Superbubble Regulation of Baryons in Cosmological Galaxy Formation

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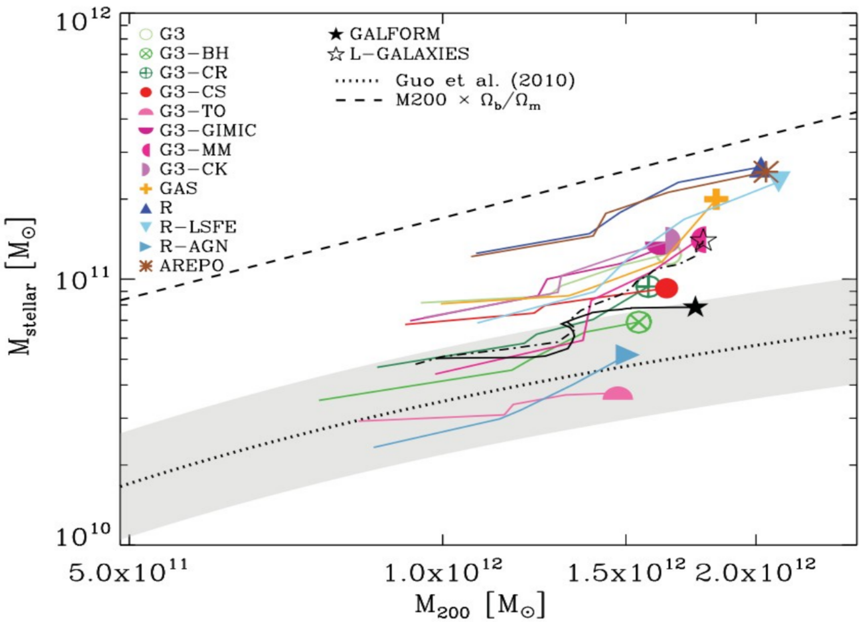
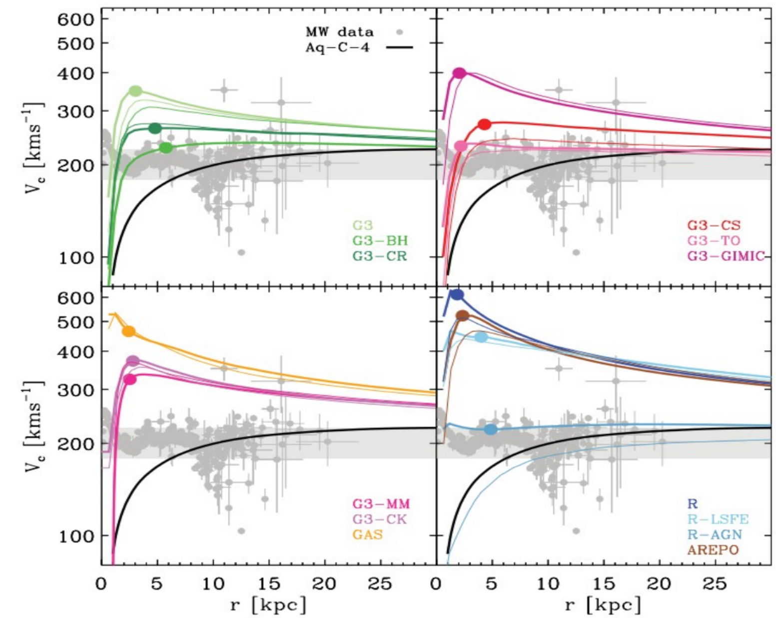
Simulations Circa 2012: Yikes!

Stellar Mass

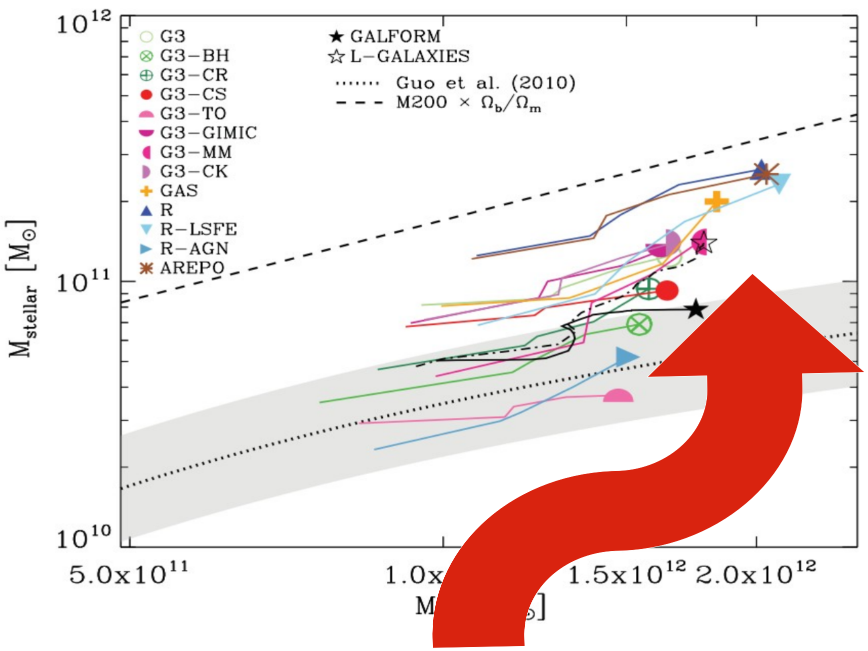


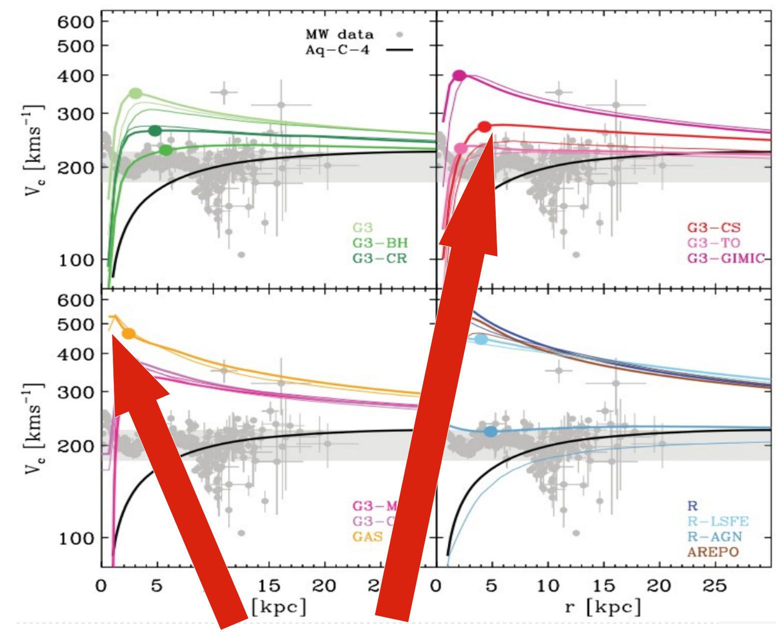
Halo Mass



- 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

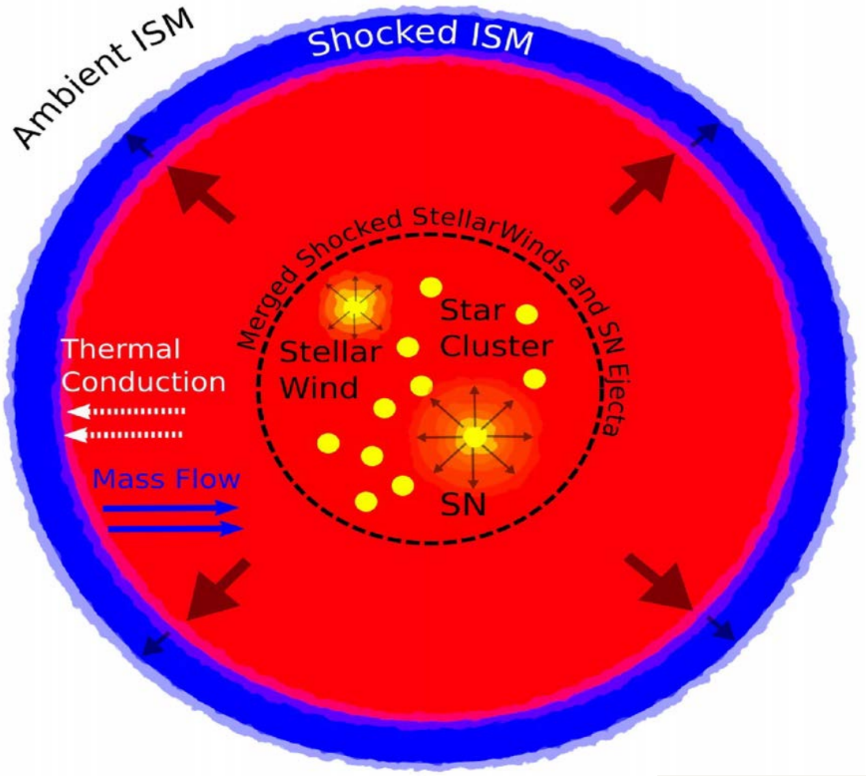
Things have improved since 2012

- ~~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)

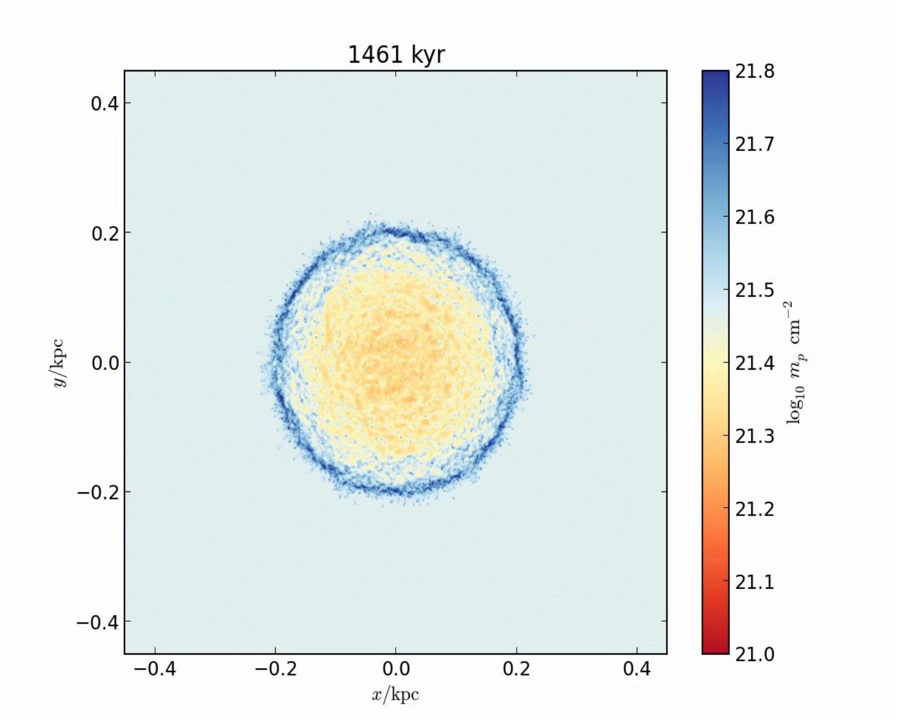
1) Resolved thermal conduction for hot, diffuse gas inside hot bubbles

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

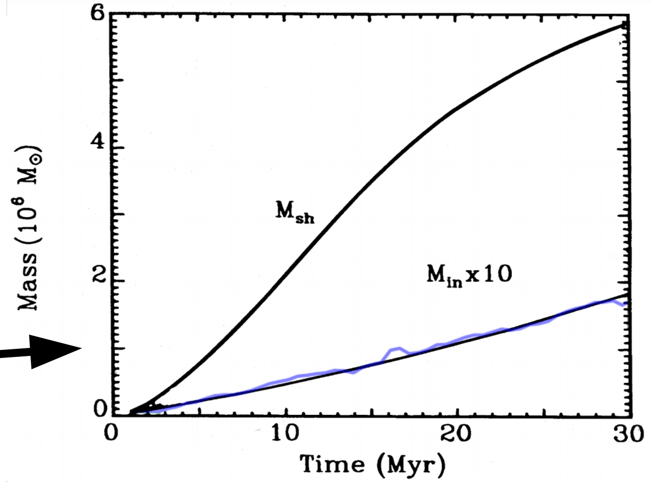
3) Two-phase particles for early phase of bubble growth, with internal evaporation to convert back to single phase

