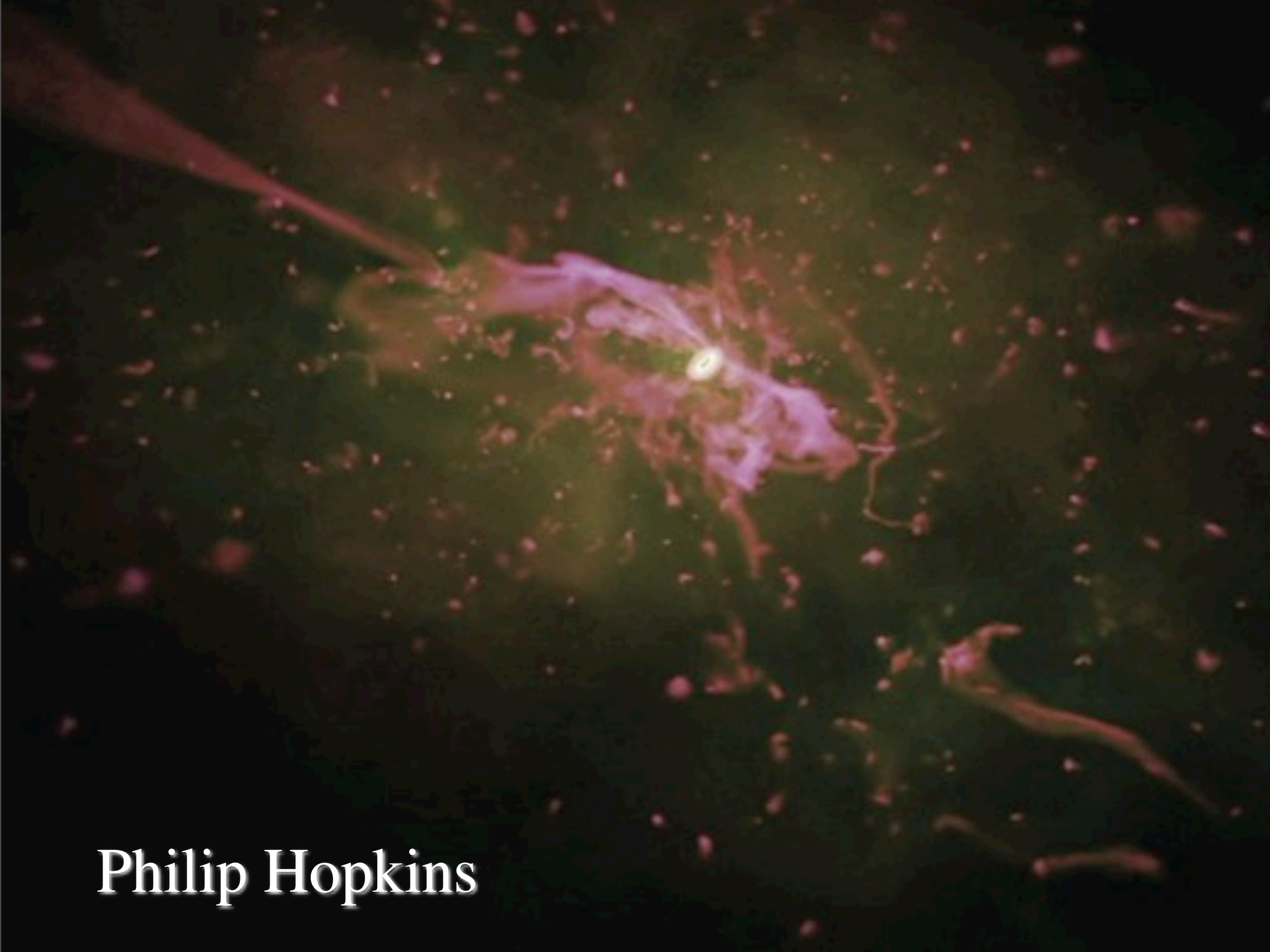
Feedback-Regulated Star Formation
(Stellar & AGN Feedback: Now with Physics!)



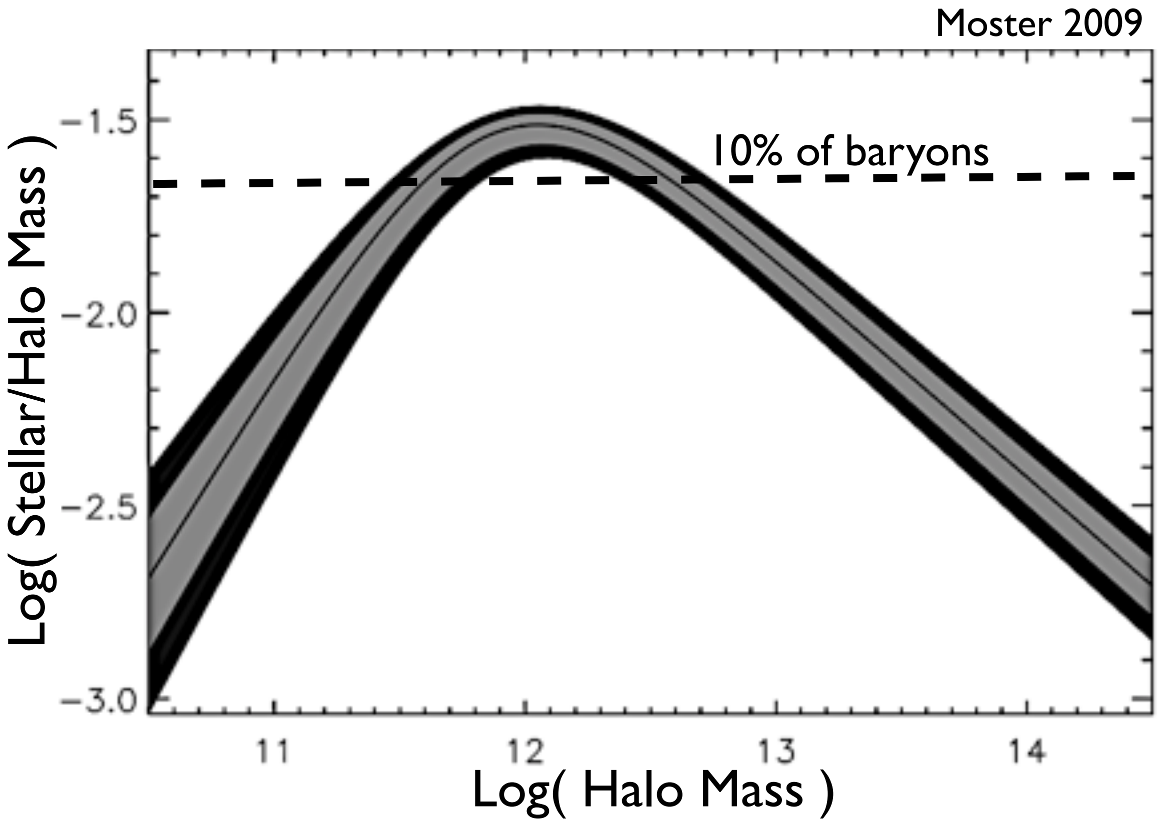
Philip Hopkins

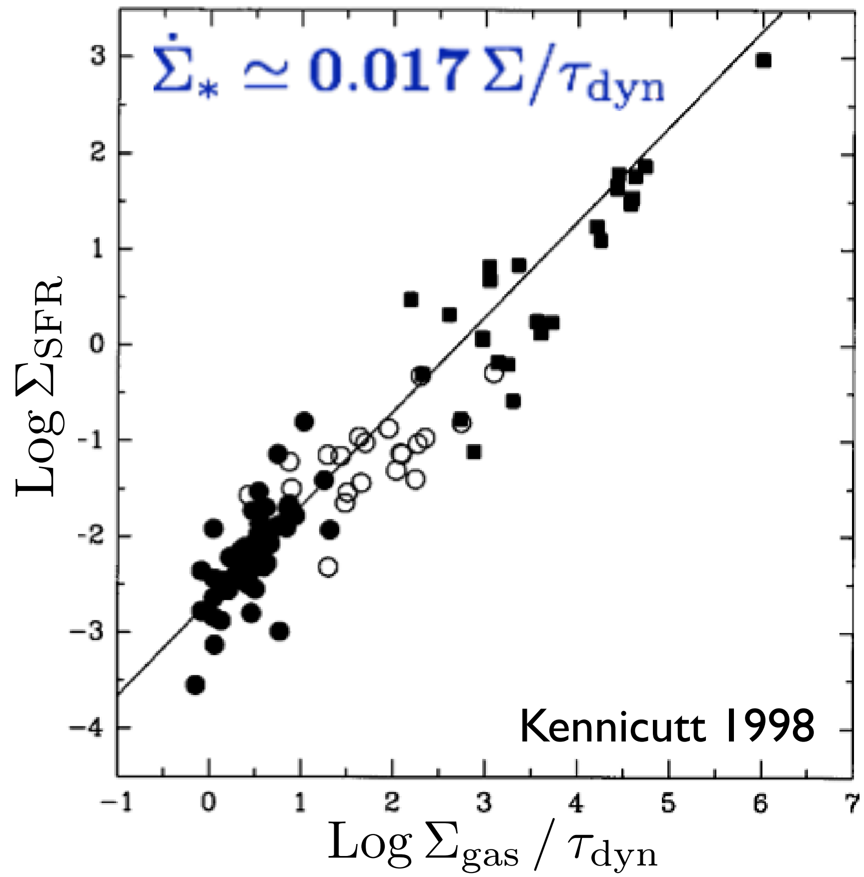
Norm Murray, Eliot Quataert,
Lars Hernquist, Todd Thompson, Dusan Keres, Chris Hayward, Stijn Wuyts,
Kevin Bundy, Desika Narayanan, Ryan Hickox, Rachel Somerville, & more


PINNACLES


PINNACLES

Q: WHY IS STAR FORMATION SO INEFFICIENT?





A: Stellar Feedback!

SO WHAT'S THE PROBLEM?

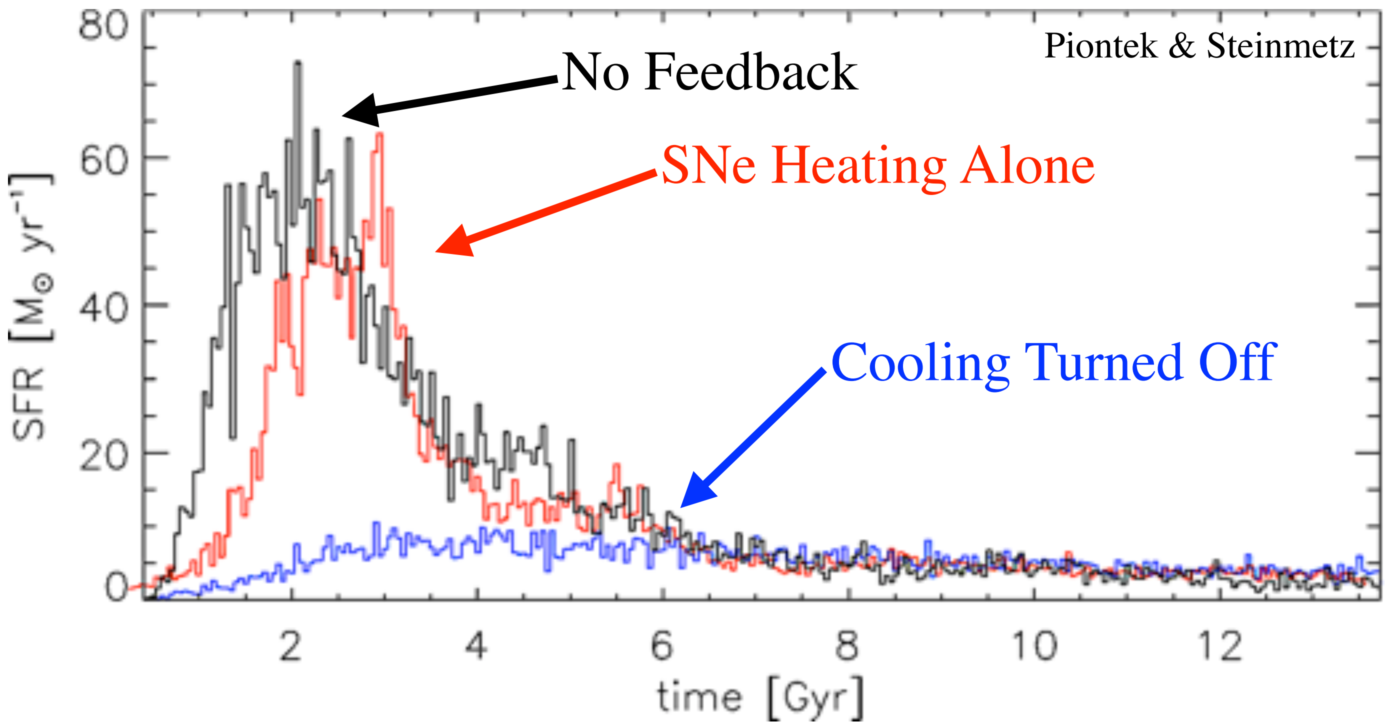
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- 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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- High-resolution (~1pc), molecular cooling (<100 K), SF only at highest densities (n_H>1000 cm^{-3})

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- Heating:
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  - Stellar Winds
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- *Explicit* Momentum Flux:
  - Radiation Pressure

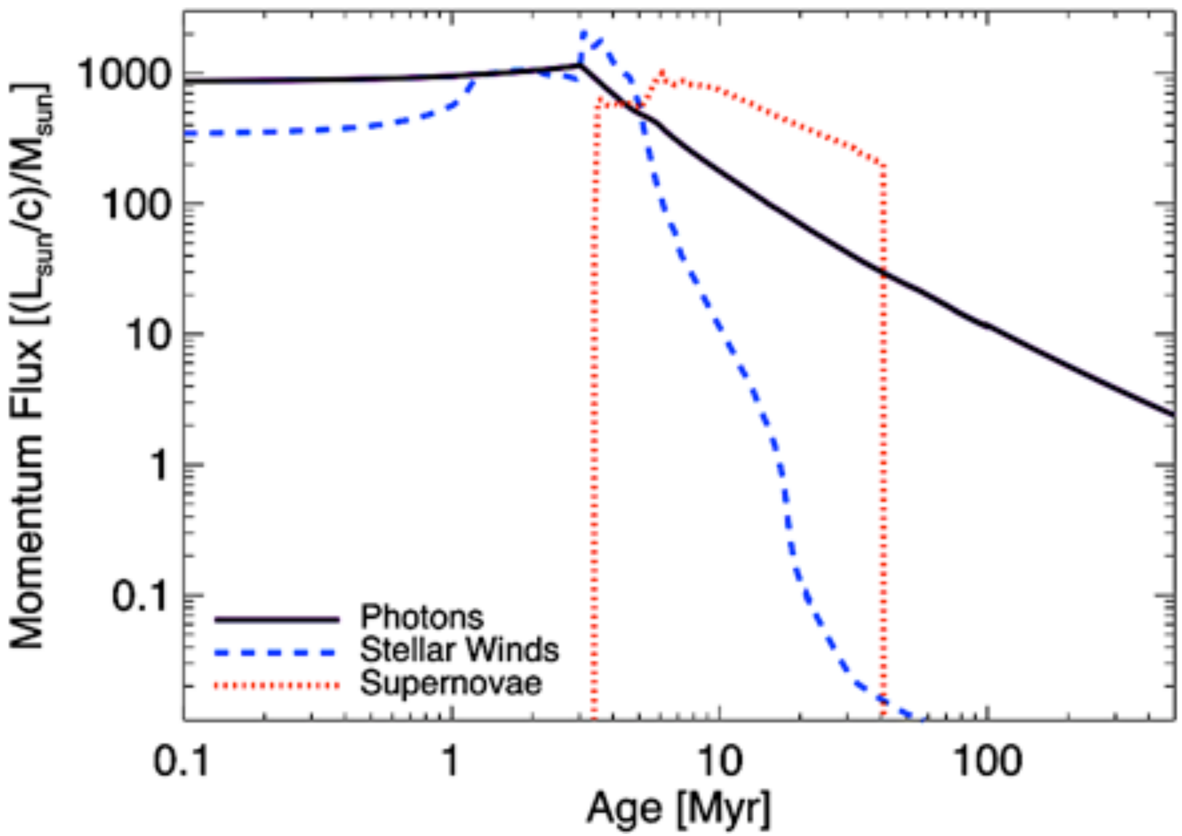
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

