Star Formation, Black Holes, and Feedback in Galaxy Formation

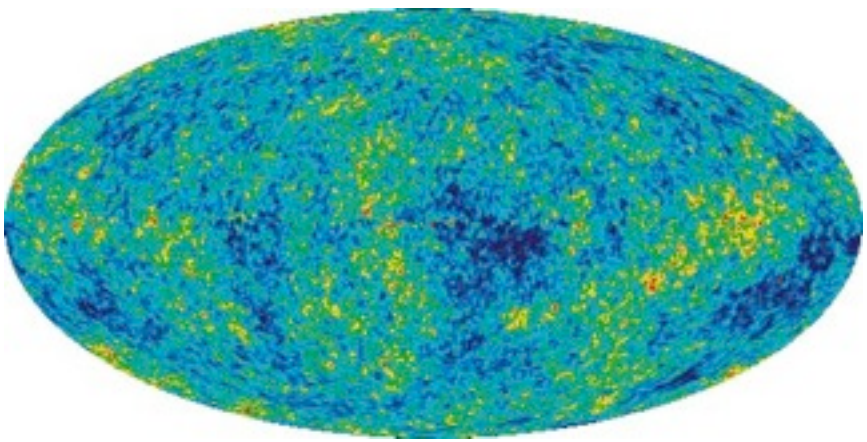
Philip Hopkins

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

Tuesday, December 25, 12

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



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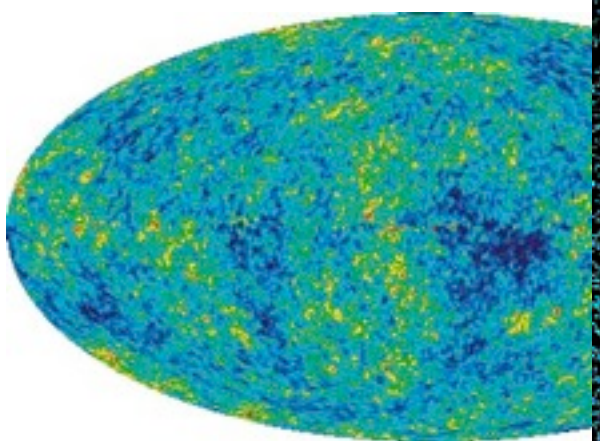

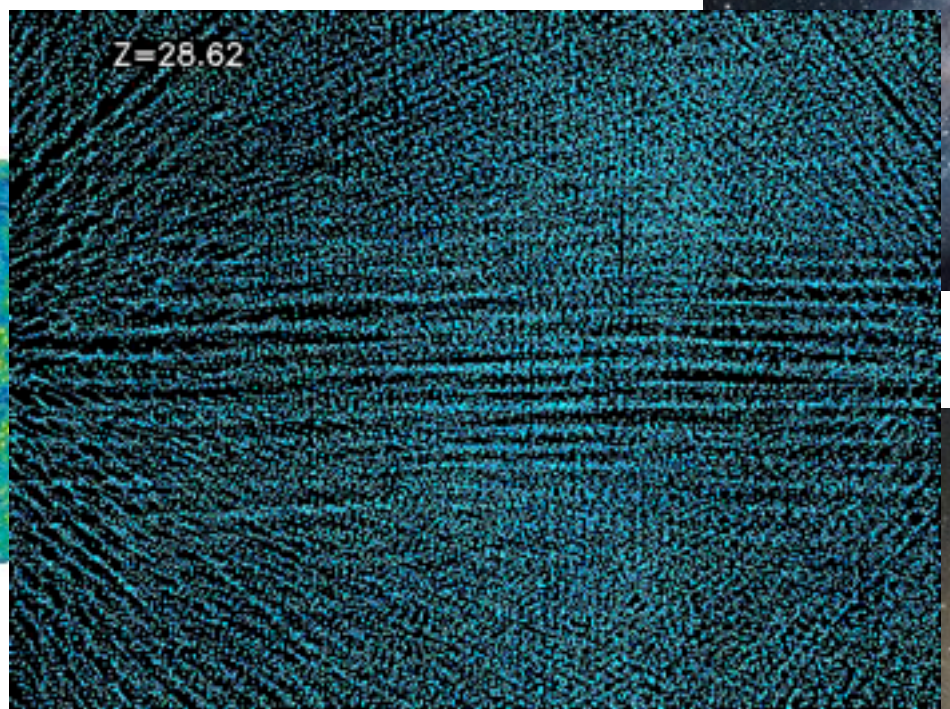
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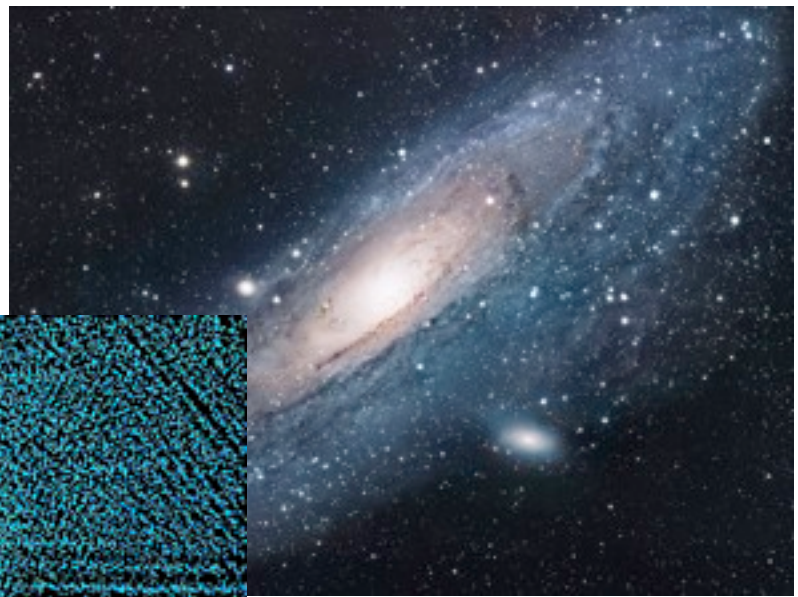
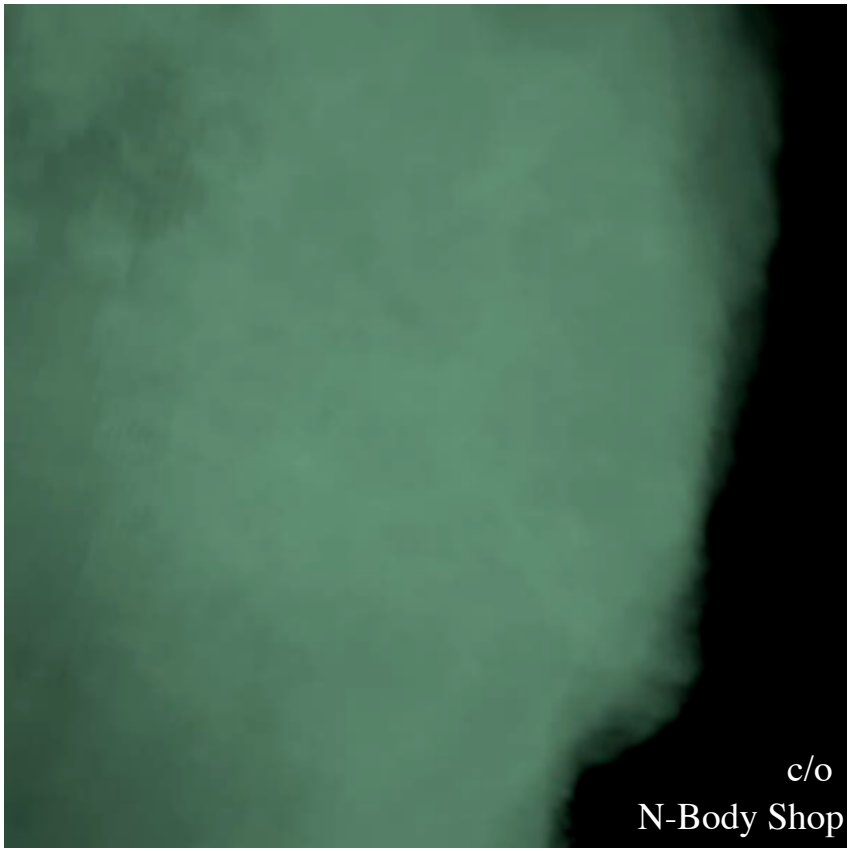
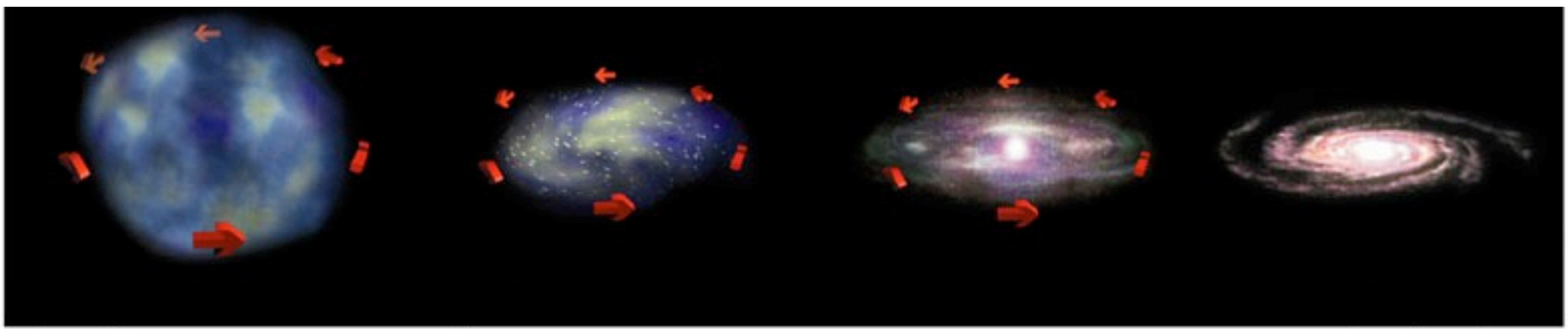


Motivation

HOW DID WE GET TO GALAXIES TODAY?



- Dark matter halos collapse: gas cools into a disk

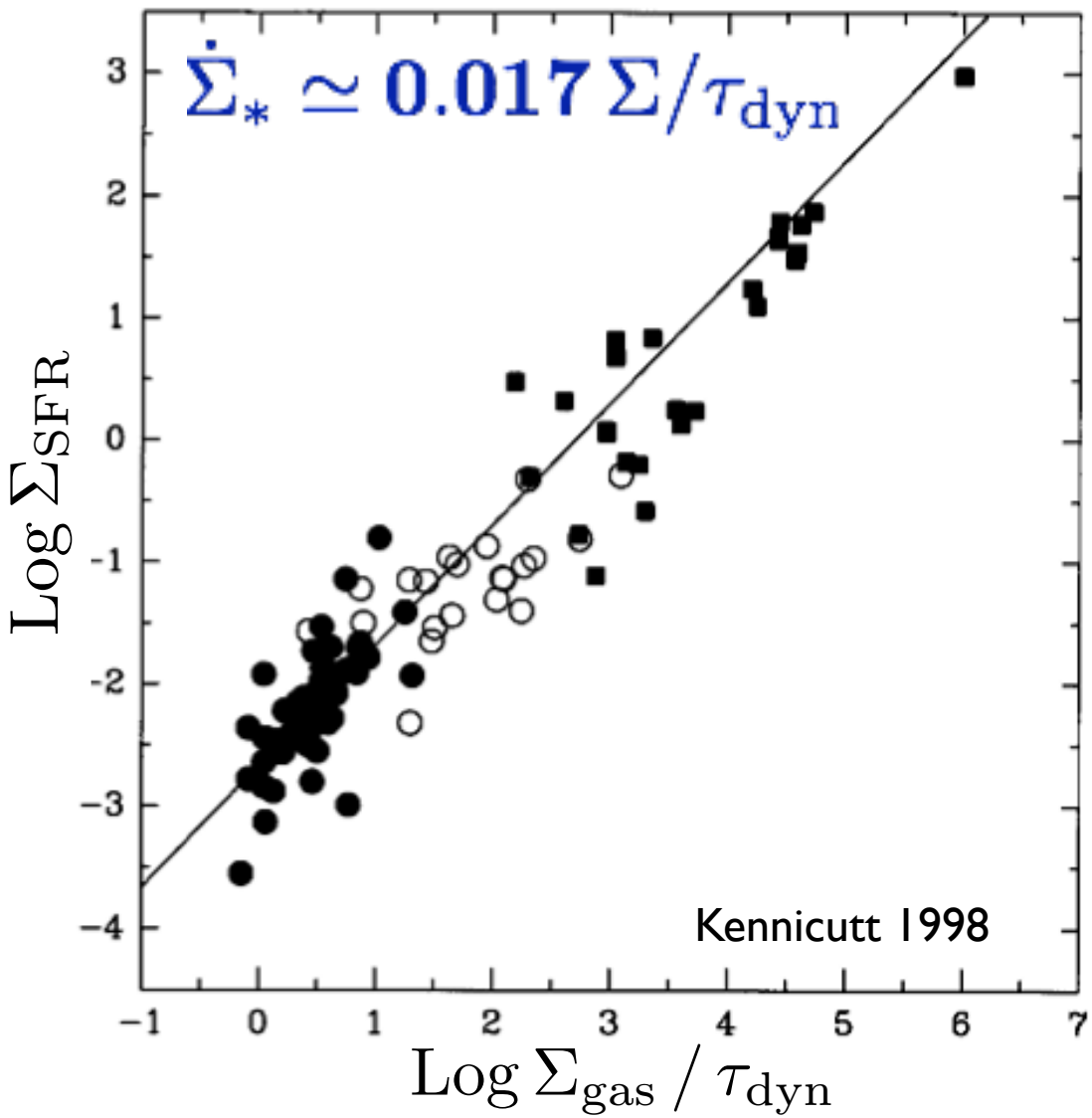


- What happens once gas is actually inside galaxies?

The Problem: Baryons

Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



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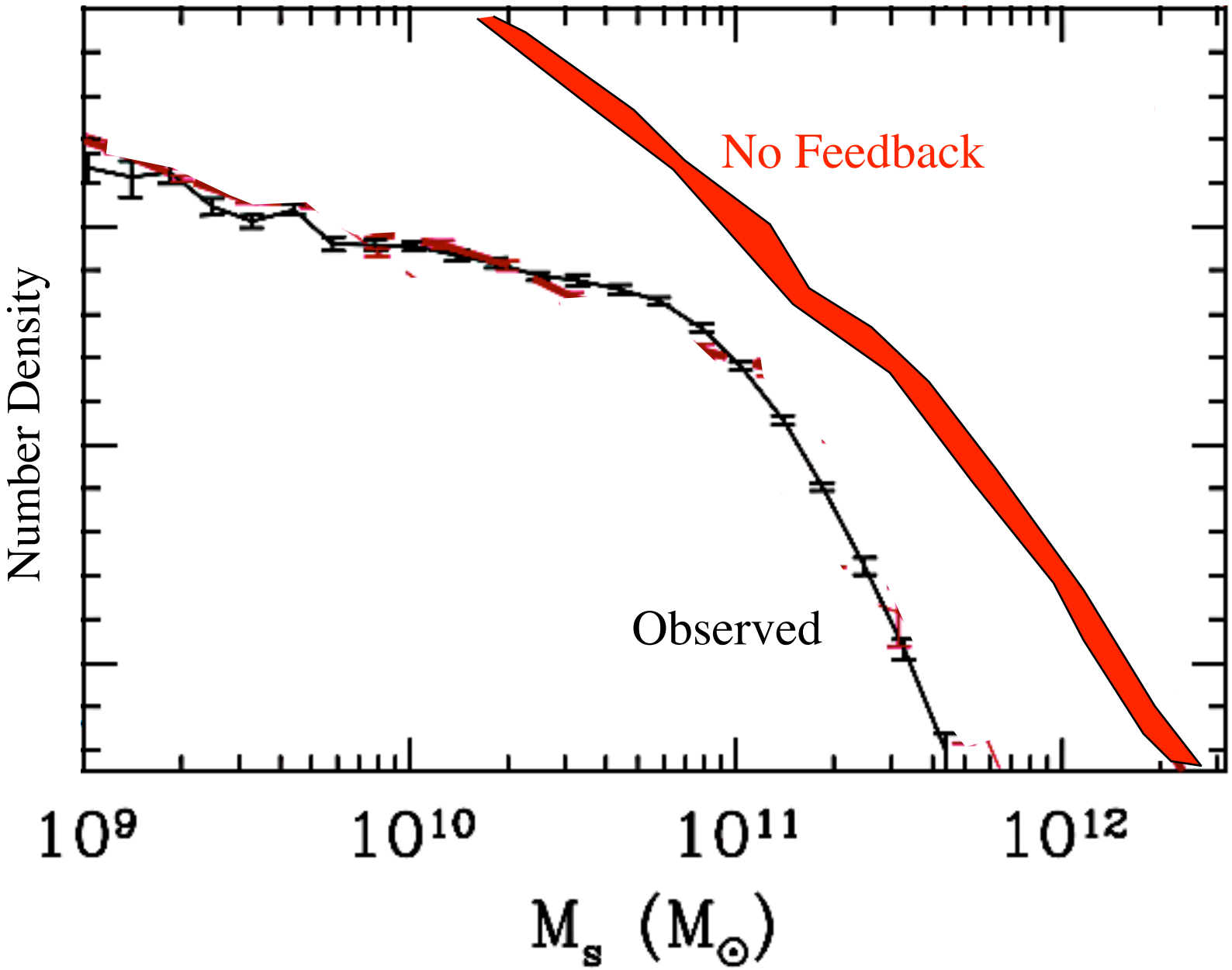

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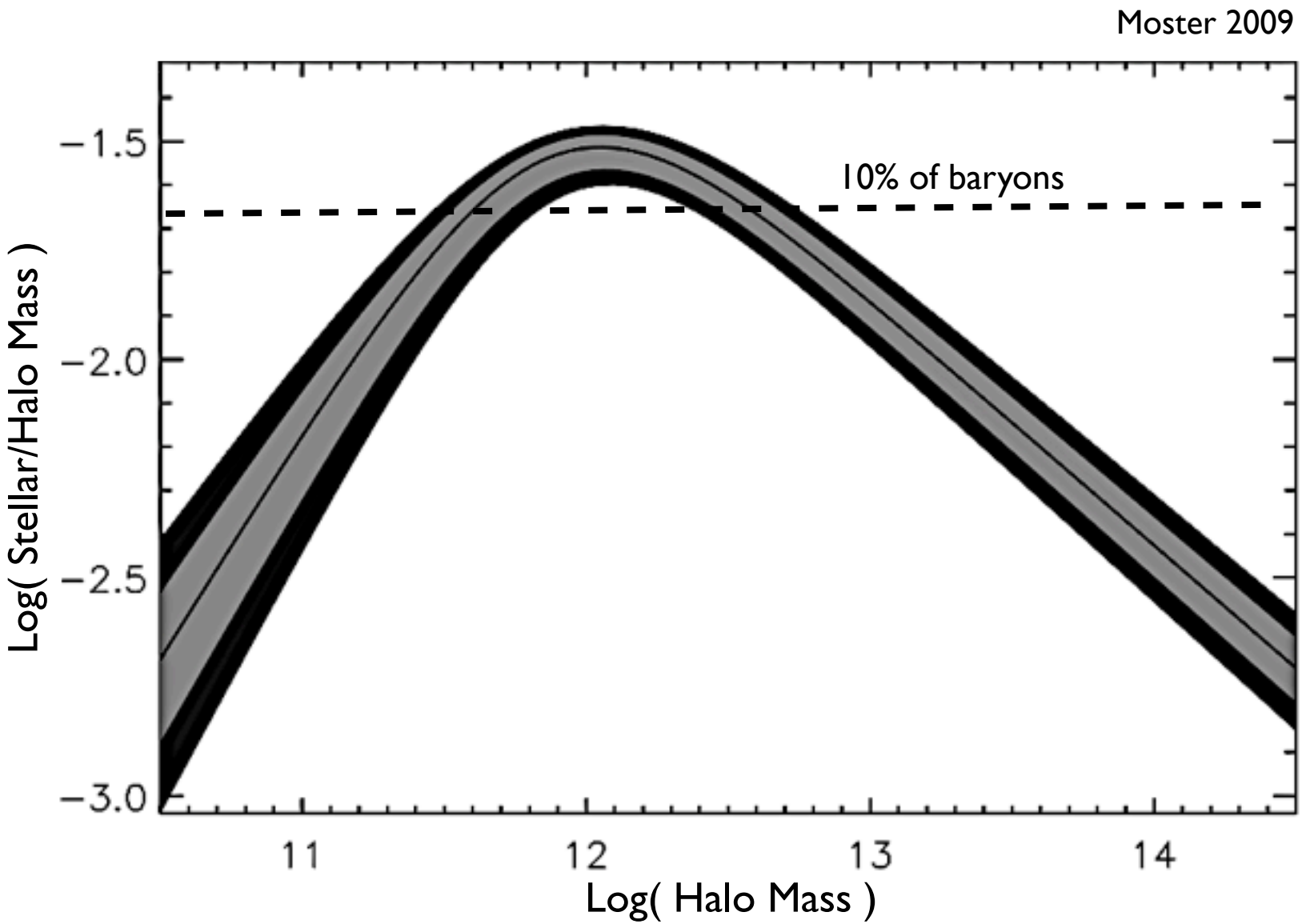

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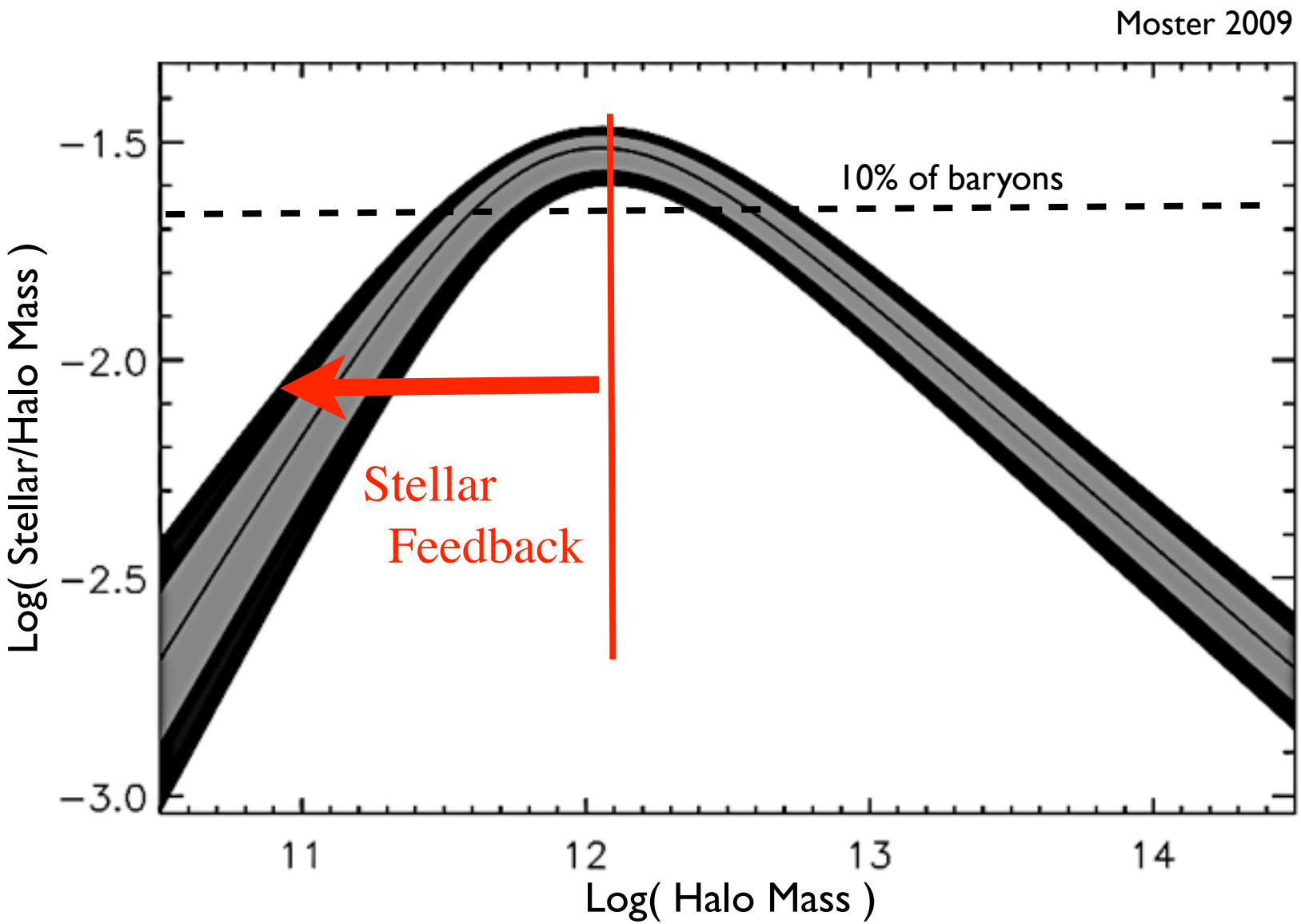

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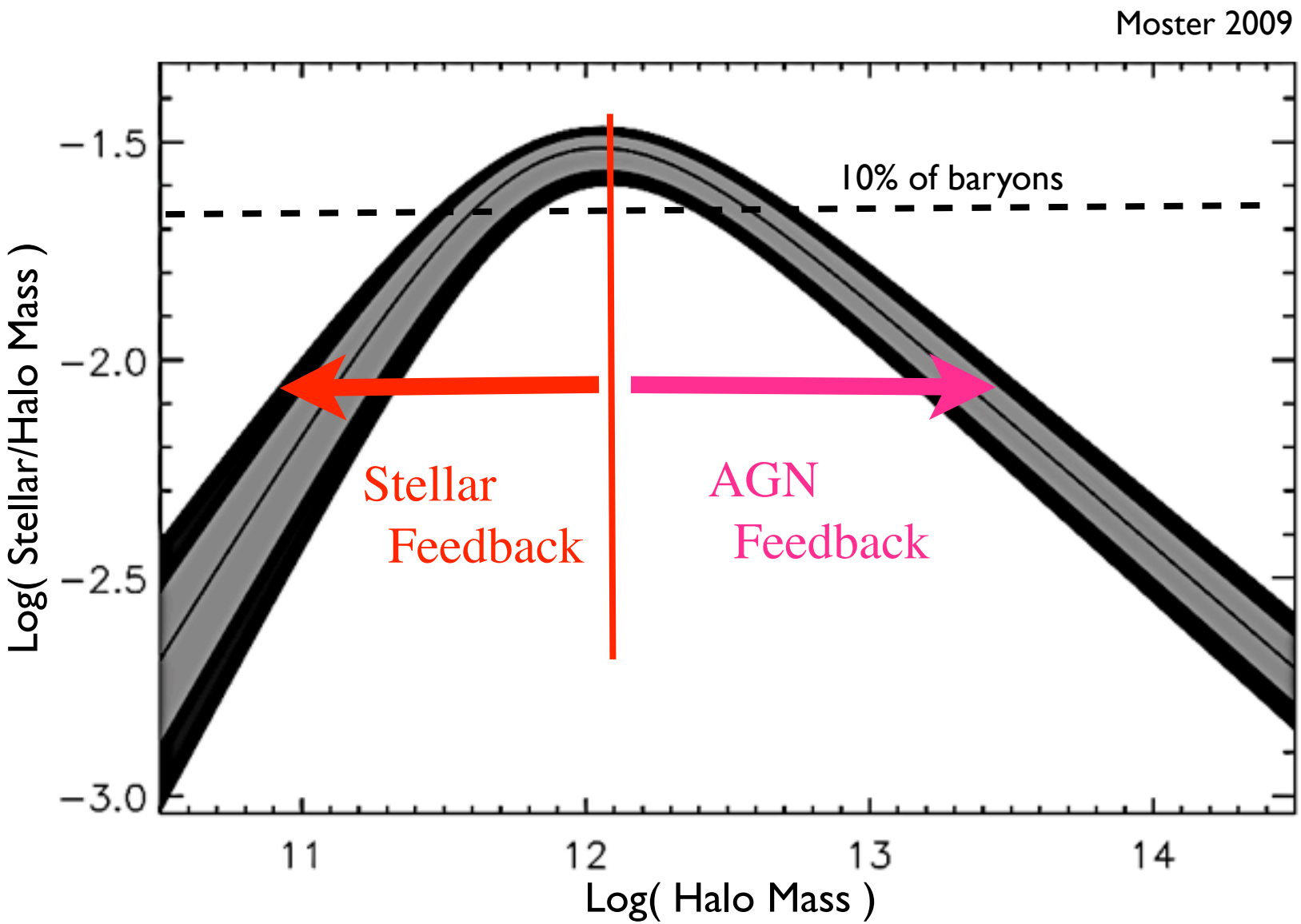


Stellar Feedback is (a/the) Key to Galaxy Formation!

SO WHAT'S THE PROBLEM?