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

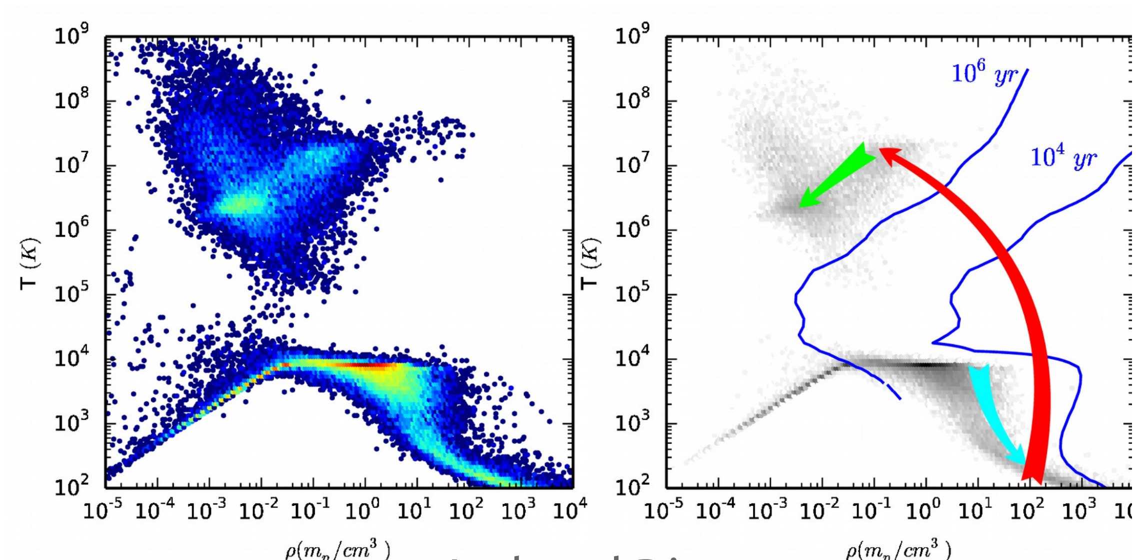


Hot Mass Matches Silich 1999

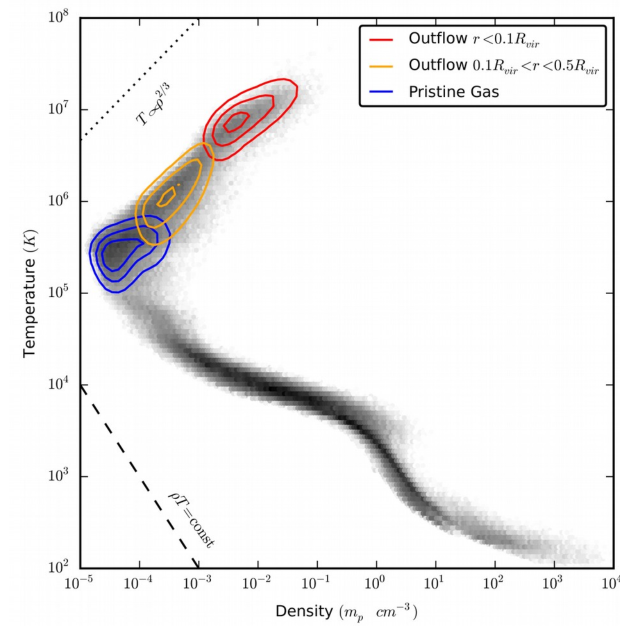


Superbubble Gas Lifecycle

Cosmological Galaxy

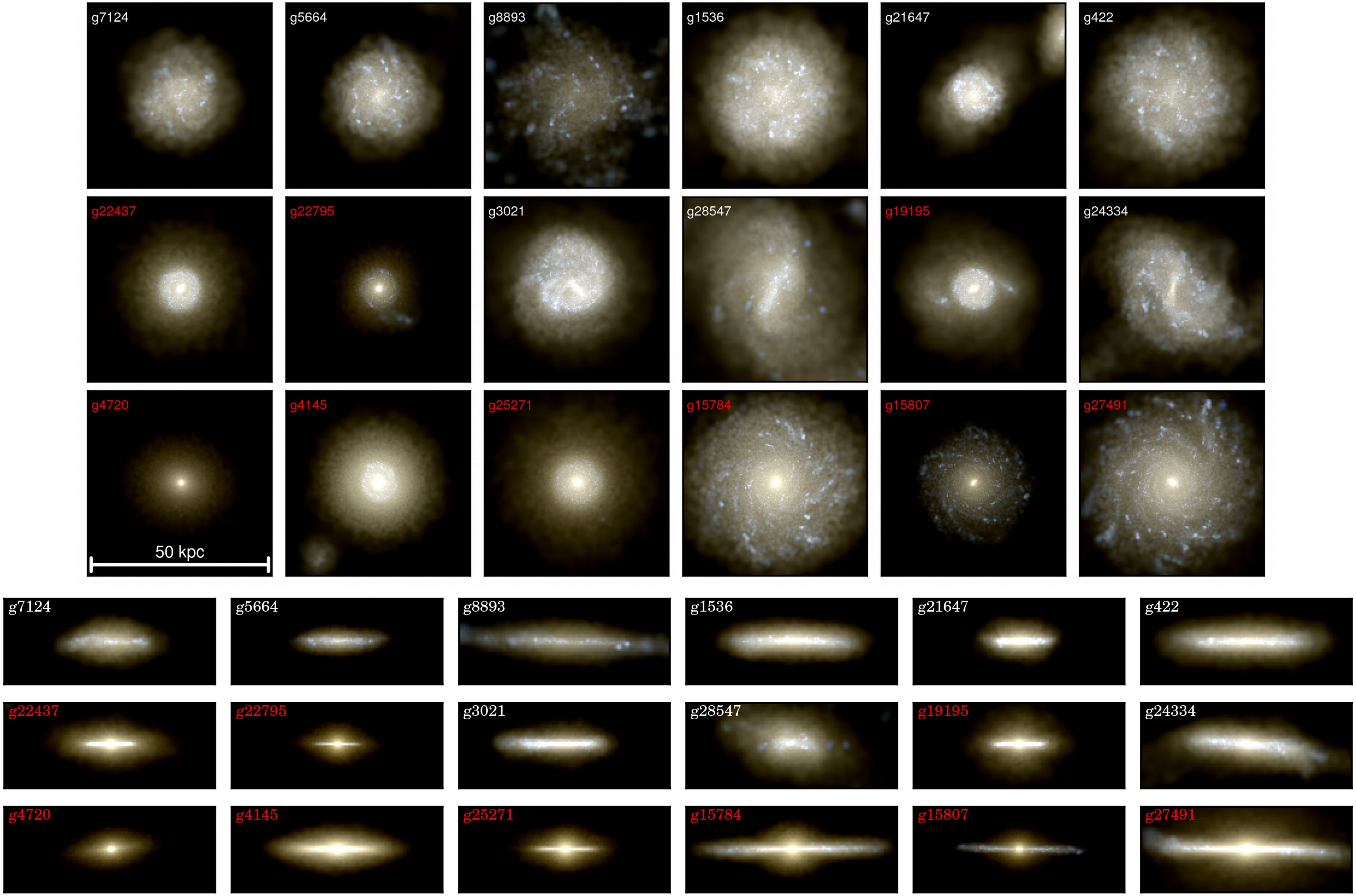


Isolated Disc



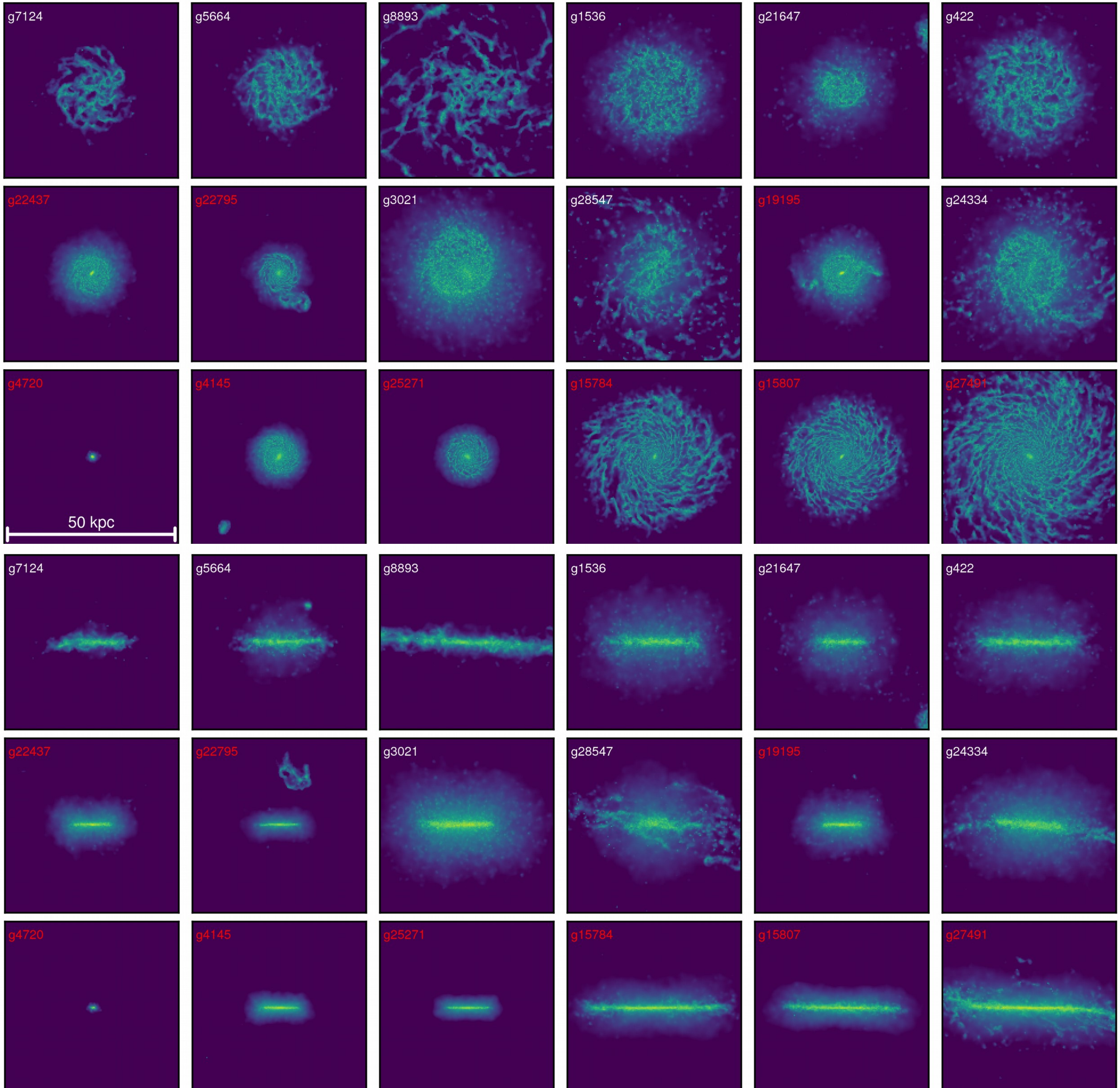
- Equilibrium WI(N)M cools, forms stars -> SN
- SN form superbubbles, begin at ~10^8K, evaporate to a few 10^6K
- Feedback-heated leaves disc, evolves adiabatically as it rises through halo. Cooling times are >> Myr

