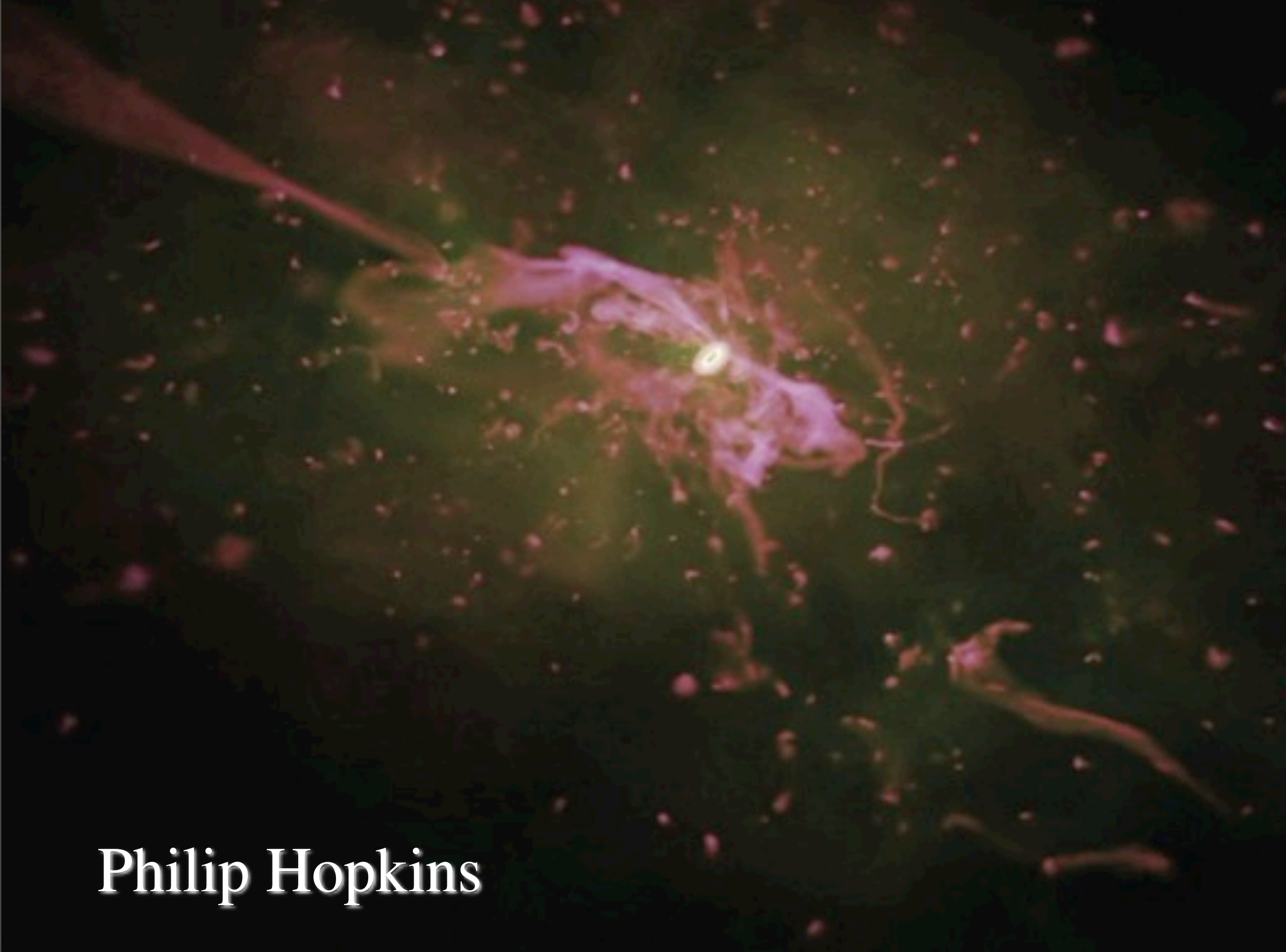
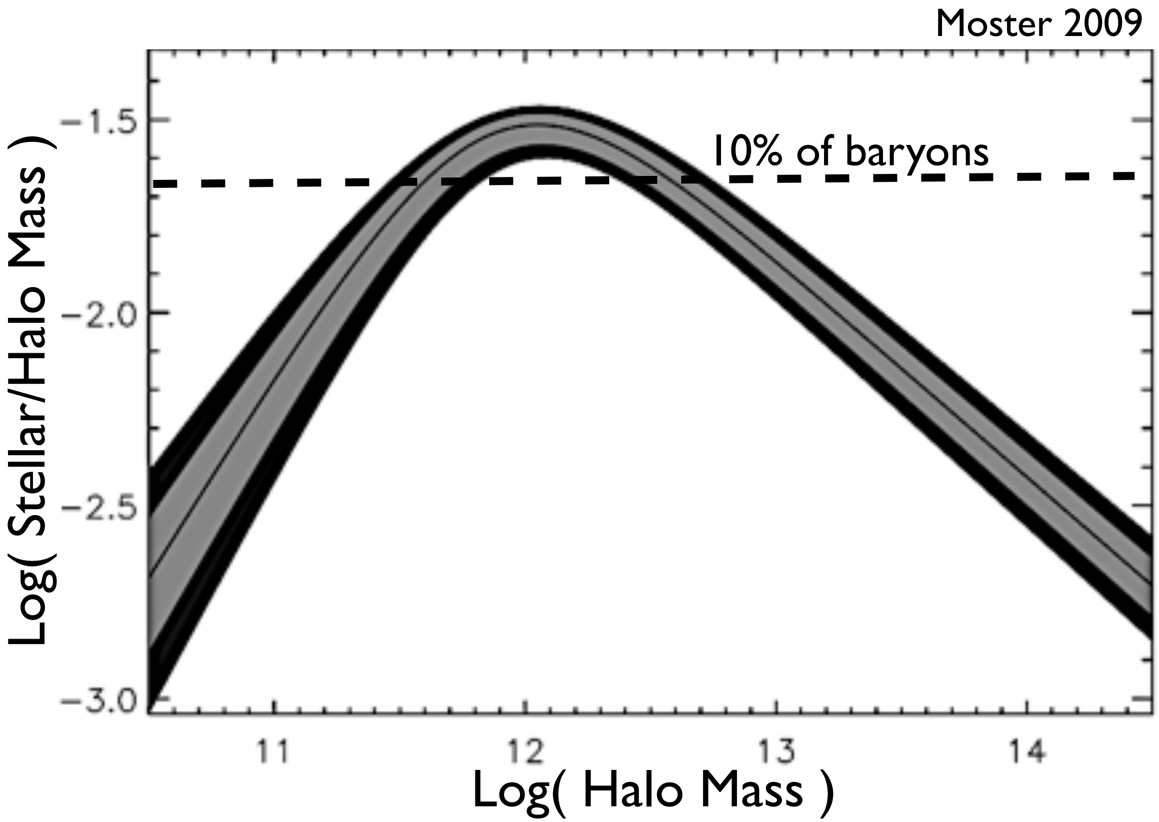
Feedback-Regulated Star Formation on Galactic Scales

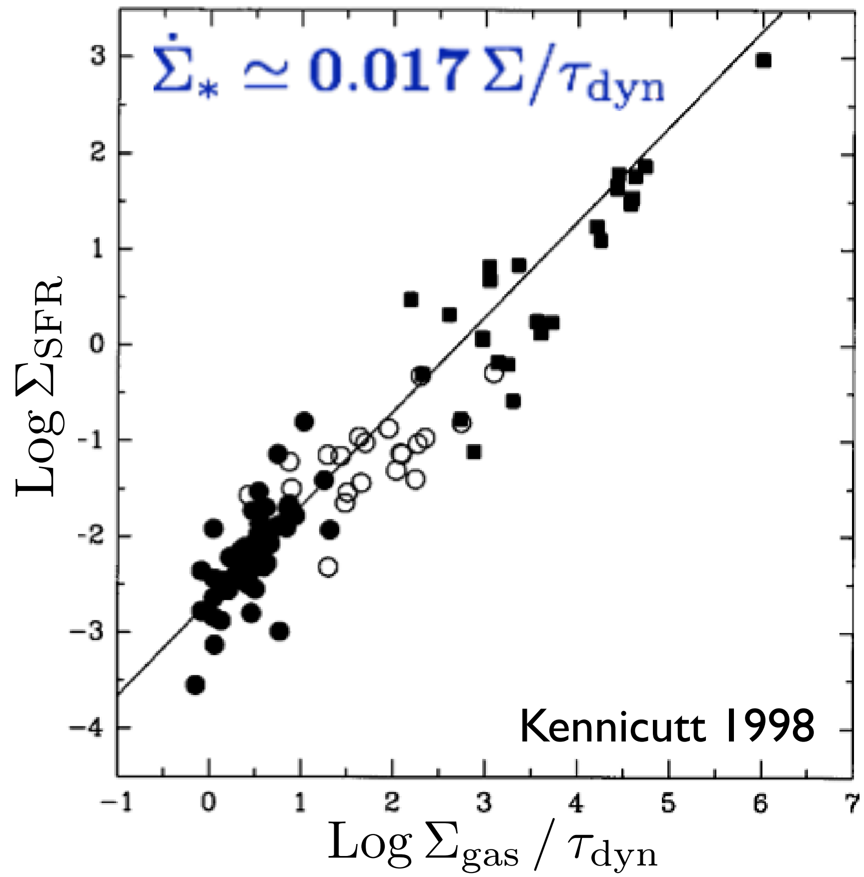


Philip Hopkins

Norm Murray, Eliot Quataert,
Lars Hernquist, Todd Thompson, Dusan Keres, Chris Hayward, Stijn Wuyts,
Kevin Bundy, Desika Narayanan, Ryan Hickox, Rachel Somerville, & more

Q: WHY IS STAR FORMATION SO INEFFICIENT?





A: Stellar Feedback!
SO WHAT'S THE PROBLEM?

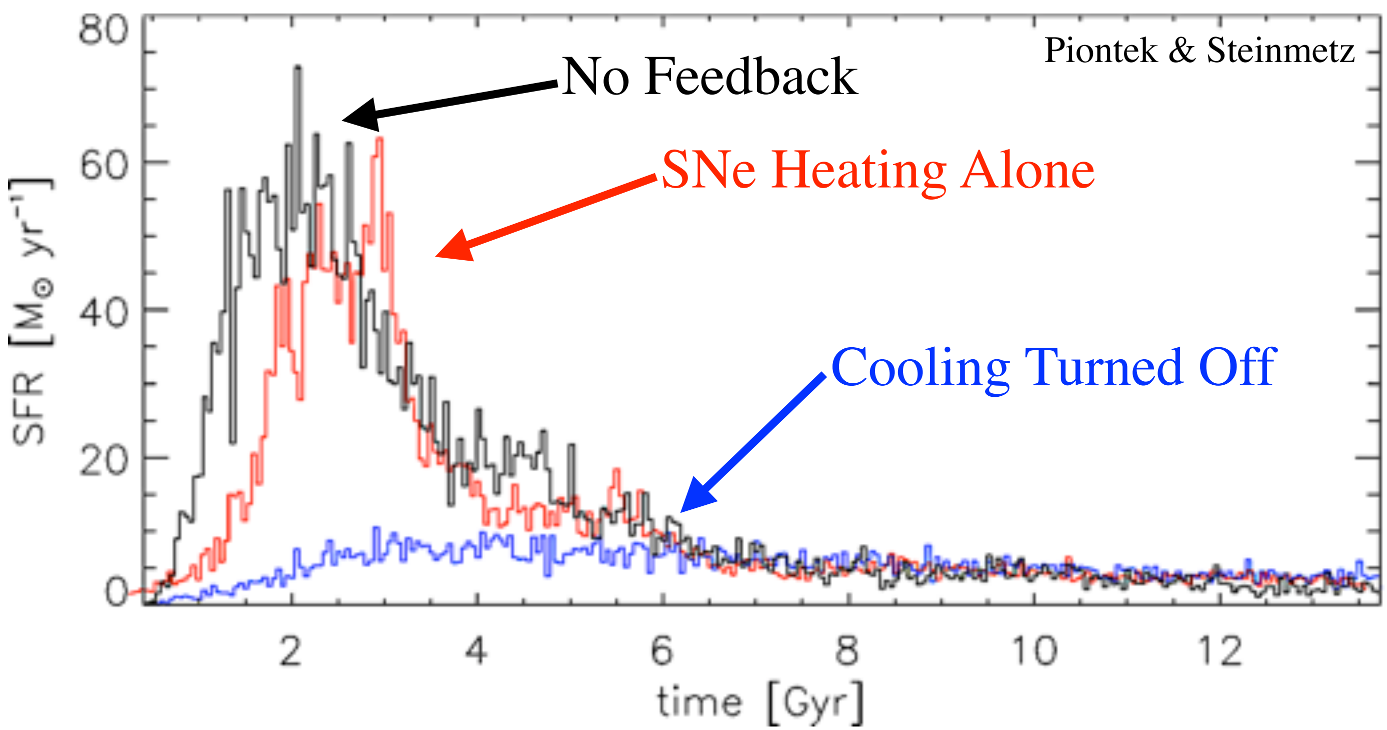
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- 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

Stellar Feedback: How Can We Do Better?

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  - Photoionization (HII Regions)

Stellar Feedback: How Can We Do Better?

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

- *Explicit* Momentum Flux:
  - Radiation Pressure

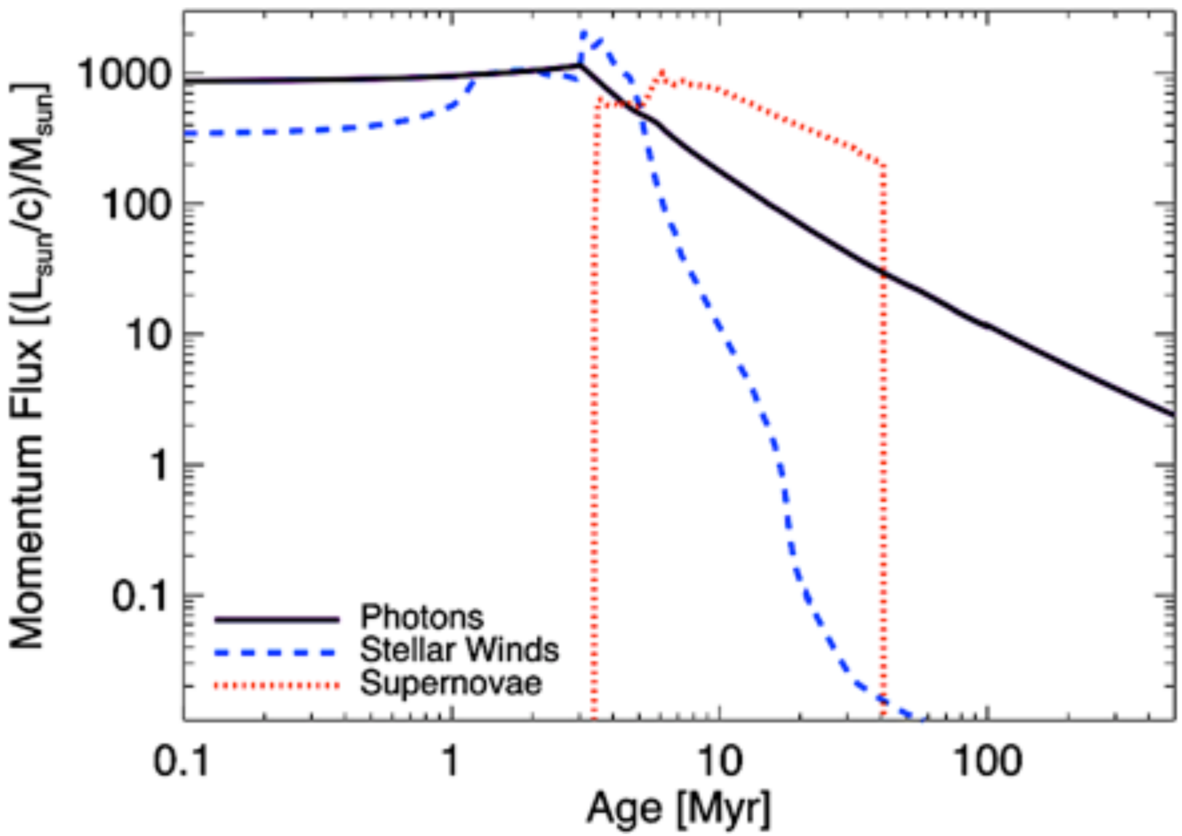
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

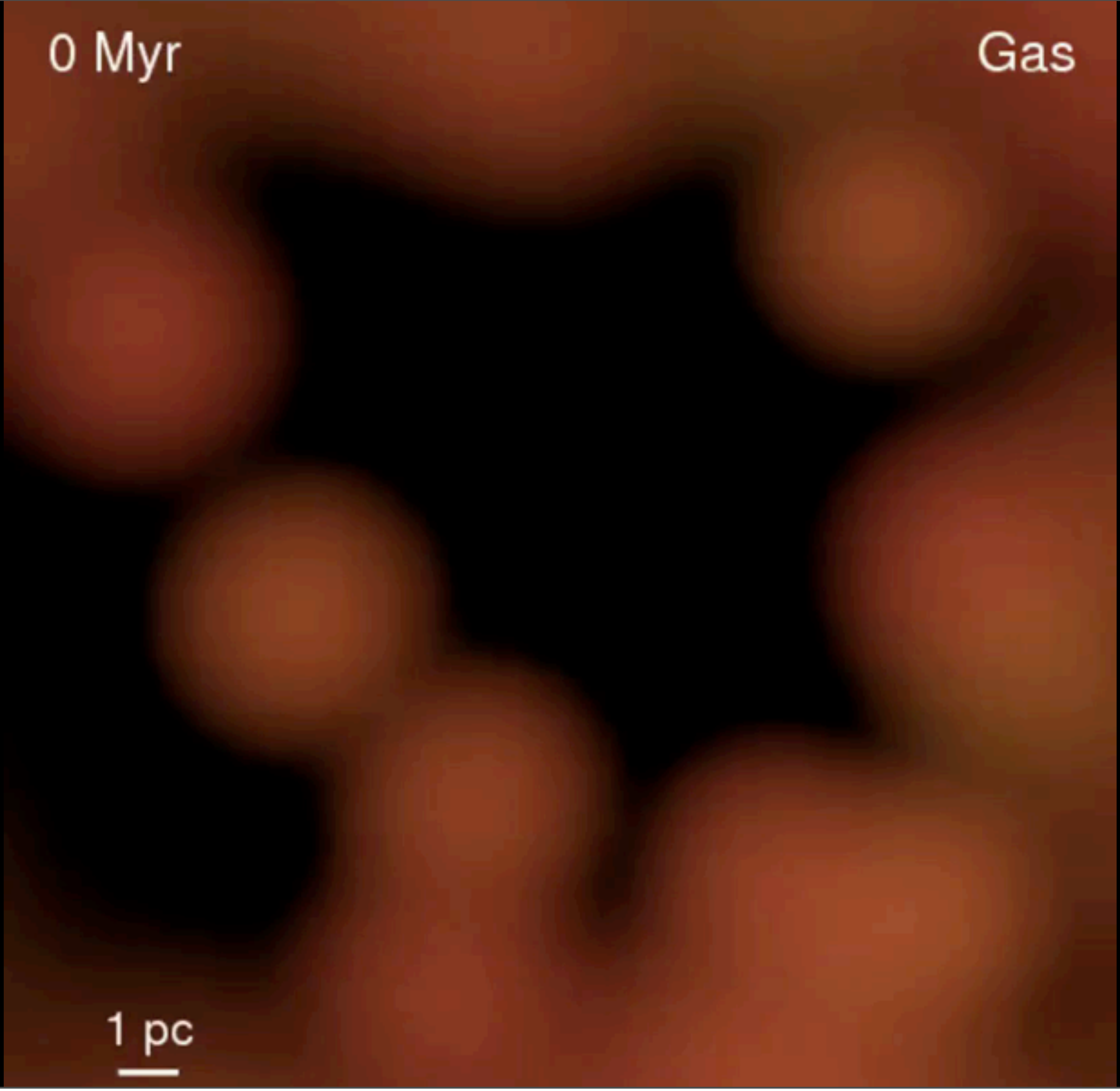
  - SNe

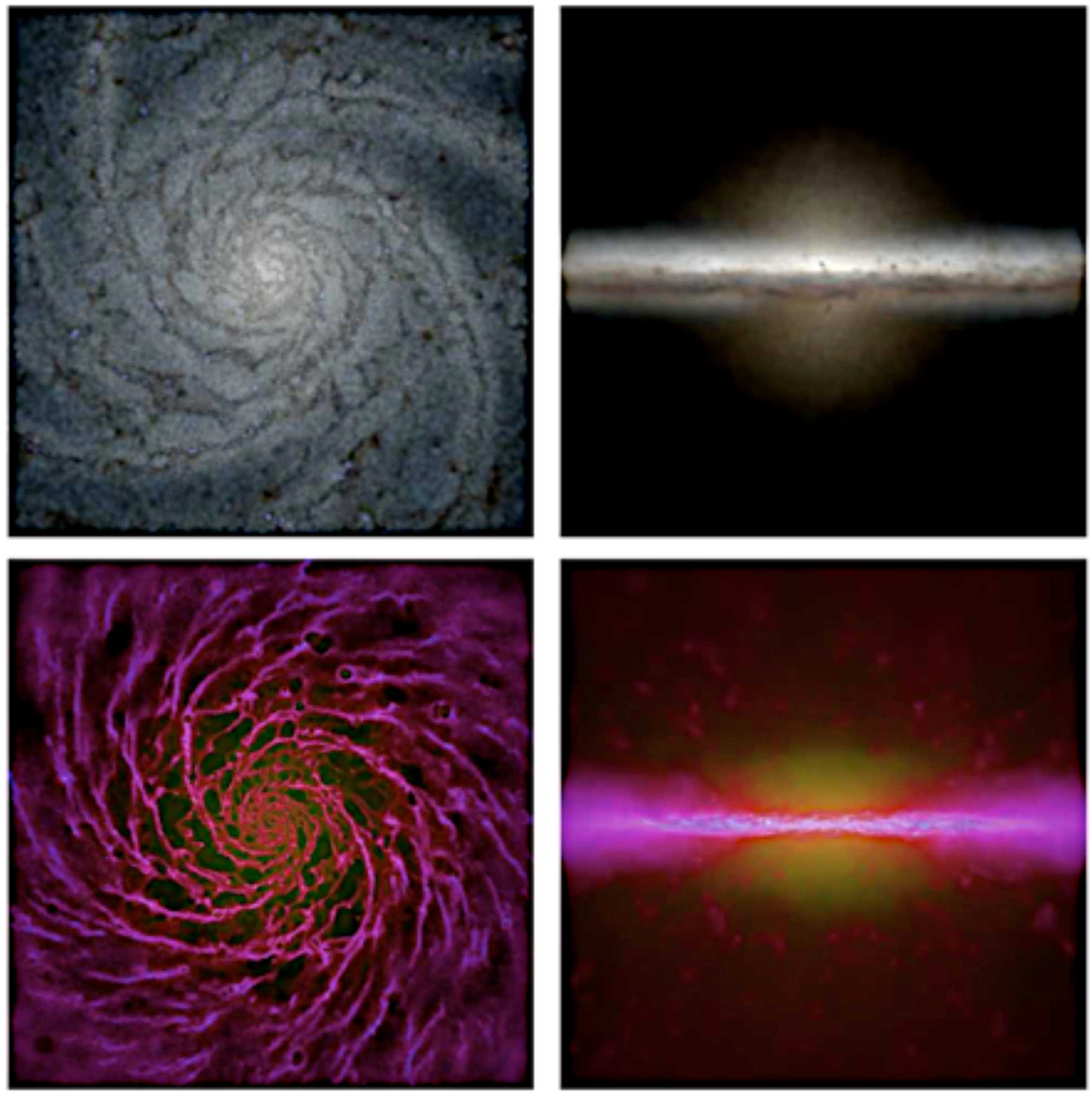
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

  - Stellar Winds

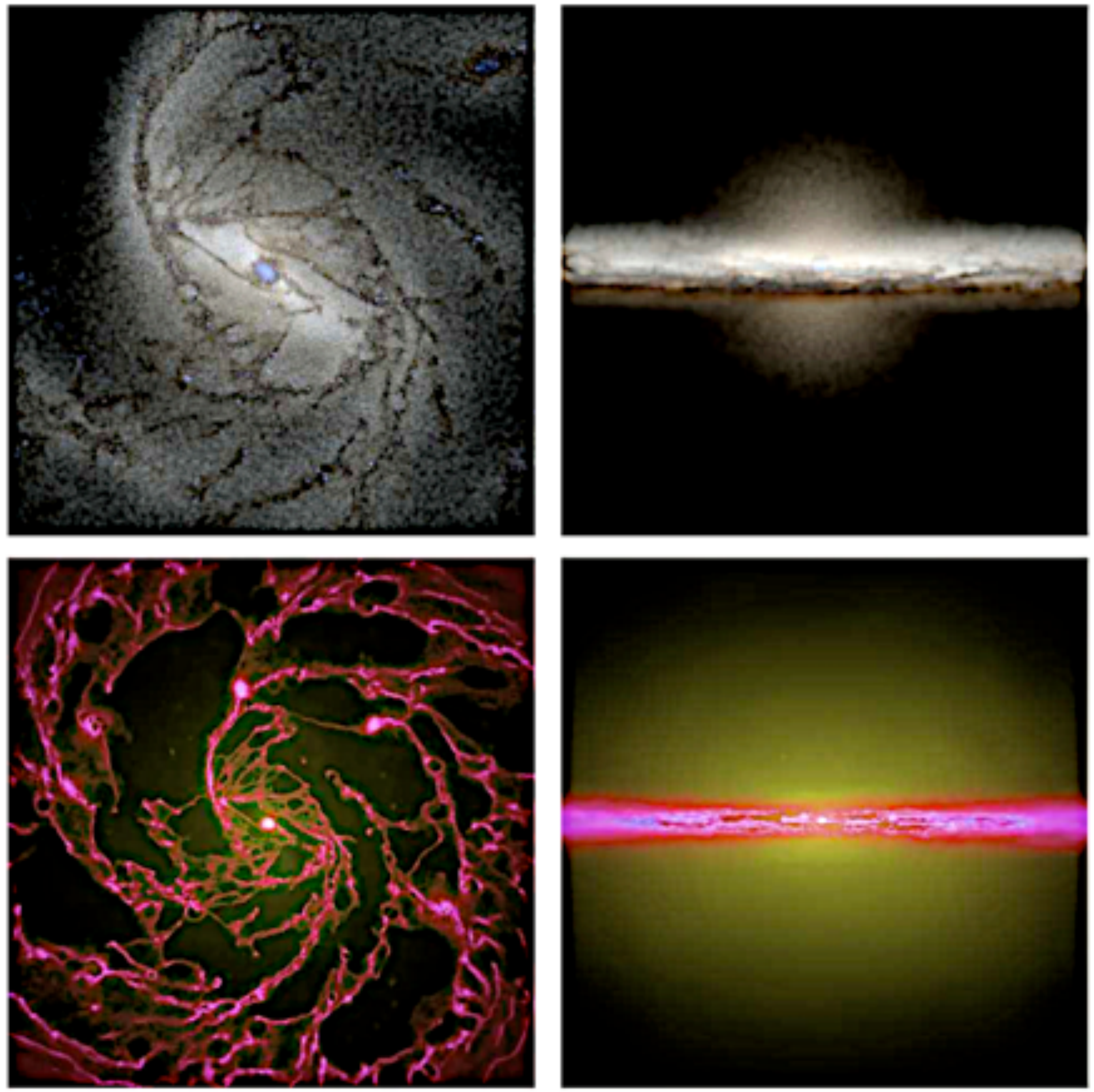
$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$




0 Myr
Gas
1 pc



Hopkins, Quataert, & Murray, in prep



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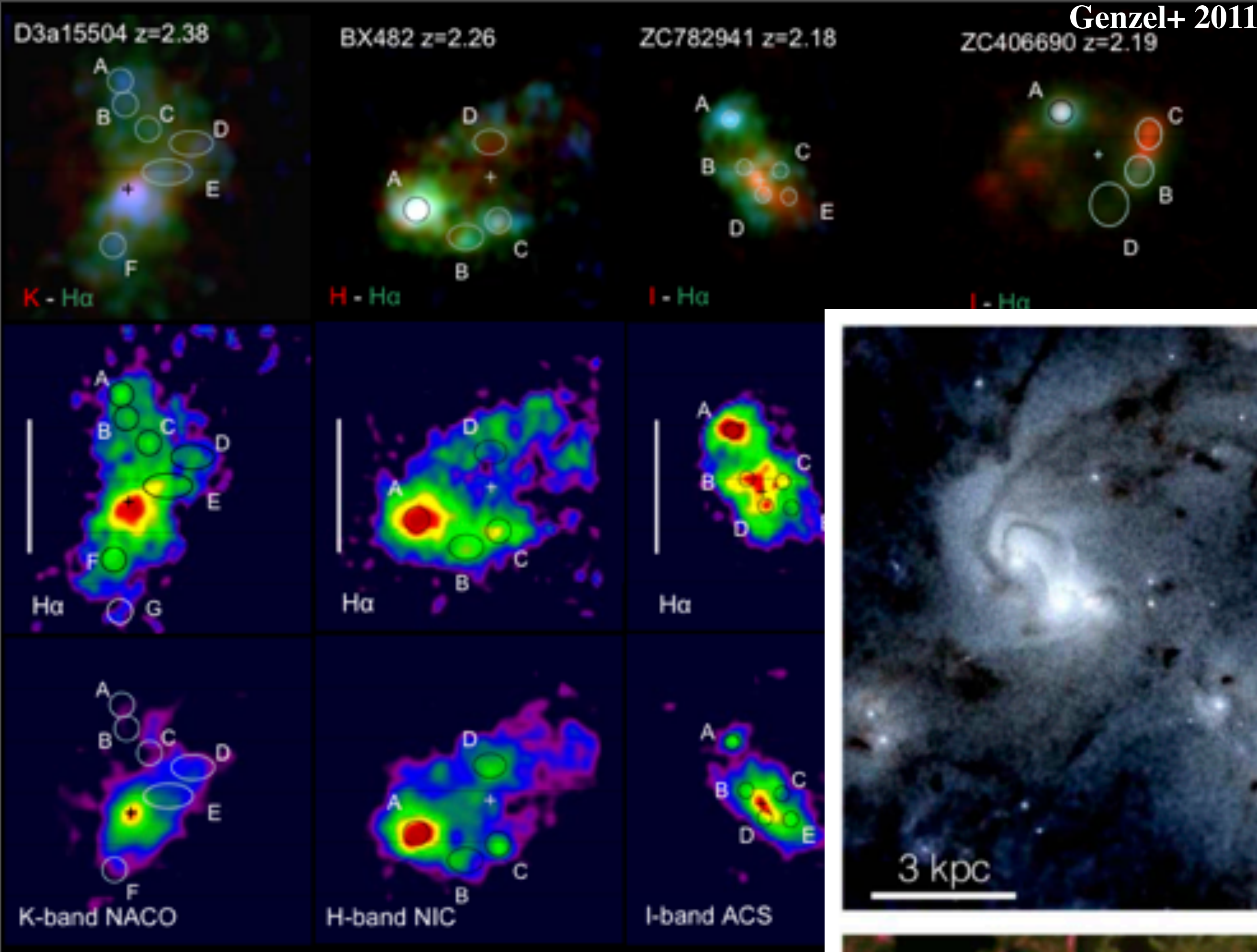

