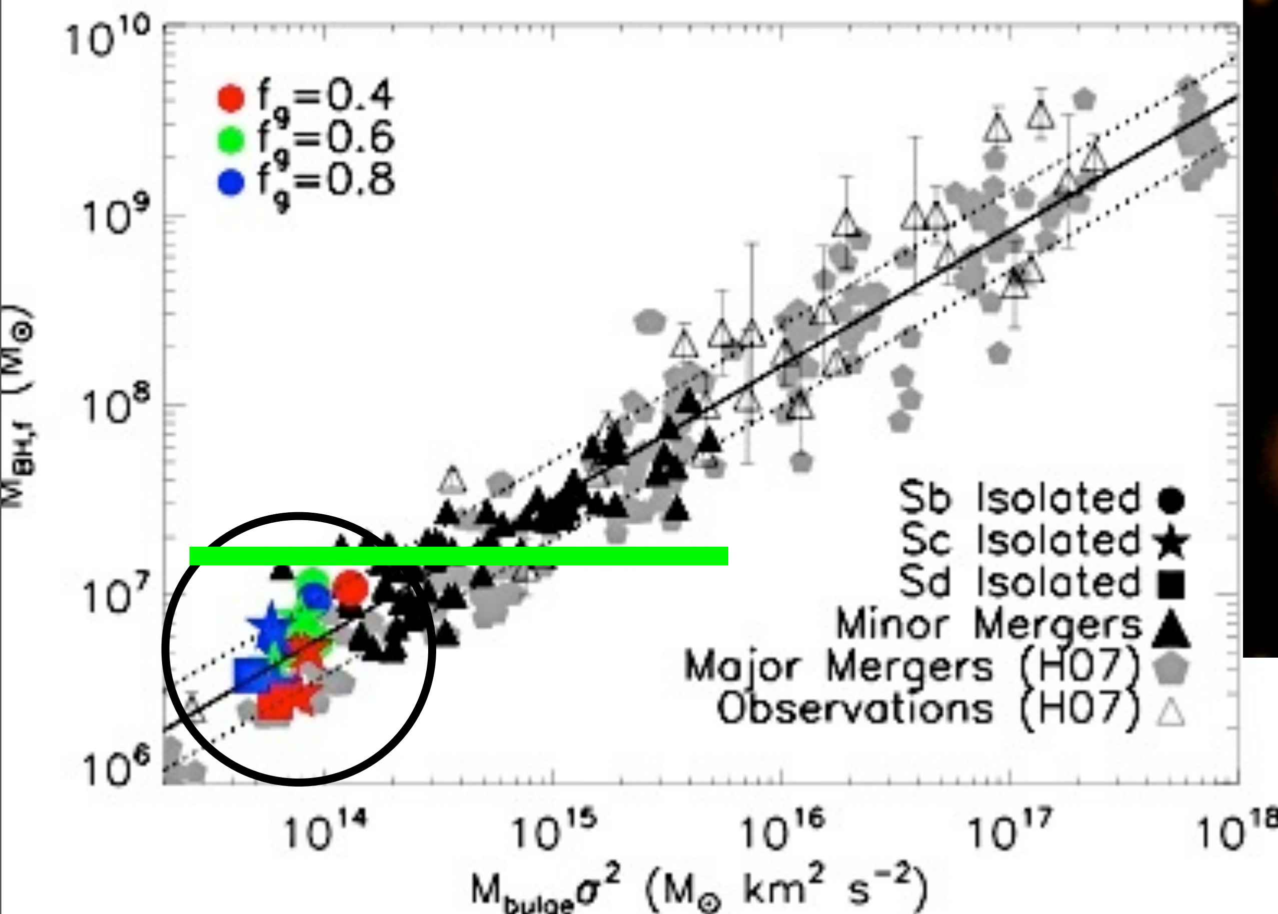
- Supports basic Silk & Rees ’98 argument:
  - BH feedback self-regulates growth in ~fixed potential
  - only “feel” the local potential of material to be unbound

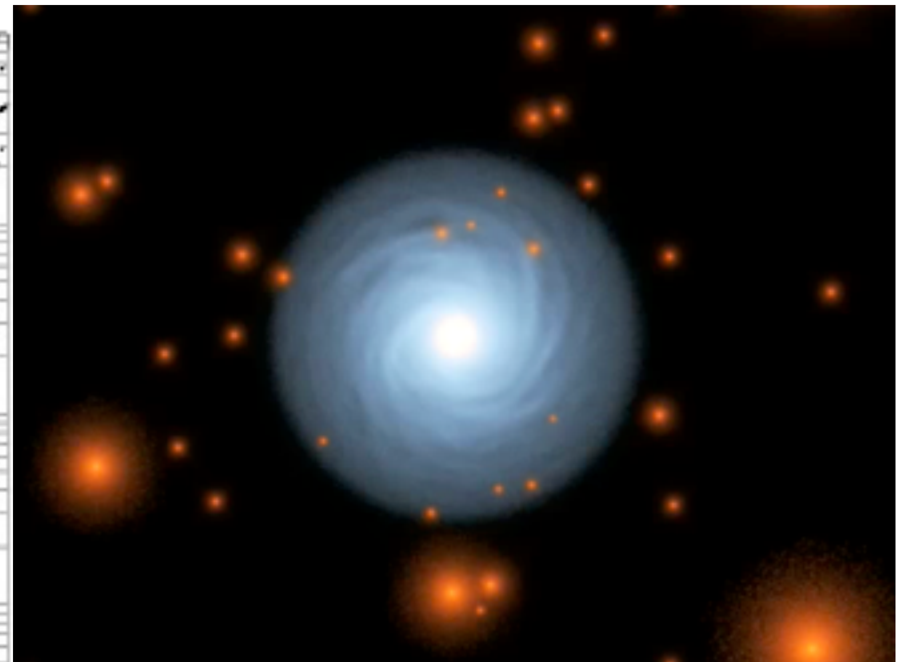
Of Course, Not *Every* AGN Needs a Merger

MORE QUIESCENT GROWTH MODES?

- $z=2$ L* QSO: 10^{11} M_{sun} in <10pc in ~t_{dyn}
- Seyfert: only 10^8 M_{sun} ~ 10^{-3} M_{gal}
    - Minor mergers?
    - Secular instabilities/bars?

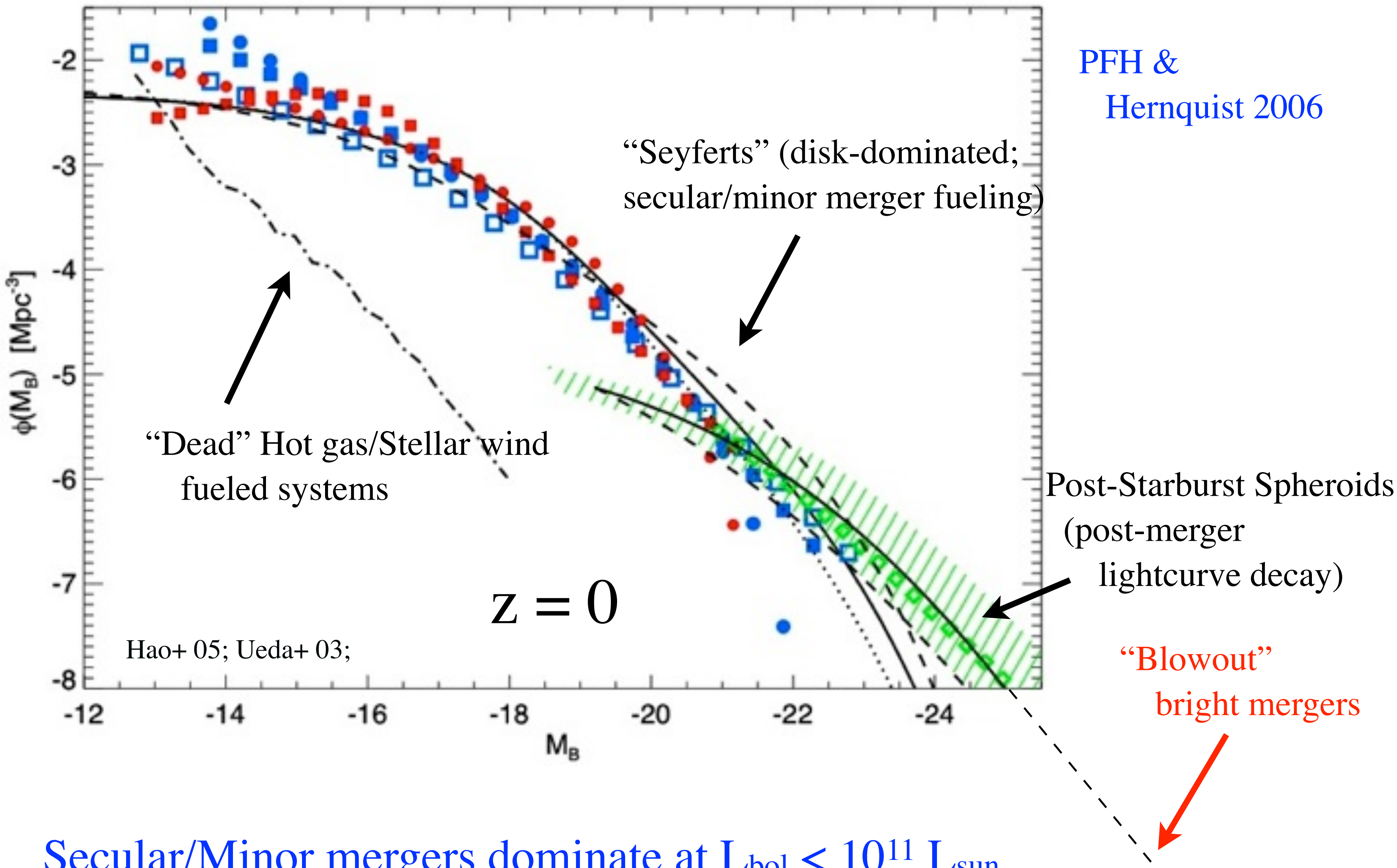






- If you don't build massive bulges, doesn't matter if you can get the gas in!

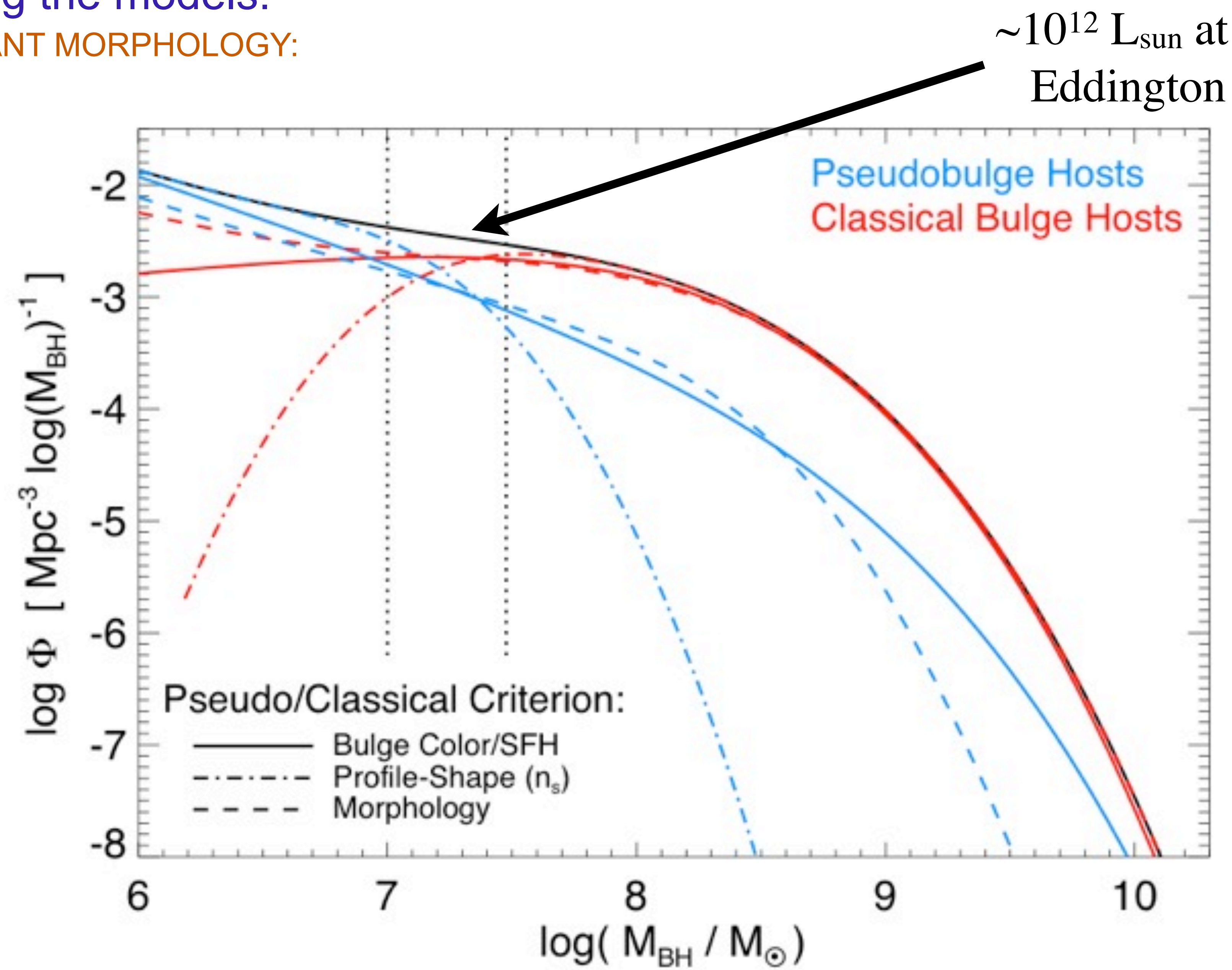
Emergent Picture:



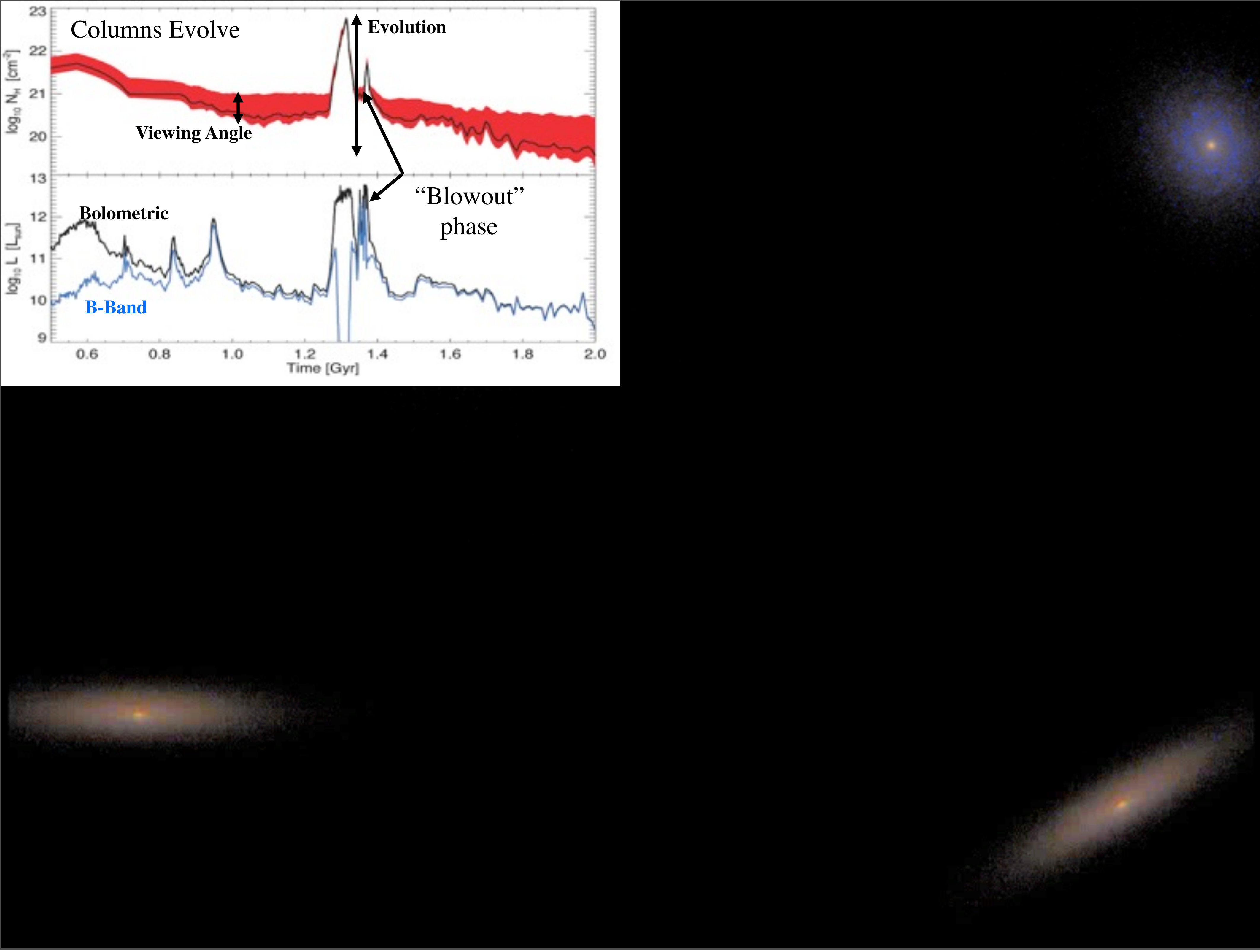
- Secular/Minor mergers dominate at $L_{bol} < 10^{11}\ L_{sun}$
  - Seyfert-Quasar divide is a good proxy!

Testing the models:

REMNANT MORPHOLOGY:



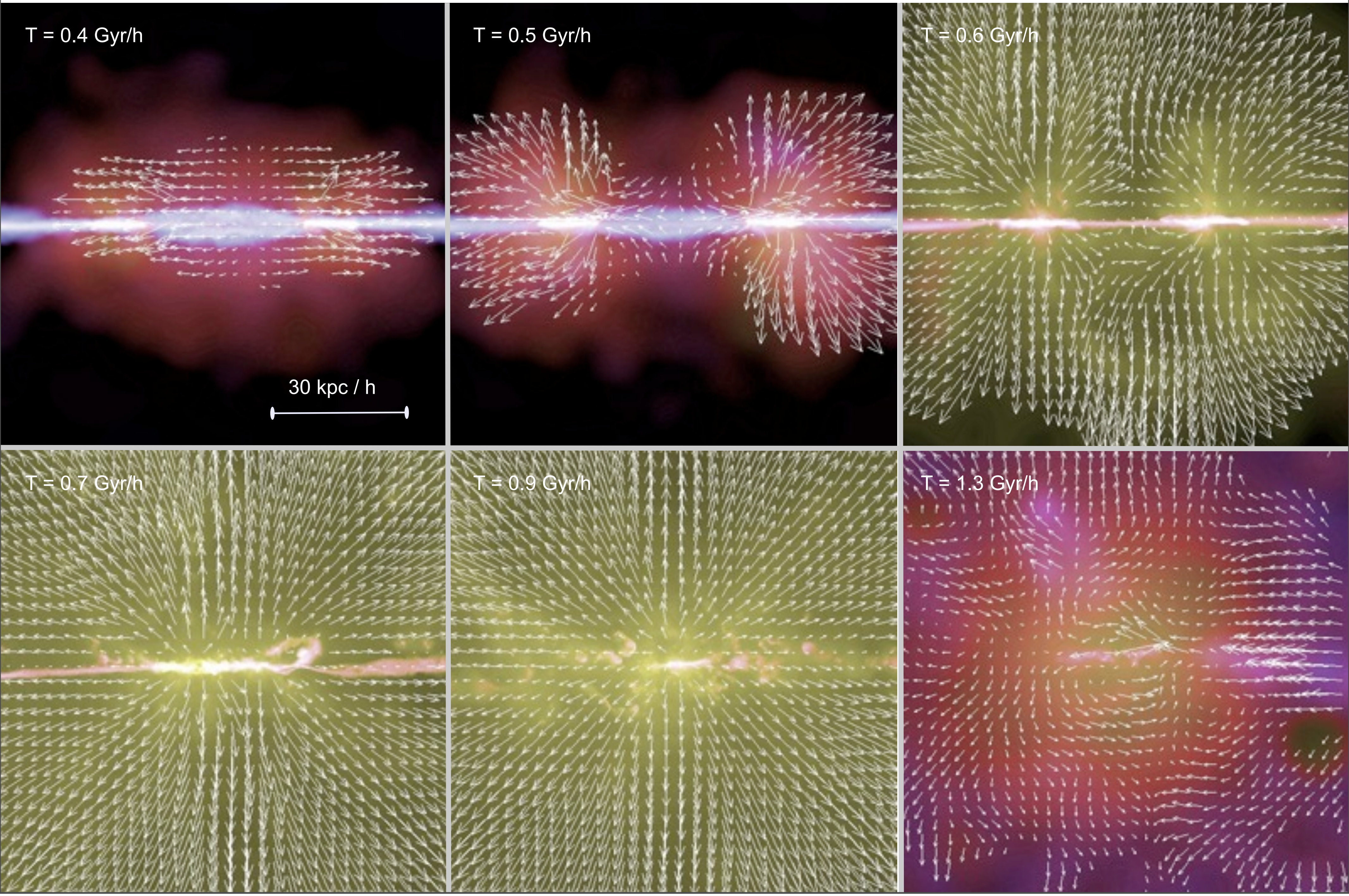
- Most mass in "classical" bulges, not "pseudobulges
  - But, *are* important below <~ Sa-types


Columns Evolve
Evolution
Viewing Angle
"Blowout"
phase
Bolometric
B-Band
$\log_{10} N_H$ [cm^{-2}]
$\log_{10}$ L [L_{sun}]
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

Where Does the Energy/Momentum Go?

