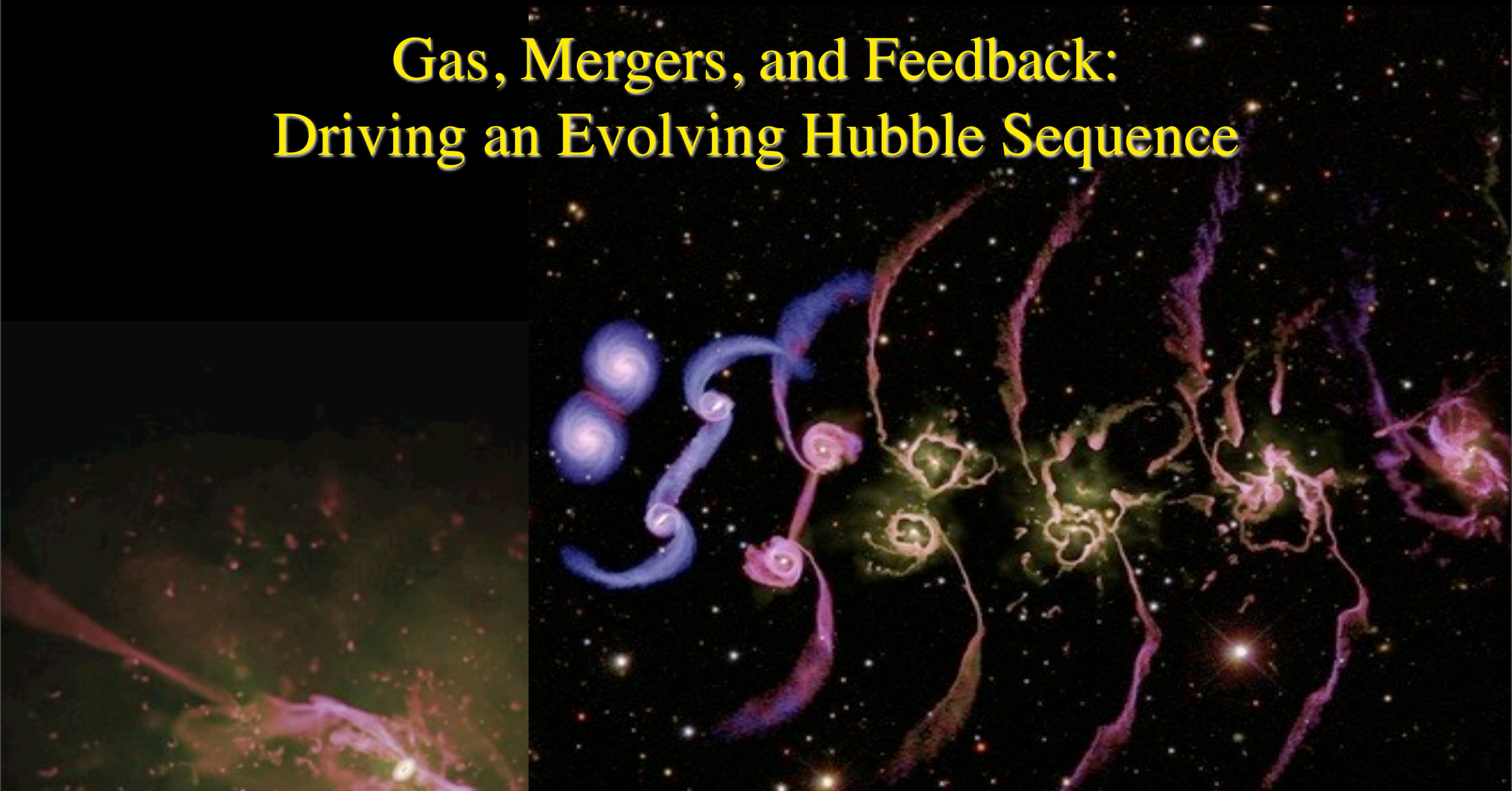
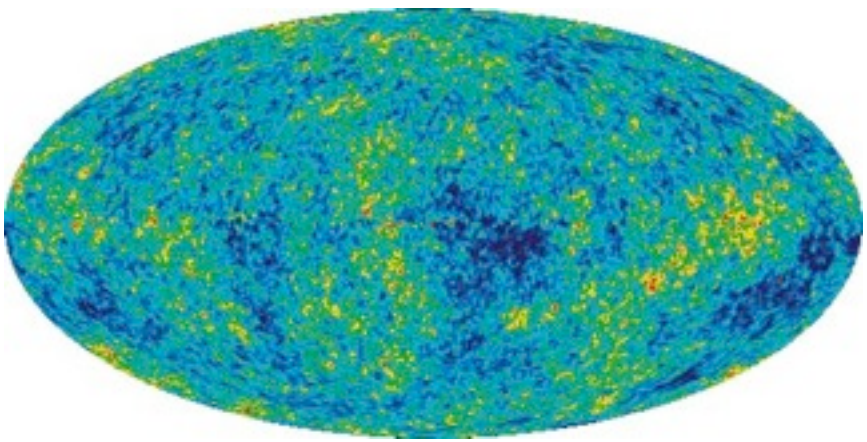
Gas, Mergers, and Feedback: Driving an Evolving Hubble Sequence

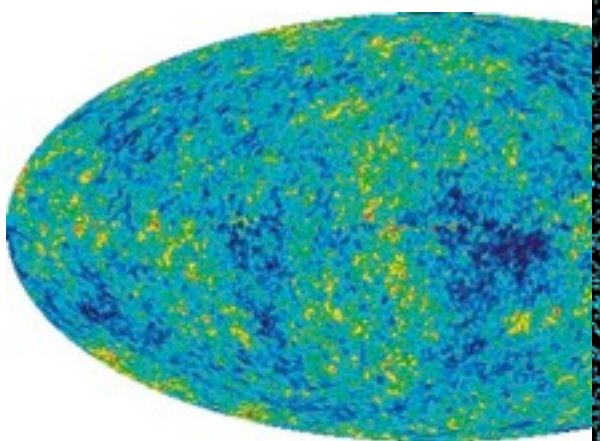


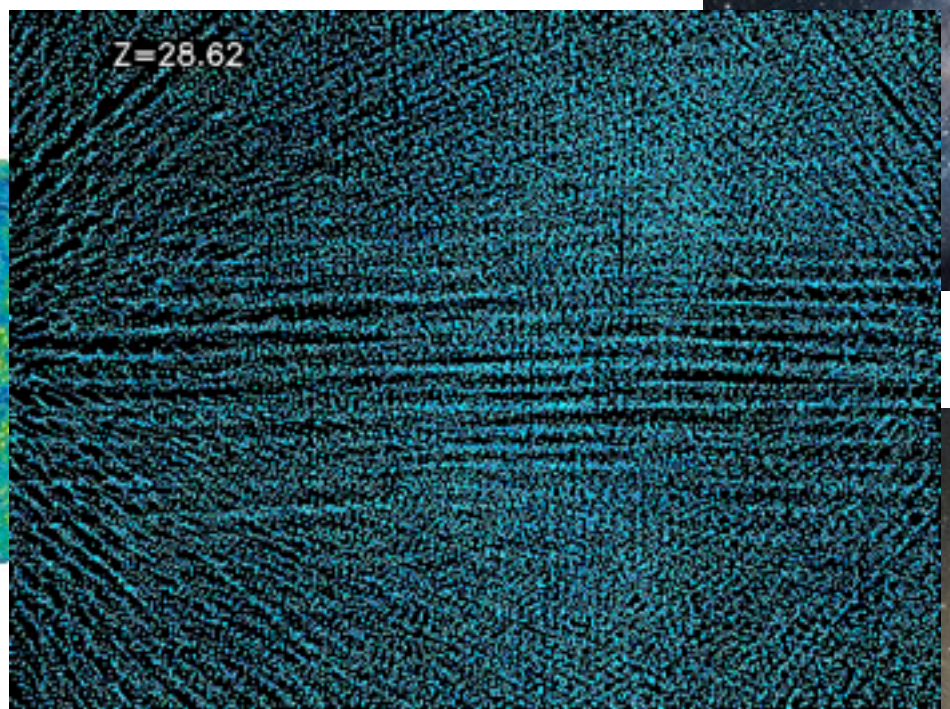
Philip Hopkins

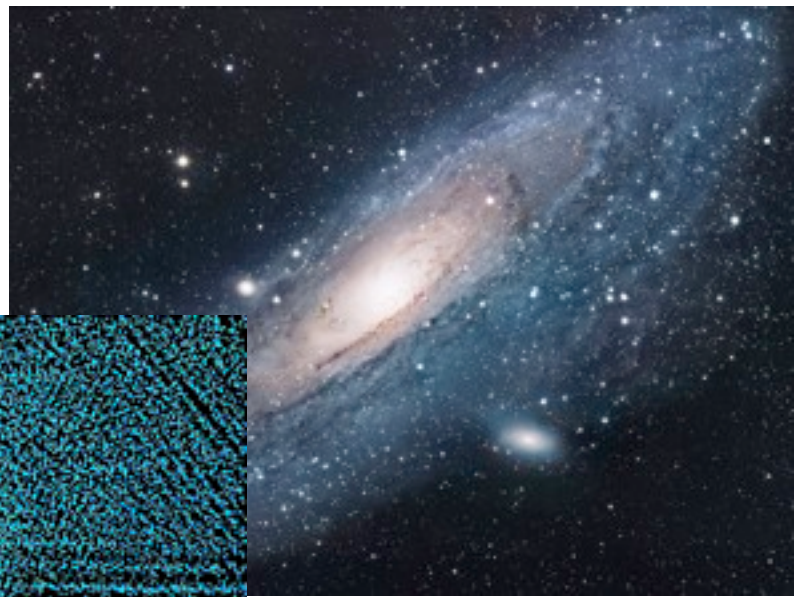
Lars Hernquist, Eliot Quataert, Chung-Pei Ma, Volker Springel, Norm Murray
John Kormendy, Tod Lauer, Kevin Bundy, Gordon Richards, Alison Coil,
Stijn Wuyts, Marijn Franx, Shardha Jogee, Paul Martini, Ryan Hickox, Caroline Foster,
T. J. Cox, Dusan Keres, Brant Robertson, Rachel Somerville, Todd Thompson, & more



?

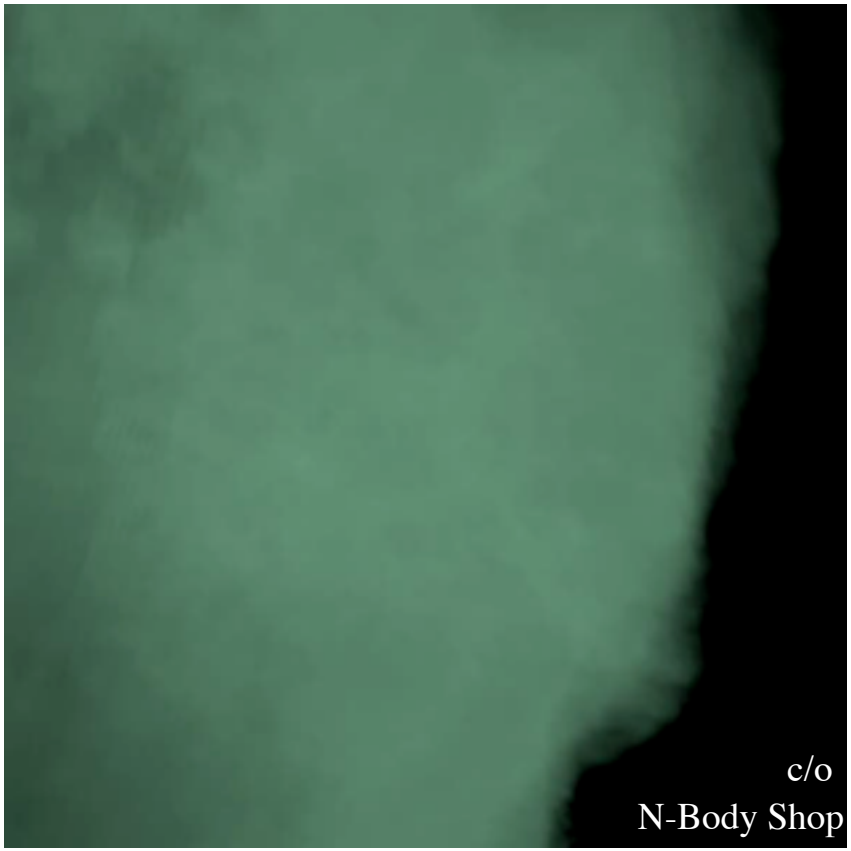



Z=28.62

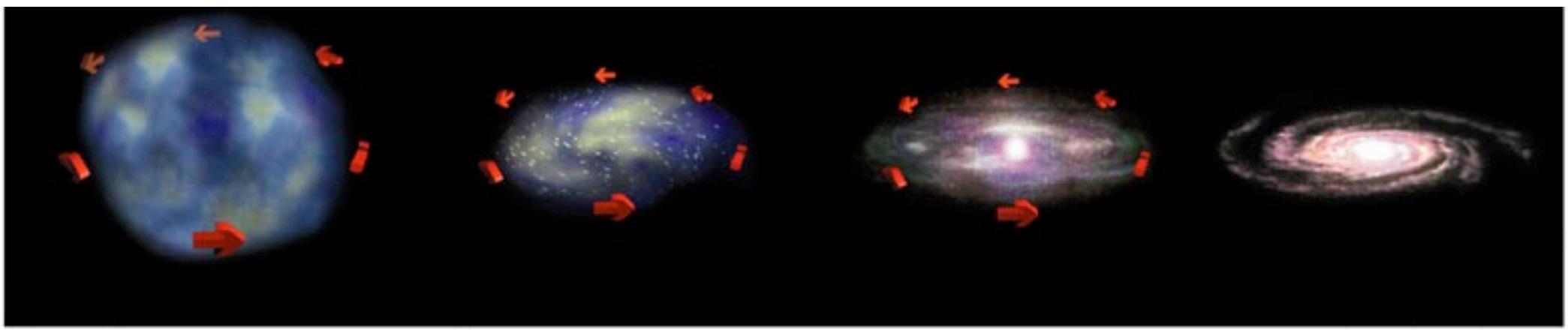


Motivation

HOW DID WE GET TO GALAXIES TODAY?

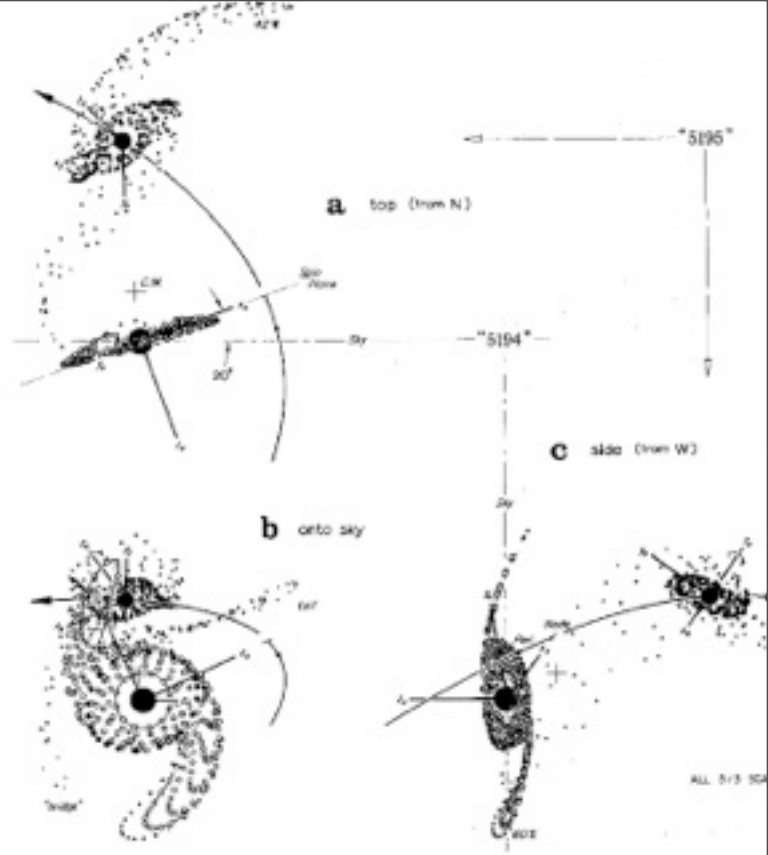


- Dark matter halos collapse: gas cools into a disk



- What happens when that starts colliding into other galaxies?

Our Conventional Wisdom (Toomre):

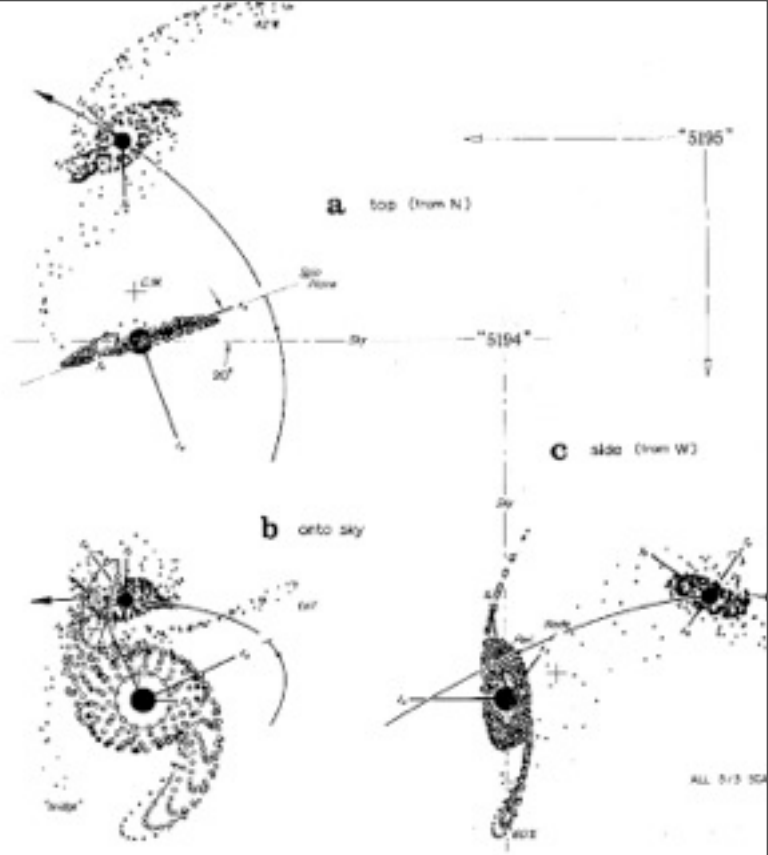


[redacted]

F. Summers

Our Conventional Wisdom (Toomre):

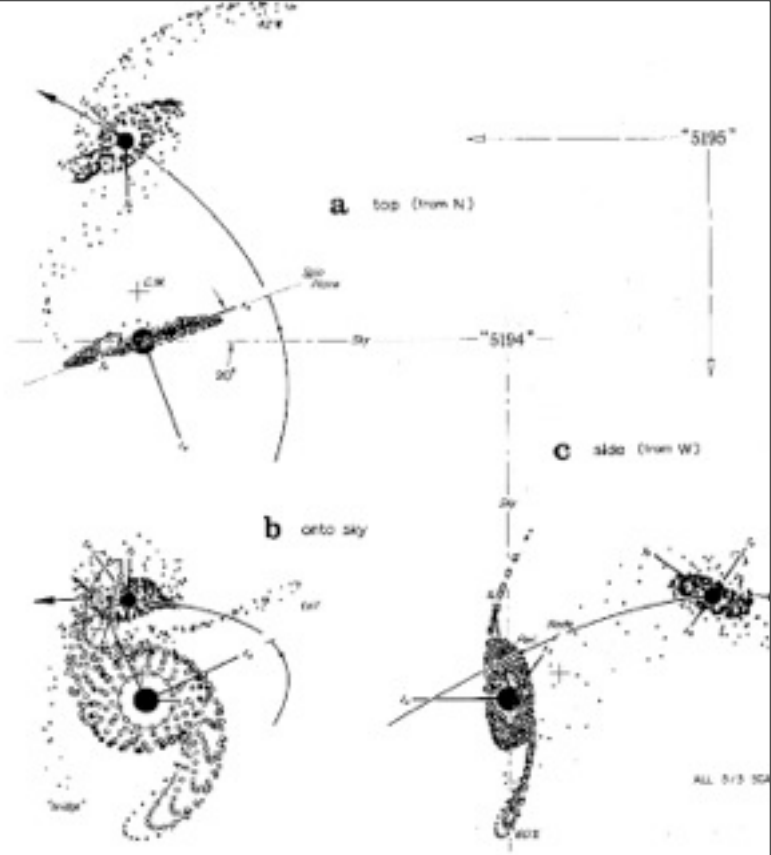
- Major mergers destroy disks



F. Summers

Our Conventional Wisdom (Toomre):

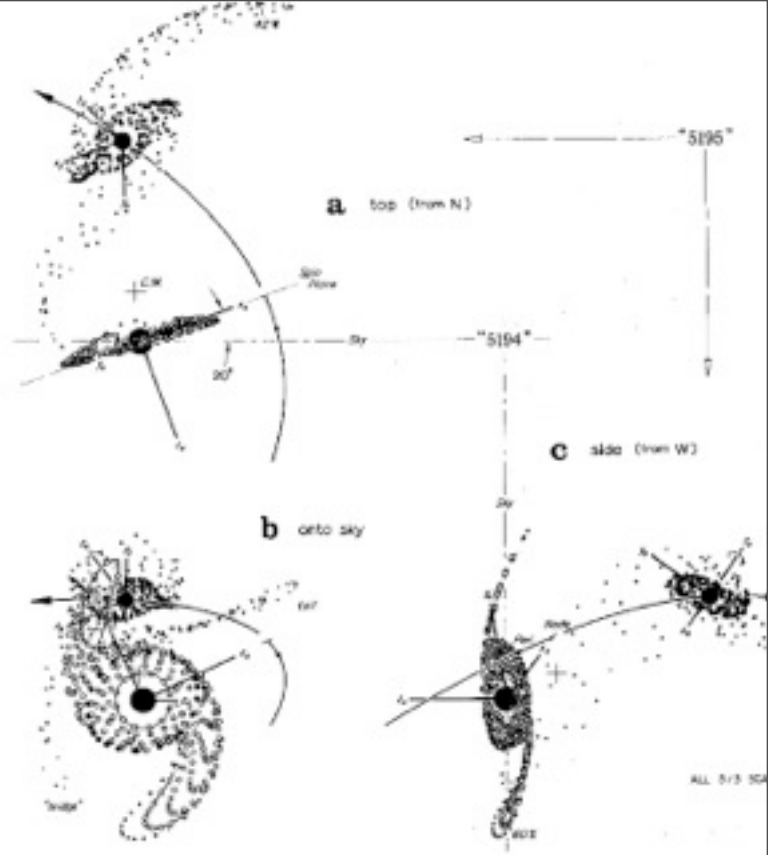
- Major mergers destroy disks
- Minor mergers make thick disk



F. Summers

Our Conventional Wisdom (Toomre):

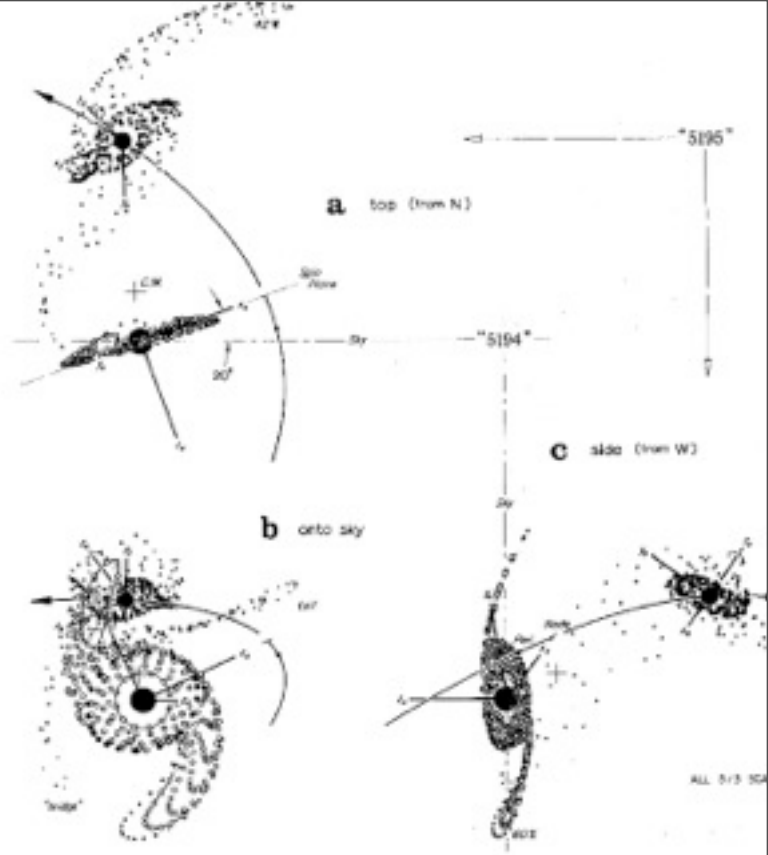
- Major mergers destroy disks
- Minor mergers make thick disk
- Remnant has an $r^{1/4}$ law profile



F. Summers

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"



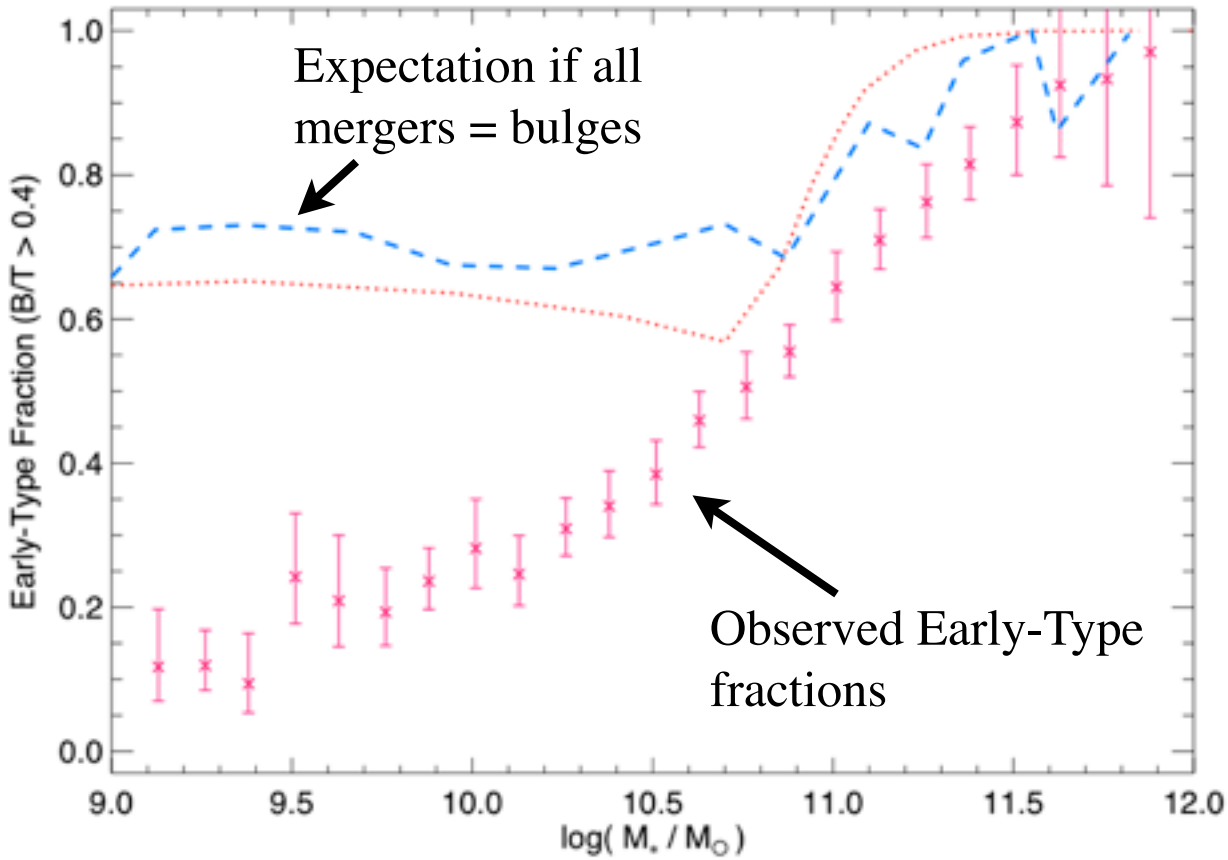
F. Summers

Our Conventional Wisdom...

Today, many of these are *problems*...

Too Many Mergers?

-- missing some physics?

