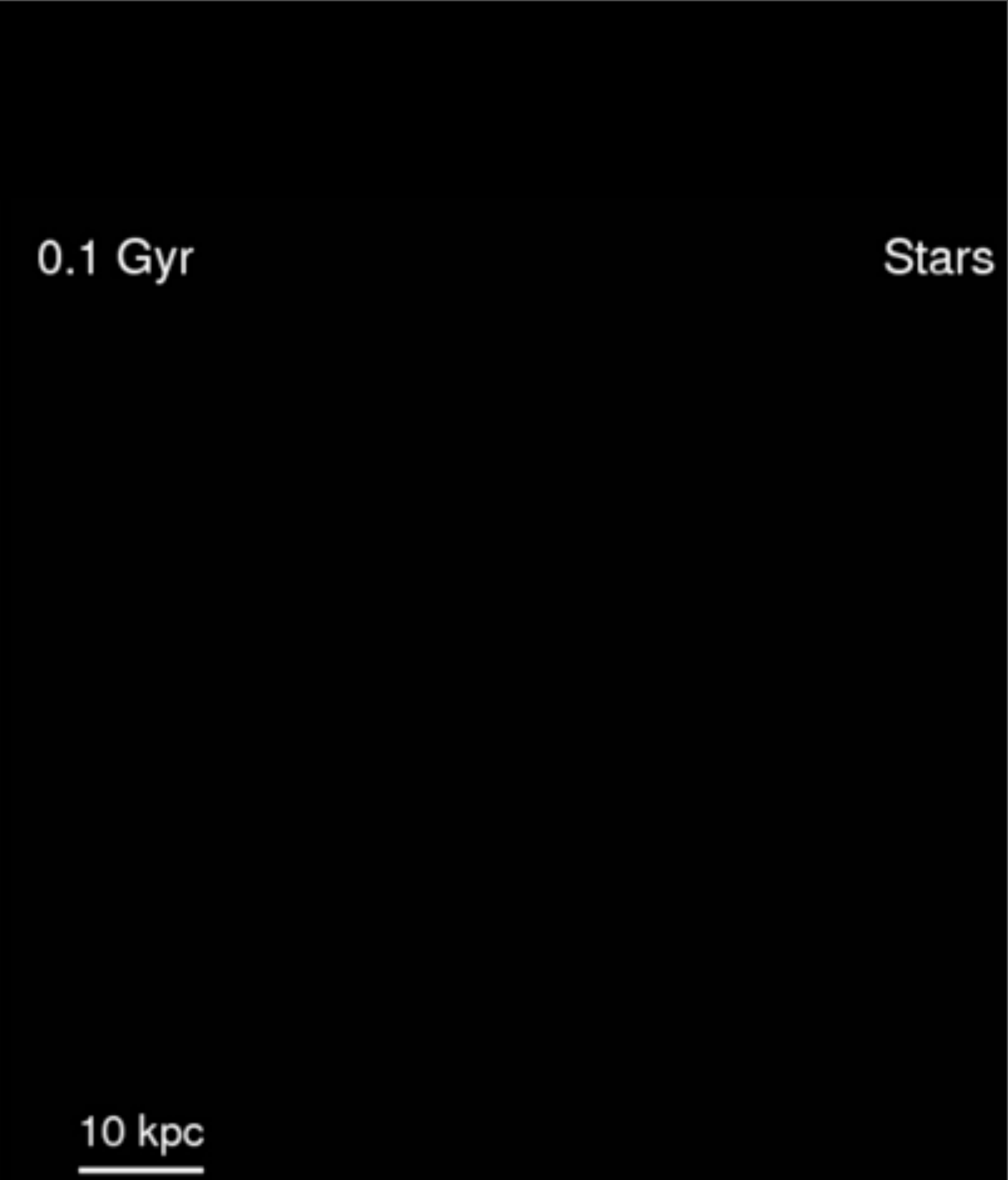
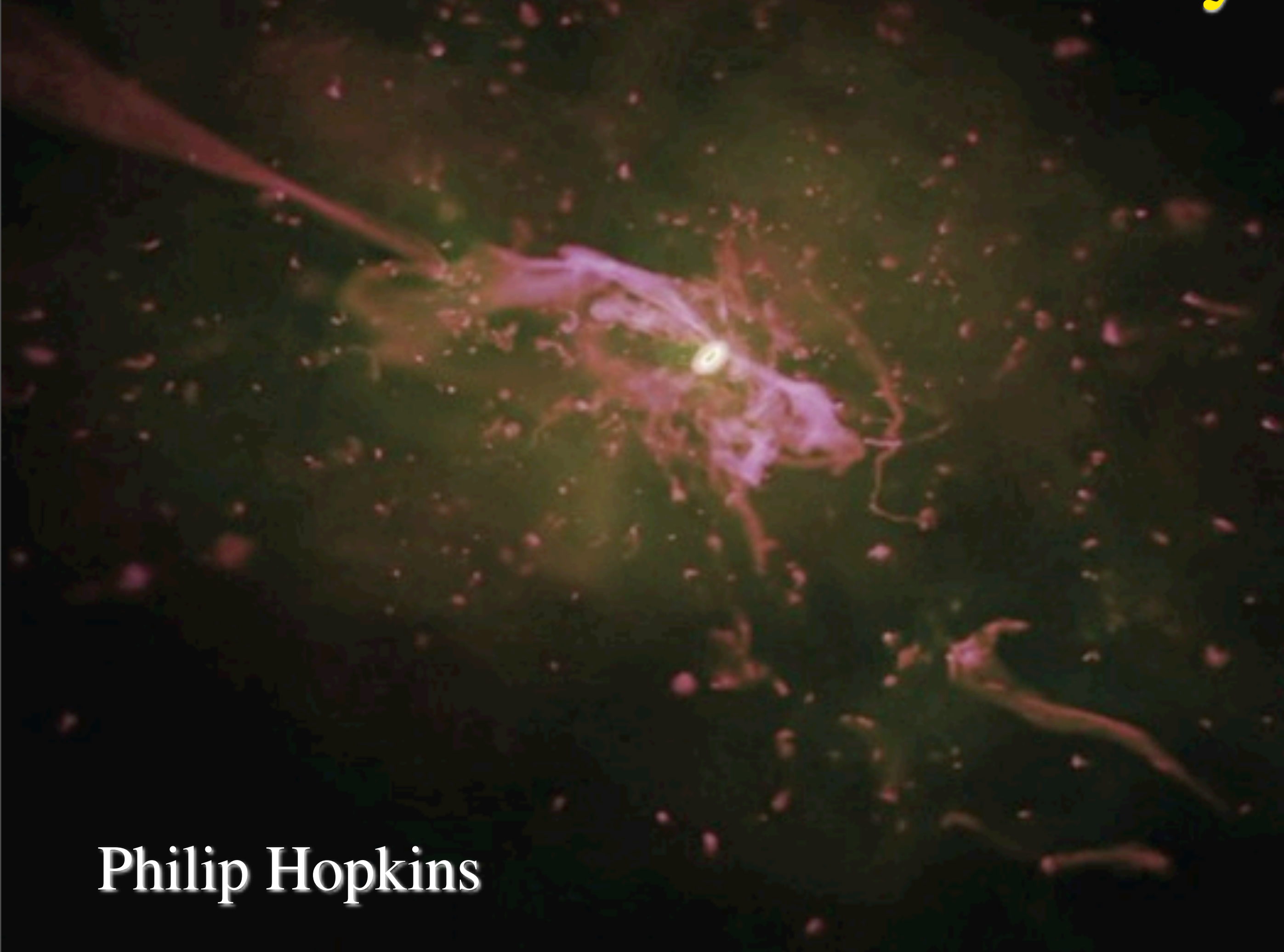

Milky Way




Starburst Disks

# Star Formation, Black Holes, and Feedback in Galaxy Formation



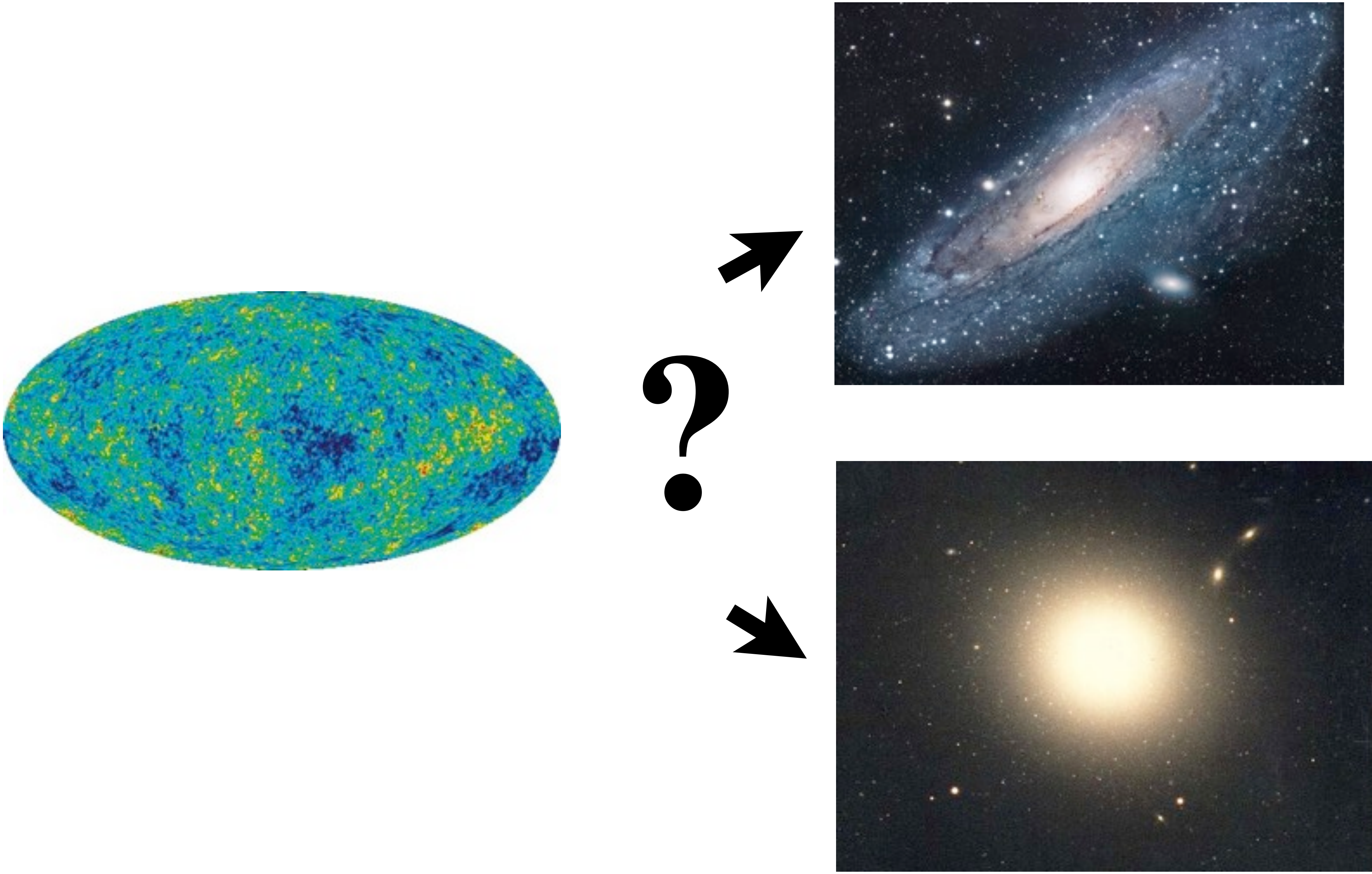
Philip Hopkins

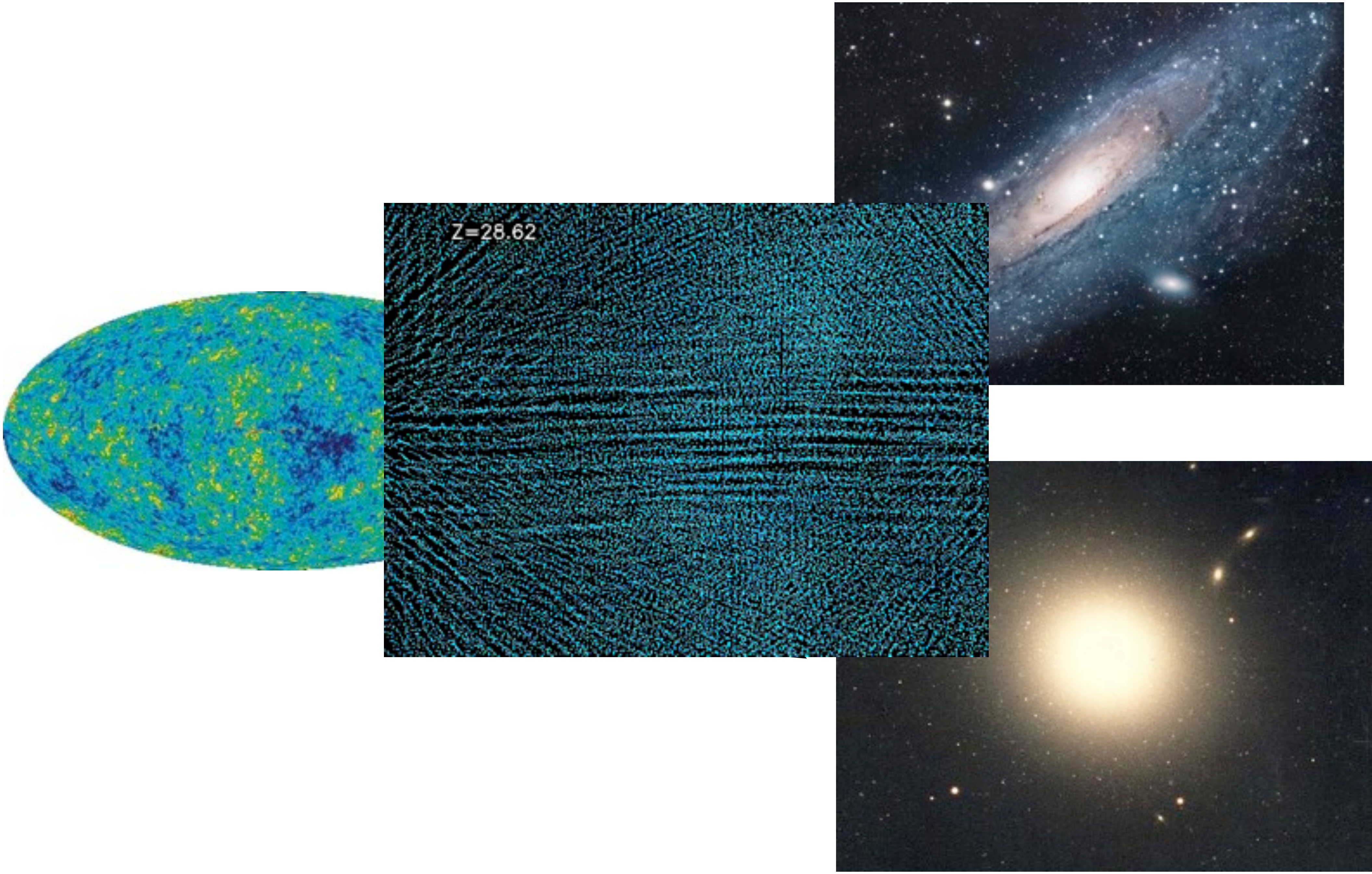
Eliot Quataert, Norm Murray,
Lars Hernquist, Dusan Keres, Todd Thompson, Desika Narayanan,
Dan Kasen, T. J. Cox, Chris Hayward, Kevin Bundy, & more


PINNACLES

# Overview

- (1) The Problem
- (2) Stellar Feedback & Consequences
  - Isolated Galaxies & the ISM
  - Interacting Galaxies & Mergers
  - High-Redshift Galaxies & the IGM
- (3) AGN Feedback in Massive Galaxies

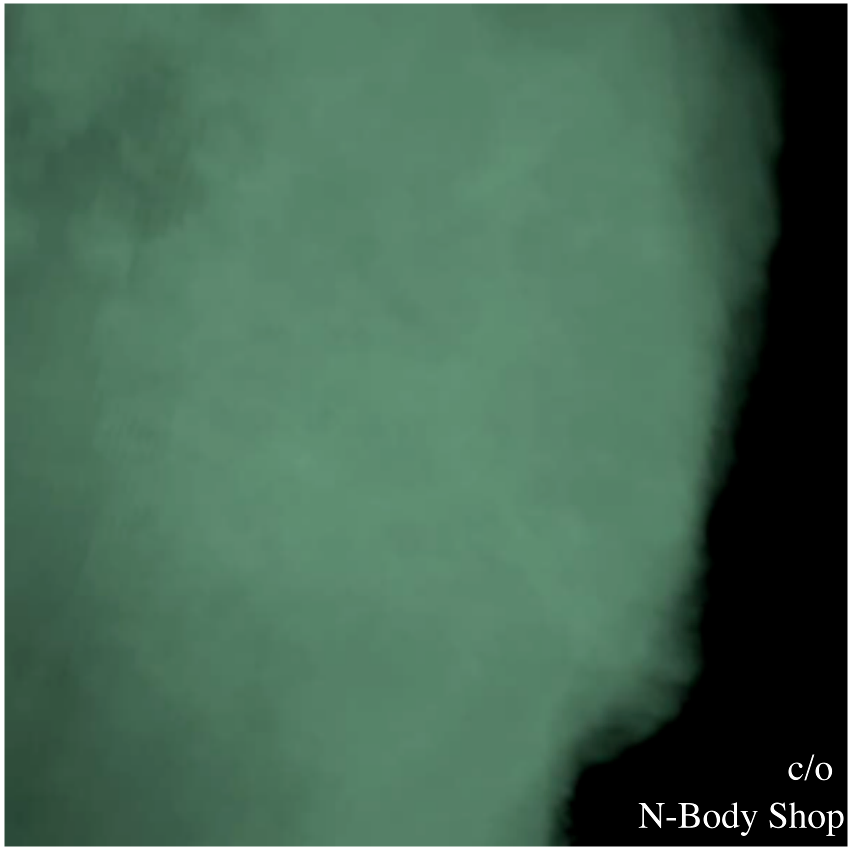


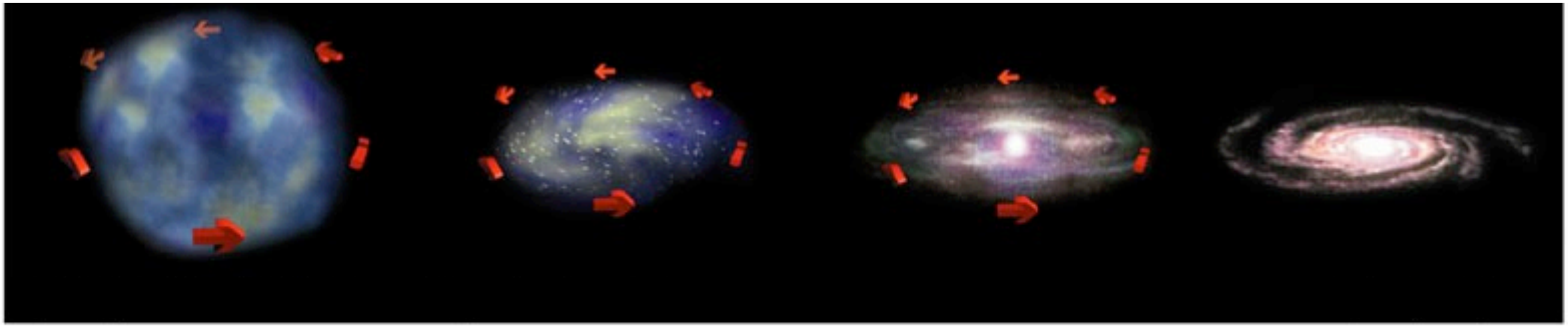

Z=28.62

# Motivation

## HOW DID WE GET TO GALAXIES TODAY?

- Dark matter halos collapse: gas cools into a disk



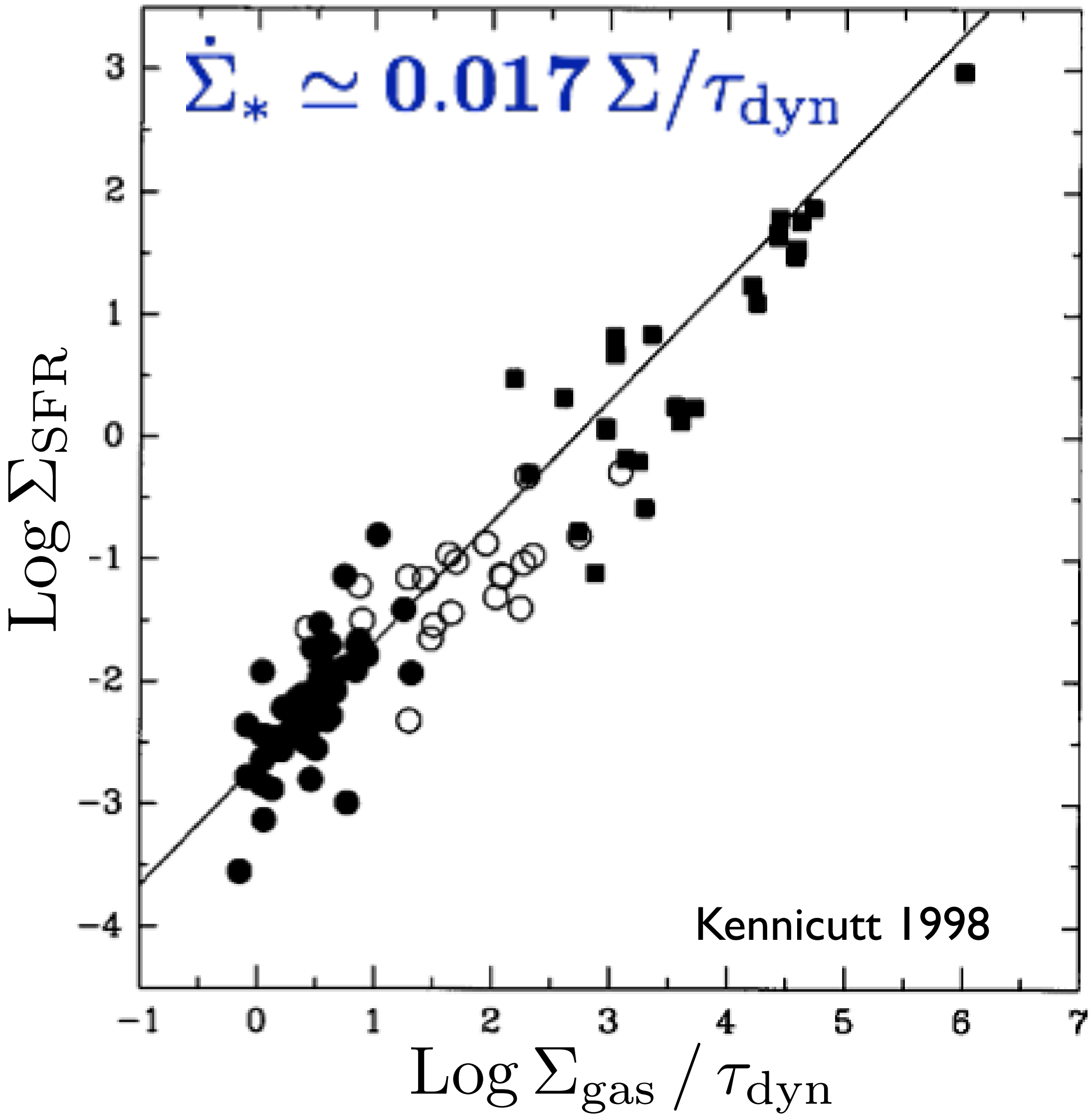



- What happens once gas is actually inside galaxies?

# The Problem: Baryons

# Motivation

## Q: WHY IS STAR FORMATION SO INEFFICIENT?



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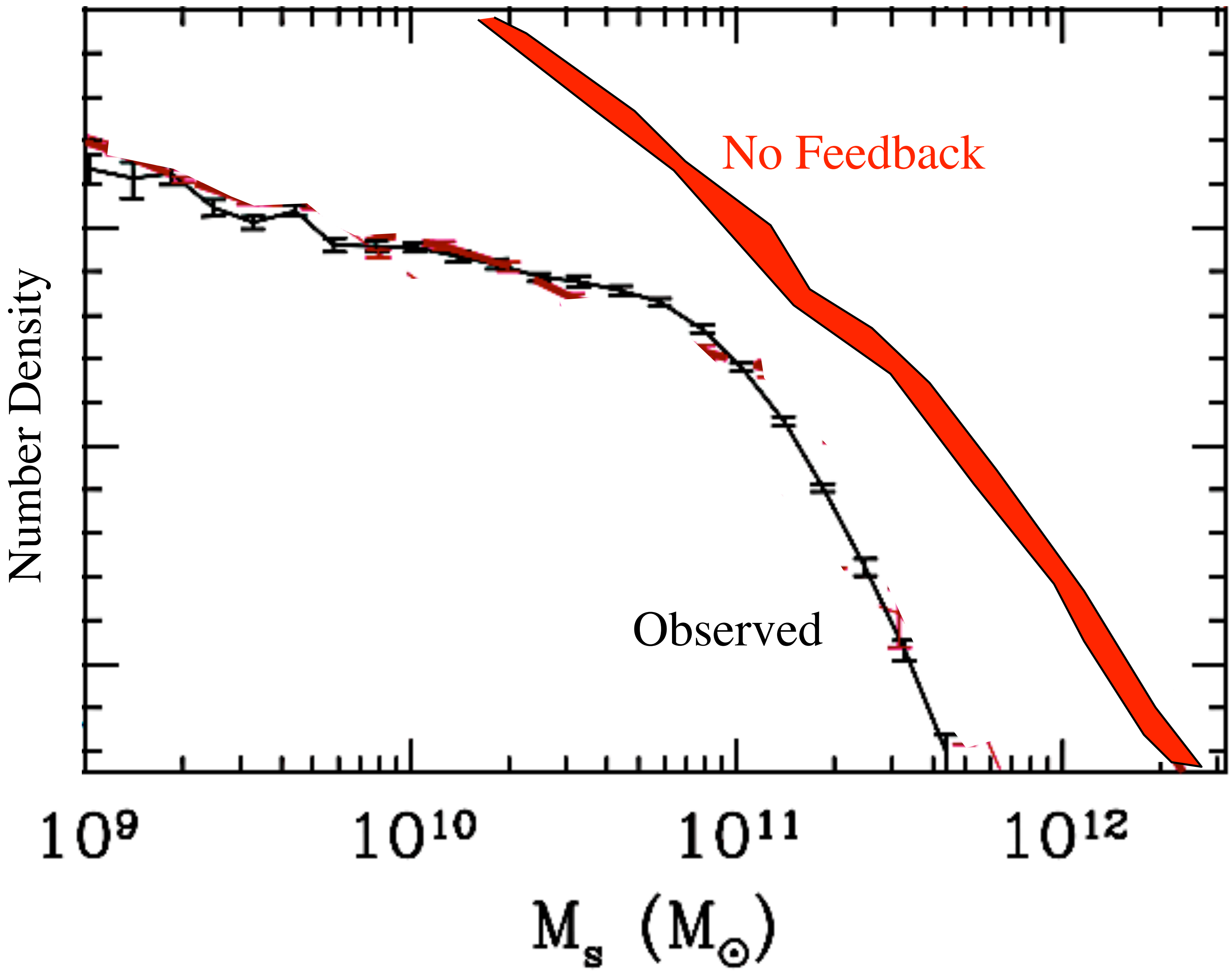

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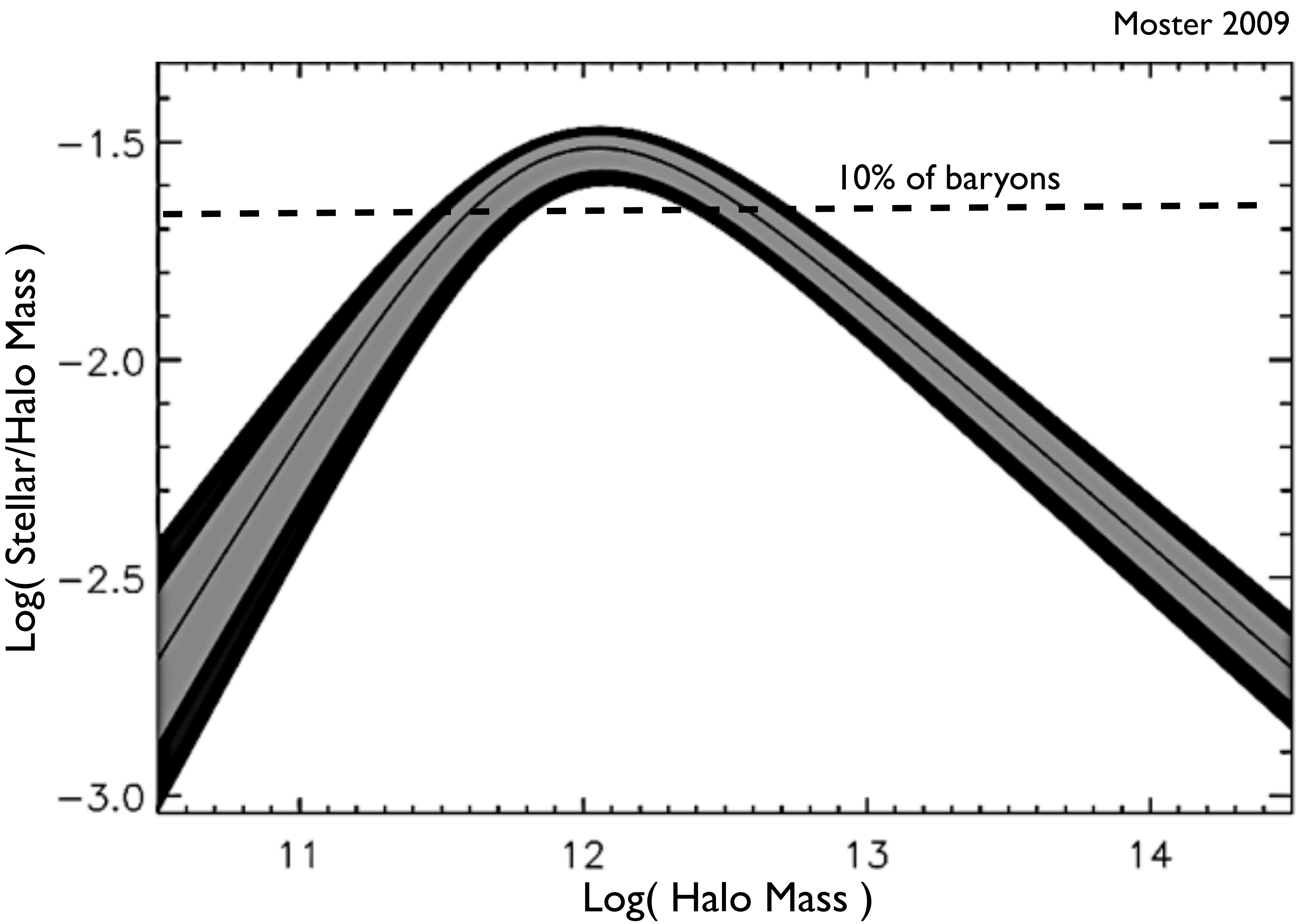

