# Supernova, Superbubbles, & Galaxy Deregulation: Too Big Not to Fail

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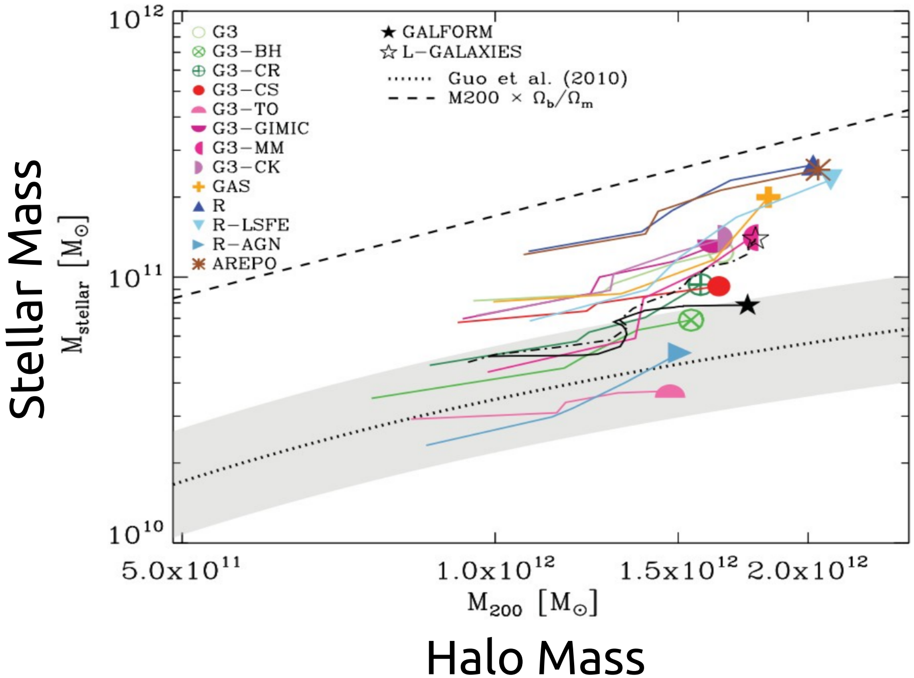
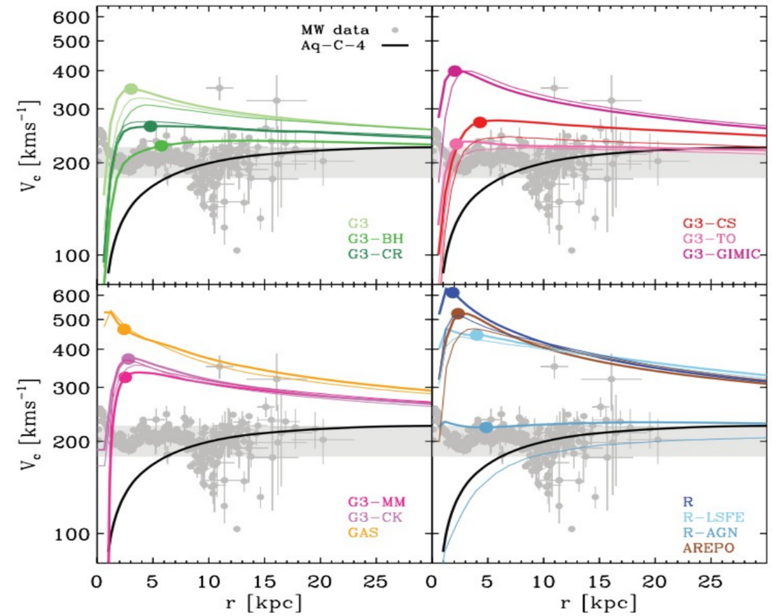
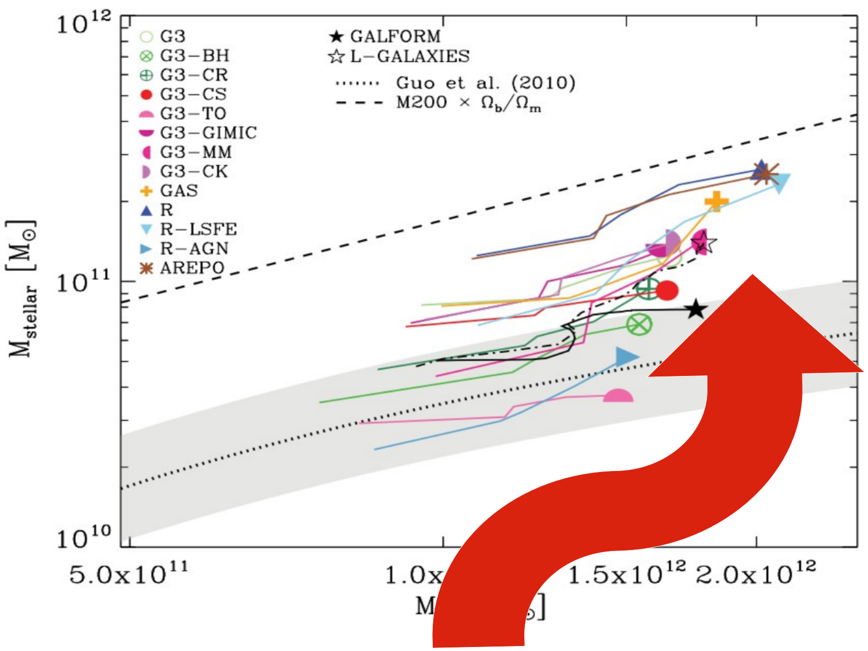
# Simulations Circa 2012: Yikes!

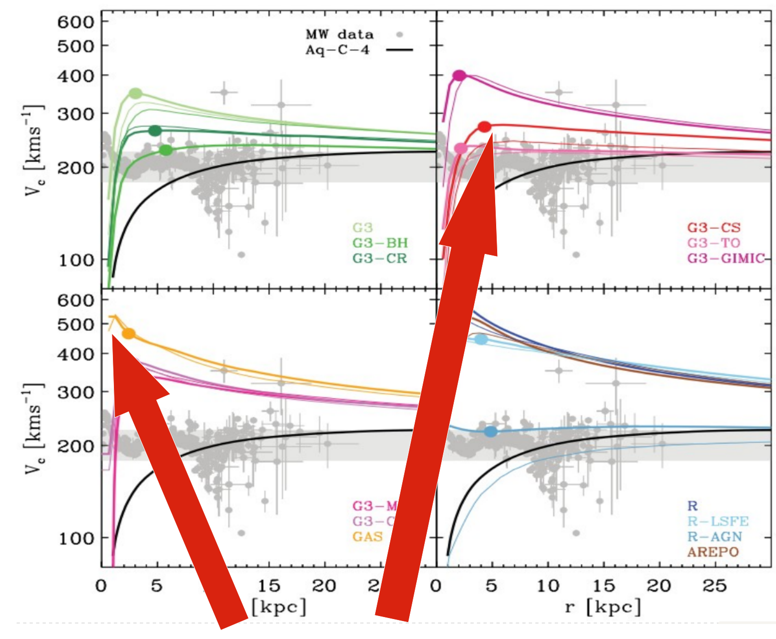



- Aquila Comparison (Scannapieco+ 2012)
  - Compared FB Models & Codes on same cosmological initial conditions
  - Most produced too many stars, too large bulge
  - None had both reasonable stellar fraction and small bulge

# 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
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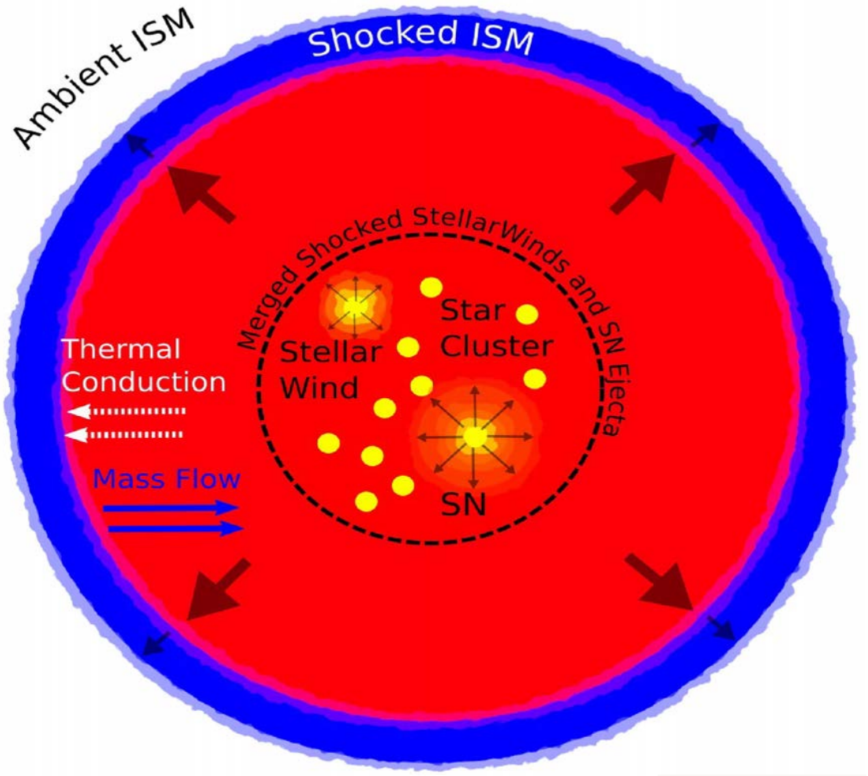
# Things have improved since 2012

- ~~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)

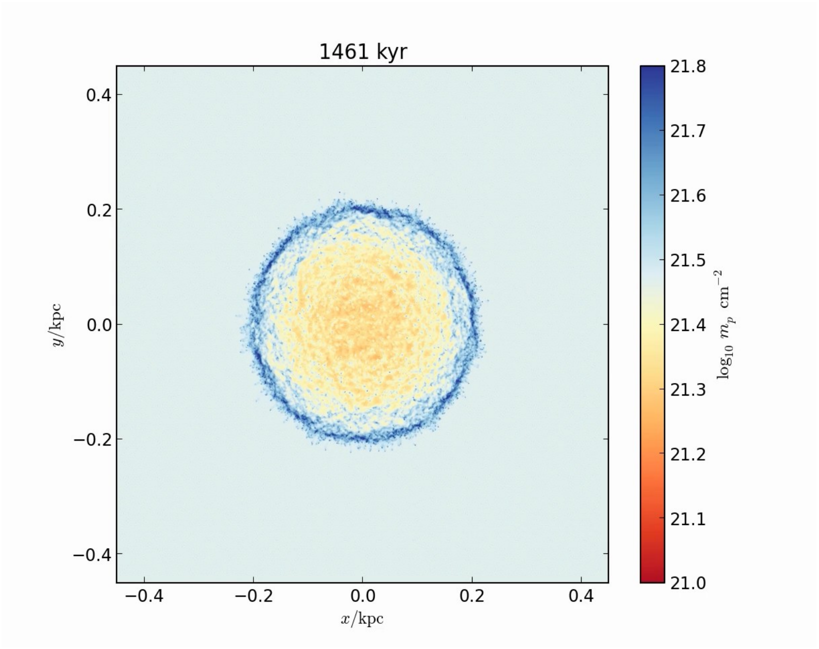
1) Resolved thermal conduction for hot, diffuse gas inside hot bubbles

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

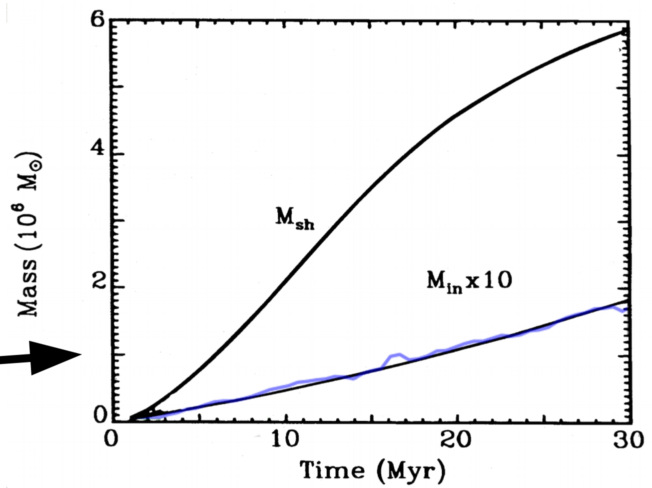
3) Two-phase particles for early phase of bubble growth, with internal evaporation to convert back to single phase