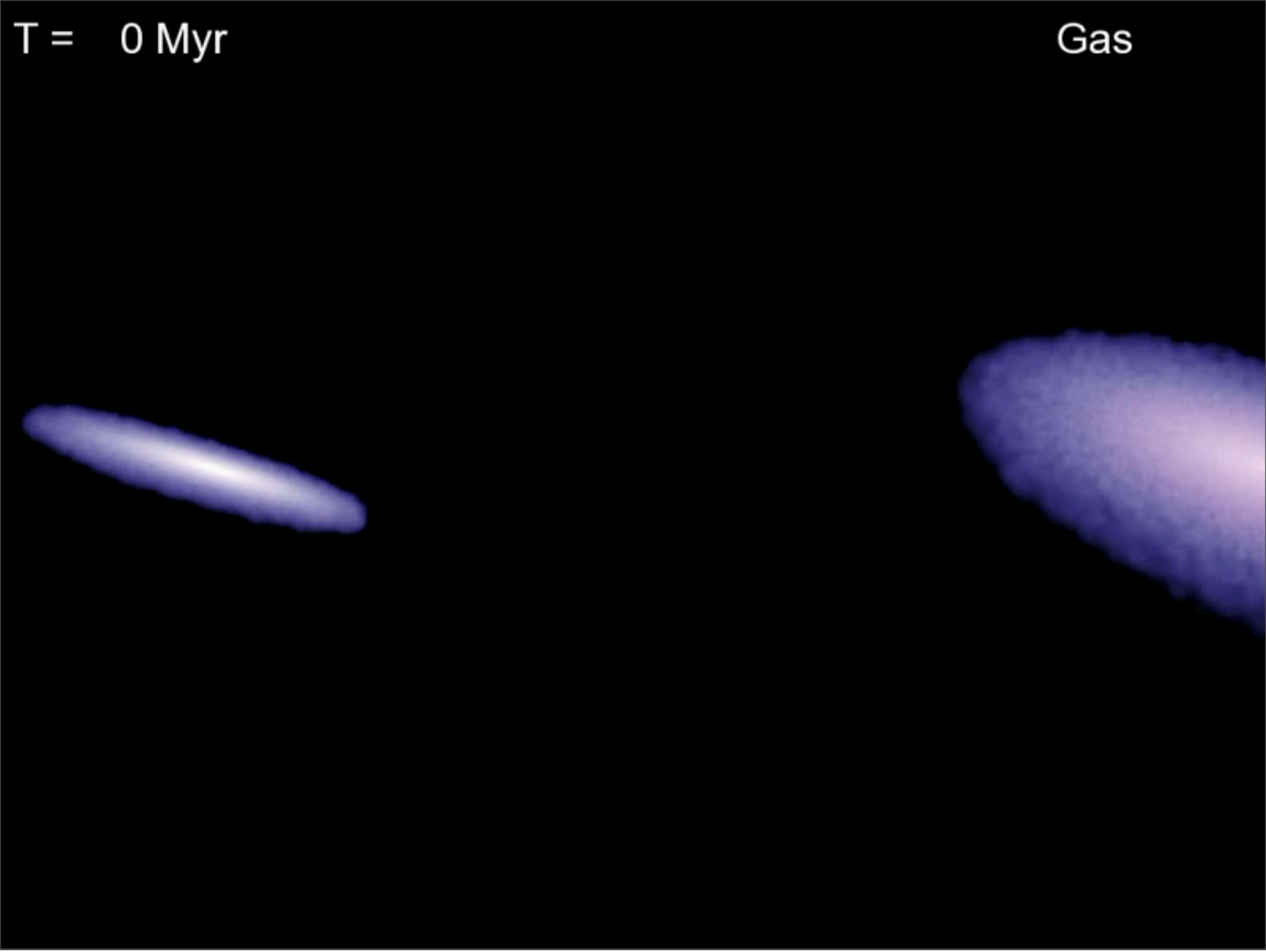


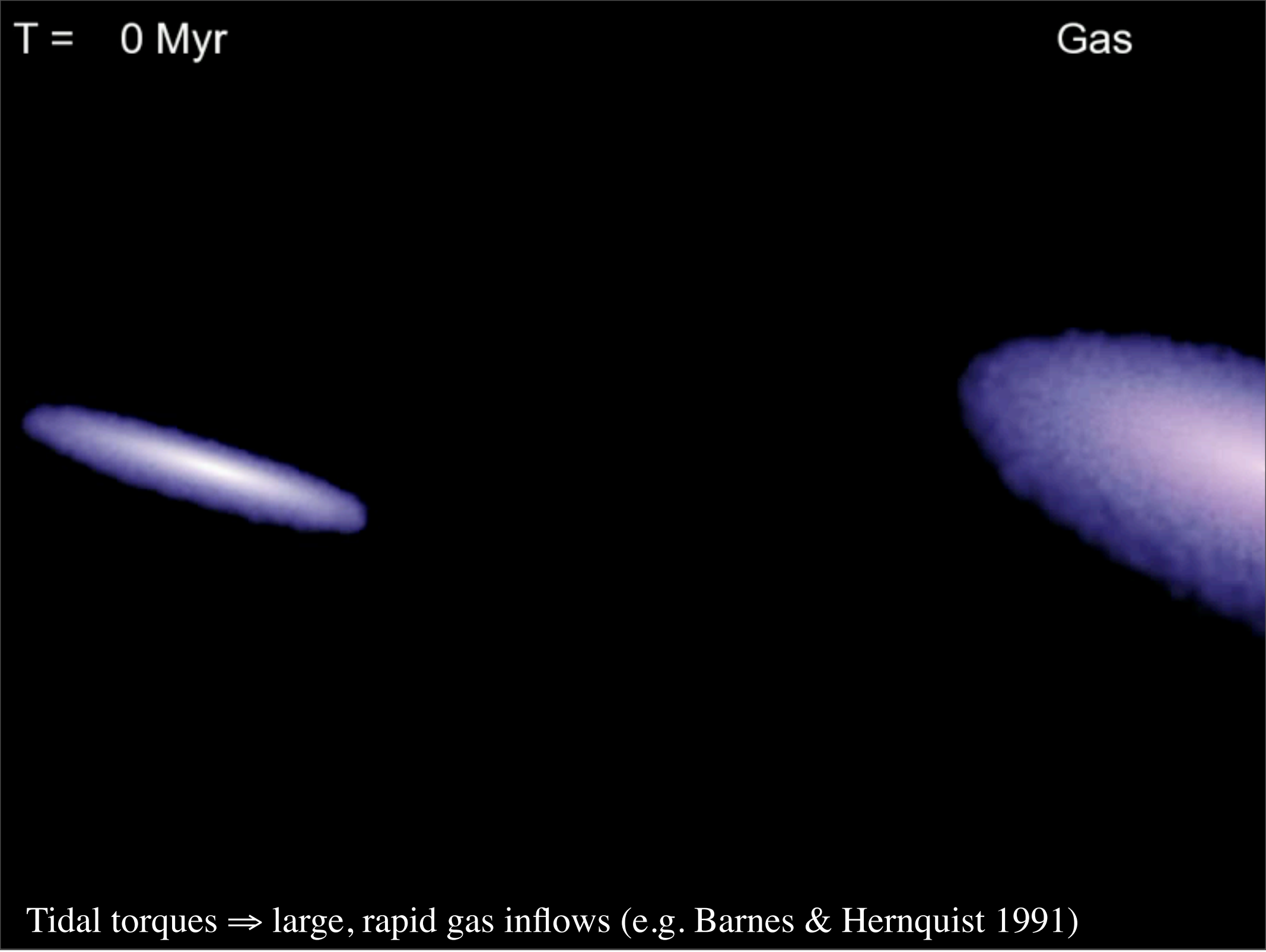
Stellar disk-disk merger remnants don't look like bulges!

-- sizes too large

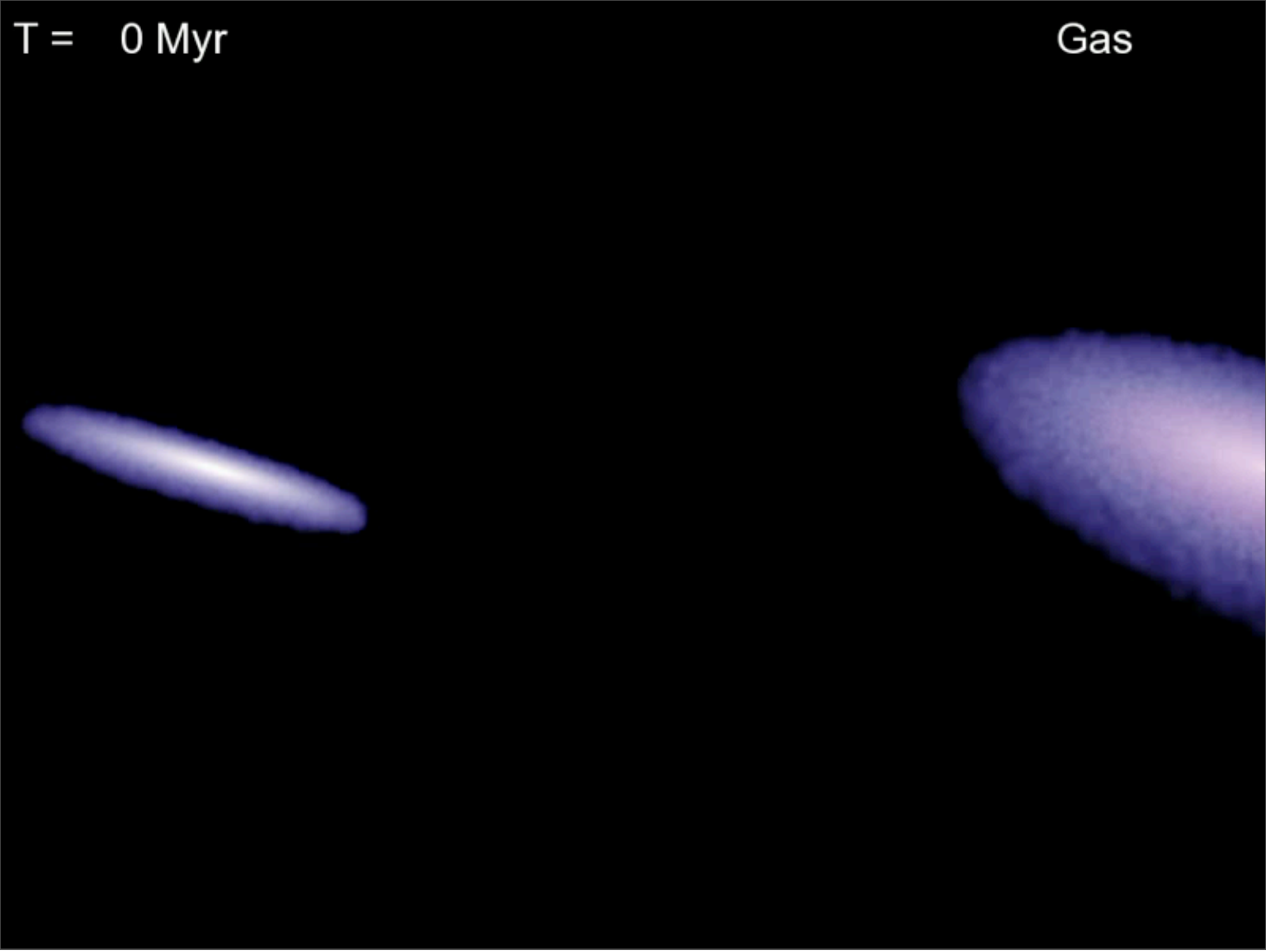
-- profiles too flat

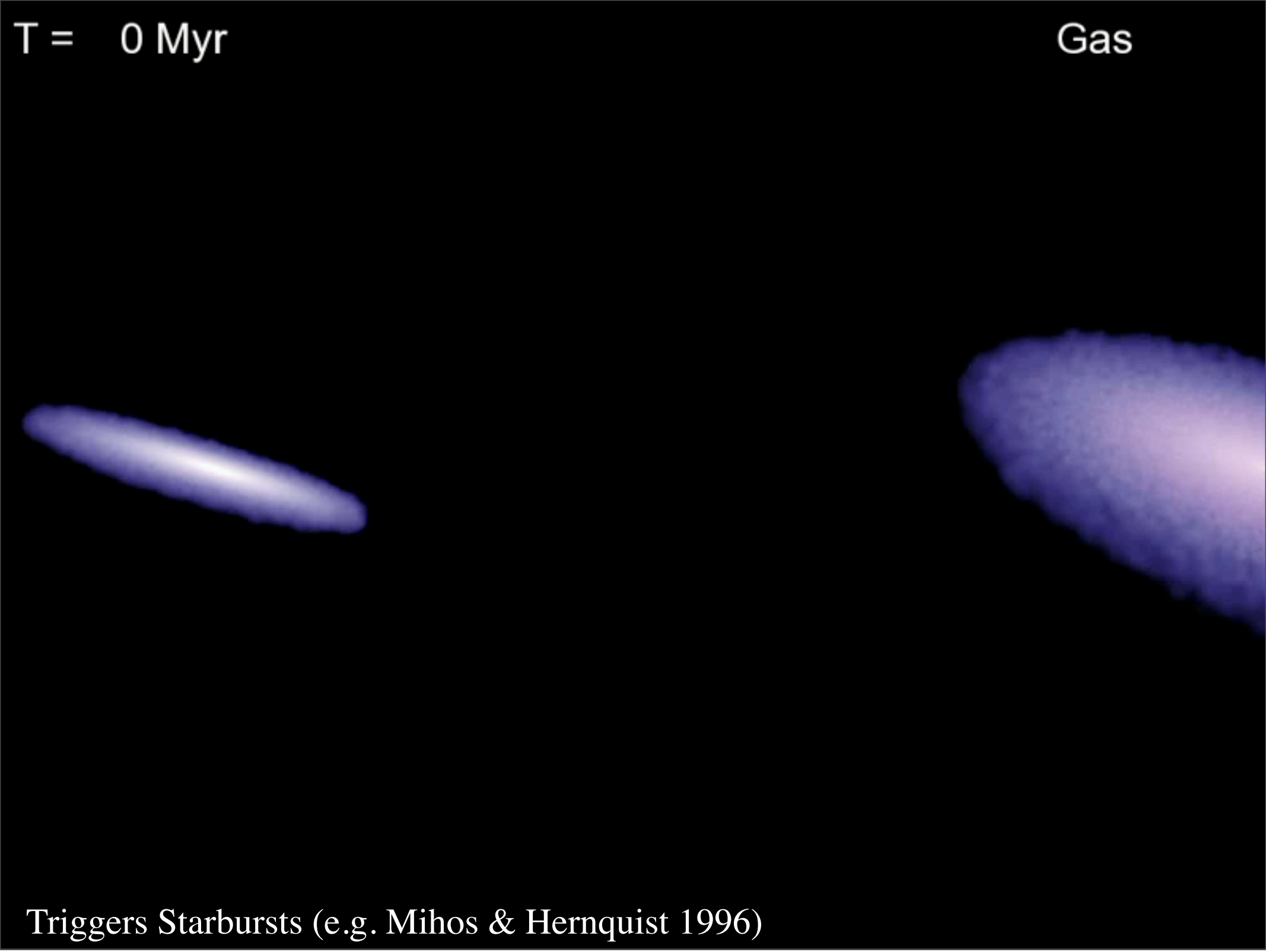
-- shapes too flattened


T = 0 Myr
Gas

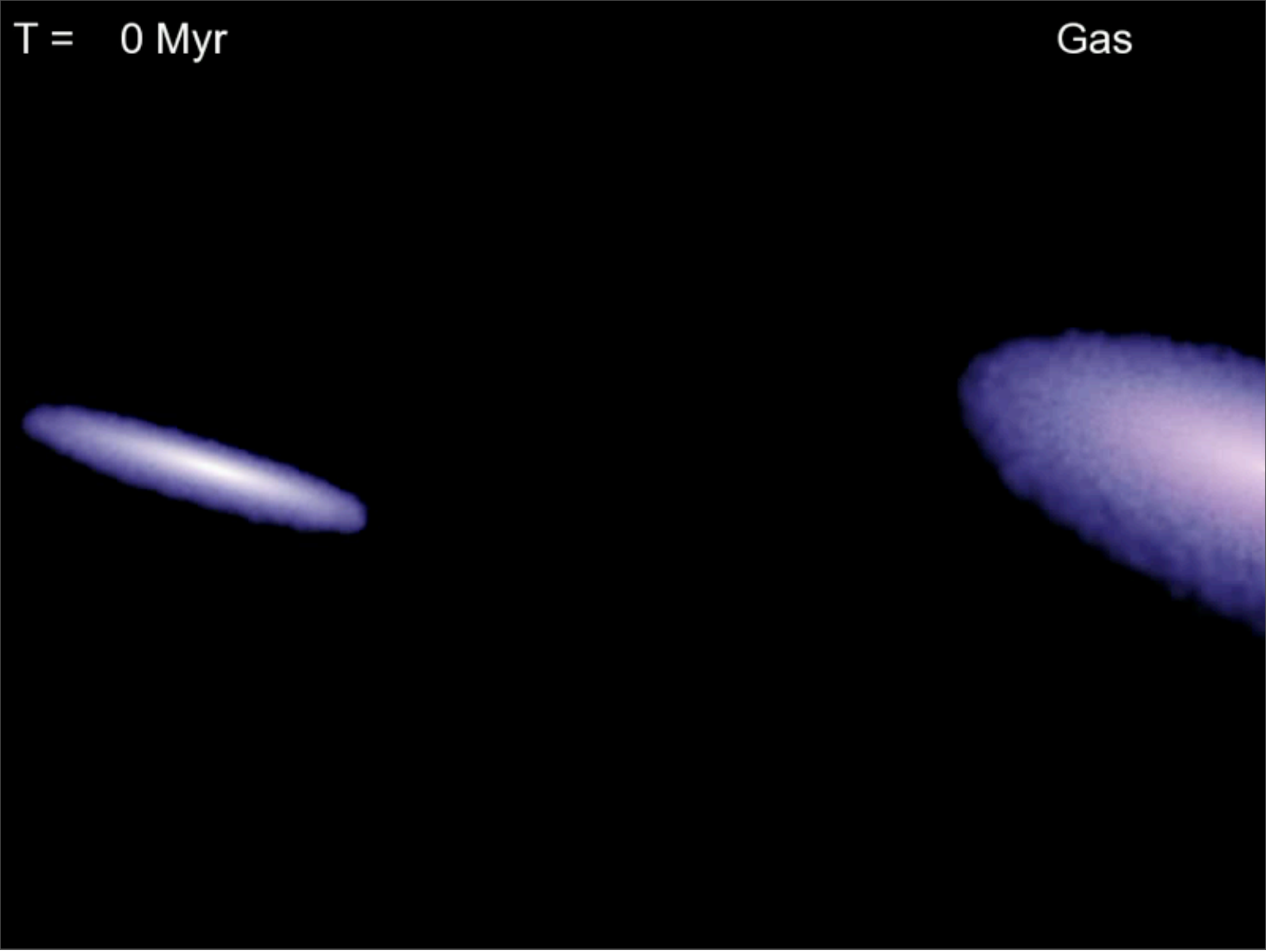


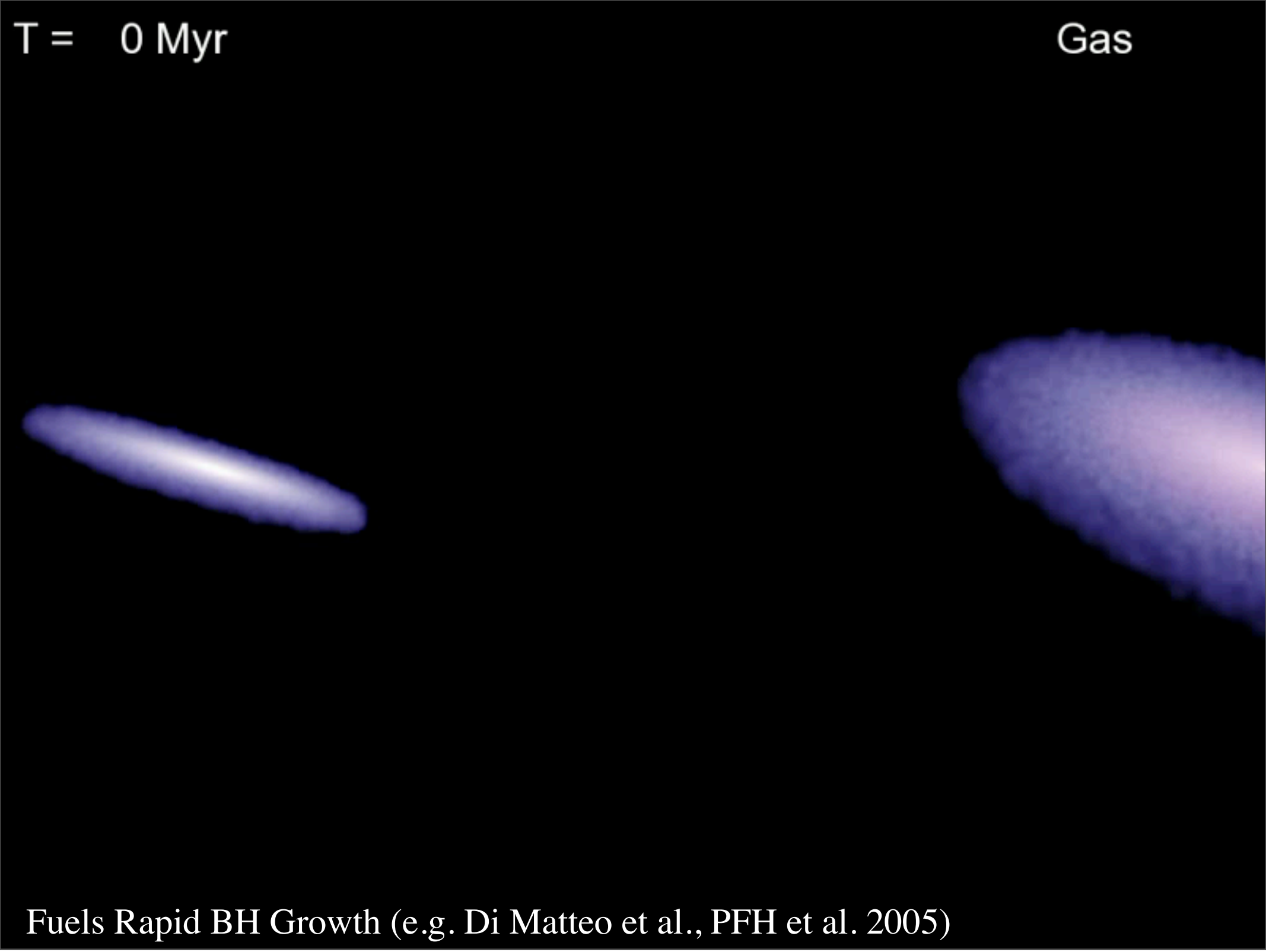
Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & Hernquist 1991)


T = 0 Myr
Gas

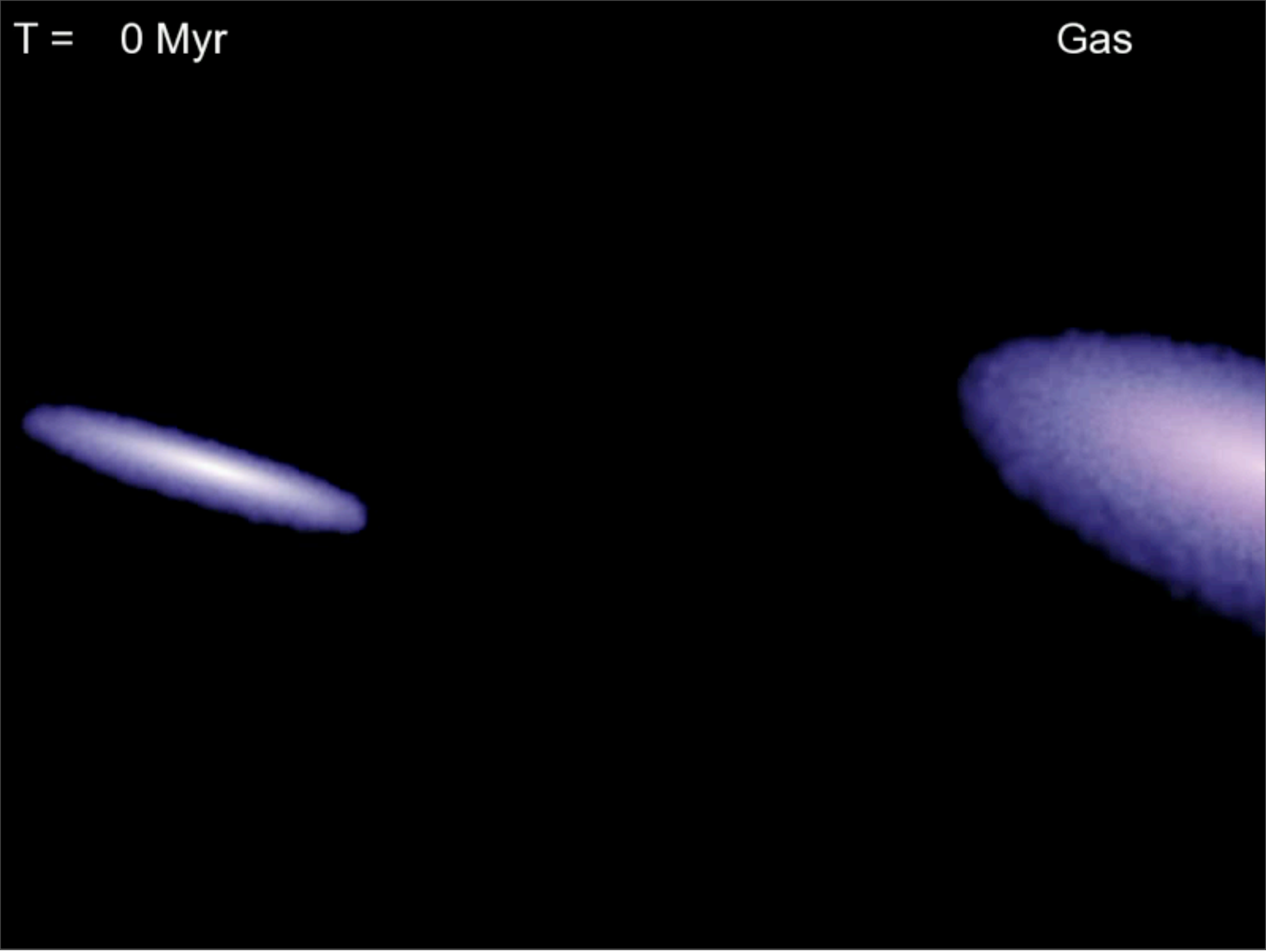


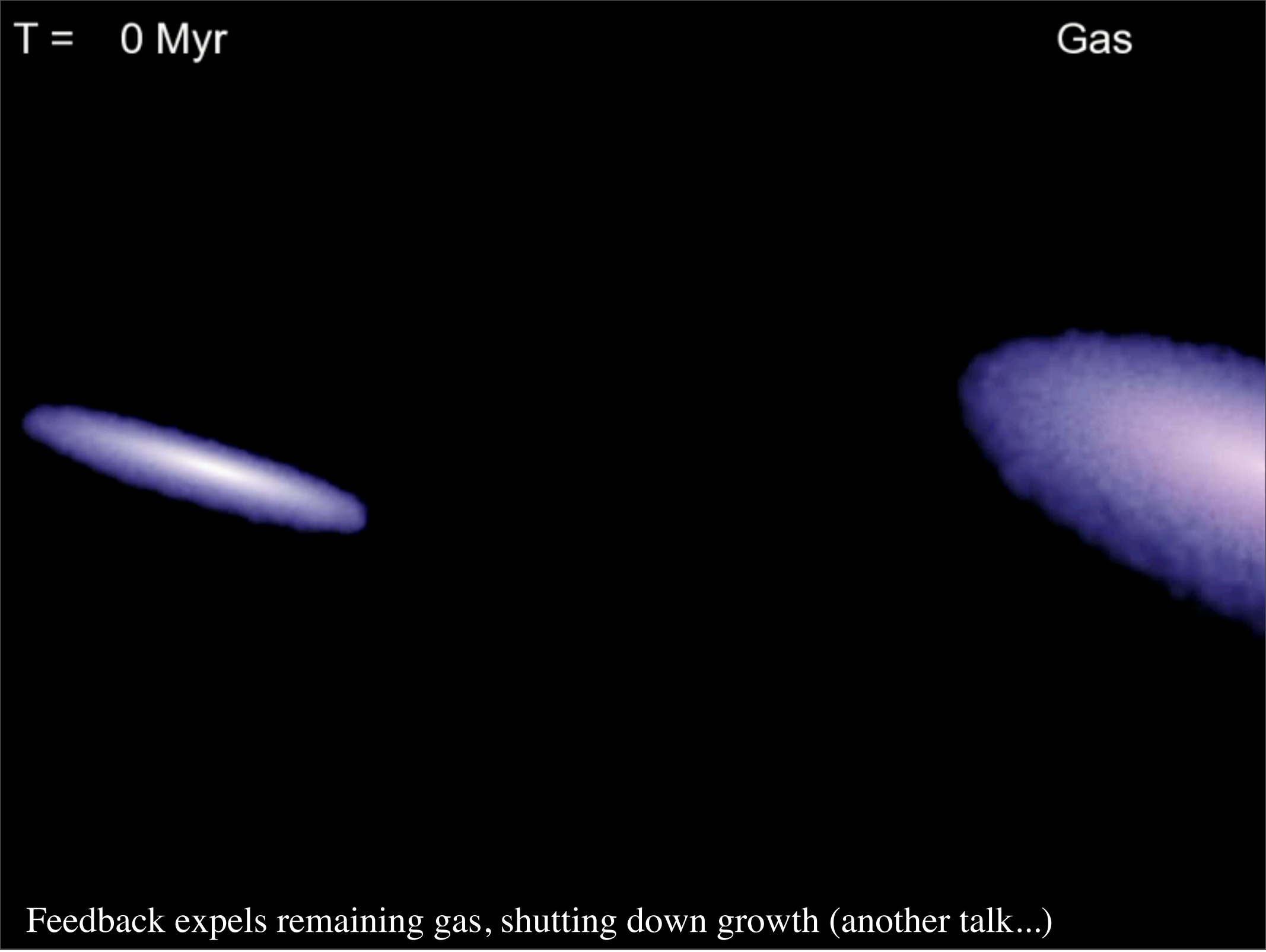
Triggers Starbursts (e.g. Mihos & Hernquist 1996)


T = 0 Myr
Gas

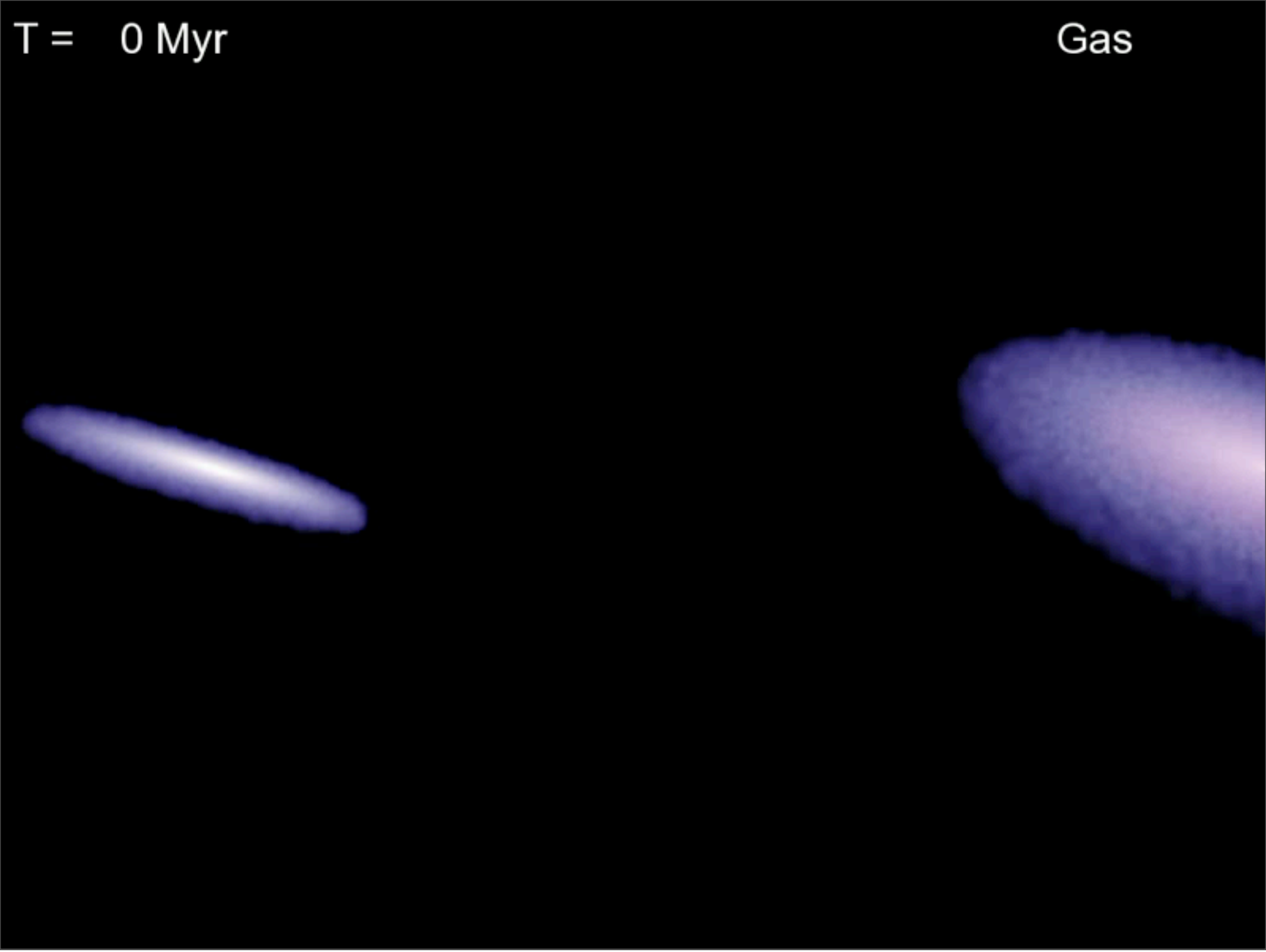


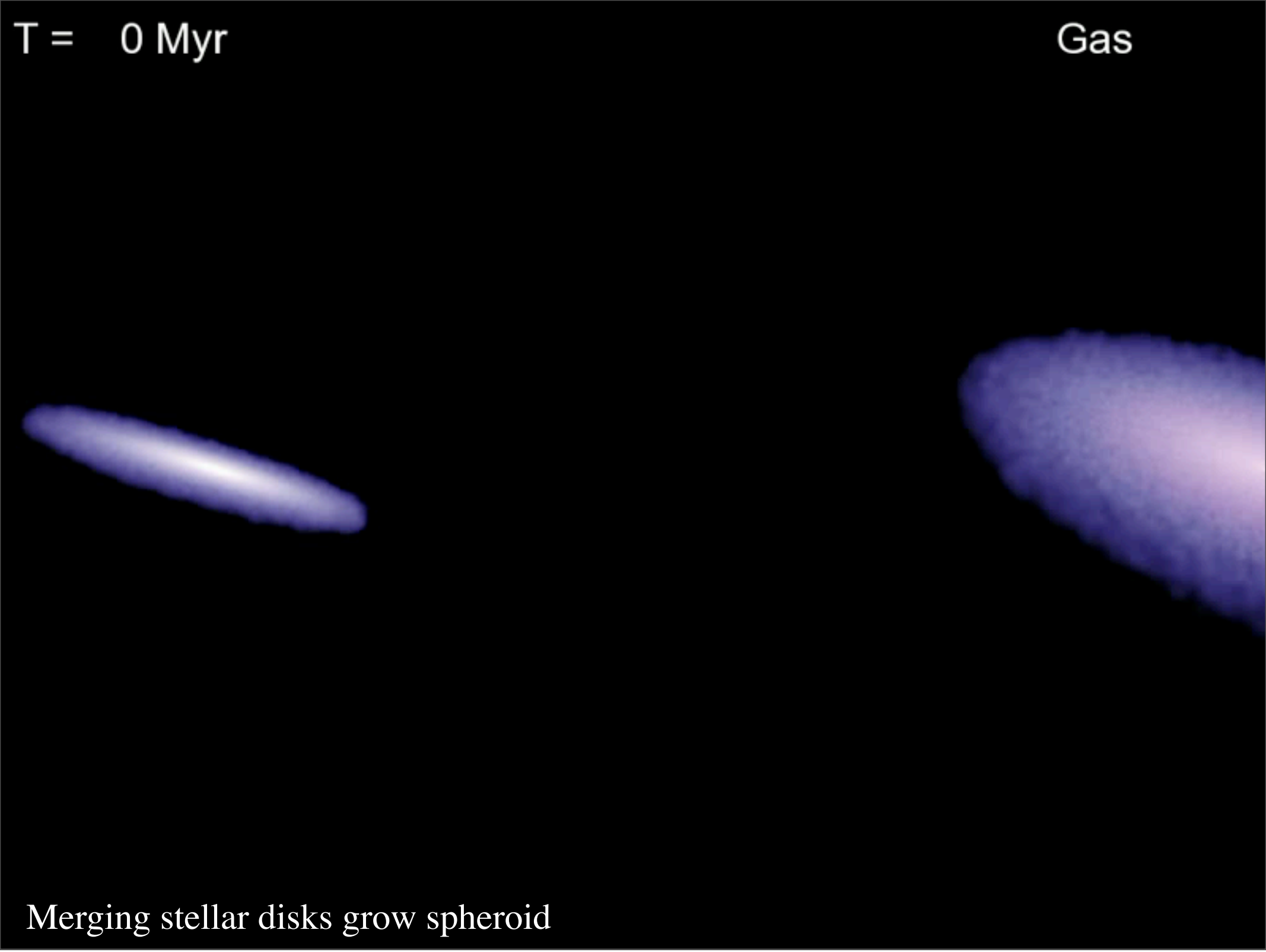
Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)


