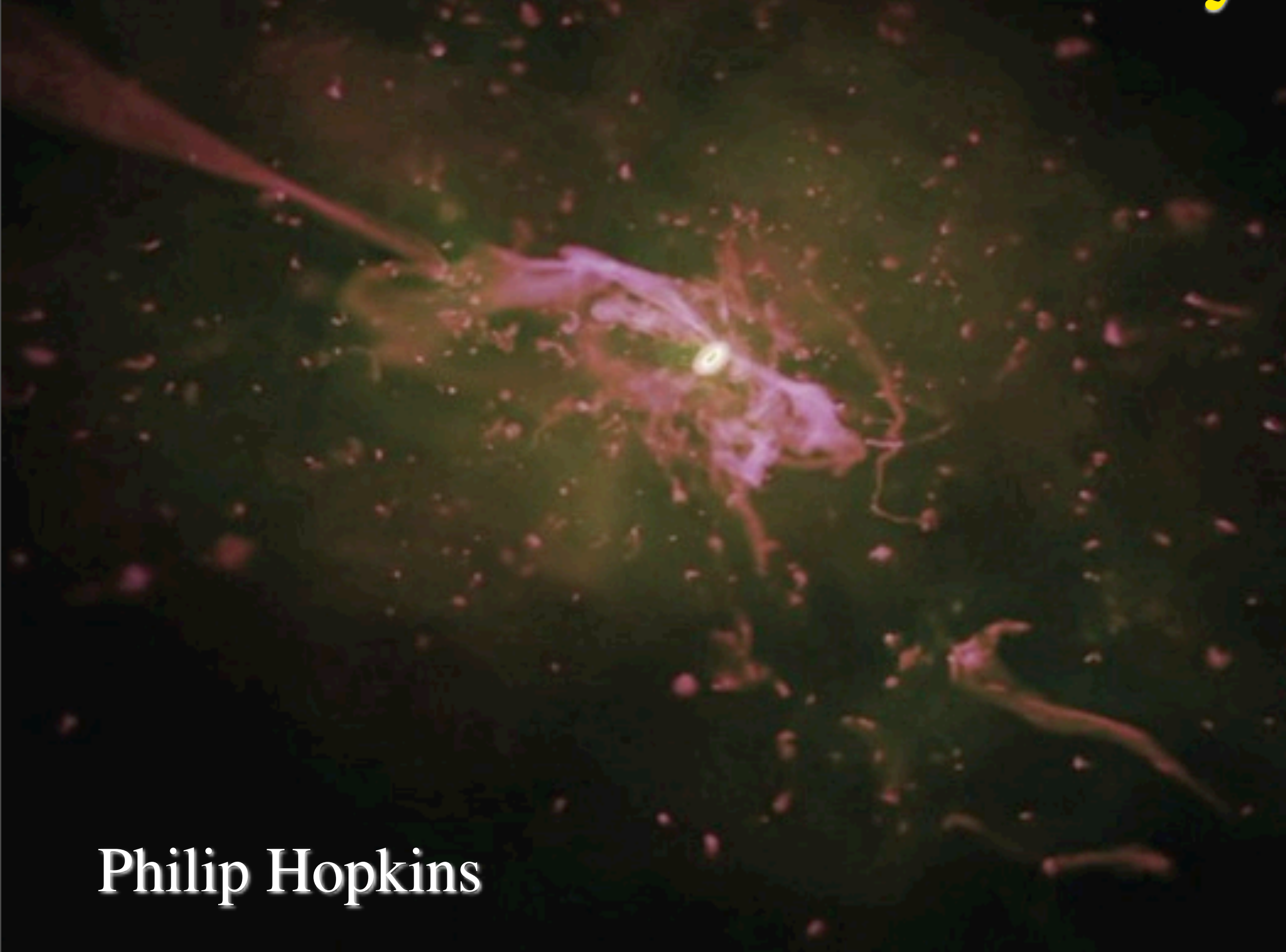
Milky Way

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

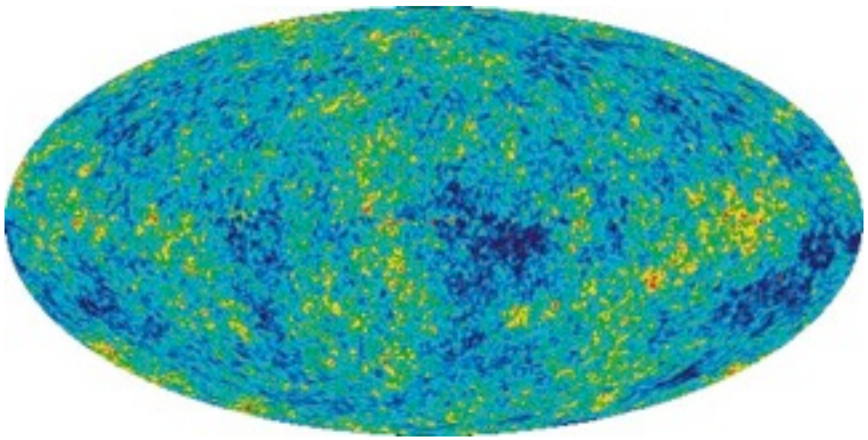
Overview

- (1) (Some) Open Problems
- (2) Stellar "Feedback" Processes:
  - Isolated Galaxies: Feedback Physics & Stars
  - ISM Structure & Galactic Outflows
  - Cosmological Implications
- (3) Super-Massive Black Holes & Accretion?

Motivation

THE BIG PICTURE

Today



?

z~1090
(t~400,000 yr)

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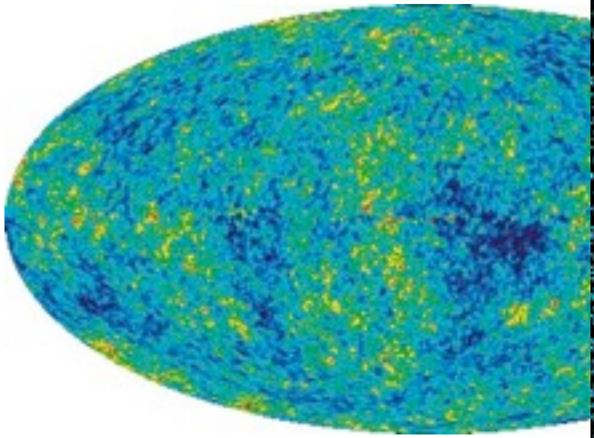

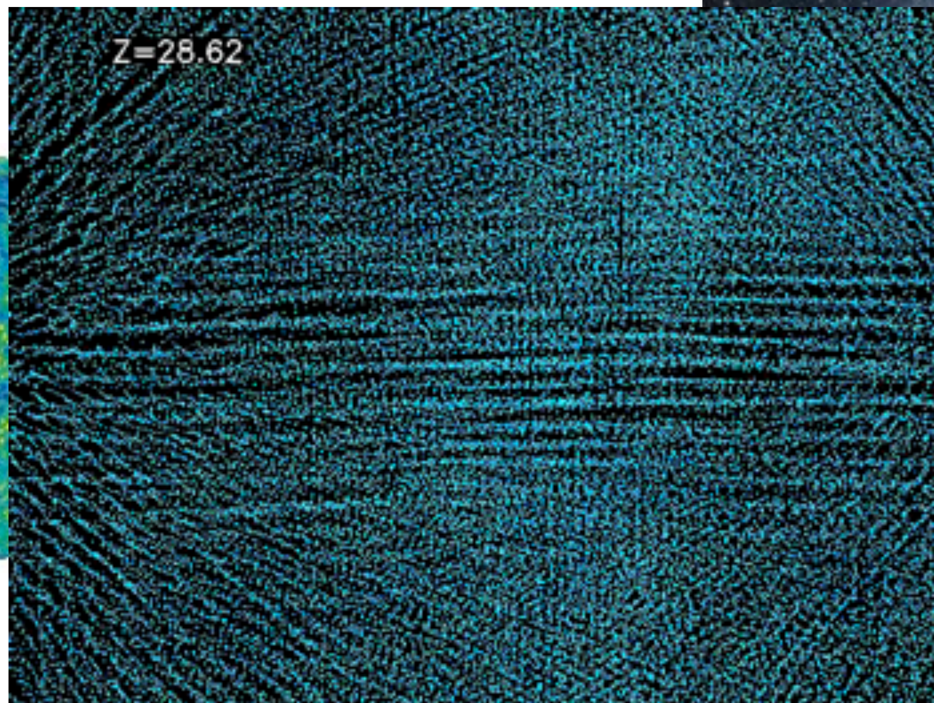

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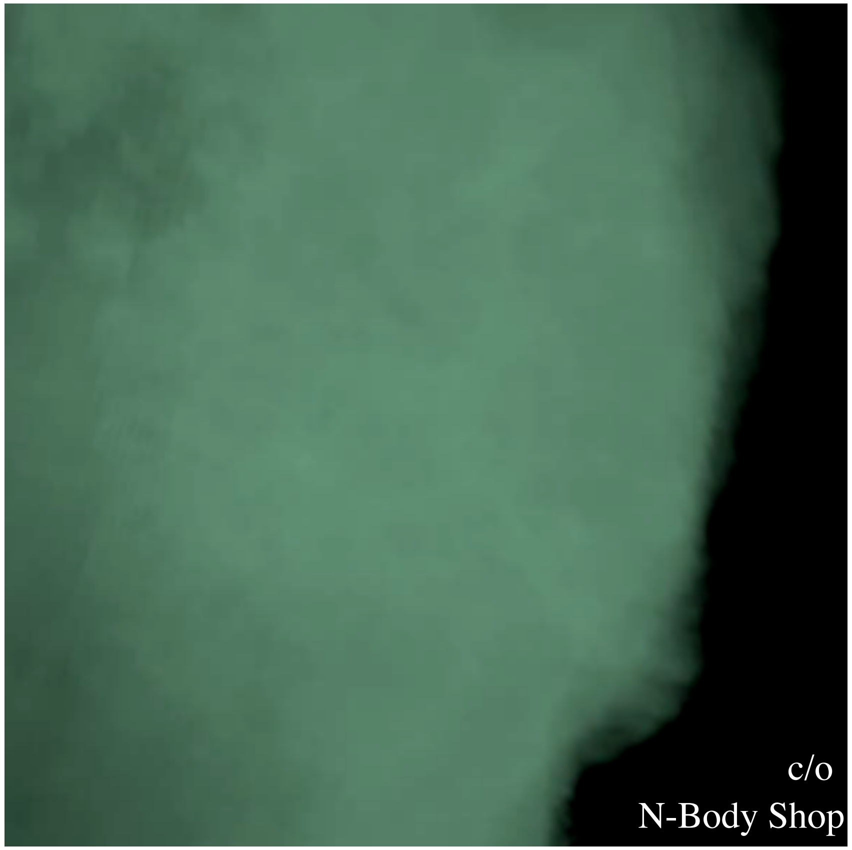
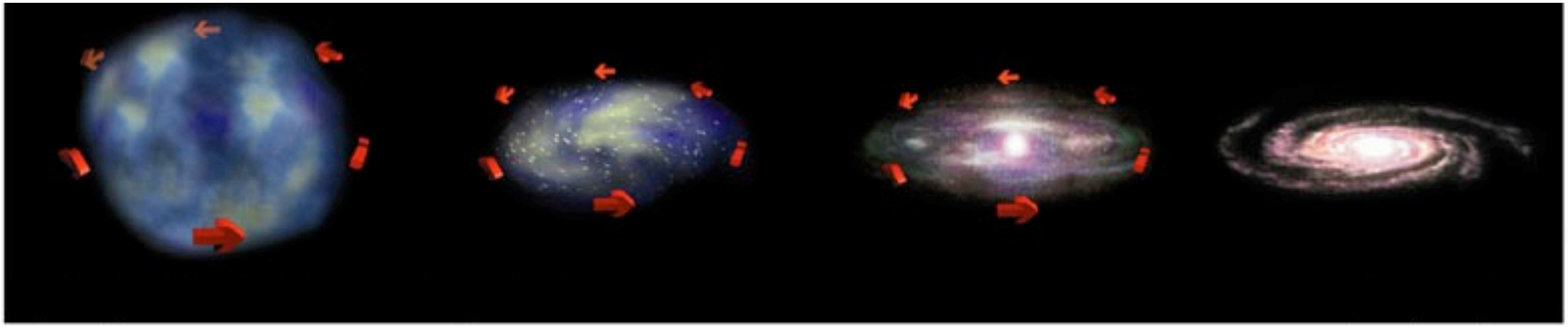
Motivation

HOW DID WE GET TO GALAXIES TODAY?

- Dark matter ‘halos’ collapse: gas cools into a disk



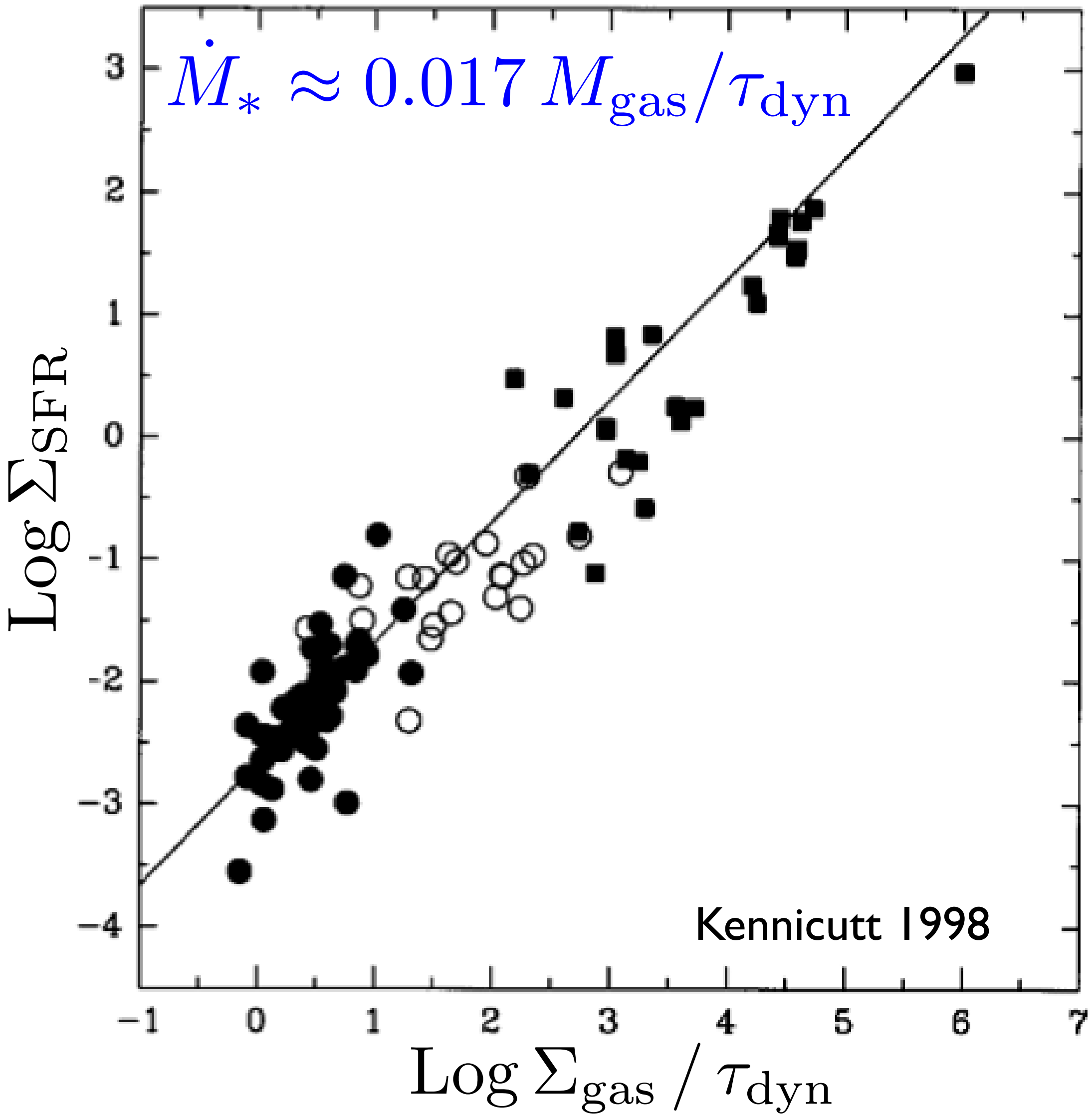


- What happens once gas is actually inside galaxies?

The Problem: Baryons

Motivation

Q: WHY IS STAR FORMATION SO INEFFICIENT?



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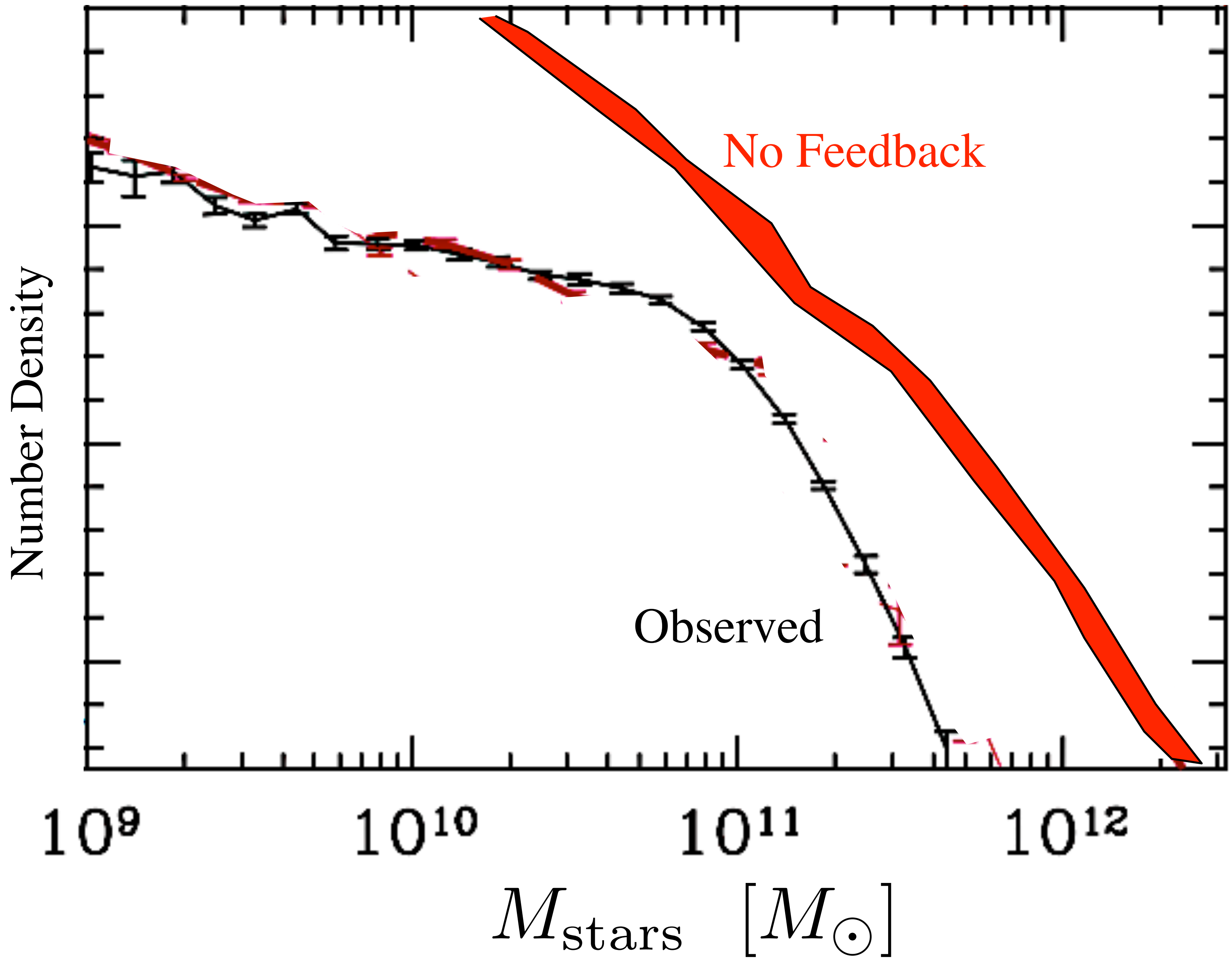

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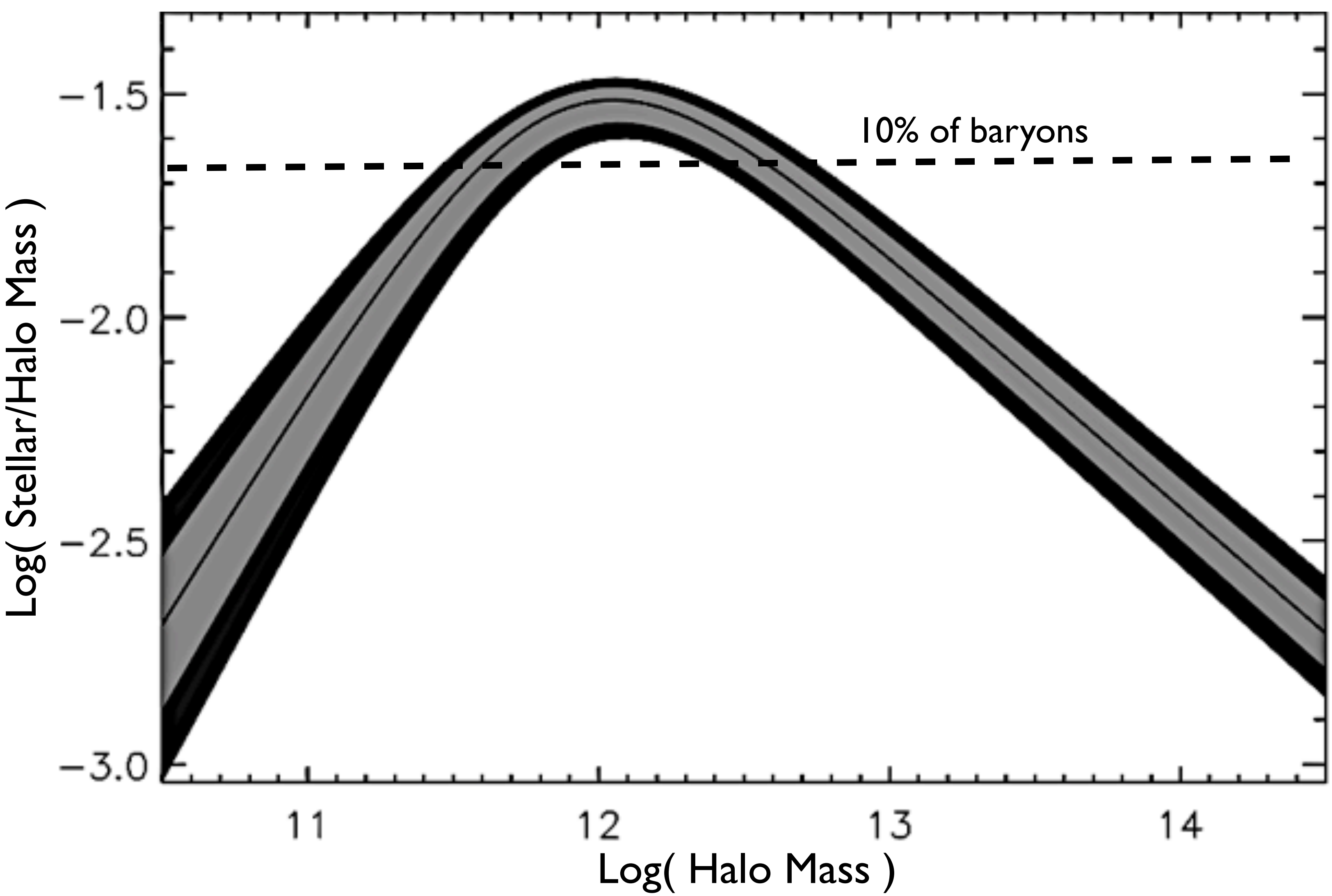
Moster 2009



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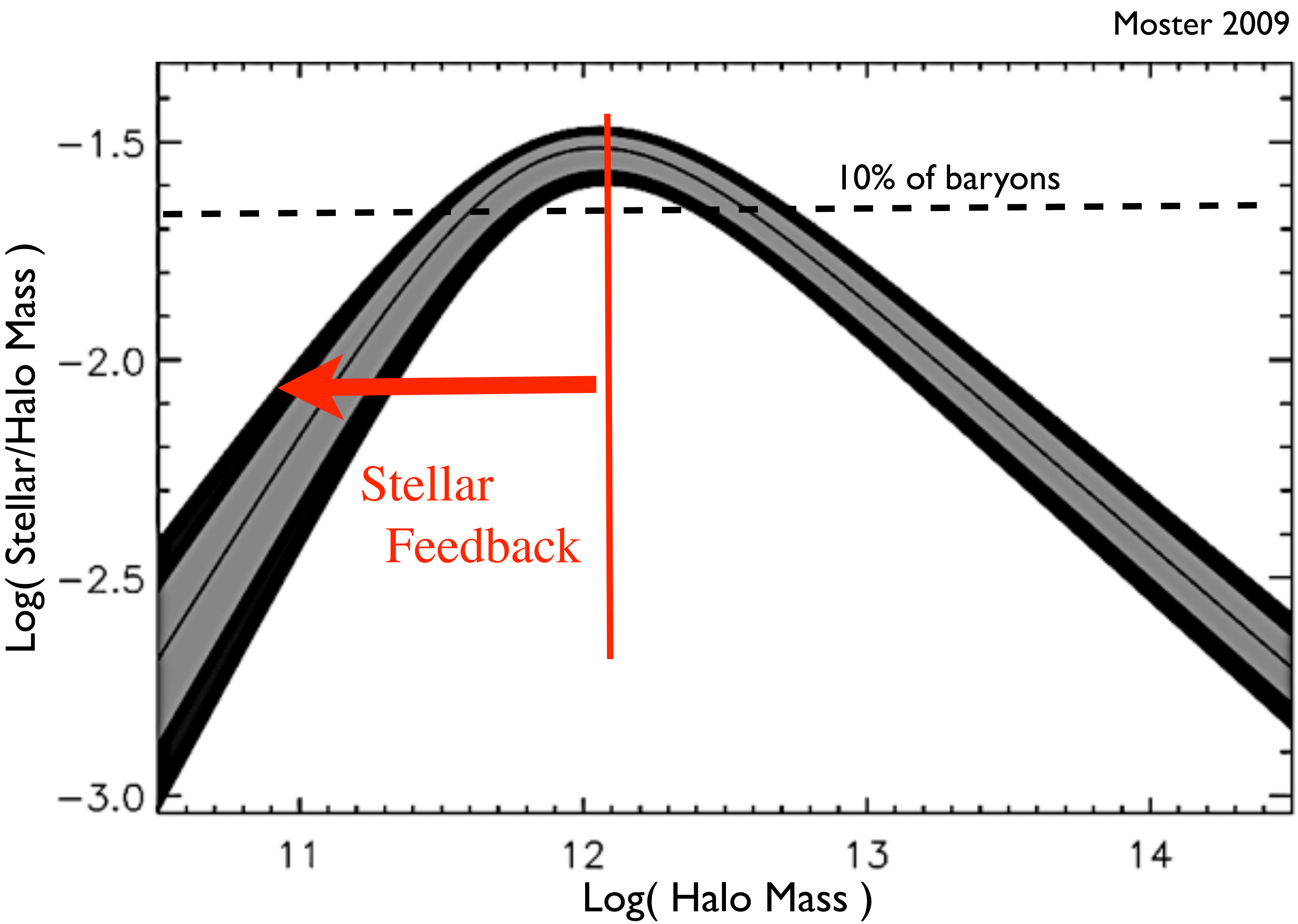

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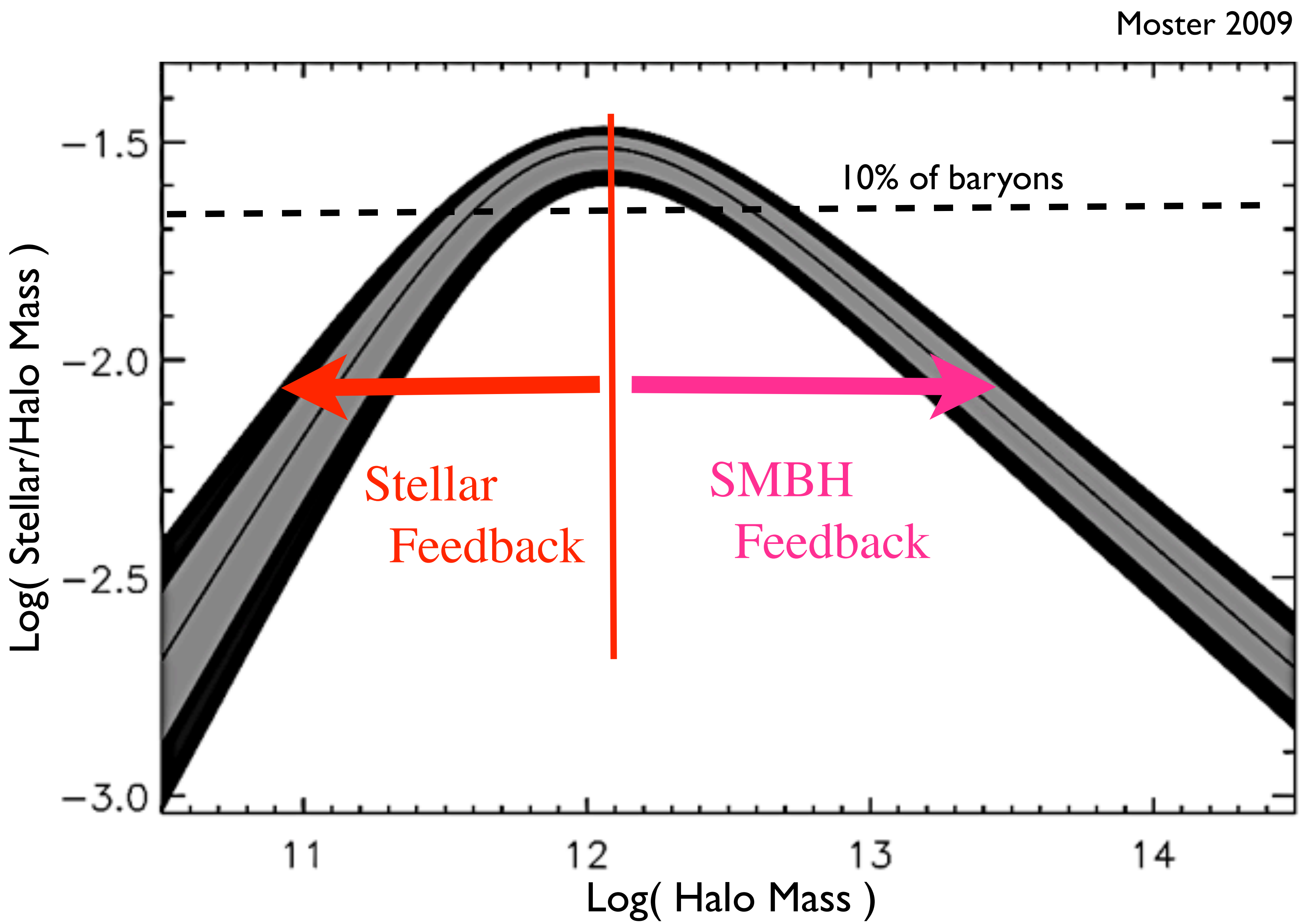


Stellar Feedback is the Key!

SO WHAT'S THE PROBLEM?

