# Superbubble Driven Outflows in Cosmological Galaxy Evolution

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CASCA 2015

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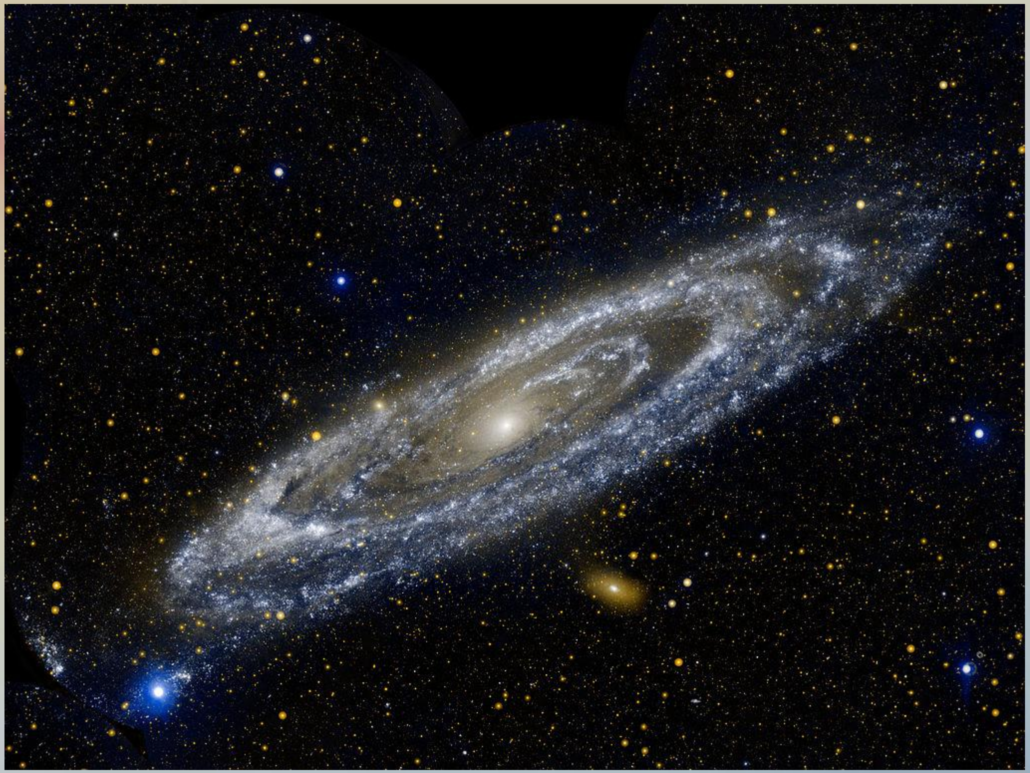
Keller, Wadsley & Couchman 2015

McMaster University

Background Image: Gas column density of IGM around a simulated L* galaxy (image is ~10$R_{vir}$ across). The dense central object is where the galaxy resides.

# L* Galaxies: Star formation Engines

- Most efficient star formers
- Stellar Mass/Halo Mass  3-5%, lowest M/L ratio
- Common! (We live in one)
- Disk Dominated
- Young Stellar Population
- Halo Mass ~$10^{12}\,M_\odot$



M31 Image: GALEX NASA

# Small Bulges!

- Most efficient starformers (highest M/L ratio)
  - S
- Con
- Stel
- ~3-5
- Halo

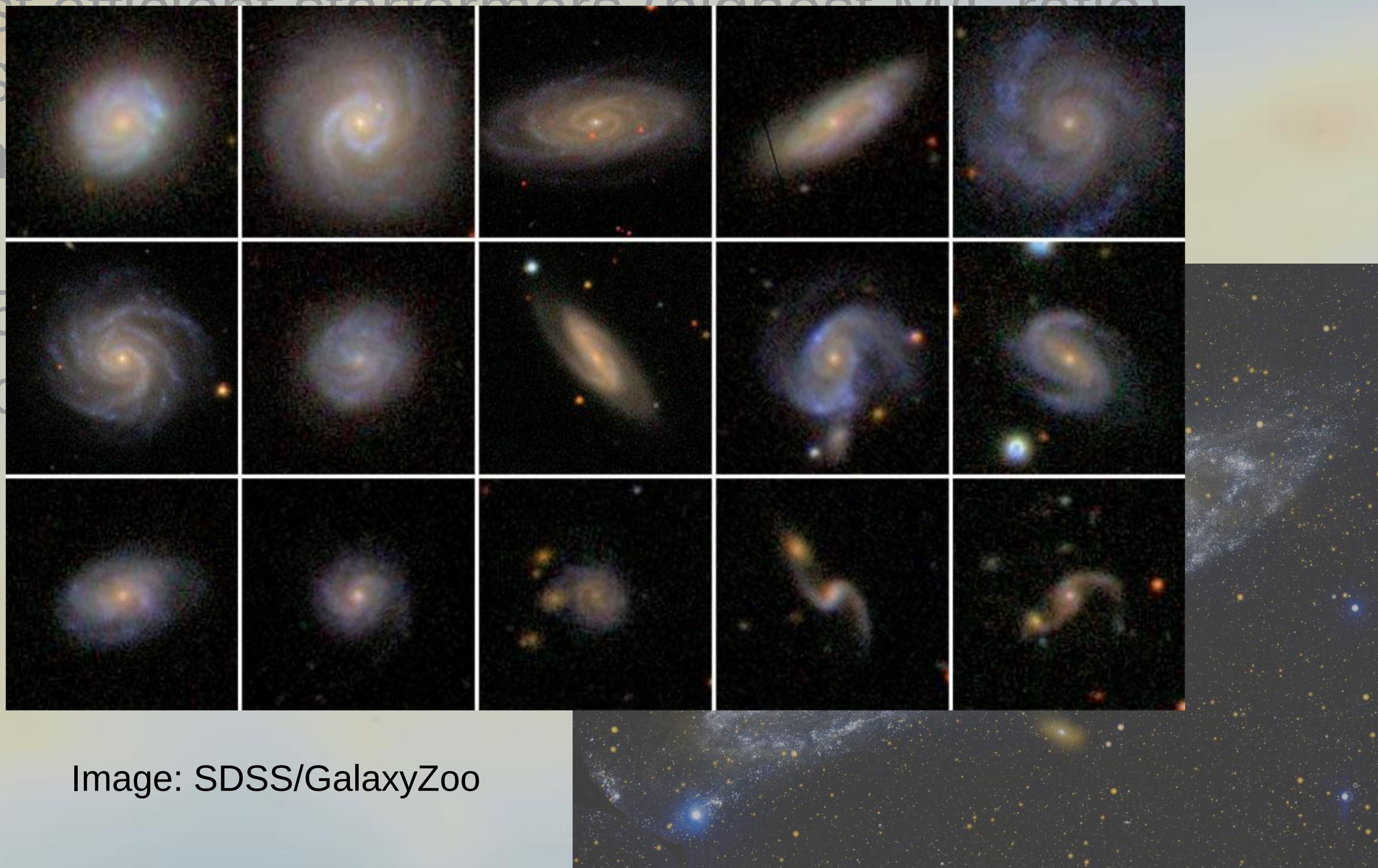
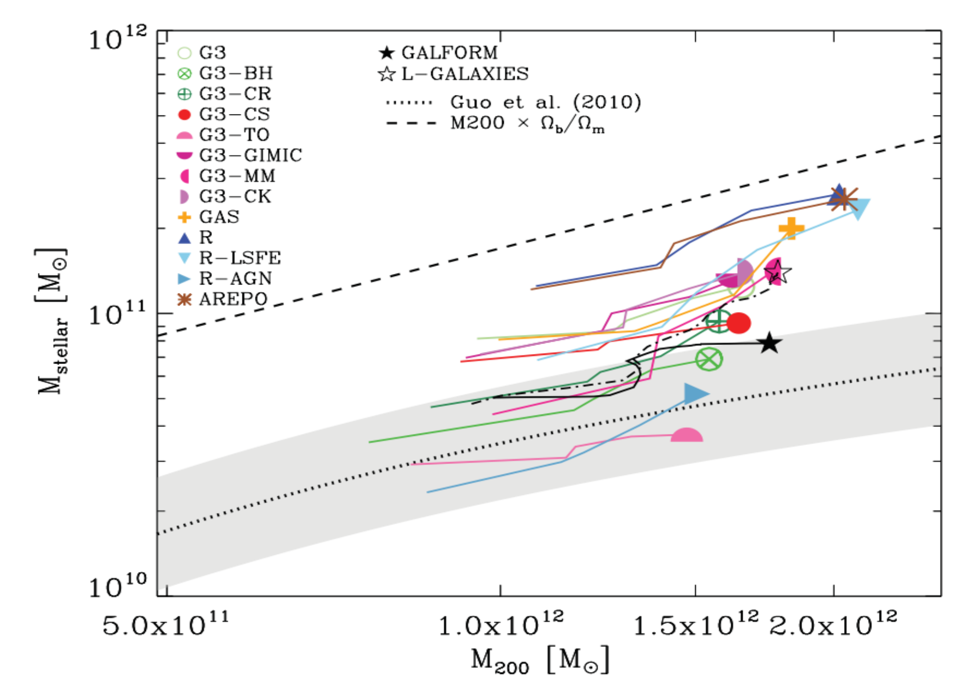
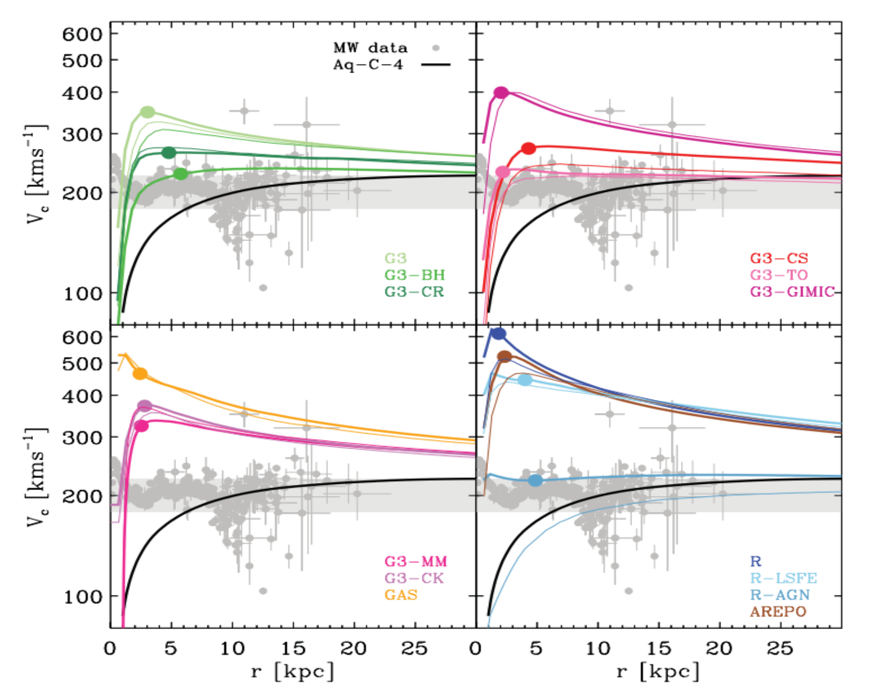


