Galactic Scale Winds

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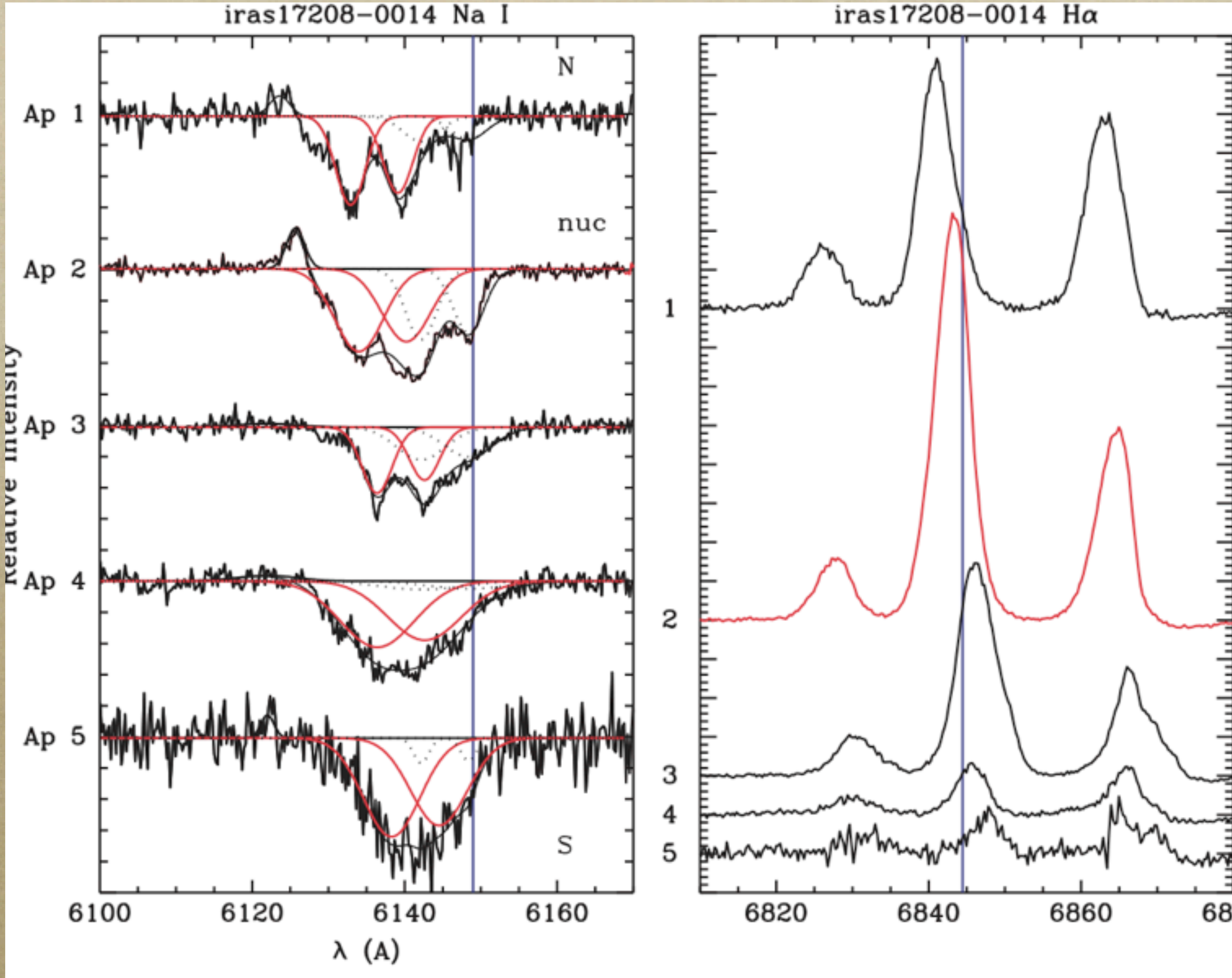
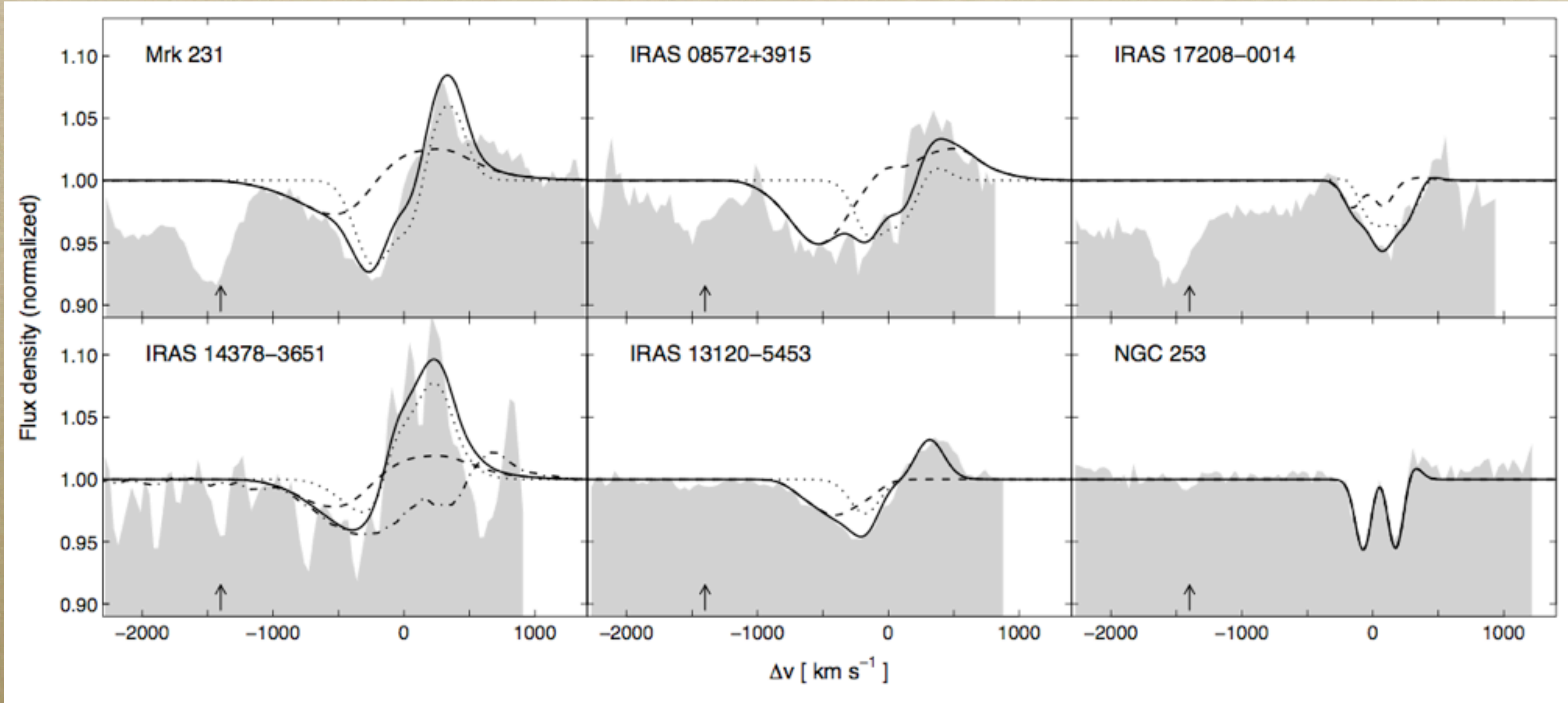
Phenomenology

- *Weiner, Koo: we see winds in most high z star forming galaxies (MgII); few AGN, so not accretion*
- *Martin, Veilleux: we see winds in ~90% of ULIRGs (NaD); also in OH*
- *lines are saturated, but not black; cover factor ~0.5*
- *=> gas covers 1/2 the disk, but comes out in nearly all directions.*