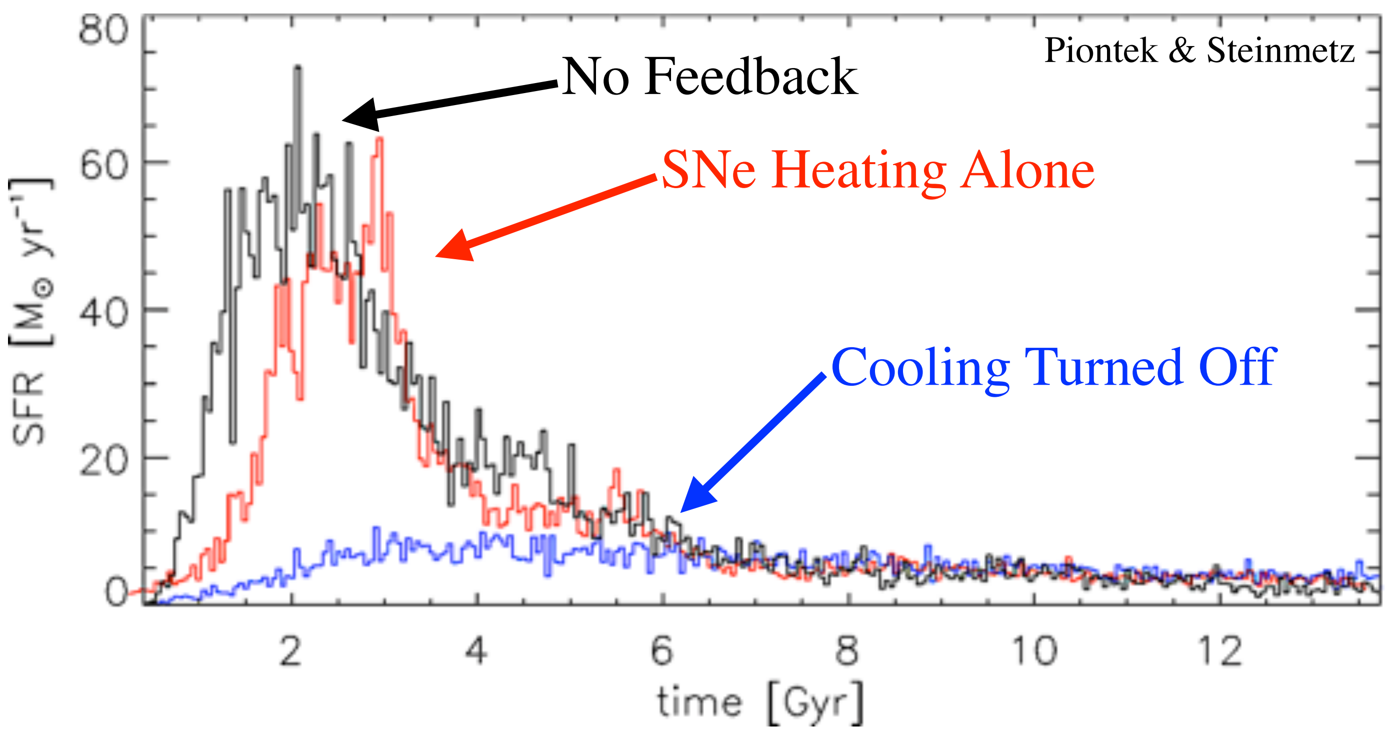
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

- 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)



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  - Photoionization (HII Regions)

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- *Explicit* Momentum Flux:
  - Radiation Pressure

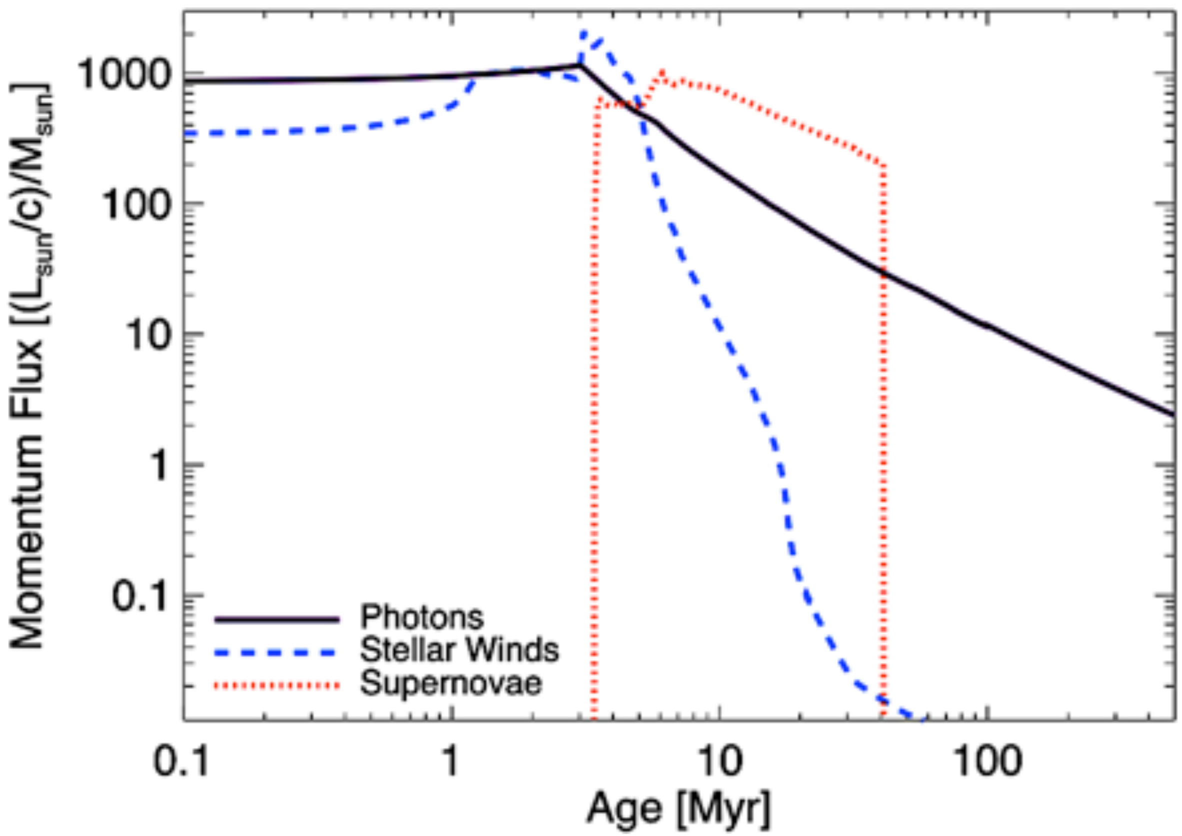
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

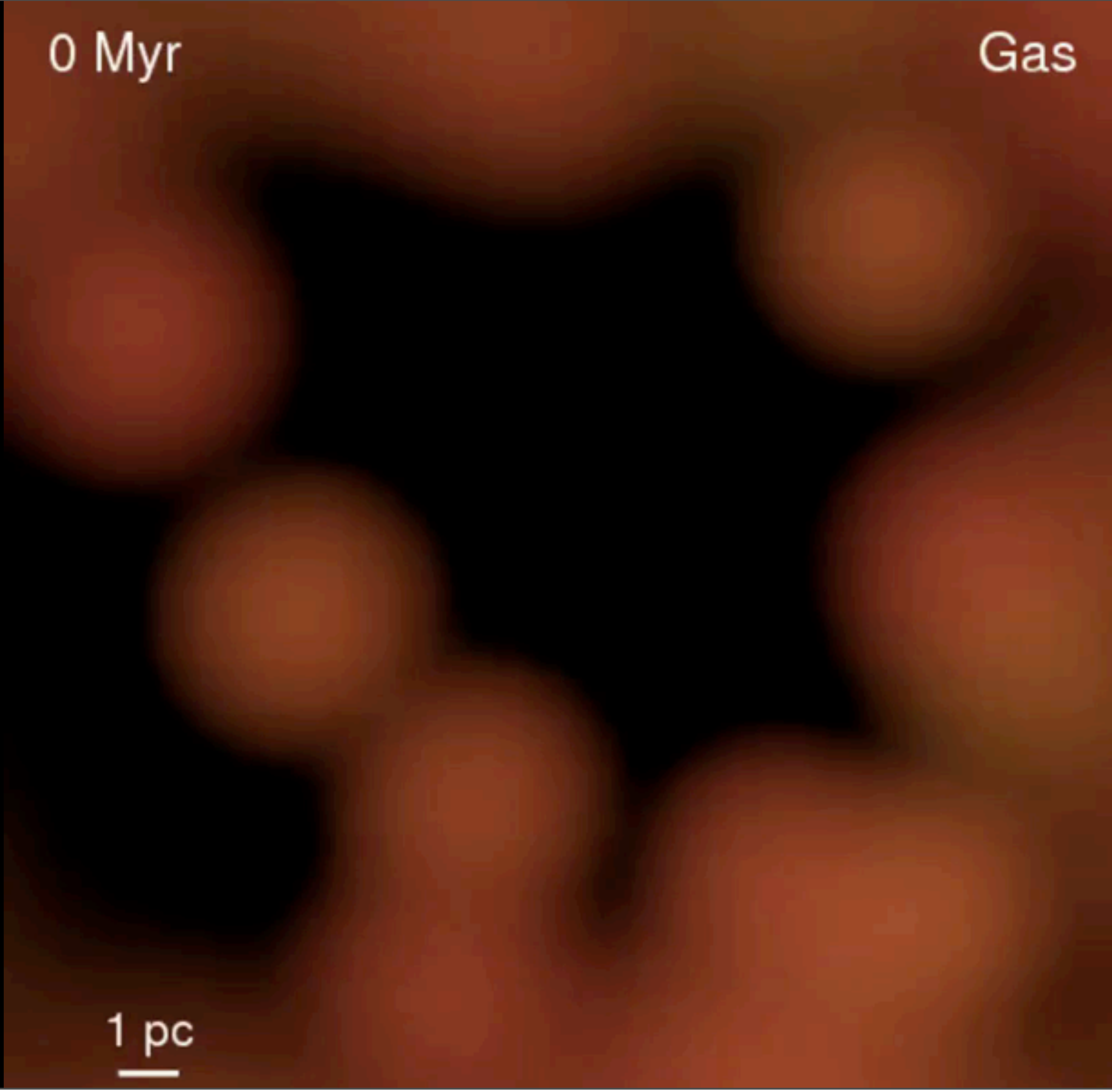
  - SNe

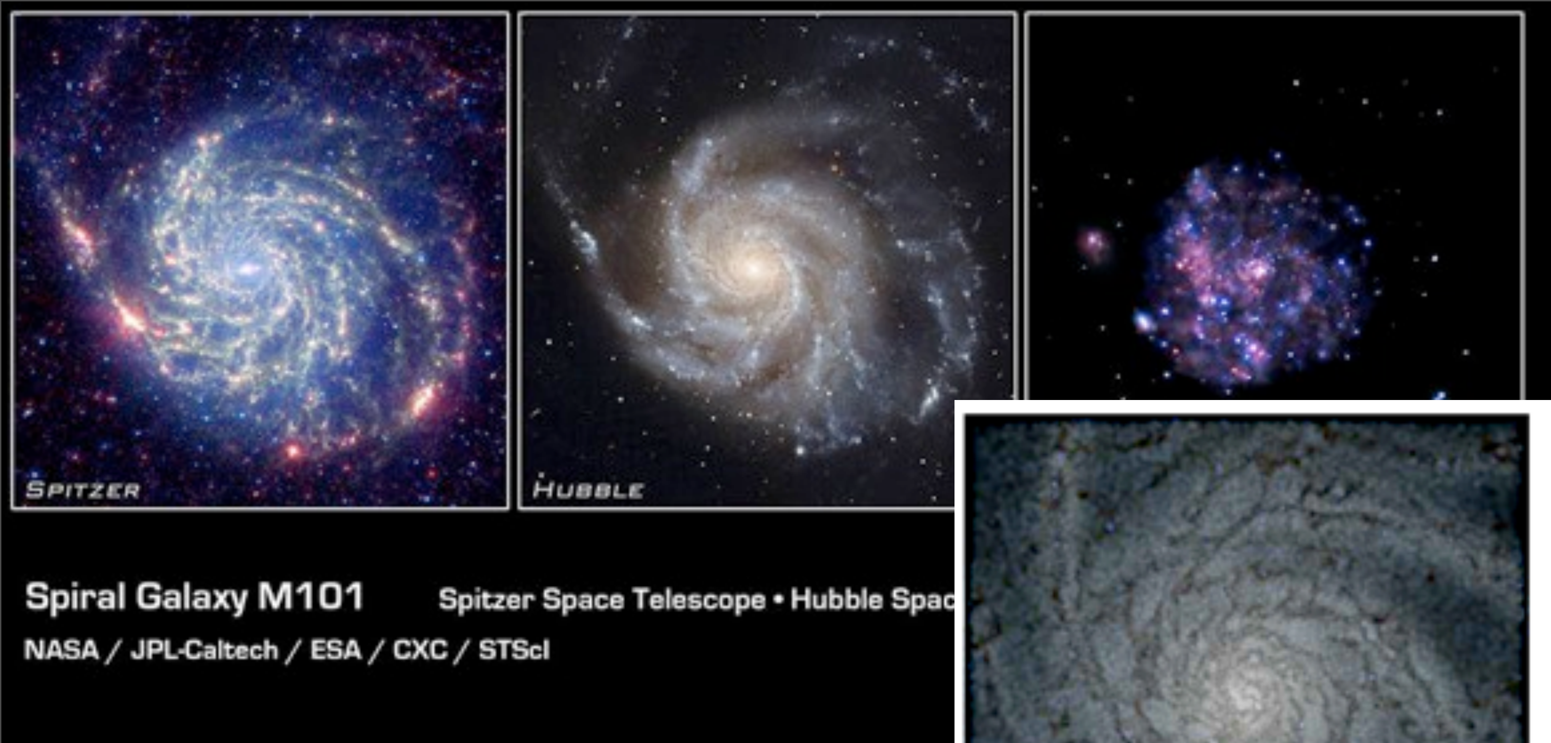
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

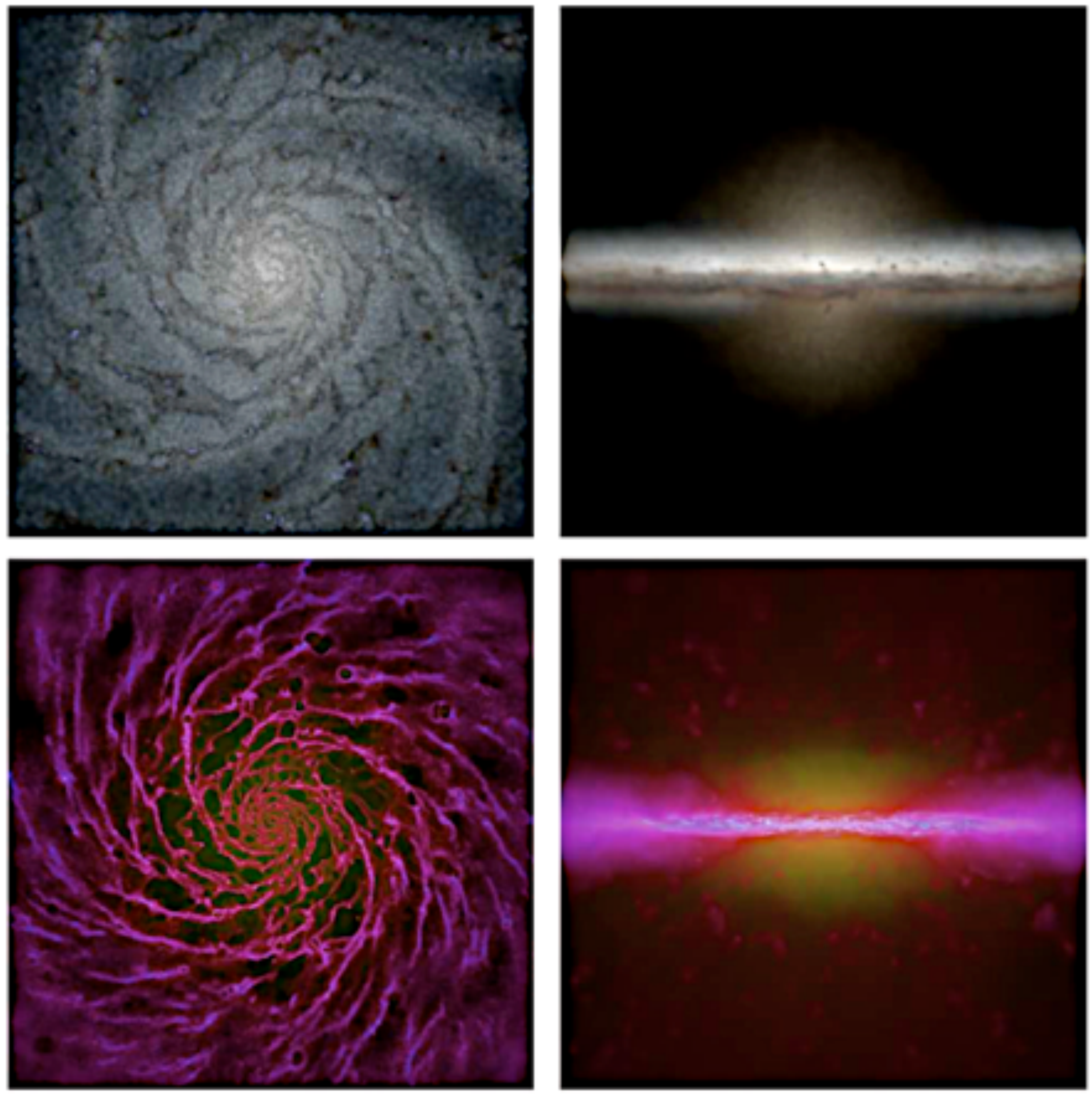
  - Stellar Winds

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

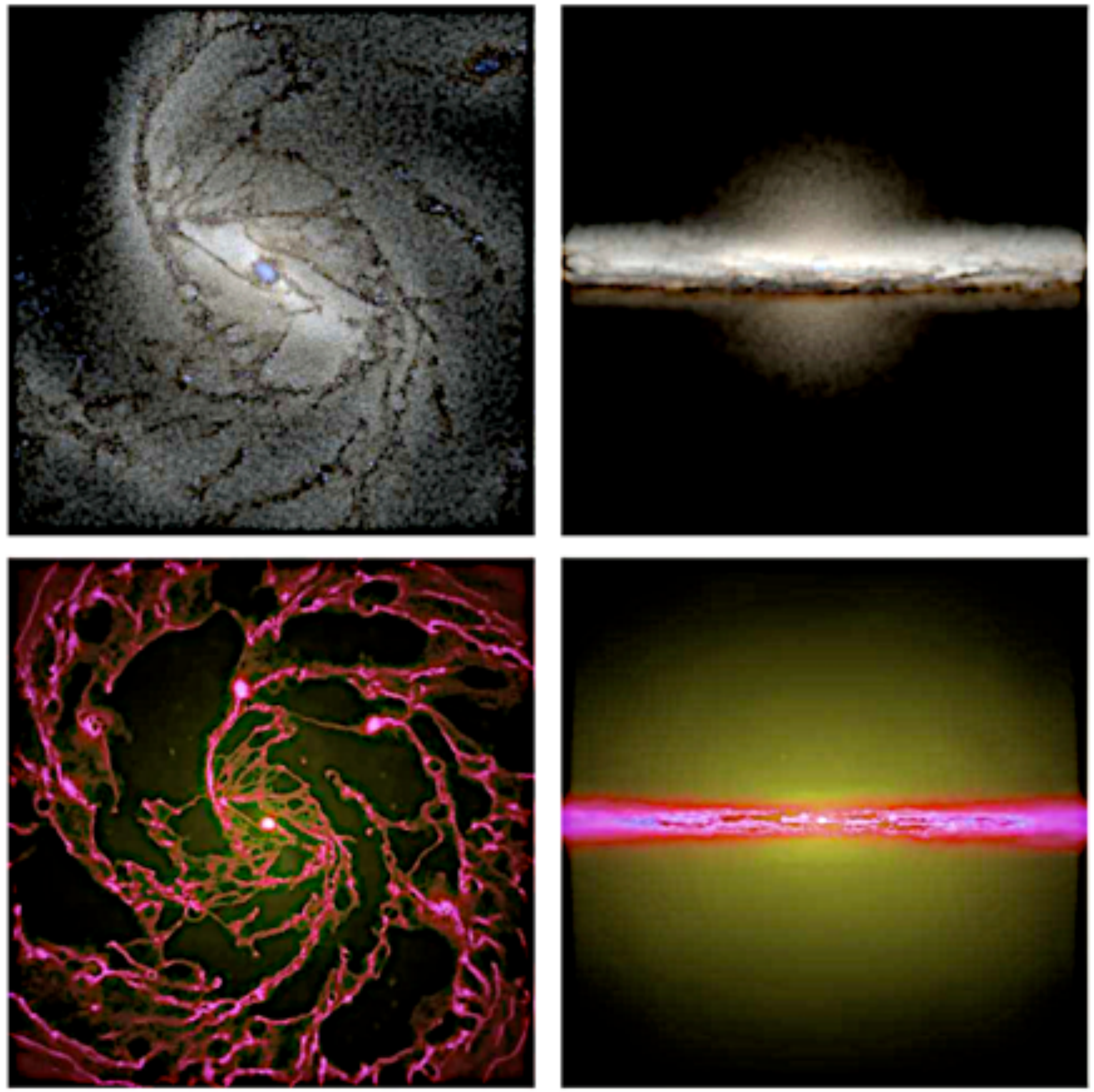



0 Myr
Gas
1 pc





Hopkins, Quataert, & Murray, 2011b



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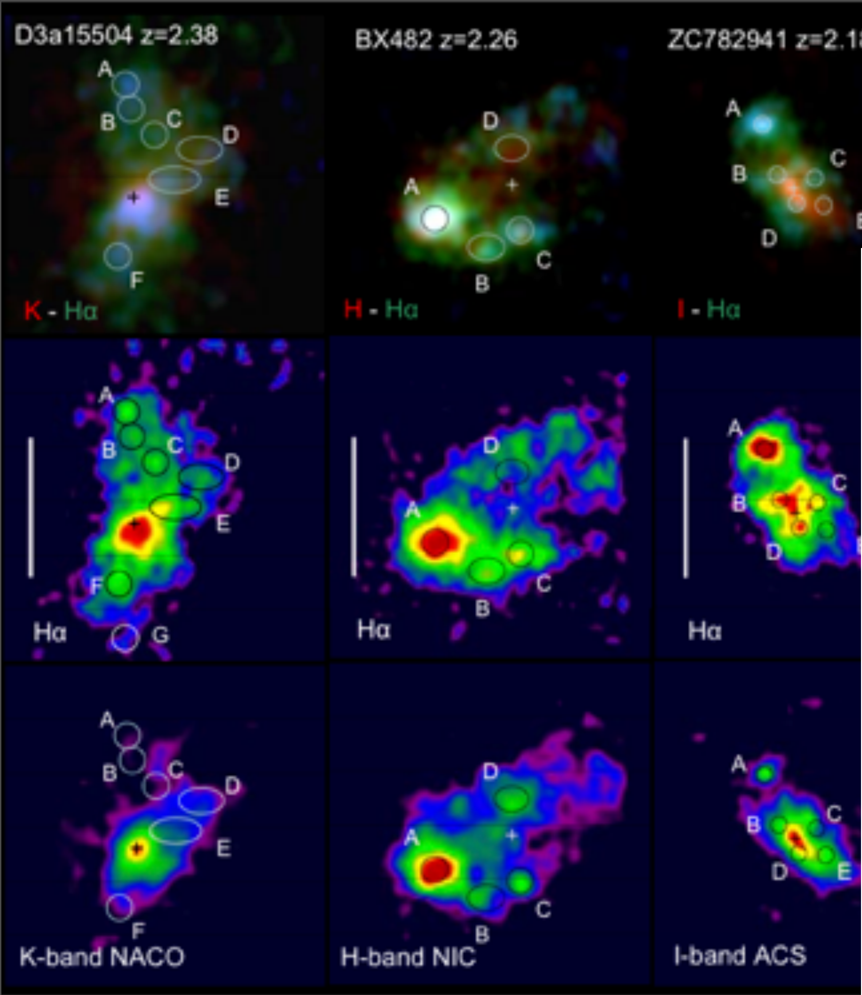
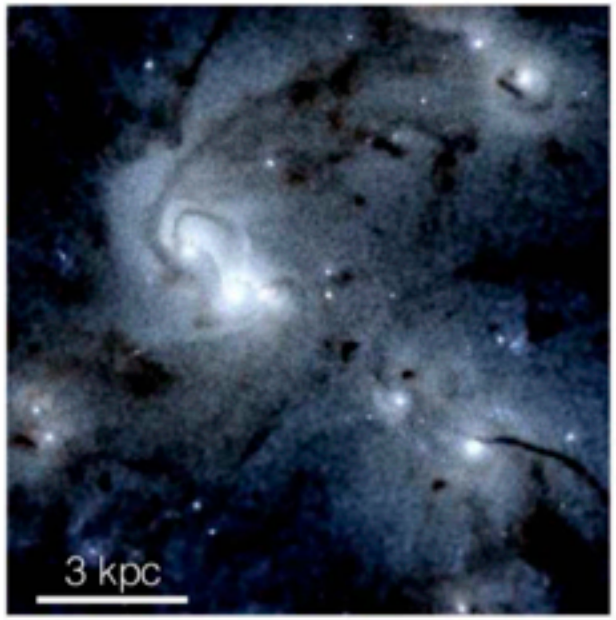
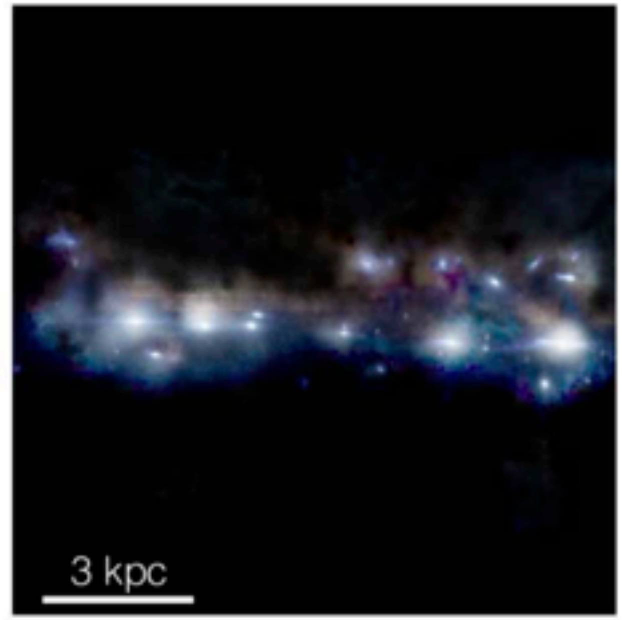
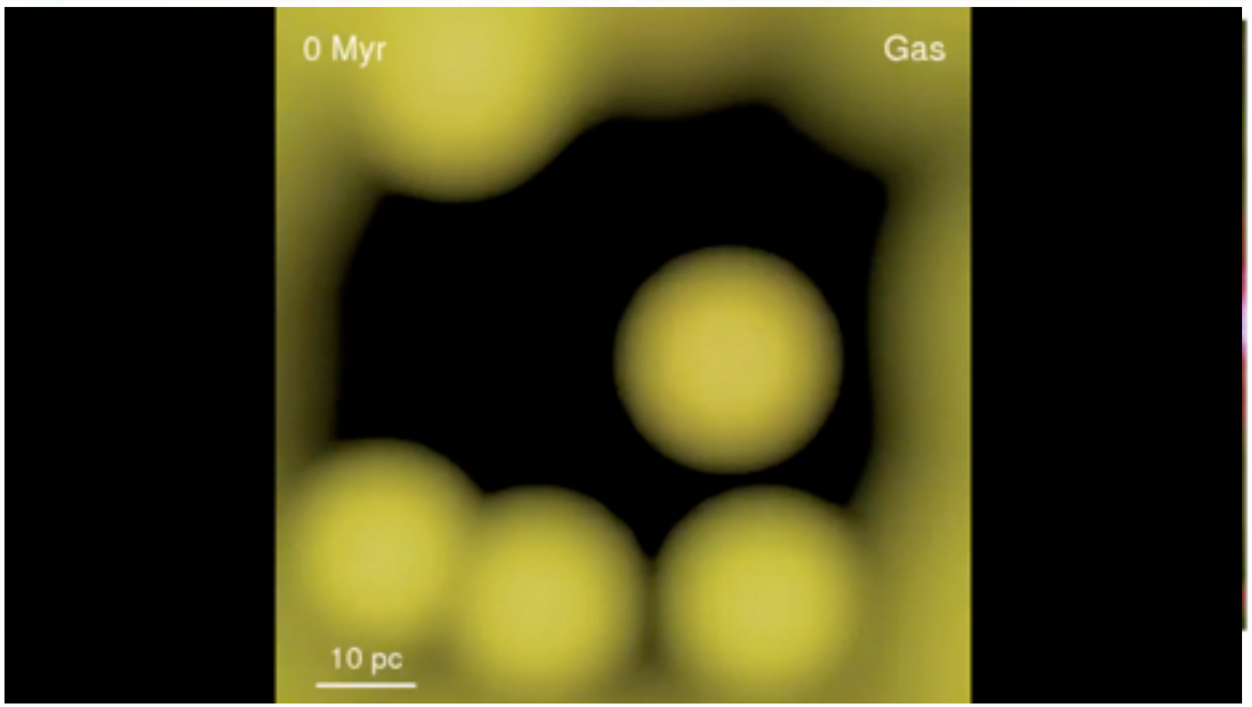
Genzel+ 2011



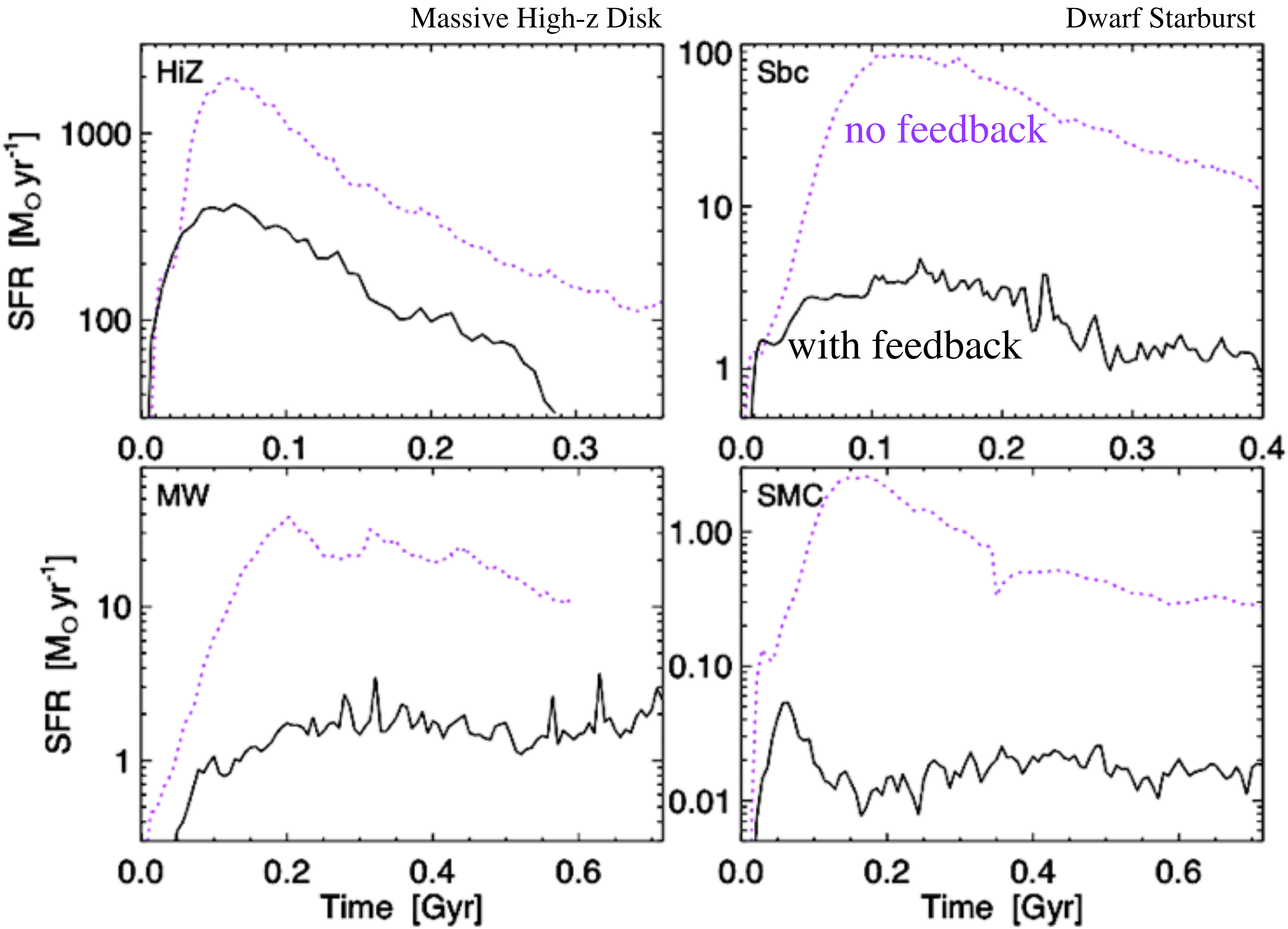






PFH, Quataert, Hernquist, 2011

Stellar Feedback gives Self-Regulated Star Formation



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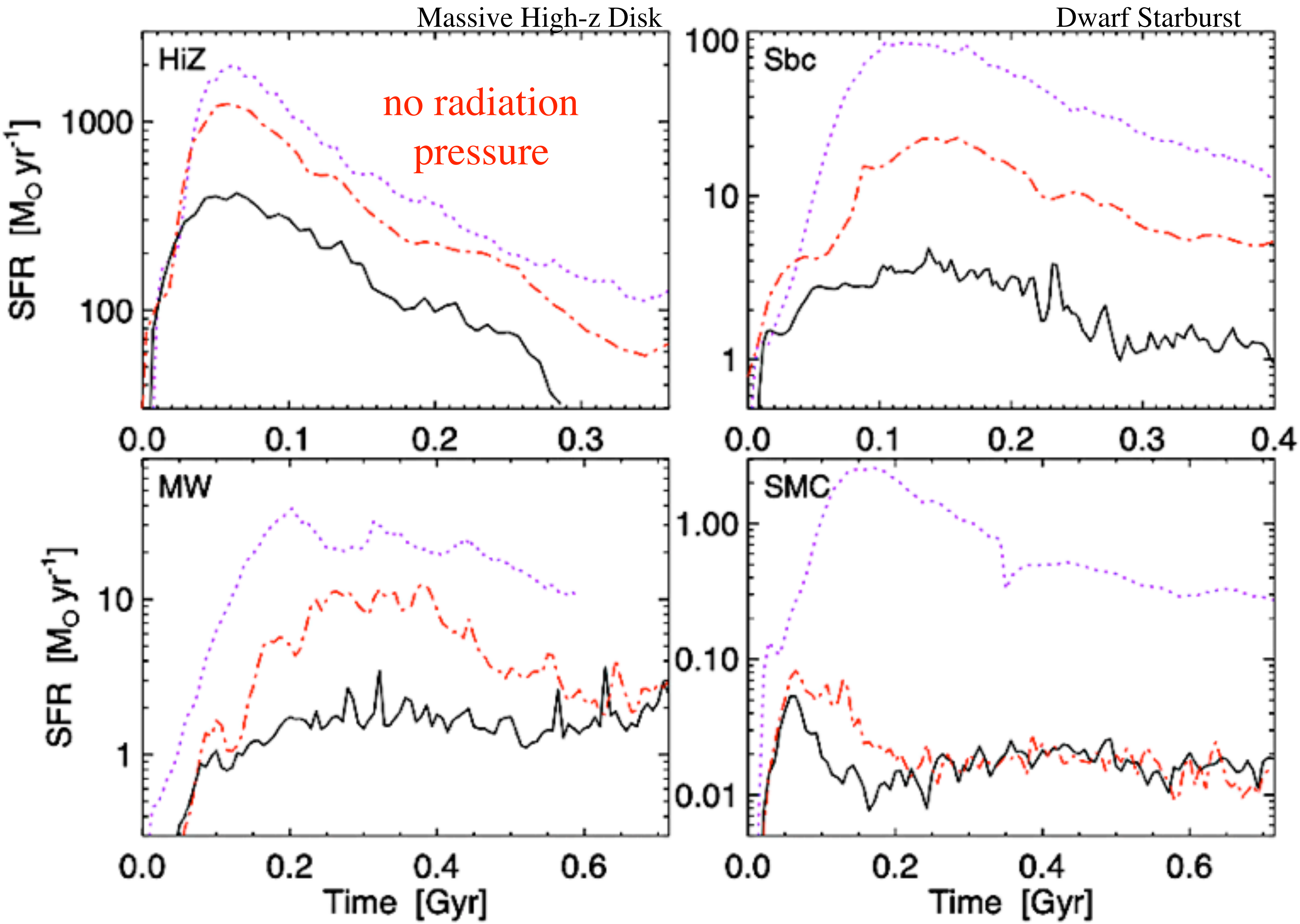

