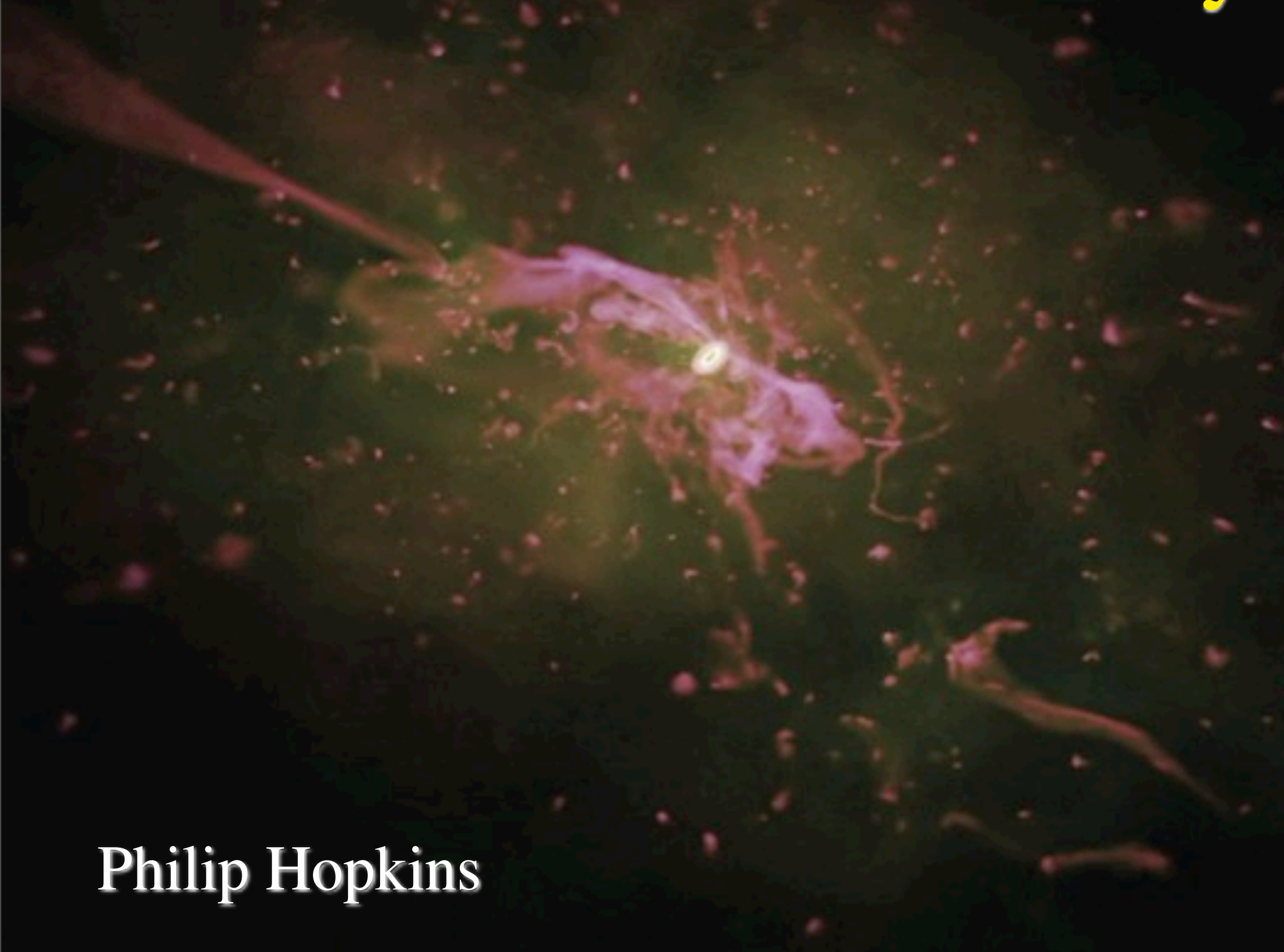
Milky Way

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

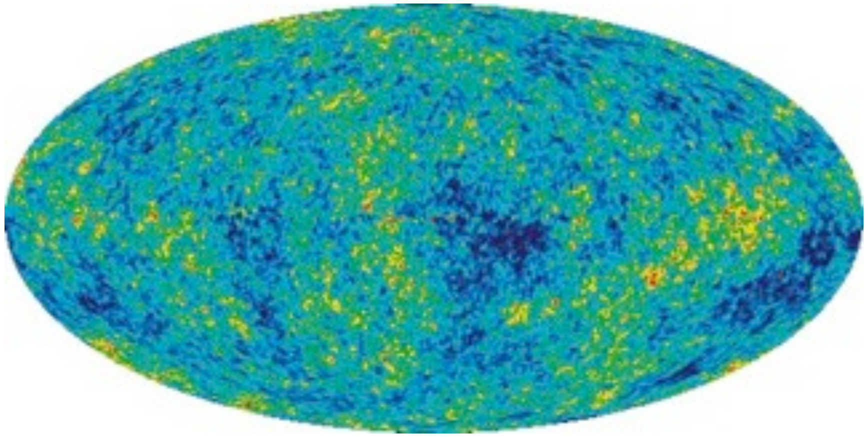
Overview

- (1) (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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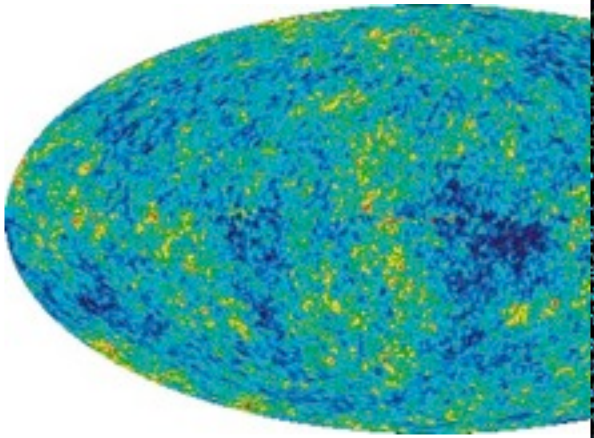

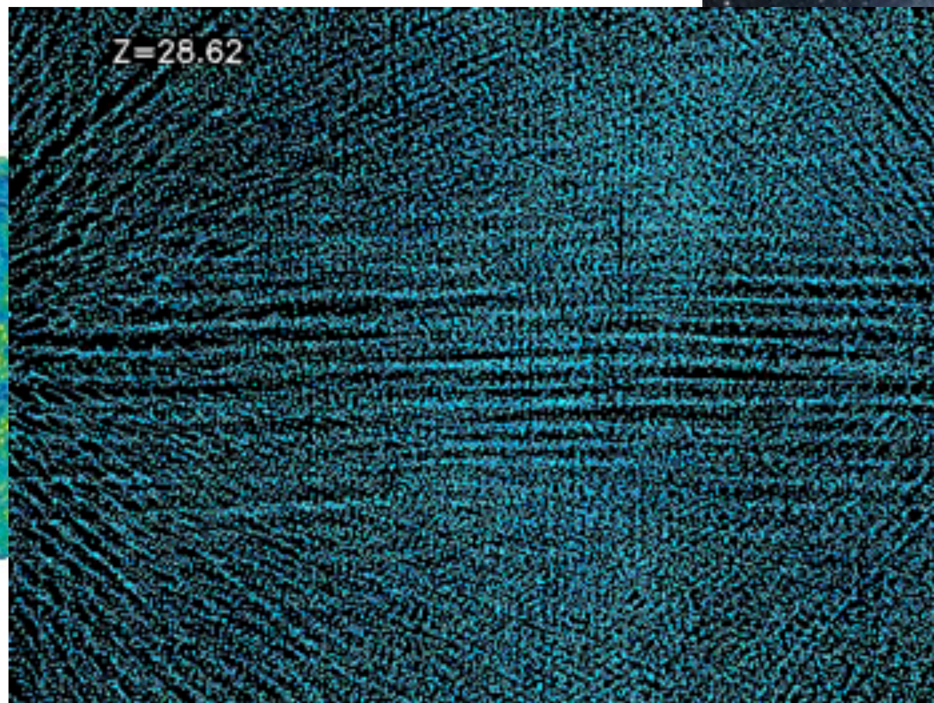

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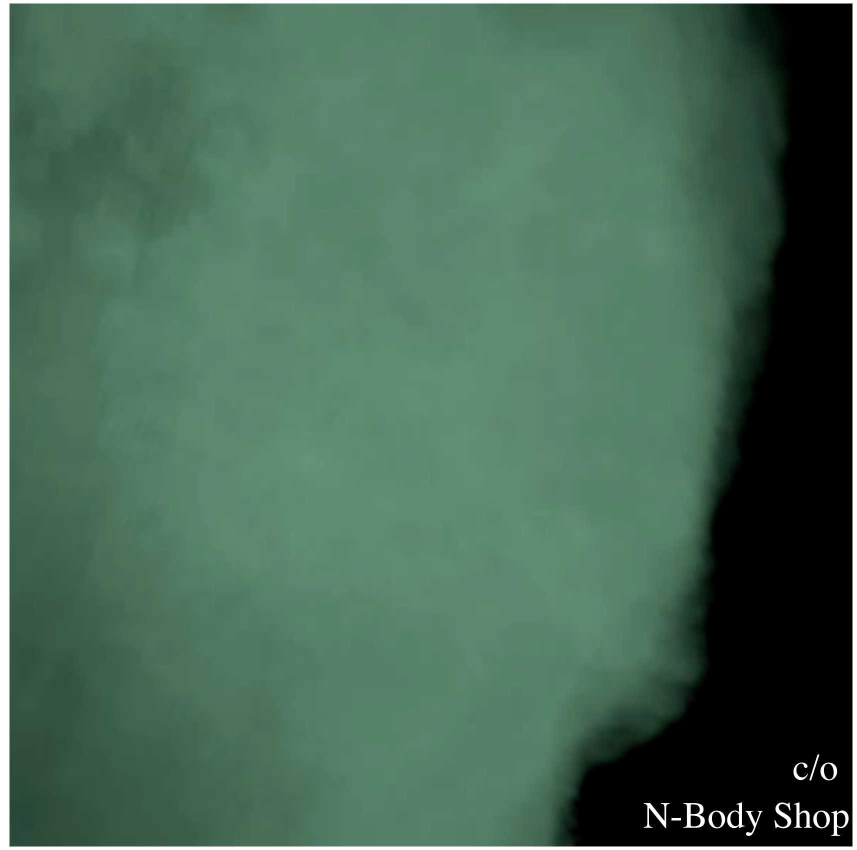
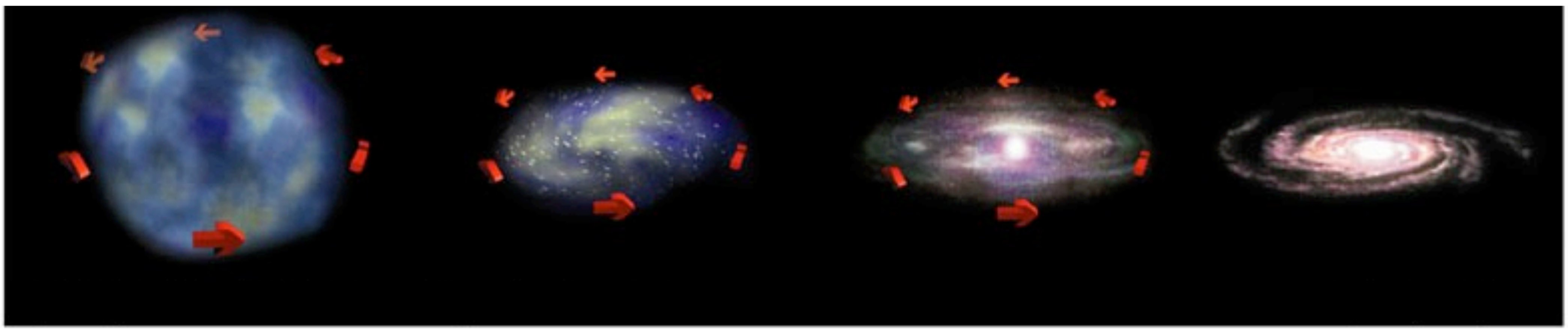
Motivation

HOW DID WE GET TO GALAXIES TODAY?



- Dark matter 'halos' collapse: gas cools into a disk

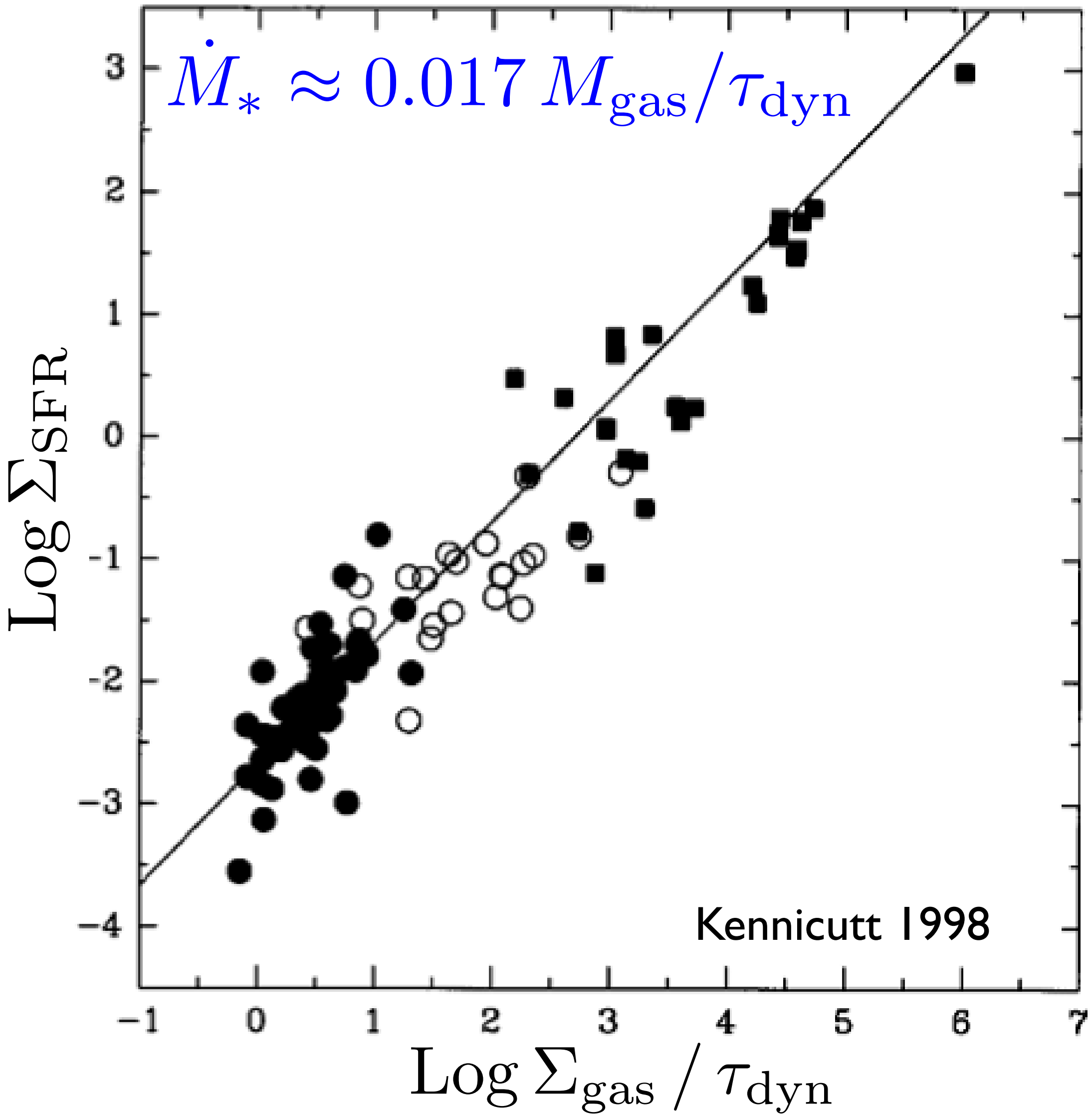


- What happens once gas is actually inside galaxies?

The Problem: Baryons

Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



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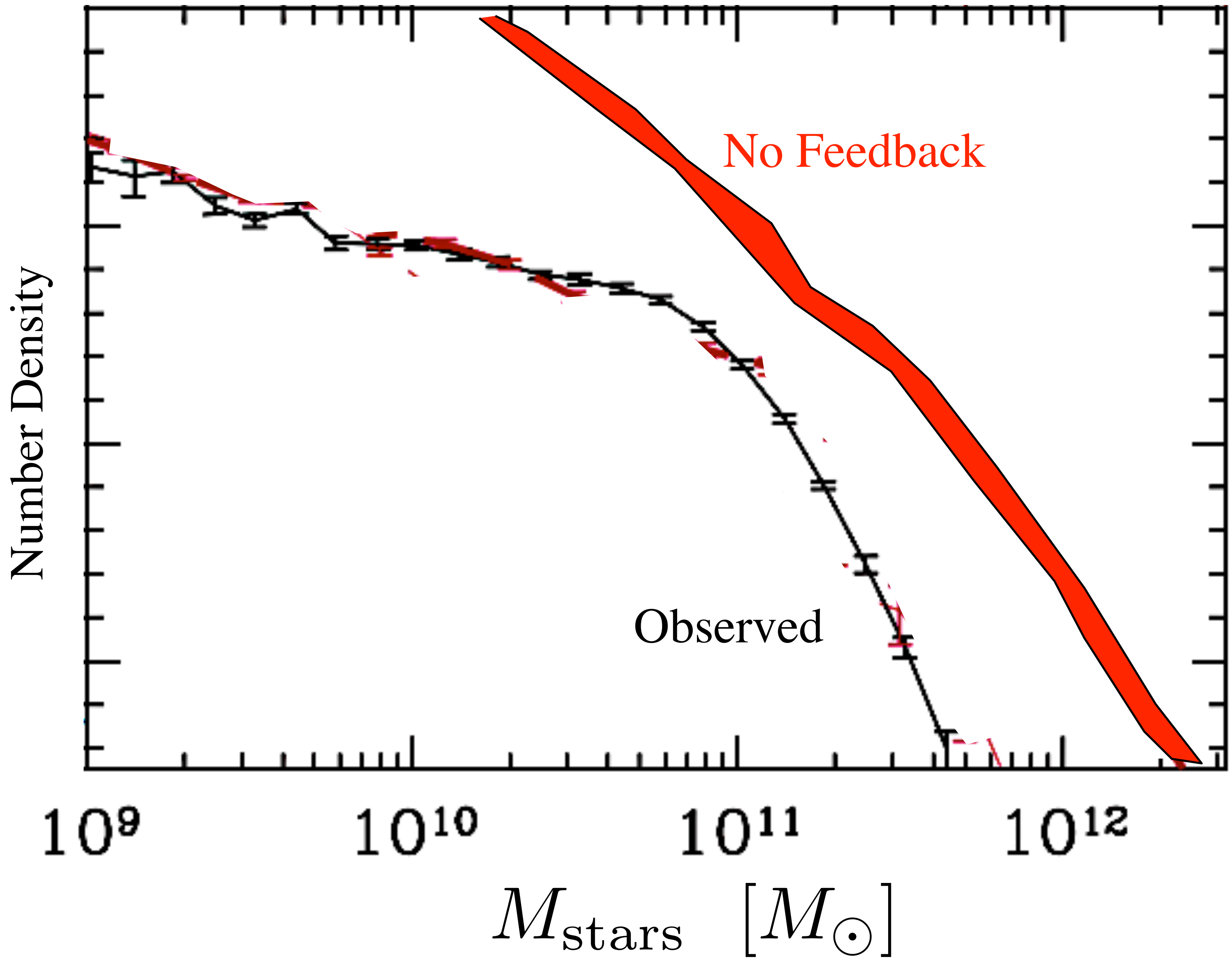

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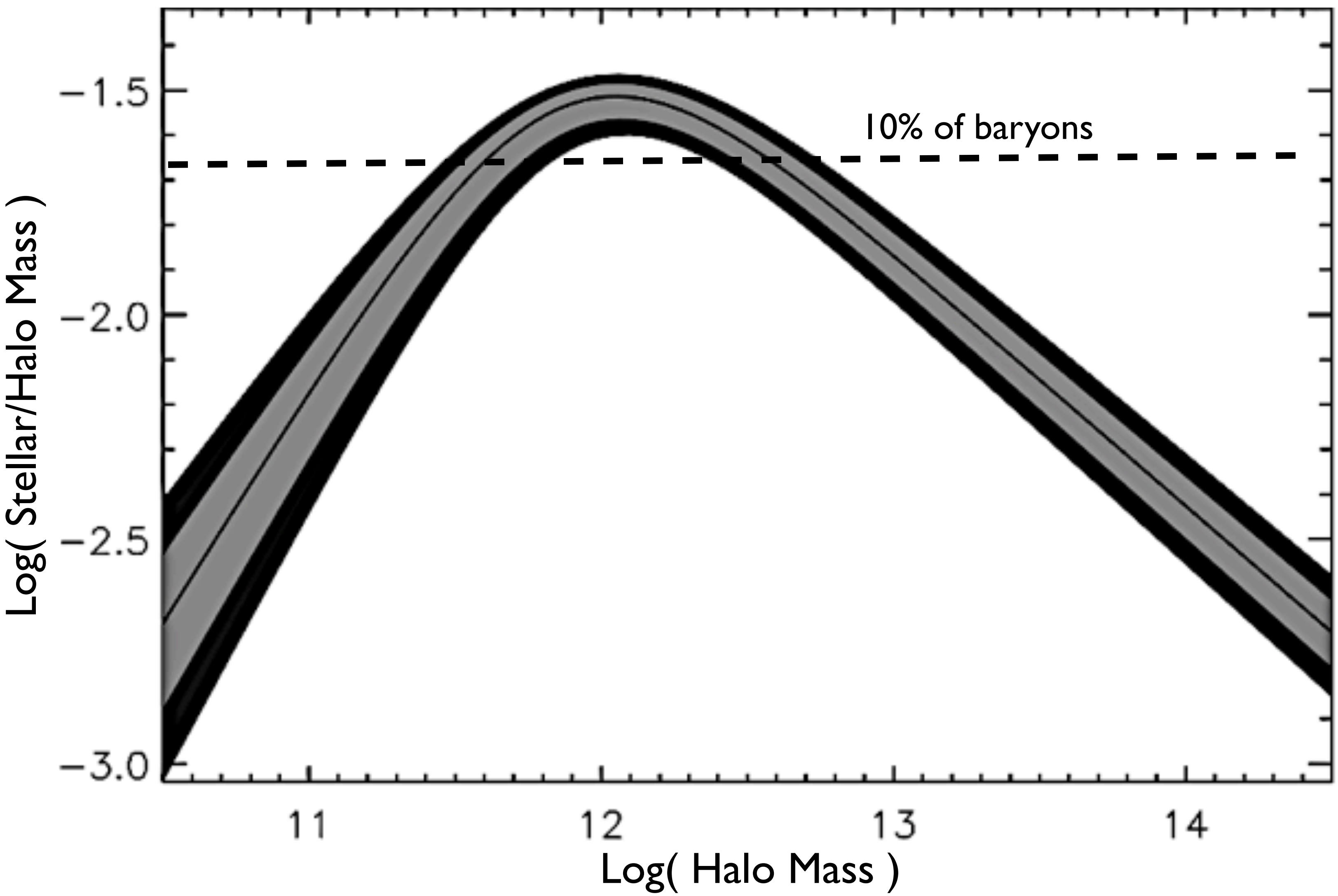
Moster 2009



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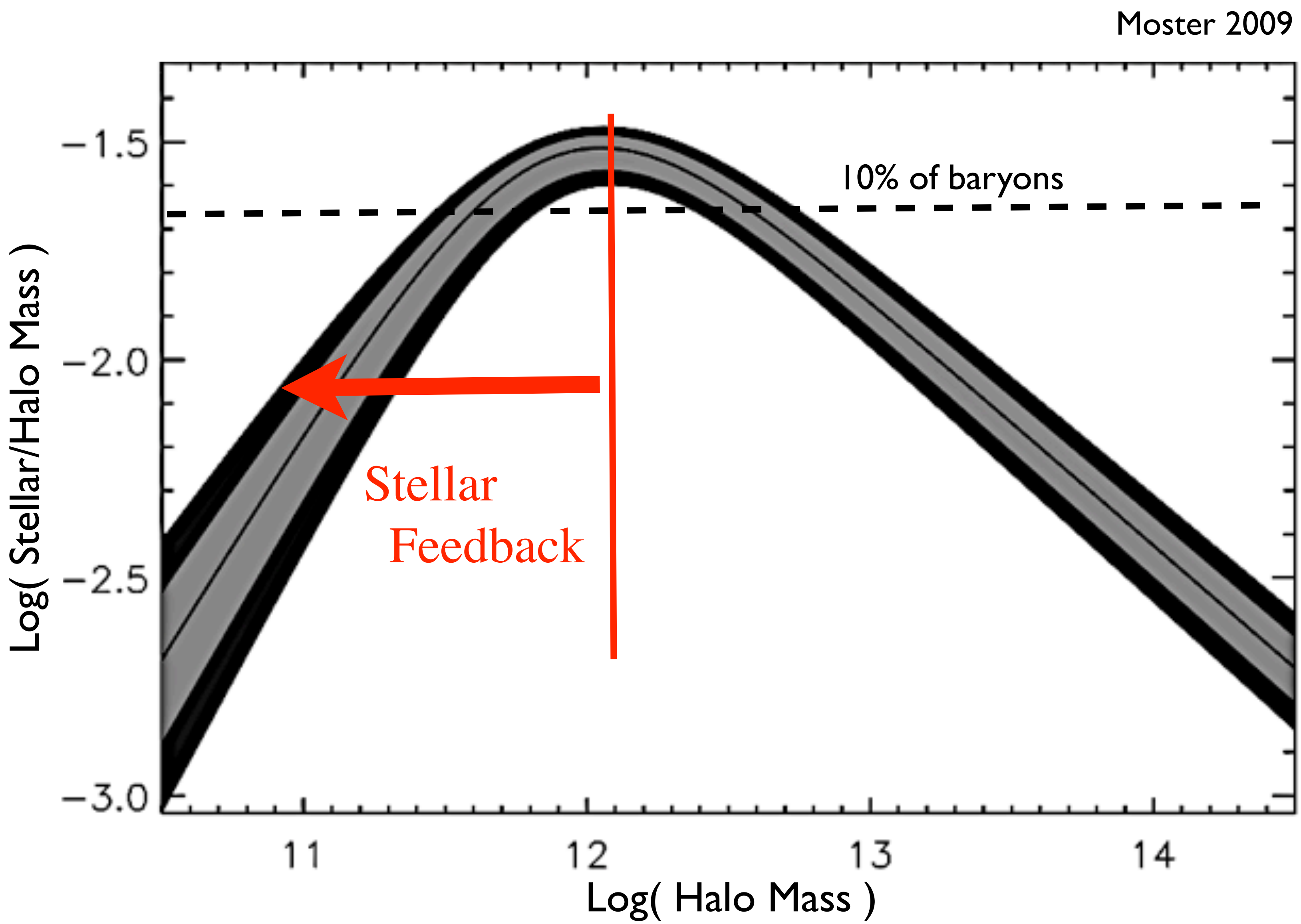

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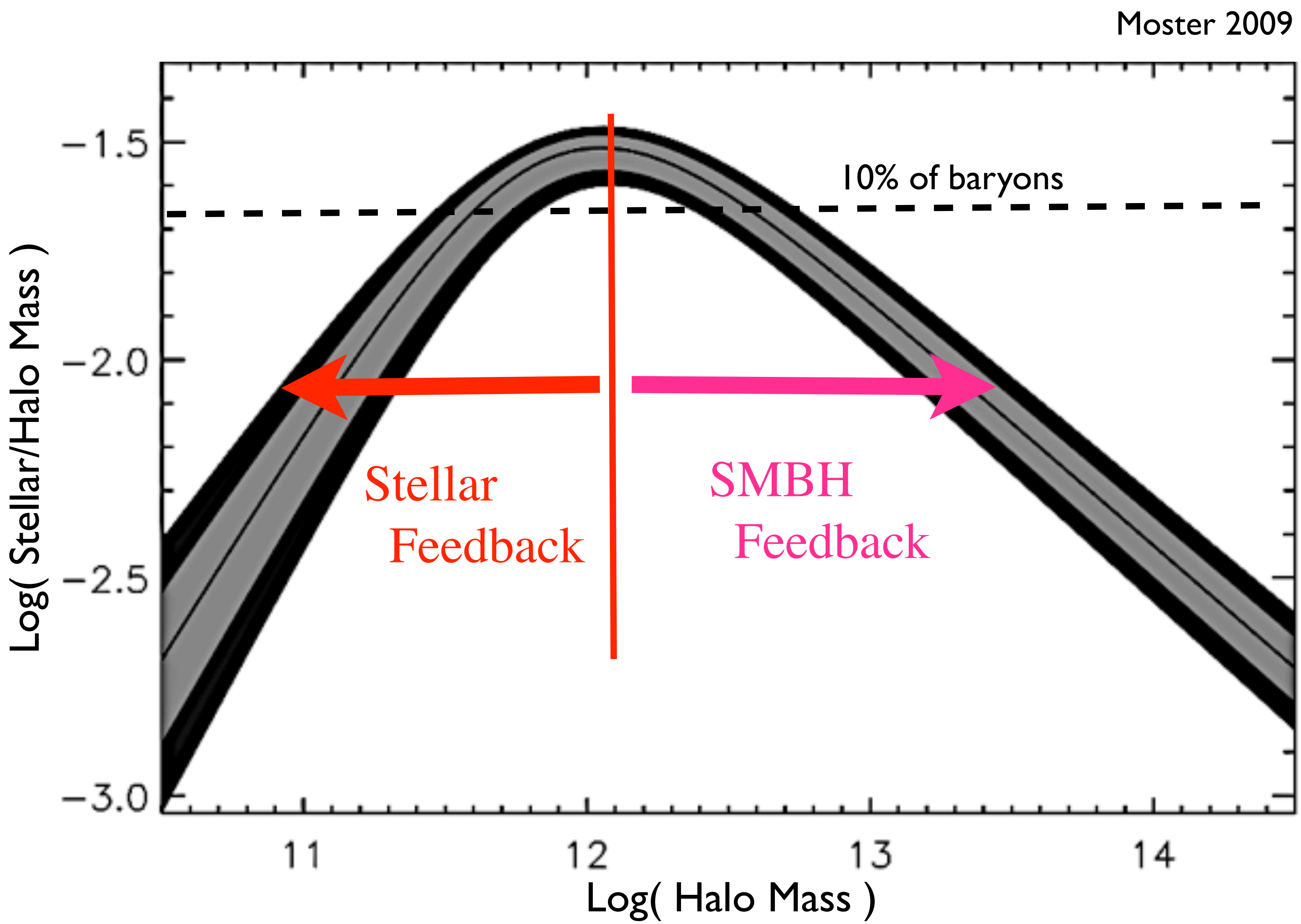


Stellar Feedback is the Key!