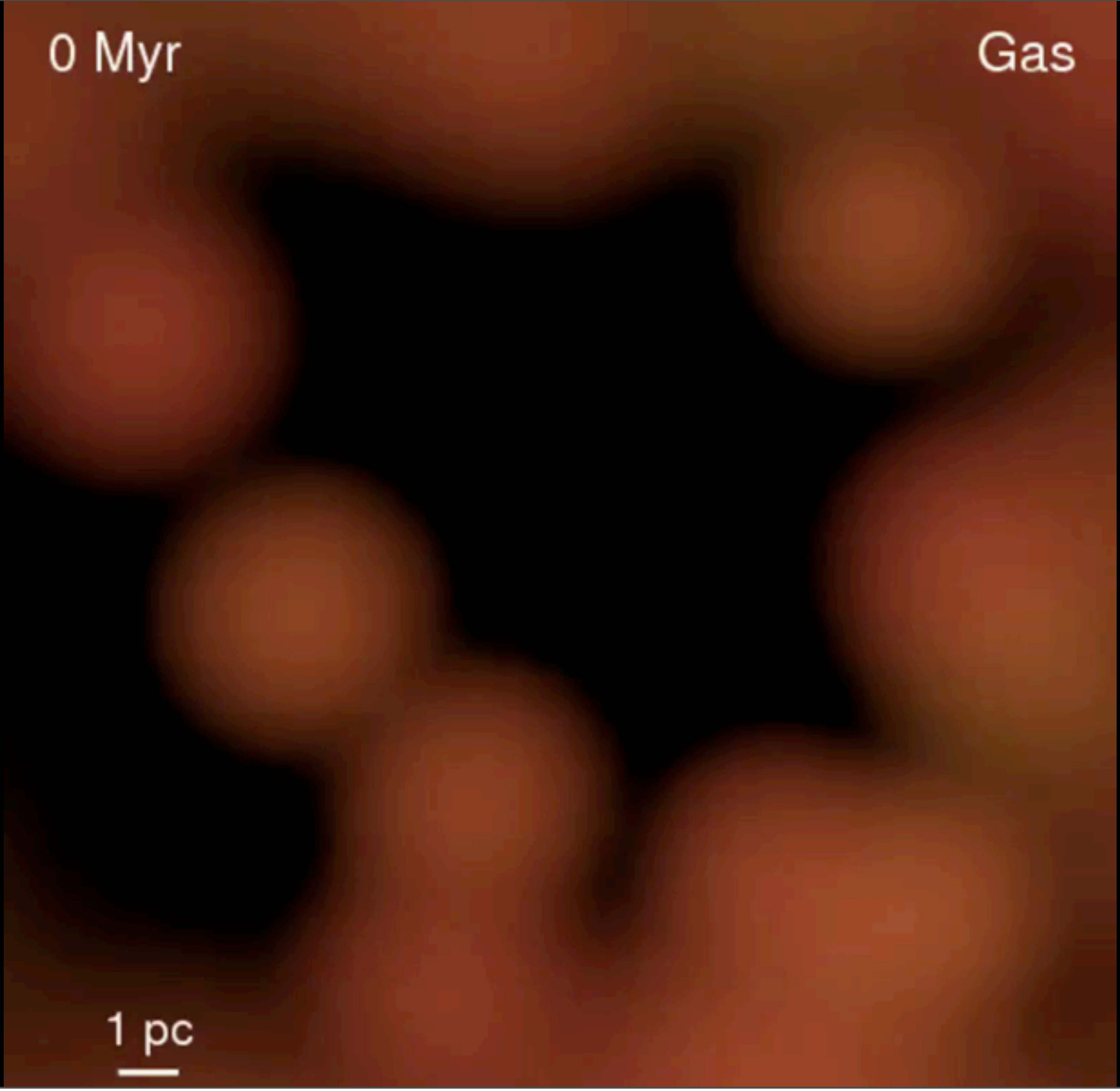
  - SNe

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

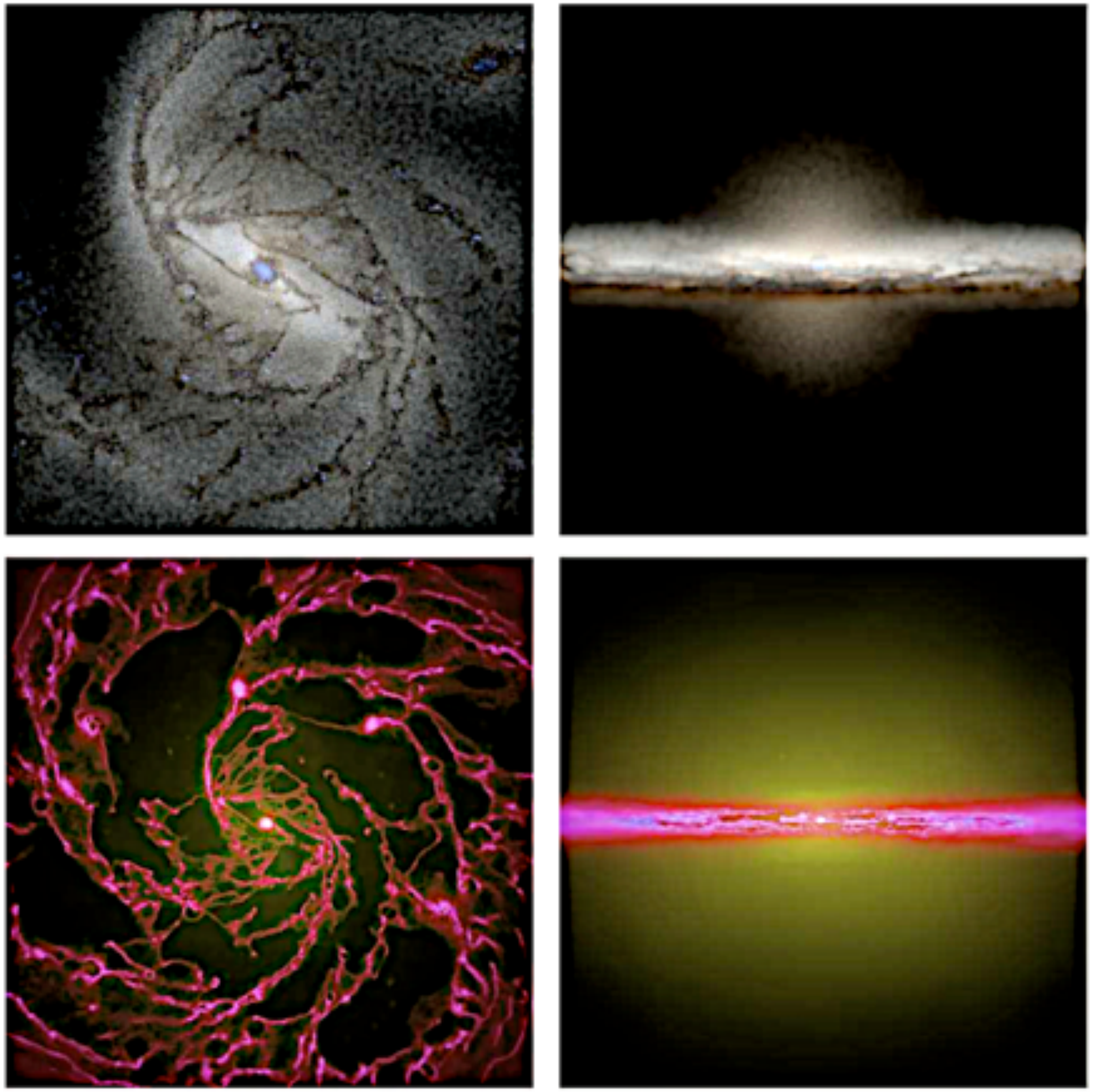
  - Stellar Winds

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




0 Myr
Gas
1 pc

Hopkins, Quataert, & Murray, in prep



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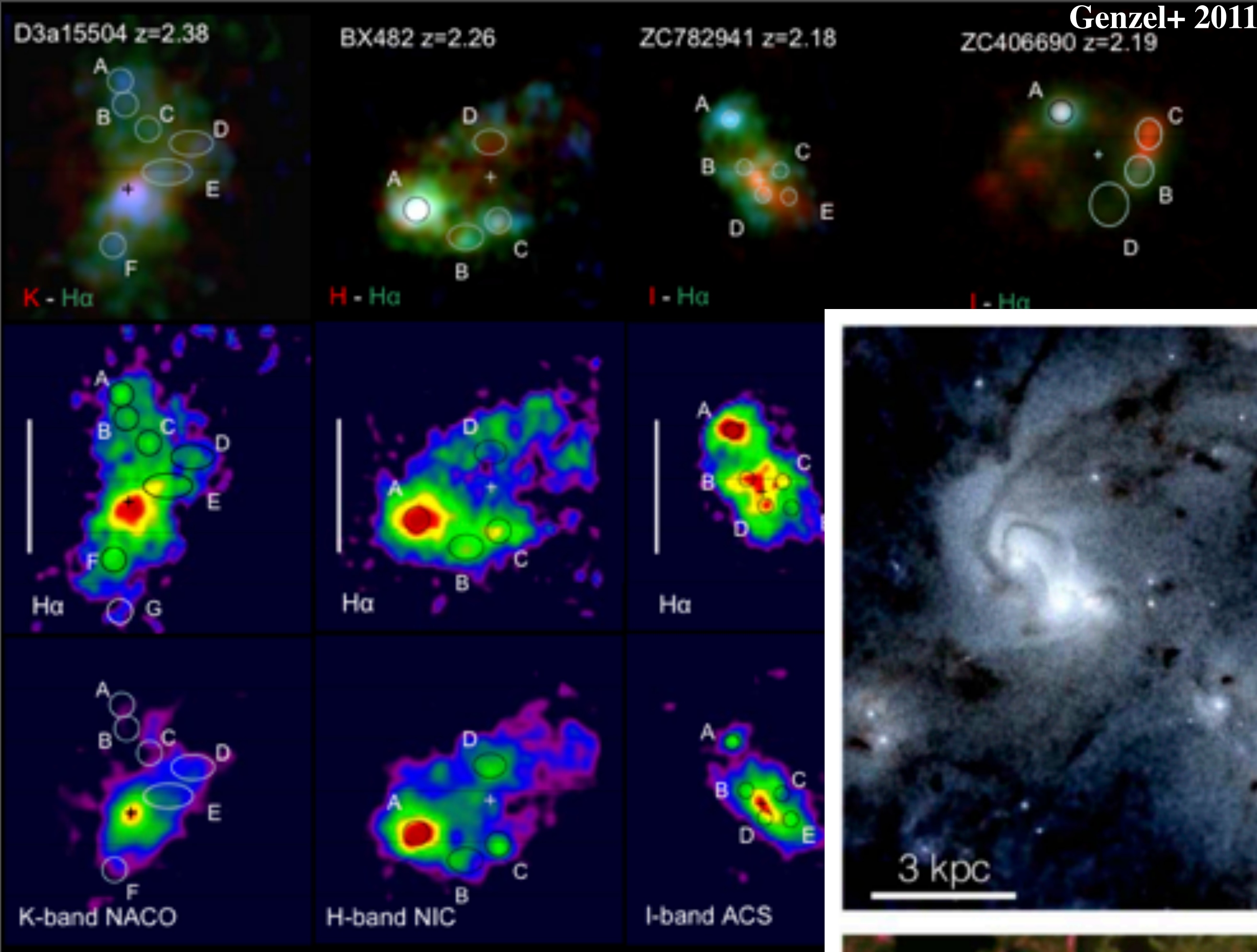
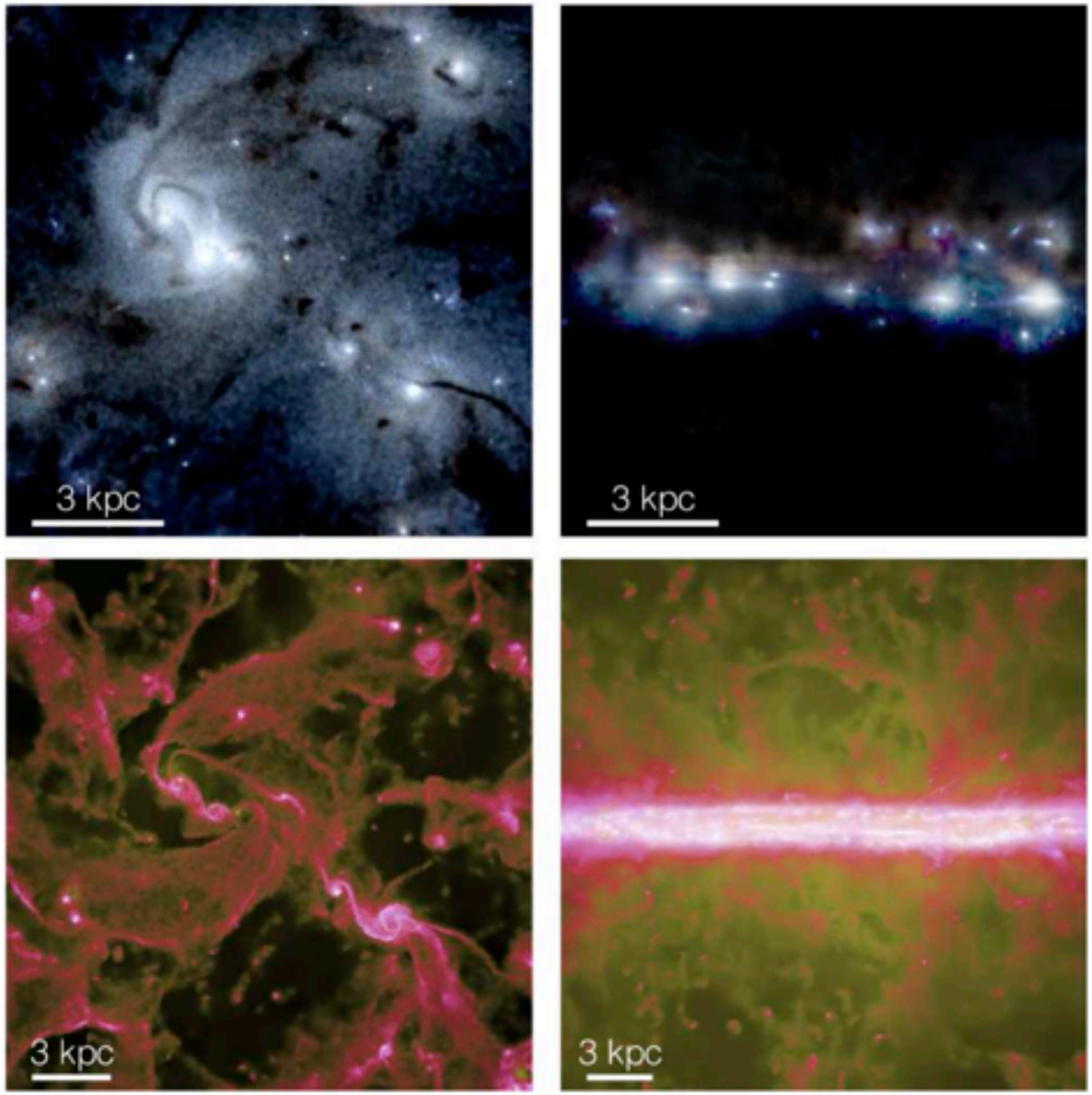


Genzel+ 2011



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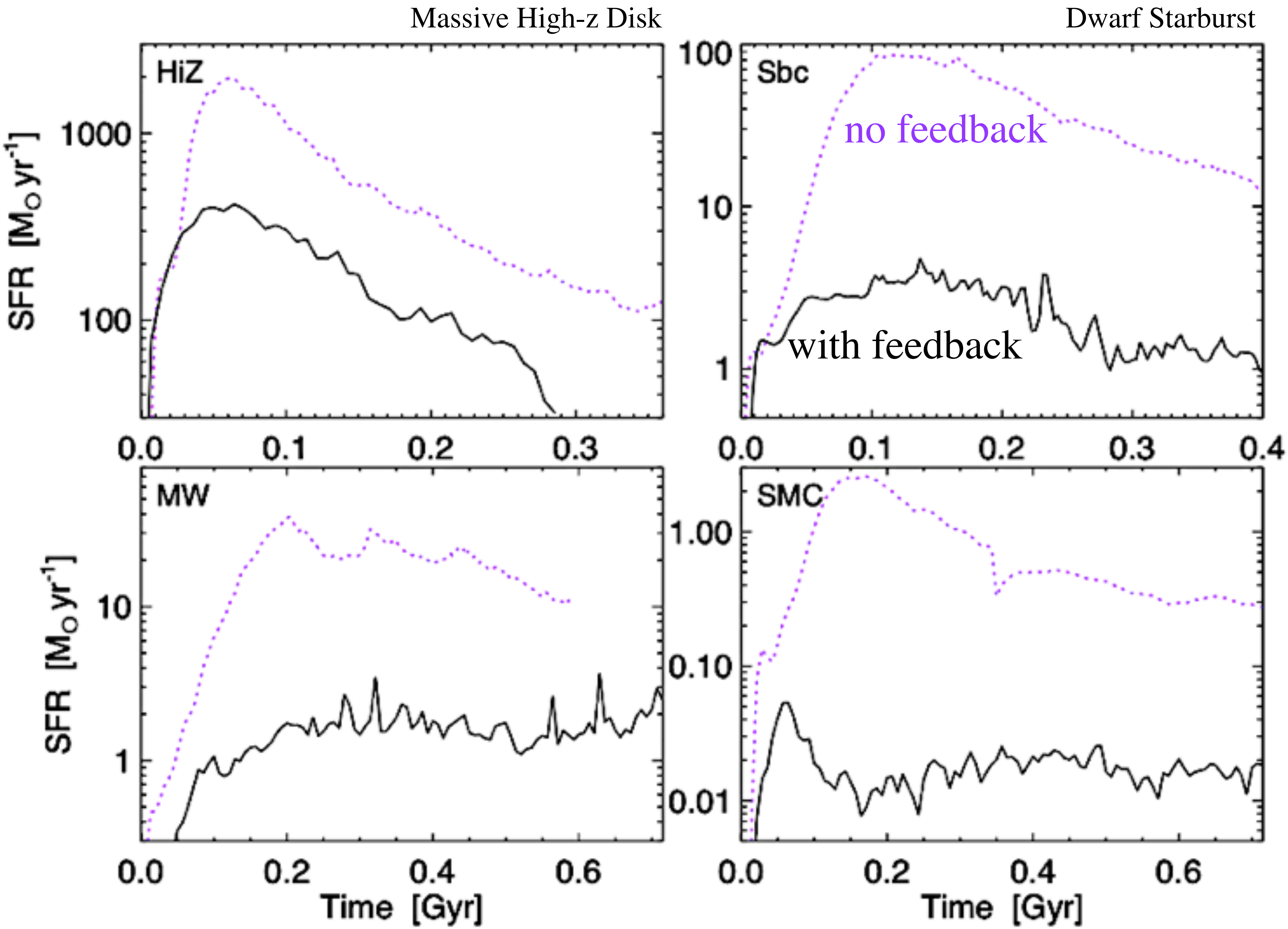
Stellar Feedback gives Self-Regulated Star Formation



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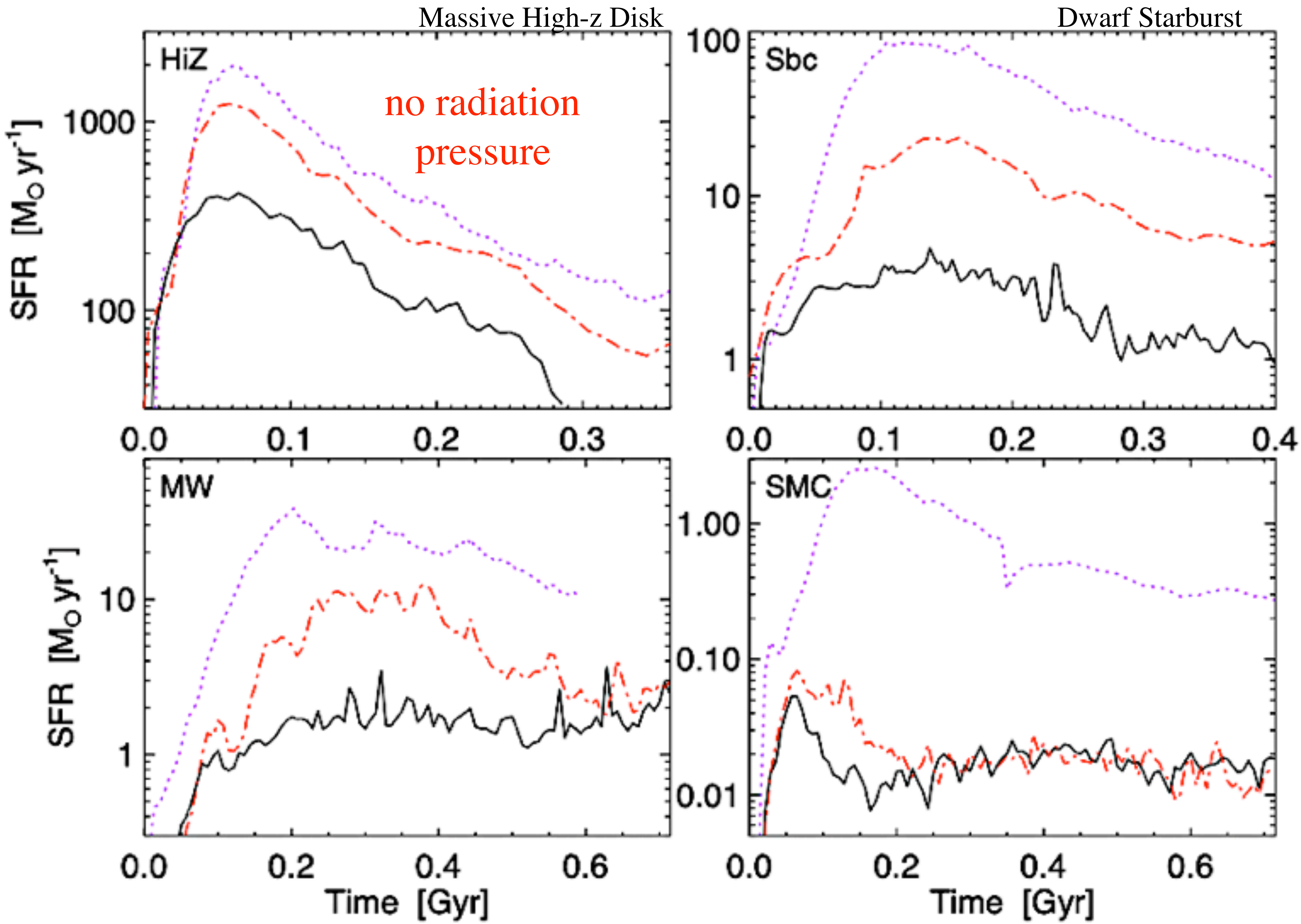

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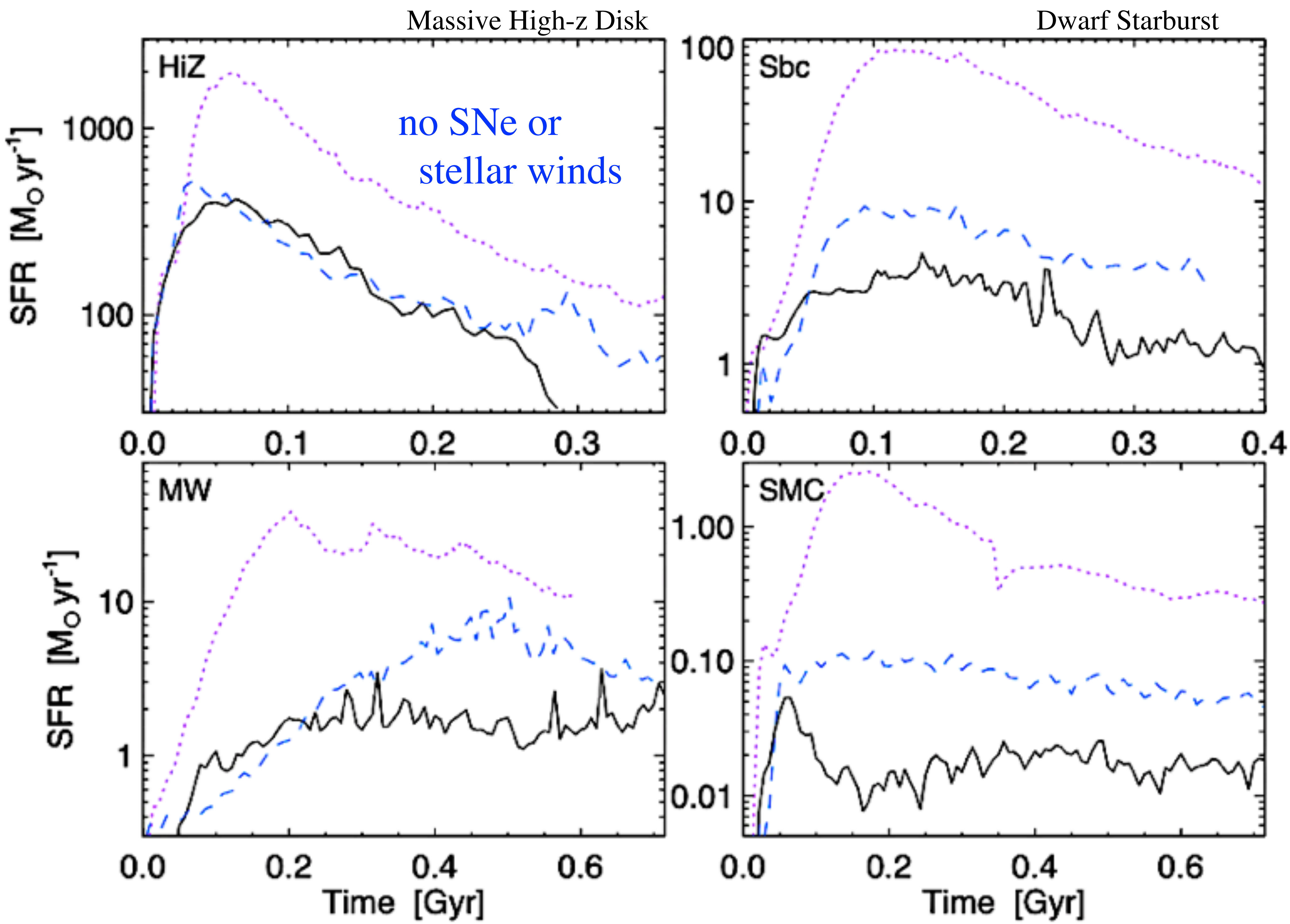

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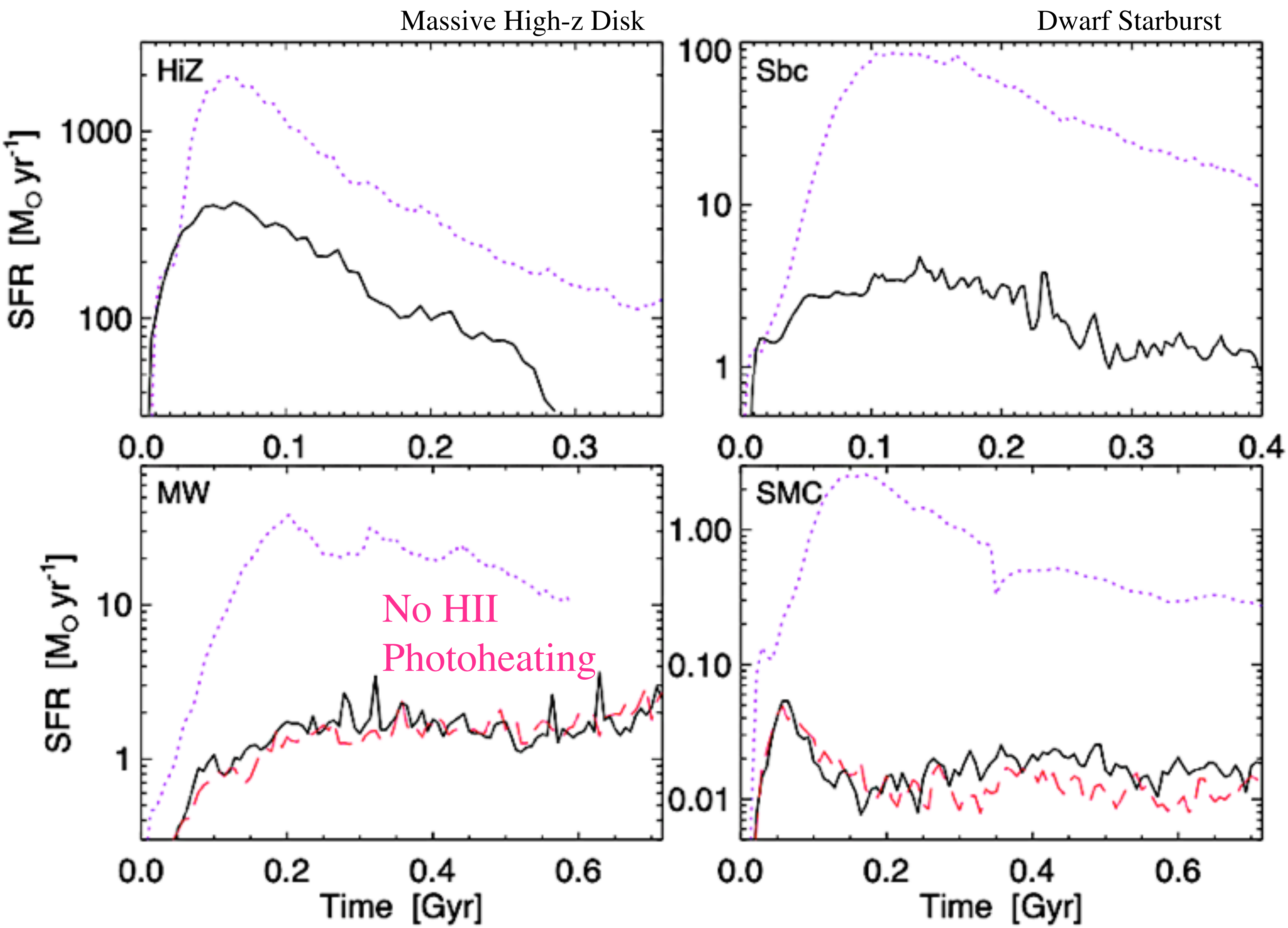
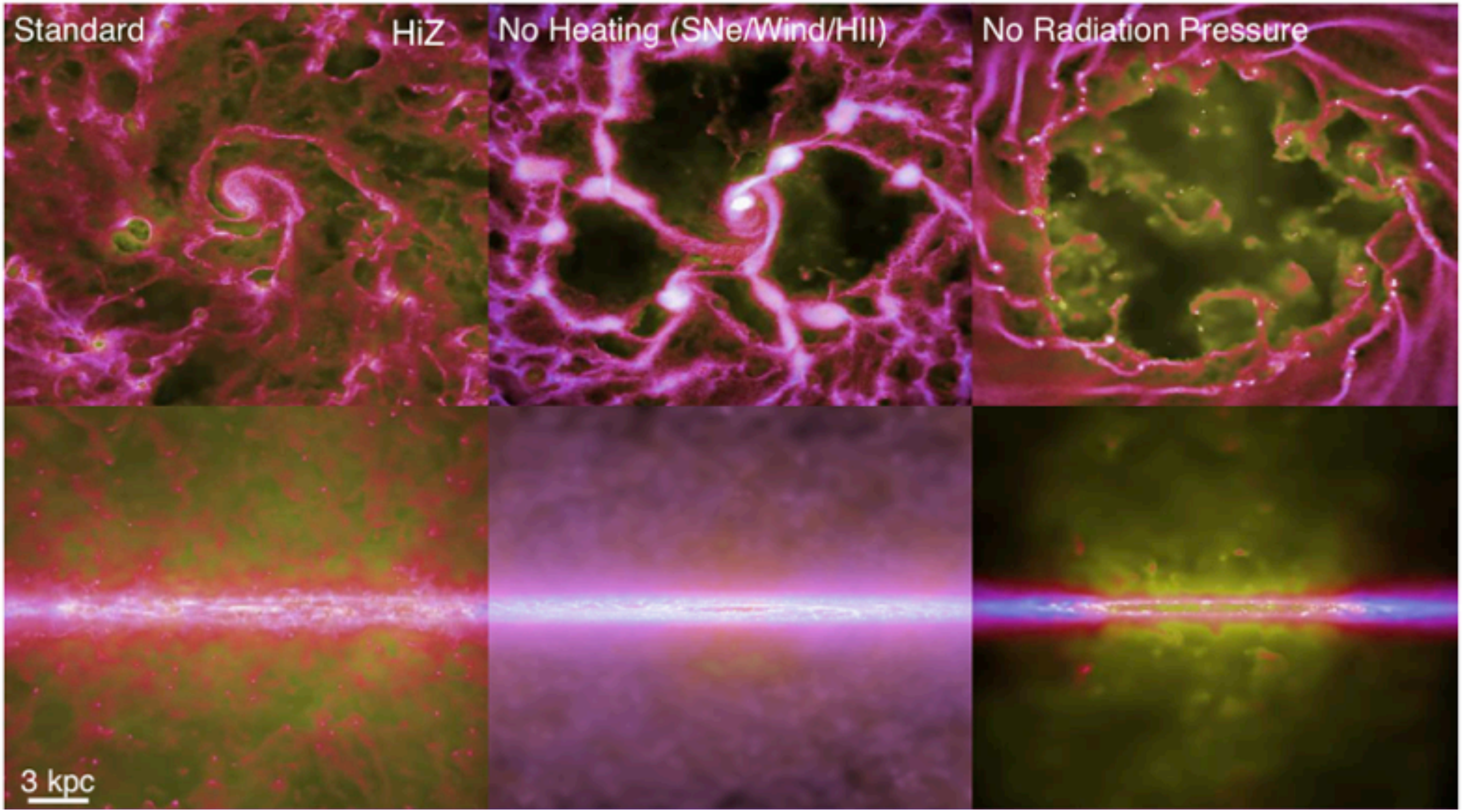


Stellar Feedback & Self-Regulation

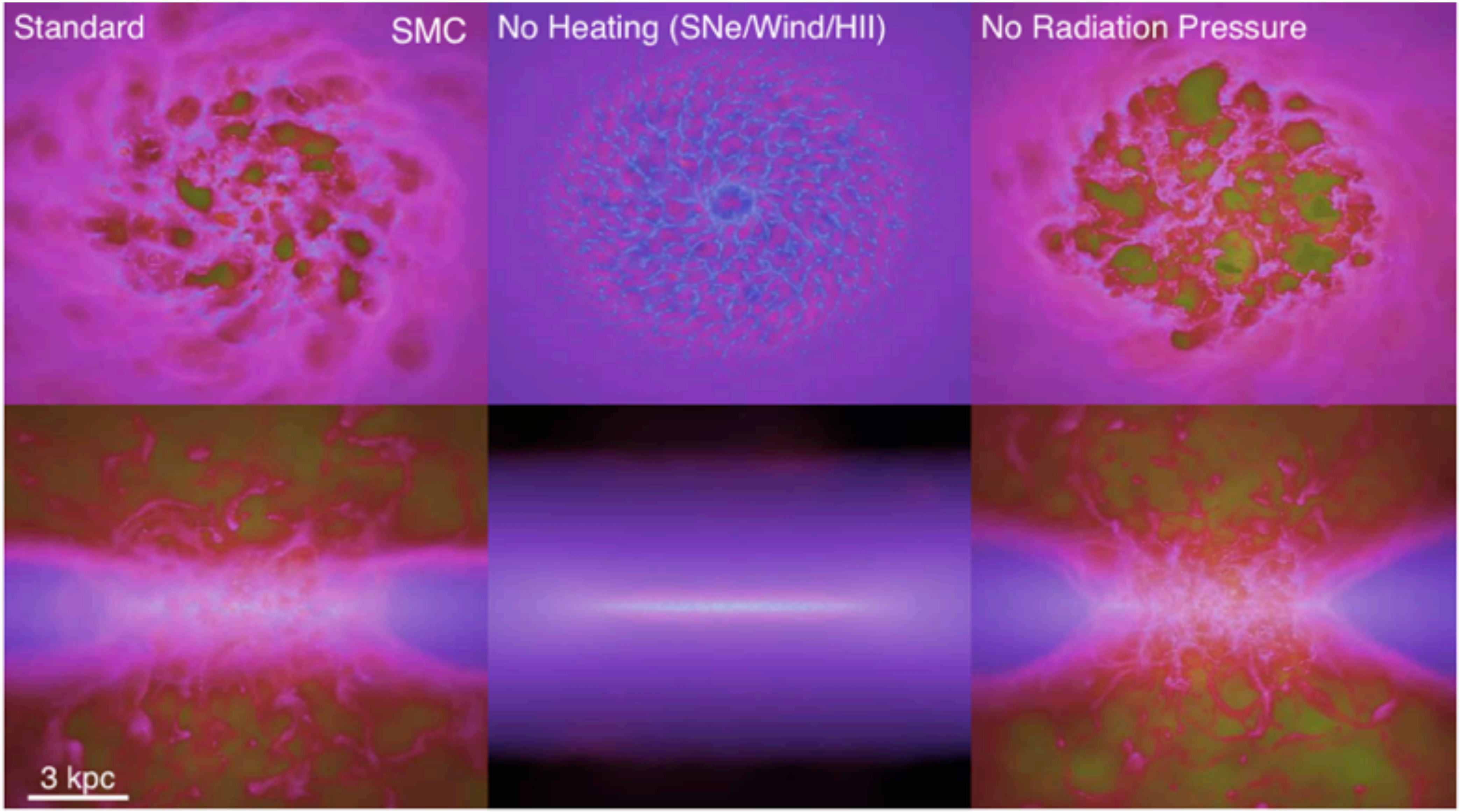
WHICH MECHANISMS MATTER?