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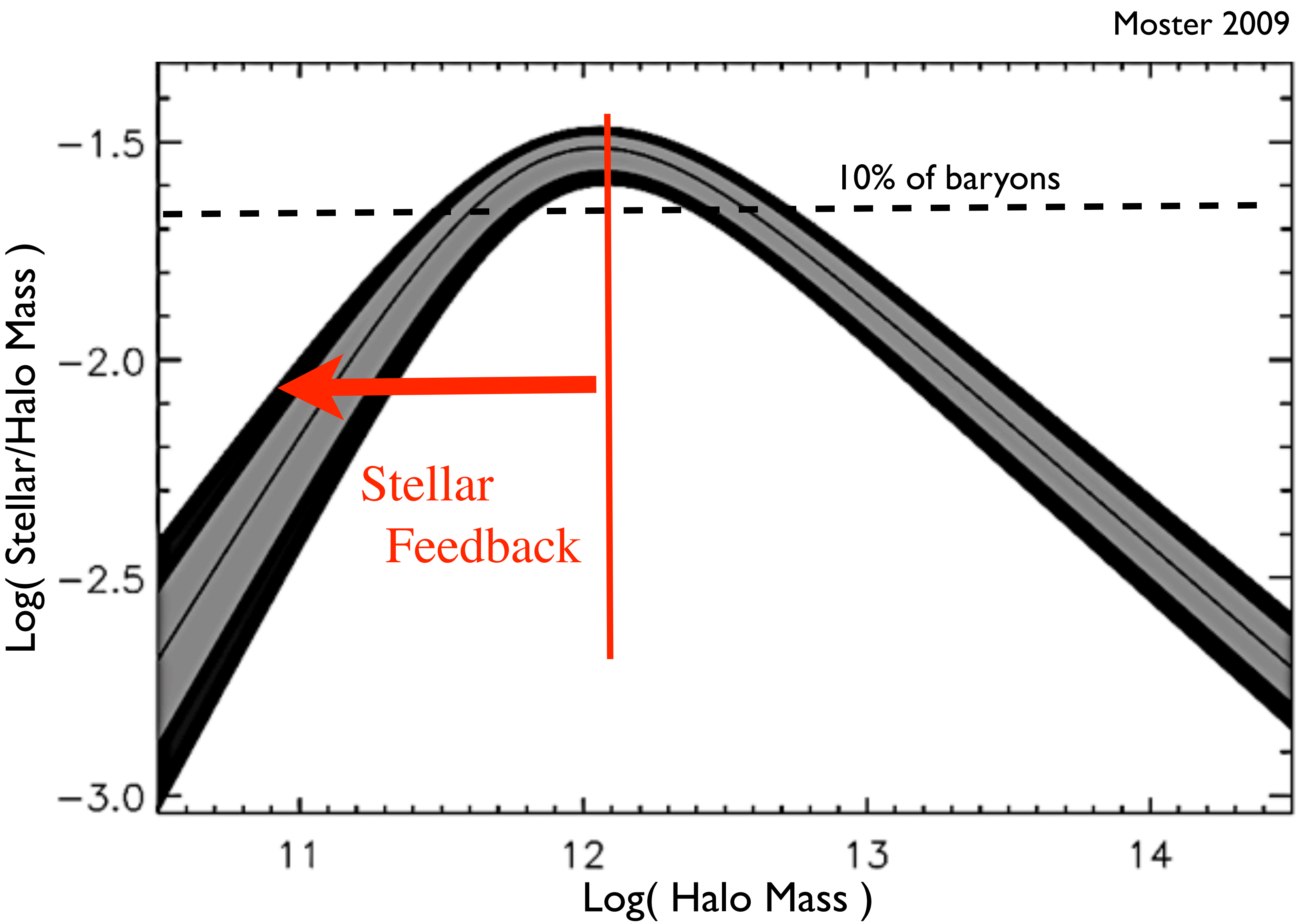

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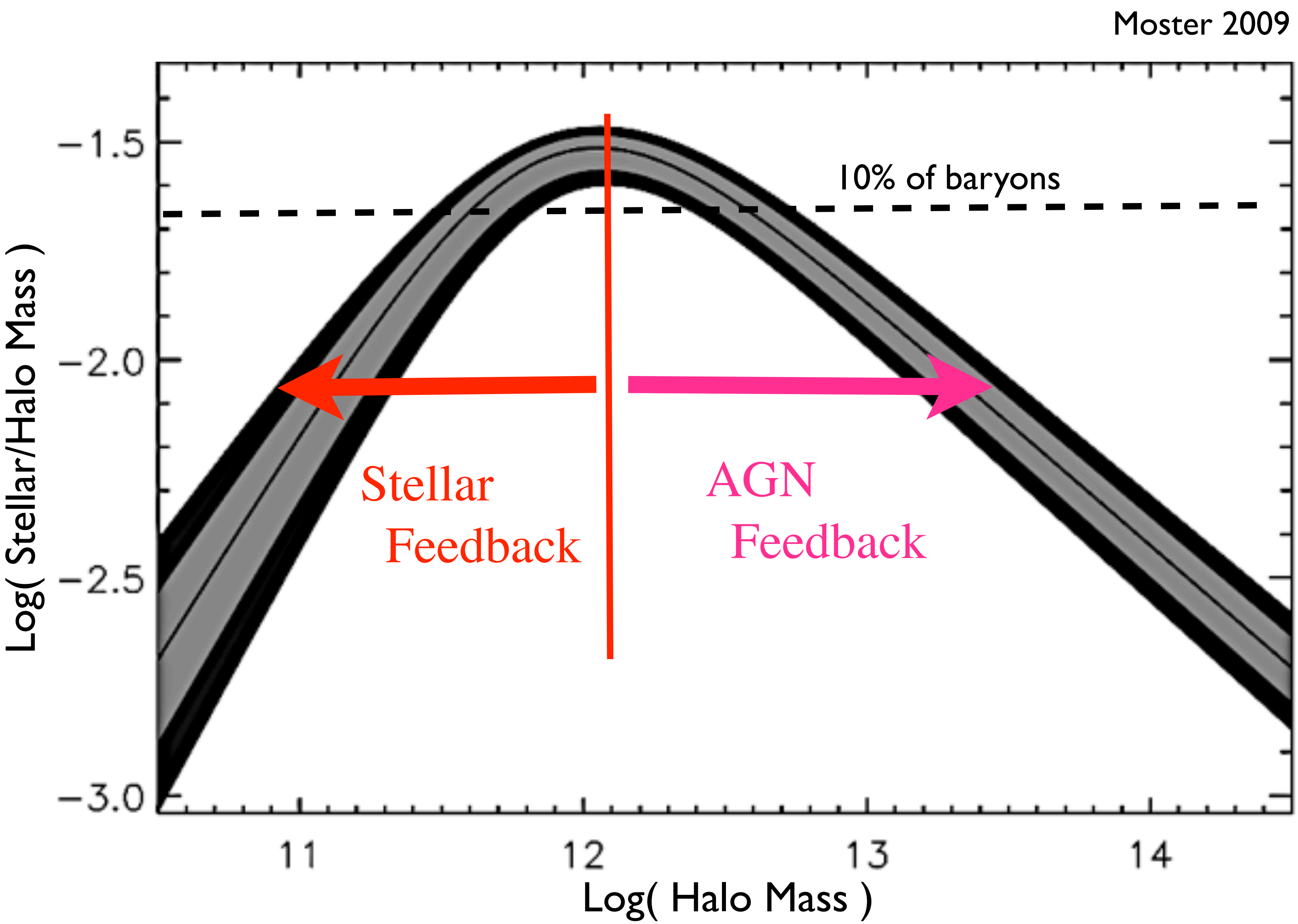


# Stellar Feedback is (a/the) Key to Galaxy Formation!

## SO WHAT'S THE PROBLEM?

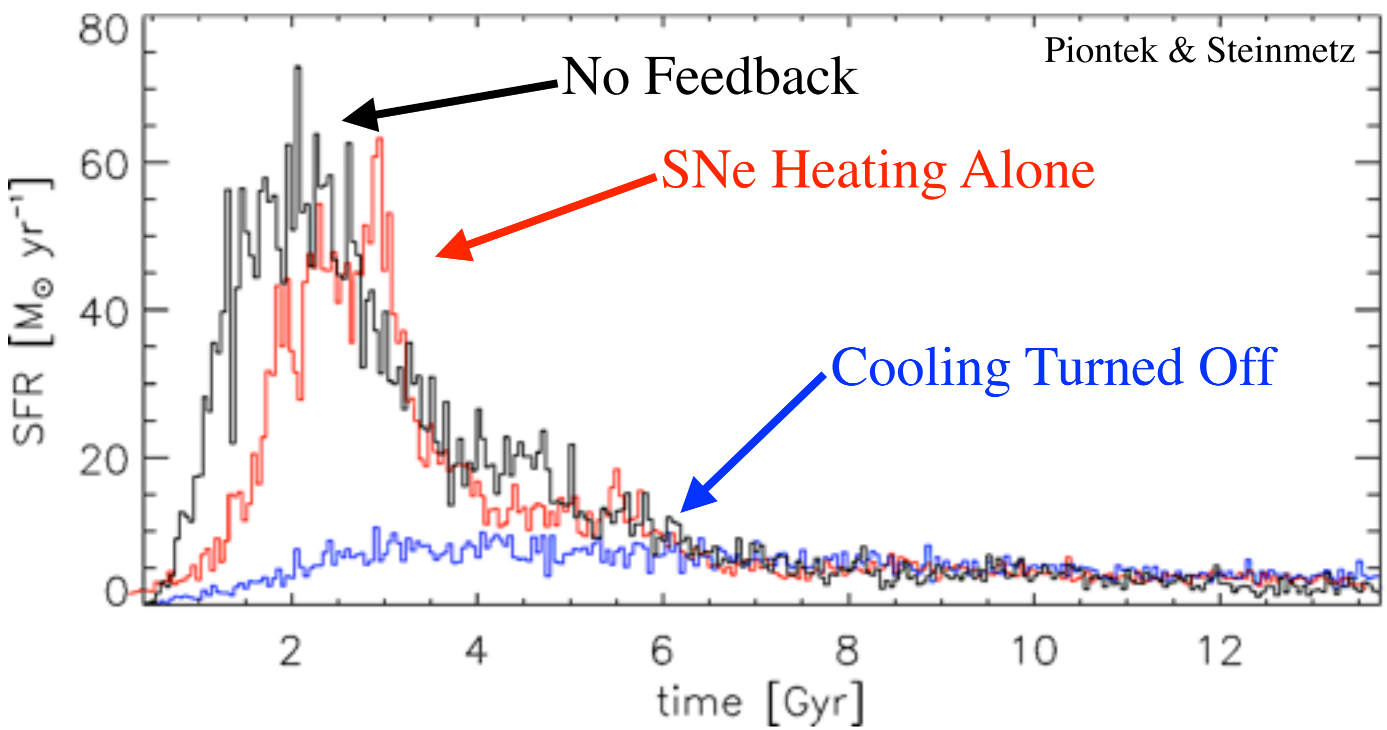
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- 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

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- *Explicit* Momentum Flux:
  - Radiation Pressure

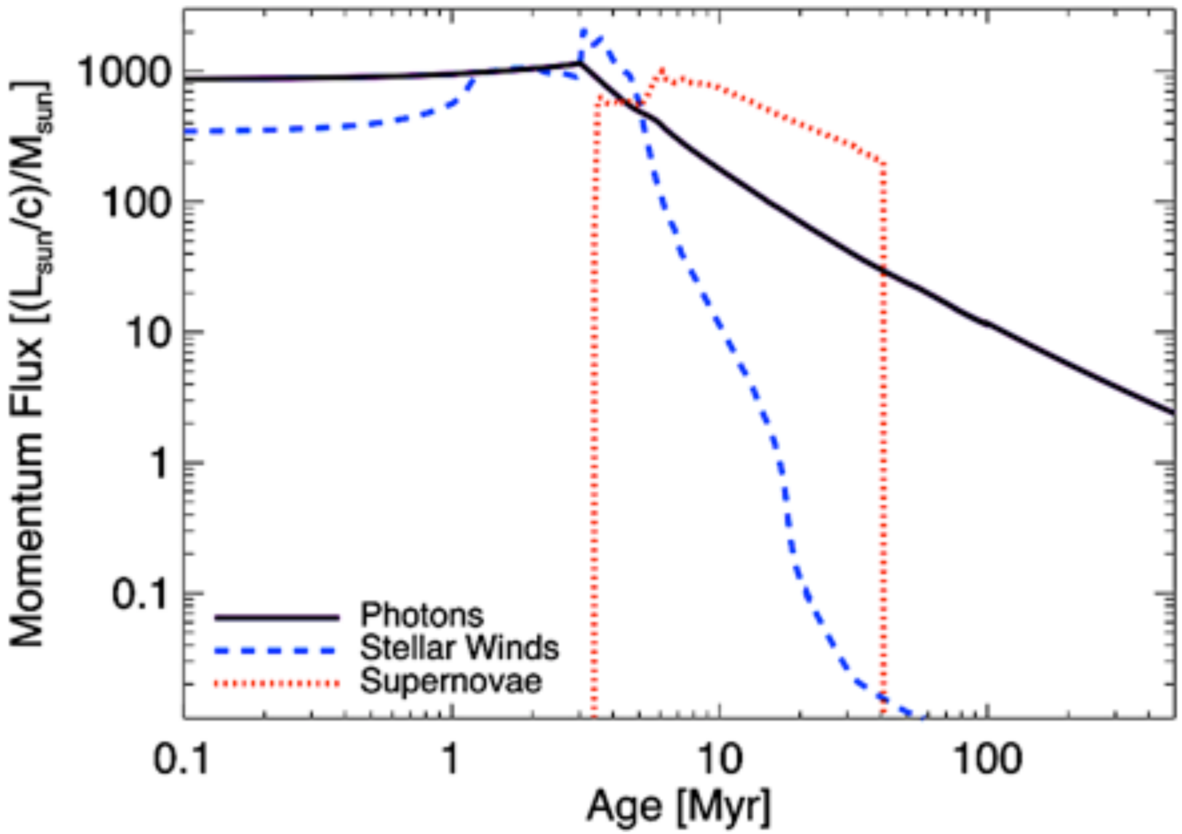
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