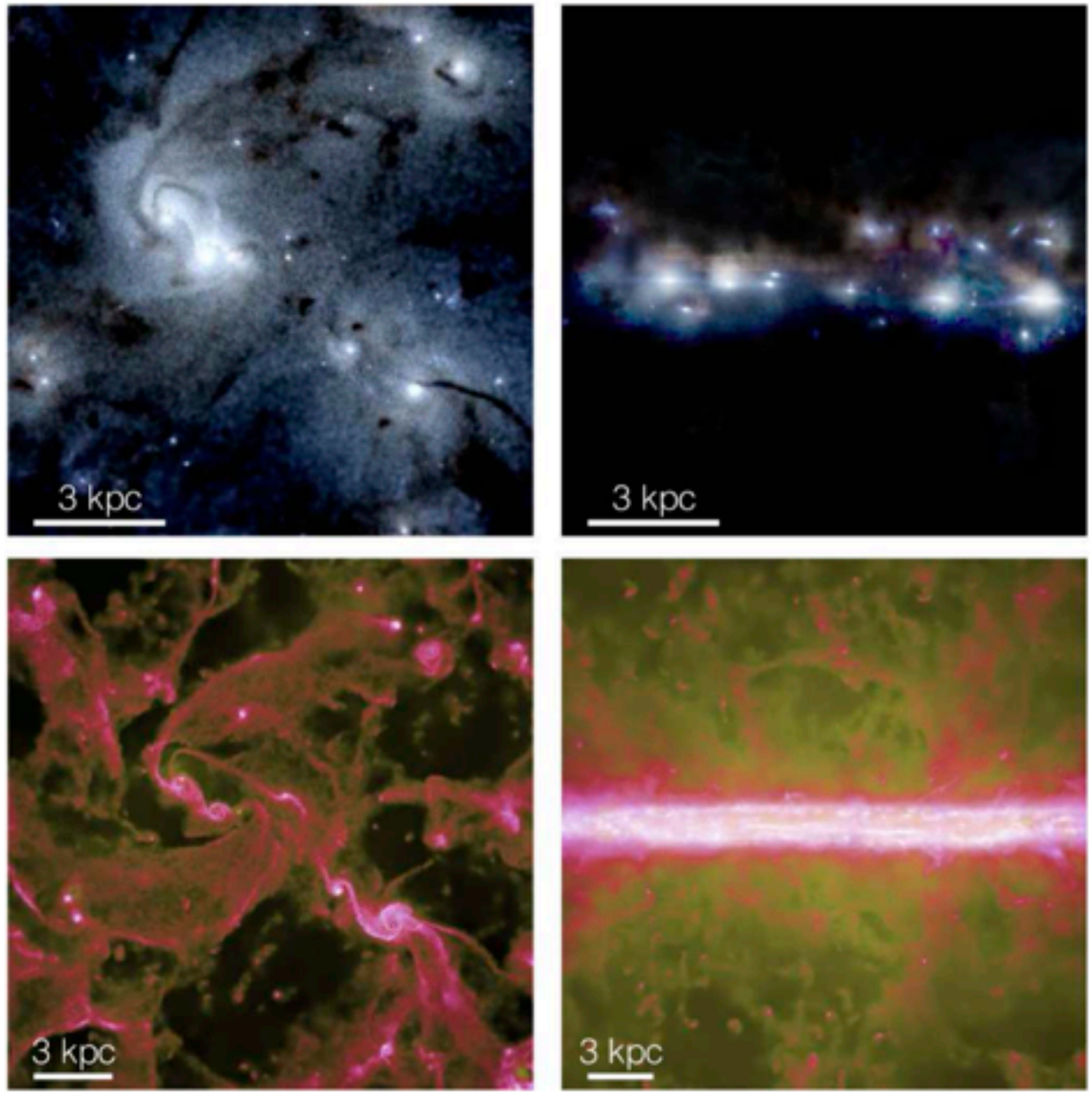

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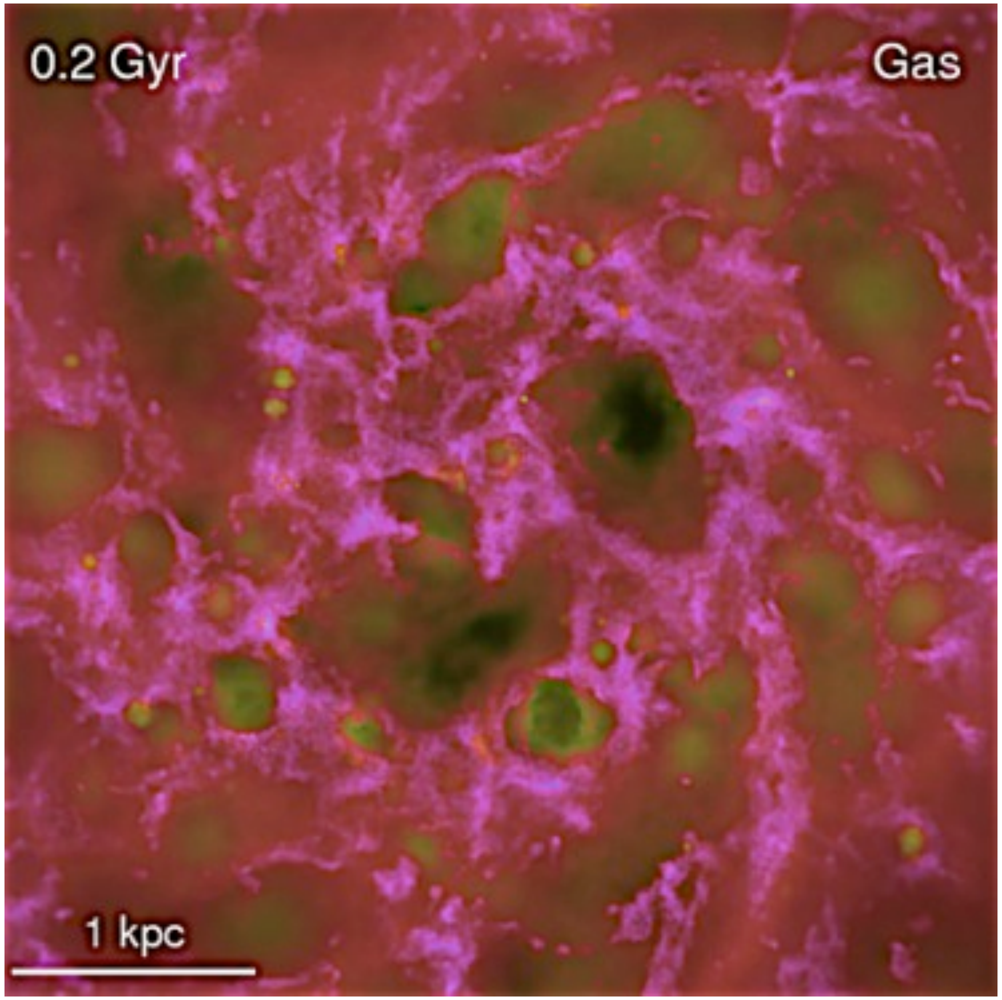

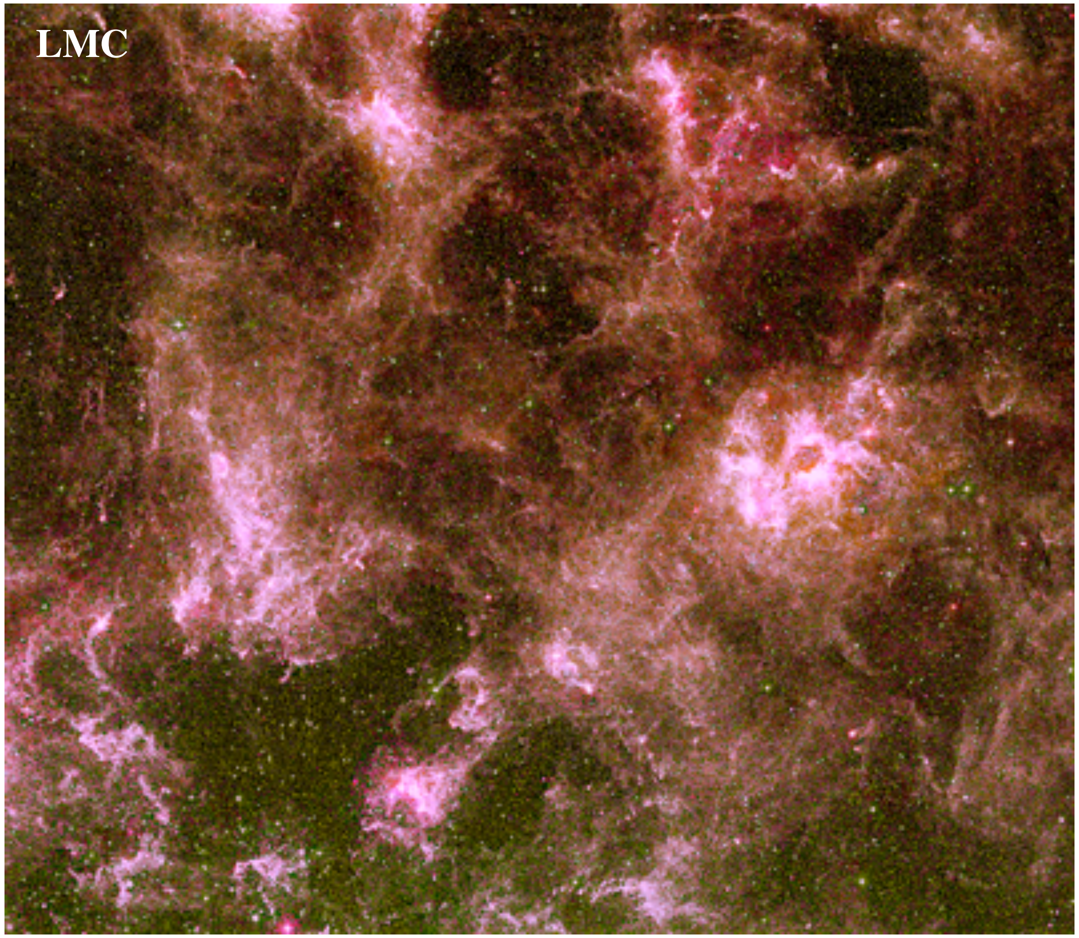

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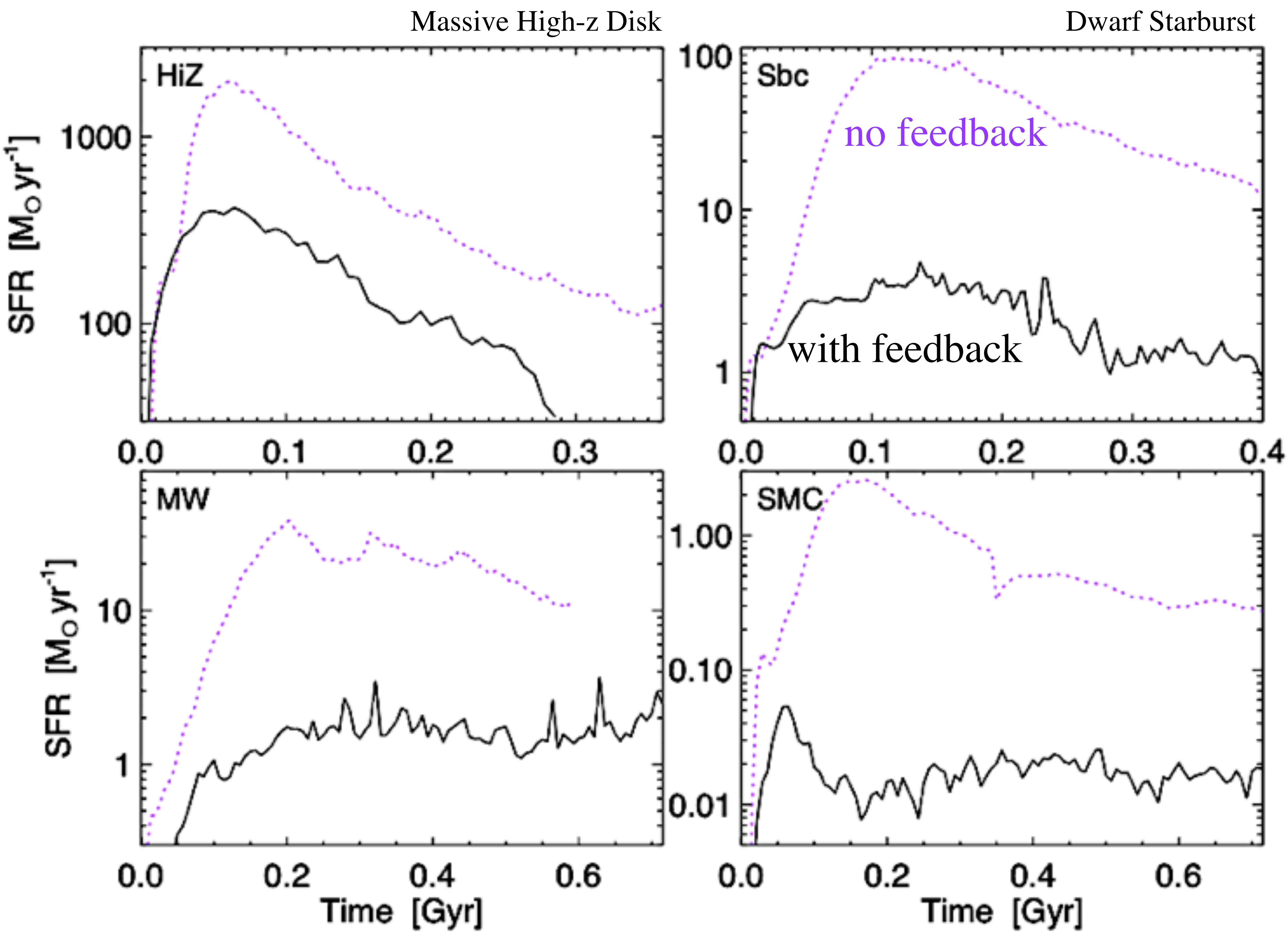
Stellar Feedback gives Self-Regulated Star Formation



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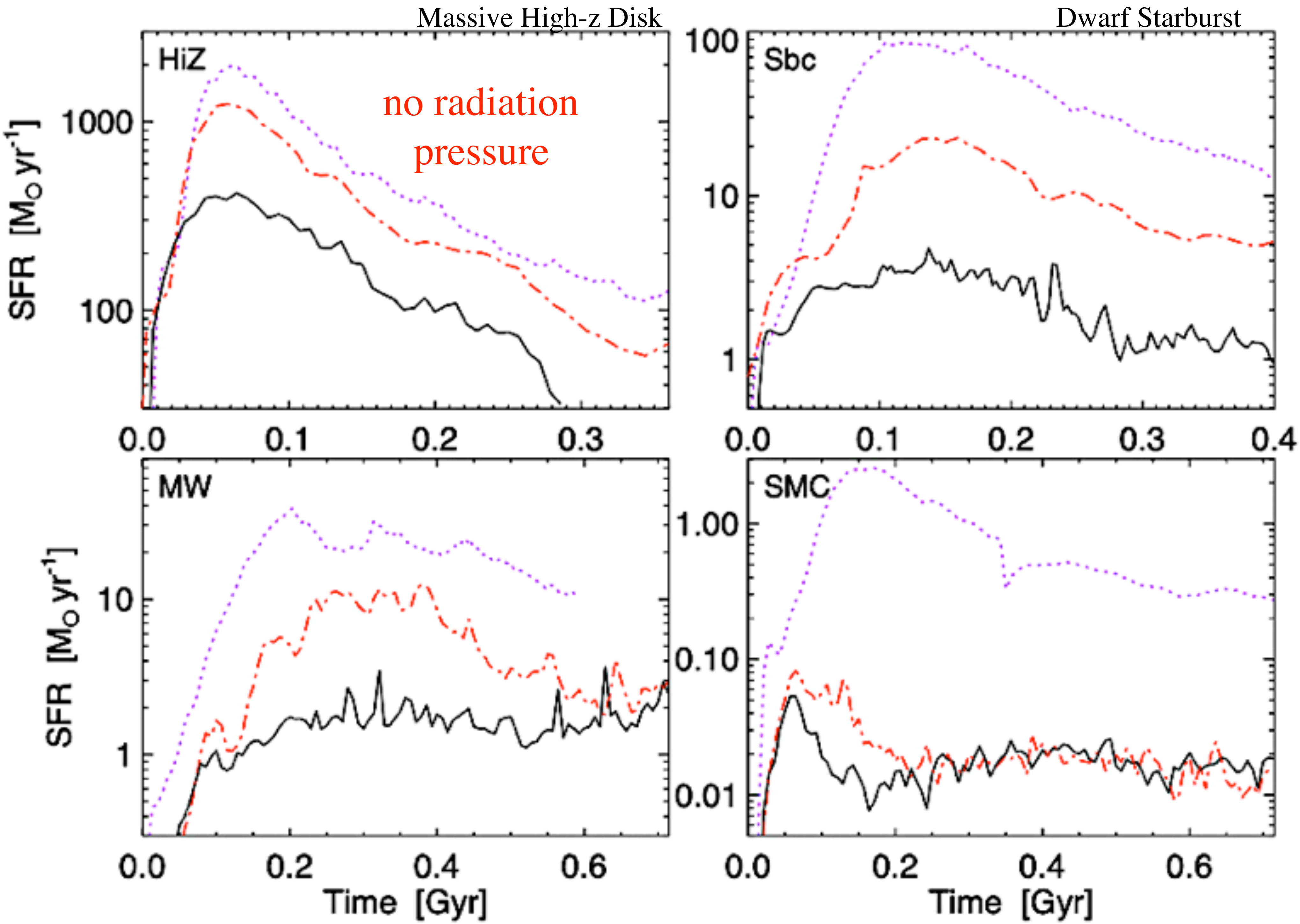

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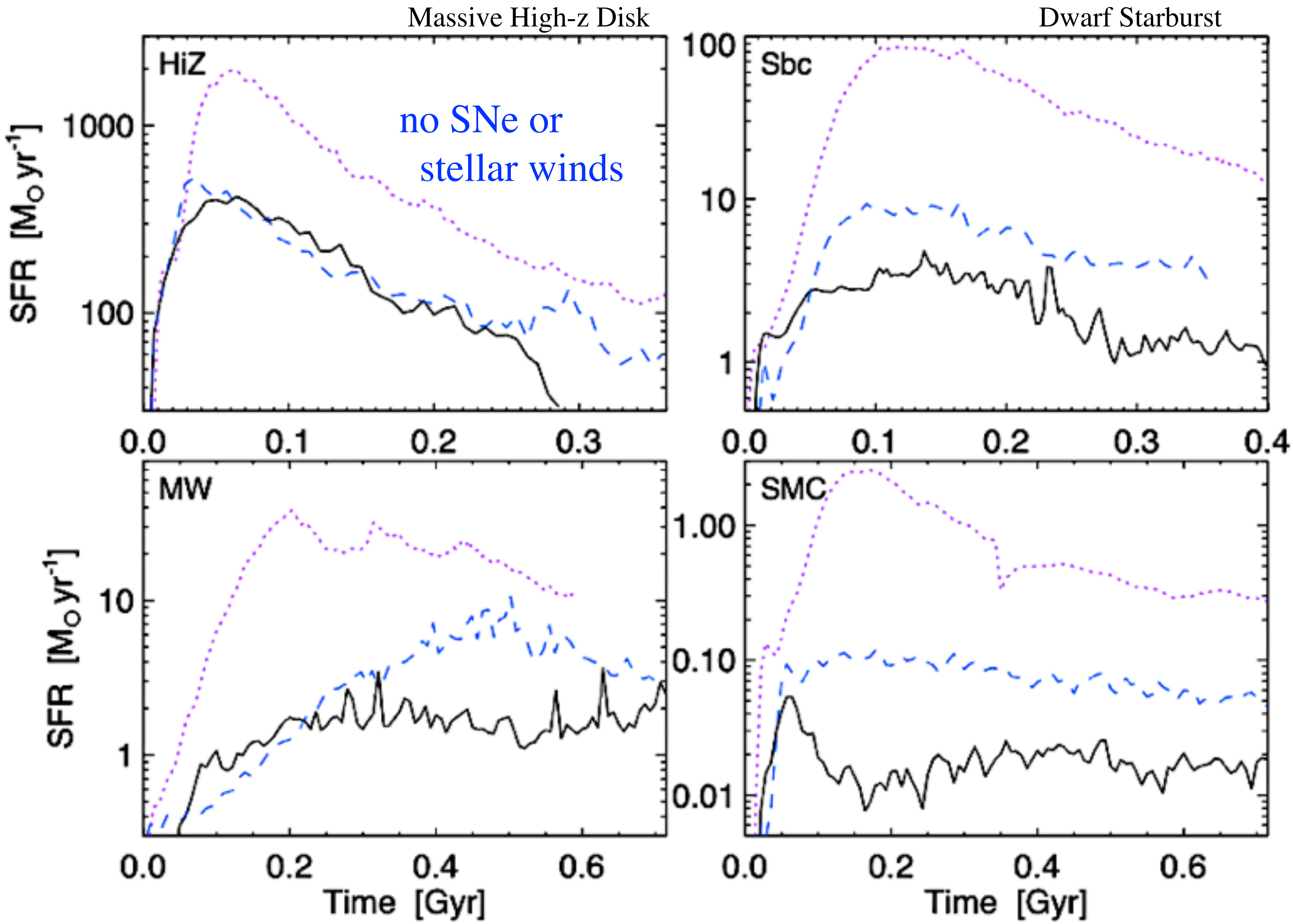

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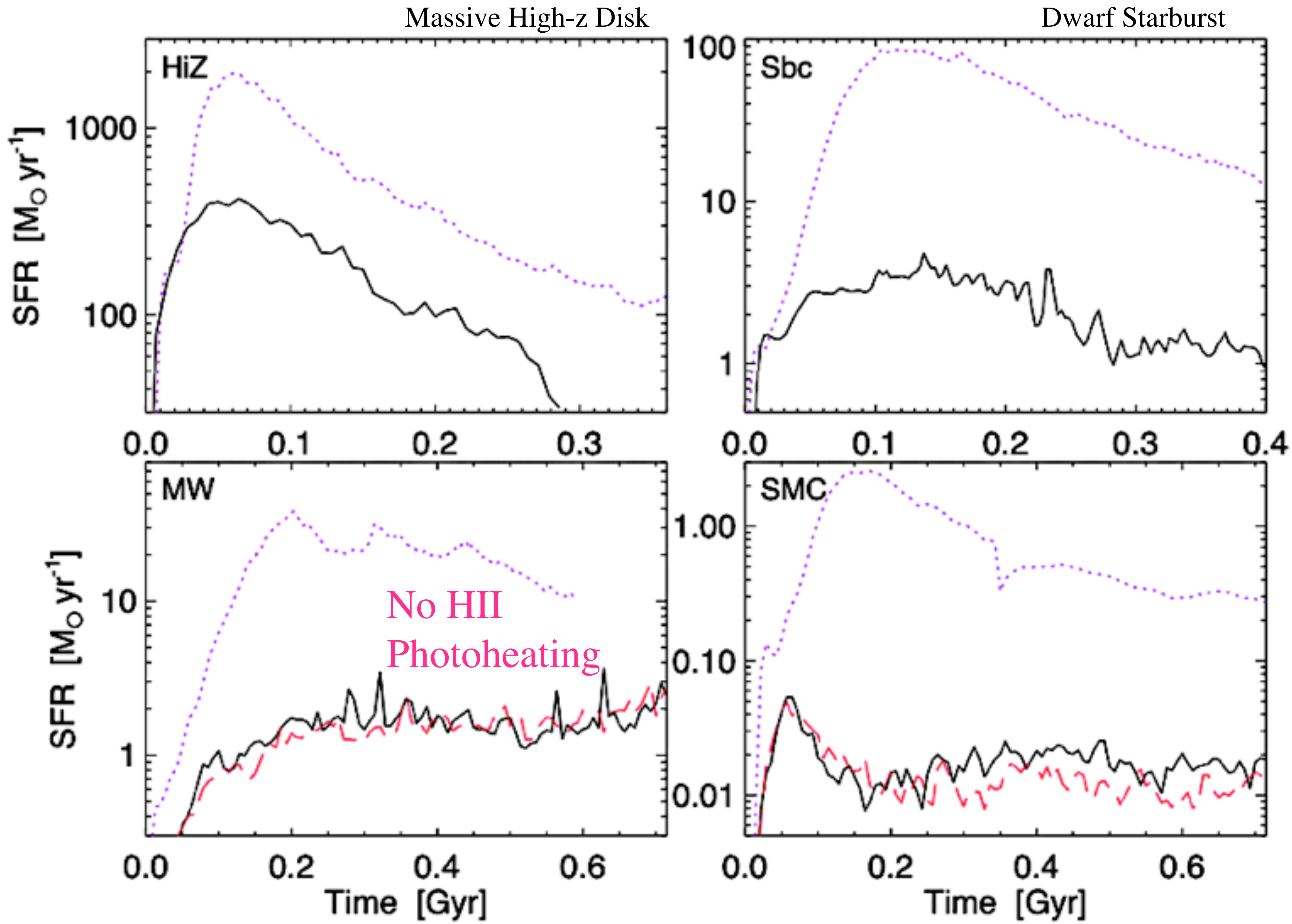
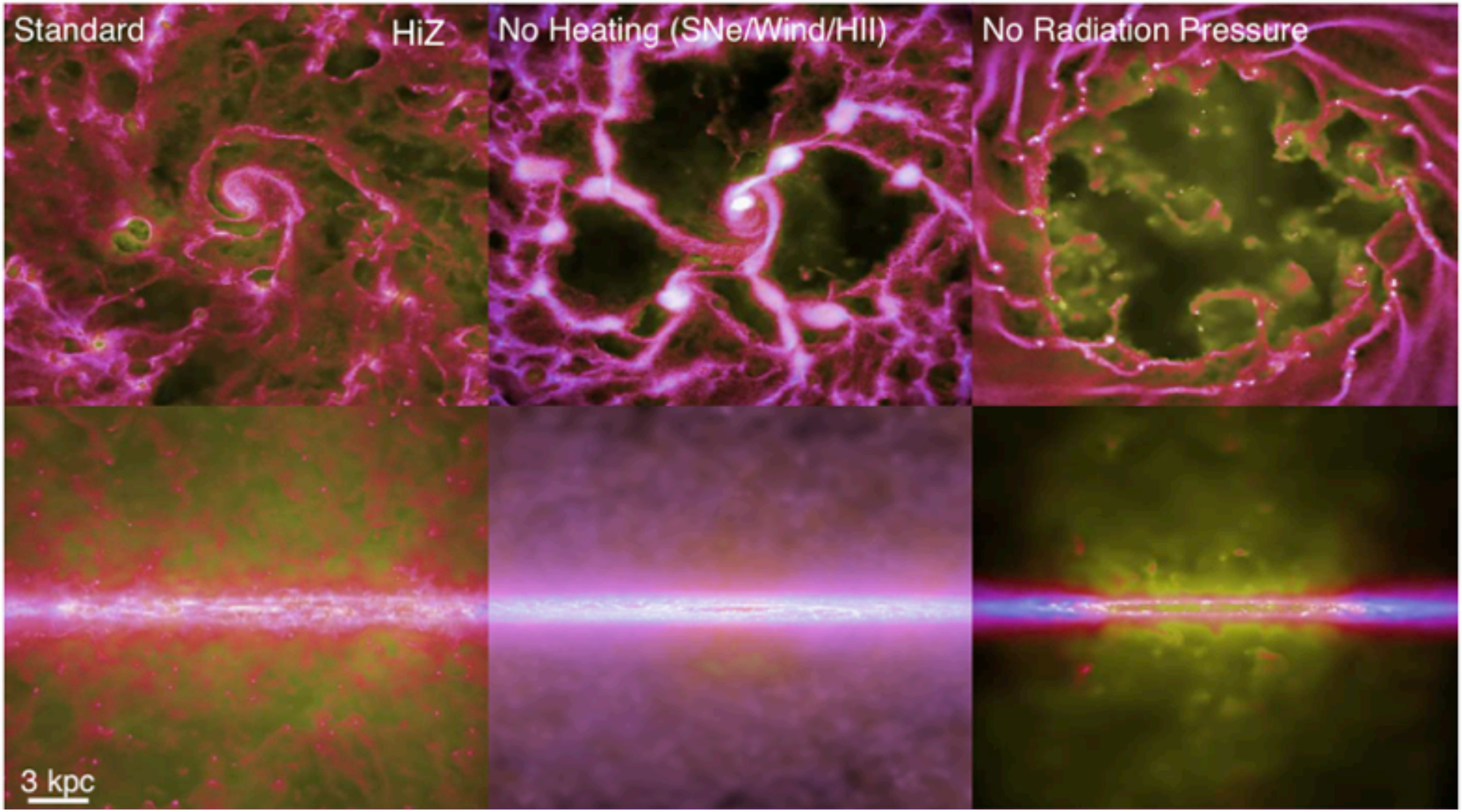


Stellar Feedback & Self-Regulation

WHICH MECHANISMS MATTER?