- SFR ~ 100+ M_{sun}/yr ($L \sim L_{EDD}$)
- Optically thick
- $\langle n \rangle \sim 100$ cm^{-3} $T_{cool} \sim 1000$ yr

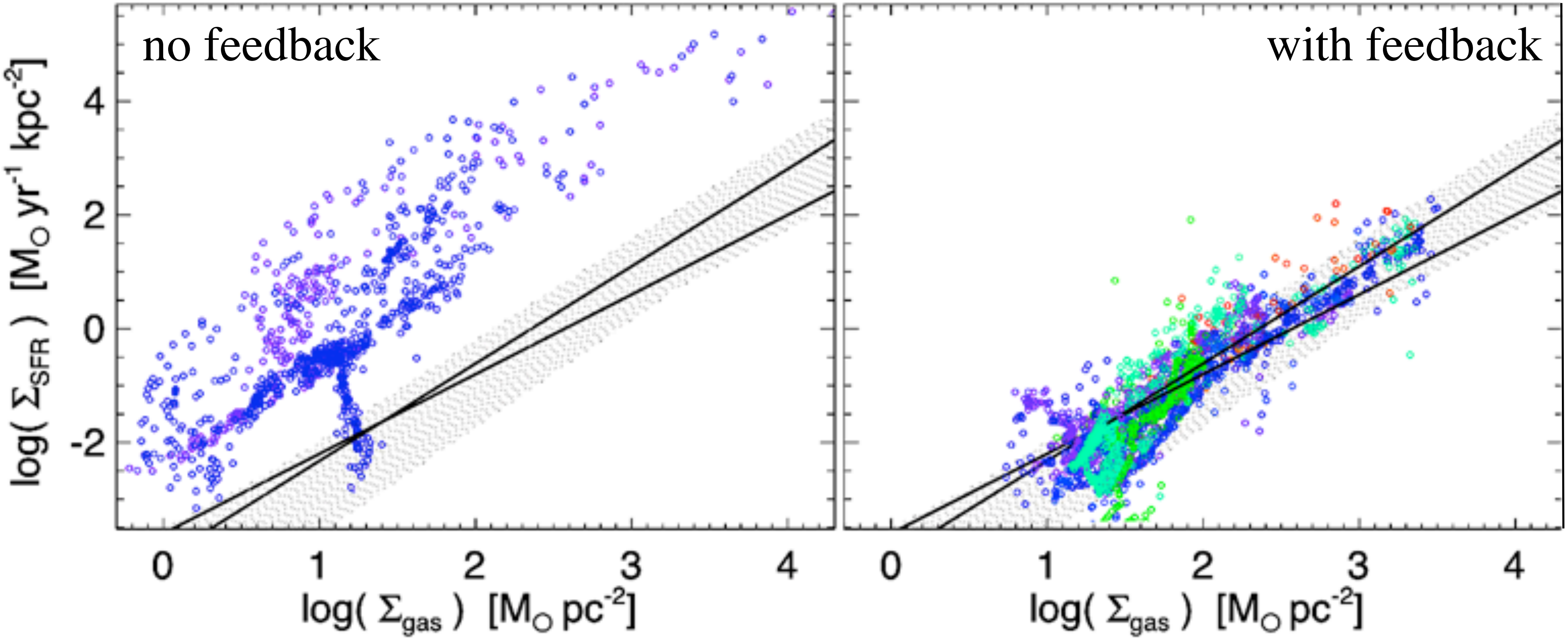
Stellar Feedback & Self-Regulation

WHICH MECHANISMS MATTER?



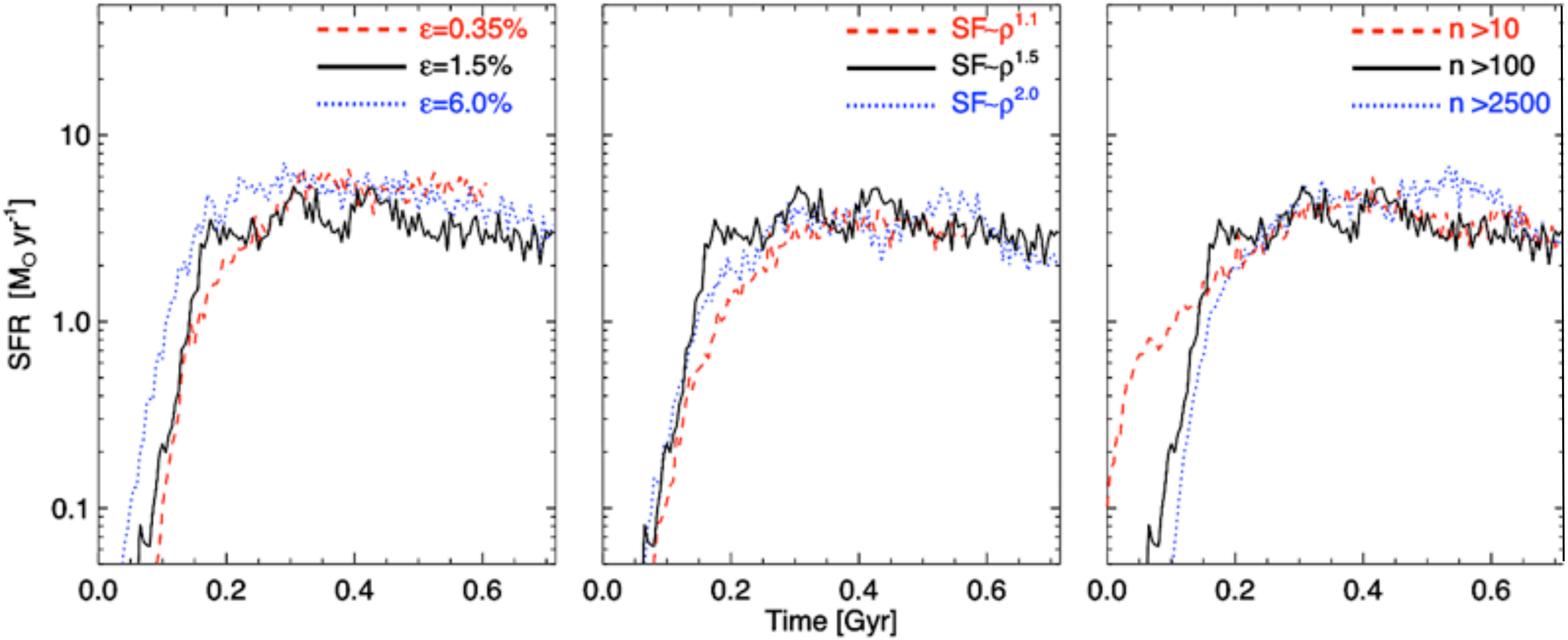
- SFR ~ 0.01 M_{sun}/yr ($L \ll L_{EDD}$)
- Optically thin
- $\langle n \rangle \sim 0.1\ cm^{-3}$ $T_{cool} \sim$ Myr

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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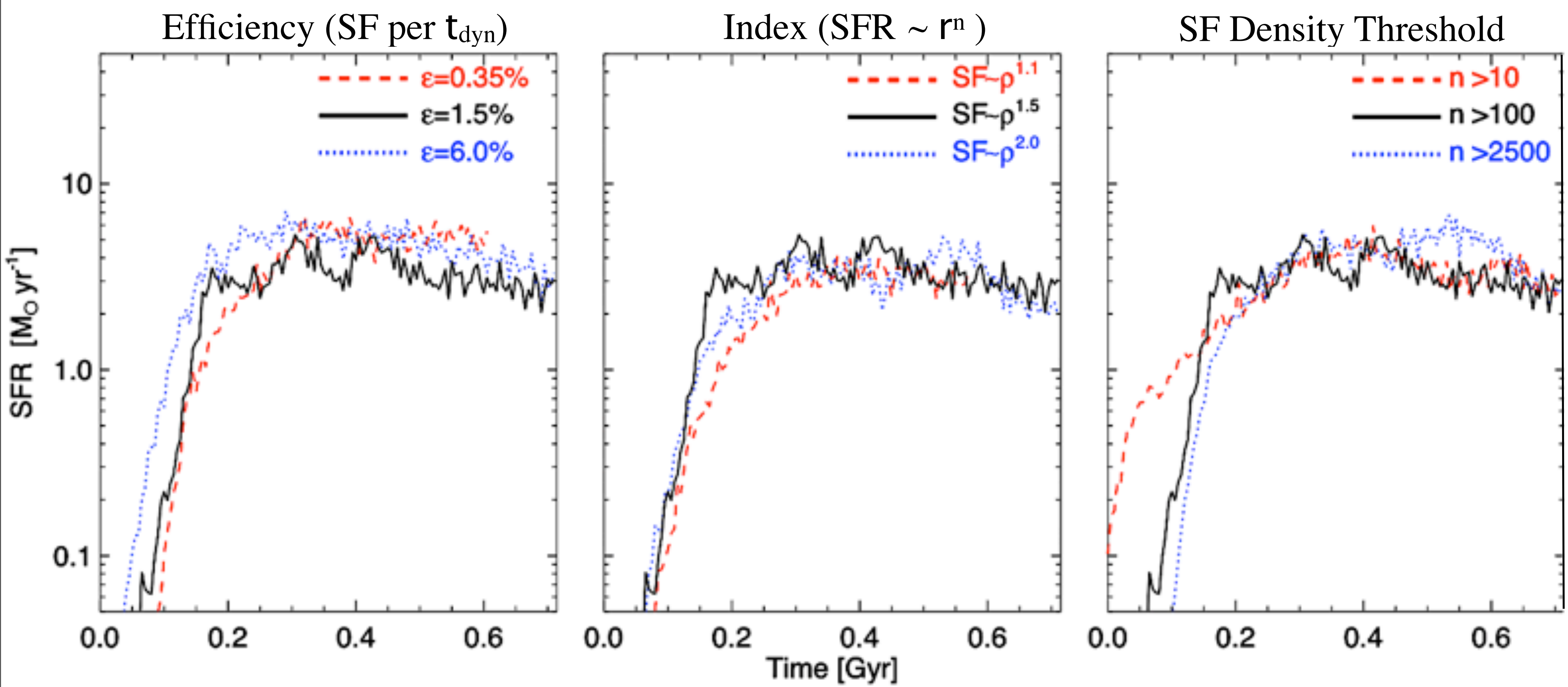

- Set by feedback (i.e. SFR) needed to maintain marginal stability

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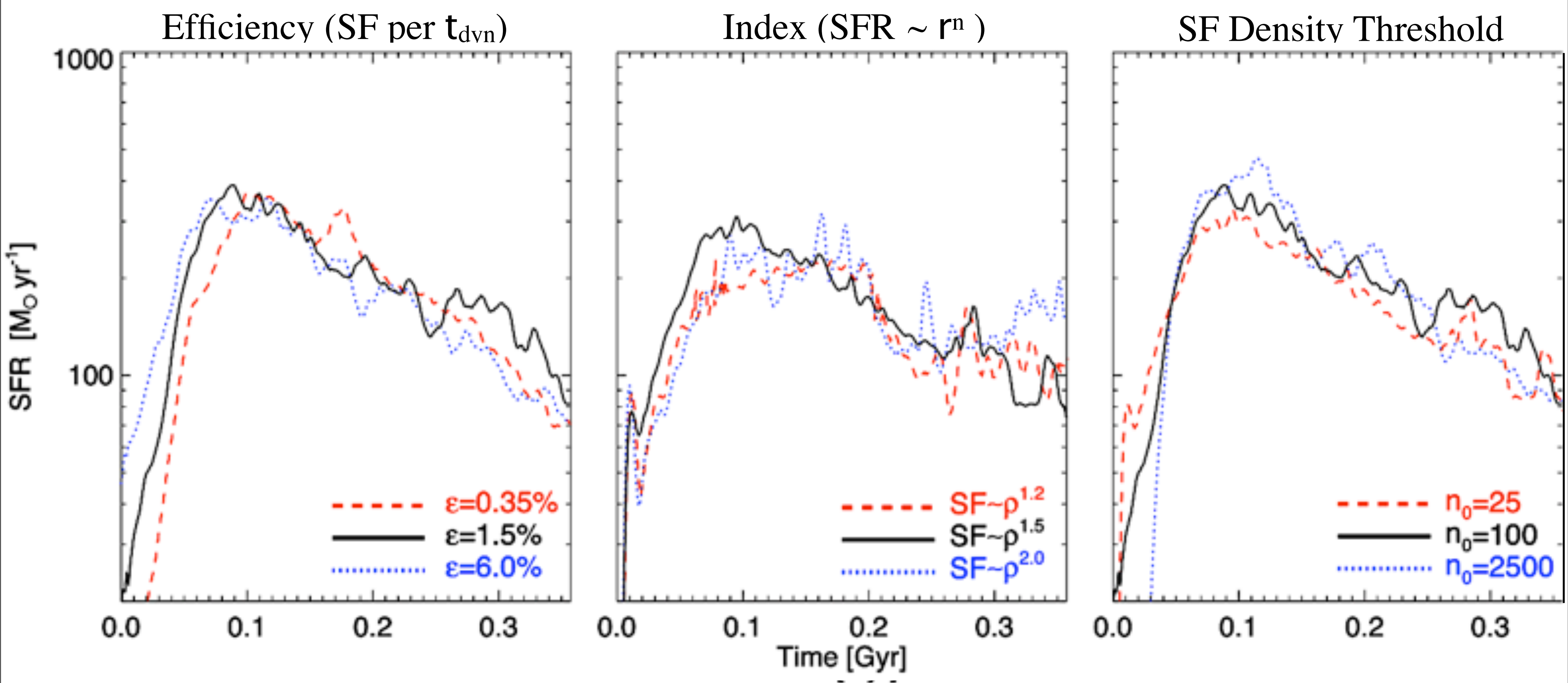

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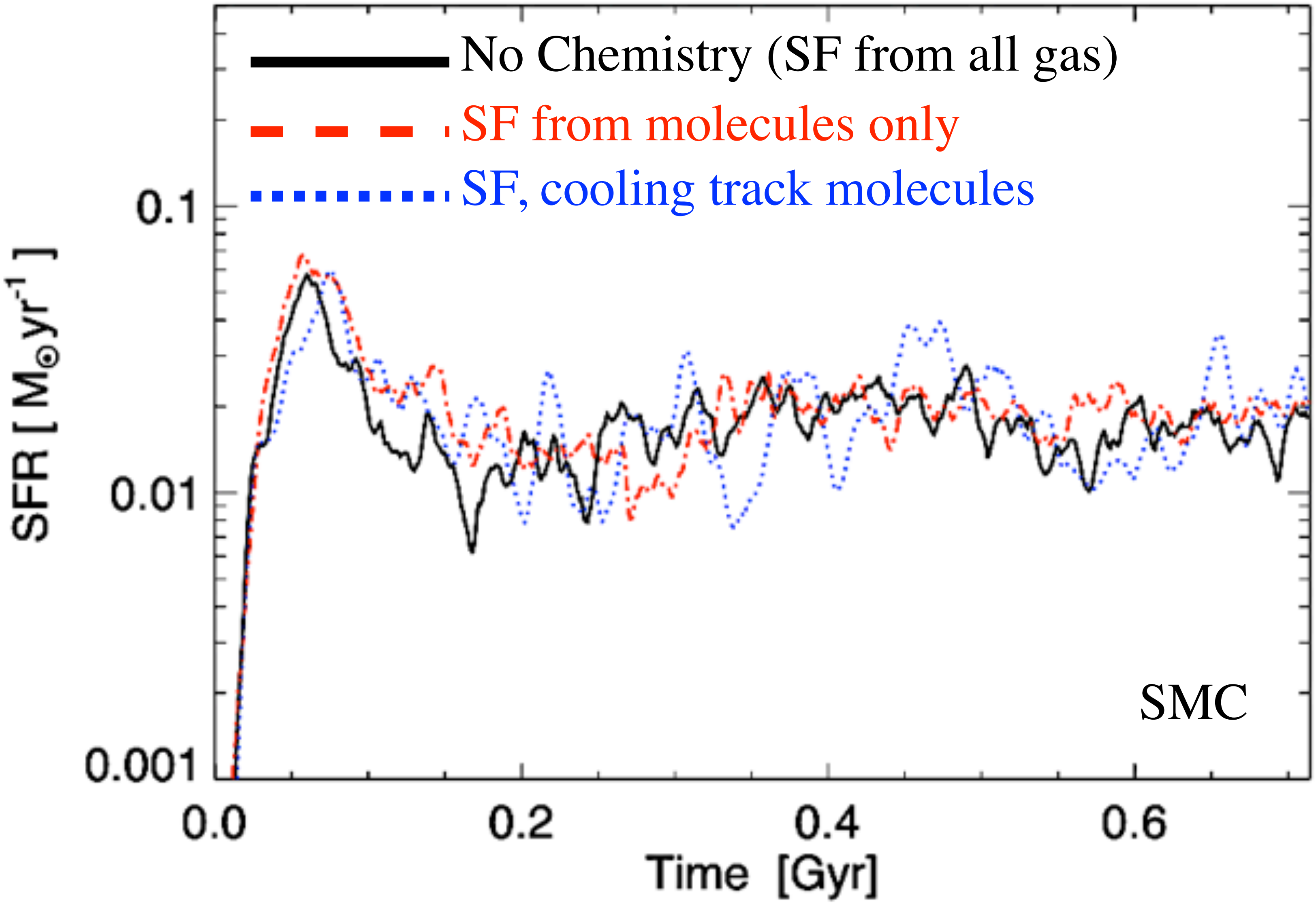
Molecular Chemistry doesn't change things above modest Metallicity

MOLECULES ARE A *TRACER*



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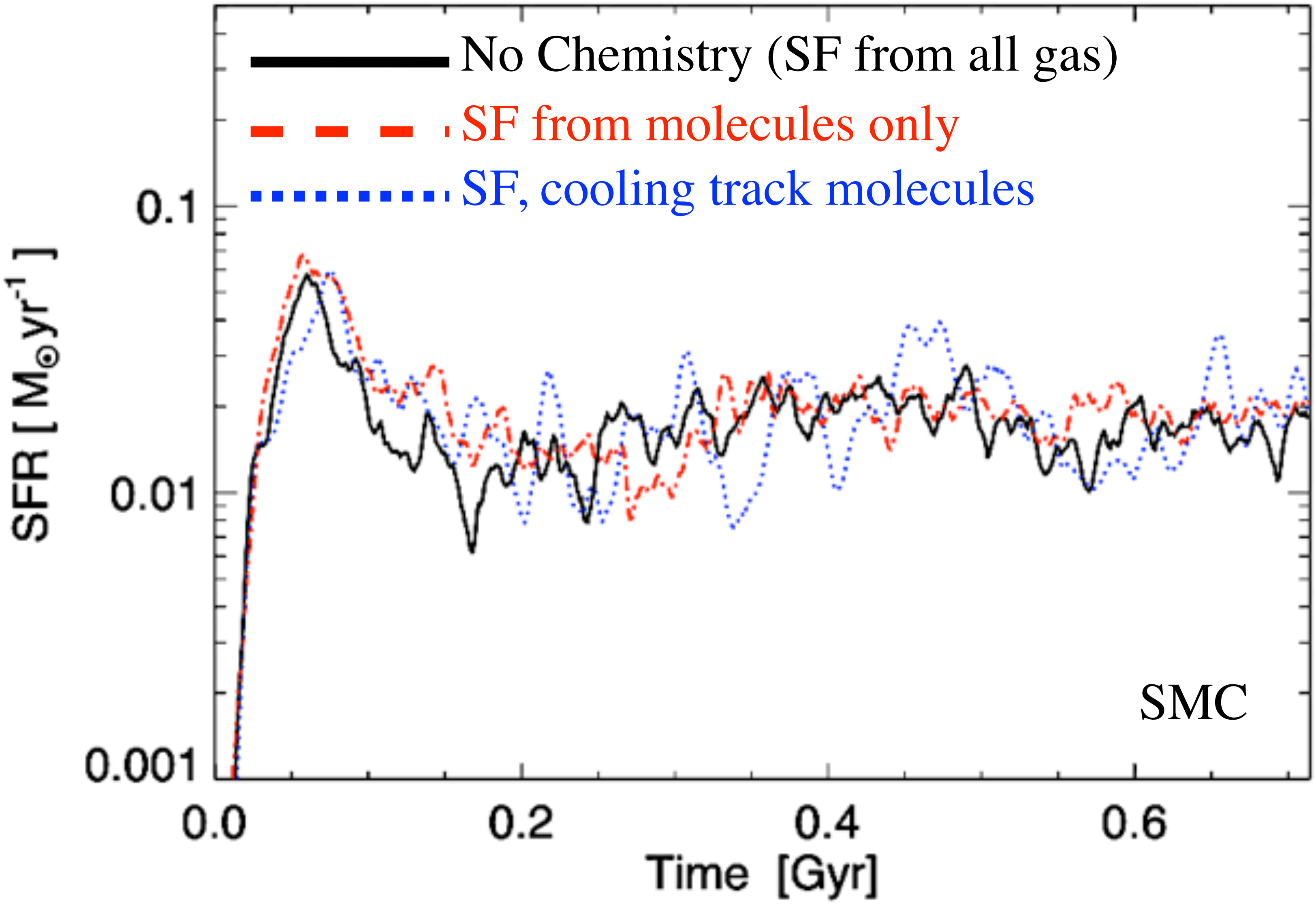
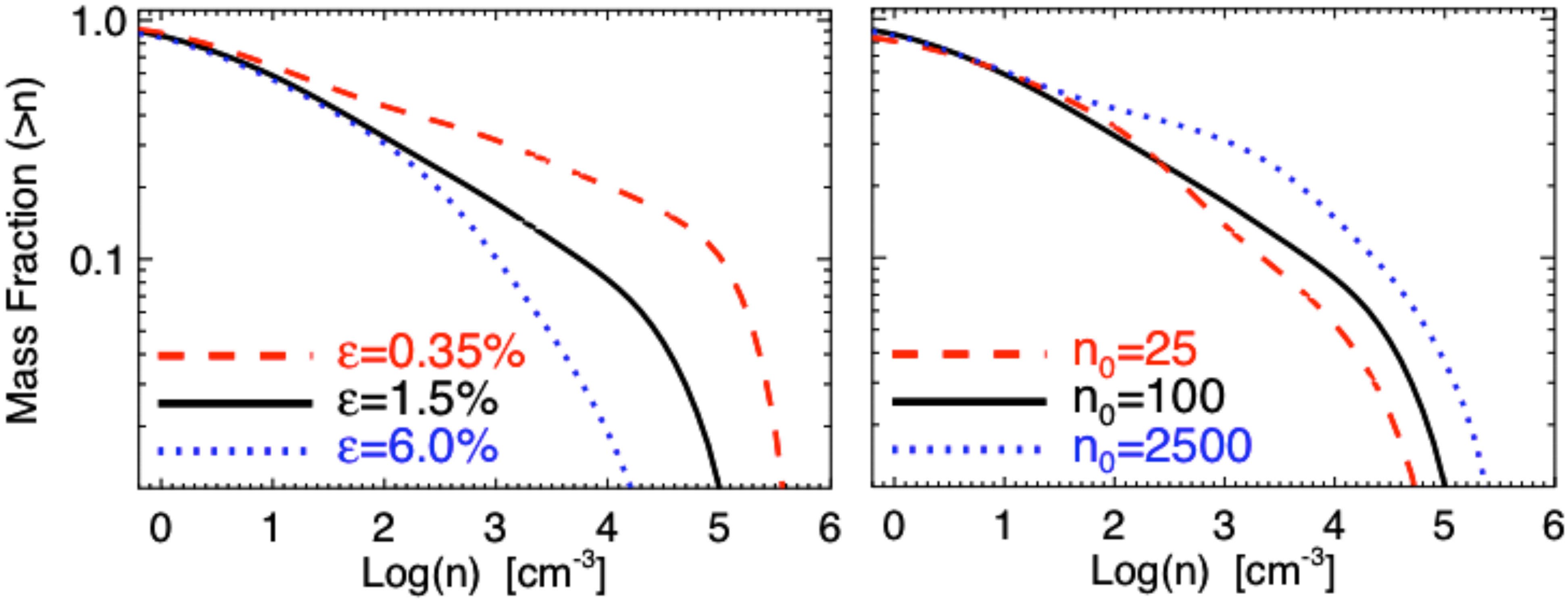


- Just need *some* cooling channel: changes at $M_{gal} < 10^6$ M_{sun}, $Z<0.01$ Z_{sun}

How Does Star Formation Self-Regulate?

