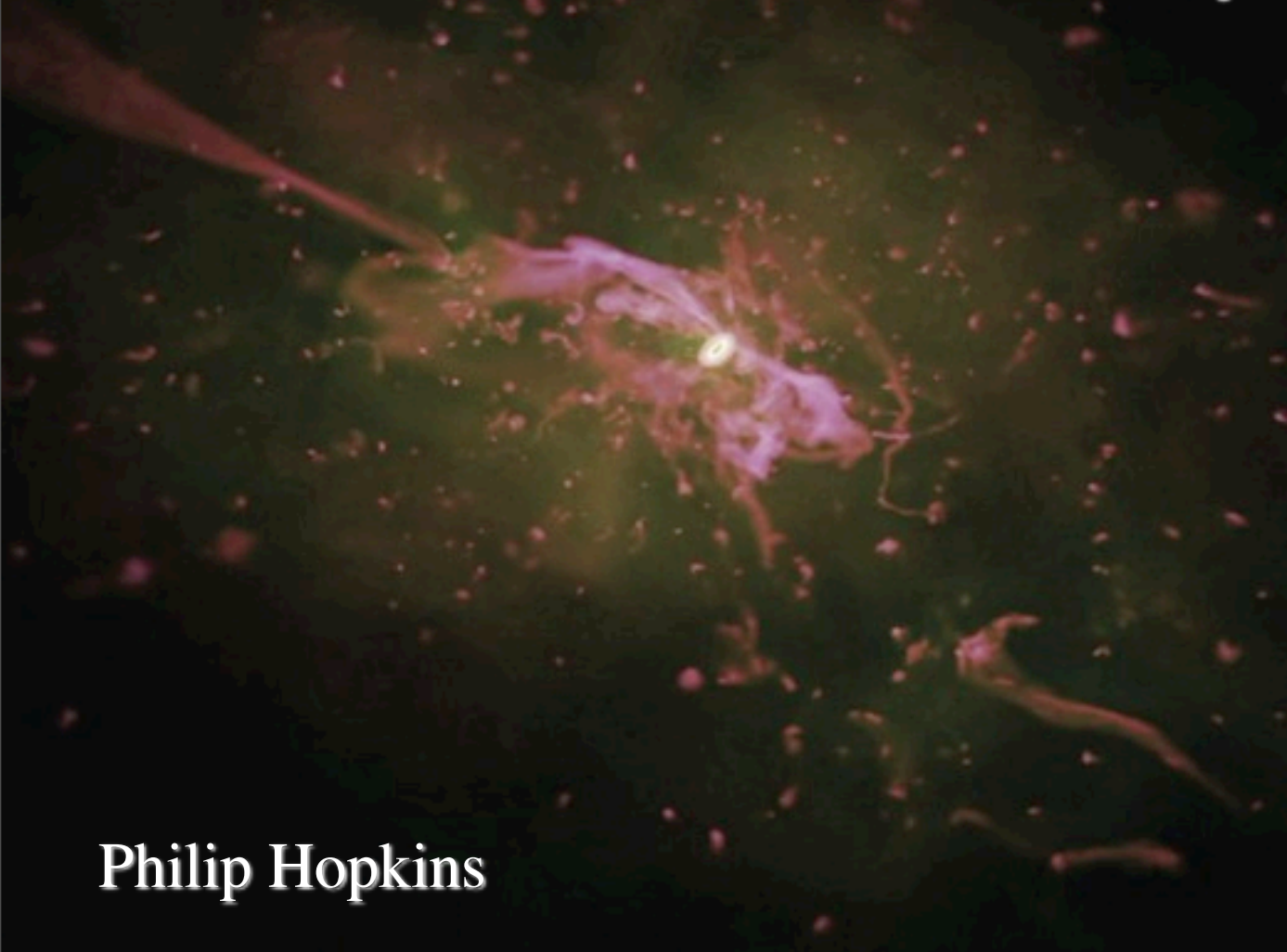


Star Formation, Black Holes, and Feedback in Galaxy Formation



Philip Hopkins



Eliot Quataert, Norm Murray,
Lars Hernquist, Dusan Keres, Todd Thompson, Desika Narayanan,
Dan Kasen, T. J. Cox, Chris Hayward, Kevin Bundy, & more

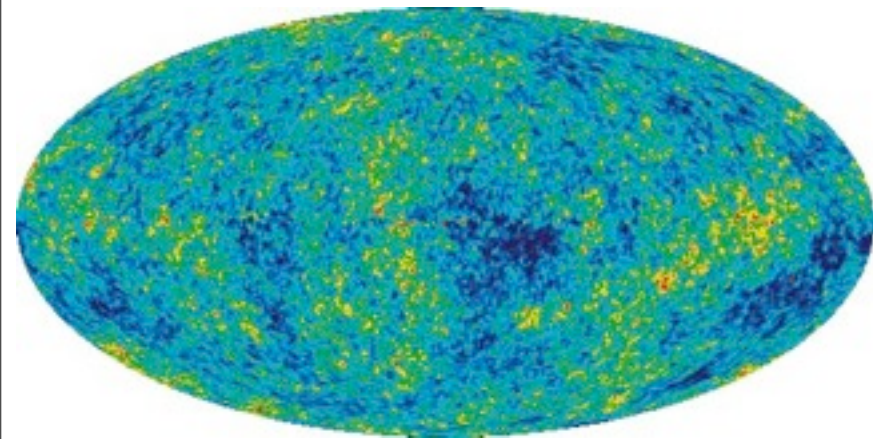
Overview

- **(1) (Some) Open Problems**
- **(2) Stellar “Feedback” Processes:**
 - **Isolated Galaxies: Feedback Physics & the ISM**
 - **Interacting/Merging Galaxies**
 - **Cosmological Implications**
- **(3) Super-Massive Black Holes & Accretion?**

Motivation

THE BIG PICTURE

Today



$z \sim 1090$
($t \sim 400,000$ yr)

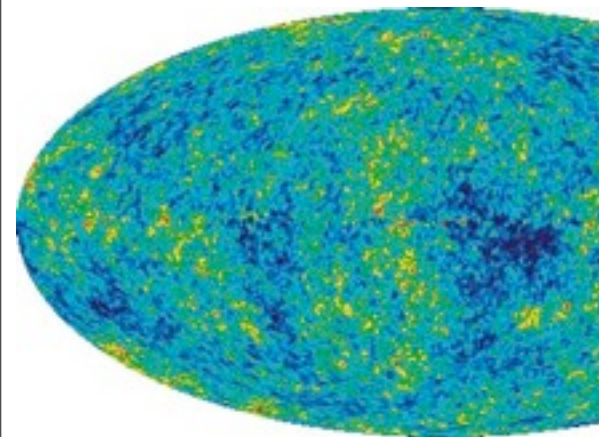
?



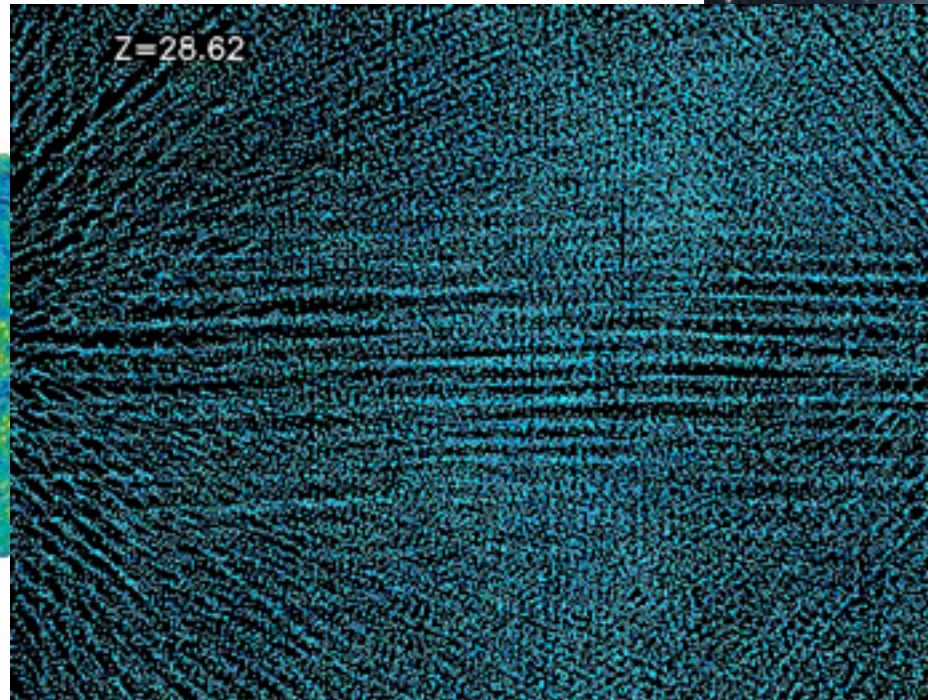
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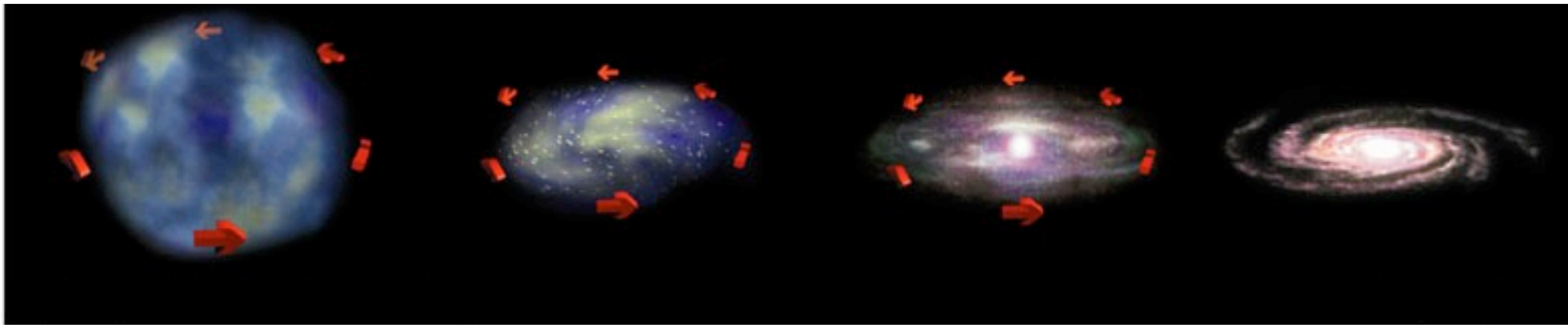
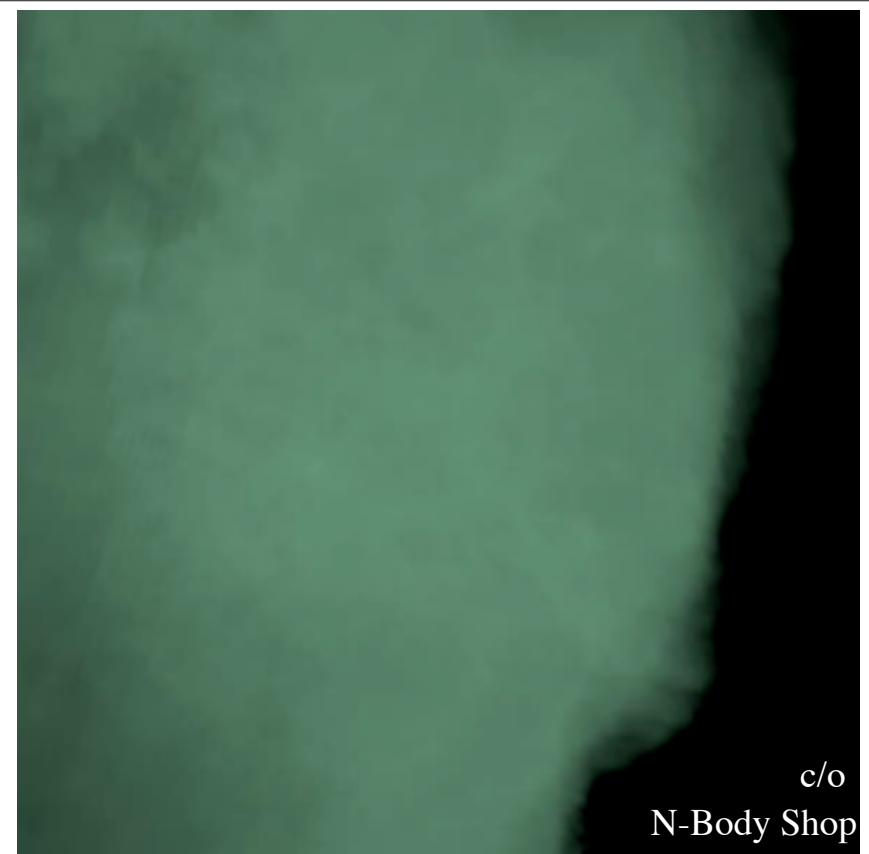
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($t \sim 400,000$ yr)



Motivation

HOW DID WE GET TO GALAXIES TODAY?

- Dark matter halos collapse:
gas cools into a disk

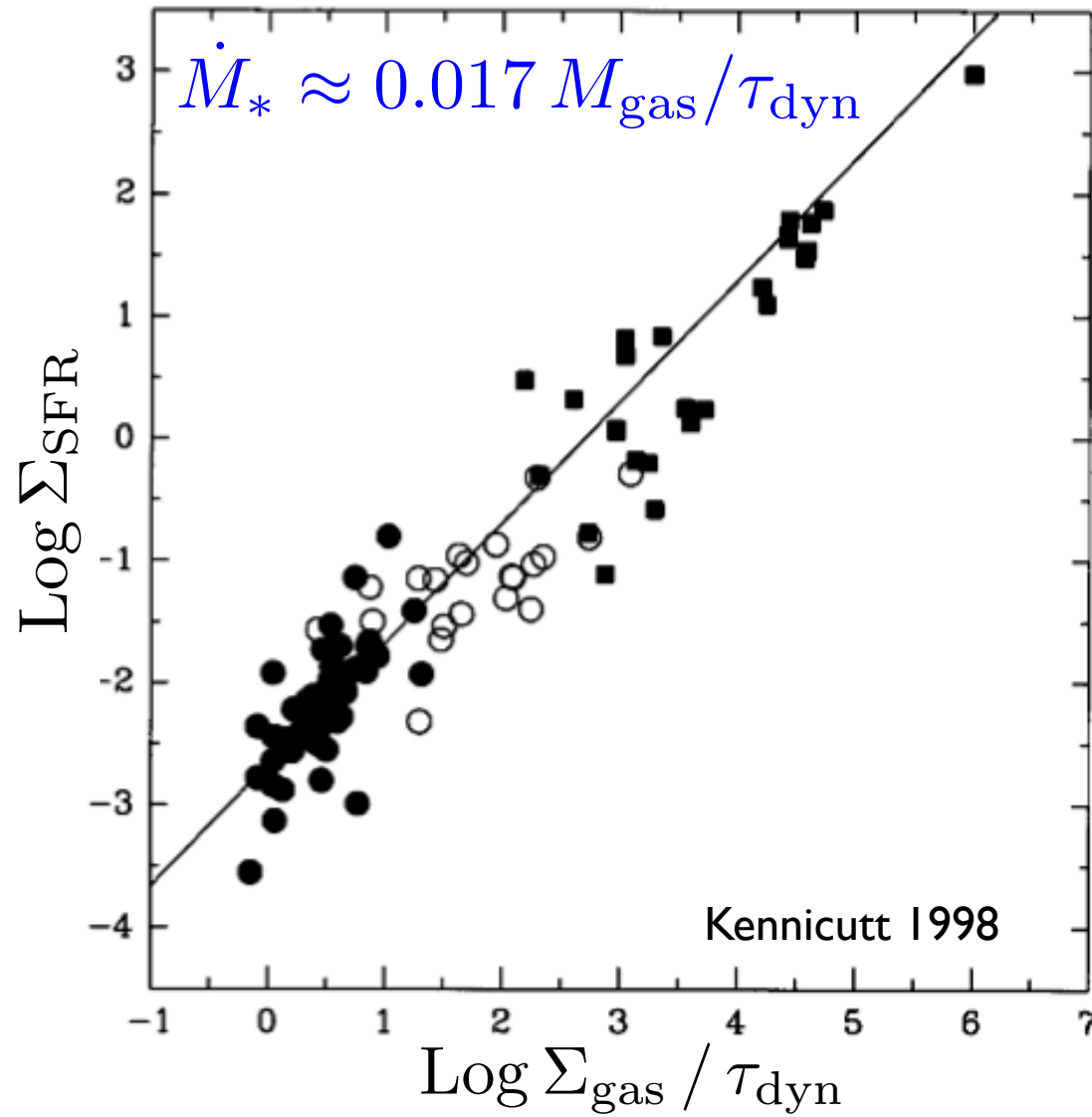


- What happens once gas is actually inside galaxies?

The Problem: Baryons

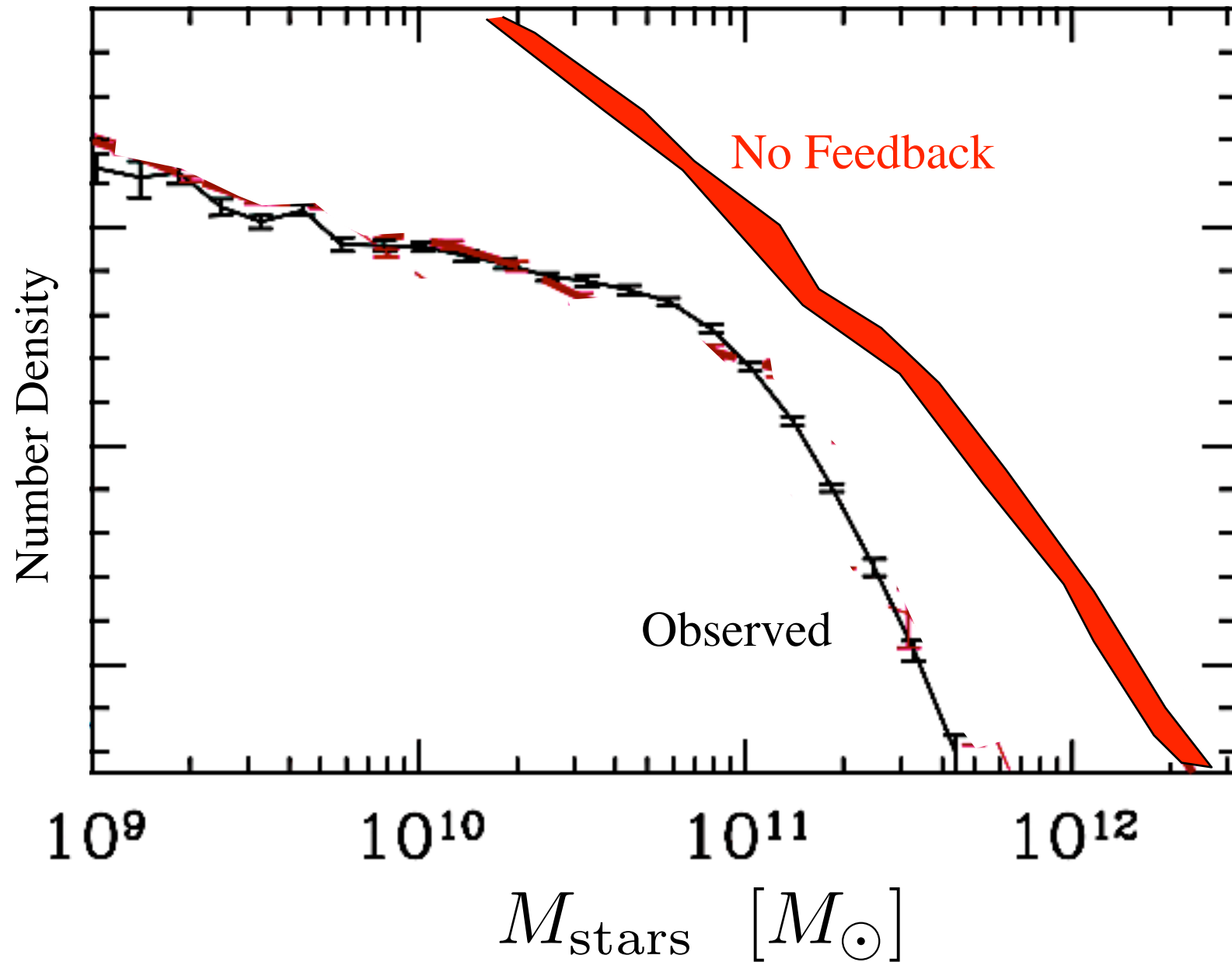
Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



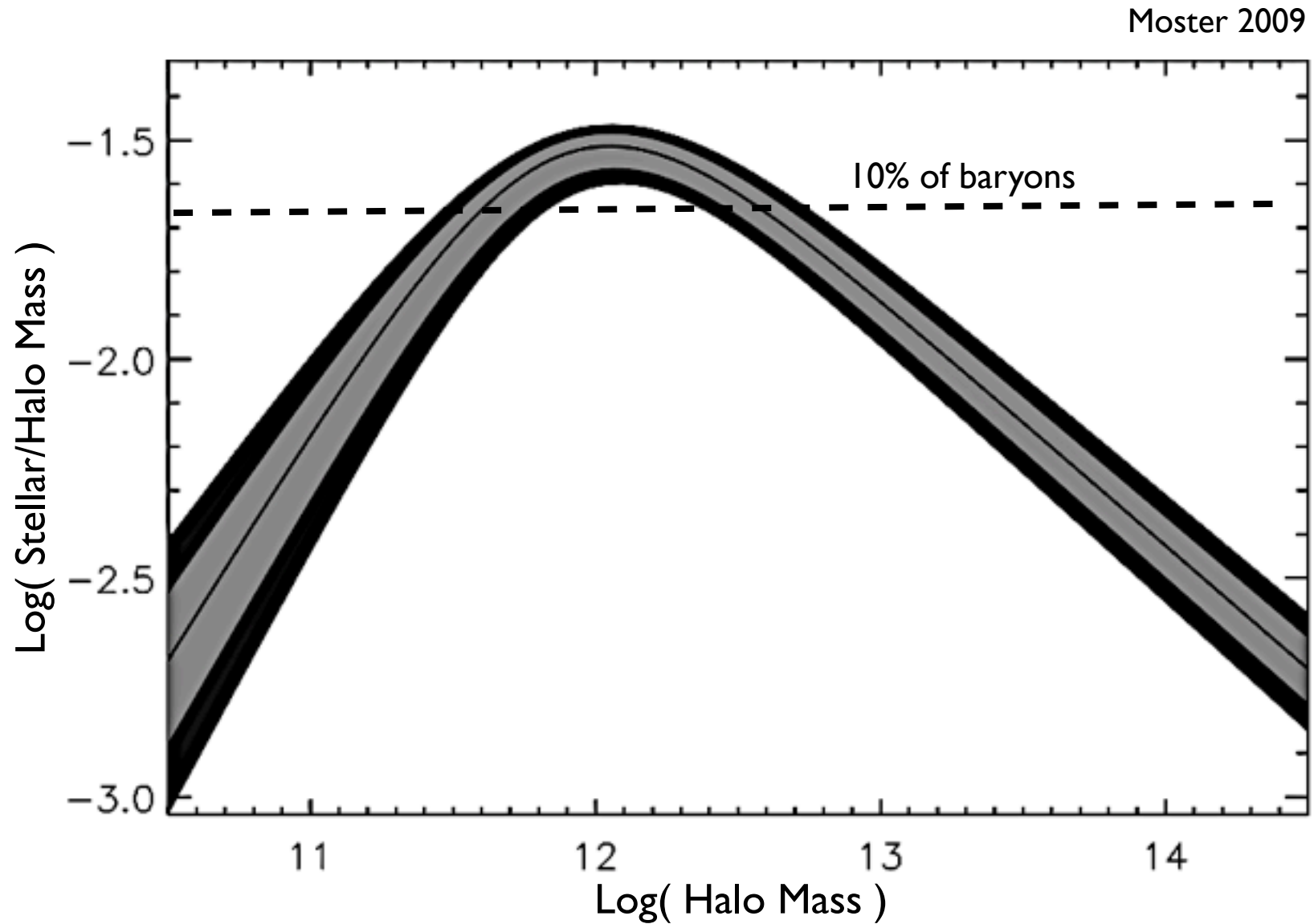
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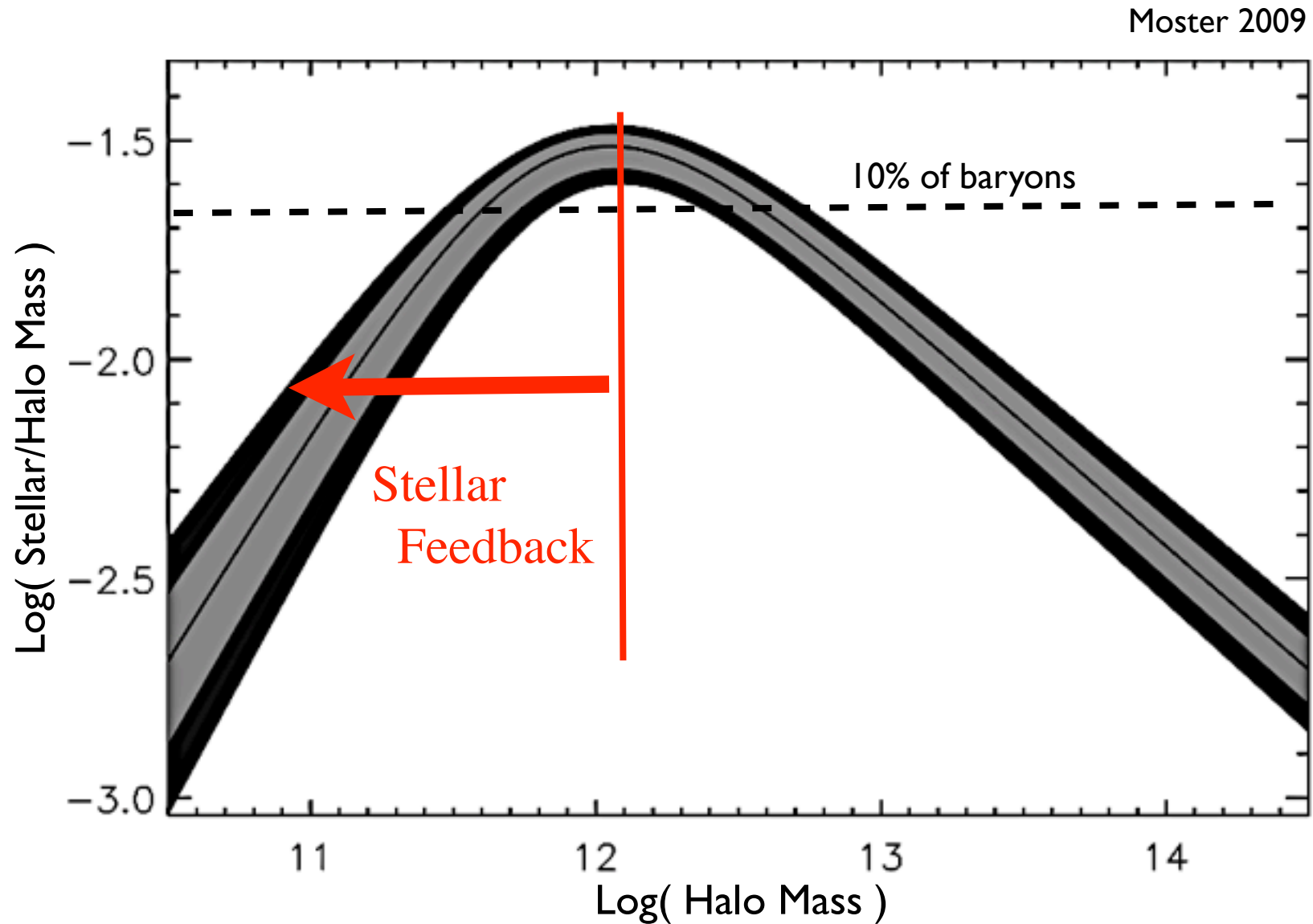
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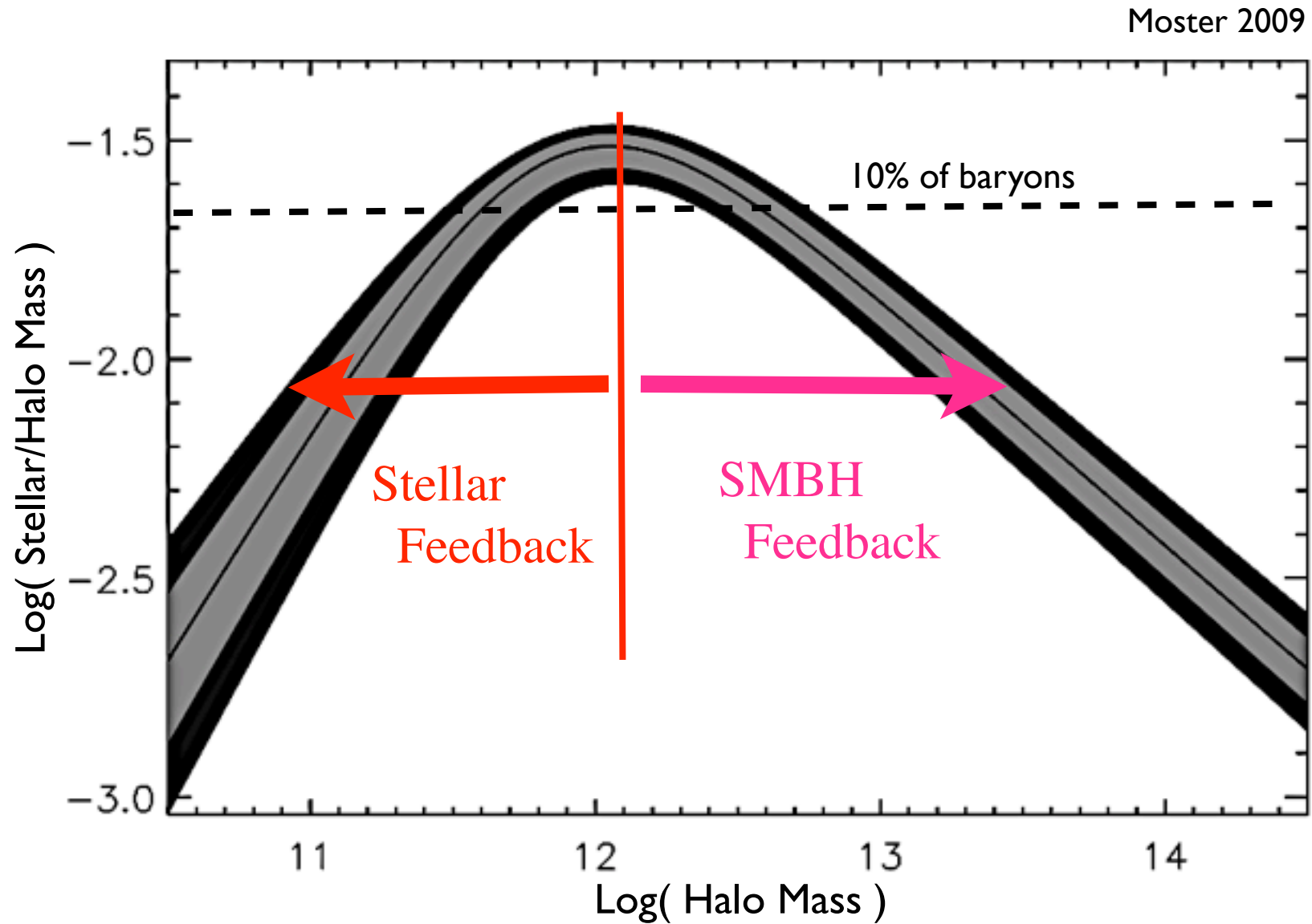
Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Stellar Feedback is the Key!

SO WHAT'S THE PROBLEM?

- Standard (in Galaxy Formation):
Couple SNe ($\sim 10^{51}$ erg/SN)
as “heating”/thermal energy

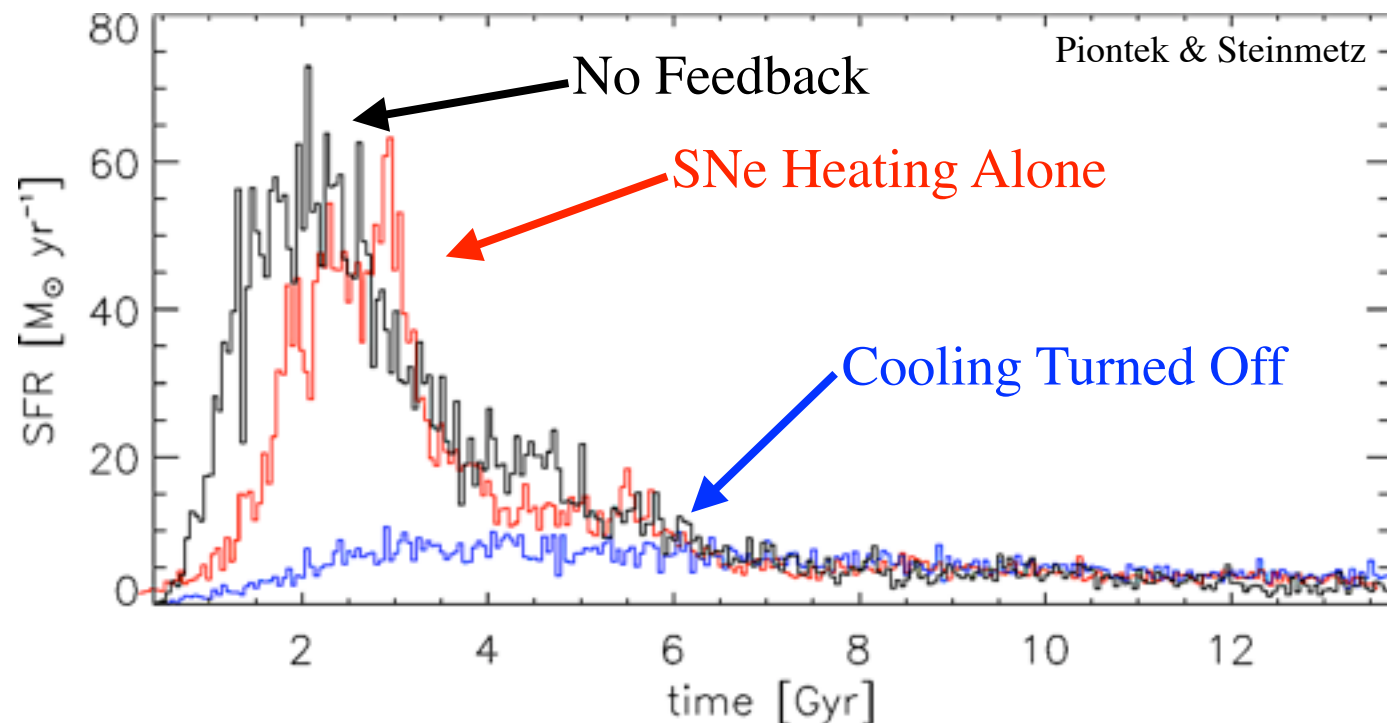
- FAILS:

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

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

- “Cheat”:

- Turn off cooling
- Force wind by hand
(‘kick’ out of galaxy)



Stellar Feedback: How Can We Do Better?