- SFR ~ 100+ M_{sun}/yr
  (L ~ L_{EDD})
- Optically thick
- <n> ~ 100 cm^{-3}
  T_{cool} ~ 1000 yr

Stellar Feedback & Self-Regulation

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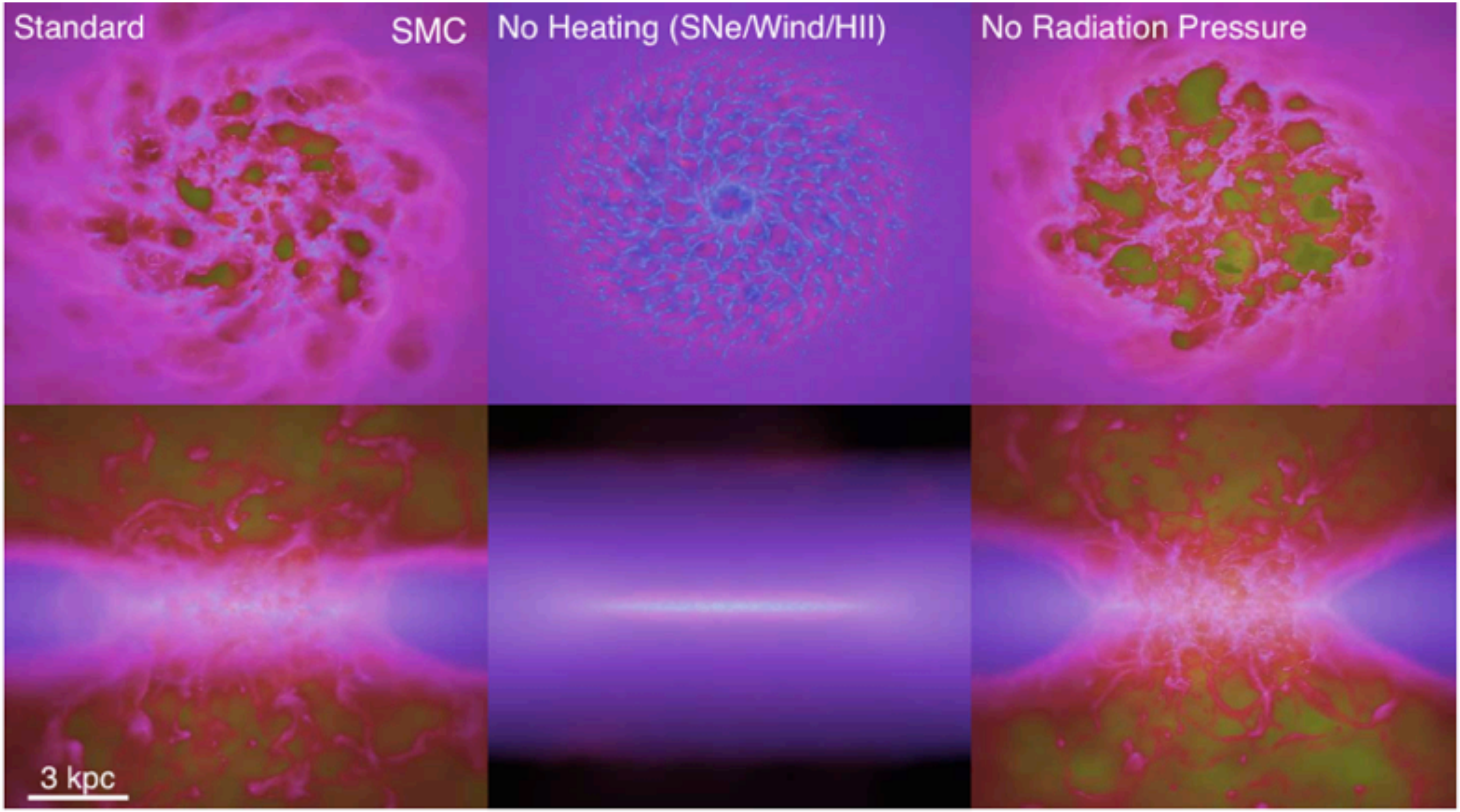
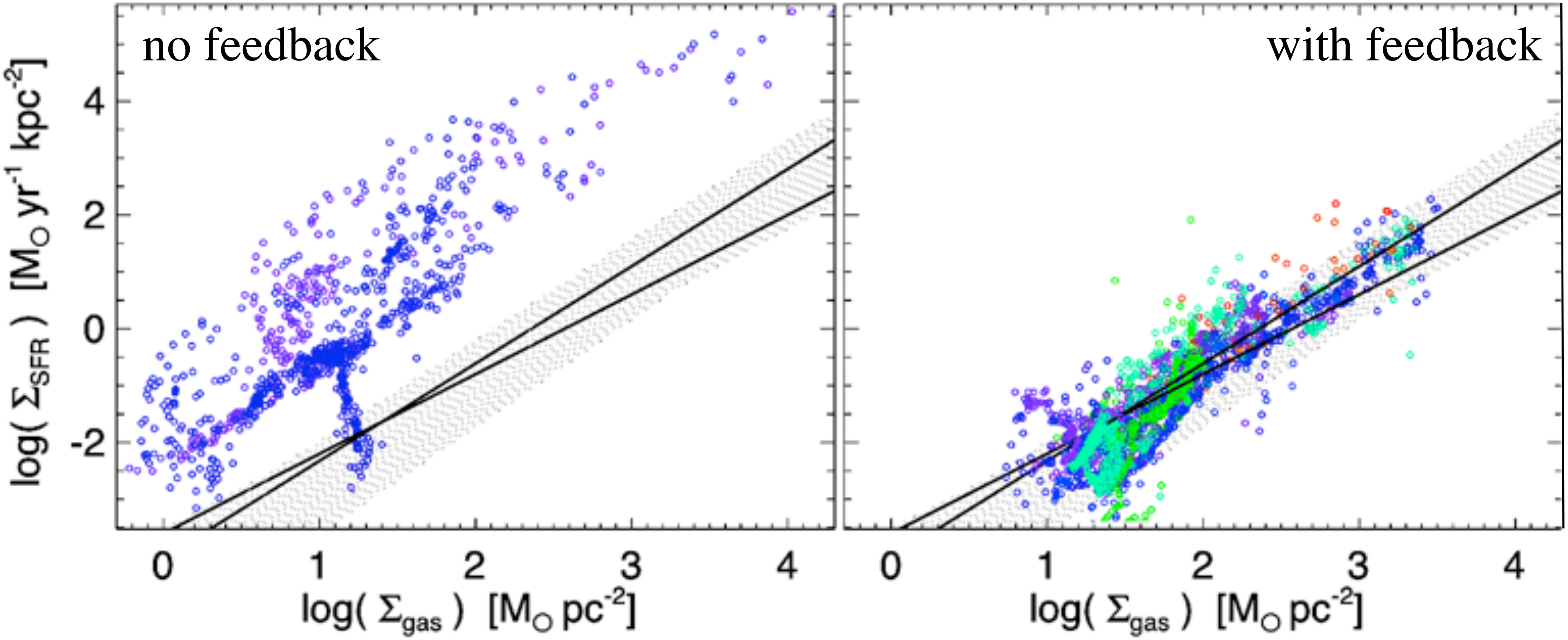


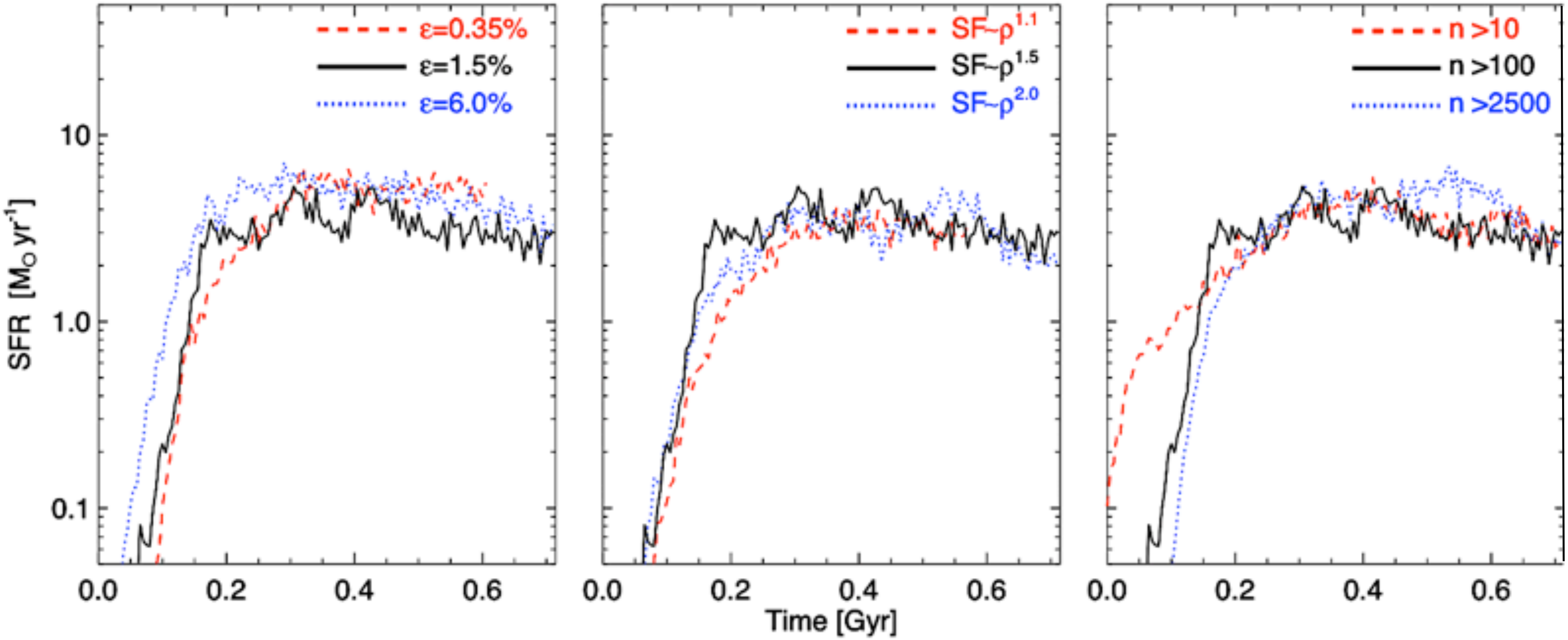
- SFR ~ 0.01 M_{sun}/yr ($L << L_{EDD}$)
- Optically thin
- <n> ~ 0.1 cm^{-3} T_{cool} ~ Myr

Kennicutt-Schmidt relation emerges naturally



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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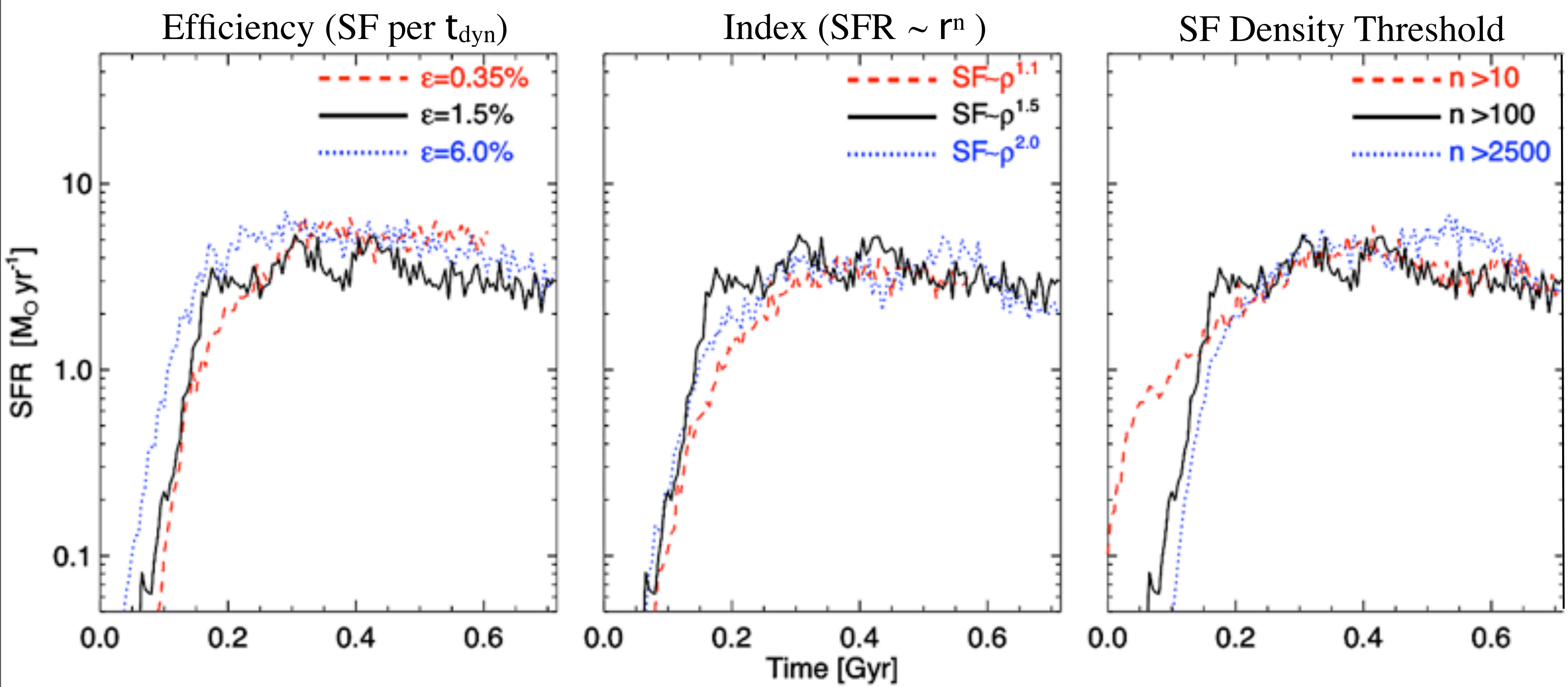

- Set by feedback (i.e. SFR) needed to maintain marginal stability

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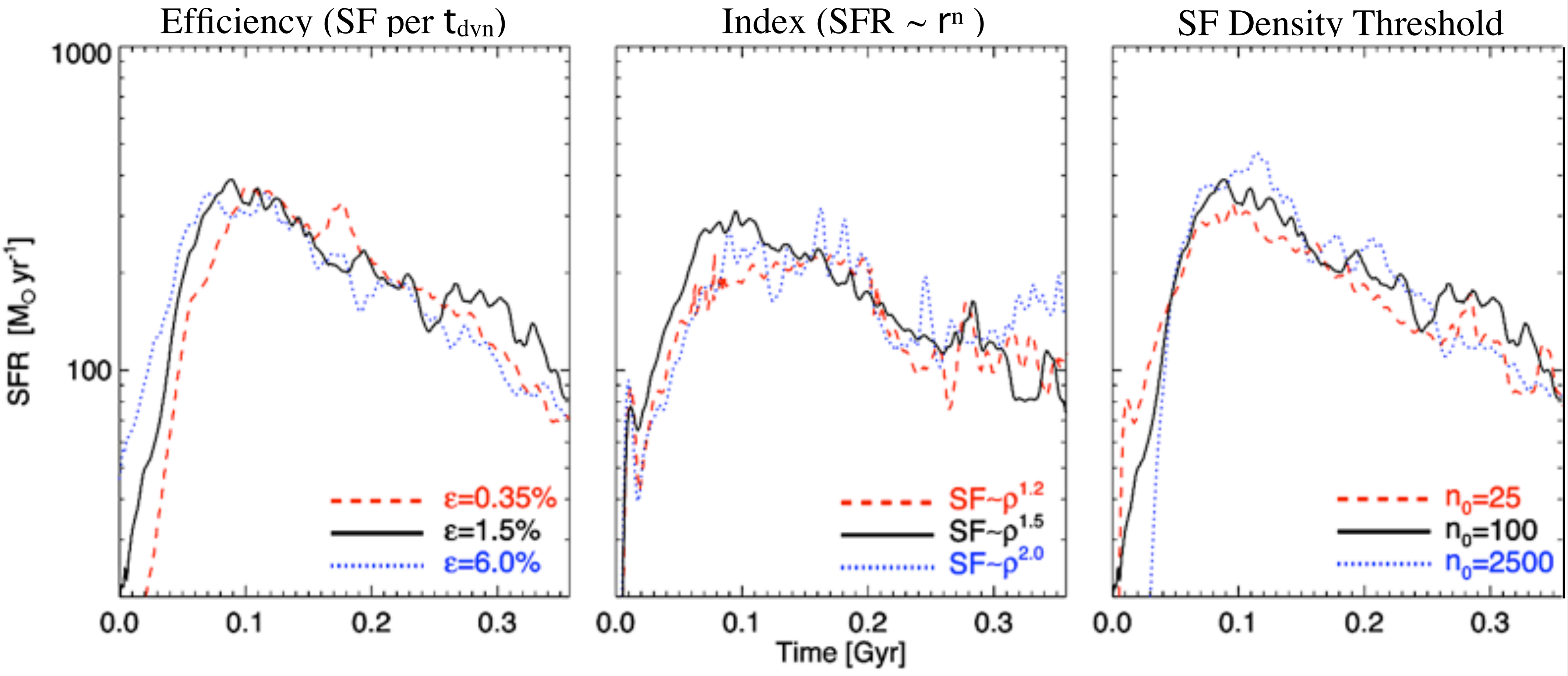

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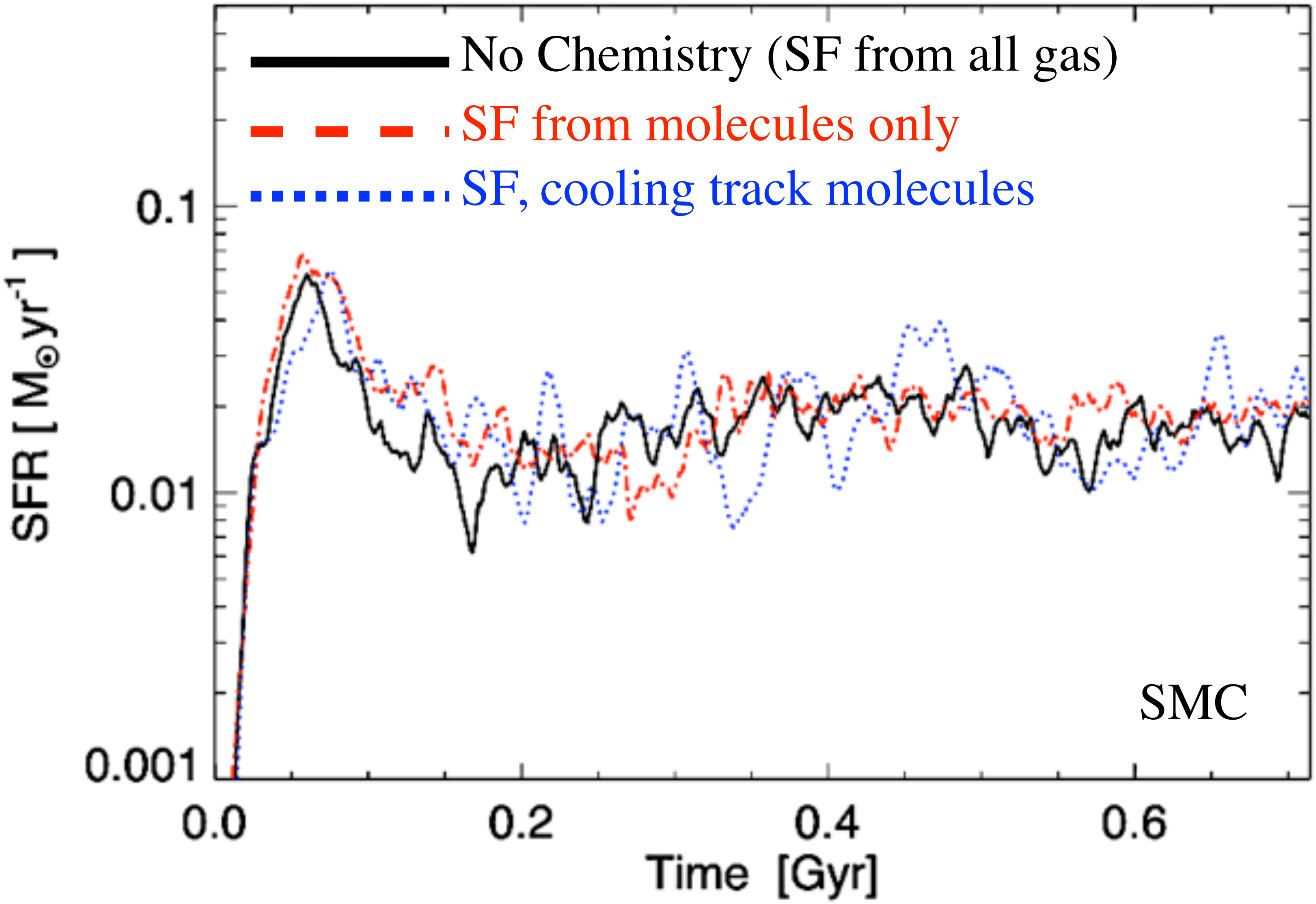
Molecular Chemistry also has No Effect

MOLECULES ARE A *TRACER*



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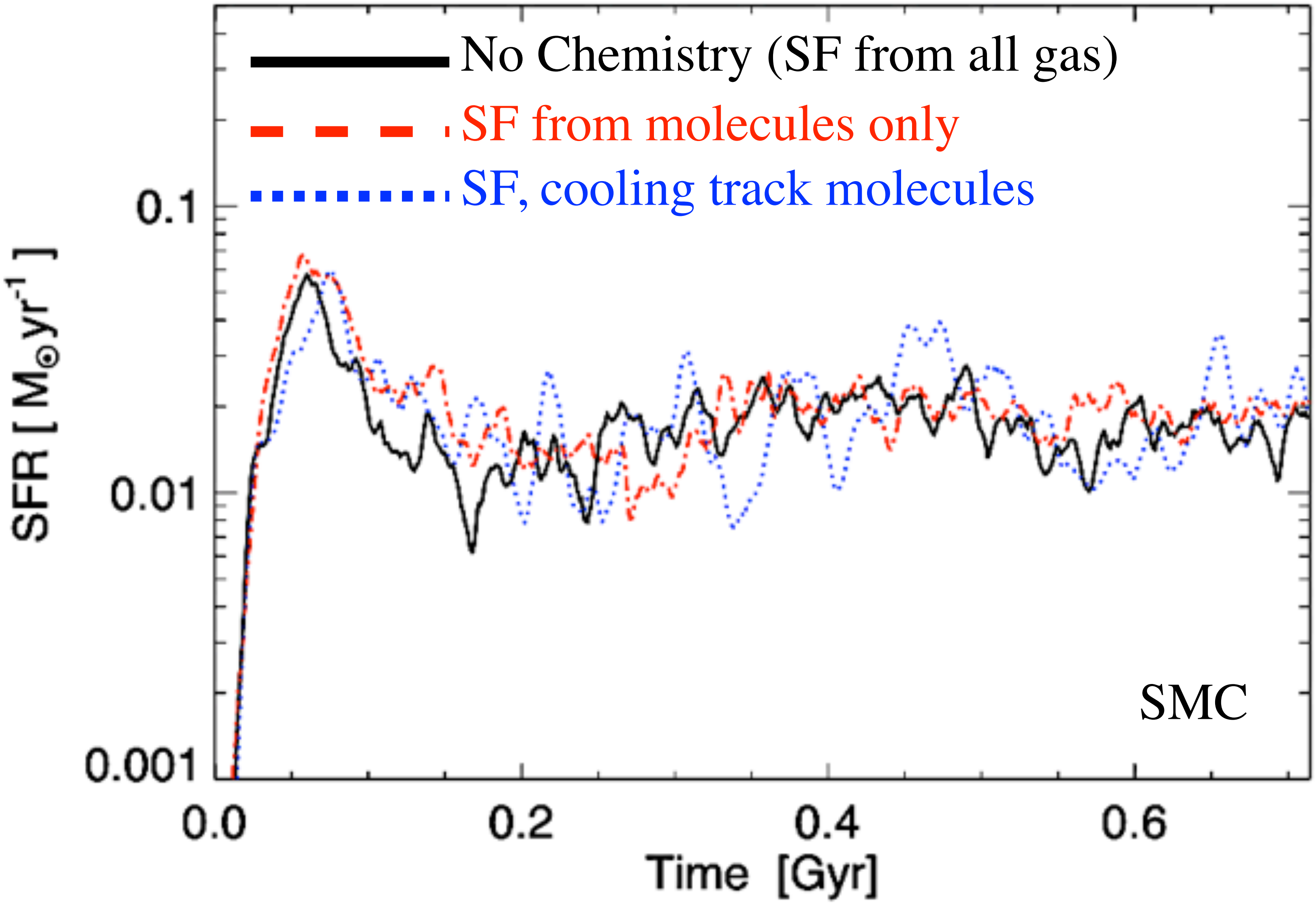
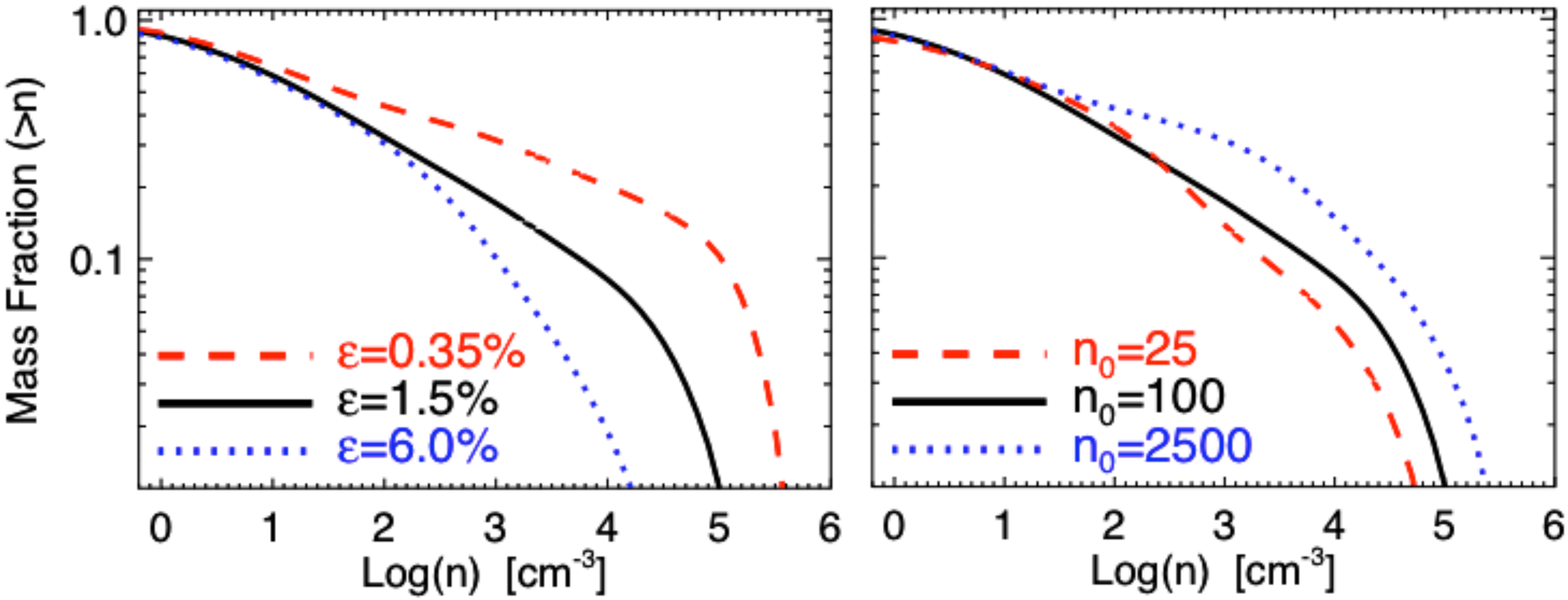


- Just need *some* cooling channel: changes at $M_{gal} < 10^6\ M_{sun}$, $Z<0.01\ Z_{sun}$

How Does Star Formation Self-Regulate?

