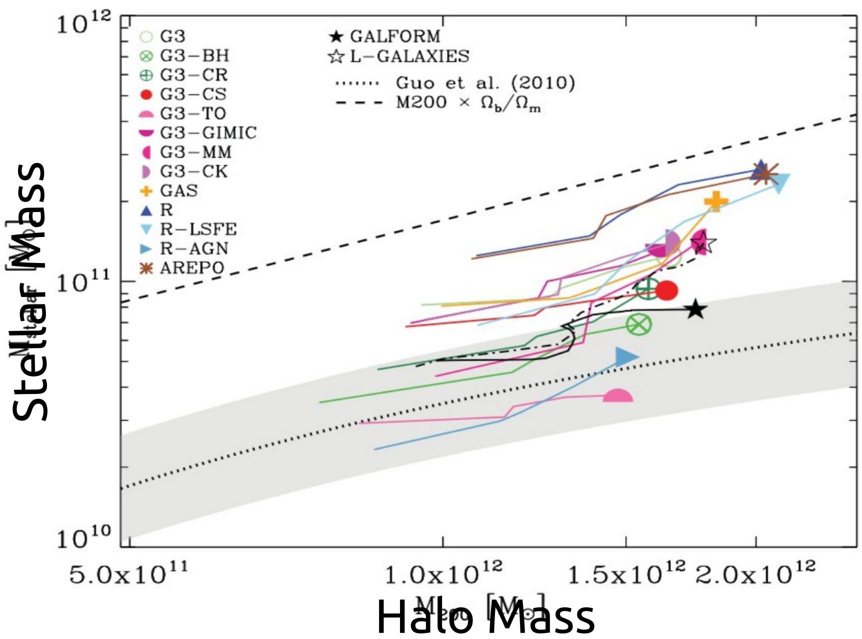
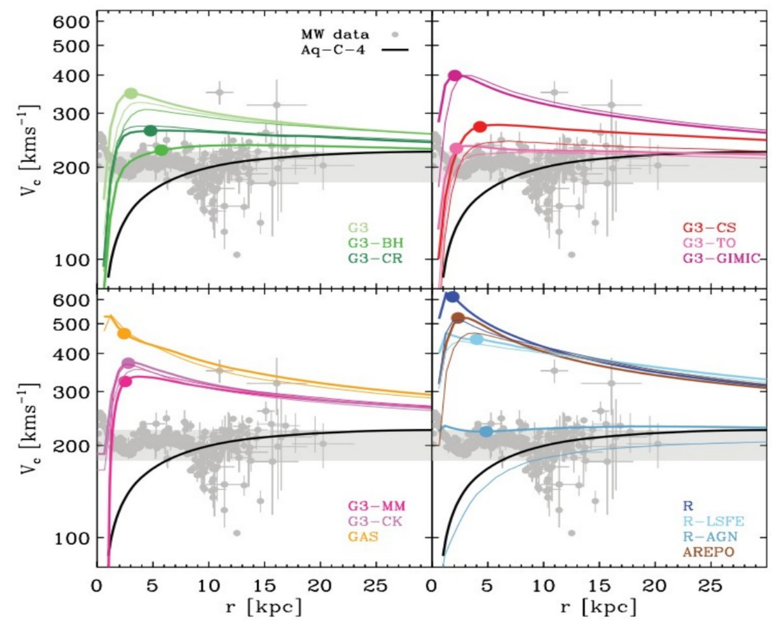
SN-driven superbubbles in cosmological galaxy evolution: outflows, regulation, and the limits of stellar feedback

Ben Keller
McMaster University

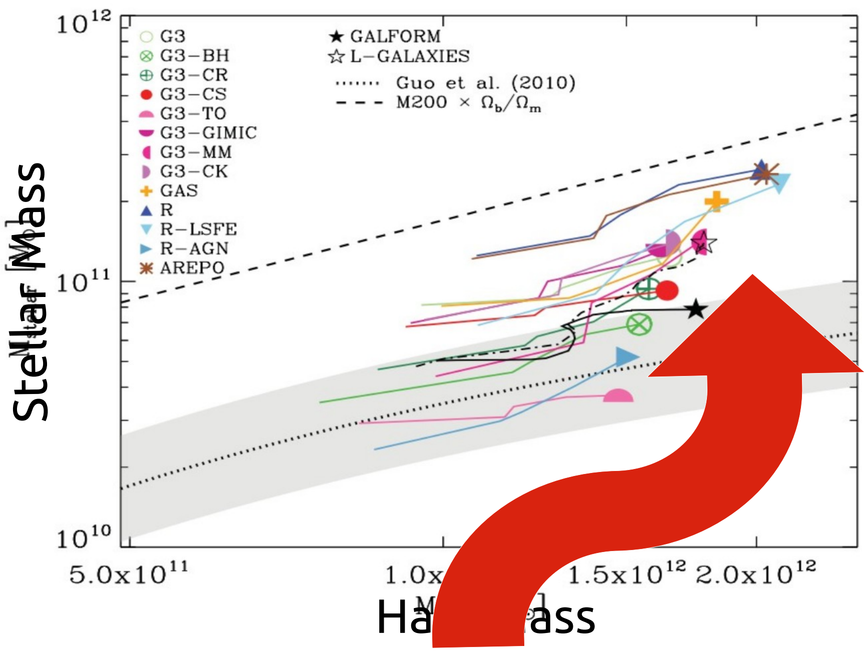
Simulations Circa 2012: Yikes!

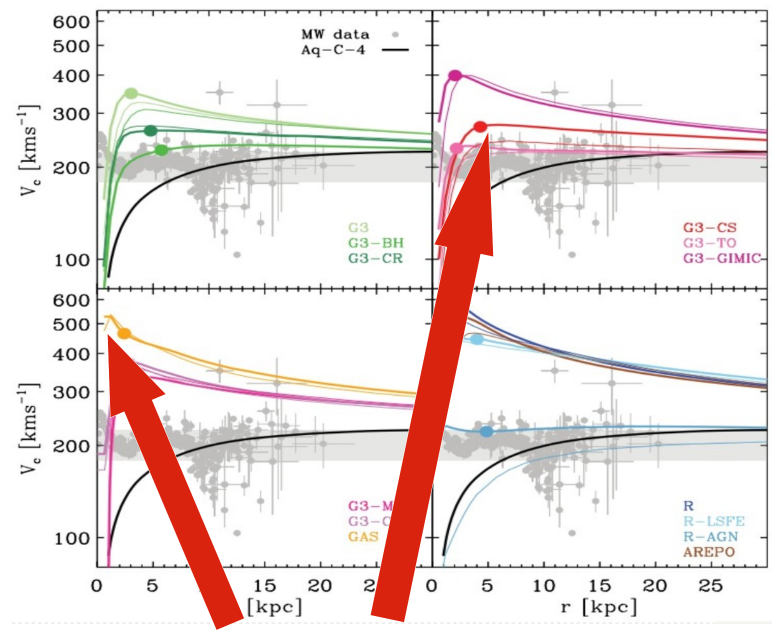




- Aquila Comparison (Scannapieco+ 2012)
  - Compared FB Models & Codes on same cosmological initial conditions
  - Most produced too many stars, too large bulge
  - None had both reasonable stellar fraction and small bulge

Missing Feature: Baryon Expulsion





Too Many Stars!

Massive Bulge = Peaked Rotation Curves

- Aquila Comparison (Scannapieco+ 2012)
  - Compared FB Models & Codes on same cosmological initial conditions
  - Most produced too many stars, too large bulge
  - None had both reasonable stellar fraction and small bulge

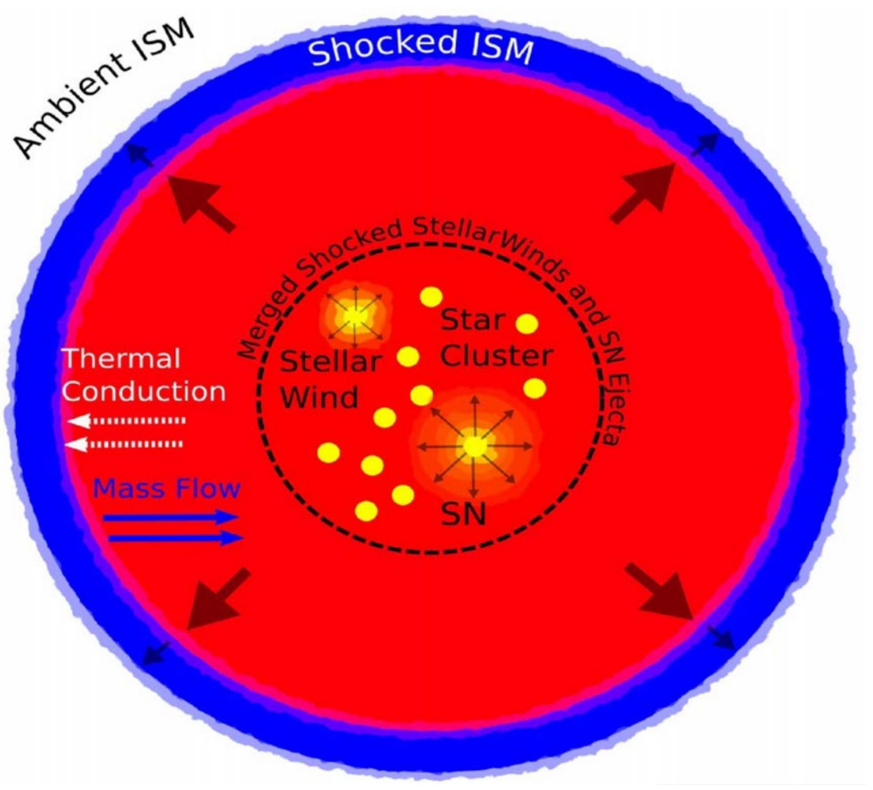
Things have improved since 2012

- ~~Extra~~ Early Feedback
  - MAGICC/NIHAO (Stinson+ 2013, Wang+ 2015)
  - FIRE (Hopkins+ 2014)
  - EAGLE/APOSTLE (Schaye+ 2015, Sawala+ 2016)
- Clever Feedback Recipes
  - Nonthermal energy (Agertz+ 2013, Dubois+ 2015)
  - Kinetic feedback (Illustris [Vogelsberger+ 2014], MUFASA [Dave+ 2016])
- Others I have certainly missed

Superbubble Feedback

- Star formation is clustered, and *feedback is non-linear*! (Mac Low & McCray 1988)
- Many SN blasts overlap to form a *superbubble*
- Cold shell evaporates due to thermal conduction:

$$\frac{\partial M_B}{\partial t} = \frac{4\pi\mu}{25 k_B} \kappa_0 T^{5/2} A_B$$



Superbubble Model (Keller+ 2014)

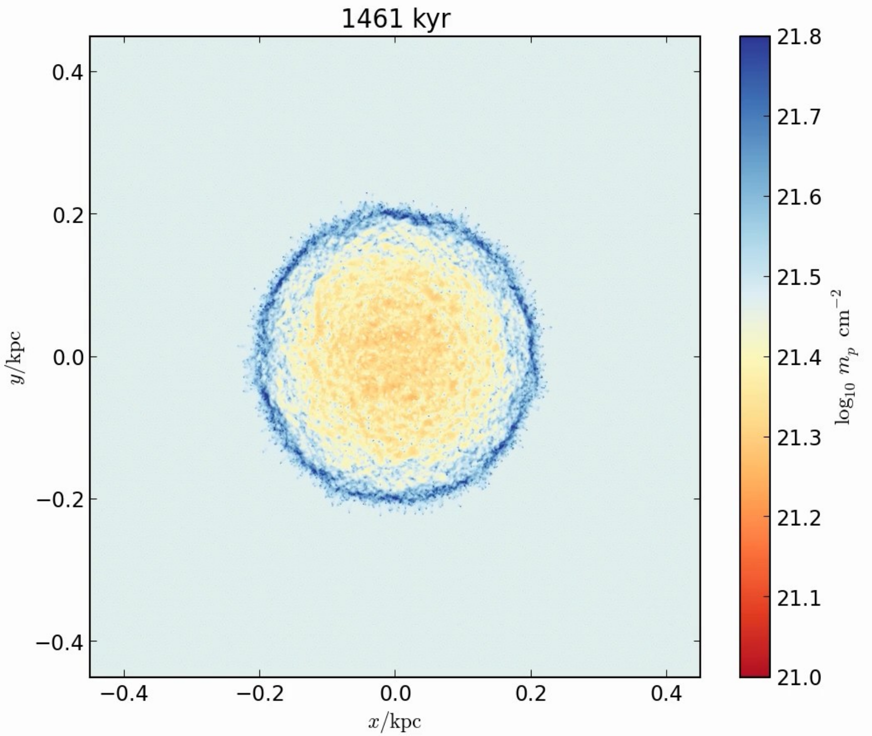
1) Resolved thermal conduction for hot, diffuse gas inside hot bubbles