SO WHAT'S THE PROBLEM?

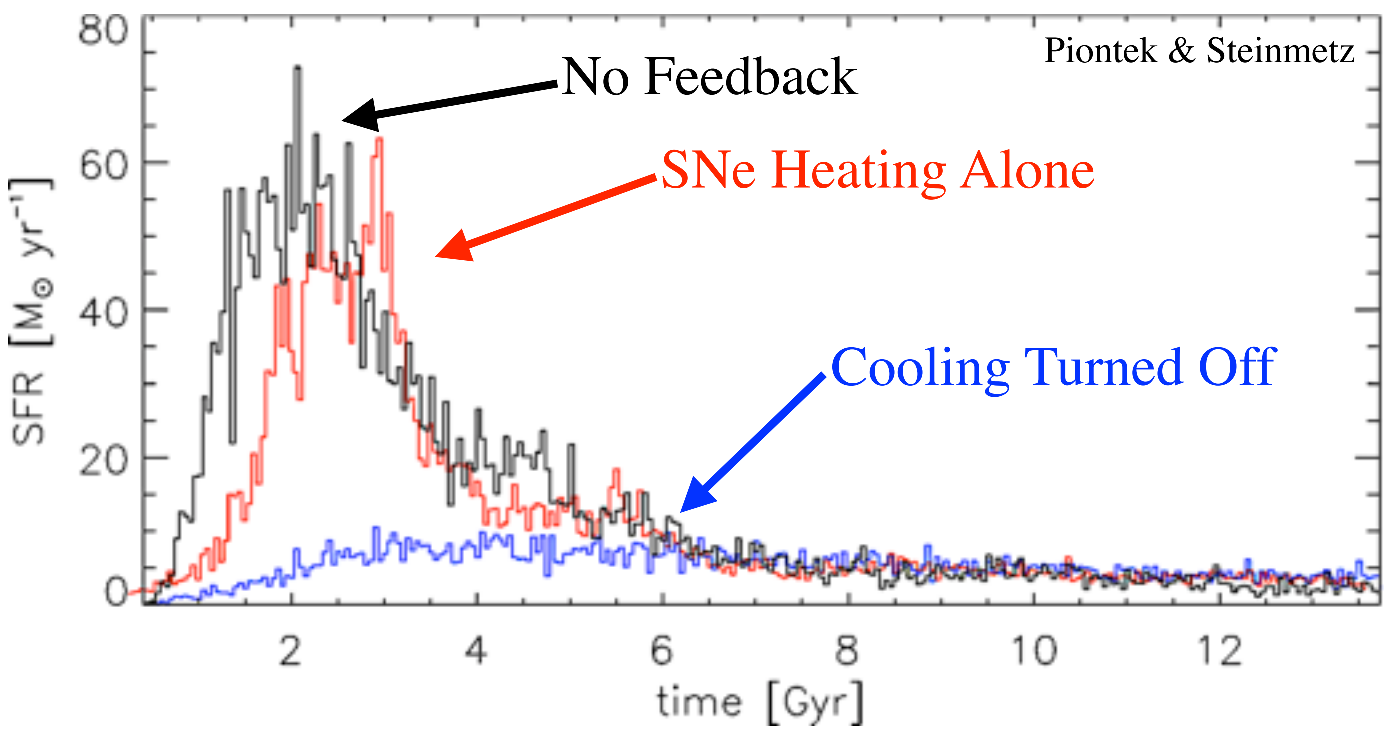
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

- 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: Understanding the key Physics

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  - Photoionization (HII Regions)

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- *Explicit* Momentum Flux:
  - Radiation Pressure

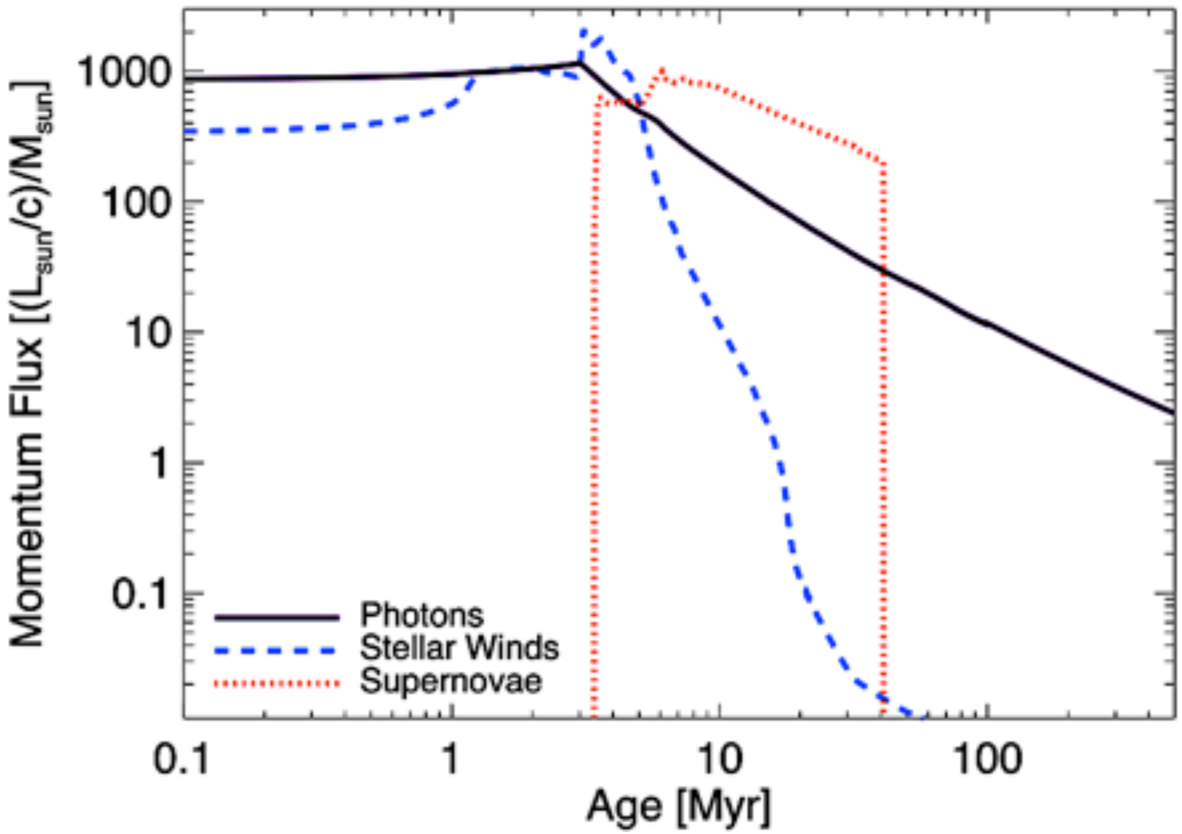
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

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



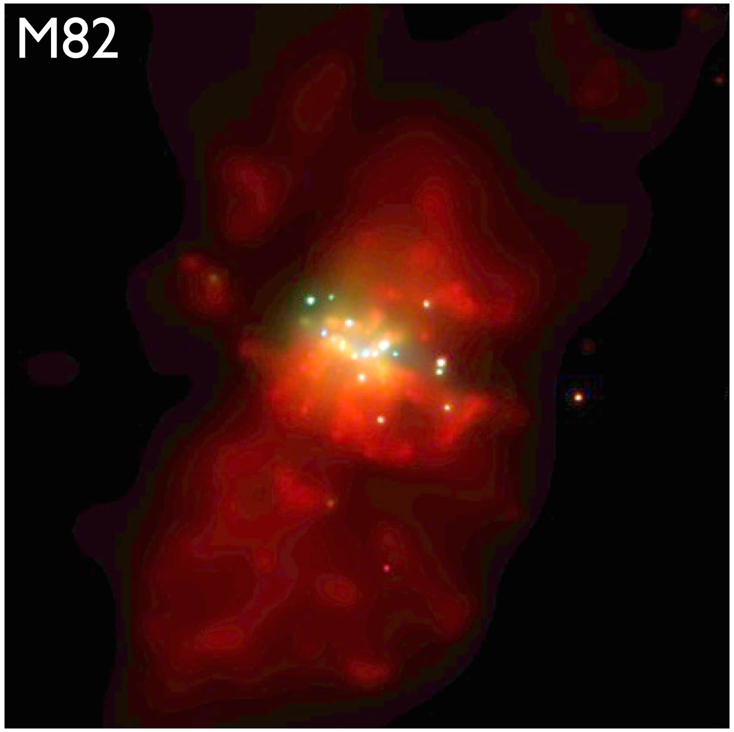
Feedback 101:

Energy

(dilute gas)

Heat to $C_s > V_{esc}$: unbound

eg: solar wind
SN-heated galactic wind



Momentum

(dense gas; energy radiated)

Force induces δV :
if $\sim V_{esc}$ drive wind

eg: O-star winds
molecular gas δV's

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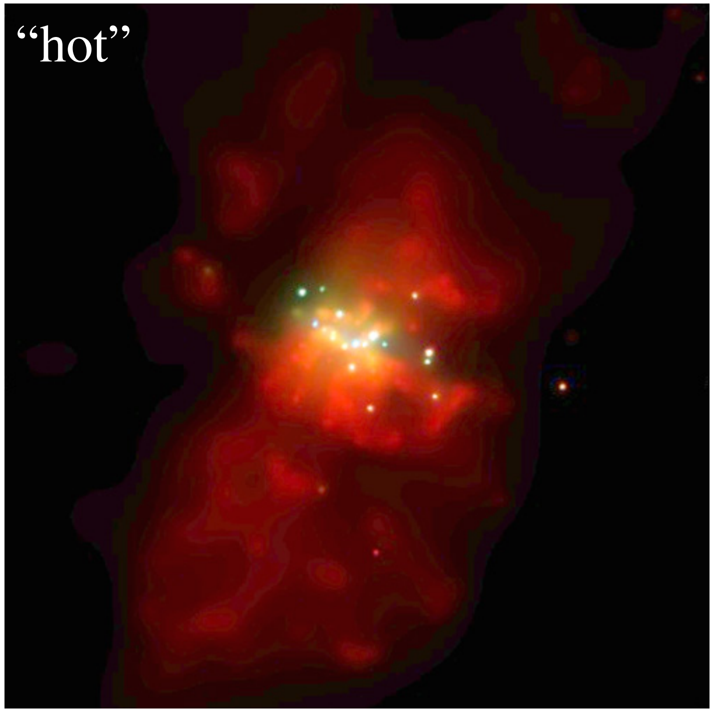
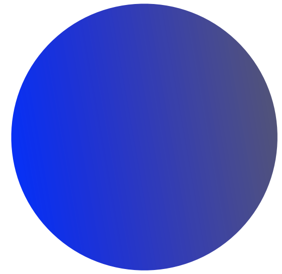


$$\Sigma_g\,(\text{cold gas}) \sim 0.1 - 100\,\mathrm{g\,cm^{-2}}$$



Equilibrium:
Pressure = $\pi G \Sigma_g^2$

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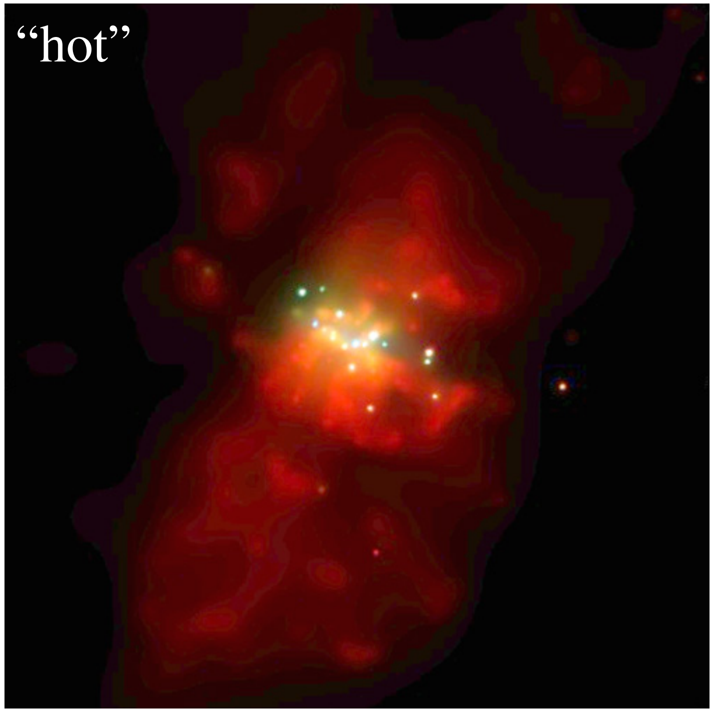

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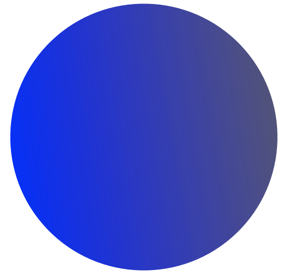

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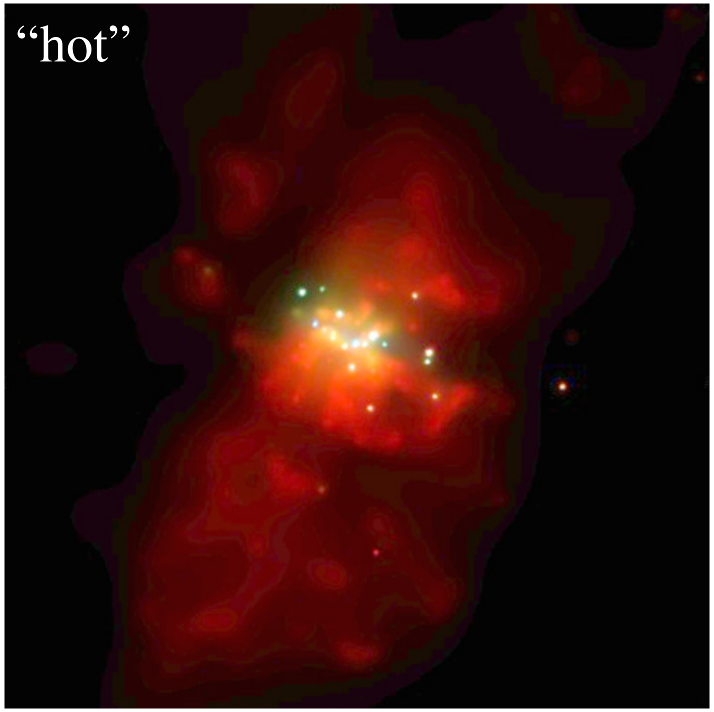

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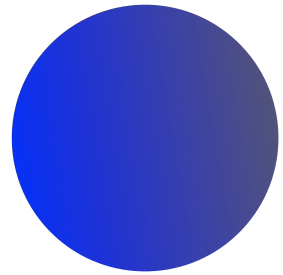

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$$p_{\rm hot} \gtrsim \pi G \Sigma_g^2 \rightarrow \dot{E}_{\rm cool} \gg \dot{E}_{\rm SNe} \text{ for } \Sigma_g \gtrsim 0.02\,\mathrm{g\,cm^{-2}}$$

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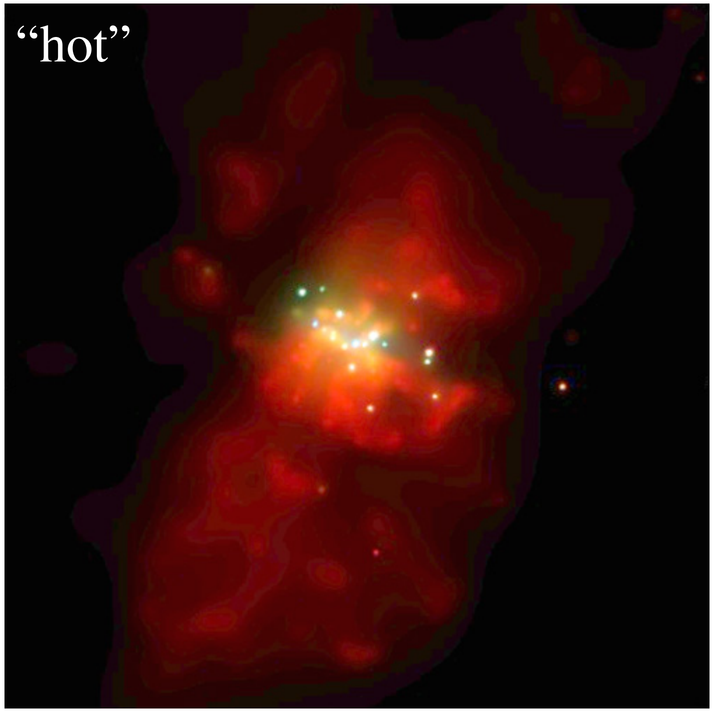

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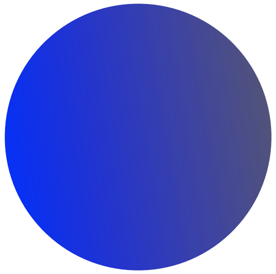

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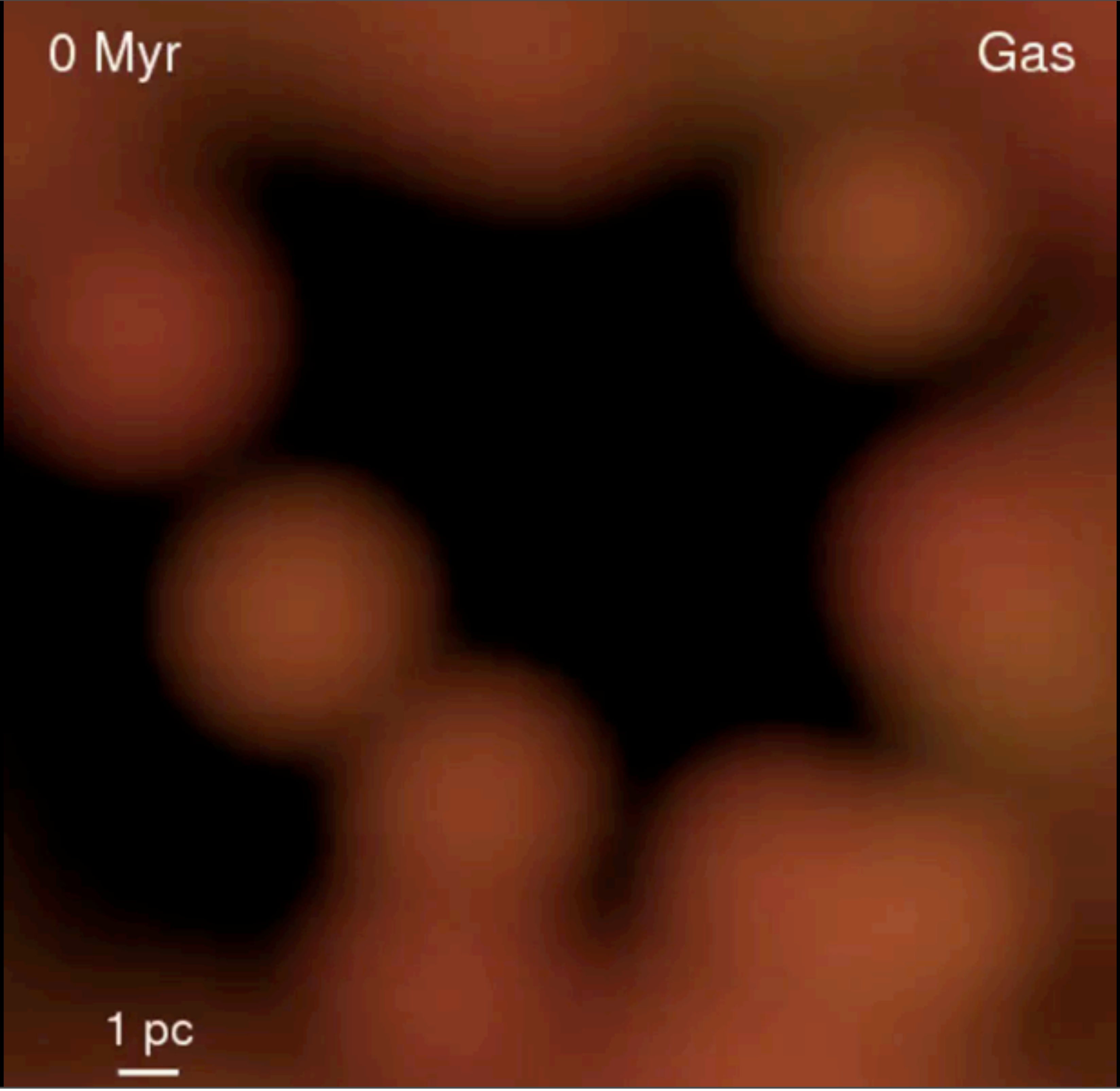
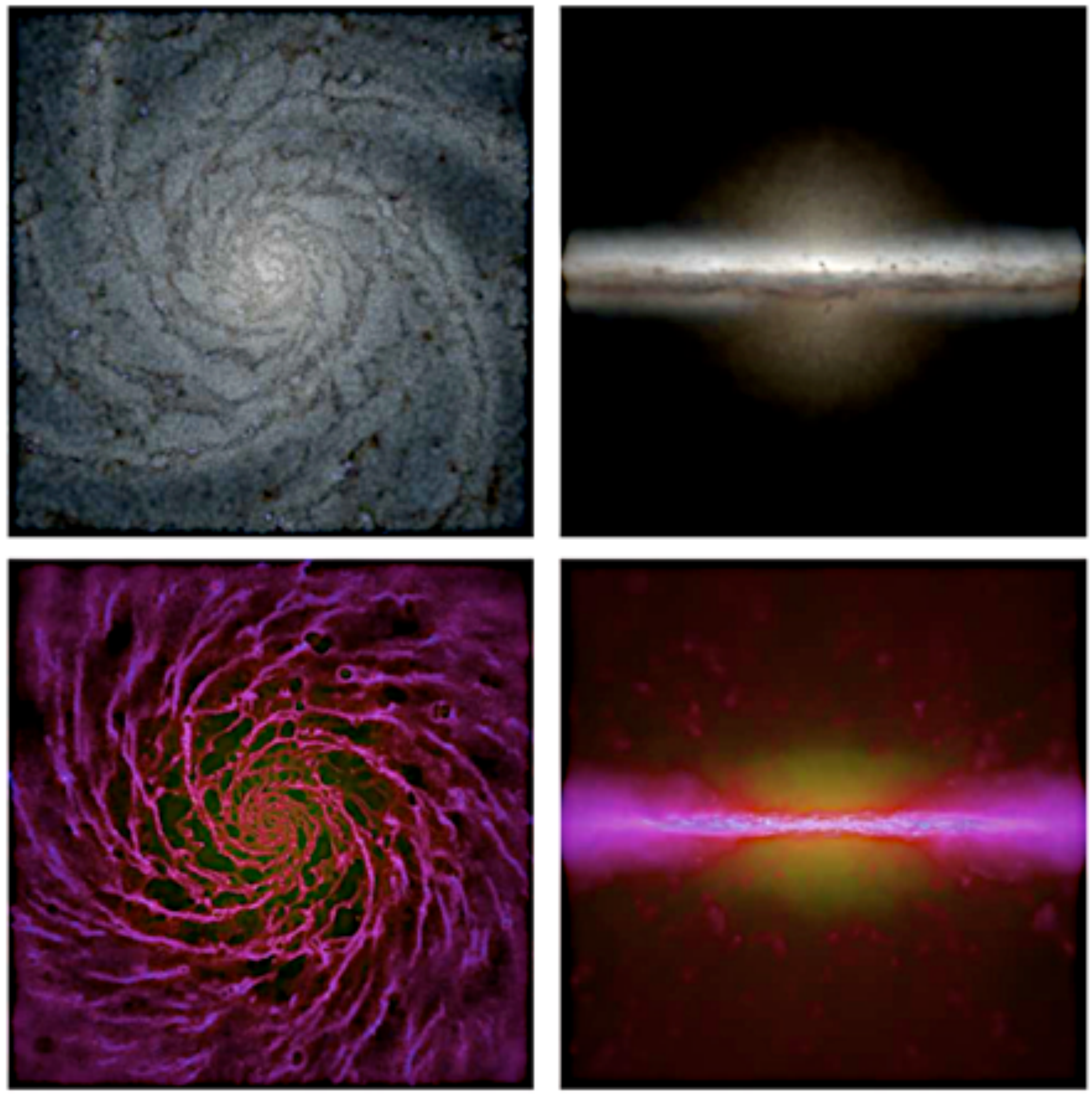
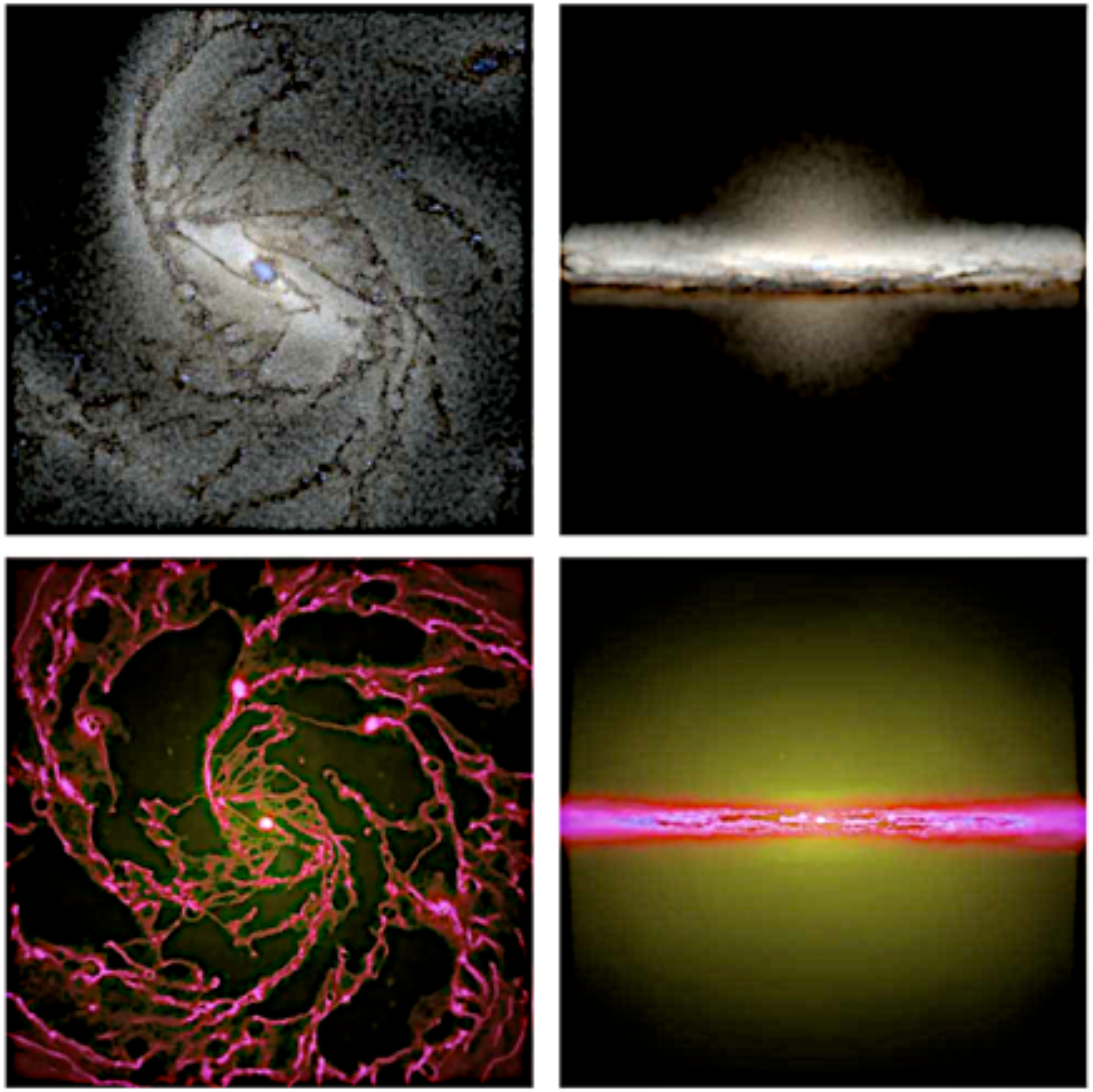
- Hot gas can *vent*: cannot affect bulk of gas mass