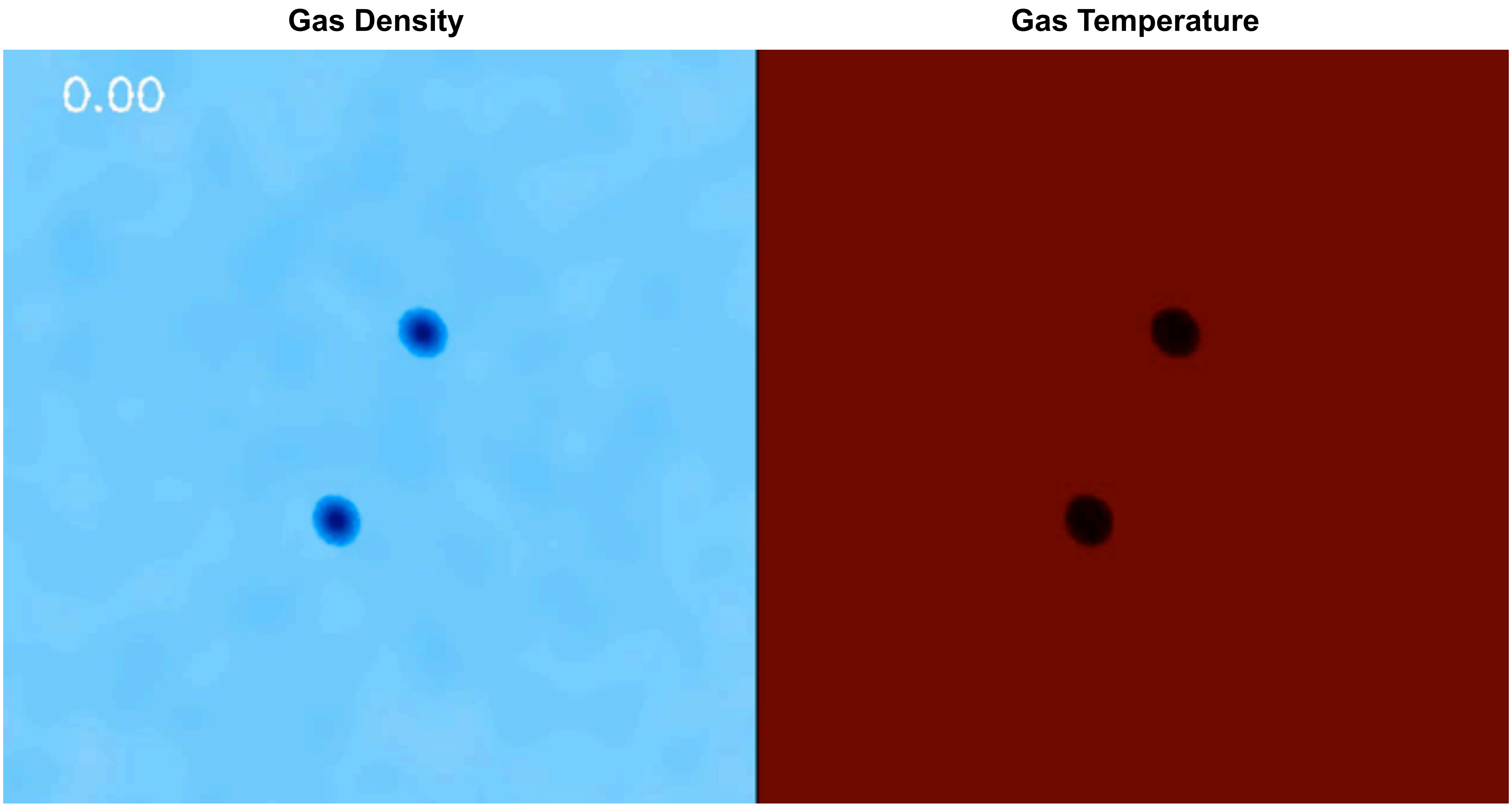
QUASAR-DRIVEN OUTFLOWS?

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



Quasar Outflows May Be Significant for the ICM & IGM

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



Quasar Outflows May Be Significant for the ICM & IGM

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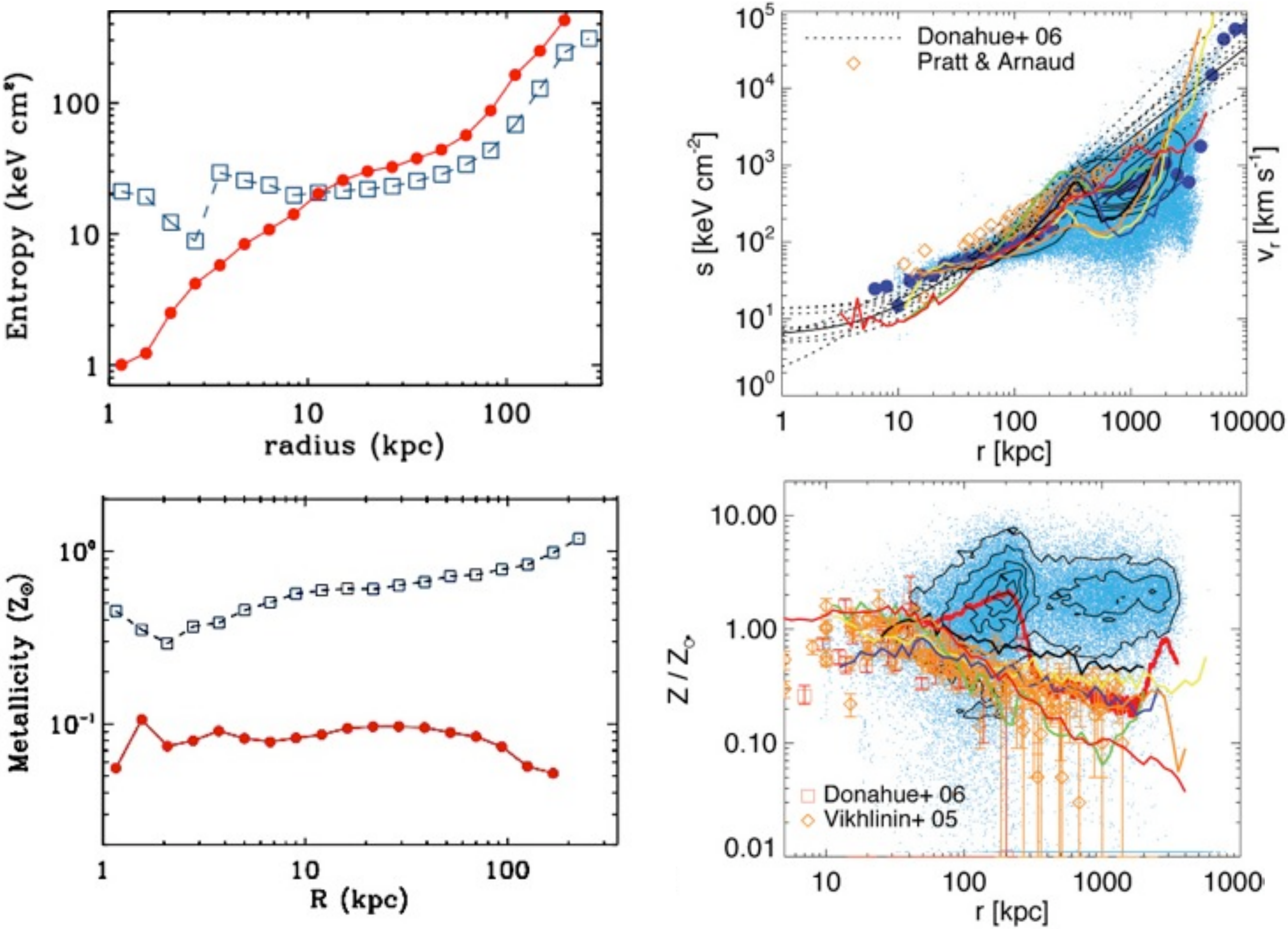
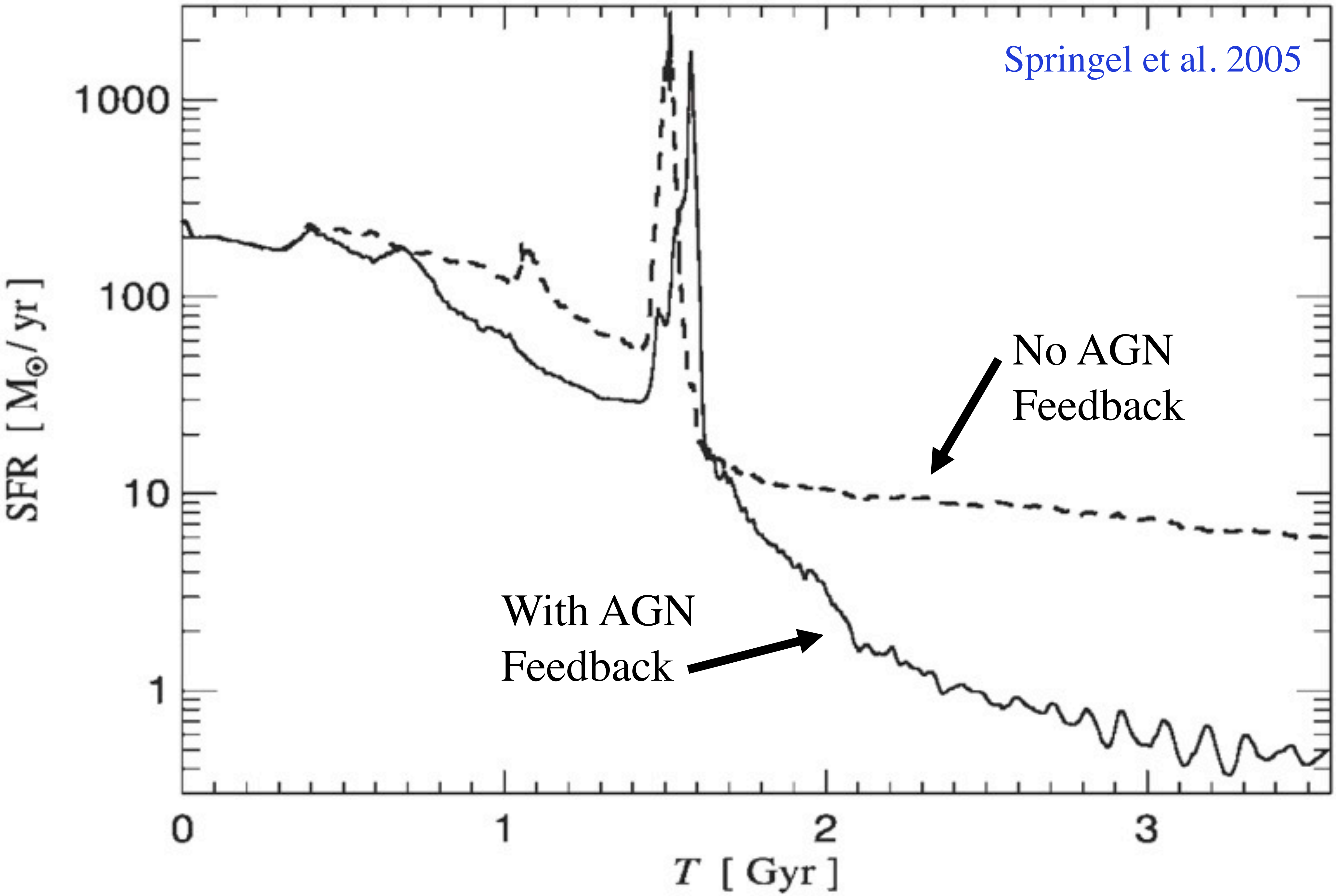


Expulsion of Gas Turns off Star Formation

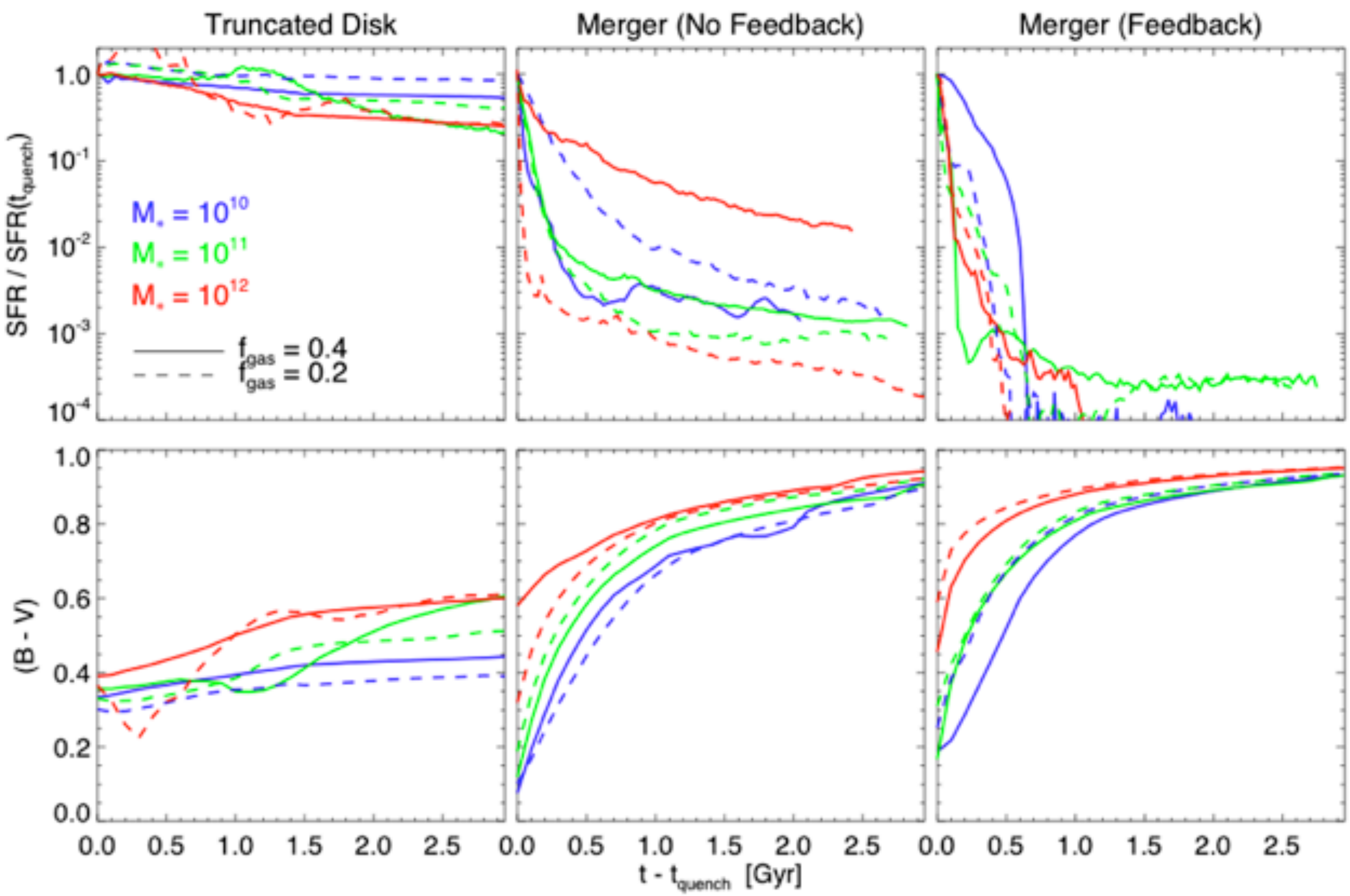
ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?



Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?

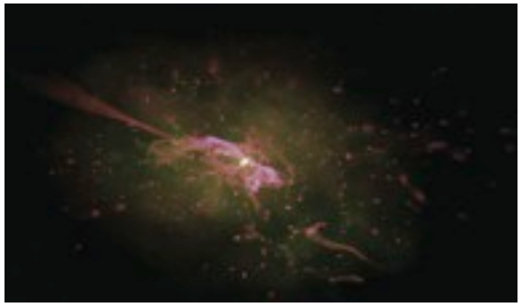
... but ...

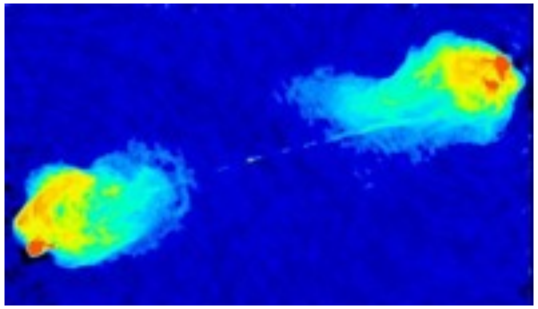


... MOST of the work is still done by star formation/stellar feedback

“Transition” vs. “Maintenance”

“Transition”	“Maintenance”
Move mass from Blue to Red	Keep it Red
Rapid	Long-lived (~Hubble time)
Small scales	Large (~halo) scales
“Quasar” mode (high mdot)	“Radio” mode (low mdot)
Morphological Transformation	Subtle morphological change
Gas-rich/Dissipational Mergers	“Dry”/Dissipationless Mergers





No reason these should be the same mechanisms... what connections?

Summary

We're closing in on answers to a number of ~30 year old questions:

- How do disks *survive* mergers?
  - Being very gas rich ($f_{gas} \sim 0.5$): no stars = no angular momentum loss
- Ellipticals are *smaller* than spirals! How do we make a *real* elliptical?
  - Gas again! Dissipation builds central mass densities, explains observed scaling laws: just need disks as gas rich as observed ($f_{gas} \sim 0.1 - 0.5$)
- How do galaxies *stop* growing?
  - Mergers exhaust gas efficiently once near low f_{gas}
  - QSO/Transition-Mode feedback "cleans up" the rest: remnant can redden
  - Radio/Maintenance-Mode feedback keeps the halo hot
- Where did these black holes come from!?
  - Growth in (mostly) mergers: self-regulation by feedback explains M_{BH}-s

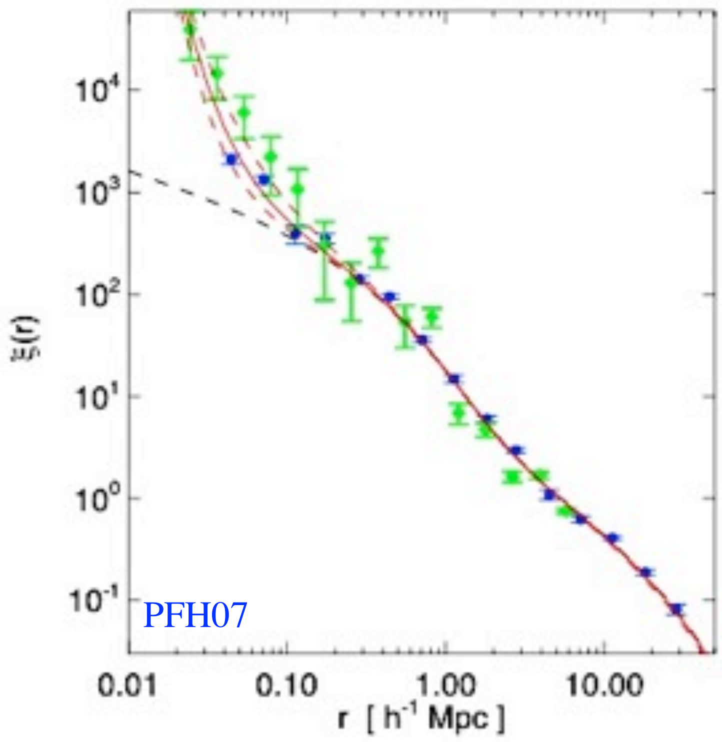
Summary

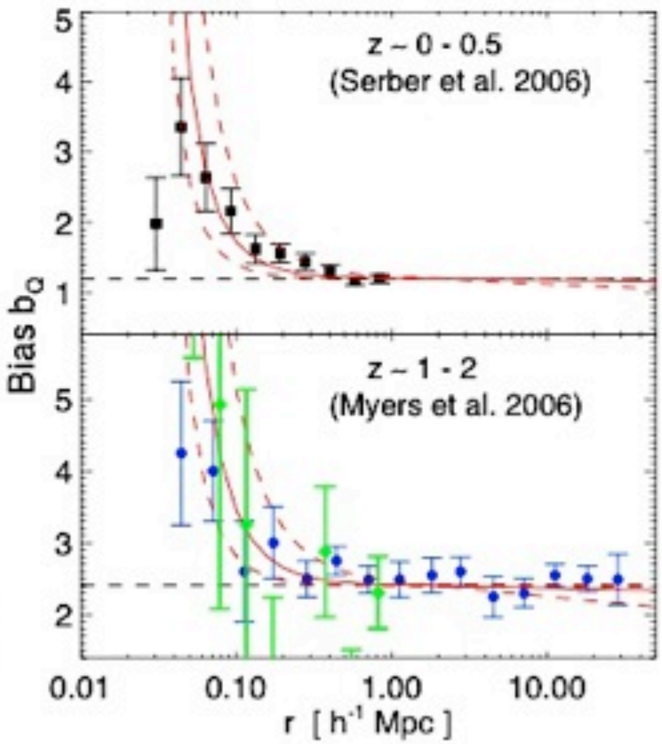
.... and raising new ones ...