2) Stochastic promotion for evaporation of the cold shell around well-resolved bubbles

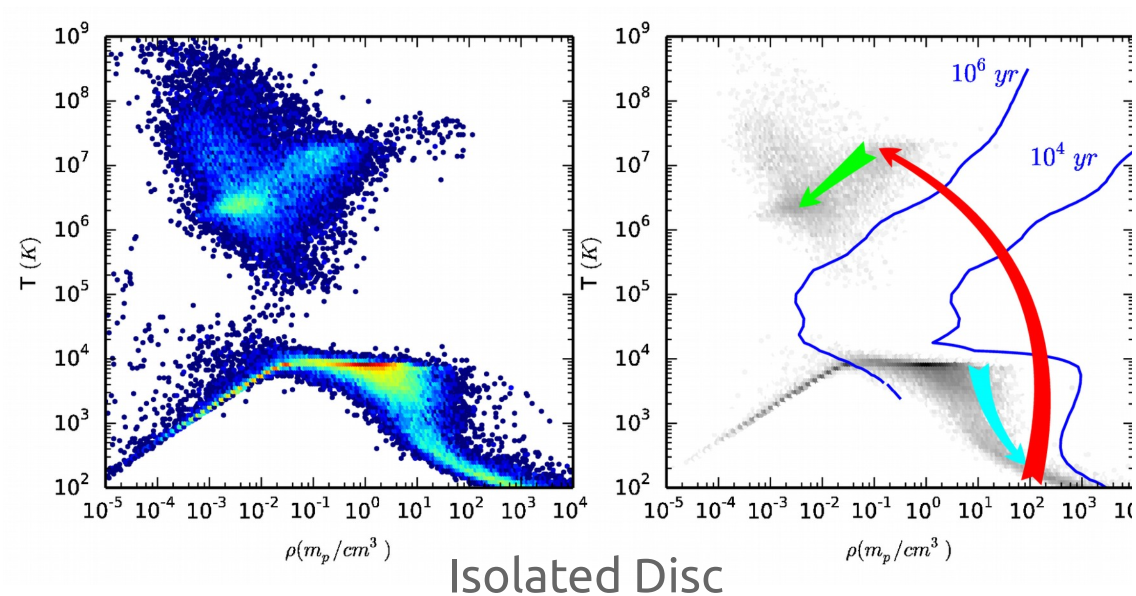
3) Two-phase particles for early phase of bubble growth, with internal evaporation to convert back to single phase

Validating the Superbubble Model

- High resolution, well resolved feedback with direct injection (no need for two phase component)
- Hot bubble mass, energy converged over ~500x range of mass resolution
- Hot bubble self-regulates to ~a few million K
- Model description in Keller+ 2014

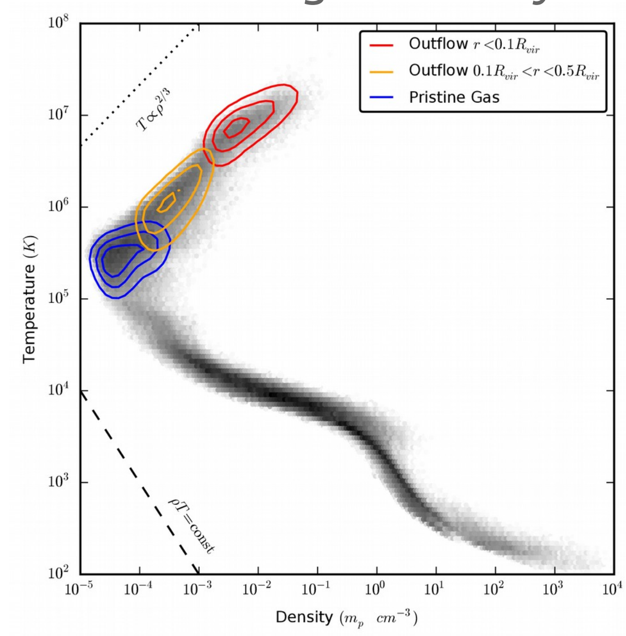


Superbubble Gas Lifecycle



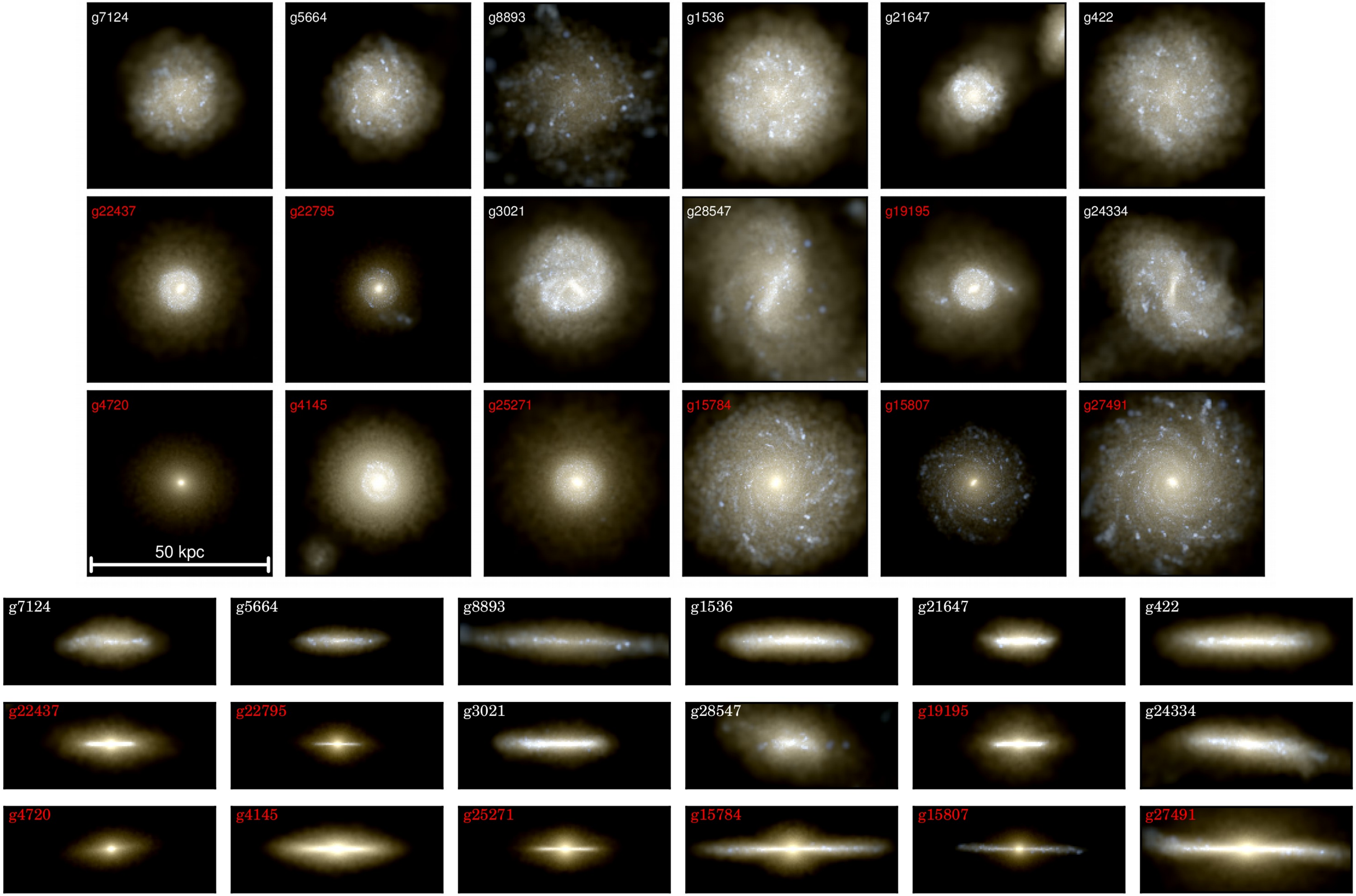
Isolated Disc

Cosmological Galaxy



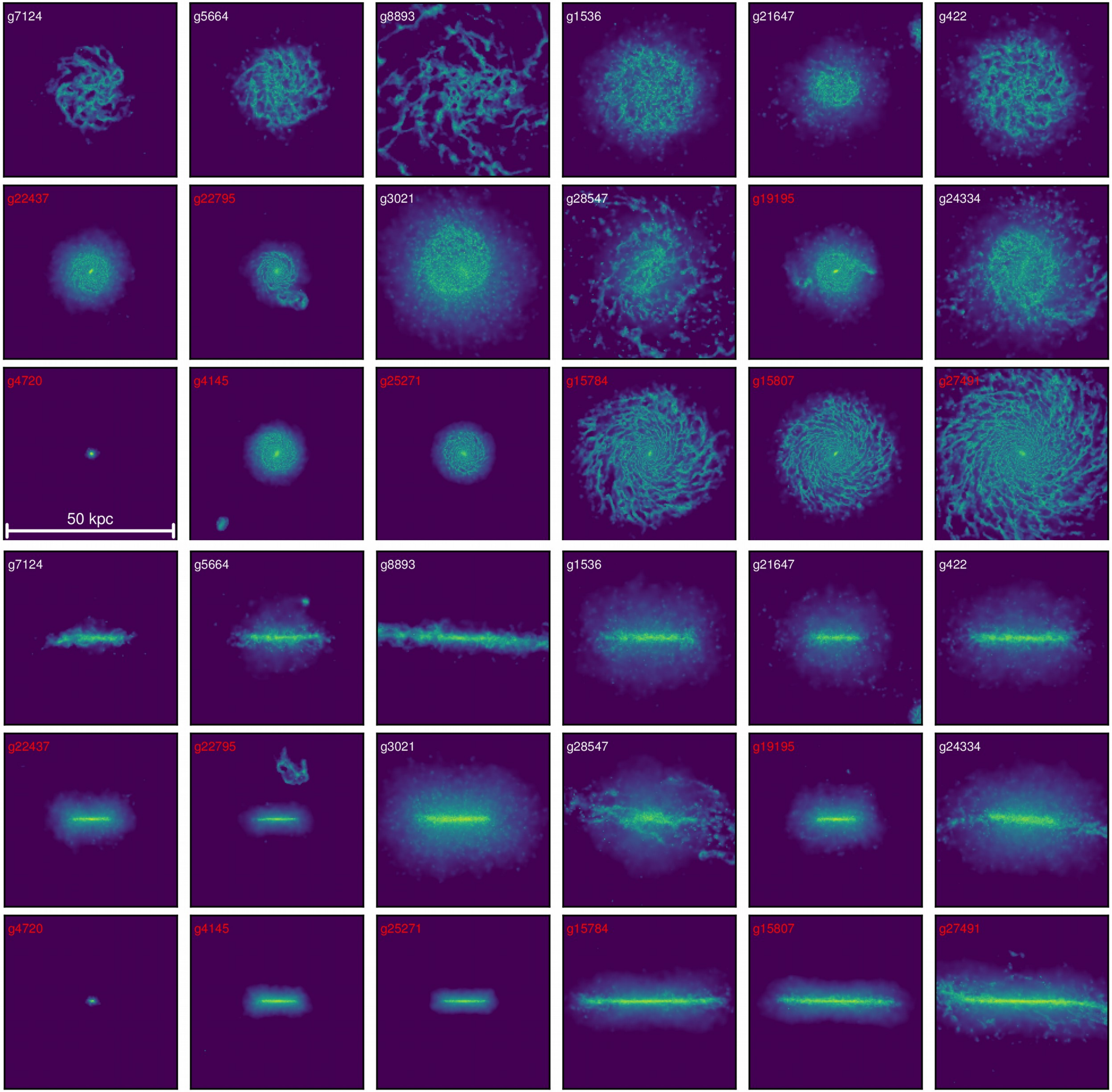
- Equilibrium WI(N)M cools, forms stars -> SN
- SN form superbubbles, begin at ~10^8K, evaporate to a few 10^6K
- Feedback-heated leaves disc, evolves adiabatically as it rises through halo. Cooling times are >> Myr