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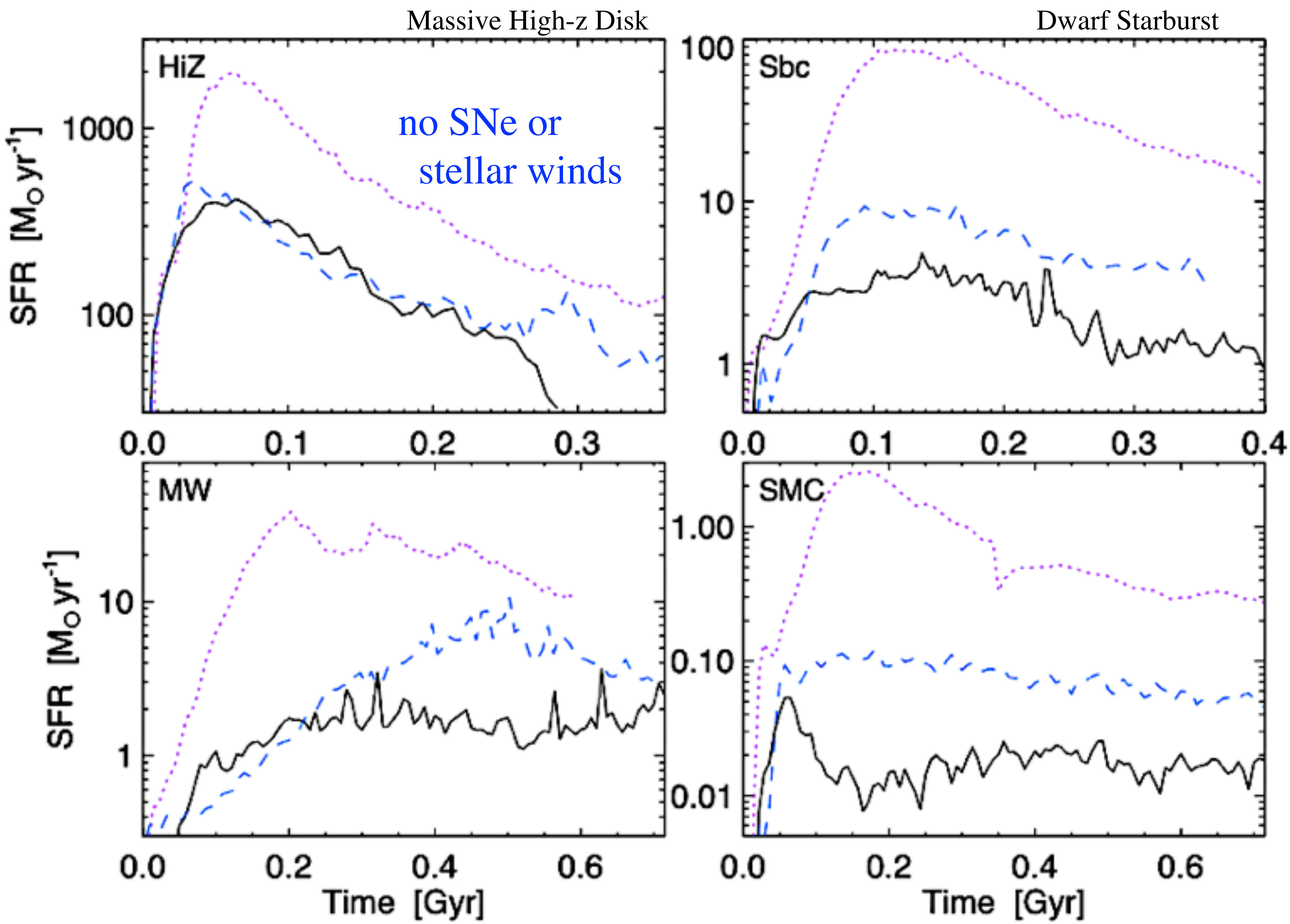
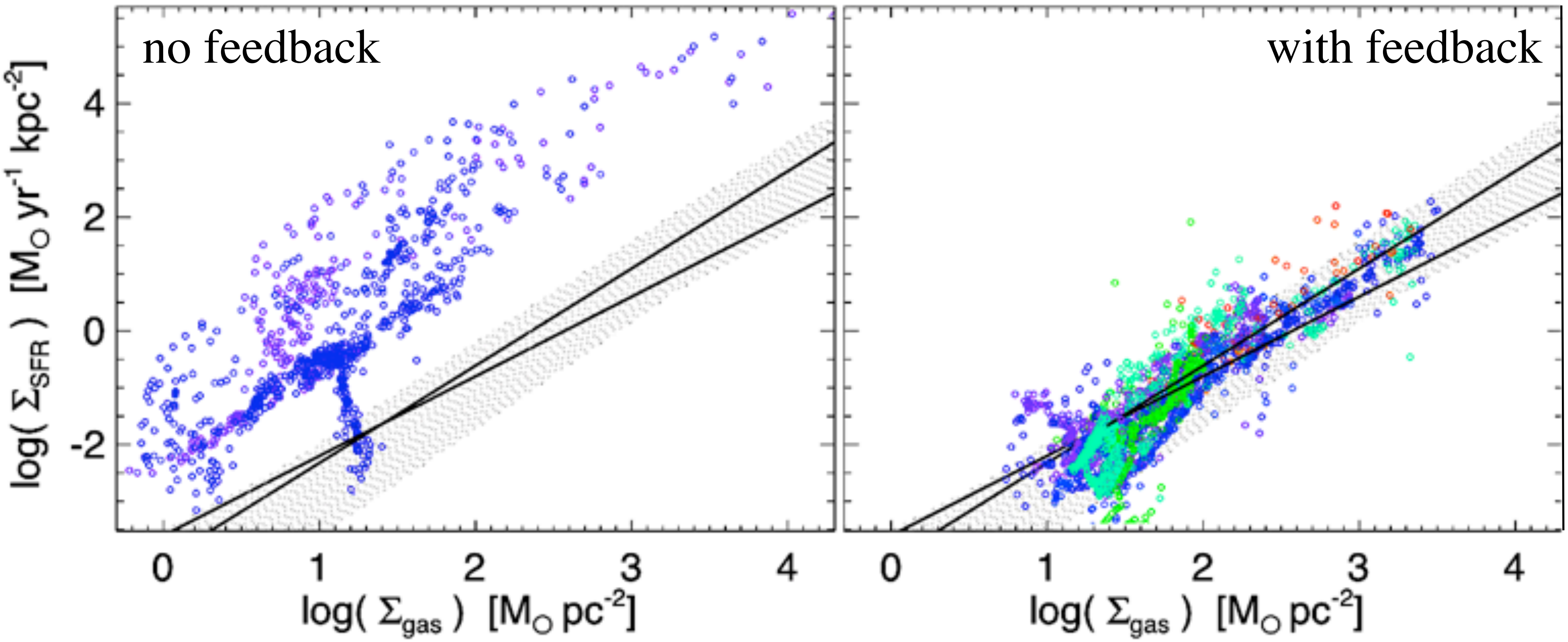


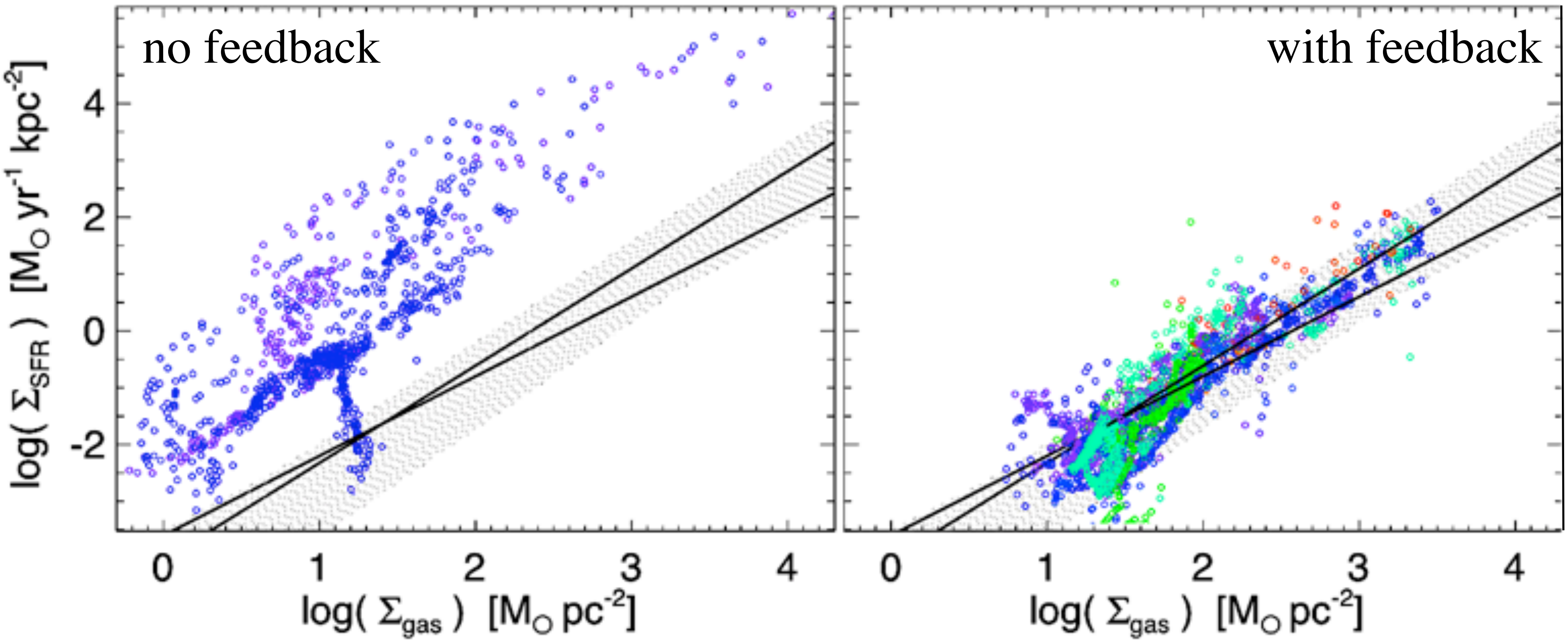
Kennicutt-Schmidt relation emerges naturally



PFH, Quataert, & Murray, 2011a

Kennicutt-Schmidt relation emerges naturally

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



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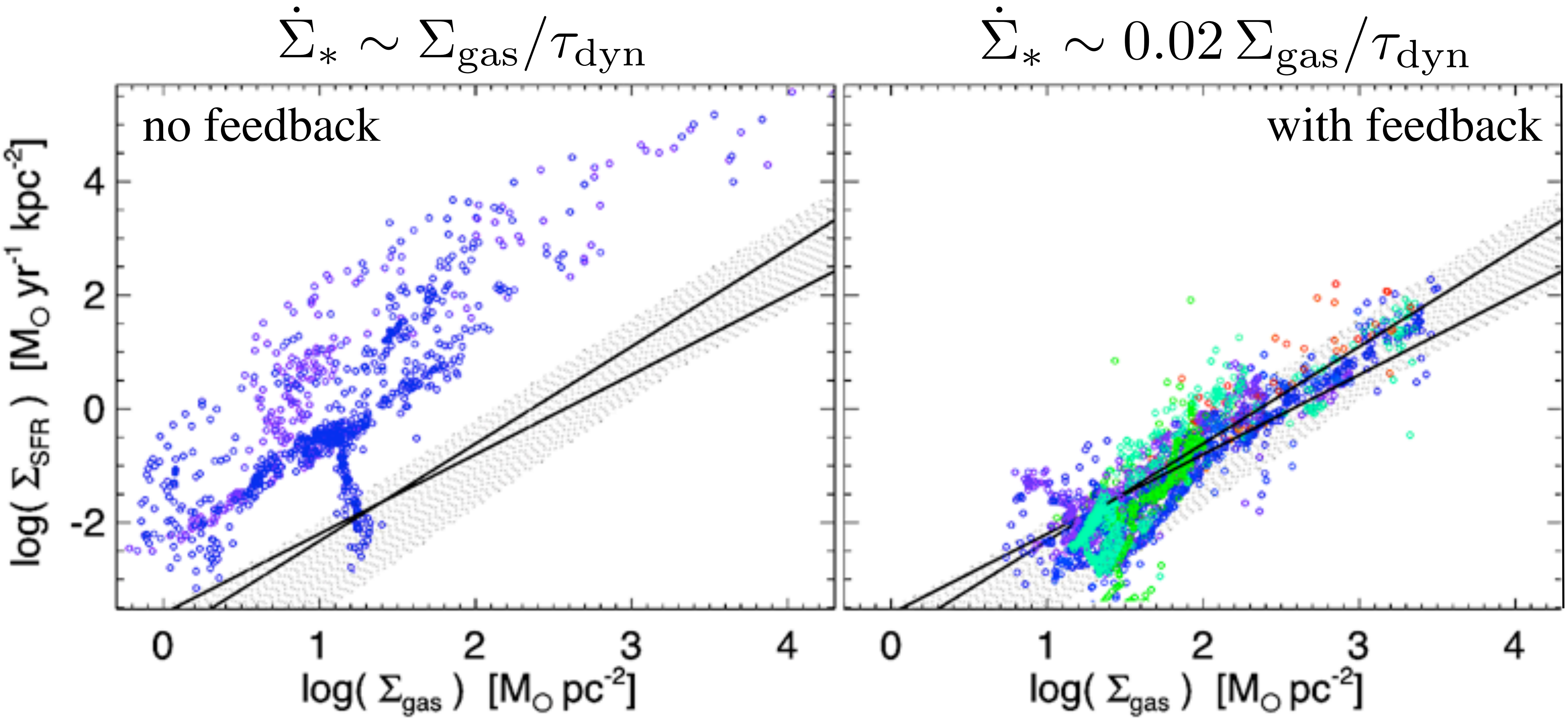

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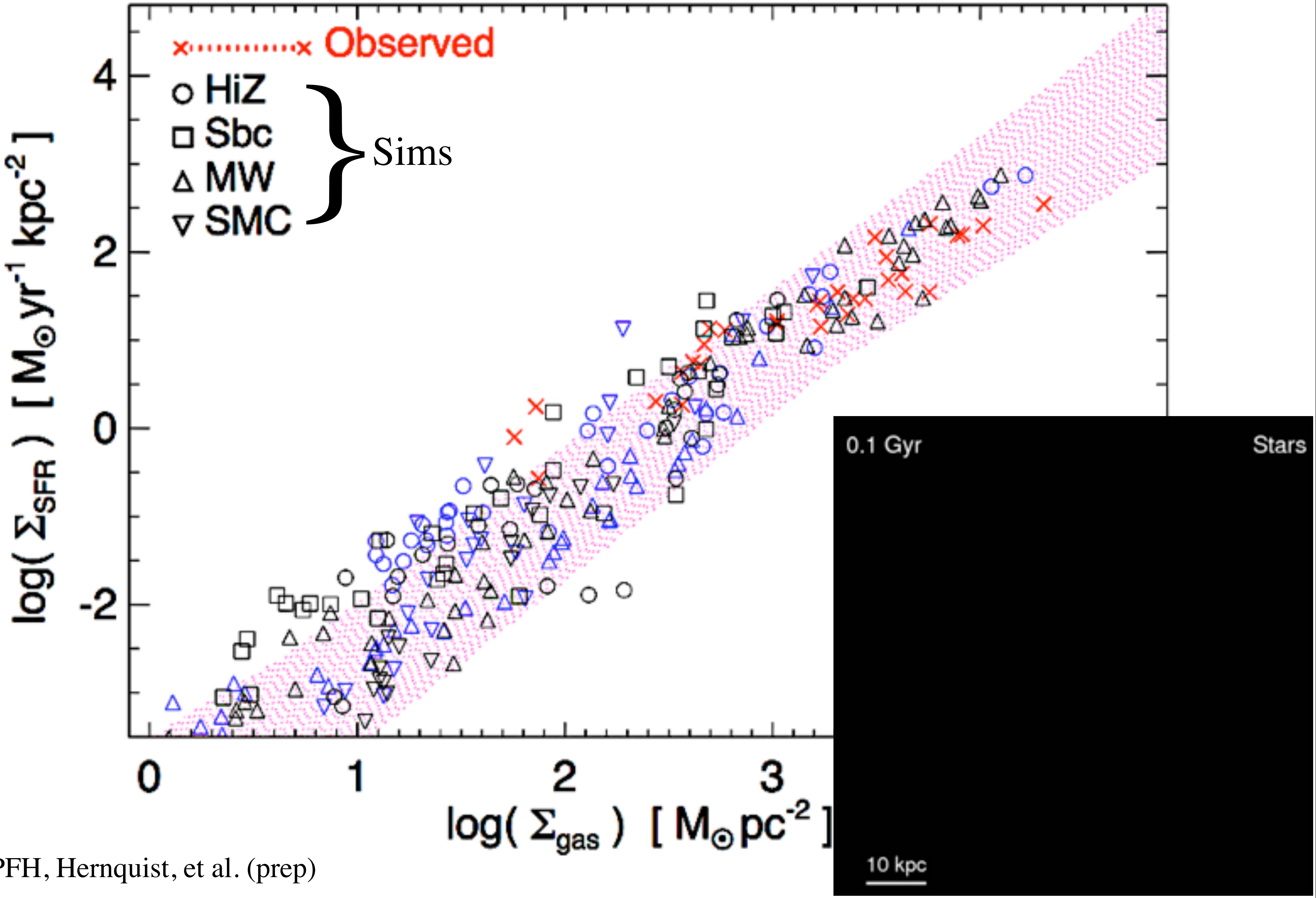
Galaxy Mergers

LABORATORY FOR STUDYING EXTREME CONDITIONS



PFH, Hernquist, et al. (prep)

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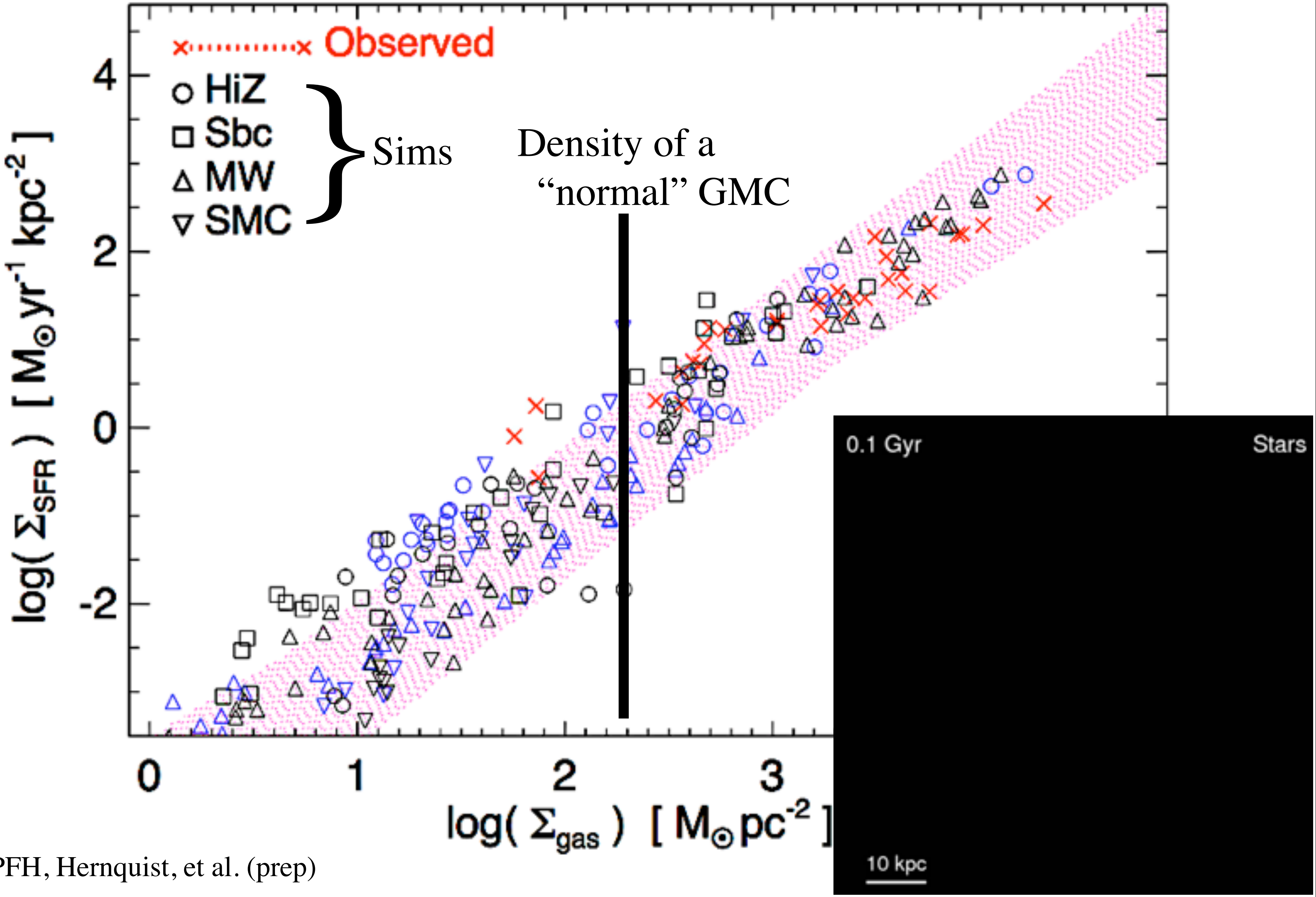

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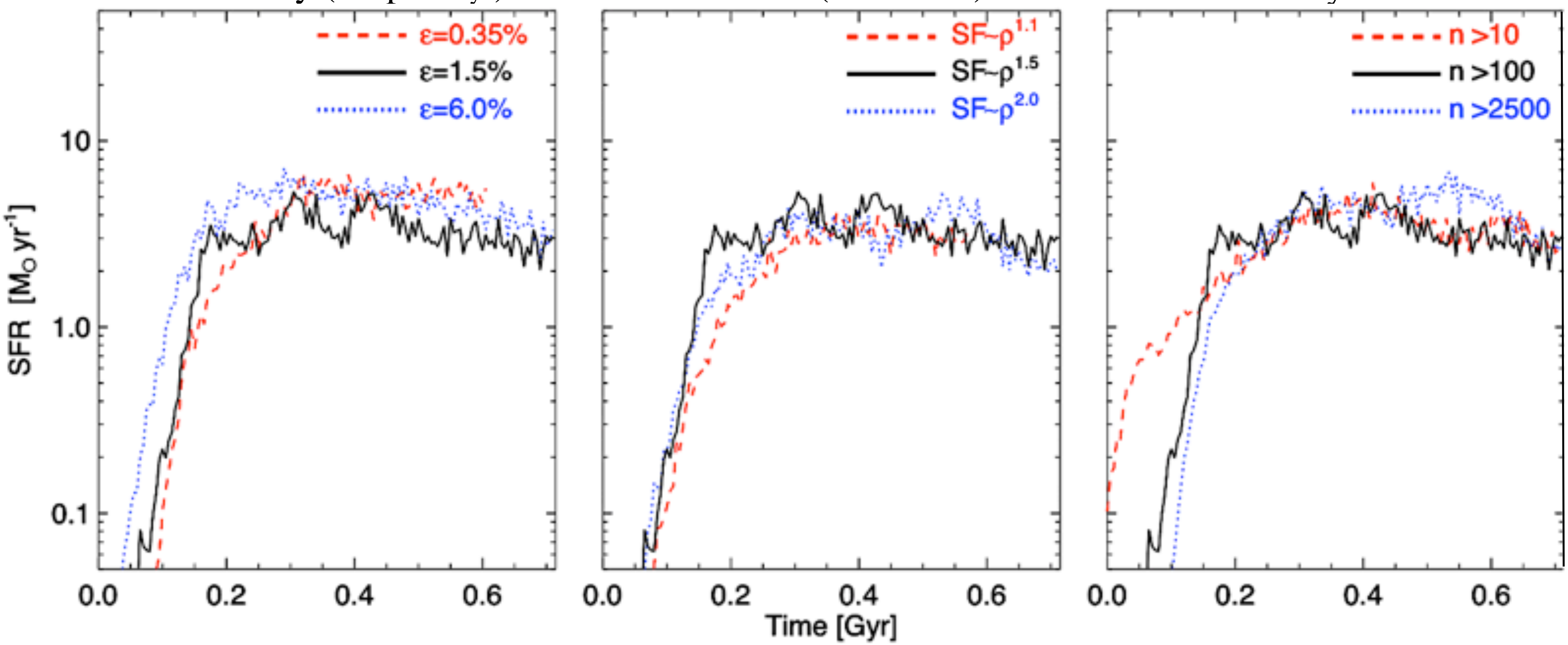
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas}\Omega \sim 0.02\, \Sigma_{\rm gas}\Omega$$

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

Efficiency (SF per t_{dyn}) Index (SFR ~ r^n) SF Density Threshold



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

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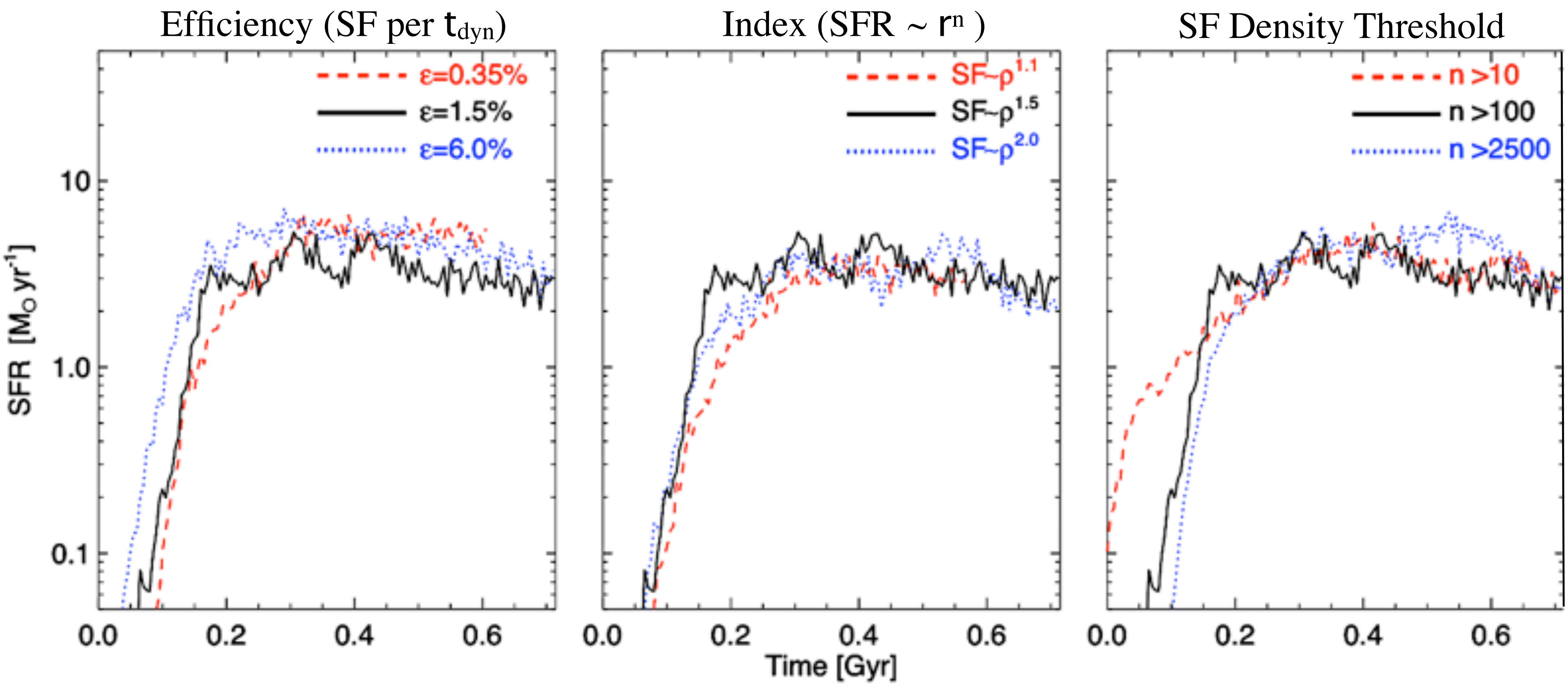


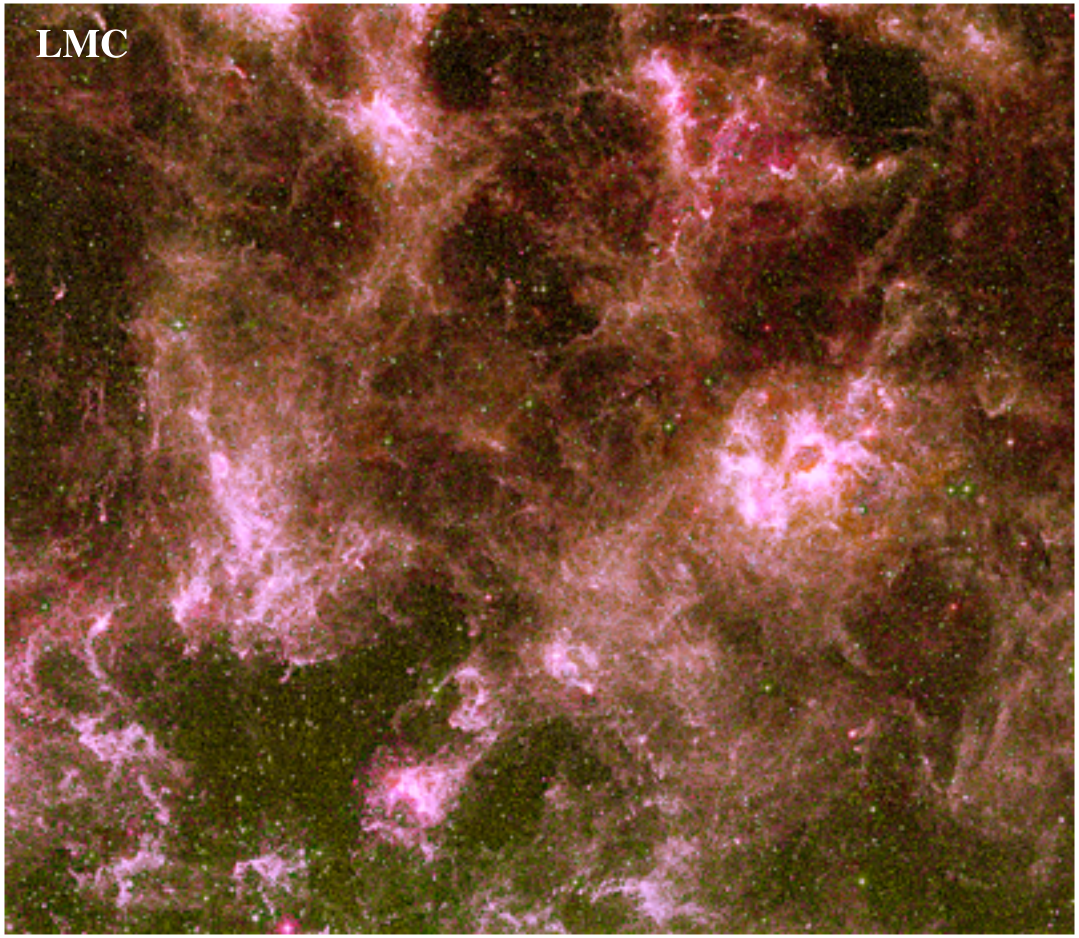
- Set by feedback (i.e. SFR) needed to maintain marginal stability

