Feedback from Stars & Black Holes in Galaxy Formation

Philip Hopkins

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


PINNACLES


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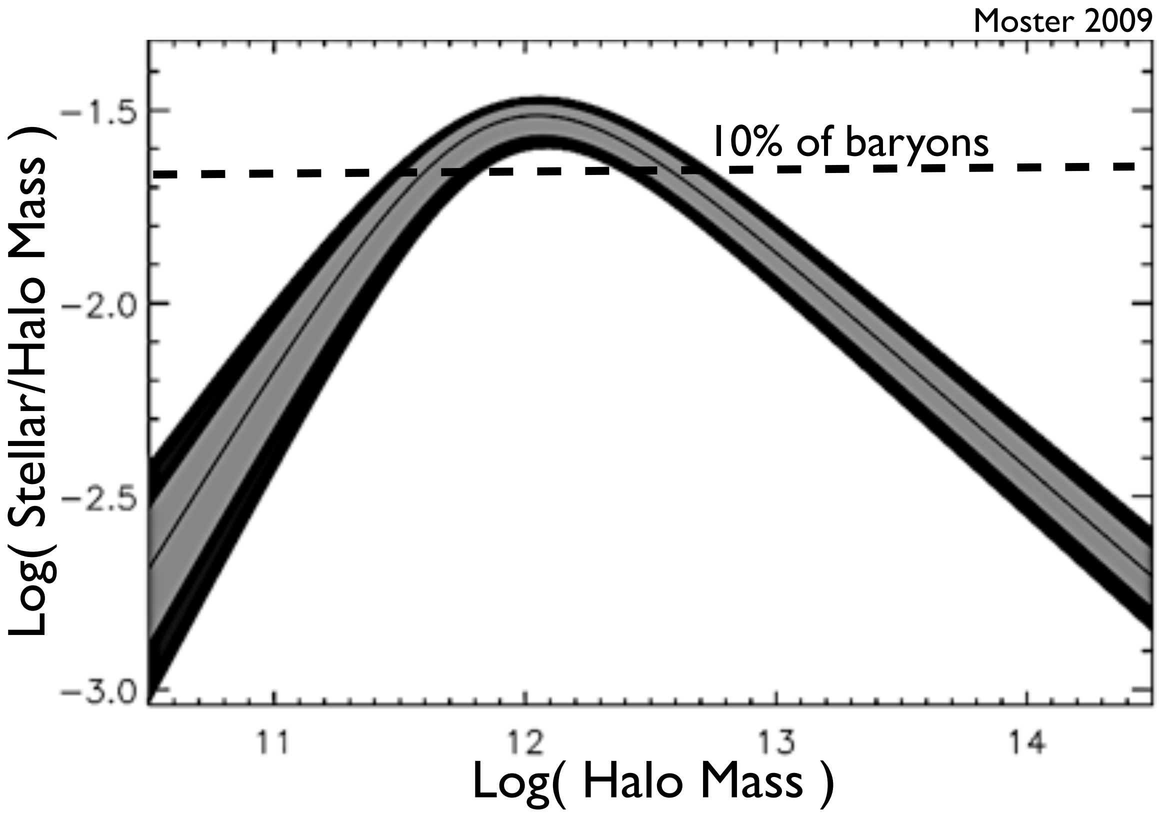
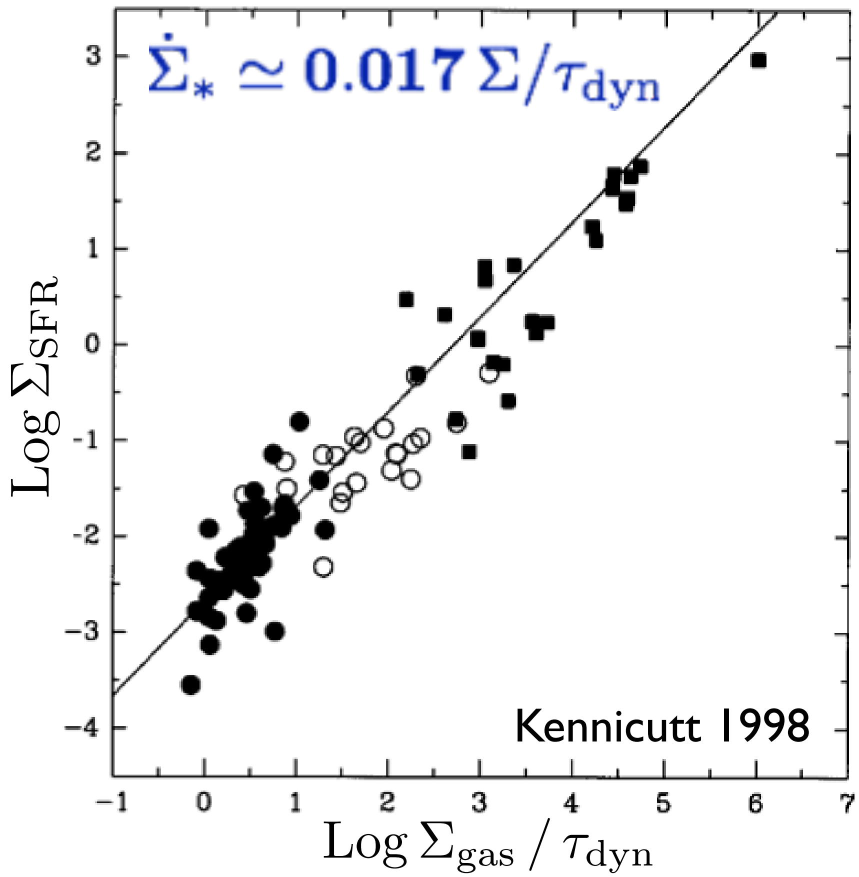
Q: WHY IS STAR FORMATION SO INEFFICIENT?





A: Stellar Feedback!

SO WHAT'S THE PROBLEM?

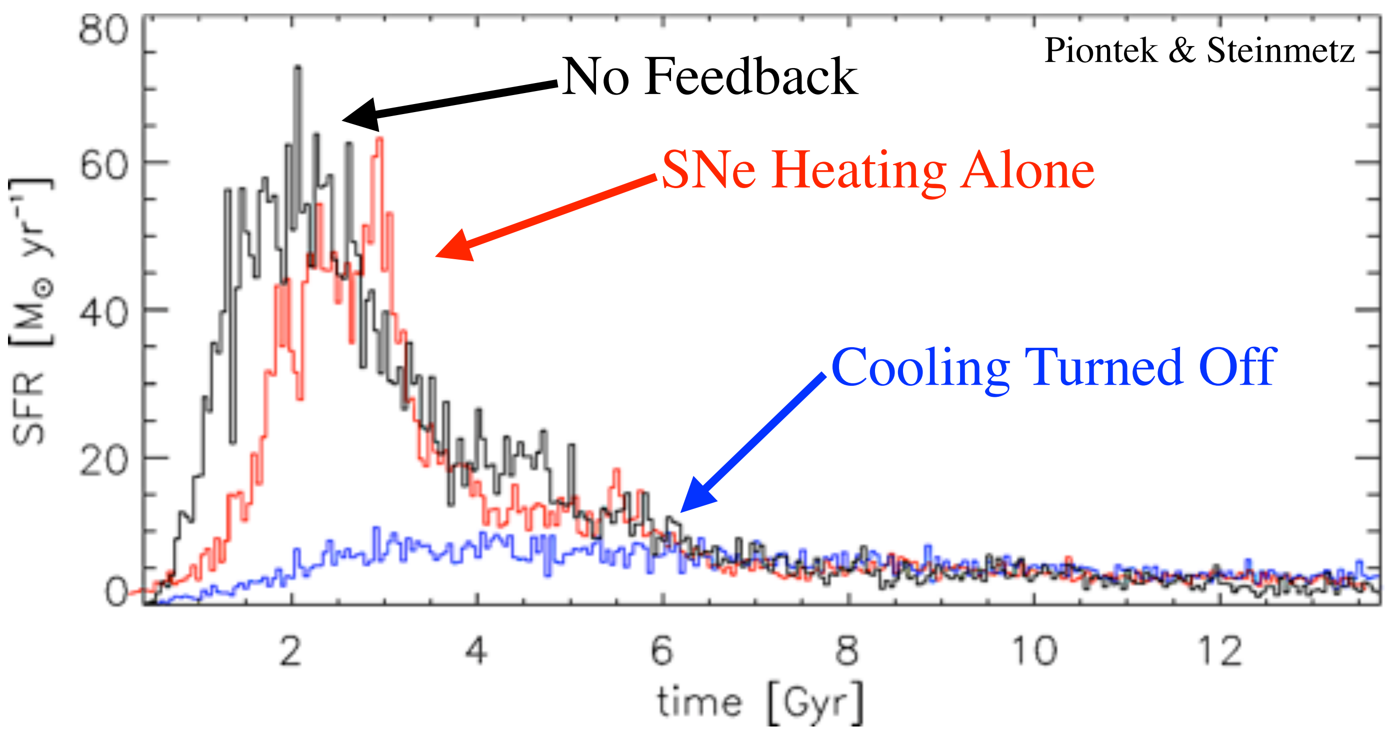
- Standard (in Galaxy Formation):
  Couple SNe energy
  as "heating"/thermal energy

- 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)

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- Heating:
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)
- *Explicit* Momentum Flux:
  - Radiation Pressure

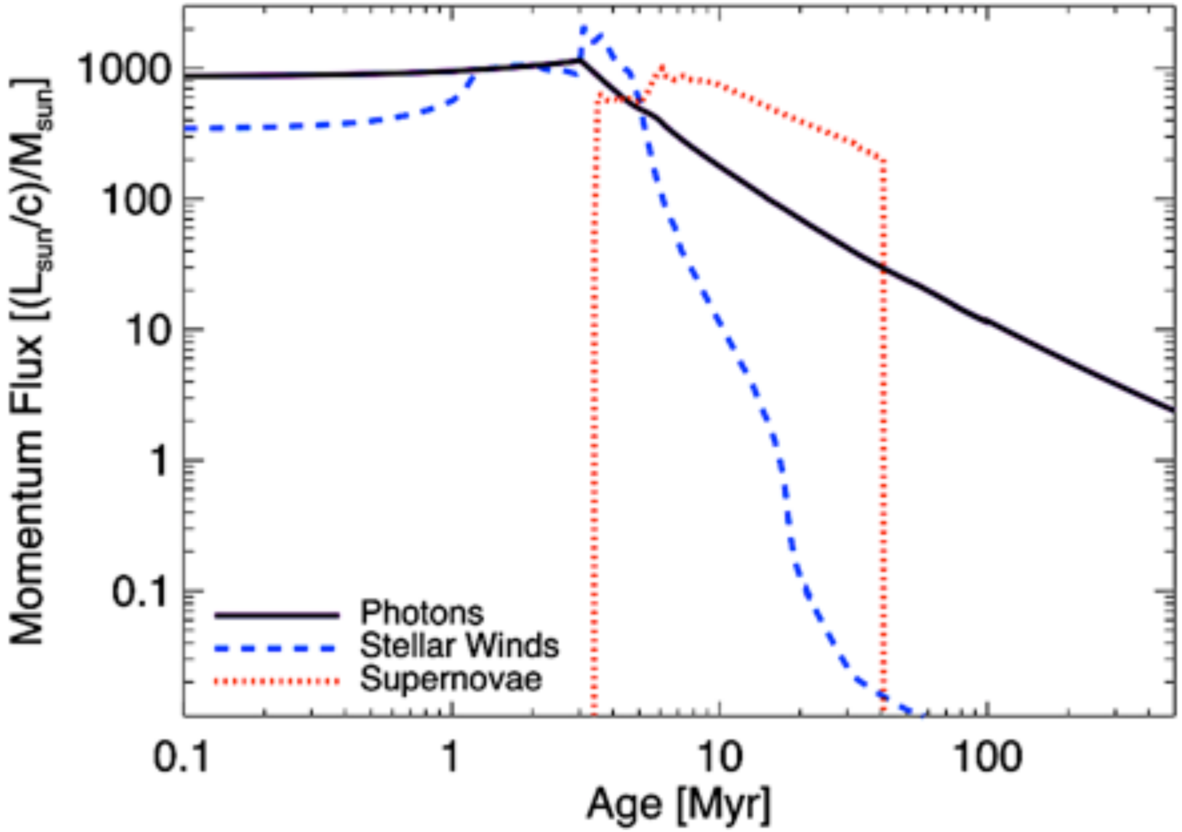
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

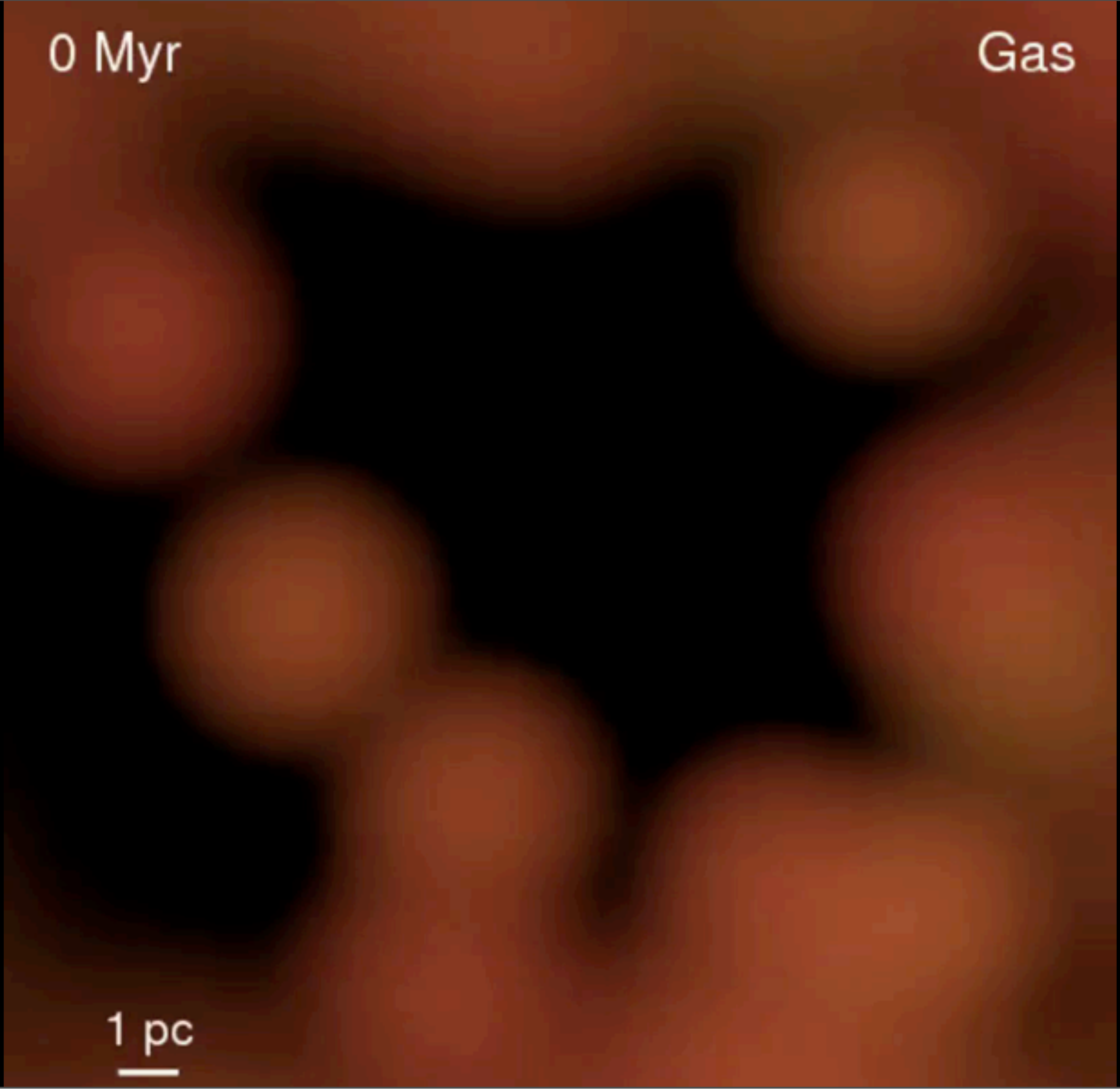
  - SNe

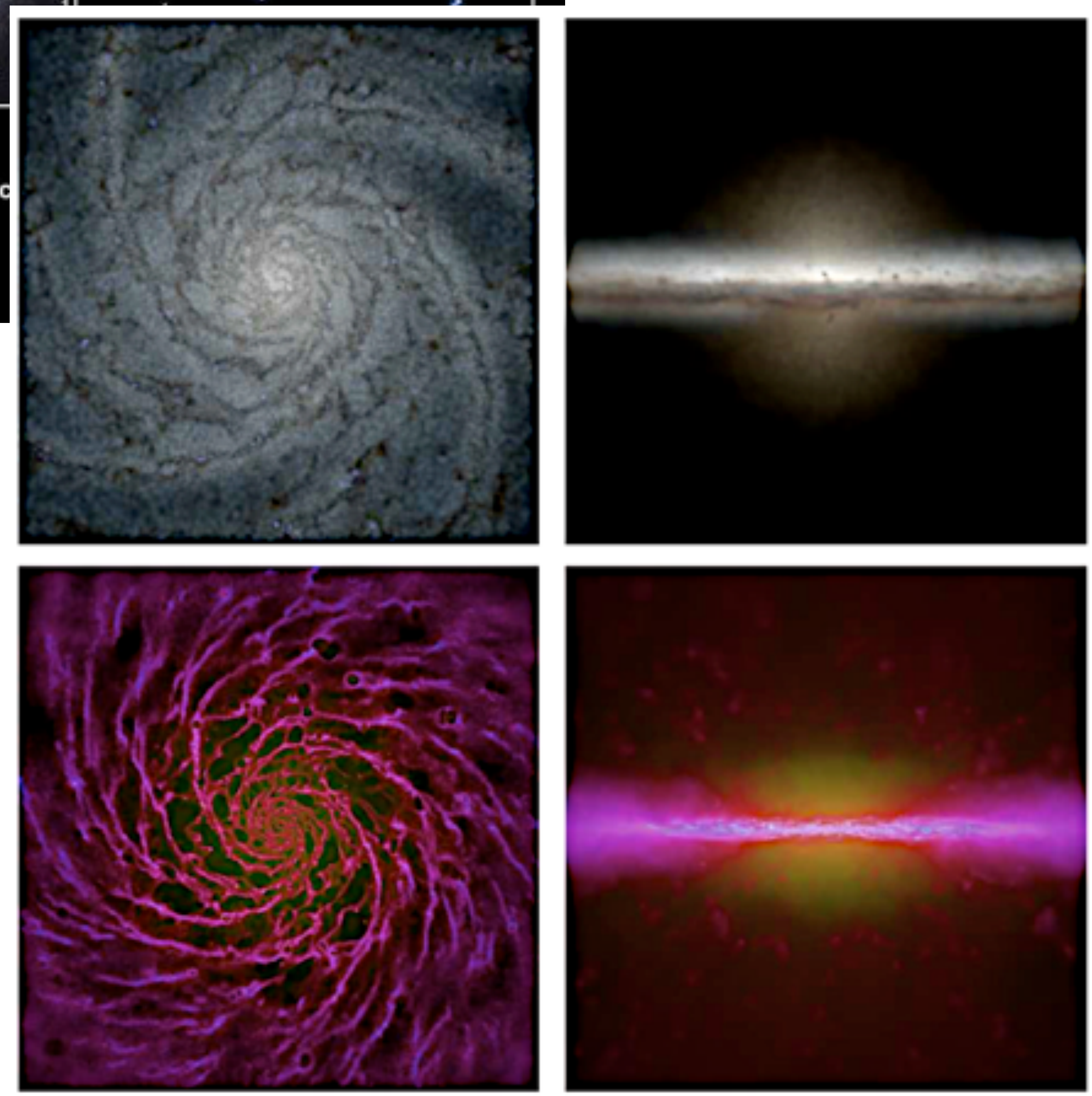
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\,v_{\rm ejecta}^{-1}$$

  - Stellar Winds

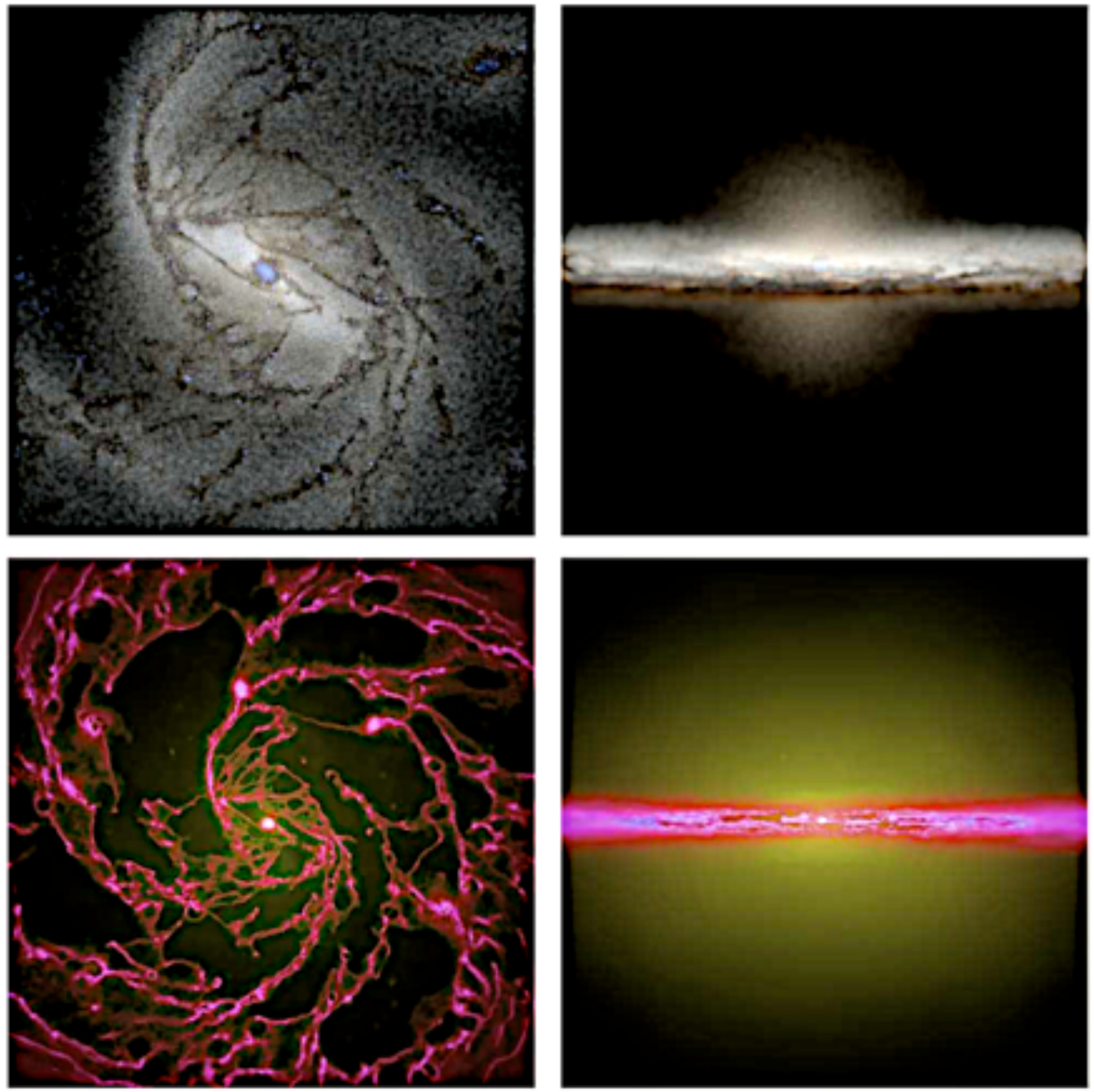
$$\dot{P}_{\rm W} \sim \dot{M}\,v_{\rm wind}$$




0 Myr
Gas
1 pc



Hopkins, Quataert, & Murray, in prep



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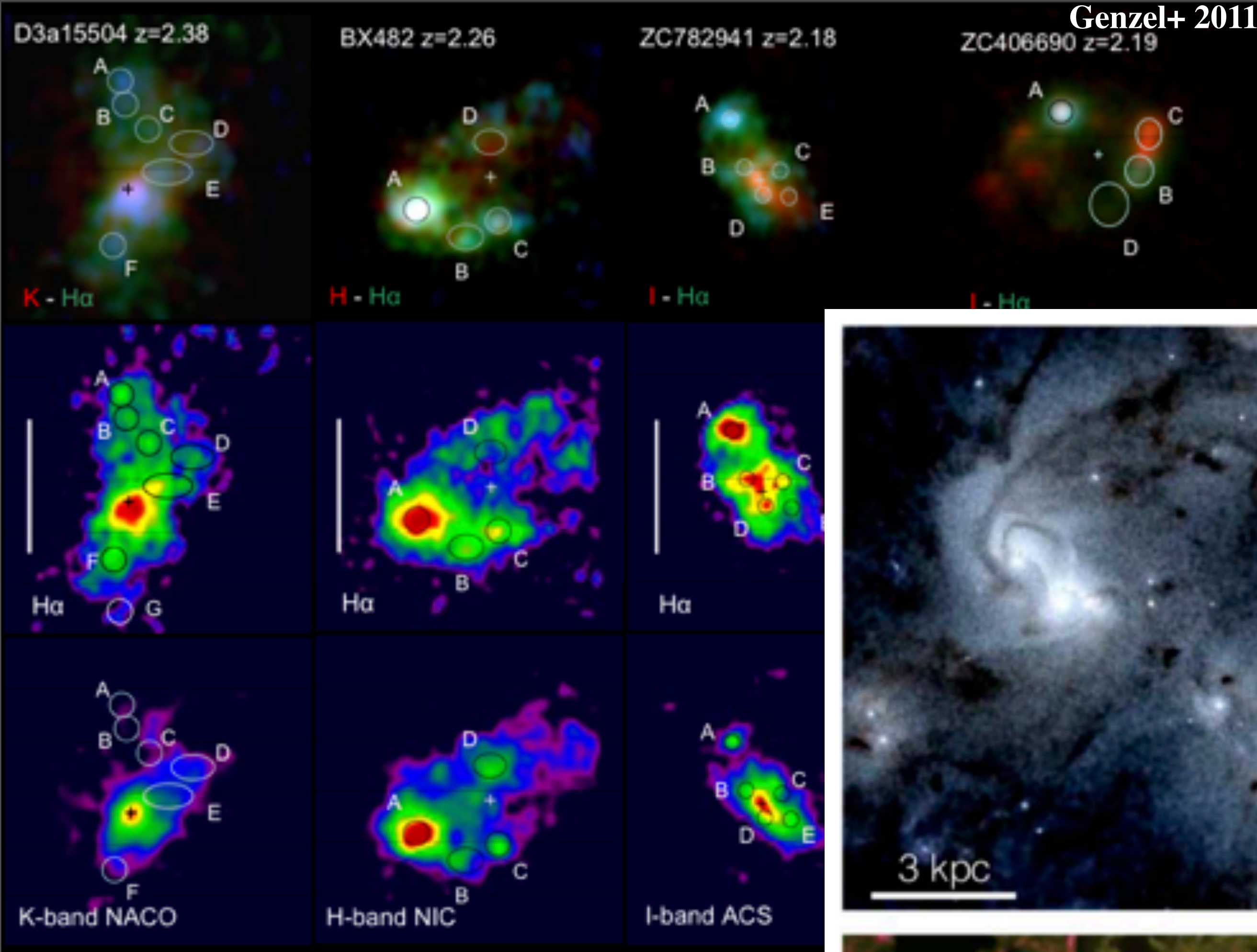
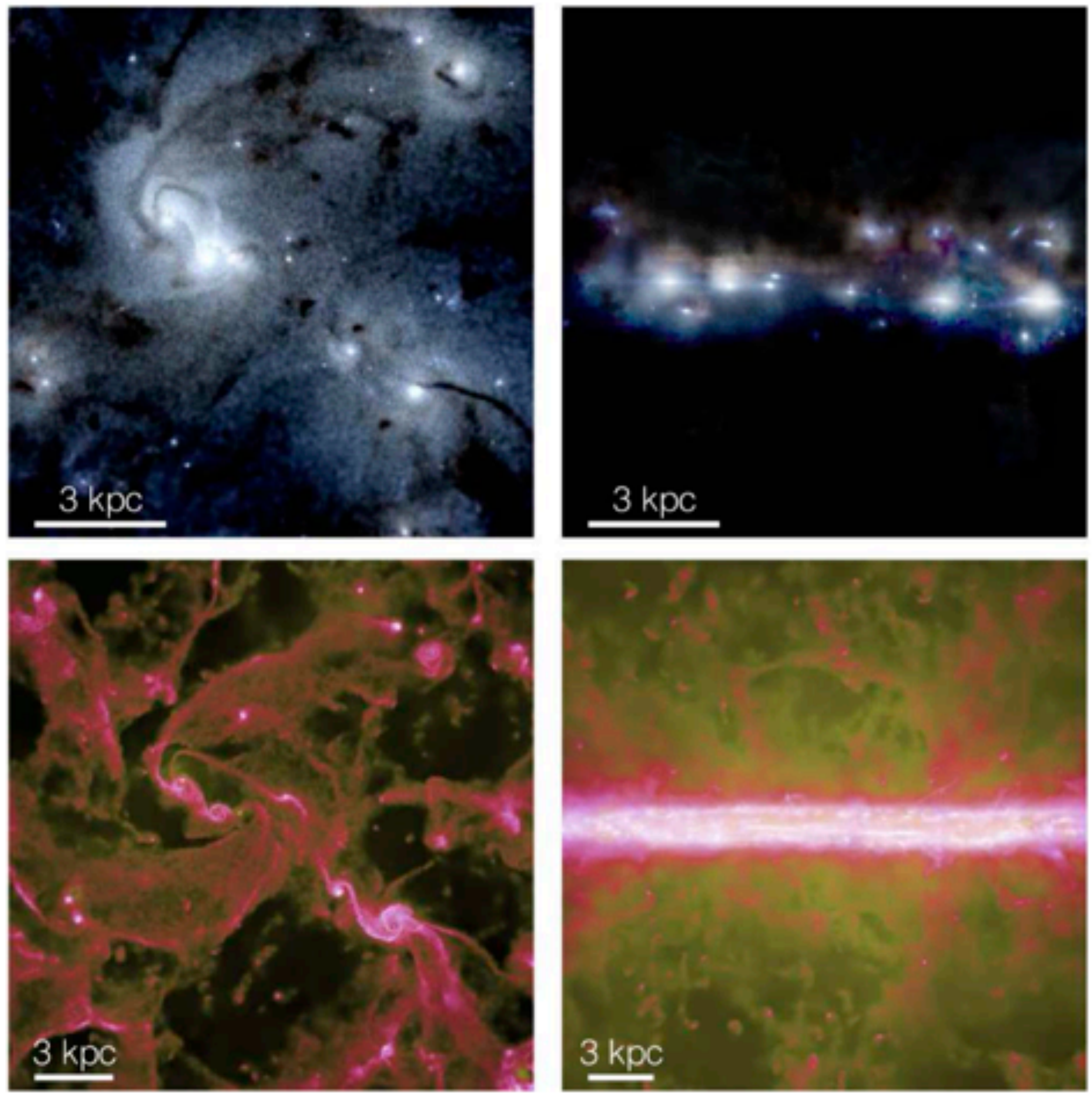
Genzel+ 2011





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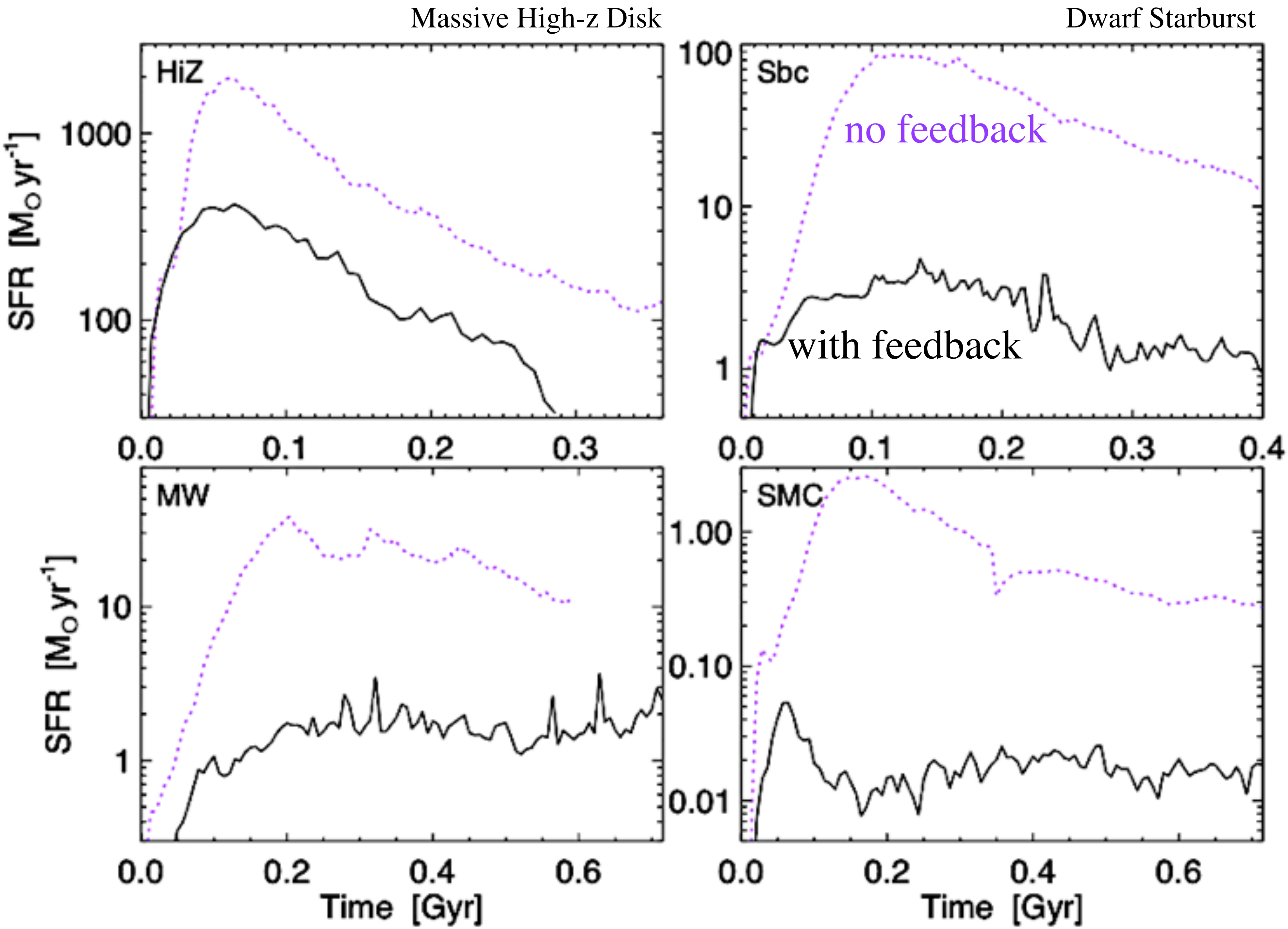
Stellar Feedback gives Self-Regulated Star Formation