IRAS 17208-0014

Martin (2006) ApJ 647 222



OH P-Cygni Profiles

Sturm 1105.1731

Phenomenology

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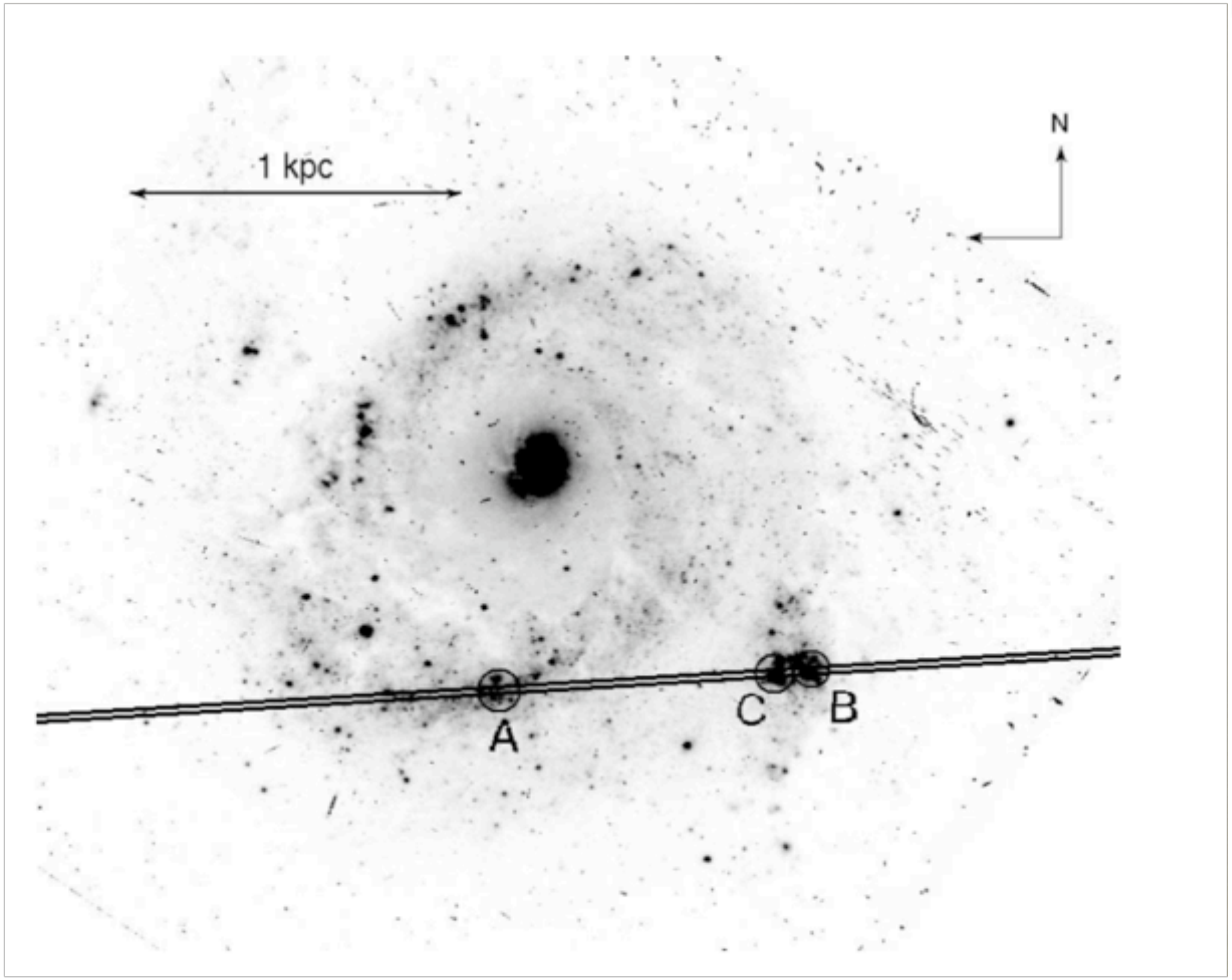
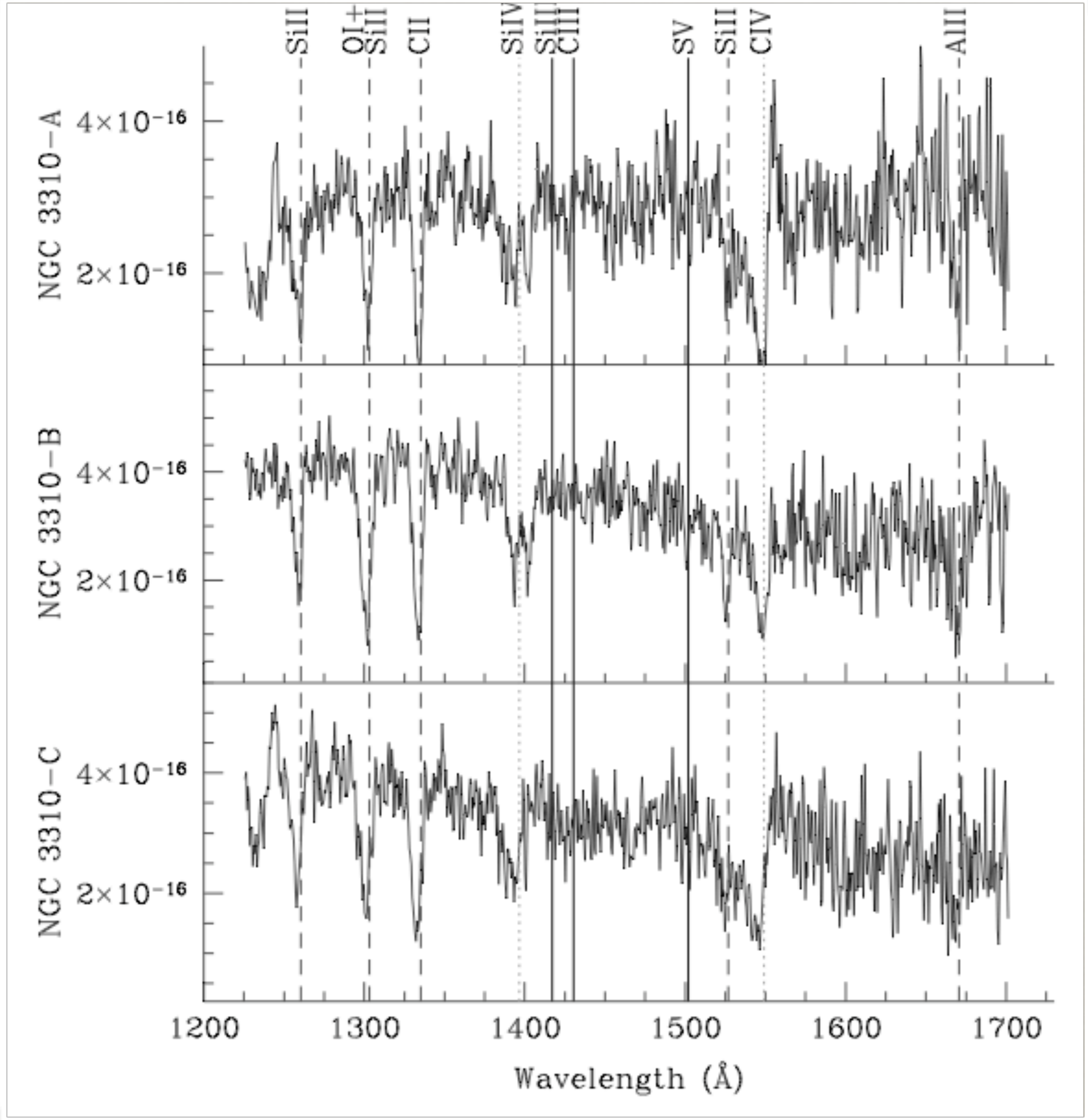
Clusters