# Validating the Superbubble Model

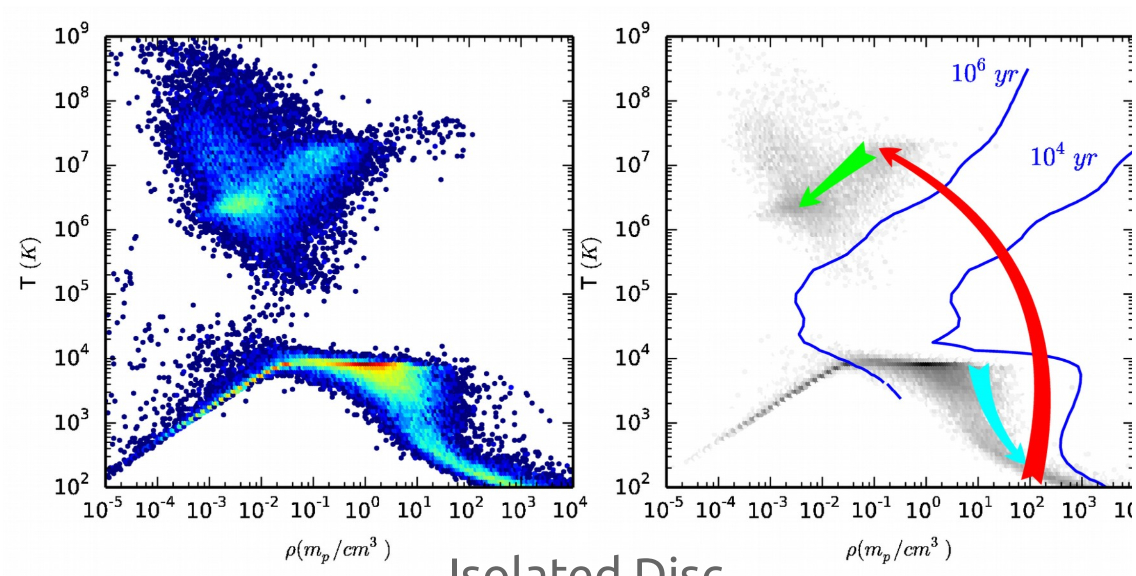
- High resolution, well resolved feedback with direct injection (no need for two phase component)
- Hot bubble mass, energy converged over ~500x range of mass resolution
- Hot bubble self-regulates to ~a few million K
- Model description in Keller+ 2014




Hot Mass Matches Silich 1999

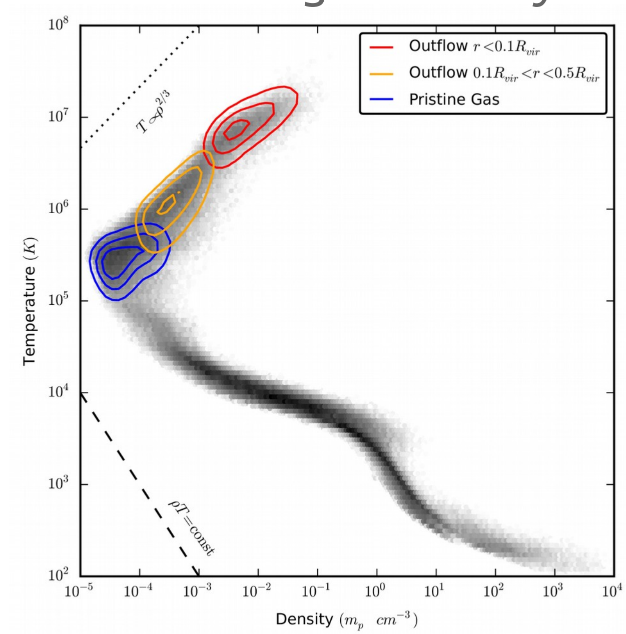


# Superbubble Gas Lifecycle



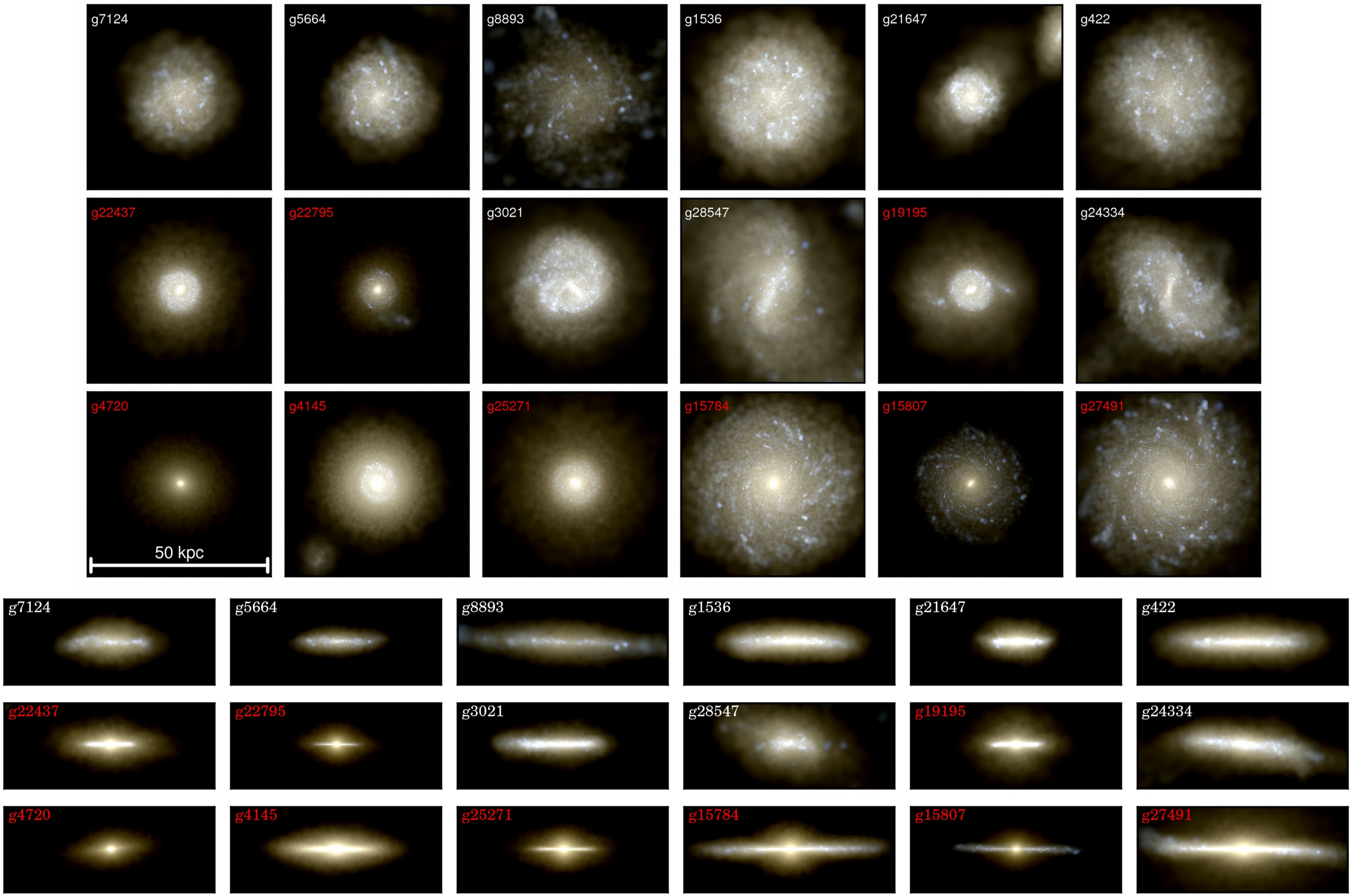

Isolated Disc

Cosmological Galaxy



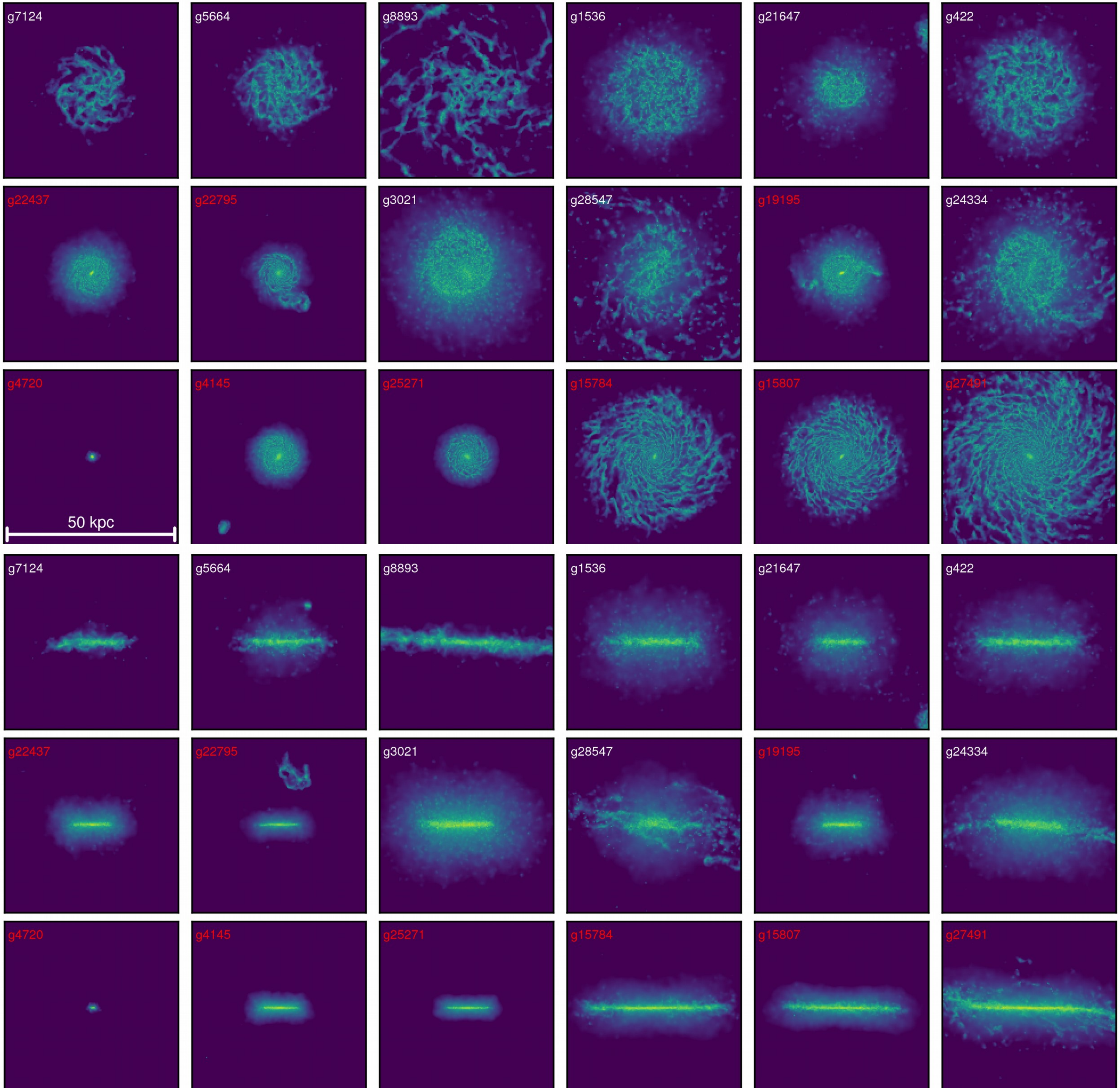

- Equilibrium WI(N)M cools, forms stars -> SN
- SN form superbubbles, begin at ~$10^8$K, evaporate to a few $10^6$K
- Feedback-heated leaves disc, evolves adiabatically as it rises through halo. Cooling times are >> Myr