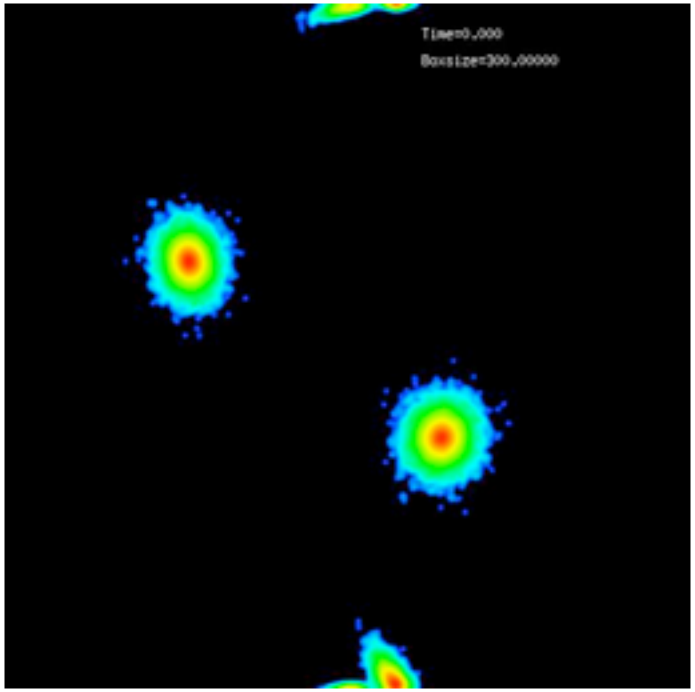
- How do disks *survive* mergers?
  - Being very gas rich (f_{gas} ~ 0.5): no stars = no angular momentum loss
    - How do we keep gas around for them in the first place? Stellar feedback?
- Ellipticals are *smaller* than spirals! How do we make a *real* elliptical?
  - Gas again! Dissipation builds central mass densities, explains observed scaling laws: just need disks as gas rich as observed (f_{gas} ~ 0.1 - 0.5)
    - Should these correlations then evolve with redshift/environment?
    - What about the most massive BCGs that first form at high-z?
- How do galaxies *stop* growing?
  - Mergers exhaust gas efficiently once near low f_{gas}
  - QSO/Transition-Mode feedback "cleans up" the rest: remnant can redden
  - Radio/Maintenance-Mode feedback keeps the halo hot
    - What are the actual feedback mechanisms? Do they work in detail?
    - Are halo "quenching" processes important?
- Where did these black holes come from!?
  - Growth in mergers: self-regulation by feedback explains M_{BH}-s
    - How does this effect BH lightcurves/growth histories? Can we test it?
    - How do other mechanisms (bars, cooling flows) contribute?

Testing the models:
CLUSTERING & ENVIRONMENT:

- Observed excess of quasar clustering (quasar-galaxy and quasar-quasar pairs) on small scales, relative to "normal" galaxies with the same masses/large-intermediate scale clustering





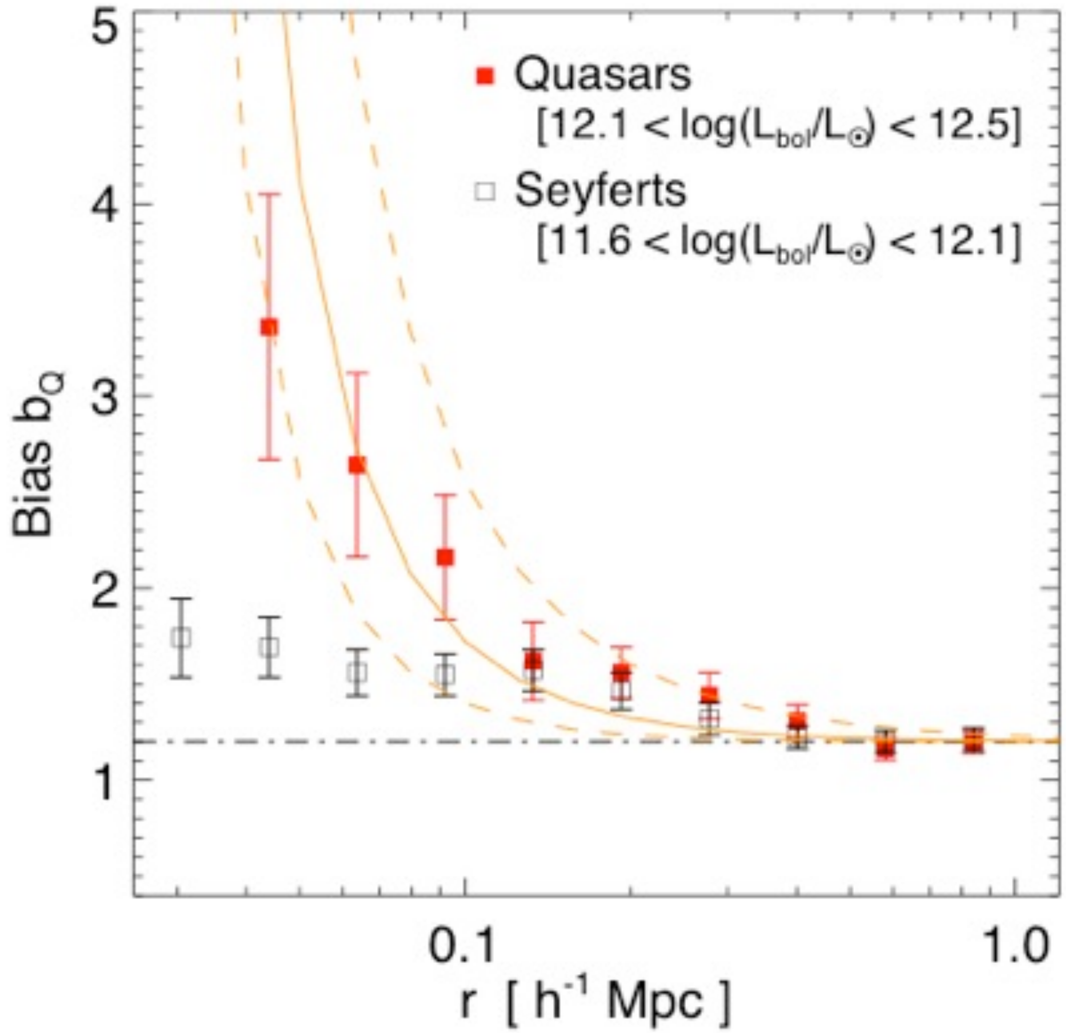


- Expected for mergers (Thacker & Scannapieco et al., PFH)
- Seen in Post-SB Galaxies (Goto et al., Hogg et al., Kauffmann et al.)

Testing the models:

CLUSTERING & ENVIRONMENT:

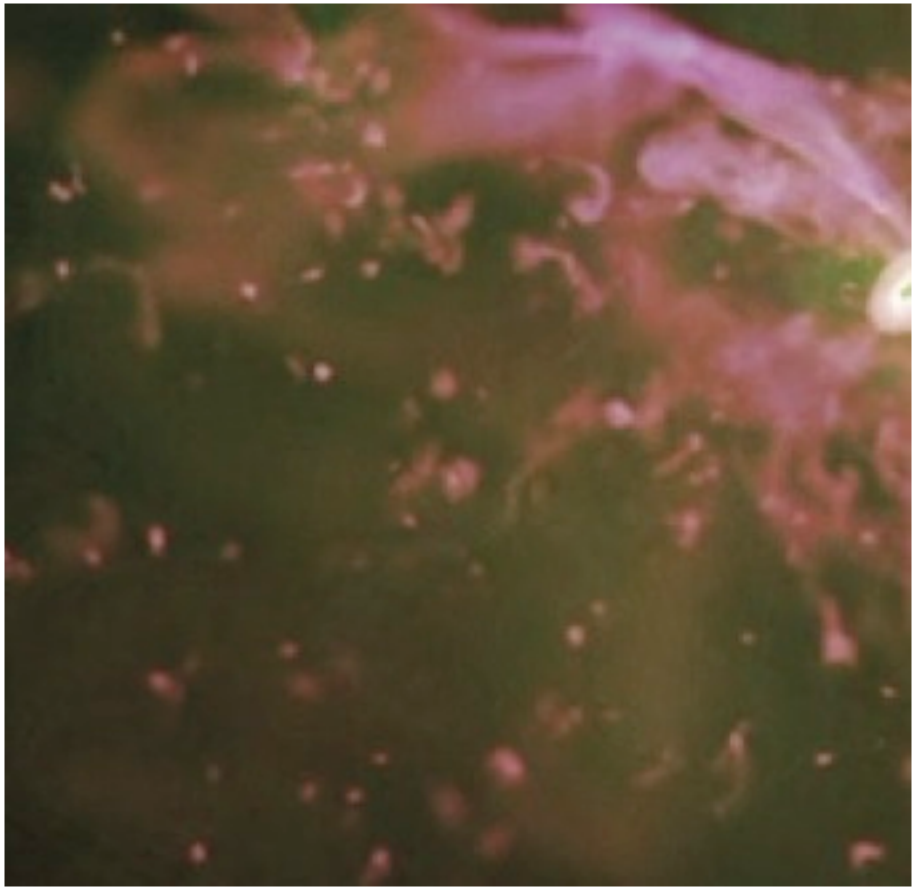
- Small-Scale Excess:
  - Not seen in Seyferts (Serber, Kauffmann)
    - Suggests different processes dominate fueling below $M_B \sim -23$ ($M_{BH} \sim 10^7$)?

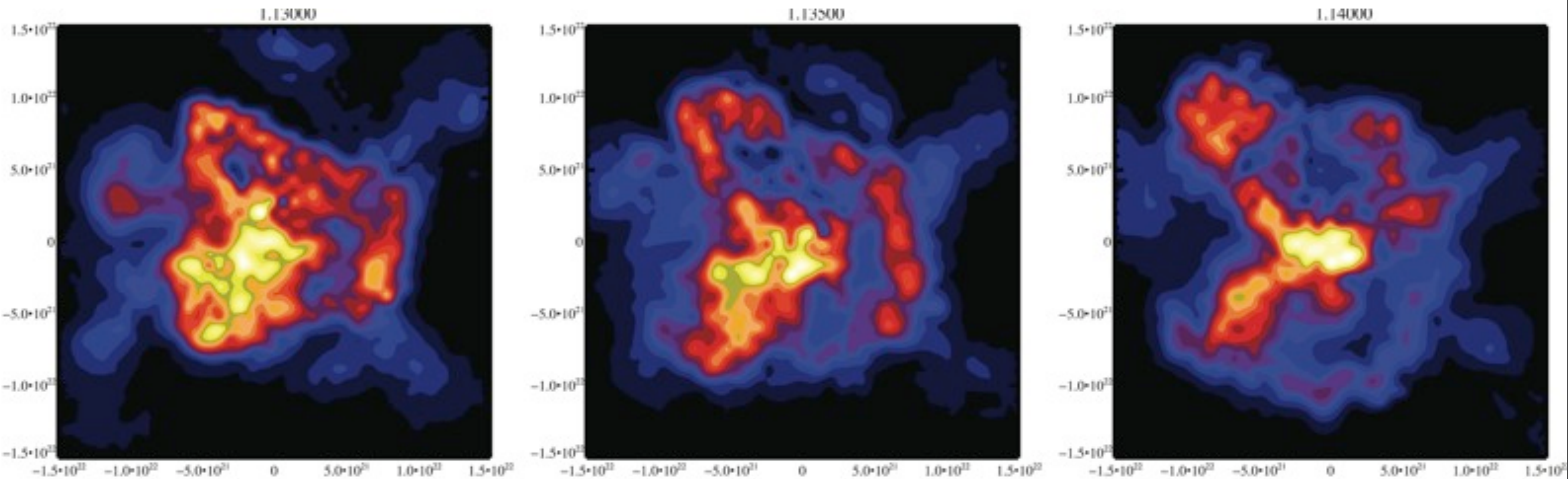


Serber et al. 2006

Outflows are Explosive and Clumpy

- Rapid BH growth => point-like injection
  - "Explosion-like", independent of coupling
- Cold, clumpy shell (through galaxy)
- Growing observations:
  Prochaska & Hennawi (active QSOs)
  Tremonti (post-SB winds ~2000 km/s)
  Arav et al. (momentum flux ~L_{QSO}/c)

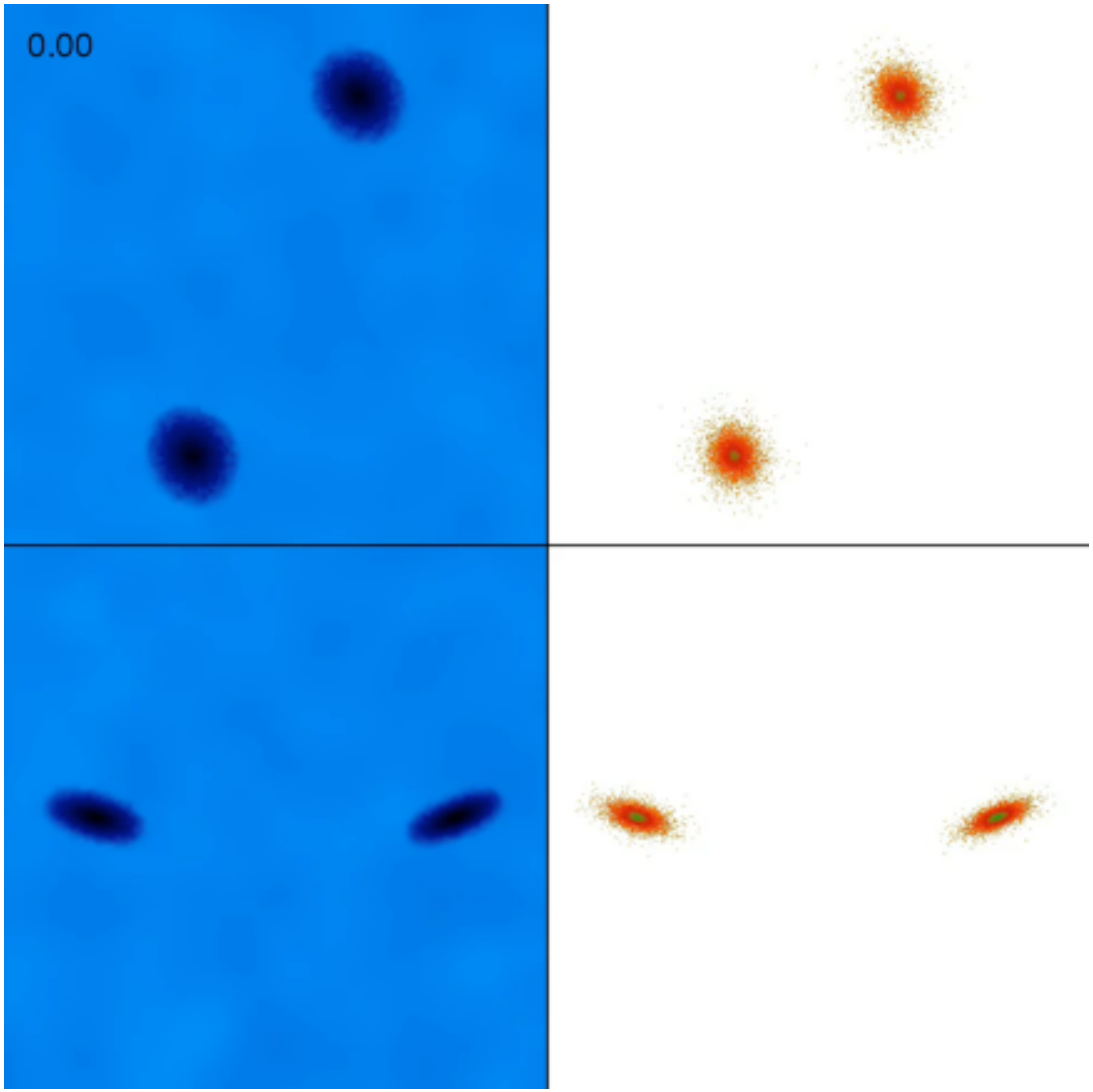


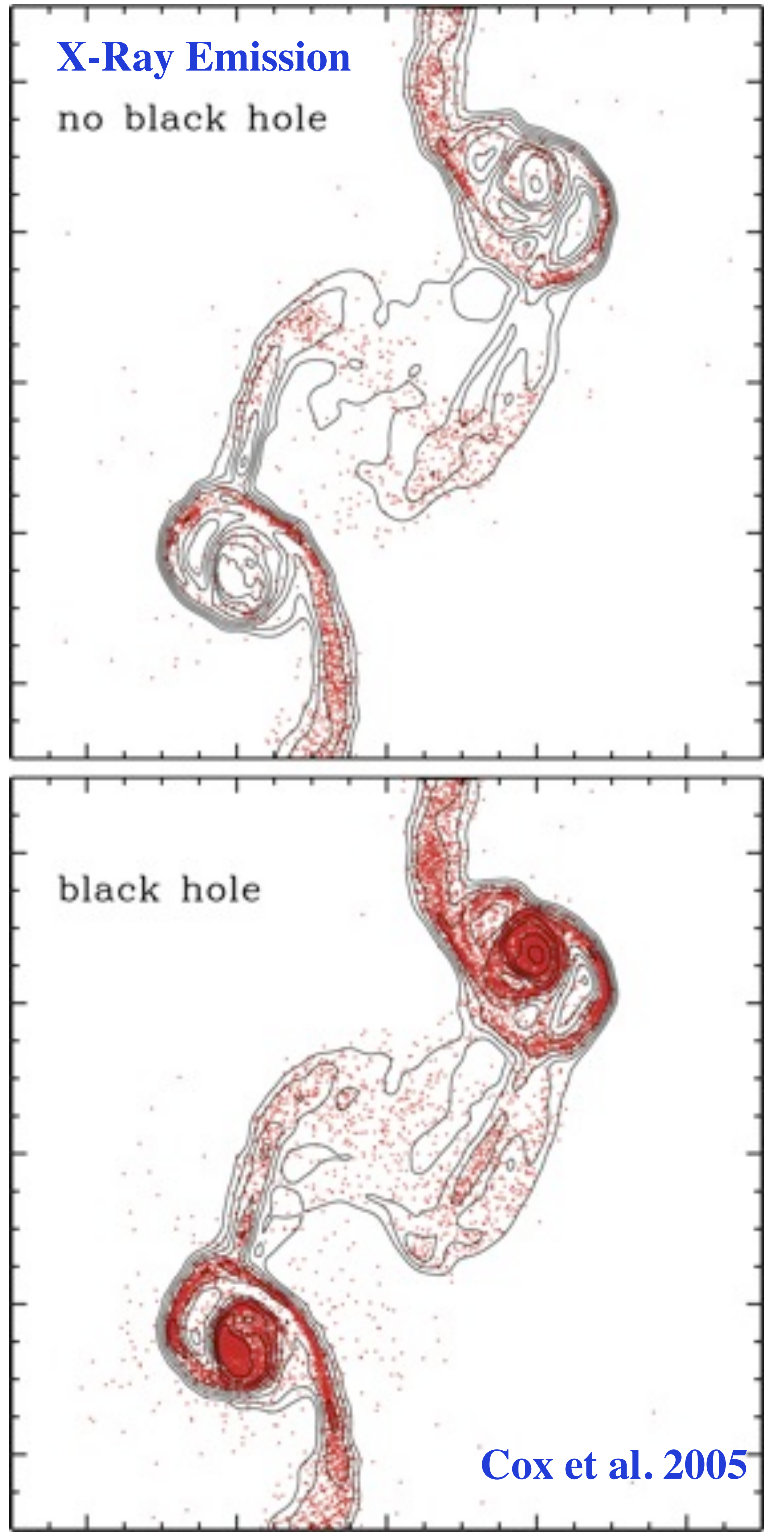


Feedback-Driven Winds

METAL ENRICHMENT & BUILDING THE X-RAY HALO

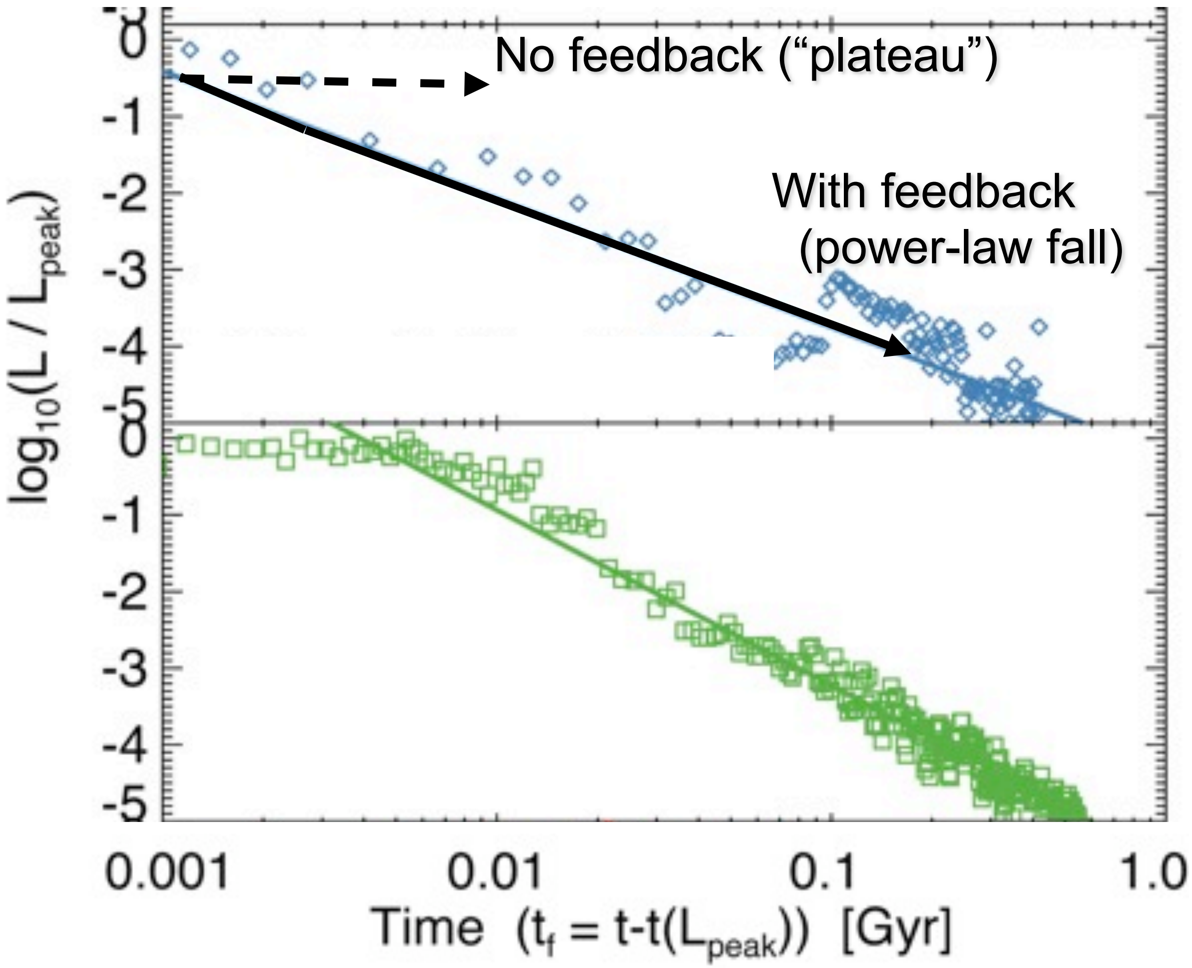
Gas Density **Stellar Density**





Quasar Light Curves & Lifetimes

- Feedback determines the decay of the quasar light curve:

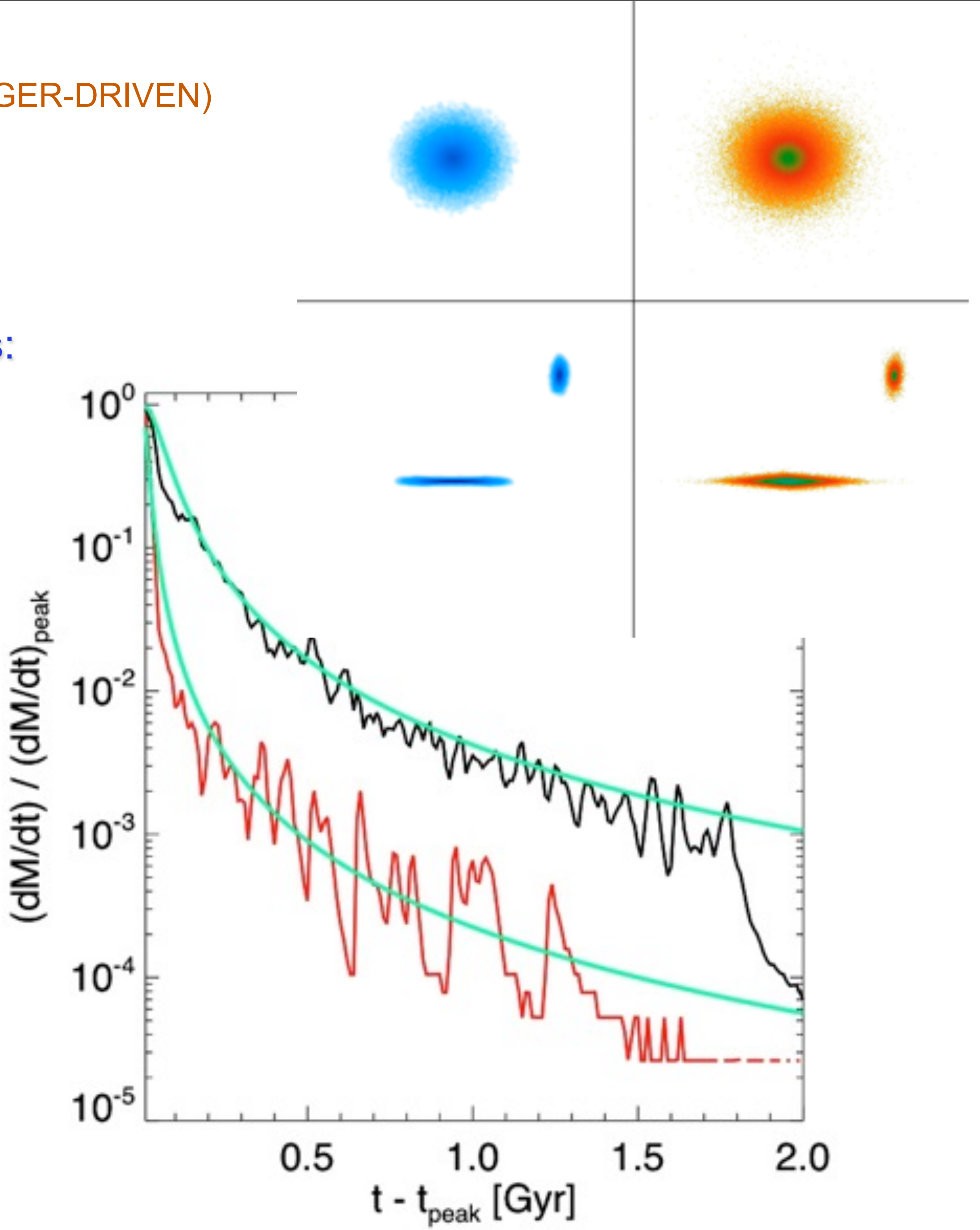


- Explosive blowout drives power-law decay in L
- No Feedback:
  - Runaway growth (exponential light curve)
  - "Plateau" as run out of gas but can't expel it (extended step function)

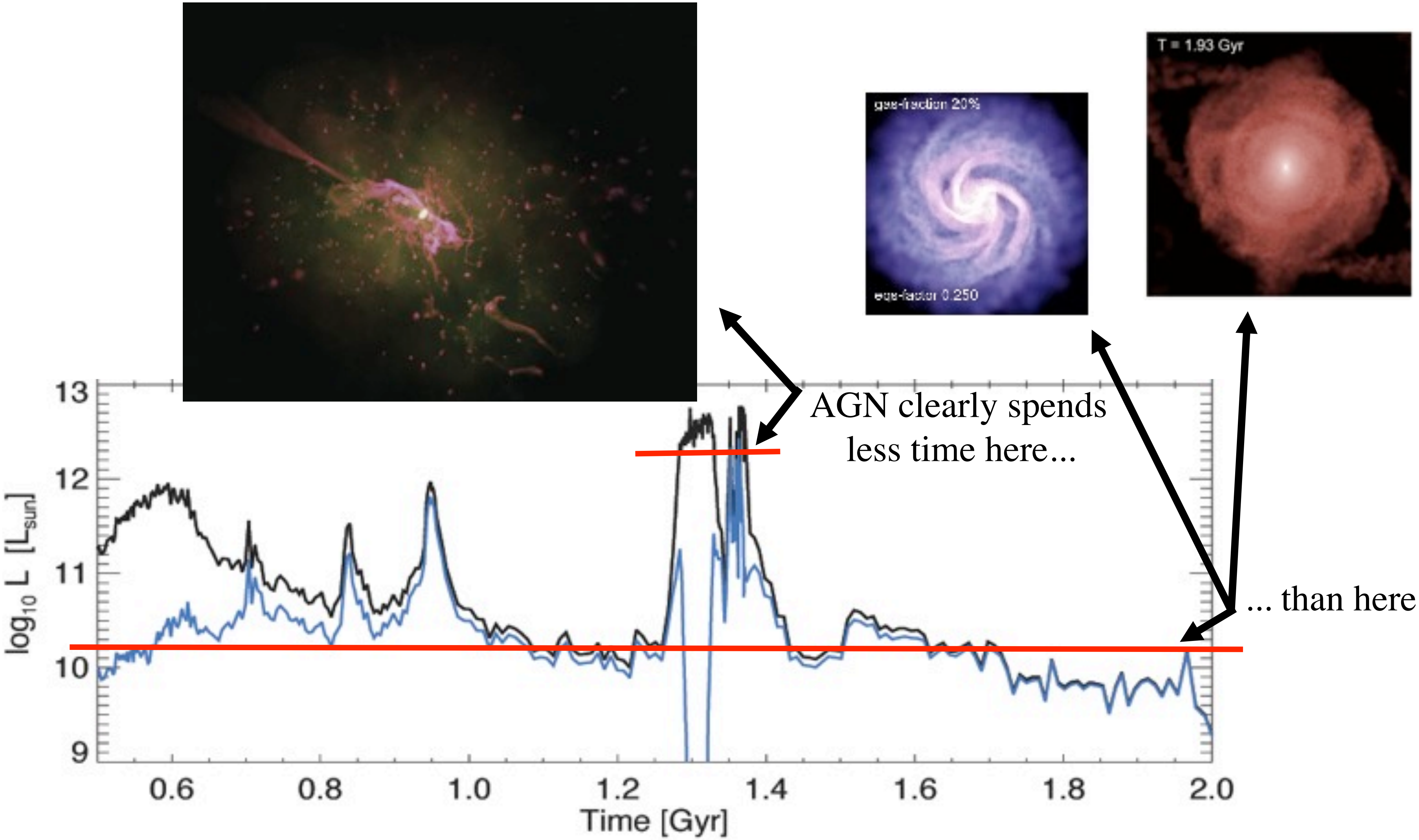
PFH et al. 2006a

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



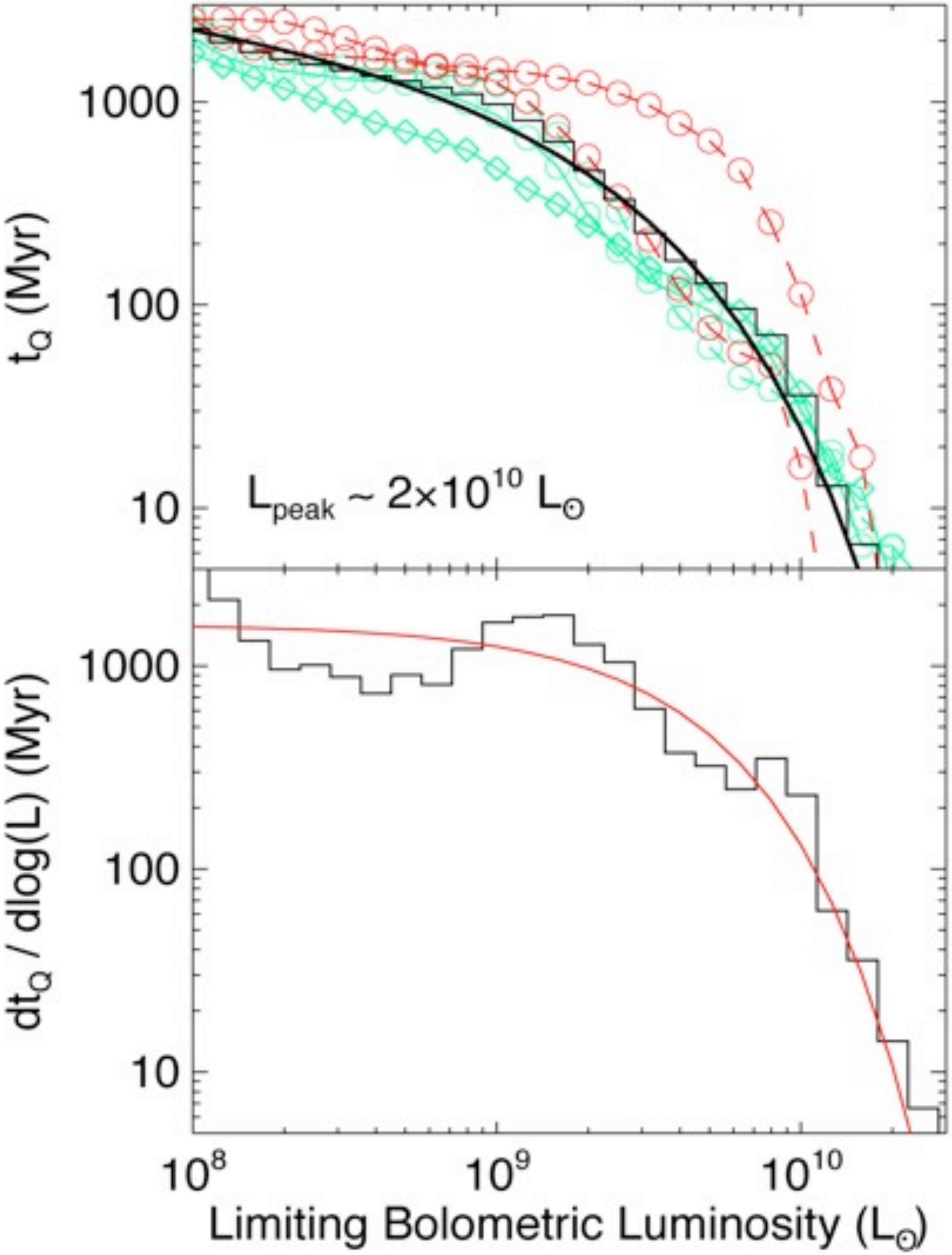
So What Is the "Quasar Lifetime"?



- "Quasar Lifetime": a conditional, *luminosity-dependent* distribution

Feedback Determines the Decay of the Quasar Light Curve

LESS OBVIOUS, BUT IMPORTANT IMPLICATIONS VIA THE QUASAR LIFETIME

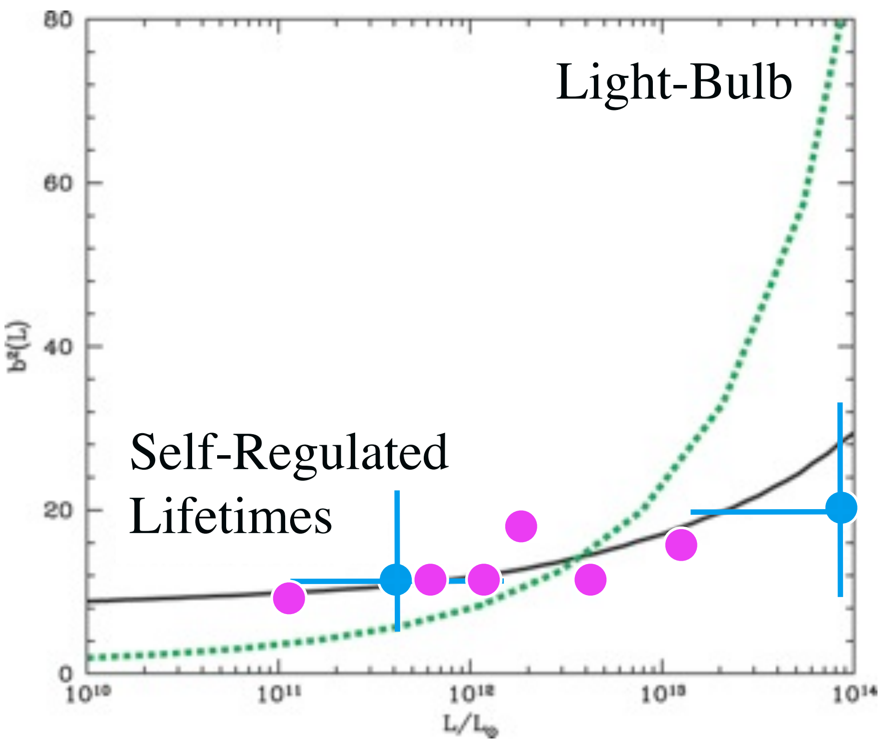


- "Quasar Lifetime": a conditional, luminosity-dependent distribution
- Robust as a function of BH mass or peak QSO luminosity

PFH et al. 2006b

Quasar Clustering is a Strong Test of this Model

IF FAINT QSOS ARE DECAYING BRIGHT QSOS - SHOULD BE IN SIMILAR HOSTS

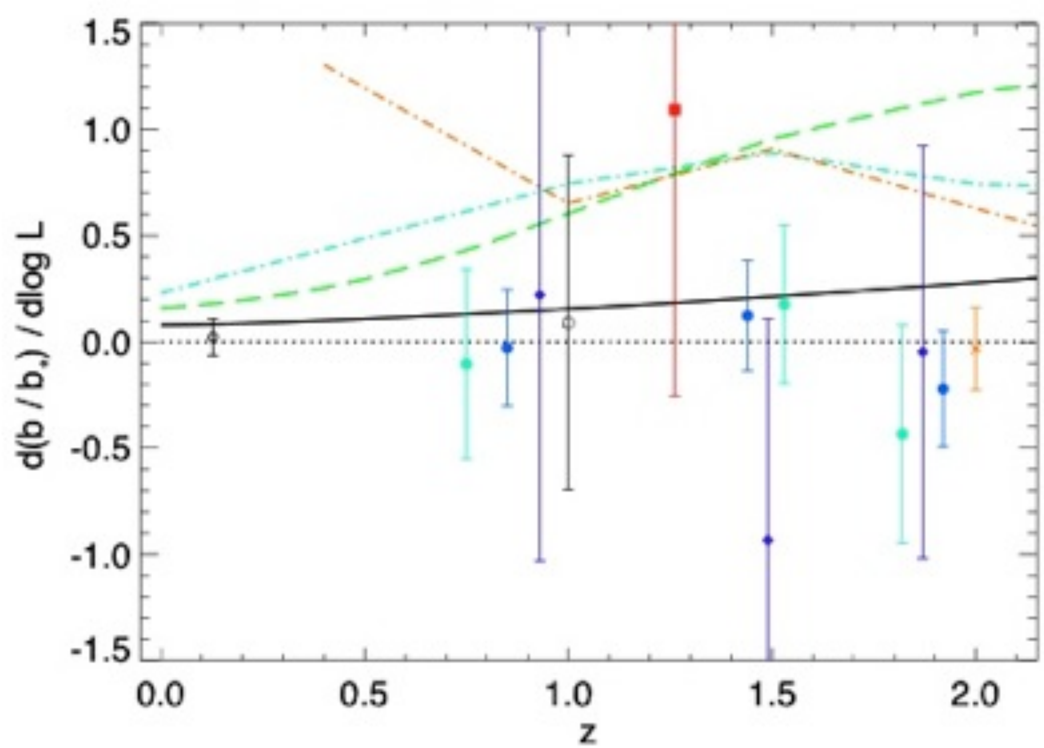


● Adelberger & Steidel 05

● Myers et al. 05

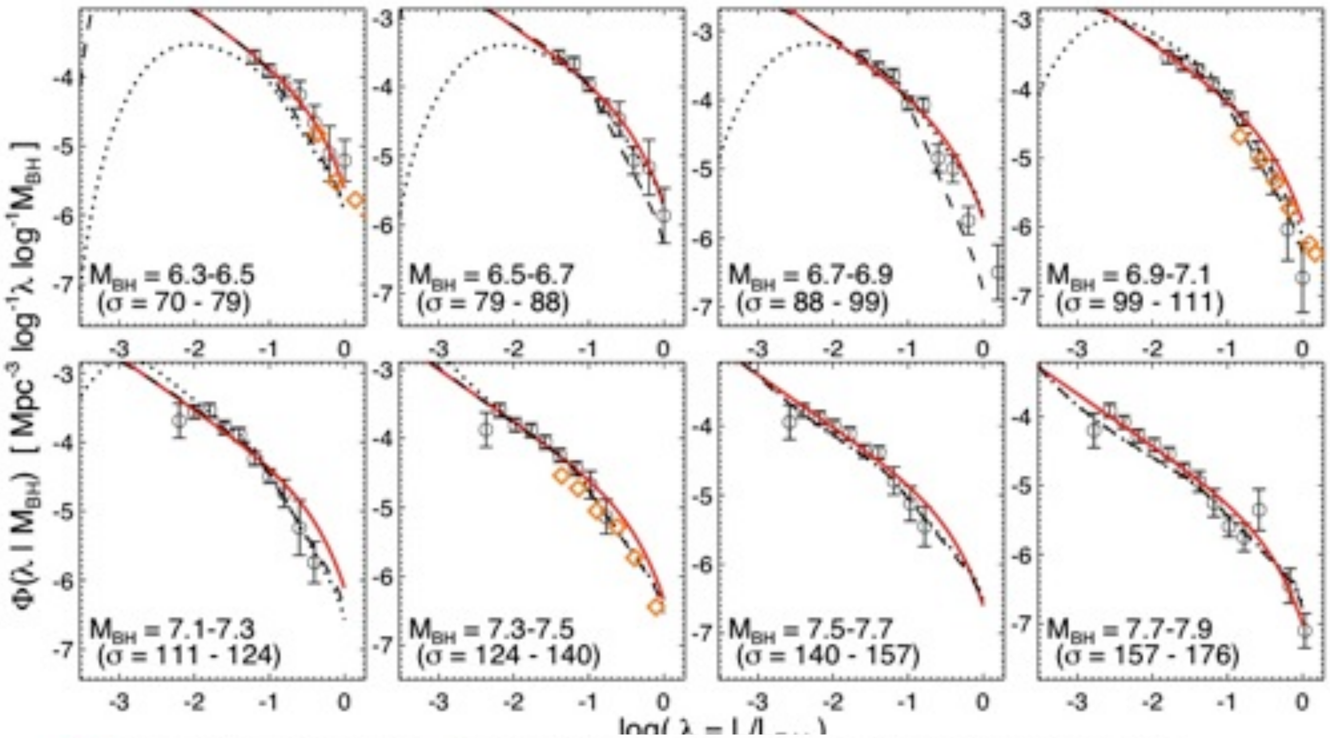
Lidz et al. 2005

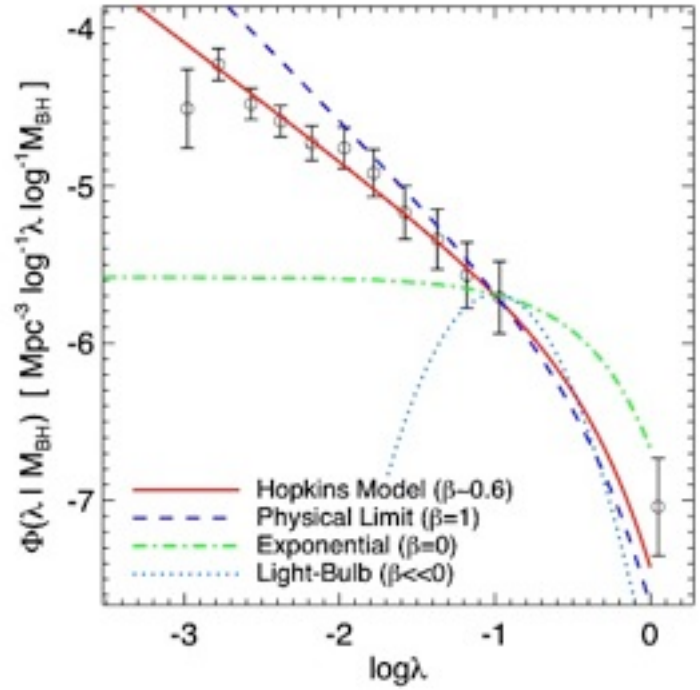
- Weak dependence of clustering on observed luminosity
  - (Croom et al., Adelberger & Steidel, Myers et al., Coil et al., Porciani et al.)