SELF-ADJUST THE MASS IN *DENSE* GAS



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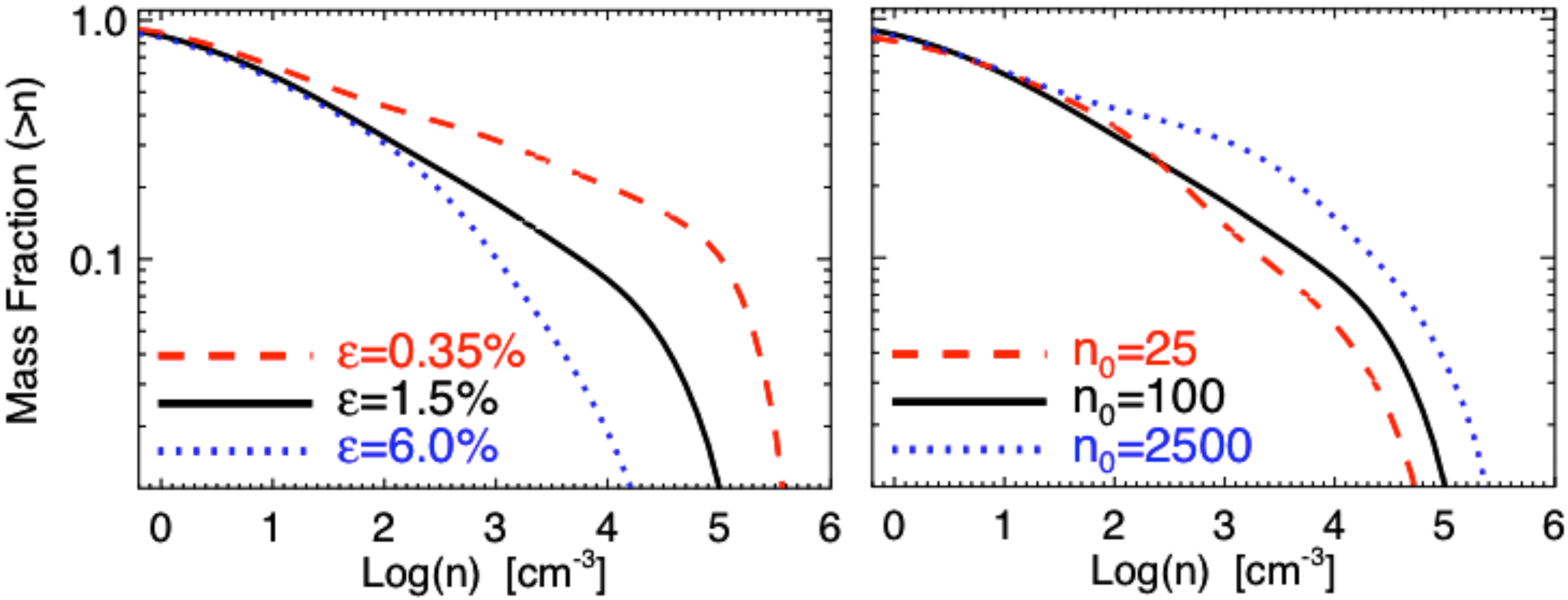

- Need net momentum injection dP/dt ~ L/c ~ SFR
  to cancel dissipation ~ M_{gas} s_{disk} W and maintain Q~1

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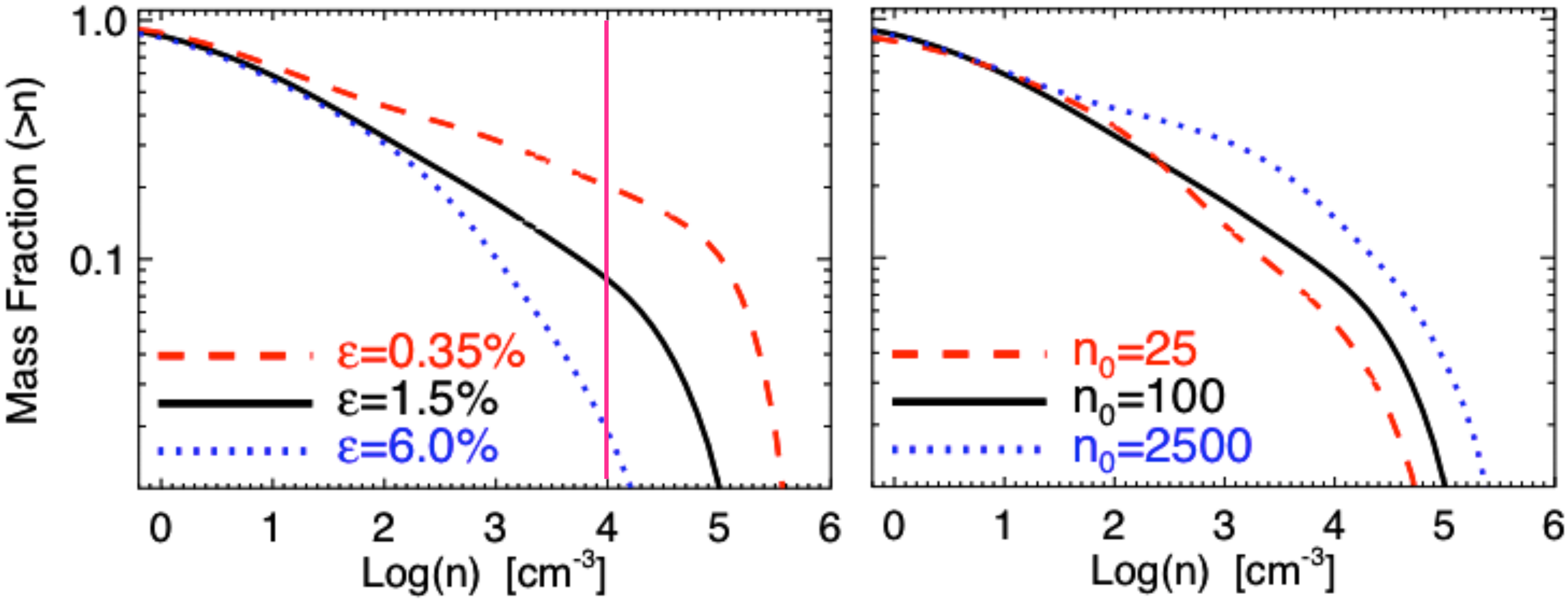

- Need net momentum injection dP/dt ~ L/c ~ SFR
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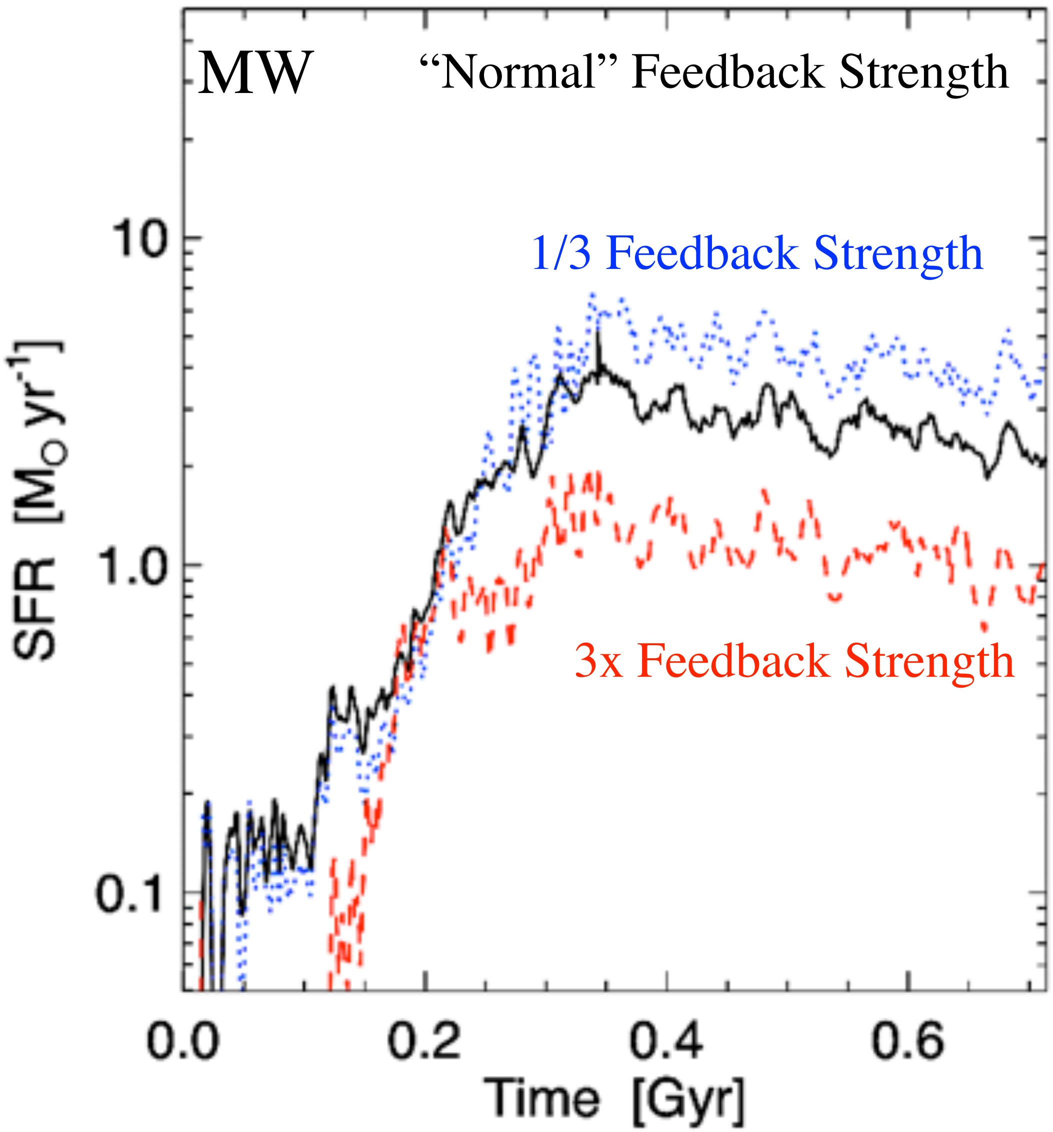
- Not just top-down collapse

Star Formation is Feedback-Regulated:

MORE FEEDBACK = LESS STAR FORMATION



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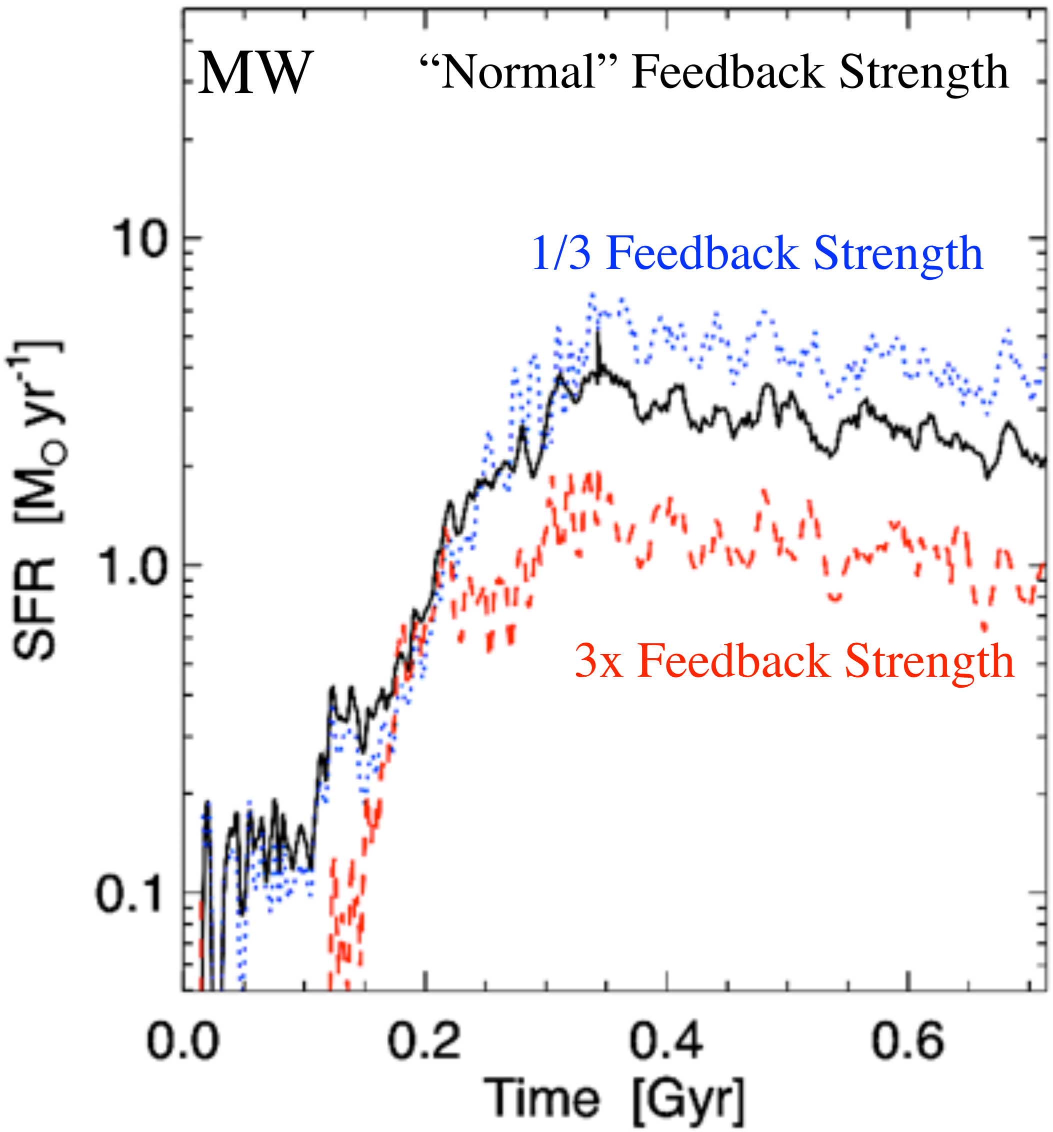
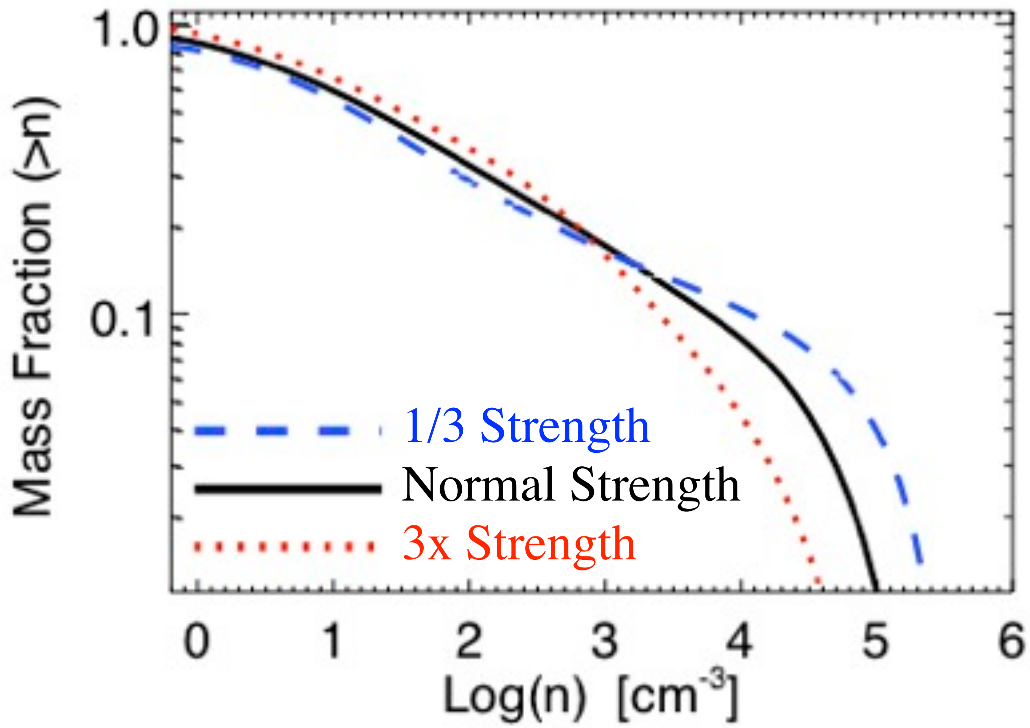
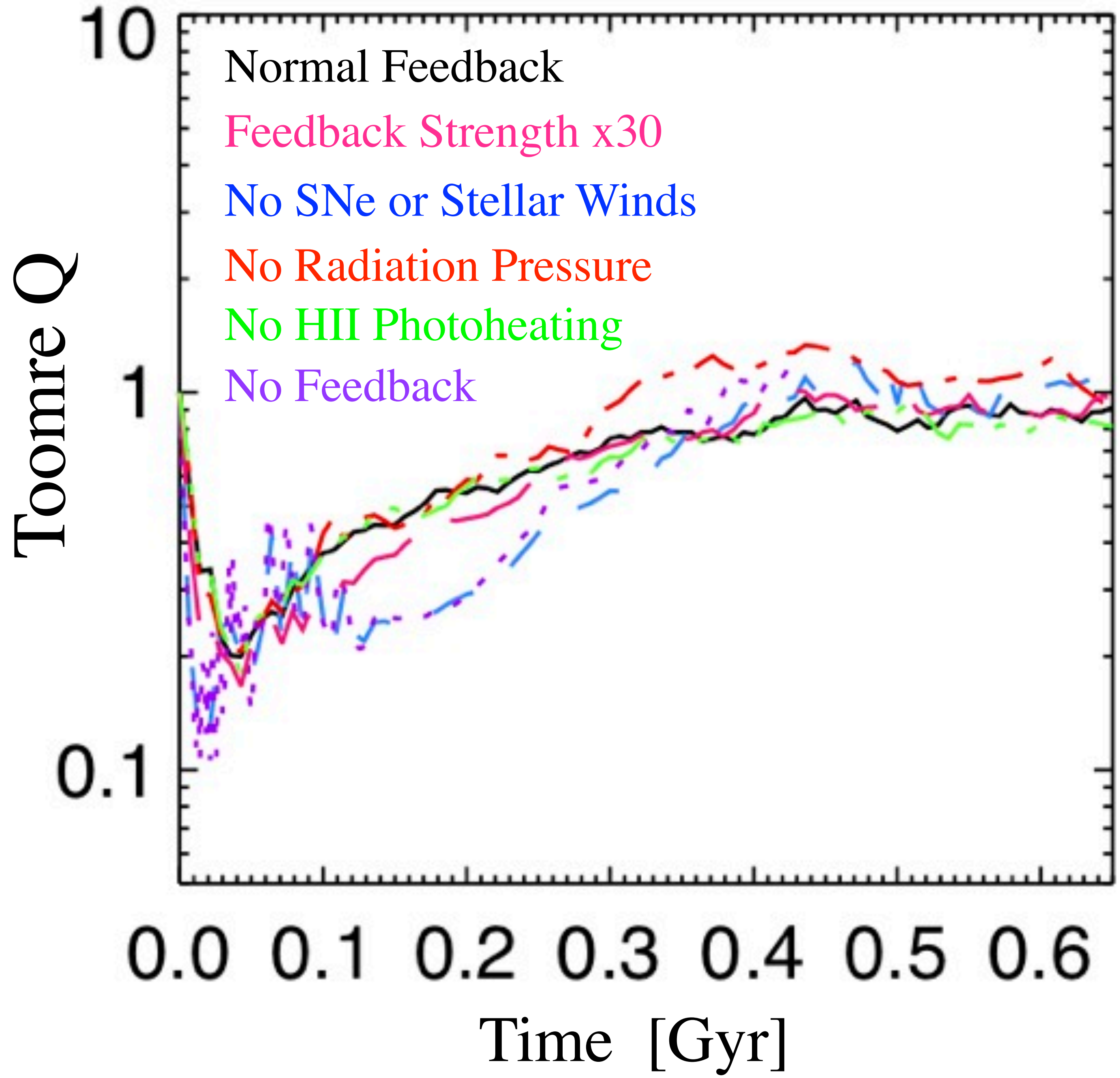




Q ~ 1 Is a Boring Diagnostic

EVERYTHING GOES TO Q~1. SERIOUSLY.