- *Winds are driven by star clusters (see talk by Sarah Newman later today)*



NGC 3310

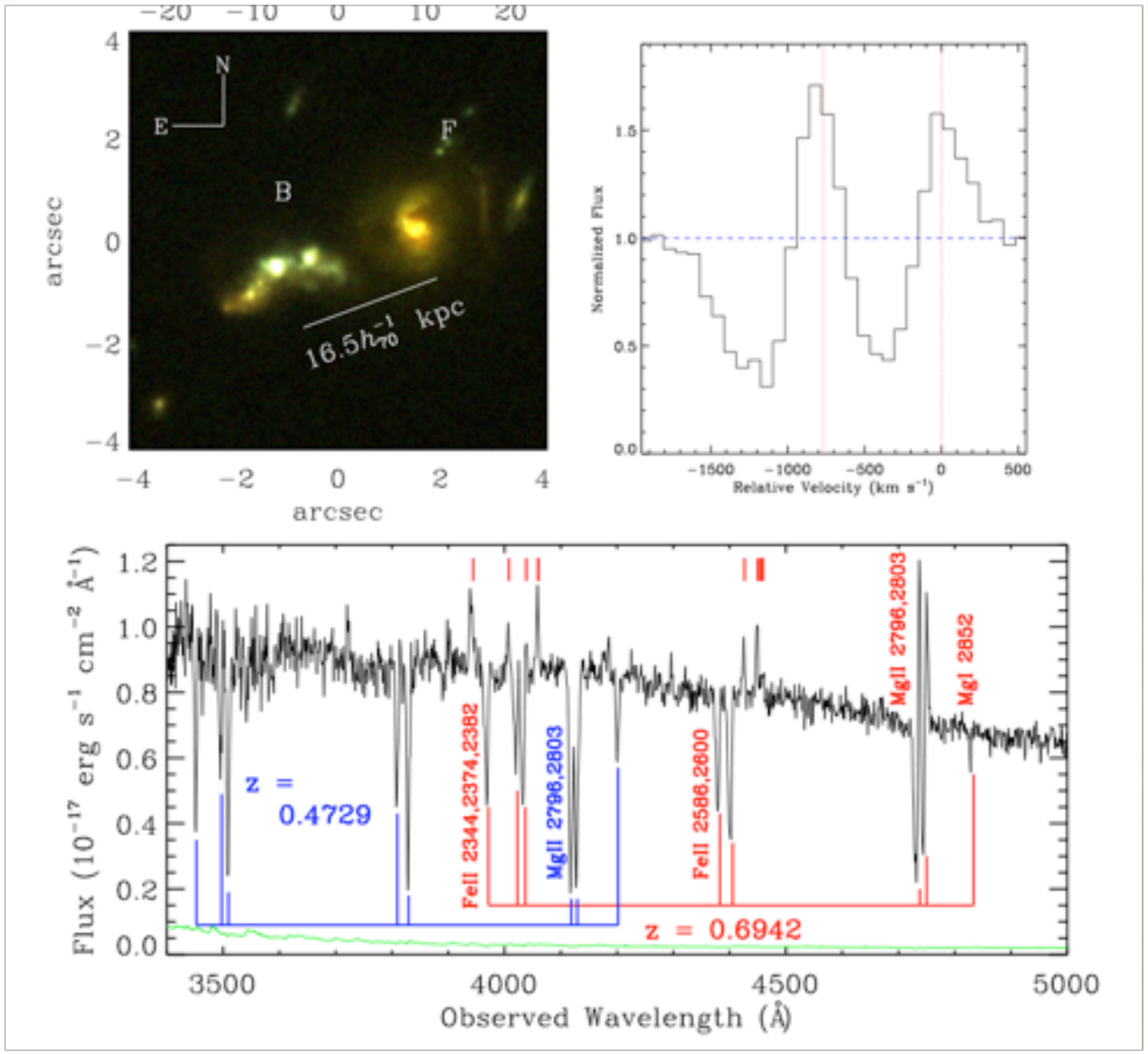
Schwartz et al. (2006) ApJ 646 858

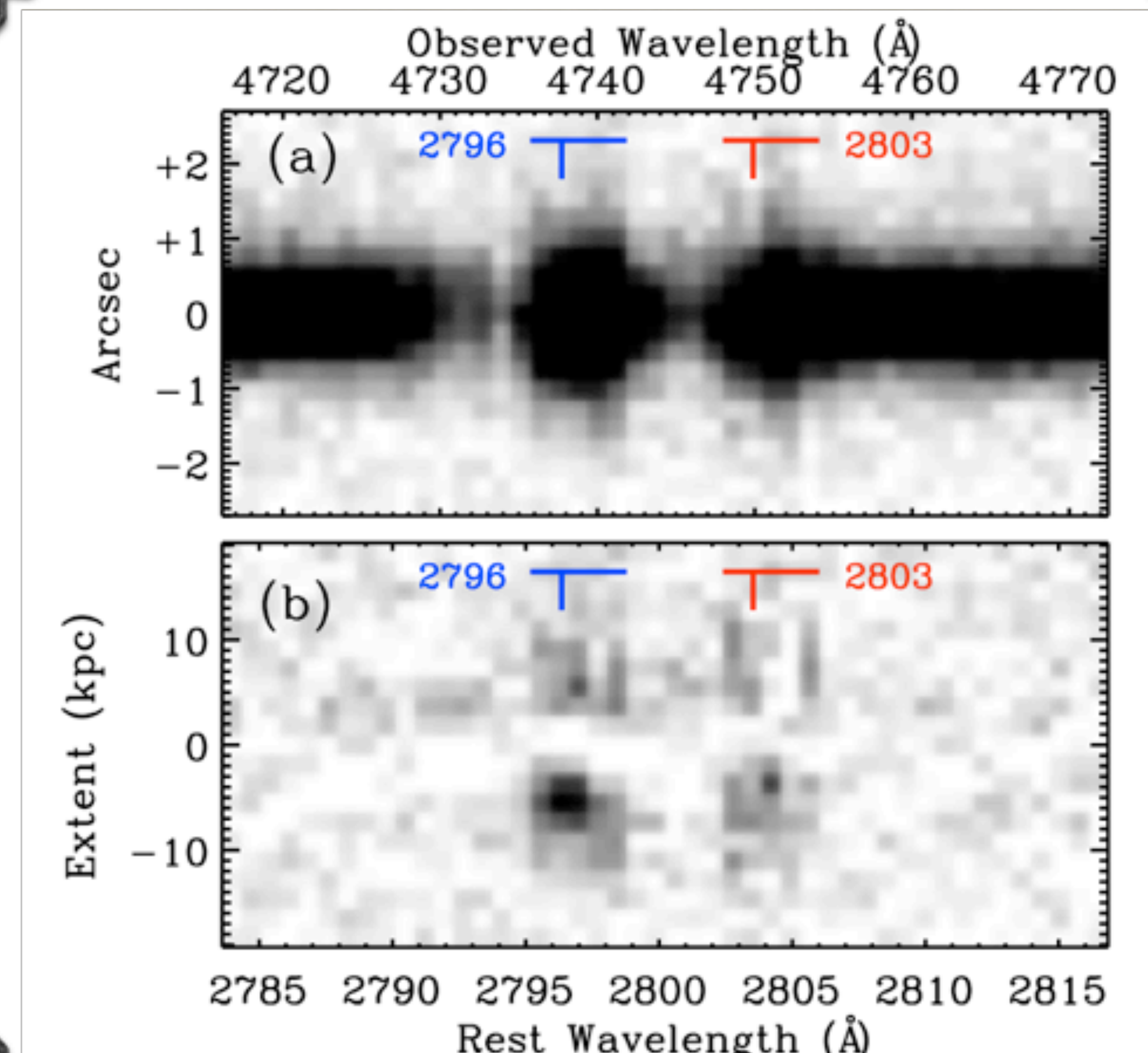


NGC 3310

Schwartz et al. (2006) ApJ 646 858

Galactic Winds Reach Large Radii





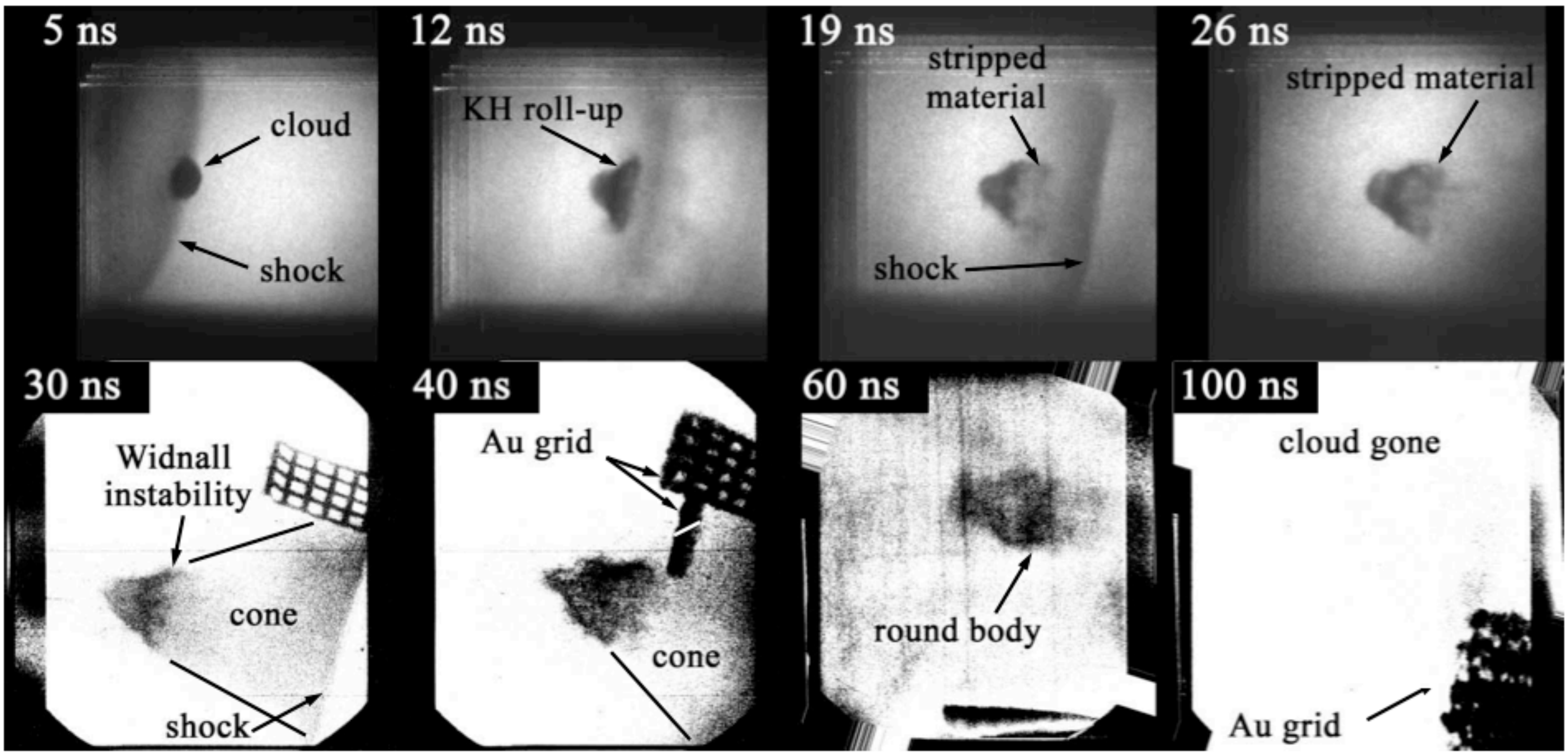
Rubin et al. ApJ 728 55 (2011)