T = 0 Myr
Gas

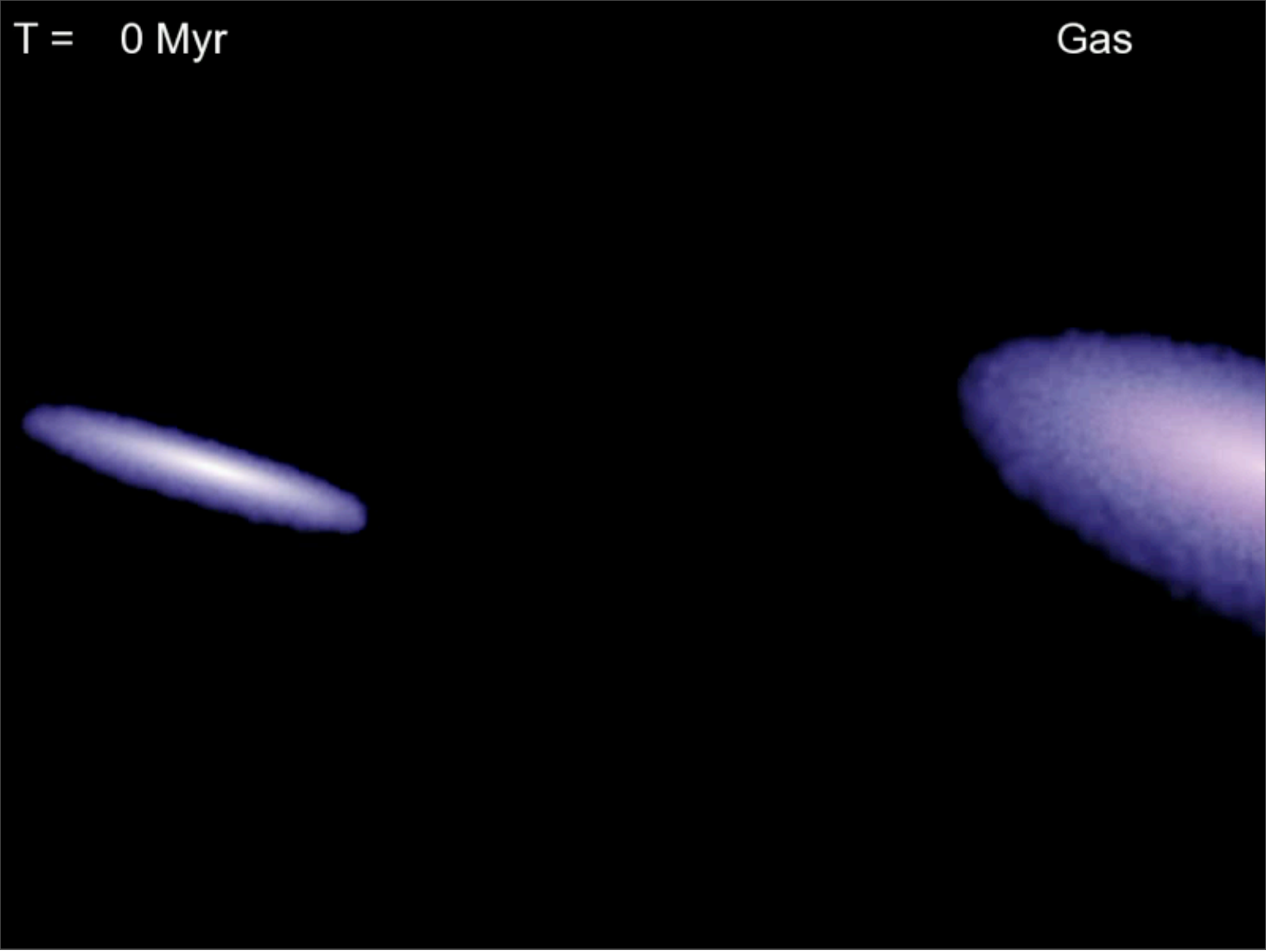


Feedback expels remaining gas, shutting down growth (another talk...)


T = 0 Myr
Gas



Merging stellar disks grow spheroid


T = 0 Myr
Gas

Starbursts & ULIRGs:

Sanders, Scoville, Soifer,
& others:

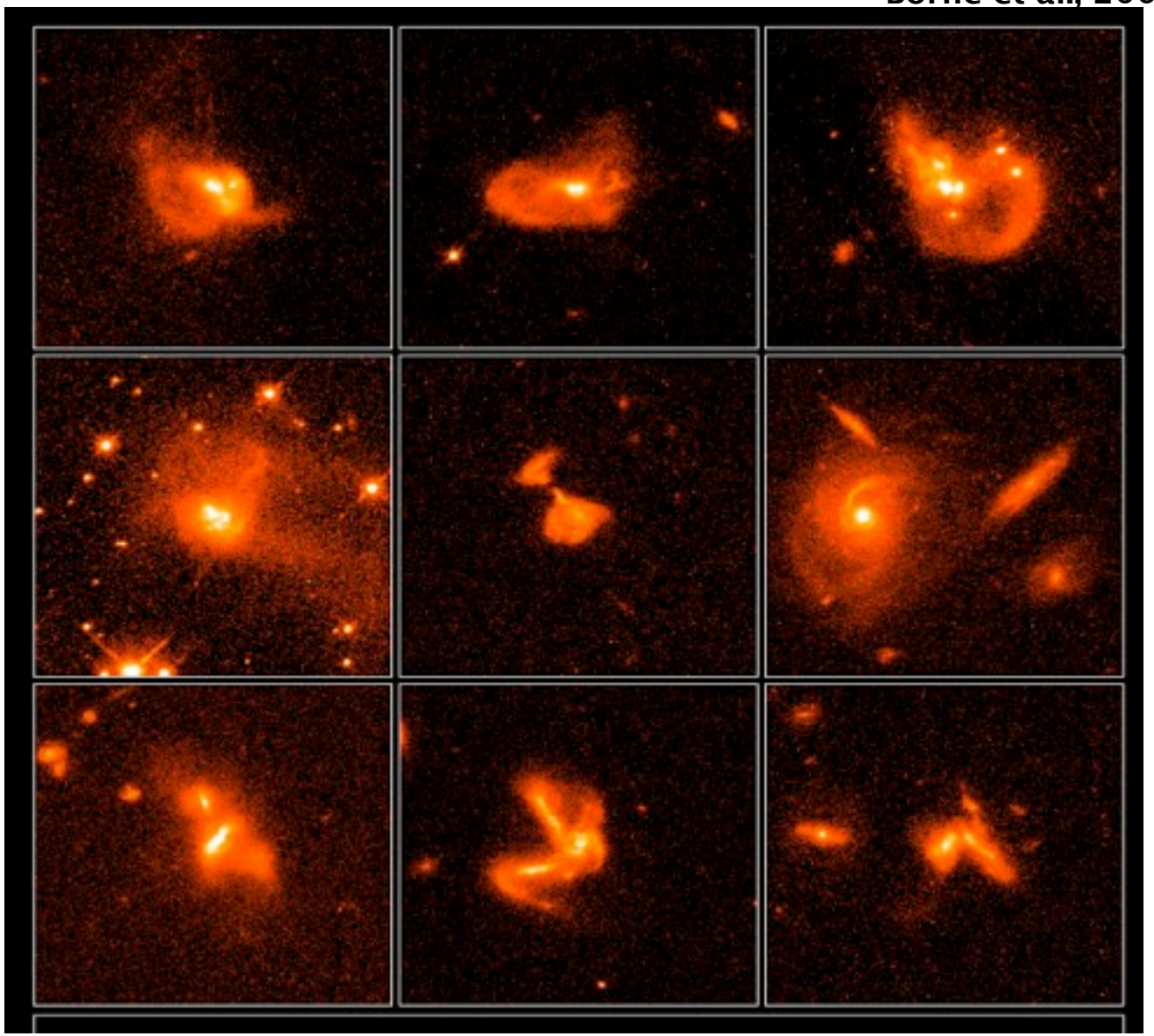
- SFRs > 100 M_{sun}/yr

- Late-stage merger remnants

- Compact (~kpc)

- SB-QSO transition?

Borne et al., 200

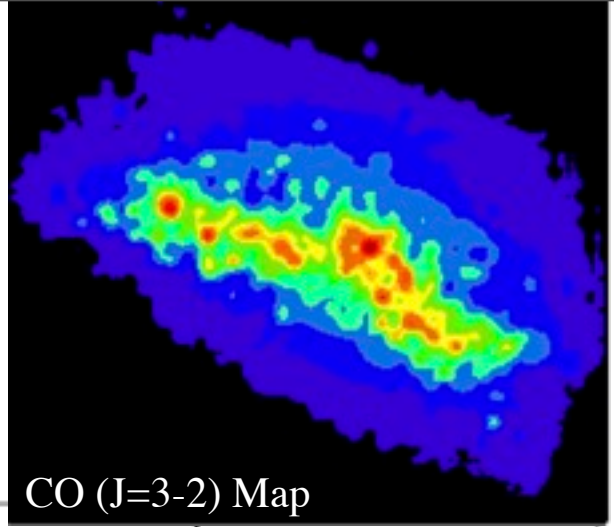


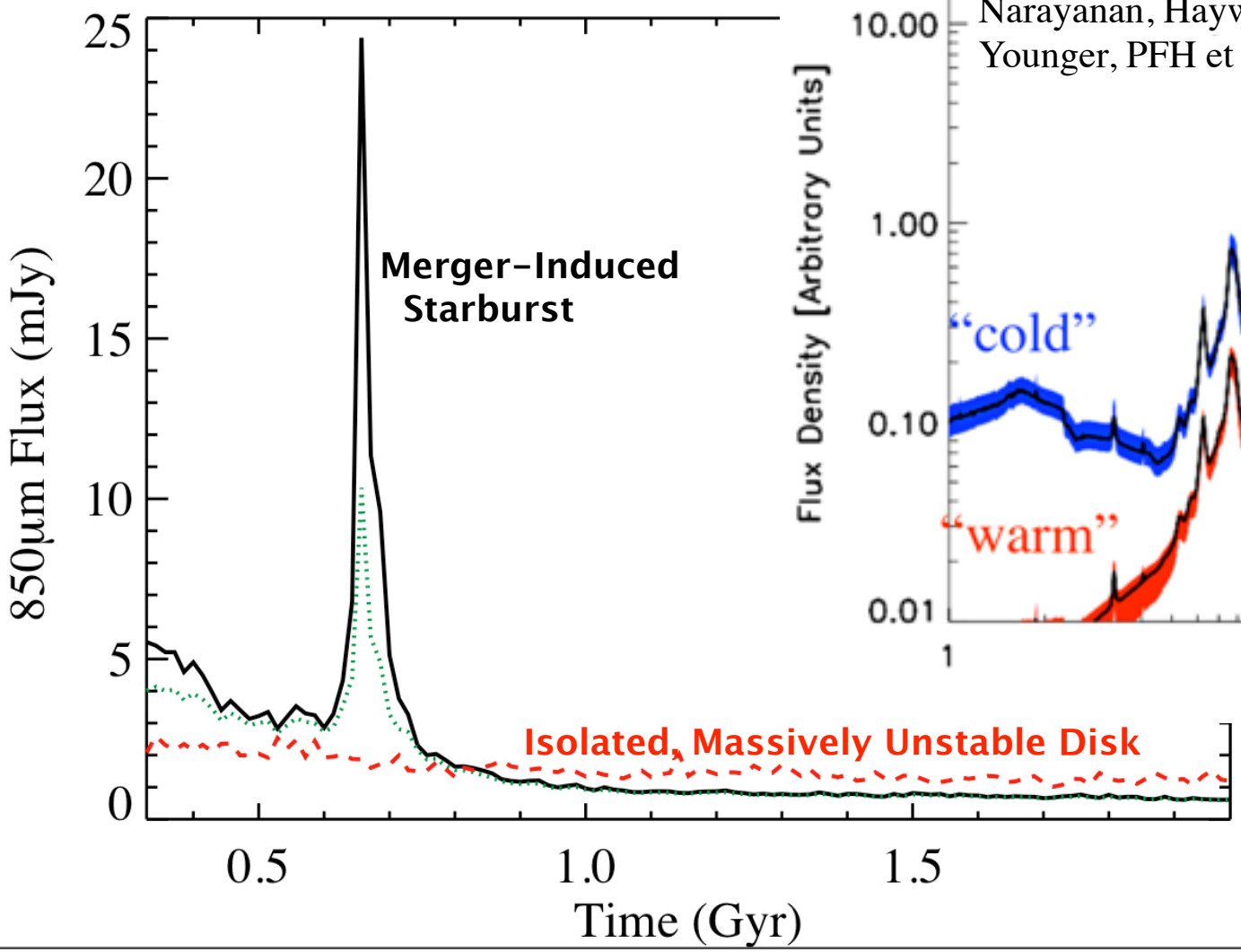
Are they the progenitors of ellipticals?

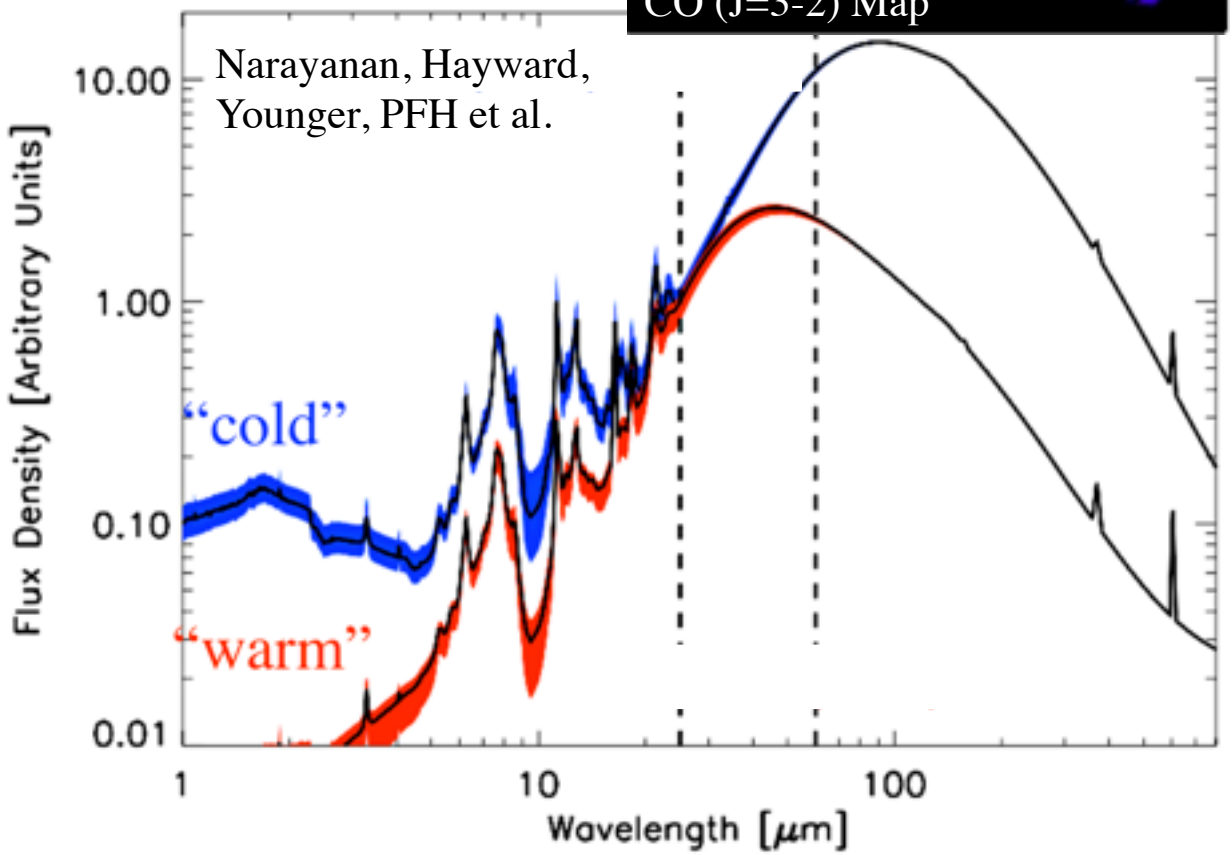
Starbusts: Catching Gas In Action?

QUANTITATIVE COMPARISONS WITH IR SEDs, Sub-mm, CO, Ha

- Radiative Transfer: SUNRISE by P. Jonsson
- Not just at z=0, but in high-redshift sub-millimeter galaxies (e.g. Genzel & co., J. Lotz & CANDELS team at lower-z)



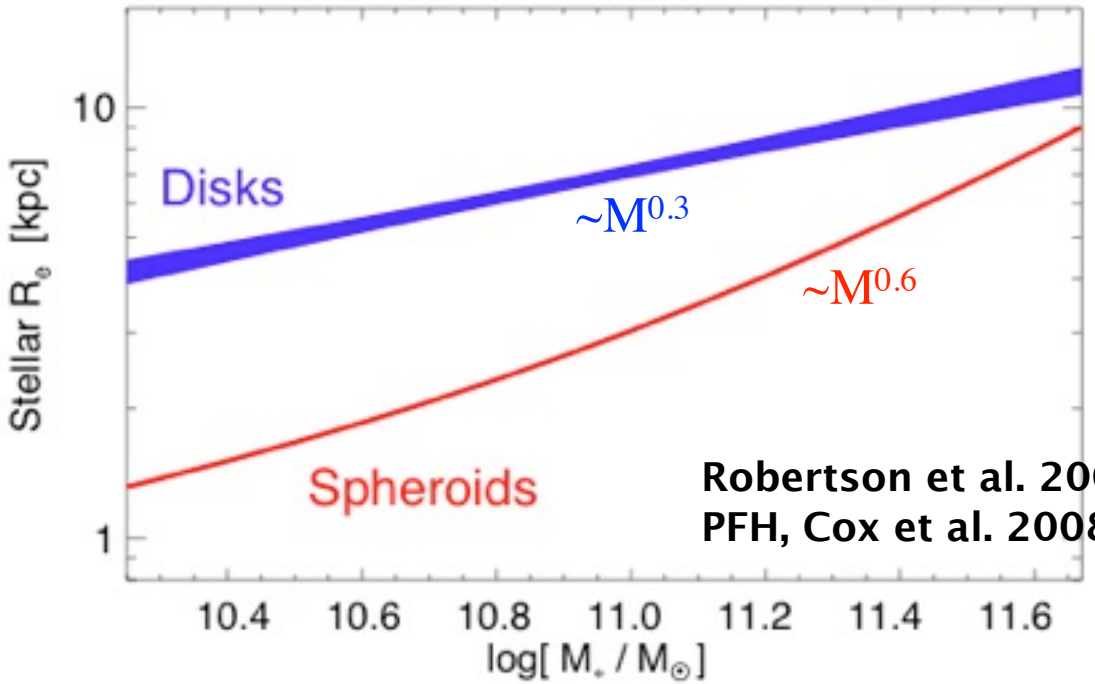




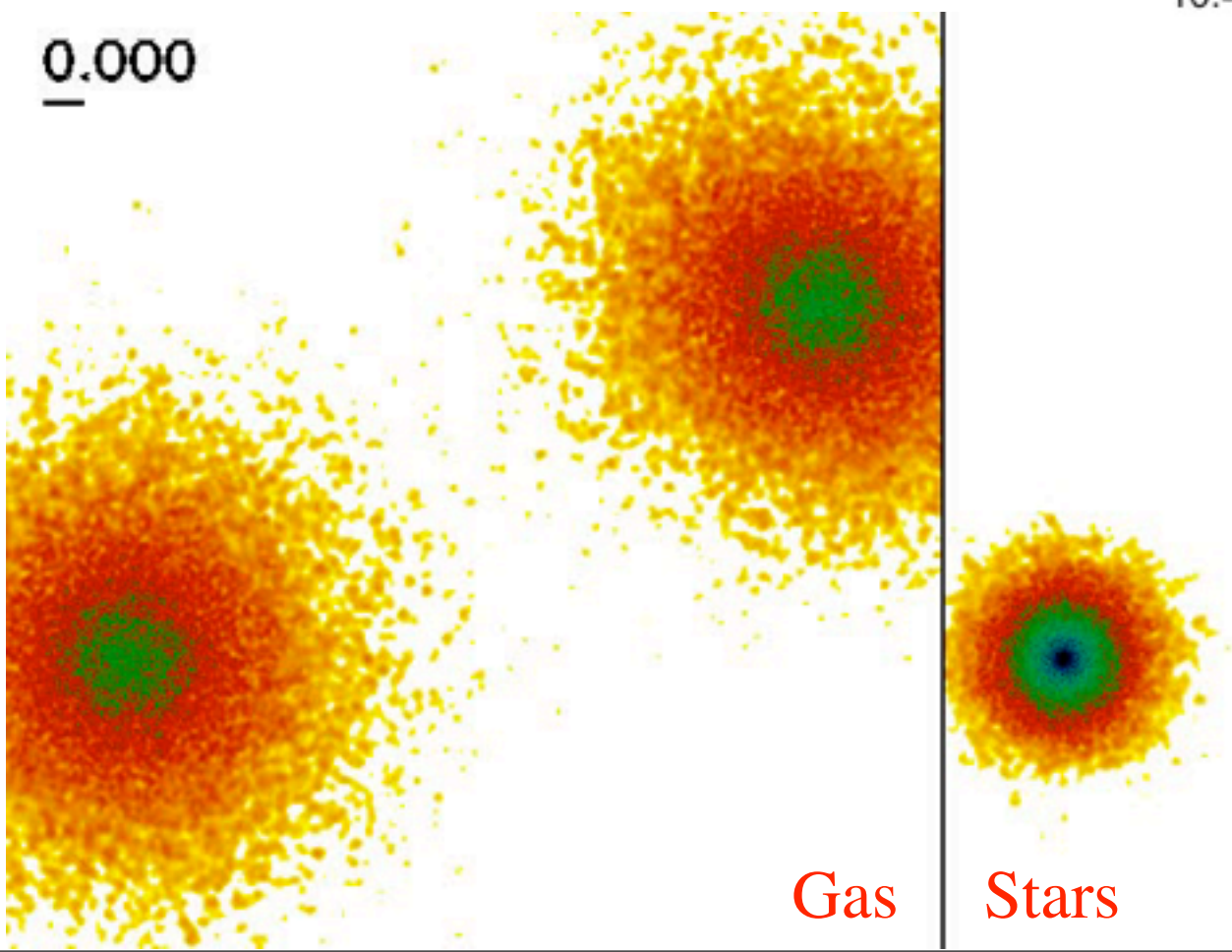
How does this relate to bulge formation?

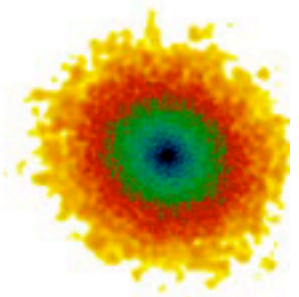
Should be ~9min

The Problem: The Fundamental Plane & Bulge Densities:



- Why are ellipticals smaller than disks? (Ostriker, Gunn, et al.)

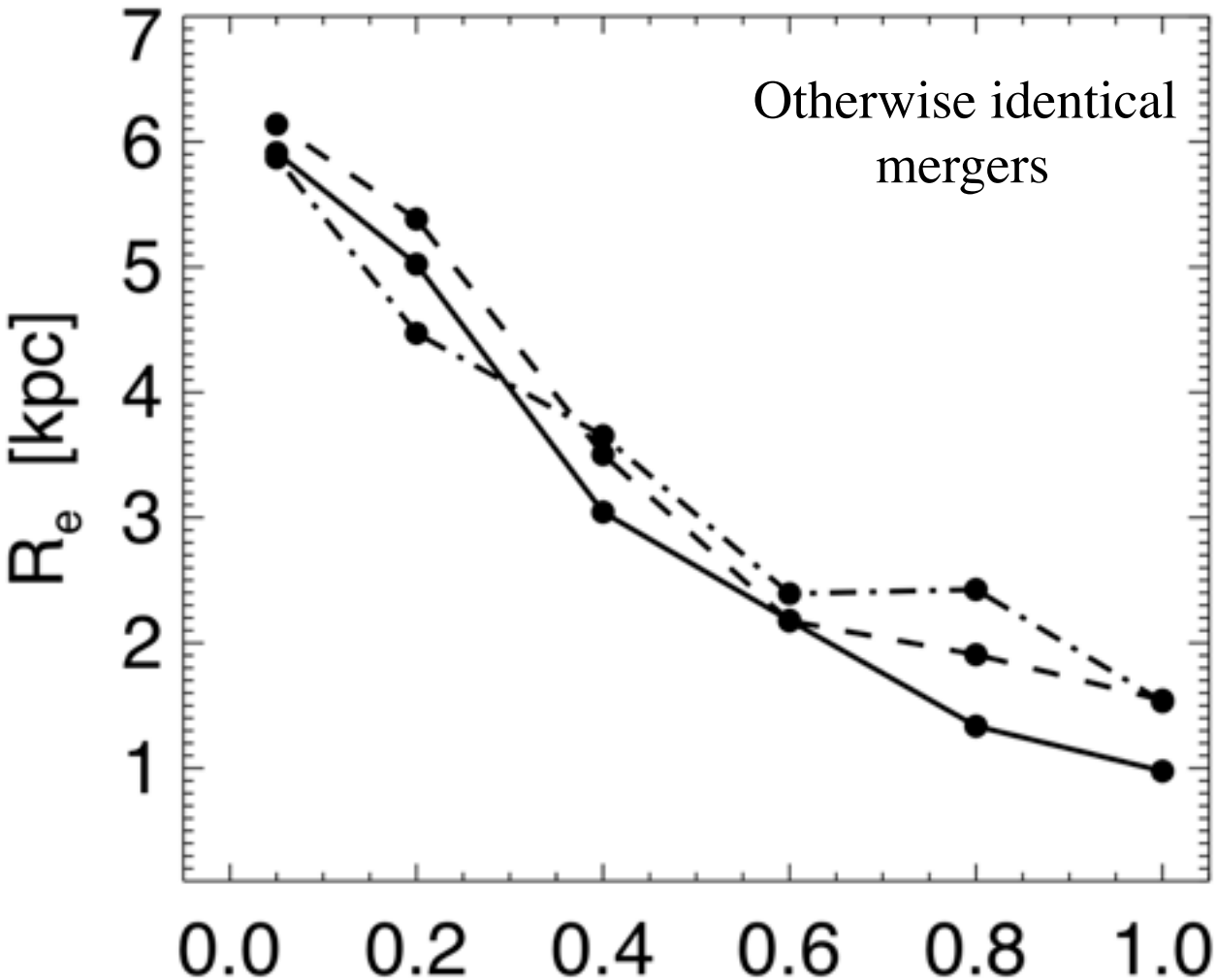




- Gas Dissipation

The Solution: Gas-Rich Mergers

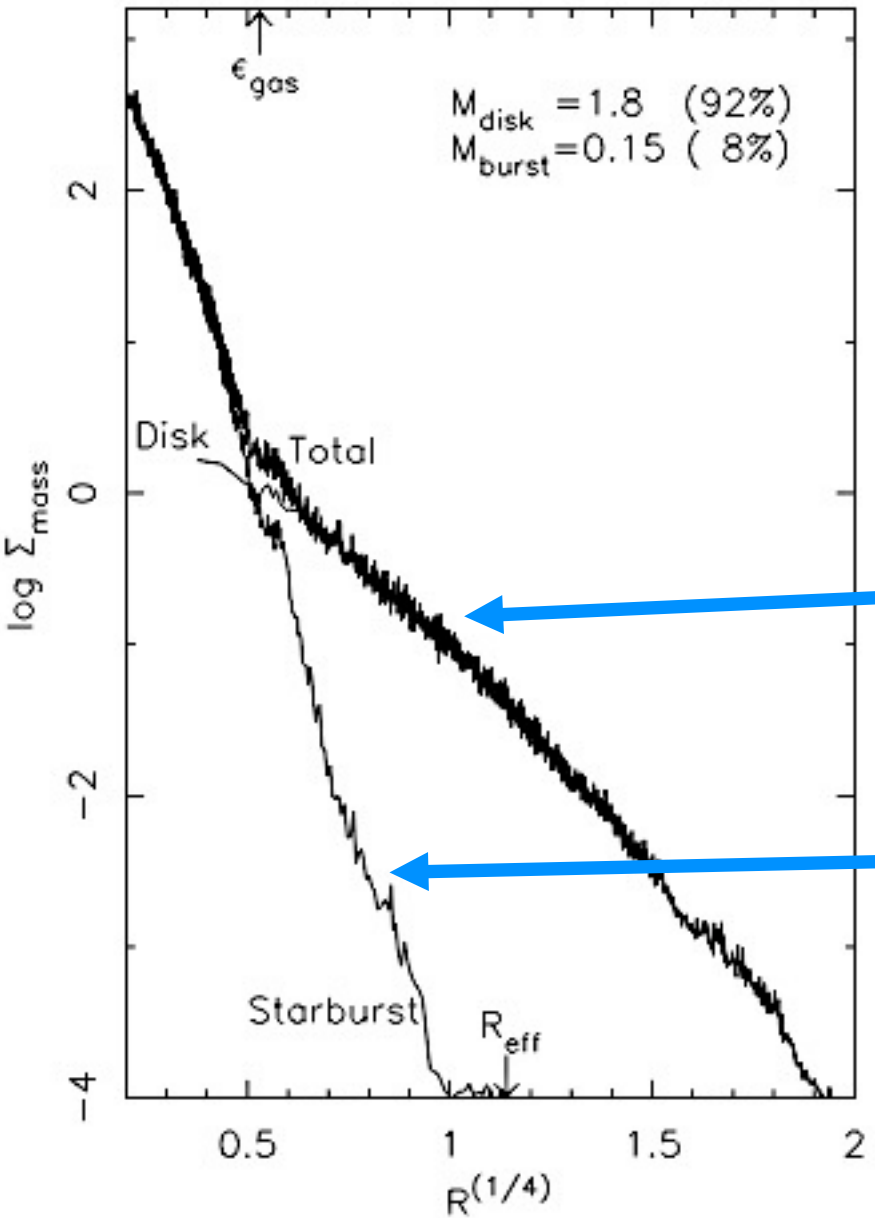
- Increased dissipation→smaller, more compact remnants (Cox; Khochfar; Naab; Robertson)