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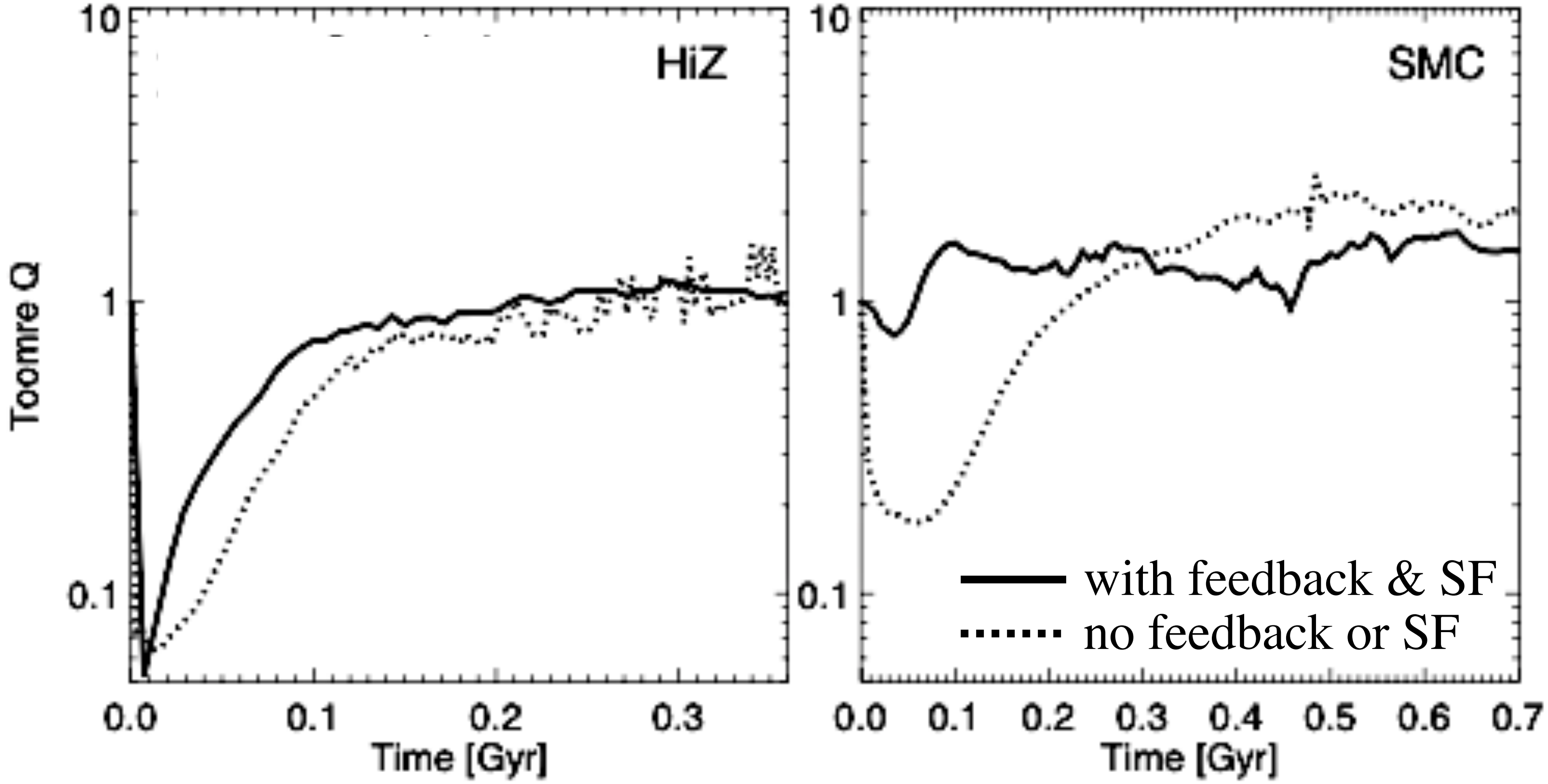
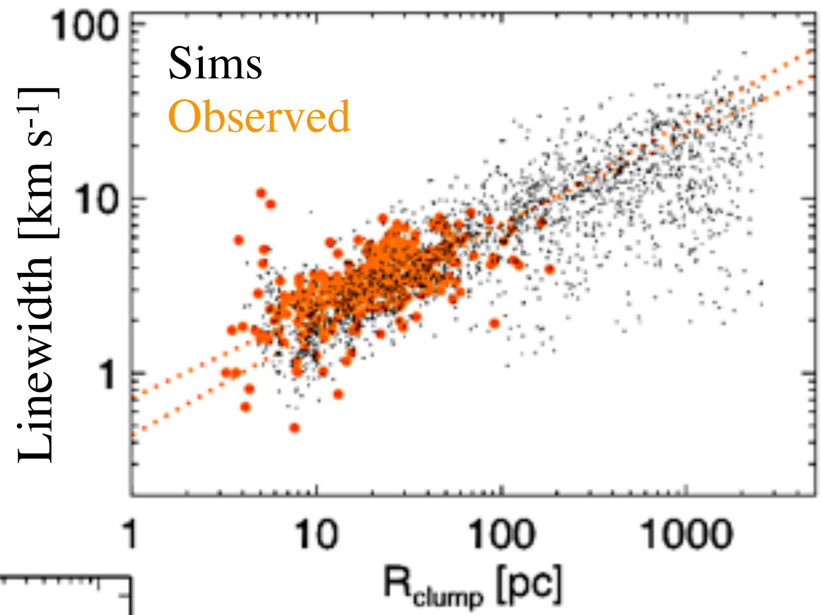
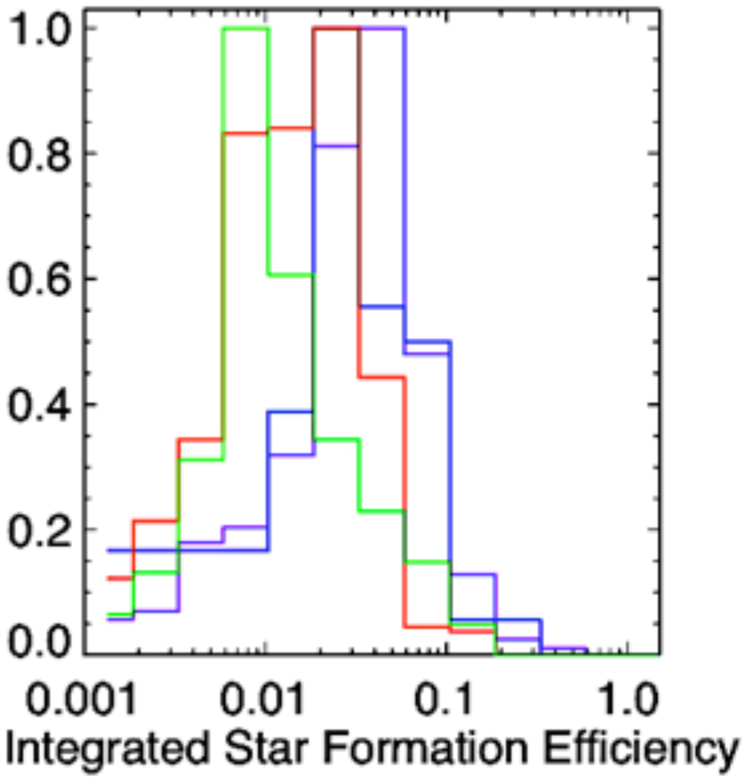
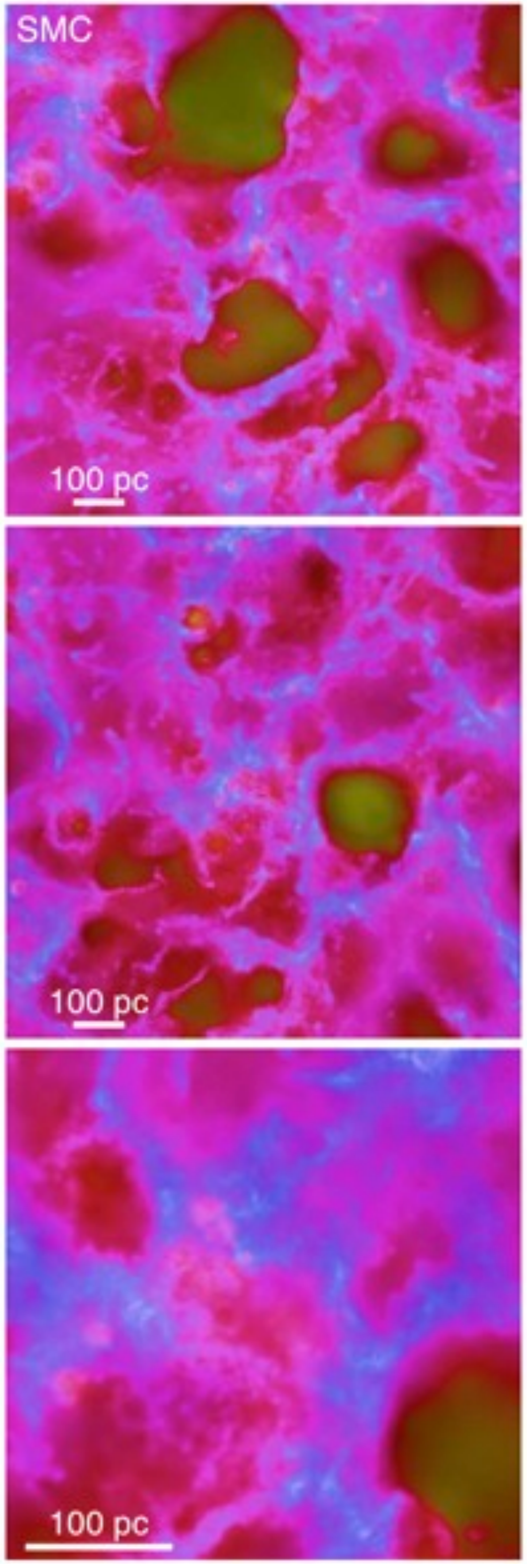


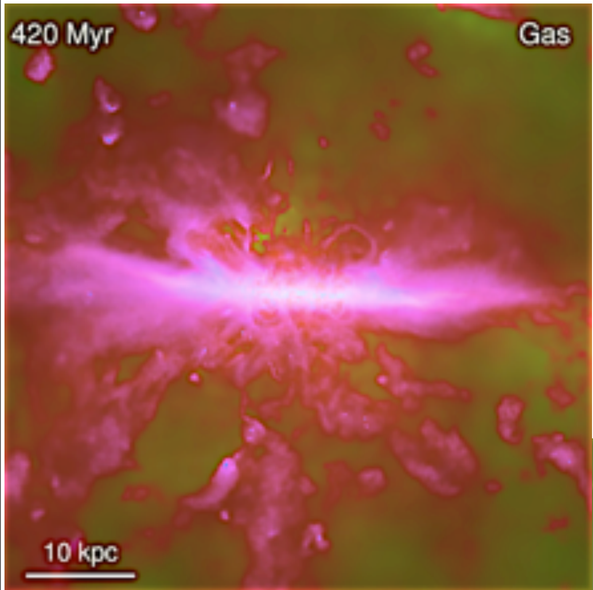
Properties of GMCs
STUFF TO EXAMINE IN THE FUTURE...

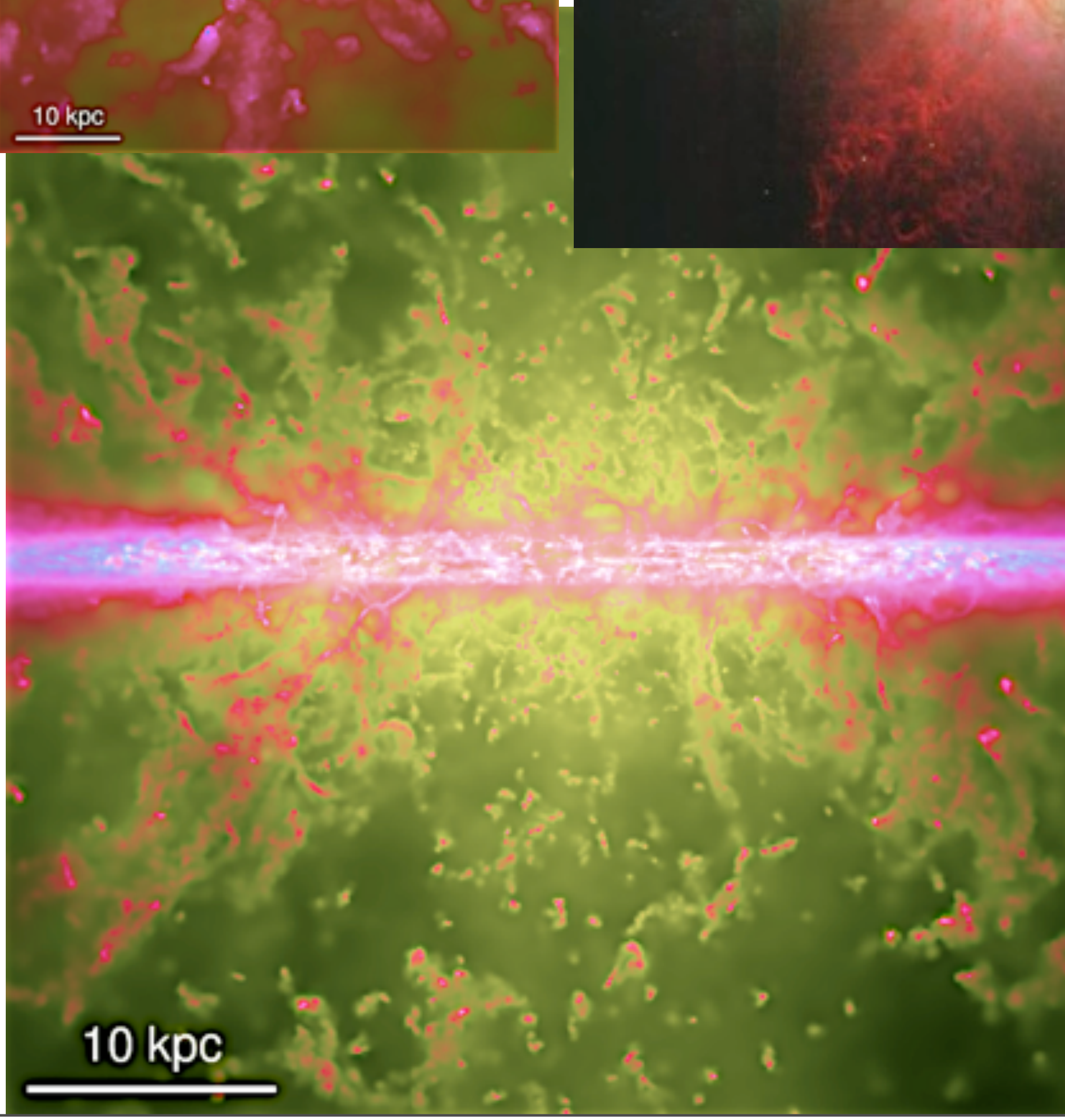


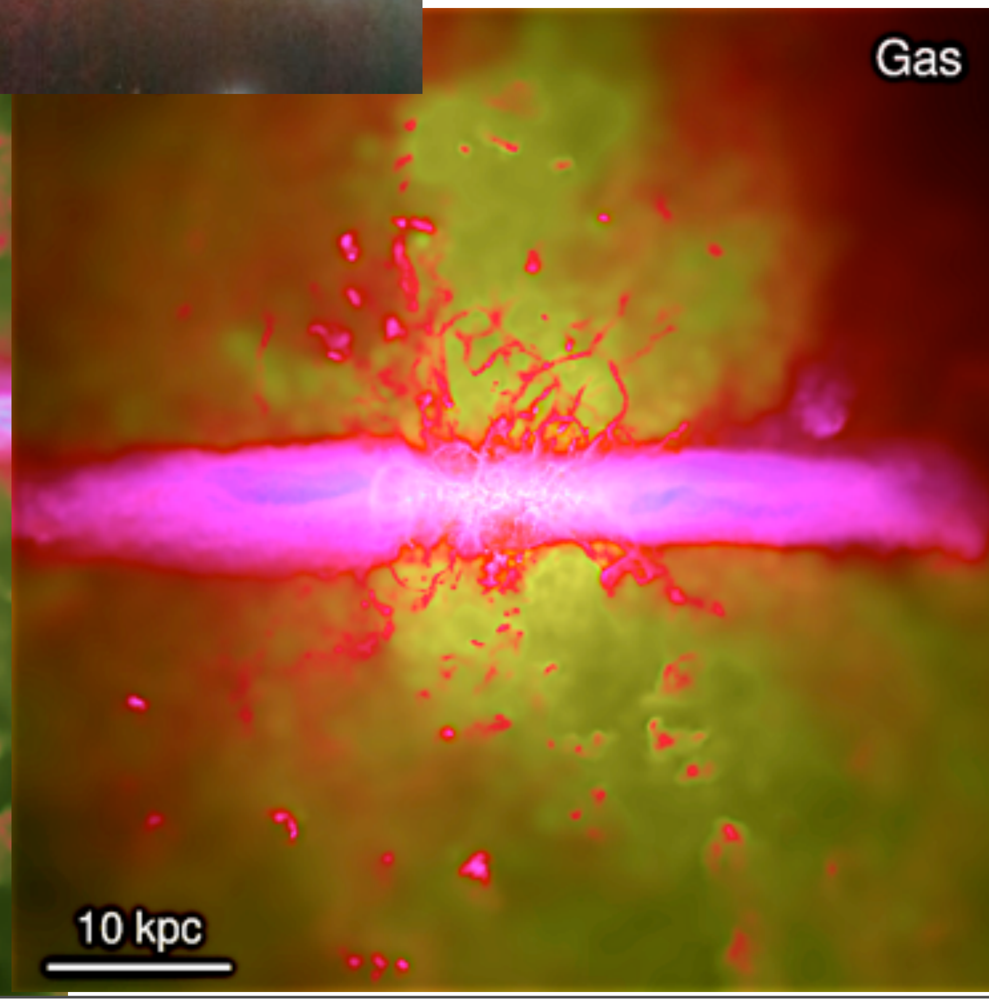


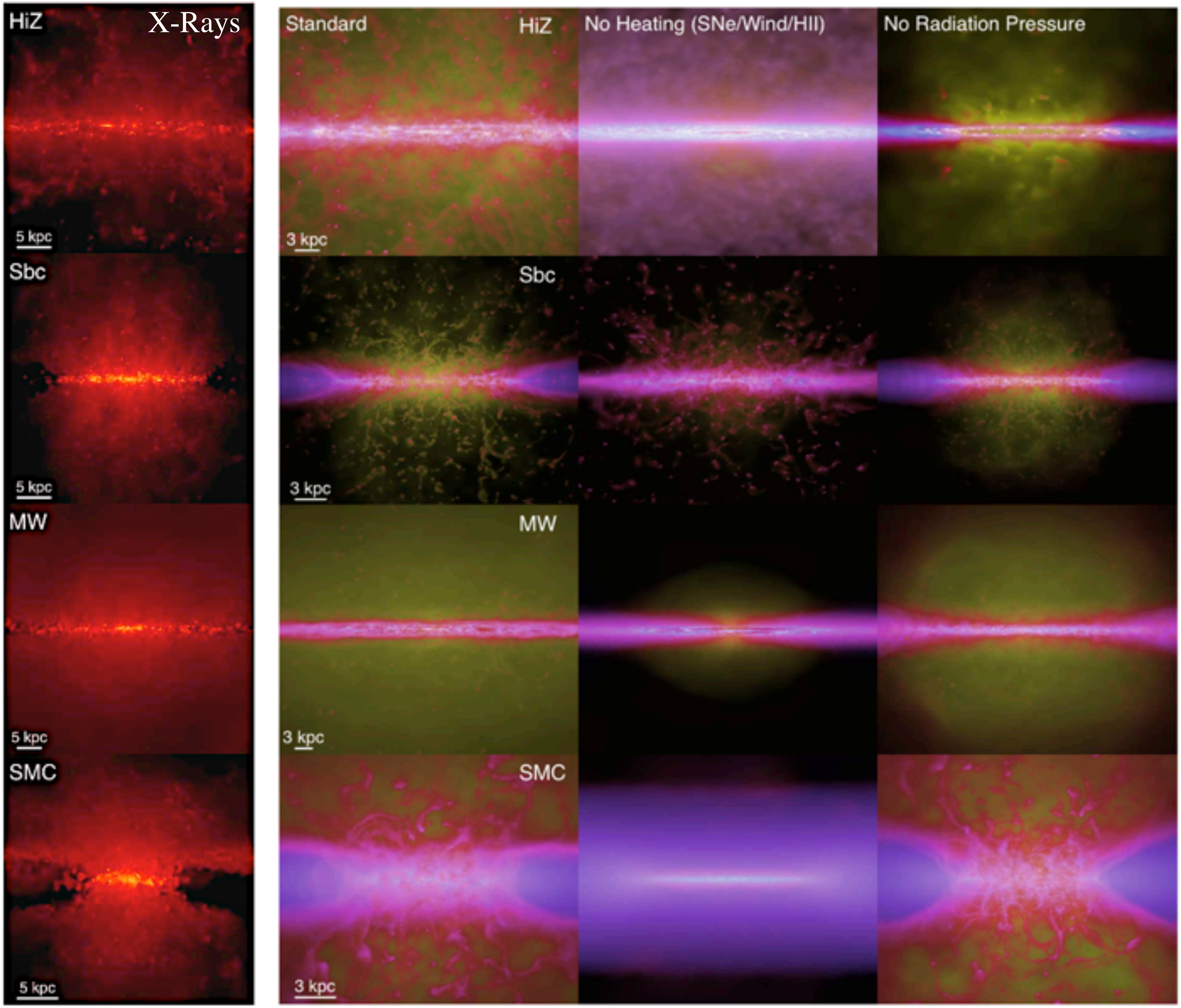


Galactic Super-Winds





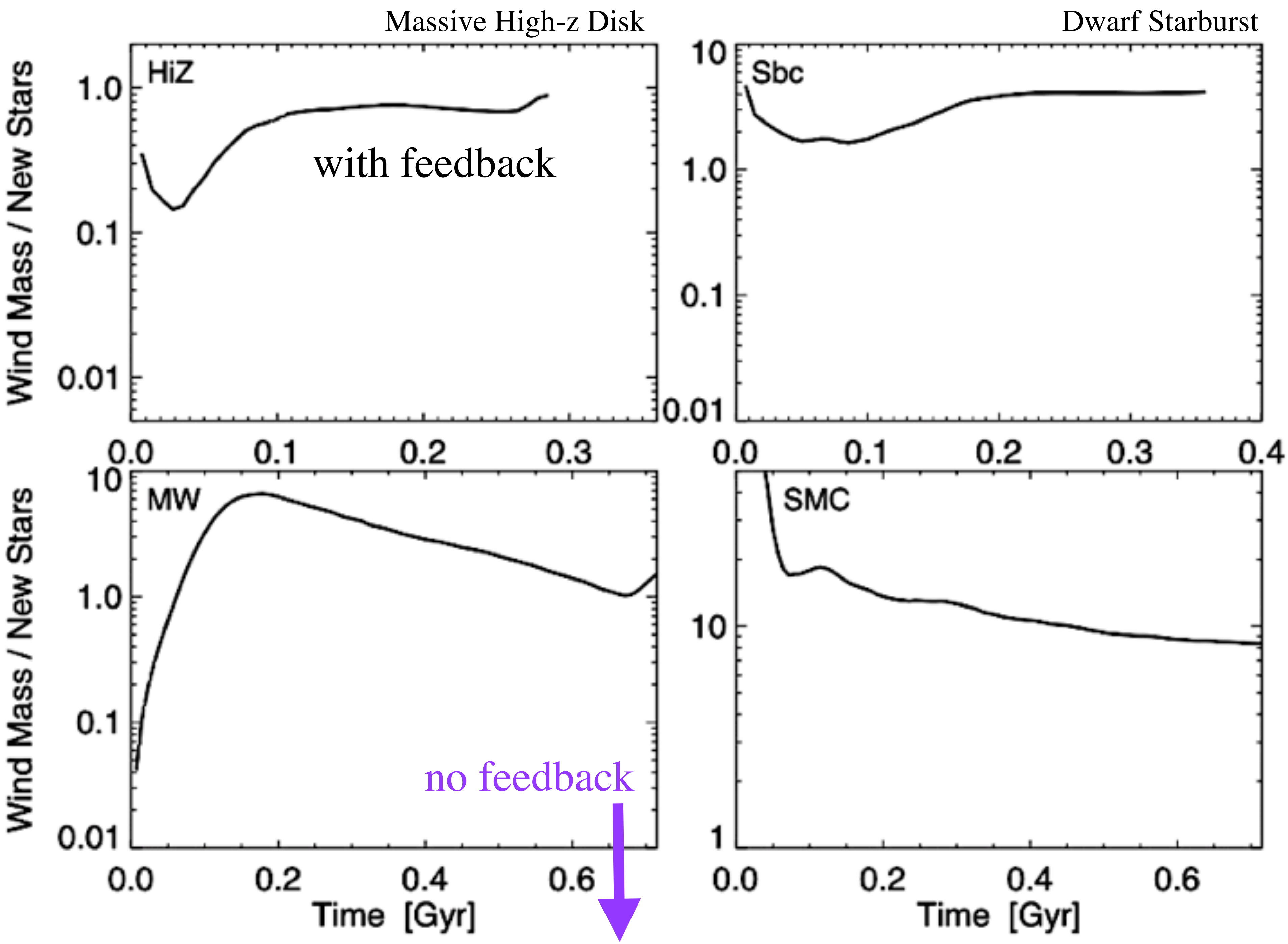




HiZ
X-Rays
5 kpc
Sbc
5 kpc
MW
5 kpc
SMC
5 kpc
Standard
HiZ
No Heating (SNe/Wind/HII)
No Radiation Pressure
3 kpc
Sbc
3 kpc
MW
3 kpc
SMC
3 kpc

How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?



