Feedback in Galaxy Formation

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Important Questions

- *Do baryons follow dark matter into halos?*
- *If so, how do they get out again?*
- *While they are there, why do they take so long to turn into stars?*

Outline

- *What is meant by "feedback"*
- *Address two astronomical questions*
  - *limiting the rate of star formation*
  - *ejecting baryons*
- *How does momentum feedback work?*
- *Starburst Winds*
- *Quasar mode feedback*

Feedback: all things to all people

- *Cluster modellers: (AGN) suppressing cooling flows*
- *Galaxy modellers: (AGN) quenching in massive galaxy halos*
- *Galaxy modellers: setting the black hole mass---galactic velocity (M-σ) relation*
- *Galaxy modellers: (stars/AGN) Removing unwanted baryons from dark matter halos*
- *Extra-galactic observers: (stars/SN) driving outflows (blue shifted absorption lines)*
- *Star formation: (protostellar jets, SN, HII, radiation) limiting the rate of star formation (Kennicutt)*
- *ISM: (SN, radiation) generating turbulence*

Feedback from a physicist's point of view

- *Energy: deposit energy into the ISM, heating it.*
  - *the resulting overpressure can push the surrounding ISM around, resulting in turbulence, or ejection of hot gas*
  - *sources: HII regions, stellar winds, SN, cosmic rays, AGN winds (BALs, Narrow line outflows), AGN radiative heating(X-rays), and AGN jets*
  - *Subject to radiative losses---not relevant in MW, but in ULIRGs and SMGs this is a major problem*
- *Momentum: deposit momentum into the ISM, pushing it around*
  - *sources: HII regions, radiation pressure, BAL winds, cosmic rays*
  - *not subject to radiative cooling*

Limiting the rate of star formation: How to halt GMC collapse?

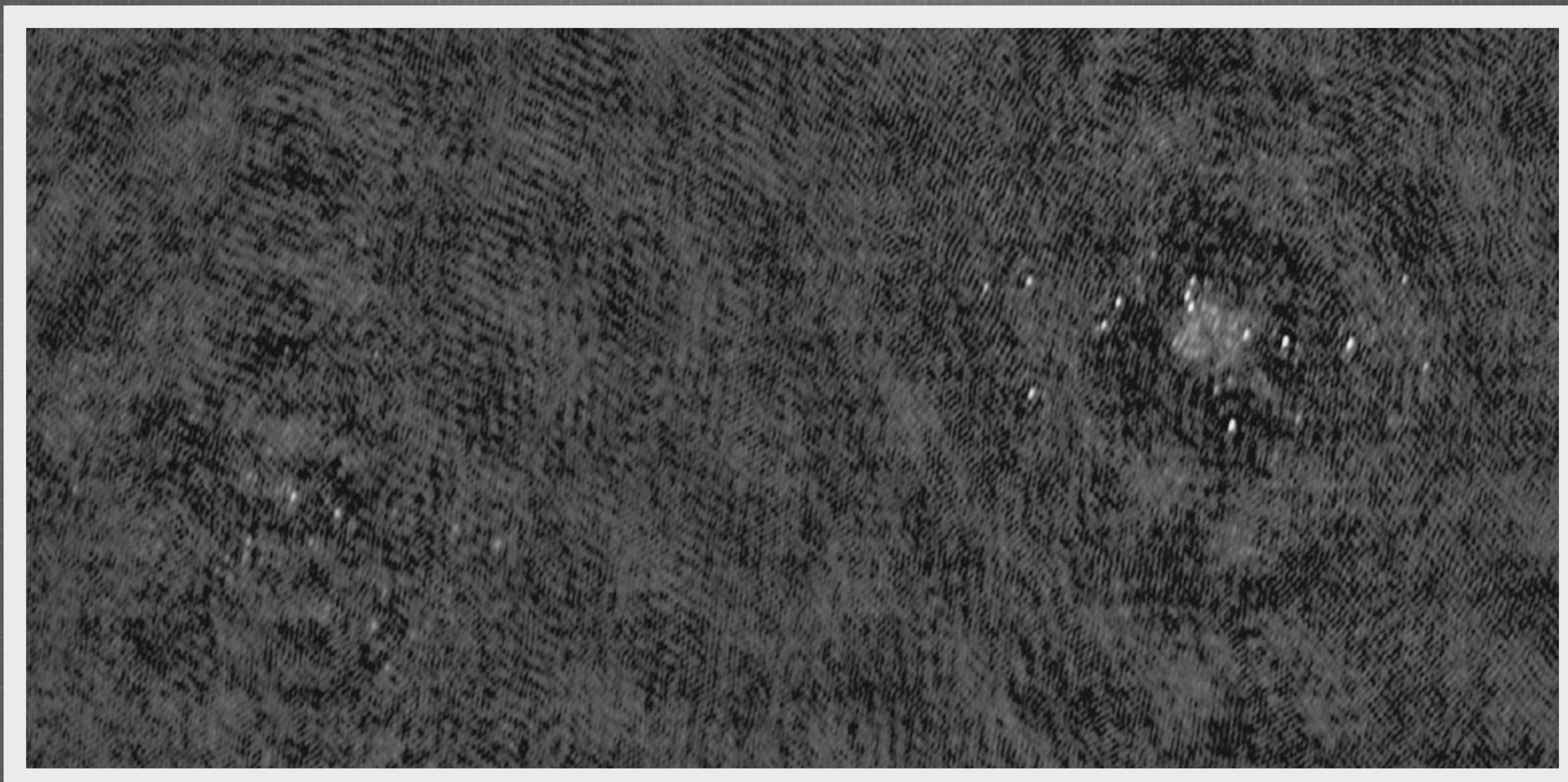
- *Magnetic pressure*
- *cosmic ray pressure*
- *thermal gas pressure*
    - *Stellar winds*
    - *HII gas*
    - *SN*
- *Radiation pressure*
- *turbulent pressure*

So many pressures, so little time

- *Extreme cases are instructive*
- *Arp 220*
- $n = 2\times10^4\ cm^{-3}$;
- $P_{dyn} \approx G\Sigma^2 \approx 3\times10^{-6} erg\ cm^{-3}$
- $P_{turb} = \varrho v_T{}^2$; $v_T \approx 85 km\ s^{-1}$ $P_{turb} \approx 3\times10^{-6} erg\ cm^{-3}$
- $L = 4\times10^{45}\ erg/s$

So many pressures, so little time

- *Supernovae---we see 4/yr in Arp 220!*
- *All have r<0.4pc (consistent with pressure confinement)*
- $L_{SN} = 4x10^{51} erg / 3.15x10^{7} s \approx 10^{44} erg/s$
- $P_{hot} = P_{dyn}$; $n_h = P_{dyn}/kT$
- $L_{cool} = \Lambda\, n_h^2 V f_h \approx 10^{46} erg/s$
- *Conclusion: SN cannot stir up the ISM*



Londale ApJ 647 185;
Parra 659 314

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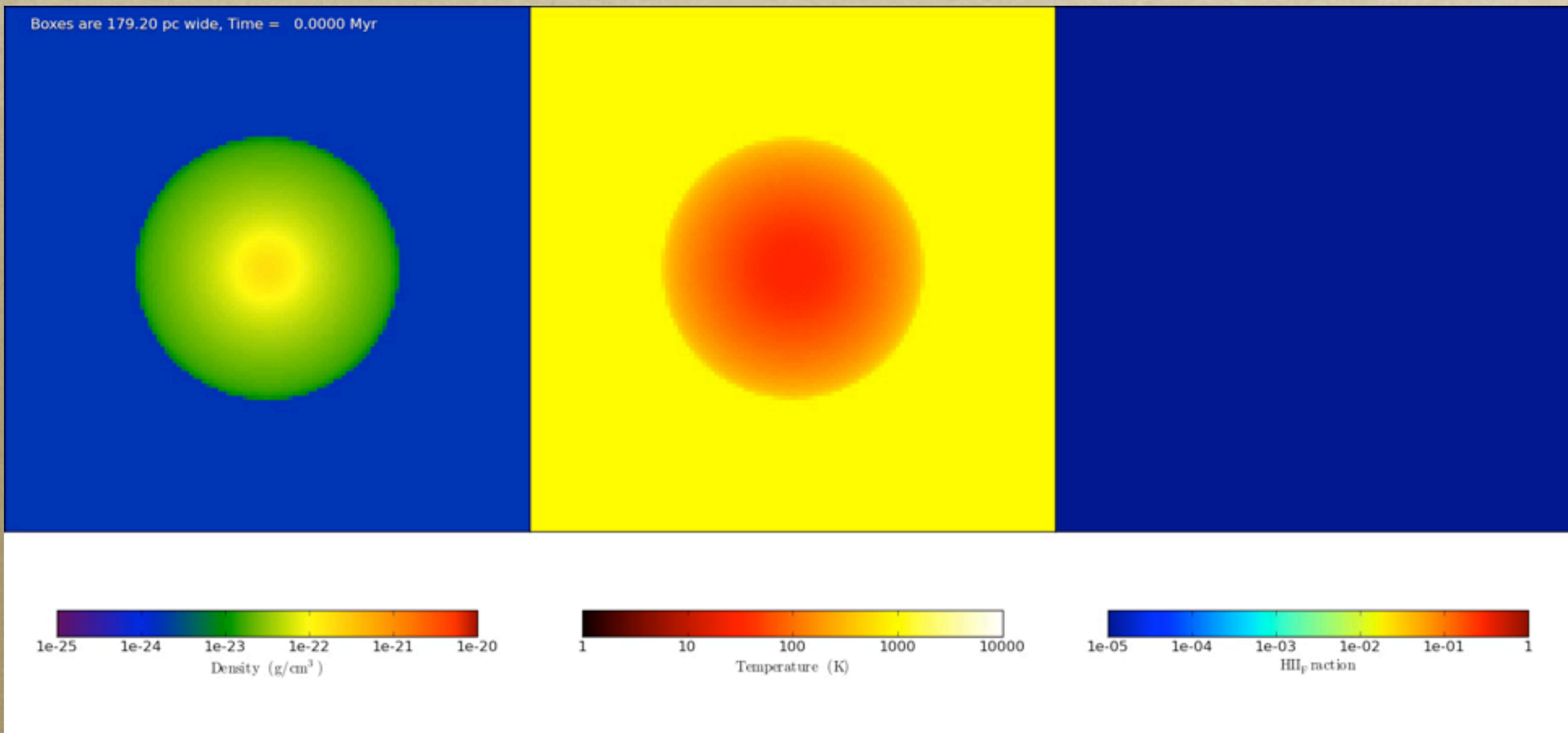
Radiative Feedback in the Milky Way