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 - Stellar Winds
 - Photoionization (HII Regions)



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- *Explicit* Momentum Flux:

- Radiation Pressure

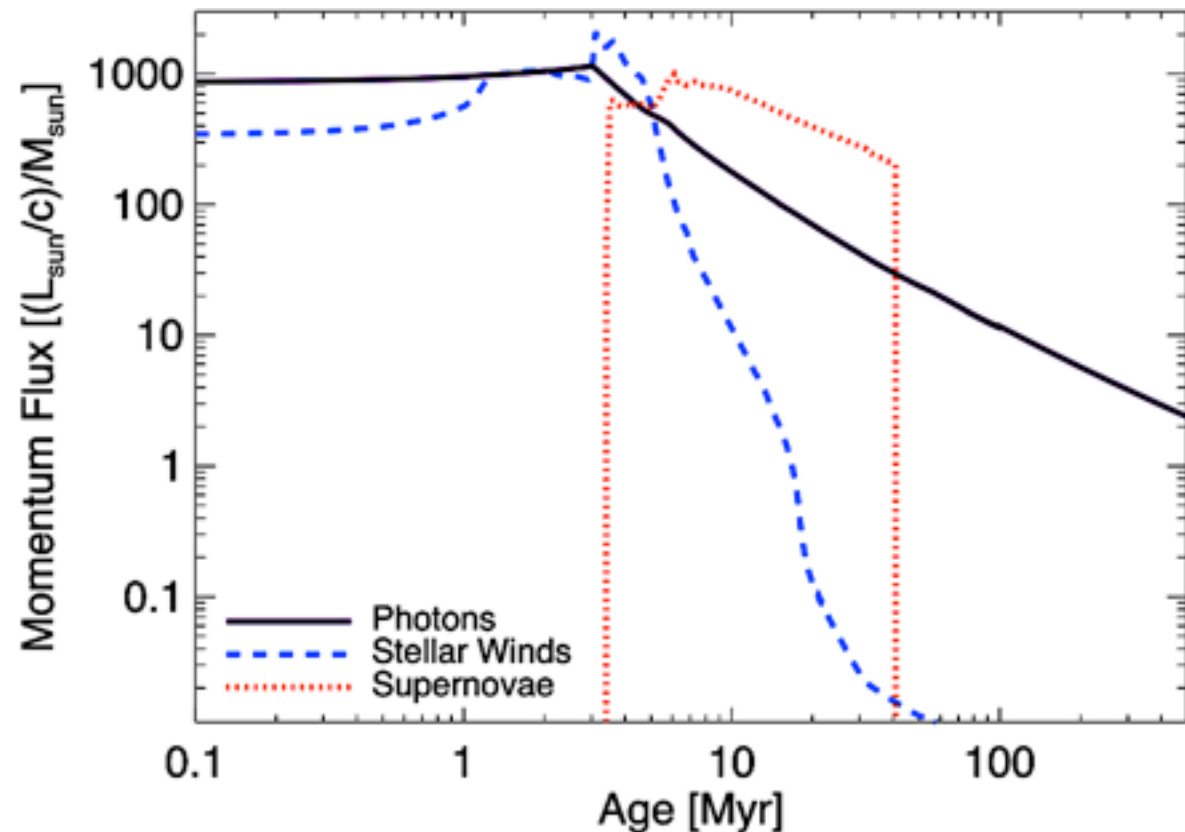
$$\dot{P}_{\text{rad}} \sim \frac{L}{c} (1 + \tau_{\text{IR}})$$

- SNe

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

- Stellar Winds

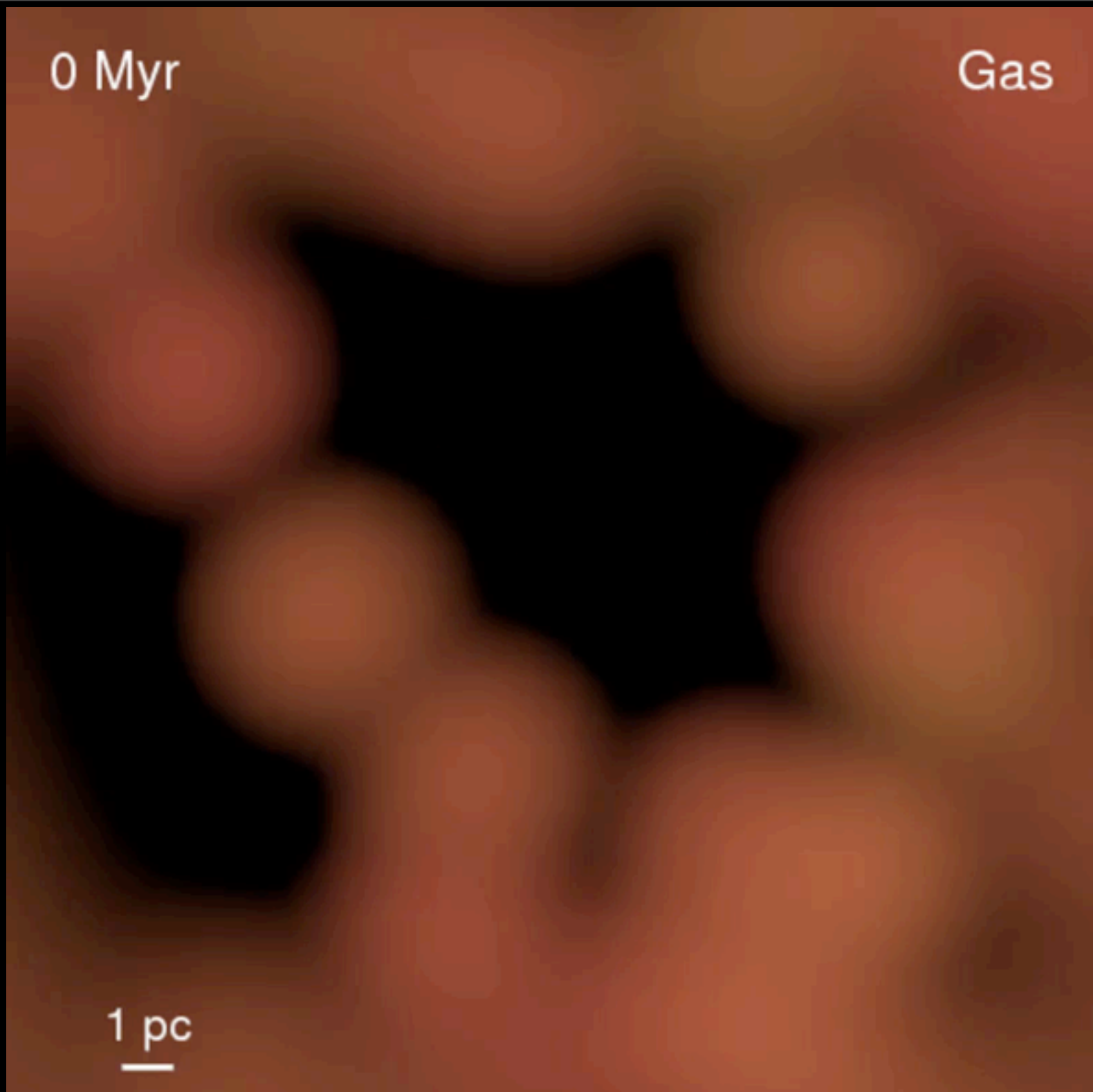
$$\dot{P}_{\text{W}} \sim \dot{M} v_{\text{wind}}$$



0 Myr

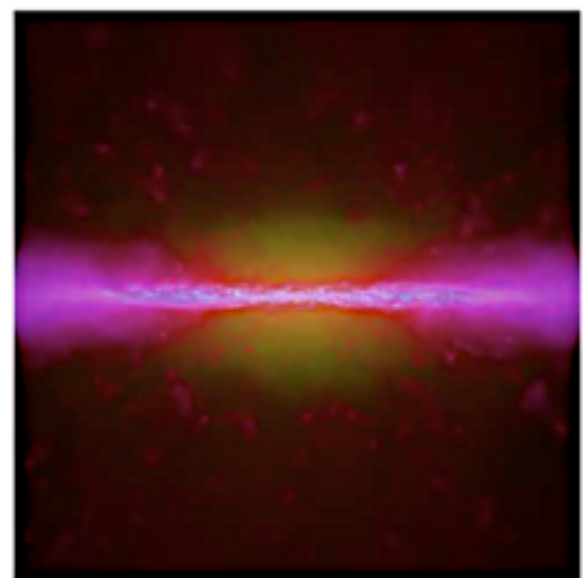
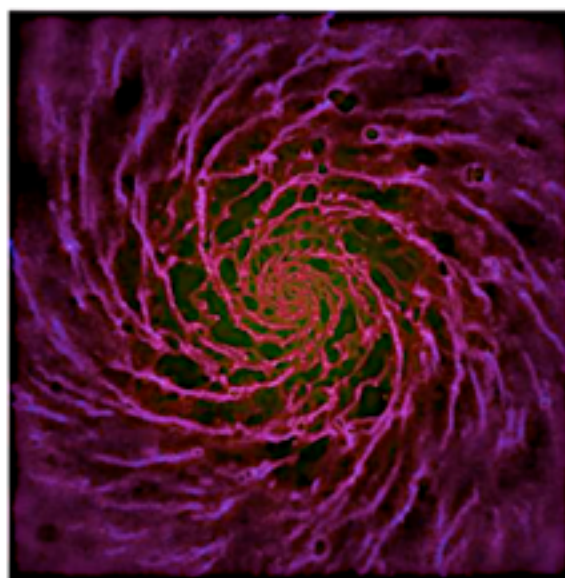
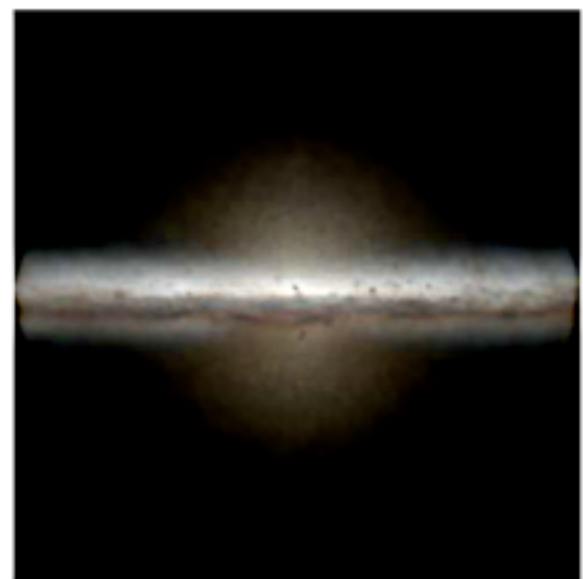
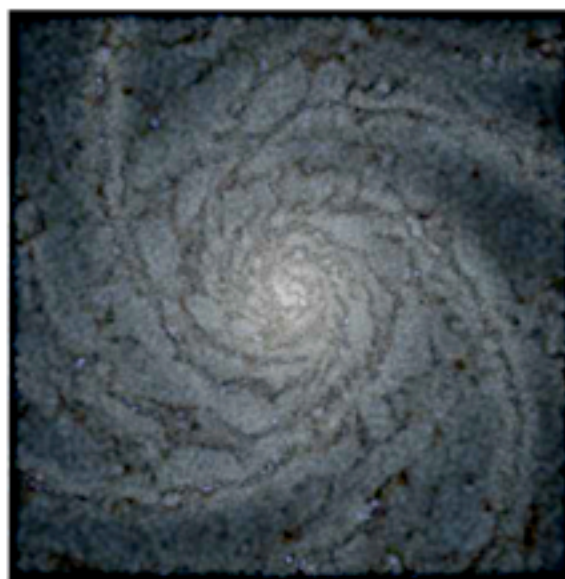
Gas

1 pc
—



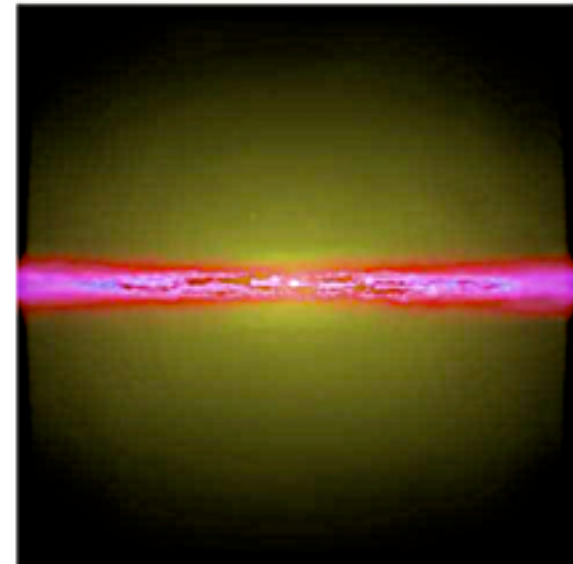
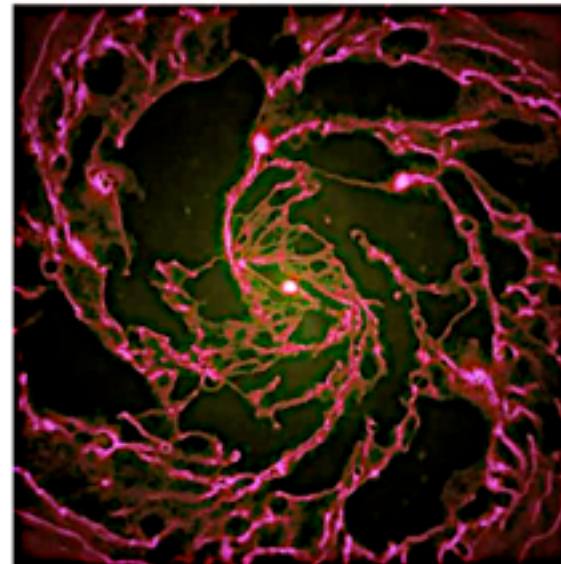
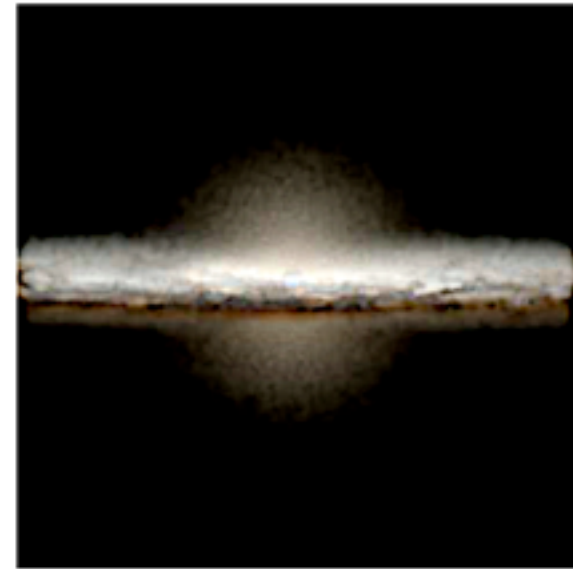
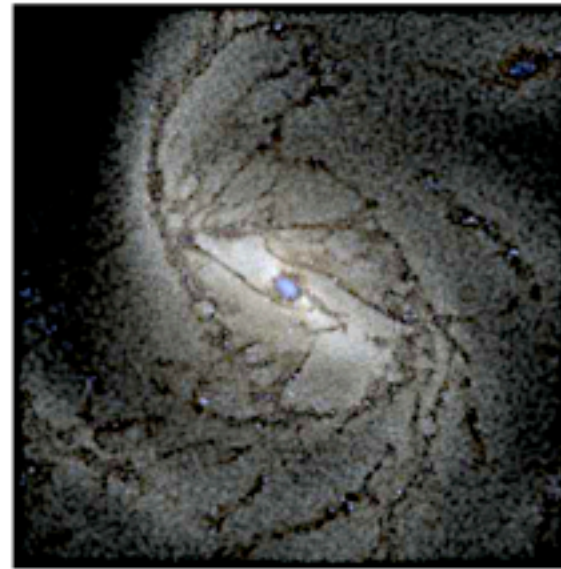


Spiral Galaxy M101 Spitzer Space Telescope • Hubble Space Telescope
 NASA / JPL-Caltech / ESA / CXC / STScI



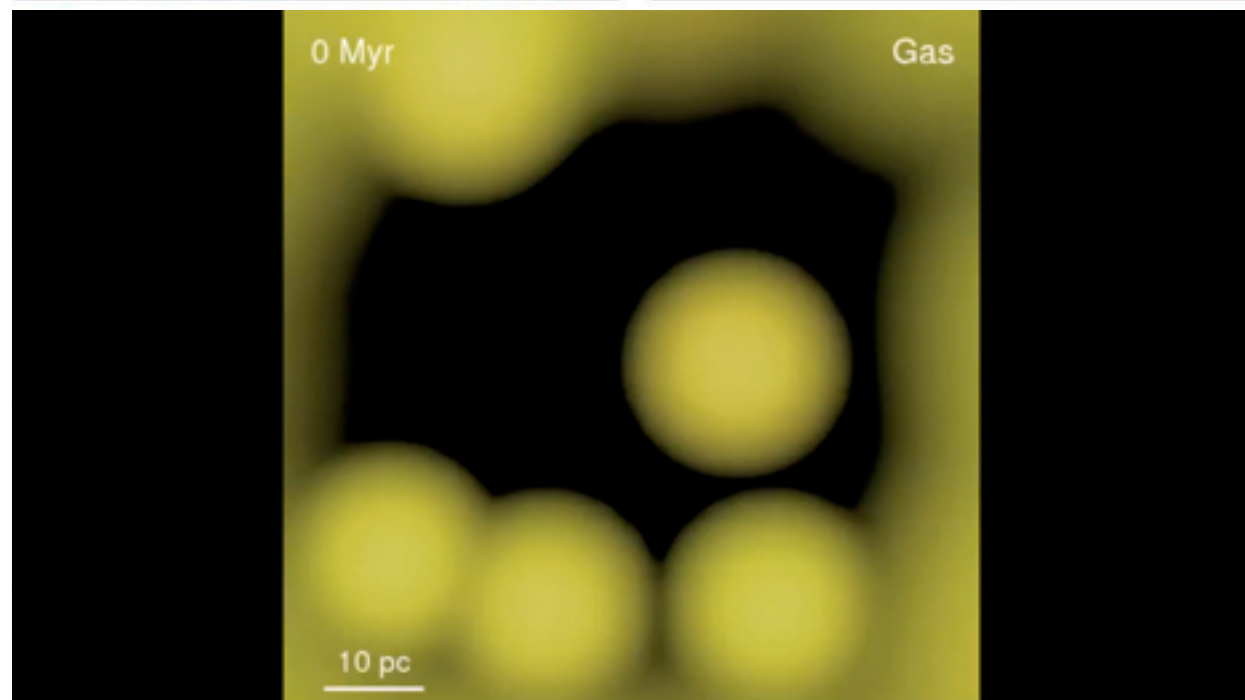
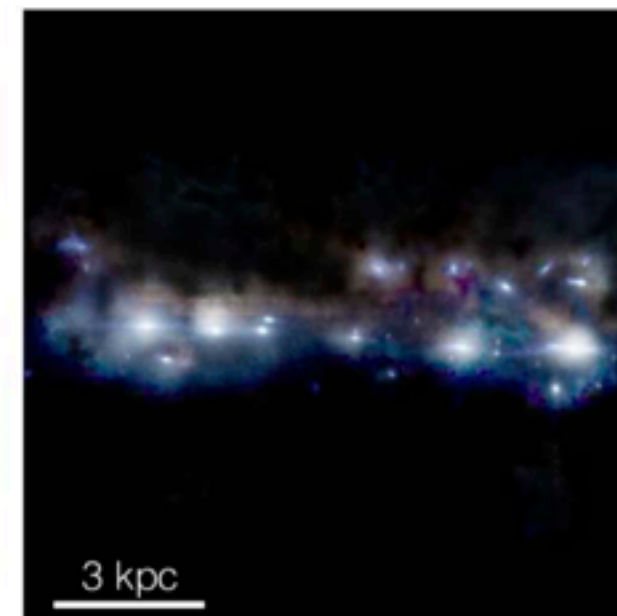
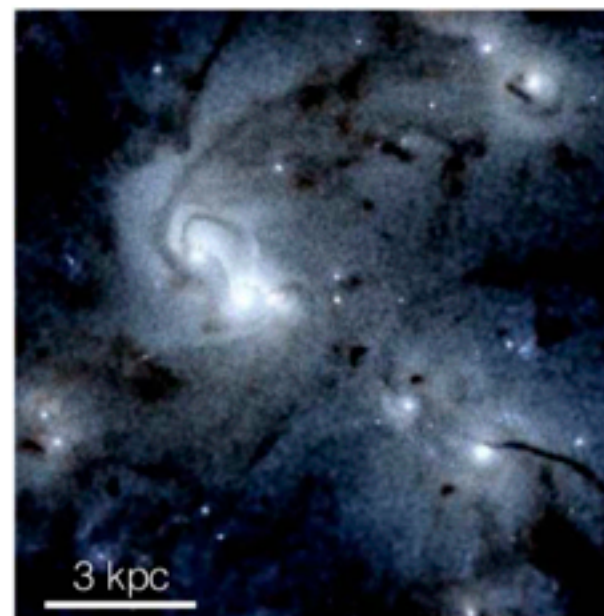
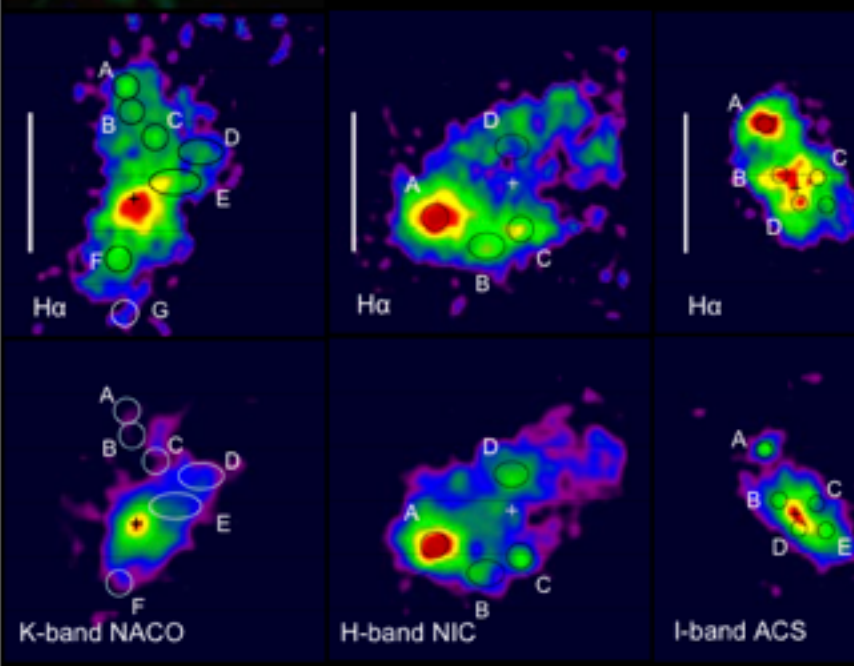
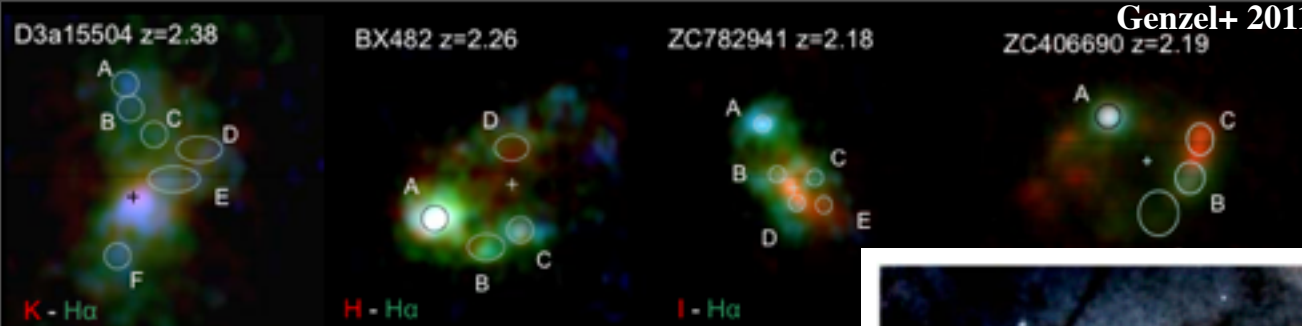
Hopkins, Quataert, & Murray, 2011b

NGC 1097 (Spitzer)



Hopkins, Quataert, & Murray, 2011b

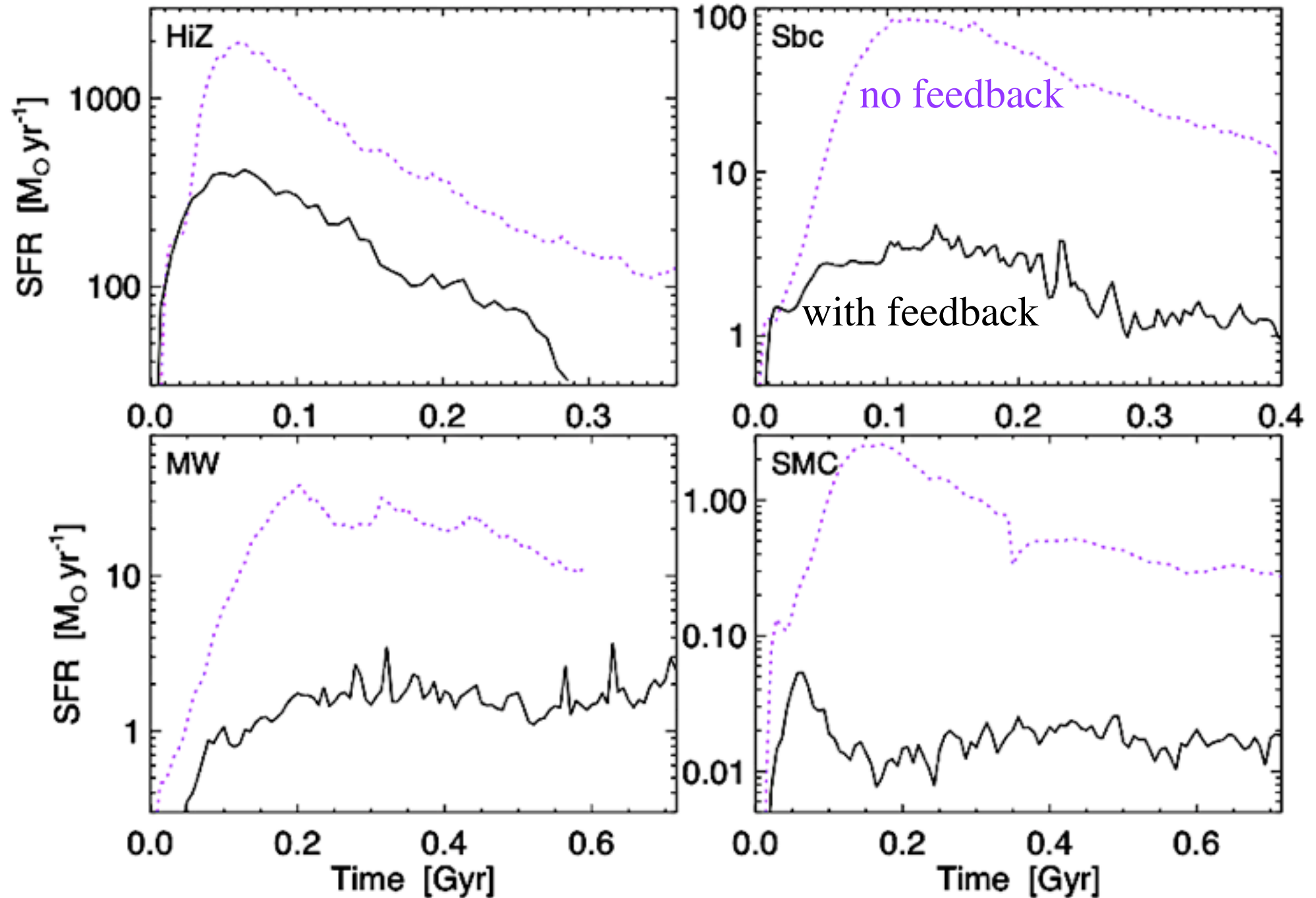
Saturday, March 9, 13



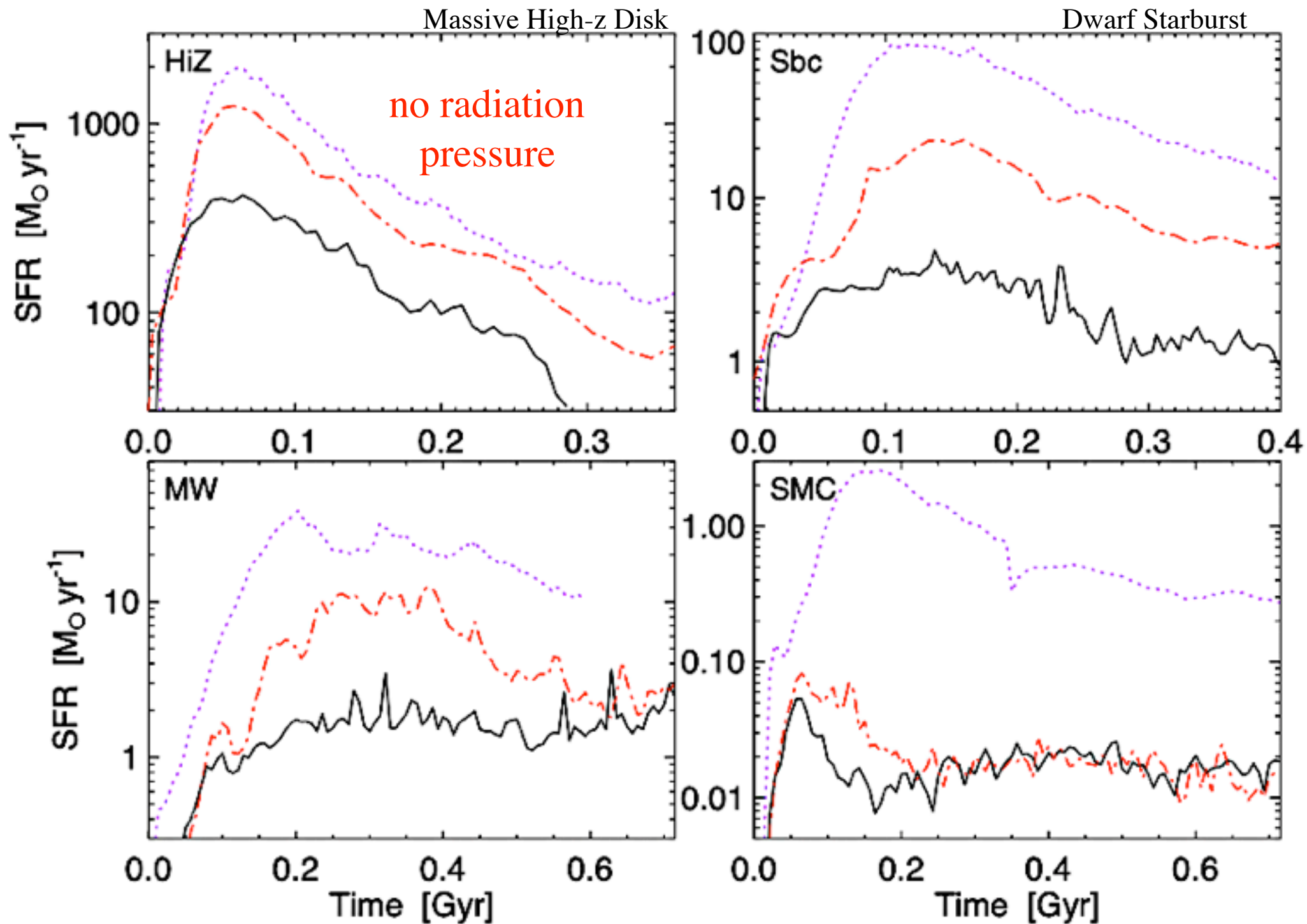
Stellar Feedback gives Self-Regulated Star Formation

