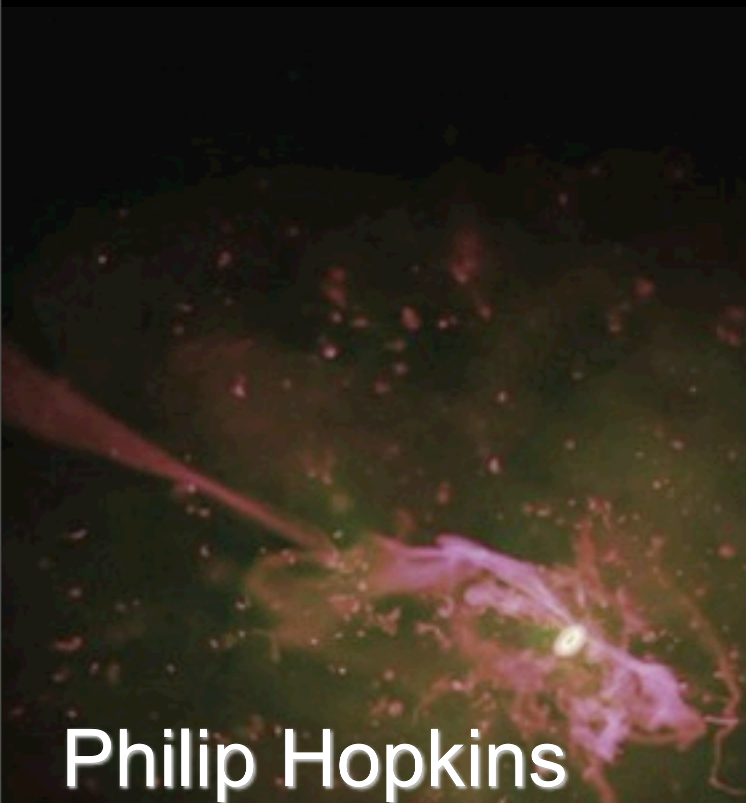
Galaxy Mergers: A Factory for Quasars, Feedback, Ellipticals, and even Disks?



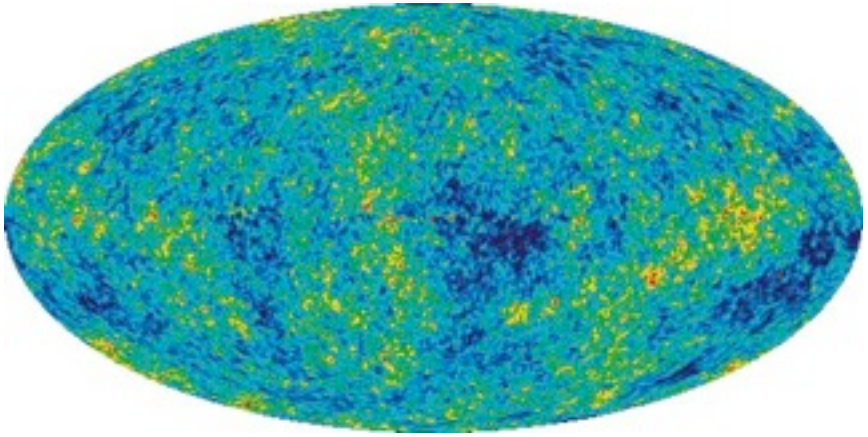
Philip Hopkins

04/14/09

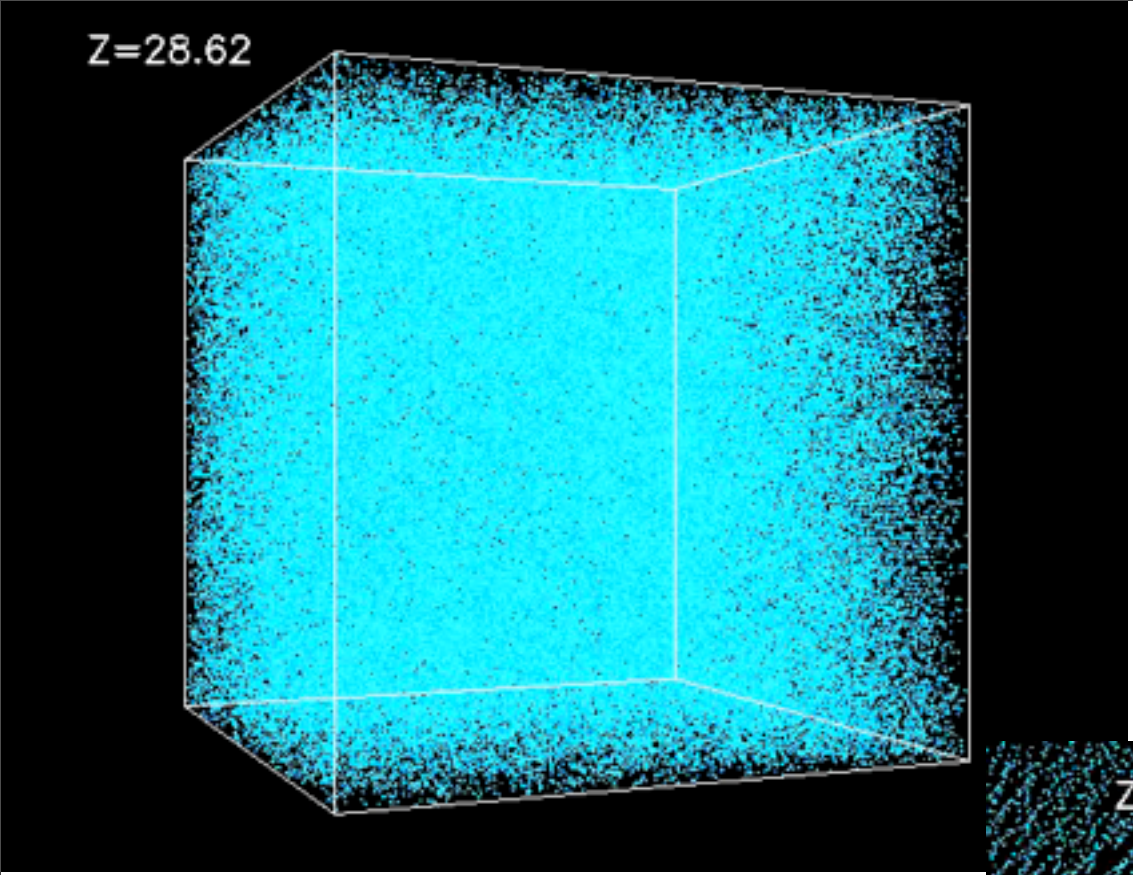
Lars Hernquist, T. J. Cox, Dusan Keres, Eliot Quataert, Chung-Pei Ma,
Josh Younger, Volker Springel, Norm Murray, Kevin Bundy,
Brant Robertson, John Kormendy, Tod Lauer, Adam Lidz, Tiziana Di Matteo,
Yuexing Li, Gordon Richards, Alison Coil, Adam Myers, and many more

Motivation

HOW DID WE GET TO GALAXIES TODAY?



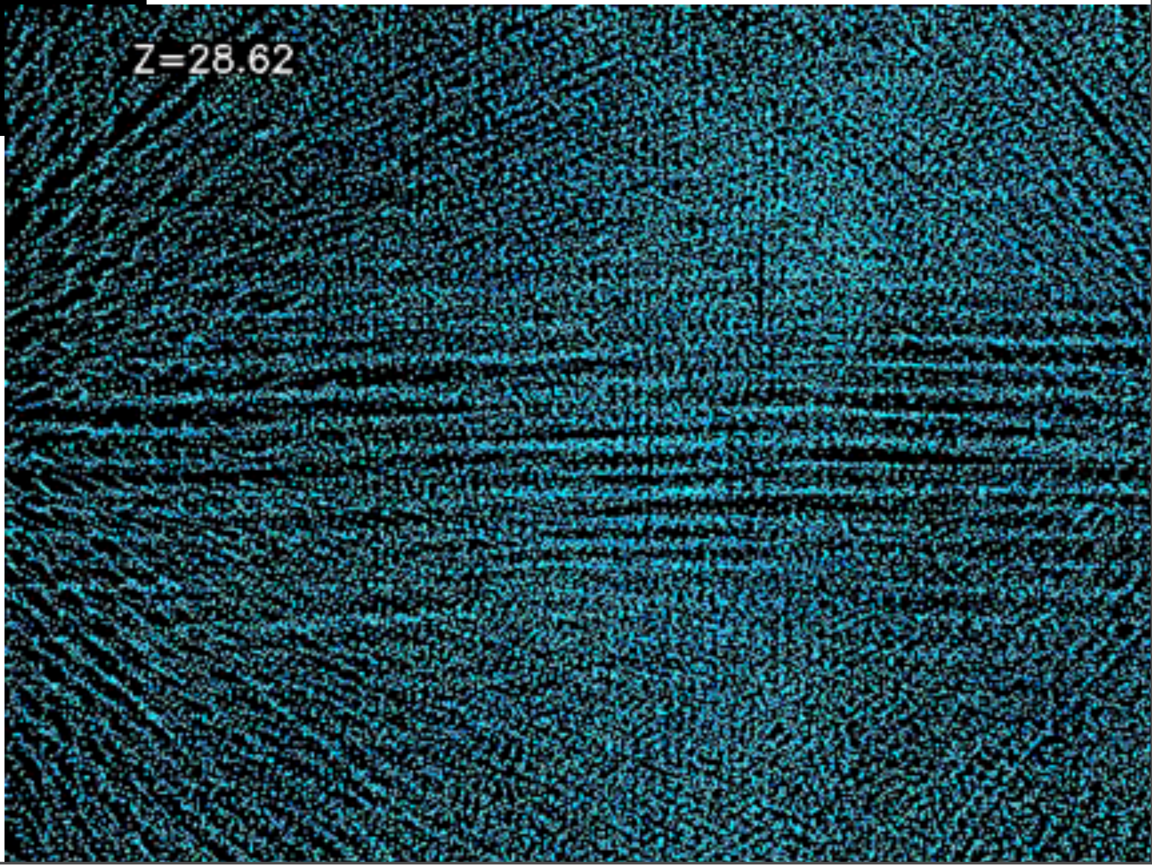
?



Motivation

HOW DID WE GET TO GALAXIES TODAY?

Kravtsov et al.

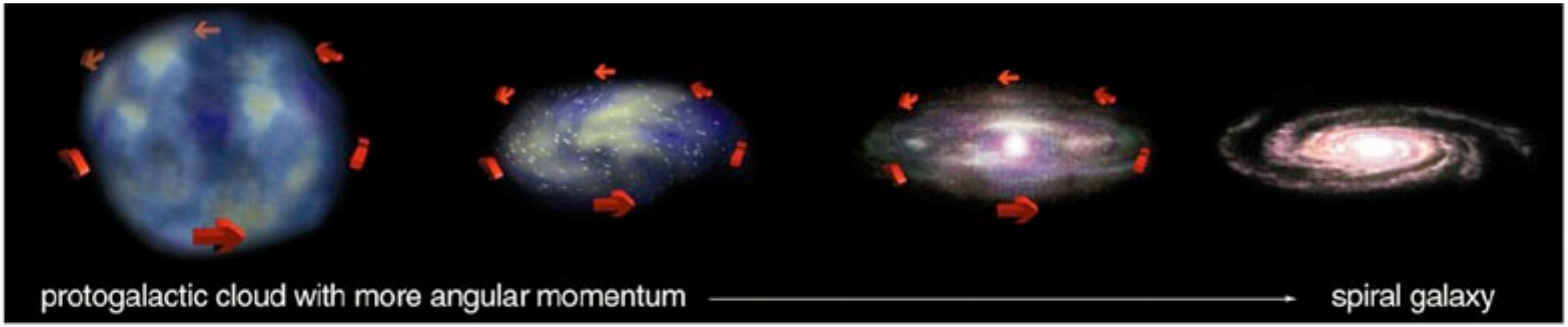


- Structure grows hierarchically: *must* understand mergers

Motivation

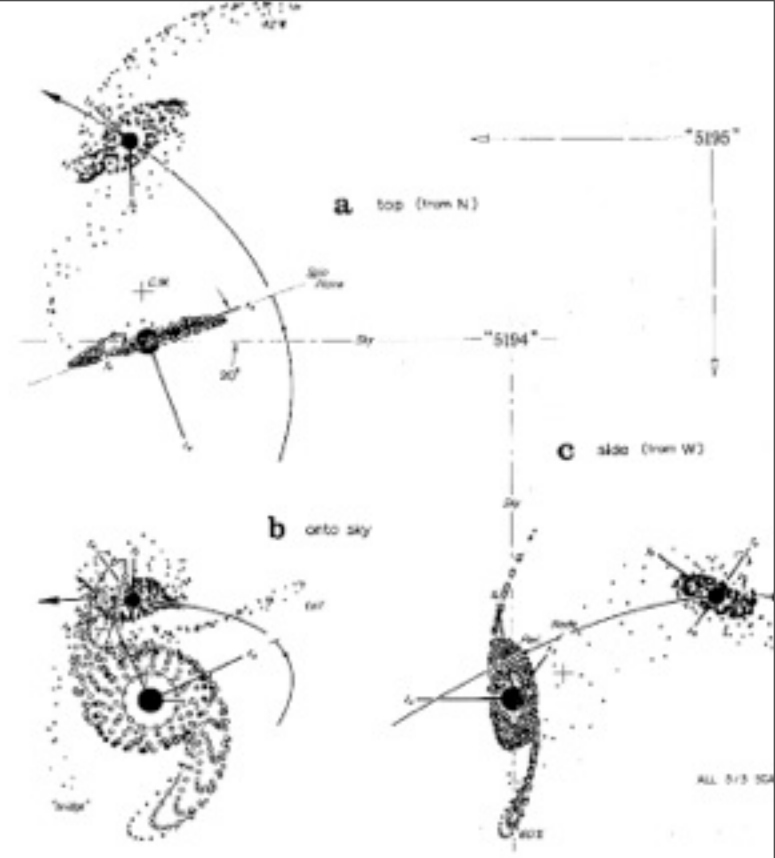
HOW DID WE GET TO GALAXIES TODAY?

- Dark matter halos collapse: gas cools into a disk



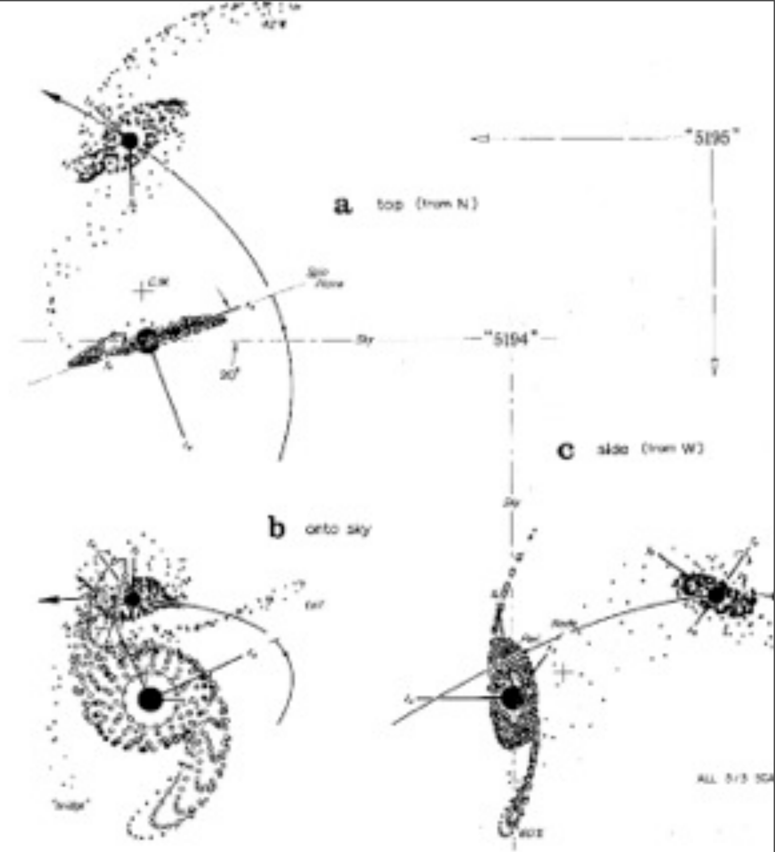
- What happens when that starts colliding into other galaxies?

Our Conventional Wisdom (Toomre):



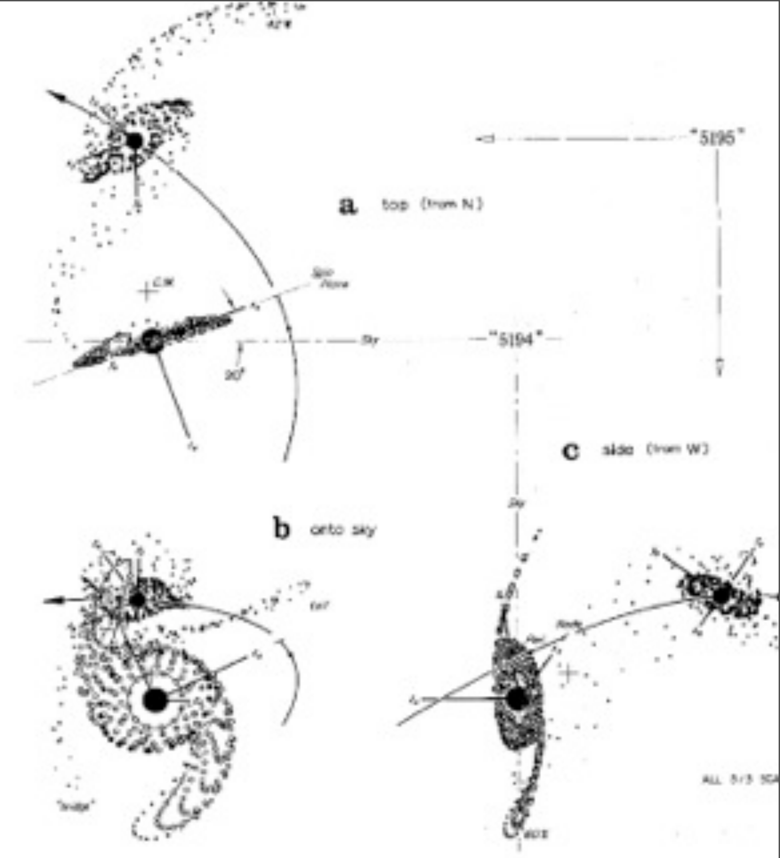
Our Conventional Wisdom (Toomre):

- Major mergers destroy disks



Our Conventional Wisdom (Toomre):

- Major mergers destroy disks
- Minor mergers make thick disk



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- Major mergers destroy disks
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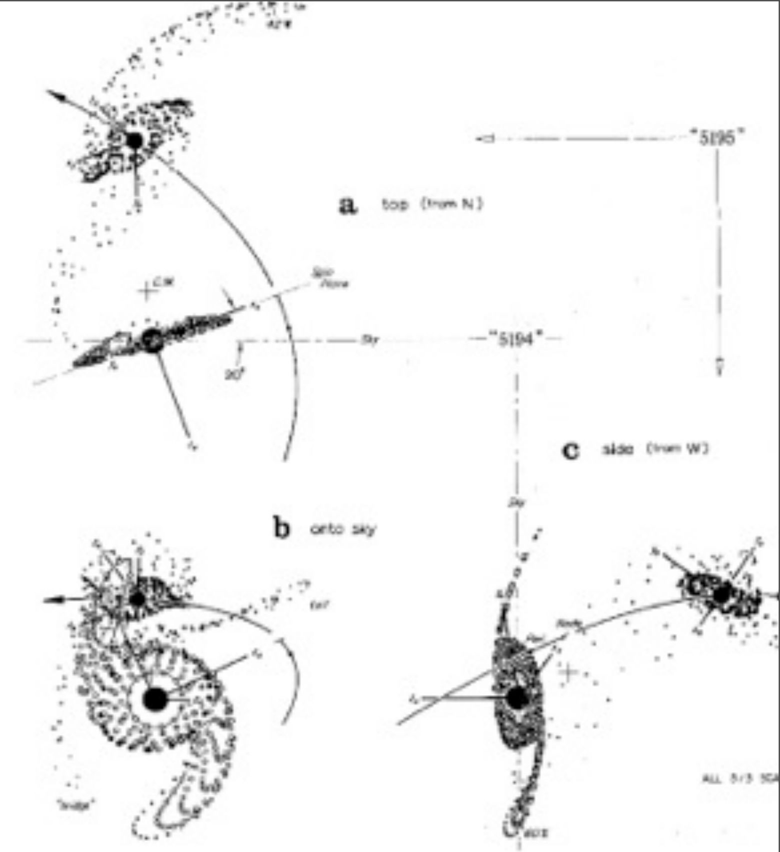
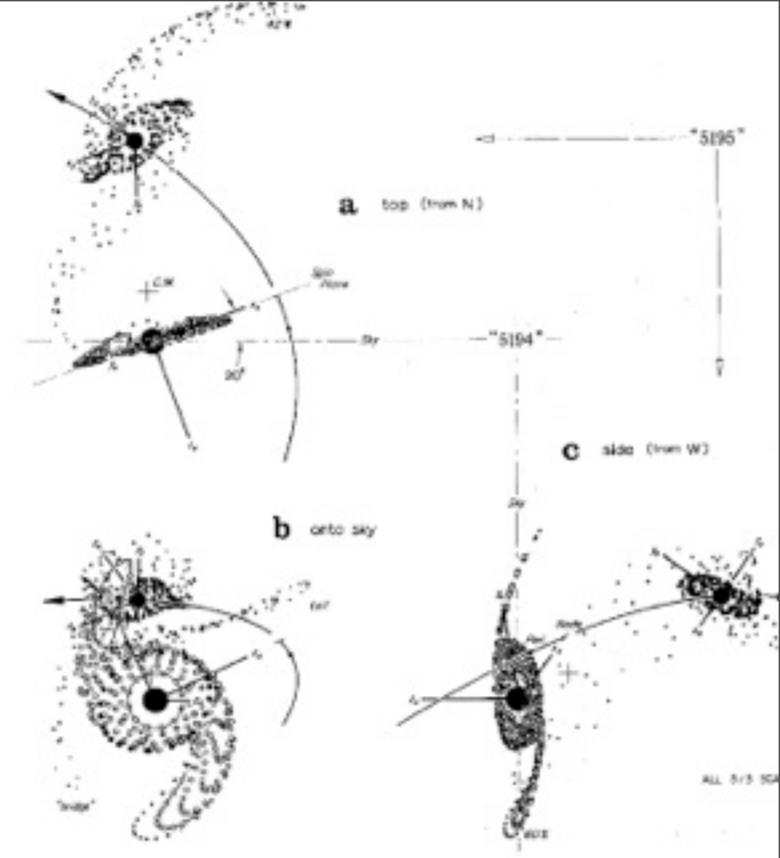
- Remnant has an $r^{1/4}$ law profile



Our Conventional Wisdom (Toomre):

- Major mergers destroy disks
- Minor mergers make thick disk
- Remnant has an $r^{1/4}$ law profile
- Remnant size/metallicity/shape retains "memory" of disk "initial conditions"



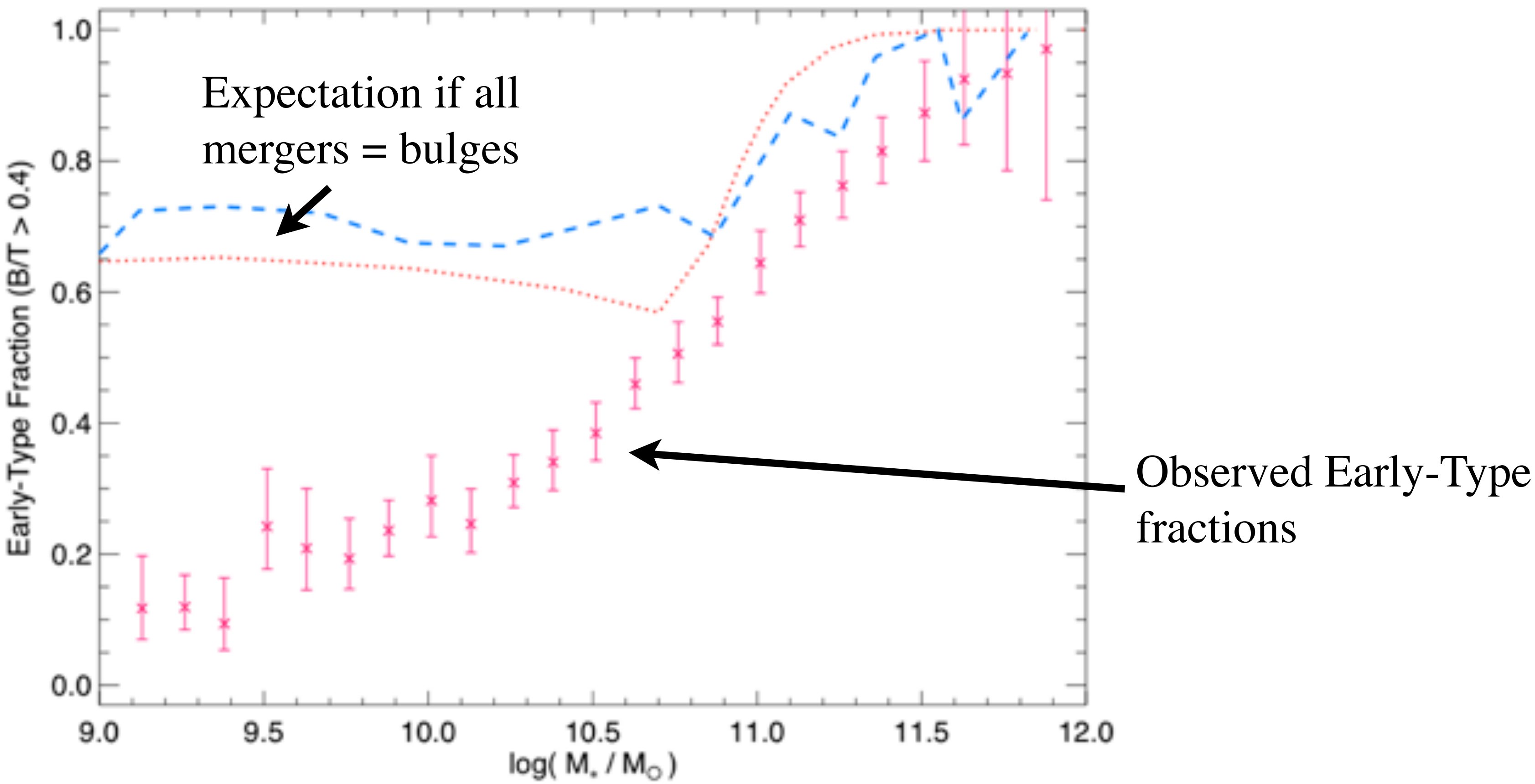
Motivation

HOW DID WE GET TO GALAXIES TODAY?

1970’s... most of these are good things

Today... problems!

Too many mergers!



Motivation

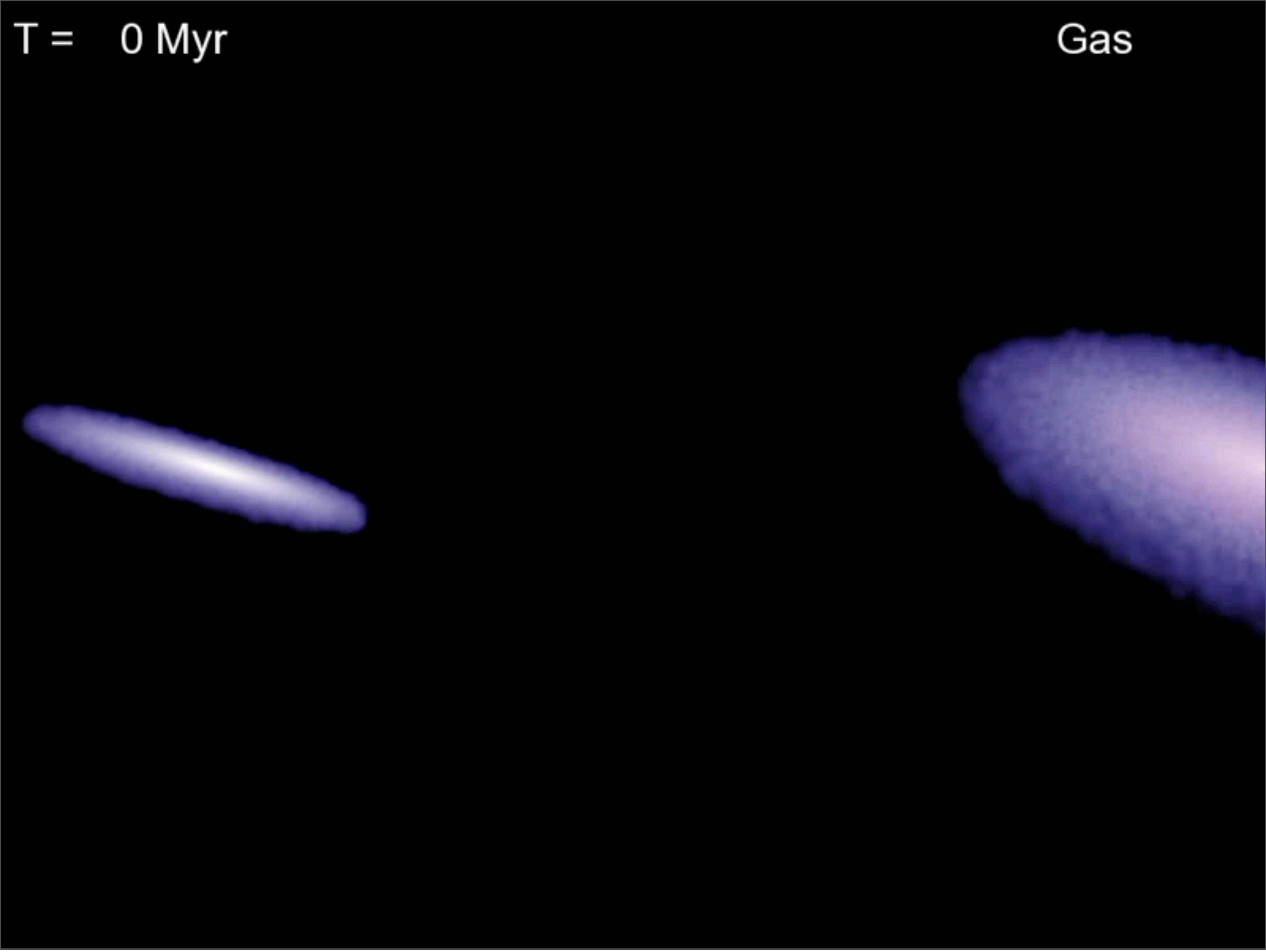
HOW DID WE GET TO GALAXIES TODAY?

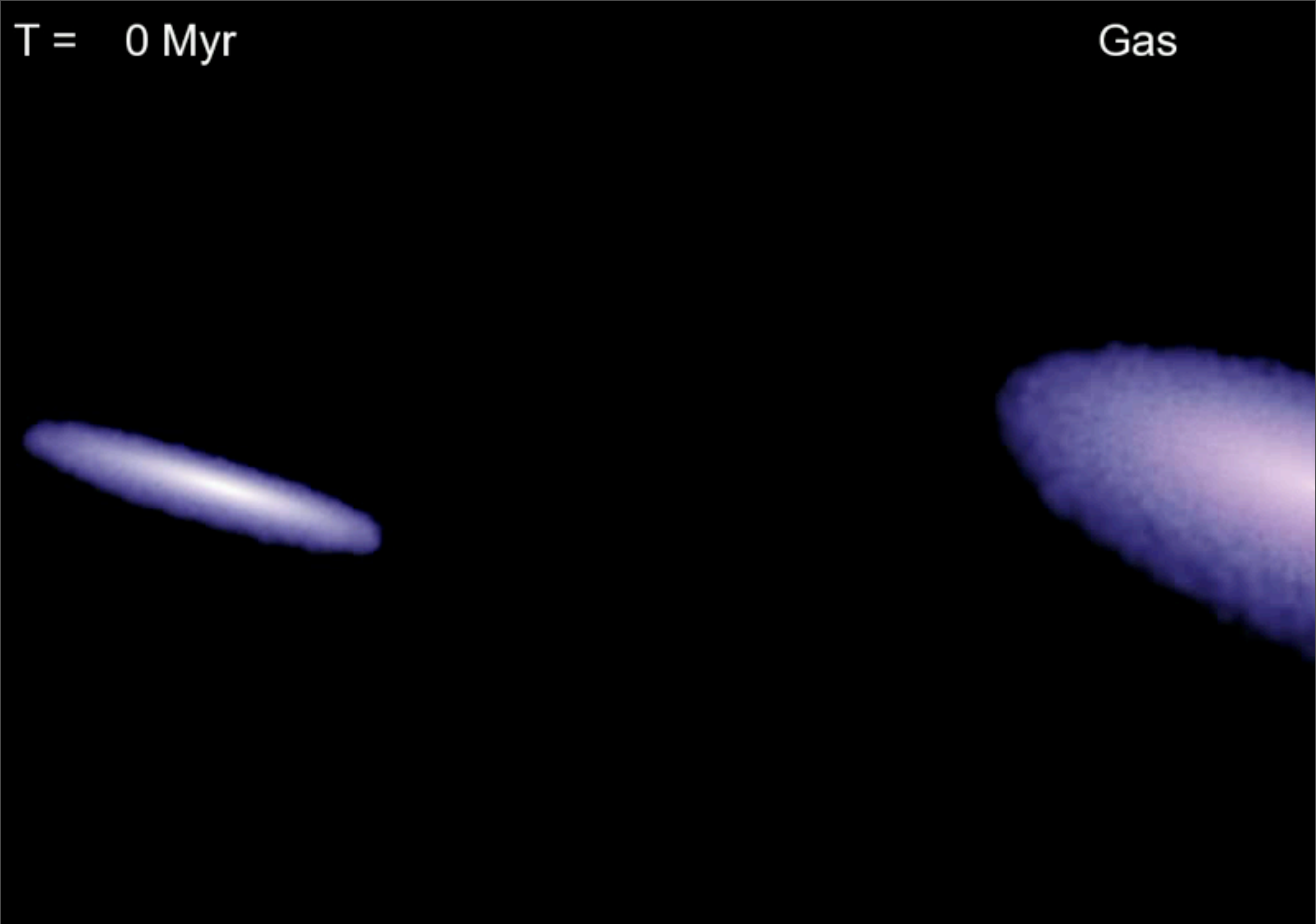
Today...