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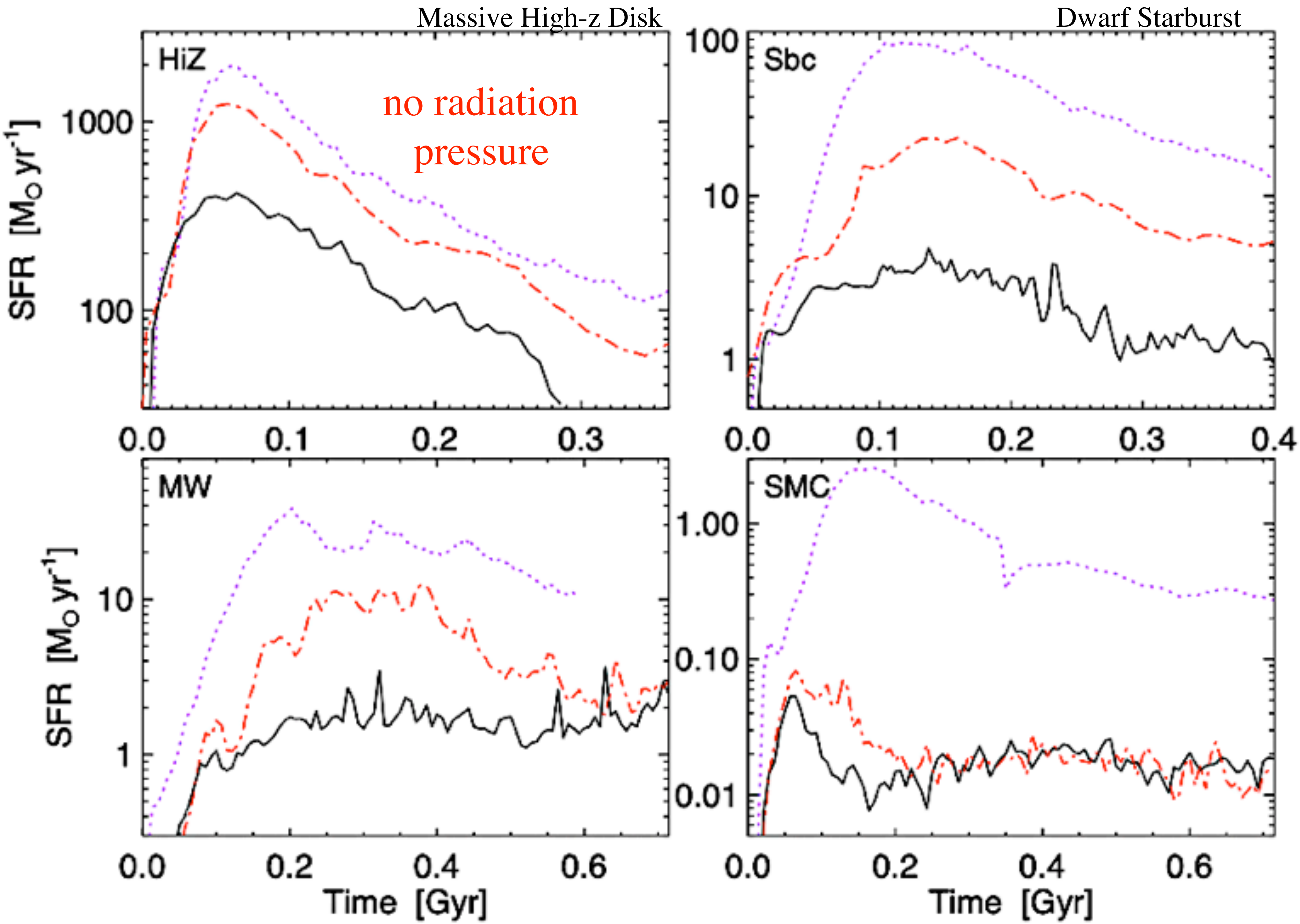

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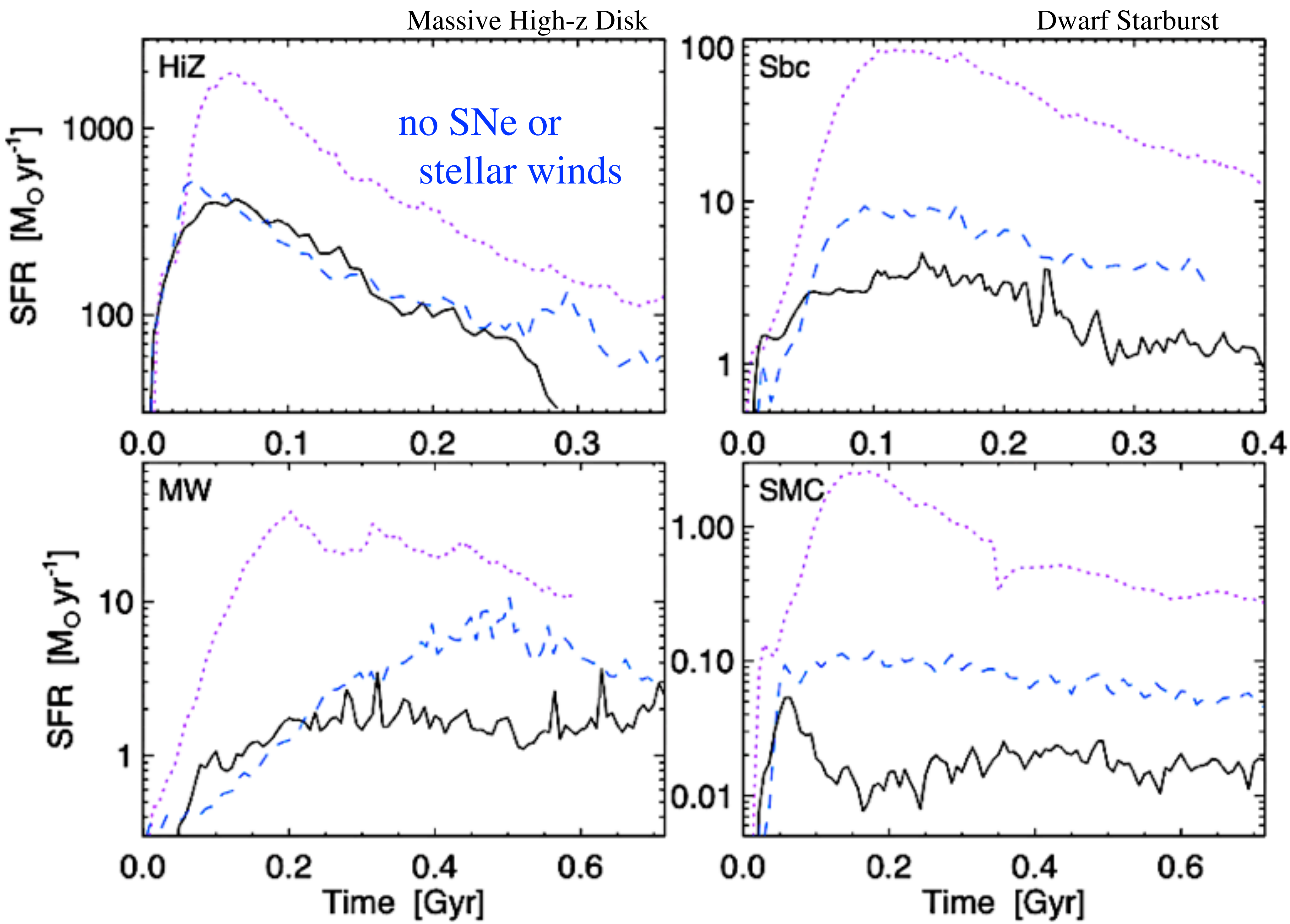

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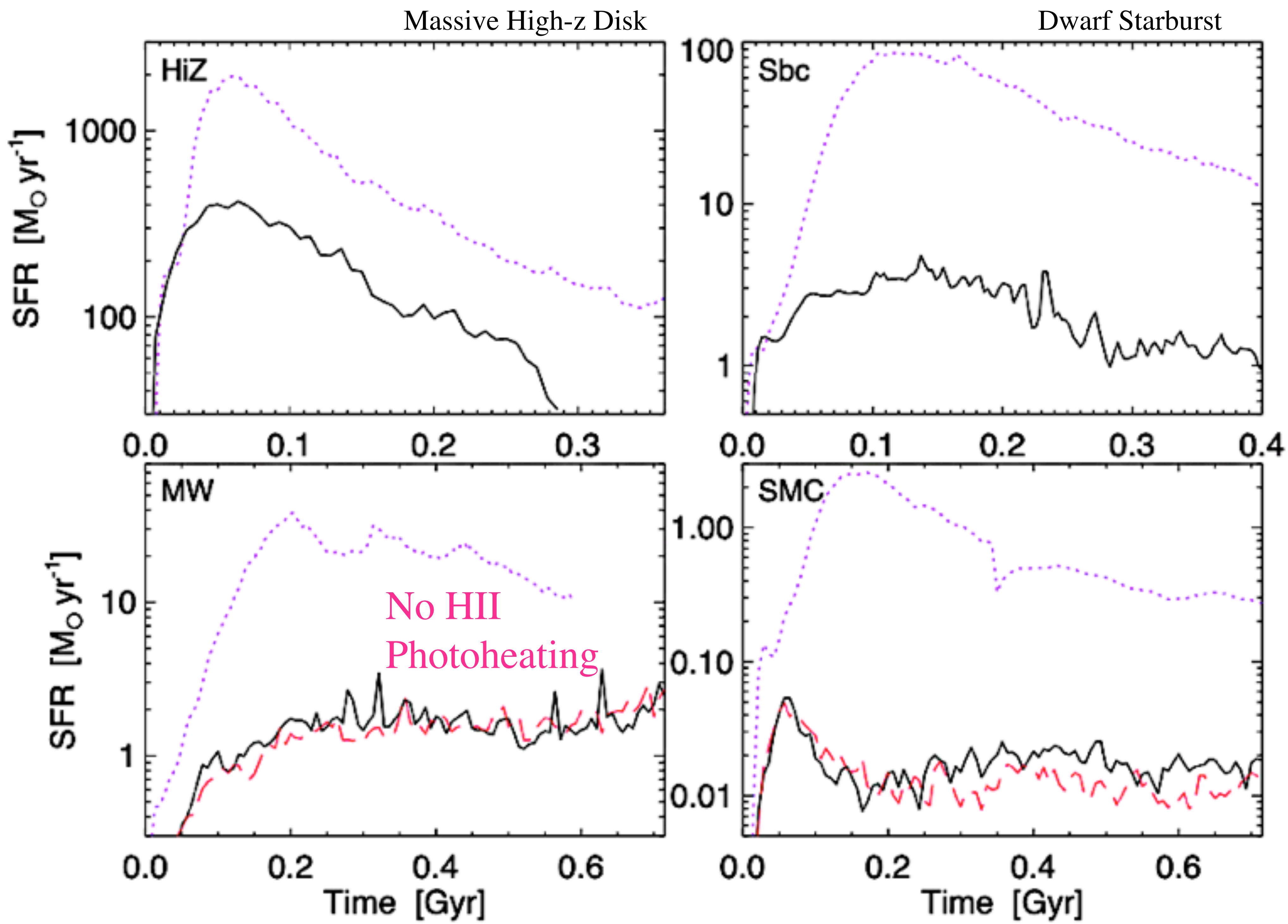
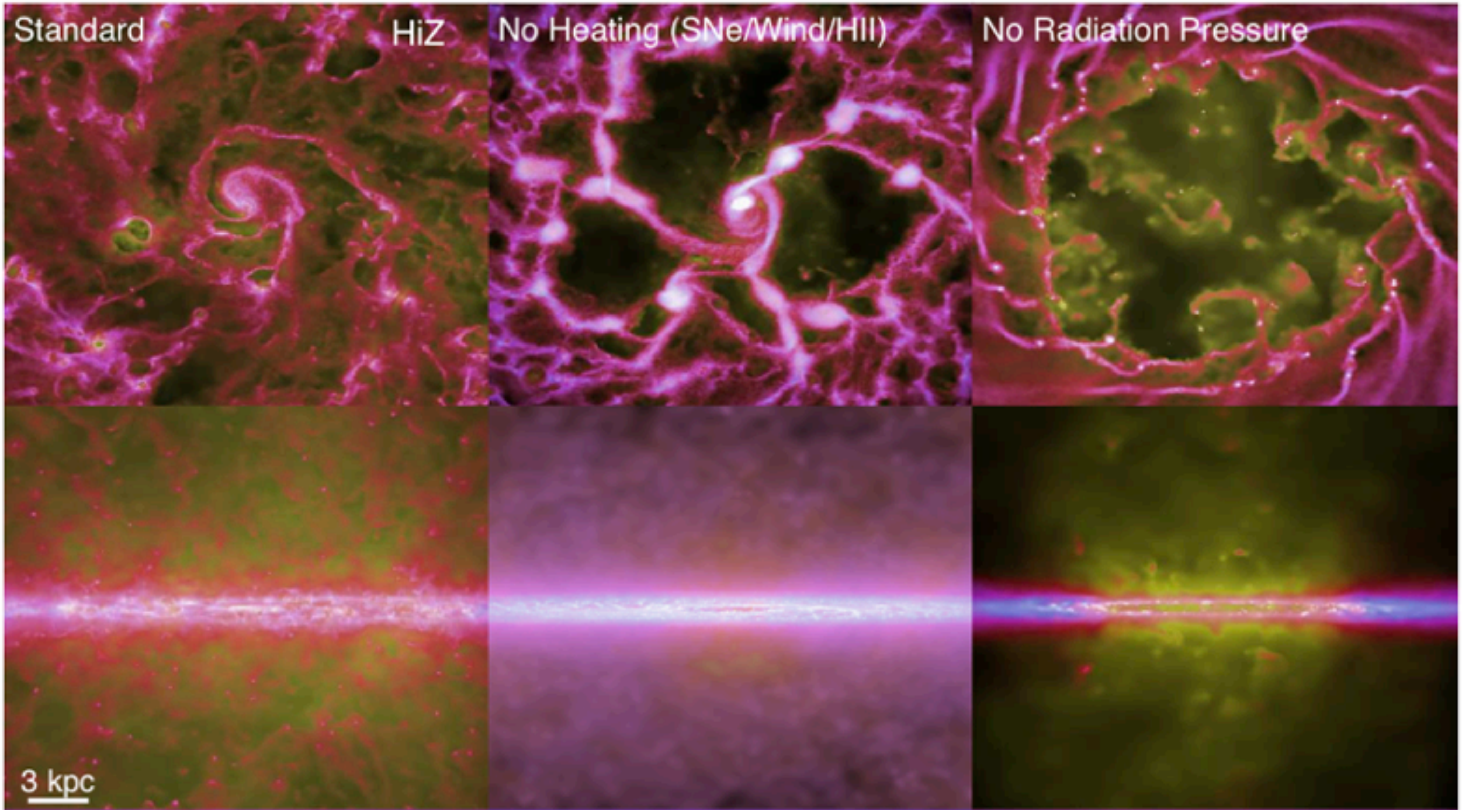


Stellar Feedback & Self-Regulation

WHICH MECHANISMS MATTER?



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

Stellar Feedback & Self-Regulation
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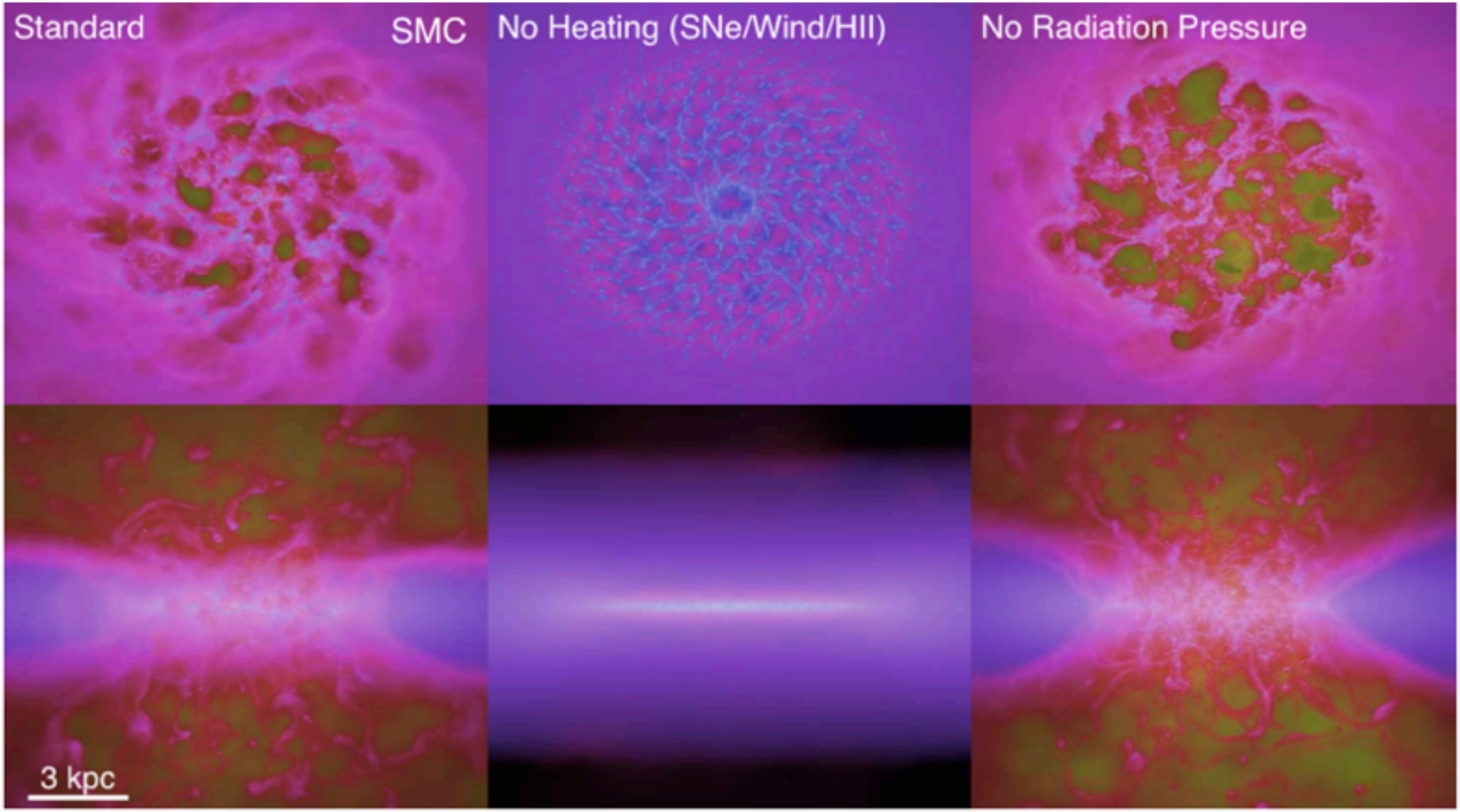
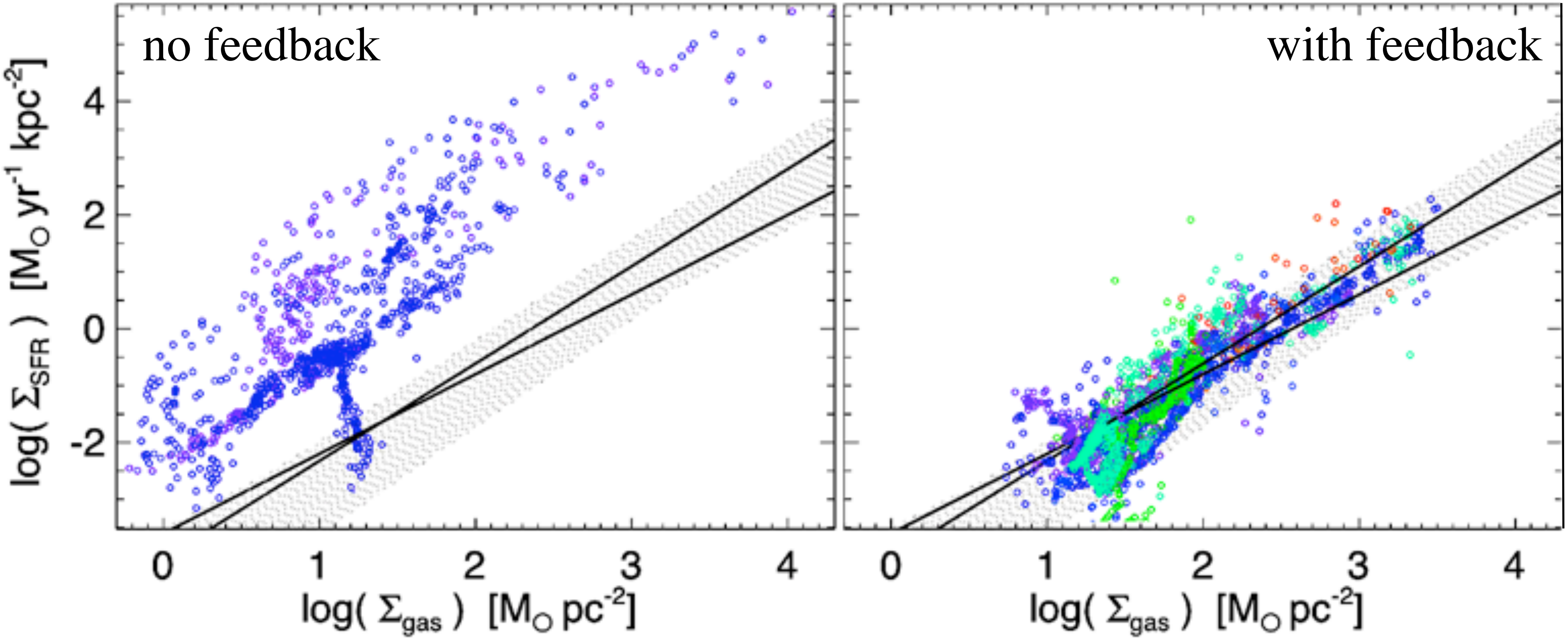


- SFR ~ 0.01 M_{sun}/yr (L << L_{EDD})
- Optically thin
- <n> ~ 0.1 cm^{-3} T_{cool} ~ Myr

Kennicutt-Schmidt relation emerges naturally



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

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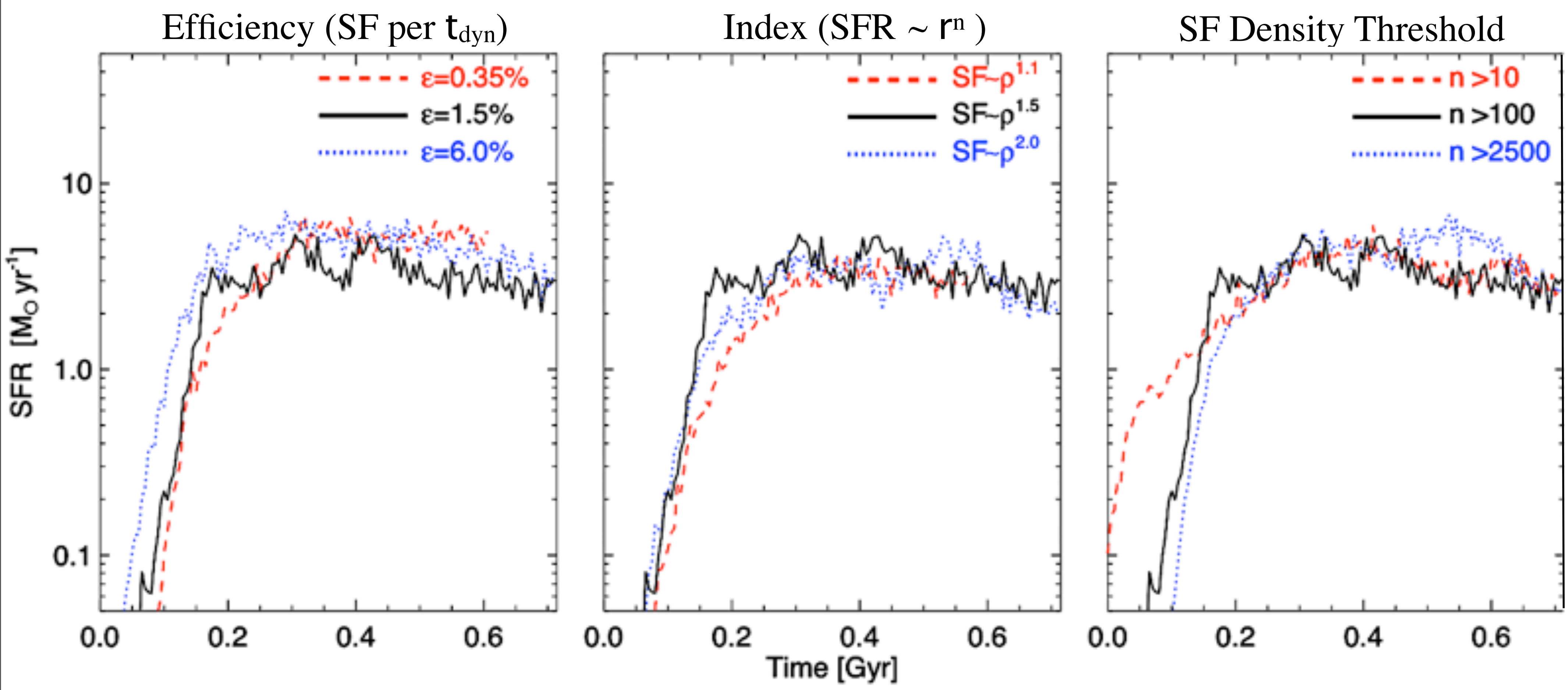
$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \Sigma_{\rm gas}\Omega \sim 0.02\, \Sigma_{\rm gas}\Omega$$

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



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

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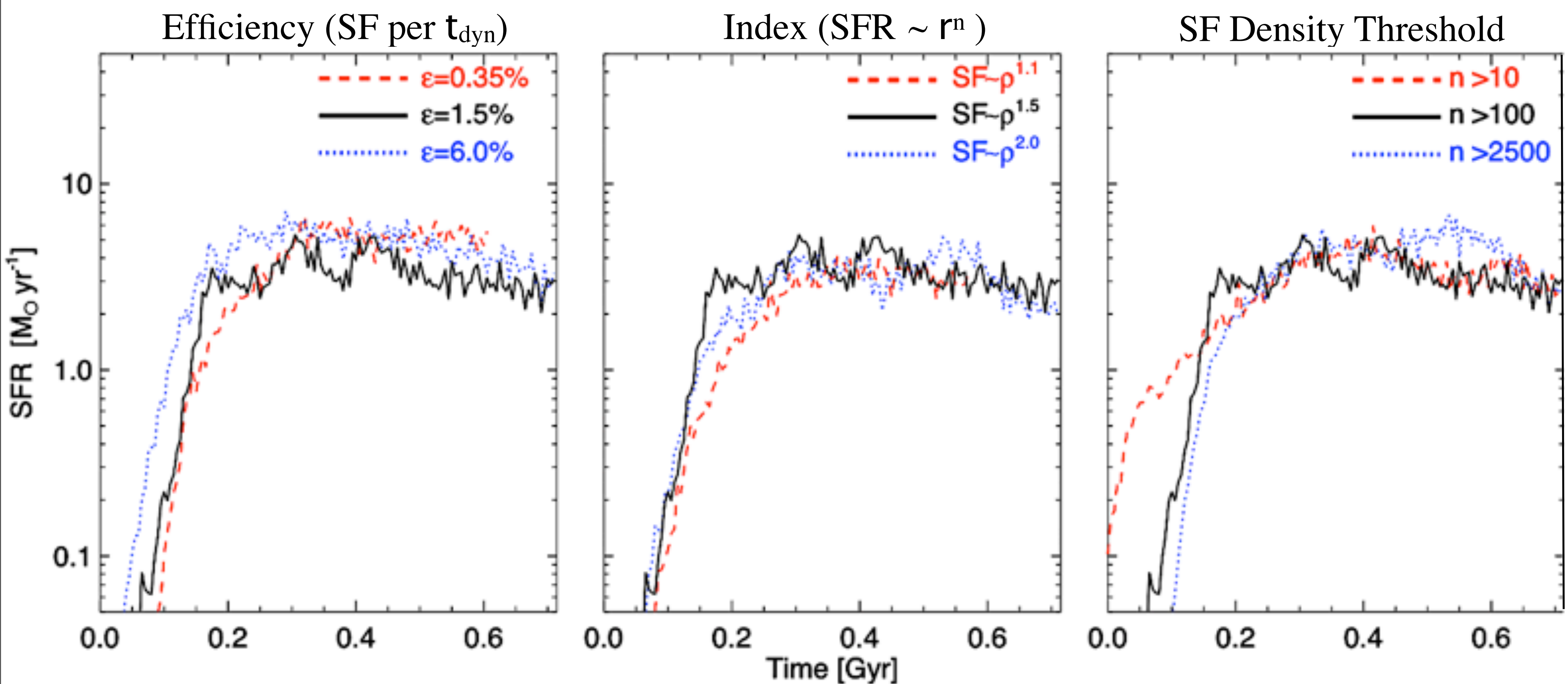


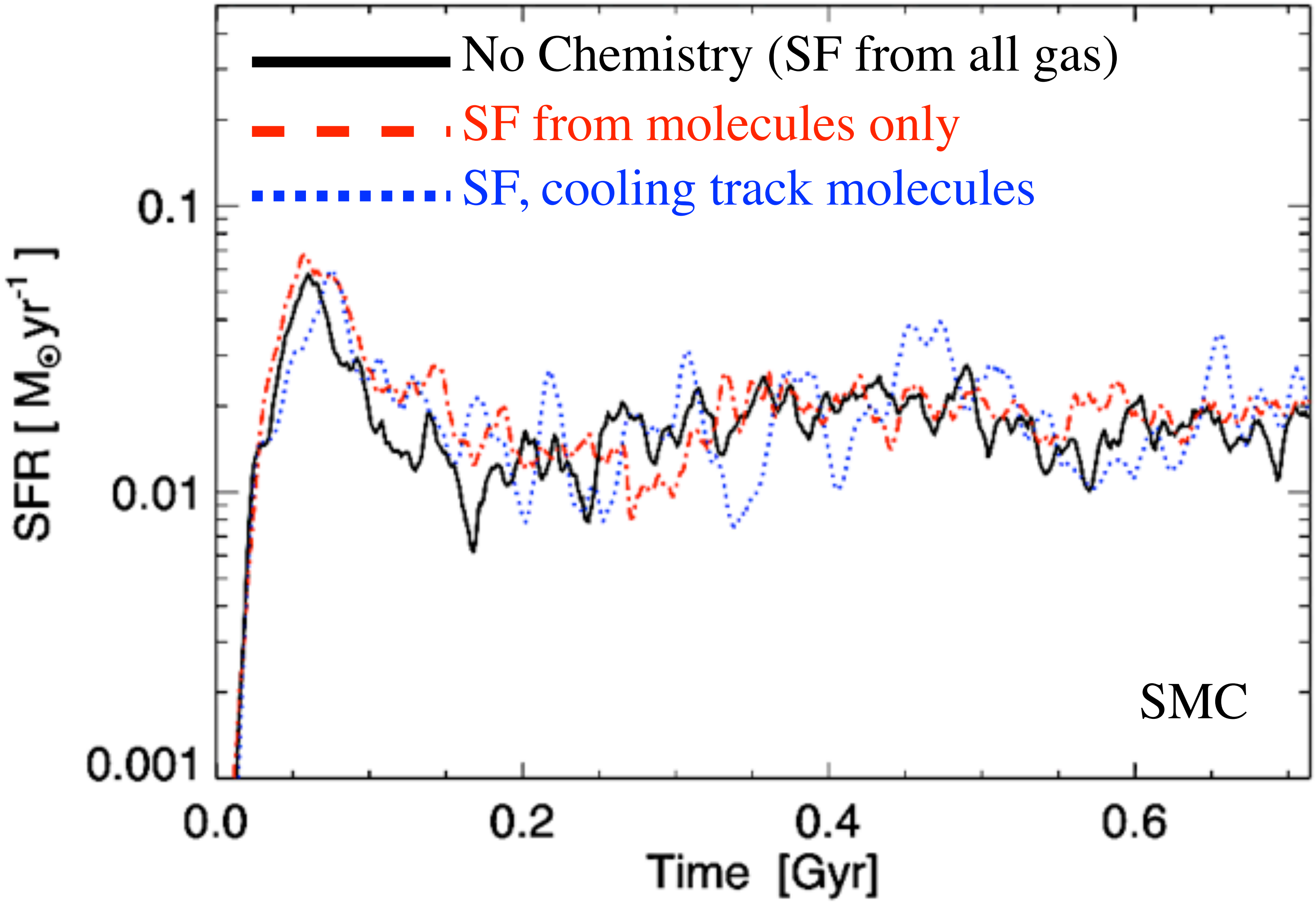
- Set by feedback (i.e. SFR) needed to maintain marginal stability