Massive High-z Disk

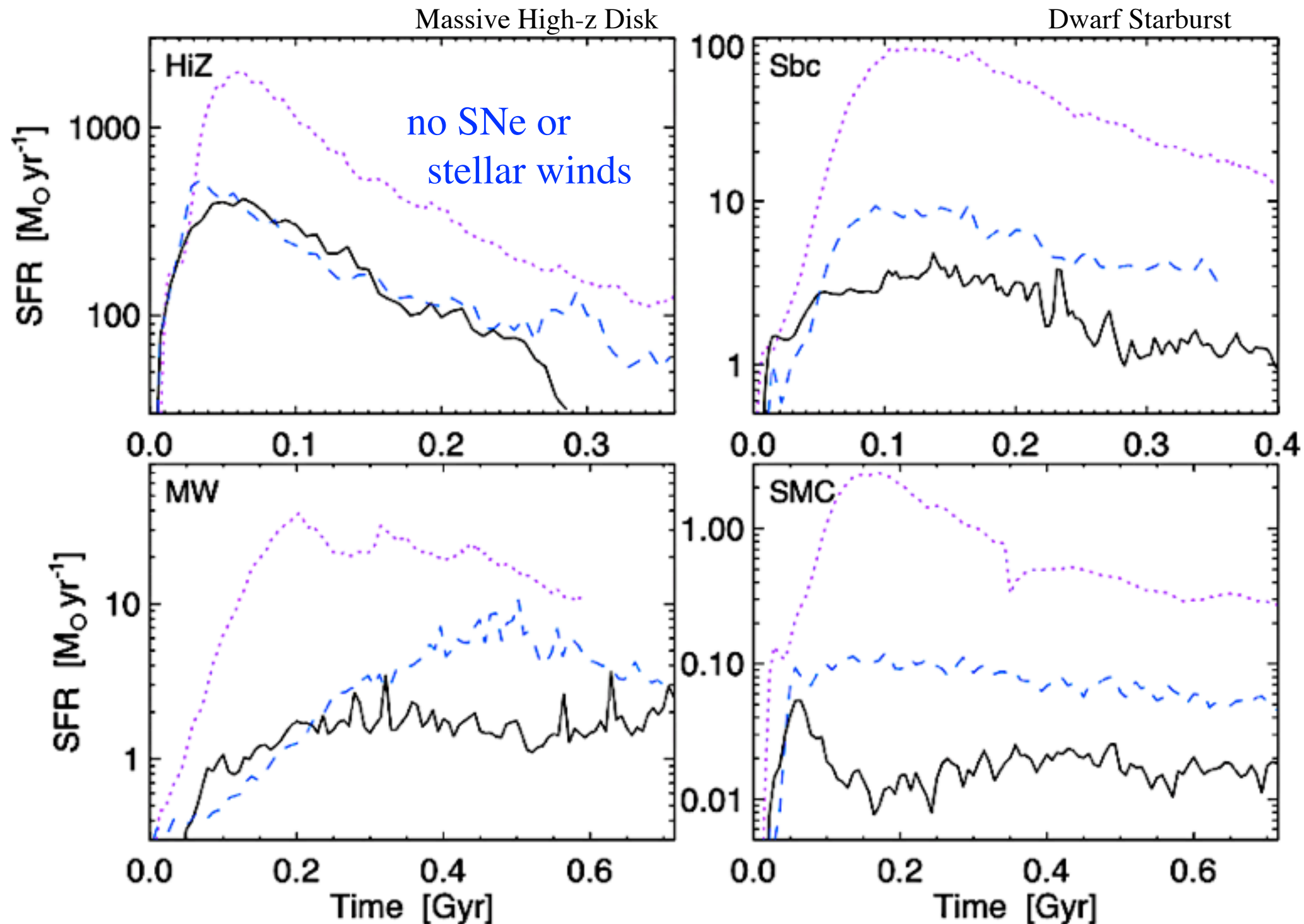
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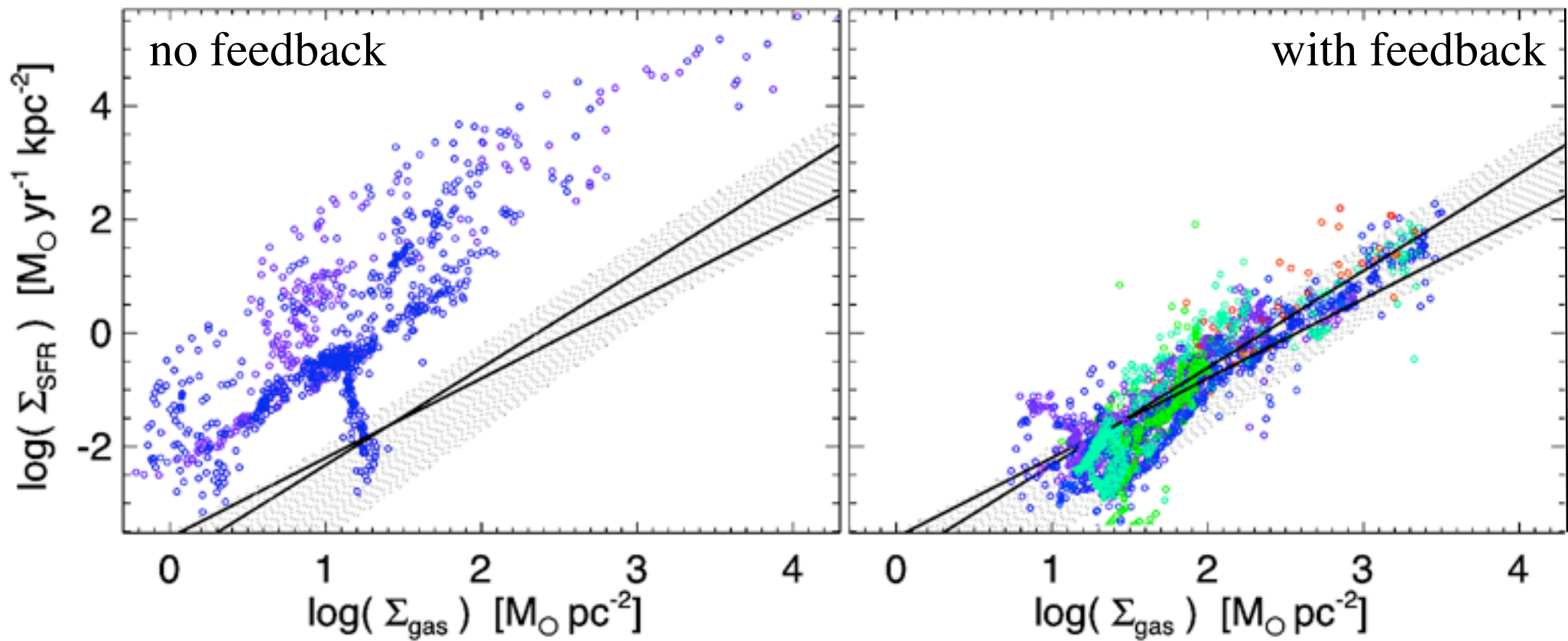
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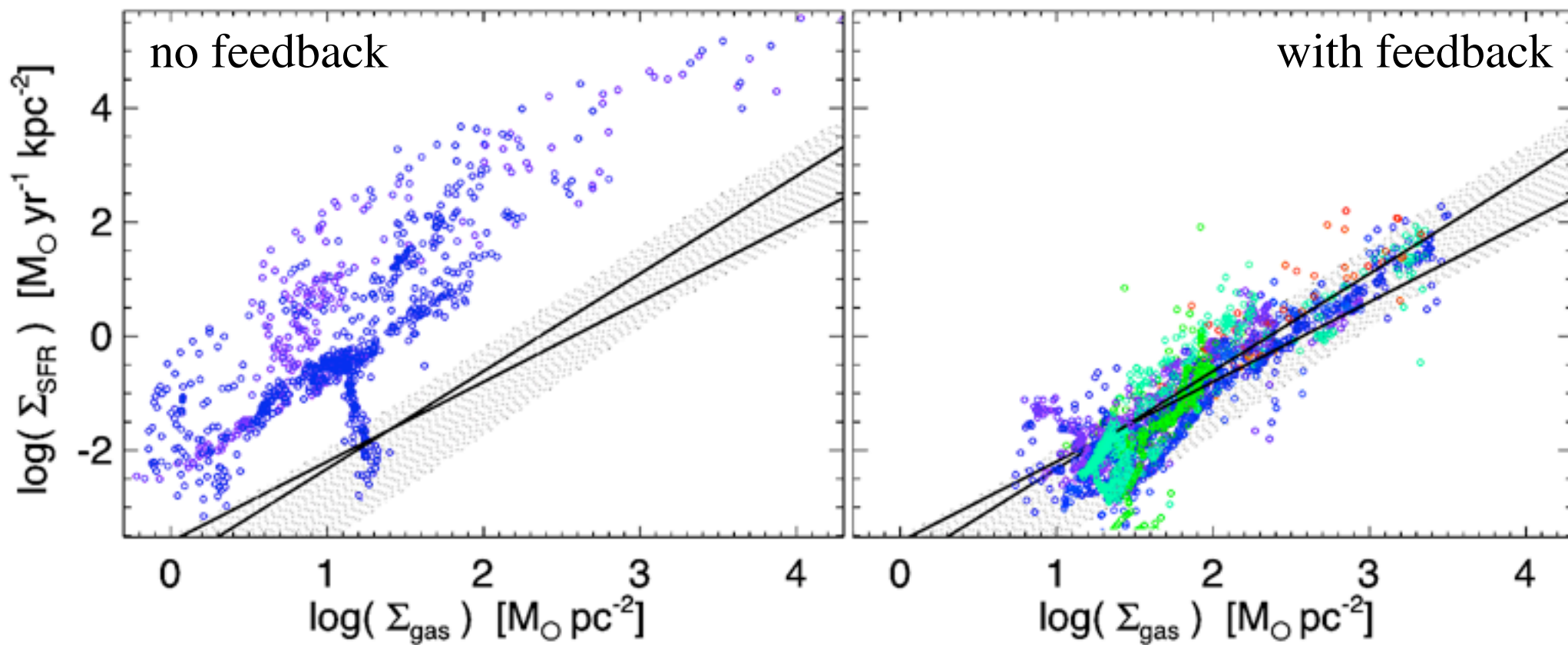


Kennicutt-Schmidt relation emerges naturally



Kennicutt-Schmidt relation emerges naturally

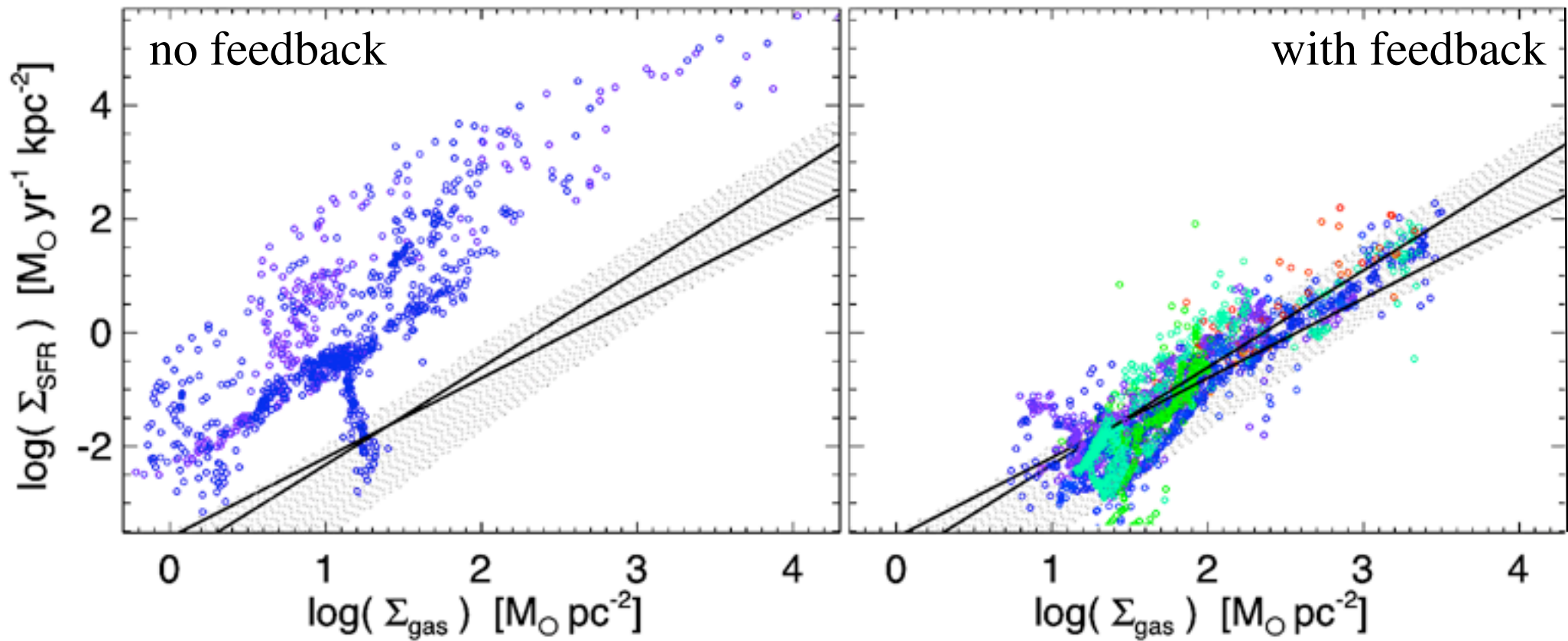
$$\dot{\Sigma}_* \sim \Sigma_{\text{gas}} / \tau_{\text{dyn}}$$



Kennicutt-Schmidt relation emerges naturally

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$$\dot{\Sigma}_* \sim 0.02 \Sigma_{\text{gas}} / \tau_{\text{dyn}}$$



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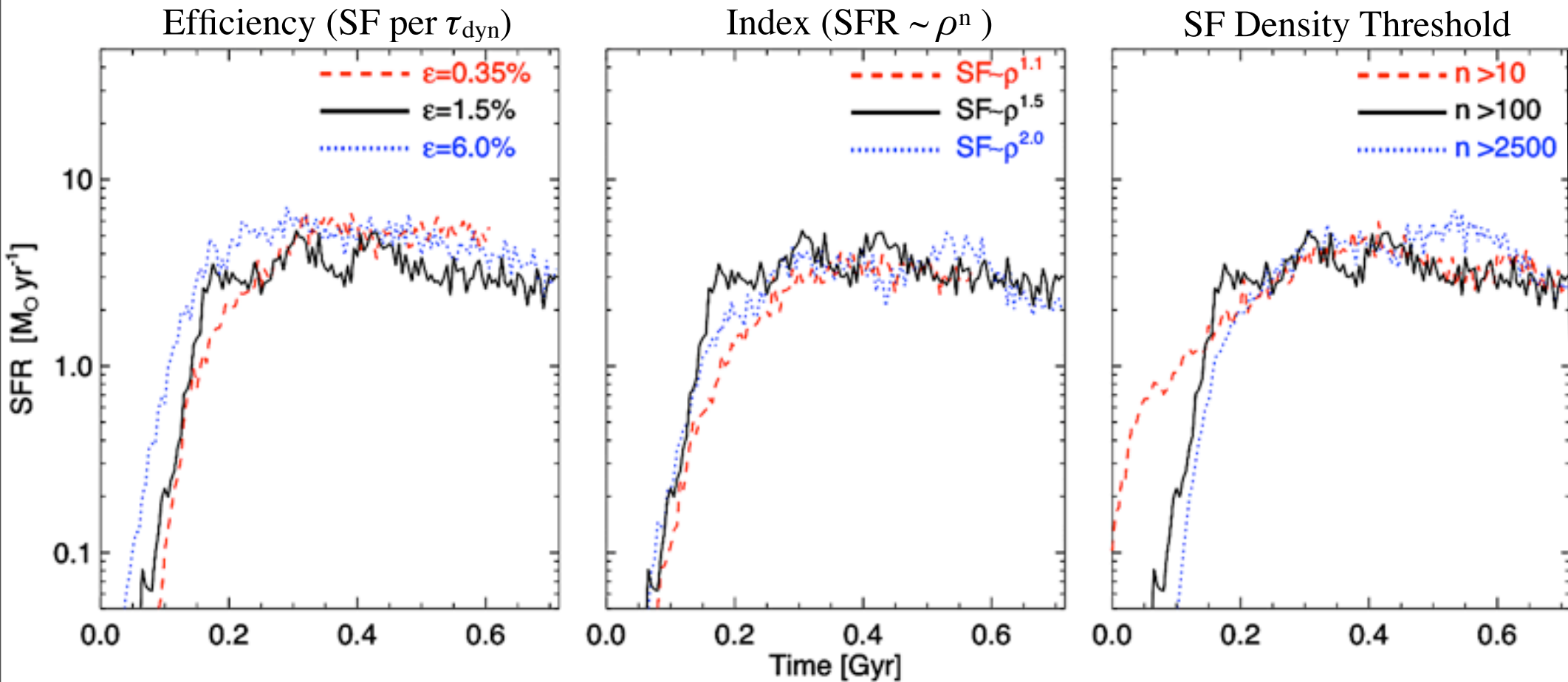
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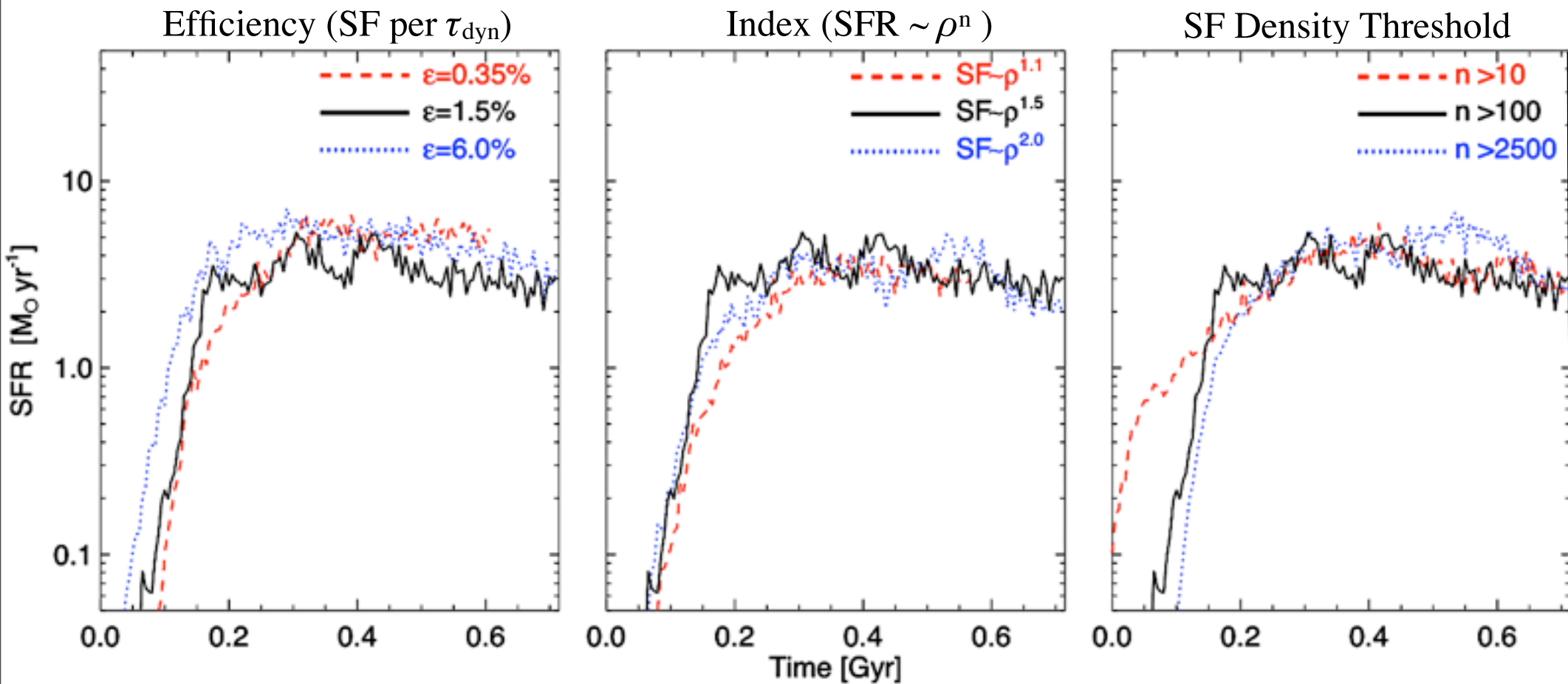
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c} \right) \Sigma_{\text{gas}} \Omega \sim 0.02 \Sigma_{\text{gas}} \Omega$$

Global Star Formation Rates are *INDEPENDENT* of High-Density SF Law



Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

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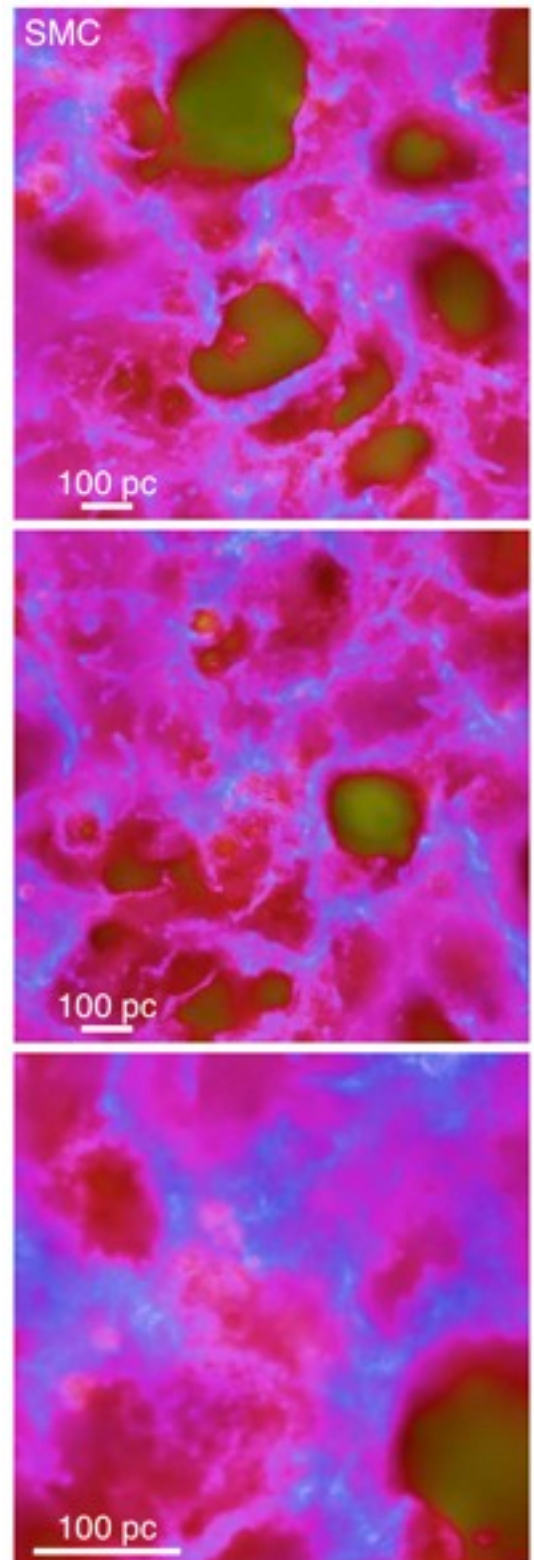
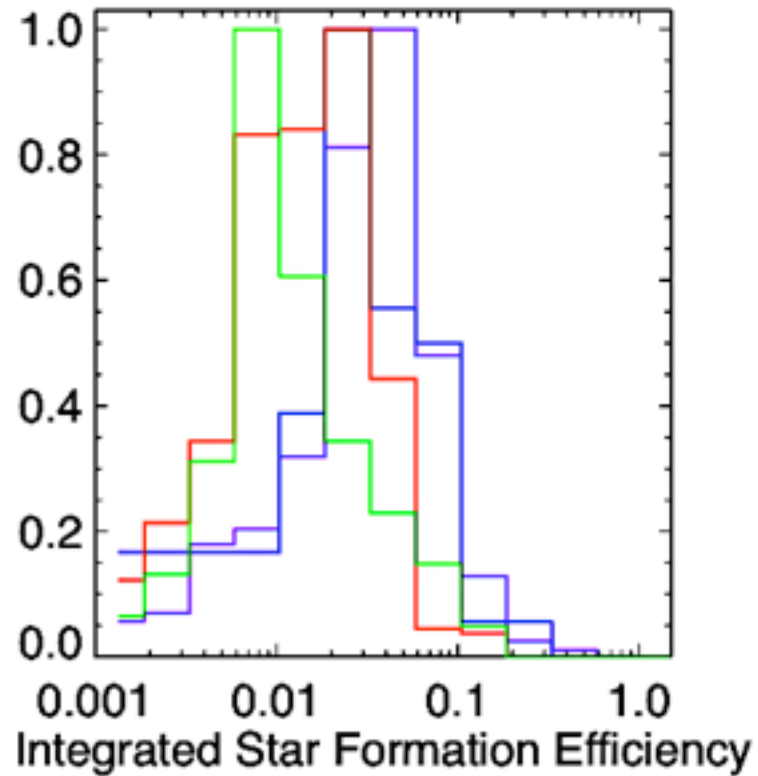
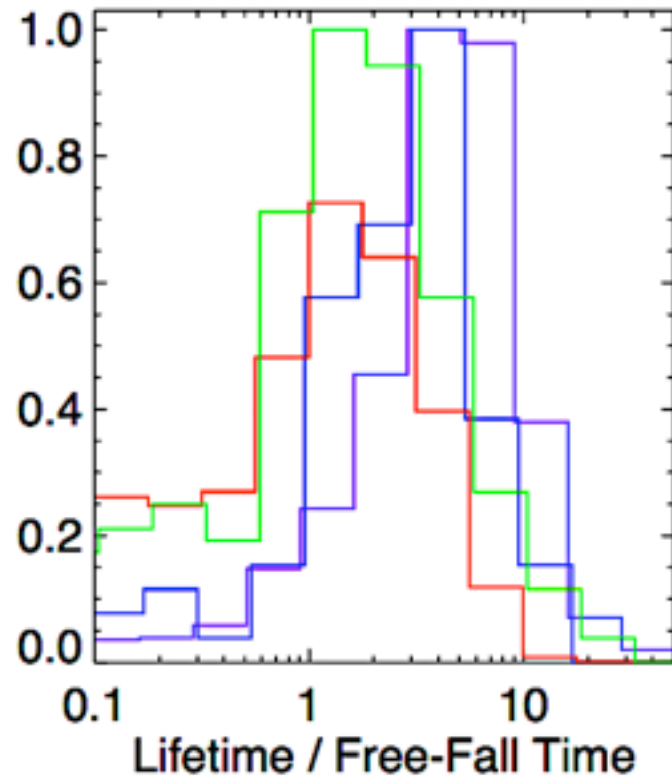
➤ Set by feedback (i.e. SFR) needed to maintain marginal stability

Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

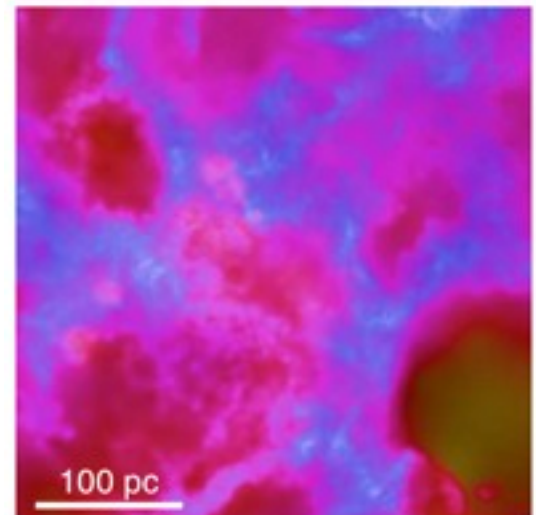
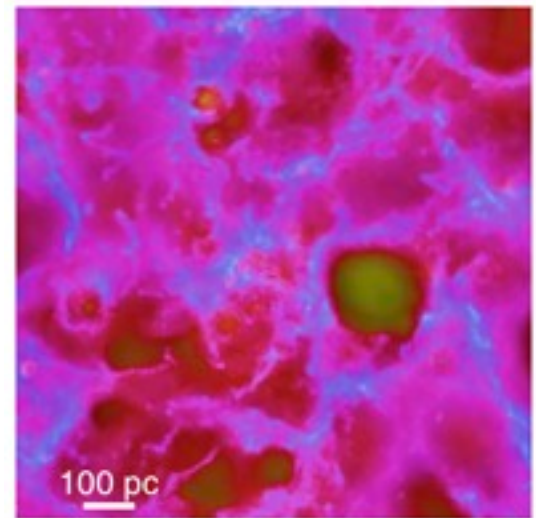
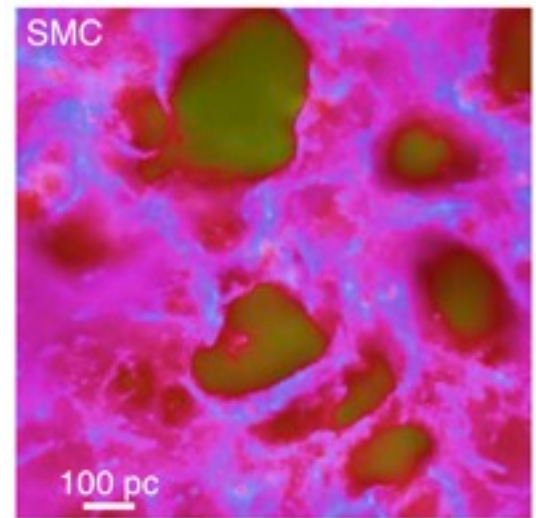
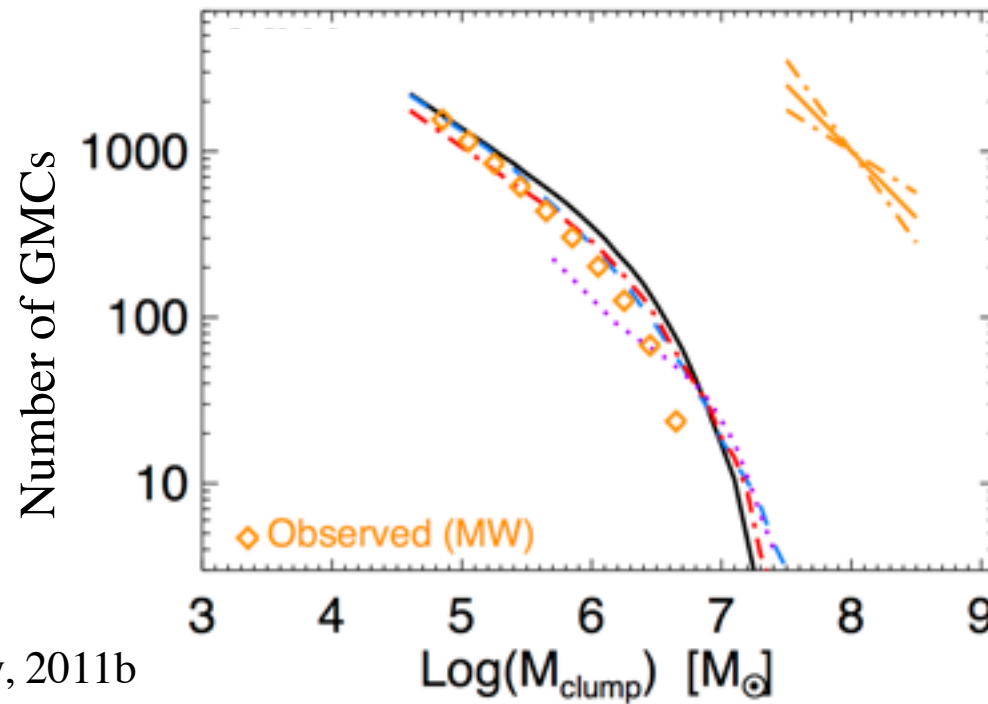
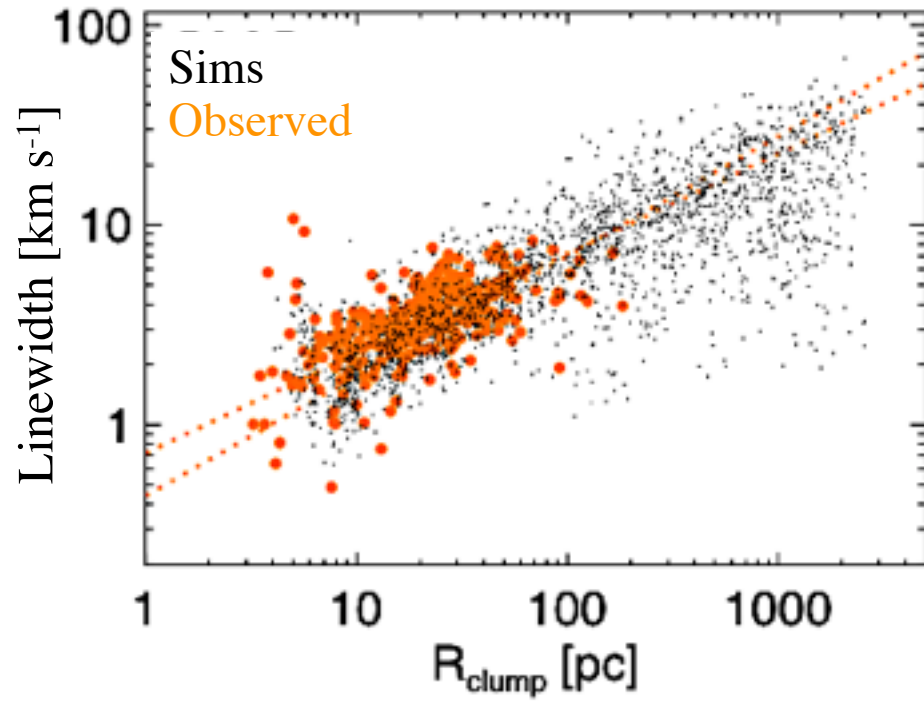
What Else Can We Study About Star Formation and the ISM?

Properties of GMCs

DEPENDENCE ON FEEDBACK AND OTHER SCALINGS

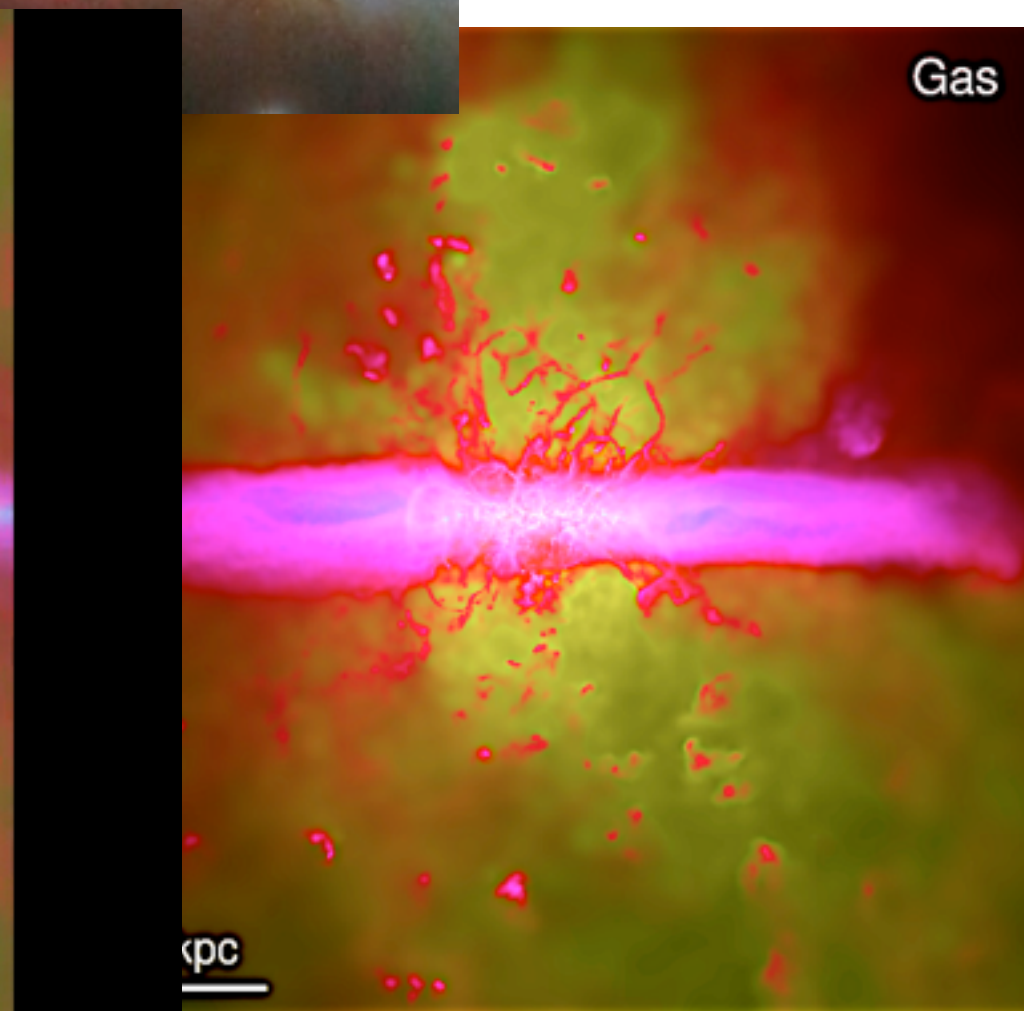
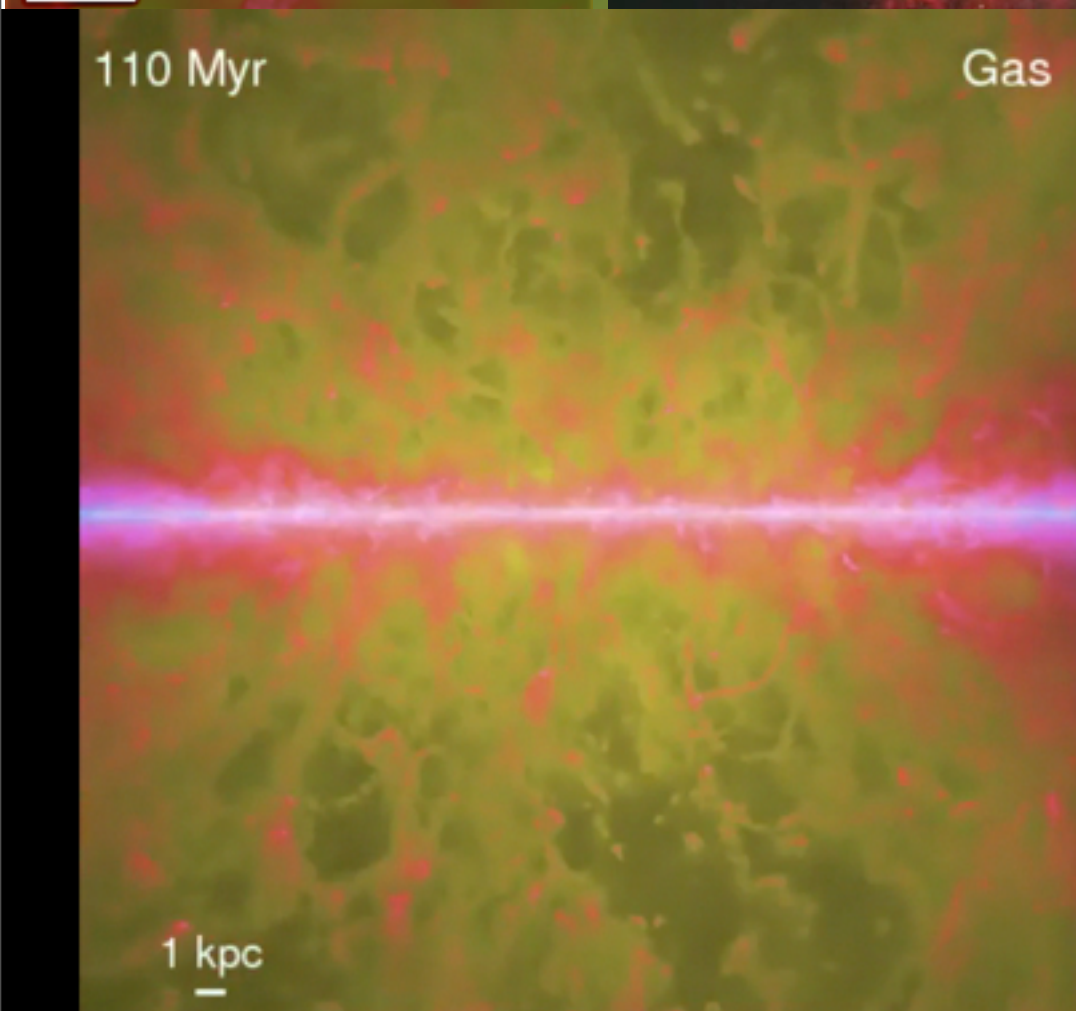
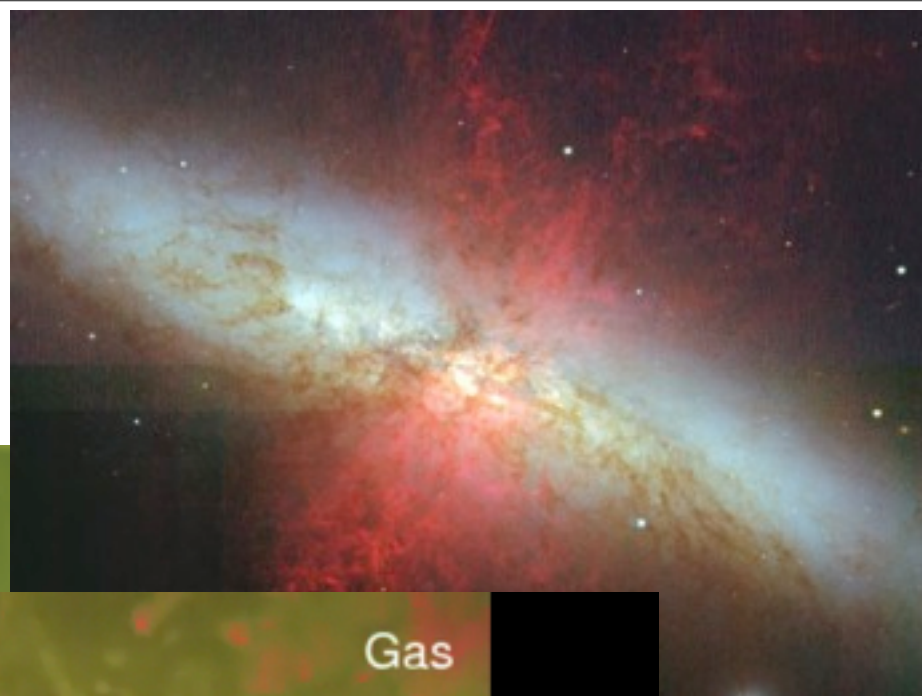
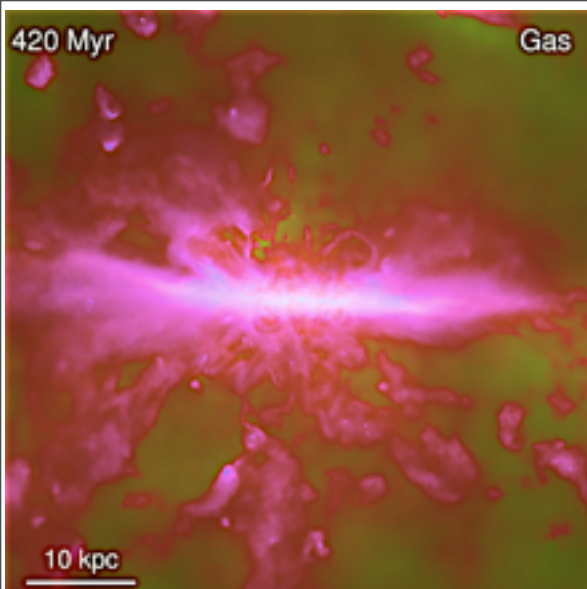