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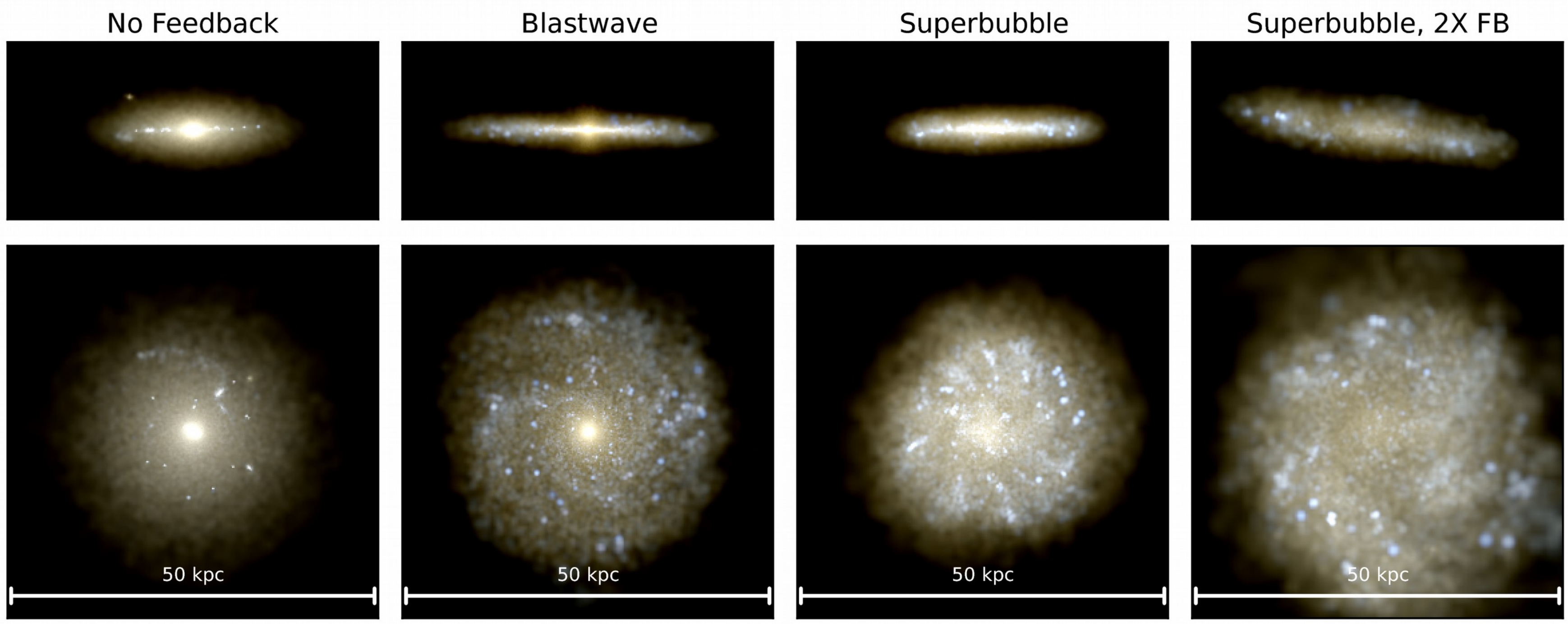
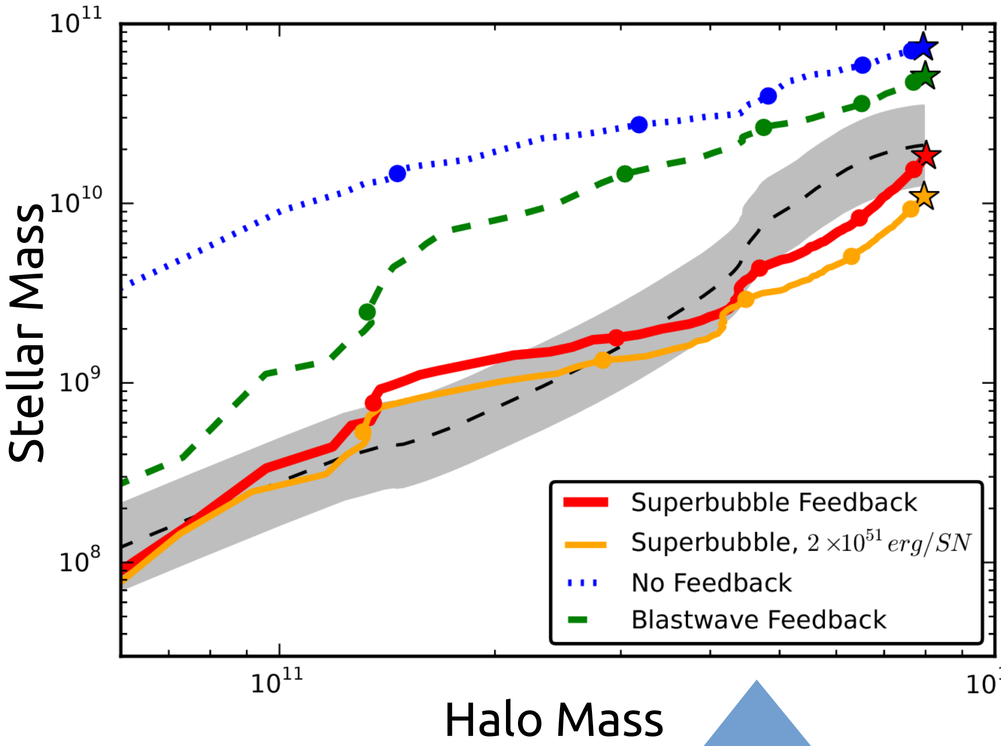
g422
g22437
g22795
g3021
g28547
g19195
g24334
g4720
g4145
g25271
g15784
g15807
g27491

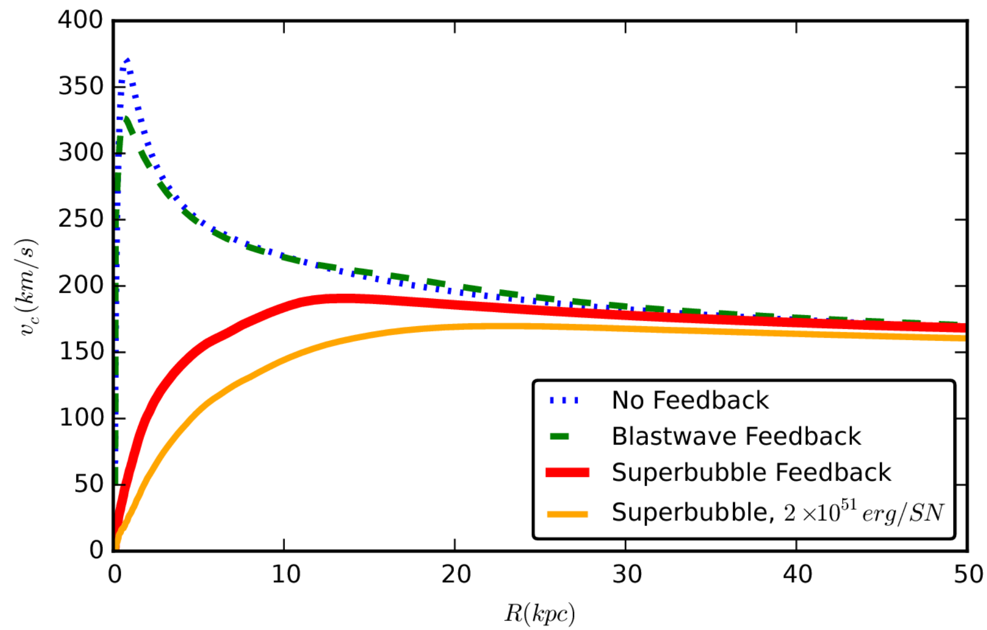
Feedback Models Matter! (Keller+ 2015

- 4 test cases:
  - No Feedback
  - Blastwave (Stinson+ 2006) feedback
  - Superbubble Feedback
  - Superbubble Feedback 2X Energy
- g1536
  - 8×10^{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