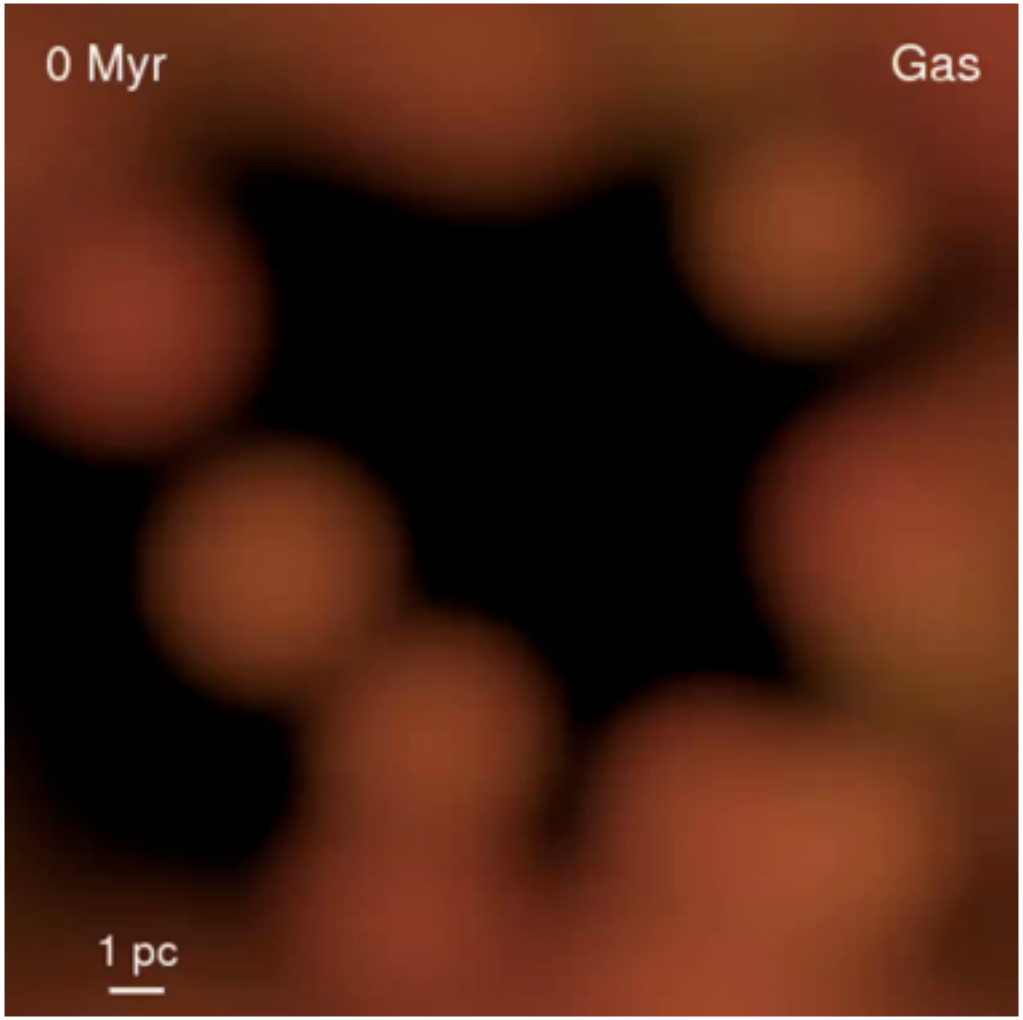
Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008

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

Super-Sonic Turbulence

DOMINATES (ALMOST) ALL SCALES



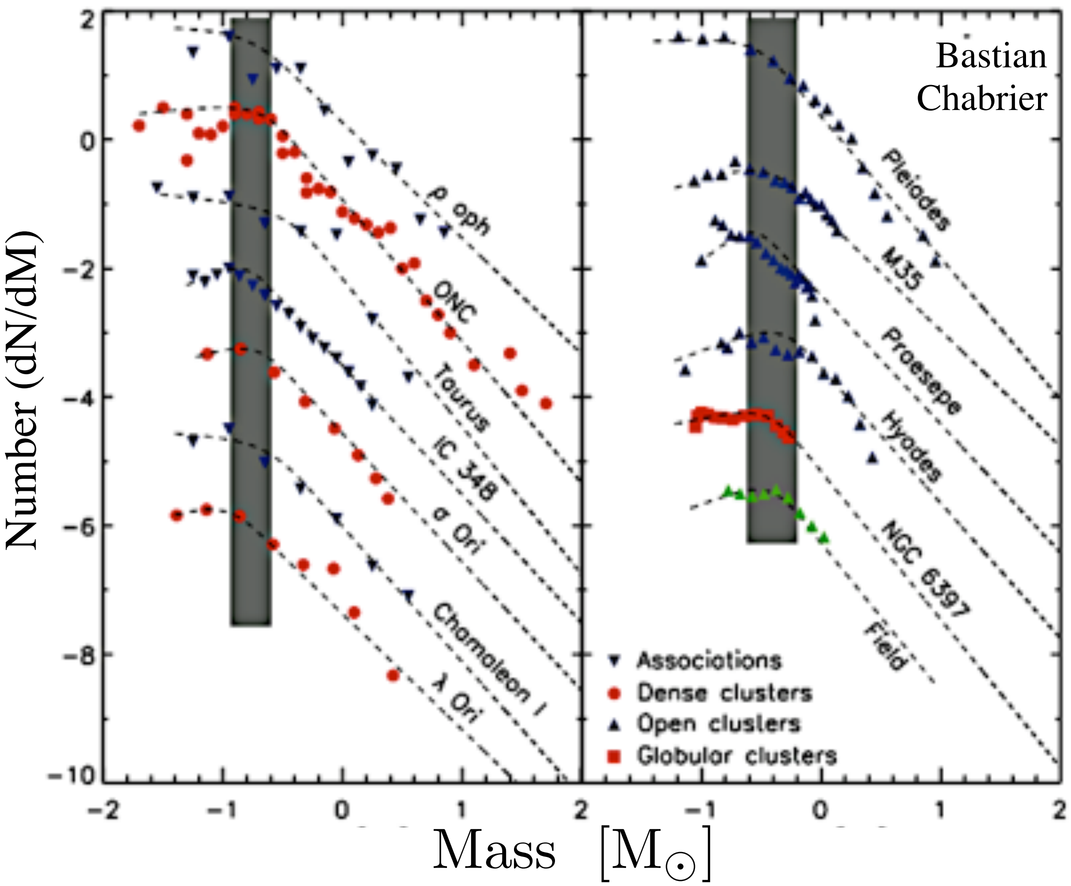


- Gravity
- Turbulence
- Magnetic, Thermal, Cosmic Ray, Radiation Pressure
- Cooling (atomic, molecular, metal-line, free-free)
- Star & BH Formation/Growth
- "Feedback": Massive stars, SNe, BHs, external galaxies, etc.

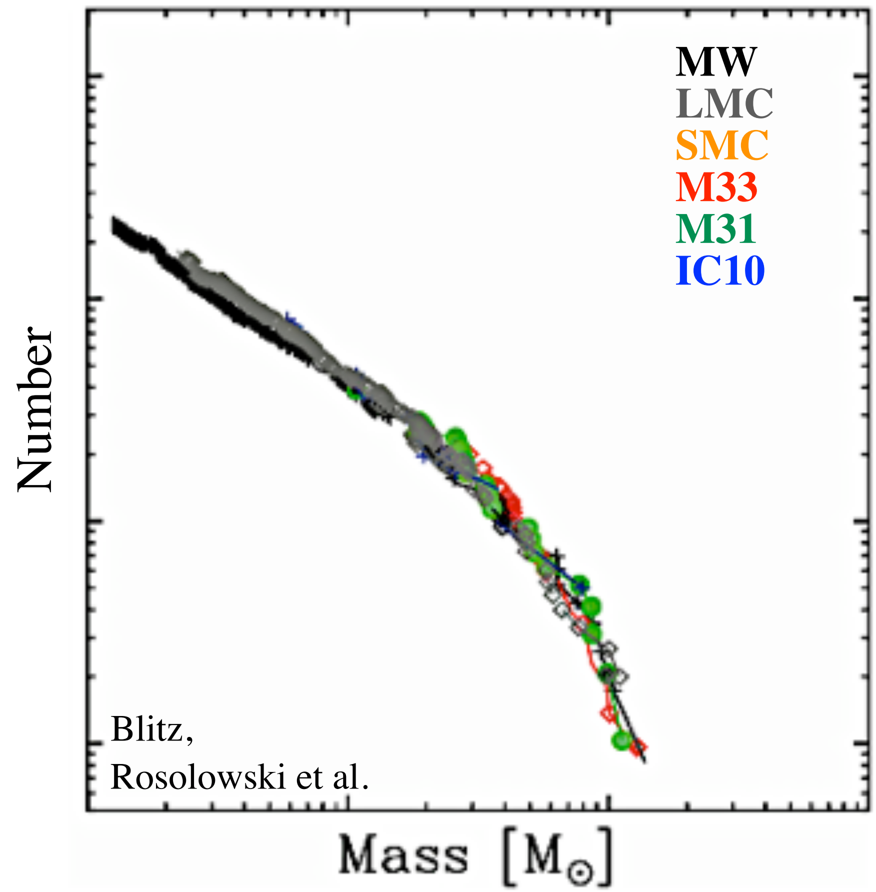
The ISM

YET THERE IS SURPRISING REGULARITY

Stars & Pre-Stellar Gas Cores:

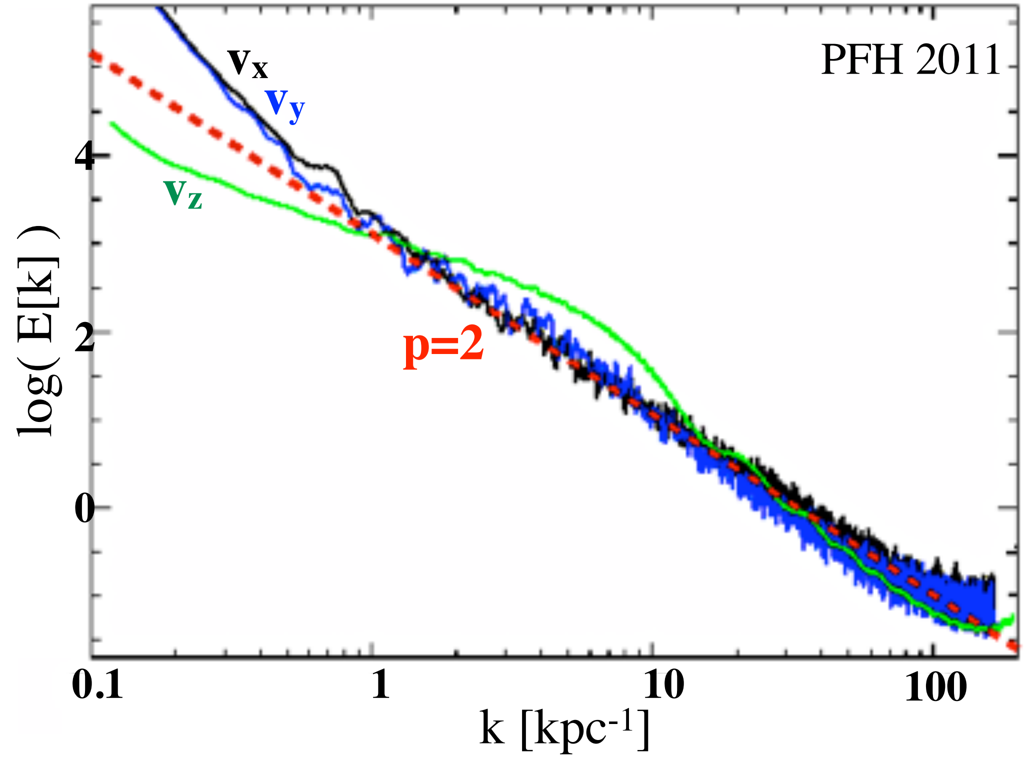


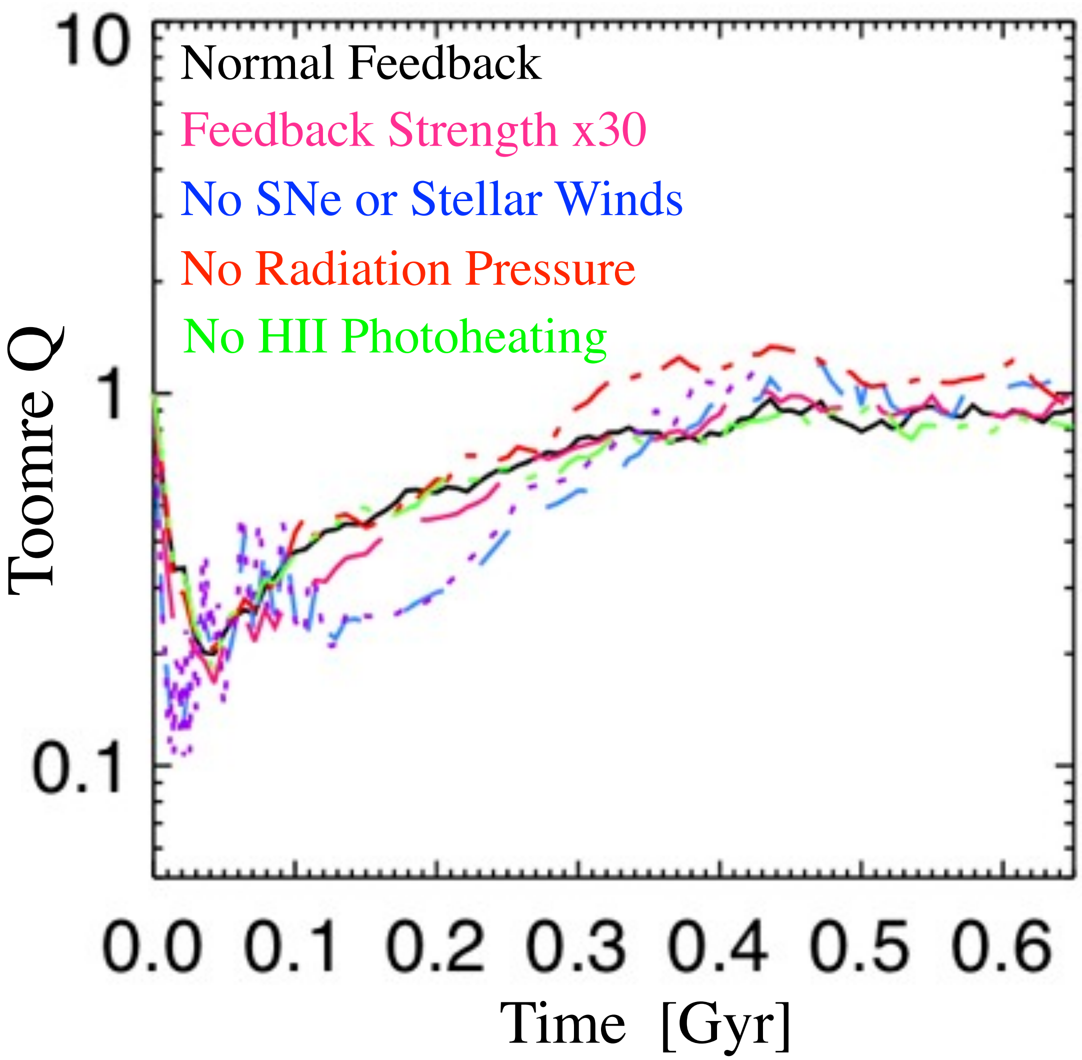
Giant Molecular Clouds:



Feedback Maintains Turbulence

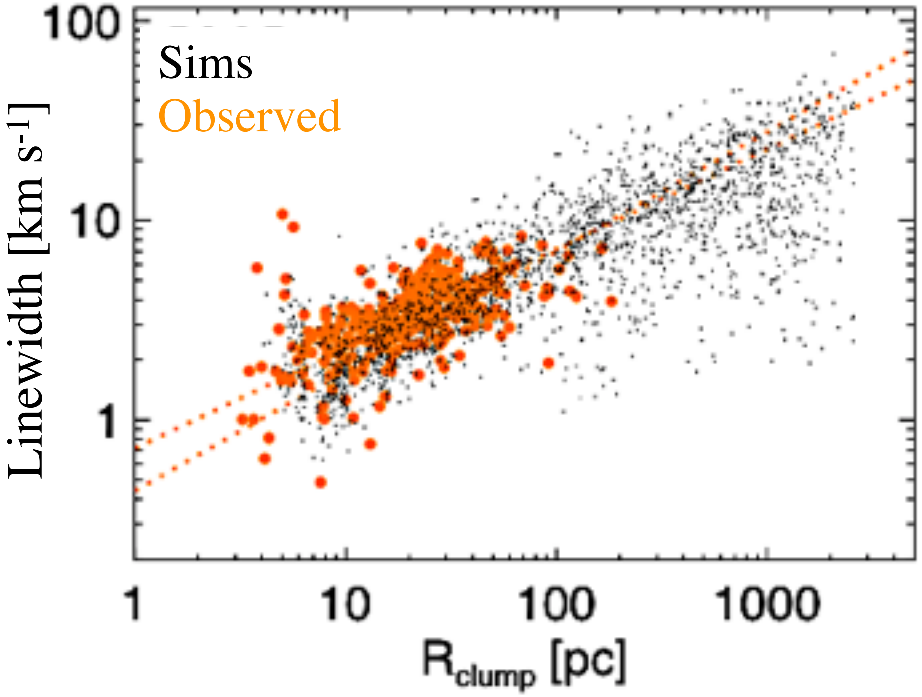
CASCADE INVARIANT TO MICROPHYSICS

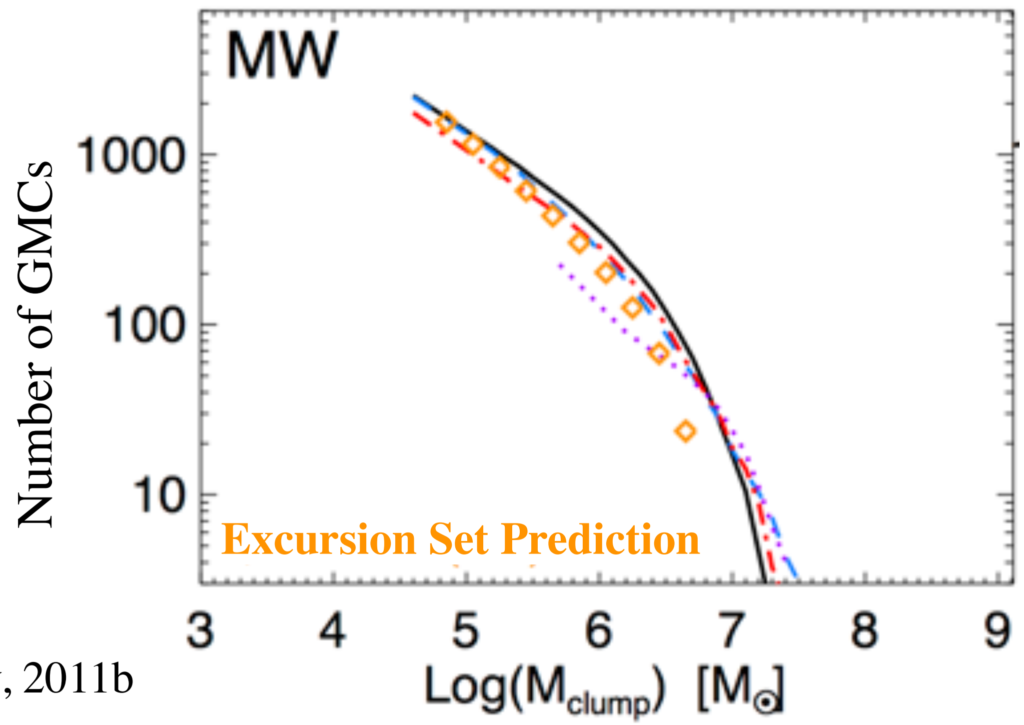


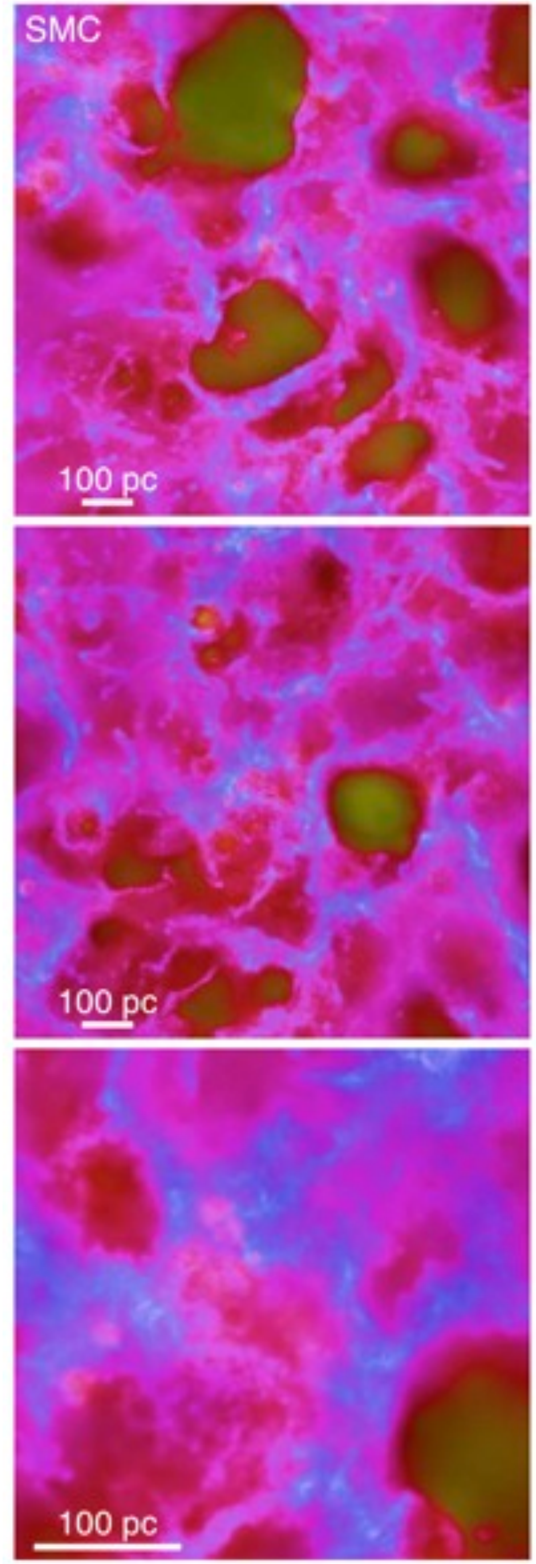


- Turbulence + Gravity:
  - **Promote** collapse (shocks)
  - **Prevent** collapse (turbulent “pressure”)

Compare Simulations & Turbulent Excursion-Set Predictions



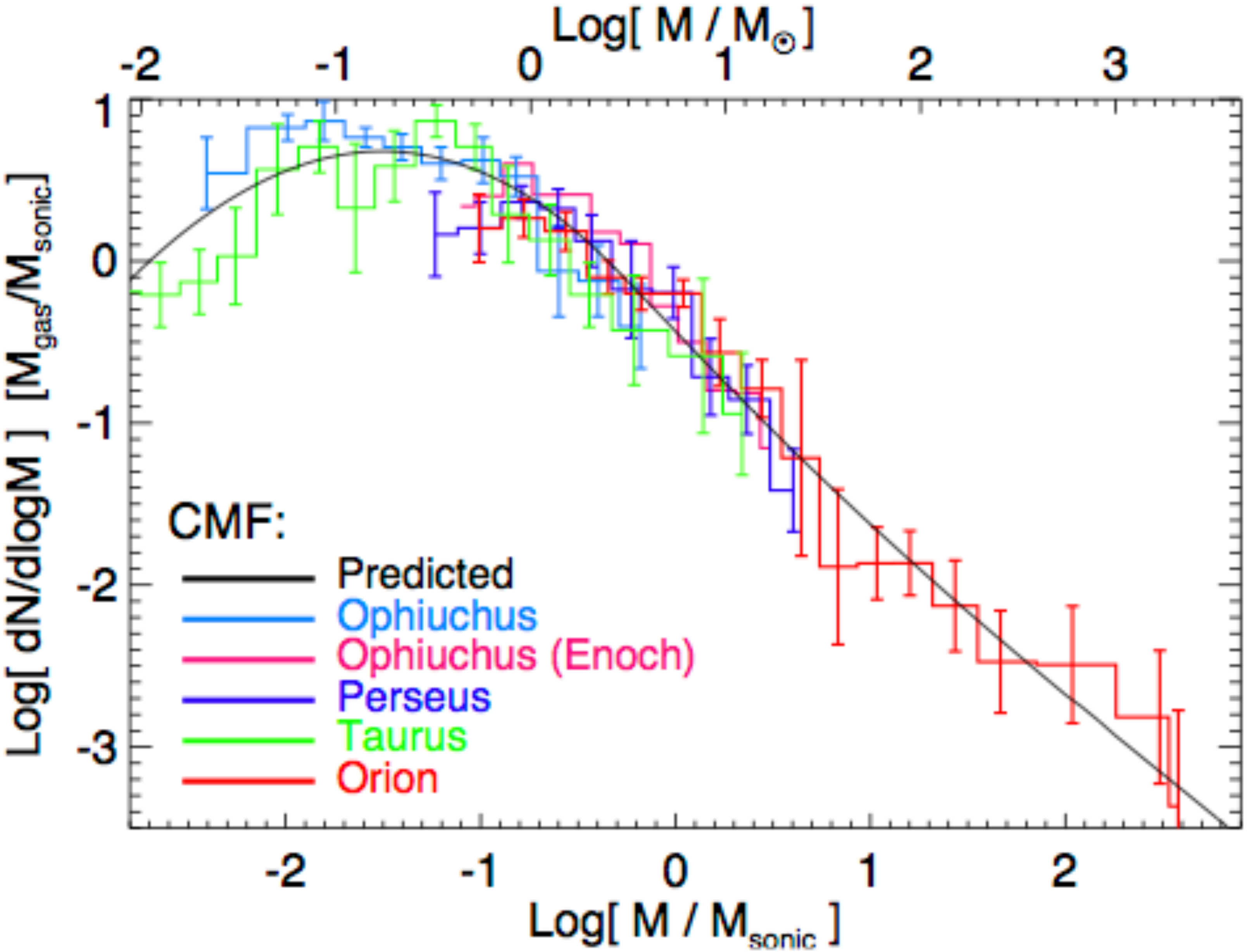




PFH, Quataert, & Murray, 2011b

The “Last Crossing” Mass Function

VS PROTOSTELLAR CORES & THE STELLAR IMF

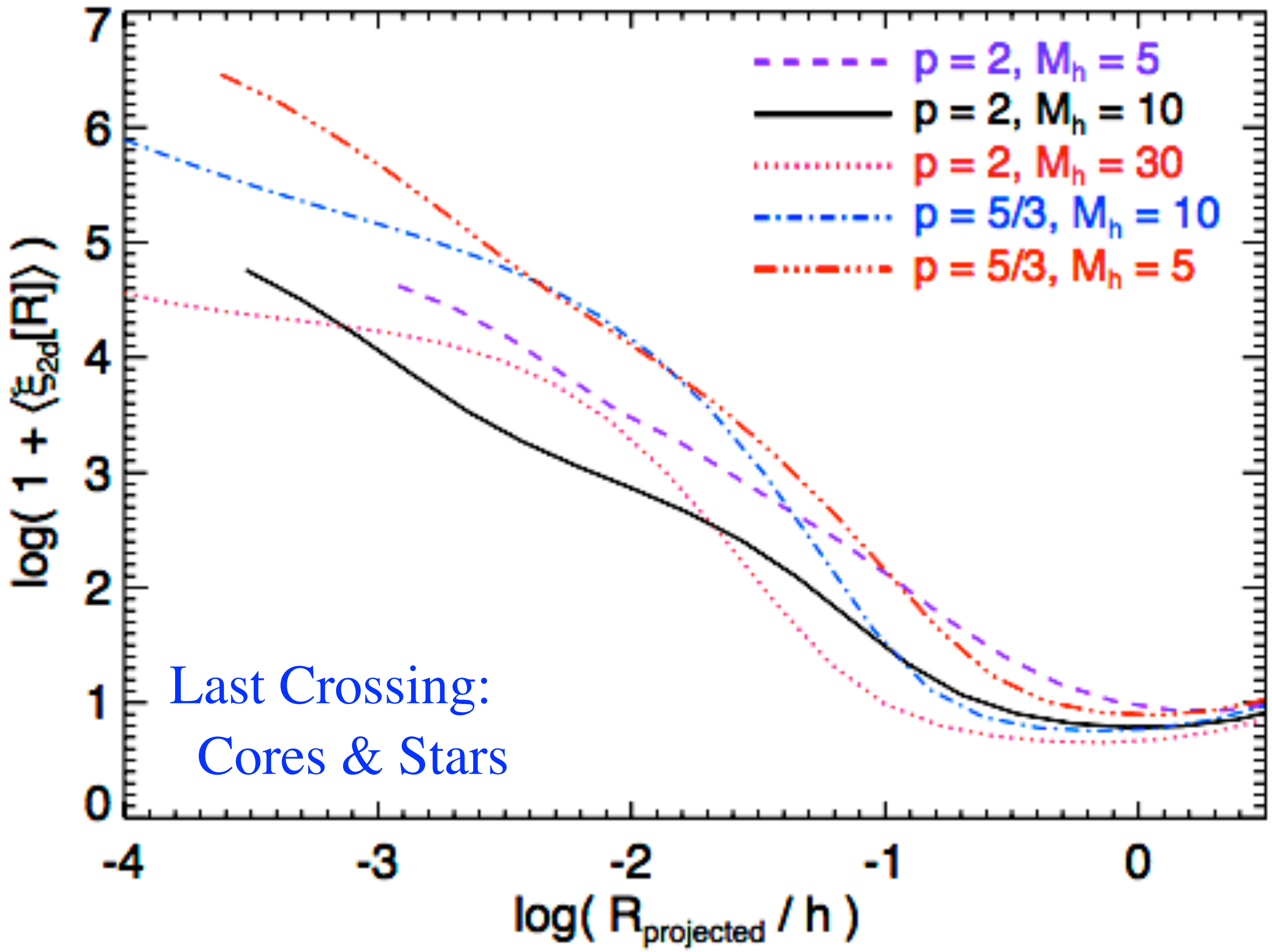


Clustering: Resolve Global GMC-Star Cluster Correlations

PREDICT N-POINT CORRELATION FUNCTIONS

$$1 + \xi(r\,|\,M) \equiv \frac{\langle n[M\,|\,r' < r]\rangle}{\langle n[M]\rangle}$$