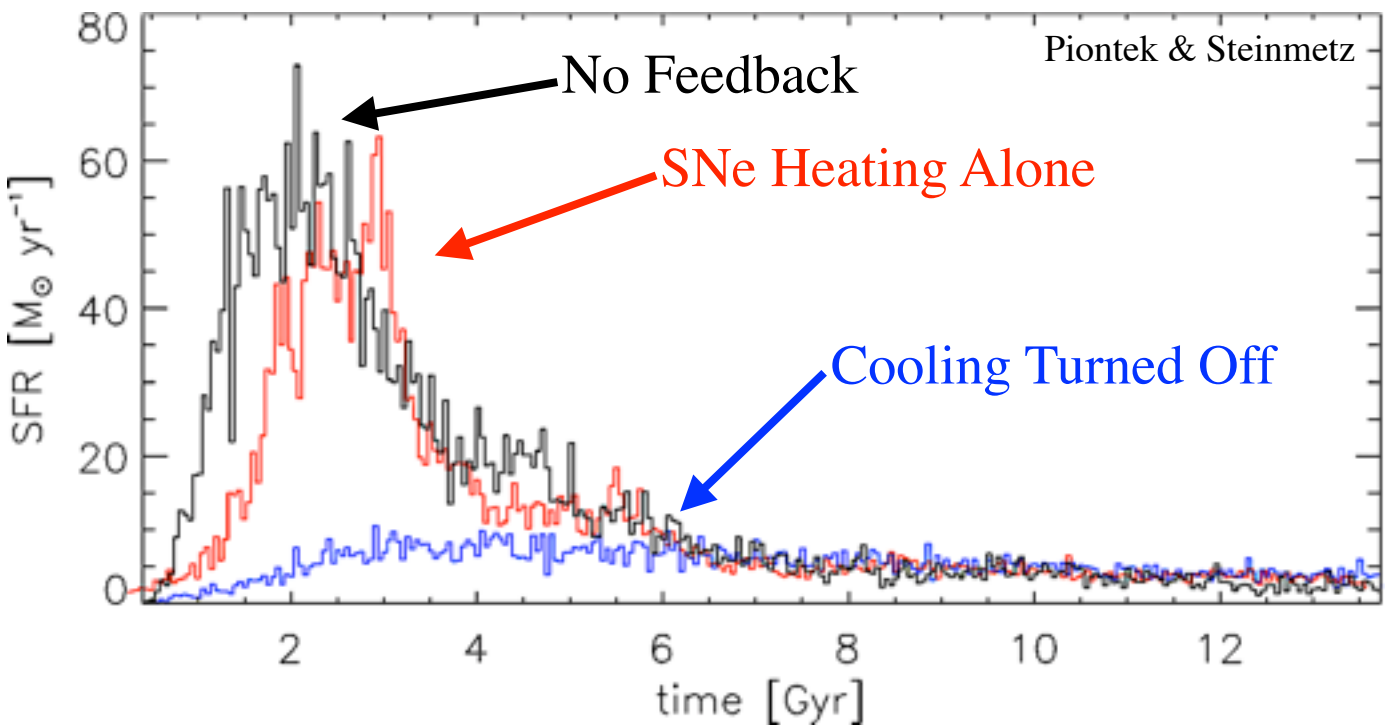
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- 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

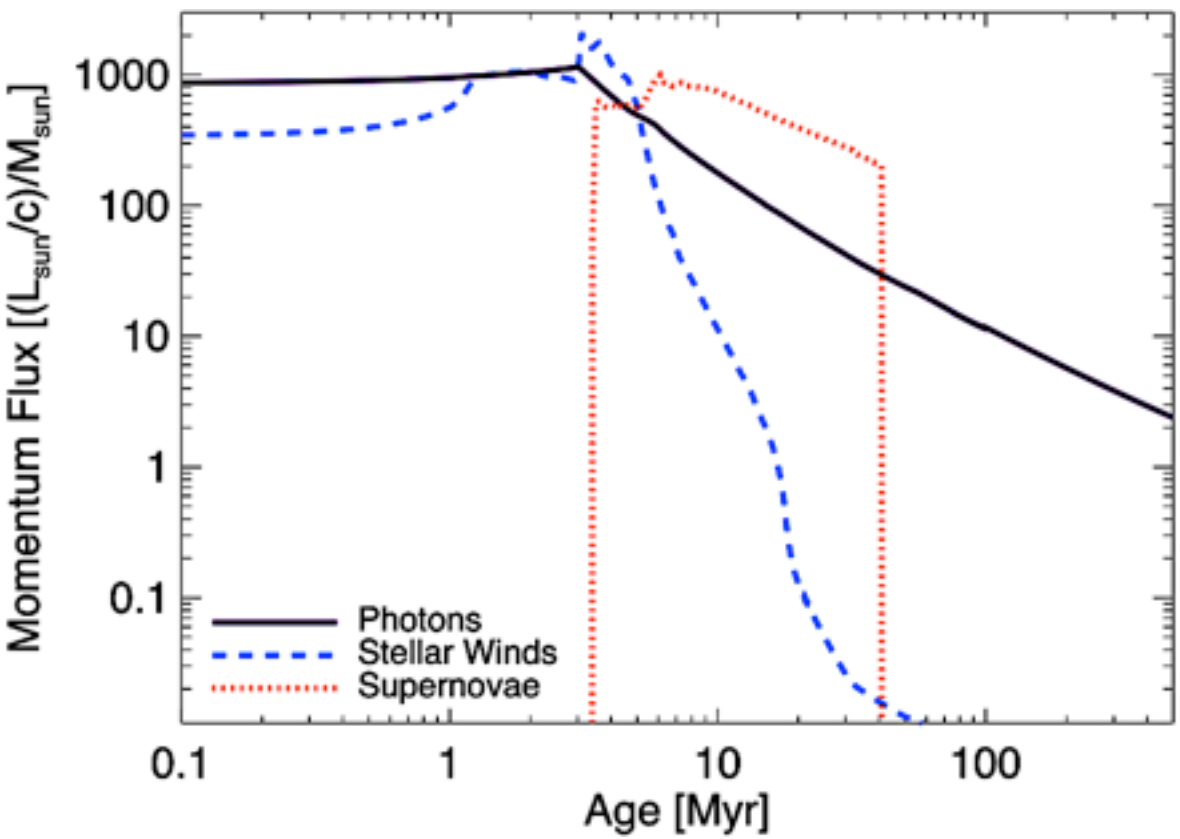
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\left(1+\tau_{\rm IR}\right)$$

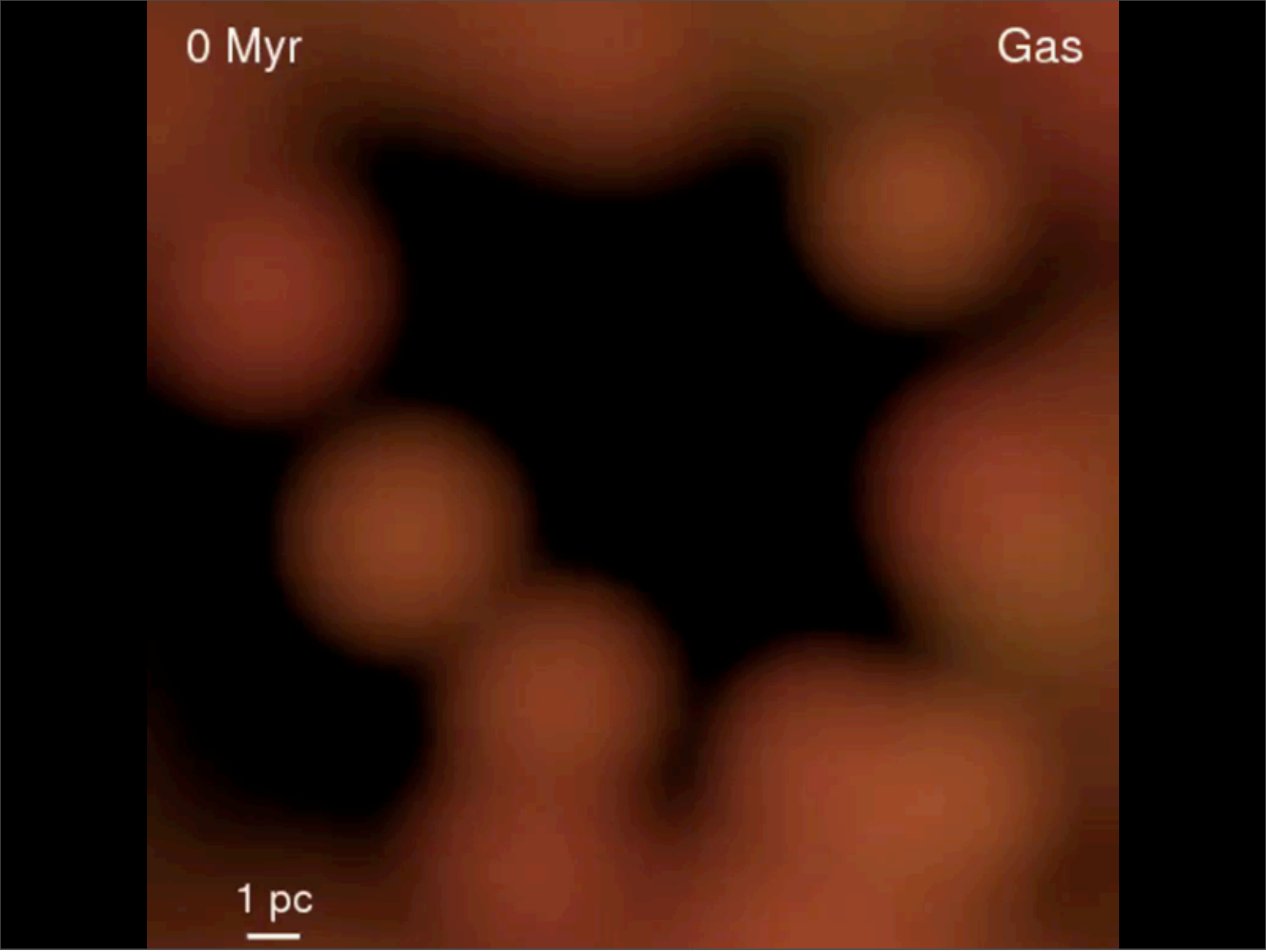
  - SNe

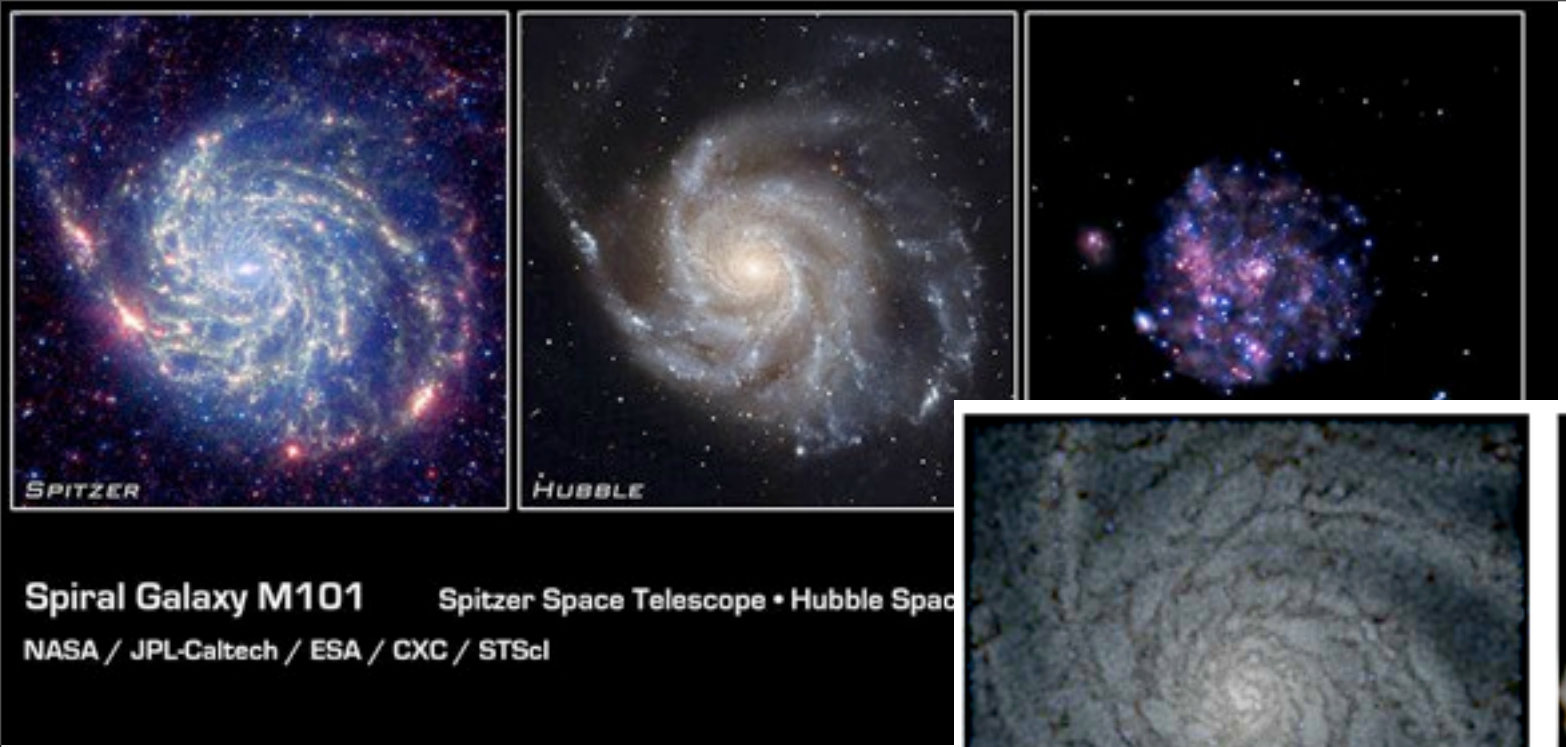
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

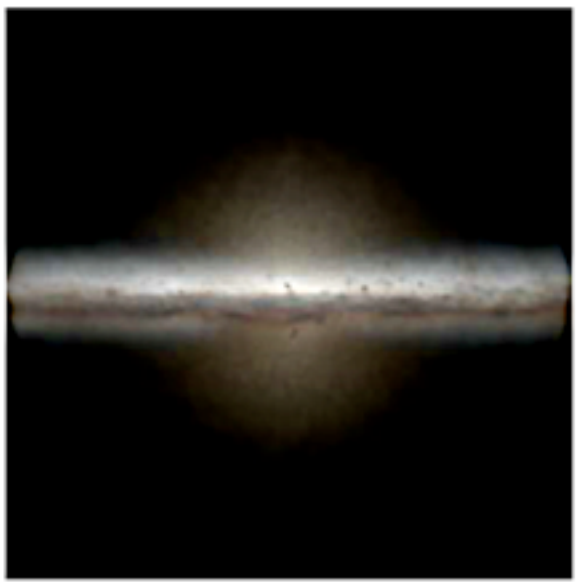
  - Stellar Winds

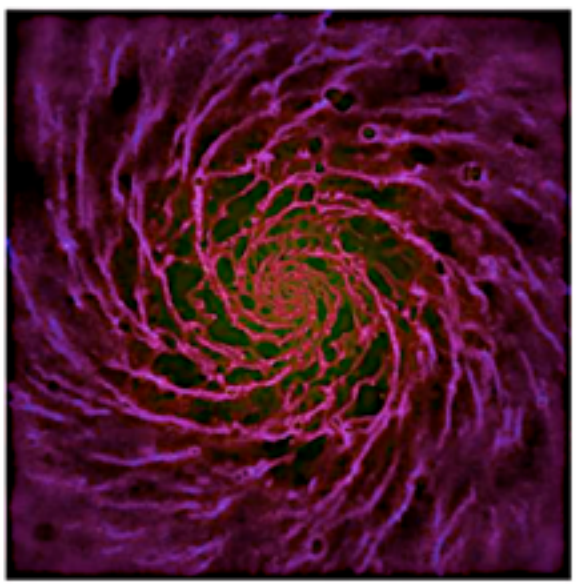
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

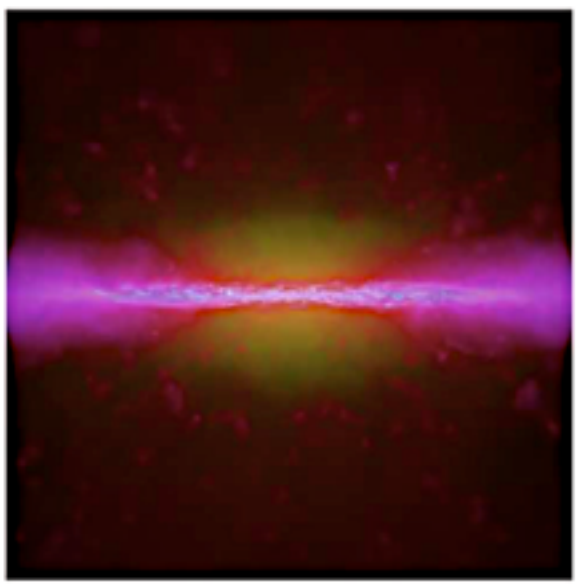



0 Myr
Gas
1 pc

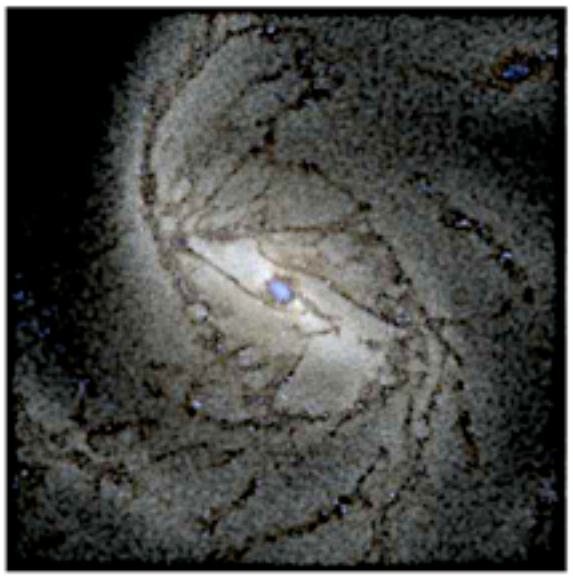


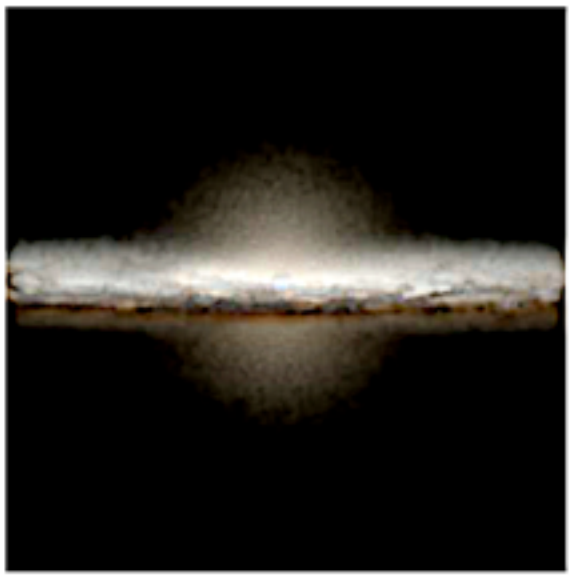


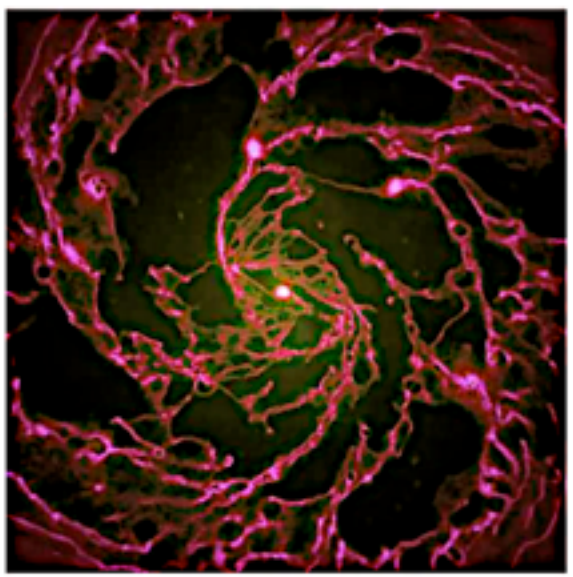


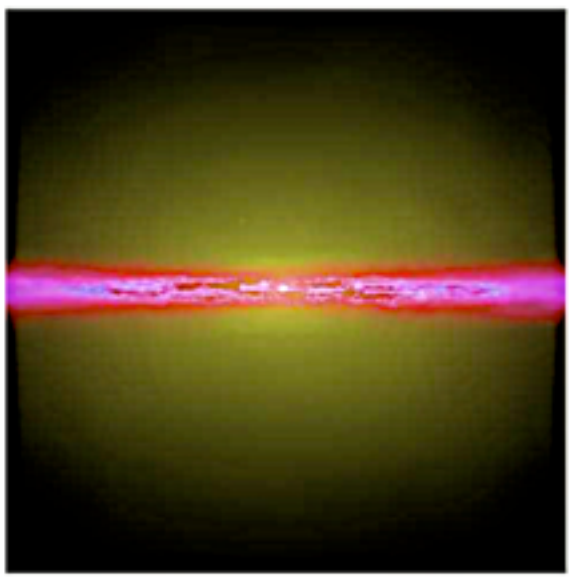


Hopkins, Quataert, & Murray, 2011









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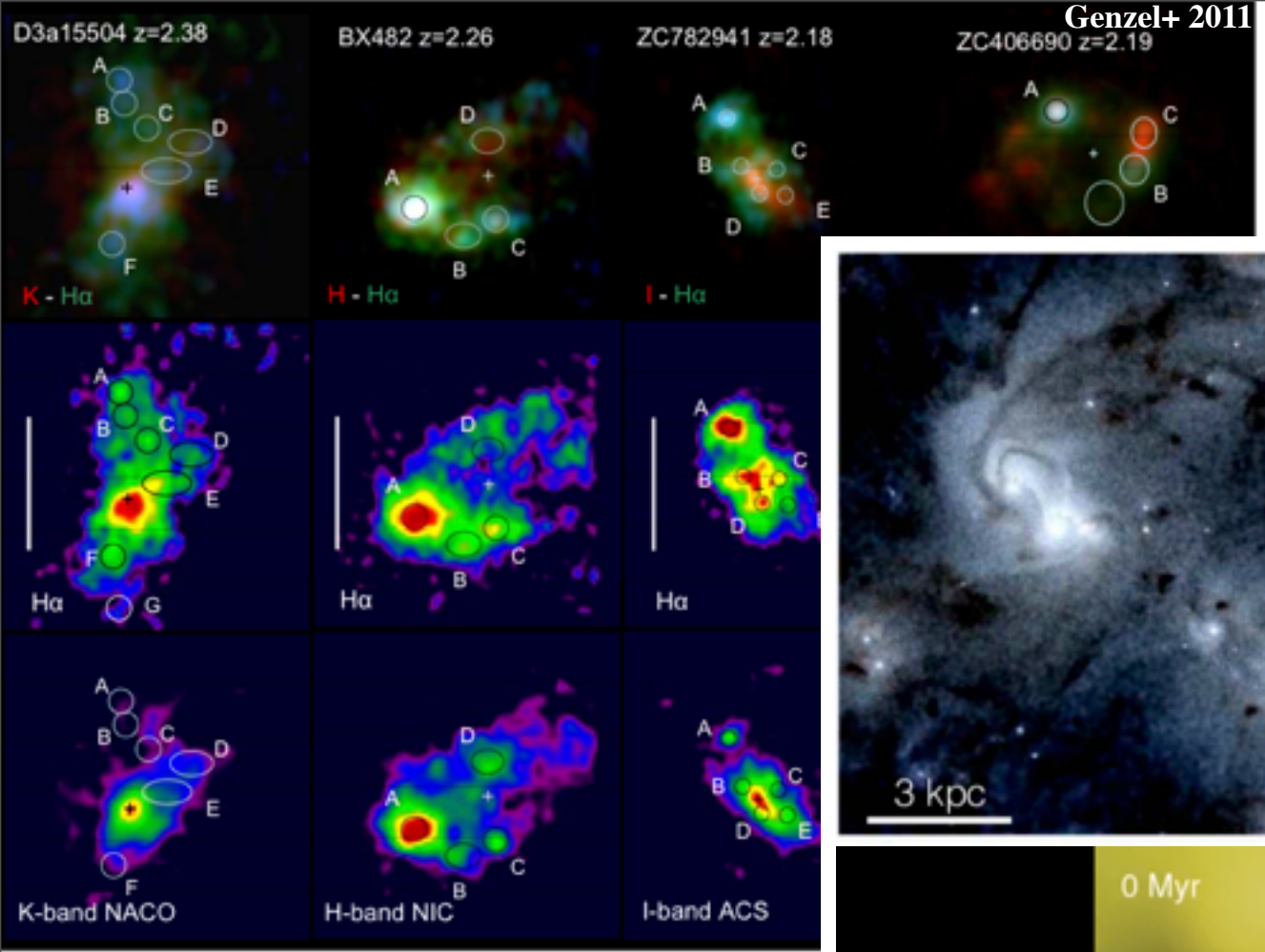
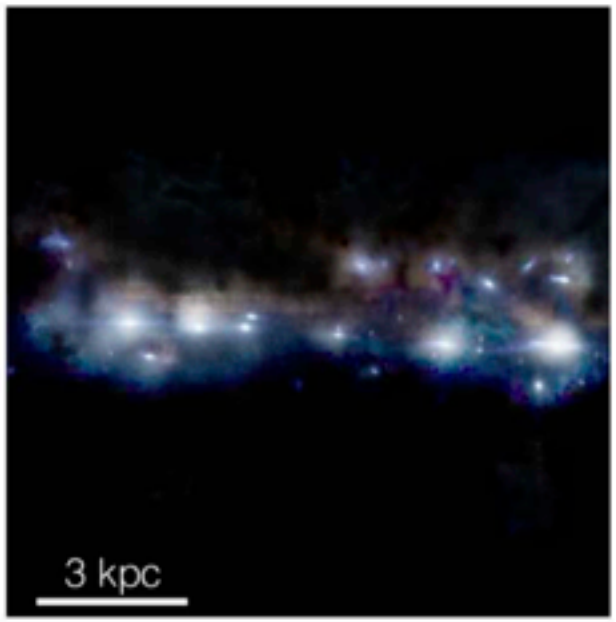
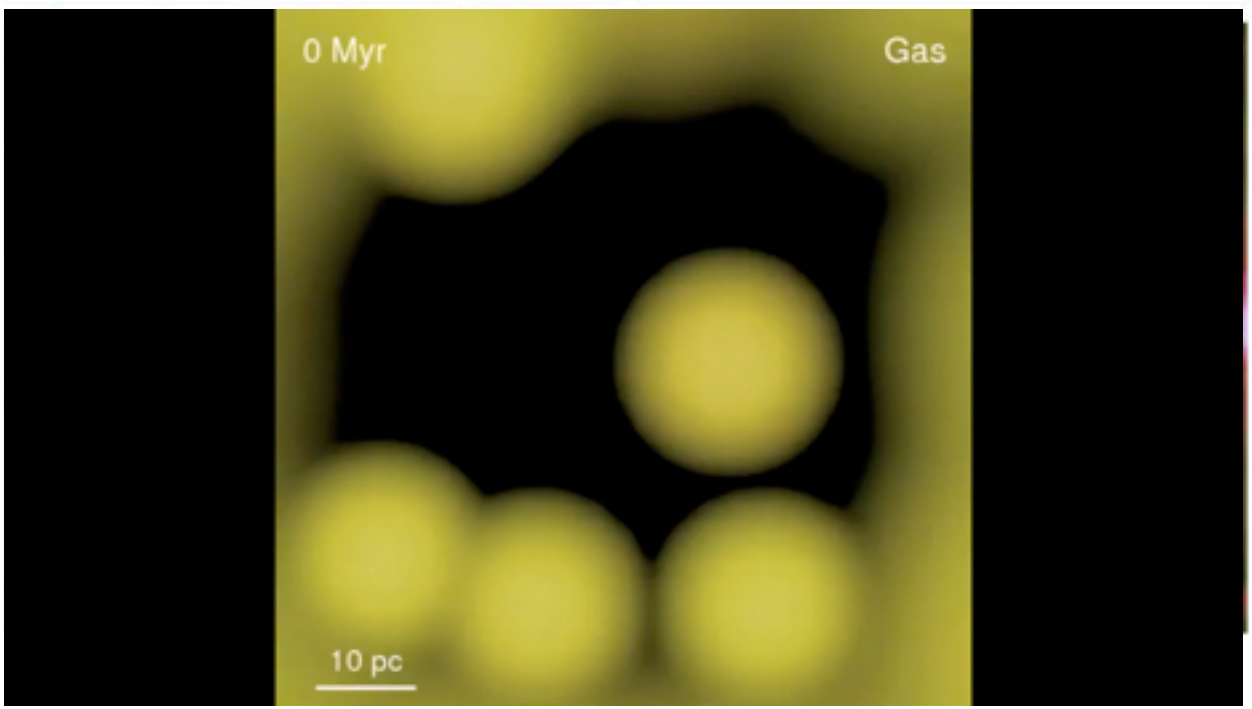
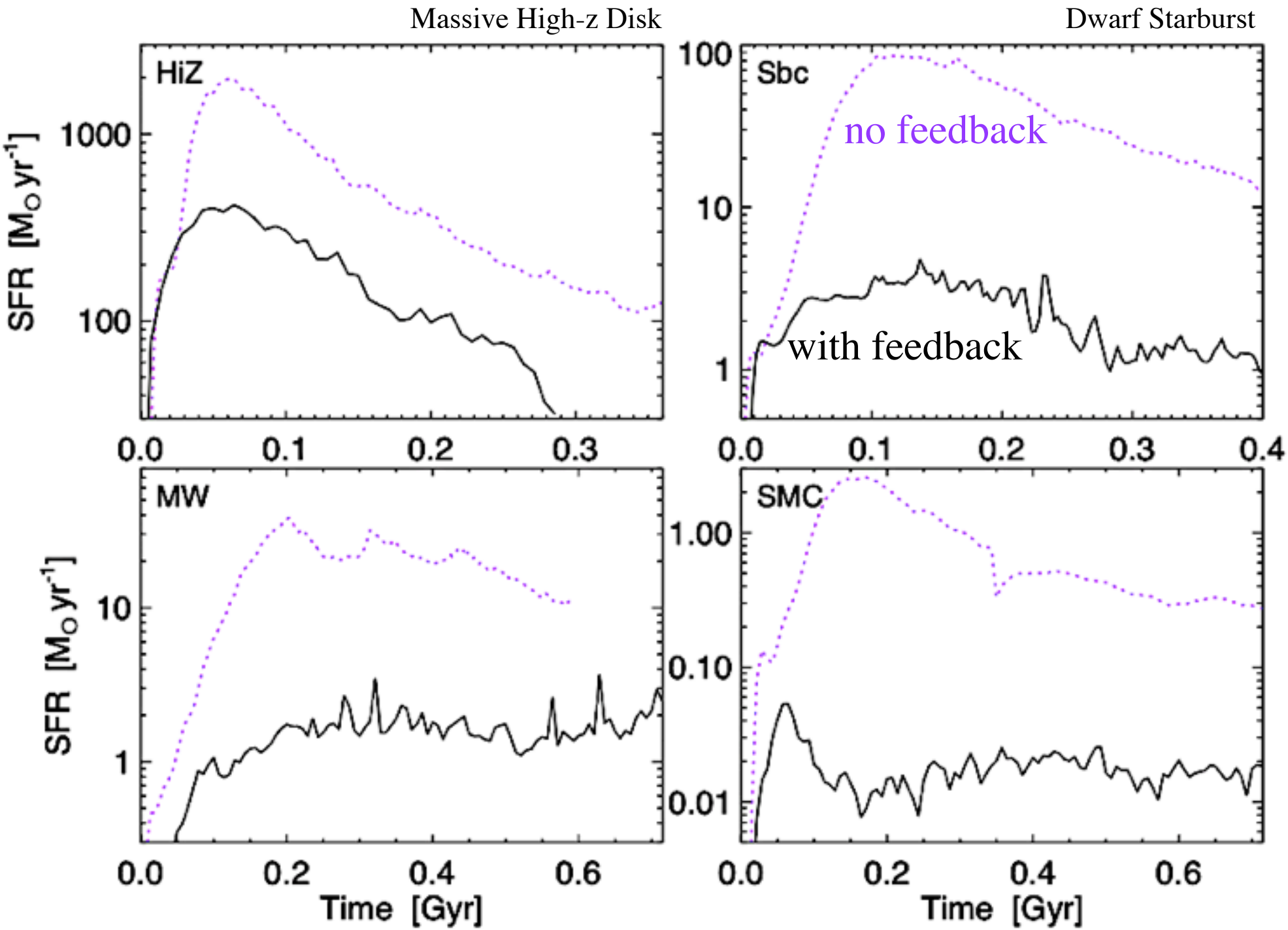






Hopkins, Quataert, & Murray

Stellar Feedback gives Self-Regulated Star Formation



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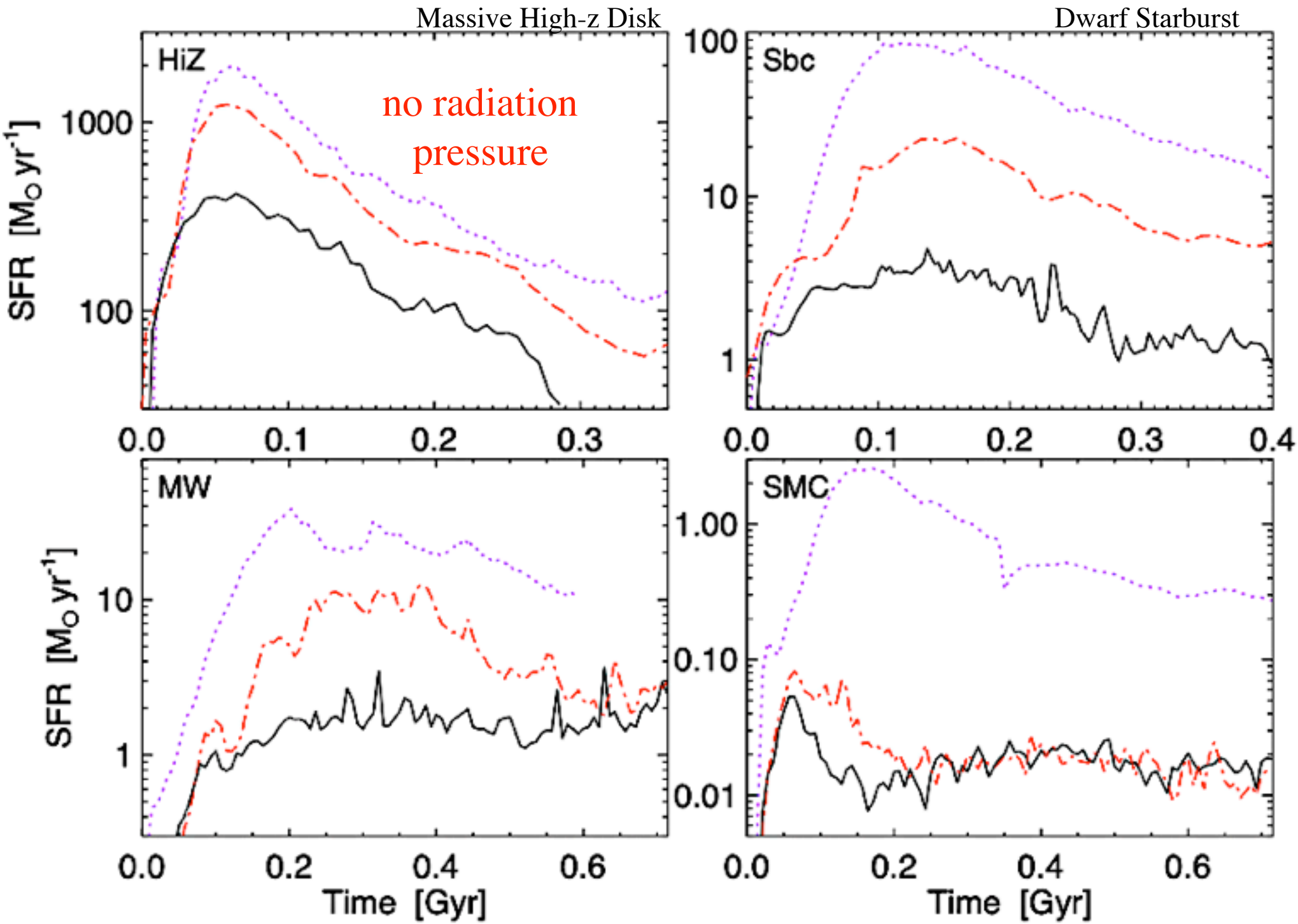