Nathan Smith/Spitzer   Carina

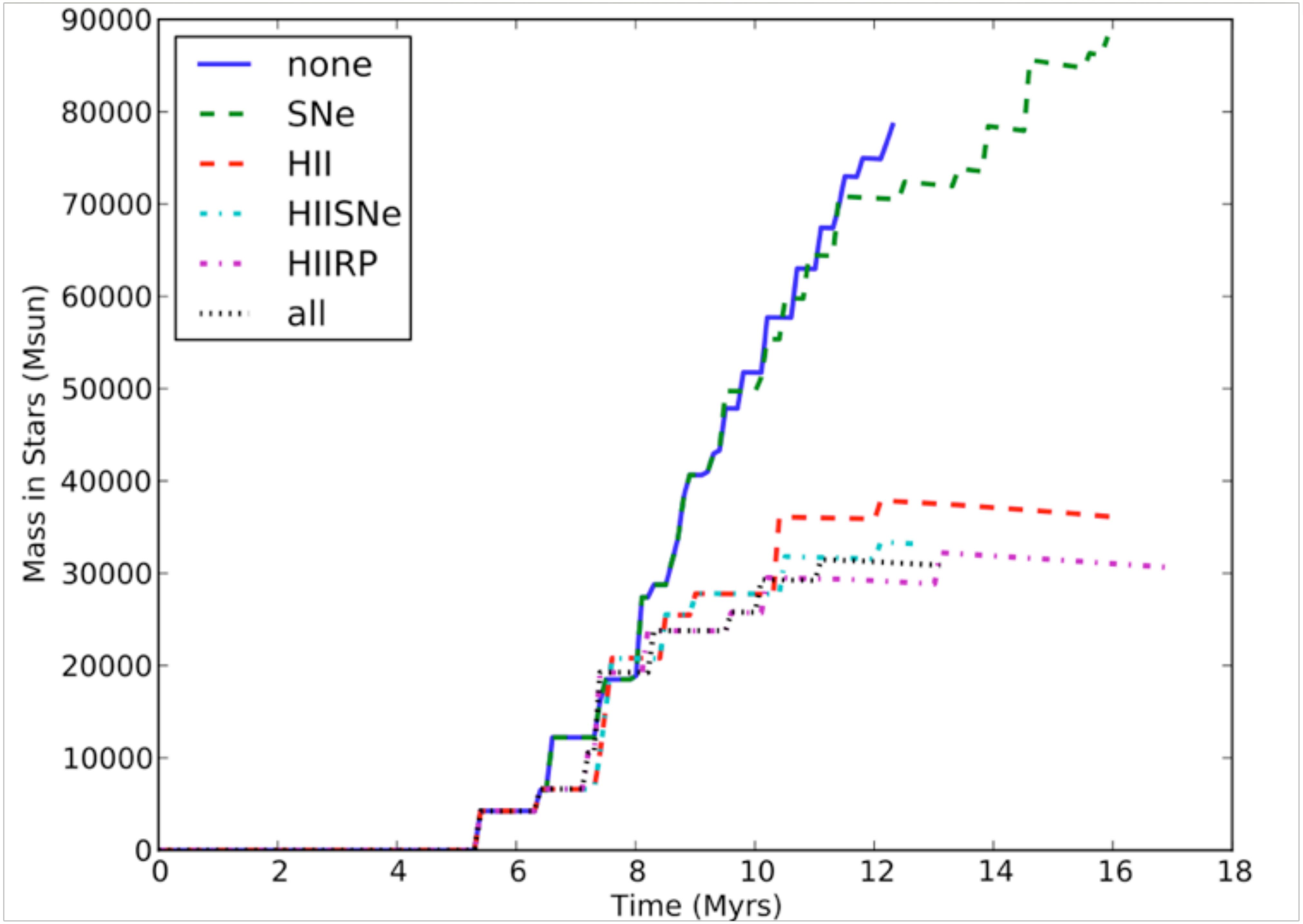
Star Formation Efficiency per GMC

- $L/c = GMM/R^2$ *(Force balance)*
- $\varepsilon_{GMC} = M_*/M = \pi Gc/(2L/M_*)\ \Sigma_{GMC}$
  $\approx \Sigma_{GMC} / (gm\ cm^{-2})$
- *Milky Way GMCs have* $\Sigma_{GMC} \approx 0.05$

Blowing up GMCs in color 3D



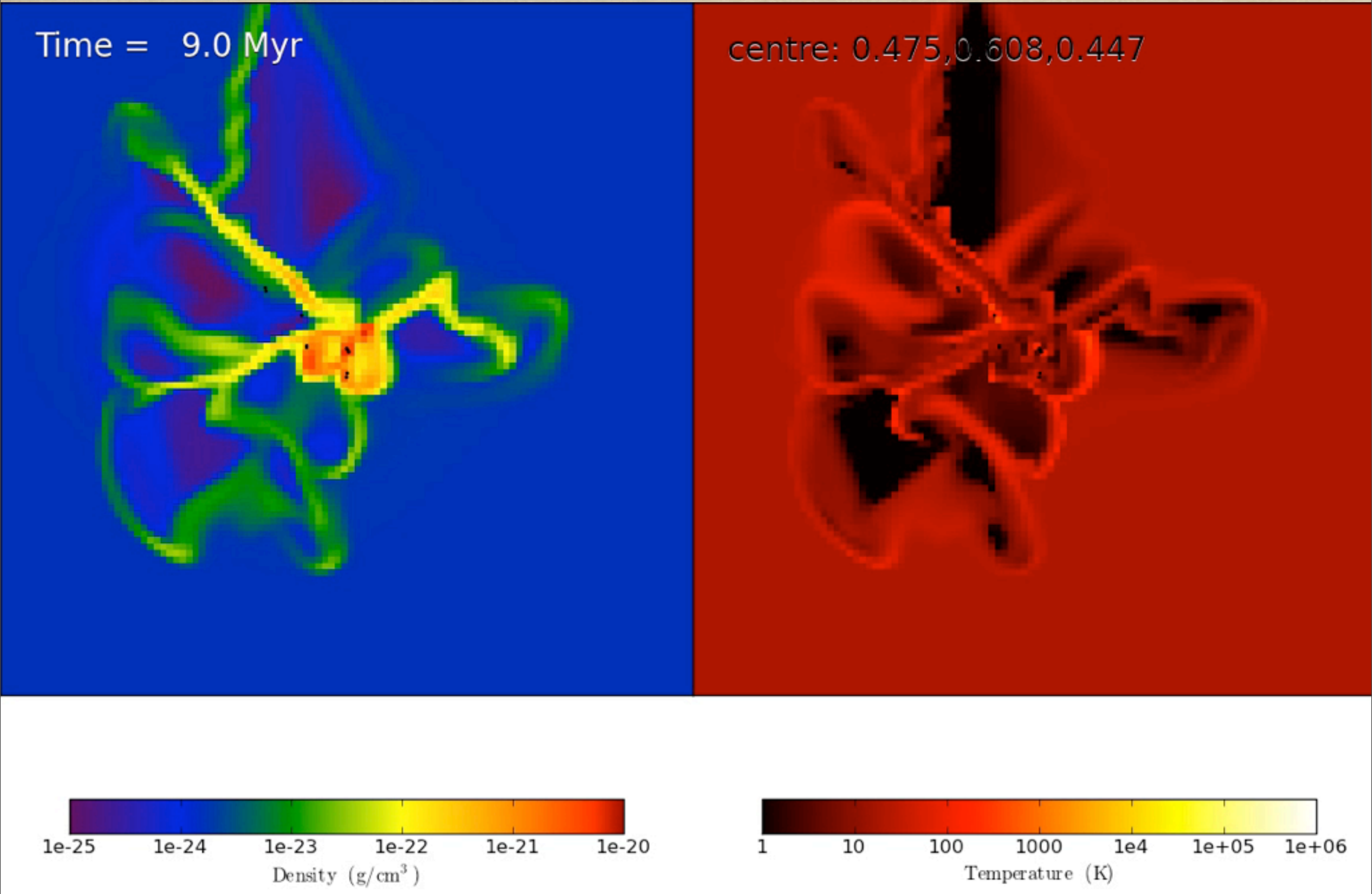
Harper-Clark; ENZO2 raytracing

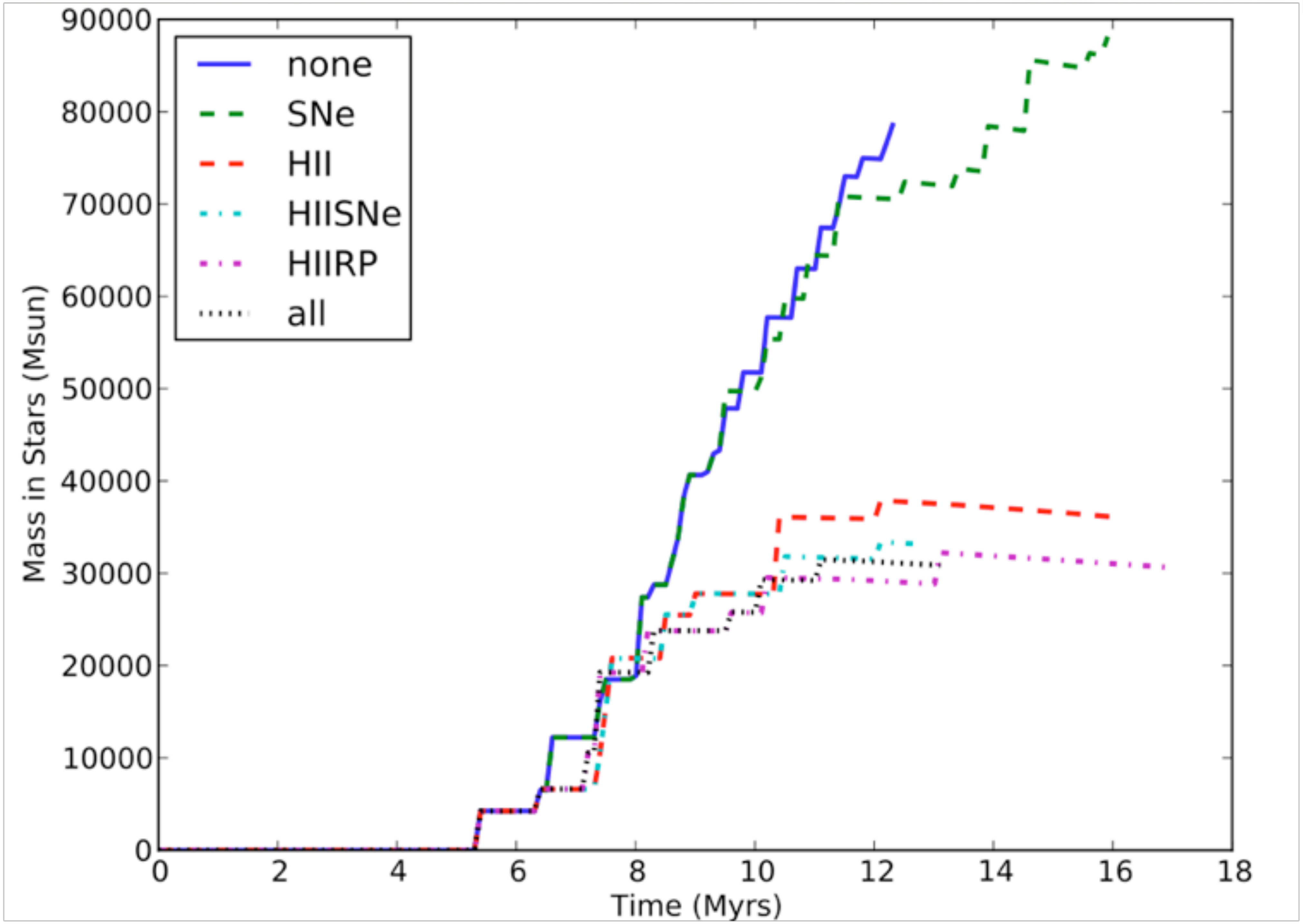


Note SN have little effect

Stellar mass vs time for different feedbacks

$\varepsilon_{GMC} \approx 0.1$


Time = 9.0 Myr
centre: 0.475,0.608,0.447
1e-25
1e-24
1e-23
1e-22
1e-21
1e-20
Density (g/cm³)
1
10
100
1000
1e4
1e+05
1e+06
Temperature (K)



