FEEDBACK AND GALAXY FORMATION

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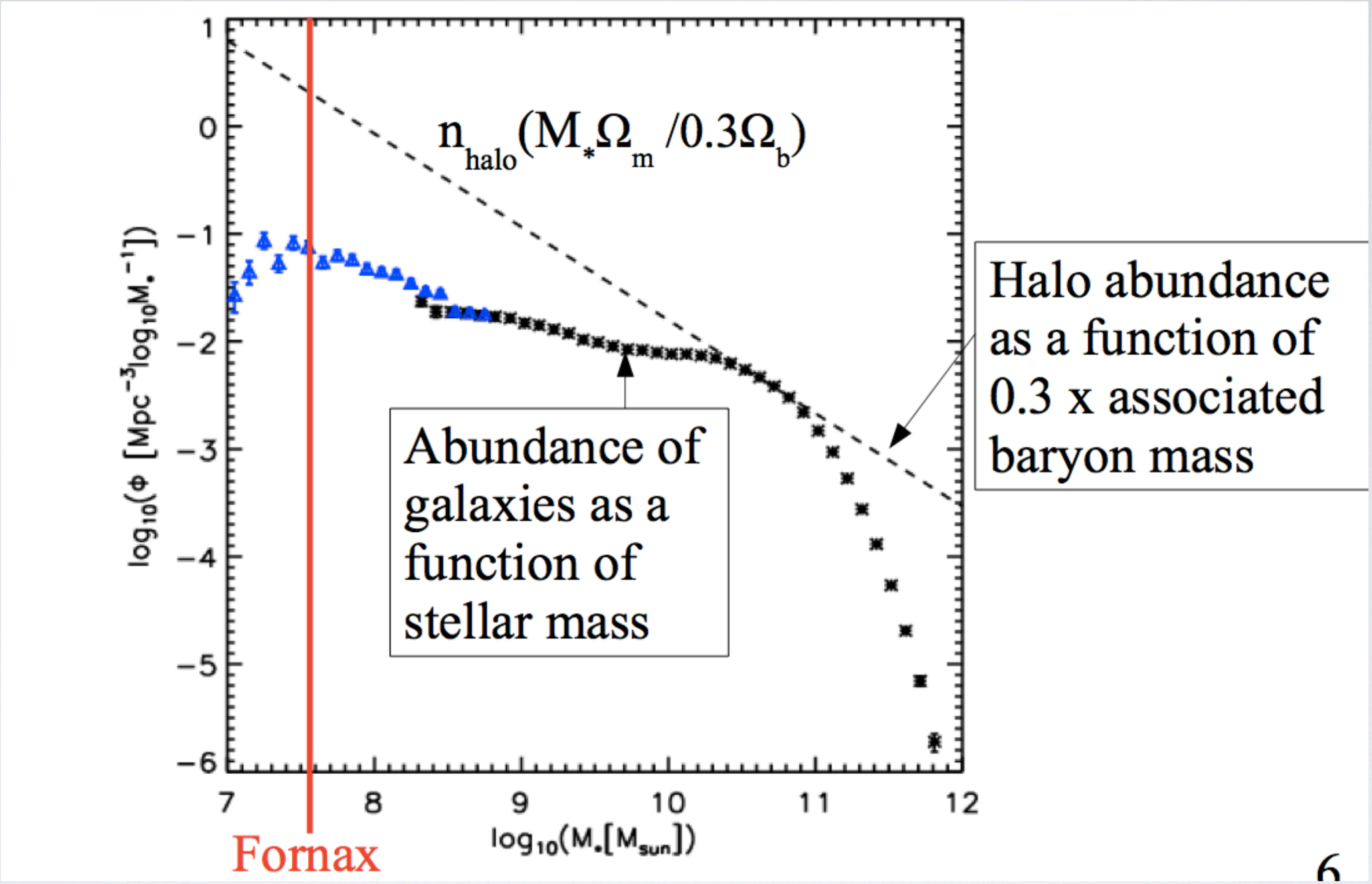
OUTLINE

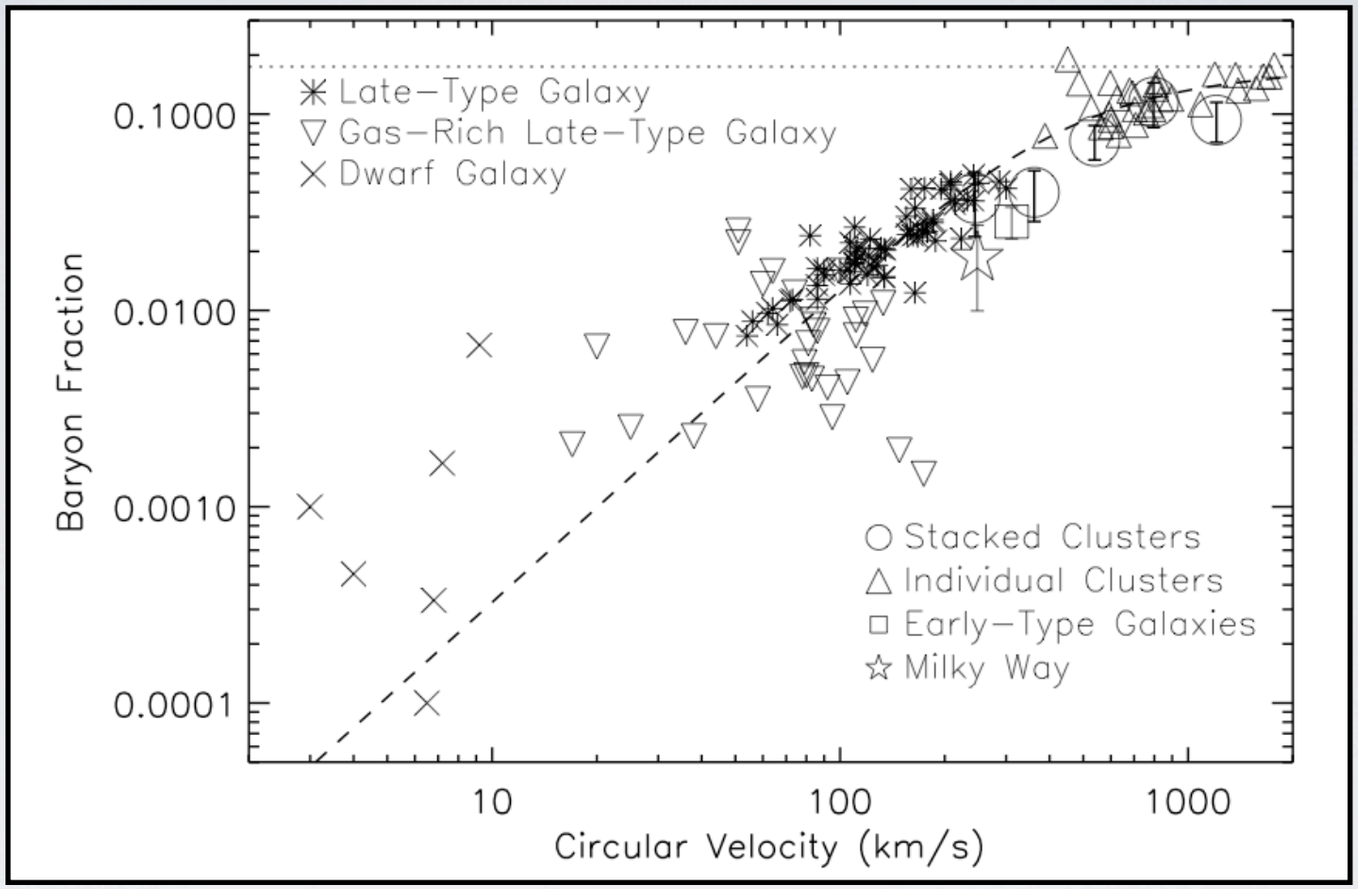
- *Galaxy Phenomenology*
- *Small scale feedback & winds*
- *GMC simulations*
- *Galaxy scale simulations of stellar driven outflows*