PFH 2012b



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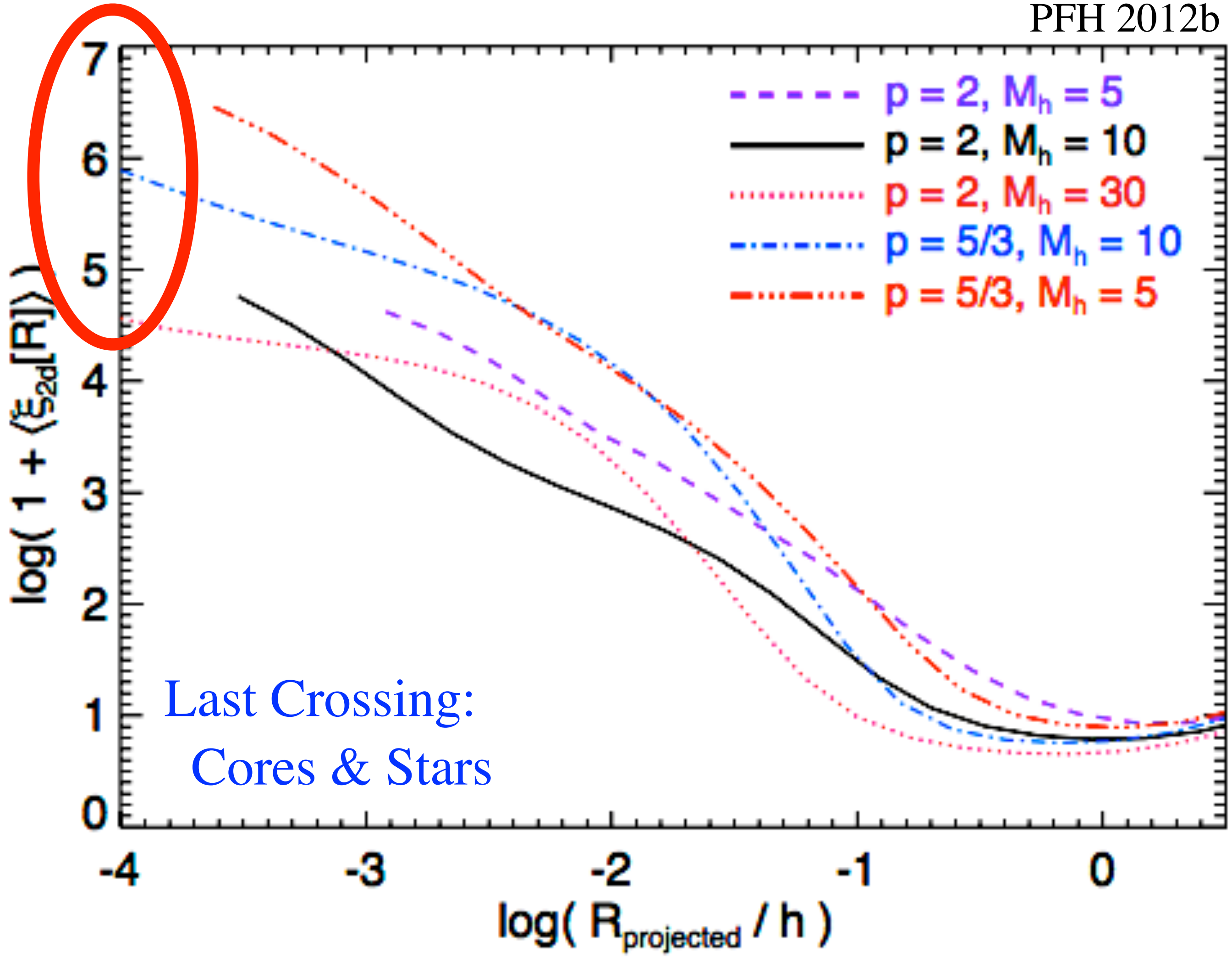

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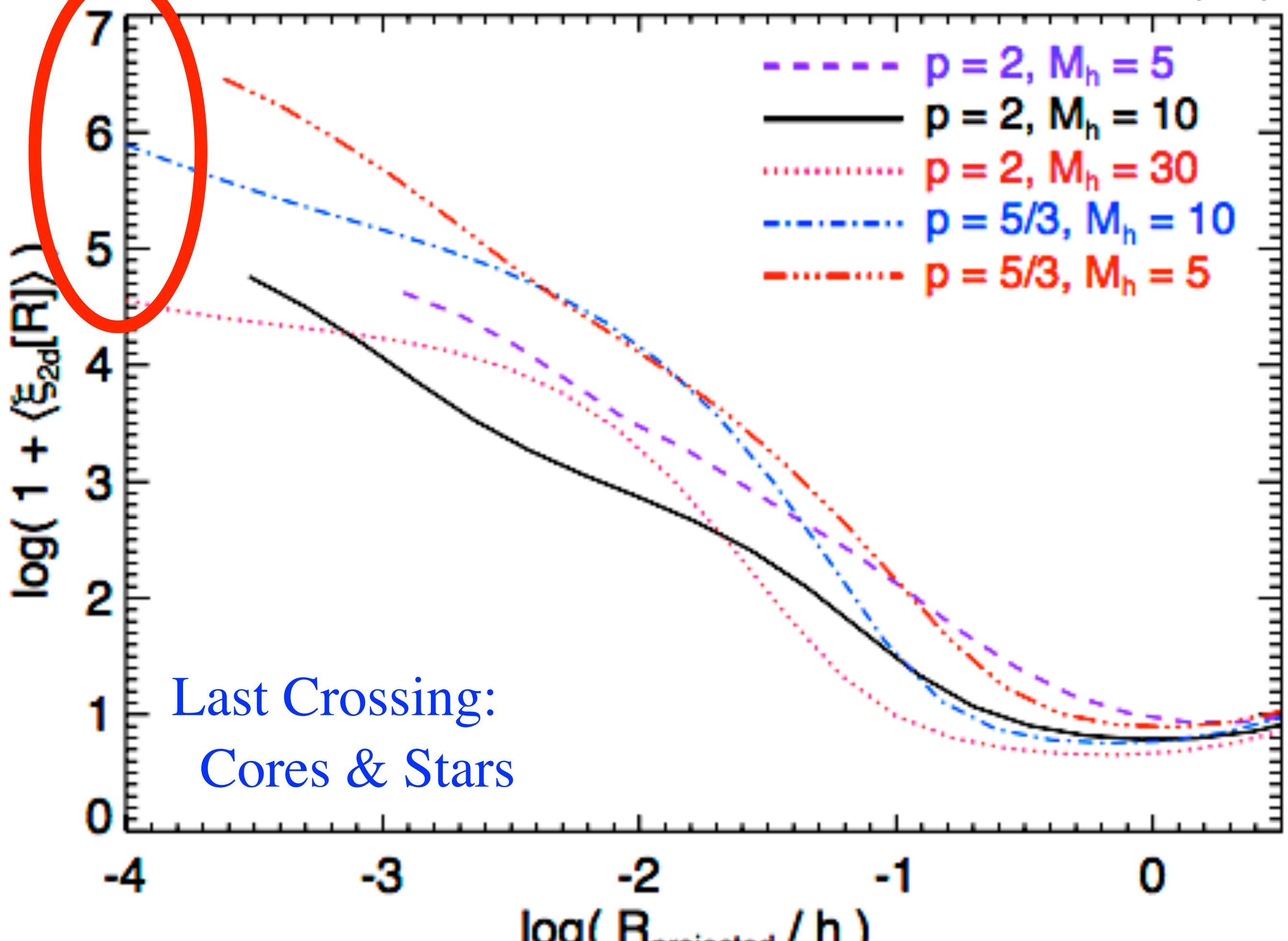
PFH 2012b

Why Do Stars Form in Clusters?

$$S \sim \ln \mathcal{M}(k)^2$$
$$\sim \ln r^{3-p}$$

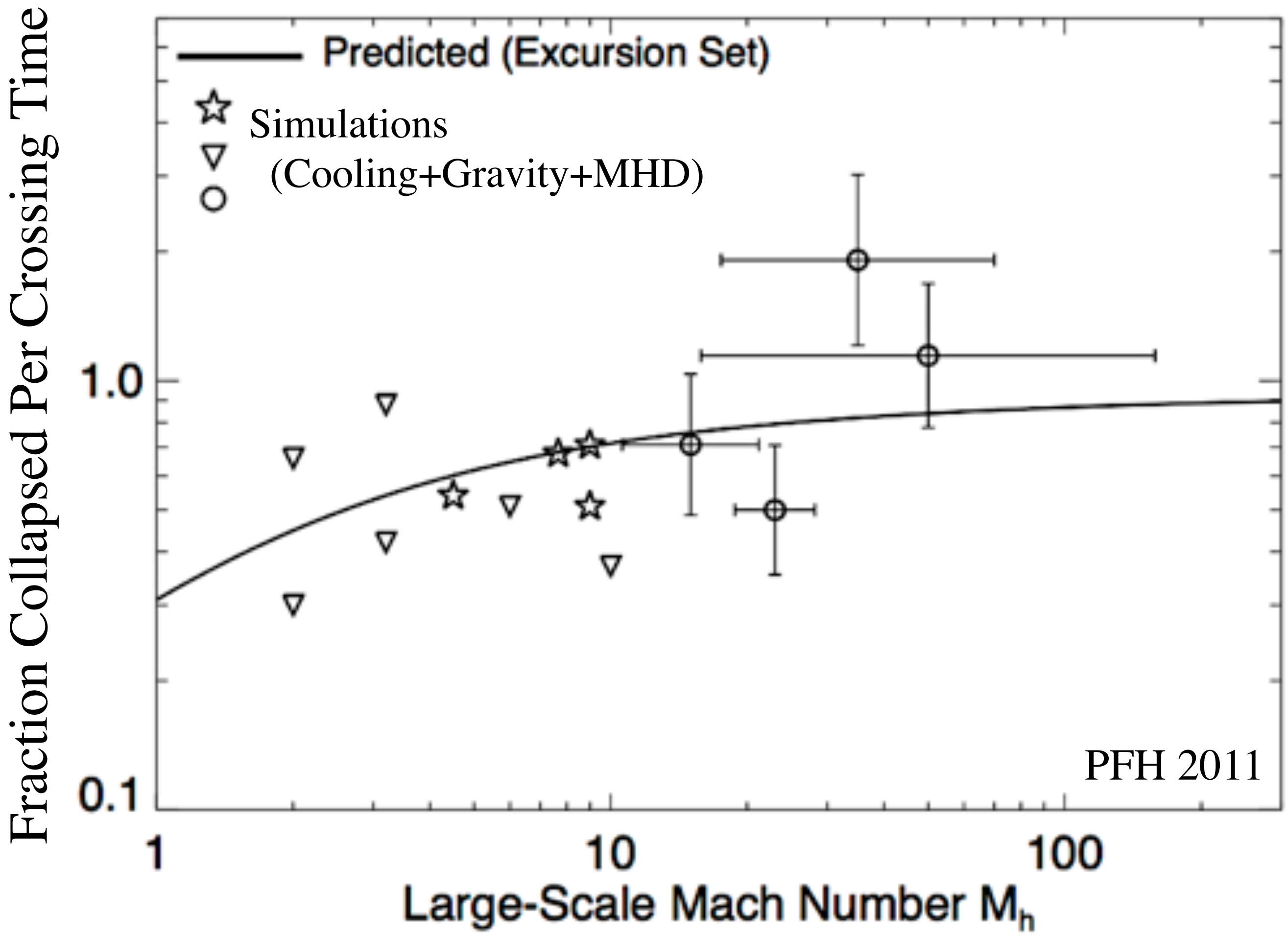


No-Feedback "Formal" Prediction for Collapse:

(FROM ANALYTIC "MERGER/FRAGMENTATION" TREES)

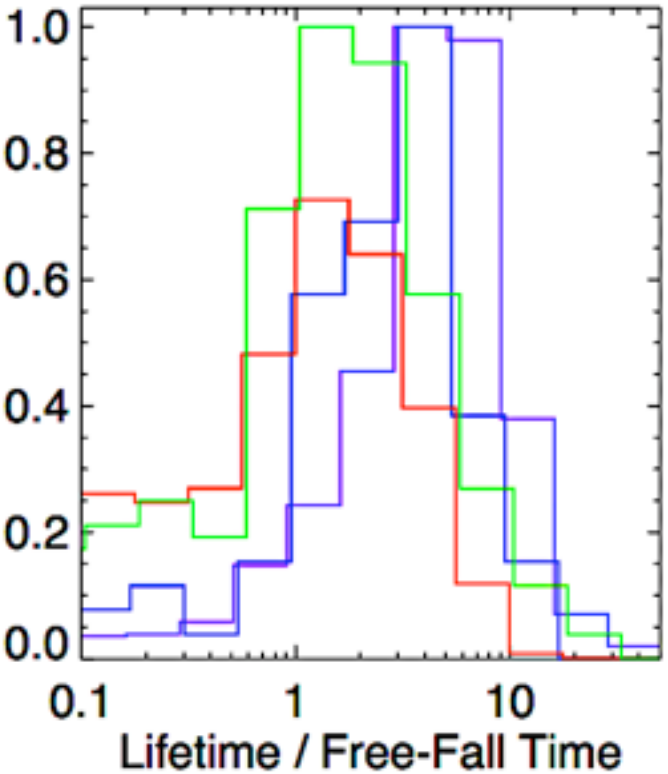
$$p(\delta\,|\,\tau) = \frac{1}{\sqrt{2\pi\,S\,(1-\exp{[-2\tau]})}}\,\exp\left[-\frac{(\delta-\delta(t=0)\,\exp{[-\tau]})^2}{2\,S\,(1-\exp{[-2\tau]})}\right]$$

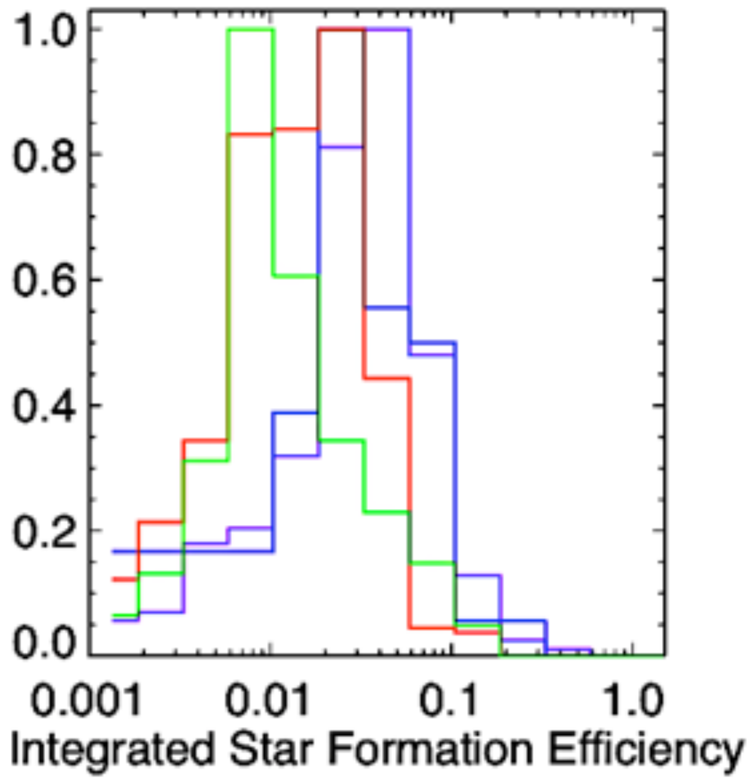
$$\tau \equiv u_t(k)\,k\,t \sim \frac{t}{t_{\rm cross}}$$

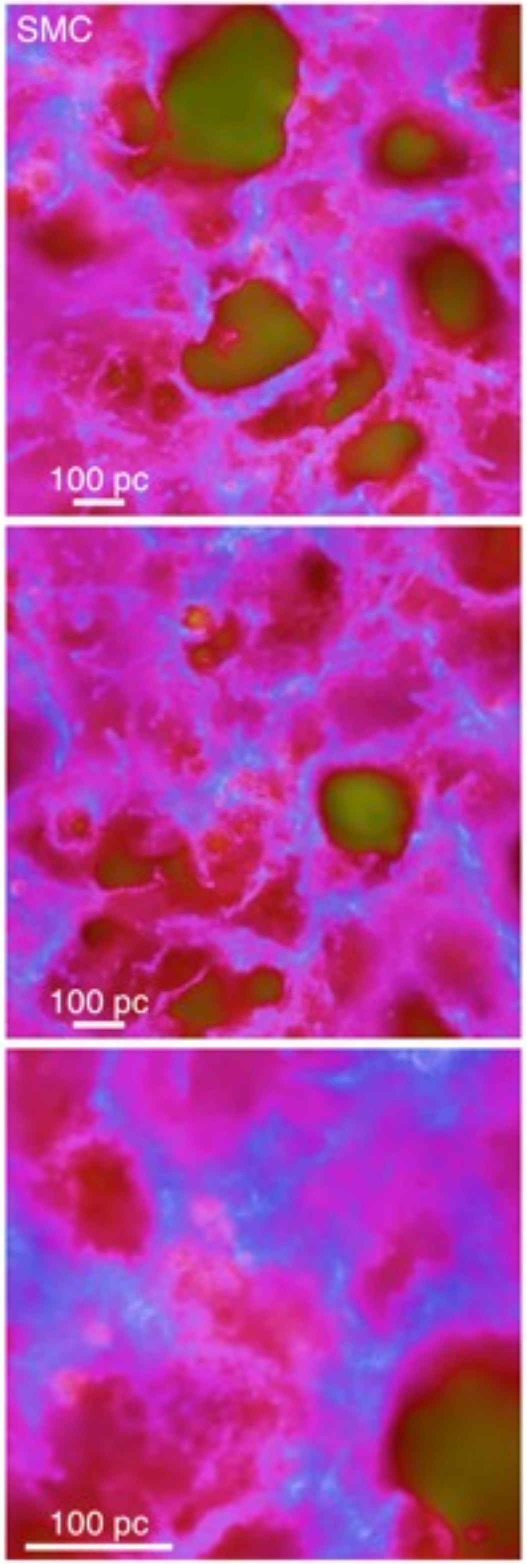


with feedback, GMCs are Short-Lived

FEEDBACK "RECYCLES" MASS: STEADY-STATE MASS FUNCTION





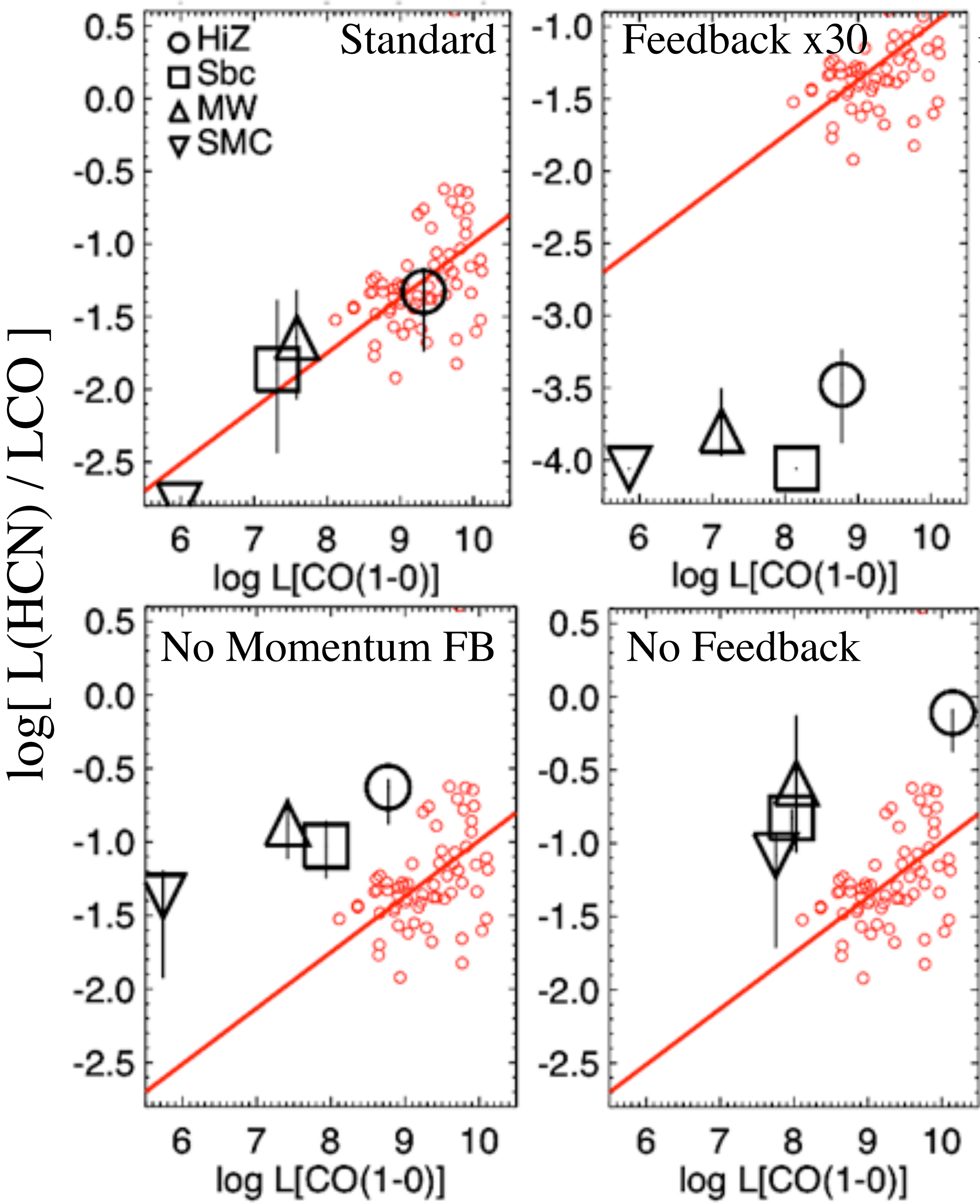


$$\dot{P}_* = \dot{\epsilon}_* \, M_* \, c > F_{\rm grav} \sim \frac{G\, M_{\rm cl}^2}{R_{cl}^2}$$

PFH, Quataert, & Murray, 2011b

Study Chemistry in Extreme Conditions

TRACERS OF SHOCKS & RADIATION IN DENSE MEDIA

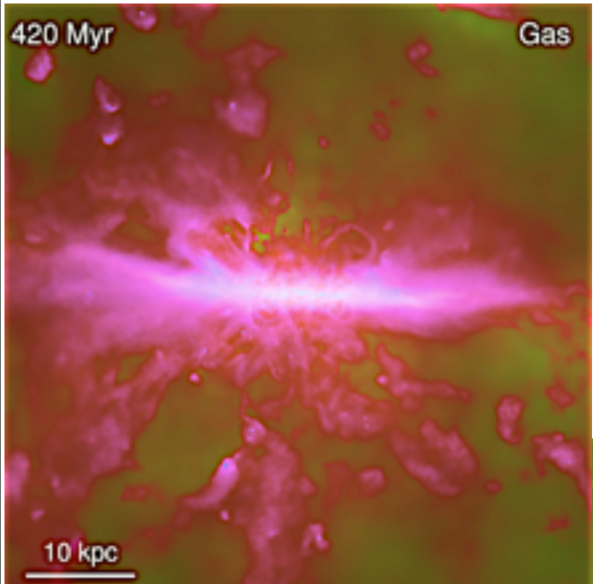


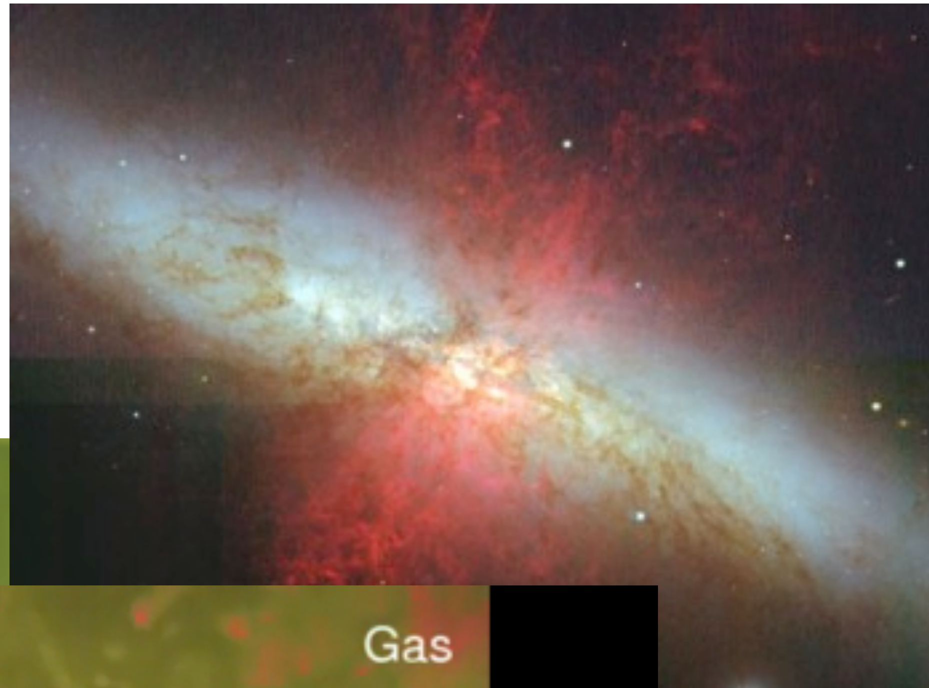
PFH, Narayanan et al. (prep)

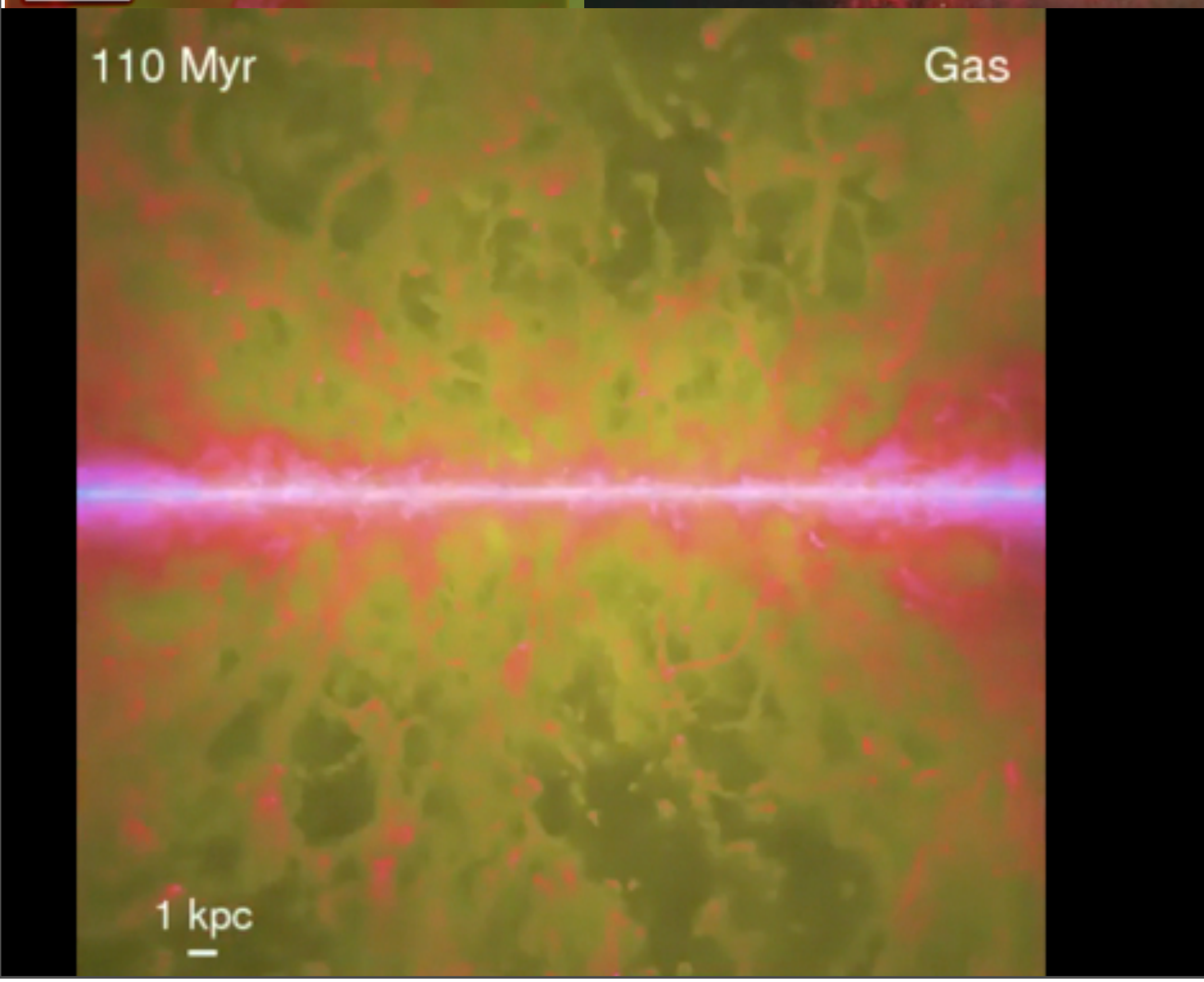
The Gas not Forming Stars:

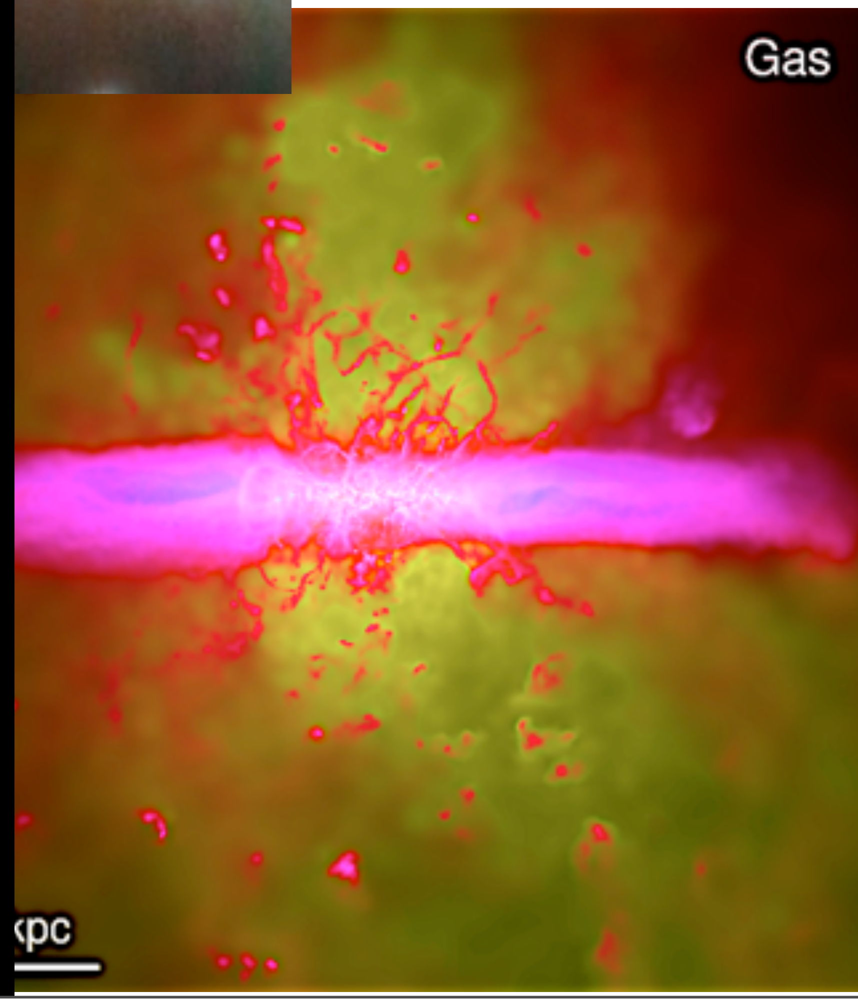
Galaxy Winds and the Baryon Cycle

Galactic
Super-Winds



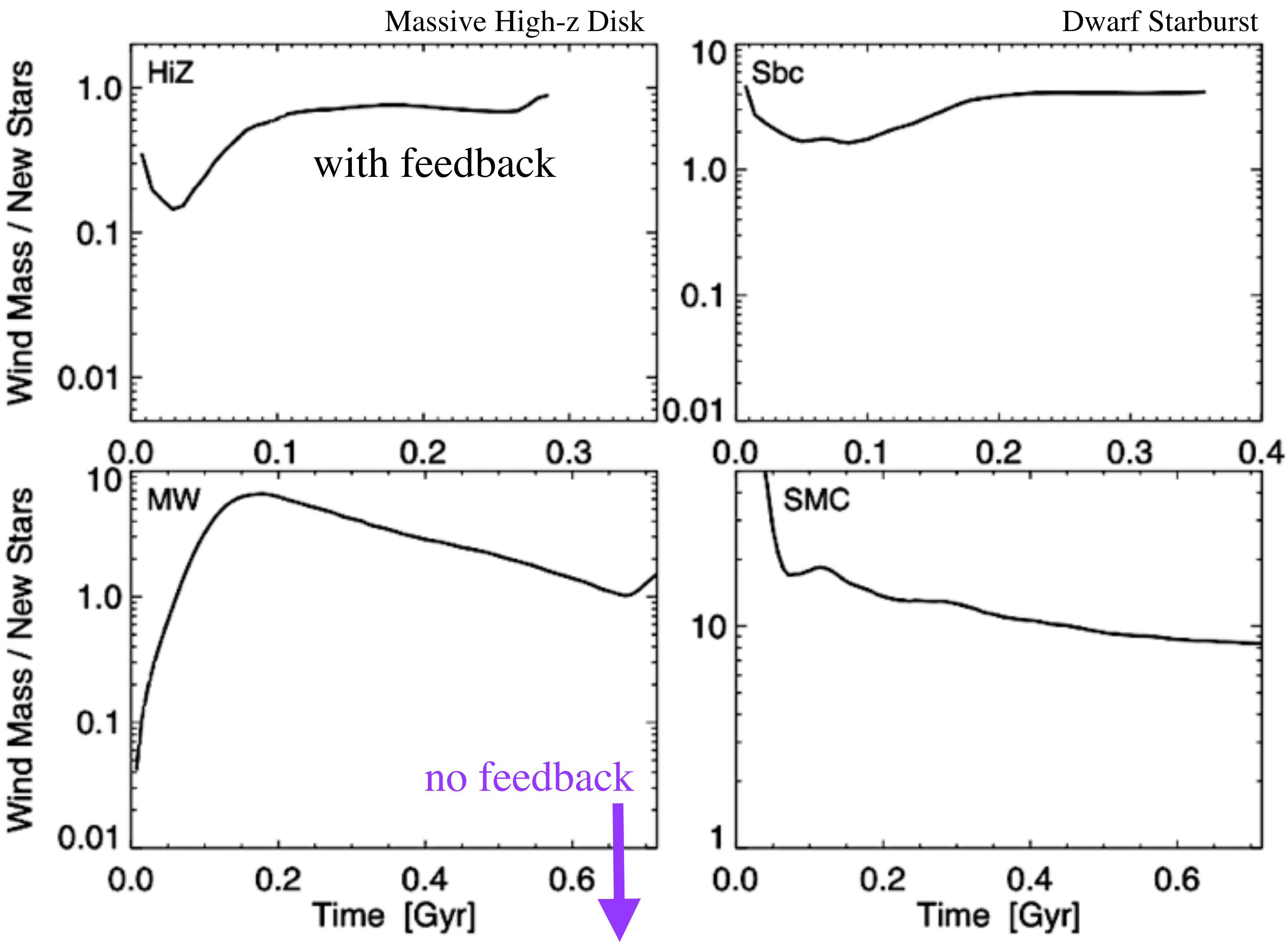






How Efficient Are Galactic Super-Winds?
AND WHAT MECHANISMS DRIVE THEM?