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*

Pushing with hot gas destroys cold clouds

Hansen et al. *ApJ 662 379 (2007)*



Pushing with hot gas destroys cold clouds

Cooper et al. ApJ 703 330 (2009)

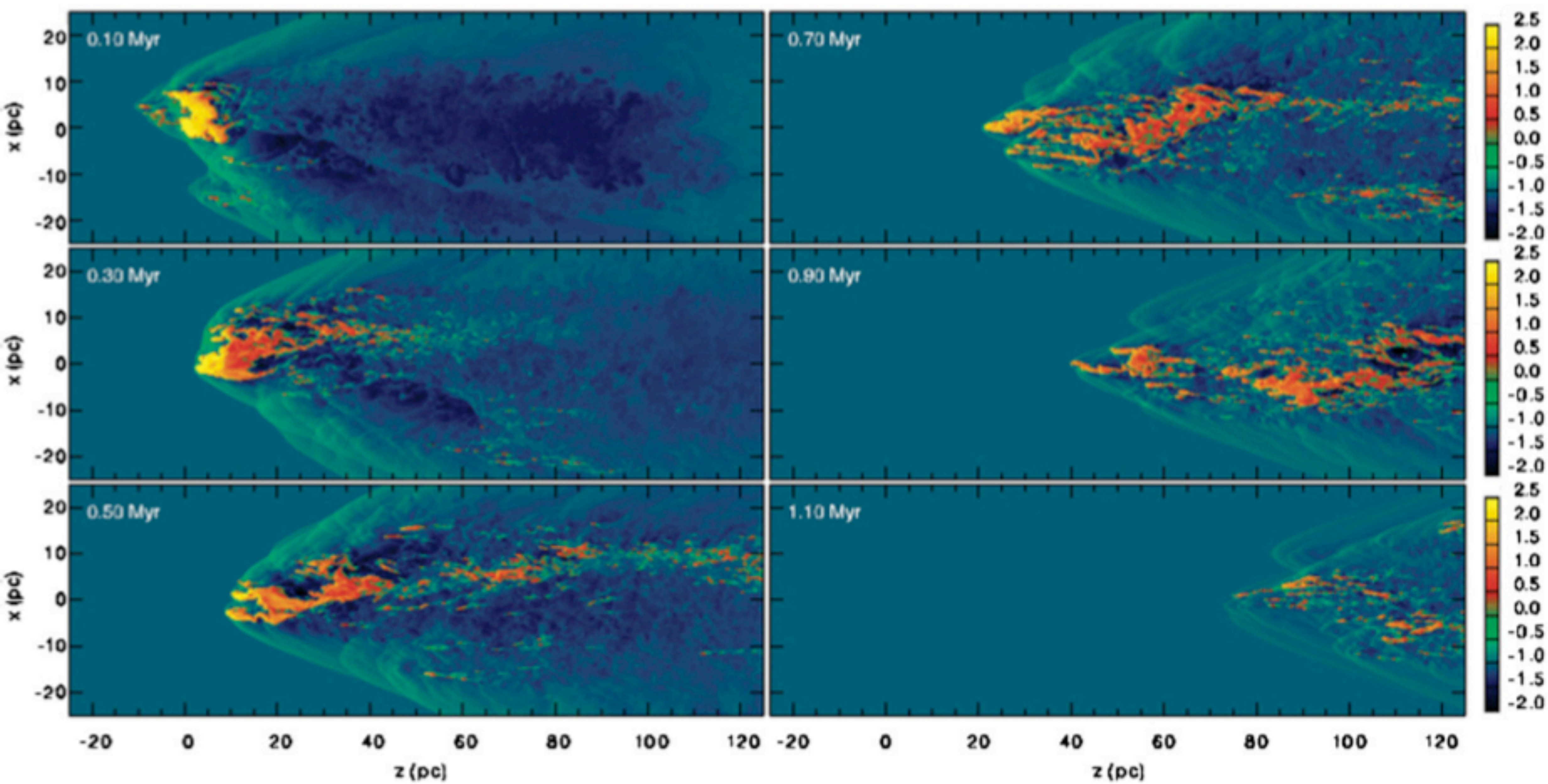


Figure 4. Logarithm of the density through the $y = 0$ plane in model rf384 showing evolution of a radiative fractal cloud.