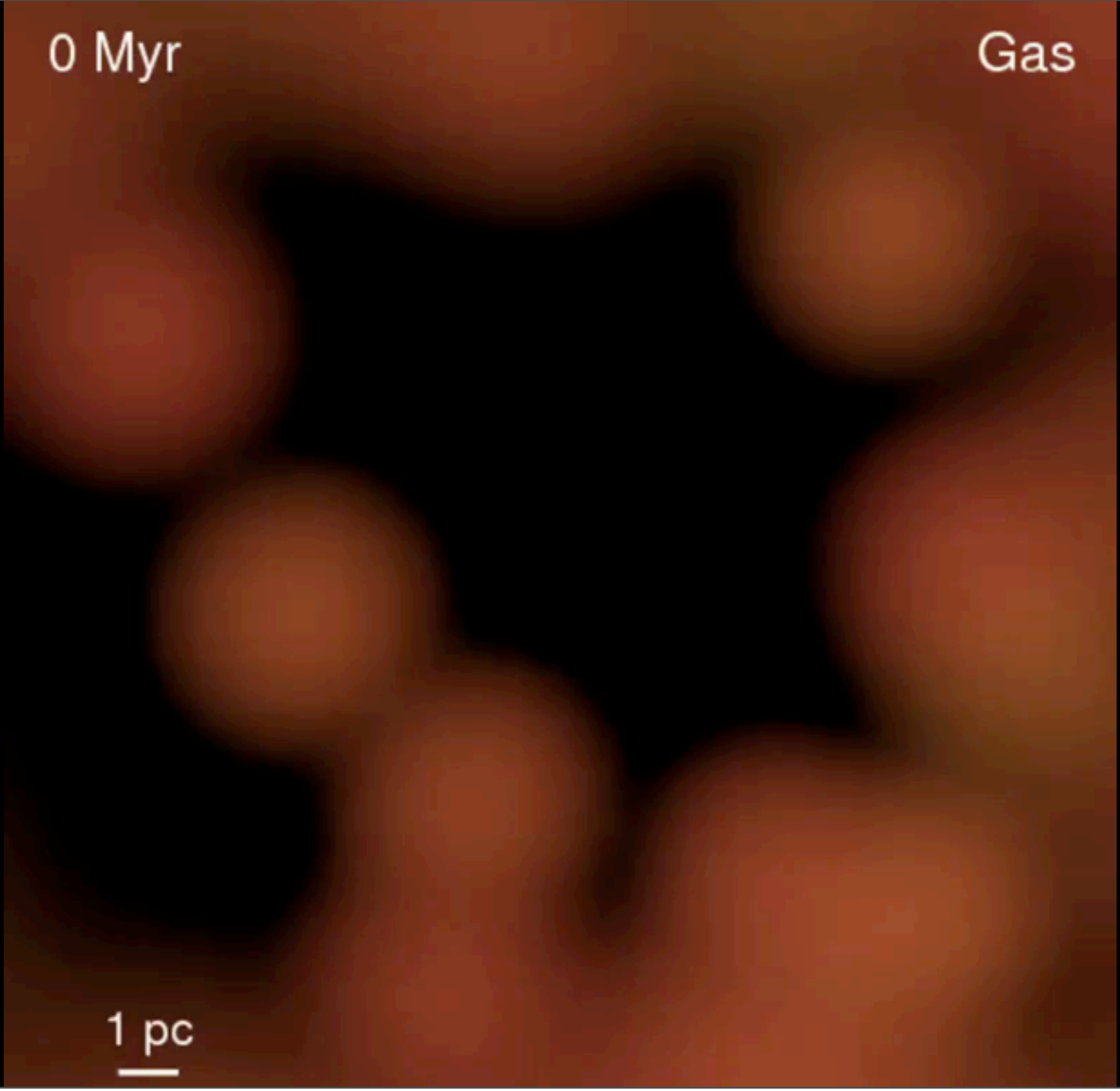
  - SNe

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

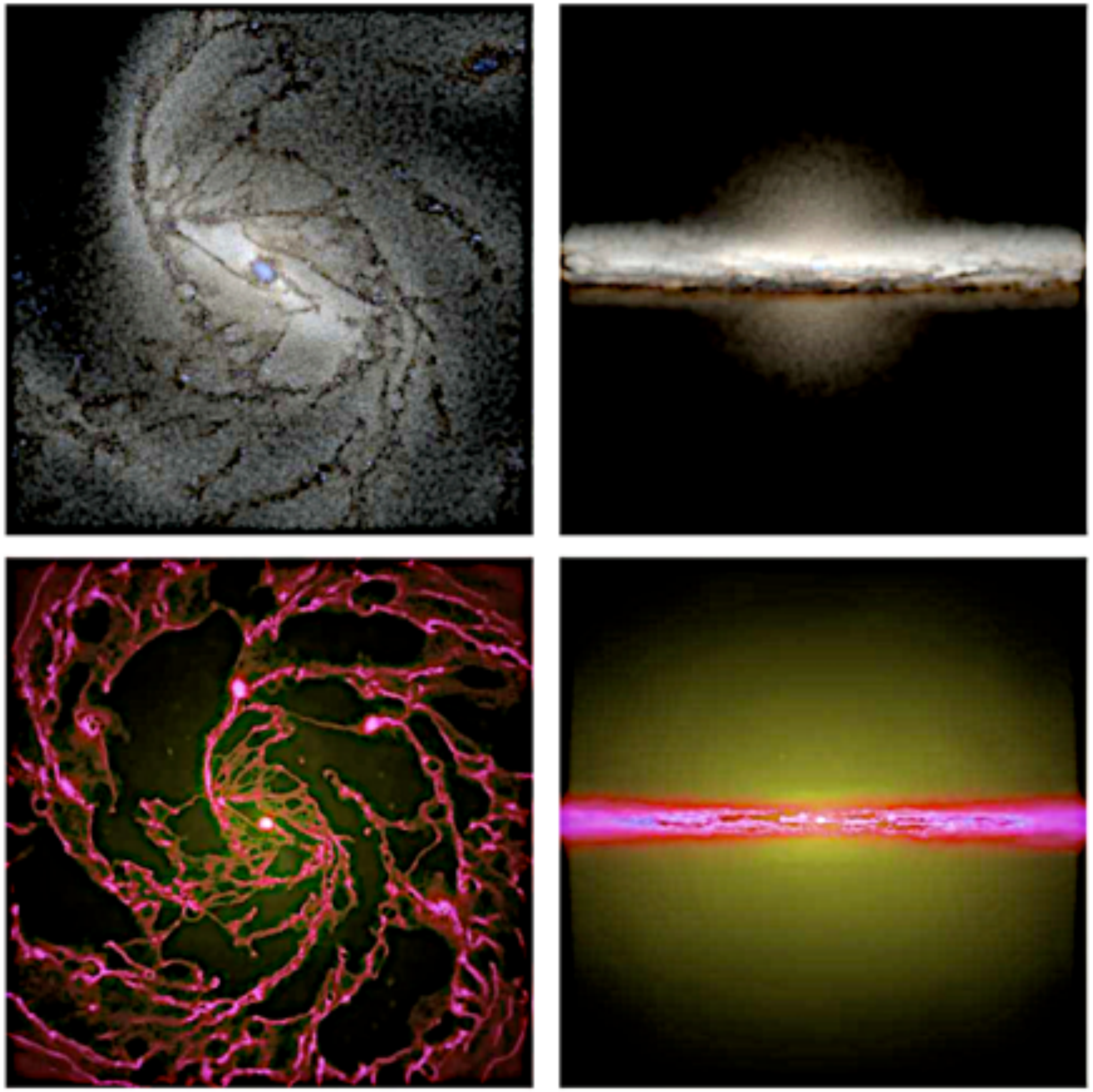
  - Stellar Winds

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

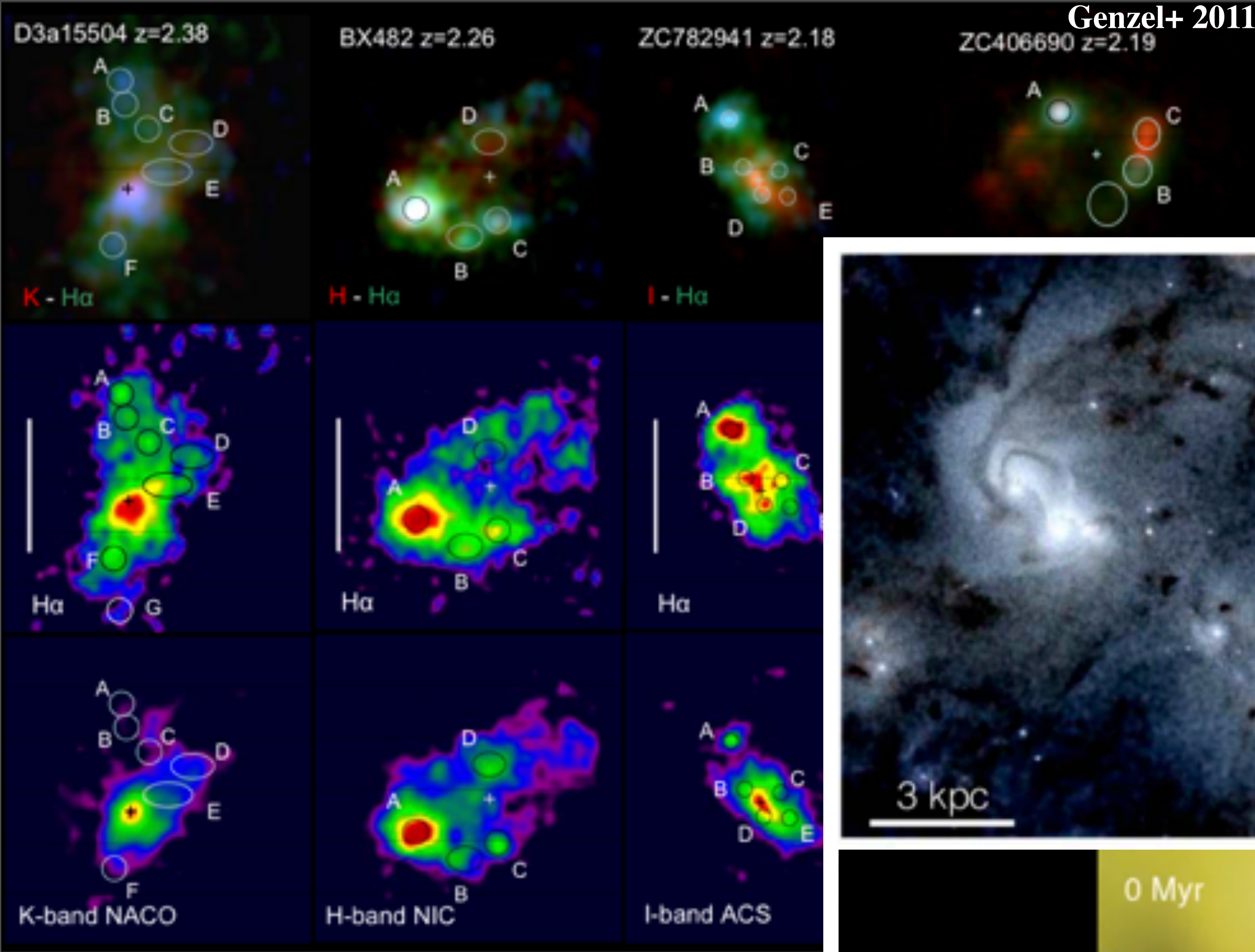


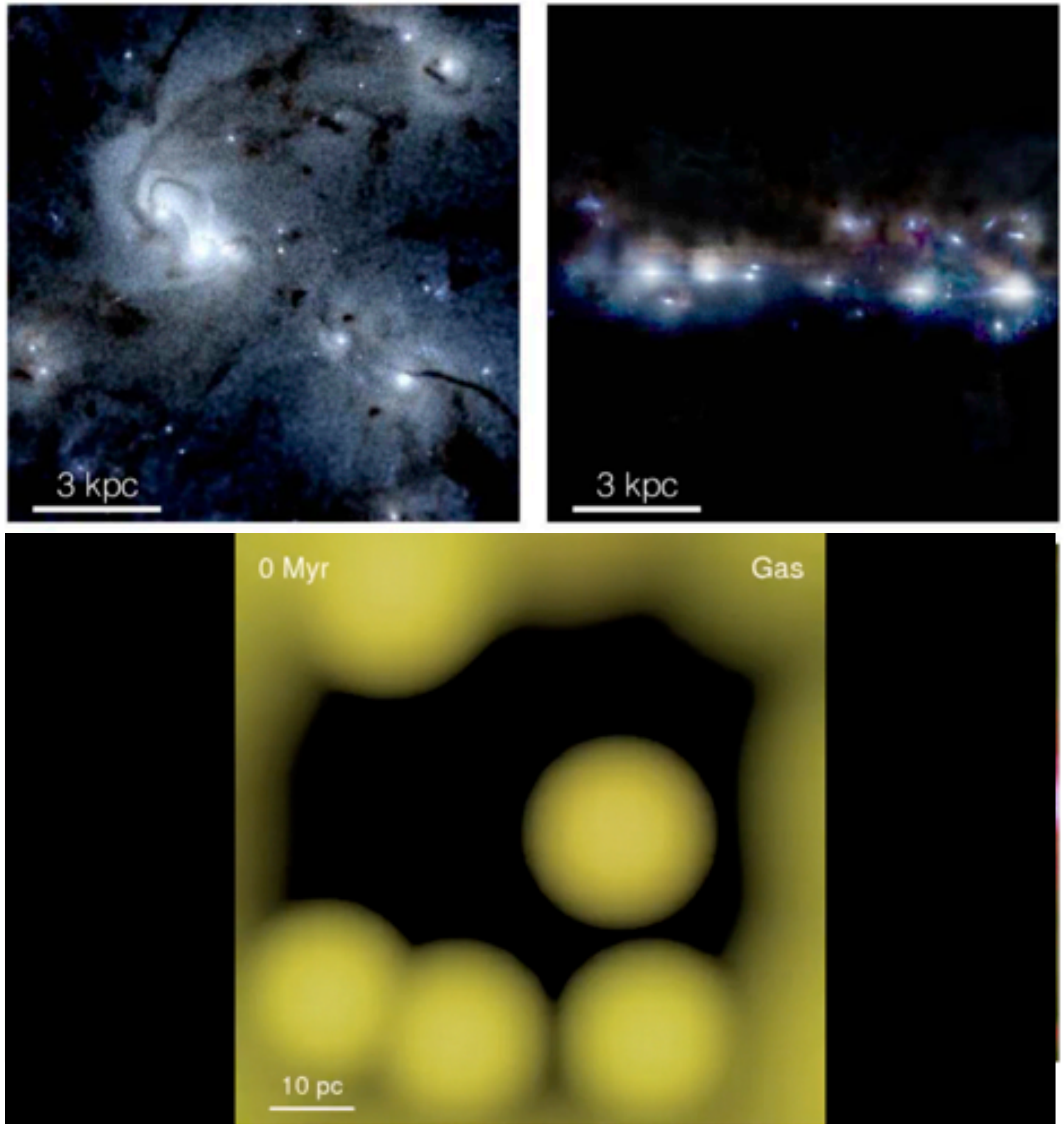

0 Myr
Gas
1 pc


Hopkins, Quataert, & Murray, 2011b

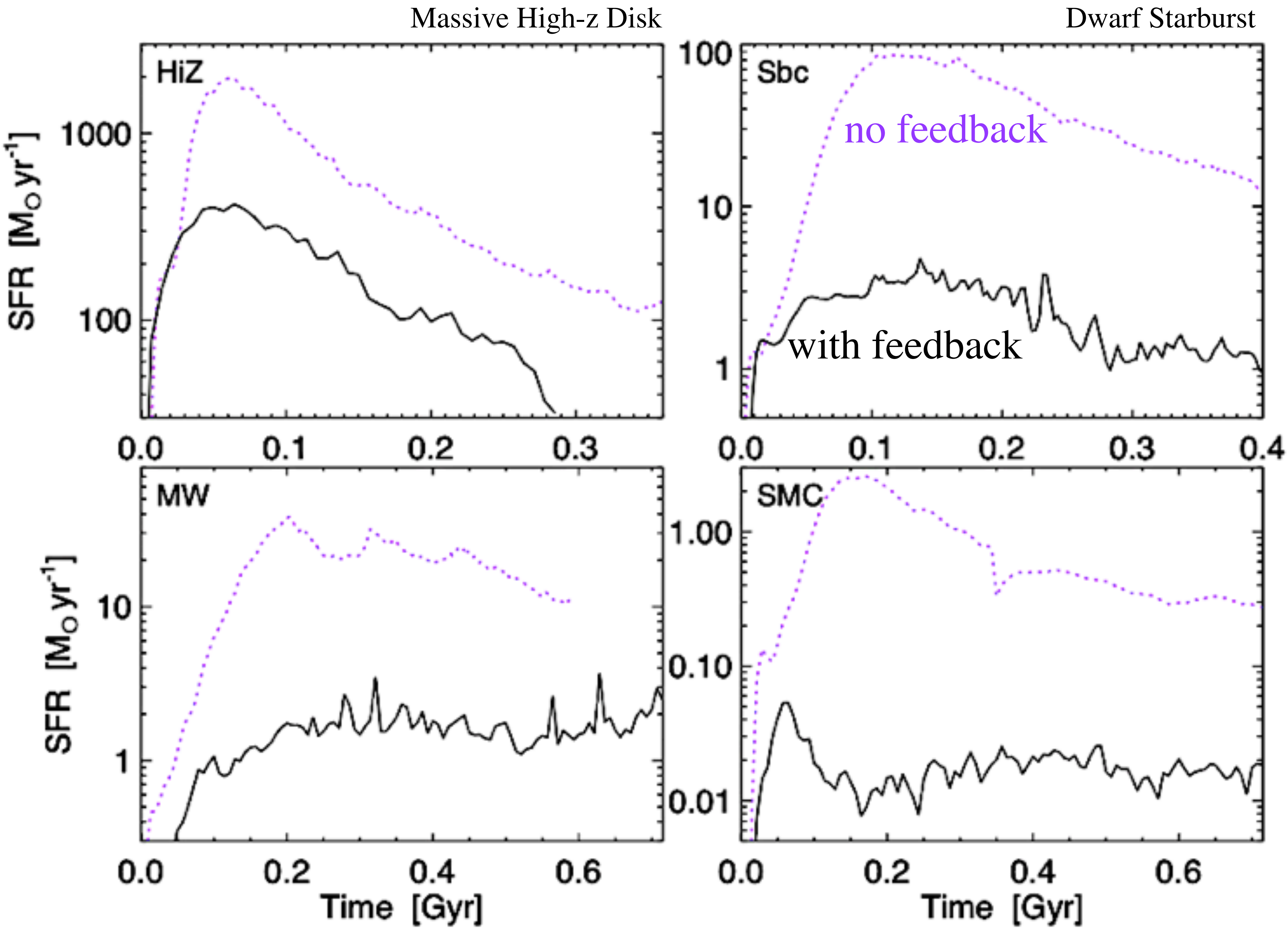
Hopkins, Quataert, & Murray, 2011b




PFH, Quataert, Hernquist, 2011

# Stellar Feedback gives Self-Regulated Star Formation



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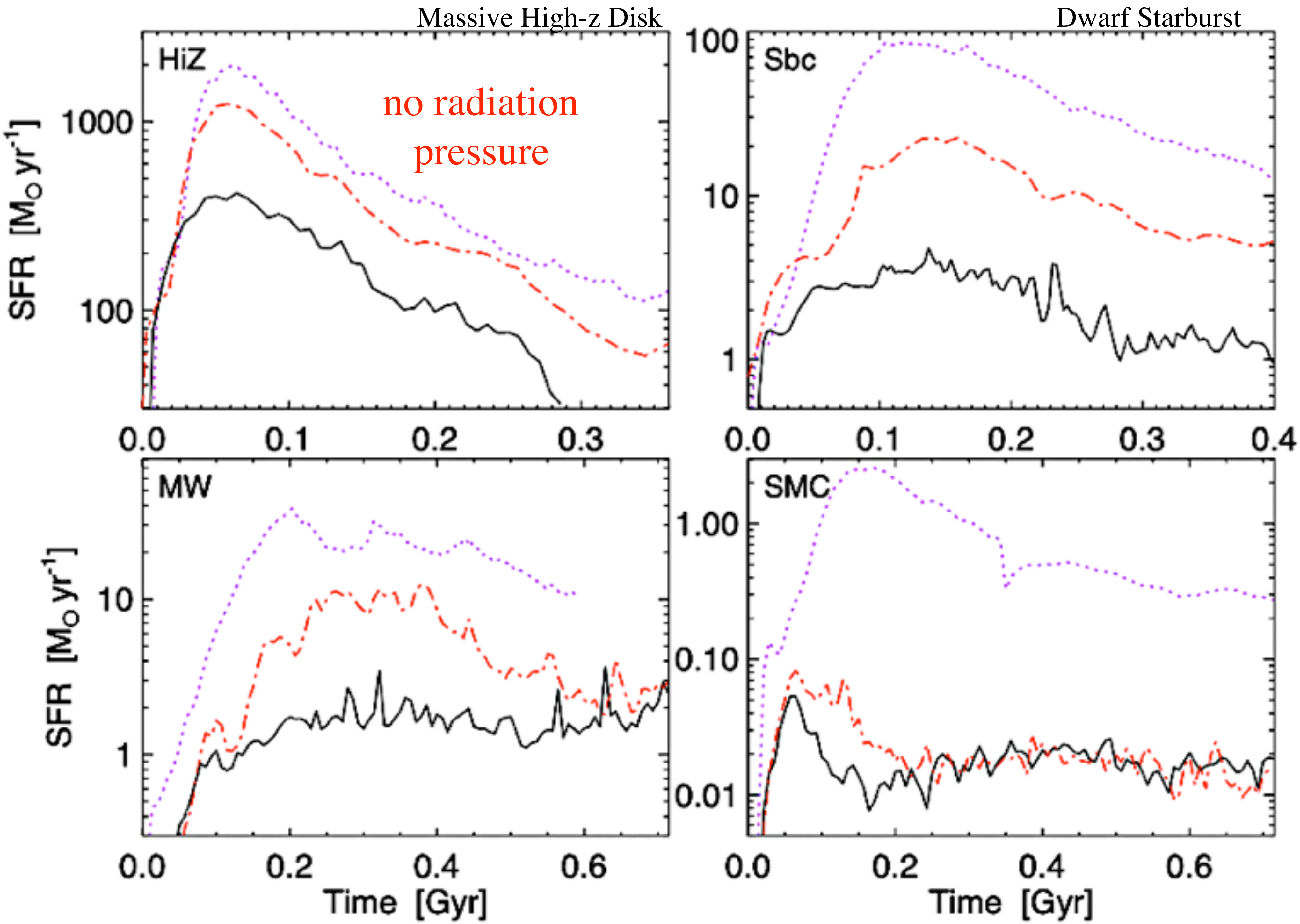

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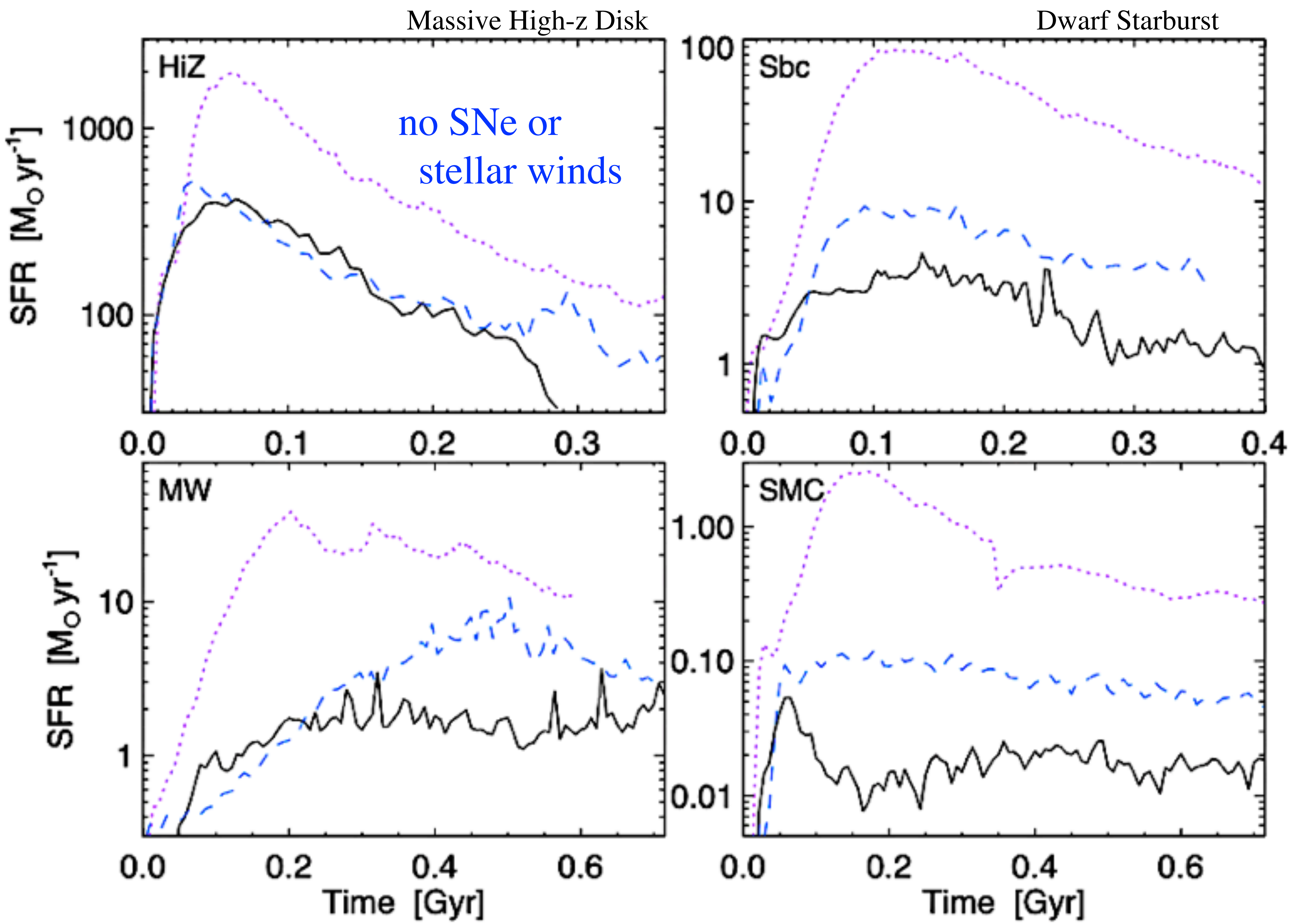
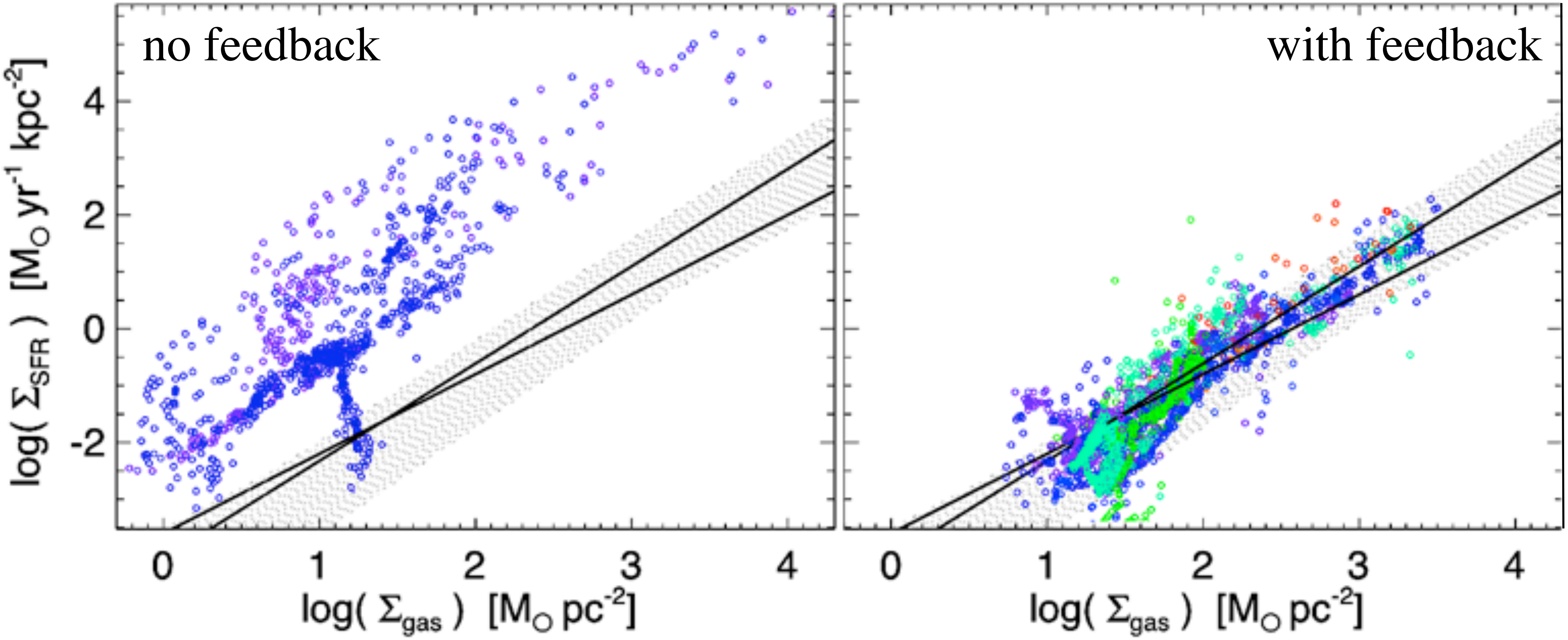


# Kennicutt-Schmidt relation emerges naturally




PFH, Quataert, & Murray, 2011a

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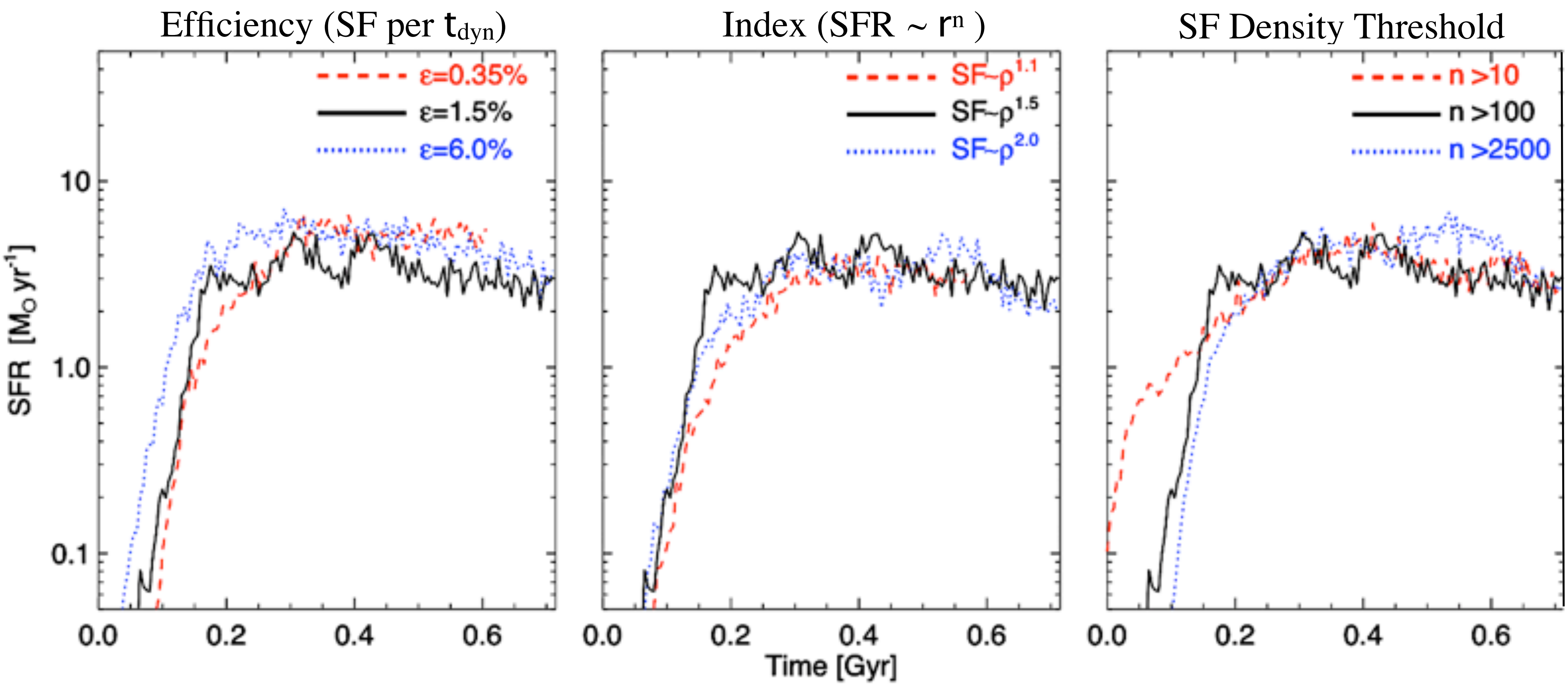
$$\longrightarrow \dot{\Sigma}_{*} \sim \left(\frac{\sigma}{\epsilon_{*} c}\right) \Sigma_{\rm gas}\Omega \sim 0.02\, \Sigma_{\rm gas}\Omega$$

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




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

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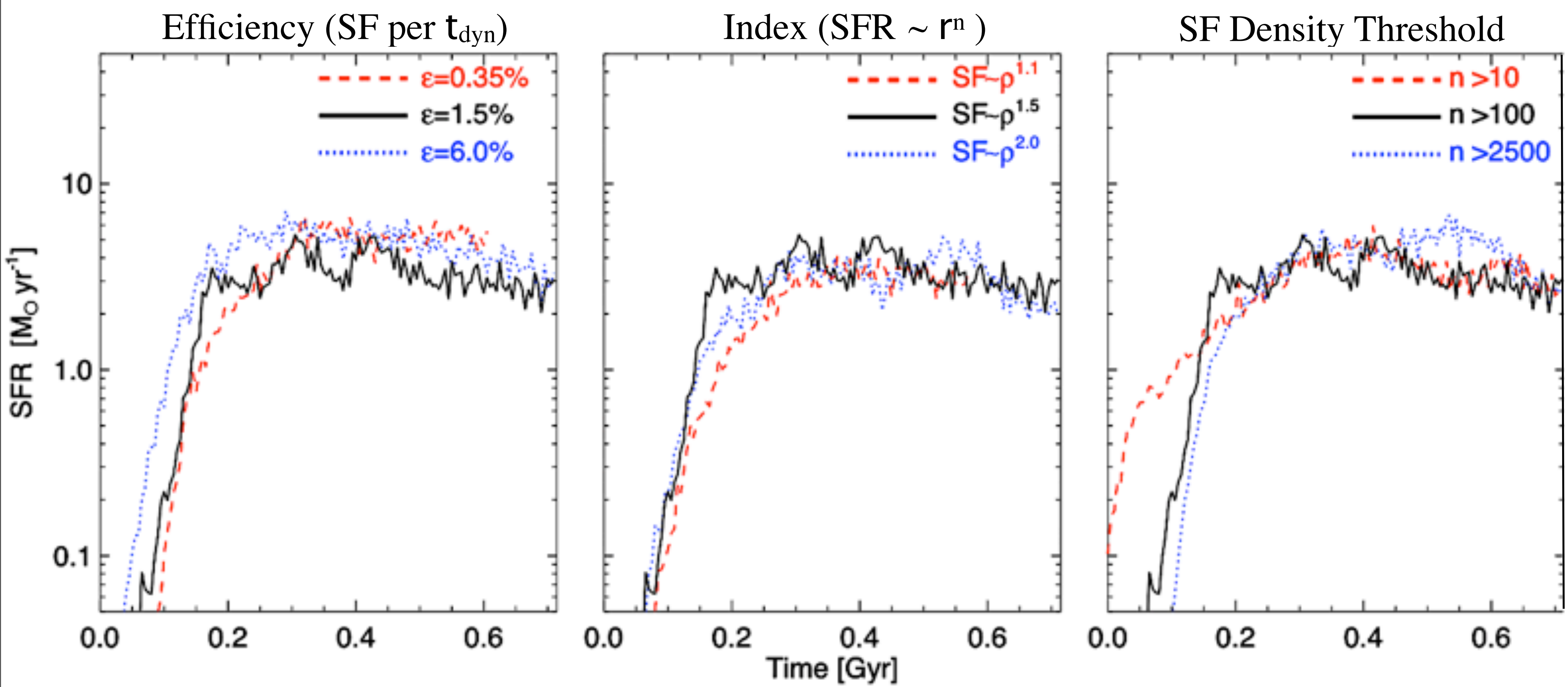


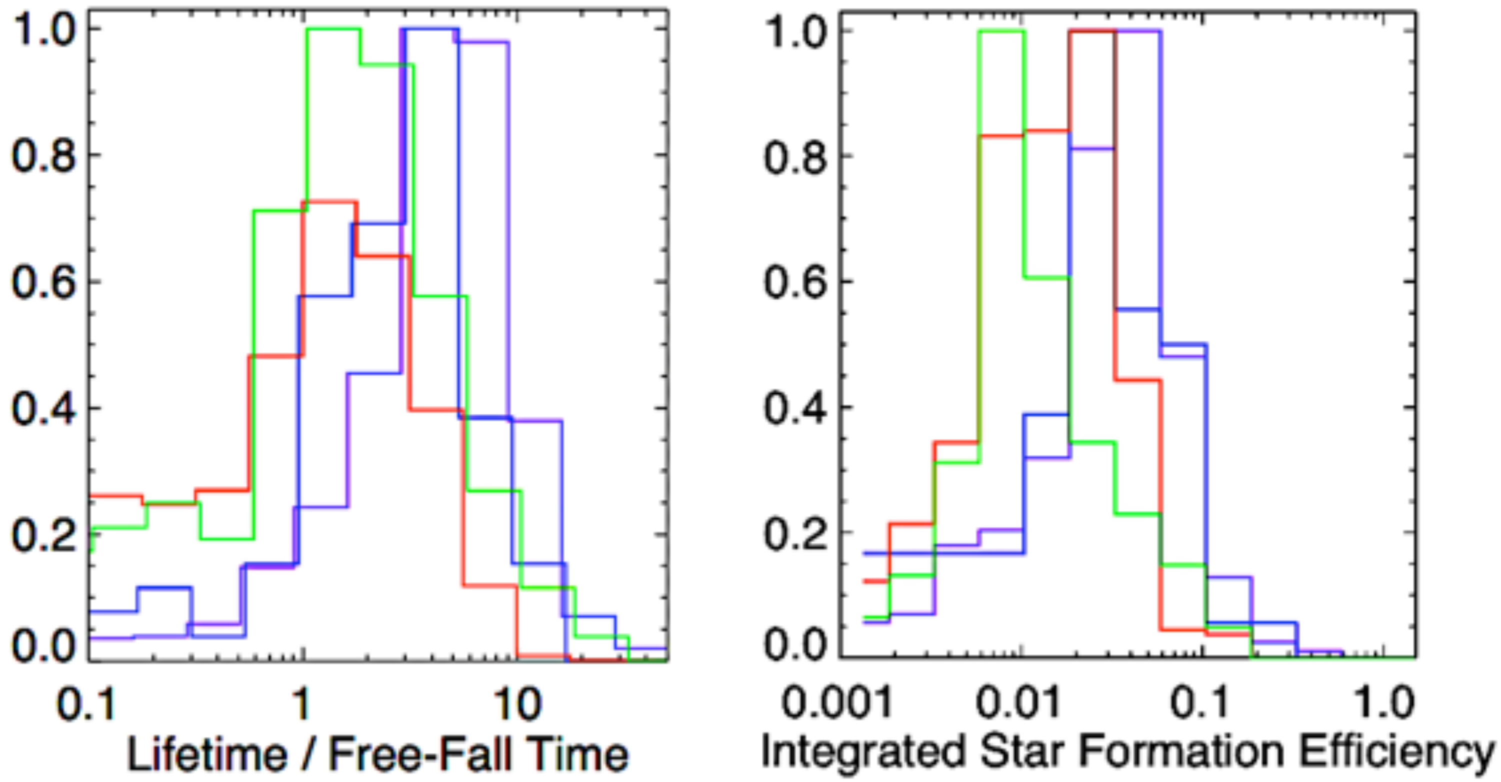

- Set by feedback (i.e. SFR) needed to maintain marginal stability

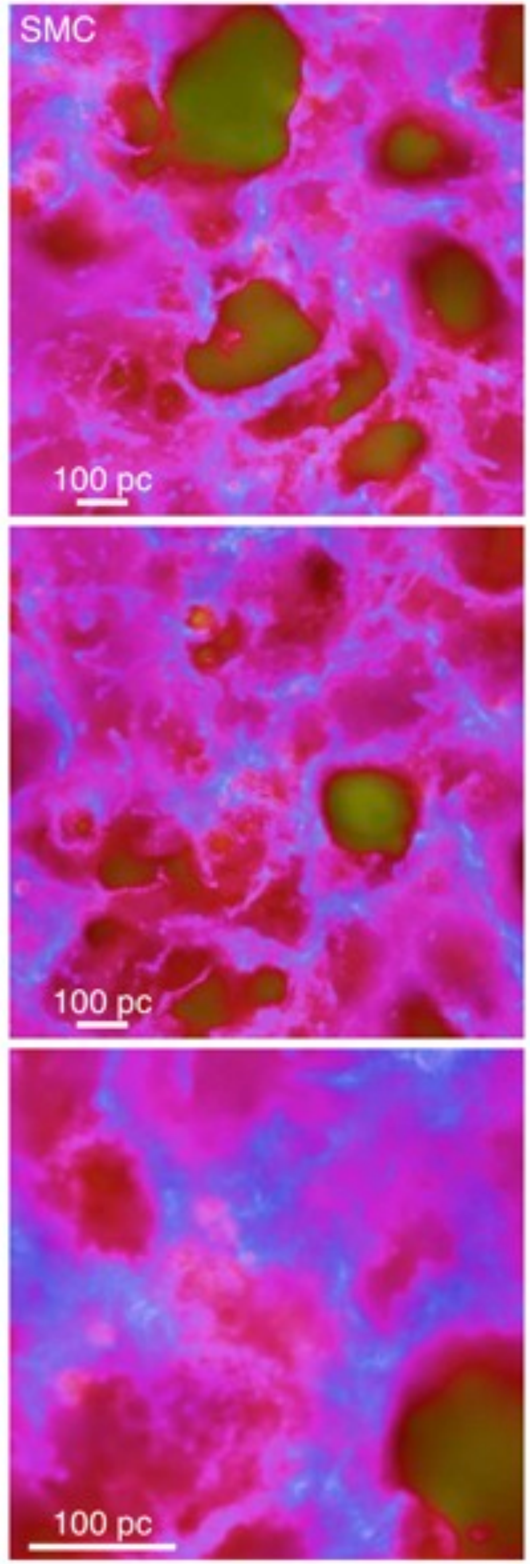
Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