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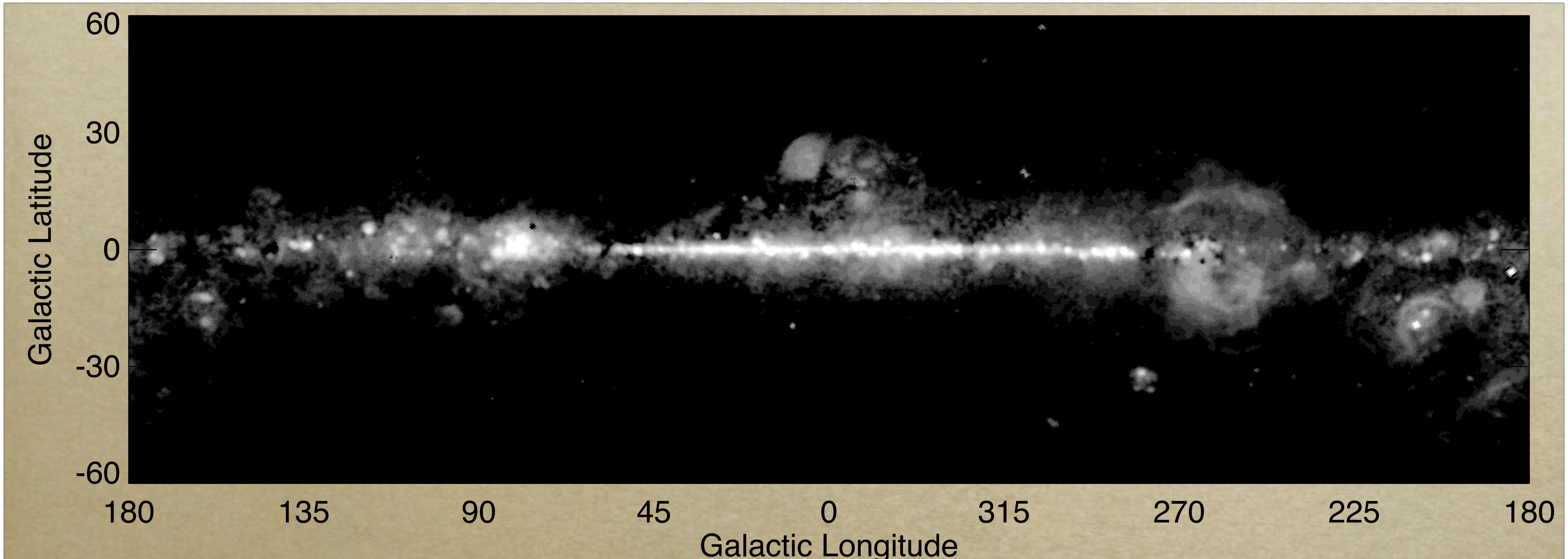
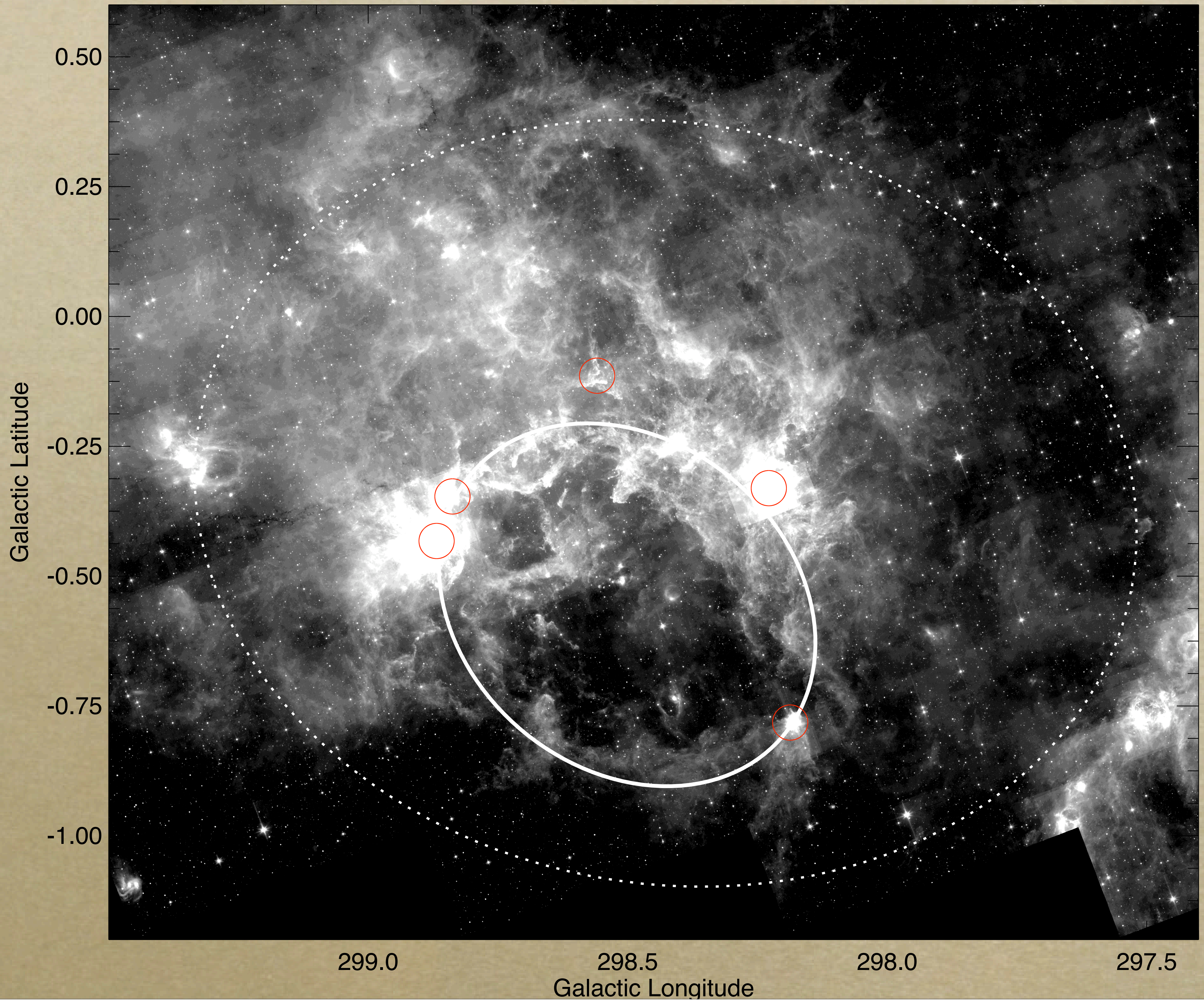
Testing the model: measure ε_{GMC}



WMAP Free-Free emission



Radiation pressure on dust

Murray & Rahaman 2010 ApJ 709 424; Rahman & Murray ApJ 719 1104

Generating Turbulence

- Supersonic turbulence is universal in the ISM
- Turbulence decays: $L_T \sim \pi R^2 \varrho v_T^3 \sim 3 \times 10^{39}$ erg/s
- Adding up the the bubbles associated with 0.8 of the star formation, we find $L \sim 2.4 \times 10^{39}$ erg/s

Galactic scale simulations
Hopkins, Quataert Gadget (sph)

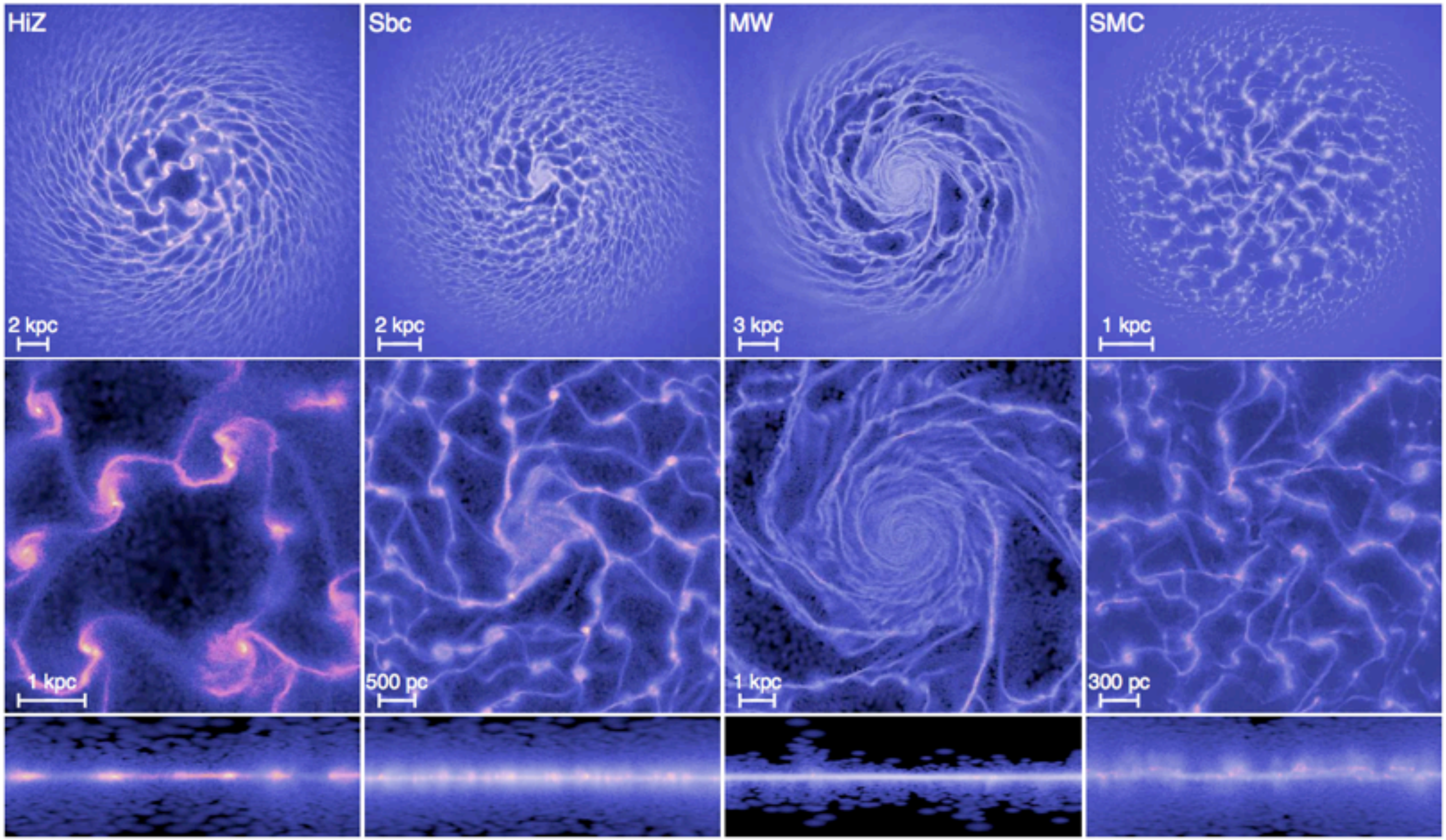
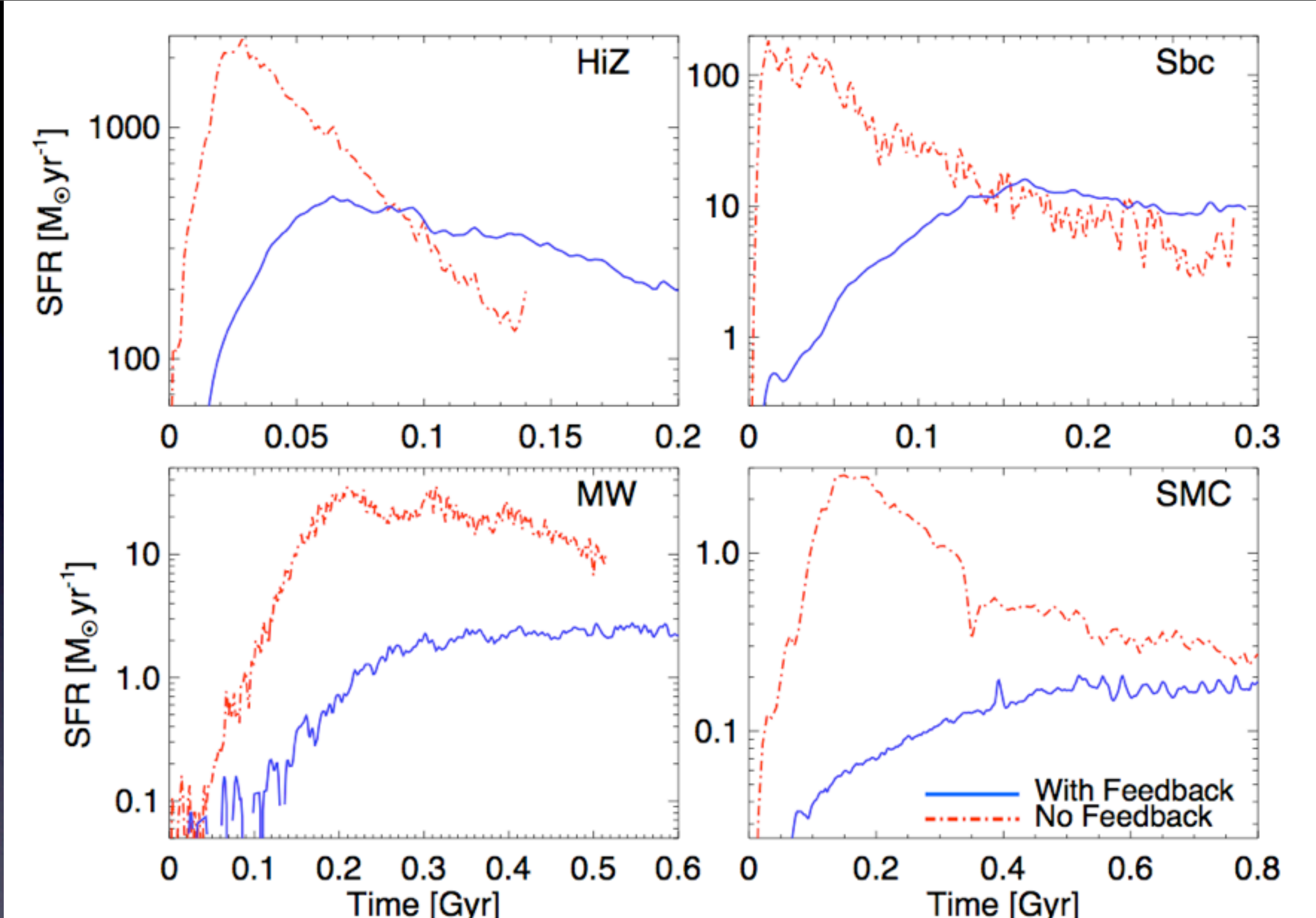