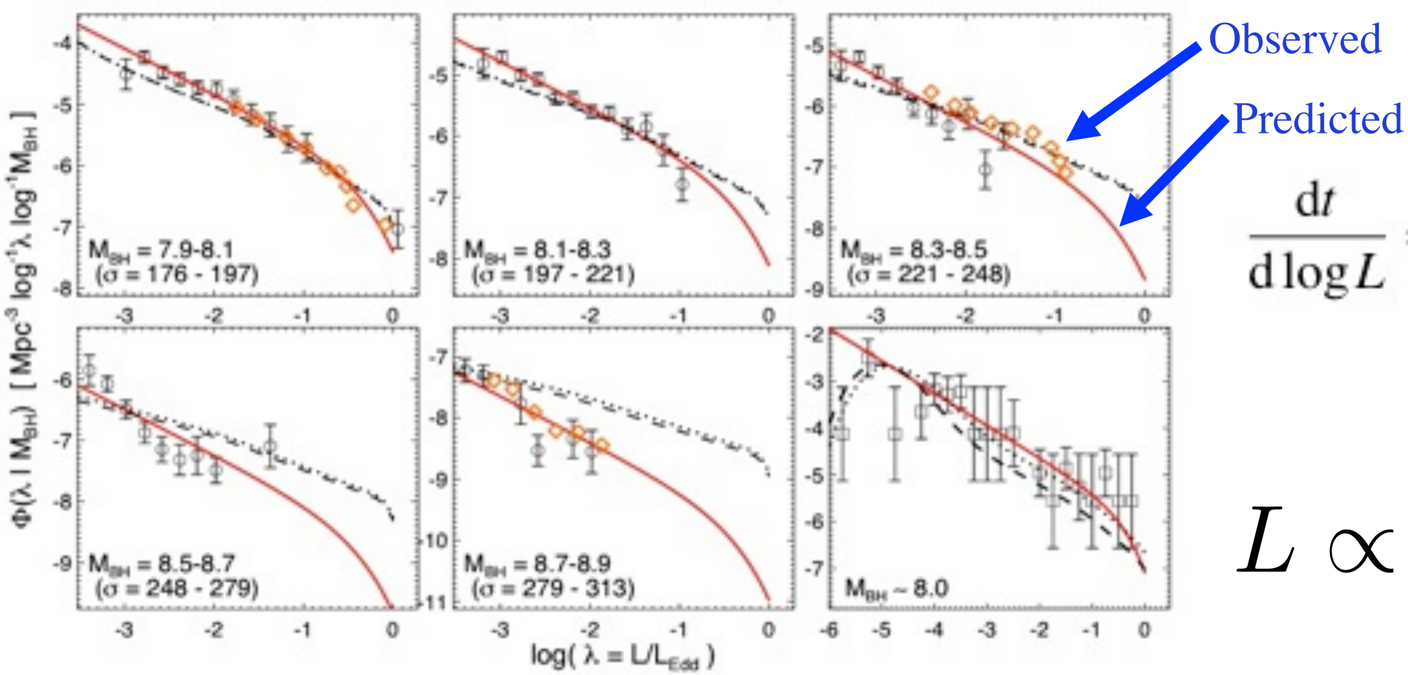


Hopkins, Lidz, Coil, Myers et al. 2007

Directly Apparent in the Observed Eddington Ratio Distribution





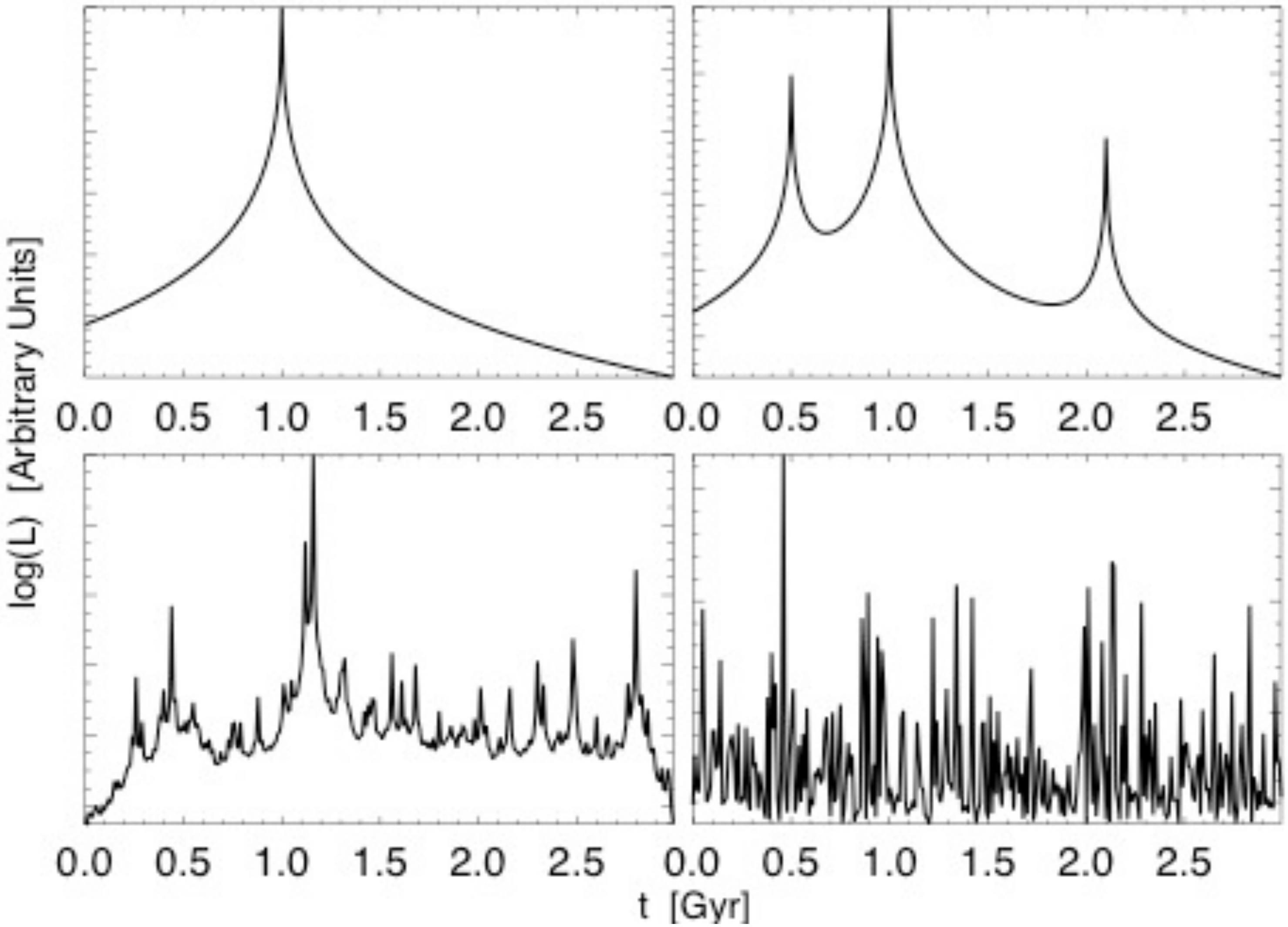


$$\frac{\mathrm{d}t}{\mathrm{d}\log L} = t_0 \left(\frac{L}{L_{\rm peak}}\right)^{-\beta} \exp\left(-L/L_{\rm peak}\right)$$

$$\Downarrow$$

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

Directly Apparent in the Observed Eddington Ratio Distribution



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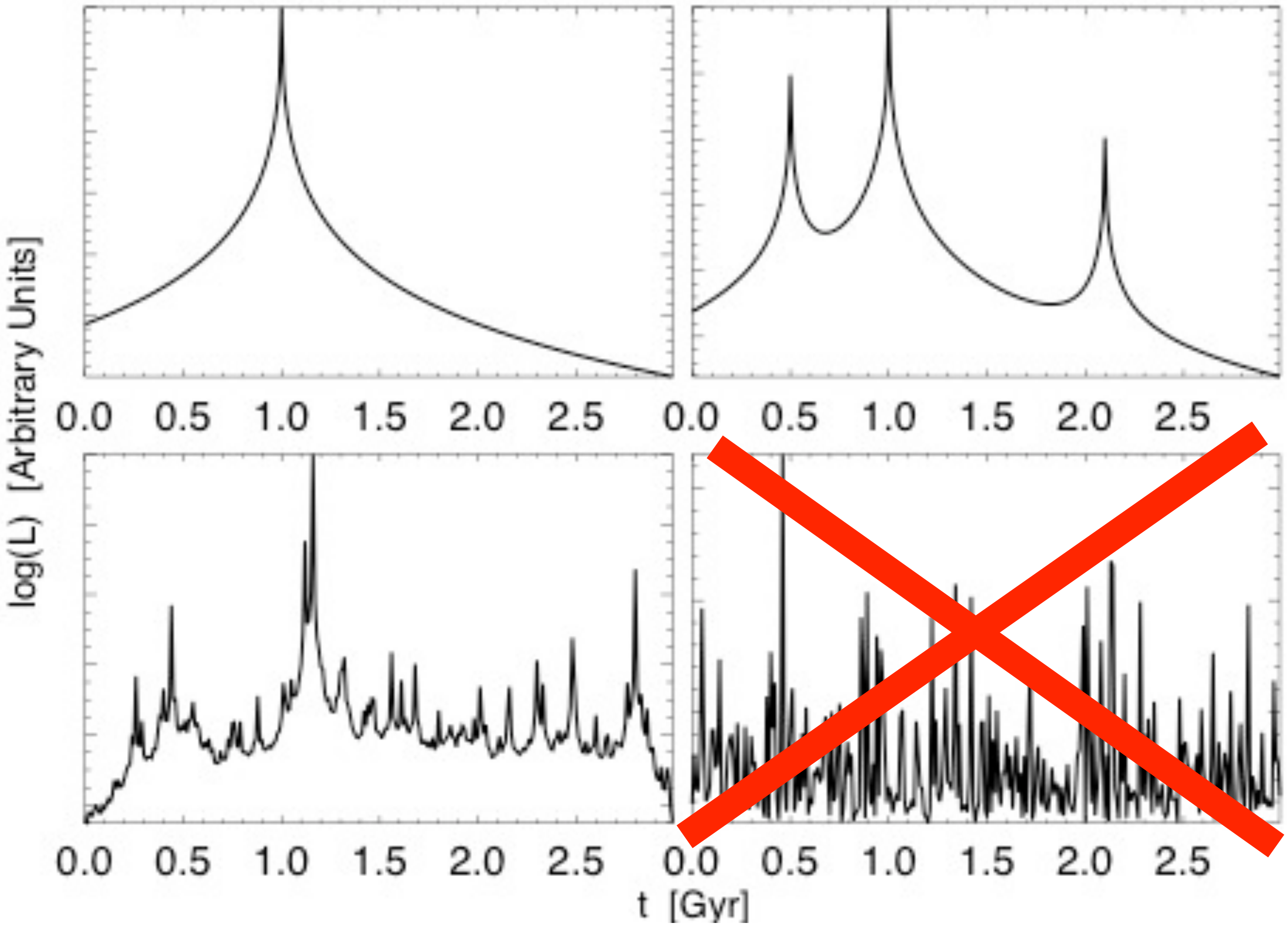
Directly Apparent in the Observed Eddington Ratio Distribution



Ruled out by transverse proximity effect

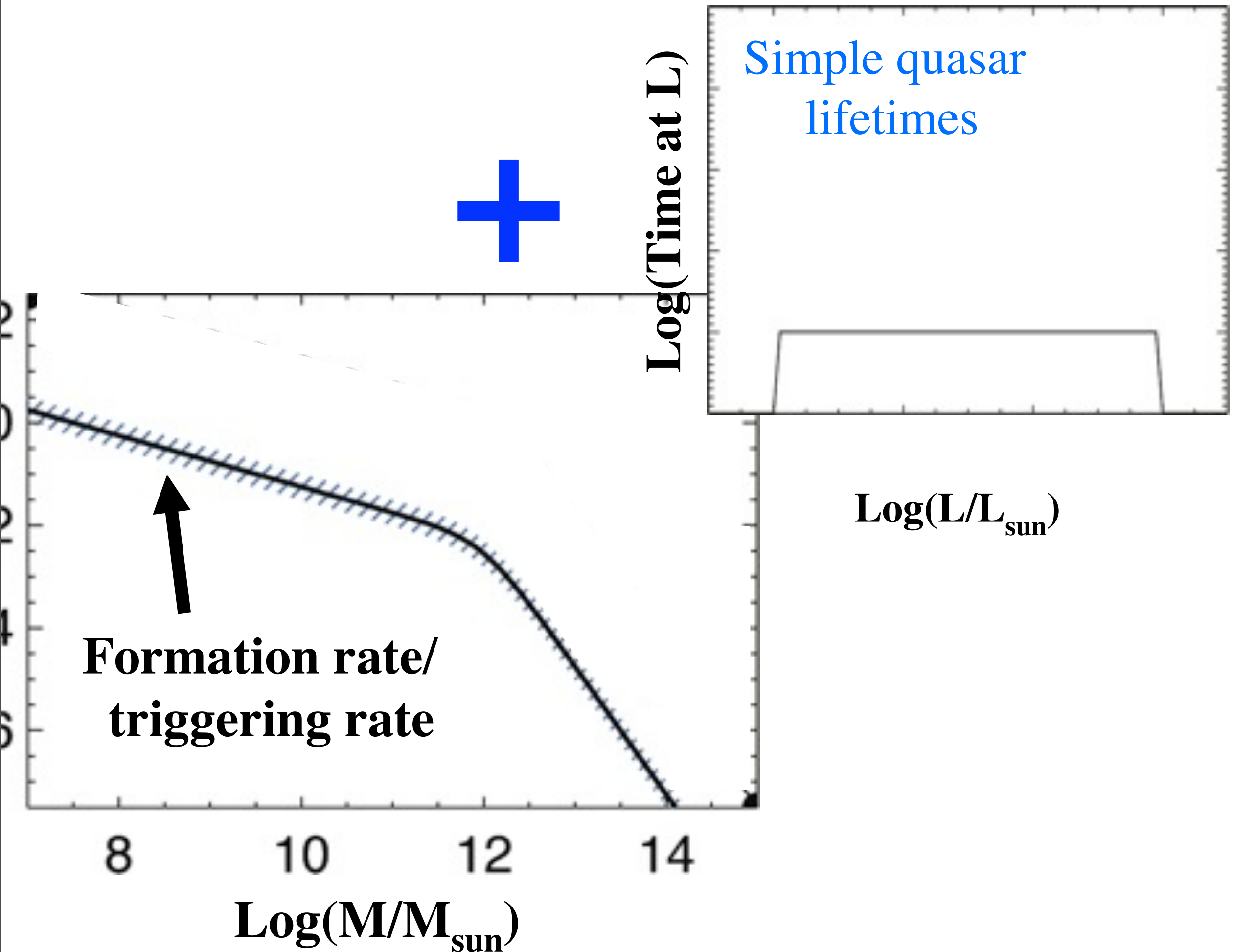
$t_{episodic} \sim t_{total}$

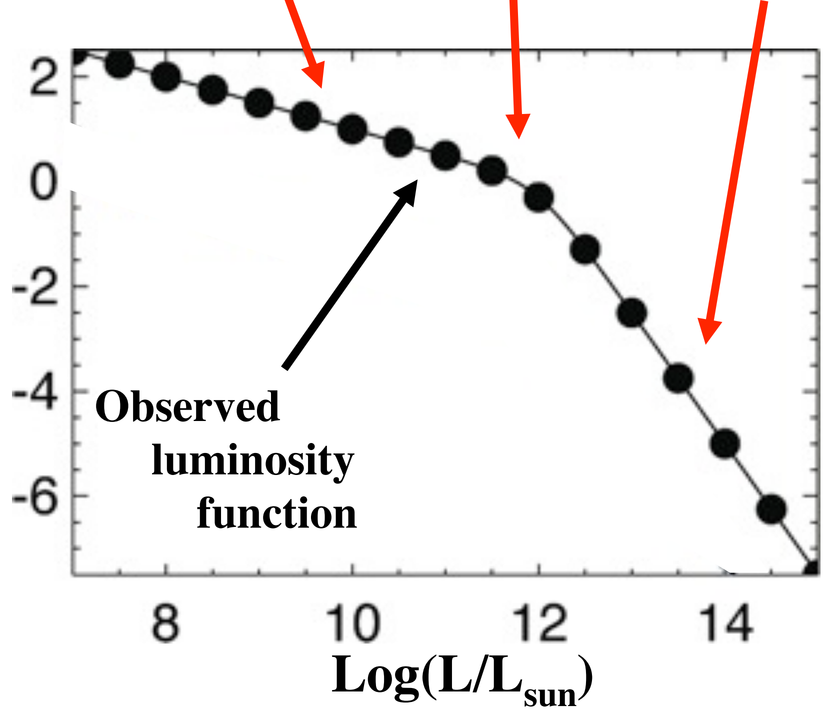
$$L \propto (t/t_Q)^{-(1.5-2.0)}$$

Given the Conditional Quasar Lifetime, De-Convolve the QLF

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

$$\phi(L) \equiv \frac{\mathrm{d}\Phi}{\mathrm{d}\log L}(L) = \int \frac{\mathrm{d}t(L, L_{\mathrm{peak}})}{\mathrm{d}\log(L)}\, \dot{n}(L_{\mathrm{peak}})\, \mathrm{d}\log(L_{\mathrm{peak}}).$$

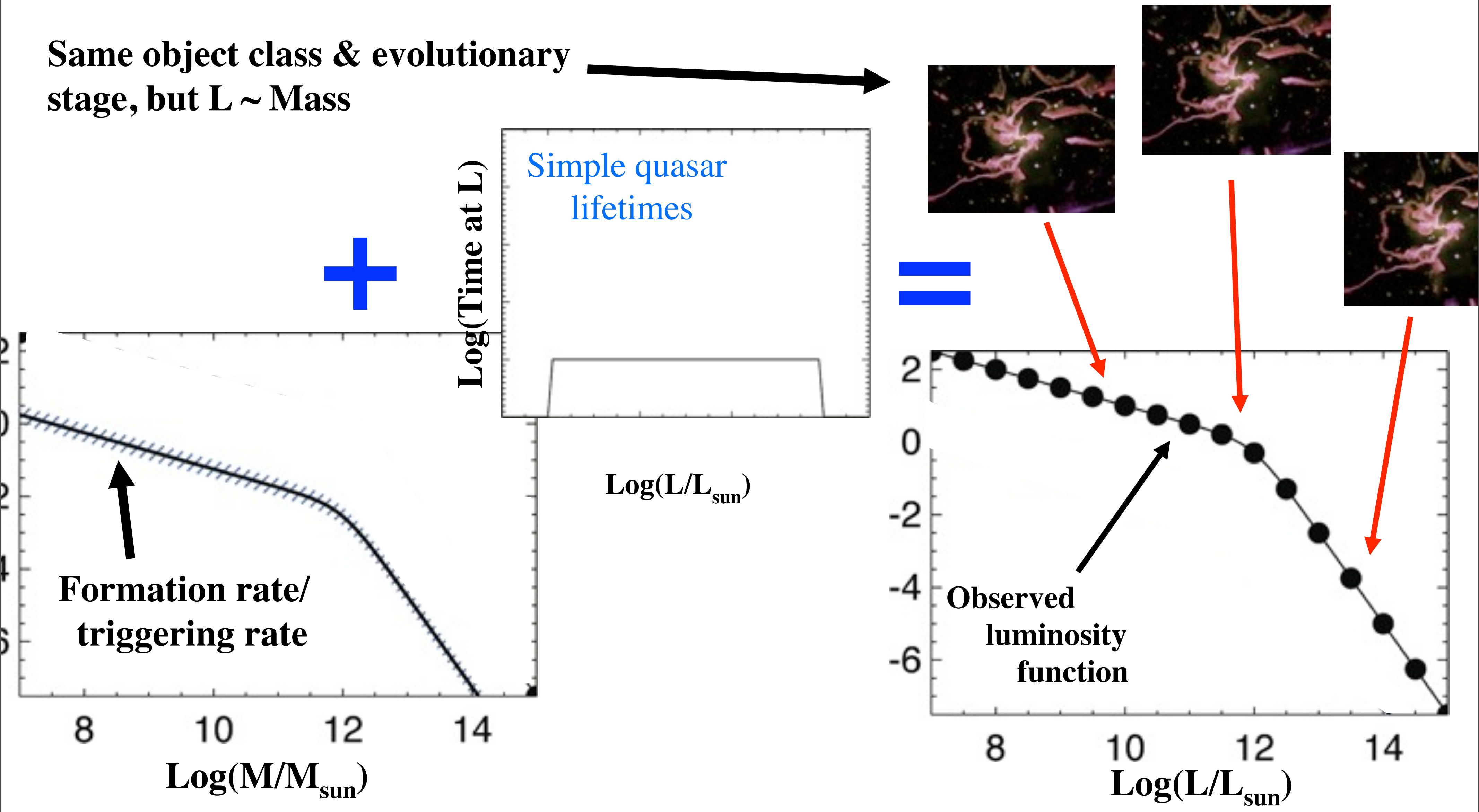




- If every quasar is at the same fraction of Eddington, the active BHMF (and host MF) is a trivial rescaling of the observed QLF