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

# Properties of GMCs

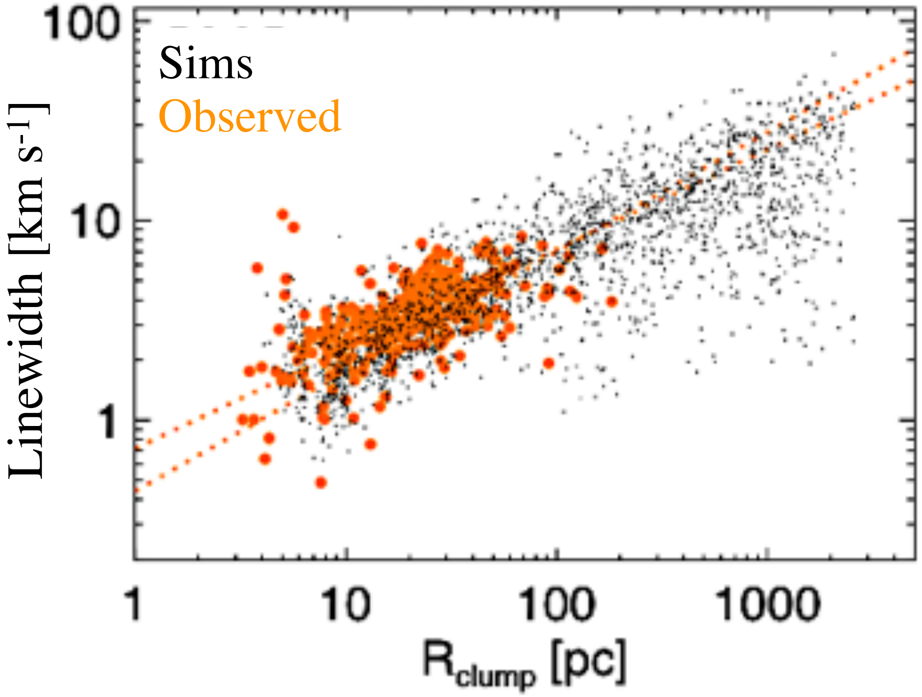
## DEPENDENCE ON FEEDBACK AND OTHER SCALINGS

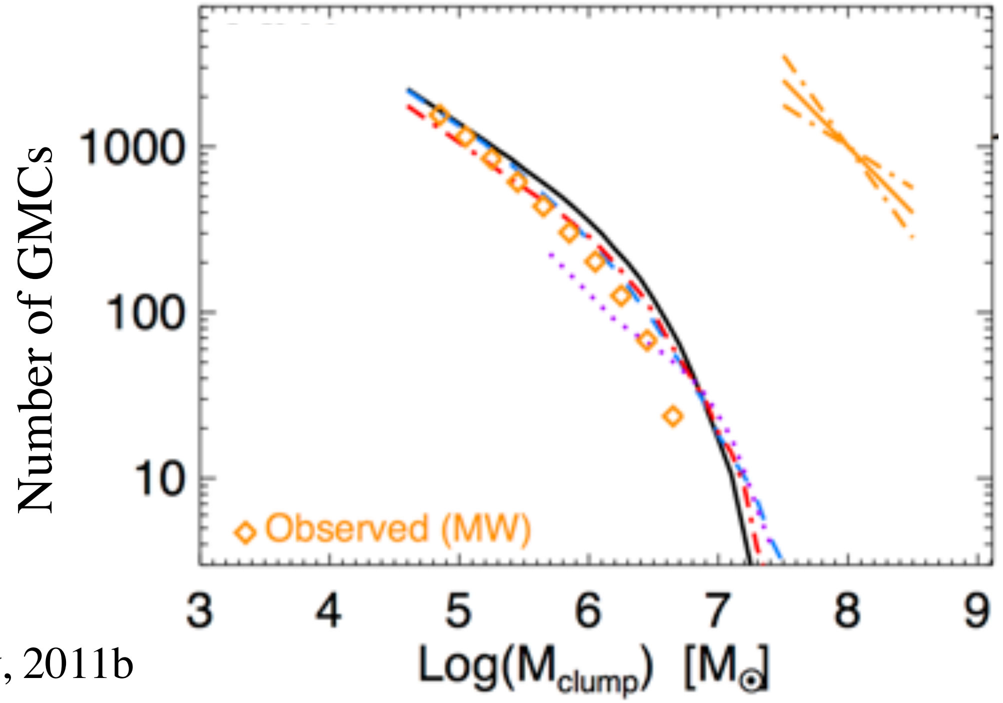


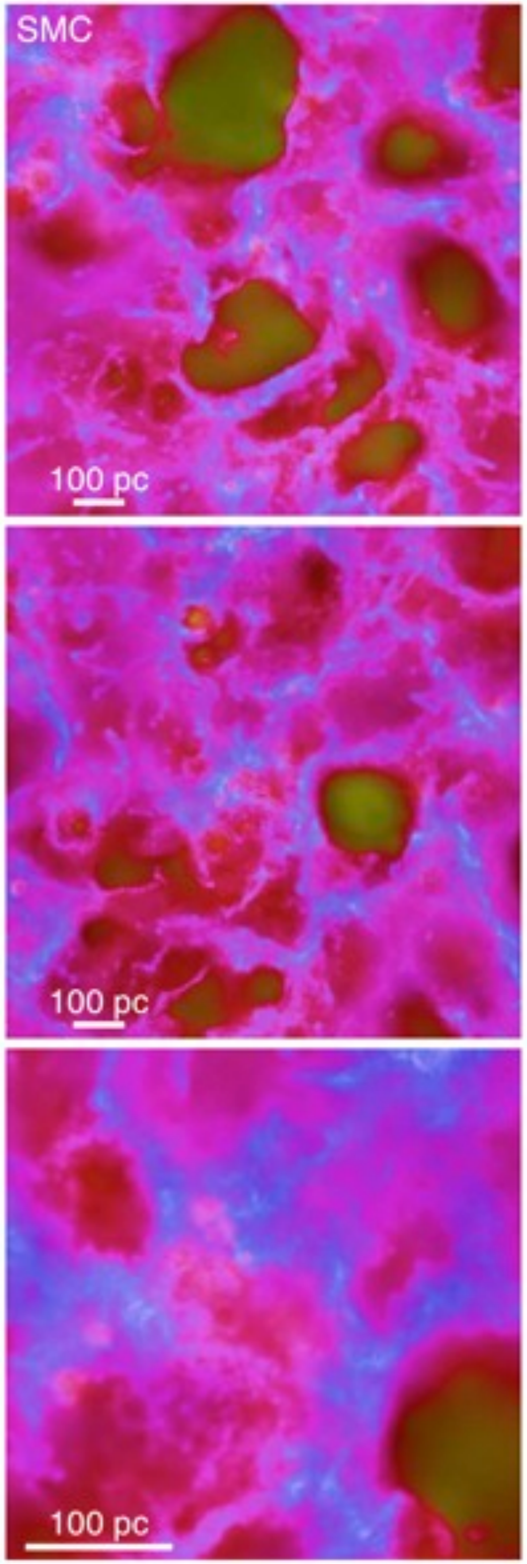




PFH, Quataert, & Murray, 2011b

# Properties of GMCs & Gas "Clumps"



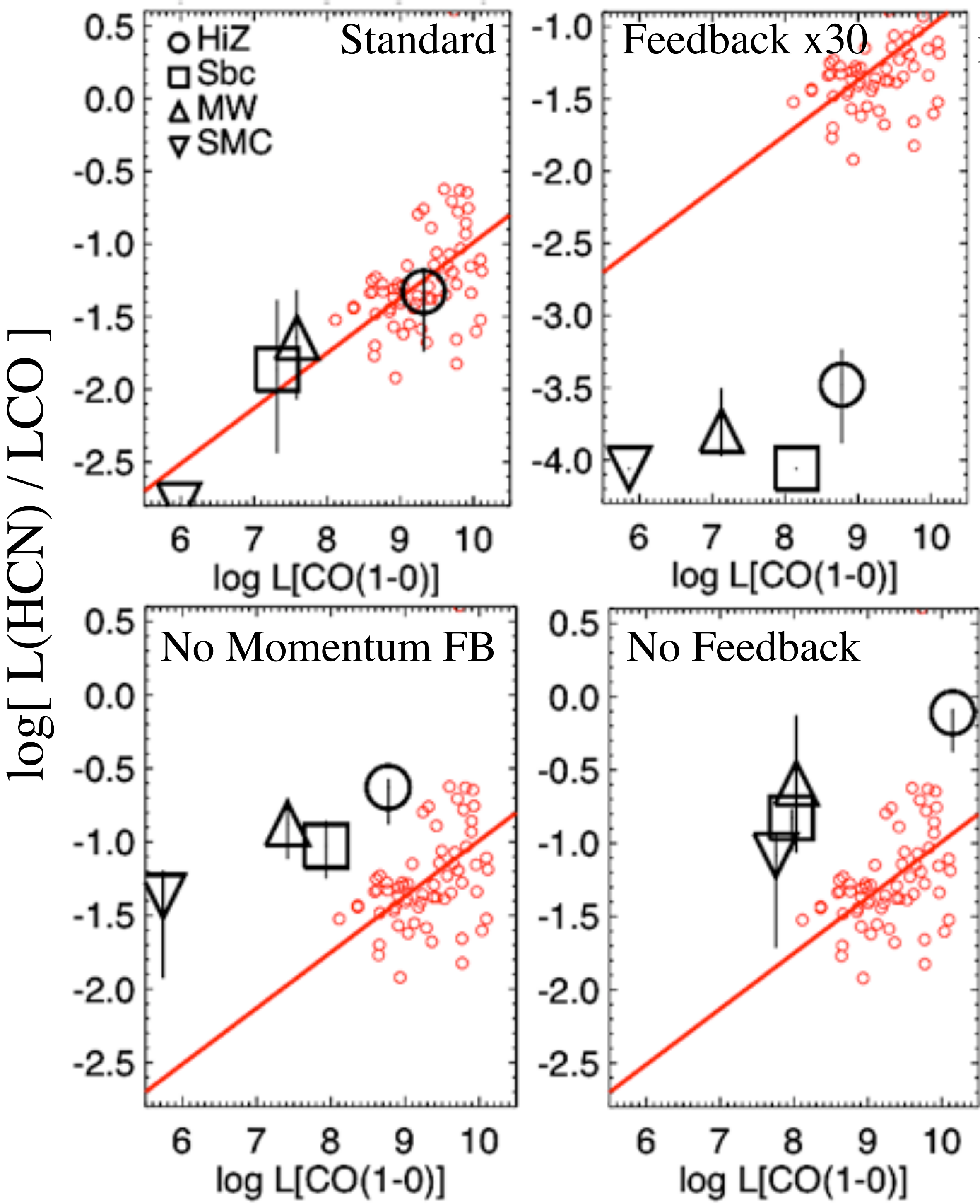




PFH, Quataert, & Murray, 2011b

# Feedback is Reflected in Dense Gas

## TRACERS OF STAR FORMATION EFFICIENCY

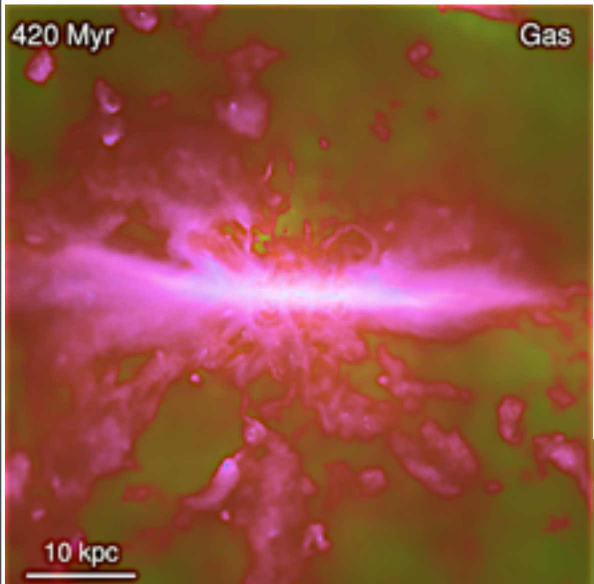


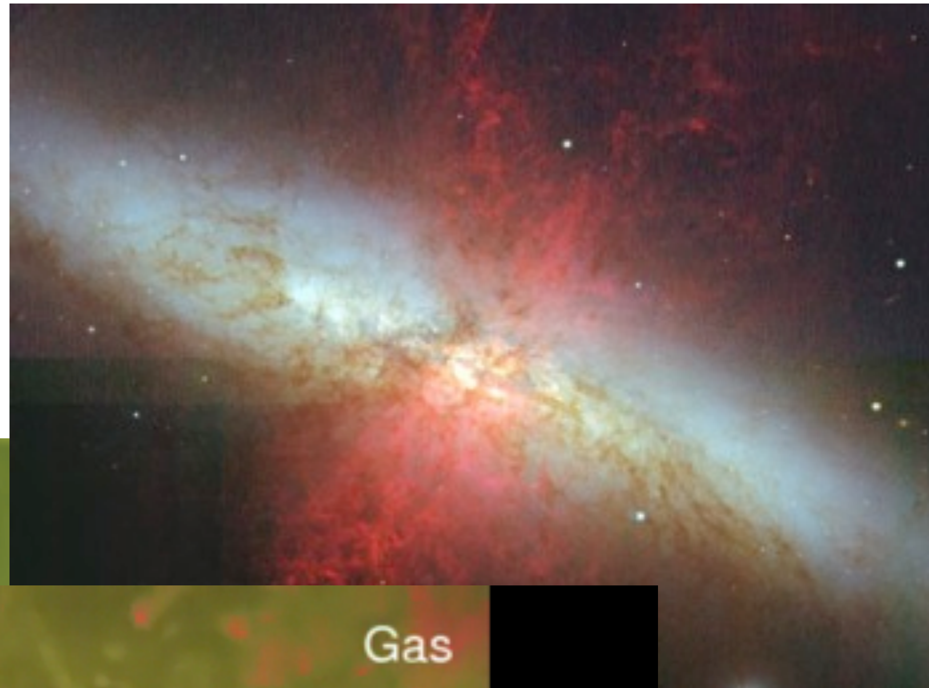

PFH, Narayanan et al. (prep)

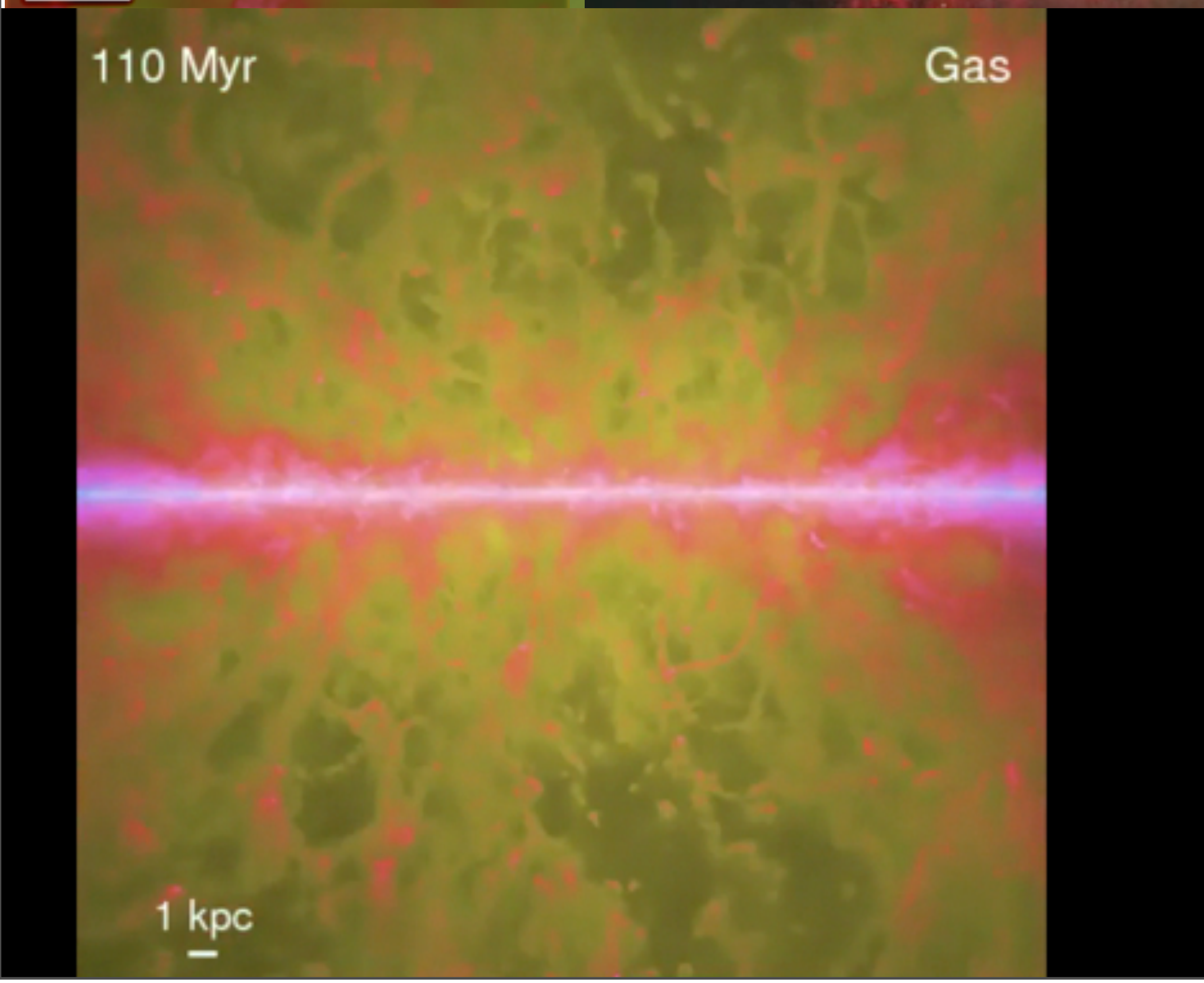
# The Gas not Forming Stars:

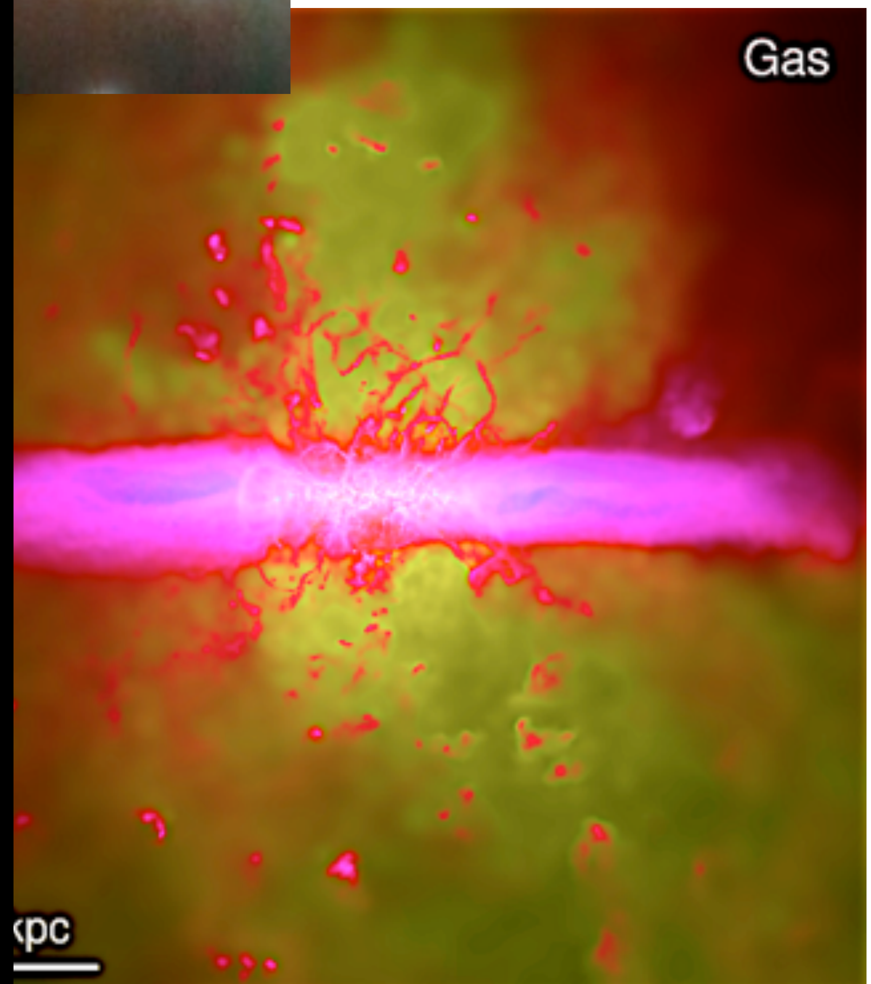
# Galaxy Winds and the Baryon Cycle

# Galactic Super-Winds



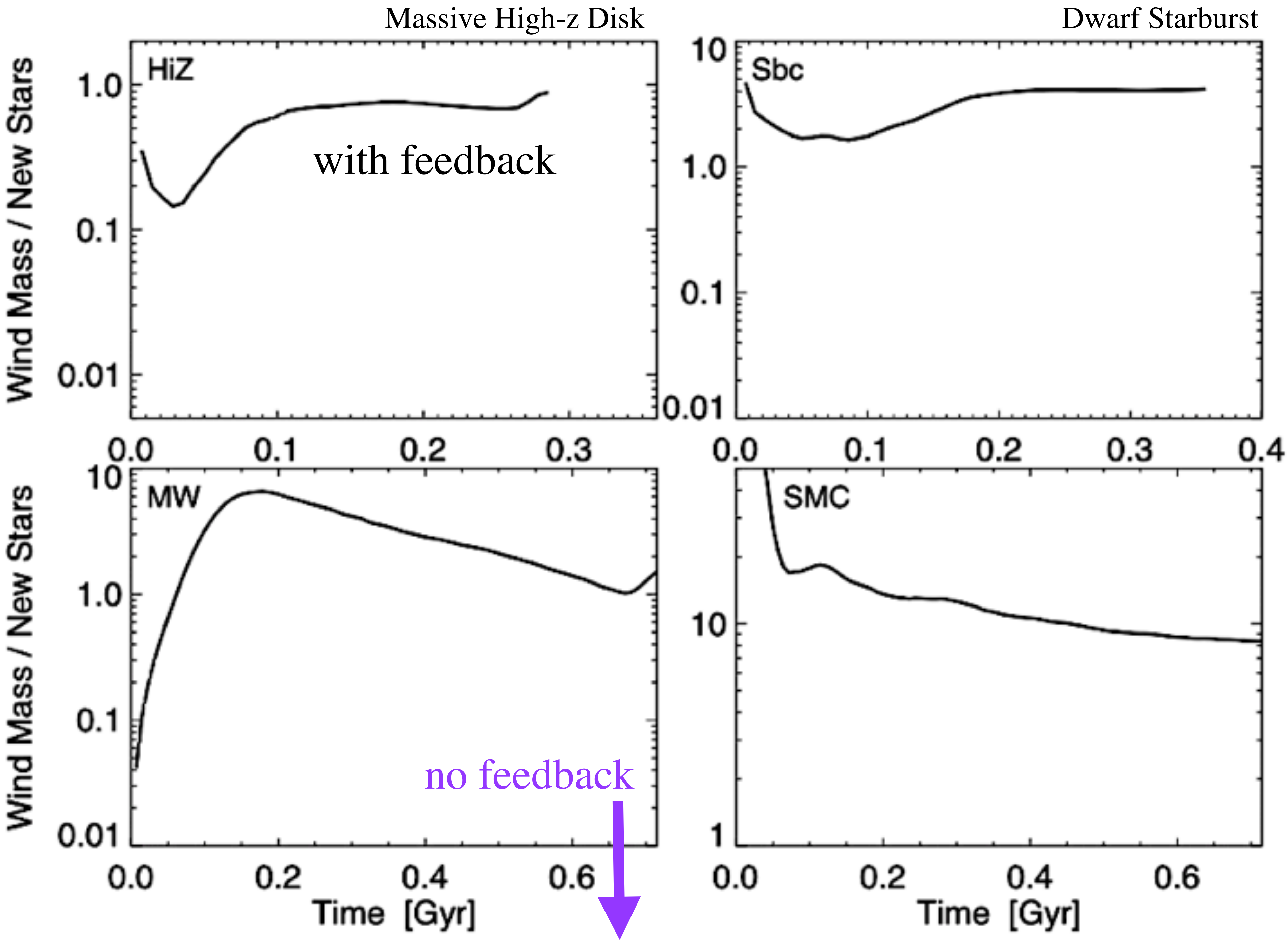


# How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?

PFH, Quataert, & Murray, 2011c



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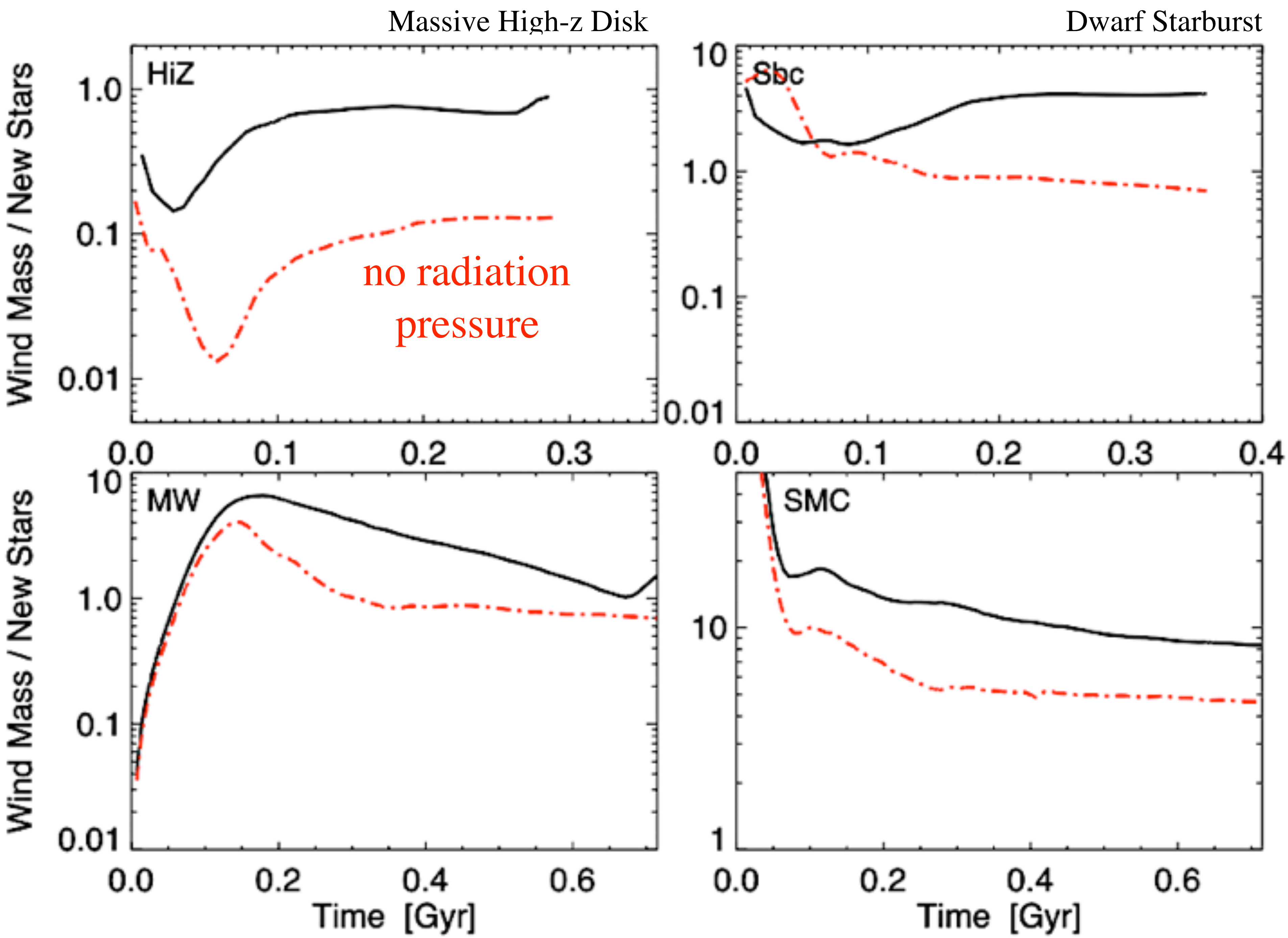

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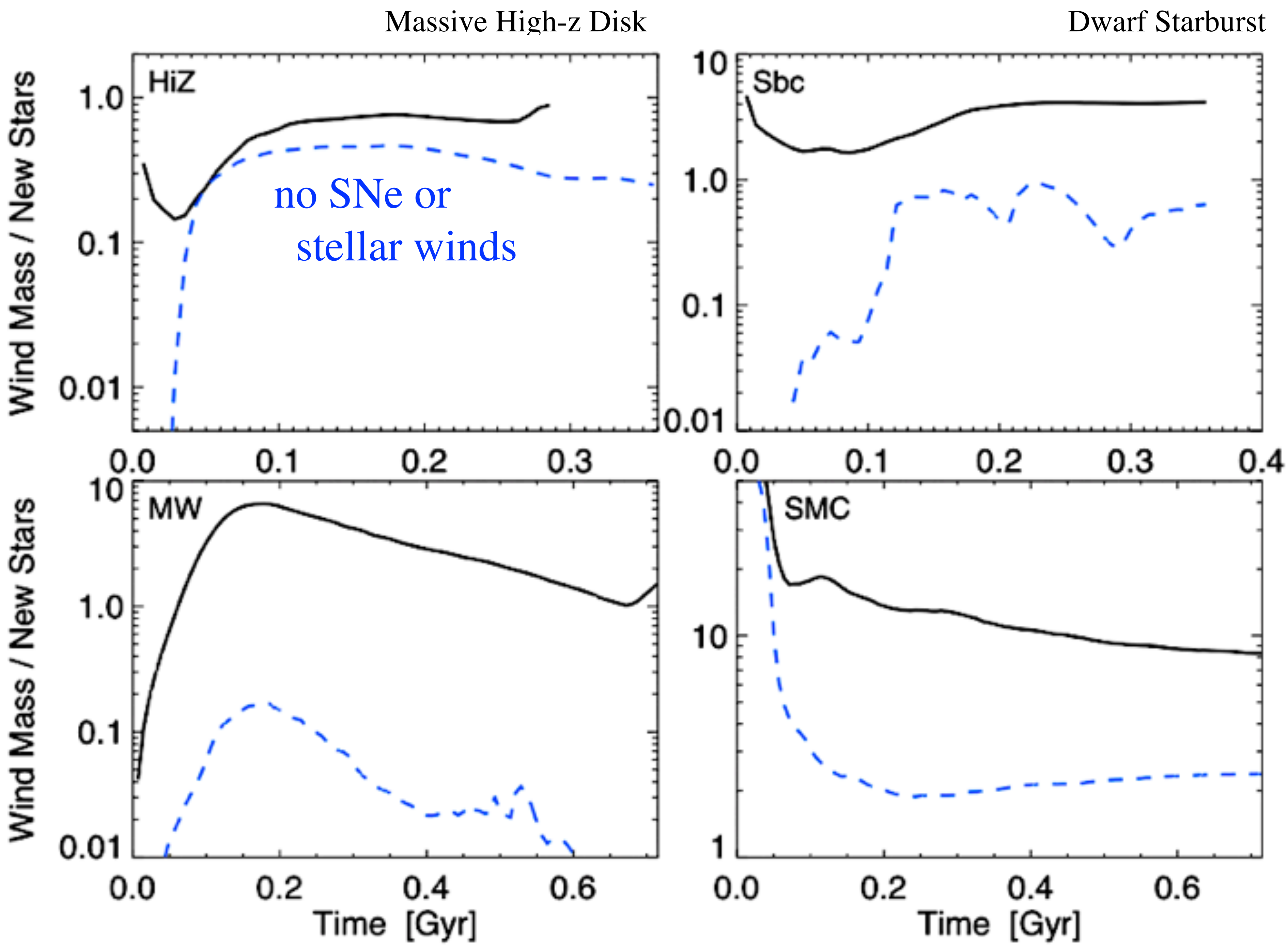