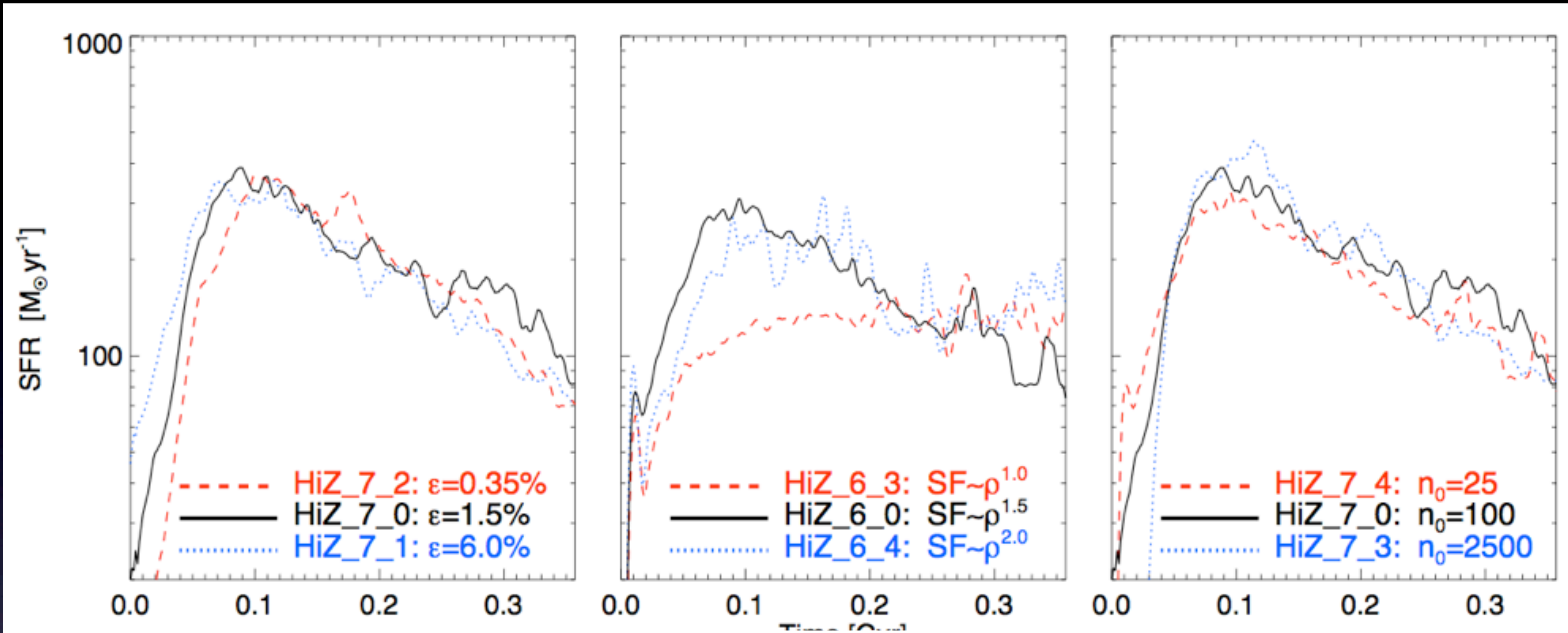
Figure 1. Images of the gas distribution for our fiducial simulations ($\eta_p = \eta_v = 1$) in the feedback-regulated quasi steady-state. Brightness shows the gas surface density while color shows the specific SFR (increasing from blue to red); both are on a logarithmic scale spanning a dynamic range of $\sim 10^6$. *Top:* Large scales out to twice the half-gas mass radius. *Middle:* Intermediate scales out to the half-SFR radius. *Bottom:* Edge-on; scale is same as the middle image. One example is shown for each of the initial conditions we model (HiZ_10_4_hr, Sbc_10_4_hr, MW_10_4_hr, and SMC_10_4_hr in Table 2). The simulations develop complex substructure and exhibit a diverse range of gas morphologies. Most stars are formed in dense but resolved giant 'molecular' cloud complexes, which are the sites of feedback as modeled here.

Modified Gadget simulations

- Particle mass from 100 solar masses
- force resolution ~ few parsecs or better
- several different types of galaxy
- no radiative transfer---instead deposit momentum from stars directly in gas
    - treat stars as being located in a single cluster near the center of their host GMCs
    - track L(t) for each star
    - calculate optical depth from location of cluster