Properties of GMCs & Gas “Clumps”



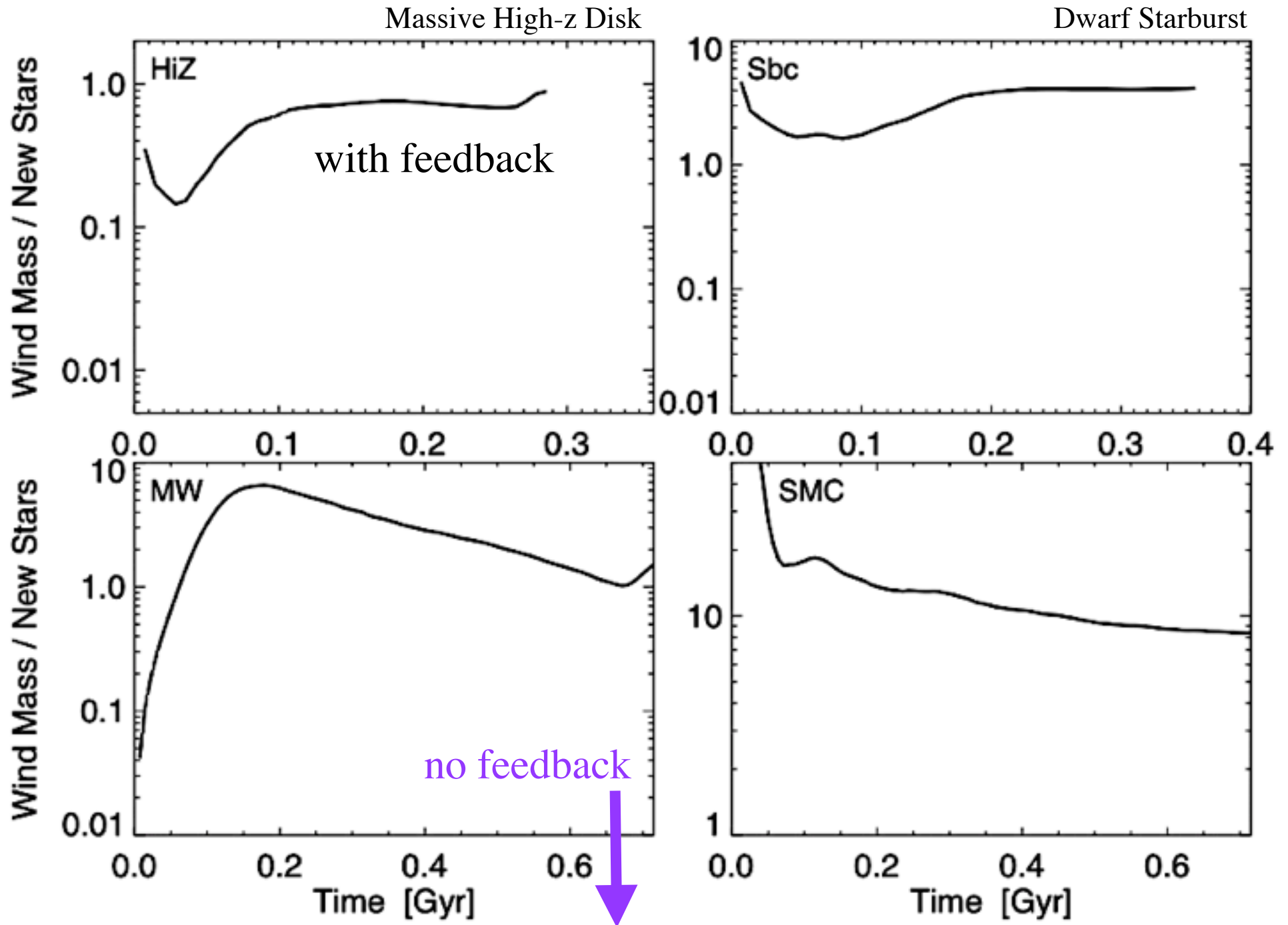
The Gas not Forming Stars: Galaxy Winds and the Baryon Cycle

Galactic Super-Winds



How Efficient Are Galactic Super-Winds? AND WHAT MECHANISMS DRIVE THEM?

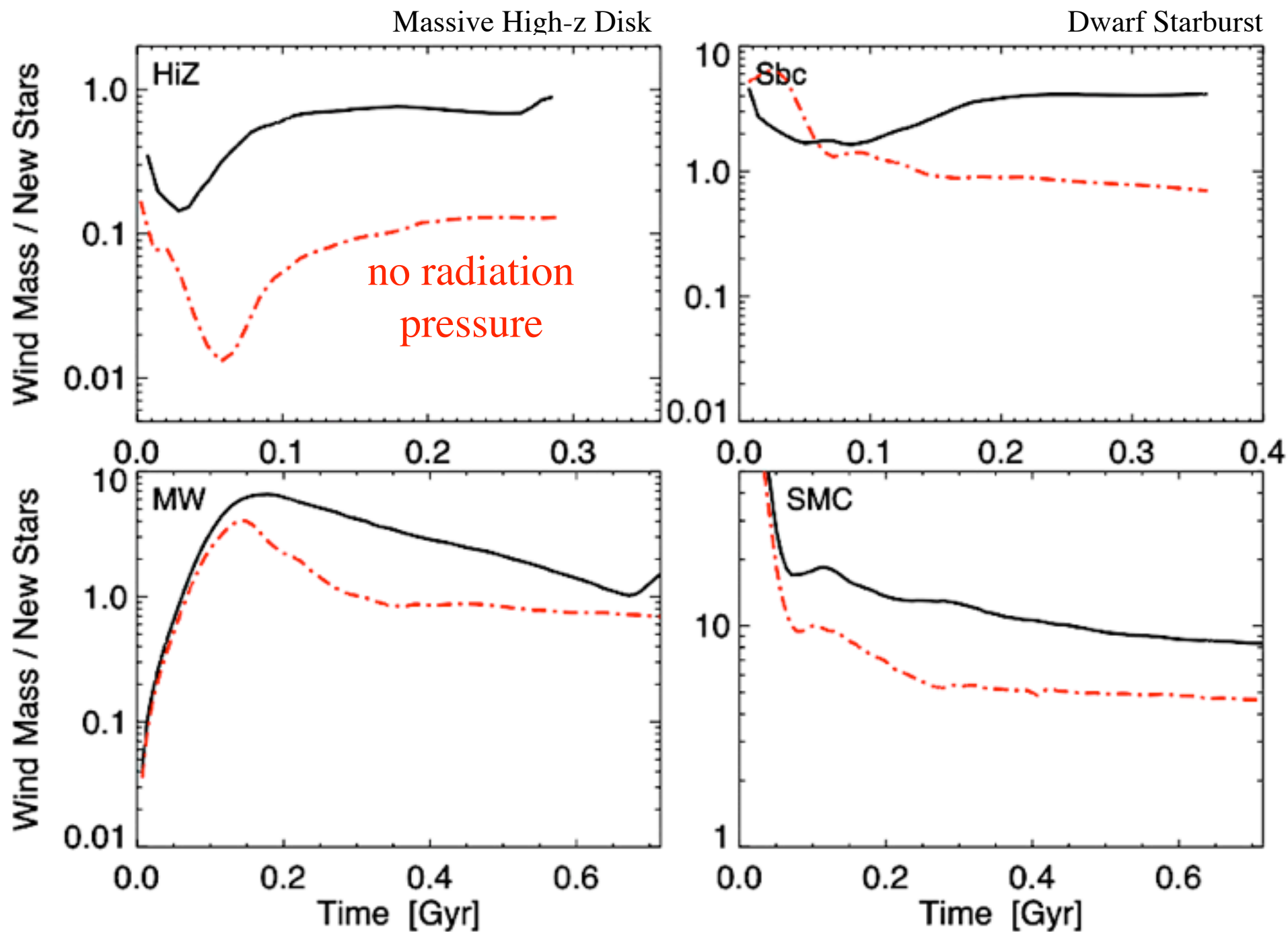
PFH, Quataert, & Murray, 2011c



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PFH, Quataert, & Murray, 2011c



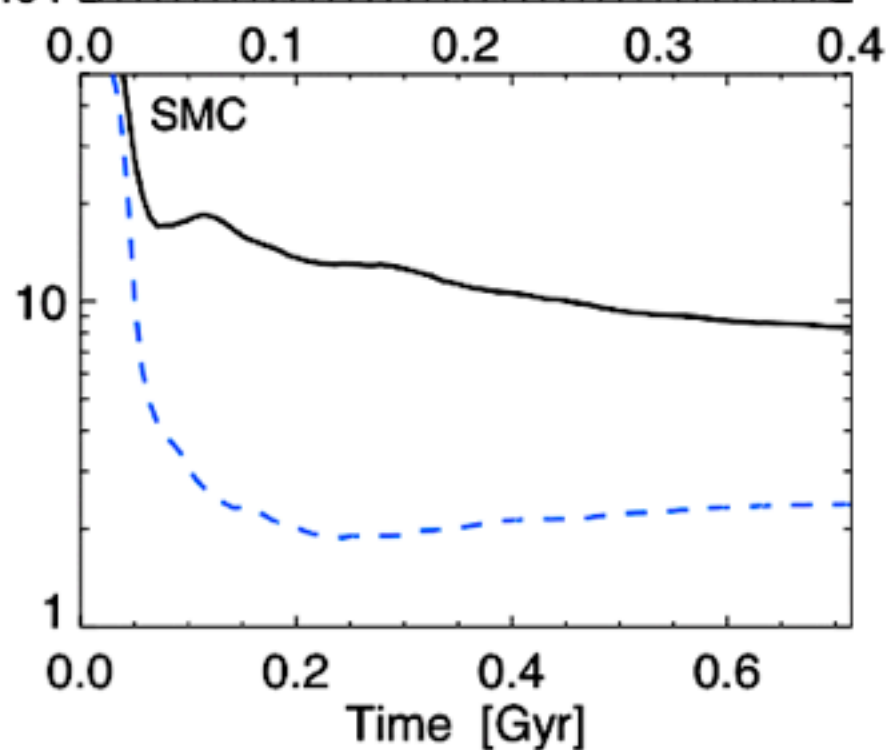
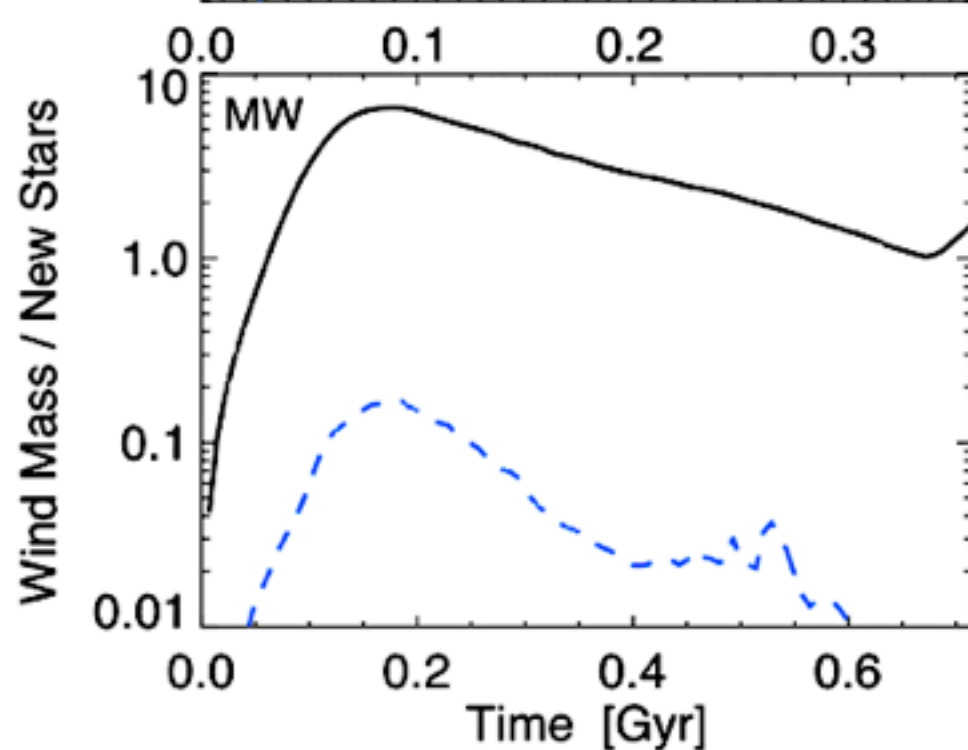
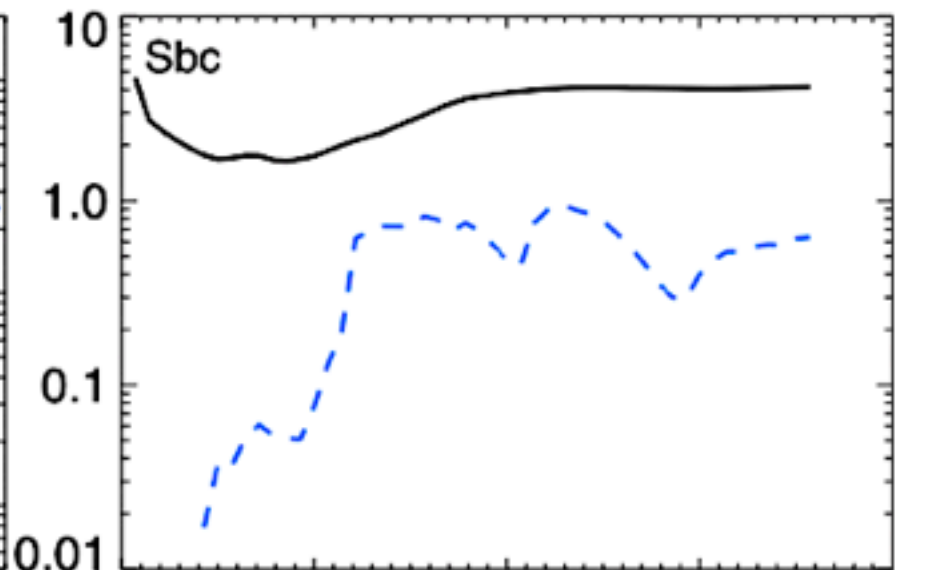
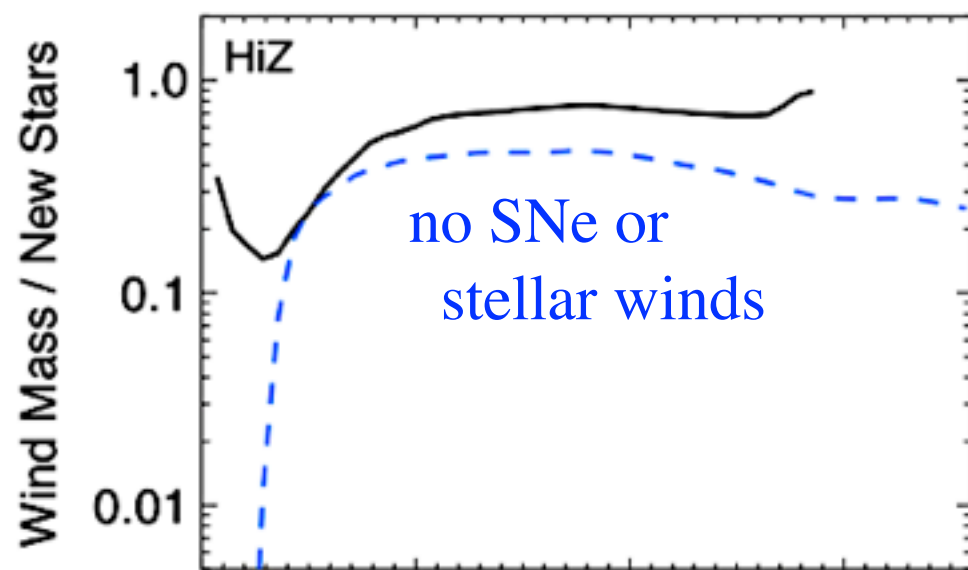
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PFH, Quataert, & Murray, 2011c

Massive High-z Disk

Dwarf Starburst



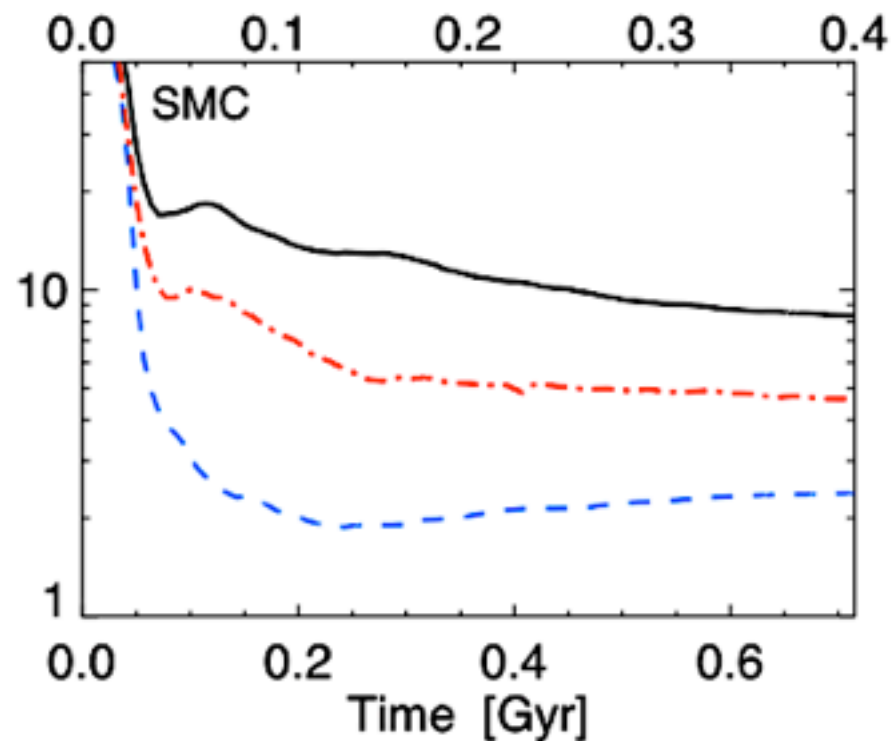
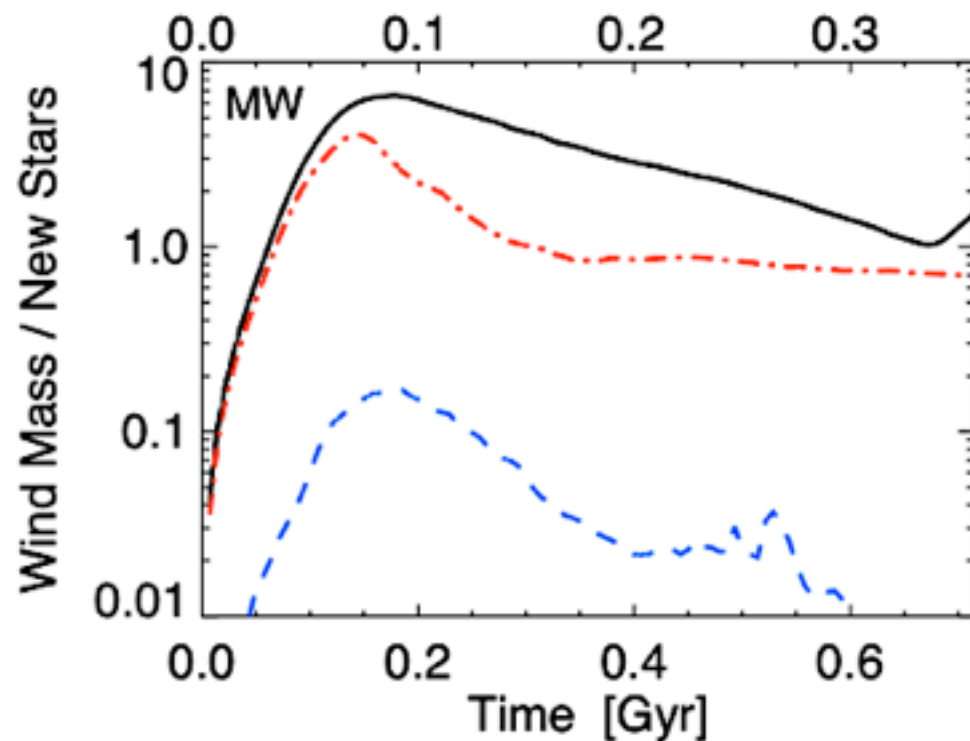
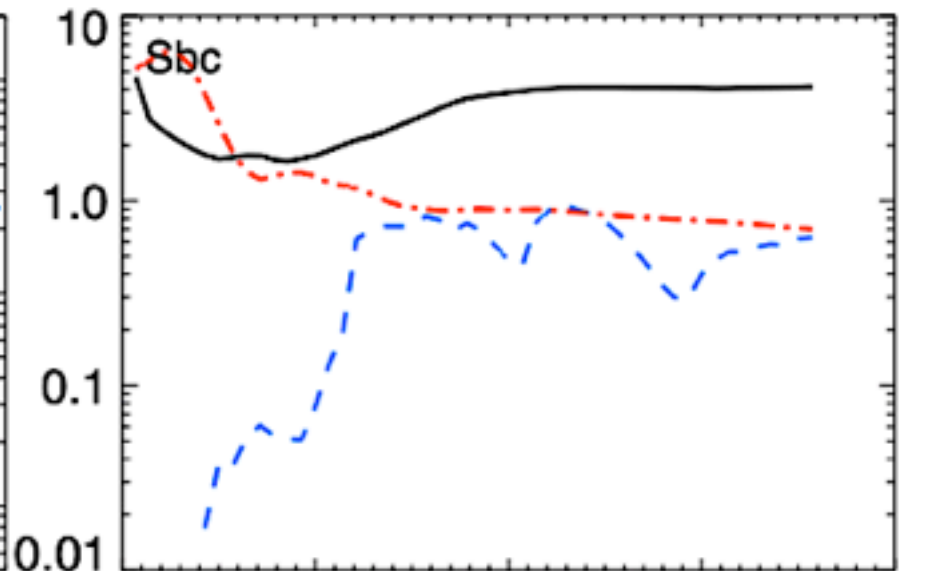
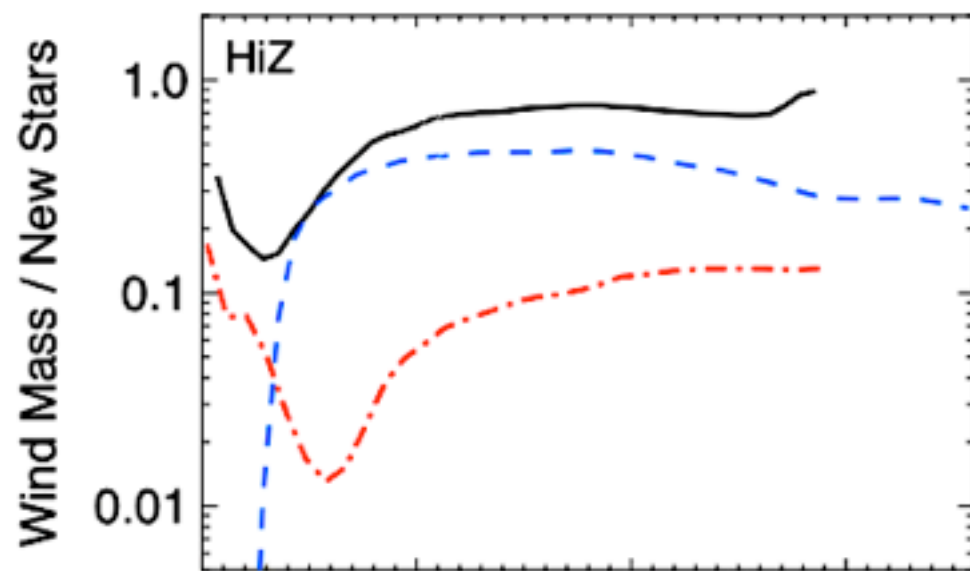
How Efficient Are Galactic Super-Winds?

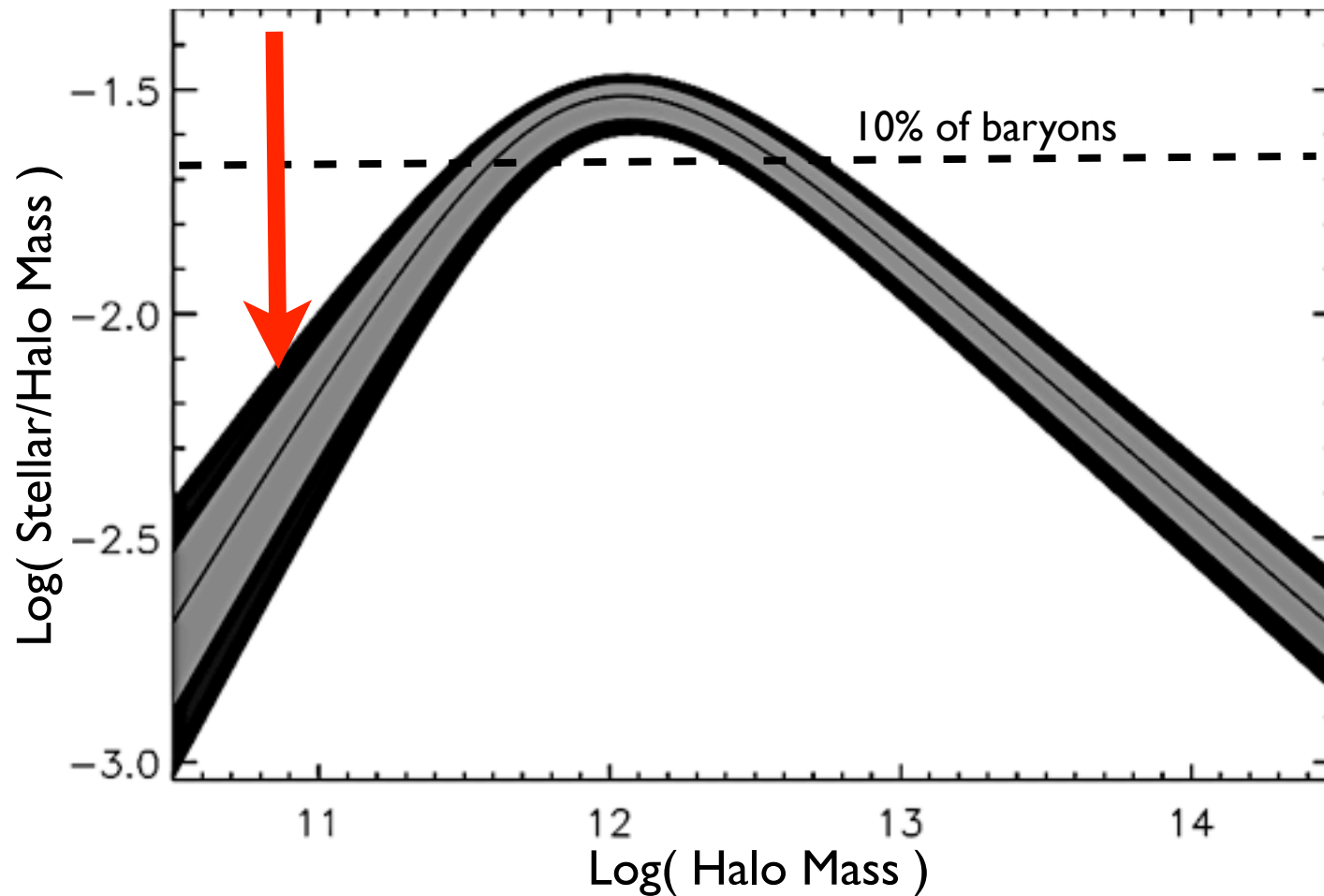
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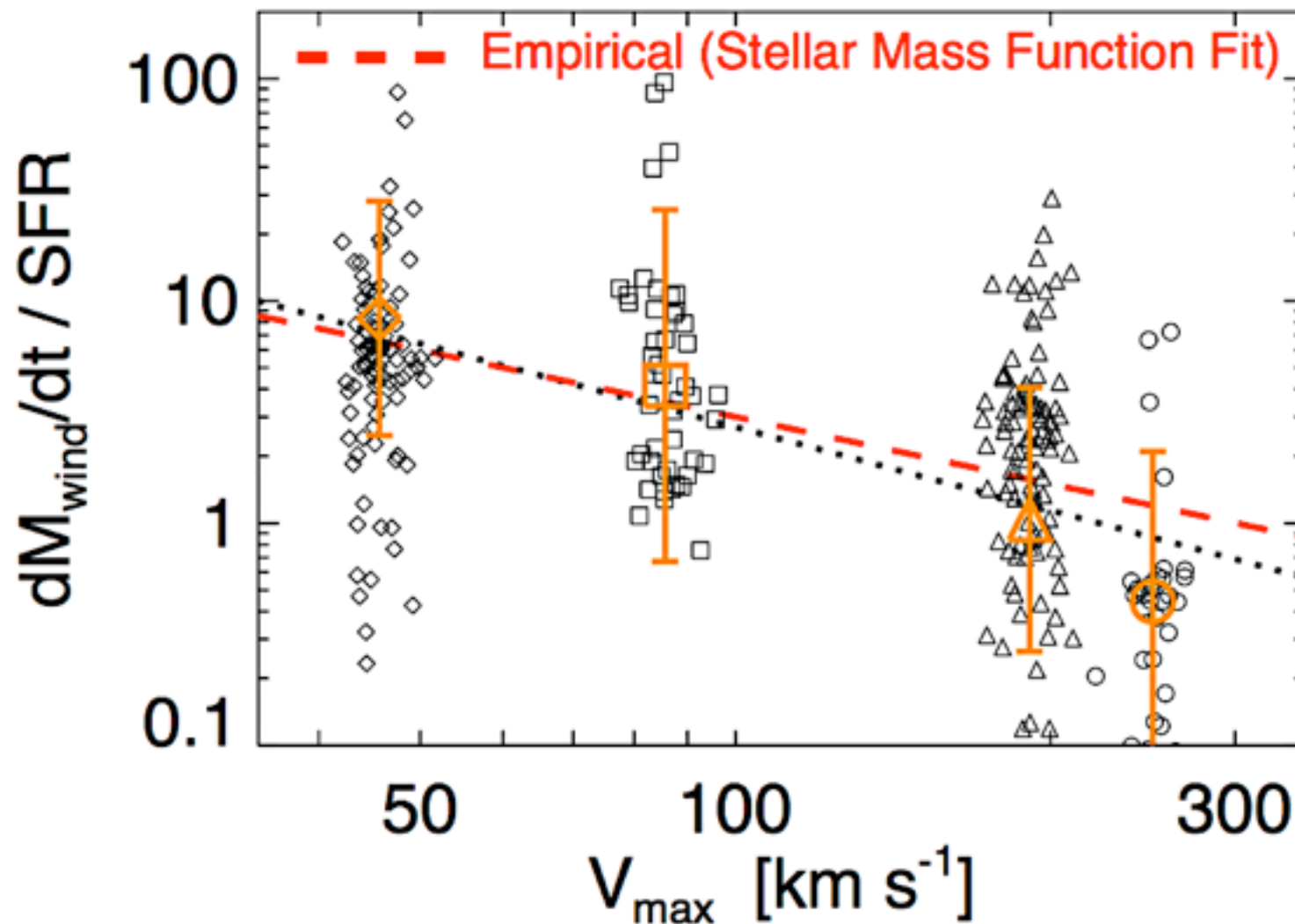
Dwarf Starburst





➤ Large mass-loading:

$$\dot{M}_{\text{wind}} \approx 10 \dot{M}_* \left(\frac{V_c}{100 \text{ km s}^{-1}} \right)^{-1.1} \left(\frac{\Sigma_{\text{gas}}}{10 M_{\odot} \text{ pc}^{-2}} \right)^{-0.5}$$

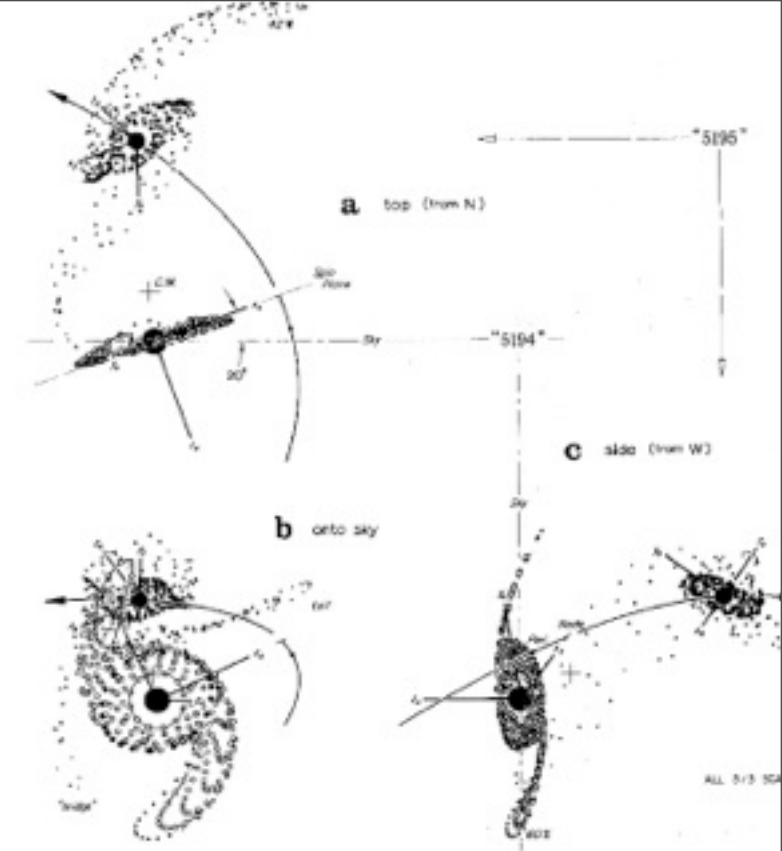


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What Happens when Galaxies Interact?