PFH, Quataert, & Murray, 2011c



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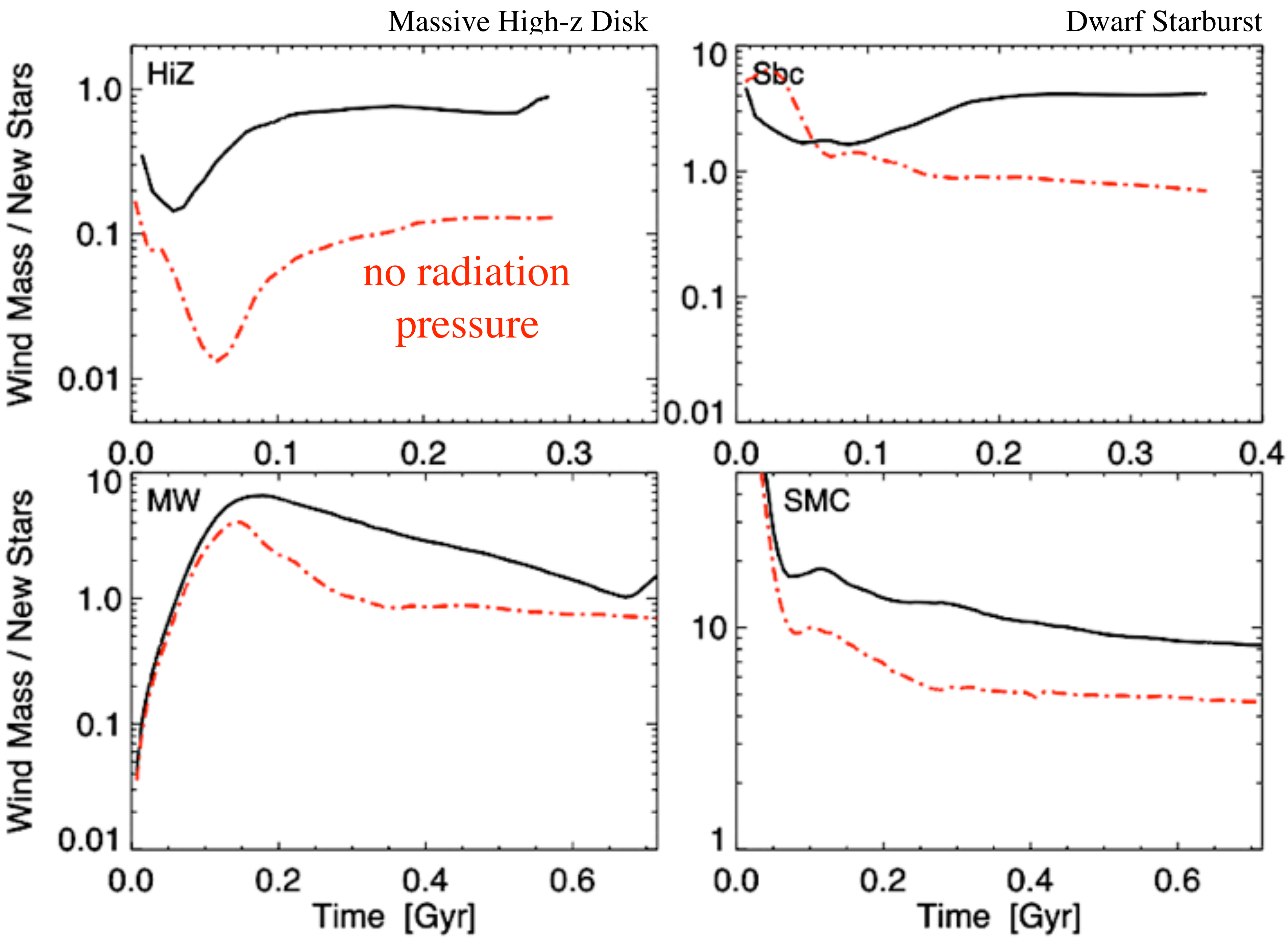

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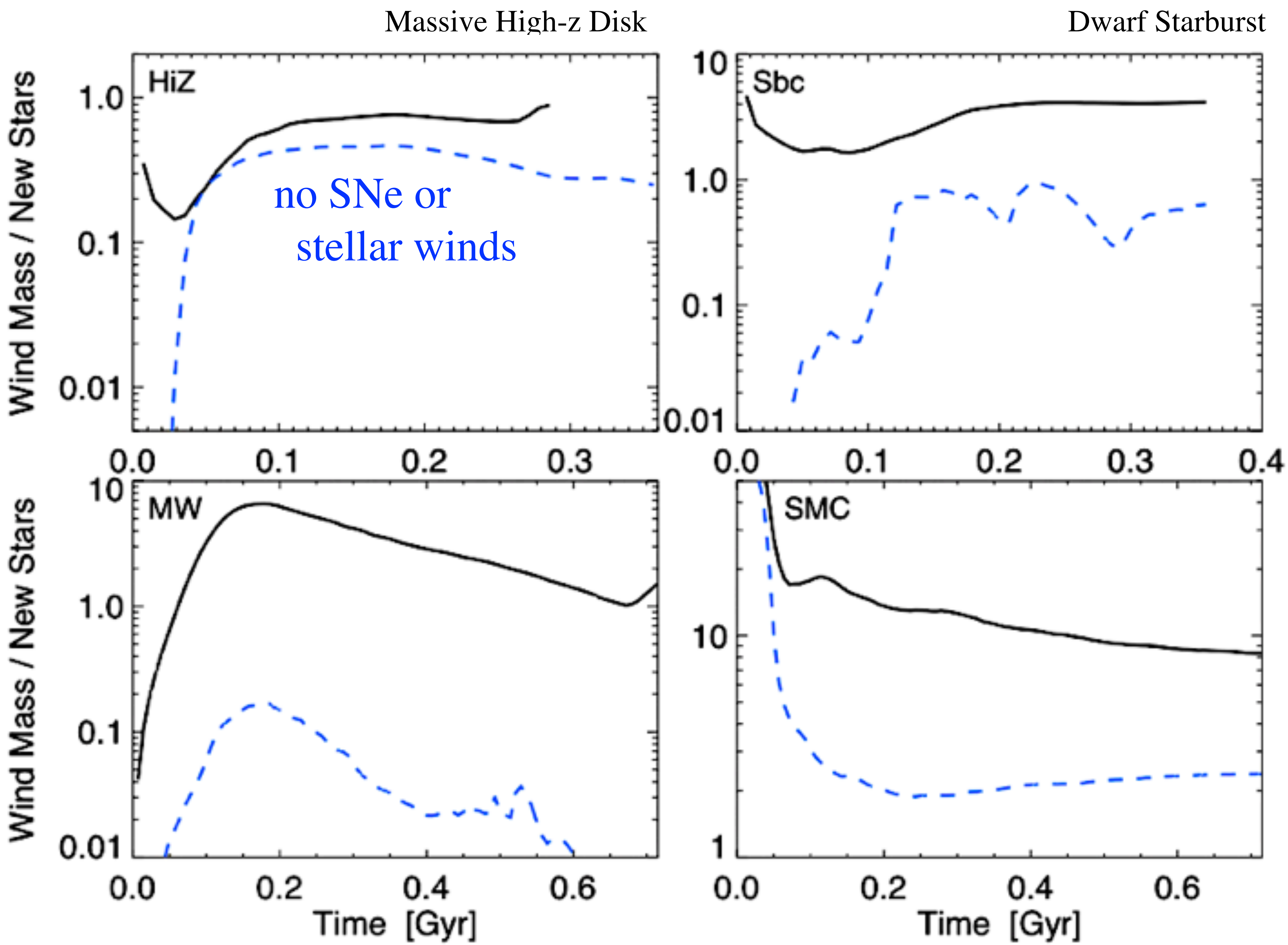

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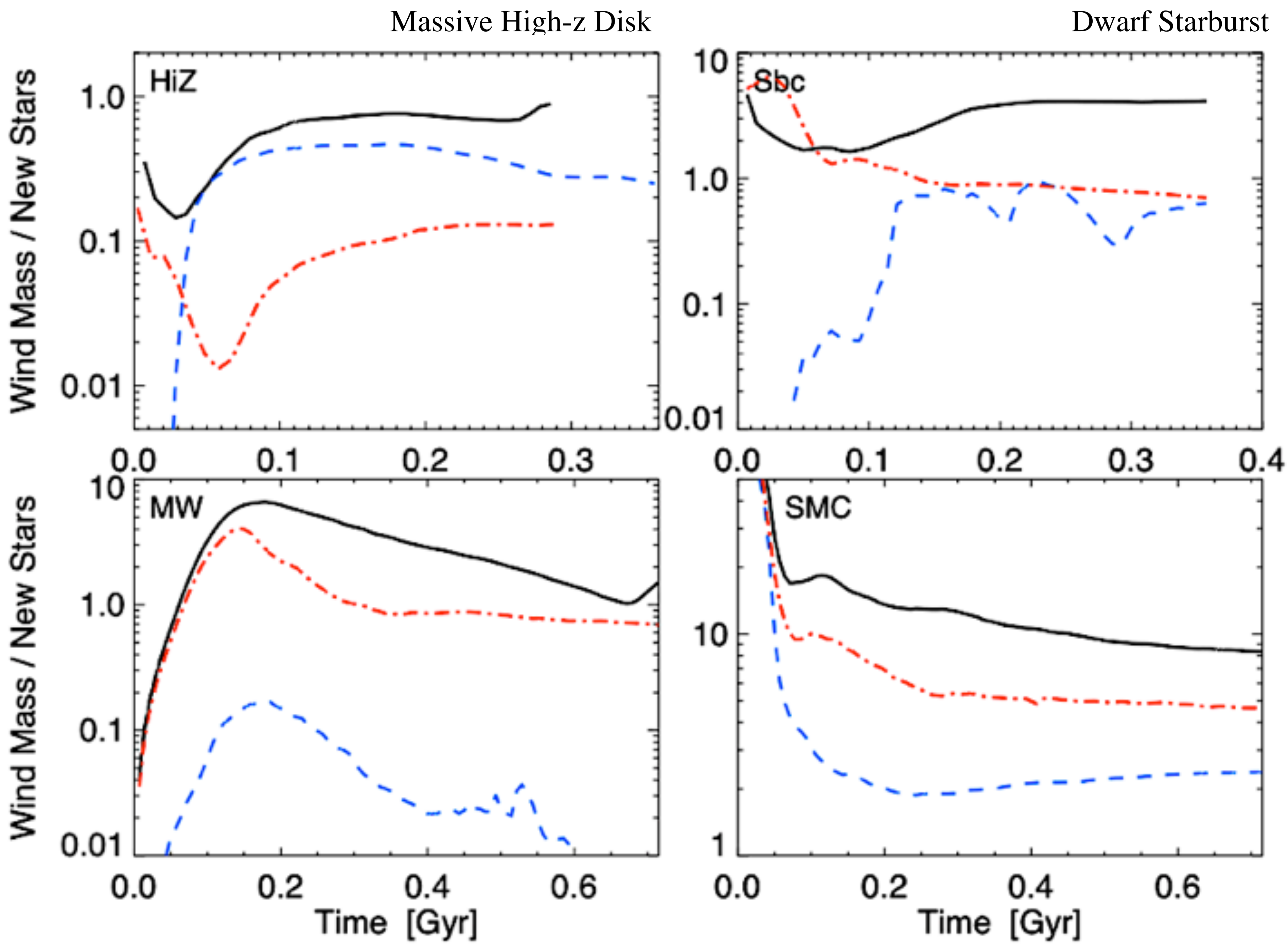

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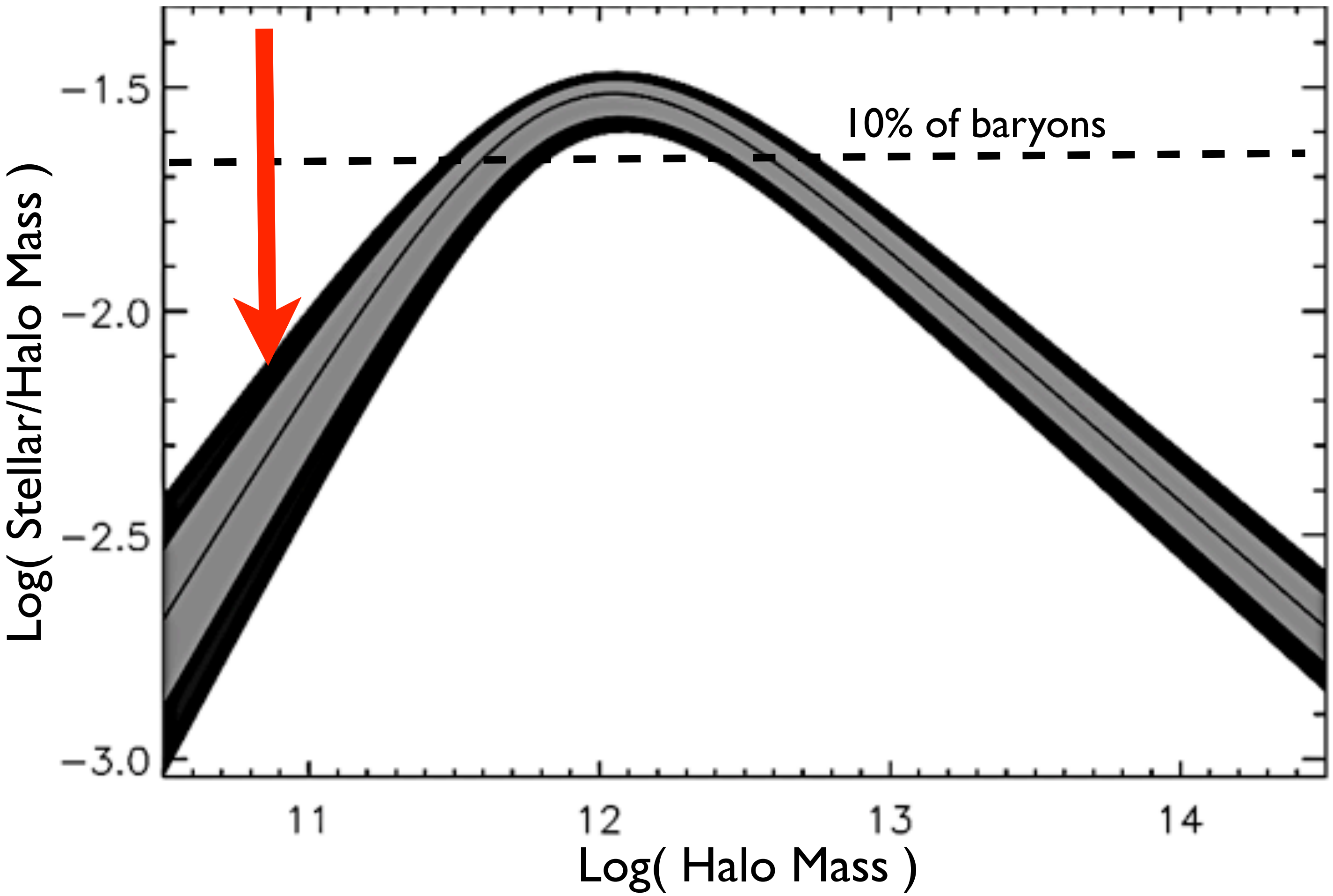
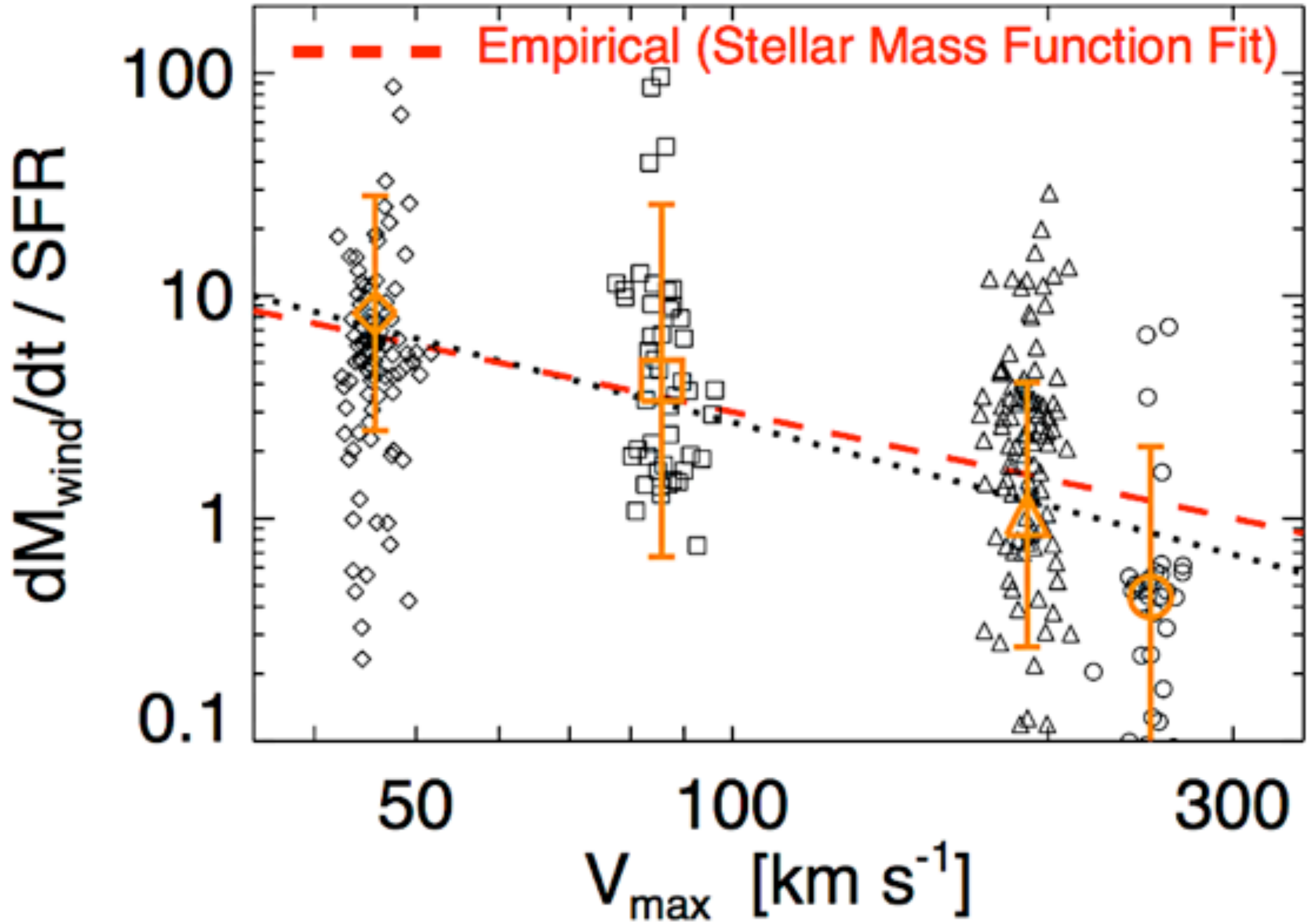


- Large mass-loading:

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



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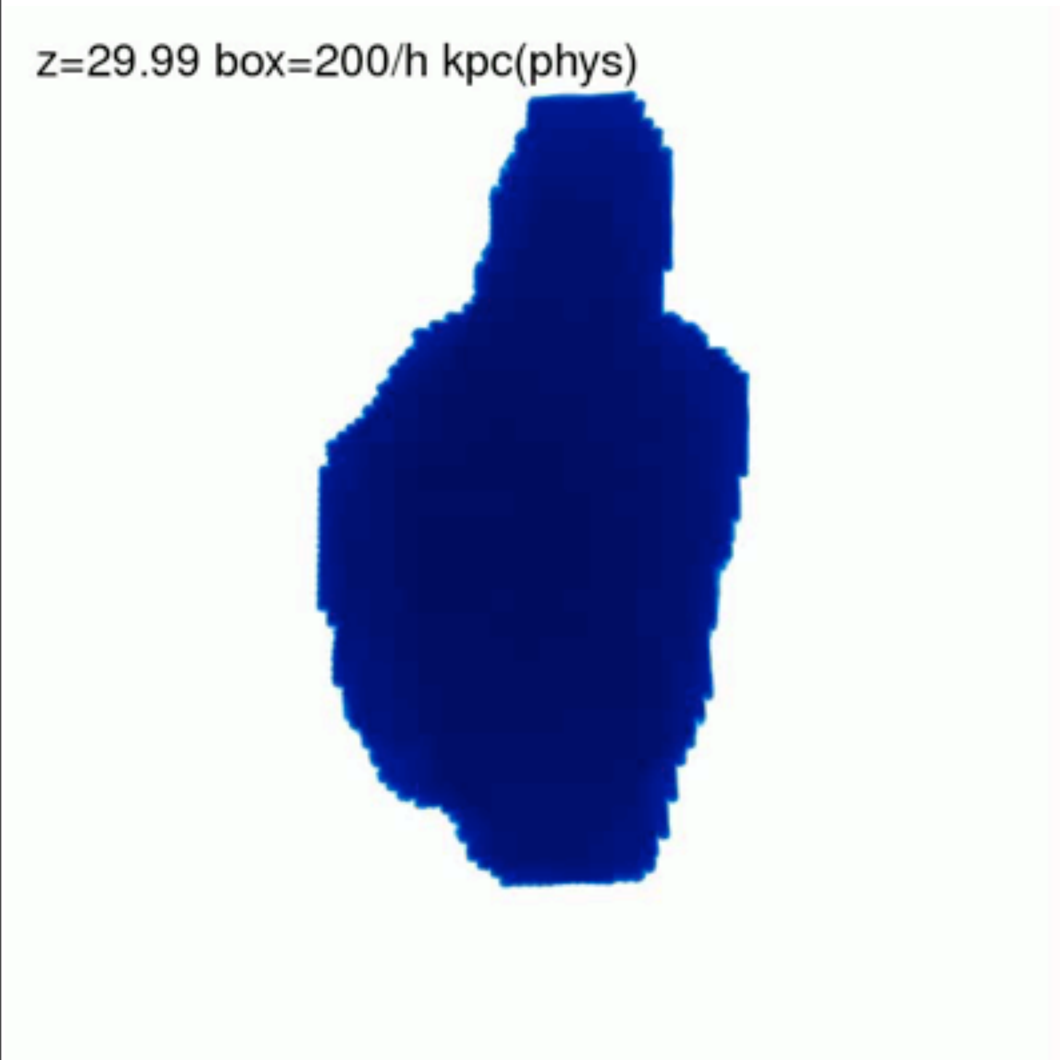
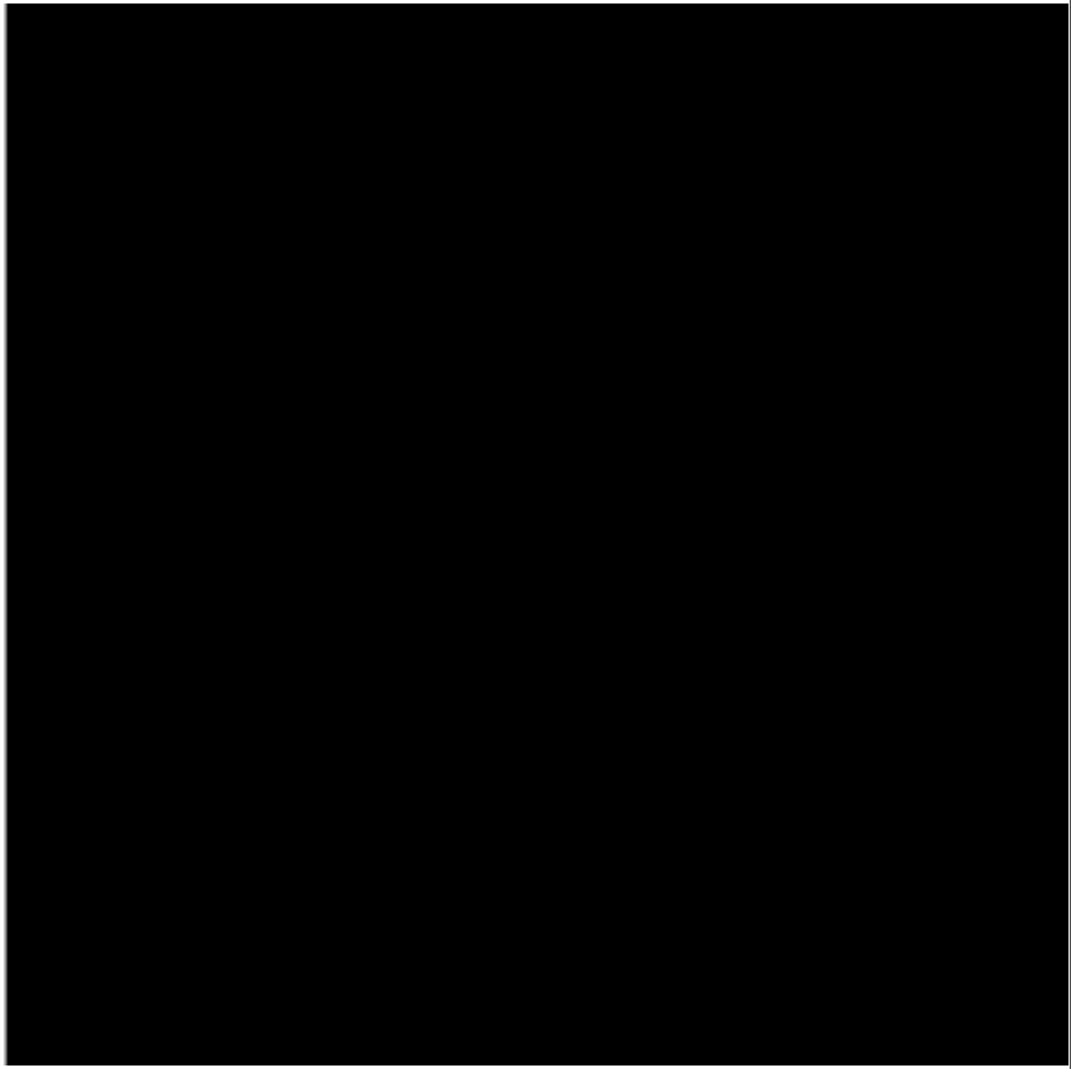
High Redshifts & The Inflow/Outflow Cycle

Cosmological Simulations

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



IGM Density

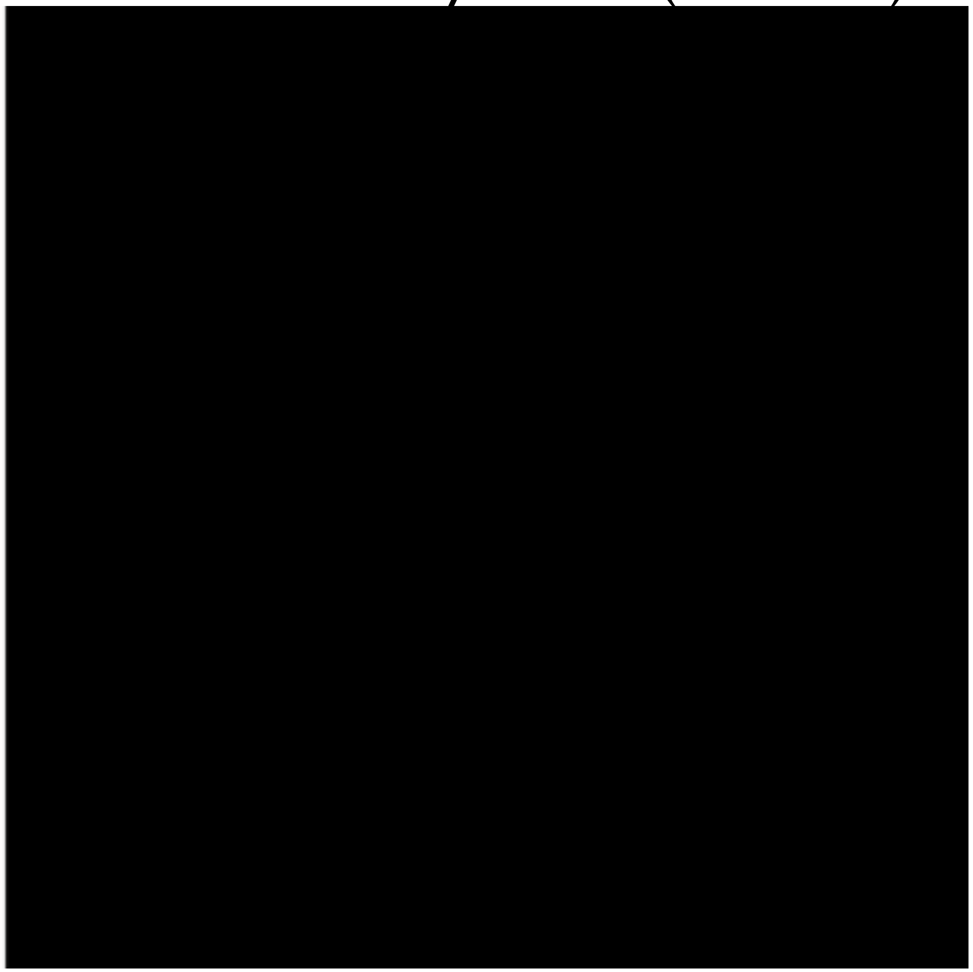


IGM Temperature

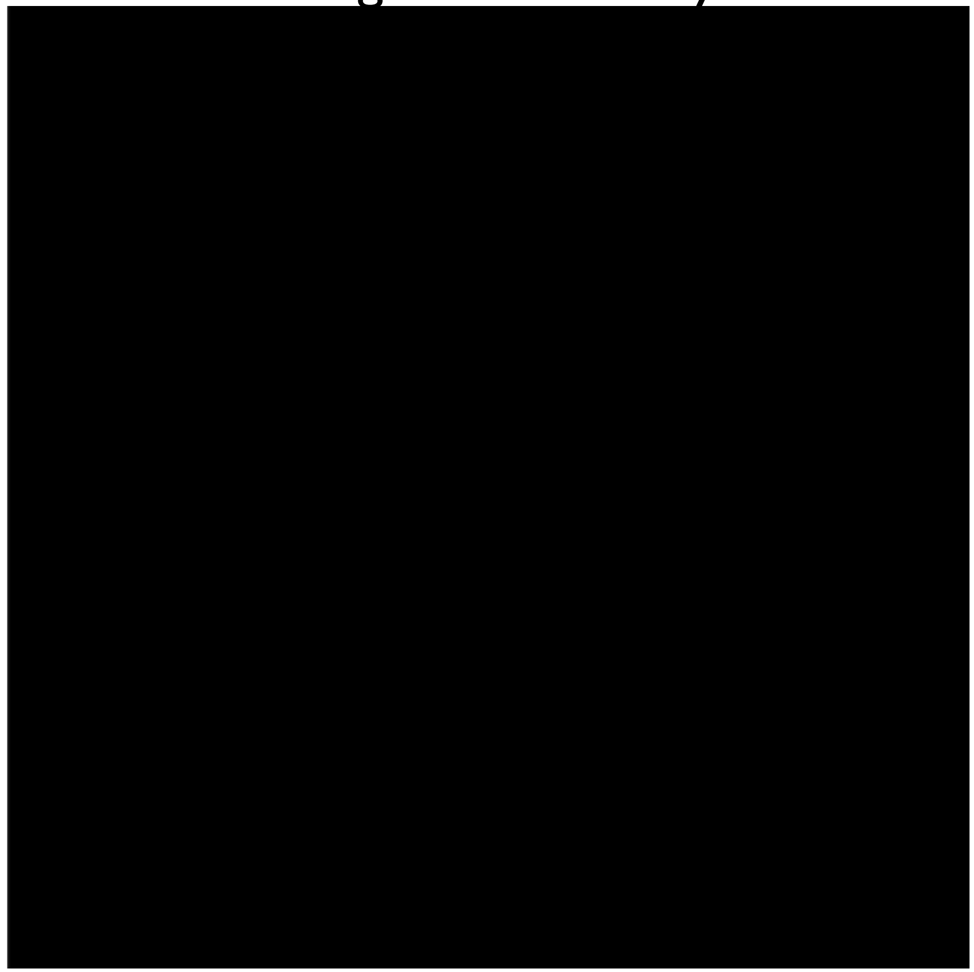
PFH & Keres et al

Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)