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

Molecular Chemistry doesn't change things above modest Metallicity

MOLECULES ARE A *TRACER*

see also Glover 2011



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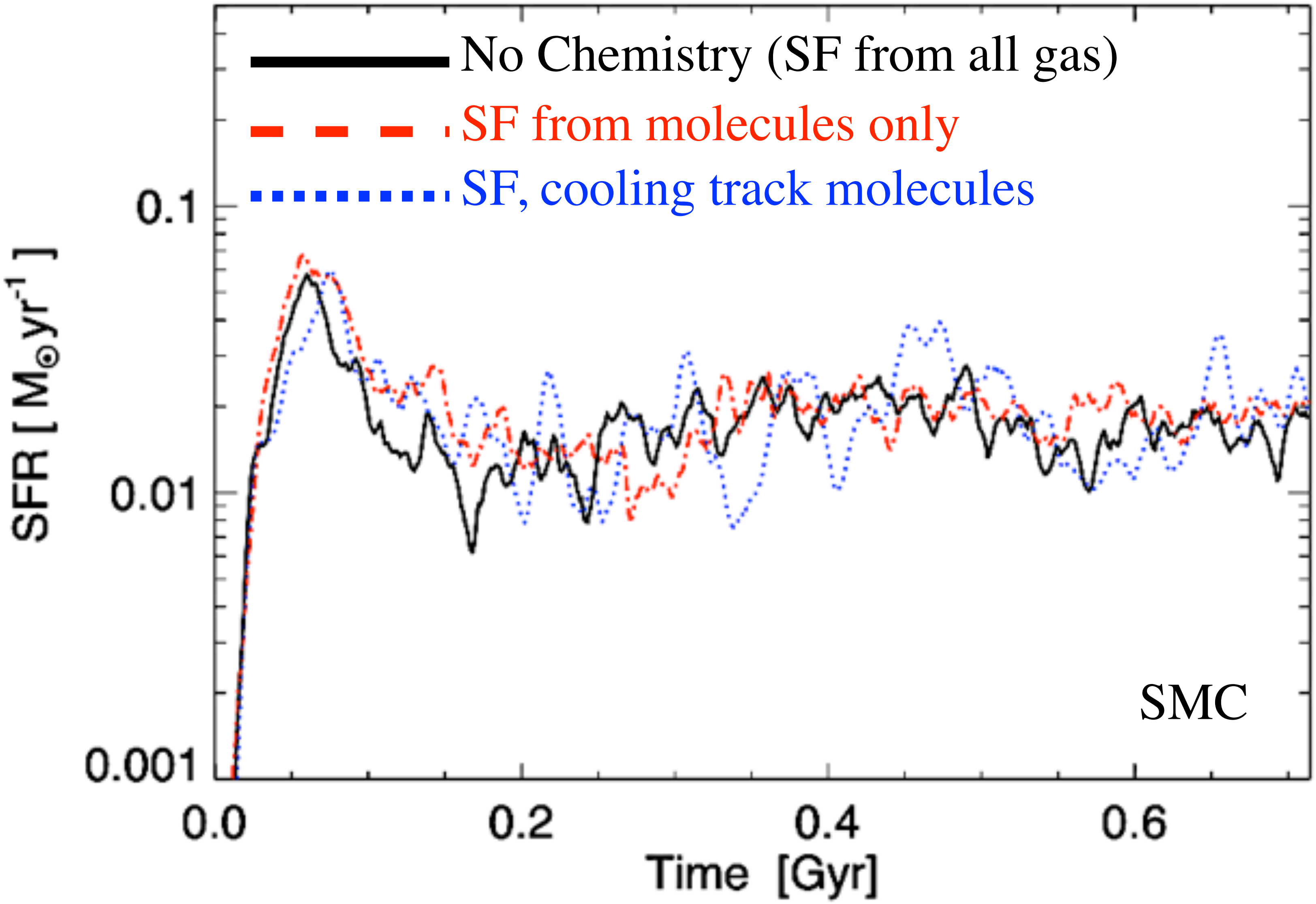
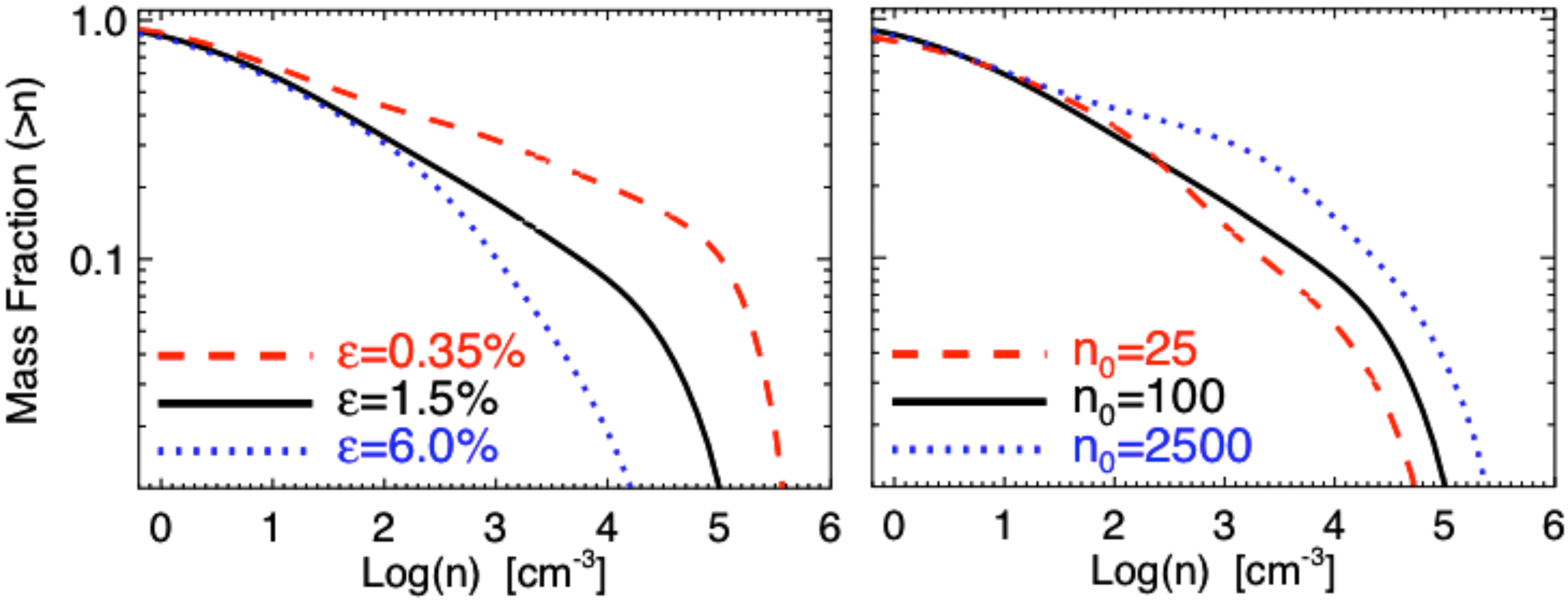


- Just need *some* cooling channel: changes at $M_{gal} < 10^6$ M_{sun}, Z<0.01 Z_{sun}

How Does Star Formation Self-Regulate?

SELF-ADJUST THE MASS IN *DENSE* GAS



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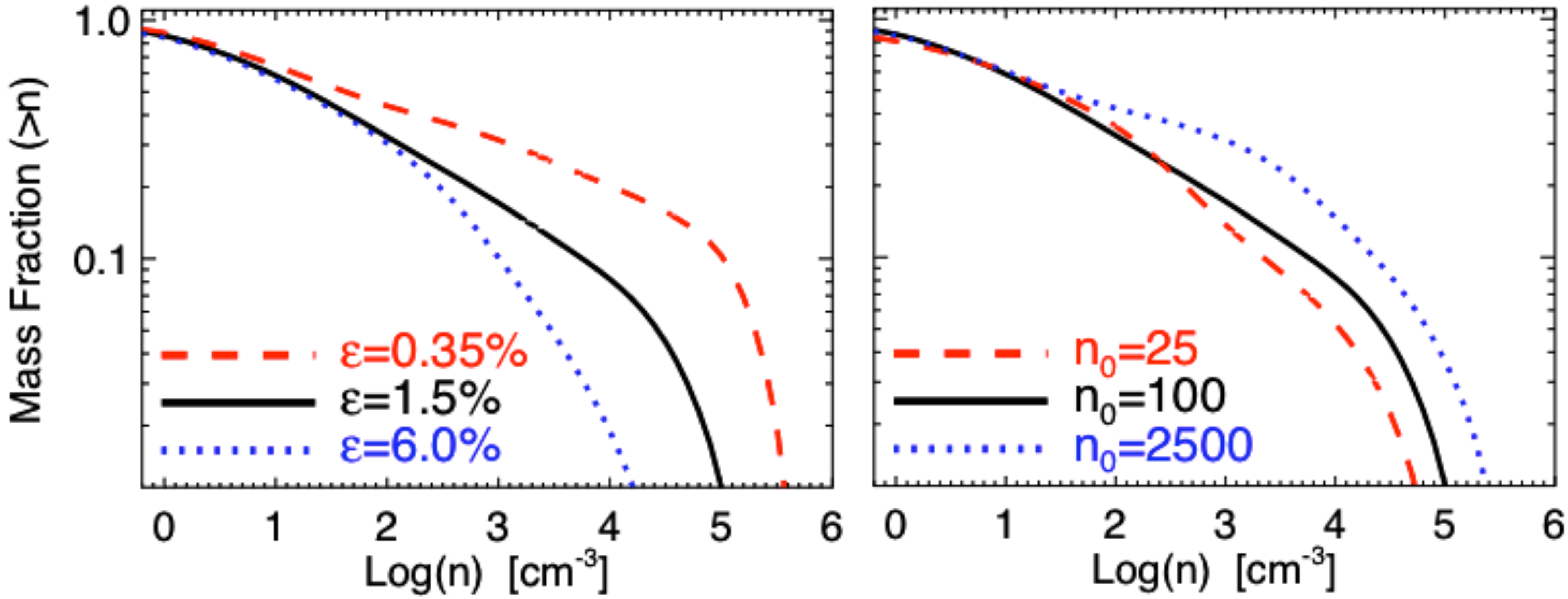

- Need net momentum injection dP/dt ~ L/c ~ SFR
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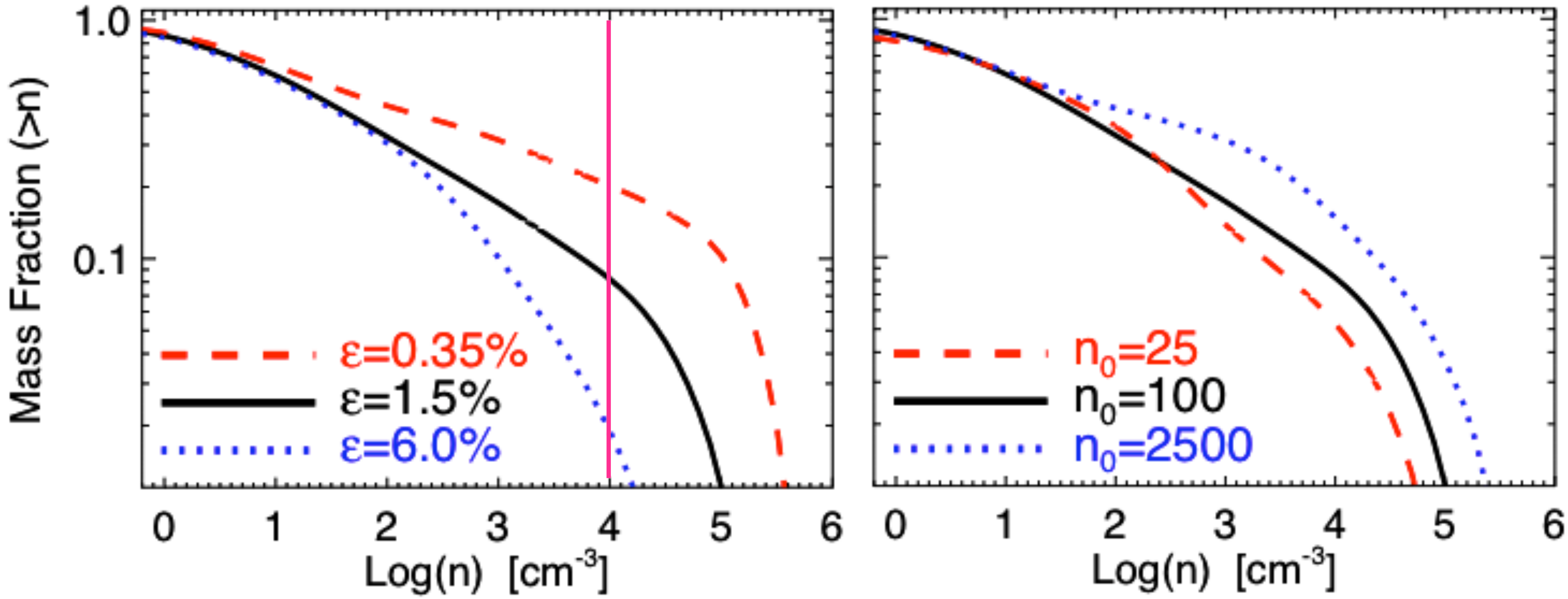

- Need net momentum injection dP/dt ~ L/c ~ SFR
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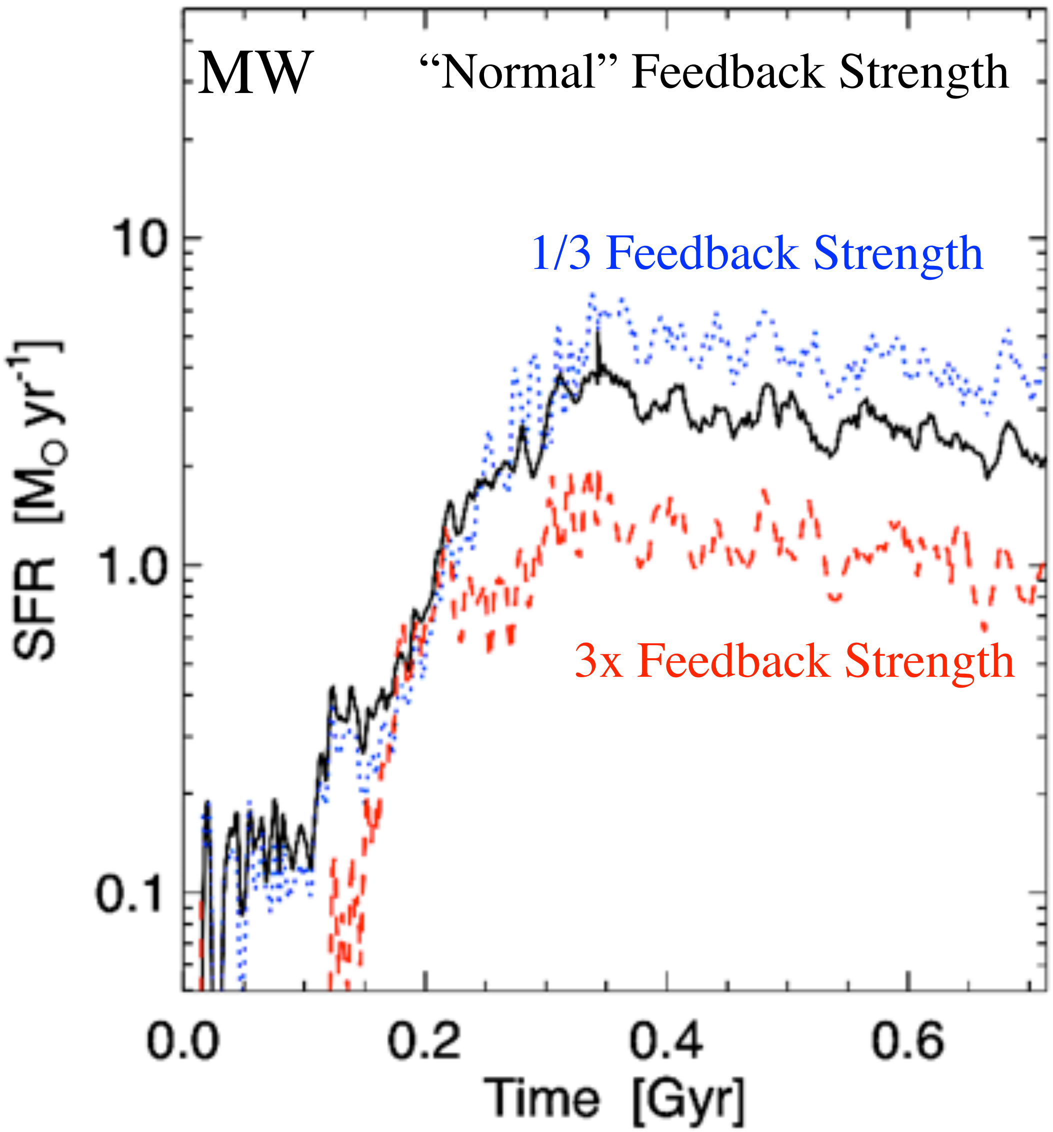
- Not just top-down collapse

Star Formation is Feedback-Regulated:

MORE FEEDBACK = LESS STAR FORMATION



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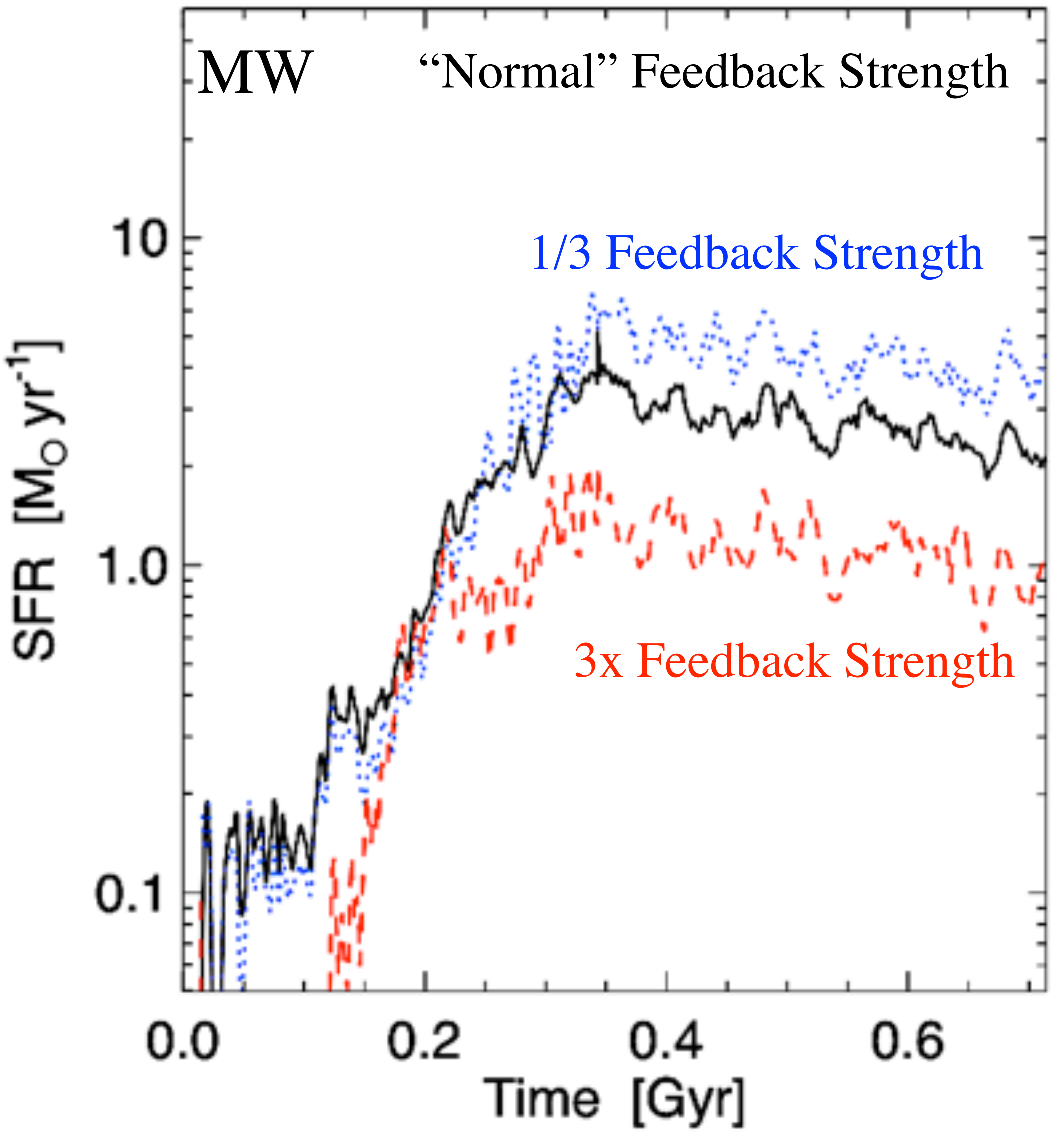
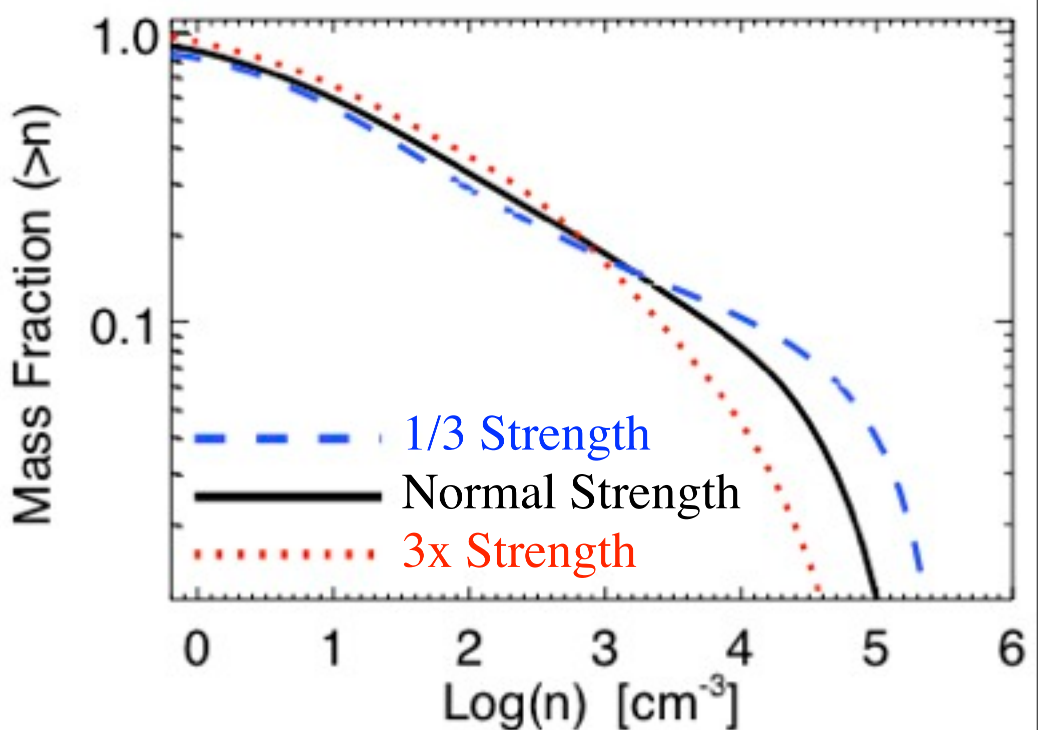
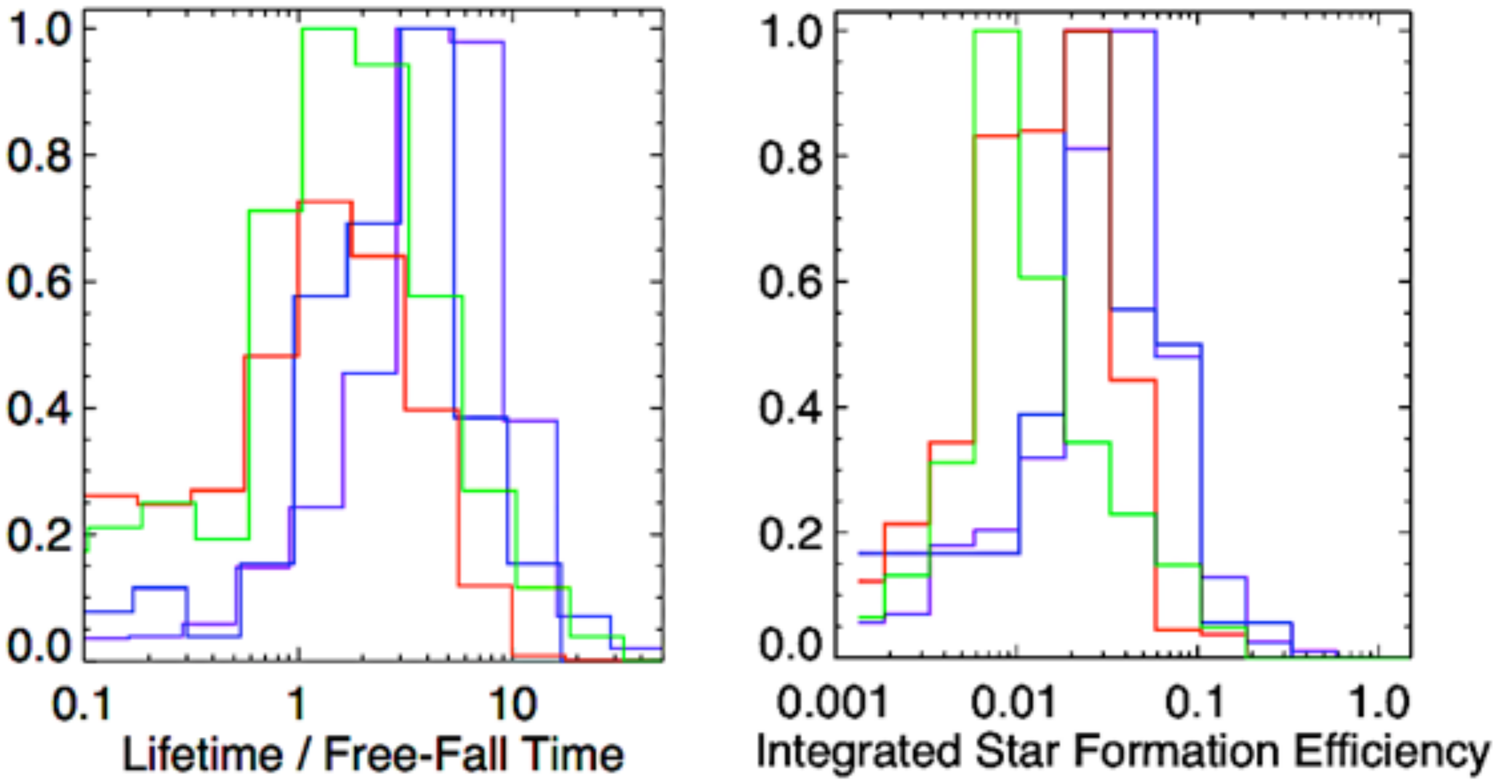
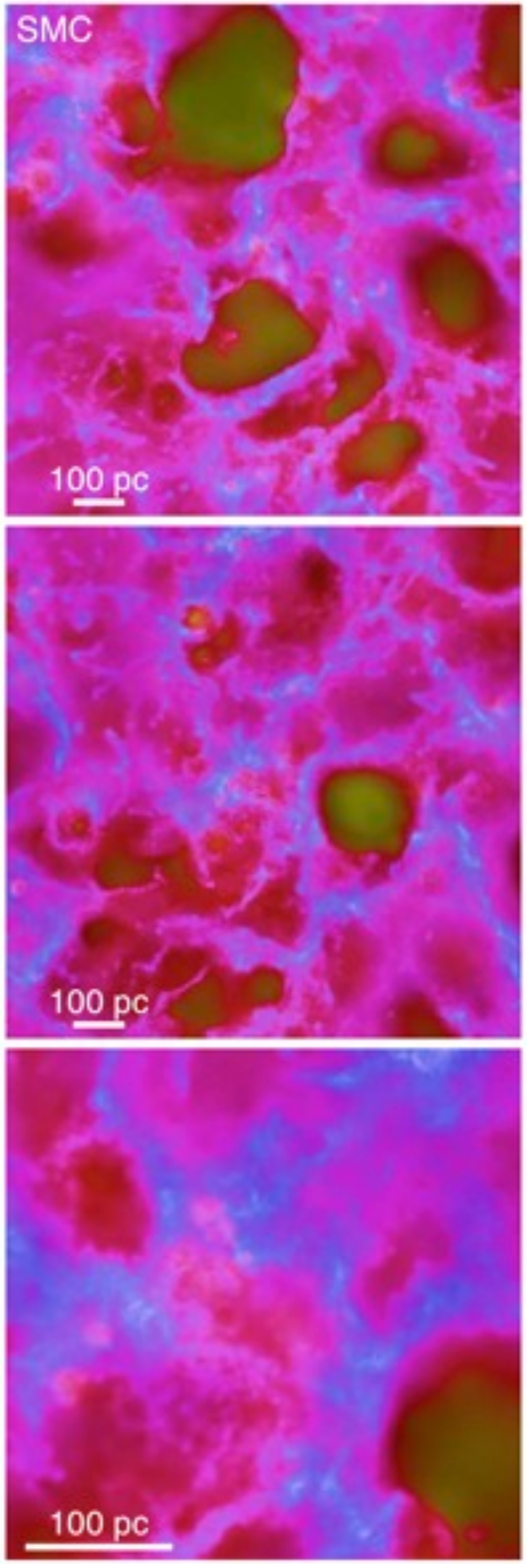




Properties of GMCs

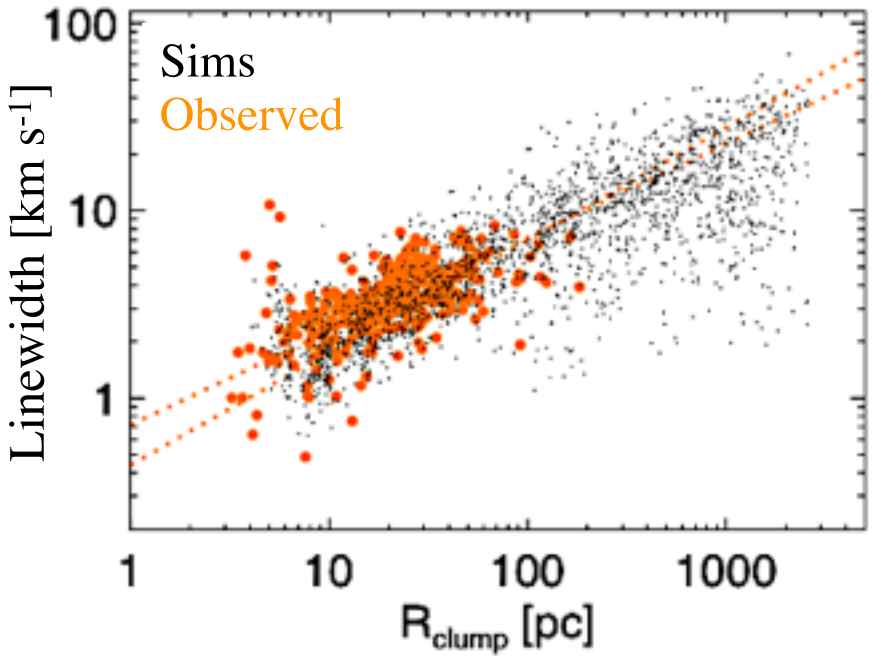
DEPENDENCE ON FEEDBACK AND OTHER SCALINGS