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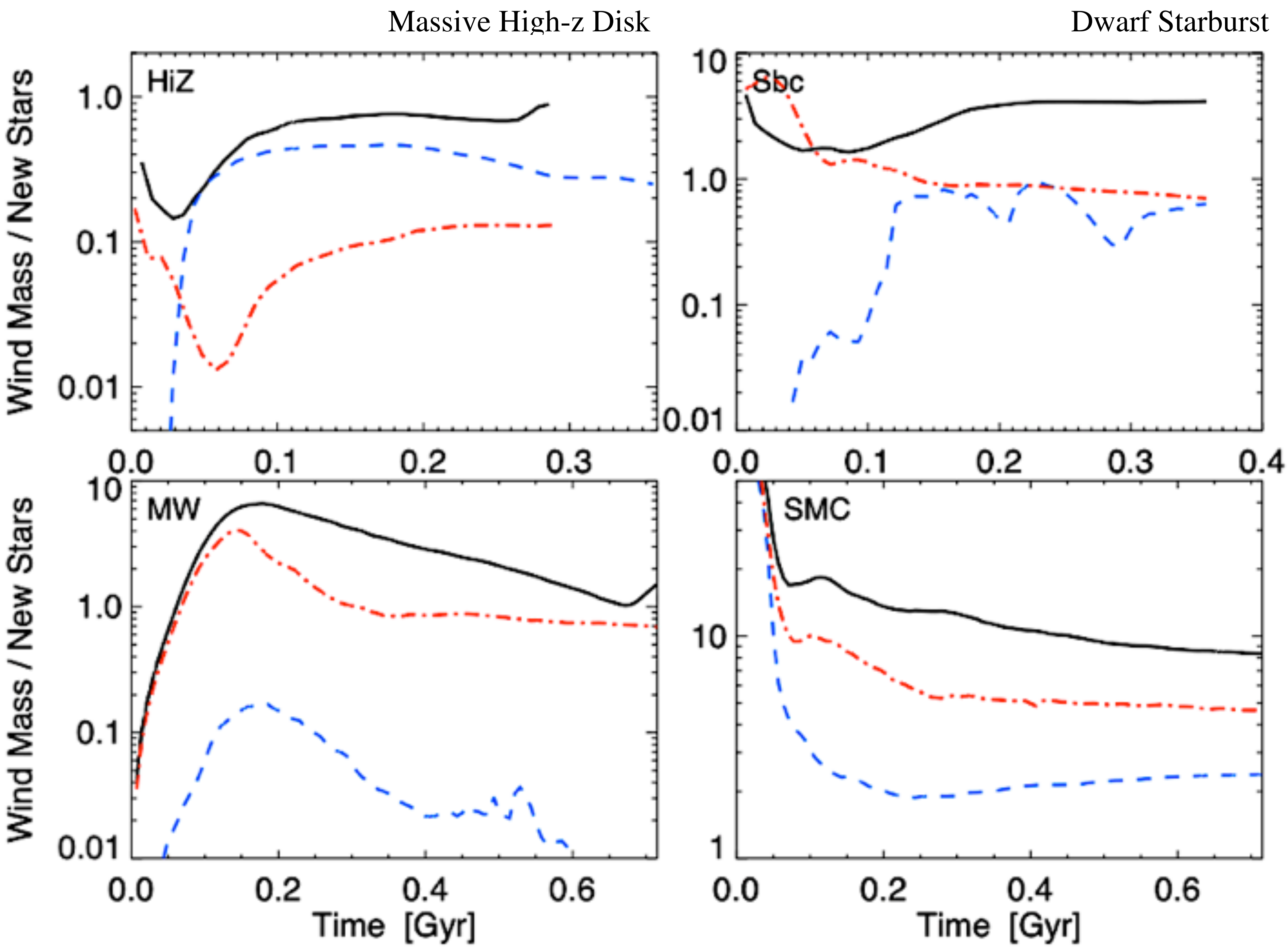

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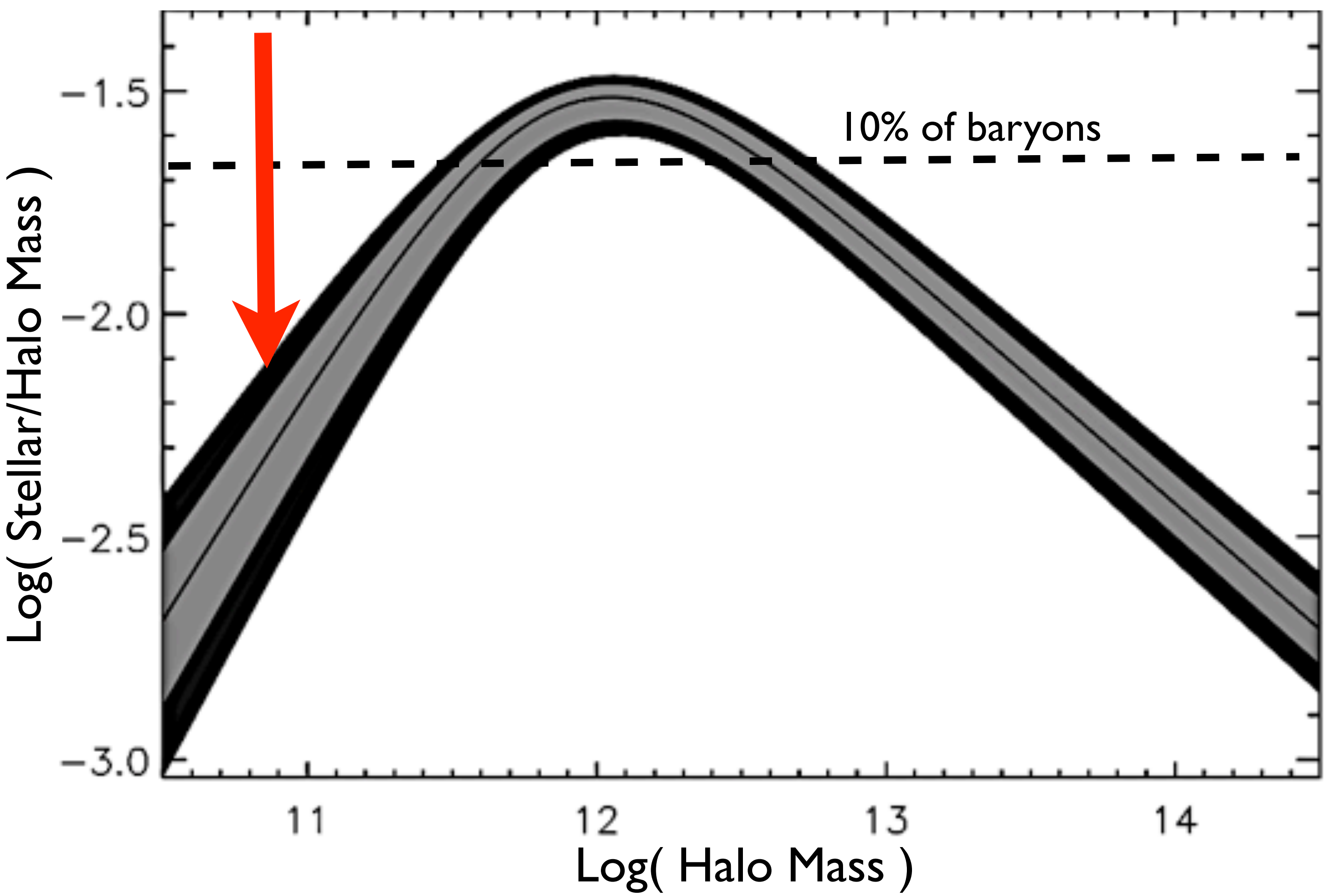


- Large mass-loading:

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

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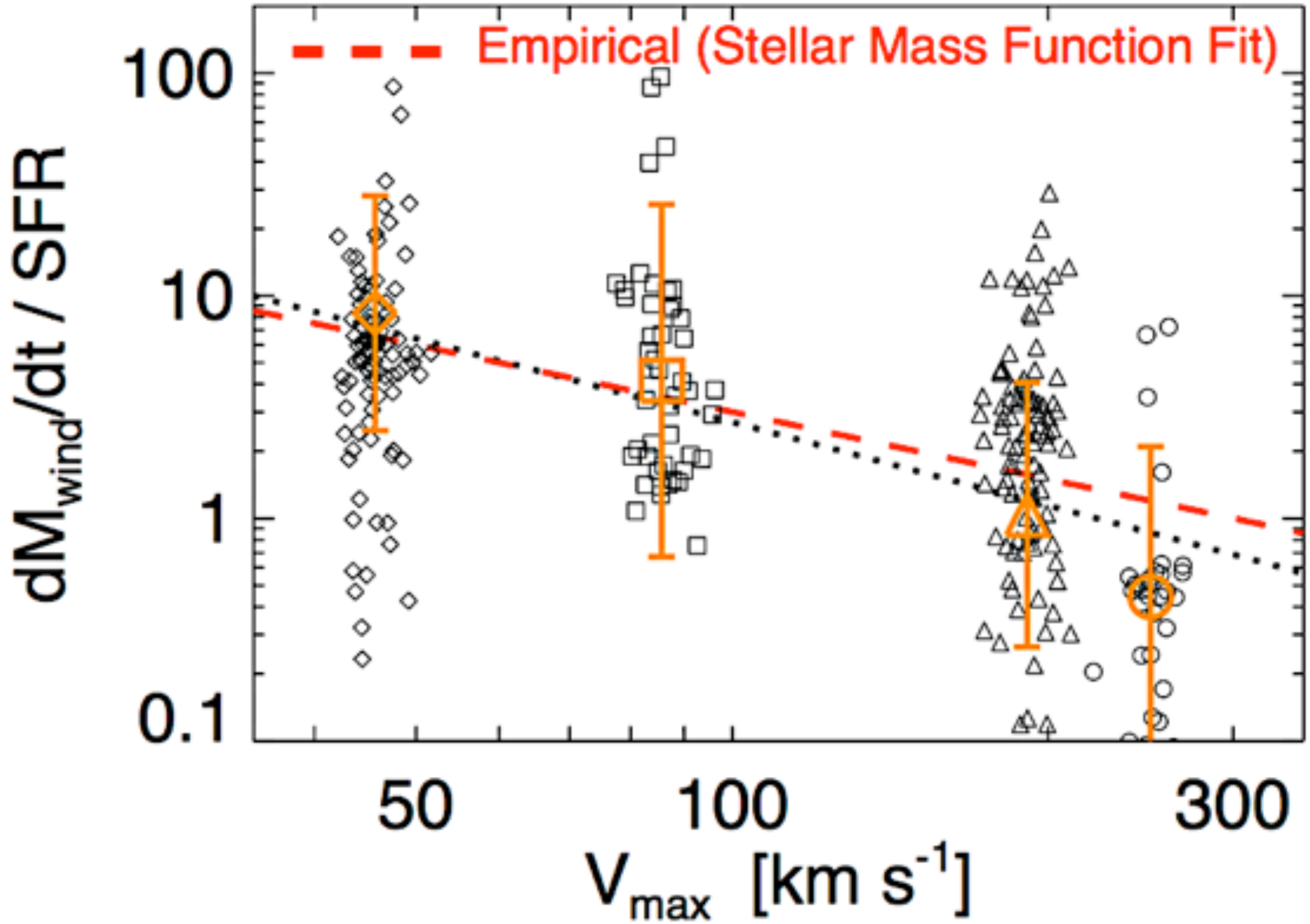


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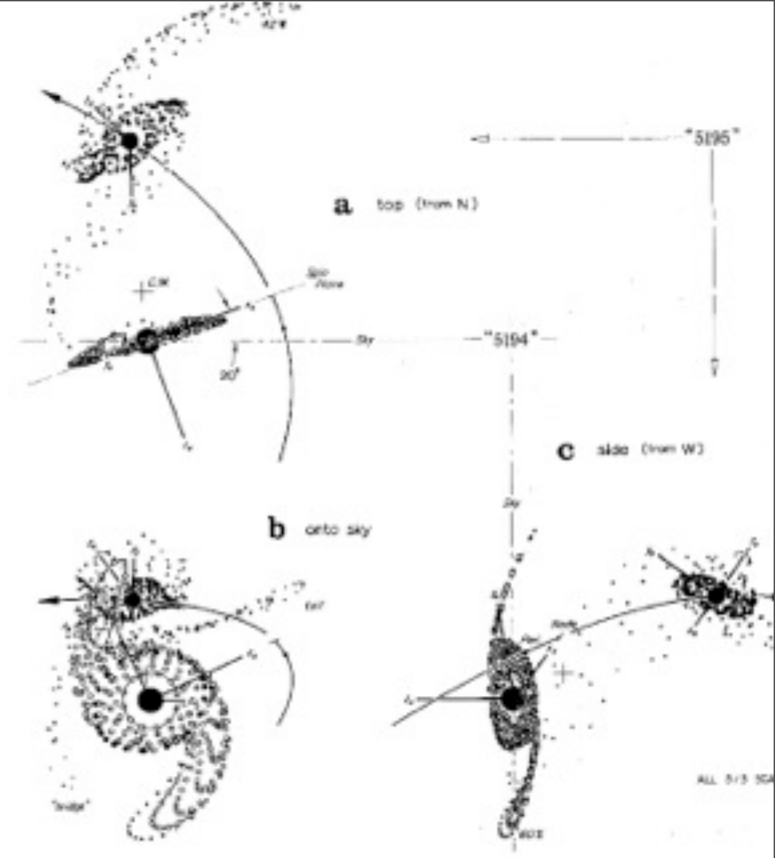
# What Happens when Galaxies Interact?

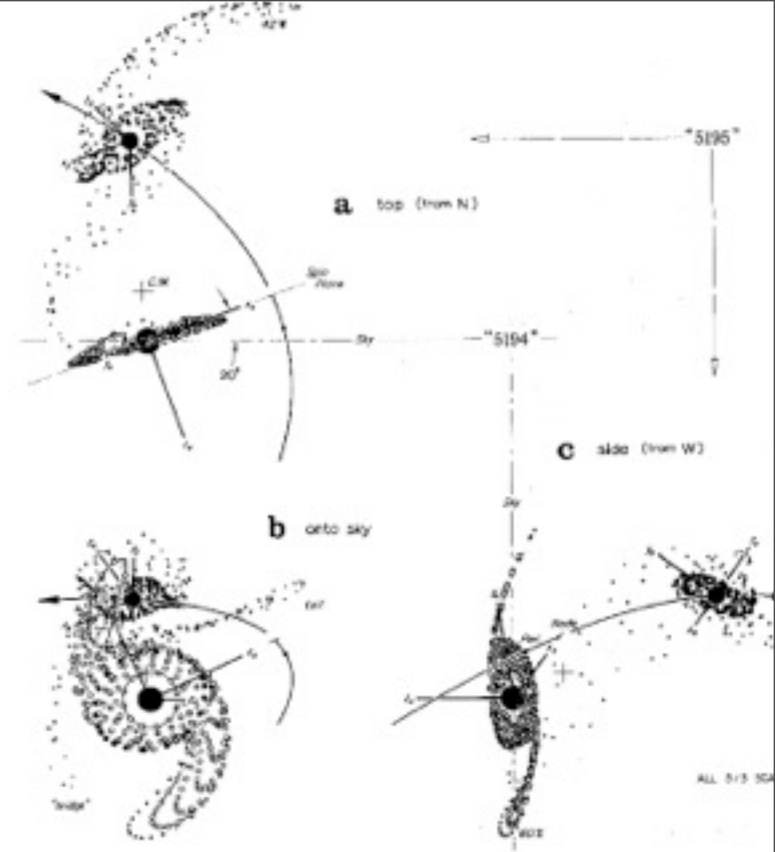
# Our Conventional Wisdom (Toomre):




F. Summers

# Our Conventional Wisdom (Toomre):

- Major mergers destroy disks

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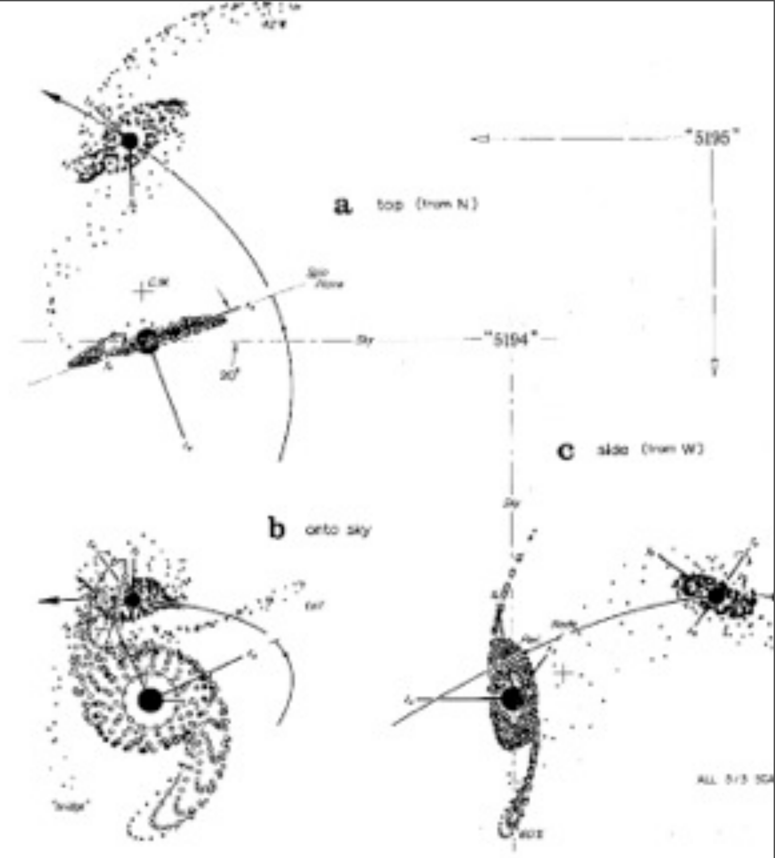
- Remnant size/metallicity/shape retains “memory” of disk “initial conditions”

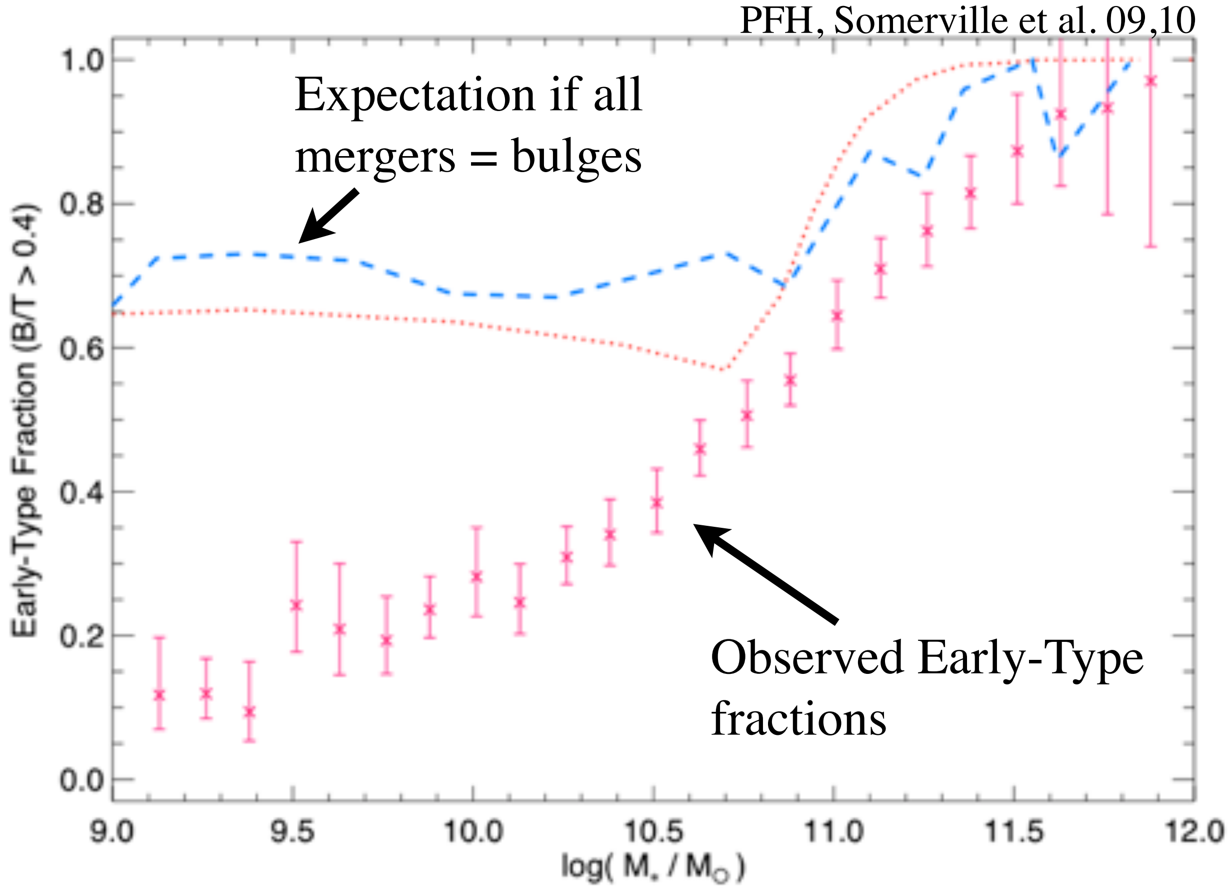



F. Summers

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

Too Many Mergers?

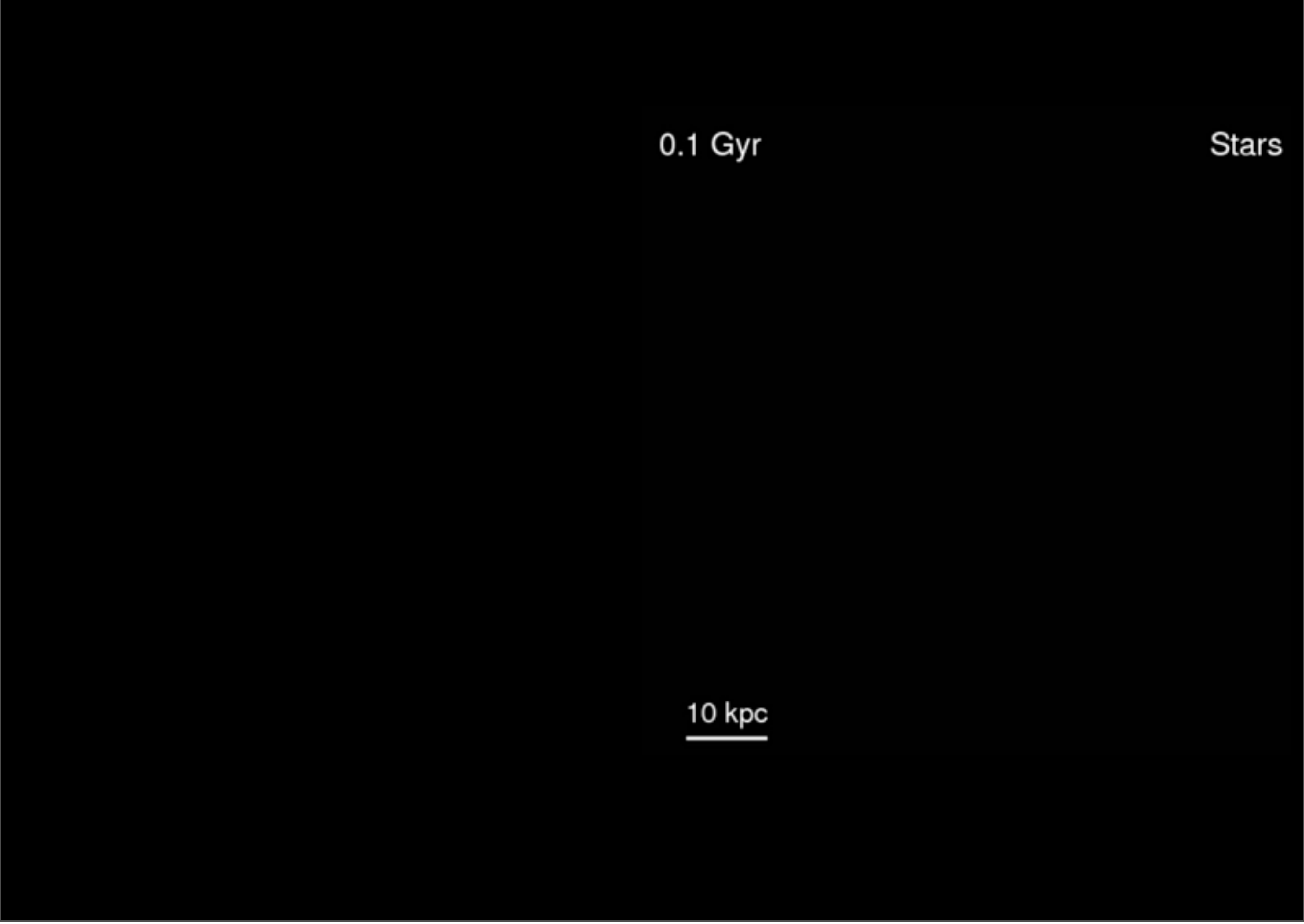
-- missing key physics?