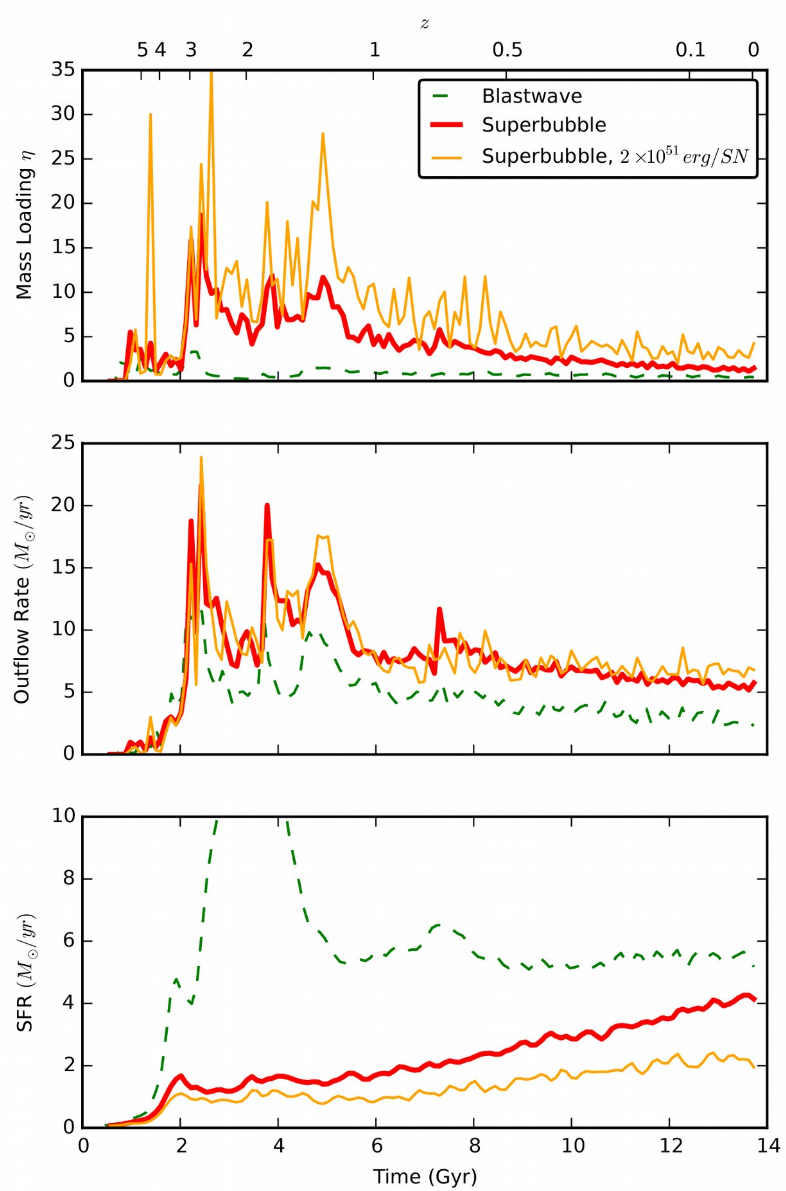




Stellar Mass Evolution Matches Behroozi+ 2012 abundance matching

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

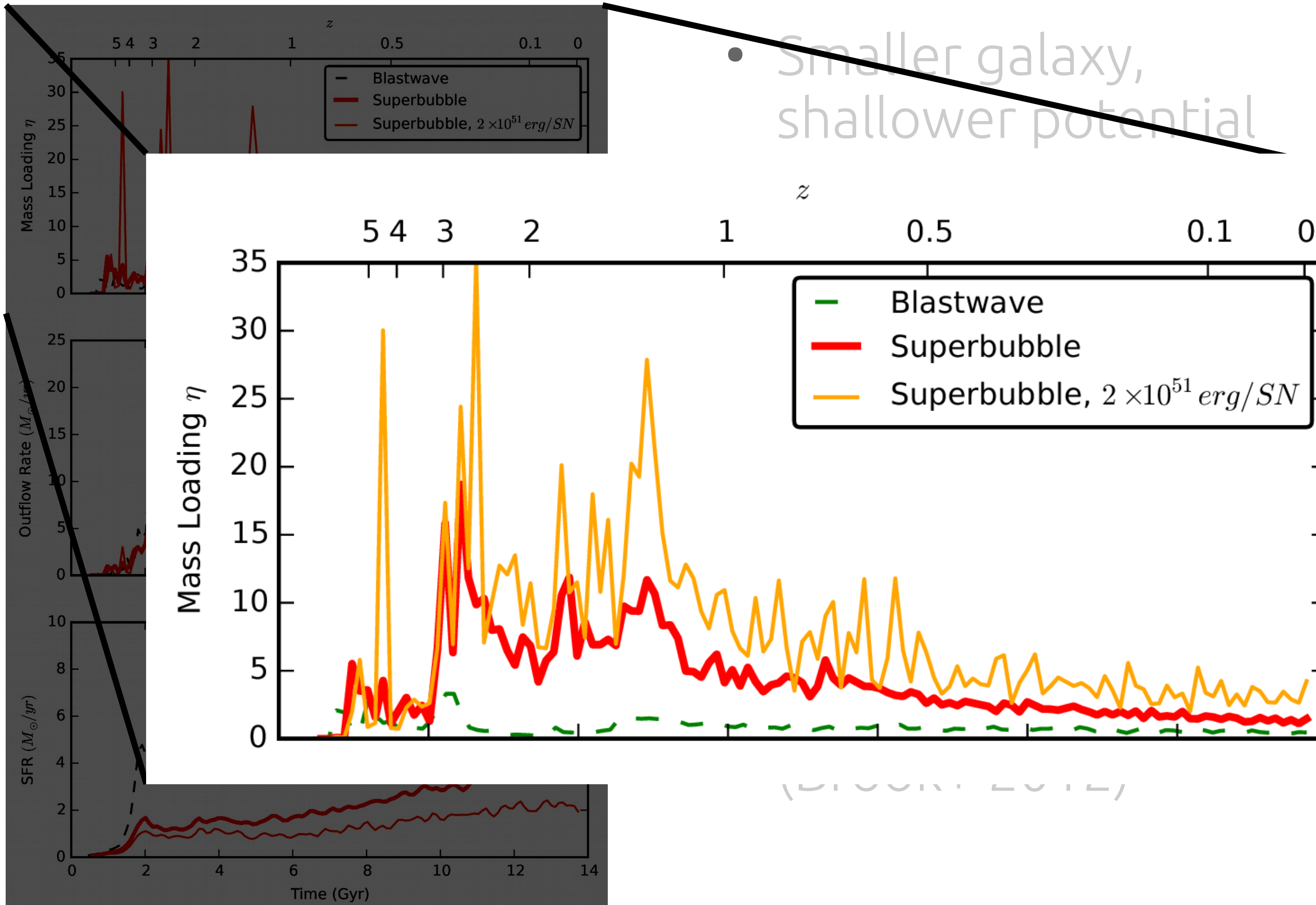


- Smaller galaxy, shallower potential well
- Higher mass loadings allow for correct stellar mass fraction, remove fuel for later star formation

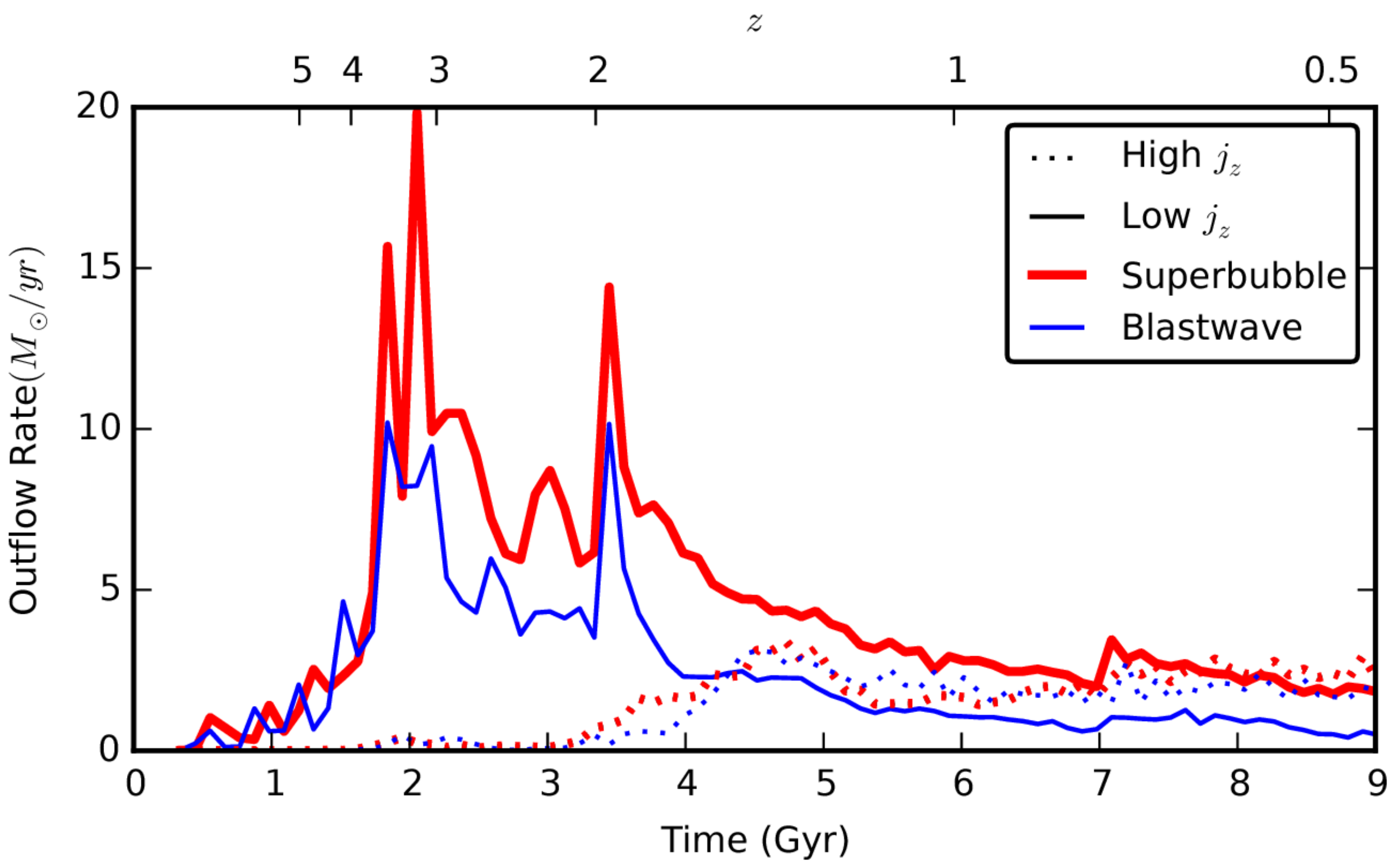
Outflows preferentially remove low-j gas! (Brook+ 2012)

Superbubbles drive outflows well

- Smaller galaxy, shallower potential



High-z outflows prevent bulges, preserve disks



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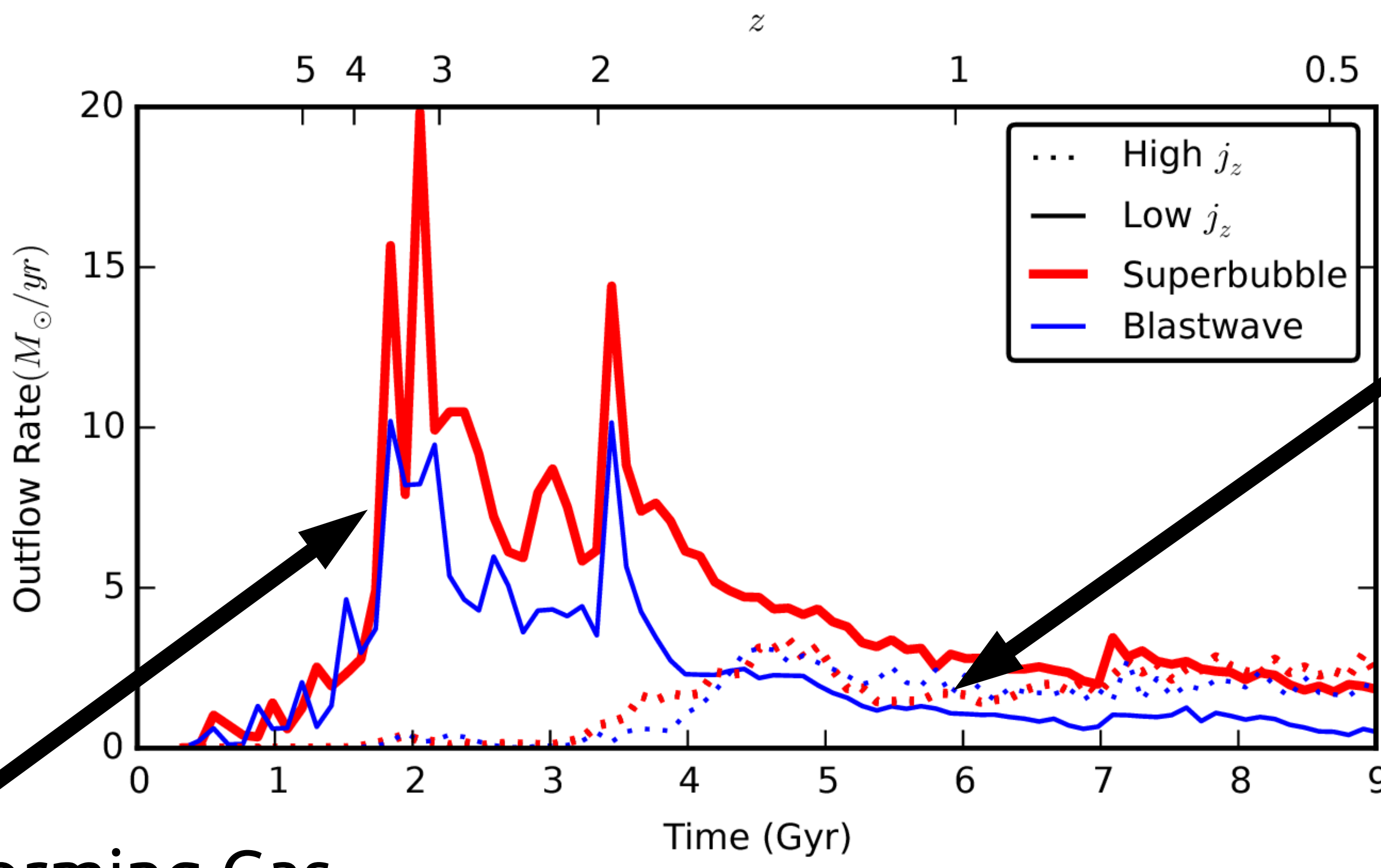
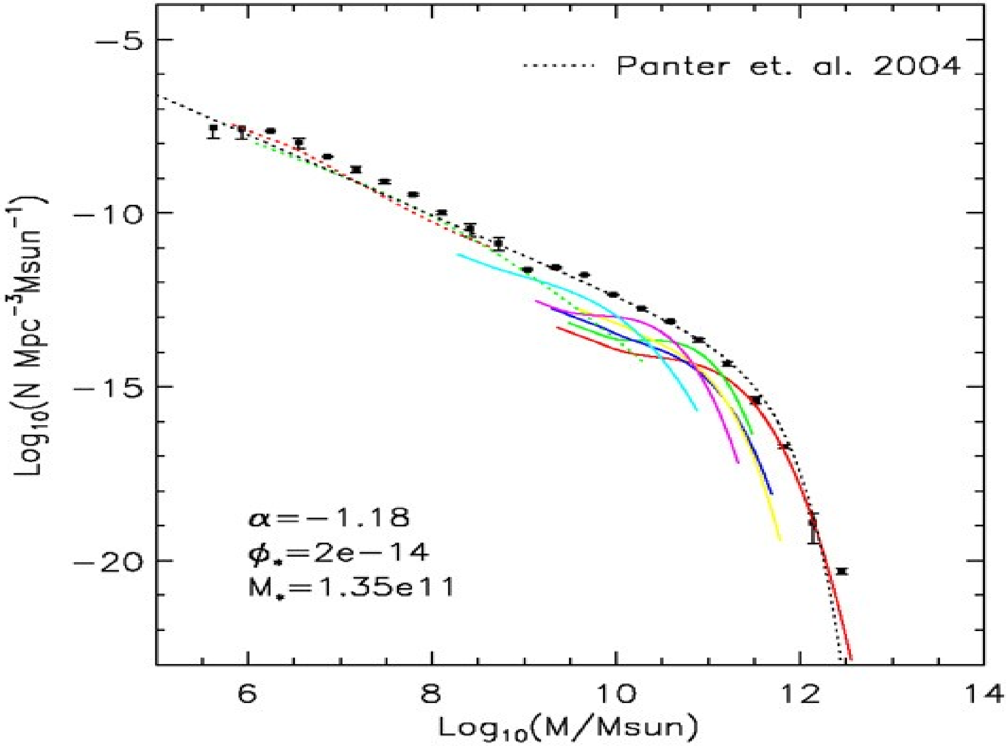
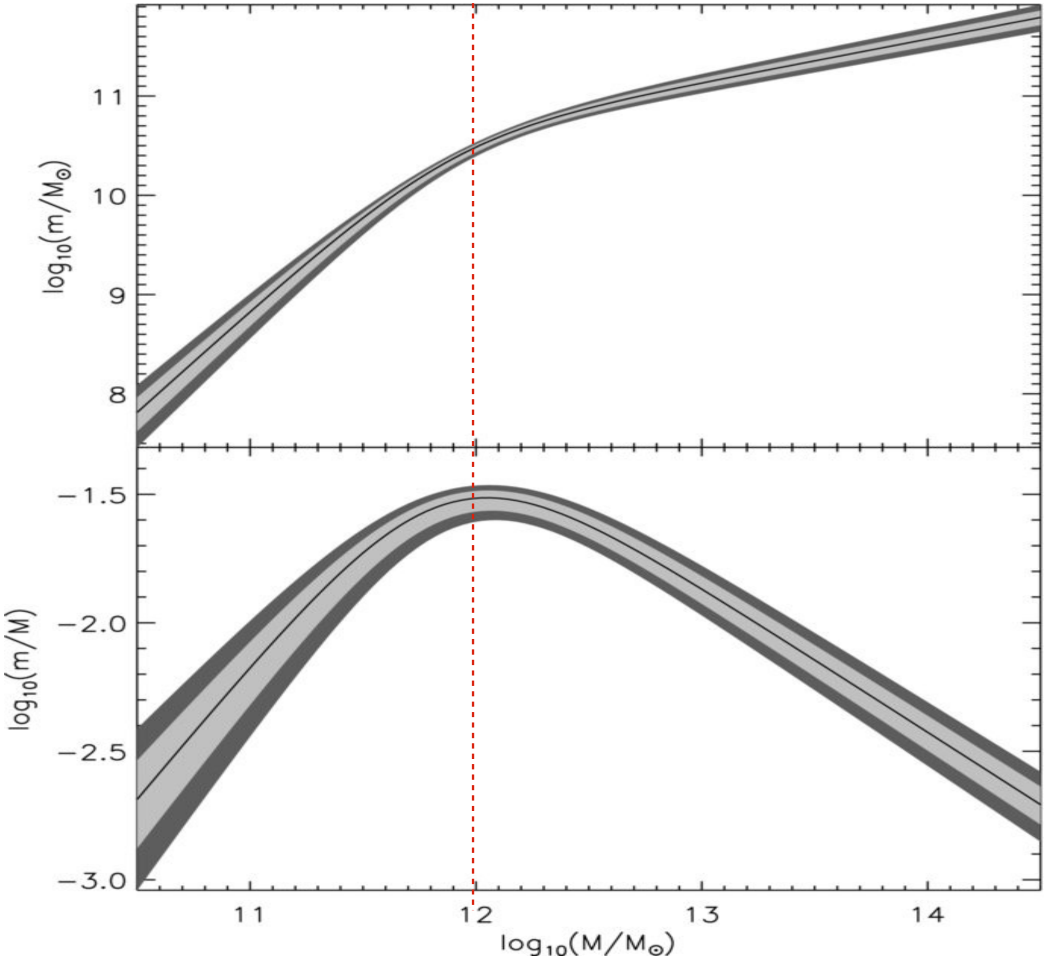