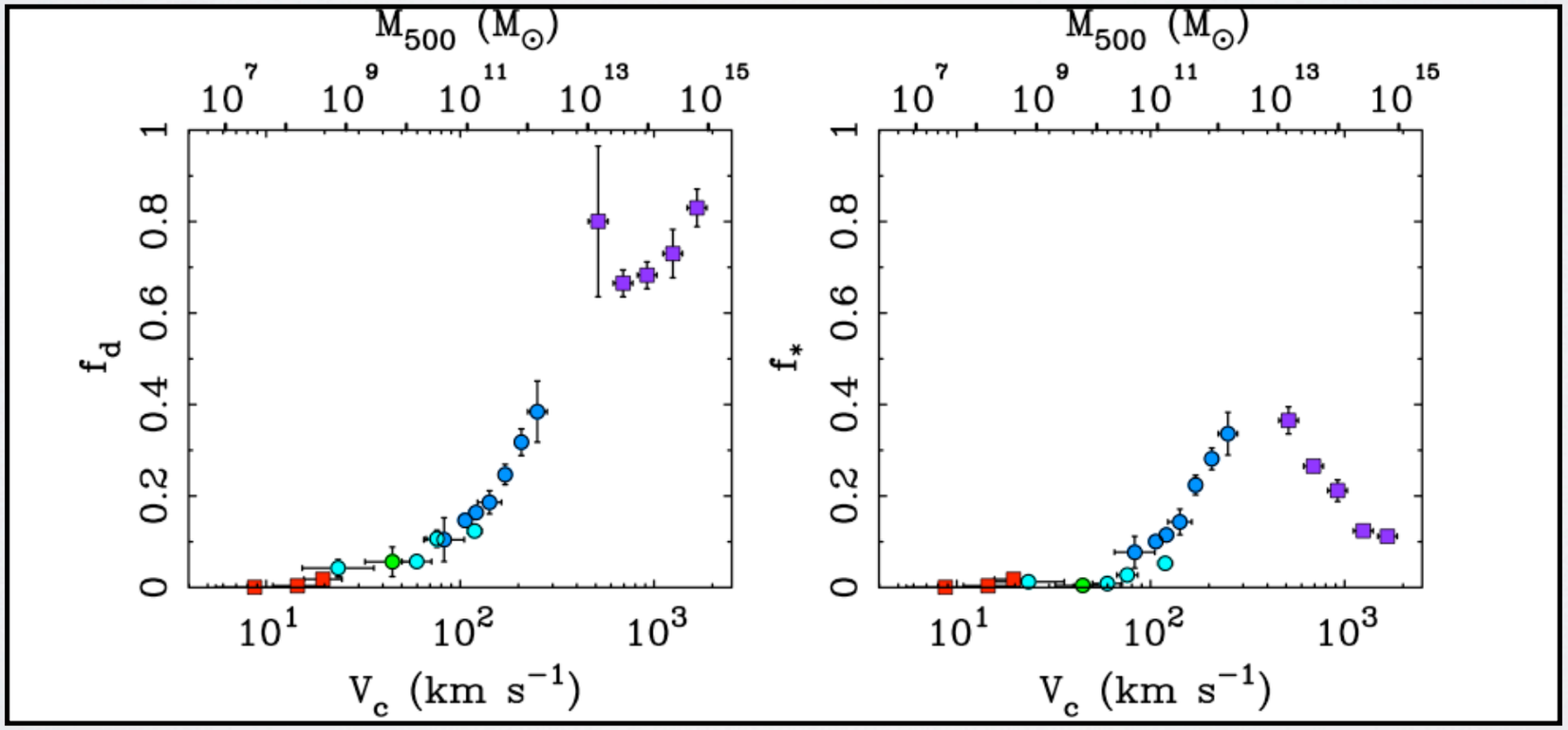


HALOS OUTNUMBER GALAXIES

Credit: Simon White

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

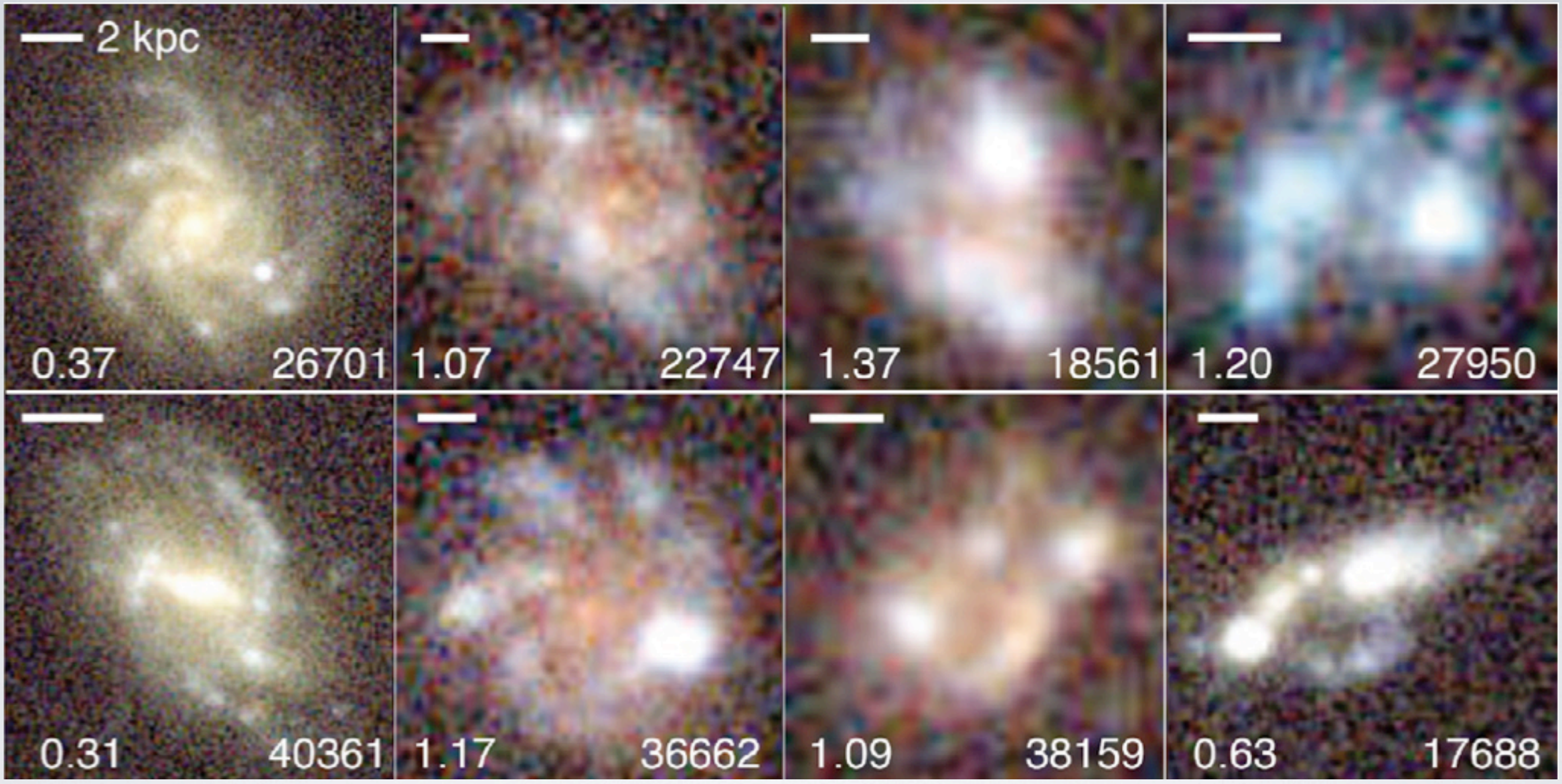




MCGAUGH ET AL. (2010) APJL, 708, 1

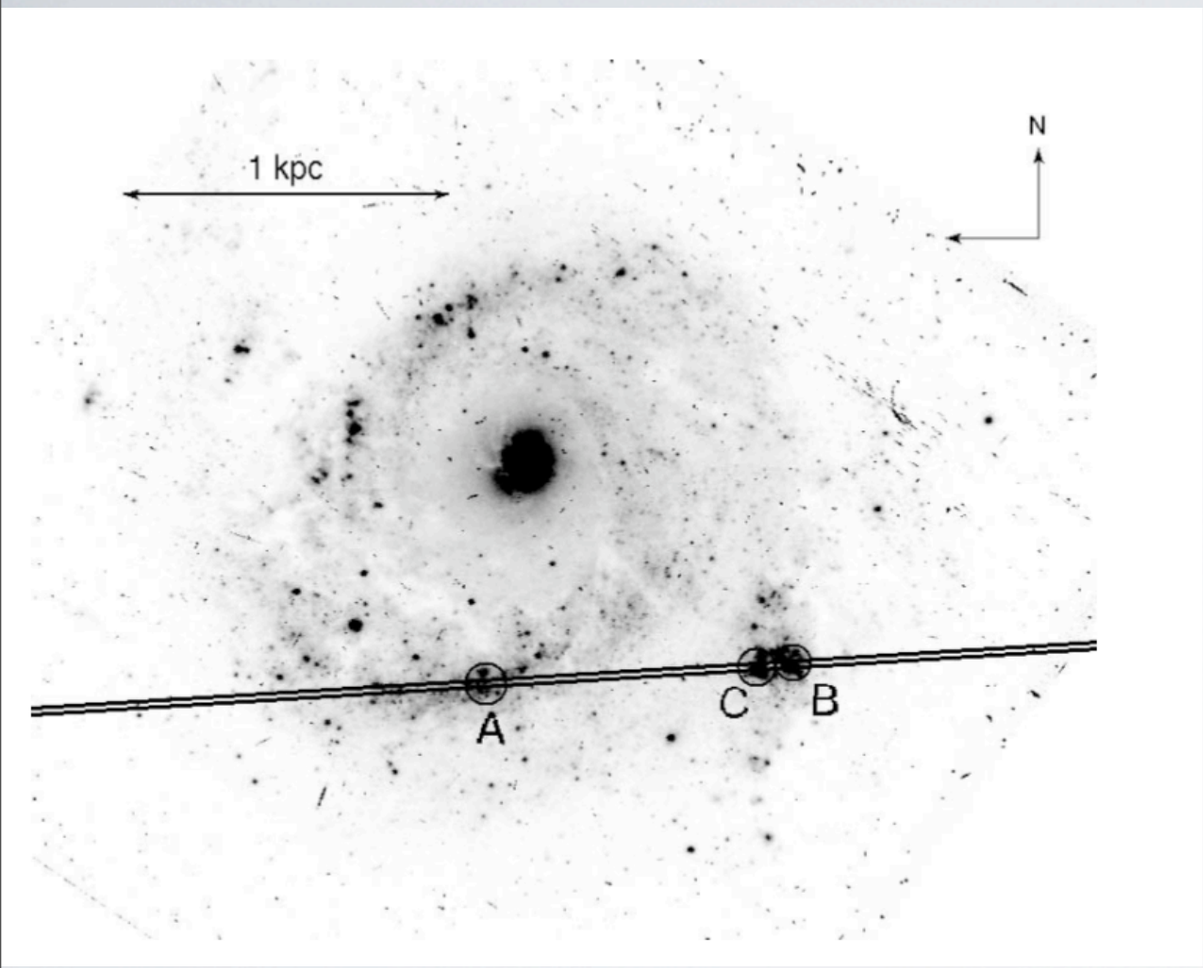
OUTFLOW PHENOMENOLOGY

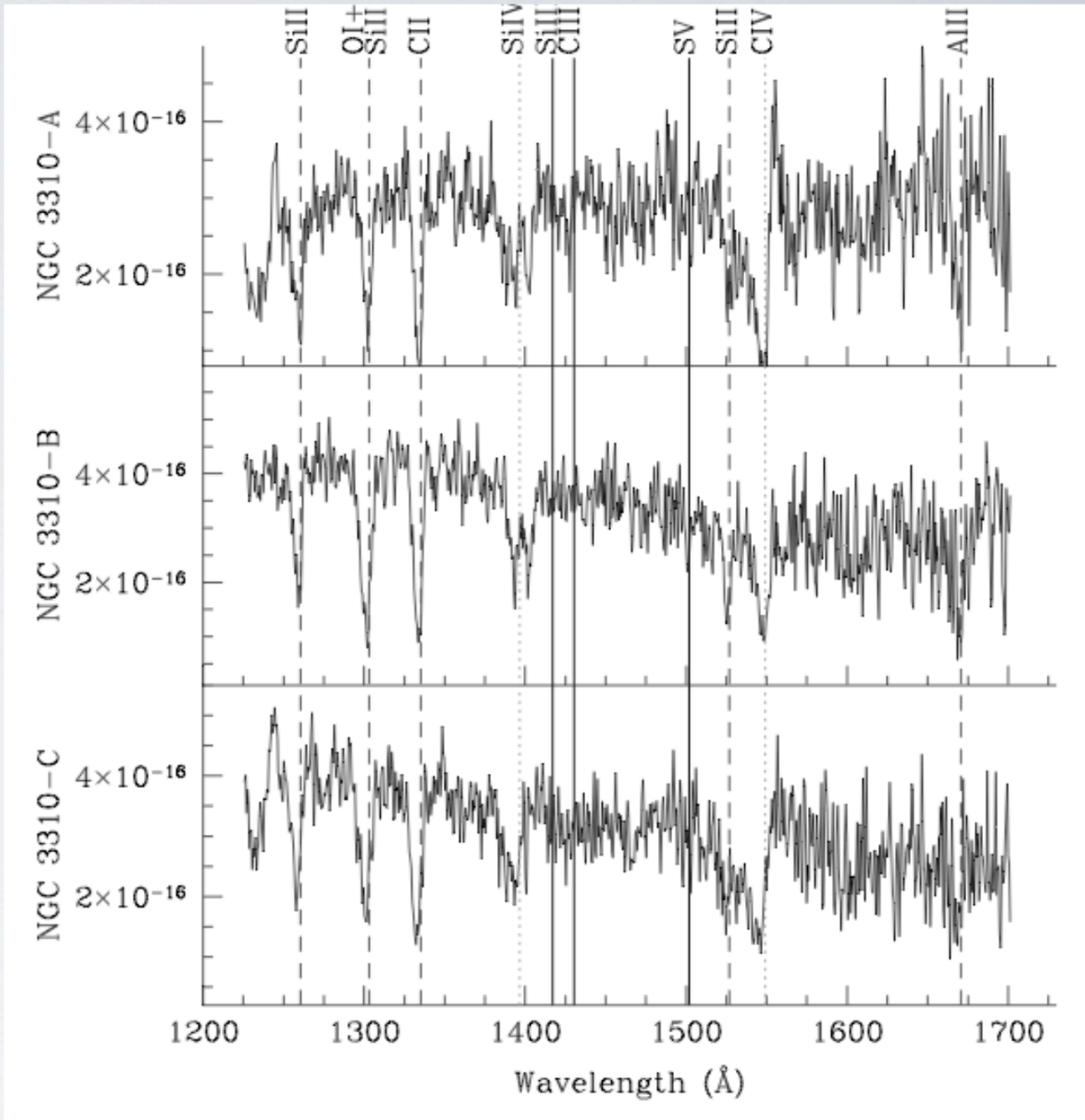
- Star forming galactic disks have $Q \approx 1$, and GMCs/clumps; disruption of GMCs requires (nuclear powered) feedback throughout the galaxy
- We see outflows of ~100s of km/s from individual star clusters and GMCs
- We see winds in all high z star forming galaxies, but few of these galaxies have AGN; so most of these winds are not accretion powered (by AGN)
- AGN have a low duty cycle (compared to star formation) so they do not drive out the bulk of the disk baryons (though they may prevent the bulk from entering!)
- Broad absorption lines show that quasars drive outflows from $r \ll 1$pc
- See >1000km/s molecular outflows in nearby AGN powered ULIRGS
- See fast outflows from radio galaxies



GMCS AND CLUMPS

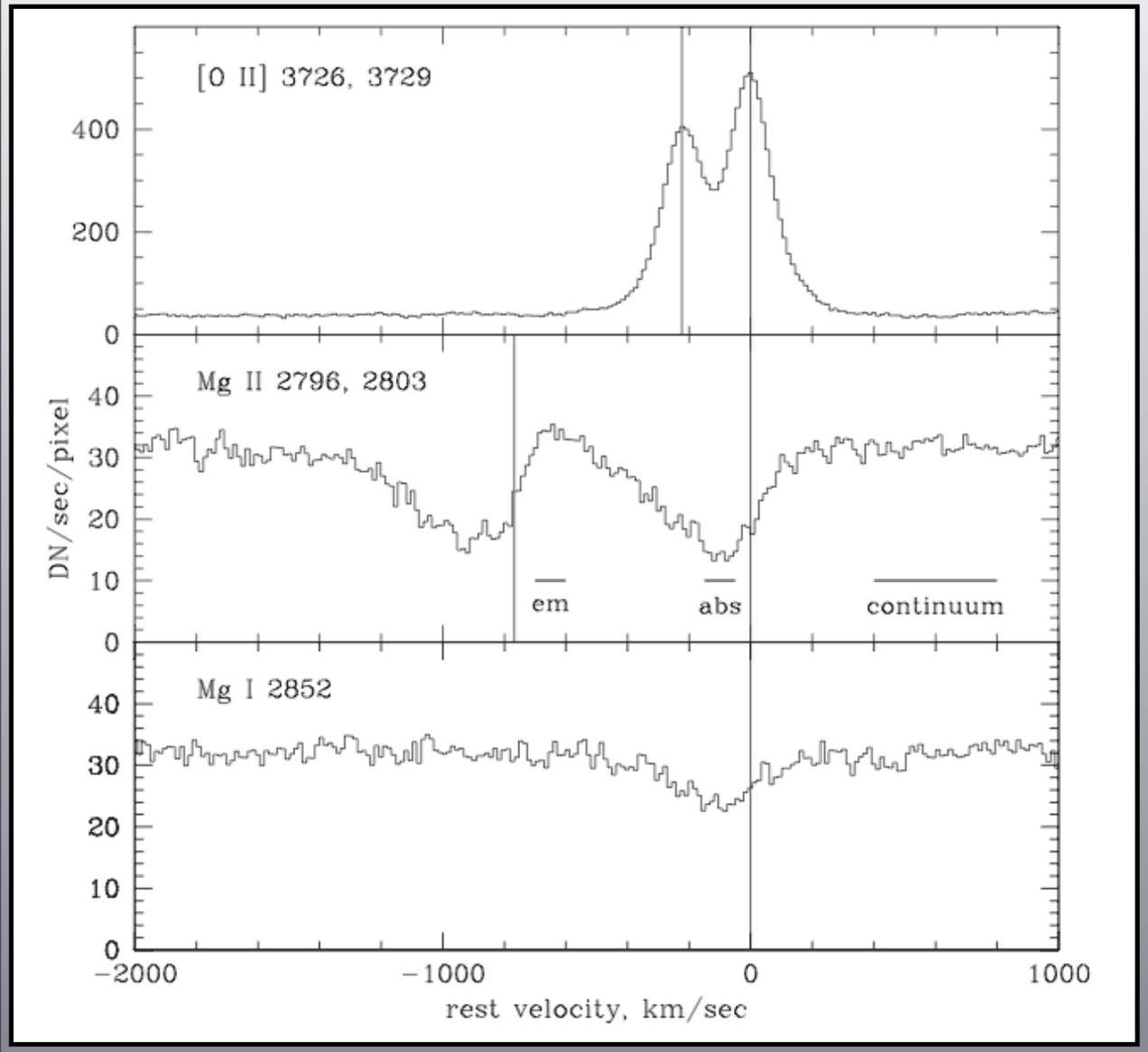
Spiral galaxies with GMCs on the left, clump galaxies on the right (Elmegreen et al ApJ 701 306 2009)