PFH, Cox et al. 2008

Starburst Stars Leave a "Footprint" 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:

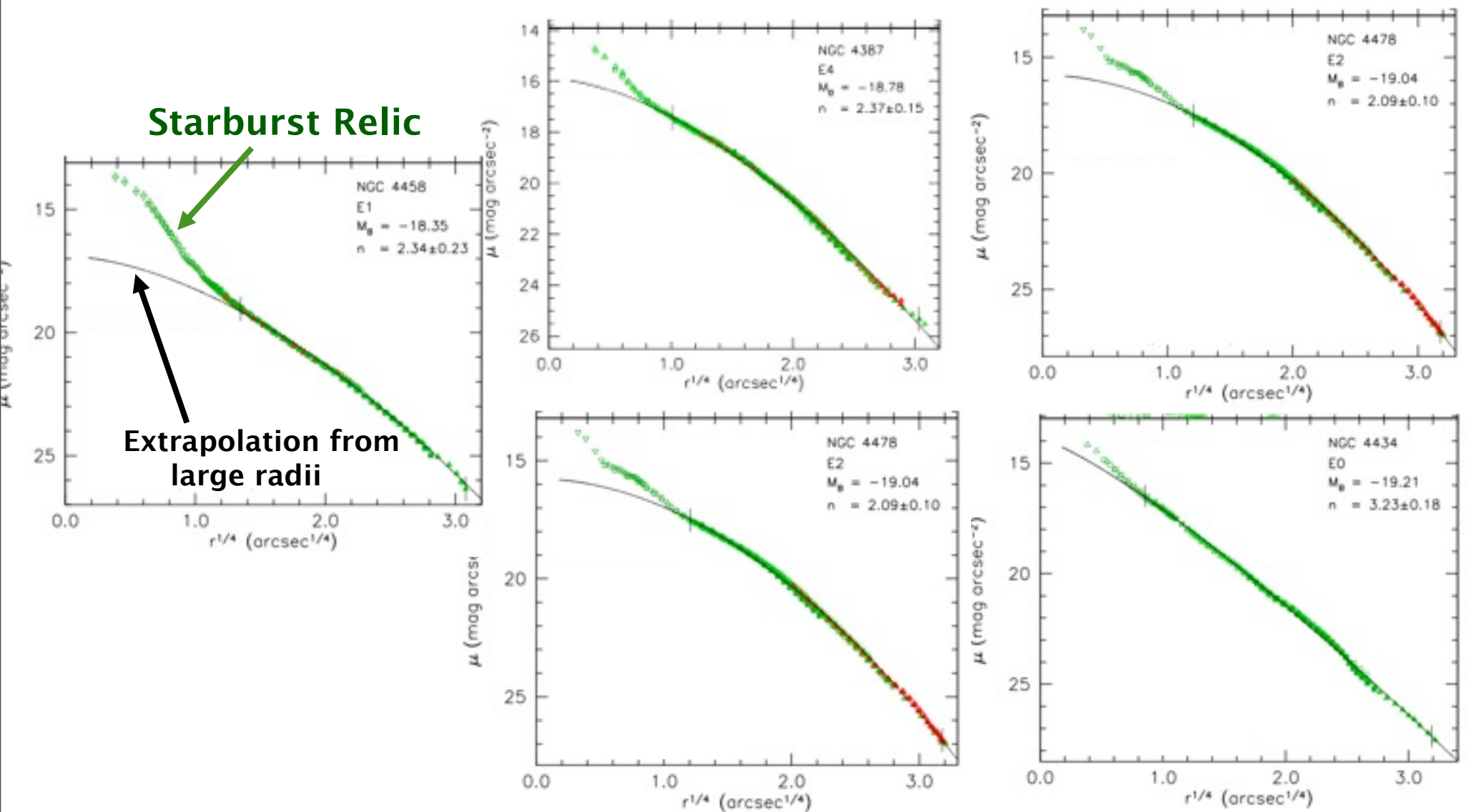
"Can the merger hypothesis be reconciled with the *lack* of dense stellar cores in most normal ellipticals?" (MH94)

Starburst Stars Leave a "Footprint" on the Profile

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

Kormendy et al. 2008
(also Hibbard & Yun,
Rothberg & Joseph,
Faber et al., Lauer et al.

- Since then...



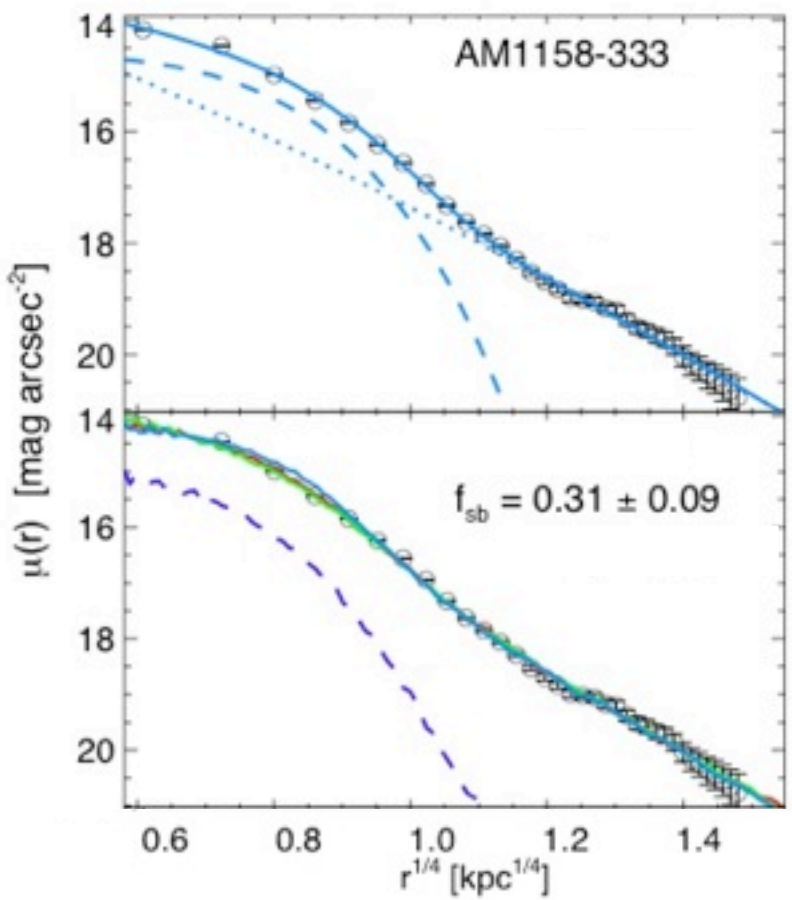
"Normal and low-luminosity ellipticals... in fact, have *extra*, not missing light at at small radii with respect to the inward extrapolation of their outer Sersic profiles."

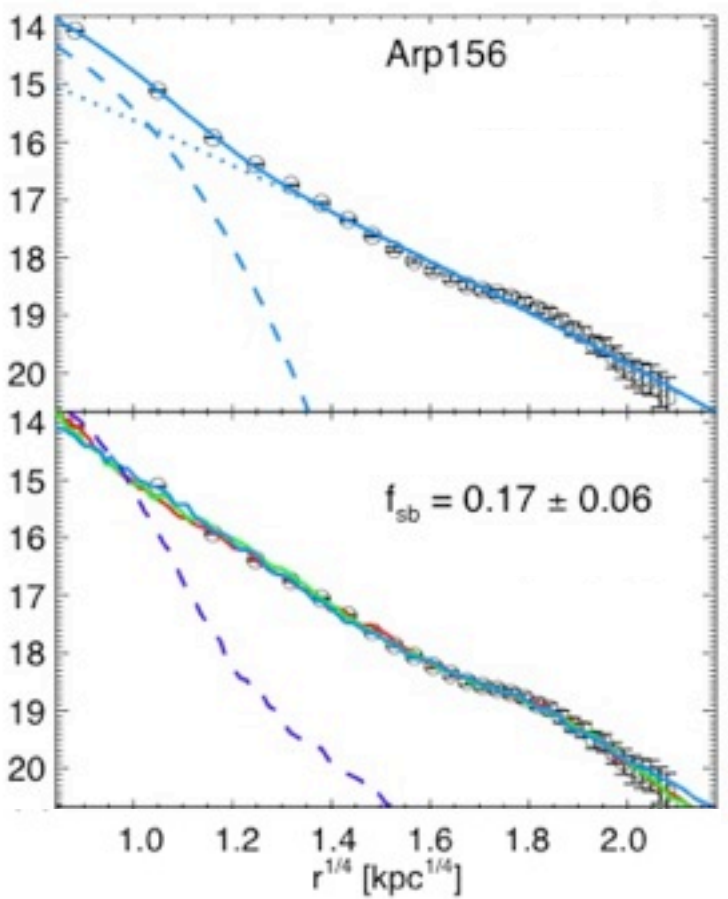
Application: Merger Remnants
RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008(a-c)

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





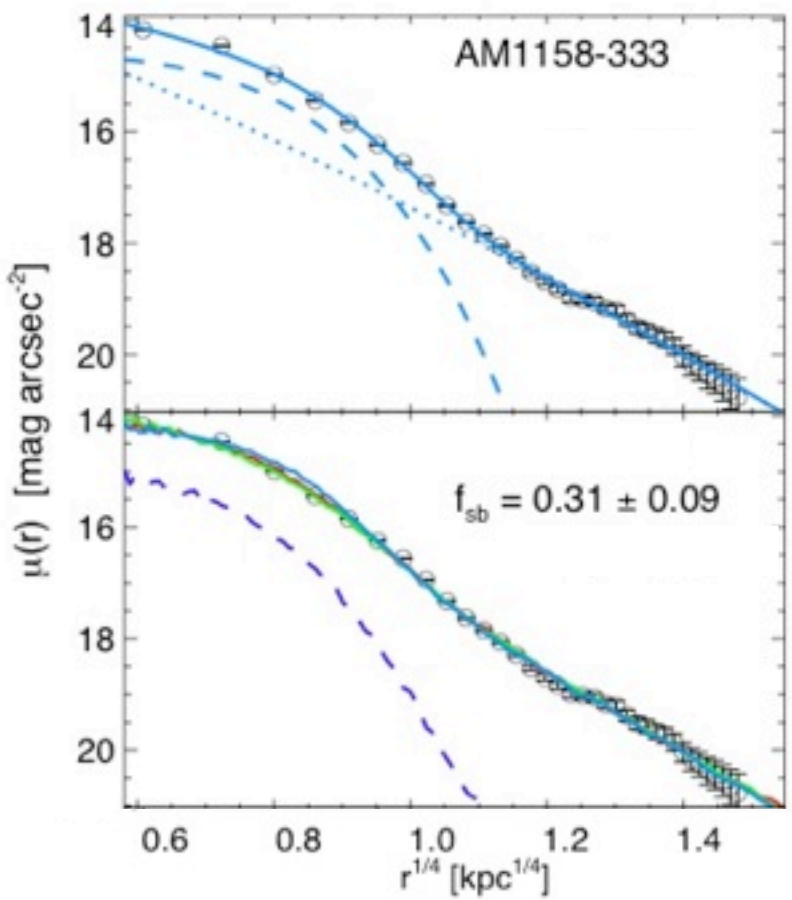
Start at ~15 min

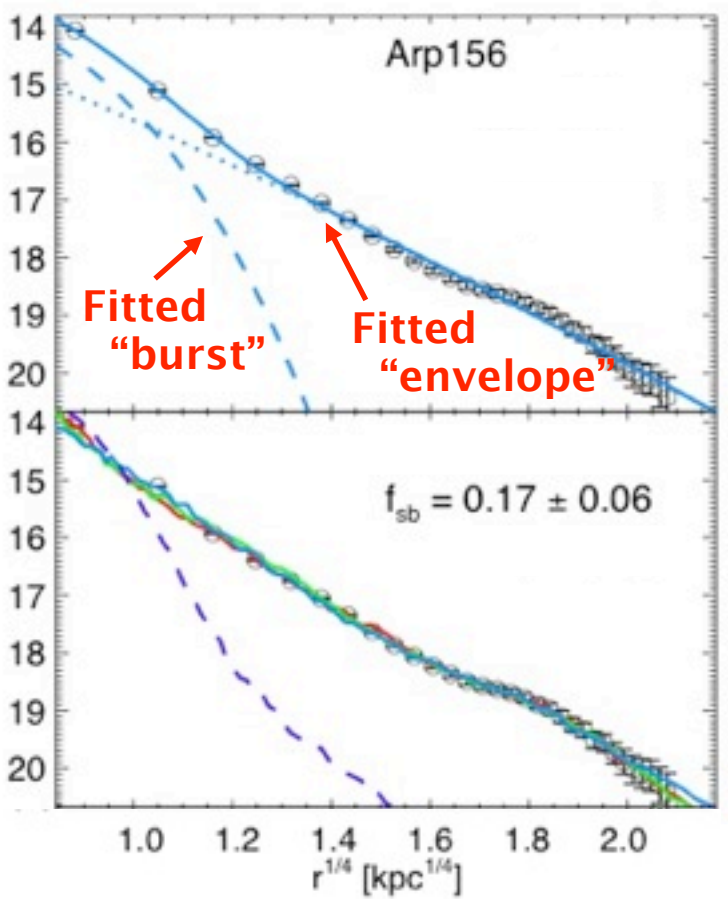
Application: Merger Remnants
RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008(a-c)

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





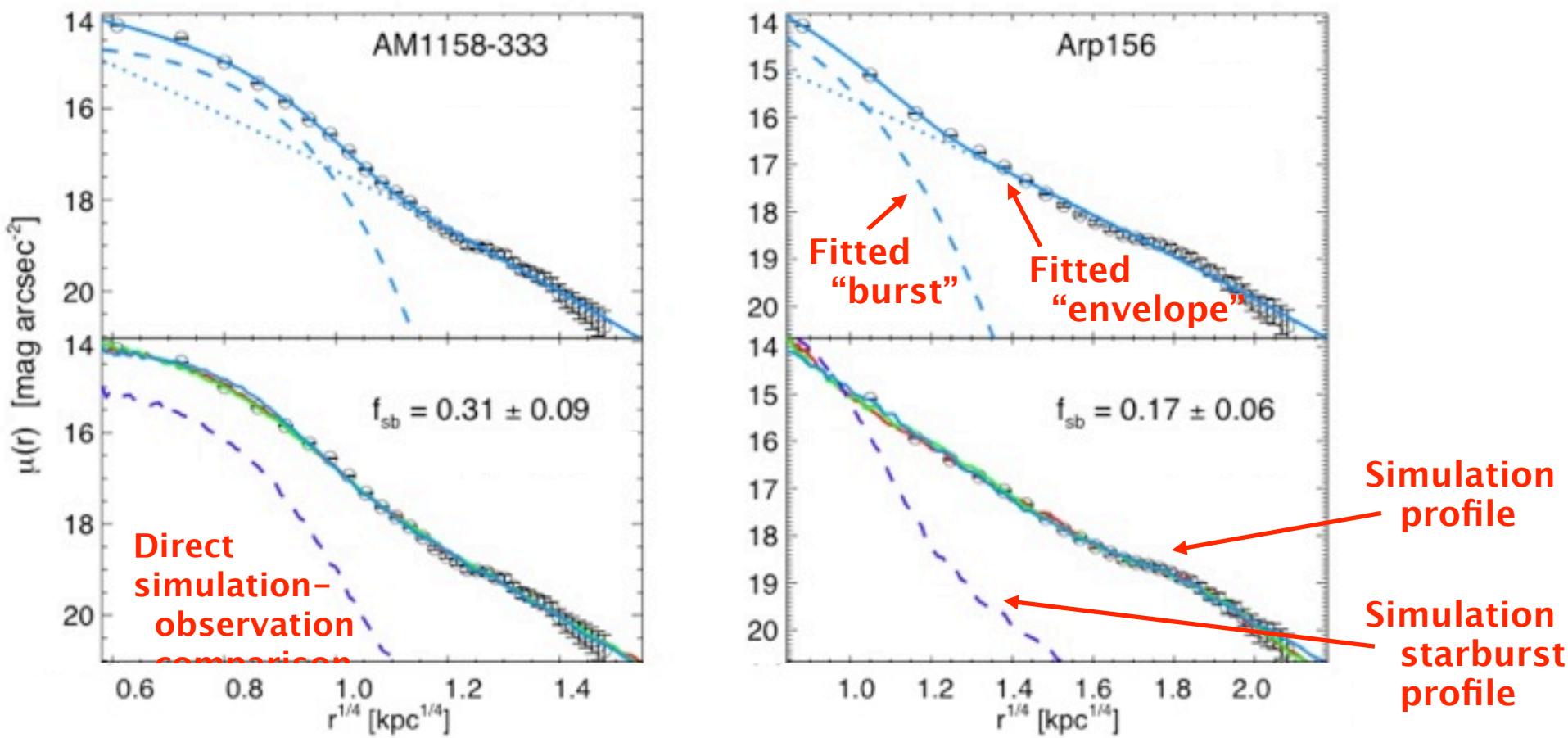
Start at ~15 min

Application: Merger Remnants
RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008(a-c)

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



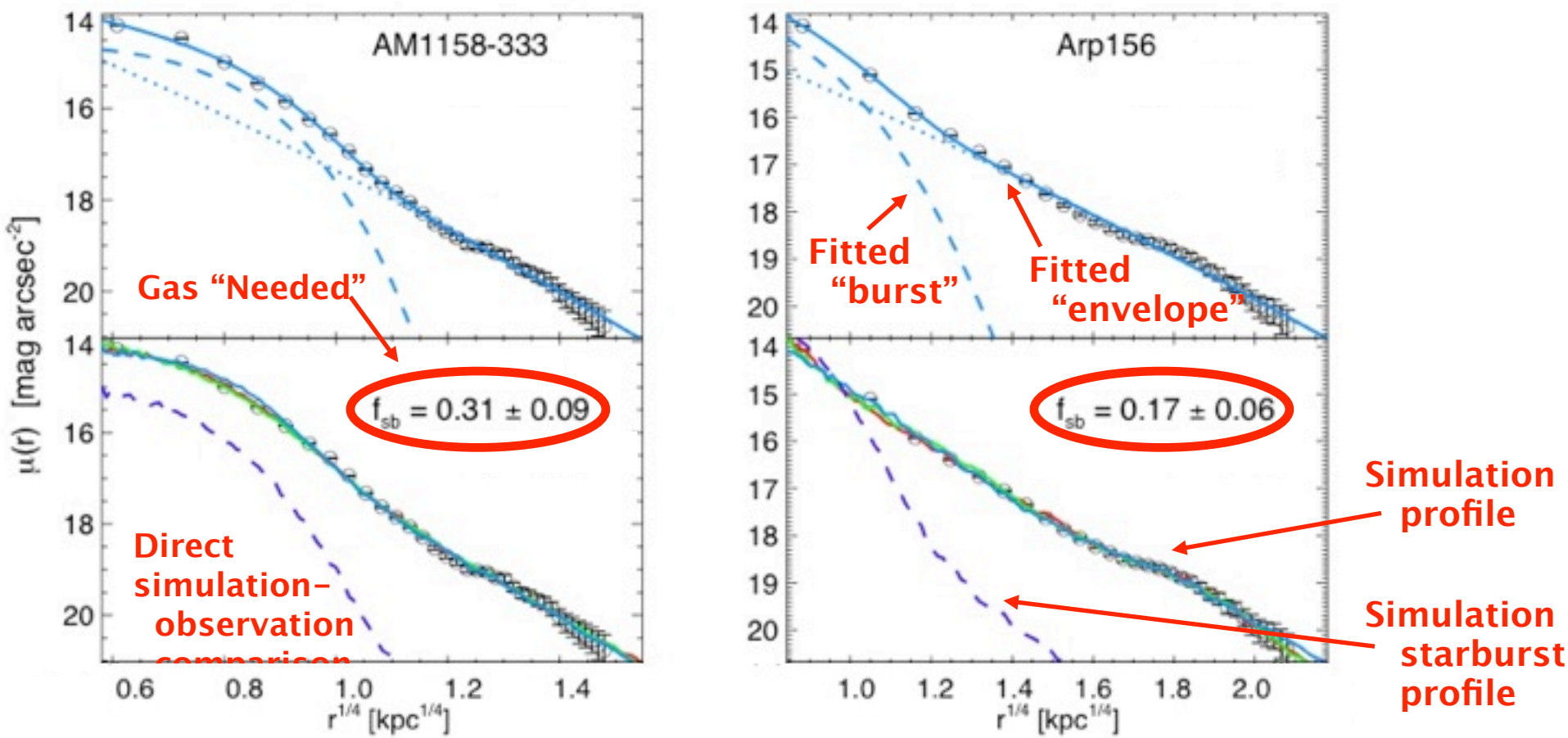
Start at ~15 min

Application: Merger Remnants
RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2008(a-c)

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

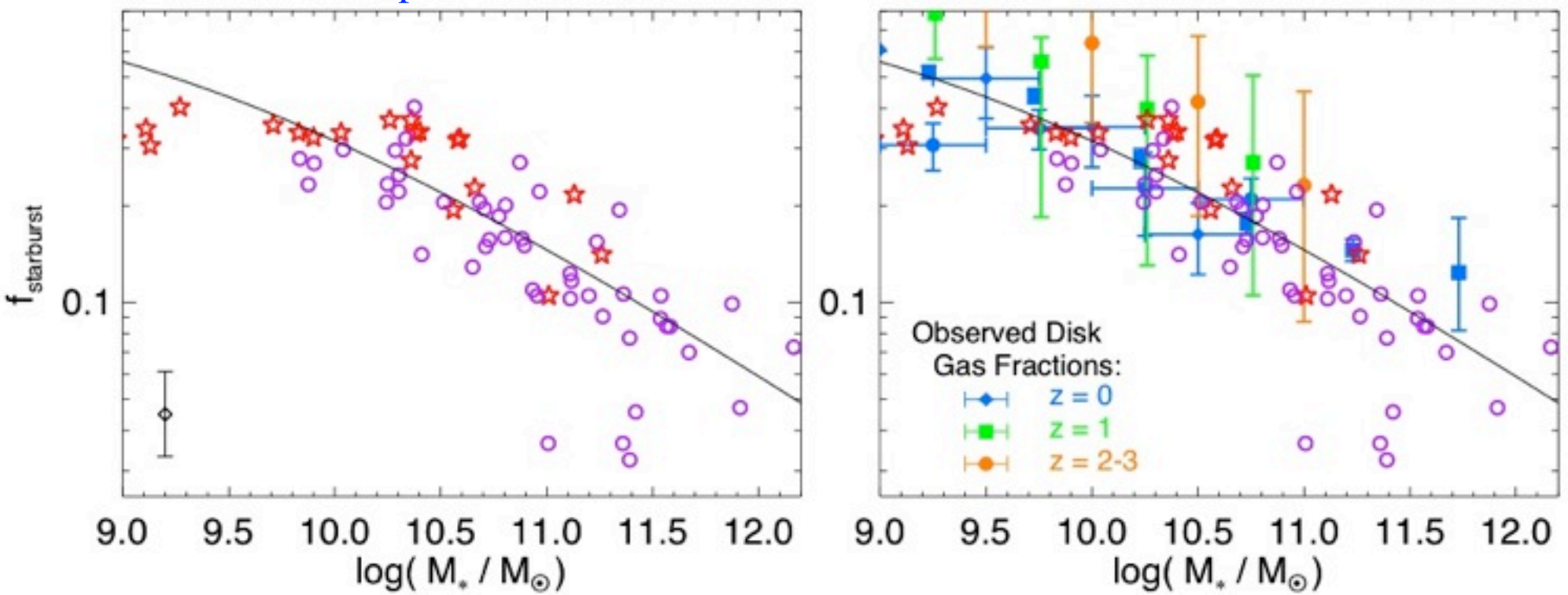


Start at ~15 min

Structure in Elliptical Light Profiles
RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008
PFH, Kormendy, & Lauer et al. 2

Starburst mass needed to match observed profile:



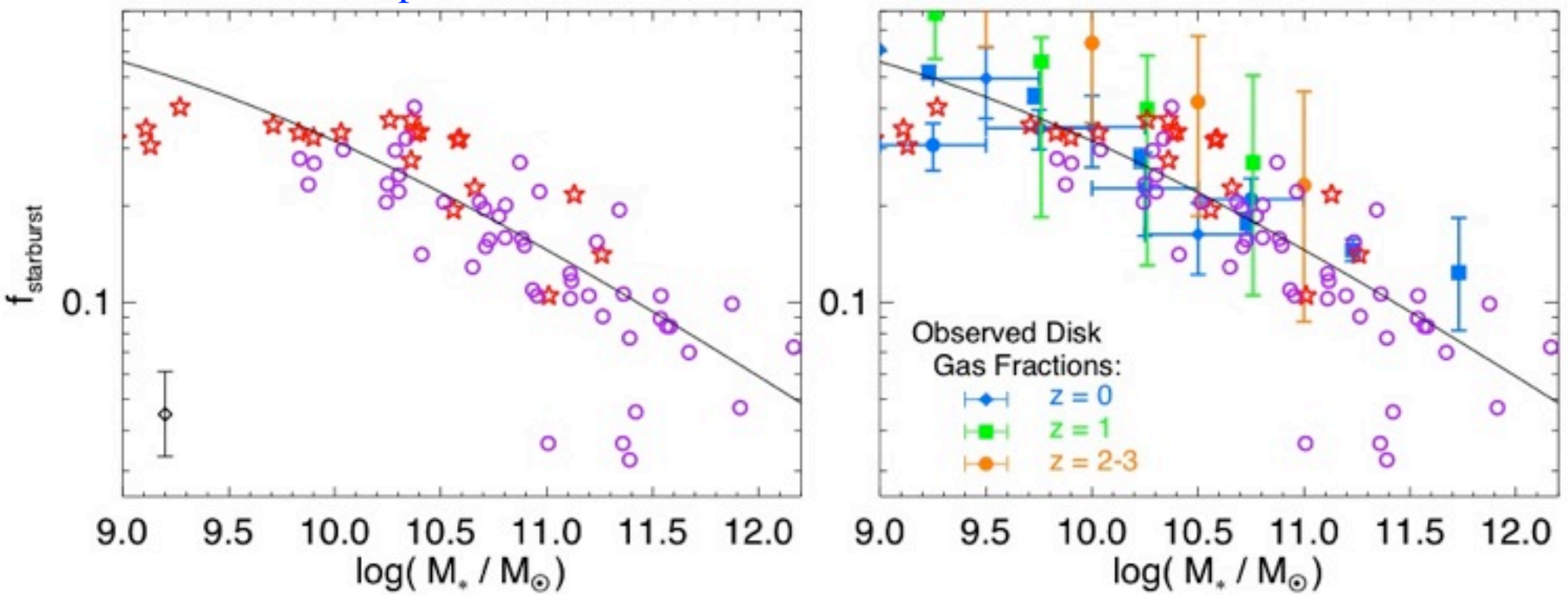
- You DO get realistic ellipticals, IF given realistic disks
- Recover the "tilt" in the fundamental plane:
  spheroid scalings = disks + dissipation

Structure in Elliptical Light Profiles
RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008

PFH, Kormendy, & Lauer et al. 2

Starburst mass needed to match observed profile:

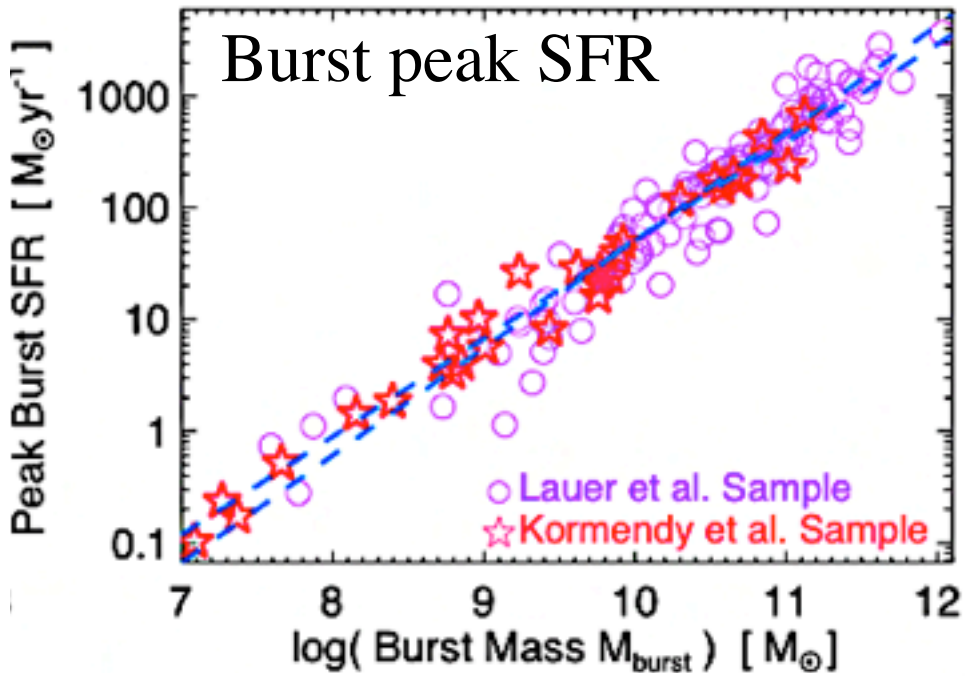


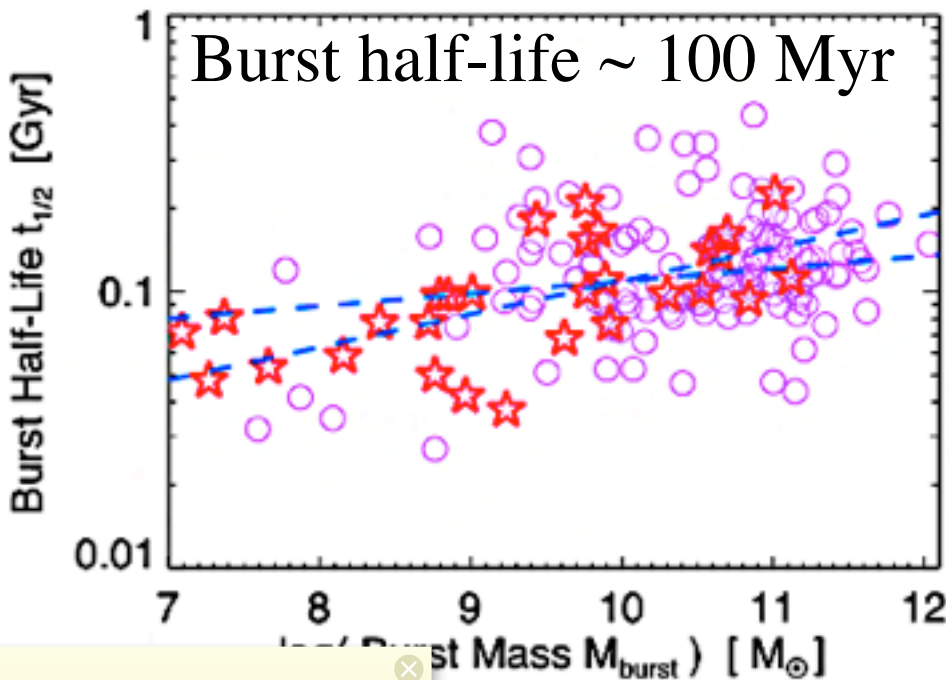
- You DO get realistic ellipticals, IF given realistic disks
- Recover the "tilt" in the fundamental plane:
  spheroid scalings = disks + dissipation

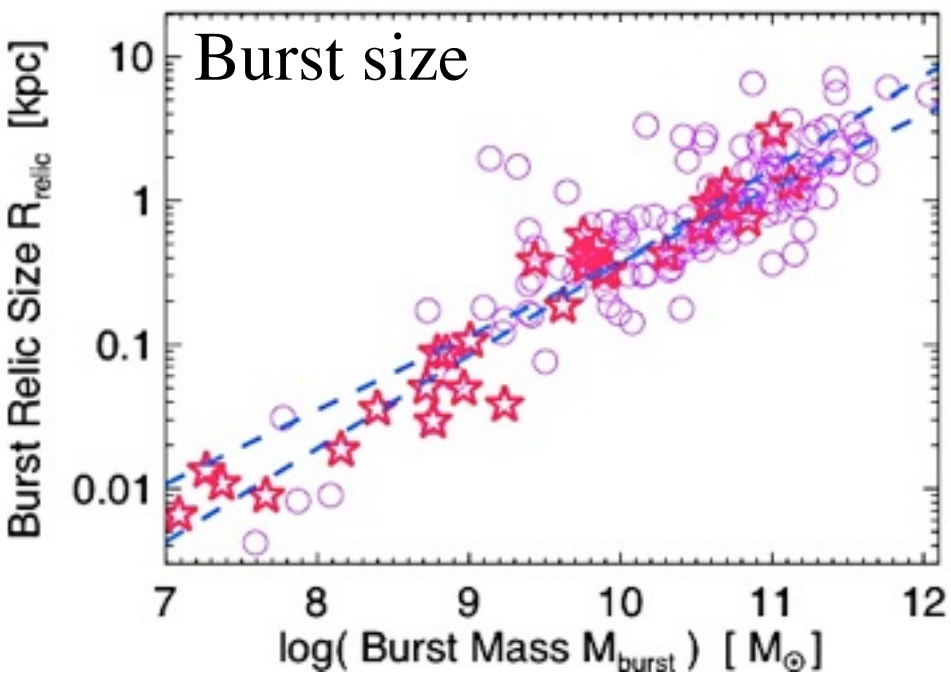
Metallicity & Stellar Pops:
Foster, Proctor PFH et al. 0

V/s & Structural Parameters:
Jogee & PFH et al. 10,11

What else can we learn from the 'relics' of gas dissipation?