Image: SDSS/GalaxyZoo

M31

# Tension between Theory & Observations




- Aquila comparison (Scannapieco+2012)
  - Compared feedback models & simulation codes on same cosmological initial conditions
  - Most produced too many stars, too large bulge/disk ratios
  - None had both reasonable stellar mass fraction and small bulge.

**Missing feature: Baryon expulsion!**

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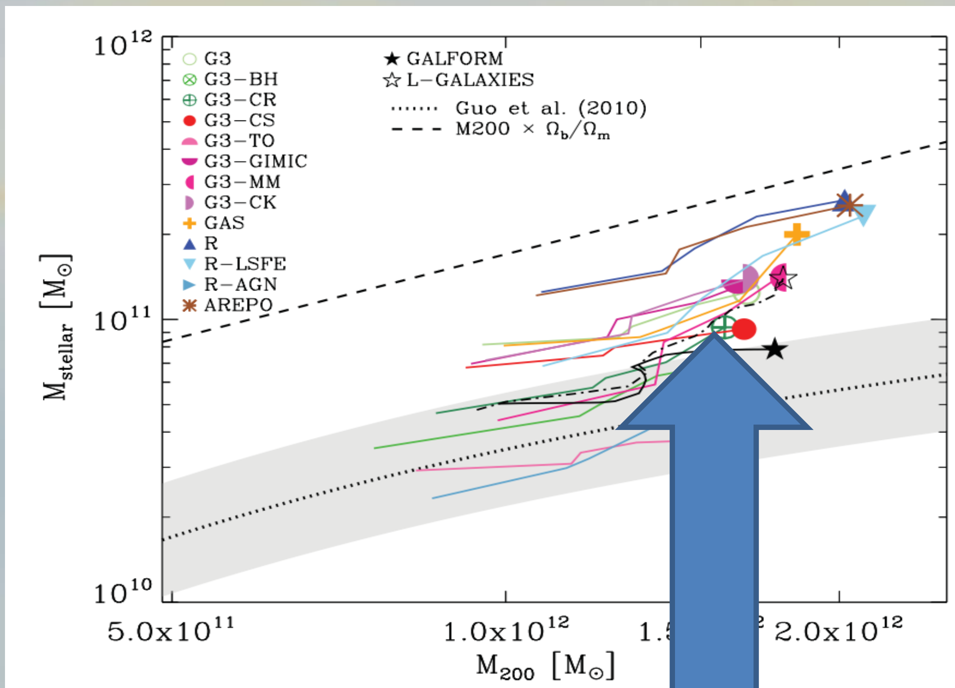


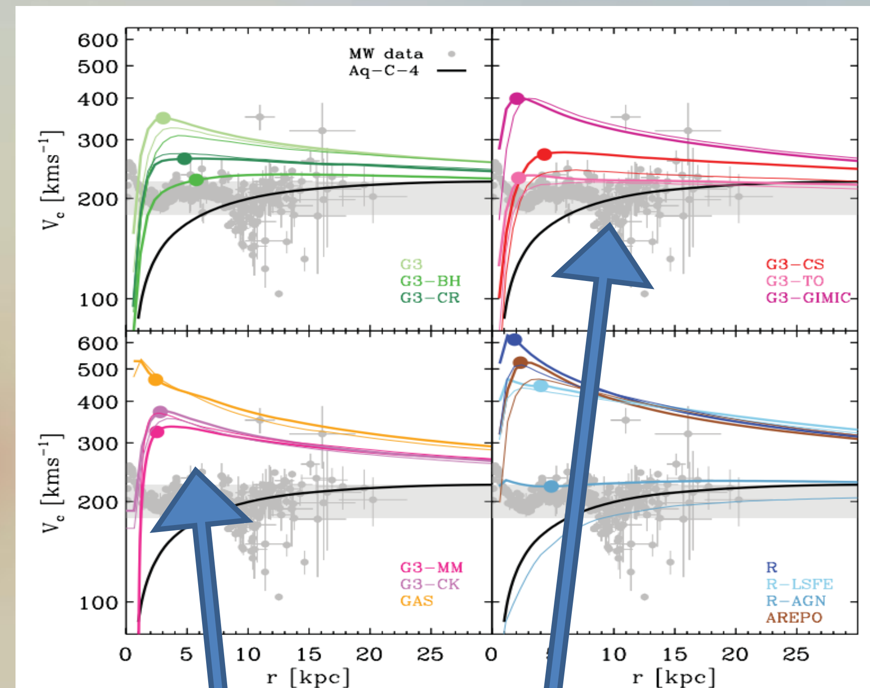


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Too Many Stars!