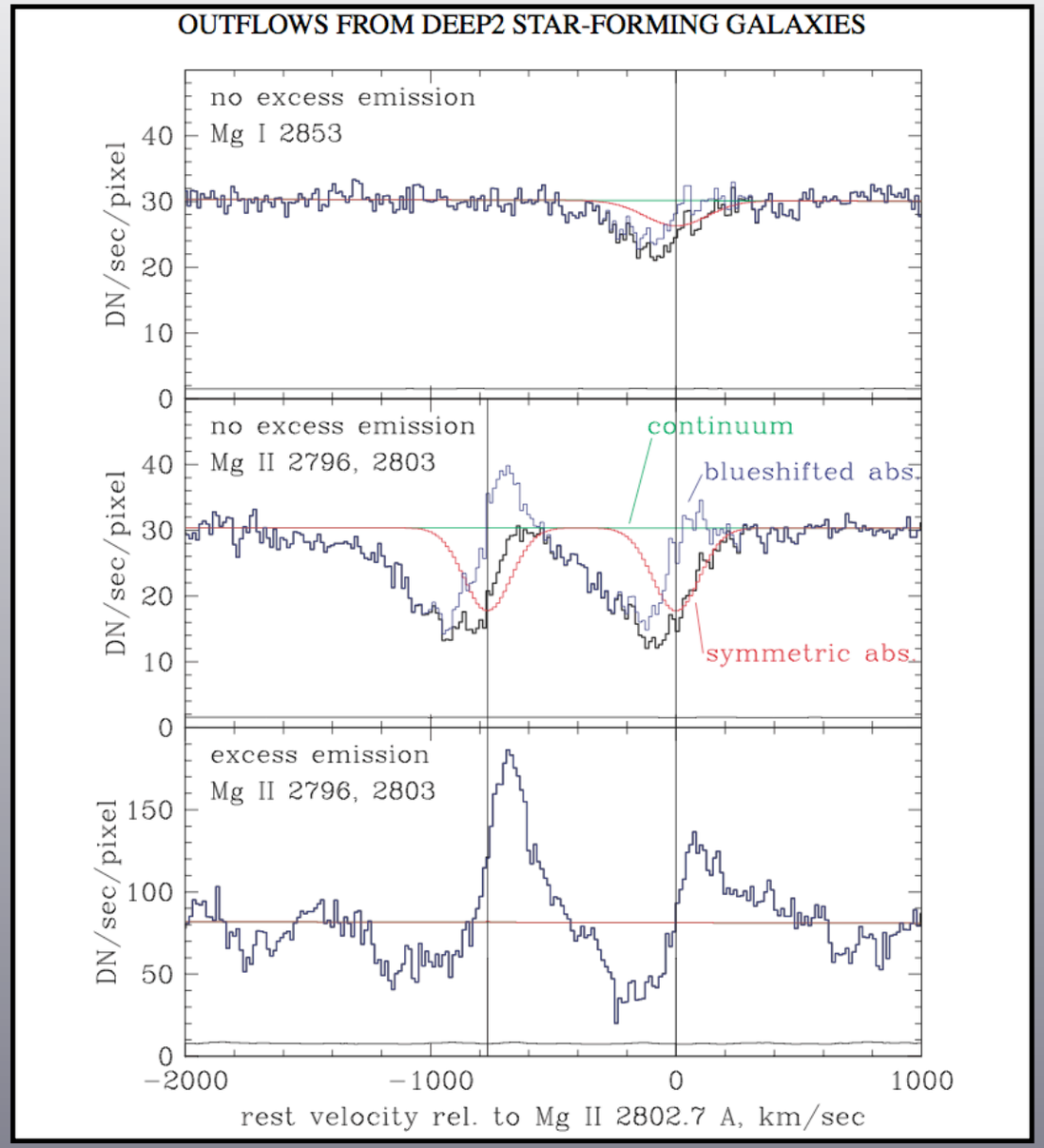




NGC 3310

Schwartz et al. (2006) ApJ 646 858





WINDS IN STACKED SPECTRA OF Z=1 GALAXIES

Weiner et al. ApJ 692 187 (2009)

DRIVING OUTFLOWS 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
  - Usually subject to radiative losses---not relevant in low mass galaxies, but in ULIRGs and SMGs this is a major problem. BALs, when shocked, may not be radiative
- Momentum: deposit momentum into the ISM, pushing it around
  - sources: HII regions, radiation pressure, BAL winds, cosmic rays, jets
  - not subject to radiative cooling

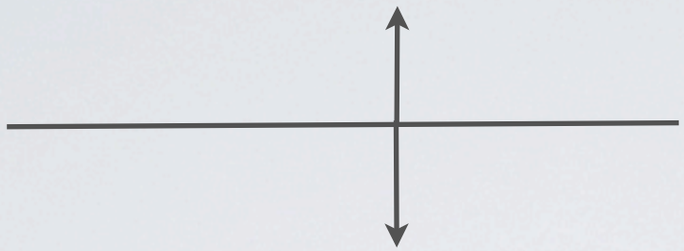
WHY IS ENERGY DRIVING ATTRACTIVE?

- Accelerating gas: $d\mathcal{P}/dt = d/dt\,(M(r)\,v) = 4\pi r^2 P$
- $P = E/V = E/r^3$ if E=const, momentum increases with time
- $\mathcal{P} = (2M_{sh}\,E)^{1/2}$; $\mathcal{P}_f = (M_f/M_{in})^{1/2}\mathcal{P}_{in}$ f=end of E cons. phase
- For SN, $\mathcal{P}/M_* = 3000$km/s
- For a single SN, $\mathcal{P}_{max} = 5\times10^{43}\,n^{1/5}$ g cm/s

WHY IS MOMENTUM DRIVING ATTRACTIVE?

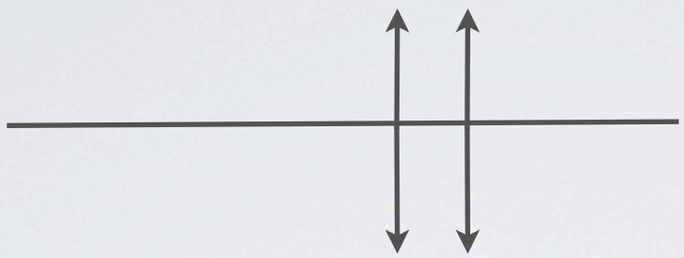
- $\rho dv/dt = -dP/dr - \rho\,(v_{dyn}^2/r) + (1+\tau)L/c + F_{cr} + \ldots\ldots$
- SN: P jumps instantly => $v >> v_c$
- L, F_{cr}, change on times longer than the dynamical time, until L/c (or other force) exceeds the local gravity, when things start to move. As a result, $v \sim v_{dyn}$
- if local gravity is v_c, then a galactic wind with $v \sim v_c$ will result

$\tau=1$



$F_{obs} = \sigma T_{eff}^4$

$\tau=2$



2F

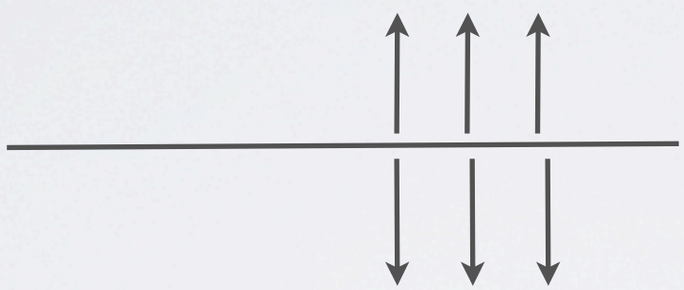
By induction

$F(\tau) = \tau F_{obs}$

$F_{obs} = \sigma T_{eff}^4$

$T(\tau) = \tau^{1/4} T_{eff}$

$\tau=3$



3F

$P_{rad} = aT^4 = a\tau T_{eff}^4$; $F_{rad} = A\Delta P_{rad} = A\tau\, aT_{eff}^4$

$= A\tau\sigma T^4/c = \tau L/c$

Need Radiative Feedback in the Milky Way

Carina: M= $5 \times 10^5 M_{sun}$ v= 10 km/s, $\mathfrak{P} = 10^{45}$, or 10 SN worth

$\mathfrak{P} = L/c * \text{age} = 4 \times 10^{44}$

Nathan Smith/Spitzer Carina

BLOWING UP GMCS IN COLOR 3D

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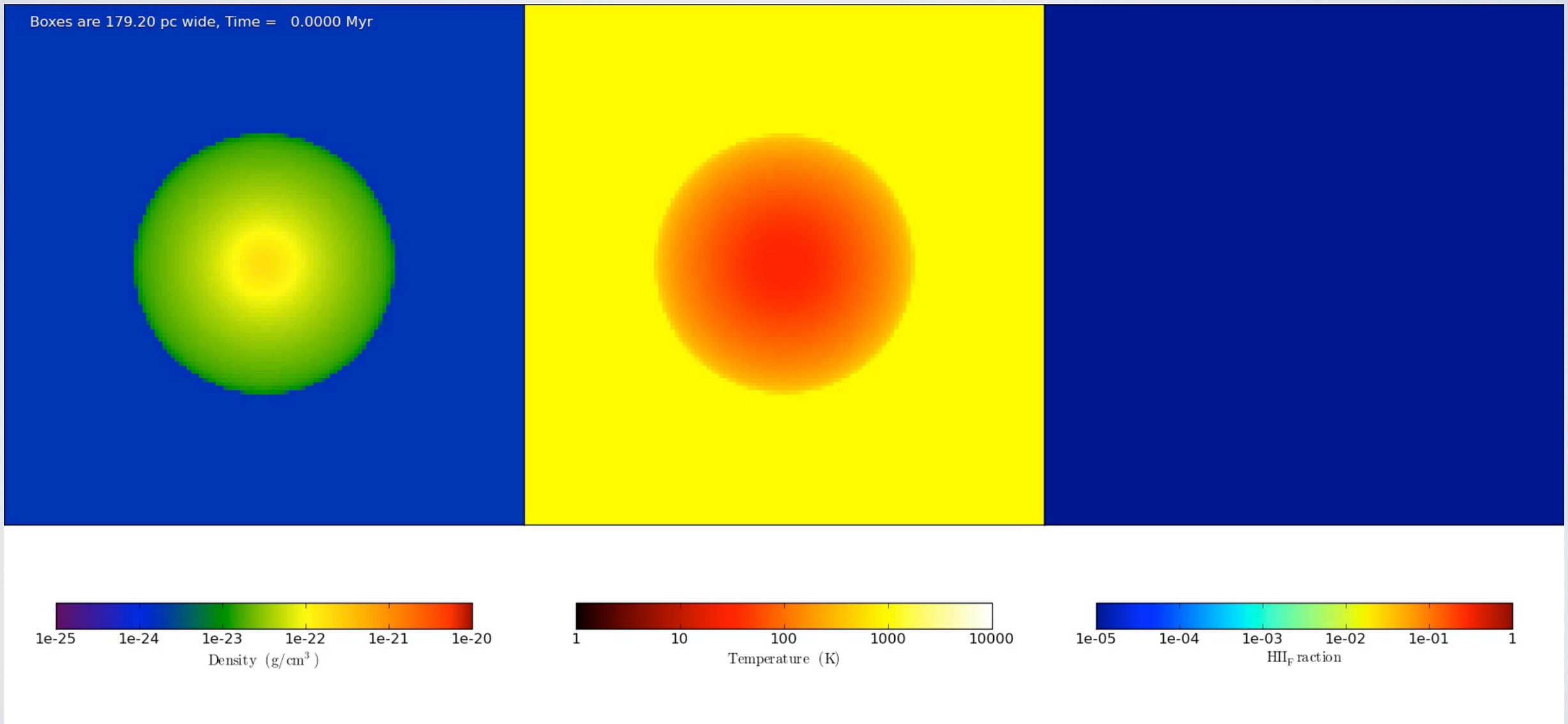
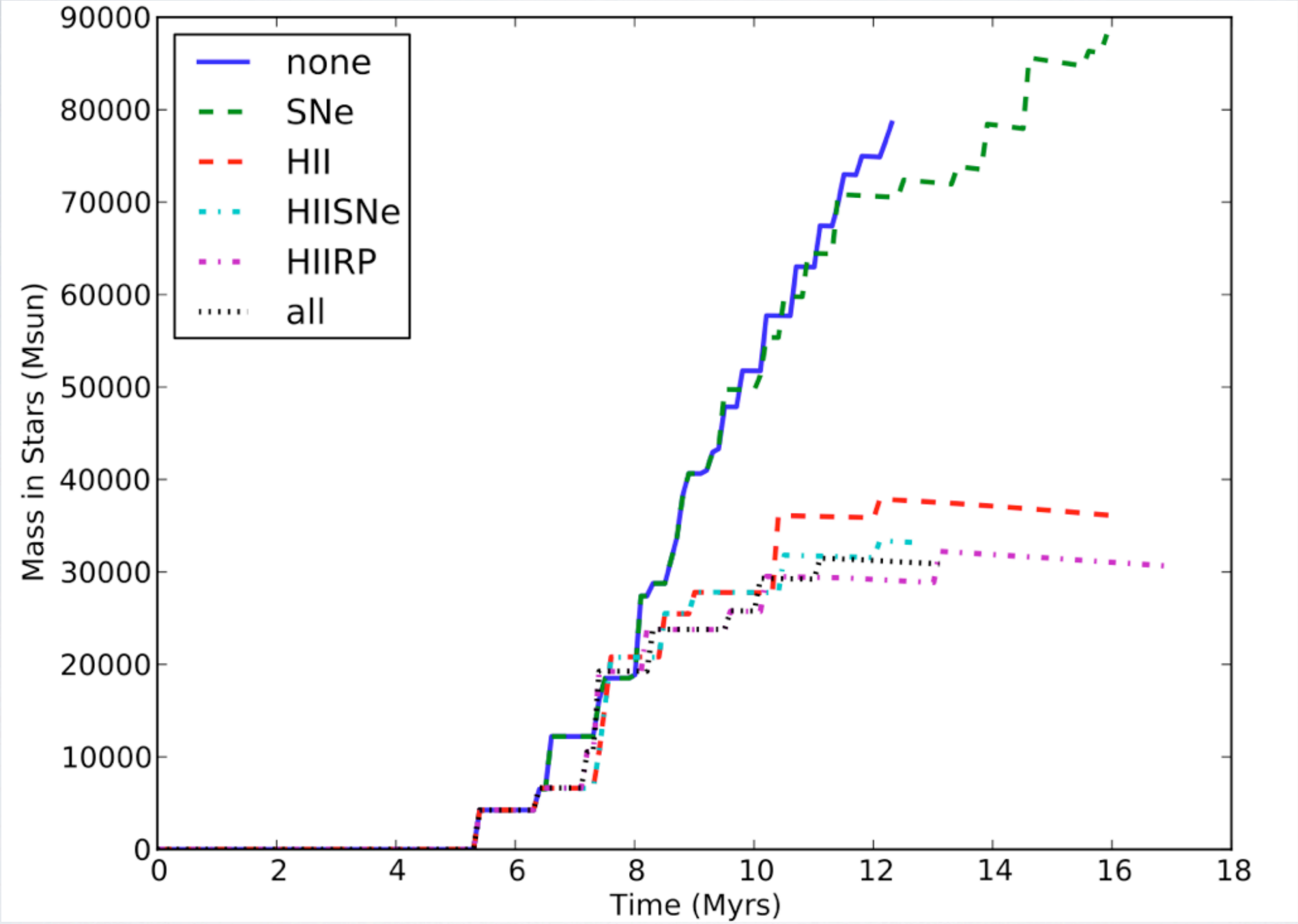
Harper-Clark; ENZO2 raytracing