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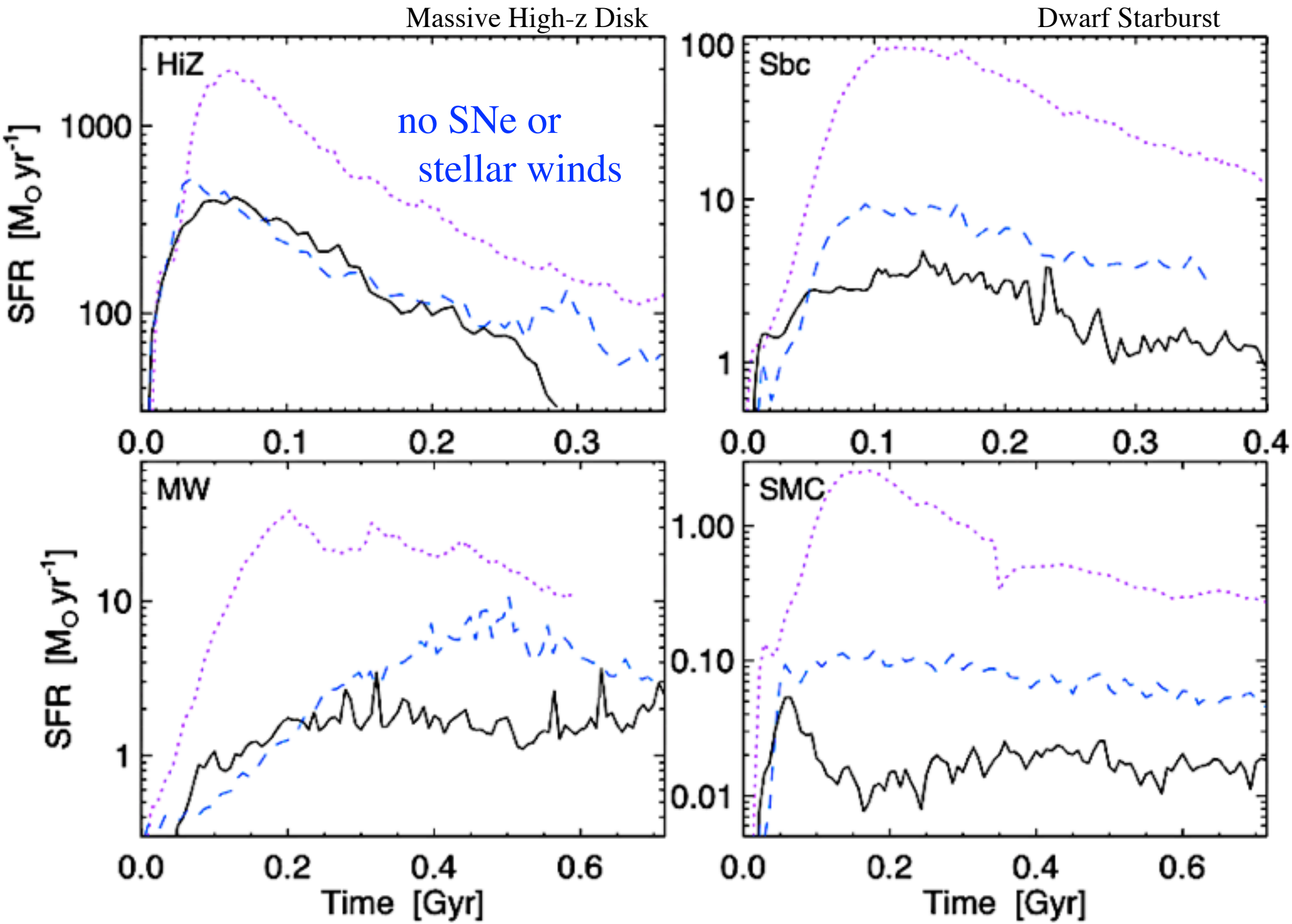
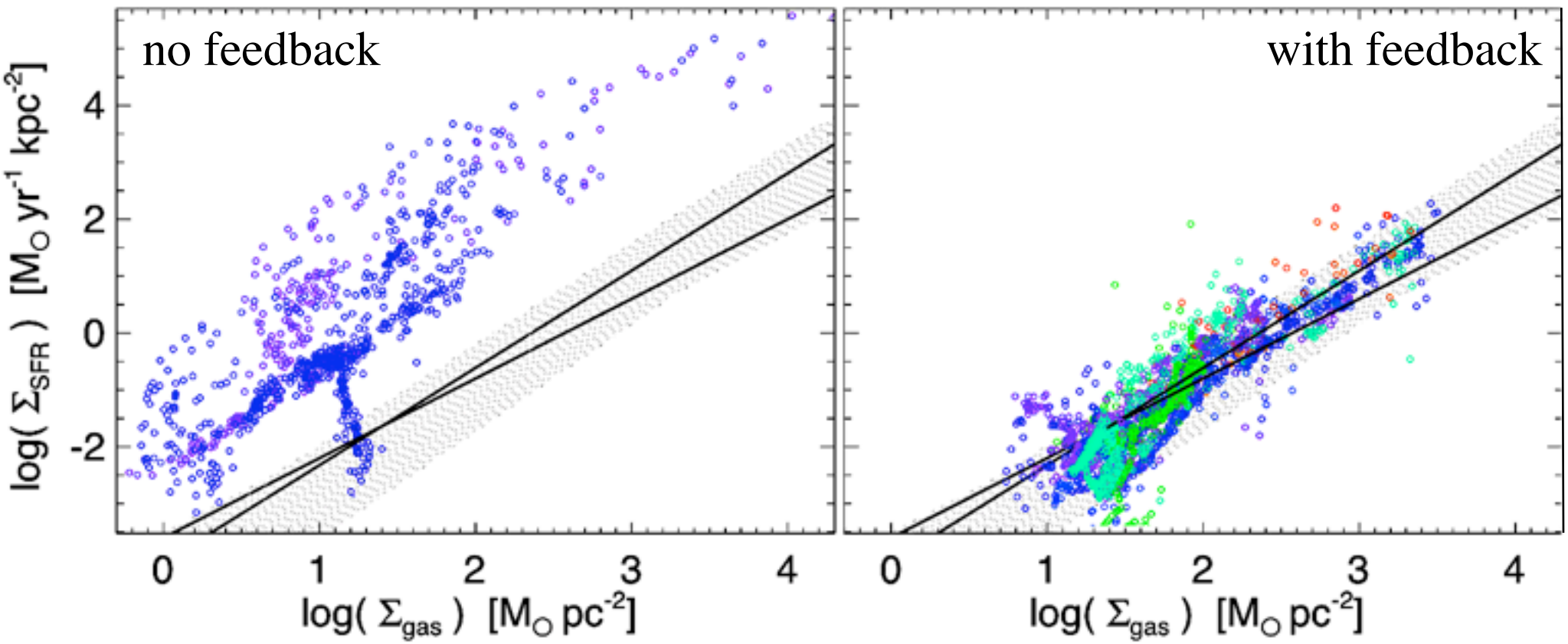


Kennicutt-Schmidt relation emerges naturally



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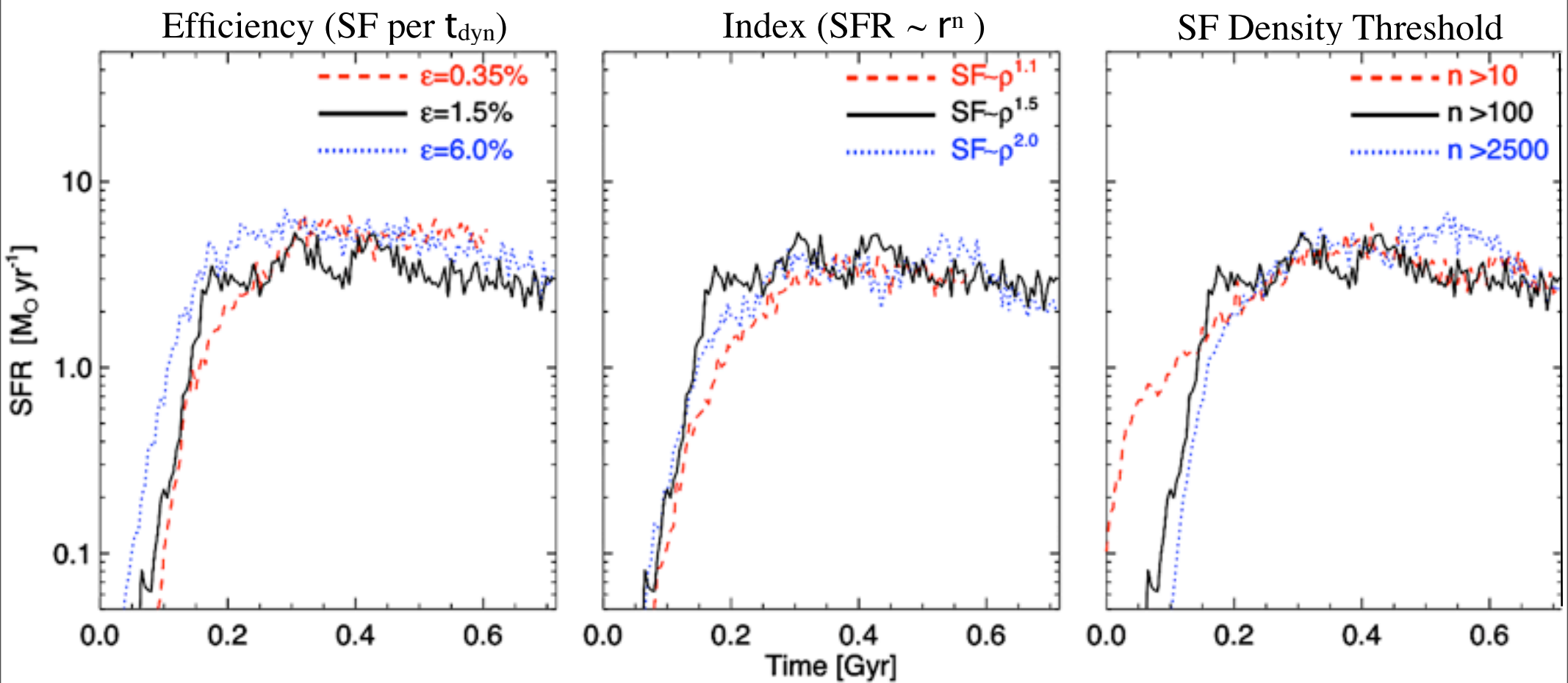
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas} \Omega \sim 0.02\, \Sigma_{\rm gas} \Omega$$

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



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

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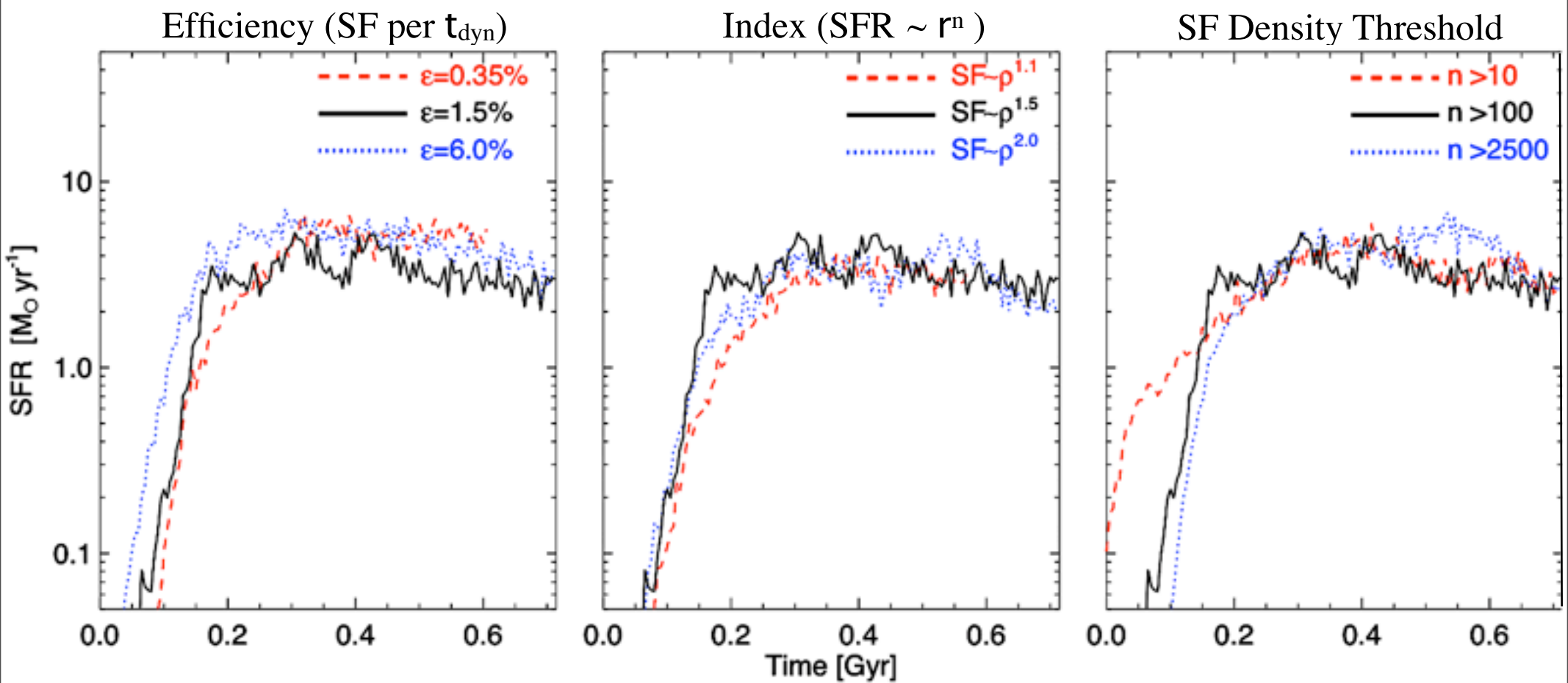

- Set by feedback (i.e. SFR) needed to maintain marginal stability

Hopkins, Quataert, & Murray 2011
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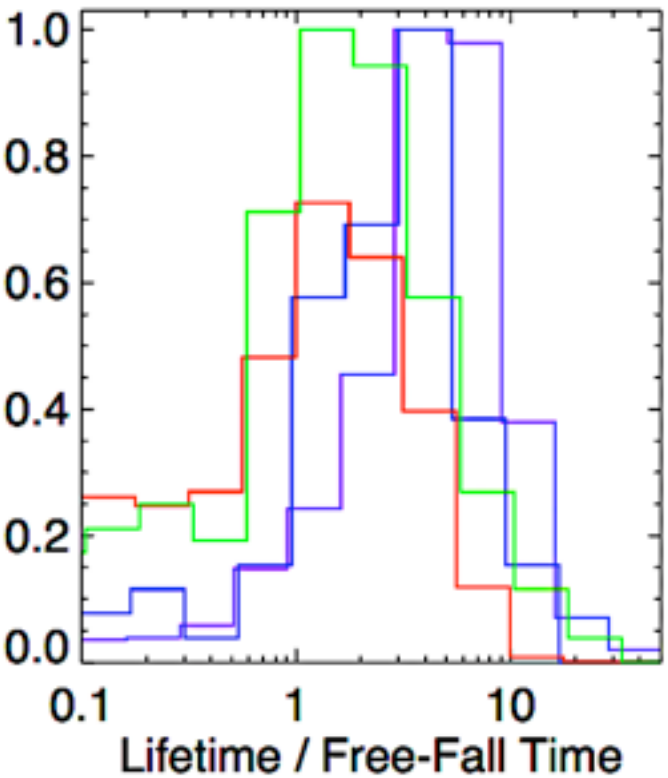
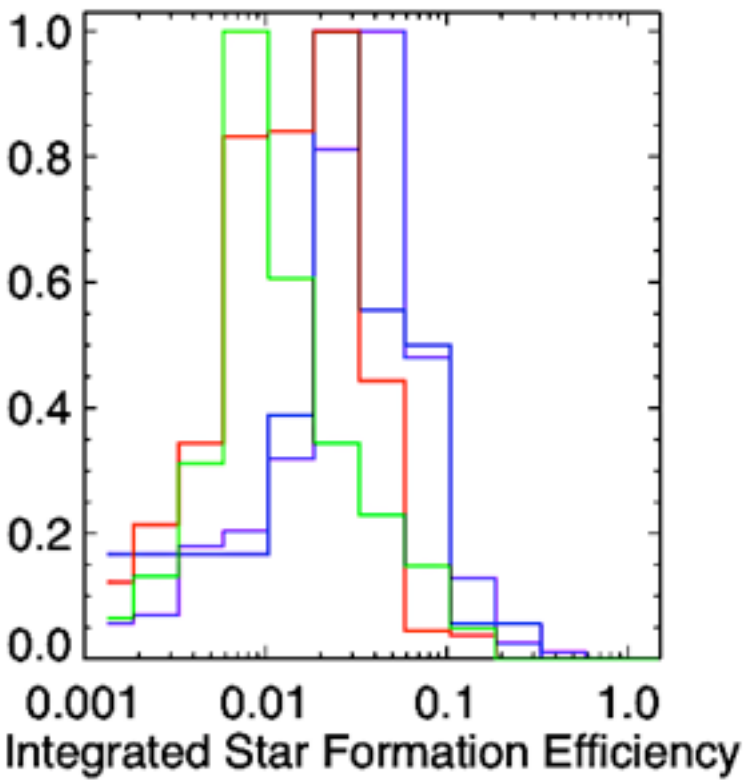
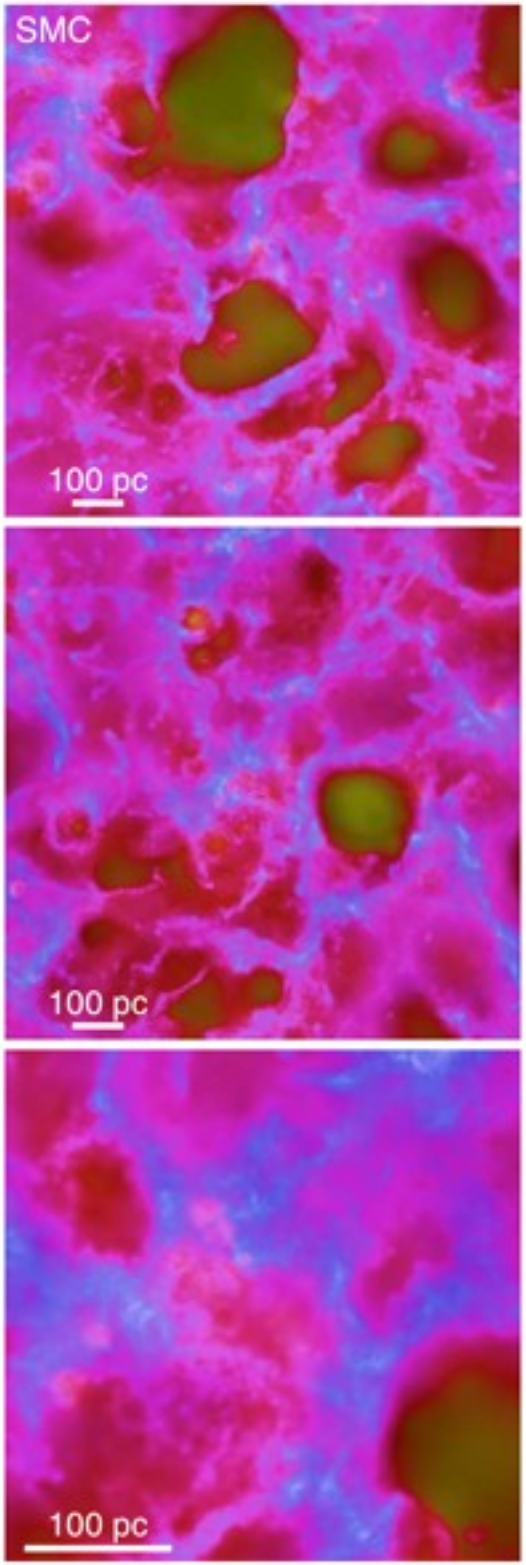
What Else Can We Study About Star Formation and the ISM?

Properties of GMCs

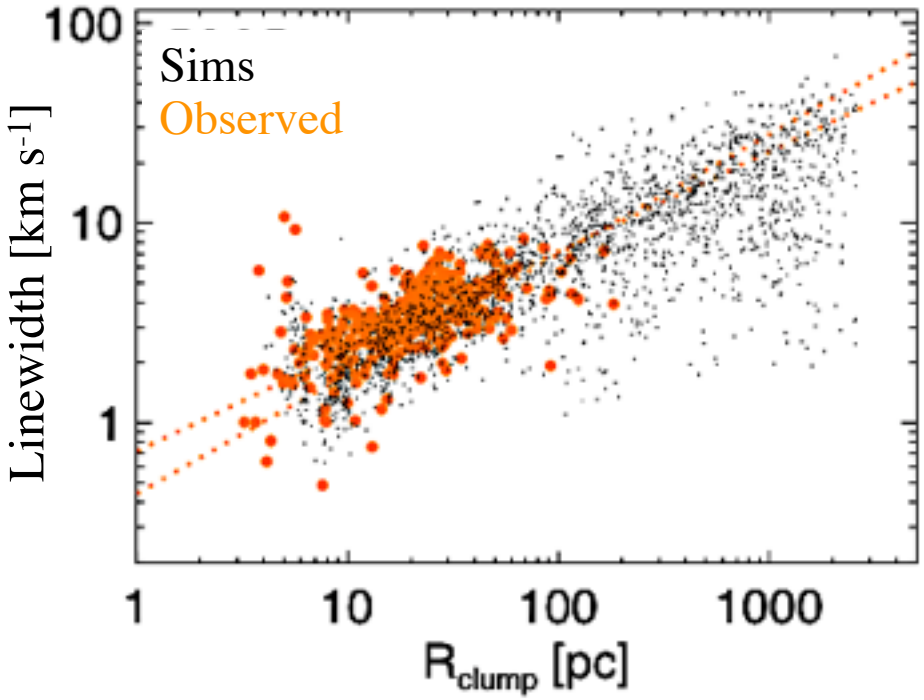
DEPENDENCE ON FEEDBACK AND OTHER SCALINGS

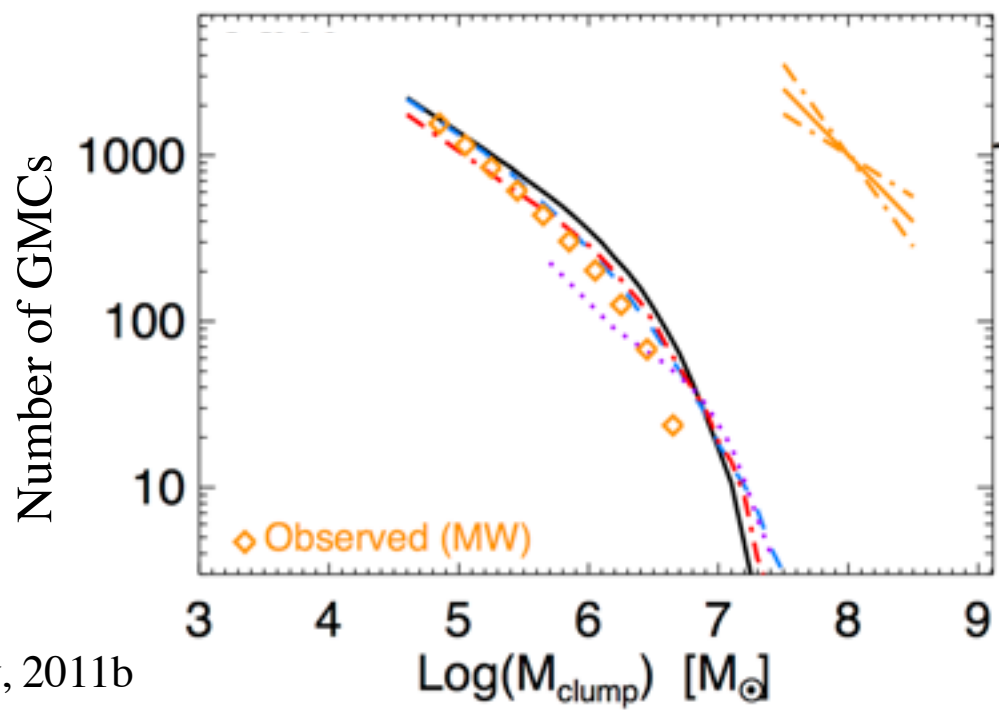


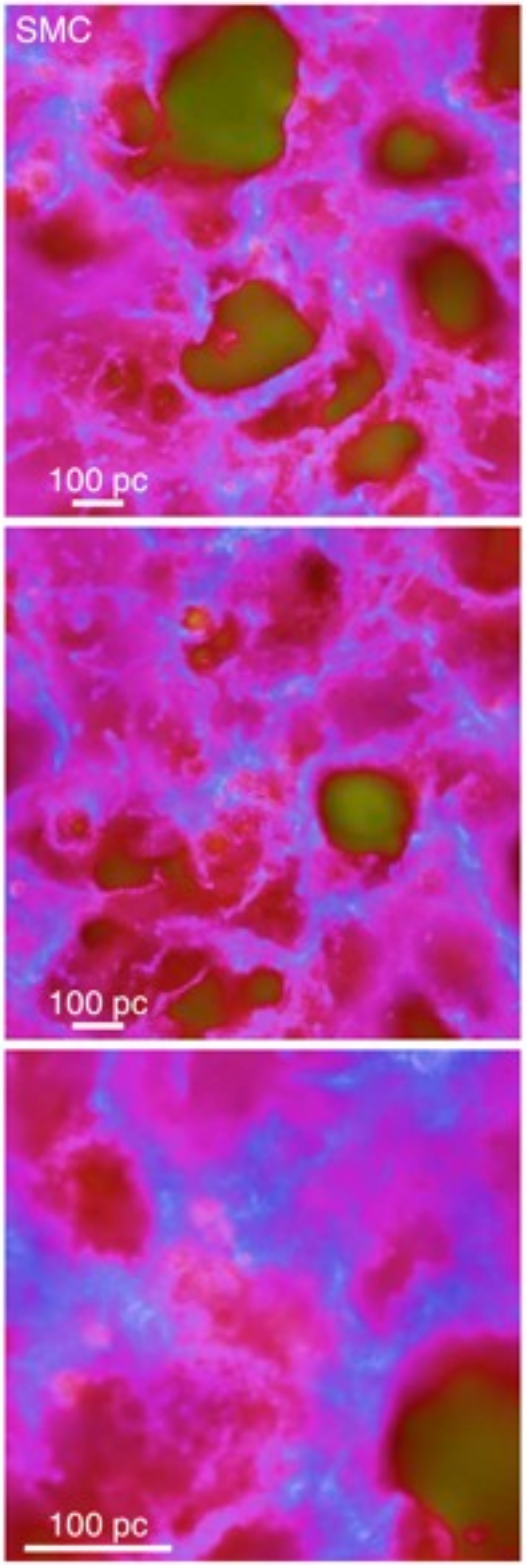




Properties of GMCs & Gas "Clumps"