MUGS2: 18 L* Galaxies



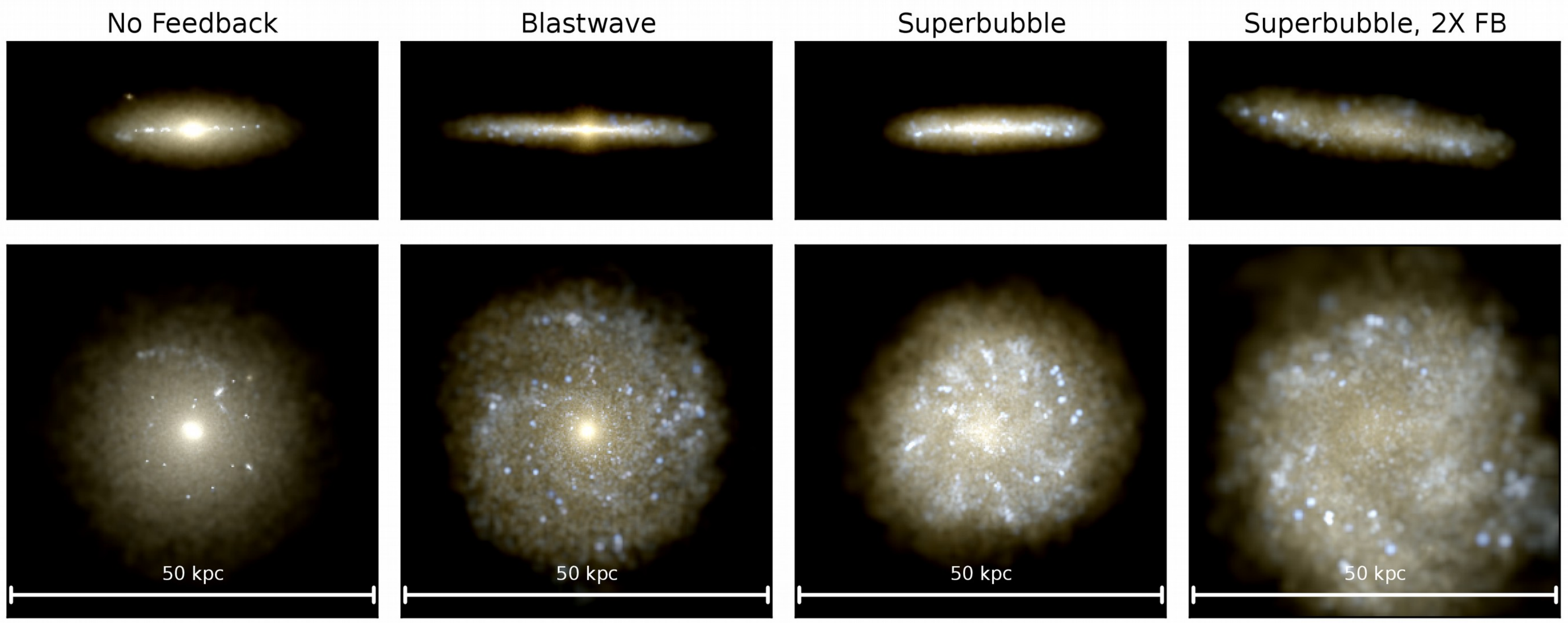
MUGS2: 18 L* Galaxies

- Cosmological zoom-in simulations, run using GASOLINE2 (Wadsley+, in prep), in a WMAP3 cosmology
- Initial conditions identical to MUGS (Stinson+ 2010), run with “classic” SPH and blast-wave feedback
- Virial Masses range from 3.7×10^{11} to $2.1 \times 10^{12} M_{sun}$
- Variety of merger histories, spin parameters
- 320pc softening, baryon mass resolution of $2.2 \times 10^{5} M_{sun}$

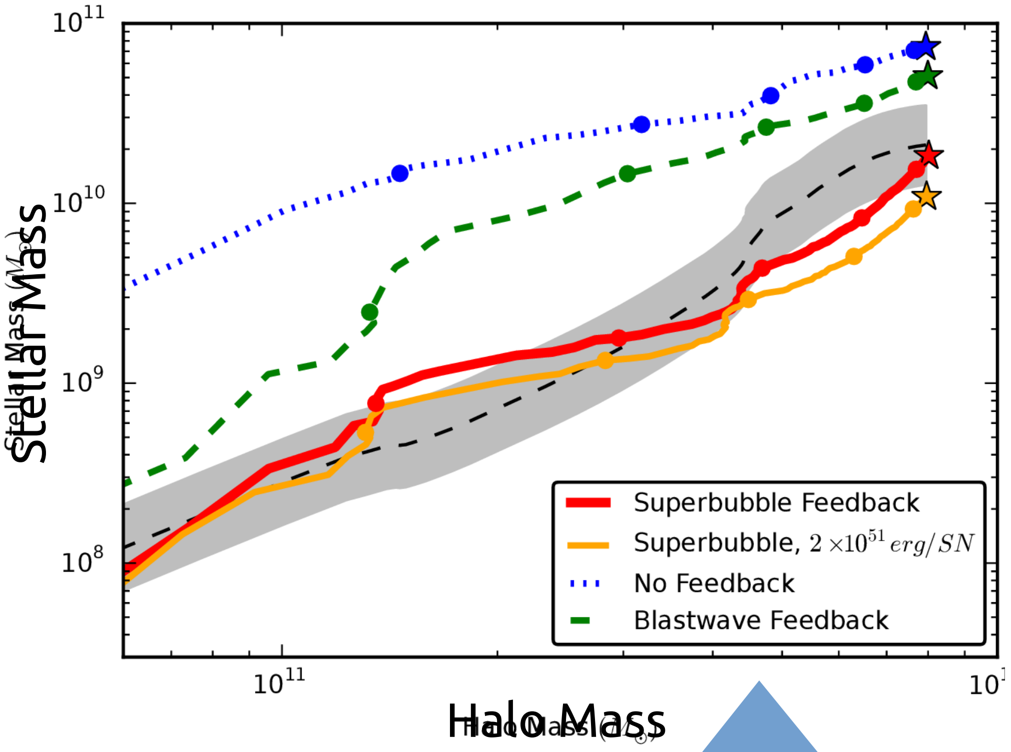

g7124
g5664
g8893
g1536
g21647
g422
g22437
g22795
g3021
g28547
g19195
g24334
g4720
g4145
g25271
g15784
g15807
g27491
50 kpc
g7124
g5664
g8893
g1536
g21647
g422
g22437
g22795
g3021
g28547
g19195
g24334
g4720
g4145
g25271
g15784
g15807
g27491

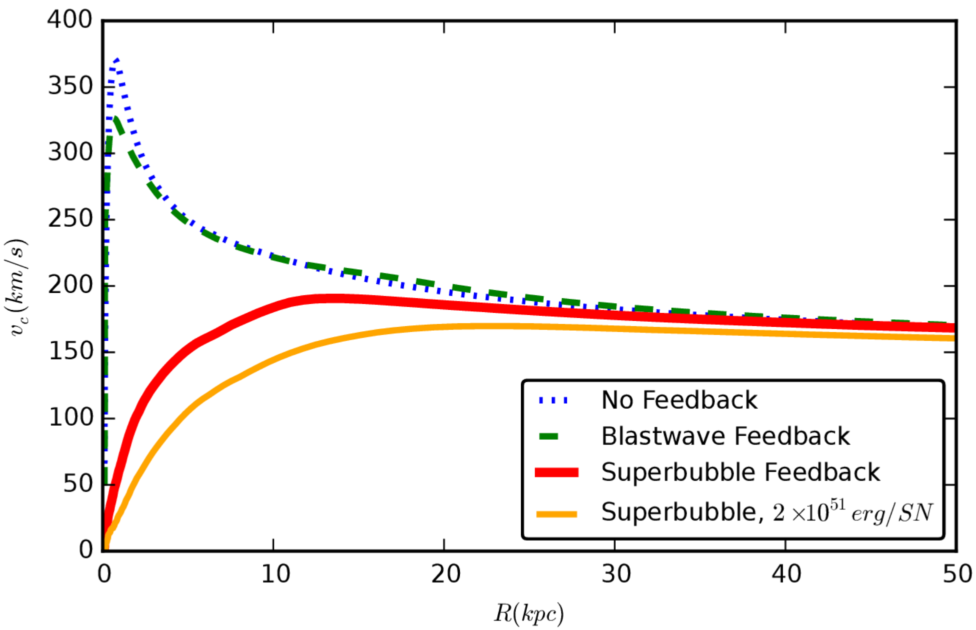
Feedback Models Matter! (Keller+ 2015

- 4 test cases:
  - No Feedback
  - Blastwave (Stinson+ 2006) feedback
  - Superbubble Feedback
  - Superbubble Feedback 2X Energy
- g1536
  - $8x10^{11}$ M_{sun} virial mass
  - Last major merger at z=4
  - Equal SN energy for Blastwave and Superbubble
  - Details in Keller+ 2015



Correct Stellar Mass, Small Bulge

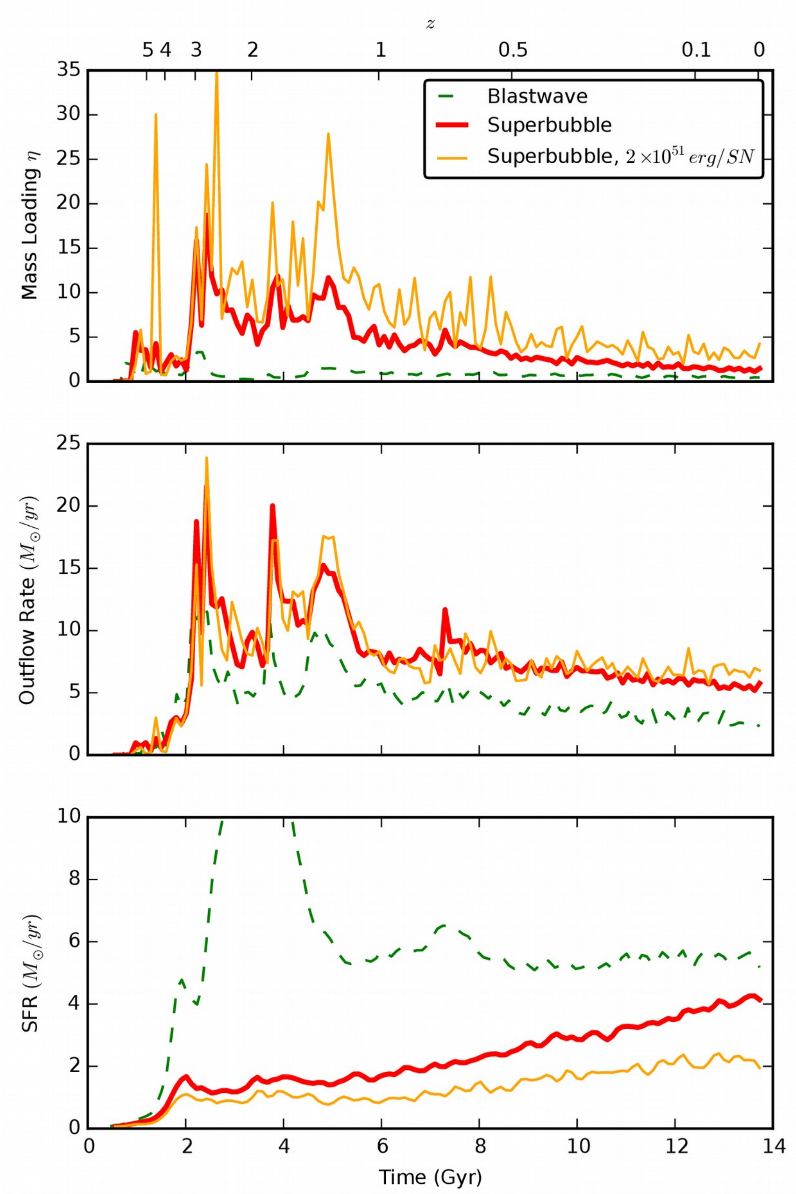




Stellar Mass Evolution Matches Behroozi+ 2012 abundance matching

Flat rotation curve == no major bulge component (B/T ratio of 0.09 vs. 0.46, MW B/T ~0.14)