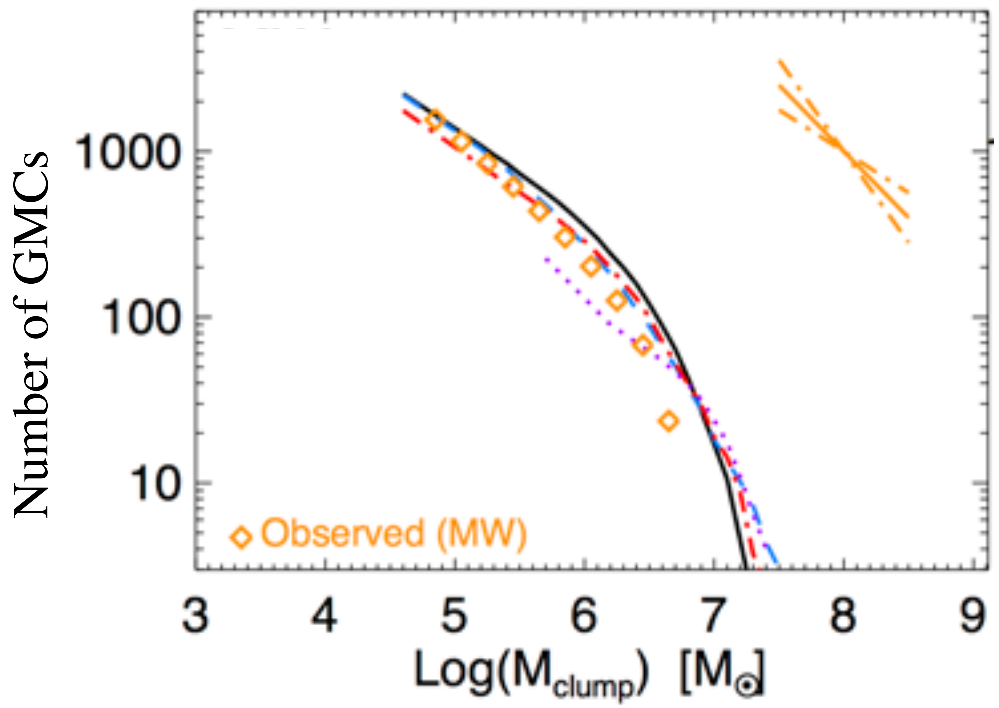


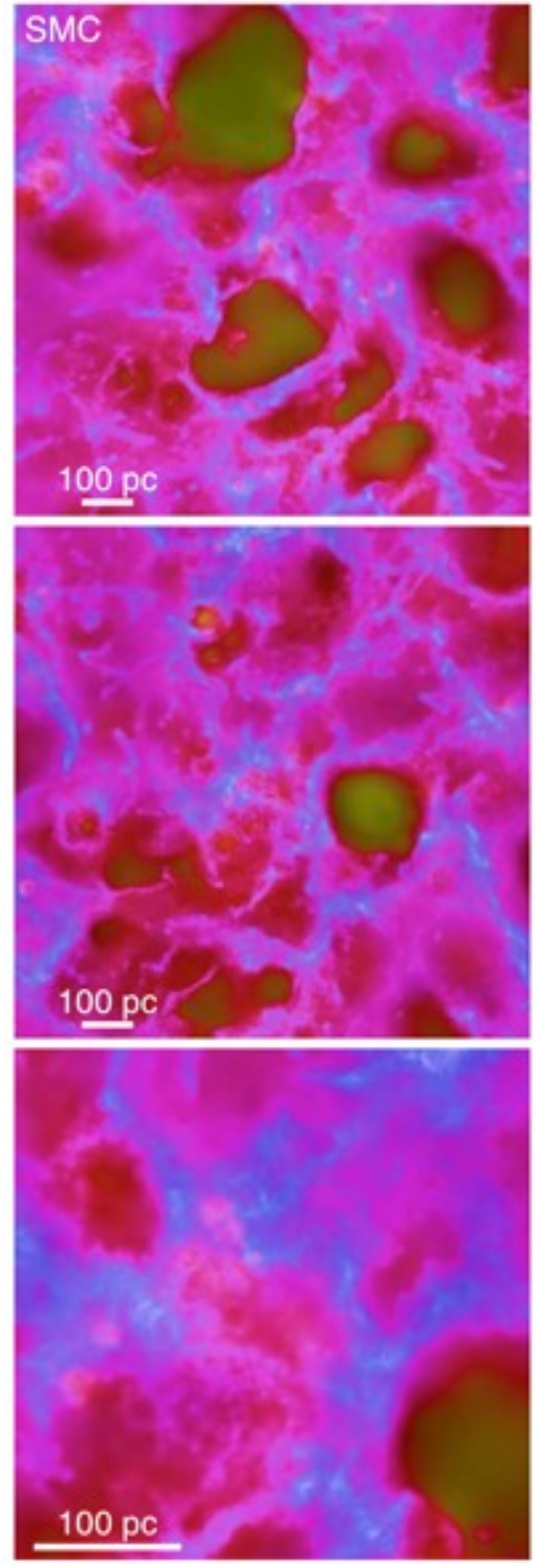


Properties of GMCs

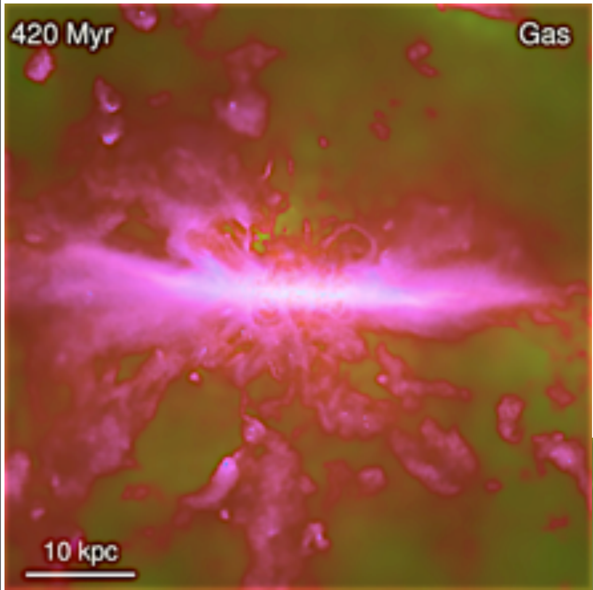
THINGS TO EXAMINE IN THE FUTURE...

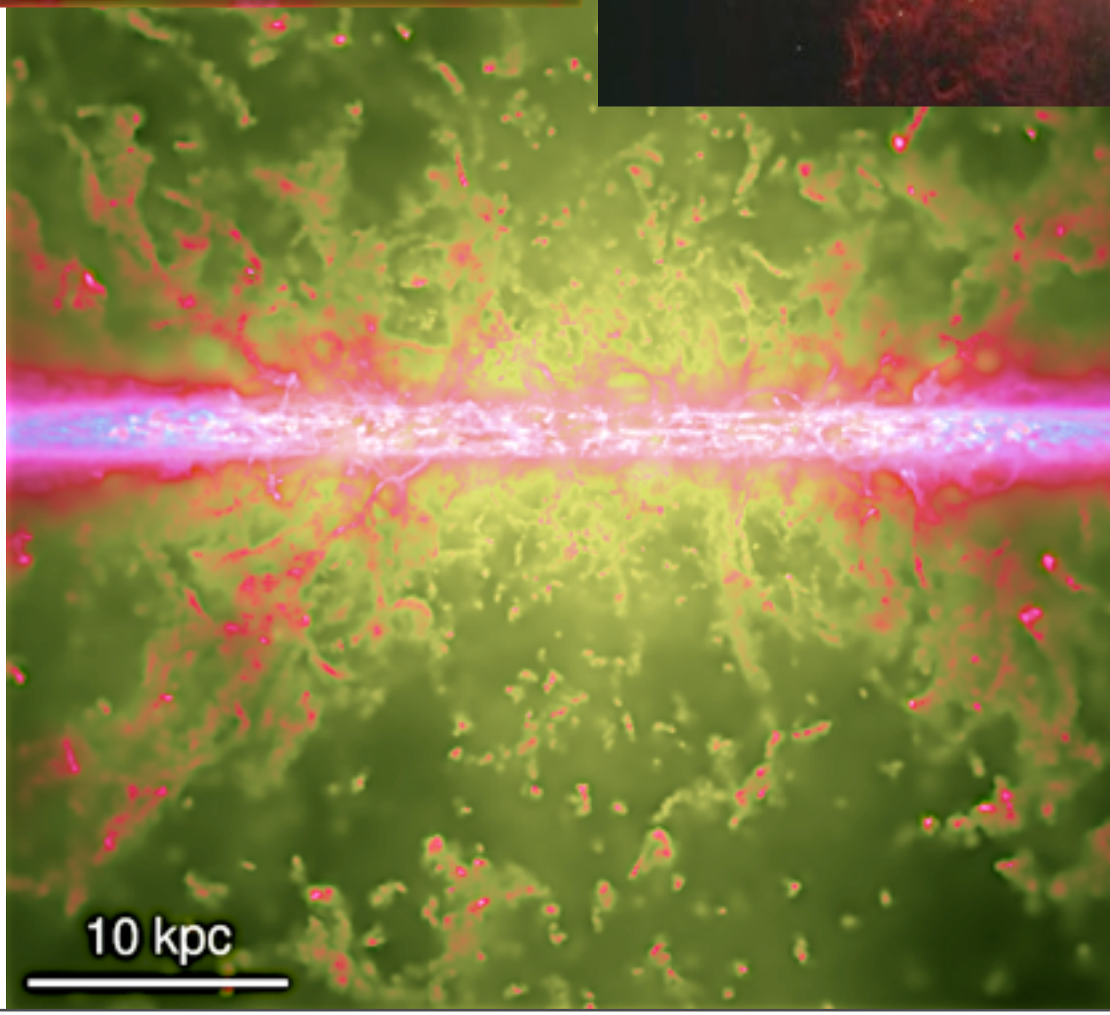


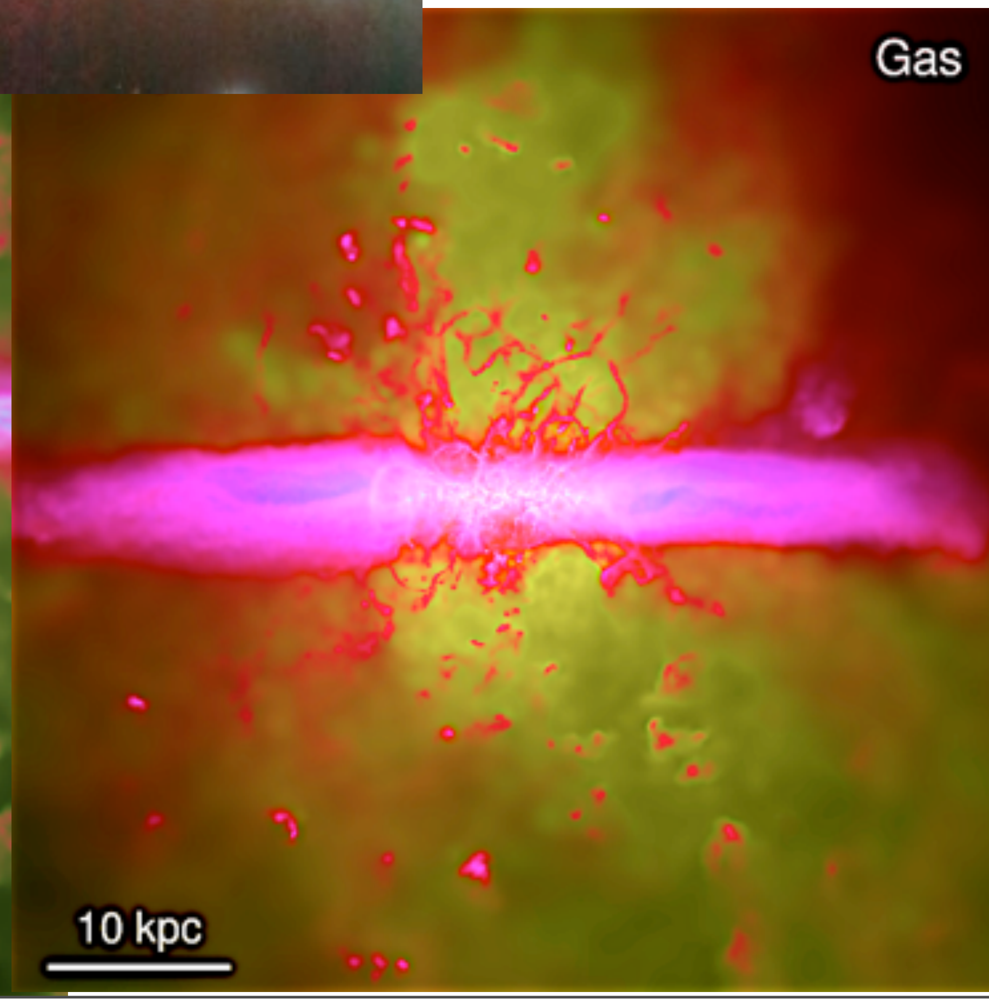


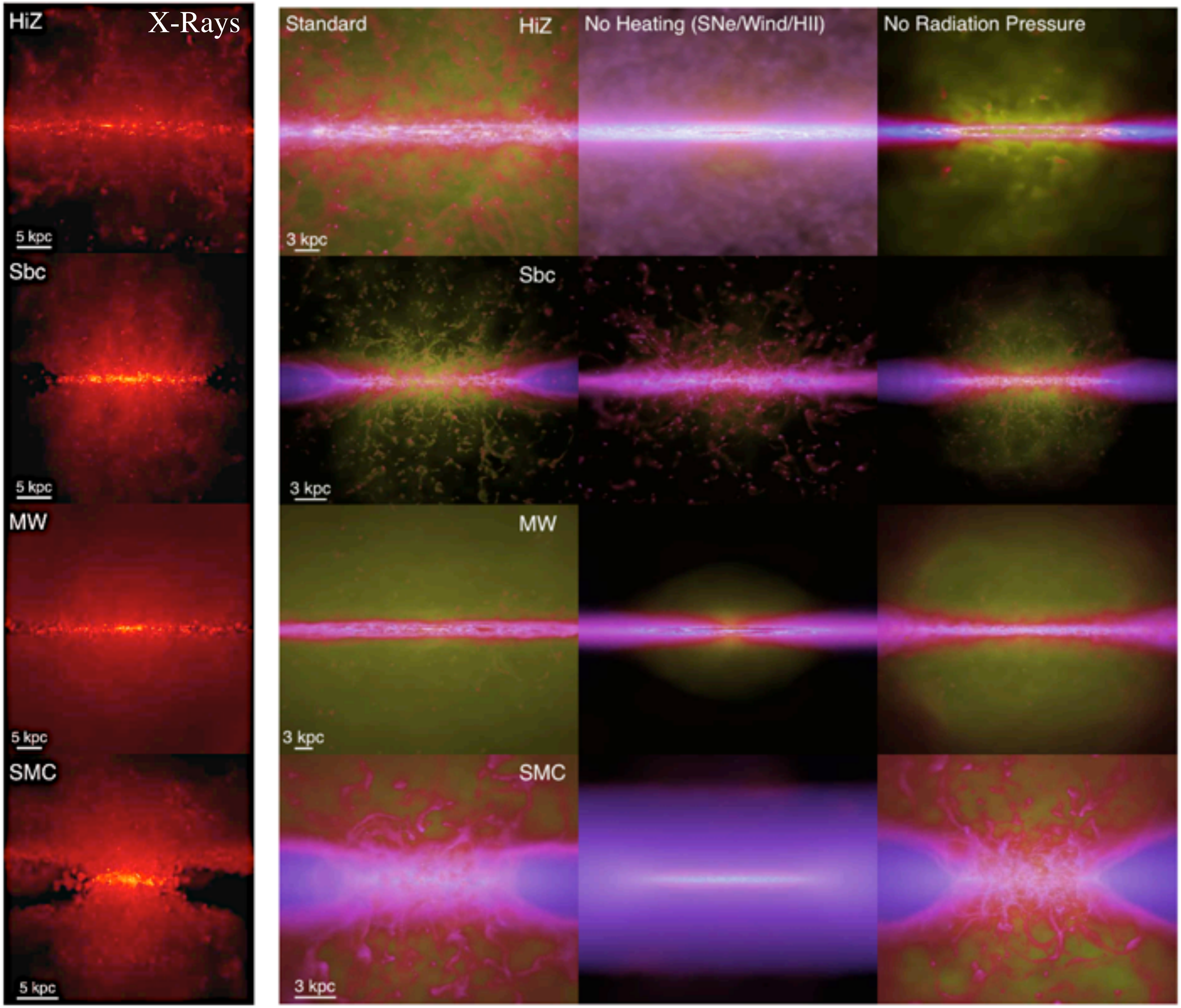


Galactic Super-Winds



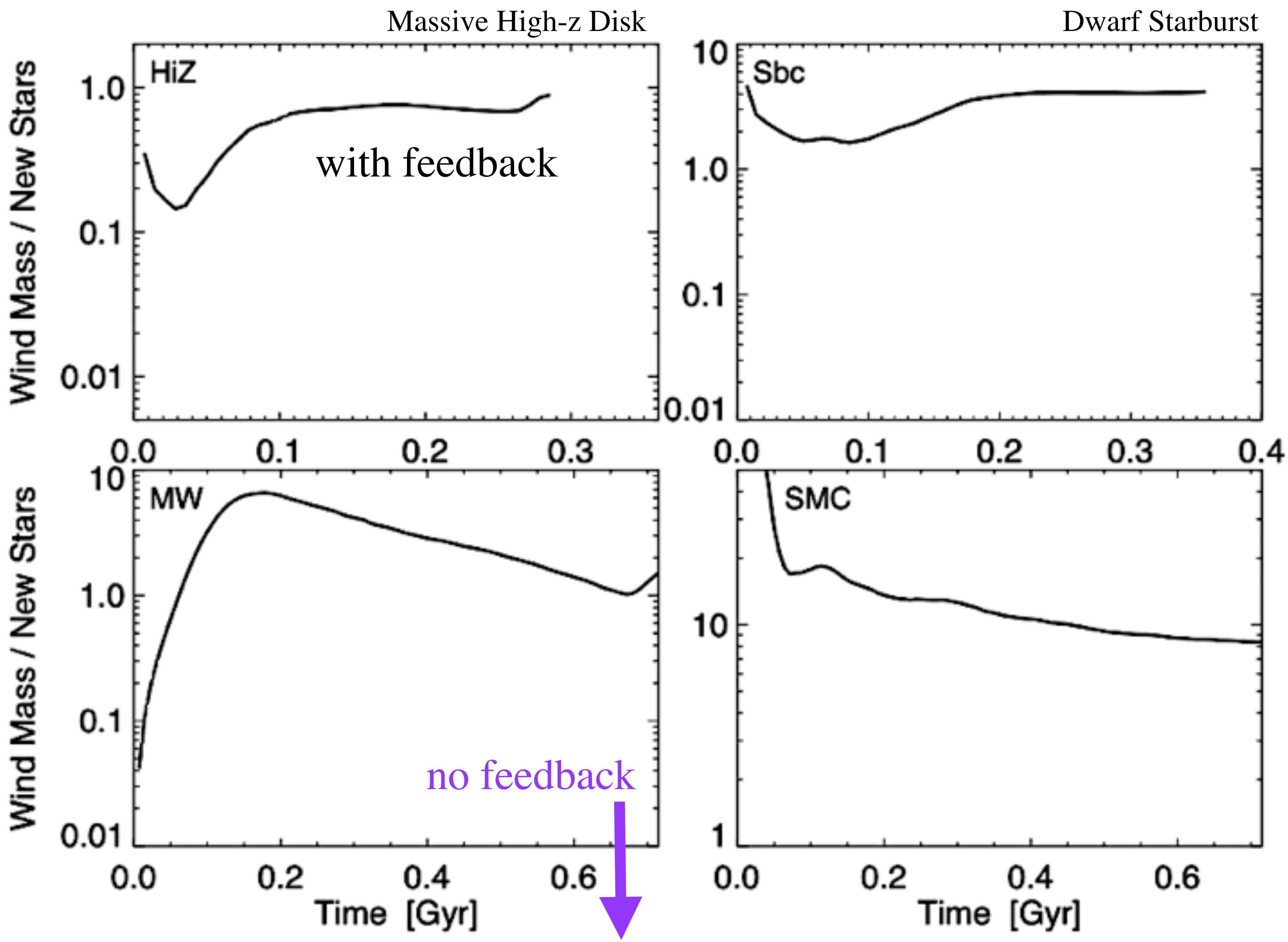





HiZ
X-Rays
5 kpc
Sbc
5 kpc
MW
5 kpc
SMC
5 kpc
Standard
HiZ
3 kpc
No Heating (SNe/Wind/HII)
No Radiation Pressure
Sbc
3 kpc
MW
3 kpc
SMC
3 kpc

How Efficient Are Galactic Super-Winds?

AND WHAT MECHANISMS DRIVE THEM?



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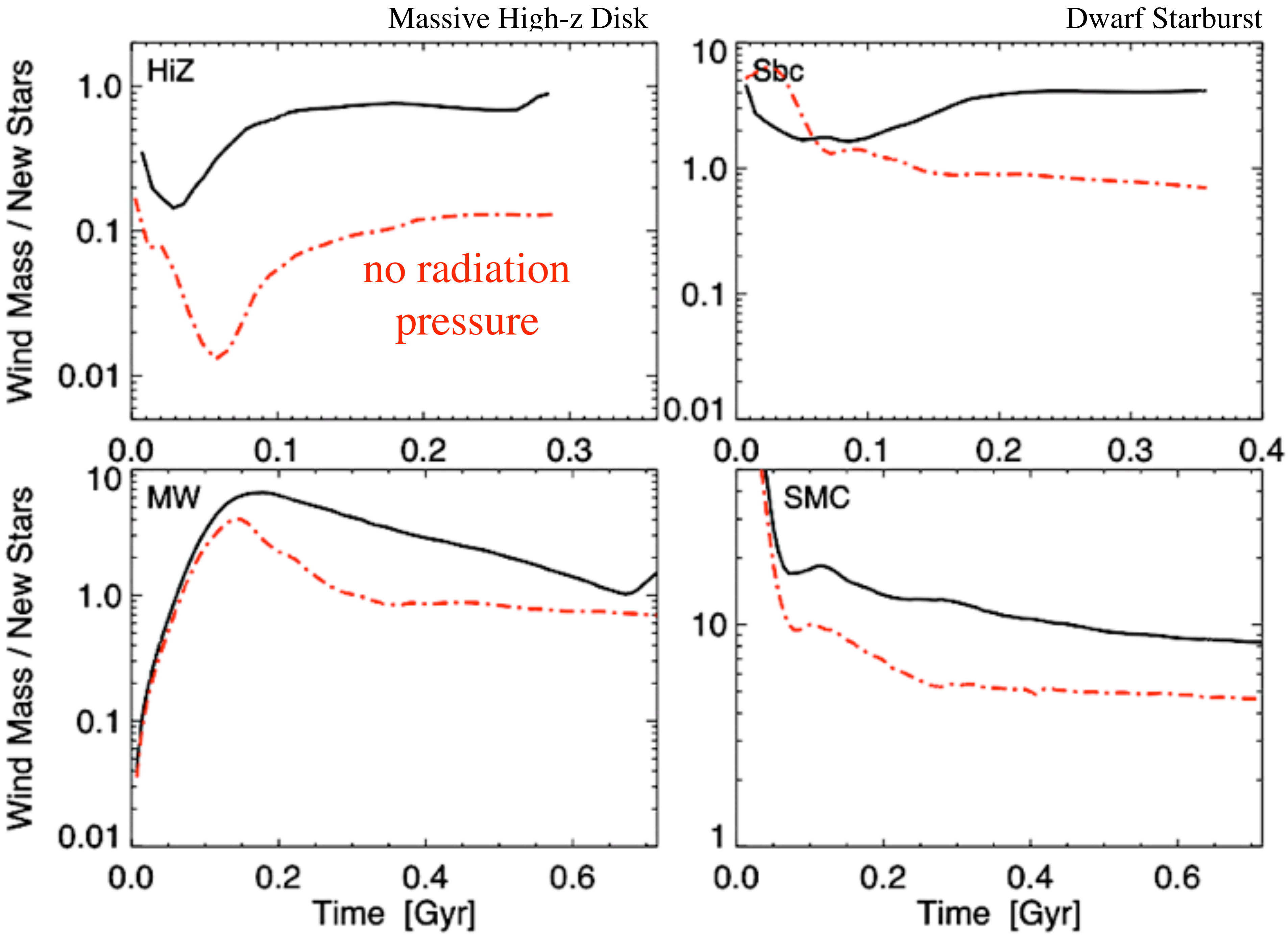

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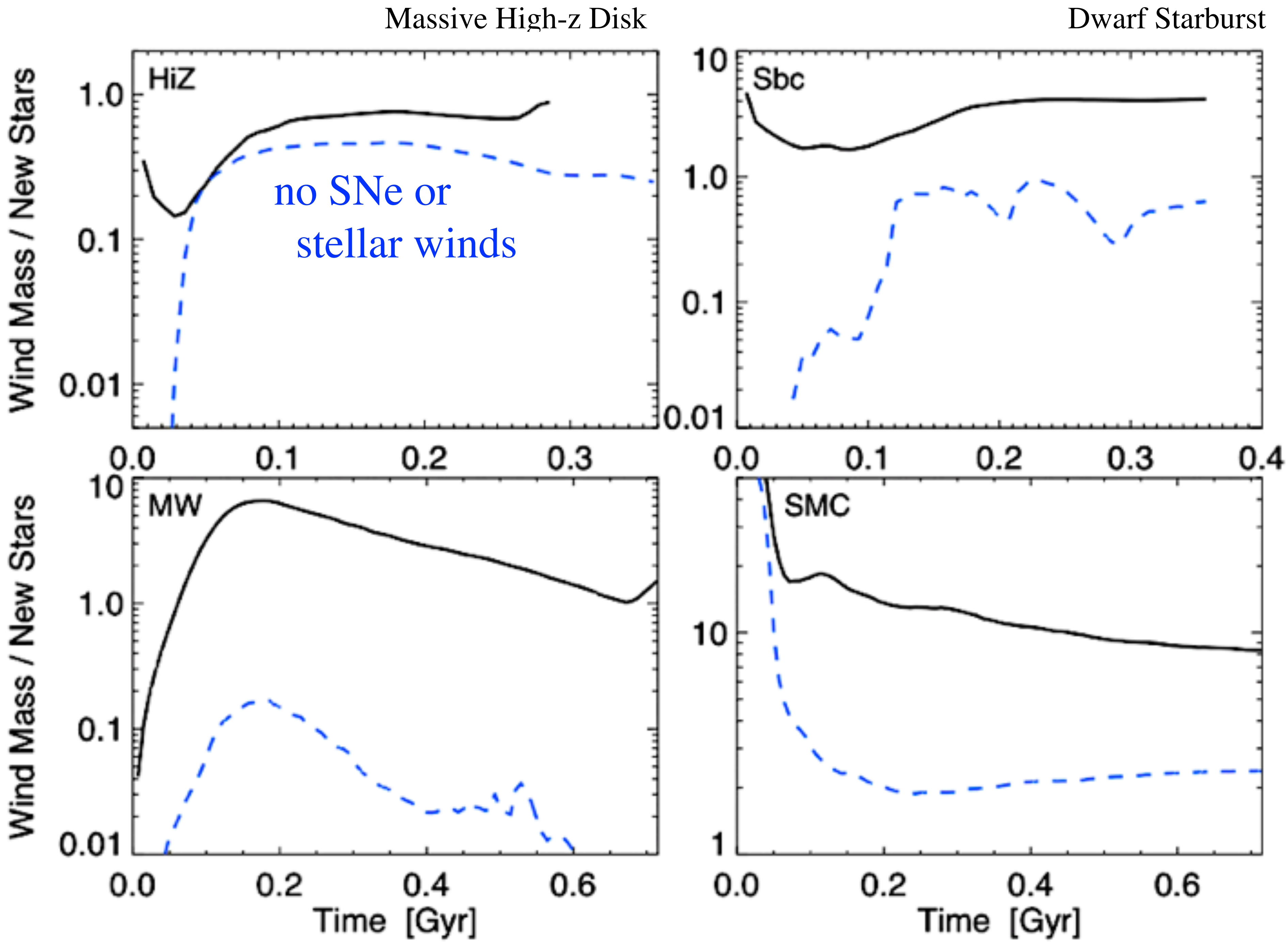

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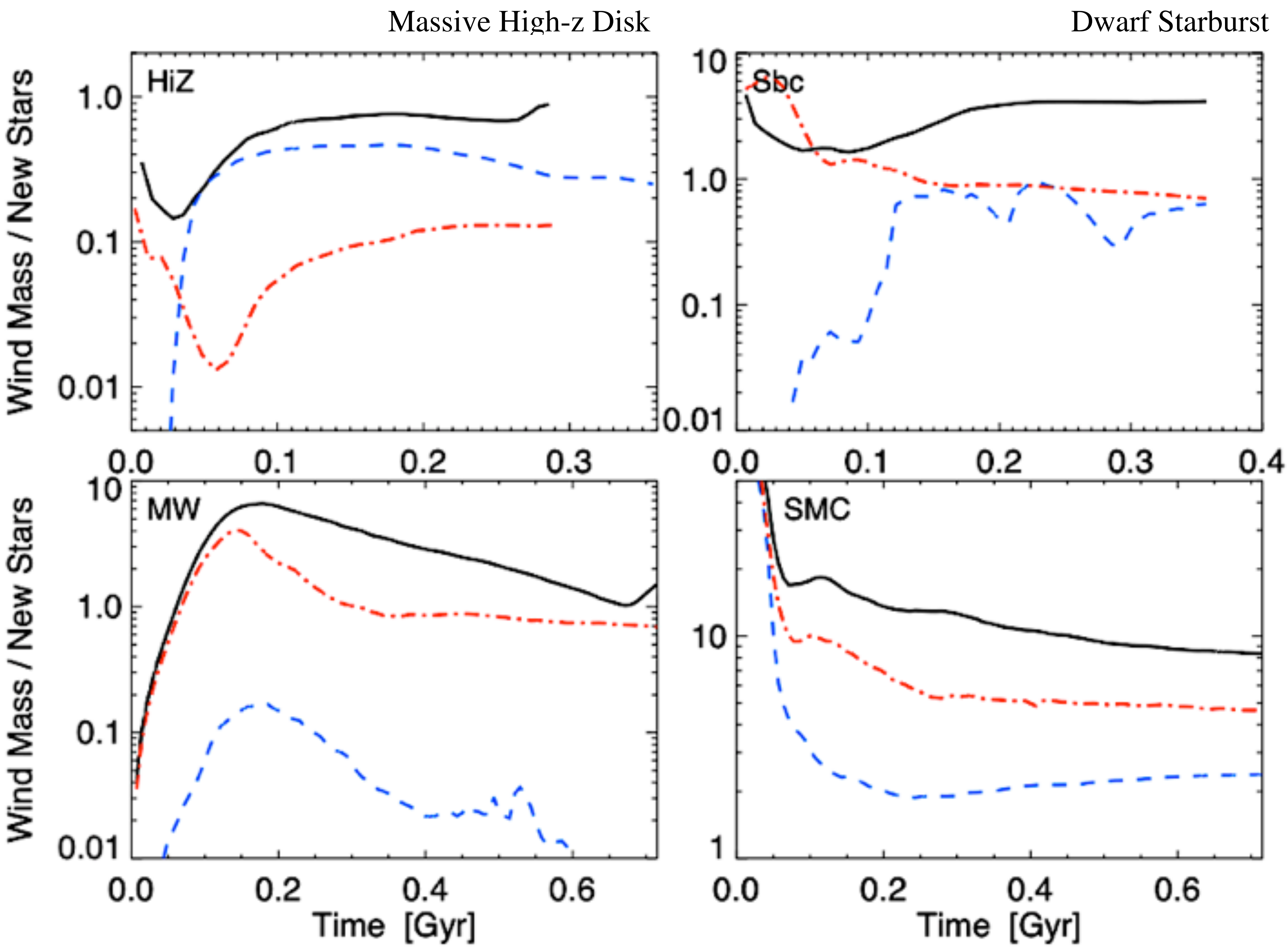

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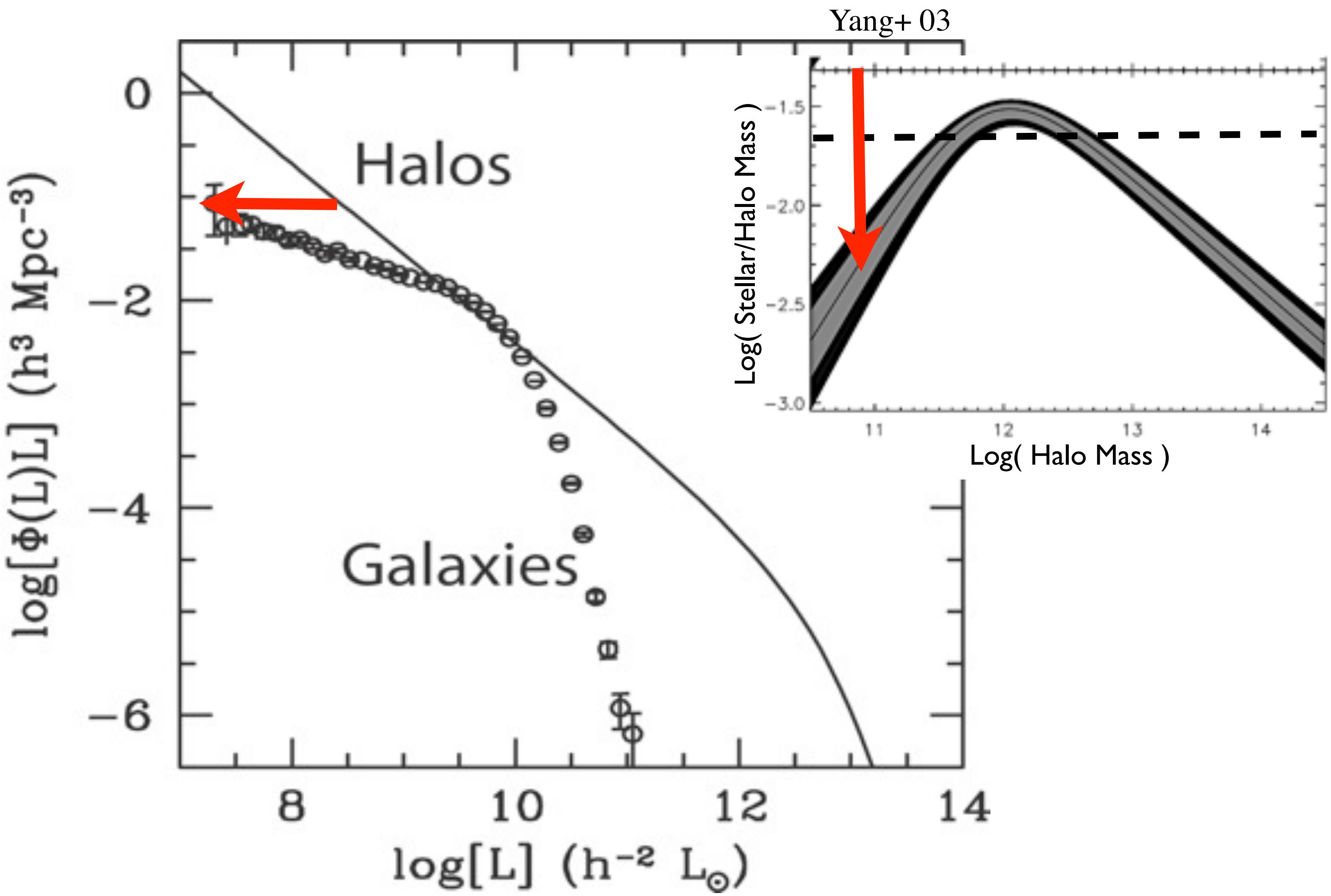