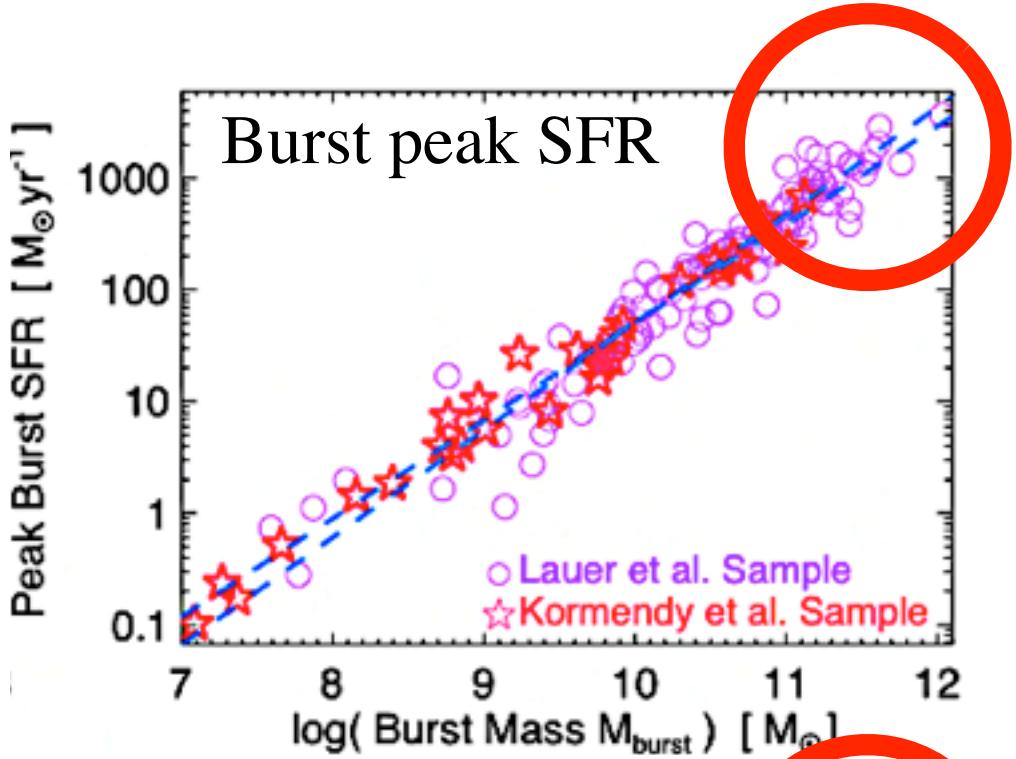


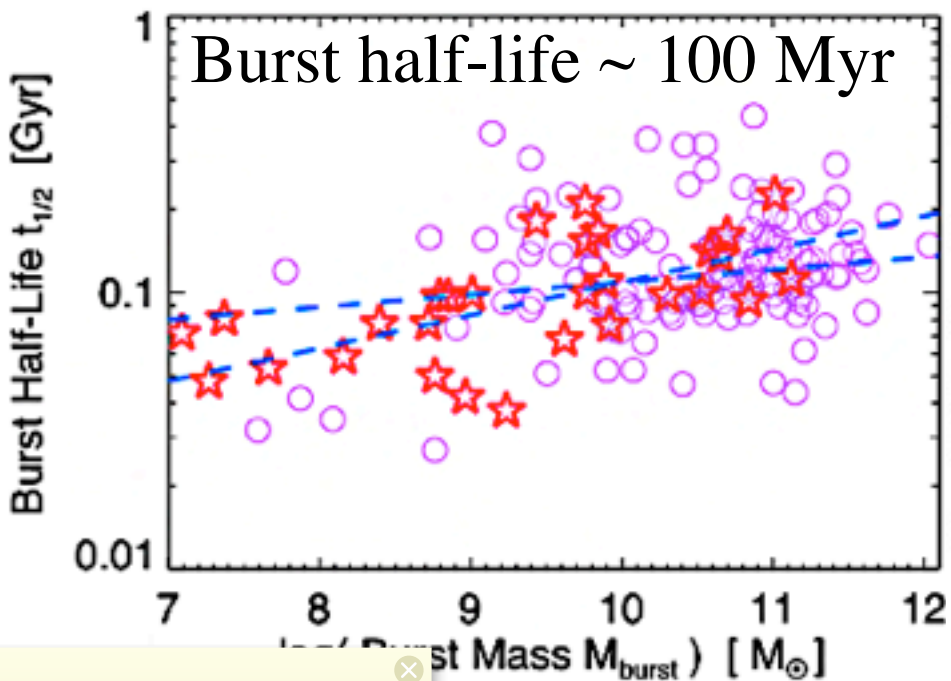


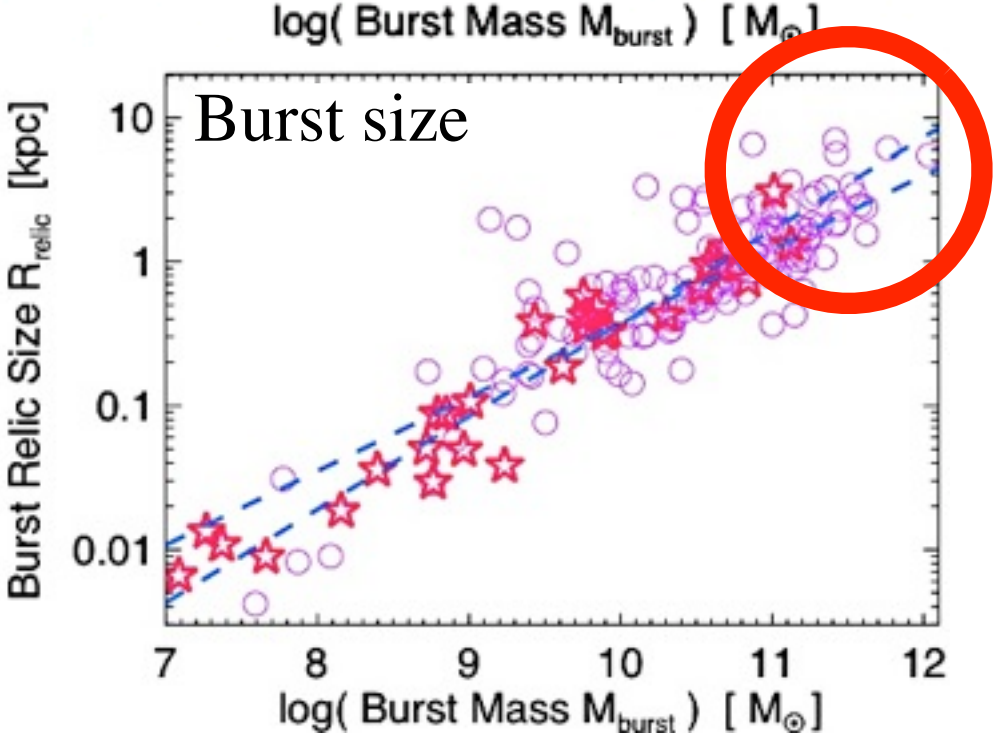


cut?

What else can we learn from the 'relics' of gas dissipation?

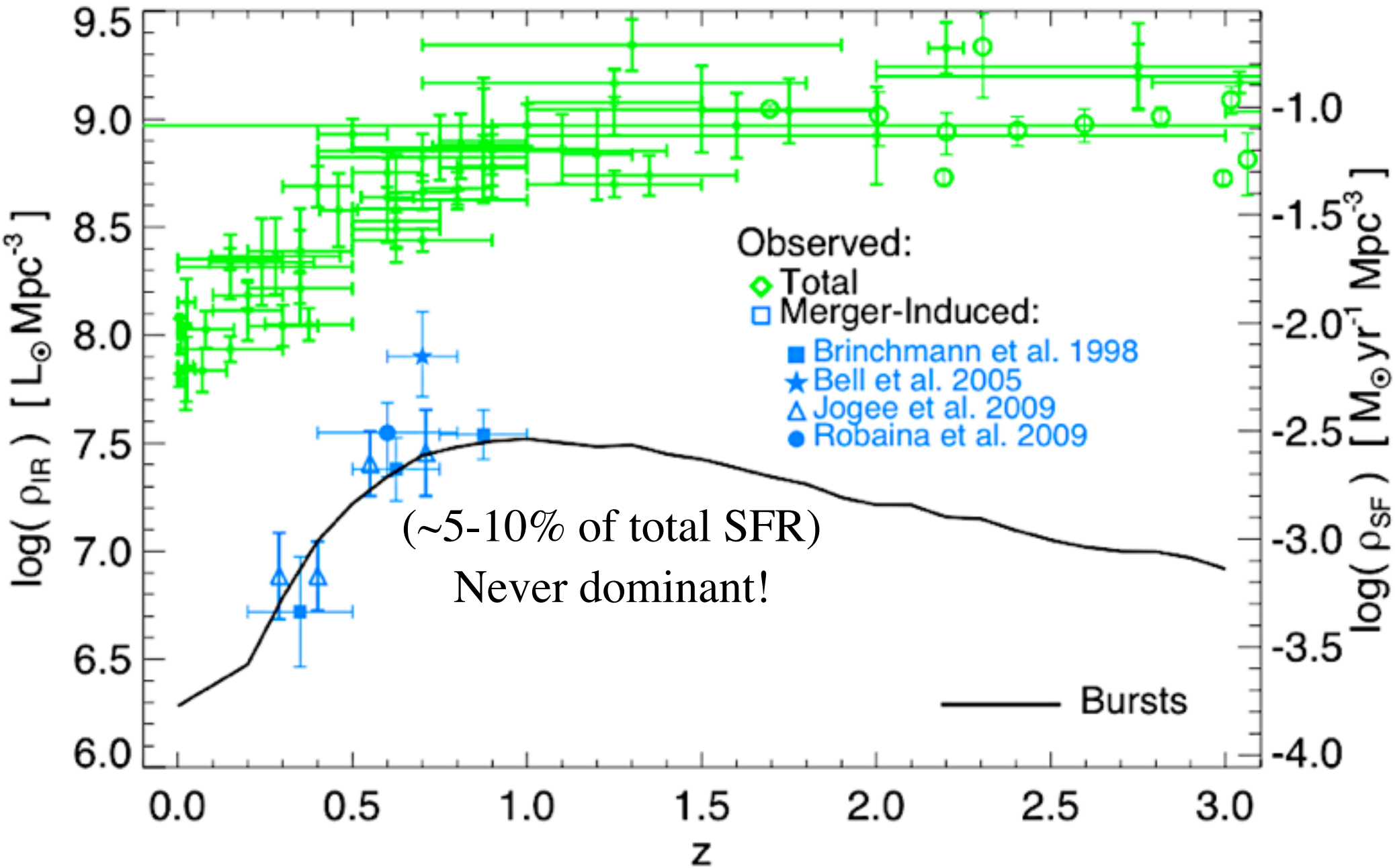






cut?

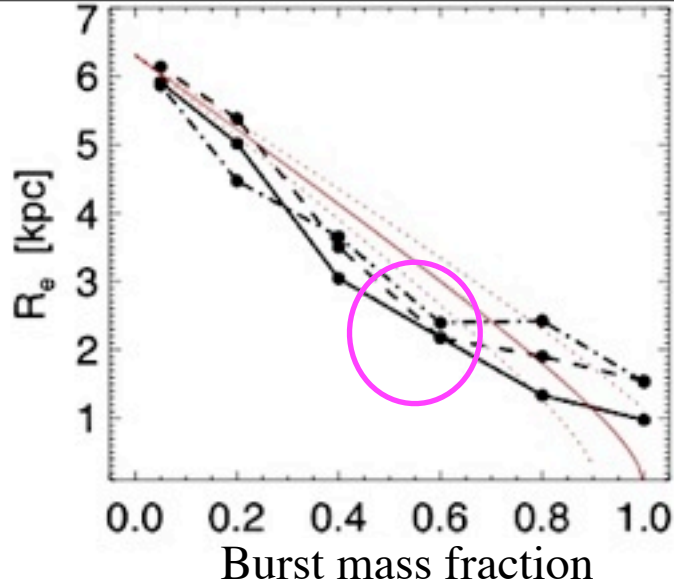
Recover the Role of Starbursts in Cosmic Star Formation:



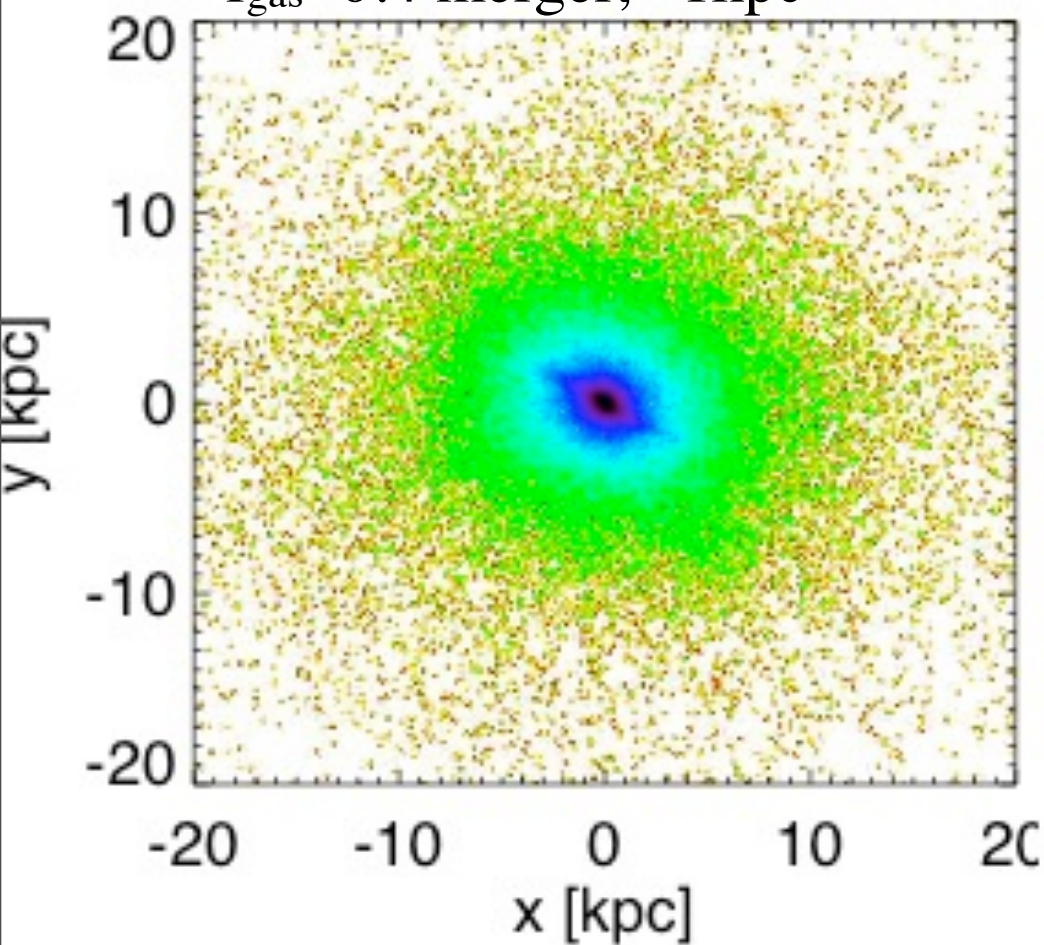
What happens as we scale up with redshift?

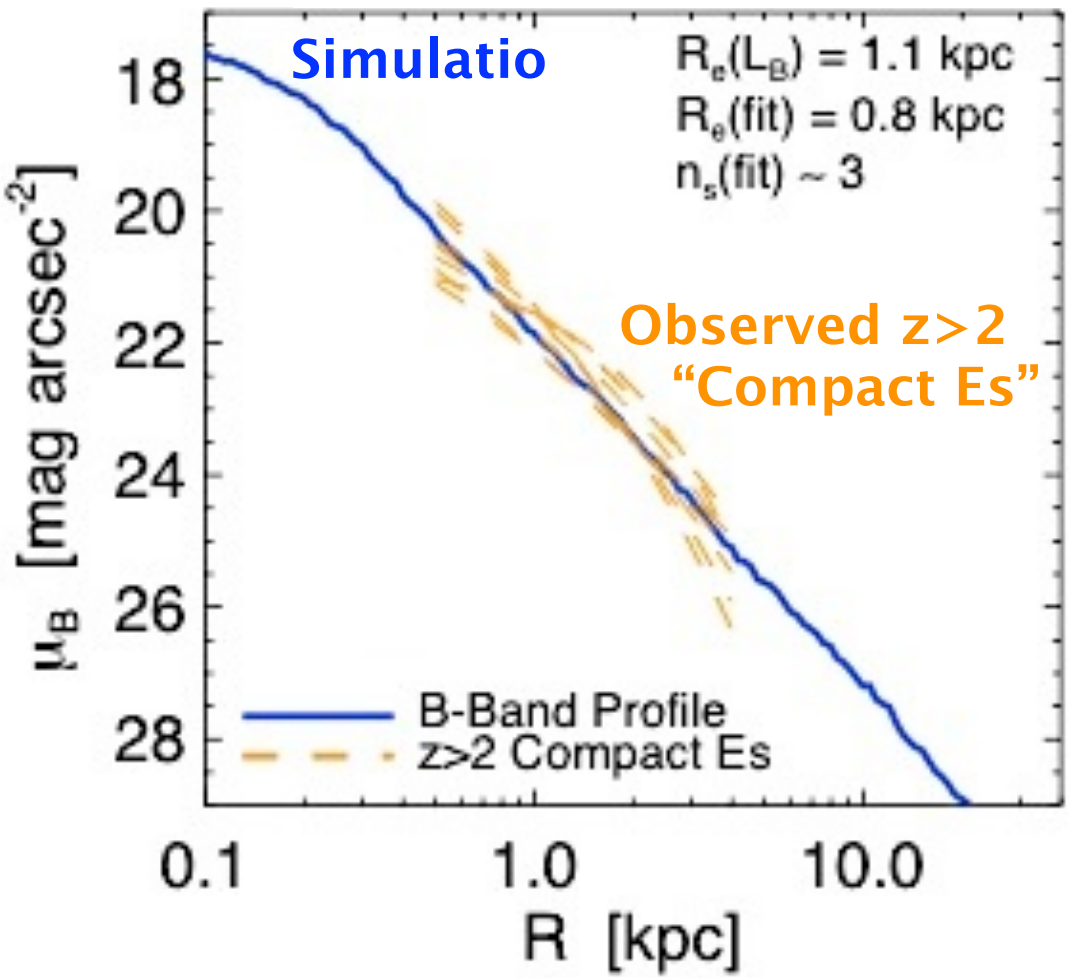
Should be ~20min (OK, lost ~5 min here... need to cut ~2-3 of those minutes)

- Typical f_{gas} in high-z massive disks up to ~40% (Erb+, Tacconi+, Manucci+)



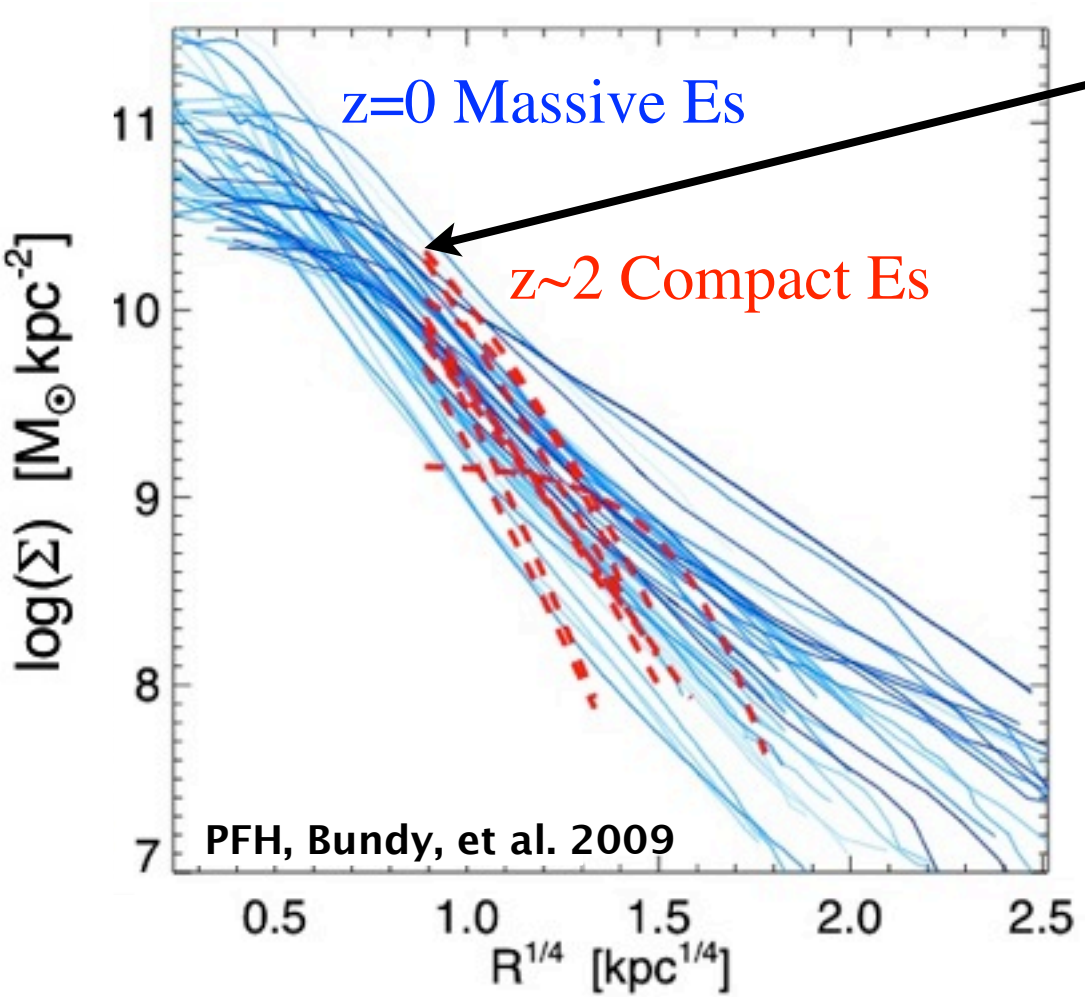
f_{gas}=0.4 merger, ~1kpc





Wuyts, PFH, Franx, Van Dokkum

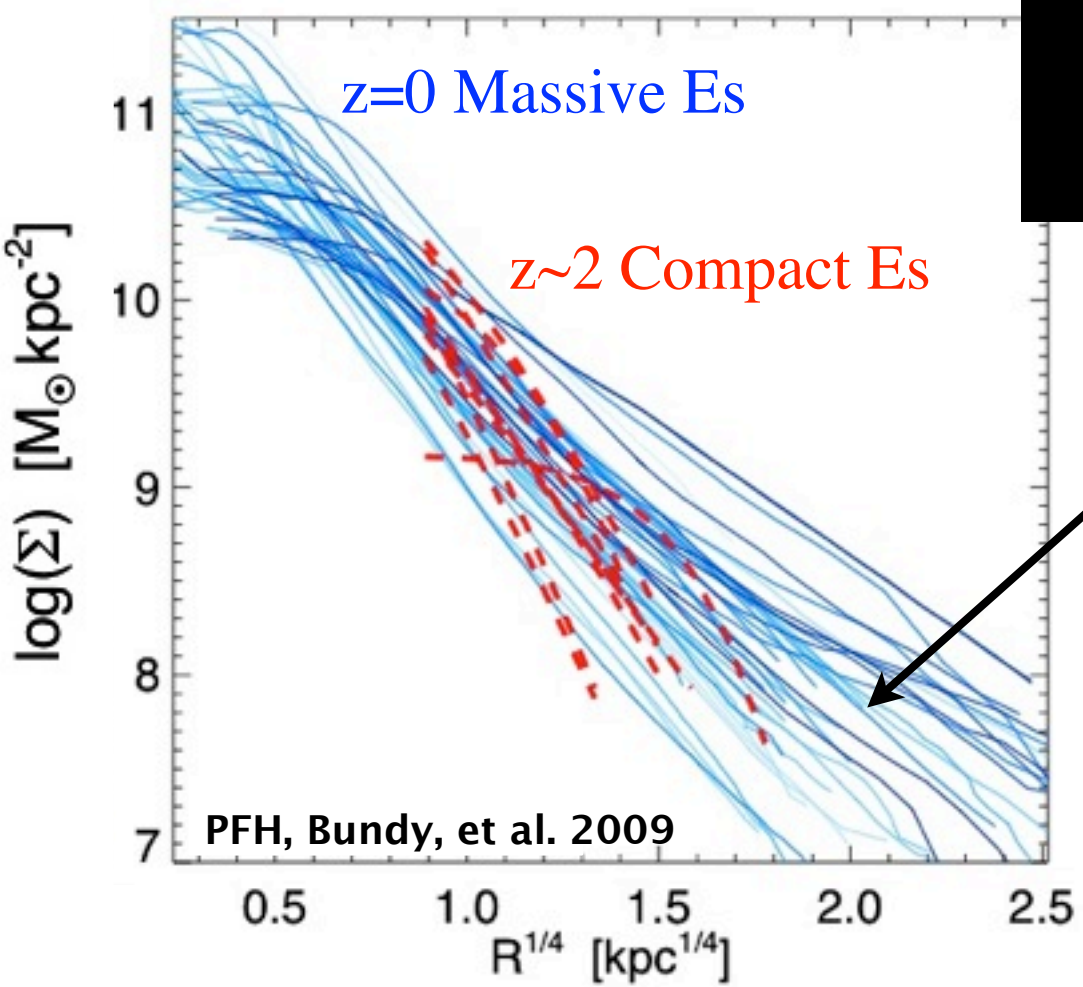
- Do we see the 'footprint' today?
- How did the high-z systems evolve to be 'normal' at z=0?



No more (*centrally*) dense than massive Es today!

(also Bezanson et al., 2009)

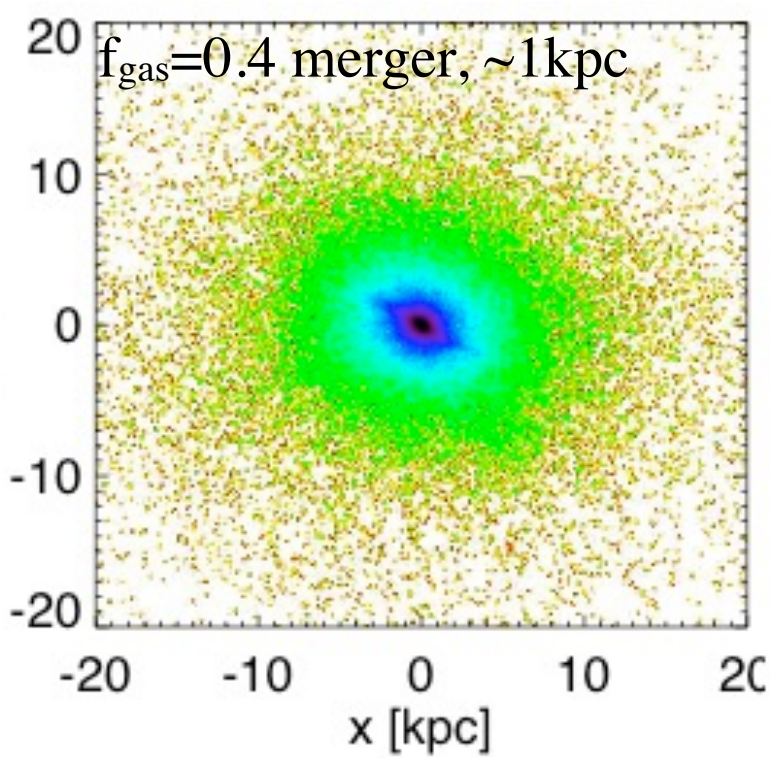
- Do we see the 'footprint' today?
- How did the high-z systems evolve to be 'normal' at z=0?