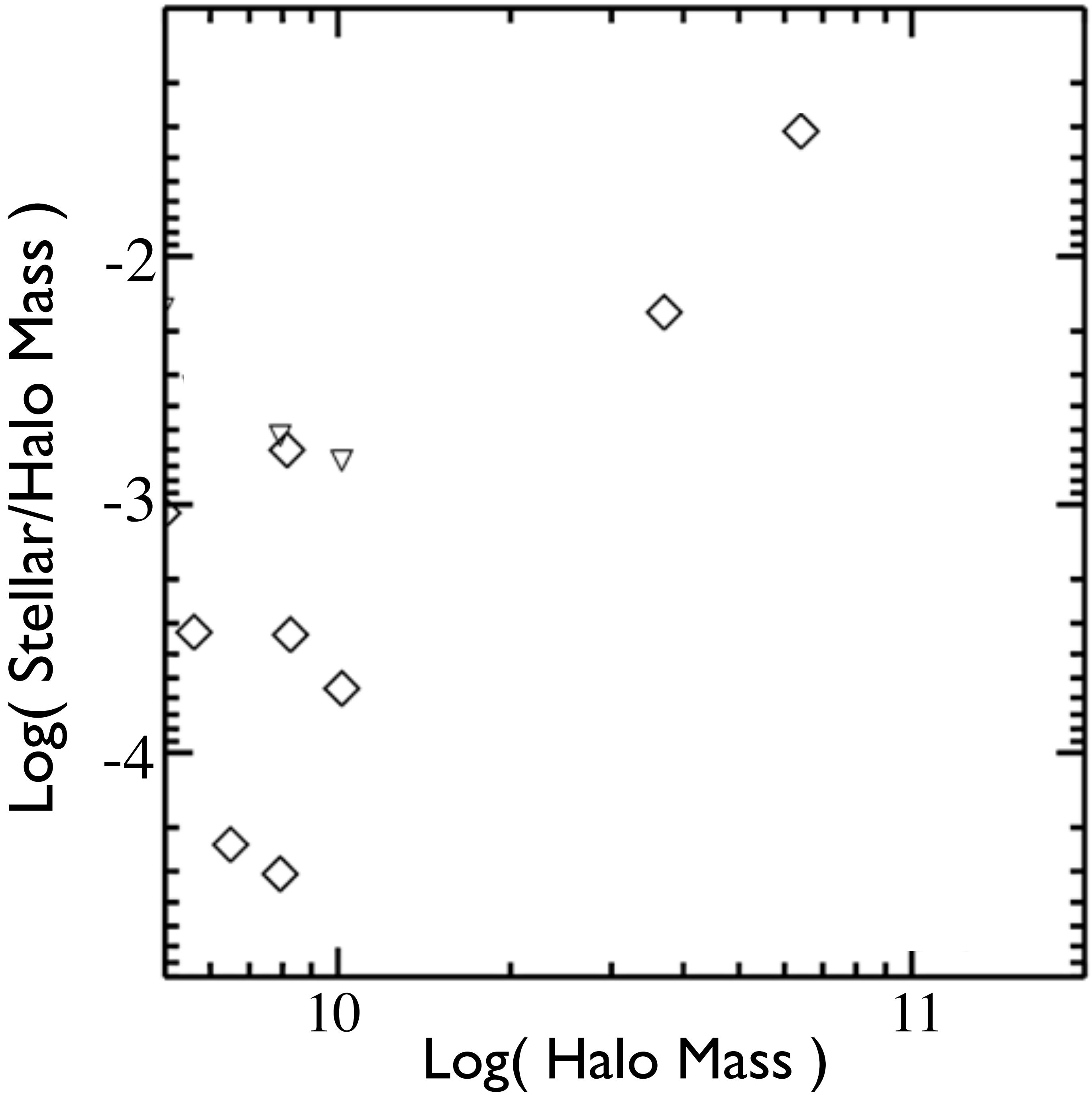
Following Feedback Physics



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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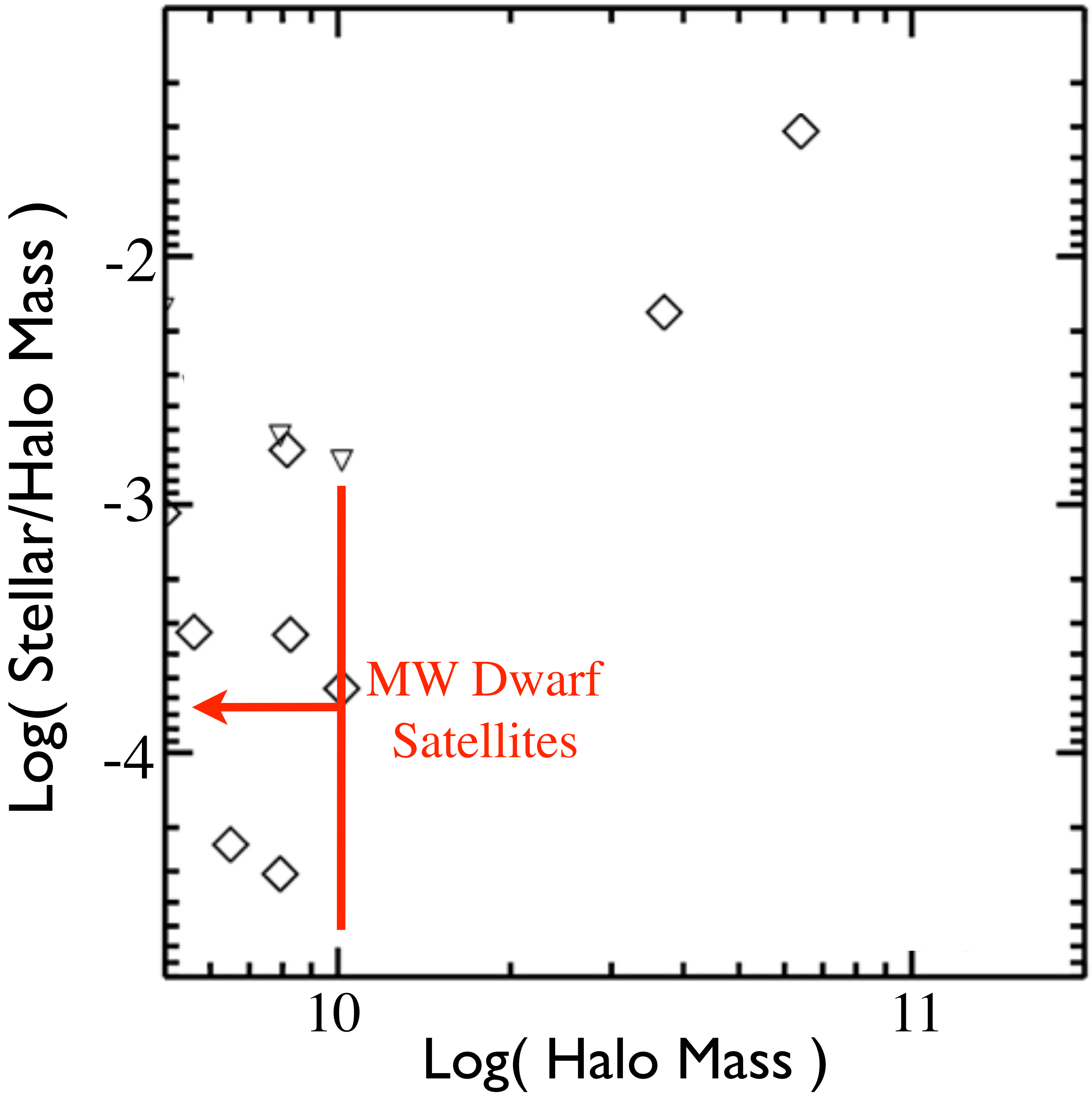

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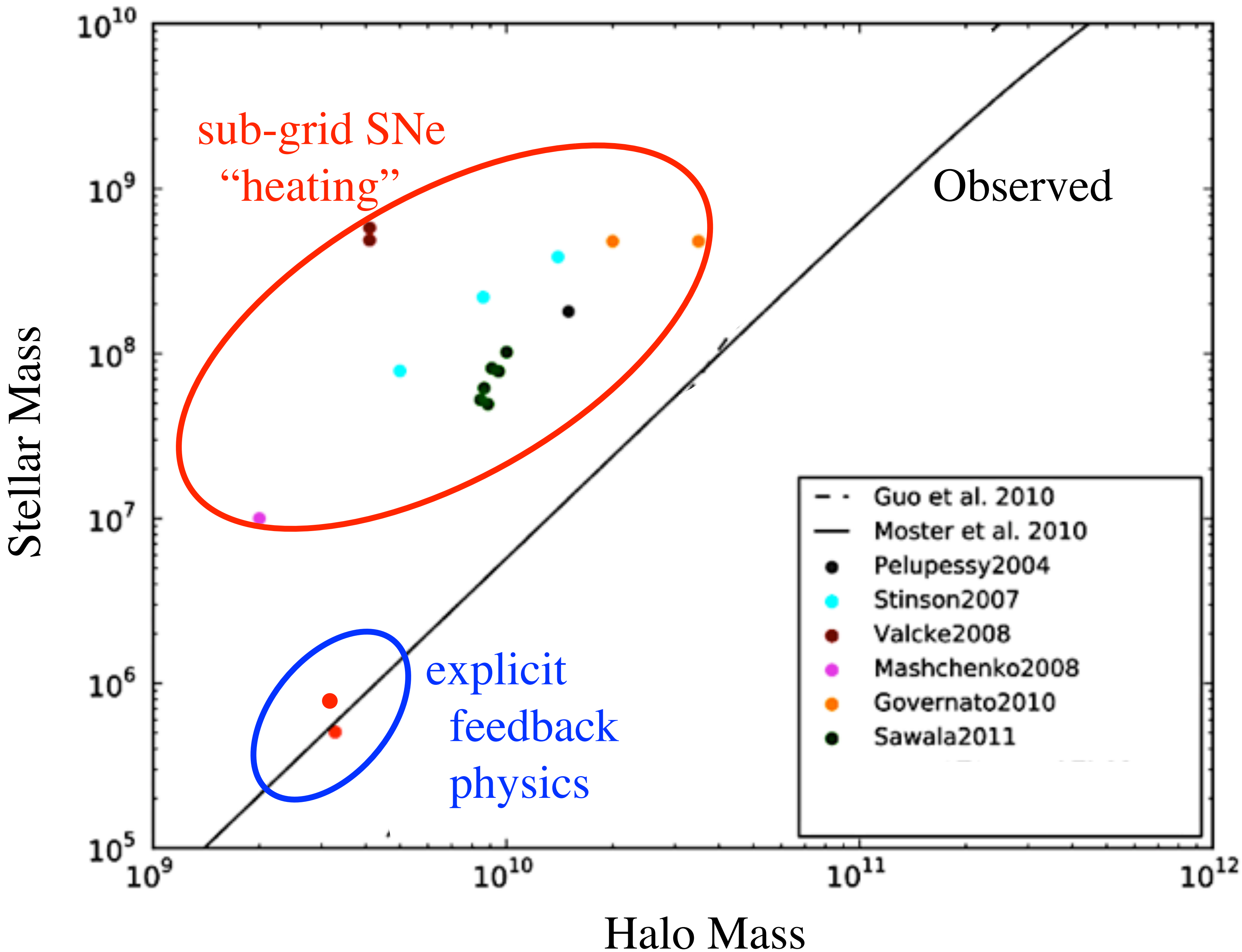

PFH & Keres et a

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Dark Matter Profiles: Baryons or Cosmology?

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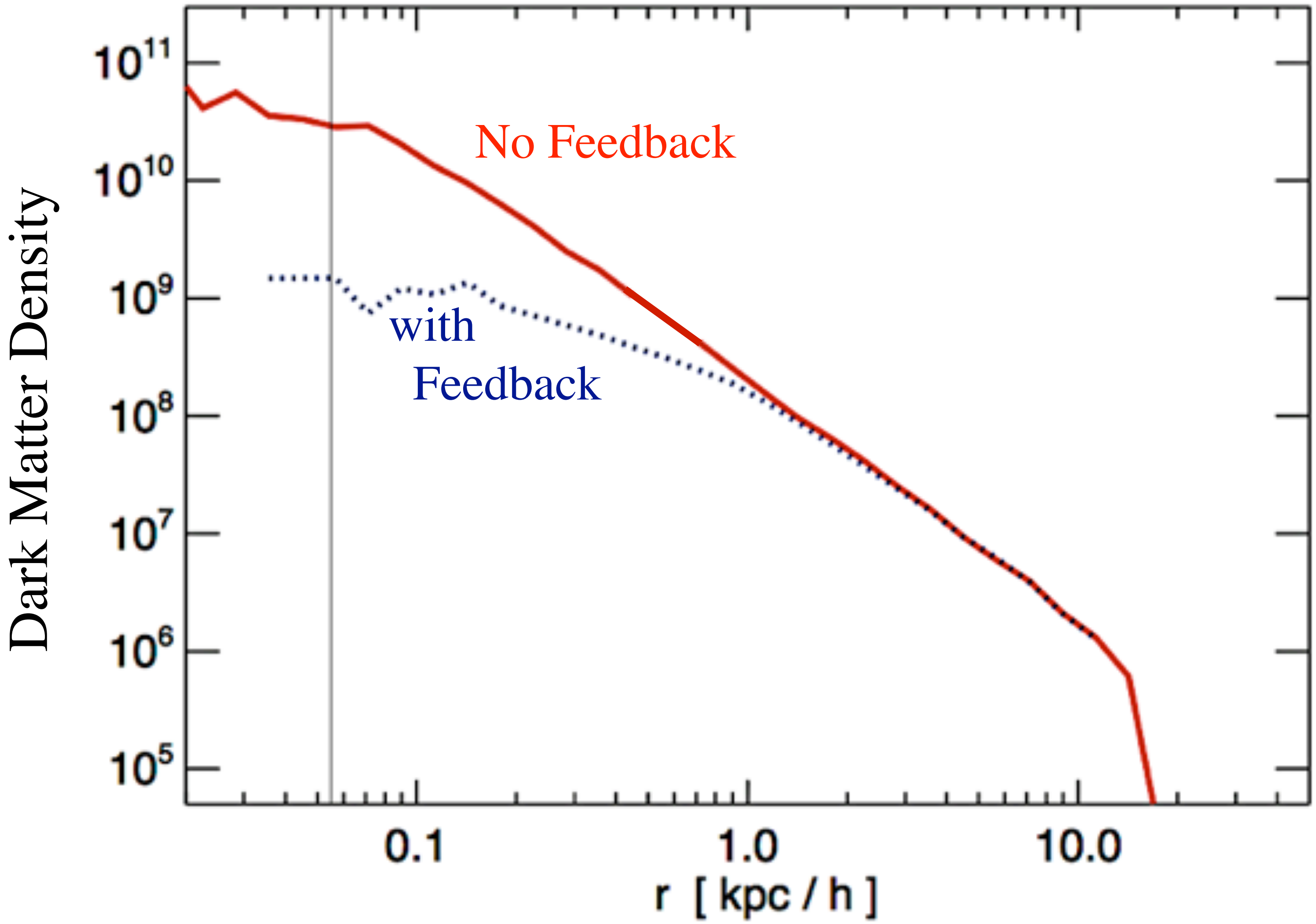
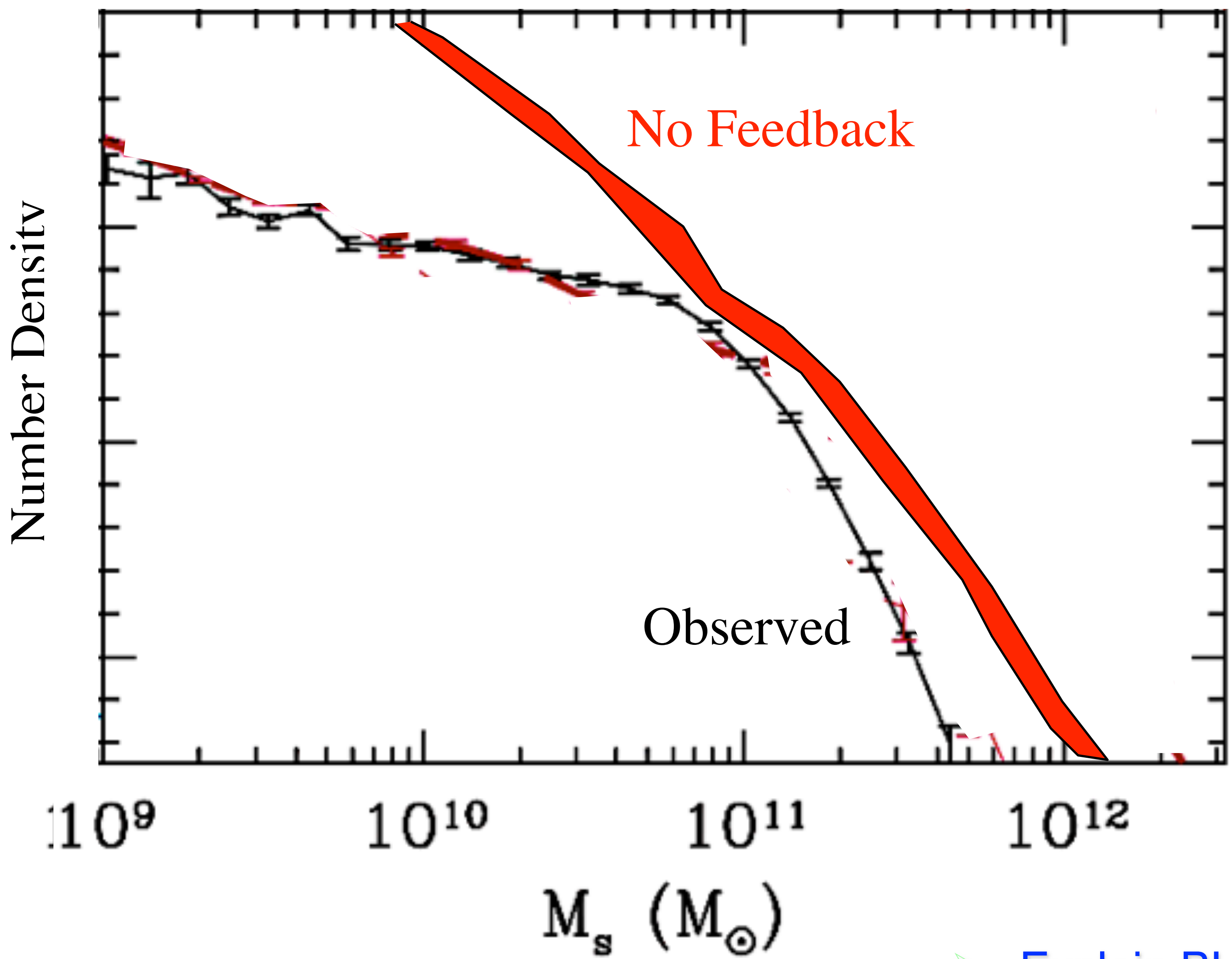


PFH & Keres et a

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

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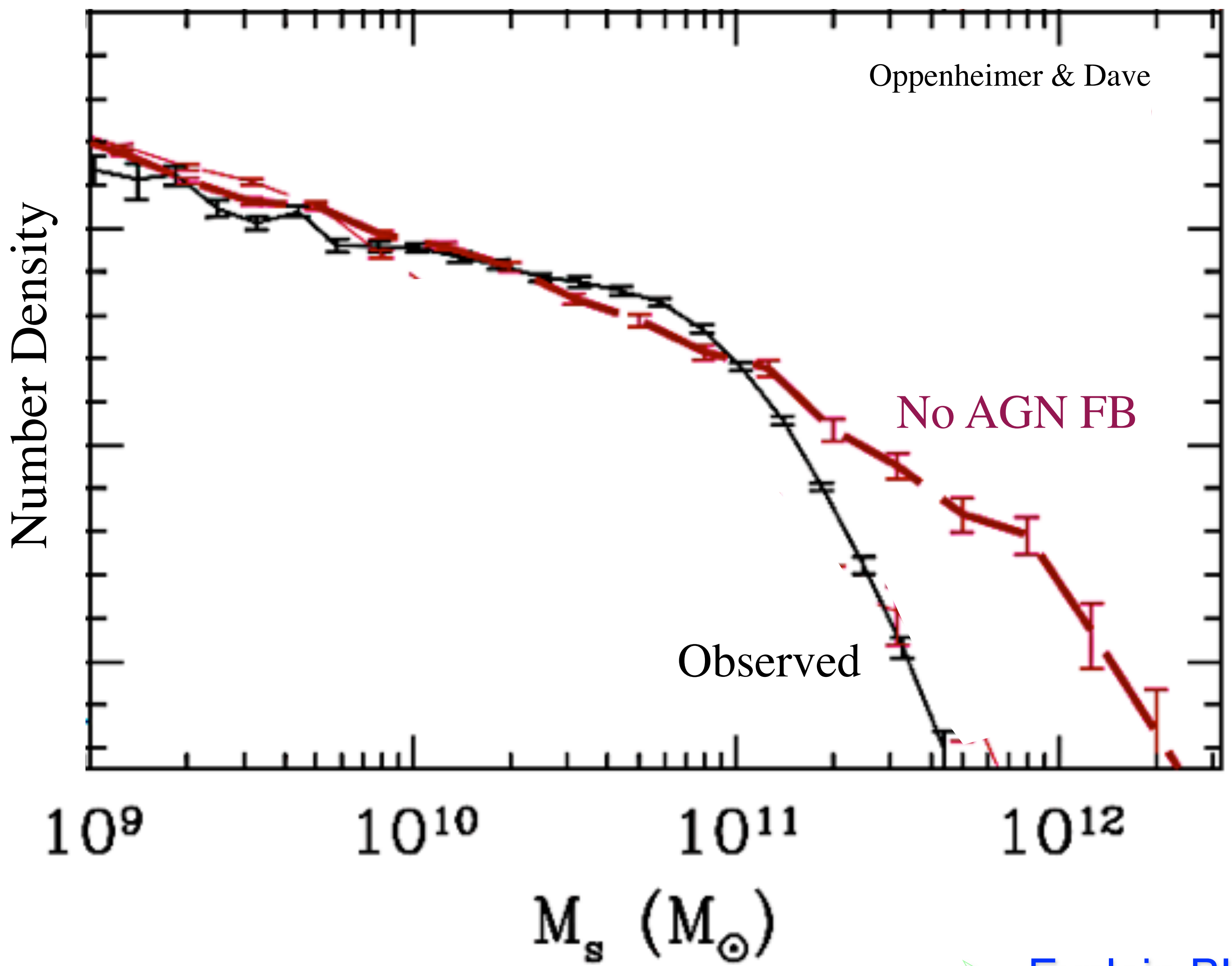

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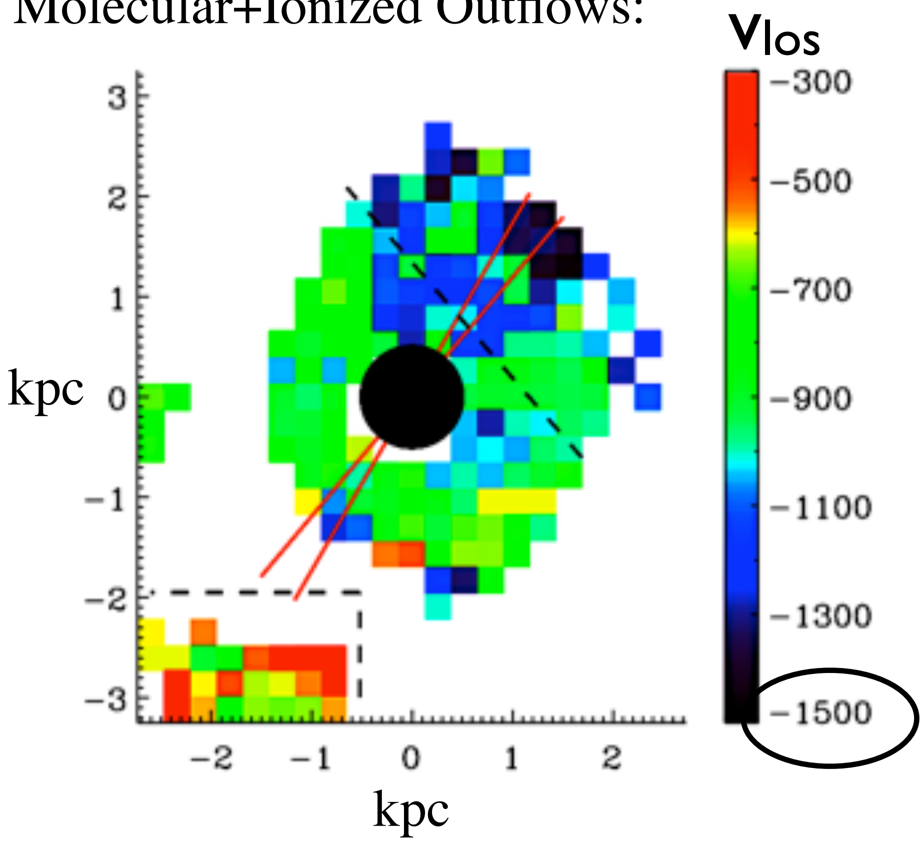
Molecular Outflows in AGN

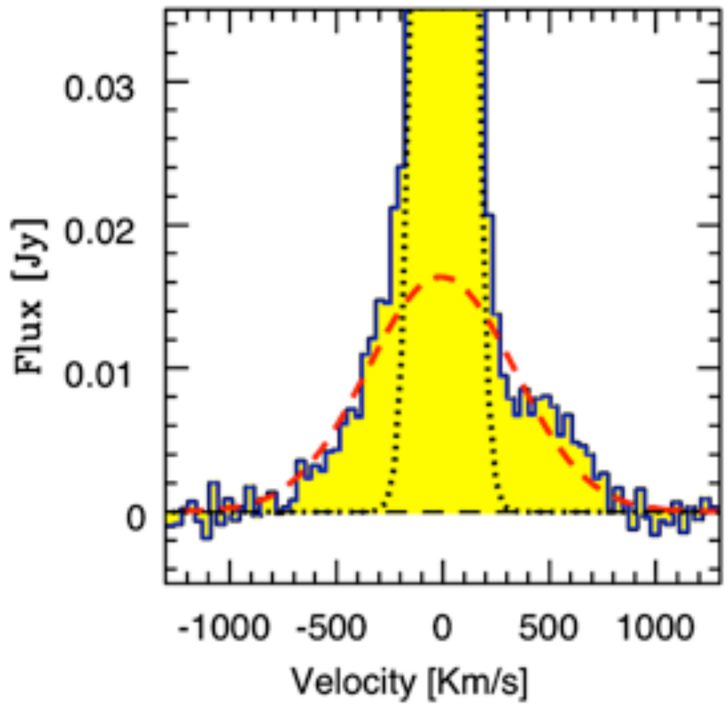
OBSERVED WINDS at >1000 km/s

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:



CO:



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

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

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

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

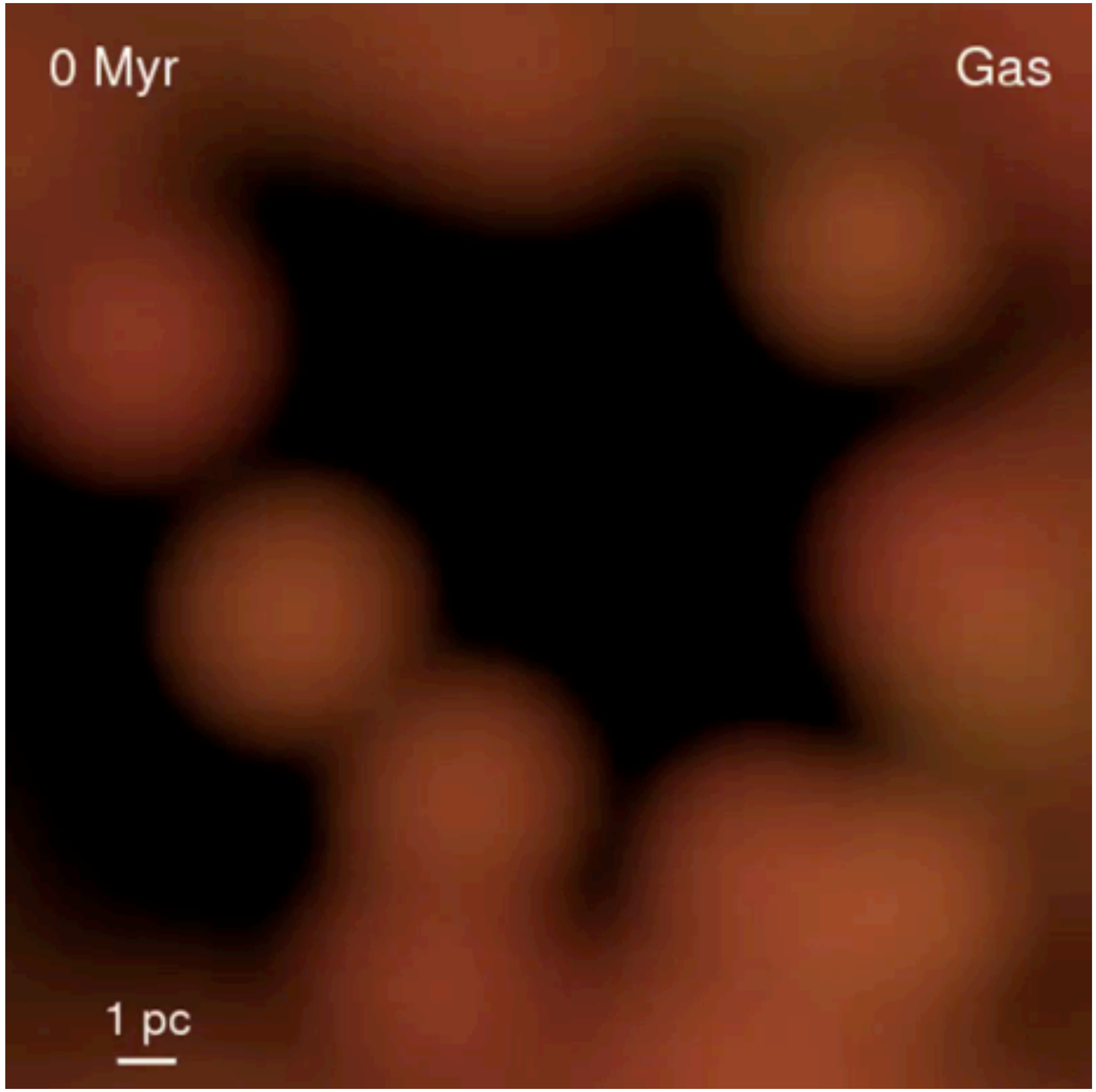
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