BLOWING UP GMCS IN COLOR 3D



Harper-Clark; ENZO2 raytracing



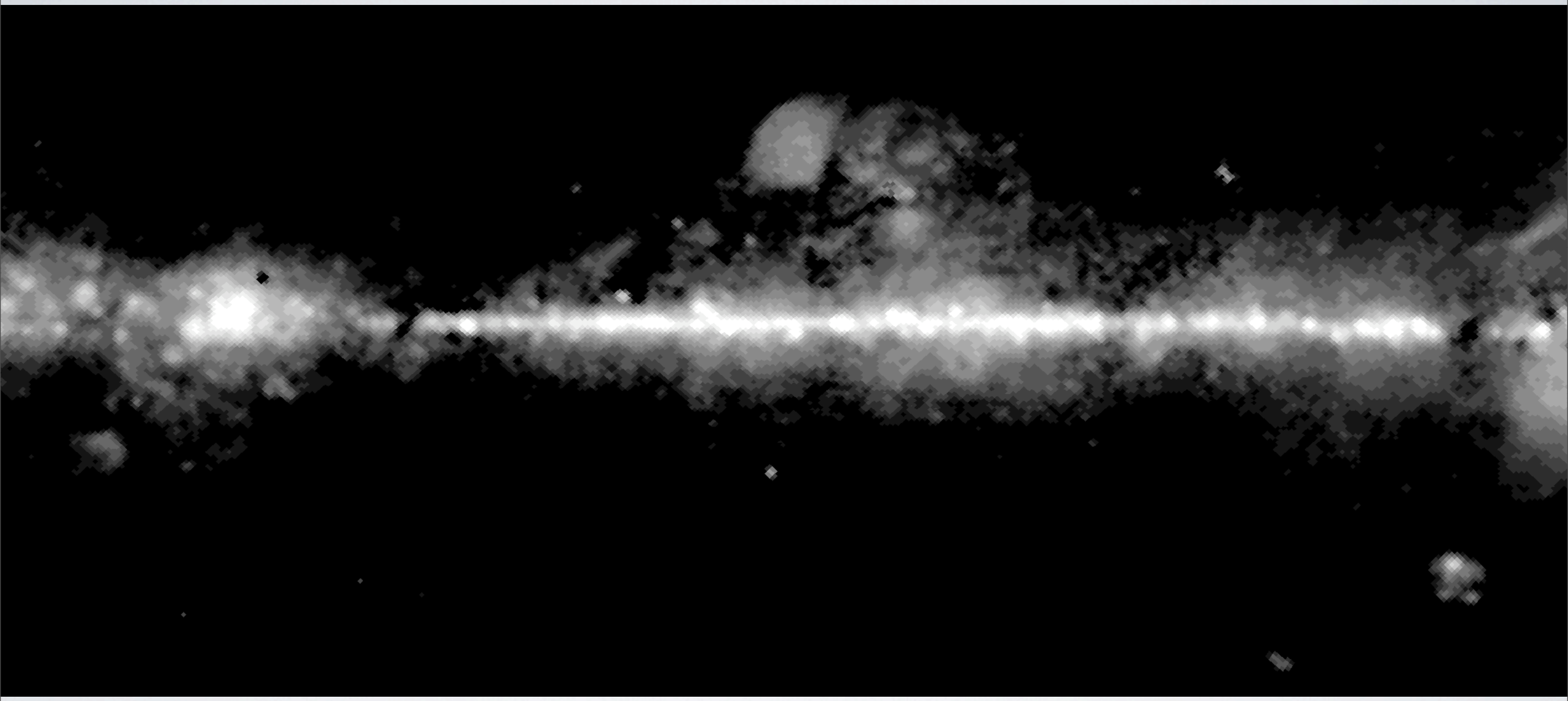
Note SN have little effect

STELLAR MASS VS TIME FOR DIFFERENT FEEDBACK

NOTE SNE MAKE NO DIFFERENCE (CYAN)!

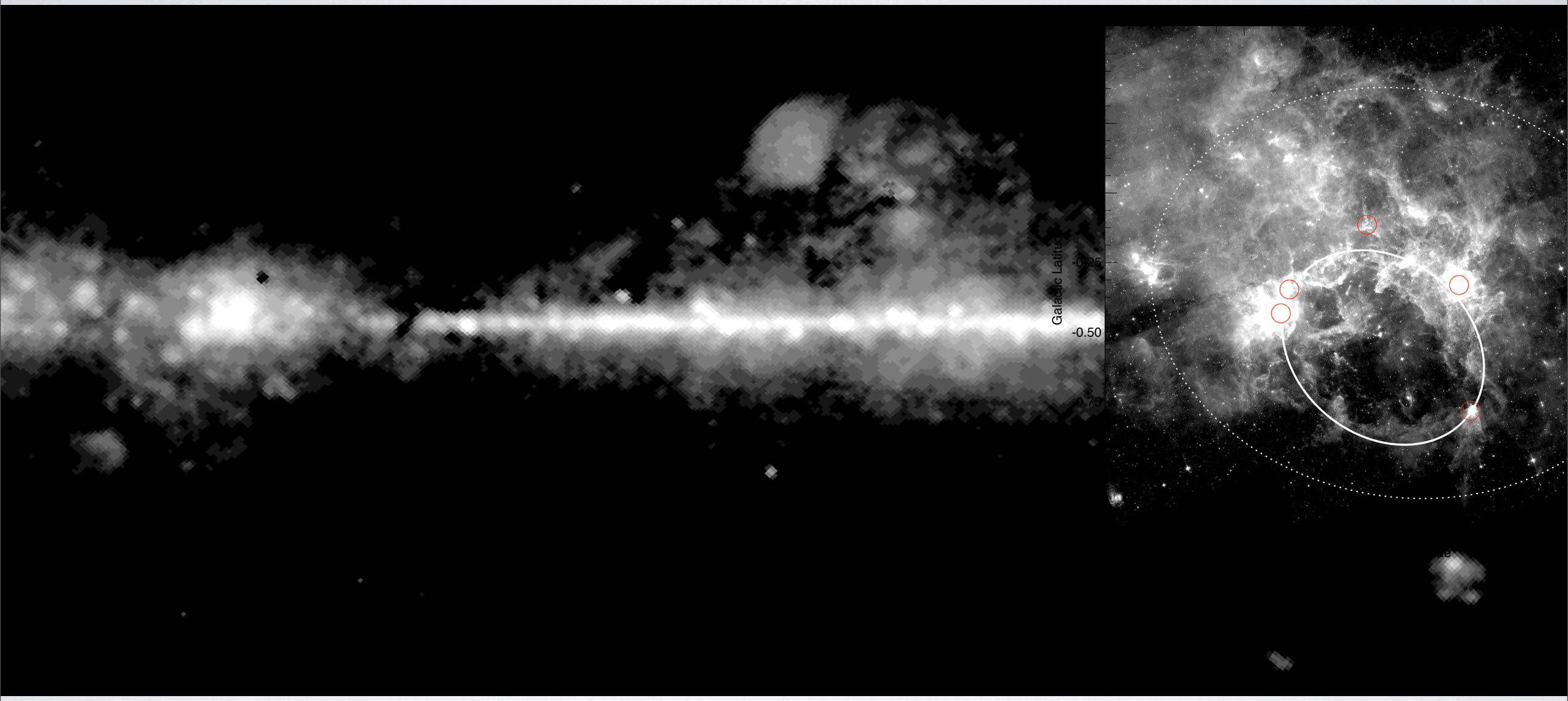
$\varepsilon_{GMC} \approx 0.1$

Star formation, and feedback, is stochastic and intermittent!



WMAP FREE-FREE EMISSION
HALF THE GALAXY'S STAR FORMATION OCCURS IN 5% OF THE GMCS

Star formation, and feedback, is stochastic and intermittent!