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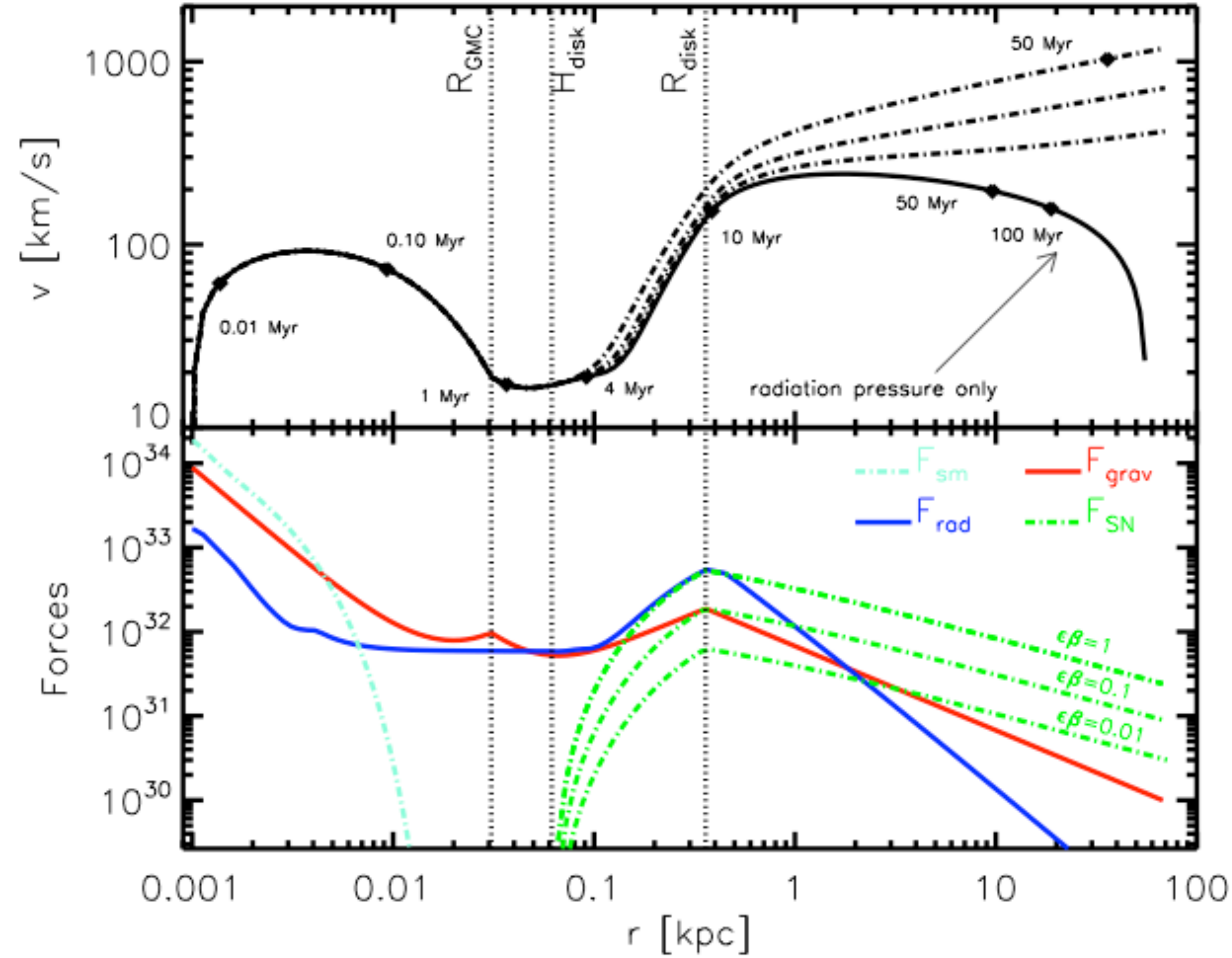
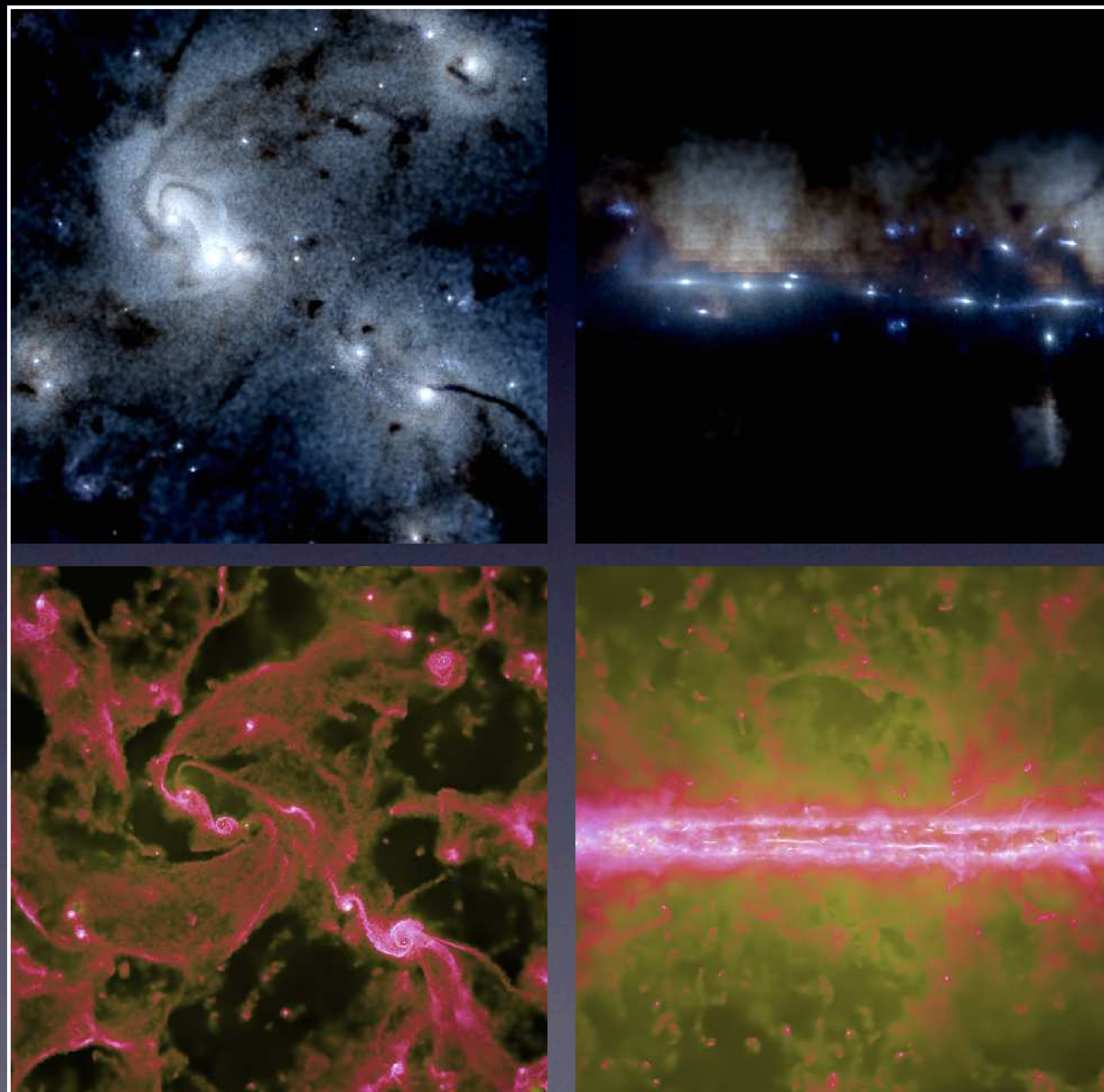