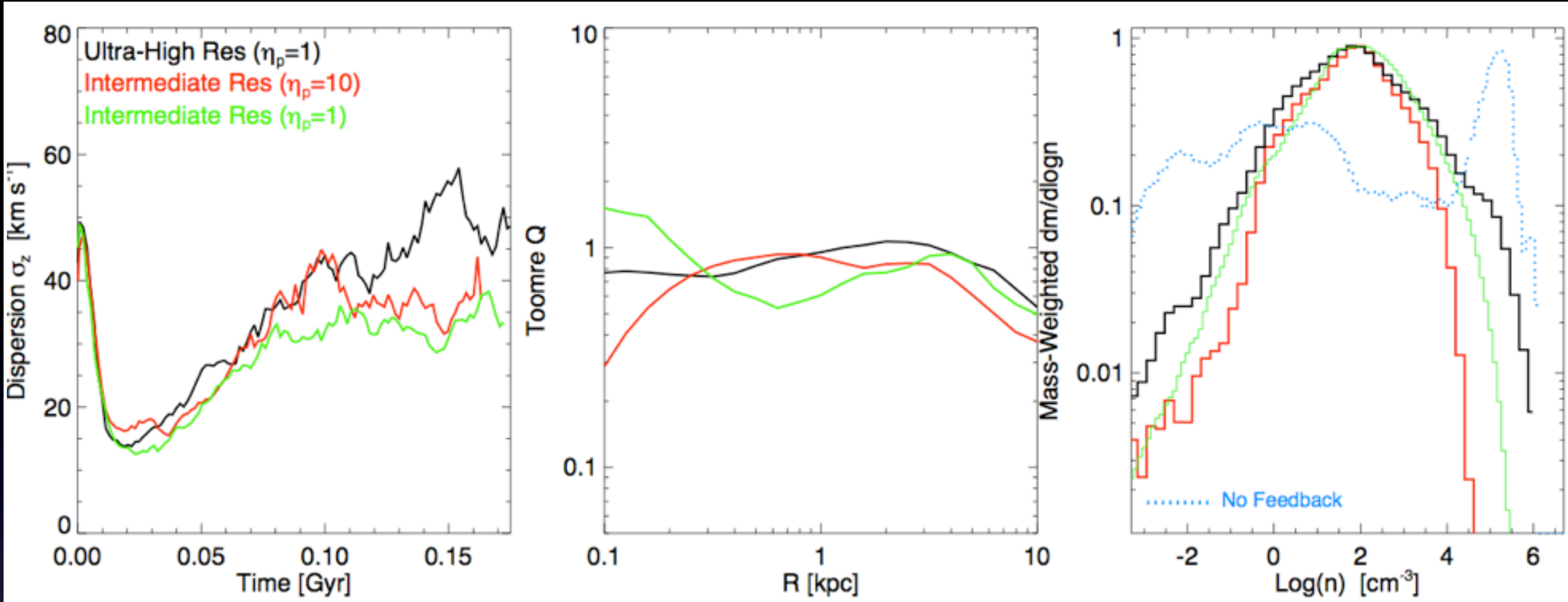


Momentum Feedback regulates star formation

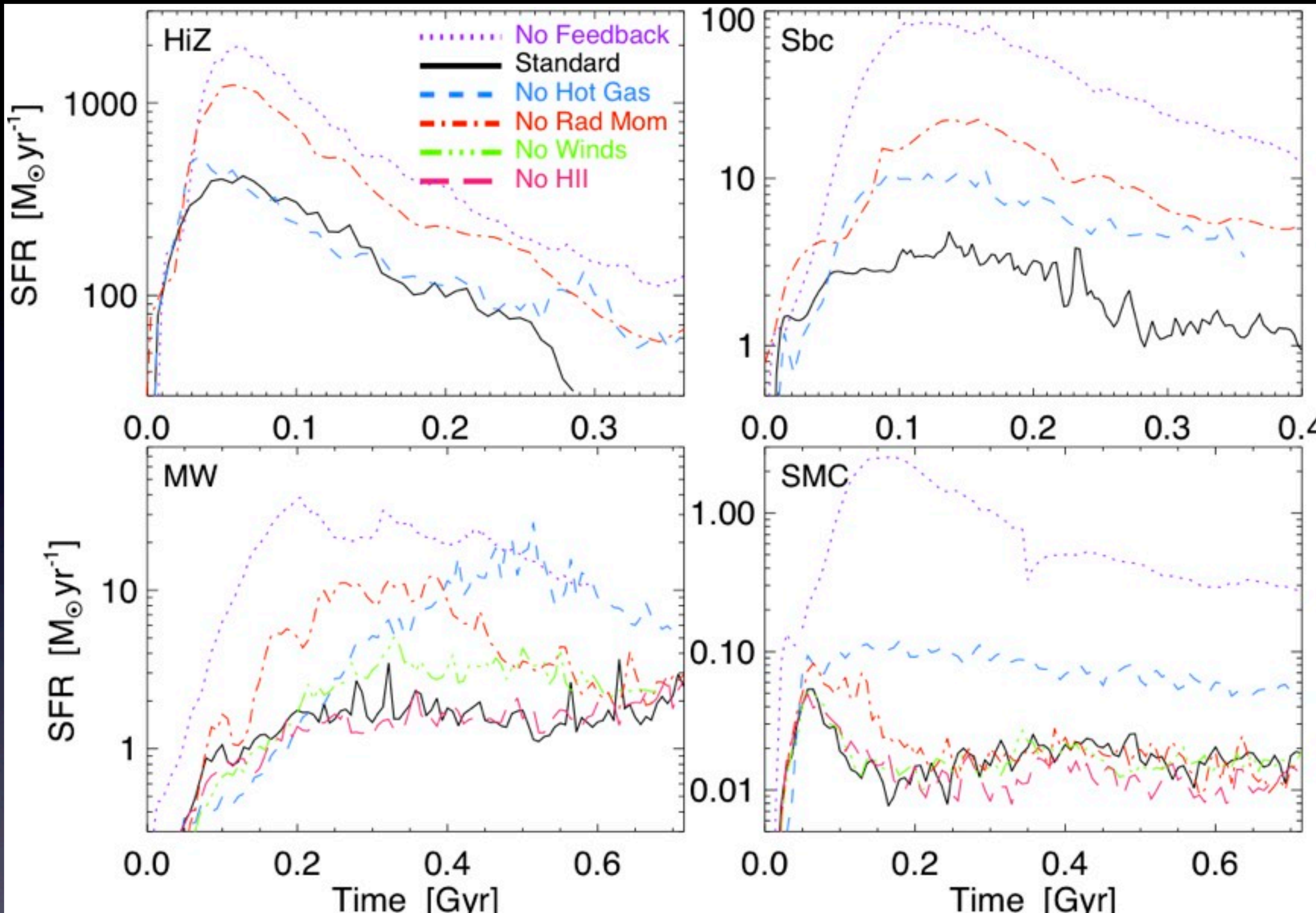


Global star formation rate

does not depend on small scale star formation rate



Varying strength of the feedback does not change SFR, but it does change the density distribtuion

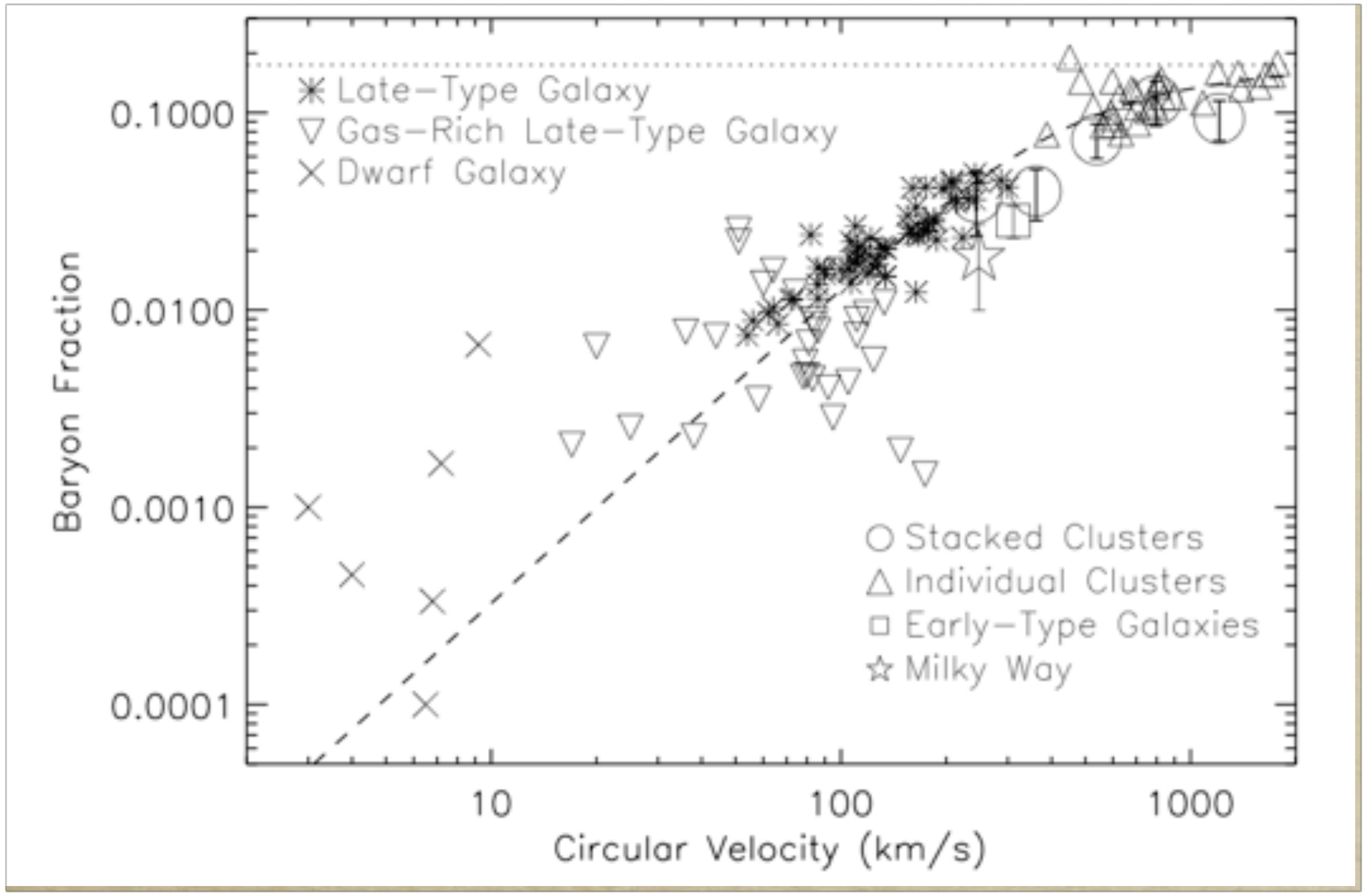


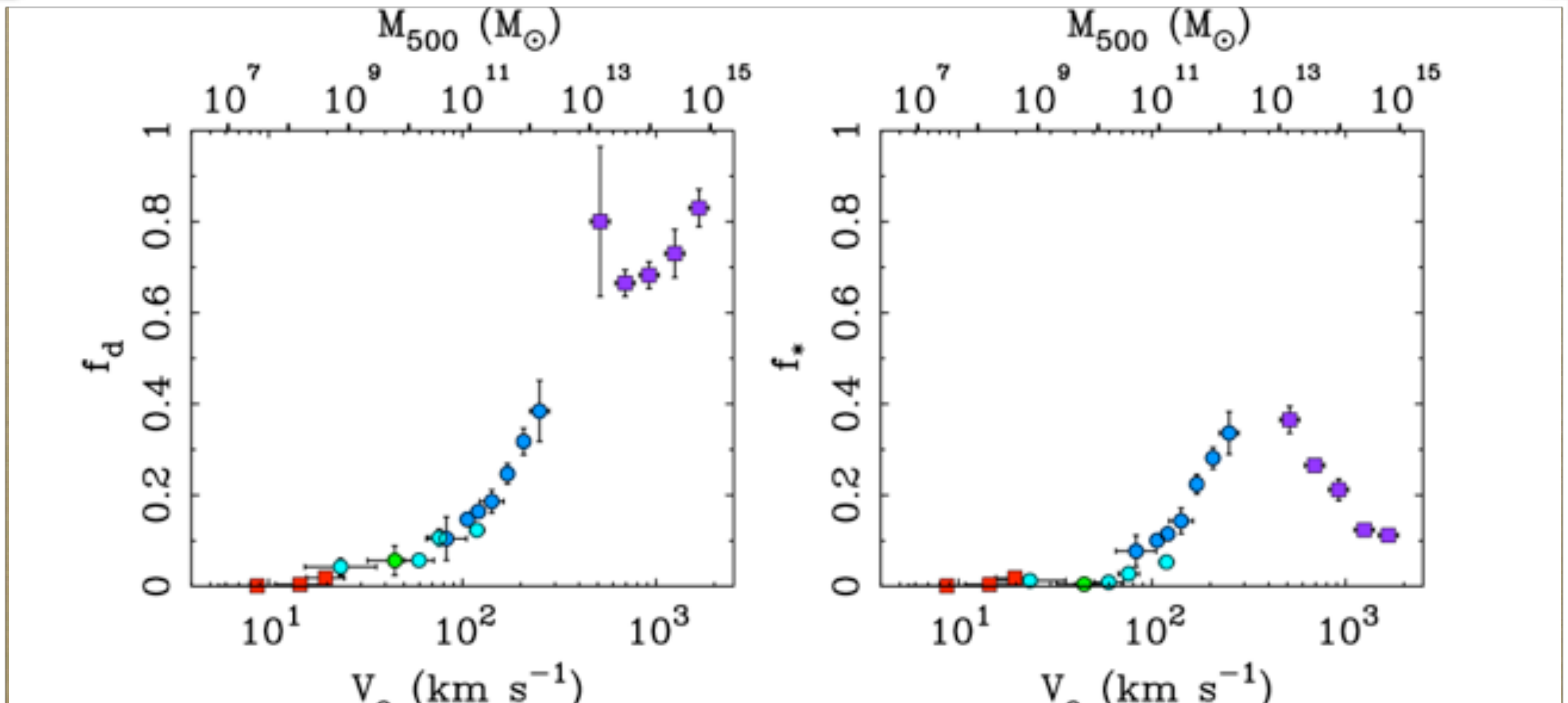
Different forms of feedback

Missing Baryons

- *To cosmologists, a galaxy is a gravitationally bound collection of dark matter they call a 'halo'*
- *The baryons are incidental, more of a bother than anything else: they don't stay where they belong, inside the halo*