# 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 $3.7 \times 10^{11}$ to $2.1 \times 10^{12} M_{sun}$
- Variety of merger histories, spin parameters
- 320pc softening, baryon mass resolution of $2.2 \times 10^{5} M_{sun}$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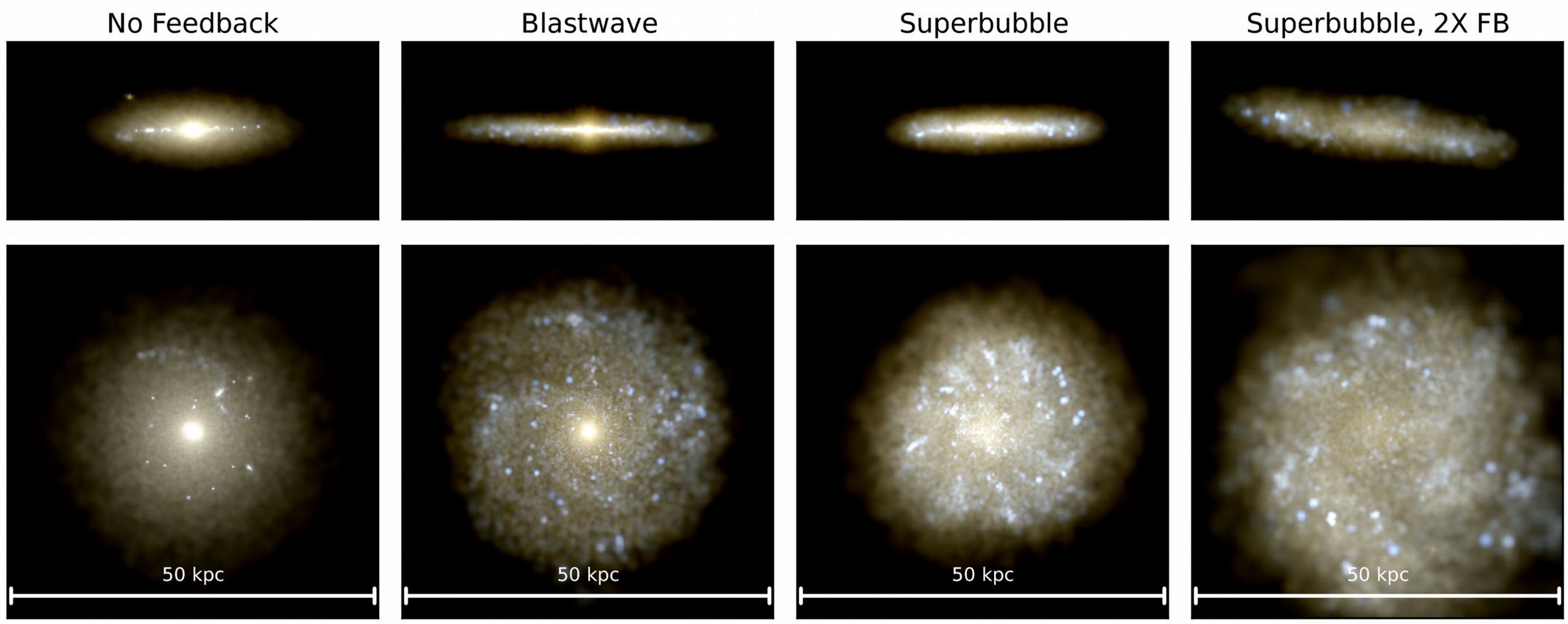
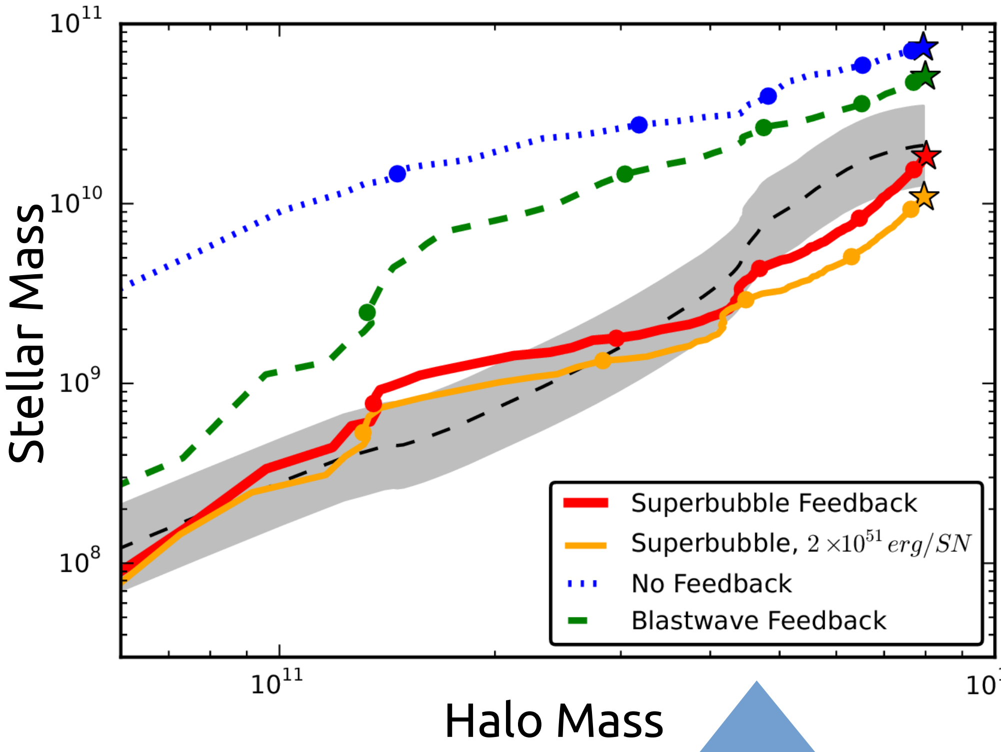
g27491

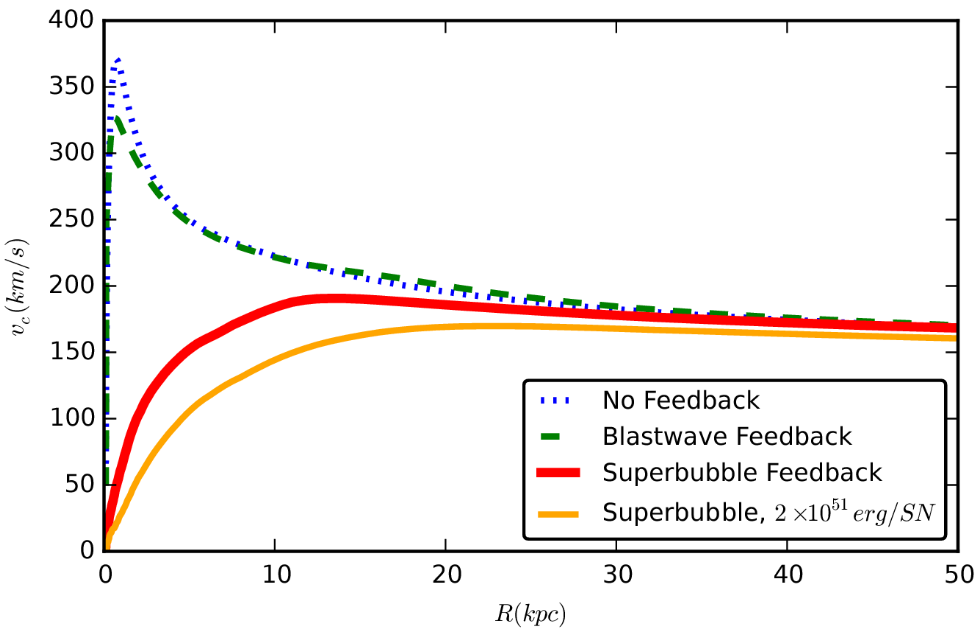
# Feedback Models Matter! (Keller+ 2015

- 4 test cases:
  - No Feedback
  - Blastwave (Stinson+ 2006) feedback
  - Superbubble Feedback
  - Superbubble Feedback 2X Energy
- g1536
  - $8 \times 10^{11}$ $M_{sun}$ virial mass
  - Last major merger at z=4
  - Equal SN energy for Blastwave and Superbubble
  - Details in Keller+ 2015



# Correct Stellar Mass, Small Bulge

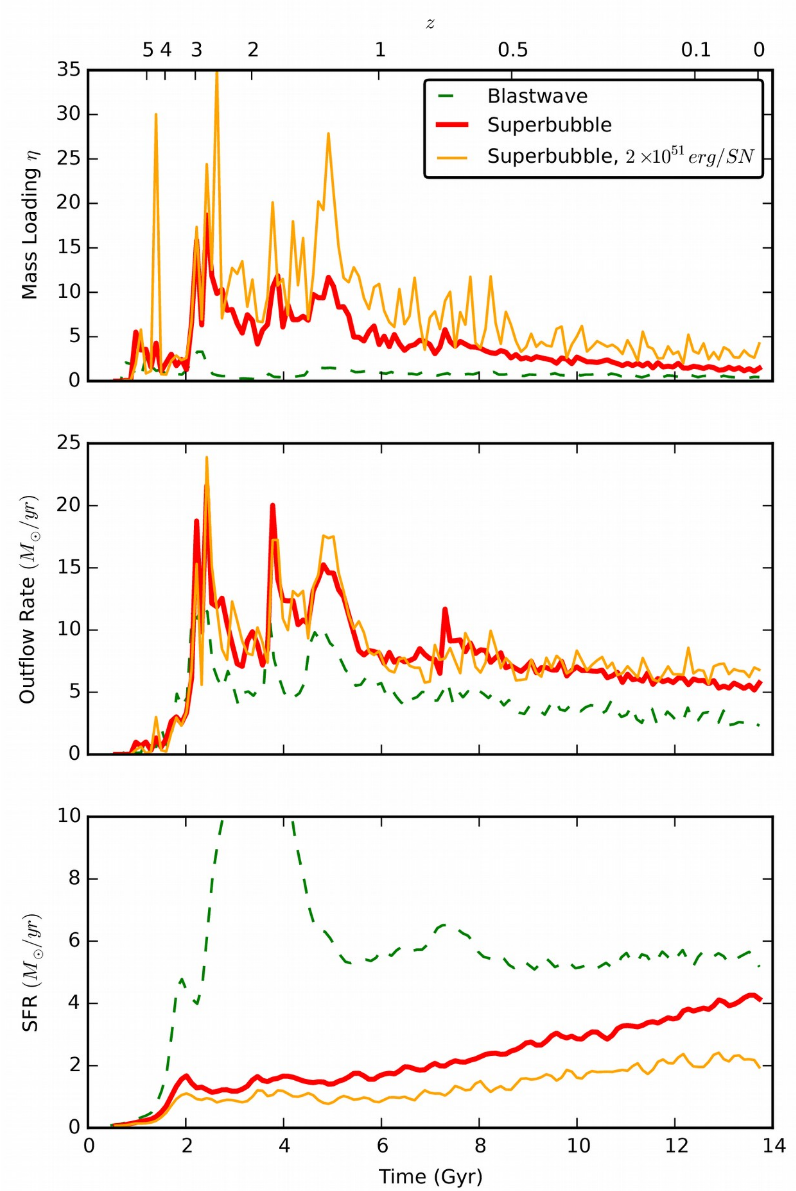



Stellar Mass Evolution Matches Behroozi+ 2012 abundance matching

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

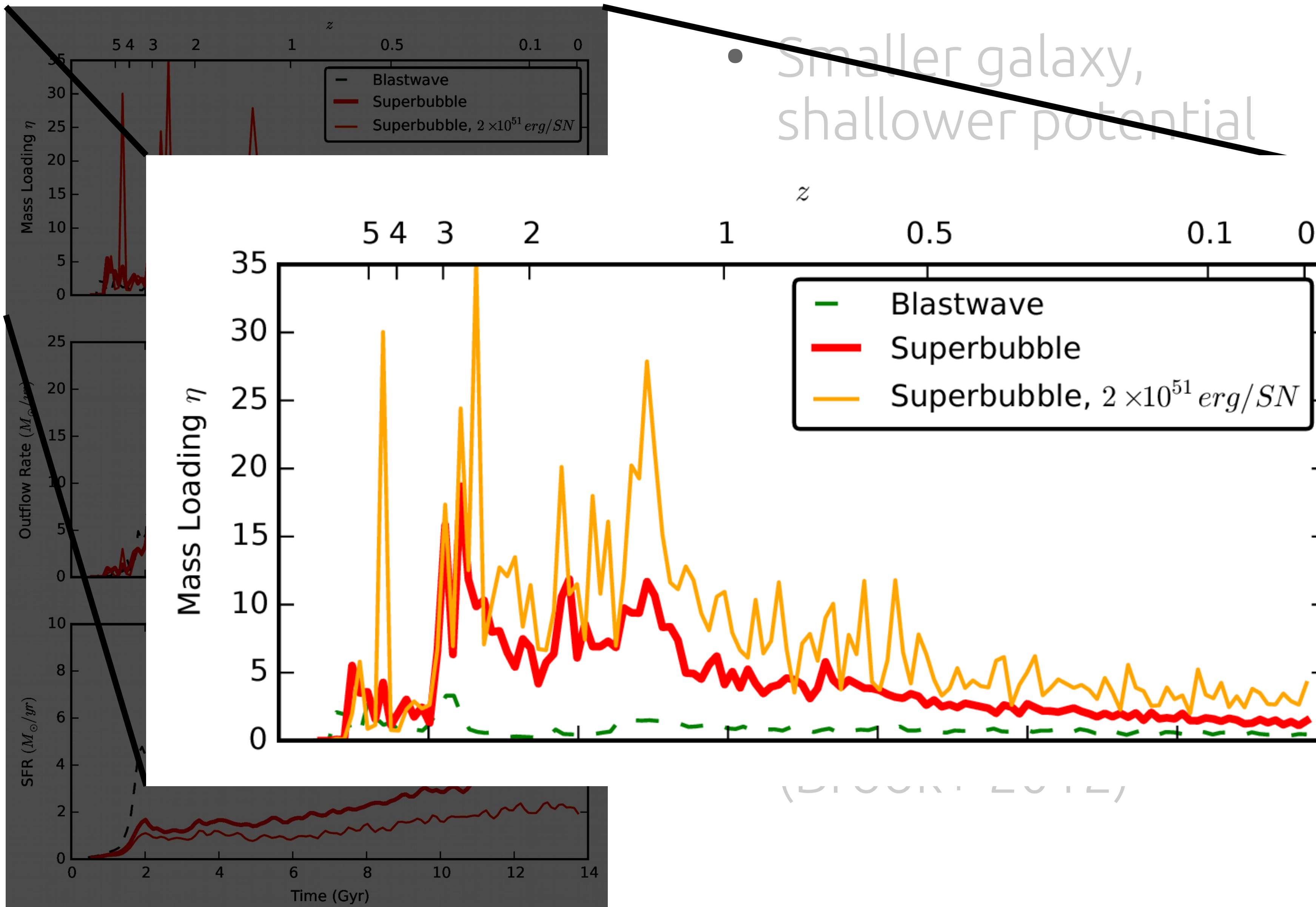



- Smaller galaxy, shallower potential well
- Higher mass loadings allow for correct stellar mass fraction, remove fuel for later star formation