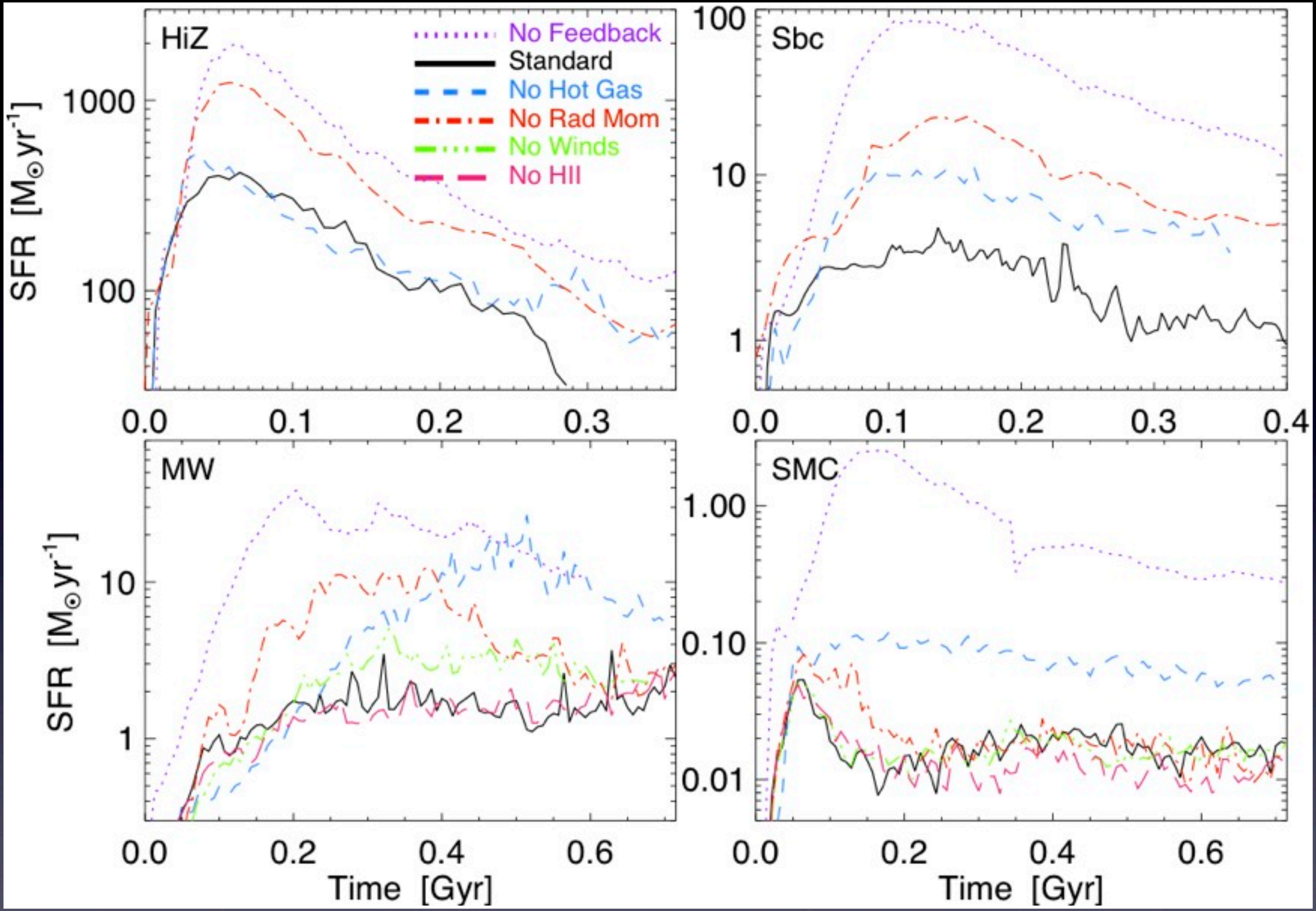
1D Numerical Models

Murray Ménard & Thompson. **ApJ 735 66 (2011)**

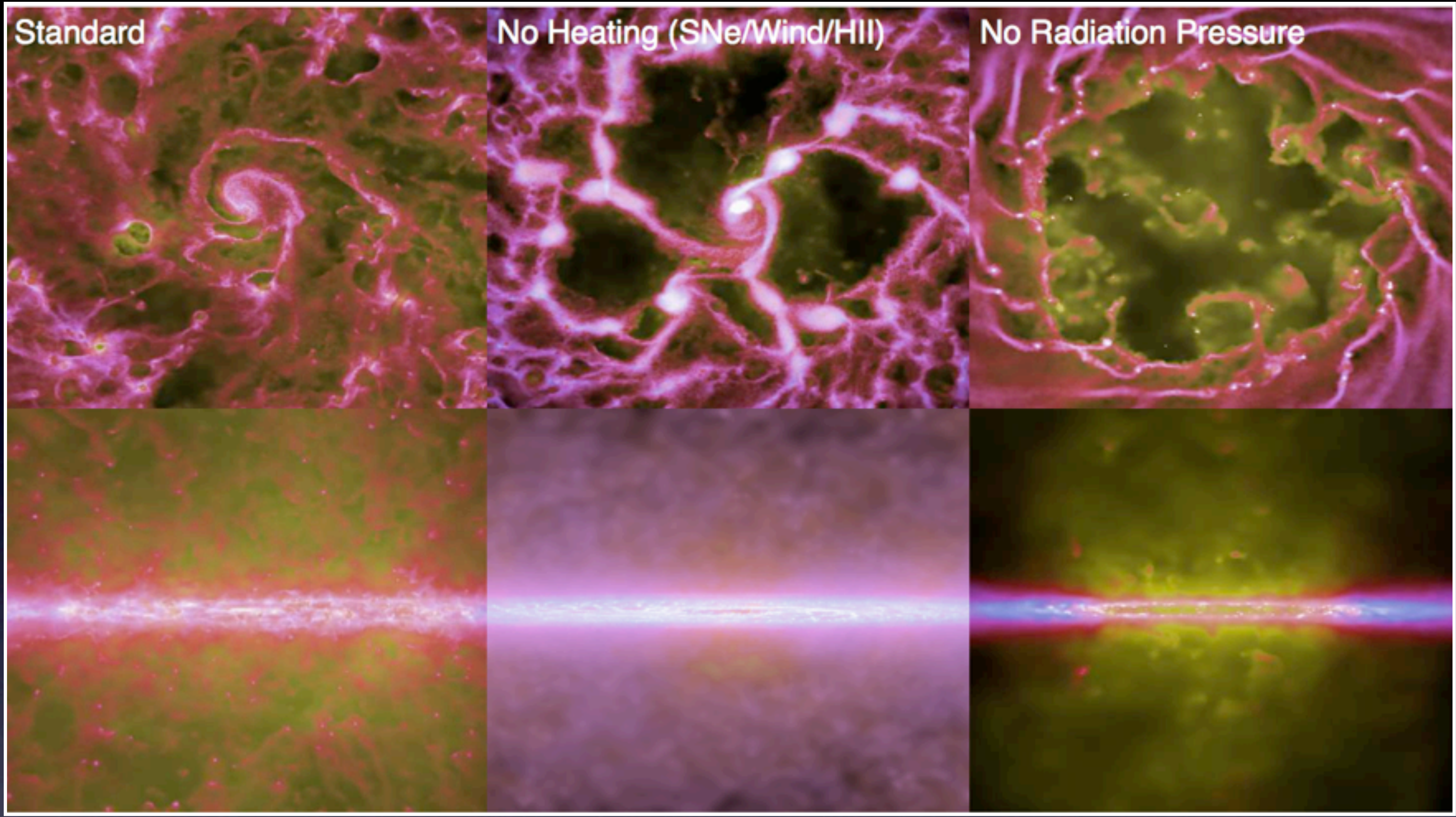
Galactic scale simulations

Hopkins, Quataert Gadget (sph)

