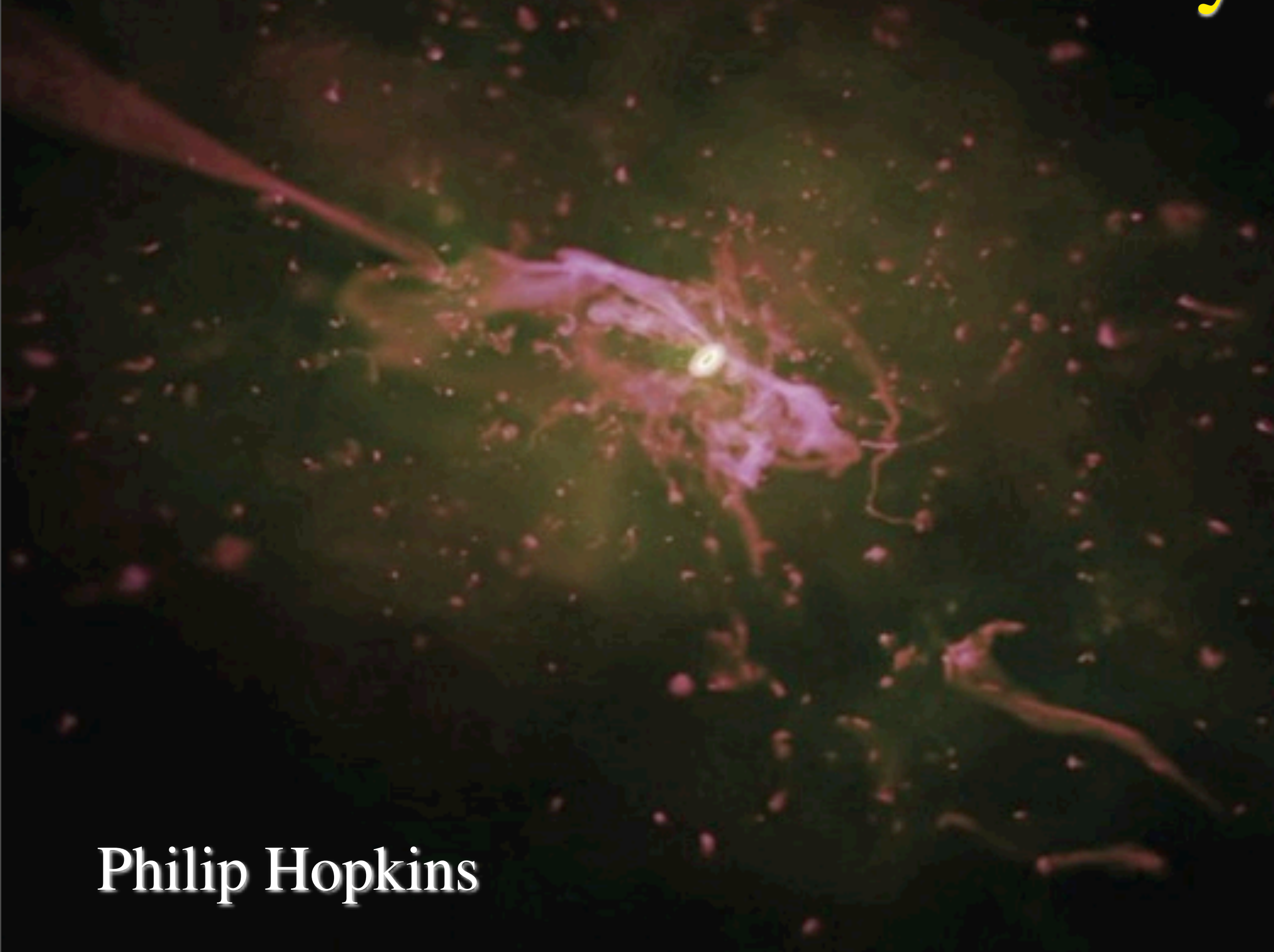
Star Formation, Black Holes, and Feedback in Galaxy Formation



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

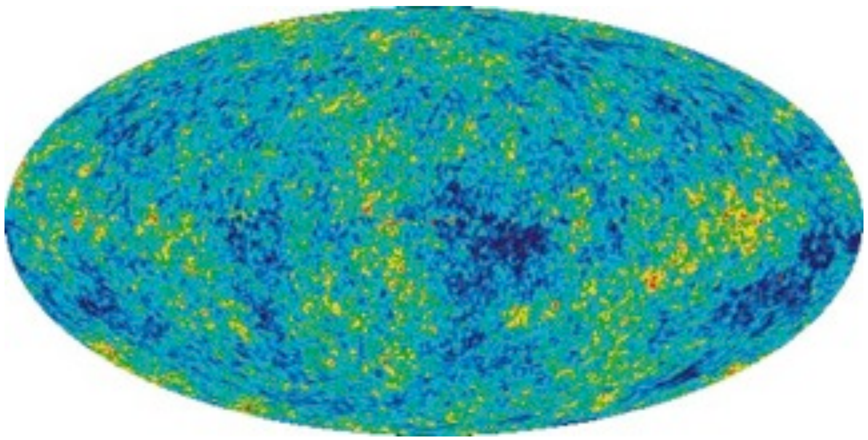
- (1) (Some) Open Problems
- (2) Stellar "Feedback" Processes:
  - Isolated Galaxies: Feedback Physics & the ISM
  - Interacting/Merging Galaxies
  - Cosmological Implications
- (3) Super-Massive Black Holes & Accretion?

Motivation

THE BIG PICTURE

Today

?



z~1090
(t~400,000 yr)

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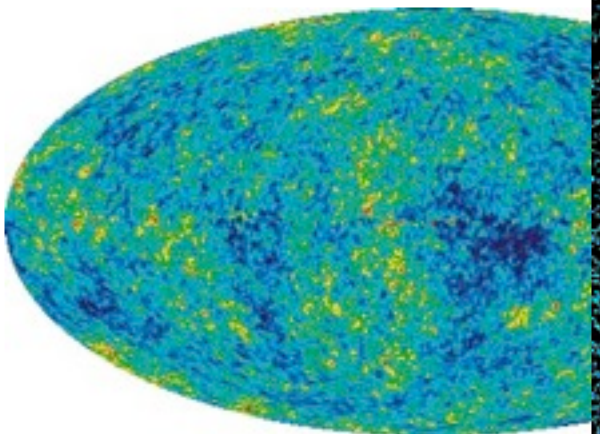

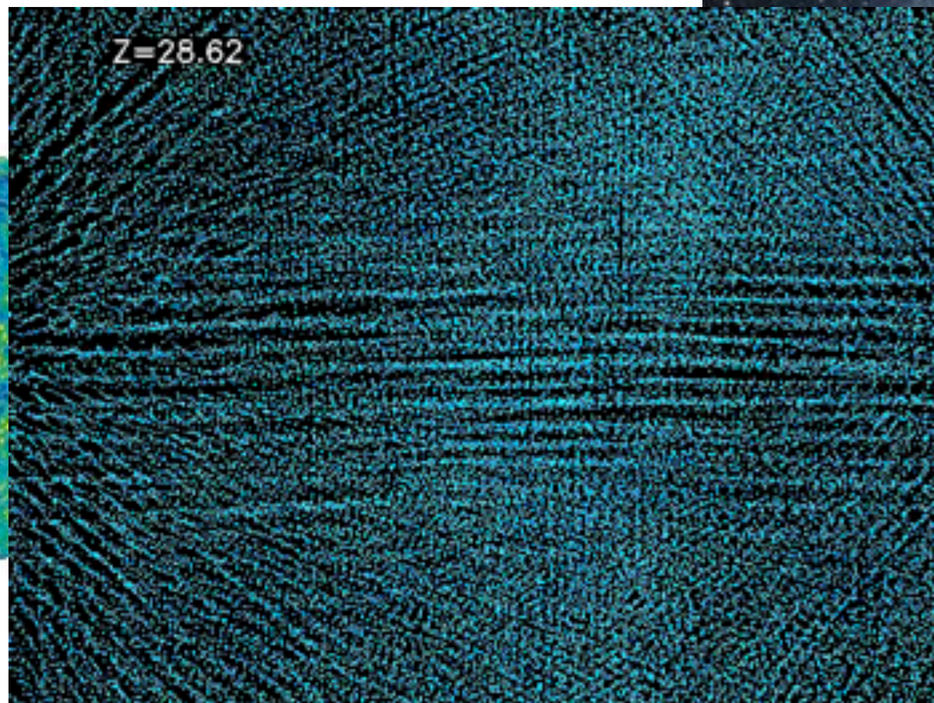

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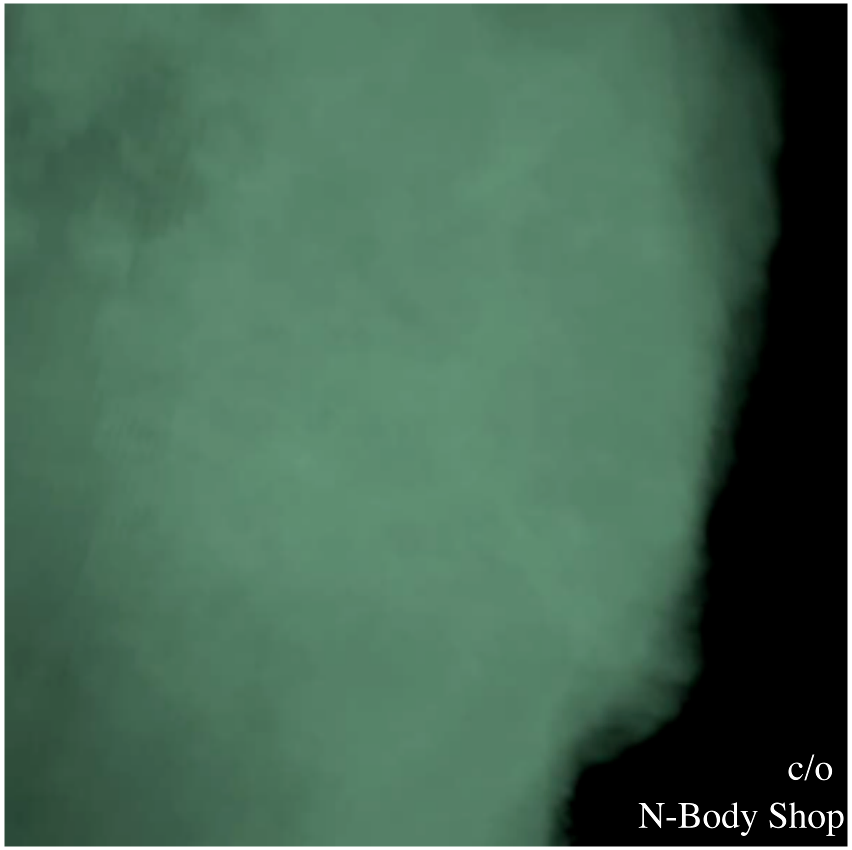
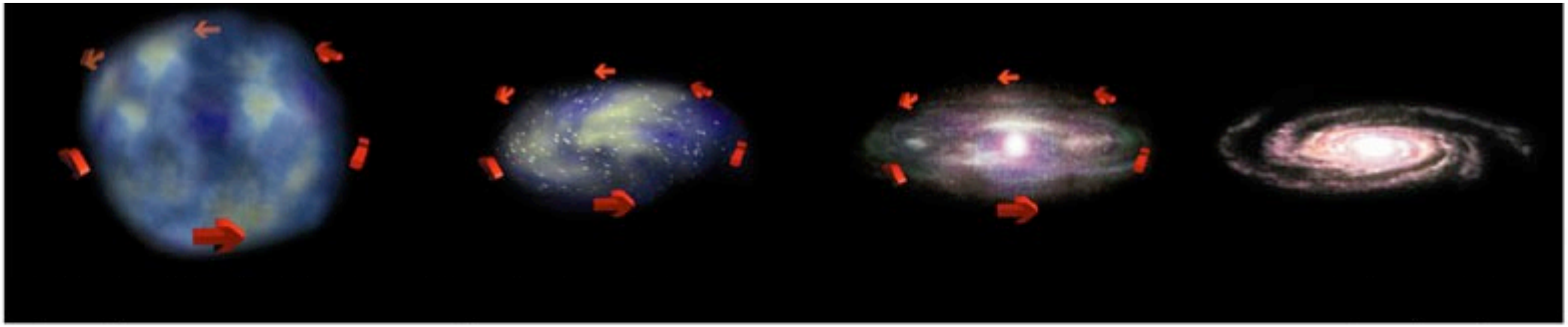
Motivation

HOW DID WE GET TO GALAXIES TODAY?

- Dark matter halos collapse:
  gas cools into a disk



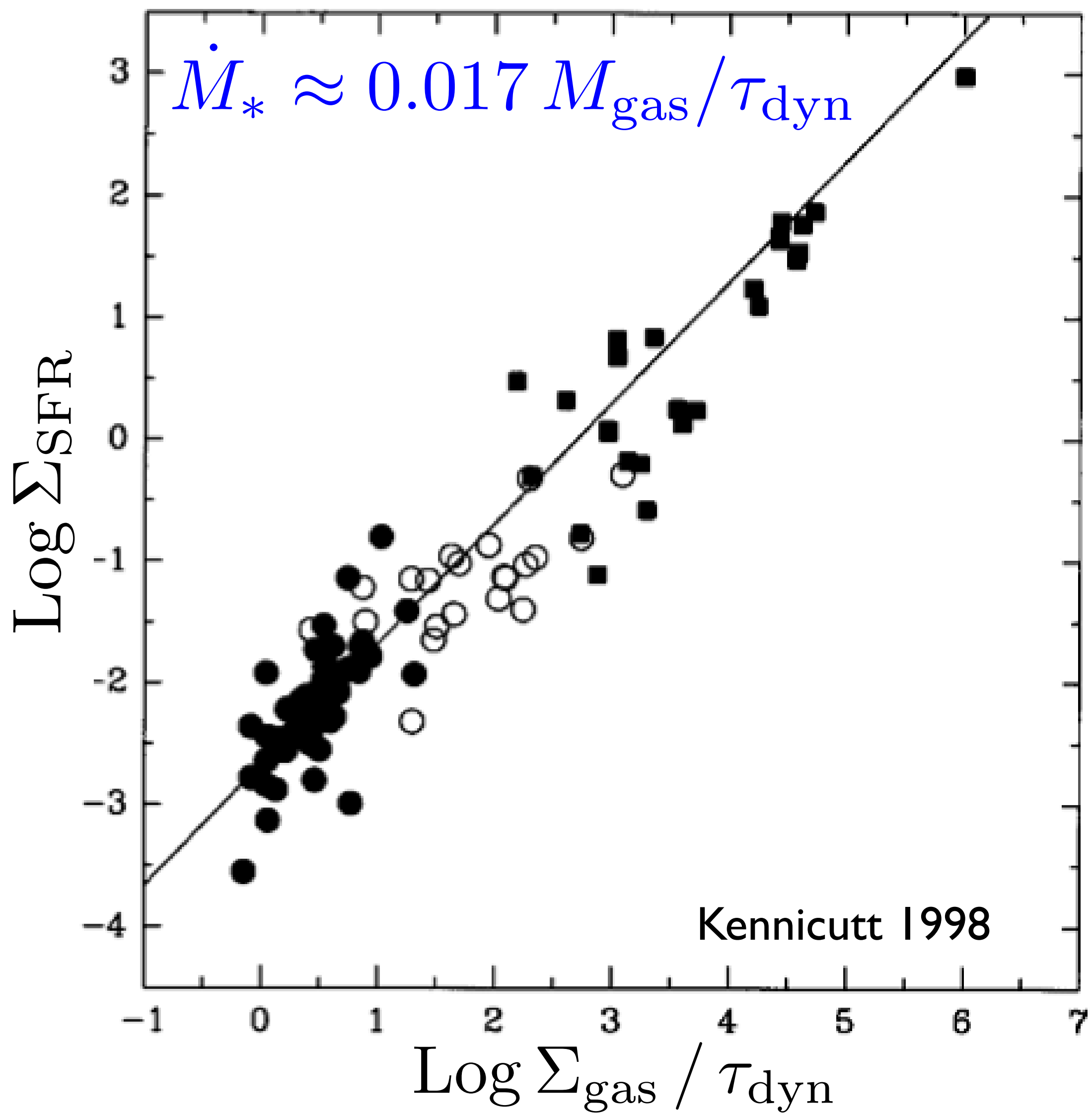


- What happens once gas is actually inside galaxies?

The Problem: Baryons

Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



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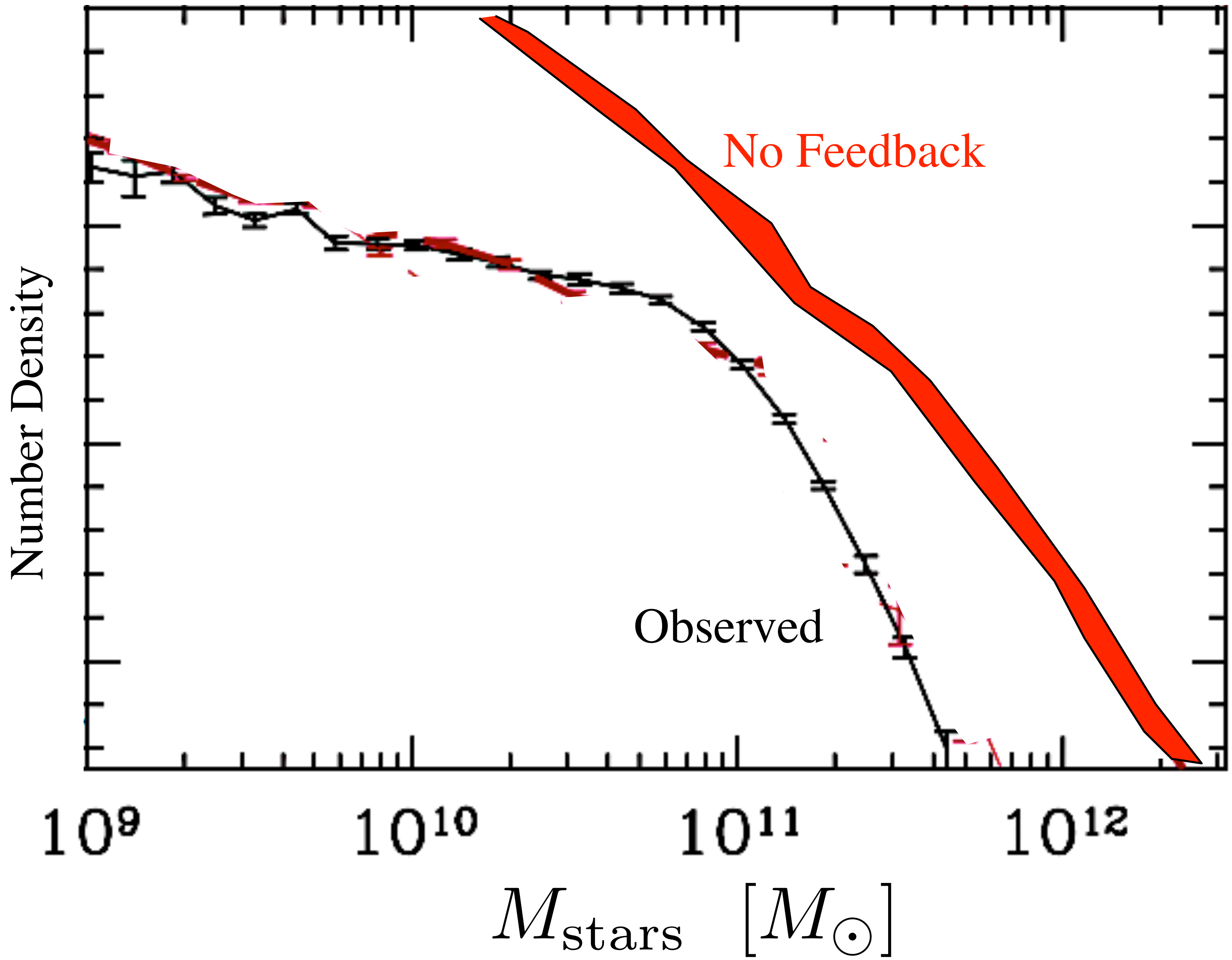

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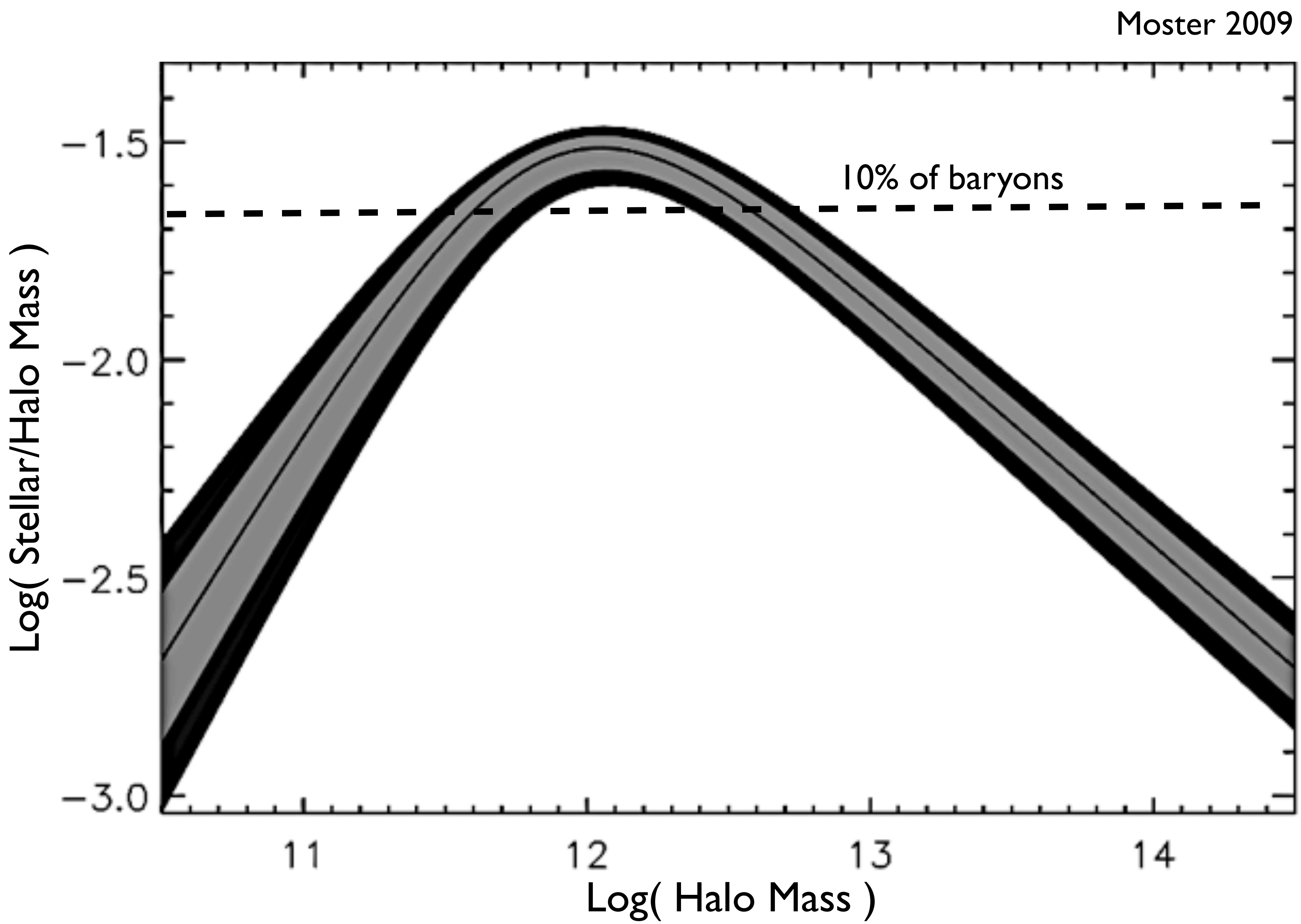

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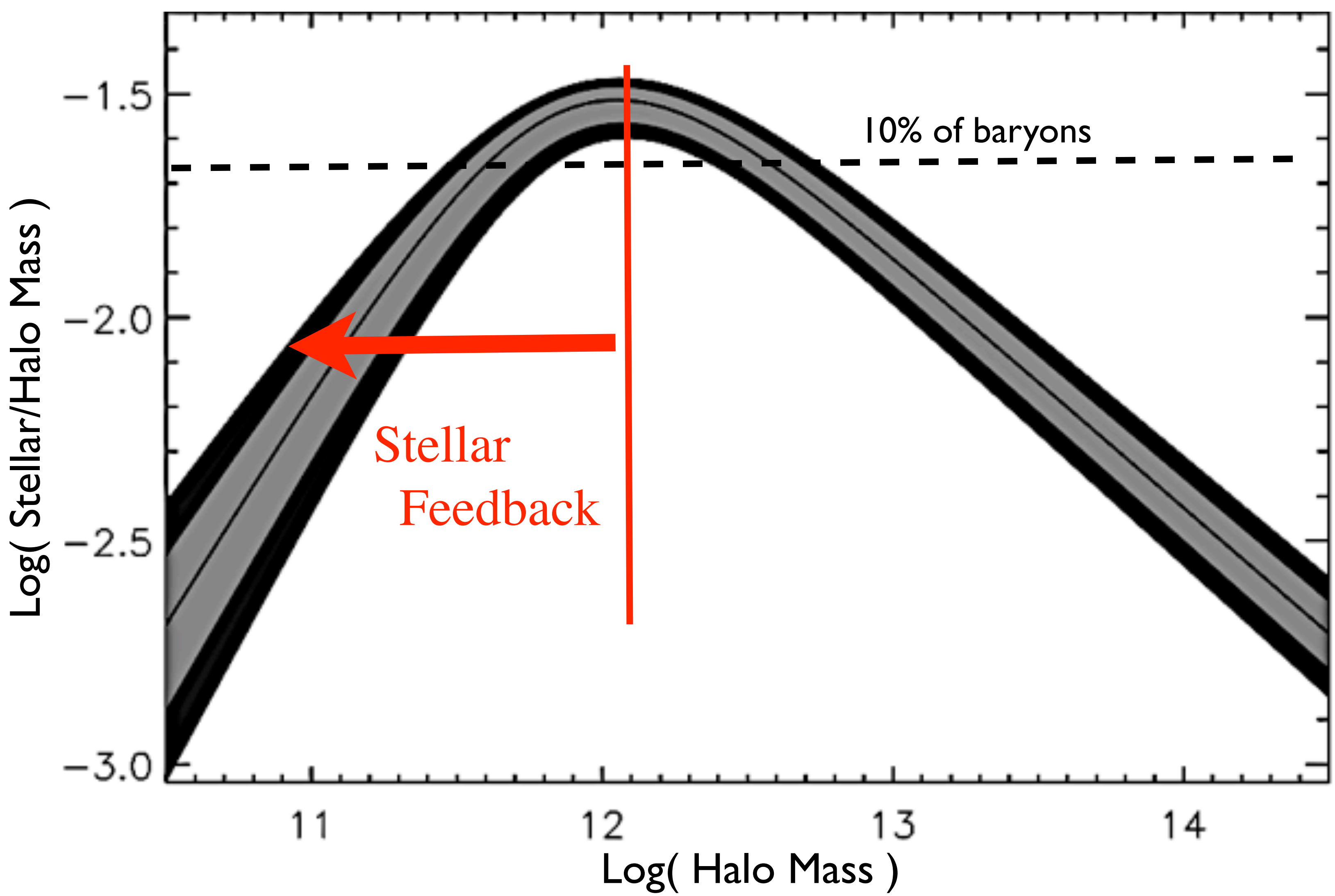
Moster 2009



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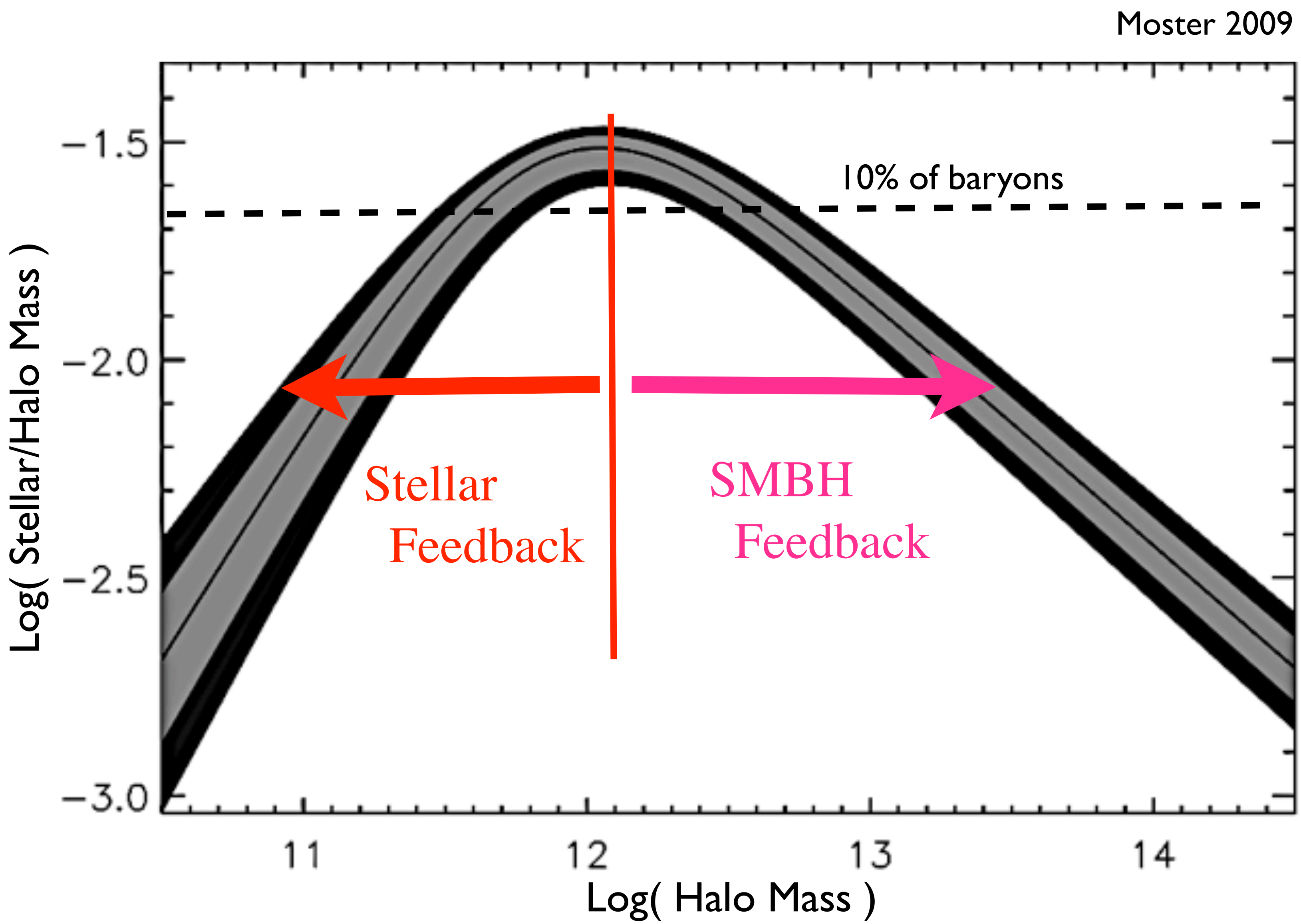


Stellar Feedback is the Key!

SO WHAT'S THE PROBLEM?

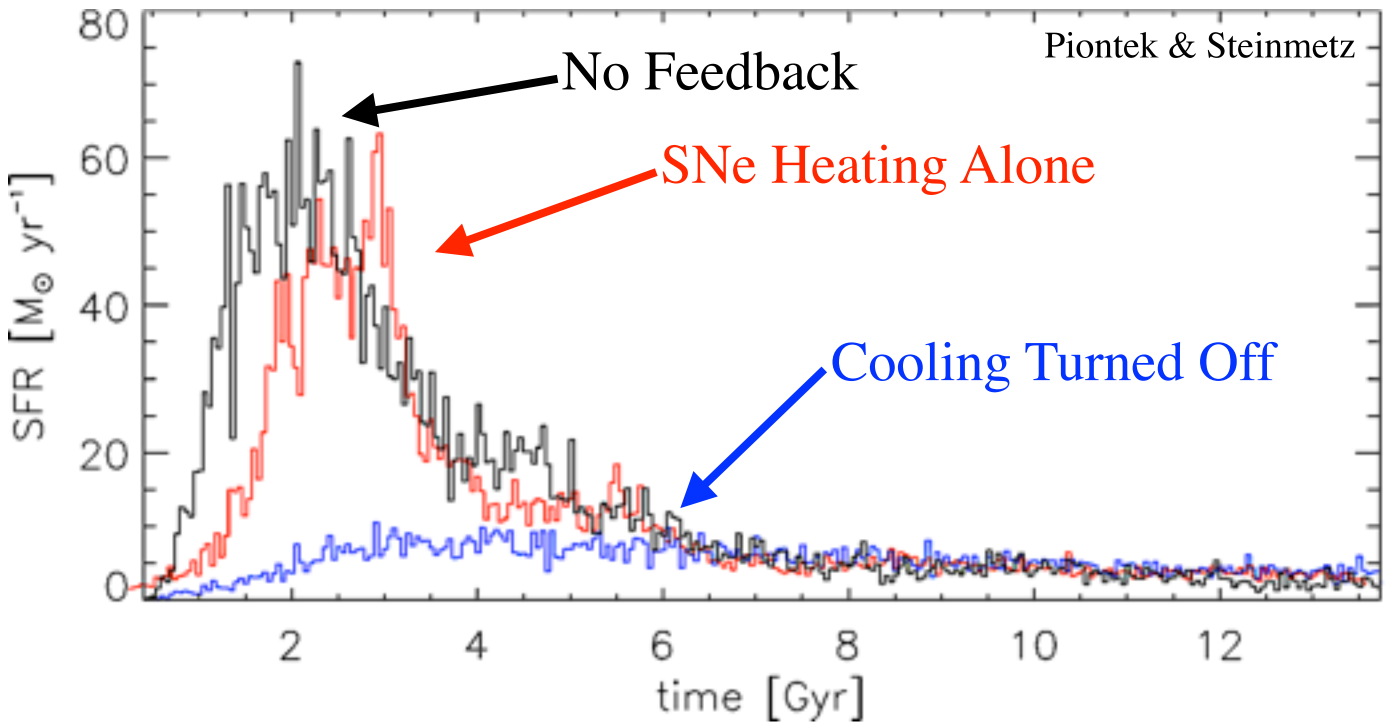
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

- 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)



Stellar Feedback: How Can We Do Better?