SELF-ADJUST THE MASS IN *DENSE* GAS



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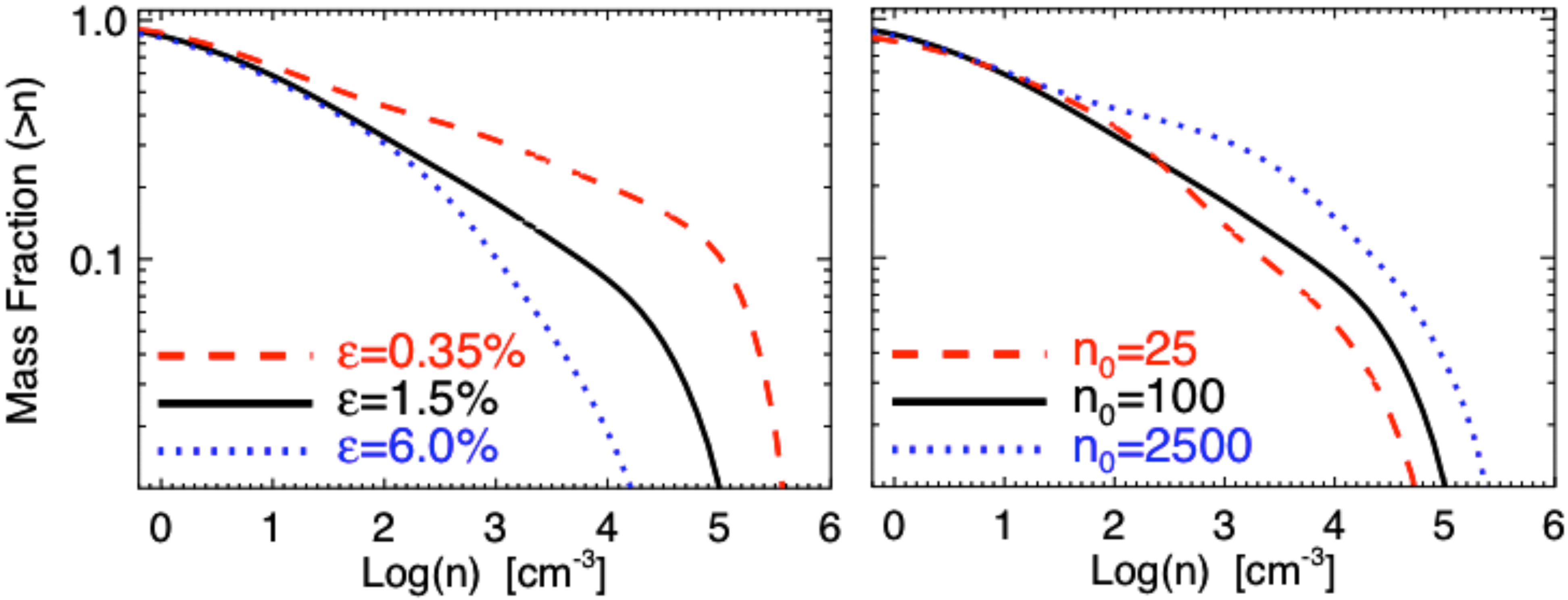

- Need net momentum injection dP/dt ~ L/c ~ SFR
  to cancel dissipation ~ M_{gas} s_{disk} W and maintain Q~1

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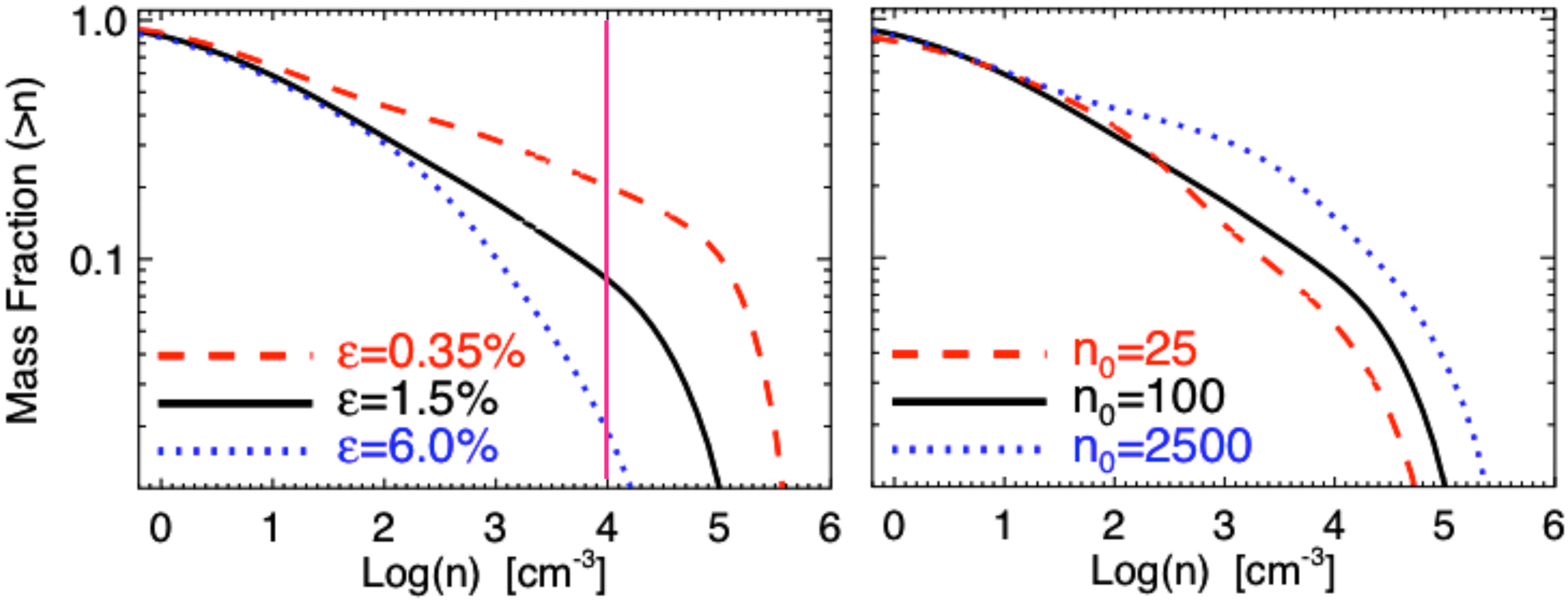
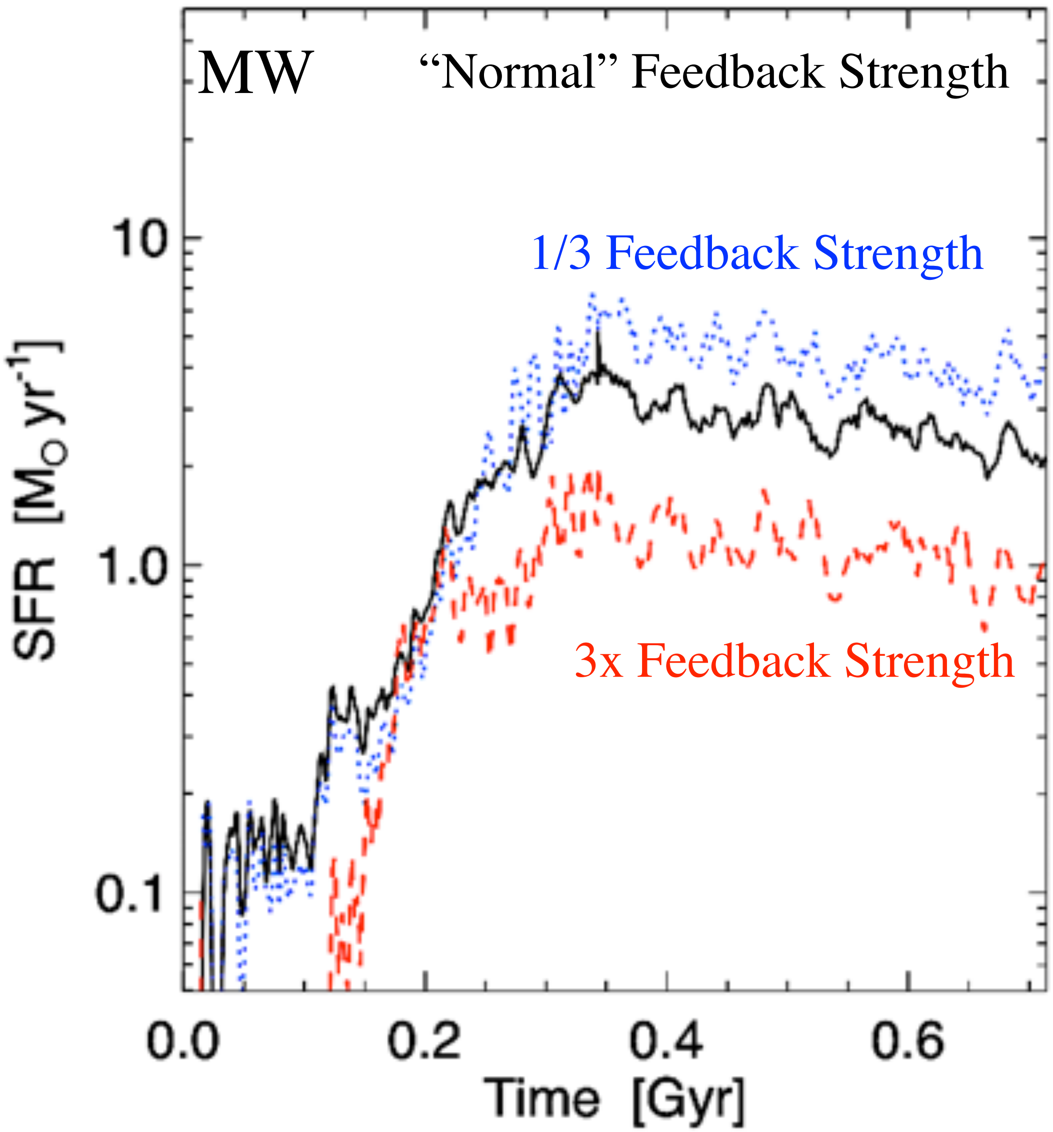


- Need net momentum injection dP/dt ~ L/c ~ SFR
  to cancel dissipation ~ M_{gas} s_{disk} W and maintain Q~1

- Not just top-down collapse

Star Formation is Feedback-Regulated:

MORE FEEDBACK = LESS STAR FORMATION



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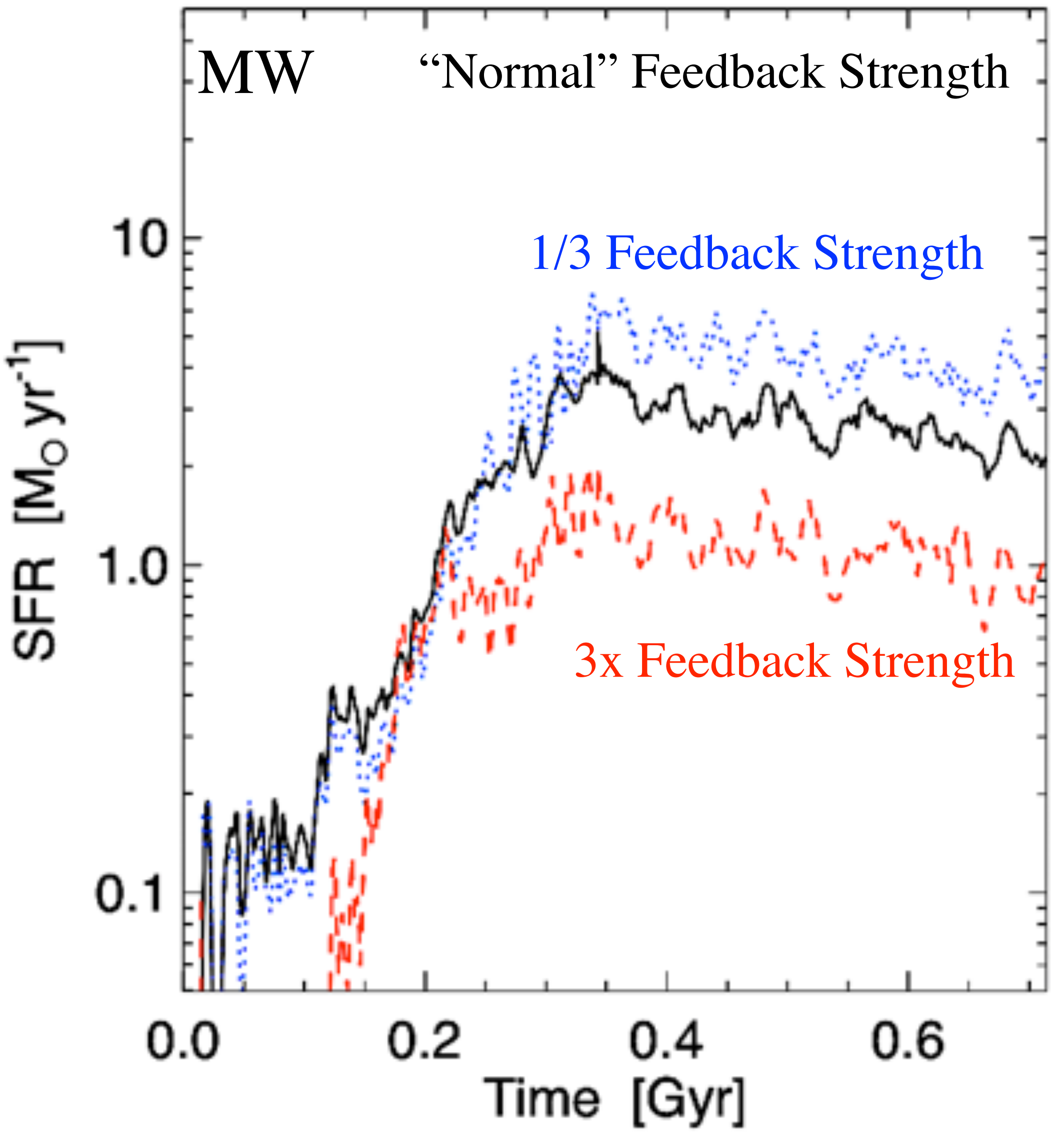
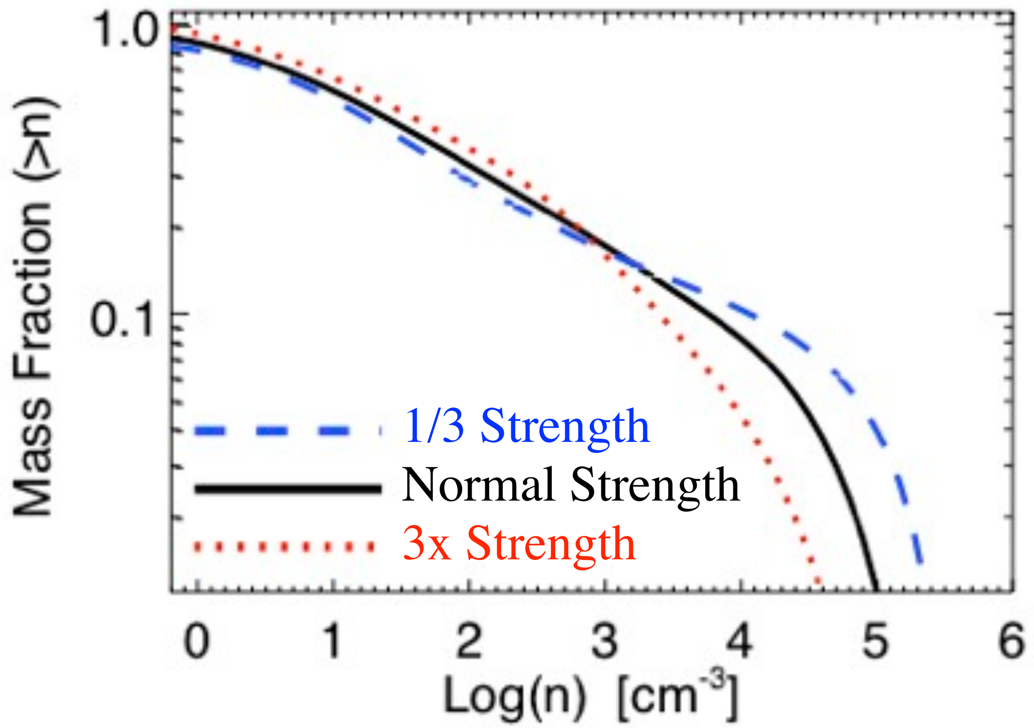
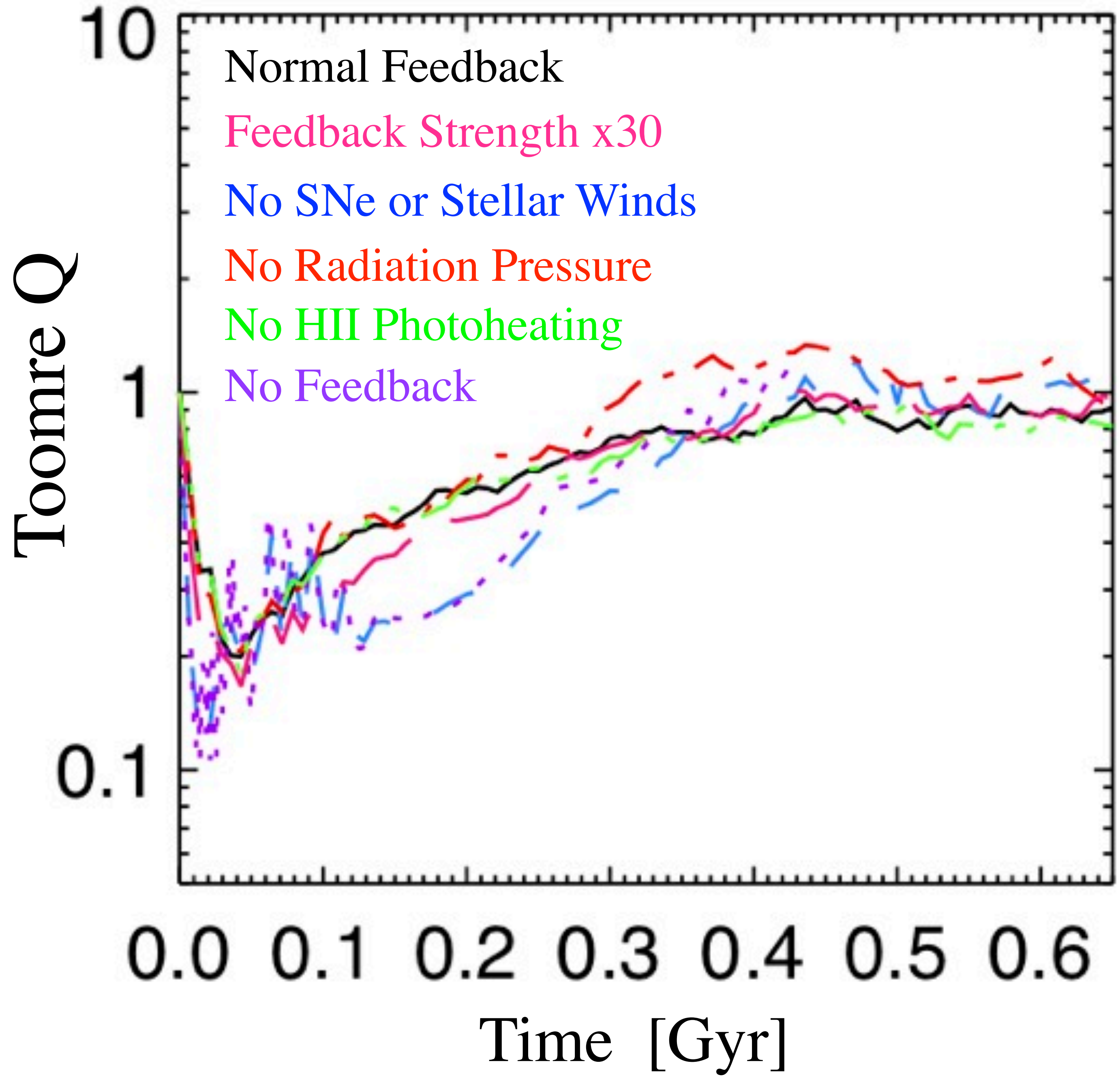




Q ~ 1 Is a Boring Diagnostic

EVERYTHING GOES TO Q~1. SERIOUSLY.



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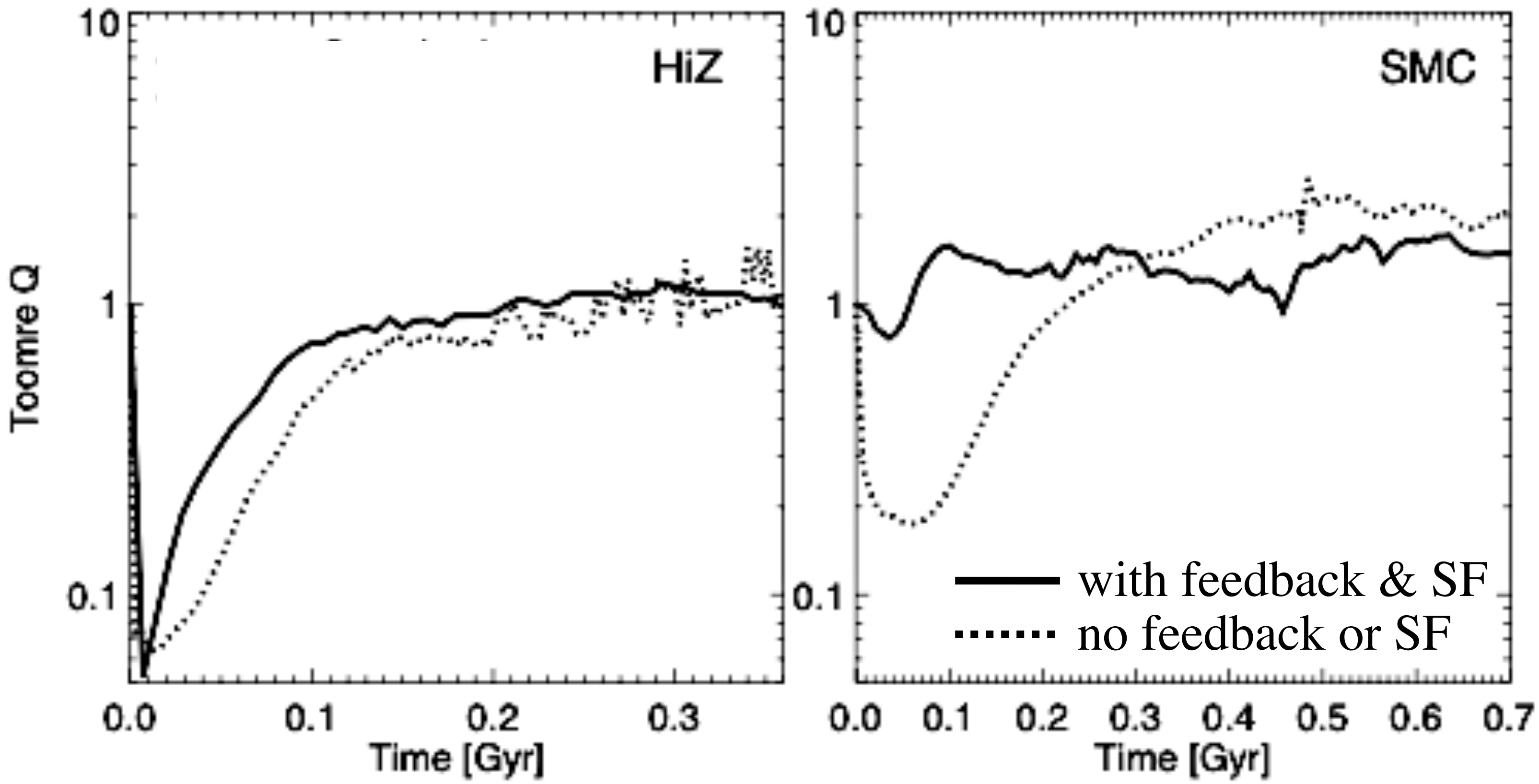
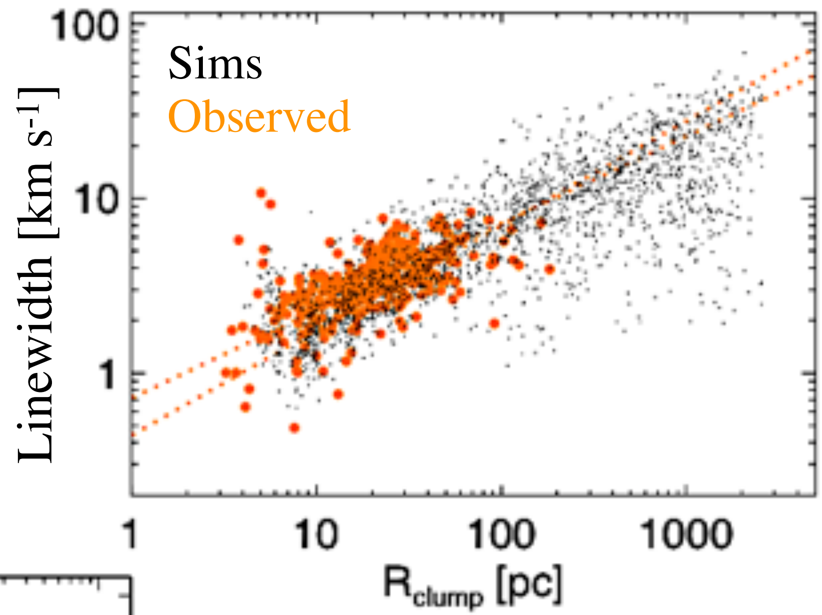
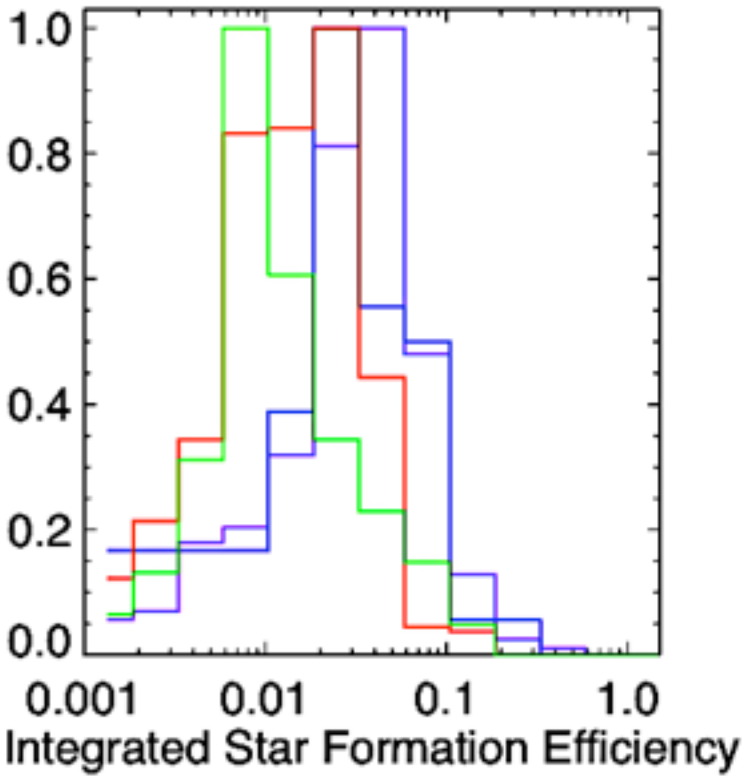
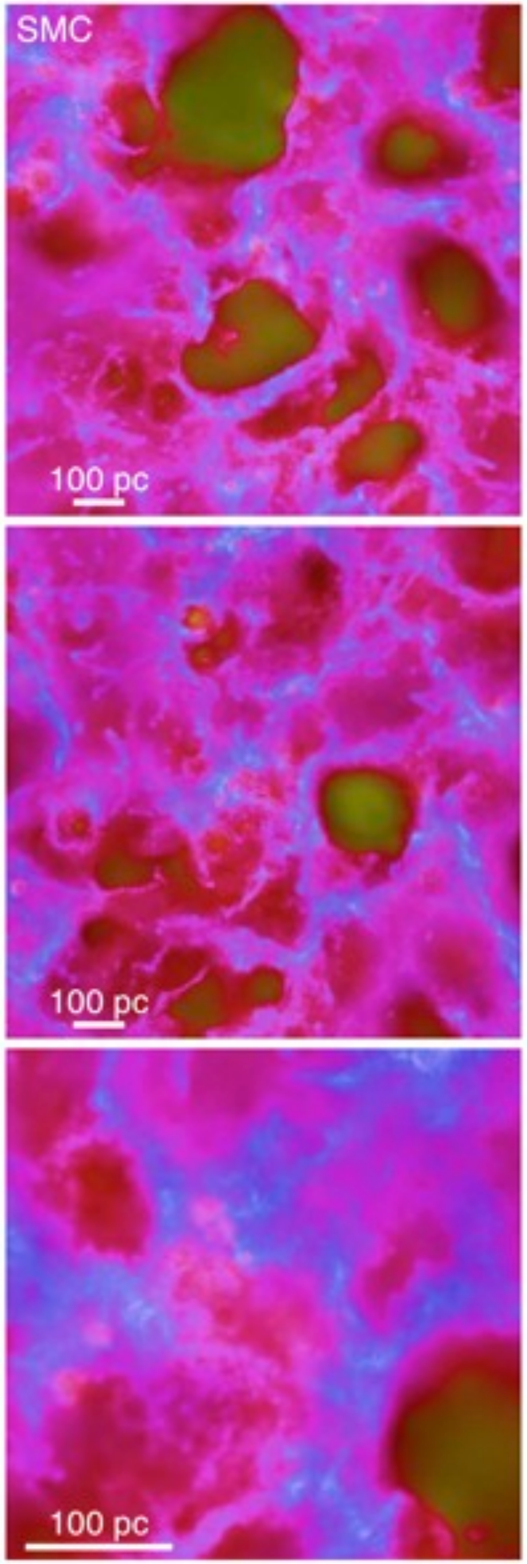


Properties of GMCs

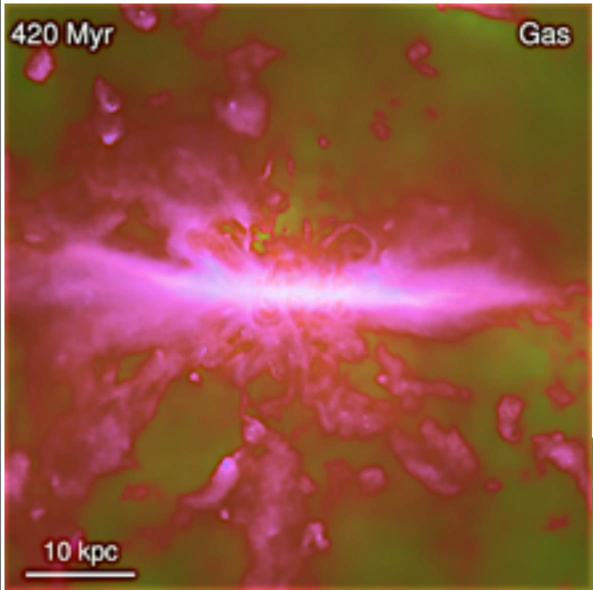
STUFF TO EXAMINE IN THE FUTURE...