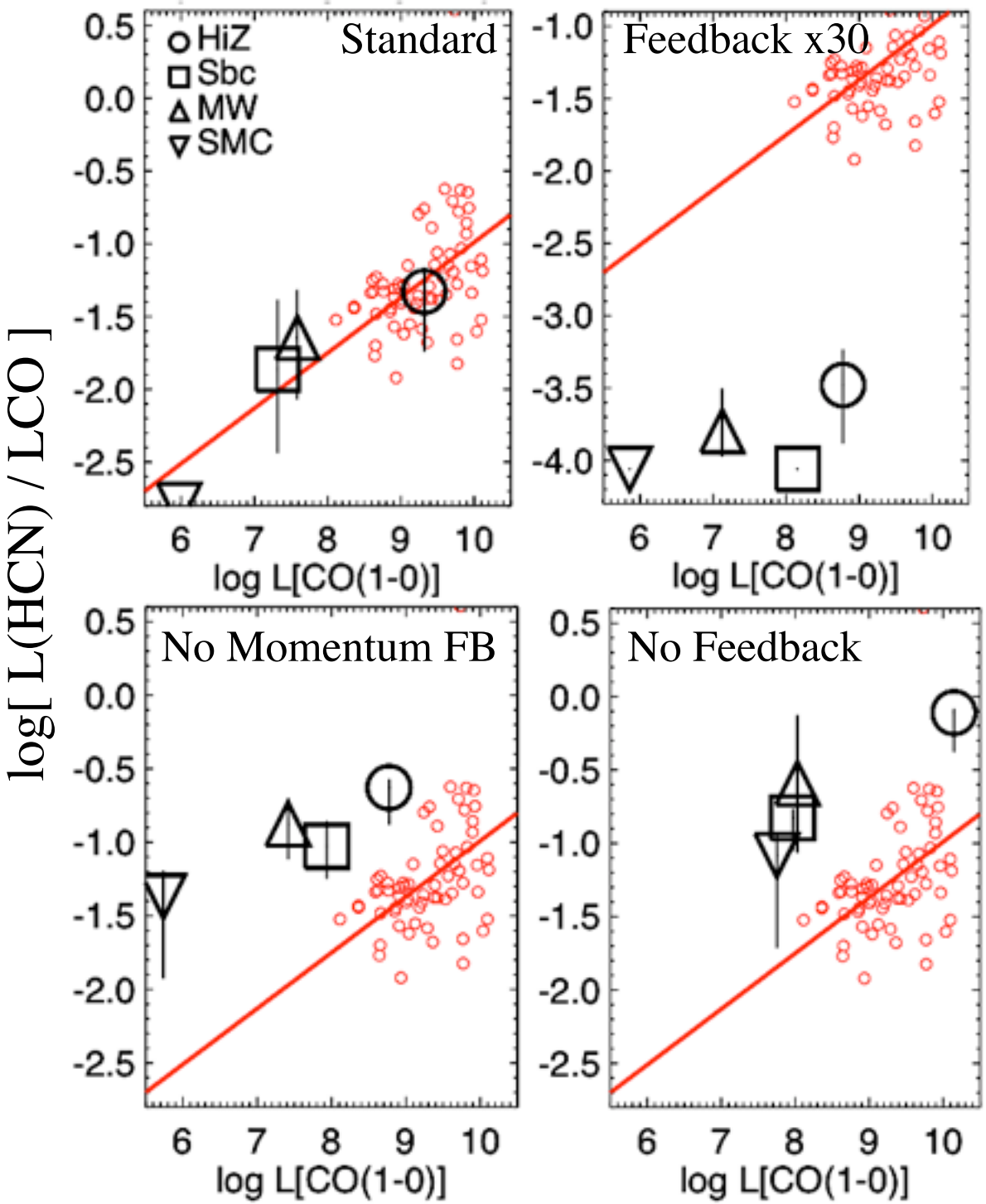




PFH, Quataert, & Murray, 2011b

Feedback is Reflected in Dense Gas

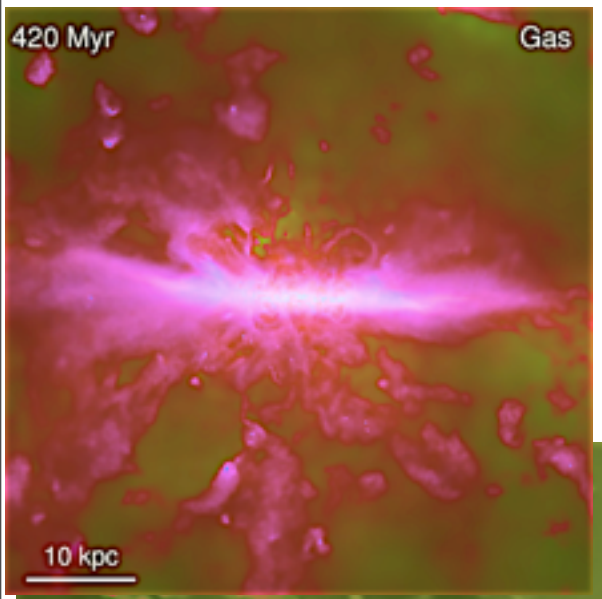
TRACERS OF STAR FORMATION EFFICIENCY

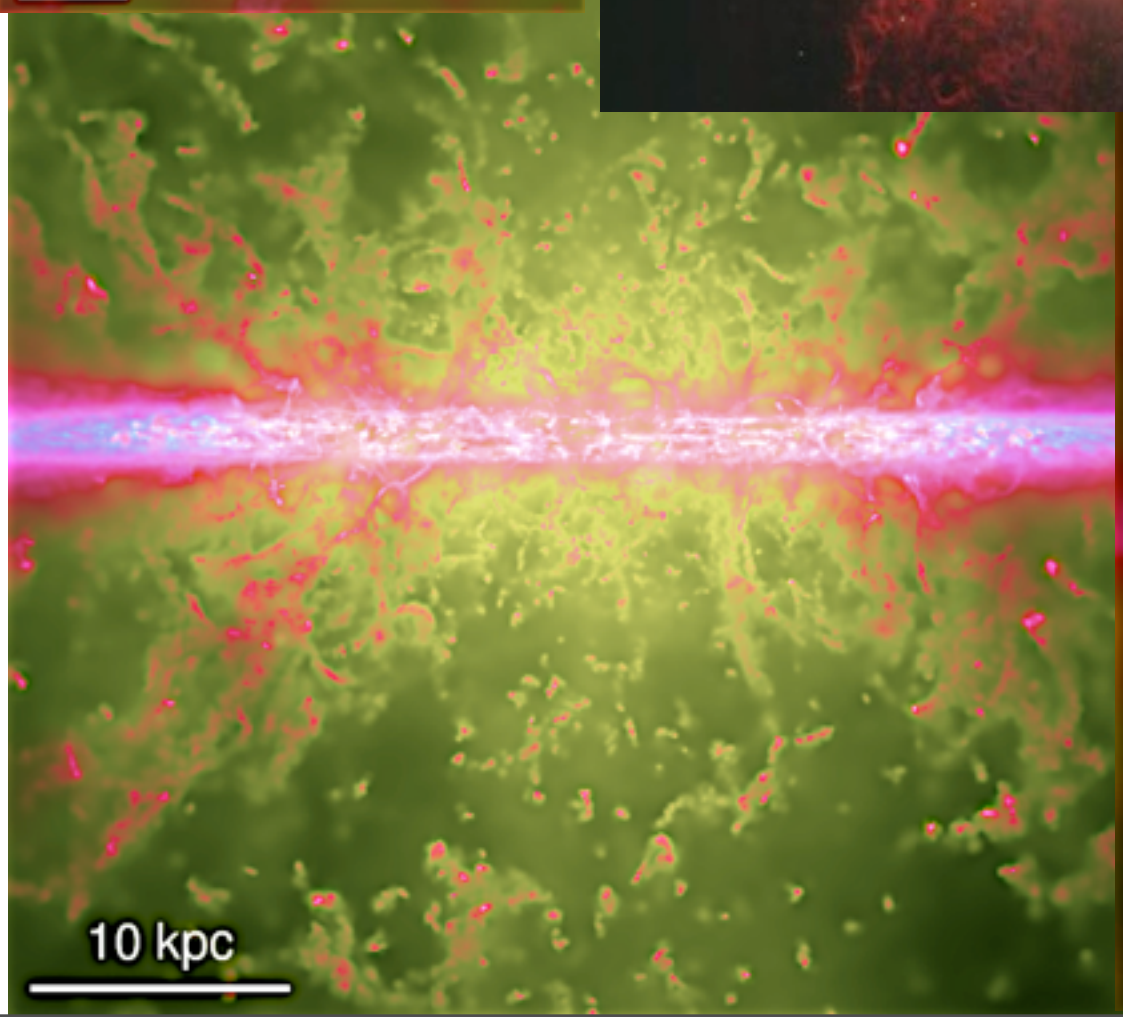


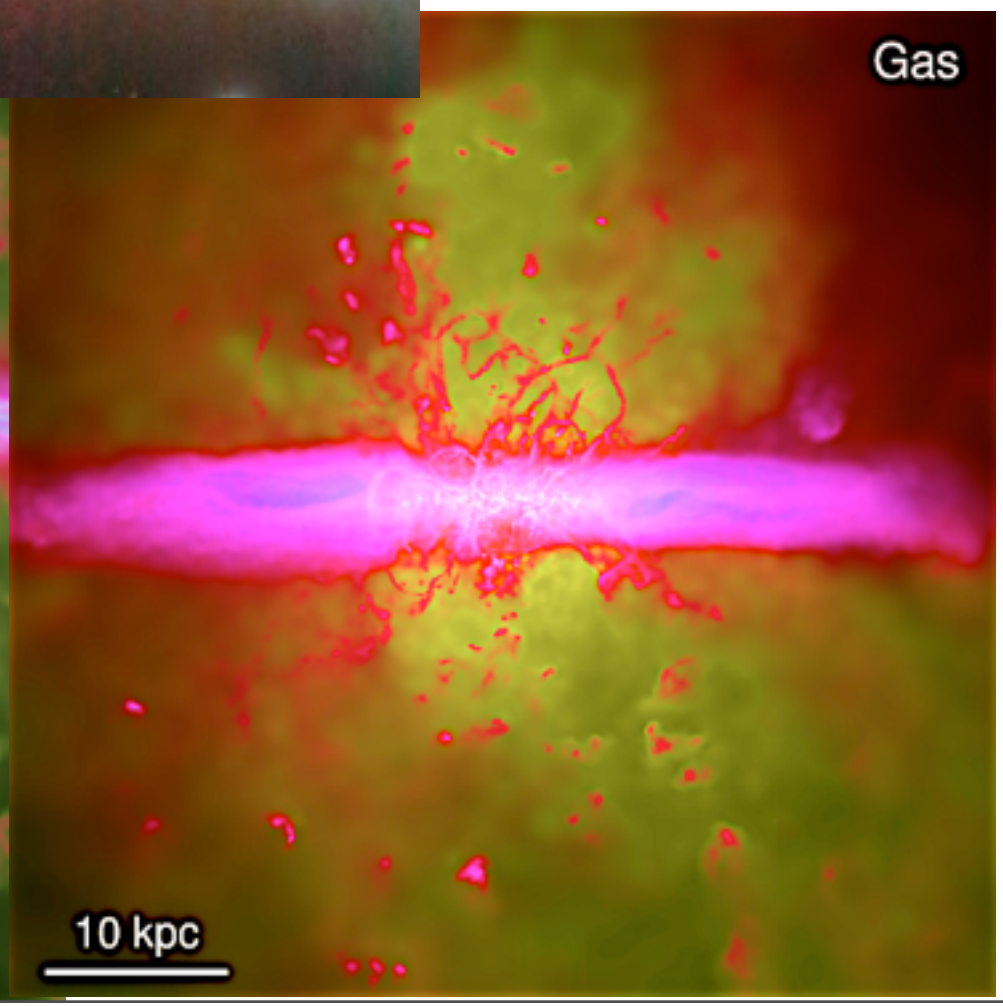
The Gas not Forming Stars:

Galaxy Winds and the Baryon Cycle

Galactic Super-Winds







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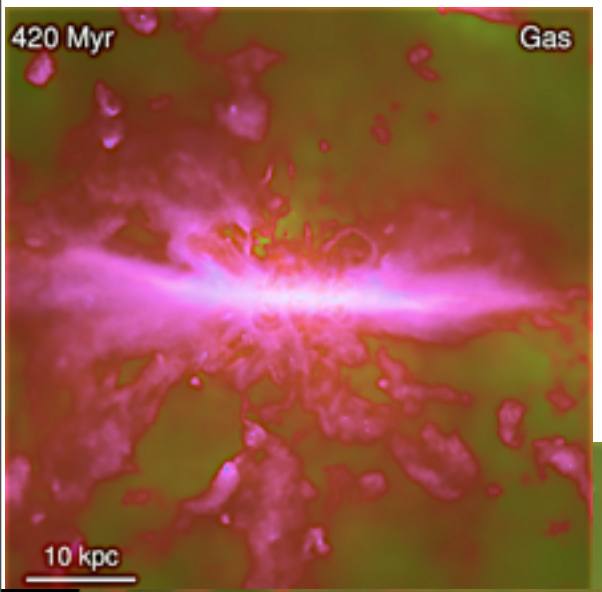
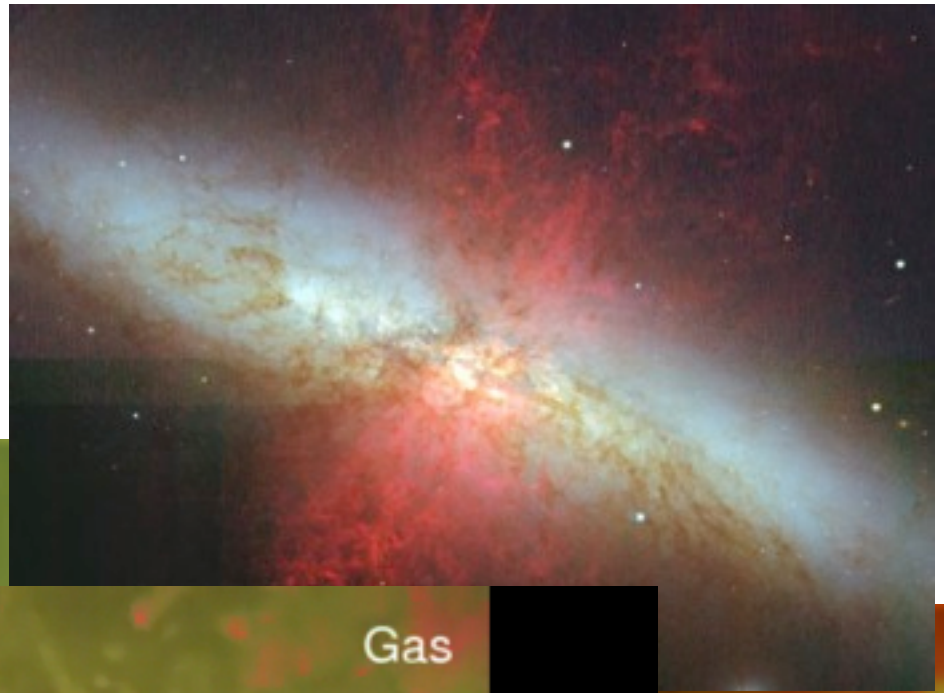
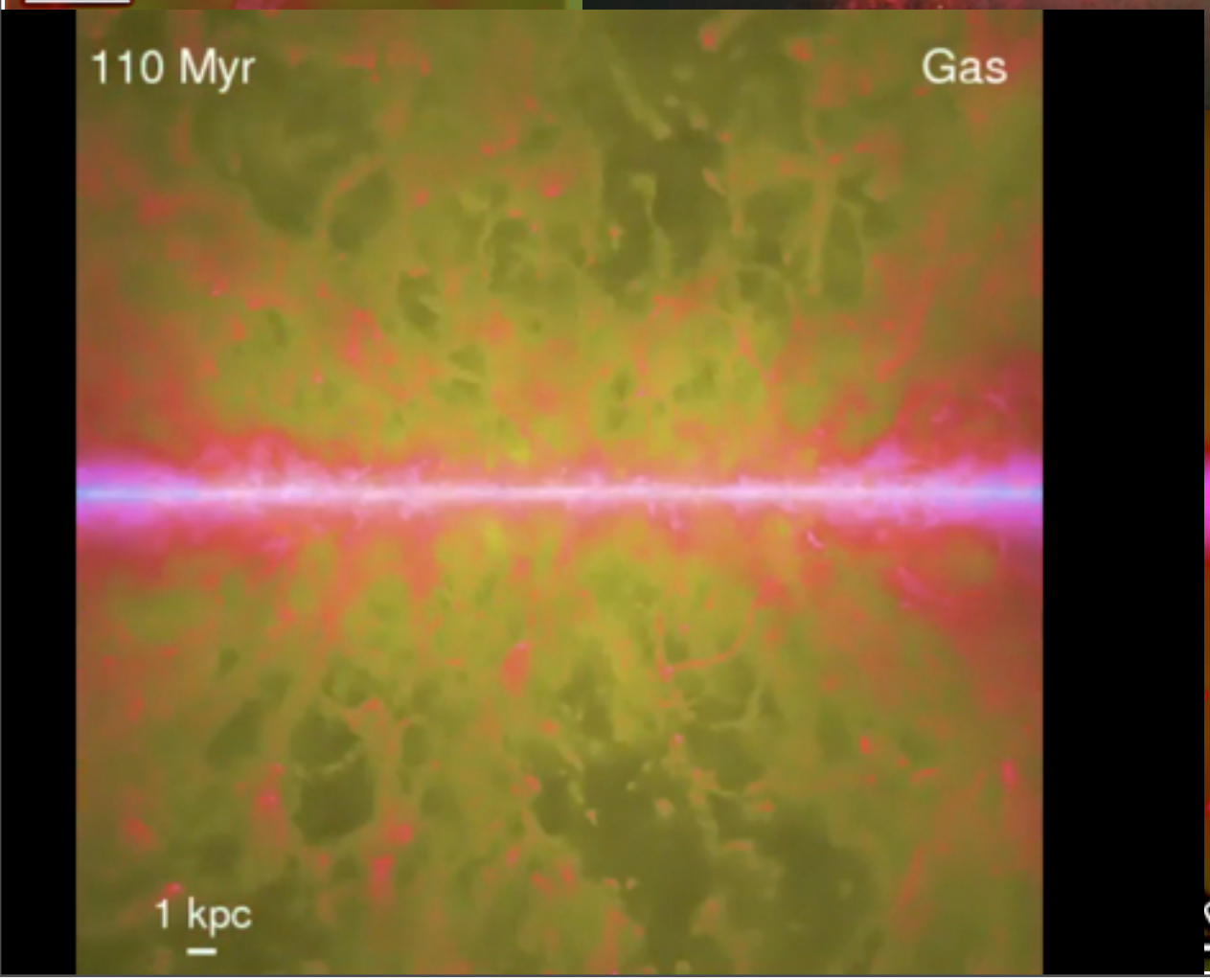
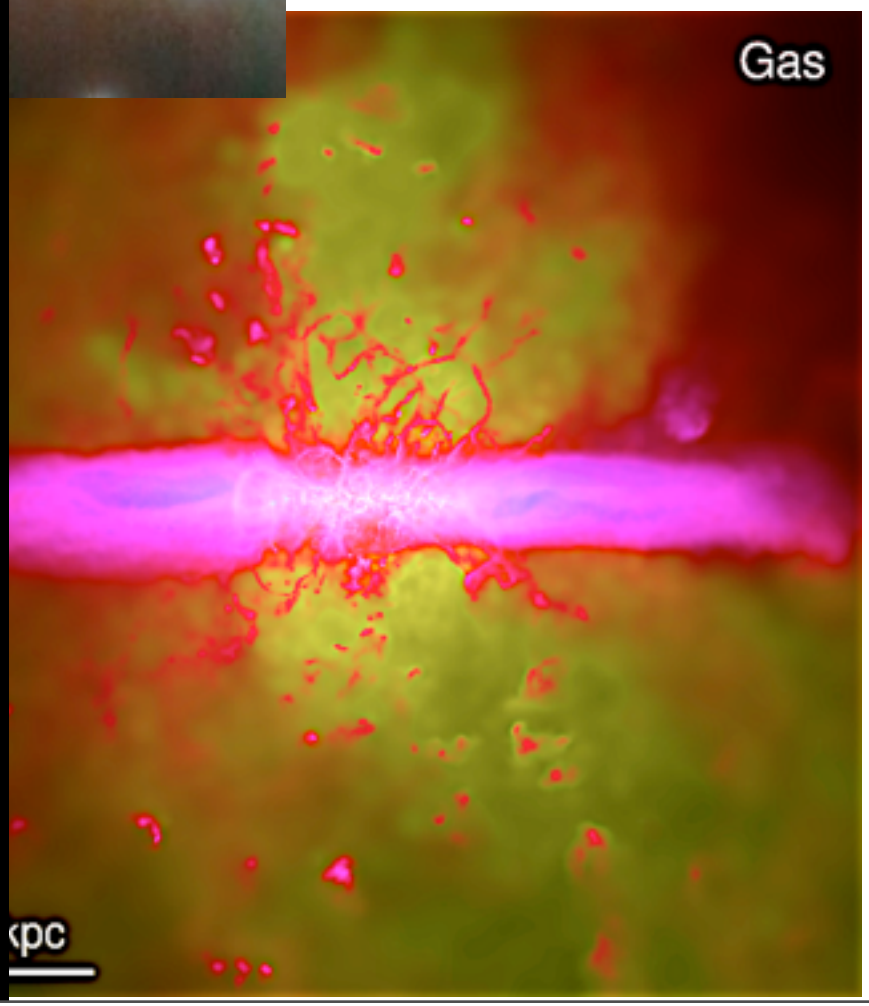


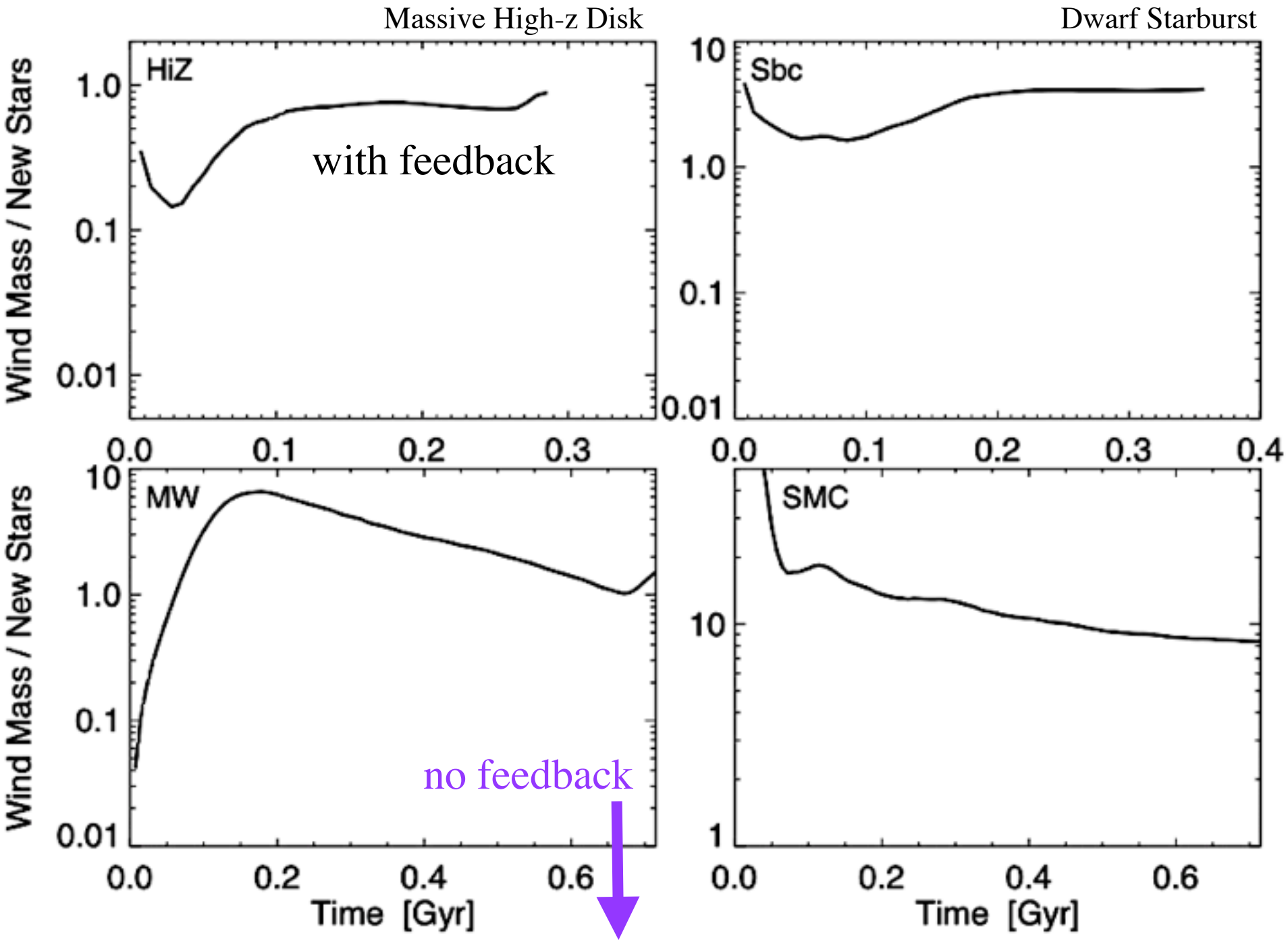






How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?



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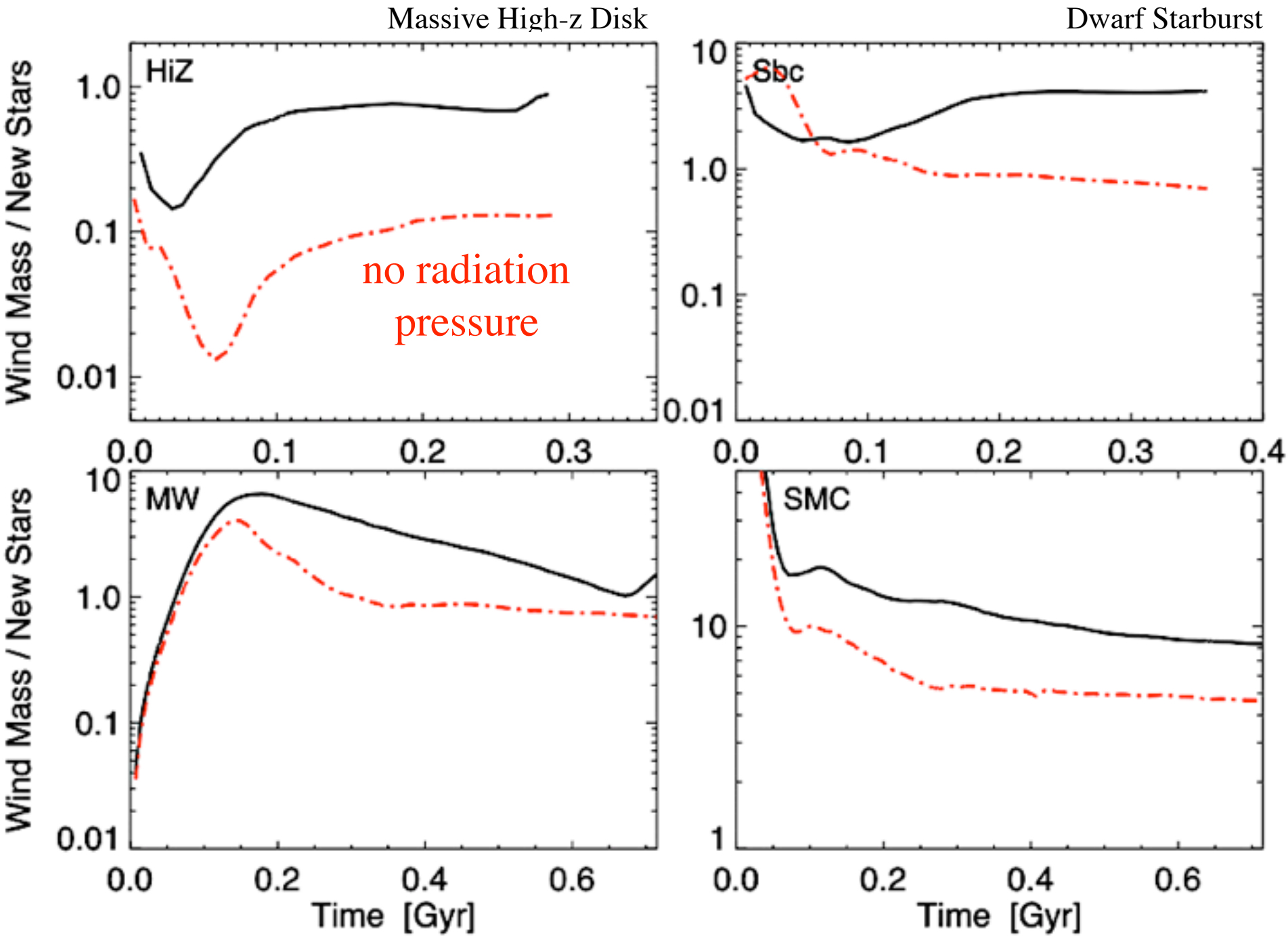

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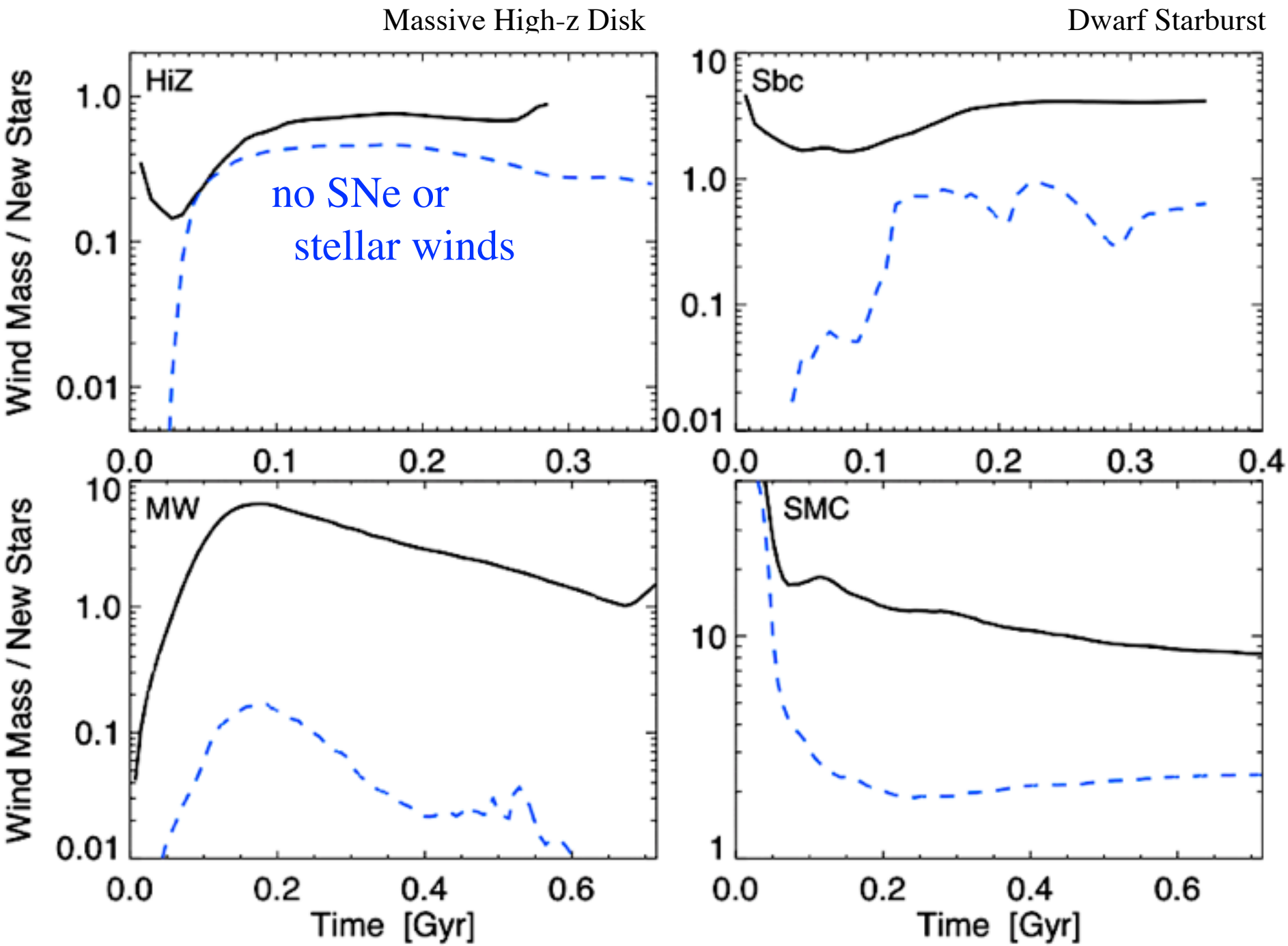

How Efficient Are Galactic Super-Winds?