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- *Explicit* Momentum Flux:
  - Radiation Pressure

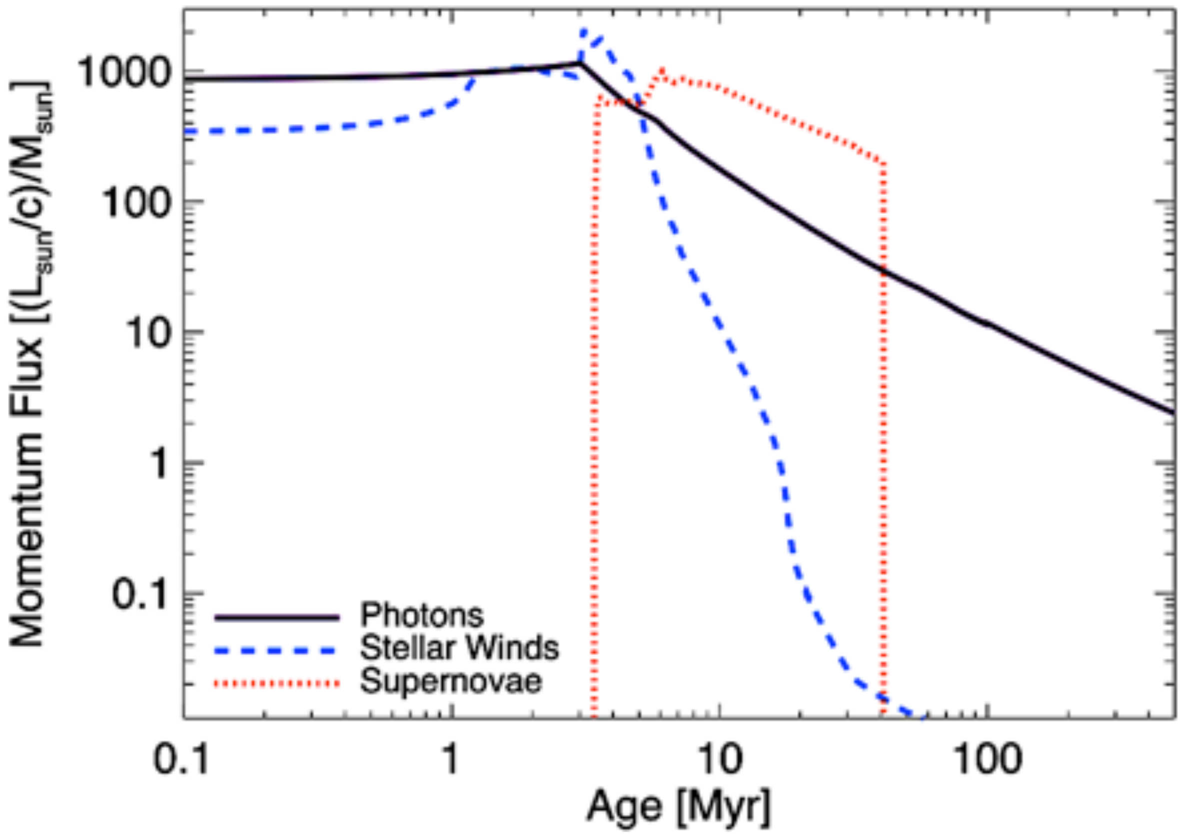
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

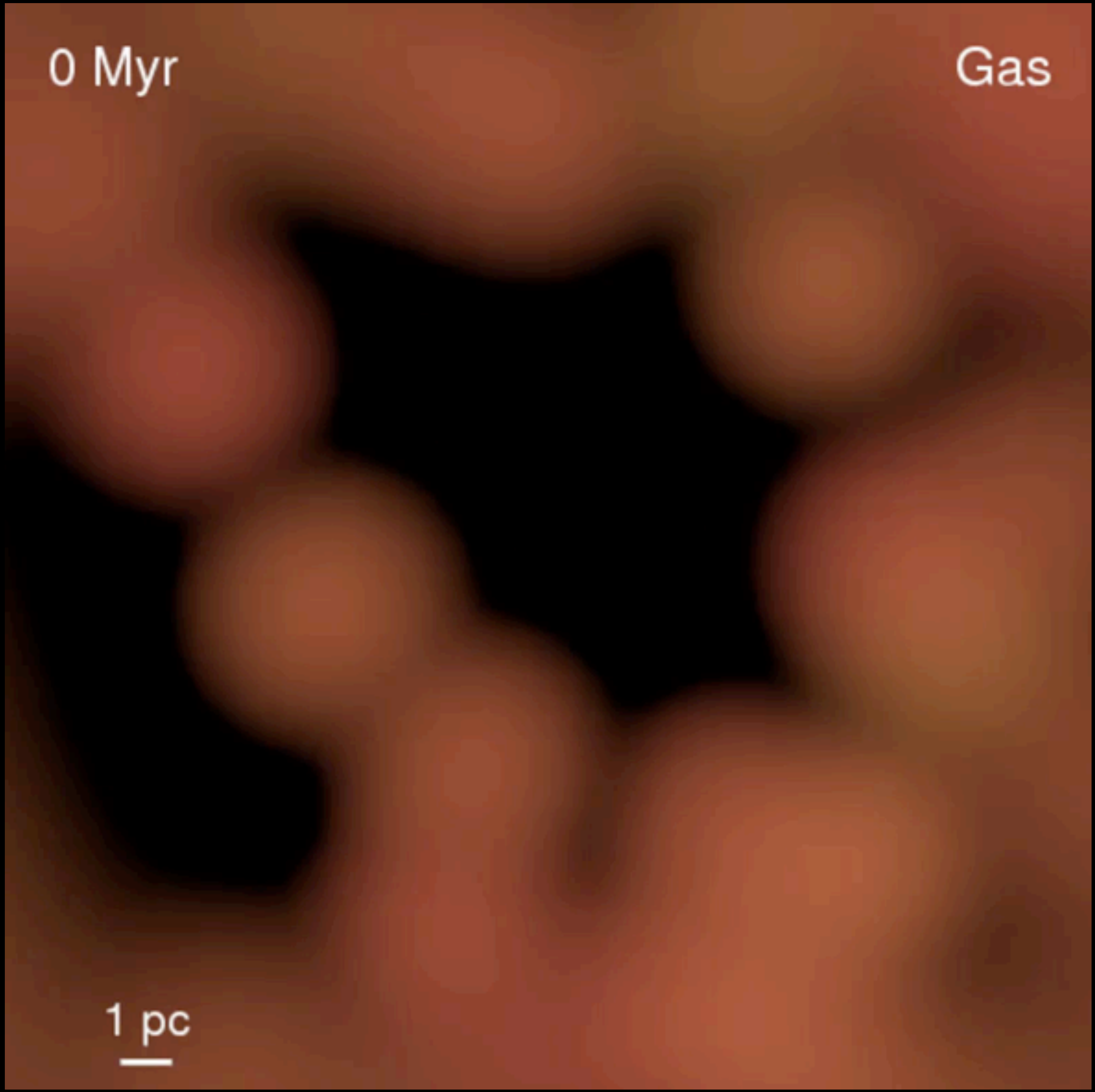
  - SNe

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

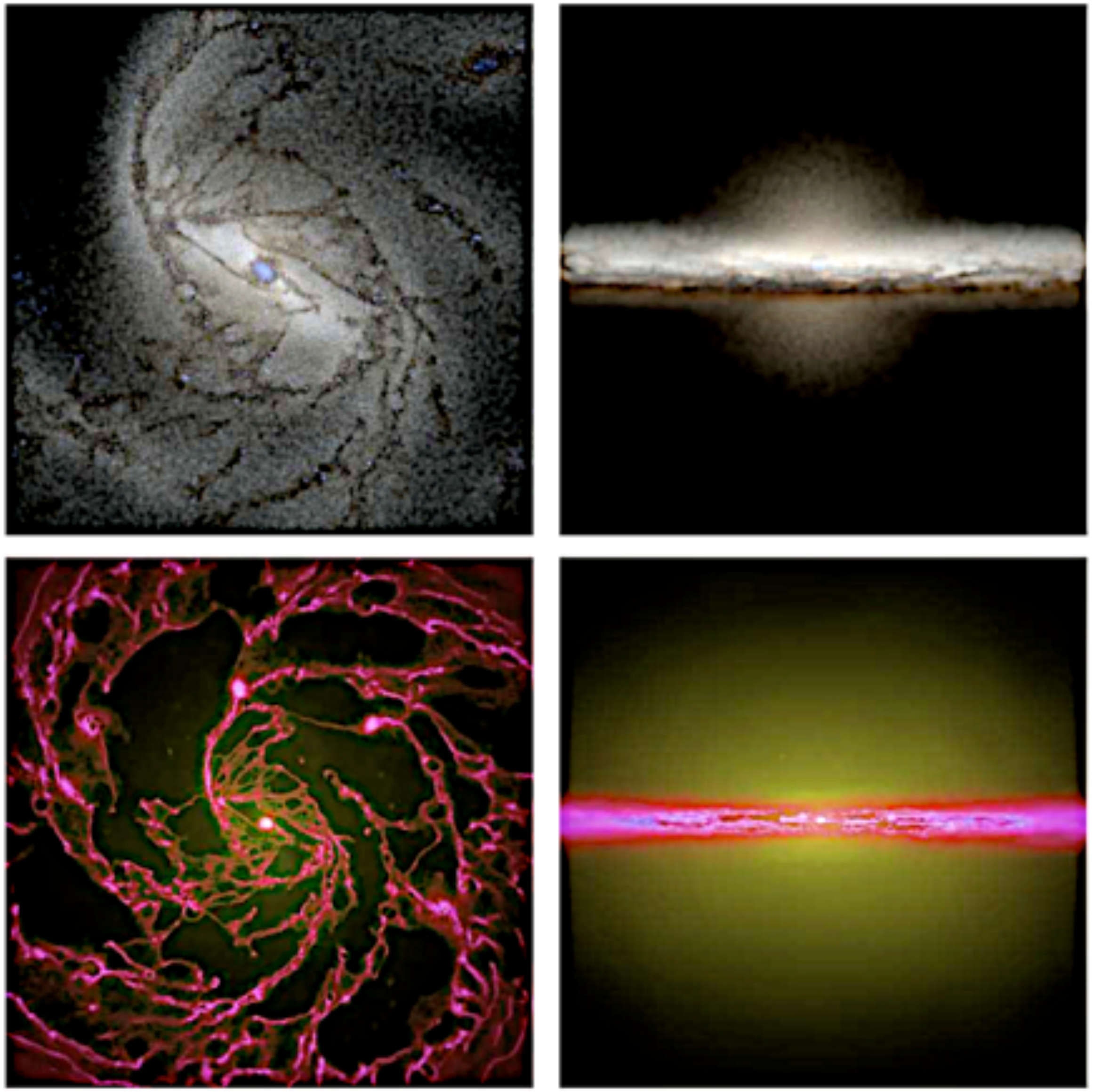
  - Stellar Winds

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



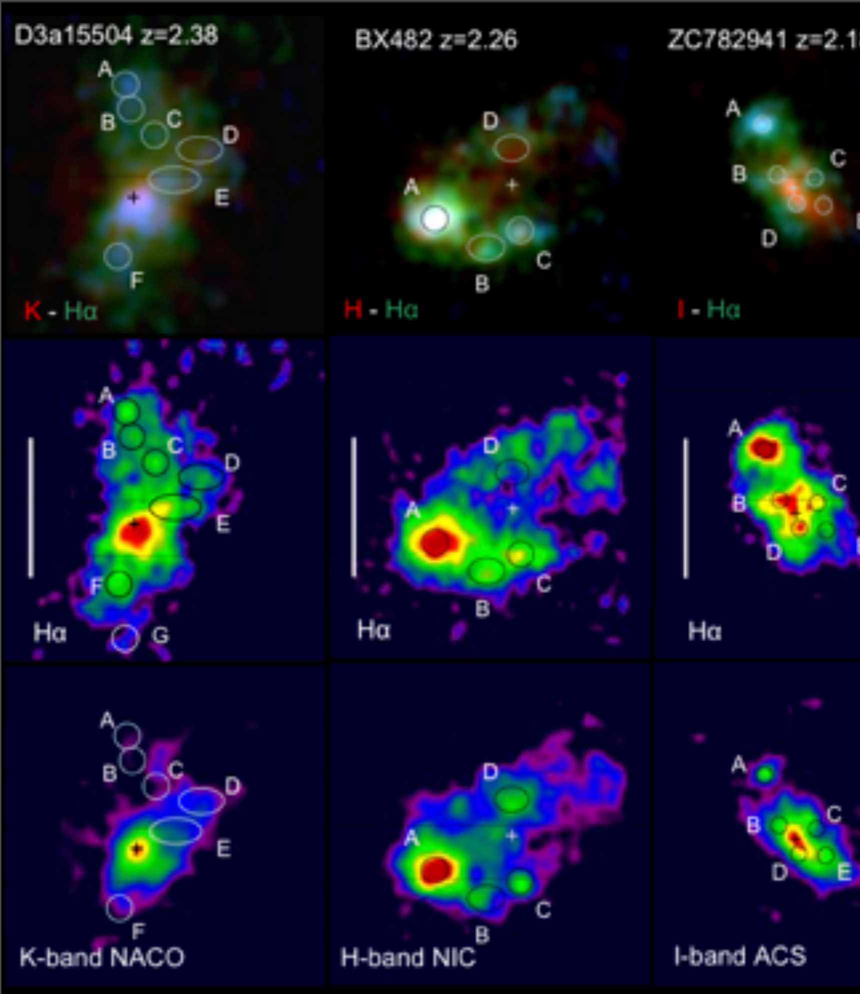

0 Myr
Gas
1 pc

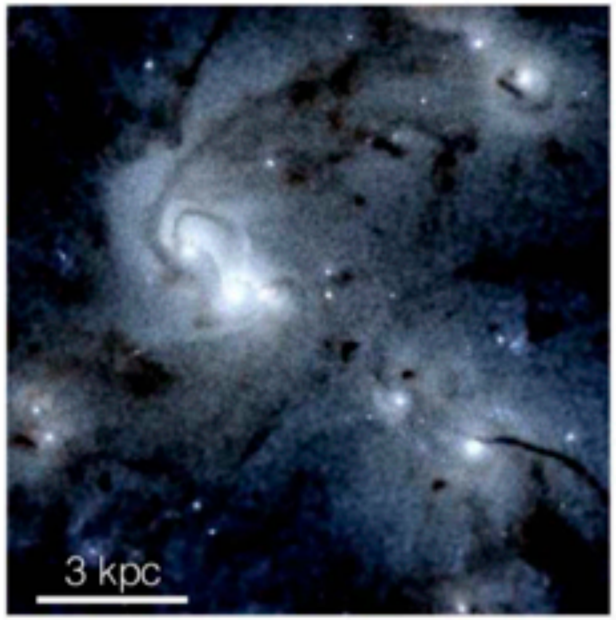
Hopkins, Quataert, & Murray, 2011b

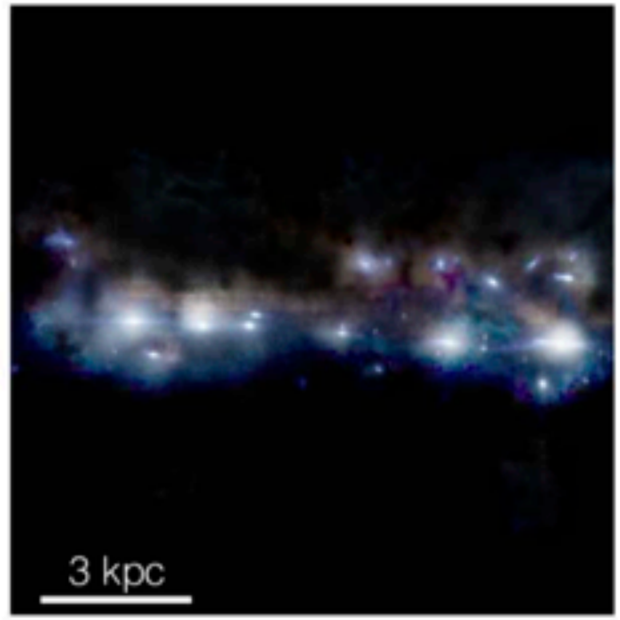


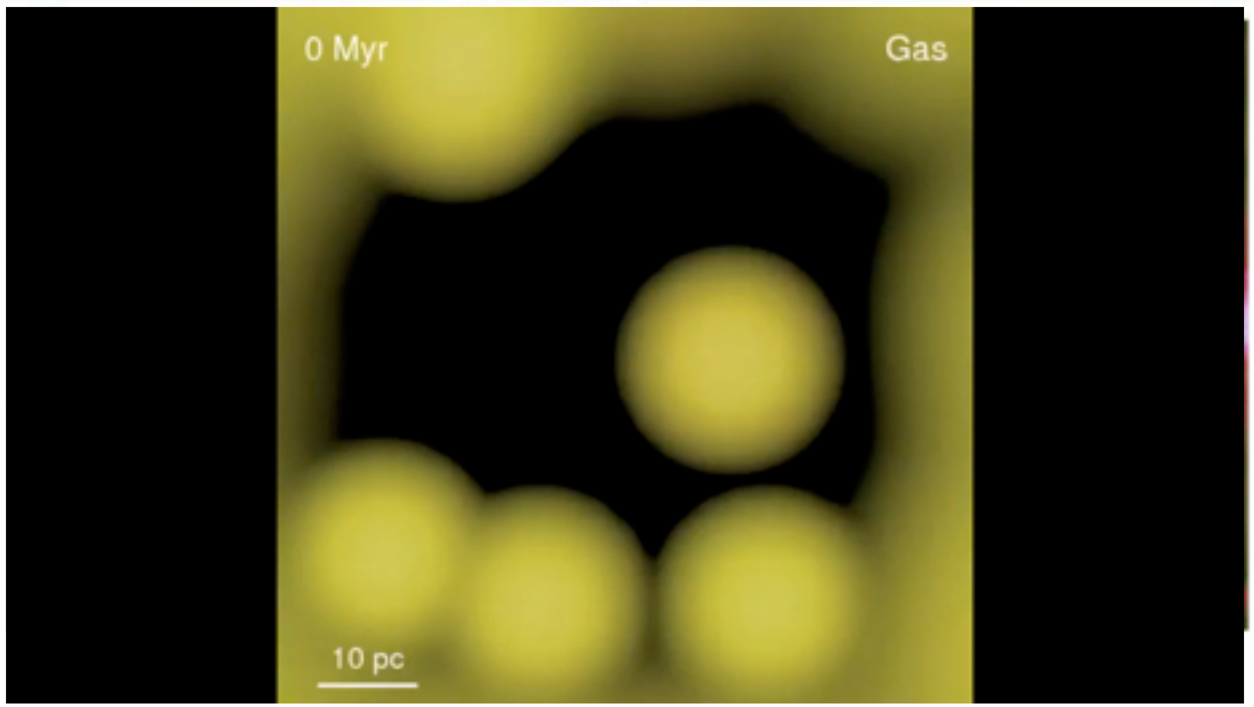
Hopkins, Quataert, & Murray, 2011b

Genzel+ 2011



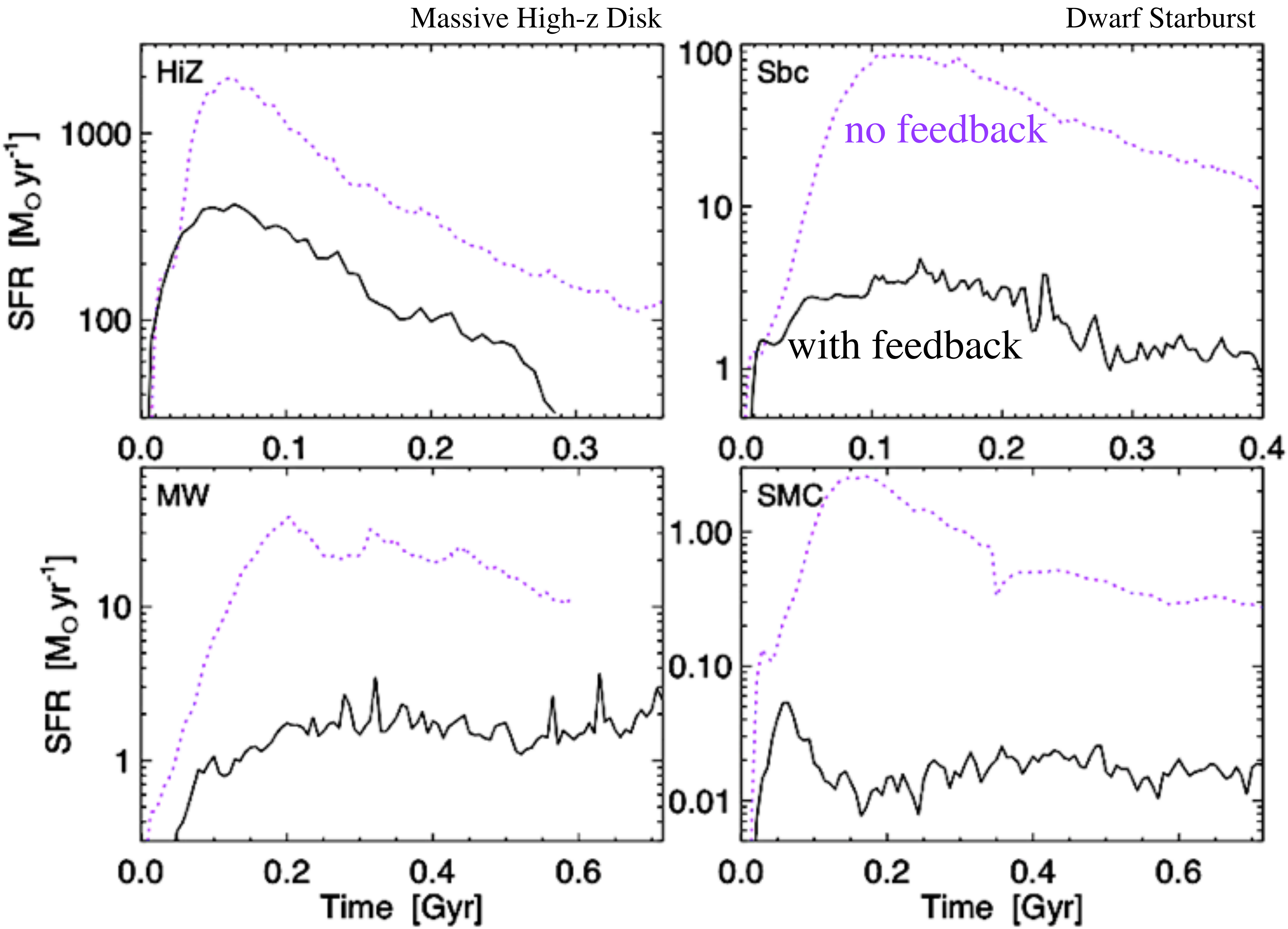






PFH, Quataert, Hernquist, 2011

Stellar Feedback gives Self-Regulated Star Formation



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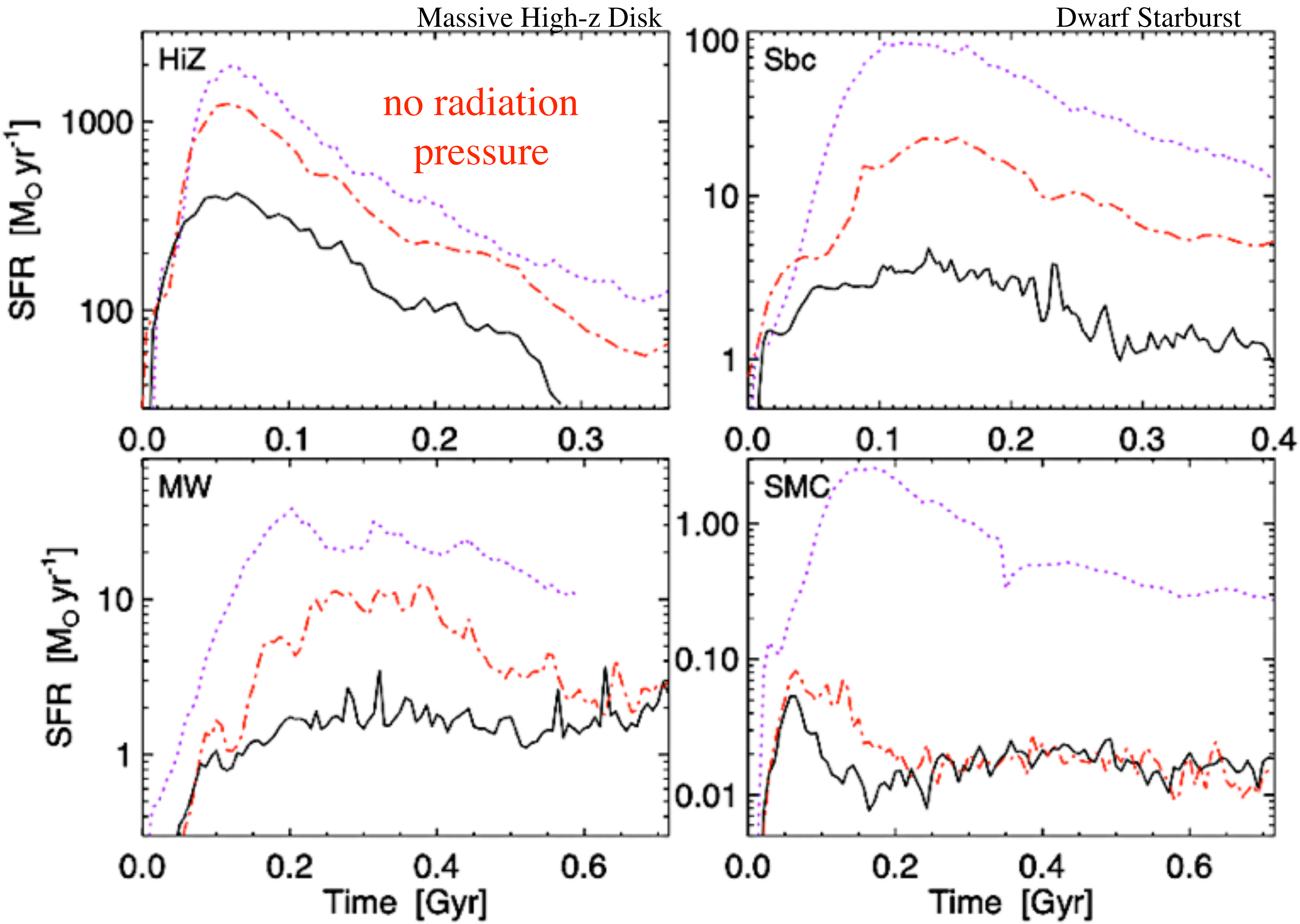

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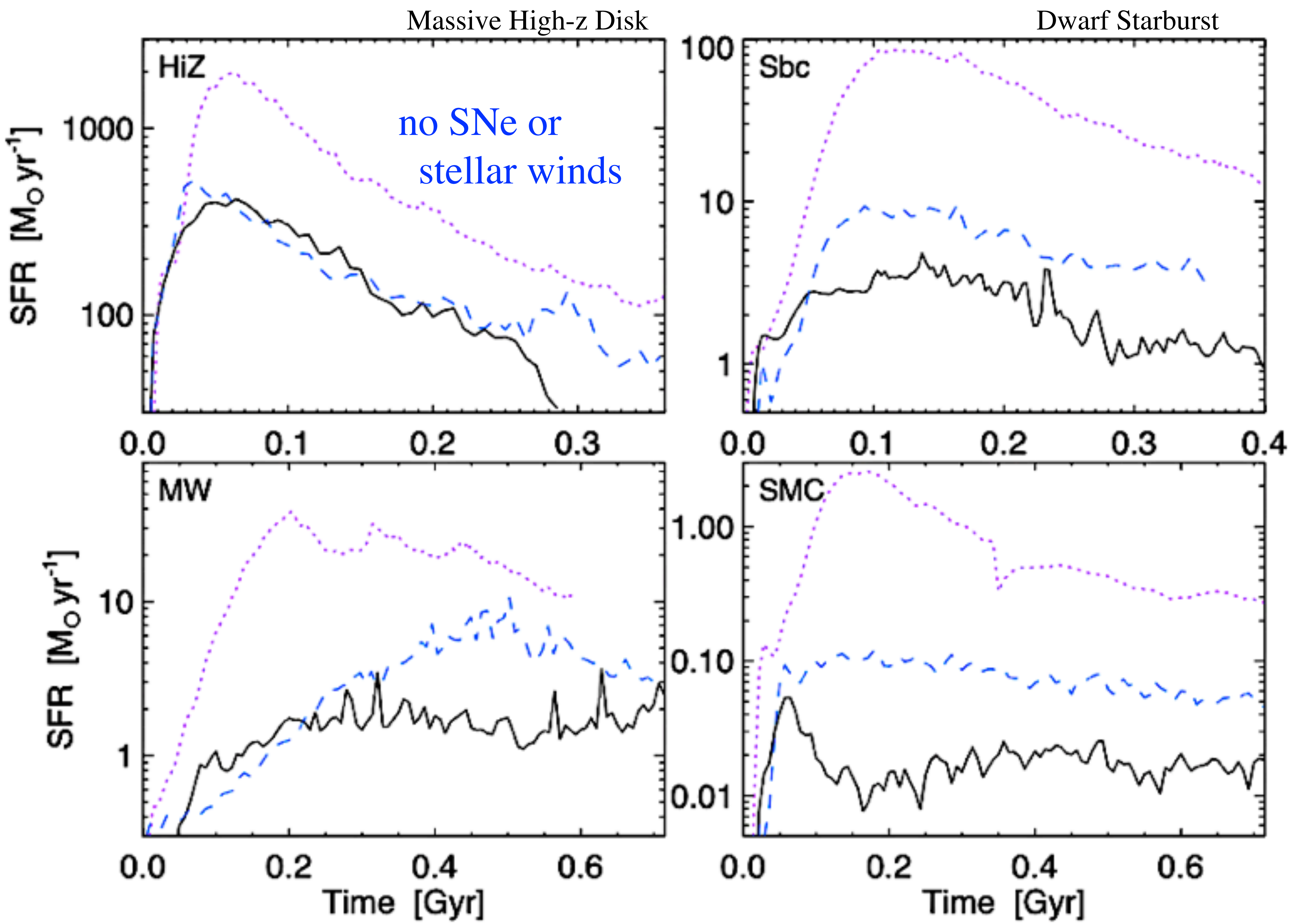
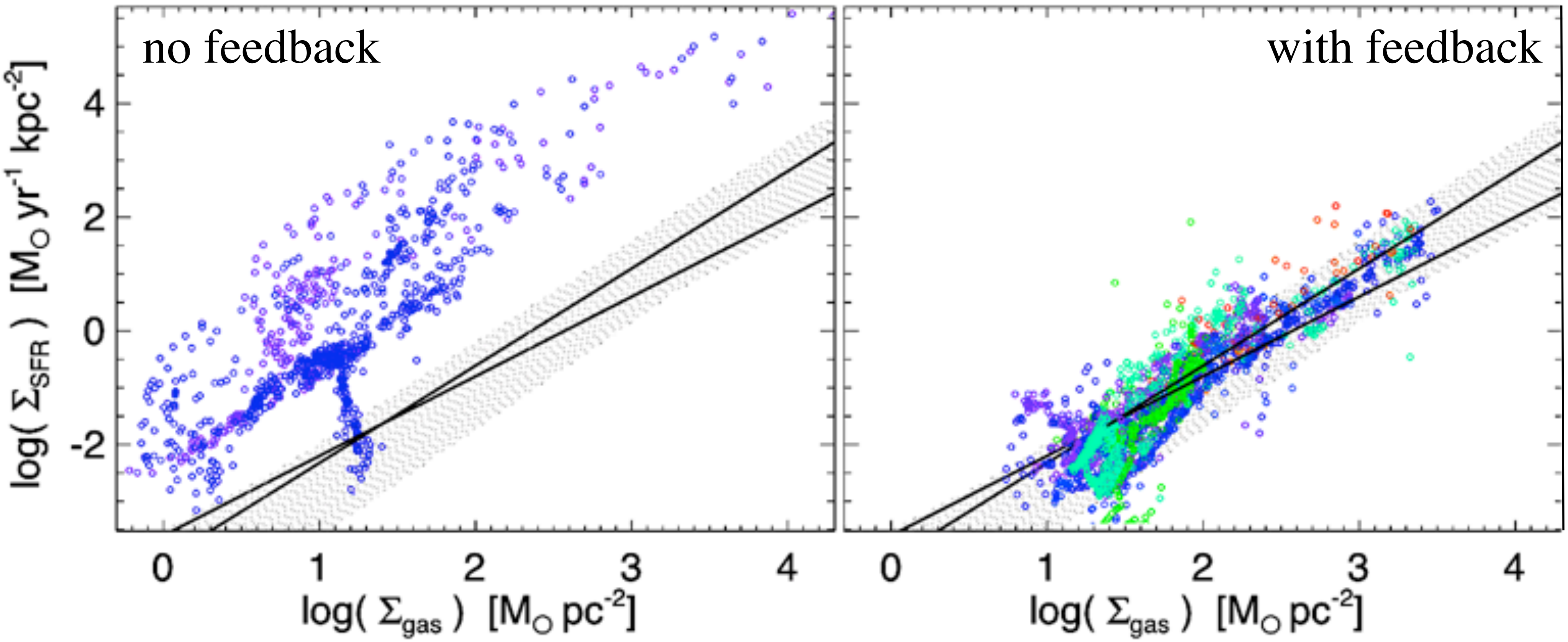