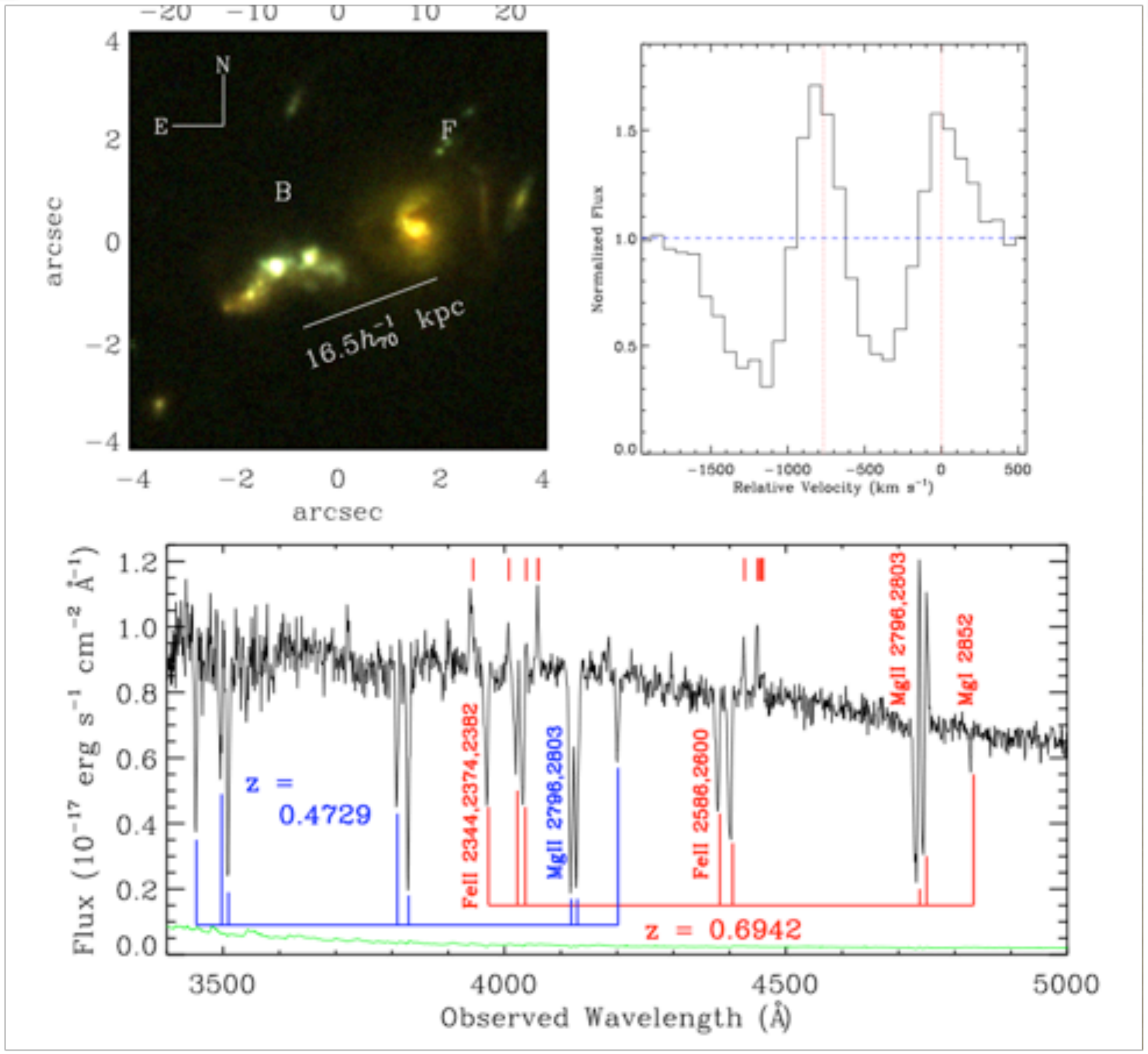
Dai et al. (2010) ApJ, 719, 119

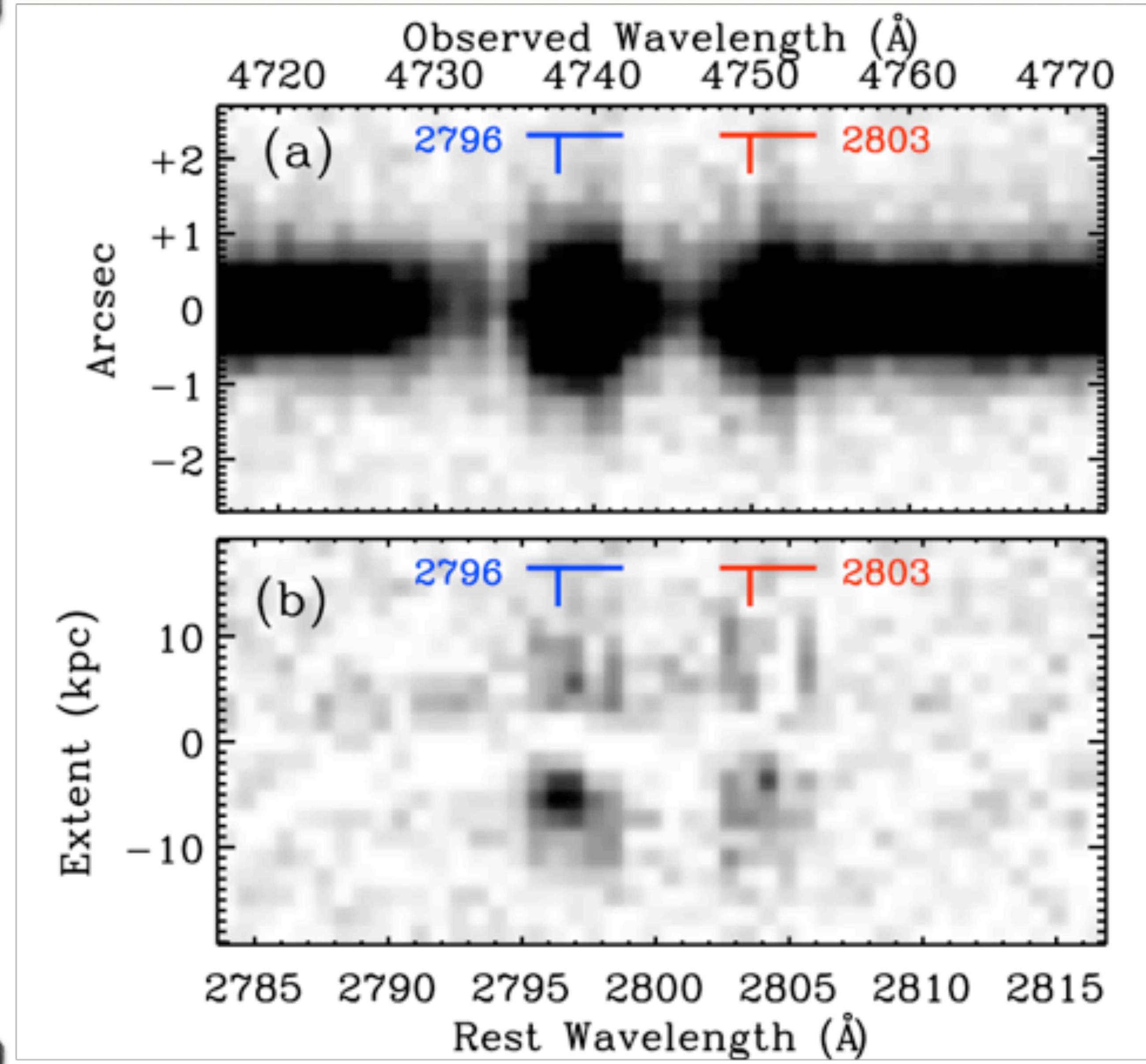




McGaugh et al. (2010) ApJL, 708, 1

Galactic Winds

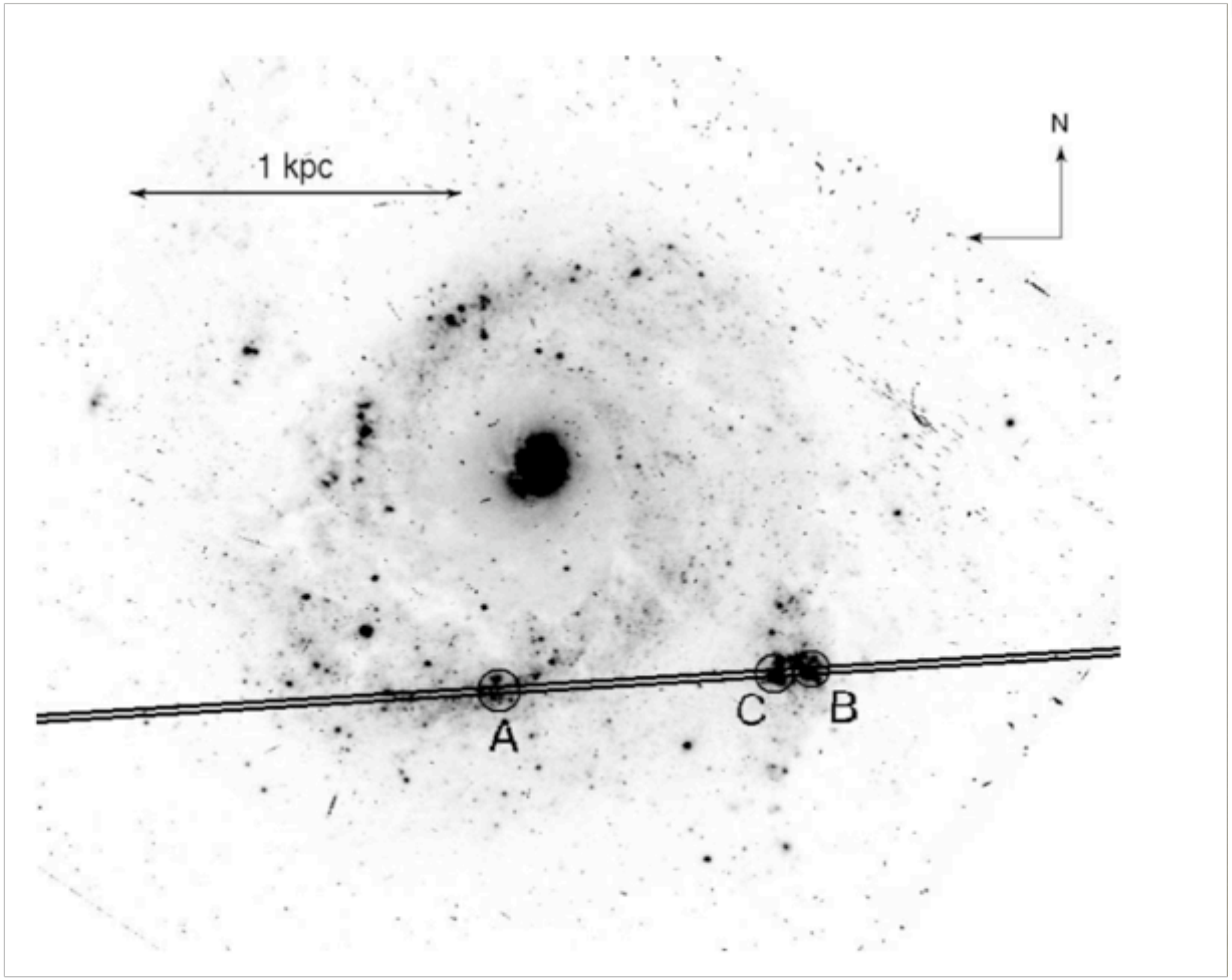




Rubin et al. ApJ 728 55 (2011)