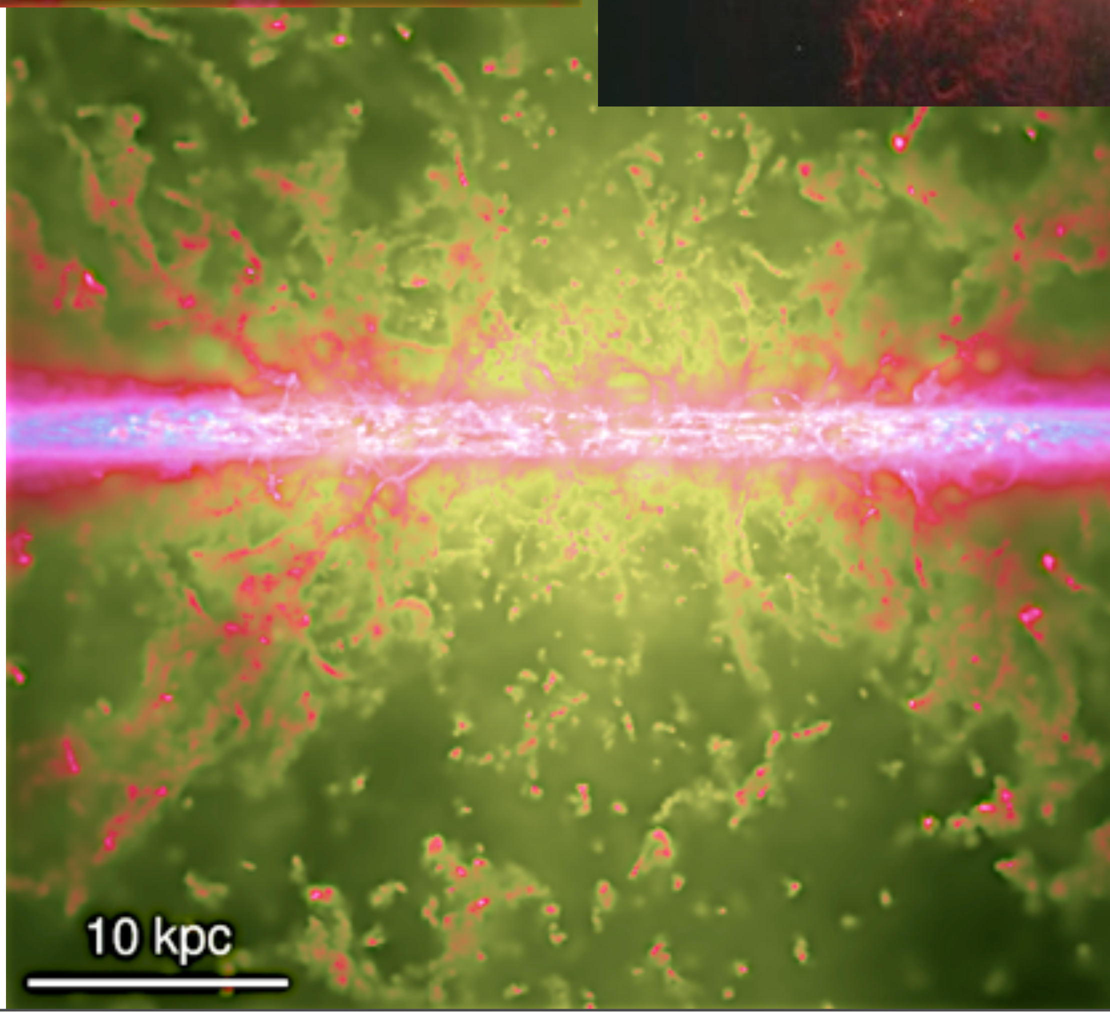


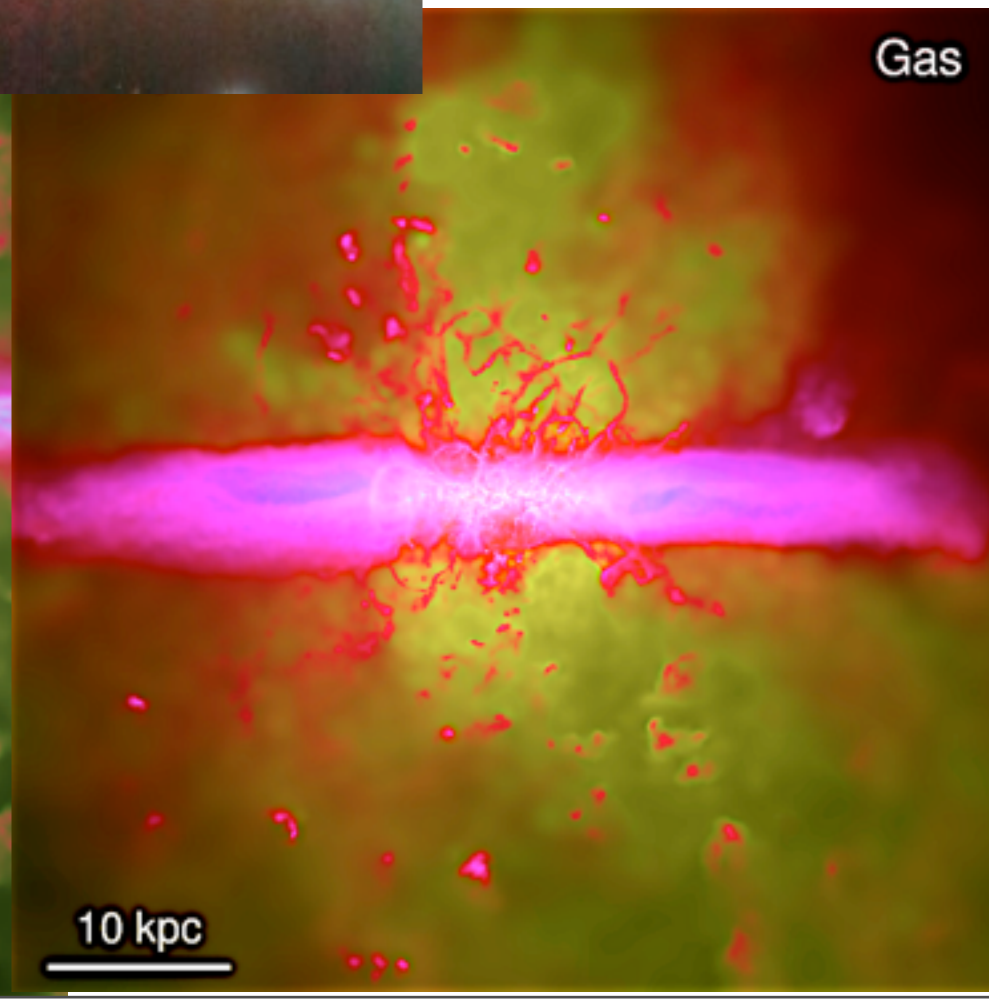


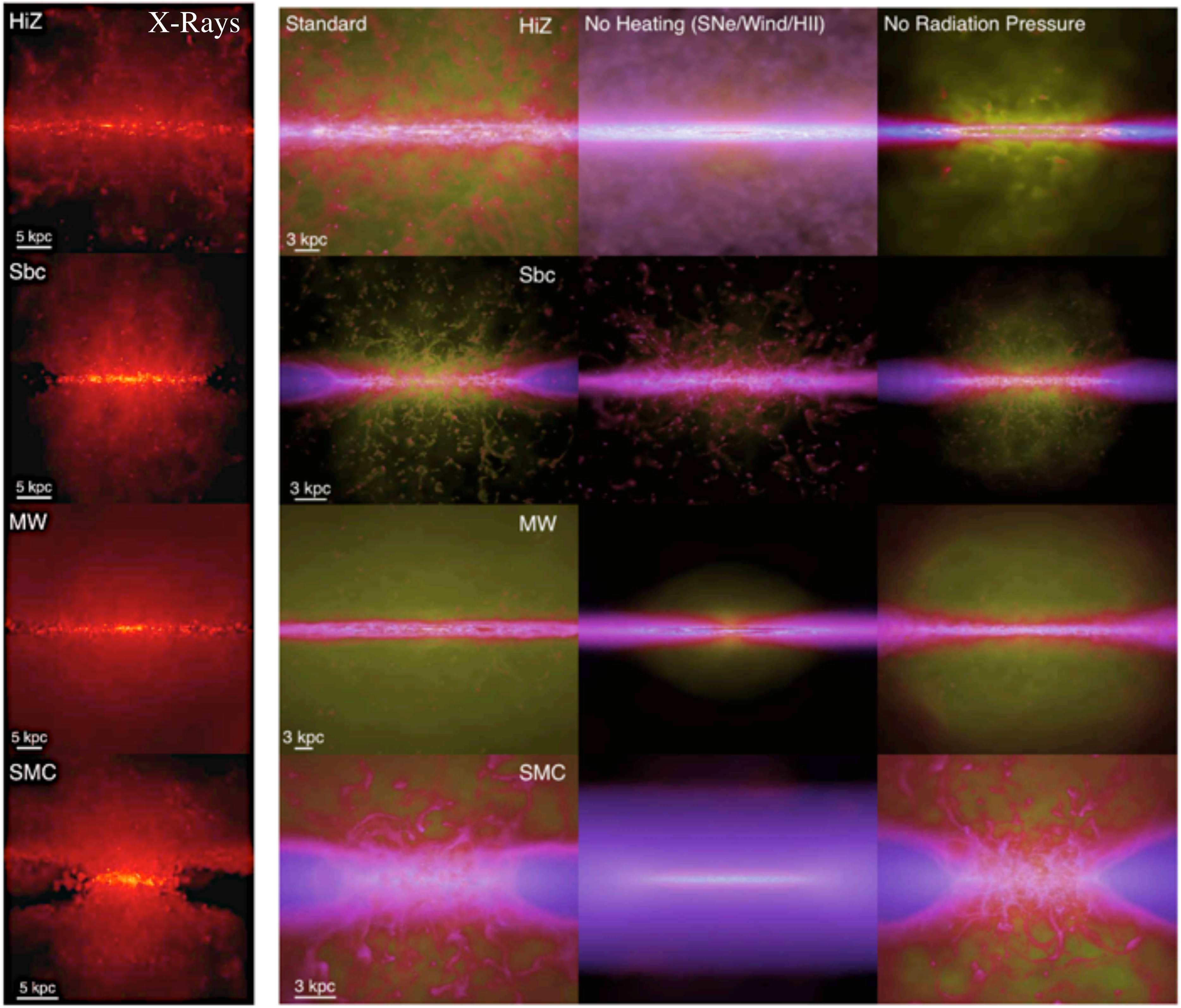


Galactic Super-Winds



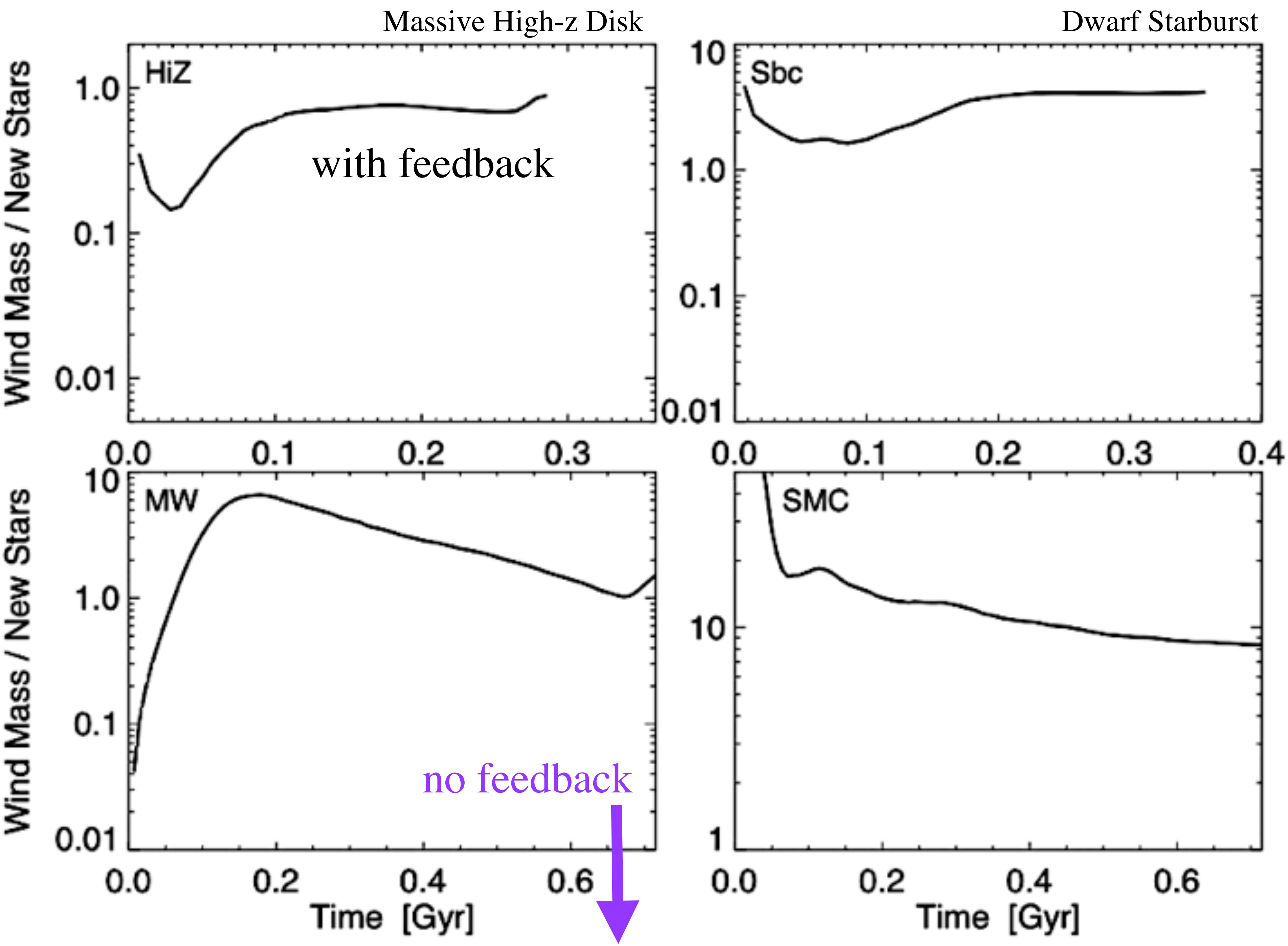





HiZ
X-Rays
5 kpc
Sbc
5 kpc
MW
5 kpc
SMC
5 kpc
Standard
HiZ
No Heating (SNe/Wind/HII)
No Radiation Pressure
3 kpc
Sbc
3 kpc
MW
3 kpc
SMC
3 kpc

How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?



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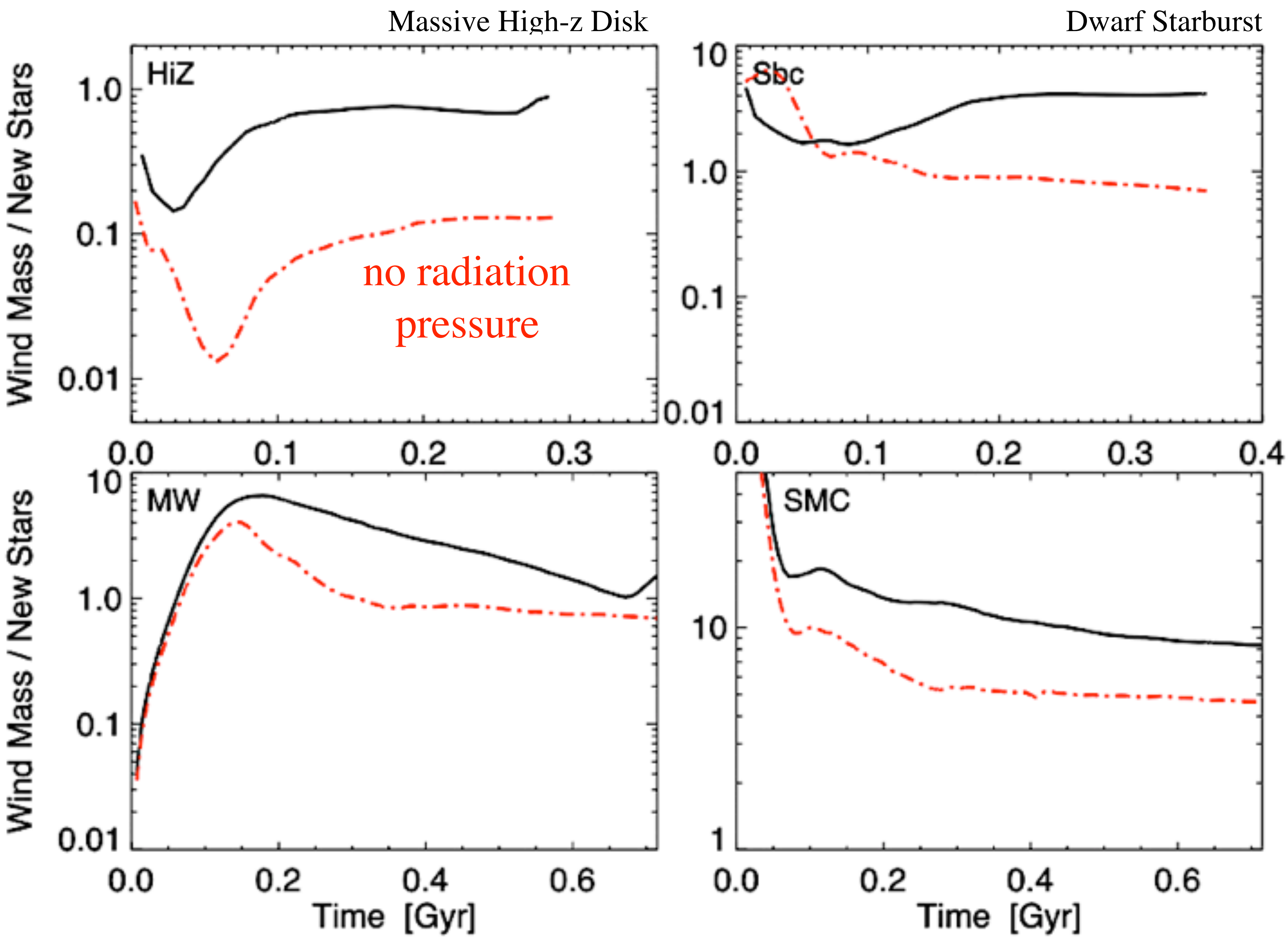

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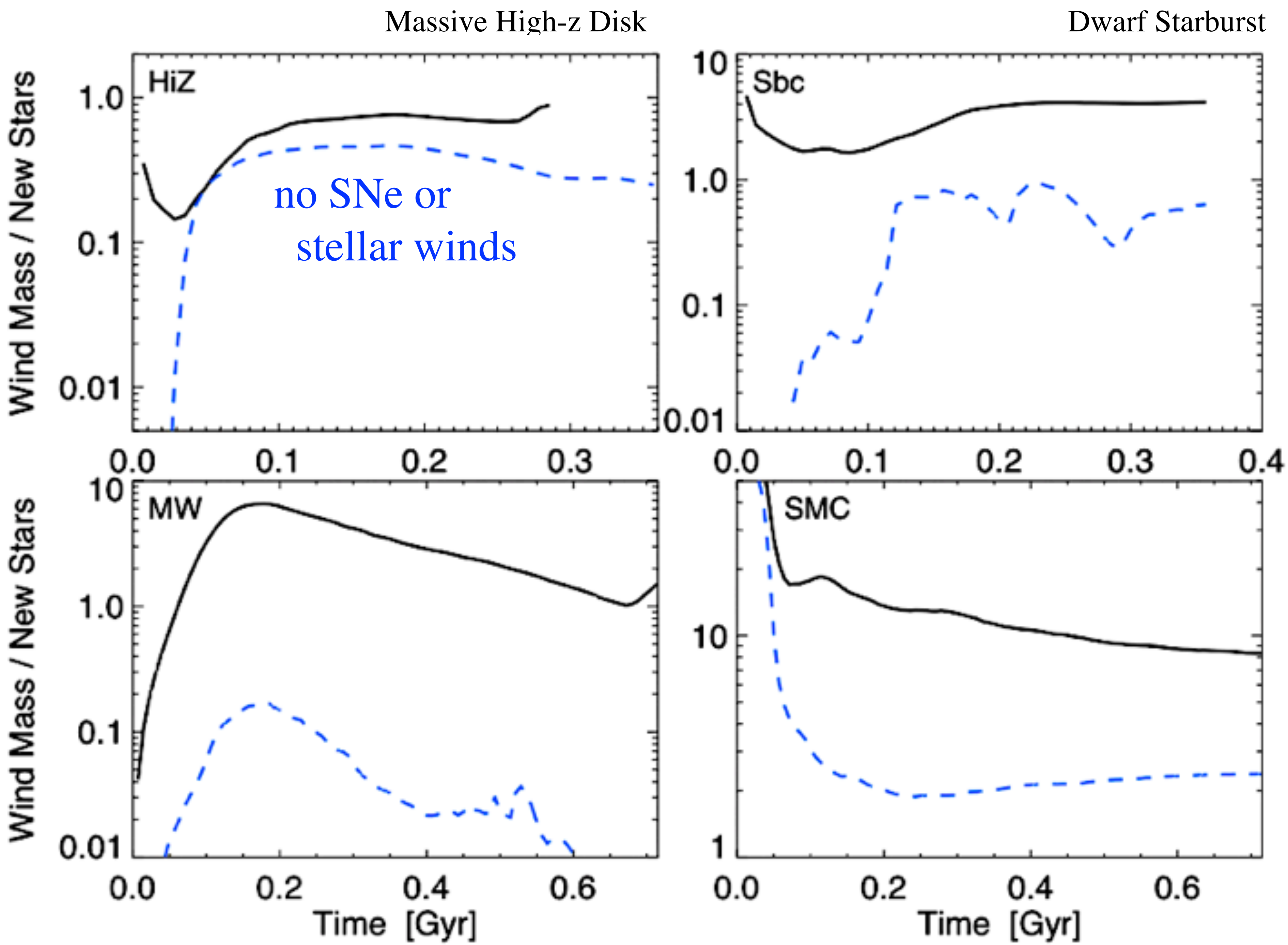

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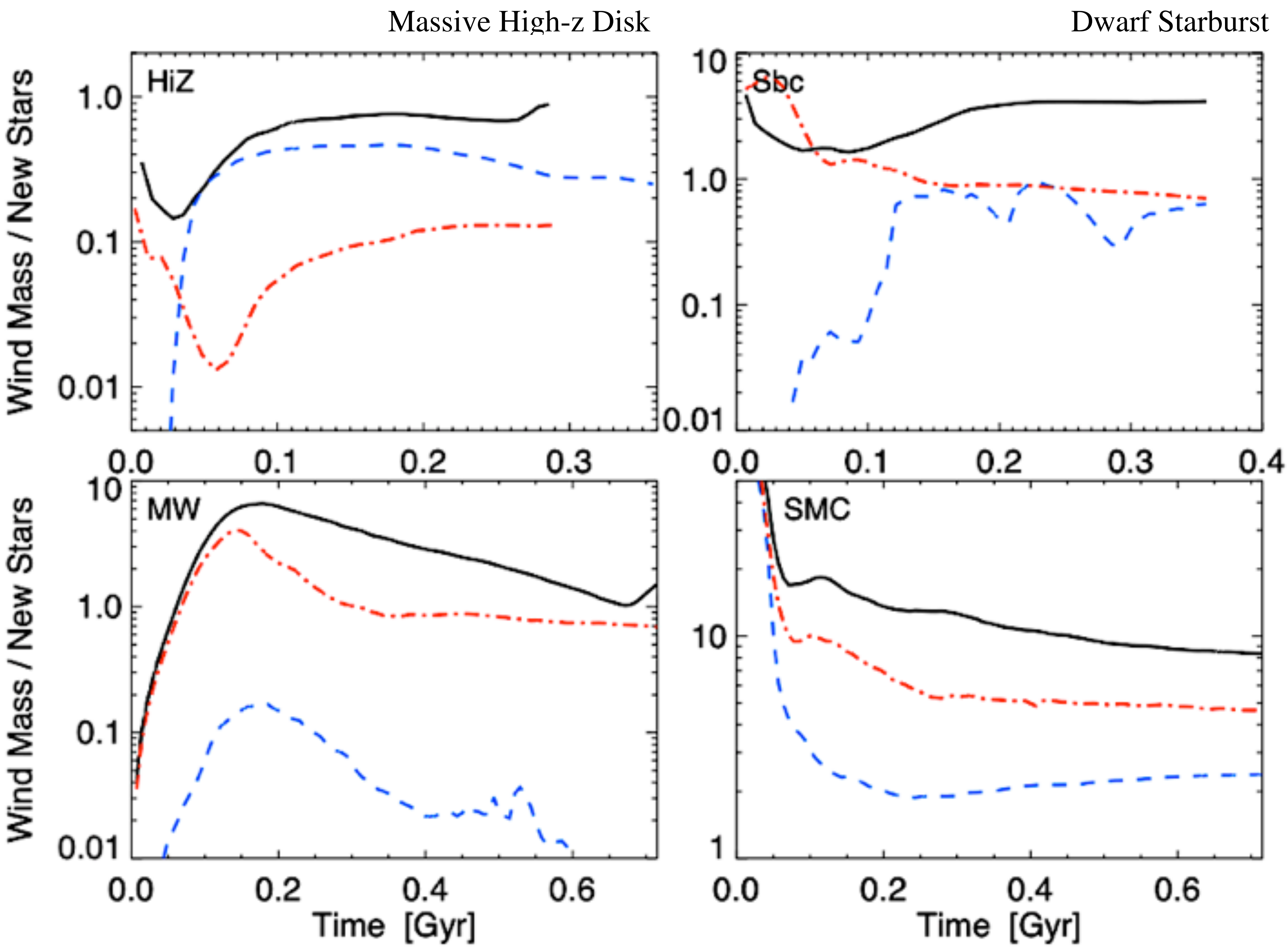

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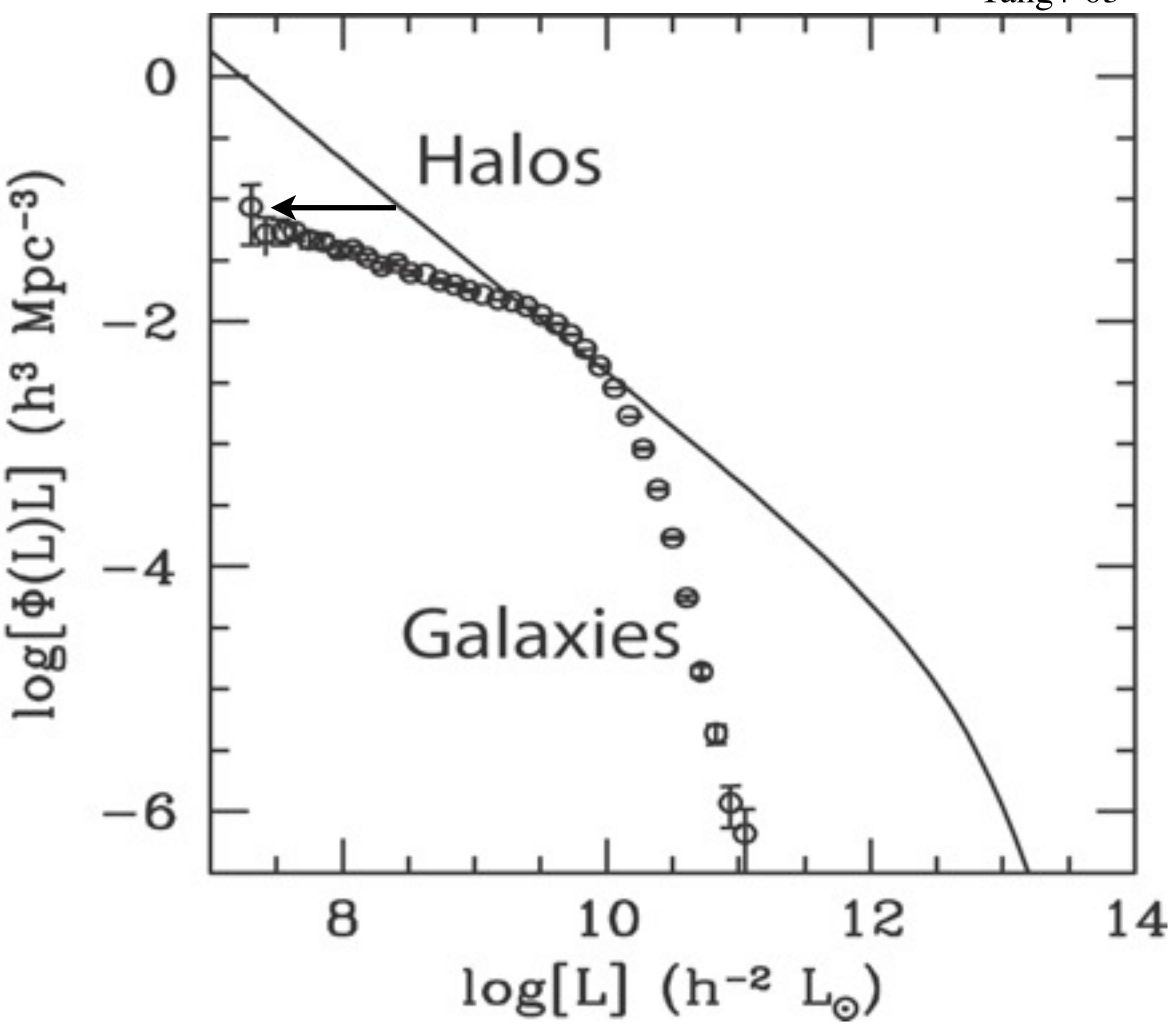
Yang+ 03



- Cosmological simulations "need":

$$\dot{M}_{\rm wind} \sim \dot{M}_* \left(\frac{300\,{\rm km\,s^{-1}}}{V_{\rm max}}\right)$$

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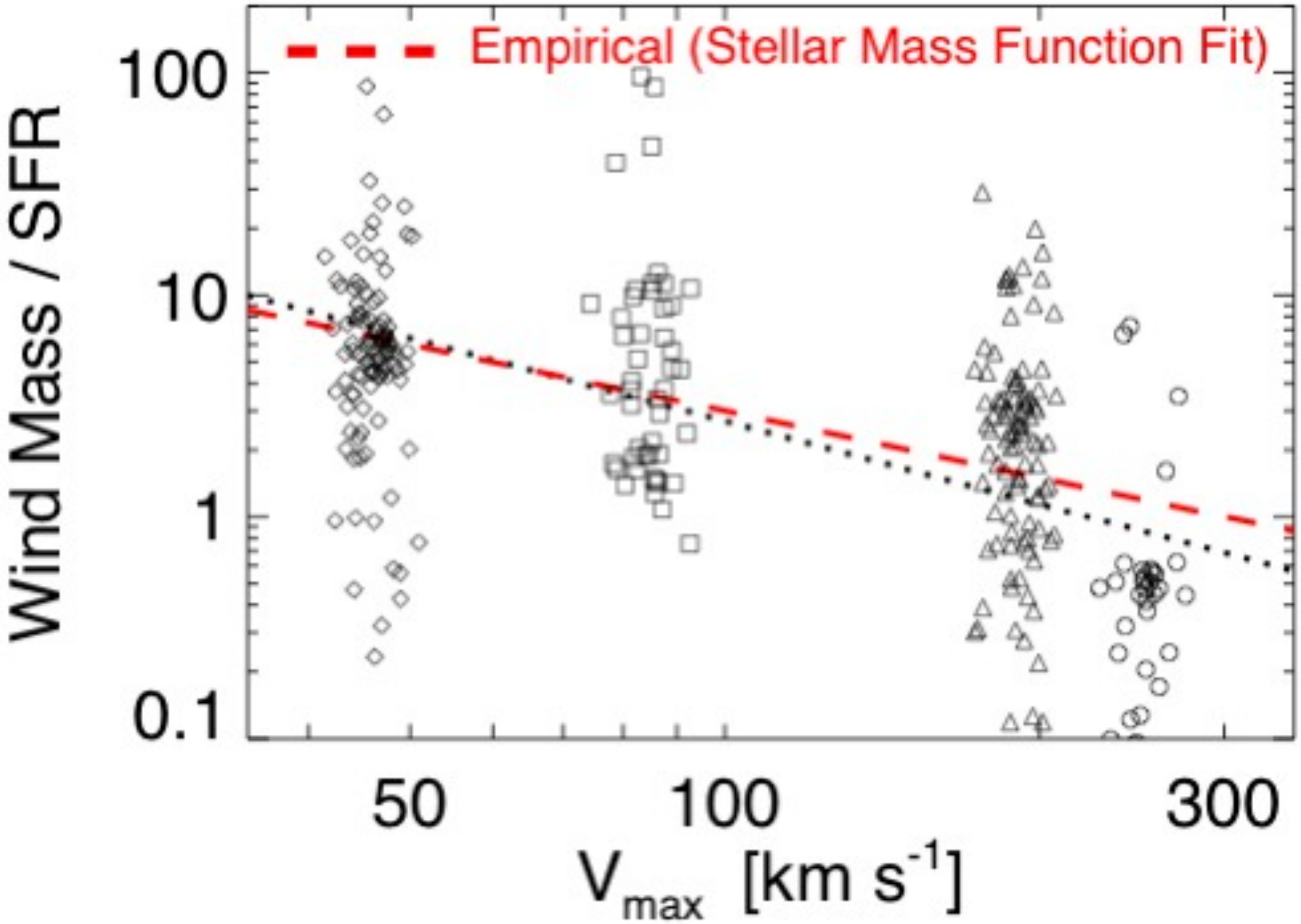

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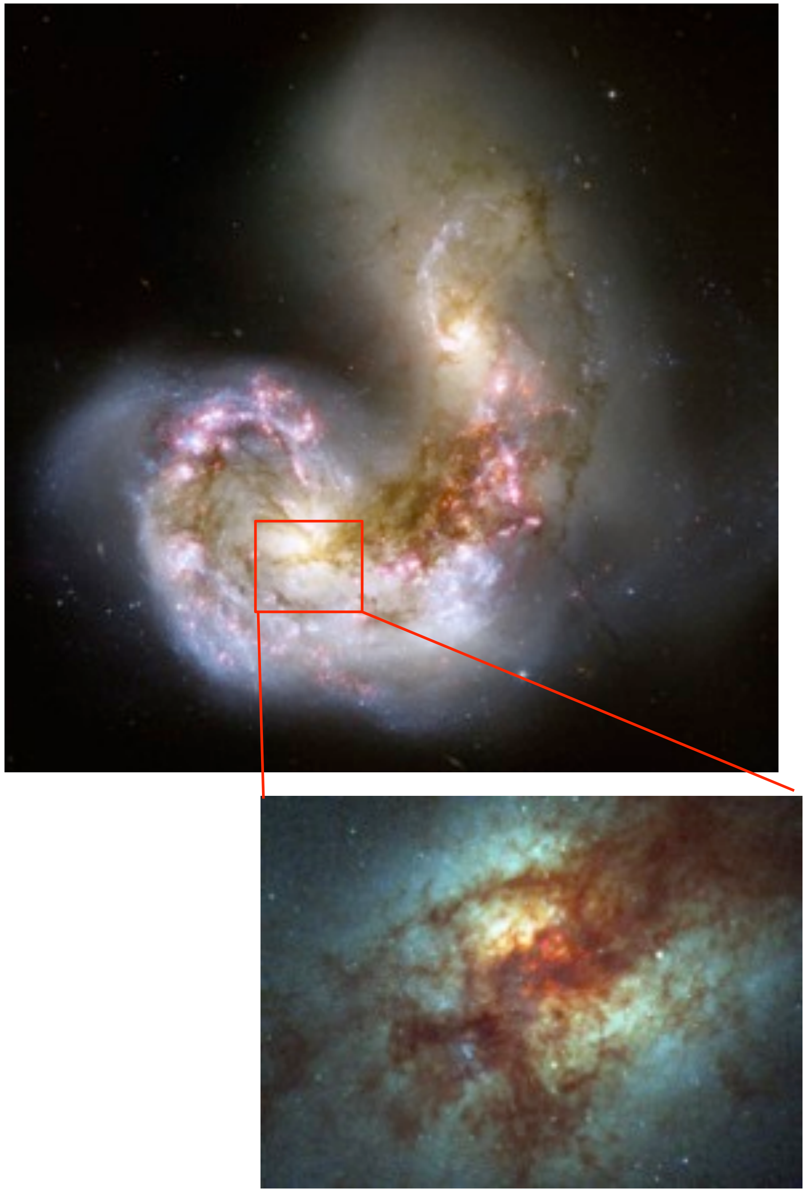
$$\dot{M}_{\rm wind} \sim \dot{M}_* \left(\frac{300\,{\rm km\,s^{-1}}}{V_{\rm max}}\right)$$

Future Directions
WHAT CAN WE EXPLORE WITH MORE REALISTIC ISM/FEEDBACK MODELS?