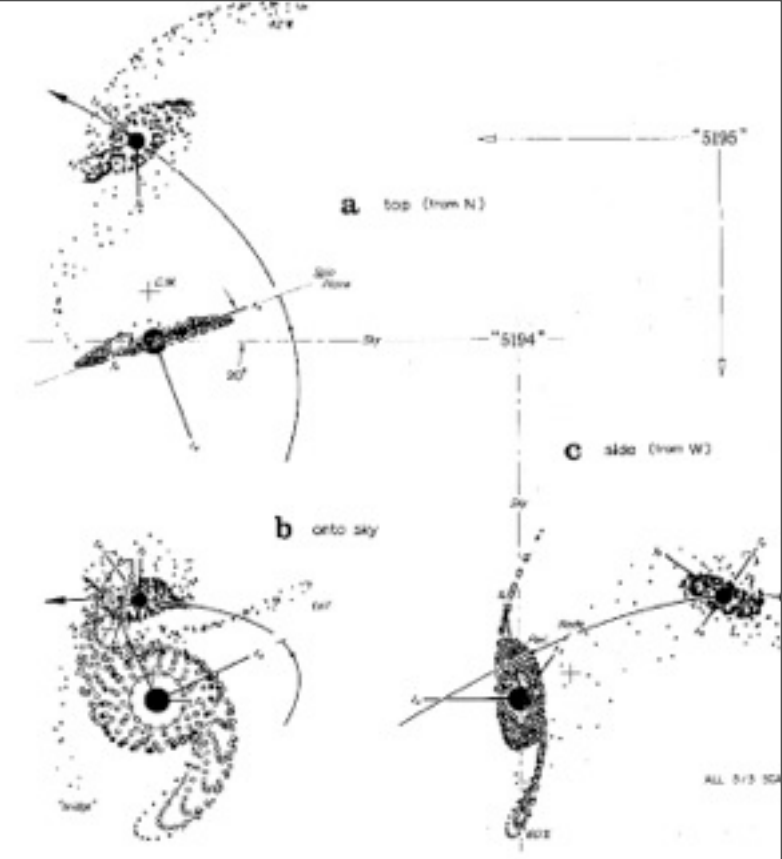
Our Conventional Wisdom (Toomre):



F. Summers

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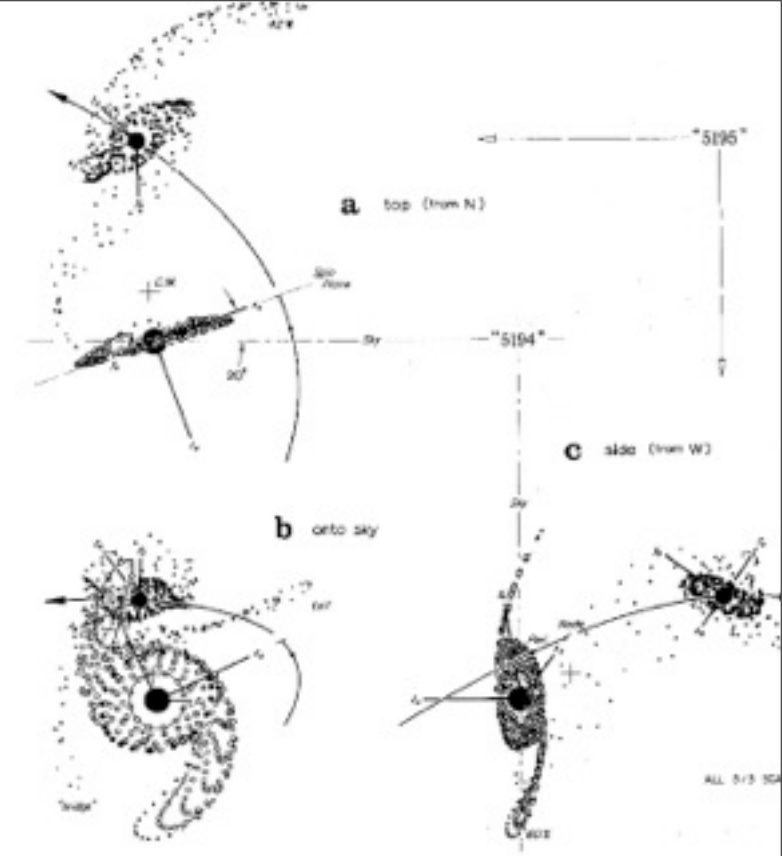
- Major mergers destroy disks



F. Summers

Our Conventional Wisdom (Toomre):

- Major mergers destroy disks
- Remnant size/metallicity/shape retains “memory” of disk “initial conditions”

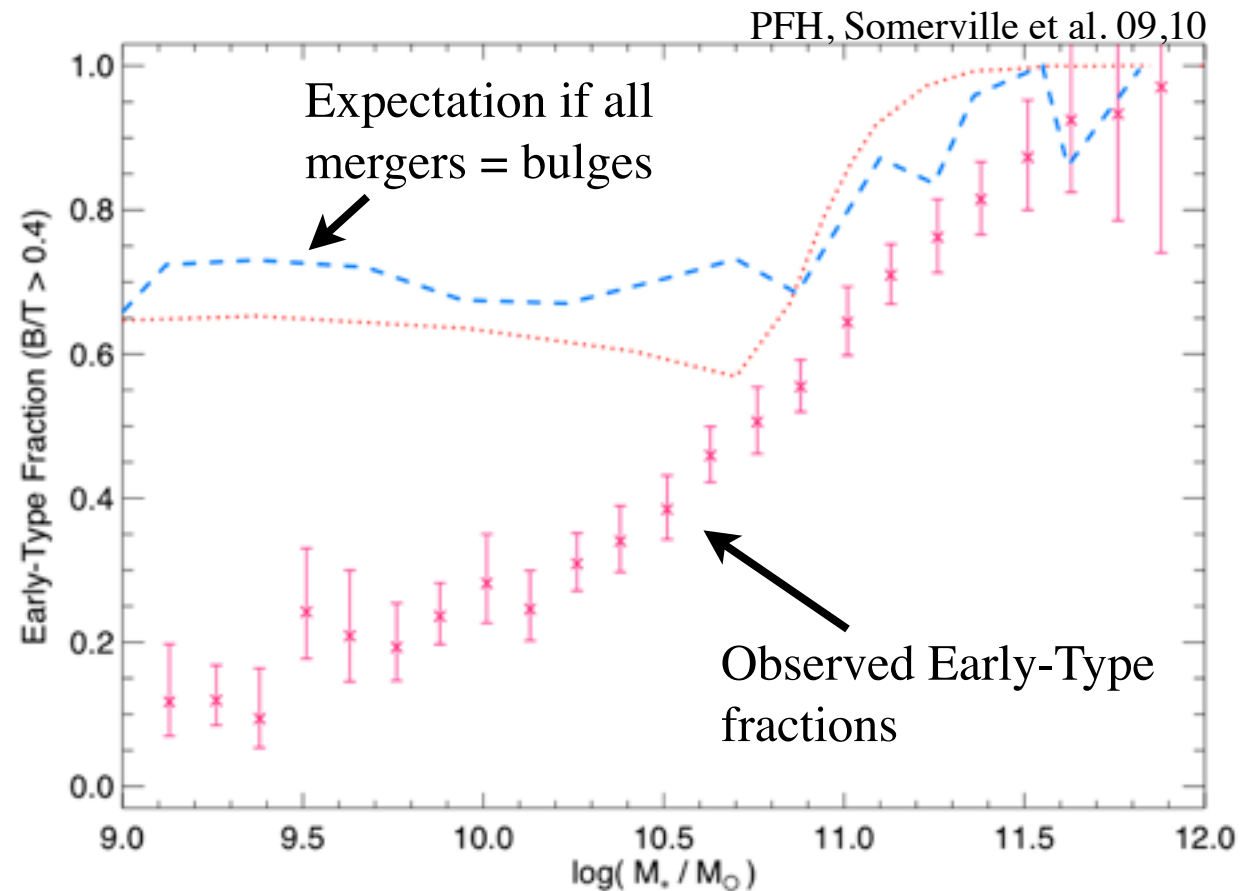


F. Summers

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

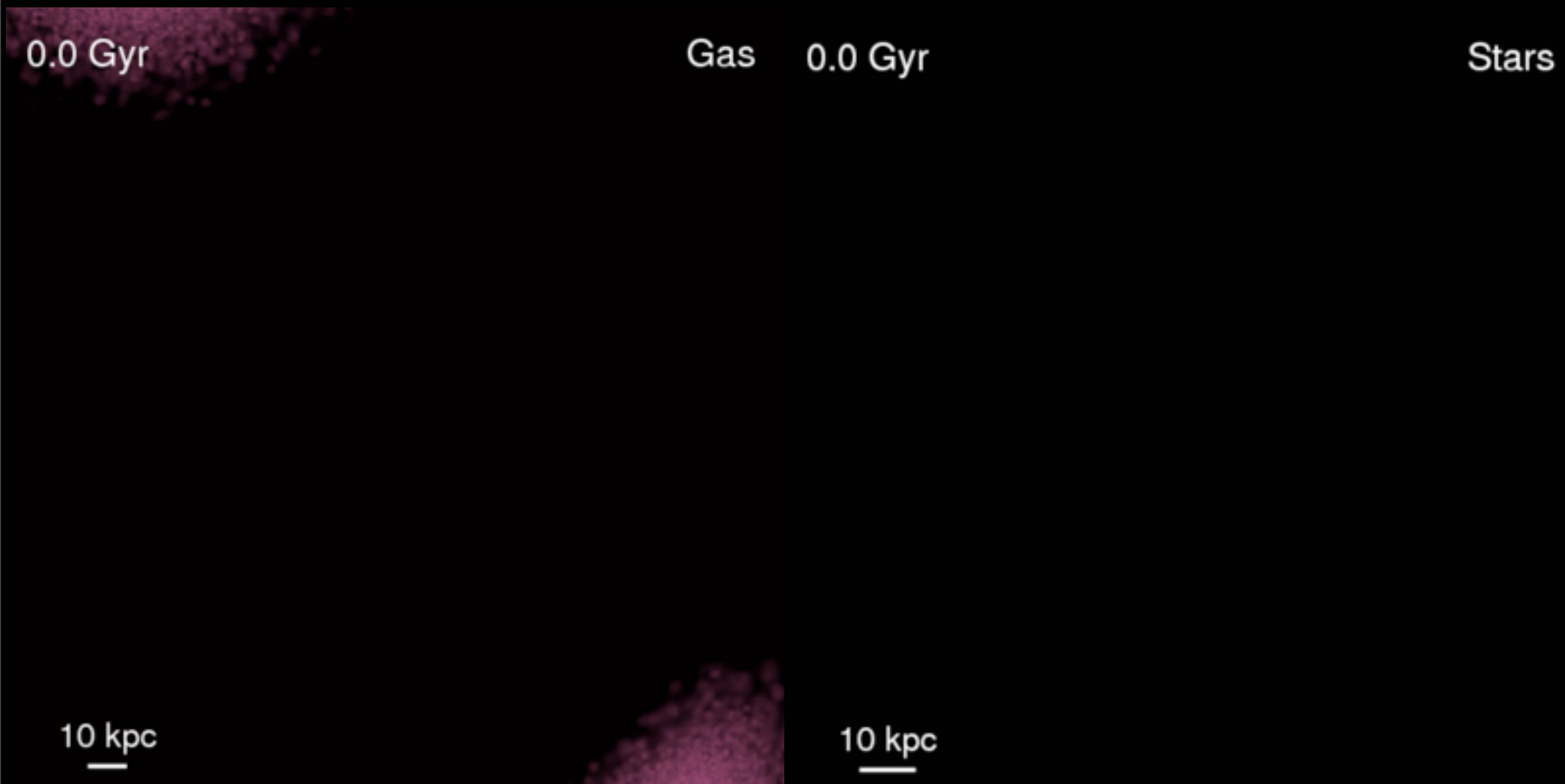
Too Many Mergers?

-- missing key
physics?

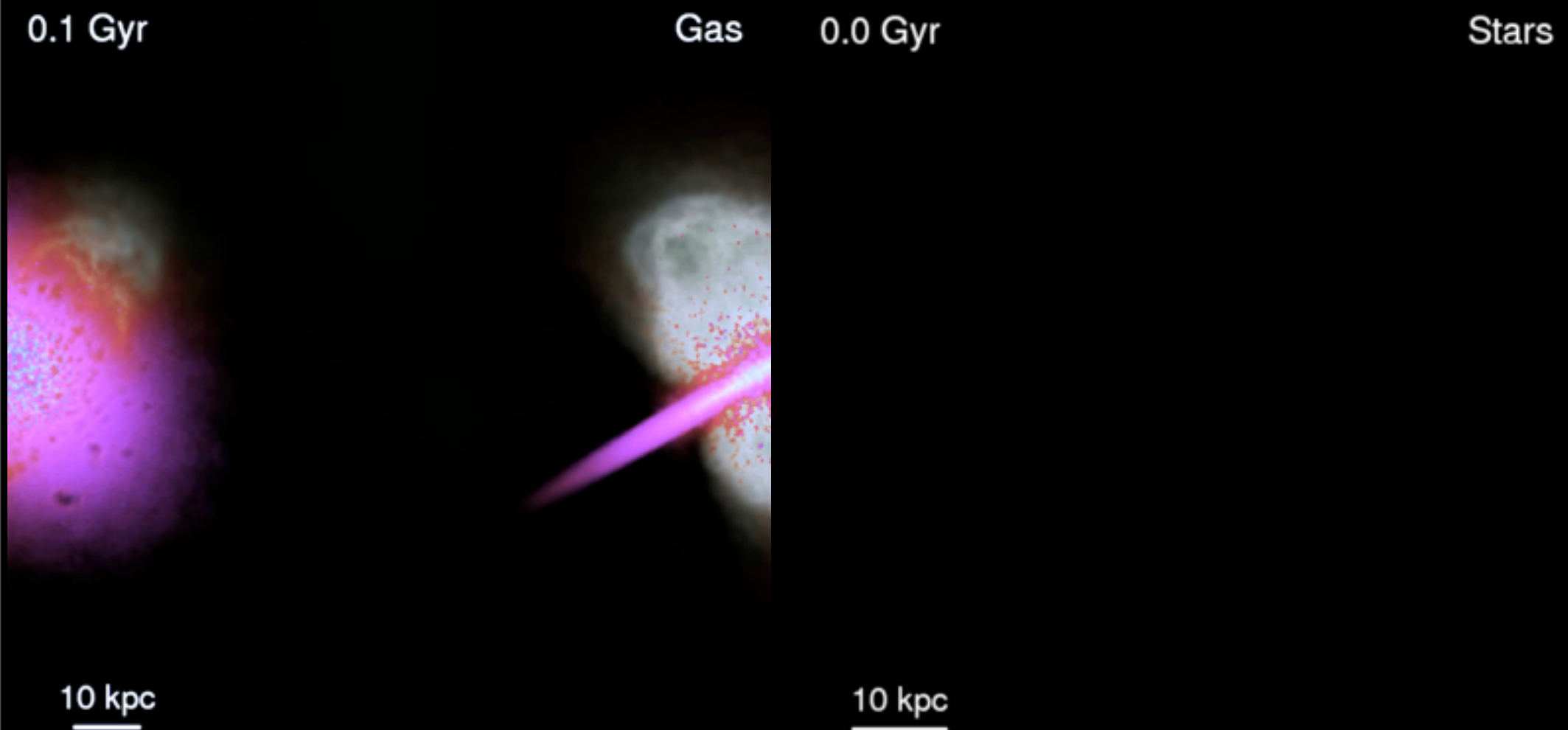


Stellar disk-disk merger remnants don't look like bulges!

Milky Way (~5% Gas) Merger



Starburst (~40% Gas) Merger



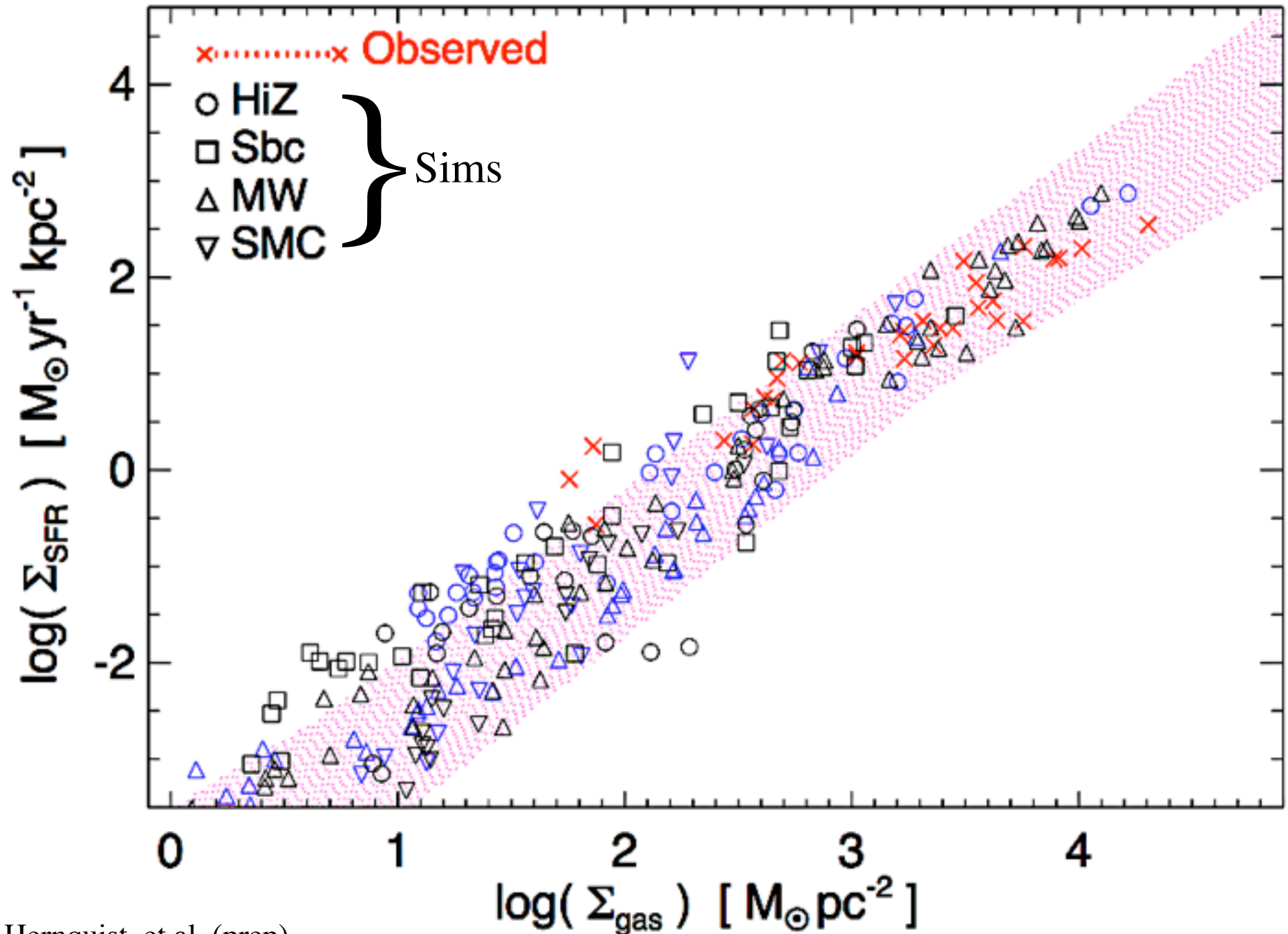
Galaxy Mergers

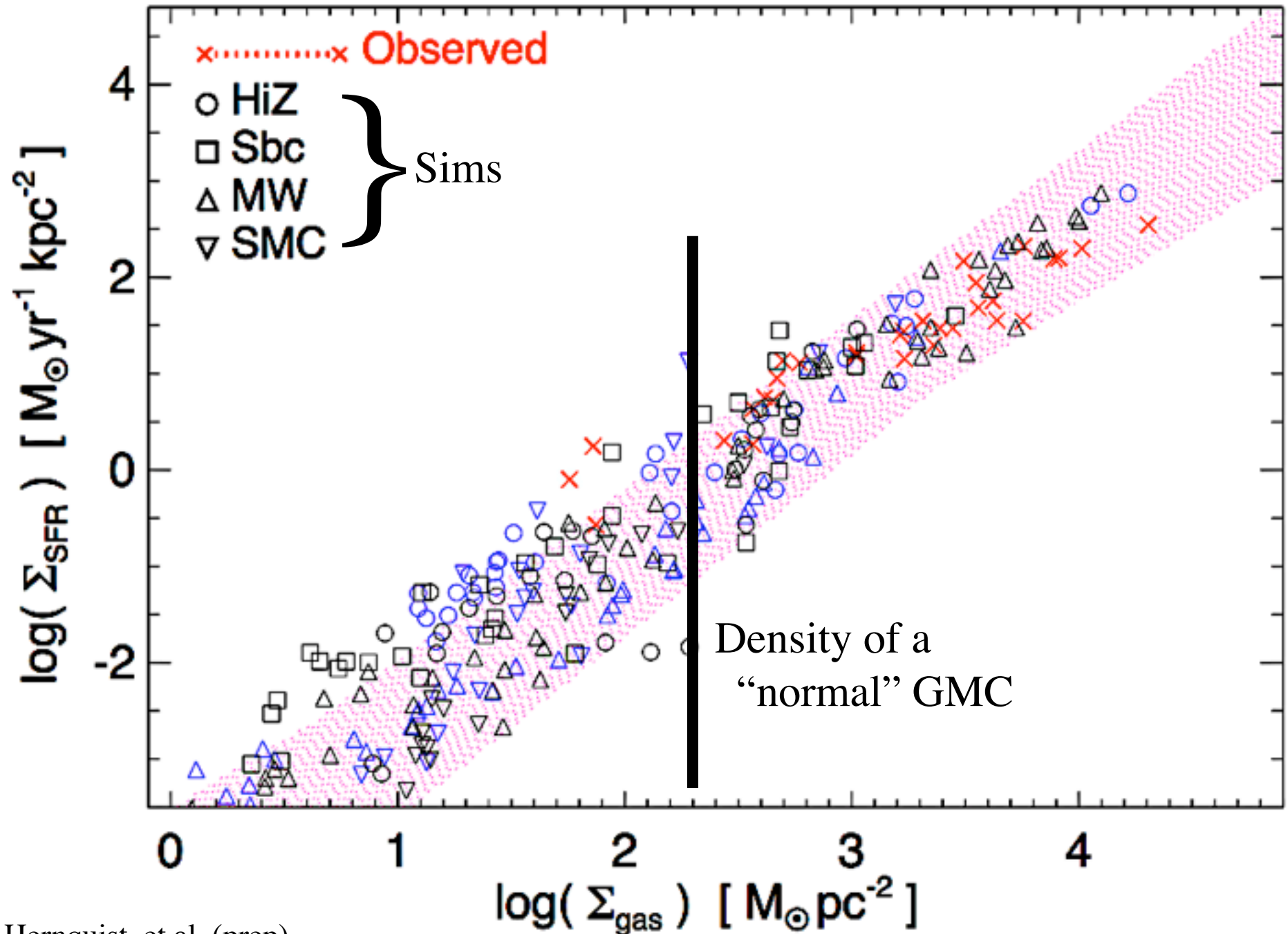
LABORATORY FOR STUDYING EXTREME CONDITIONS

PFH, Kormendy & Lauer et al.

- Fraction of star formation in mergers
- Effects on galaxy:
 - Sizes
 - Kinematics
 - Structure
- Star formation in starbursts and tidal shocks
- Super-winds:
 $\sim 10\text{-}500 M_{\text{sun}}/\text{yr}$

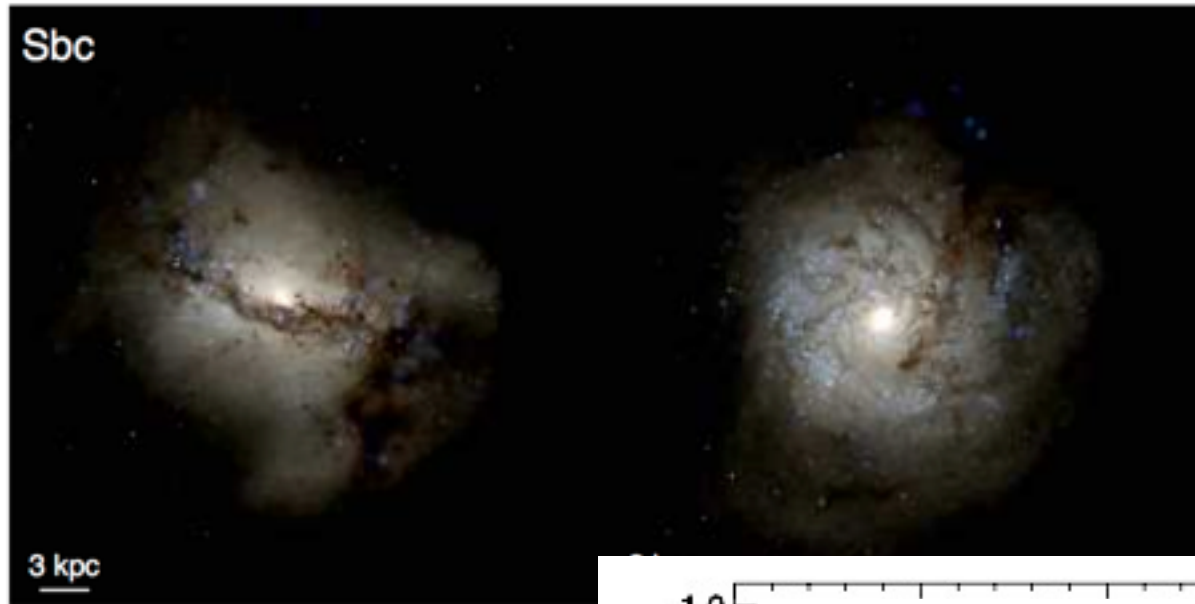




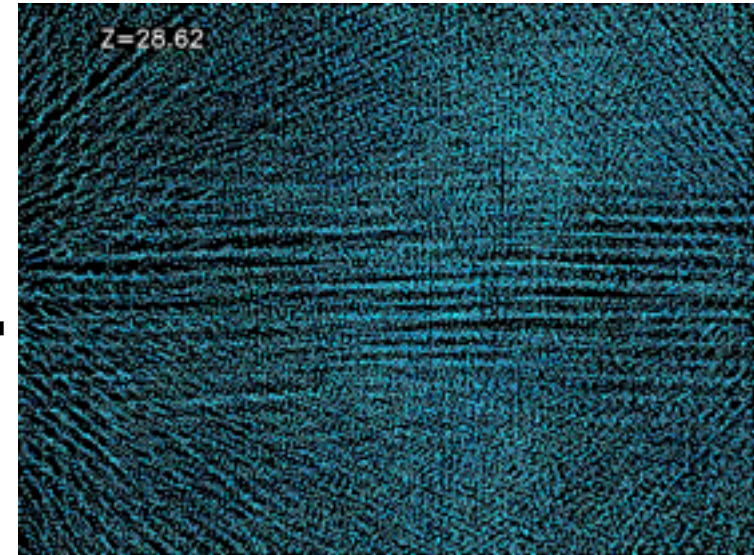


Disks can Survive & Re-Form After Mergers

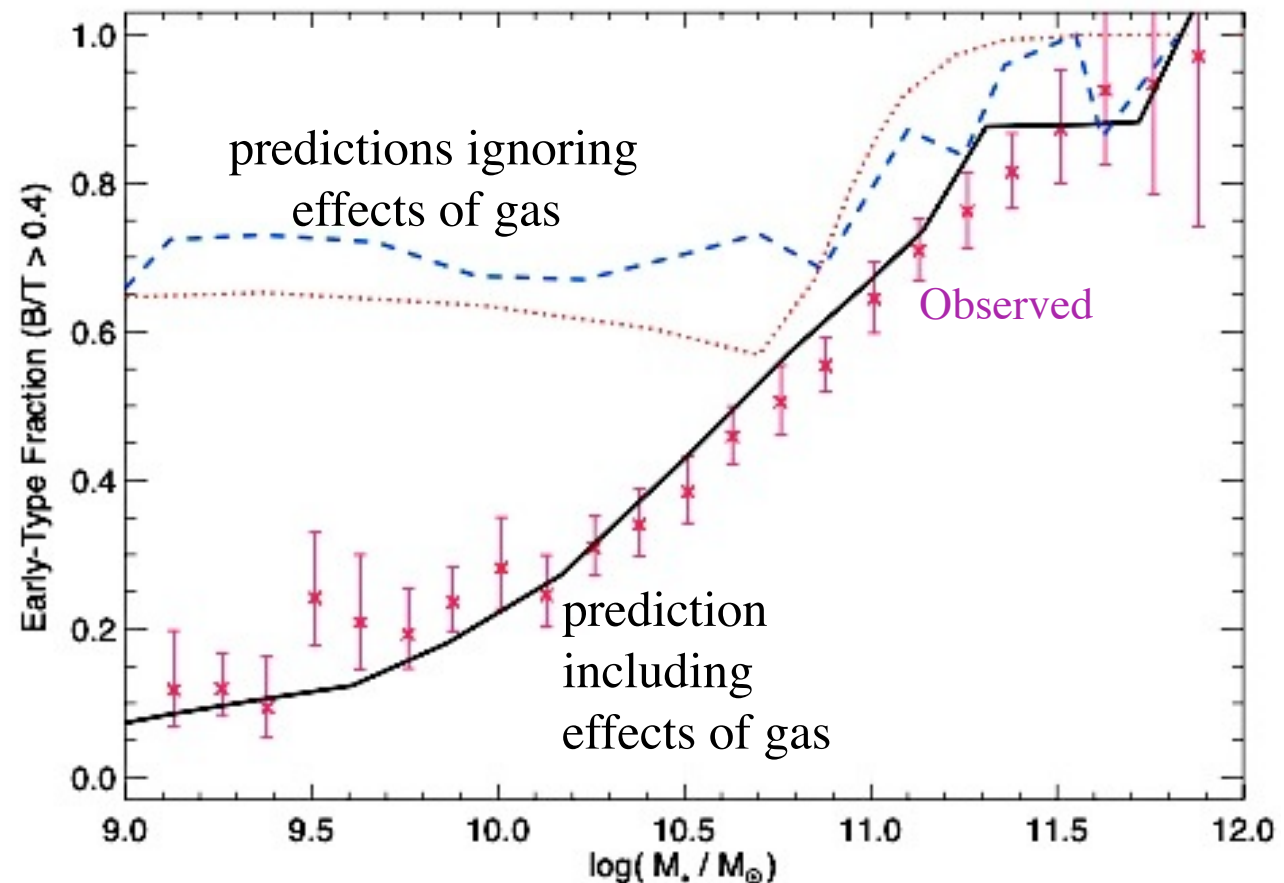
NOT AS FRAGILE AS WE THOUGHT!