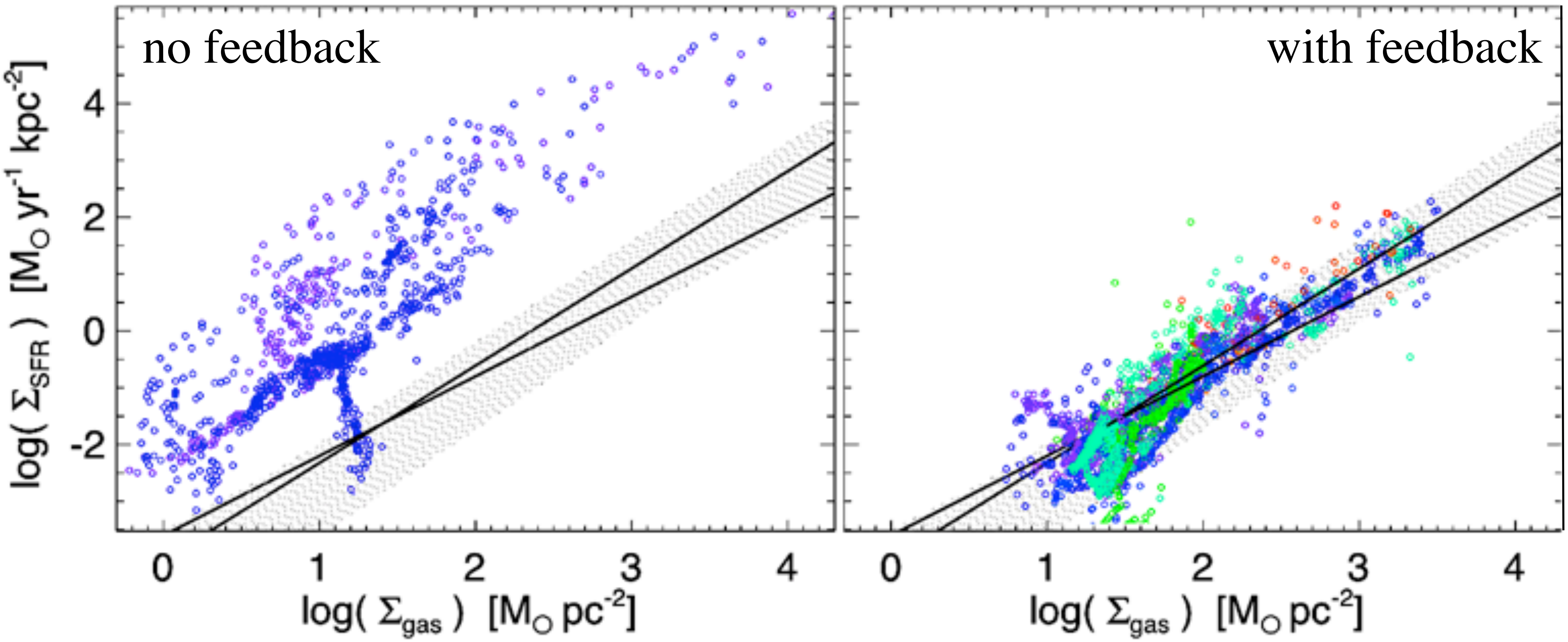
Kennicutt-Schmidt relation emerges naturally



PFH, Quataert, & Murray, 2011a

Kennicutt-Schmidt relation emerges naturally

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



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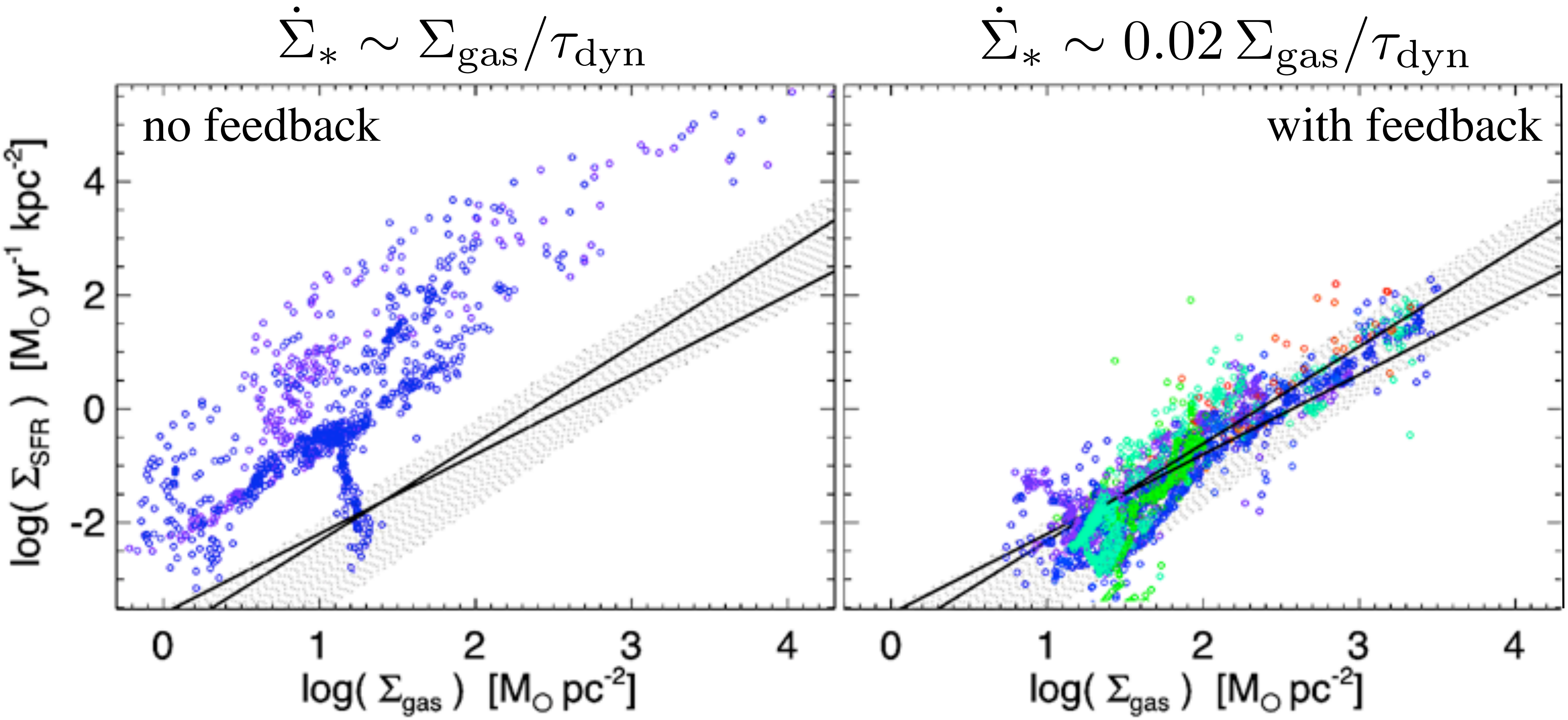

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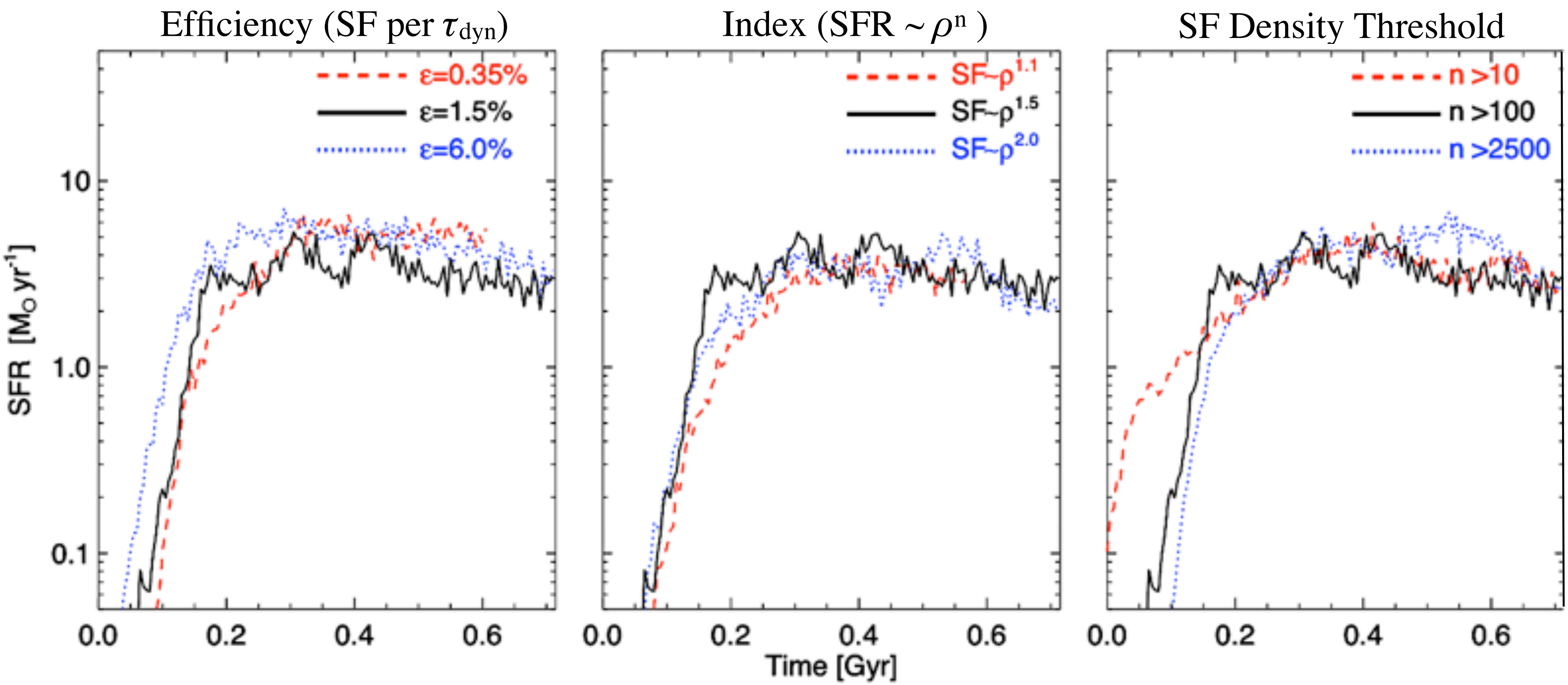
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas}\Omega \sim 0.02\, \Sigma_{\rm gas}\Omega$$

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



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

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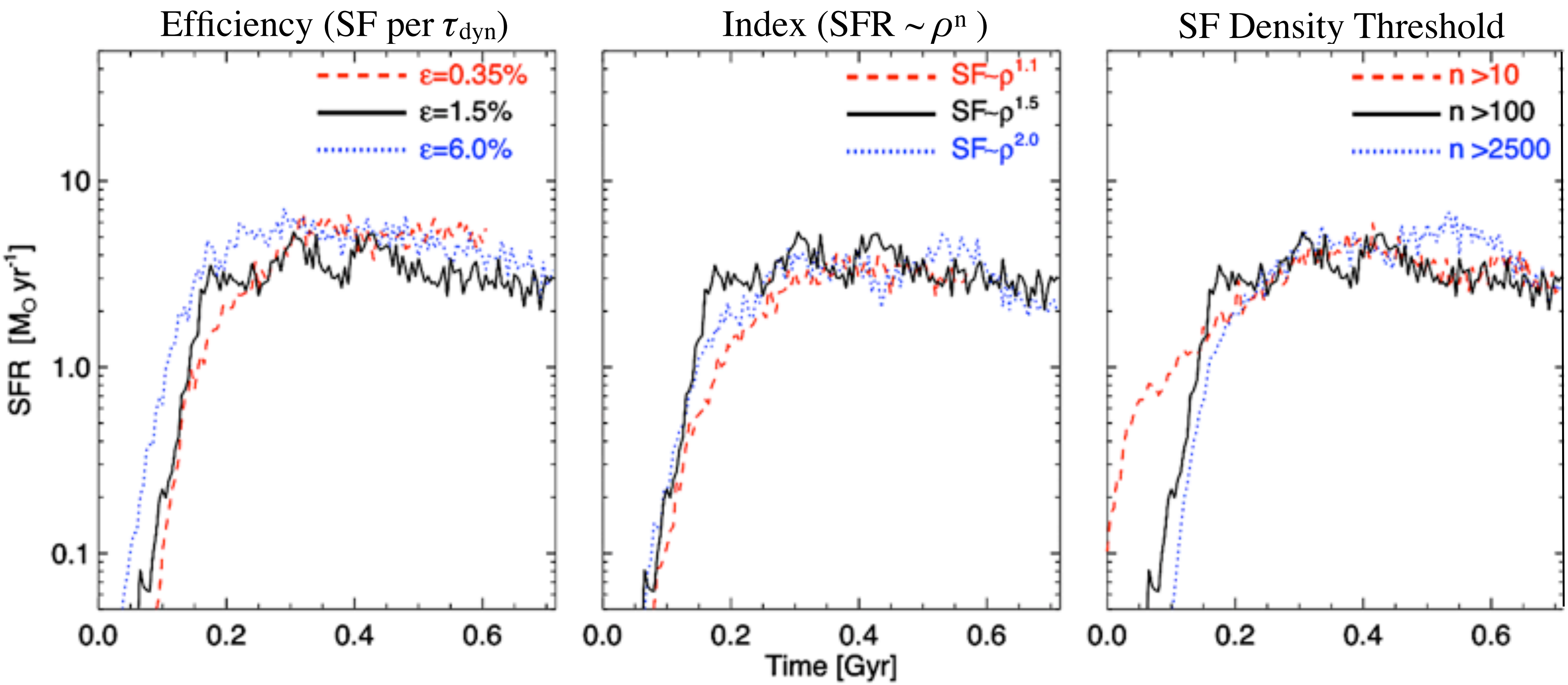
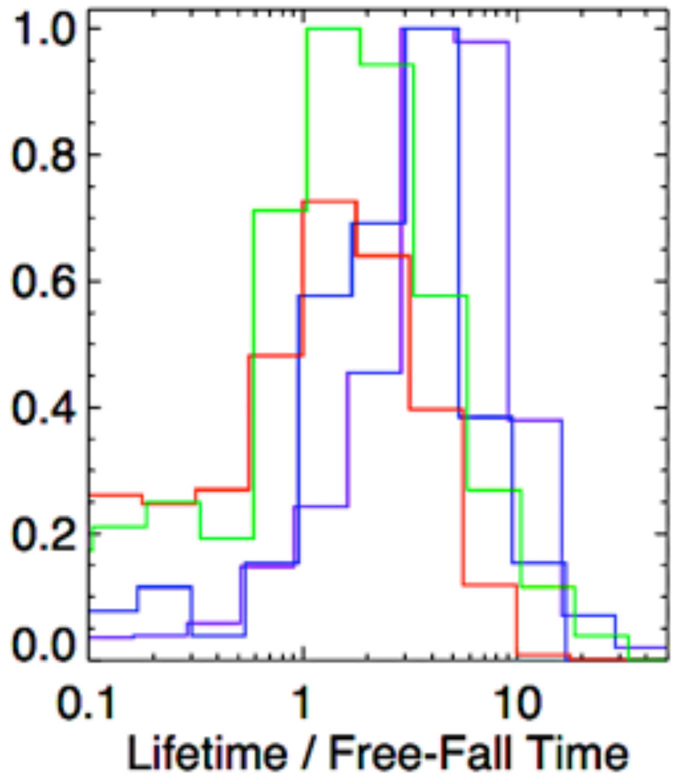


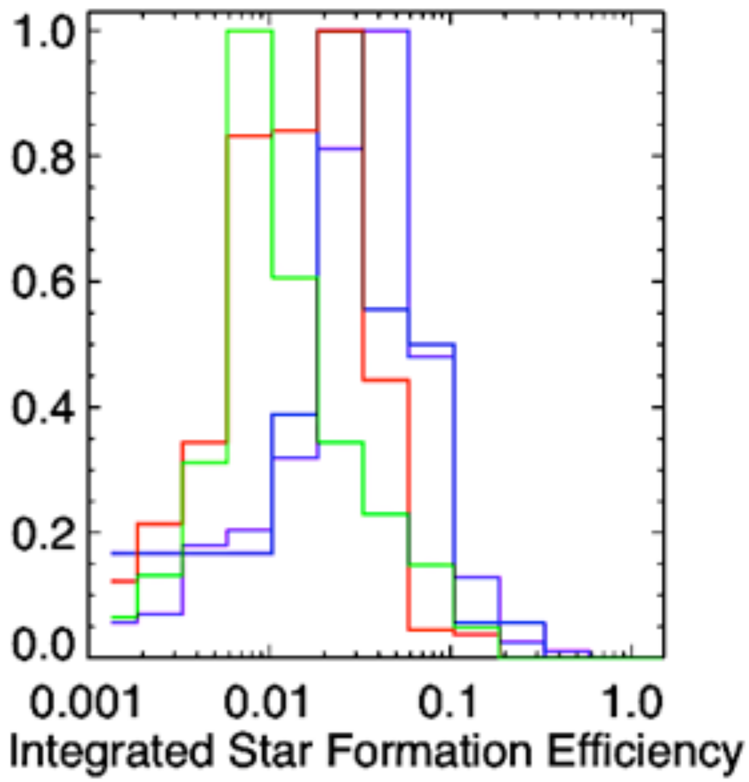
- Set by feedback (i.e. SFR) needed to maintain marginal stability

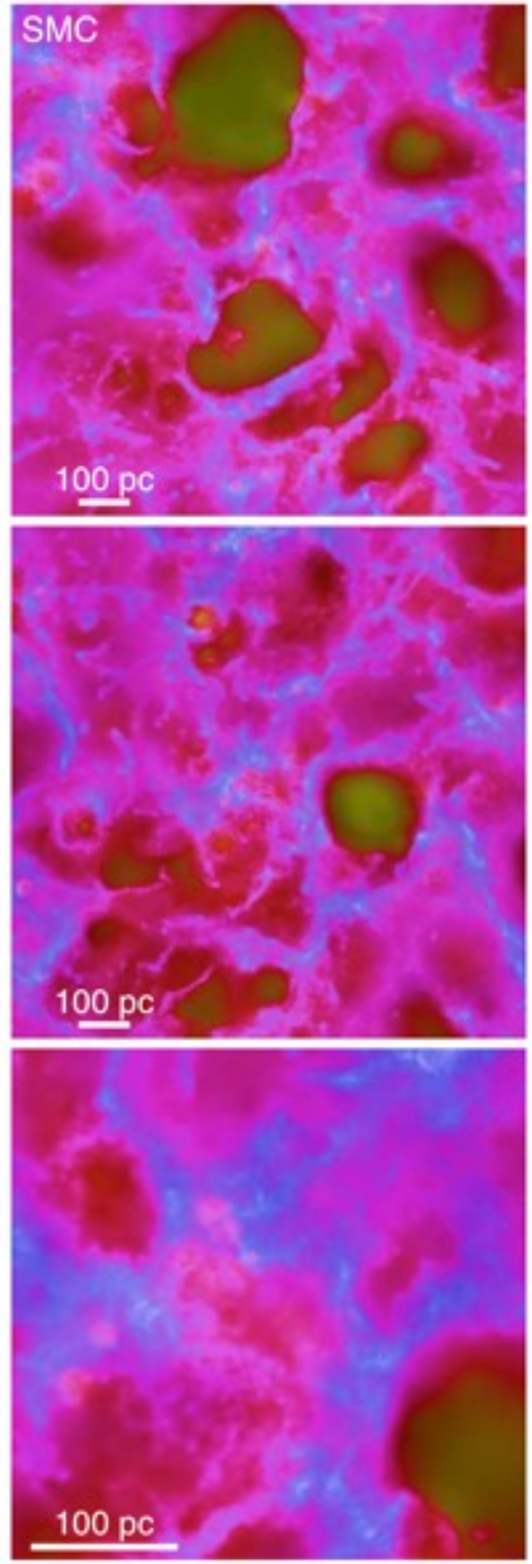
Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

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

Properties of GMCs
DEPENDENCE ON FEEDBACK AND OTHER SCALINGS

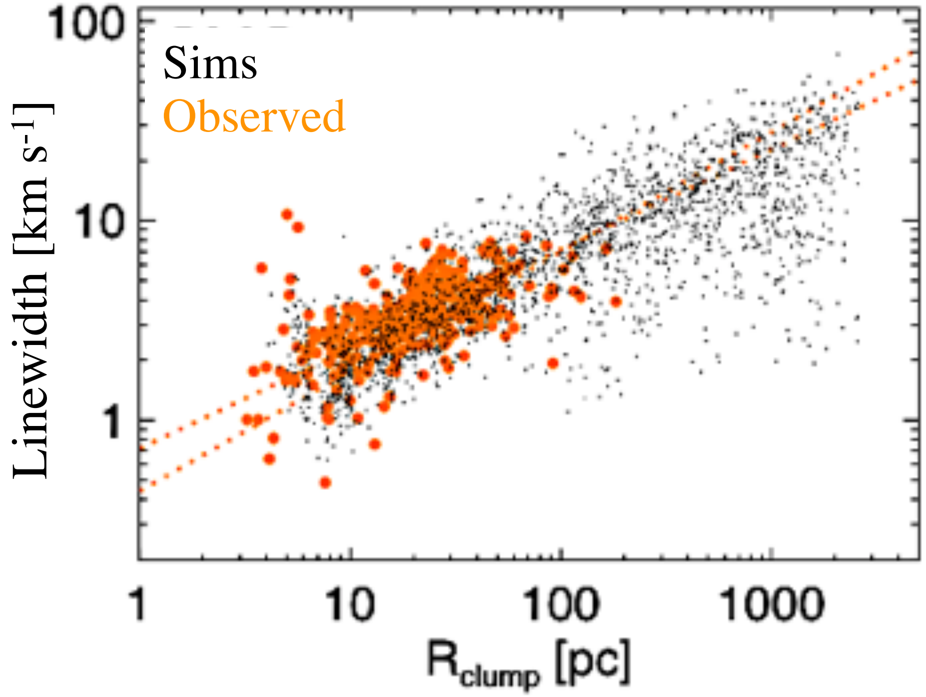


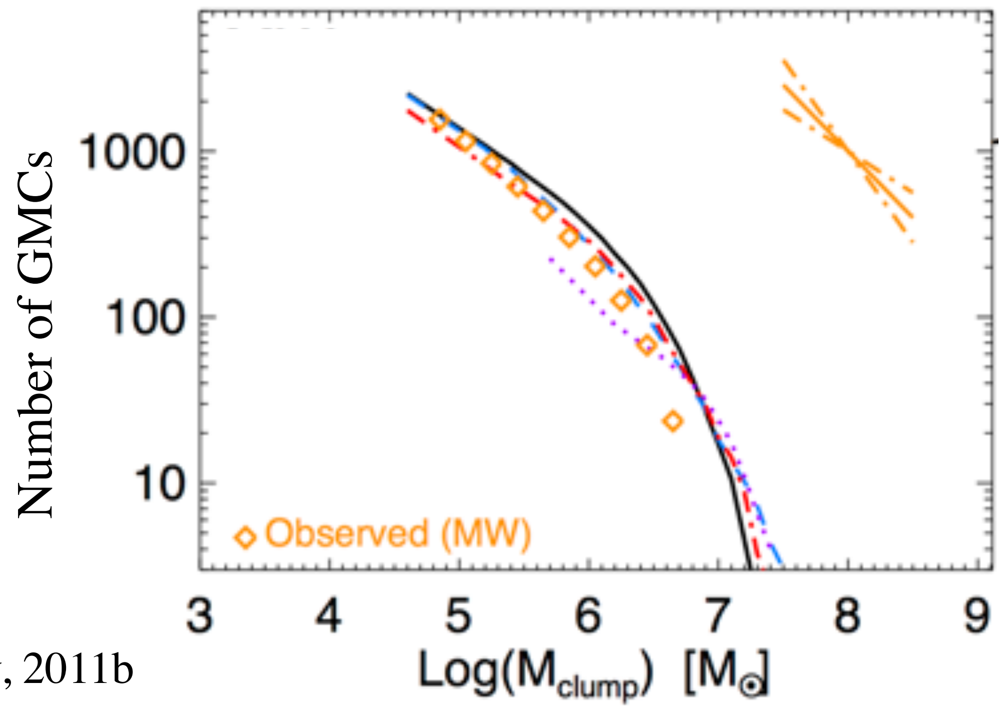


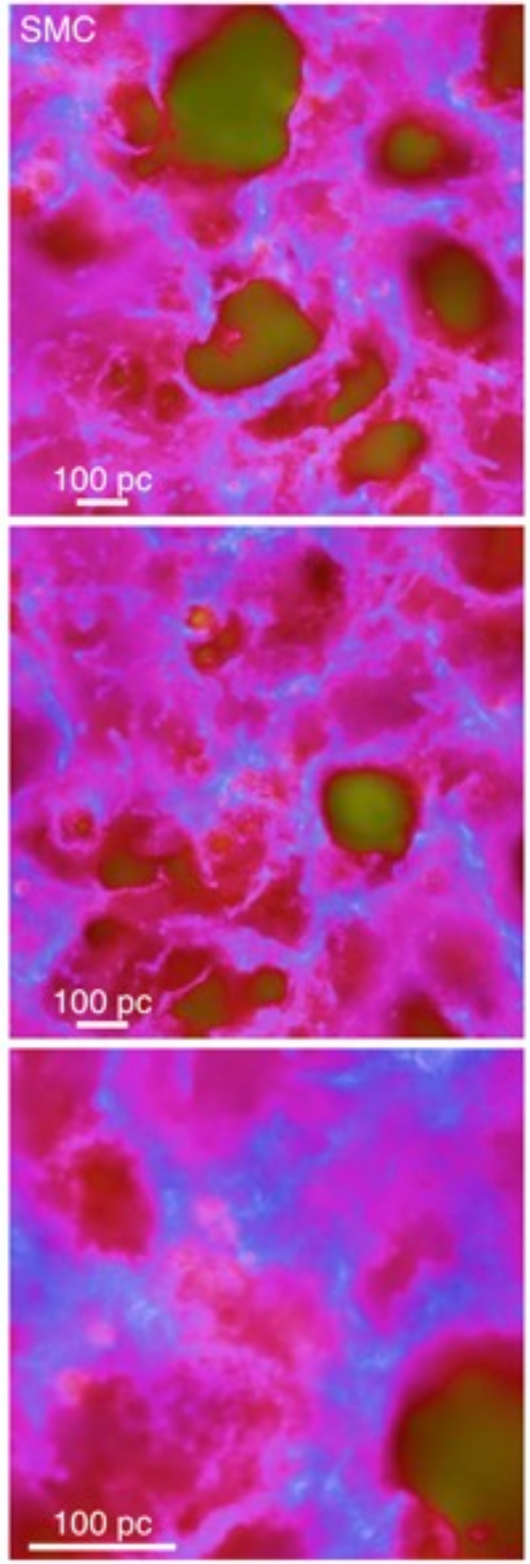


PFH, Quataert, & Murray, 2011b

Properties of GMCs & Gas "Clumps"





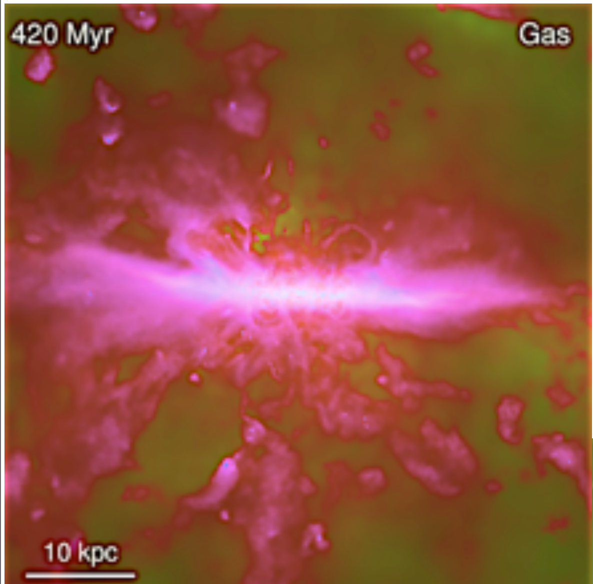


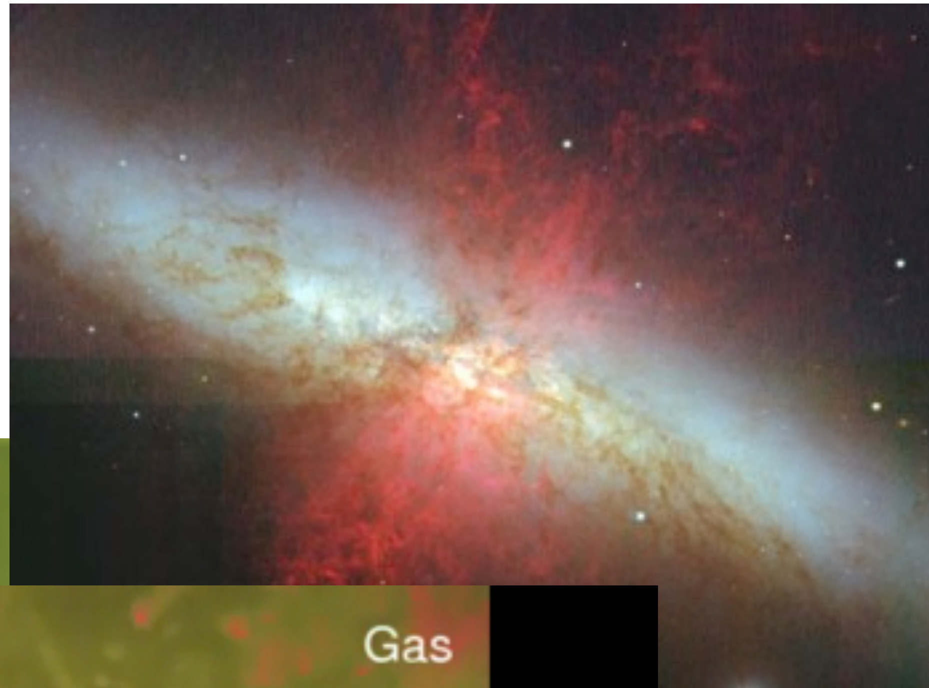
PFH, Quataert, & Murray, 2011b

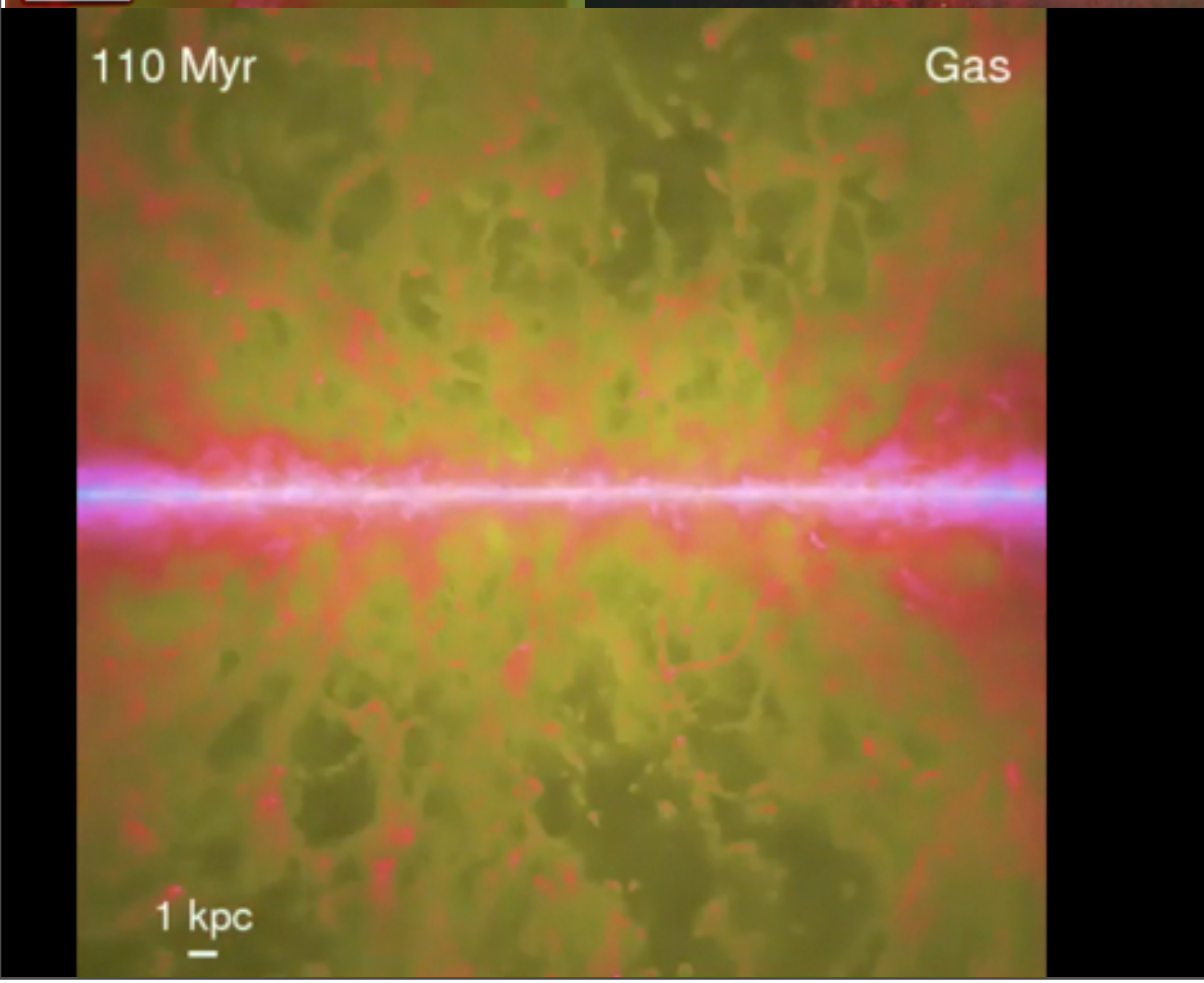
The Gas not Forming Stars:

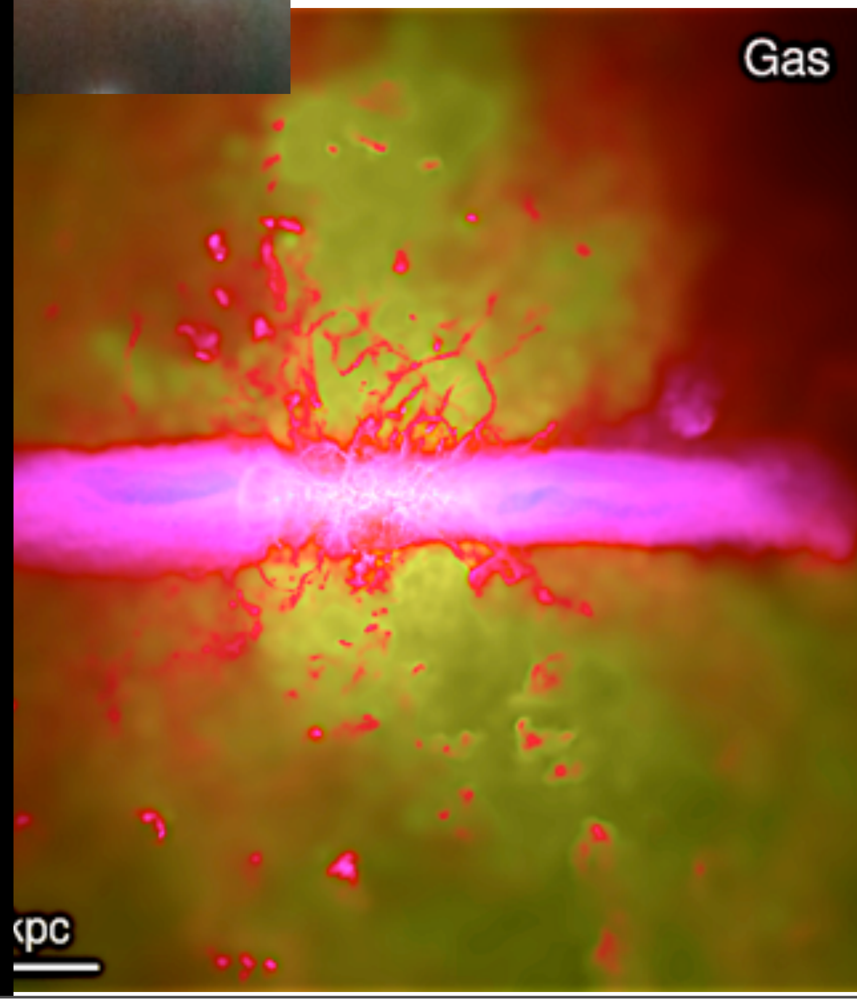
Galaxy Winds and the Baryon Cycle

Galactic Super-Winds





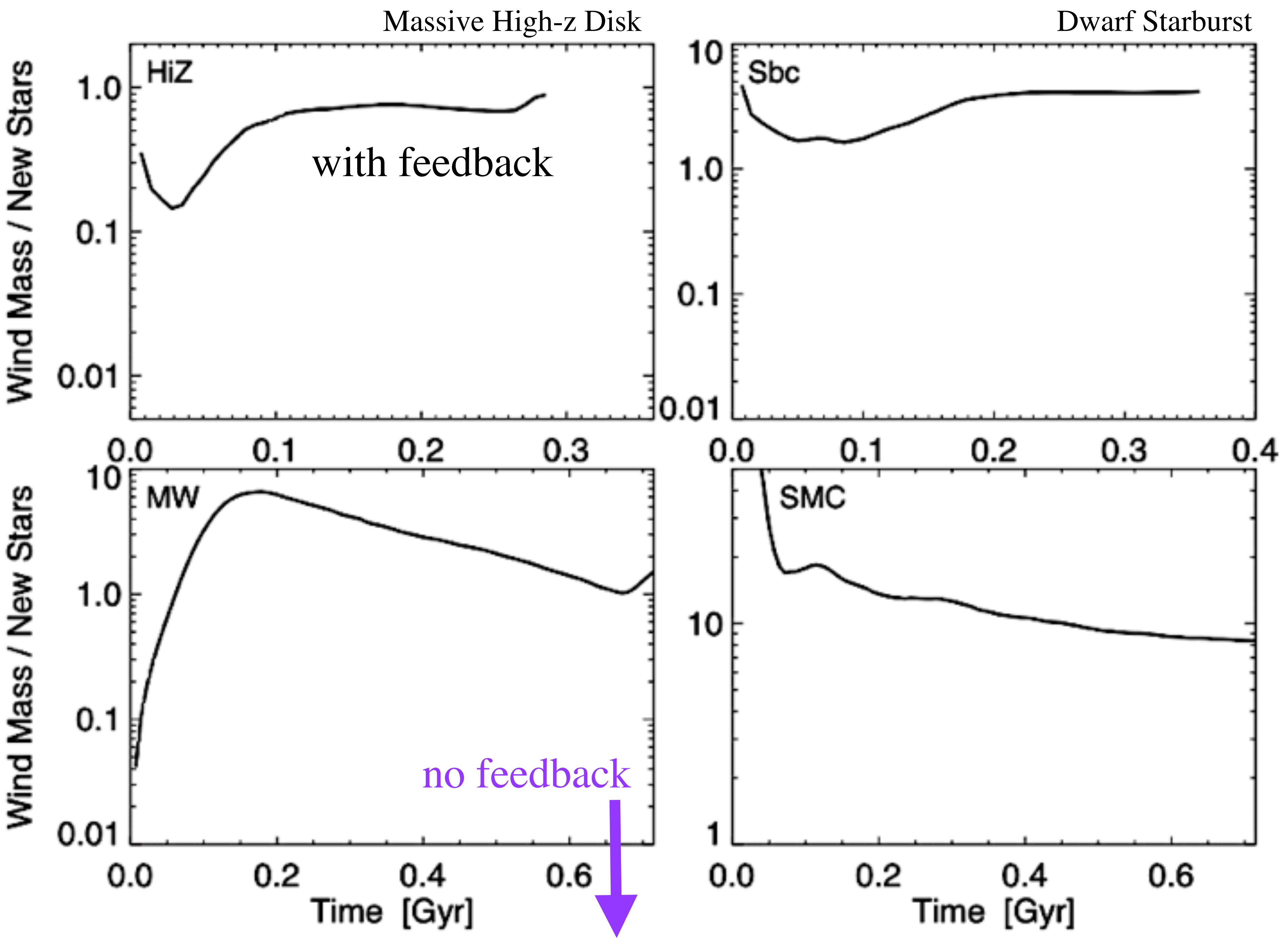




How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?

PFH, Quataert, & Murray, 2011c



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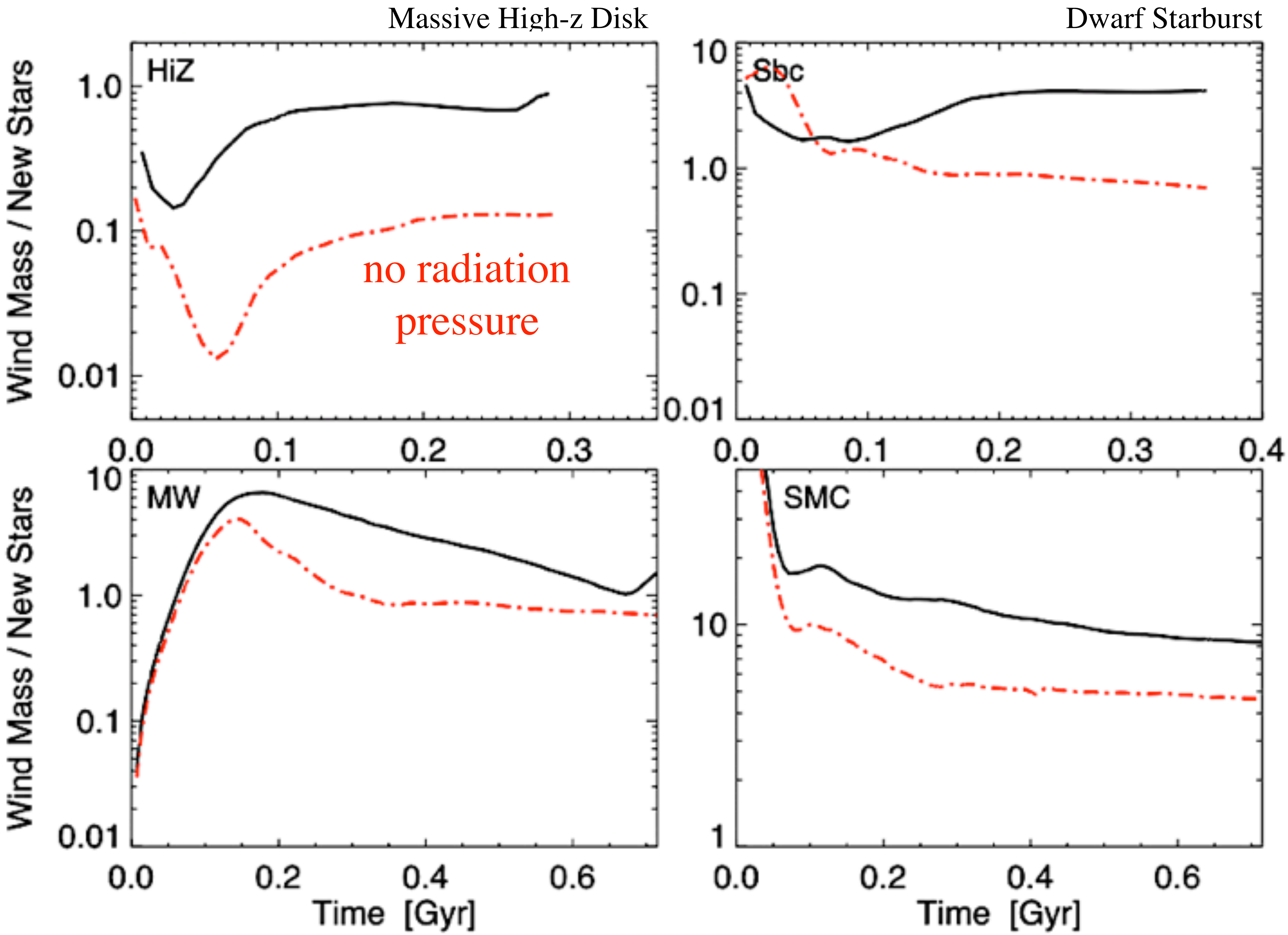

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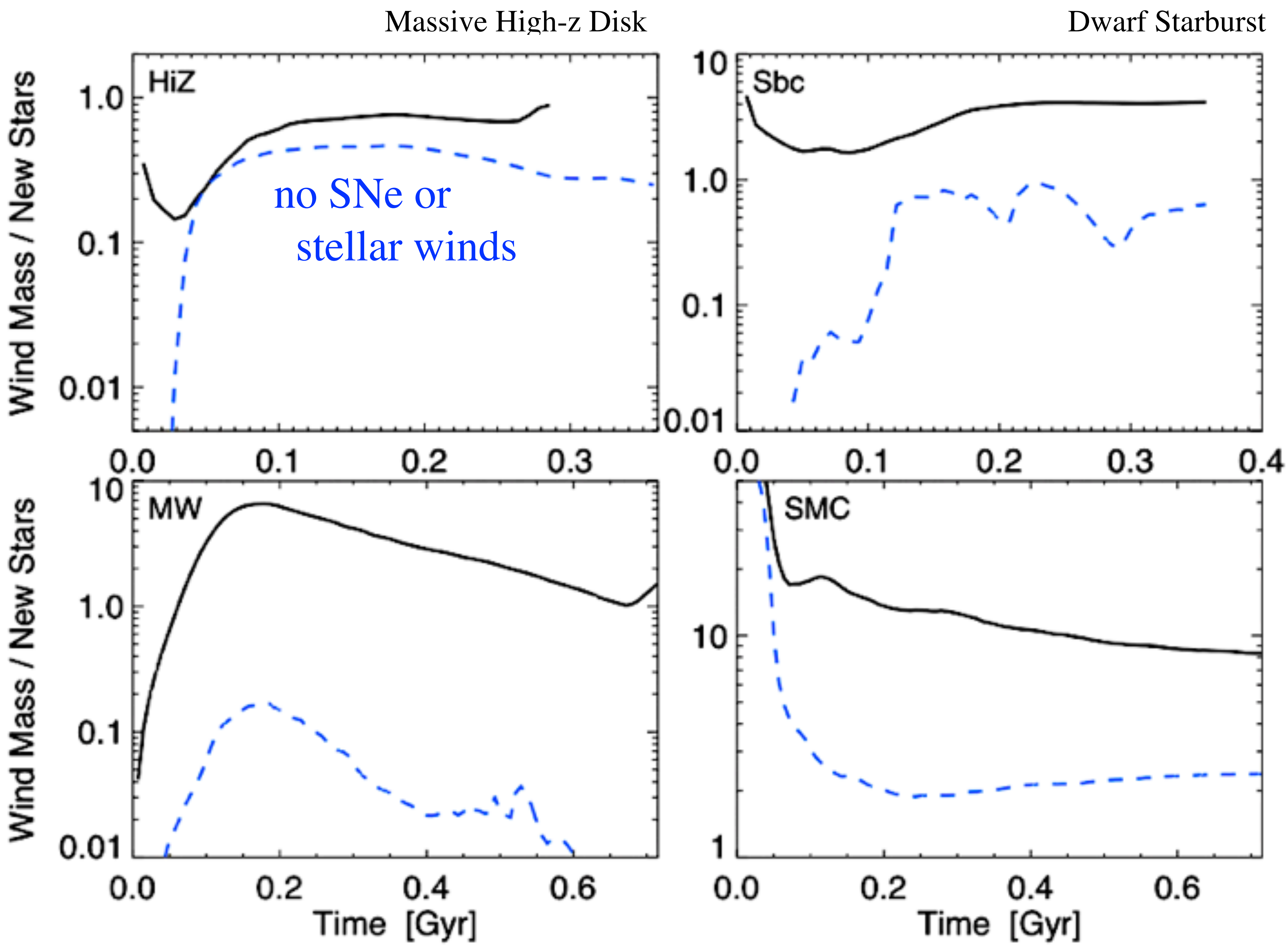

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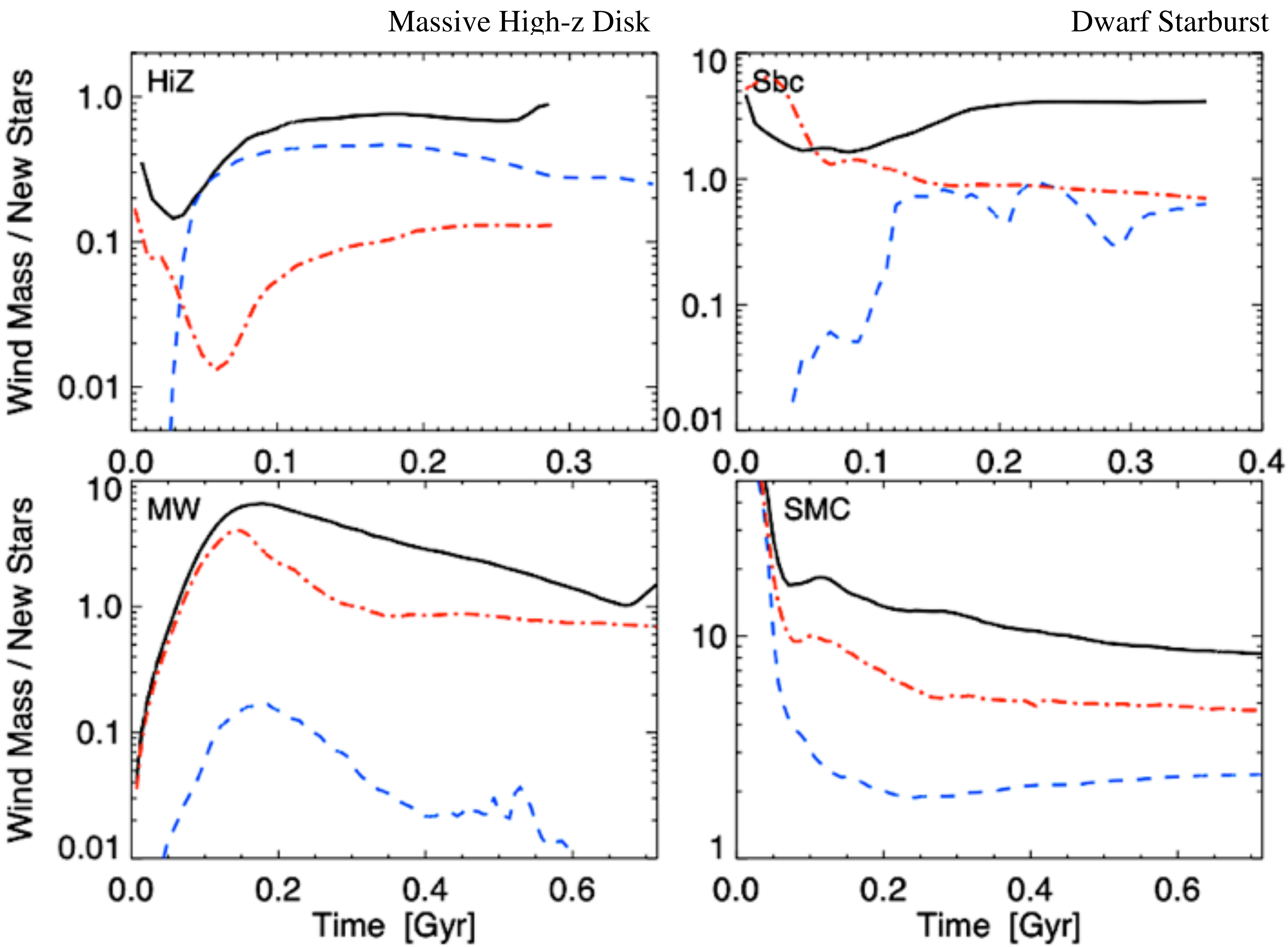

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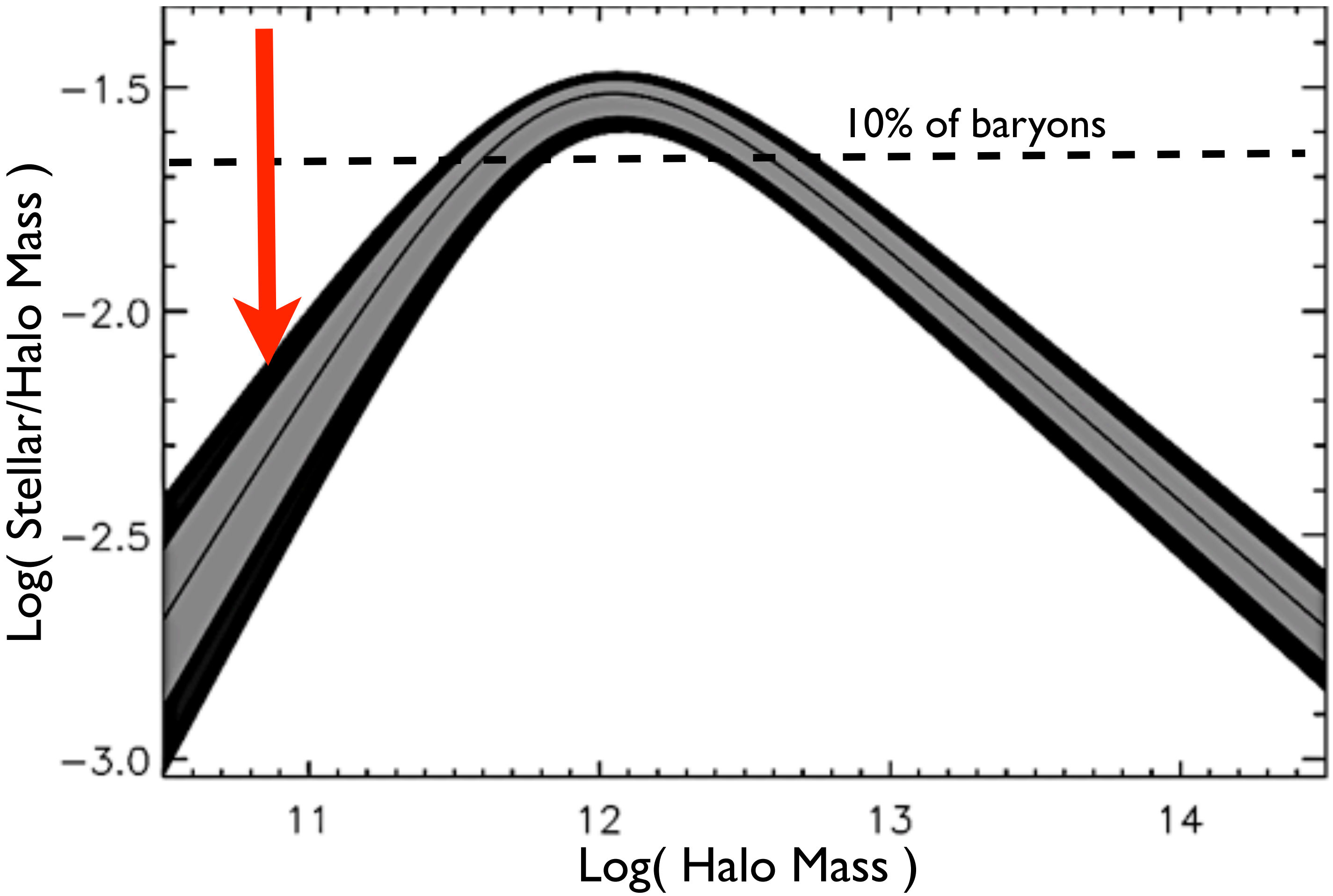

- Large mass-loading:

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

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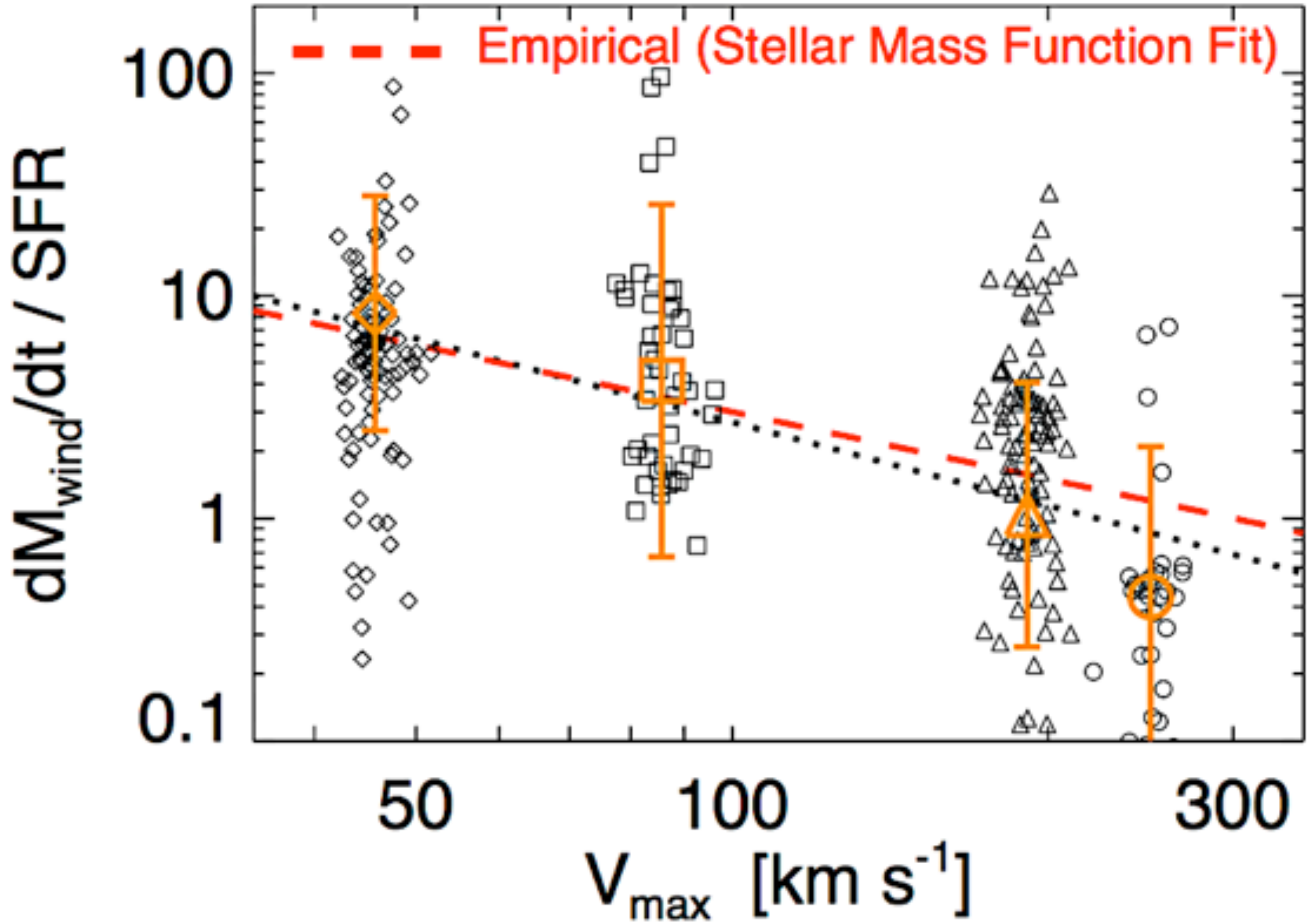

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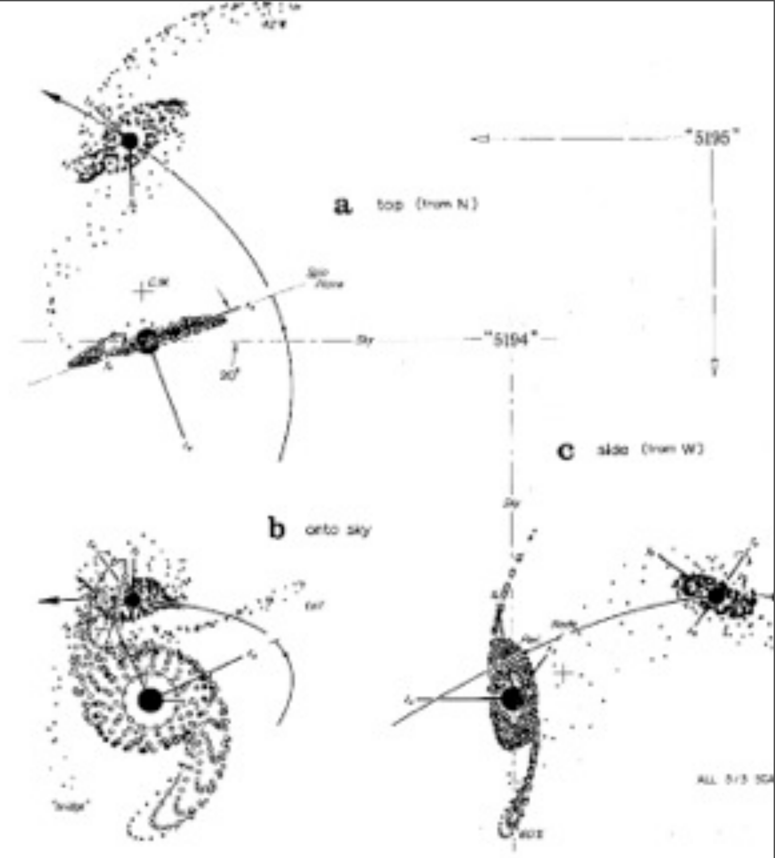
What Happens when Galaxies Interact?