Too Many Mergers!

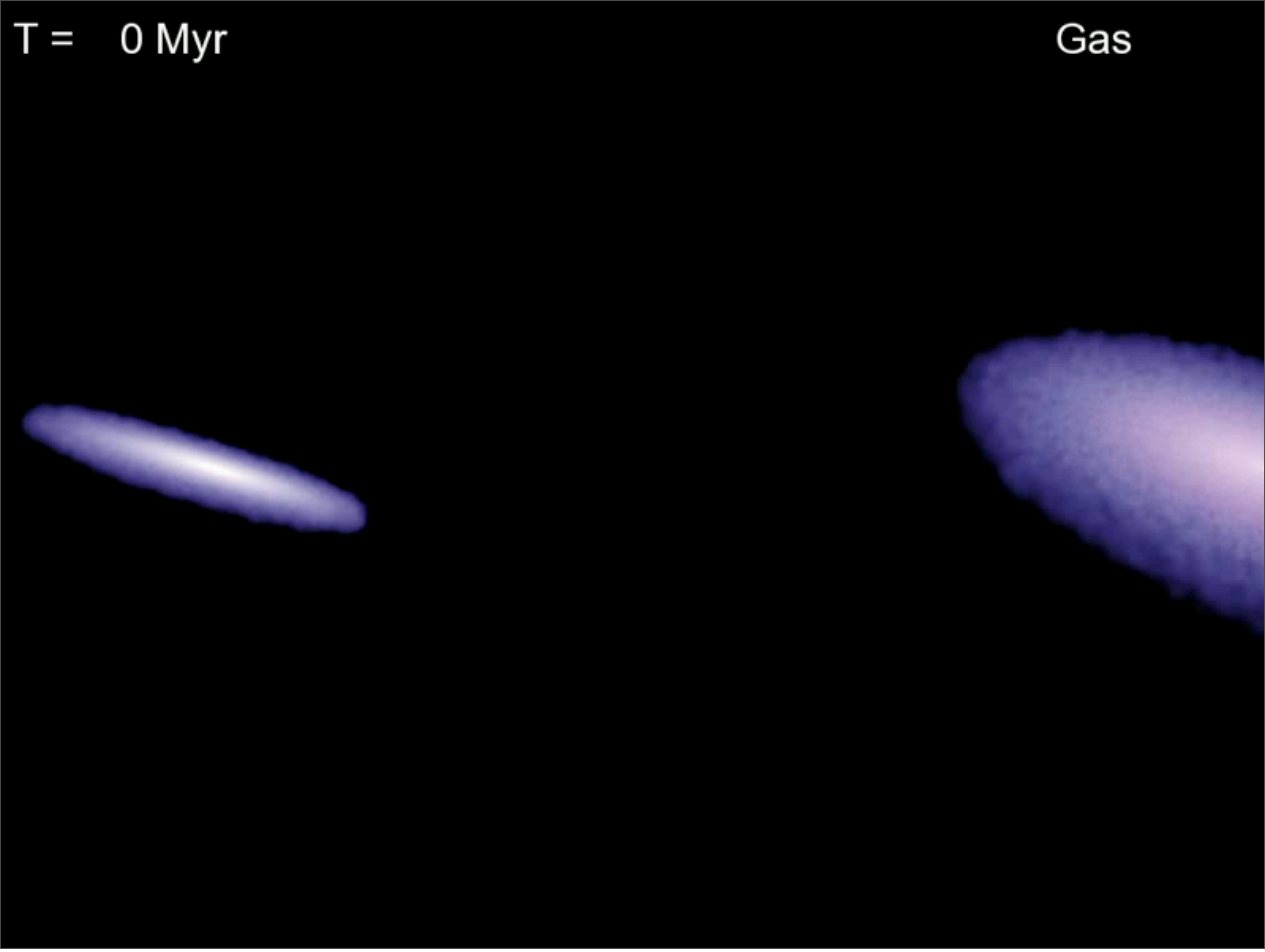
Stellar disk-disk merger remnants don't look like bulges!

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


T = 0 Myr
Gas



Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)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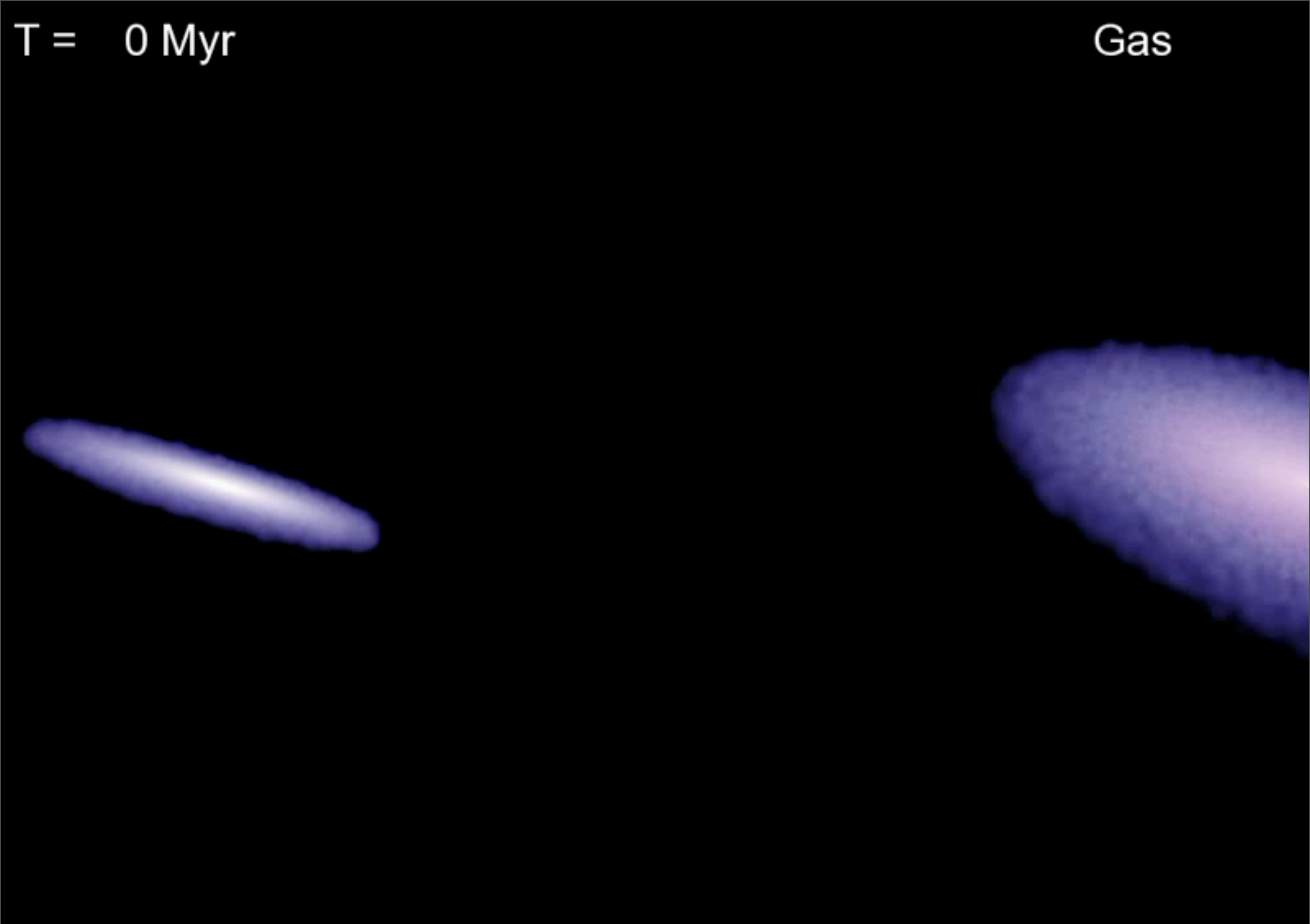
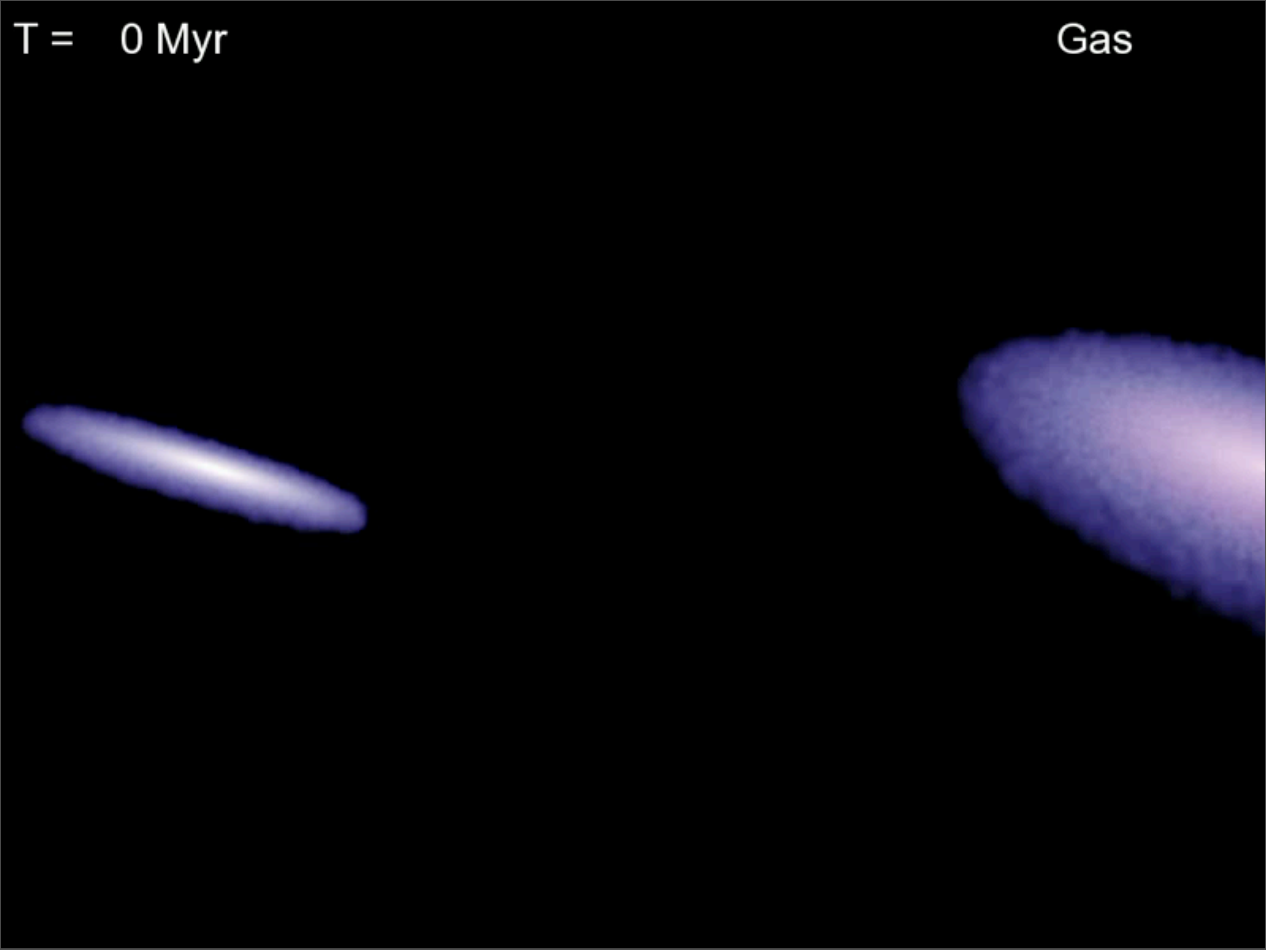


Triggers Starbursts (e.g. Mihos & Hernquist 1996)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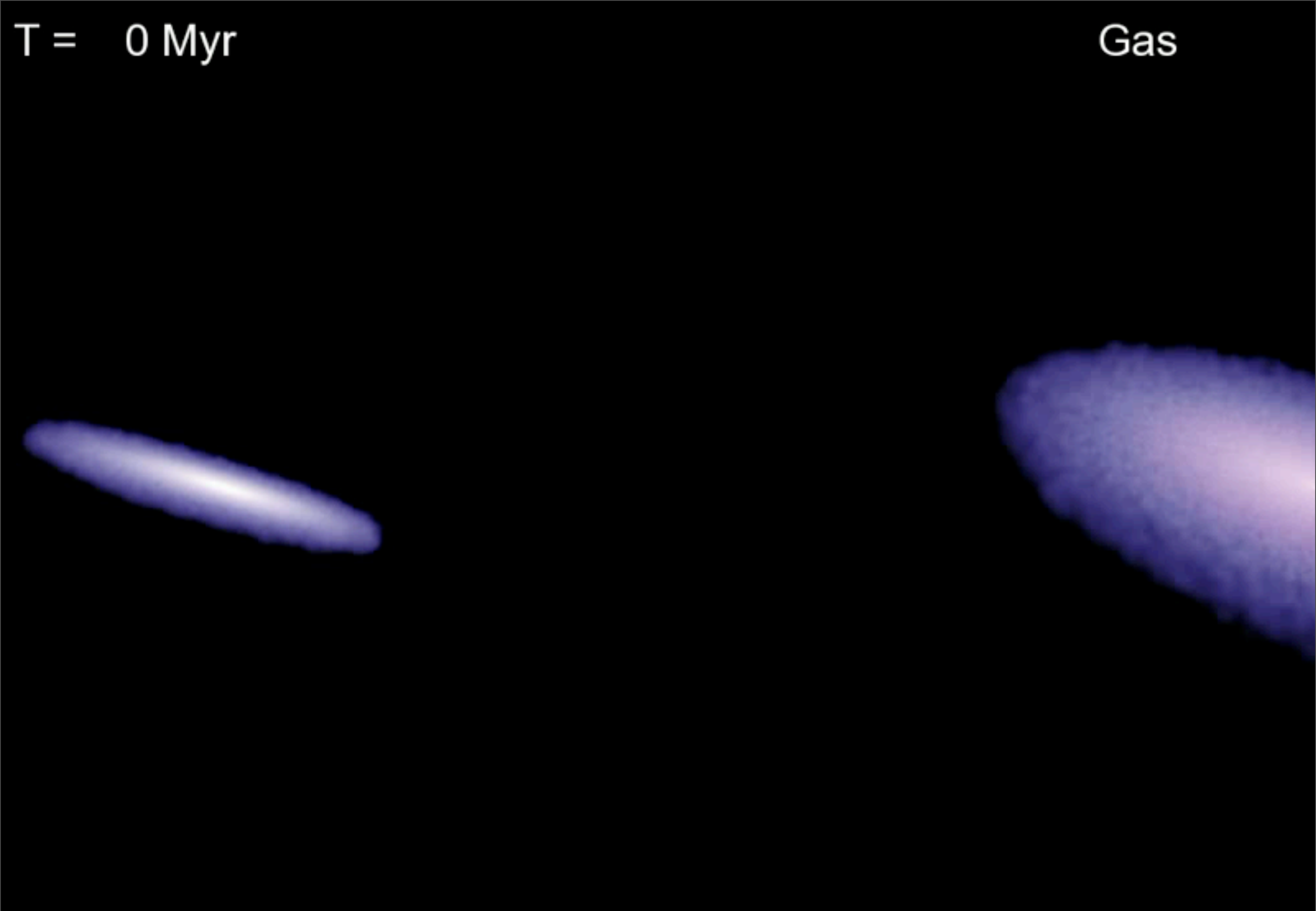
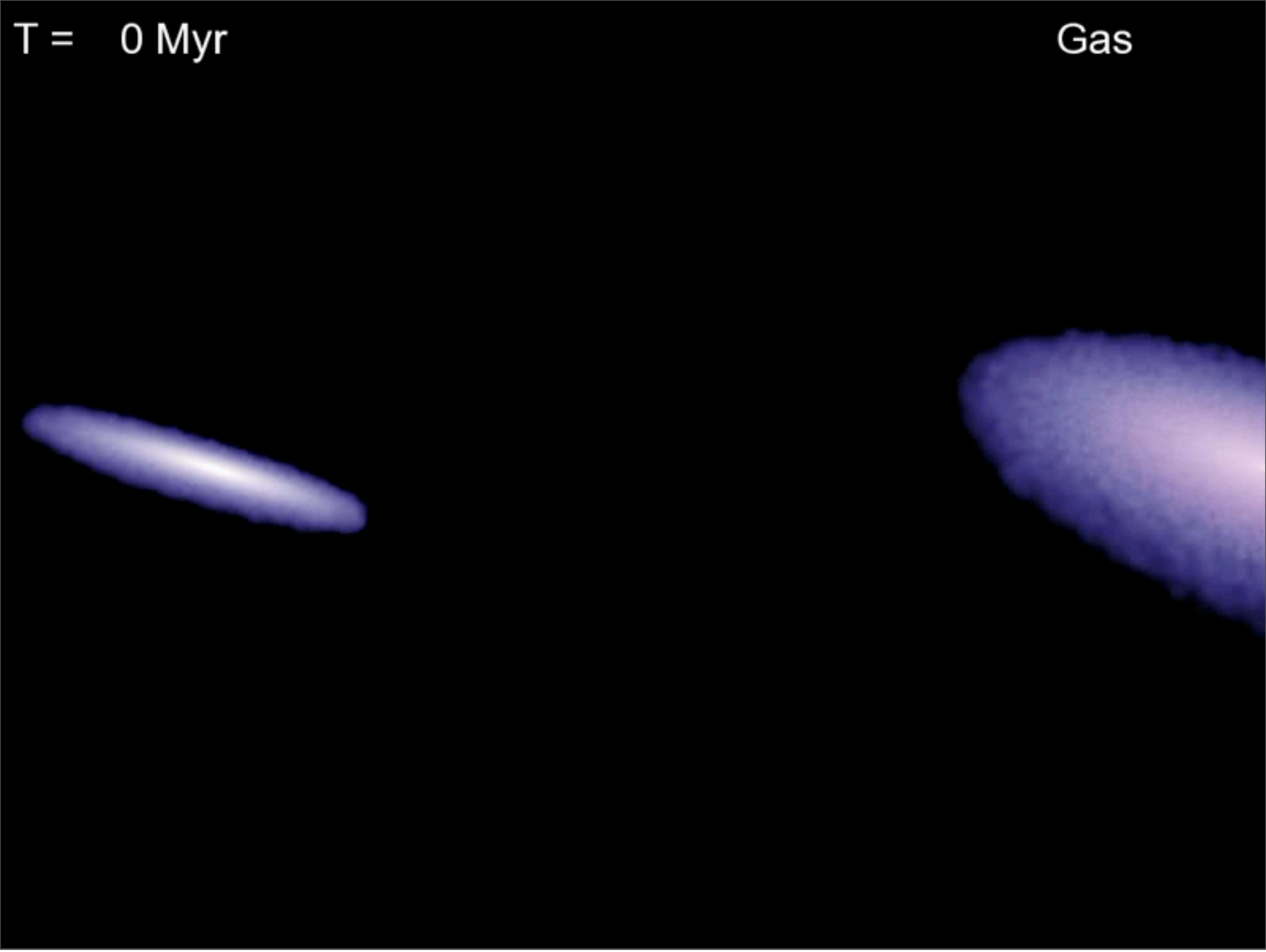


Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)


T = 0 Myr
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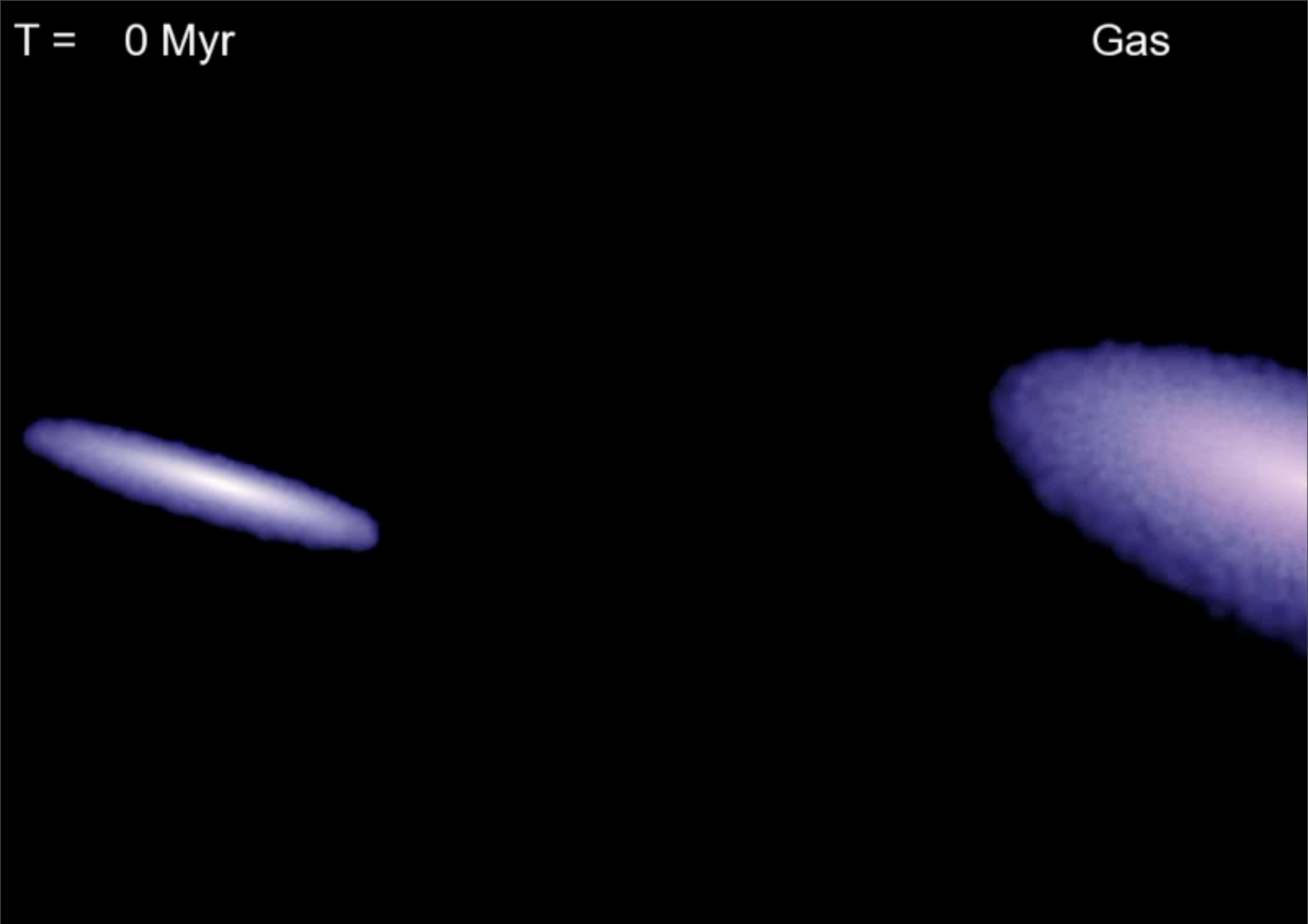
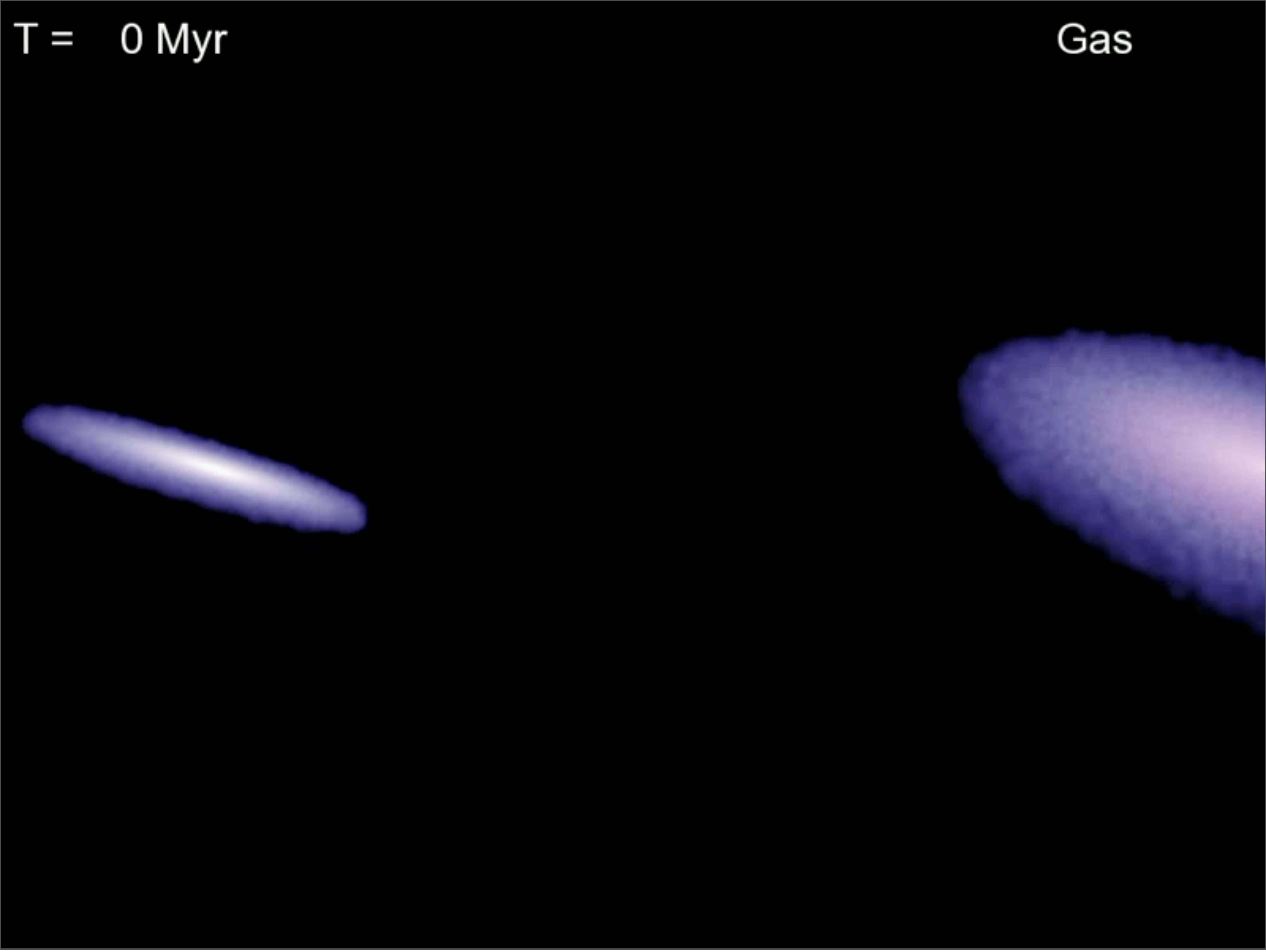
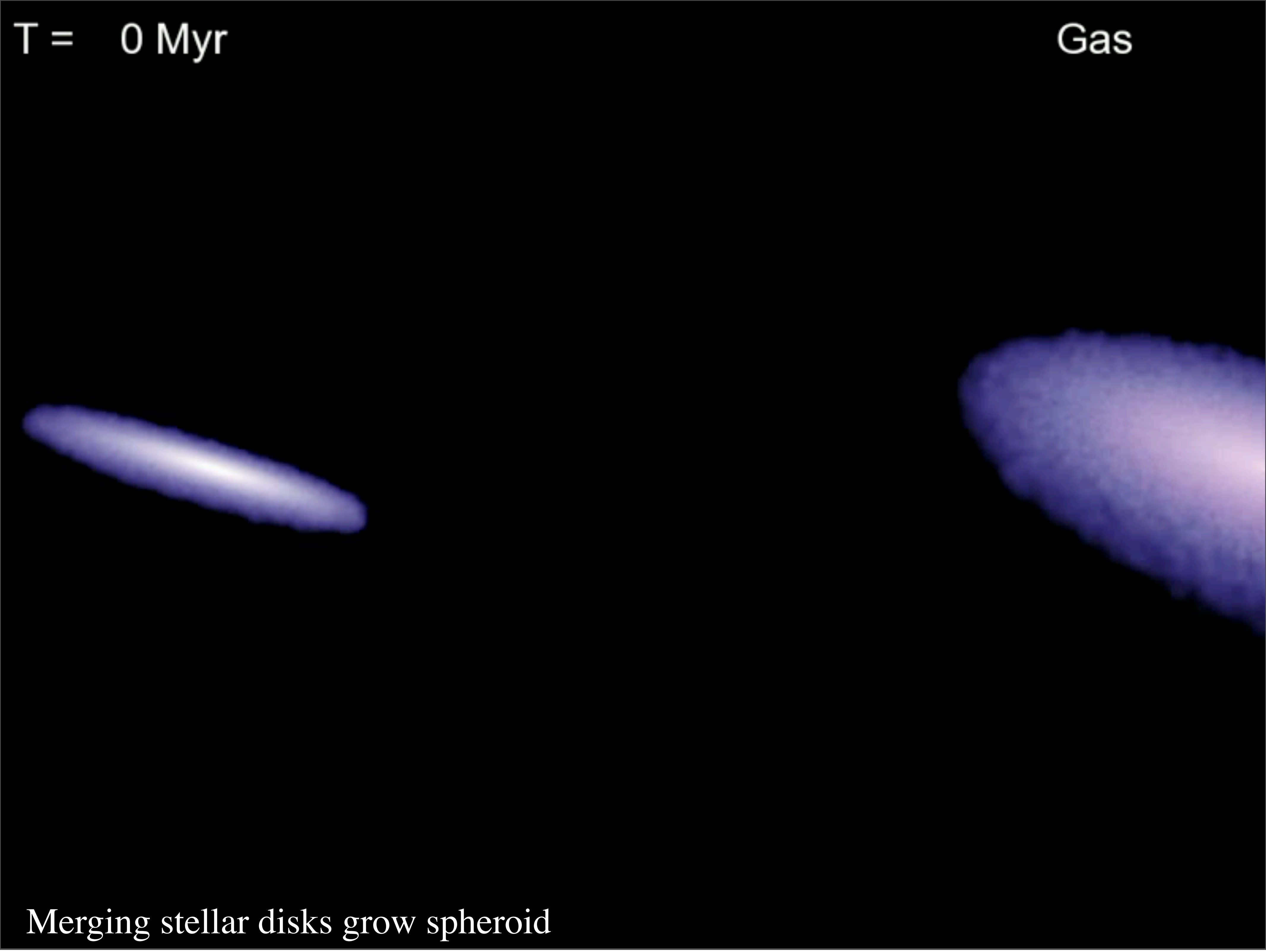
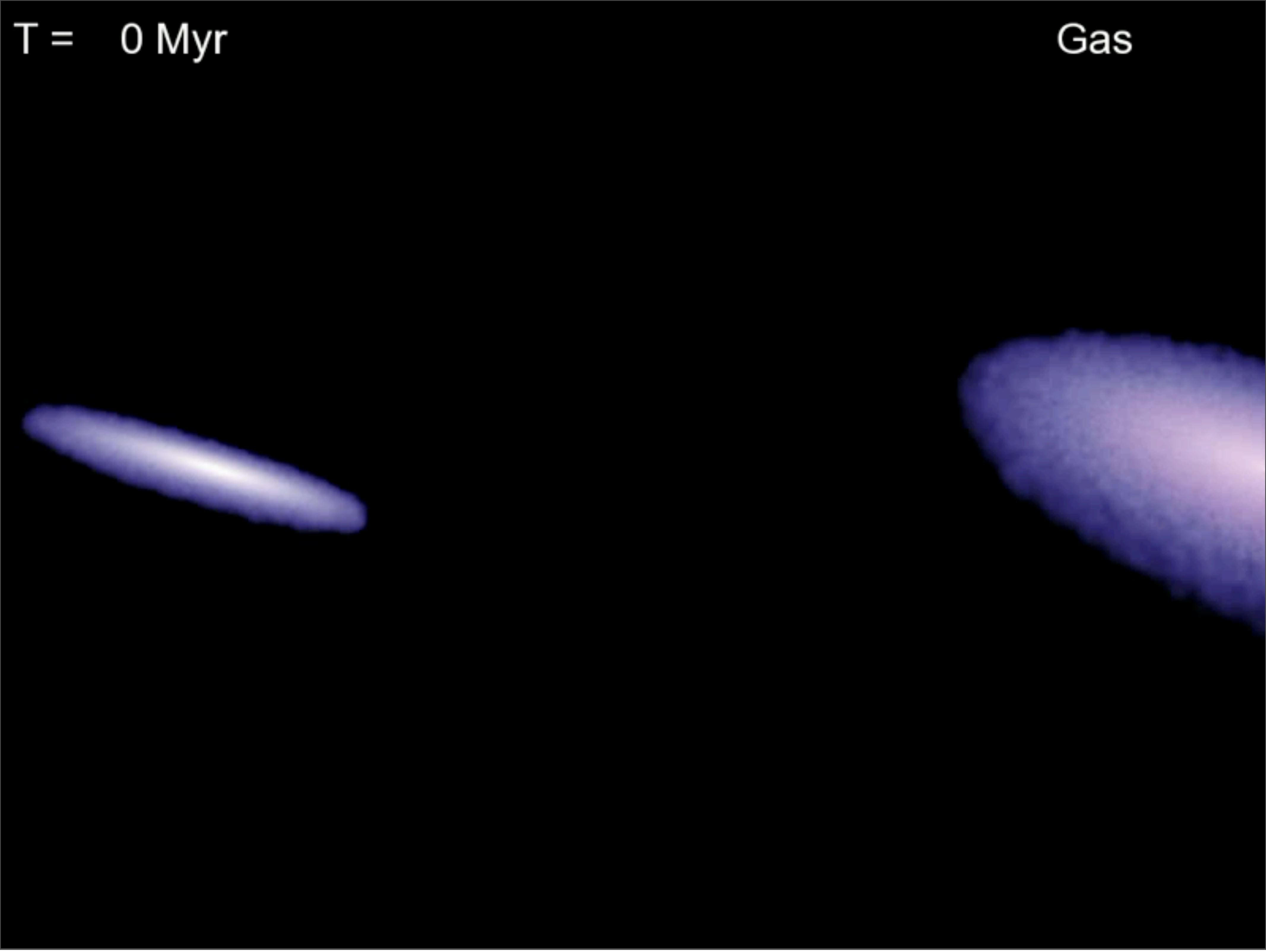


Feedback expels remaining gas, shutting down growth (more later...)