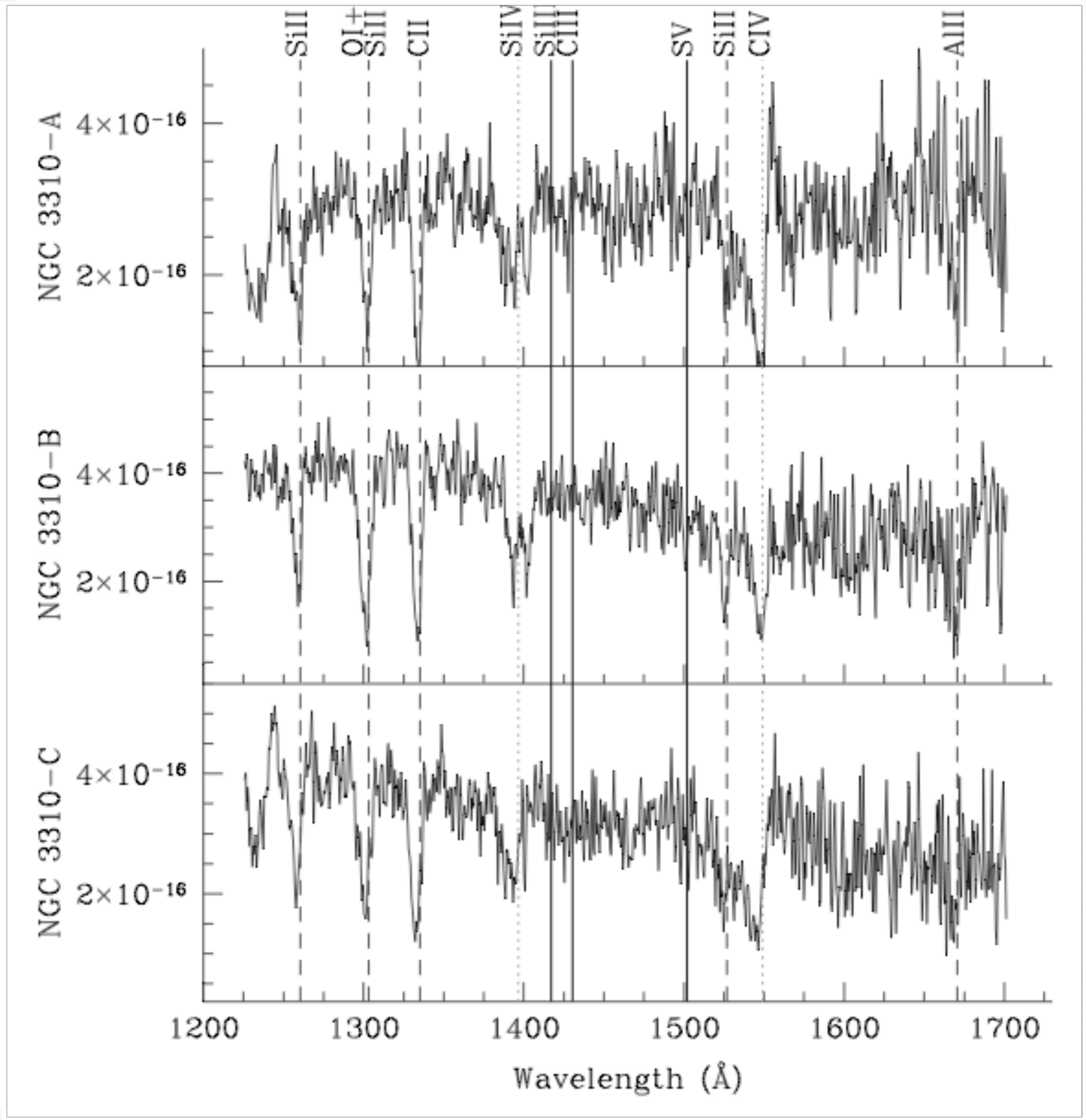
Launching Winds from Massive Star Clusters

- *Cluster mass scales with star formation rate*
- *Massive clusters have high escape velocities---they can radiatively launch winds that escape the galactic disk*
- *This happens before SN explode, protecting the 'cool' (10^4) gas*
- *ε_{GMC} as in bubble models; more gas leaves the galaxy than is retained in stars*
- *Cool gas survives to large distances (5-10kpc) where hot gas ram pressure takes over*



NGC 3310

Schwartz et al. (2006) ApJ 646 858



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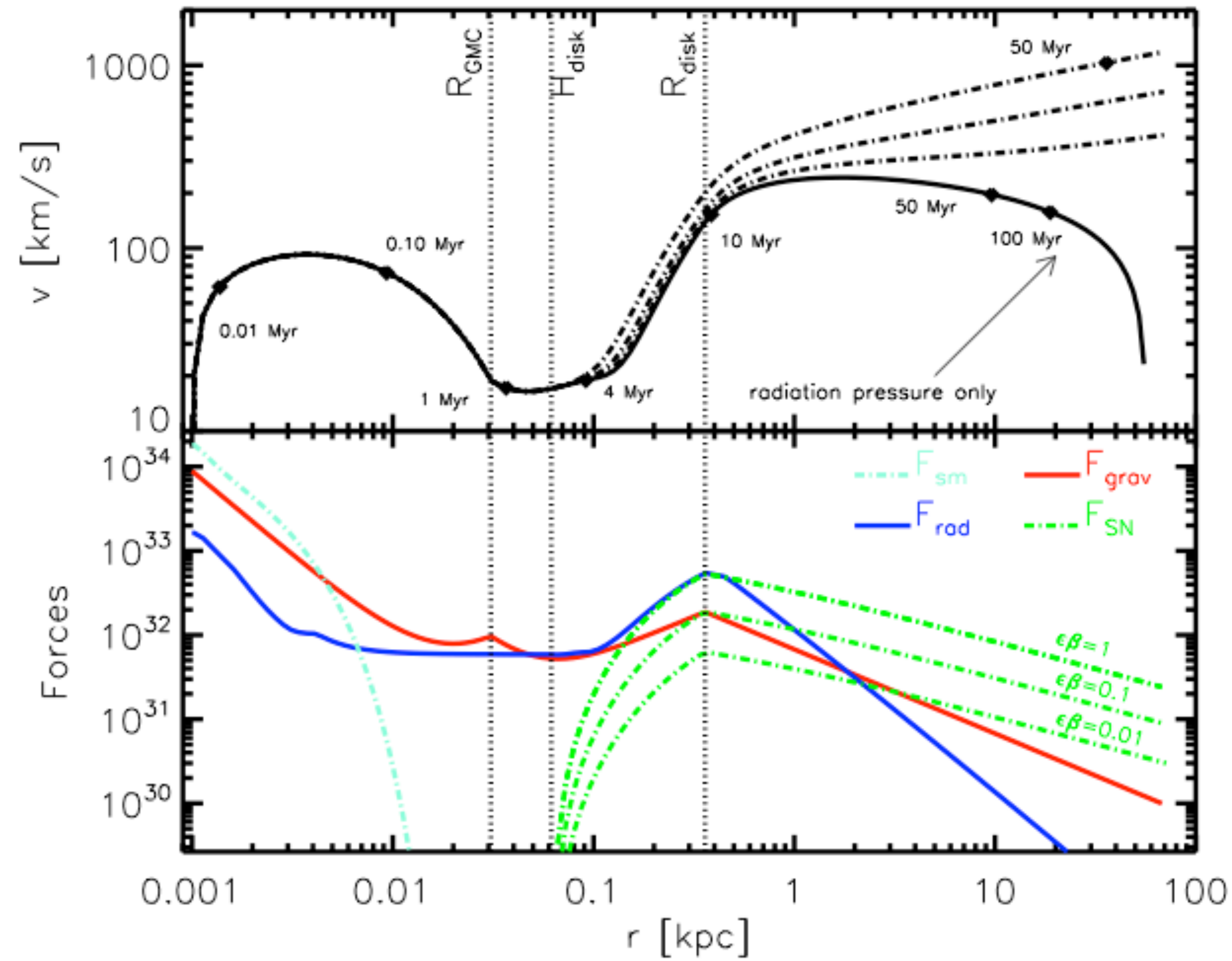
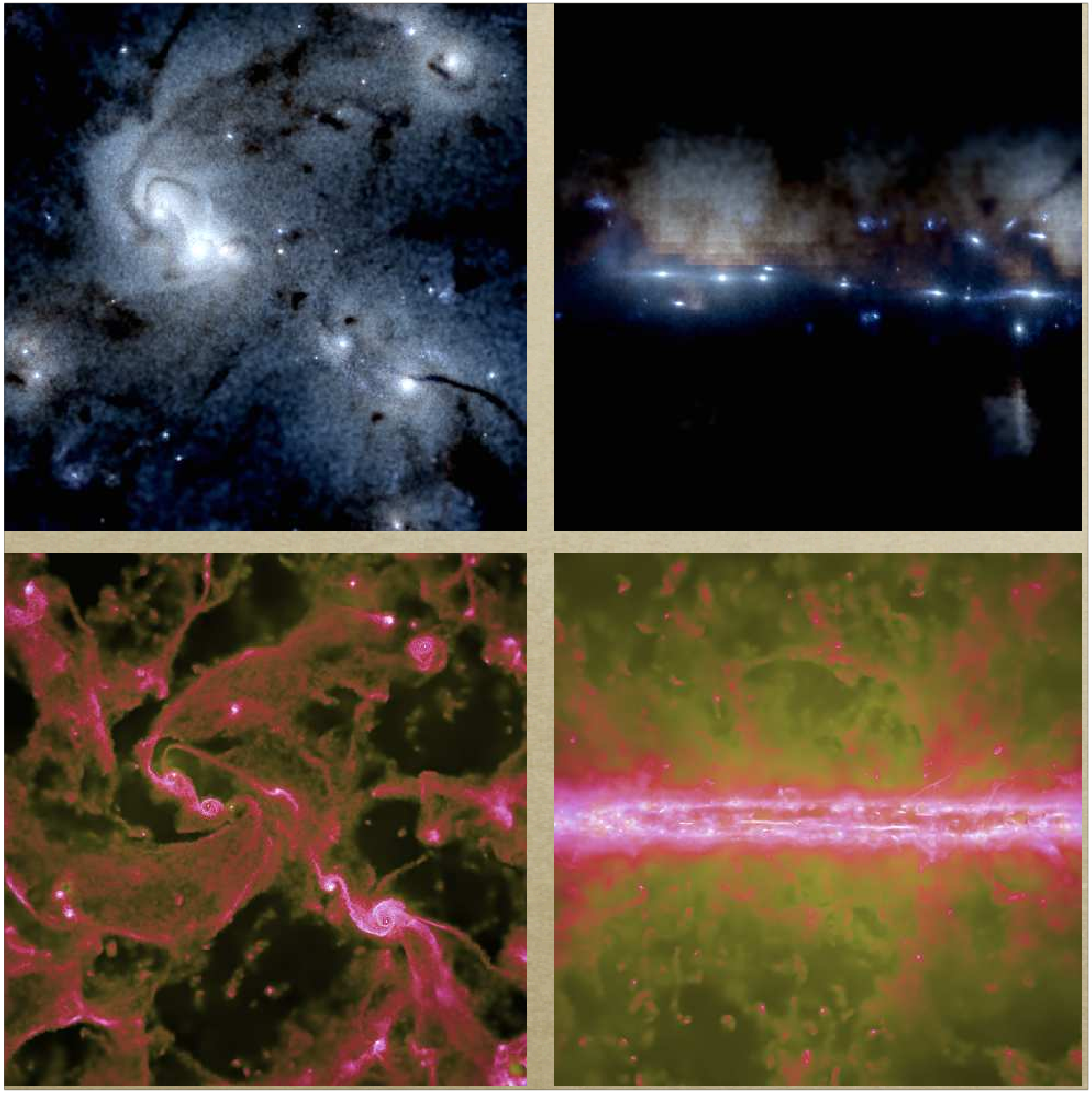
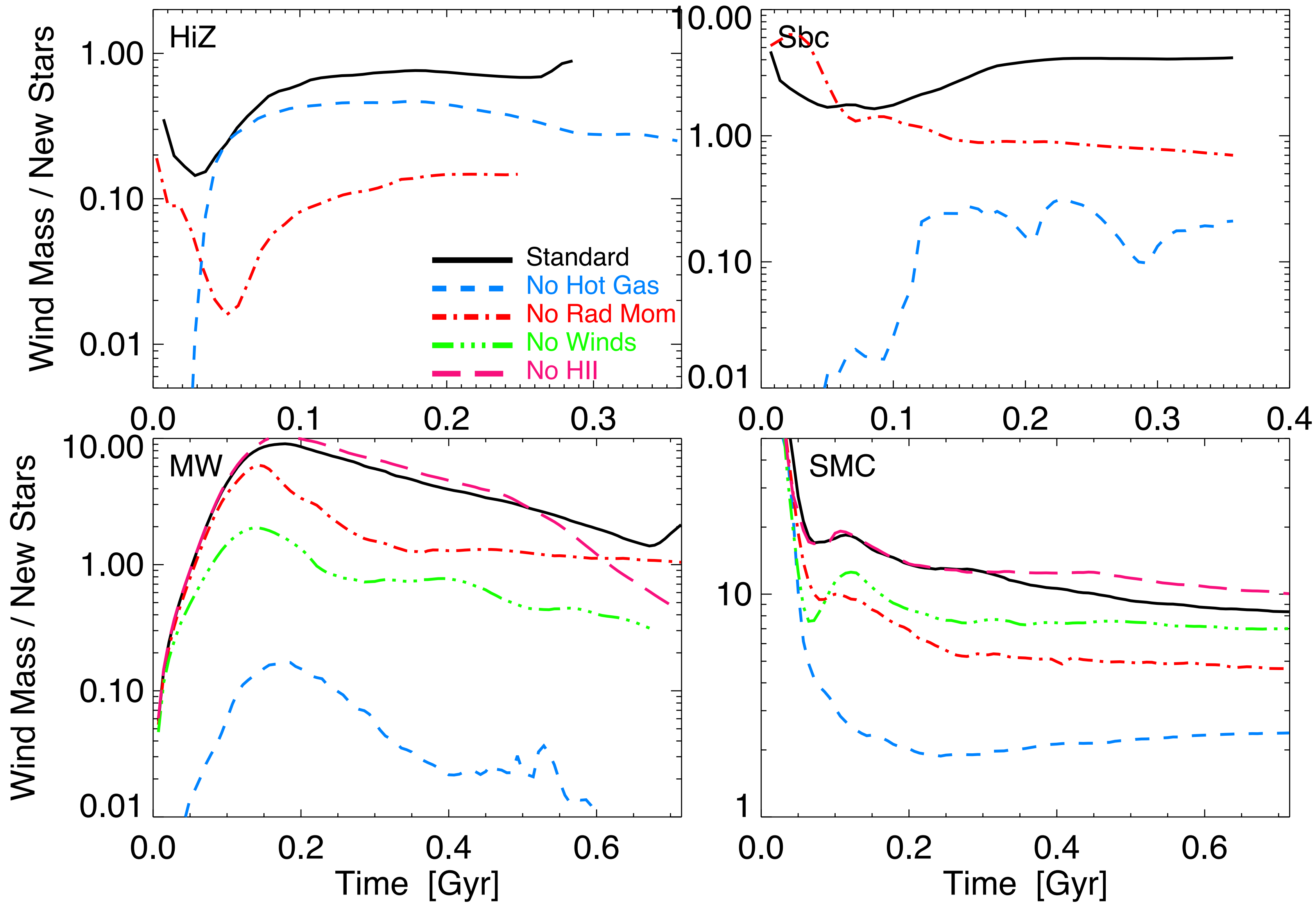