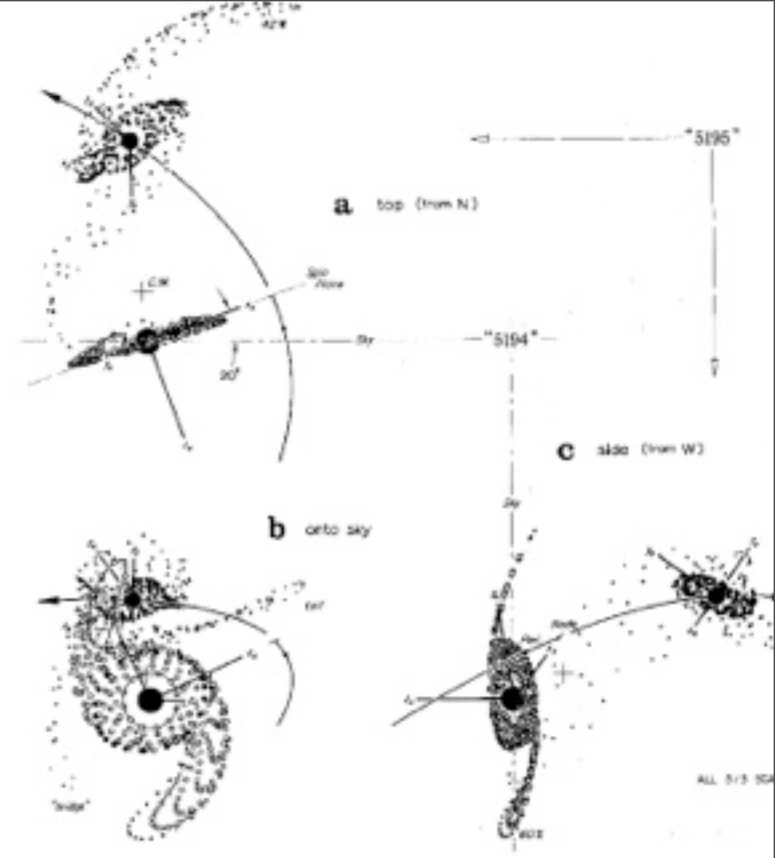
Our Conventional Wisdom (Toomre):



F. Summers

Our Conventional Wisdom (Toomre):

- Major mergers destroy disks



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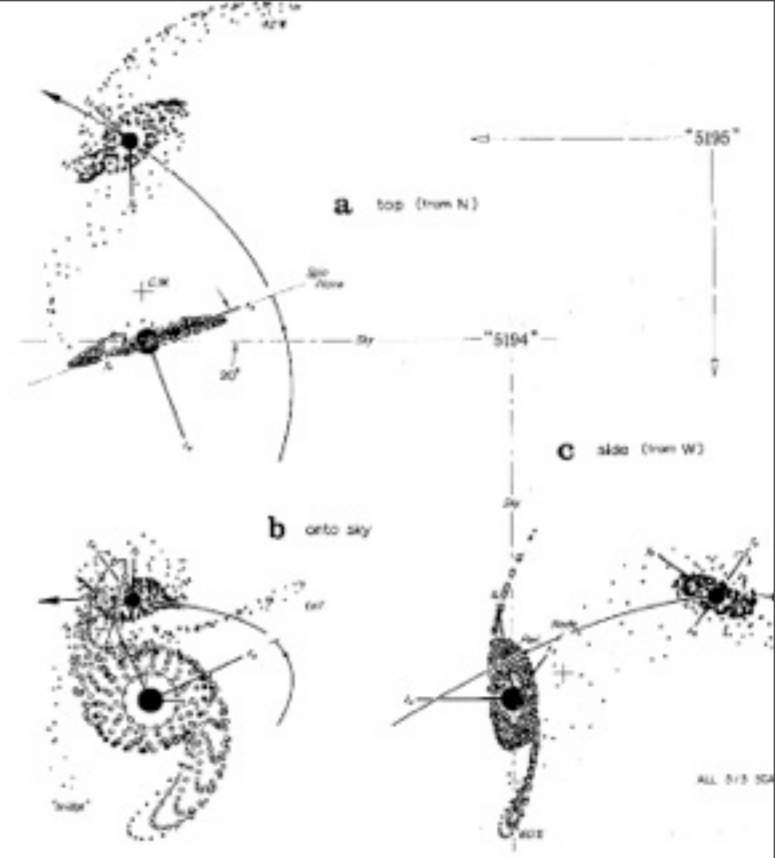
- Remnant size/metallicity/shape retains "memory" of disk "initial conditions"



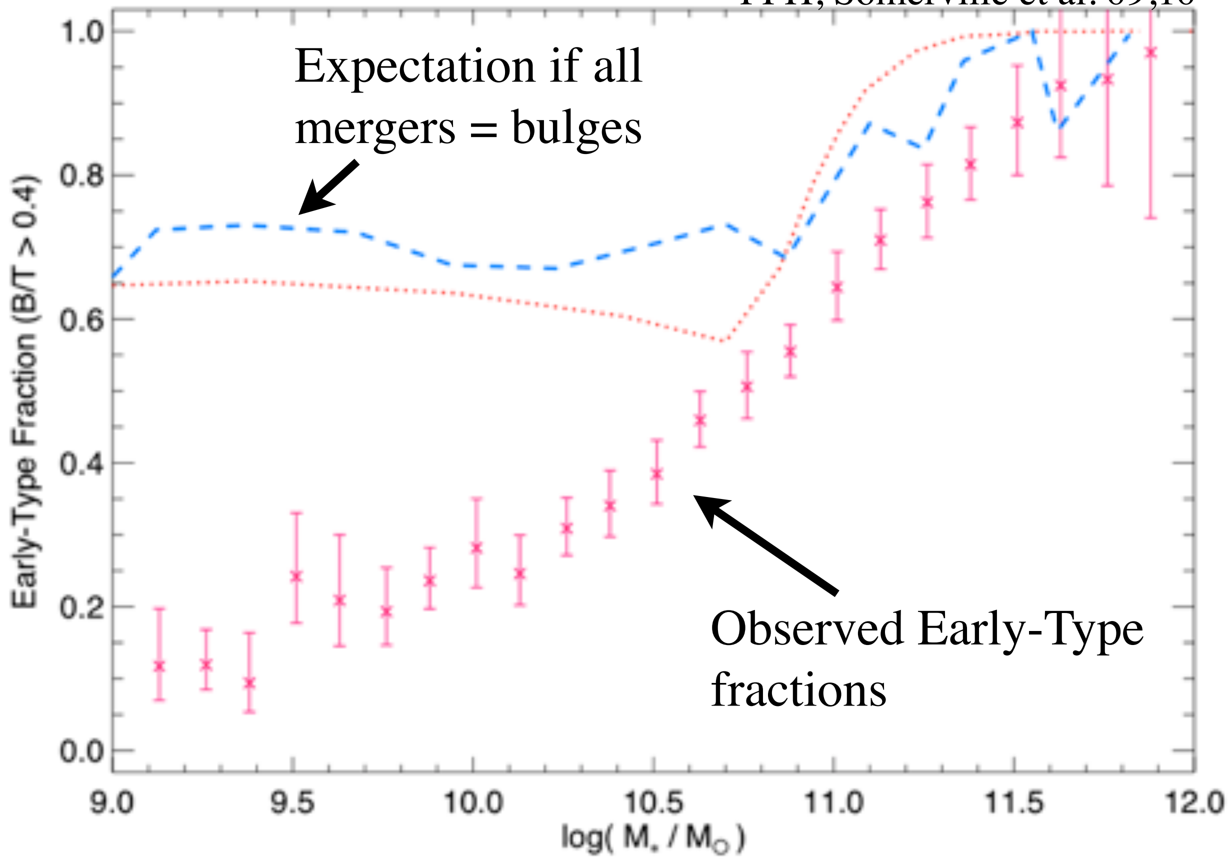
F. Summers

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

Too Many Mergers?

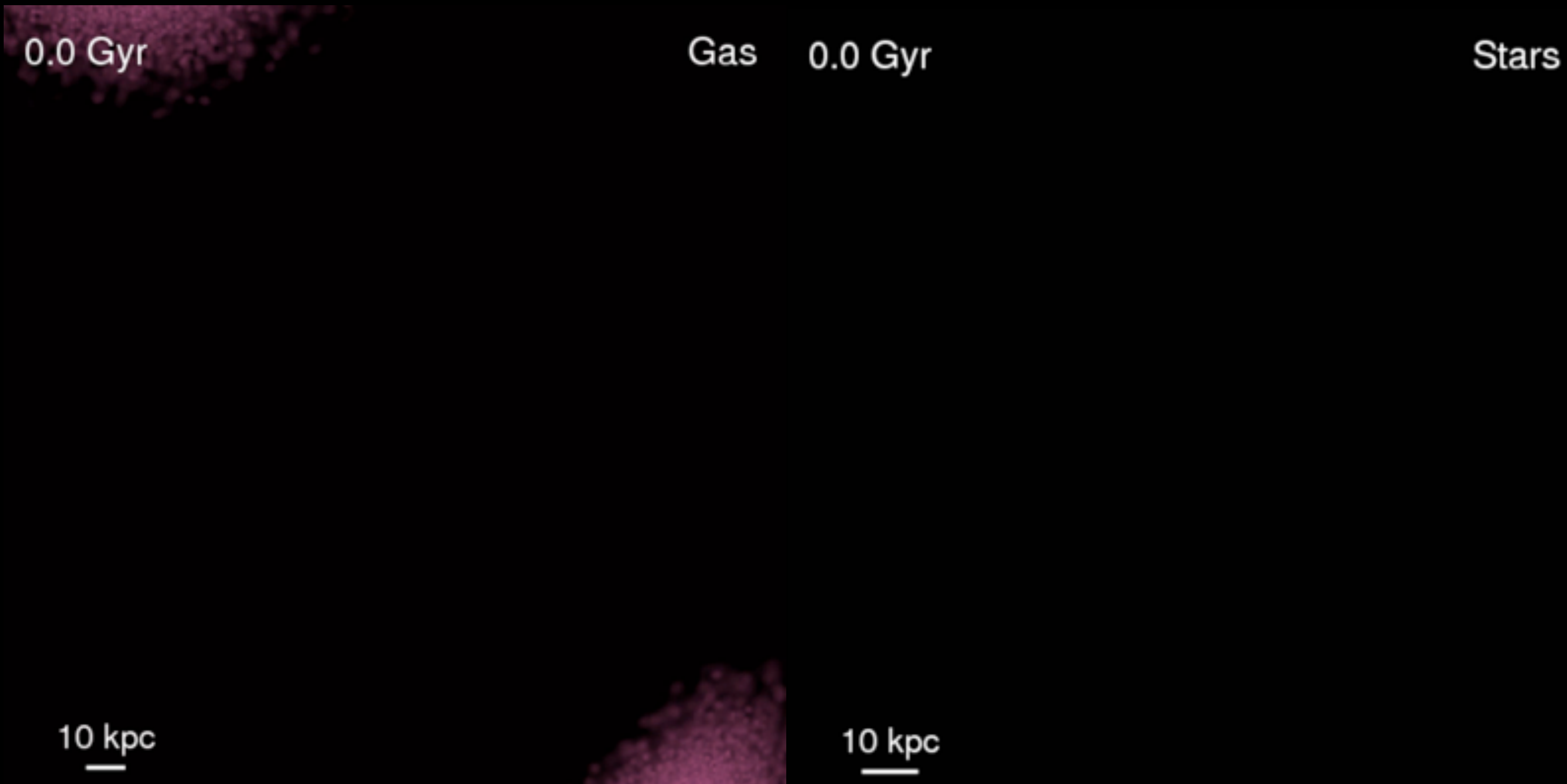
-- missing key physics?

PFH, Somerville et al. 09,10



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

Milky Way (~5% Gas) Merger



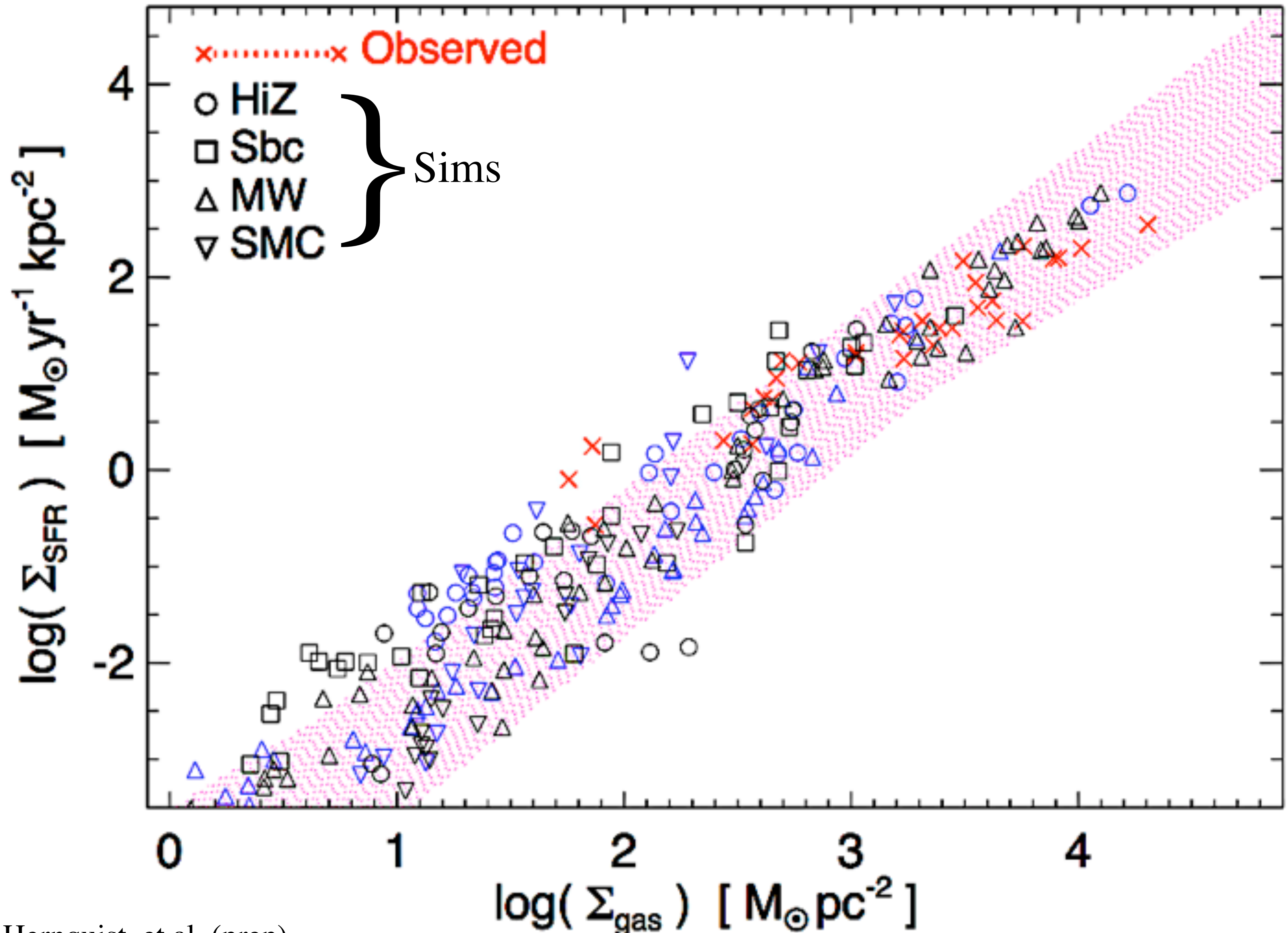
Starburst (~40% Gas) Merger

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: ~10-500 M_{sun}/yr

Galaxy Mergers
LABORATORY FOR STUDYING EXTREME CONDITIONS



PFH, Hernquist, et al. (prep)

Galaxy Mergers
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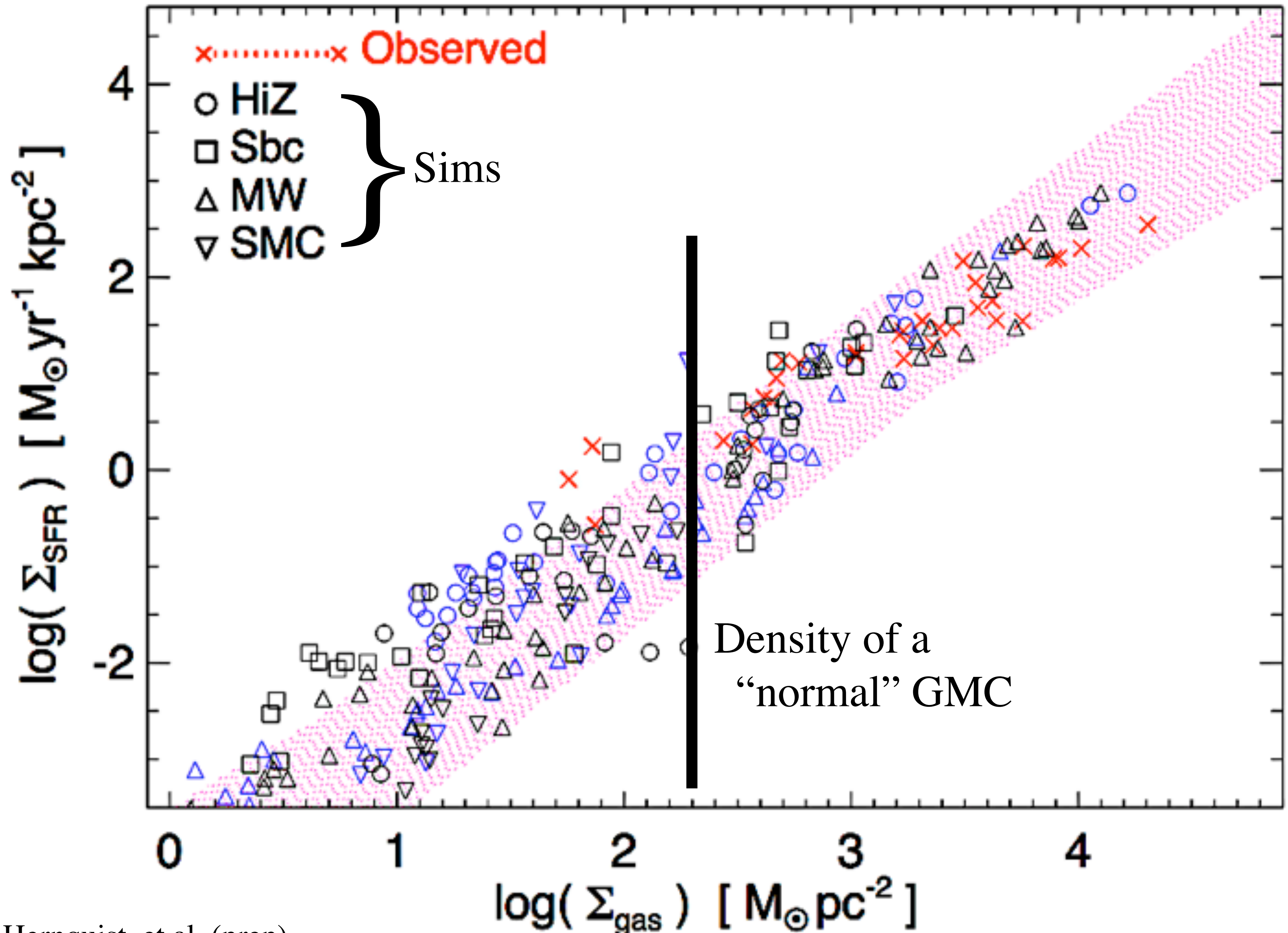
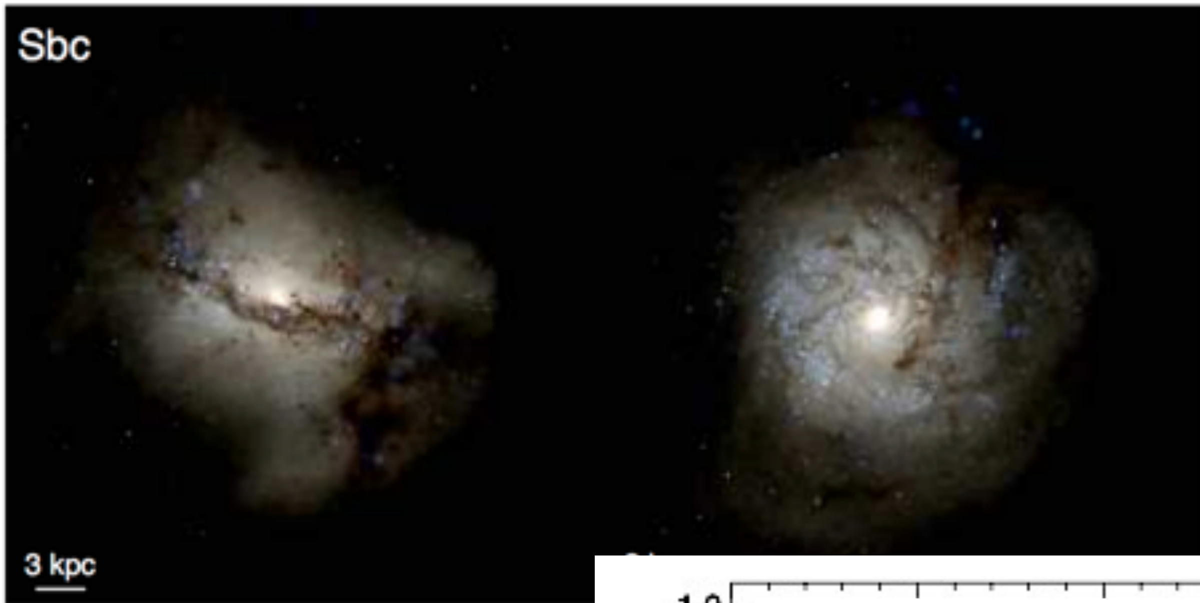


PFH, Hernquist, et al. (prep)

Disks can Survive & Re-Form After Mergers

NOT AS FRAGILE AS WE THOUGHT!



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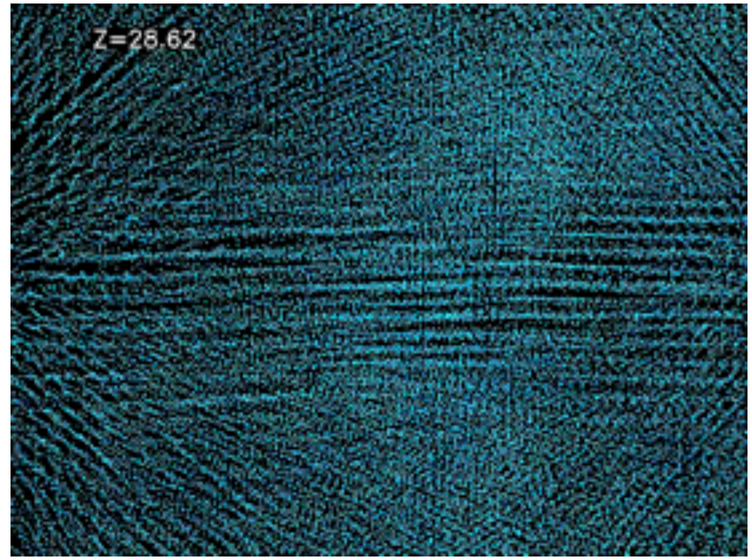

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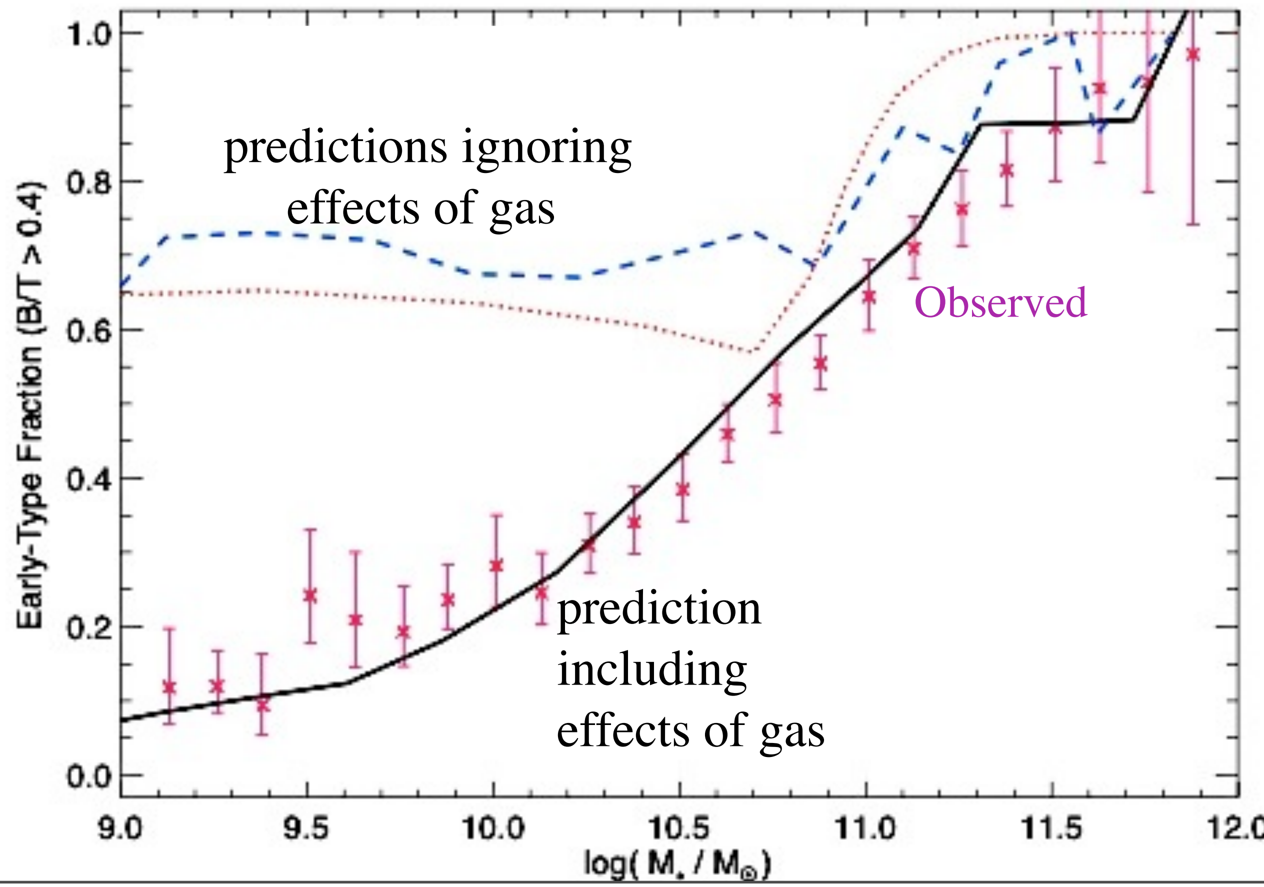
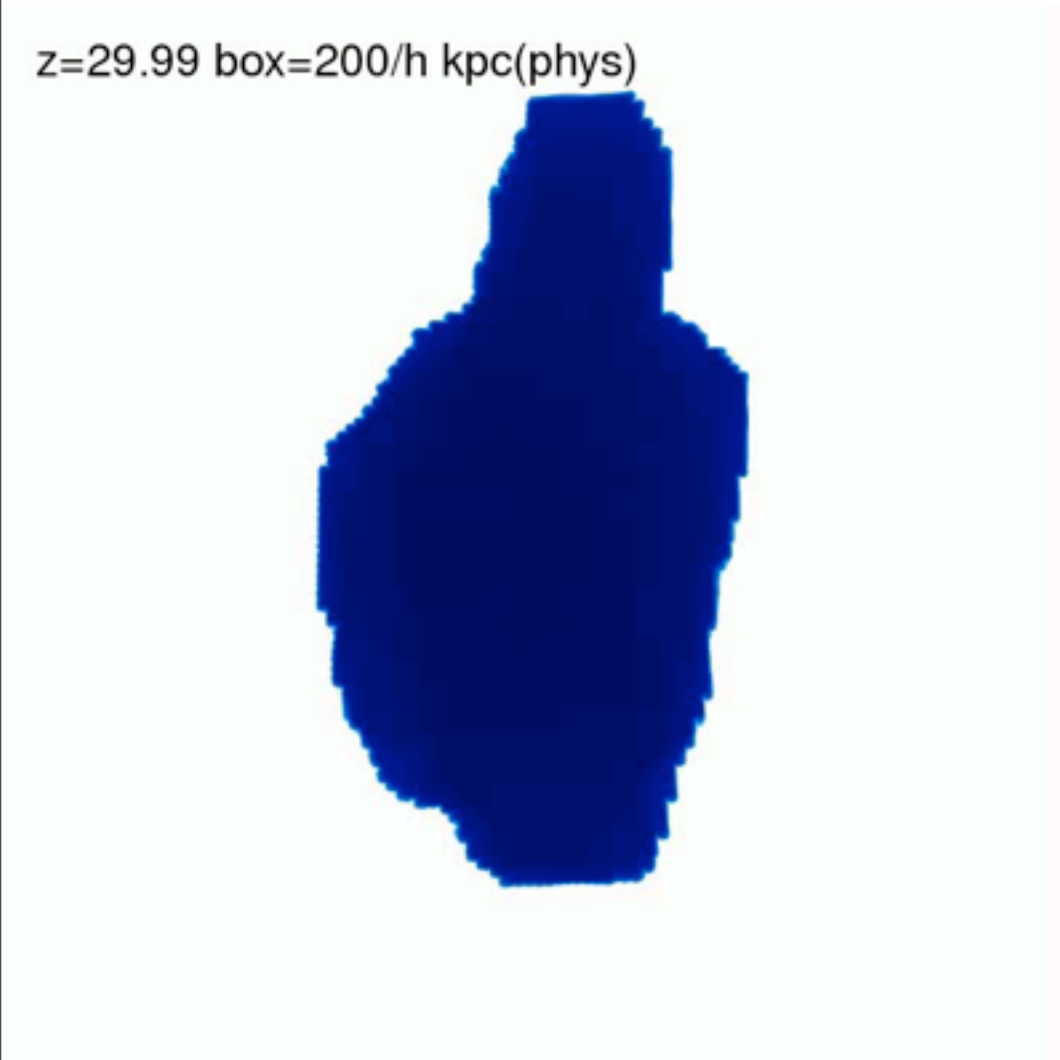


PFH & Somerville et al. 2009

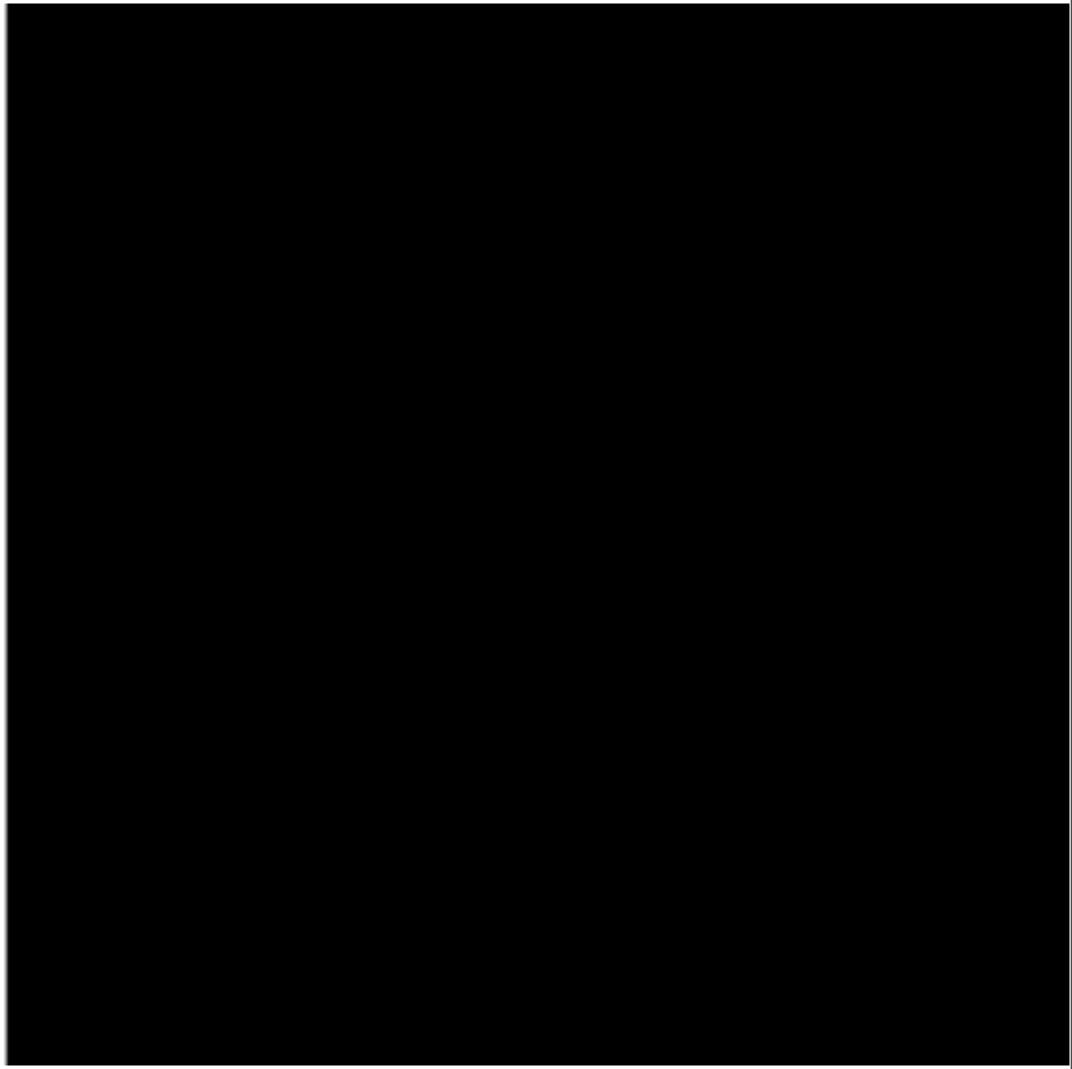
High Redshifts & The Inflow/Outflow Cycle