0 Myr
Gas
1 pc

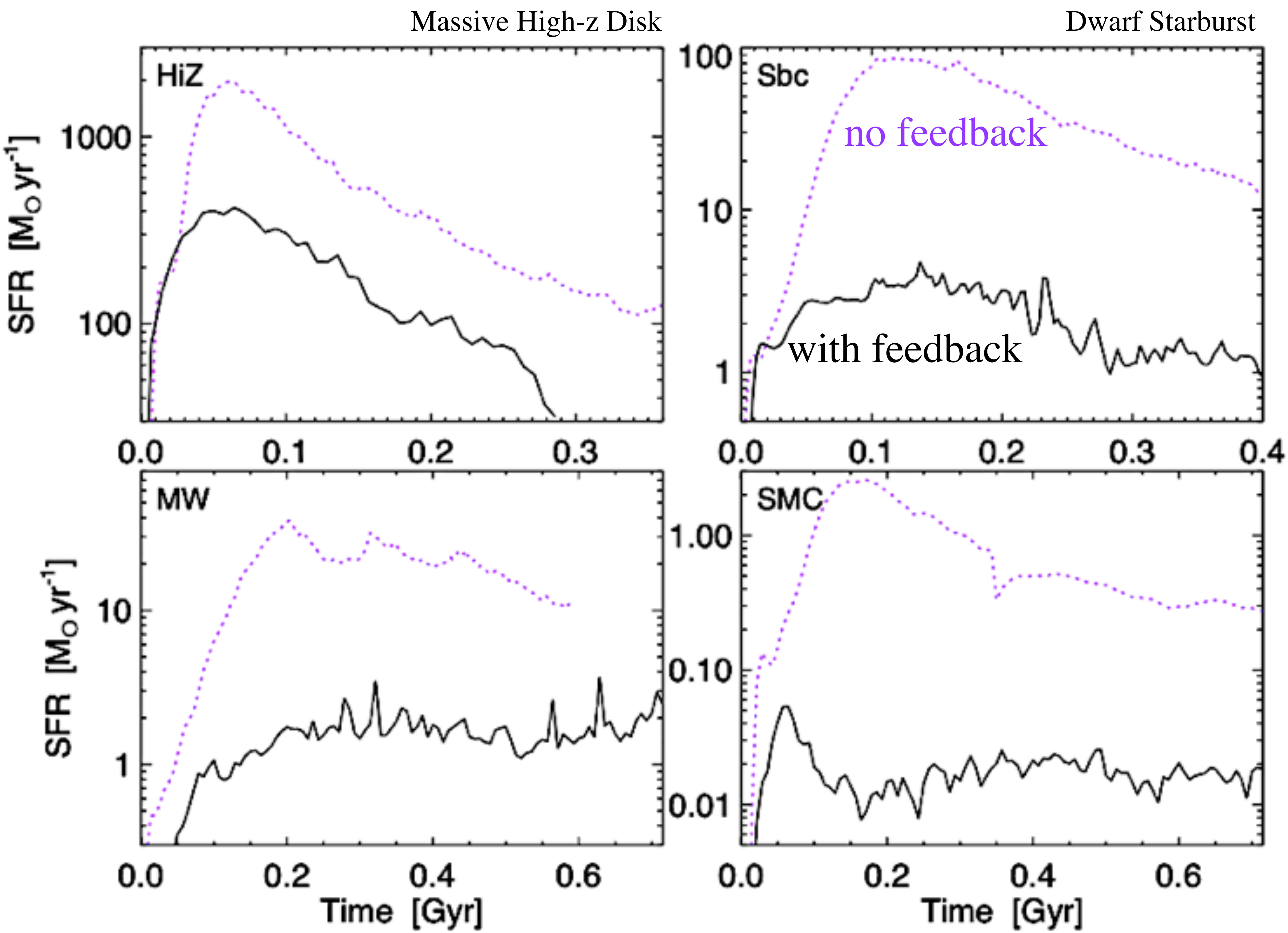


Hopkins, Quataert, & Murray, 2011b



Hopkins, Quataert, & Murray, 2011b

Stellar Feedback gives Self-Regulated Star Formation



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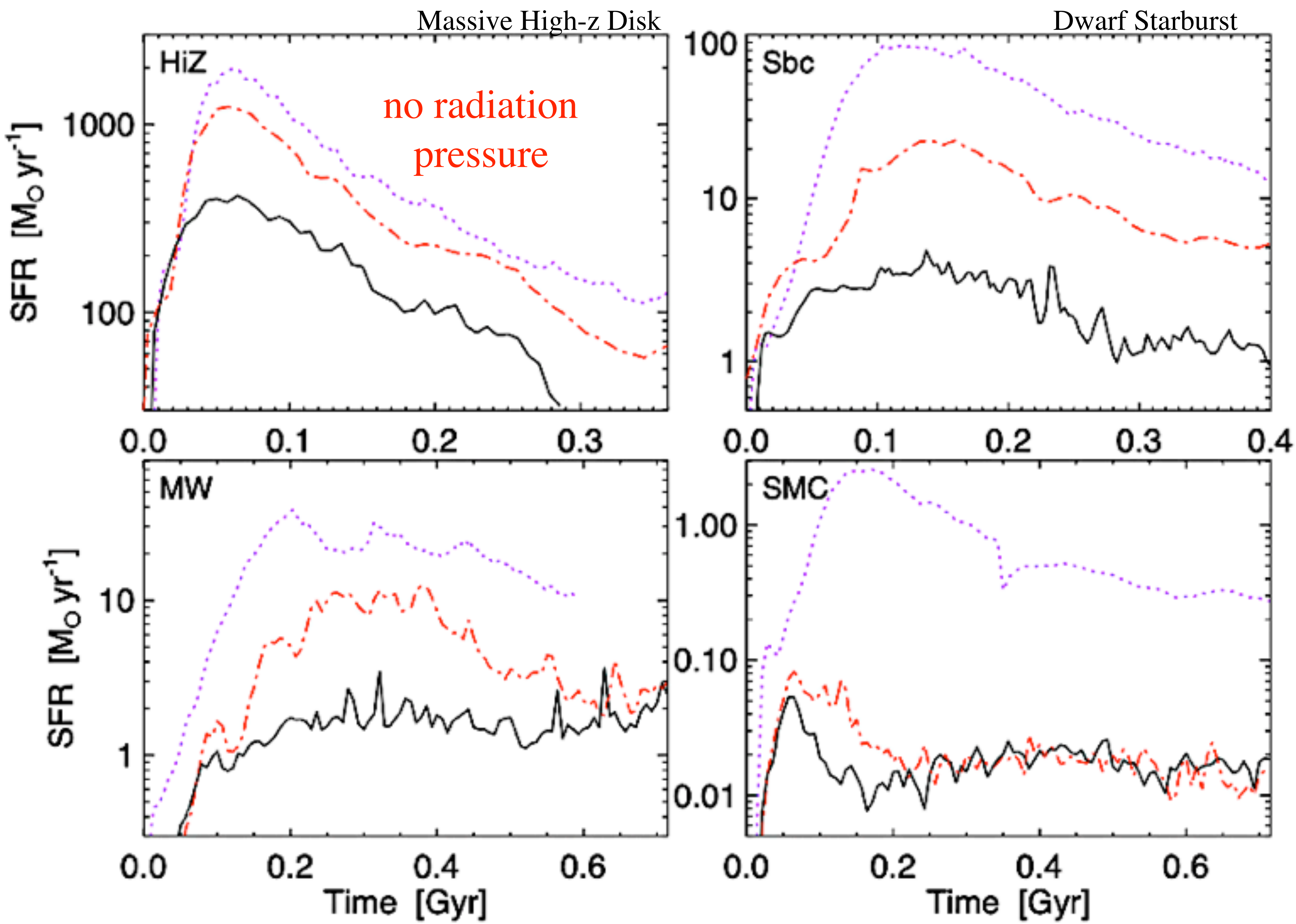

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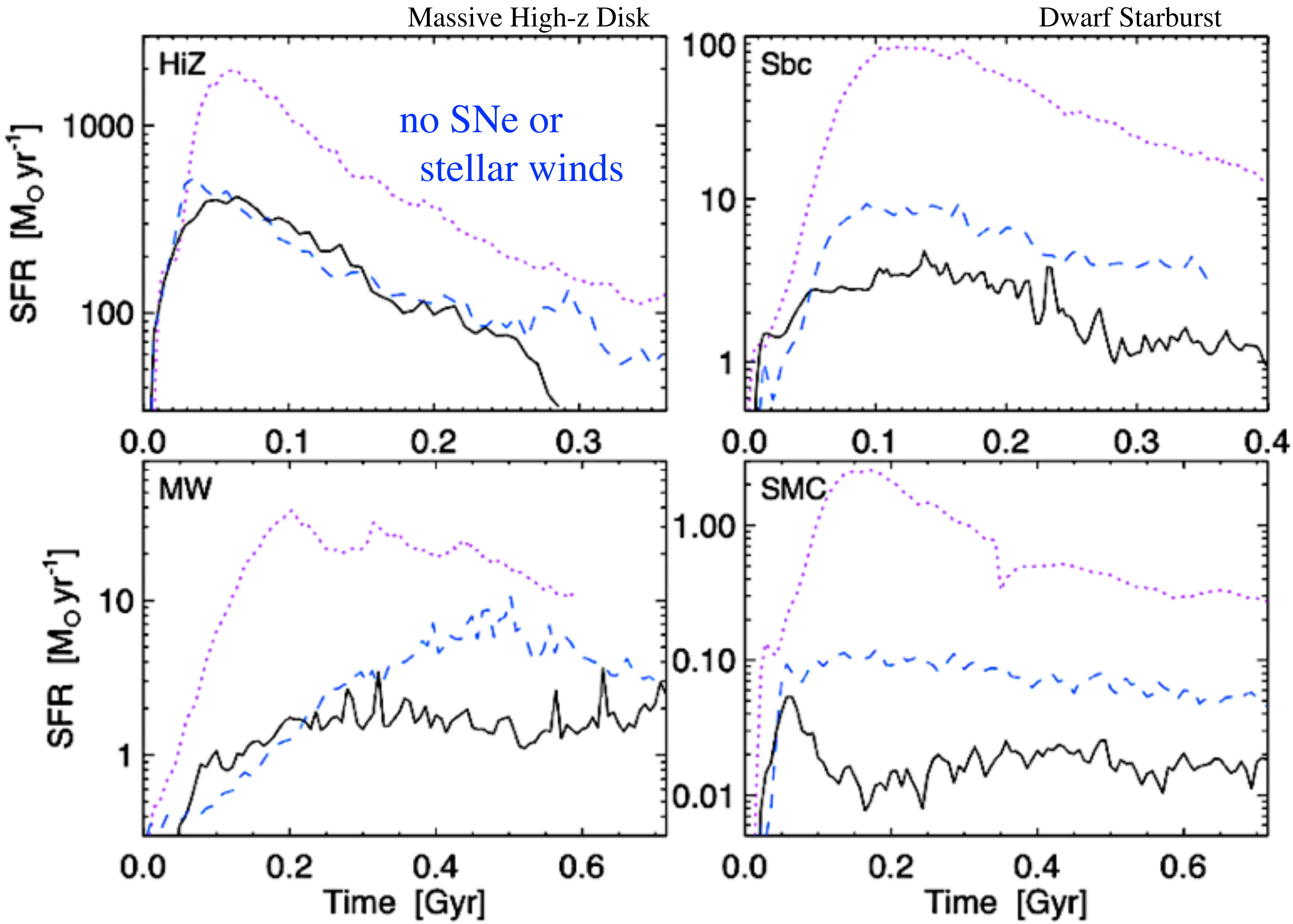
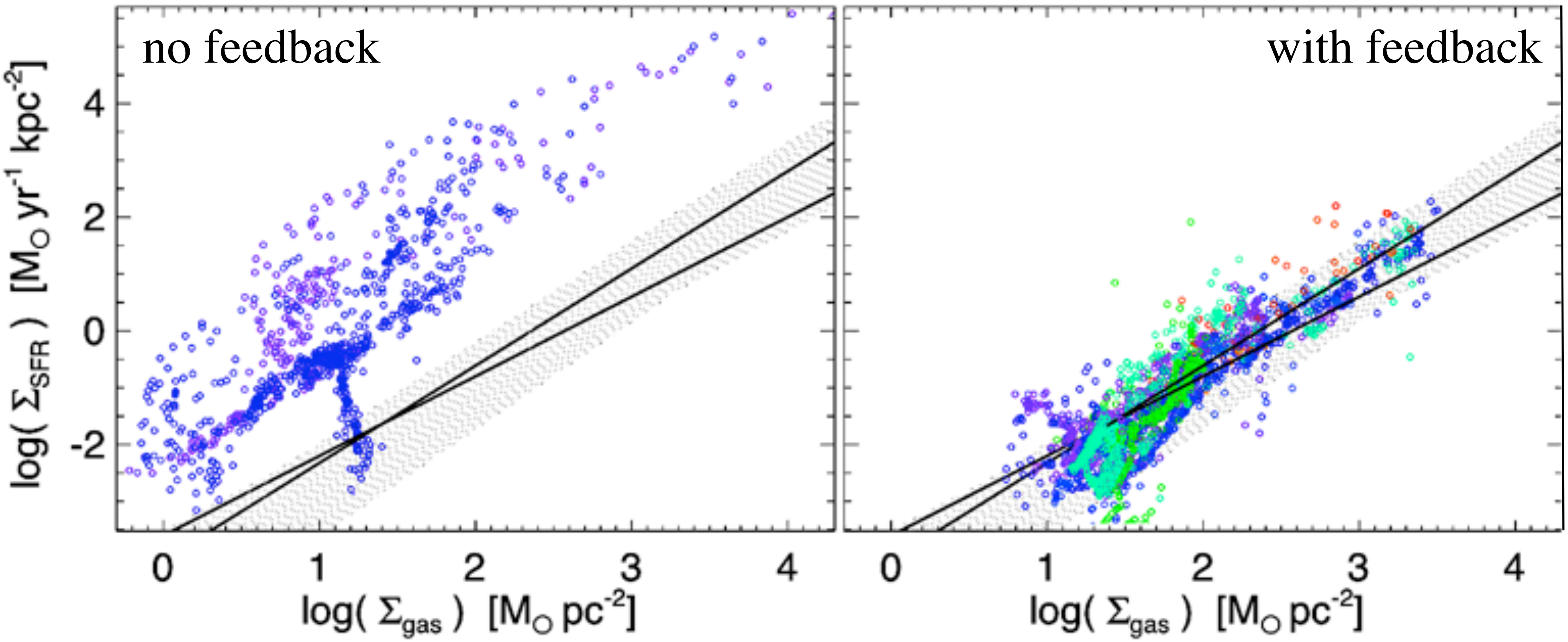


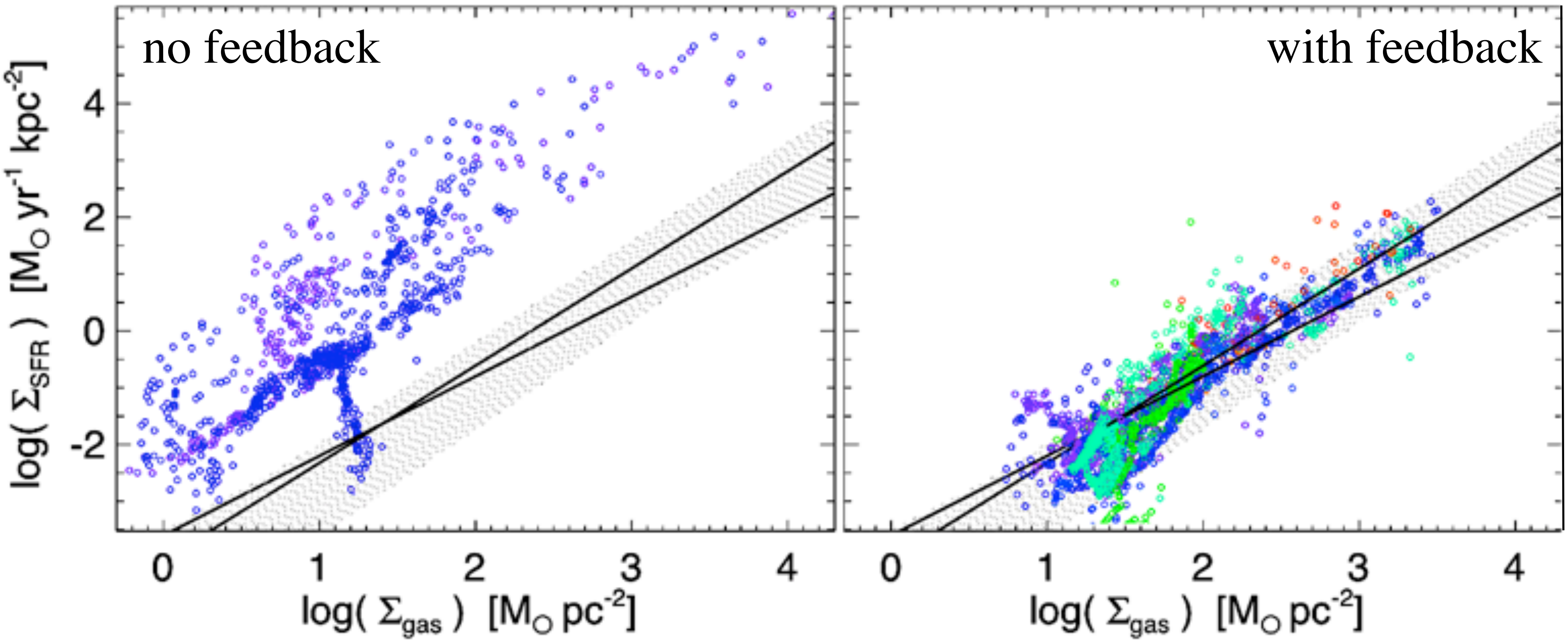
Kennicutt-Schmidt relation emerges naturally



PFH, Quataert, & Murray, 2011a

Kennicutt-Schmidt relation emerges naturally

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



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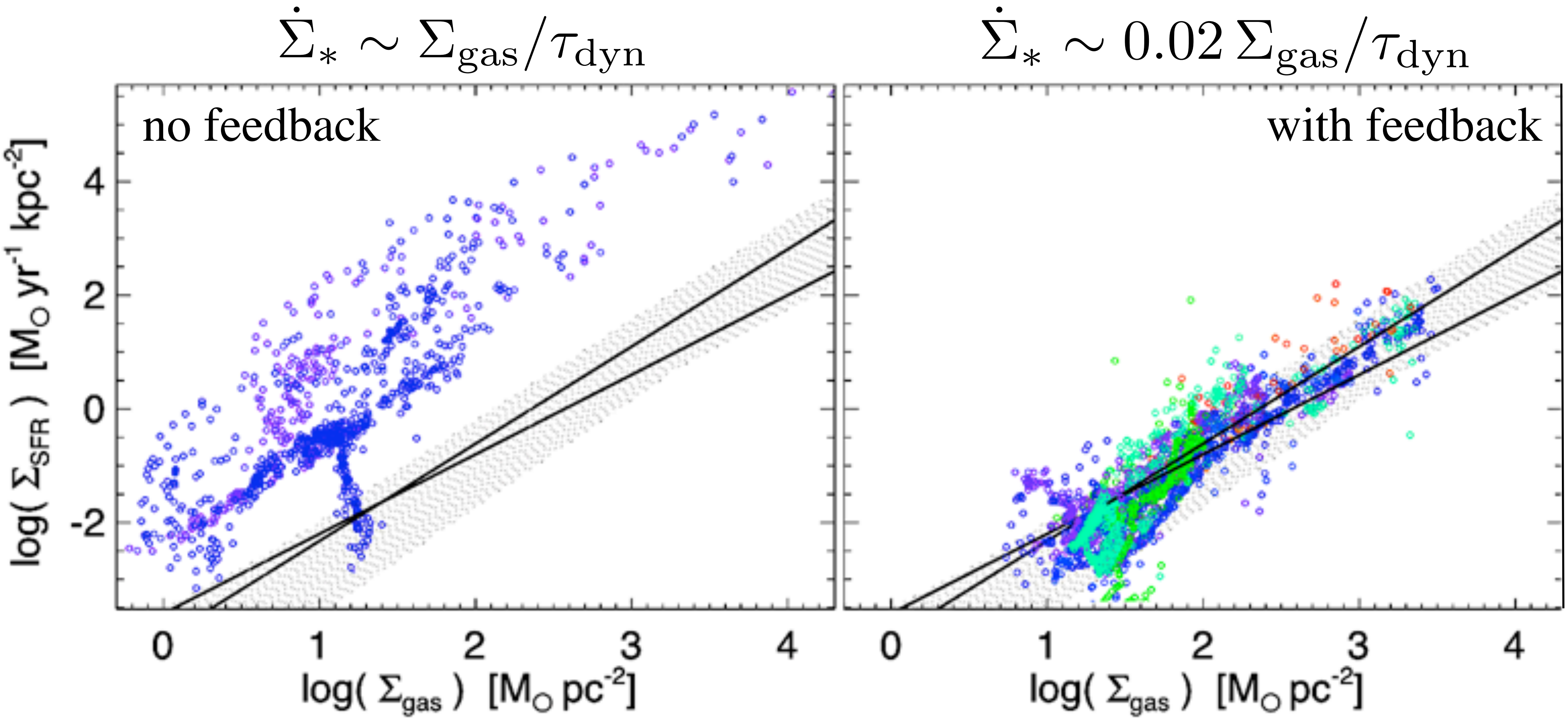