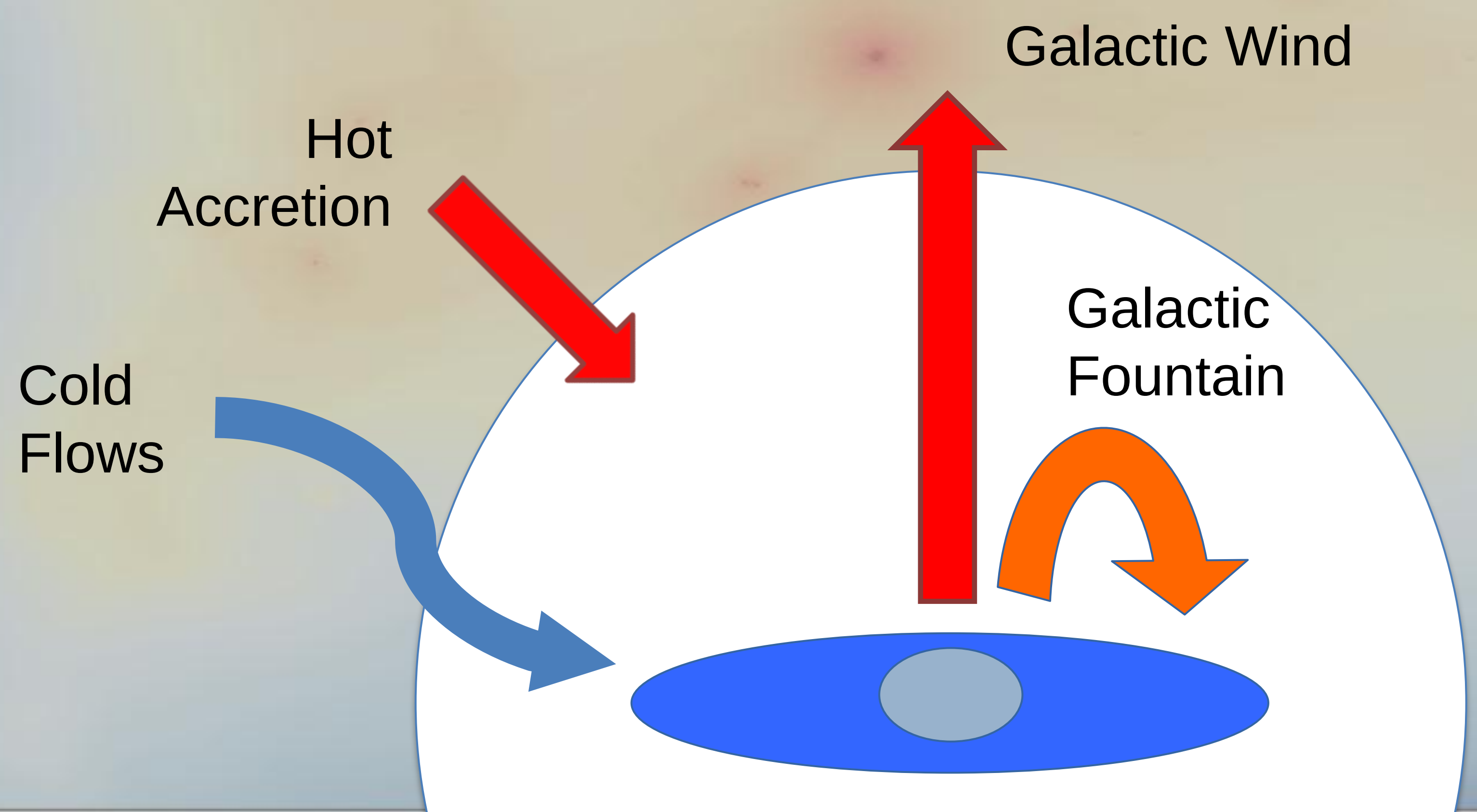
Massive Bulge = Peaked Rotation Curves

**Missing feature: Baryon expulsion!**

# How Galaxies Get Gas

- Gas accreted and removed over galaxy's history
- Cold flows dominate early (Woods+ 2014)
- Fountains fuel low z star formation (Marasco+ 2012)

But: What powers outflows?



# Galactic Outflows

- Observational evidence abounds
  - UV absorption (Wiener+ 2009)
  - Hα emission lines (Heckman+ 1987)

Supernova powered superbubbles may power them (Larson 1974)

M82 Image: HST NASA/ESA

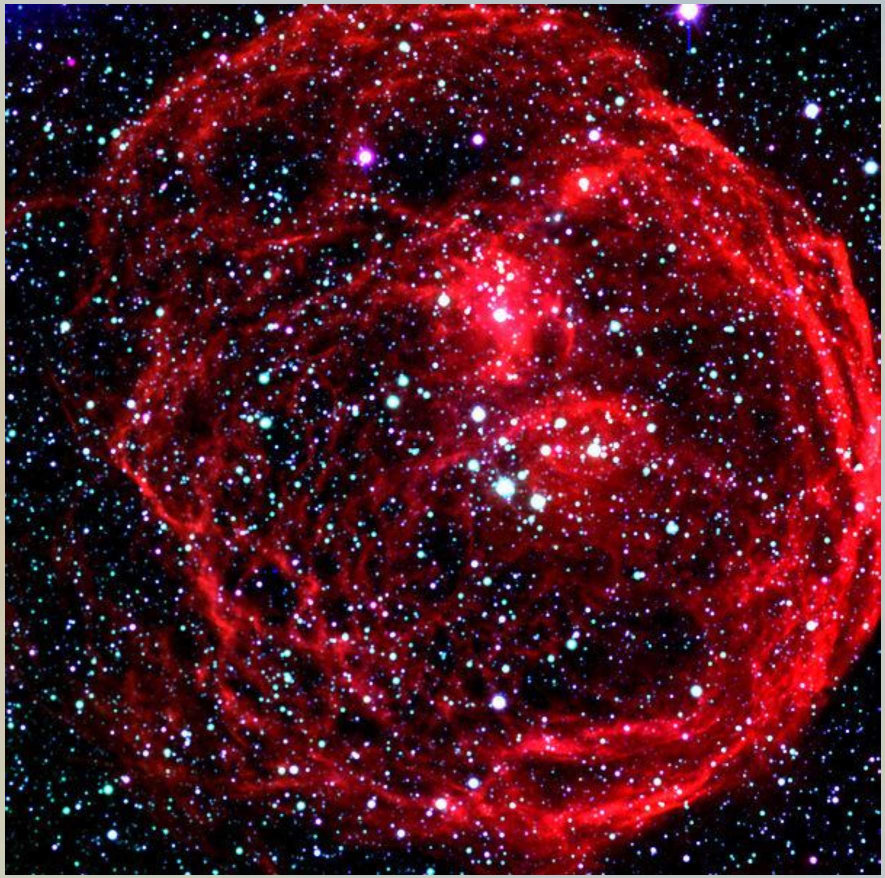
# Superbubble features

Natural unit of feedback is a <u>superbubble</u> combining feedback from 100+ massive stars

Classic model:

- Stellar winds + supernovae shock and thermalize in bubble
- Negligible Sedov-phase
- Mechanical Luminosity

  $L=10^{34}$ erg/s/$M_\odot$
- Much more efficient than individual SN (e.g. Stinson 2006 Blastwave feedback model)



N70 Superbubble LMC Image: ESO

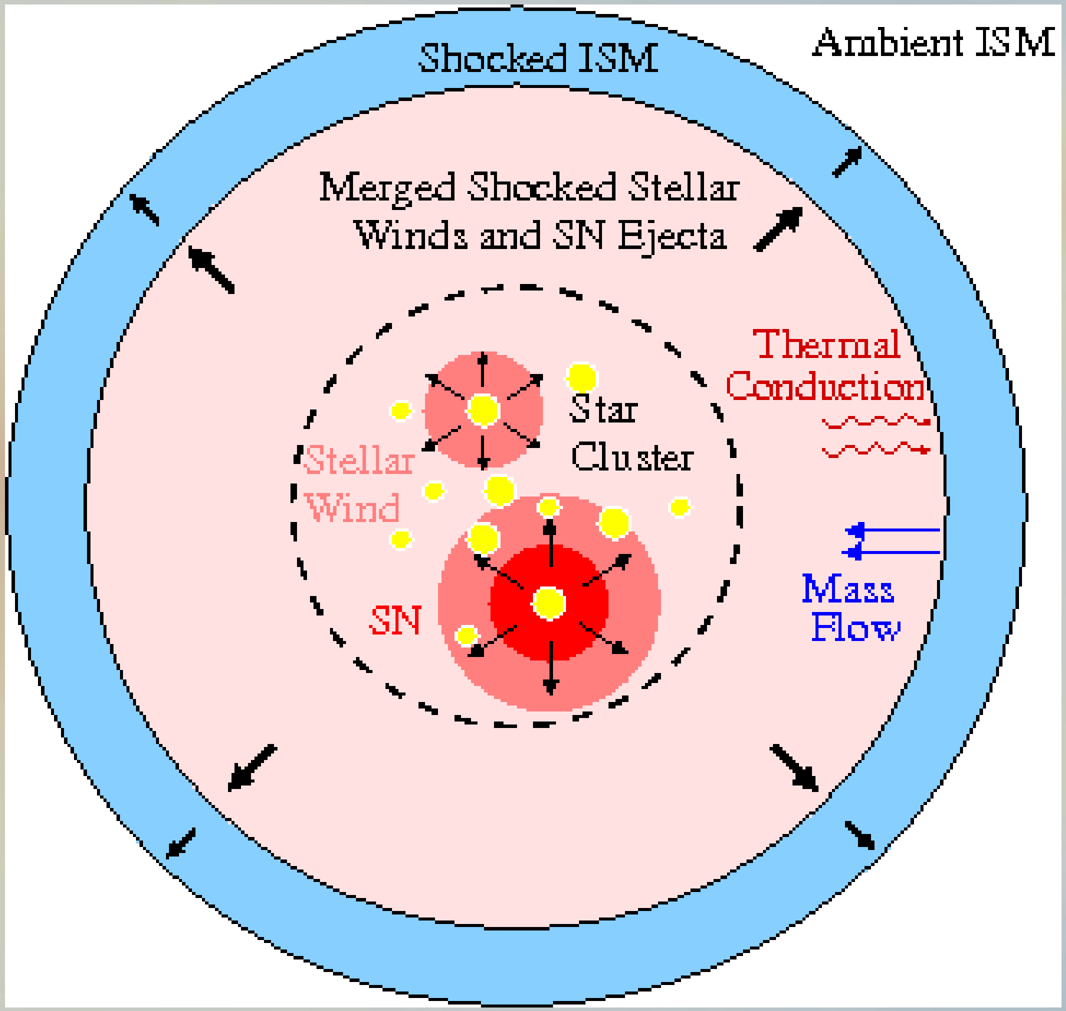
D 100 pc Age: 5 Myr v ~ 70 km/s

Driver: OB assoc. 1000+ stars

MacLow & McCray 1988, Weaver+ 1977, Silich+ 1996

# Superbubble Feedback

- Key physical component is *Thermal Conduction*
  - Evaporates cold shell
  - Determines how much mass is heated by feedback (mass loading)
- Keller+ 2014 developed model based on these physical processes
  - Low resolution sensitivity
  - Highly effective in isolated galaxies