Cosmological Simulations

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



IGM Density



IGM Temperature

PFH & Keres et al

Cosmological Simulations

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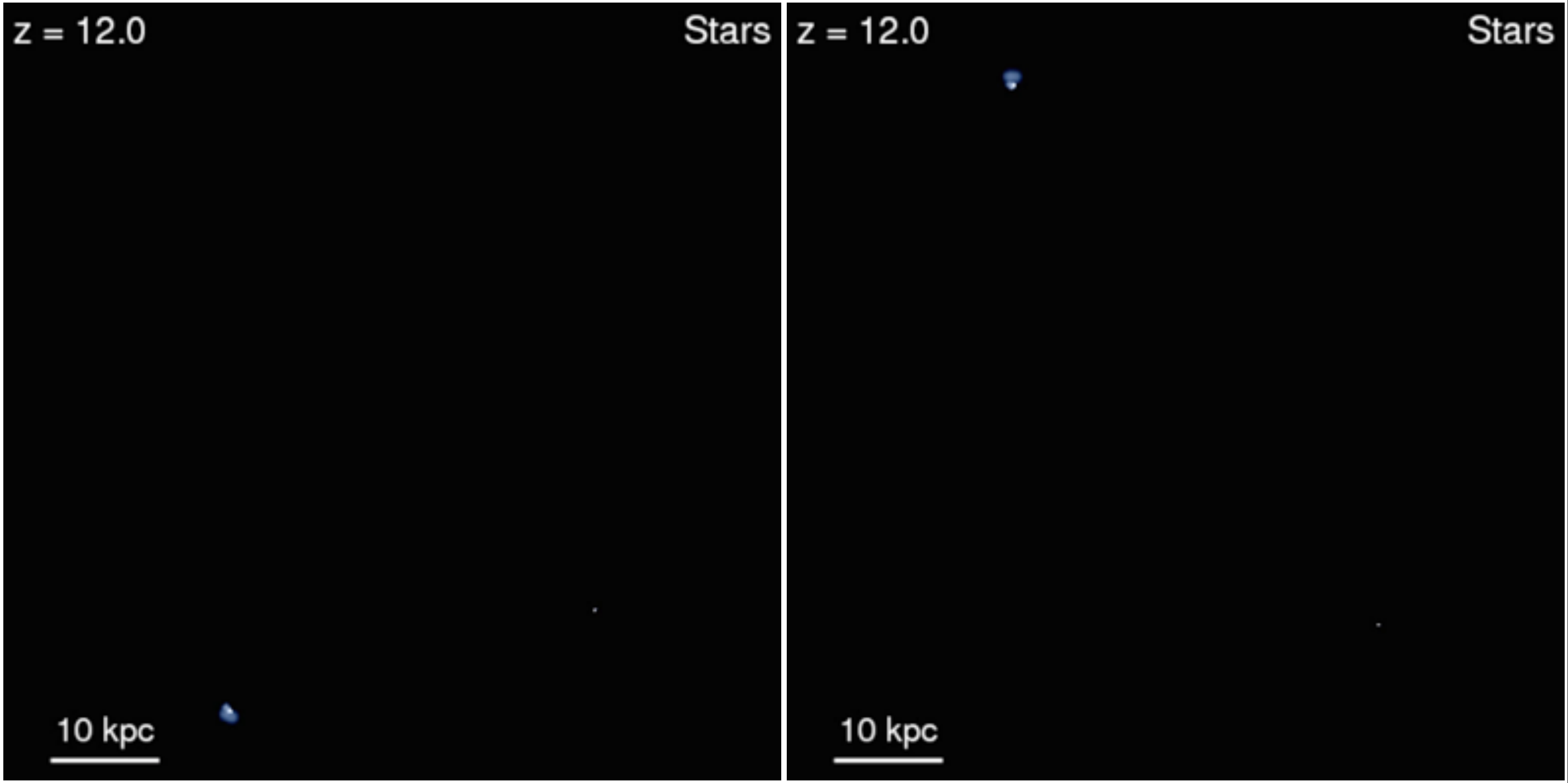
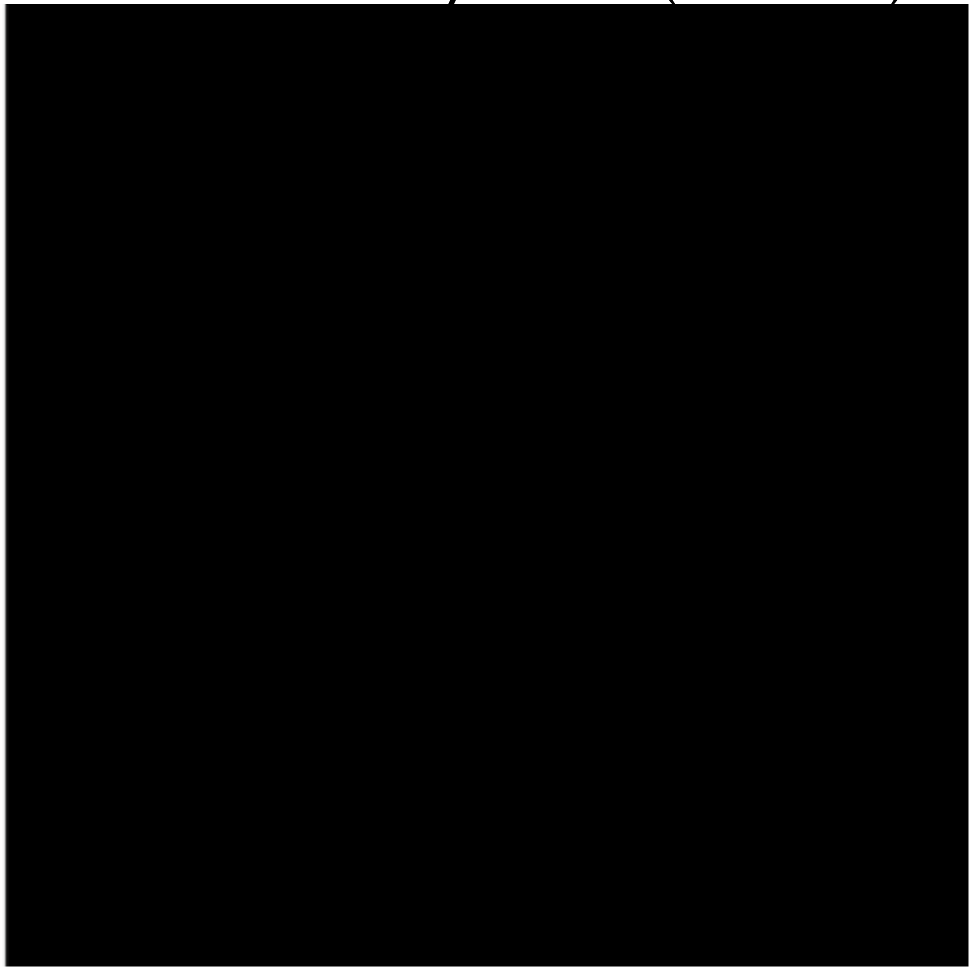


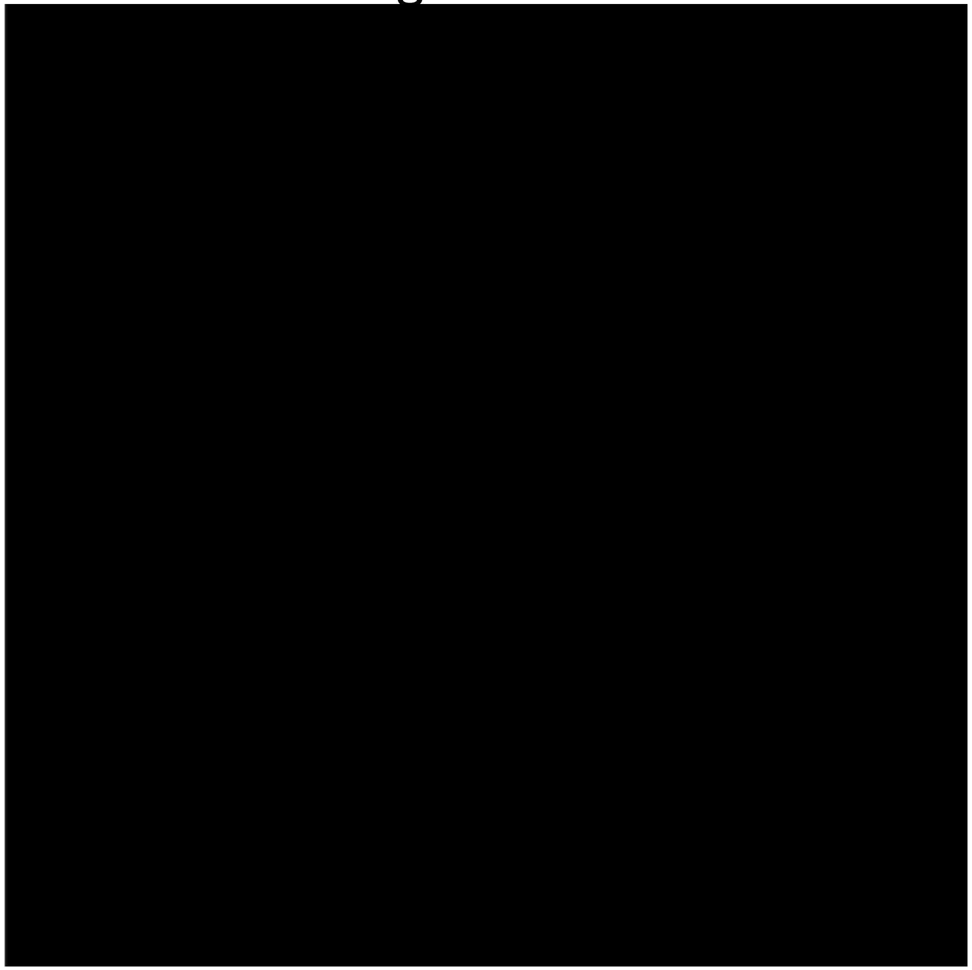
PFH & Keres et al.

Proto-MW: Gas Temperature:

Insert Winds “By Hand” (Sub-Grid)

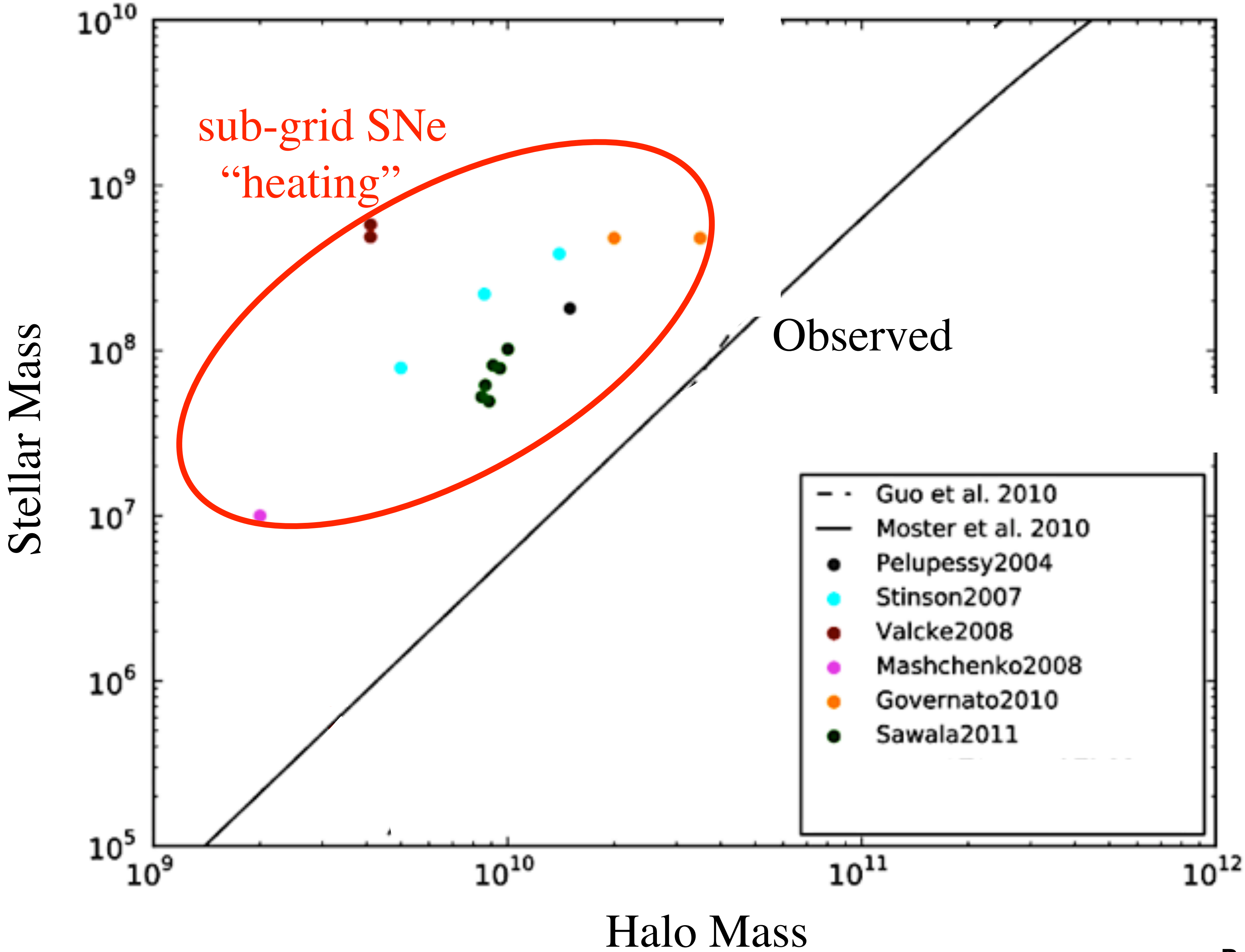


Following Full Feedback



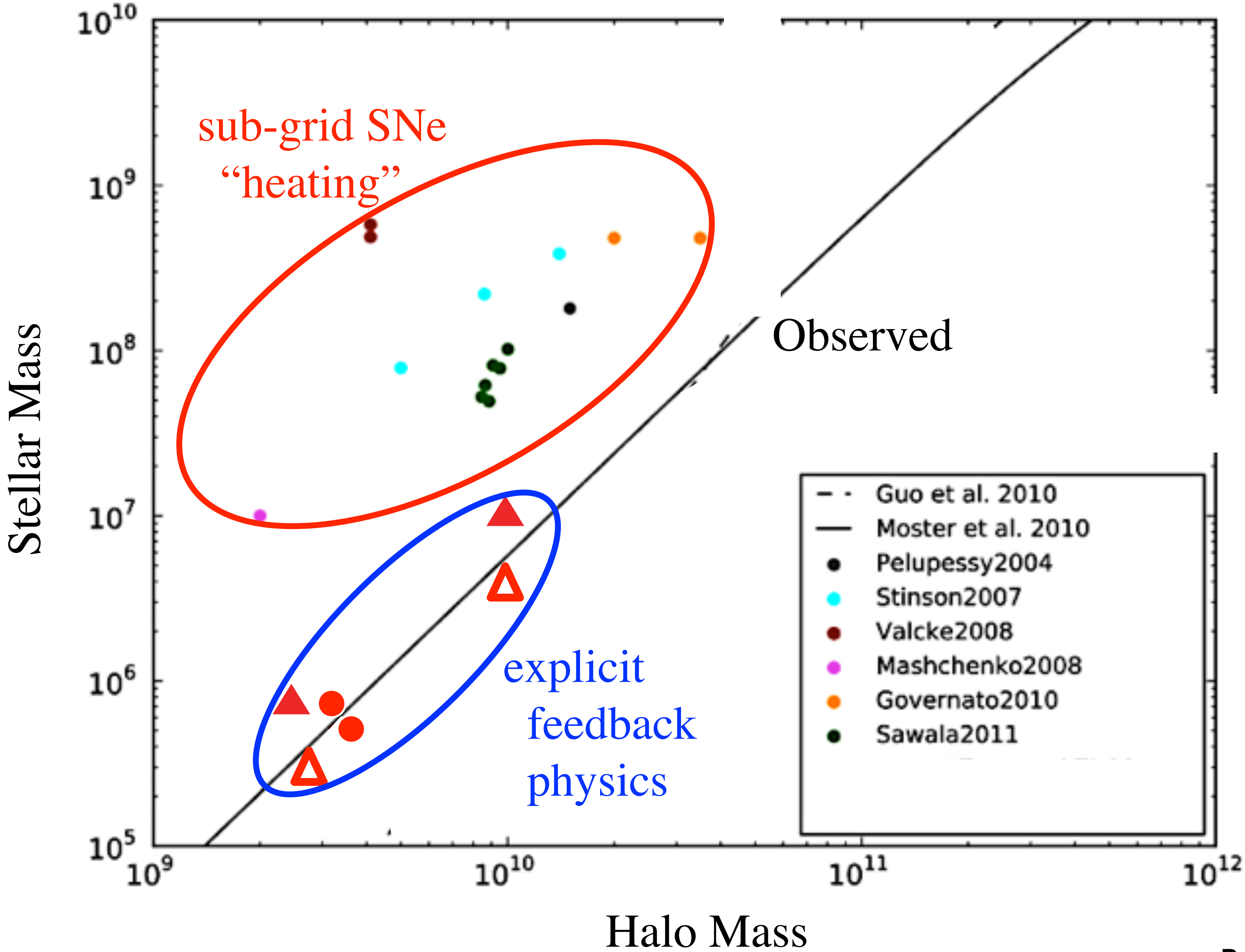
PFH & Keres et al

Is Star Formation Inefficient?



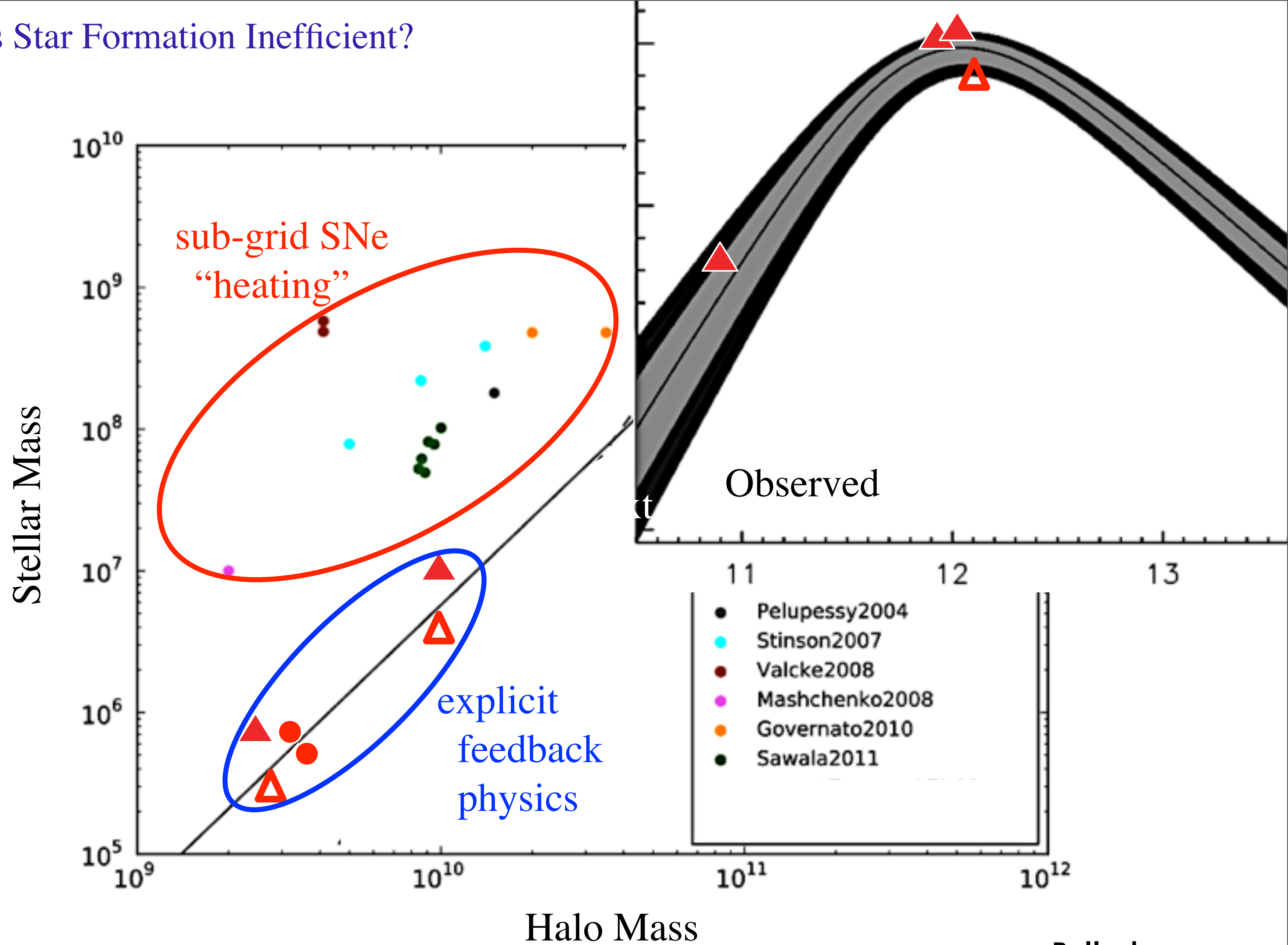
Bullock, & Onorbe et al.

Is Star Formation Inefficient?



Bullock, & Onorbe et al.

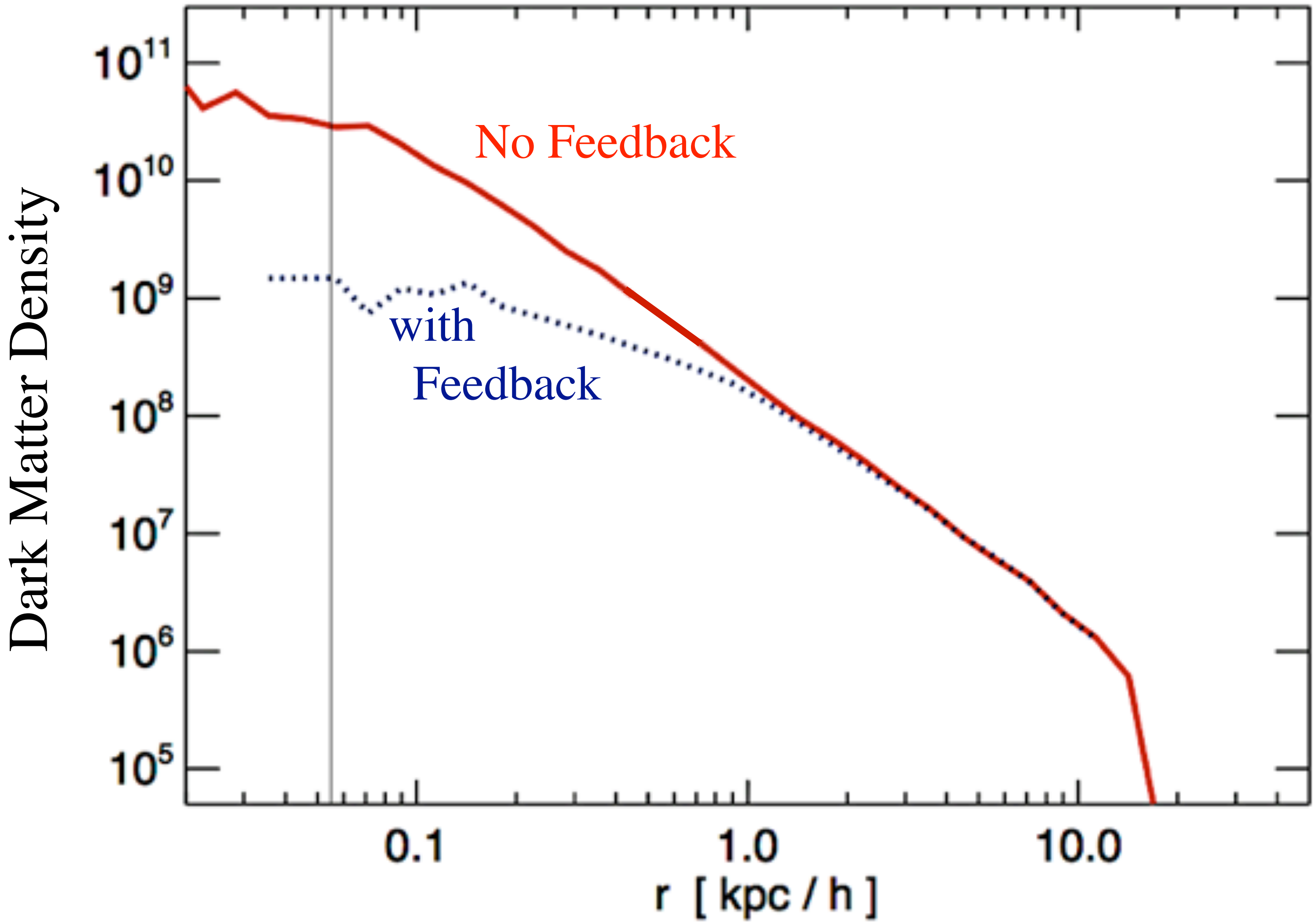
Is Star Formation Inefficient?



Bullock,
& Onorbe et al.

Dark Matter Profiles: Baryons or Cosmology?

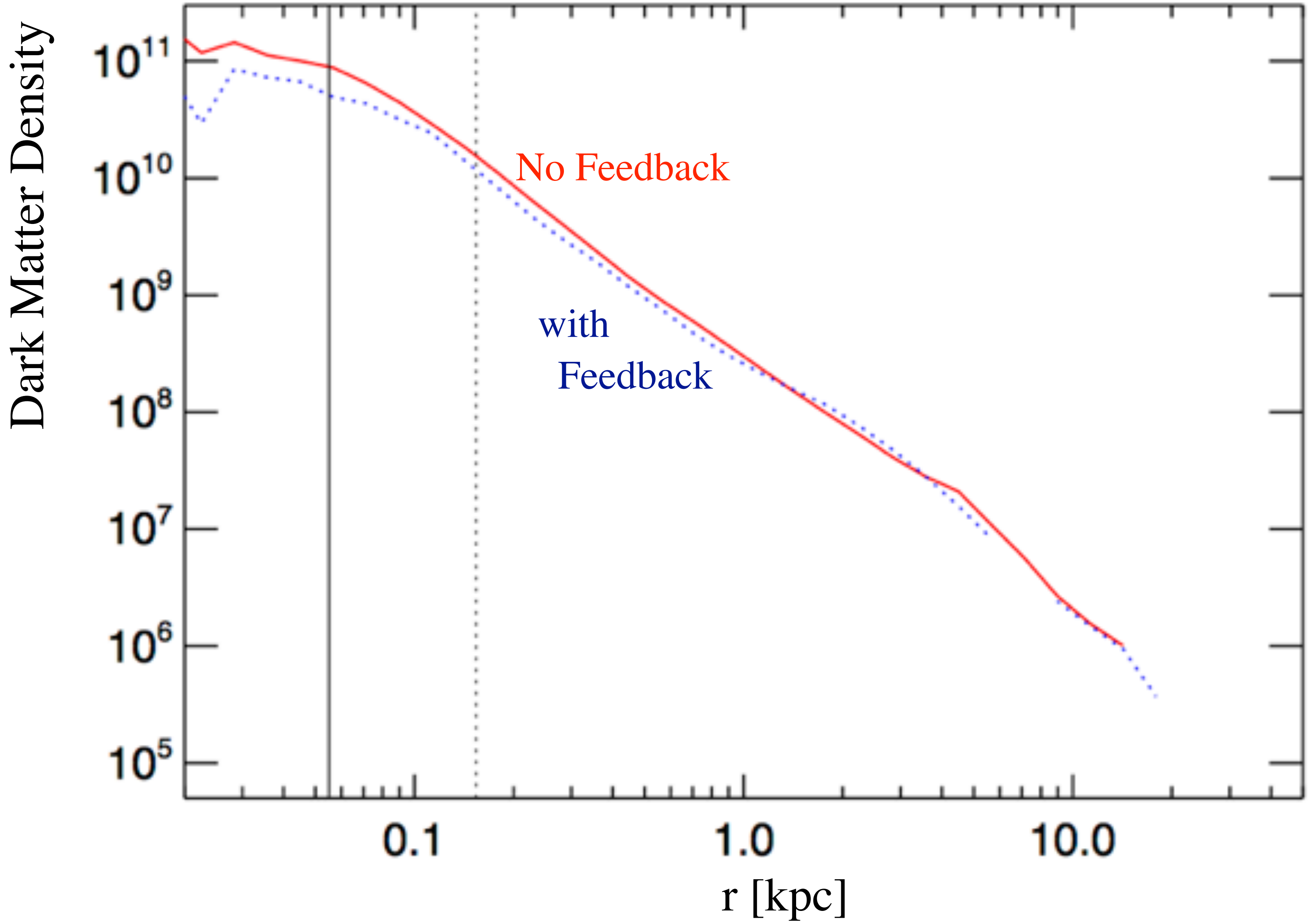
WHAT CAN WE LEARN ABOUT COSMOLOGY AND STRUCTURE FORMATION?



PFH & Keres et a

PFH, Bullock,
& Onorbe et a

BUT...



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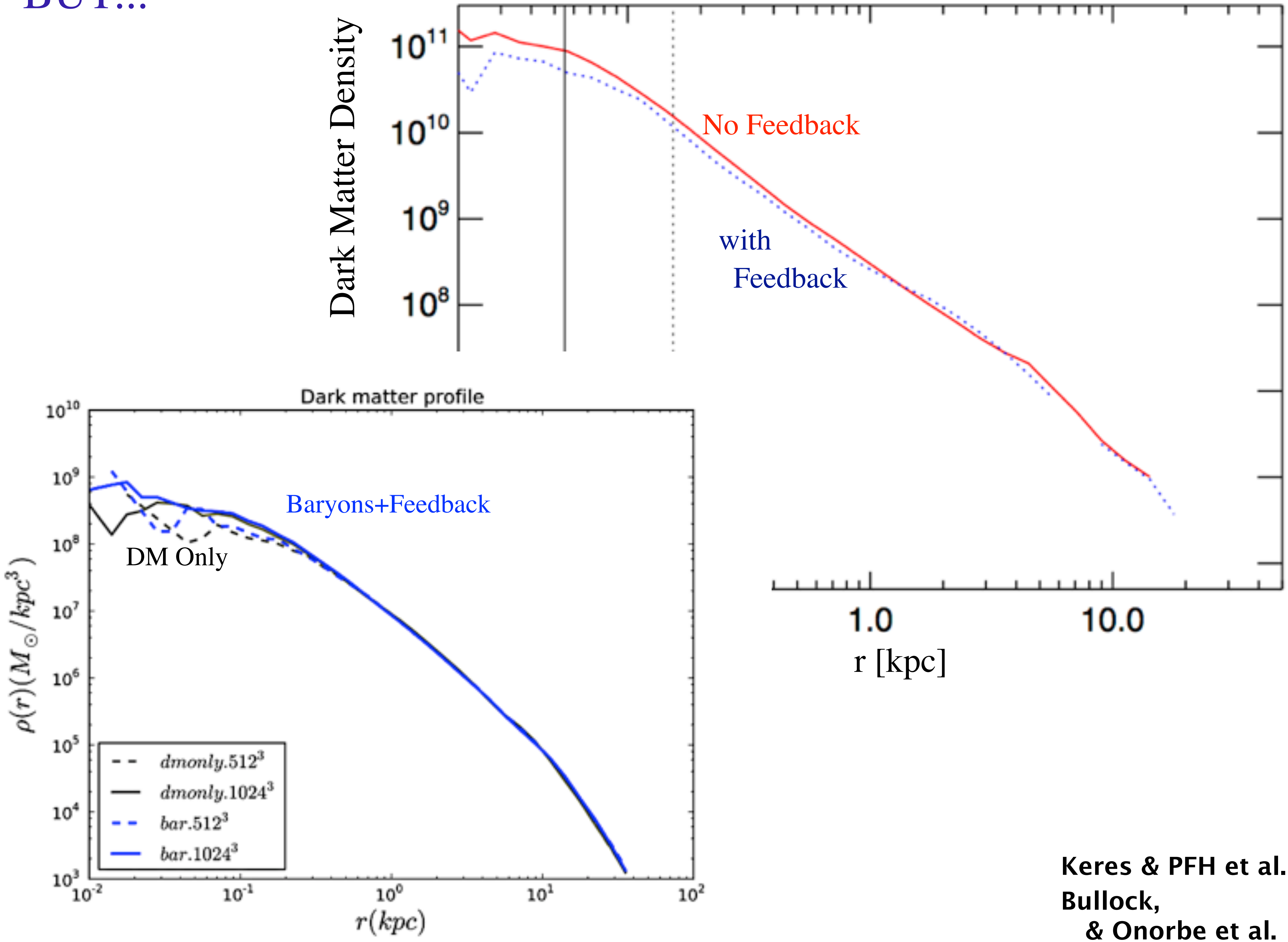
BUT...