Given the Conditional Quasar Lifetime, De-Convolve the QLF

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



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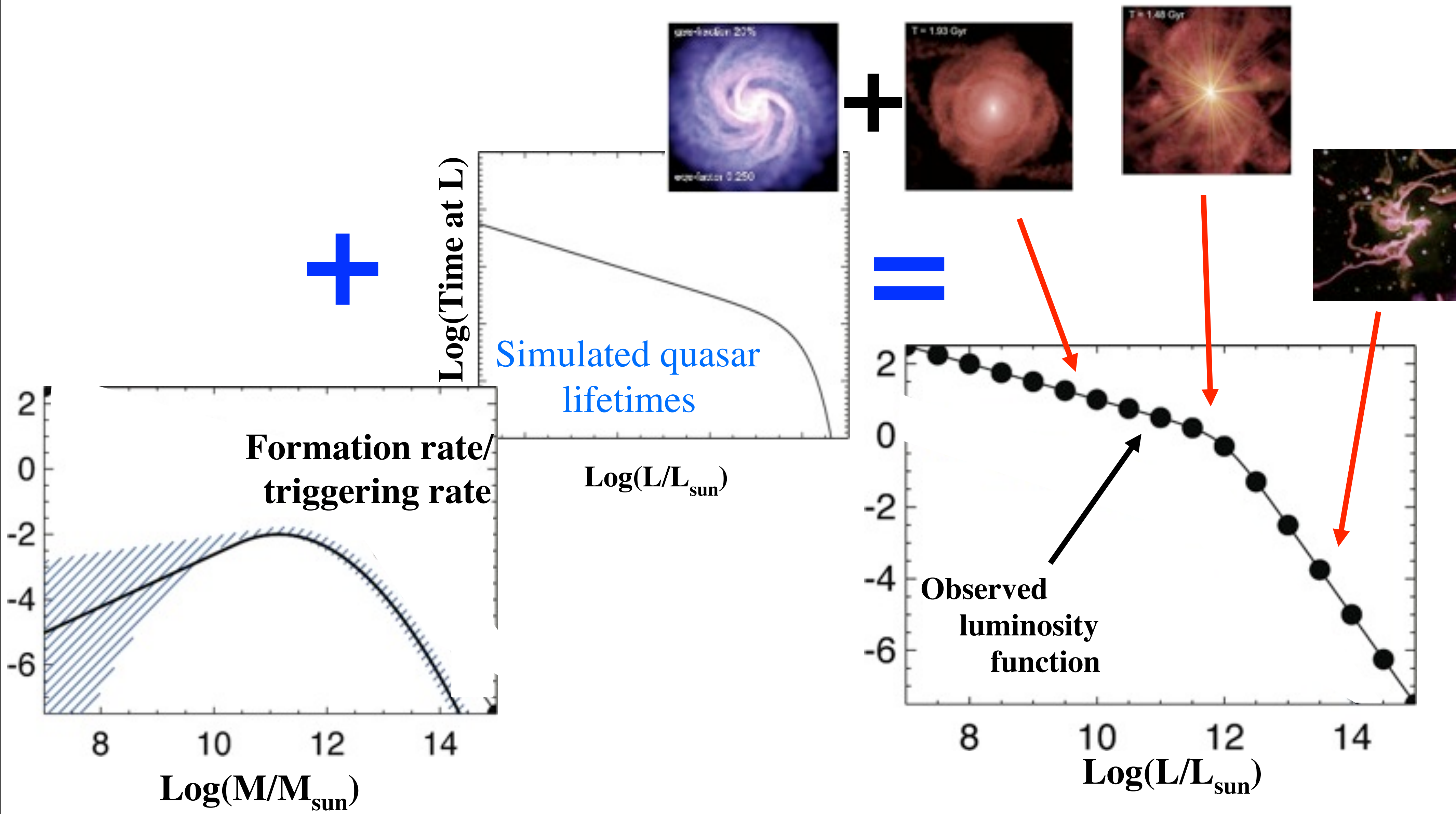
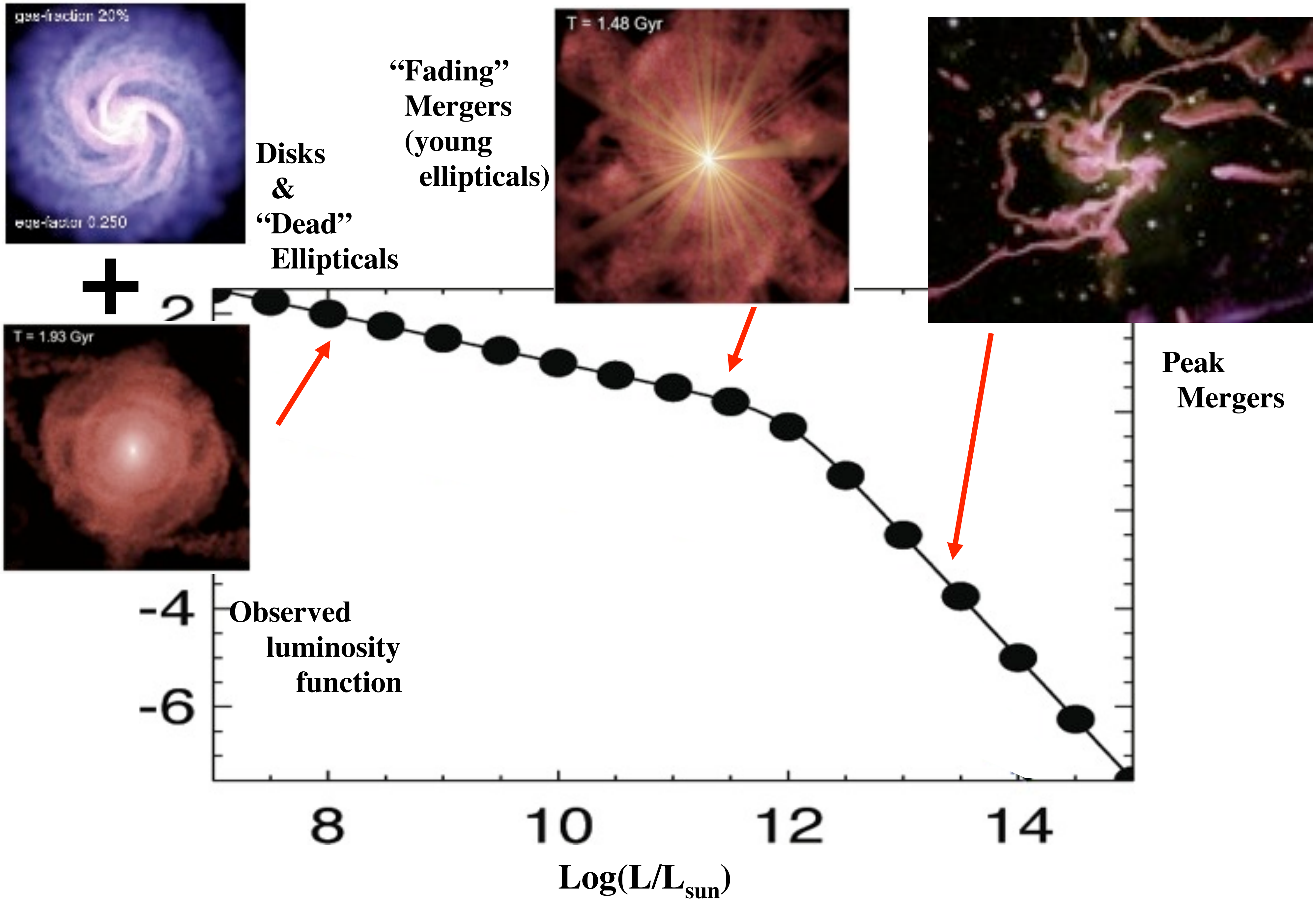


- *Different* shapes
- Much stronger turnover in formation/merger rate
- Faint-end QLF dominated by decaying sources with much larger peak luminosity/hosts

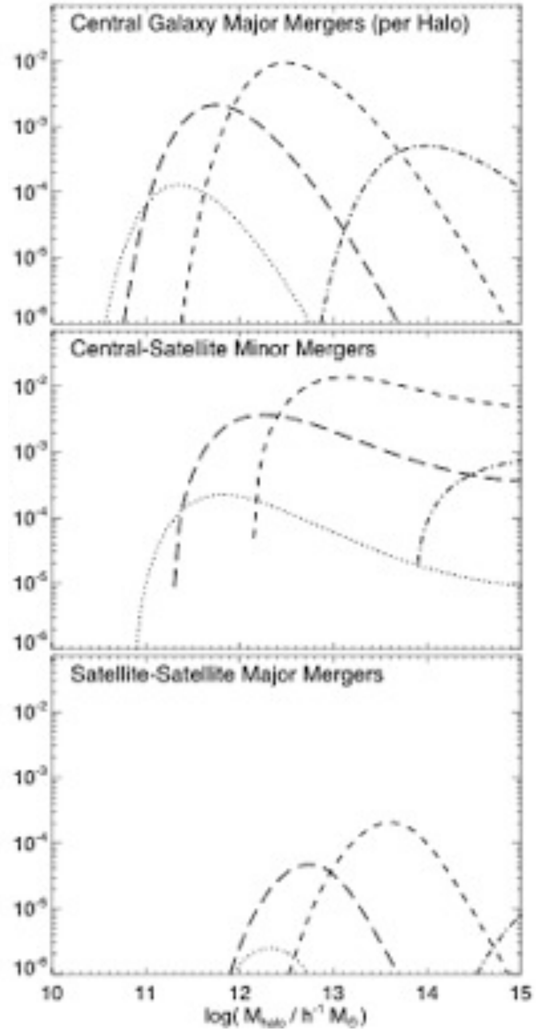


- Similar populations at different (short) *evolutionary* stages dominate QLF

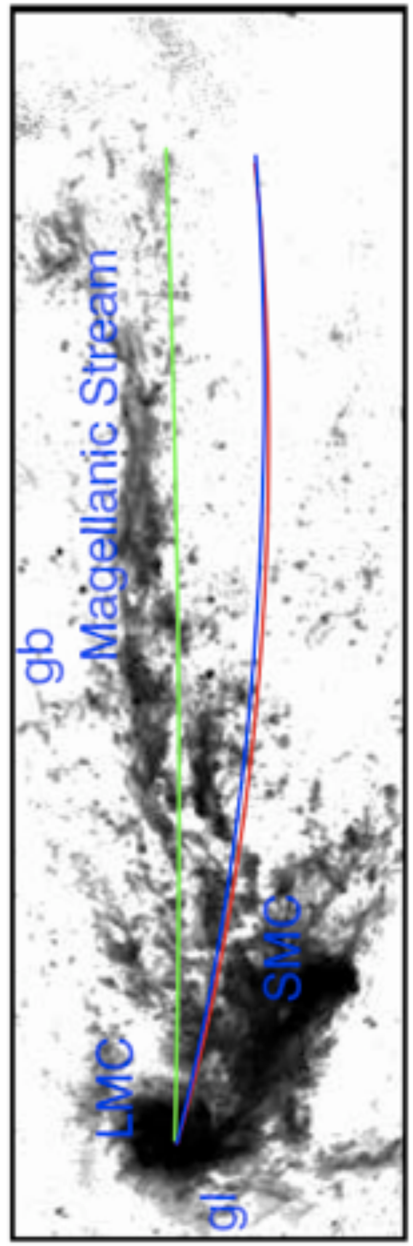
Other Fueling Mechanisms: Minor Mergers

left: Projected gas density
right: Projected stellar density
XY, the orbital plane

Isolated Disk (Sbc) Galaxy
Run: execute/G3G1-u3
T.J. Cox & Patrik Jonsson, UC Santa Cruz
UC Santa Cruz, 2004

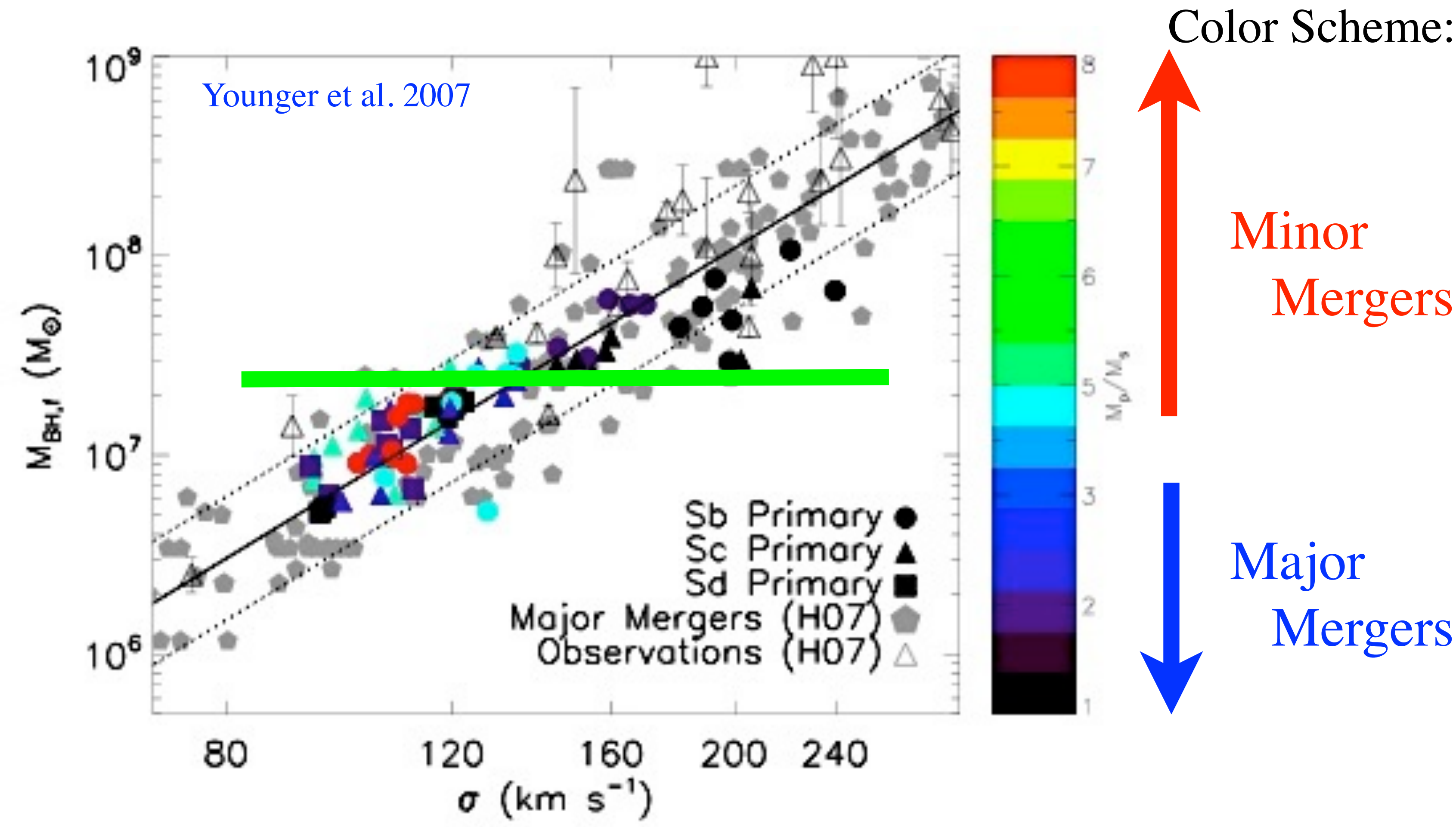


- Minor Mergers
  - Not so violent -probably don't dominate spheroid formation (LMC/SMC)
  - Not very efficient: even if growth ~ M_secondary/M_primary, major mergers "win"



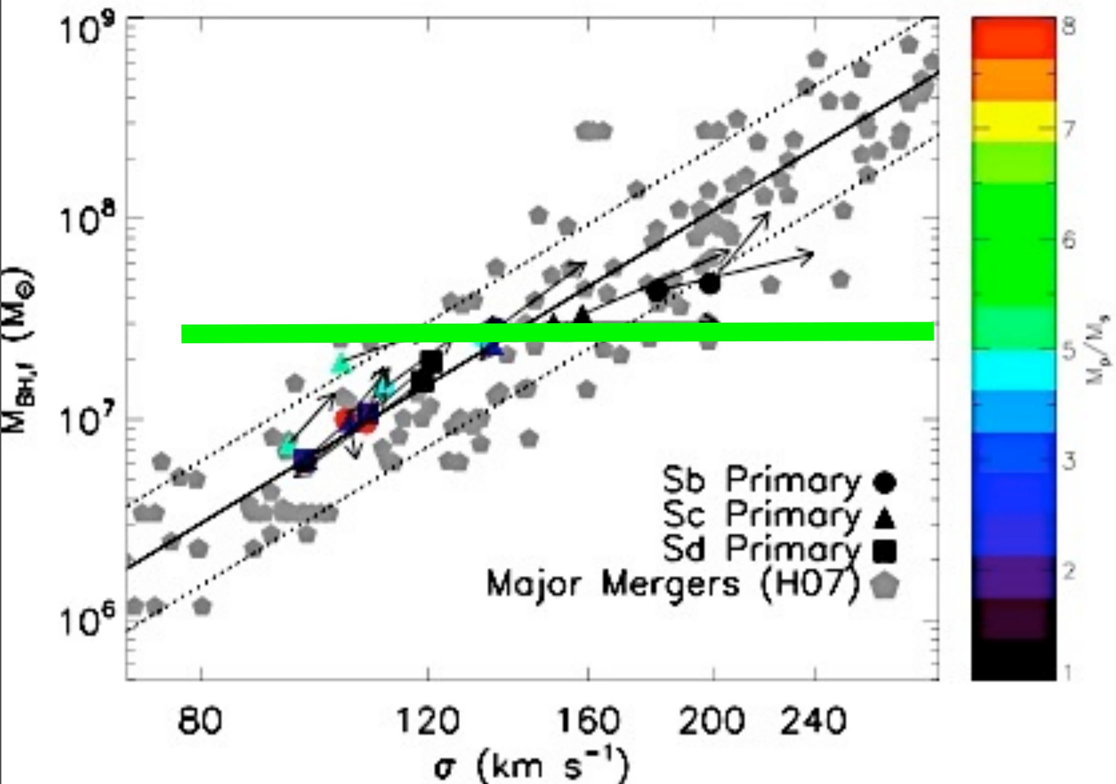
Besla et al. (2007)

Other Fueling Mechanisms: Minor Mergers



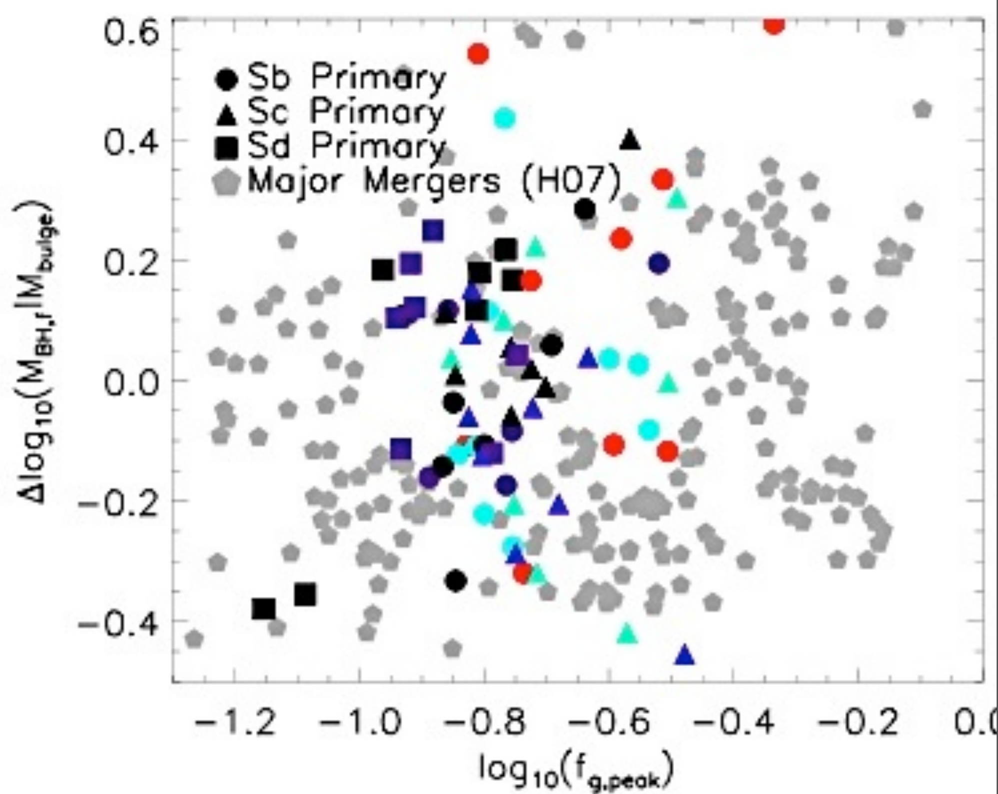
- Minor Mergers
  - Can get to ~1-2 10^7 M_sun ::: *very* hard to push beyond this