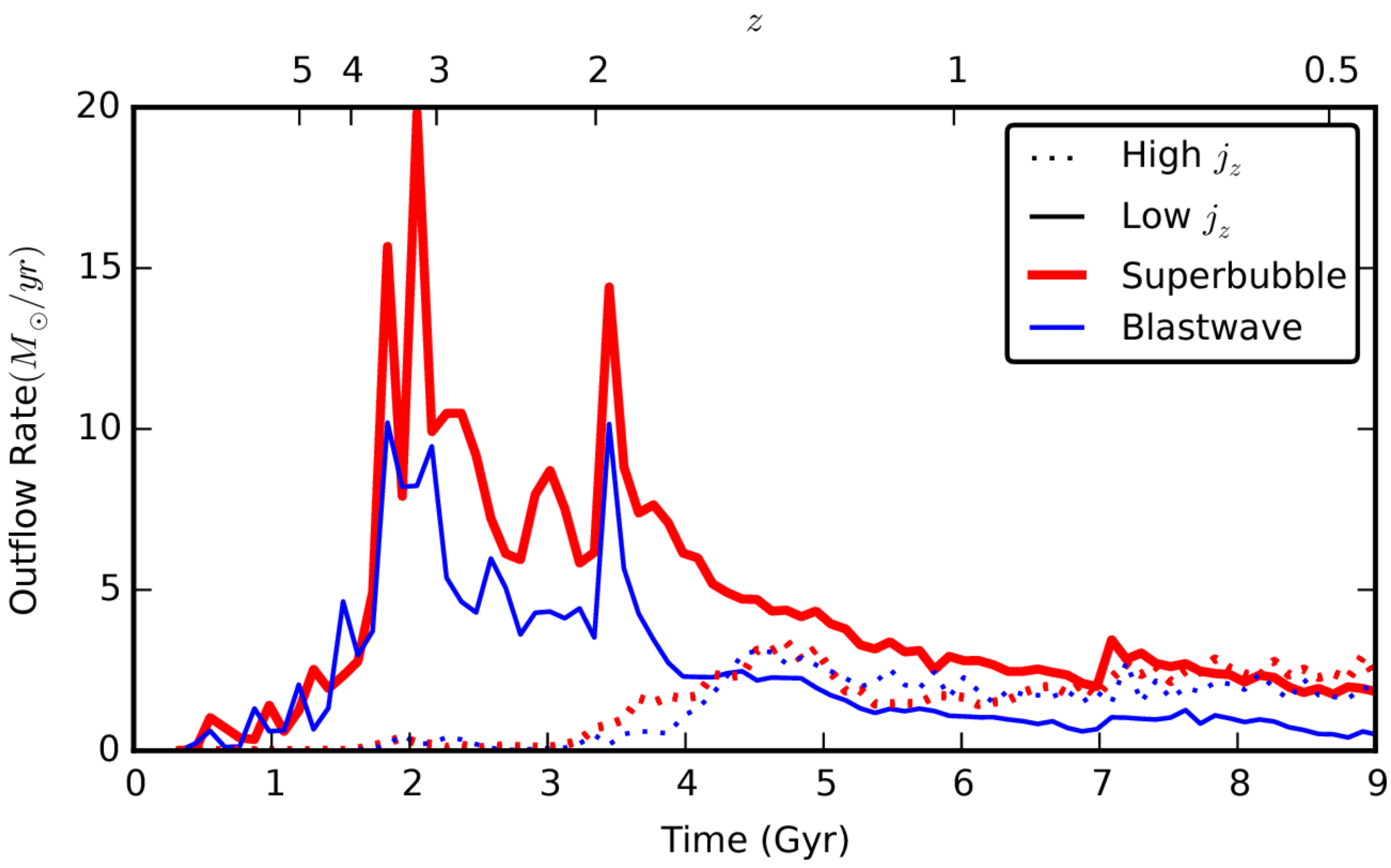
Outflows preferentially remove low-j gas! (Brook+ 2012)

# Superbubbles drive outflows well

- Smaller galaxy, shallower potential



# High-z outflows prevent bulges, preserve disks



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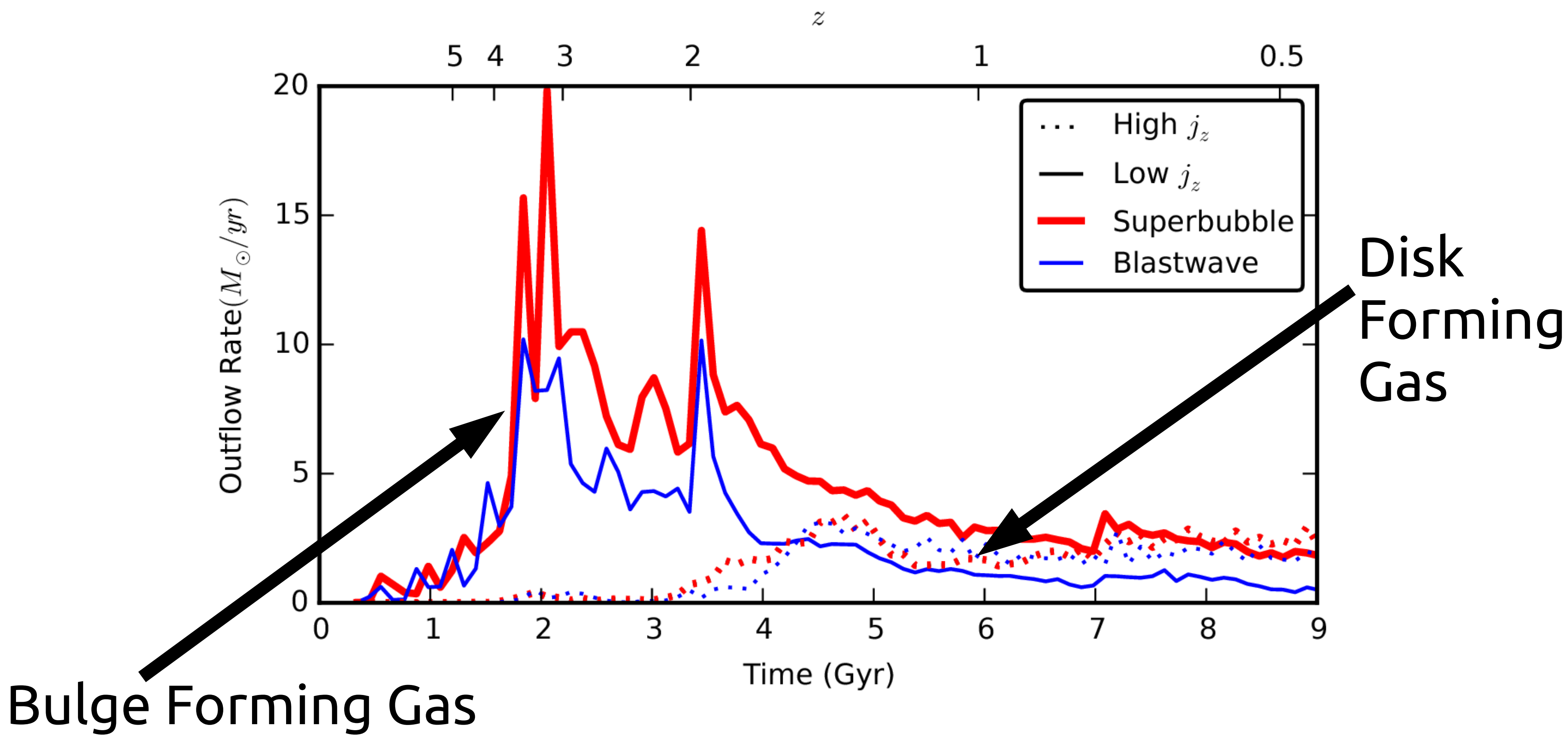
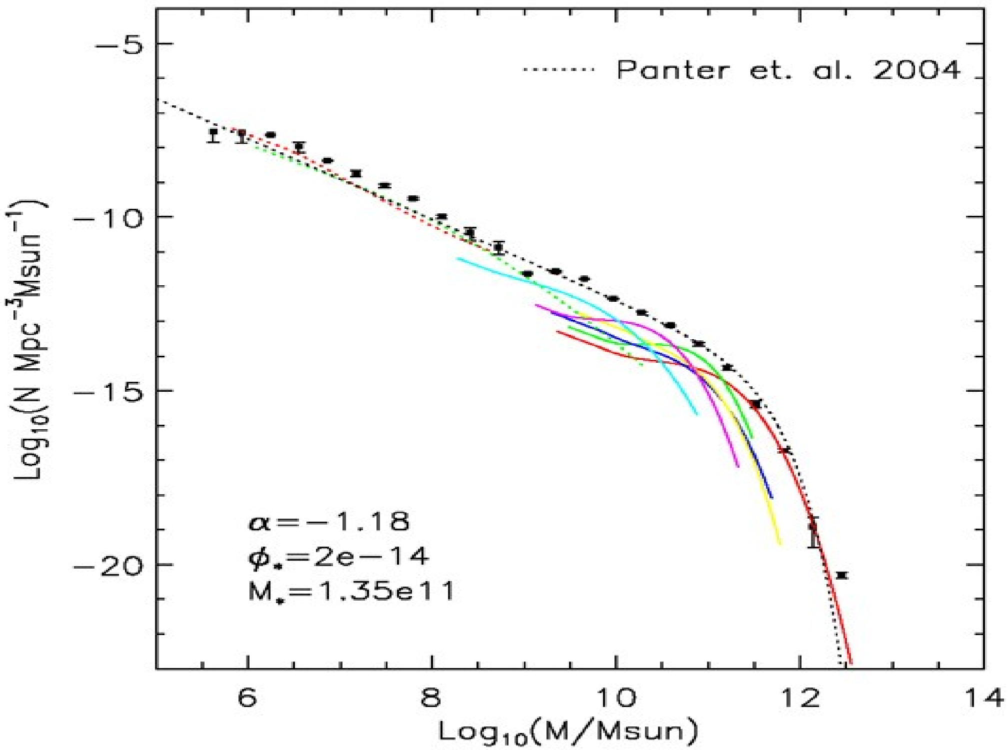
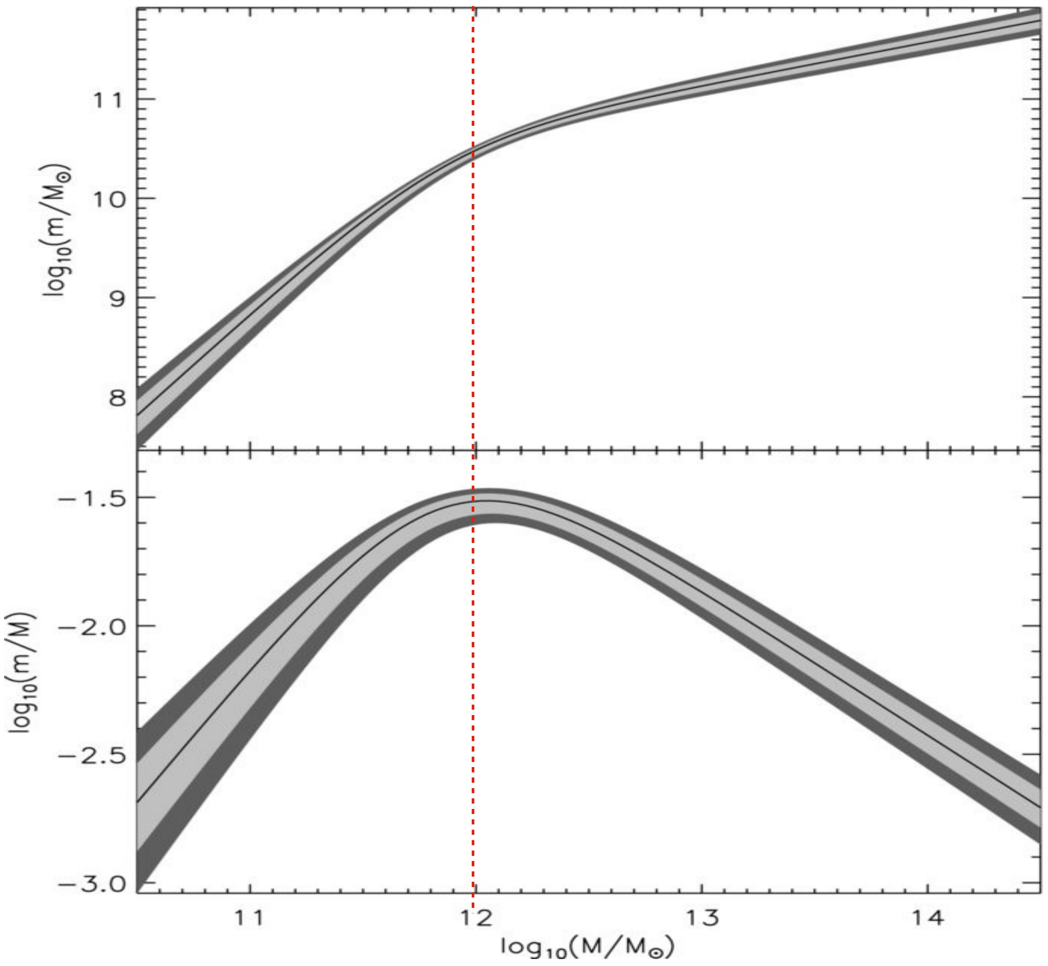