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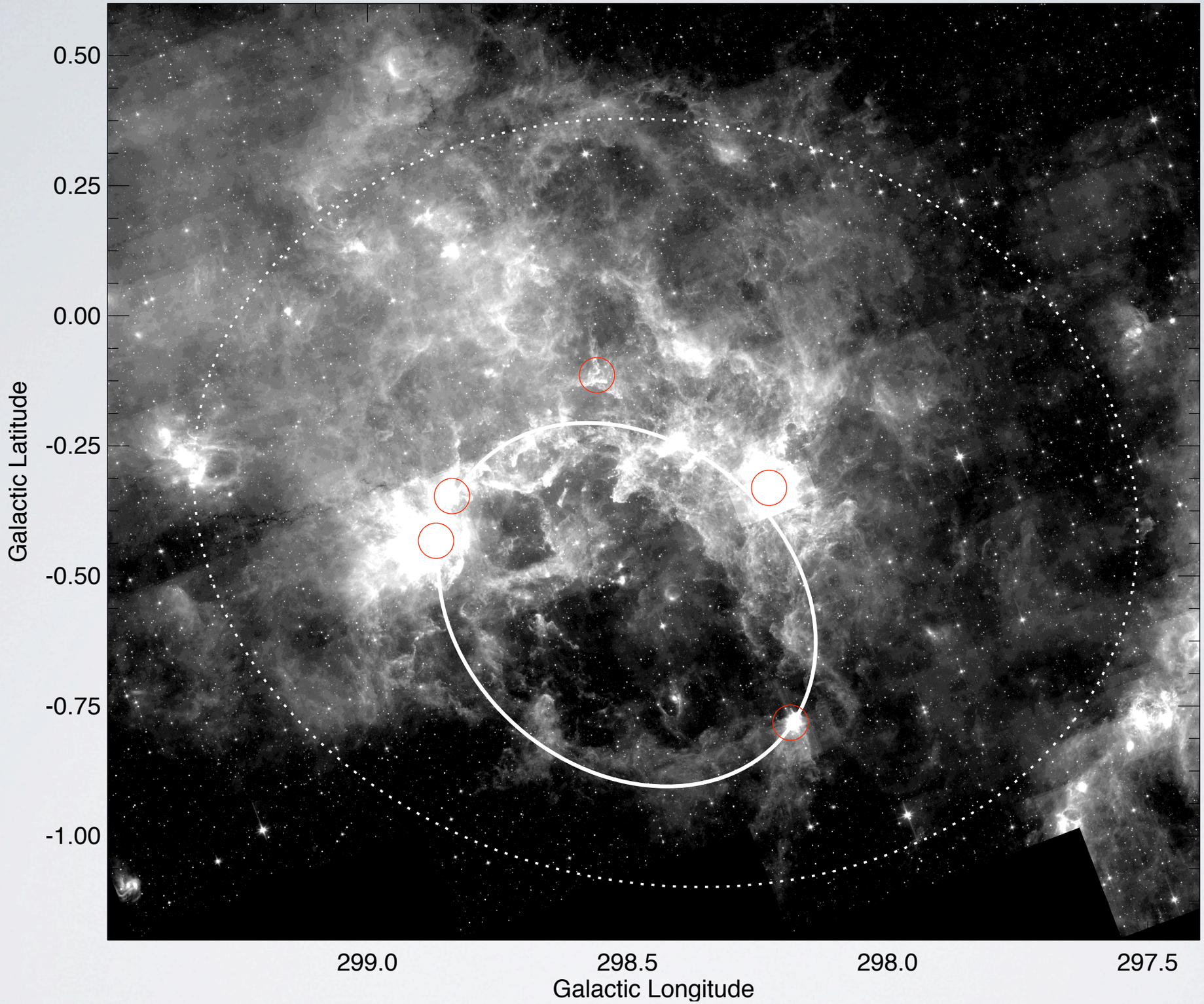
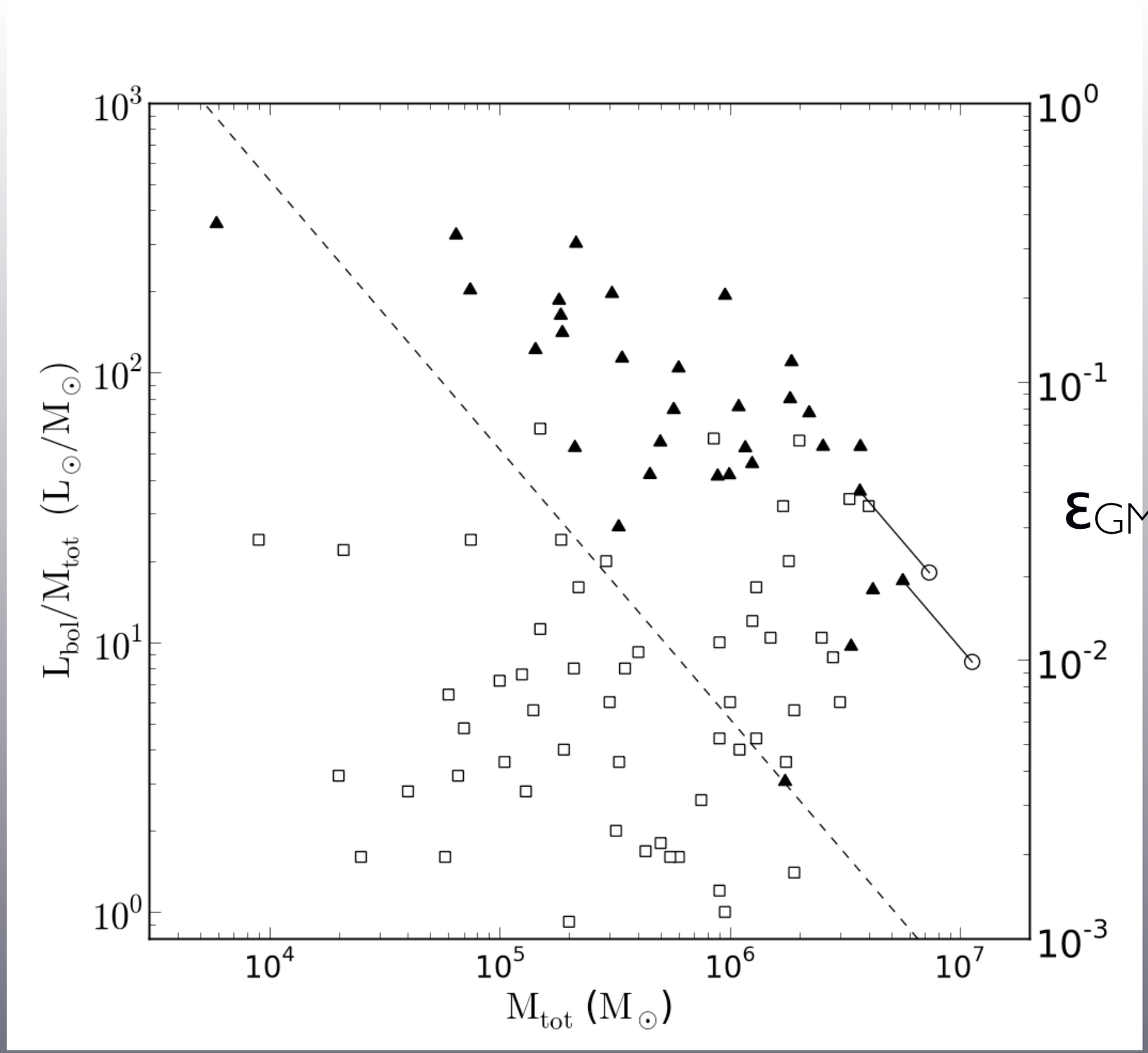
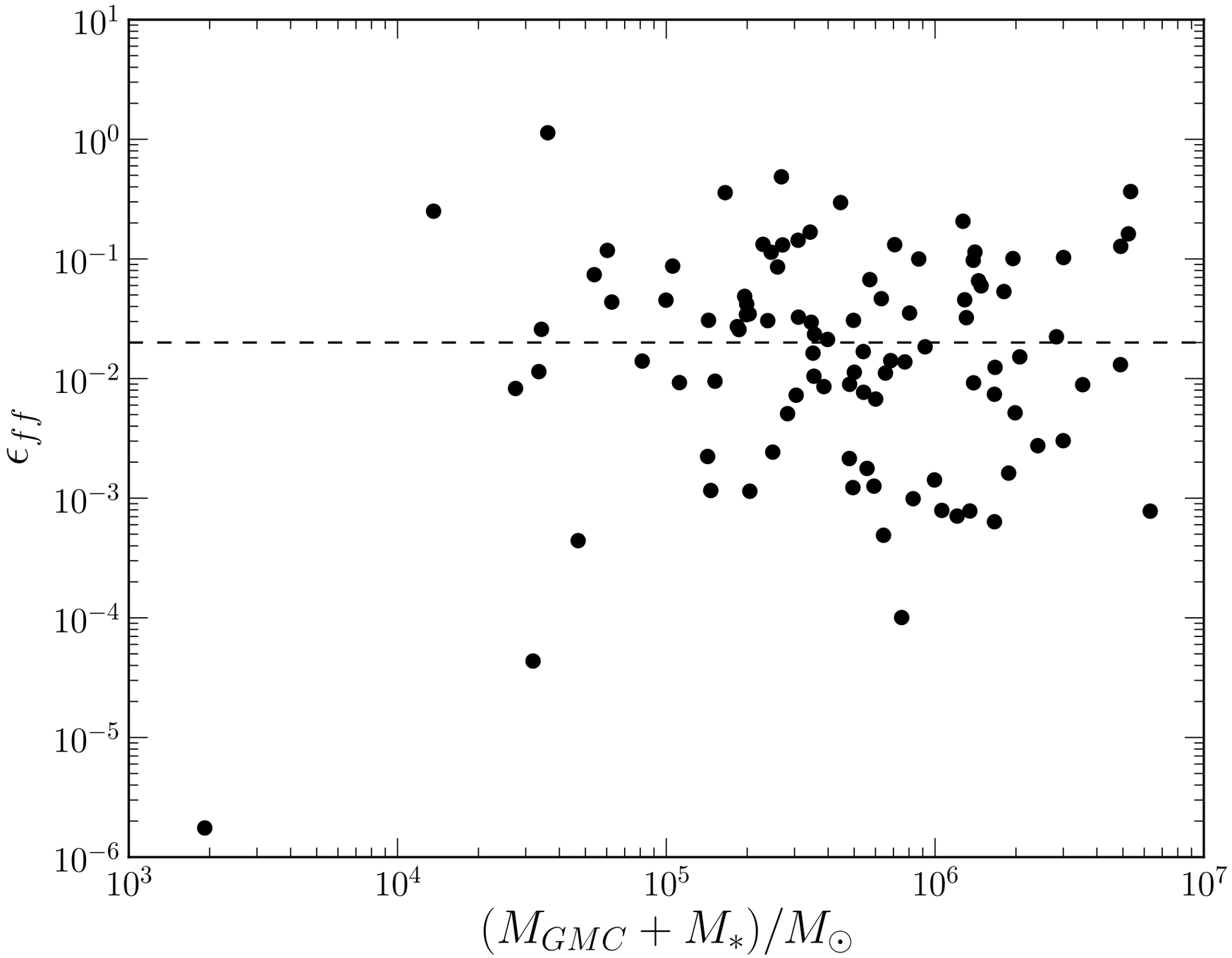


A MASSIVE STAR CLUSTER (~$10^5 M_{SUN}$)

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



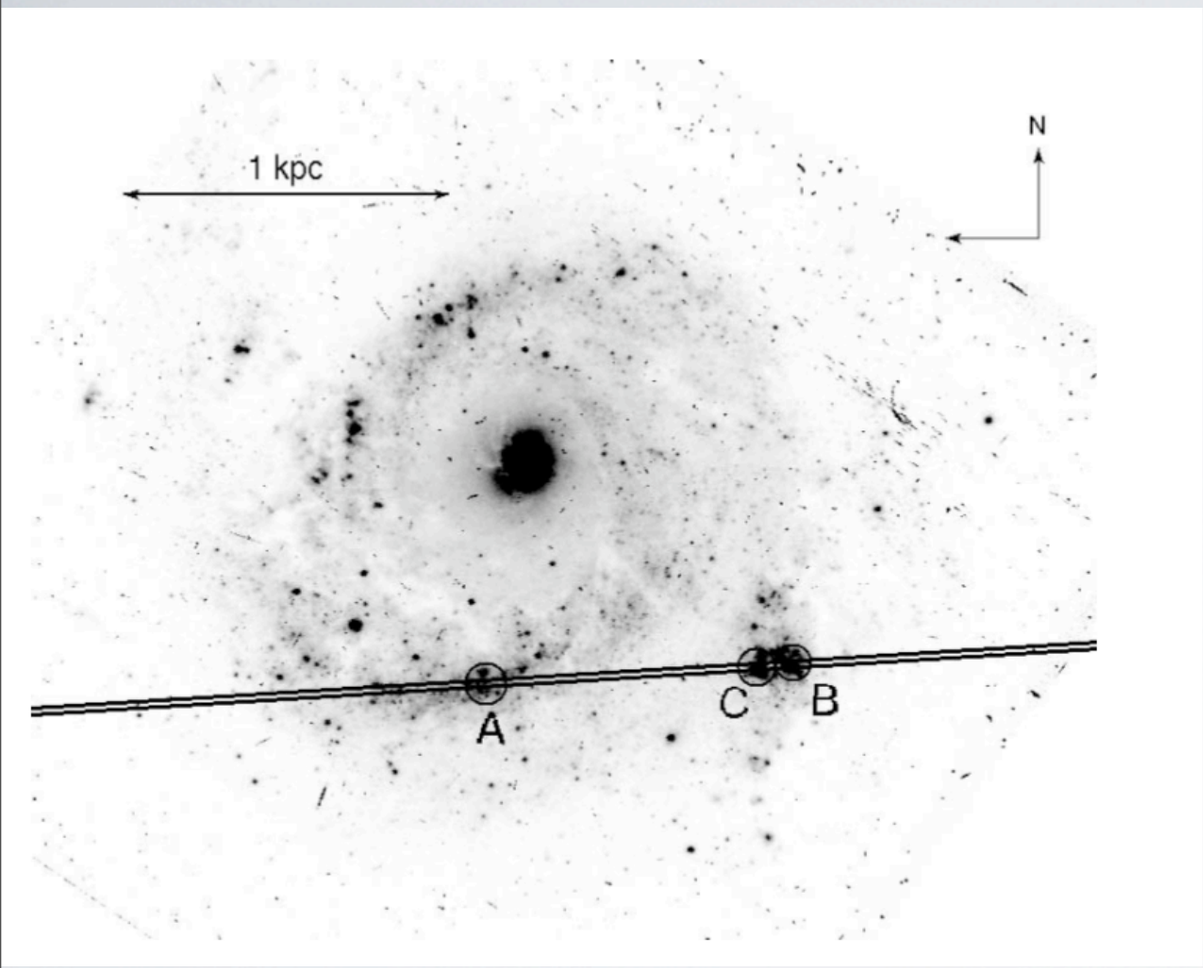
Mooney& Solomon ApJ 334 51 (1988)

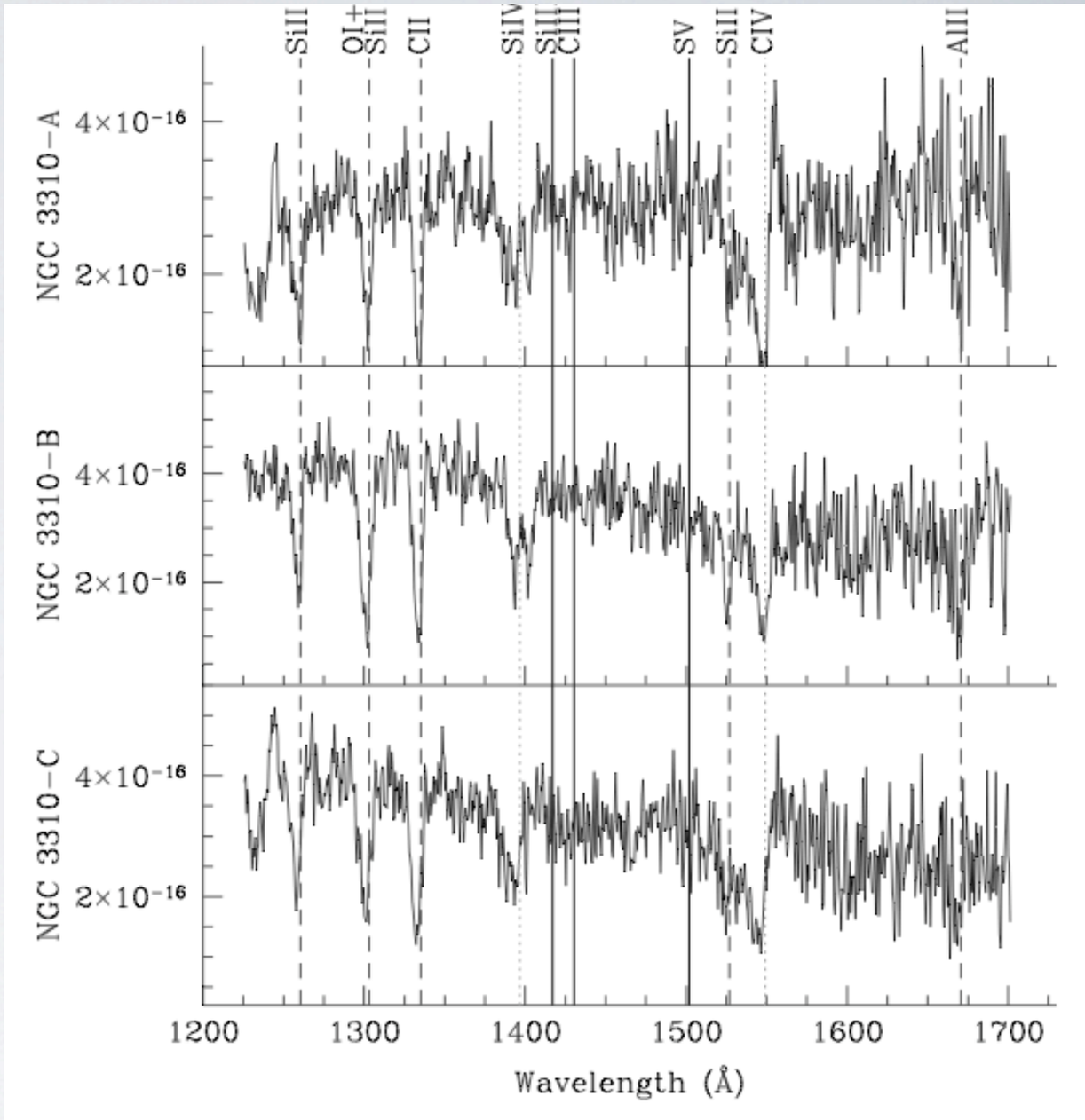


RAPID STAR FORMATION IN THE MILKY WAY

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

PUSHING WITH HOT GAS DESTROYS COLD CLOUDS

Cooper et al. ApJ 703 330 (2009)