Other Fueling Mechanisms: Minor Mergers



- Increase f_gas to ~0.8-1.0: *same* upper limits

Final M_BH relative to mean

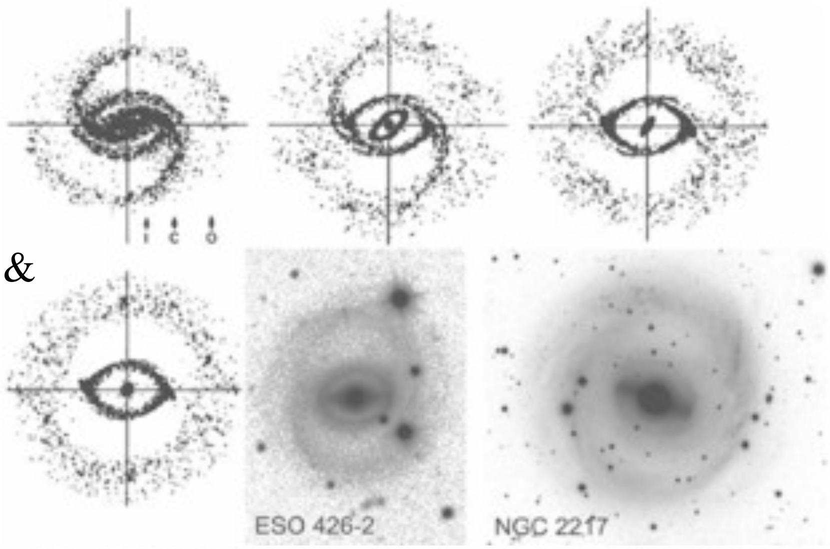


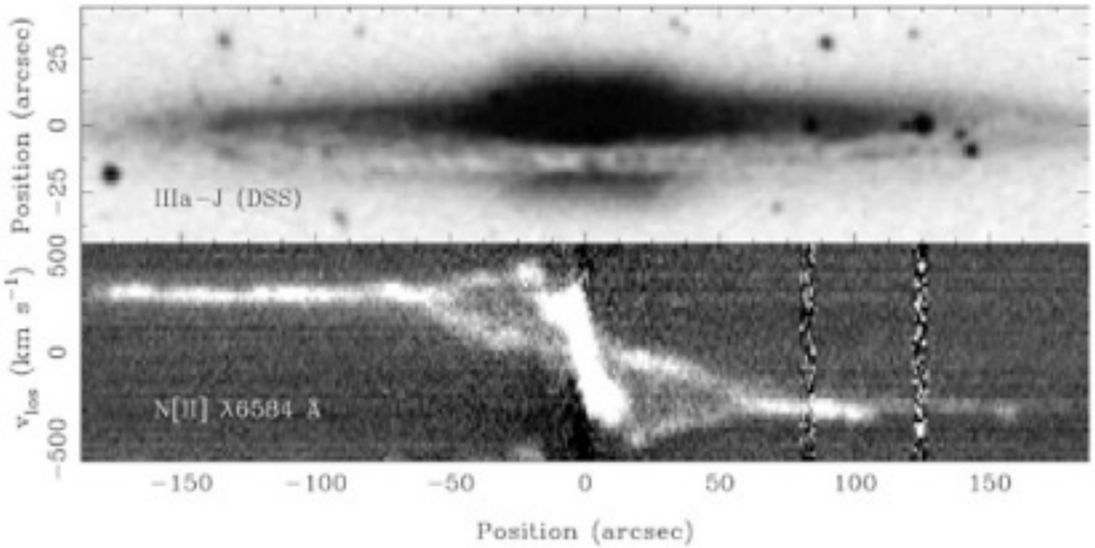
Mass of gas supplied to BH

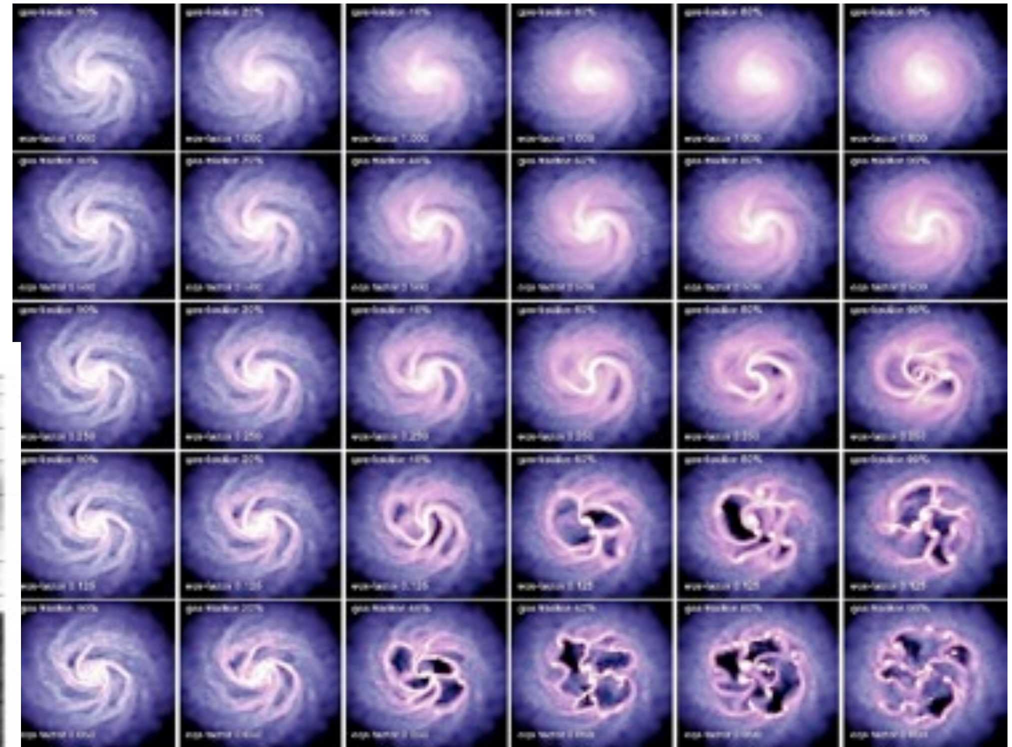
- BH doesn't care how much gas you give it:: building the potential depth is the hard part -- the BH will easily "catch up"

Other Fueling Mechanisms: Disk/Bar Instabilities

Kormendy & Kennicutt





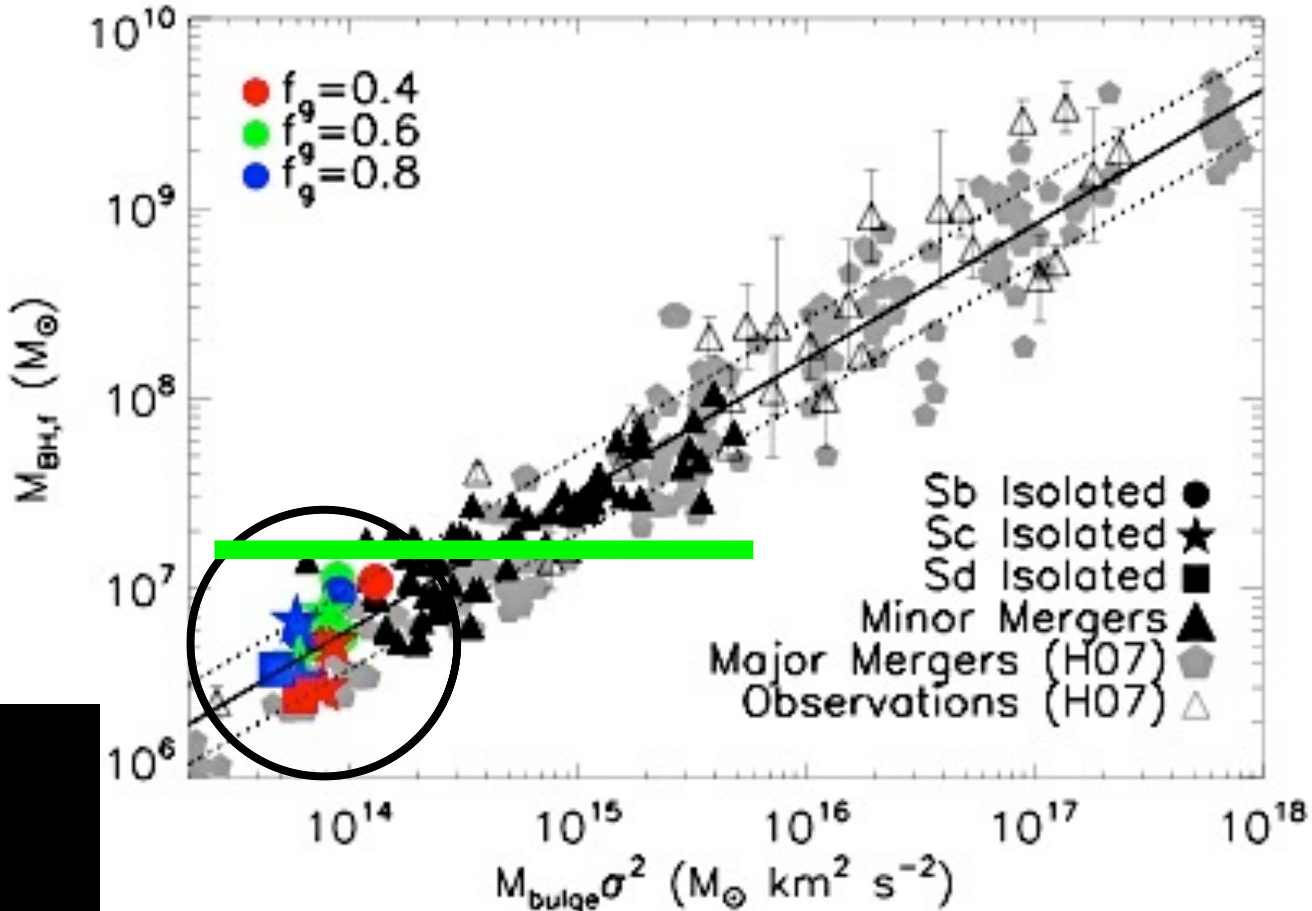


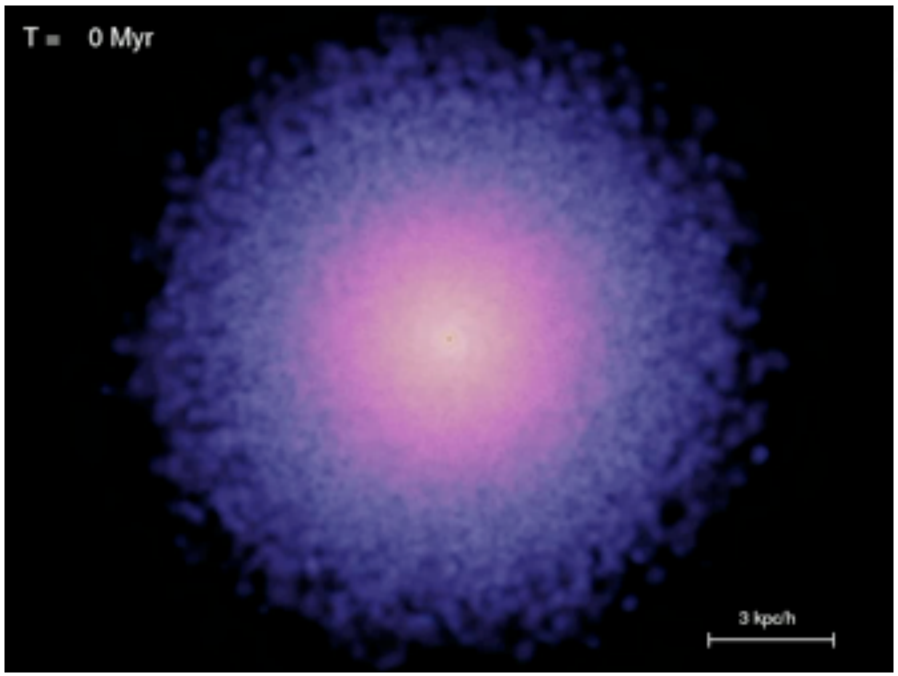
Springel et al. (2005)

- Secular Evolution/Disk Instabilities
  - Most mass in “classical” bulges, not “pseudobulges”:
    - But, *are* important below <~ Sa-types
  - Does it really solve the angular momentum problem? (Jogee et al.)

Other Fueling Mechanisms: Disk/Bar Instabilities

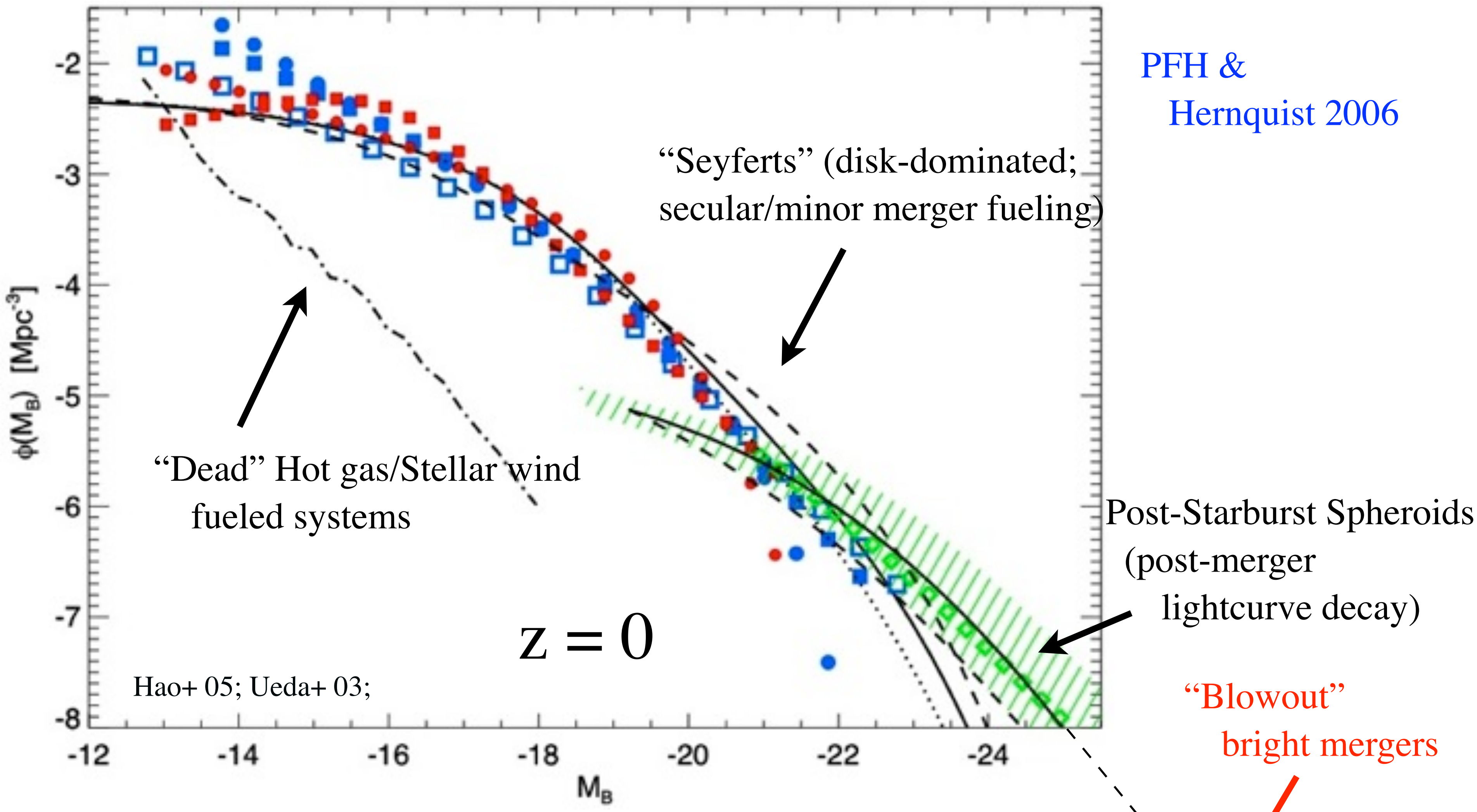
Bar & Toomre-unstable disk simulations:





- Same caveats as minor mergers:
  don't build massive bulges:
  doesn't matter if you can get the gas in!

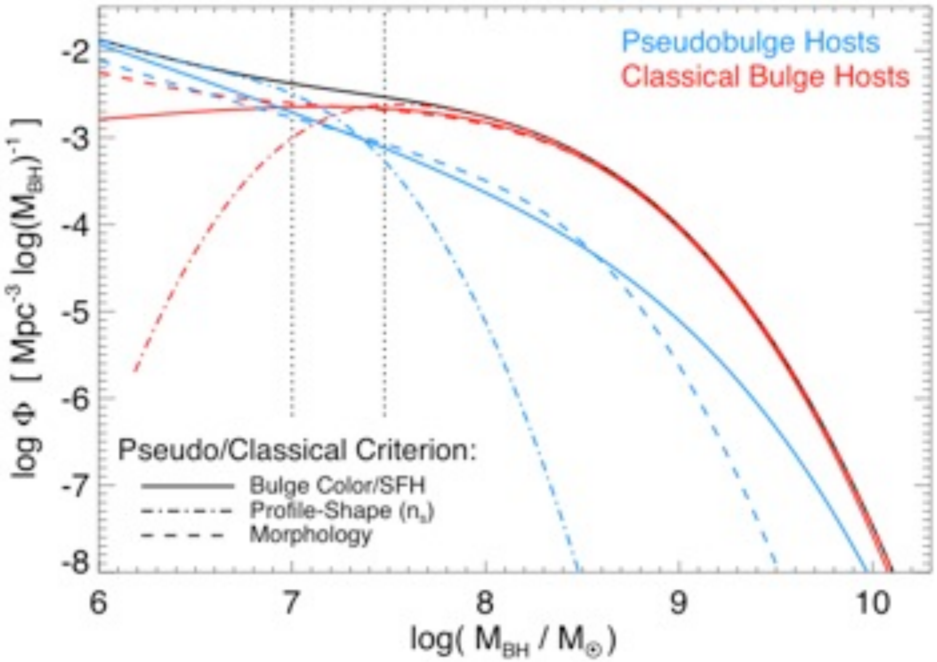
Emergent Picture:

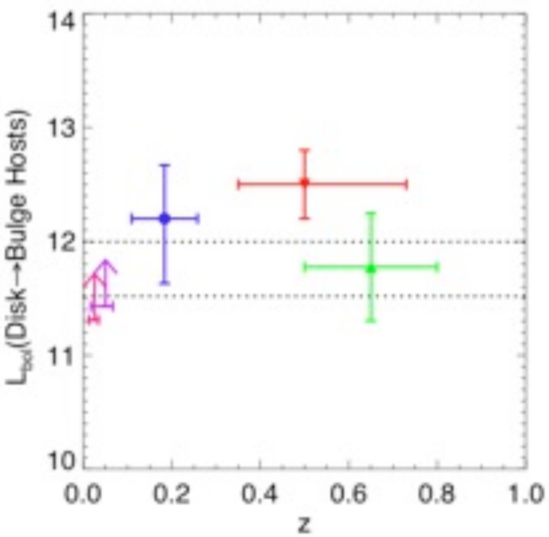


- Secular/Minor mergers dominate at M_B <~ -22 to -23:
  (L_x <~ a few 10^43)
  - Seyfert-Quasar divide is a good proxy!

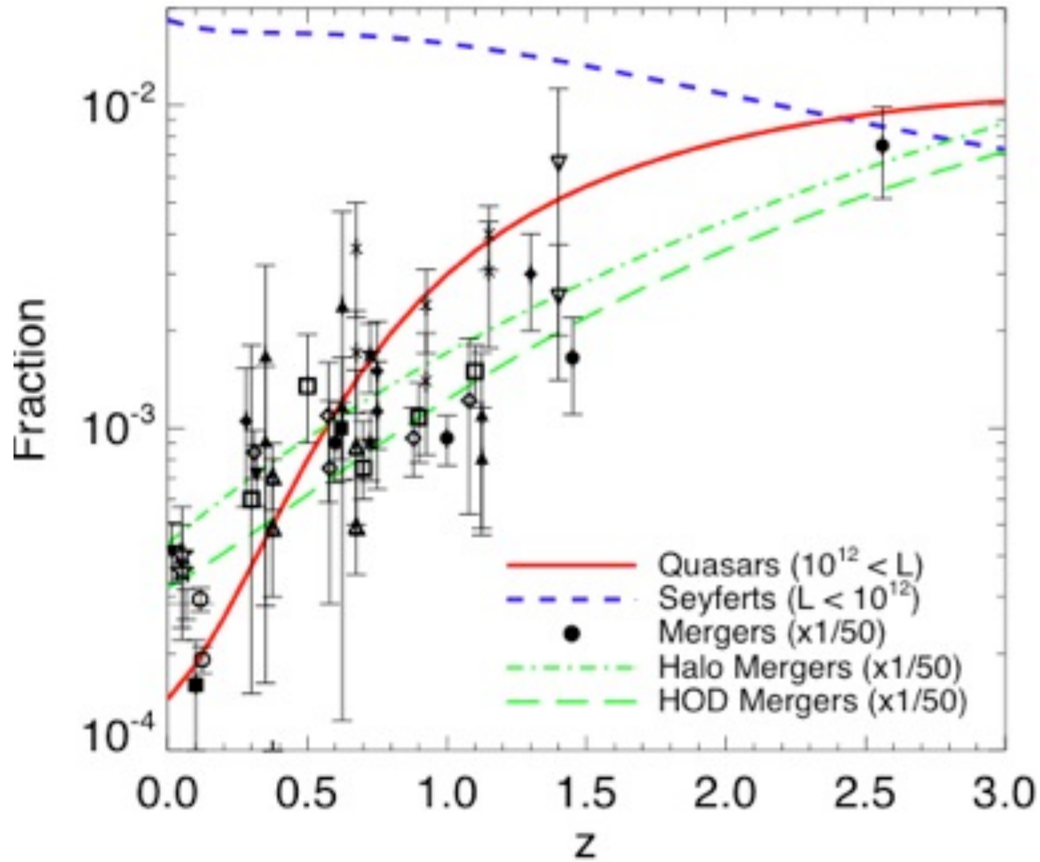
Does that picture hold up?

Appears to be true for hosts...



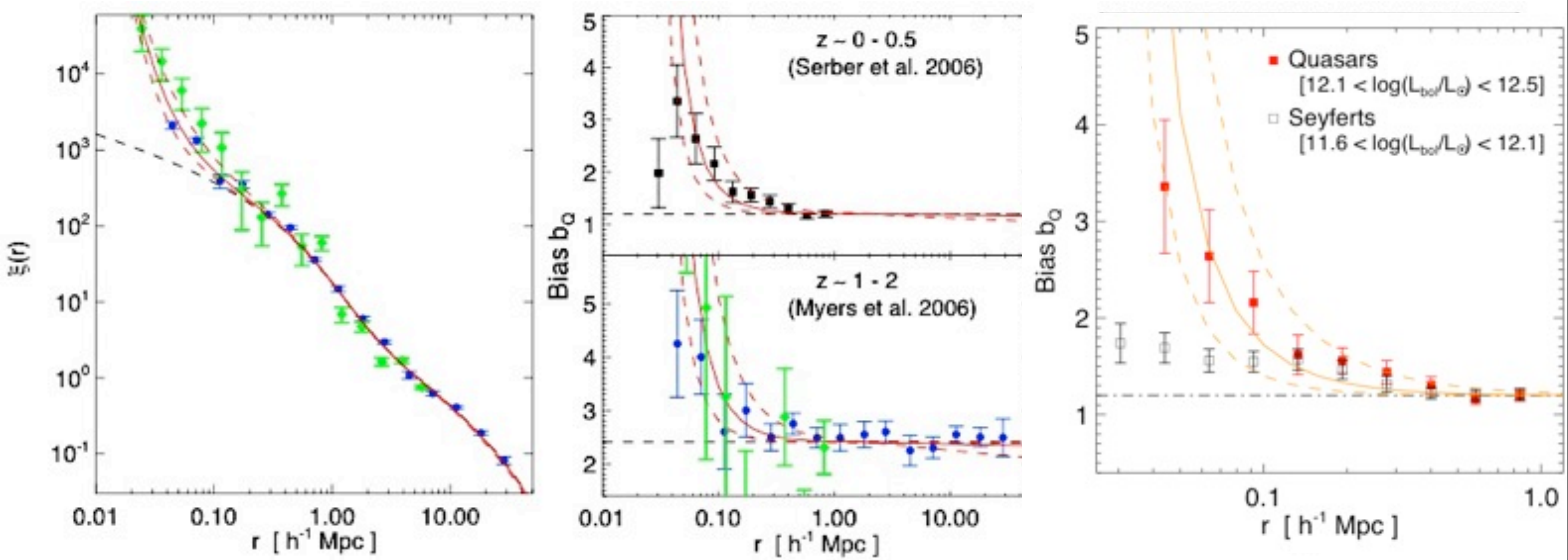


And may explain "downsizing" of AGN populations



Does that picture hold up?