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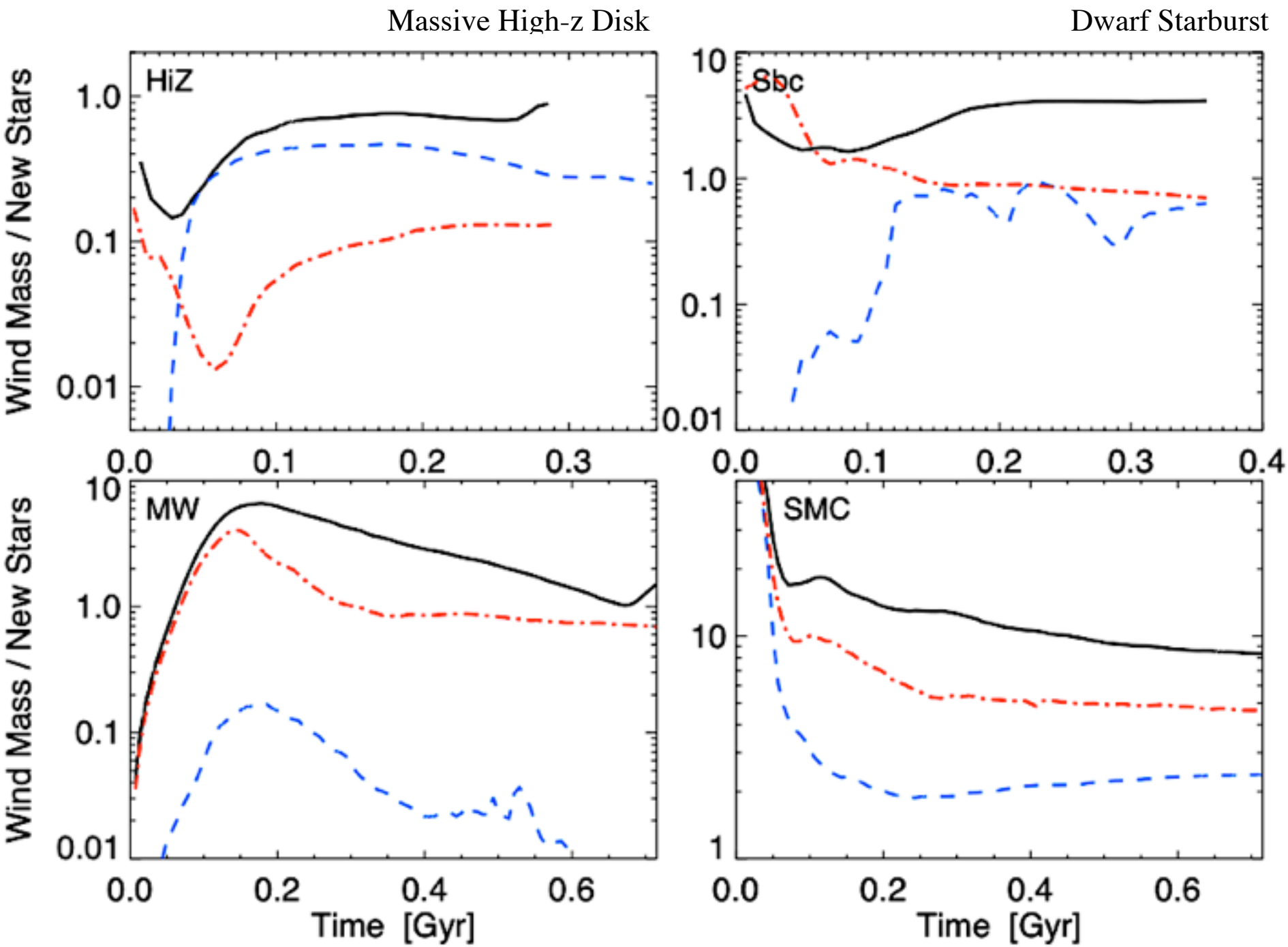

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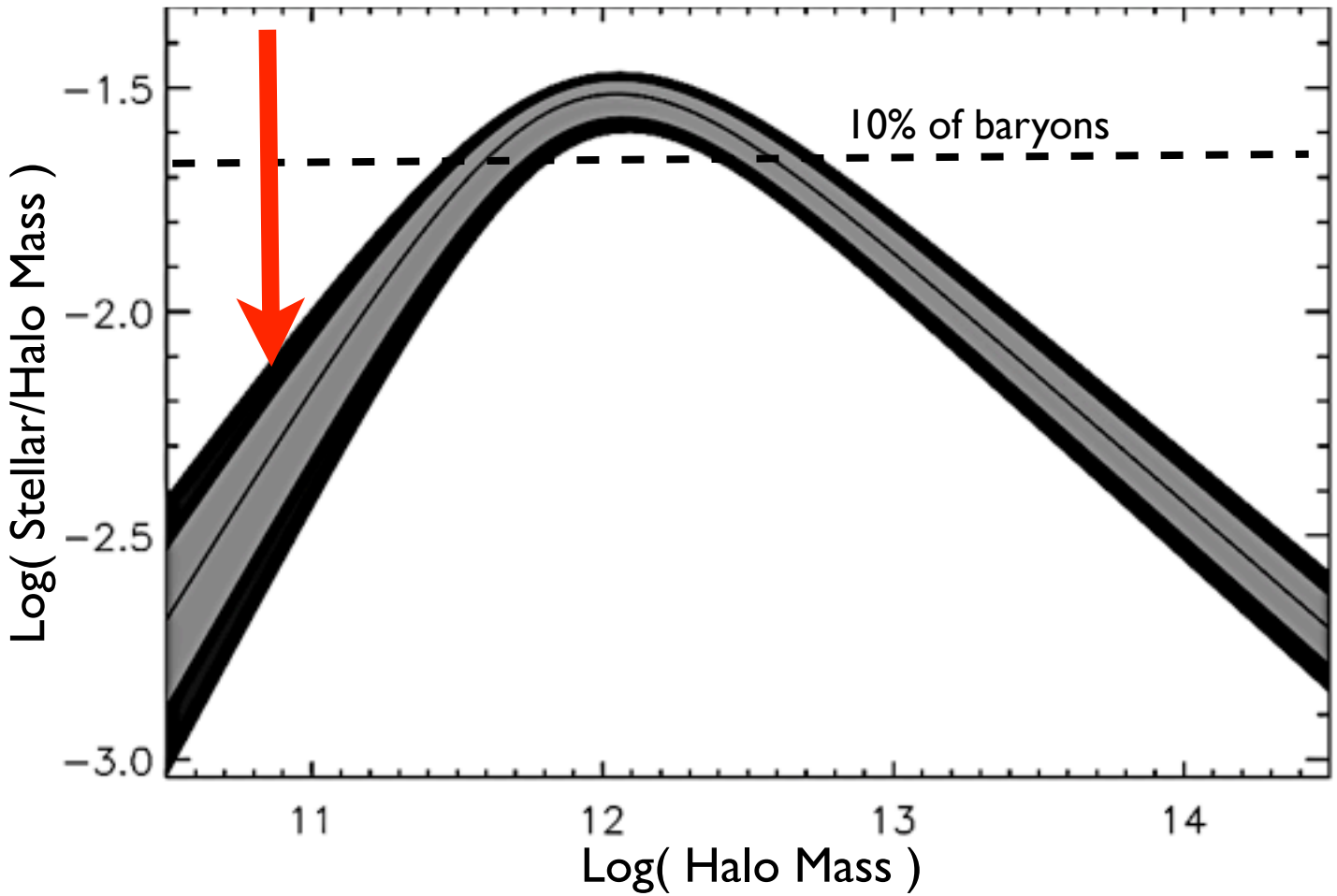
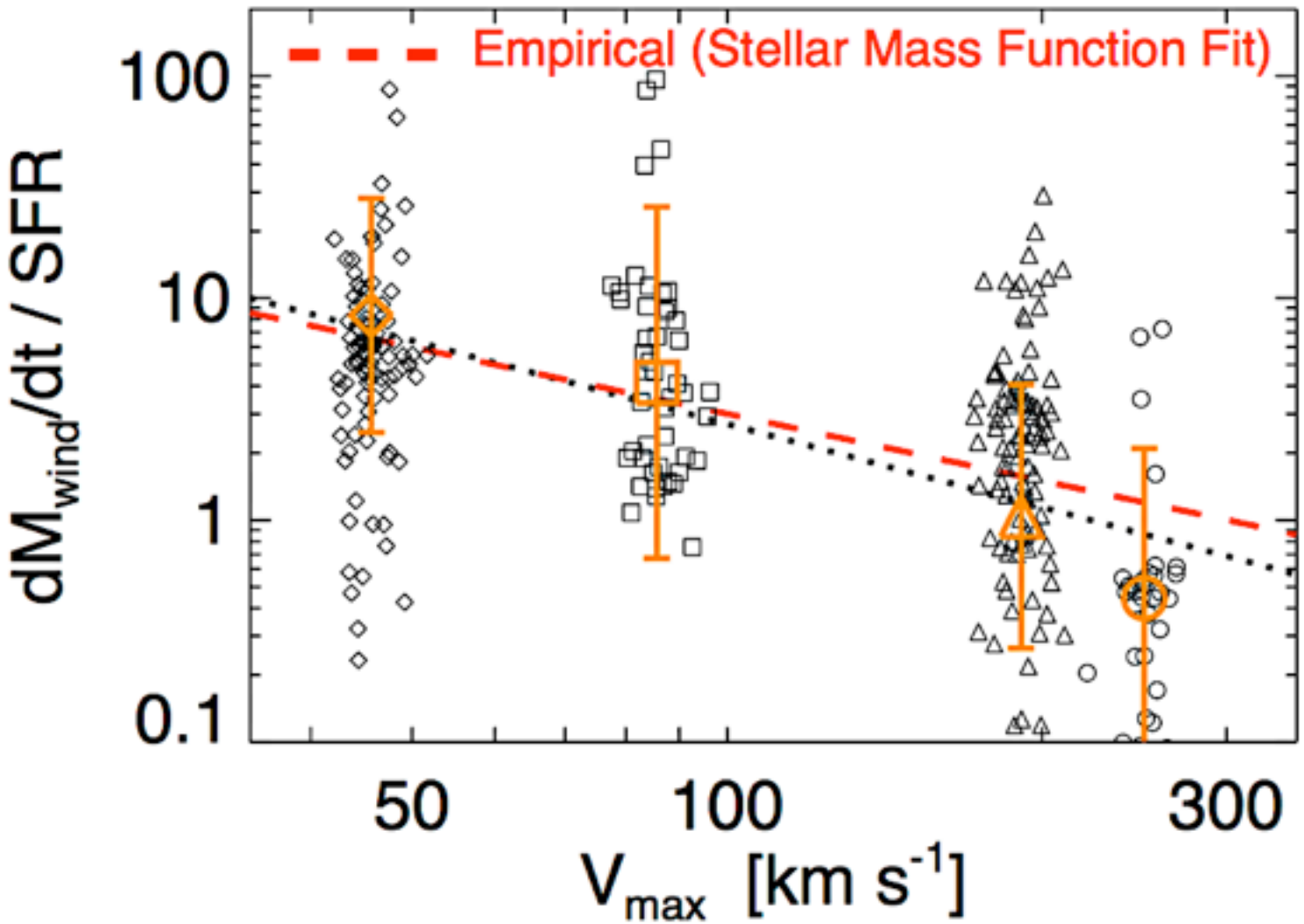


- Large mass-loading:

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

How Efficient Are Galactic Super-Winds?



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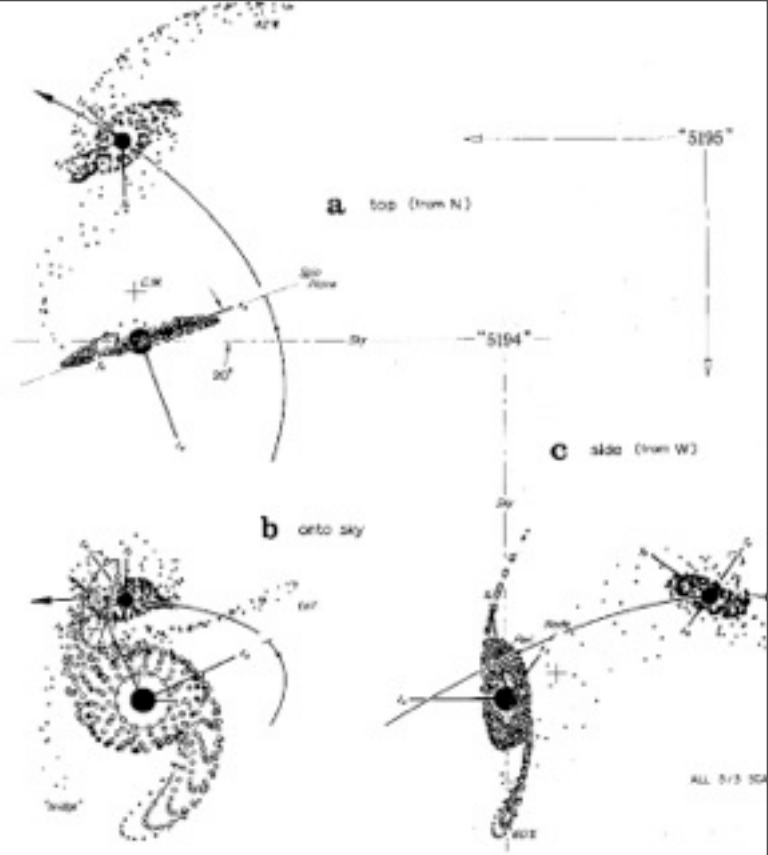
What Happens when Galaxies Interact?

Our Conventional Wisdom (Toomre):

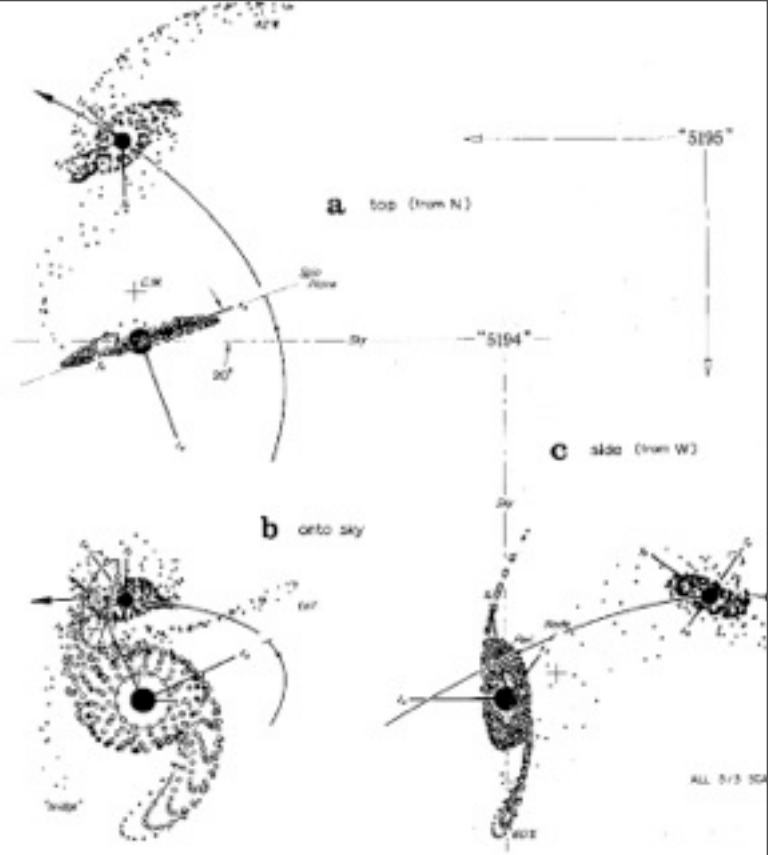


[redacted]

F. Summers

Our Conventional Wisdom (Toomre):

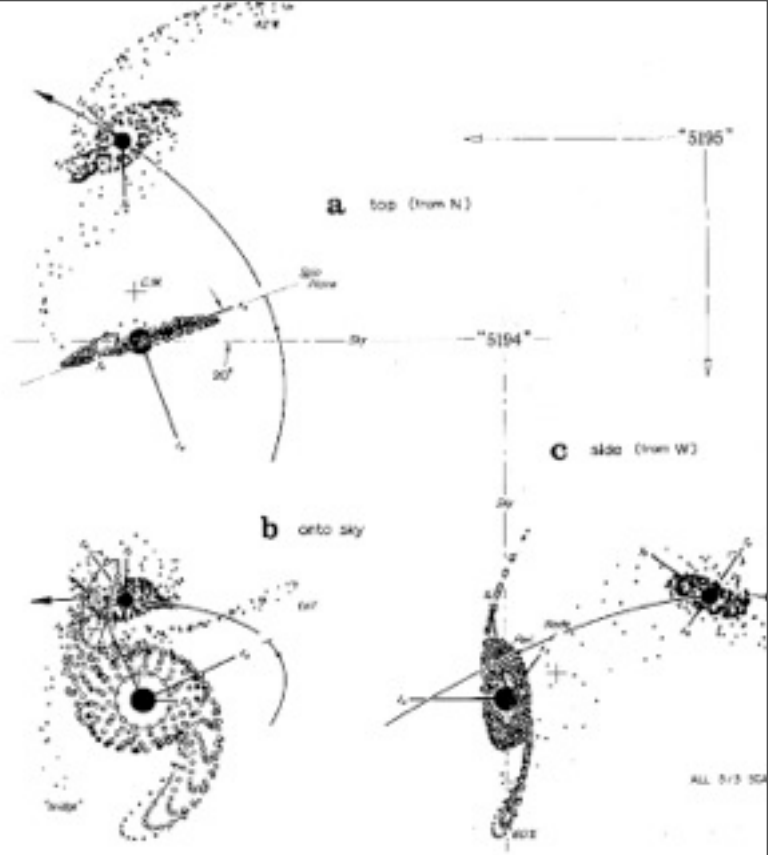
- Major mergers destroy disks



F. Summers

Our Conventional Wisdom (Toomre):

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

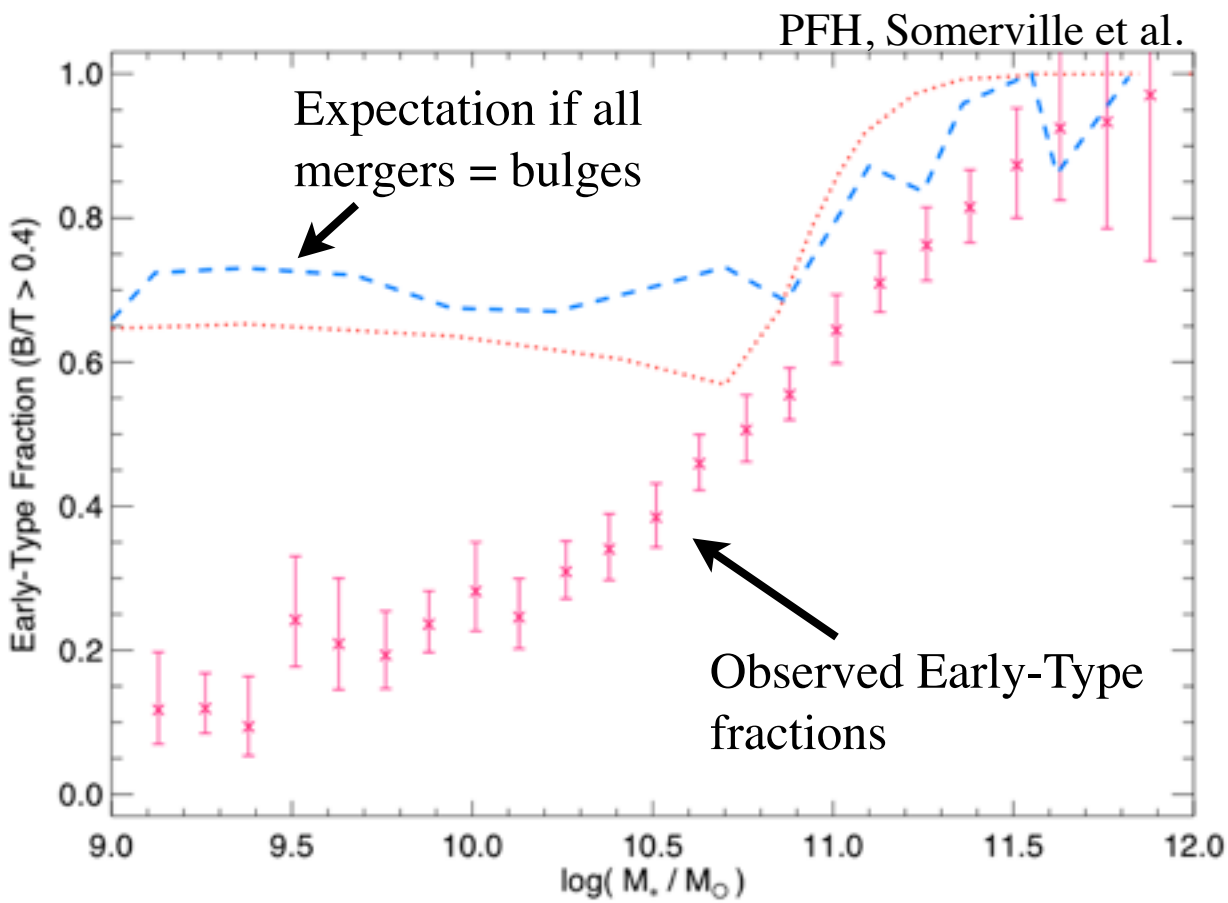


F. Summers

Our Conventional Wisdom...

Too Many Mergers?

-- missing some physics?



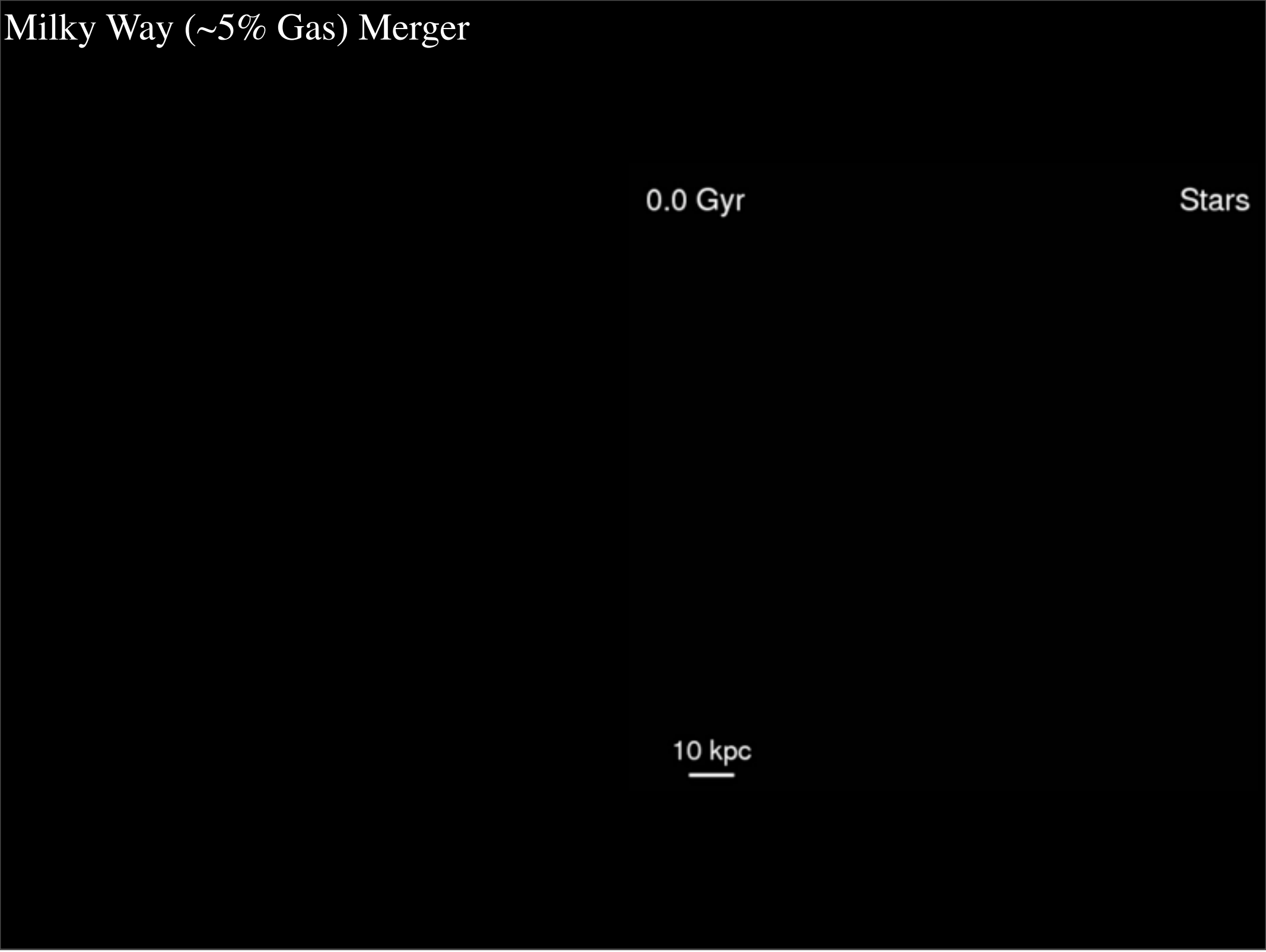
Stellar disk-disk merger remnants don't look like bulges!

-- sizes too large

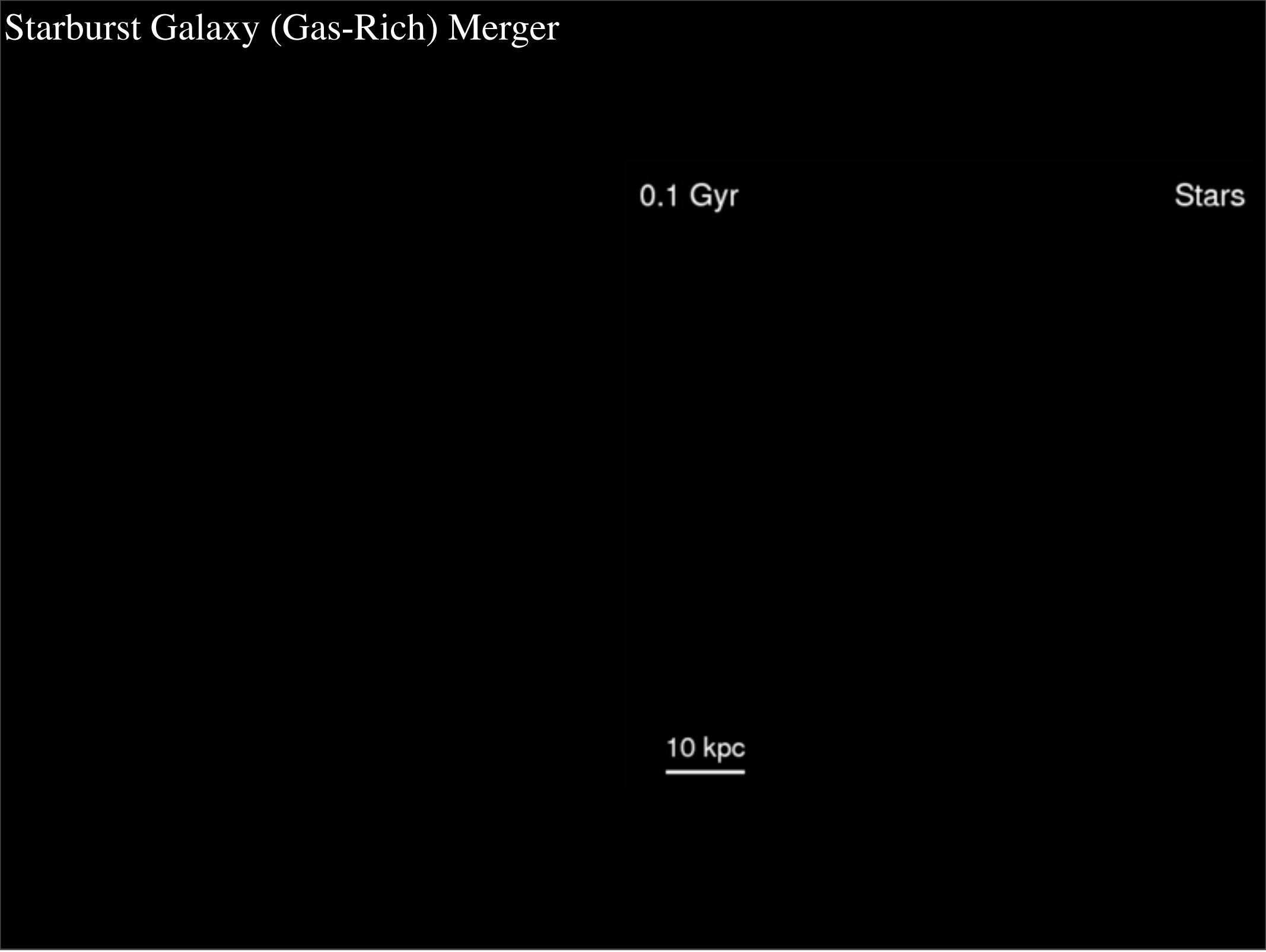
-- profiles too flat

-- shapes too flattened

Milky Way (~5% Gas) Merger



Starburst Galaxy (Gas-Rich) Merger



Galaxy Mergers

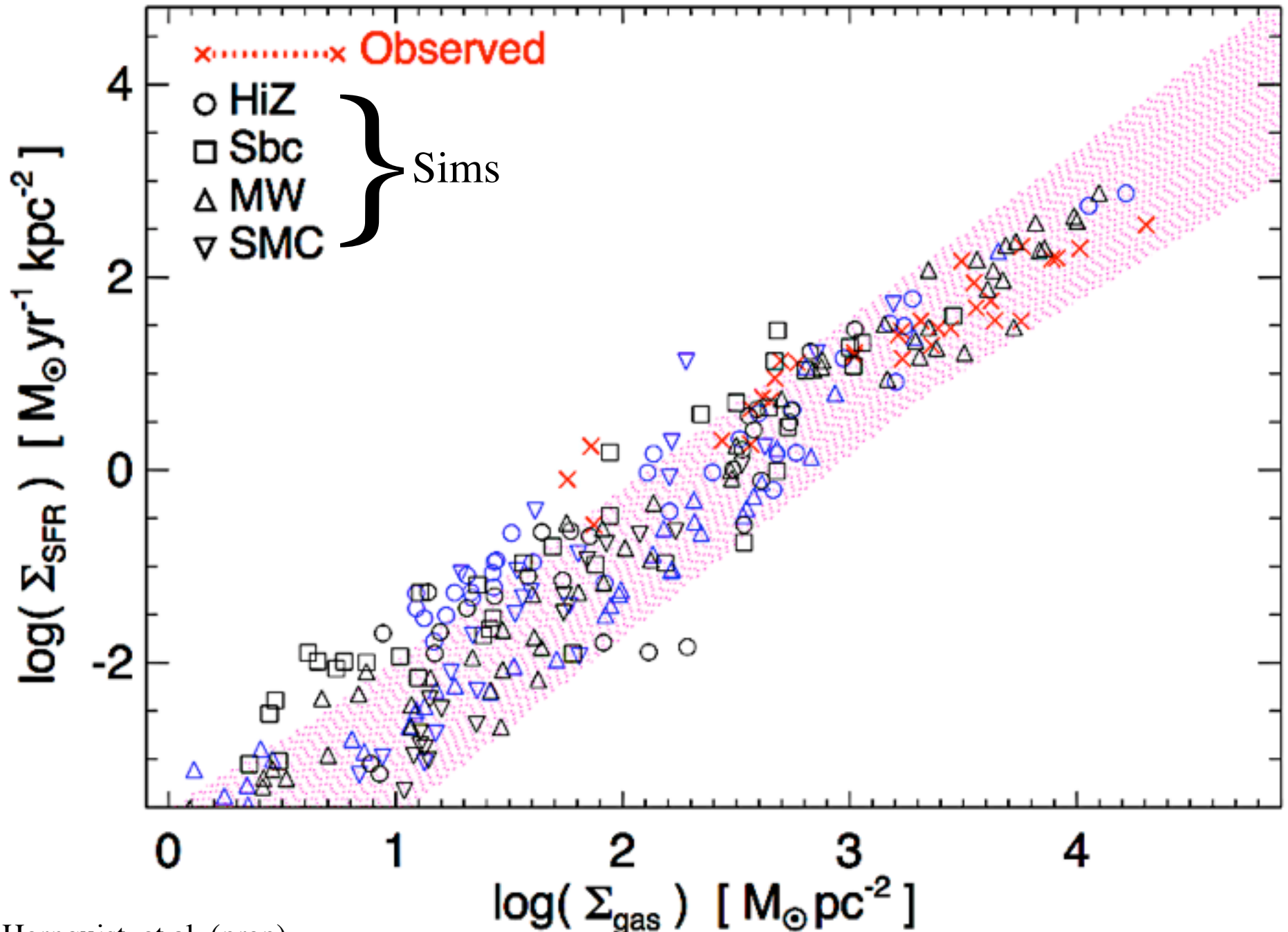
LABORATORY FOR STUDYING EXTREME CONDITIONS

- 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

PFH, Kormendy & Lauer et al.