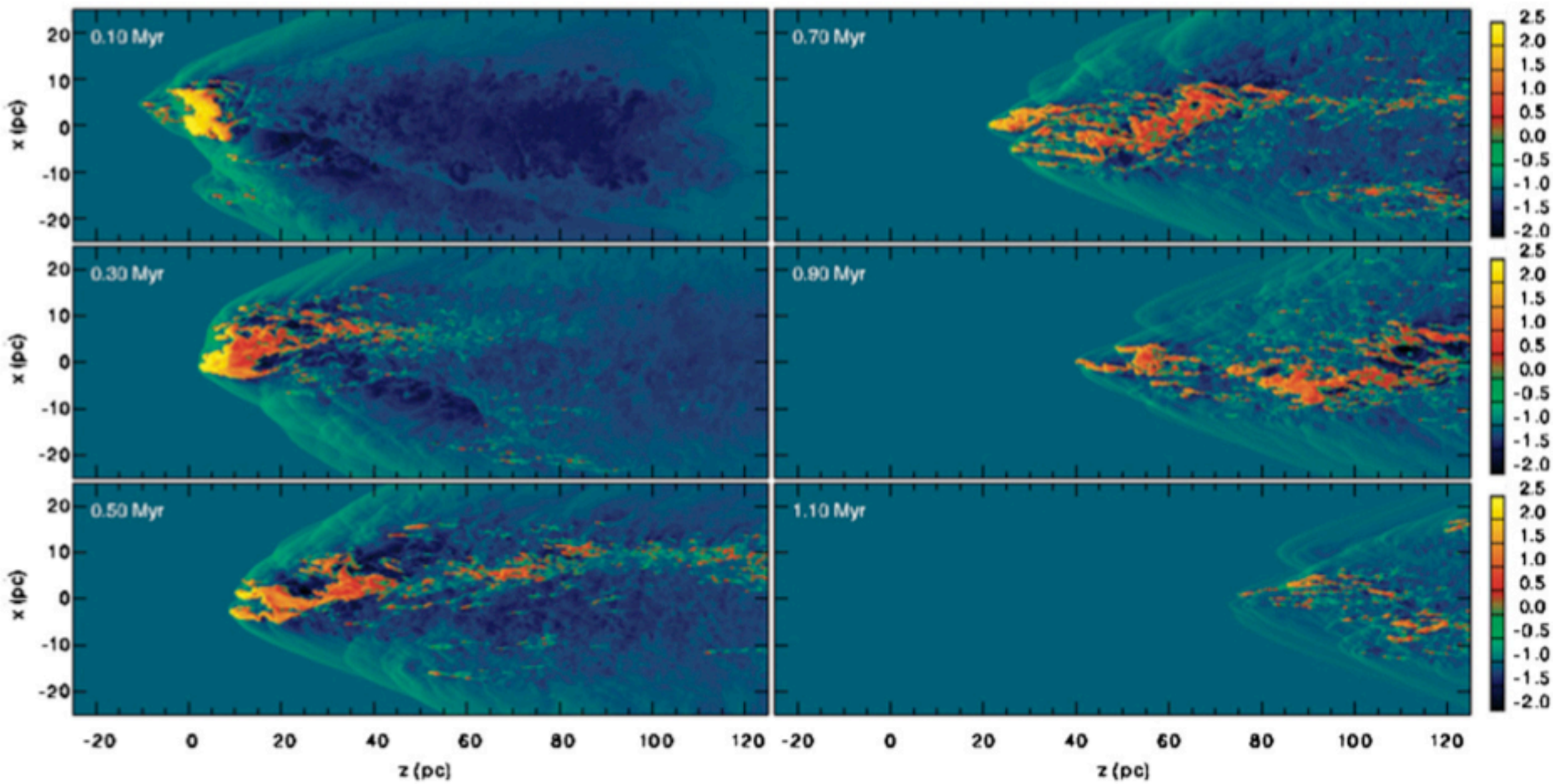
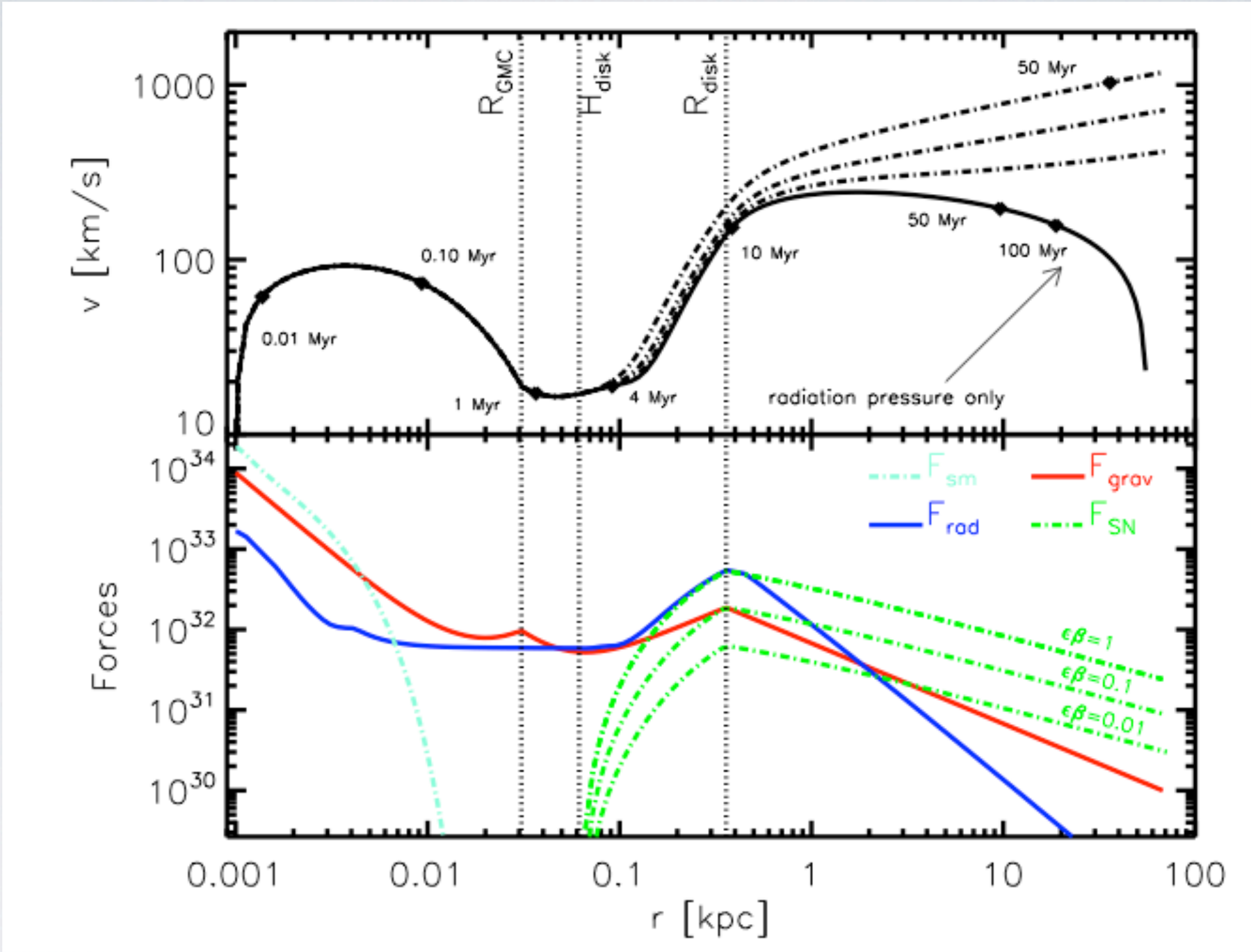
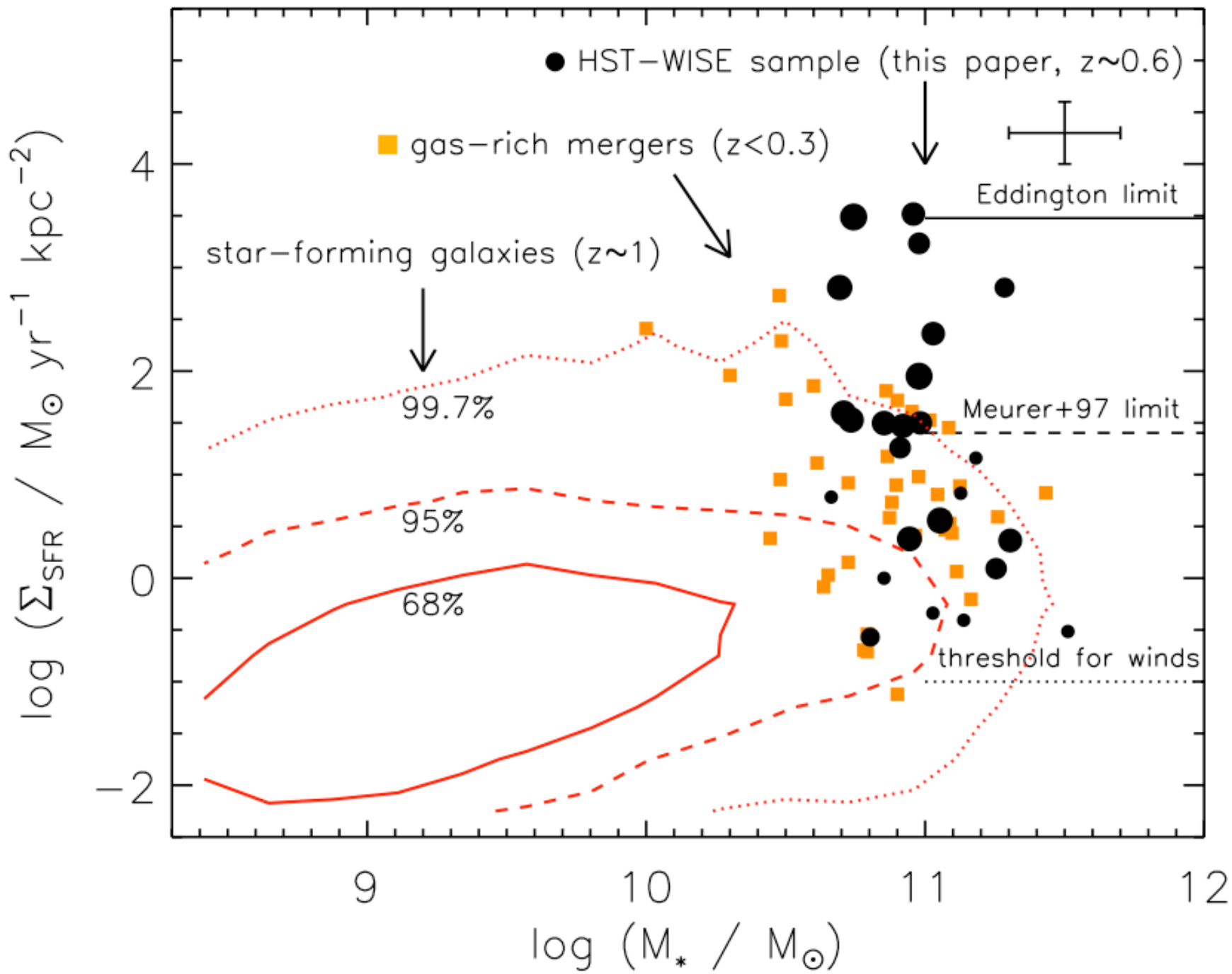


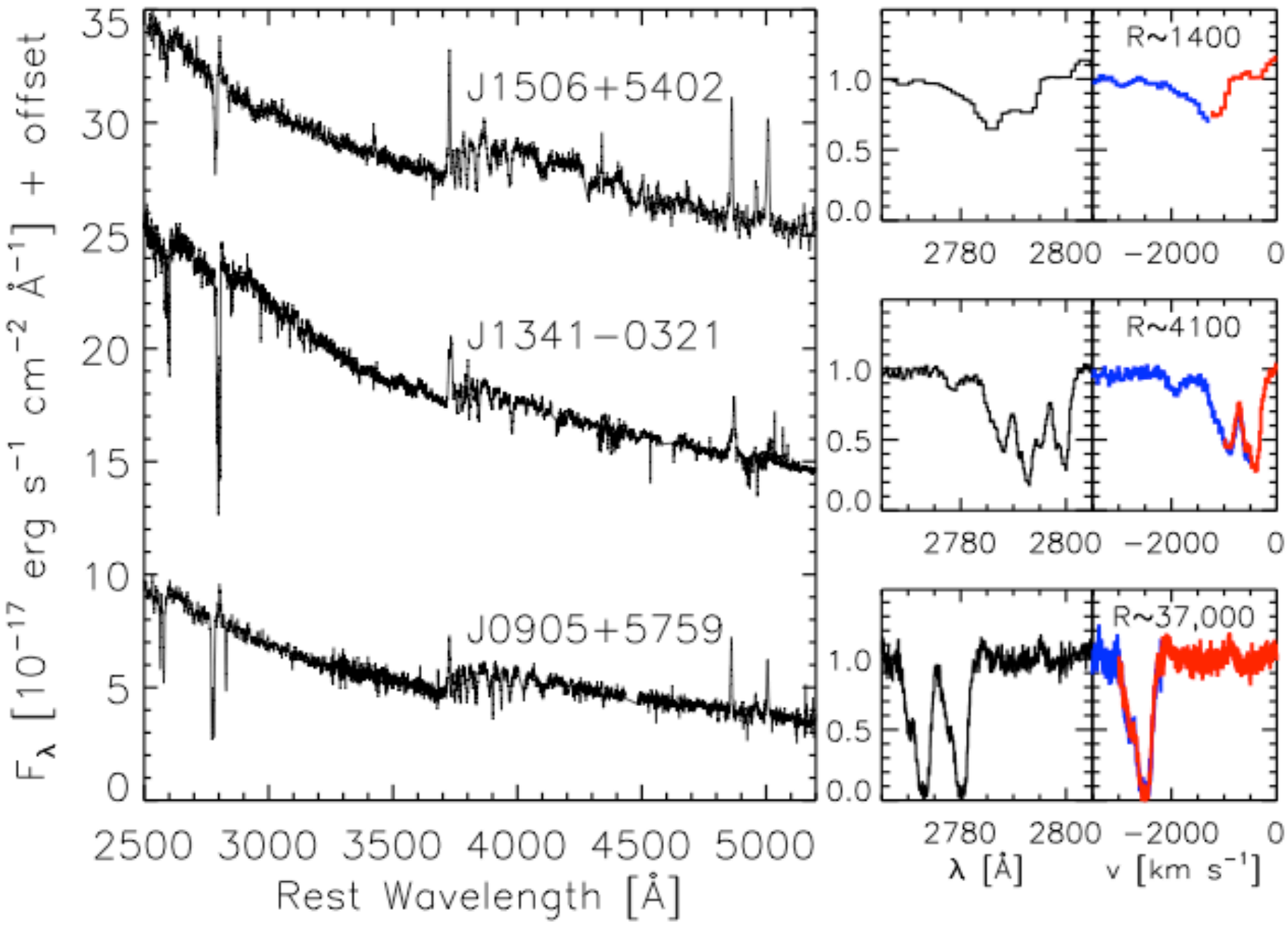
Figure 4. Logarithm of the density through the $y = 0$ plane in model rf384 showing evolution of a radiative fractal cloud.