- Mergers:
  - Star cluster formation? Starburst environments?
- AGN Feedback:
  - How does it couple to a multi-phase ISM?
- Cosmological simulations:
  - "Zoom-in" disk formation simulations (D. Keres)
  - Cosmological volume AMR: dwarf populations and mass function evolution (M. Kuhlen)
- GMCs & ISM Structure:
  - Formation & destruction of GMCs, lifetimes, star formation efficiencies

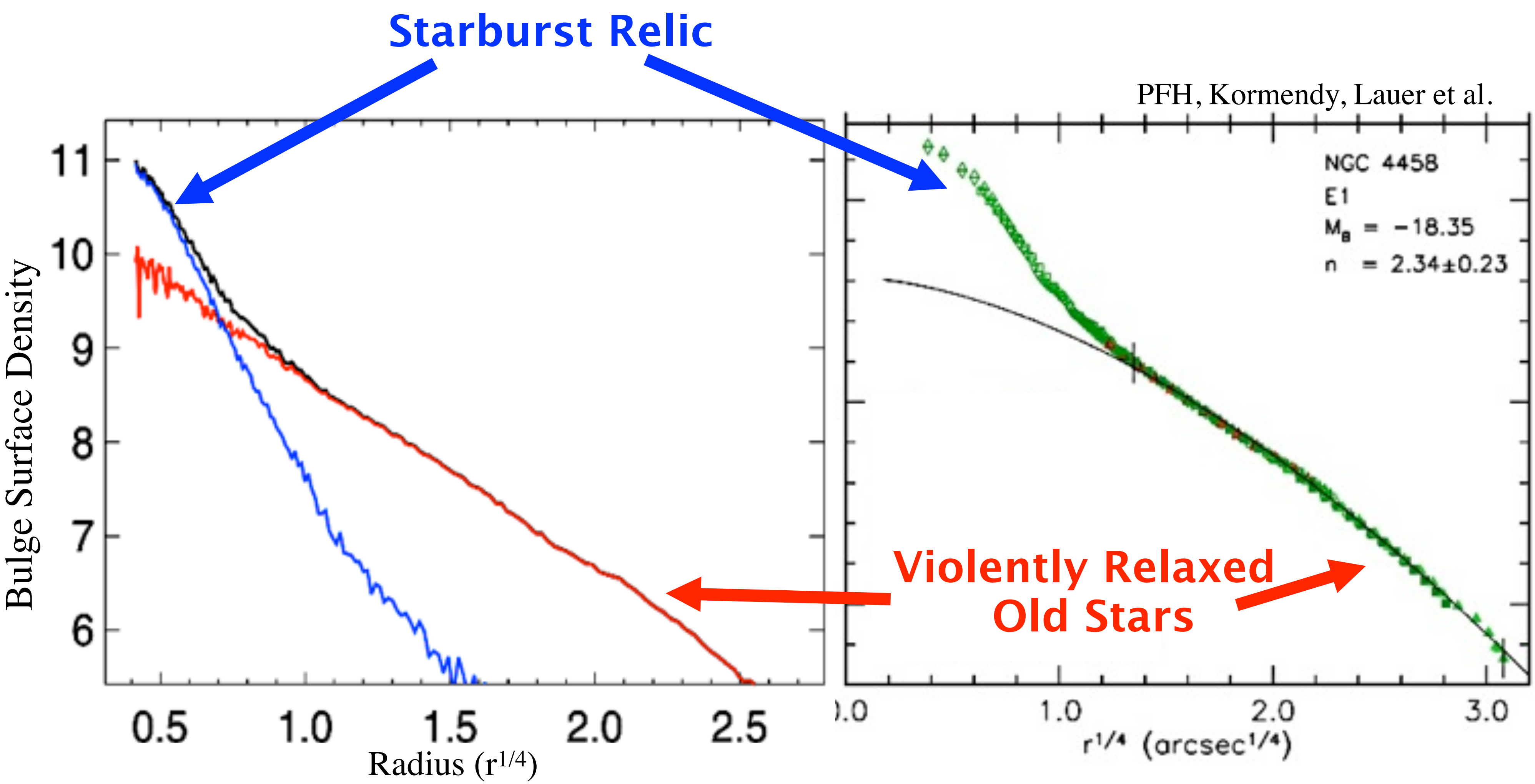


~30 sec

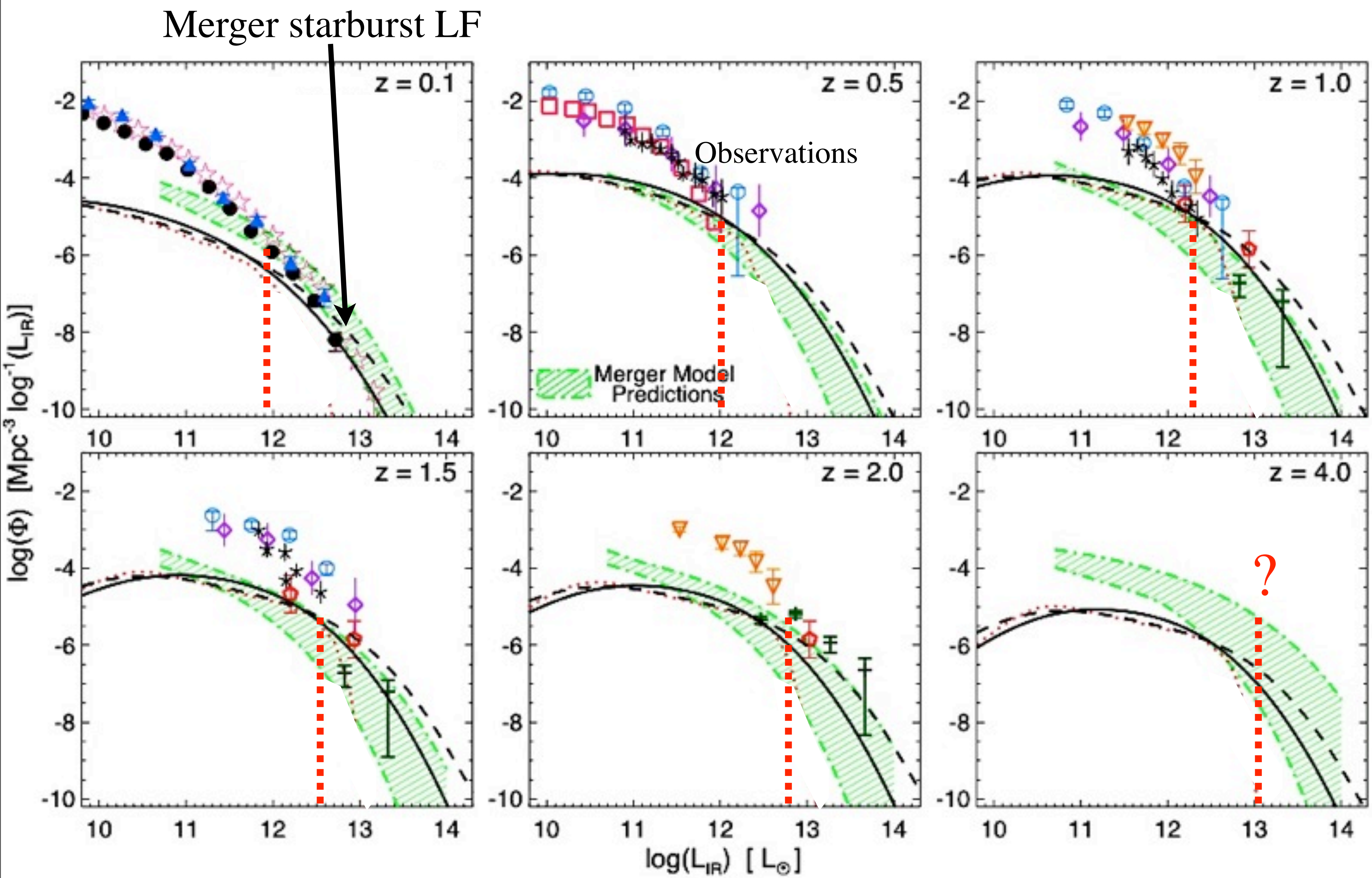
A Few Words on Mergers...
WHY DO WE CARE ABOUT THEIR STAR FORMATION

Mihos & Hernquist 94
Kormendy+99,05,08,10
Lauer+98,05,07
Hopkins, Kormendy, Lauer 10a-d
Ferrarese+06, Cote+08

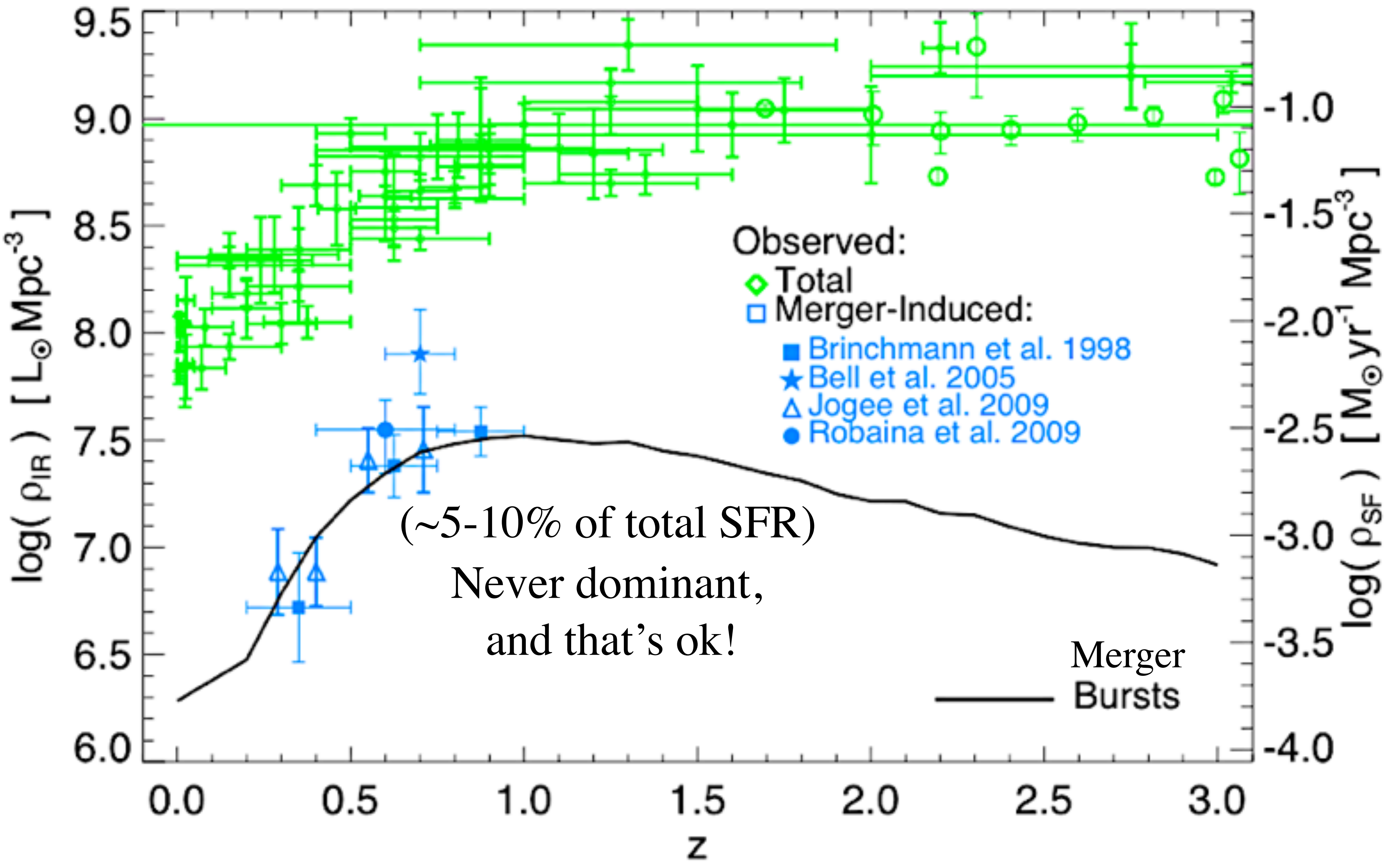
Elliptical structure is fundamentally two-component:



Mergers always dominate at highest L, but the threshold shifts

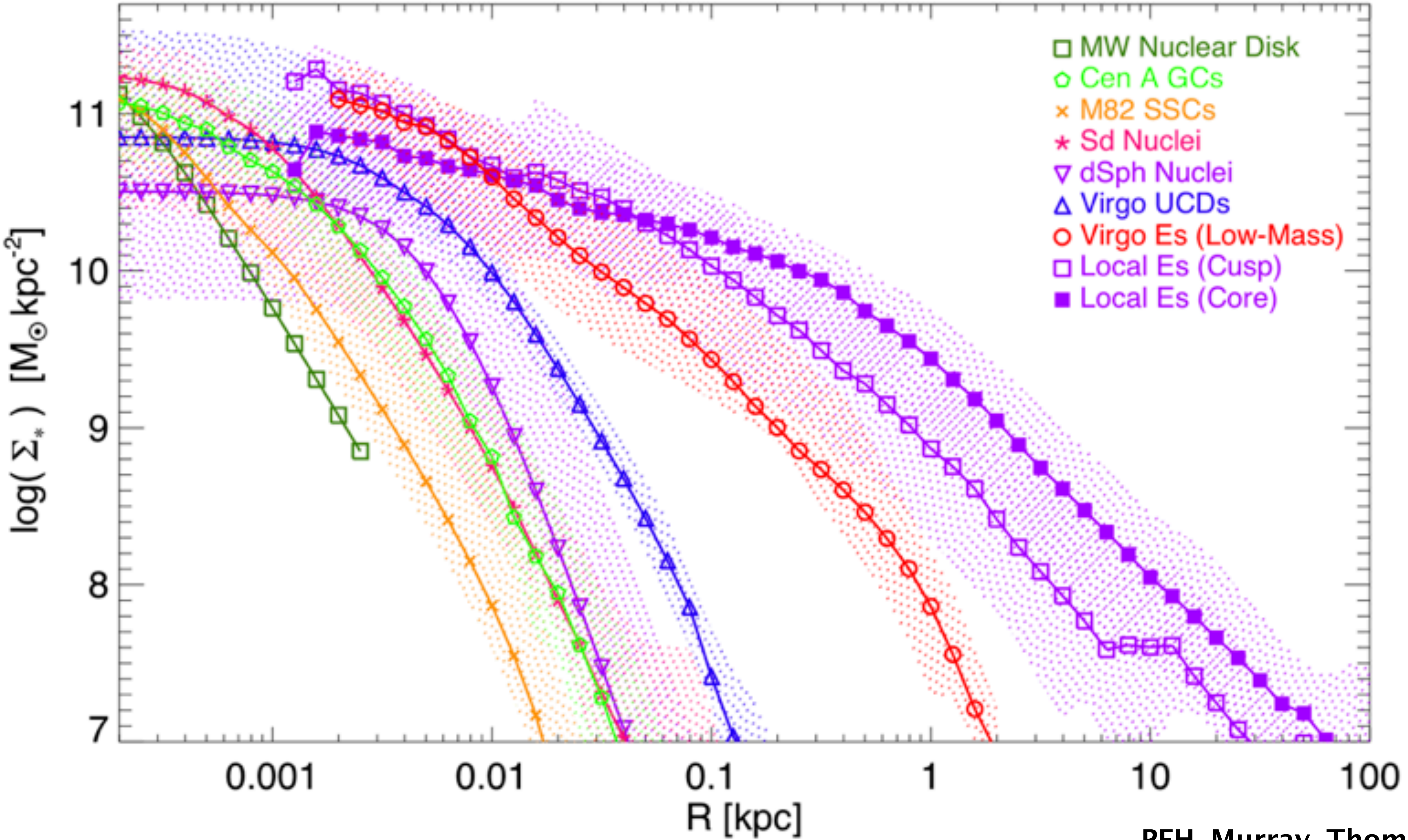


The Role of Starbursts in Cosmic Star Formation:

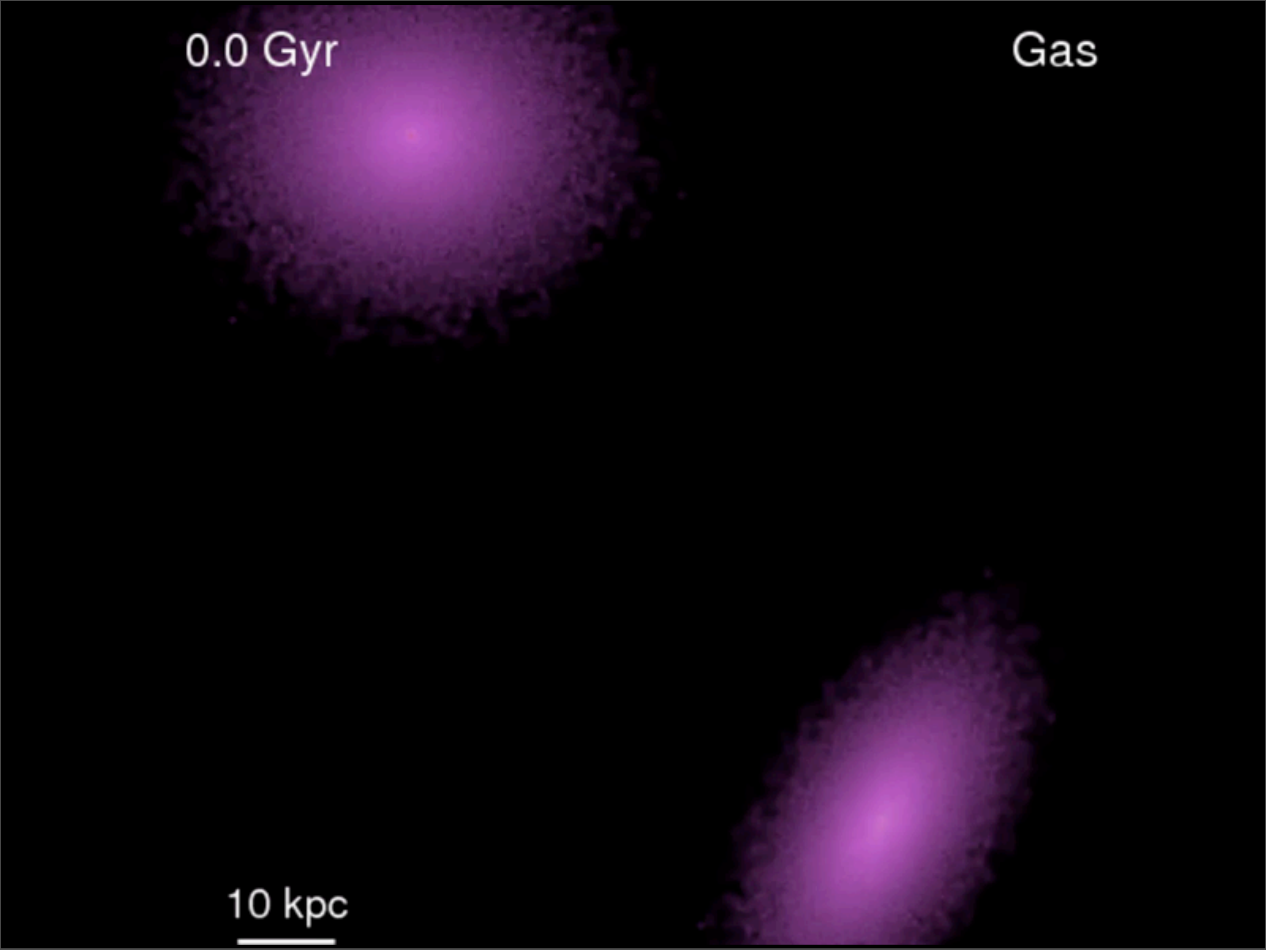


This Accounts for the Centers of (nearly all) Ellipticals

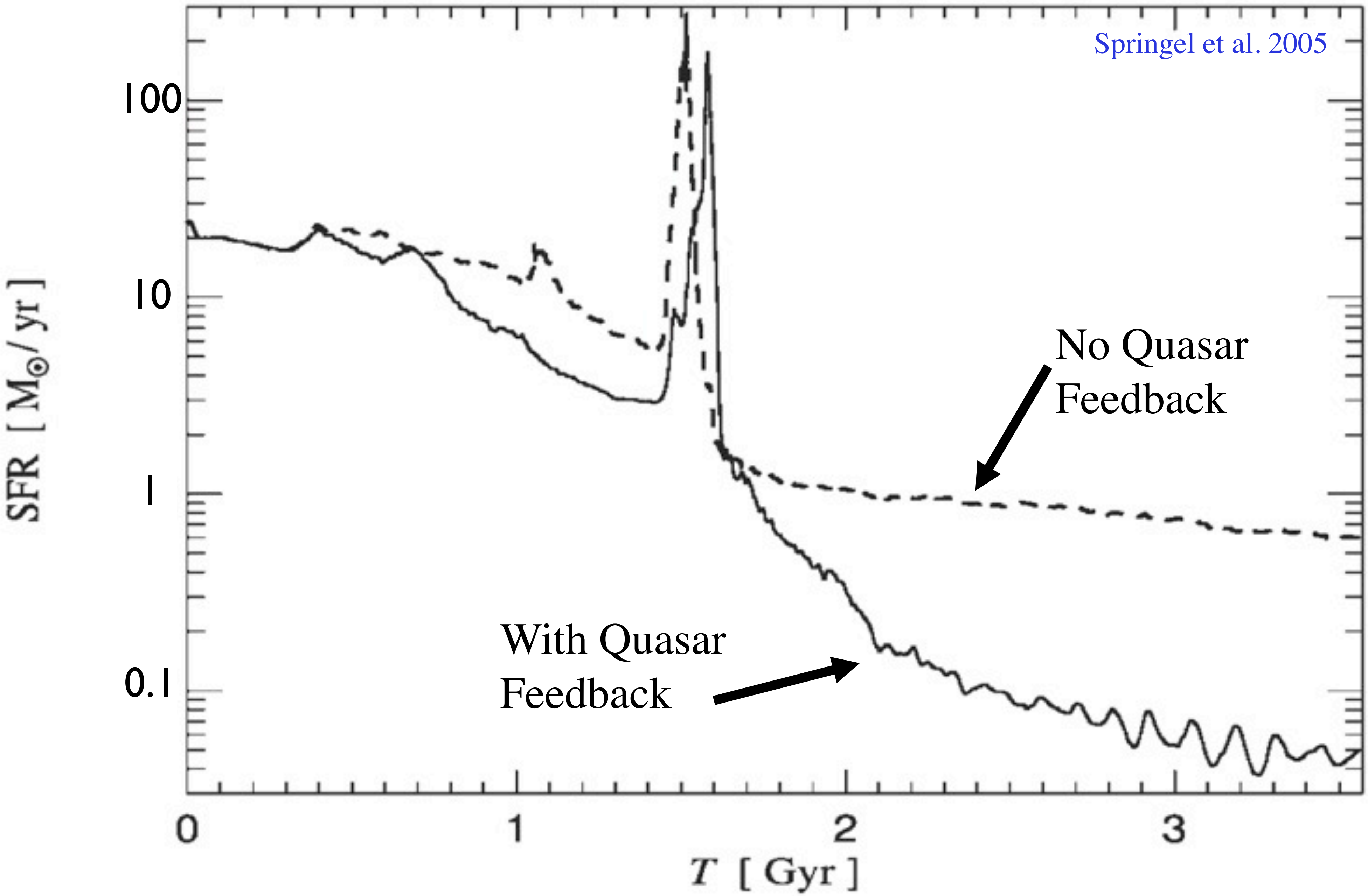
WHAT ARE THE PHYSICS AT WORK?



PFH, Murray, Thomps
et al. 2009


0.0 Gyr
Gas
10 kpc

Do we still need 'Quasar Mode' Feedback?



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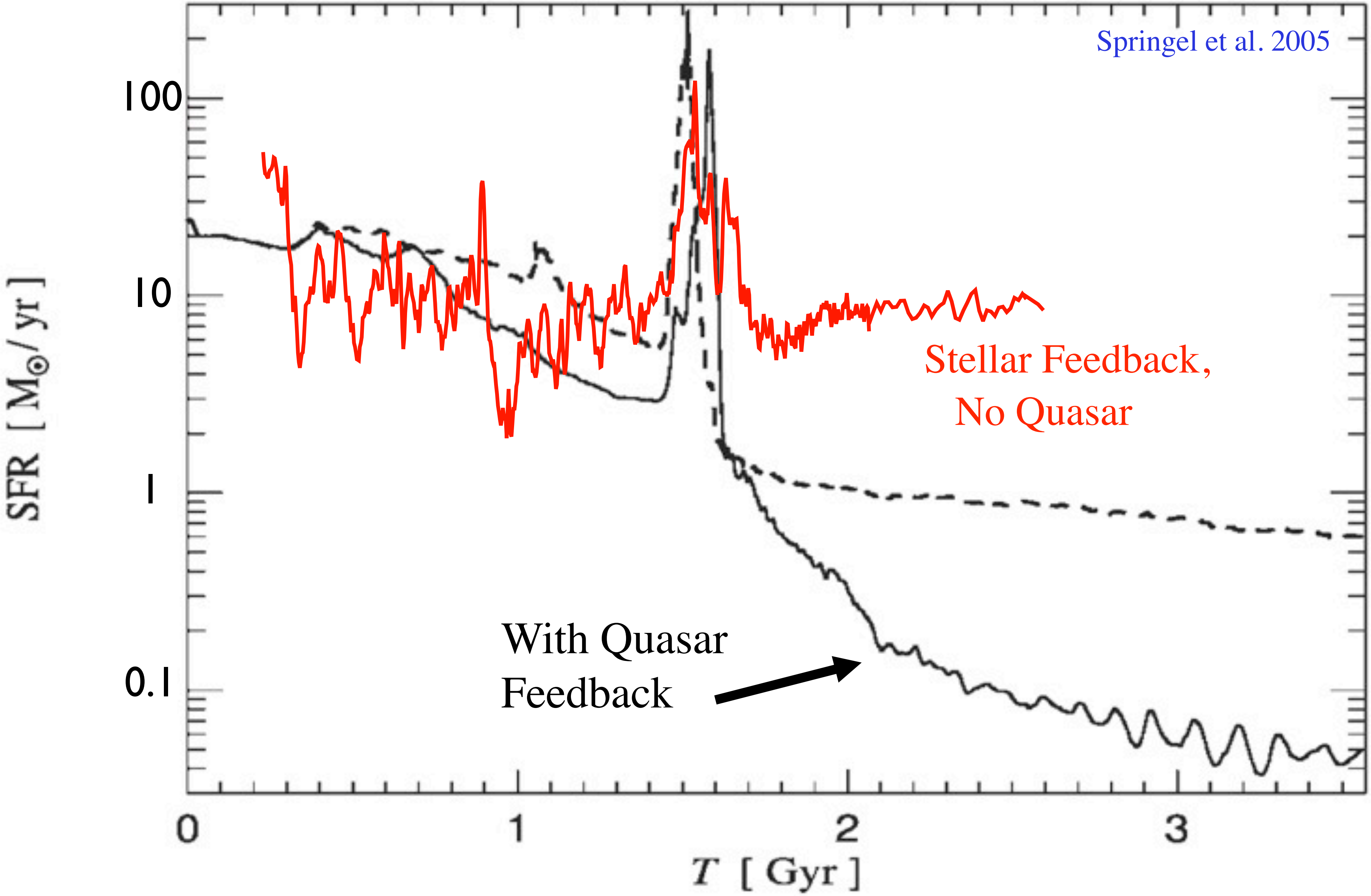


Summary:

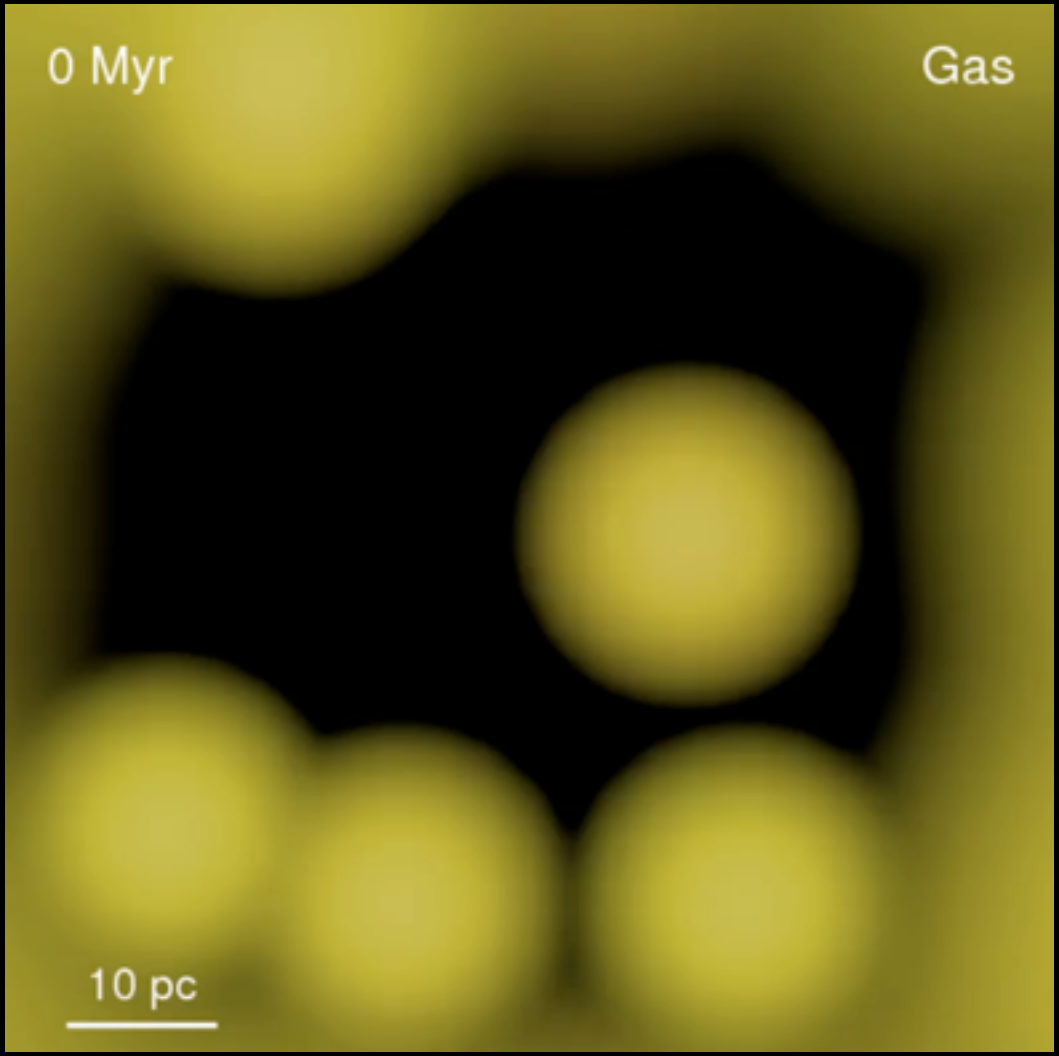
- Global **Star formation is Feedback-Regulated**: *independent* of small-scale SF 'law' (same for molecular chemistry, cooling, etc)
    - Need 'enough' stars to offset dissipation (set by gravity)

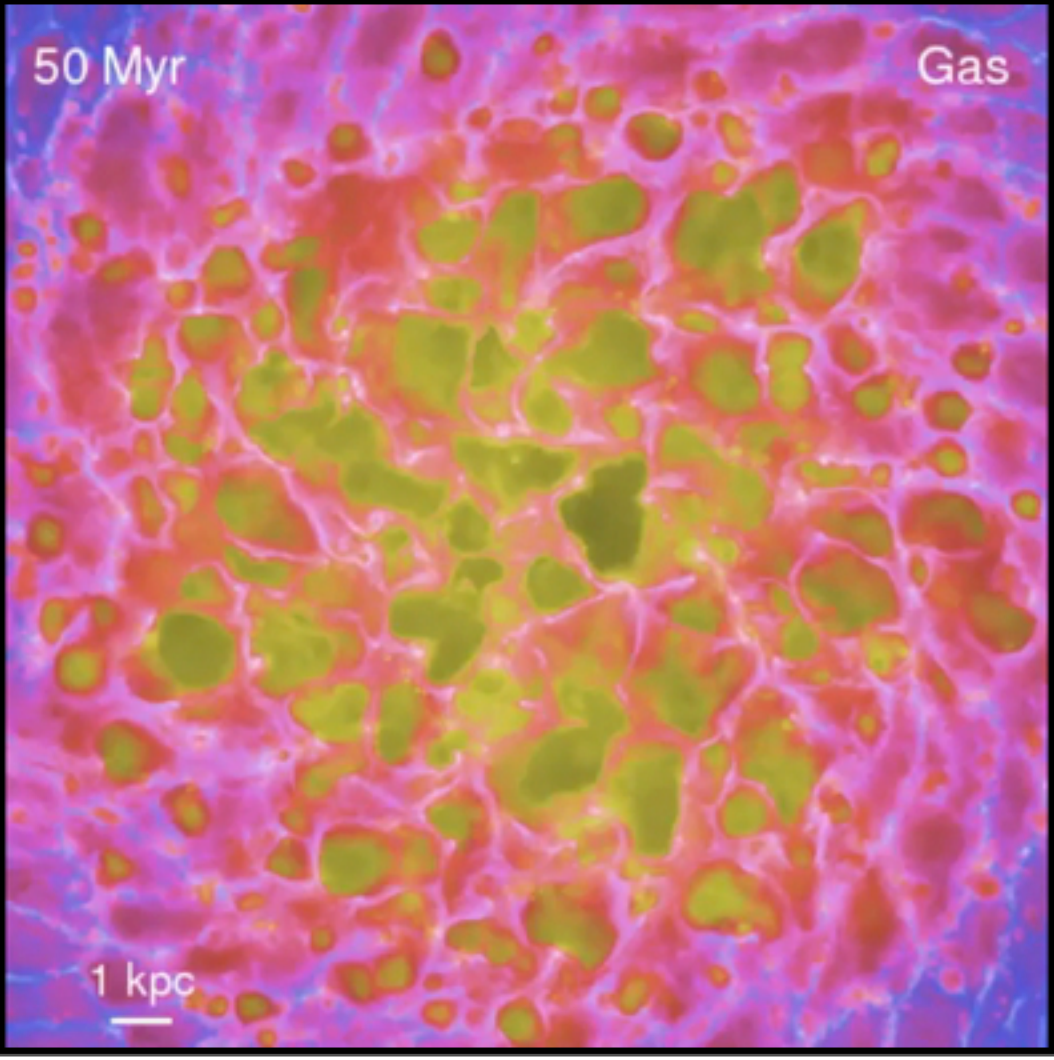
- 'Gravity+turbulence' alone fails. Badly.
  - That said, galaxies will find a way to get to Q~1:
    s(gas) independent of feedback.... even when driven by feedback

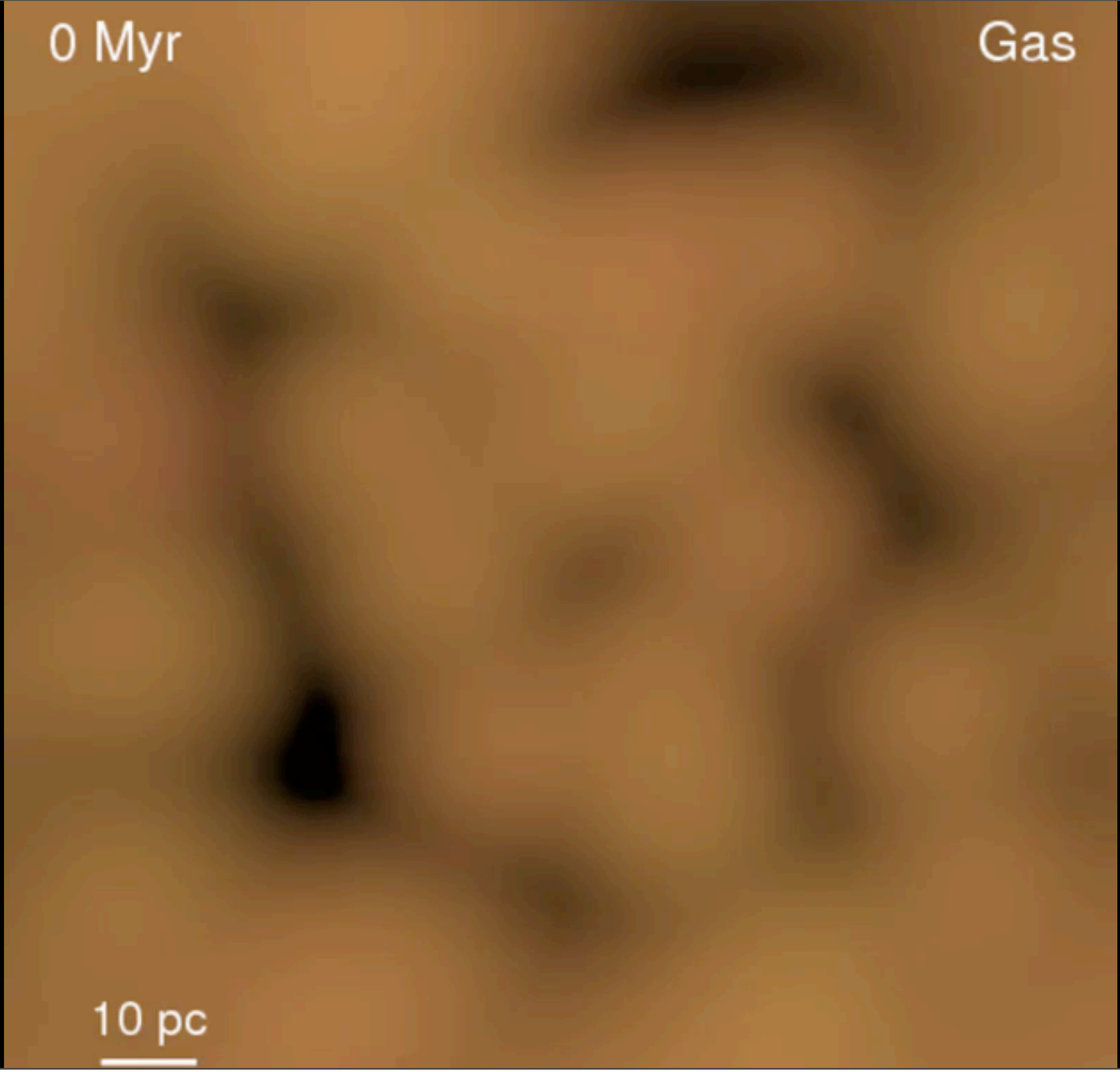
- Feedback leads to Kennicutt relation & super-winds:
  - Mass-loading $\dot{M}_{\rm wind} \propto \dot{M}_{*}/V_c$

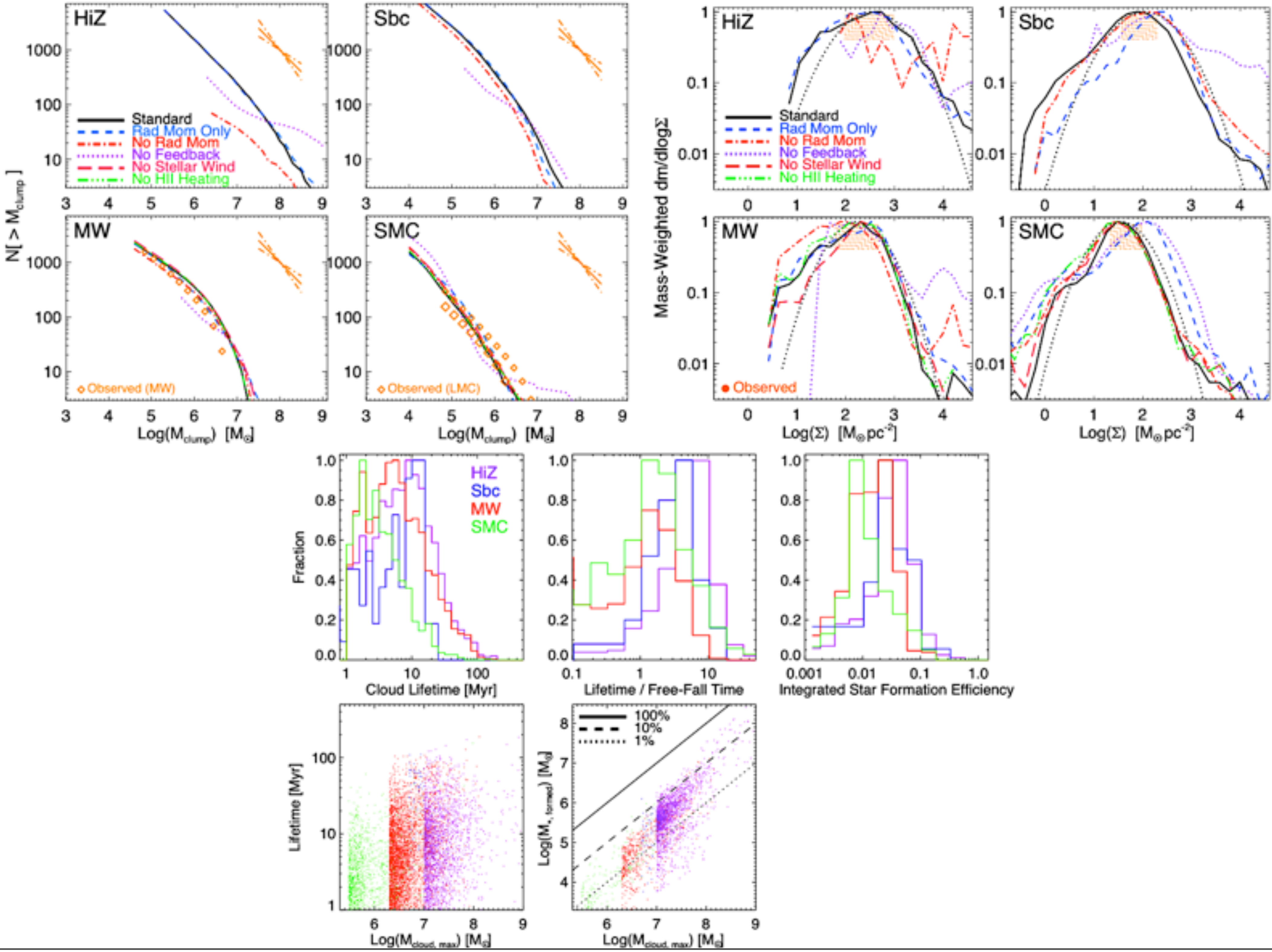
- Different feedback mechanisms dominate different regimes:
  - High densities: radiation pressure
  - Intermediate densities: HII heating, stellar wind momentum
  - Low densities: SNe & stellar wind shock-heating
    - Extremely non-linear coupling between them!
    - **No *one* mechanism works**

- Even if every bulge forms in a merger, only ~10% of stars
  - (an important 10%!)
    - Bulge kinematics, shapes, dispersions, mass densities, kinematic subcomponents
    - Fuels SMBH growth?

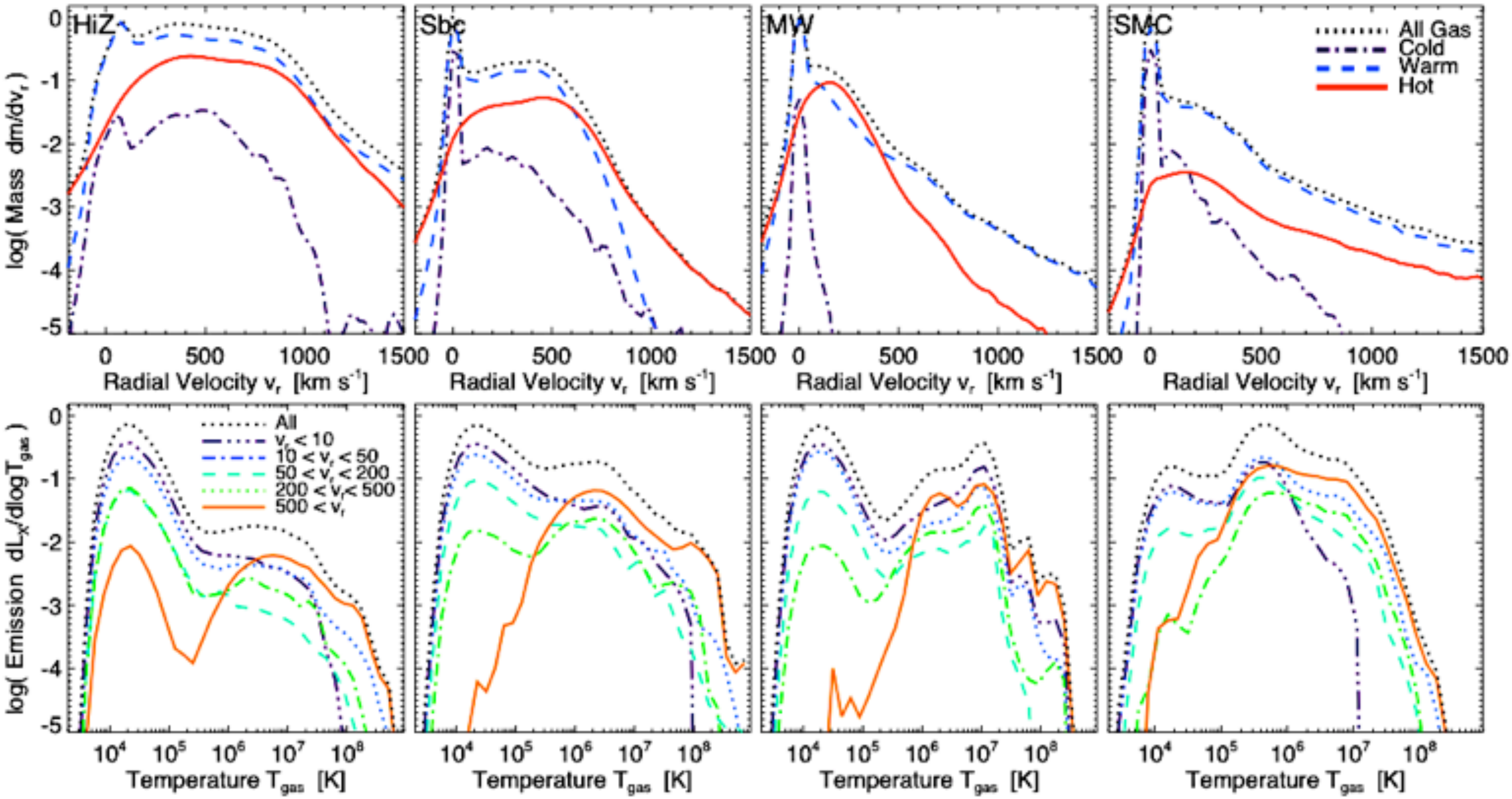

0 Myr
Gas
10 pc


50 Myr
Gas
1 kpc


0 Myr
Gas
10 pc



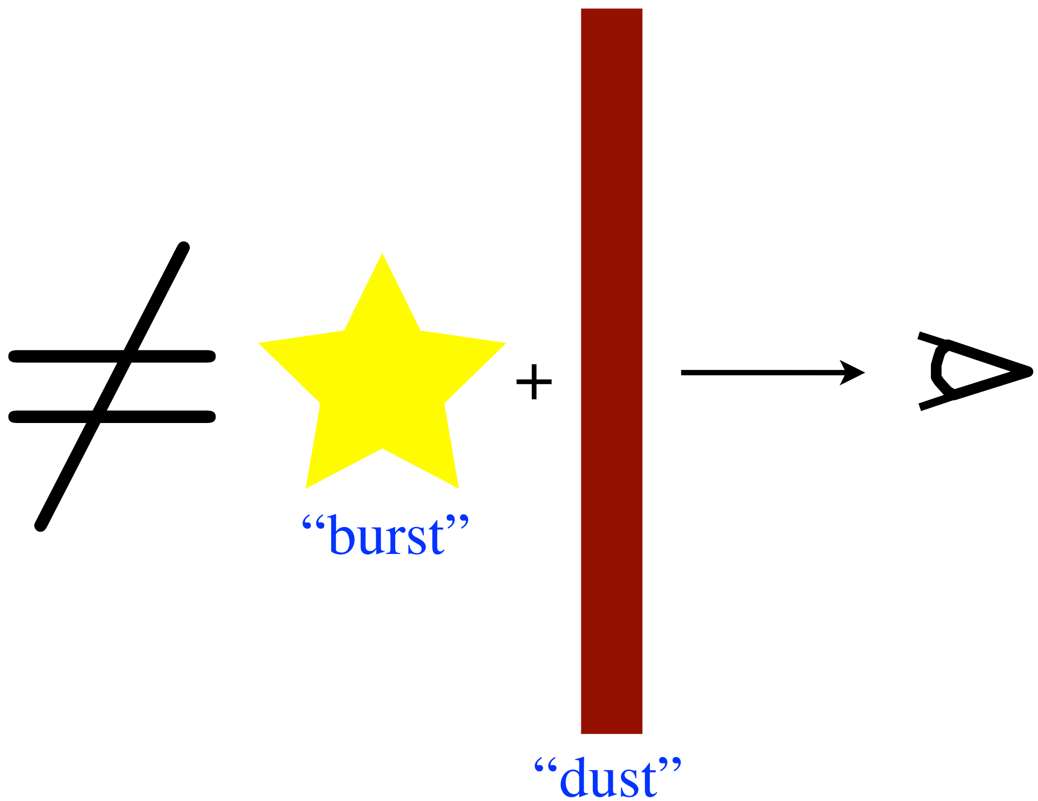
HiZ
Sbc
MW
SMC
Standard
Rad Mom Only
No Rad Mom
No Feedback
No Stellar Wind
No HII Heating
N[> M_clump]
Log(M_clump) [M_⊙]
Observed (MW)
Observed (LMC)
Mass-Weighted dm/dlogΣ
Log(Σ) [M_⊙pc^-2]
Observed
Fraction
Cloud Lifetime [Myr]
Lifetime / Free-Fall Time
Integrated Star Formation Efficiency
Lifetime [Myr]
Log(M_cloud, max) [M_⊙]
Log(M_*, formed) [M_⊙]
100%
10%
1%


HiZ
Sbc
MW
SMC
All Gas
Cold
Warm
Hot
log(Mass dm/dv$_r$)
Radial Velocity v$_r$ [km s^{-1}]
All
v$_r$ < 10
10 < v$_r$ < 50
50 < v$_r$ < 200
200 < v$_r$ < 500
500 < v$_r$
log(Emission dL$_X$/dlogT$_{gas}$)
Temperature T$_{gas}$ [K]

What About the Gas that Does Lose Angular Momentum?

STARBURSTS: ON THEIR WAY TO ELLIPTICALS?

- Radiative Transfer: SUNRISE by P. Jonsson
- Not just at z=0, but in high-redshift sub-millimeter galaxies (e.g. work by Melbourne, Narayanan, Genzel & co.)



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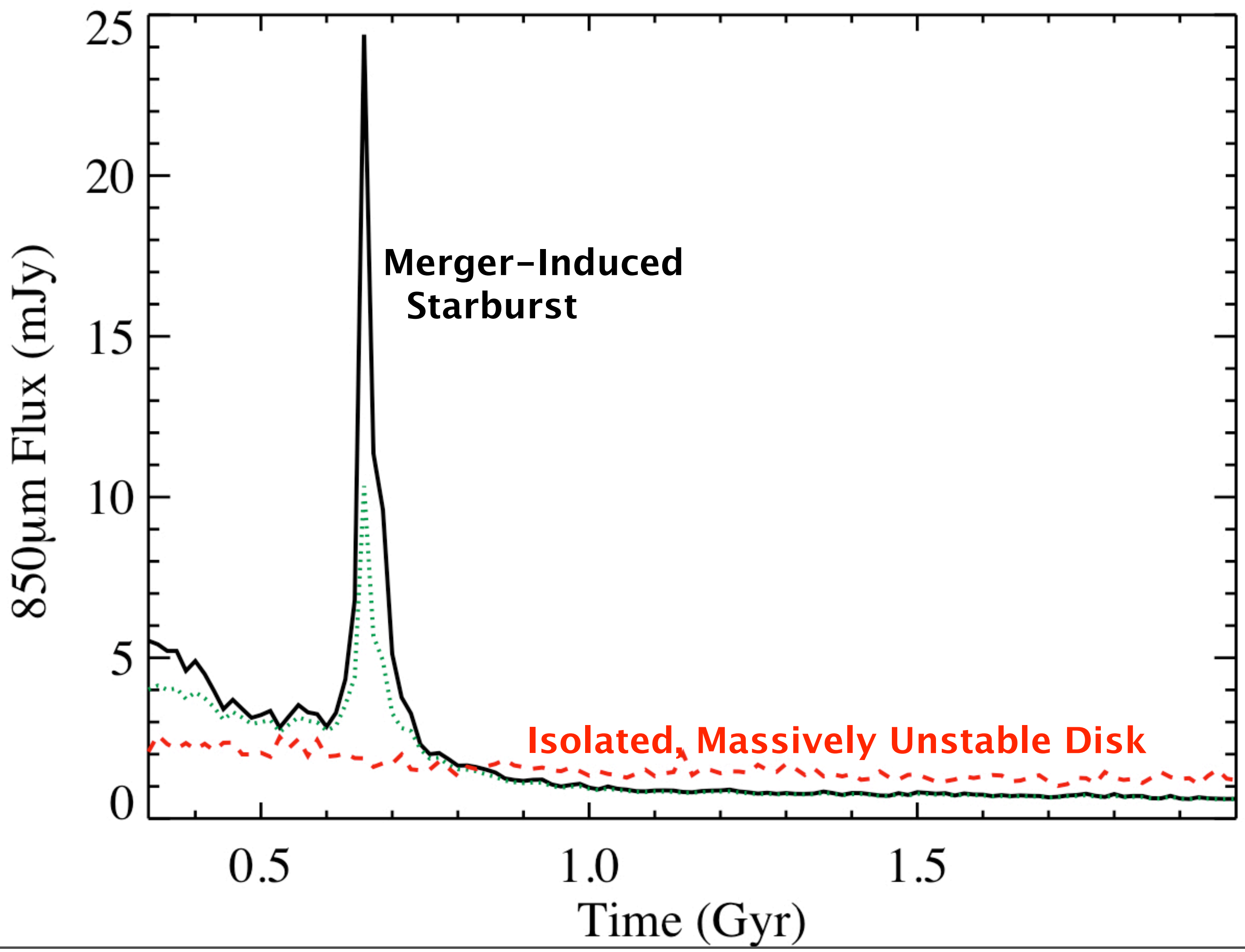

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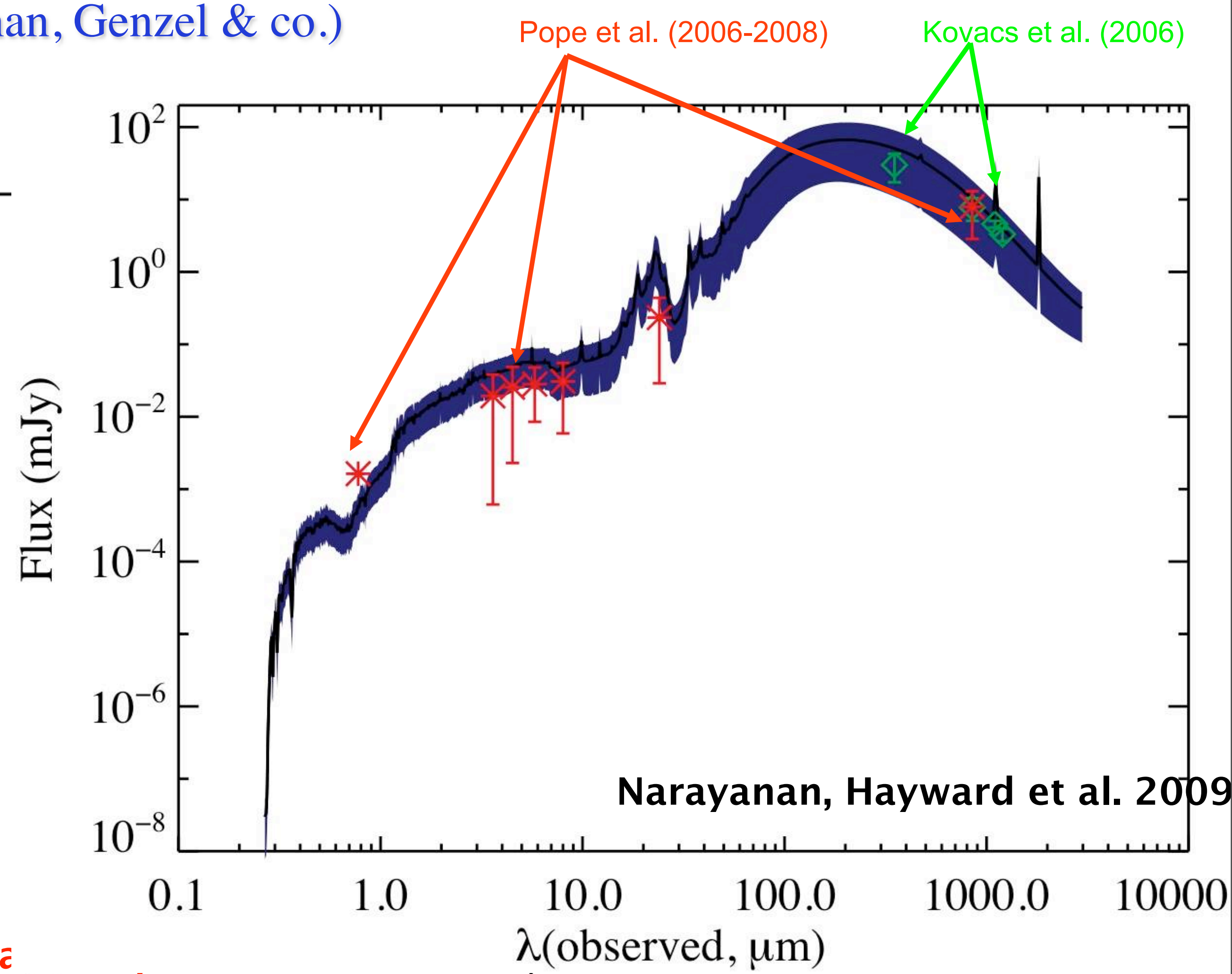