- Large mass-loading:

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

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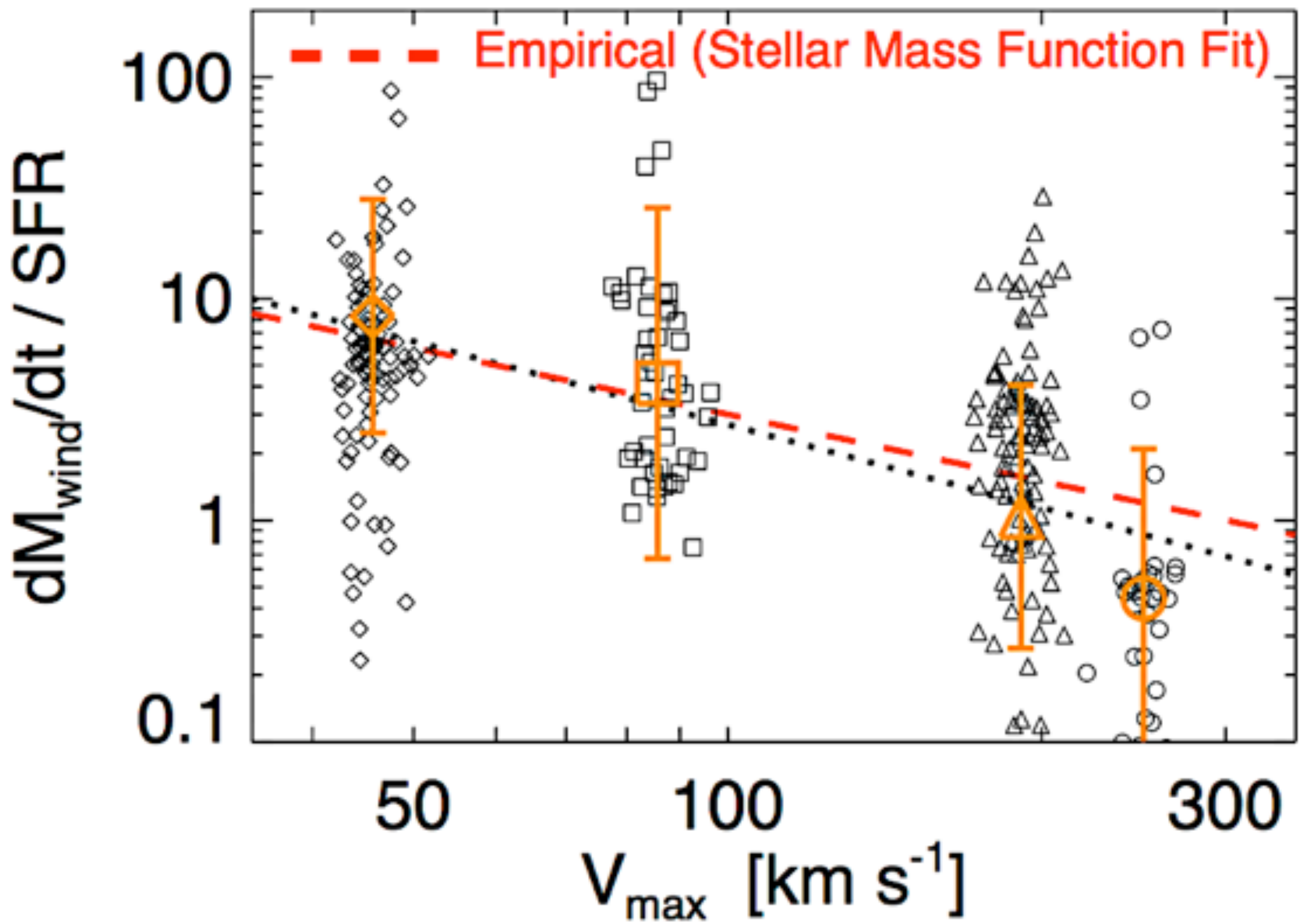

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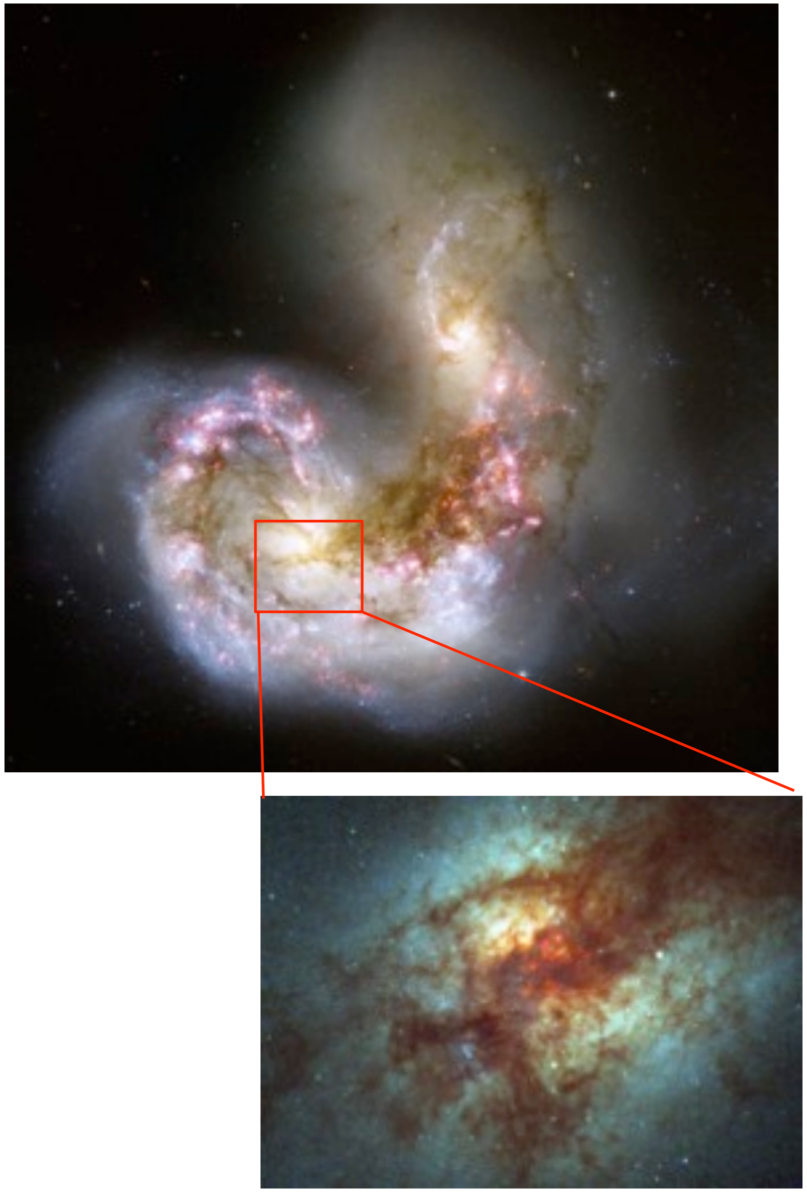
Future Directions

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

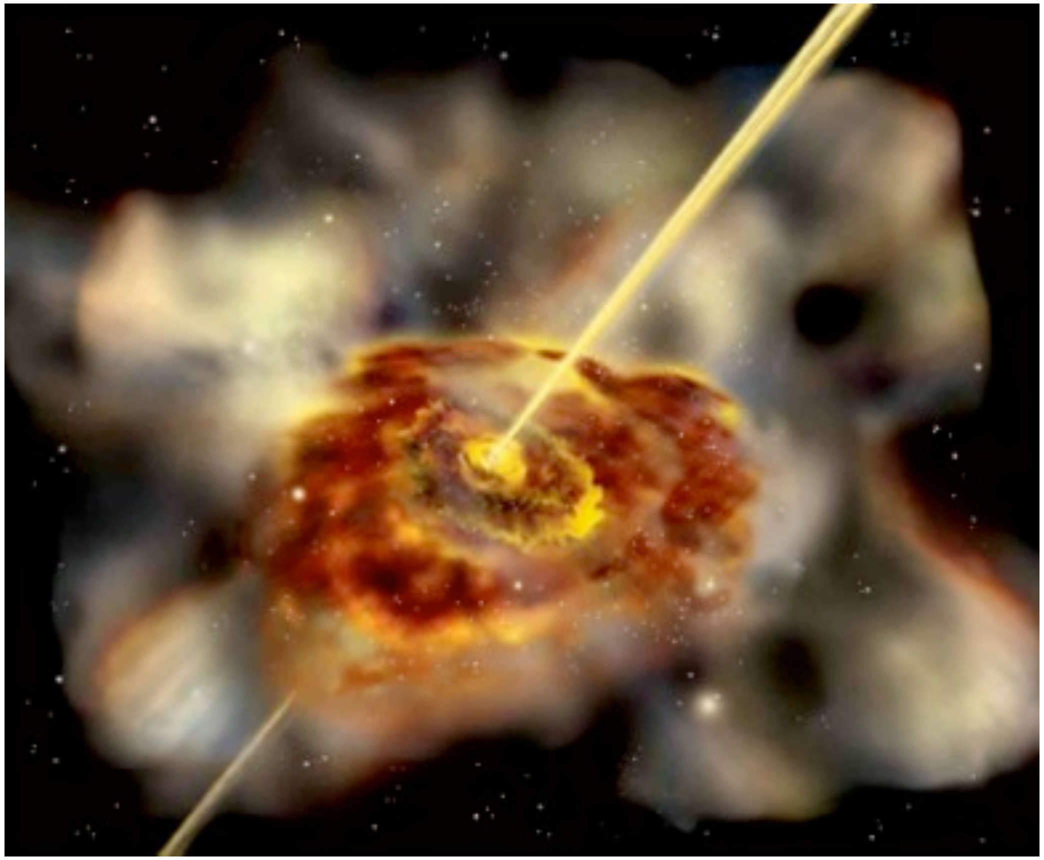
- Mergers:
  - Star cluster formation? Starburst environments?
- AGN Feedback:
  - How does it couple to a multi-phase ISM?
- Cosmological simulations:
  - “Zoom-in” disk formation simulations (D. Keres)
  - Cosmological volume AMR: dwarf populations and mass function evolution (M. Kuhlen)
- GMCs & ISM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



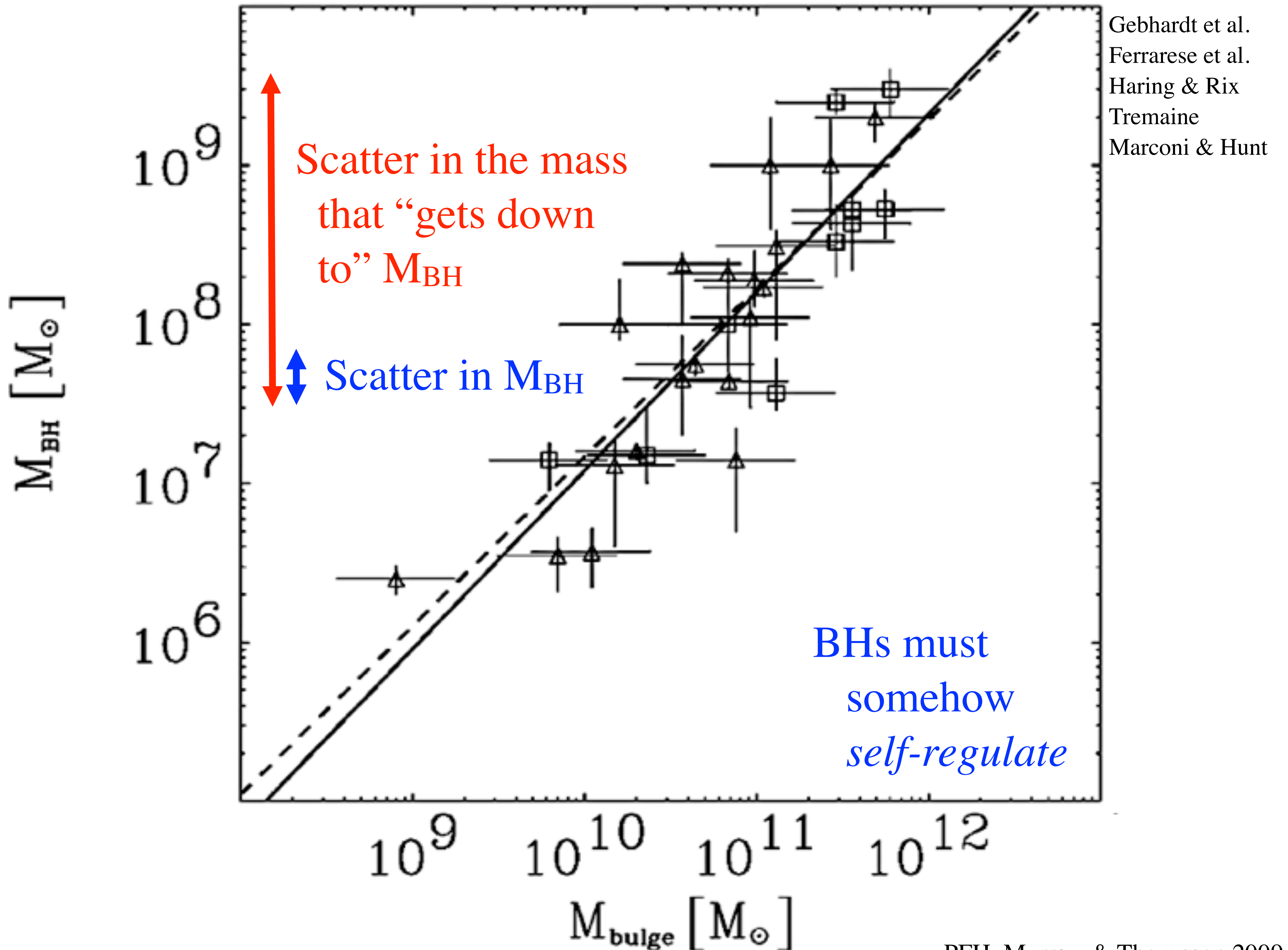
~30 sec

What About the AGN?

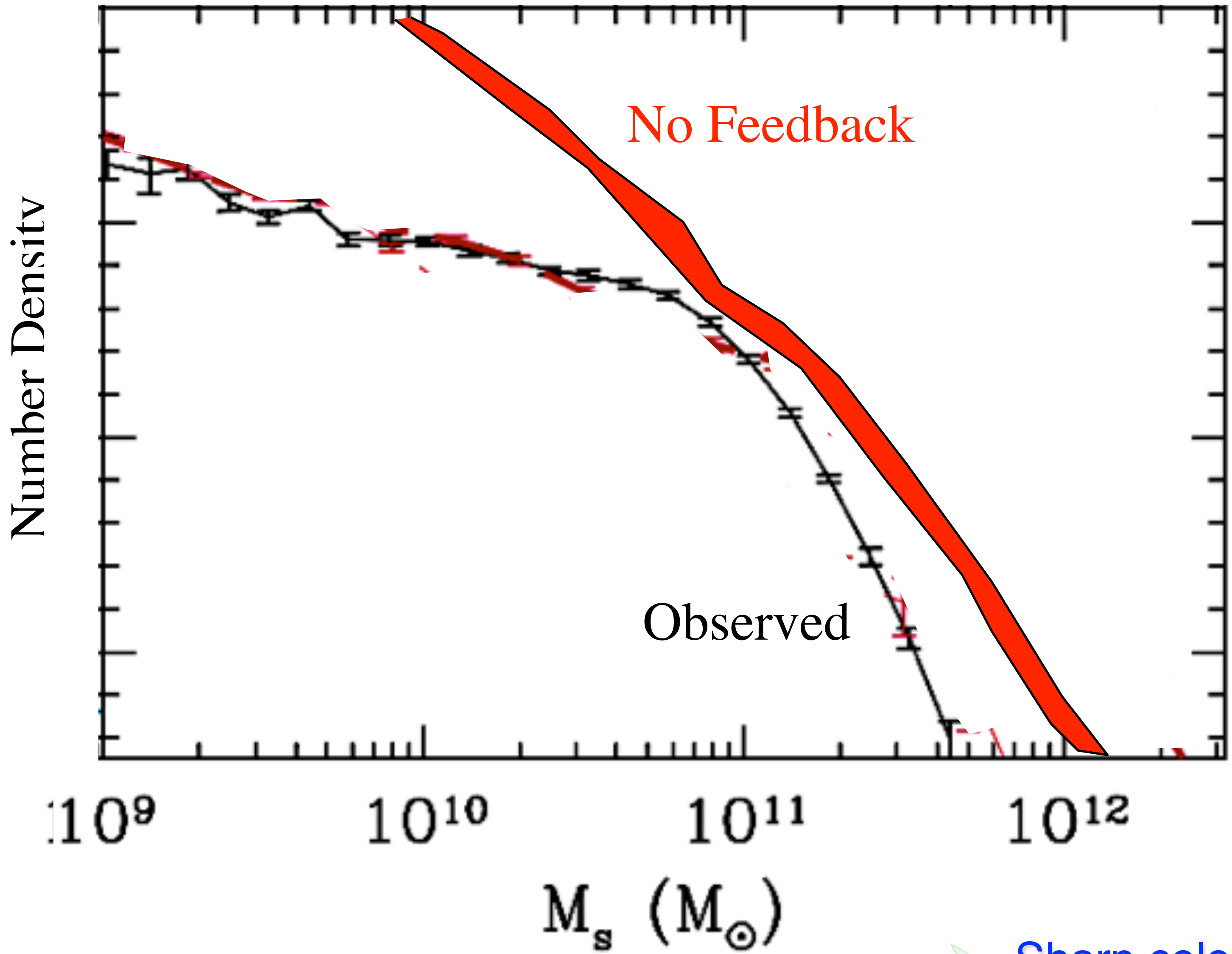
- Every massive galaxy hosts a supermassive black hole



- Mass accreted in ~couple bright quasar phase(s)
  (Soltan, Salucci+, Tremaine+, Yu & Lu, PFH, Shankar, et al.)


Scatter in the mass
that "gets down
to" M_BH
Scatter in M_BH
BHs must
somehow
self-regulate
M_BH [M_⊙]
10^6
10^7
10^8
10^9
10^9
10^10
10^11
10^12
M_bulge [M_⊙]
Gebhardt et al.
Ferrarese et al.
Haring & Rix
Tremaine
Marconi & Hunt
PFH, Murray, & Thompson 2009

What can AGN Feedback Do For You?



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

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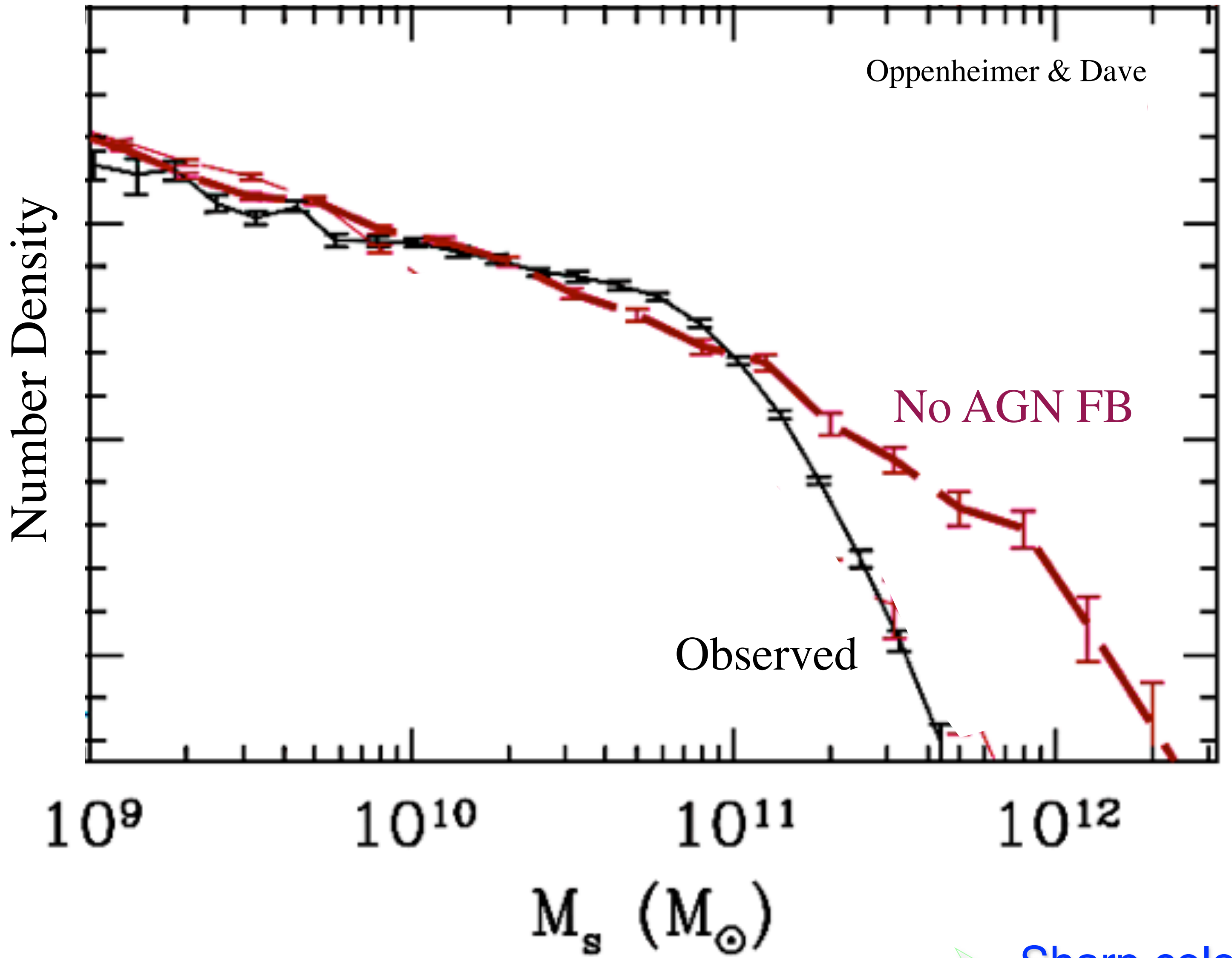

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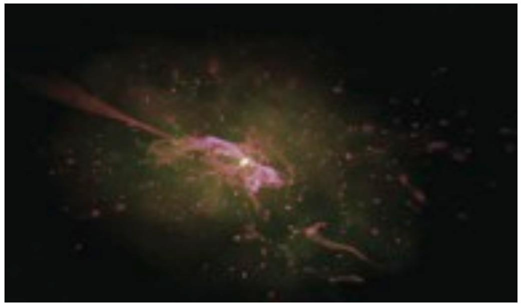
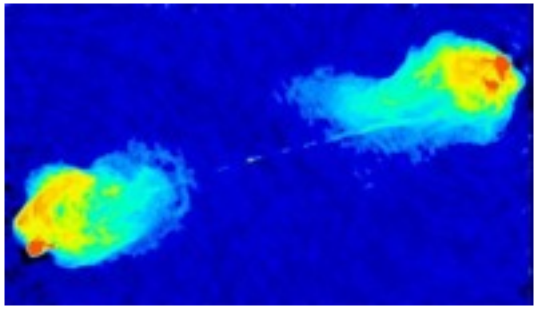
“Transition” vs. “Maintenance”

- **“Quasar”** mode (high mdot)
- Move mass from Blue to Red?
- Rapid (~10^7 yr)
- Small(er) scales (~pc-kpc)
- Morphological Transformation
- Gas-rich/Dissipational Mergers?



- Regulates *Black Hole* Mass

- **“Radio”** mode (low mdot)
- Keep it Red
- Long-lived (~Hubble time)
- Large (~halo) scales
- Subtle morphological change
- Hot Halos & Dry Mergers



- Regulates *Galaxy* Mass

What Can Quasar Feedback Do?

Feedback Energy:

SILK & REES '98

$$L = \epsilon_r \, \dot{M}_{\rm BH} \, c^2 \qquad (\epsilon_r \sim 0.1)$$

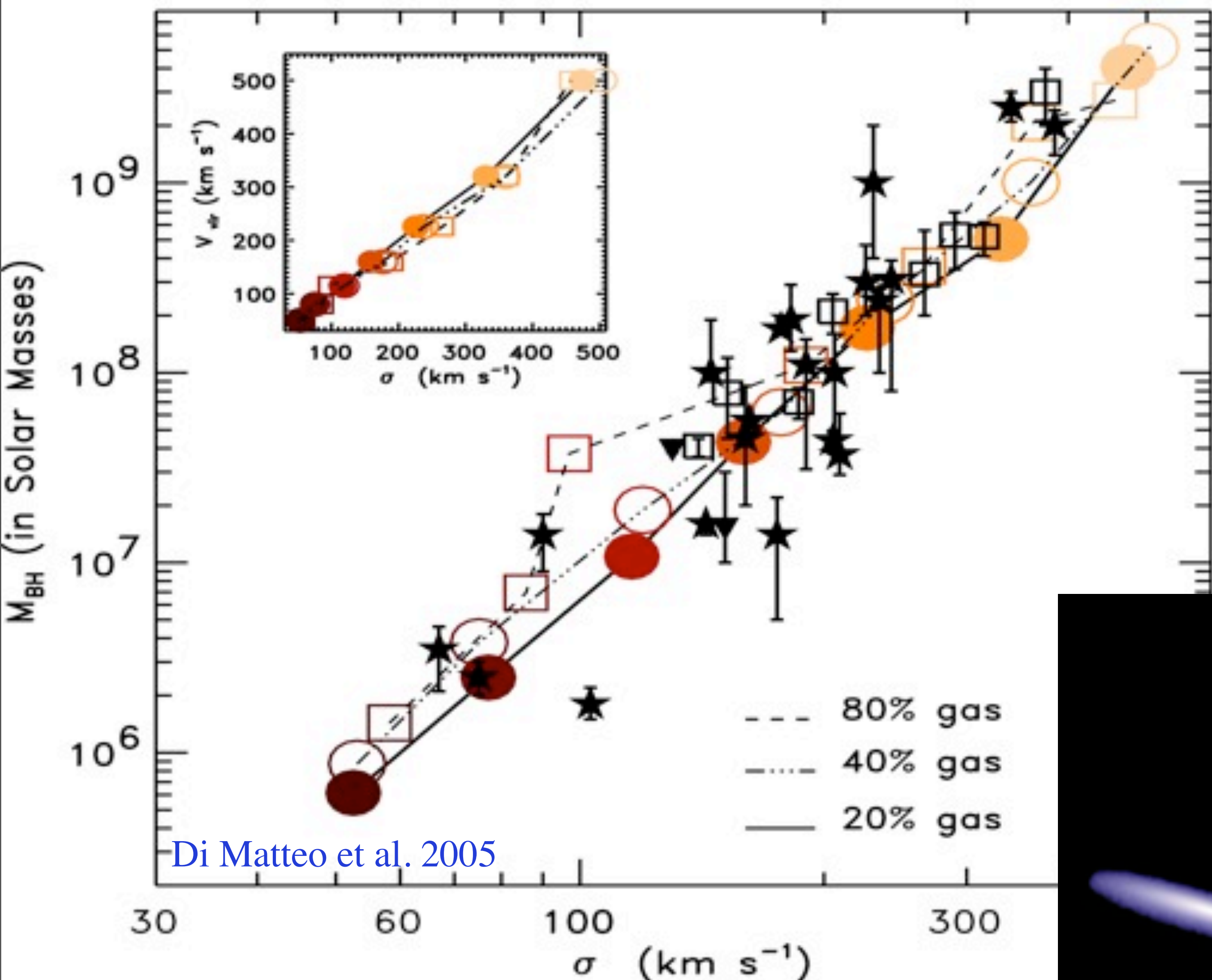
$$\rightarrow E_{\rm rad} \sim 0.1 \, M_{\rm BH} \, c^2 \sim 10^{61} \, {\rm erg}$$

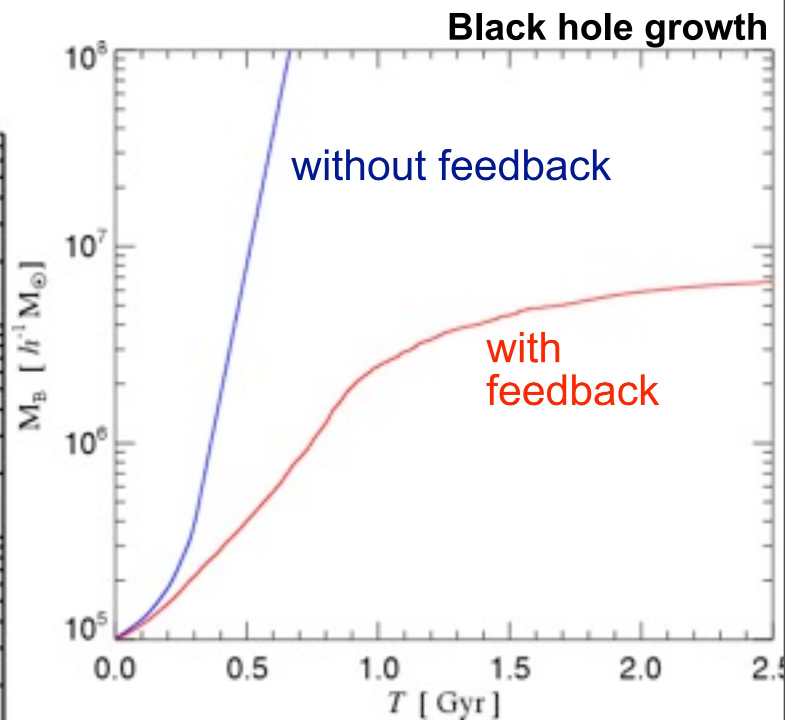
$$(M_{\rm BH} \sim 10^8 \, M_\odot)$$

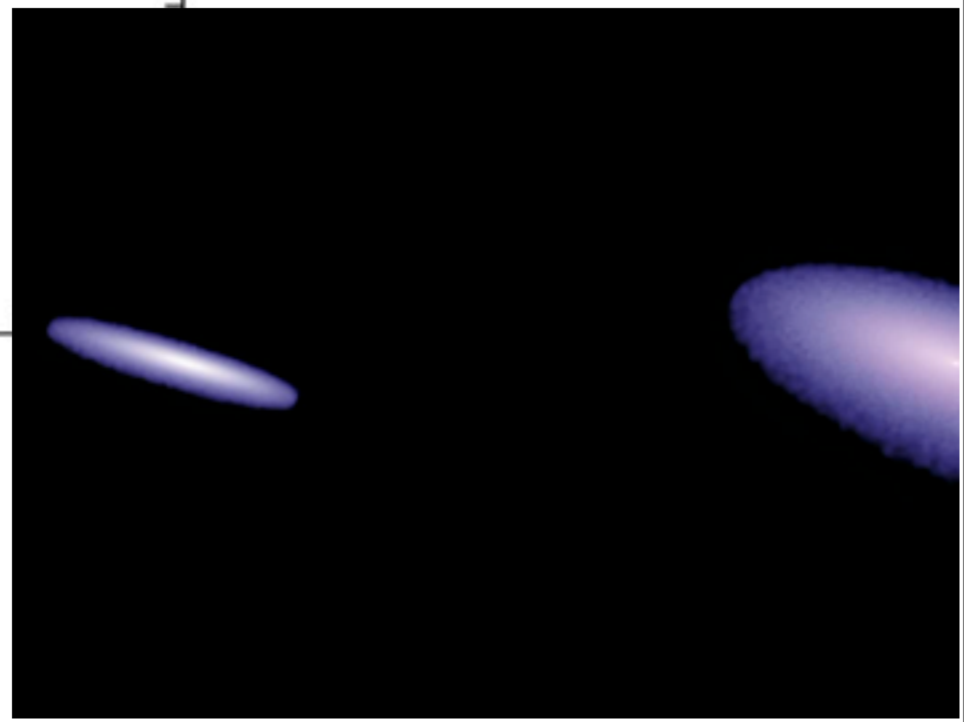
$$E_{\rm gal} \sim M_{\rm gal} \, \sigma^2 \sim (10^{11} \, M_\odot) \, (200 \, {\rm km/s})^2 \sim 10^{59} \, {\rm erg}$$