1D NUMERICAL MODELS

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


HST−WISE sample (this paper, z∼0.6)
gas−rich mergers (z<0.3)
Eddington limit
star−forming galaxies (z∼1)
99.7%
Meurer+97 limit
95%
68%
threshold for winds
log (Σ_SFR / M⊙ yr^−1 kpc^−2)
log (M* / M⊙)
4
2
0
−2
9
10
11
12

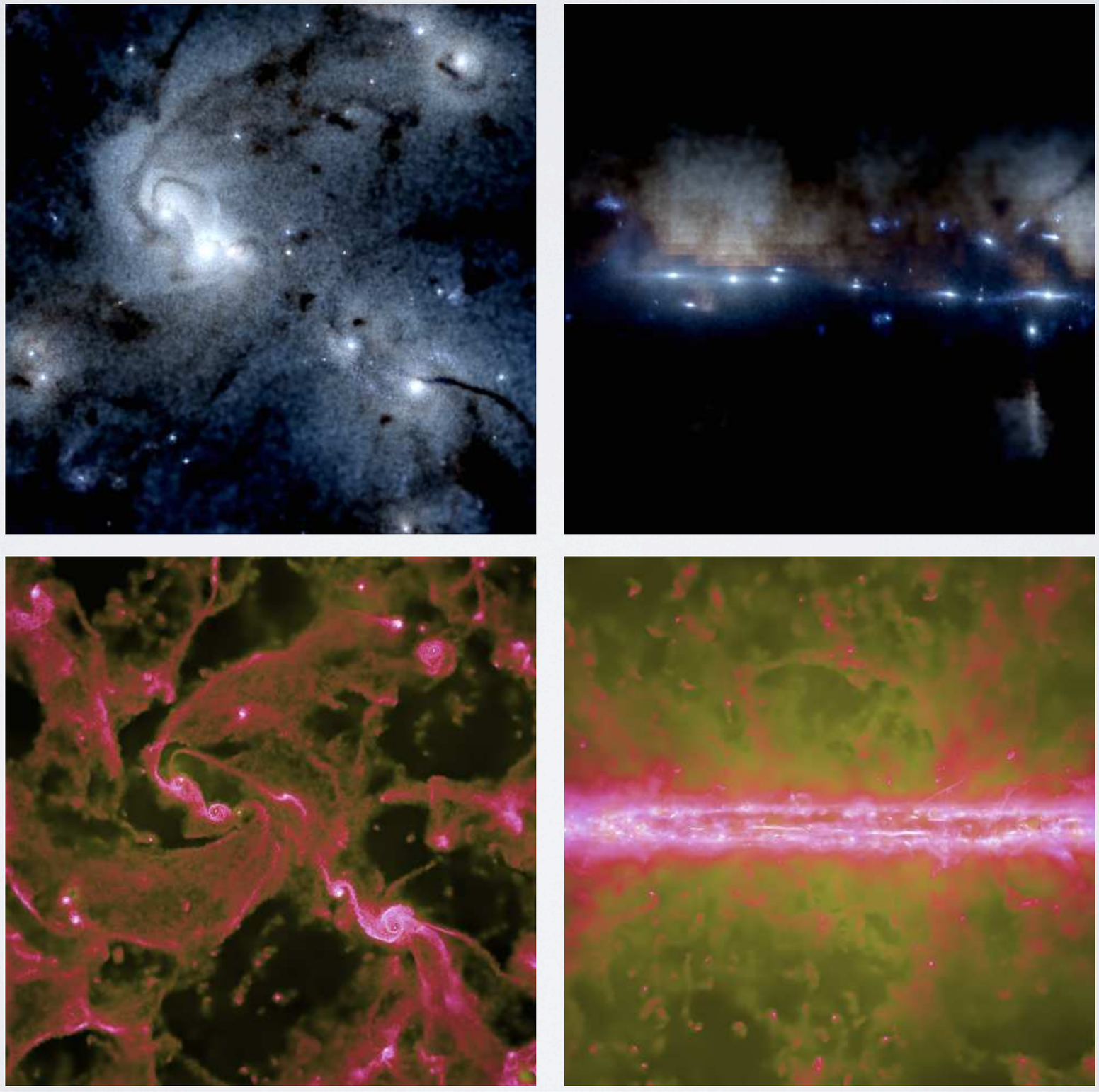


Diamond-Stanic 1205.2368

GALACTIC SCALE SIMULATIONS

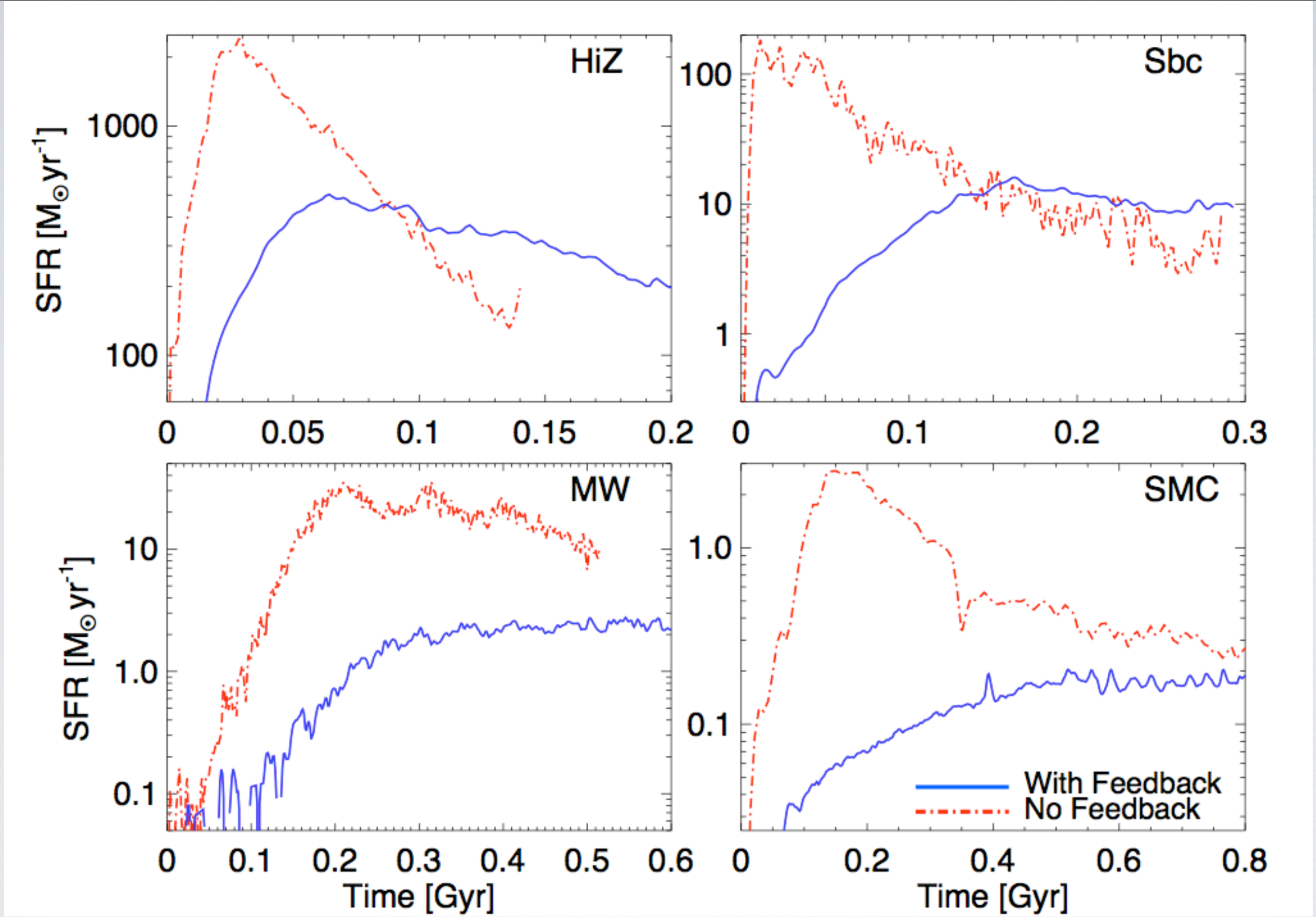
FEEDBACK SLOWS STAR FORMATION AND DRIVES WINDS

HOPKINS, QUATAERT Gadget (sph)

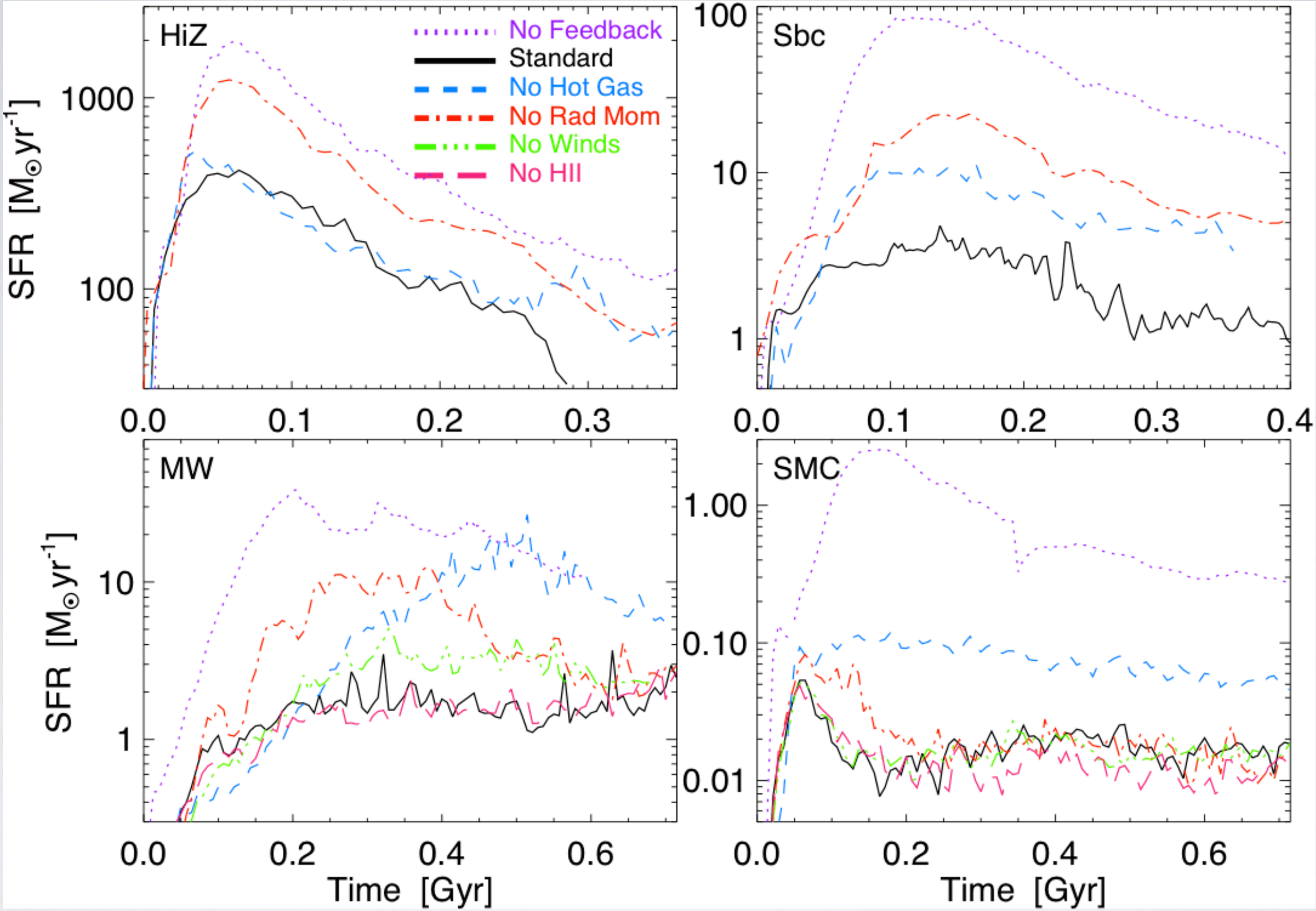


MODIFIED GADGET SIMULATIONS

- Particle mass from 100 solar masses
- force resolution ~ 0.3-3 parsecs
- 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