Disk Forming Gas

Bulge Forming Gas

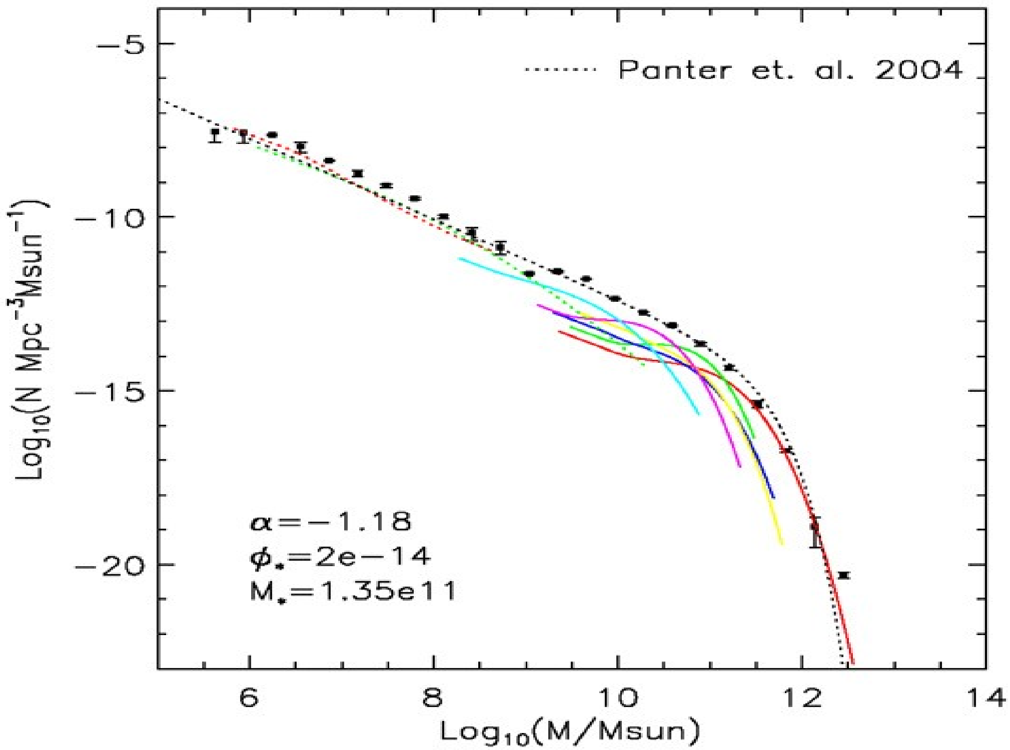
Can Supernovae do it all?

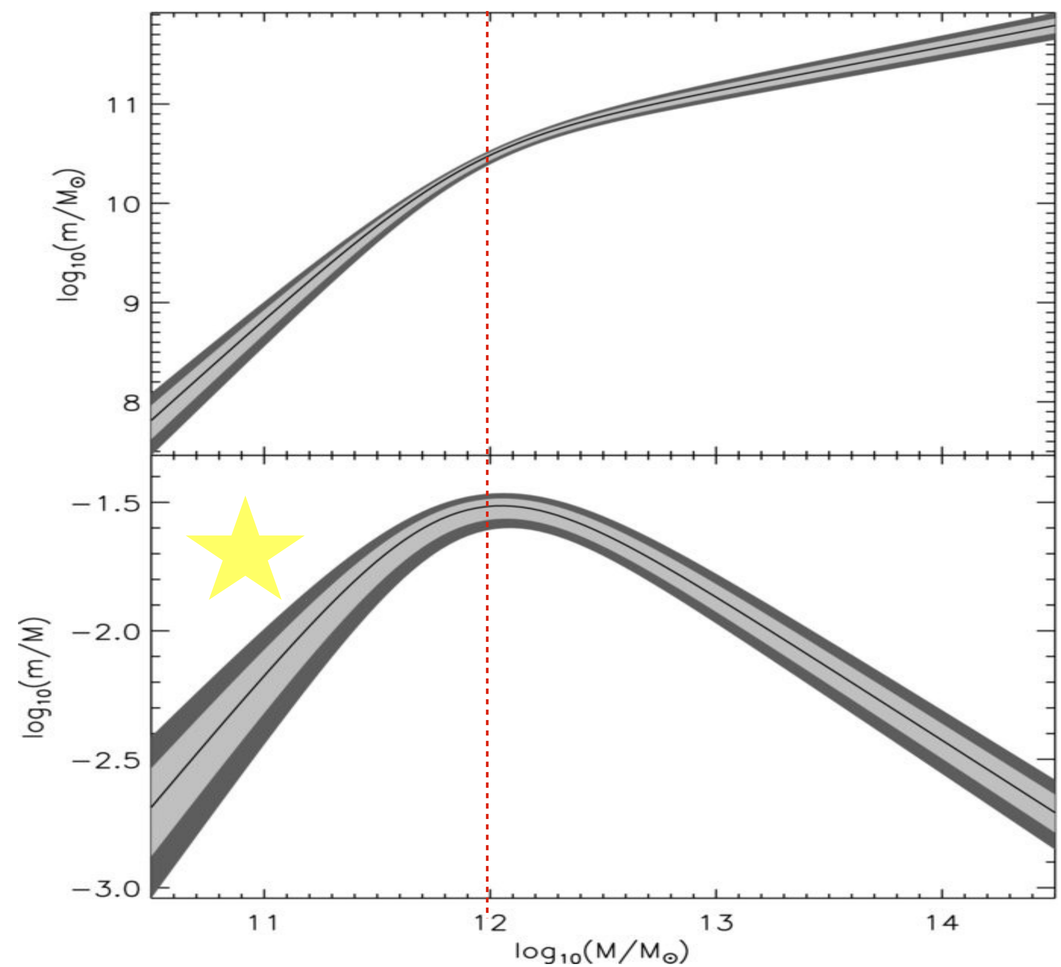




Moster+ 2010

Can Supernovae do it all?