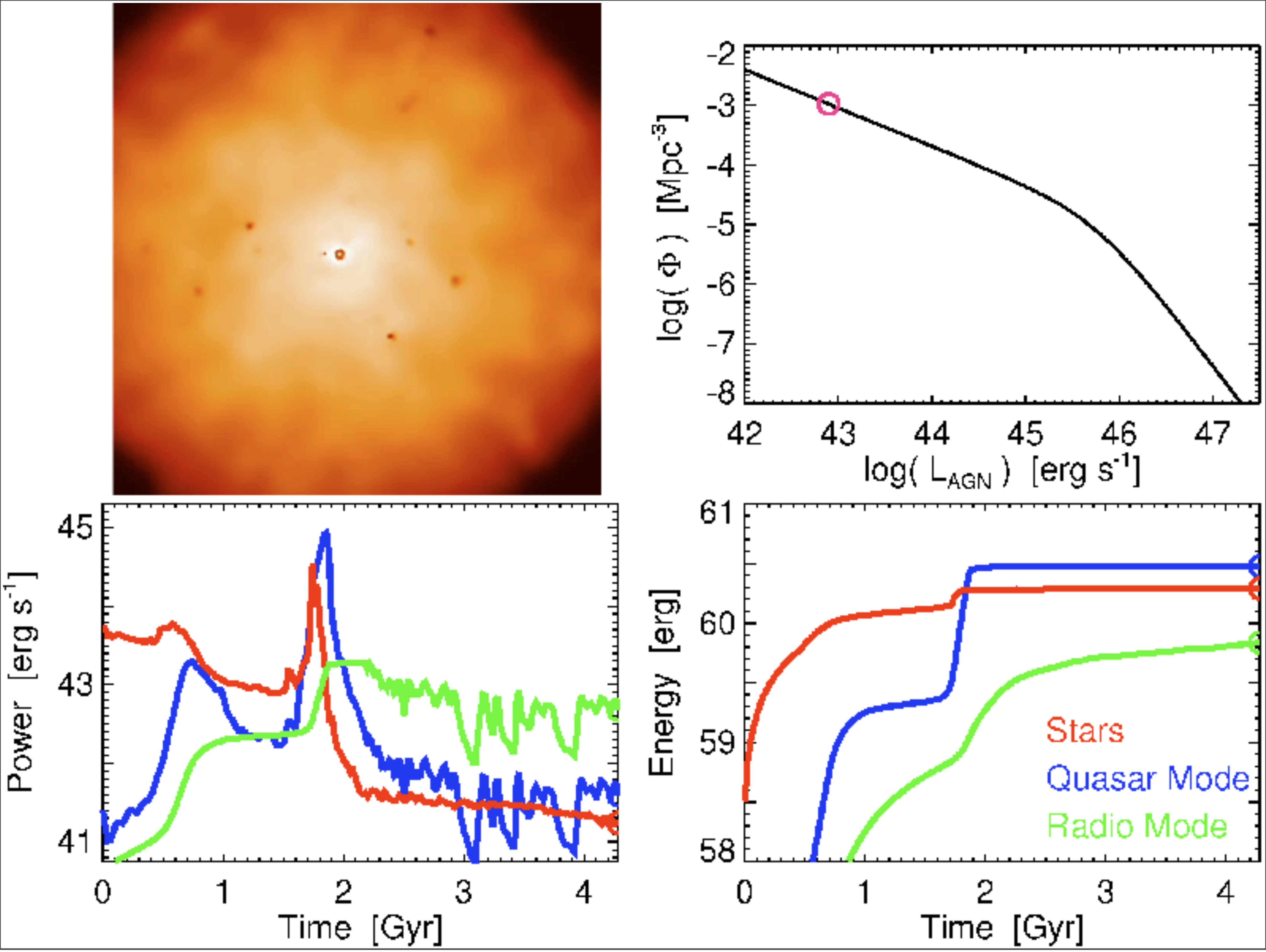
M-sigma Suggests *Self-Regulated* BH Growth

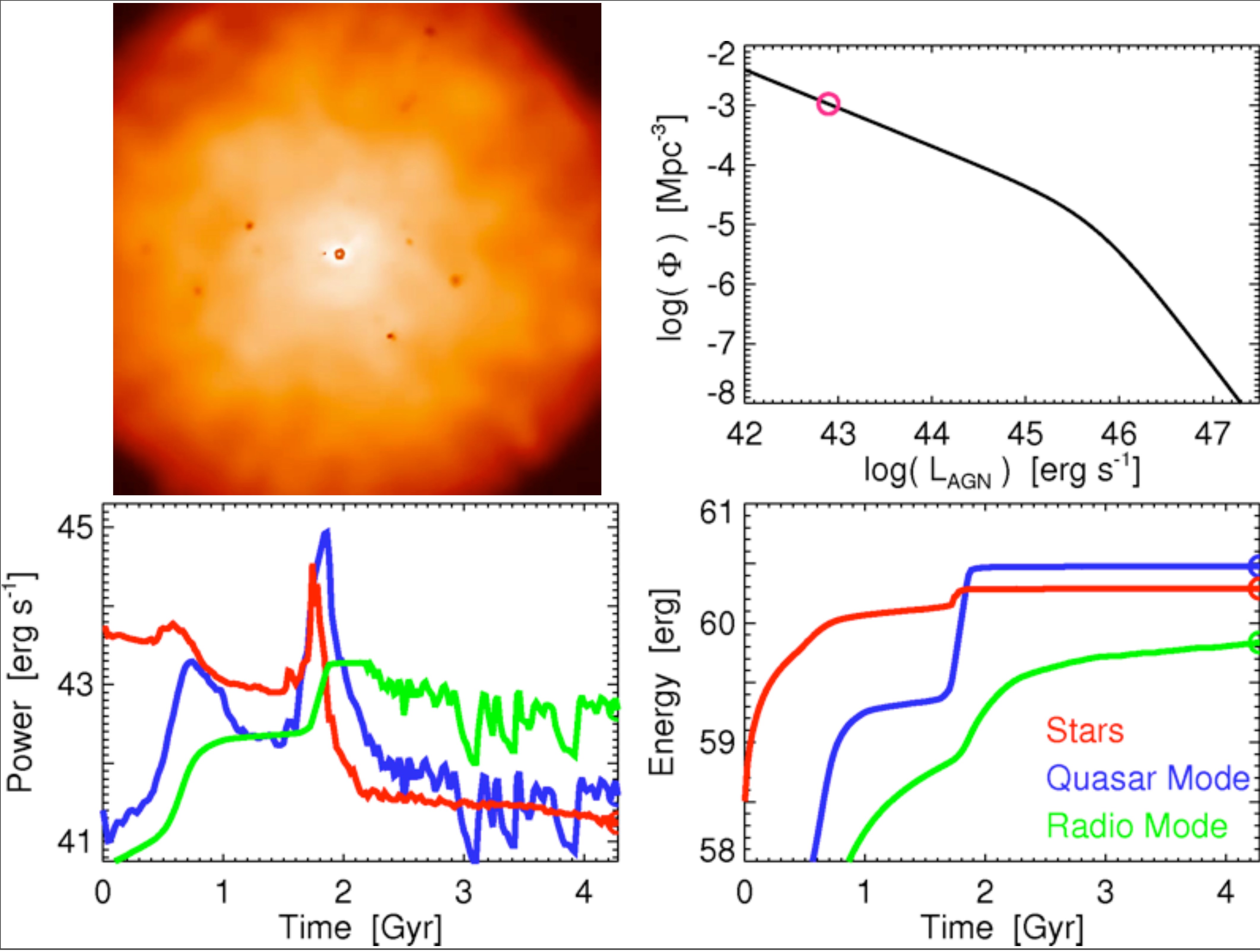
PREVENTS RUNAWAY BLACK HOLE GROWTH







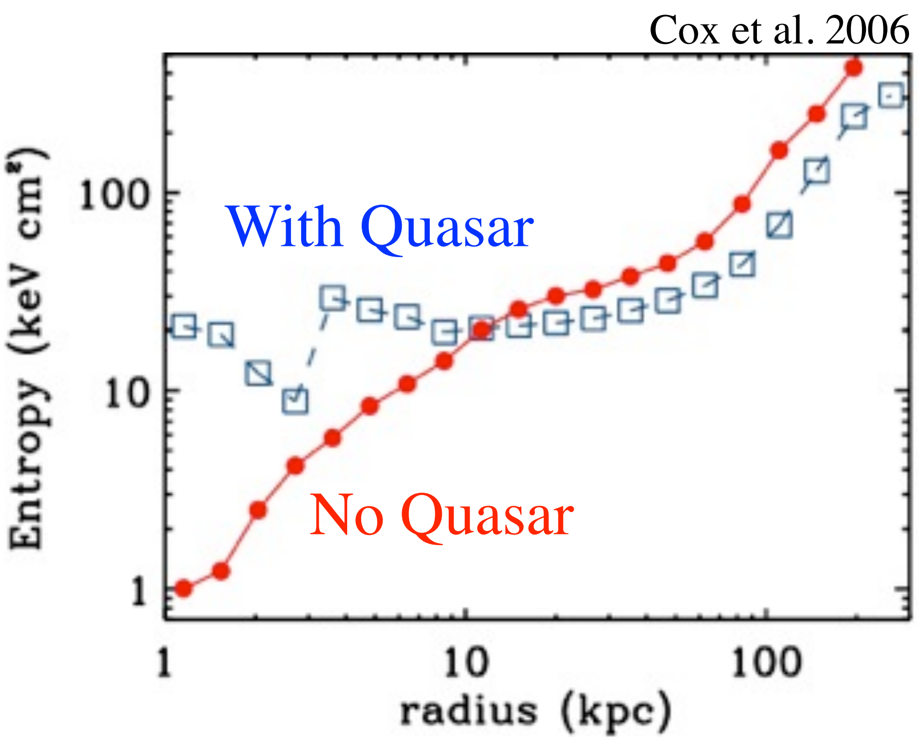

log(Φ) [Mpc^-3]
log(L_AGN) [erg s^-1]
Power [erg s^-1]
Time [Gyr]
Energy [erg]
Time [Gyr]
Stars
Quasar Mode
Radio Mode

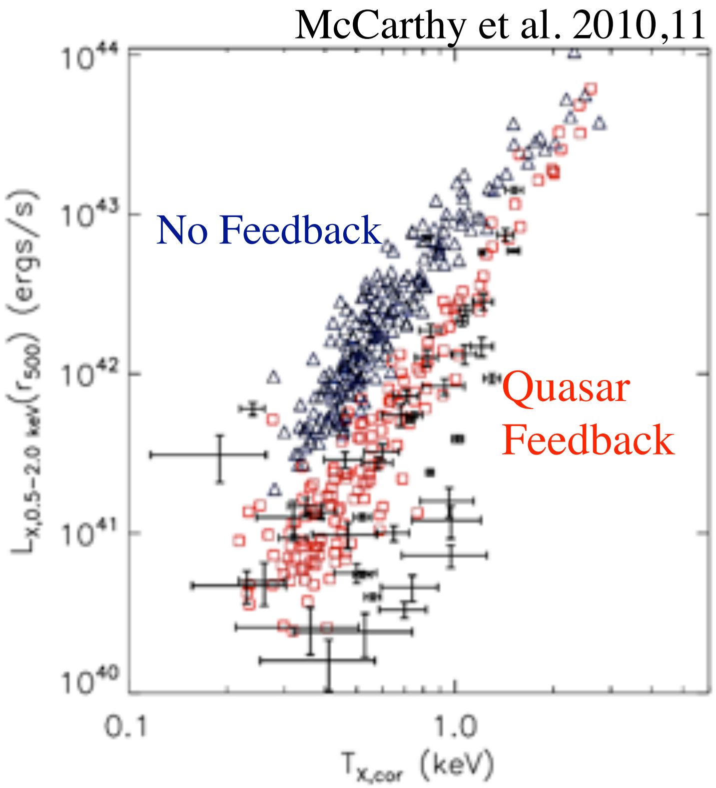


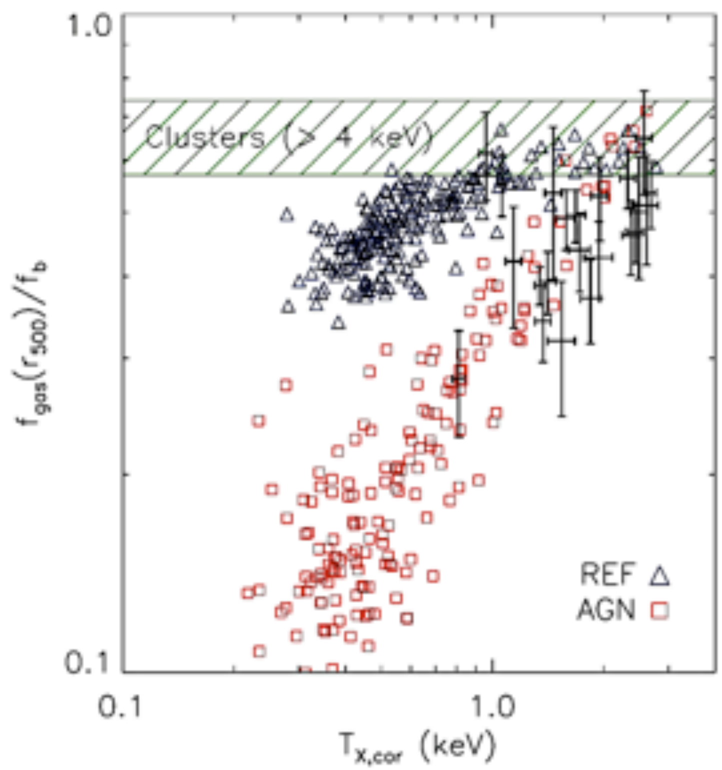
log(Φ) [Mpc^{-3}]
-2
-3
-4
-5
-6
-7
-8
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]
Power [erg s^{-1}]
45
43
41
0
1
2
3
4
Time [Gyr]
Energy [erg]
61
60
59
58
0
1
2
3
4
Time [Gyr]
Stars
Quasar Mode
Radio Mode

Quasar Outflows: Heating Halo Gas

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

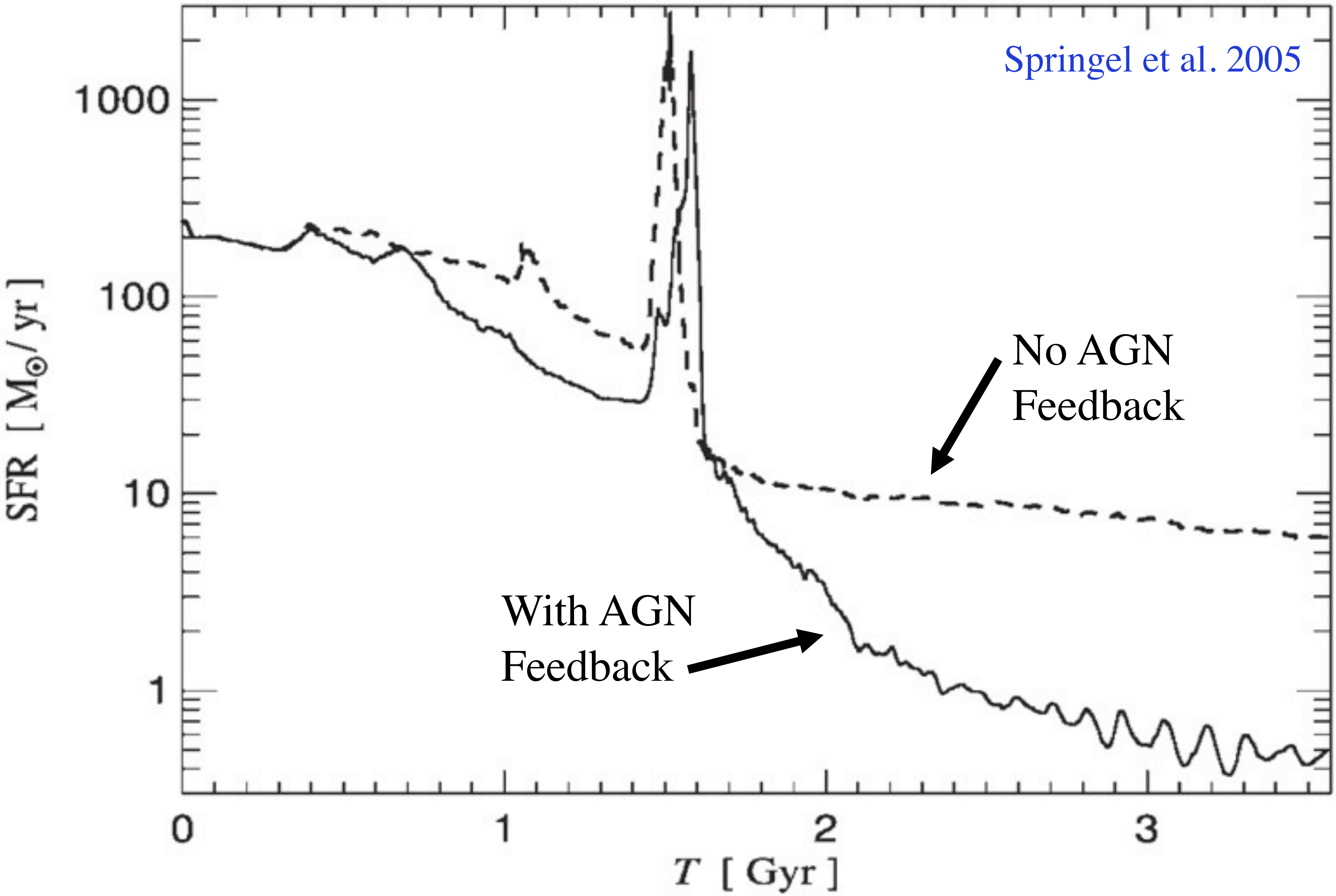




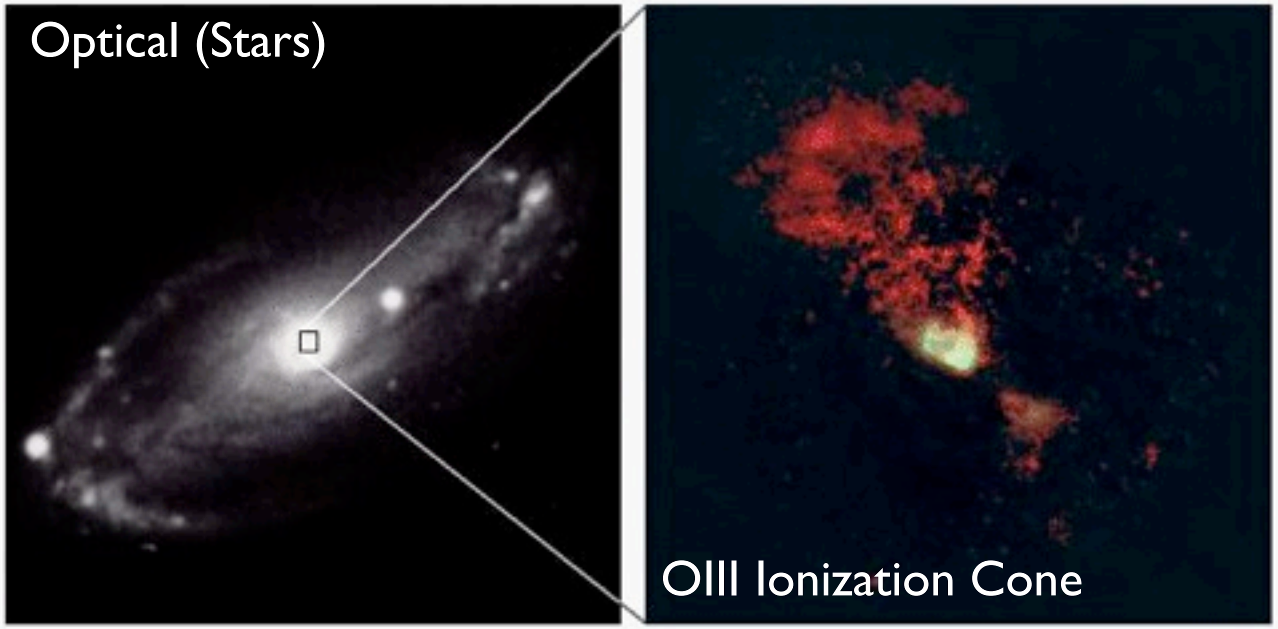


Expulsion of Gas Turns off Star Formation

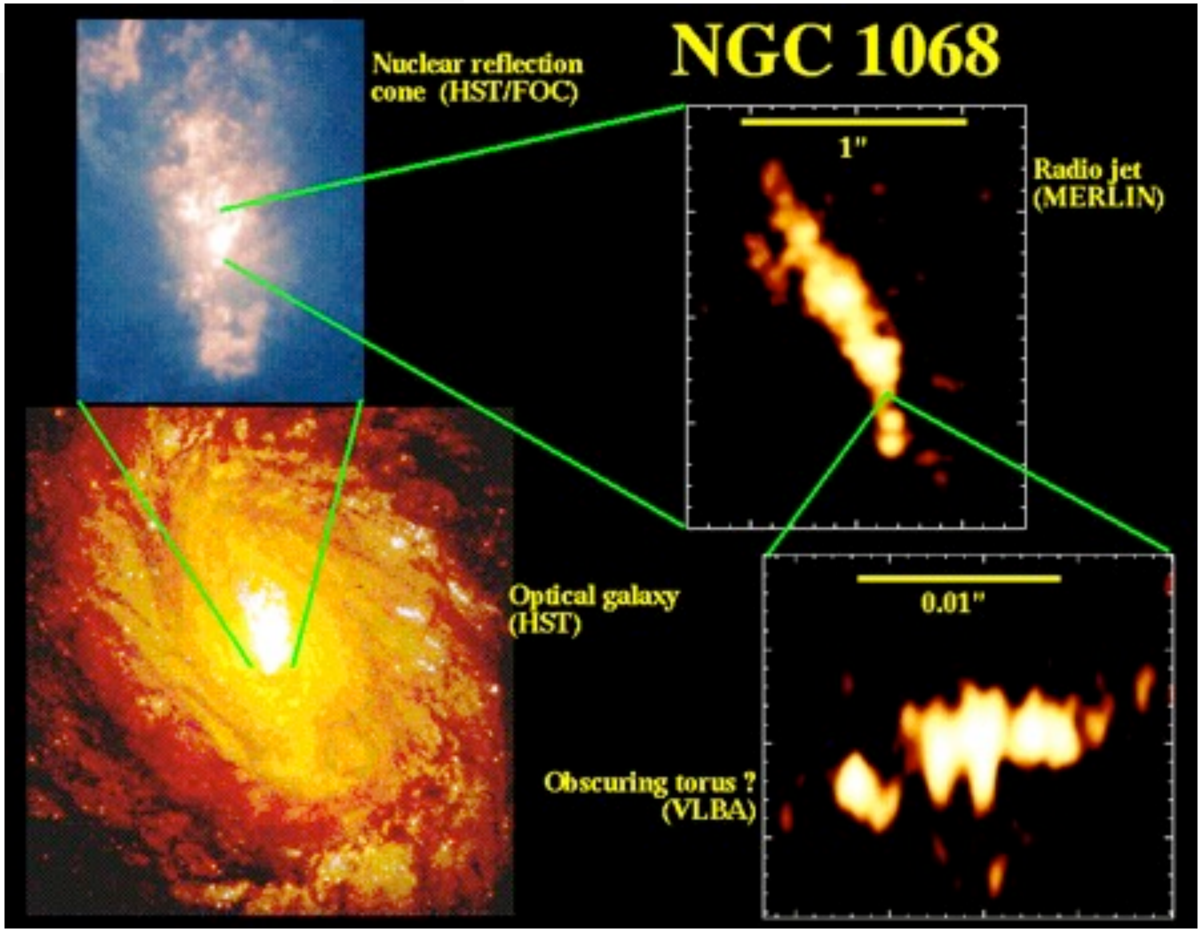
ENSURES ELLIPTICALS ARE SUFFICIENTLY “RED & DEAD”?



But Does Quasar Mode Feedback Exist?

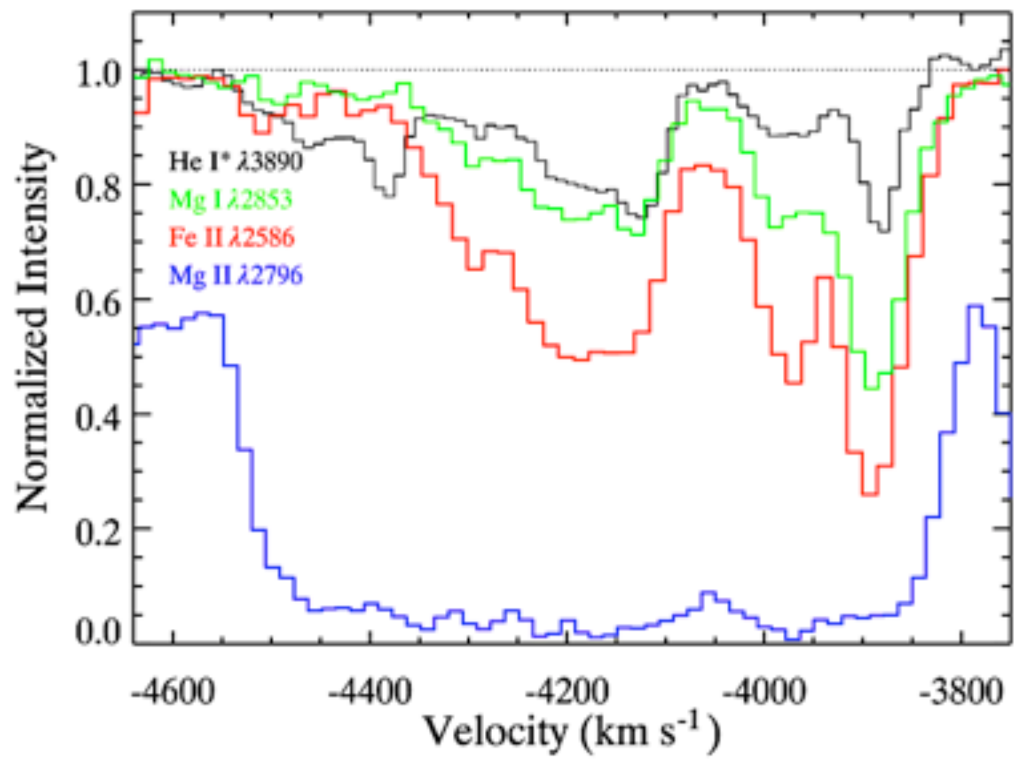

Optical (Stars)
OIII Ionization Cone

NGC 5728


NGC 1068
Nuclear reflection cone (HST/FOC)
1"
Radio jet (MERLIN)
Optical galaxy (HST)
0.01"
Obscuring torus ? (VLBA)

Broad Absorption Line Quasars

- Preferentially in high-L quasars
- Covering factor ~20%



- ~12 (16) objects now,
  10/12 confirmed:

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

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

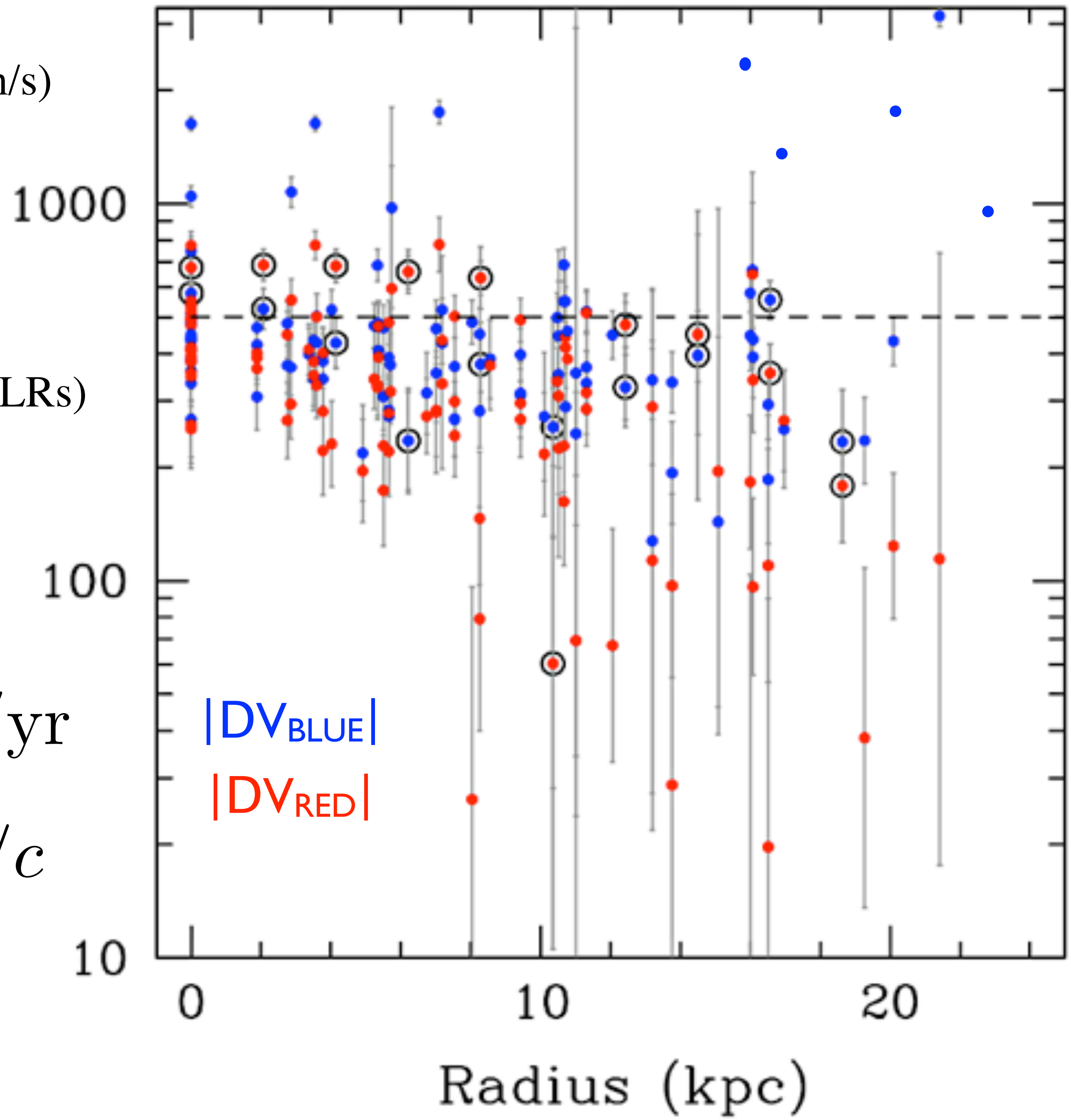
Arav et al.
Wampler et al. 1995
Hamann et al. 2001
de Kool et al. 2001&2
Korista et al. 2008
Moe et al. 2009
Dunn et al. 2010
Aoki et al. 2011
Kaastra et al. 2011

“Broad wings in Narrow Lines” in Type-2 (Narrow-Line) *Quasars*

Laor et al., Crenshaw et al.
(lower-luminosity, v ~ 100-400 km/s)