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

  - Stellar Winds

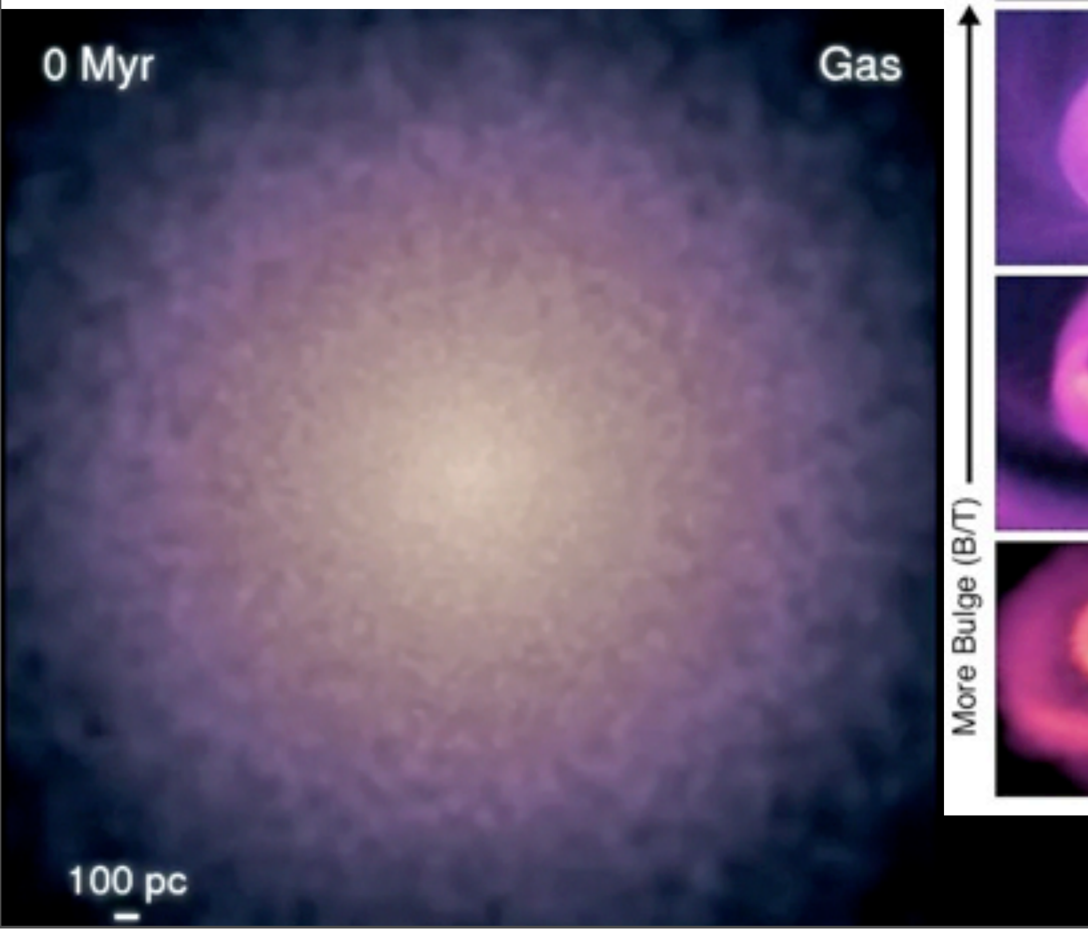
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$

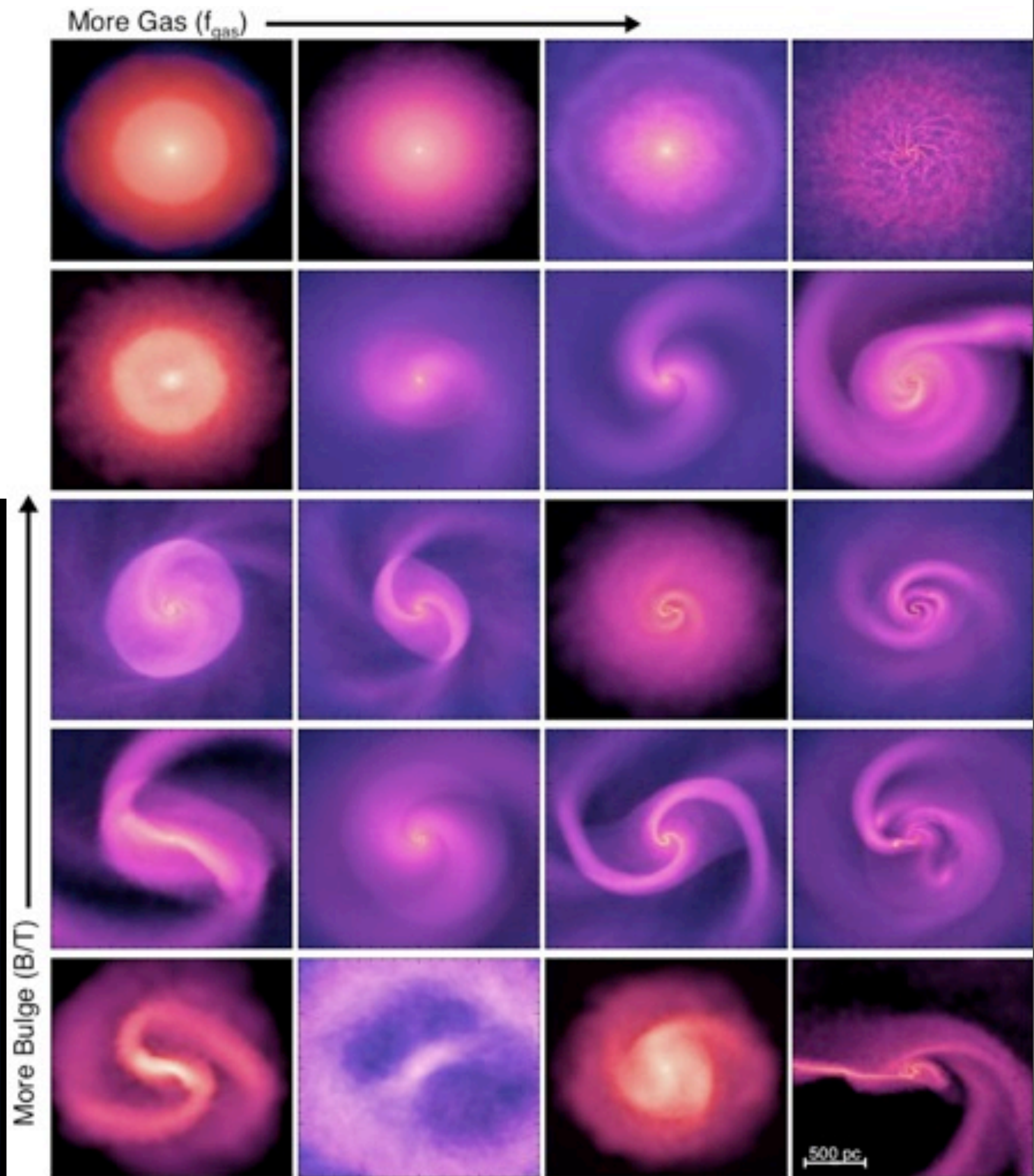


Step 2: Inflow

- 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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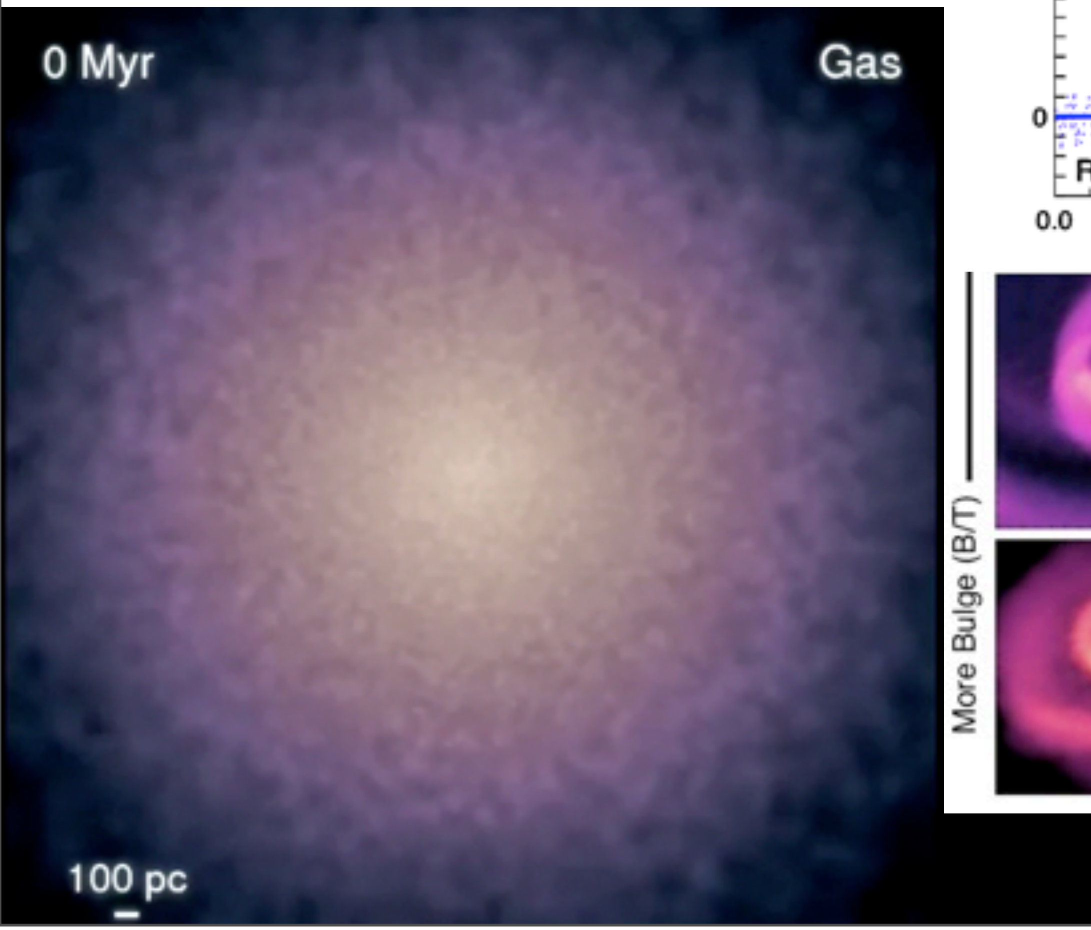
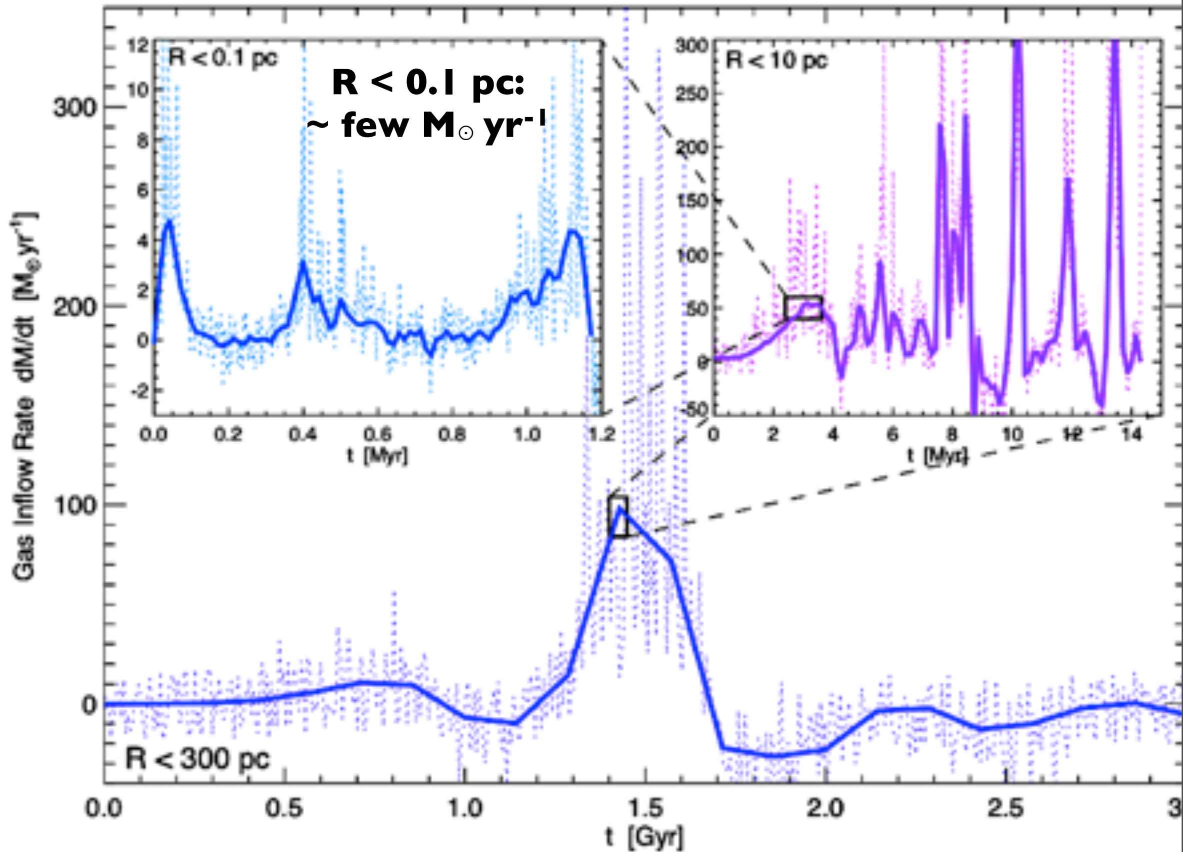
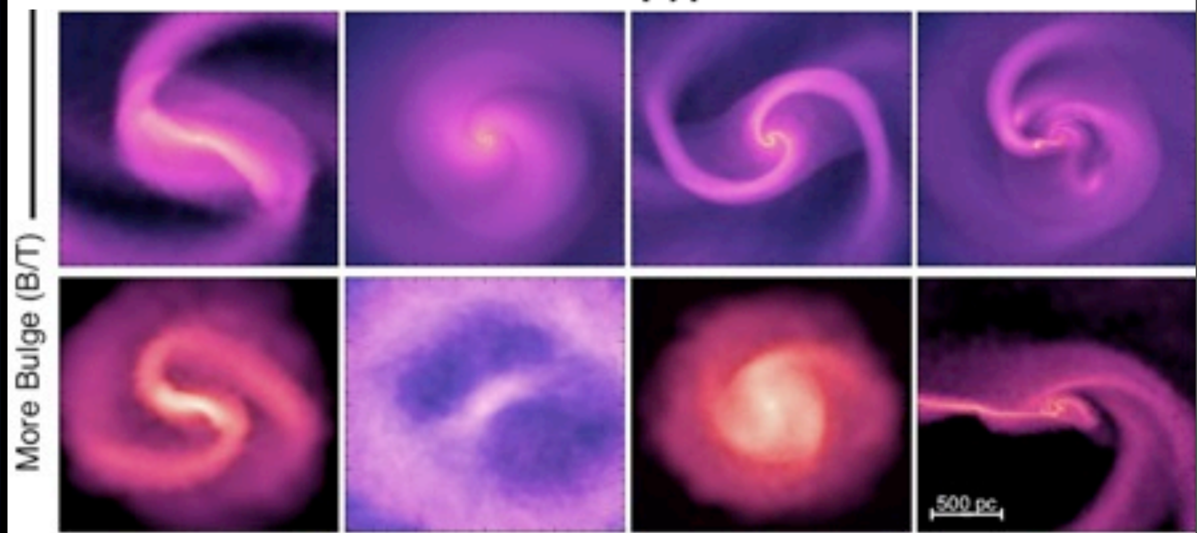
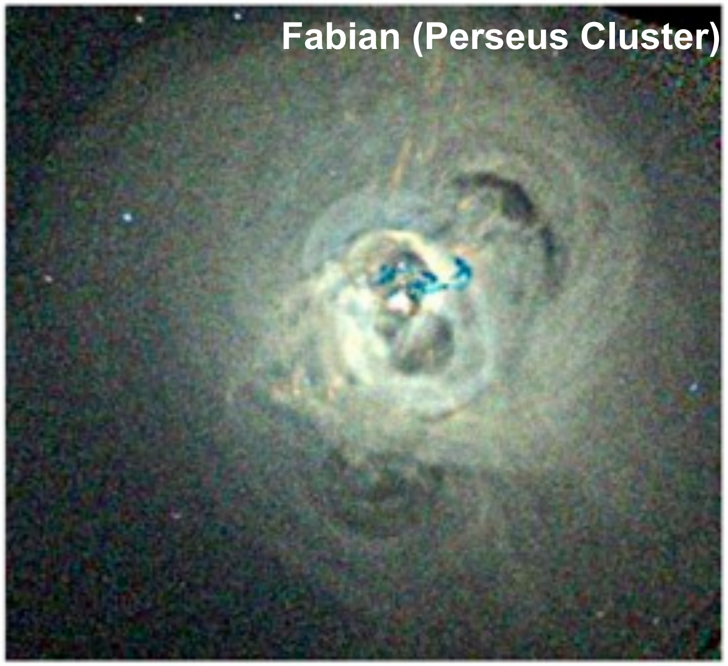






Step 3: Observed Sources of AGN Feedback



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

Step 3: Observed Sources of AGN Feedback

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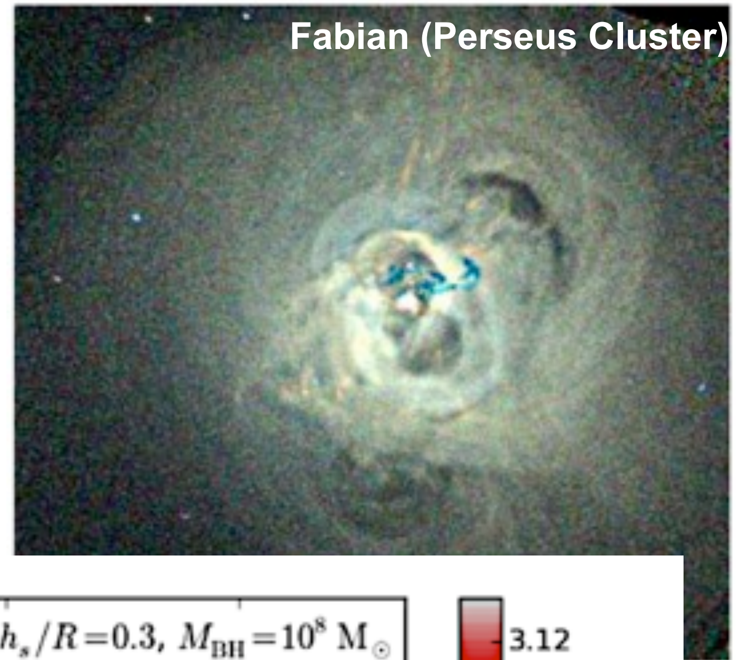
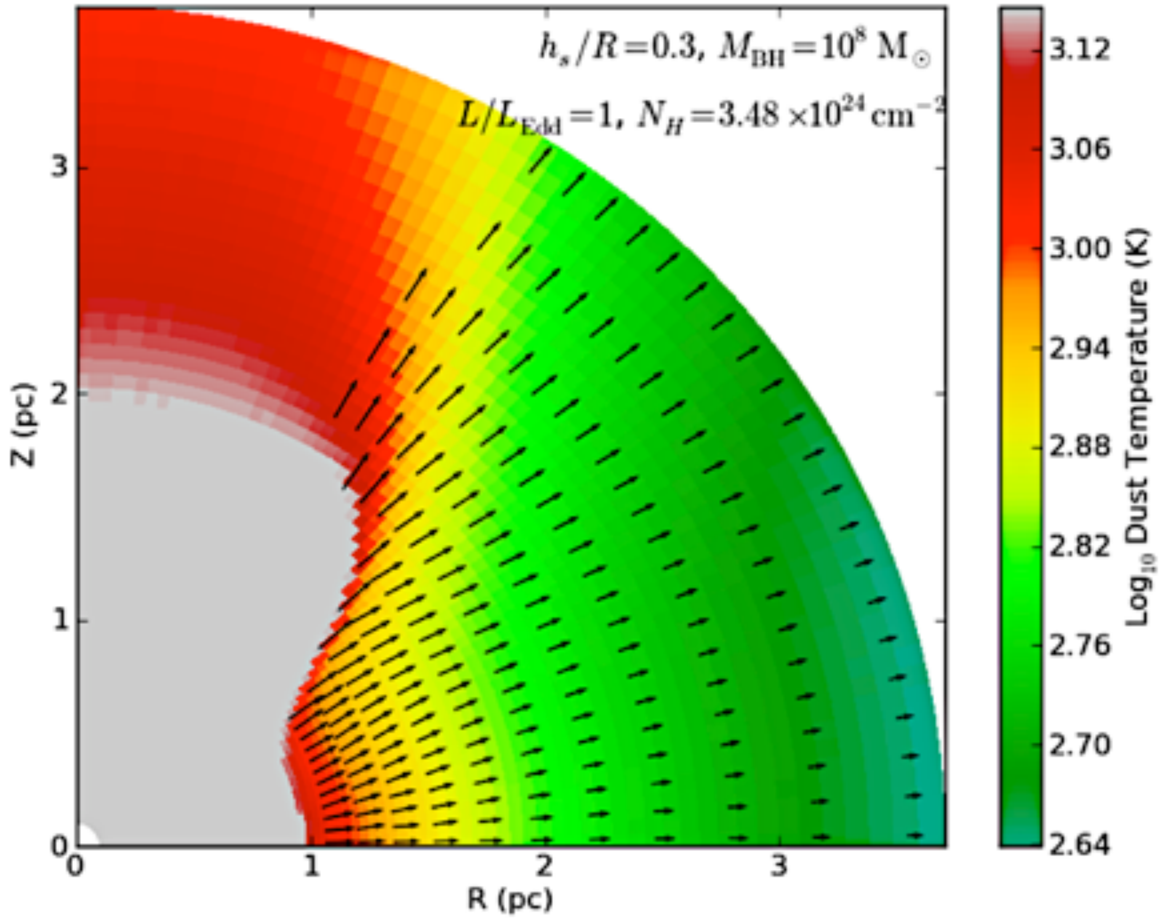
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$





Roth, Kasen, Quataert, PFH in prep

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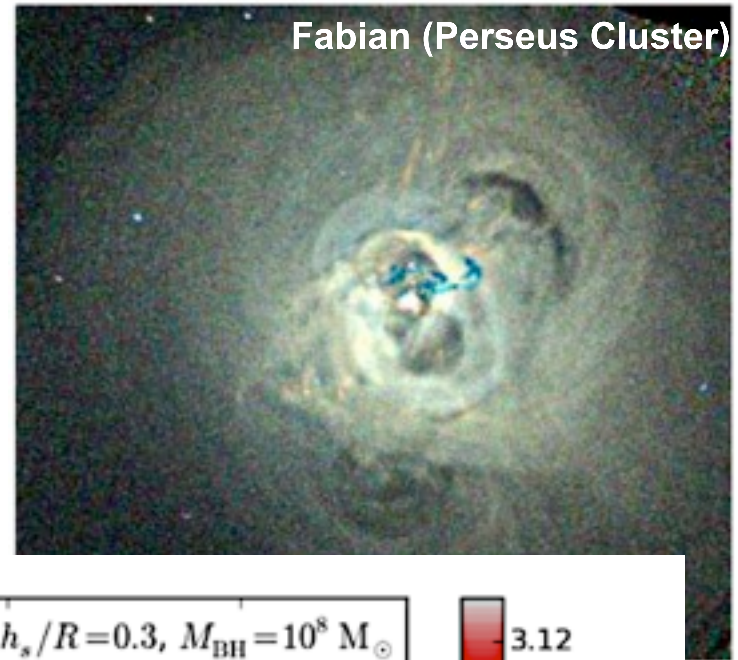
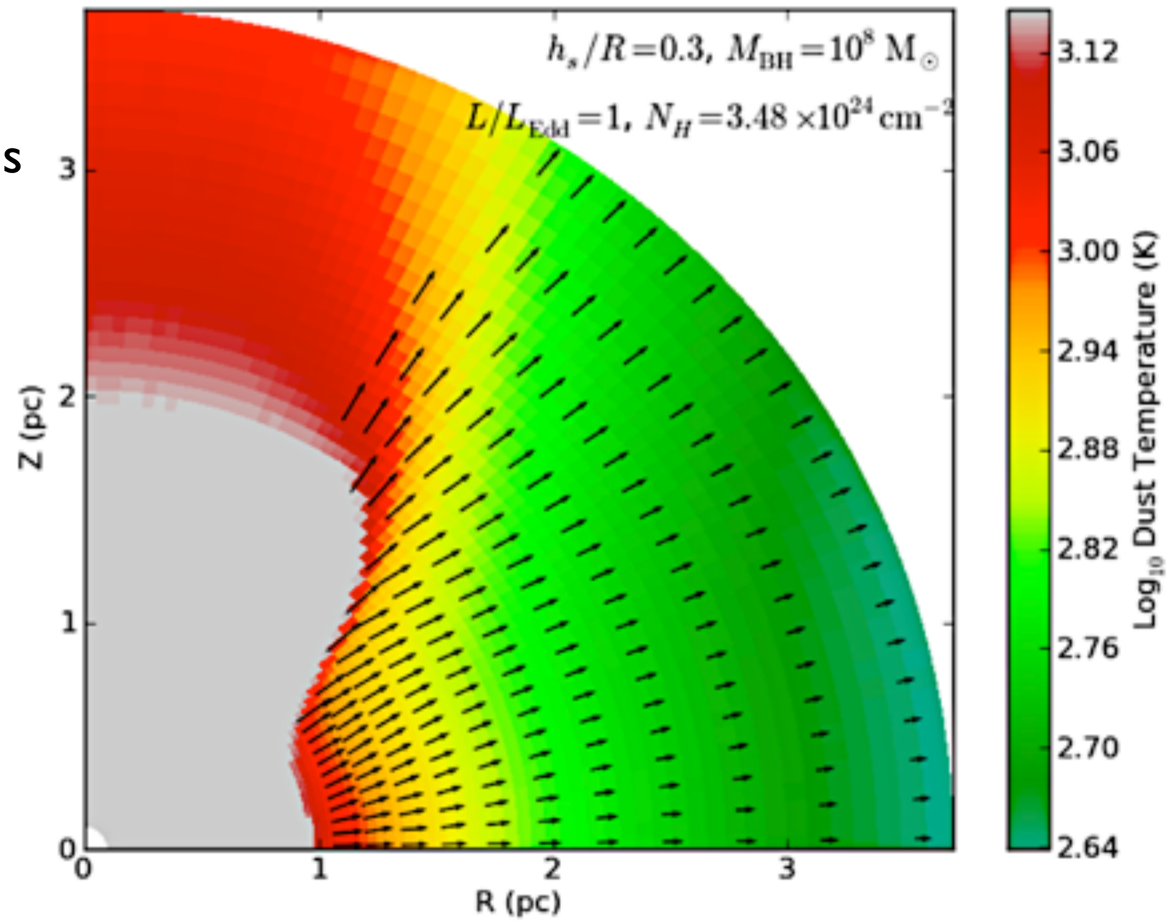


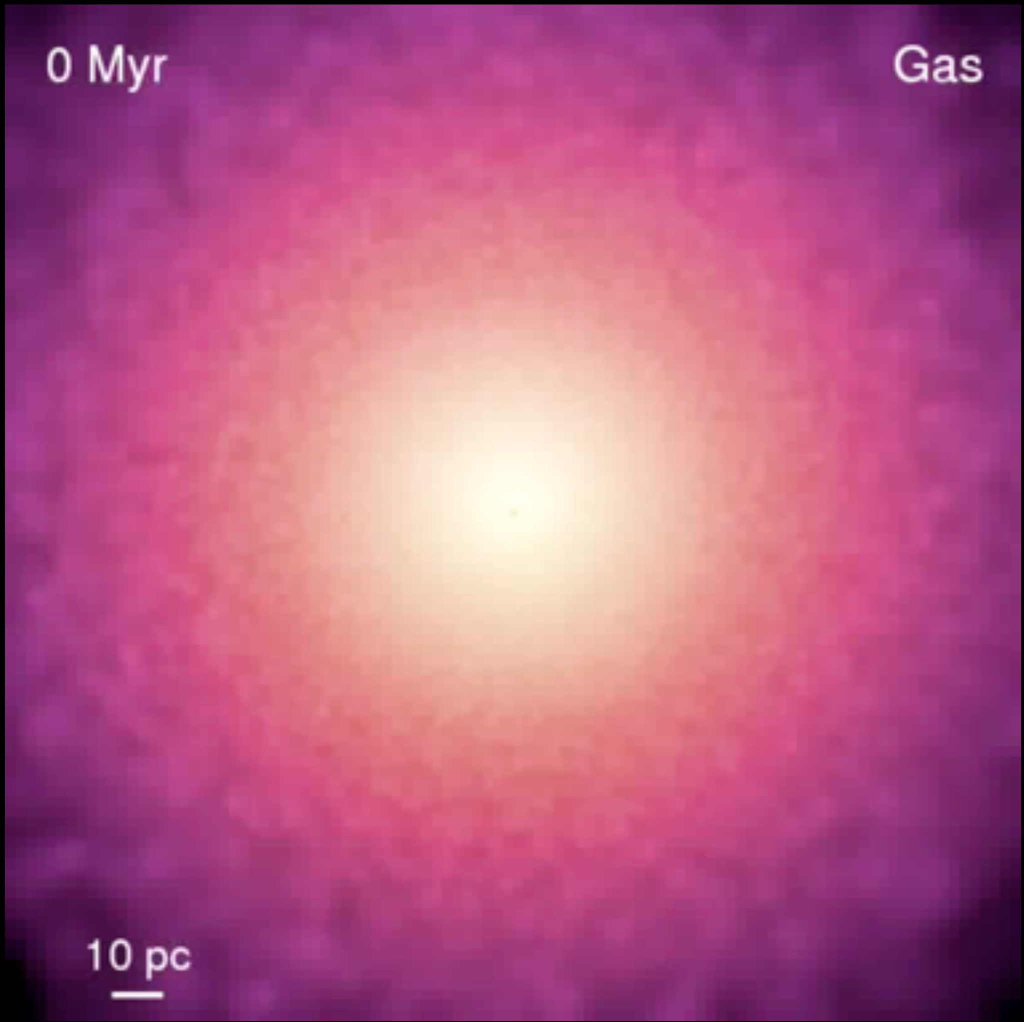
- Jets
  - heat IGM/ICM (low-density), but not dense ISM
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$
- Accretion Disk Winds
  - Broad Absorption Line Winds

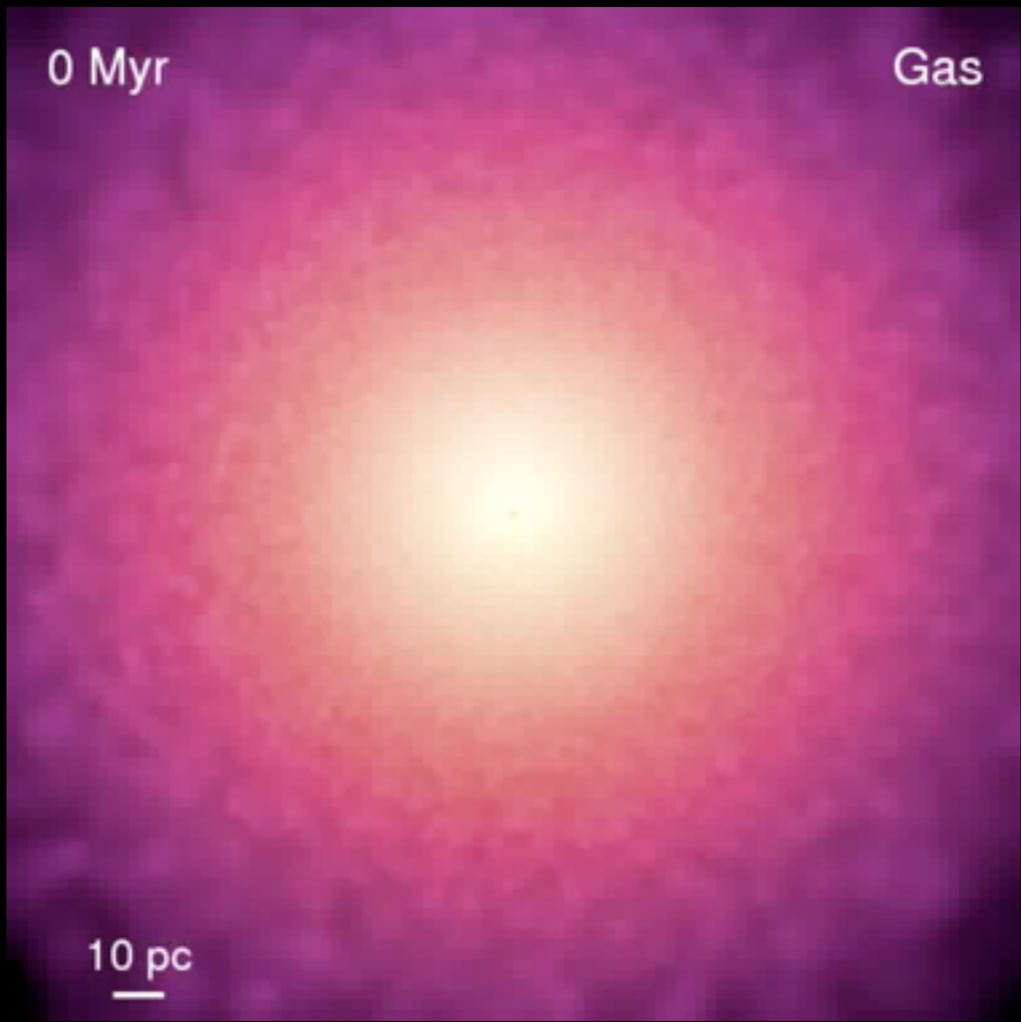


Roth, Kasen, Quataert, PFH in prep

BAL Winds on ~1pc - 1kpc scales:

PFH in prep
Wada et al.





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

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

Summary:

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