PFH, Quataert, & Murray, 2011a

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set by global properties:

$$Q \equiv \frac{\sigma \Omega}{\pi G \Sigma}$$

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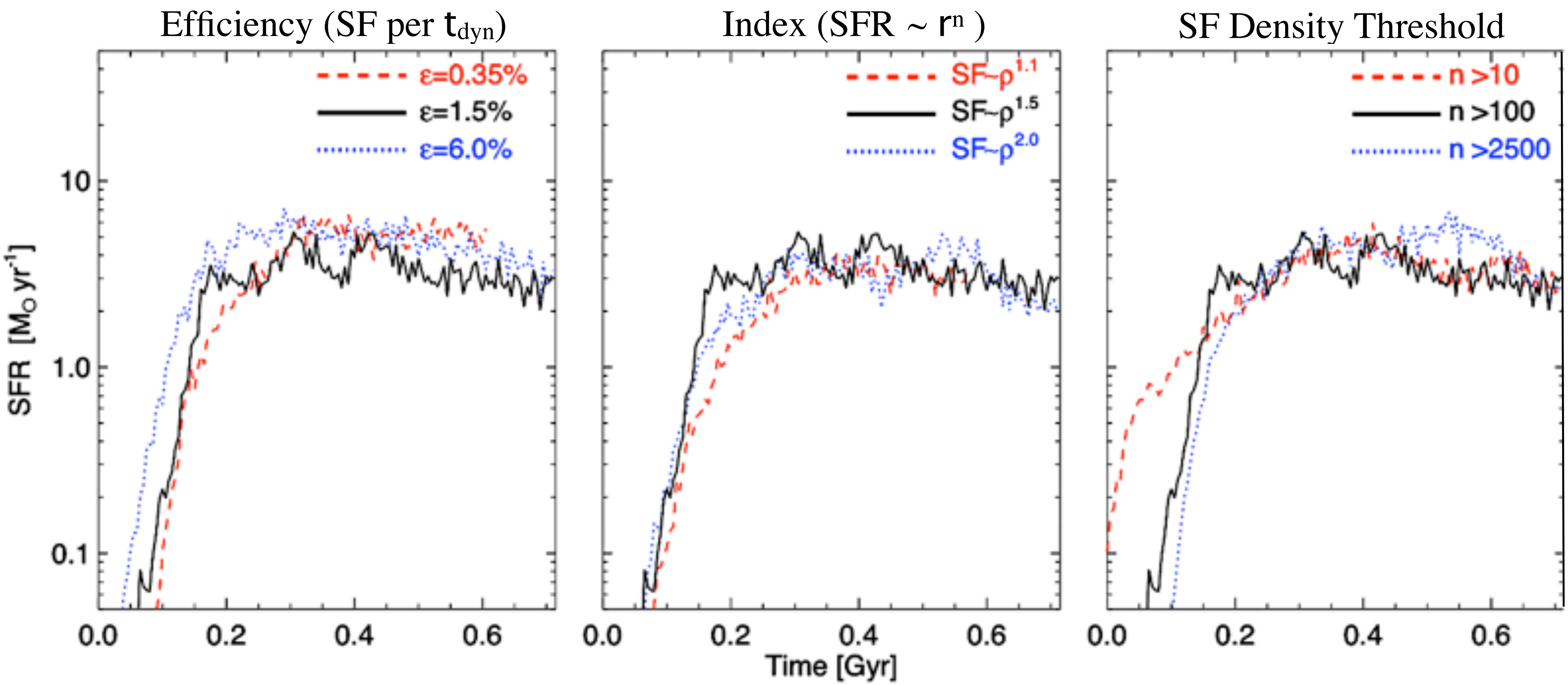
$$\longrightarrow \dot{\Sigma}_{*} \sim \left(\frac{\sigma}{\epsilon_{*} c}\right) \Sigma_{\rm gas}\Omega \sim 0.02\, \Sigma_{\rm gas}\Omega$$

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



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

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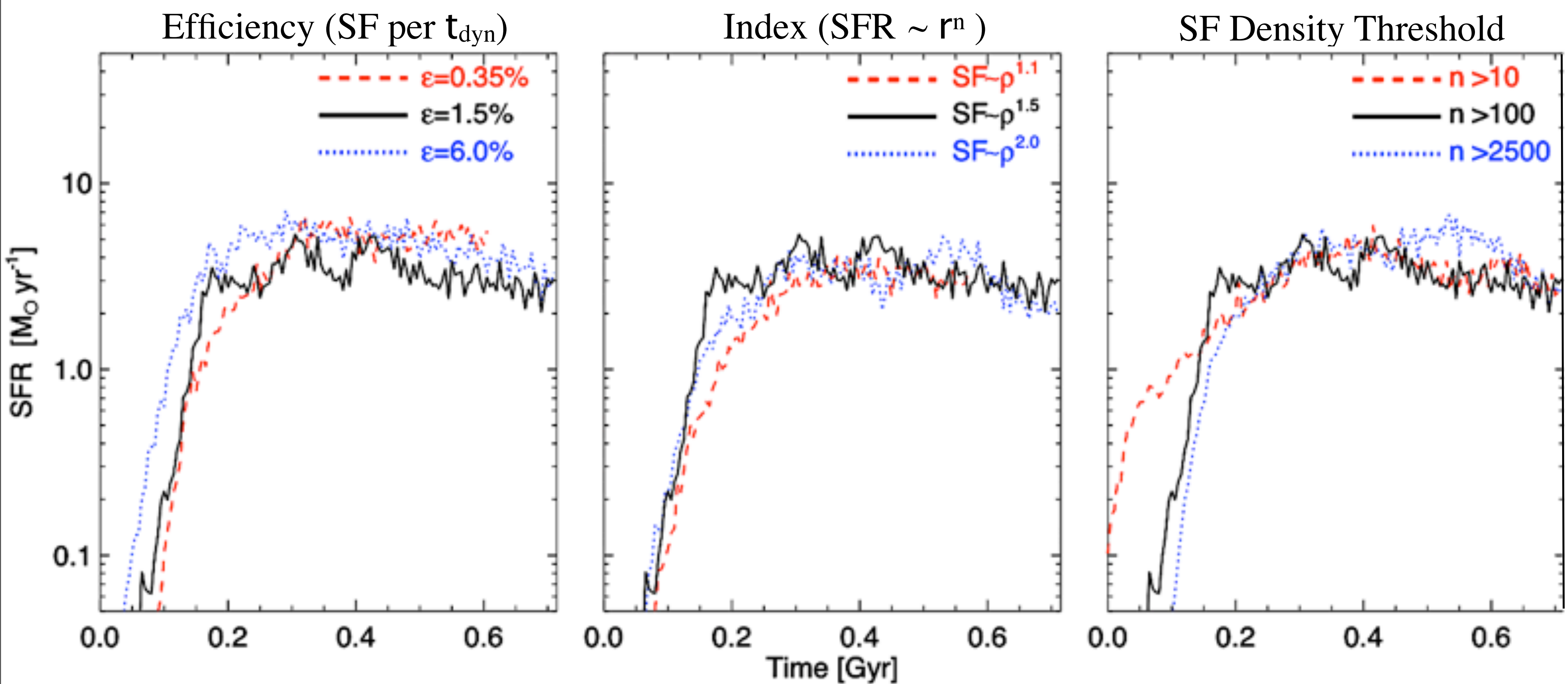


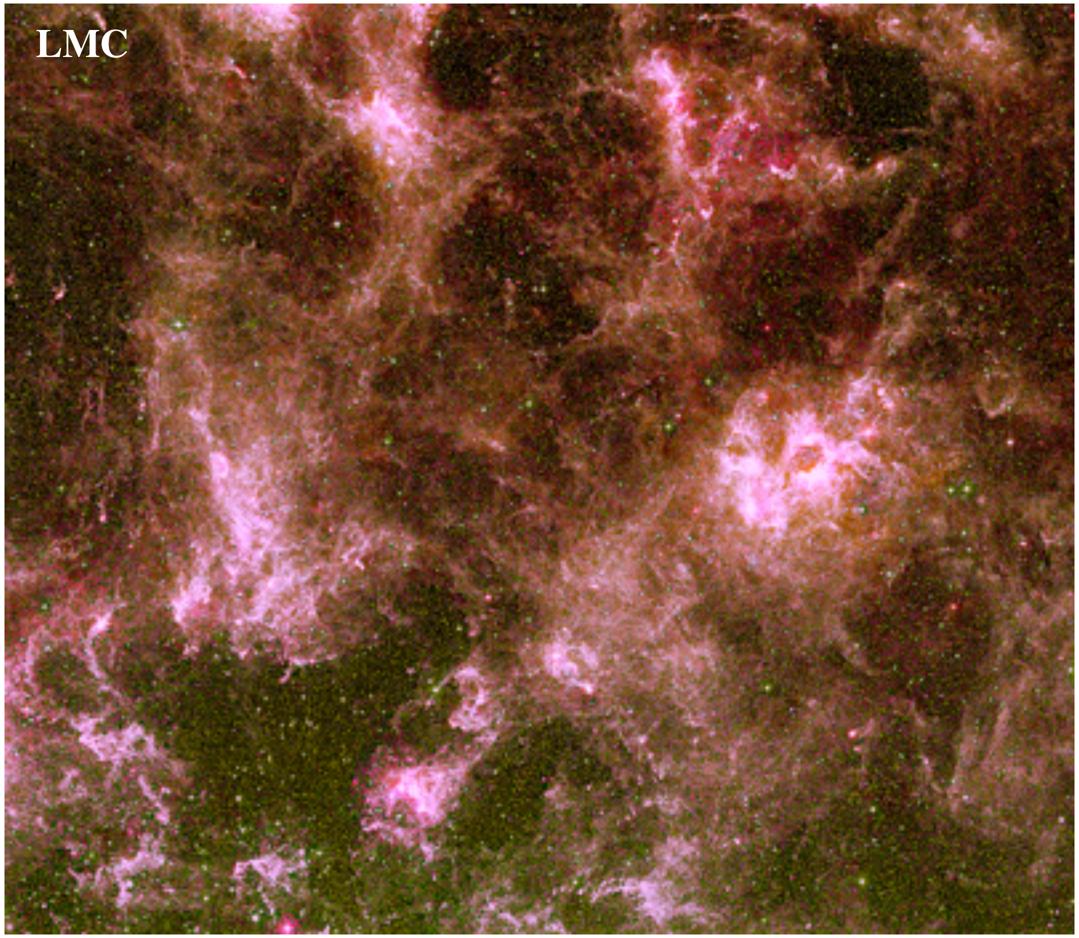
- Set by feedback (i.e. SFR) needed to maintain marginal stability

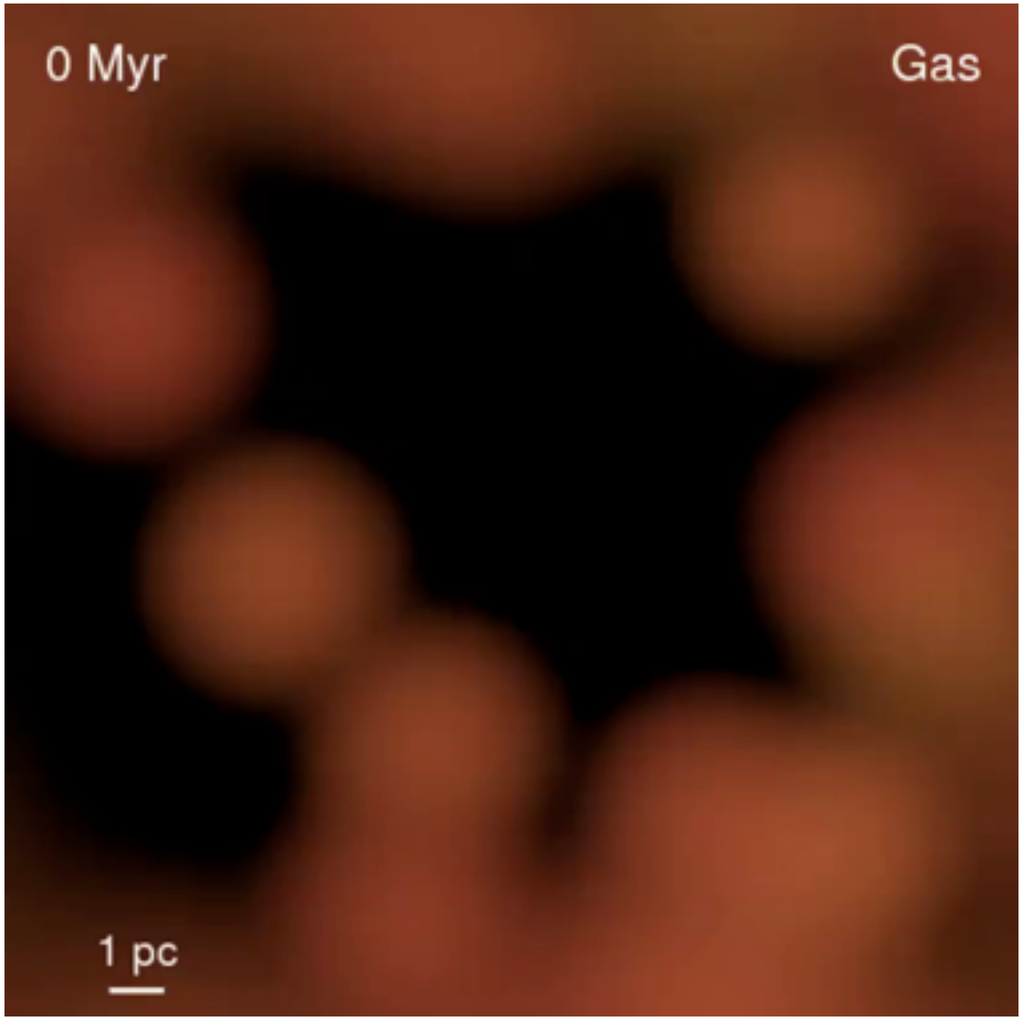
Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

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

Super-Sonic Turbulence

DOMINATES (ALMOST) ALL SCALES

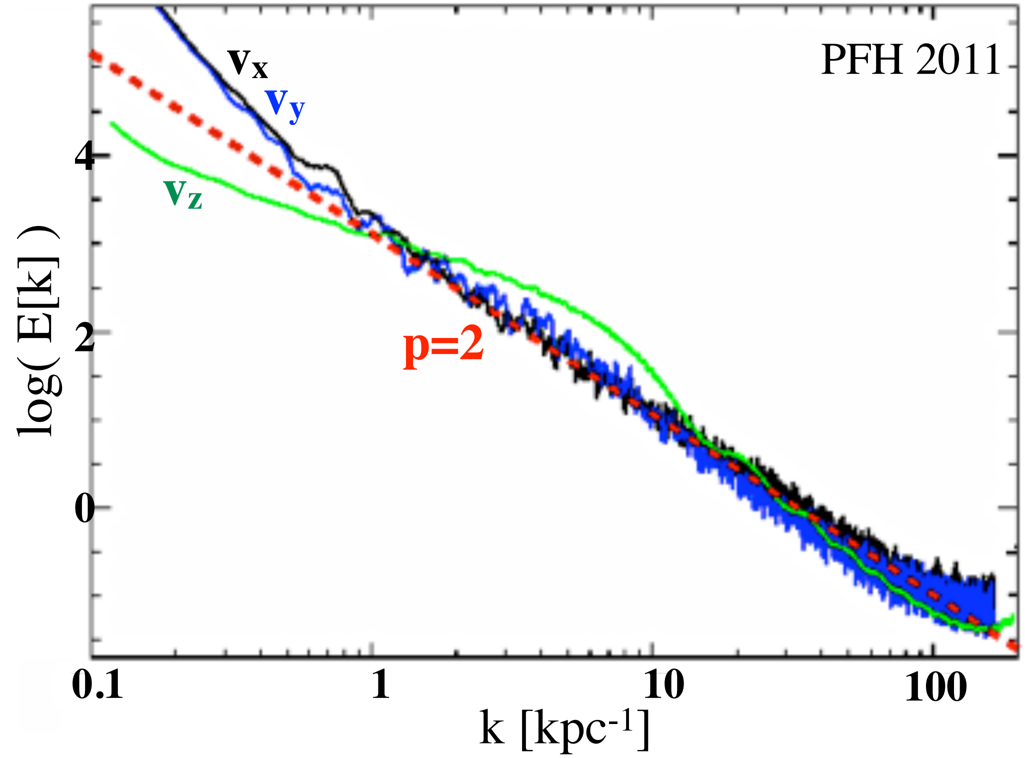


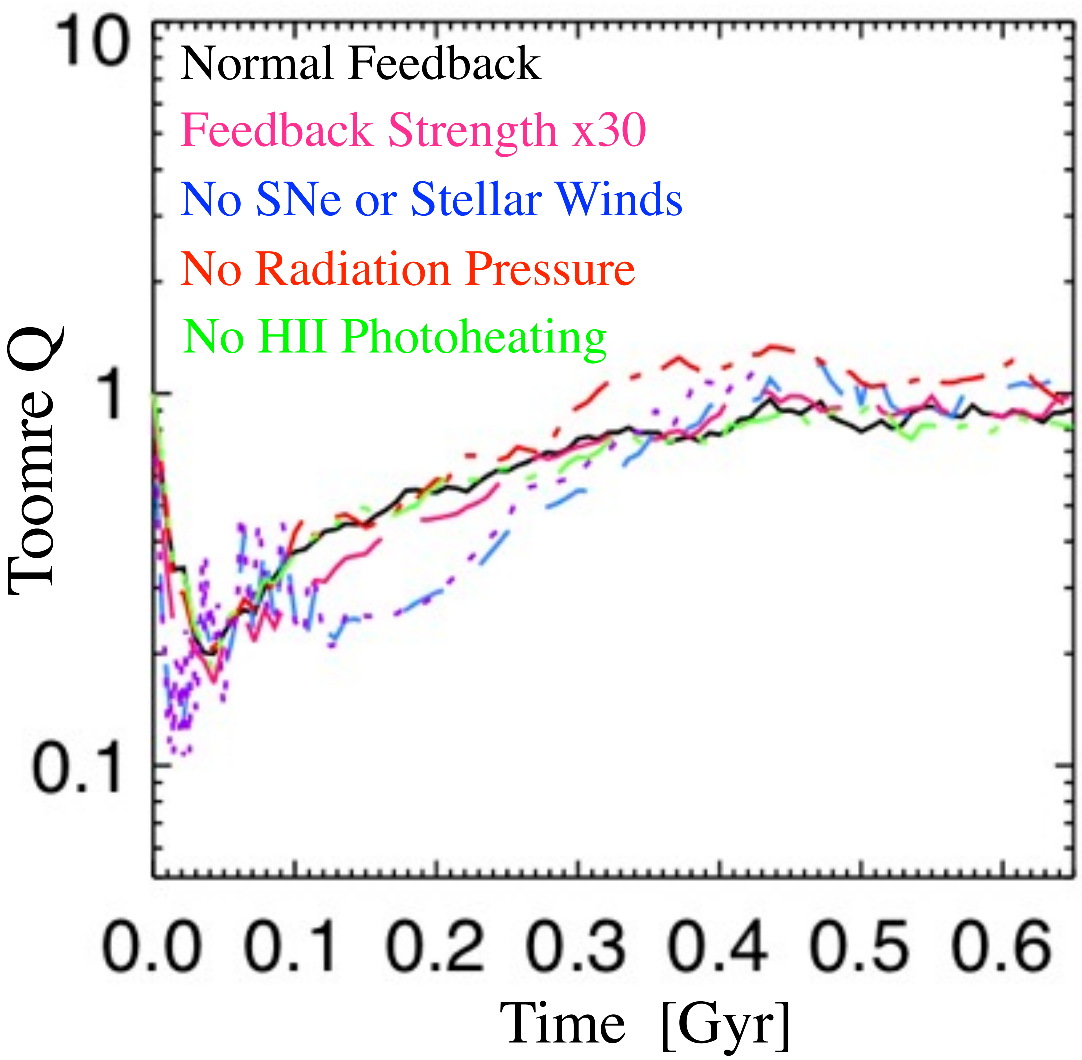


- Gravity
- Turbulence
- Magnetic, Thermal, Cosmic Ray, Radiation Pressure
- Cooling (atomic, molecular, metal-line, free-free)
- Star & BH Formation/Growth
- "Feedback": Massive stars, SNe, BHs, external galaxies, etc.

Feedback Maintains Turbulence

CASCADE INVARIANT TO MICROPHYSICS

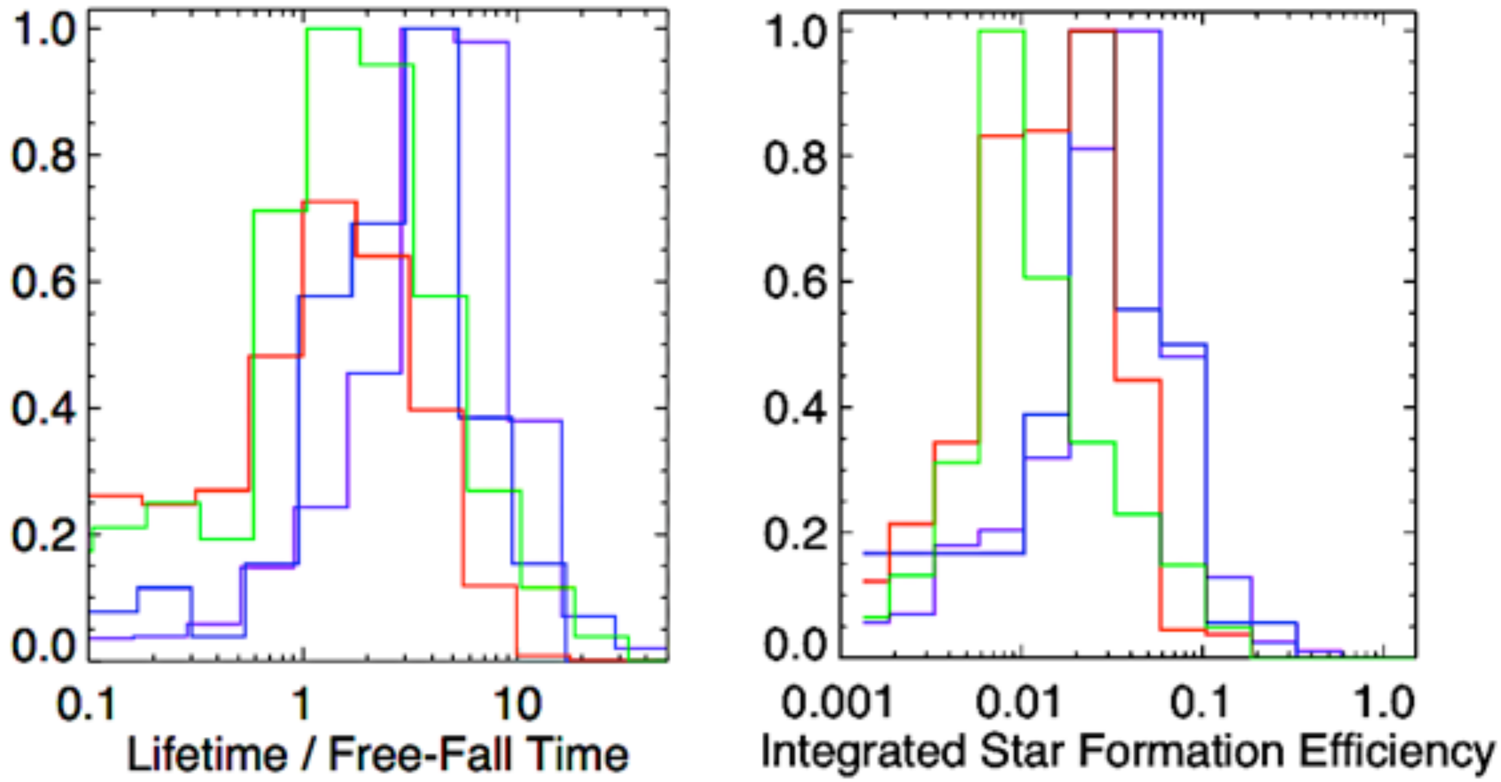


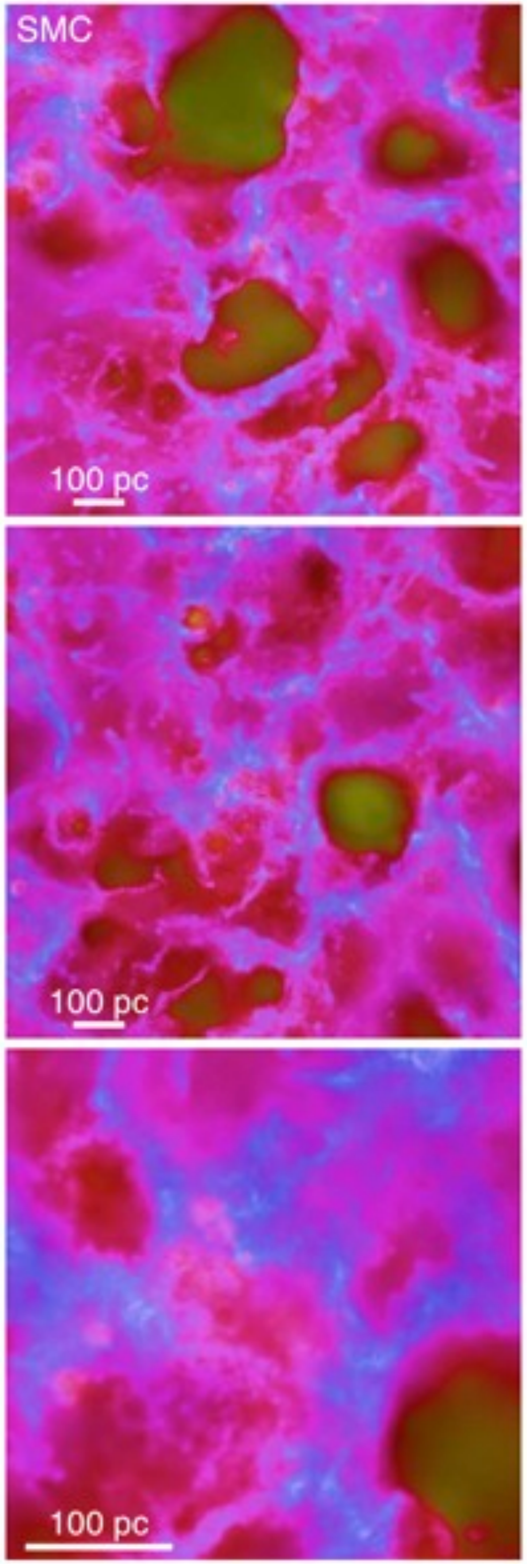


- Turbulence + Gravity:
  - **Promote** collapse (shocks)
  - **Prevent** collapse (turbulent "pressure")

Properties of "Giant Molecular Clouds"

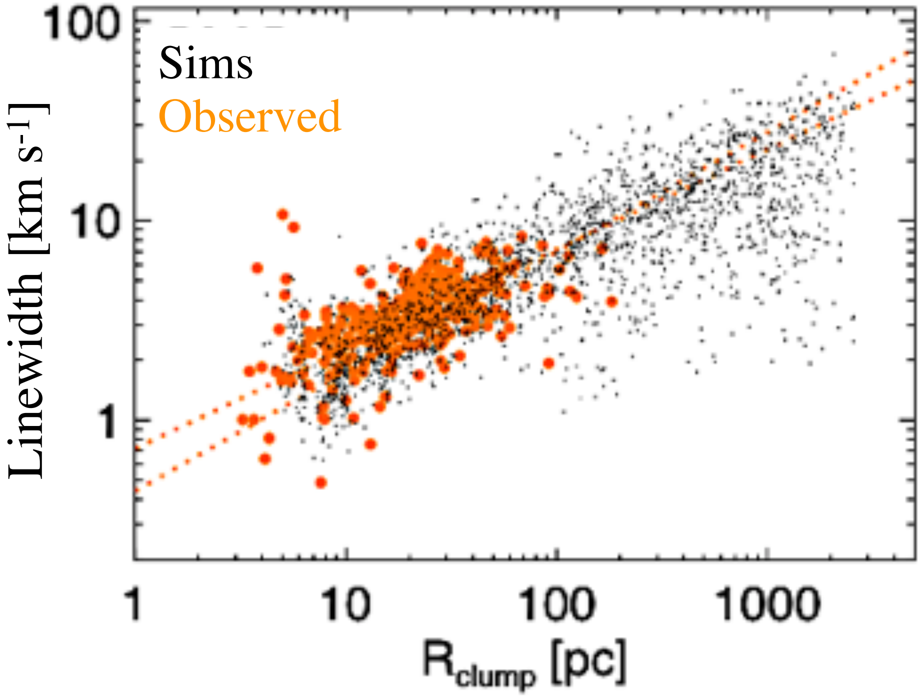
DEPENDENCE ON FEEDBACK AND OTHER SCALINGS