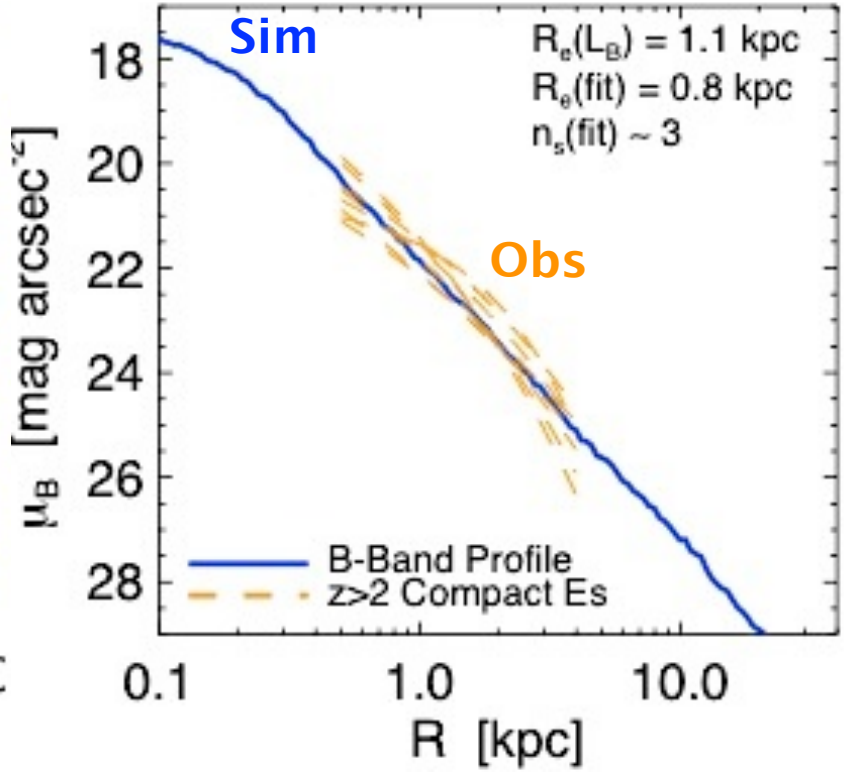


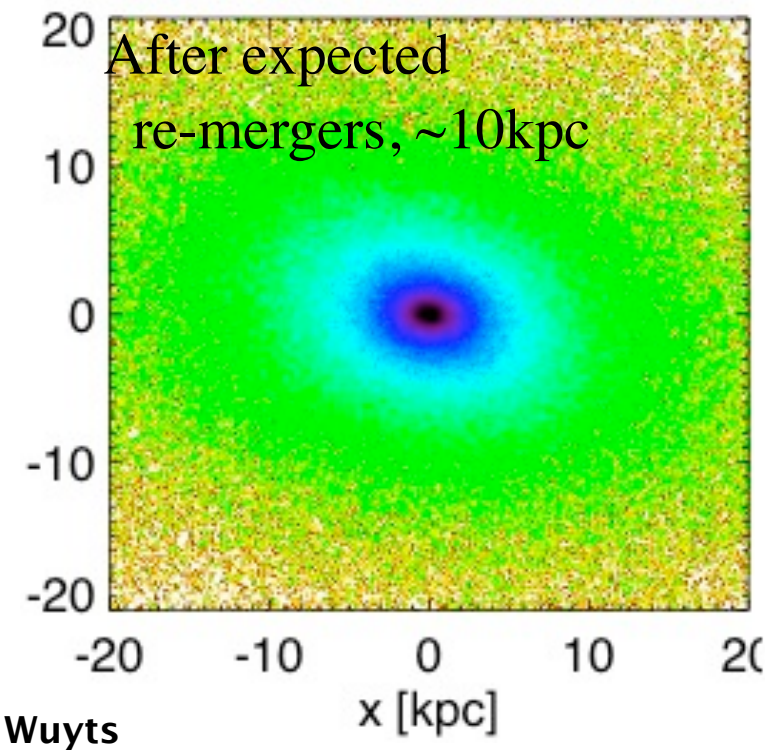
Missing the low-density "wings":

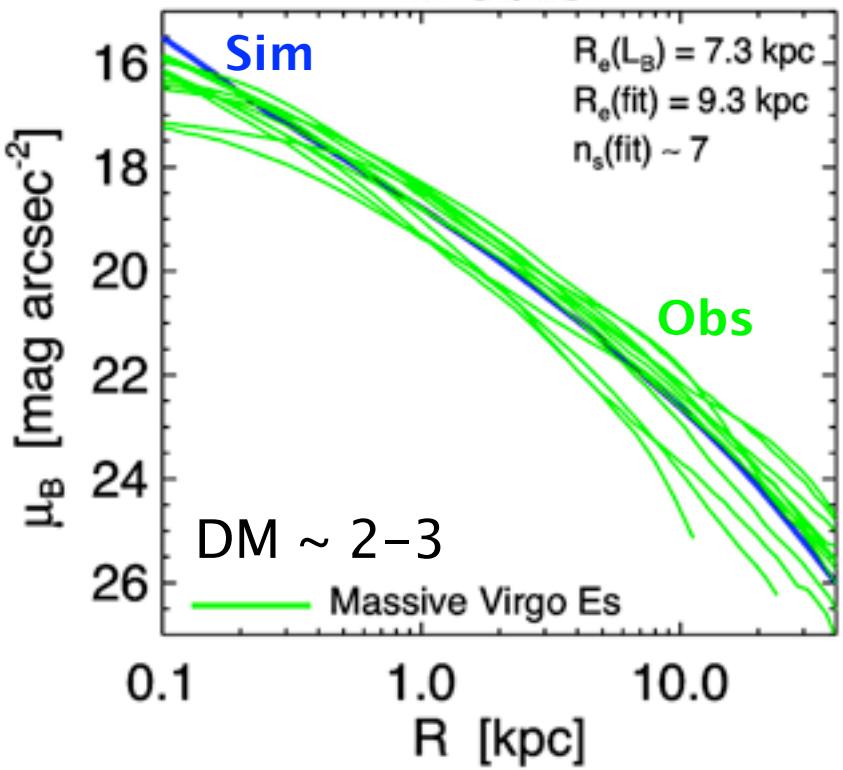
Only need to accrete ~M_{gal} in "fluff", to increase R_e by a factor ~6!

Naab et al. 2009 (& in pr







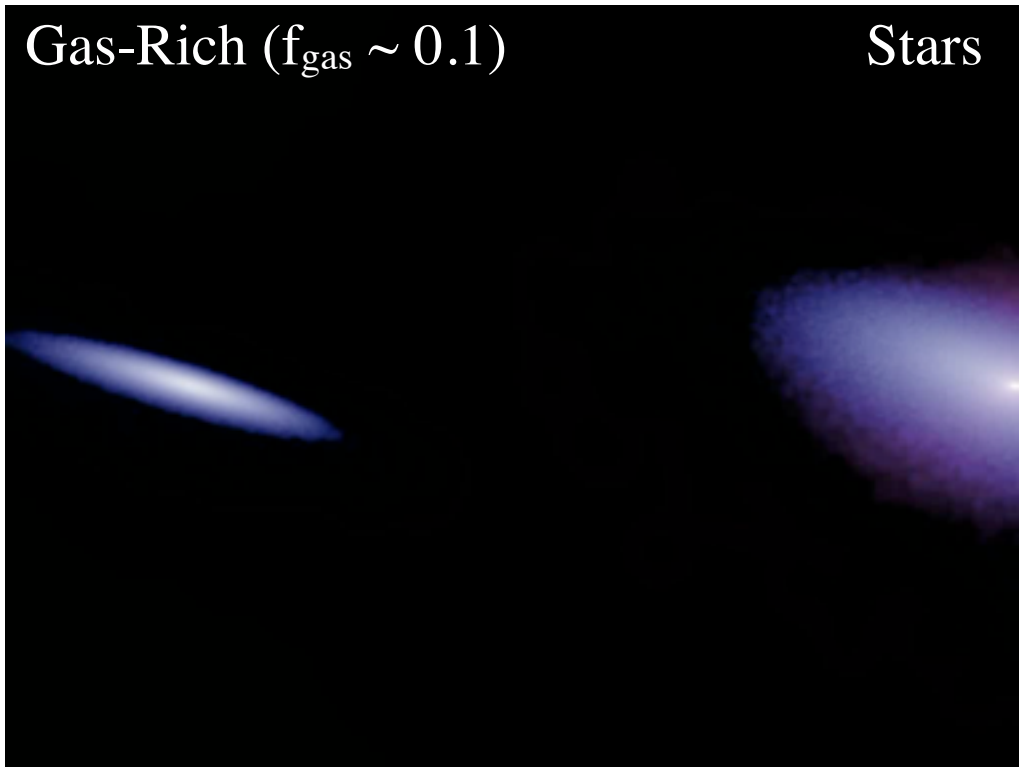


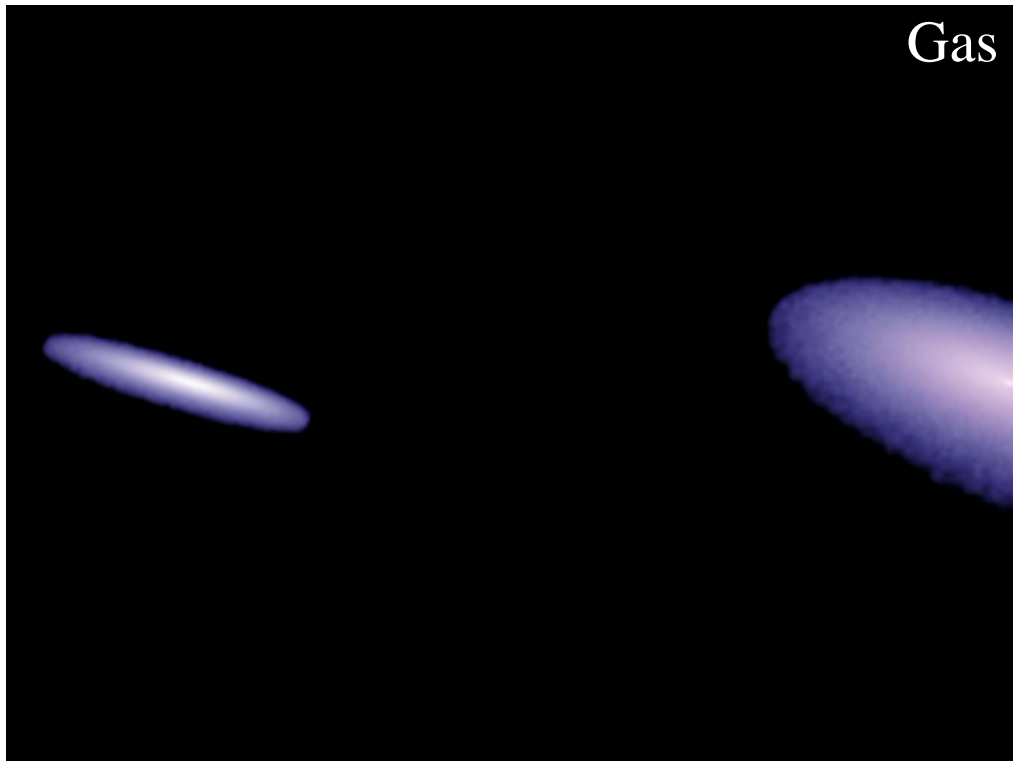
PFH, Bundy, Wuyts et al. 2010

But what about the highest gas fractions?

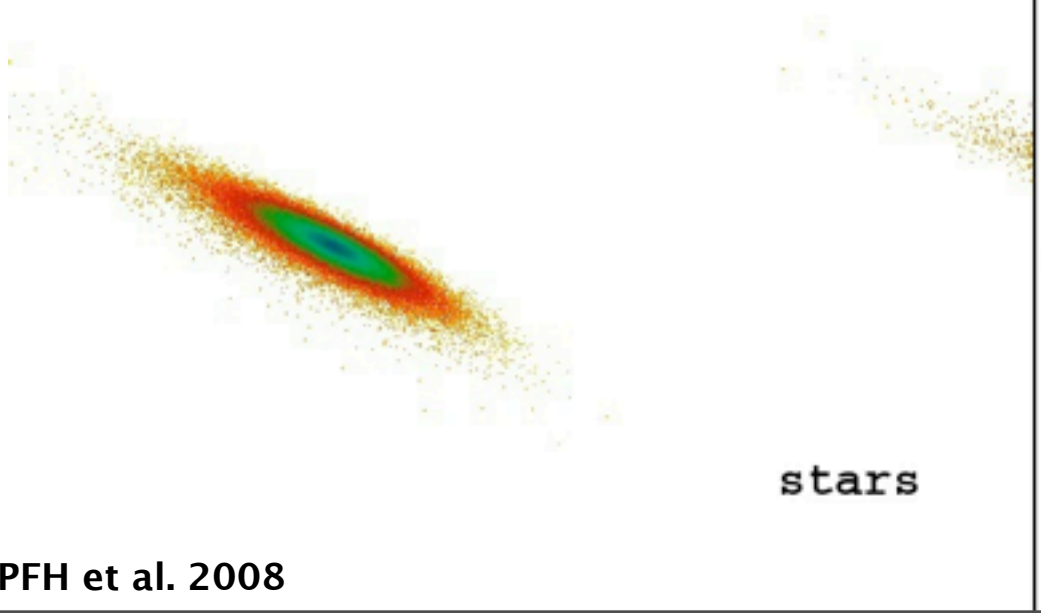
Should be ~25min

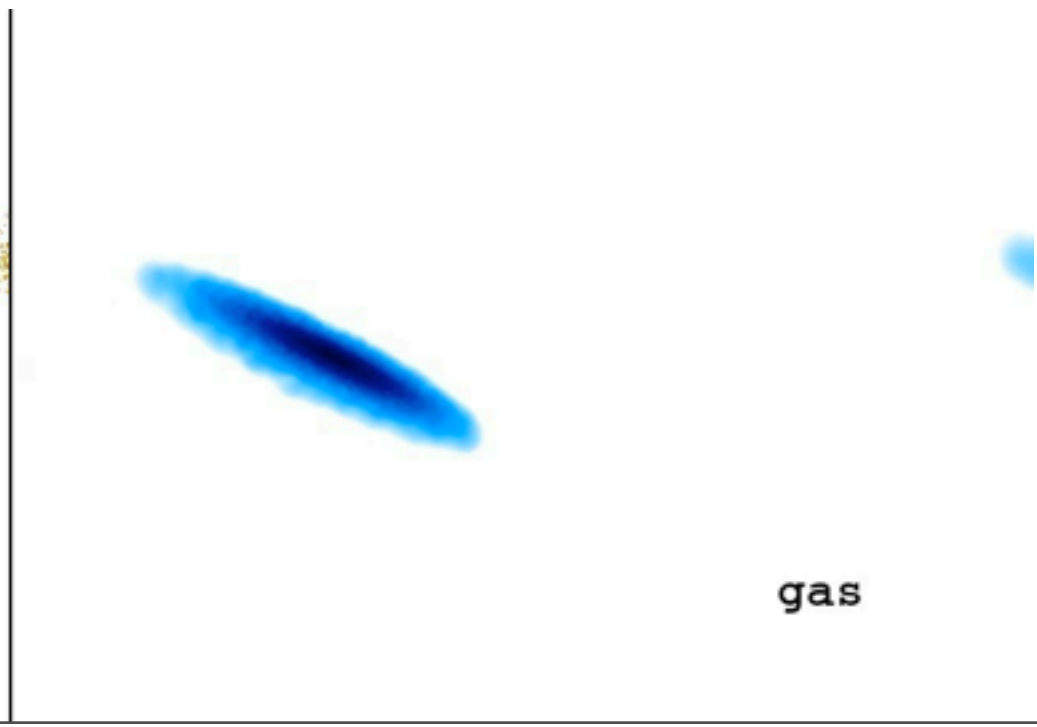
How Good Is Our Conventional Wisdom?





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

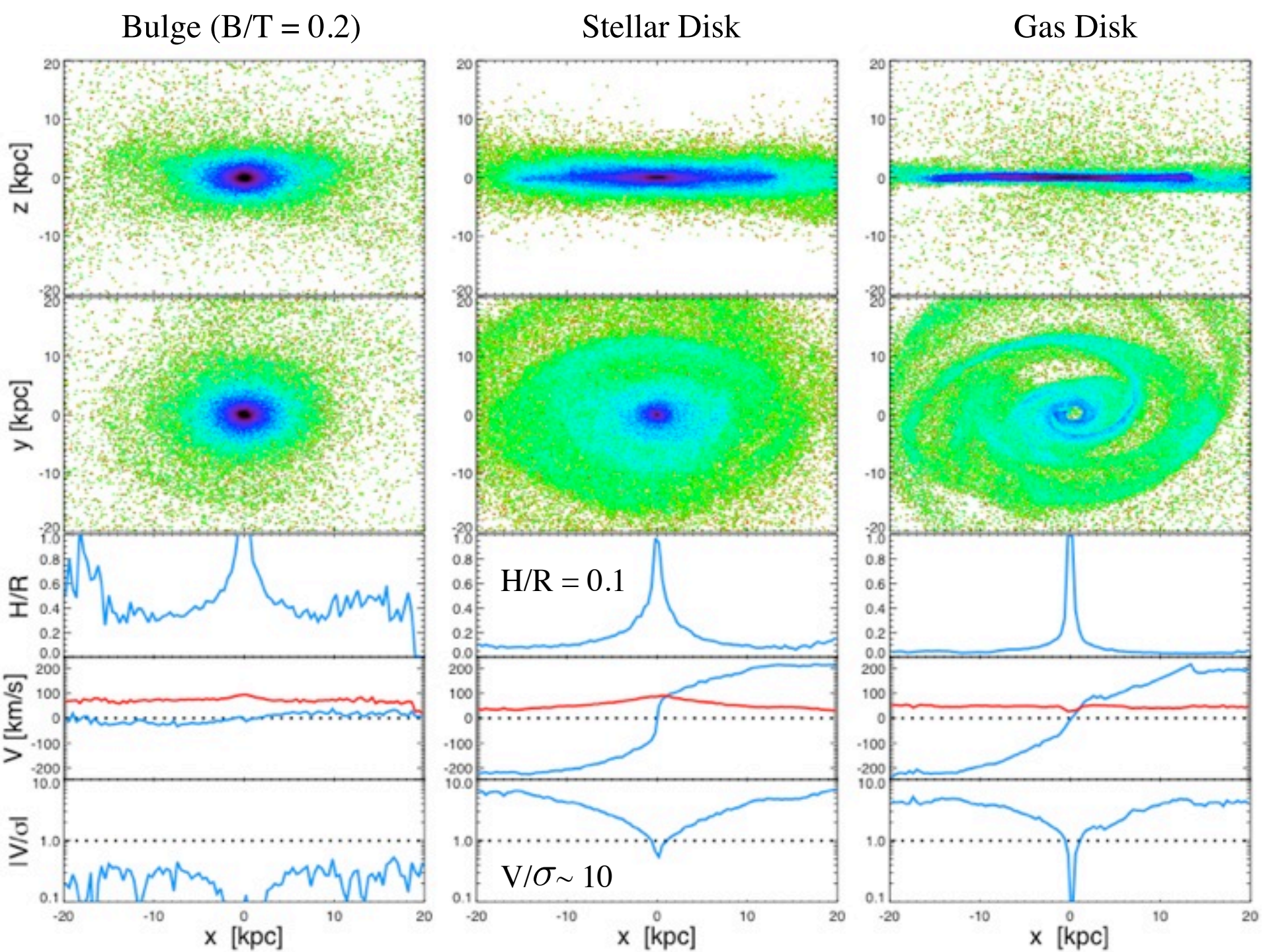




PFH et al. 2008

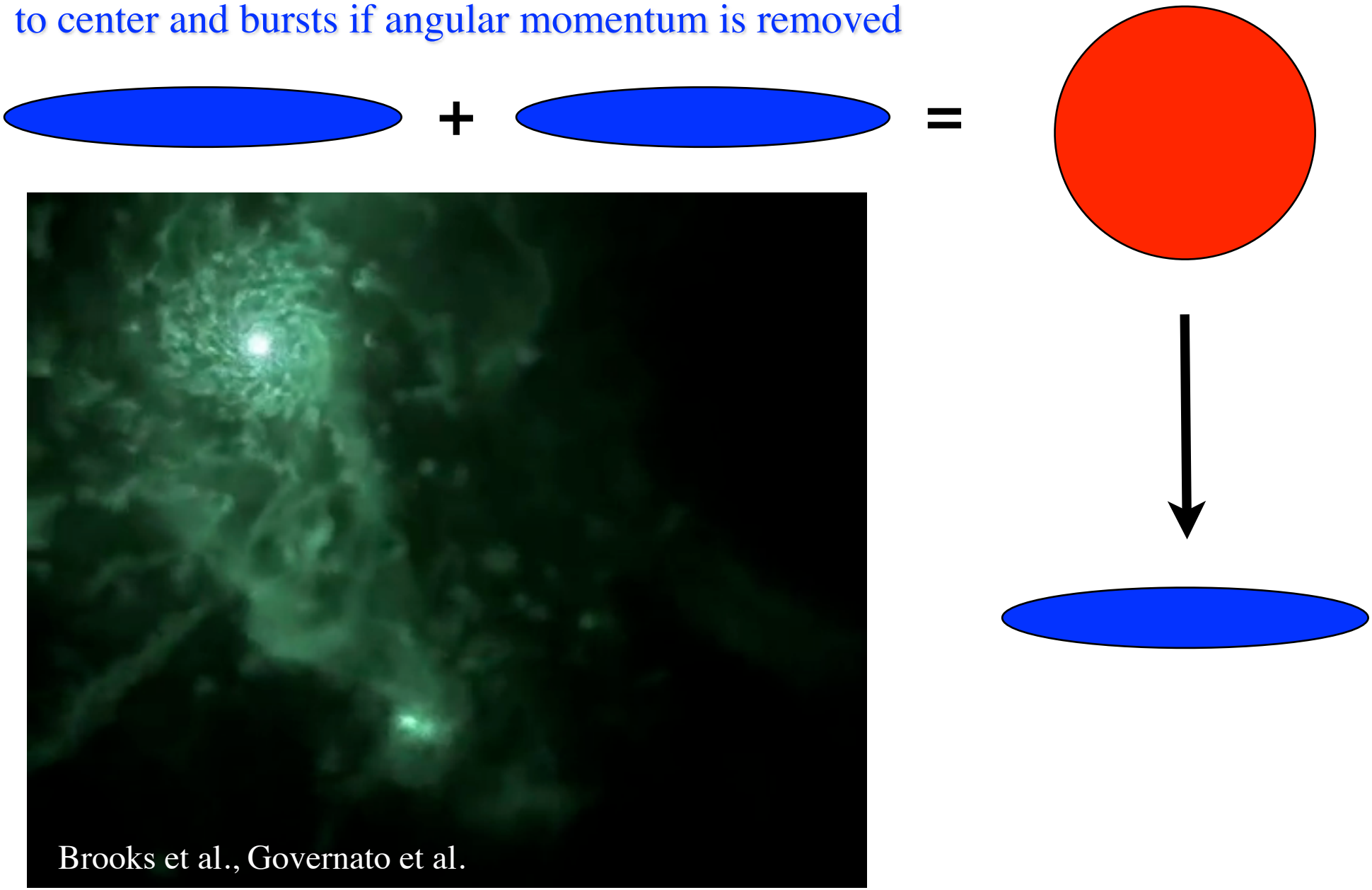
Major Merger Remnants

DO MERGERS DESTROY DISKS?



The Unsolved Questions
HOW CAN A DISK SURVIVE?

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

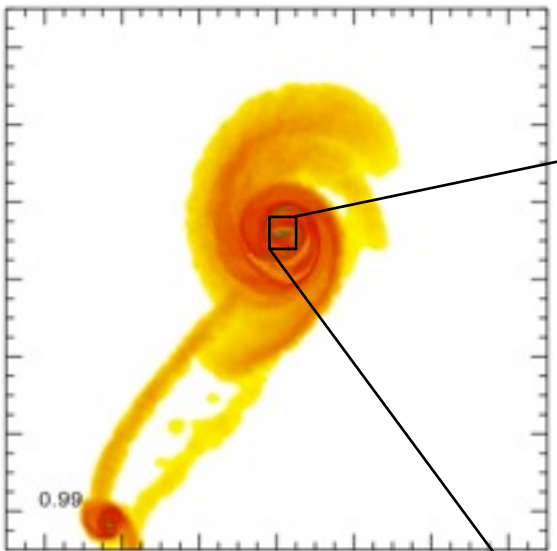


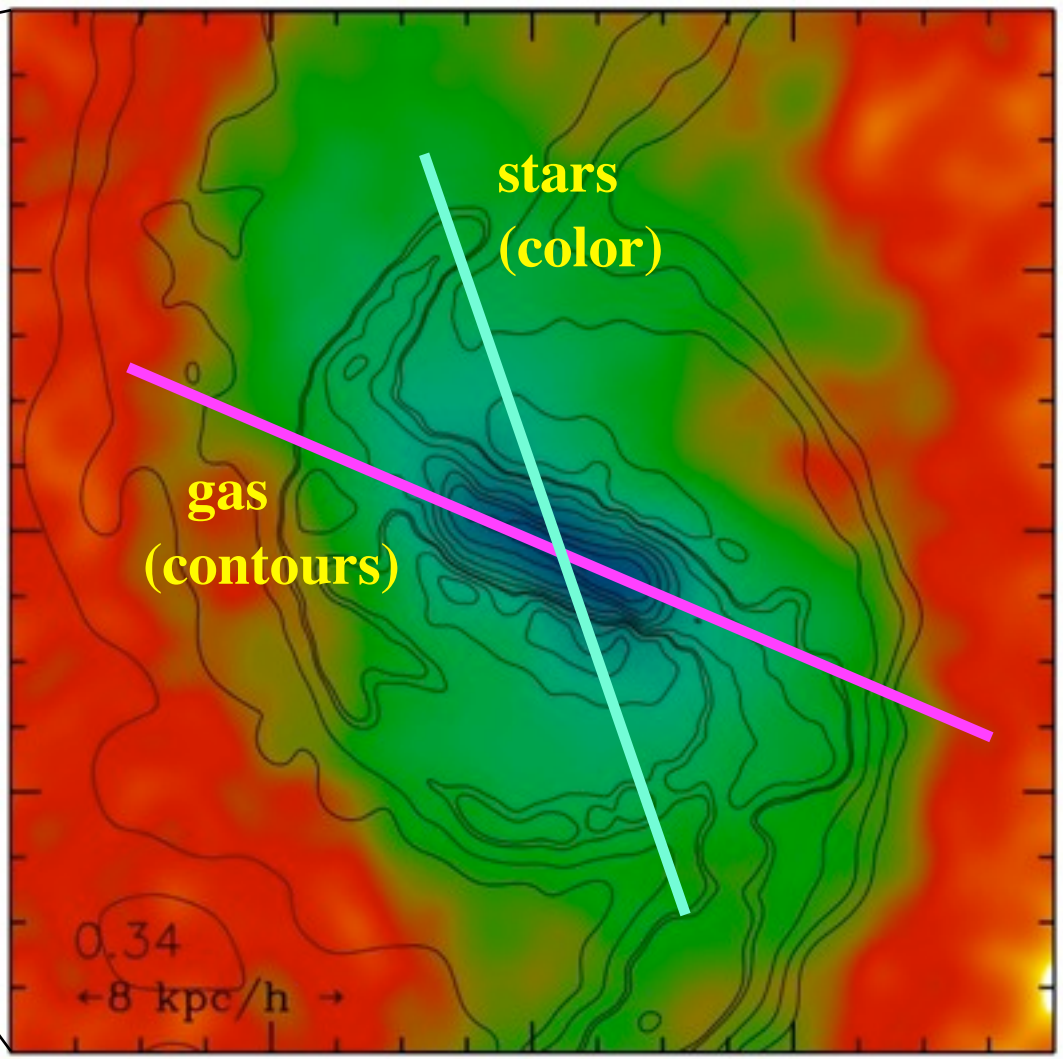
How Do Disks Survive Mergers?

PFH et al. 2008

companions -- bars -- gas/star offset -- torques -- gas inflow

(see, e.g., Barnes 92, PFH et al. 08, PFH & Quataert 2010)





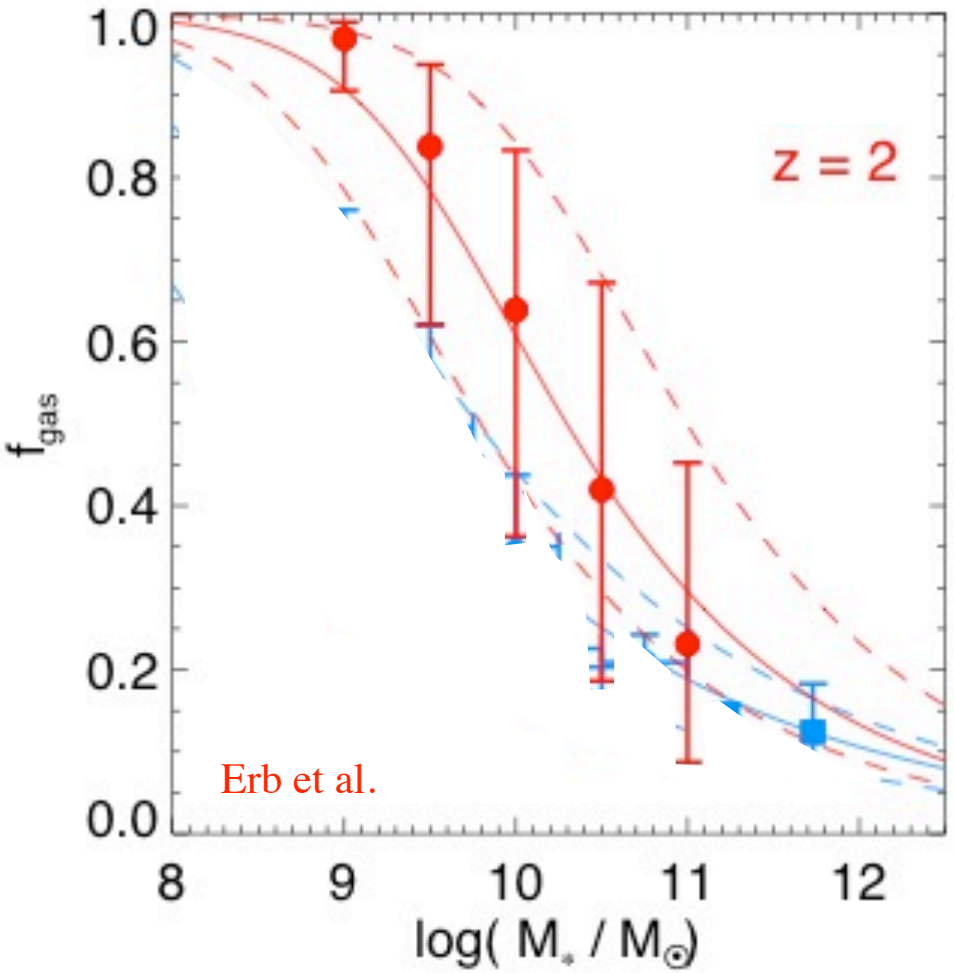
- What does the torquing?
  - Stars in the same galaxy

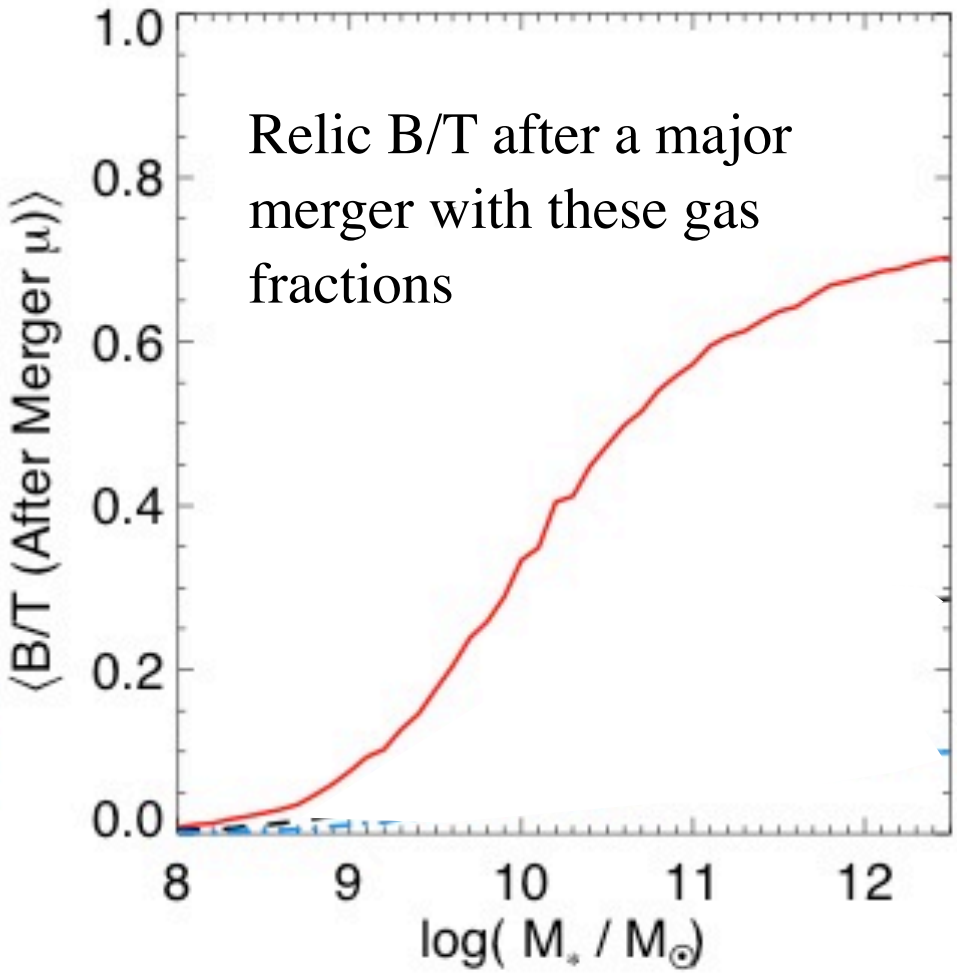
Why Do We Care?