Humphrey et al. 2010
Green & Zakamska et al. 2011

Shen et al. 2011 (Double-Peaked NLRs)



$$\dot{M} \sim 50 - 1000\, M_{\odot}/\mathrm{yr}$$

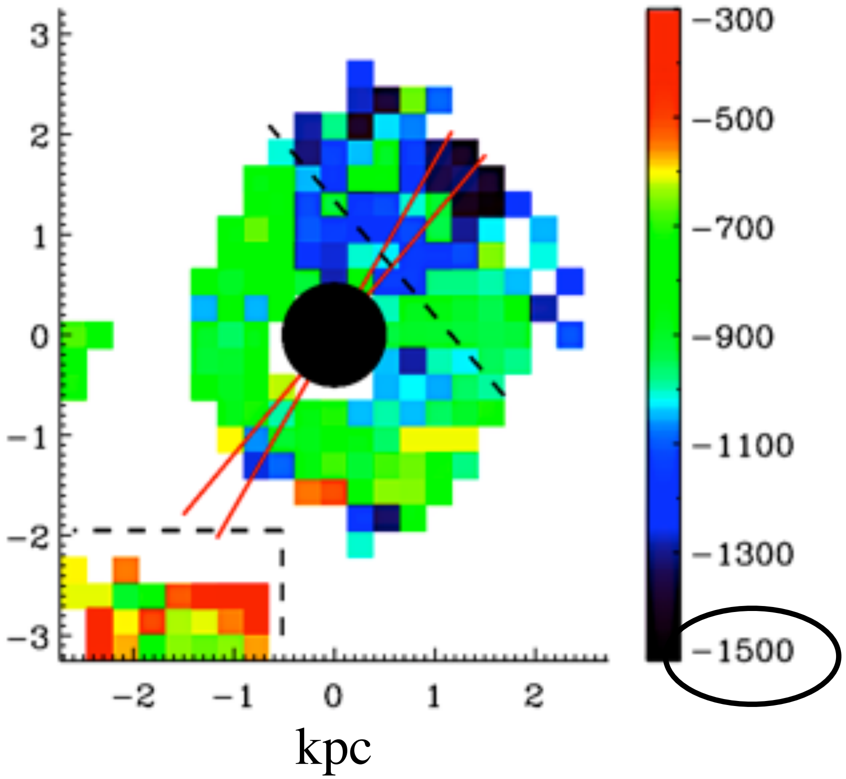
$$\dot{M}\, v \sim 1 - 30\, L_{\mathrm{AGN}}/c$$

$$L_{\mathrm{wind}} \sim 0.01\, L_{\mathrm{AGN}}$$

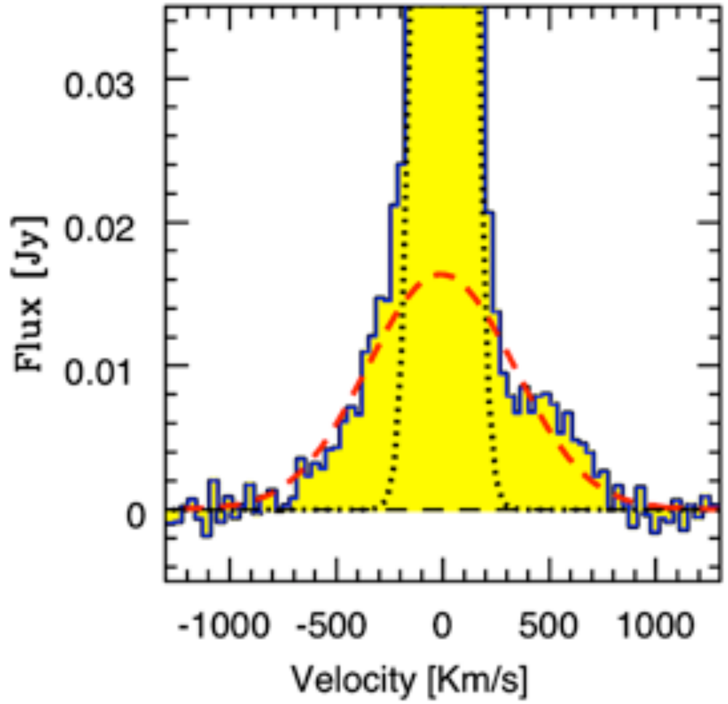
Molecular Outflows in AGN ULIRGs

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

Molecular+Ionized Outflows:



CO:



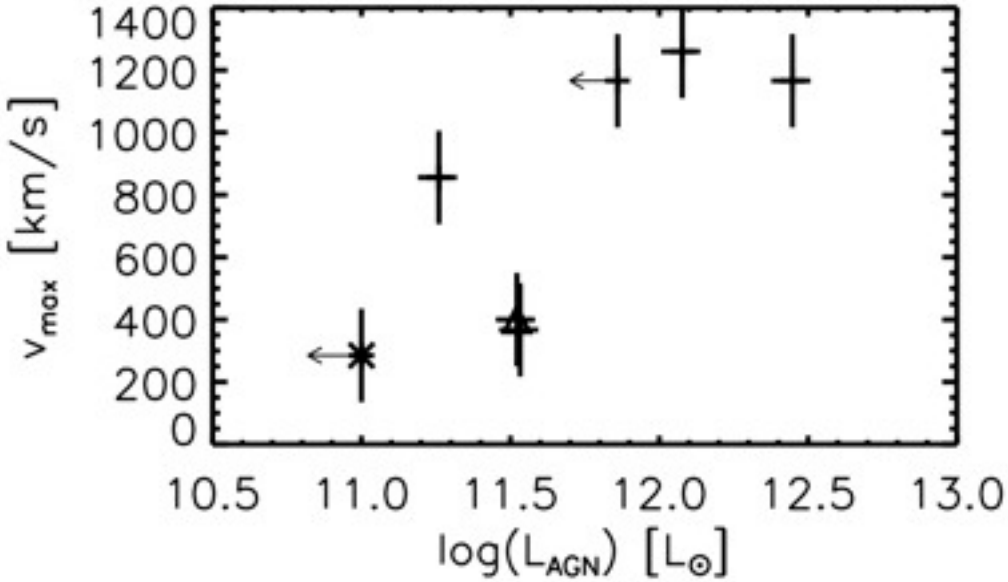
$$R_{\rm wind} \sim 1 - 4\,{\rm kpc}$$

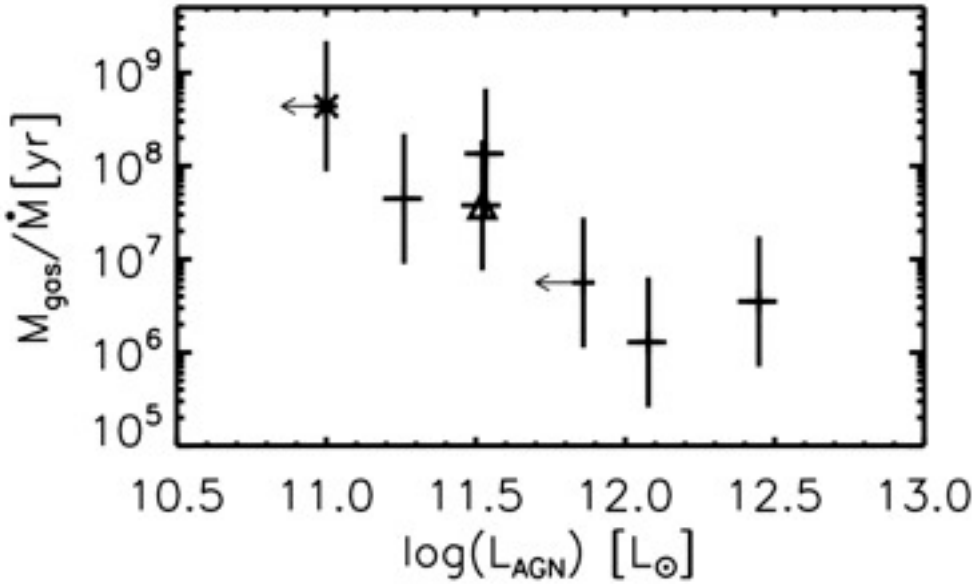
$$v > 500\,{\rm km\,s^{-1}}$$

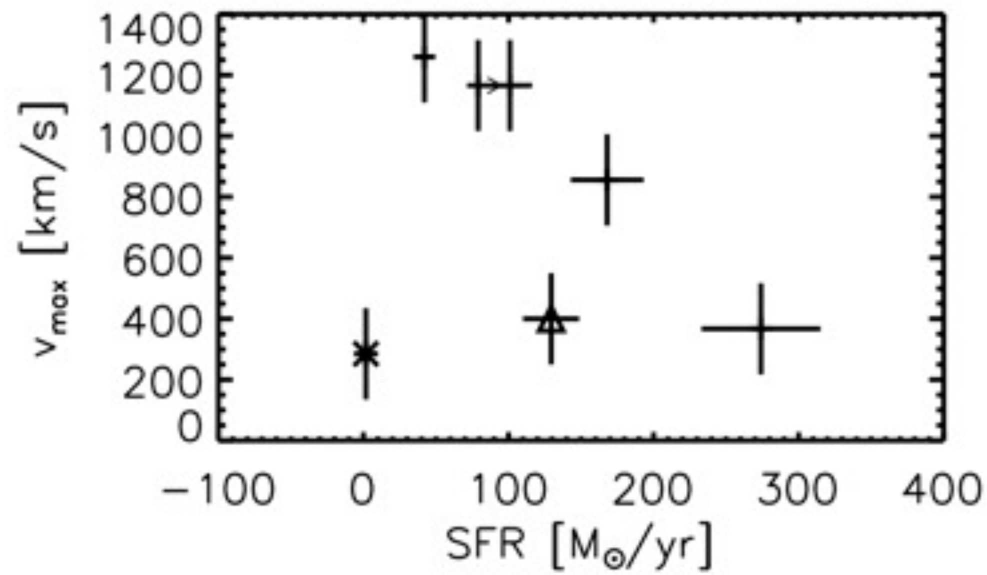
$$\dot{M}_{\rm wind} \gtrsim 1000\,M_\odot\,{\rm yr}^{-1}$$

Molecular Outflows in AGN ULIRGs

Sturm et al. 2011:







$$\dot{M} \sim 100 - 1000 \, M_\odot/\mathrm{yr}$$

$$\dot{M} \, v \sim 5 - 30 \, L_{\rm AGN}/c$$

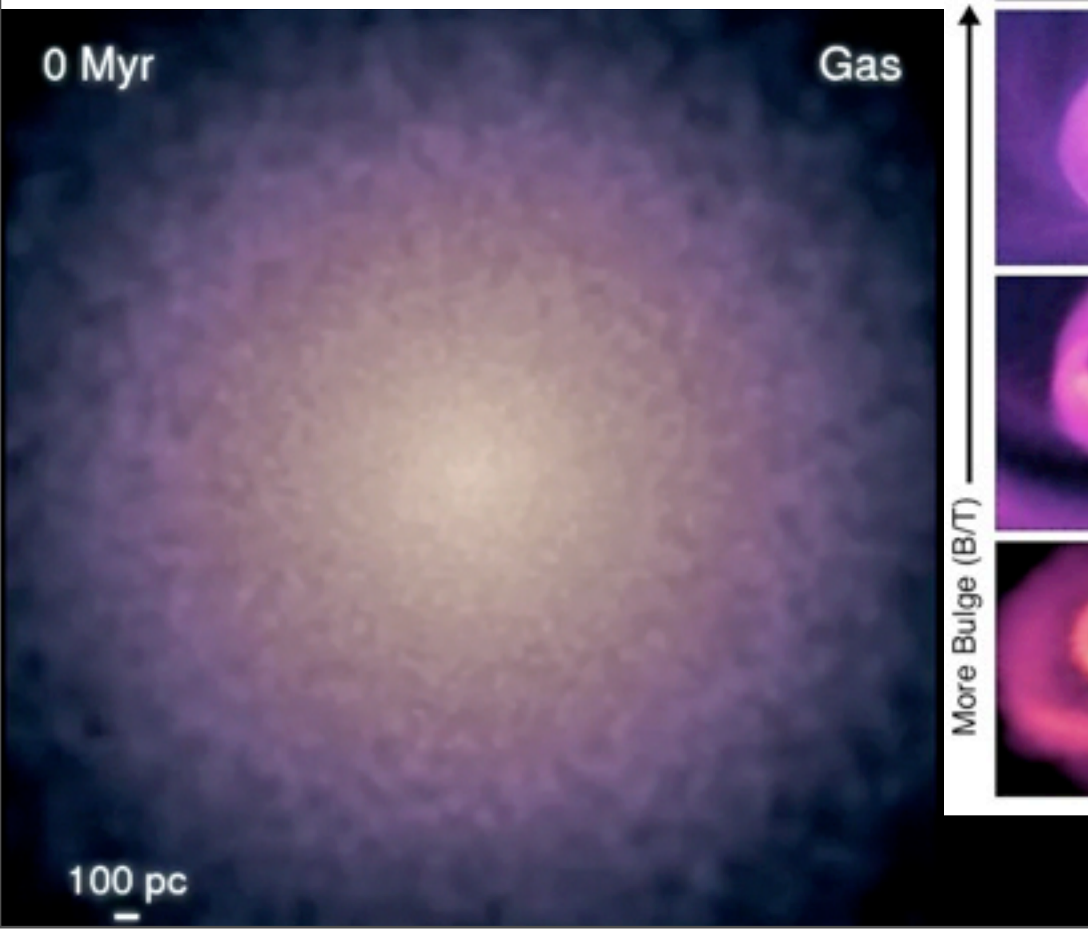
$$L_{\rm wind} \sim 0.03 - 0.10 L_{\rm AGN}$$

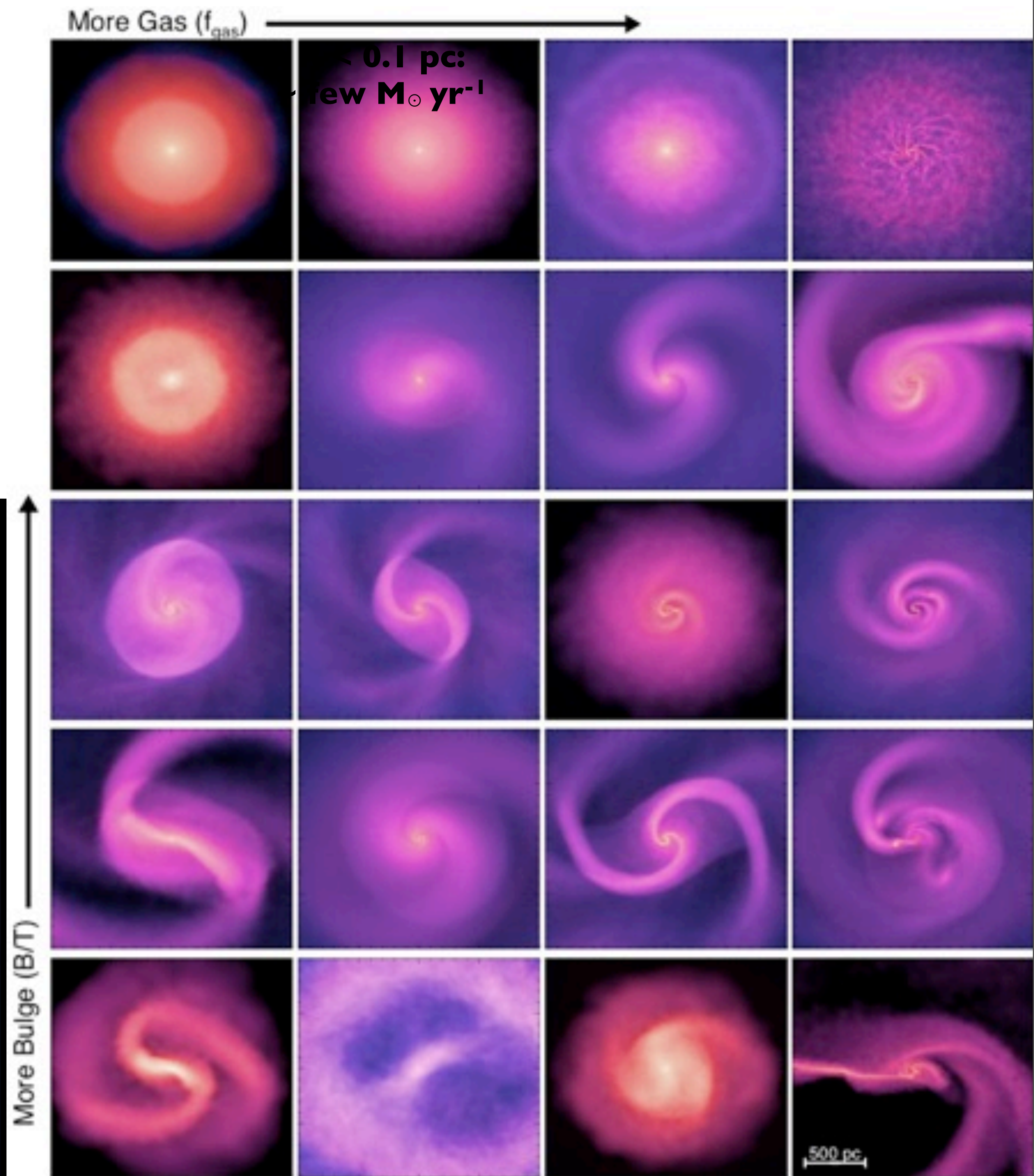
Where to now? How Do We Model This?

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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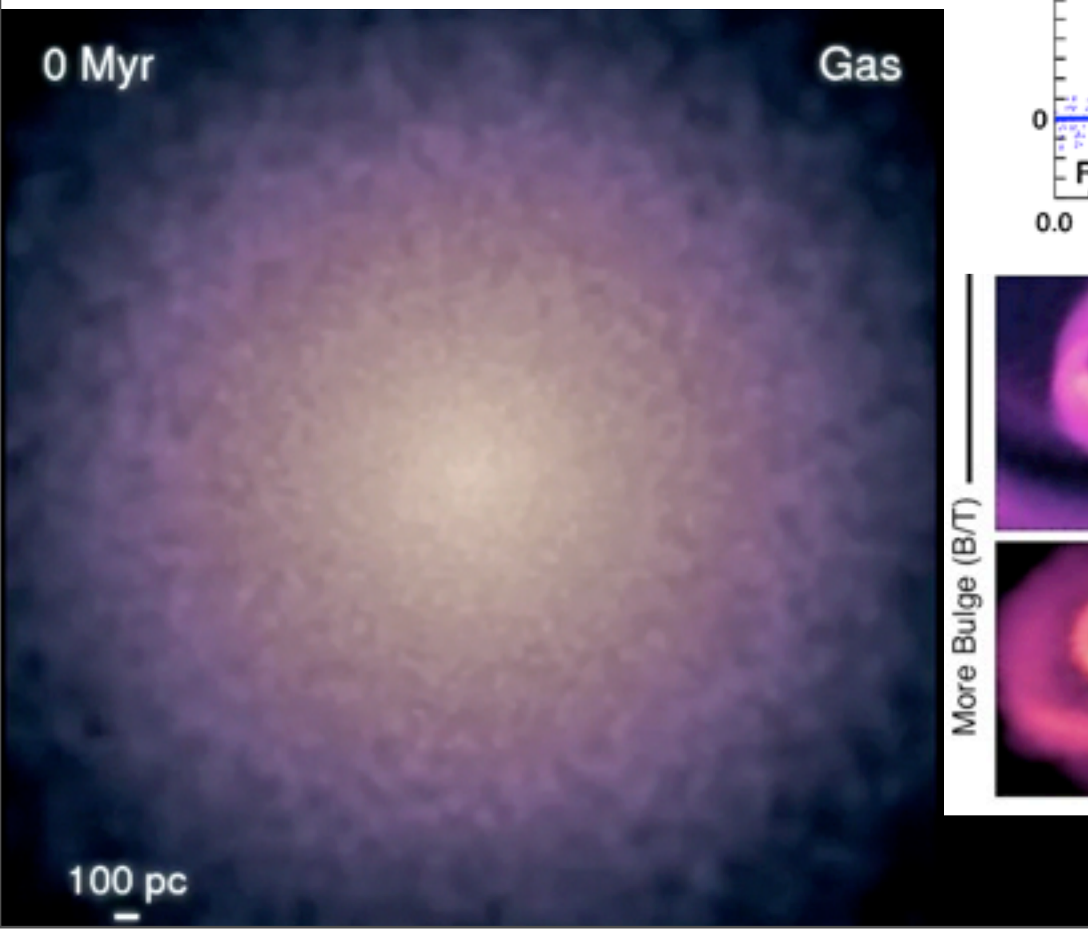
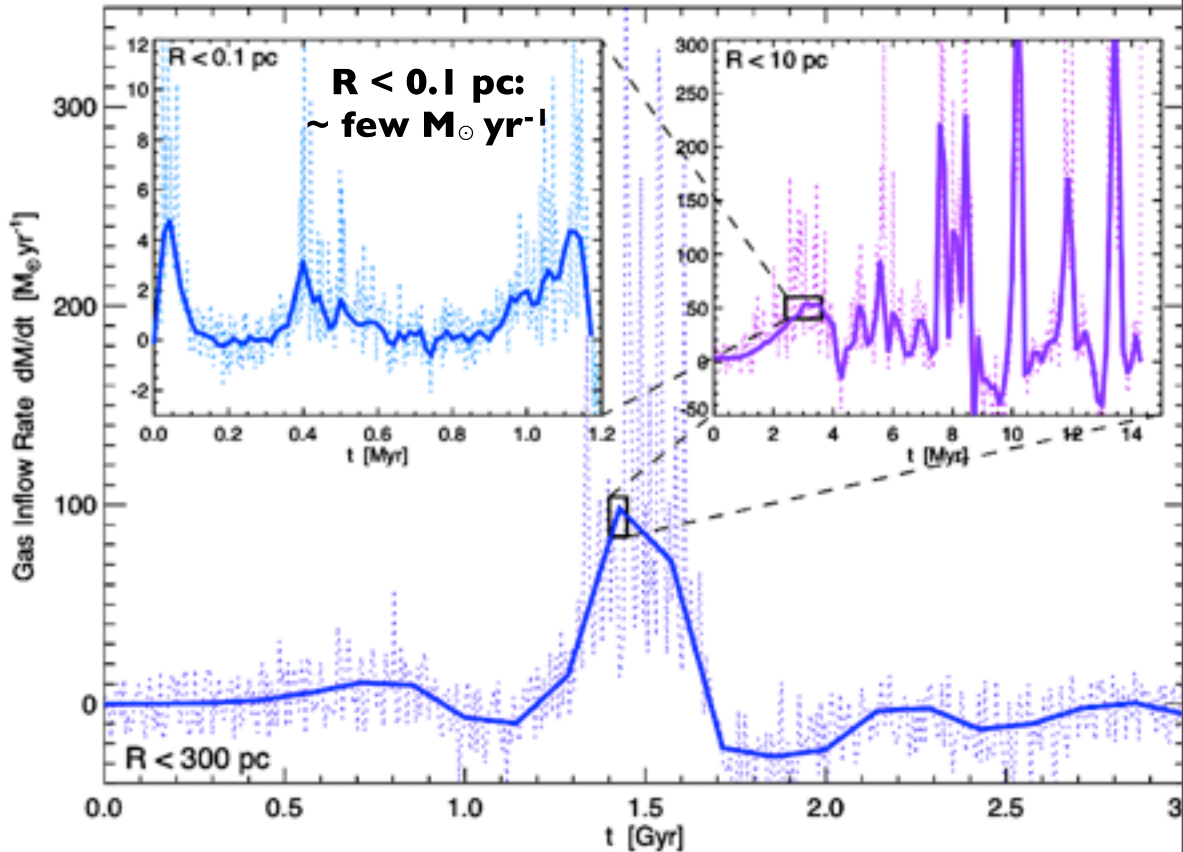
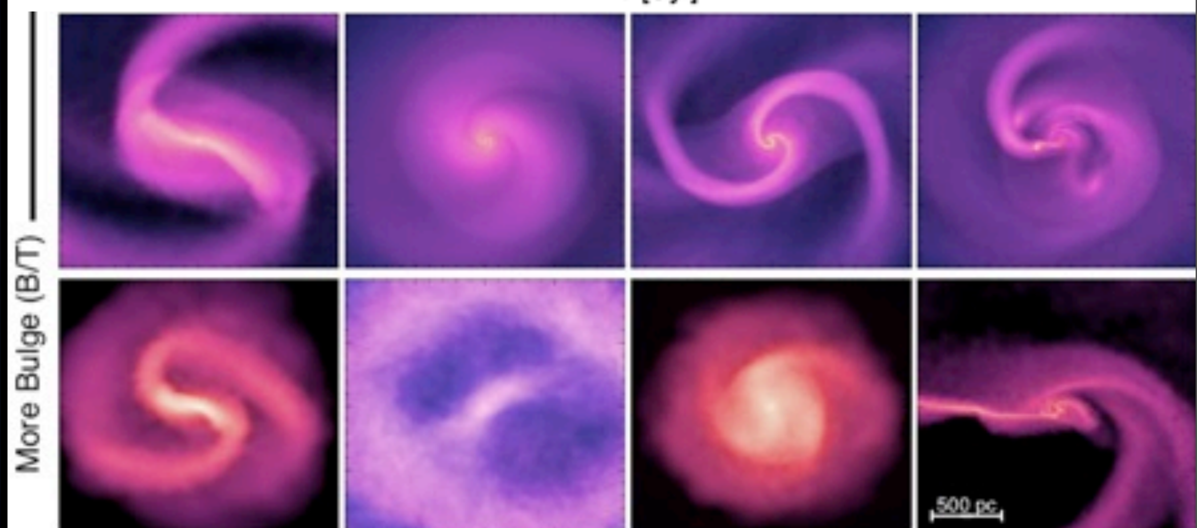






Bars w/in Bars

(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 ..."

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

Bars w/in Bars

(Shlosman et al. 1989)

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

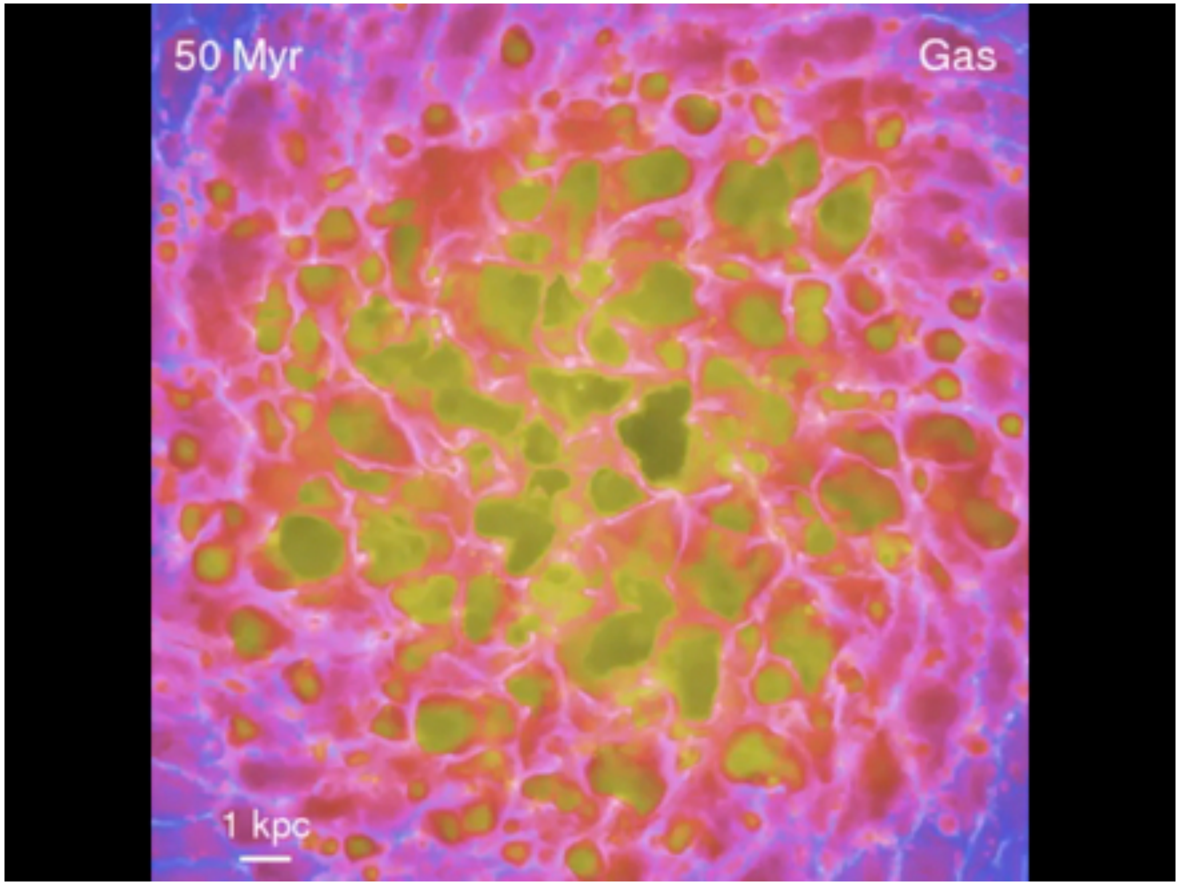
More accurately ...

"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: *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

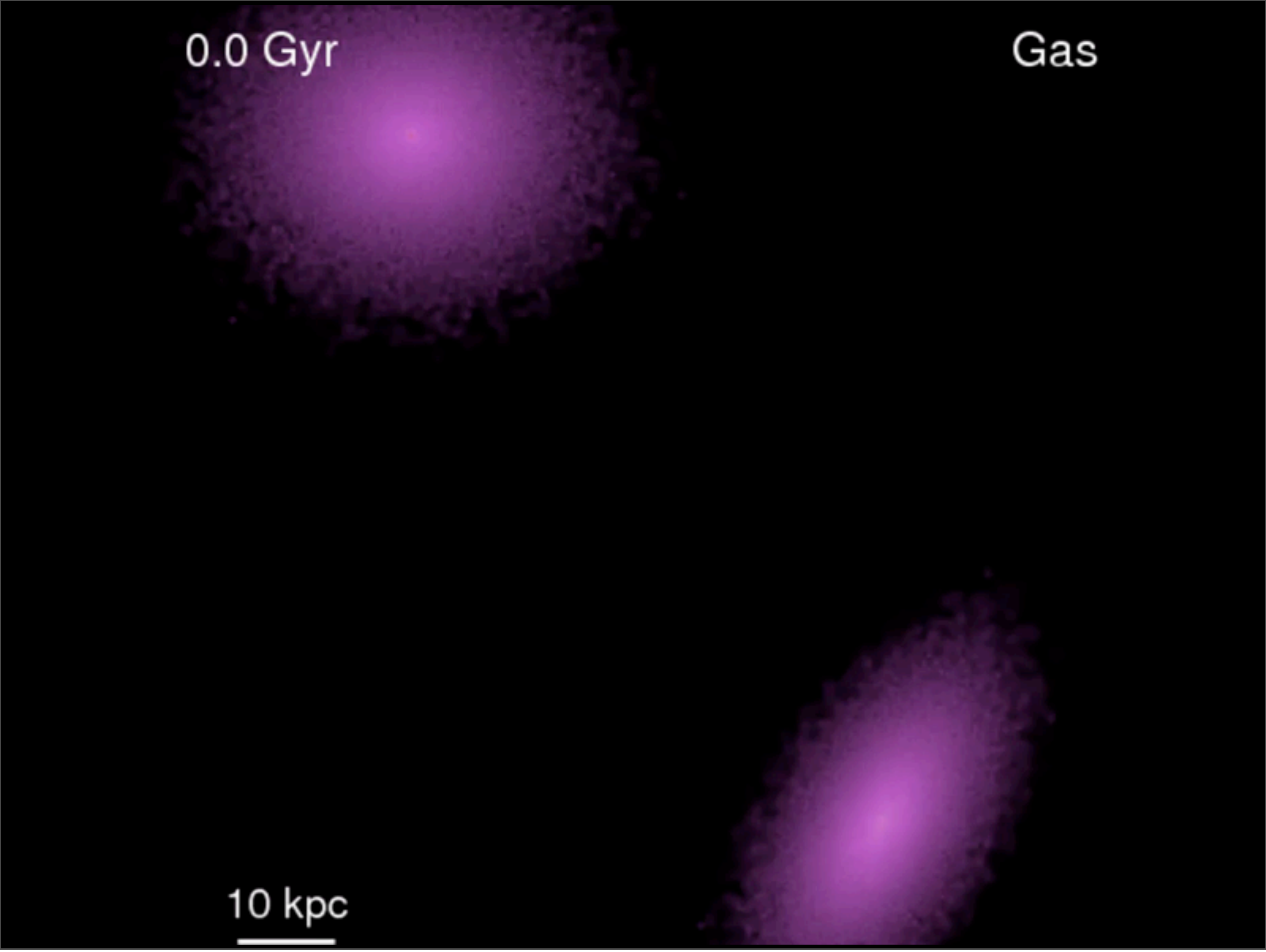
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

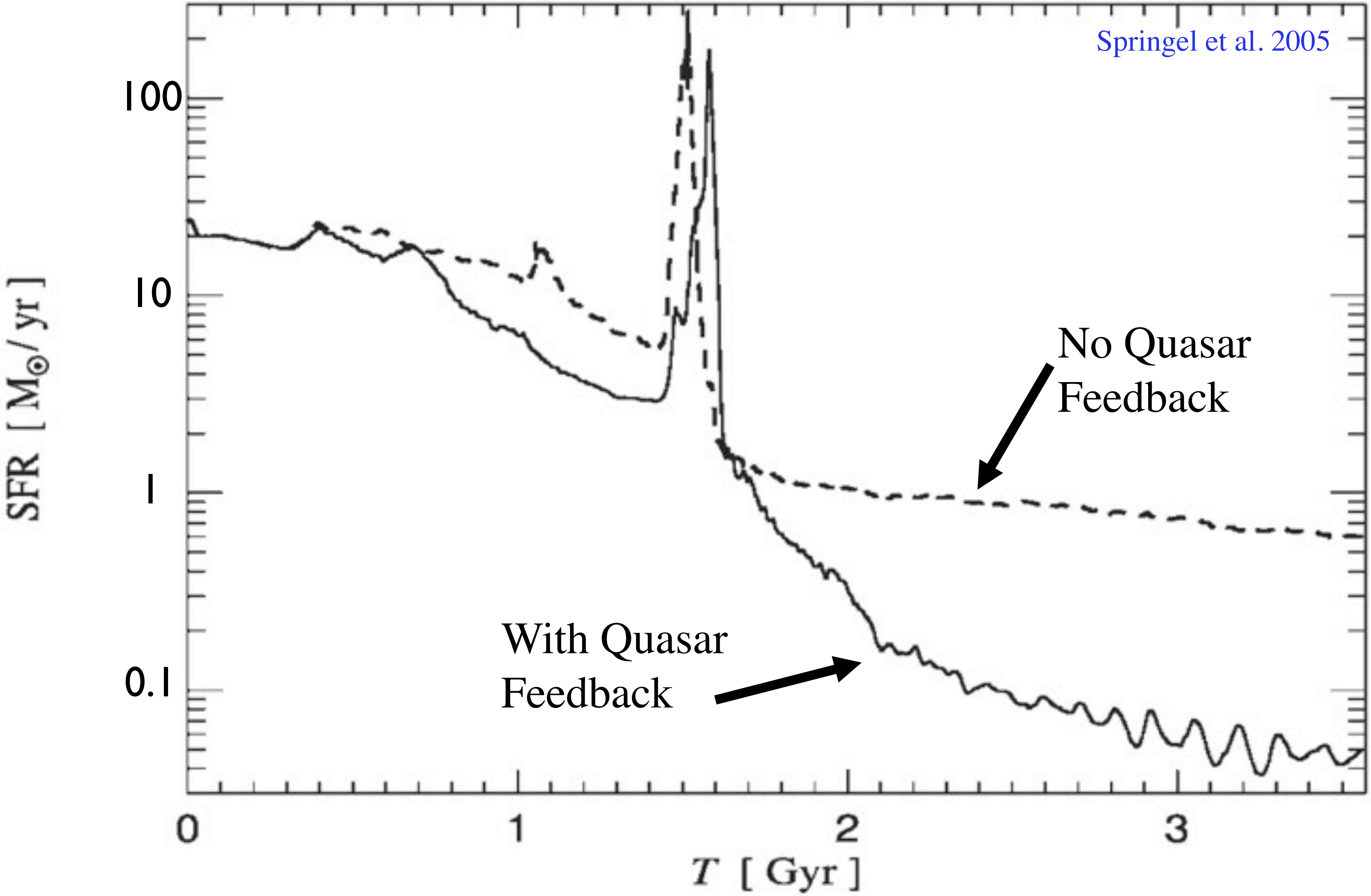
$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\,v_{\rm ejecta}^{-1}$$