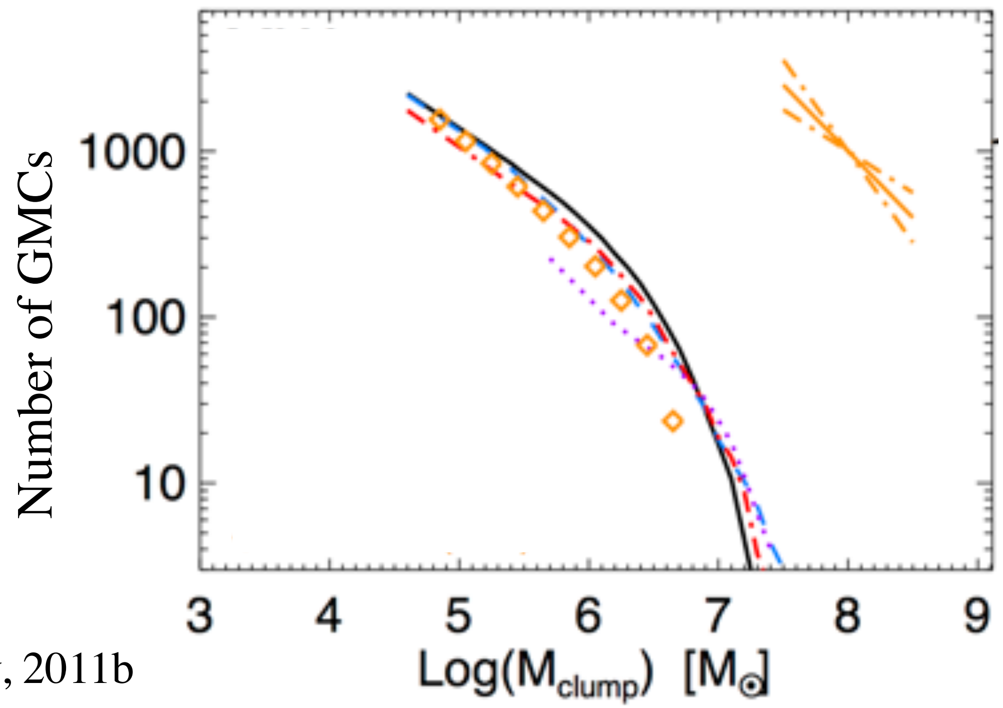


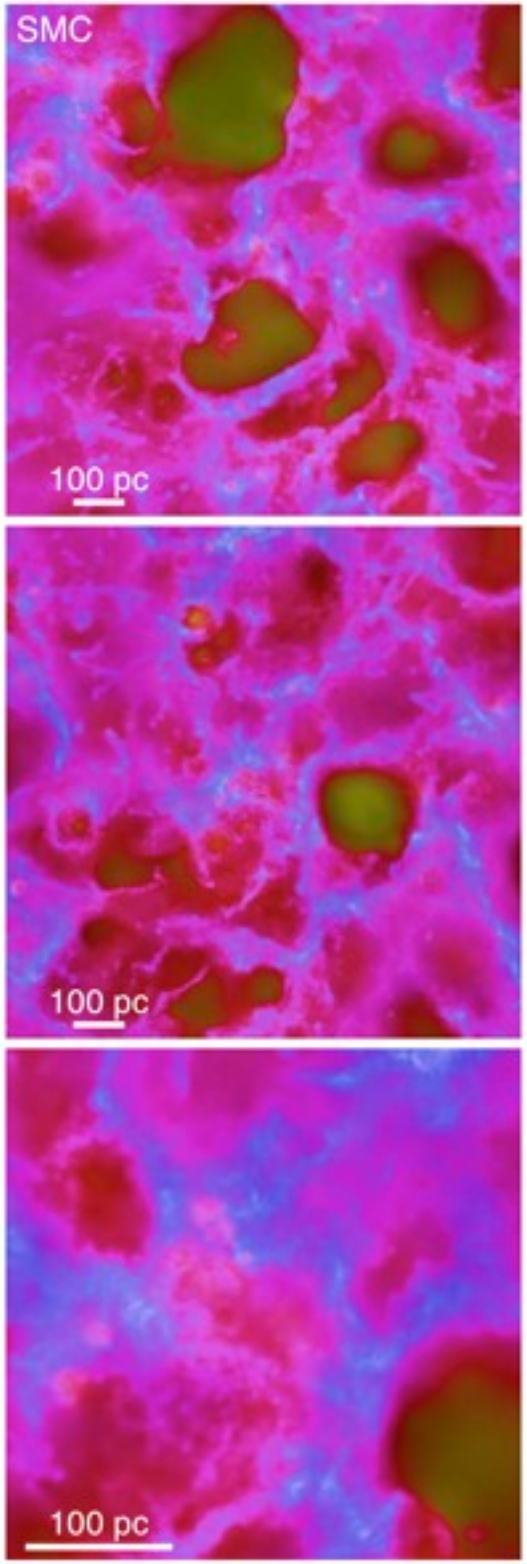


PFH, Quataert, & Murray, 2011b

Properties of Self-Gravitating GMCs & Gas “Clumps”



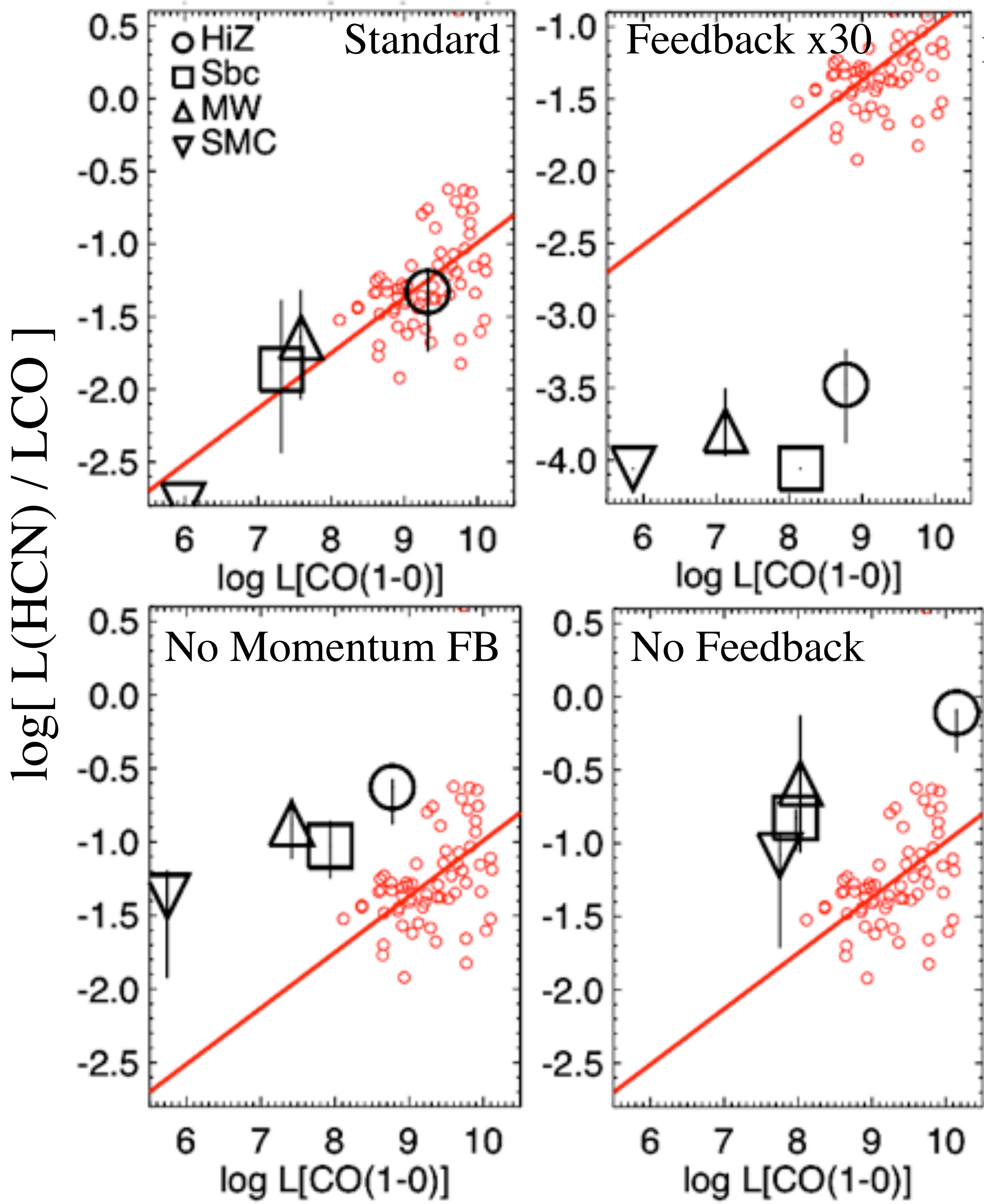




PFH, Quataert, & Murray, 2011b

Study Chemistry in Extreme Conditions

TRACERS OF SHOCKS & RADIATION IN DENSE MEDIA

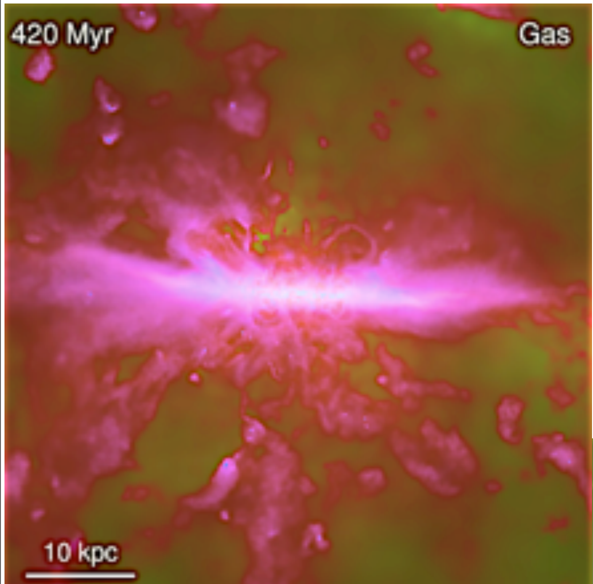


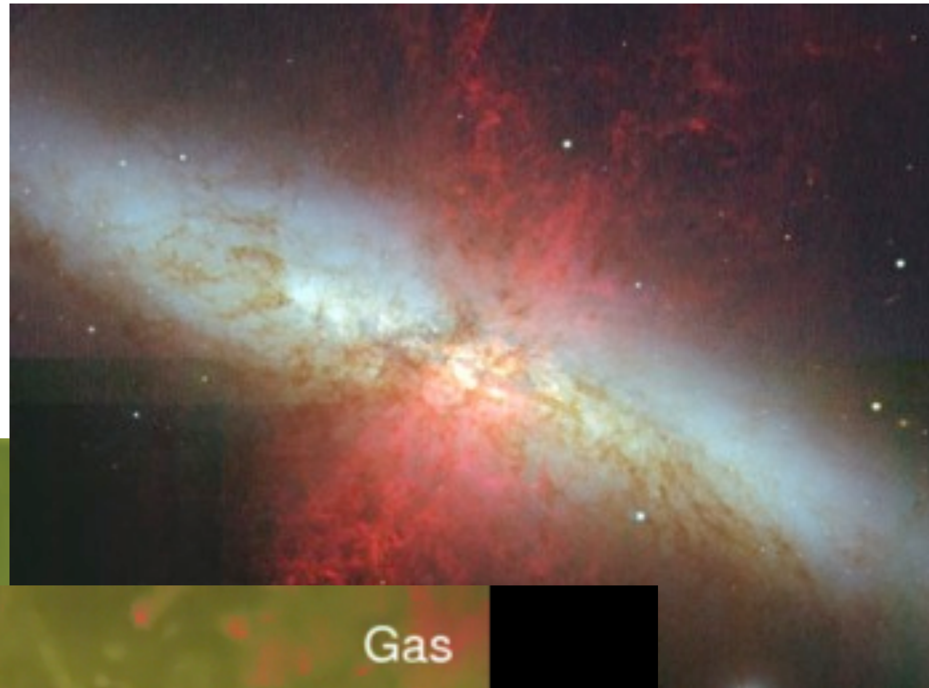
PFH, Narayanan et al. (prep)

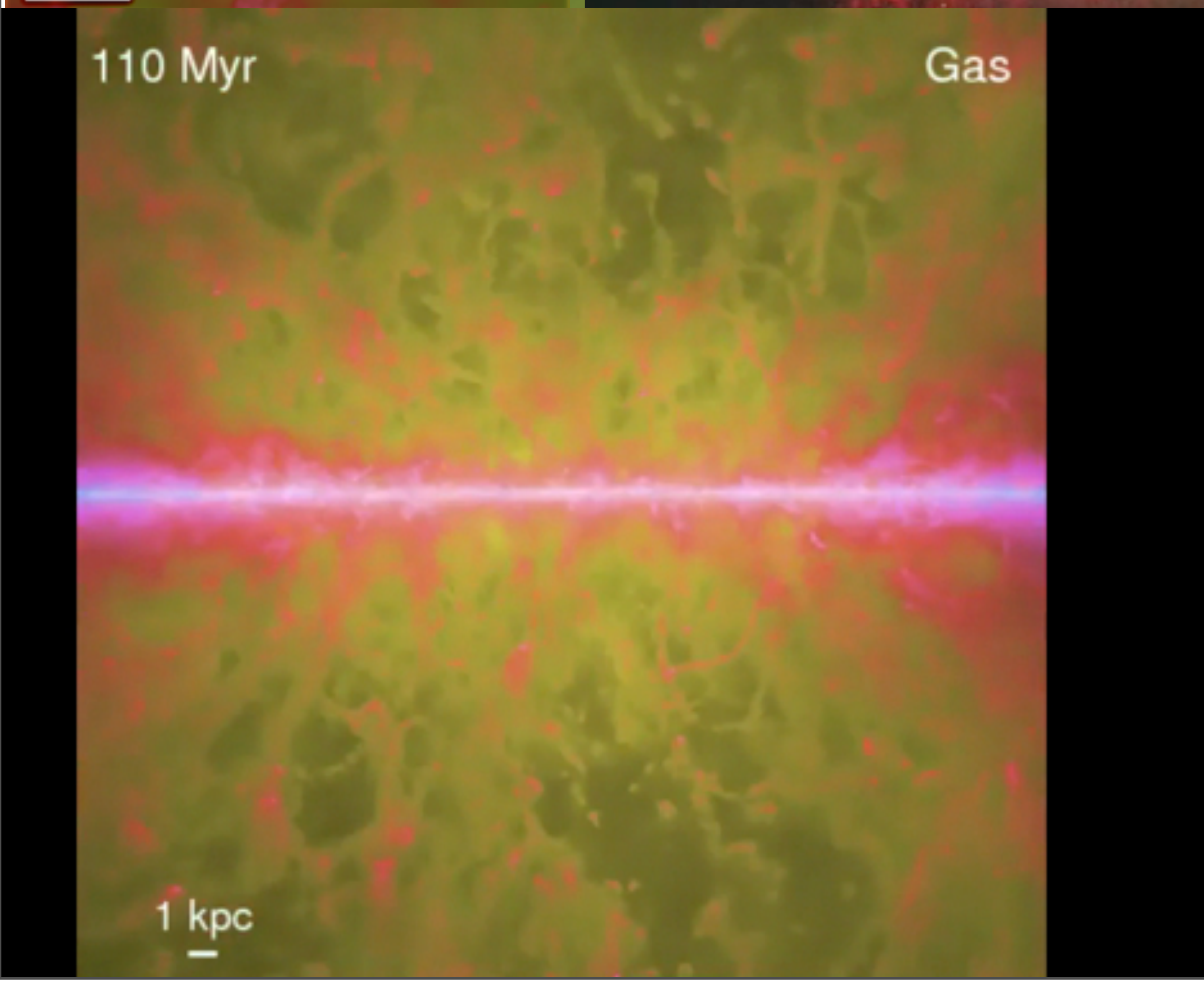
The Gas not Forming Stars:

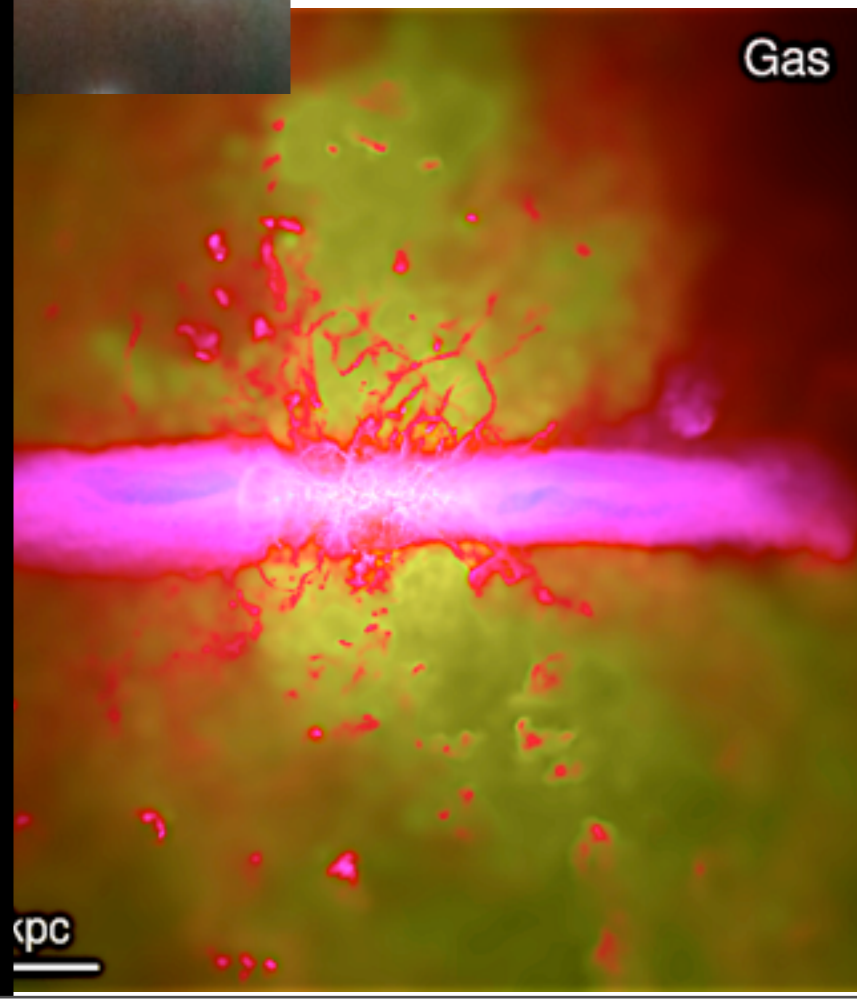
Galaxy Winds and the Baryon Cycle

Galactic Super-Winds





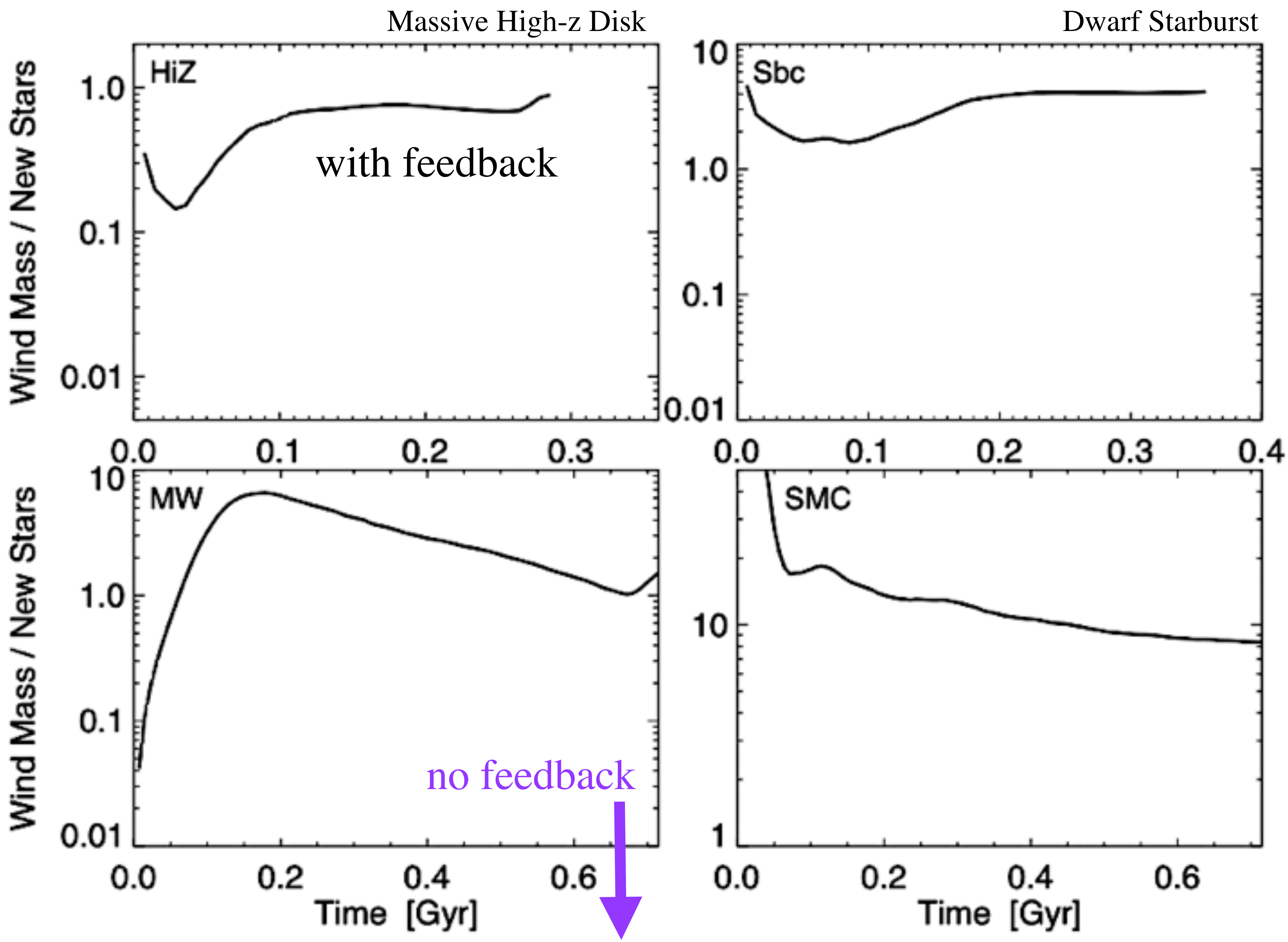




How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?

PFH, Quataert, & Murray, 2011c



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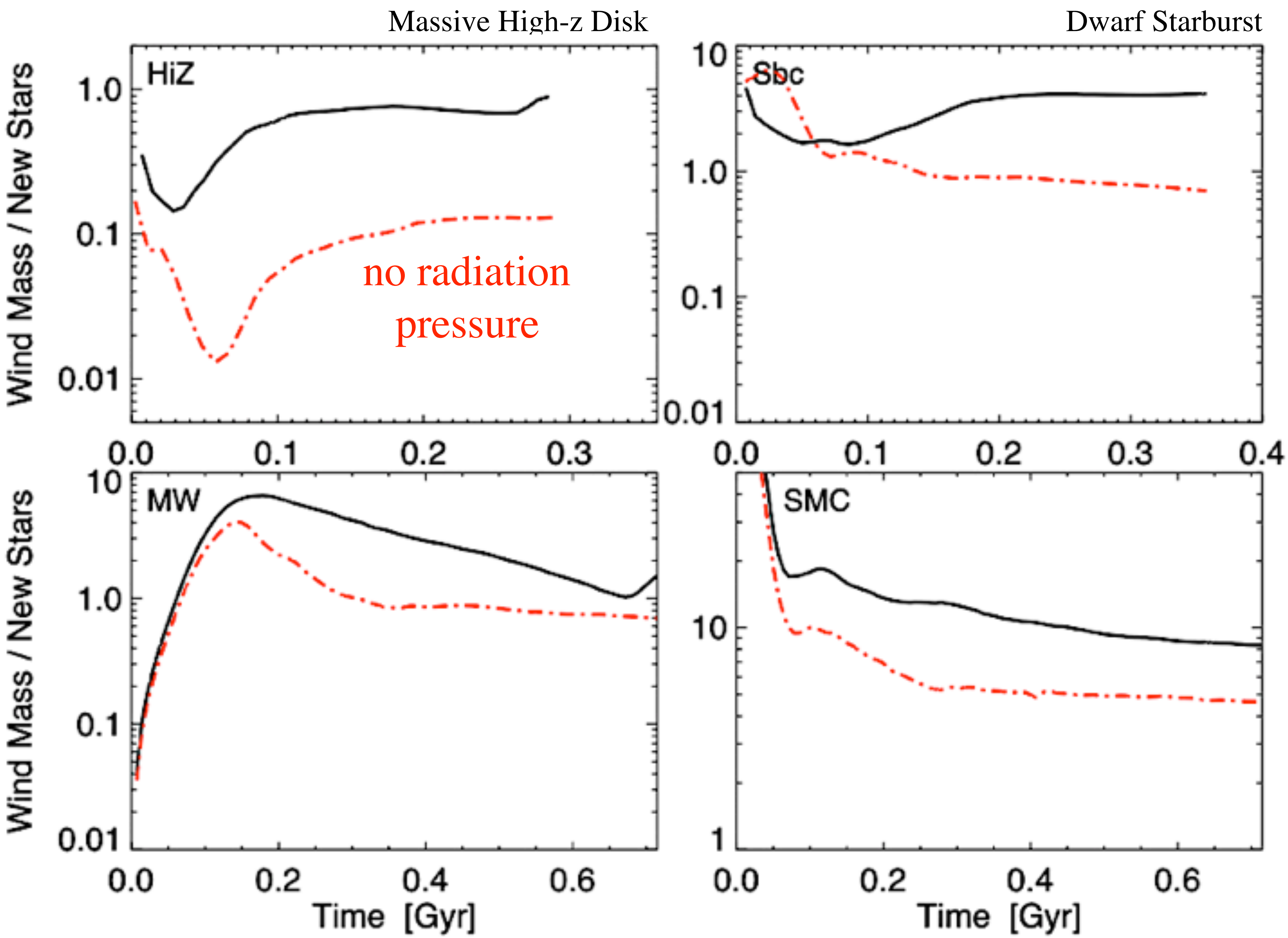
AND WHAT MECHANISMS DRIVE THEM?