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

# Milky Way (~5% Gas) Merger

# Starburst Galaxy (Gas-Rich) 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
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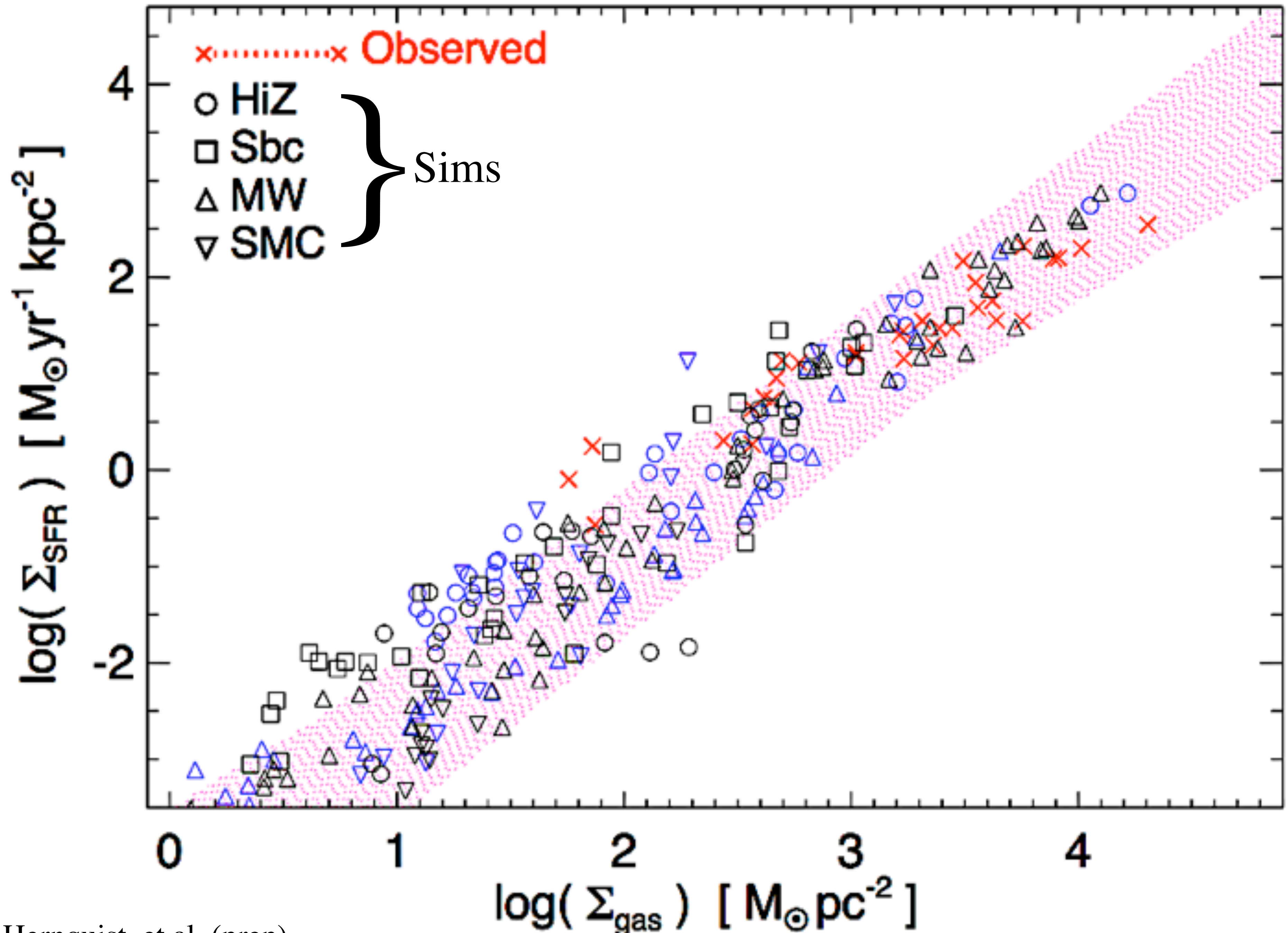


PFH, Hernquist, et al. (prep)

# Galaxy Mergers

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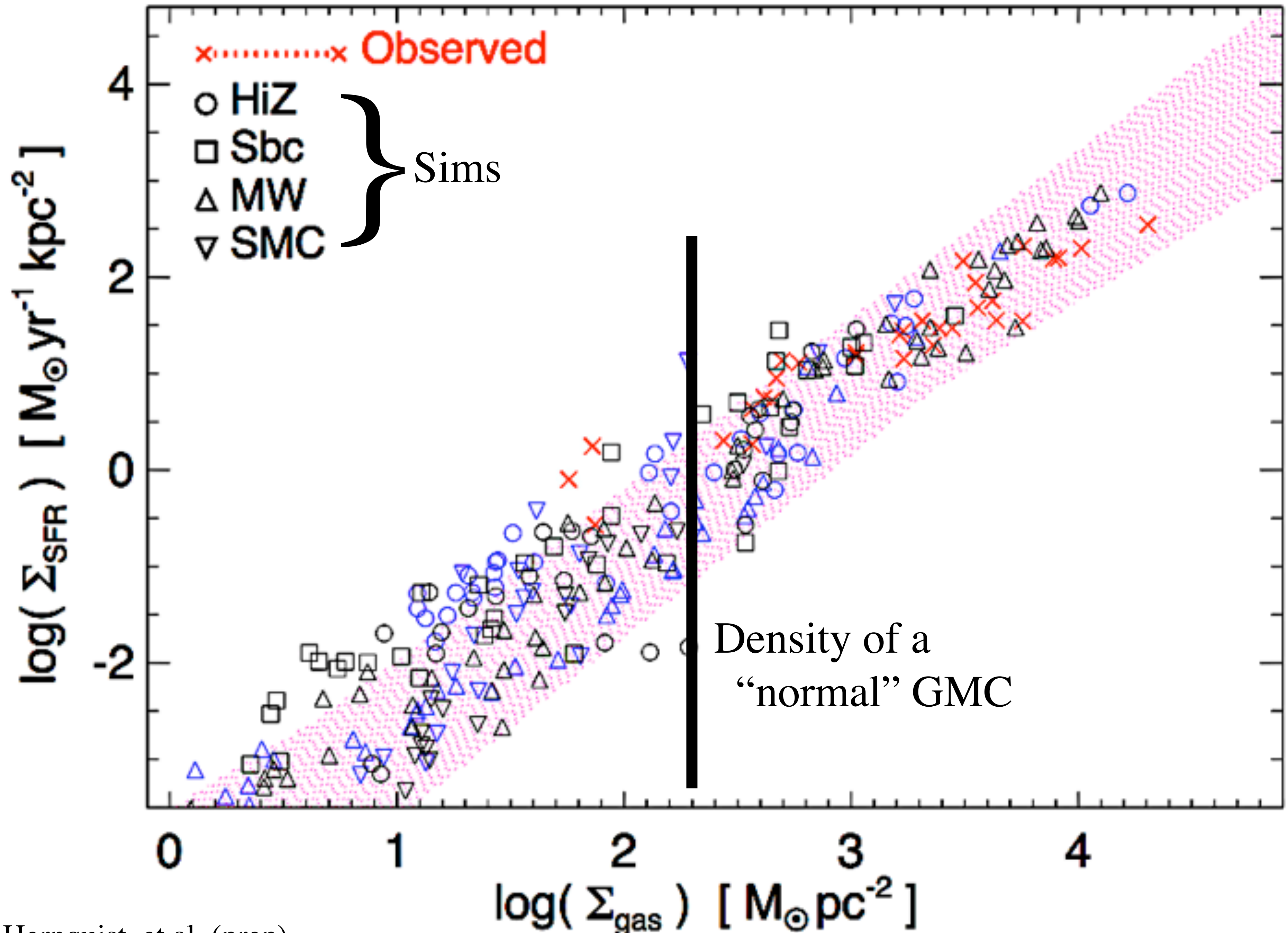
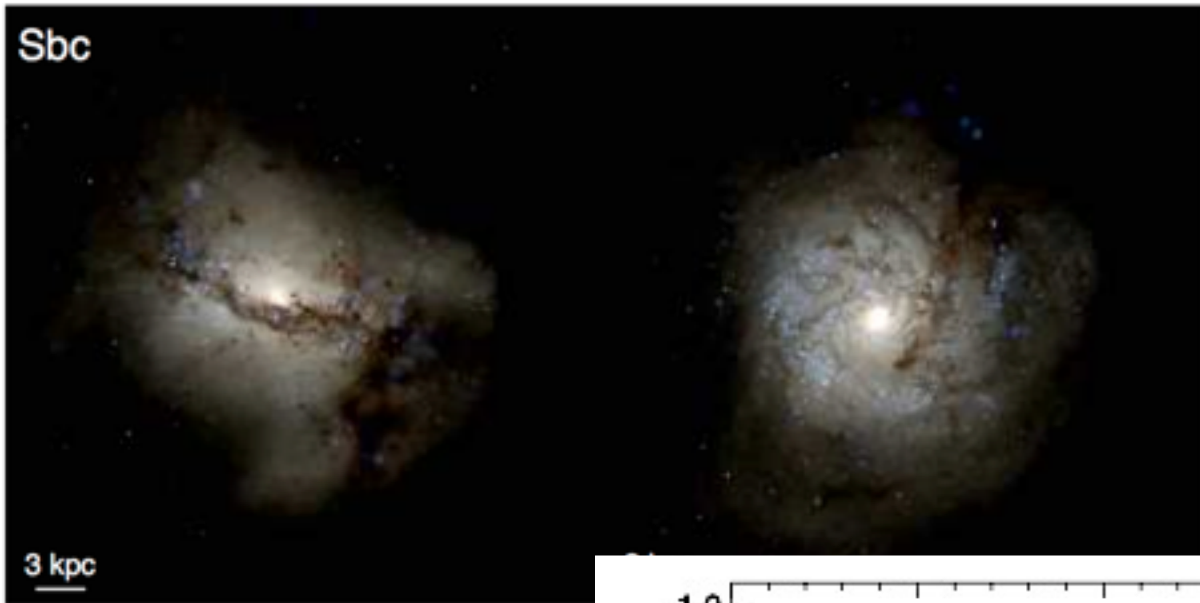



PFH, Hernquist, et al. (prep)

# Disks can Survive & Re-Form After Mergers

## NOT AS FRAGILE AS WE THOUGHT!

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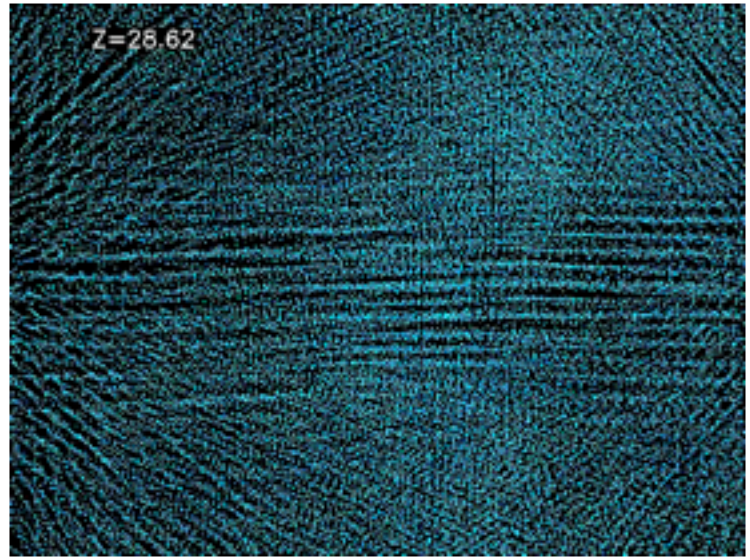


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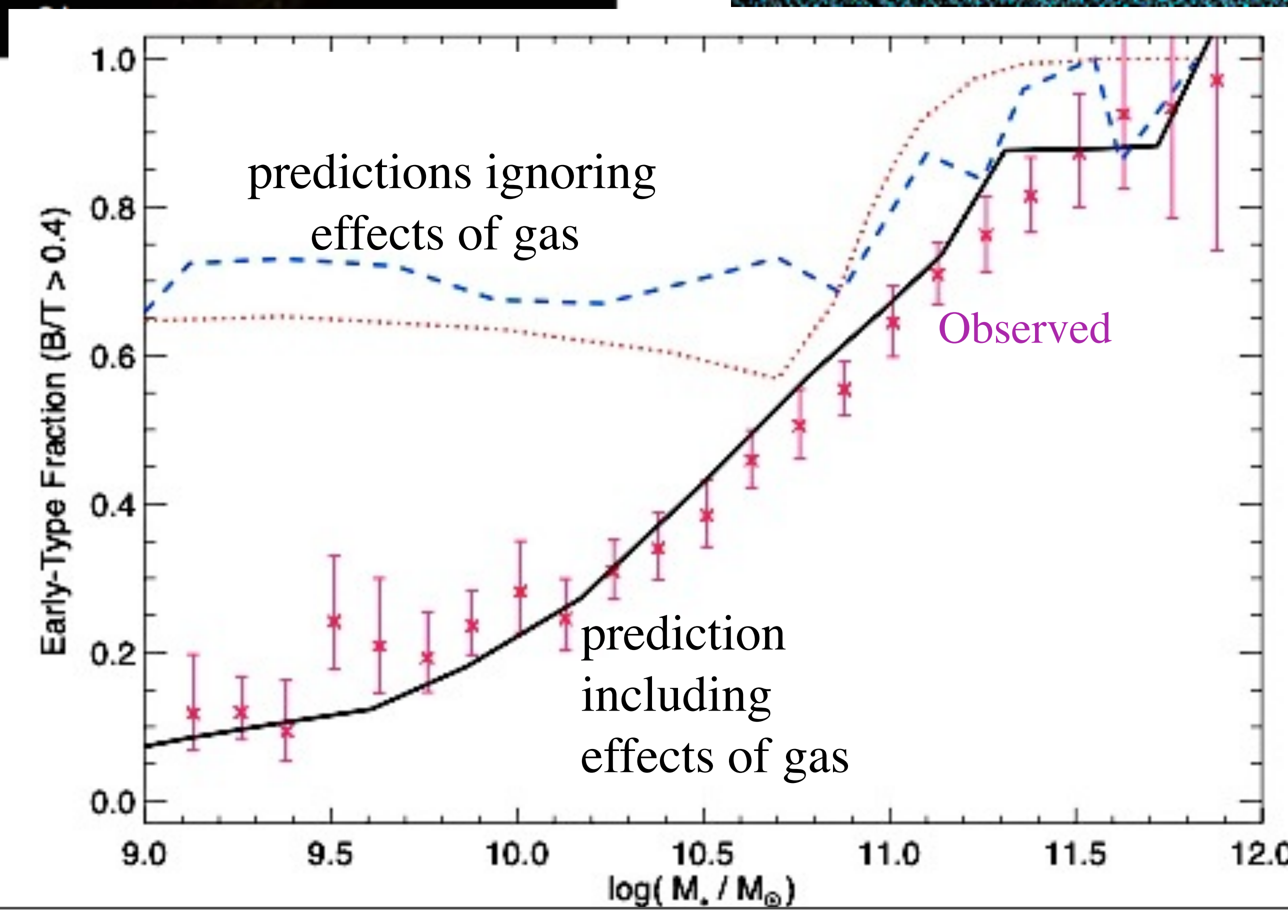
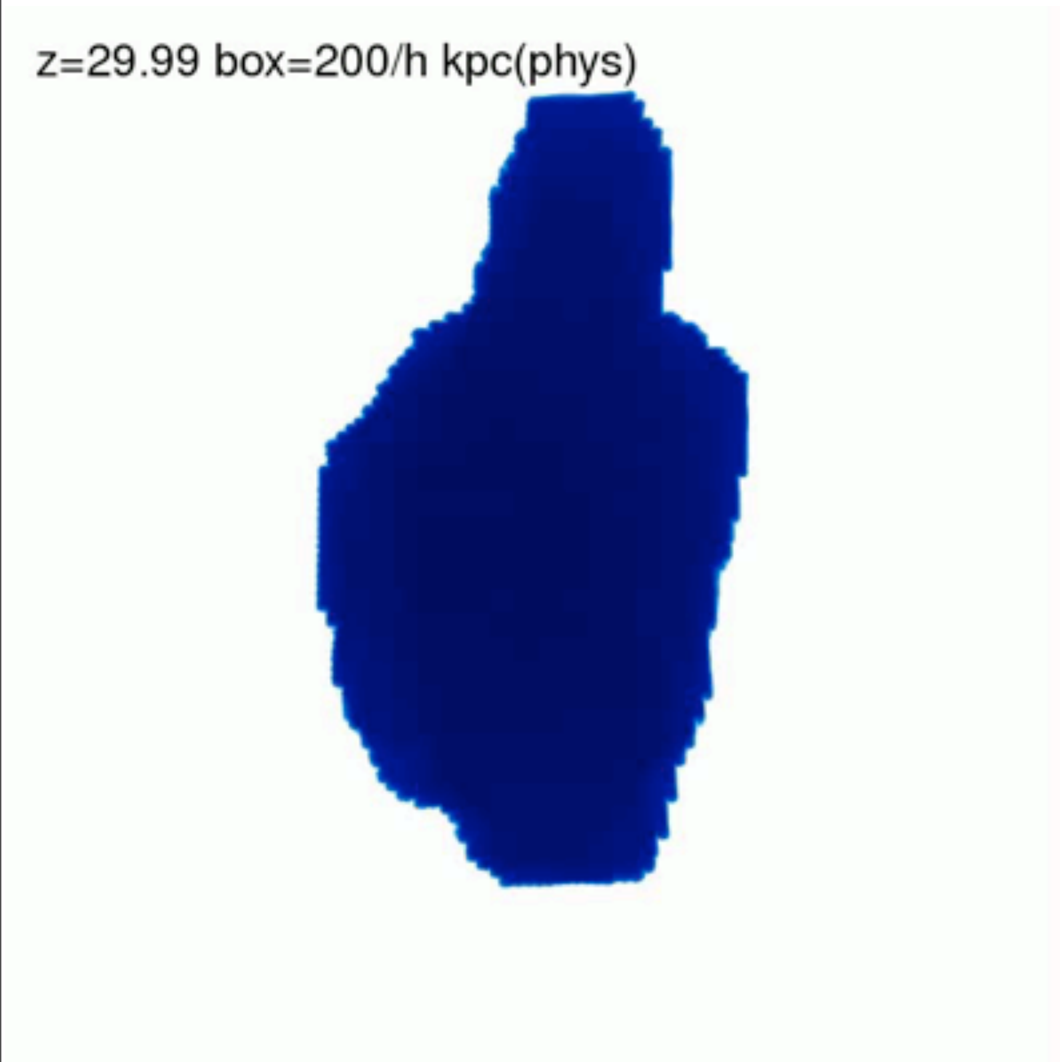



**PFH & Somerville et al. 2009**

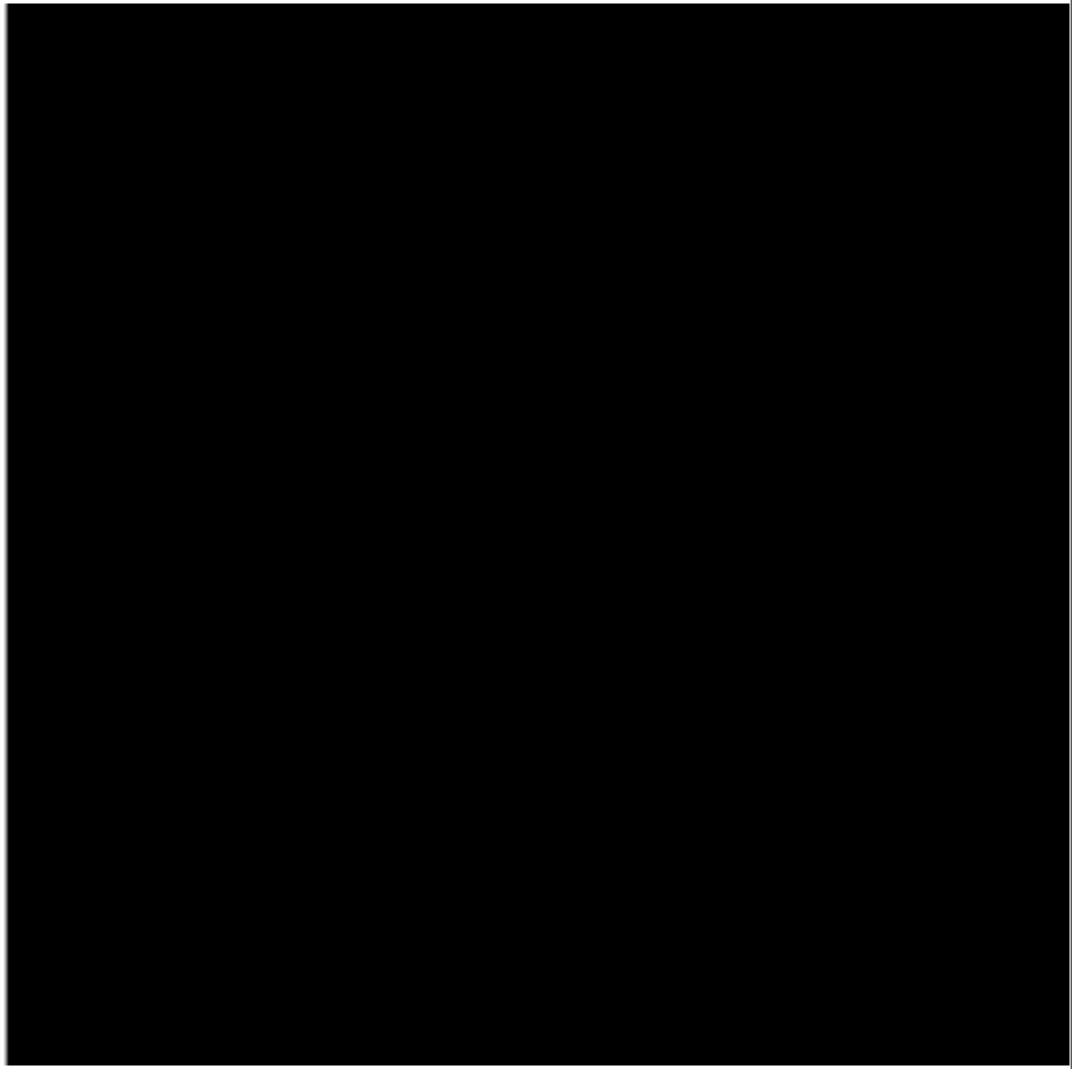
# High Redshifts & The Inflow/Outflow Cycle

# Cosmological Simulations

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




IGM Density

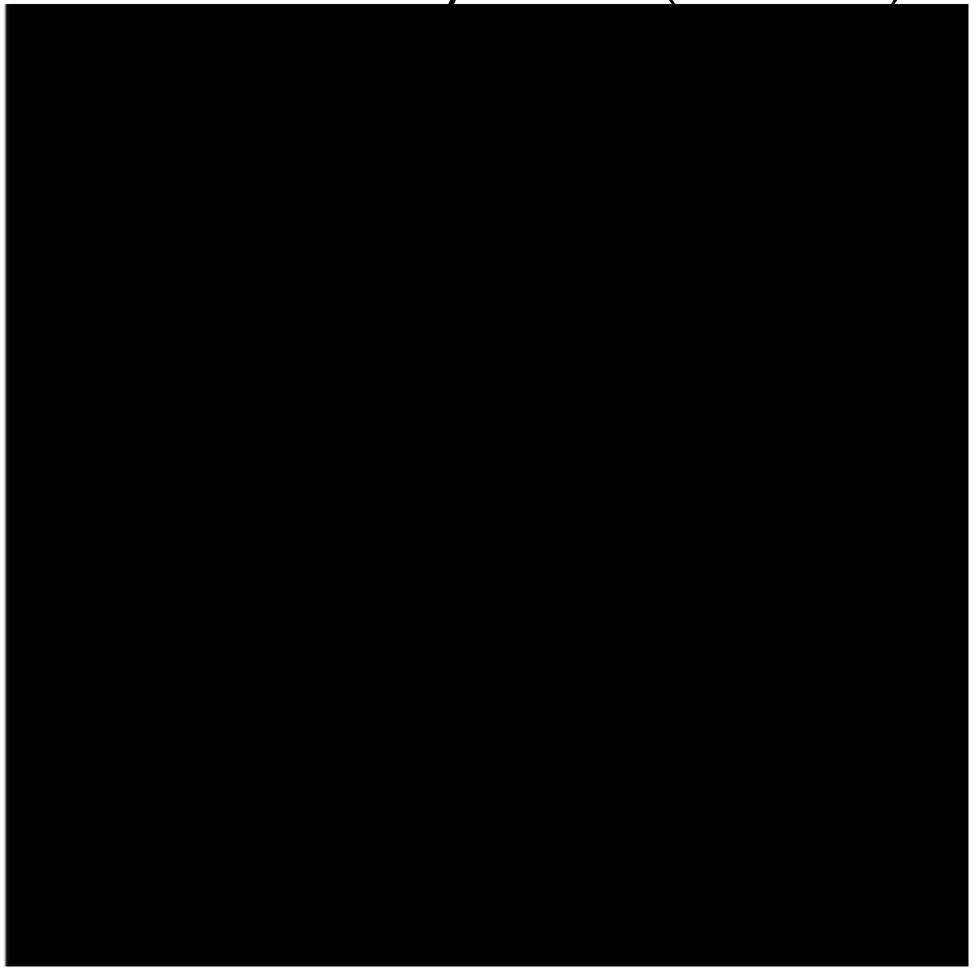


IGM Temperature

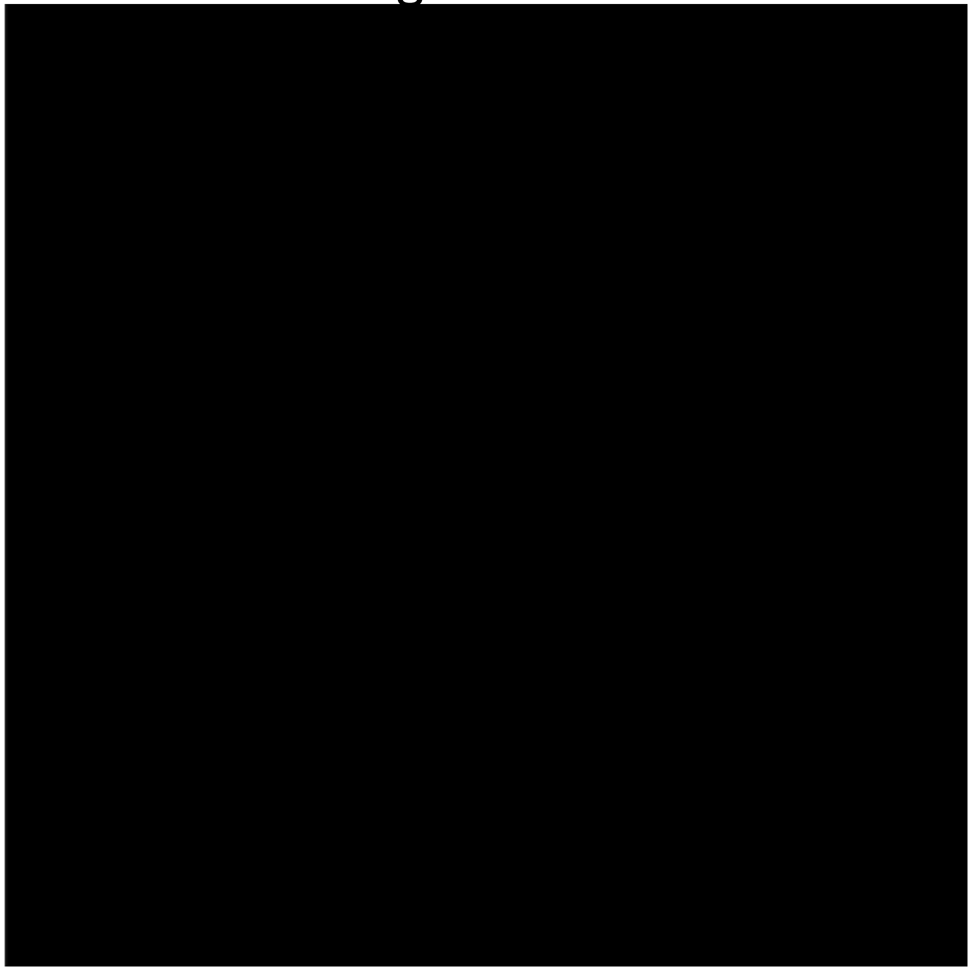
**PFH & Keres et al**

# Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)



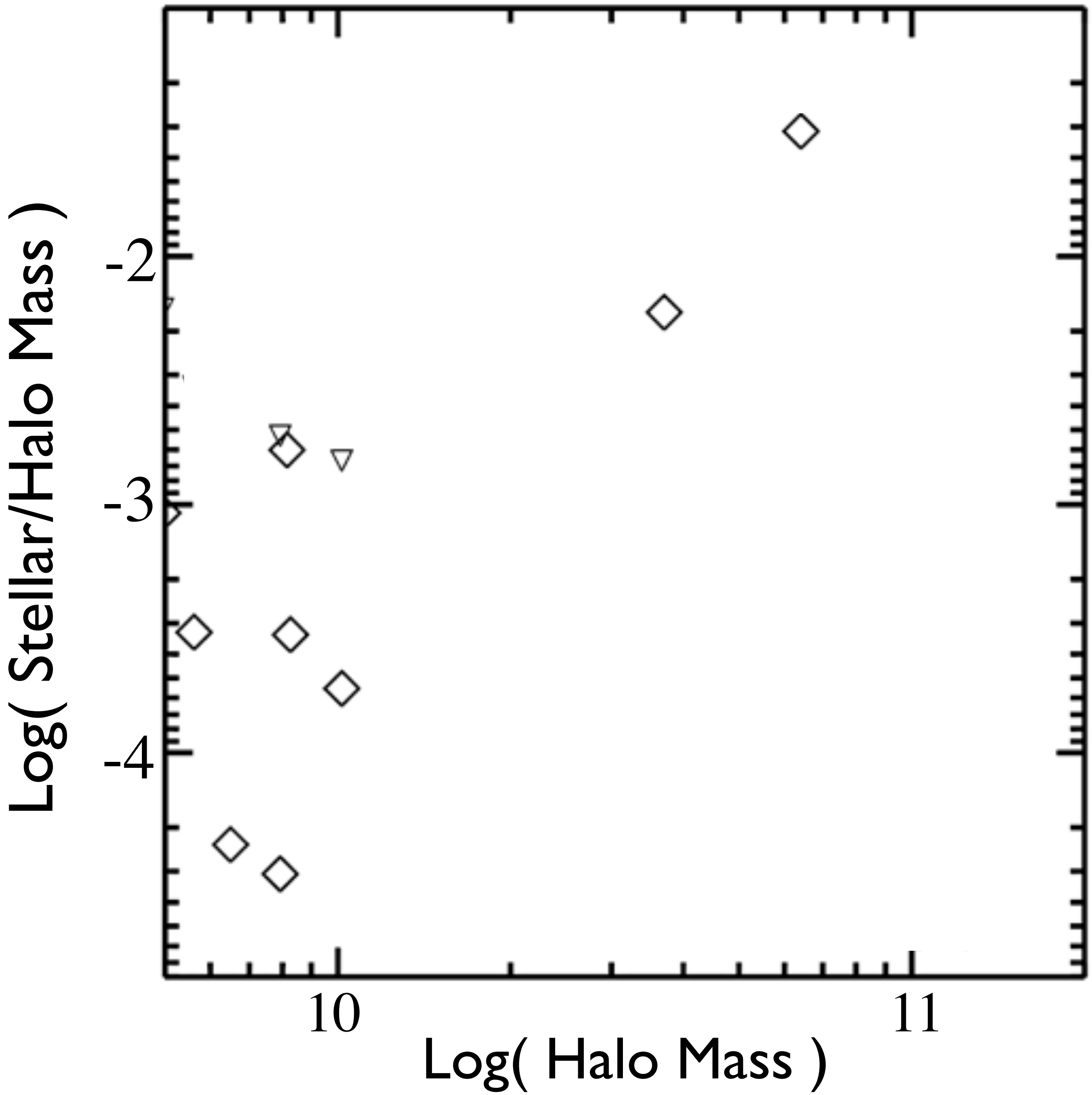
Following Full Feedback



**PFH & Keres et al**

## *Should* Galaxy Formation be Inefficient?

HOW DO THESE WINDS CHANGE OUR PICTURE?