- Observed excess of quasar clustering (quasar-galaxy and quasar-quasar pairs) on small scales, relative to "normal" galaxies with the same masses/large-intermediate scale clustering

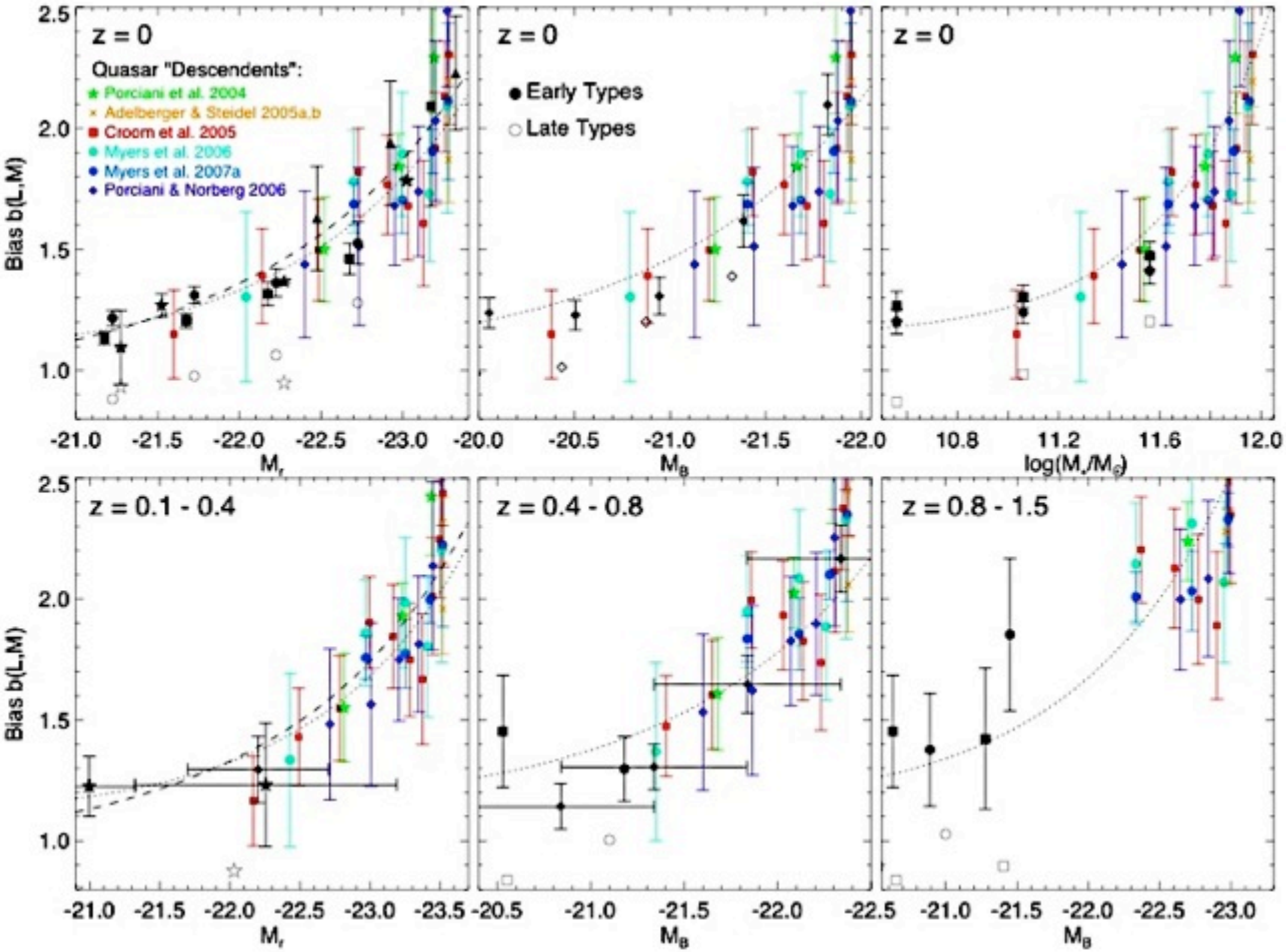


- Predicted by merger models (Thacker & Scannapieco et al., PFH)

Motivation

WHAT DO AGN MATTER TO THE REST OF COSMOLOGY?

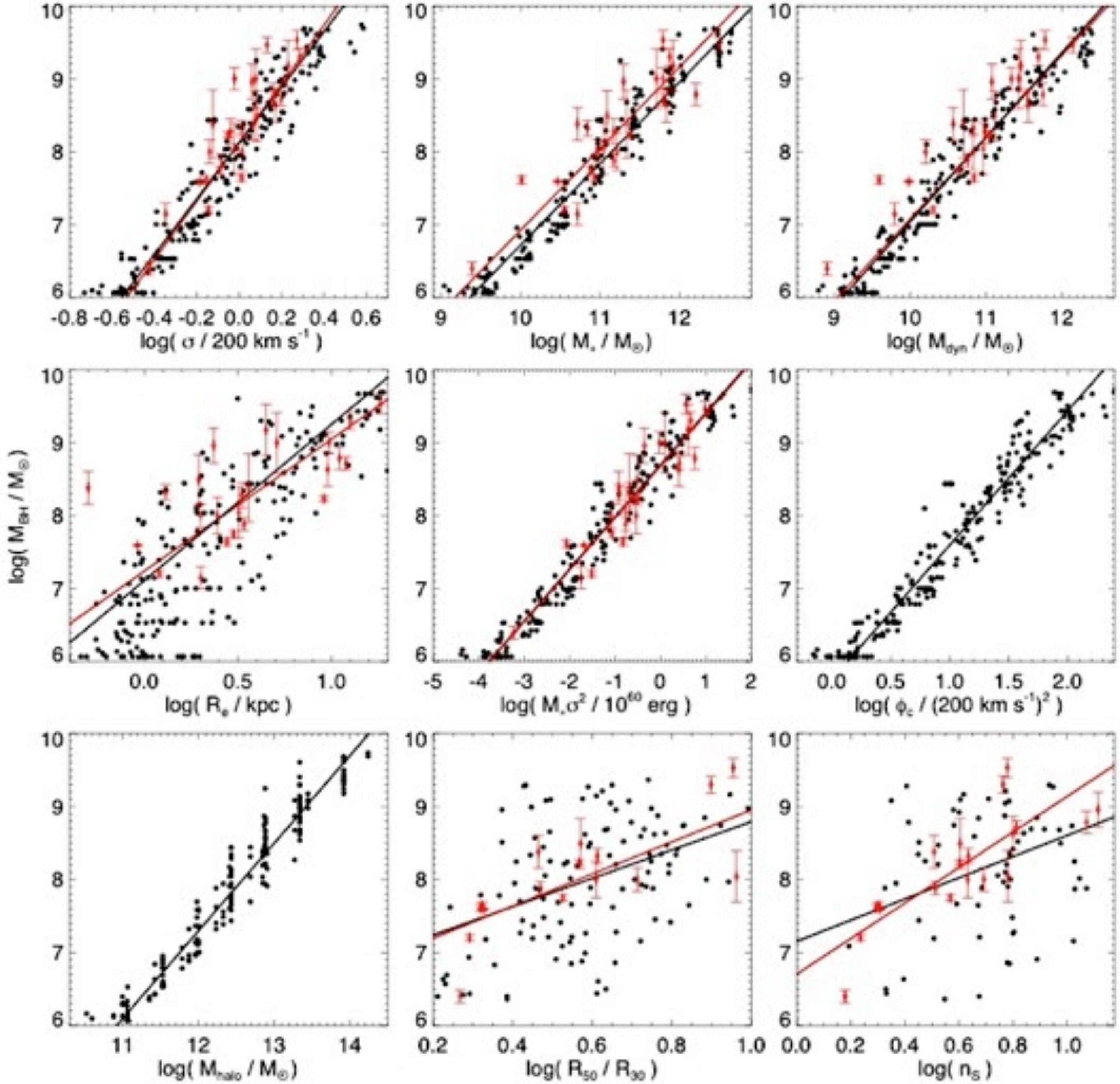
- Yesterday's Quasar is today's Red, Early-Type Galaxy:



PFH, Lidz, Coil, Myers+

Explains all the observed BH-Host Correlations

BUT WHAT IS THE "FUNDAMENTAL" CORRELATION?



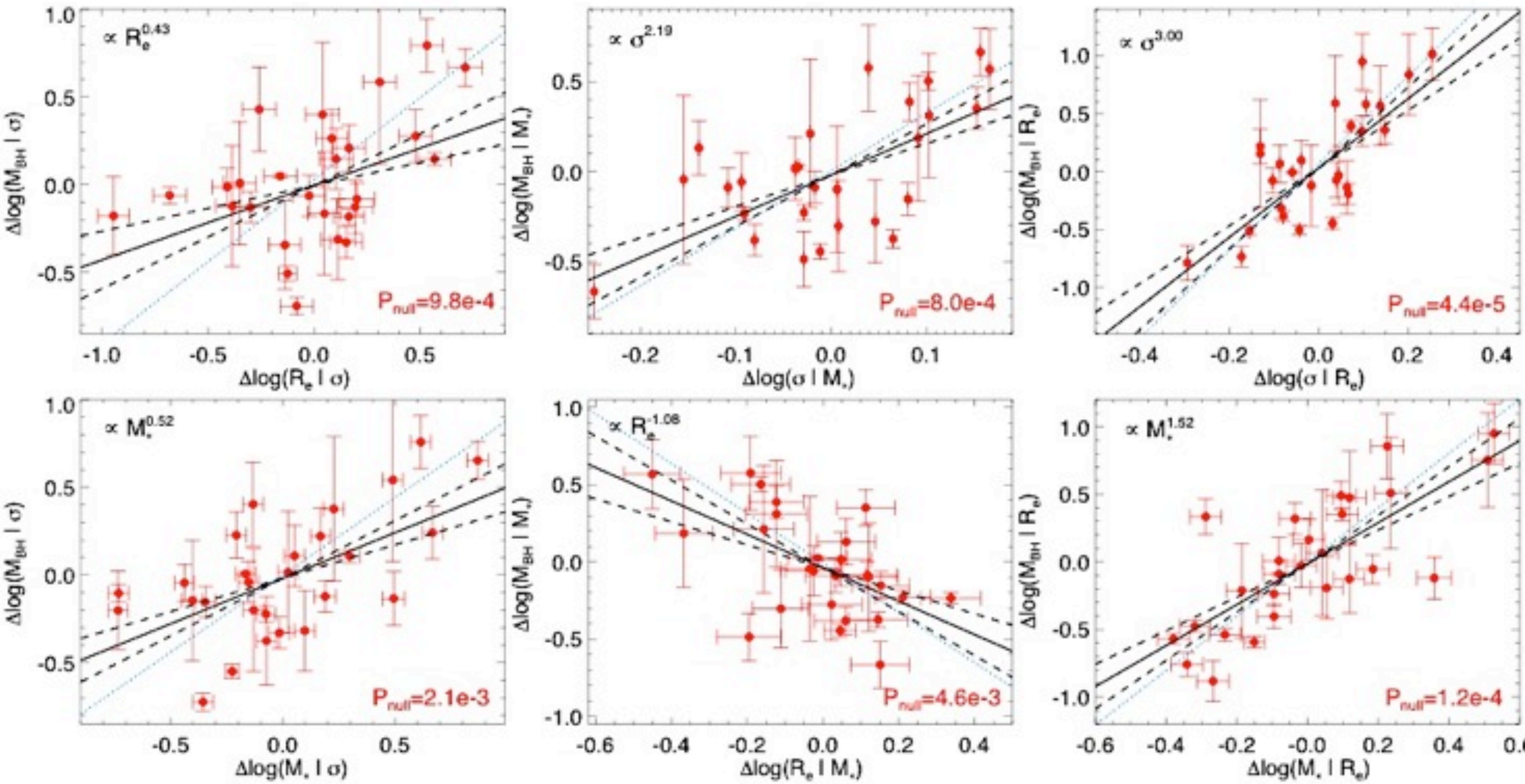
PFH et al. 2007

Which Correlation Is “Most Fundamental”?

PFH et al. 2007

COMPARE RESIDUALS

at fixed sigma: at fixed M_bul: at fixed R_e:

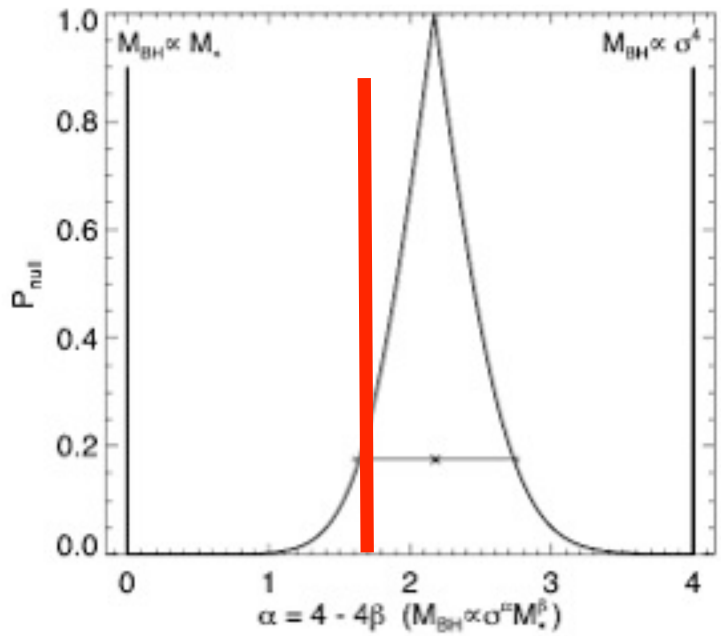


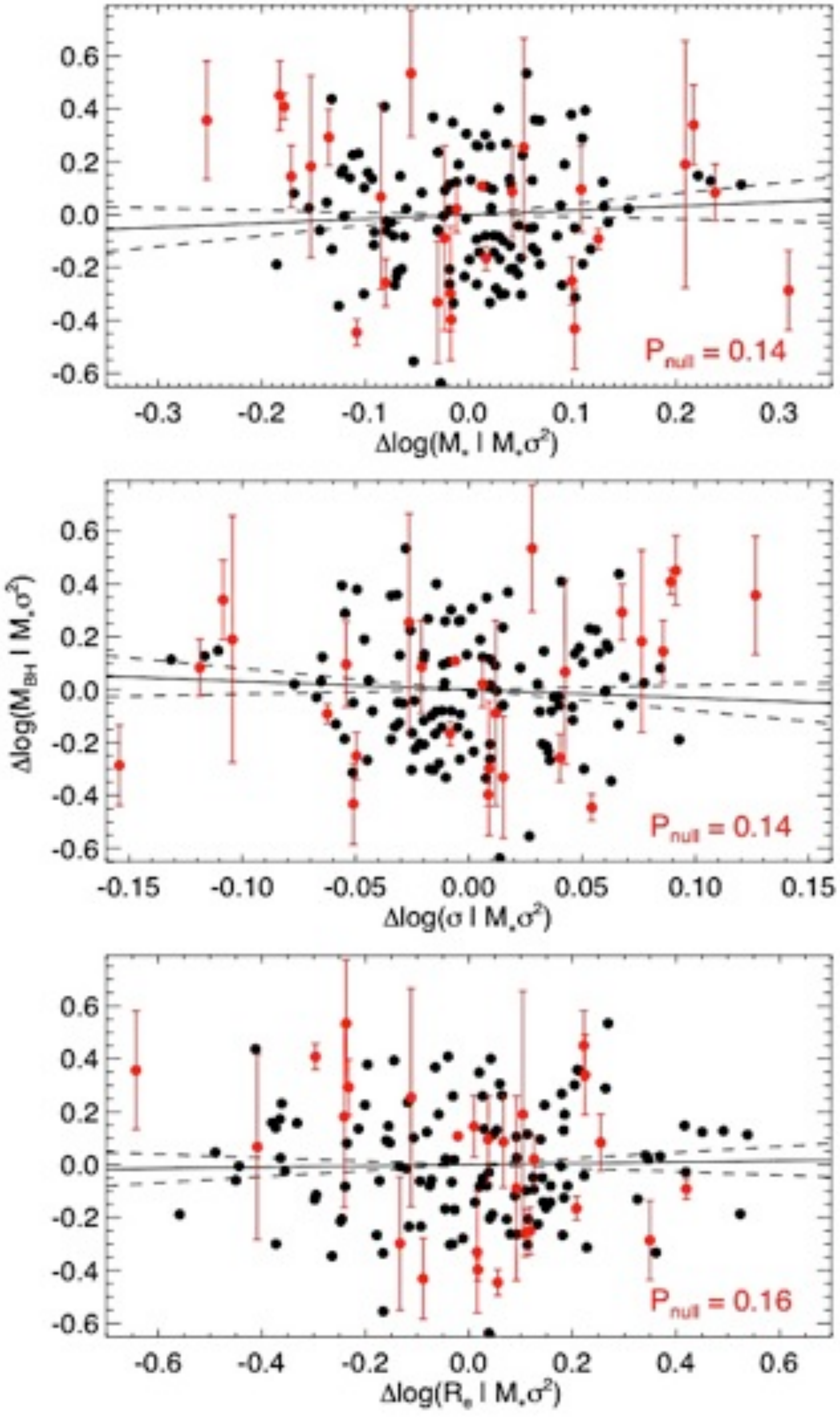
~3s significant residual trend with respect to ANY single variable correlation!

Which Correlation Is "Most Fundamental"?

WHAT ELIMINATES THE SECONDARY VARIABLES?

- Find a FP-like correlation:
  - $M_{bh} \sim M_{bul}^{a}\, s^{b}$
  - $M_{bh} \sim R_{e}^{a}\, s^{b}$
  - $M_{bh} \sim M_{bul}^{a}\, R_{e}^{b}$
- Roughly, bulge binding energy:
  - $M_{bh} \sim E_{binding}^{0.7\text{-}0.8} \sim (M_{bul}\, s^{2})^{0.7\text{-}0.8}$





PFH et al. 2007

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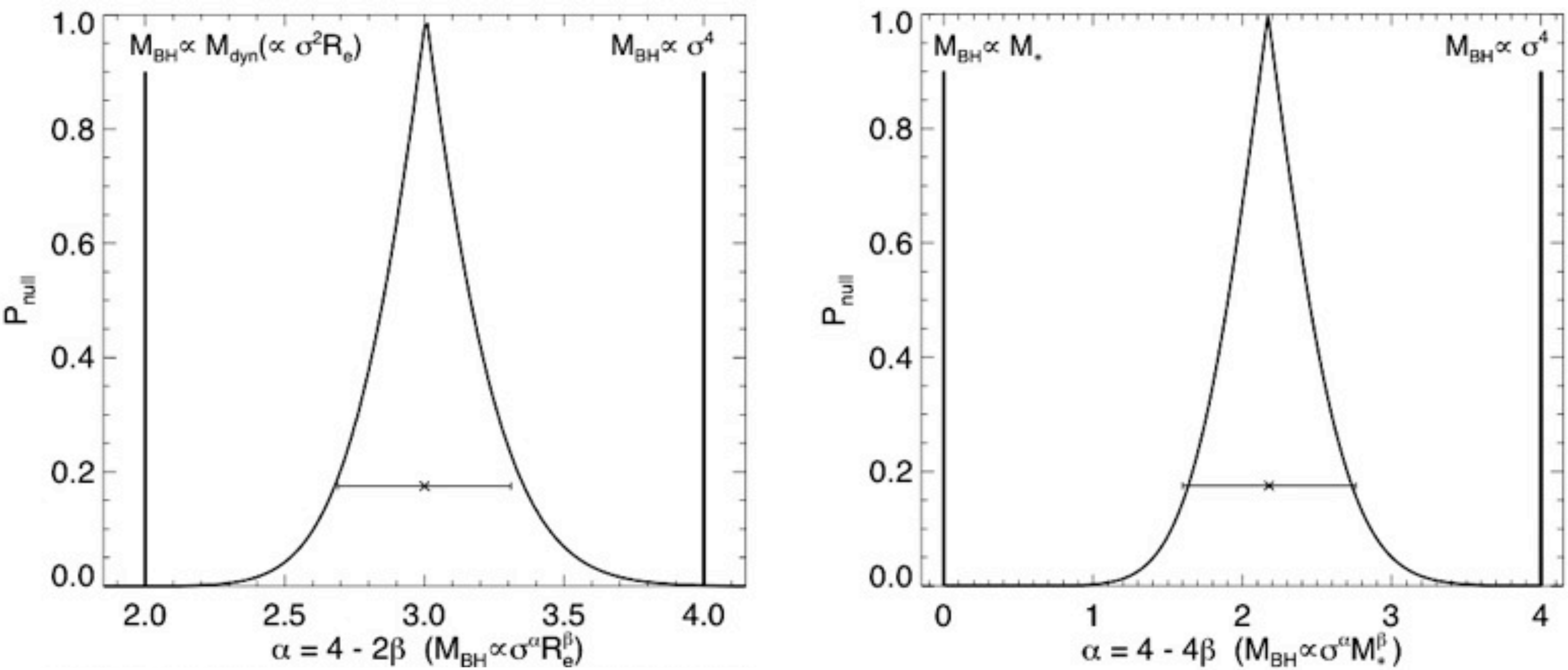

PFH et al. 2007

What about other fueling mechanisms?

BLACK HOLE MASSES IN ISOLATED GALAXIES AND MERGER REMNANTS