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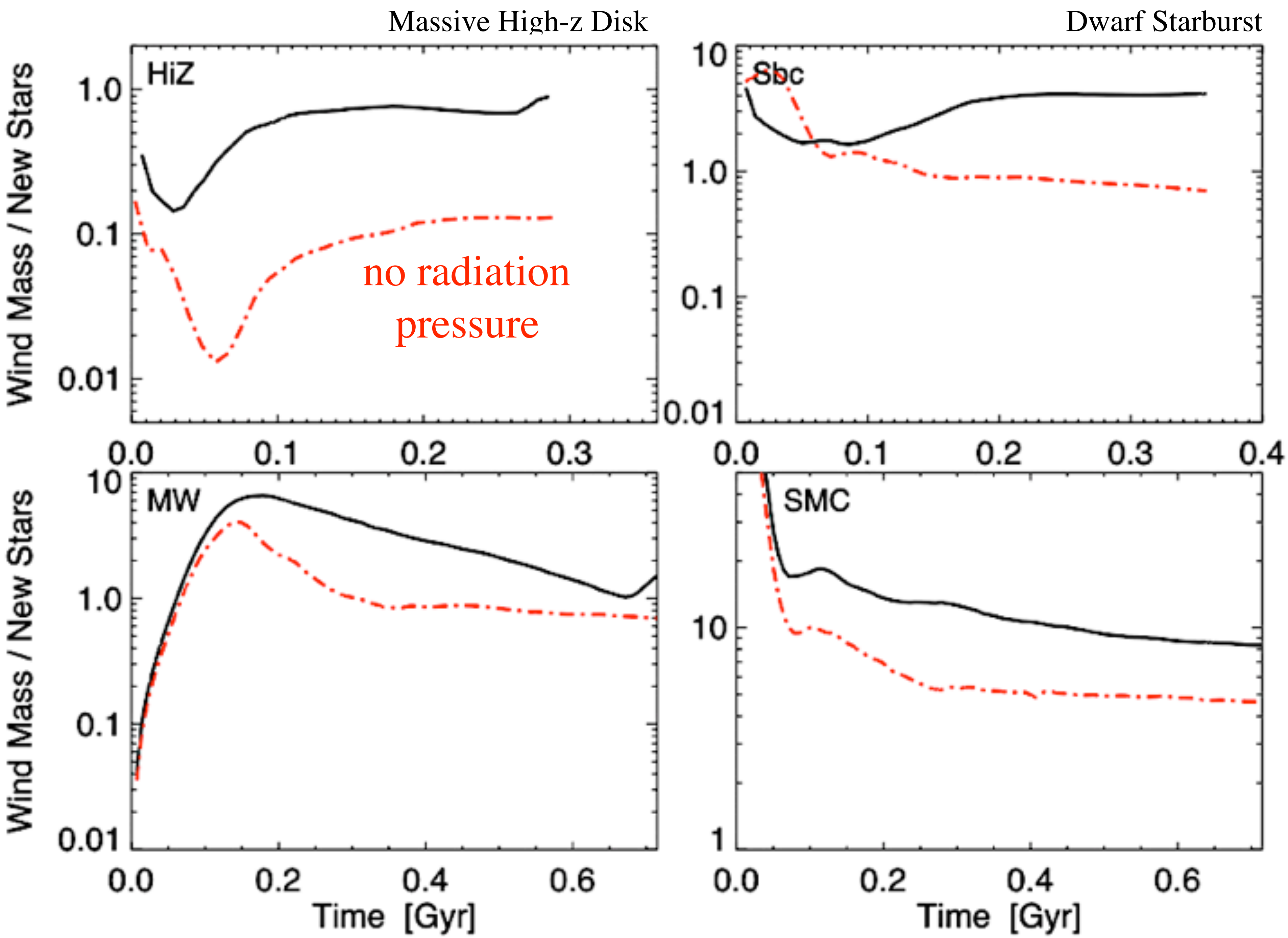

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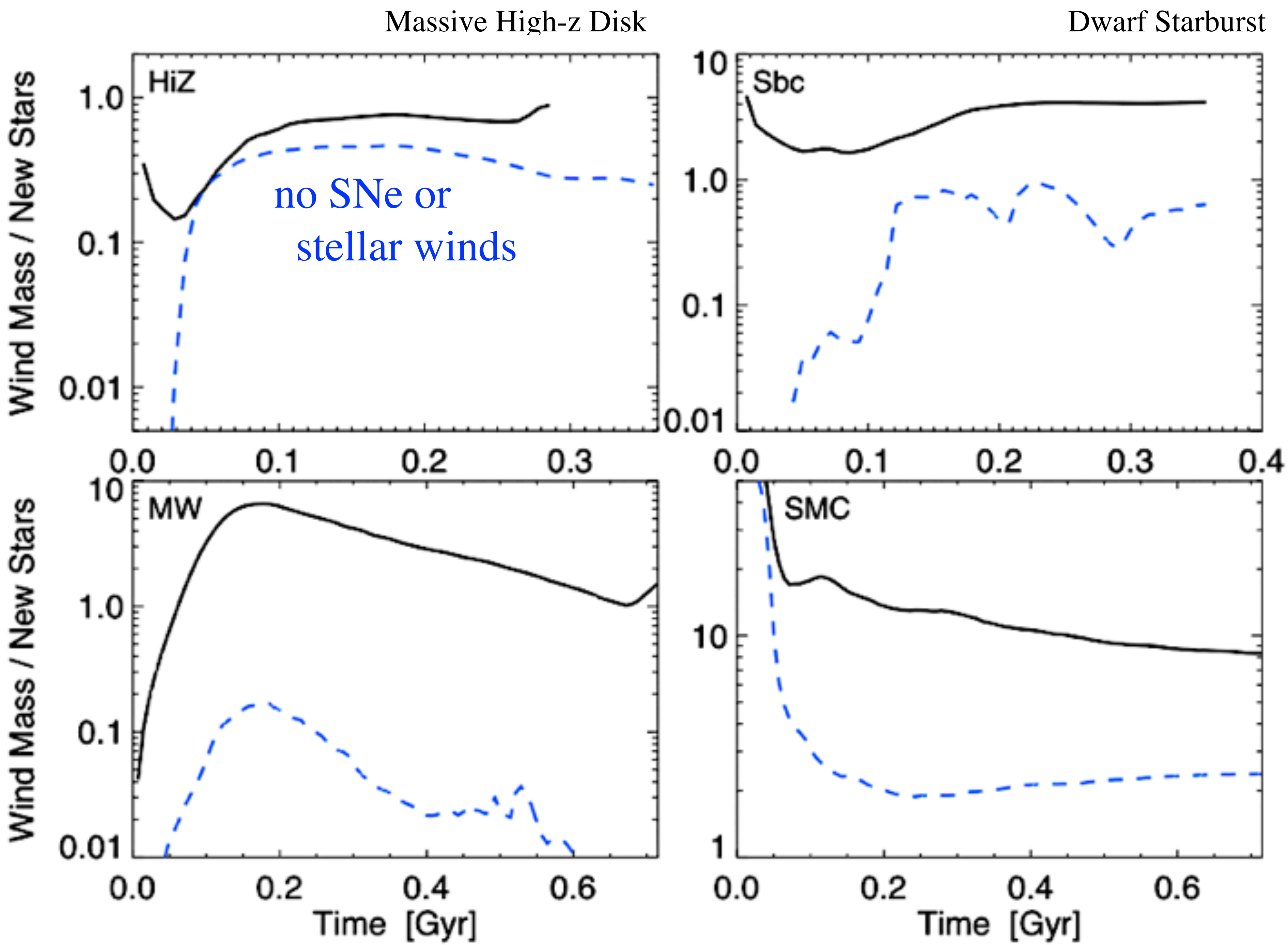

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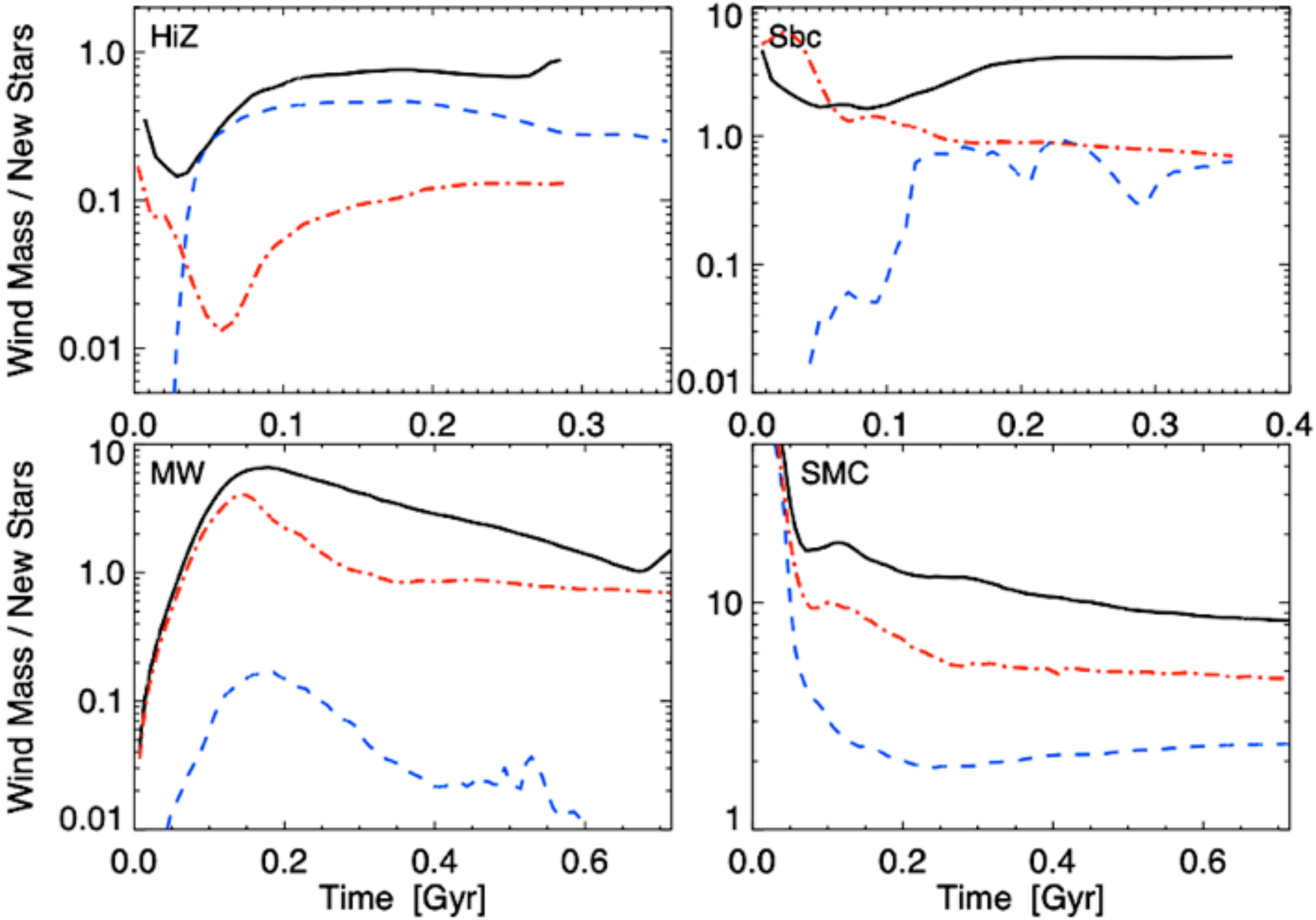
Massive High-z Disk

Dwarf Starburst



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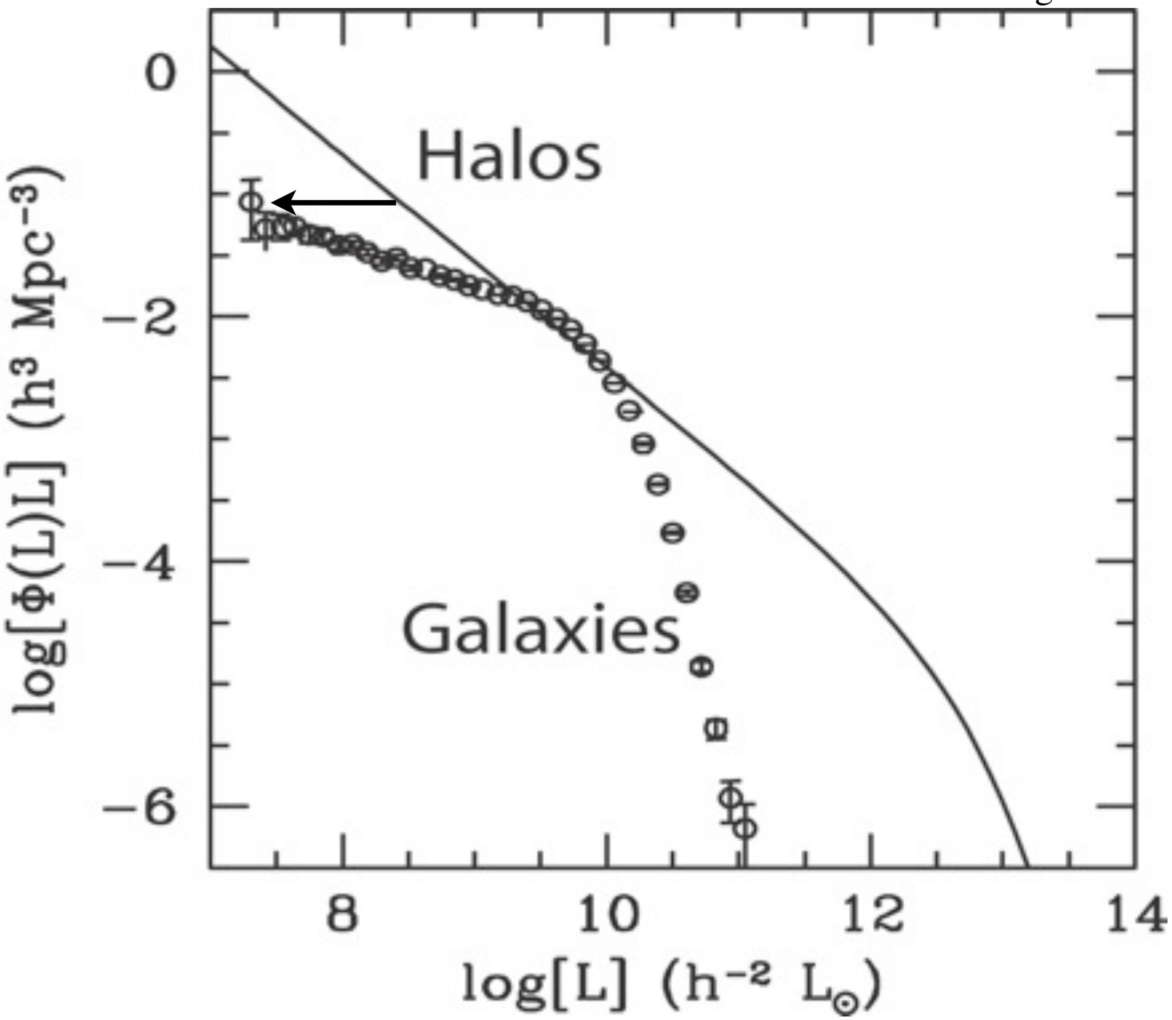
Yang+ 03



- 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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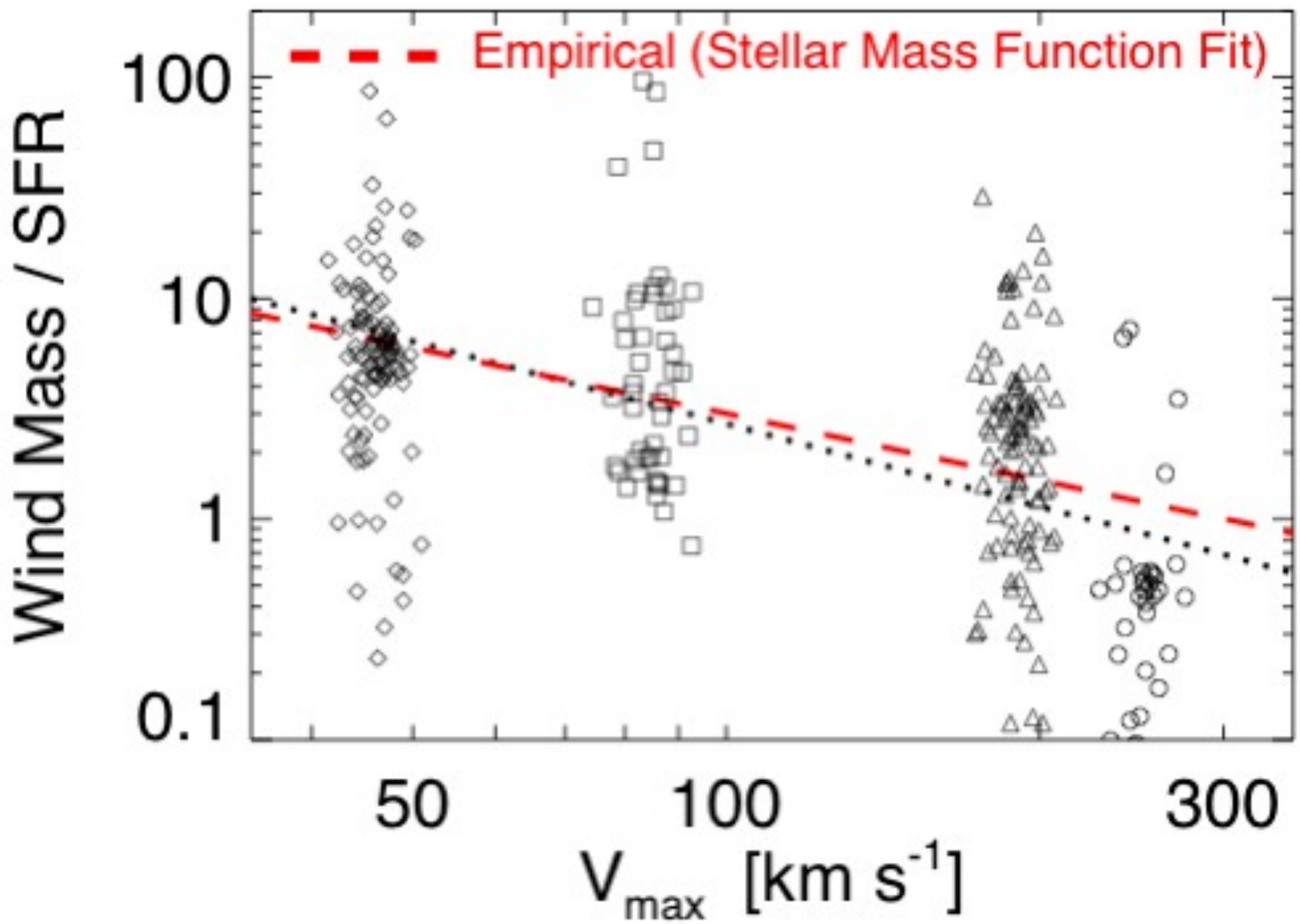

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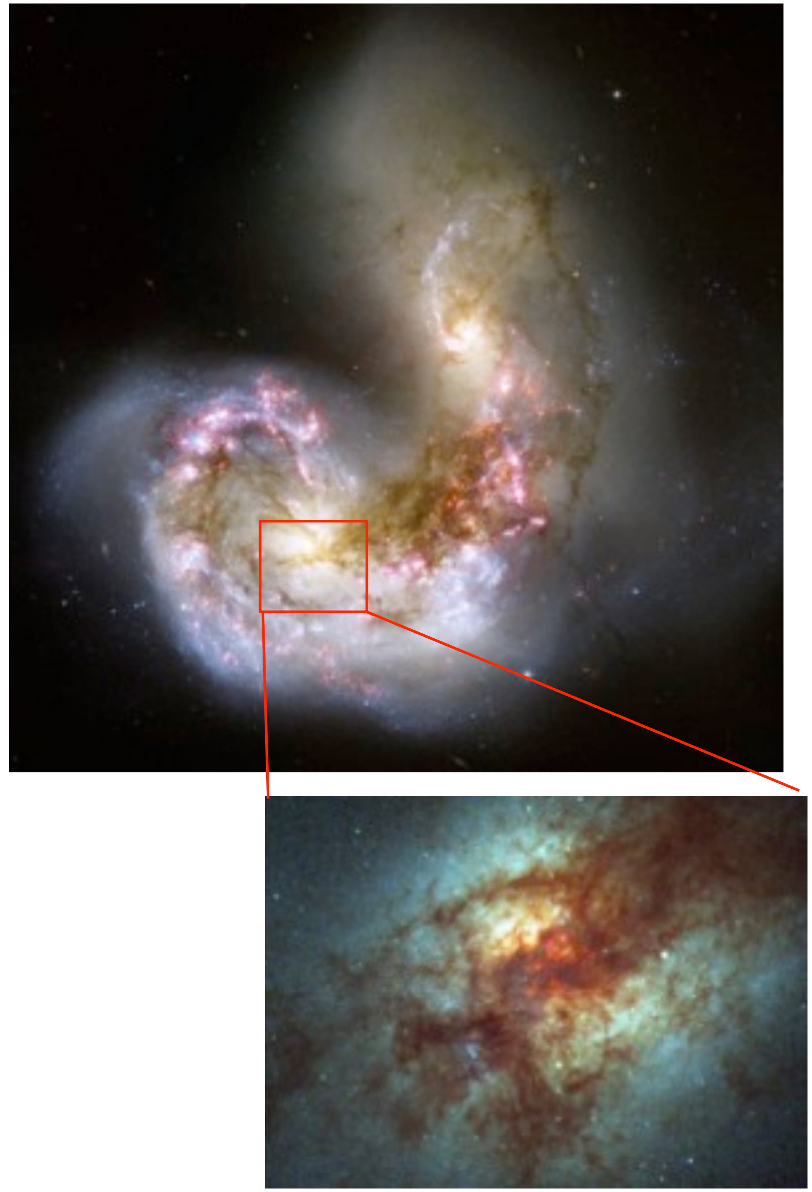
Future Directions

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

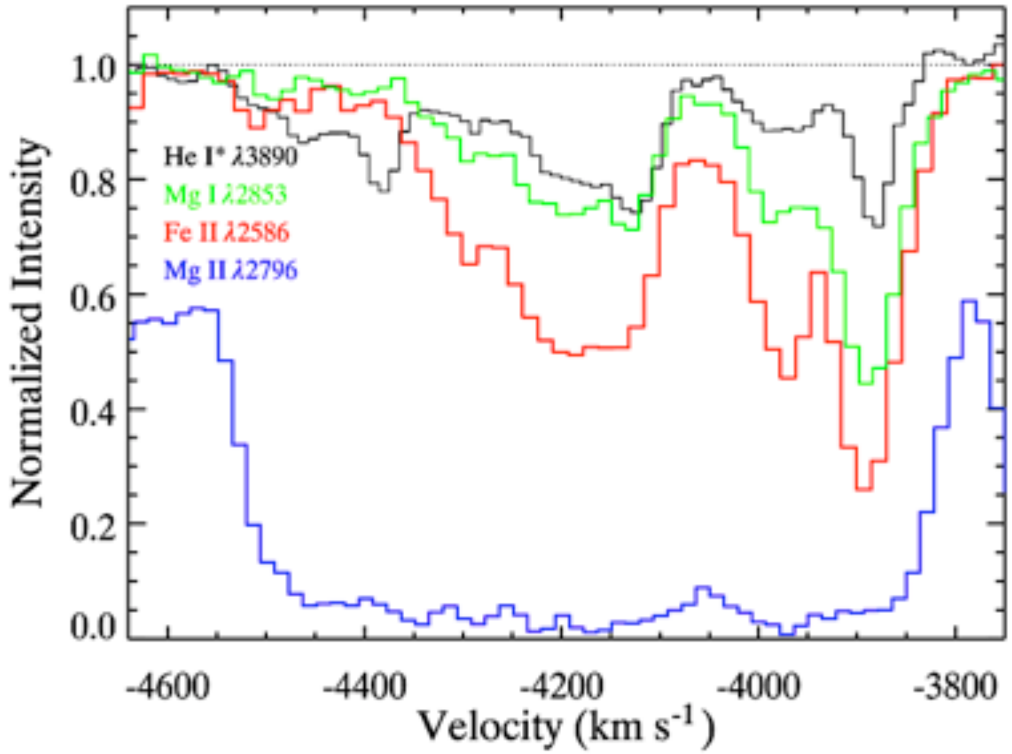


~30 sec

What About The Quasars?

- BALs:
  Preferentially in high-L quasars
- Covering factor ~20%
- of ~16 measured, 14 have:

$$\dot{M}_{\rm wind}\, v \gtrsim L_{\rm AGN}/c$$
$$L_{\rm wind} \gtrsim 0.01\, L_{\rm AGN}$$

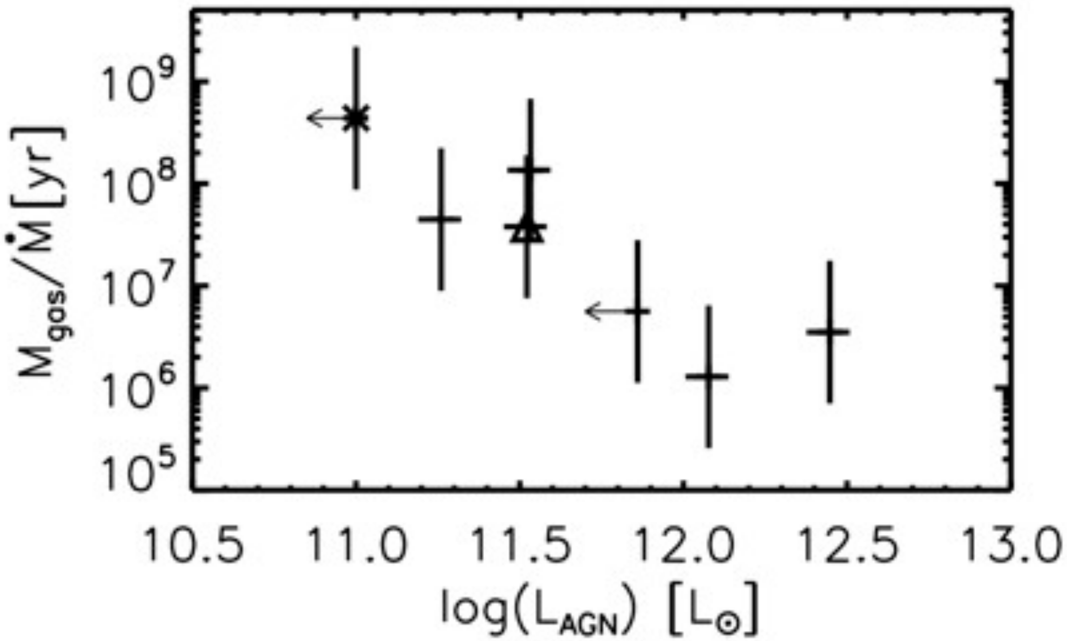


$$R_{\rm wind} \sim 1 - 20\,{\rm kpc}$$
$$v \gtrsim 1000\,{\rm km\,s^{-1}}$$
$$\dot{M}_{\rm wind} \sim 100 - 600\,M_{\odot}\,{\rm yr}^{-1}$$

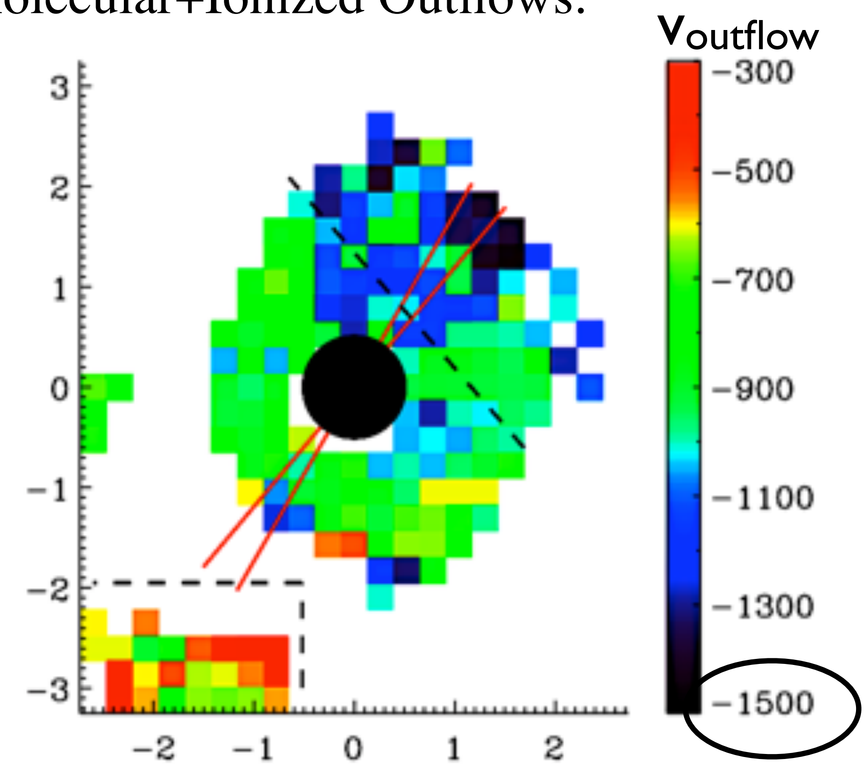
Arav et al.
Wampler et al. 1995
Hamann et al. 2001
de Kool et al. 2001&2
Korista et al. 2008
Moe et al. 2009
Dunn et al. 2010
Aoki et al. 2011
Kaastra et al. 2011