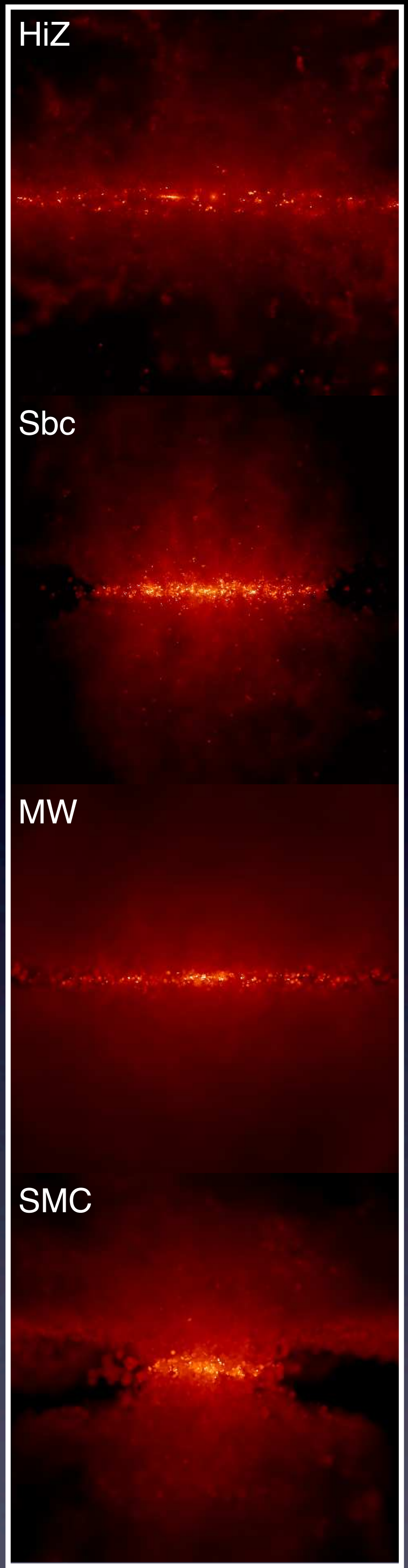




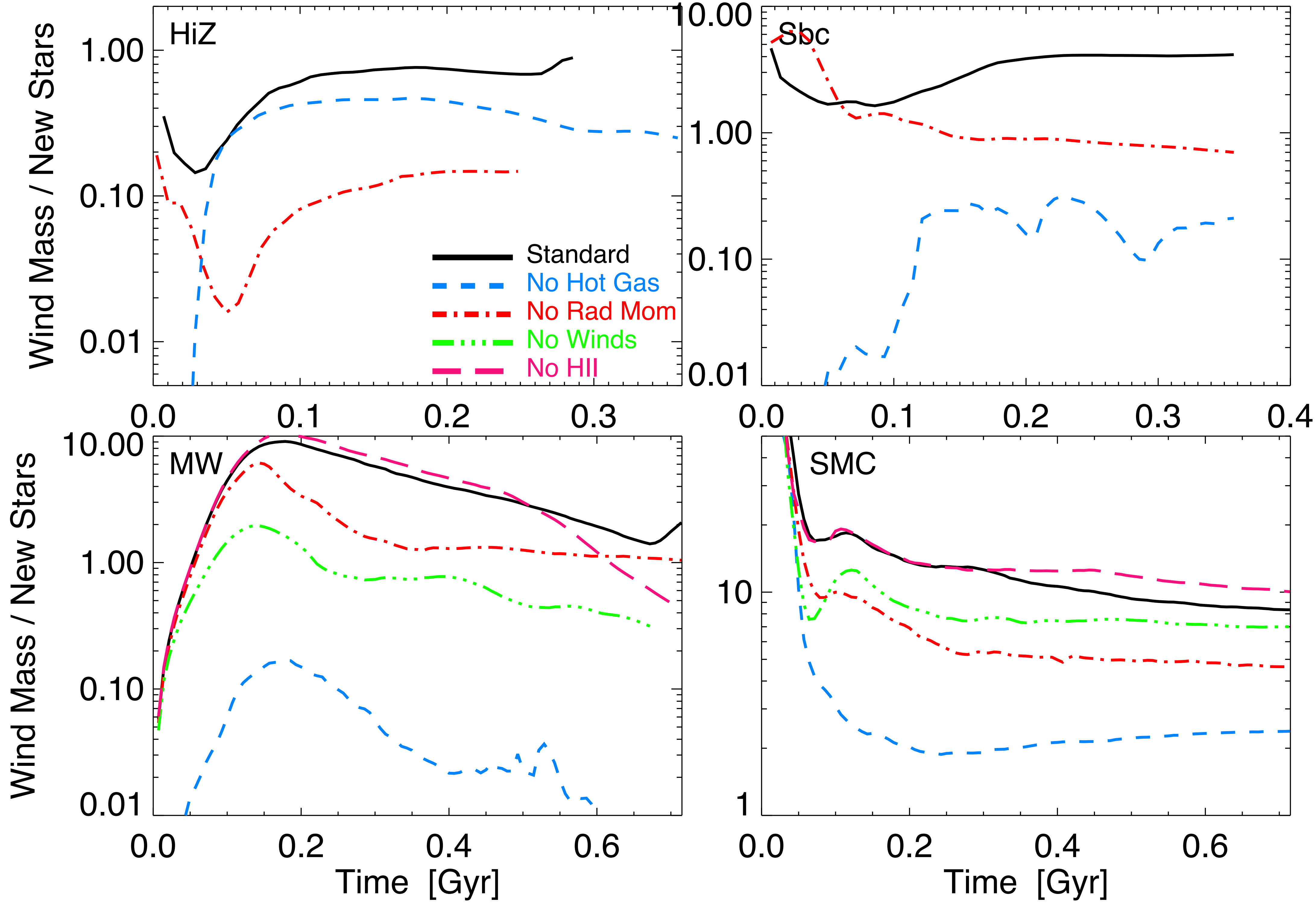
Different forms of feedback



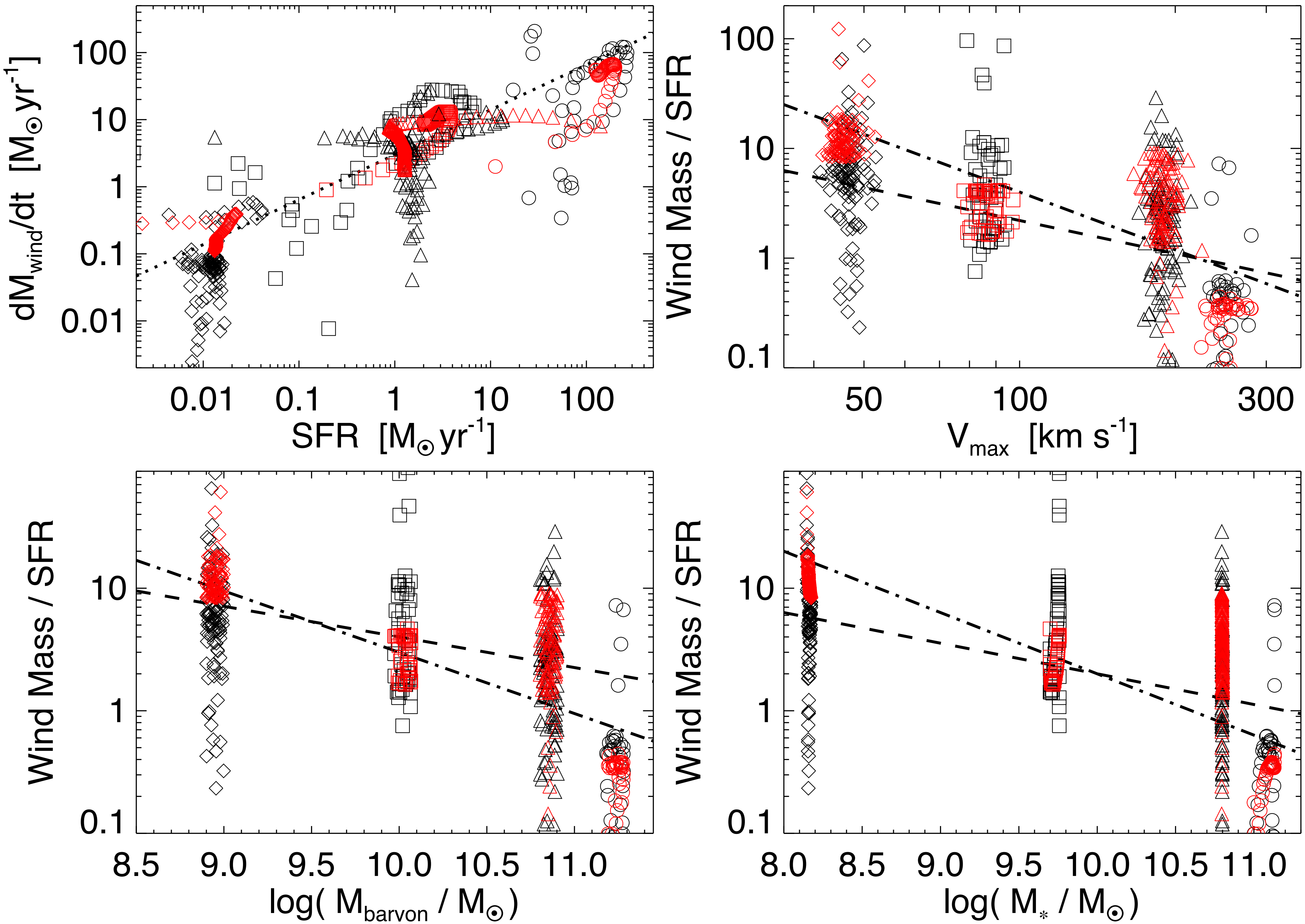
Different forms of feedback



simulated x-ray images



Wind Efficiency

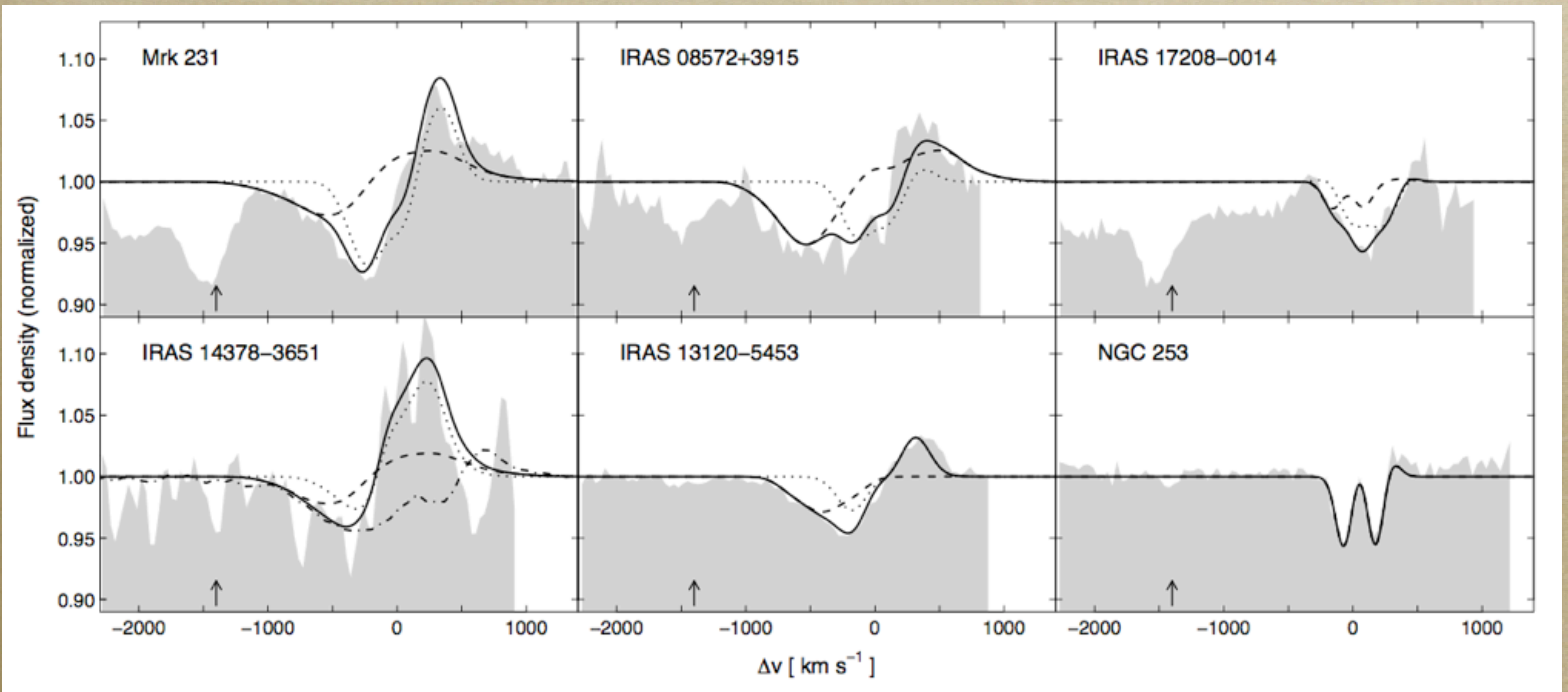


$$dM_w/dt = (dM_*/dt)\ v_c^{-1.1}\ \Sigma^{-0.5}$$

Conclusions

- *Radiative feedback is seen to act in the Milky Way (bubbles)*
- *Simple 1-D models, 3-D radiative MHD, and high resolution 3-D hydro calculations suggest radiation pressure is important in driving winds (and limiting the rate of star formation) in starburst/high z galaxies*
- *It looks promising as a way launching galactic winds and removing baryons from L_* galaxy halos, and aids SN in low mass halos*

Quaser mode feedback



Sturm 1105.1731

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*
- $E_{binding}=M_g v_c^2 = 10^{58} (M_g/10^{10}M_{sun})$ *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*
- $L_{cool}= \Lambda n^2 V =(\Lambda/4\pi m_p^2) v_c^4 f_g/(GR_d) \approx 7x10^{46} (v_c/280km/s)^4 (1kpc/R_d)$ *erg/s*