PFH, Quataert, & Murray, 2011c



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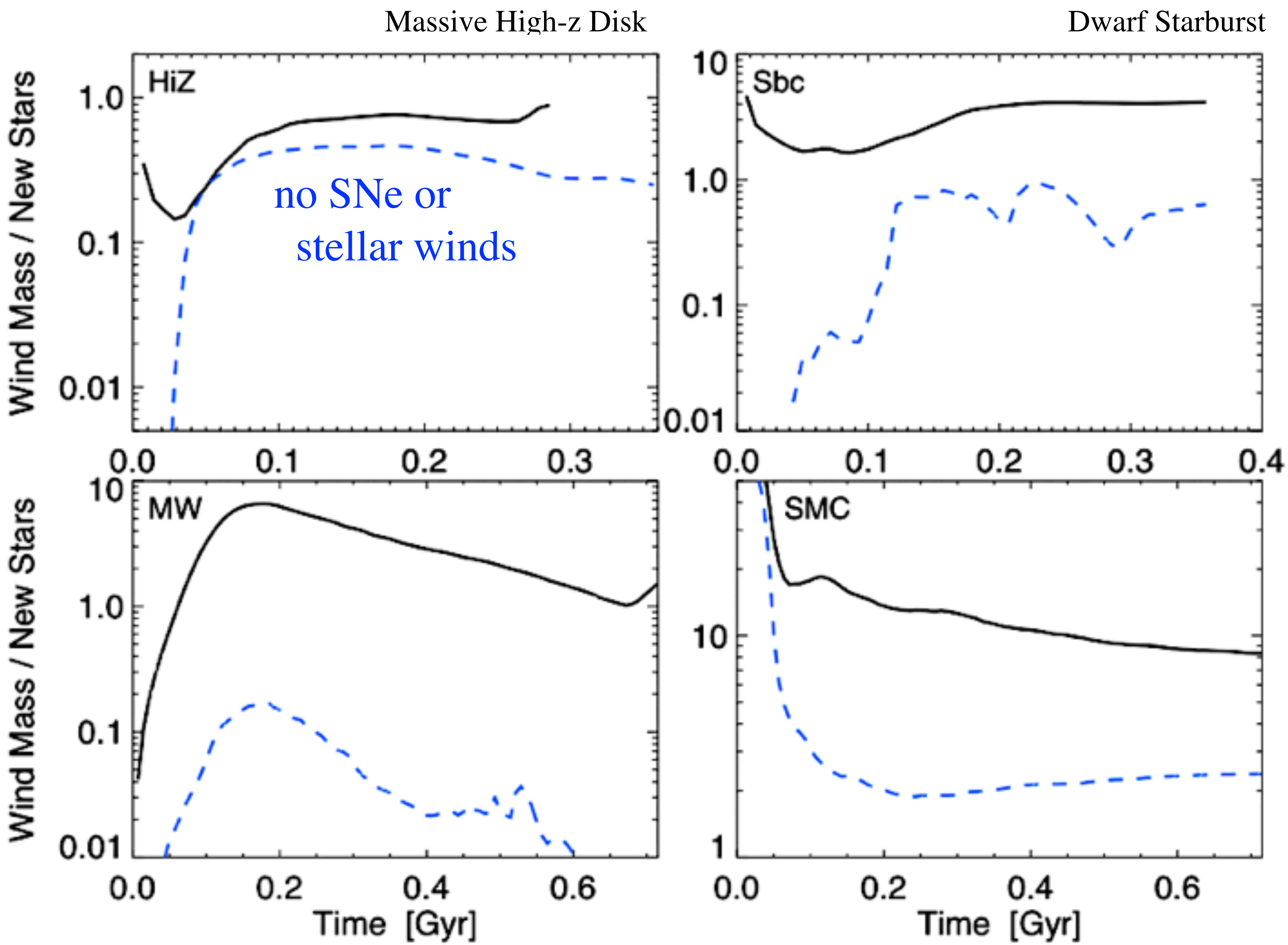

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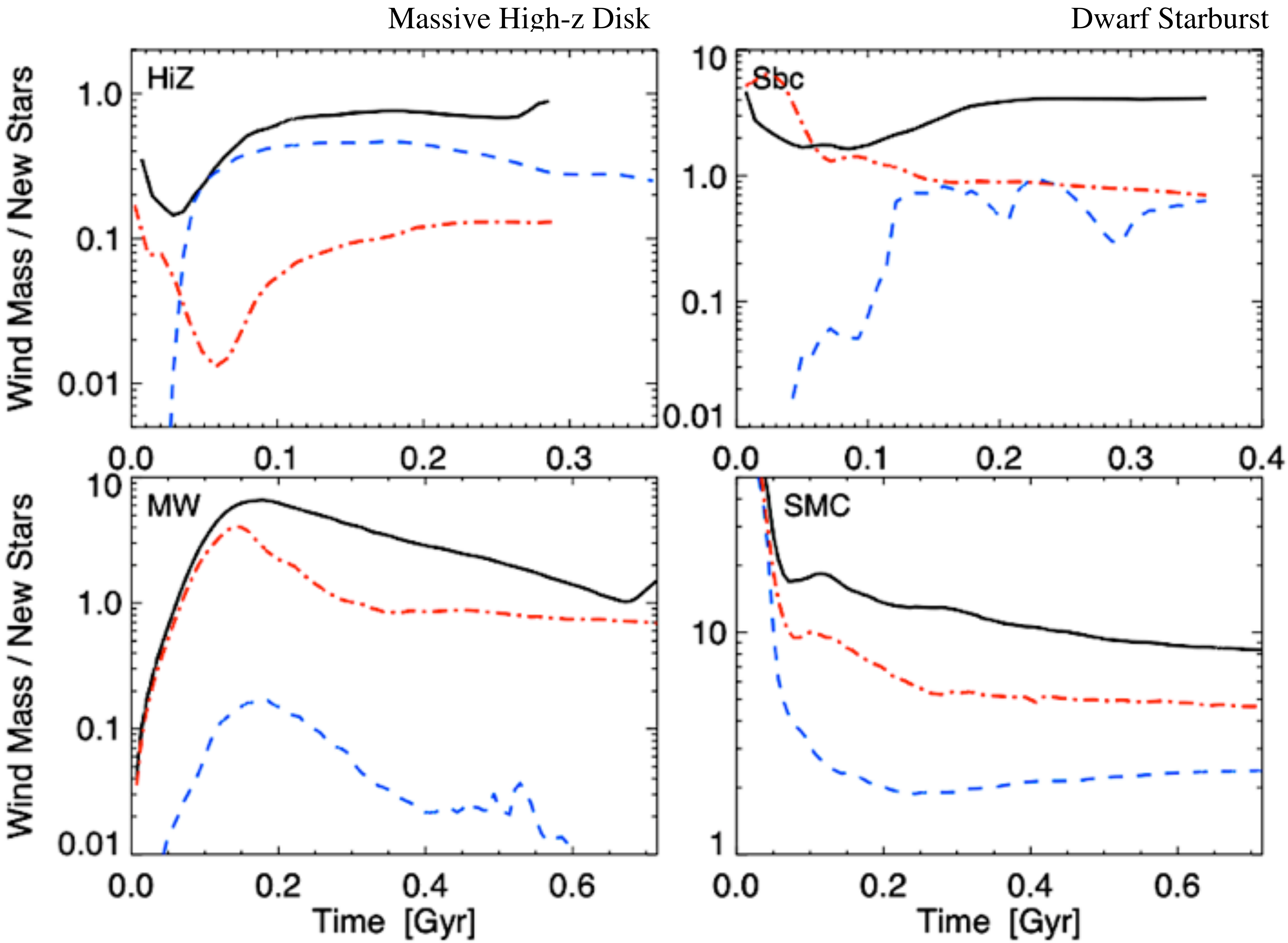

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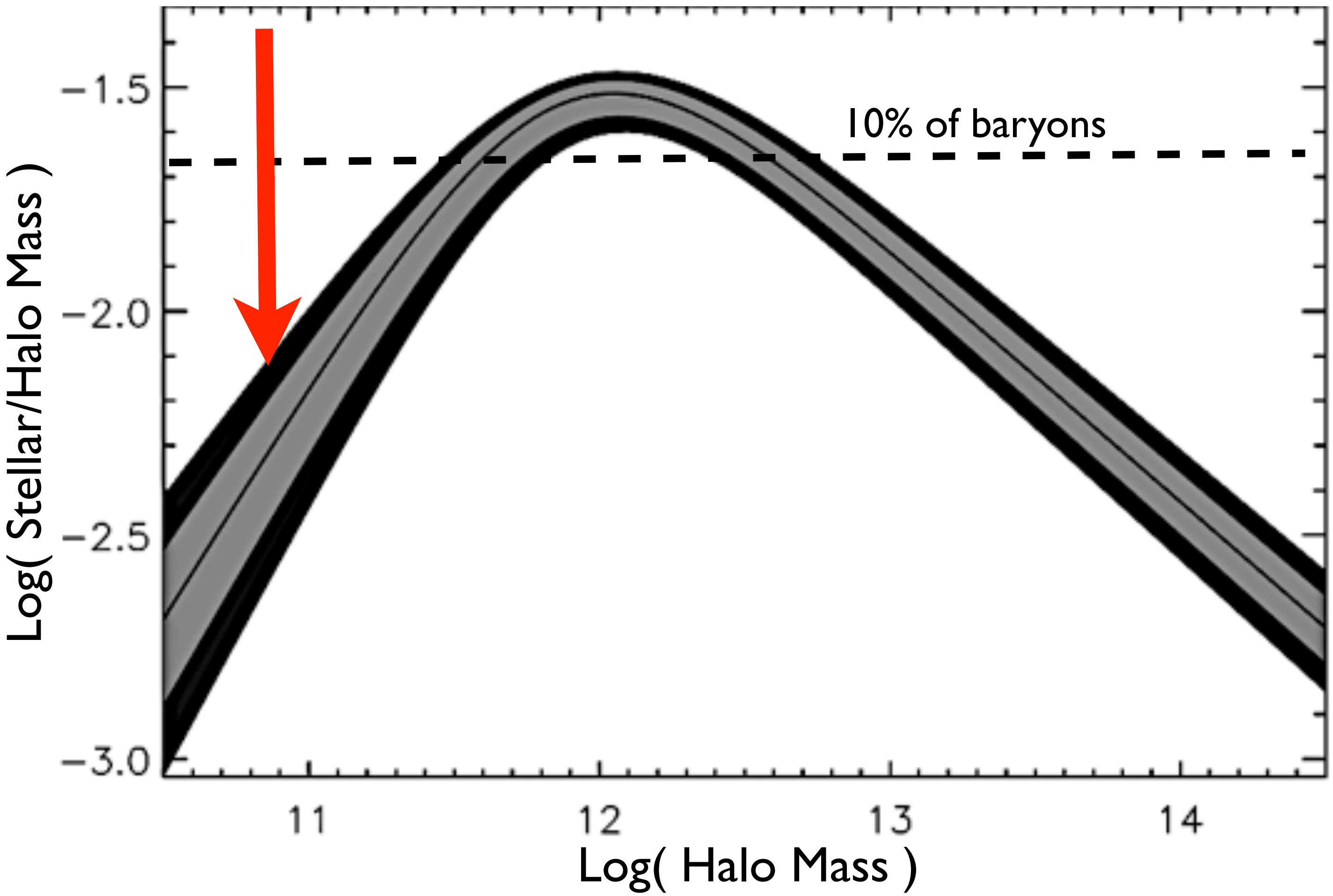

- Large mass-loading:

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

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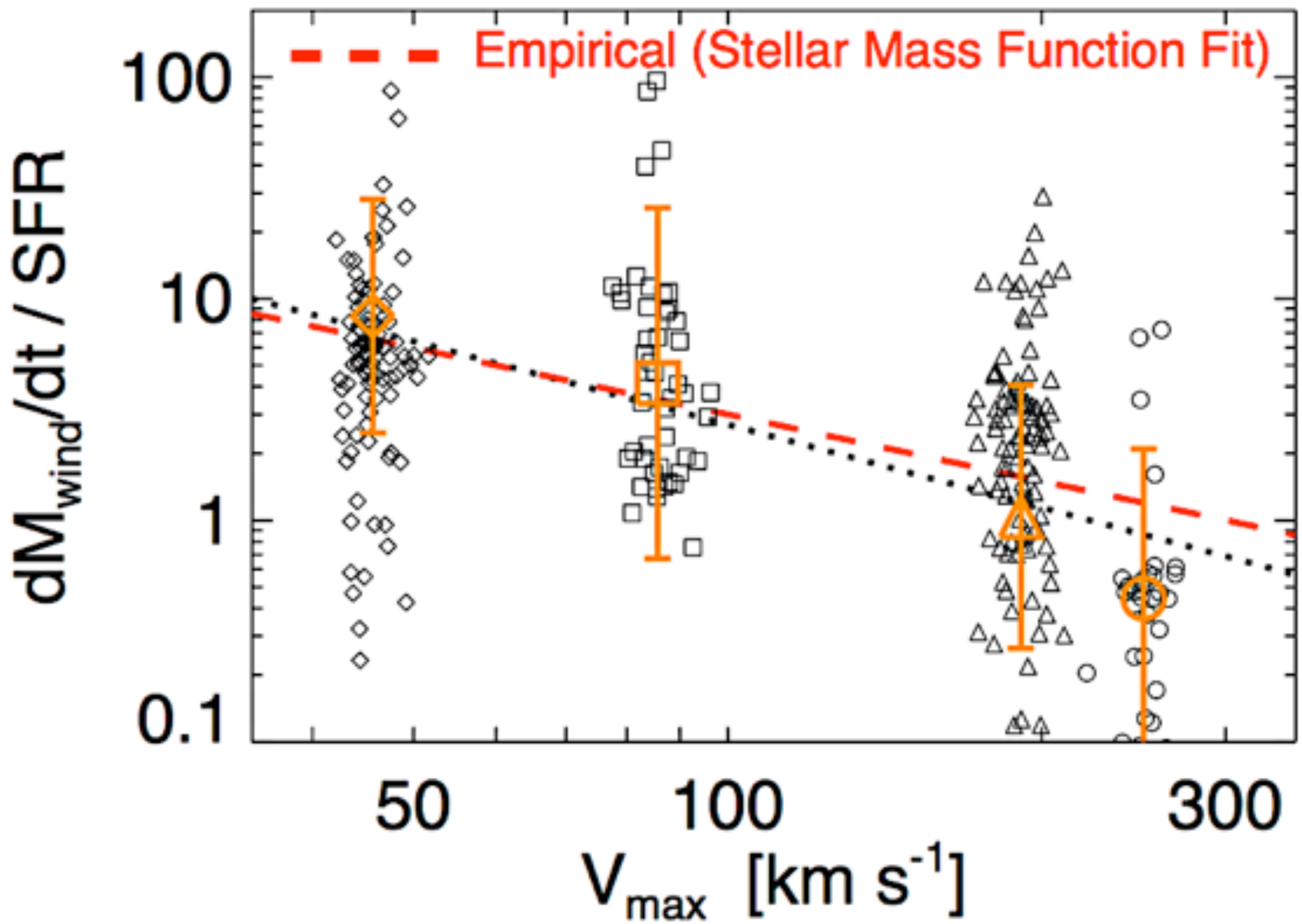

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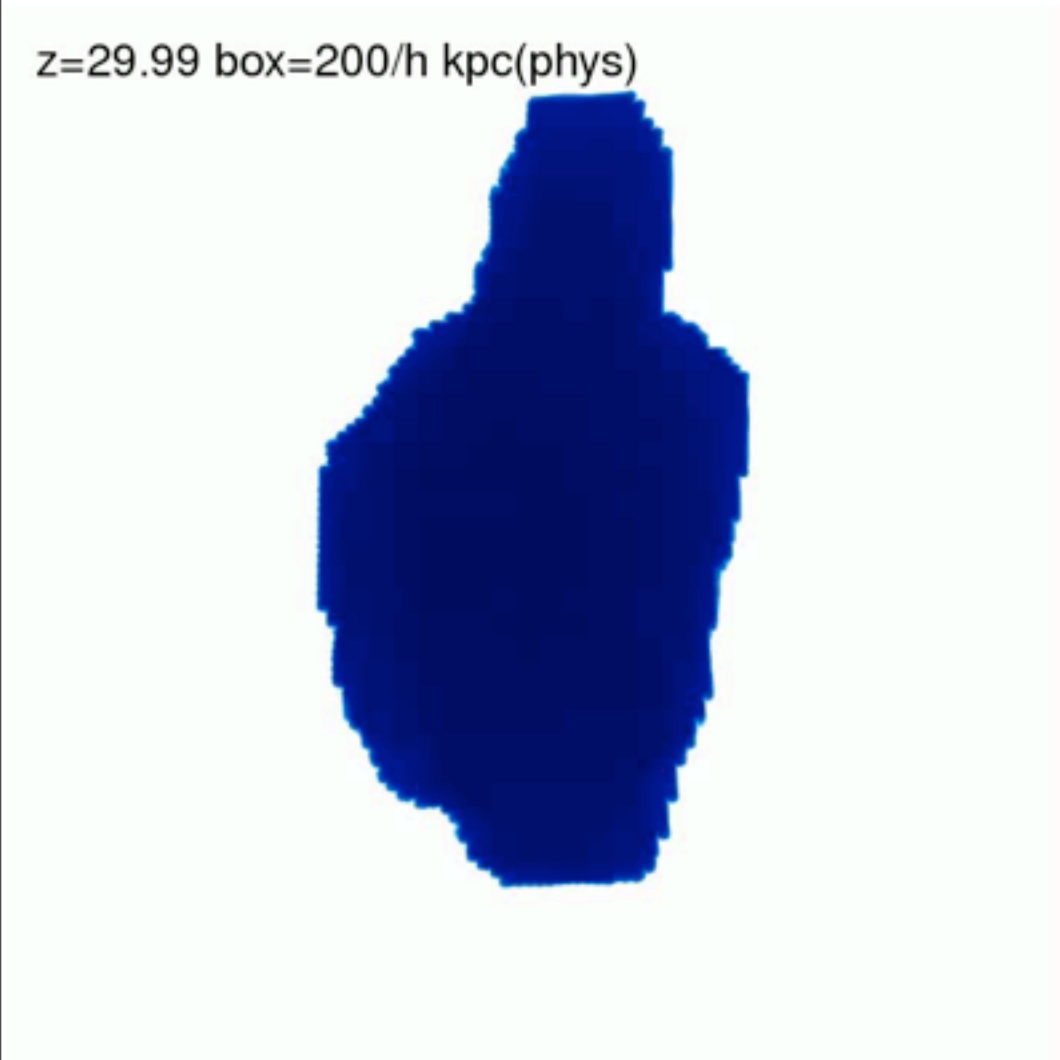
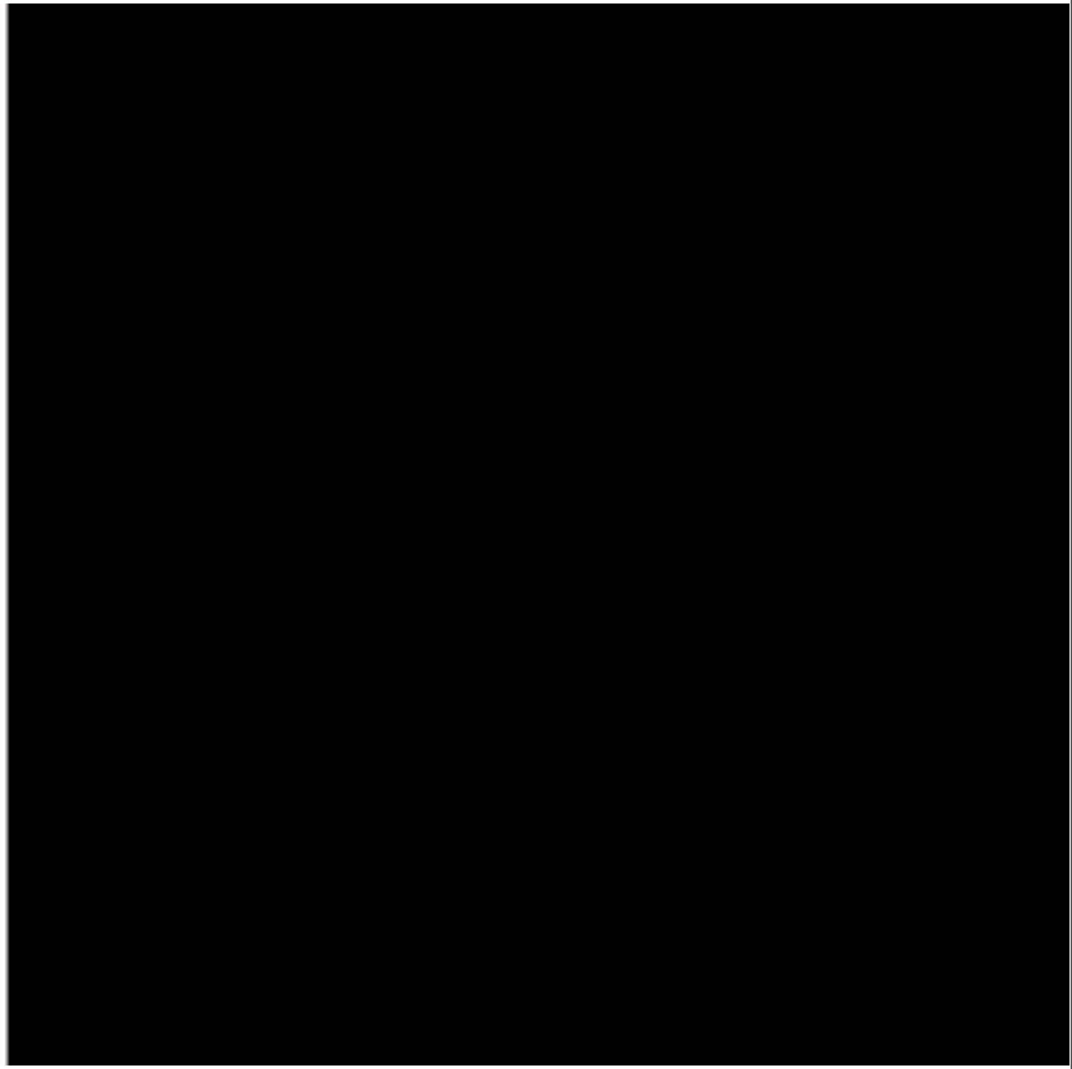
High Redshifts & The Inflow/Outflow Cycle

Cosmological Simulations

"ZOOM-IN" ON THE FORMATION OF A MASSIVE GALAXY



IGM Density

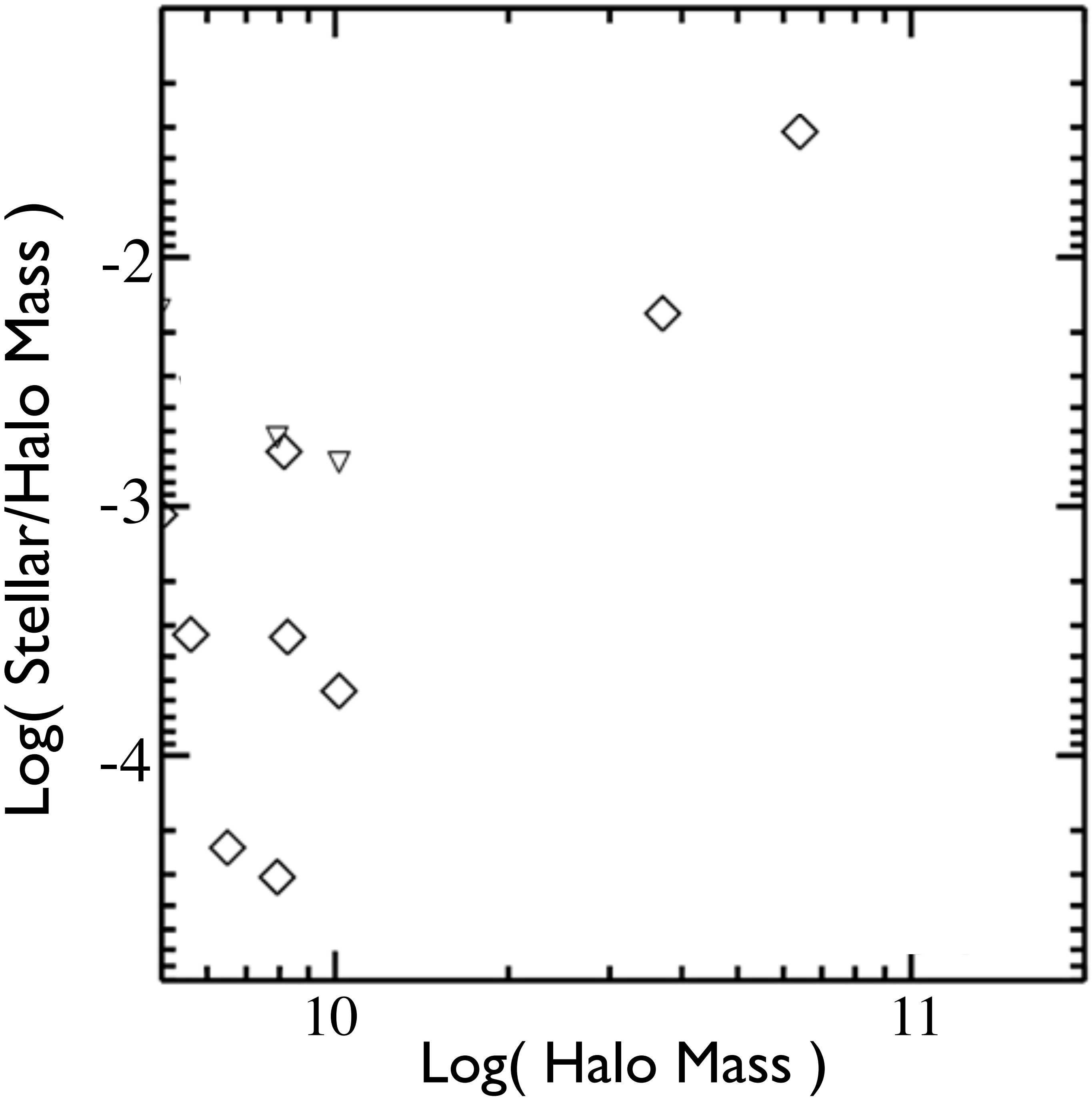


IGM Temperature

PFH & Keres et al

Should Galaxy Formation be Inefficient?

WHAT CAN WE LEARN ABOUT COSMOLOGY AND STRUCTURE FORMATION?