Molecular Outflows in AGN ULIRGs

Rupke & Veilleux 2005,2011
Fischer et al. 2010 (Mrk 231)
Feruglio et al. 2010 (Mrk 231)
Alatalo et al. 2011 (NGC 1266)
Sturm et al. 2011 (6 Herschel gal)



Molecular+Ionized Outflows:



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

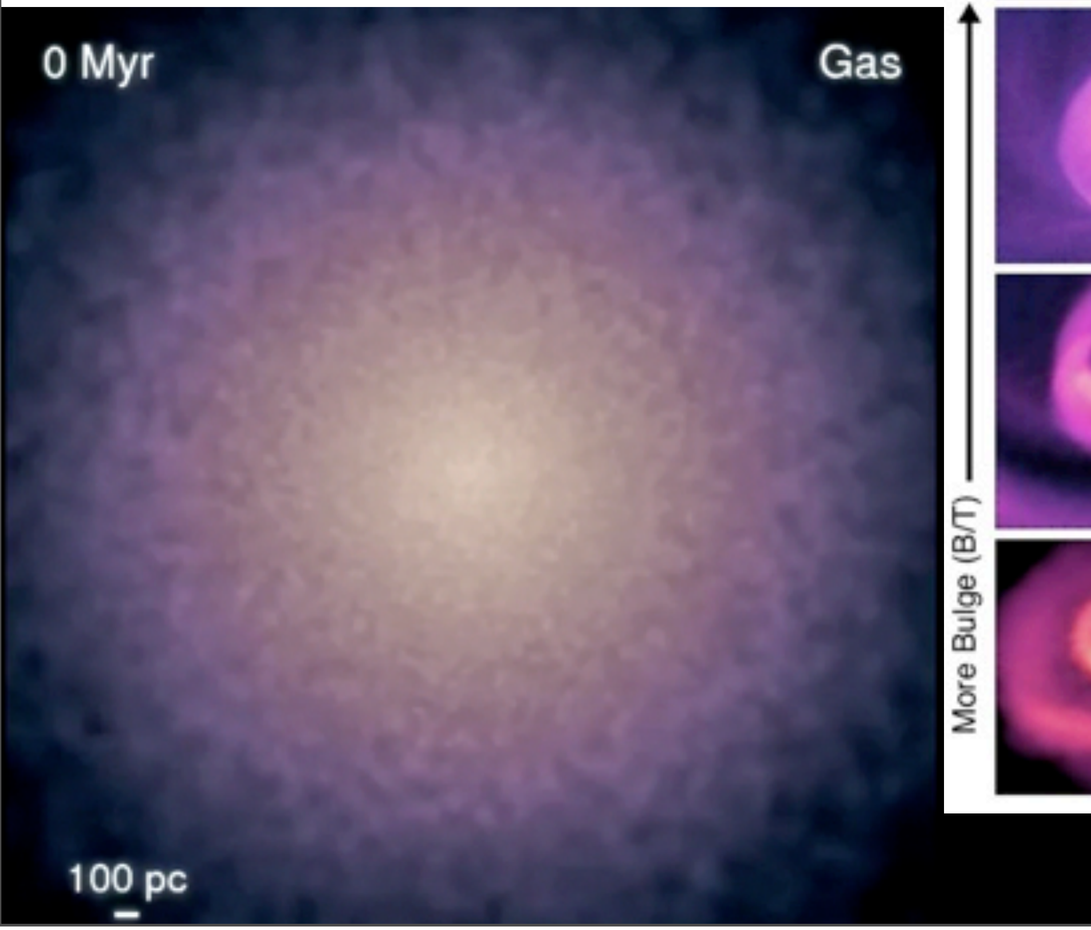
$$v > 500\,{\rm km\,s^{-1}}$$

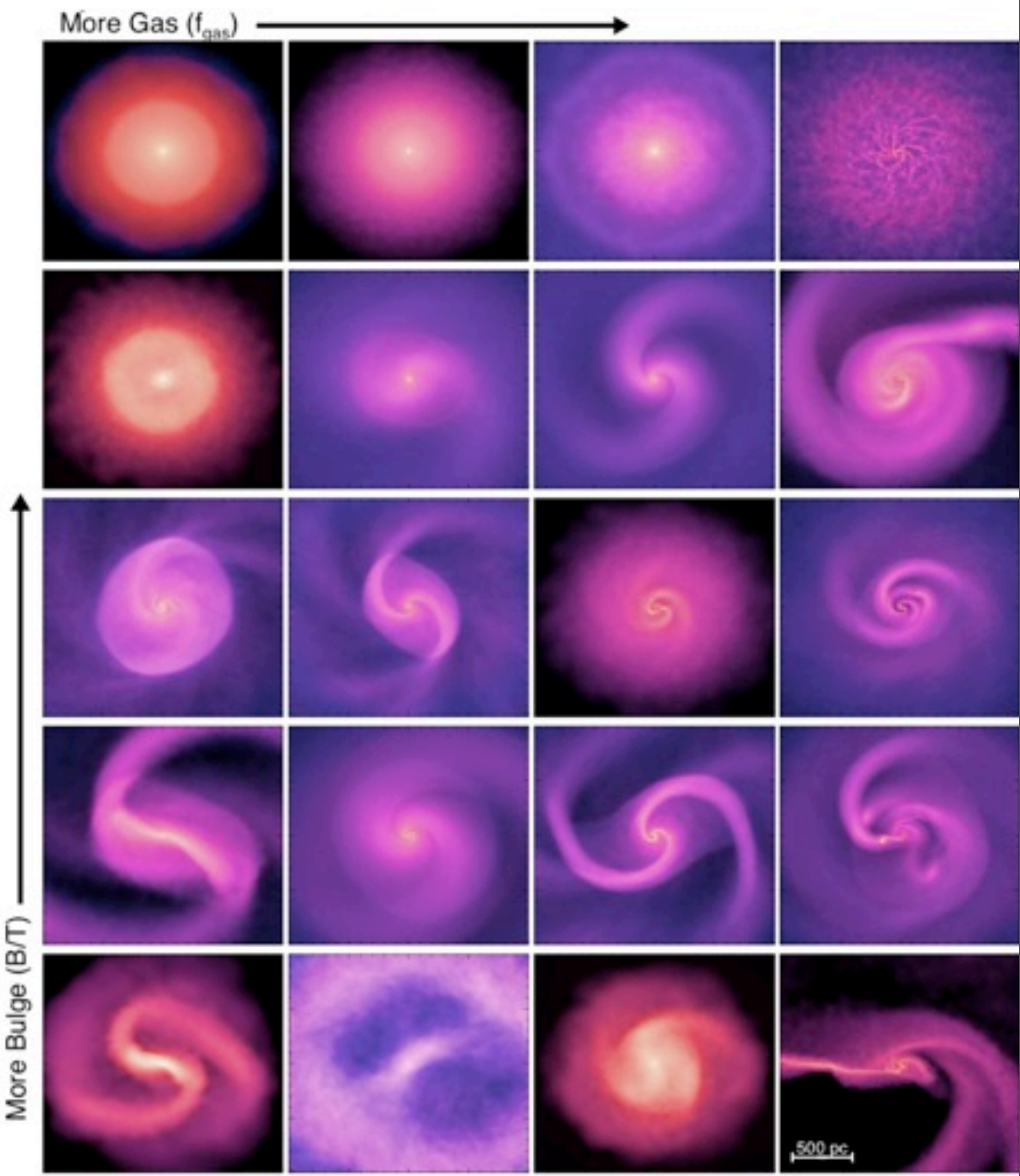
$$\dot{M}_{\rm wind} \gtrsim 1000\,M_\odot\,{\rm yr^{-1}}$$

Step 1: 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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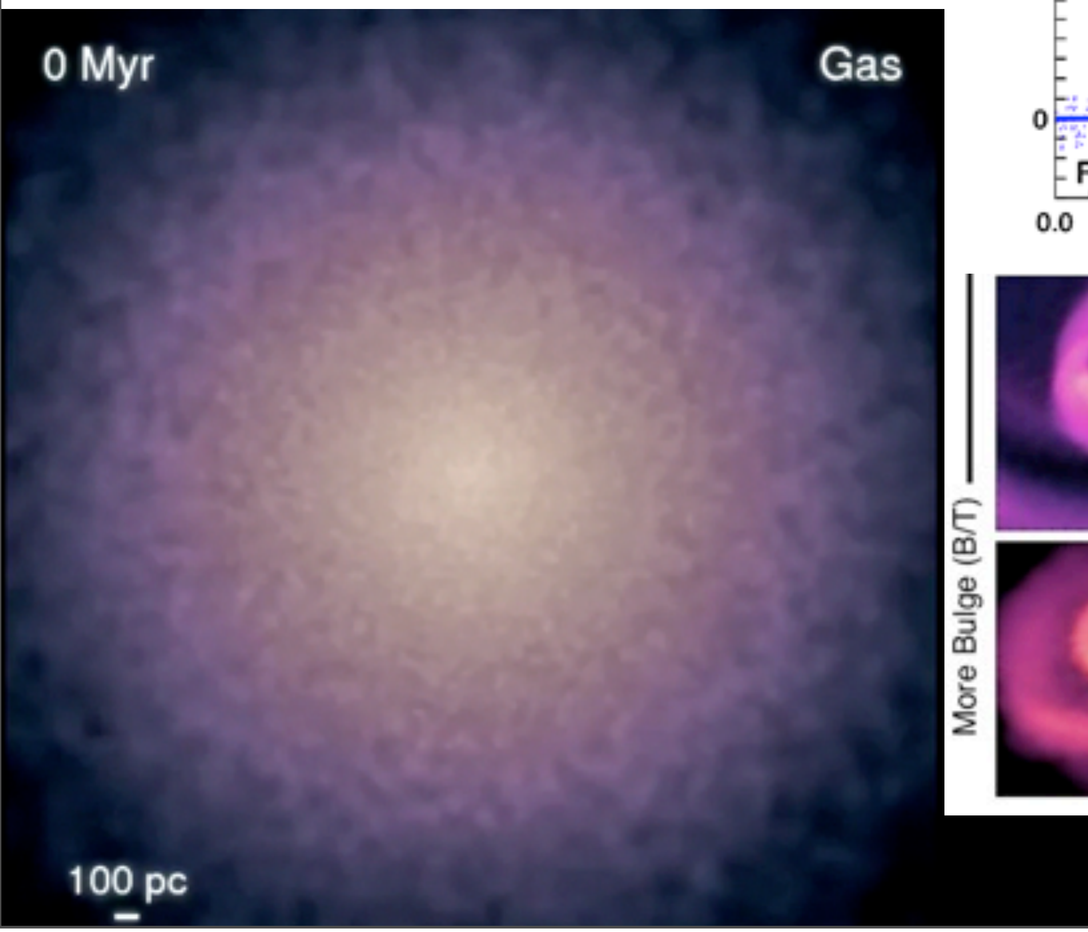
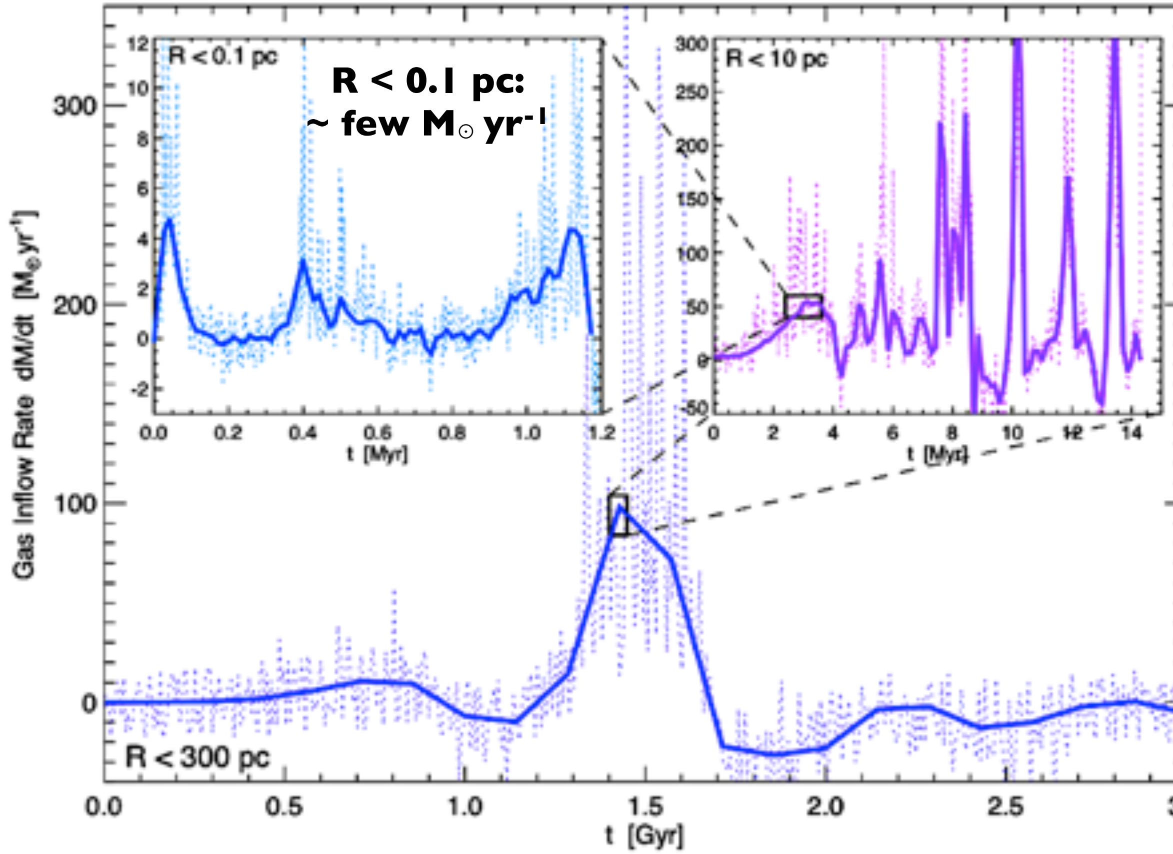
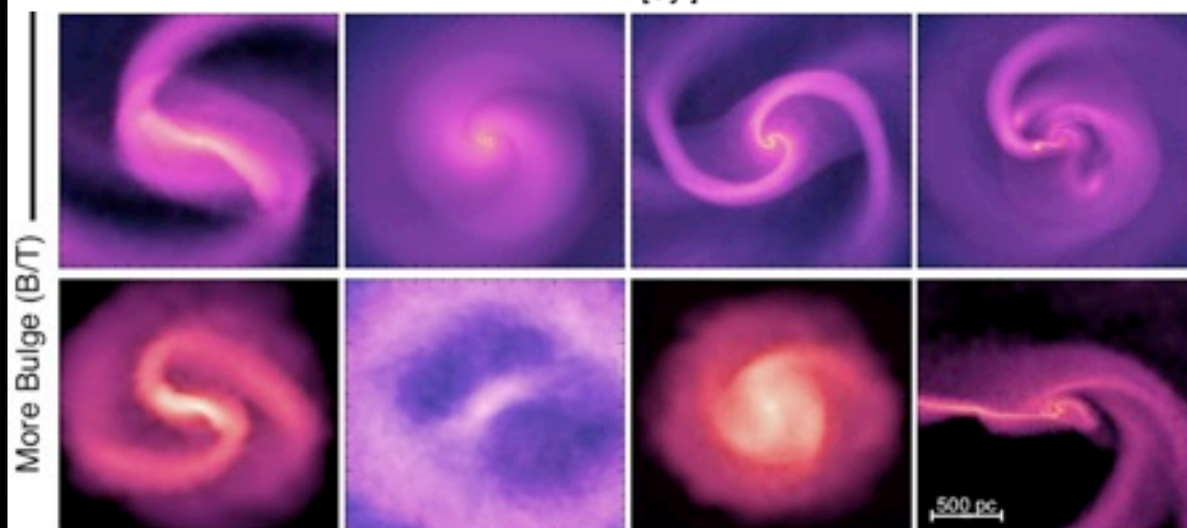






(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

“It’s Bars all the Way Down ...”

(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

"It's Bars all the Way Down ..."

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

(PFH & Quataert 2010)

Bars w/in Bars

(Shlosman et al. 1989)

“It’s Bars all the Way Down ...”

More accurately ...

“It’s Non-axisymmetric Features all the Way Down ...”

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

Step 2: Feedback

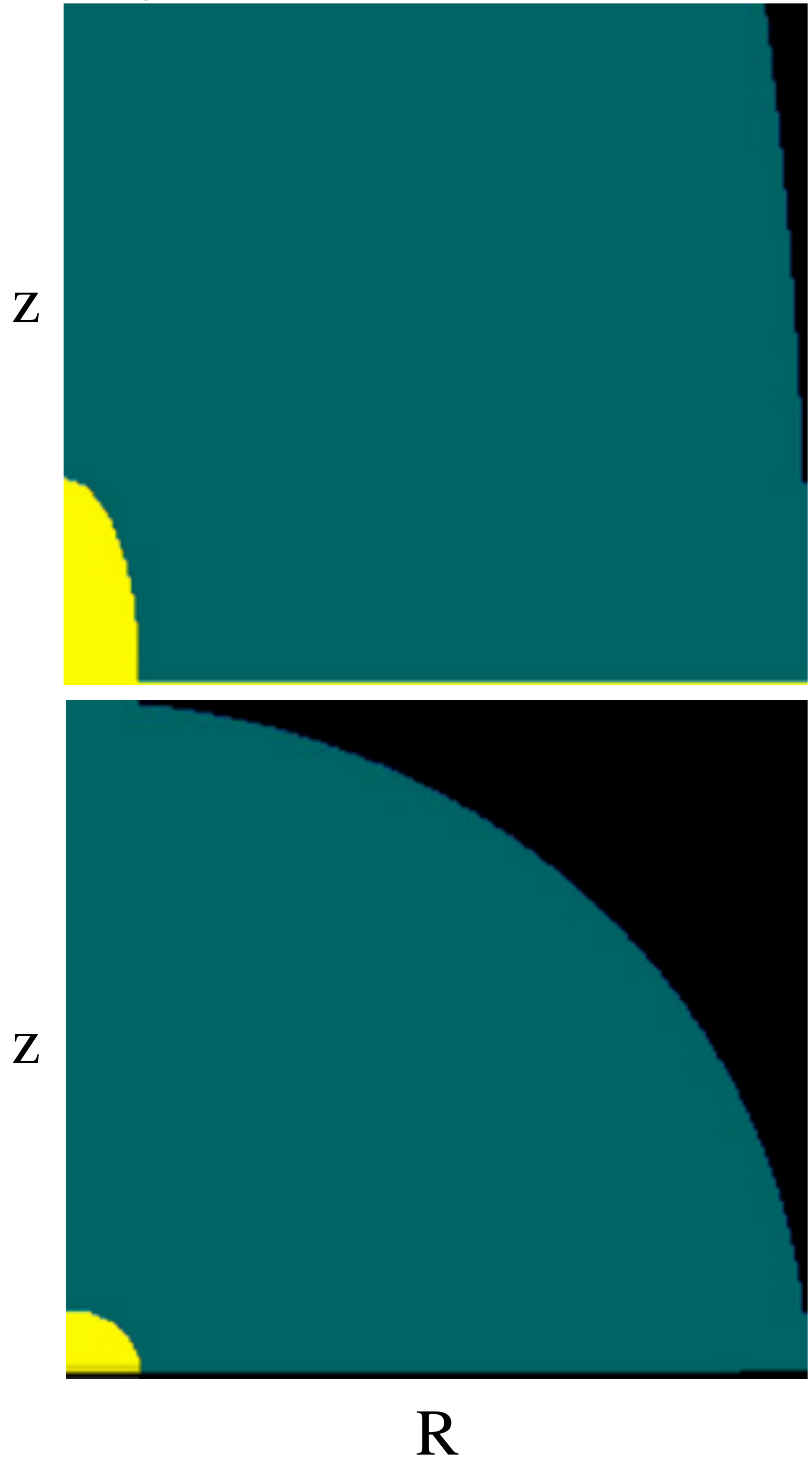
Proga et al. 00-07; Kurosawa et al. 08-11

- L/L_{Edd} >~ 0.1
- Covering factor ~10-30%

- Launched at < pc

$$\dot{M}_{\rm launch} \sim \dot{M}_{\rm BH}$$

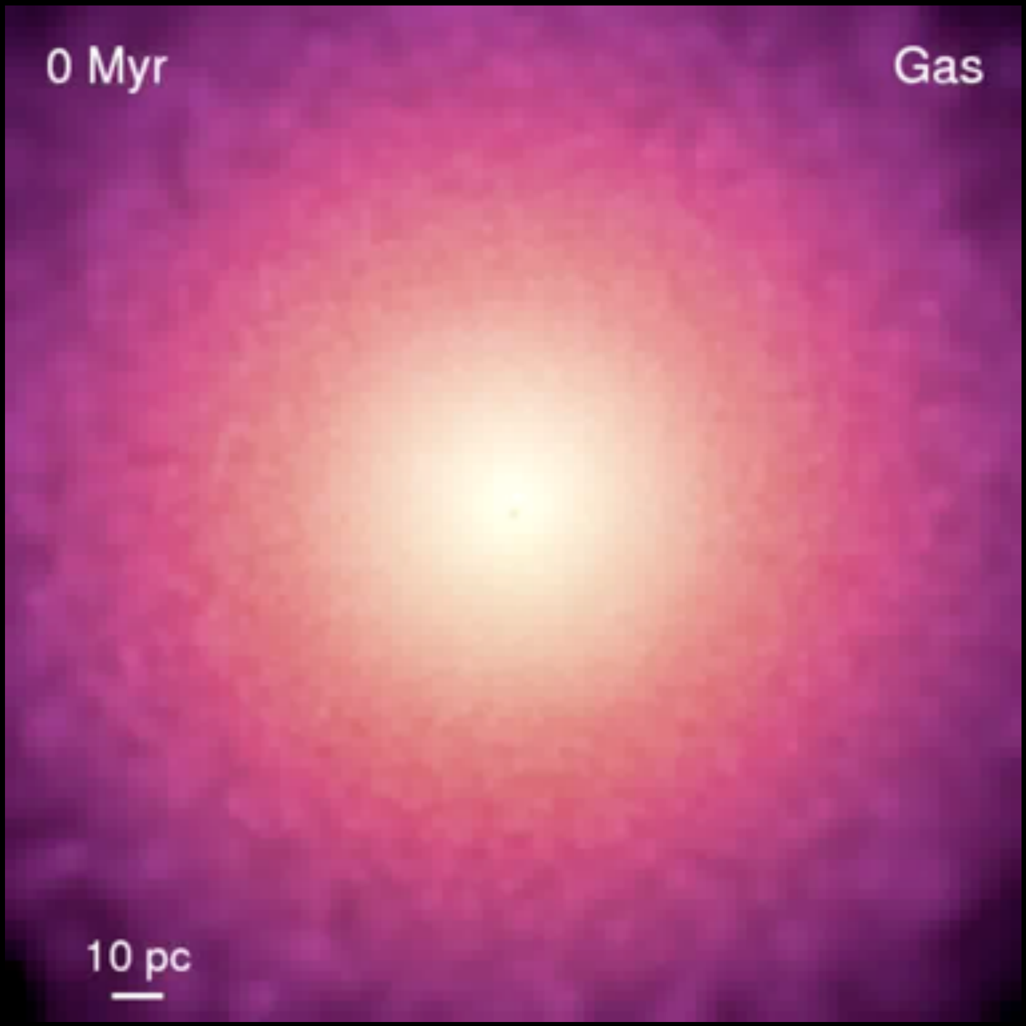
$$v_{\rm launch} \sim 30,000\,{\rm km/s}$$



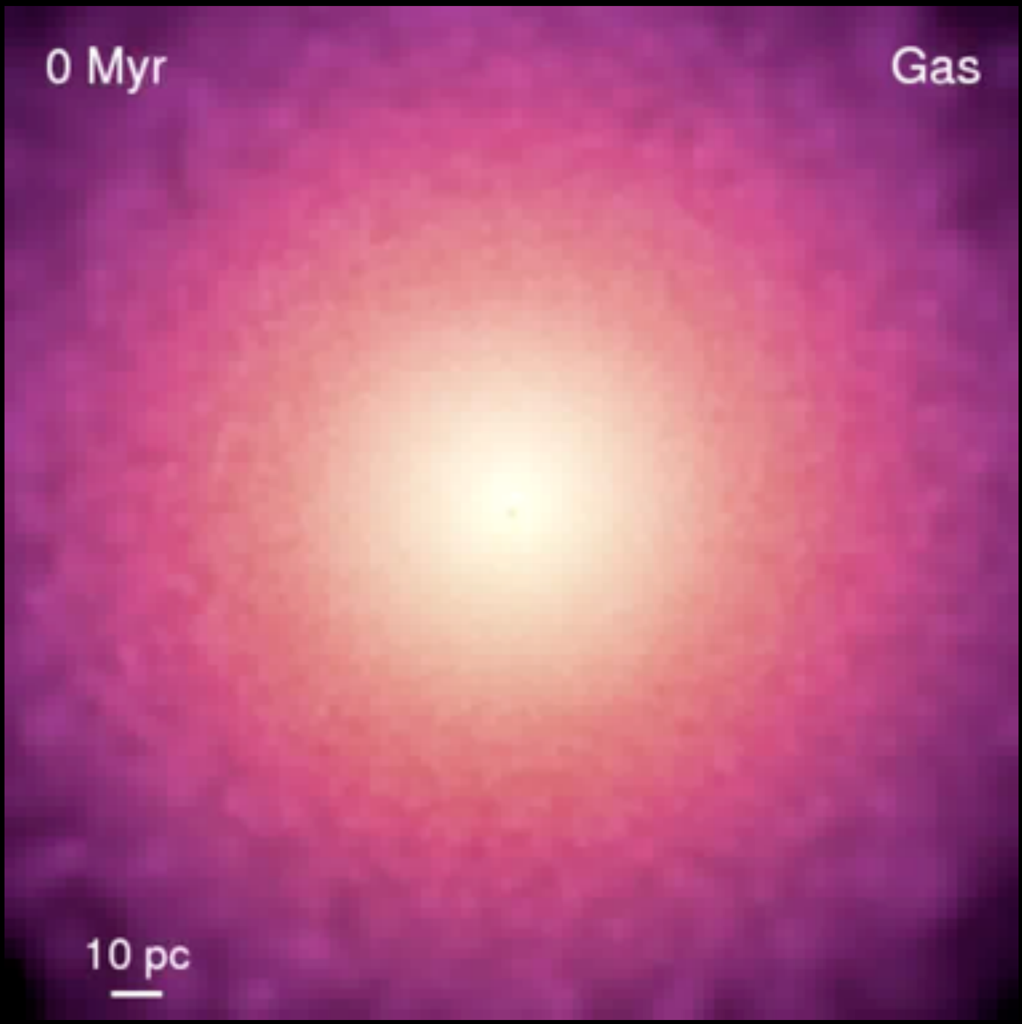
BAL Winds on ~1pc - 1kpc scales:

PFH in prep
Wada et al.