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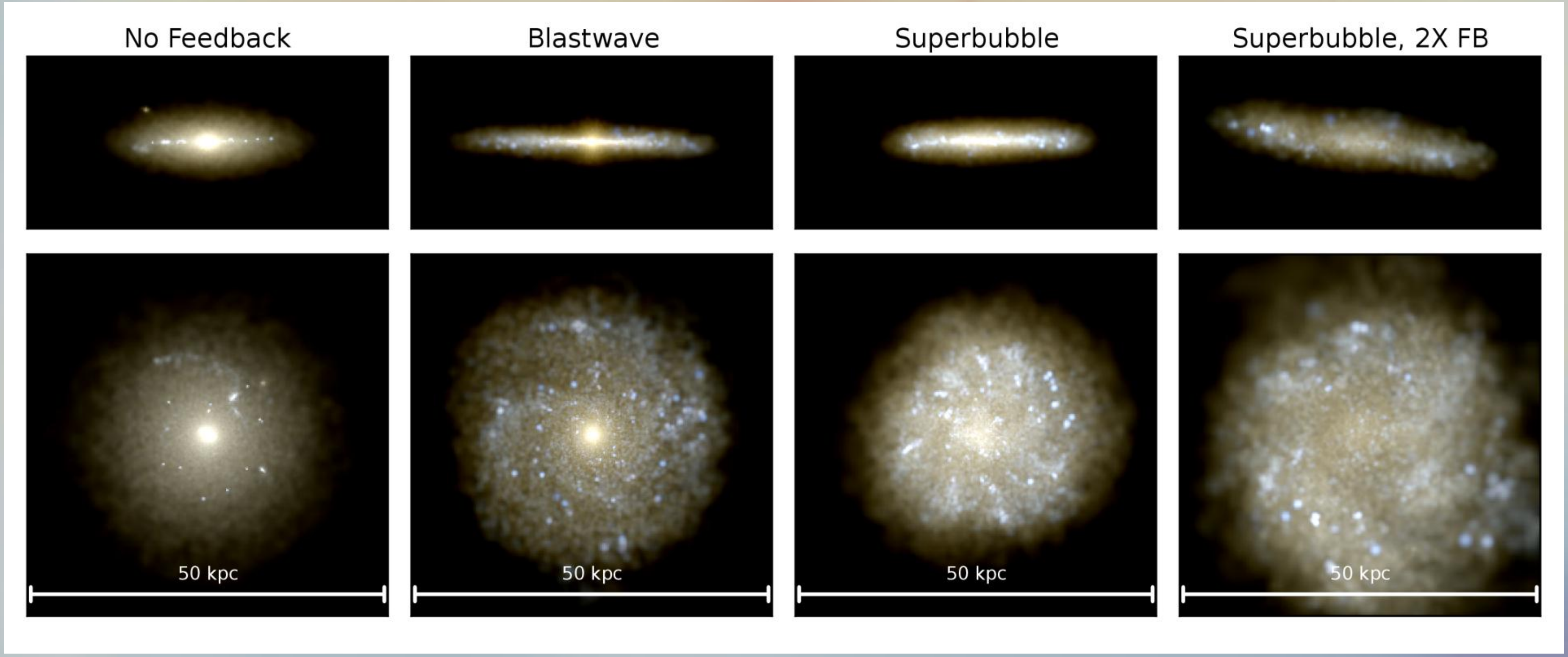
# Gasoline


- N-body Solver (Tree Method) and Smoothed Particle Hydrodynamics
- Physics: Gravity, Hydrodynamics, Atomic Chemistry (Radiative Heating, Cooling), Radiative Transfer (Woods et al, in prep)
- Subgrid Physics: Star Formation, Turbulent Diffusion

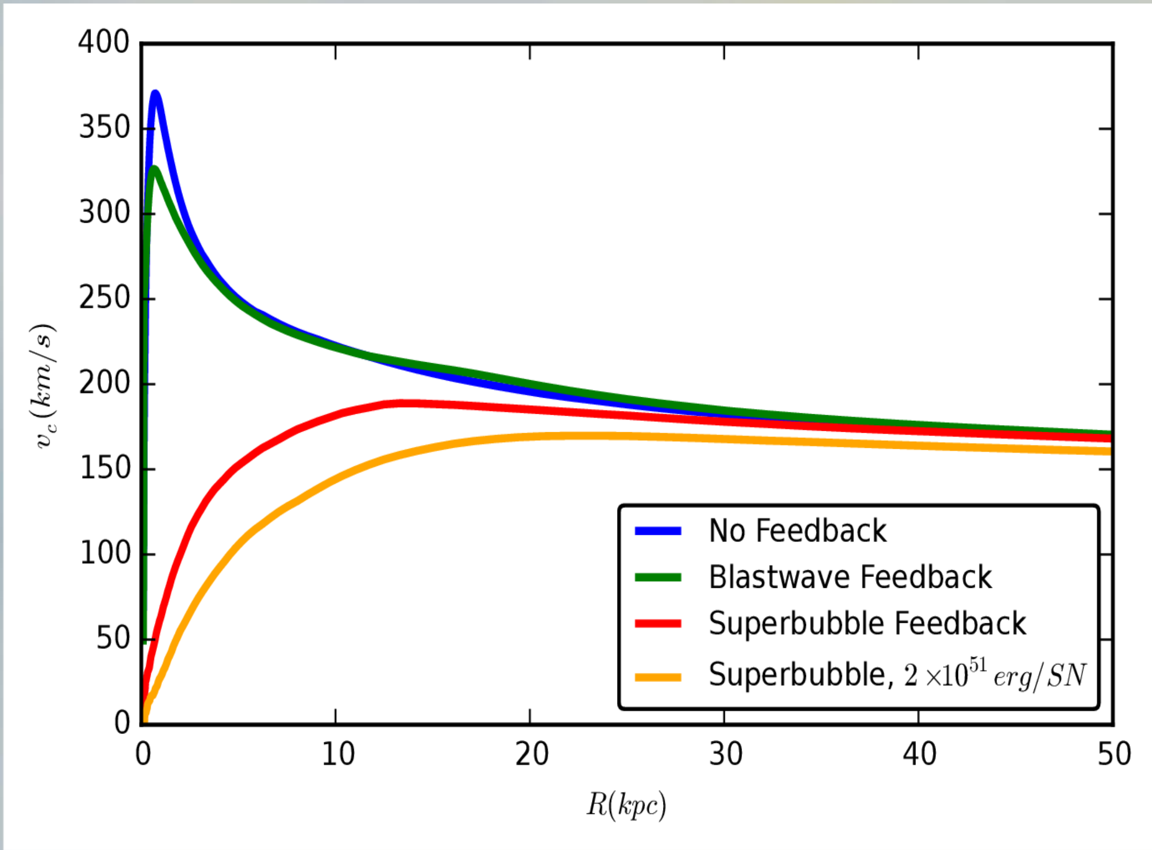
Wadsley+ 2004

# Simulations

- 4 test cases:
  - No Feedback
  - Blastwave (old Feedback)
  - Superbubble Feedback
    $E=10^{51}$erg/SN
  - Superbubble Feedback  E x 2
- Initial Conditions
  - 8 x $10^{11}M_{sun}$ halo
  - Cosmological zoom-in
  - Last major merger at z=2.9

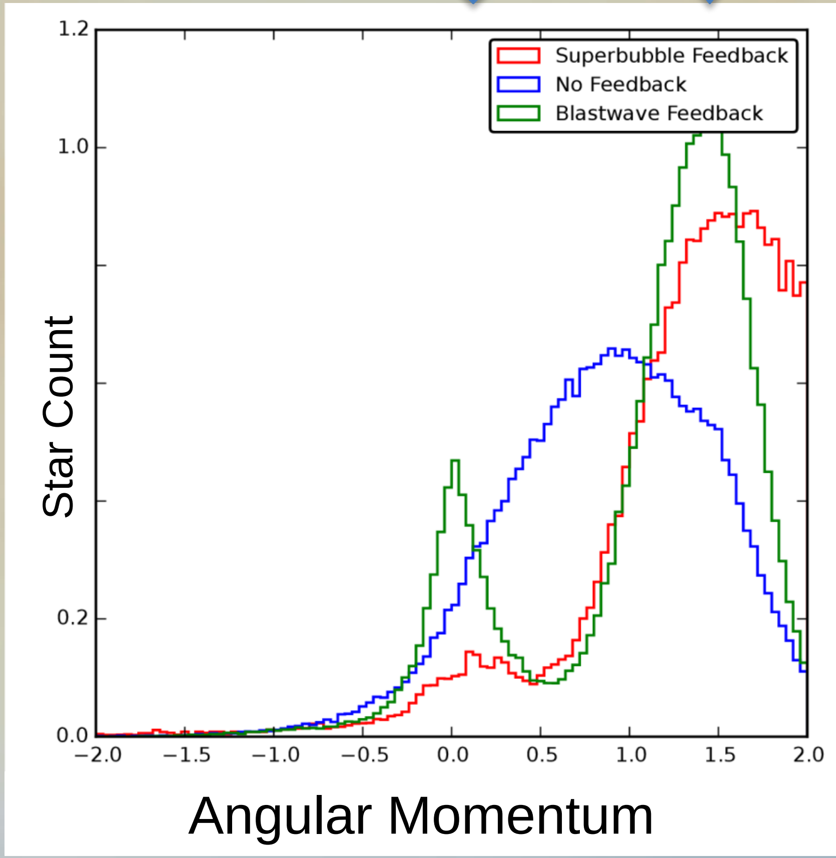


# Rotation Curves




Disk

Bulge




Flat rotation curves with SN only!
(c.f. Aquila, Scannapieco+ 2012)