T = 0 Myr
Gas


T = 0 Myr
Gas
Merging stellar disks grow spheroid


T = 0 Myr
Gas

What About the Gas that Does Lose Angular Momentum?

CAN WE MAKE A REAL ELLIPTICAL?

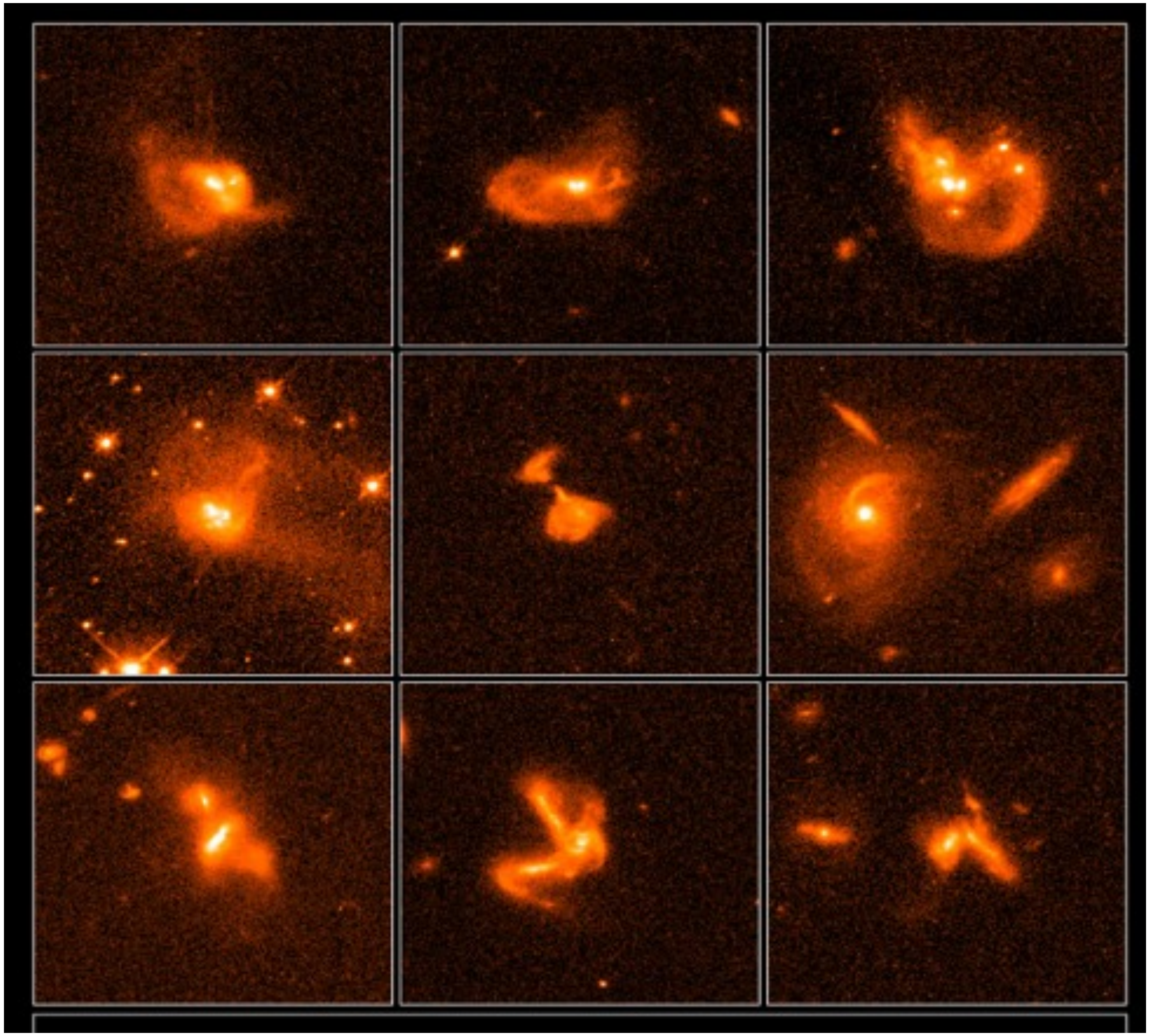
Funneled to the center -> massive starbursts

Look at late-stage merger remnants

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

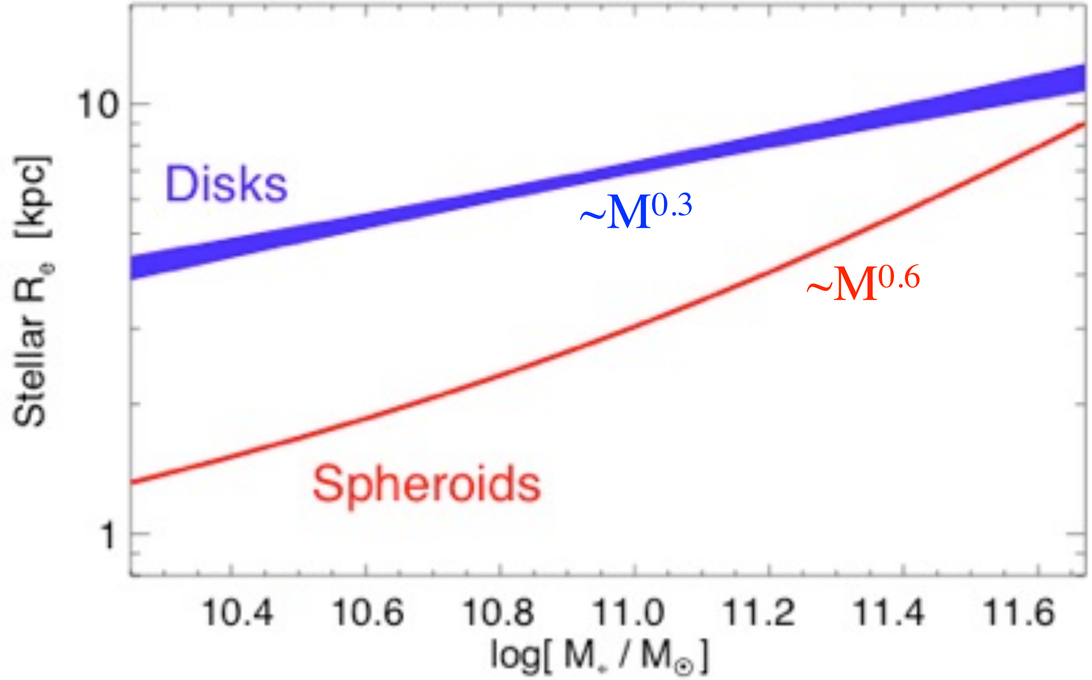
Compact (<kpc scales)

Borne et al., 2000

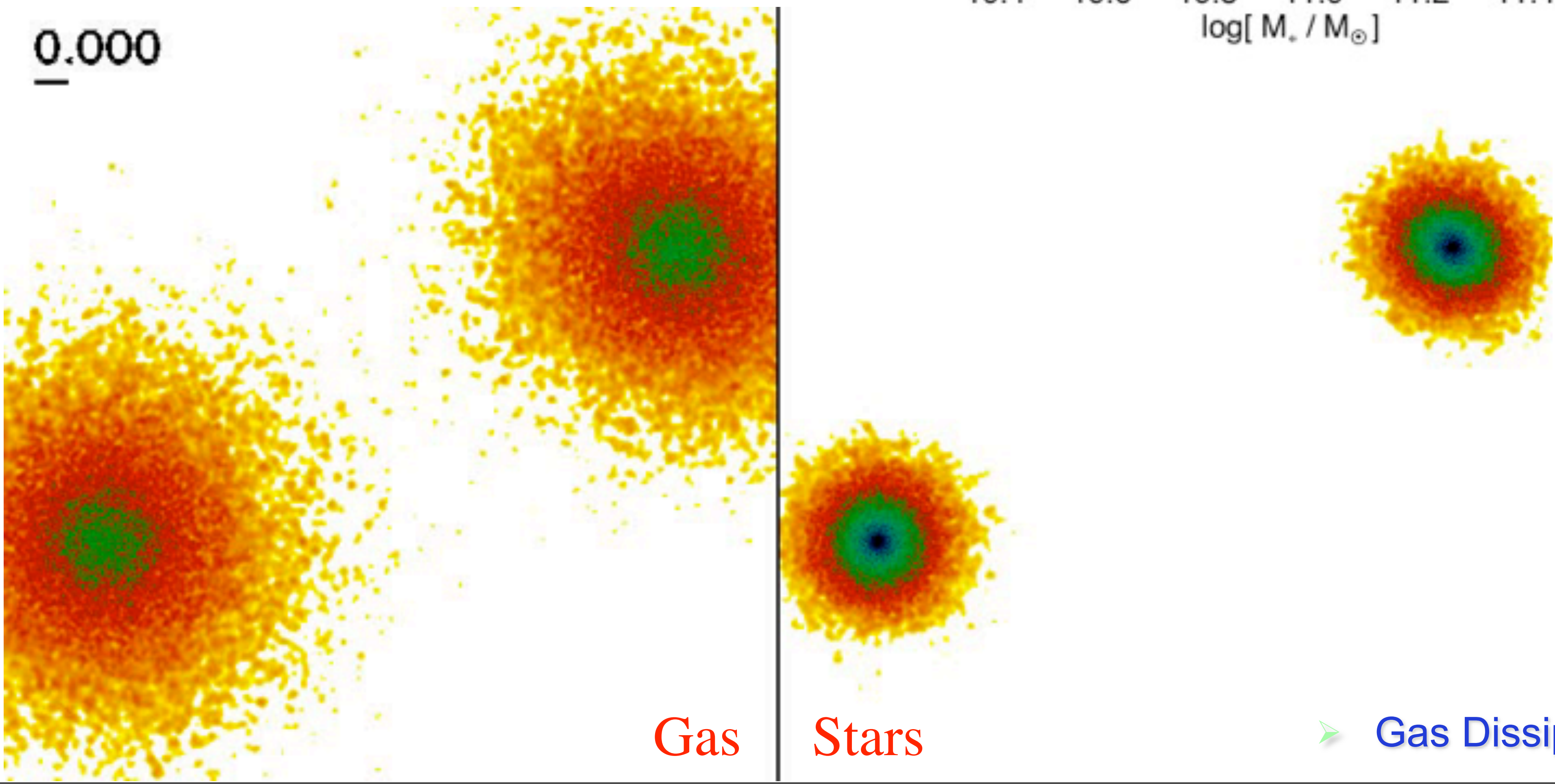


Most luminous starbursts in the Universe: are they the progenitors of ellipticals?

The Problem: The Fundamental Plane & Bulge Densities:



- Why are ellipticals smaller than disks?

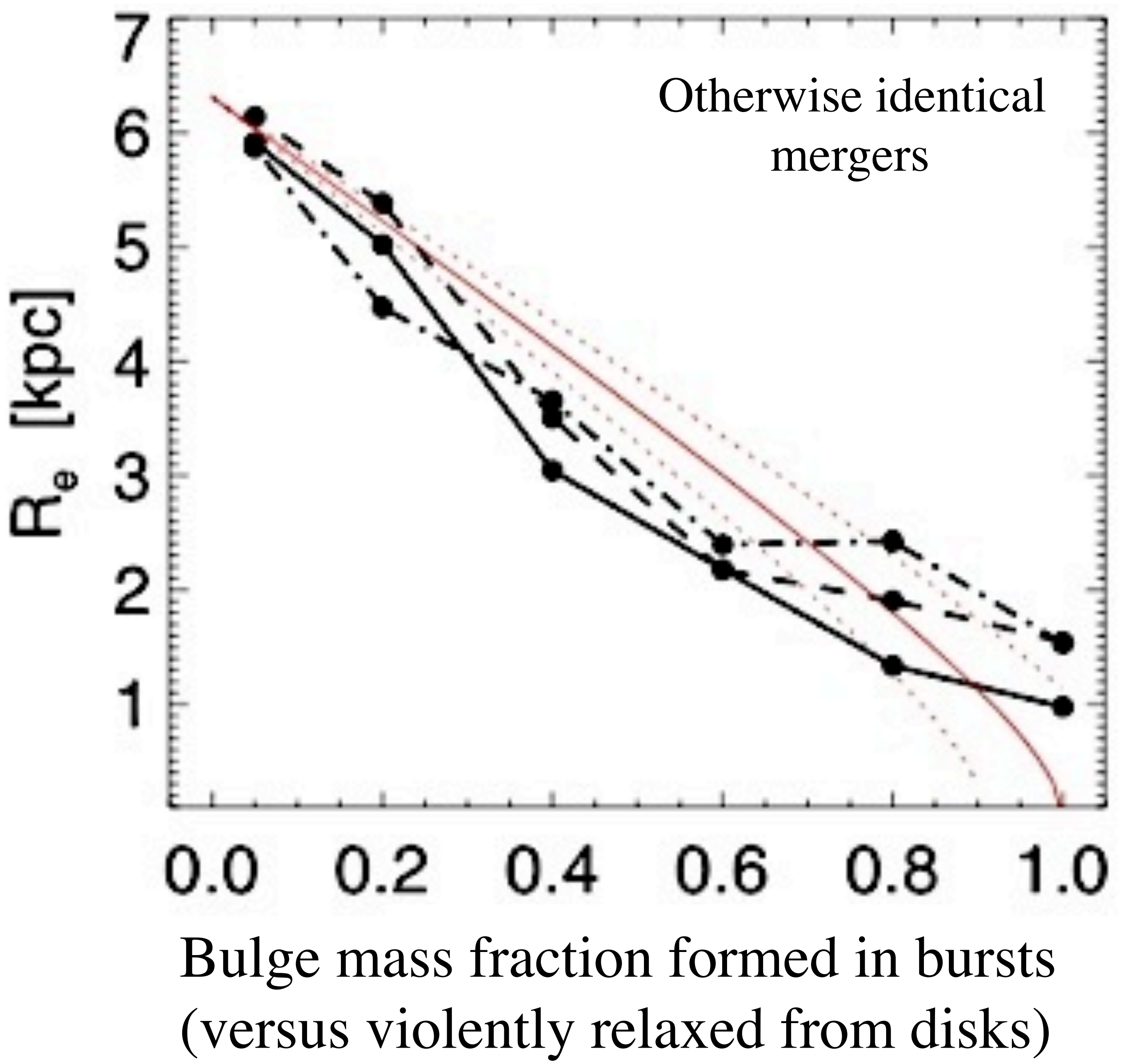


- Gas Dissipation

The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

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



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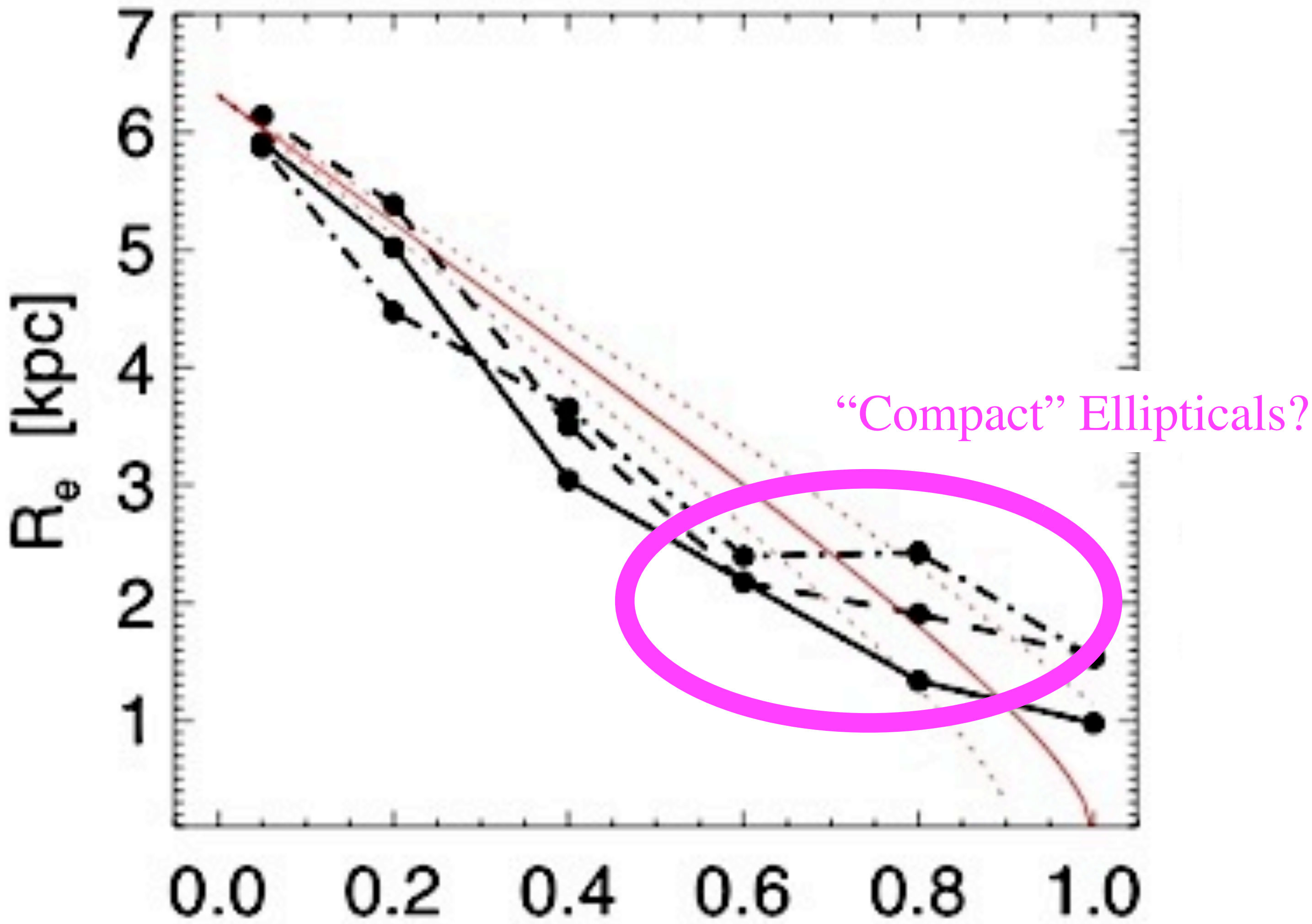


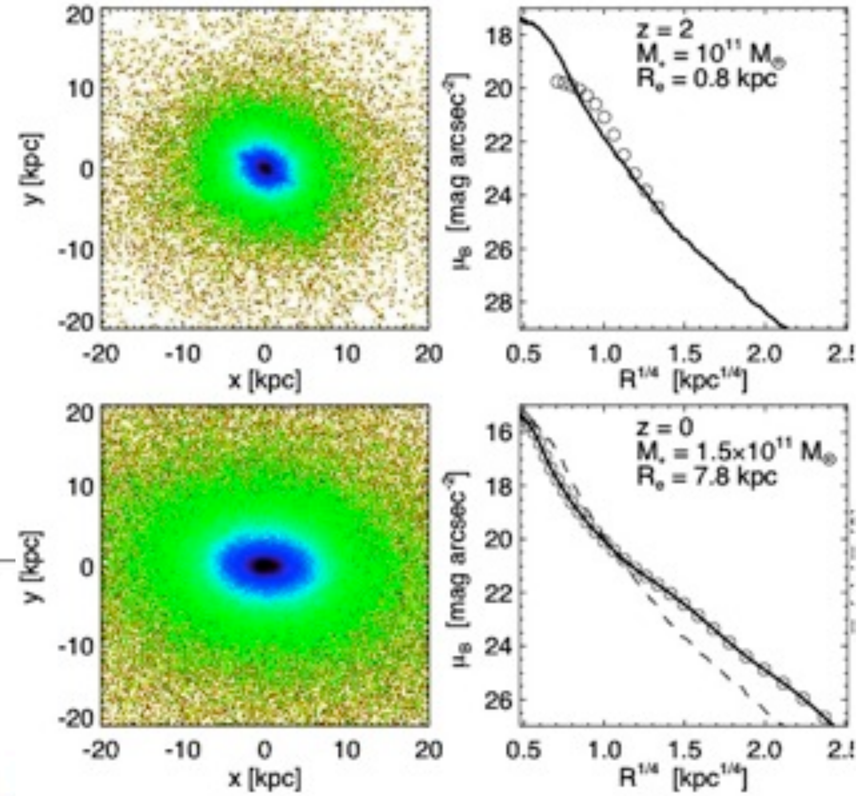
Bulge mass fraction formed in bursts
(versus violently relaxed from disks)

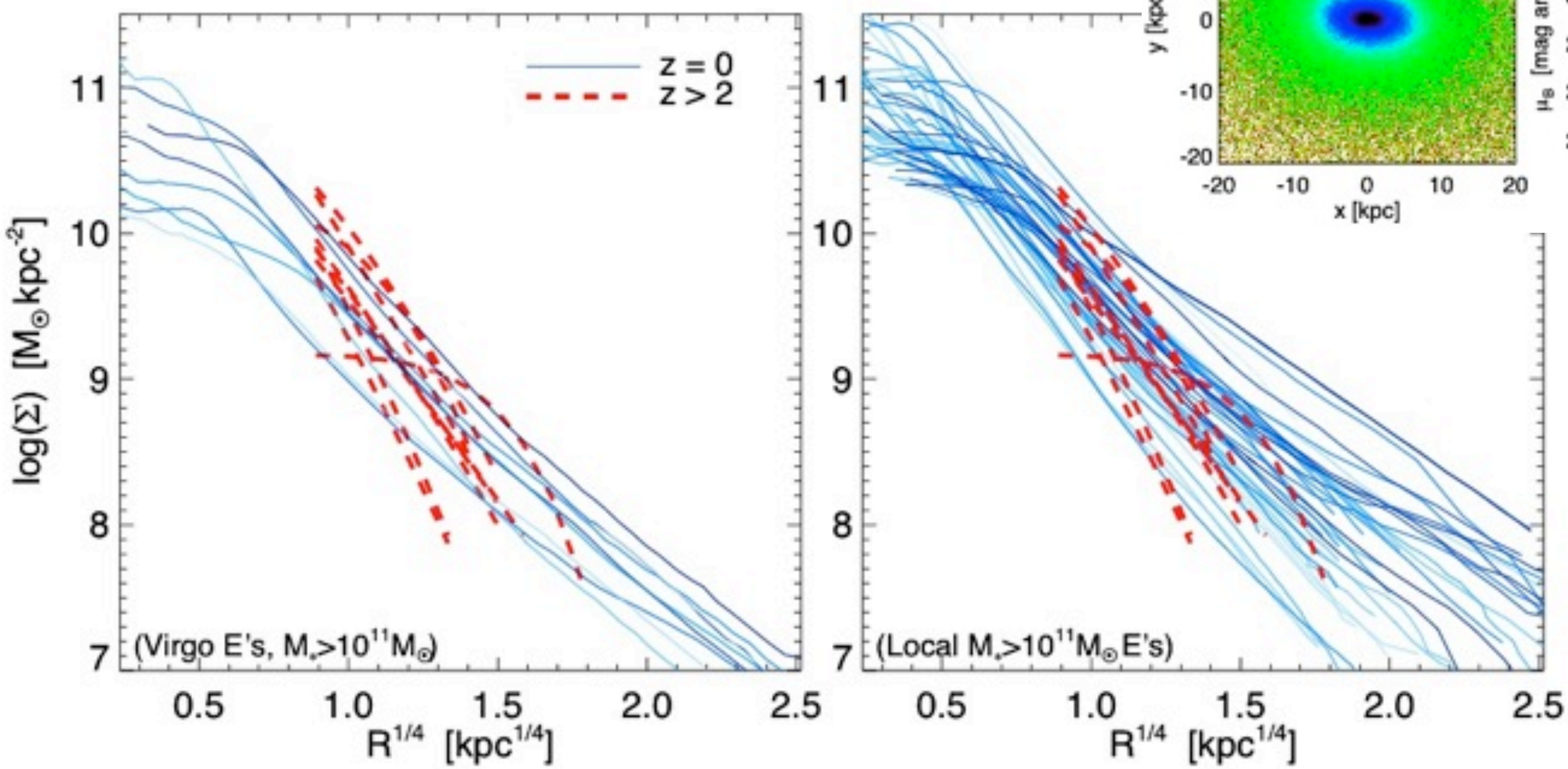
The Problem

FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

- Compare: massive spheroids at z=2 to those today

- ... vs gas-rich merger with later low-density/minor mergers

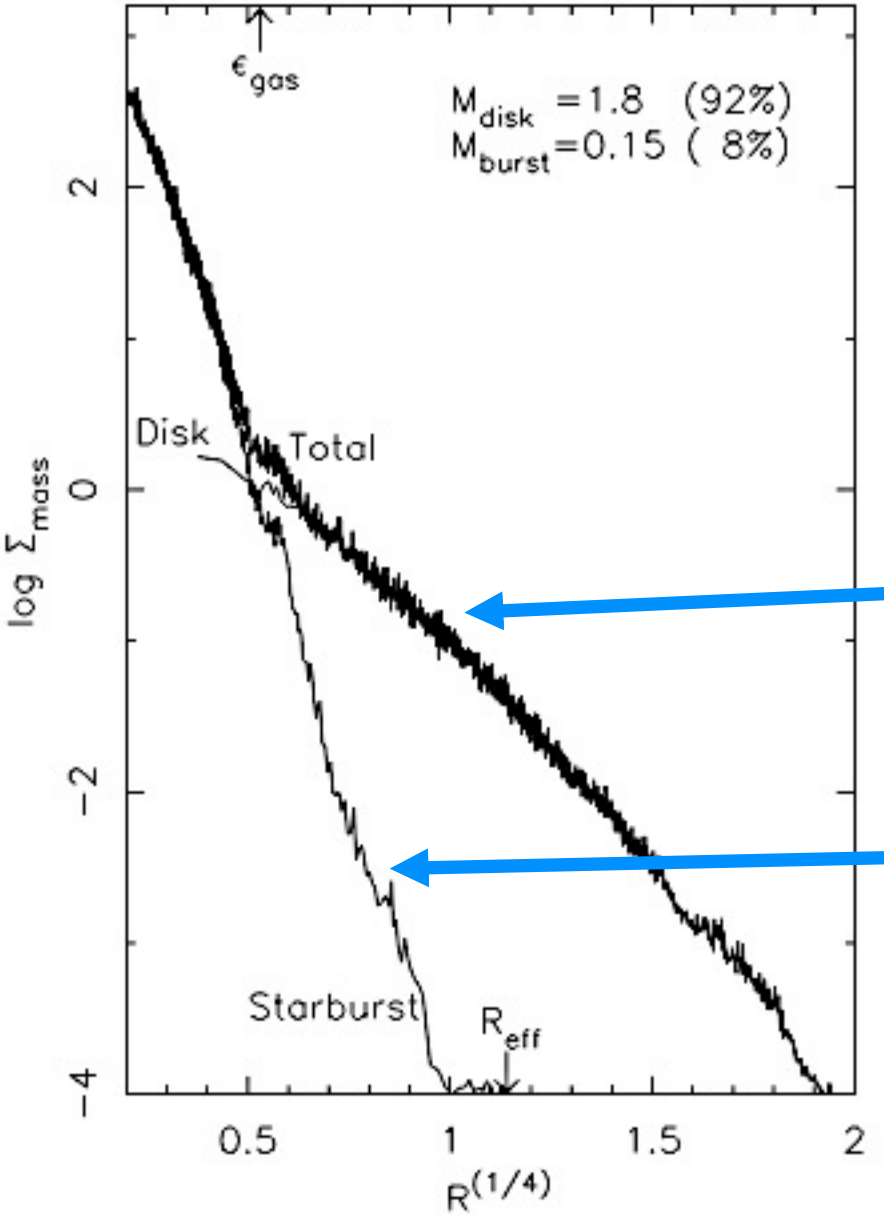




PFH, Murray, et al. 2009

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:

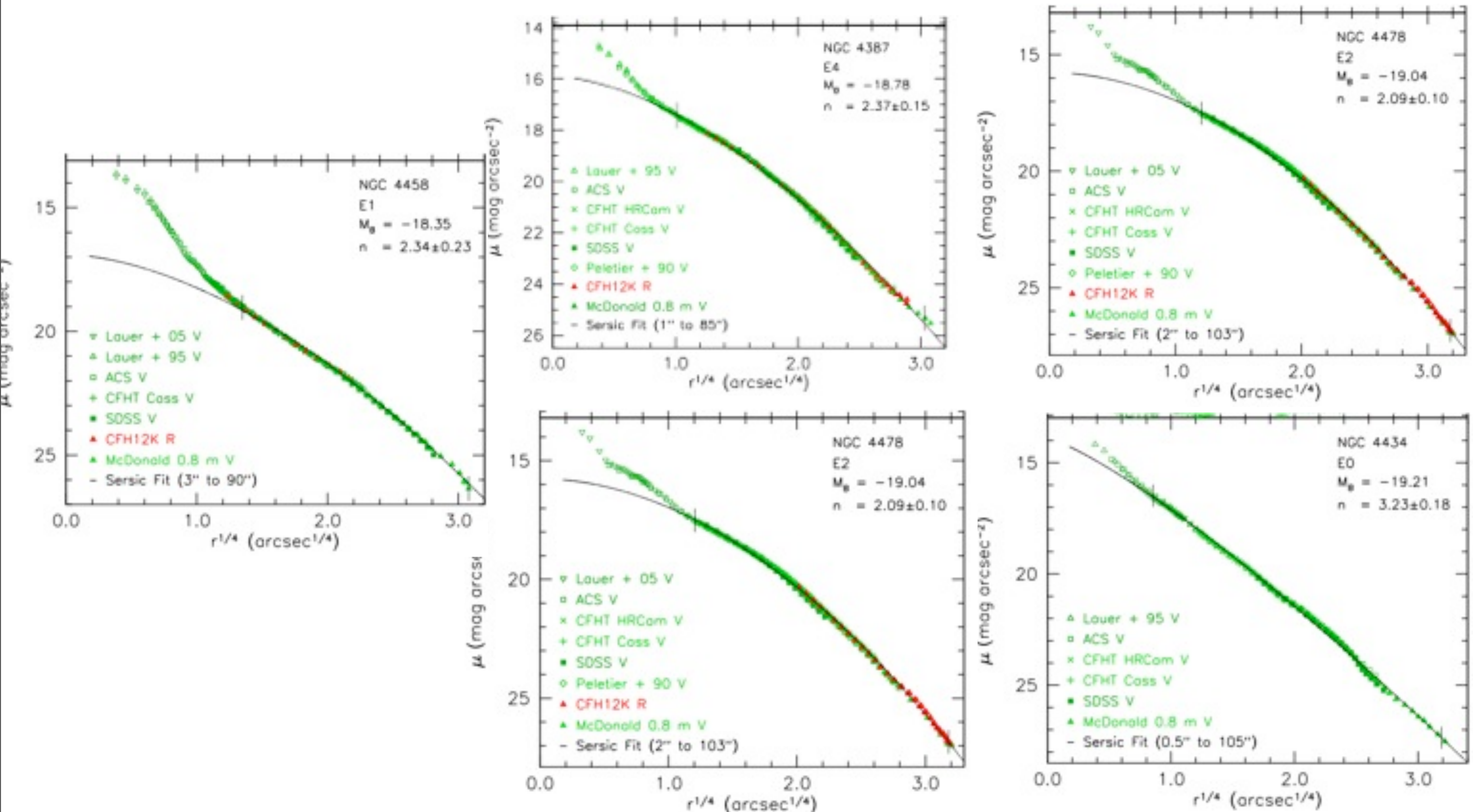
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

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

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

- Since then...

Kormendy et al. 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.”