+



=



PFH & Somerville et al. 2009

High Redshifts & The Inflow/Outflow Cycle

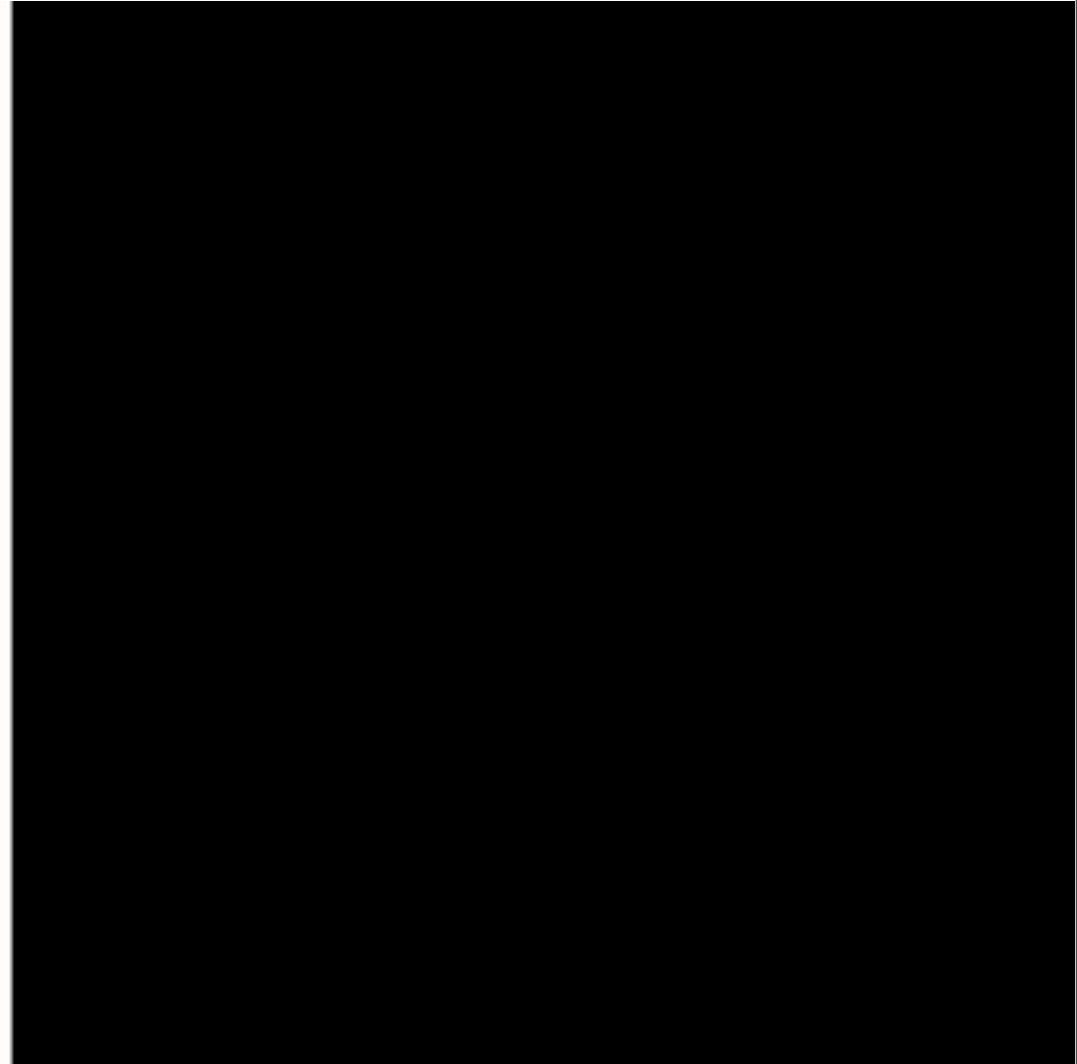
Cosmological Simulations

“ZOOM-IN” ON THE FORMATION OF A MASSIVE GALAXY

$z=29.99$ box=200/h kpc(phys)



IGM Density

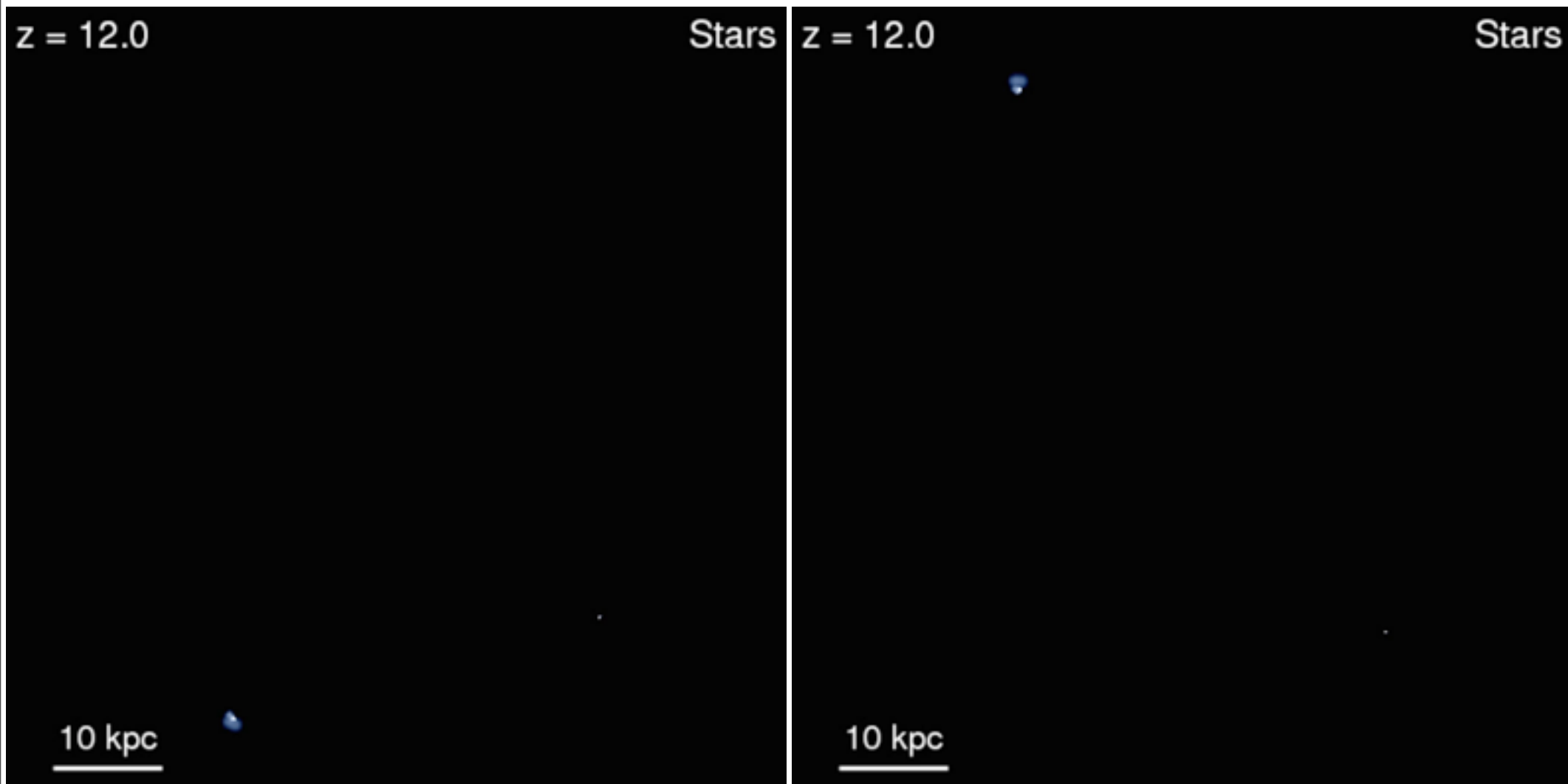


IGM Temperature

PFH & Keres et al

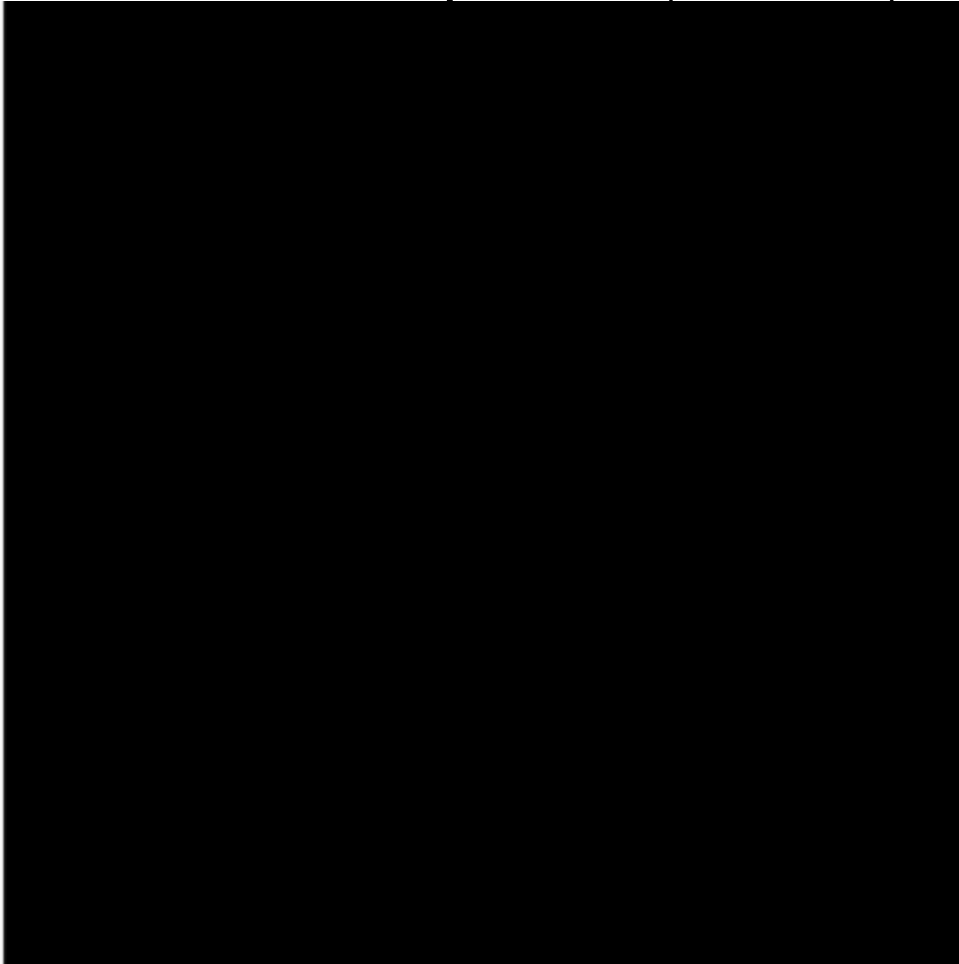
Cosmological Simulations

“ZOOM-IN” ON THE FORMATION OF A MASSIVE GALAXY

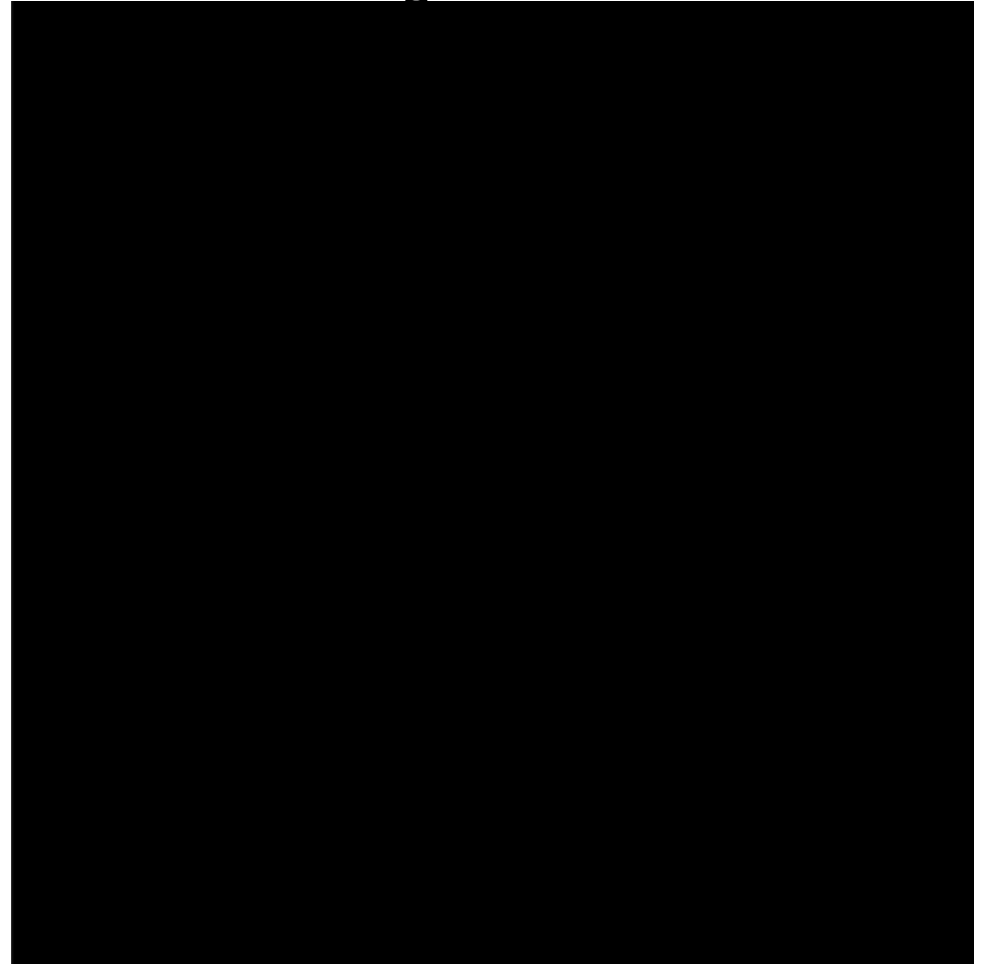


Proto-MW: Gas Temperature:

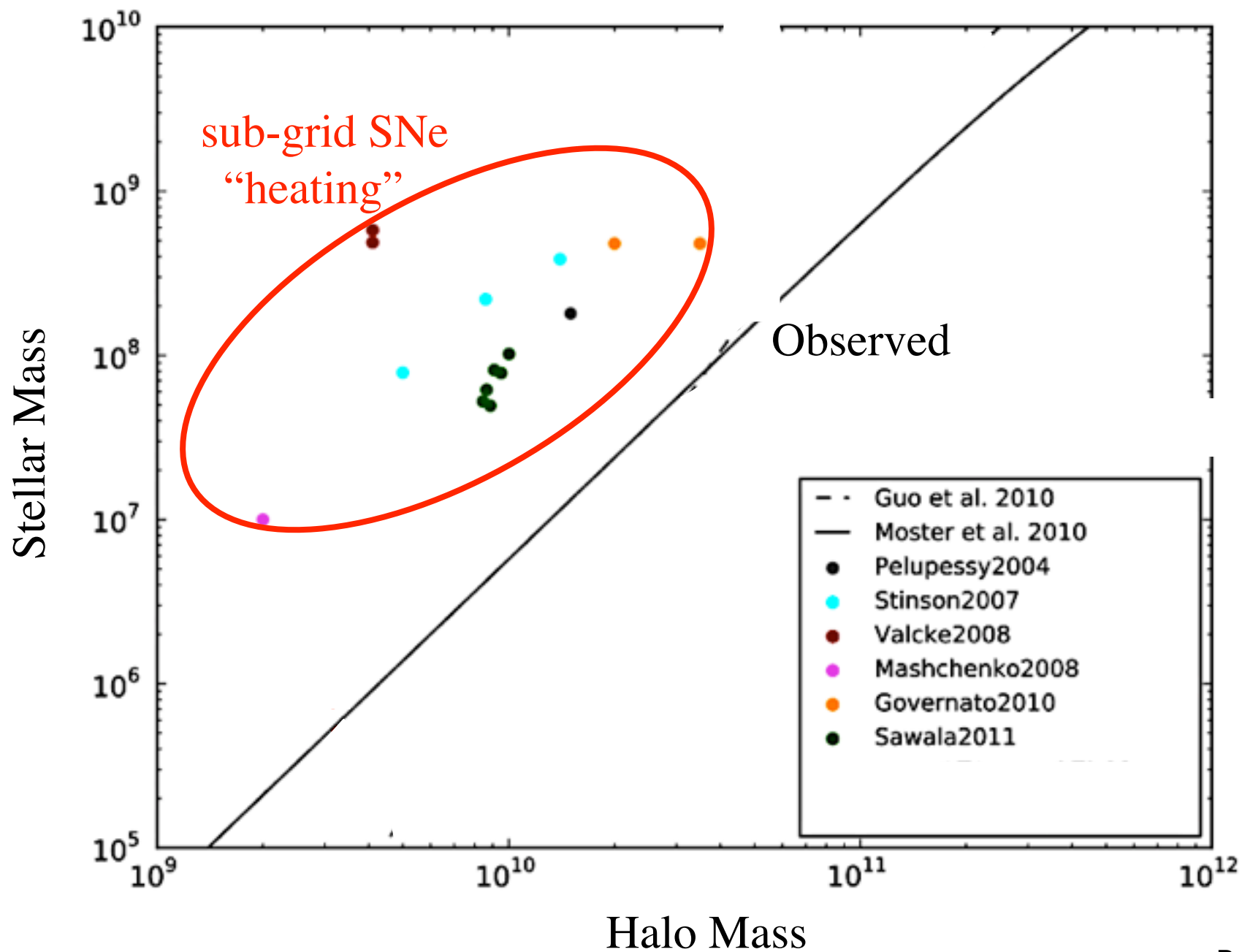
Insert Winds “By Hand” (Sub-Grid)



Following Full Feedback

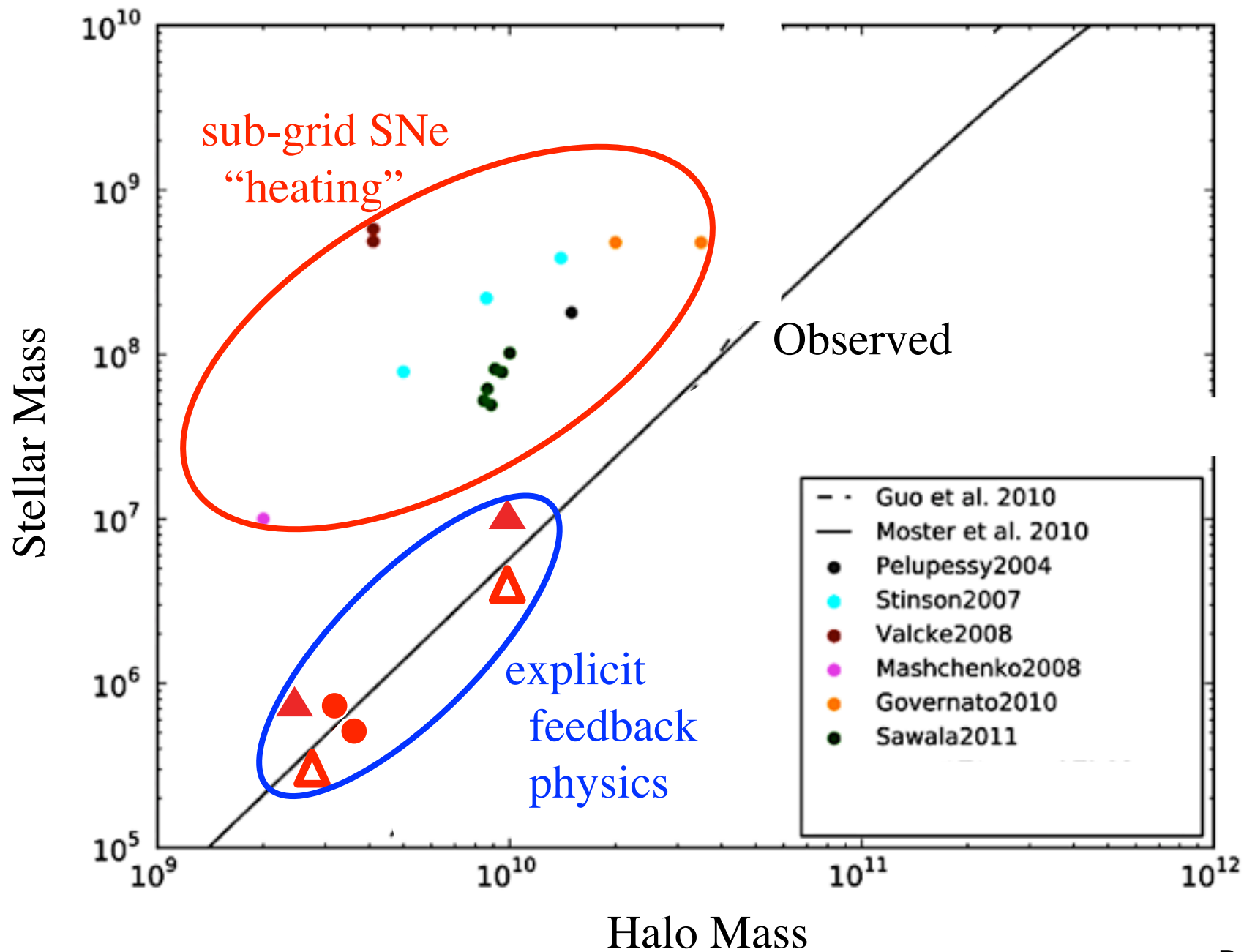


Is Star Formation Inefficient?



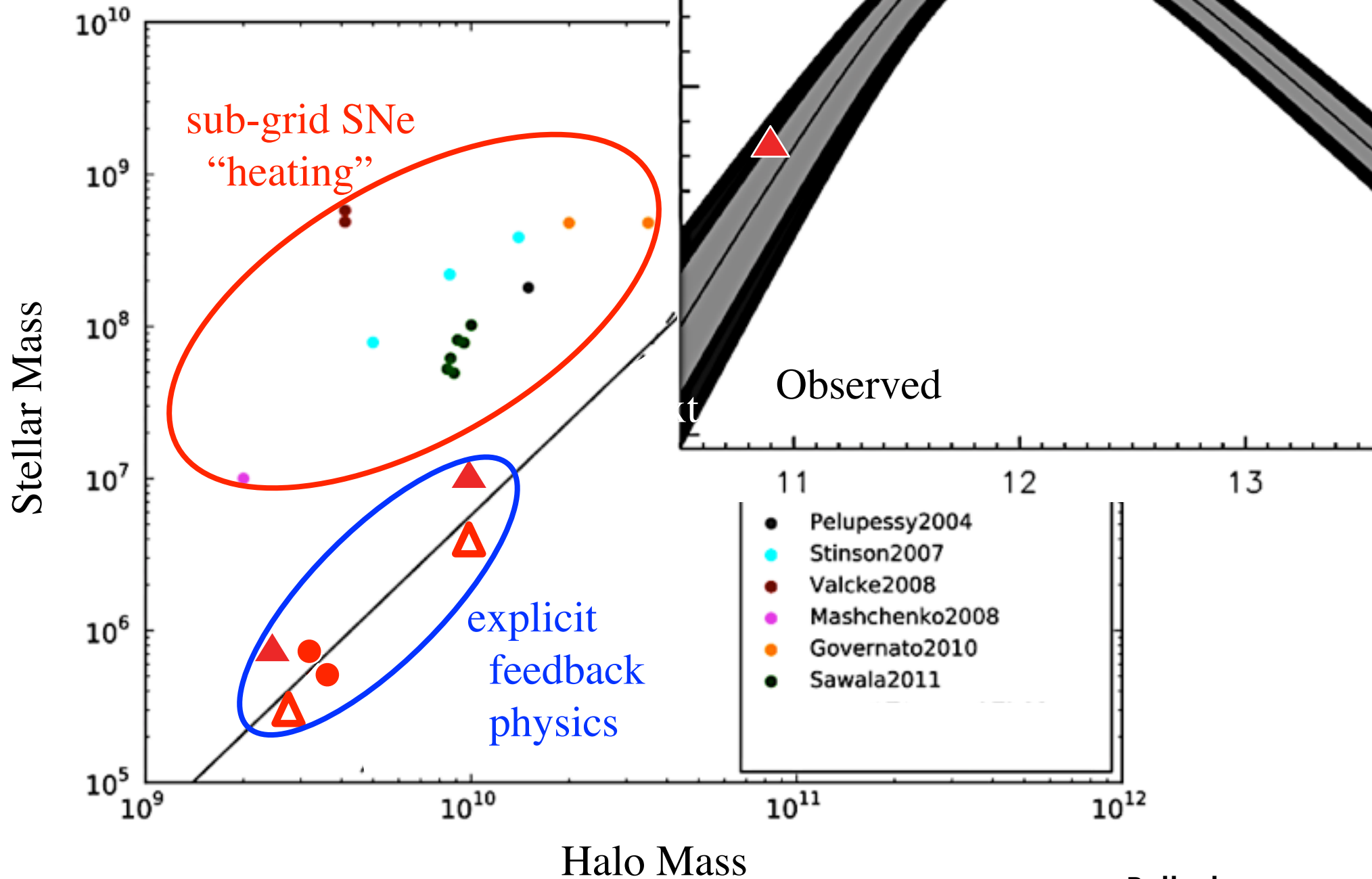
Bullock,
& Onorbe et al.

Is Star Formation Inefficient?



Bullock,
& Onorbe et al.

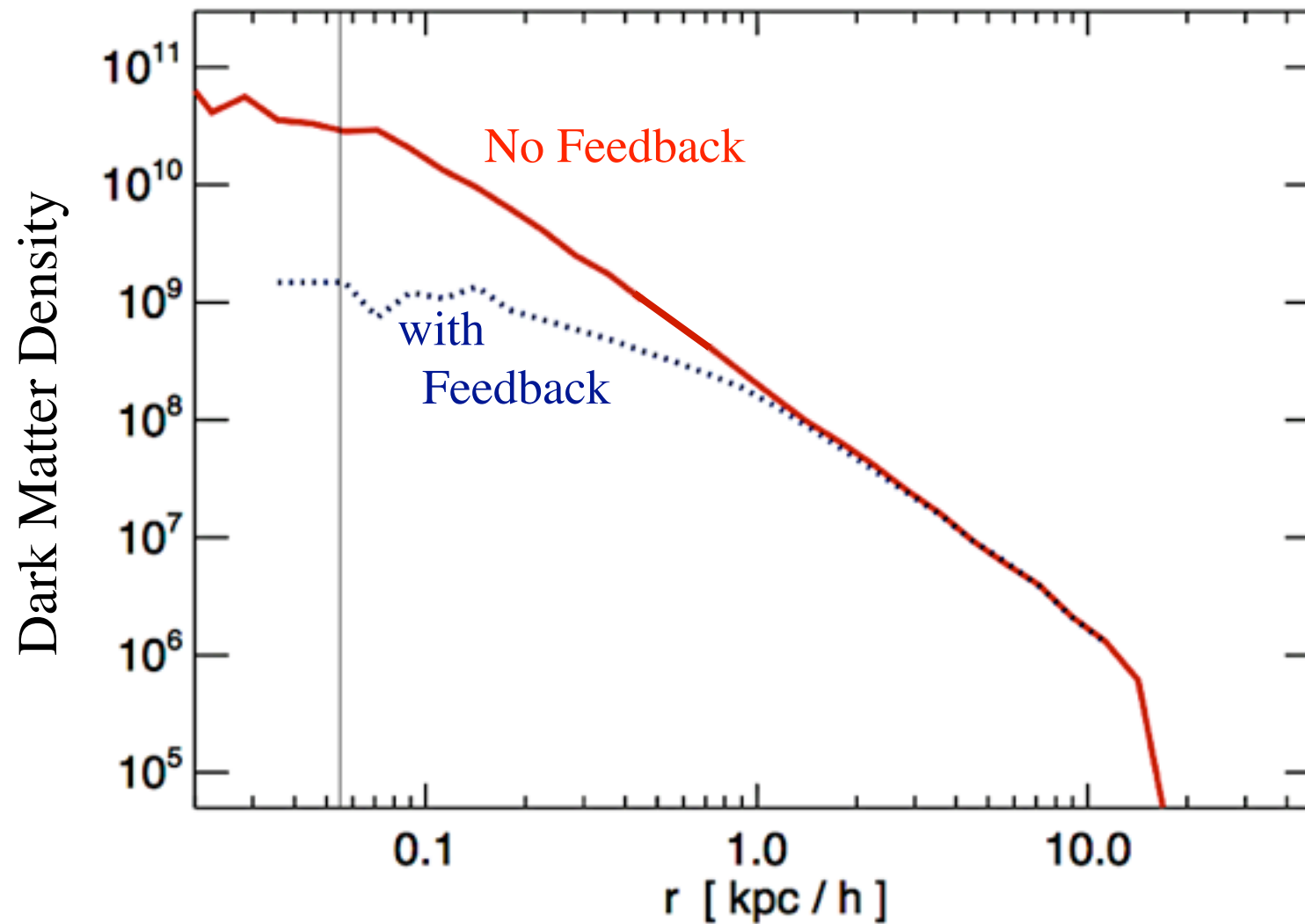
Is Star Formation Inefficient?



Bullock,
& Onorbe et al.

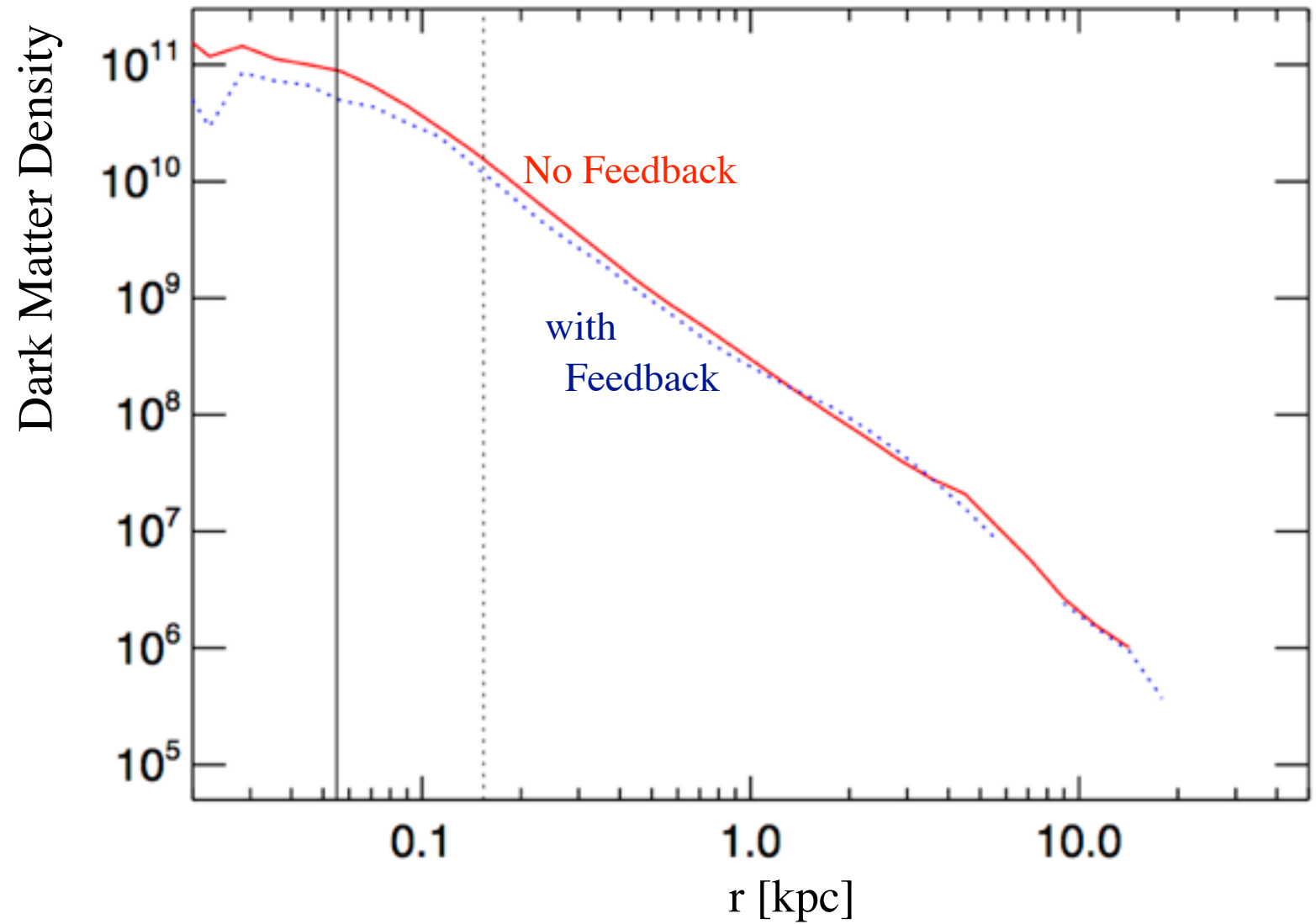
Dark Matter Profiles: Baryons or Cosmology?

WHAT CAN WE LEARN ABOUT COSMOLOGY AND STRUCTURE FORMATION?



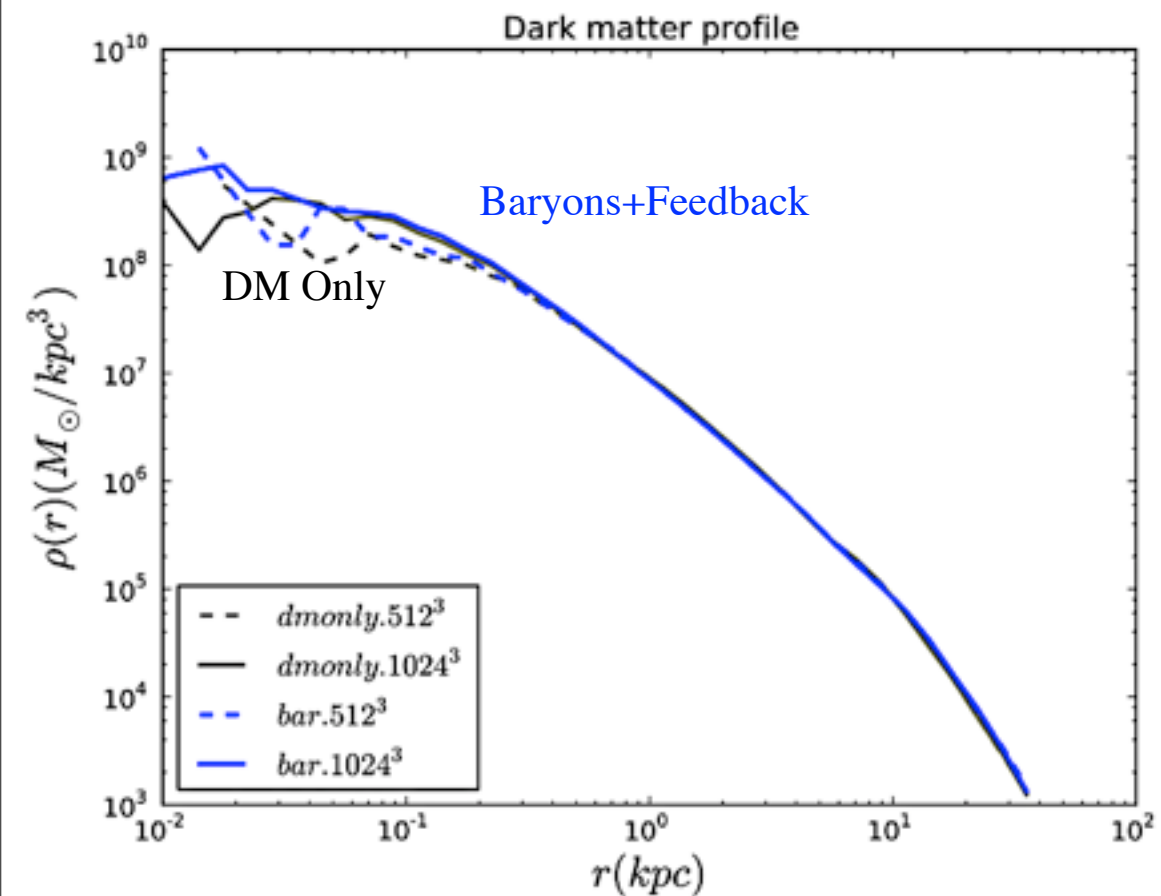
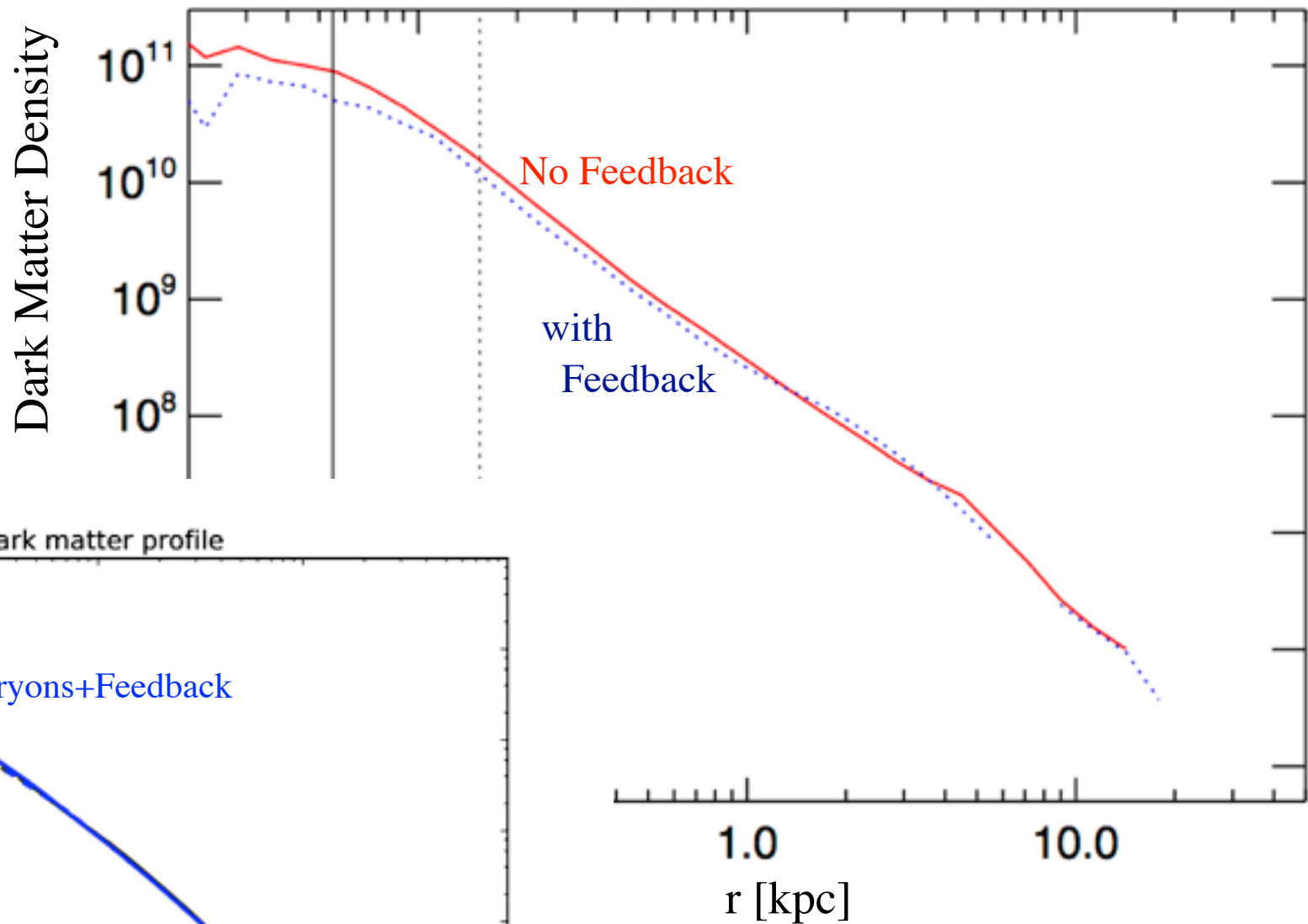
PFH & Keres et al
PFH, Bullock,
& Onorbe et al

BUT...