Galaxy Mergers

LABORATORY FOR STUDYING EXTREME CONDITIONS



PFH, Hernquist, et al. (prep)

Galaxy Mergers

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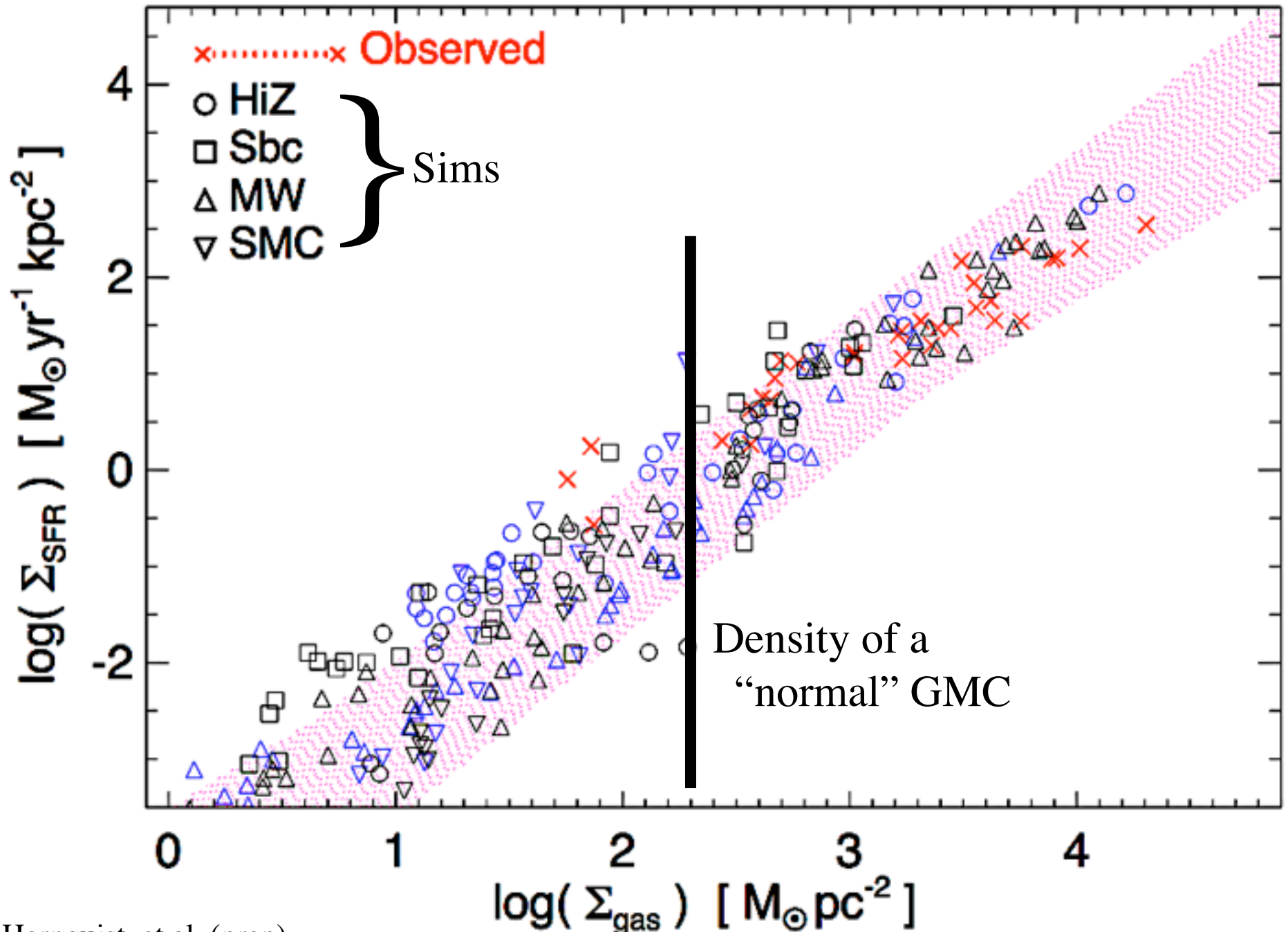
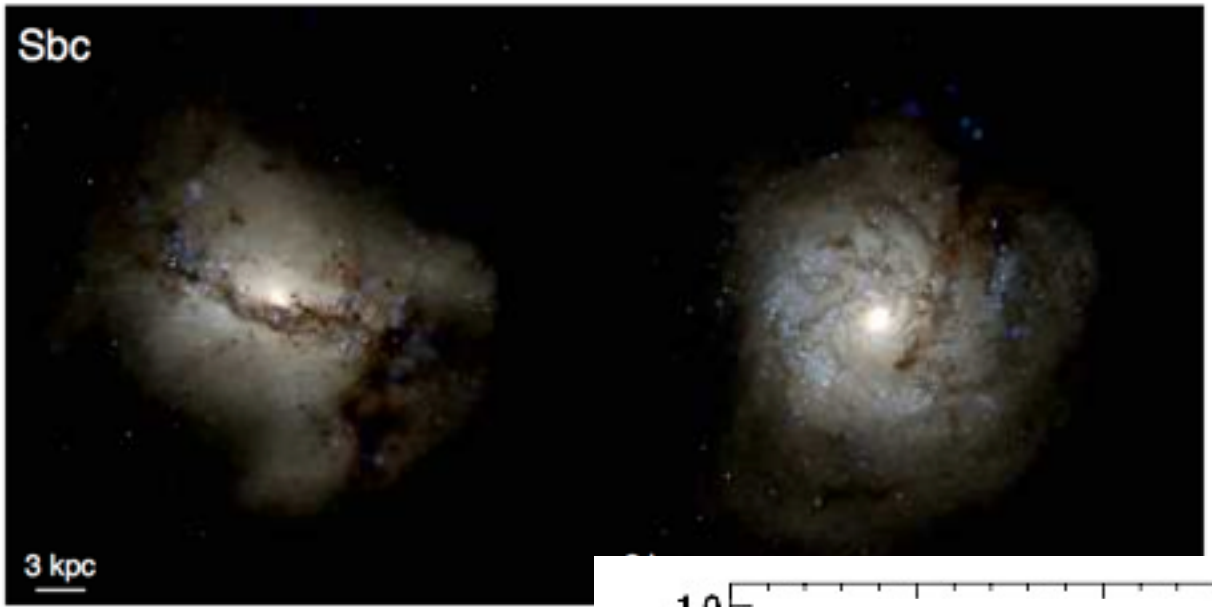


PFH, Hernquist, et al. (prep)

Disks can Survive & Re-Form After Mergers

NOT AS FRAGILE AS WE THOUGHT!



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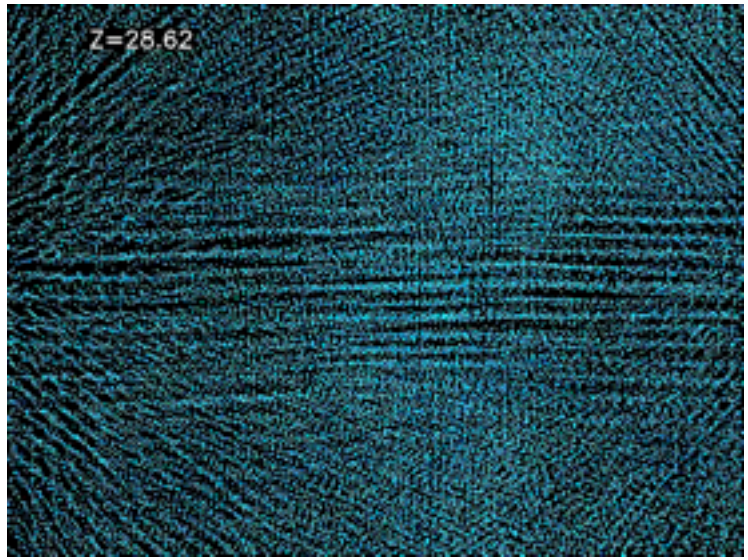

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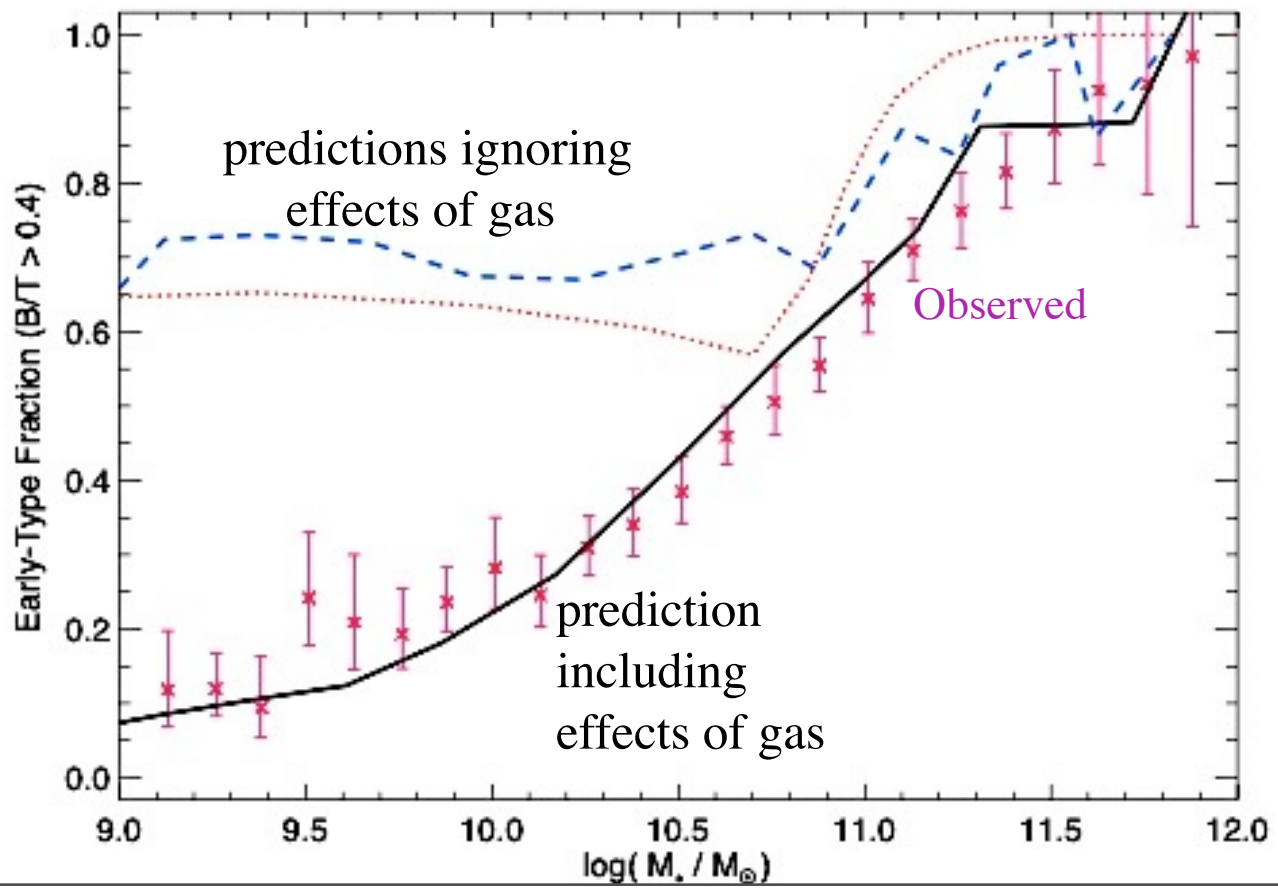
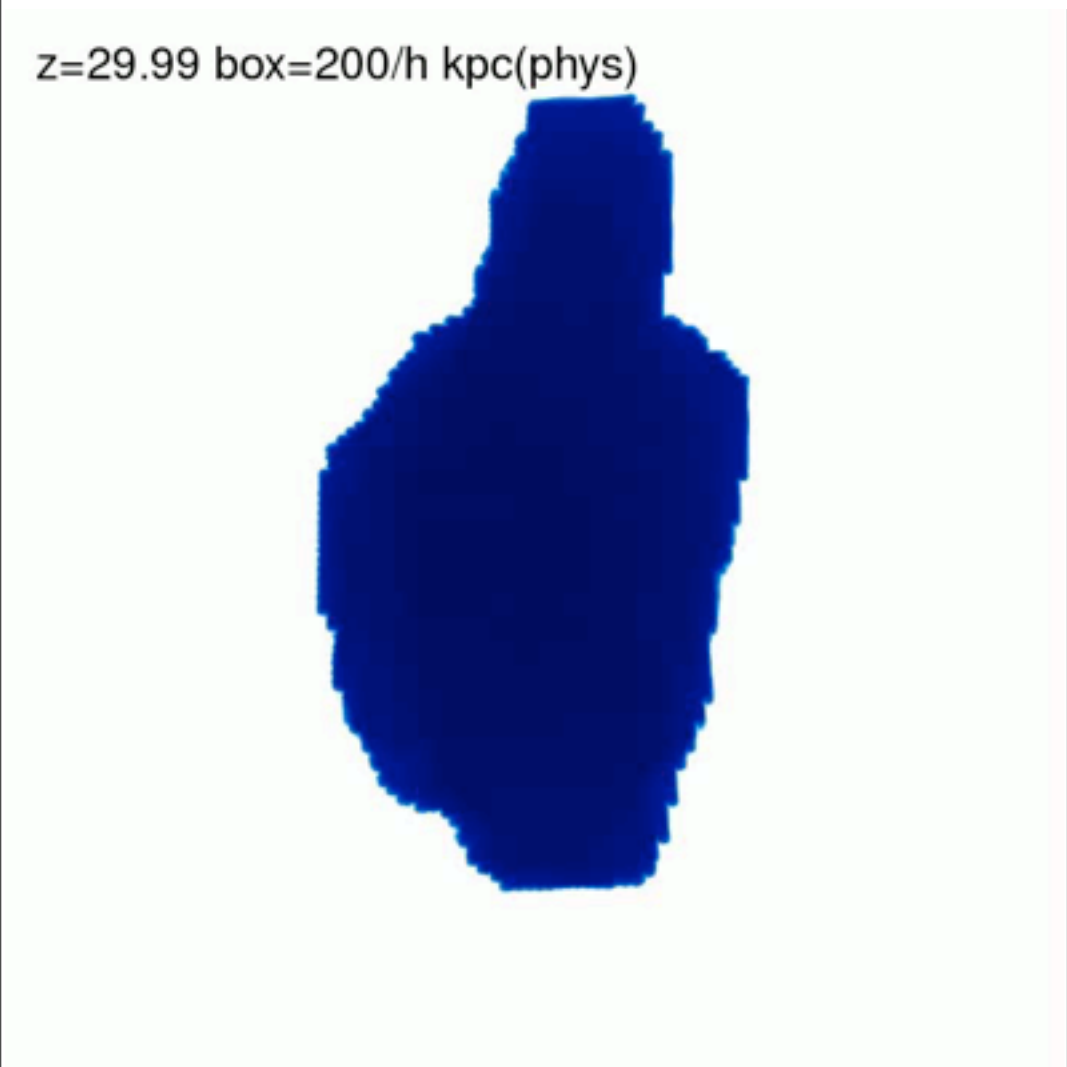


PFH & Somerville et al. 2009

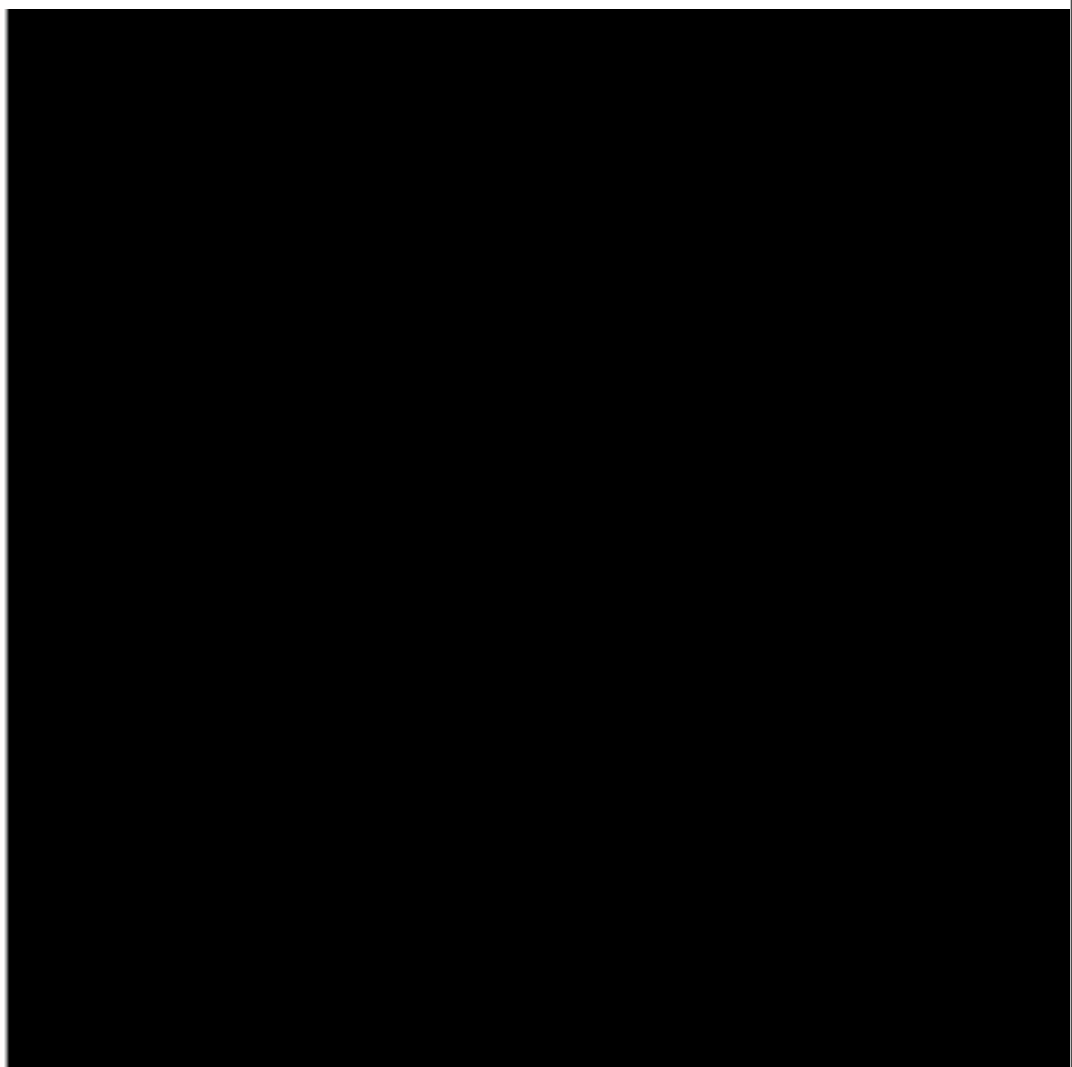
High Redshifts & The Inflow/Outflow Cycle

Cosmological Simulations

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



IGM Density



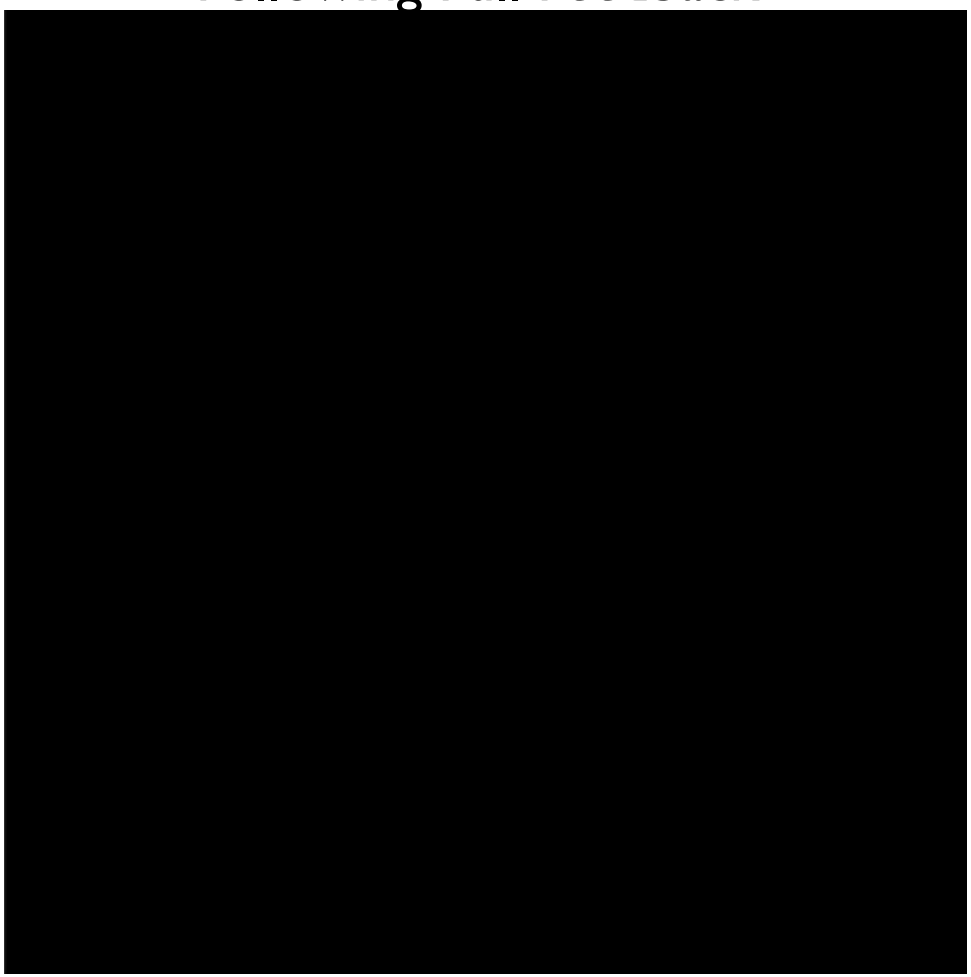
IGM Temperature

PFH & Keres et al

Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)

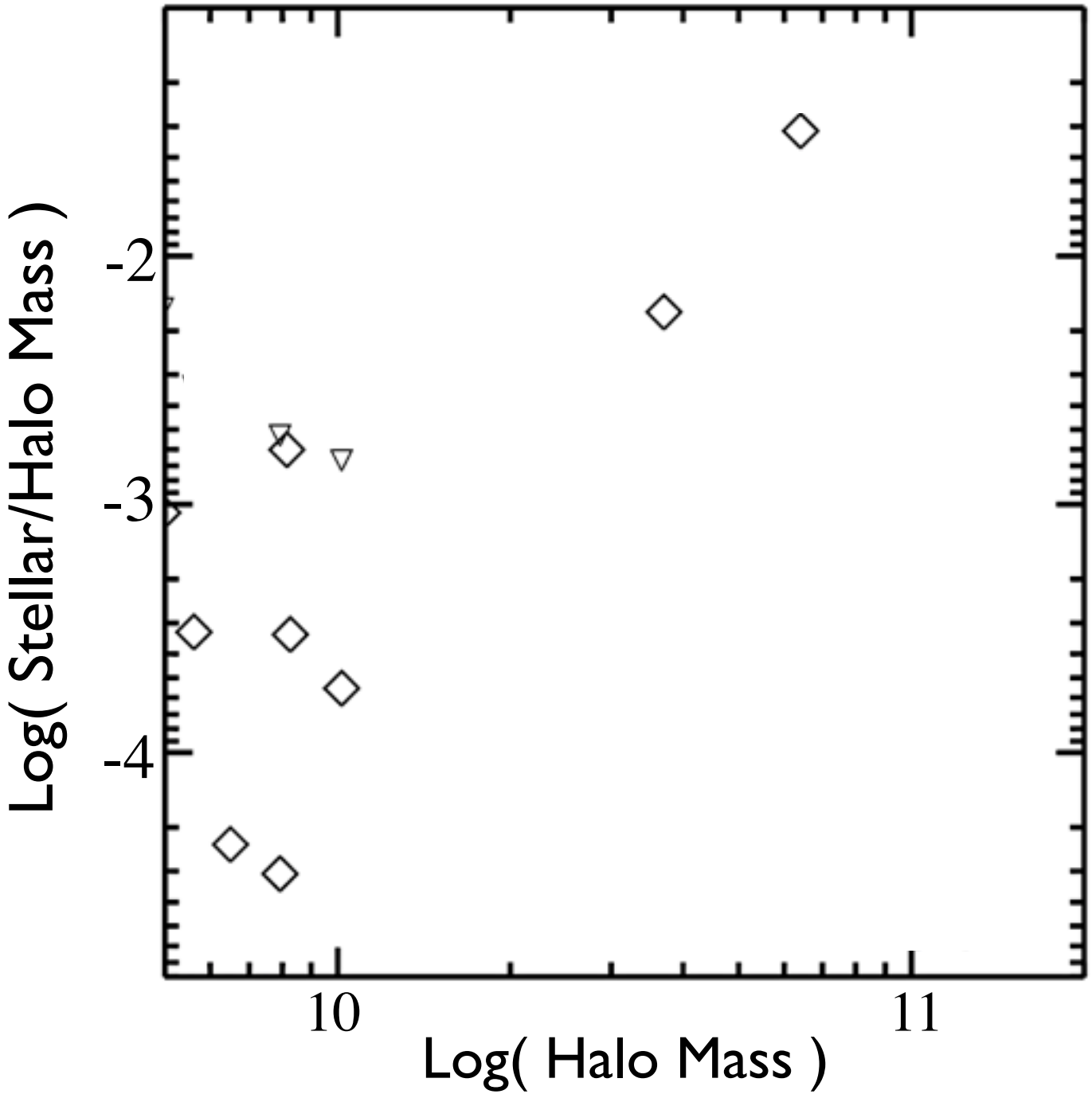
Following Full Feedback



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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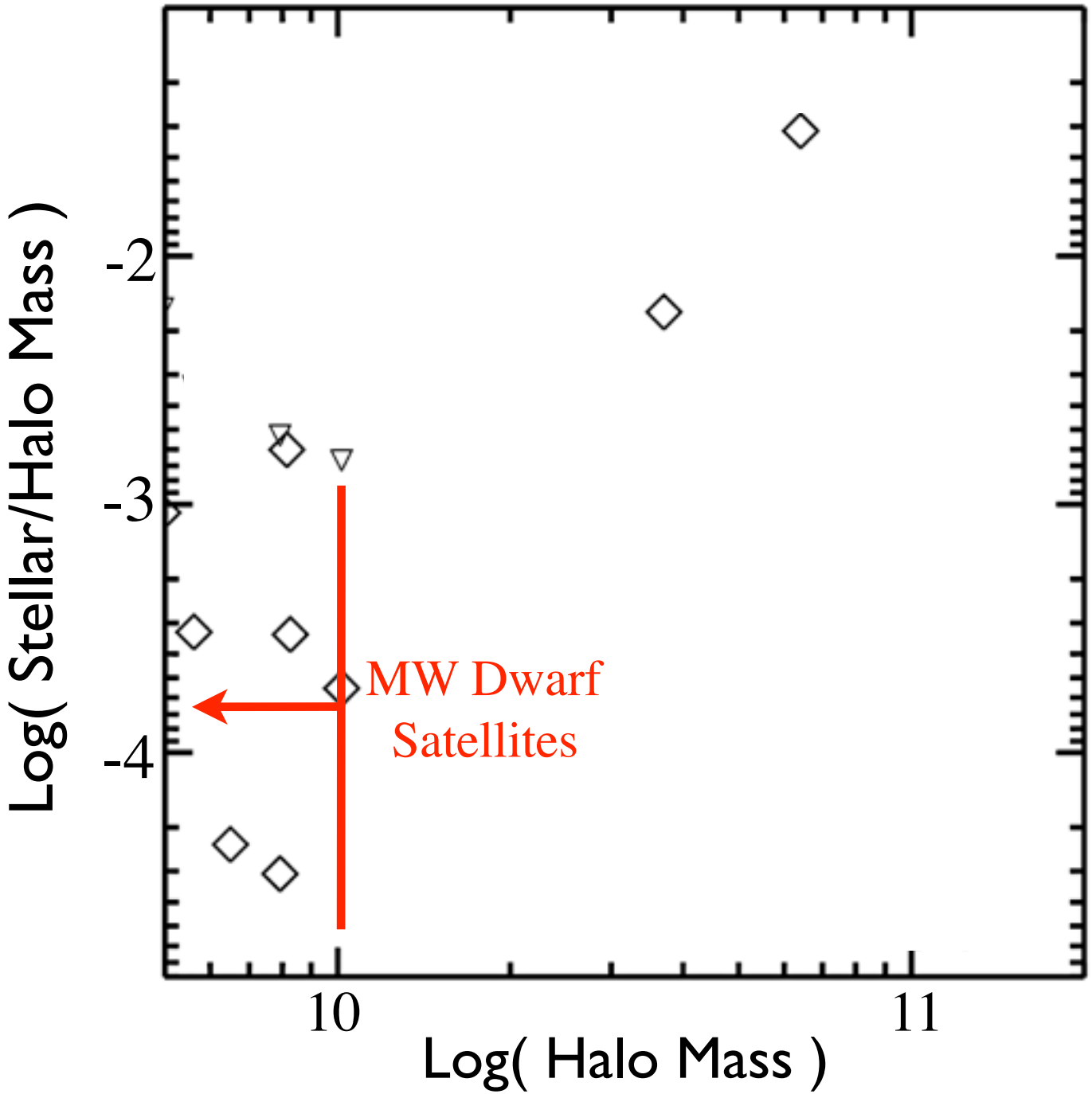
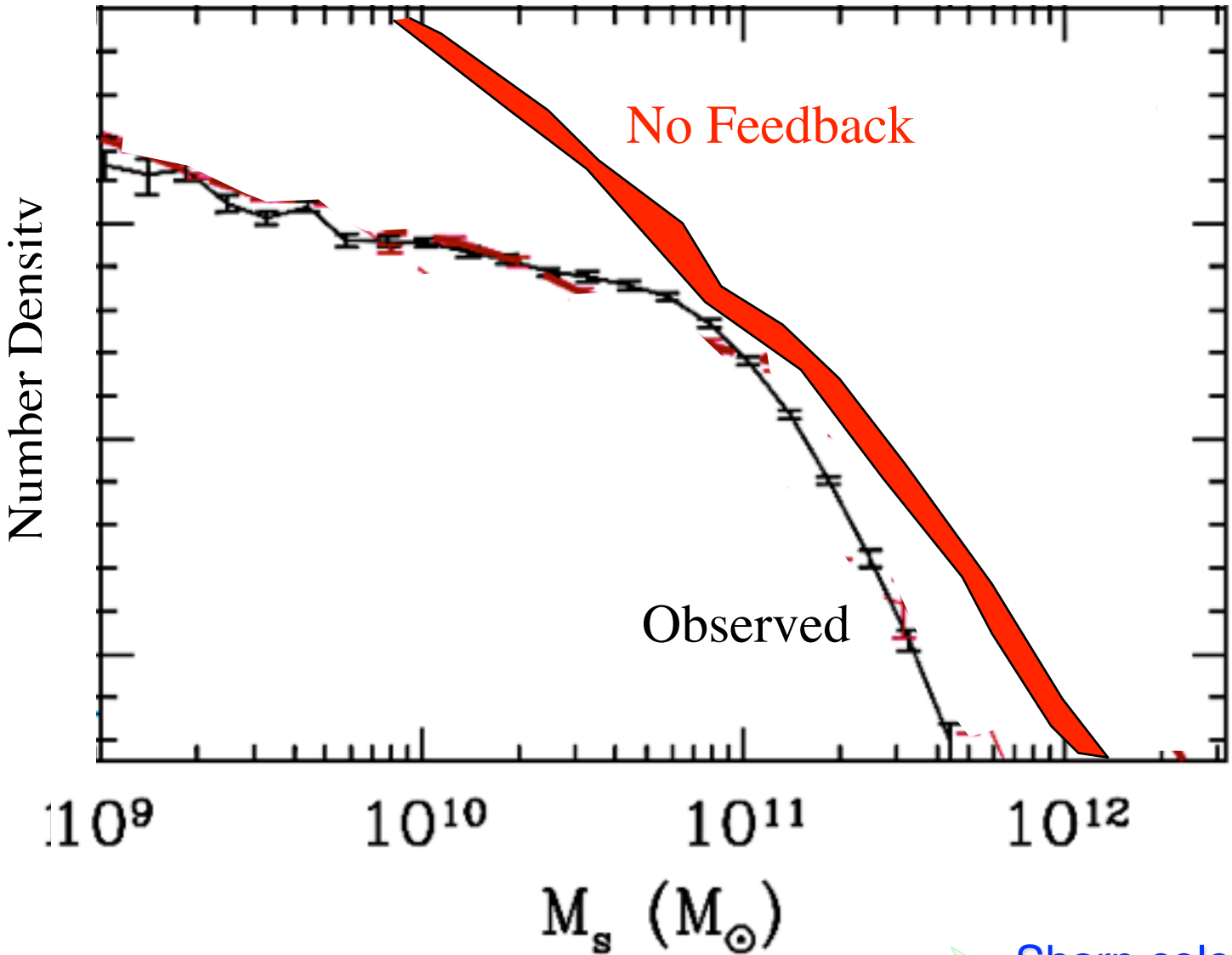


PFH & Keres et a
PFH, Bullock,
& Onorbe et a

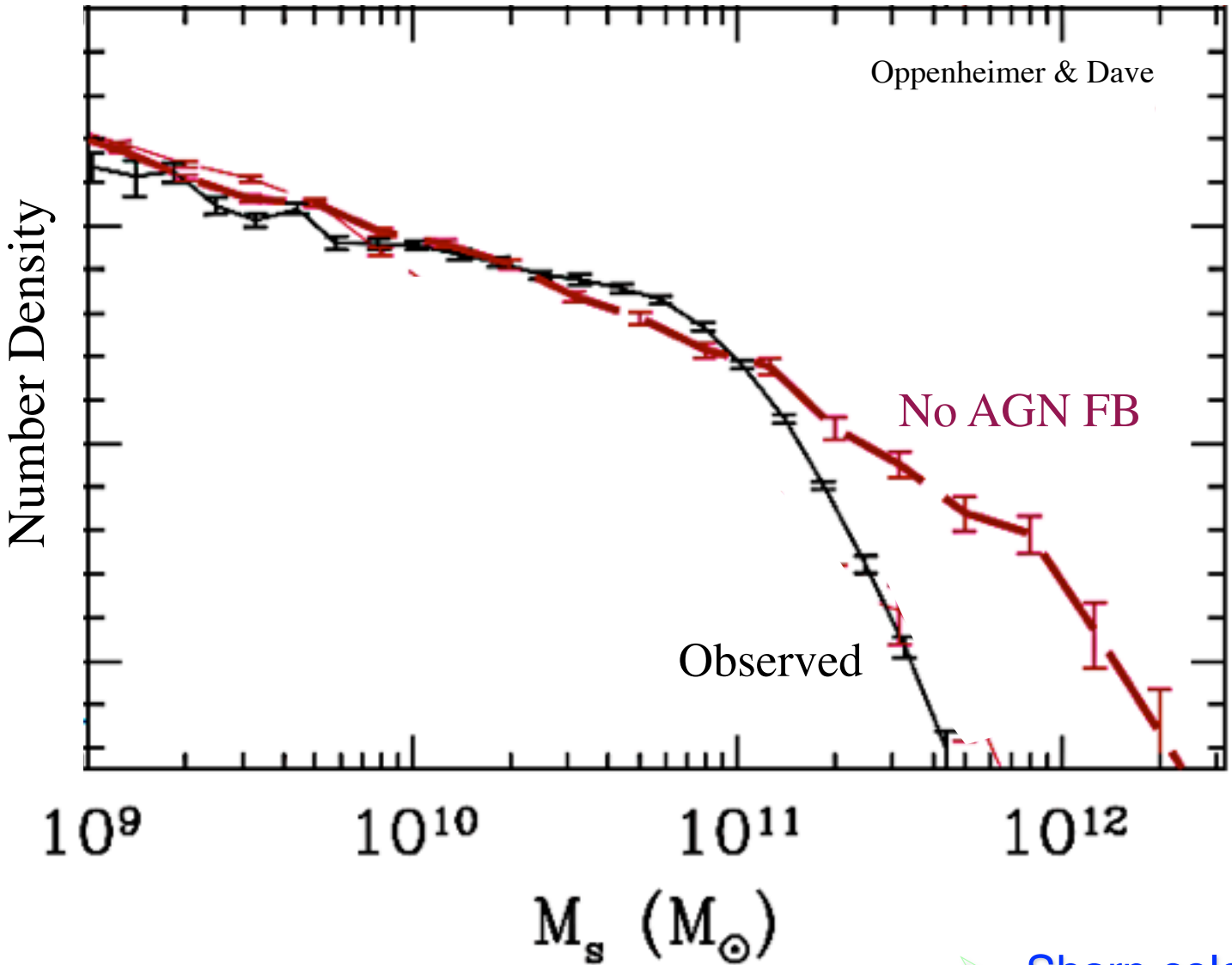
What About High-Mass Galaxies?