PFH & Keres et a

PFH, Bullock,
& Onorbe et a

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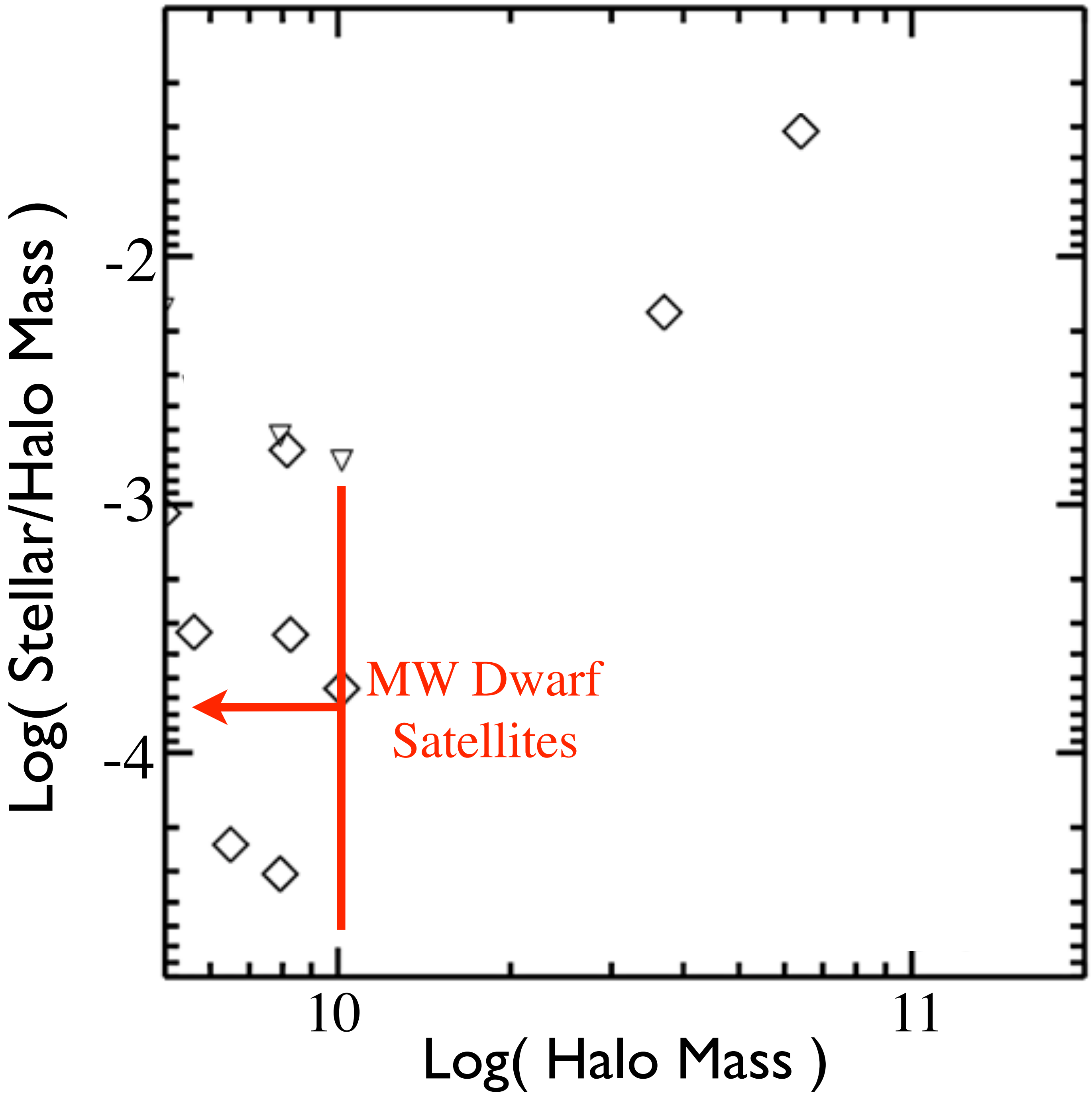

PFH & Keres et a

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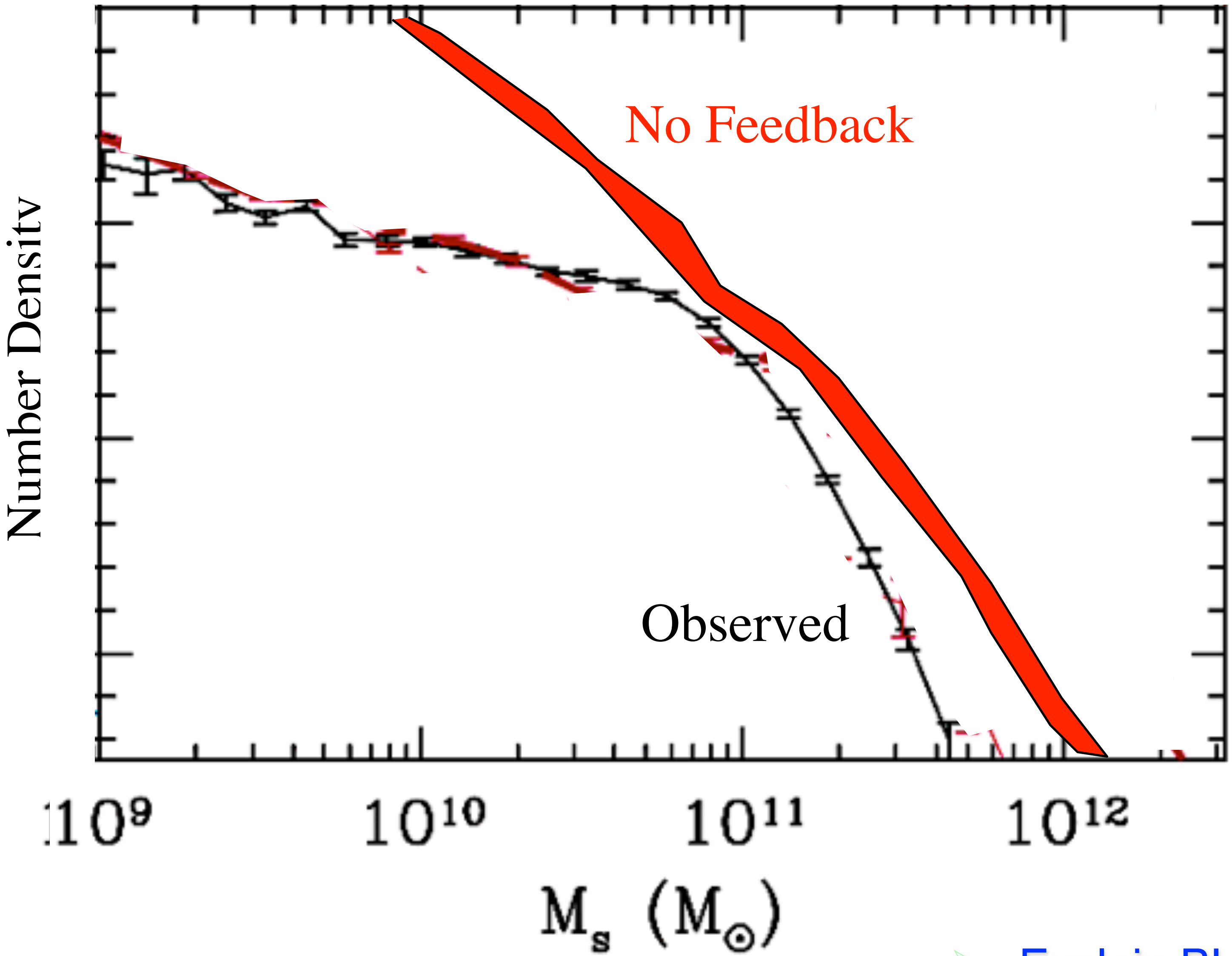
What About High-Mass Galaxies?

Why Do We Need AGN Feedback?



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

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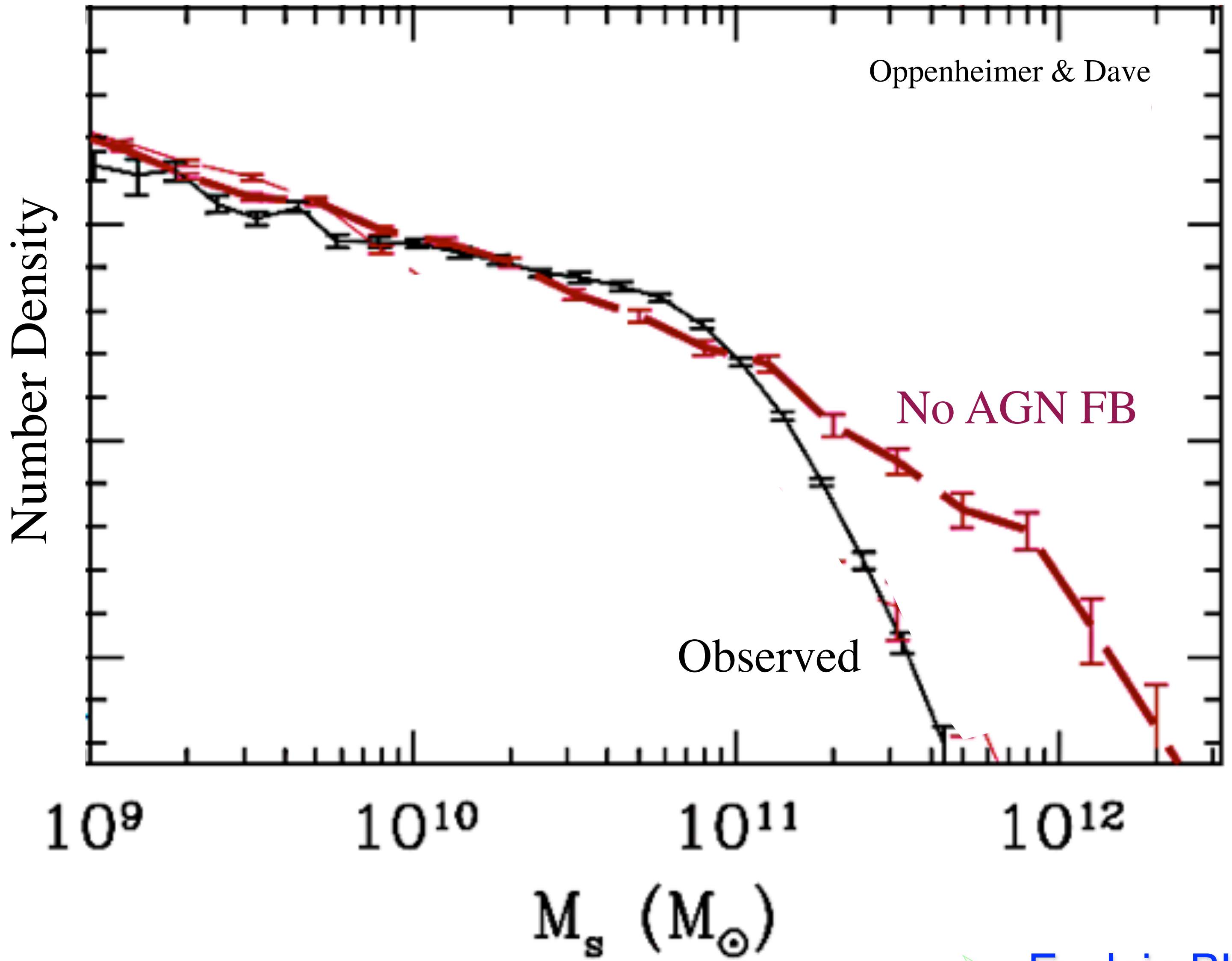

- Explain BH-host correlations
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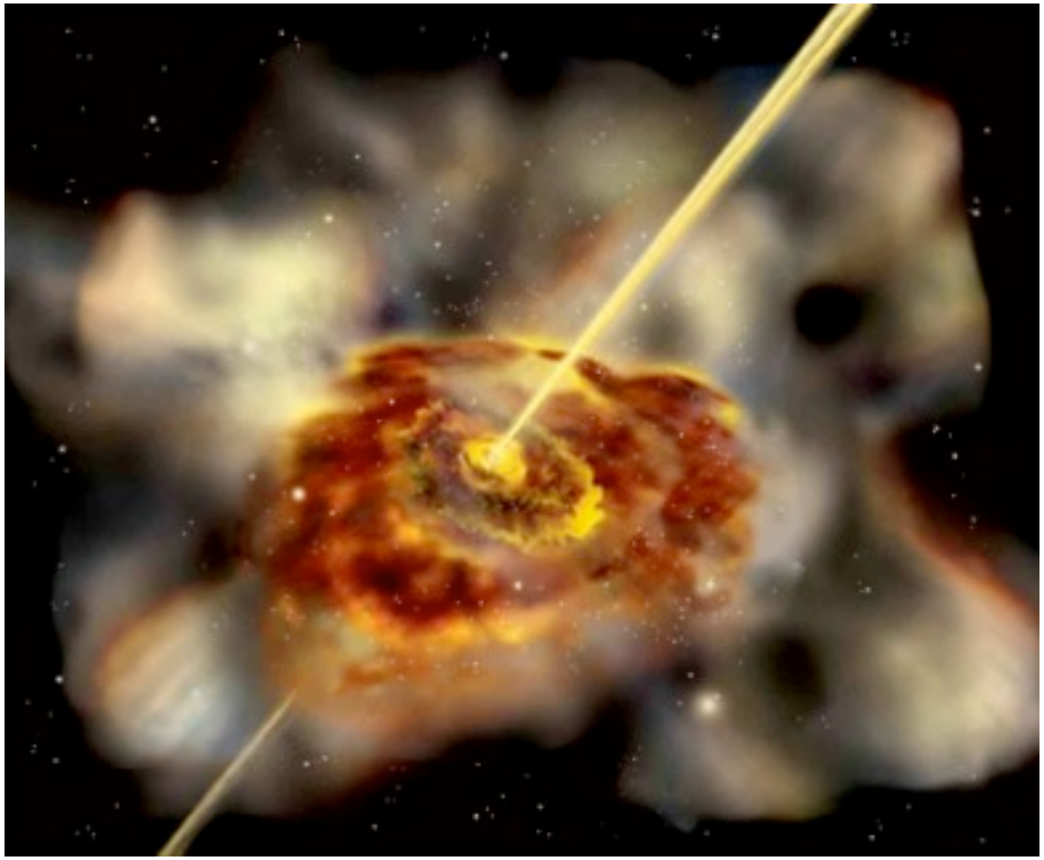
Every Massive Galaxy Hosts a Super-Massive Black Hole

MASS ACCRETED IN ~COUPLE BRIGHT QUASAR PHASES

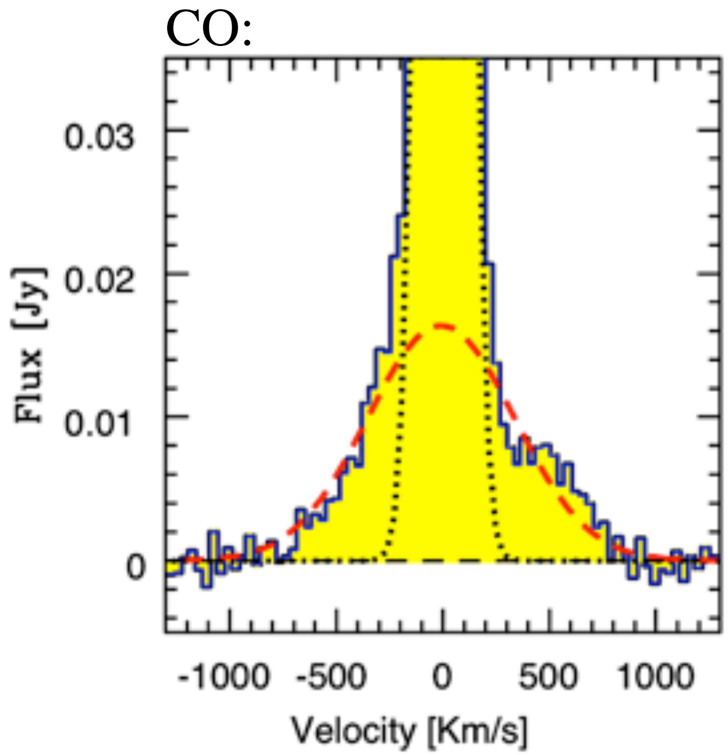


- Radiate ~10-30% of $M_{BH}c^2$:
  ~100x the binding $E_{gravity}$ of the galaxy!

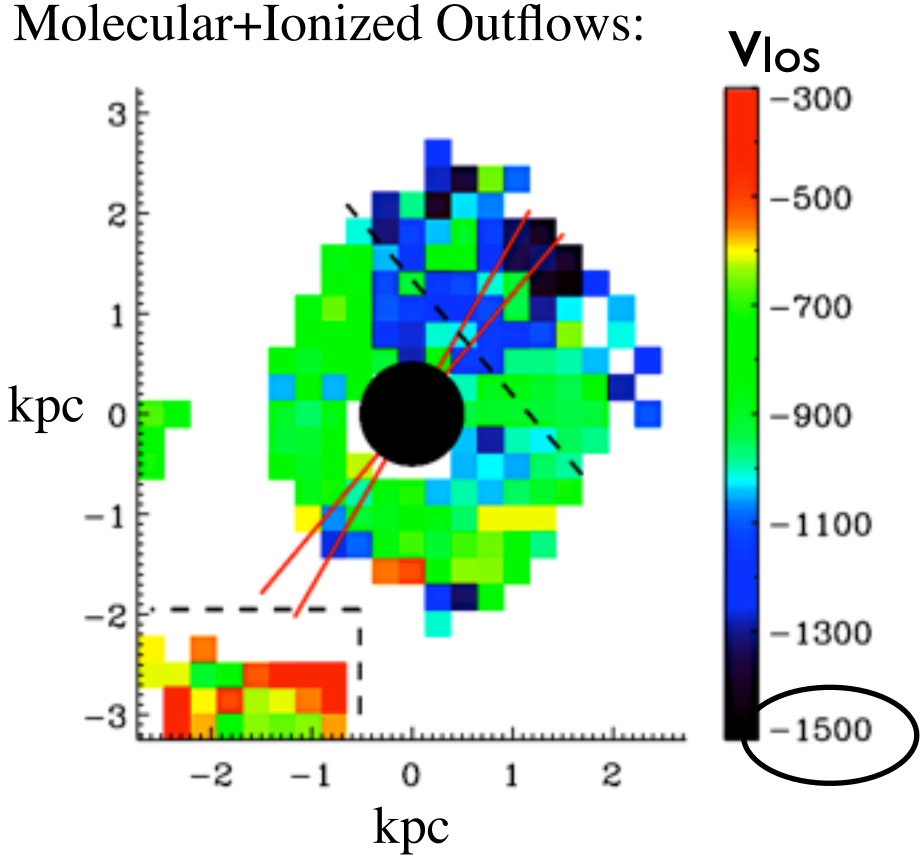
Molecular Outflows in AGN

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:



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

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

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

Where to Now? How Do We Understand 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

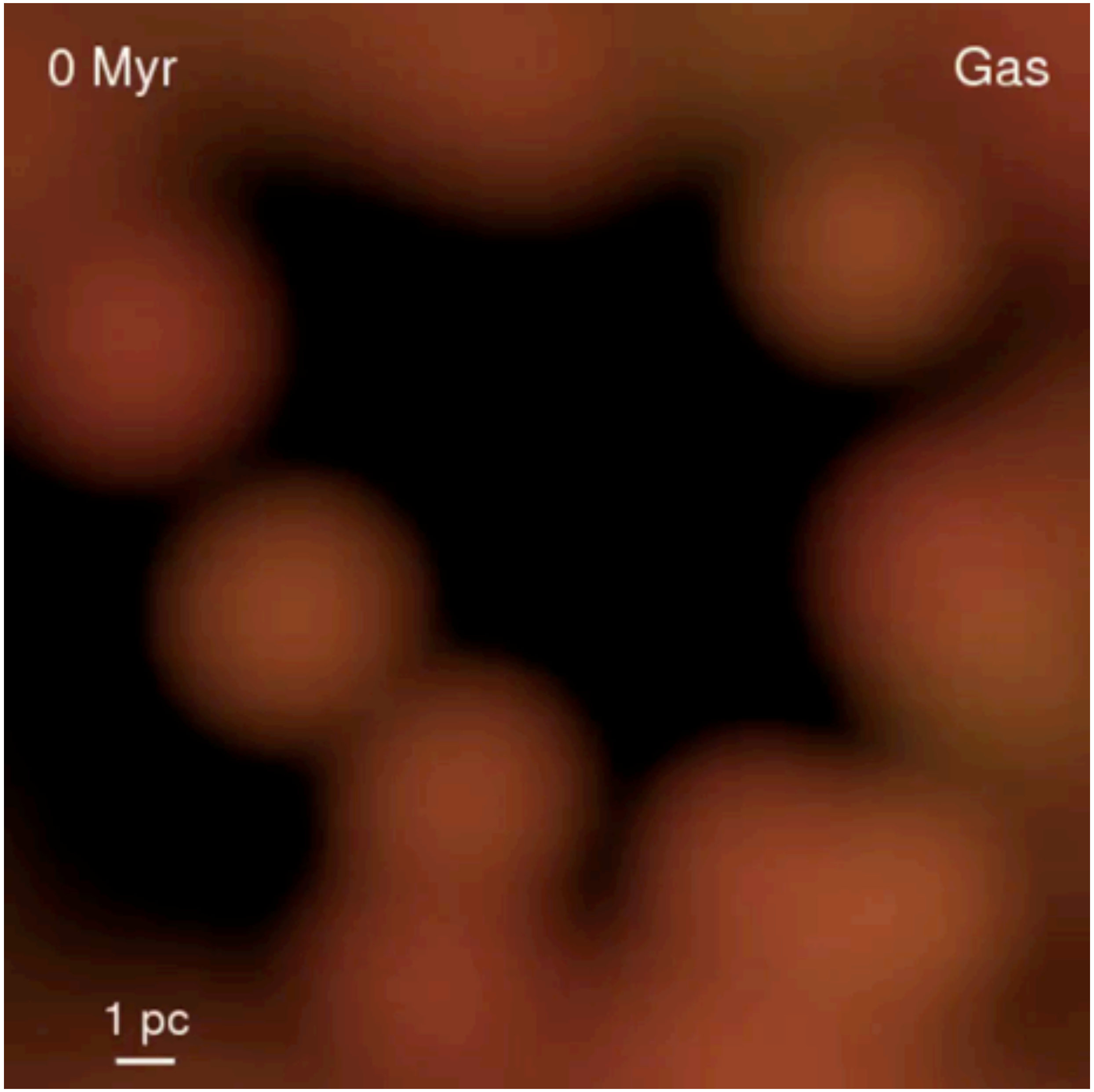
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

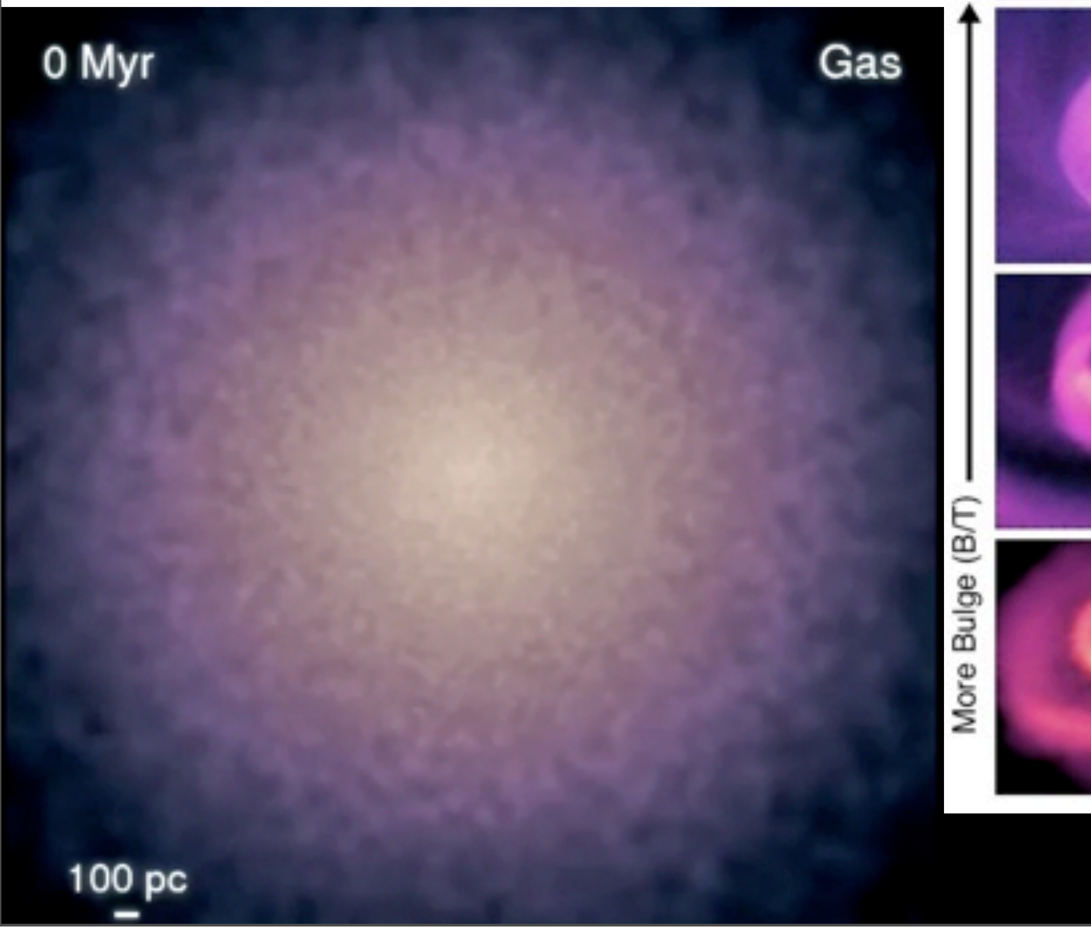
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