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:* $dM_w/dt\ v_w \le L/c$
    - $dM_w/dt \le \eta (c/v_w)\ dM_{acc}/dt$
- $L_w = (1/2)\ dM_w/dt\ \ v_w^2 = (1/2)(v_w/c)\ L << L$
- *Dunn et al. ApJ 709 611 estimate* $dM_w/dt \sim Lc/v_w$ *to several* 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* $\le L/c$*, which is what radiation pressure acting directly on the ISM gives---unless the AGN is completely shrouded.*

Quasar Mode Feedback

- *Momentum driving:* $dM/dt \leq L/(cv_c) \approx 200\Omega_{disk}$ *solar masses per year*
- *Since* $H/R = \sigma/v_c \approx 1/4$, $dM/dt \approx 50\ M_{sun}\ yr^{-1}$
- *Compare to 100-1000* $M_{sun}\ yr^{-1}$*; endgame only*
- *But, if either (or both) the photons and hot (shocked) BAL wind are confined can drive gas to* $v \geq 1000 km/s$*, which is difficult to do with stars, AND increase* dP/dt

Conclusions

- *Radiative feedback is seen to act in the Milky Way (bubbles)*
- *Simple 1-D 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 currently lacks a compelling physical mechanism for removing gas from the ISM during the peak of a starburst: but there are some live possibilities*