Why Do We Need AGN Feedback?



- Sharp color bimodality
- Lowering mass of >M* galaxies
- Removing/heating gas in groups

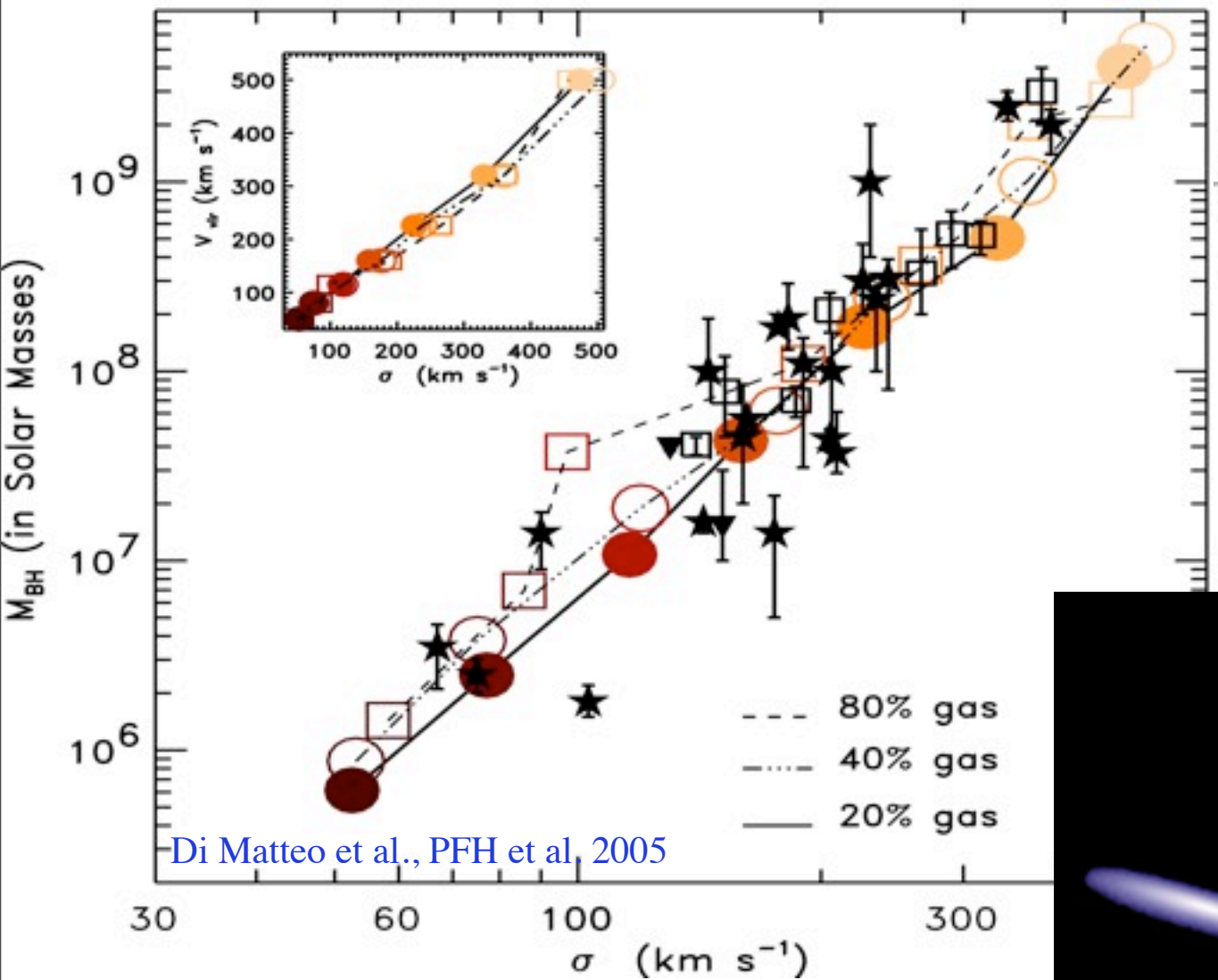
Why Do We Need AGN Feedback?

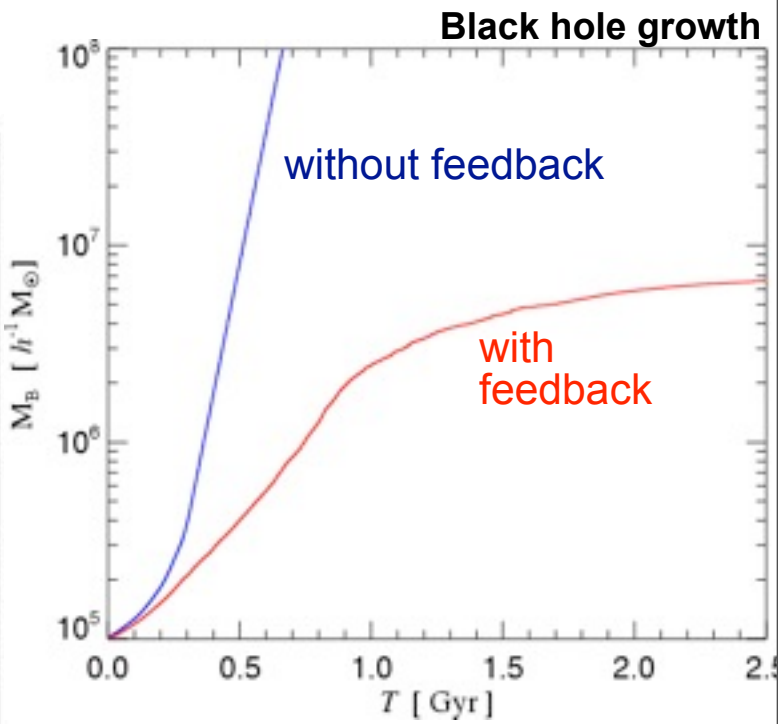


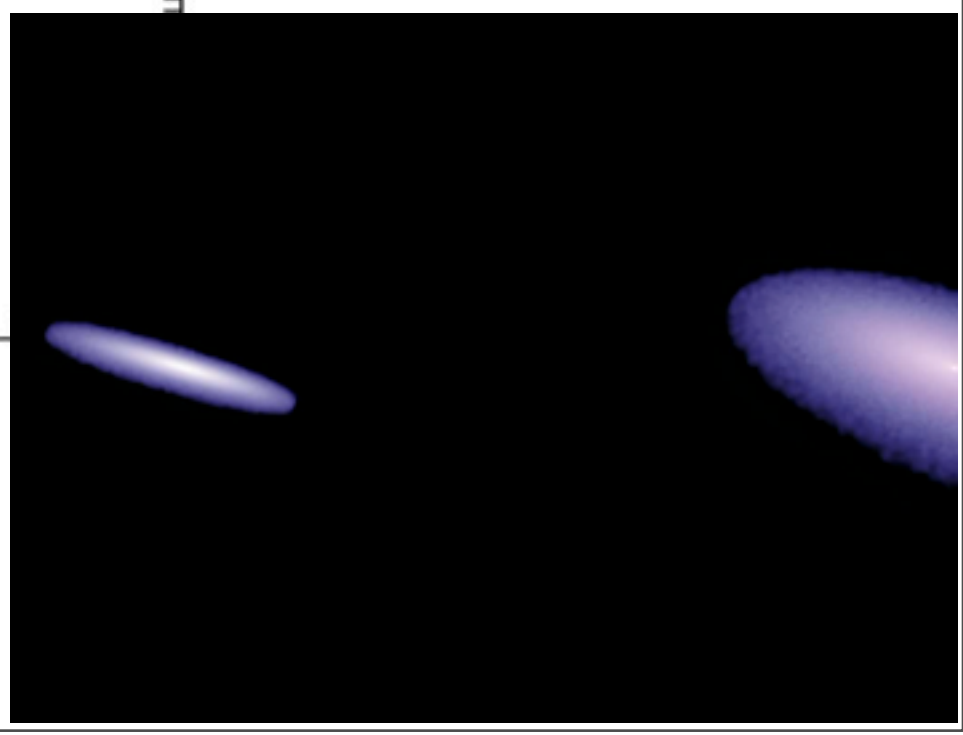
- Sharp color bimodality
- Lowering mass of >M* galaxies
- Removing/heating gas in groups

M-sigma Suggests *Self-Regulated* BH Growth

FEEDBACK PREVENTS RUNAWAY BLACK HOLE GROWTH



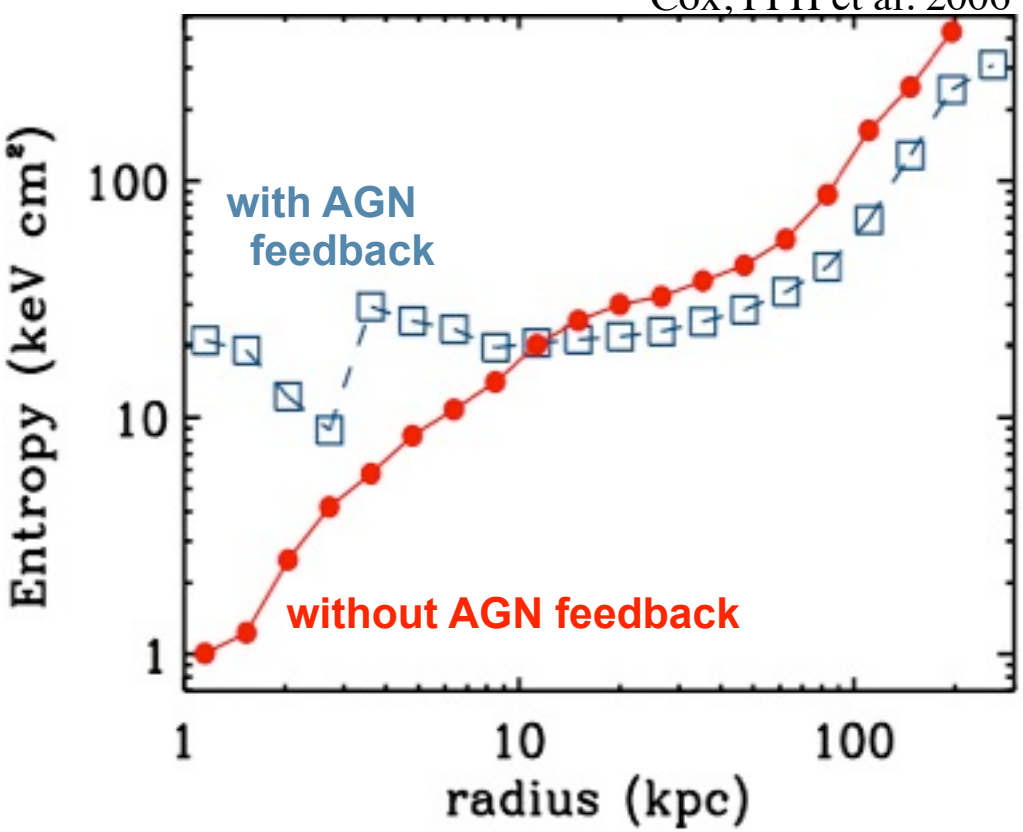


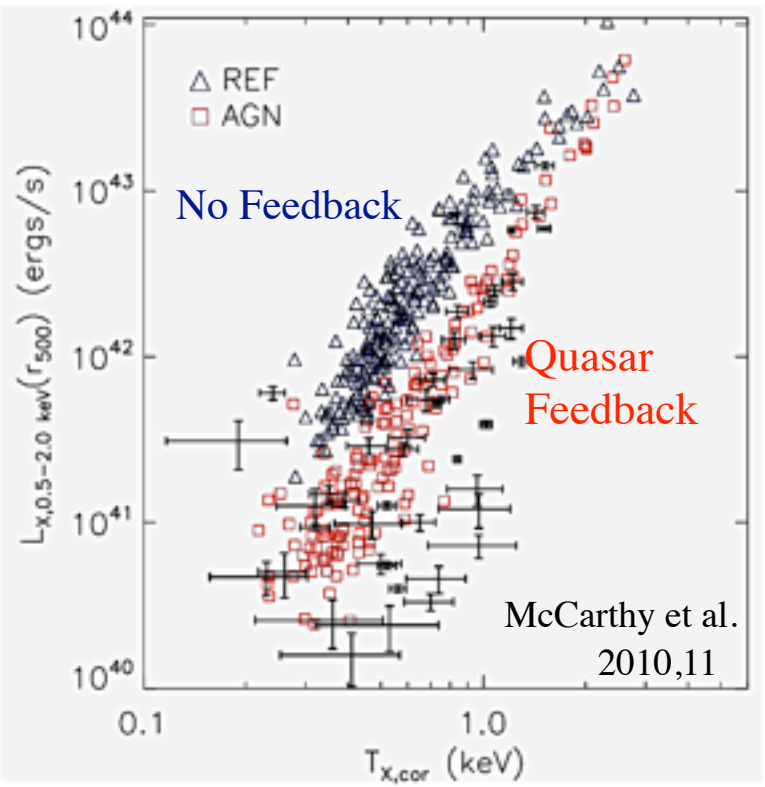


Quasar Outflows: Heating Halo Gas

SHUT DOWN COOLING AND/OR "SET UP" RADIO MODE

Cox, PFH et al. 2006



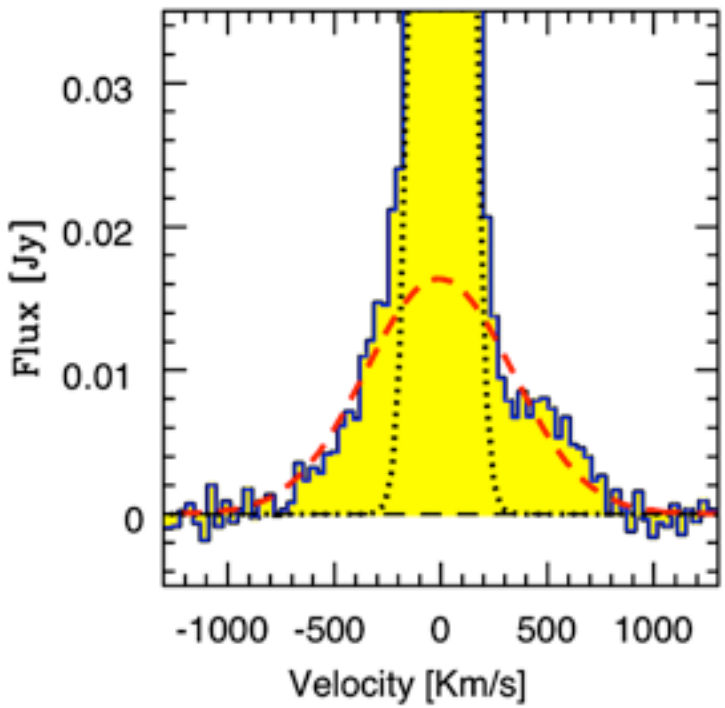


Molecular Outflows in AGN & ULIRGs

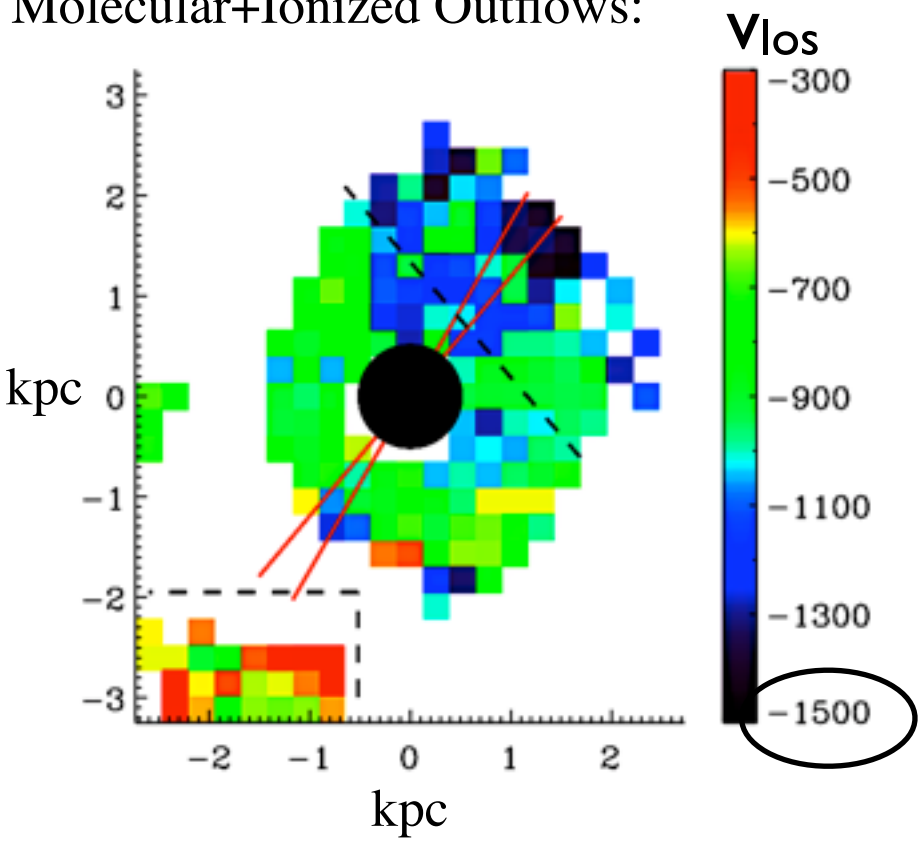
OBSERVED WINDS at >1000 km/s

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

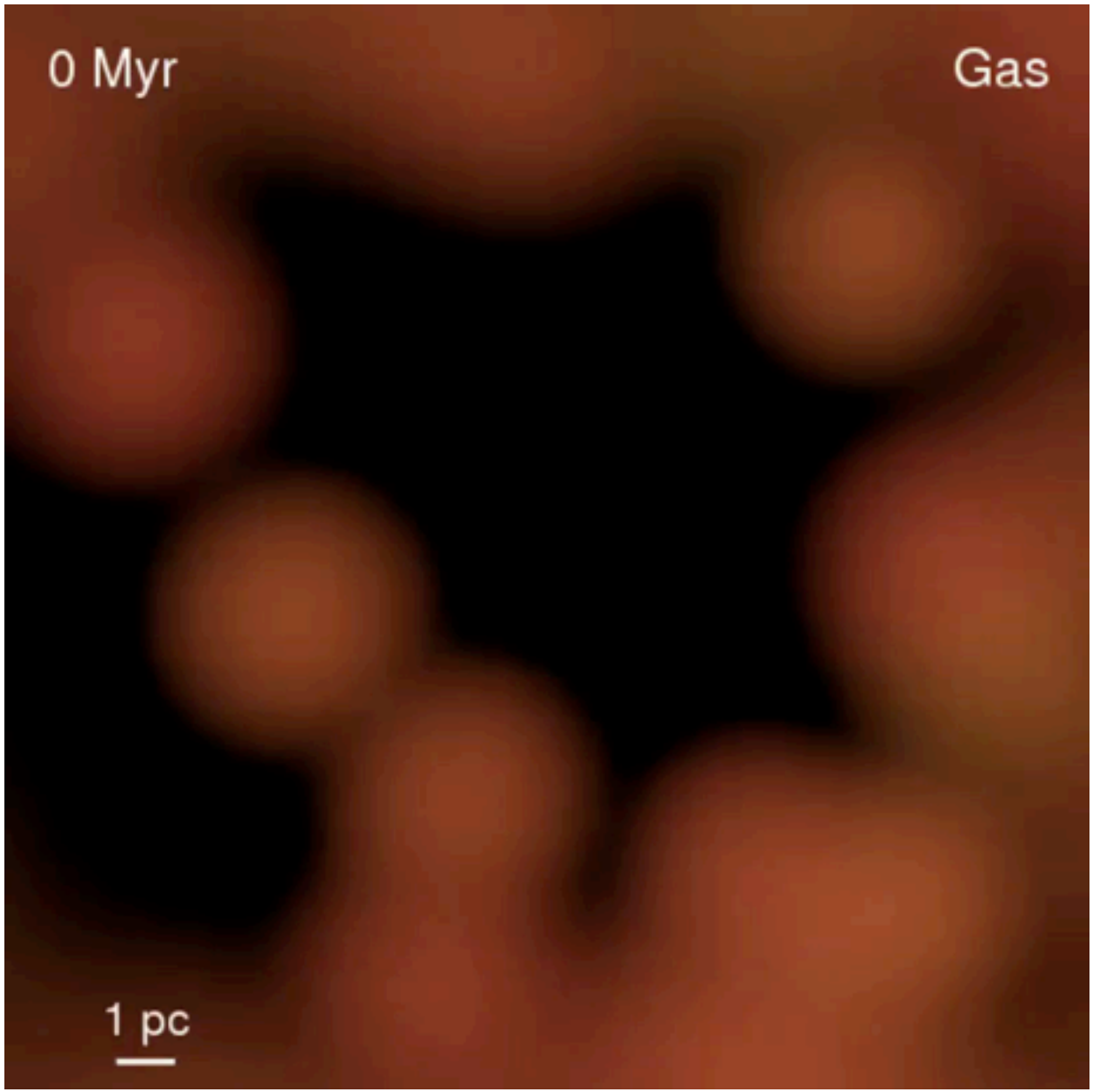
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

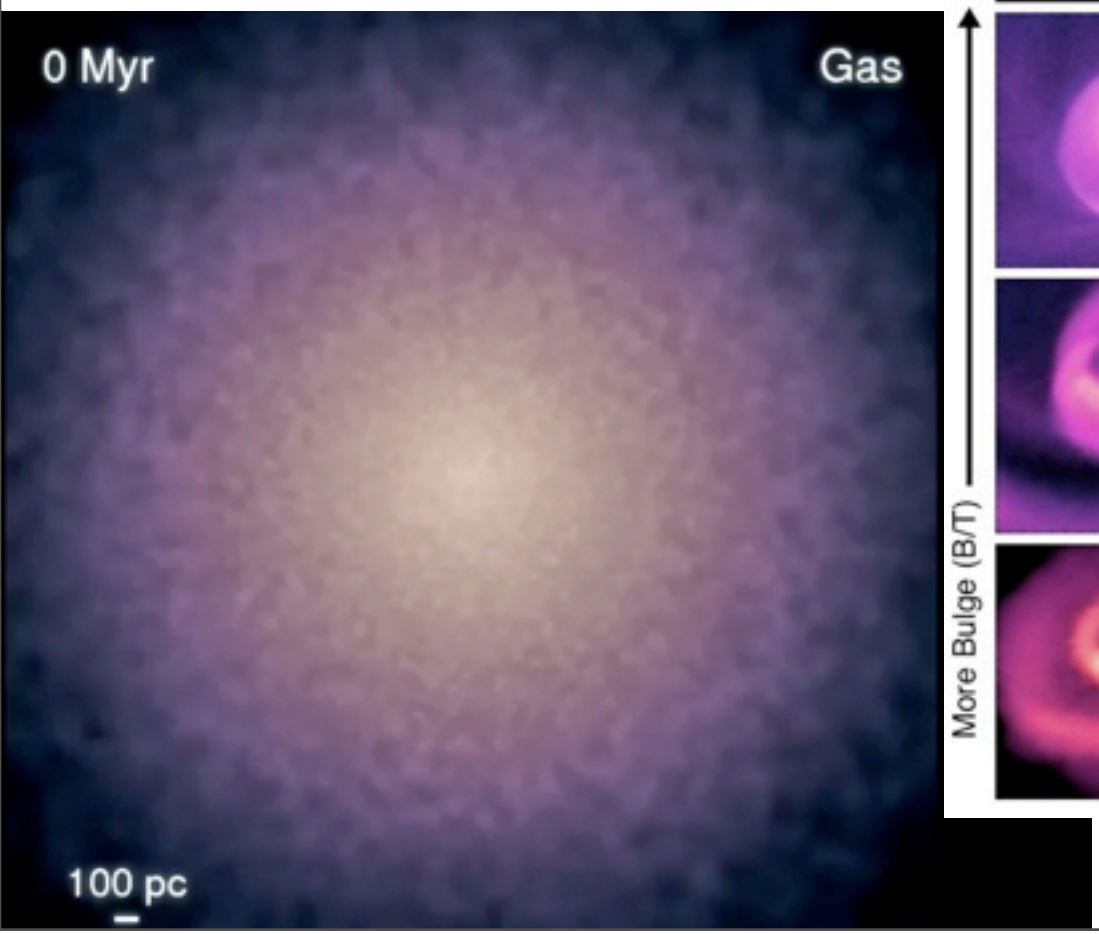
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