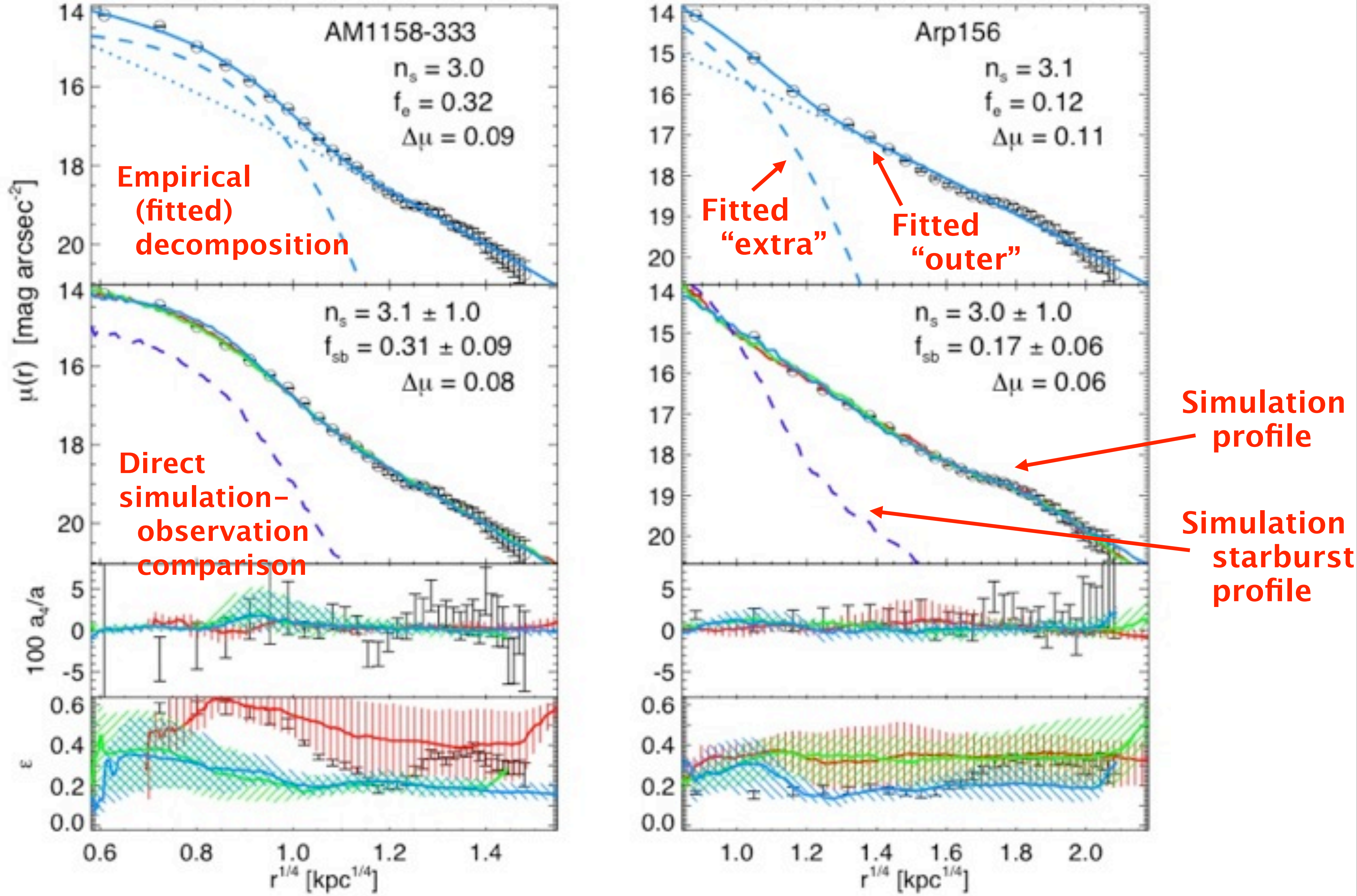
Application: Merger Remnants

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:



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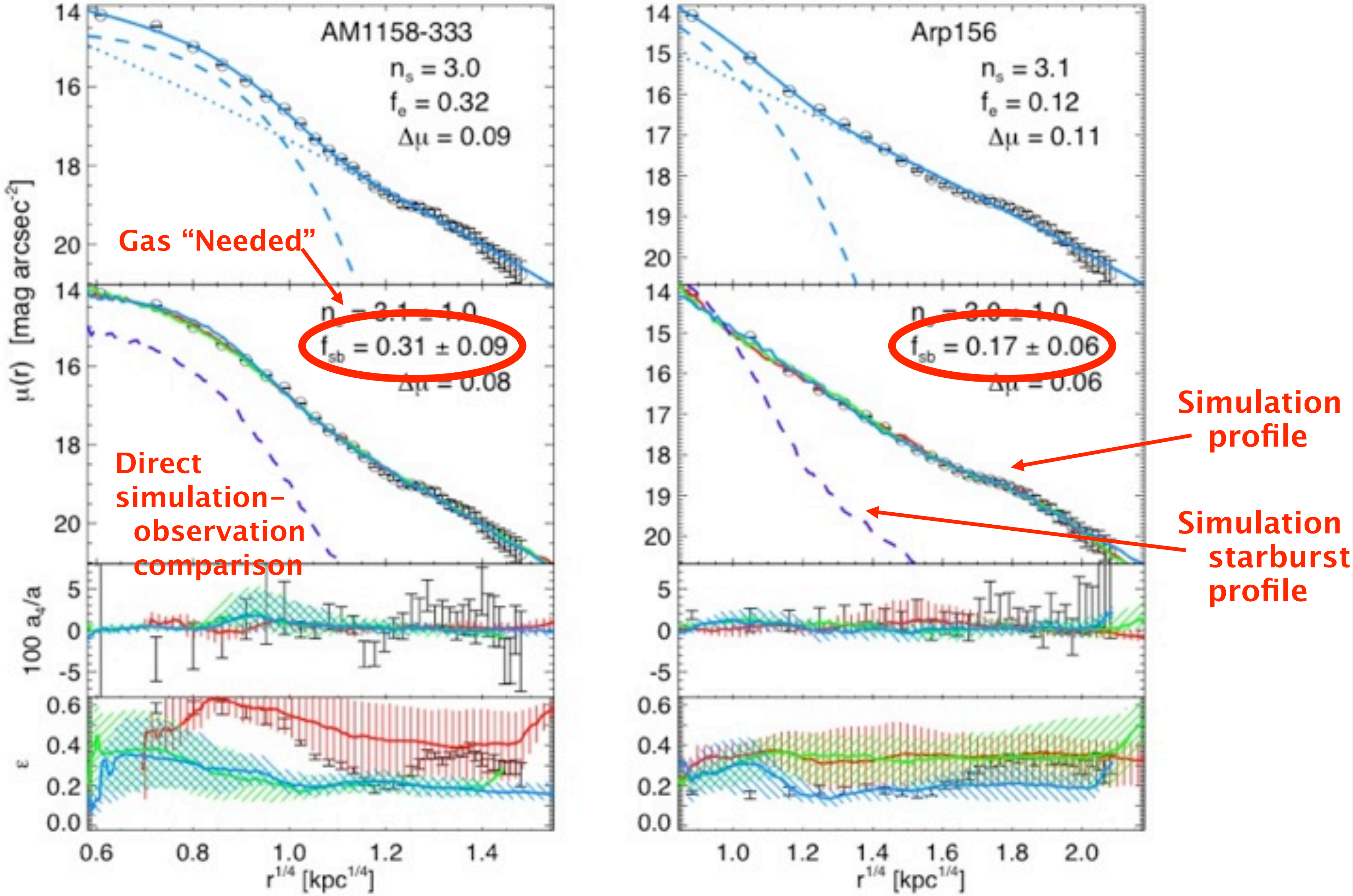


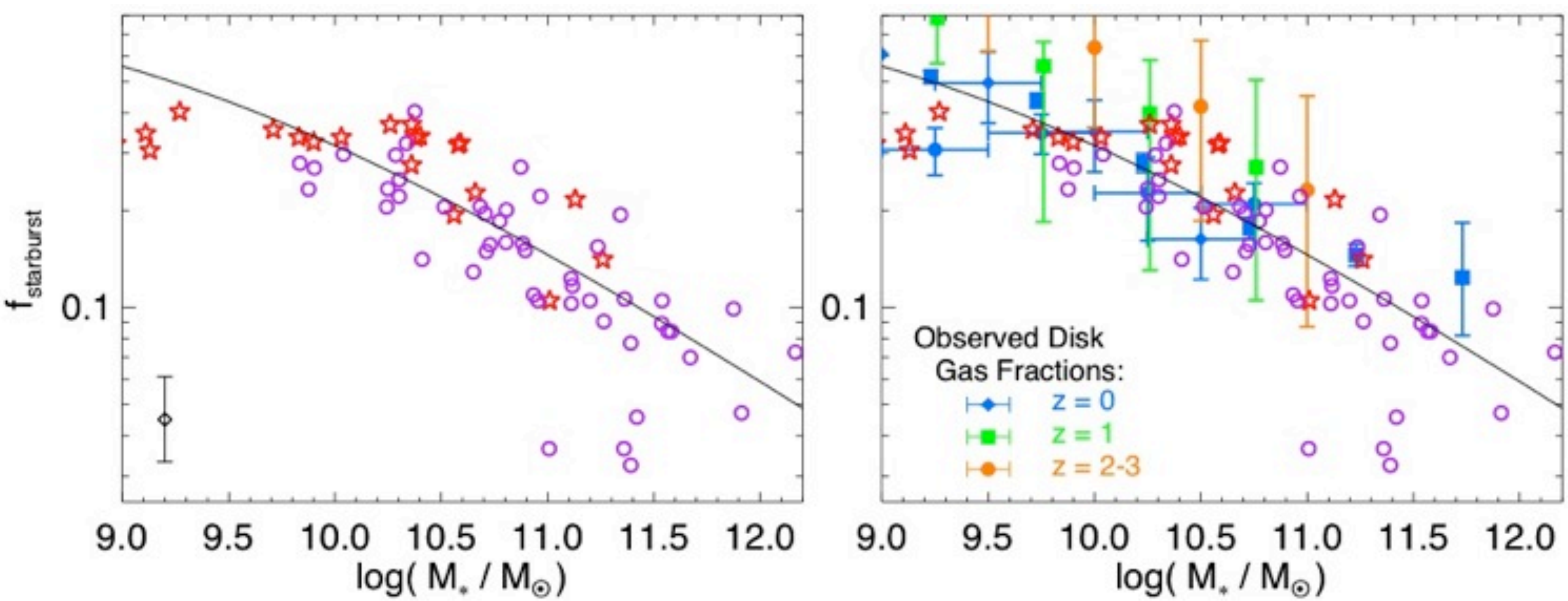
Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

PFH & Rothberg et al. 2008

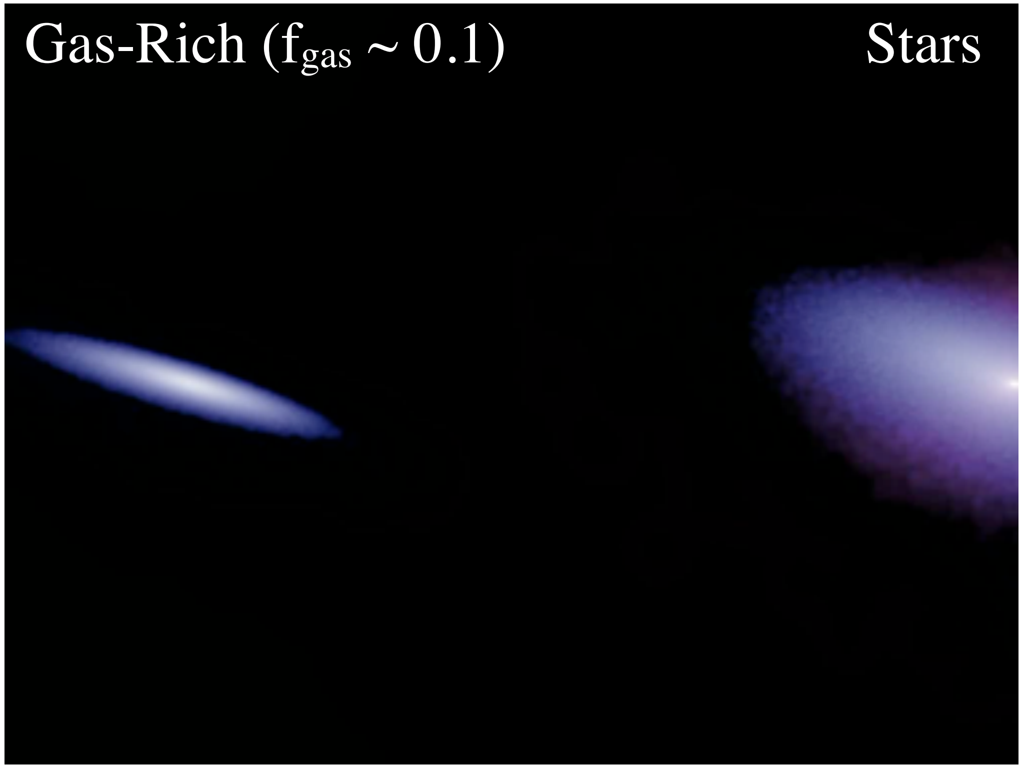
PFH, Kormendy, & Lauer et al. 2008

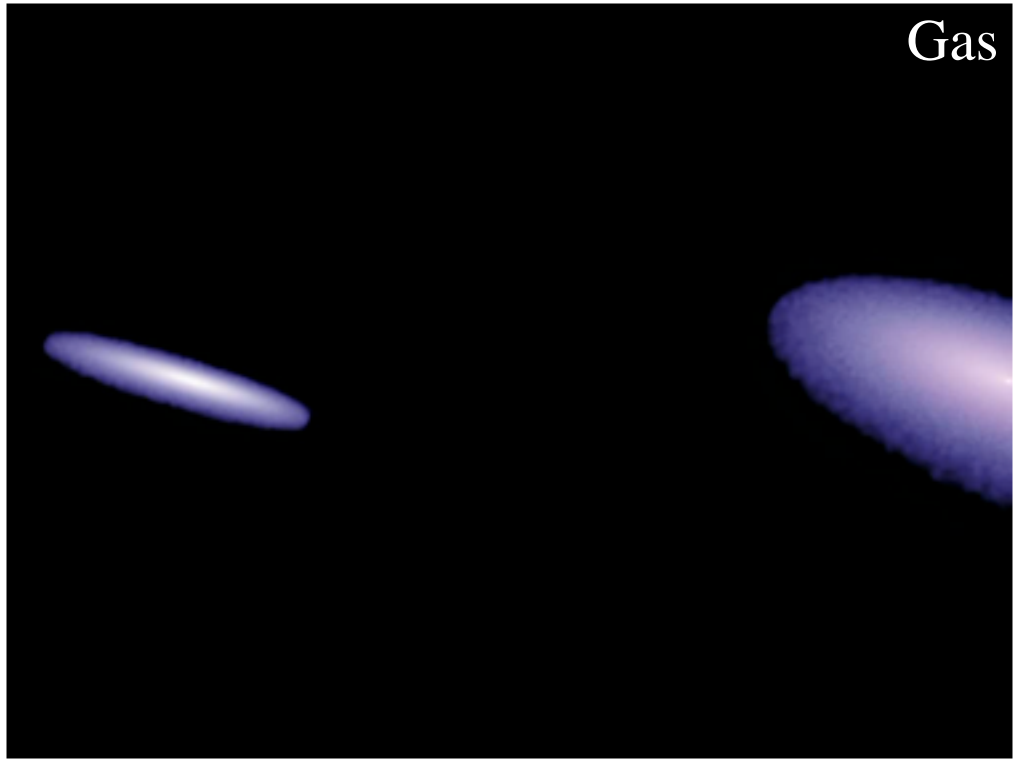
Starburst gas mass needed to match observed profile (or fitted to profile shape):



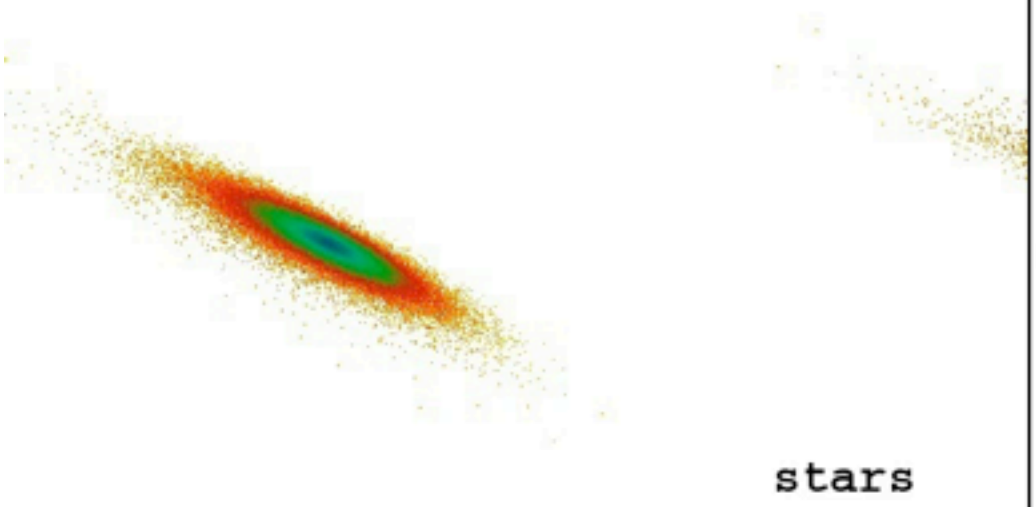
- You can and *do* get realistic ellipticals given the observed amount of gas in progenitor disks
  - Independent checks: stellar populations (younger burst mass); metallicity/color/age gradients; isophotal shapes; kinematics; recent merger remnants; enrichment patterns

How Good Is Our Conventional Wisdom?



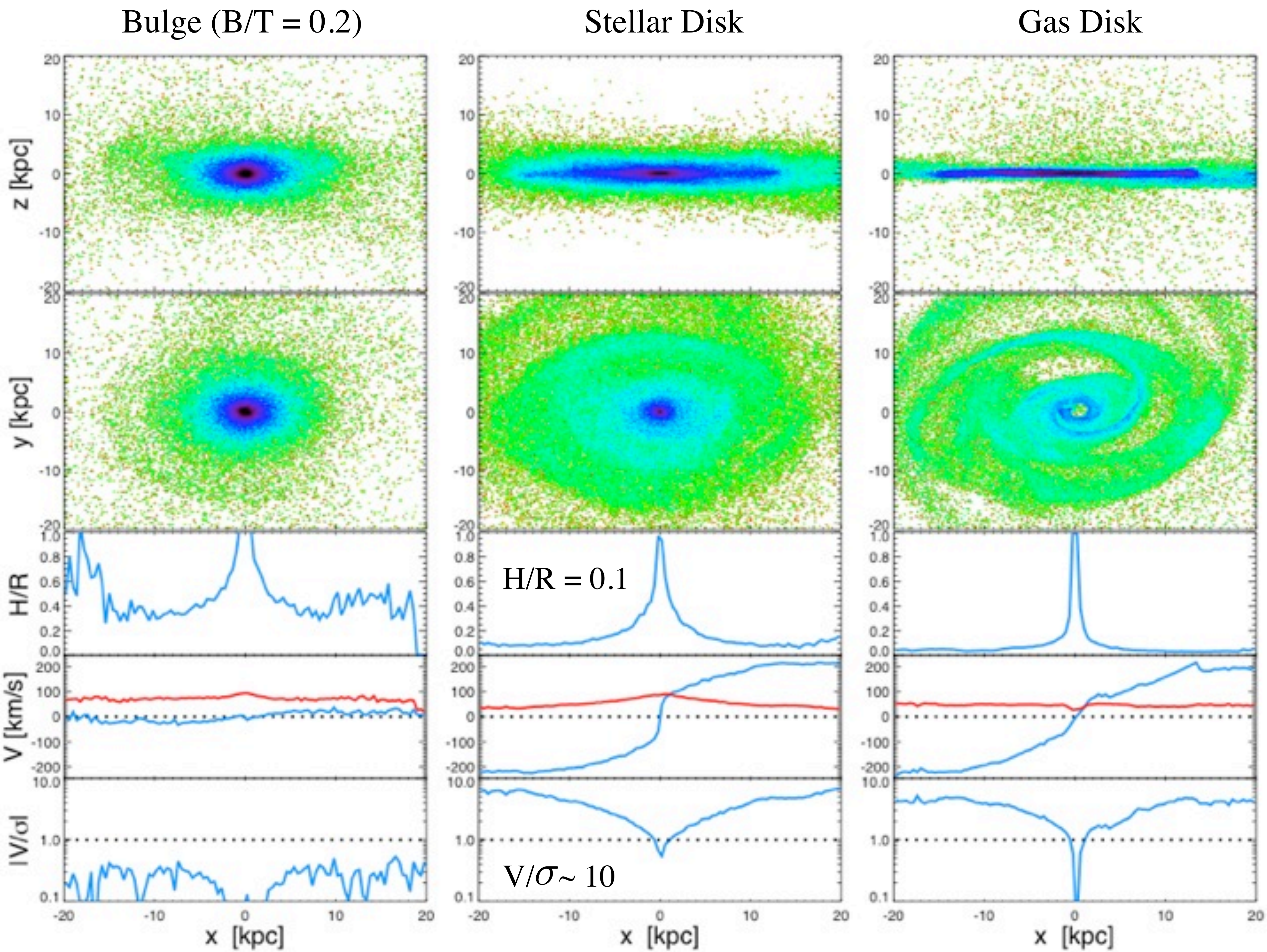


Gas-Richer ($f_{gas} \sim 0.4$)



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

+

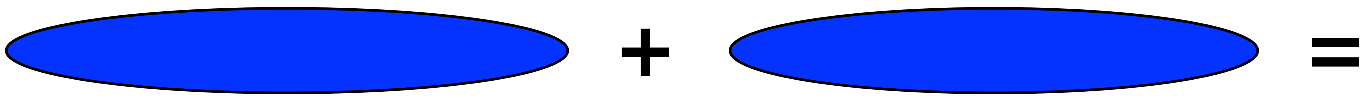
=

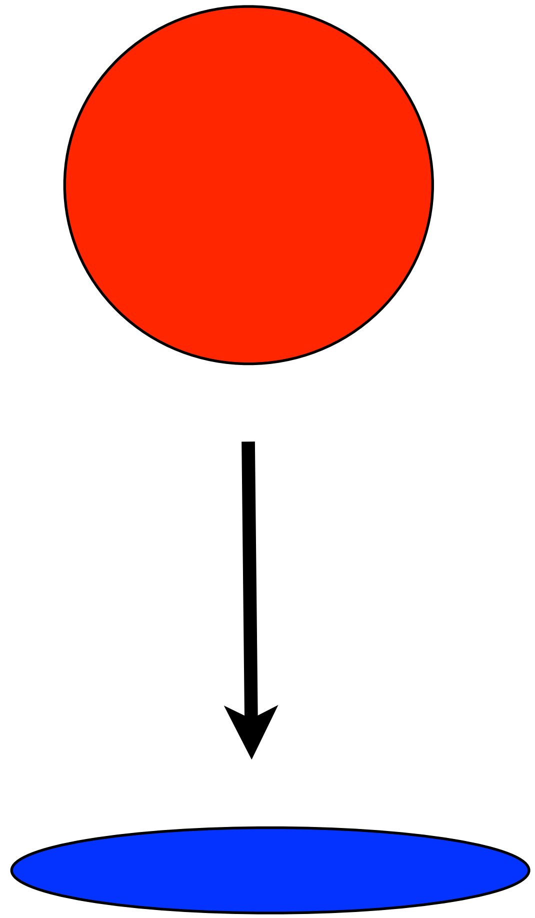
- Can’t “cool” into a new disk

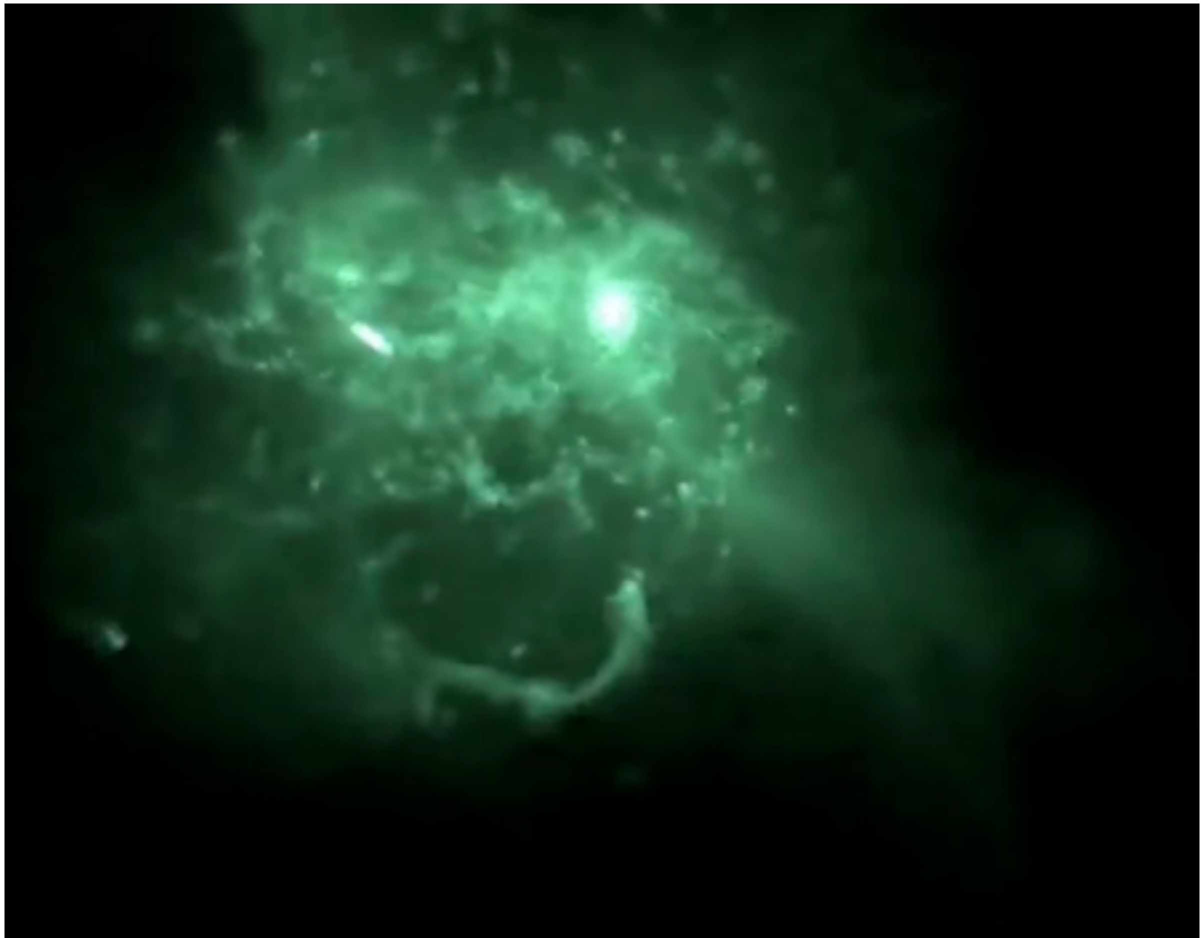
The Unsolved Questions

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





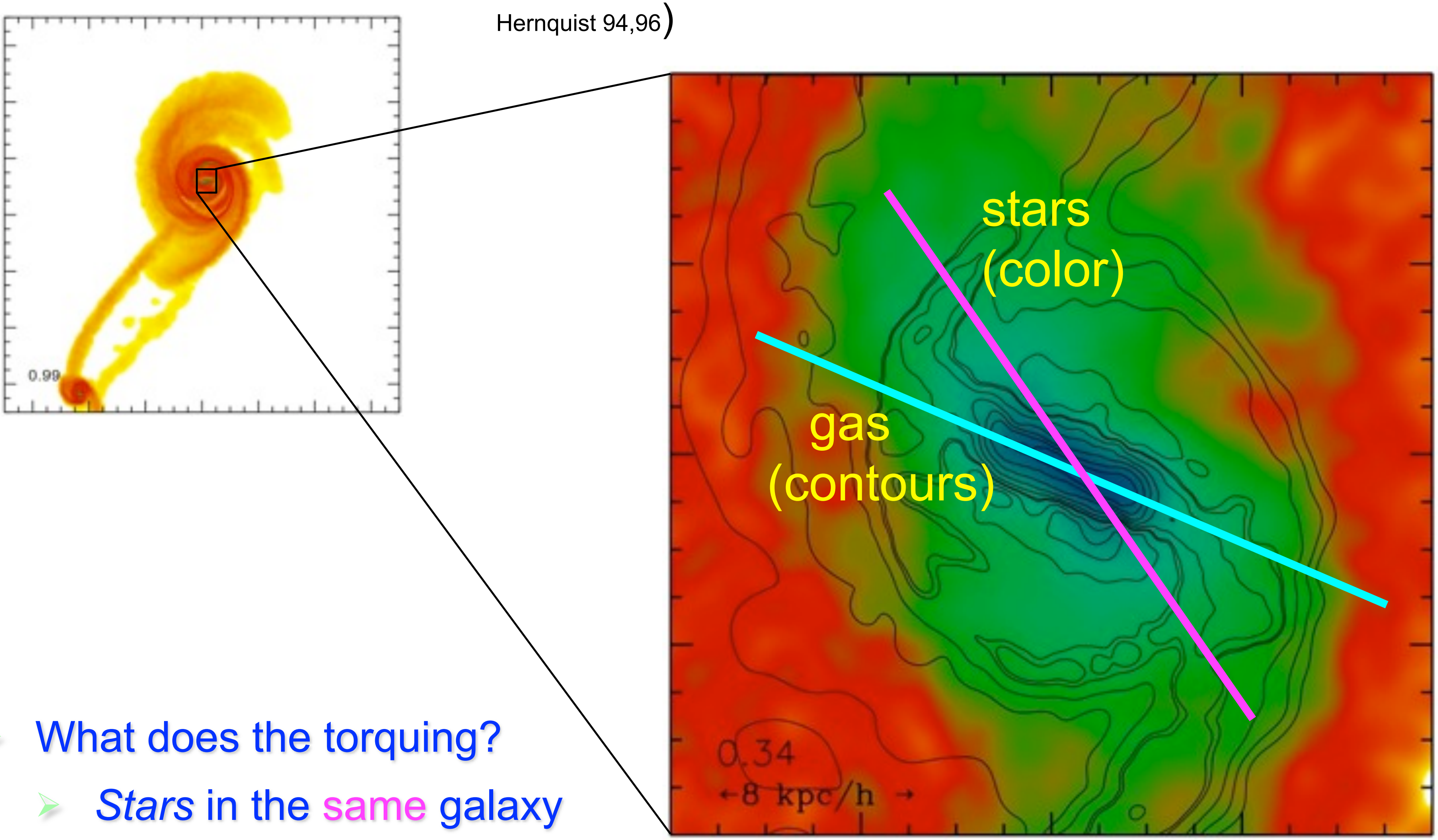


Governato et al.

How Do Disks Survive Mergers?

PFH et al. 2008

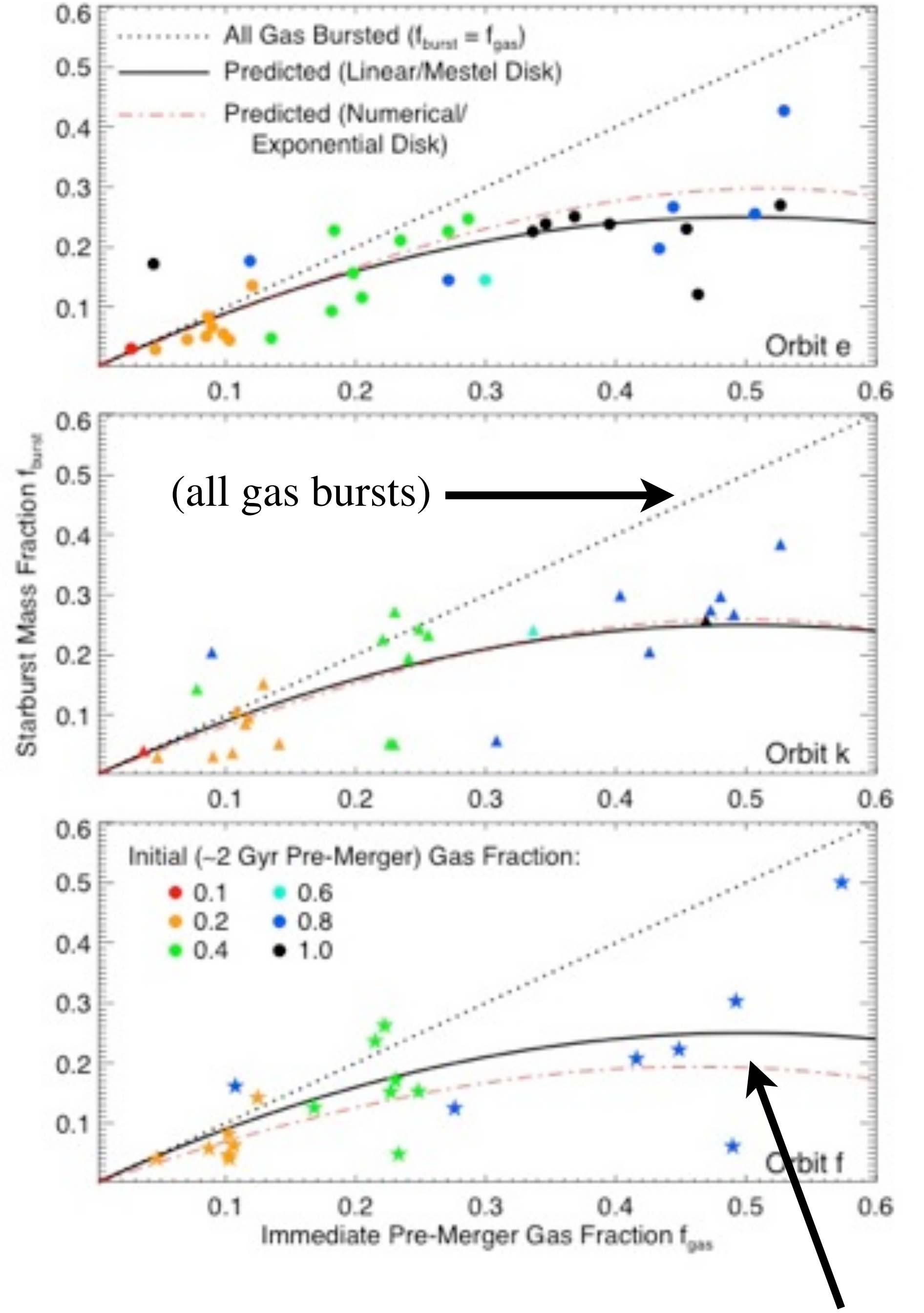
companions -- bars -- gas/star offset -- torques -- gas inflow (see, e.g., Barnes 92, Barnes & Hernquist 96, Mihos & Hernquist 94,96)



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

How Do Disks Survive Mergers?