# Can Supernovae do it all?




Moster+ 2010

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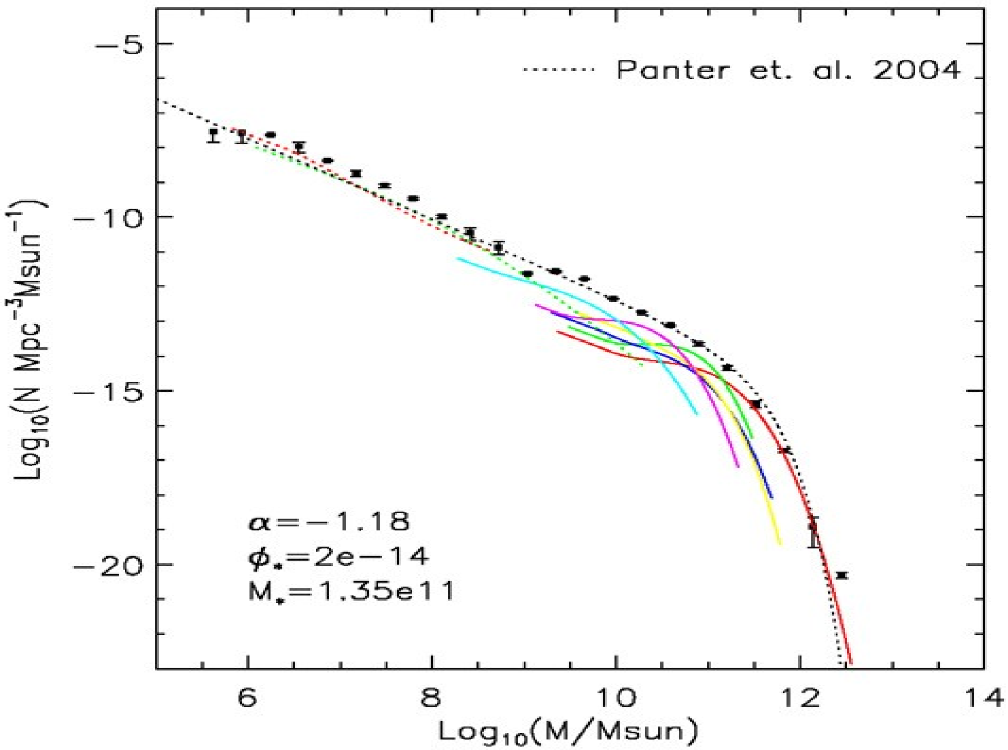


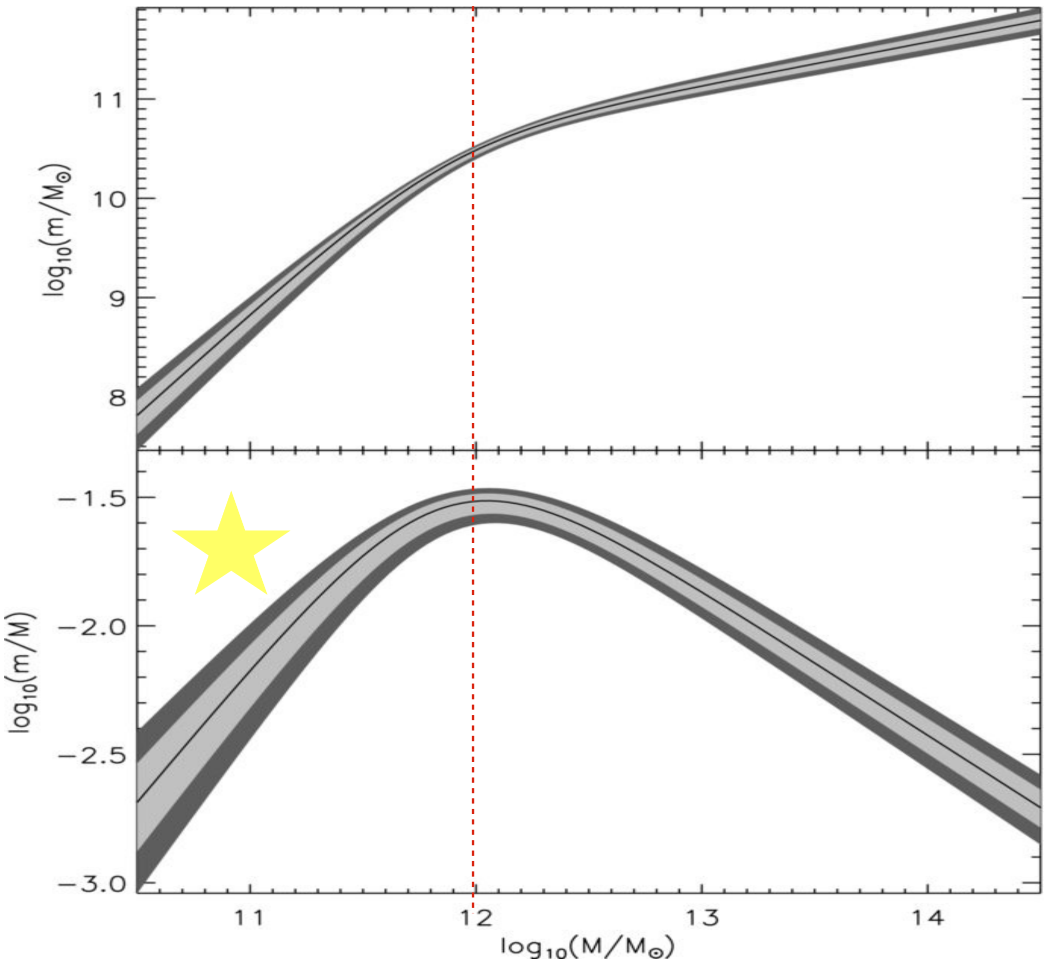


Moster+ 2010

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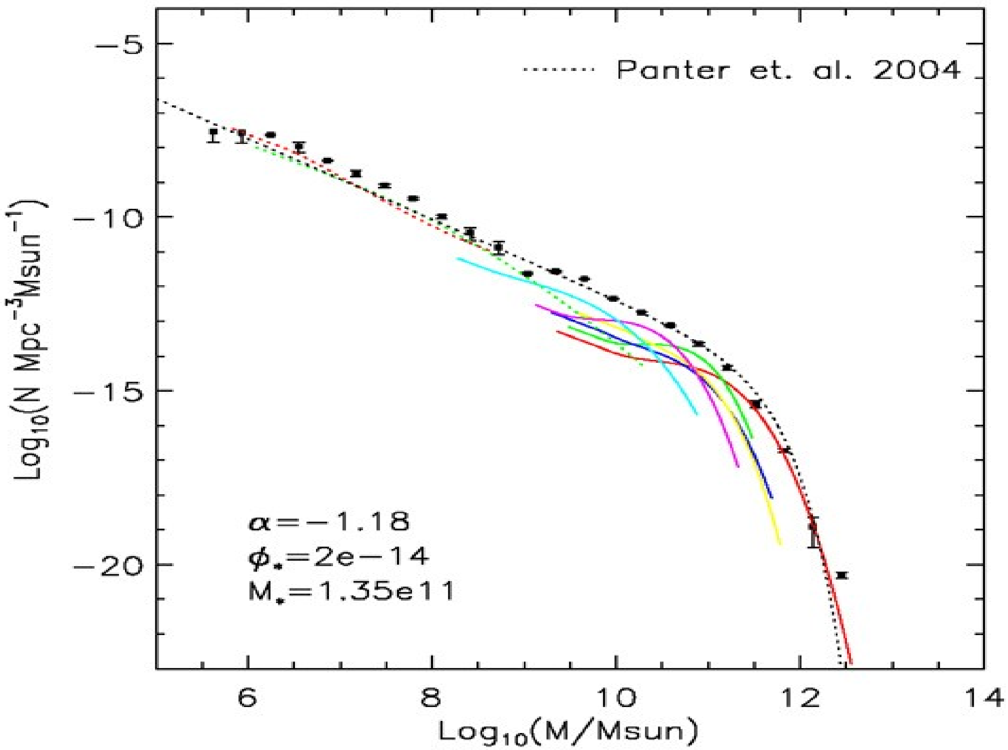