**PFH & Keres et a**

**PFH, Bullock,**
**& Onorbe et a**

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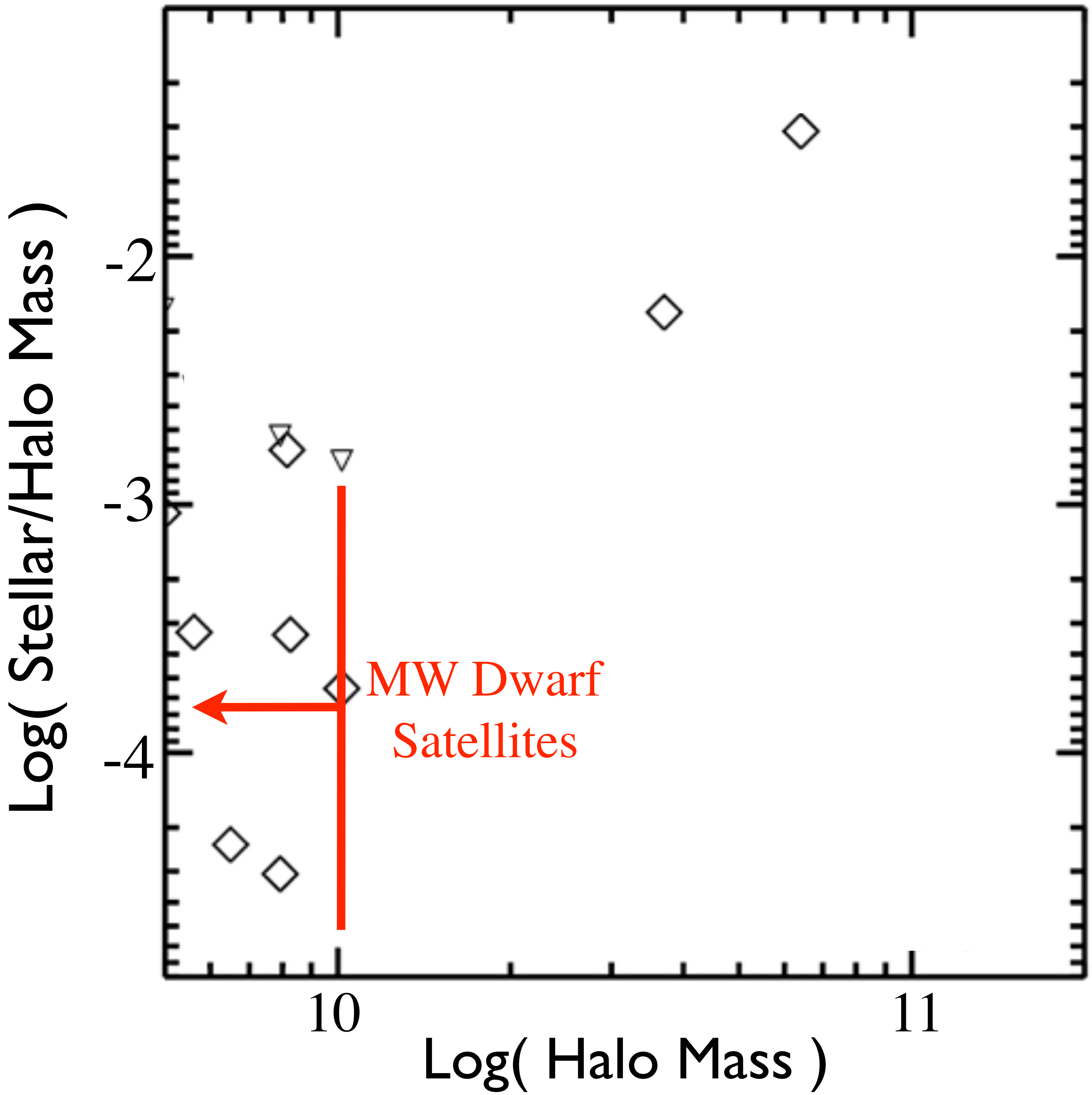


PFH & Keres et a
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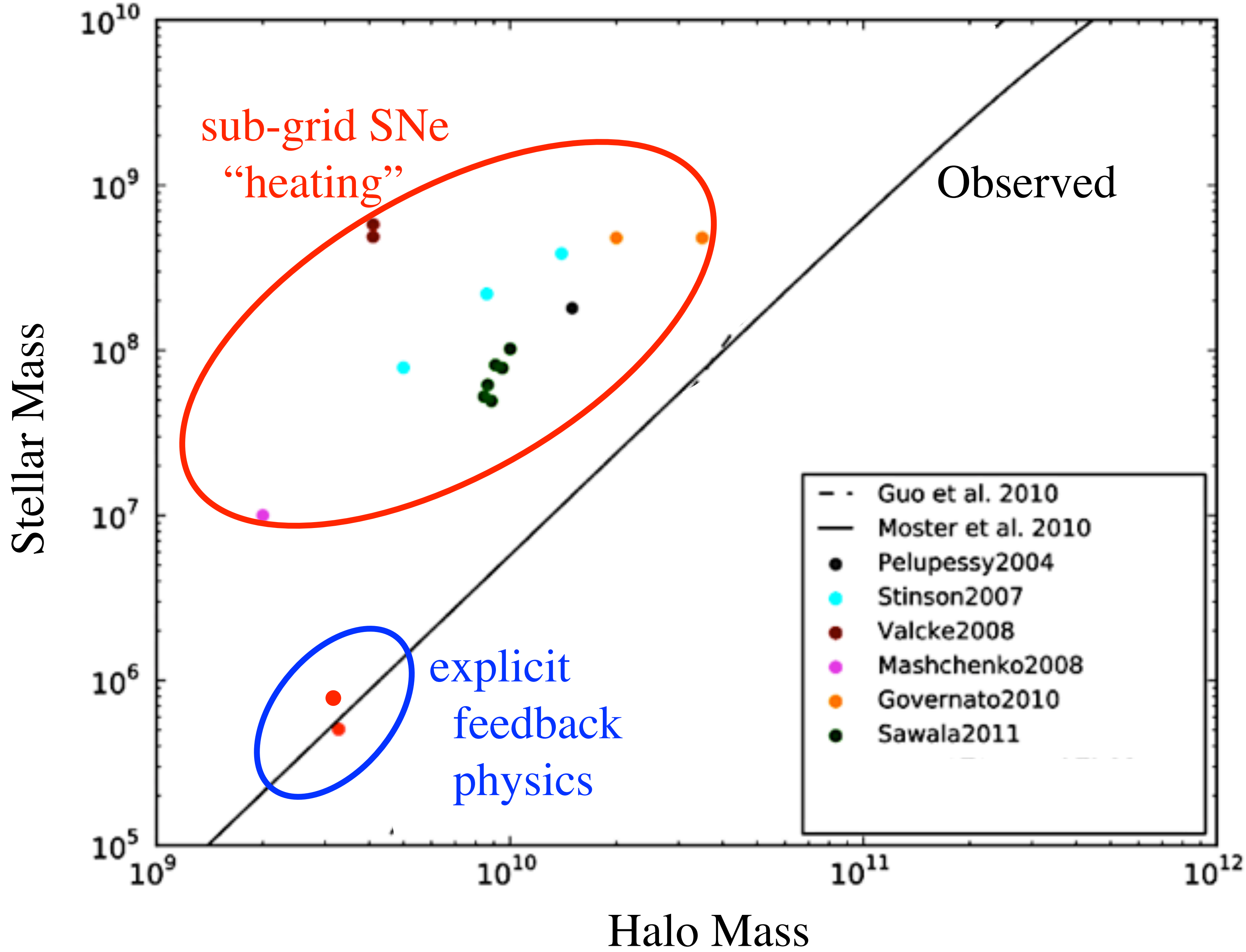
## *Should* Galaxy Formation be Inefficient?

WHAT CAN WE LEARN ABOUT COSMOLOGY AND STRUCTURE FORMATION?

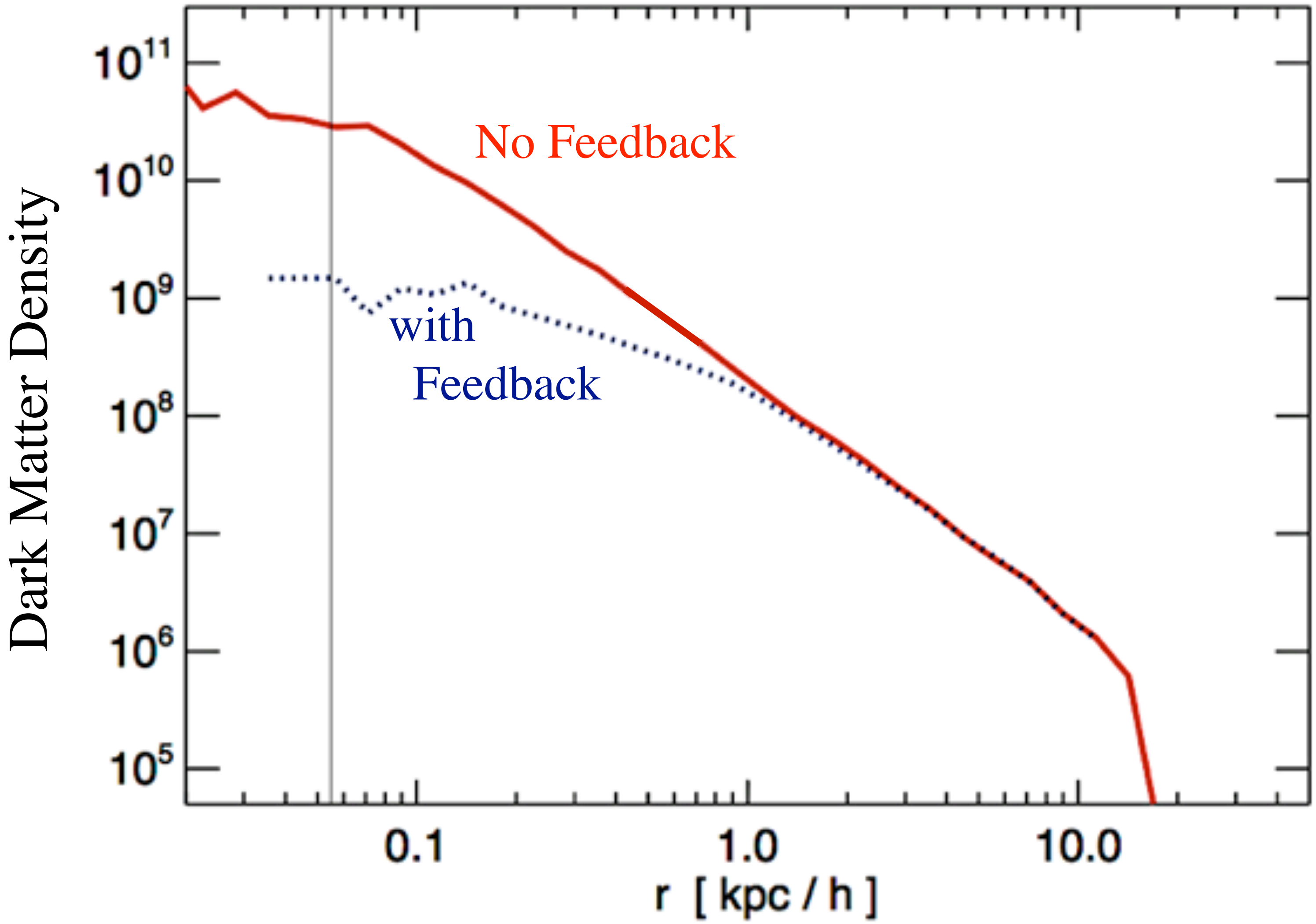



PFH & Keres et a

PFH, Bullock,
& Onorbe et a

# Dark Matter Profiles: Baryons or Cosmology?

WHAT CAN WE LEARN ABOUT COSMOLOGY AND STRUCTURE FORMATION?

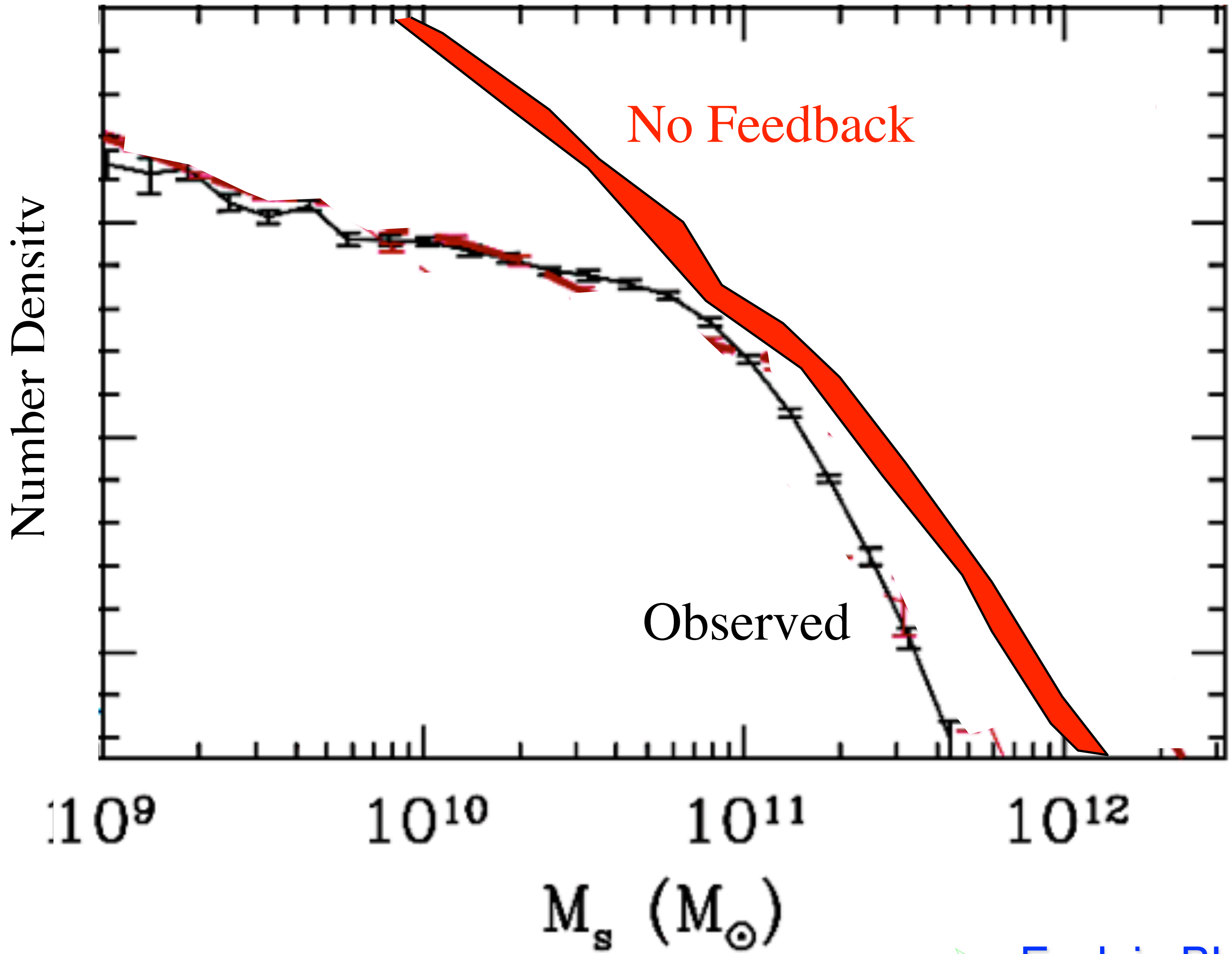



PFH & Keres et a

PFH, Bullock,
& Onorbe et a

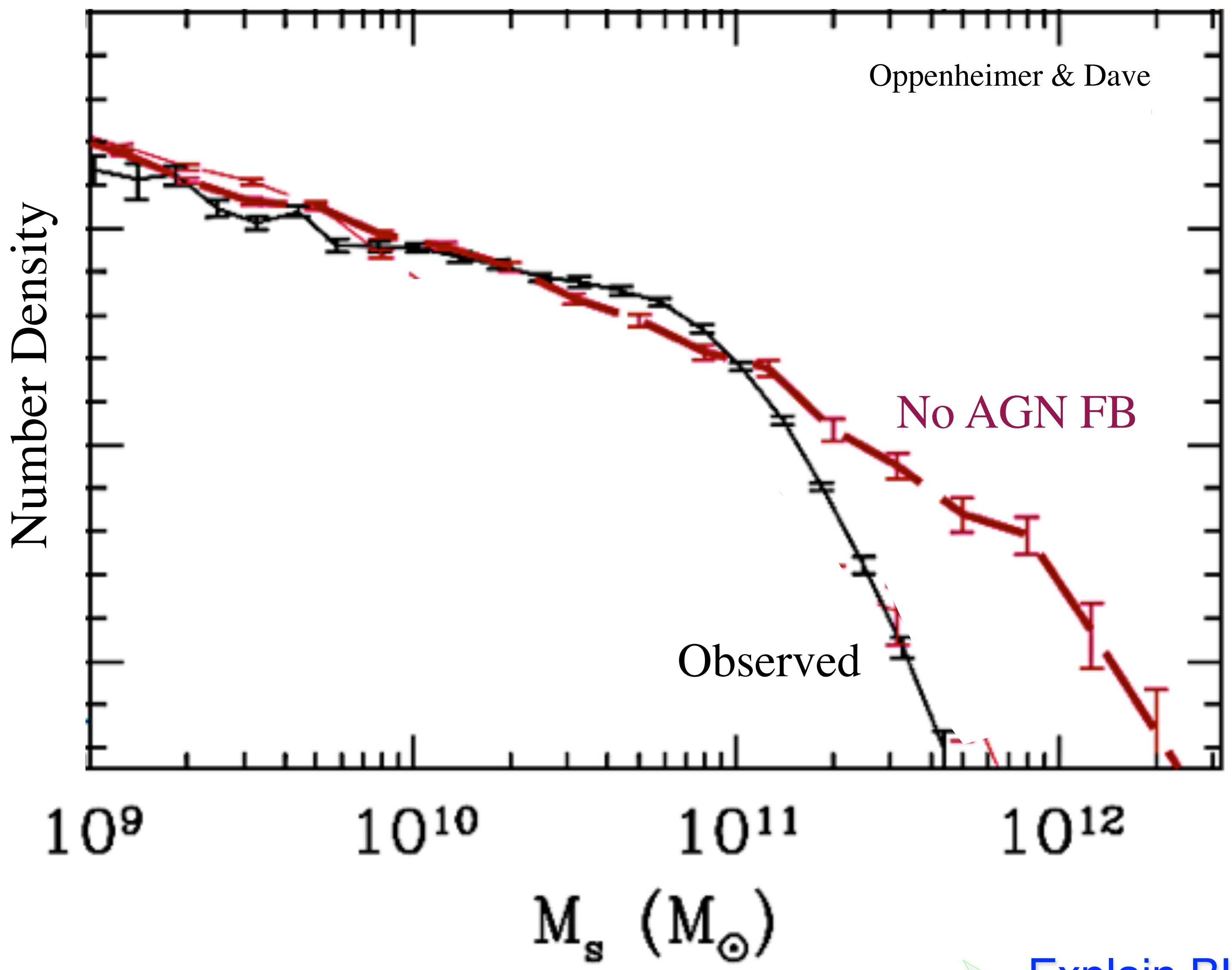
## What About High-Mass Galaxies?

# Why Do We Need AGN Feedback?




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

# Why Do We Need AGN Feedback?



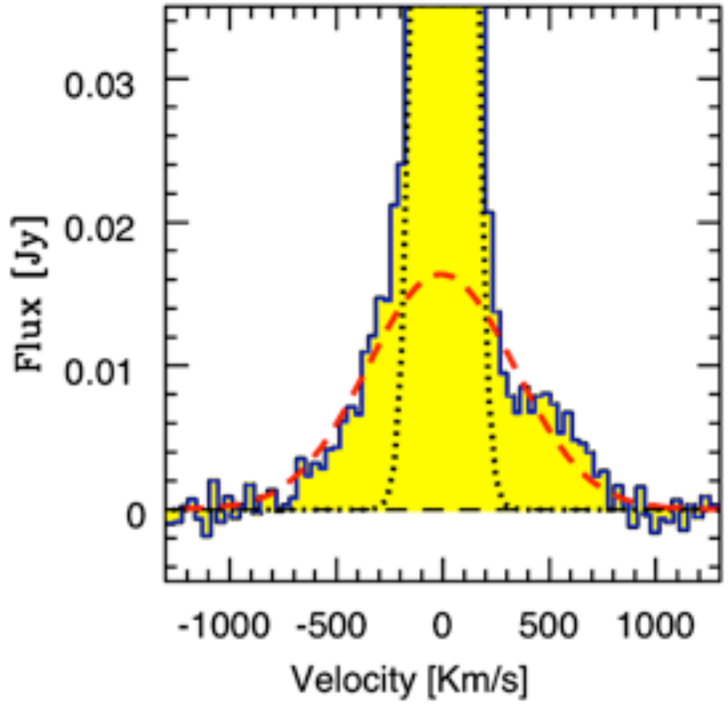

- Explain BH-host correlations
- Sharp color bimodality
- Removing/heating gas in groups

# Molecular Outflows in AGN & ULIRGs

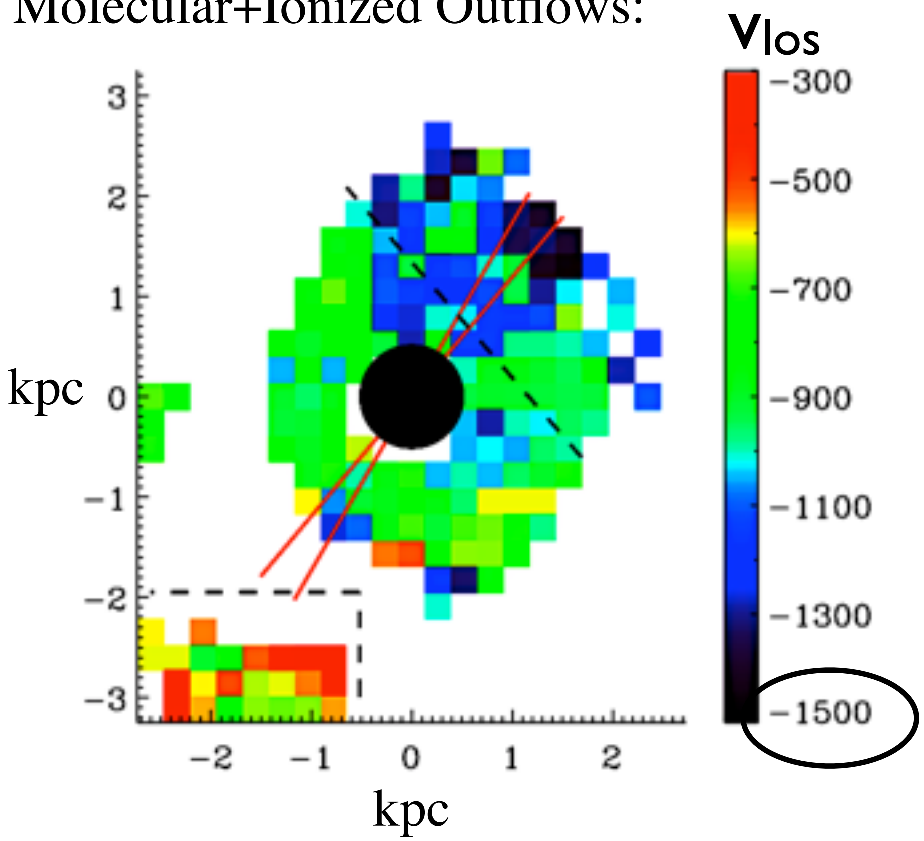
## OBSERVED WINDS at >1000 km/s

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

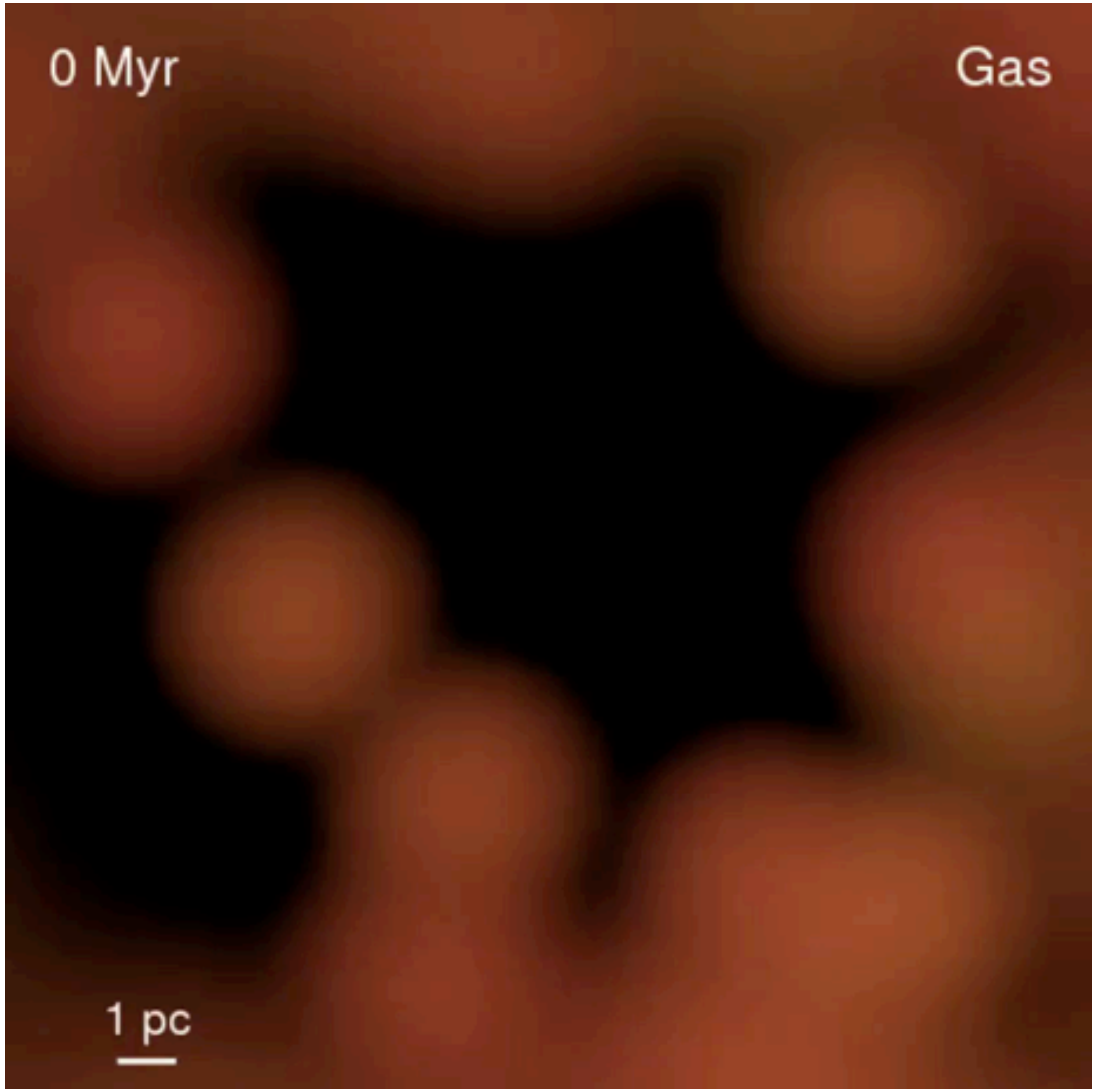
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

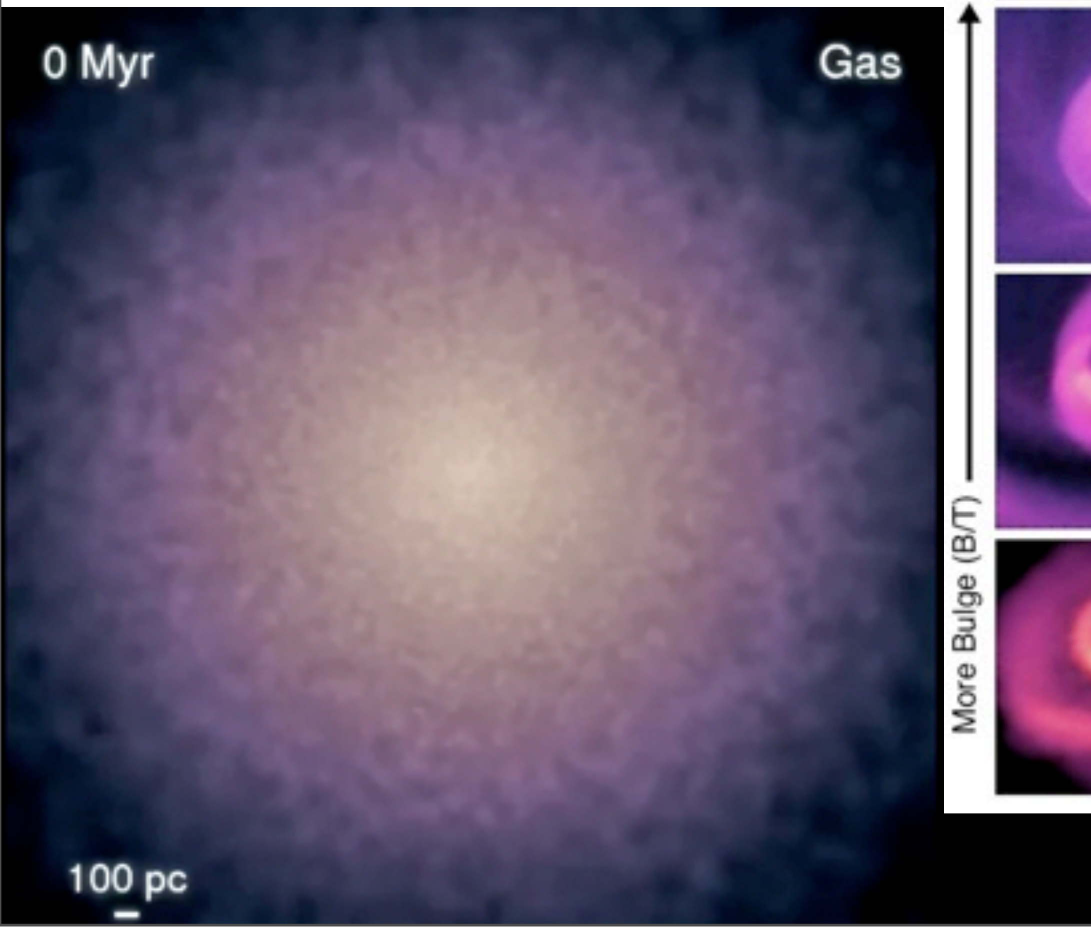
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