Moster+ 2010

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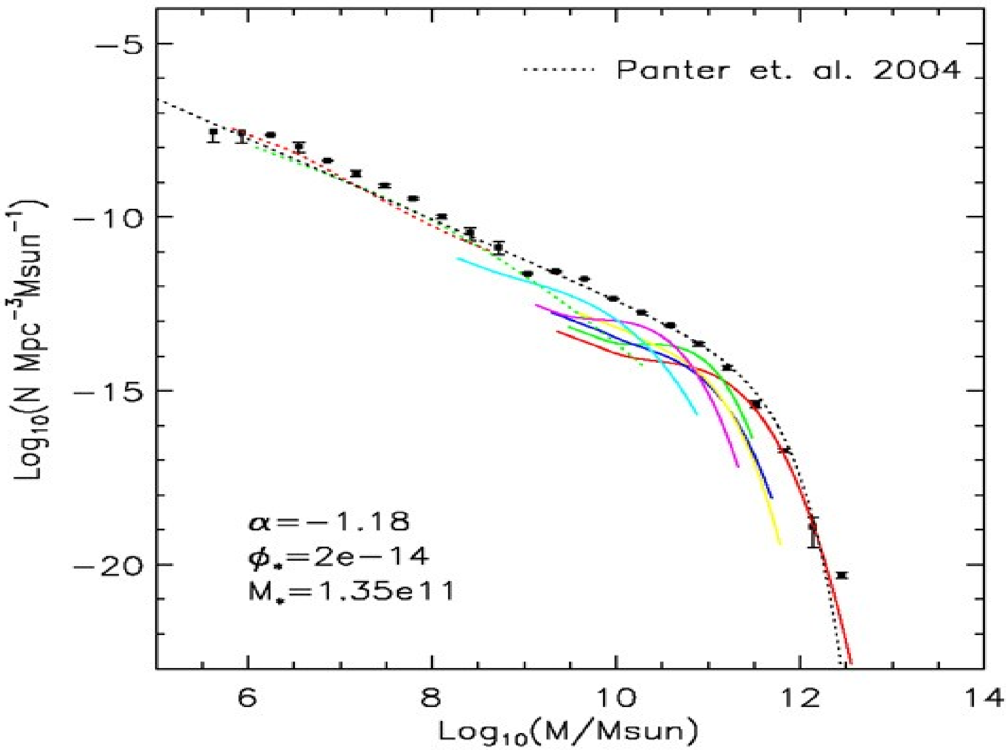
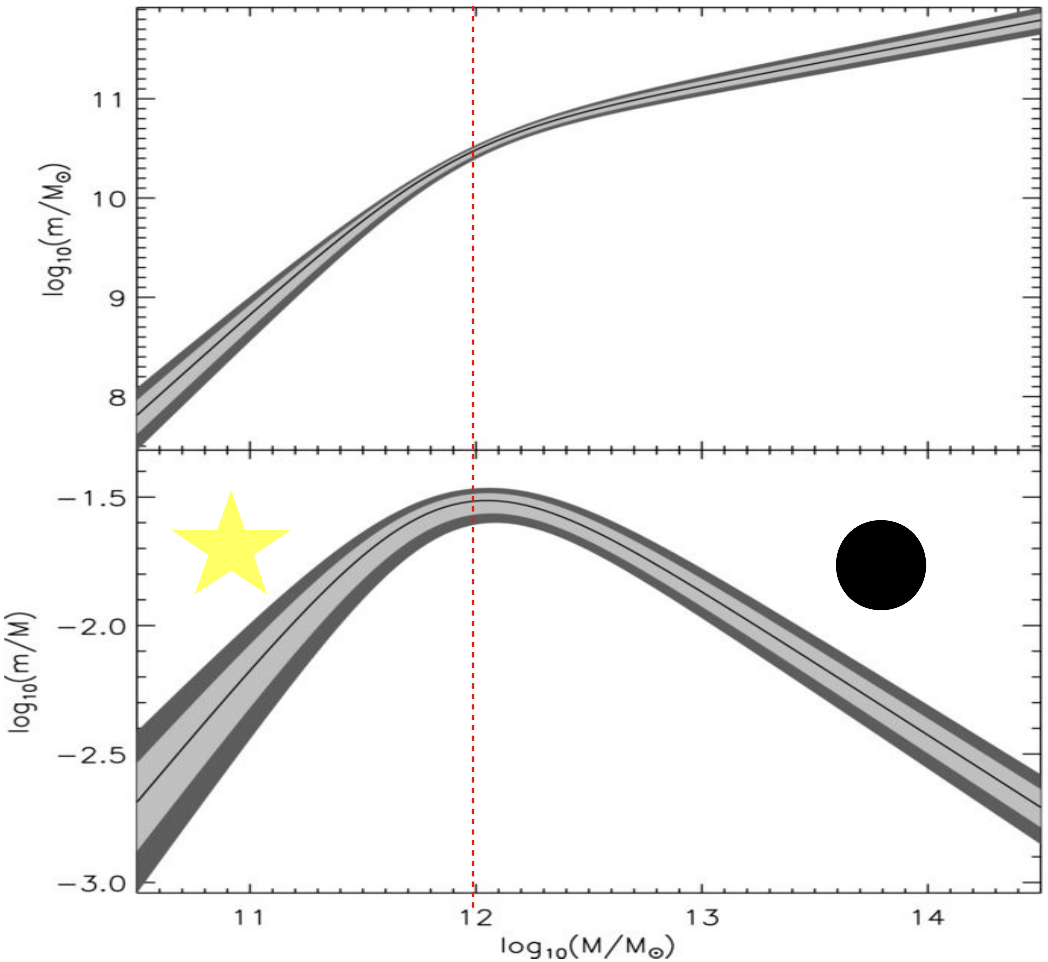
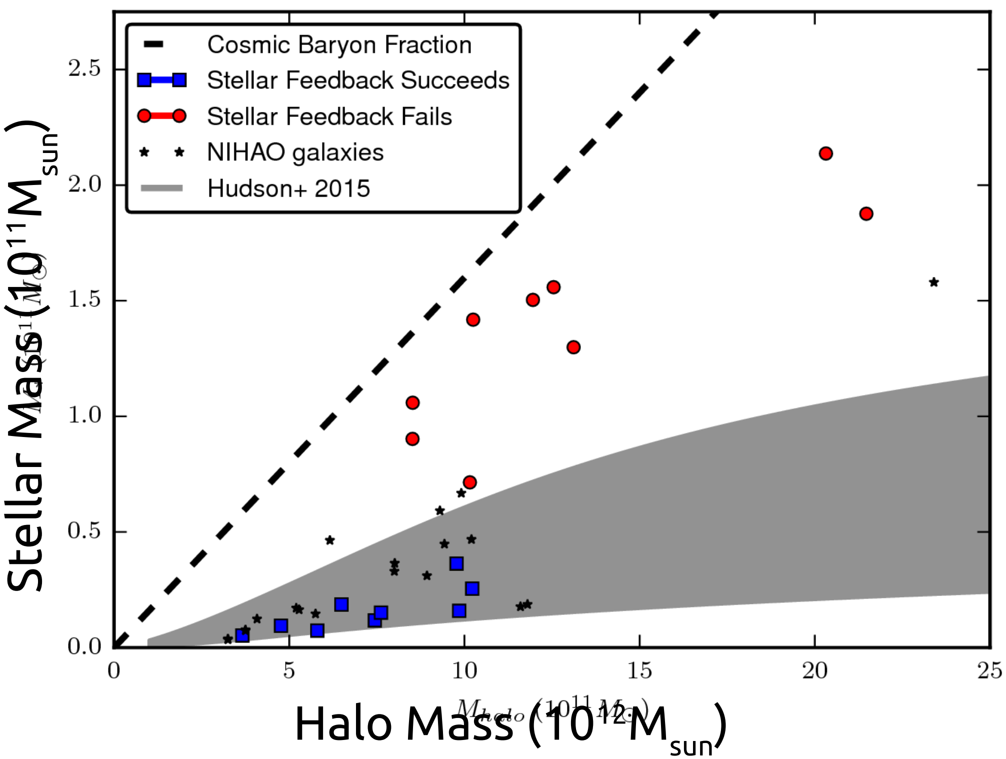
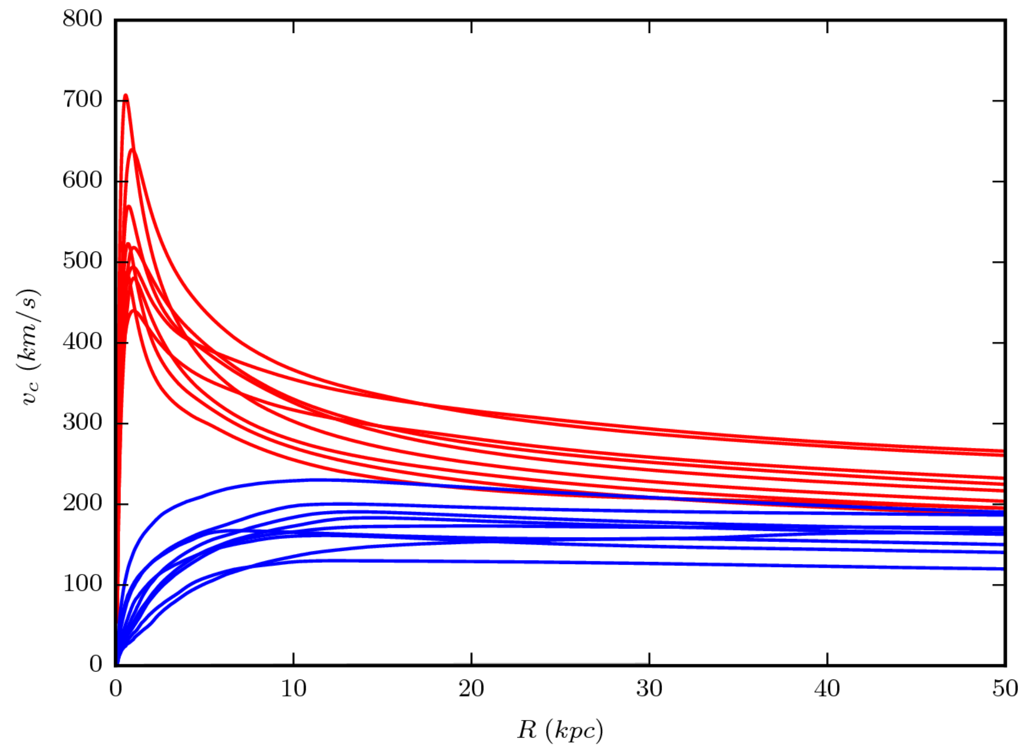




Moster+ 2010

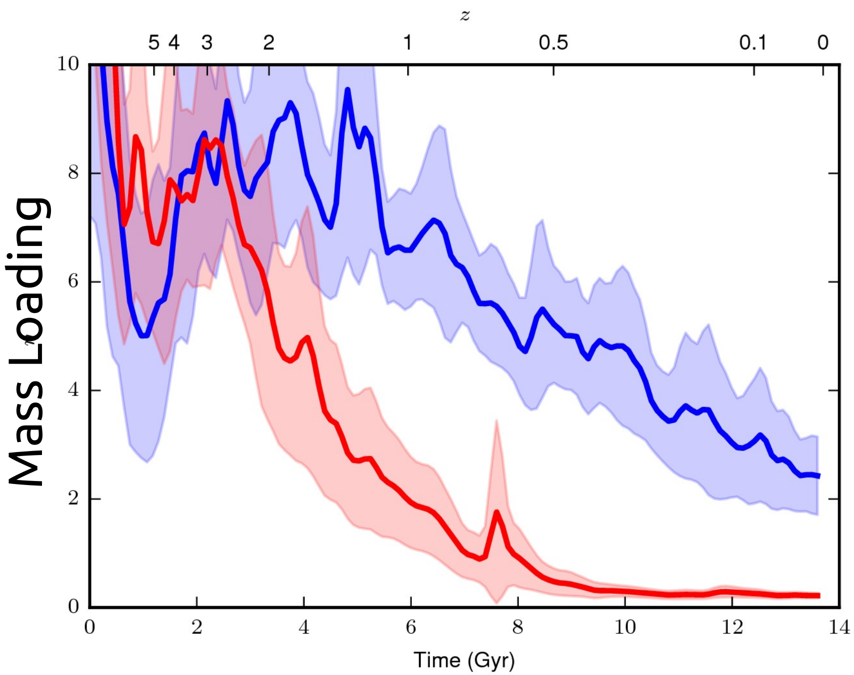
Can Supernovae do it all?

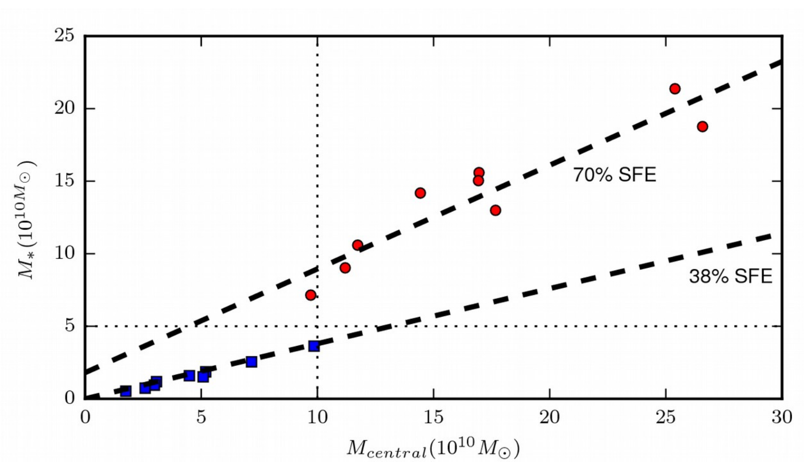




Answer: No! (Keller+ 2016)

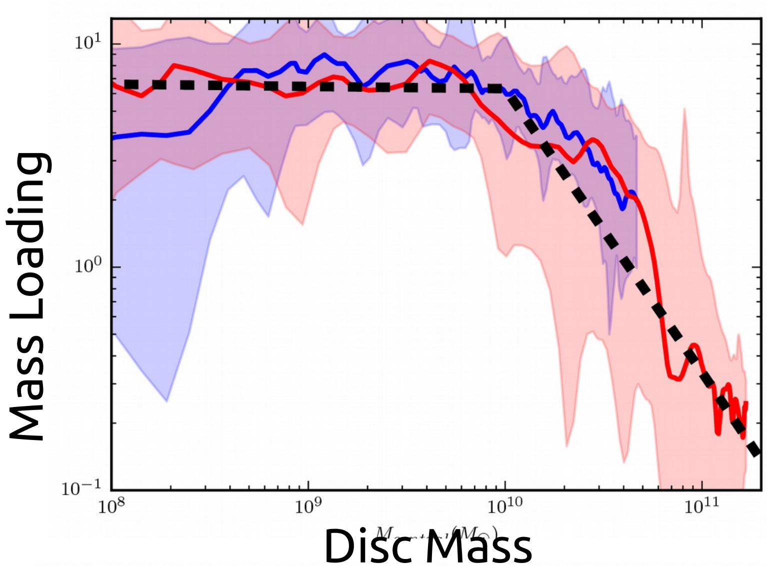
What Determines where SN Fail?