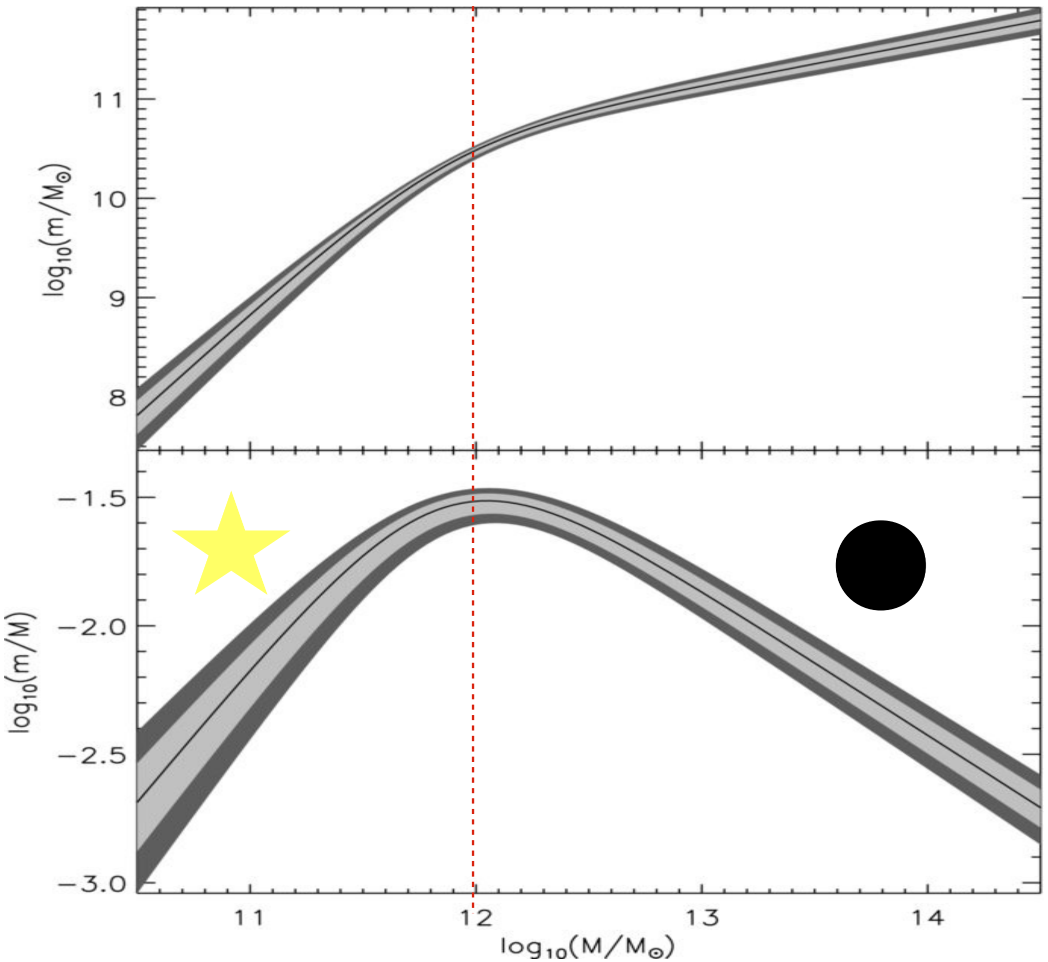


Moster+ 2010

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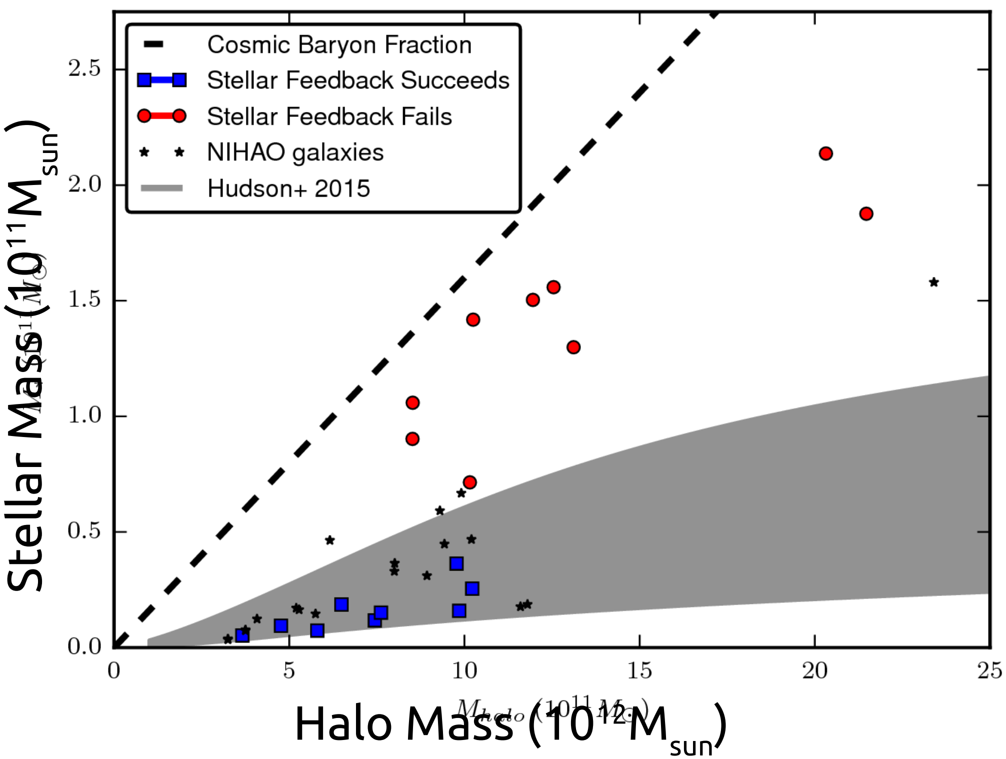
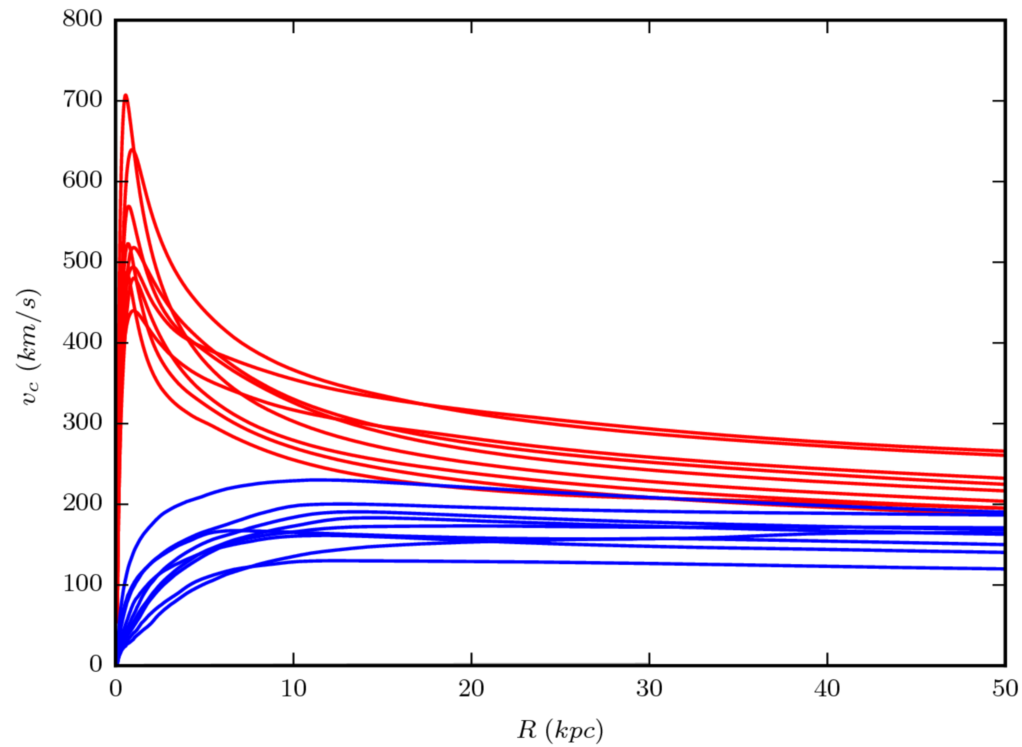
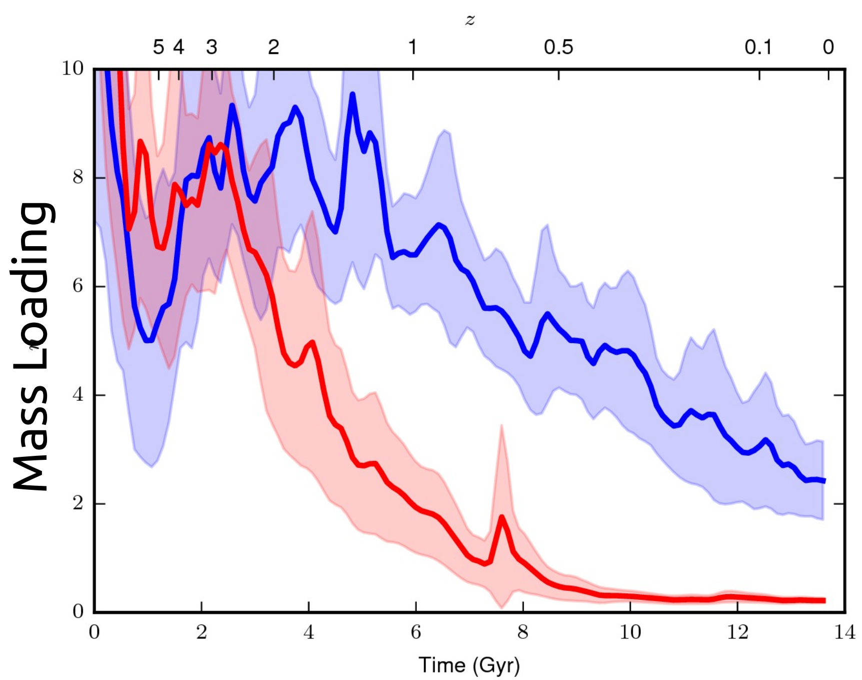
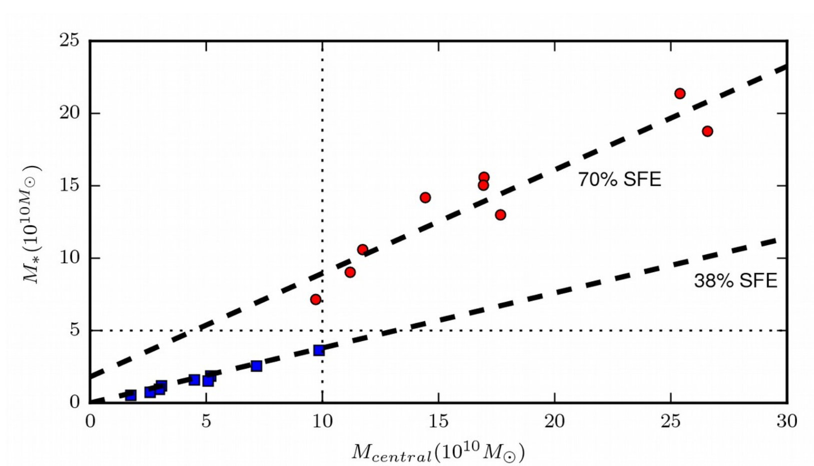



Answer: No! (Keller+ 2016)

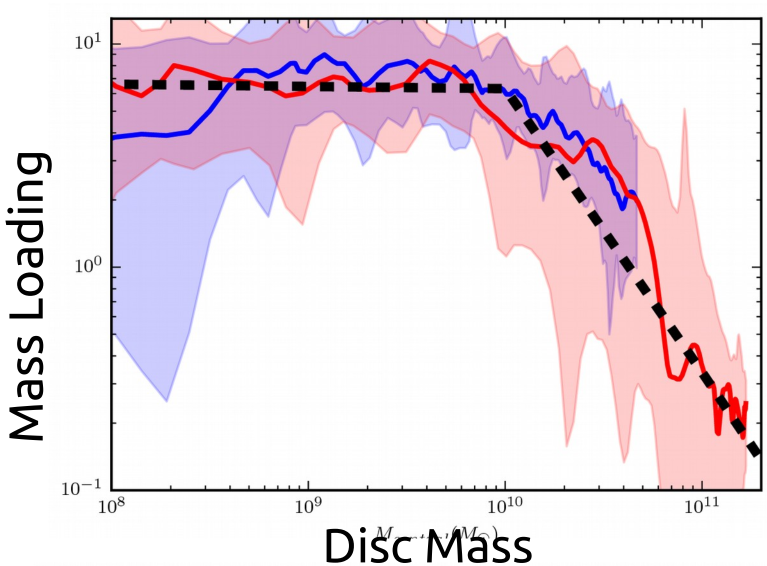
# What Determines where SN Fail?

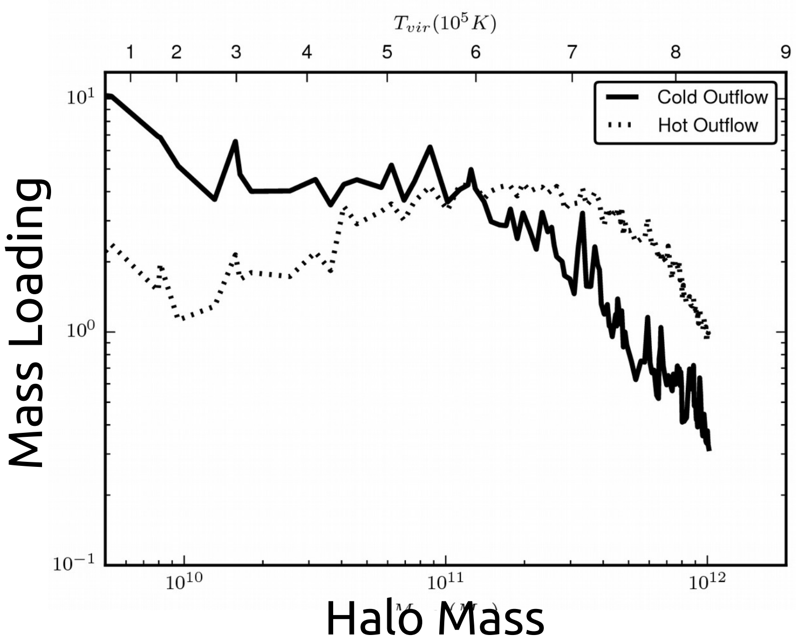



- Galaxies diverge from observed SMHMR rapidly, building a massive stellar bulge in a few 100 Myr
- The average "unregulated" galaxy has its wind mass loadings fall < 1 at z~1
- No galaxy with disc (<$0.1R_{vir}$) mass >$10^{11}M_{sun}$, or stellar mass >$5\times10^{10}M_{sun}$ have correct stellar mass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