HOW DISK SURVIVAL IN MERGERS IS IMPORTANT

PFH & Somerville et al. 200

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

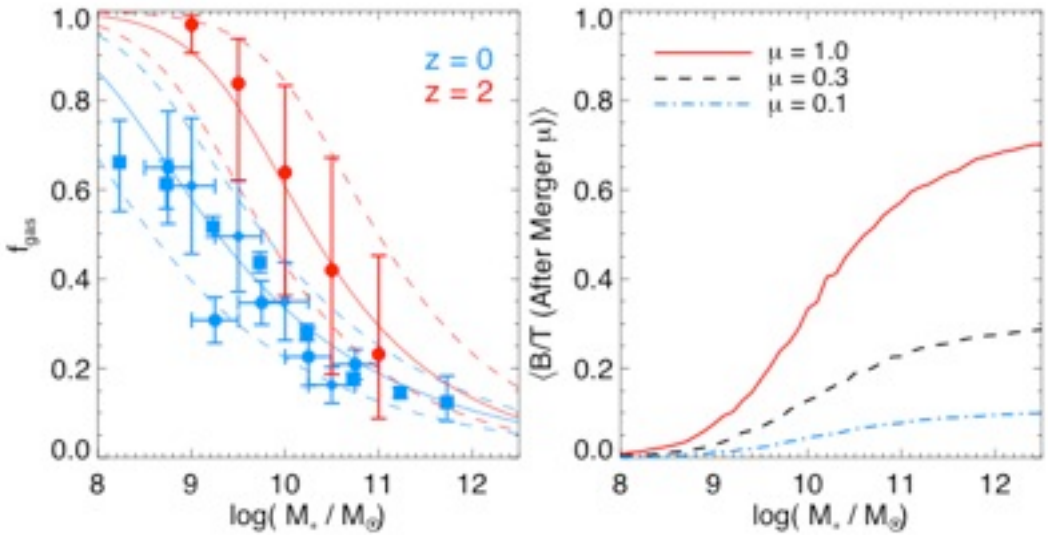




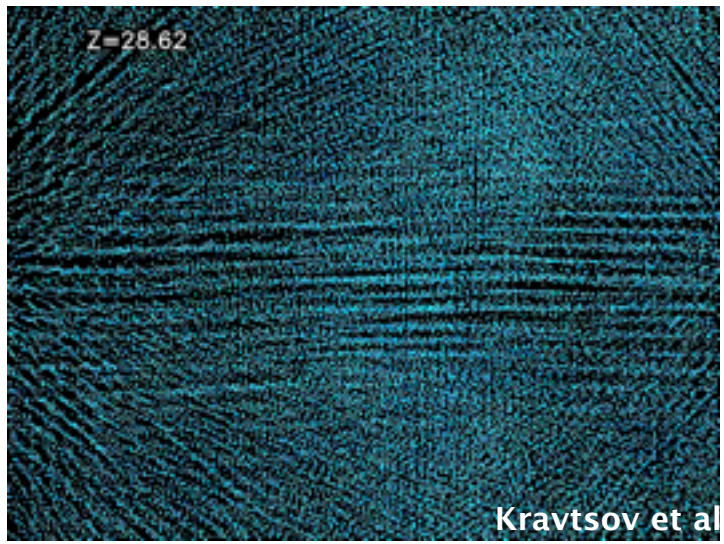
- Low-mass galaxies have high gas fractions: less B/T for the same mergers

Why Do We Care?

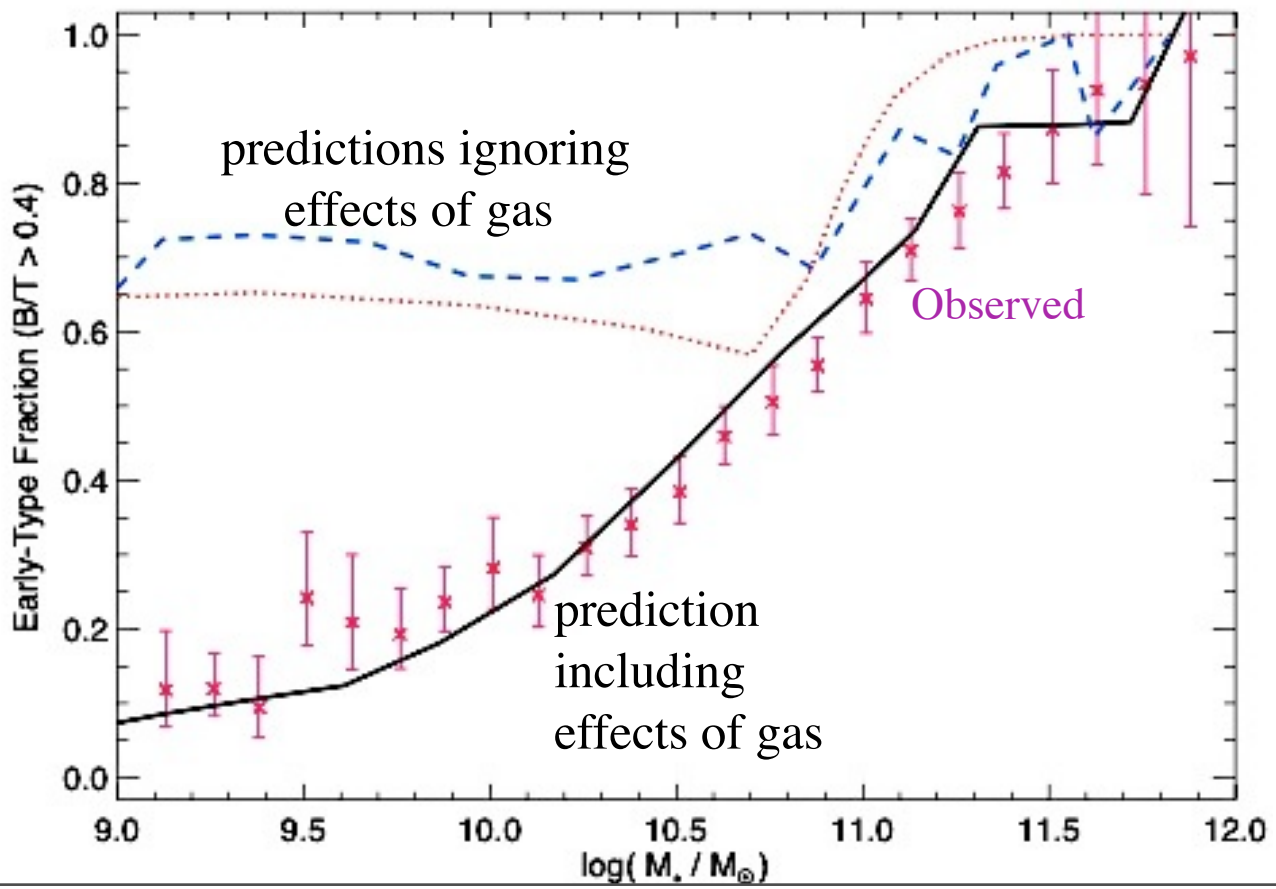
HOW DISK SURVIVAL IN MERGERS IS IMPORTANT



+



=



PFH & Somerville et al. 2009

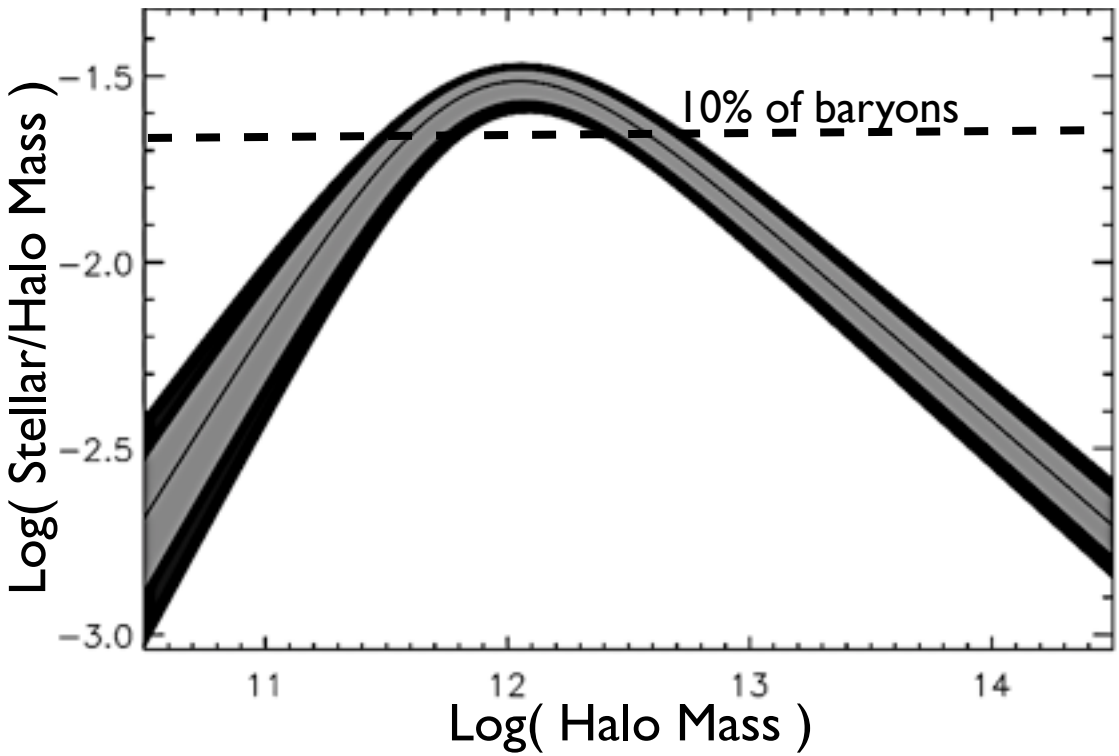
Where to from here?

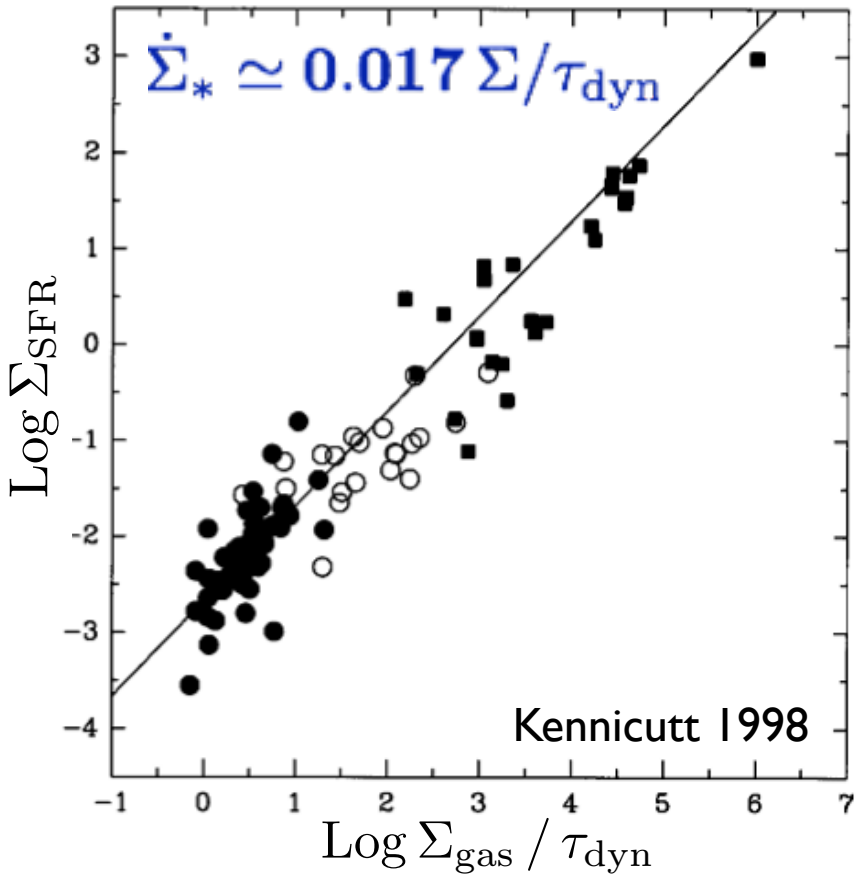
Should be ~32min

Where to from here?

- Why are galaxies gas rich? What does “feedback” do?

Should be ~32min





- Why is star formation so inefficient?

Should be ~32min

Stellar Feedback:
SO WHAT'S THE PROBLEM?

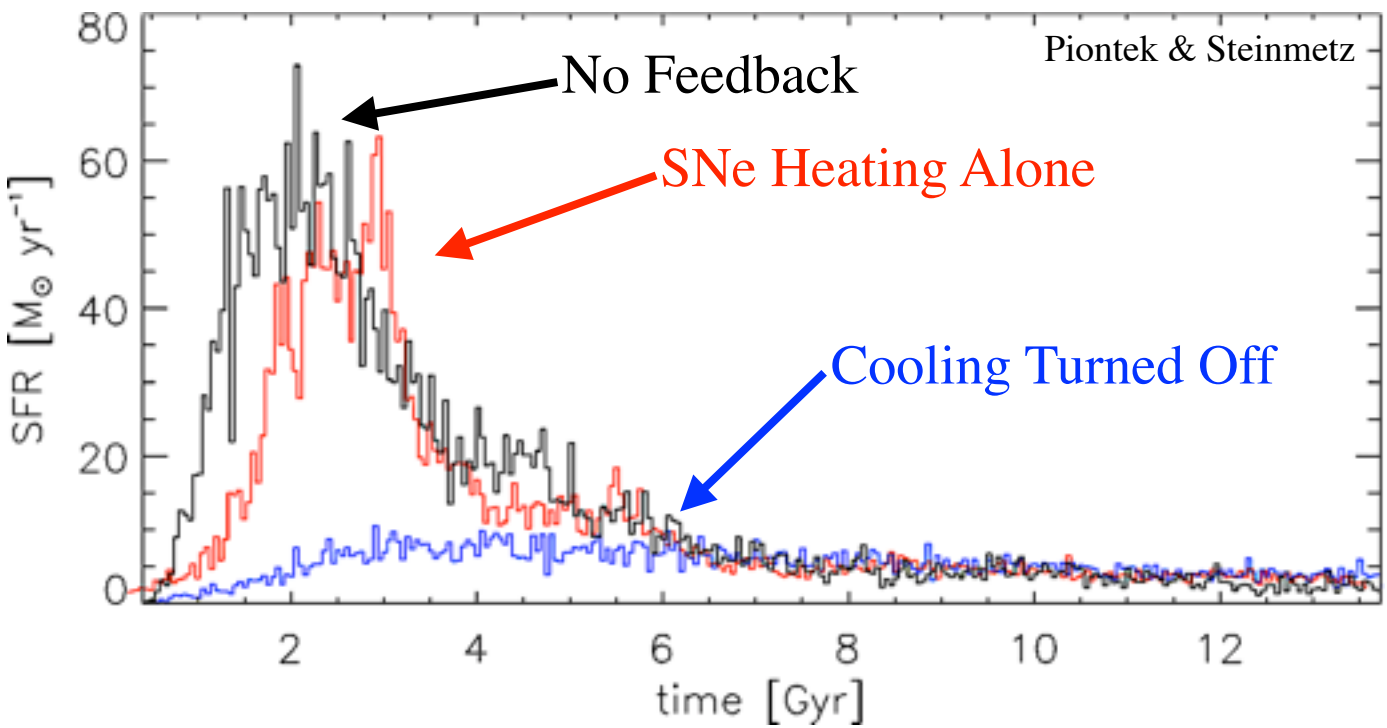
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- FAILS:

$$t_{\rm cool} \sim 4000\,{\rm yr}\left(\frac{n}{\rm cm^{-3}}\right)^{-1}$$

$$t_{\rm dyn} \sim 10^{8}\,{\rm yr}\left(\frac{n}{\rm cm^{-3}}\right)^{-1/2}$$

- "Cheat":
  - Turn off cooling
  - Force wind by hand
    ('kick' out of galaxy)



make really ~1 min

Stellar Feedback: How Can We Do Better?

Stellar Feedback: How Can We Do Better?

- High-resolution (~1pc), molecular cooling (<100 K), SF only at highest densities (n_H>1000 cm^{-3})

Stellar Feedback: How Can We Do Better?

- High-resolution (~1pc), molecular cooling (<100 K), SF only at highest densities (n_H>1000 cm^{-3})

- Heating (*with* cooling):
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)

Stellar Feedback: How Can We Do Better?

- High-resolution (~1pc), molecular cooling (<100 K), SF only at highest densities (n_H>1000 cm^{-3})

- Heating (*with* cooling):
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)

- *Explicit* Momentum Flux:
  - Radiation Pressure

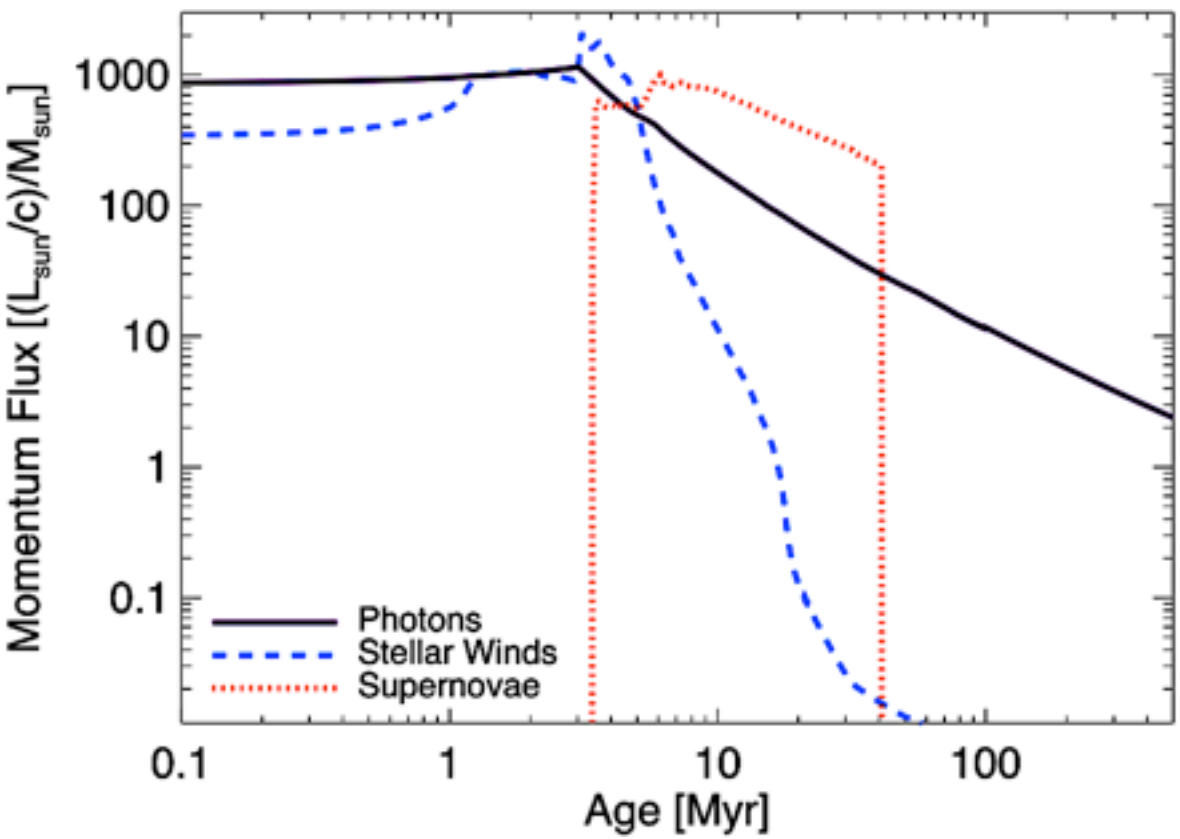
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\left(1+\tau_{\rm IR}\right)$$

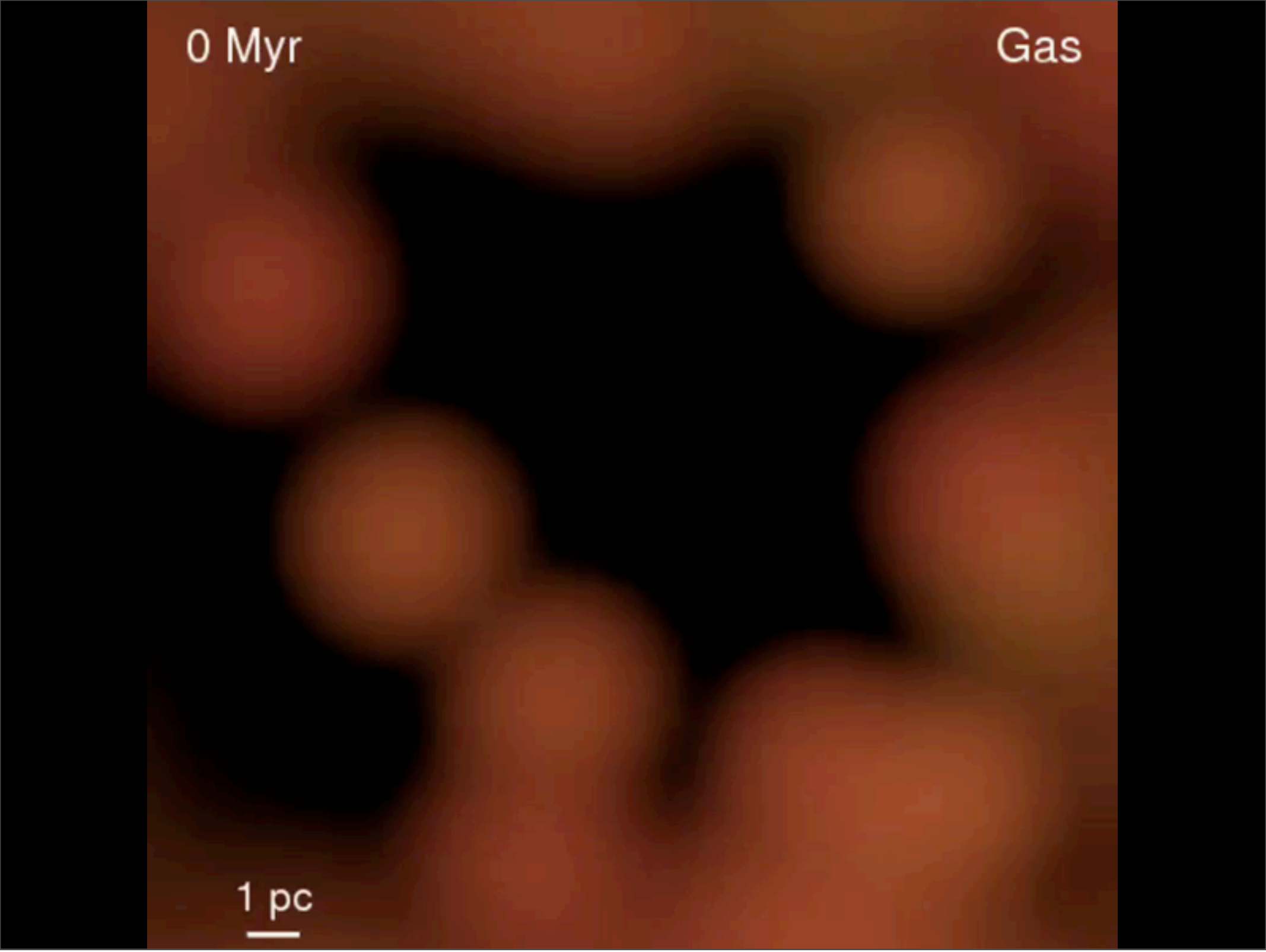
  - SNe

$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

  - Stellar Winds

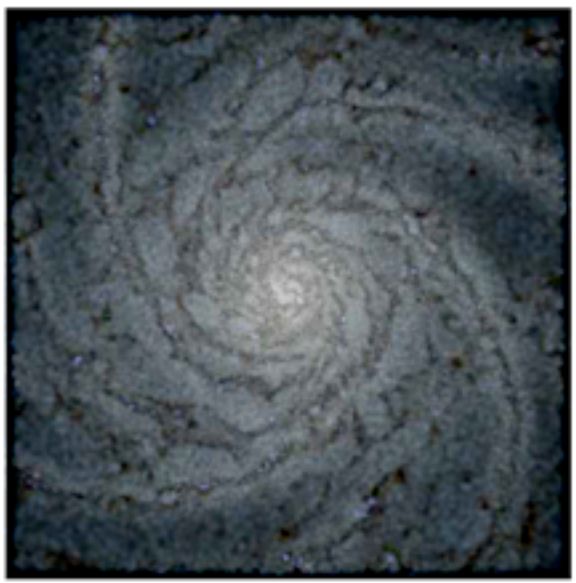
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

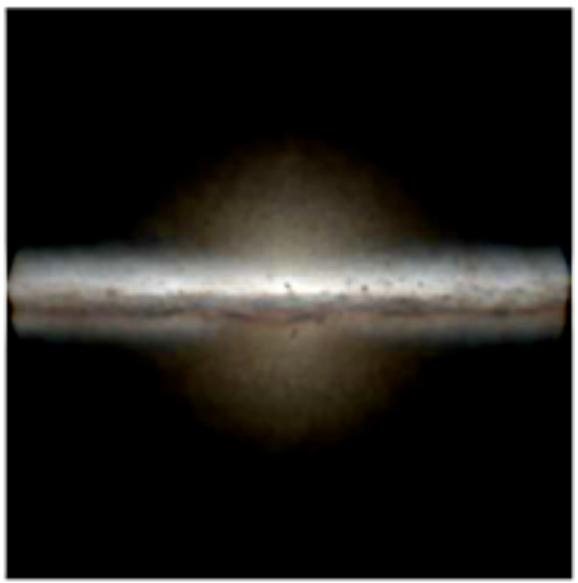



0 Myr
Gas
1 pc

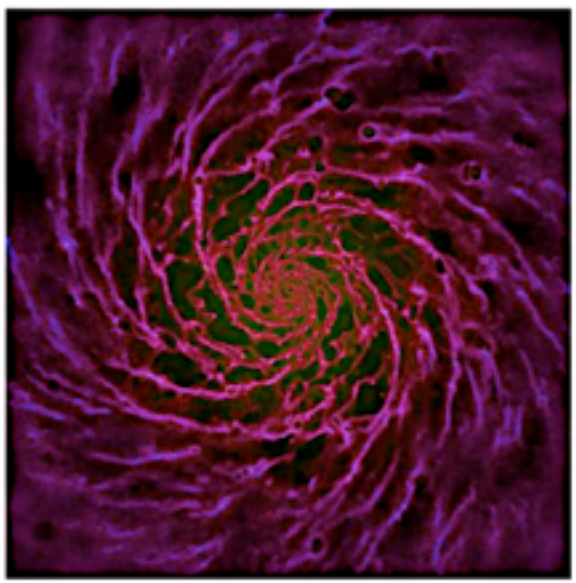
Spiral Galaxy M101 Spitzer Space Telescope • Hubble Spac