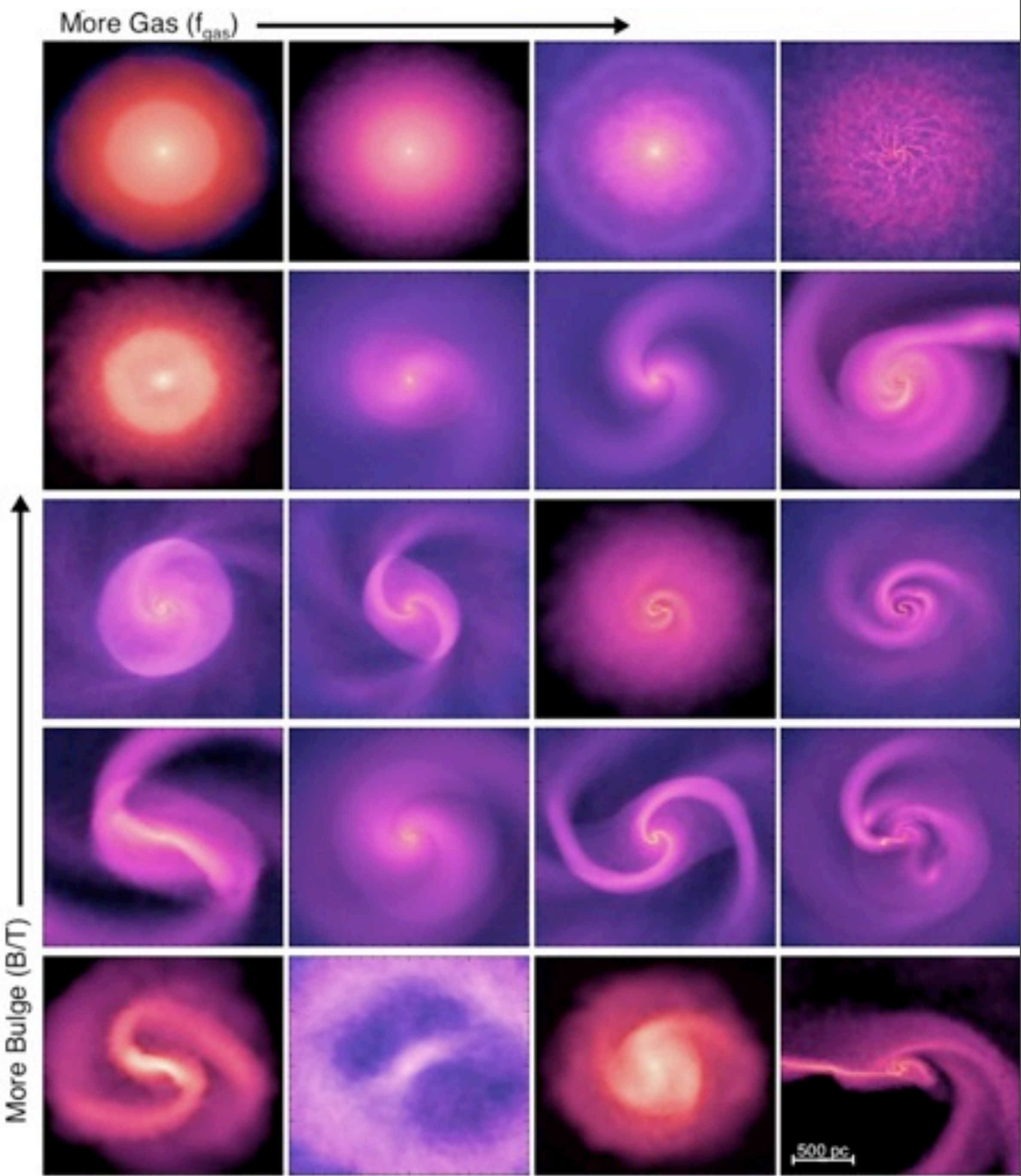


Step 2: Inflow

- 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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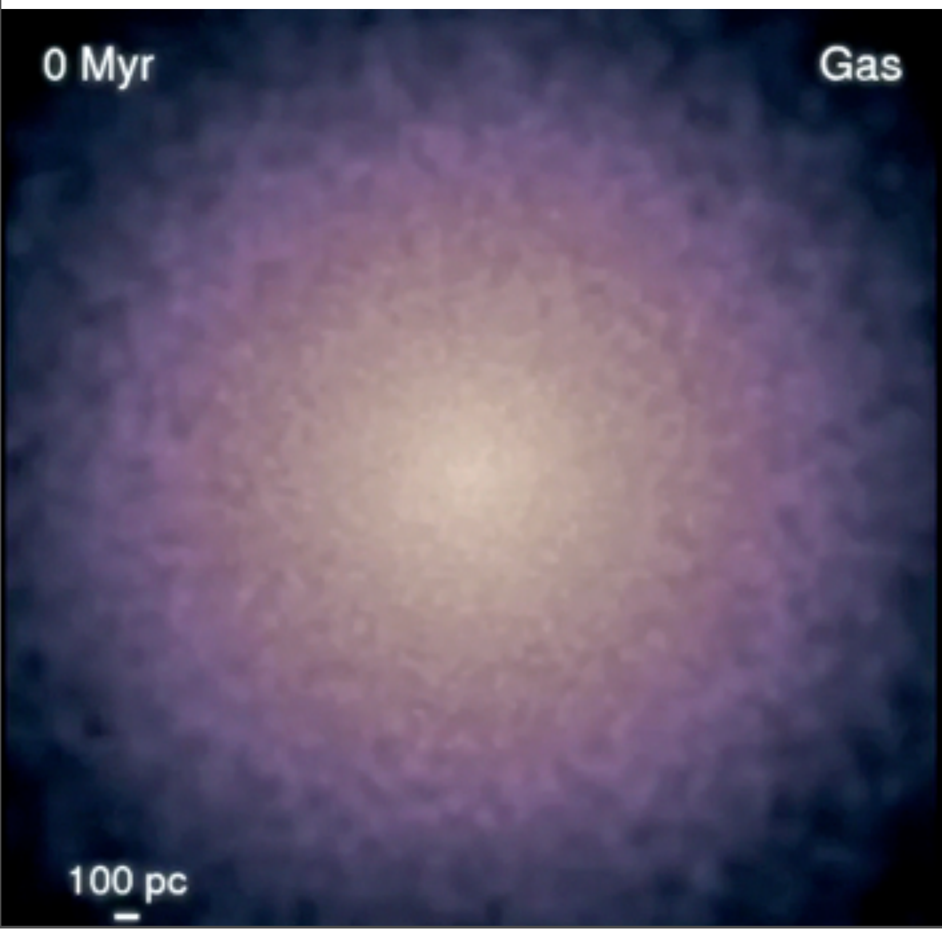
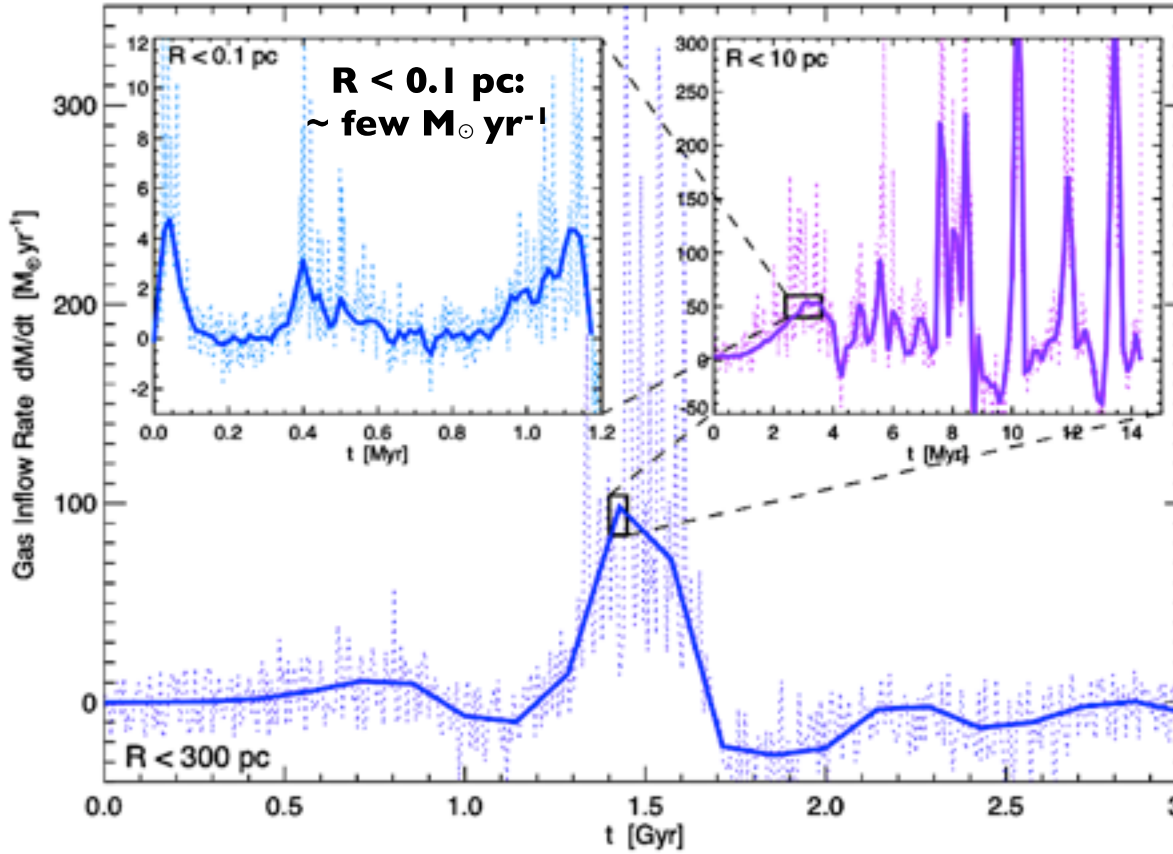
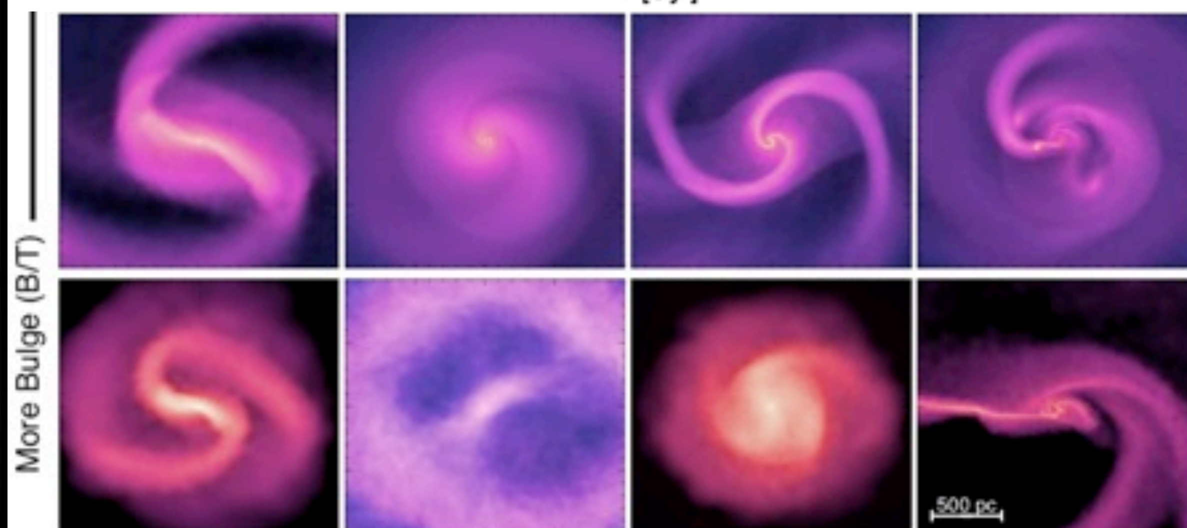
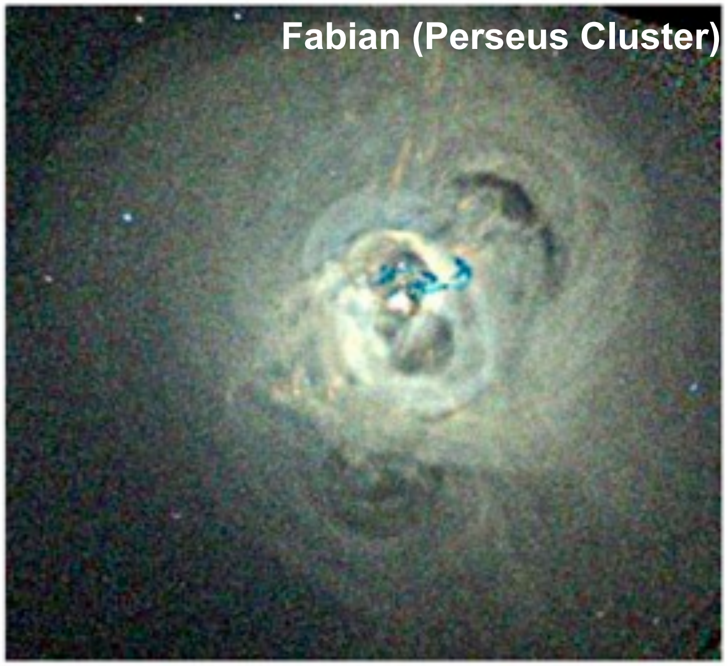






Step 3: Observed Sources of AGN Feedback



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

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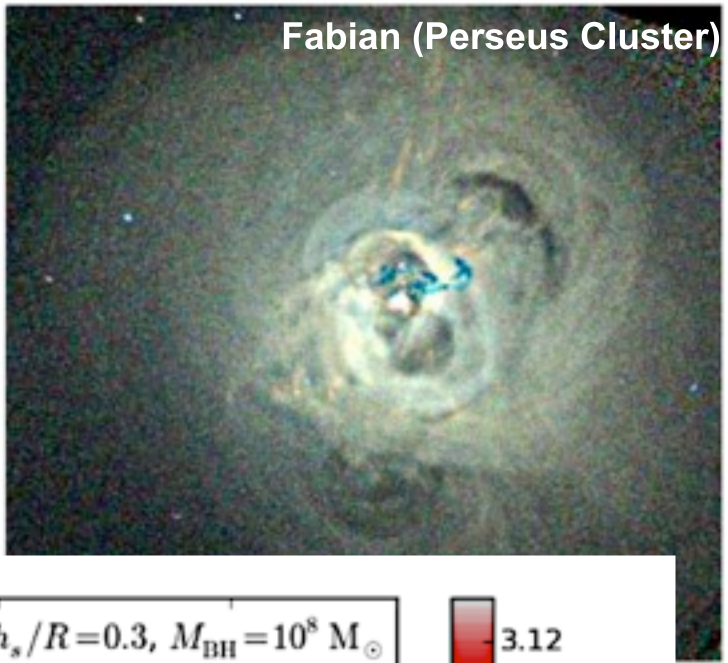
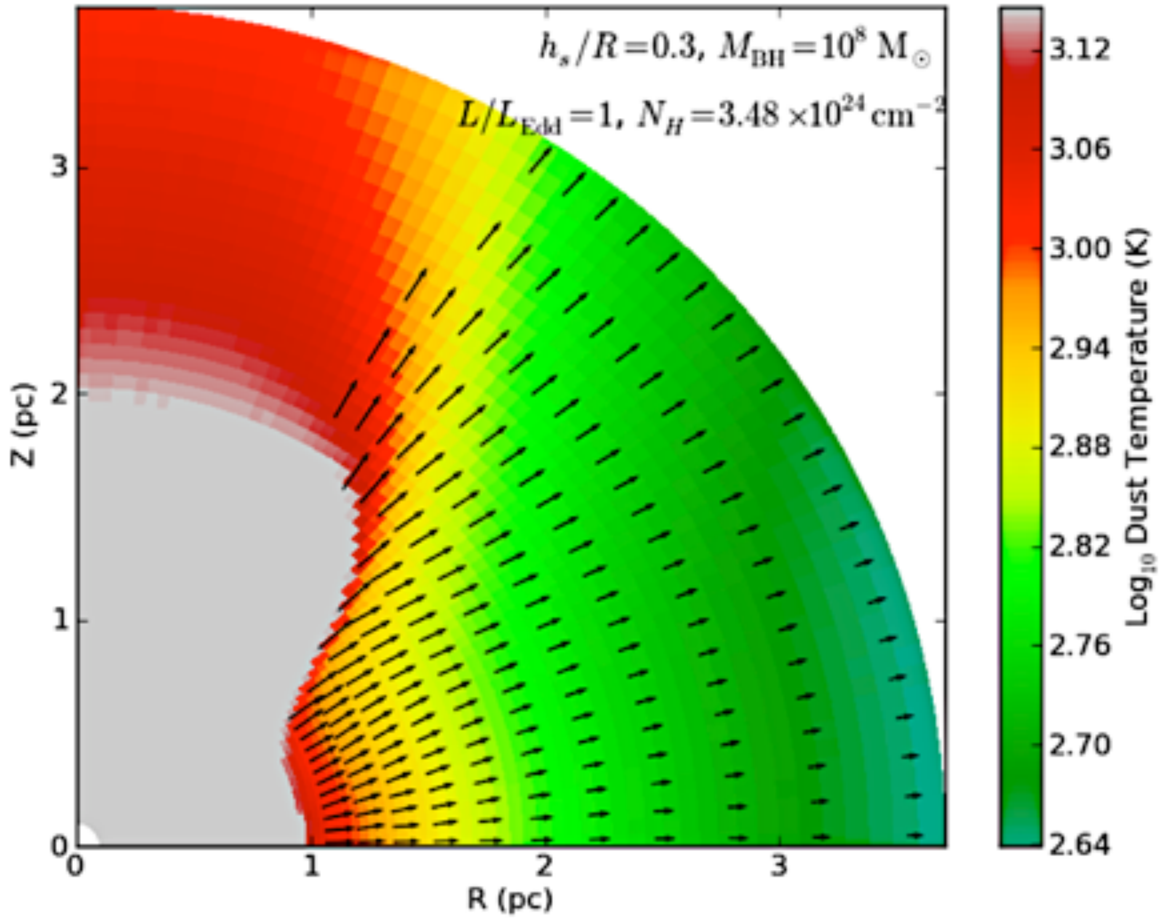
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$





Roth, Kasen, Quataert, PFH in prep

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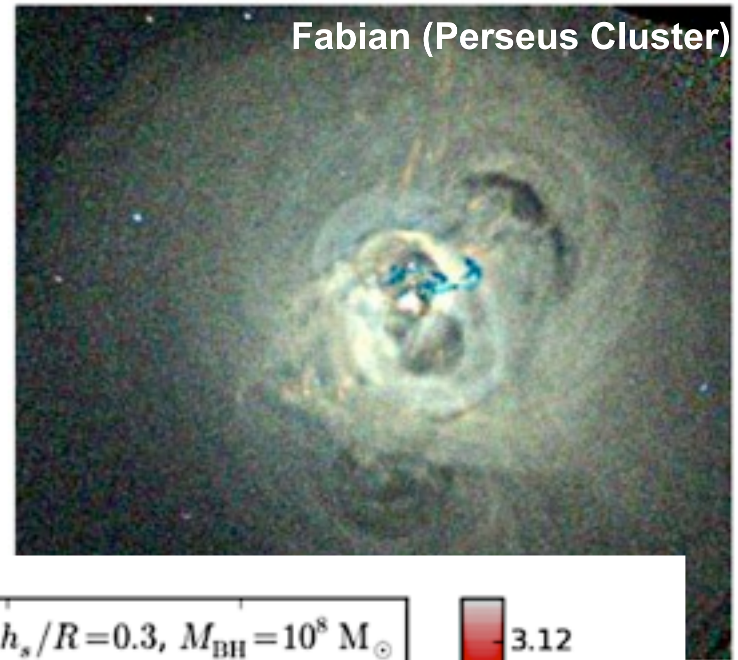
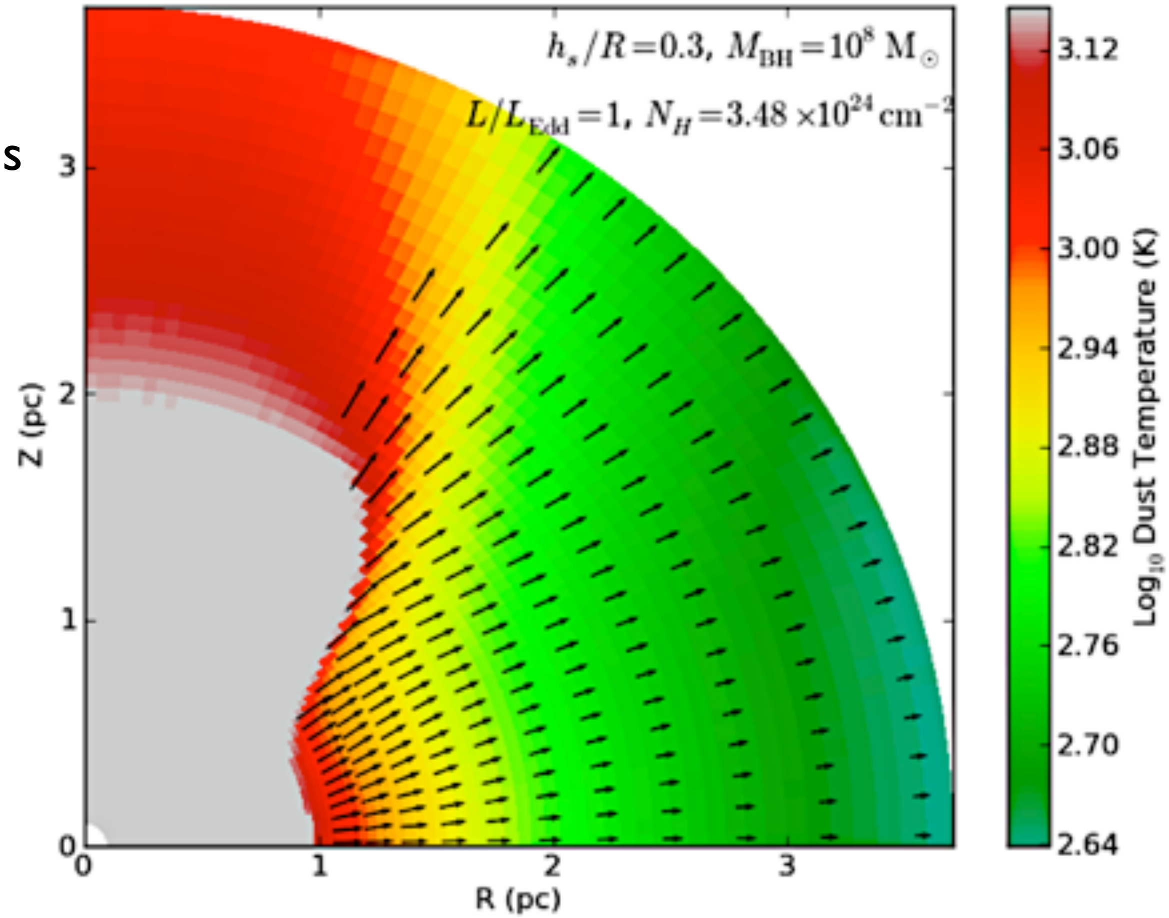


- Jets
  - heat IGM/ICM (low-density), but not dense ISM
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$
- Accretion Disk Winds
  - Broad Absorption Line Winds



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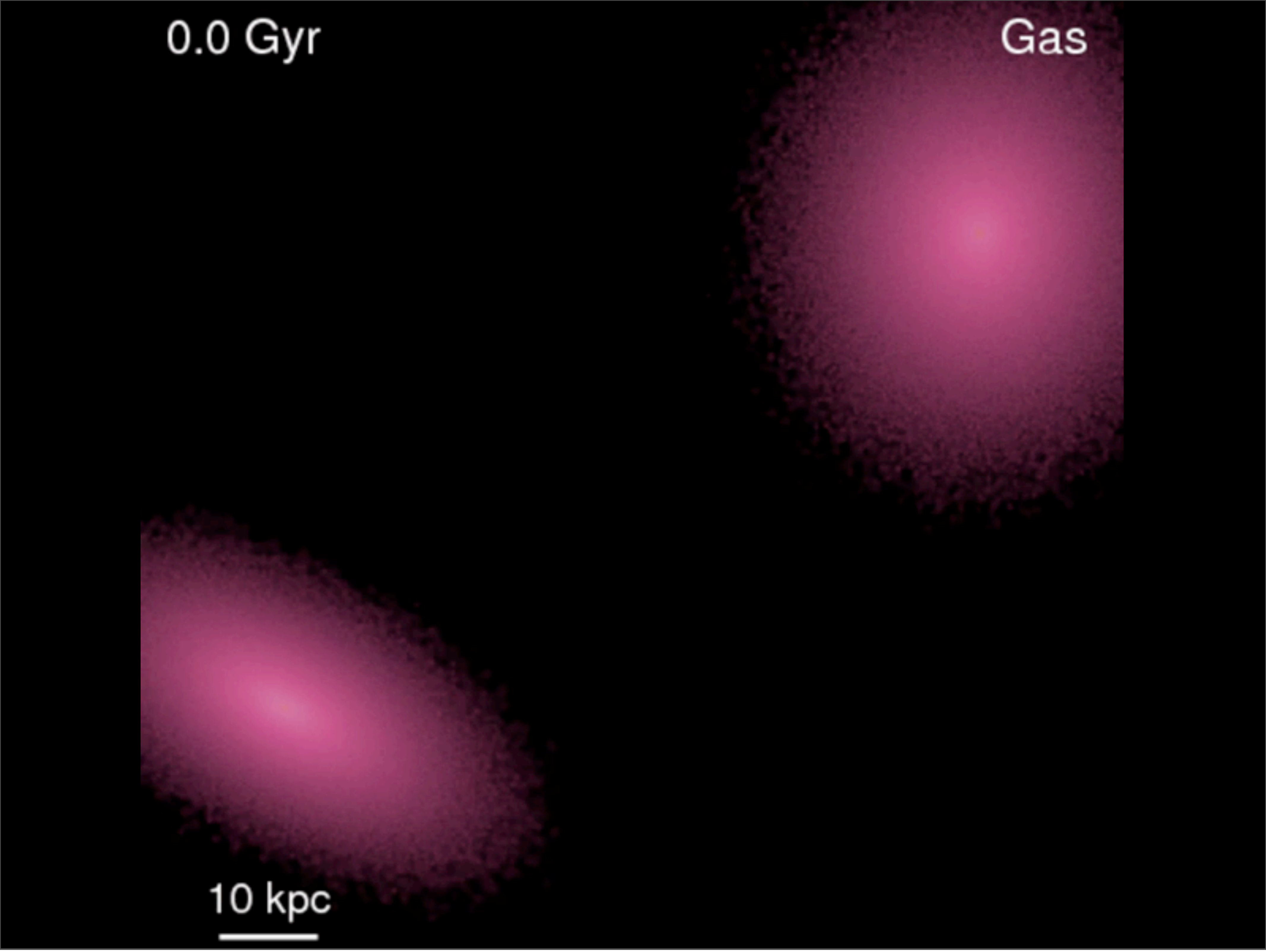

0.0 Gyr
Gas
10 kpc

Summary:

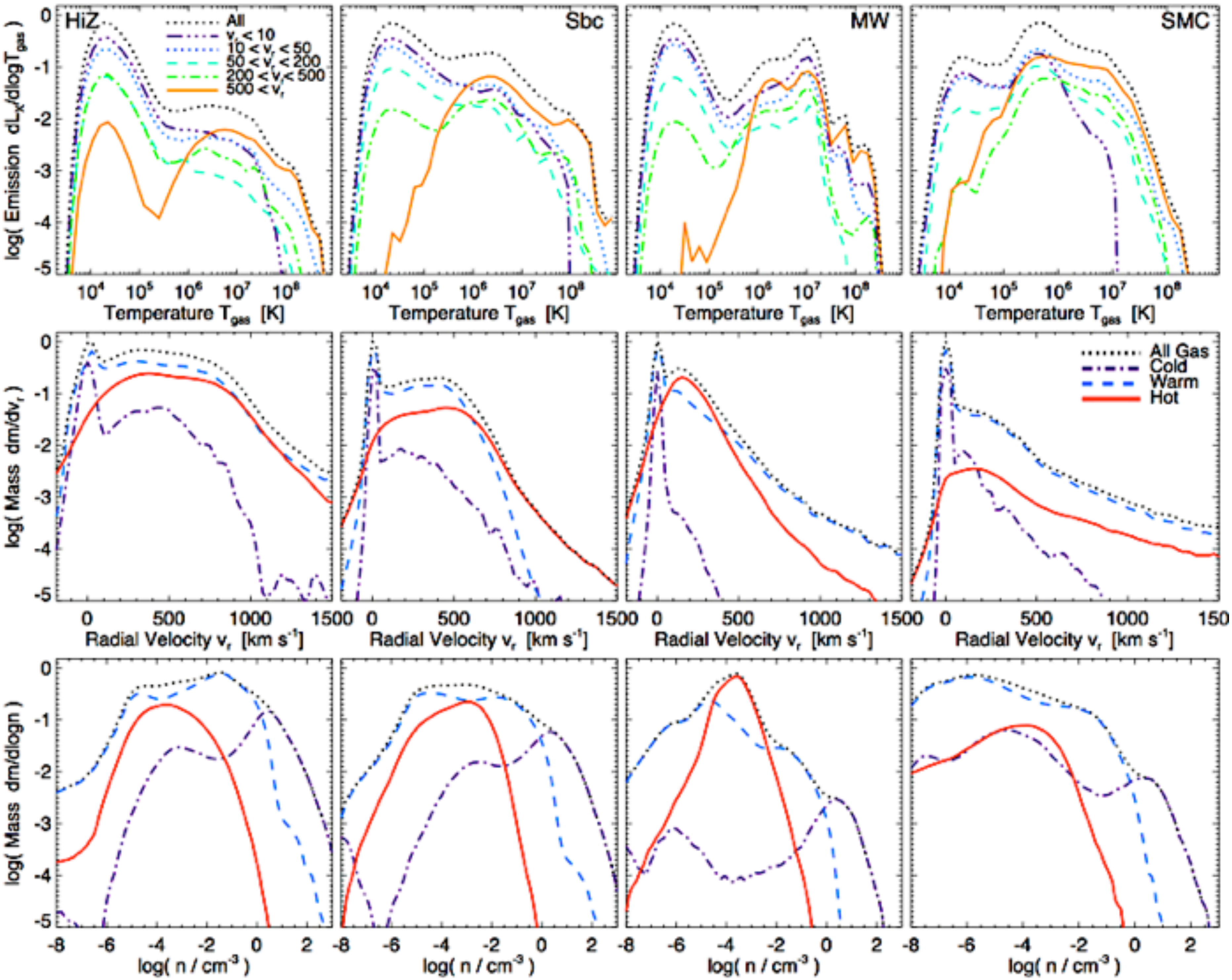
- **Star formation is Feedback-Regulated**: *independent* of small-scale SF 'law'
  - Need enough stars to offset dissipation (gravity)
  - Leads to SFR-galaxy correlations & **super-winds**

- 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 is sufficient to explain observations**

- 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})