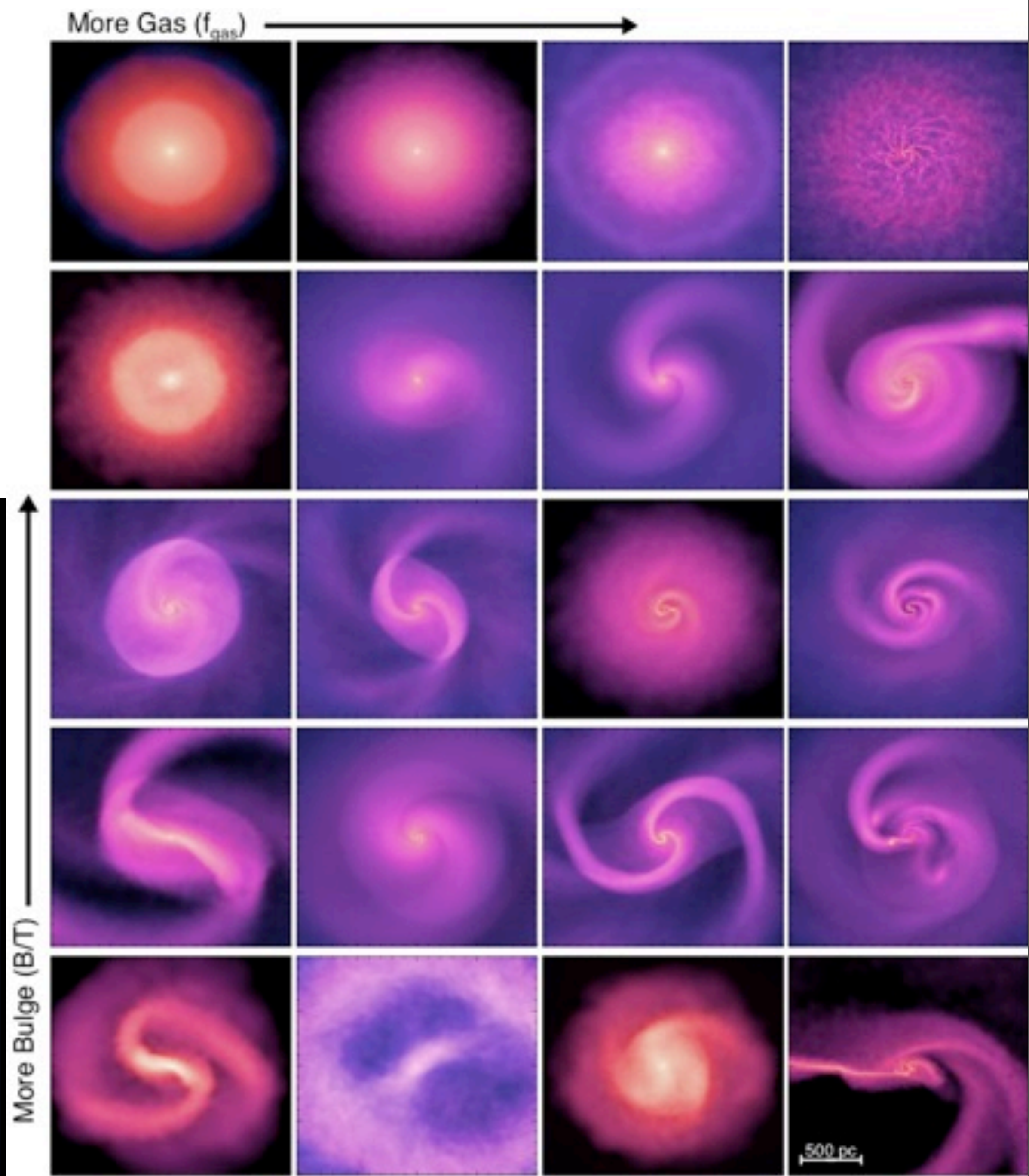


# Step 2: Inflow

- 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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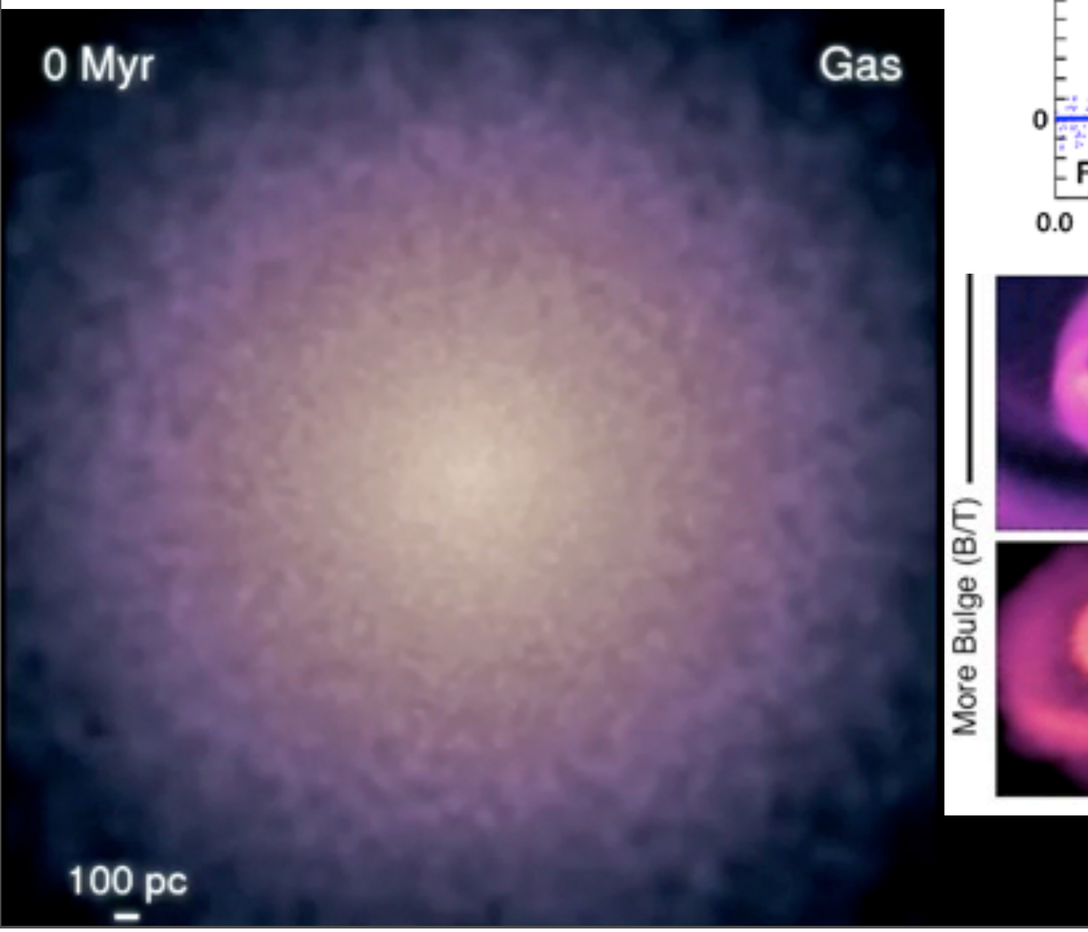
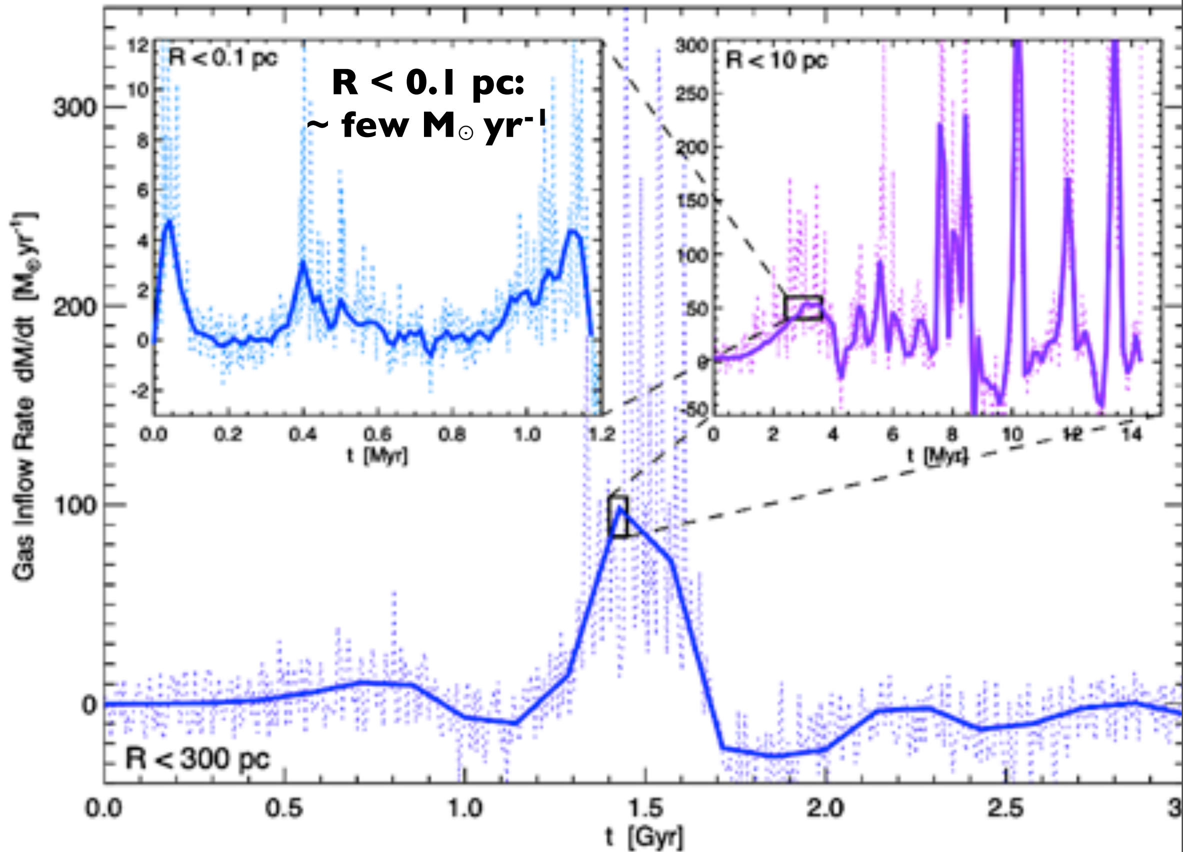
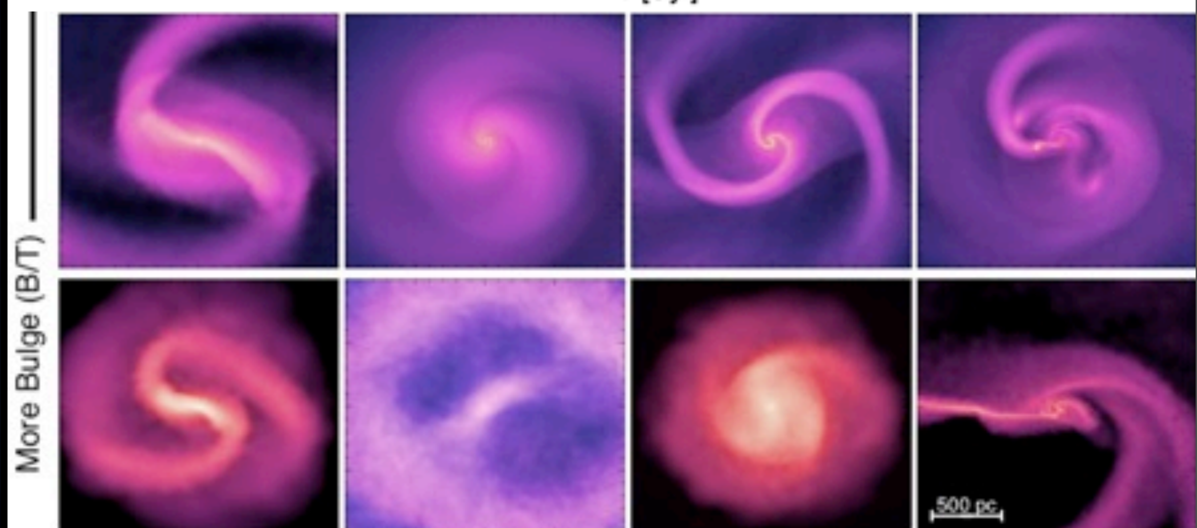
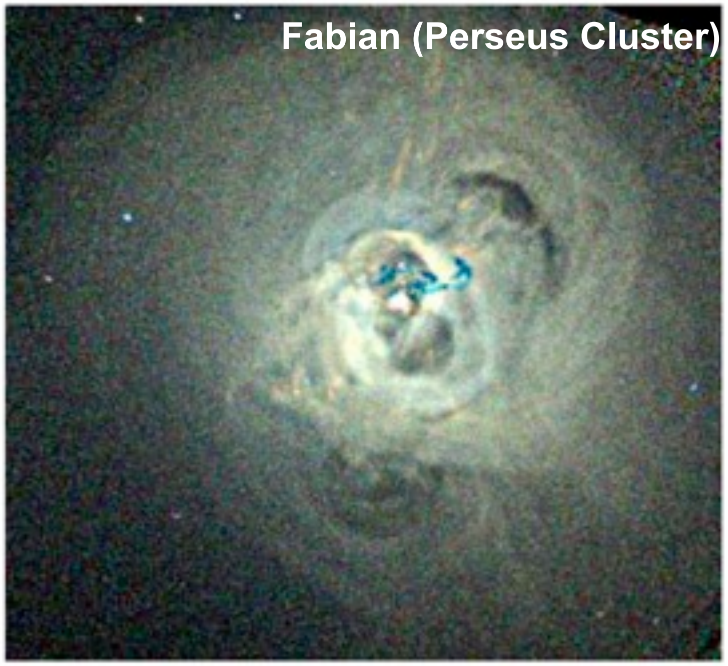


# Step 3: Observed Sources of AGN Feedback




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

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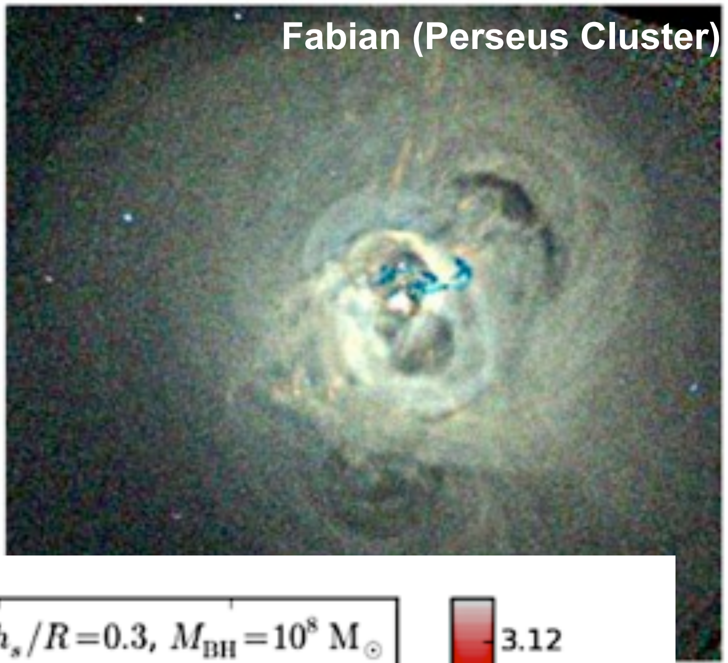
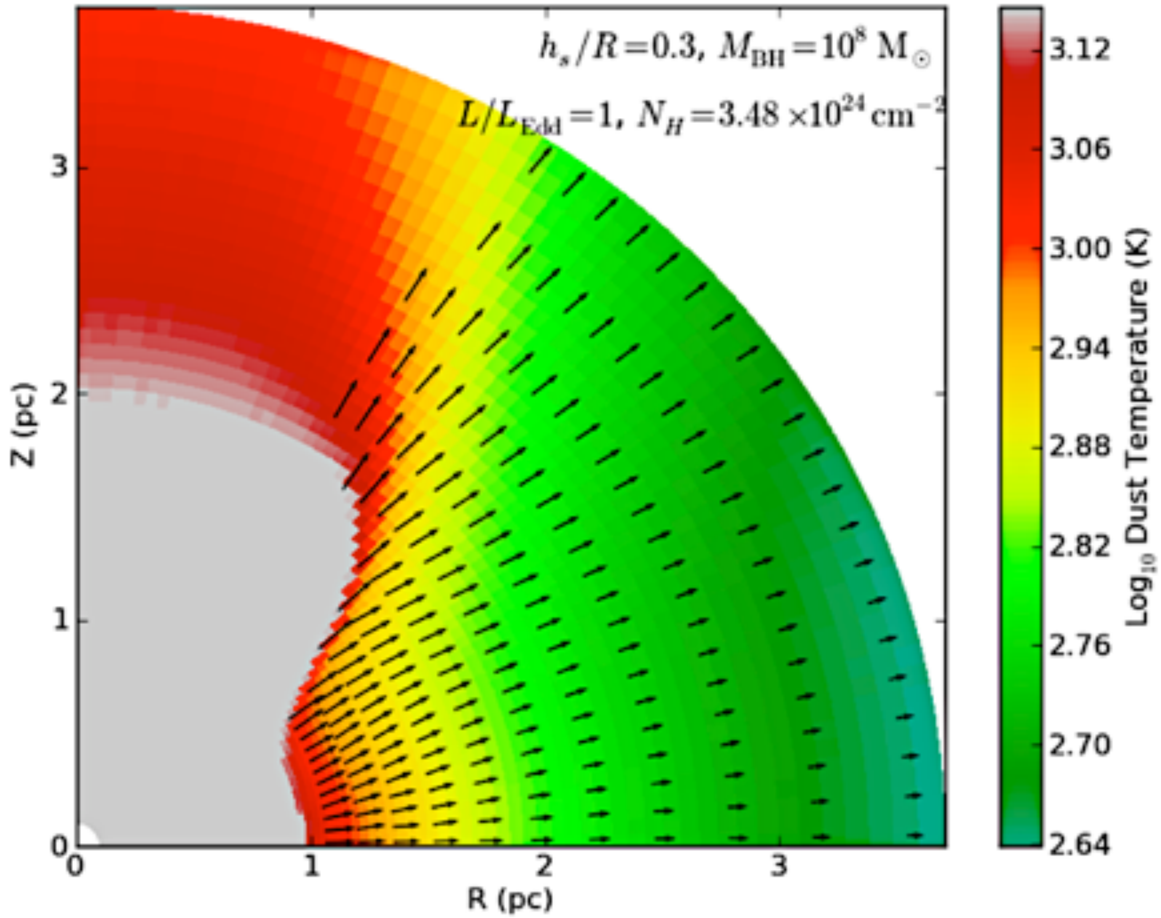
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$




Roth, Kasen, Quataert, PFH in prep

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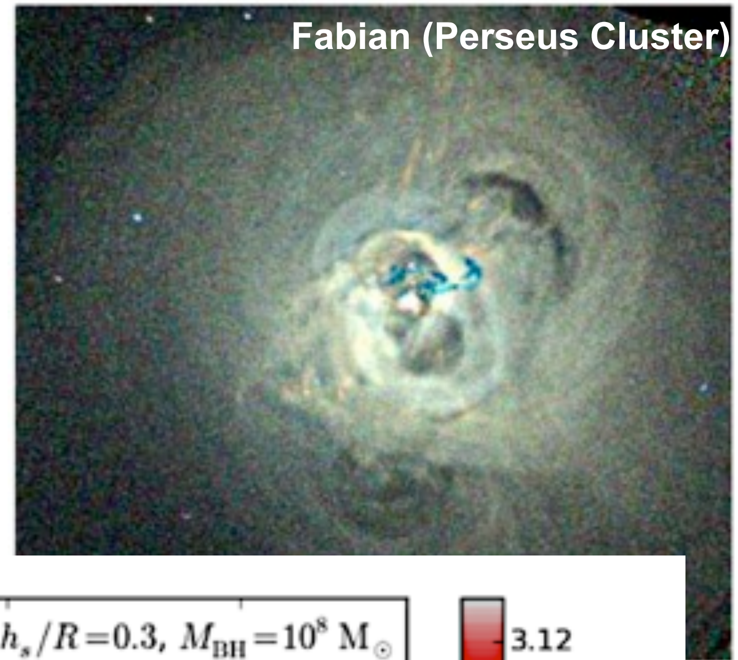
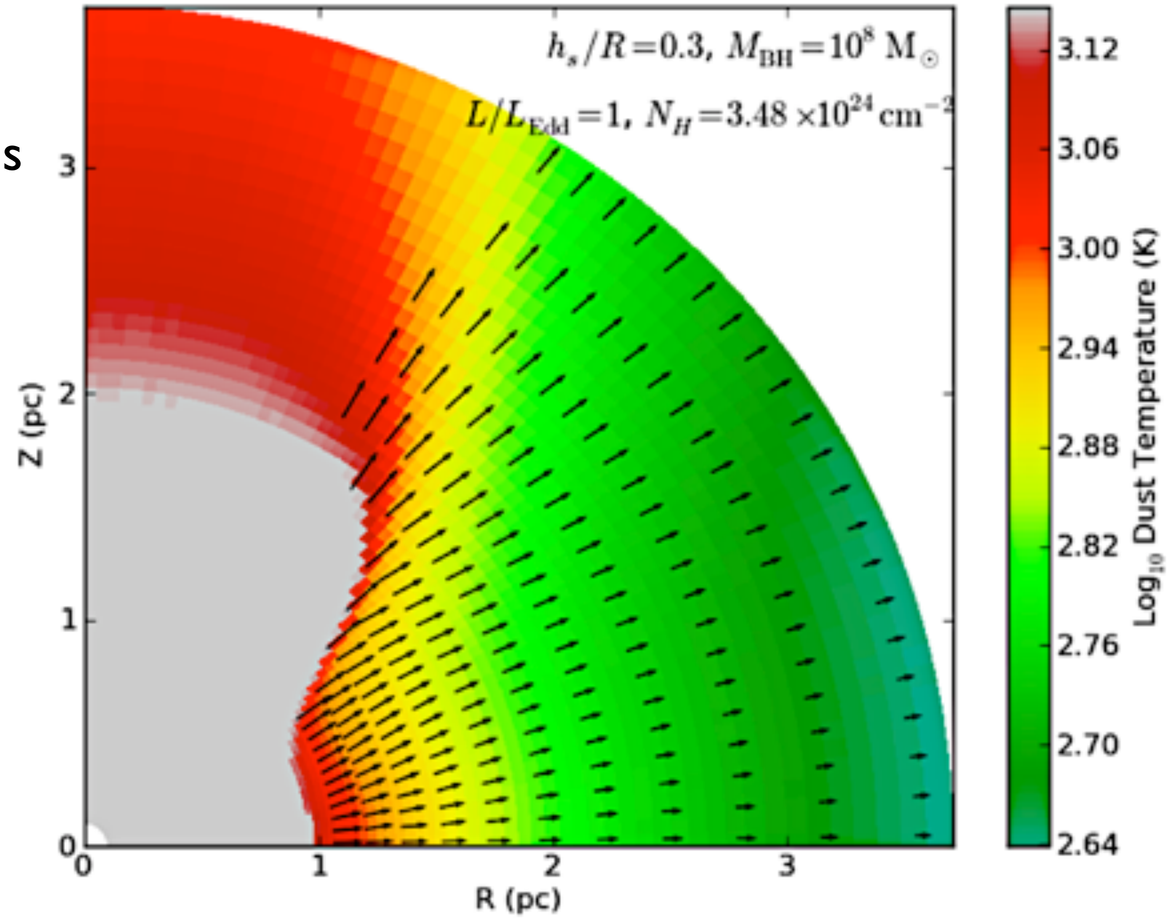



- Jets
  - heat IGM/ICM (low-density), but not dense ISM
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$
- Accretion Disk Winds
  - Broad Absorption Line Winds


Roth, Kasen, Quataert, PFH in prep

# Summary:

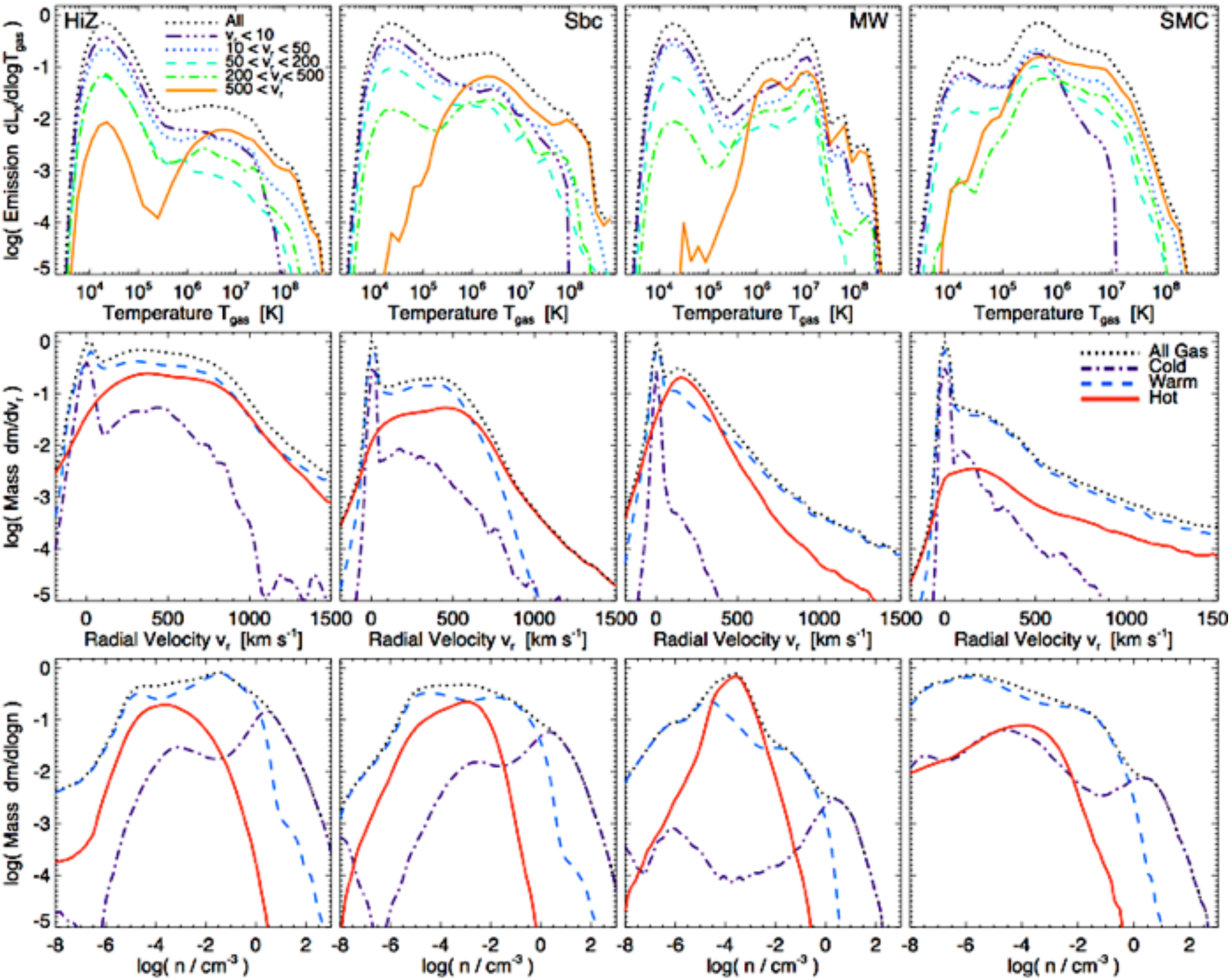
- **Star formation is Feedback-Regulated**: *independent* of small-scale SF 'law'
    - Need enough stars to offset dissipation (gravity)
    - Leads to Kennicutt relation & **super-winds**

- Different mechanisms dominate different regimes:
  - High-r: radiation pressure
  - Intermediate: HII heating, stellar wind momentum
  - Low-r: SNe & stellar wind shock-heating
    - **No *one* mechanism works**

- Mergers: Extreme laboratory (>100x GMC densities!)
  - **Efficient disk survival**
  - Super-winds: ~10-500 $M_{sun}$/yr

- Cosmologically: *Not* just top-down inflows:
  - Winds determine **IGM enrichment, temperature, & subsequent inflow** structure

- Most Massive Galaxies: Need "AGN" Feedback!
  - Disk Winds+Radiation Pressure+Jets: Explain $M_{BH}$-s & suppress SF


HiZ
Sbc
MW
SMC
All
$v_r$ < 10
10 < $v_r$ < 50
50 < $v_r$ < 200
200 < $v_r$ < 500
500 < $v_r$
log( Emission $dL_X/d\log T_{gas}$ )
Temperature $T_{gas}$ [K]
All Gas
Cold
Warm
Hot
log( Mass $dm/dv_r$ )
Radial Velocity $v_r$ [km $s^{-1}$]
log( Mass $dm/d\log n$ )
log( n / $cm^{-3}$ )