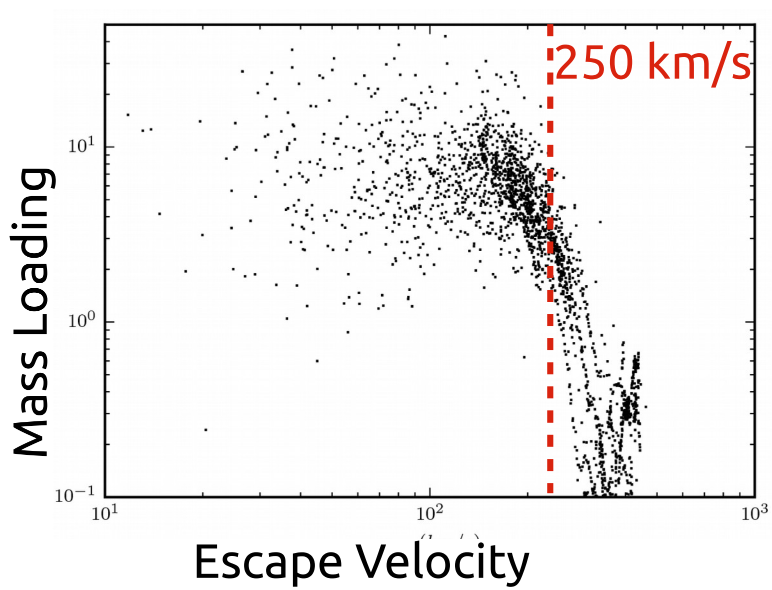
# Mass loading has universal scaling

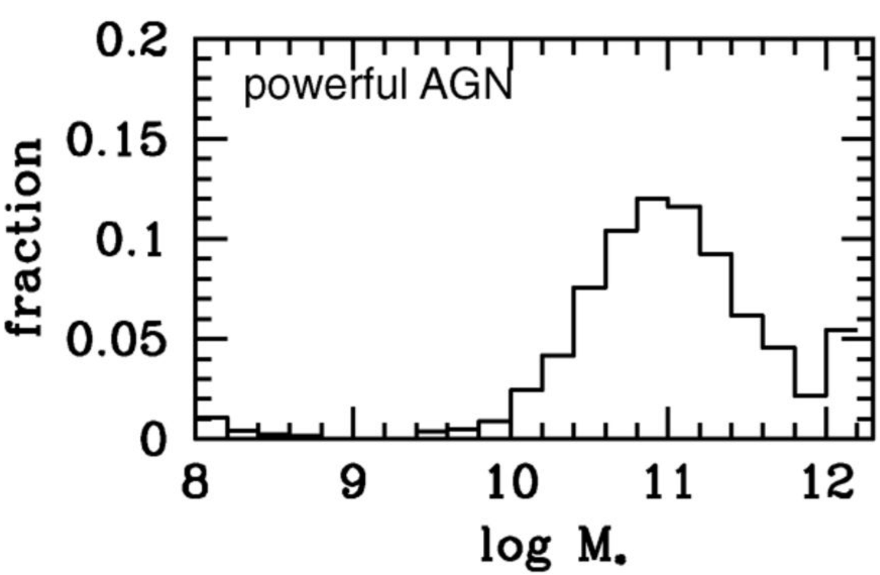



- As disc/halo mass grows, outflows must fight out of deeper potential well.
- Mass-loading begins to fall from ~10 when disc is ~$10^{10}M_{sun}$, halo is ~$2x10^{11}M_{sun}$
- Eventually, only the hottest superbubbles are able to escape

# The Limits of Supernovae



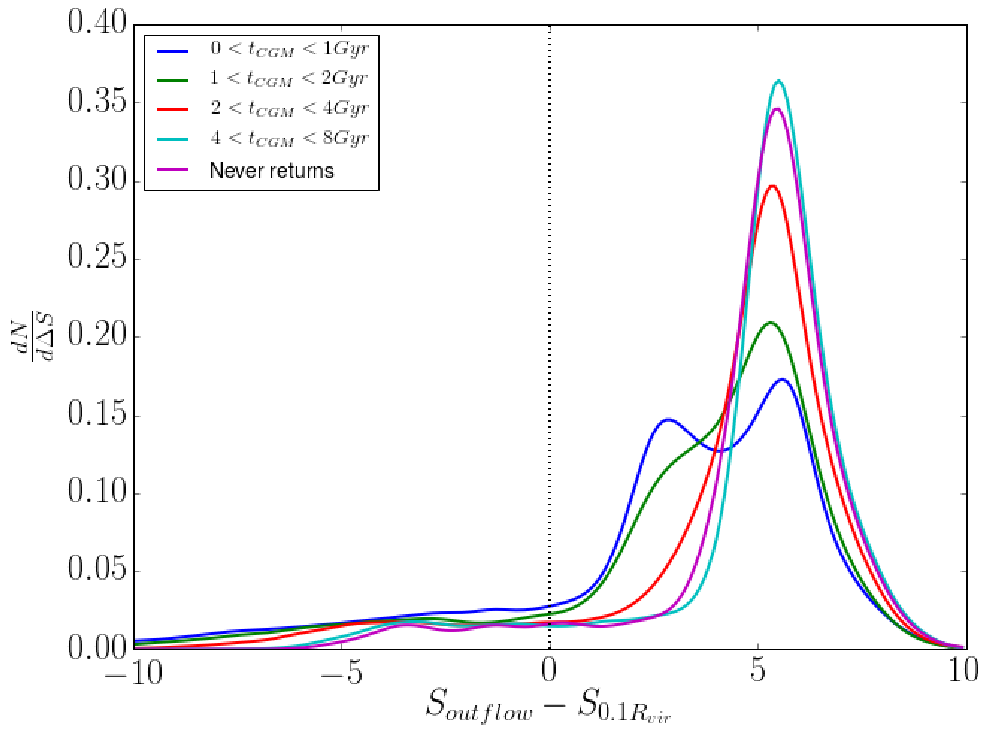

Kaufmann+ 2003

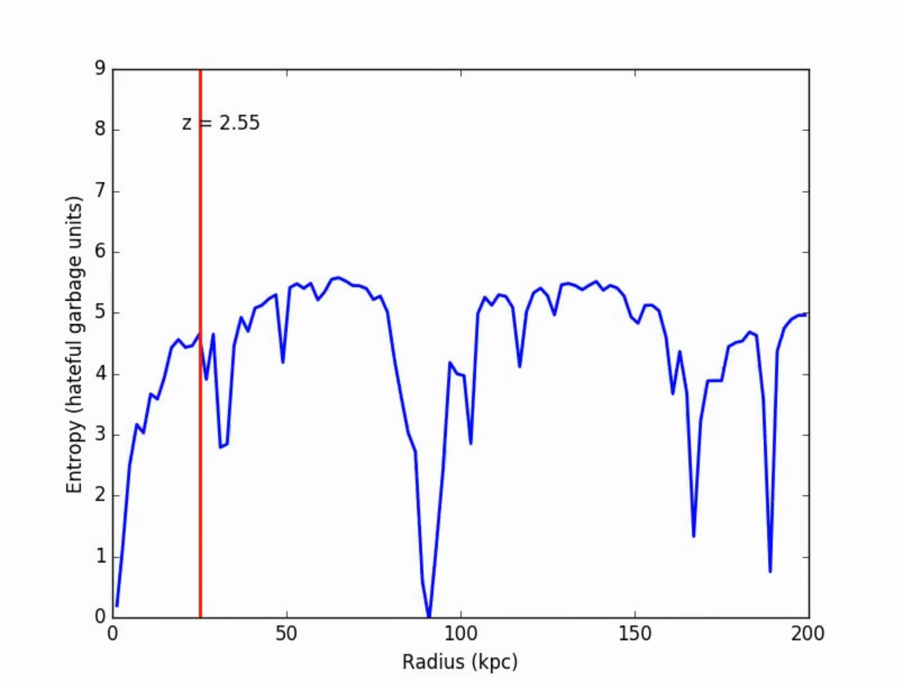
- Mass loading falls rapidly once disc escape velocity > 250 km/s
- Without cooling, η~10 gives T~2.7x10$^6$K
- 2.7x10$^6$K gas has $c_s$~210km/s (below the escape velocity of discs with M~10$^{10}$$M_{sun}$)
- SDSS observations find powerful AGN kick in here!
- Dubois+ 2015 simulations found AGN regulation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

PRELIMINARY

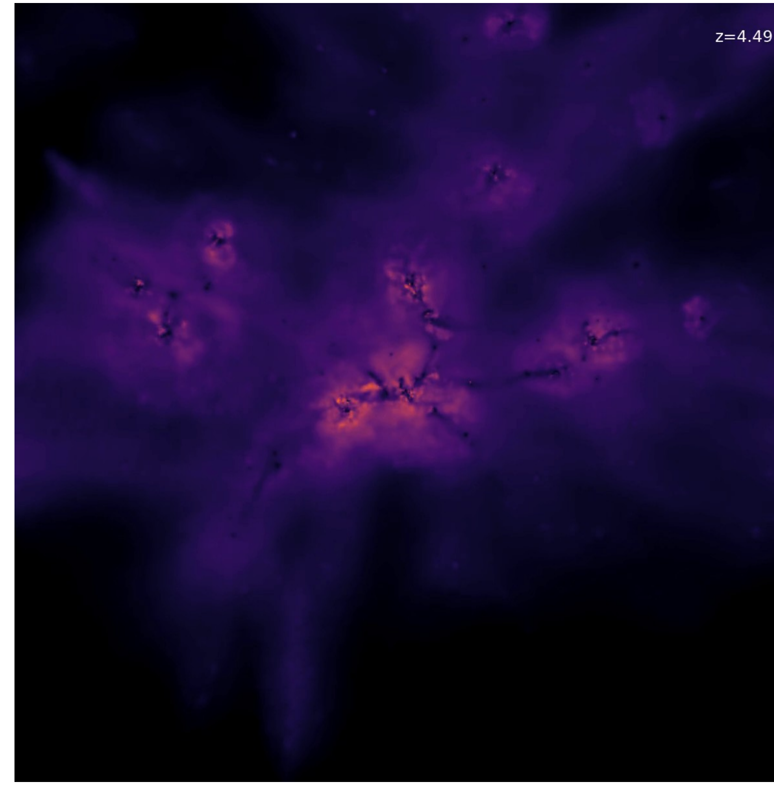
# Buoyancy & Convection in the CGM

$$S = \ln\left(\frac{T}{\rho^{2/3}}\right) \qquad \frac{dS}{dr} > 0 \Rightarrow stable$$



# Conclusions

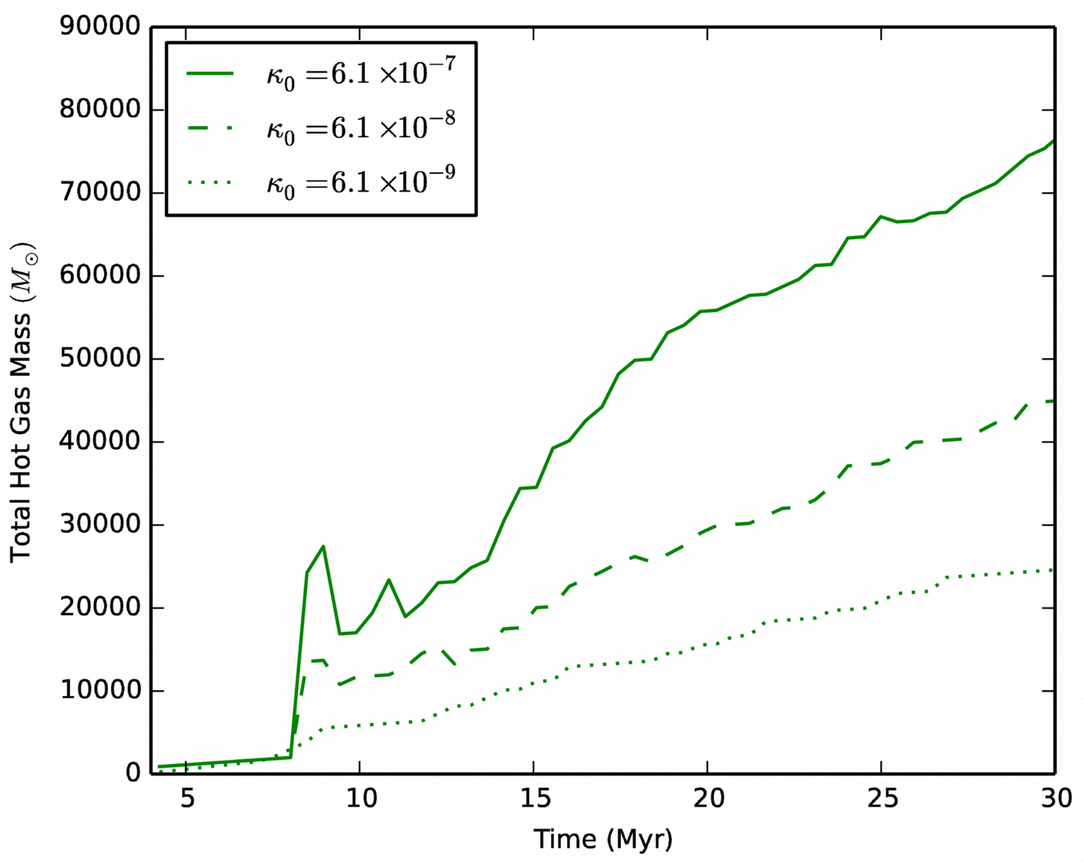



- Superbubble physics required for realistic gas behaviour, high mass loadings for winds in L* galaxies
- Winds prevent runaway bulge growth, give realistic stellar mass evolution and rotation curves
- Galaxies w/ $M_{vir}>10^{12}M_{sun}$ or $M_{*} >5x10^{10}M_{sun}$, SN feedback becomes ineffective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