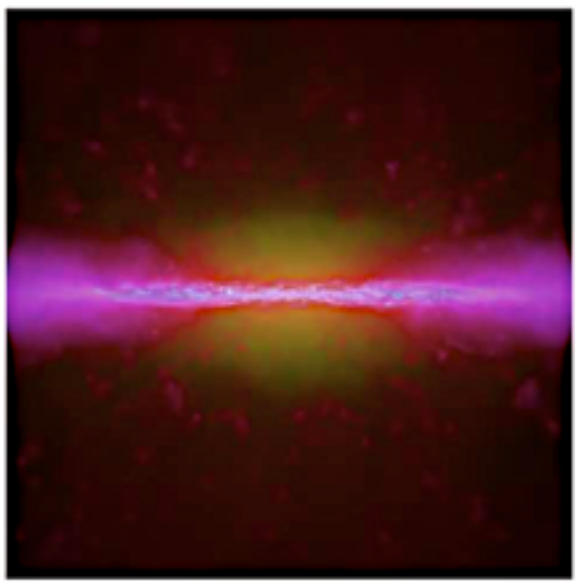
NASA / JPL-Caltech / ESA / CXC / STScI



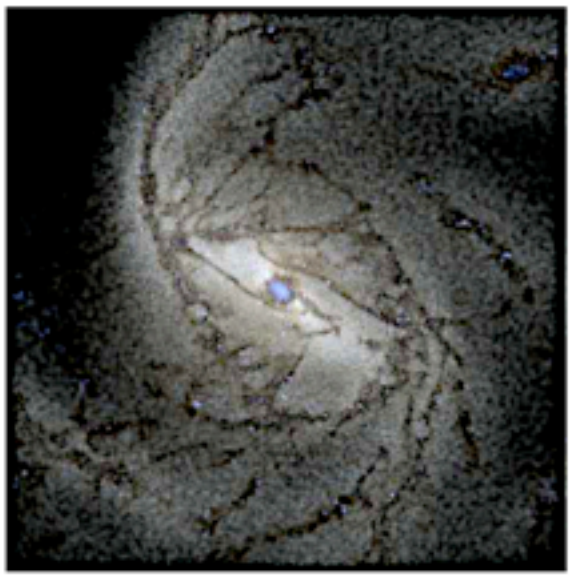


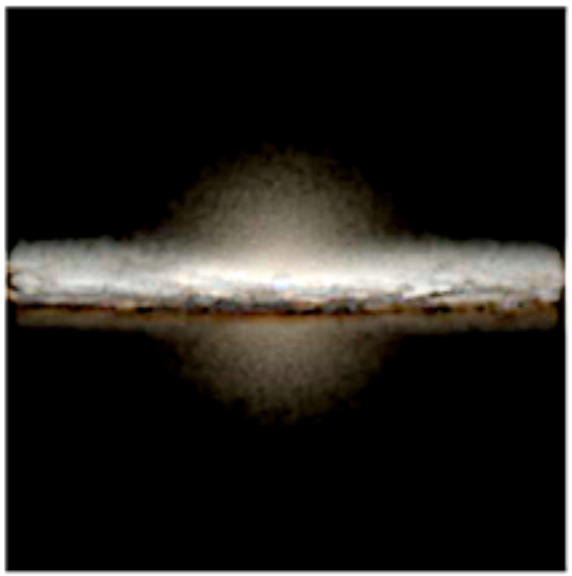
~30 sec

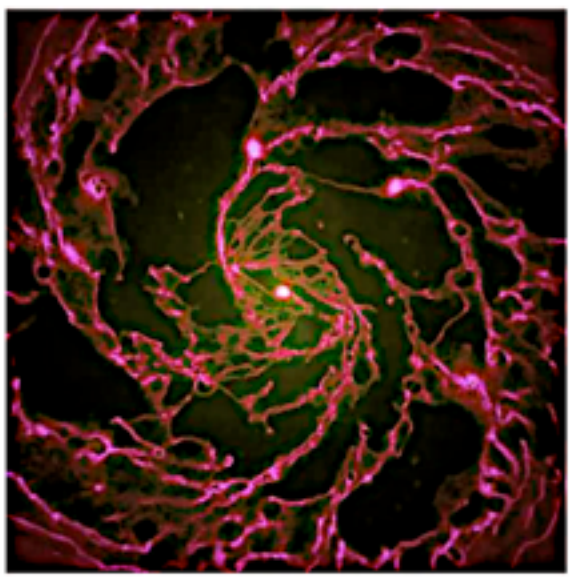


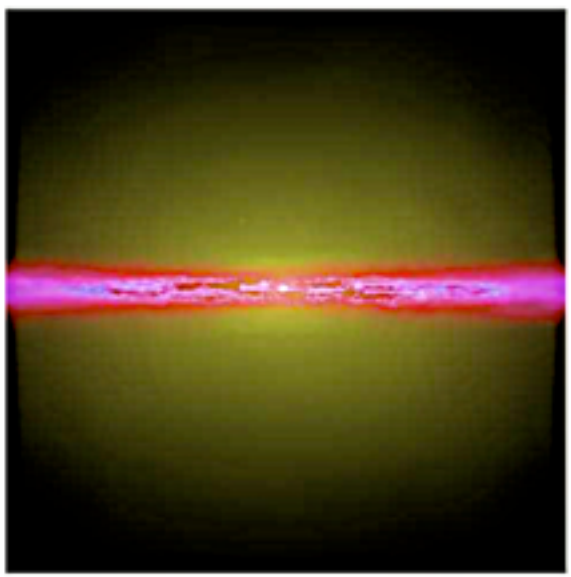


Hopkins, Quataert, & Murray, in prep



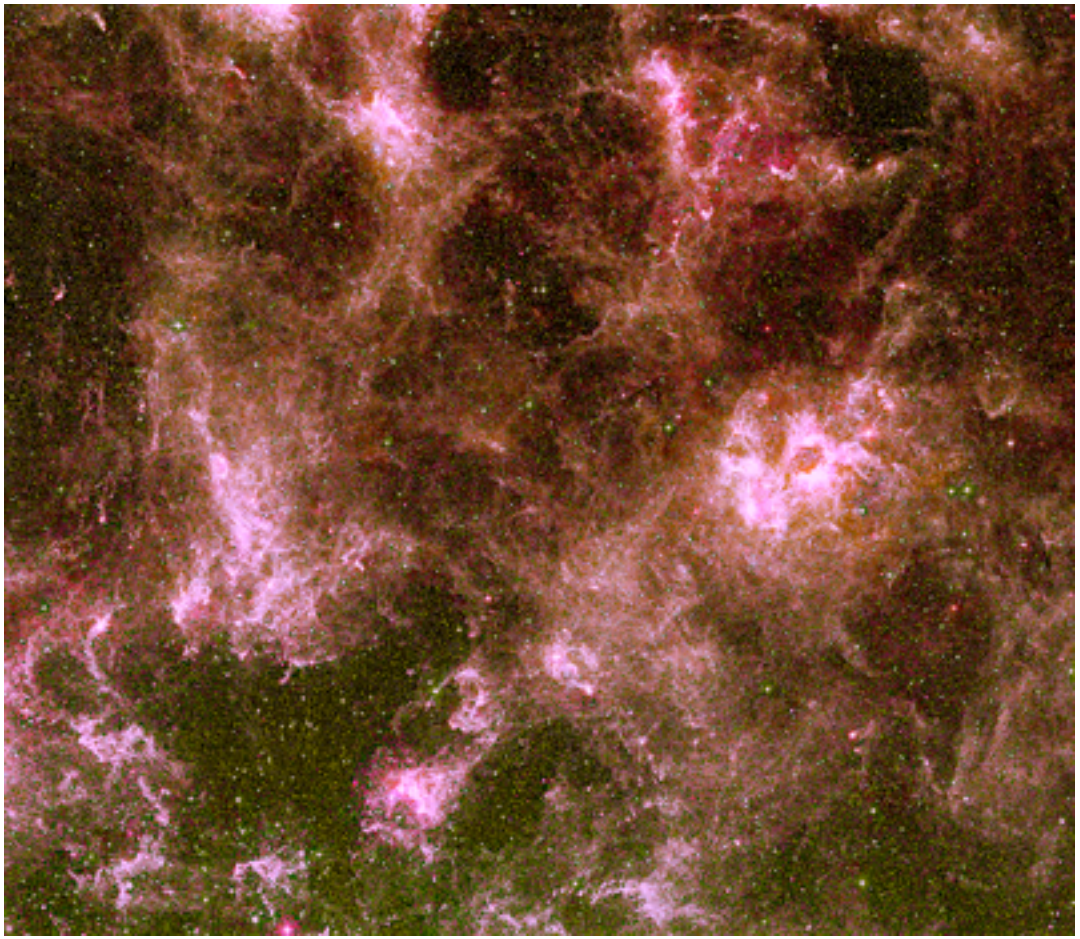


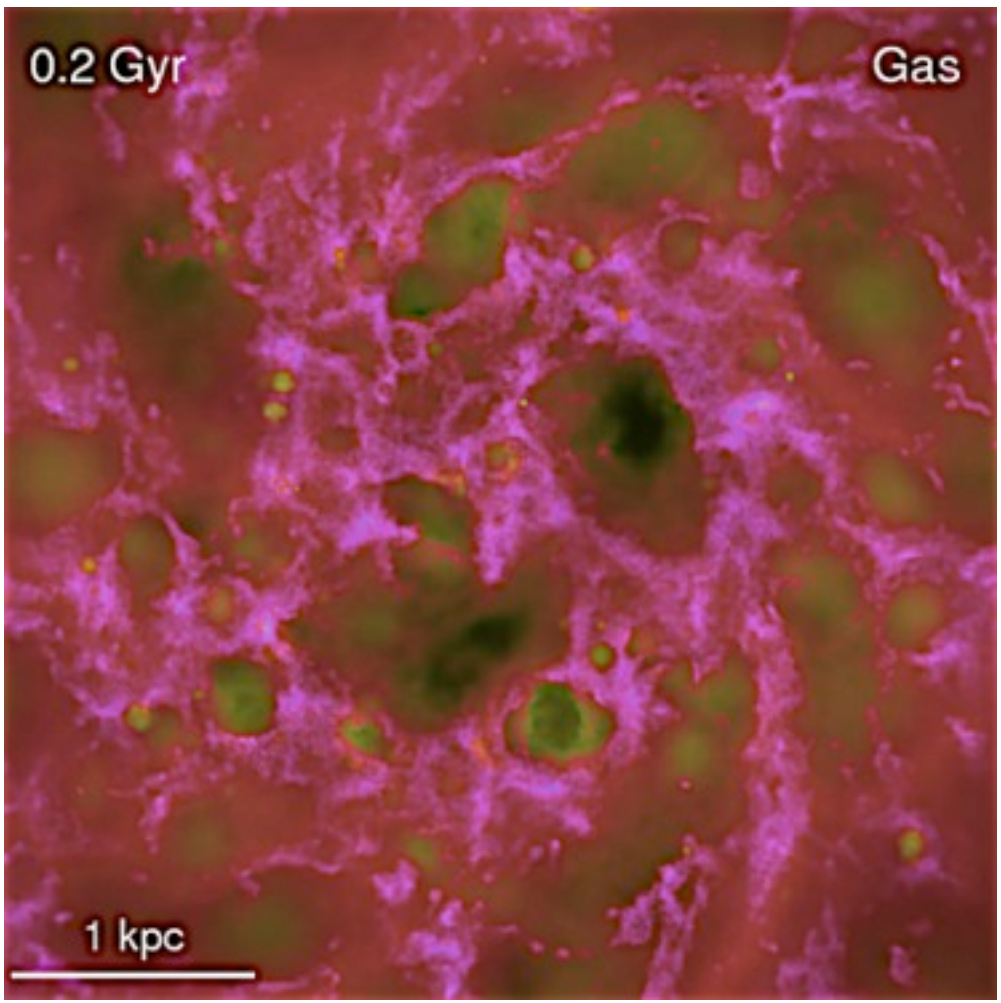




~30 sec

Hopkins, Quataert, & Murray, in prep



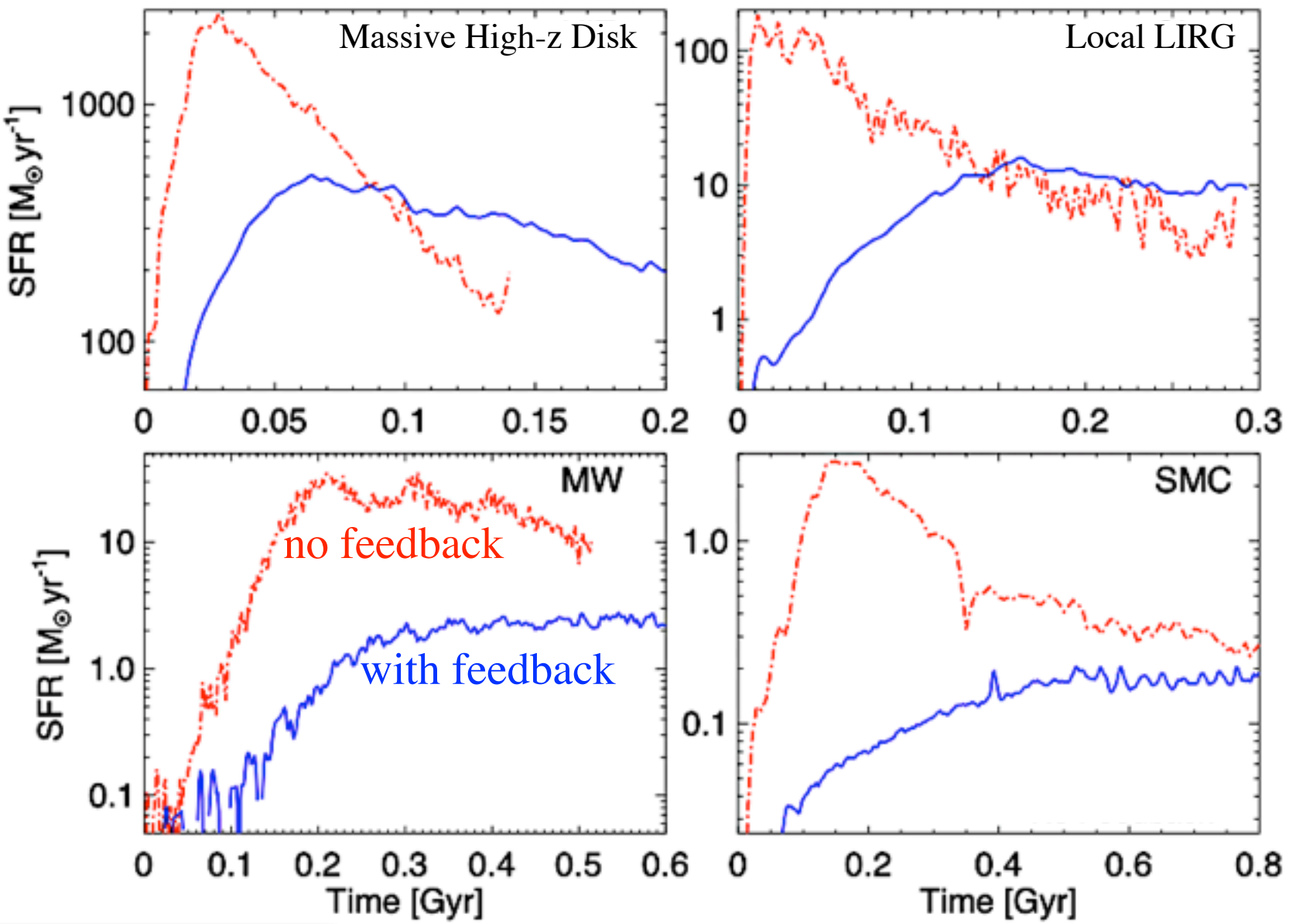


~30 sec

Hopkins, Quataert, & Murray, in prep

Stellar Feedback gives Self-Regulated Star Formation

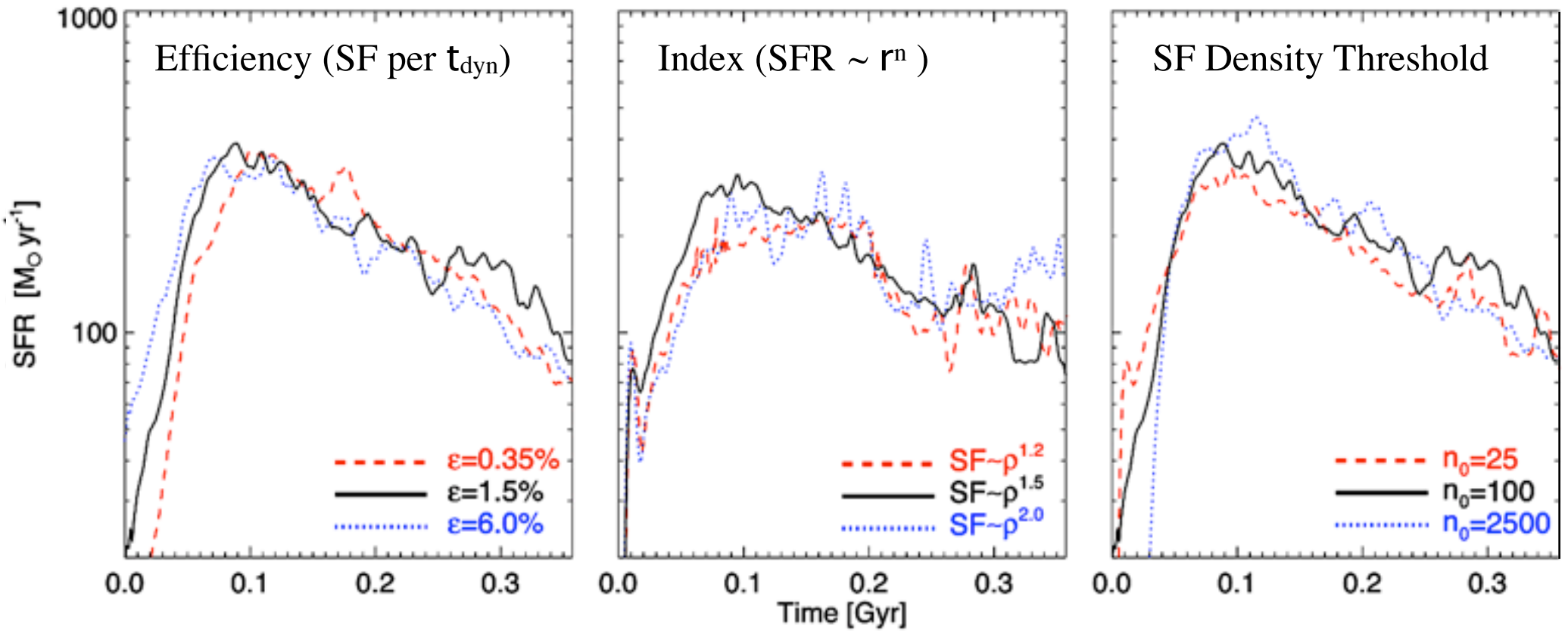
MOMENTUM INJECTION EXPLAINS KENNICUTT, *WITHOUT* TURNING OFF COOLING



~1 MINUTE!

Hopkins & Quataert, in prep

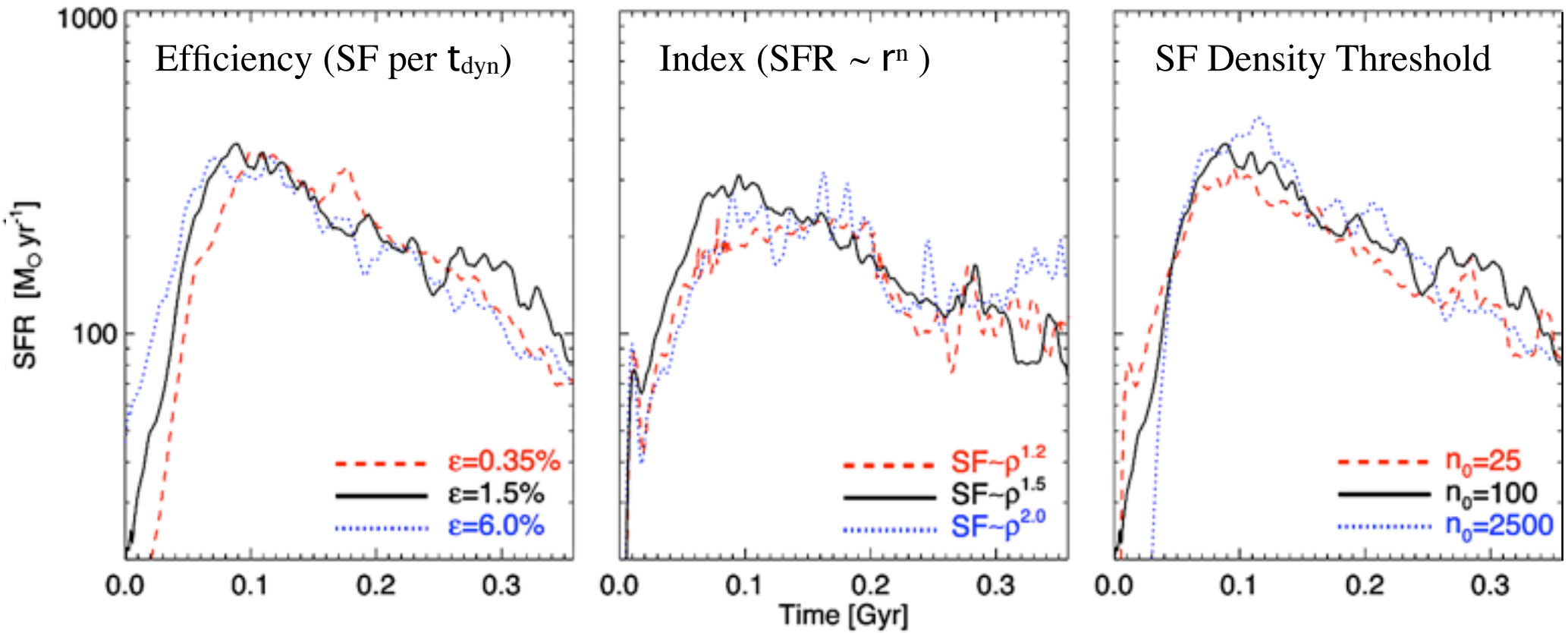
Schmidt-Kennicutt Law Emerges *INDEPENDENT* of High-Density SF Law



~1 MINUTE!

Hopkins & Quataert, in prep

Schmidt-Kennicutt Law Emerges *INDEPENDENT* of High-Density SF Law

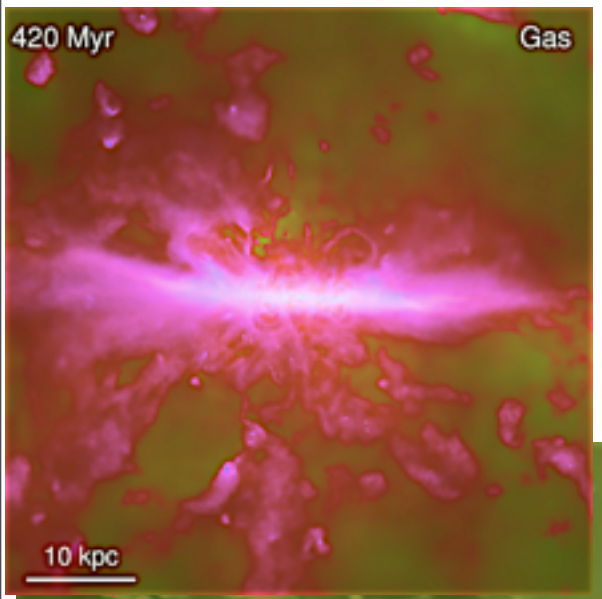


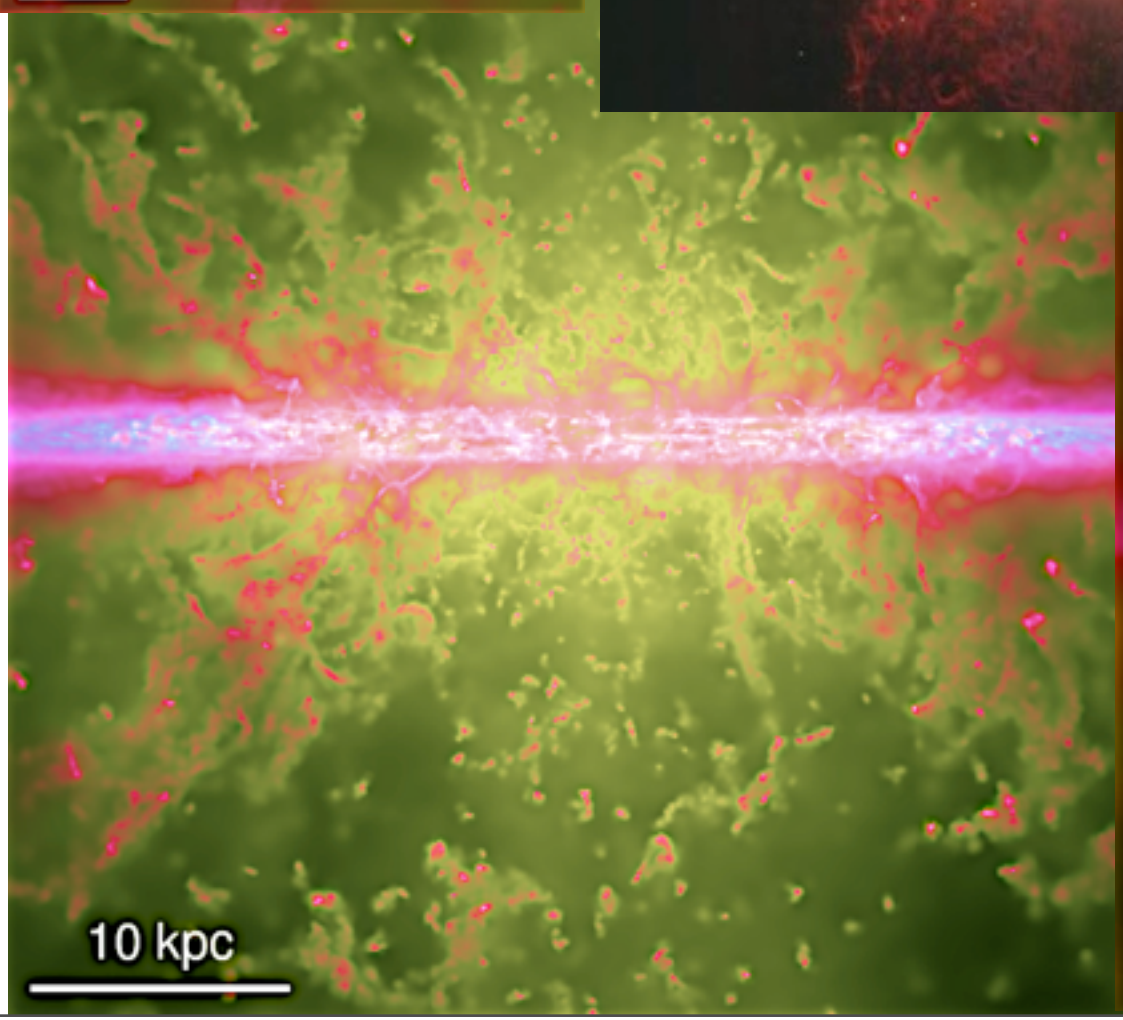
- Set by feedback (i.e. SFR) needed to maintain marginal stability

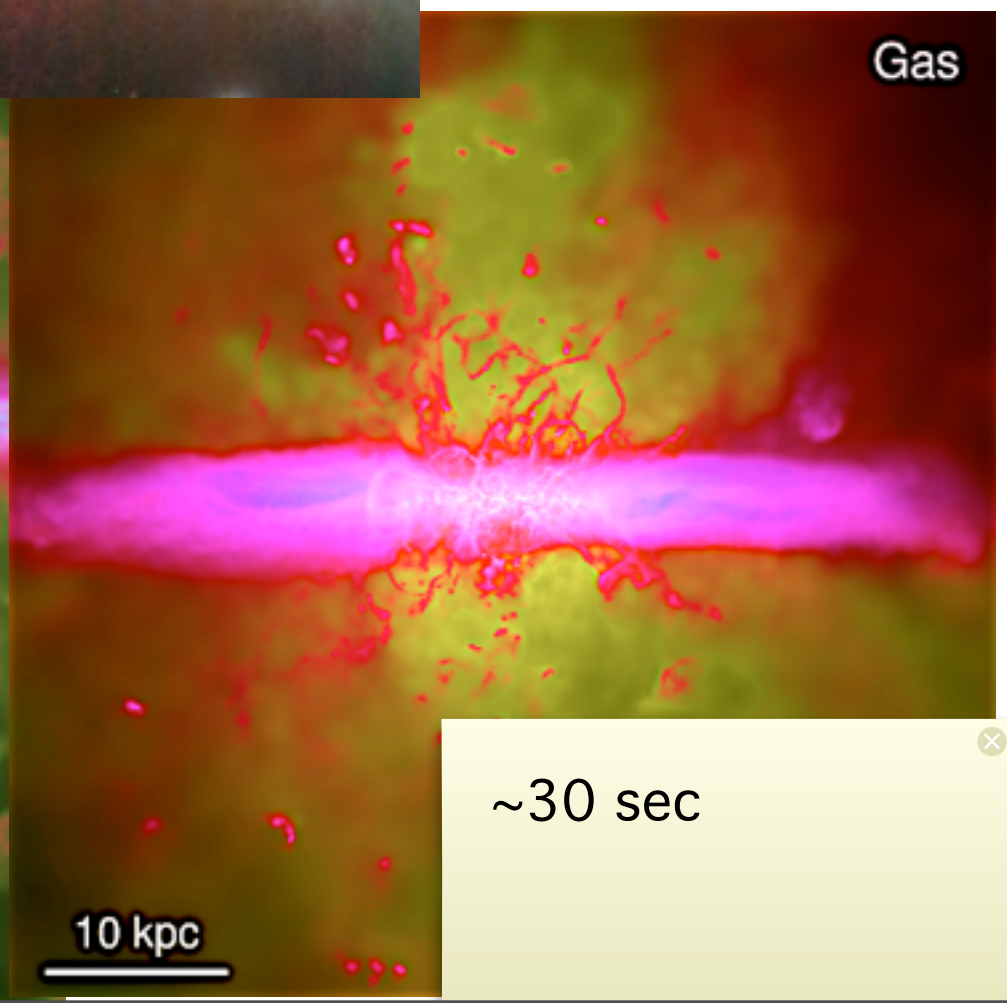
~1 MINUTE!

Hopkins & Quataert, in prep

Galactic Super-Winds





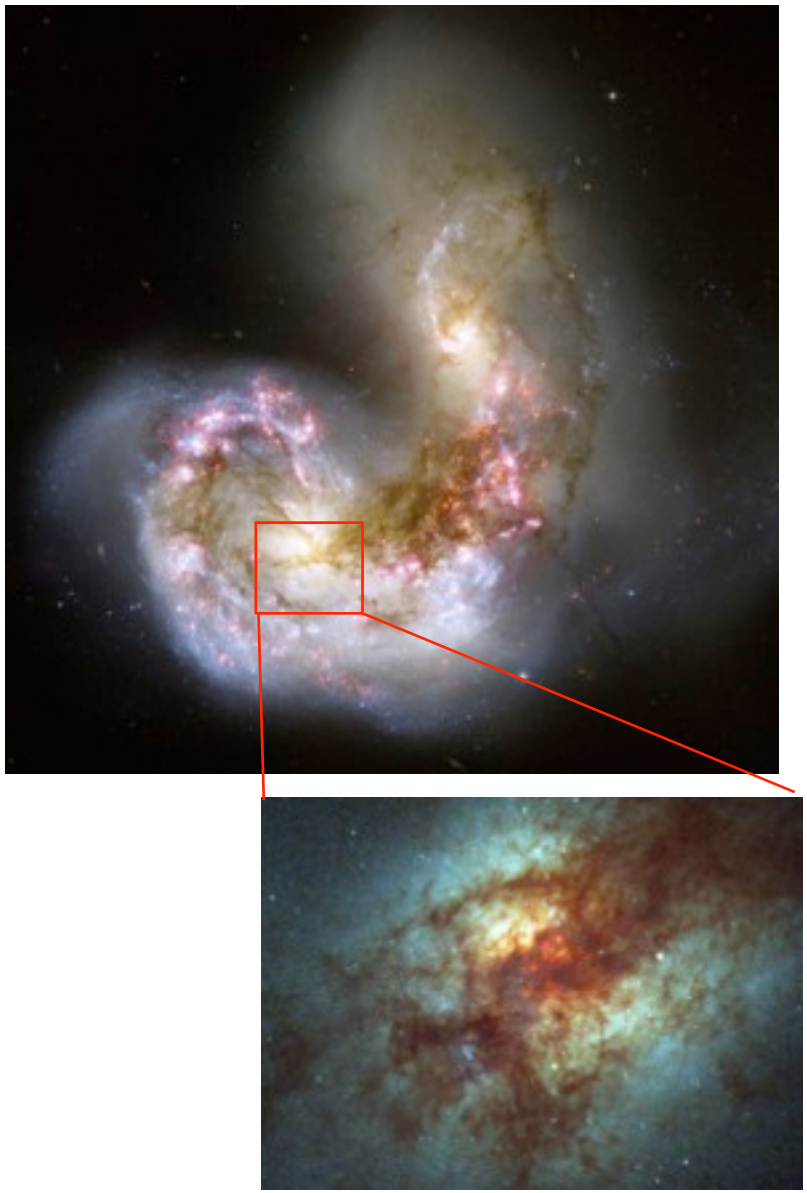


~30 sec

Future Directions

WHAT CAN WE EXPLORE WITH MORE REALISTIC ISM/FEEDBACK MODELS?

- Mergers:
  - Star cluster formation? Starburst environments?
- AGN Feedback:
  - How does it couple to a multi-phase ISM?
- Cosmological simulations:
  - "Zoom-in" disk formation simulations (D. Keres)
  - Cosmological volume AMR: dwarf populations and mass function evolution (M. Kuhlen)
- GMCs & ISM Structure:
  - Formation & destruction of GMCs, lifetimes, star formation efficiencies



~30 sec

Summary:

Gas dissipation & star formation are critical to understanding galaxy formation

- Why are ellipticals smaller than spirals?
  - Gas "needed" just follows *observed* disk gas content
    - Explains sizes, unique profile shapes ("cusps"), and scaling laws
  - Gas fractions higher at z~2 : evolution in sizes & scalings
    - Look just like the "cores" of the most massive galaxies today
    - "Inside-out" growth with accreted "fluffy" wings

- Relics of starbursts are important in today's Universe
  - Signatures allow "archeology" on local, old galaxies
  - Match populations of IR-luminous starbursts now seen at high redshift
    - But, tells us most star formation was not in bursts!

- How do disks survive mergers? (How do we avoid making all ellipticals?)
  - Gas! No stars = No angular momentum loss
    - Particularly important at high-z: unique kinematic s

- Next generation of models: stellar feedback & GMC for
  - AGN? (a talk for another day...)

took ~14 minutes on previous ~9 slides to get here. condense the verbiage. ok reduced to ~13, but still too much!