Superbubbles drive outflows well

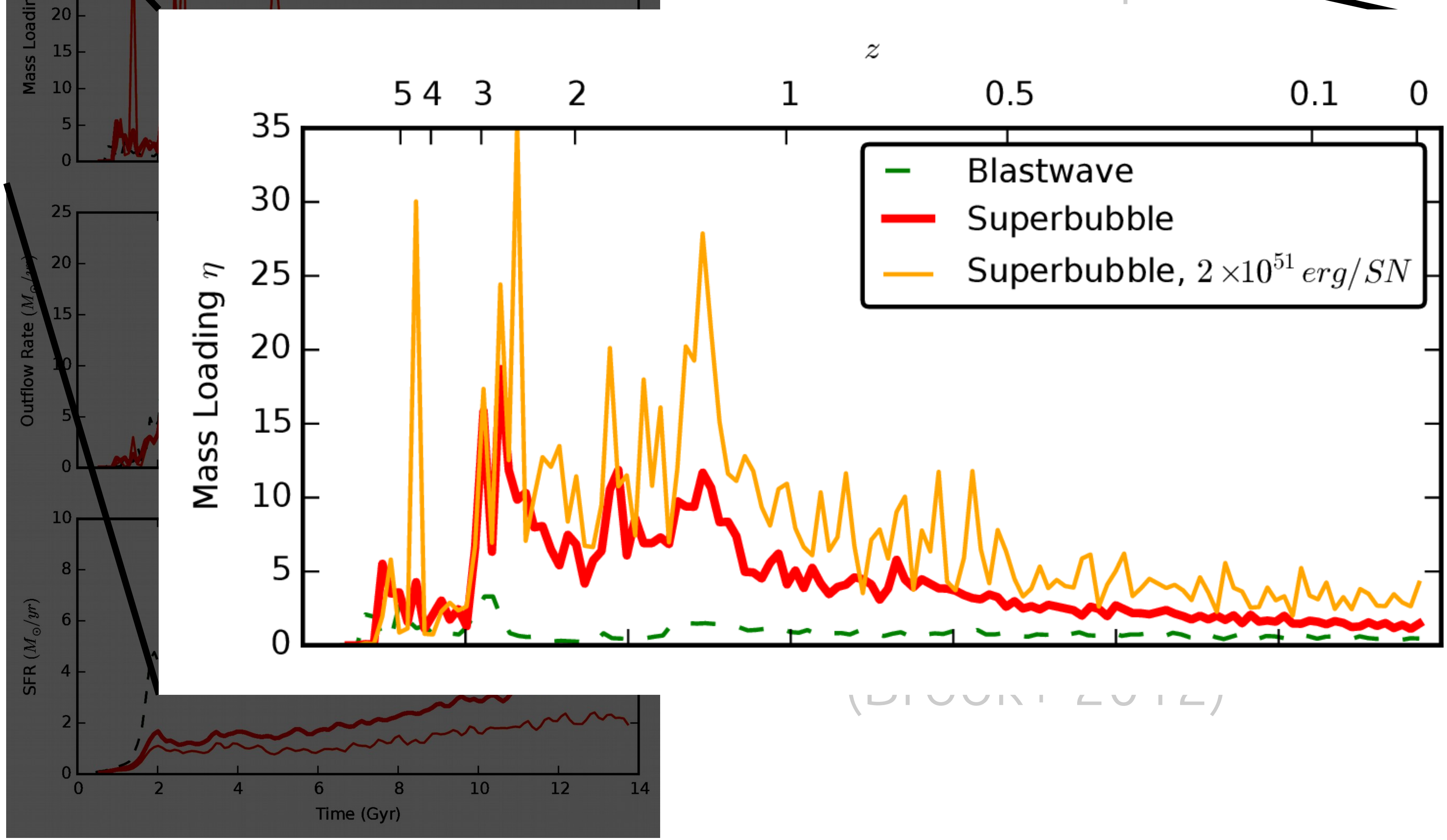


- Smaller galaxy, shallower potential well
- Higher mass loadings allow for correct stellar mass fraction, remove fuel for later star formation

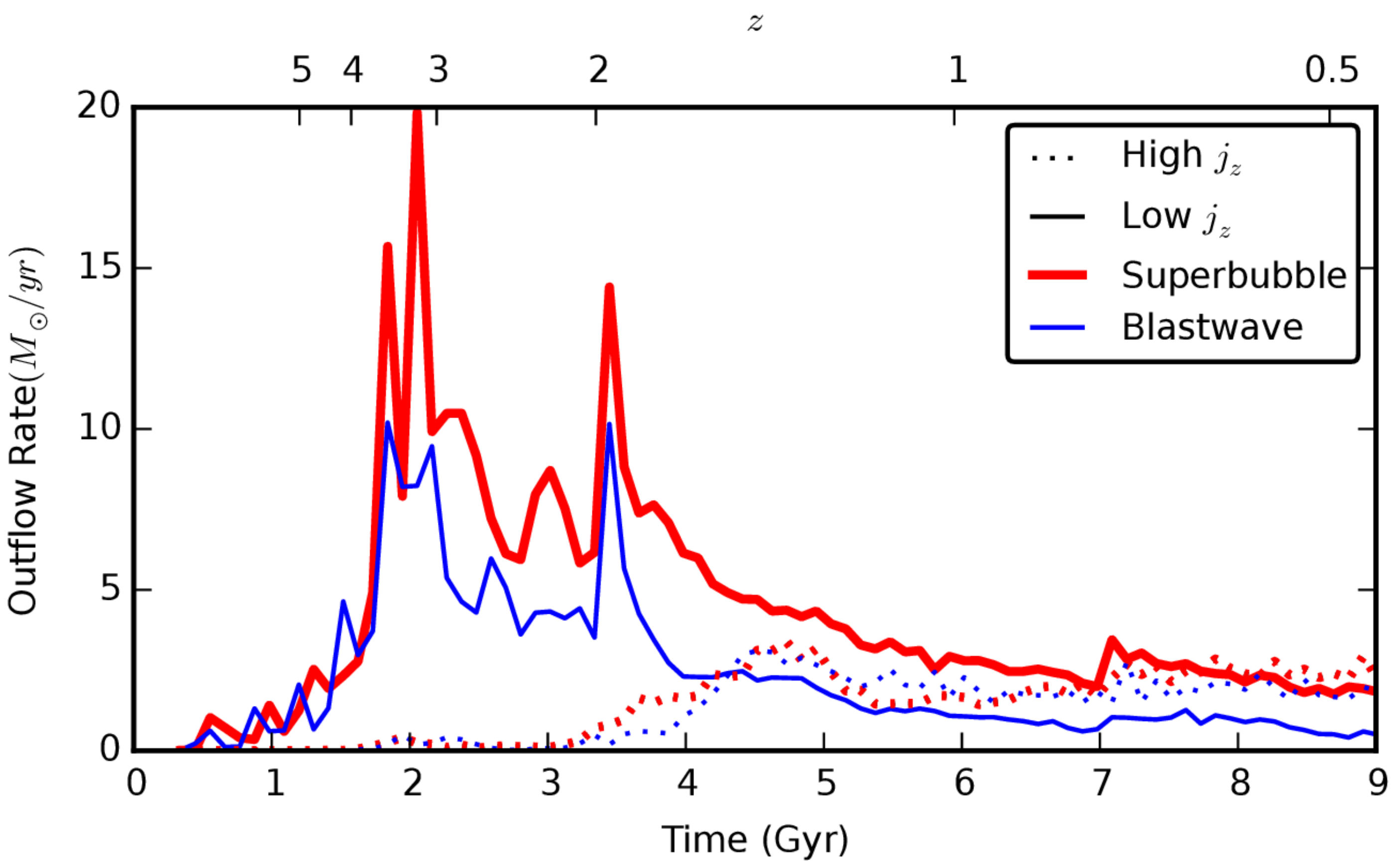
Outflows preferentially remove low-j gas! (Brook+ 2012)

Superbubbles drive outflows well

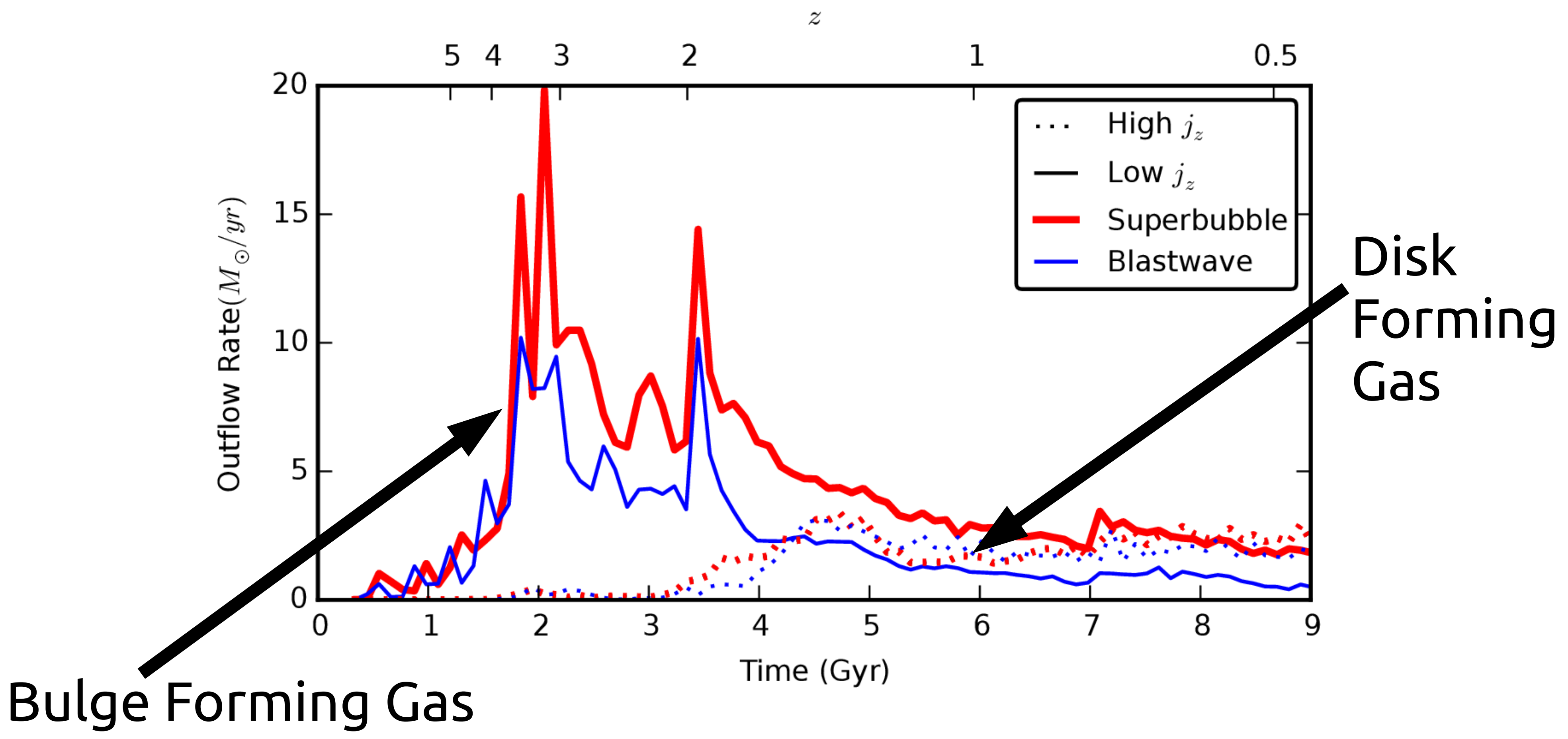
- Smaller galaxy, shallower potential



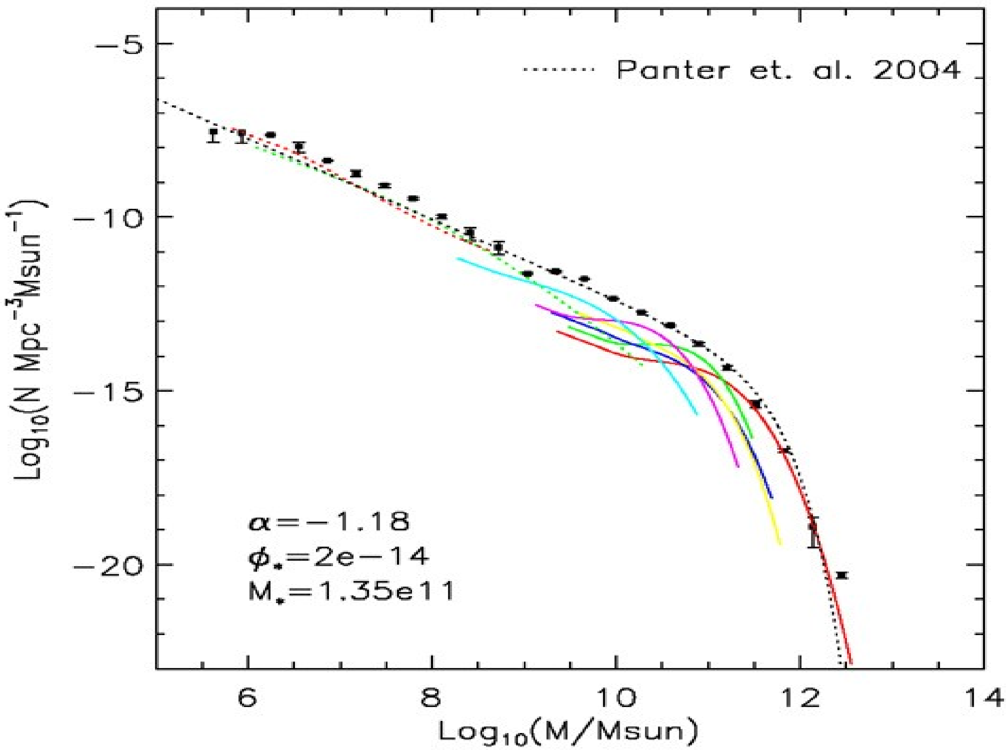
High-z outflows prevent bulges, preserve disks