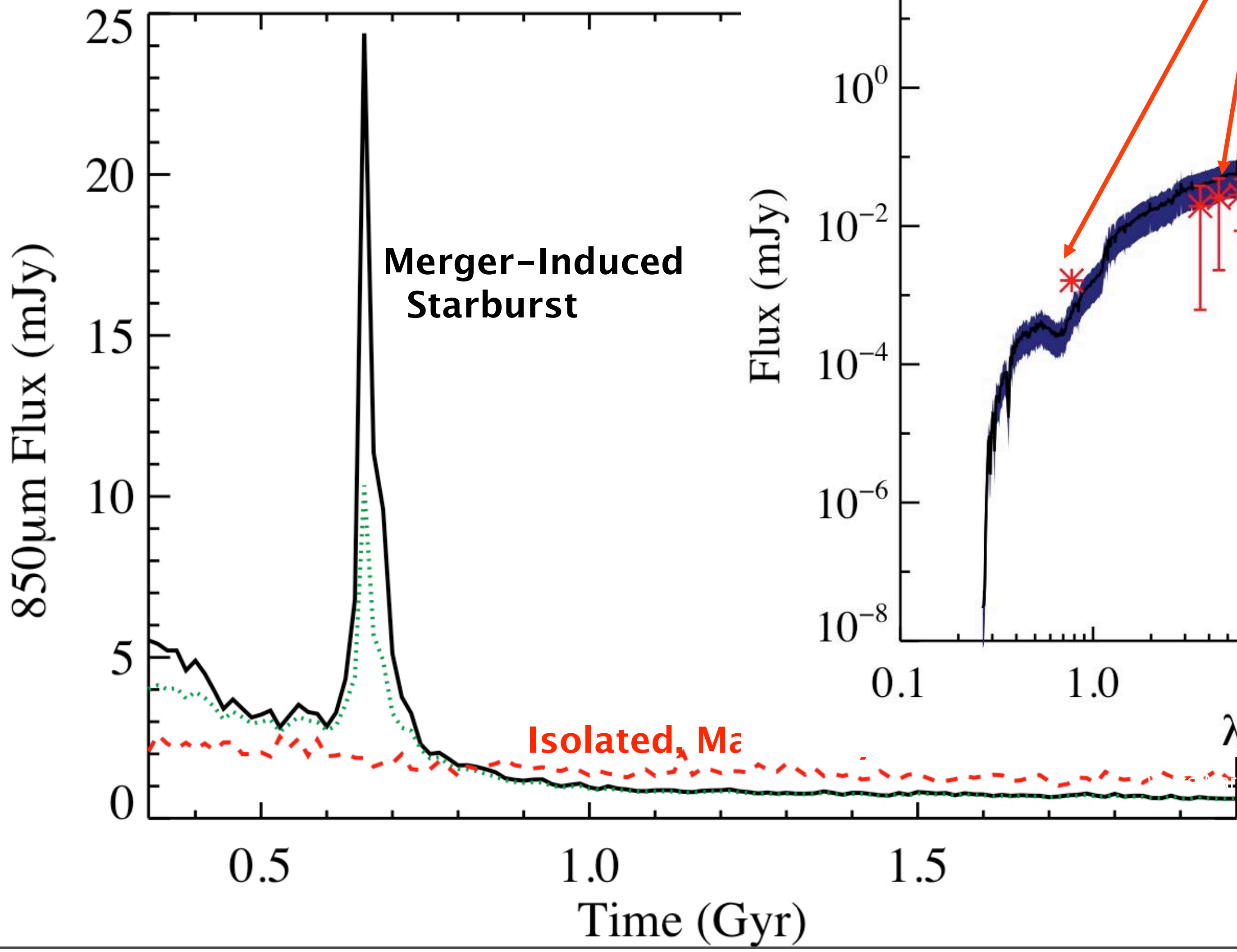

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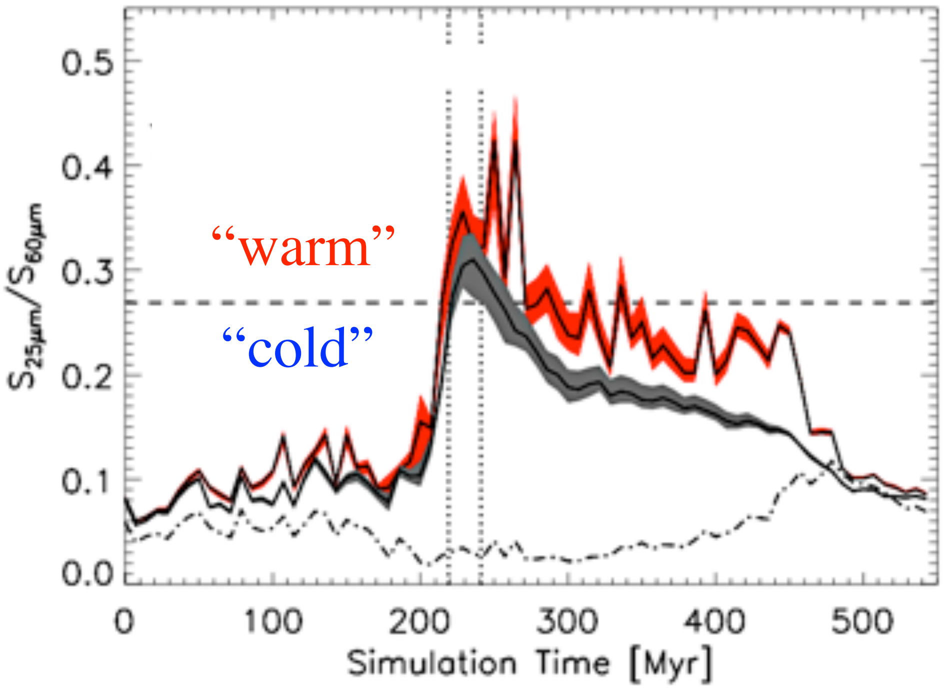
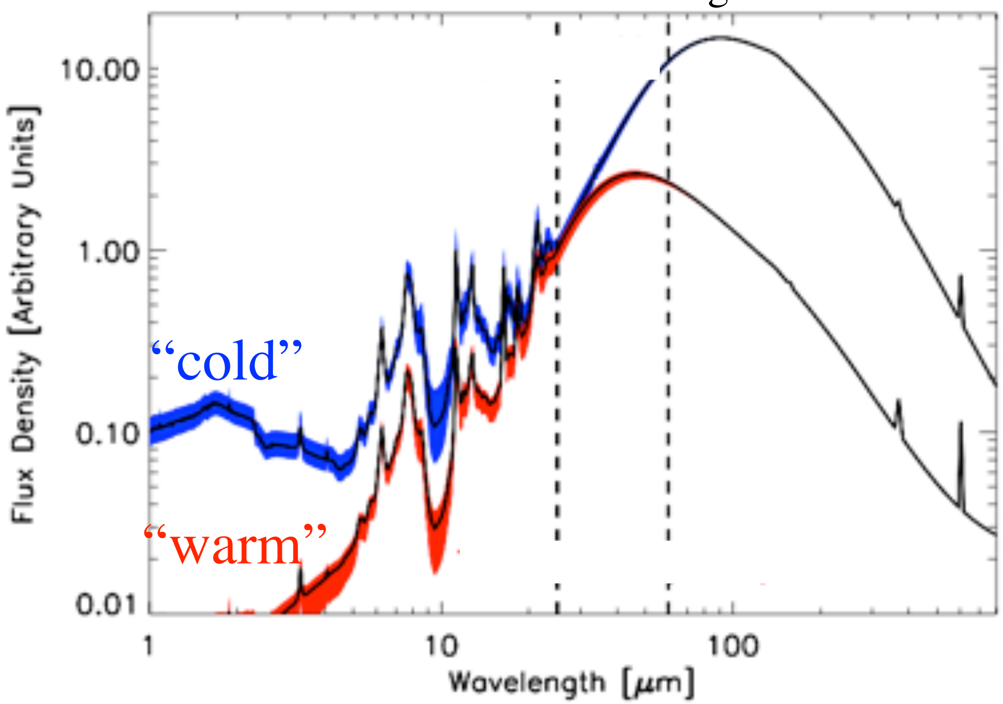
Narayanan et al. 2010,
Younger et al. 2010

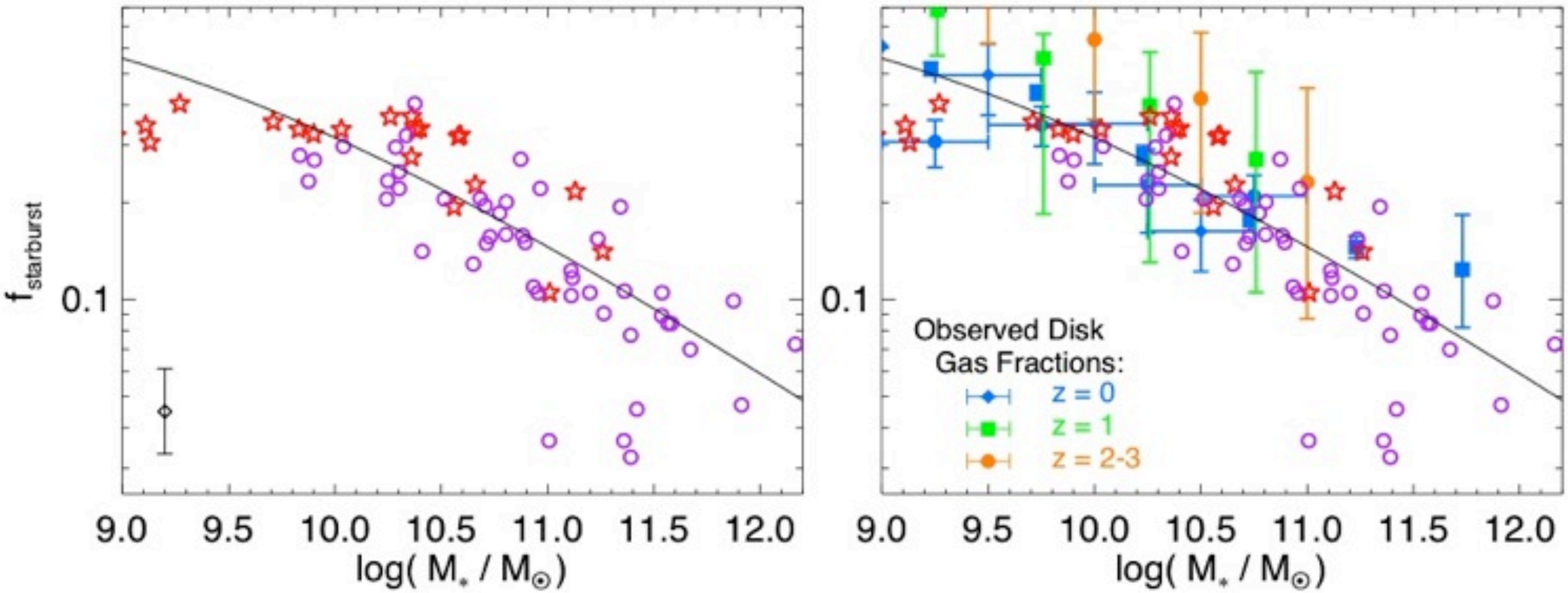




Structure in Elliptical Light Profiles
RECOVERING THE ROLE OF GAS

PFH & Rothberg et al. 2008
PFH, Kormendy, & Lauer et al. 2

Starburst mass needed to
match observed profile:



- You DO get realistic ellipticals, IF given realistic disks
- Recover the "tilt" in the fundamental plane:
  spheroid scalings = disks + dissipation

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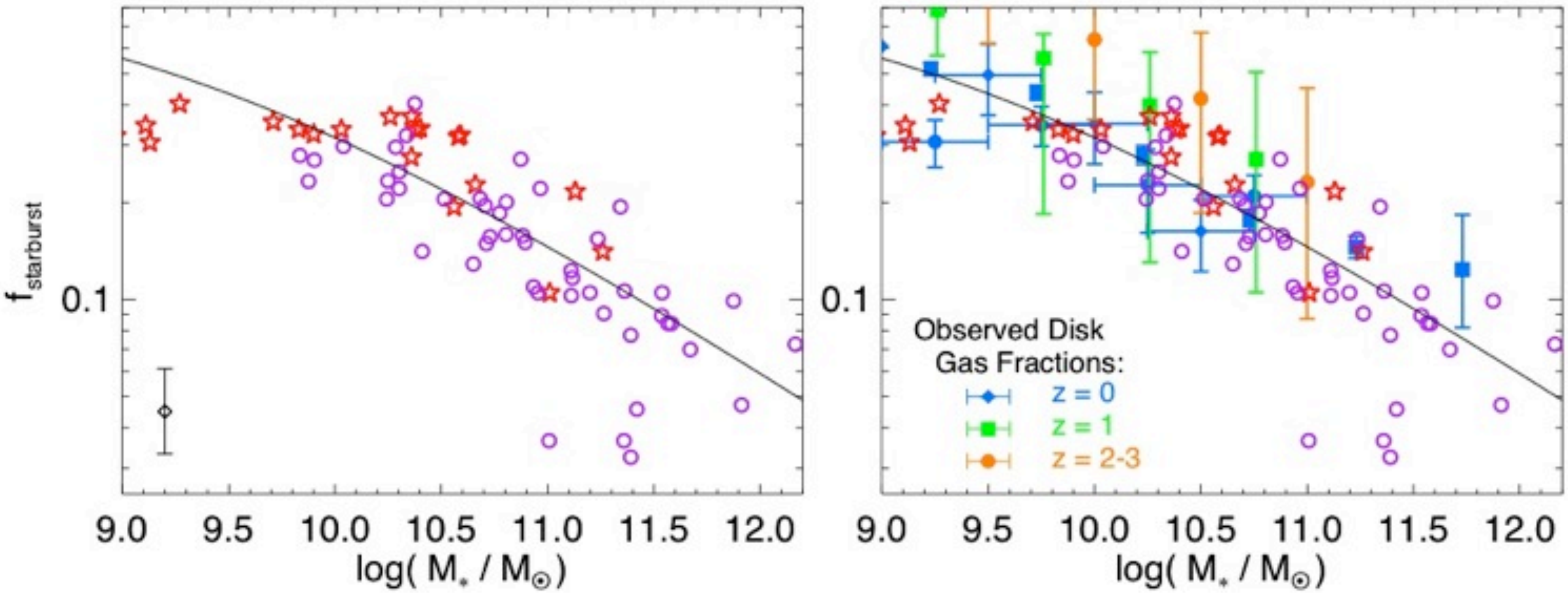

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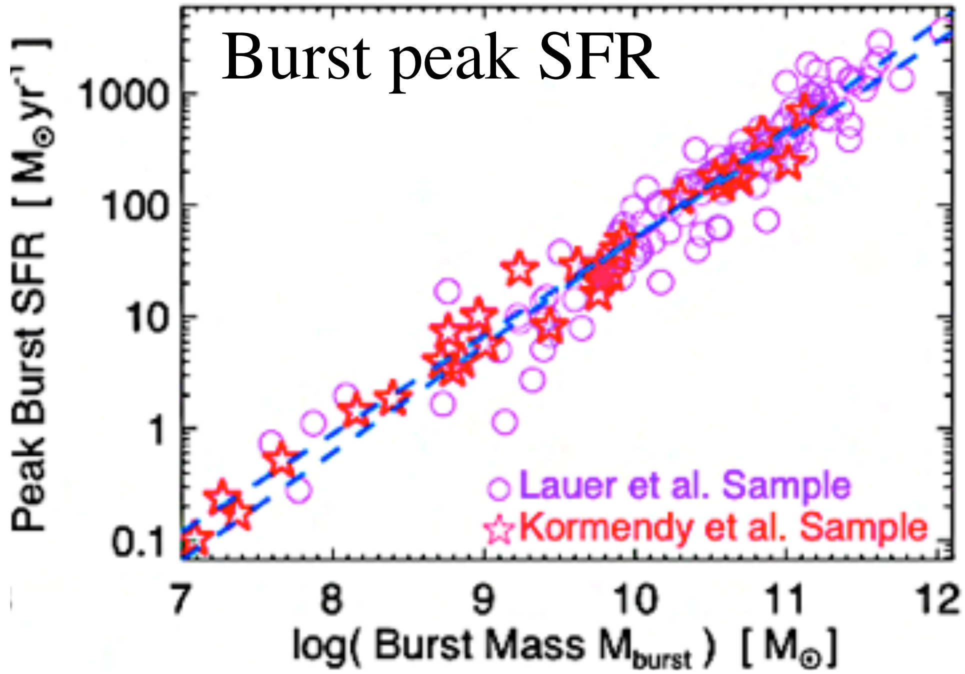
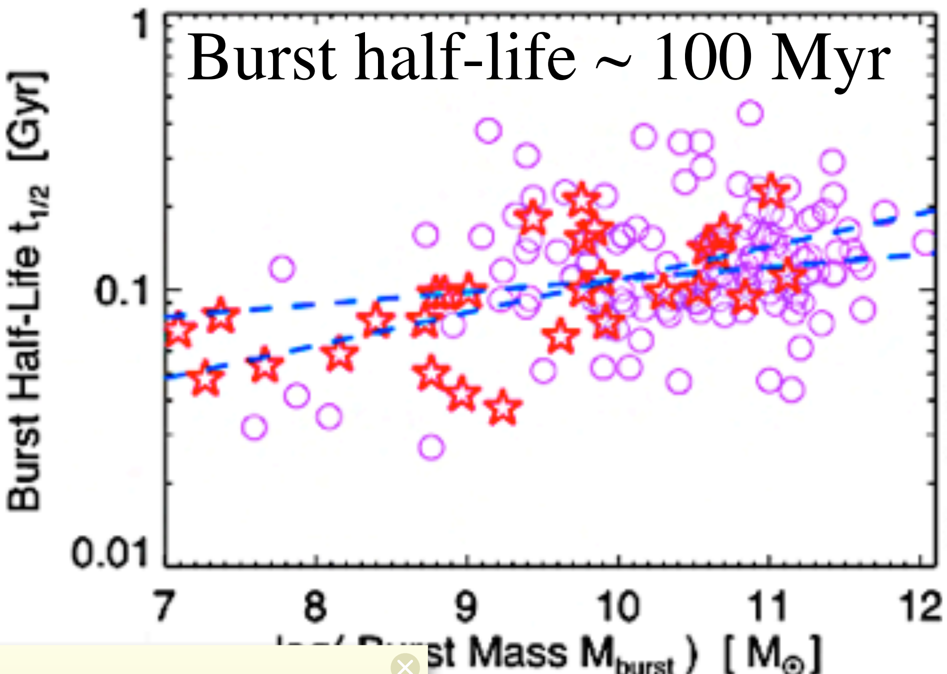
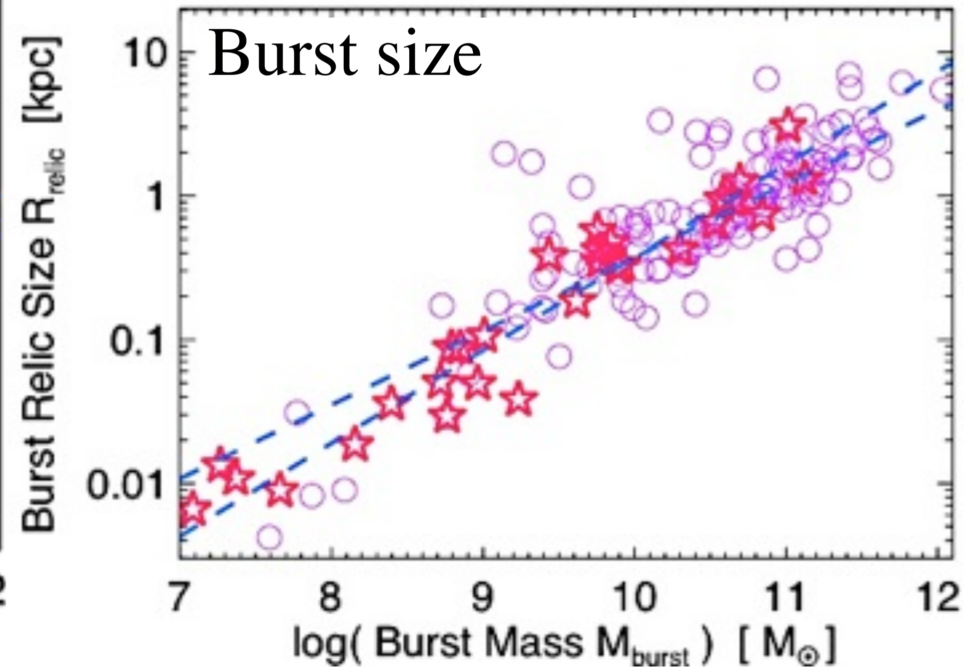
Metallicity & Stellar Pops:
Foster, Proctor PFH et al. 0

V/s & Structural Parameters:
Jogee & PFH et al. 10,11

What else can we learn from
the ‘relics’ of gas dissipation?







cut?

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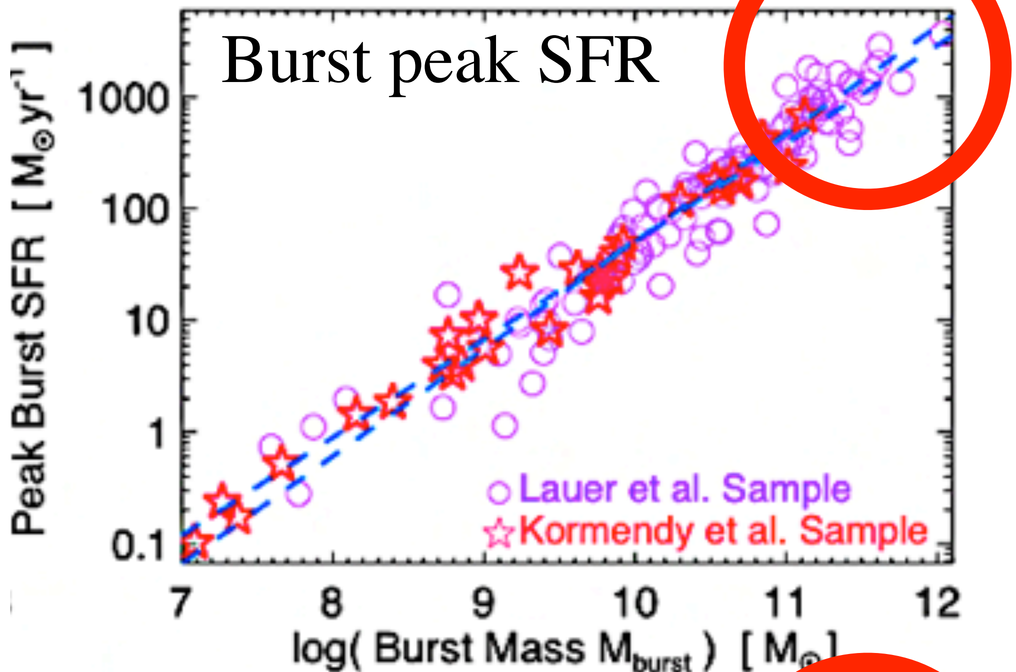
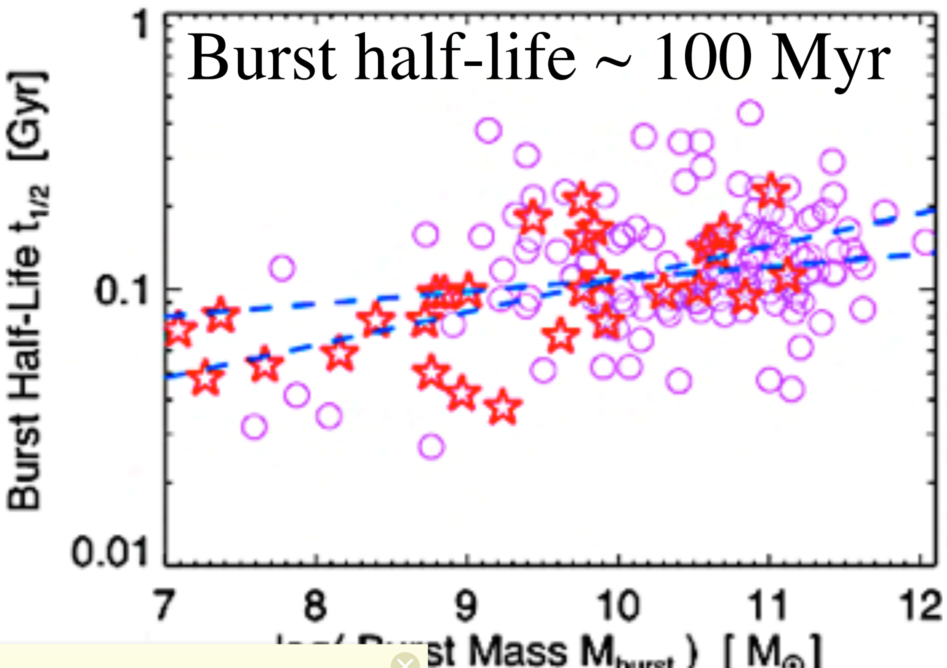
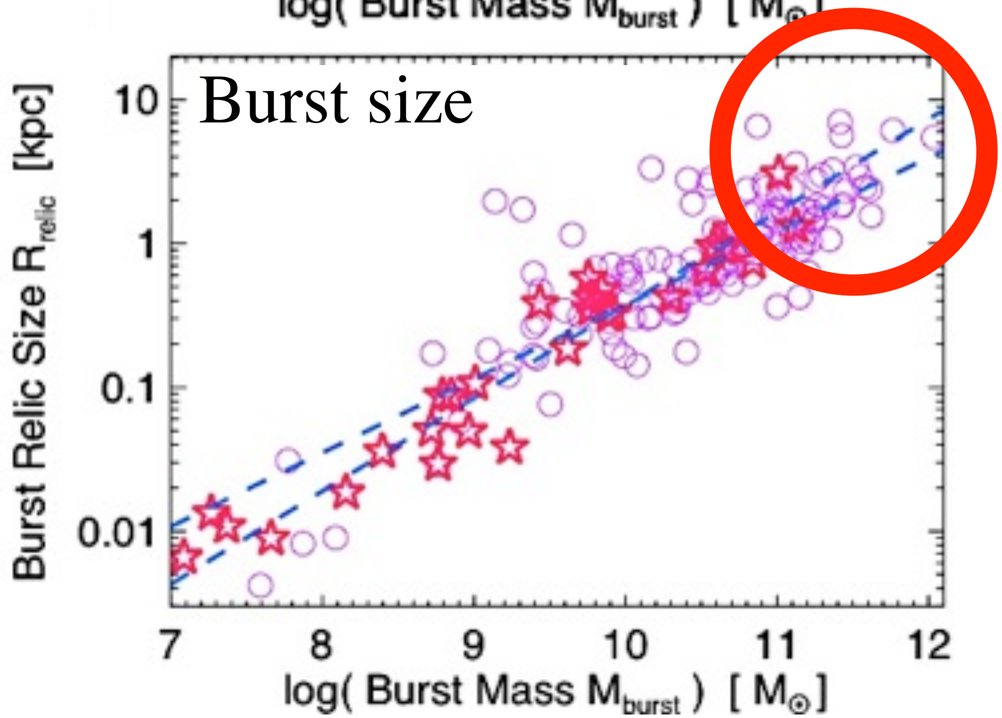
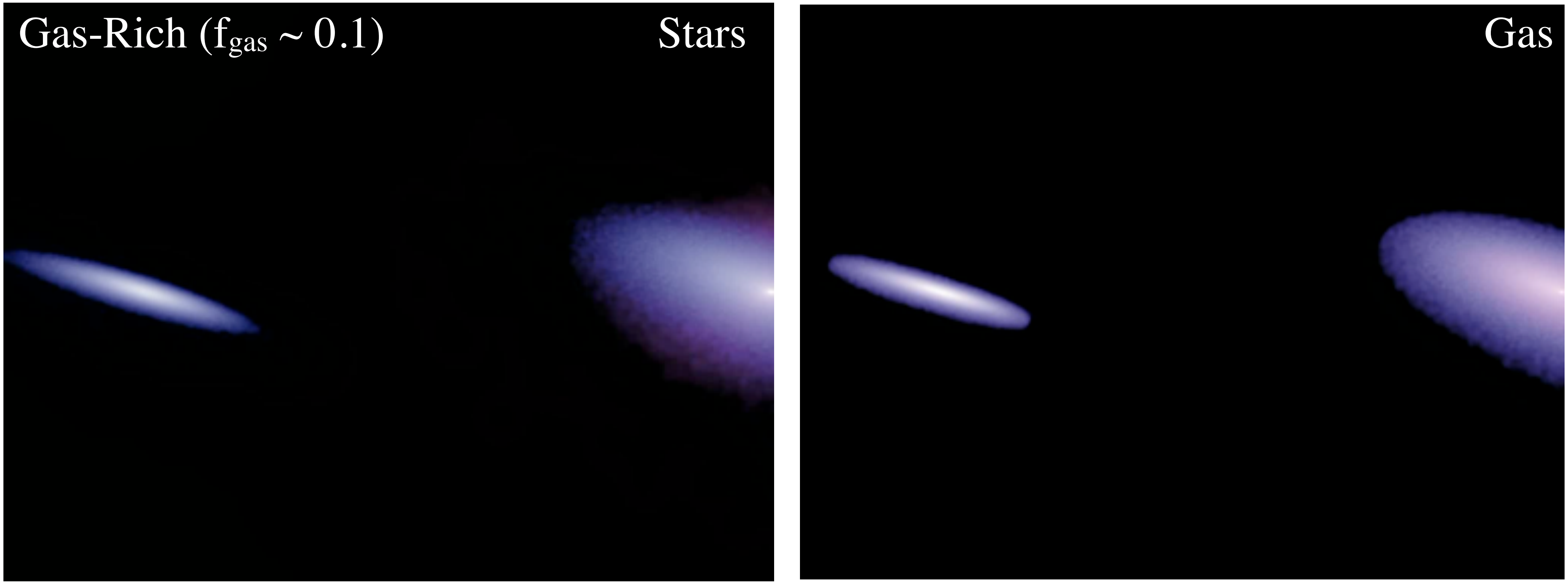


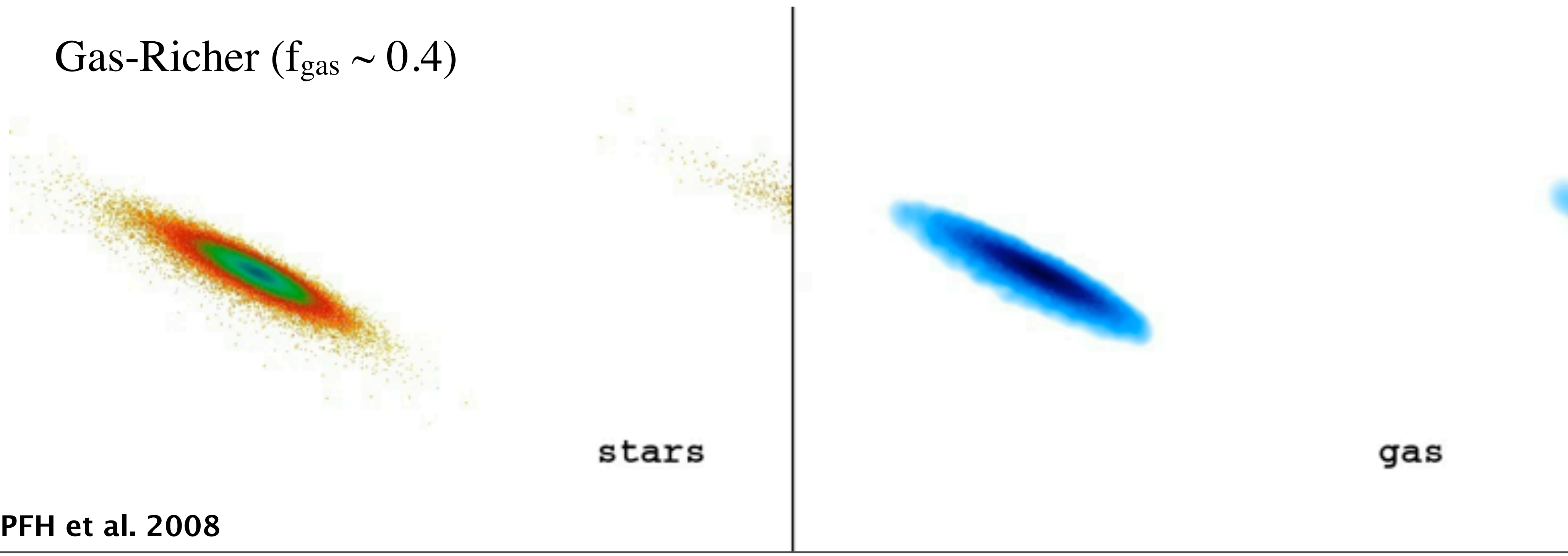




cut?

How Good Is Our Conventional Wisdom?





PFH et al. 2008

Major Merger Remnants

DO MERGERS DESTROY DISKS?