1D Numerical Models

Murray Menard & Thompson. **arXiv:1005.4419**

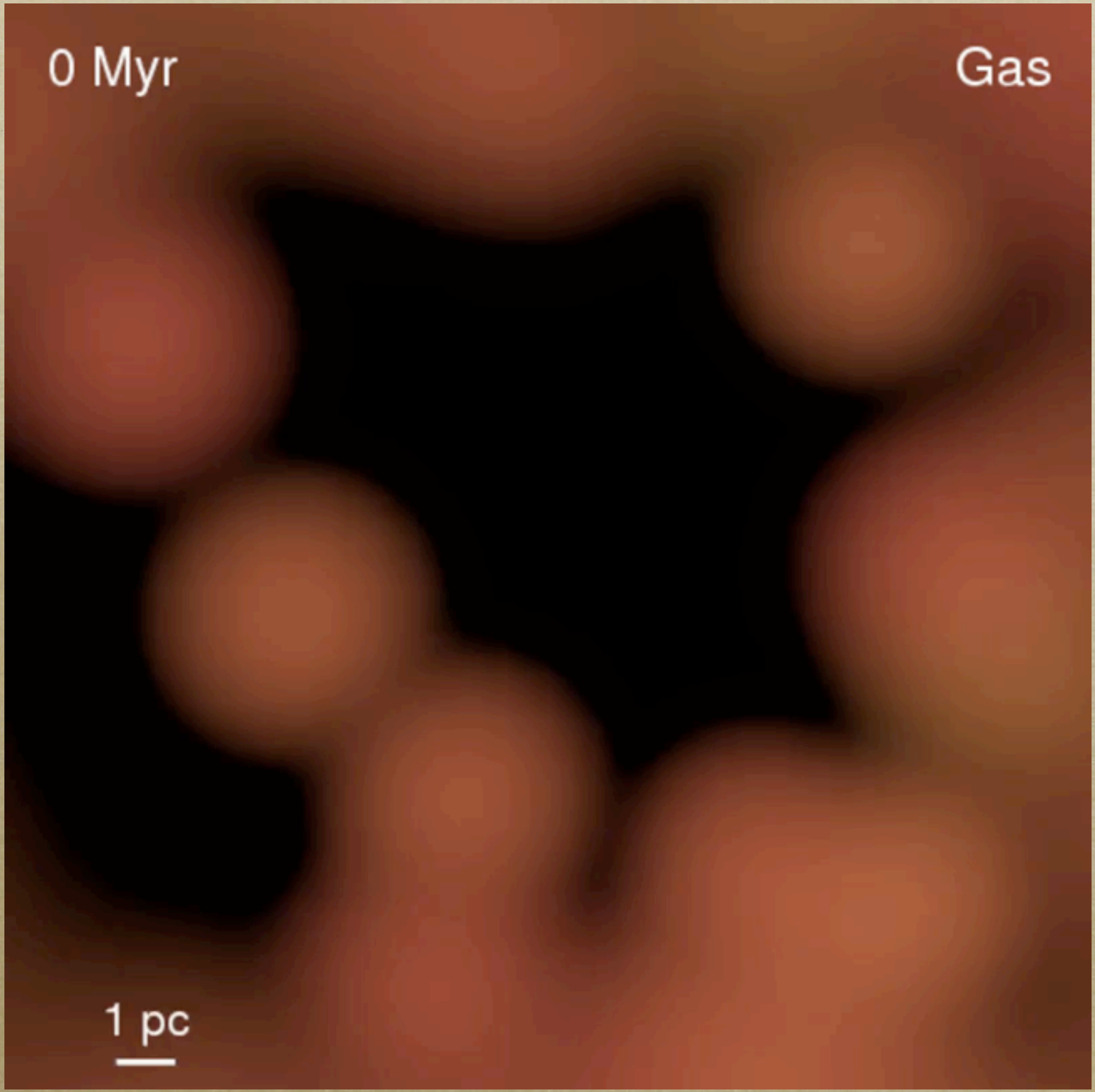


3D Models



3-D Wind Models

3-D Gadget Models



Quasar Mode Feedback

- *Jets; can push gas, but very narrow*
- *Energy deposition by UV/X-rays, but radiated away unless $L > L_{cool}$*
- *radiation pressure, but galactic disks are thin*
- *BAL winds*

Quasar Mode Feedback: Energy

- *Plenty of energy to disrupt the gas, but the difficulty is depositing it into the ISM*
- $E_{binding}=M_g v_c^2 = 10^{58}erg$
- $L\, \tau_{dyn} = 10^{46}$ erg s^{-1} x $10^{15}s = 10^{61}erg$
- *But, as usual, the ISM will radiate away the energy as fast as it is put in*

Quasar Mode Feedback---BAL Winds

- $L = \eta dM_{acc}/dt\ c^2$
- $L_w = (1/2)dM_w/dt\ v_w^2$
  - line driven winds: $dM_w/dt\ v_w \leq L/c$
  - $dM_w/dt \leq \eta(c/v_w)\ dM_{acc}/dt$
- $L_w = (1/2)\ dM_w/dt\ \ v_w^2 = (1/2)(v_w/c)\ L << L$
- *Dunn et al. ApJ 709 611 estimate* $dM_w/dt \sim Lc/v_w$
- *Using this as a bomb would work, but it is hard to confine a shocked wind, since the galaxy is not spherical*
- *Momentum flux is ≤L/c, which is what radiation pressure acting directly on the ISM gives.*

Quasar Mode Feedback

- *Momentum driving:* $dM/dt \leq L/(cv_c) \approx 200\Omega_{disk}$ *solar masses per year*
- *Since* $H/R = \sigma/v_c \approx 1/4$, $\approx 50\ M_{sun}\ yr^{-1}$
- *Compare to* $100\text{-}1000\ M_{sun}\ yr^{-1}$*; endgame only*
- *But, if you settle for less mass loss, can drive gas to* $v \geq 1000 km/s$*, which is difficult to do with stars*

Conclusions

- *Radiative feedback is seen to act in the Milky Way (bubbles)*
- *It supplies a turbulent luminosity comparable to that dissipated in the Milky Way, and may maintain Q=1*
- *Simple models, 3-D radiative MHD, and high resolution 3-D hydro calculations suggest radiation pressure is important in limiting the rate of star formation in all disk galaxies*
- *It looks promising as a way launching galactic winds and removing baryons from L_* galaxy halos, and aids SN in low mass halos*
- *Quasar mode feedback lacks a compelling physical mechanism for removing gas from the ISM during the peak of a starburst: it may supply the coup de grace at the end of a merger.*