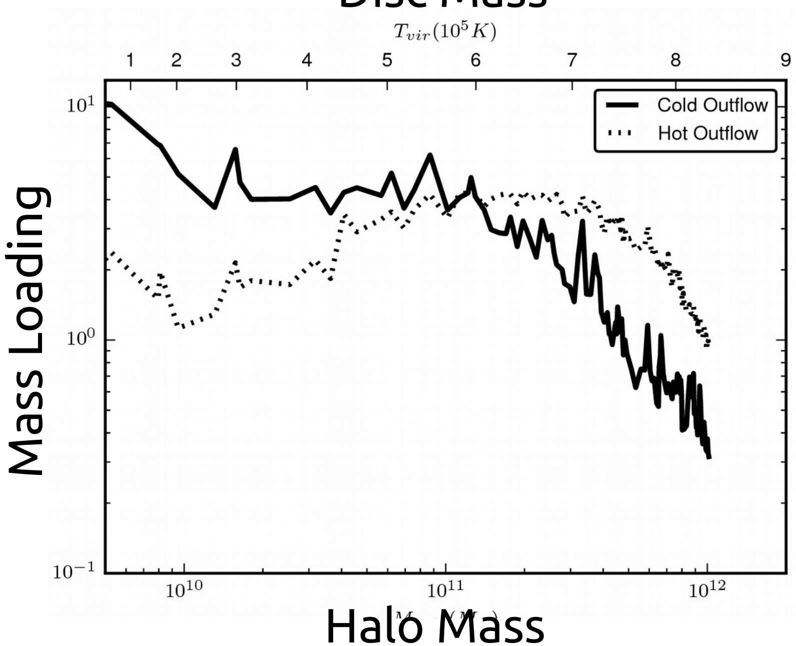




- Galaxies diverge from observed SMHMR rapidly, building a massive stellar bulge in a few 100 Myr
- The average "unregulated" galaxy has its wind mass loadings fall < 1 at z~1
- No galaxy with disc (<$0.1R_{vir}$) mass >$10^{11}M_{sun}$, or stellar mass >$5\times10^{10}M_{sun}$ have correct stellar mass fractions or flat rotation curves
- Well-regulated galaxies have z=0 SFE of ~40%, unregulated galaxies have ~70% SFE

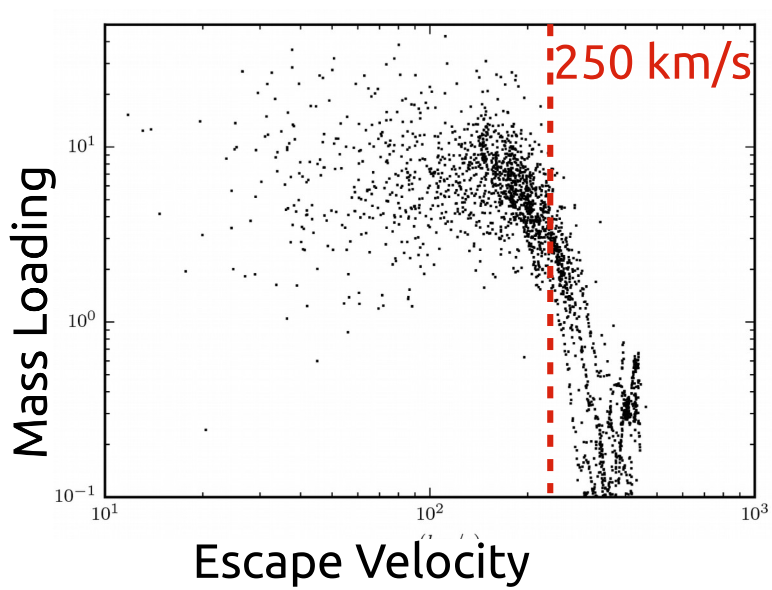
Mass loading has universal scaling

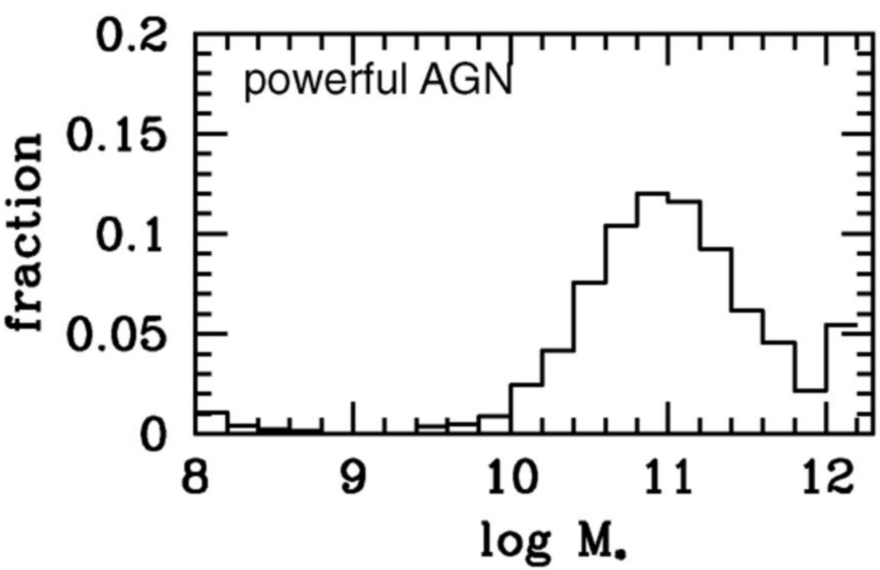




- As disc/halo mass grows, outflows must fight out of deeper potential well.
- Mass-loading begins to fall from ~10 when disc is ~$10^{10}M_{sun}$, halo is ~$2\text{x}10^{11}M_{sun}$
- Eventually, only the hottest superbubbles are able to escape

The Limits of Supernovae



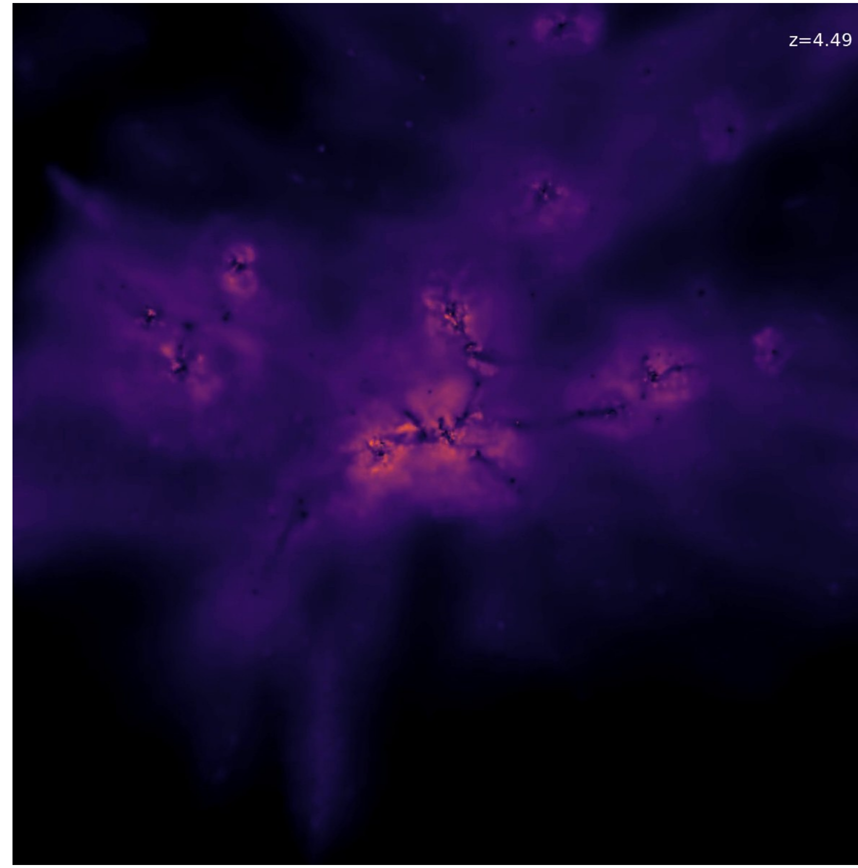


Kaufmann+ 2003

- 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

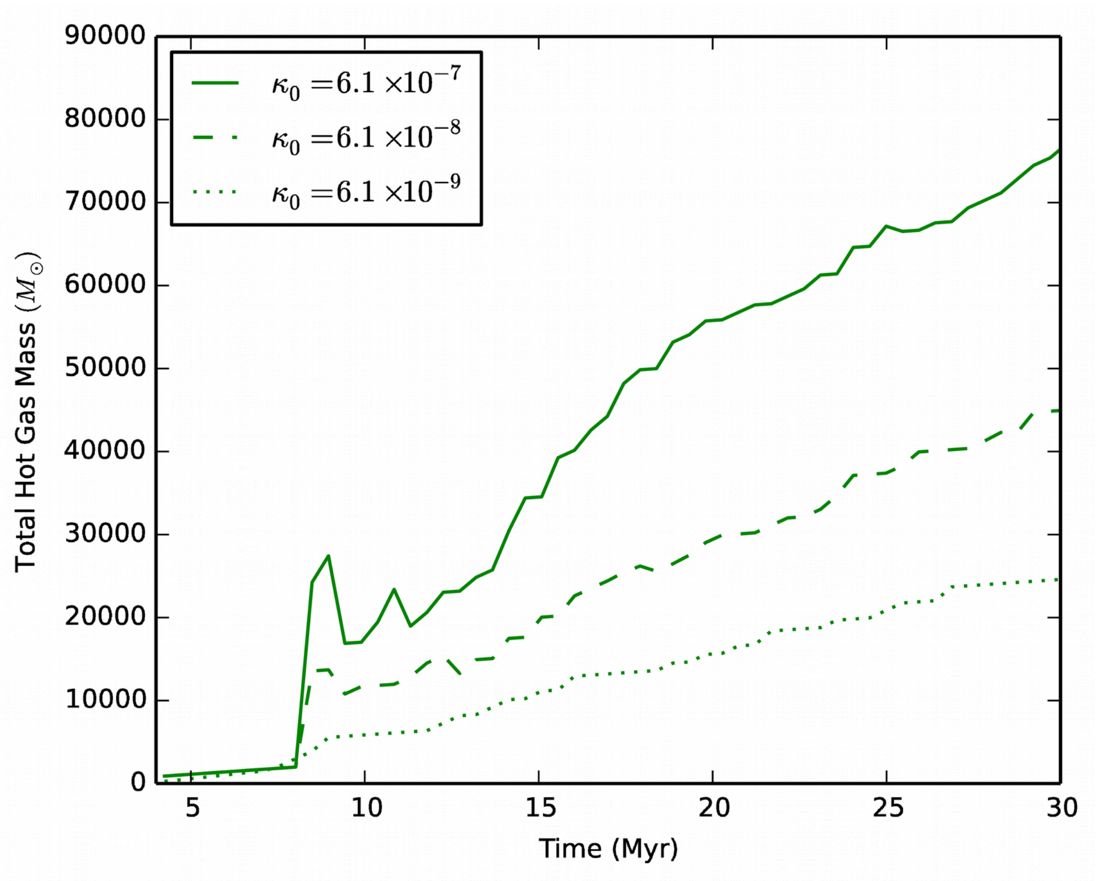
- Superbubble physics required for realistic gas behaviour, high mass loadings for winds in L* galaxies
- Winds prevent runaway bulge growth, give realistic stellar mass evolution and rotation curves
- Galaxies w/ $M_{vir}>10^{12}M_{sun}$ or $M_{*}>5x10^{10}M_{sun}$, SN feedback becomes ineffective
  - For hot gas to escape, it must have $\eta<<10$, 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

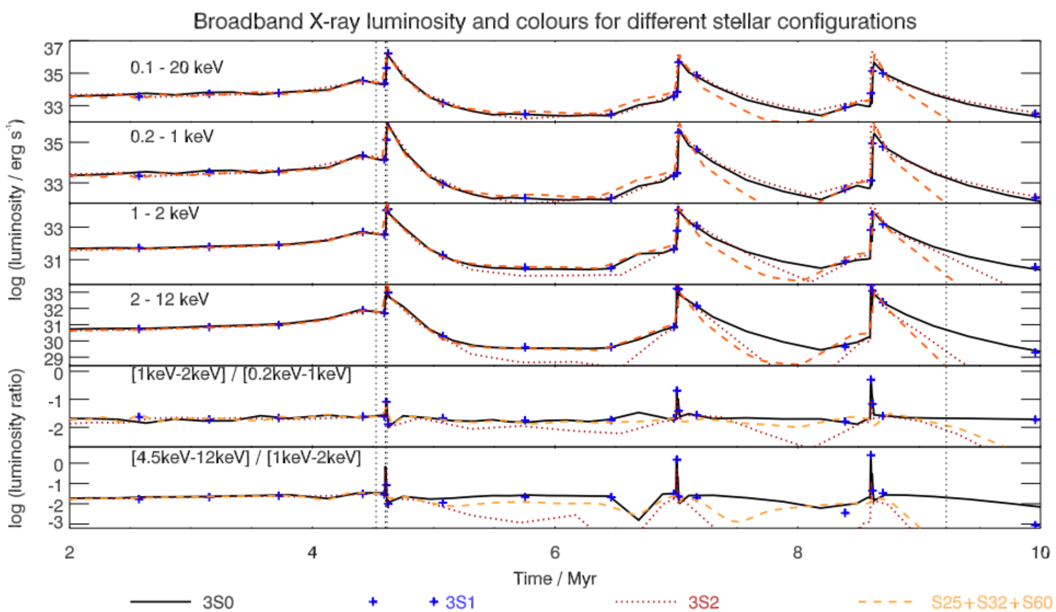
- Conduction suppressed across magnetic field lines
- 100x reduction in conduction rate κ0 results in only factor of ~2 reduction in hot bubble mass