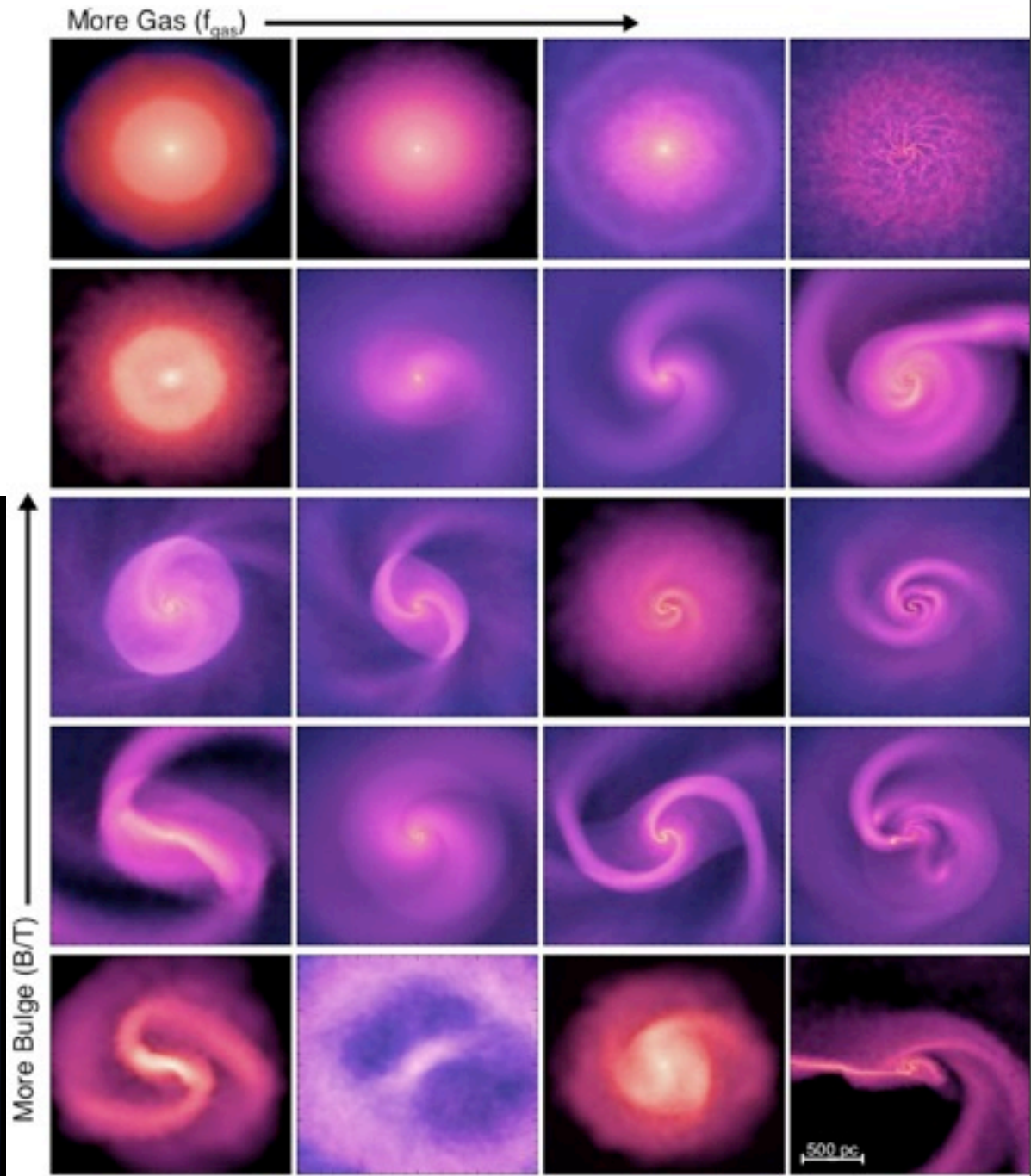


Step 2: Inflow

- 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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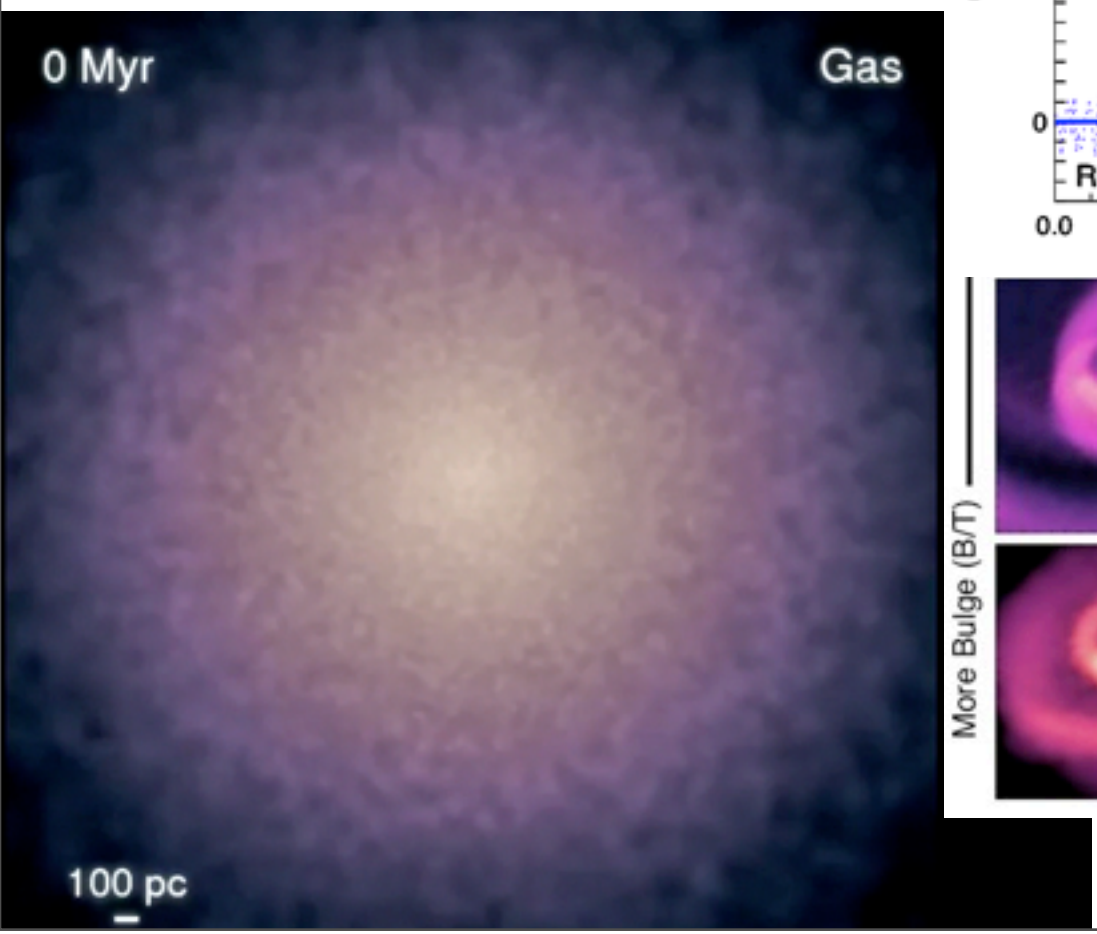
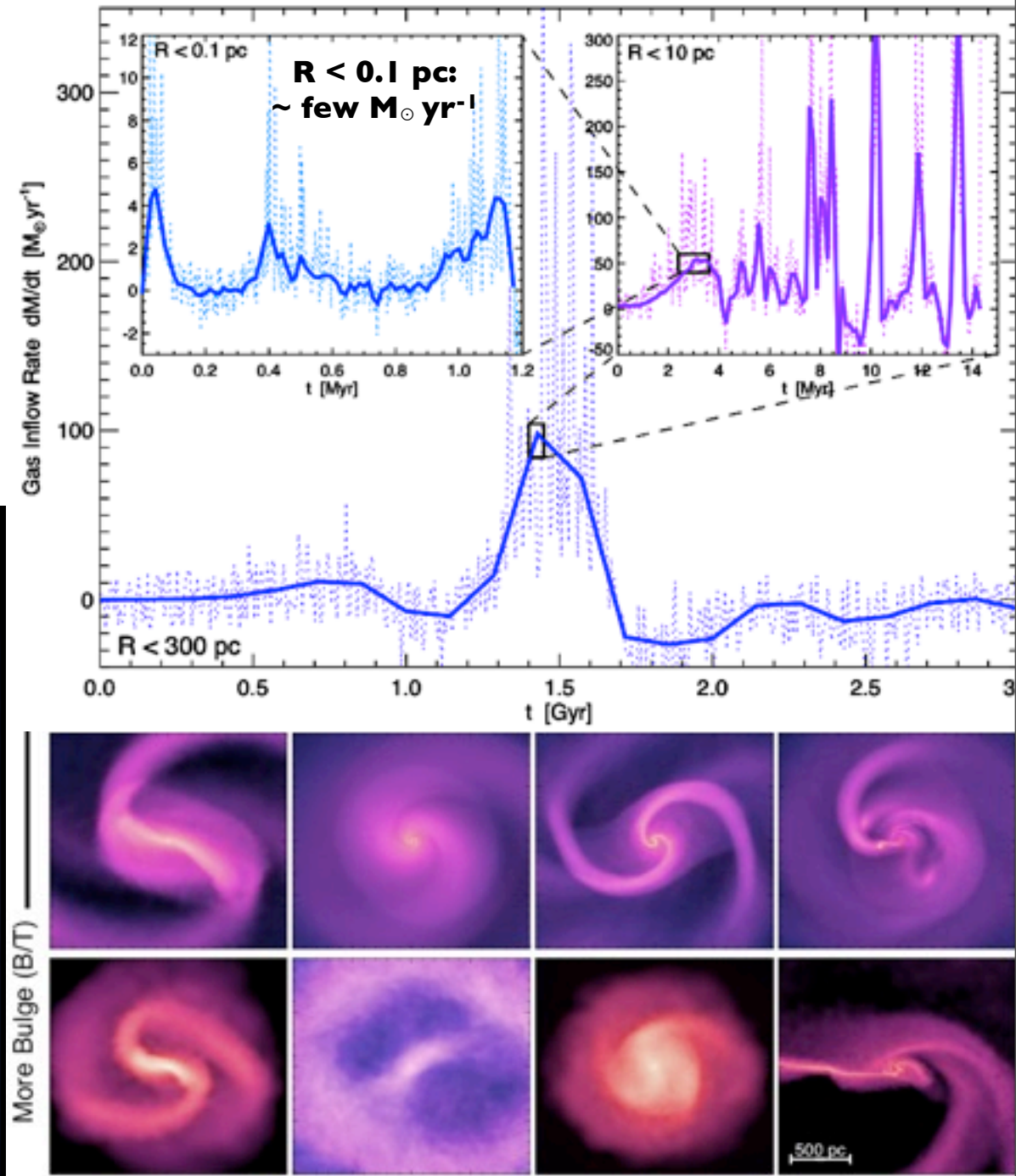
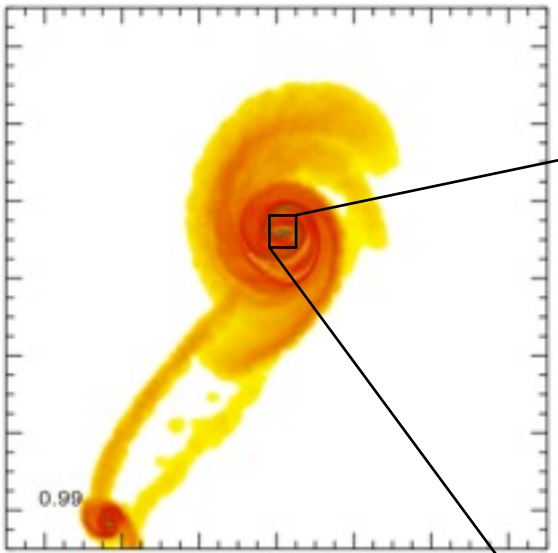
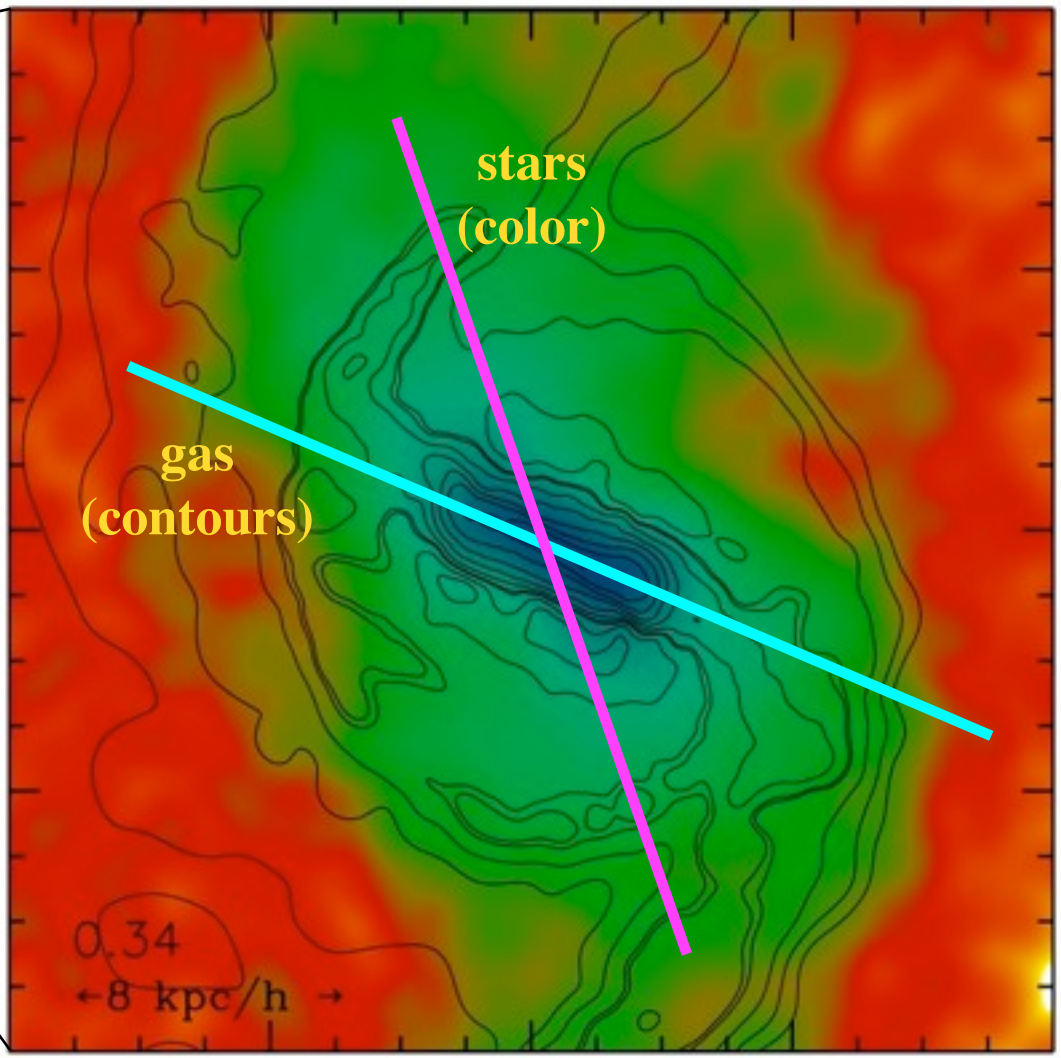




- Gravity dominates torques from 0.1 - 10,000 pc:



- *Stars* torquing on *gas*



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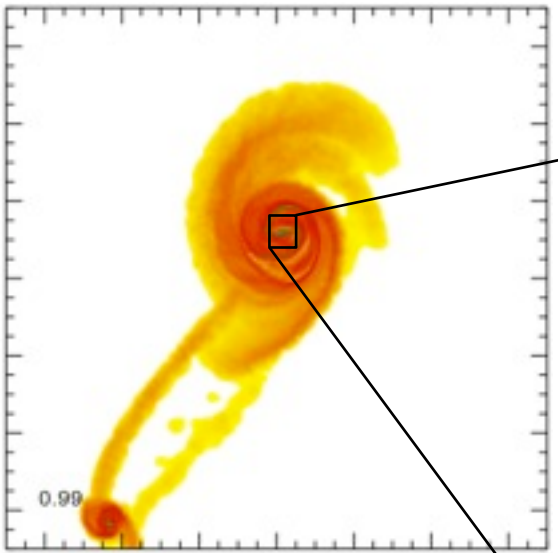

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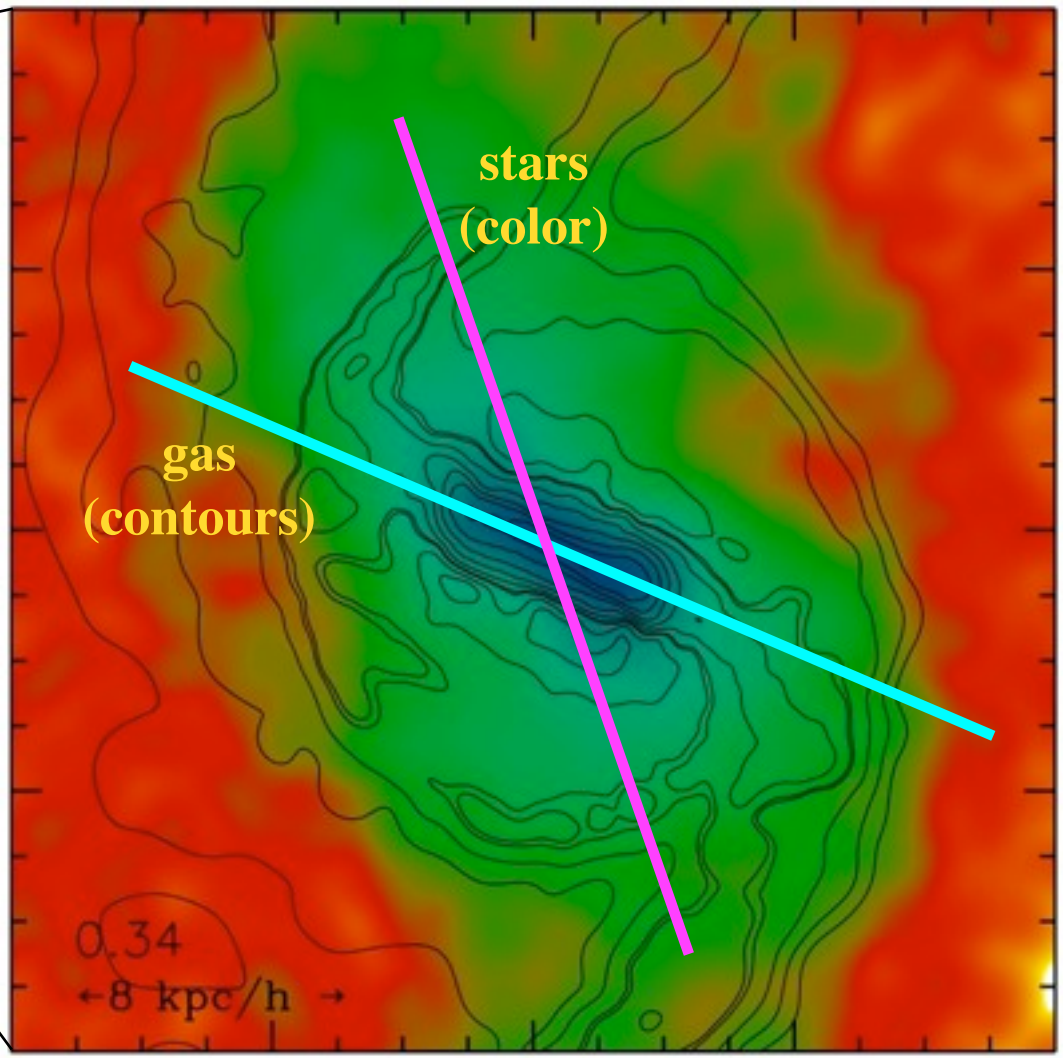
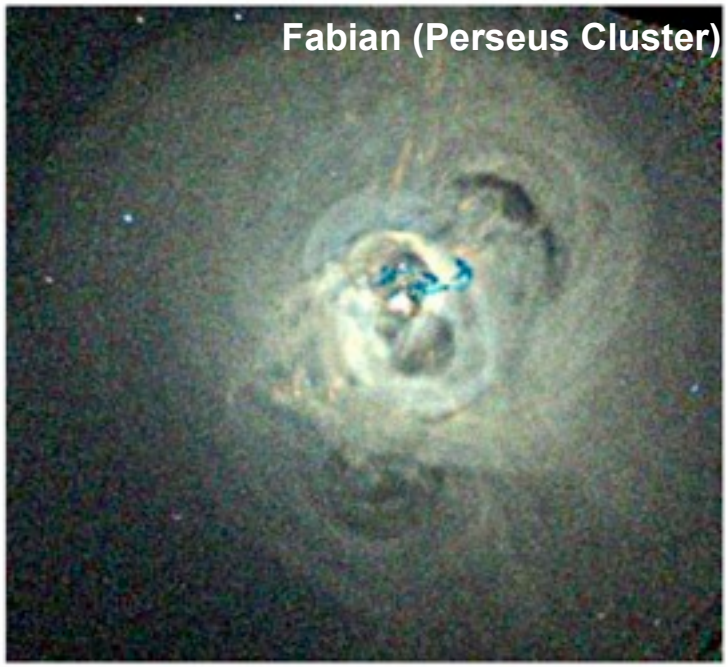


Derive 'Instability' Rate:

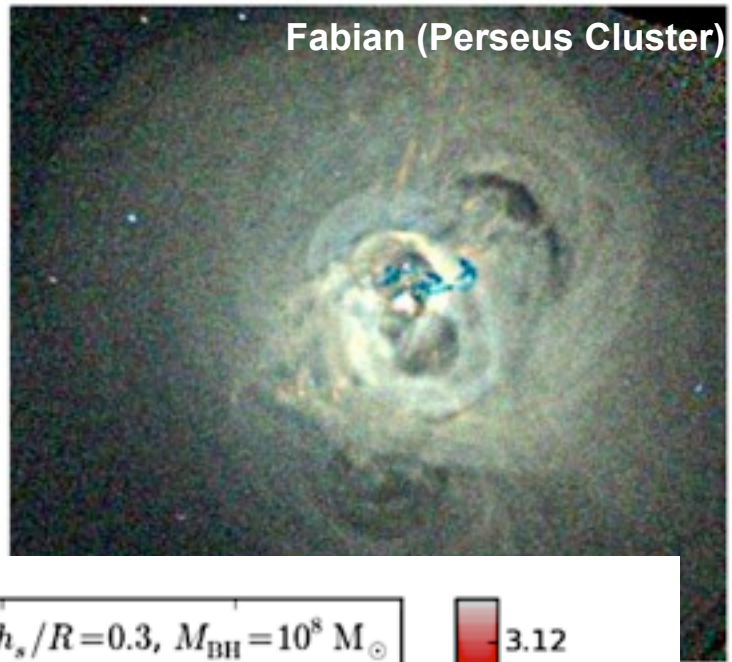
$$\dot{M} \approx 10\, M_\odot\, \mathrm{yr}^{-1} \left(\frac{\mathrm{Disk}}{\mathrm{Total}}\right)^{5/2} M_{\mathrm{BH},\,8}^{-1/6}\, M_{\mathrm{gas},\,9}\, R_{0,100}^{-3/2}$$

Step 3: Observed Sources of AGN Feedback

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

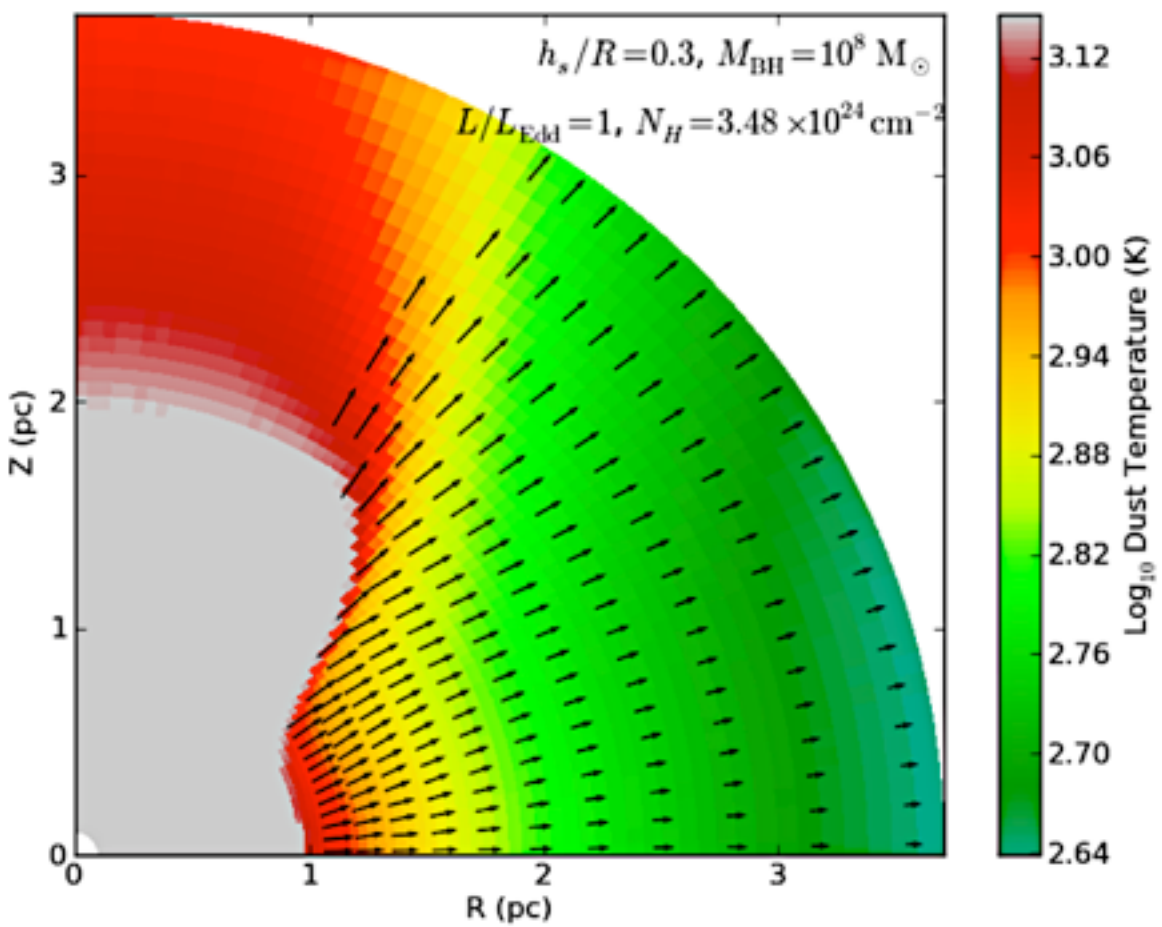


Step 3: Observed Sources of AGN Feedback



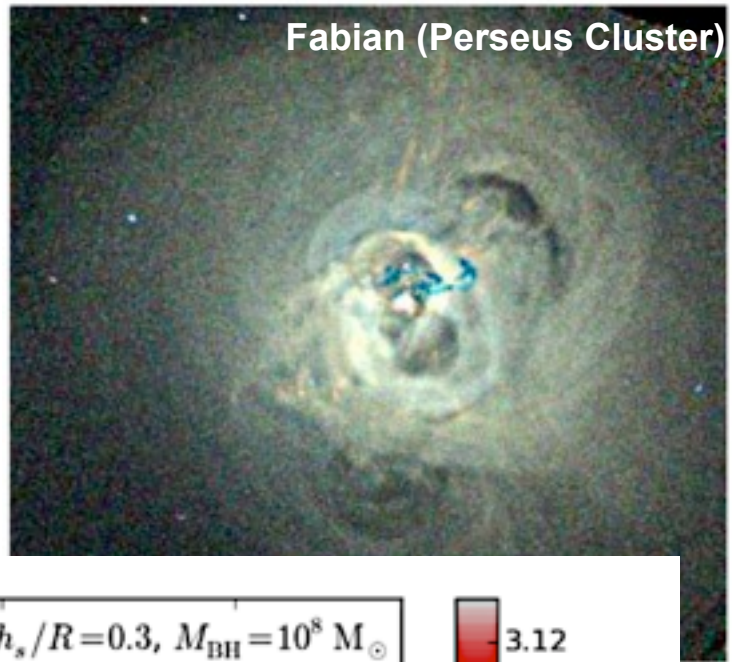
- Jets
  - heat IGM/ICM (low-density), but not dense ISM

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

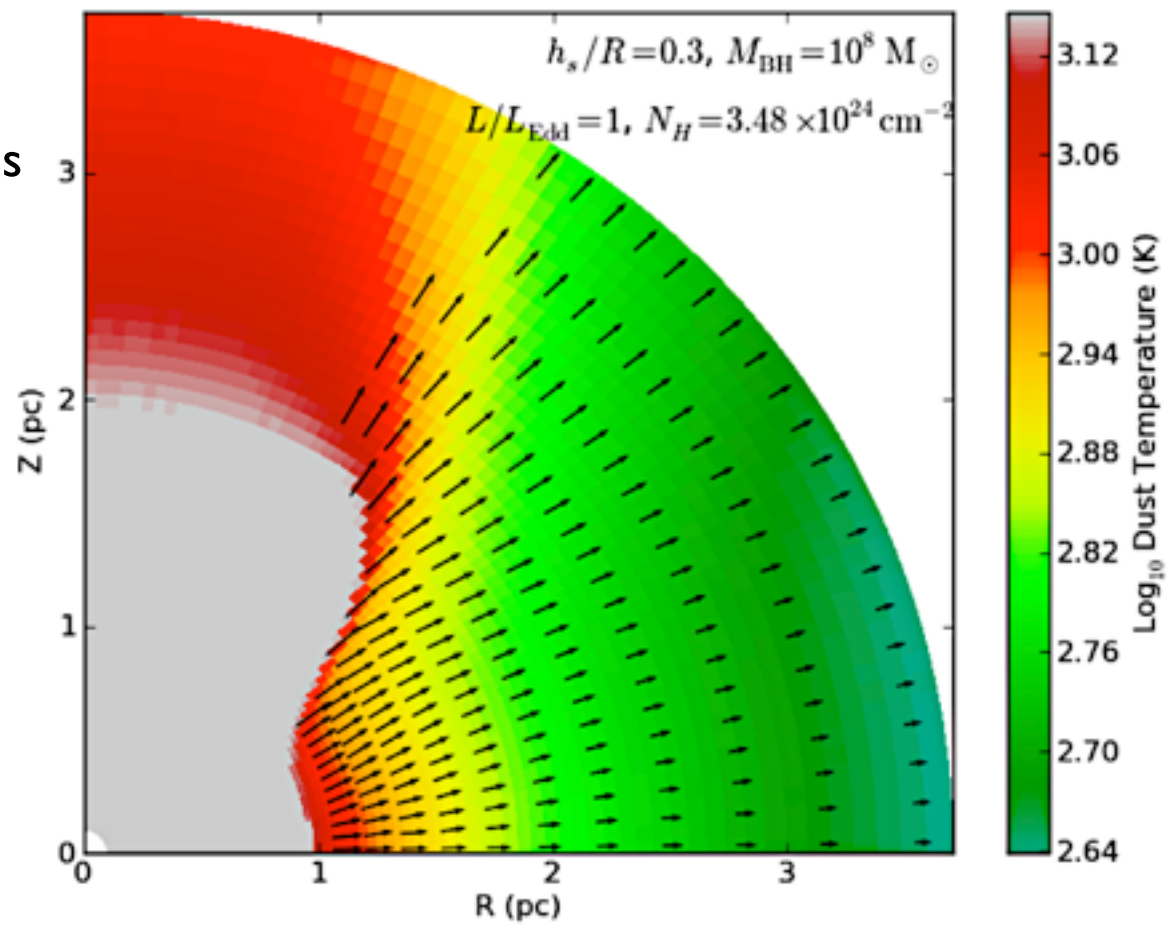


Roth, Kasen, Quataert, PFH in prep

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

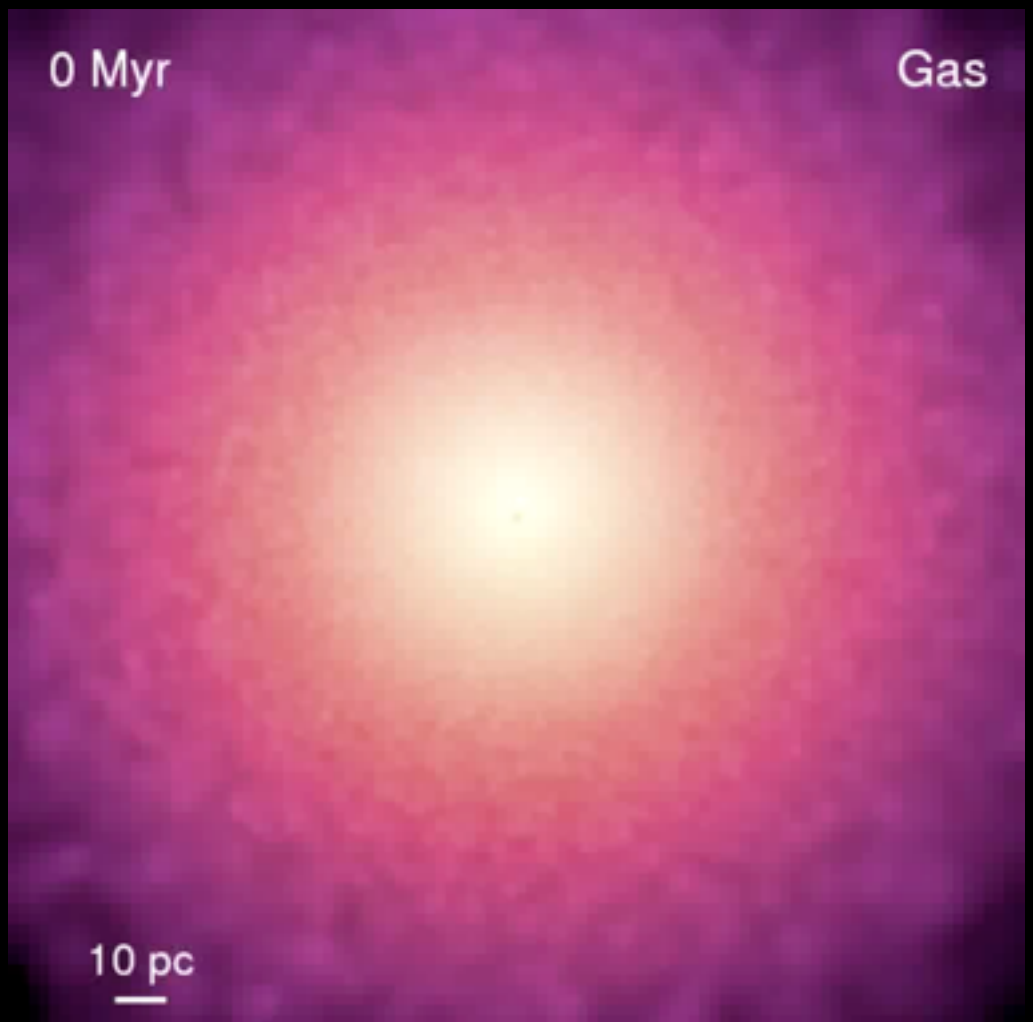


Roth, Kasen, Quataert, PFH in prep

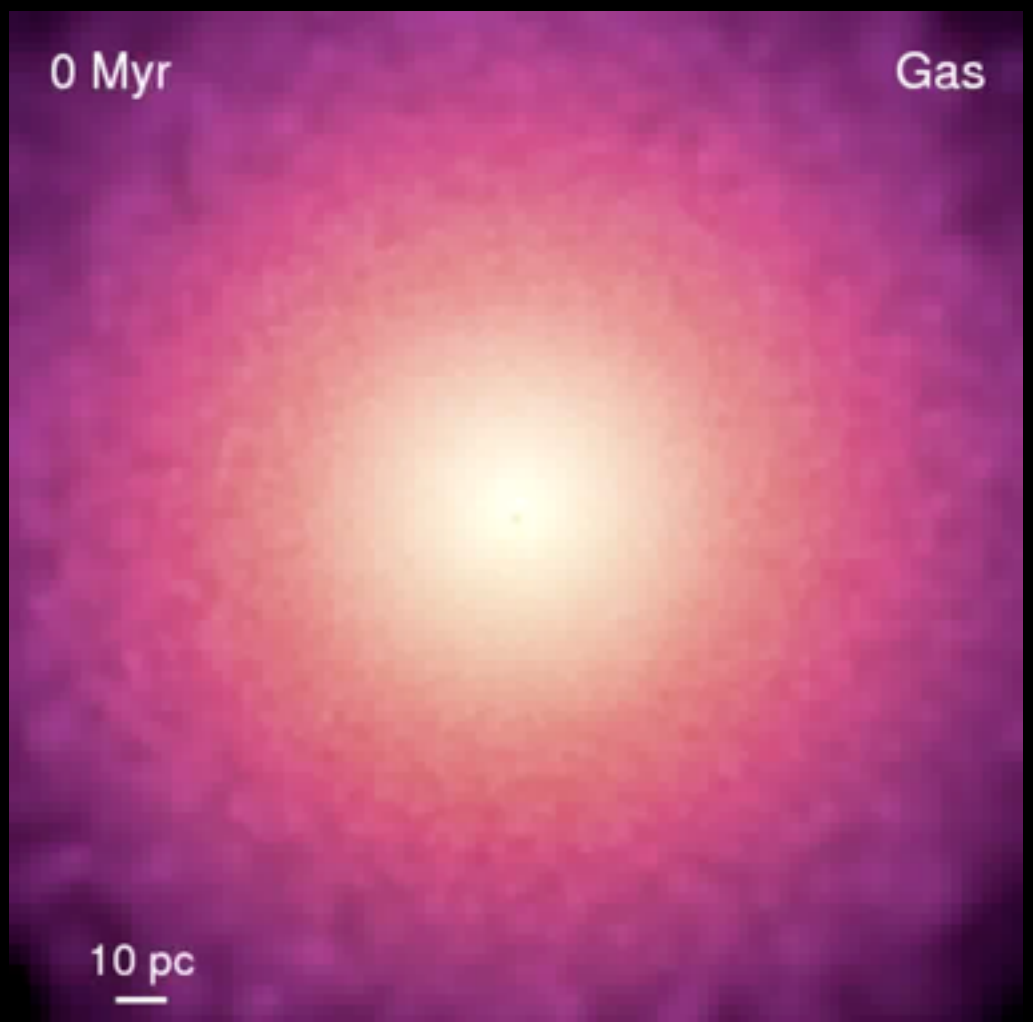
BAL Winds on ~1pc - 1kpc scales:

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 (set by gravity)
  - Leads to Kennicutt relation & **super-winds**:

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

- Mergers: Laboratory for extreme conditions (>100 times GMC densities!)
  - **Efficient disk survival**
  - Super-winds with ~10-500 M_{sun}/yr

- Cosmologically: Not just a top-down, inflow cycle:
  - Winds determine **IGM enrichment, temperature**, even subsequent inflow structure

- **Can't Quench Without "AGN" Feedback**!
  - Quasar BAL Winds+Radiation Pressure+Jets: Explain M_{BH}-s, and *WILL* suppress SFRs