Keres & PFH et al.
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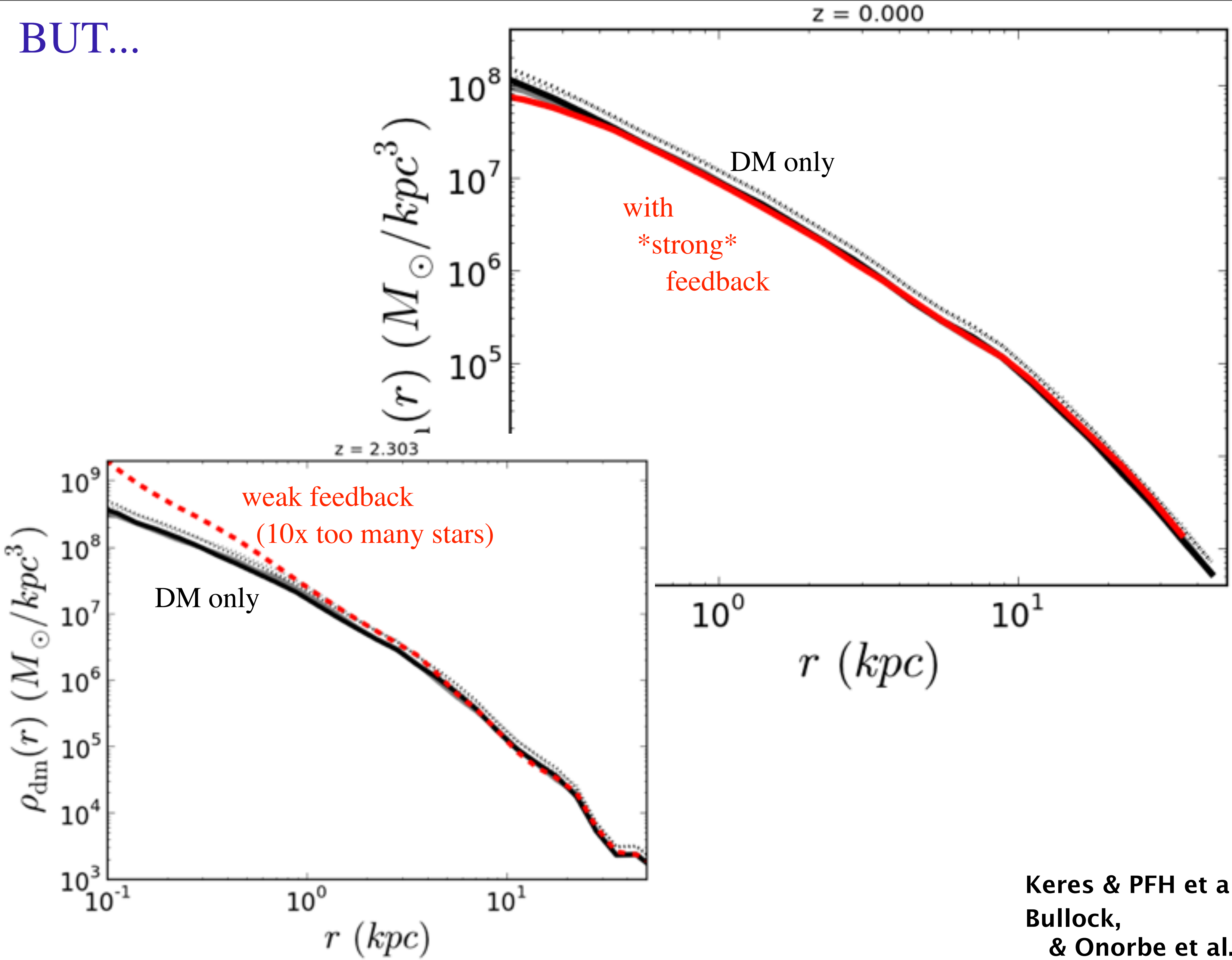
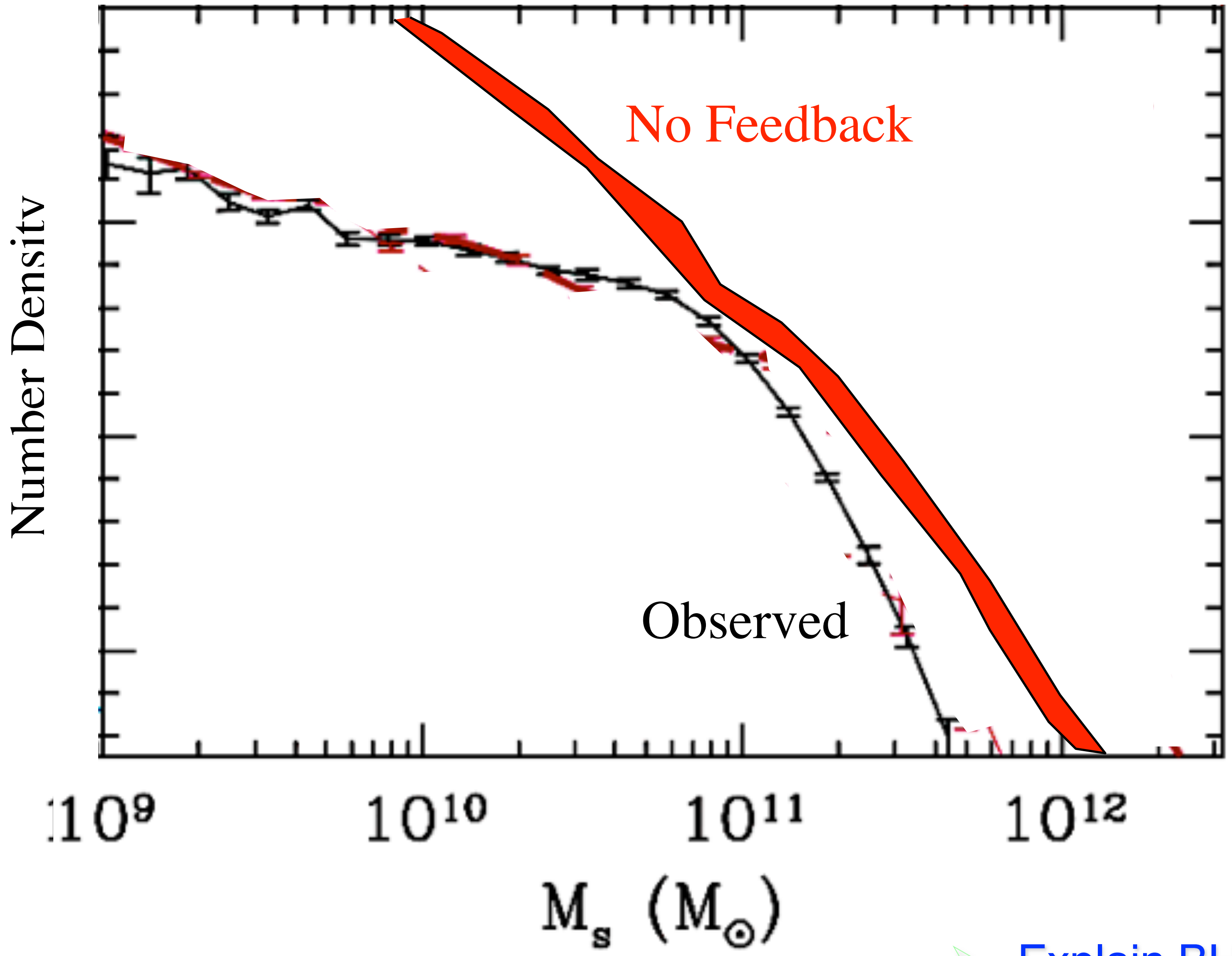
BUT...



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

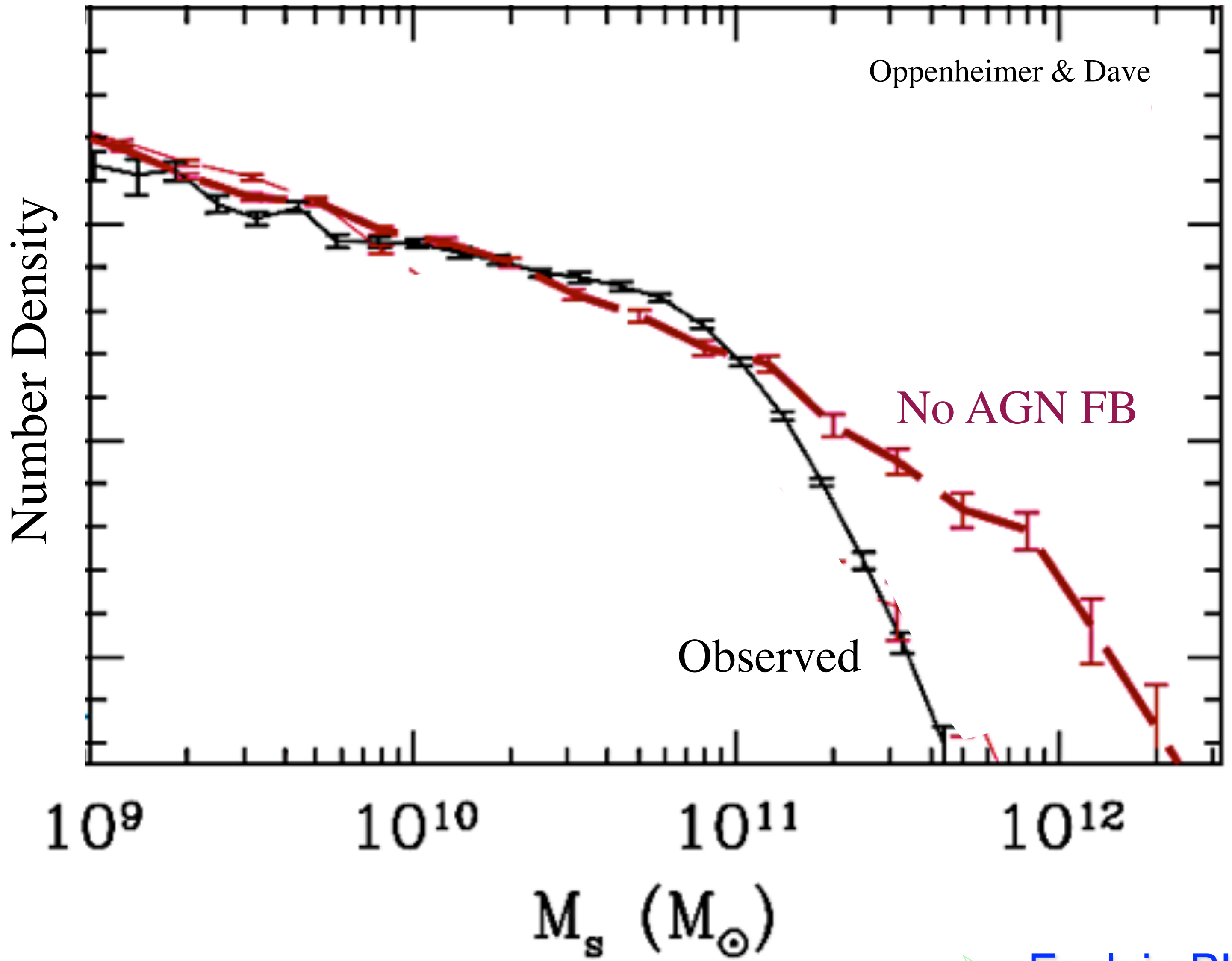
What About High-Mass Galaxies?

Why Do We Need AGN Feedback?



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

Why Do We Need AGN Feedback?



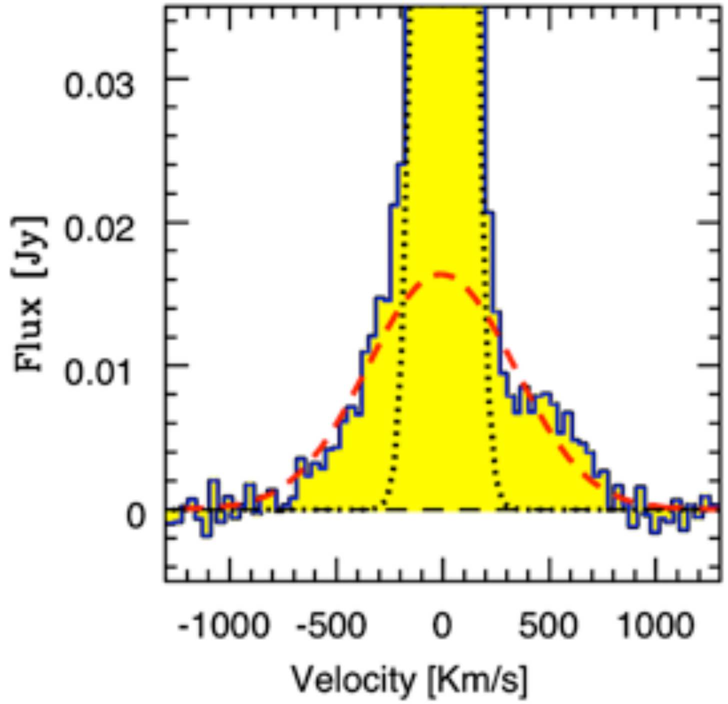
- Explain BH-host correlations
- Sharp color bimodality
- Removing/heating gas in groups

Molecular Outflows in AGN & ULIRGs

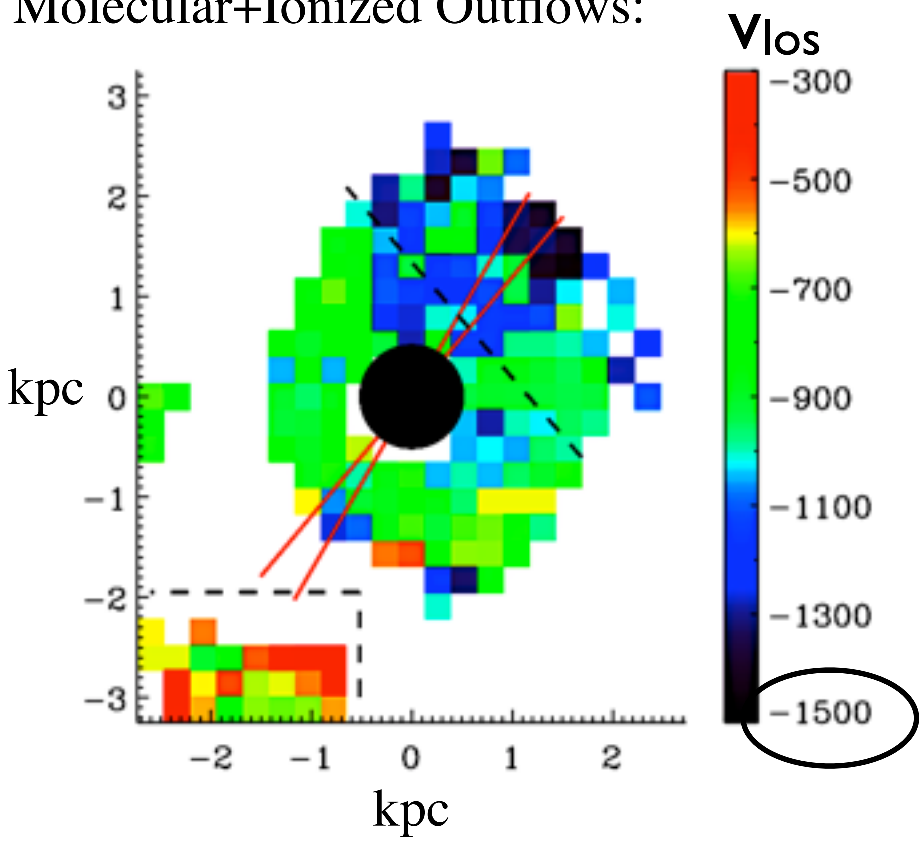
OBSERVED WINDS at >1000 km/s

Rupke & Veilleux 2005,2011
Fischer et al. 2010 (Mrk 231)
Feruglio et al. 2010 (Mrk 231)
Alatalo et al. 2011 (NGC 1266)

CO:



Molecular+Ionized Outflows:



$$R_{\rm wind} \sim 1 - 4\,{\rm kpc}$$

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

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

Where to Now? How Do We Model This?

Step 1: *Stellar* Feedback & the ISM

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

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

- *Explicit* Momentum Flux:
  - Radiation Pressure

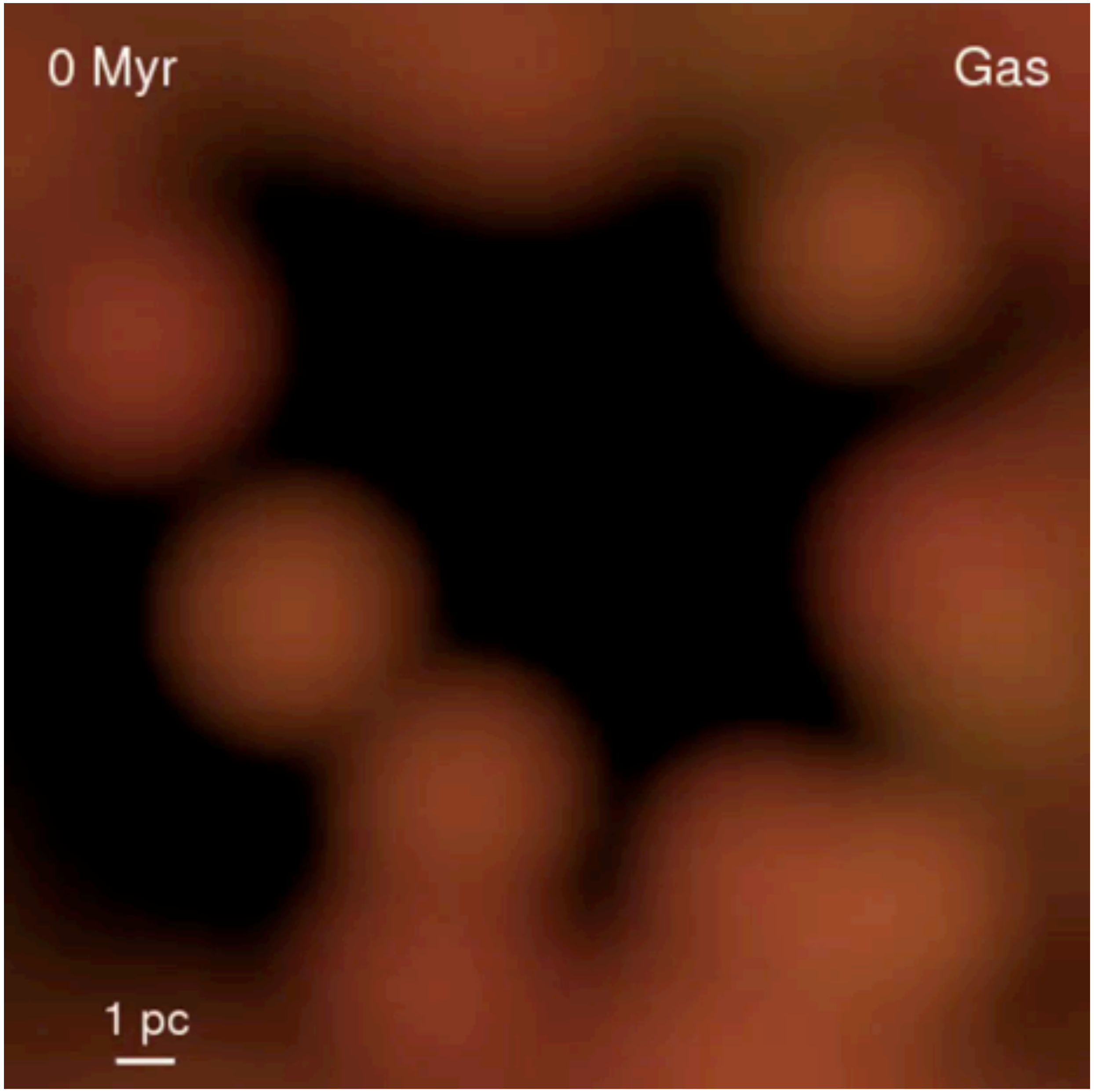
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

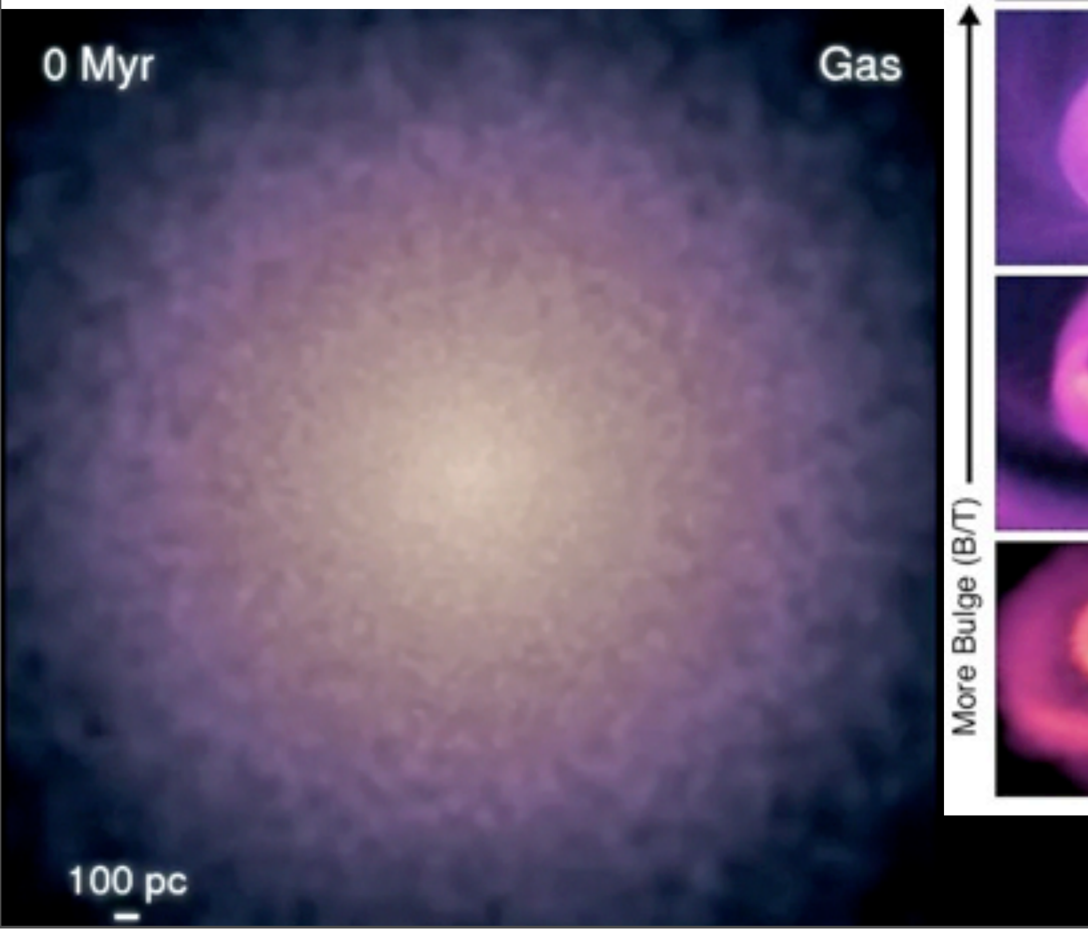
$$\dot{P}_{\rm W} \sim \dot{M}\,v_{\rm wind}$$

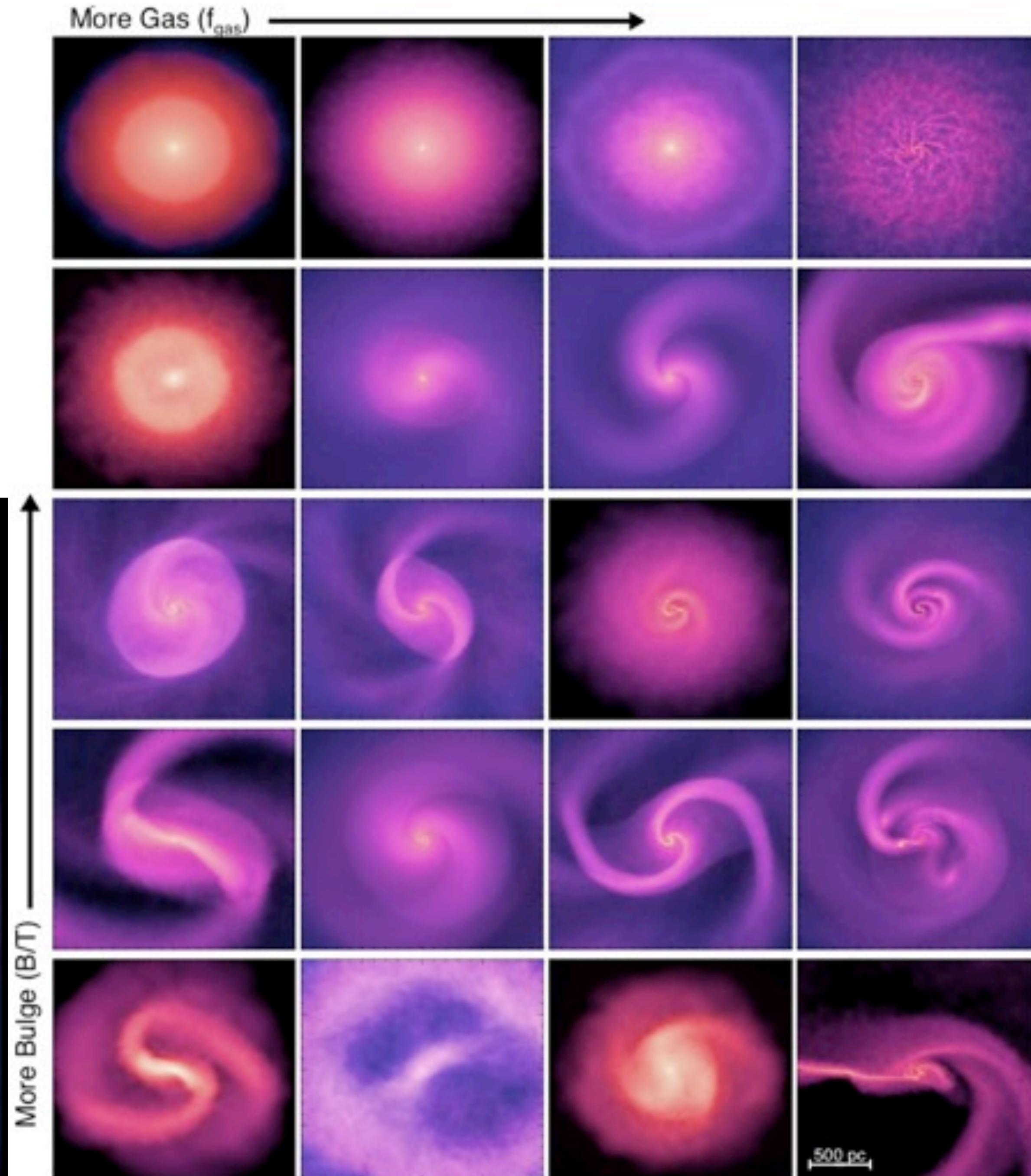


Step 2: Inflow

- Beginning to directly follow inflow to sub-pc scales

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





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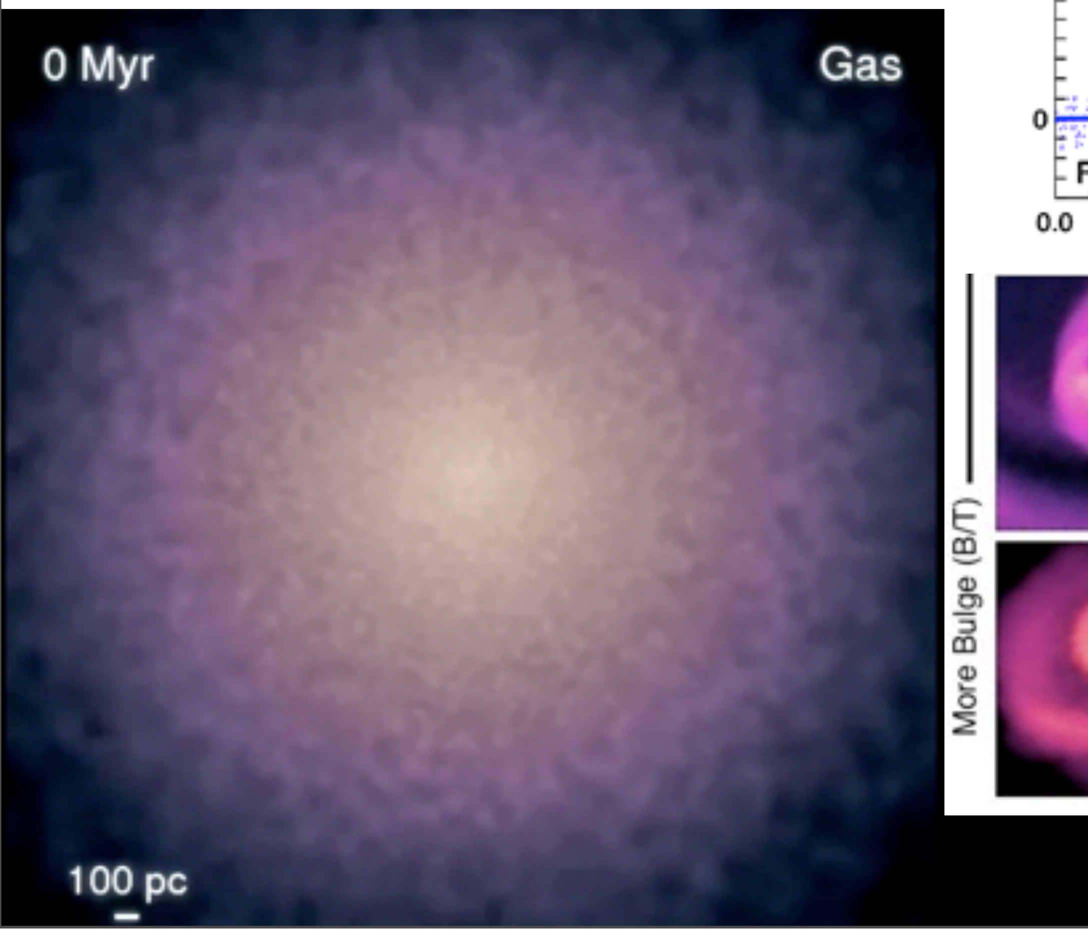
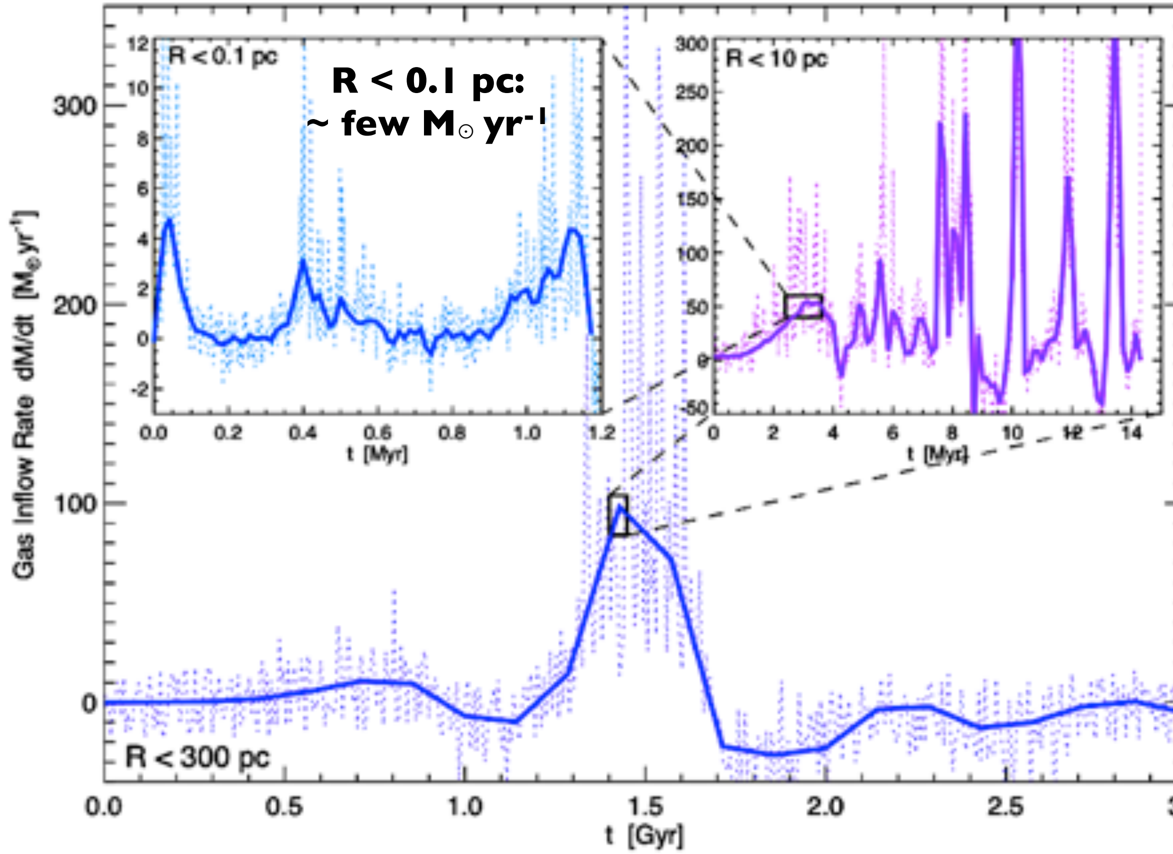
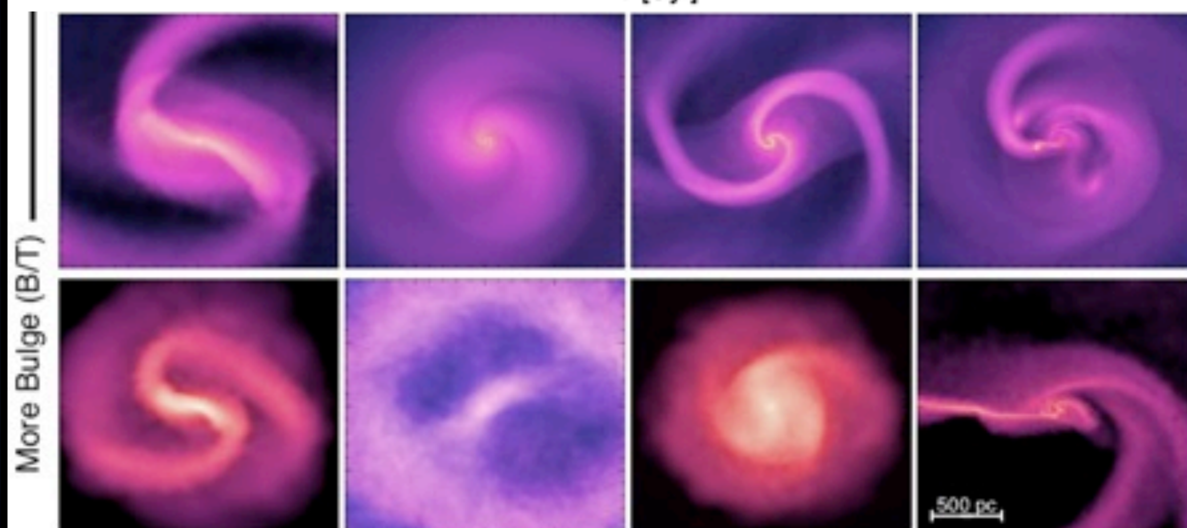
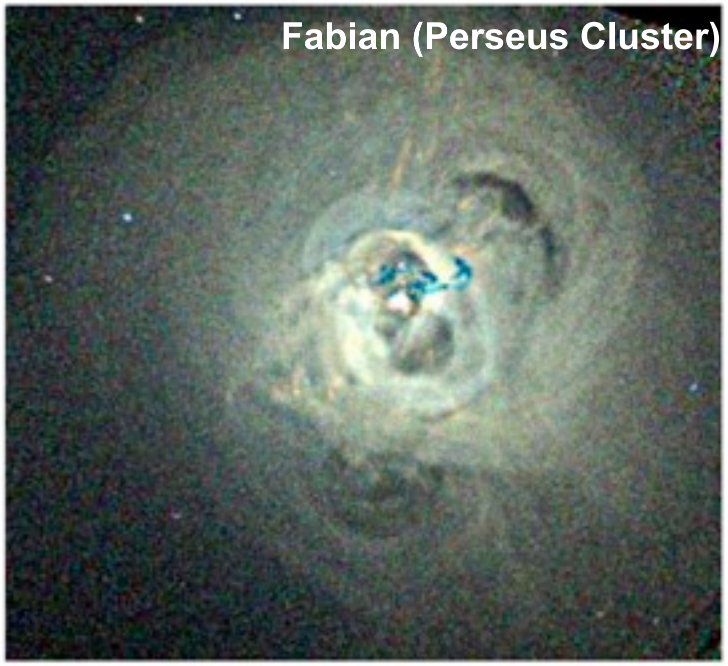