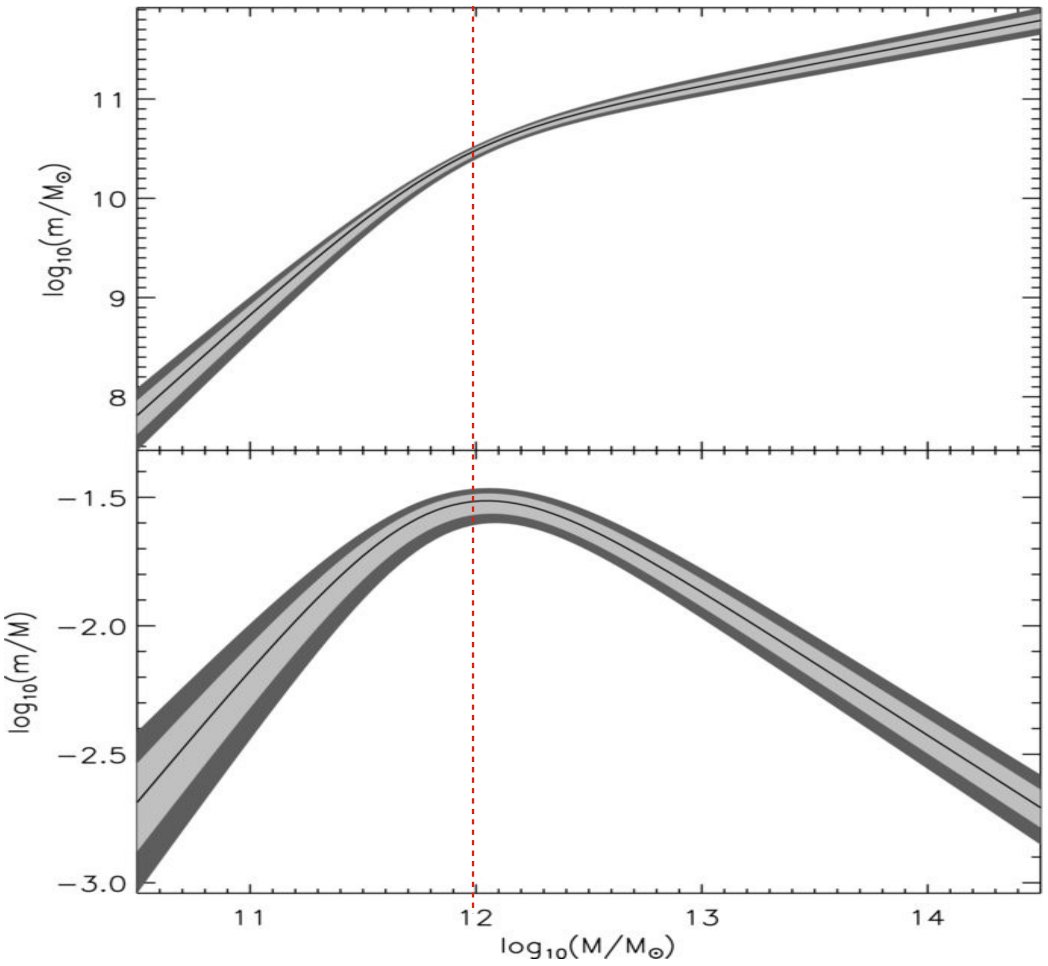


High-z outflows prevent bulges, preserve disks



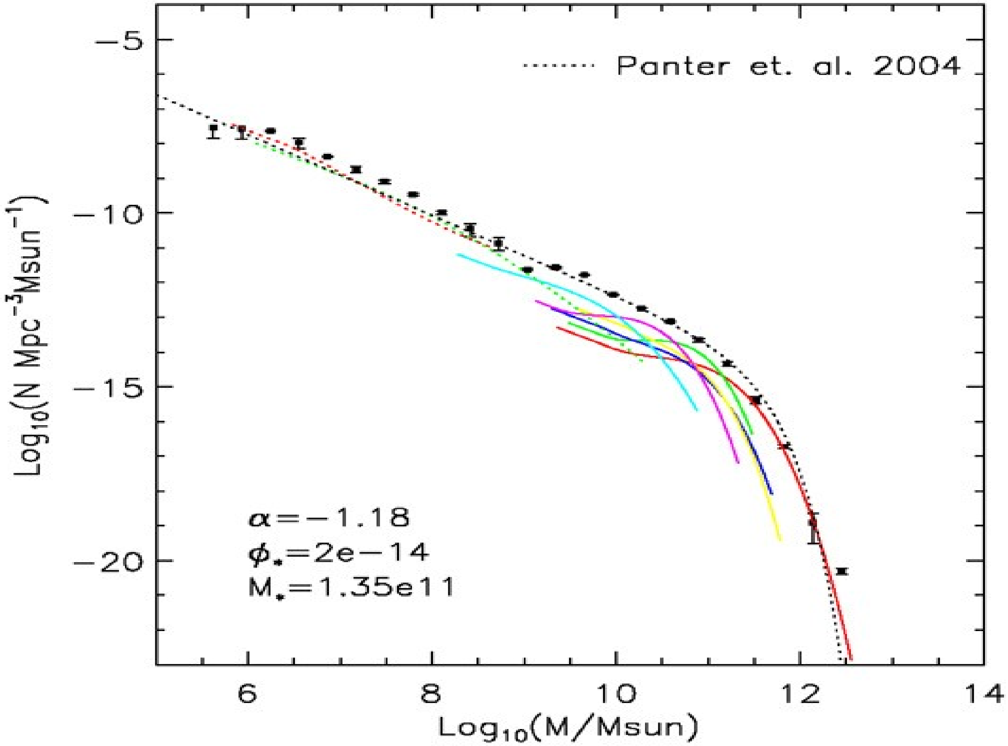
Can Supernovae do it all?

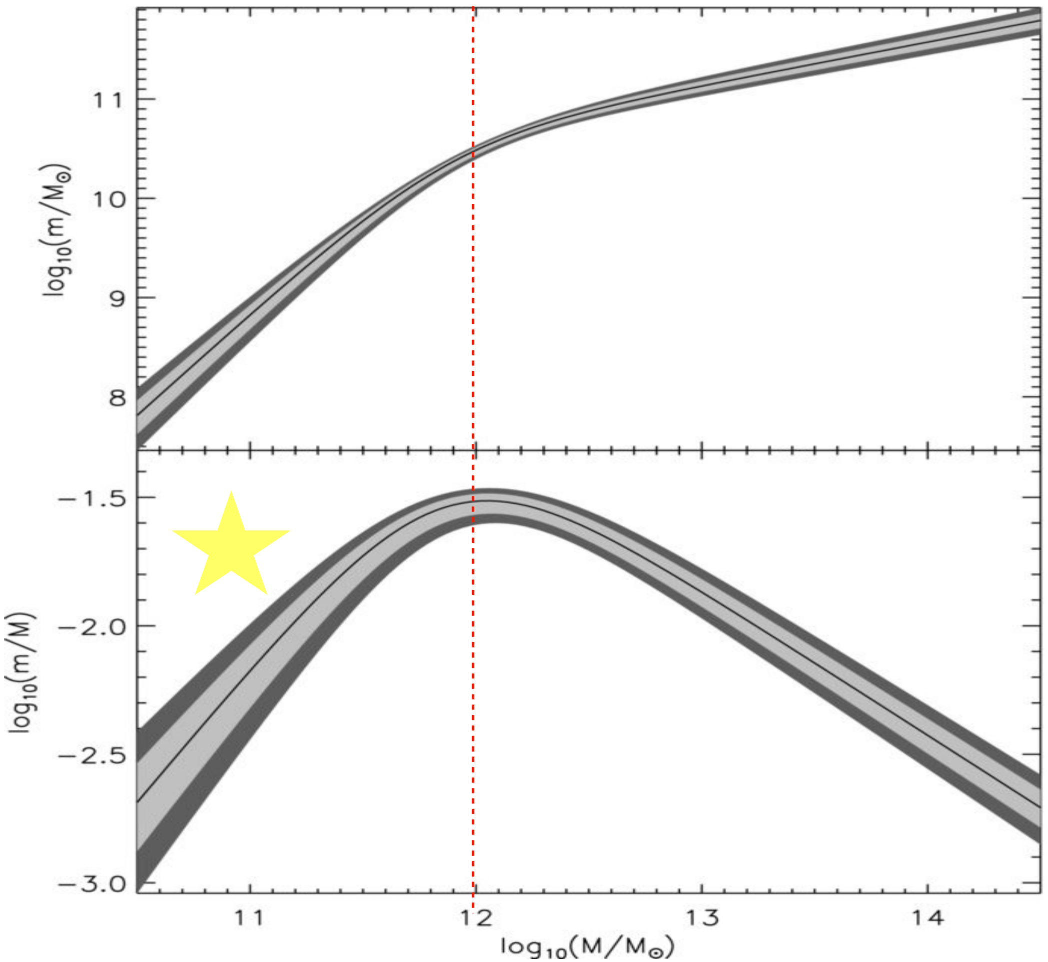




Moster+ 2010

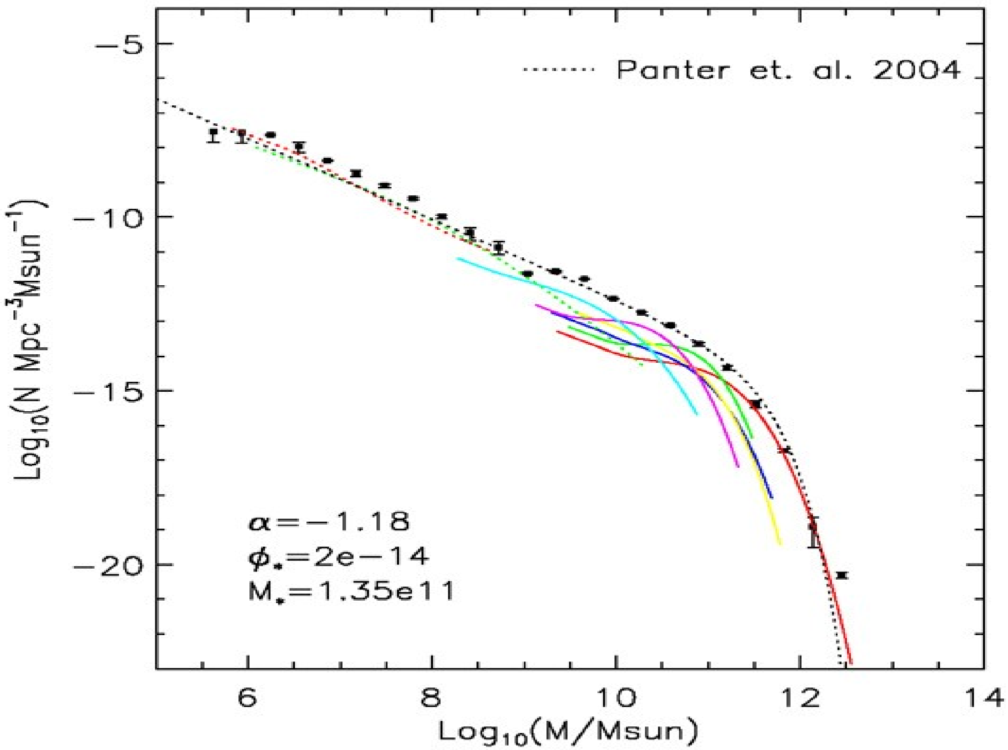
Can Supernovae do it all?