Burst mass vs. f_{gas}



(gas-dependent prediction)

Torque on gas:

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

For the same merger/perturbation:

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

PFH et al. 2008 ("How Do Disks Survive Mergers?")

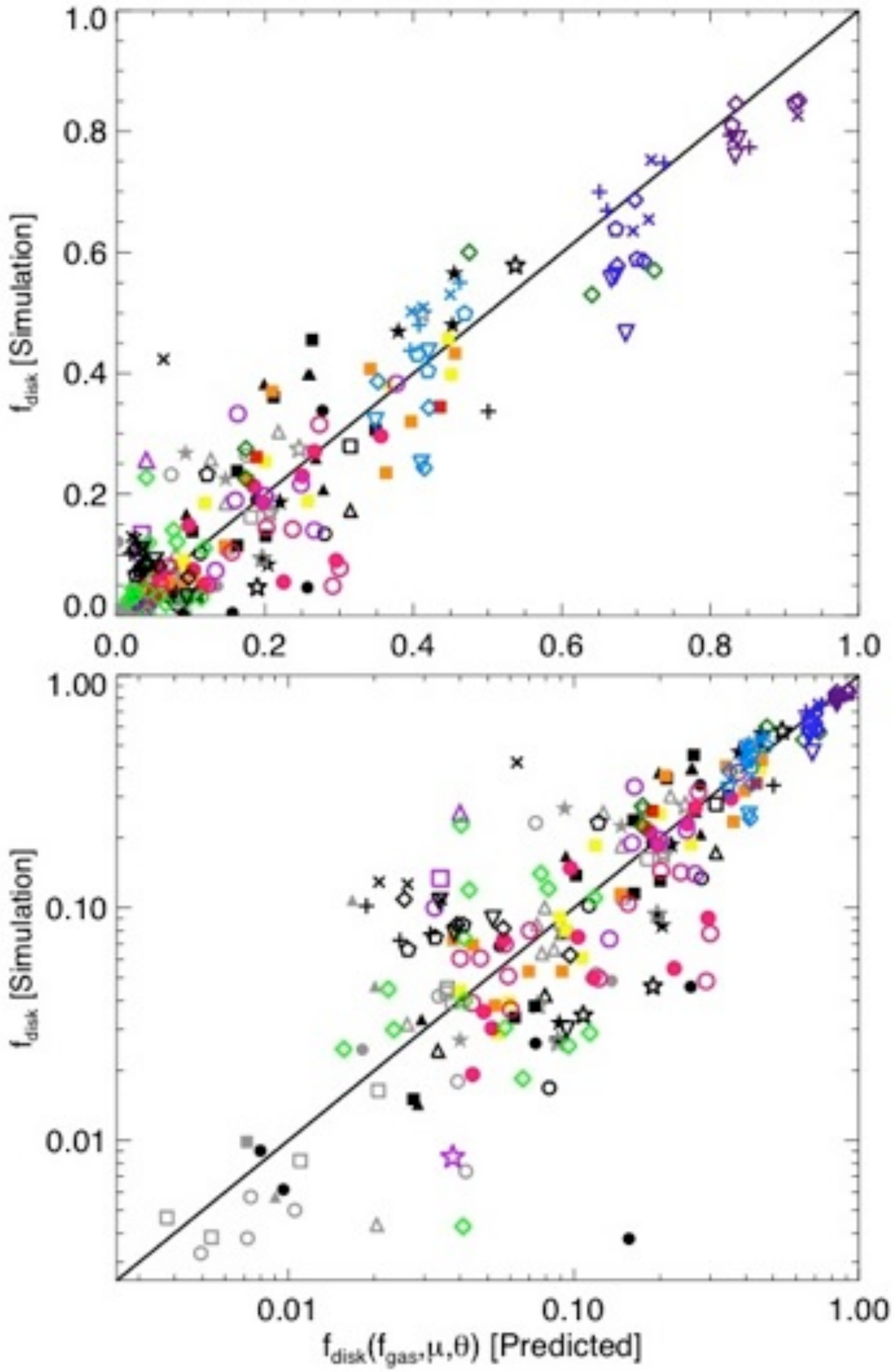
How Do Disks Survive Mergers?

PFH et al. 2008

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

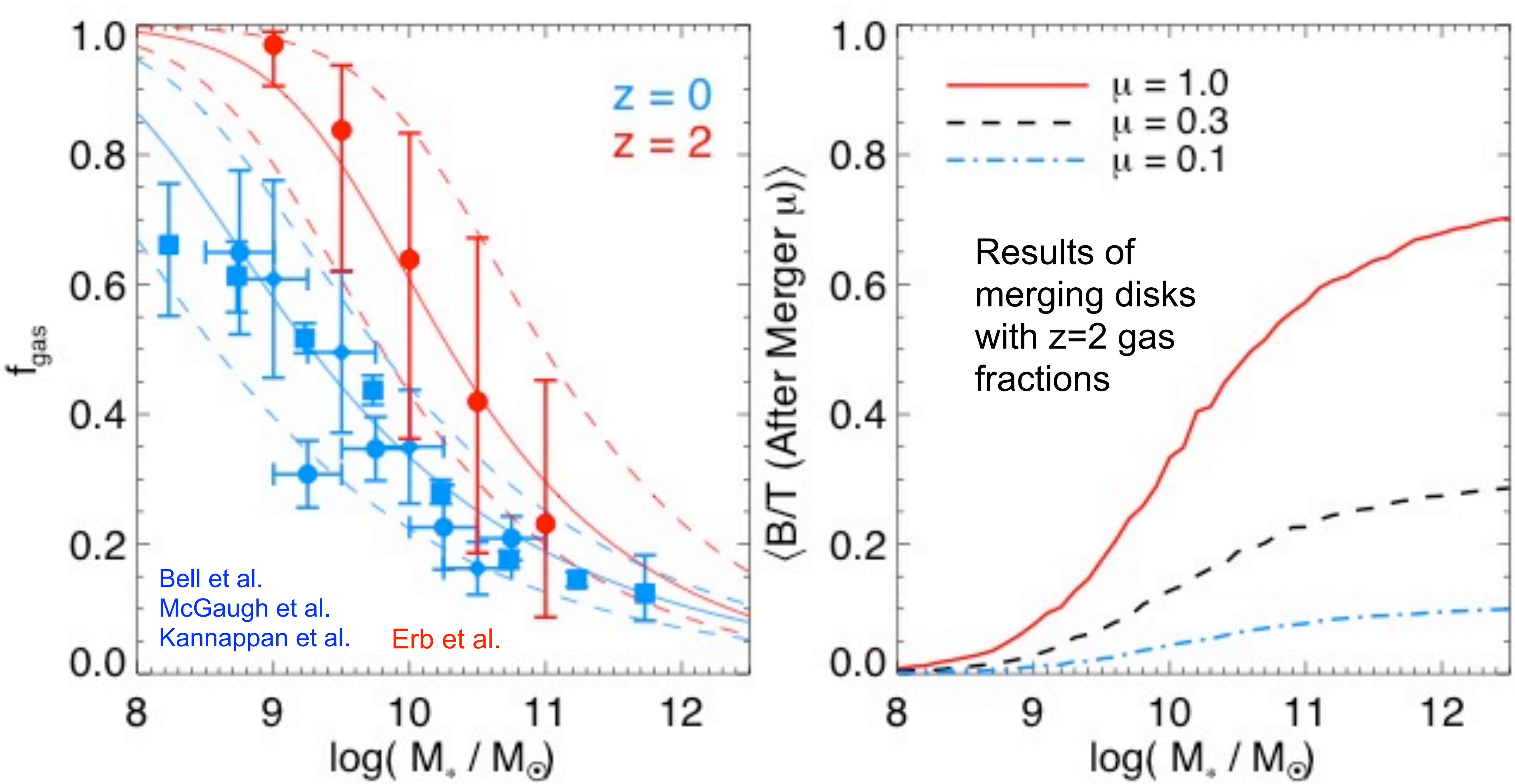
Purely gravitational process:
- *Independent* of feedback
- *Must* happen

Why Do We Care?

PFH & Somerville et al. 2009

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

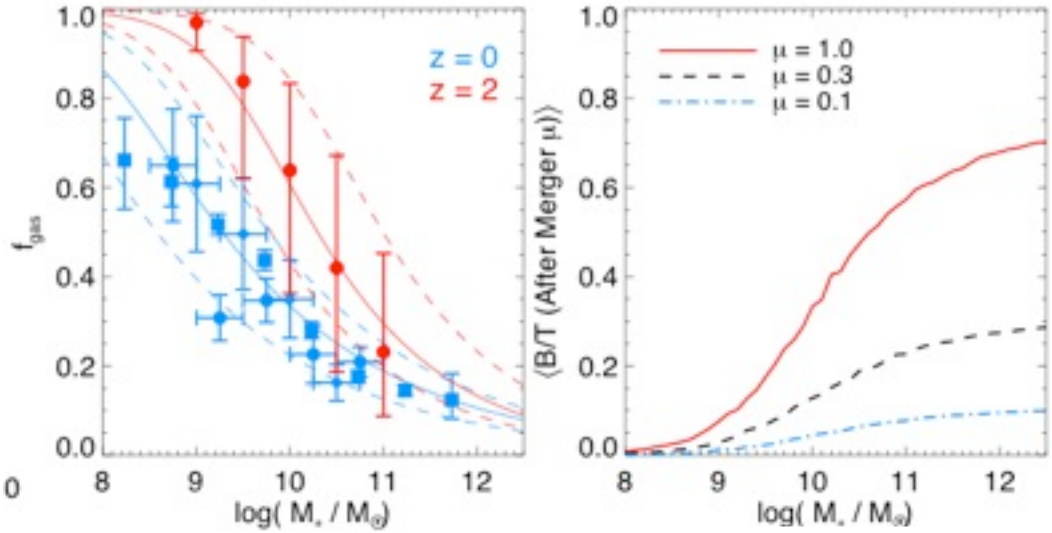
- Fold this into a cosmological model: why do we care?



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

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT



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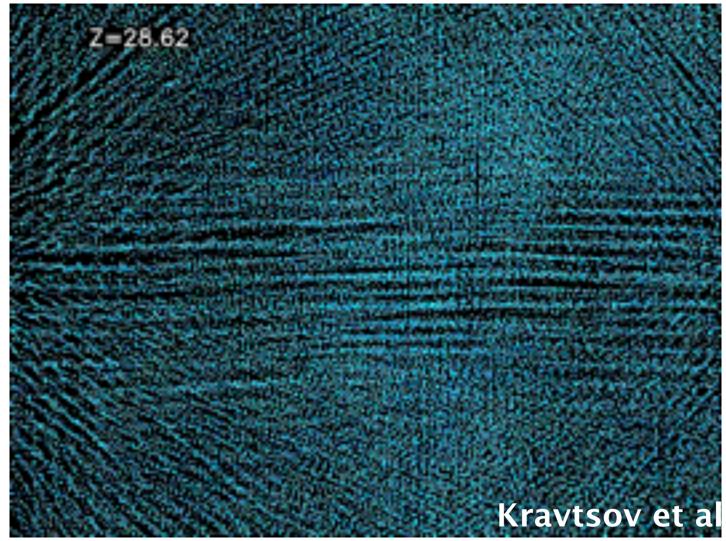

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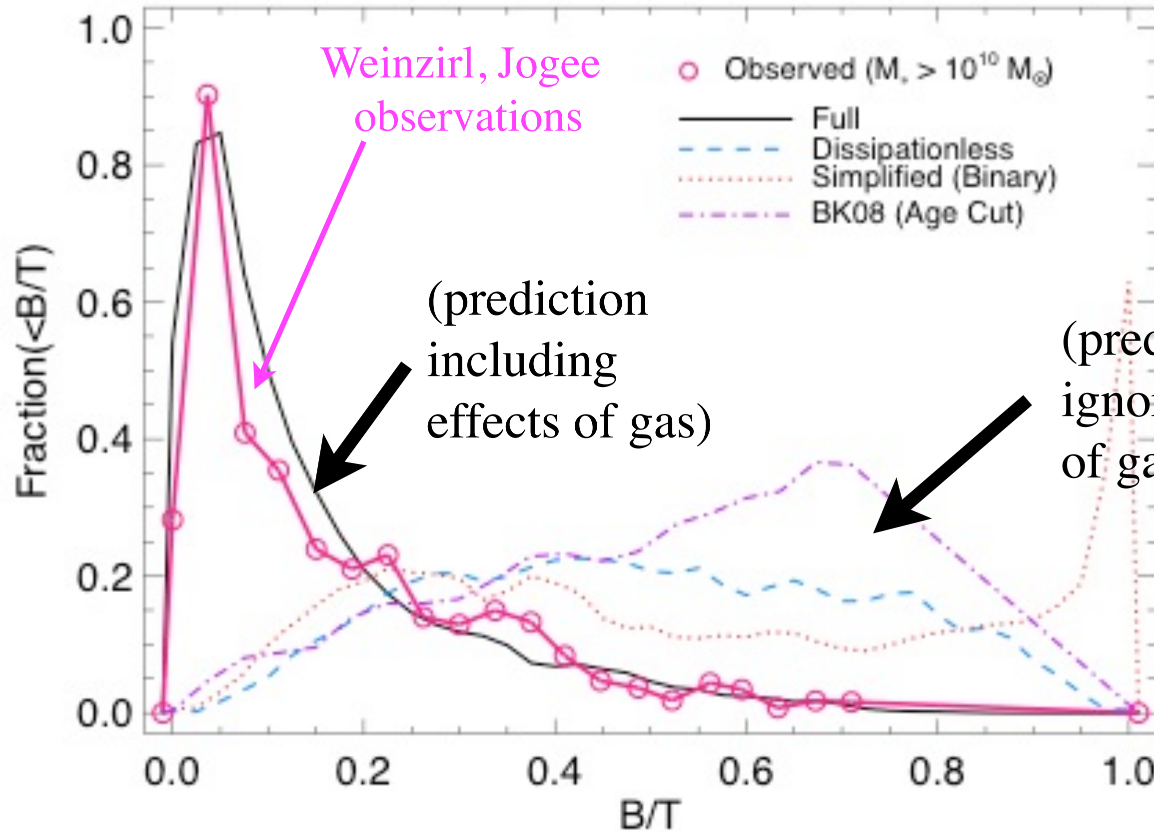

PFH & Somerville et al. 2009

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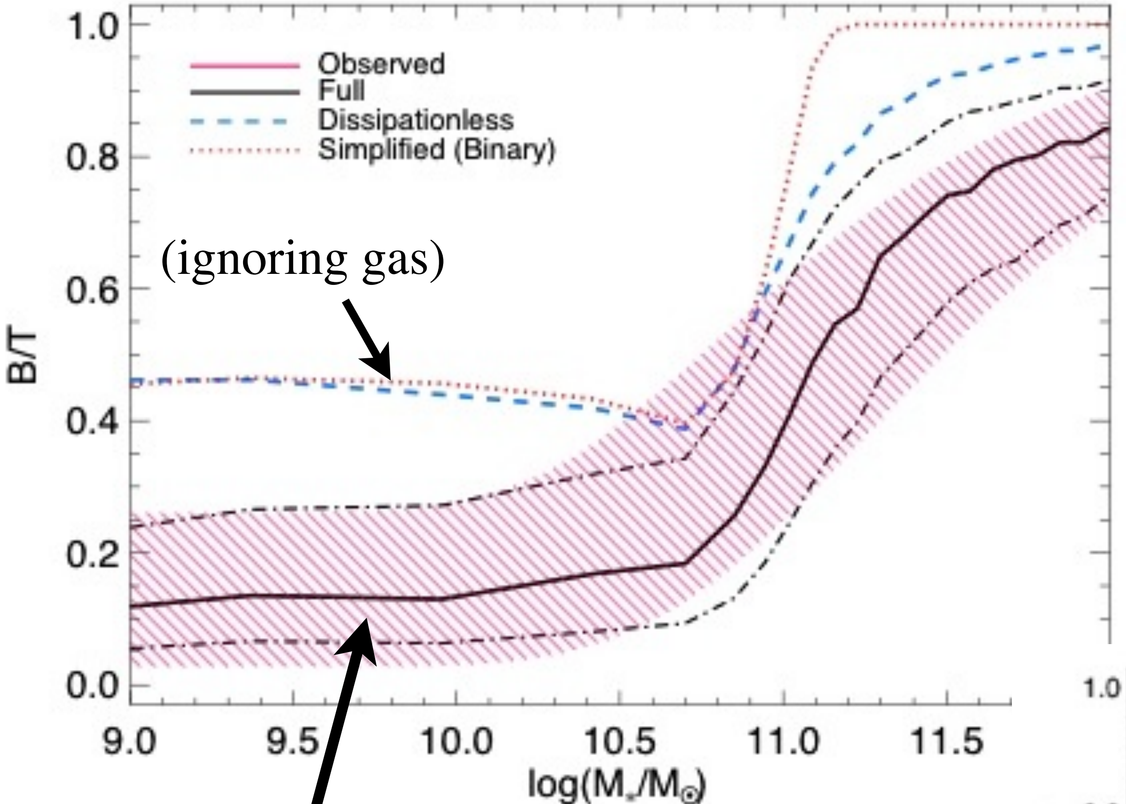
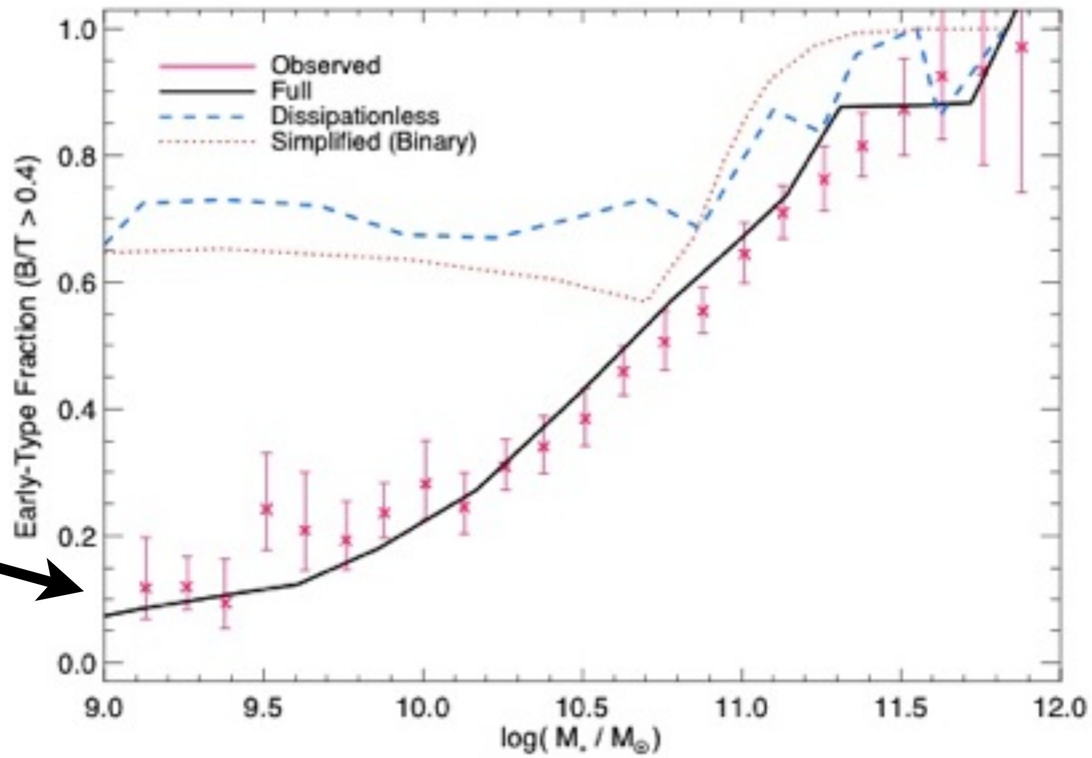


(ignoring gas)

(including effects of gas)

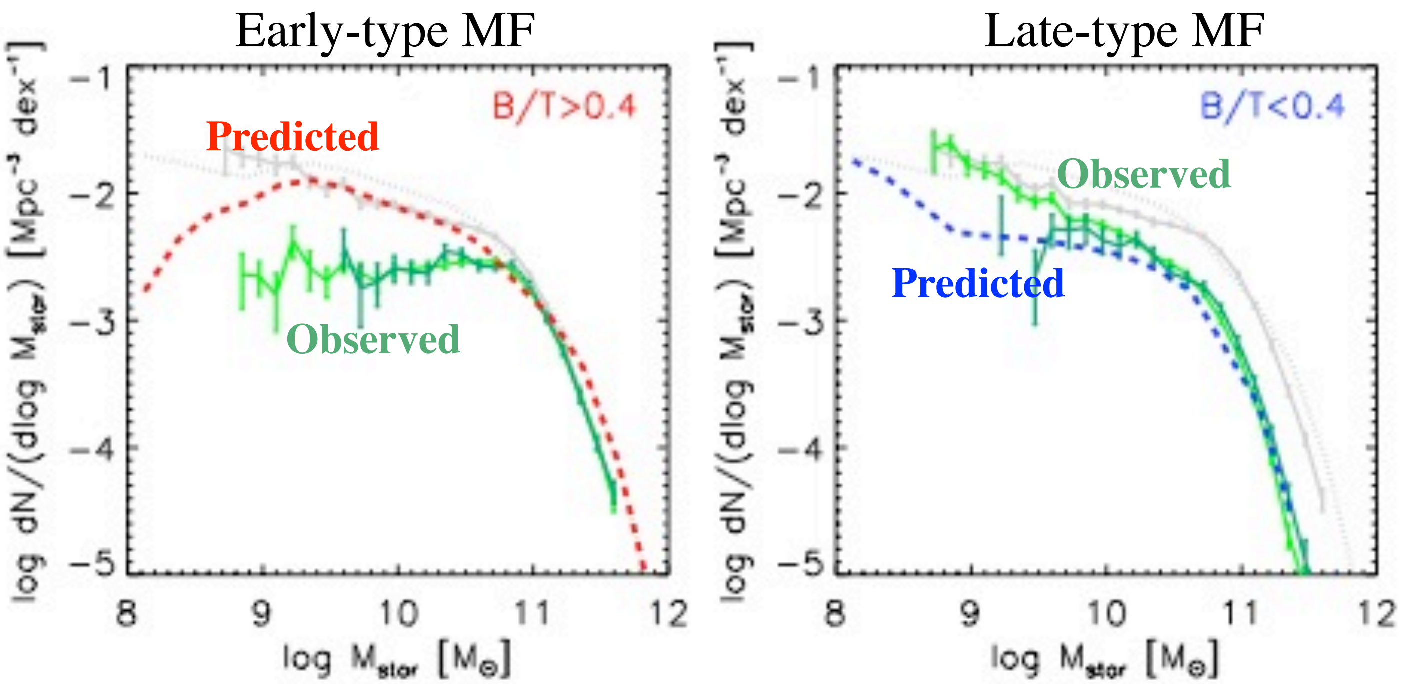
- Morphology-mass relation:
  - Natural consequence of f_{gas}-mass



Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

Gas-blind models:



Somerville SAMs:

Hundreds of model runs with ~10-20 parameters: still overproduce low-mass bulges

Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

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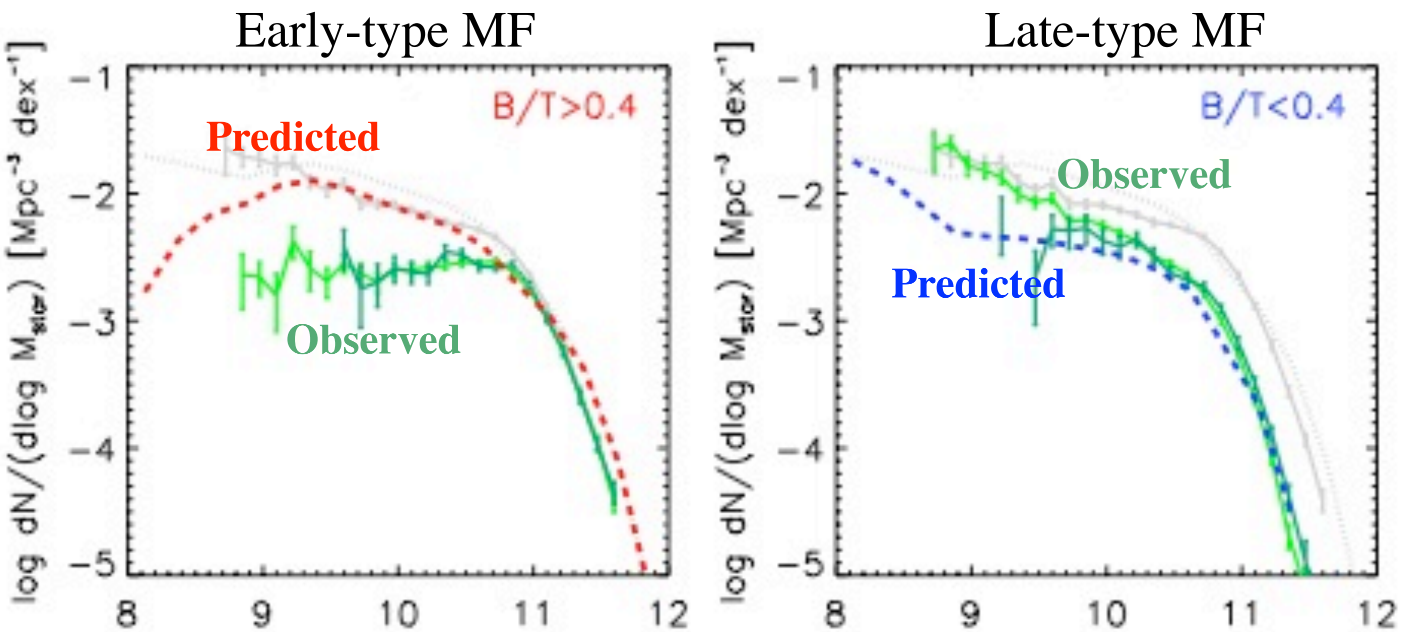
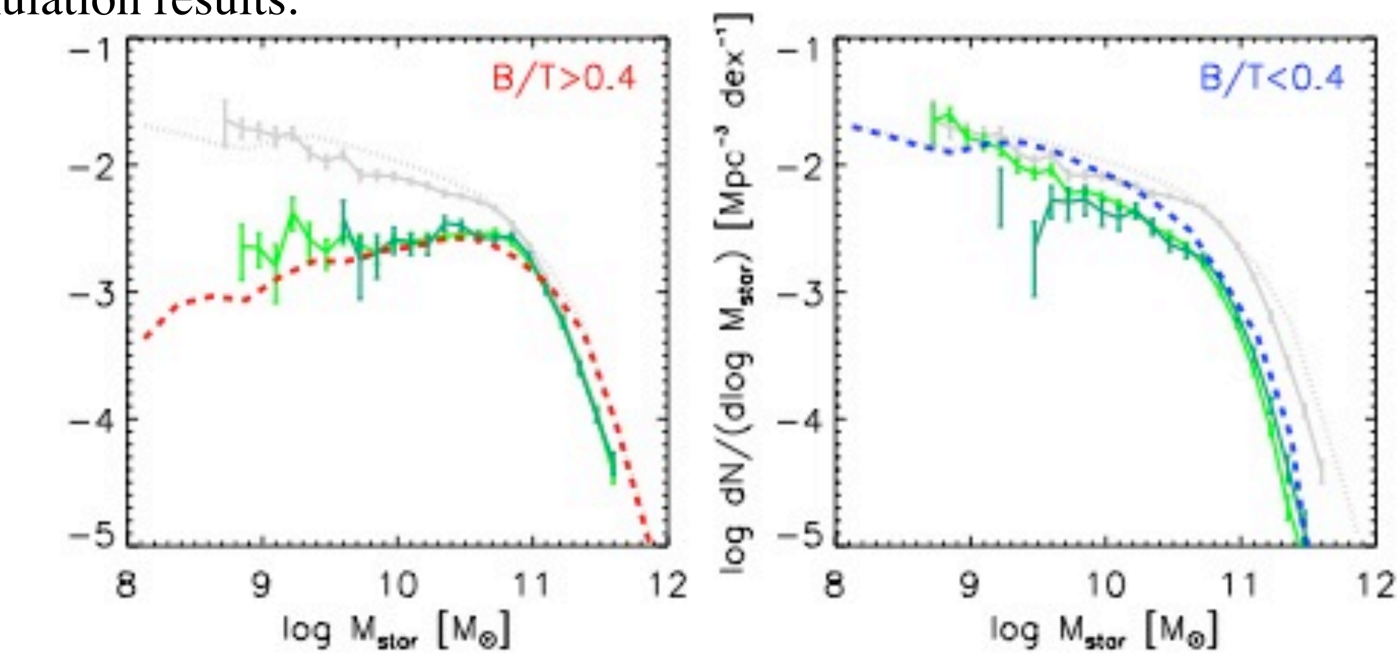


Exact same model, adding f_{gas}-dependent simulation results:

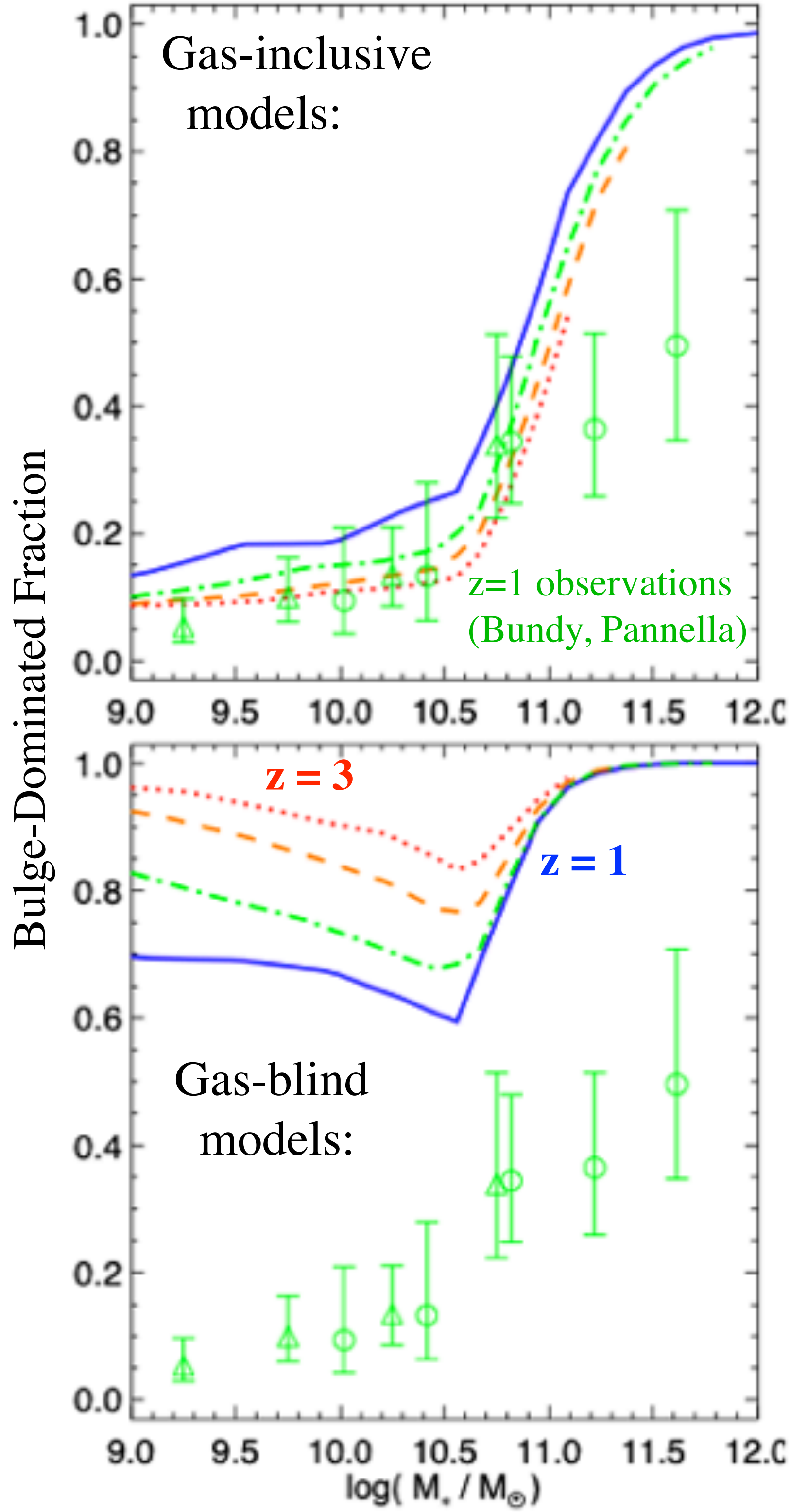


Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

Predict lots of high-z disks!

- Needed for their existence
  - We see them
  - (Genzel, Tacconi, Erb, Law, et al.)
- *May* explain some properties (turbulence etc.)
  - (Robertson & Bullock)



What About Disk Heating?

WON'T YOU OVER-PRODUCE THE THICK DISK?

- Toth & Ostriker (1992): Rigid satellite in static potential, decay by dynamical friction on circular orbit:

$$\text{Heating :} \quad \frac{\Delta H}{R} \propto \frac{M_2}{M_1}$$

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- Toth & Ostriker (1992): Rigid satellite in static potential, decay by dynamical friction on circular orbit:

Heating : $$\frac{\Delta H}{R} \propto \frac{M_2}{M_1}$$

- Satellite mass functions: $$\frac{dN}{dlog(M_2/M_1)} \propto \left(\frac{M_2}{M_1}\right)^{-1}$$

Equal contributions to thick disk from all intervals in M_2/M_1!