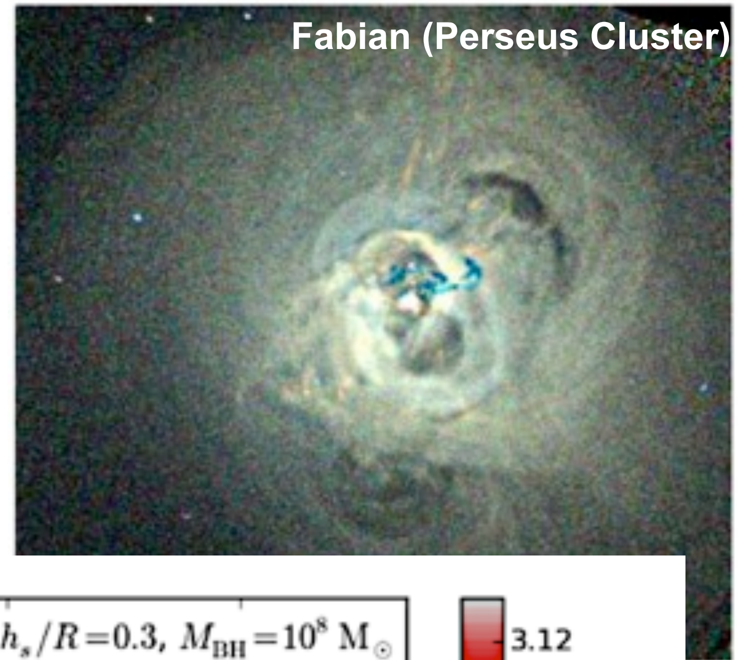
Step 3: Observed Sources of AGN Feedback

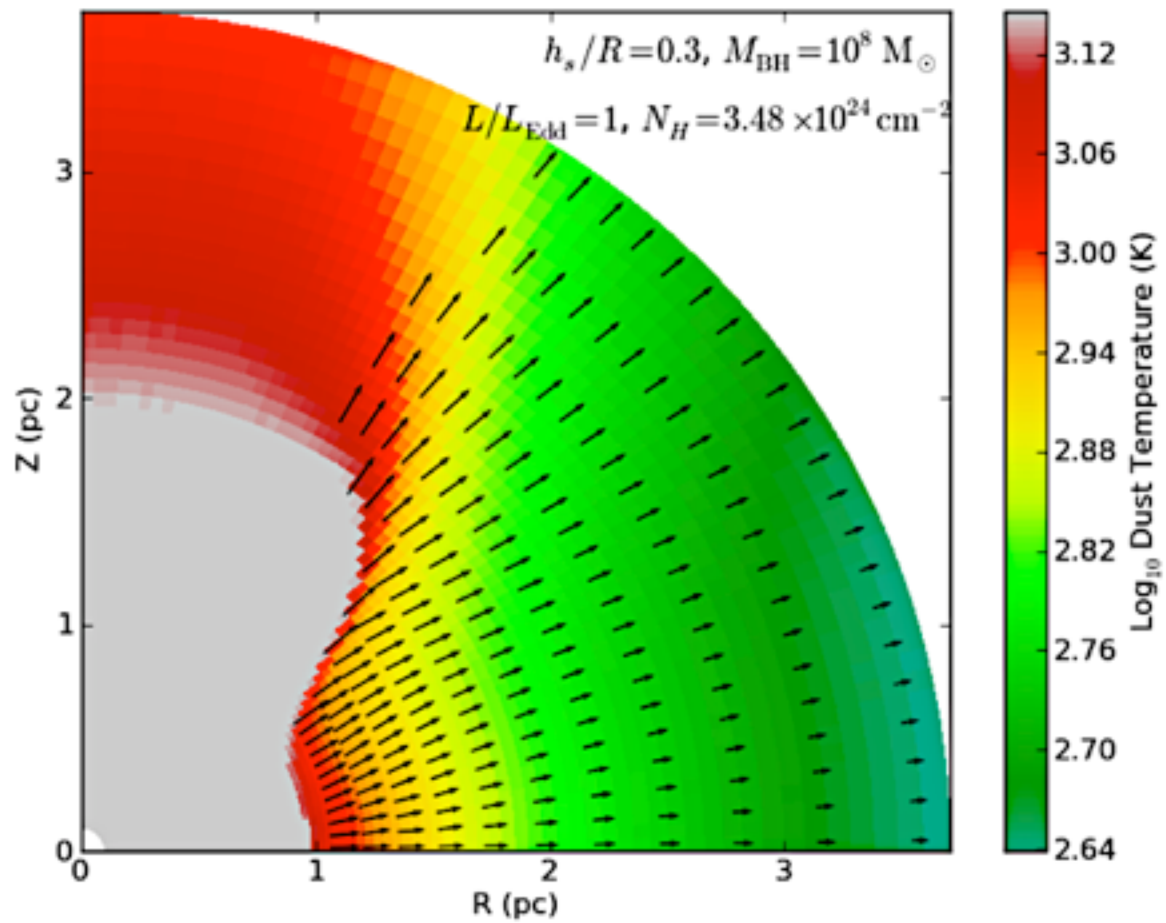
- Jets
  - heat IGM/ICM (low-density), but not dense ISM



Step 3: Observed Sources of AGN Feedback

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

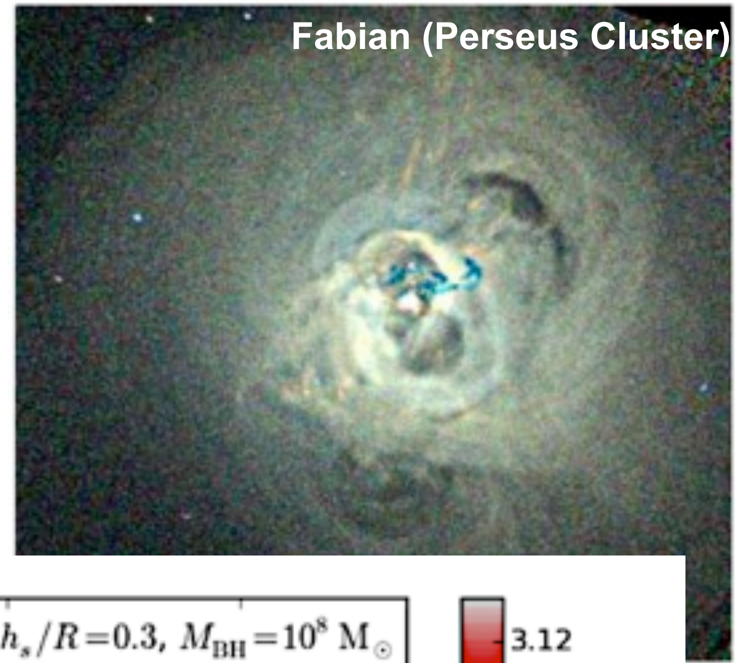


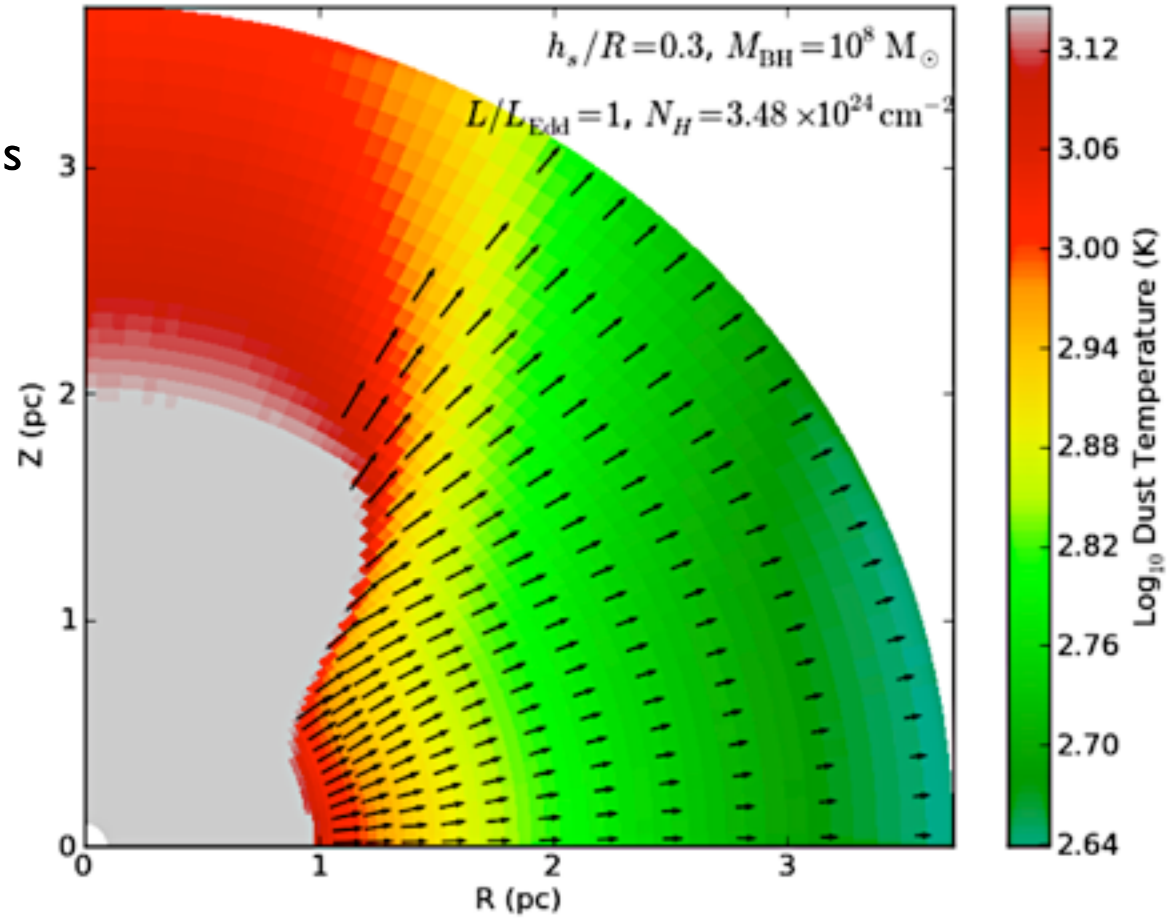


Roth, Kasen, Quataert, PFH in prep

Step 3: Observed Sources of AGN Feedback

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



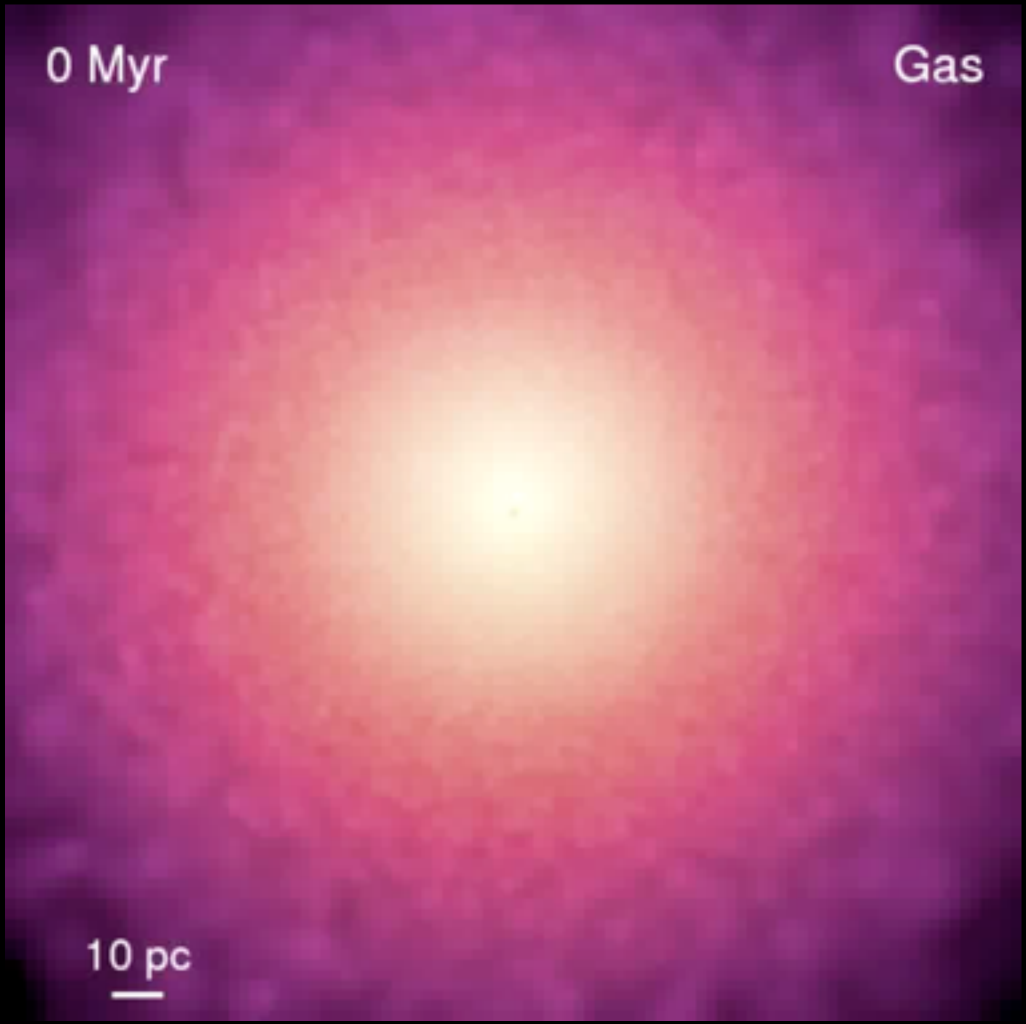


Roth, Kasen, Quataert, PFH in prep

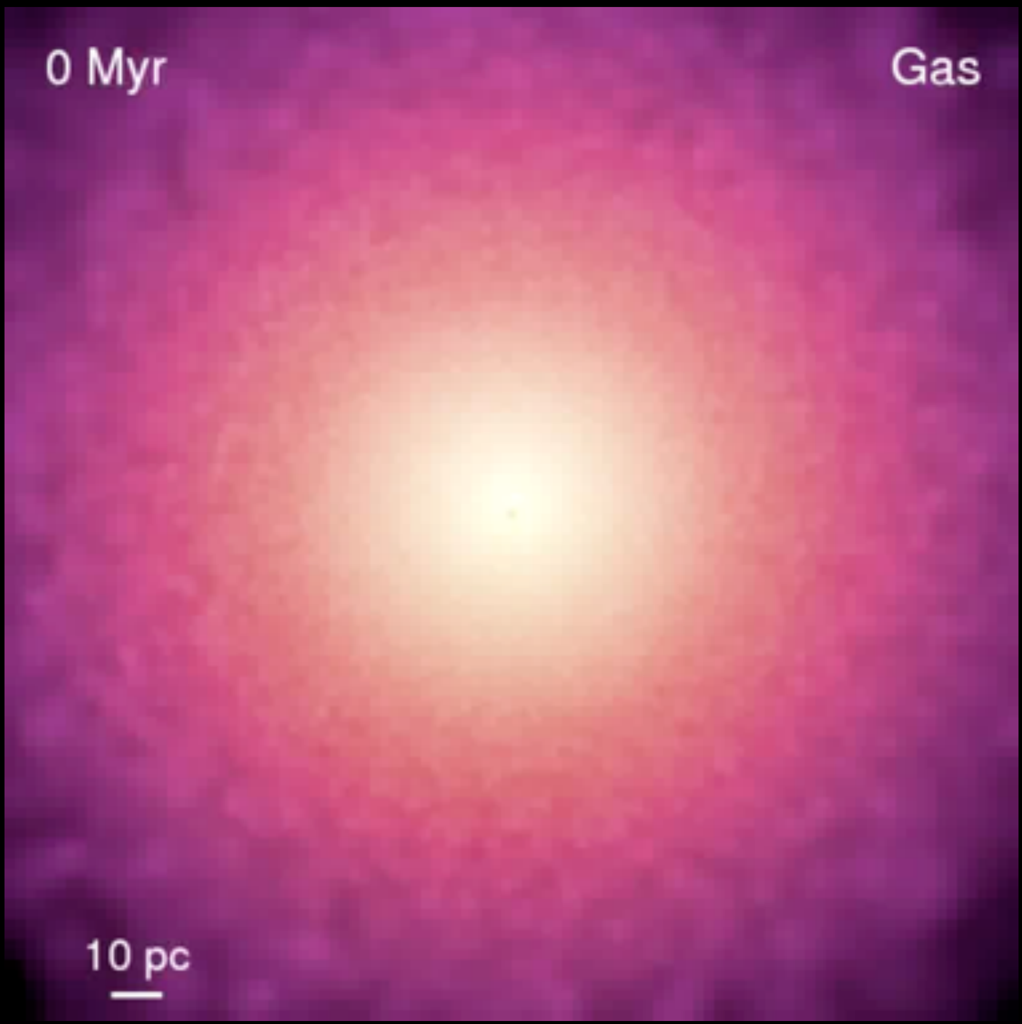
BAL Winds on ~1pc - 1kpc scales:

PFH in prep
Wada et al.

No BAL Winds



With BAL Winds

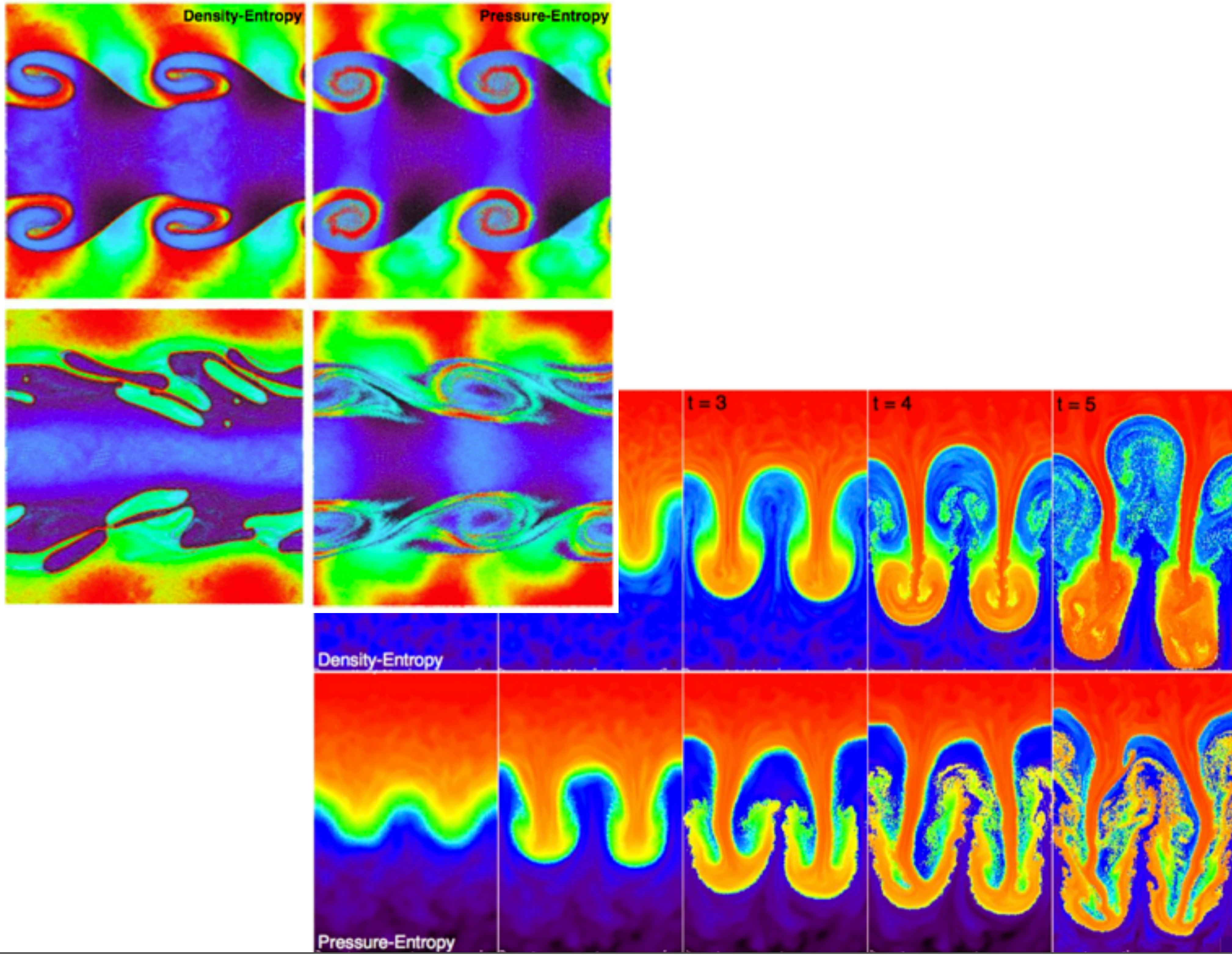


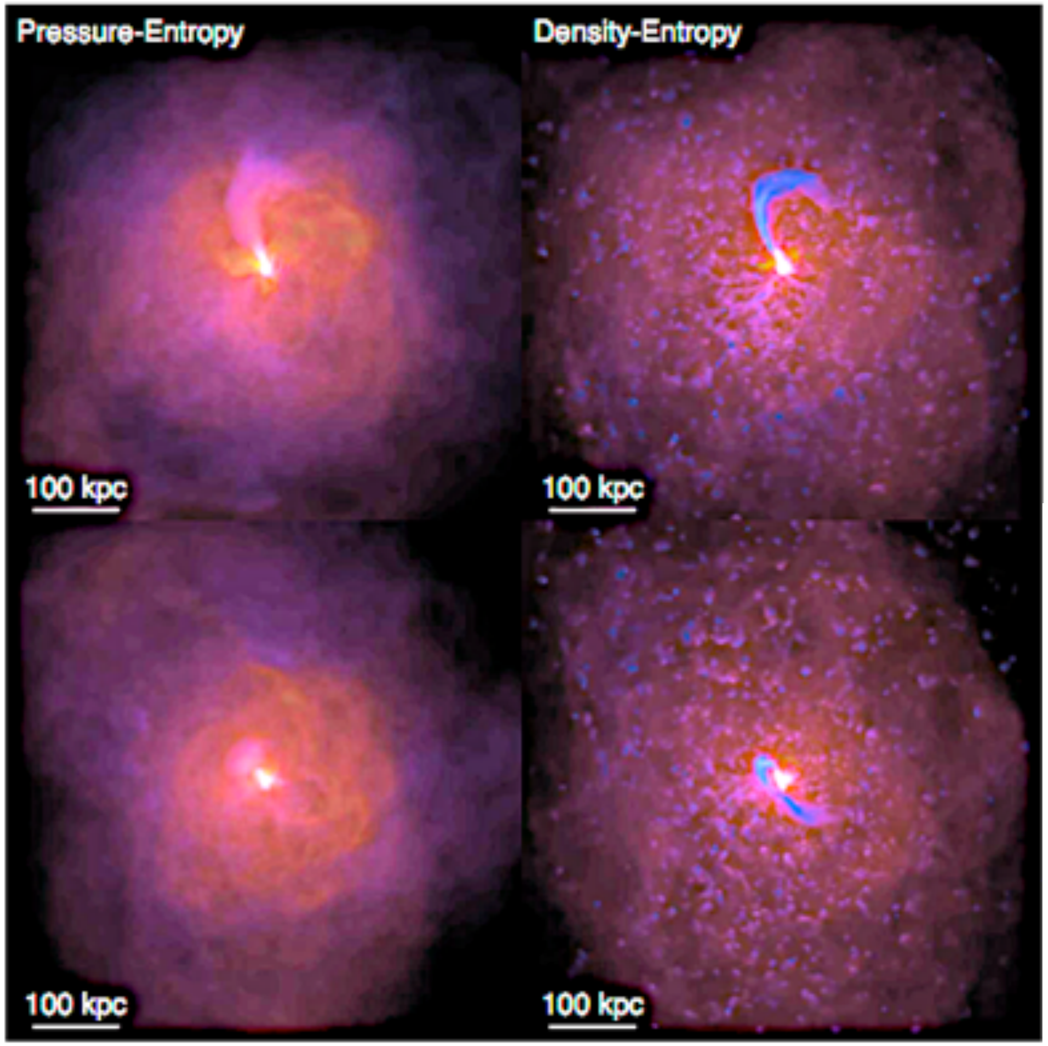
$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

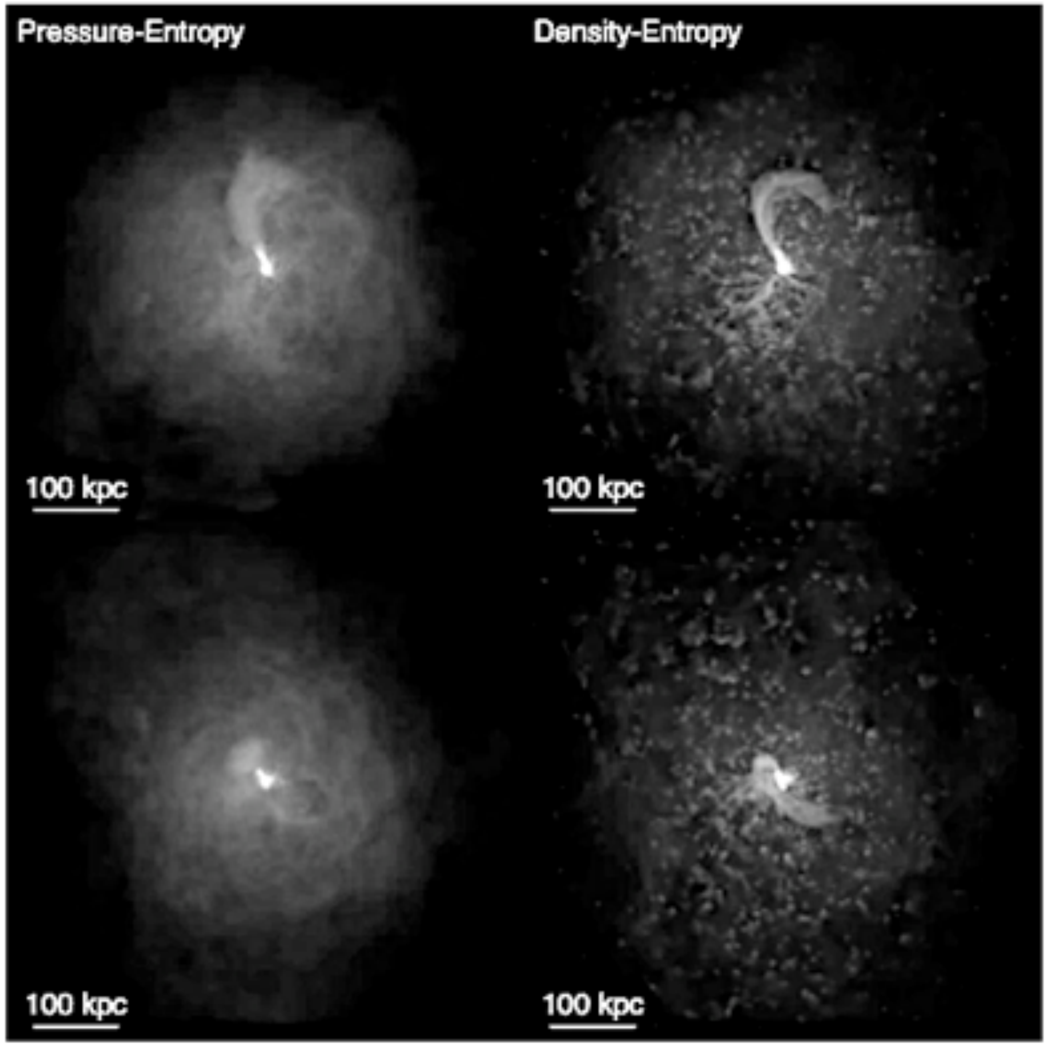
$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$

Summary:

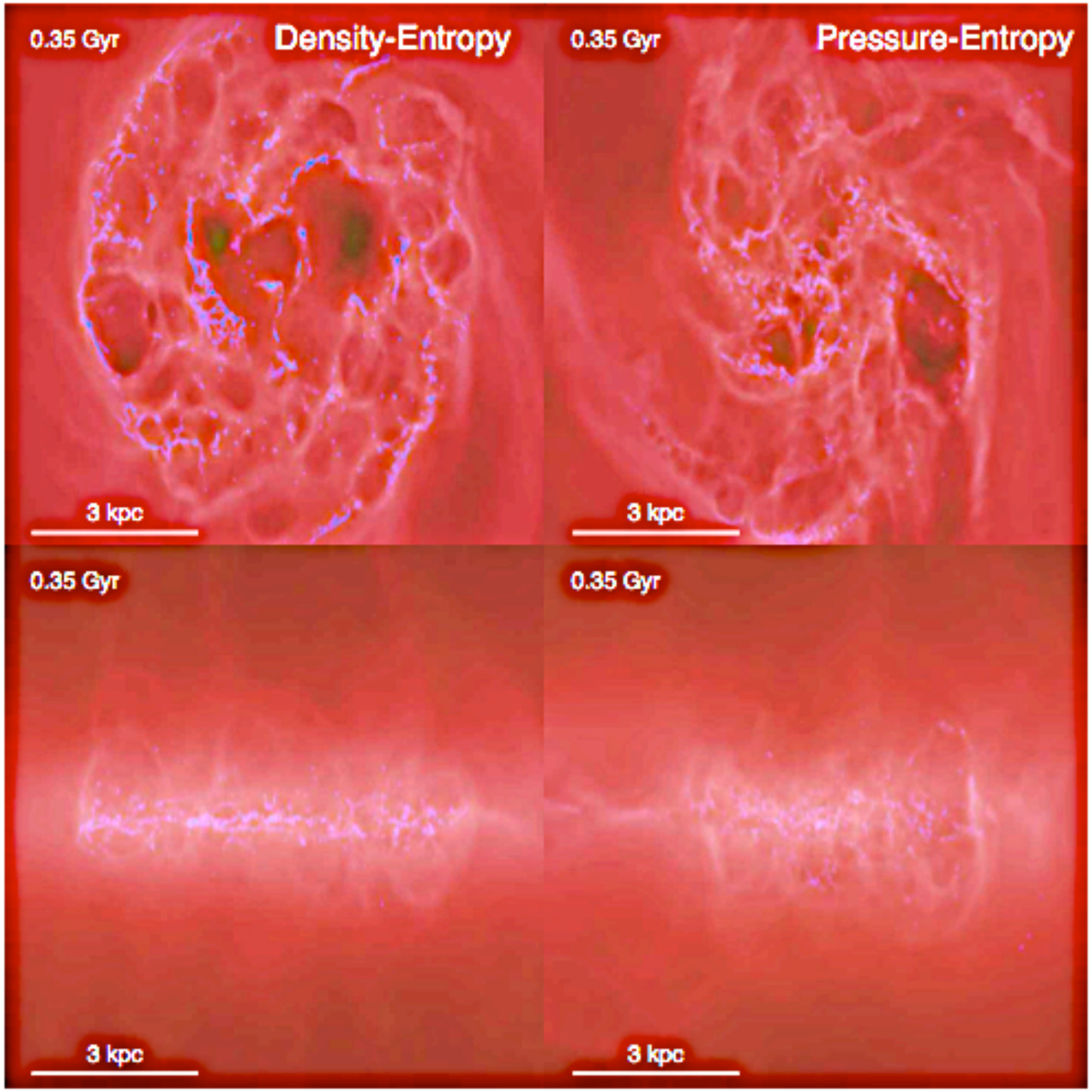
- **Star formation is Feedback-Regulated**: *independent* of small-scale SF 'law'
    - Need enough stars to offset dissipation (gravity)
    - Leads to Kennicutt relation & **super-winds**
- Different mechanisms dominate different regimes:
    - High-ρ: radiation pressure
    - Intermediate: HII heating, 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_{BH}-σ & suppress SF


Density-Entropy
Pressure-Entropy
t = 3
t = 4
t = 5
Density-Entropy
Pressure-Entropy


Pressure-Entropy
Density-Entropy
100 kpc
100 kpc
100 kpc
100 kpc


Pressure-Entropy
Density-Entropy
100 kpc
100 kpc
100 kpc
100 kpc

SPH in Pressure-Entropy Formulation



SPH in Pressure-Entropy Formulation