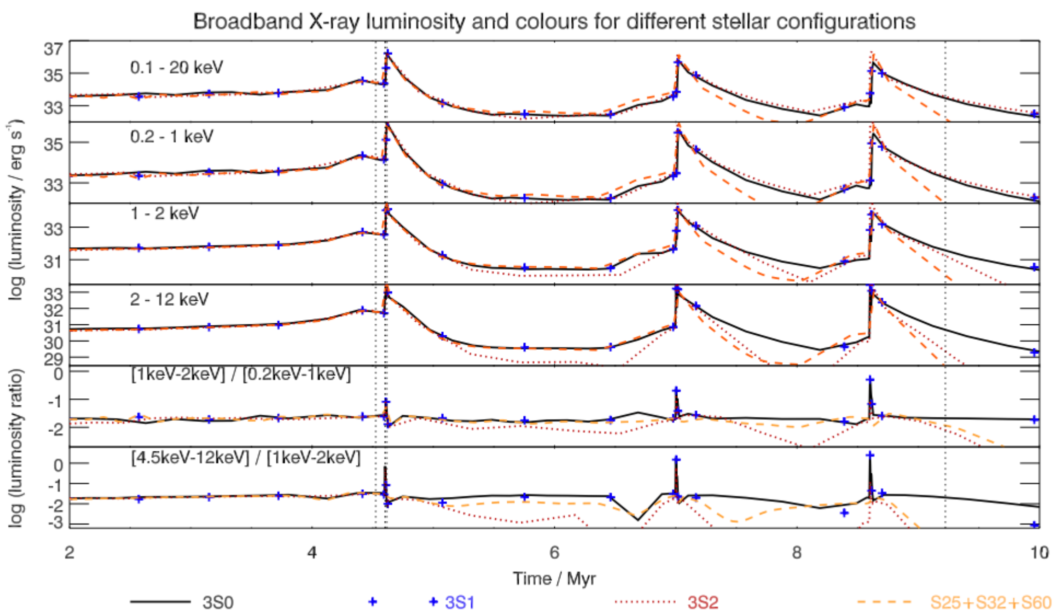
- Conduction suppressed across magnetic field lines
- 100x reduction in conduction rate κ0 results in only factor of ~2 reduction in hot bubble mass



# Superbubble X-Ray Luminosities

**Table 1.** Physical Properties of Hot Gas in Bubble Interiors

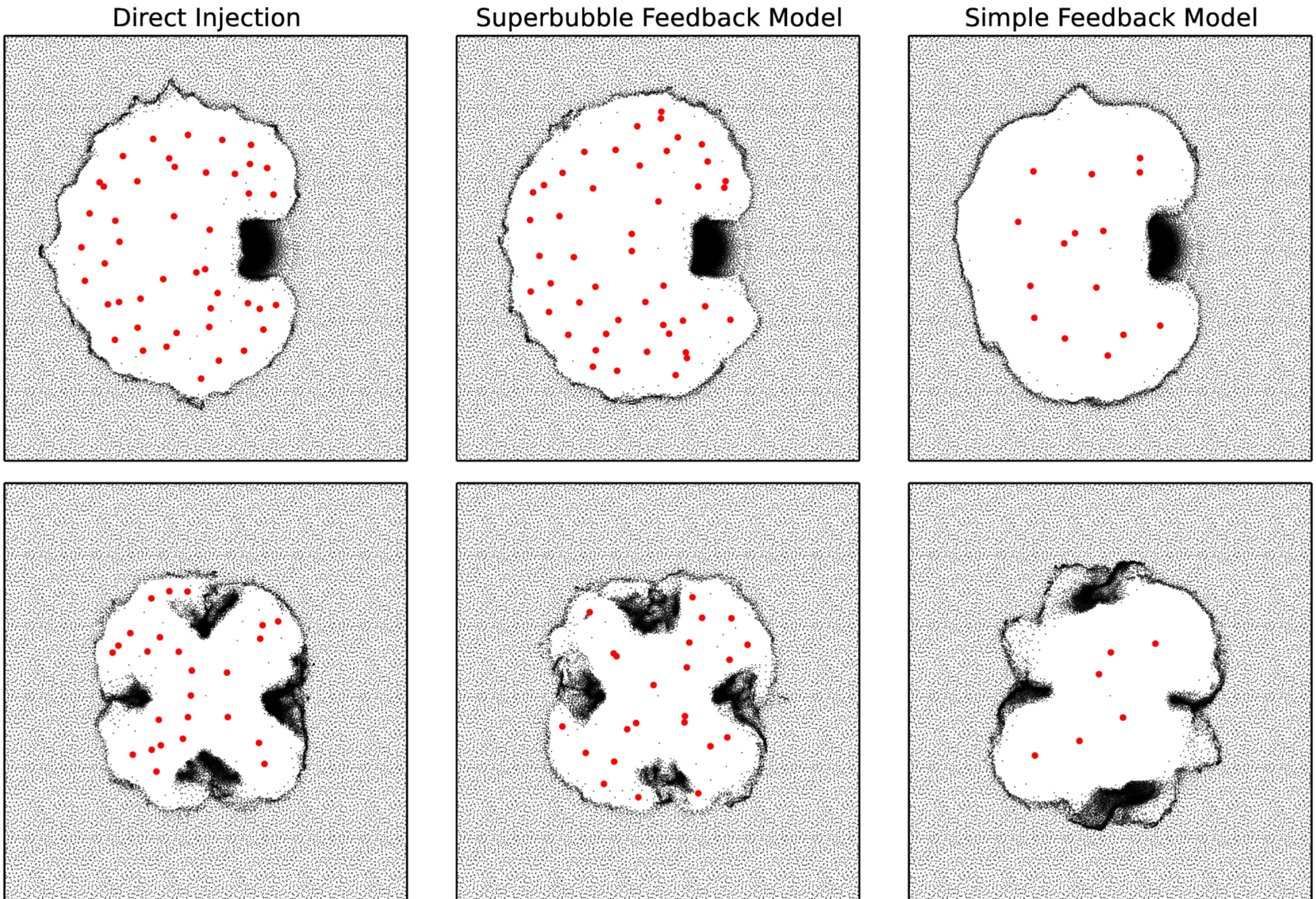
| Bubble Type | $T_e$ [$10^6$ K] | $N_e$ [cm$^{-3}$] | $L_X$ [erg s$^{-1}$] |
|---|---|---|---|
| Orion Bubble | 2 | 0.2–0.5 | $5 \times 10^{31}$ |
| WR Bubble | 1–2 | 1 | $10^{33} - 10^{34}$ |
| M17 Superbubble | 1.5, 7 | 0.3 | $3.4 \times 10^{33}$ |
| Planetary Nebula | 2–3 | 100 | $10^{31} - 10^{32}$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




Krause+ 2014

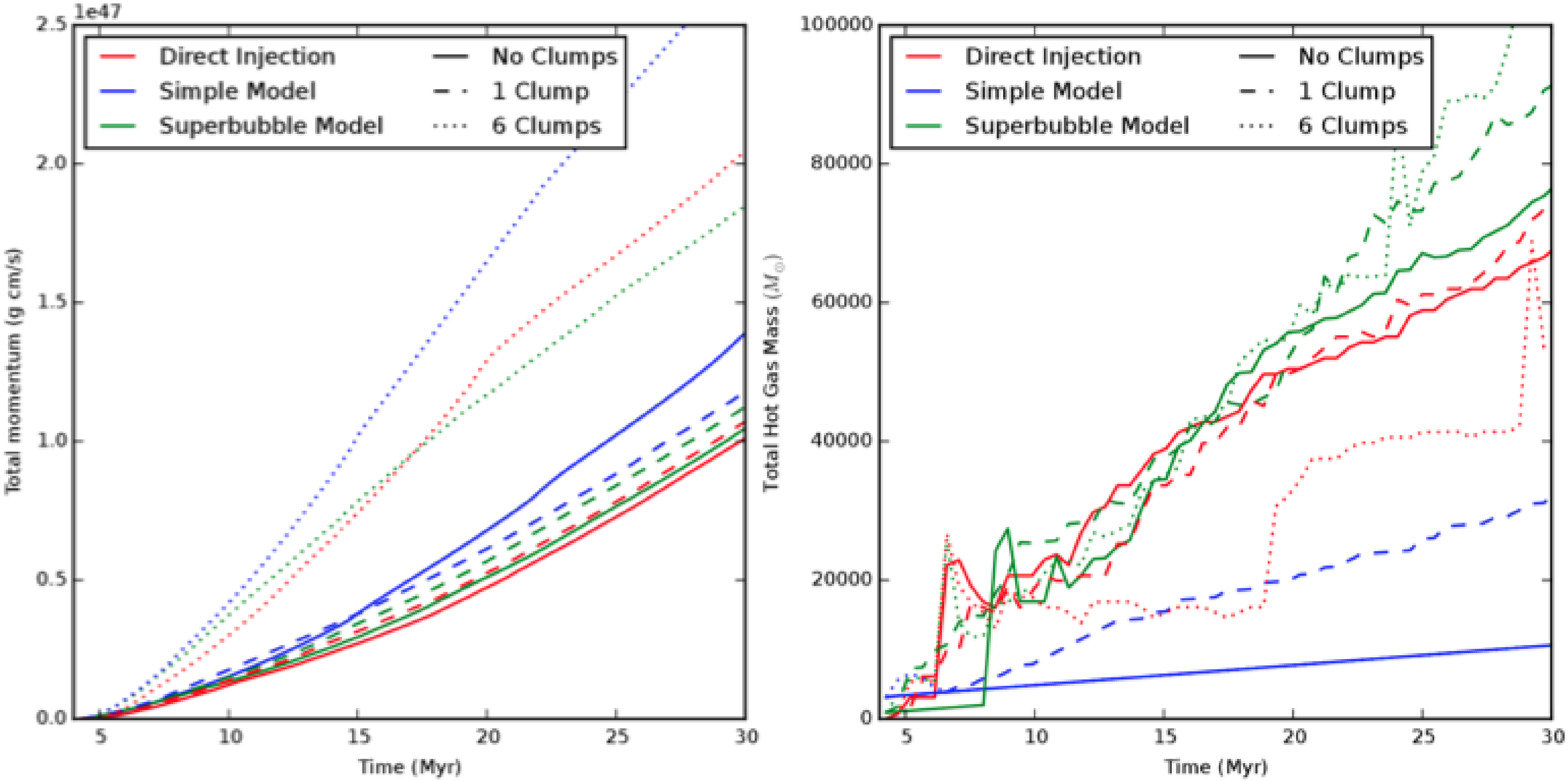
- X-Ray luminosity highly variable over space, time
- Very few observations, large scatter in observed LX
- Leaking of interior, B-field amplification in shell may explain some reduced luminosities (see Rosen+ 2014)

# Clumpy ISM



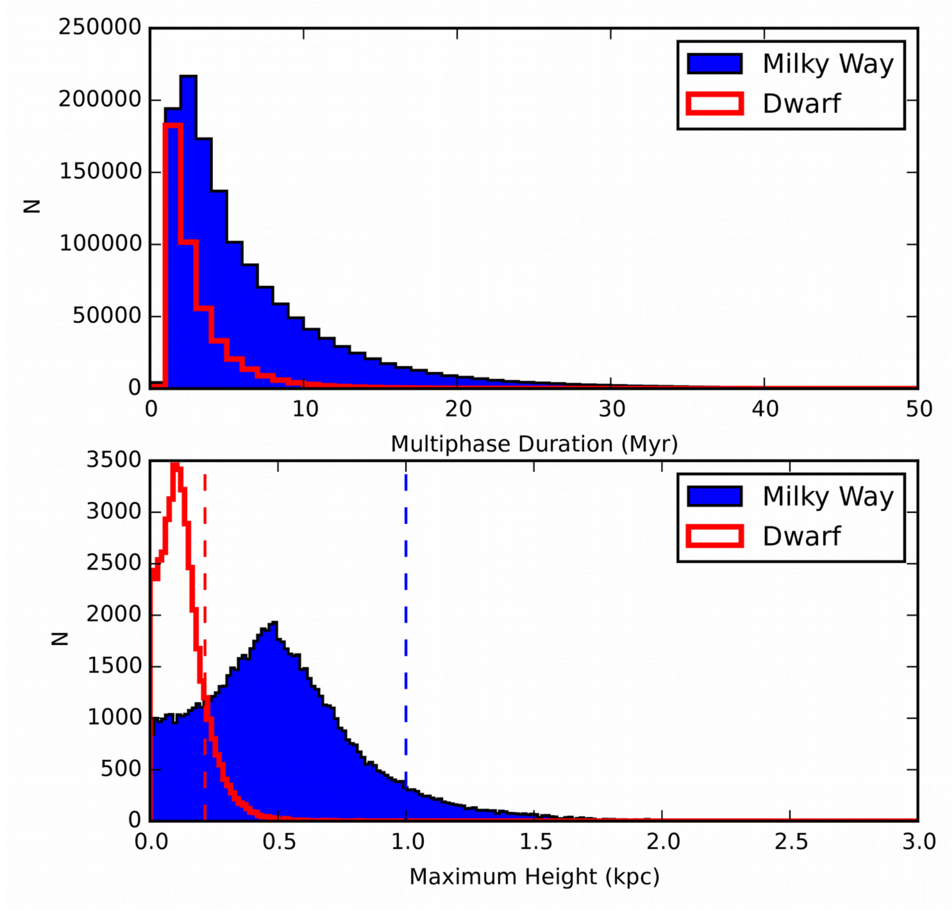
Direct Injection
Superbubble Feedback Model
Simple Feedback Model

# Clumpy ISM




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

# Multiphase Properties




- Median multiphase lifetime < 5Myr