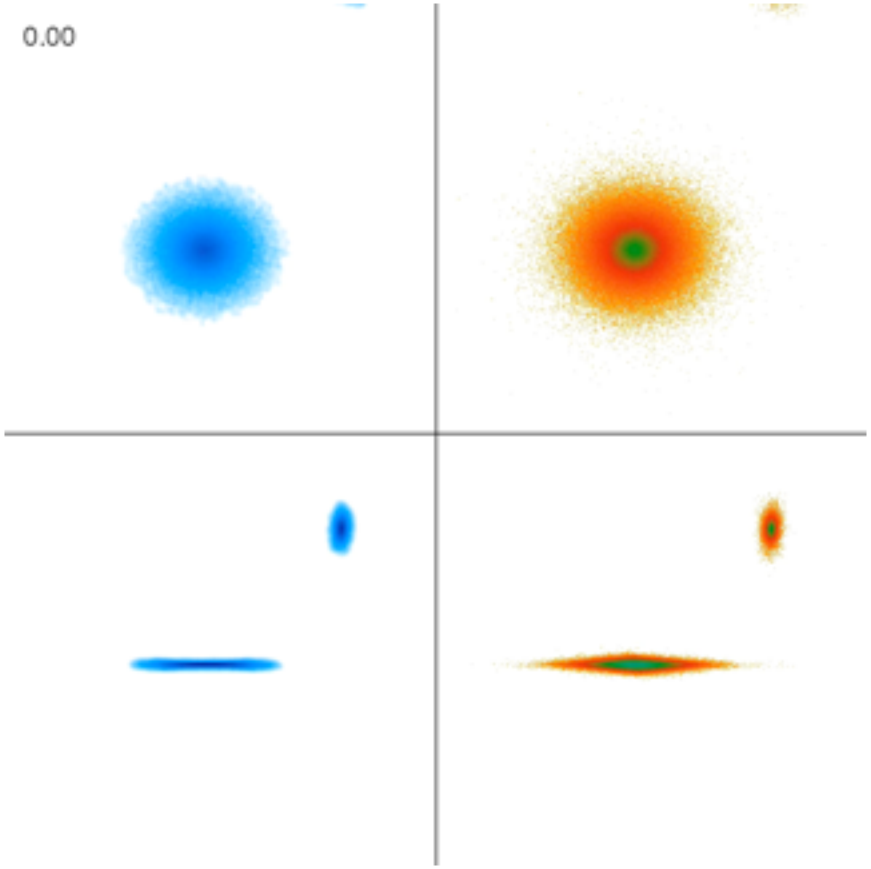
- No more than ~10% MW growth from any mass ratios since z~1-2!

What About Disk Heating?

WON'T YOU OVER-PRODUCE THE THICK DISK?

- In fact, orbits are <u>radial</u>, satellites strip, potentials are live:

Gives: $$\frac{\Delta H}{R} \propto \left(\frac{M_2}{M_1}\right)^2$$



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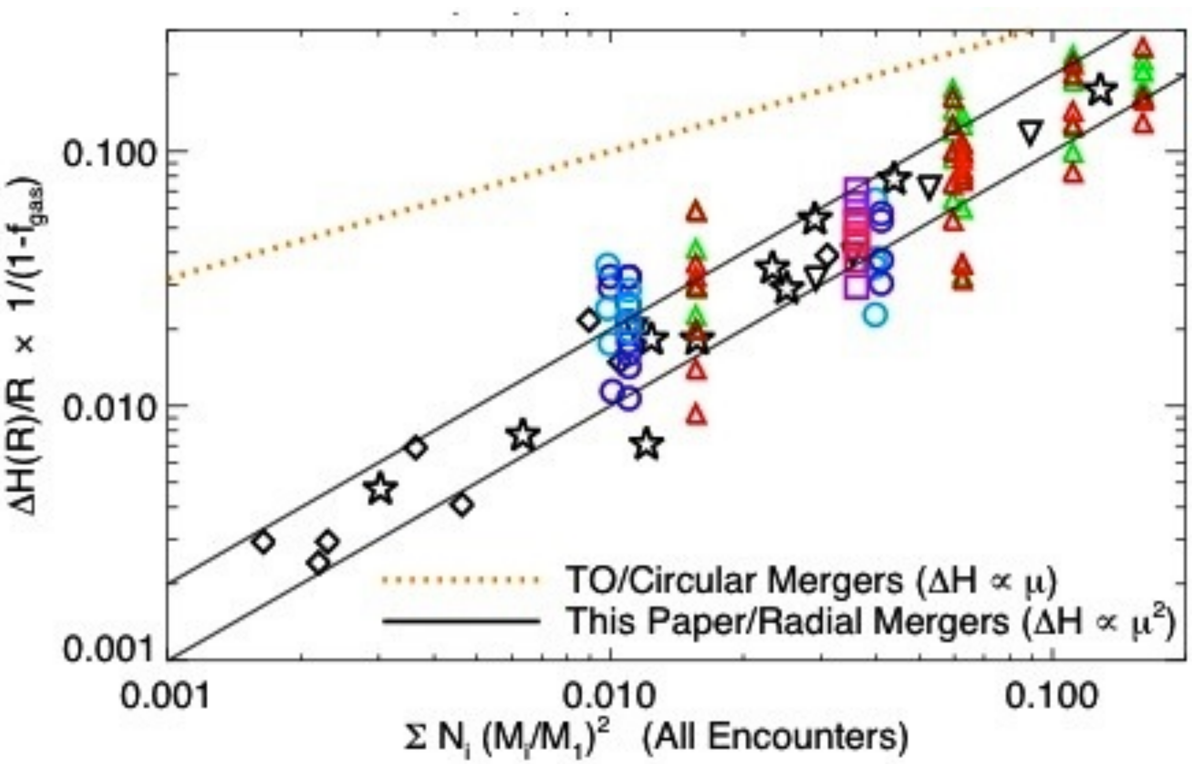

See in "live" simulations:
Velazquez & White,
Villalobos & Helmi

& with cosmological ICs:
Purcell et al.,
Kazantzidis et al.

What About Disk Heating?

WON'T YOU OVER-PRODUCE THE THICK DISK?

- In fact, orbits are radial, satellites strip, potentials are live:

Gives: $$\frac{\Delta H}{R} \propto \left(\frac{M_2}{M_1}\right)^2$$

- Heating dominated by few big events
  - Super-thin disks can exist
  - More variation in thick disks

- Thick disk doesn't constrain total MW growth, does constrain the biggest event MW could have experienced

What About Disk Heating?

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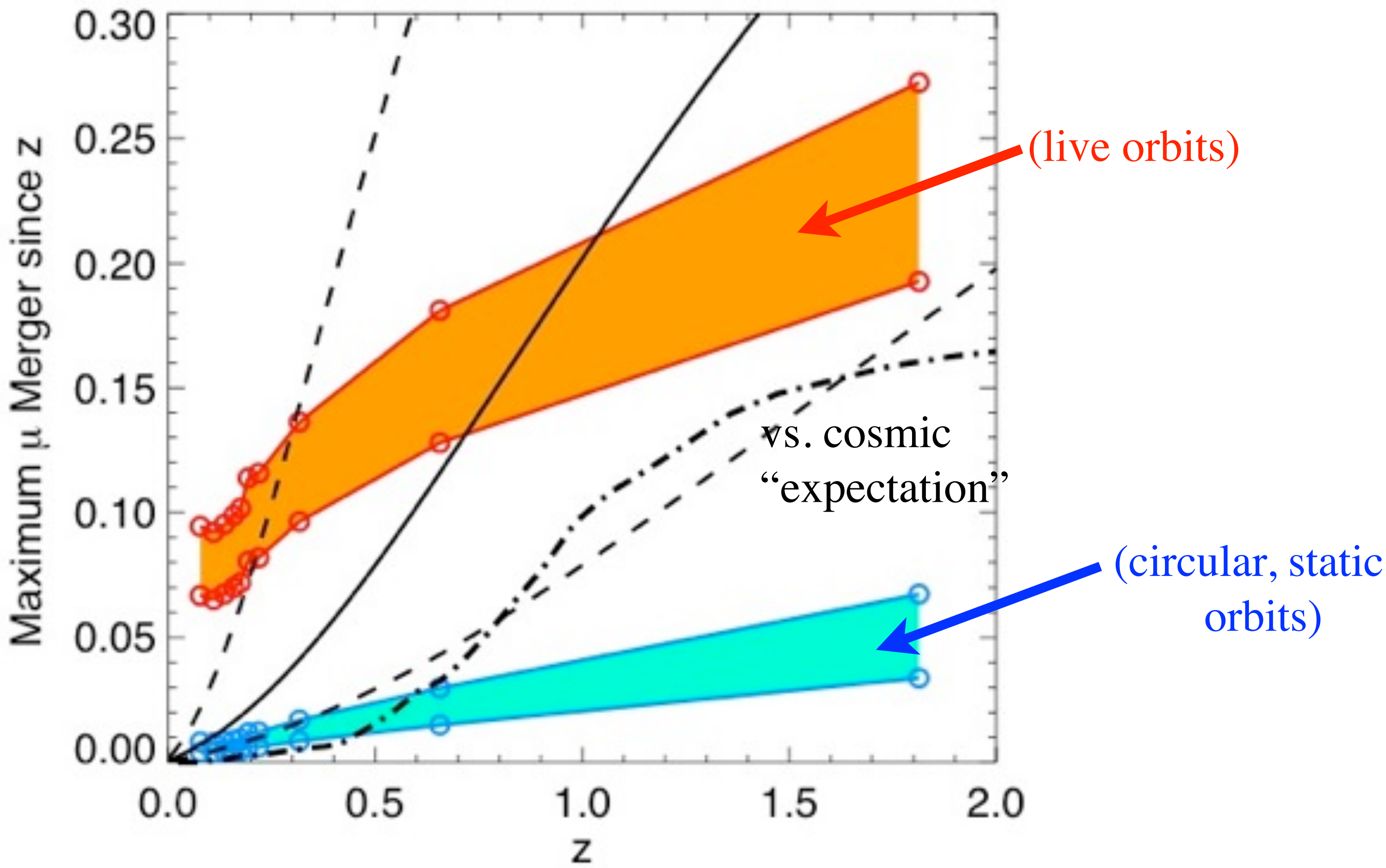


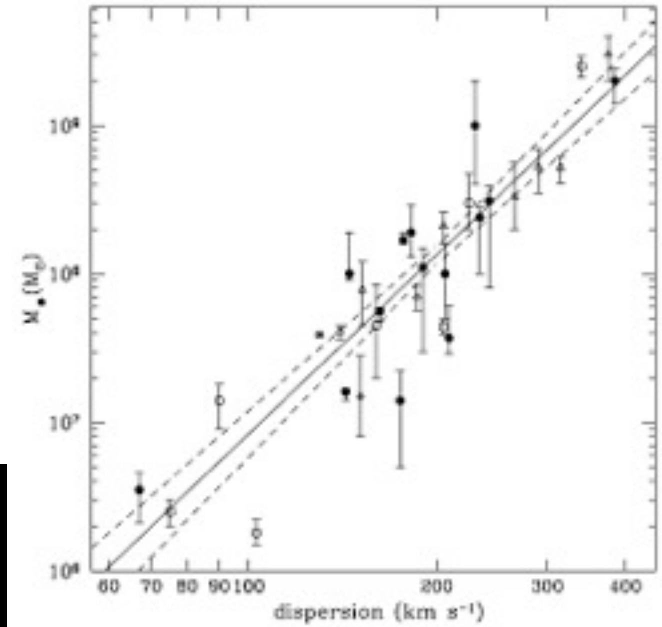
(Constraint from dispersions in solar neighborhood; Nordstrom et al., Seabroke & Gilmore)

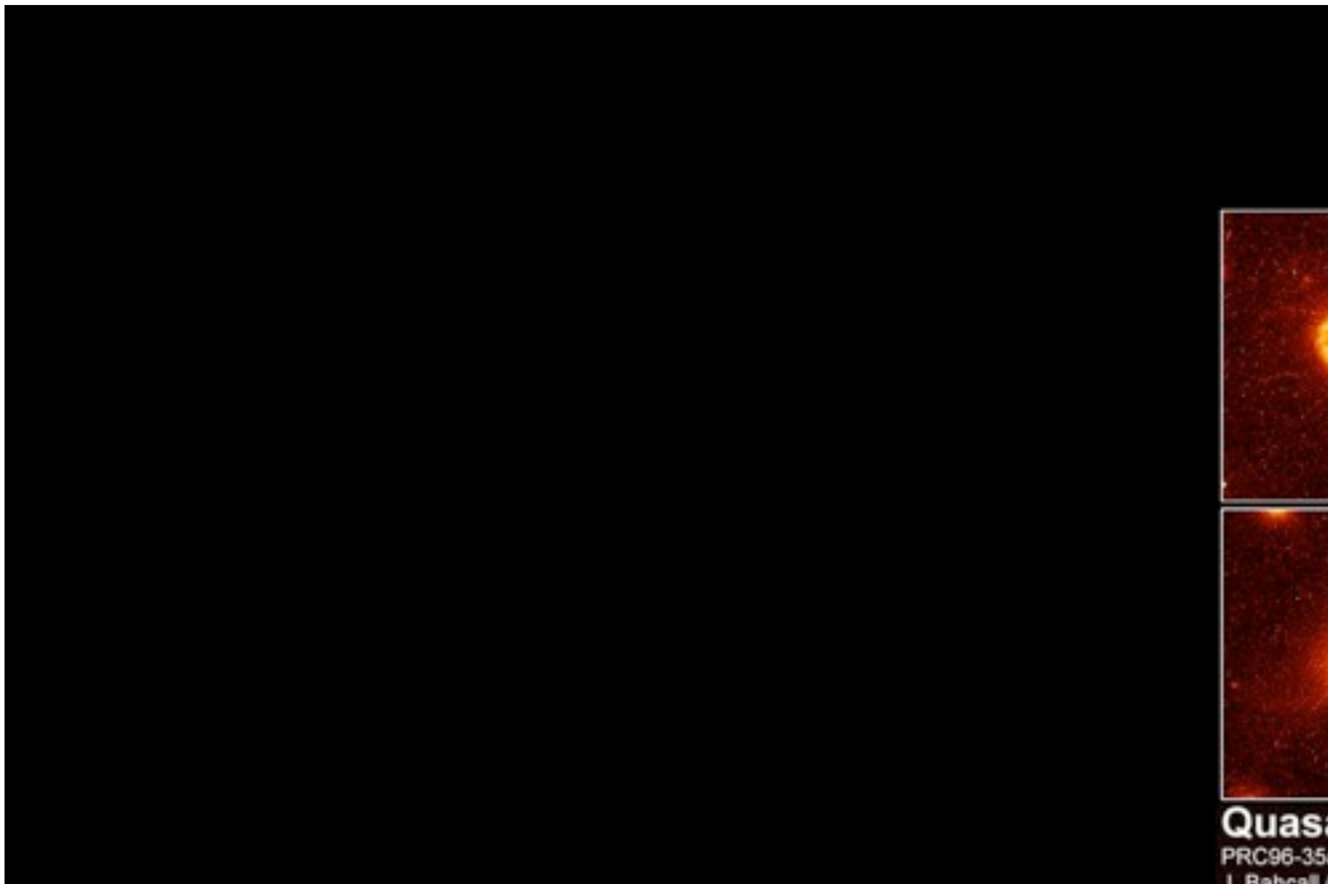
With all this gas getting to the center of the galaxy, what is the black hole doing?

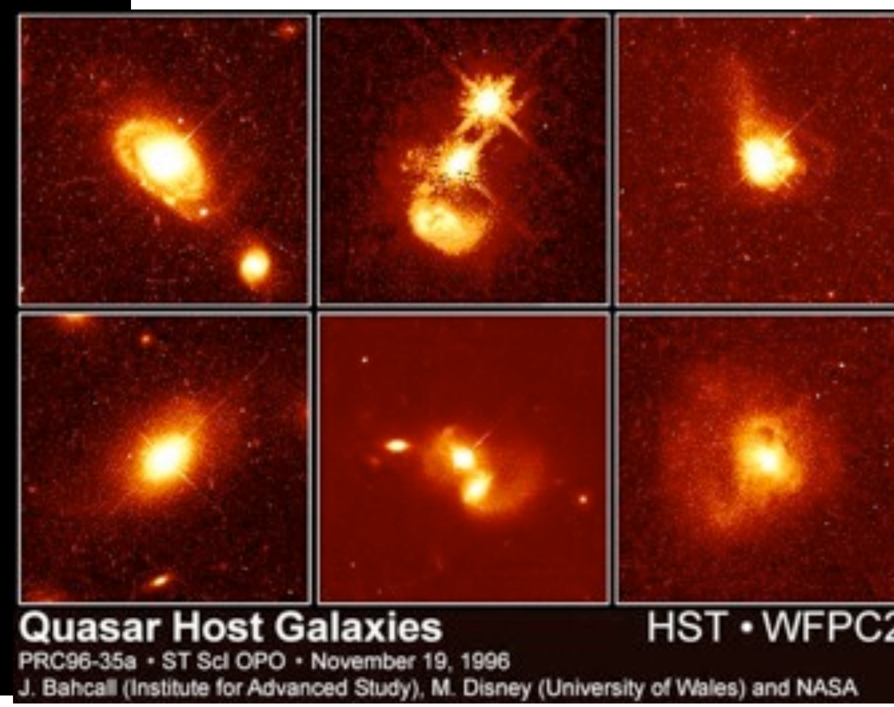
Triggering & Fueling: “Feeding the Monster”

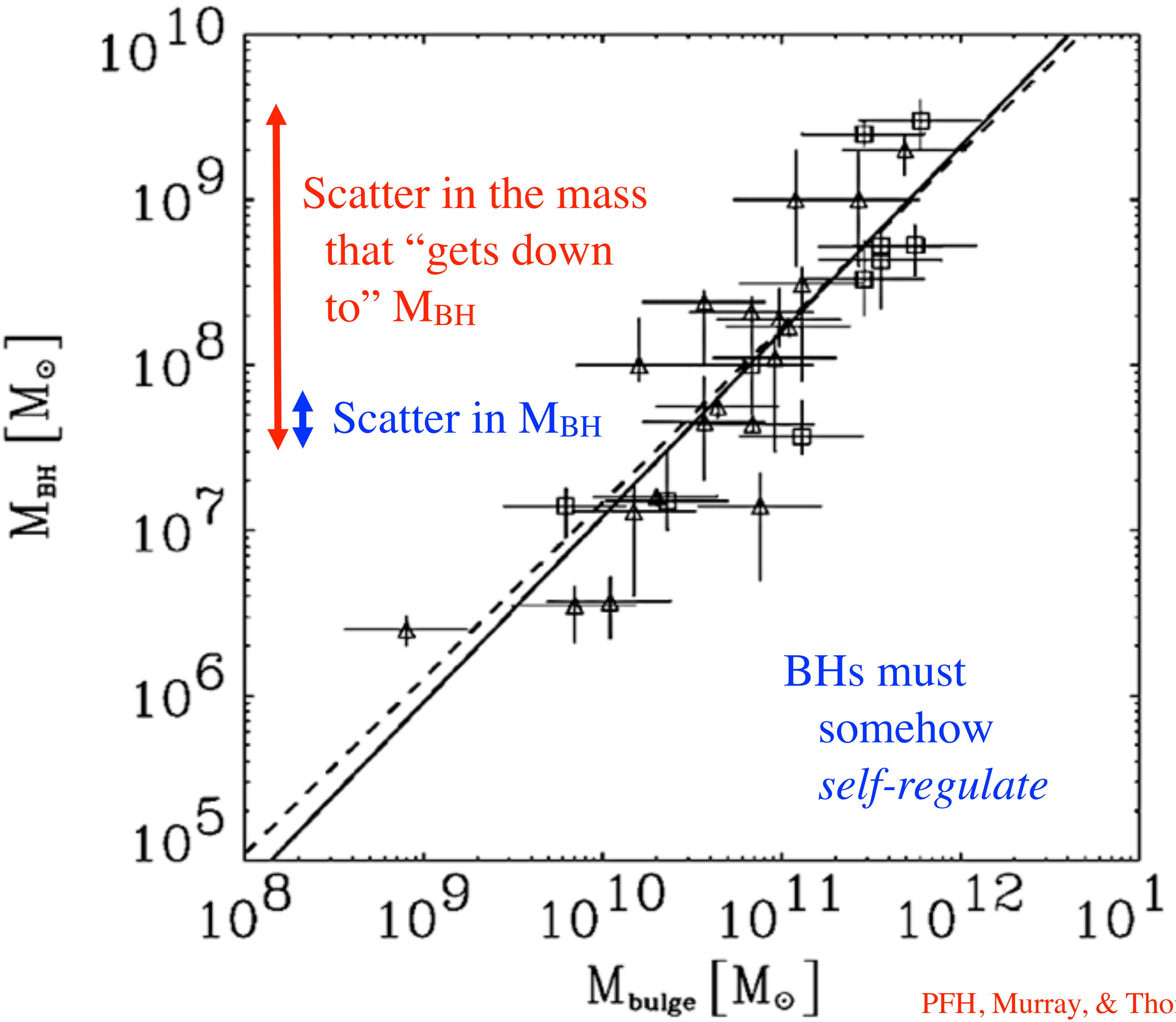
WHAT CAN BREAK DEGENERACIES IN DIFFERENT FUELING MODELS?

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









PFH, Murray, & Thompson 2009

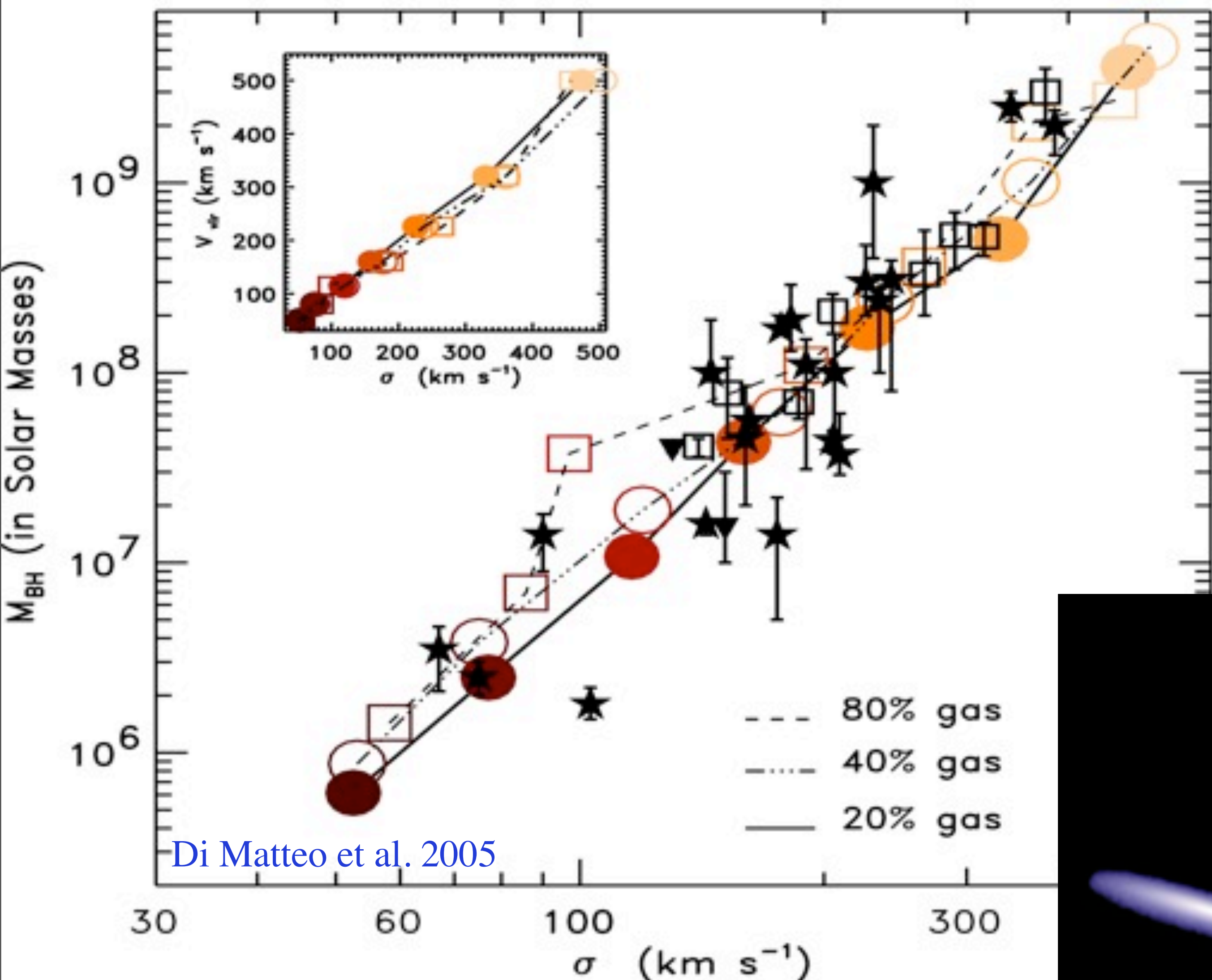
Simplest Idea:

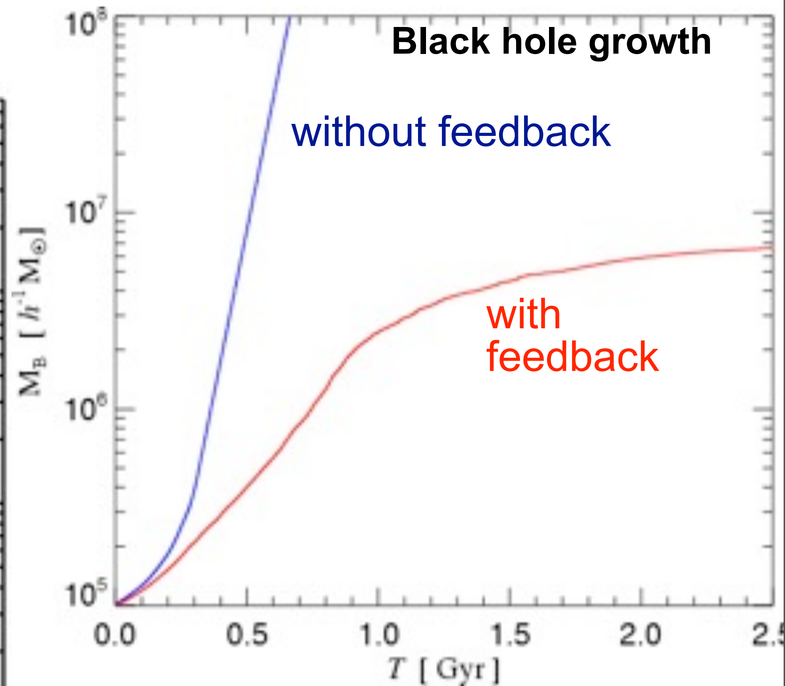
FEEDBACK ENERGY BALANCE (SILK & REES '98)

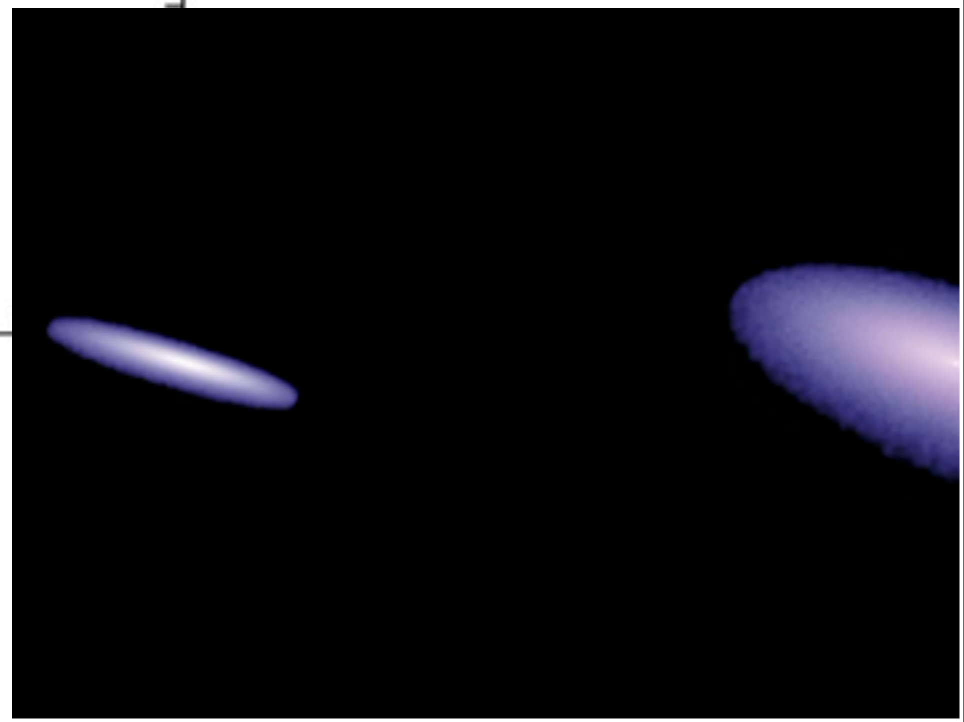
- Luminous accretion disk near the Eddington limit radiates an energy:
  - $L = e_r\,(dM_{BH}/dt)\,c^2$ ($e_r \sim 0.1$)
- Total energy radiated:
  - $\sim 0.1\,M_{BH}\,c^2 \sim 10^{61}$ ergs in a typical $\sim 10^8\,M_{sun}$ system
- Compare this to the gravitational binding energy of the galaxy:
  - $\sim M_{gal}\,s^2 \sim (10^{11}$ Msun$)\,(200$ 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
      - $MBH \sim (a/he_r)\,M_{gal}\,(s/c)^2 \sim 0.002\,M_{gal}$

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

PREVENTS RUNAWAY BLACK HOLE GROWTH



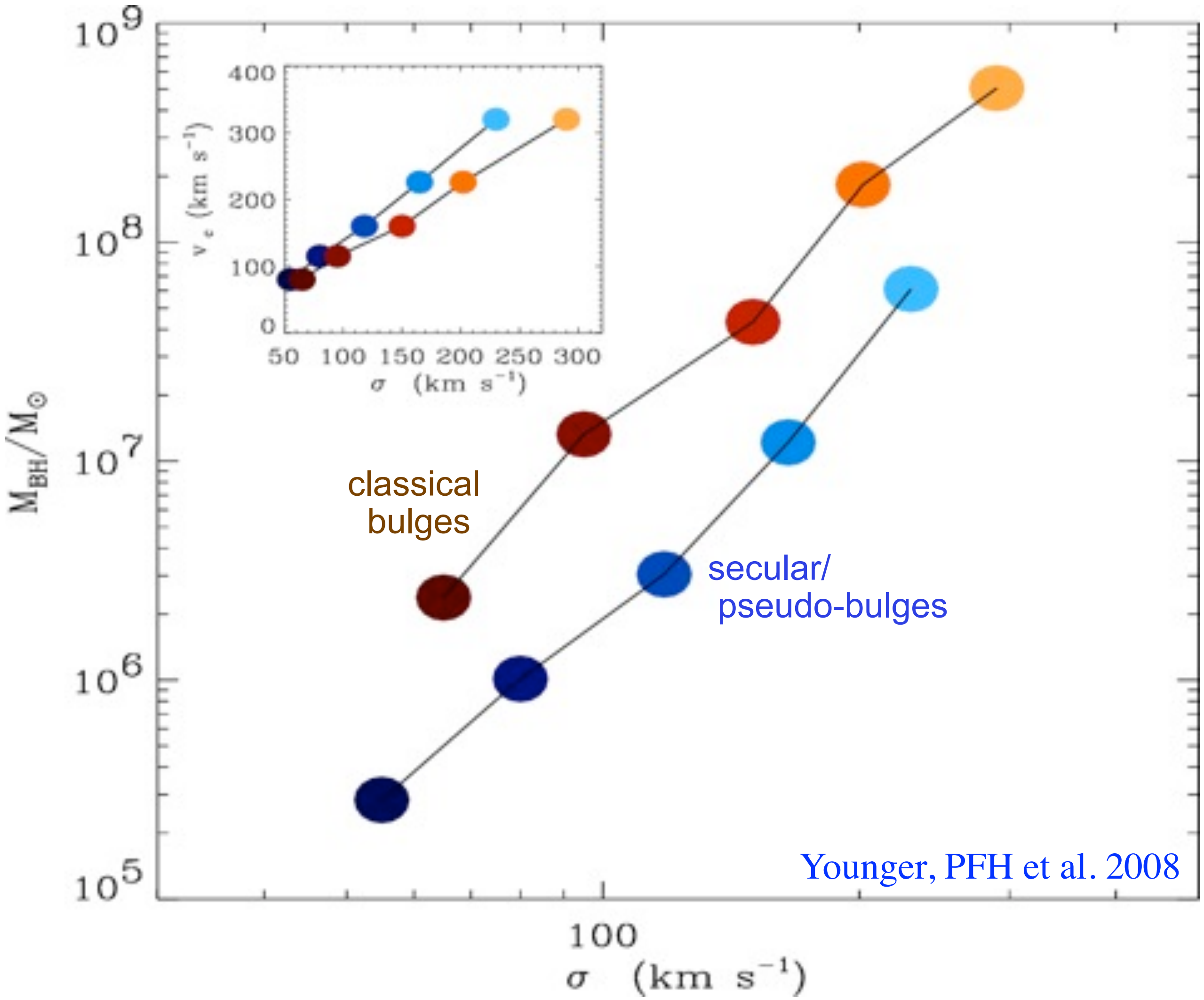




Observations & Simulations Suggest this Simple Picture Works

MAKES UNIQUE PREDICTIONS:

- What is the “fundamental” correlation? M_{BH}-$E_{binding}$: BH “fundamental plane” (PFH et al.)
- Different correlation for “classical” and “pseudobulges”
  - Both tentatively observed (PFH et al.; Aller; Greene et al.; Hu)