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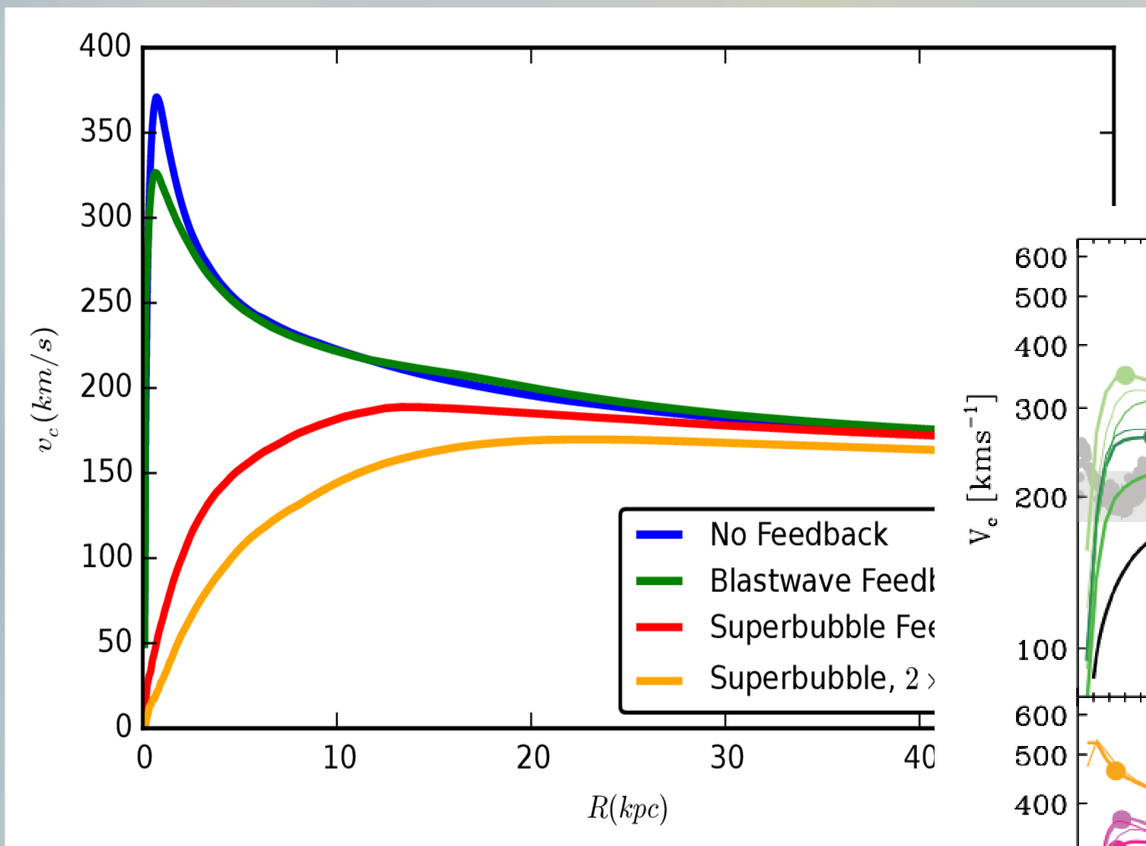