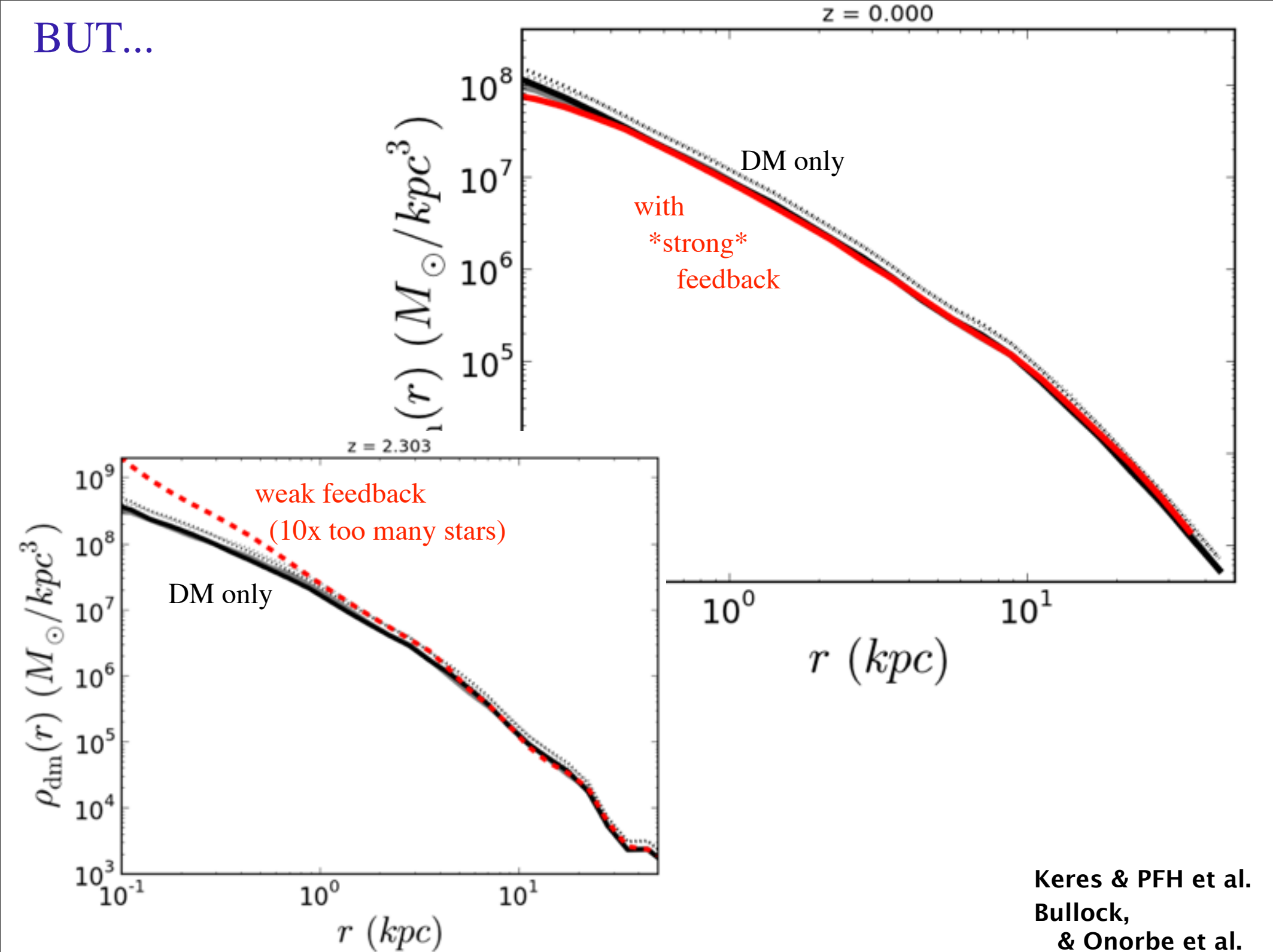
Keres & PFH et al.
Bullock,
& Onorbe et al.

BUT...



Keres & PFH et al.
Bullock,
& Onorbe et al.

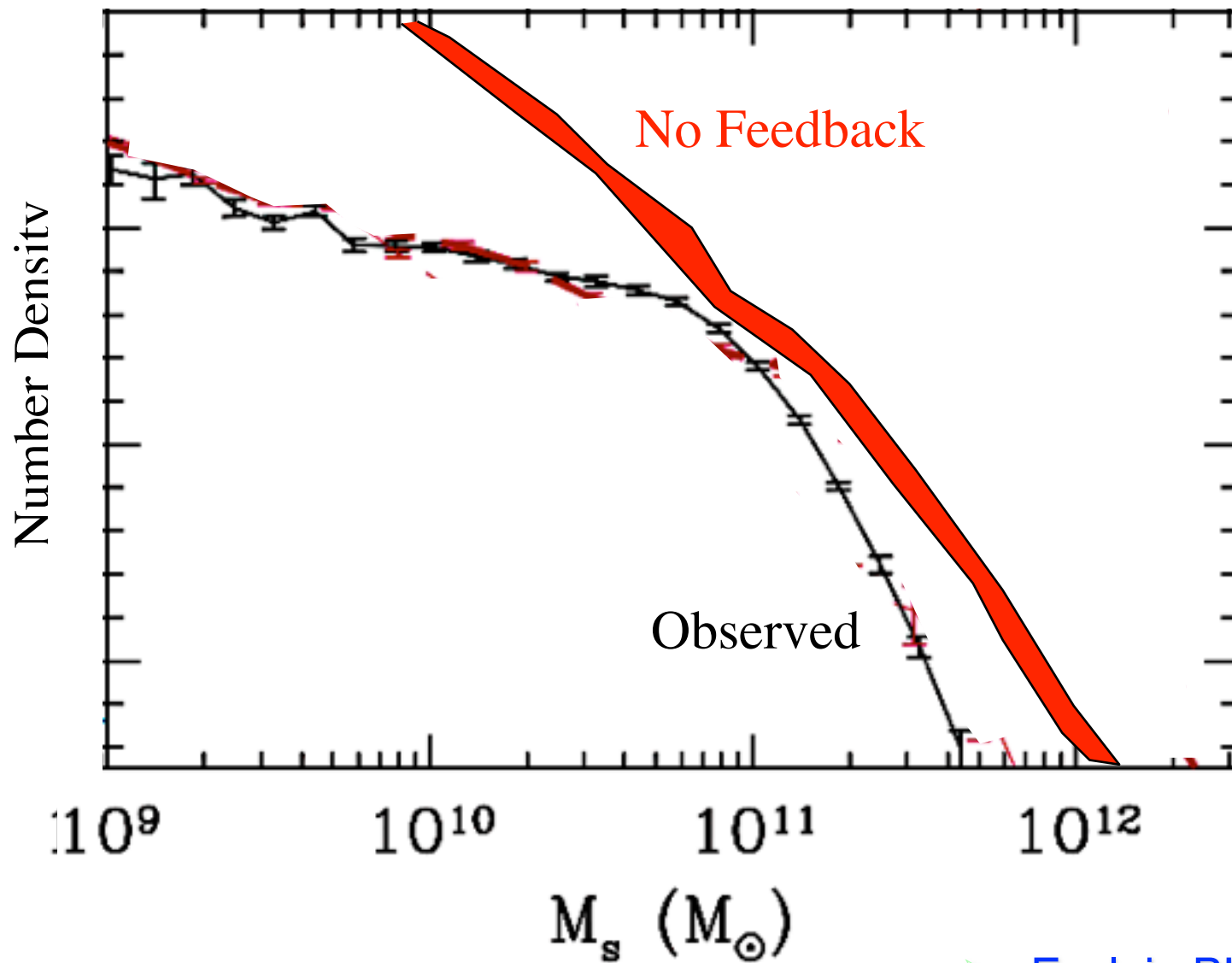
BUT...



Keres & PFH et al.
Bullock,
& Onorbe et al.

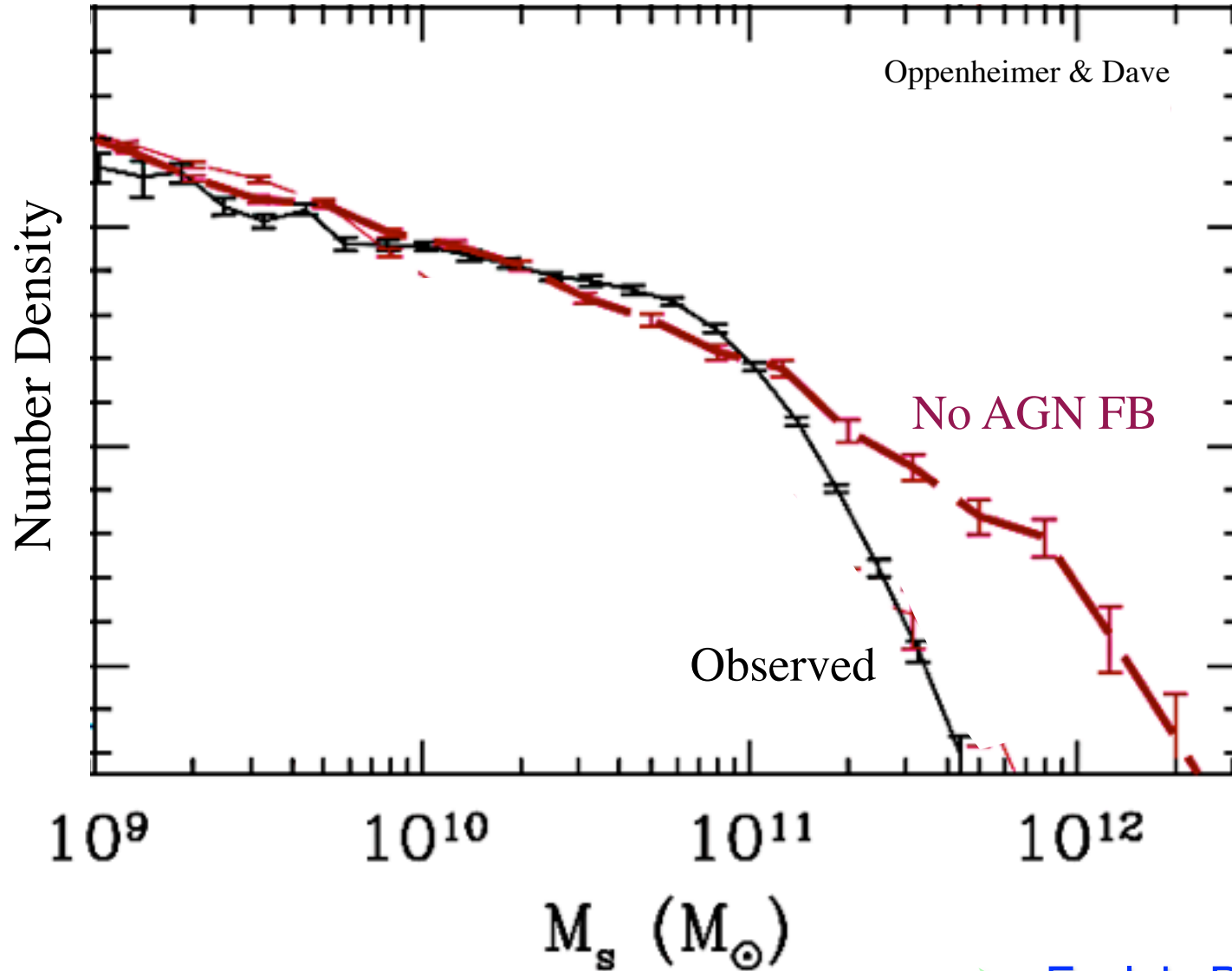
What About High-Mass Galaxies?

Why Do We Need AGN Feedback?



- Explain BH-host correlations
- Sharp color bimodality
- Removing/heating gas in groups

Why Do We Need AGN Feedback?



- Explain BH-host correlations
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Molecular Outflows in AGN & ULIRGs

OBSERVED WINDS at >1000 km/s

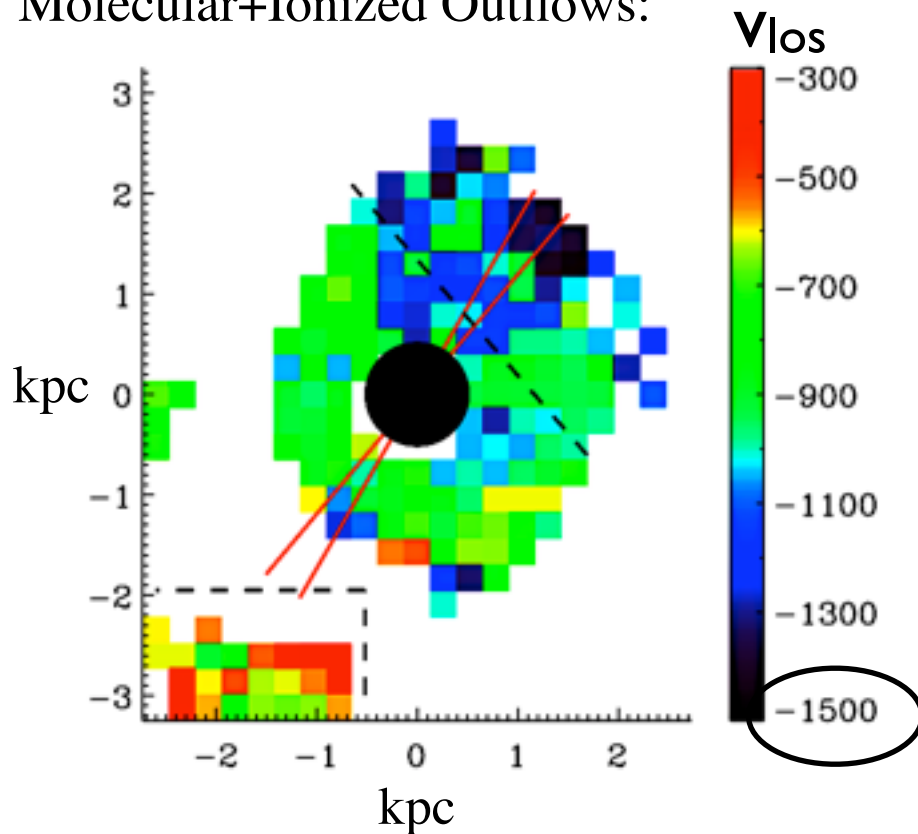
Rupke & Veilleux 2005,2011

Fischer et al. 2010 (Mrk 231)

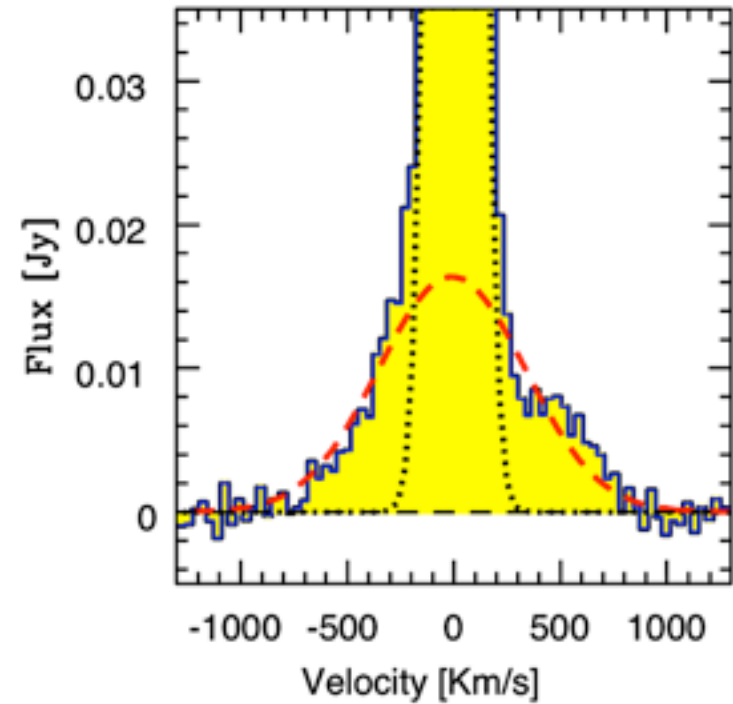
Feruglio et al. 2010 (Mrk 231)

Alatalo et al. 2011 (NGC 1266)

Molecular+Ionized Outflows:



CO:



$$R_{\text{wind}} \sim 1 - 4 \text{ kpc}$$

$$v > 500 \text{ km s}^{-1}$$

$$\dot{M}_{\text{wind}} \gtrsim 1000 M_{\odot} \text{ yr}^{-1}$$

Where to Now? How Do We Model This?

Step 1: *Stellar* Feedback & the ISM

- High-resolution ($\sim 1\text{pc}$), molecular cooling ($<100\text{ K}$), SF only at highest densities ($n_{\text{H}} > 1000\text{ cm}^{-3}$)

- Heating:

- SNe (II & Ia)
- Stellar Winds
- Photoionization (HII Regions)

- *Explicit* Momentum Flux:

- Radiation Pressure

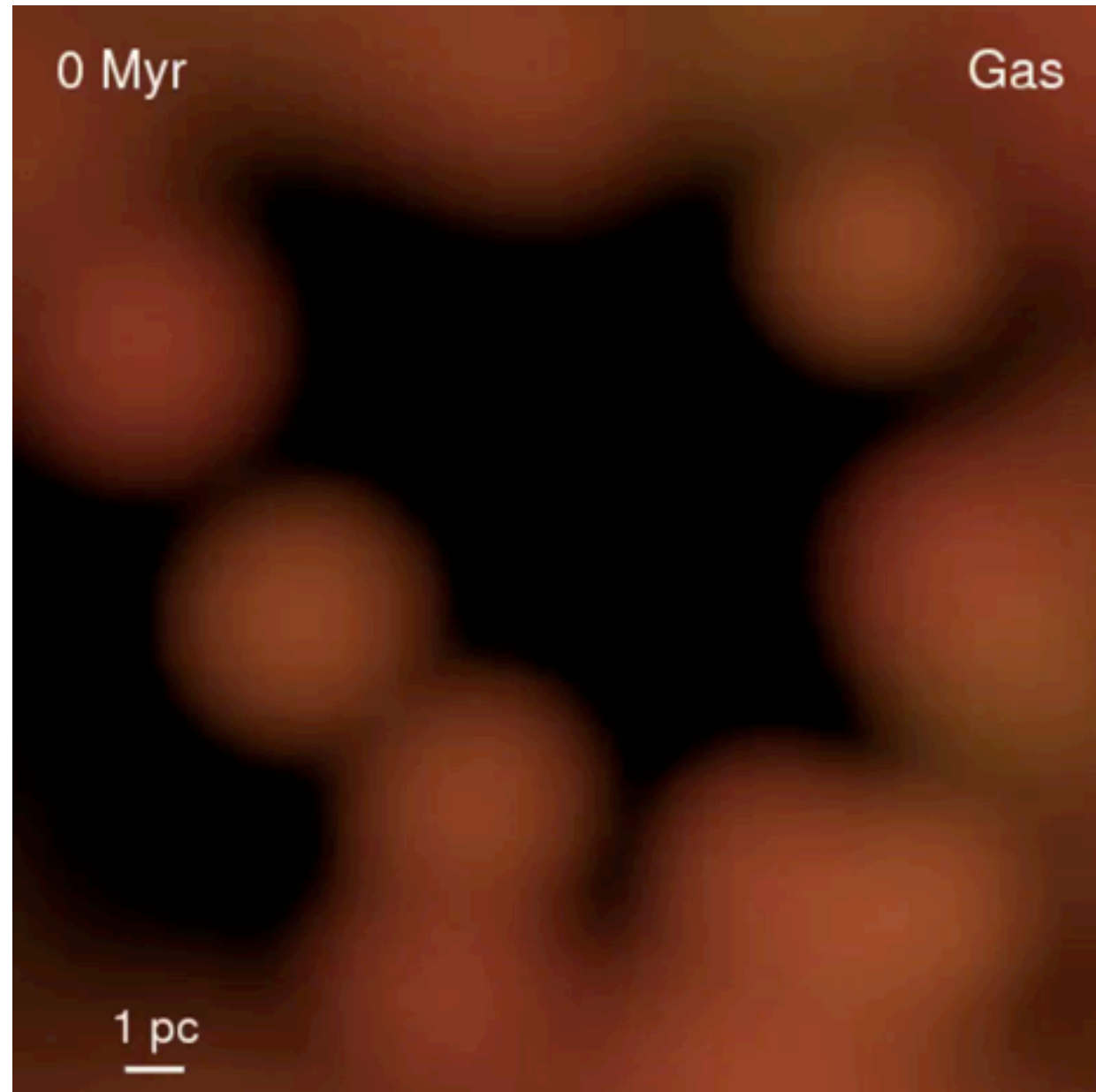
$$\dot{P}_{\text{rad}} \sim \frac{L}{c} (1 + \tau_{\text{IR}})$$

- SNe

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

- Stellar Winds

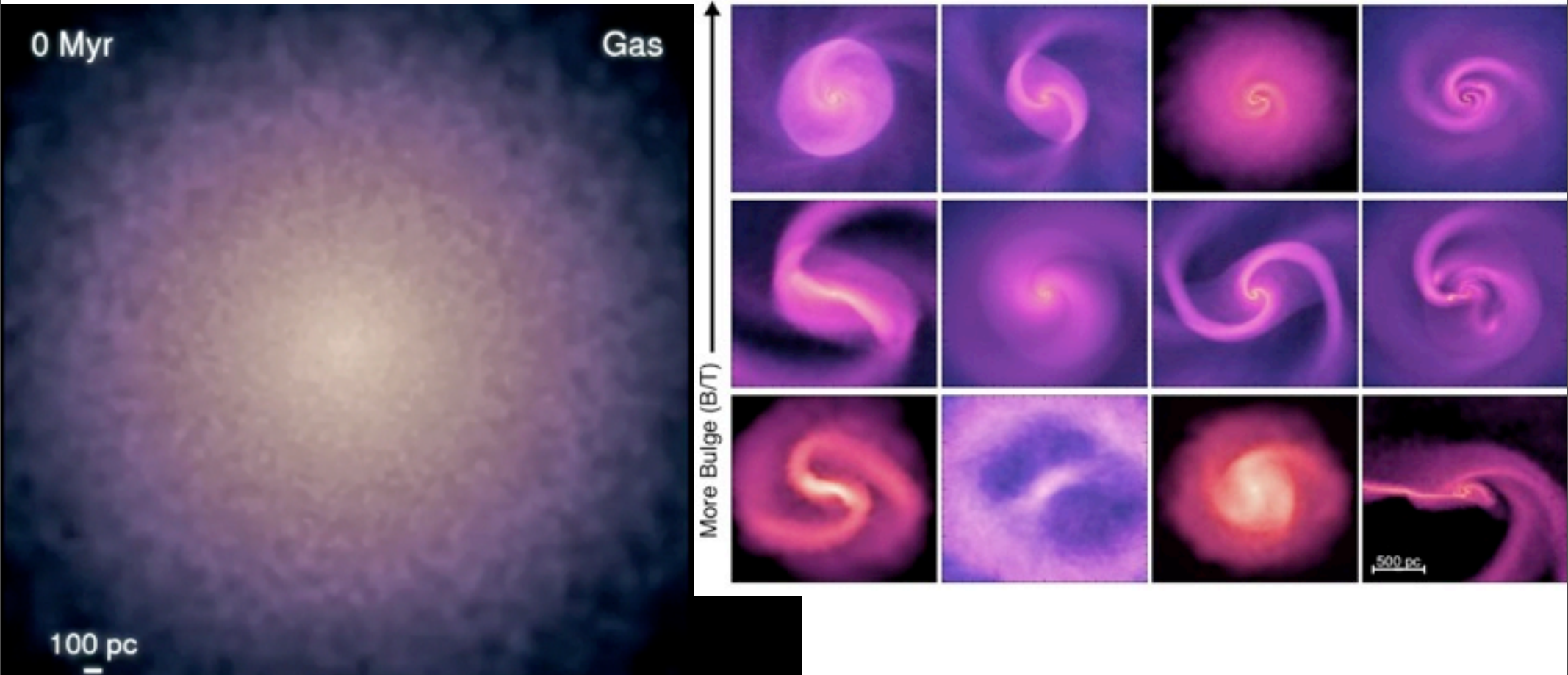
$$\dot{P}_{\text{W}} \sim \dot{M} v_{\text{wind}}$$



Step 2: Inflow

- Beginning to directly follow inflow to sub-pc scales

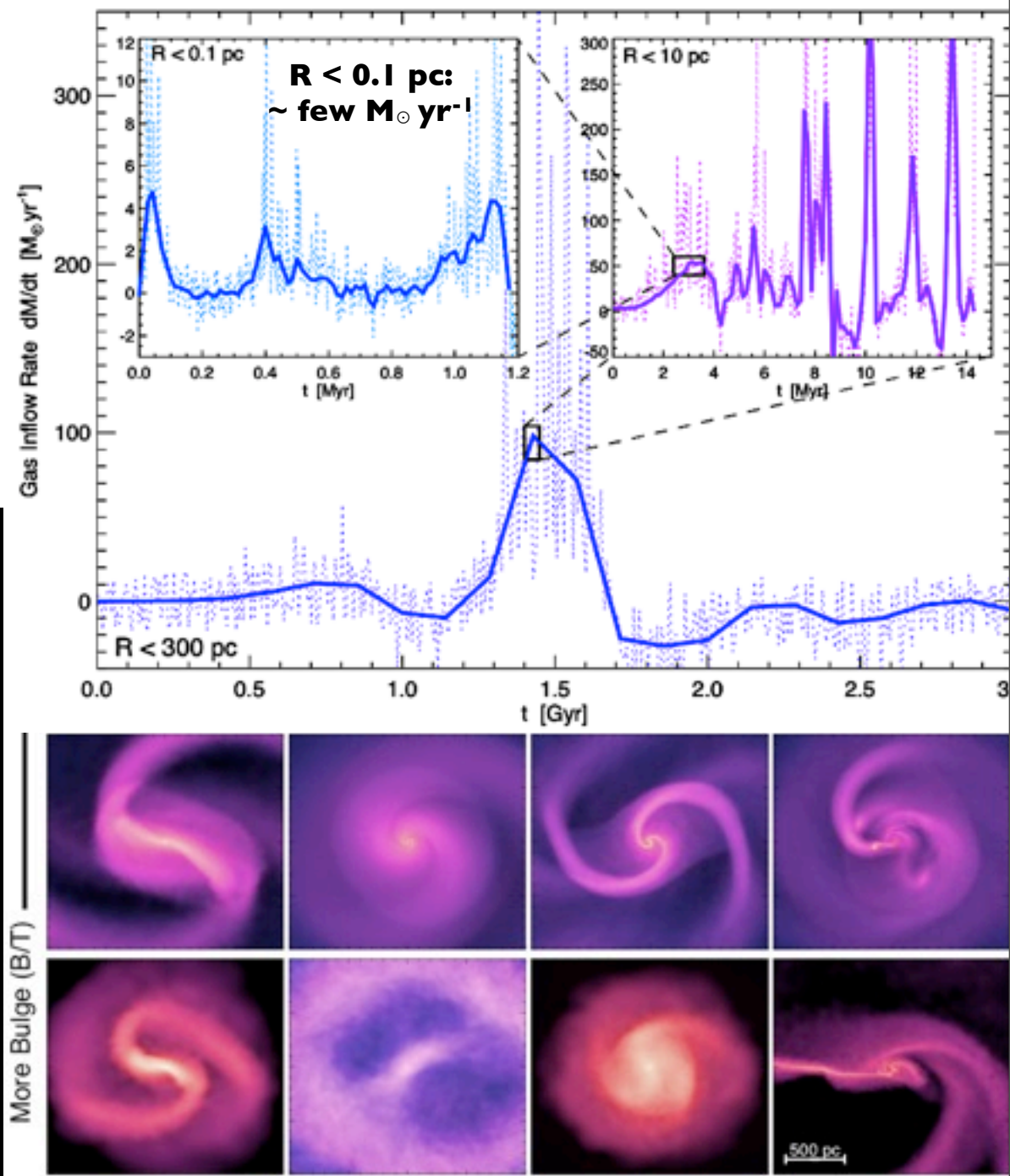
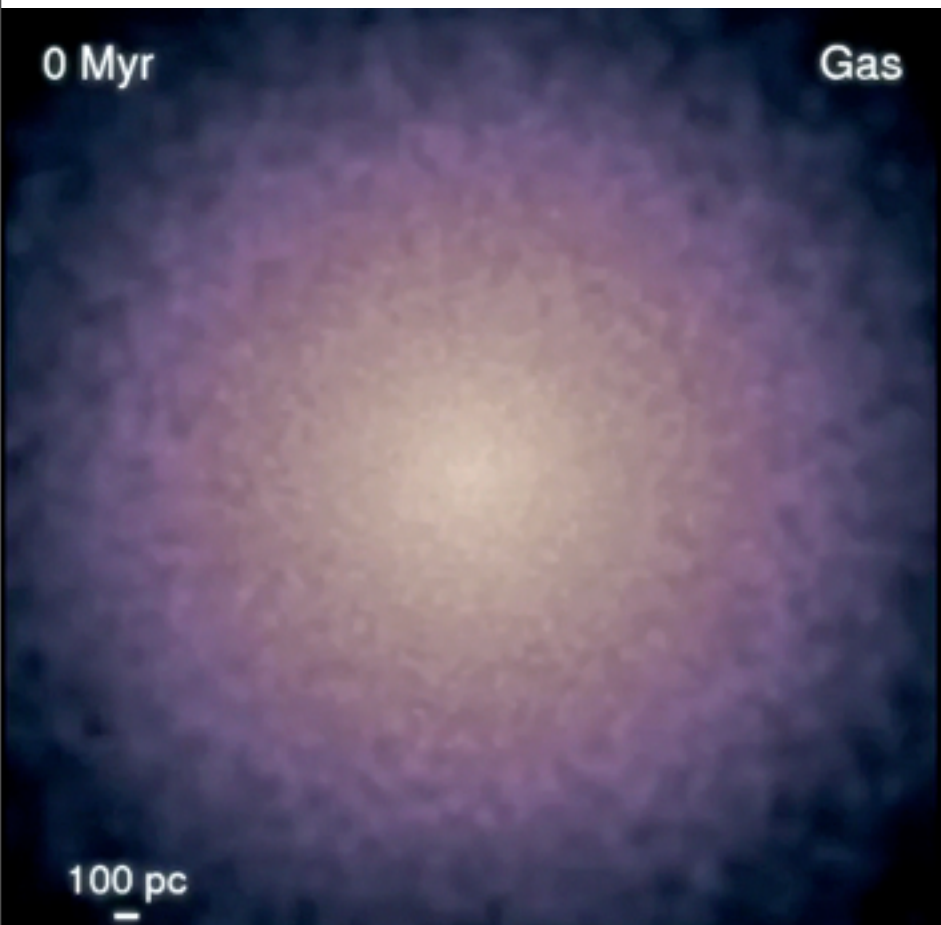
PFH & Quataert 2009,10,11
Levine, Gnedin, Kravtsov 09,10
Mayer, Callegari, 09,10



Step 2: Inflow

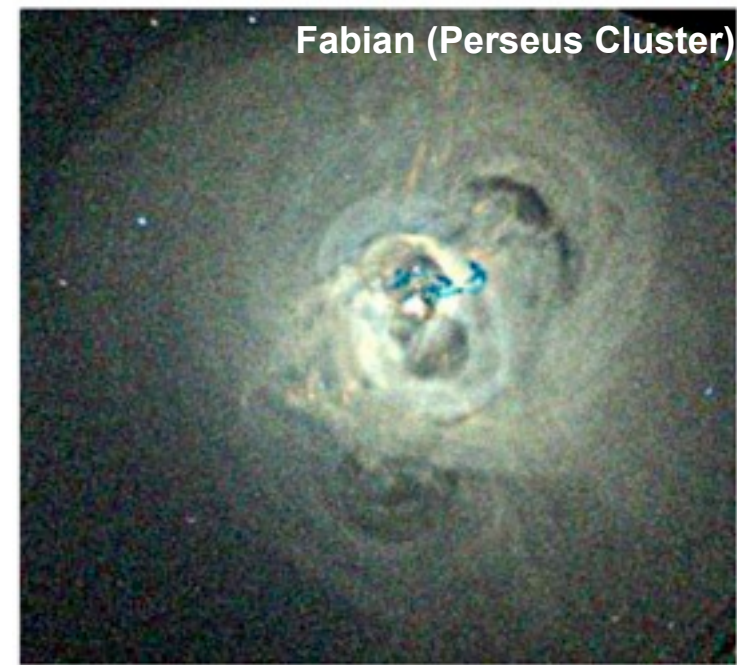
- Beginning to directly follow inflow to sub-pc scales