Superbubble X-Ray Luminosities

Table 1. Physical Properties of Hot Gas in Bubble Interiors

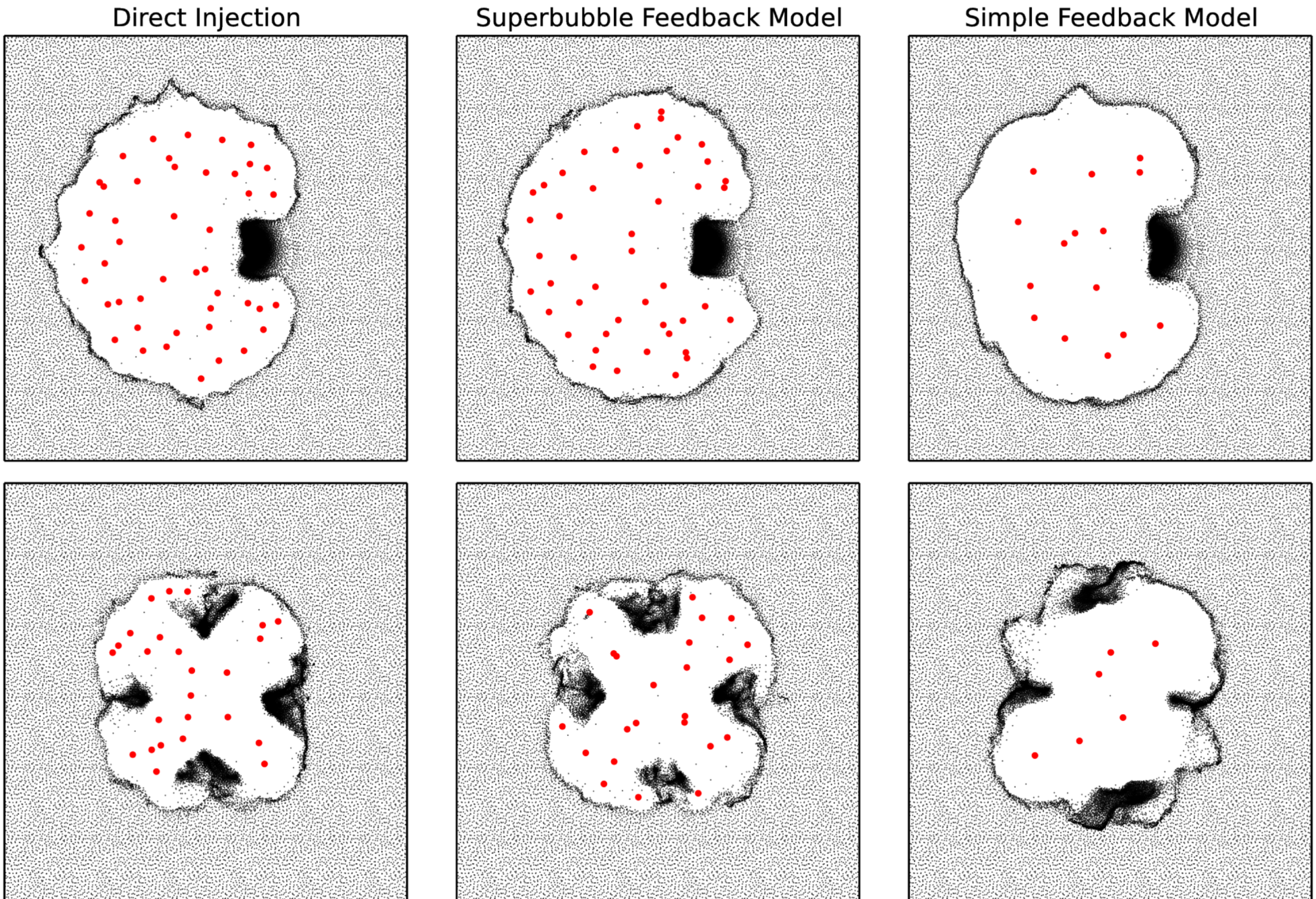
Bubble Type	T_e [10^6 K]	N_e [cm^{-3}]	L_X [erg s^{-1}]
Orion Bubble	2	0.2–0.5	5×10^{31}
WR Bubble	1–2	1	$10^{33} - 10^{34}$
M17 Superbubble	1.5, 7	0.3	3.4×10^{33}
Planetary Nebula	2–3	100	$10^{31} - 10^{32}$



Krause+ 2014

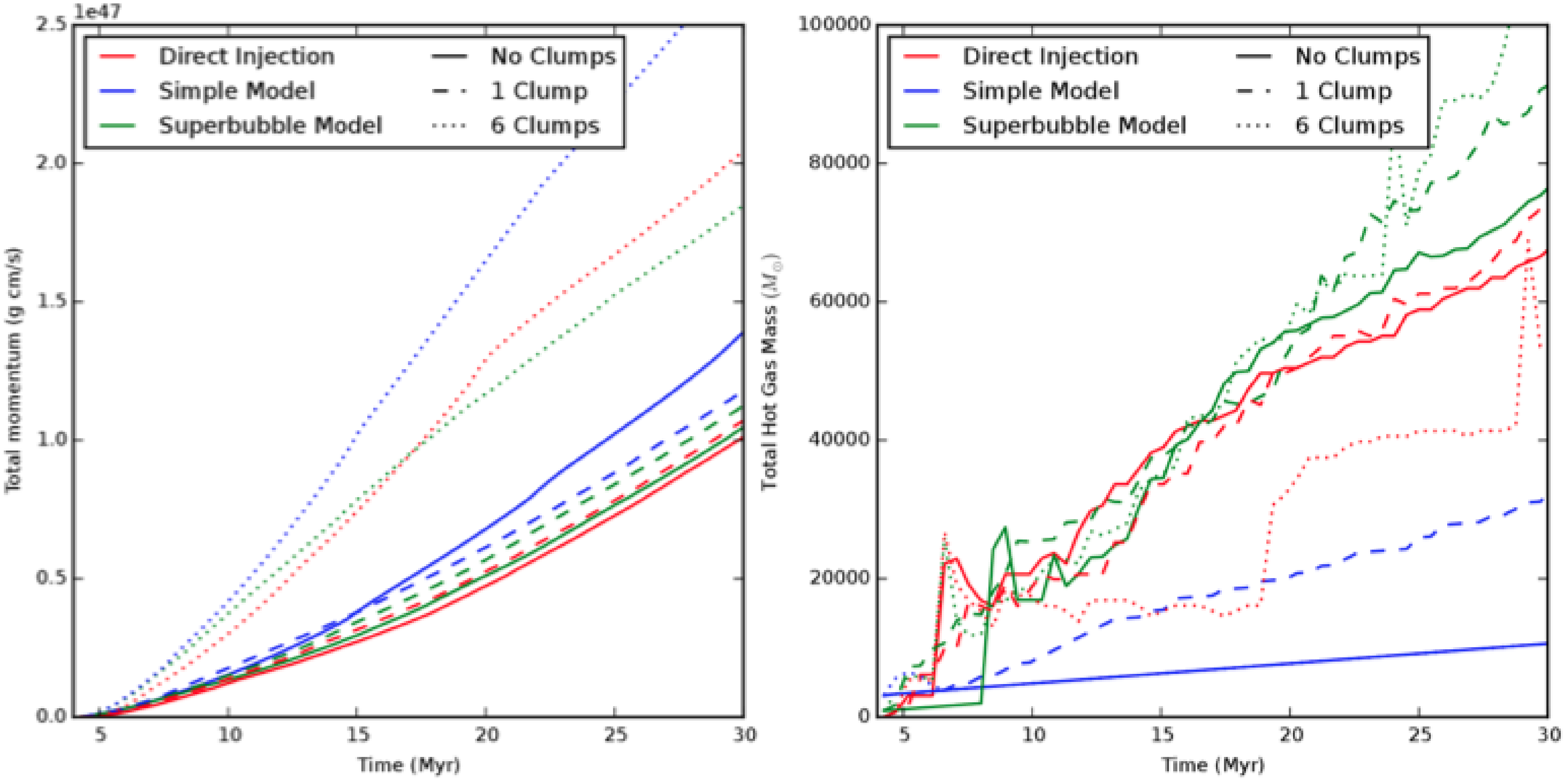
- X-Ray luminosity highly variable over space, time
- Very few observations, large scatter in observed LX
- Leaking of interior, B-field amplification in shell may explain some reduced luminosities (see Rosen+ 2014)

Clumpy ISM



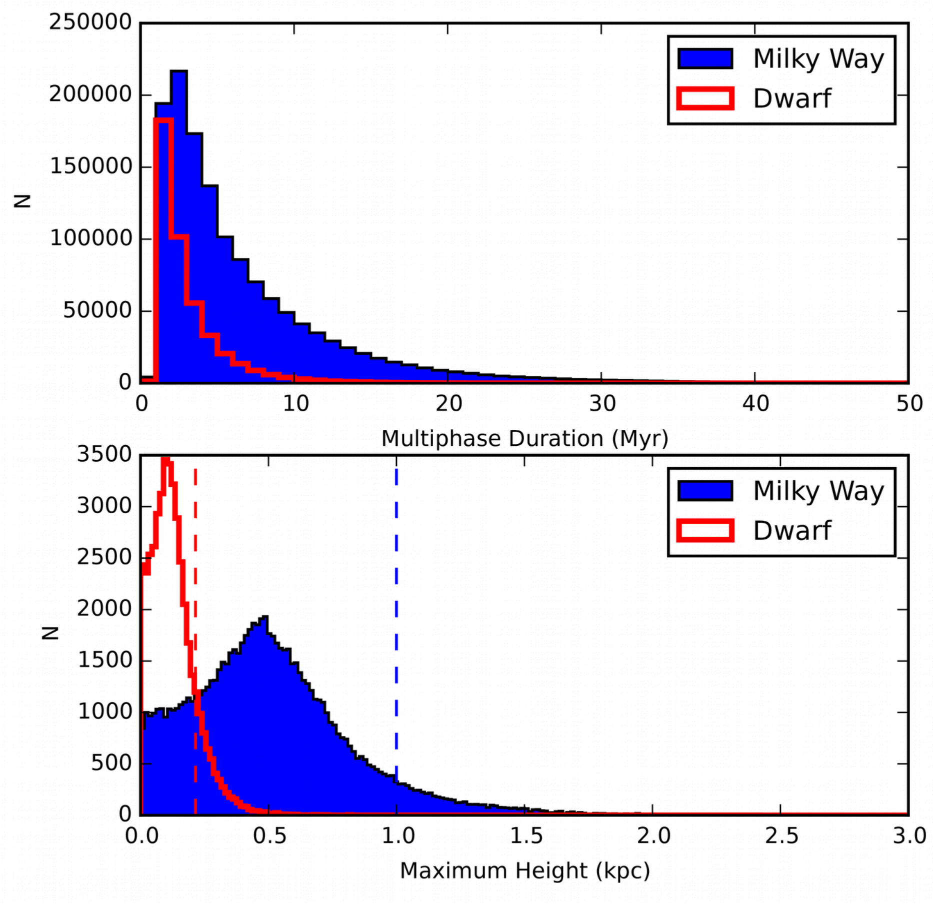
Direct Injection
Superbubble Feedback Model
Simple Feedback Model

Clumpy ISM



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

Multiphase Properties



- Median multiphase lifetime < 5Myr