No BAL Winds

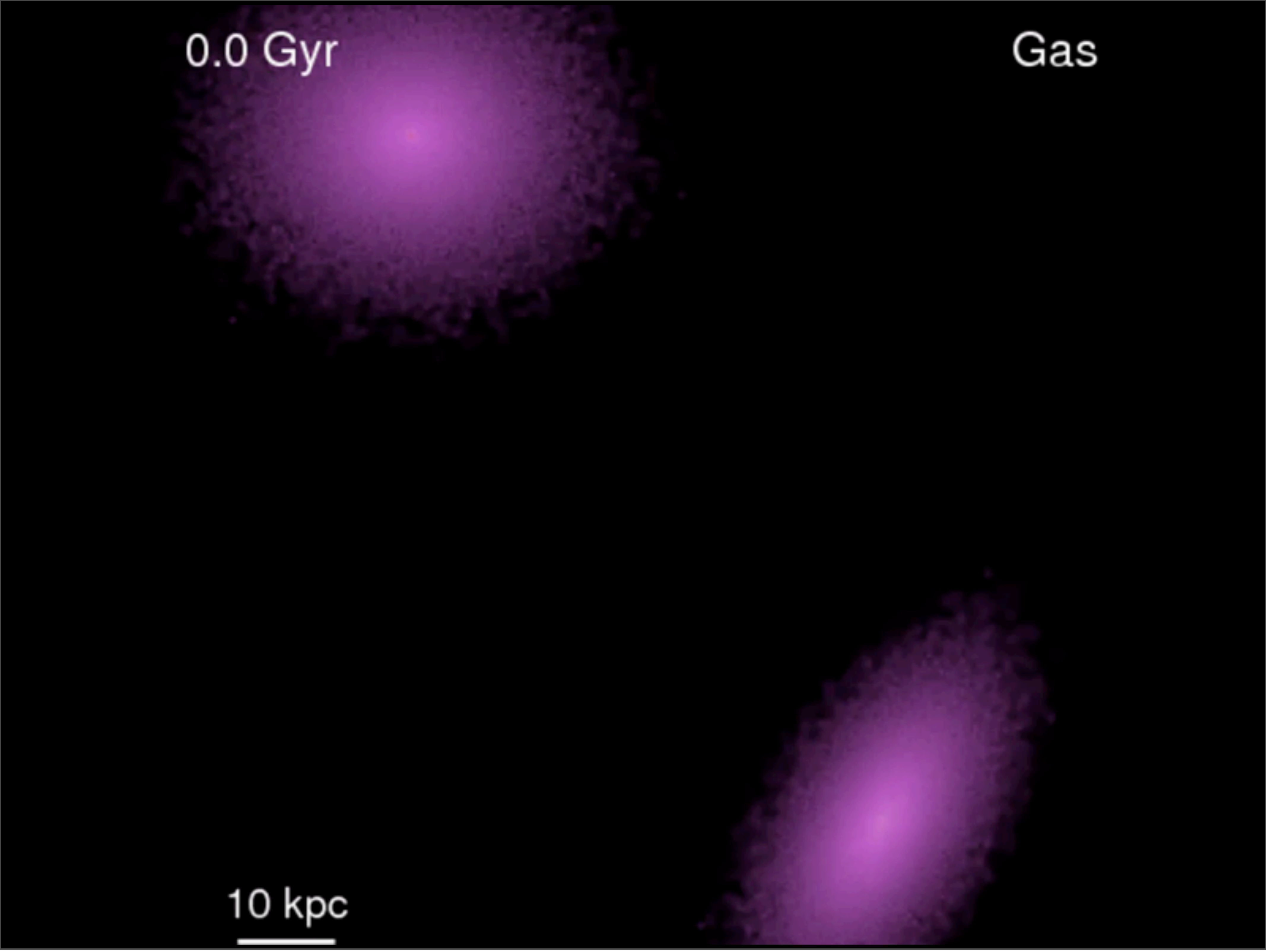


With BAL Winds

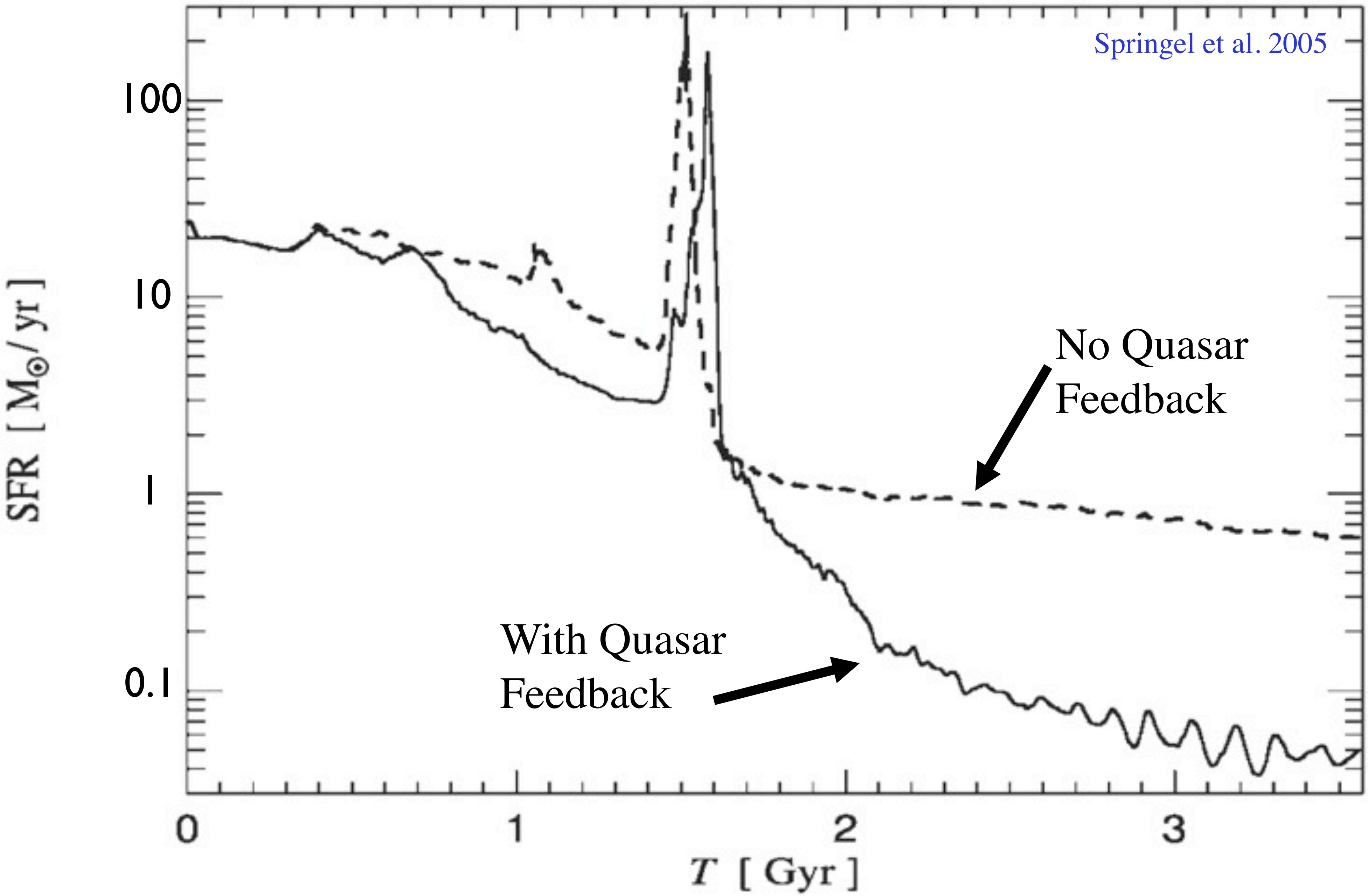


$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

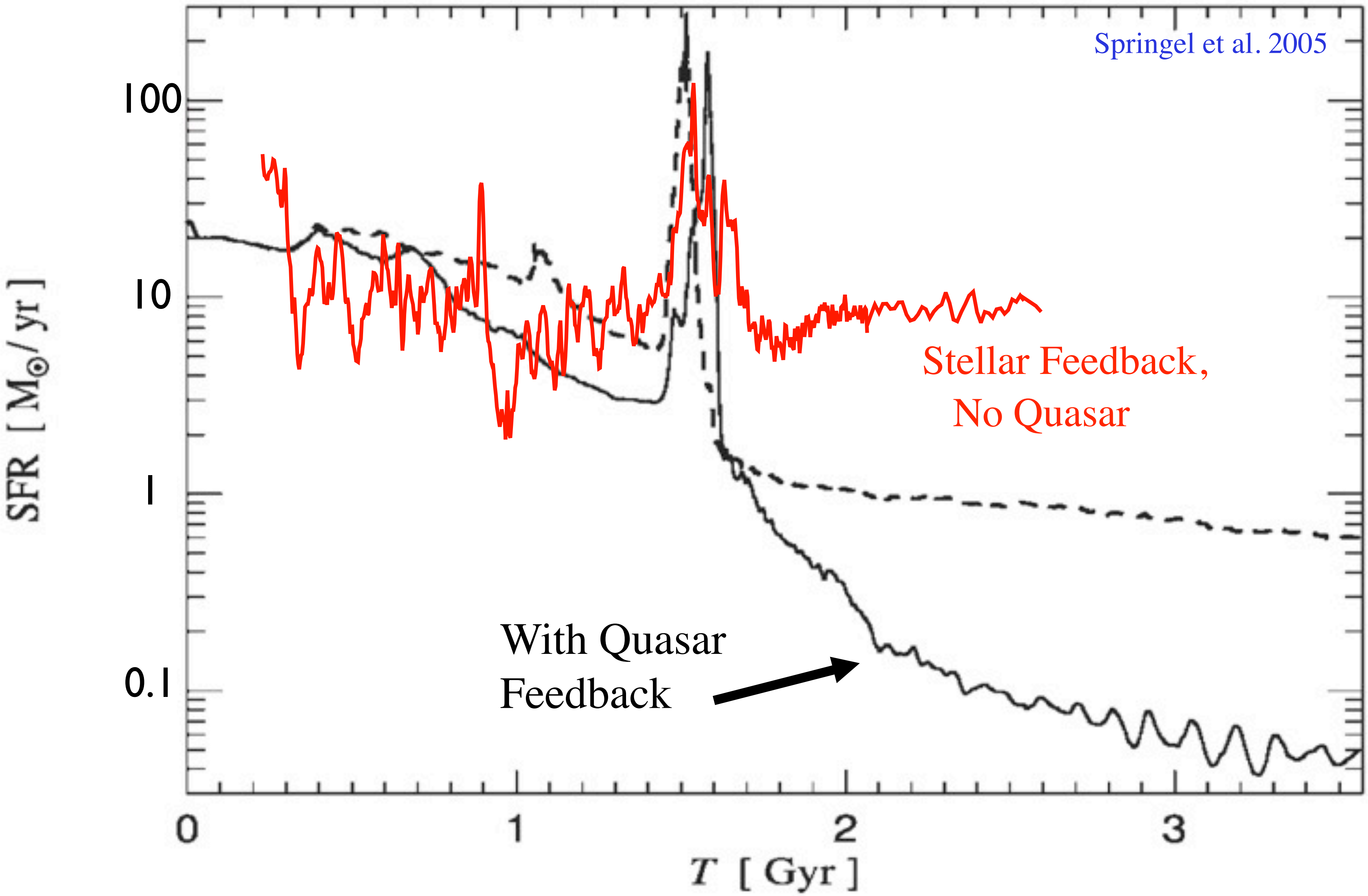
$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$


0.0 Gyr
Gas
10 kpc

Do we still need 'Quasar Mode' Feedback?



Do we still need ‘Quasar Mode’ Feedback?



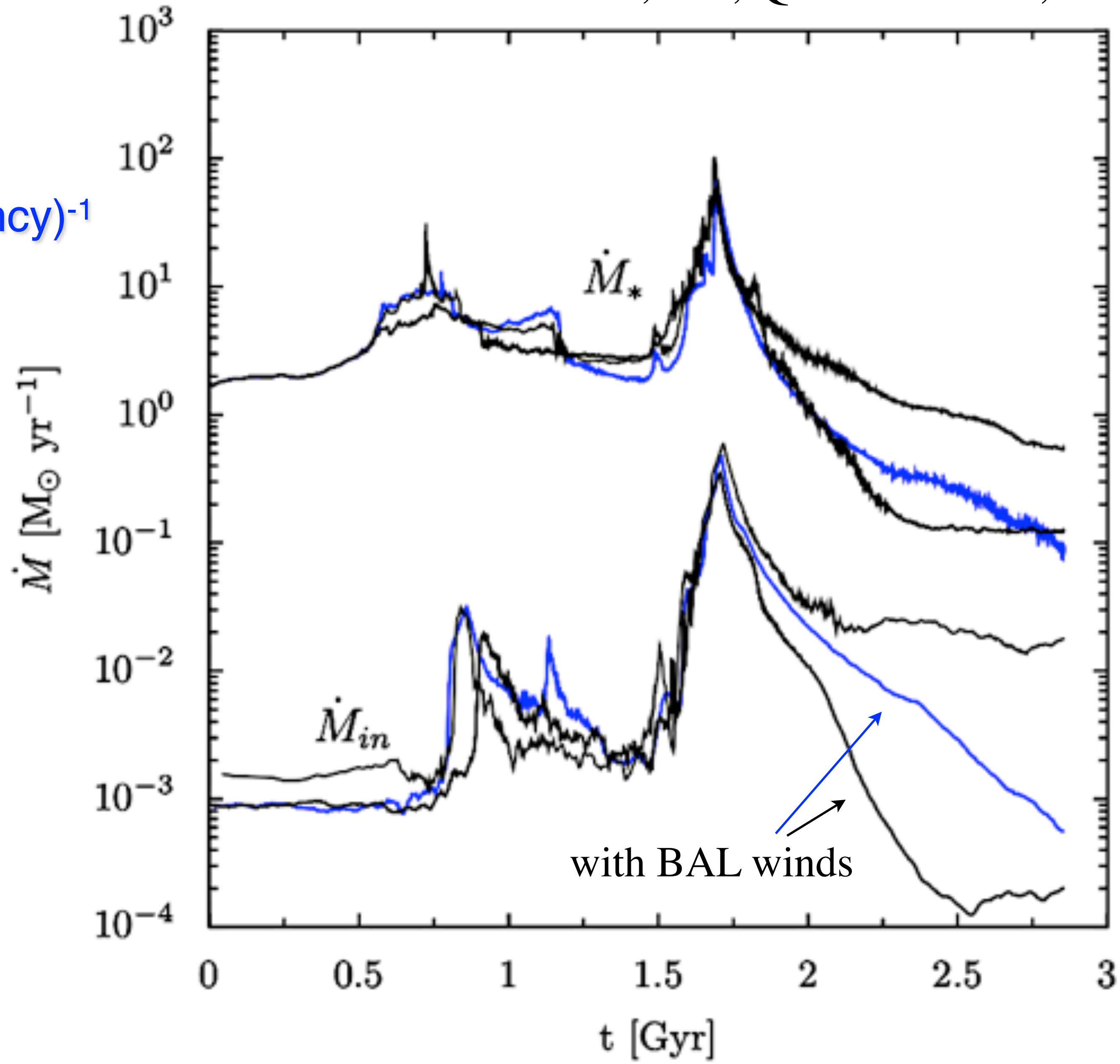
Step 3: Profit

CAN IT REALLY AFFECT STAR FORMATION?

Novak et al. 2010,11

Debuhr, Ma, Quataert 2010,11

- Recover M-s
  - Normalization ~ (efficiency)$^{-1}$
- Launch ~1000 km/s "tail" in winds
- Suppress SFR



Summary:

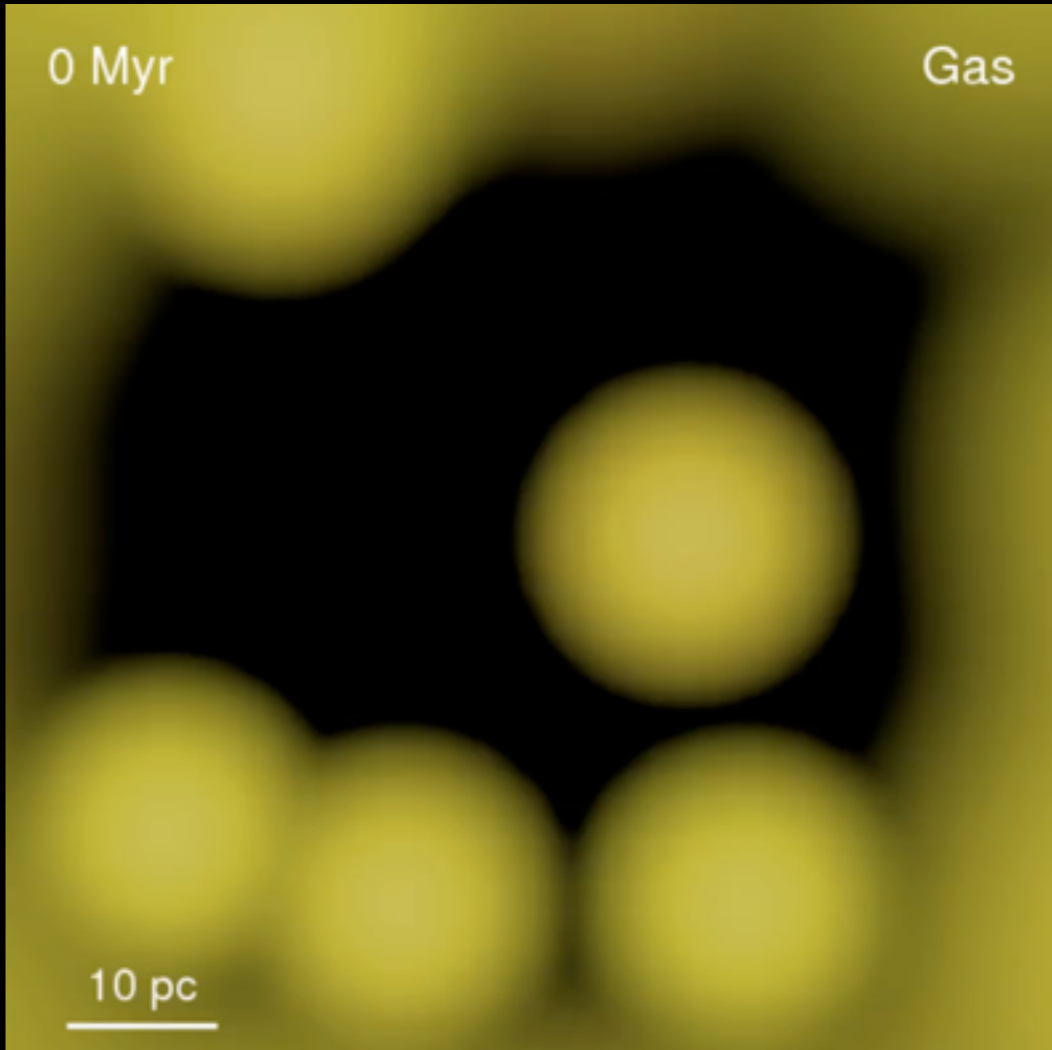
- Global **Star formation is Feedback-Regulated**: *independent* of small-scale SF 'law'
    - Need 'enough' stars to offset dissipation (set by gravity)
- Feedback leads to Kennicutt relation & super-winds:

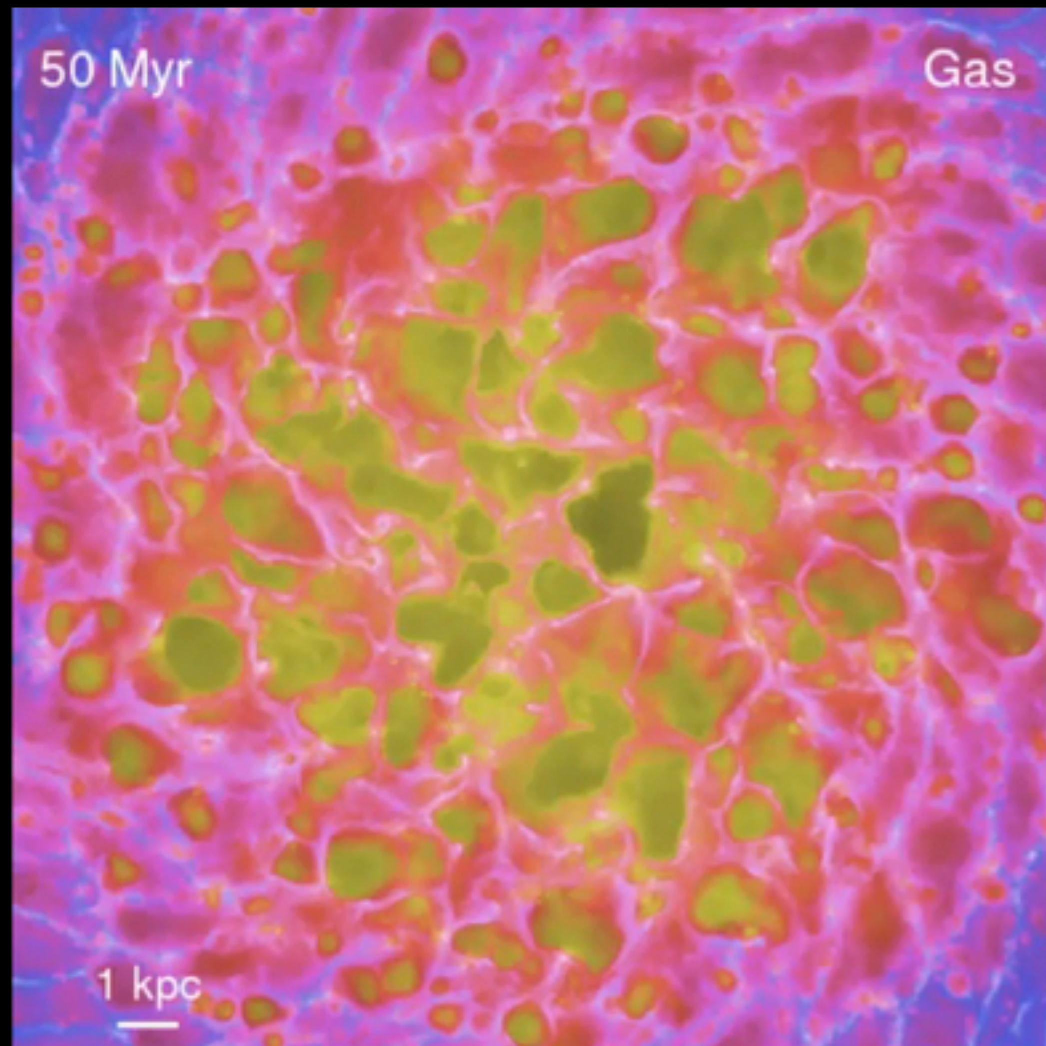
$$\dot{M}_{\rm wind} \approx 10\,\dot{M}_* \left(\frac{V_c}{100\,{\rm km\,s^{-1}}}\right)^{-1.1} \left(\frac{\Sigma_{\rm gas}}{10\,{\rm M_\odot\,pc^{-2}}}\right)^{-0.5}$$

Standing!

- 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**
- Quasar feedback is here to stay:
    - BAL Winds:
        - *CAN* explain M_{BH}-s
        - *WILL* suppress SFRs
        - *SHOULD* heat & help clear IGM & Proto-Group Environments
- Inflows: "Stuff within Stuff": Cascade of instabilities with diverse morphology

$$\dot{M}_{\rm BH} \propto f({\rm B/T})\,M_{\rm gas}(R)/t_{\rm dyn}$$


0 Myr
Gas
10 pc


50 Myr
Gas
1 kpc