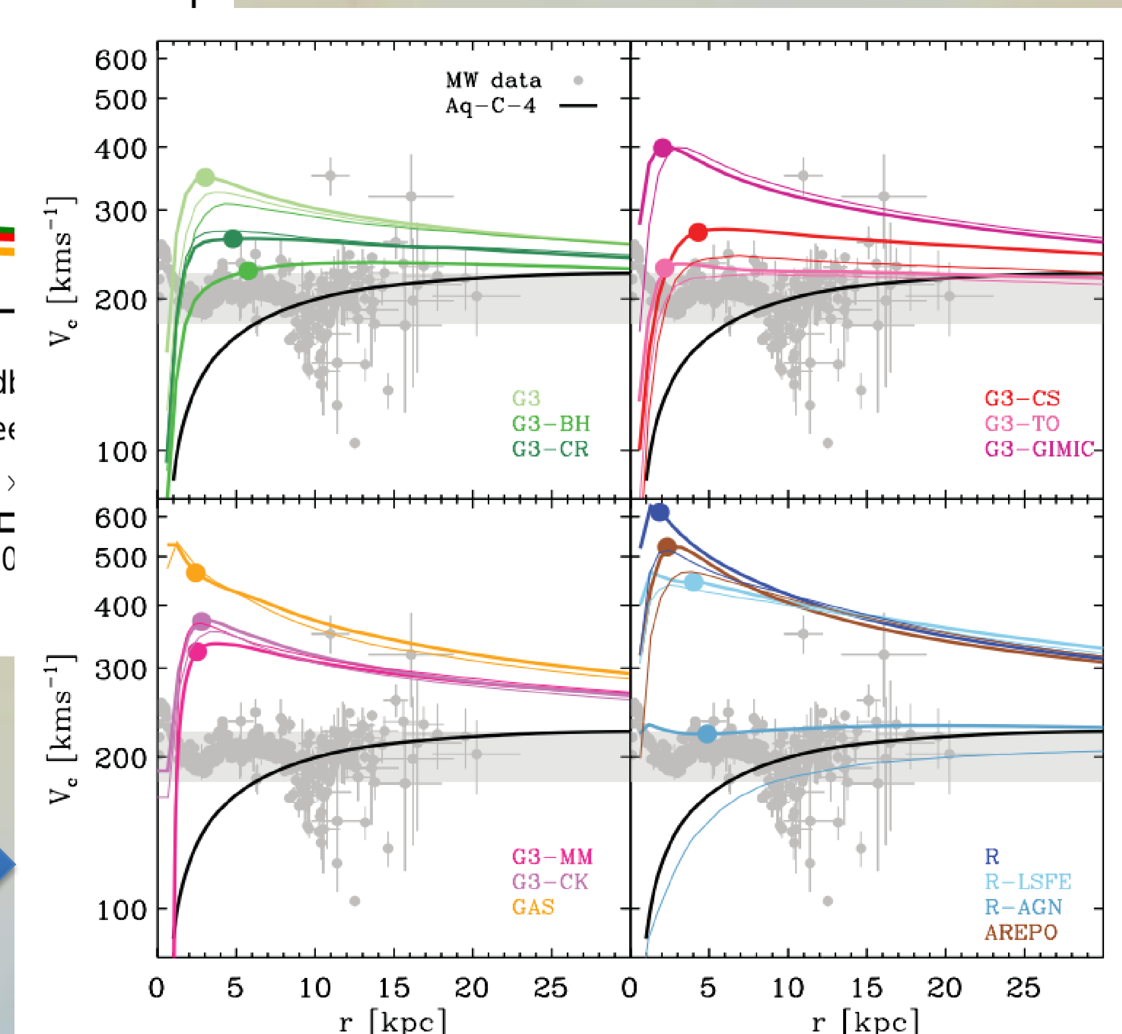


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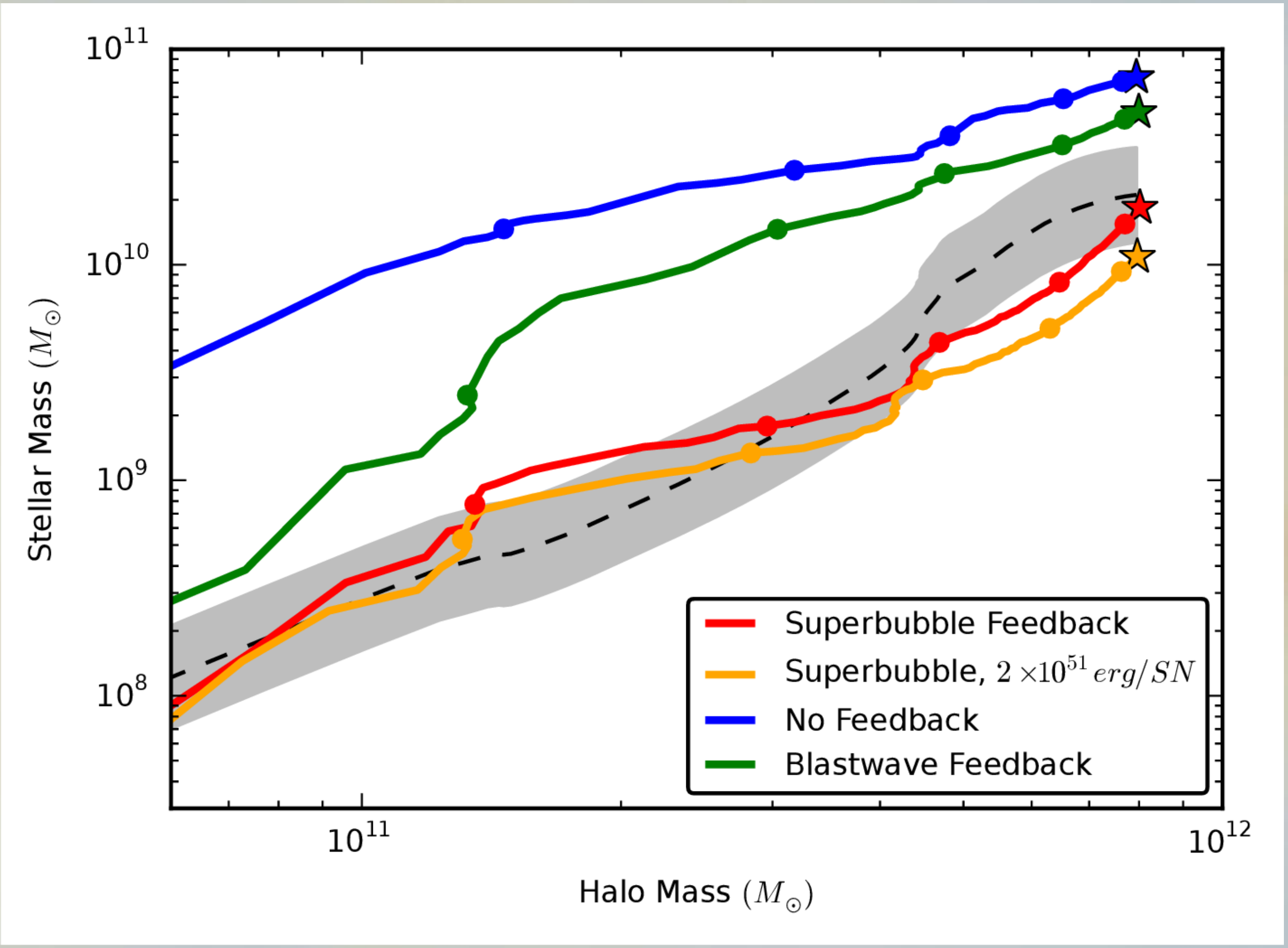
# Stellar Mass Fraction




Abundance Matched Stellar Mass History: Behroozi+ 2013

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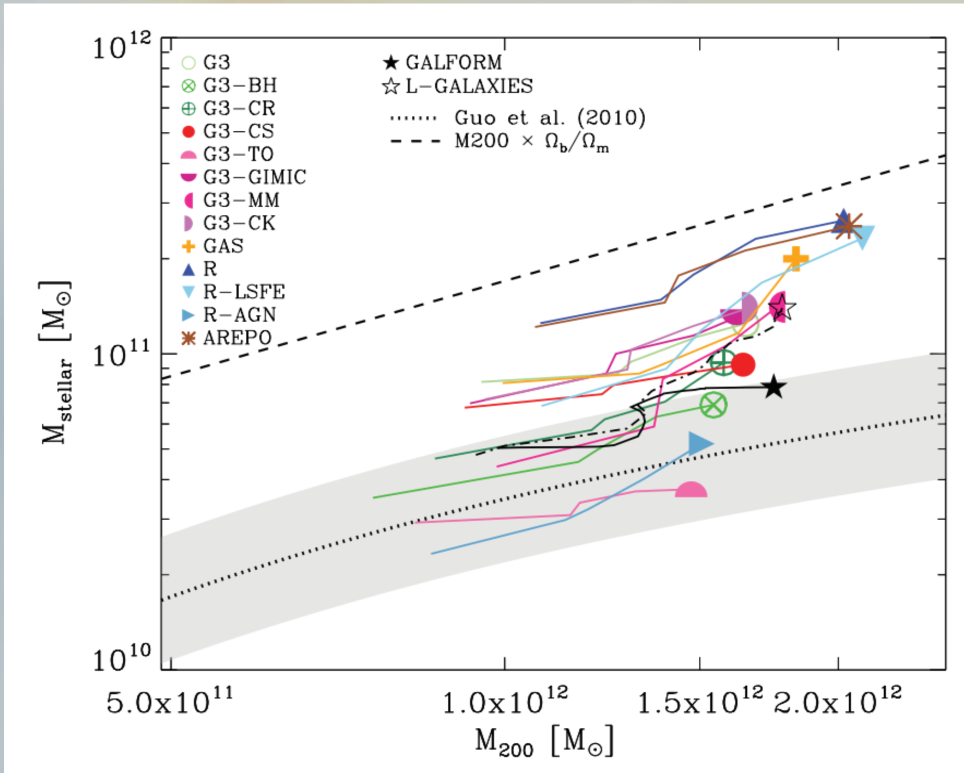