  - Stellar Winds

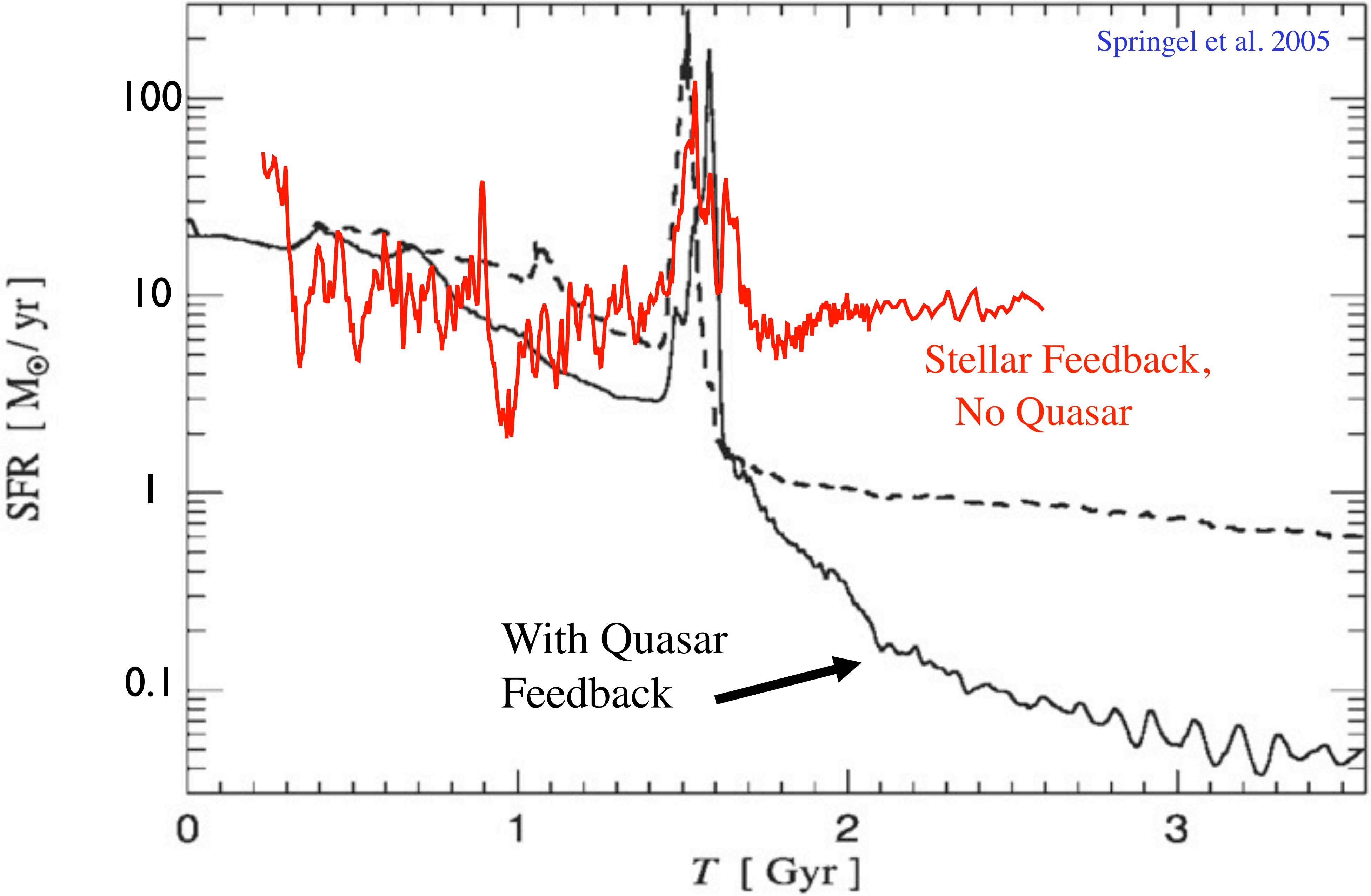
$$\dot{P}_{\rm W} \sim \dot{M}\,v_{\rm wind}$$


0.0 Gyr
Gas
10 kpc

Do we still need 'Quasar Mode' Feedback?



Do we still need 'Quasar Mode' Feedback?



Step 3: Physical Sources of AGN Feedback

mechanical (jets & winds) & **radiative**

Jets

heat IGM/ICM (low ρ), but not dense ISM

Winds

BAL-QSO winds

equatorial

$\dot{P}$ up to ~ 5L/c (Arav+)

Photons

UV: $\dot{P}$ ~ L/c (absorbed by dust): $\kappa_{UV} \sim 10^3\ cm^2\ g^{-1} \sim 10^3$ e scatt

FIR: $\dot{P} \sim \tau L/c$ (τ ~ dust FIR optical depth ~ 10-100): $\kappa_{FIR} \sim 10$ e scatt

Compton Heating (only low density gas)

Outstanding Problem: Which Dominates?

Different physics in ISM & IGM

Step 2: Feedback

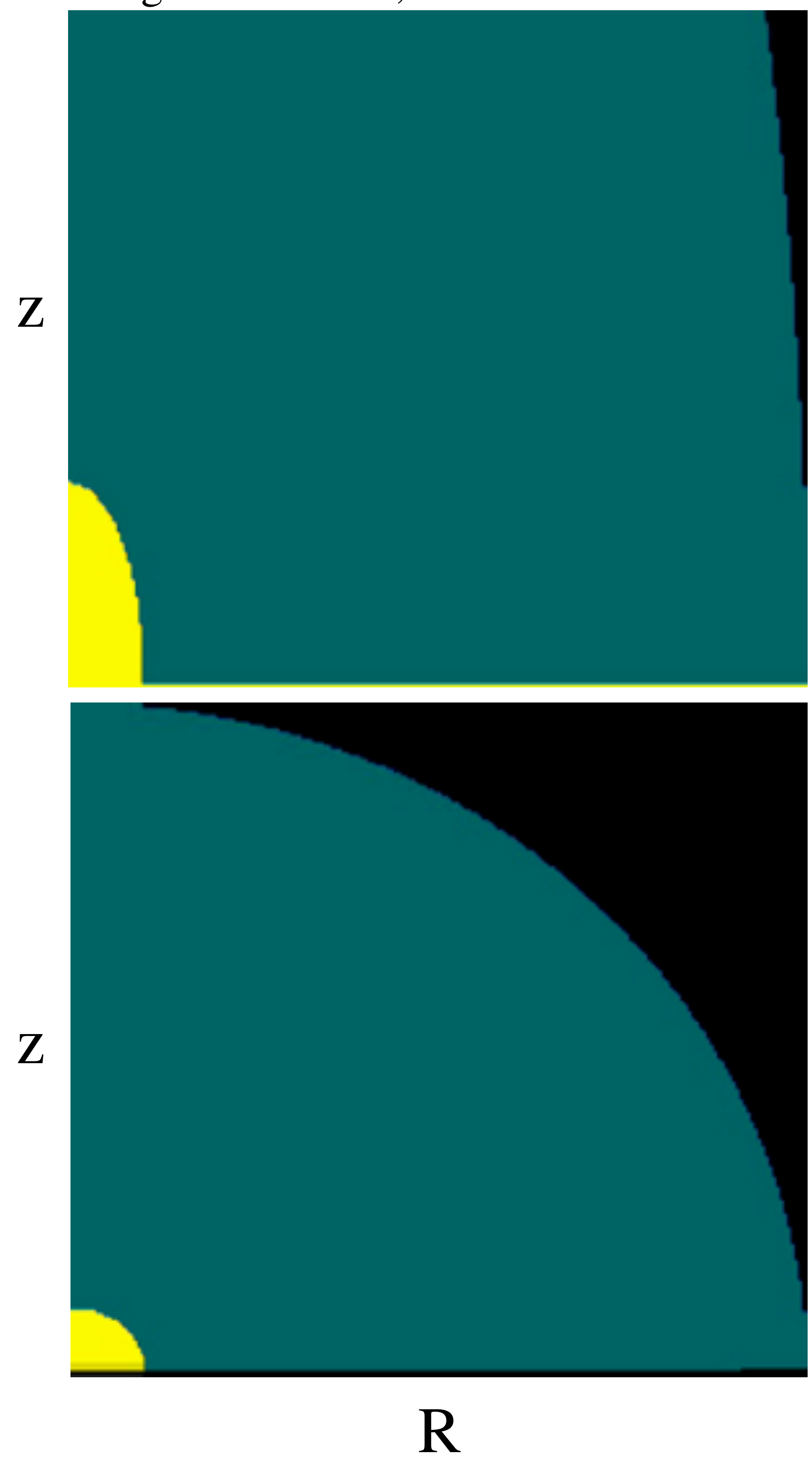
Proga et al. 00-07; Kurosawa et al. 08-11

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

- Launched at < pc

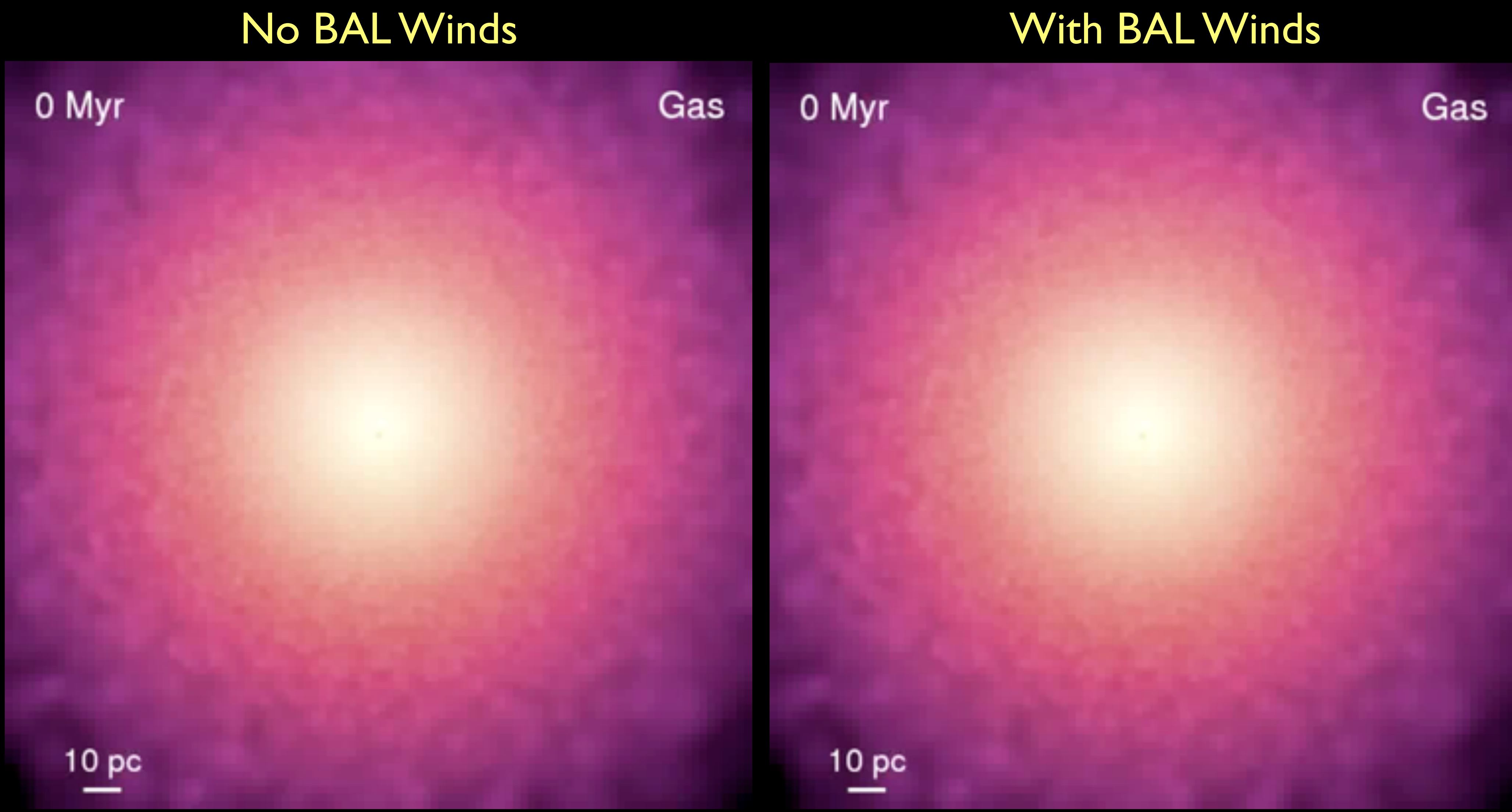
$$\dot{M}_{\rm launch} \sim \dot{M}_{\rm BH}$$

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



BAL Winds on ~1pc - 1kpc scales:

PFH in prep
Wada et al.



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

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

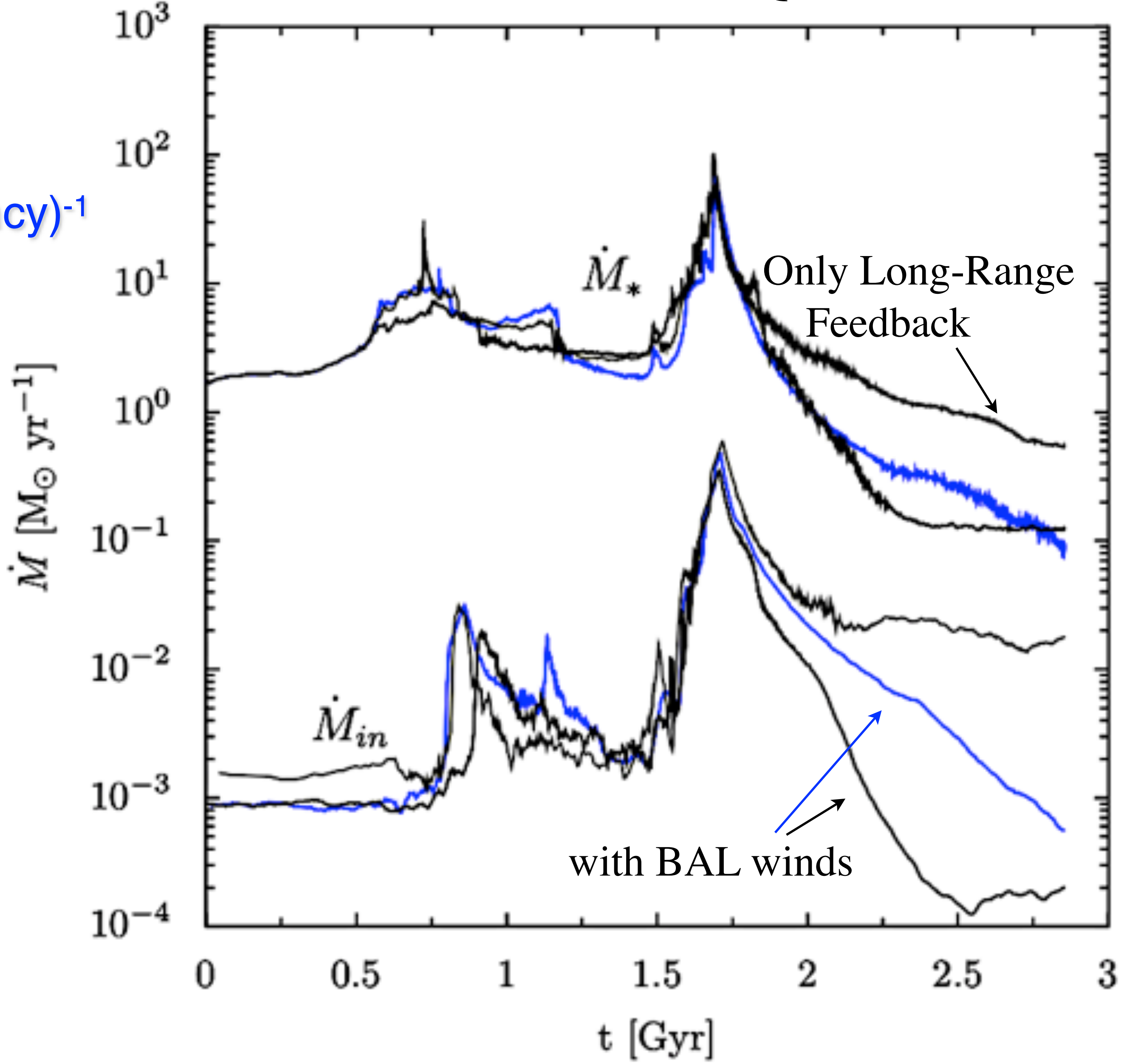
BAL Winds on Galactic Scales

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:

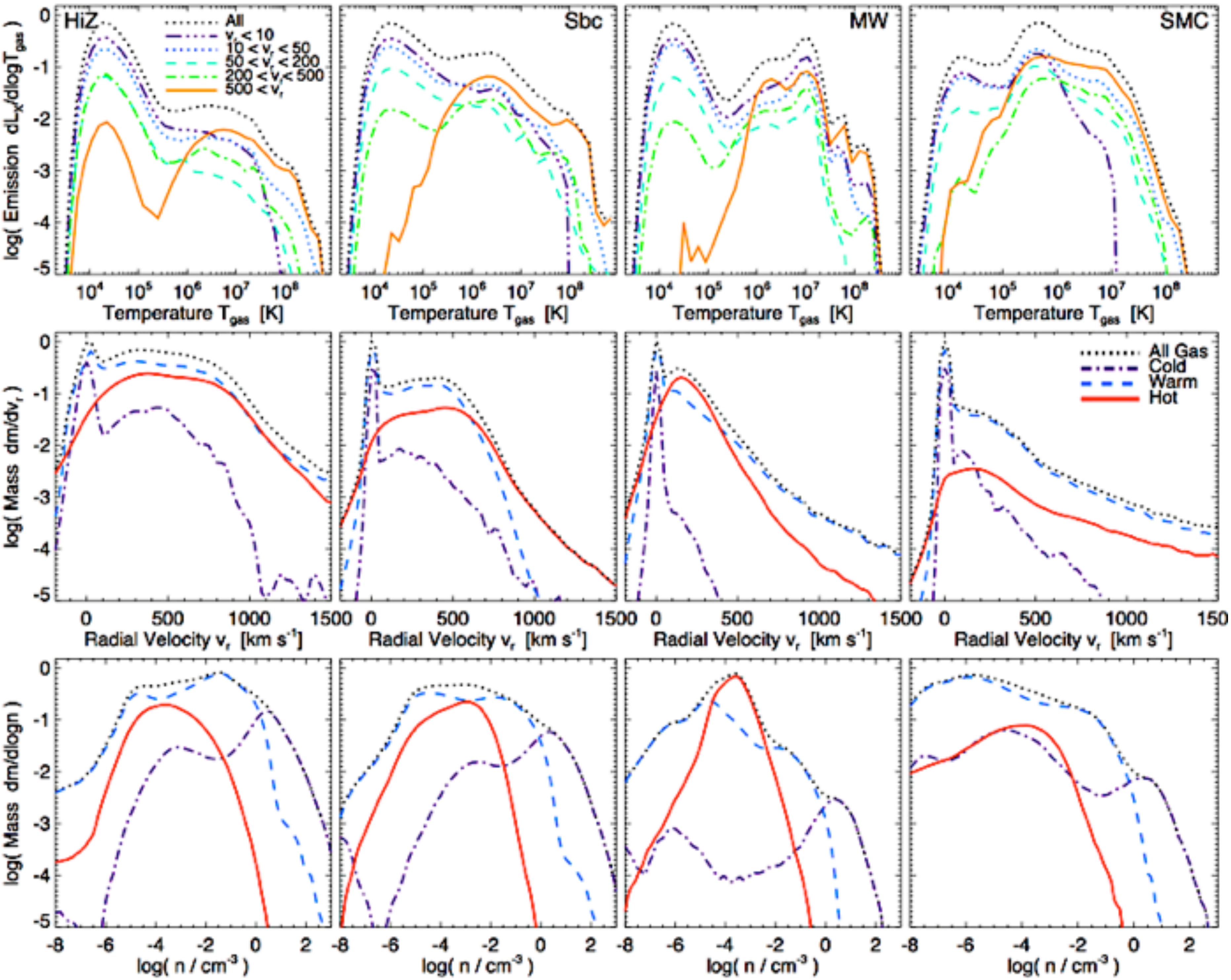
$$\dot{M}_{\rm wind} \approx 10\,\dot{M}_{*}\left(\frac{V_c}{100\,{\rm km\,s^{-1}}}\right)^{-1.1}\left(\frac{\Sigma_{\rm gas}}{10\,{\rm M_{\odot}\,pc^{-2}}}\right)^{-0.5}$$

- 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**

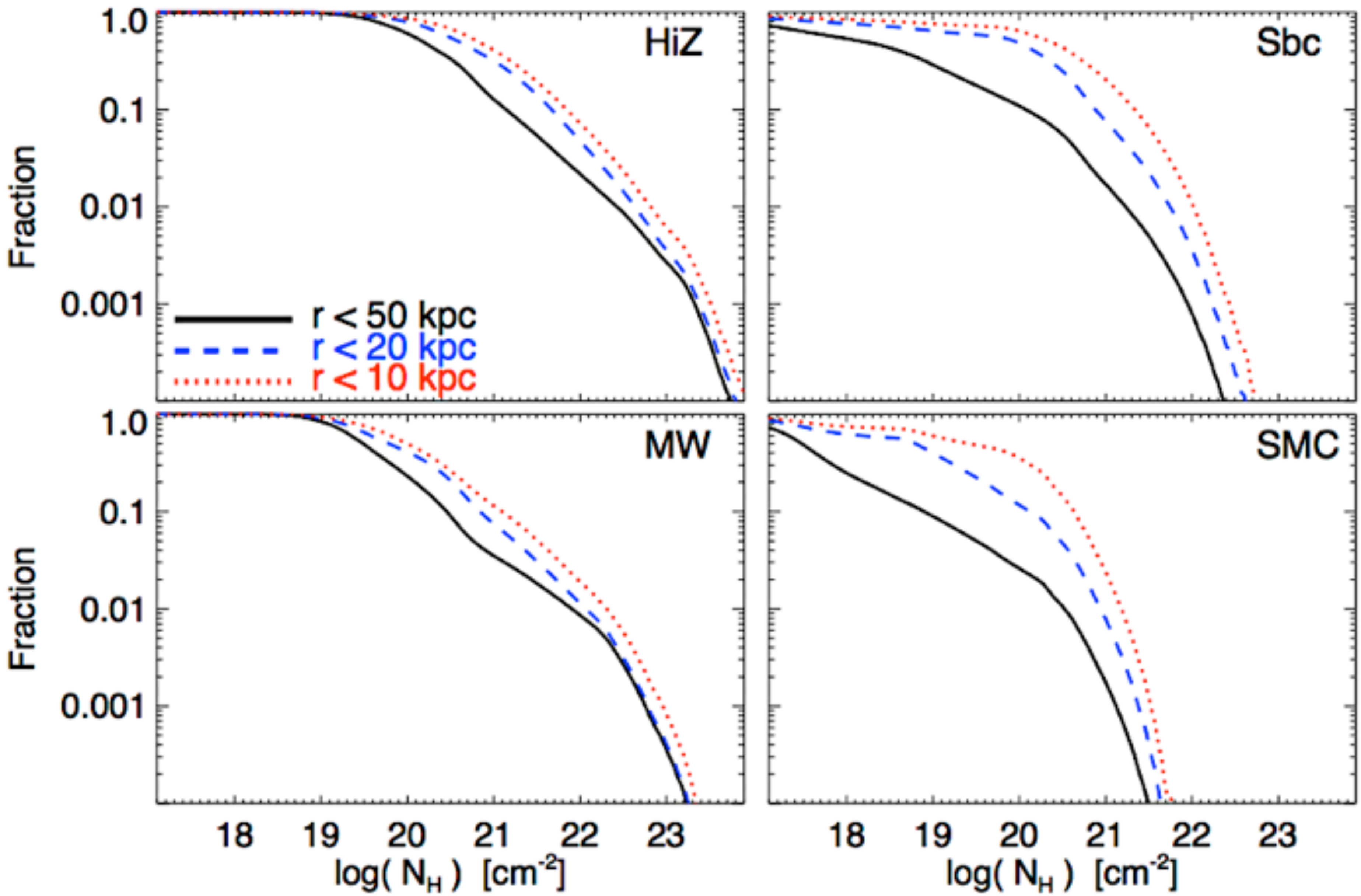
Thanks!

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

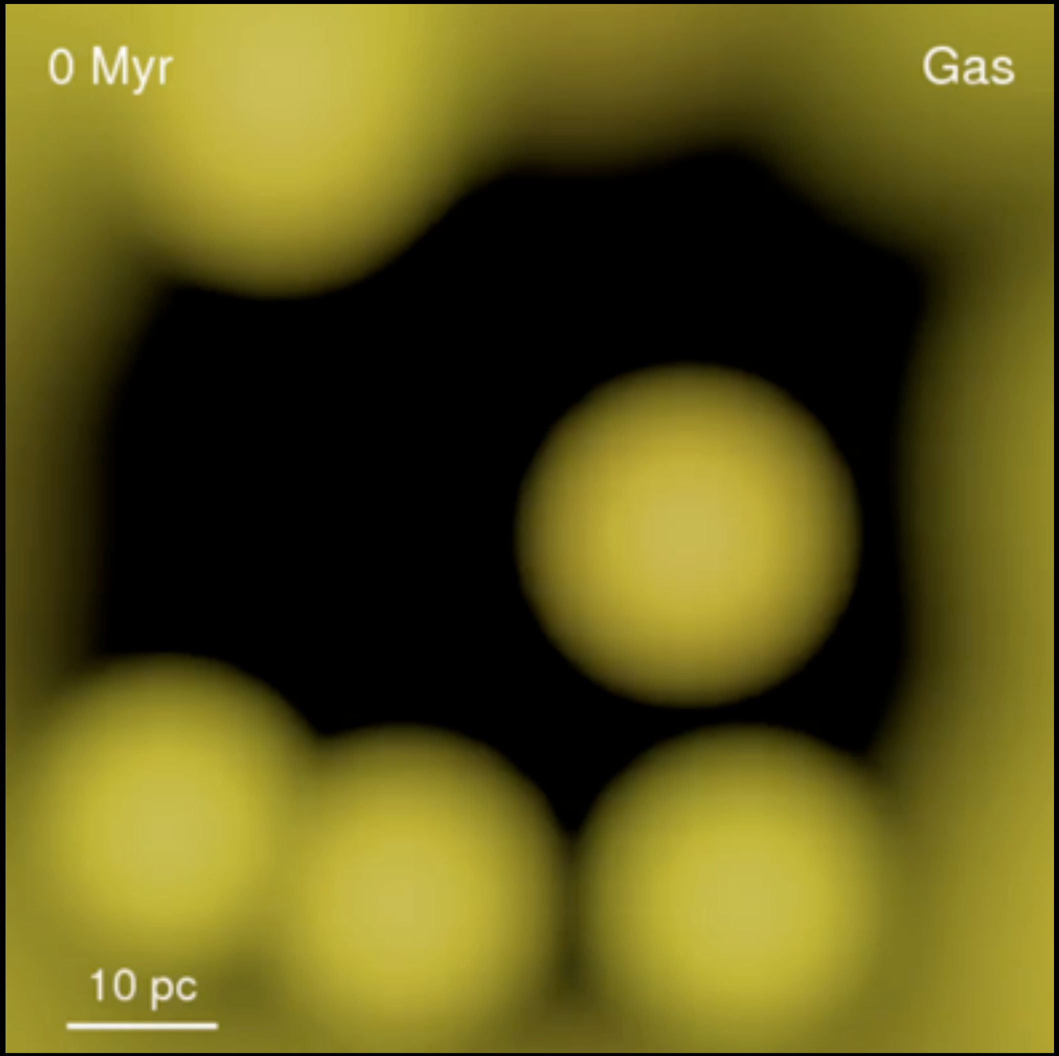
$$\dot{M}_{\rm BH} \propto f({\rm B/T})\,M_{\rm gas}(R)/t_{\rm dyn}$$

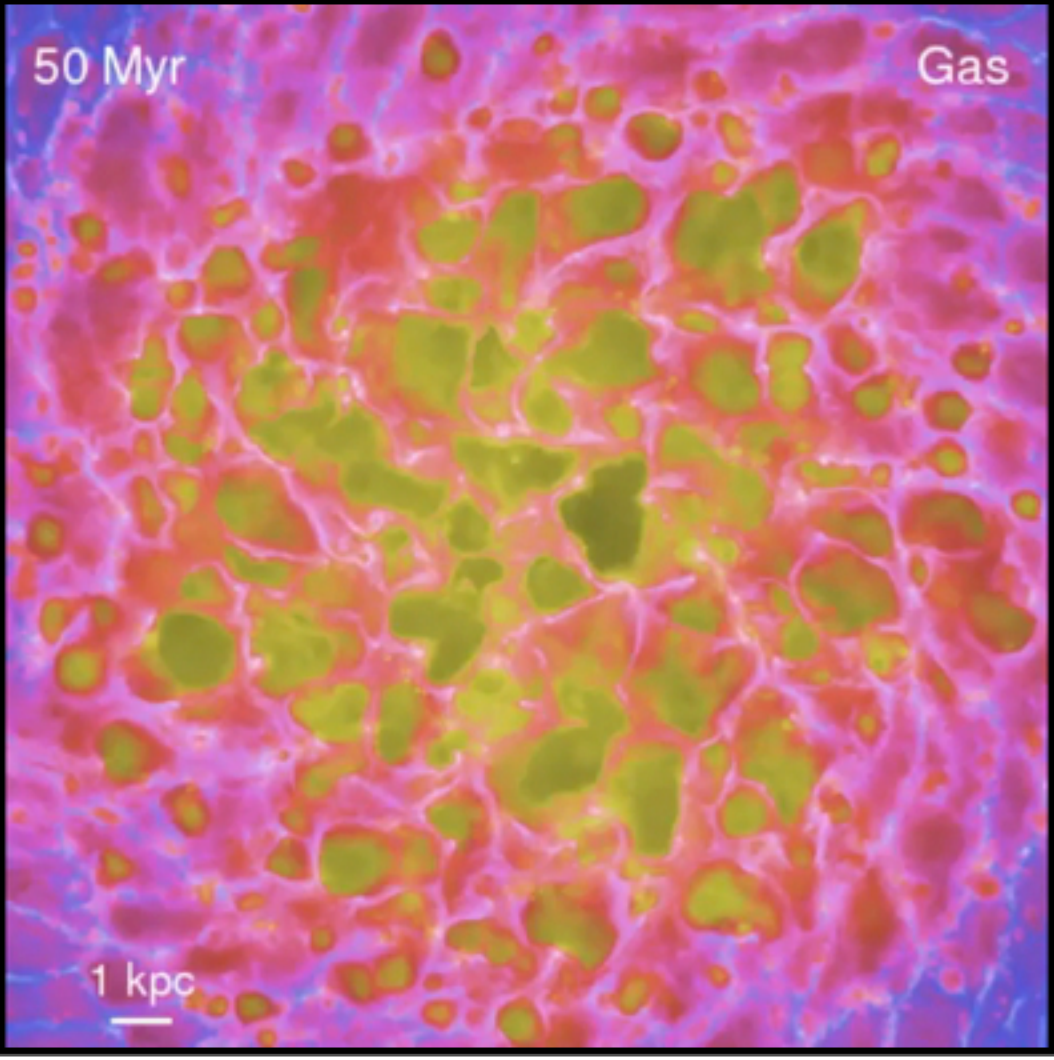


HiZ
Sbc
MW
SMC
All
$v_r < 10$
$10 < v_r < 50$
$50 < v_r < 200$
$200 < v_r < 500$
$500 < v_r$
log(Emission $dL_X/d\log T_{gas}$)
Temperature T_{gas} [K]
All Gas
Cold
Warm
Hot
log(Mass dm/dv_r)
Radial Velocity v_r [km s^{-1}]
log(Mass dm/dlogn)
log(n / cm^{-3})



HiZ
Sbc
MW
SMC
Fraction
1.0
0.1
0.01
0.001
r < 50 kpc
r < 20 kpc
r < 10 kpc
18
19
20
21
22
23
log(N_H) [cm^{-2}]


0 Myr
Gas
10 pc


50 Myr
Gas
1 kpc