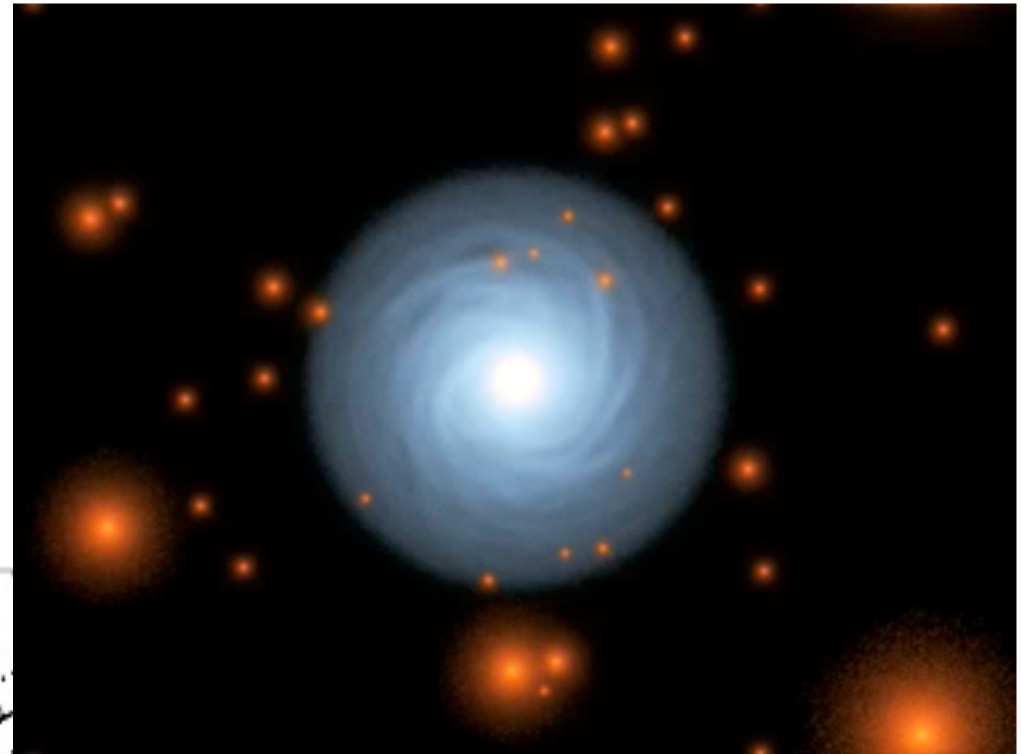


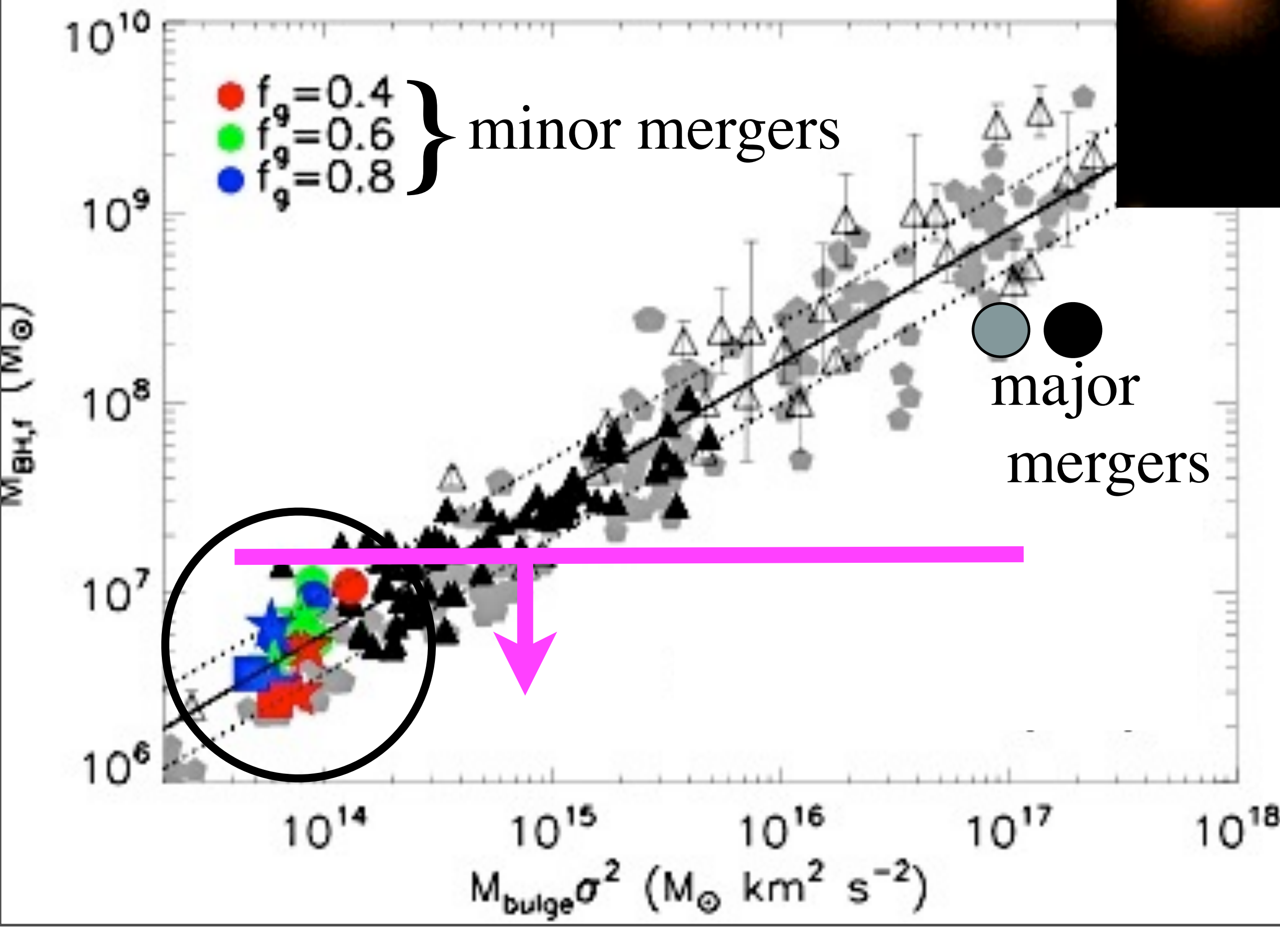
- Basic argument:
  - BH feedback self-regulates growth in ~fixed potential
  - only “feel” the local potential of material to be unbound

Of Course, Not *Every* AGN Needs a Merger

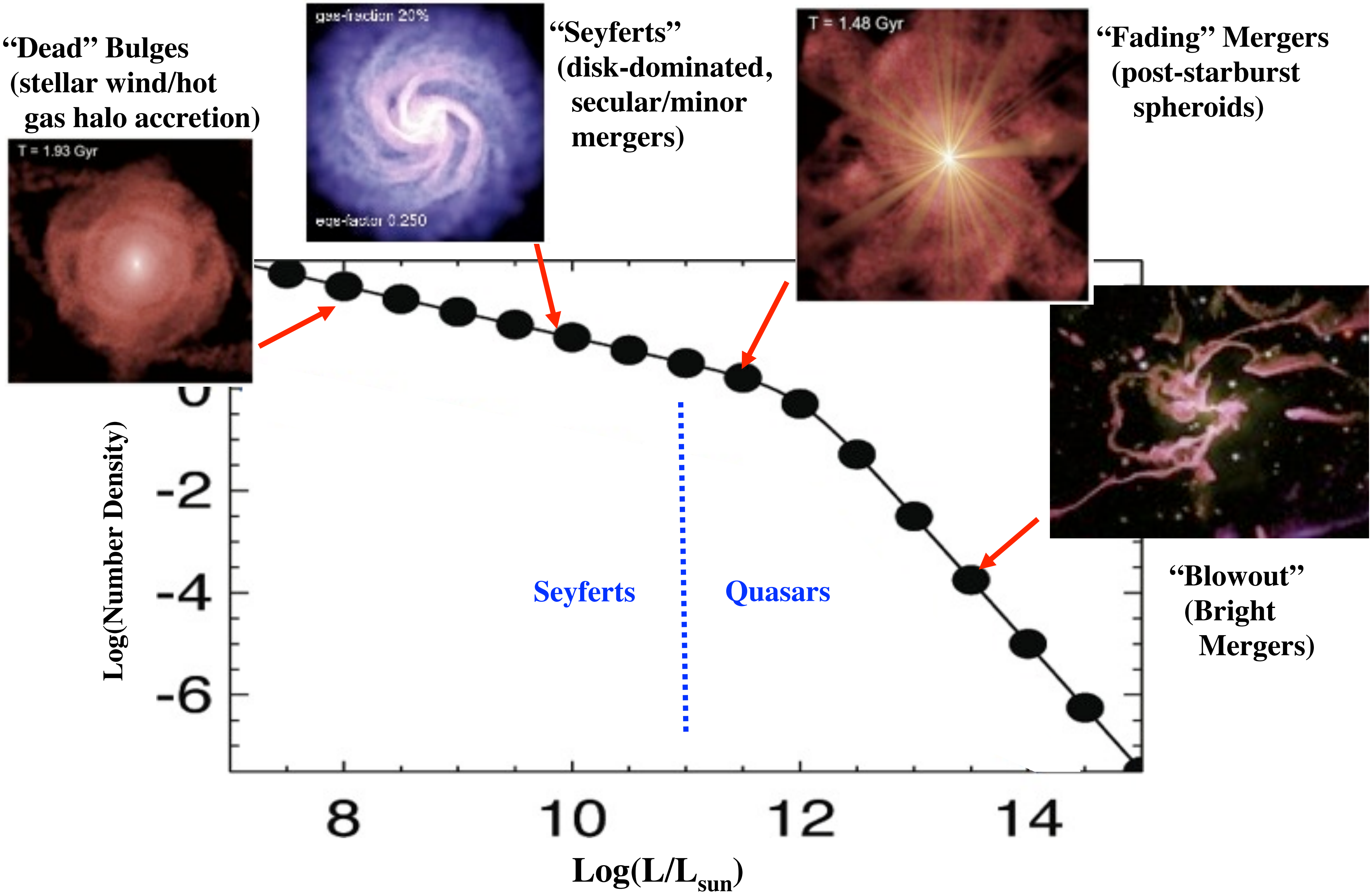
MORE QUIESCENT GROWTH MODES?

- z~2 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!

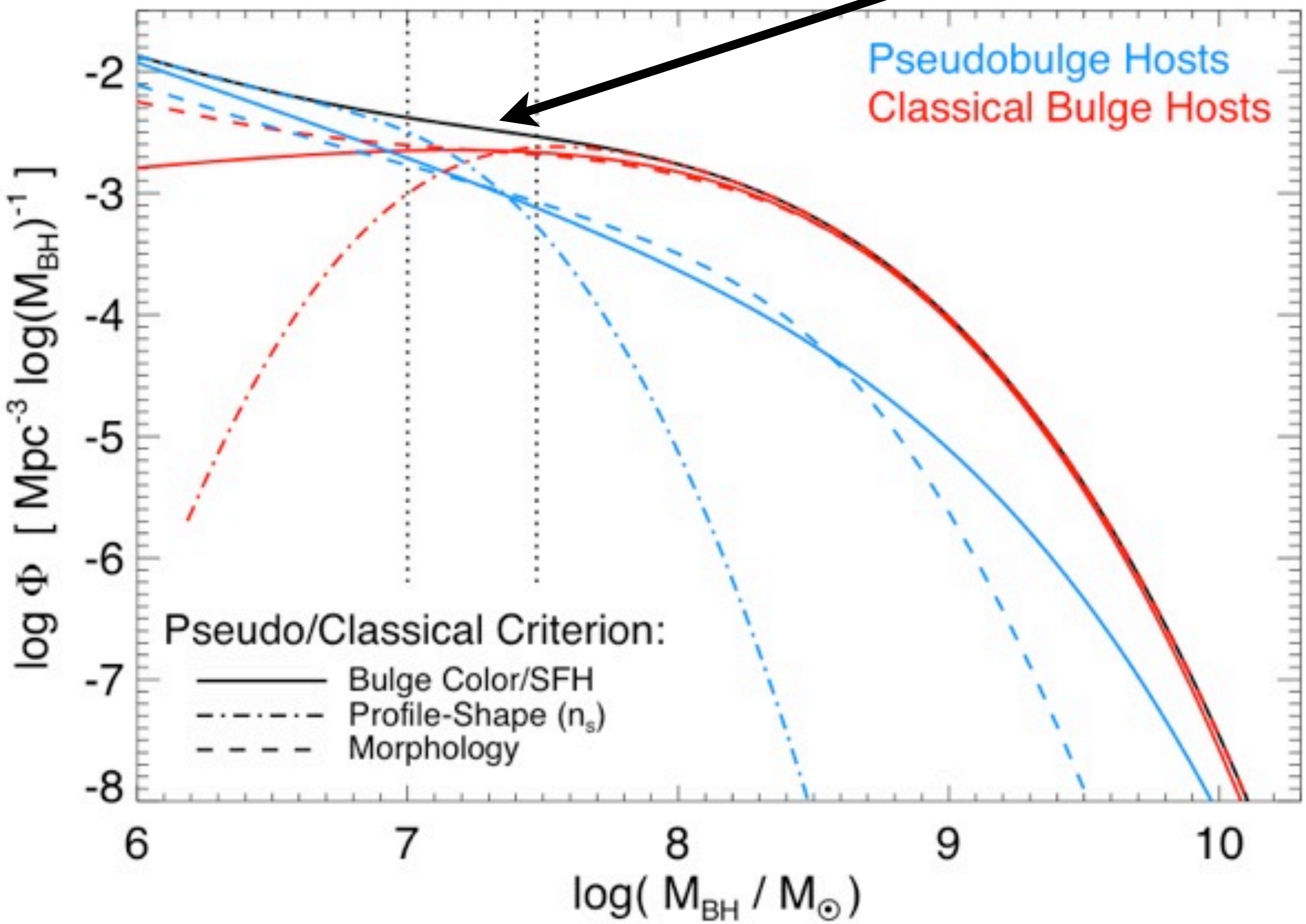


- Observed luminosity function: populations at different *evolutionary* stages

Testing the models:

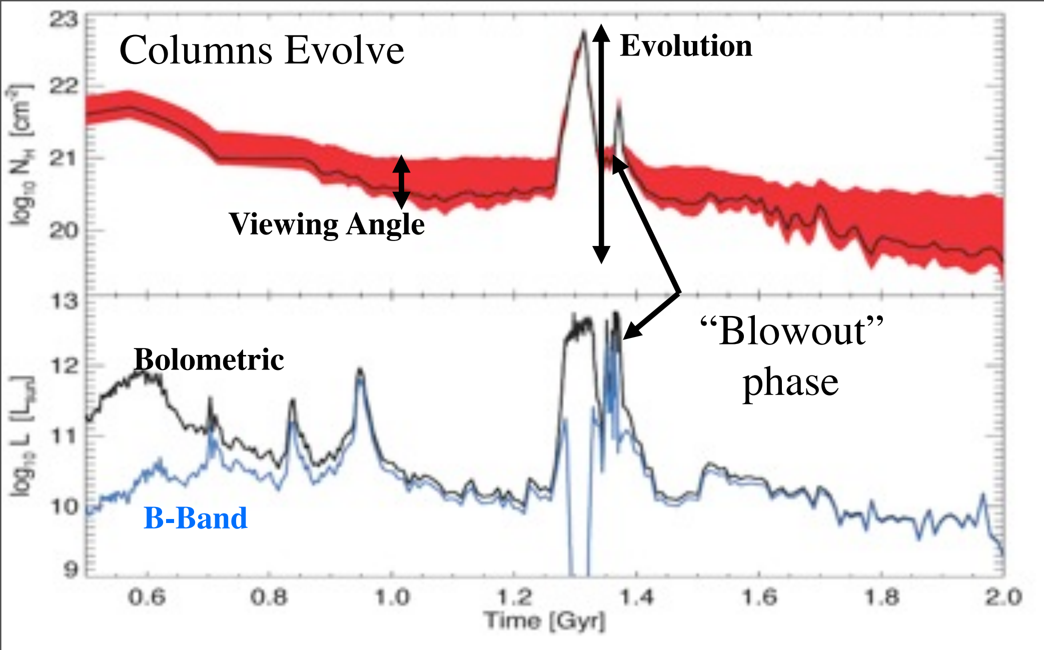
REMNANT MORPHOLOGY:

~Seyfert-Quasar threshold at Eddington



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

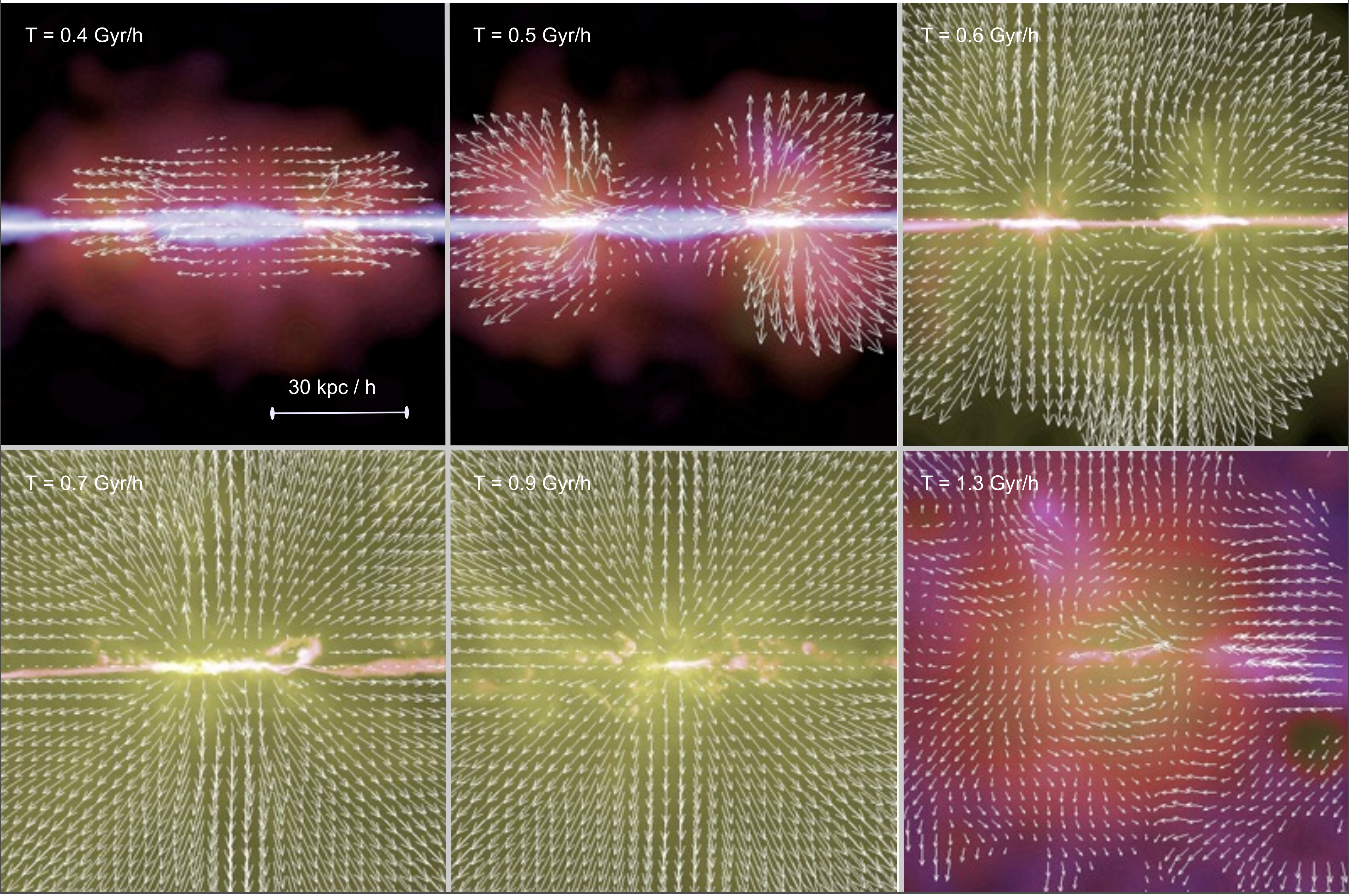
PFH & Hernquist 2008


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

Where Does the Energy/Momentum Go?

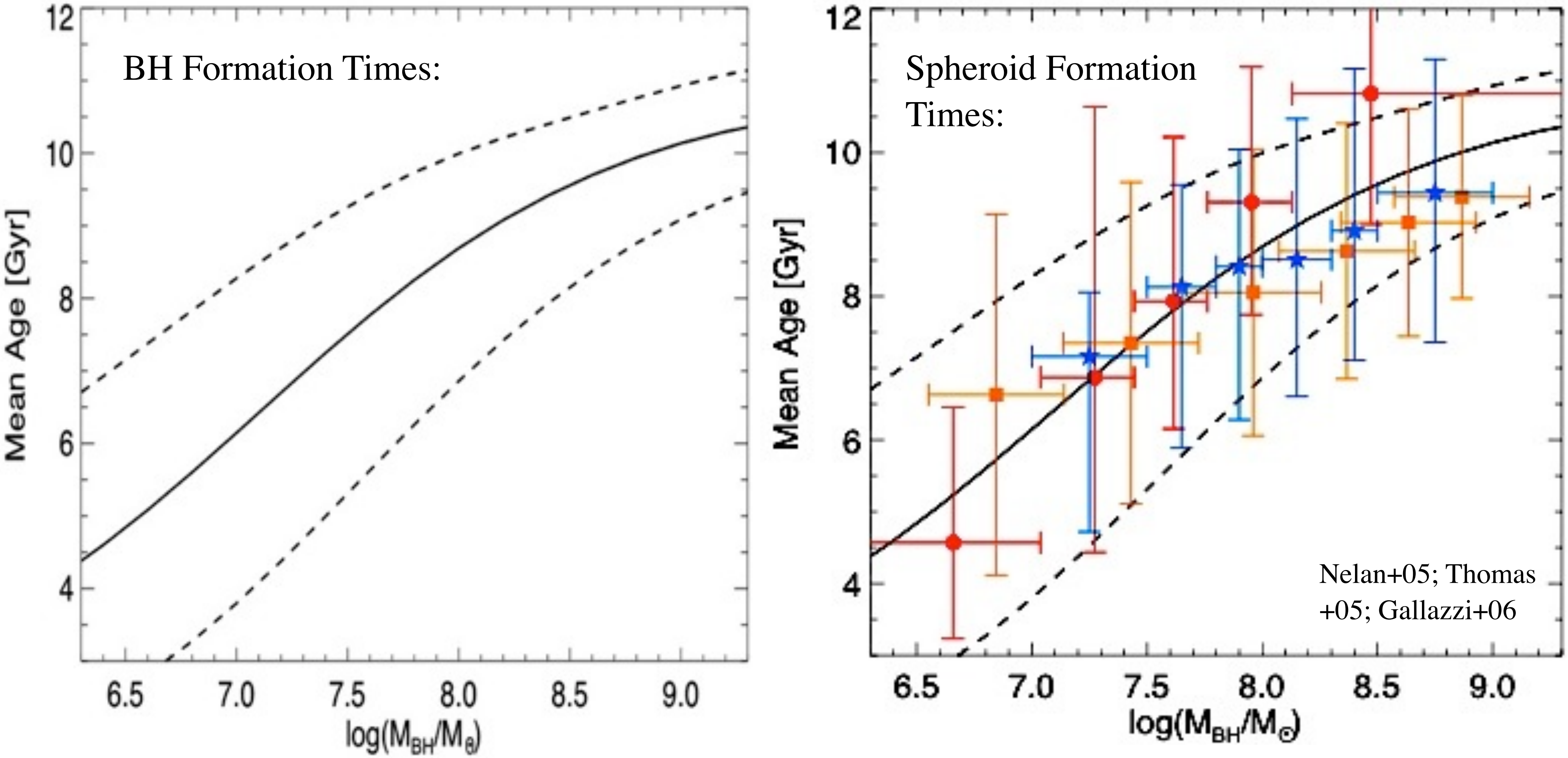
QUASAR-DRIVEN OUTFLOWS?

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



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

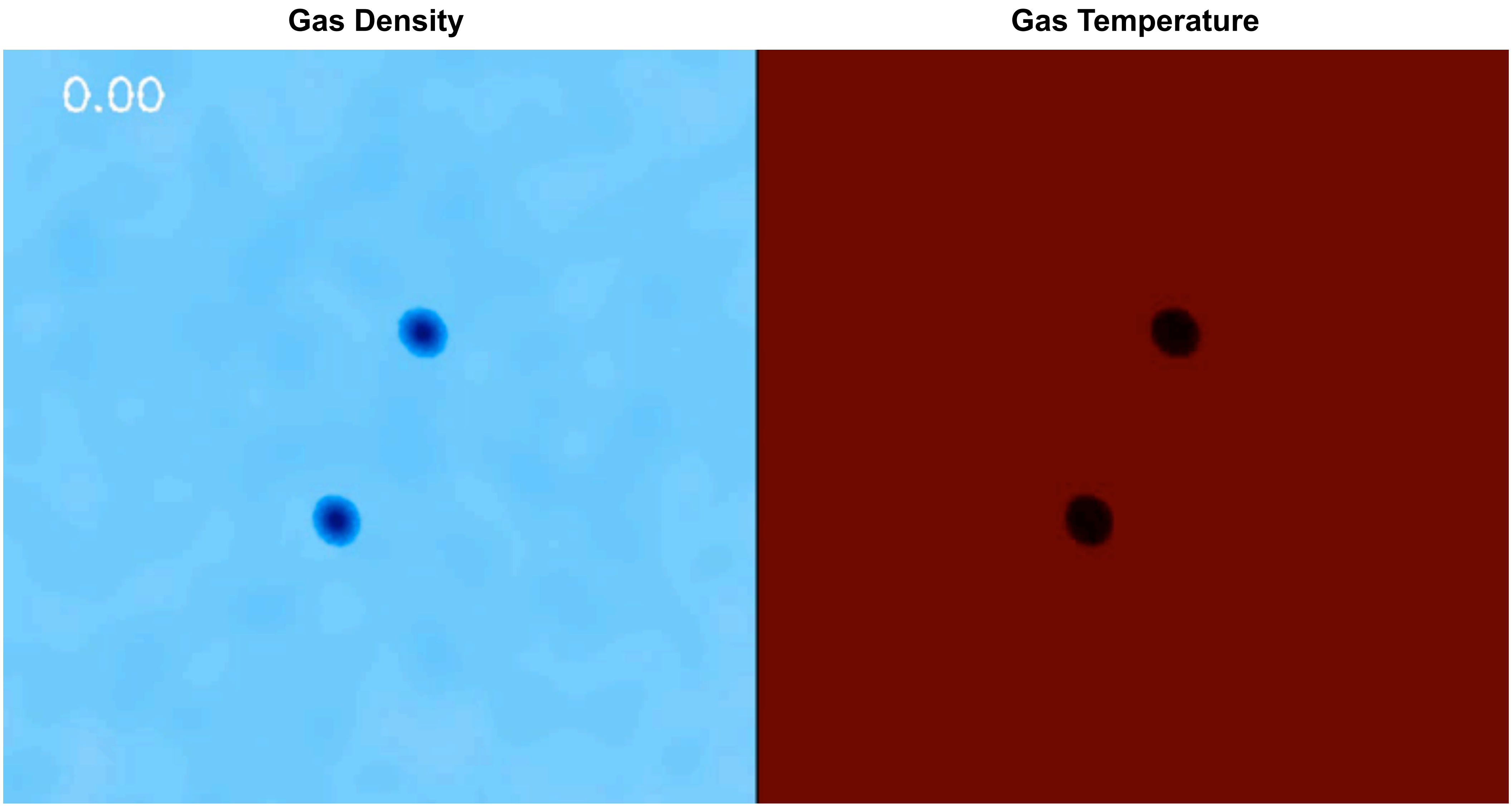
- Quasars were active/BHs formed when SF shut down...



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

Quasar Outflows May Be Significant for the ICM & IGM

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



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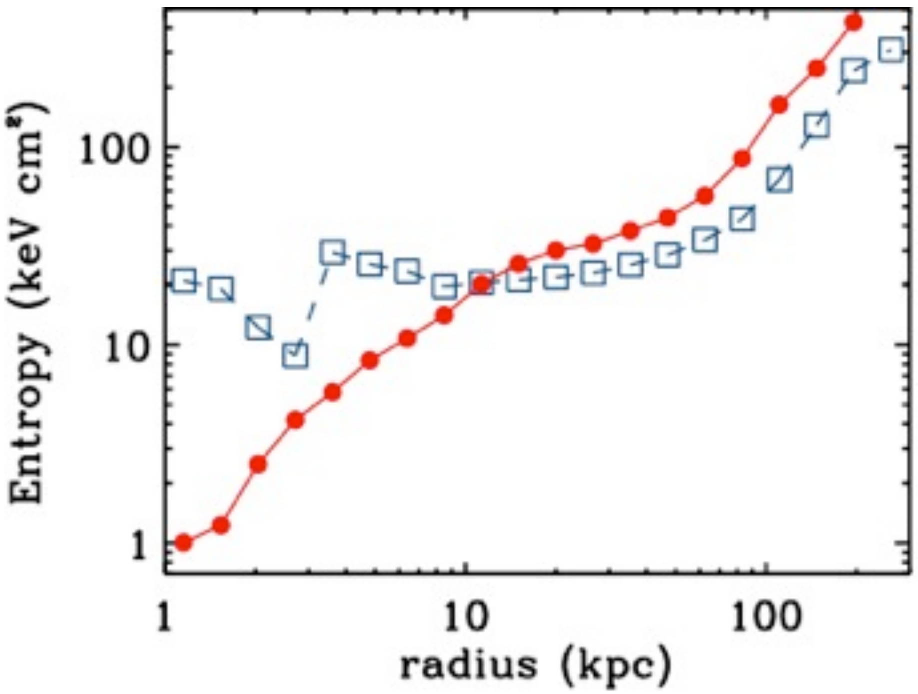
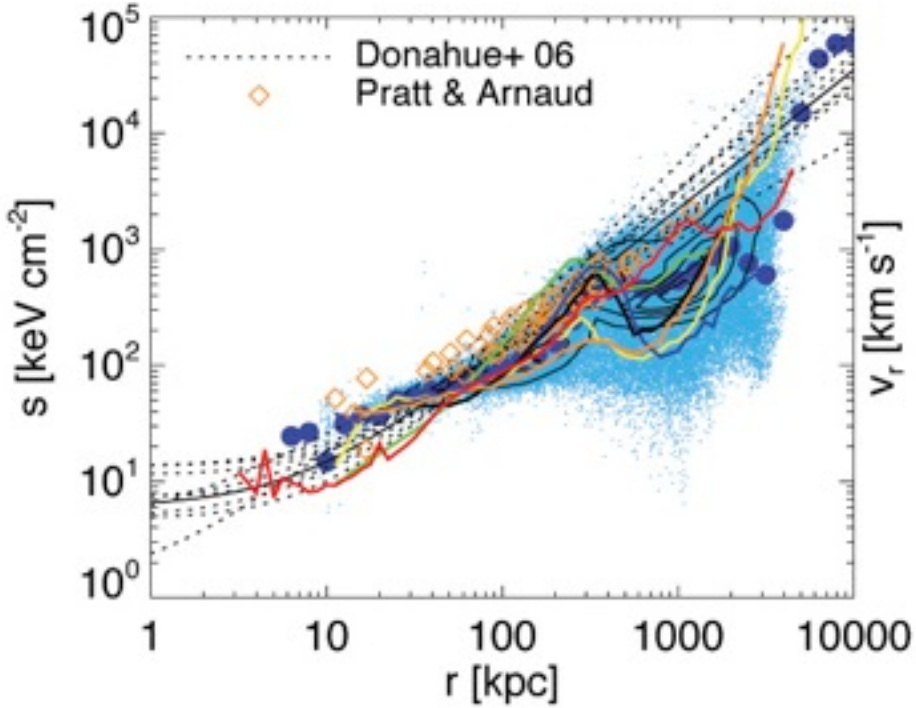
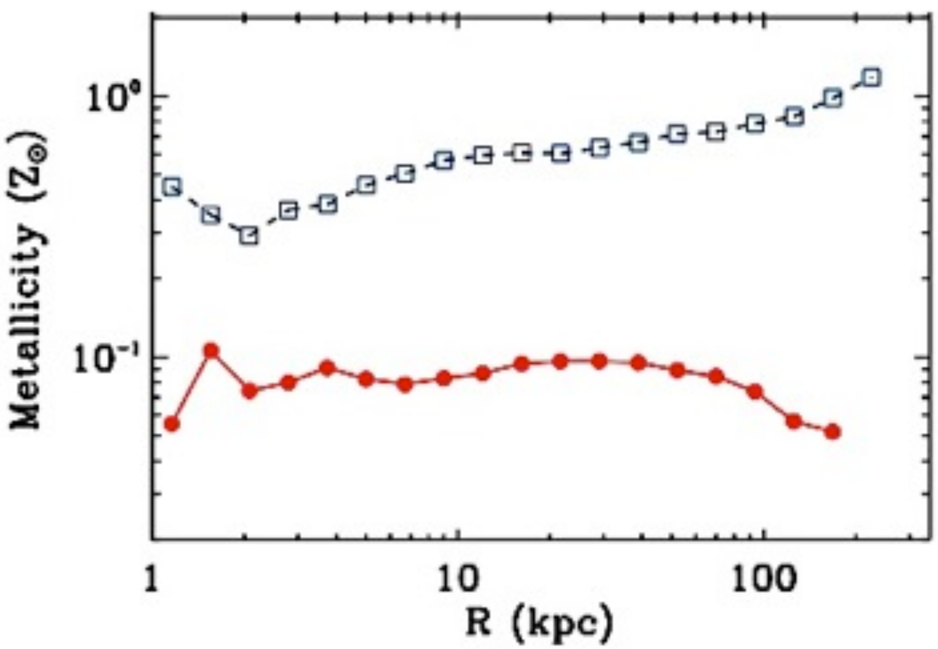
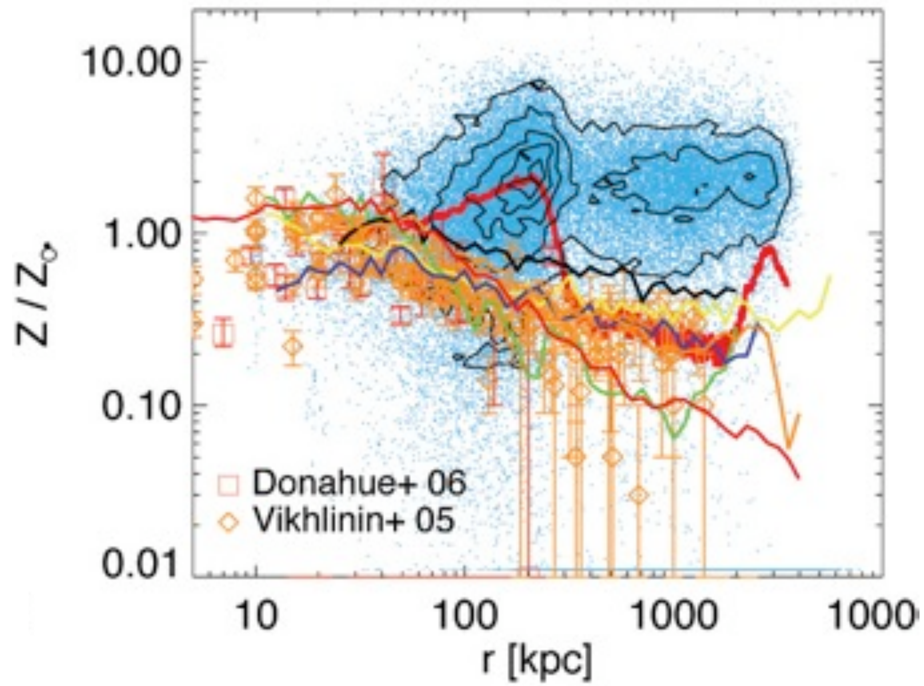