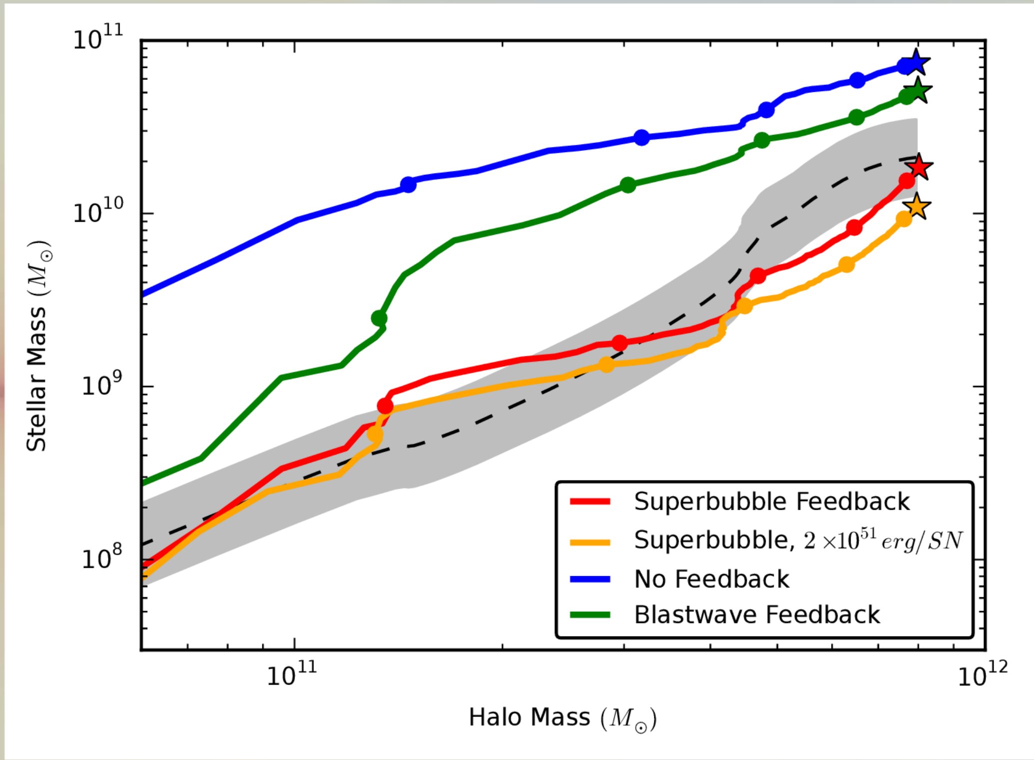


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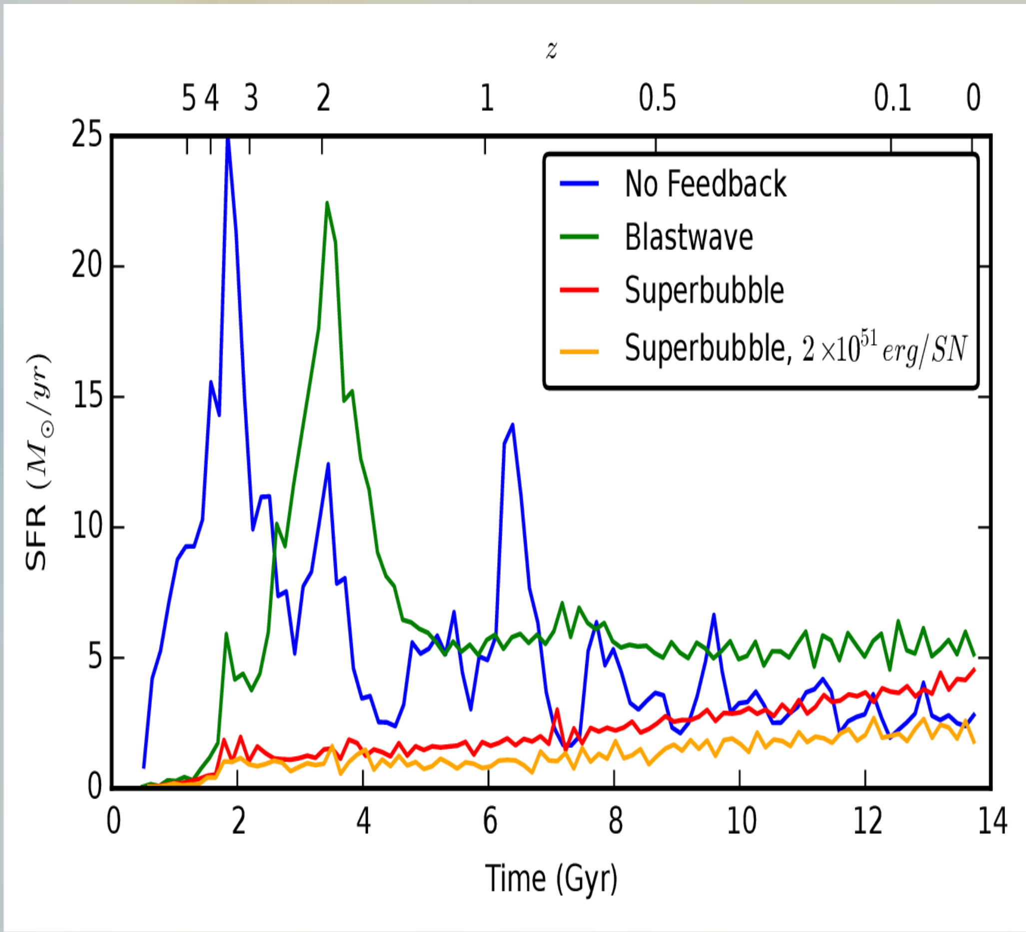
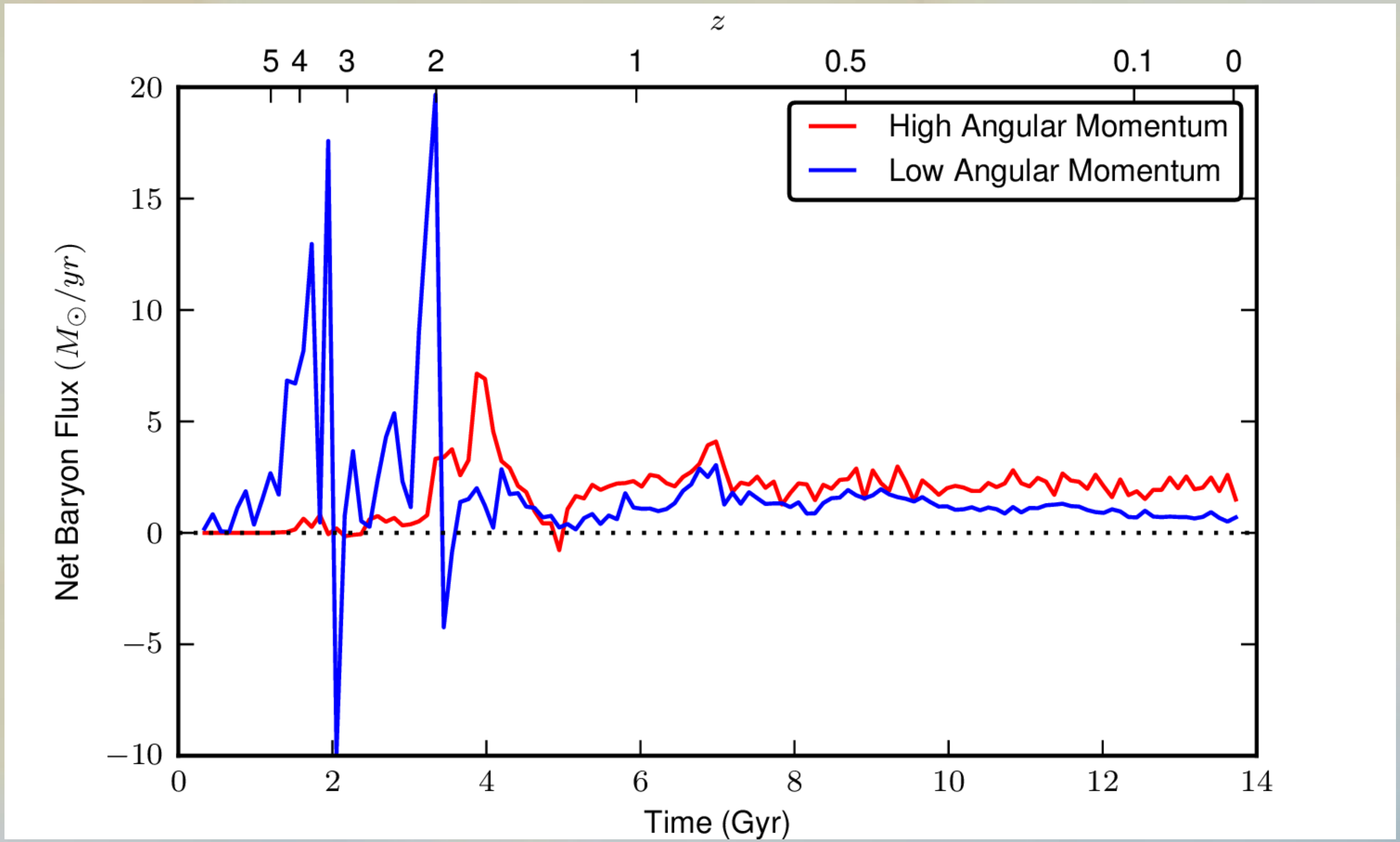
# Star formation Rates




- L* galaxies form ~90% of their stars after z=2.5
- Older stars tend to live in bulge, halo

Could low angular momentum material be accreted early?

# Accretion separated into high and low angular momentum gas



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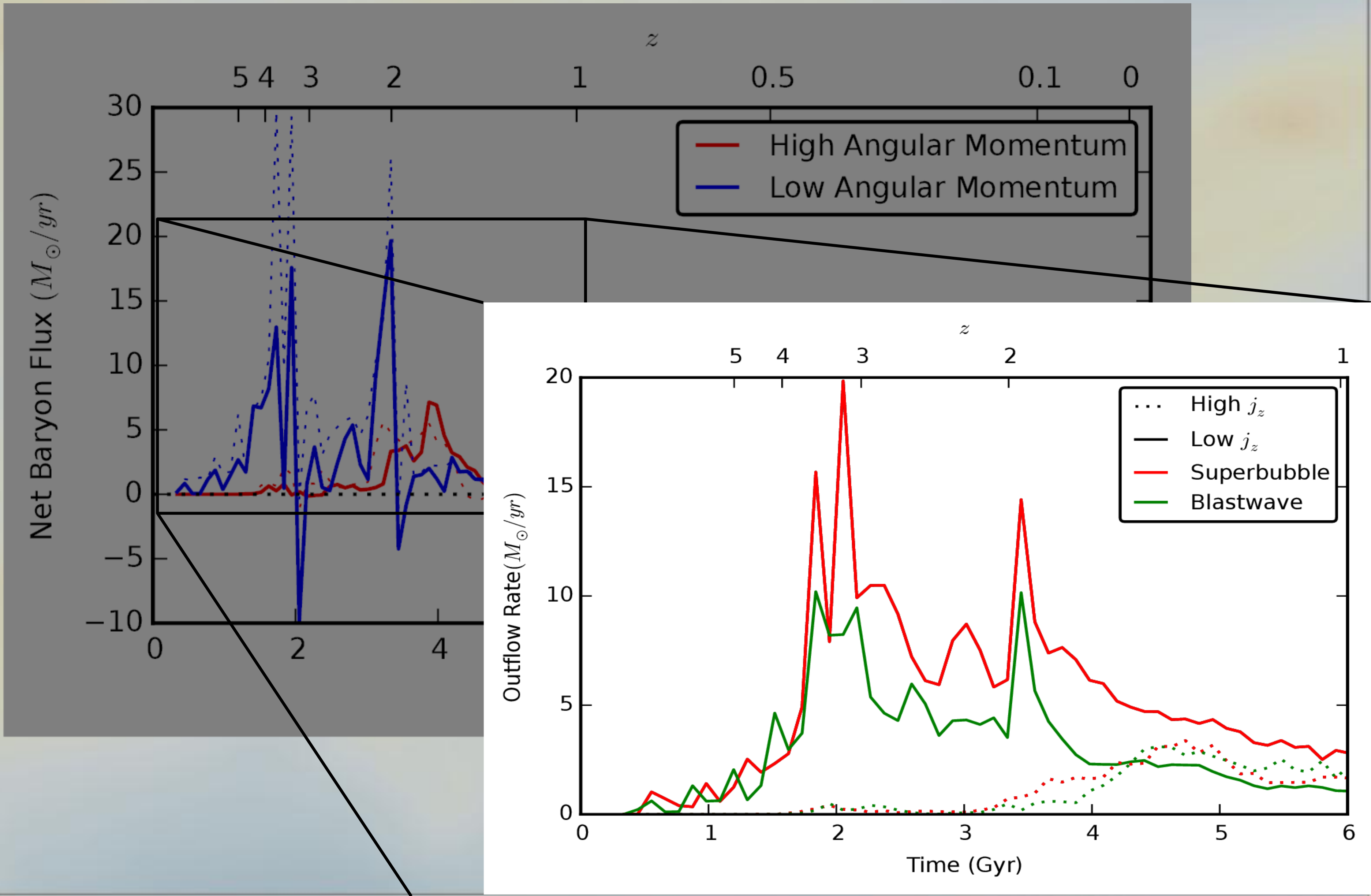