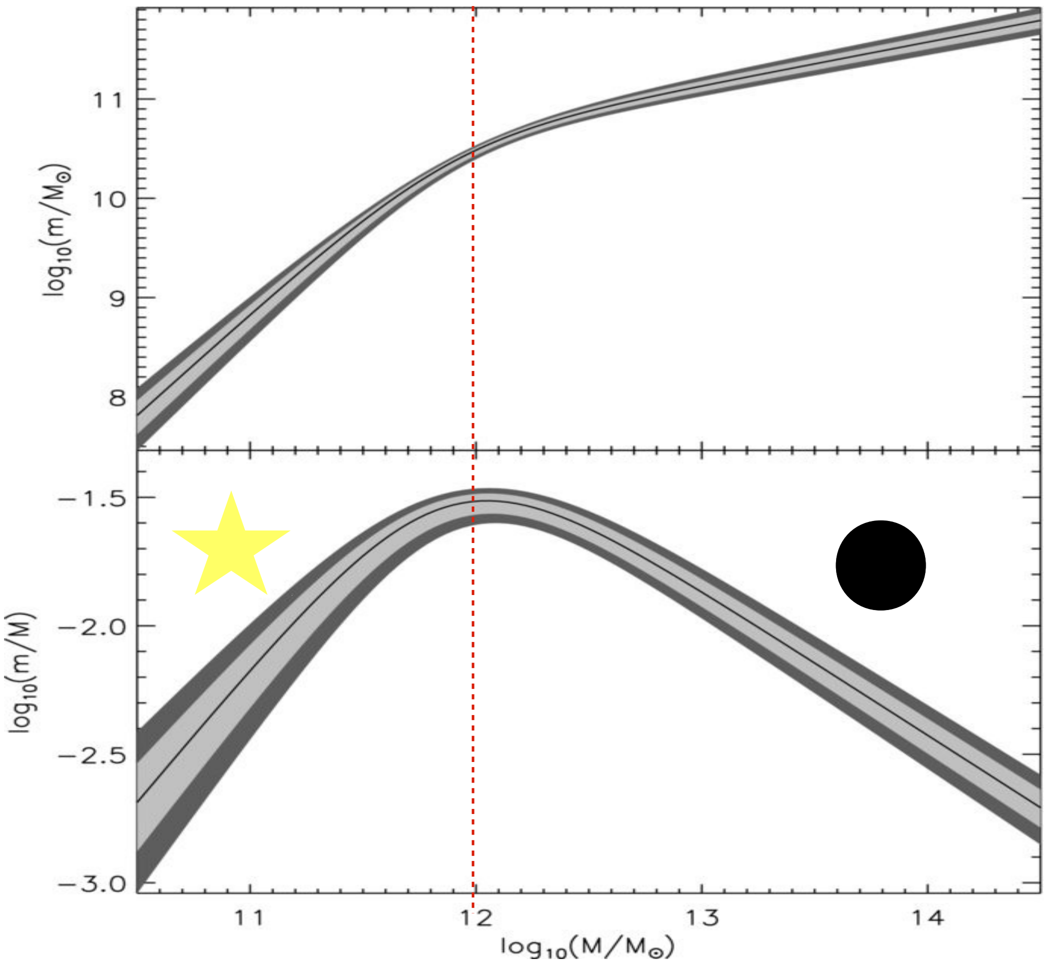




Moster+ 2010

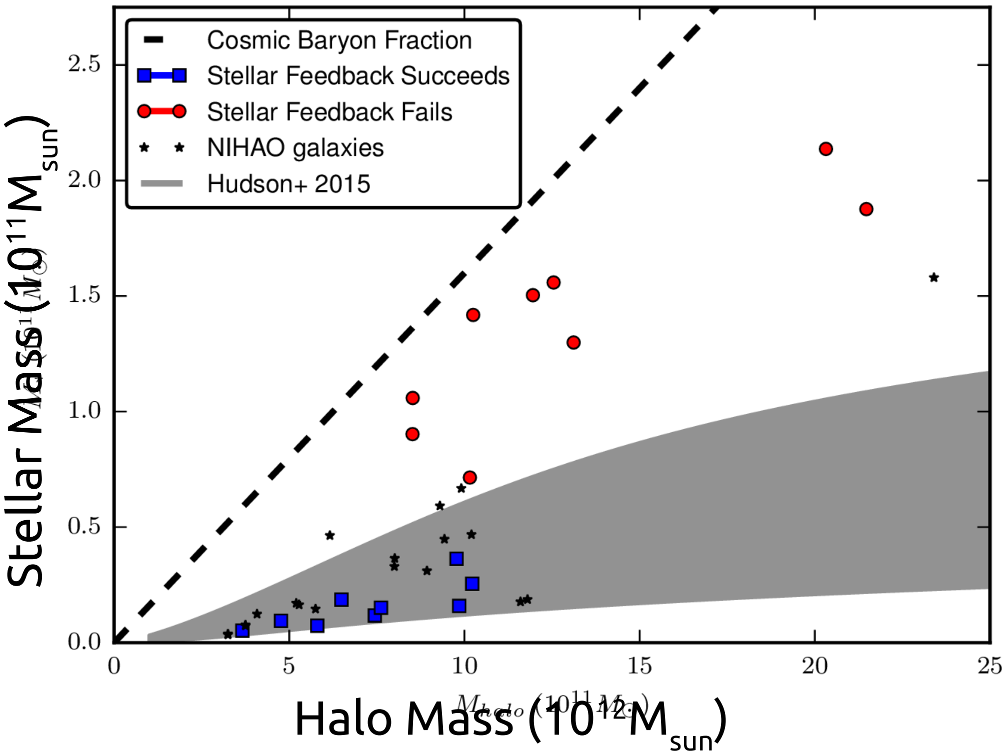
Can Supernovae do it all?

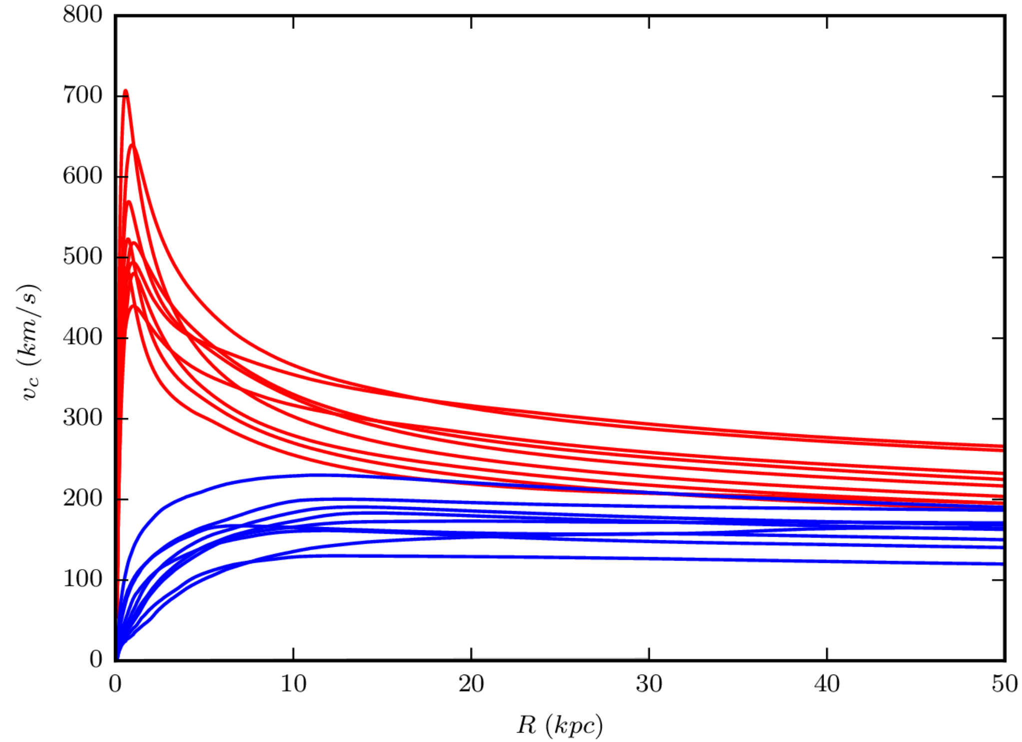




Moster+ 2010

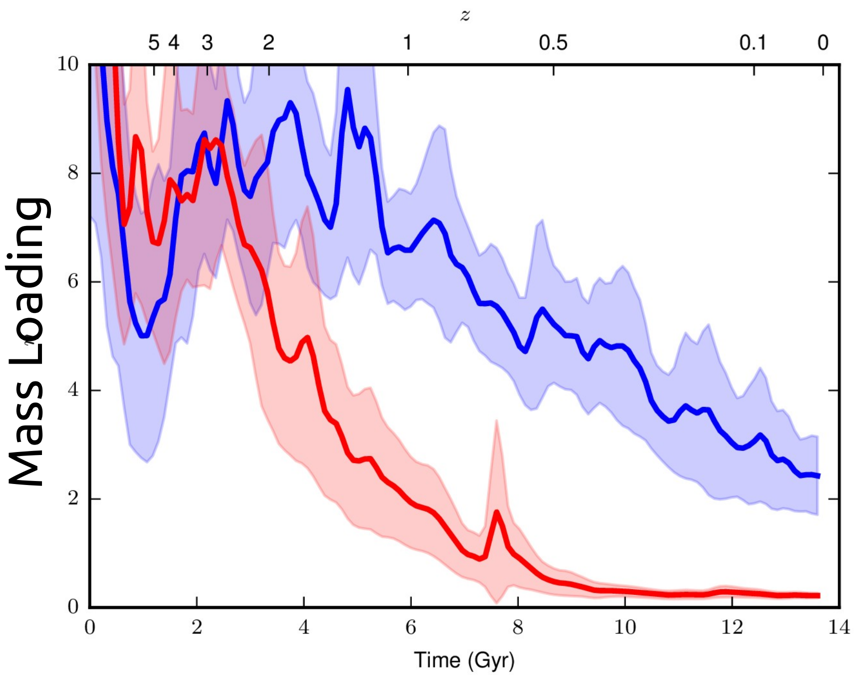
Can Supernovae do it all?

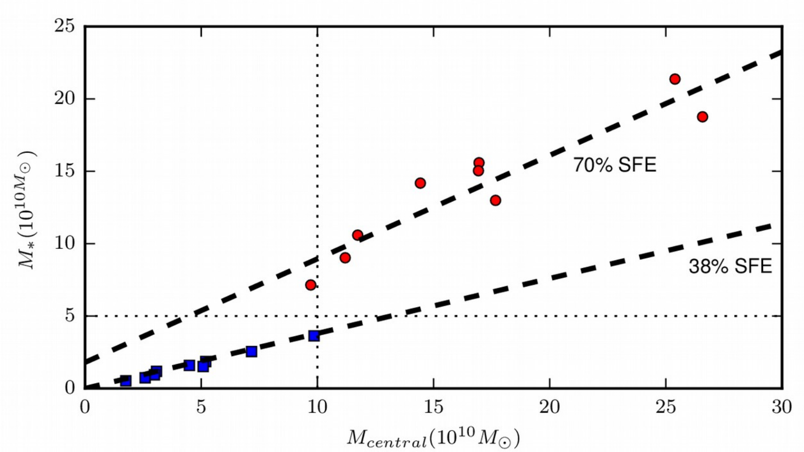




Answer: No! (Keller+ 2016)

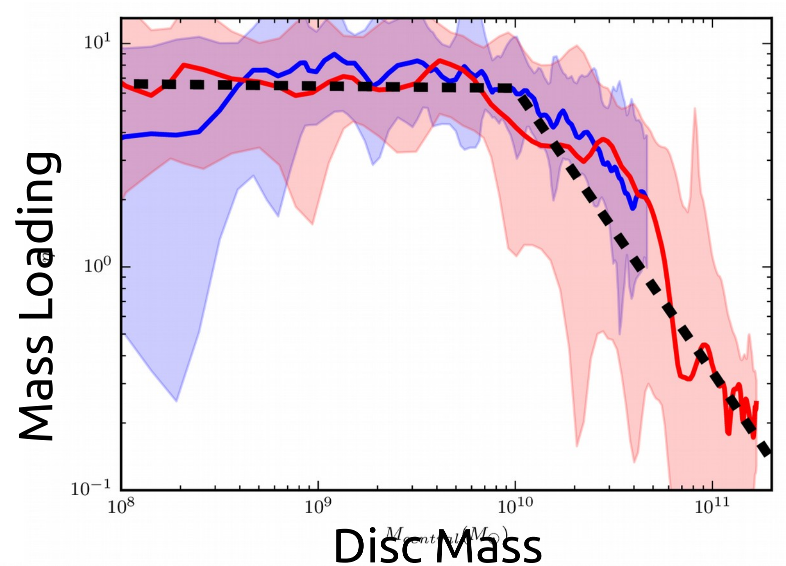
What Determines where SN Fail?