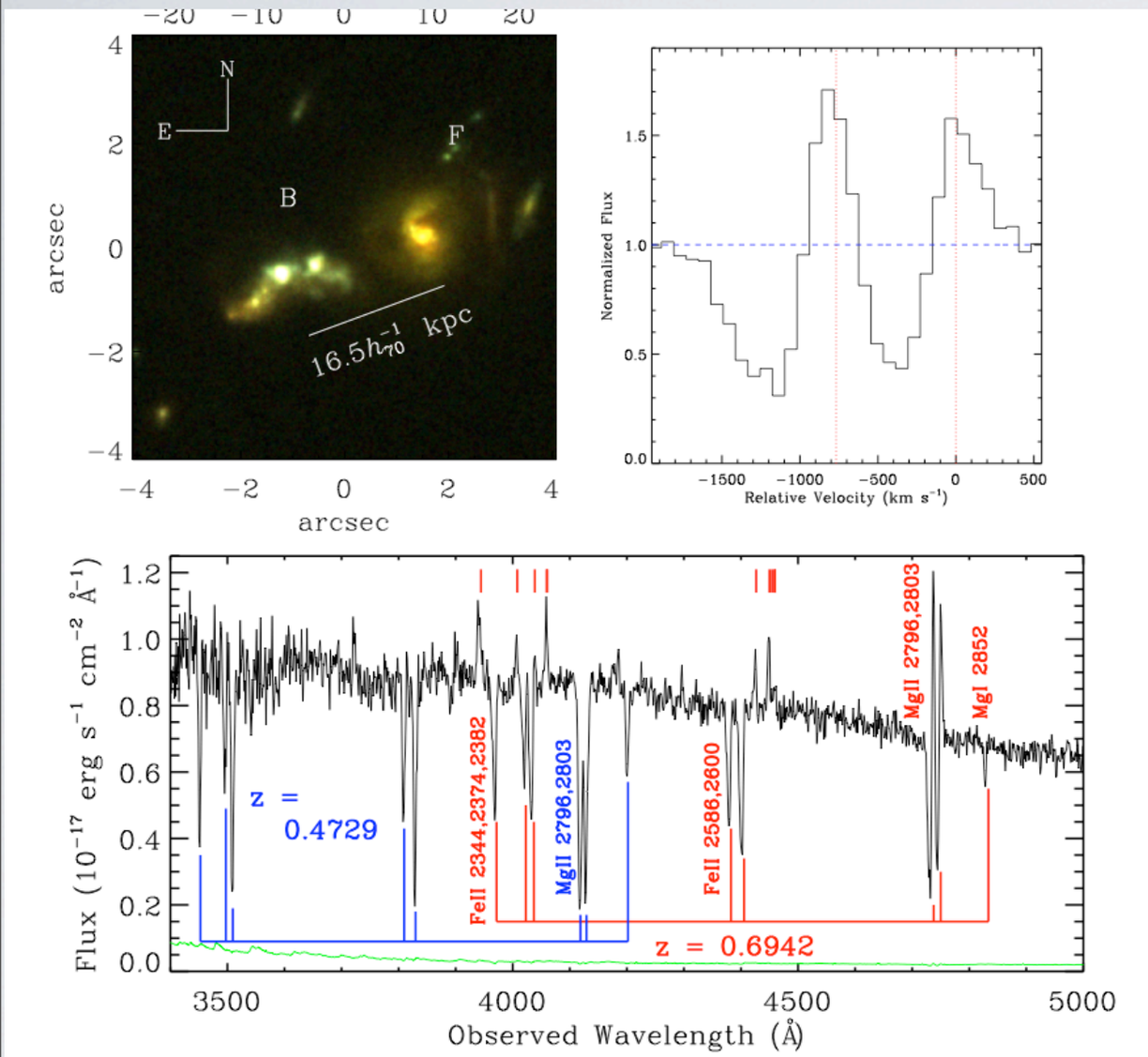


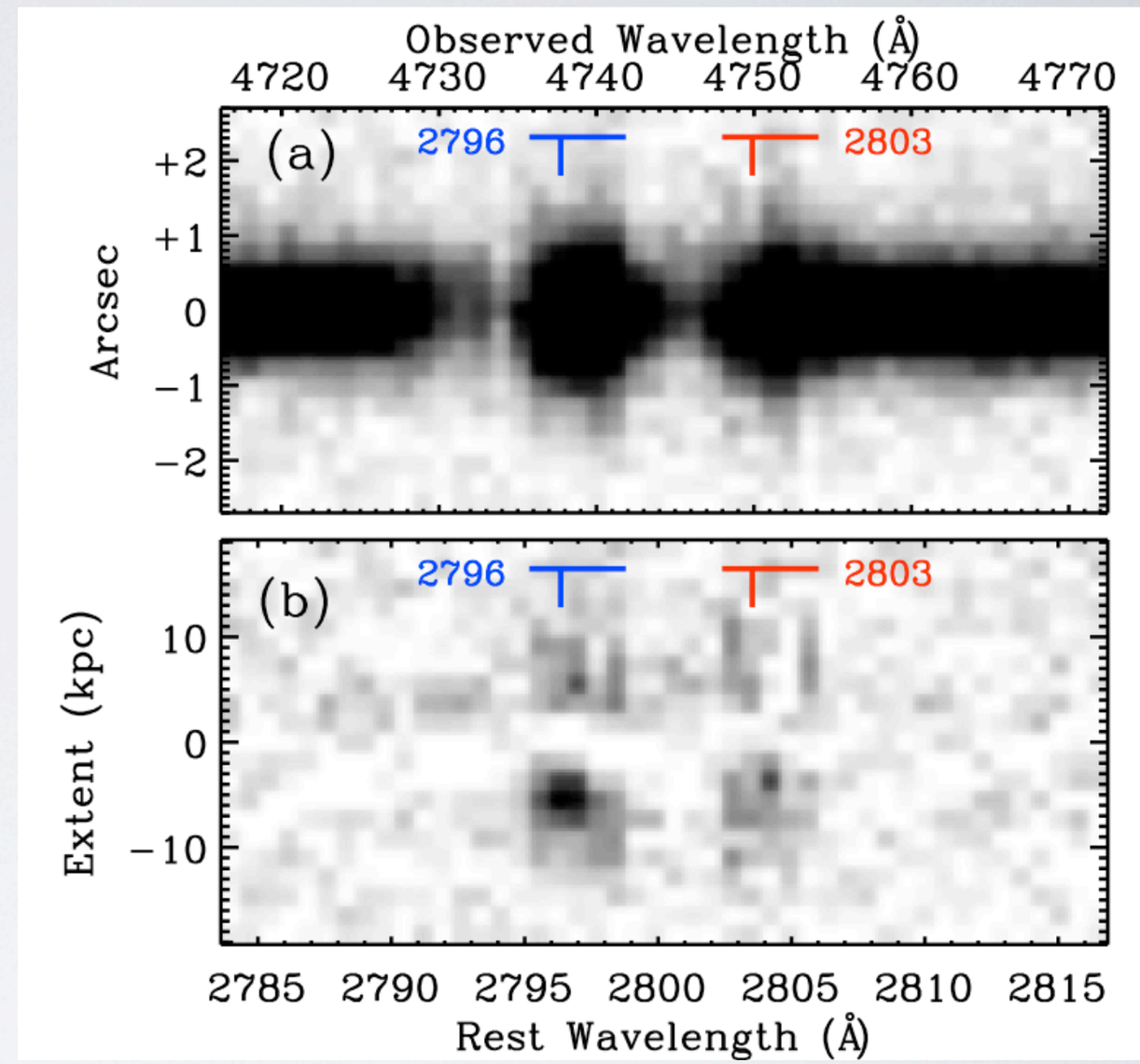
MOMENTUM FEEDBACK REGULATES STAR FORMATION



DIFFERENT FORMS OF FEEDBACK

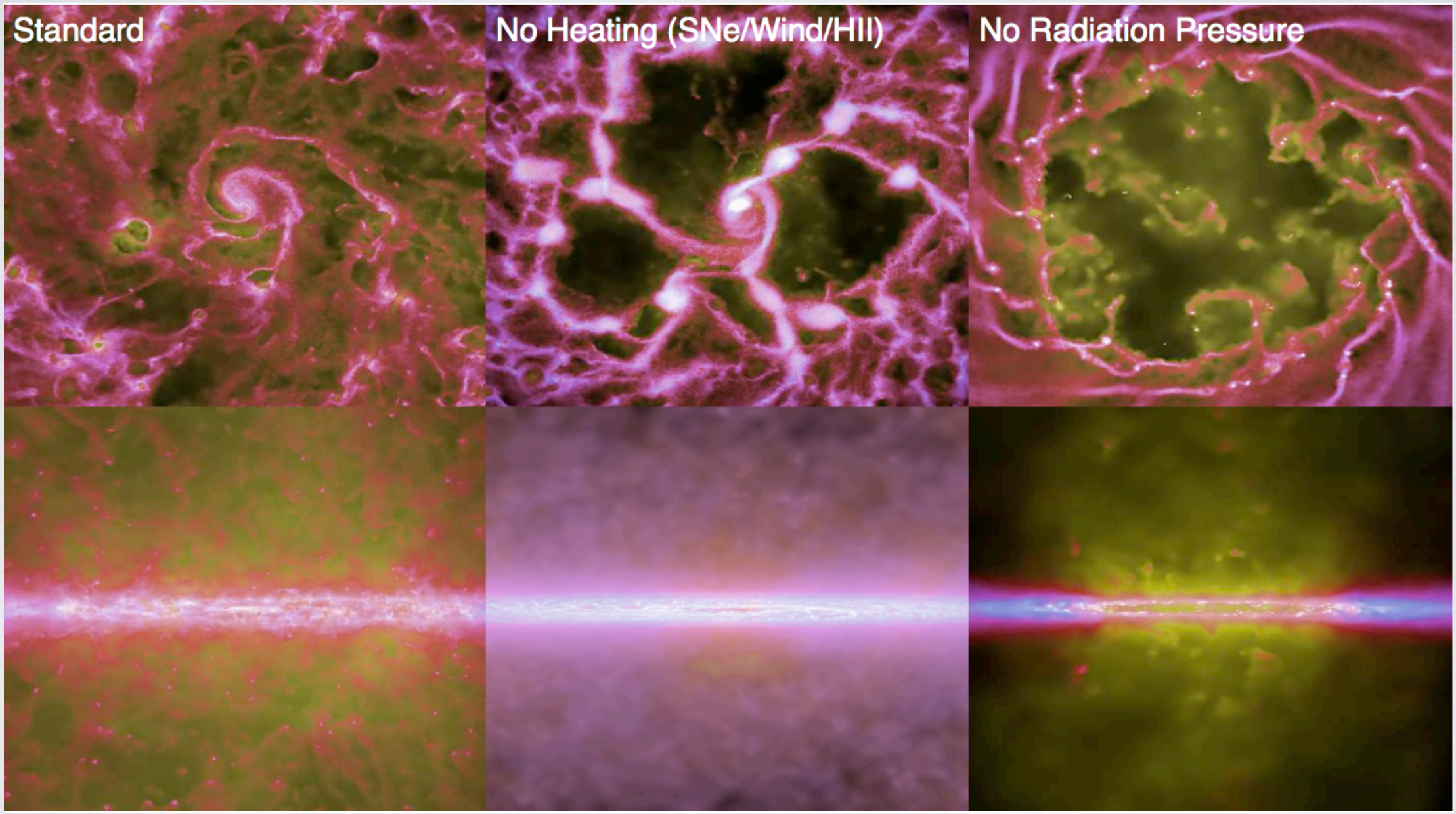
Galactic Winds



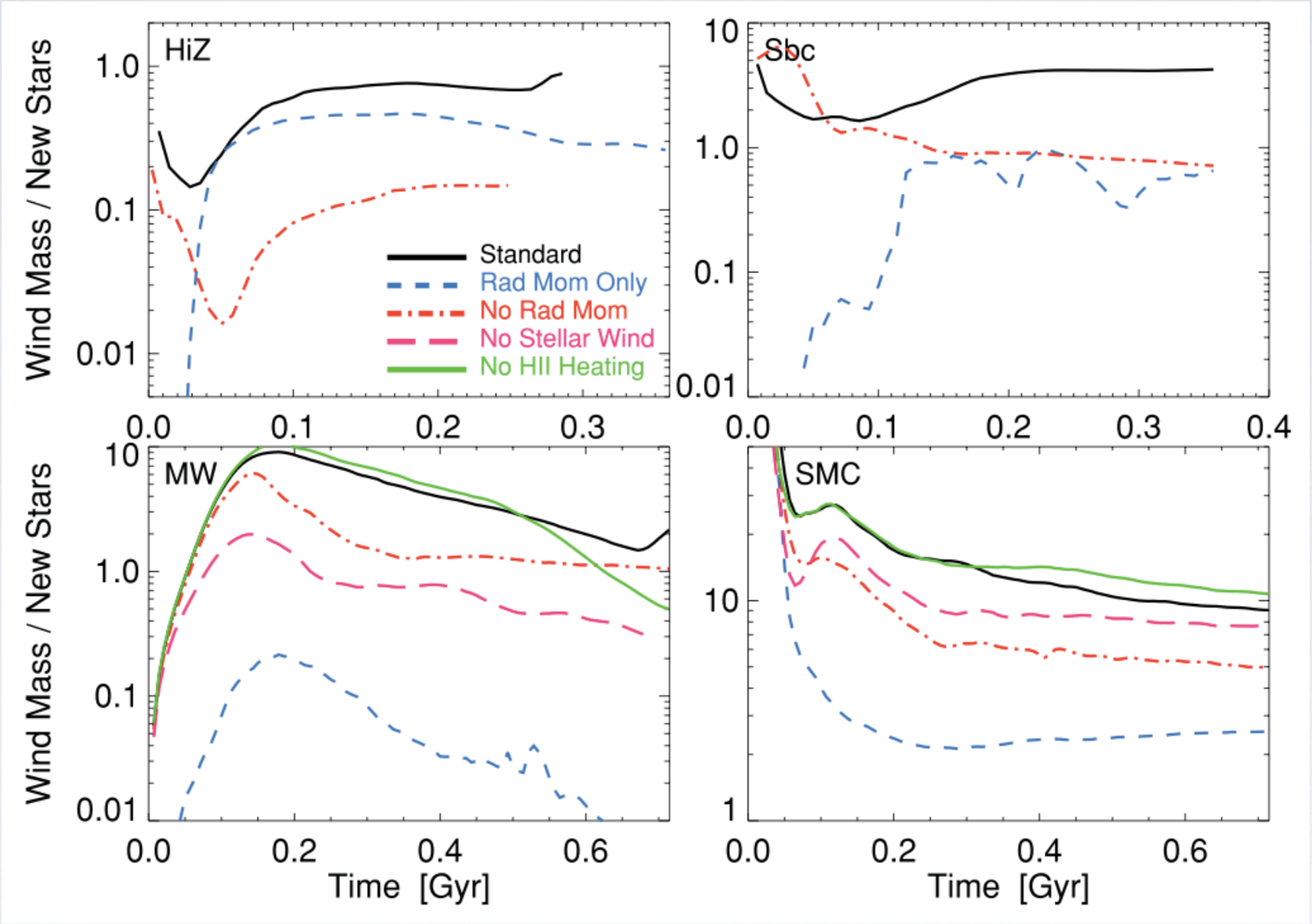


Rubin et al. ApJ 728 55 (2011)

3D Hydrodynamic Winds



DIFFERENT FORMS OF FEEDBACK



3-D WIND MODELS

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
  - Contribution of SN in Milky Way uncertain
  - SN dominate in the Small Magellenic Cloud
- A combination of radiation pressure and SNe ram pressure driving looks promising as a way launching galactic winds and removing baryons from L_* galaxy halos