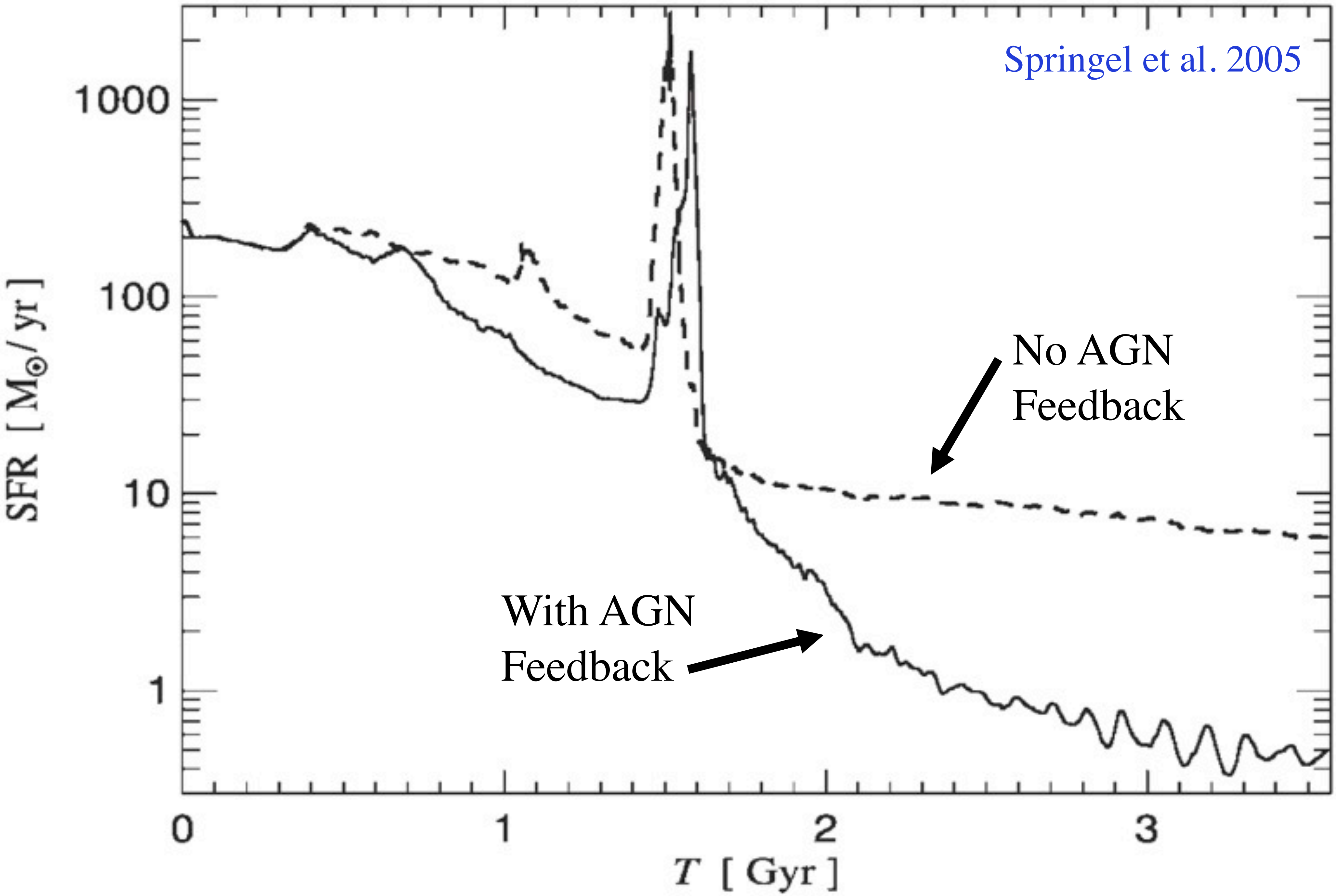






Expulsion of Gas Turns off Star Formation

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?

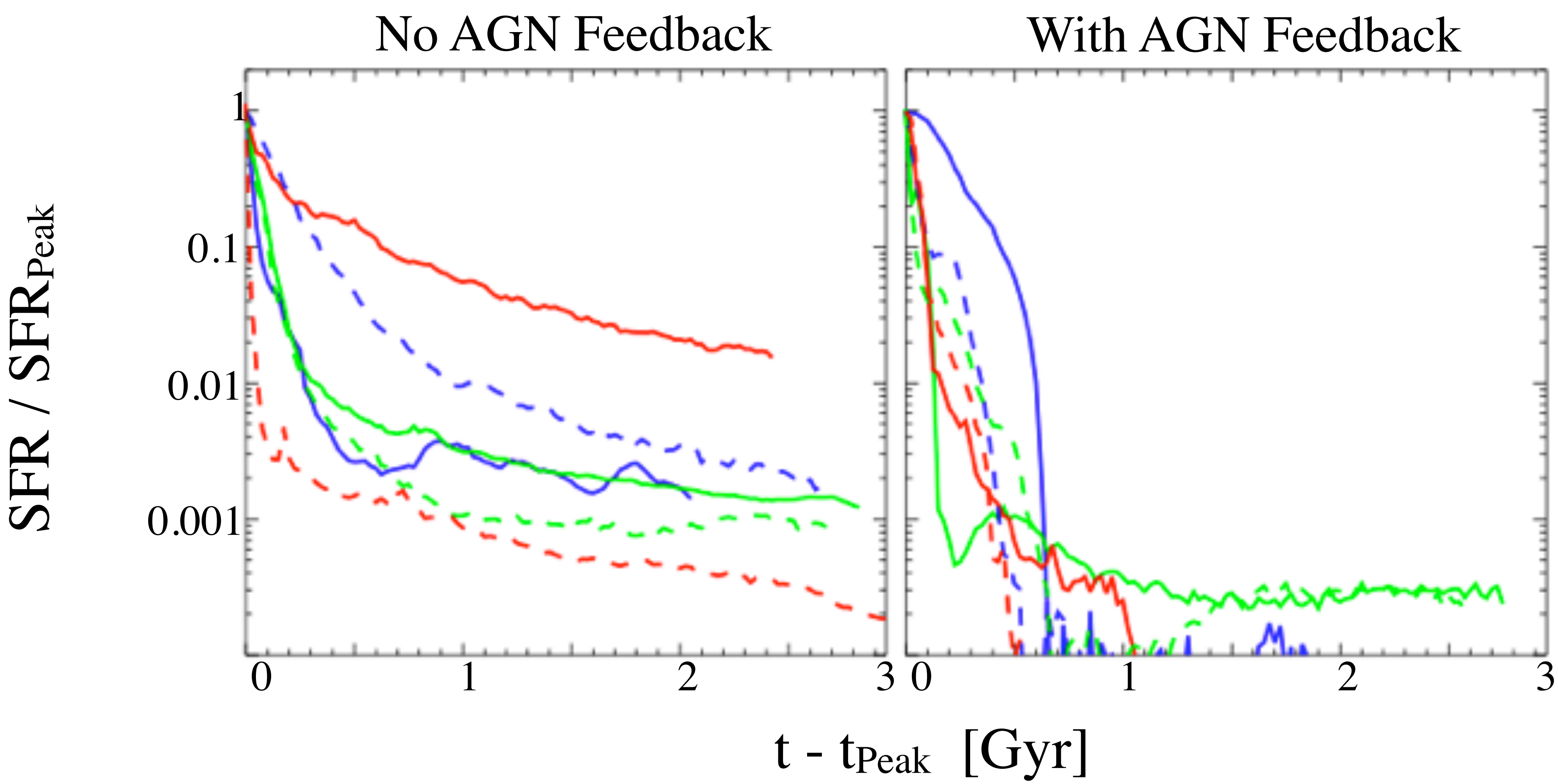


Expulsion of Gas Turns off Star Formation

PFH, Keres et al. 2008

ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?

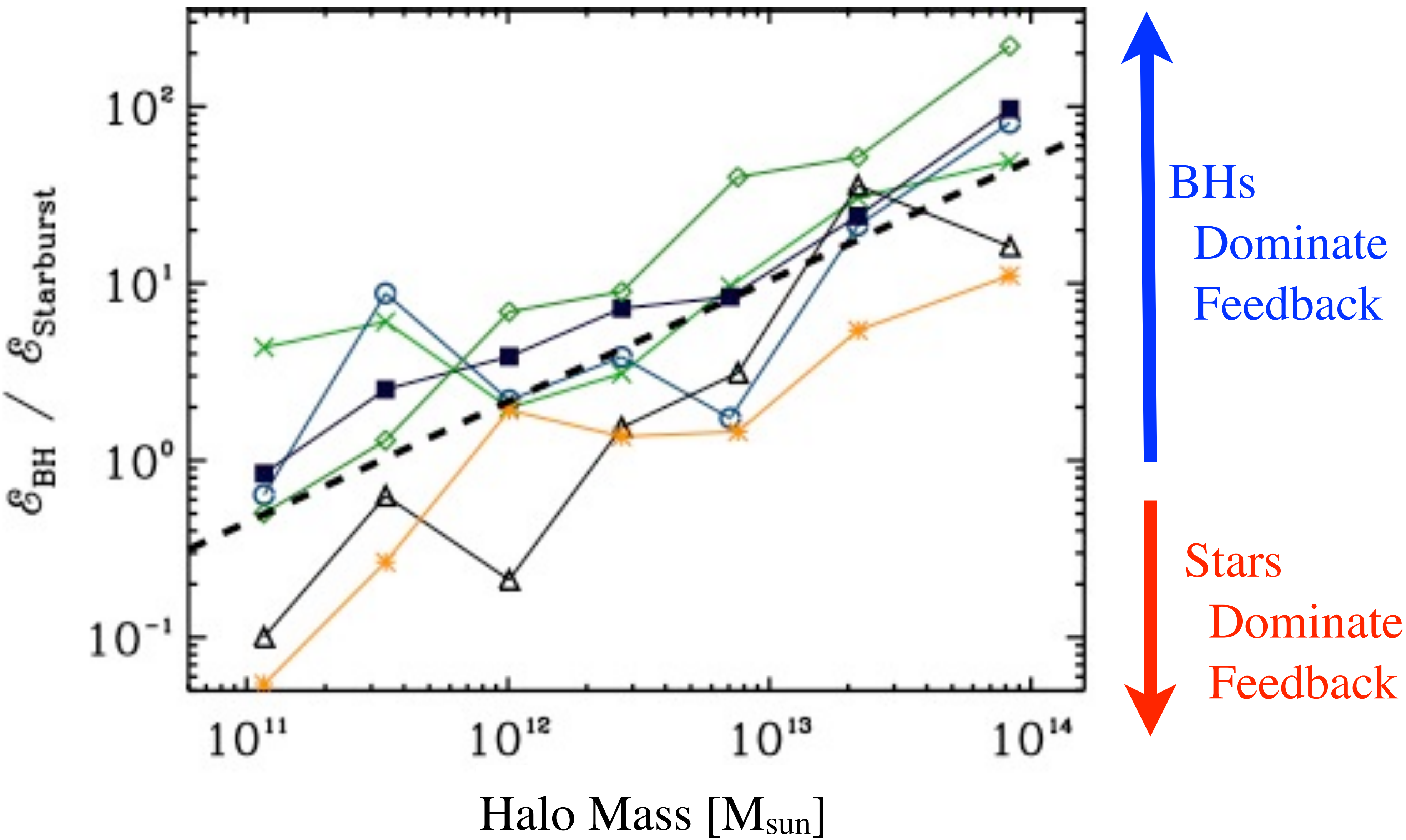
... but ...



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

AGN or Starburst-Driven Winds?

WHICH ARE MORE IMPORTANT?



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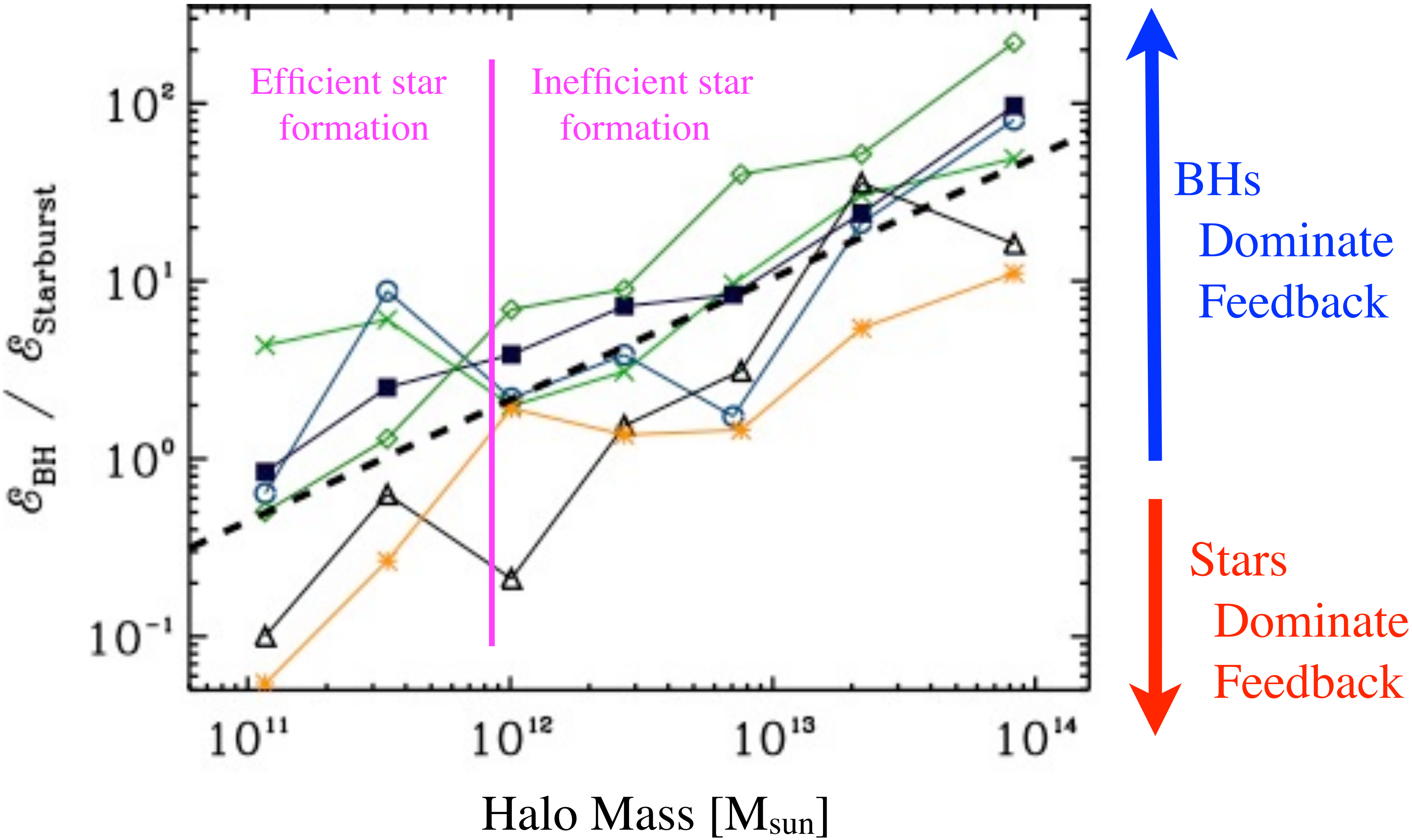
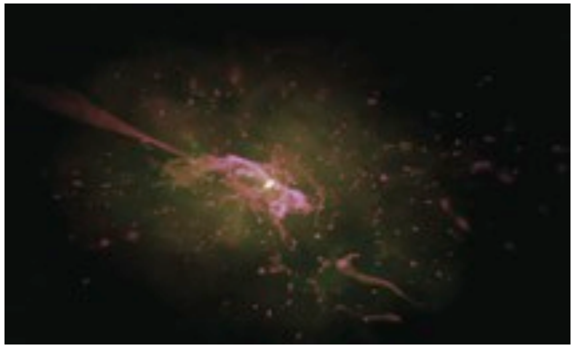
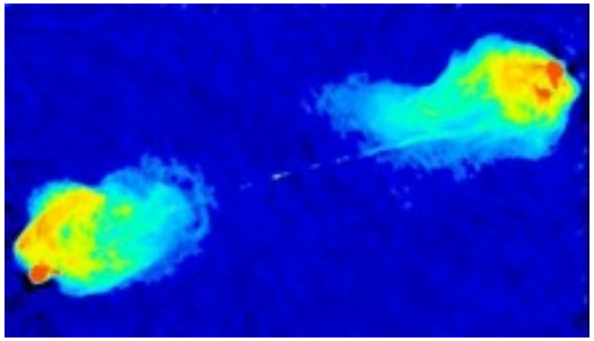


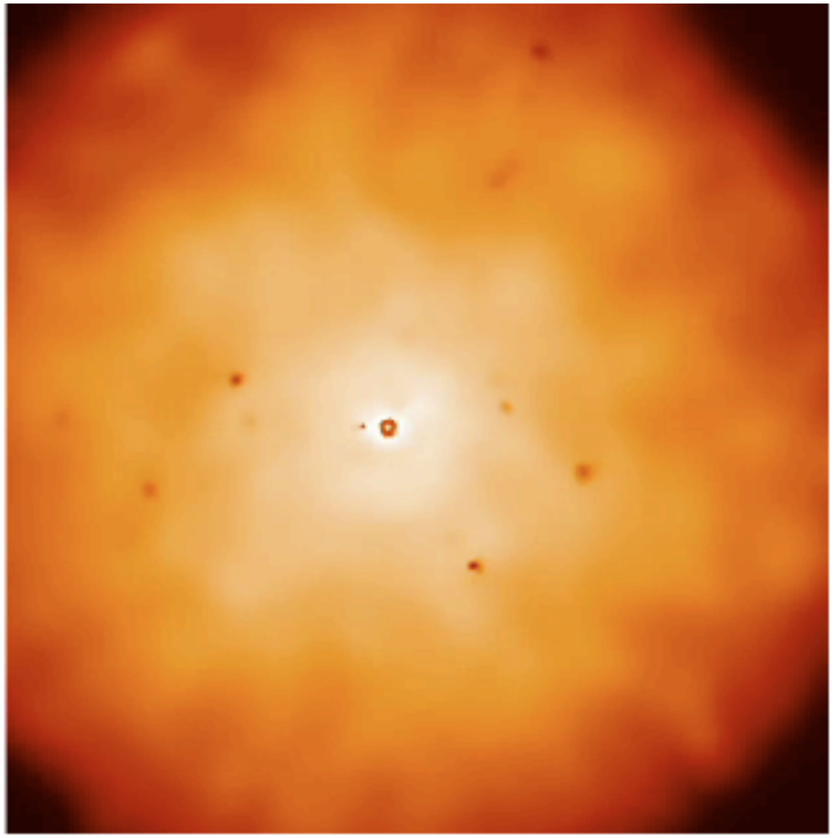
“Transition” vs. “Maintenance”

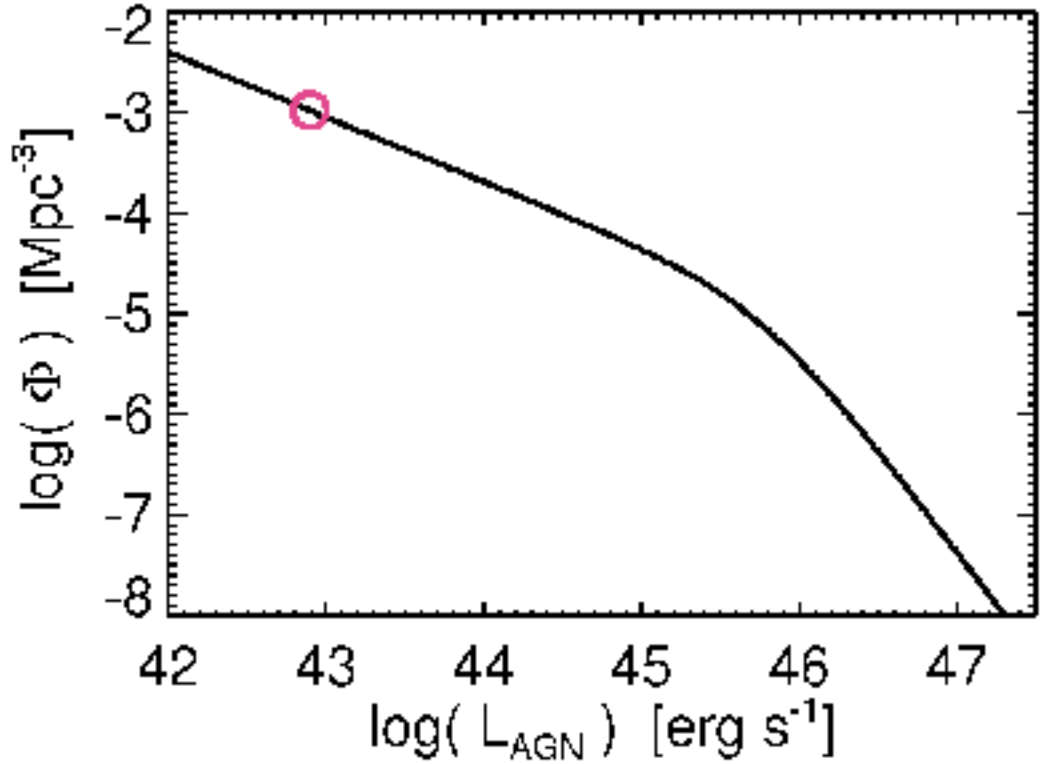
“Transition”	“Maintenance”
Move mass from Blue to Red	Keep it Red
Rapid	Long-lived (~Hubble time)
Small scales	Large (~halo) scales
“Quasar” mode (high mdot)	“Radio” mode (low mdot)
Morphological Transformation	Subtle morphological change
Gas-rich/Dissipational Mergers	“Dry”/Dissipationless Mergers



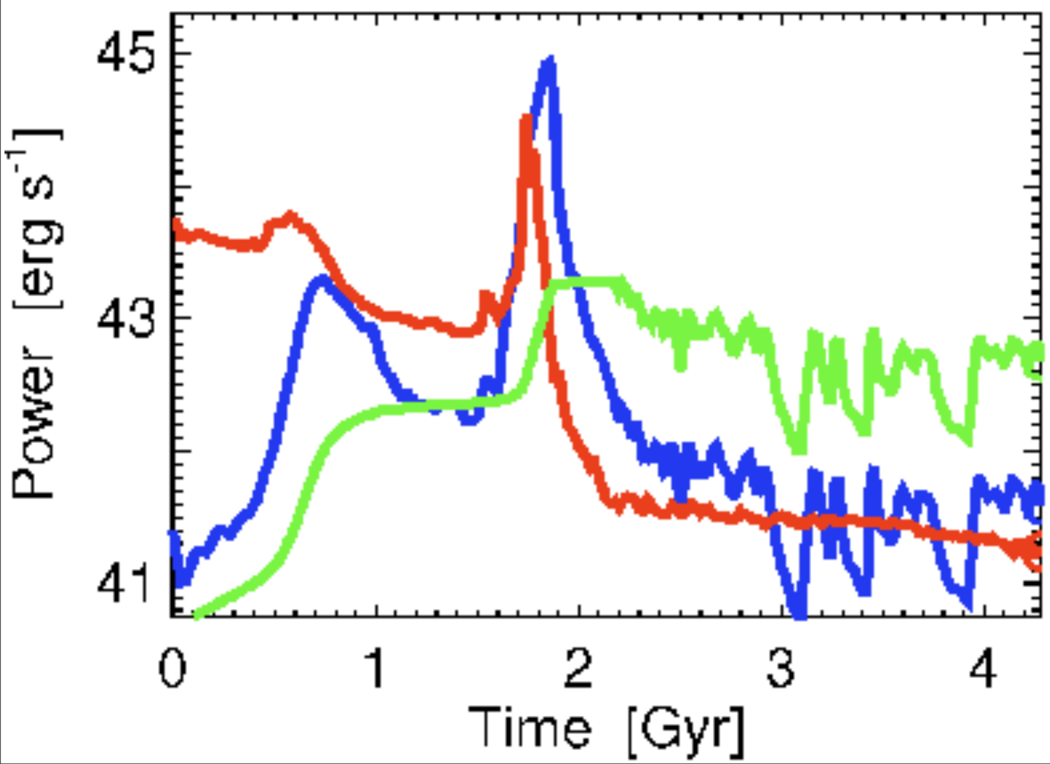


No reason these should be the same mechanisms... what connections?

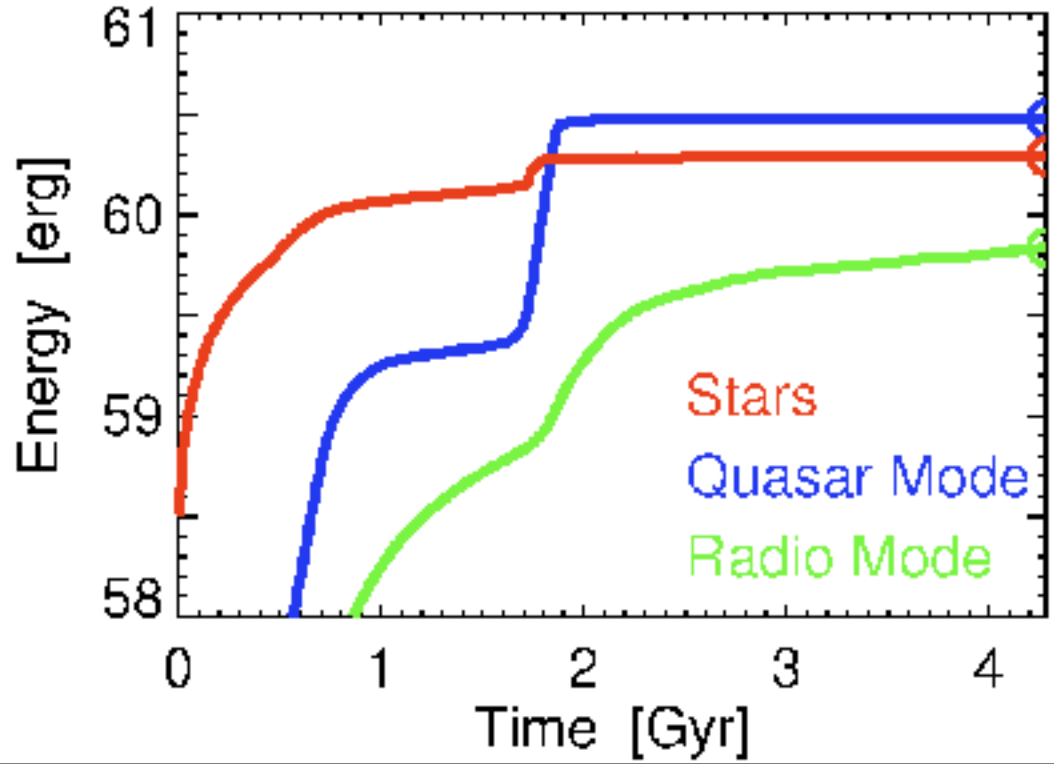




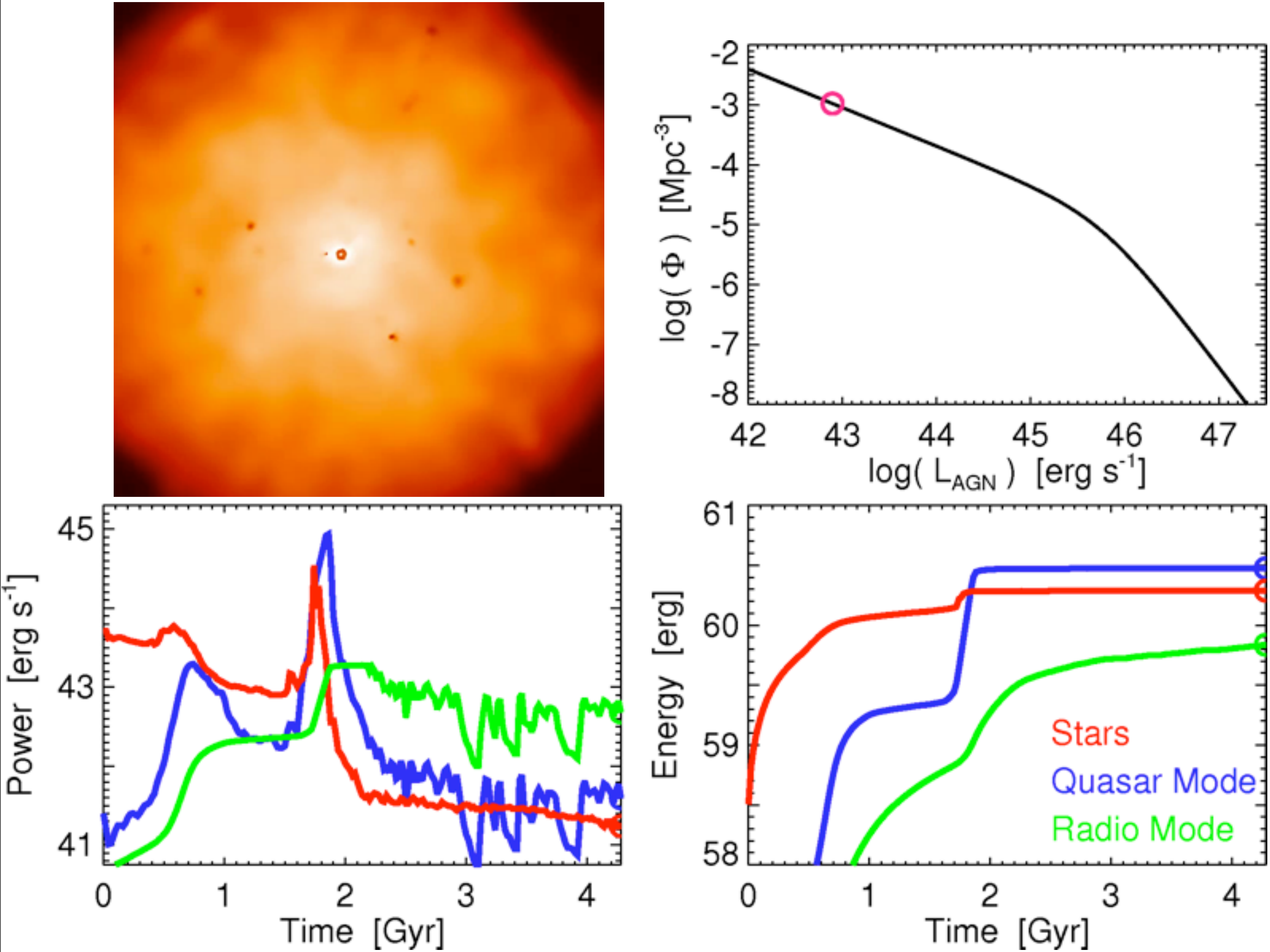
-2
-3
-4
-5
-6
-7
-8
log(Φ) [Mpc^-3]
42
43
44
45
46
47
log(L_AGN) [erg s^-1]



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]


log(Φ) [Mpc^-3]
log(L_AGN) [erg s^-1]
-2
-3
-4
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-6
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42
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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

Summary

- Ellipticals are *smaller* than spirals! How do we make a *real* elliptical?
  - Gas! Dissipation builds central mass densities, explains observed scaling laws: just need disks as gas rich as observed (f_{gas} ~ 0.1 - 0.5)
  - Explains compact z~2 galaxy (and SMG) sizes?
- How do disks *survive* mergers? (How do we ***avoid*** making all ellipticals?)
  - Being very gas rich (f_{gas} ~ 0.5):
    no stars = no angular momentum loss
  - Particularly important at high-z
- Where did these black holes come from!?
  - Growth in (mostly) mergers: self-regulation by feedback explains M_{BH}-s
- 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