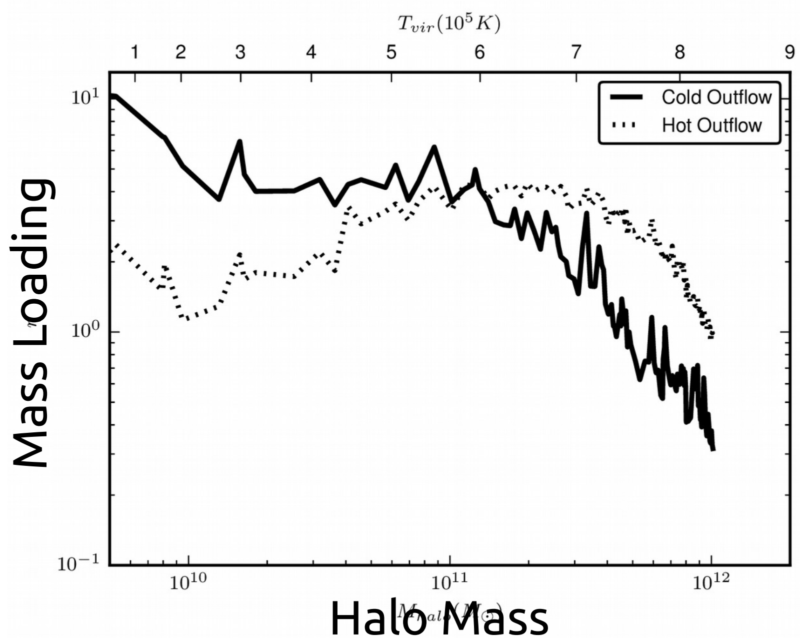




- Galaxies diverge from observed SMHMR rapidly, building a massive stellar bulge in a few 100 Myr
- The average "unregulated" galaxy has its wind mass loadings fall < 1 at z~1
- No galaxy with disc (<0.1R_{vir}) mass >$10^{11}M_{sun}$, or stellar mass >$5x10^{10}M_{sun}$ have correct stellar mass fractions or flat rotation curves
- Well-regulated galaxies have z=0 SFE of ~40%, unregulated galaxies have ~70% SFE

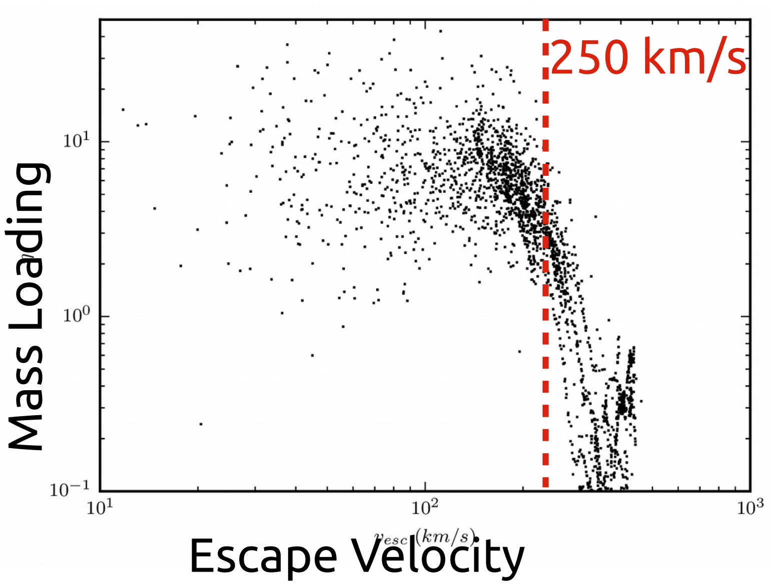
Mass loading has universal scaling

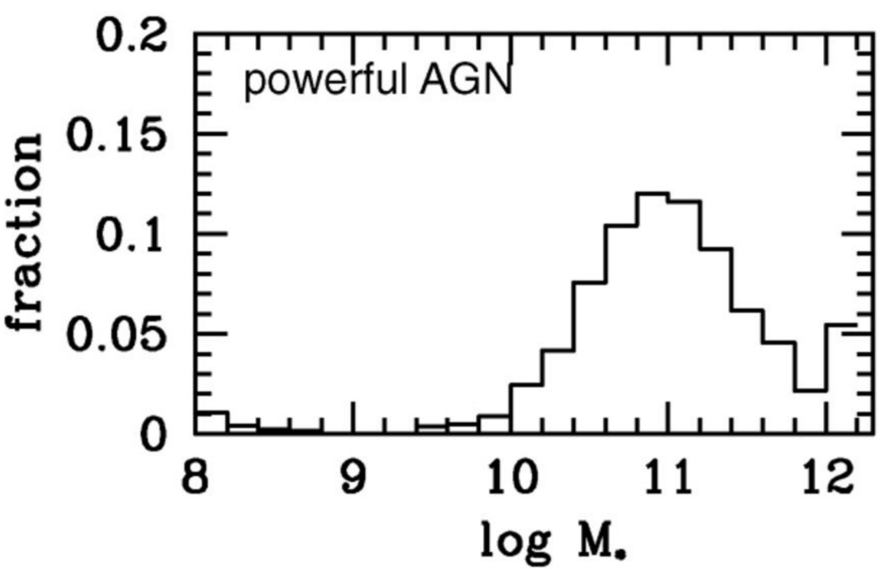




- As disc/halo mass grows, outflows must fight out of deeper potential well.
- Mass-loading begins to fall from ~10 when disc is ~$10^{10}M_{sun}$, halo is ~$2x10^{11}M_{sun}$
- Eventually, only the hottest superbubbles are able to escape

The Limits of Supernovae



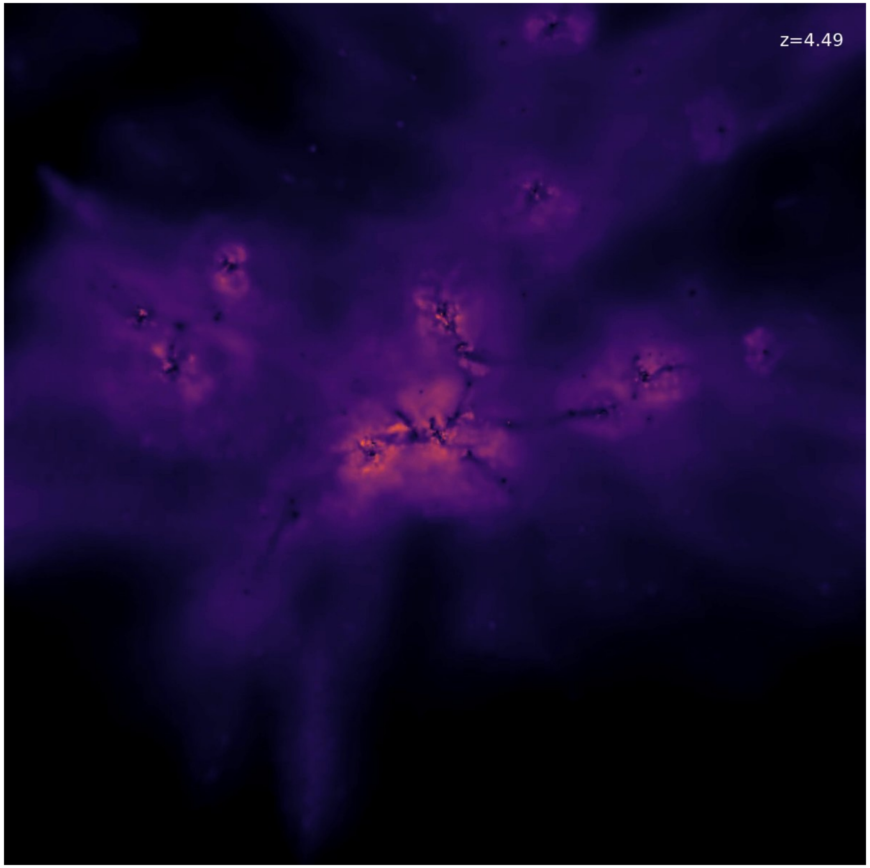


Kaufmann+ 2003

- Mass loading falls rapidly once disc escape velocity > 250 km/s
- Without cooling, η~10 gives T~2.7x10^{6}K
- 2.7x10^{6}K gas has c_s~210km/s (below the escape velocity of discs with M~10^{10}M$_{sun}$)
- SDSS observations find powerful AGN kick in here!
- Dubois+ 2015 simulations found AGN regulation began at 280 km/s bulge v_{esc} at high z

Conclusions

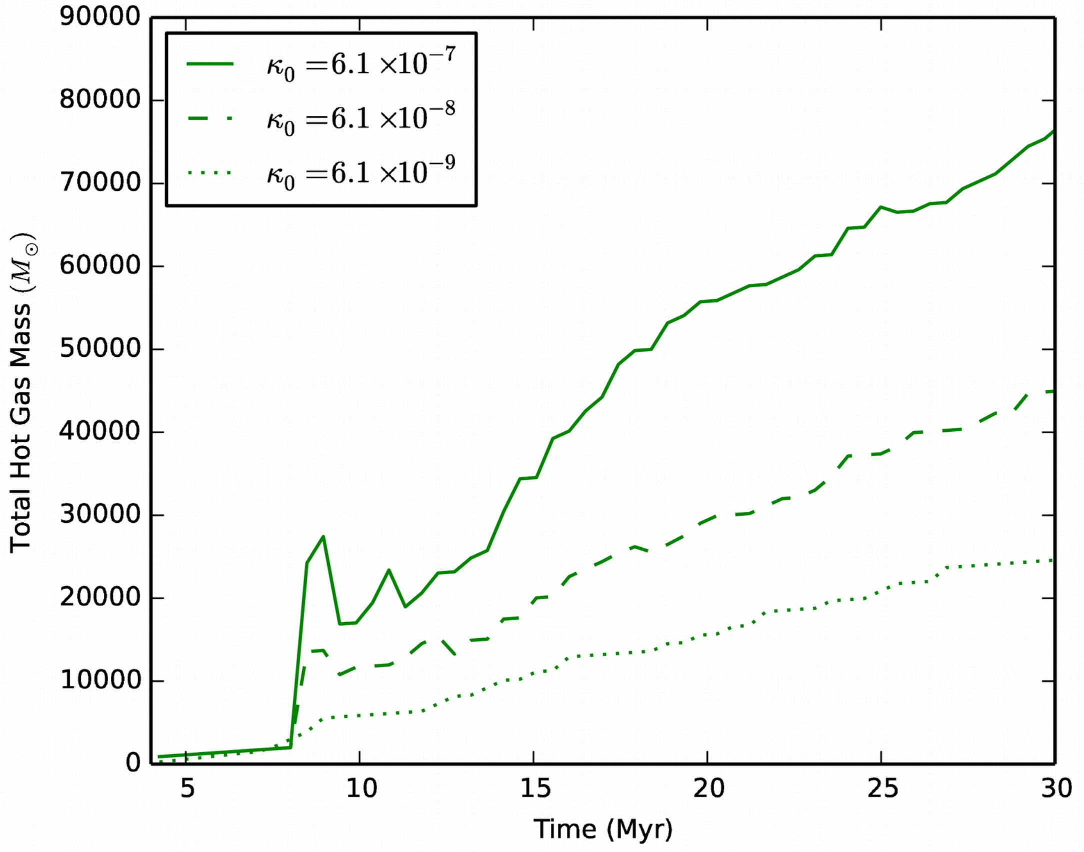
- Superbubble physics required for realistic gas behaviour, high mass loadings for winds in L* galaxies
- Winds prevent runaway bulge growth, give realistic stellar mass evolution and rotation curves
- Galaxies w/ $M_{vir}>10^{12}M_{sun}$ or $M_* >5x10^{10}M_{sun}$, SN feedback becomes ineffective
  - For hot gas to escape, it must have η<<10, and it can no longer prevent runaway bulge growth/star formation
- SN fail exactly where AGN are observed, and expected to become important
  - Runaway bulge growth = runaway SMBH growth (Magorrian+ 1998)



Scan Here to read my papers :)