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



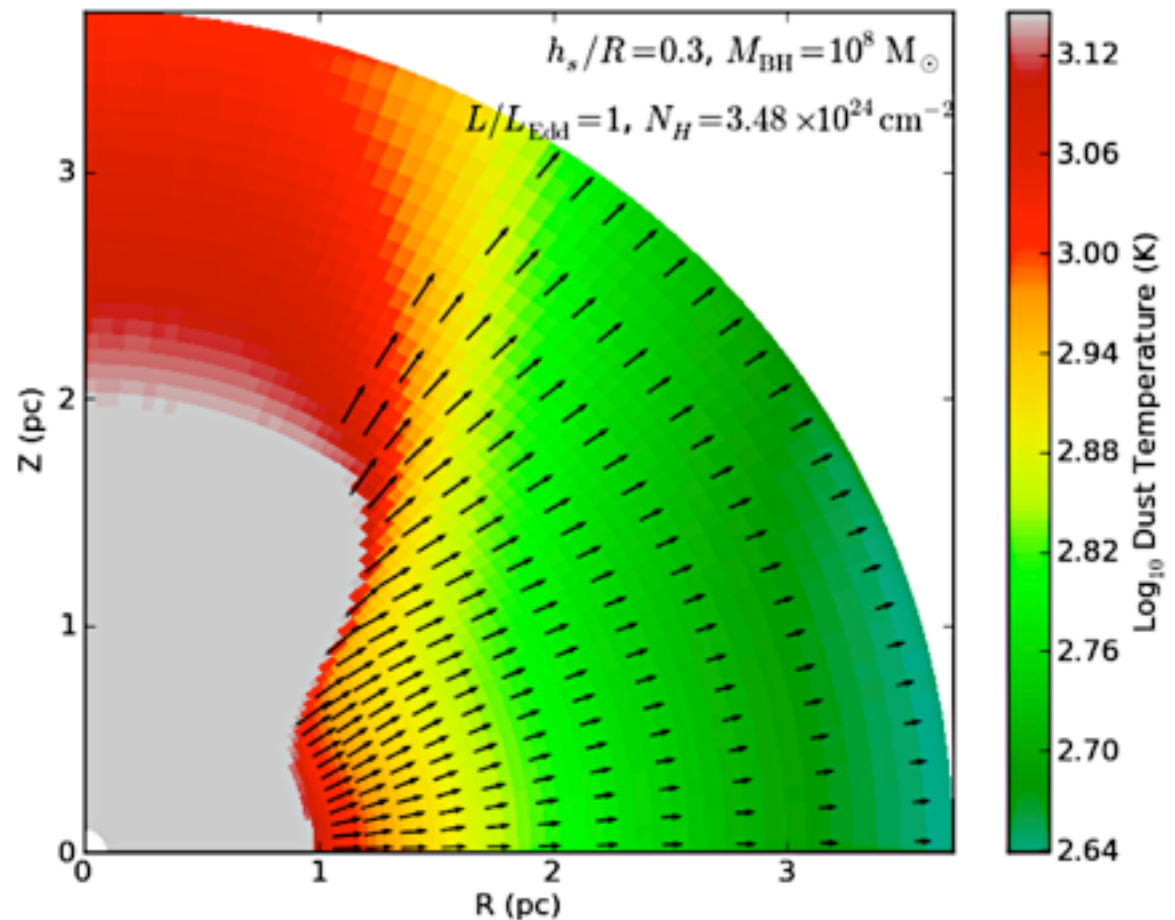
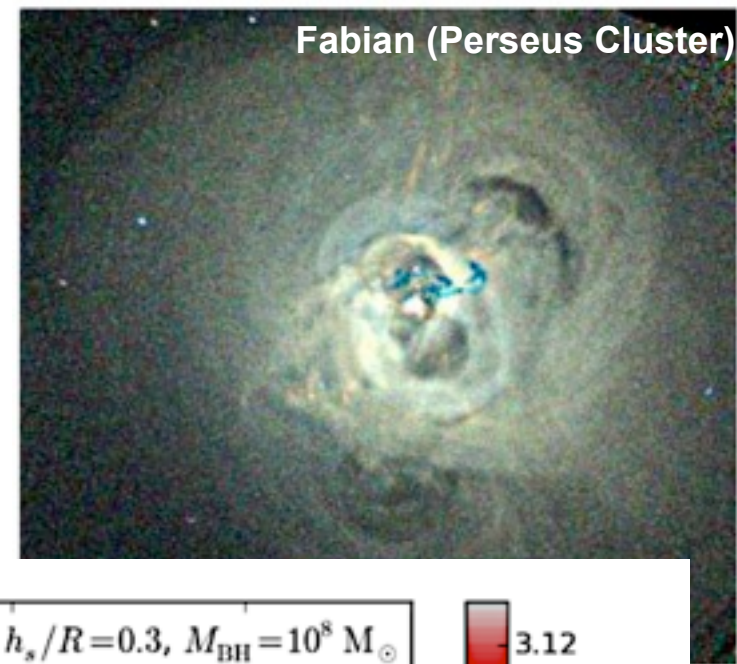
Step 3: Observed Sources of AGN Feedback

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



Step 3: Observed Sources of AGN Feedback

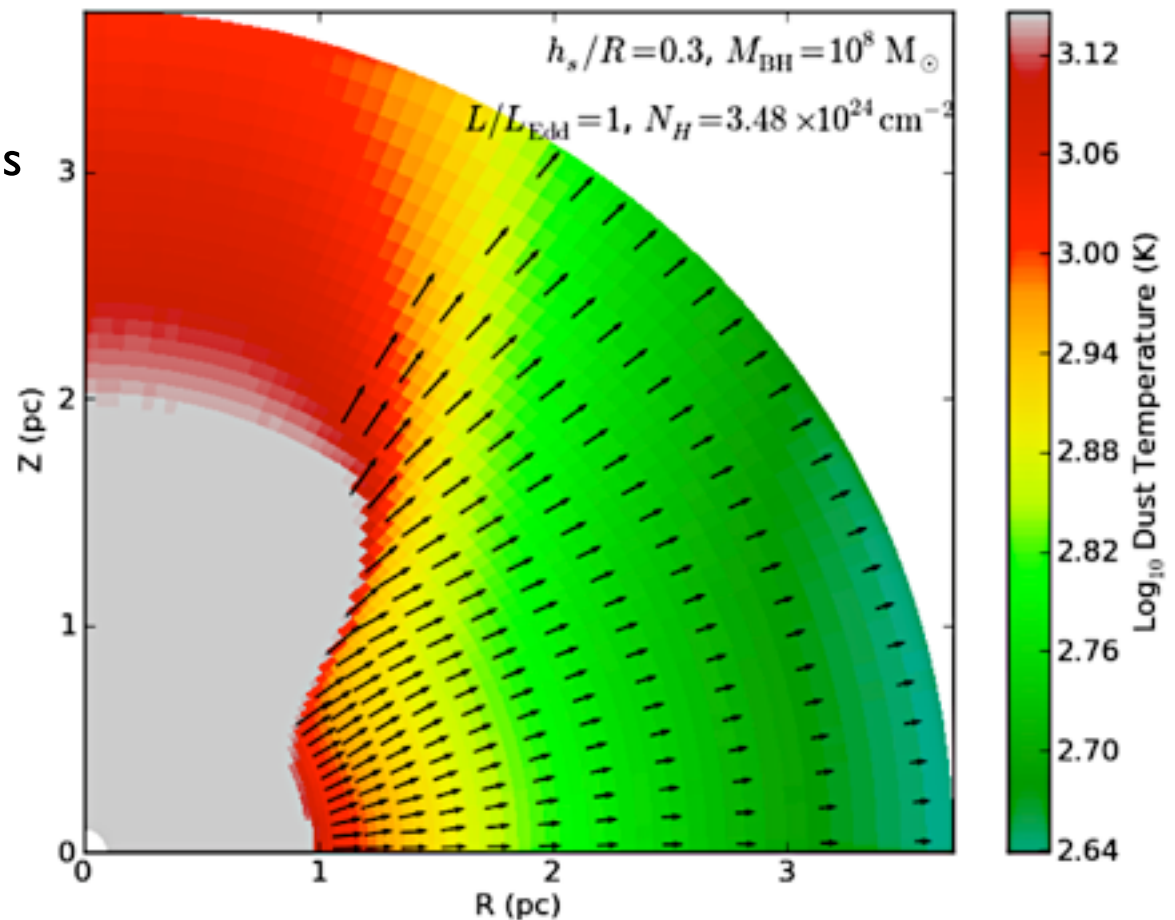
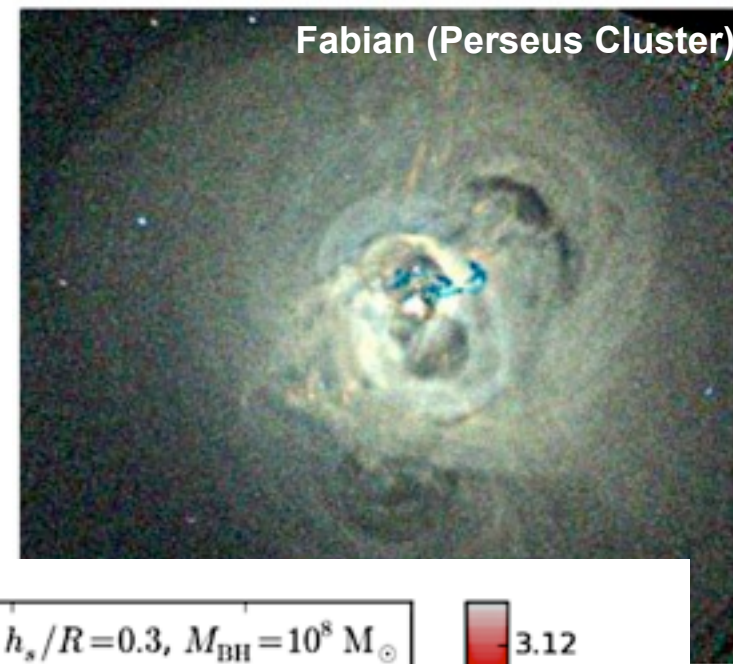
- Jets
 - heat IGM/ICM (low-density), but not dense ISM
- Radiation Pressure
 - $L_{\text{AGN}} \gg L_{\text{stars}}$



Roth, Kasen, Quataert, PFH in prep

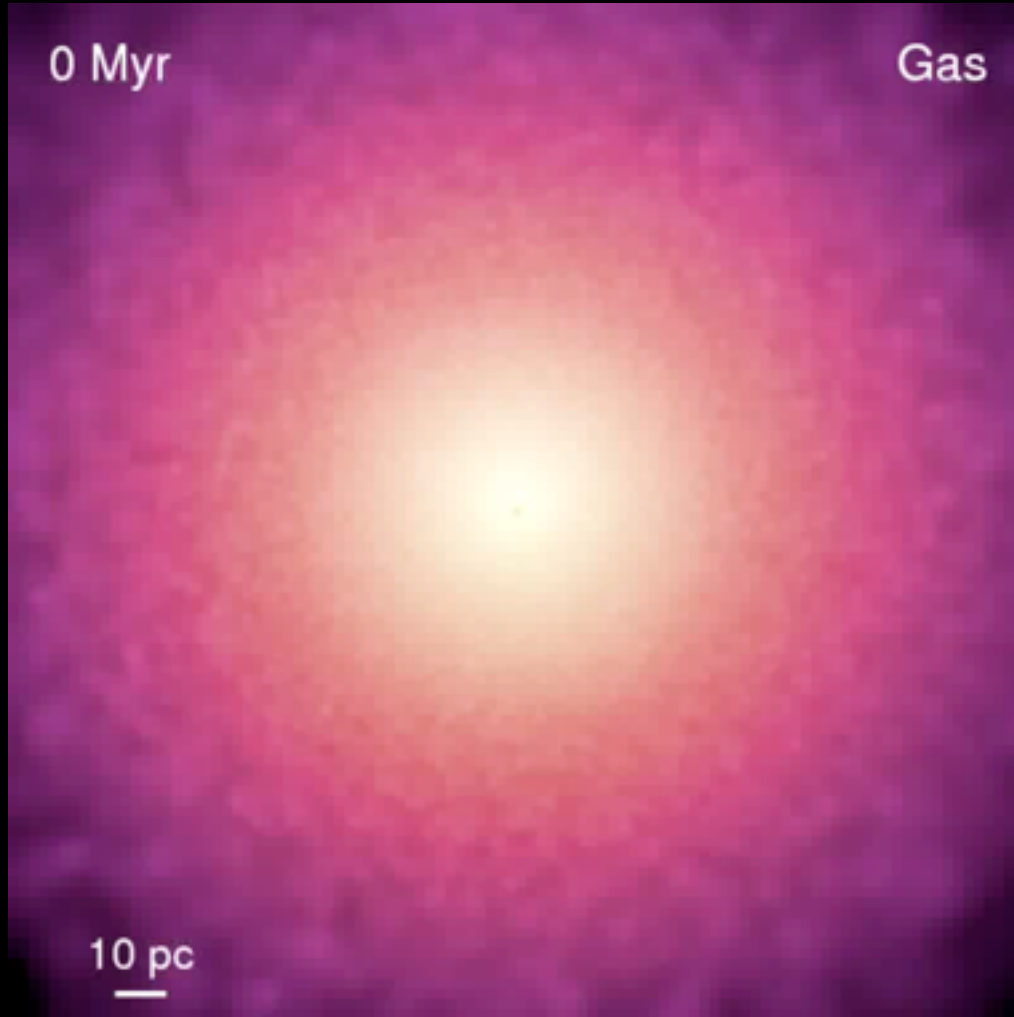
Step 3: Observed Sources of AGN Feedback

- Jets
 - heat IGM/ICM (low-density), but not dense ISM
- Radiation Pressure
 - $L_{\text{AGN}} \gg L_{\text{stars}}$
- Accretion Disk Winds
 - Broad Absorption Line Winds

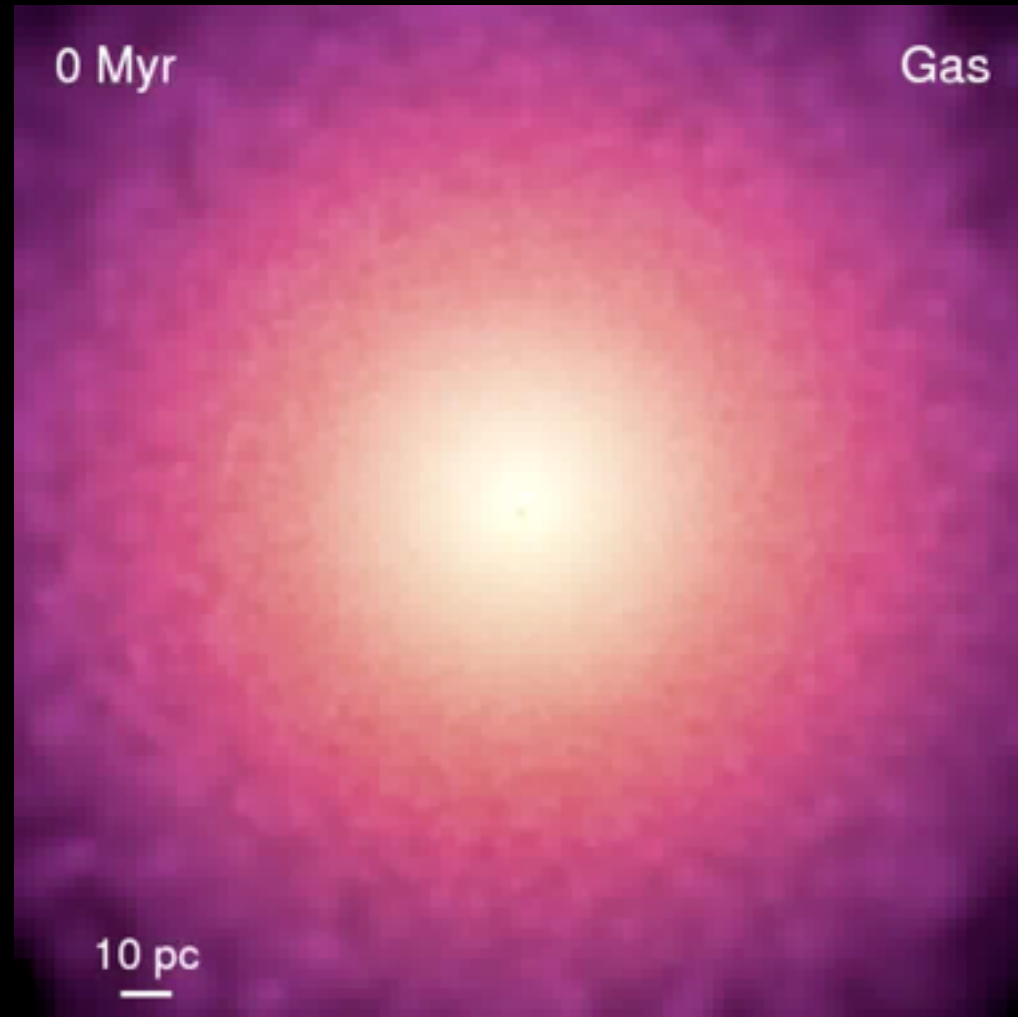


Roth, Kasen, Quataert, PFH in prep

No BAL Winds



With BAL Winds

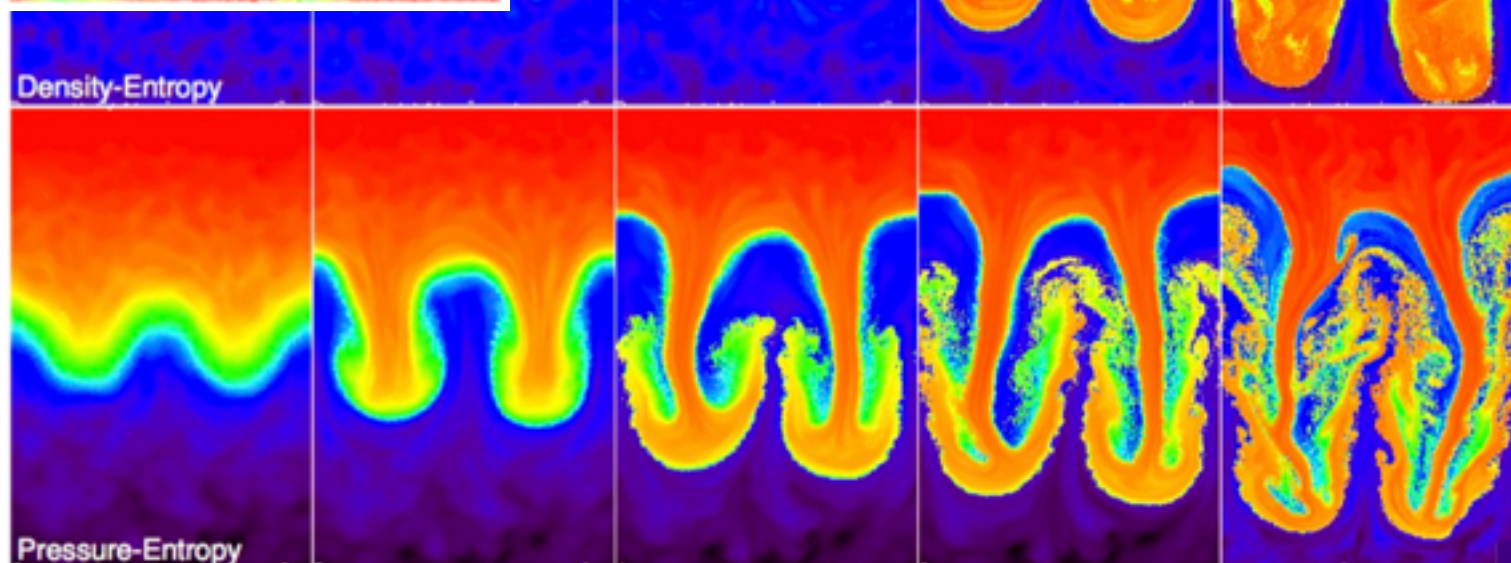
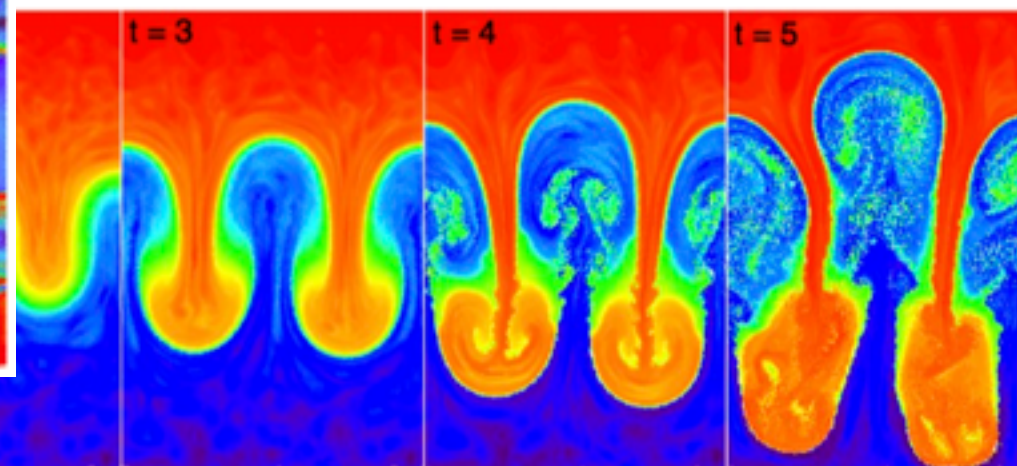
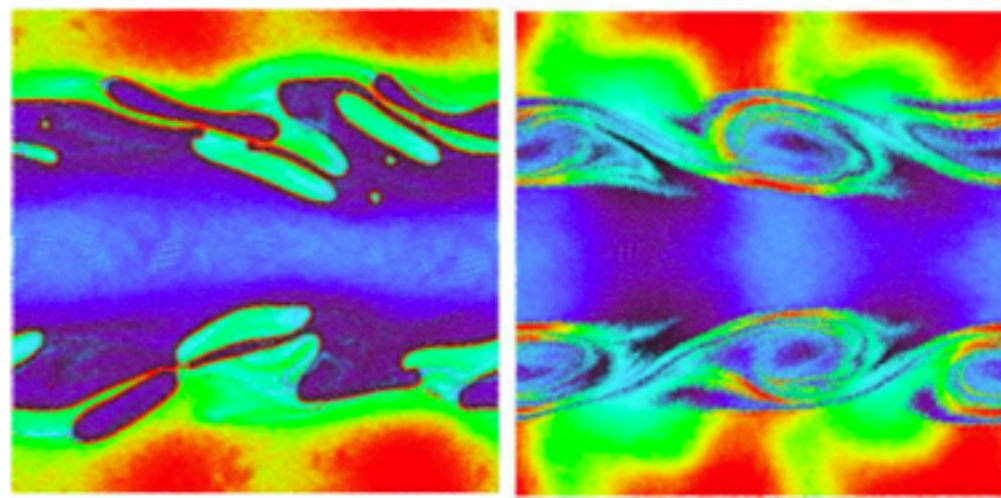
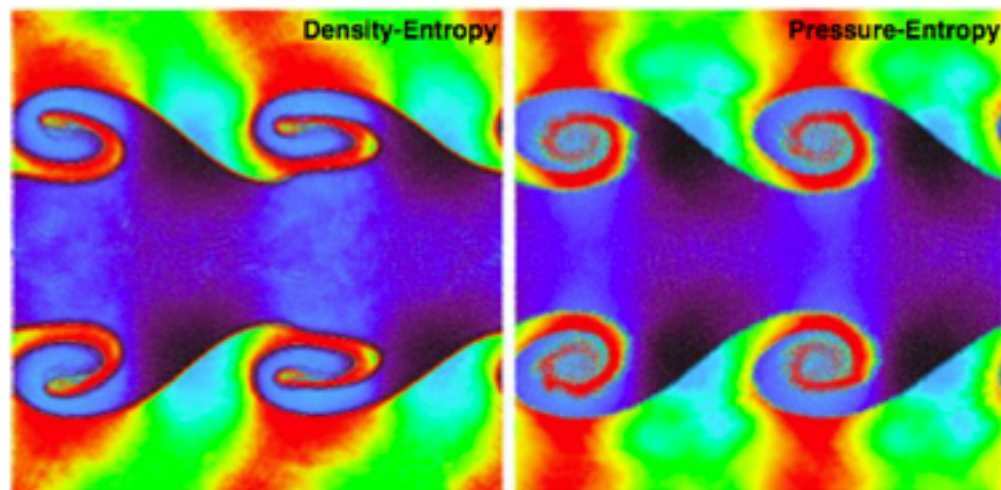


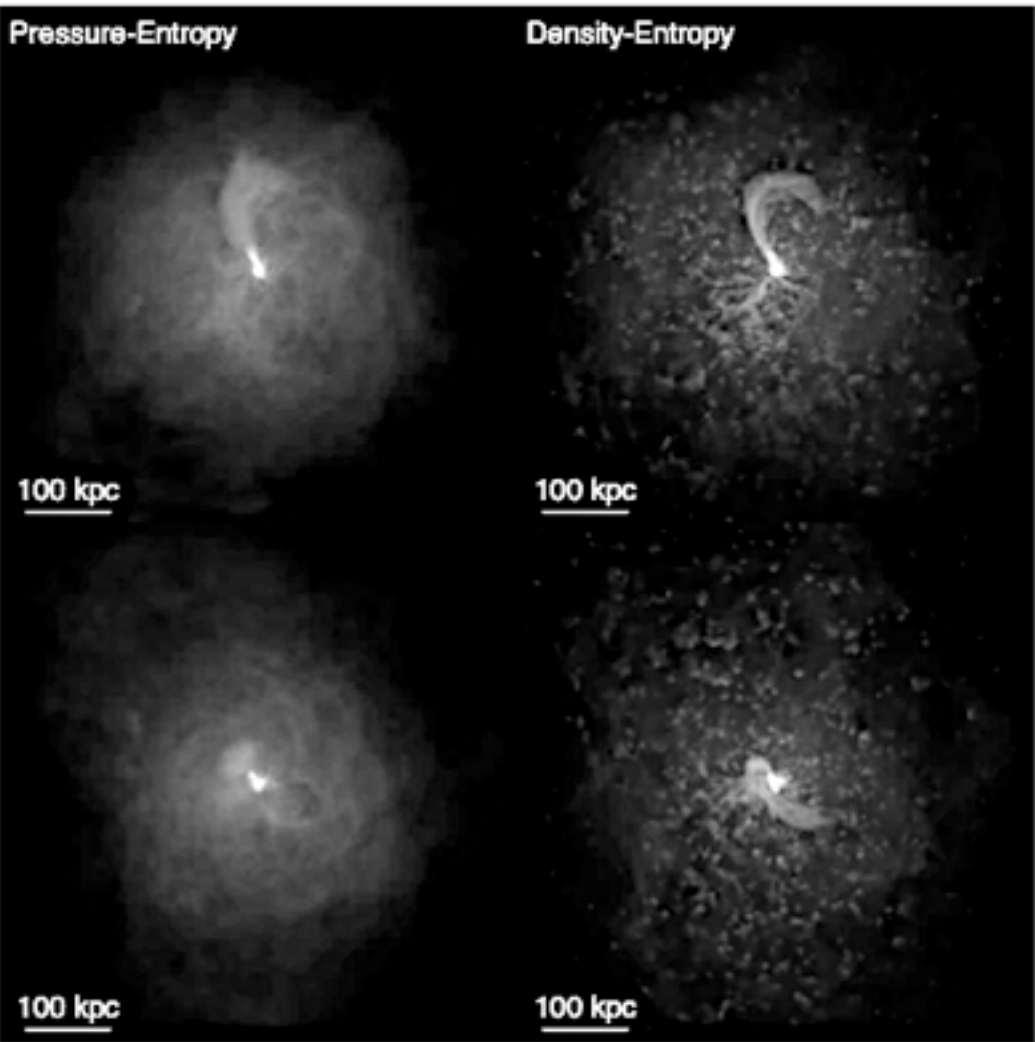
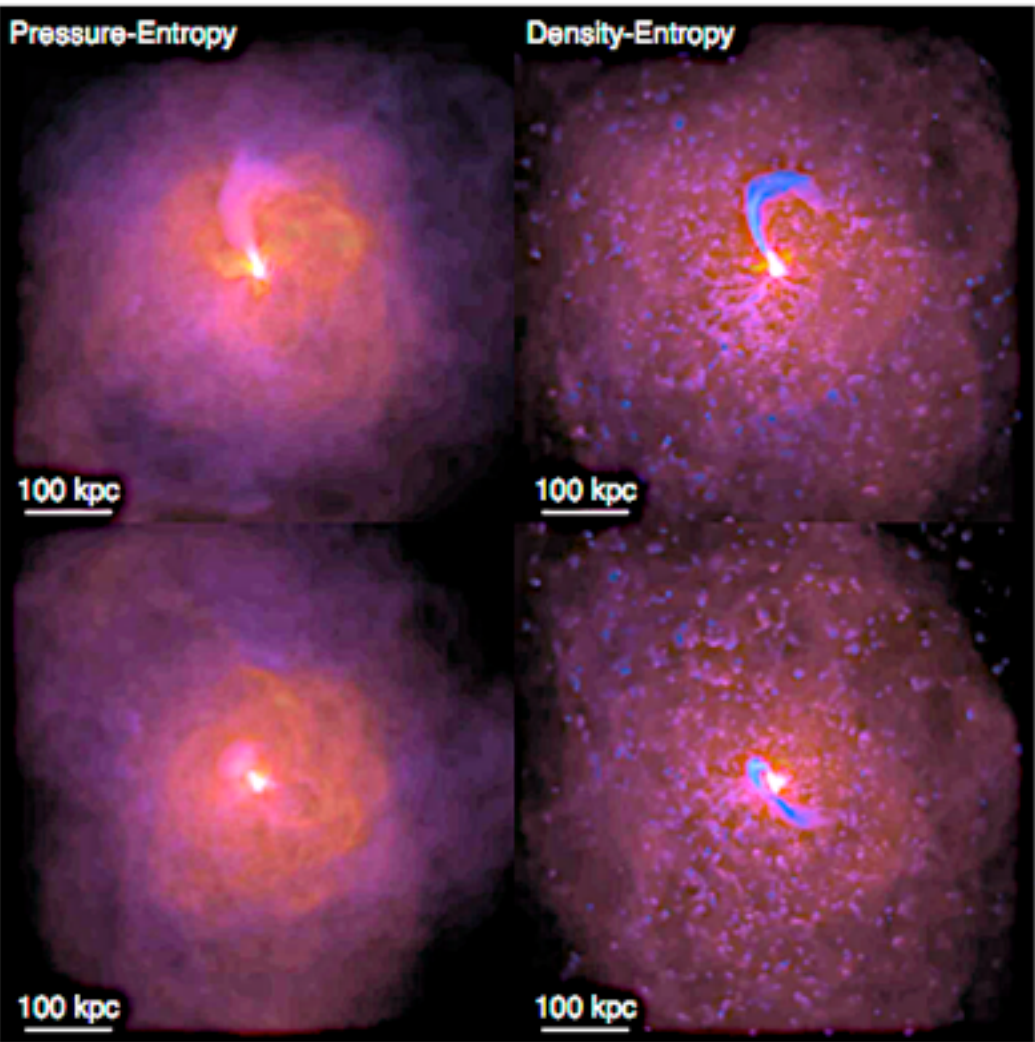
$$\dot{M}_{\text{launch}}(0.1 \text{ pc}) = 0.5 \dot{M}_{\text{BH}}$$

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

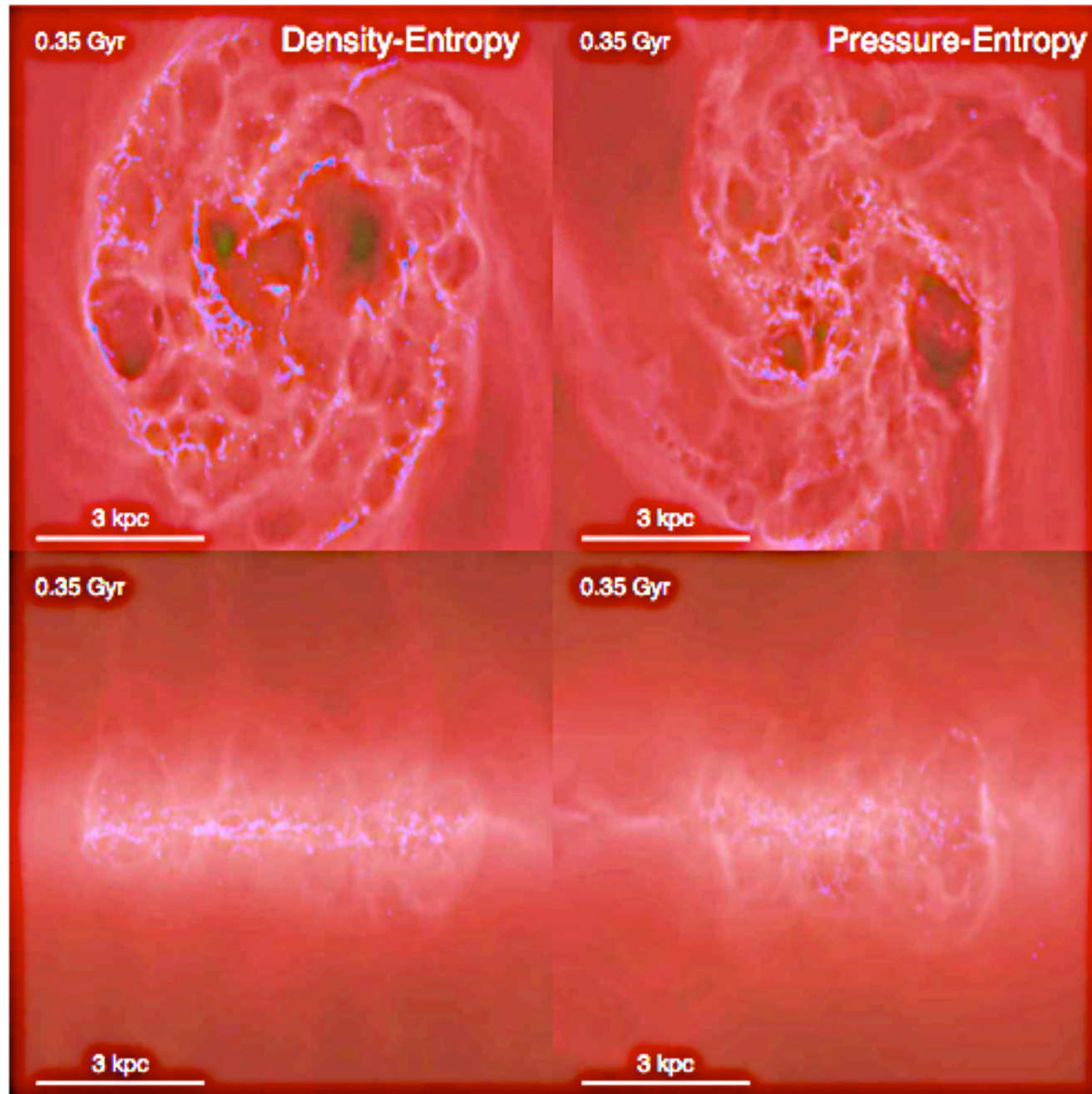
Summary:

- **Star formation is Feedback-Regulated:** *independent* of small-scale SF ‘law’
 - Need enough stars to offset dissipation (gravity)
 - Leads to Kennicutt relation & **super-winds**
- Different mechanisms dominate different regimes:
 - High- ρ : radiation pressure
 - Intermediate: HII heating, stellar wind momentum
 - Low- ρ : SNe & stellar wind shock-heating
 - **No *one* mechanism works**
- Mergers: Extreme laboratory (>100x GMC densities!)
- Cosmologically: *Not* just top-down inflows:
 - Winds determine **IGM enrichment, temperature, & subsequent inflow** structure
- Most Massive Galaxies: Need “AGN” Feedback!
 - Jets+Disk Winds+Radiation Pressure: Explain $M_{\text{BH}}-\sigma$ & suppress SF





SPH in Pressure-Entropy Formulation



SPH in Pressure-Entropy Formulation