Magnetic Fields & Reduced Conduction

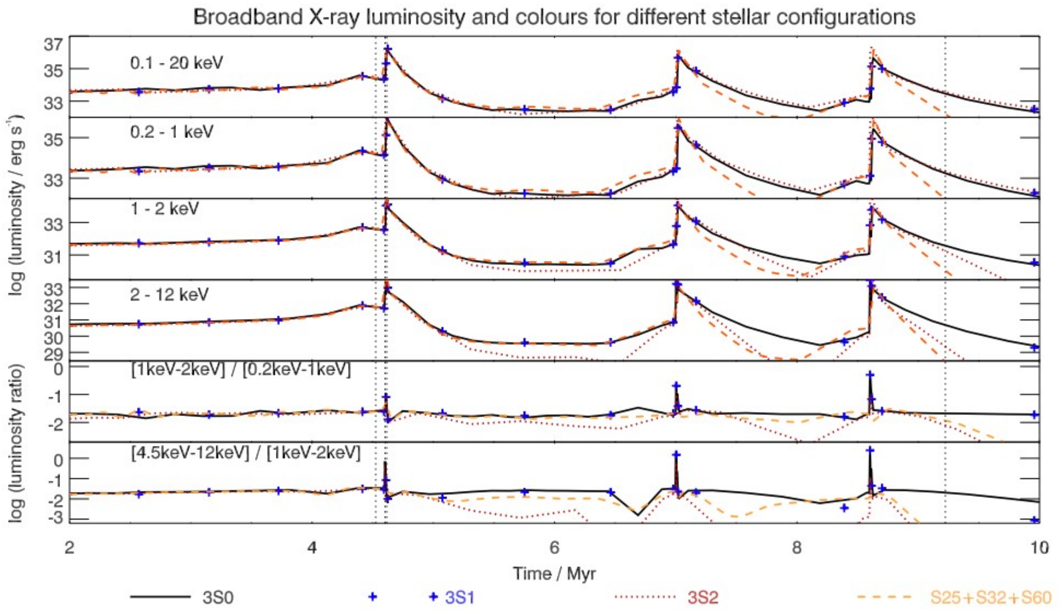
- Conduction suppressed across magnetic field lines
- 100x reduction in conduction rate κ0 results in only factor of ~2 reduction in hot bubble mass



Superbubble X-Ray Luminosities

Table 1. Physical Properties of Hot Gas in Bubble Interiors

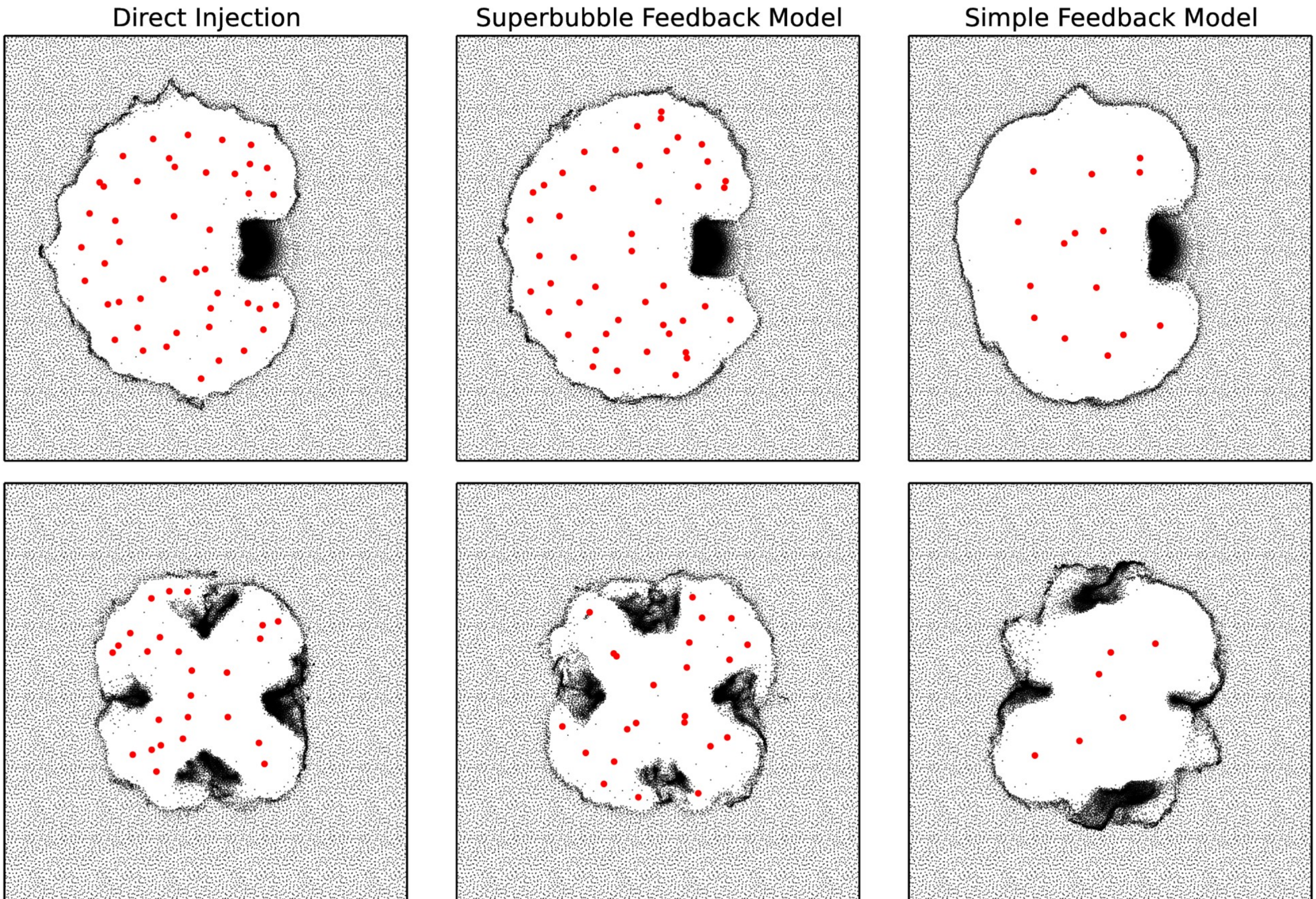
Bubble Type	T_e [10^6 K]	N_e [cm^{-3}]	L_X [erg s^{-1}]
Orion Bubble	2	0.2–0.5	5×10^{31}
WR Bubble	1–2	1	$10^{33} - 10^{34}$
M17 Superbubble	1.5, 7	0.3	3.4×10^{33}
Planetary Nebula	2–3	100	$10^{31} - 10^{32}$



Krause+ 2014

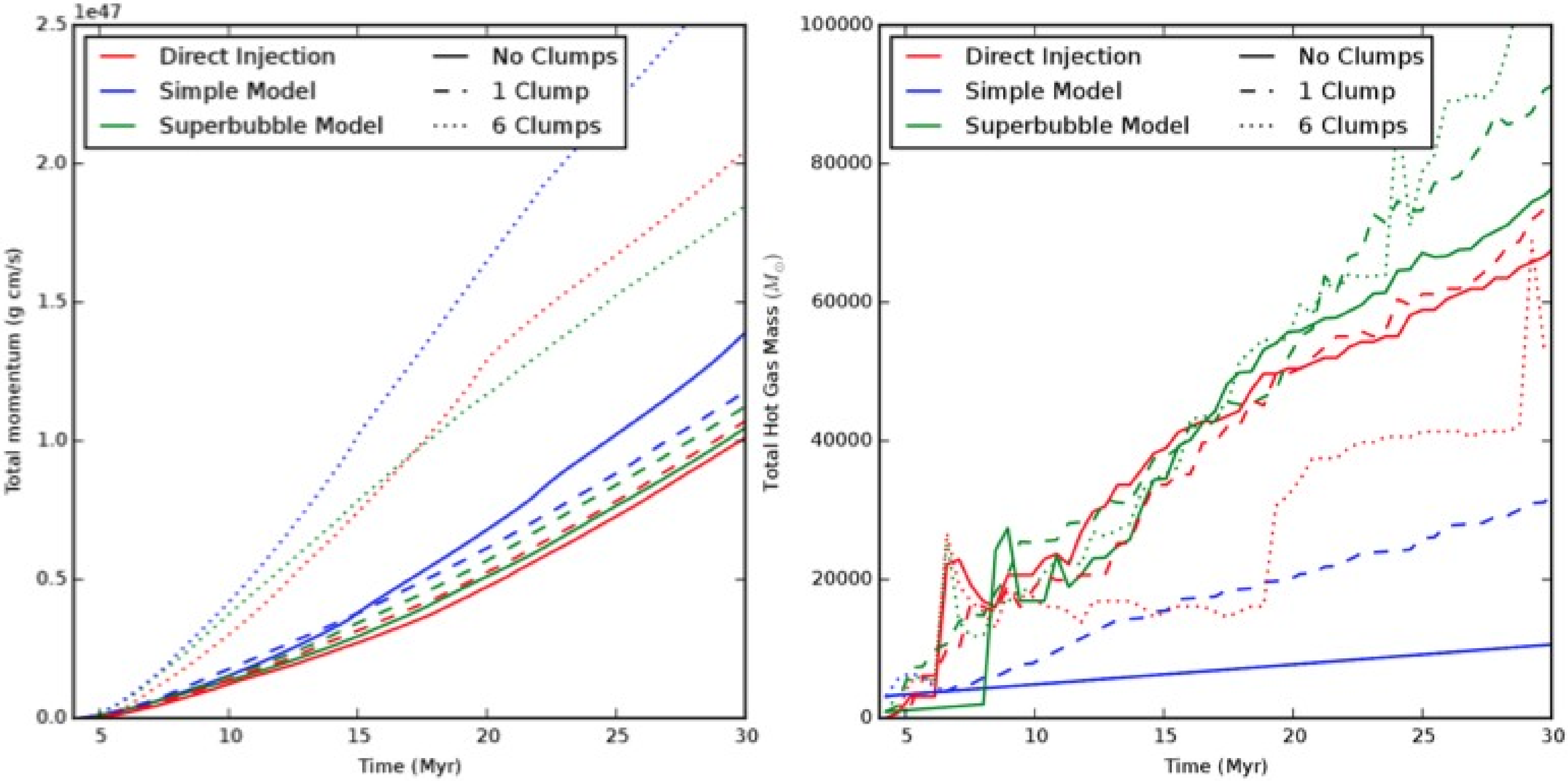
- X-Ray luminosity highly variable over space, time
- Very few observations, large scatter in observed LX
- Leaking of interior, B-field amplification in shell may explain some reduced luminosities (see Rosen+ 2014)

Clumpy ISM



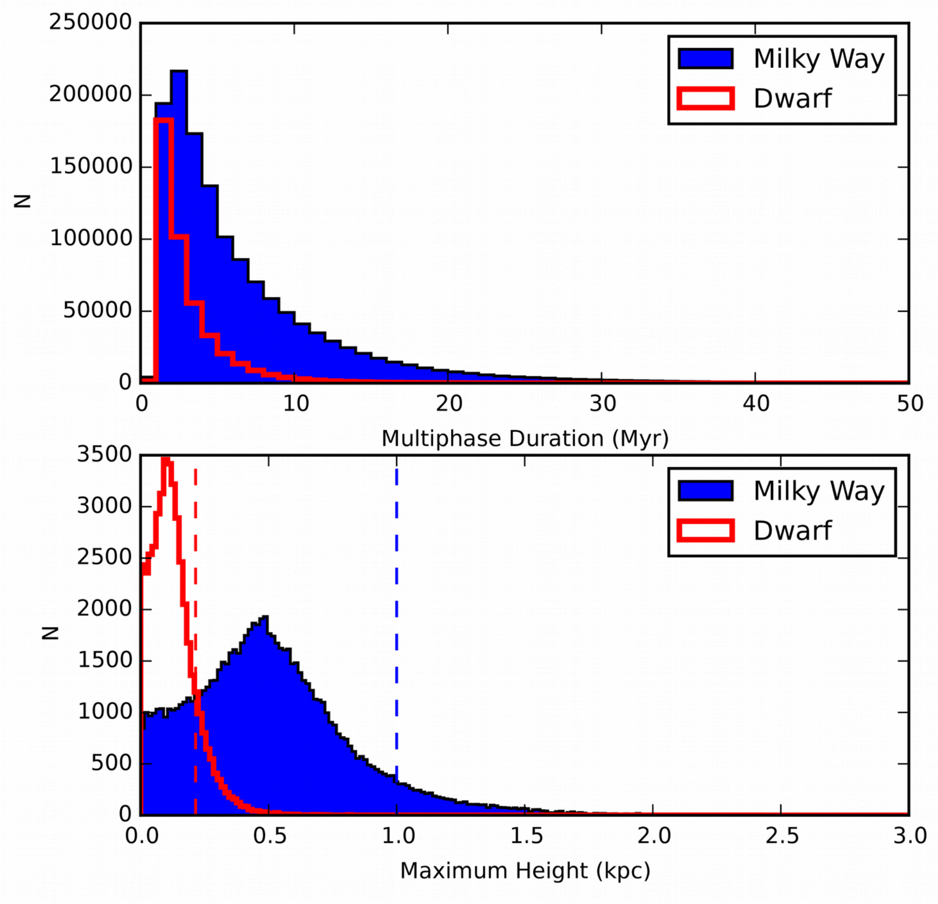
Direct Injection
Superbubble Feedback Model
Simple Feedback Model

Clumpy ISM



- Some changes in bubble mass/momentum
- Agreement with direct model still good

Multiphase Properties



- Median multiphase lifetime < 5Myr