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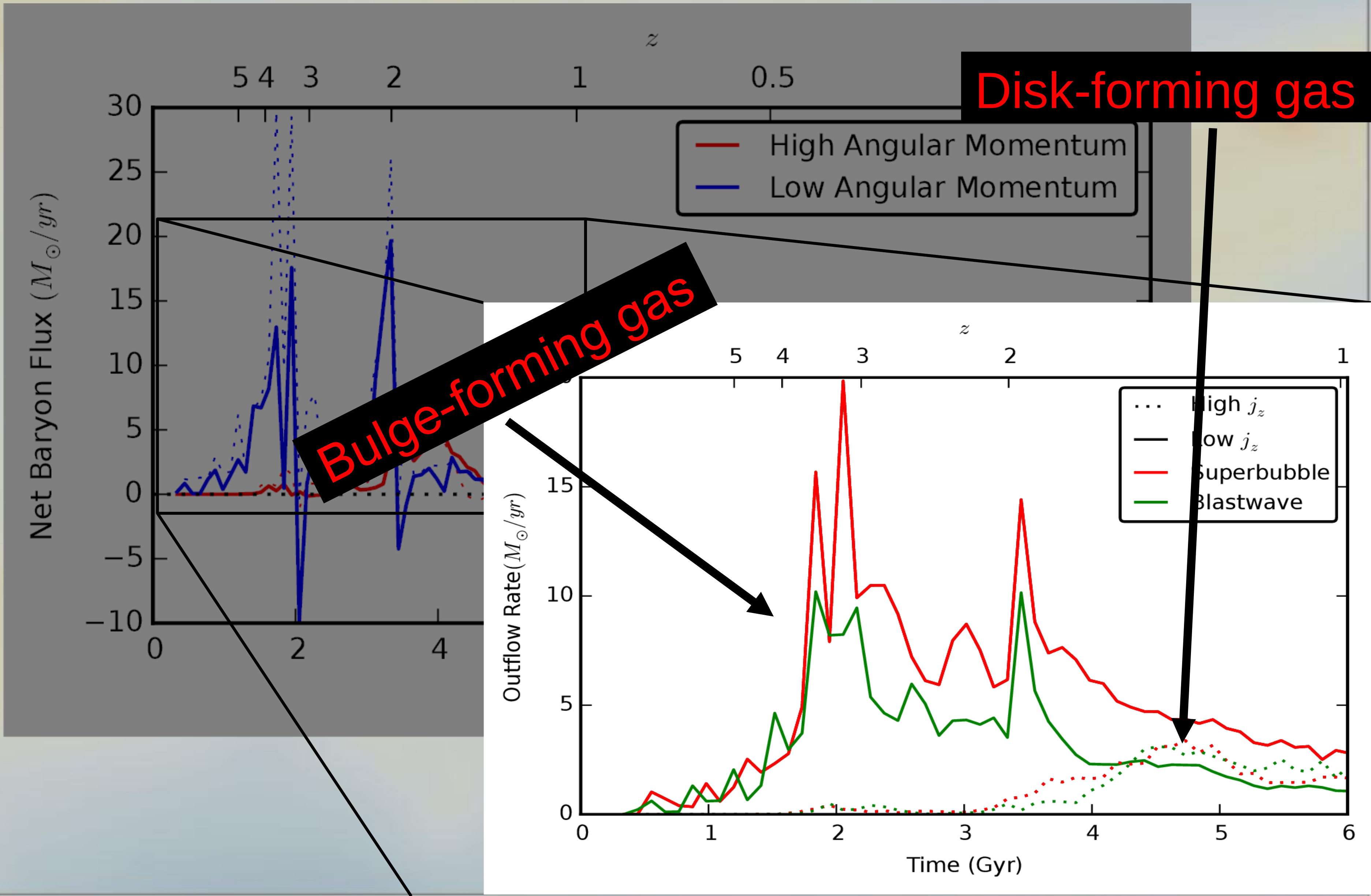
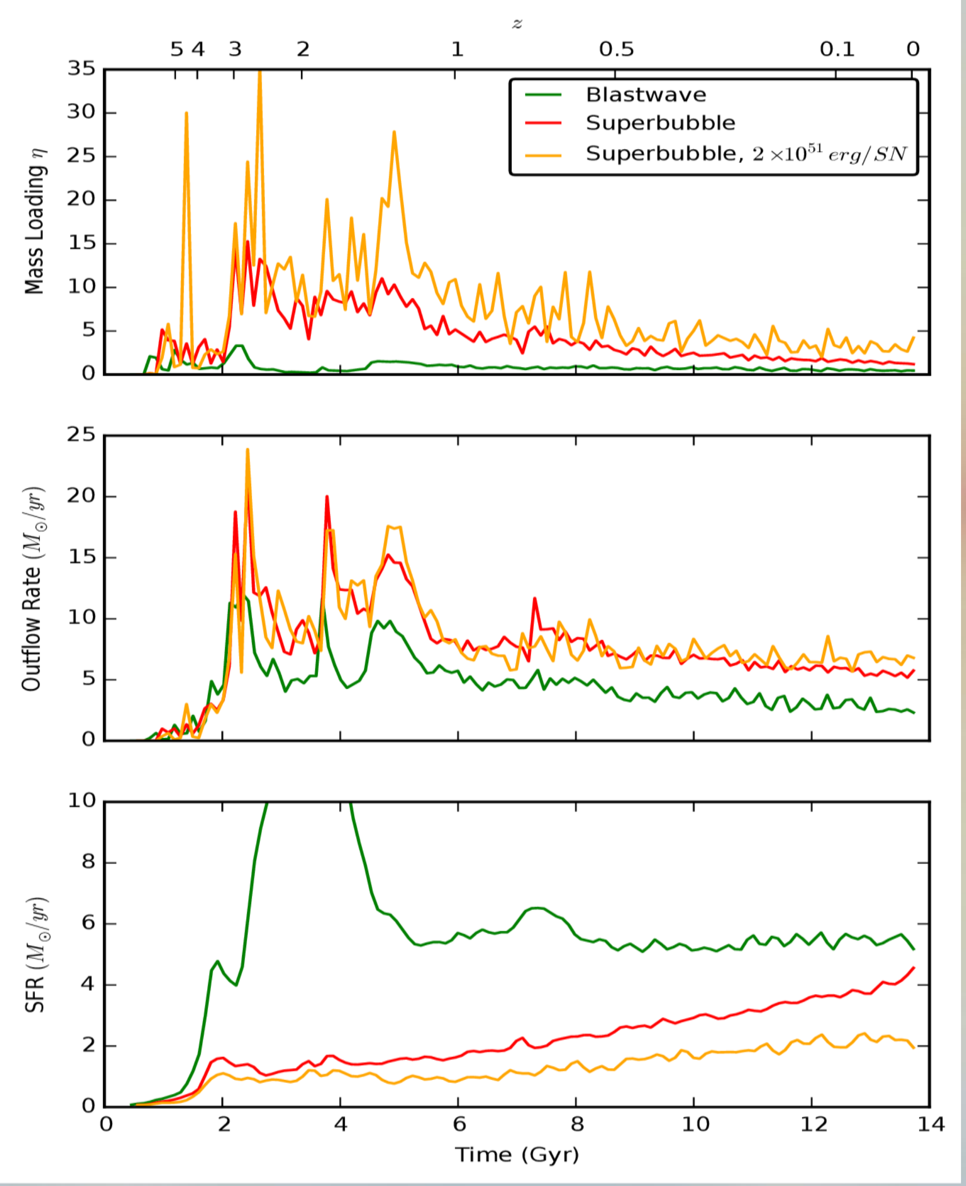


# High Redshift Outflows Are Key




- Potential well is shallow
- High mass loadings: correct stellar mass fraction

Preferentially remove low angular momentum gas!

# High Redshift Outflows Are Key

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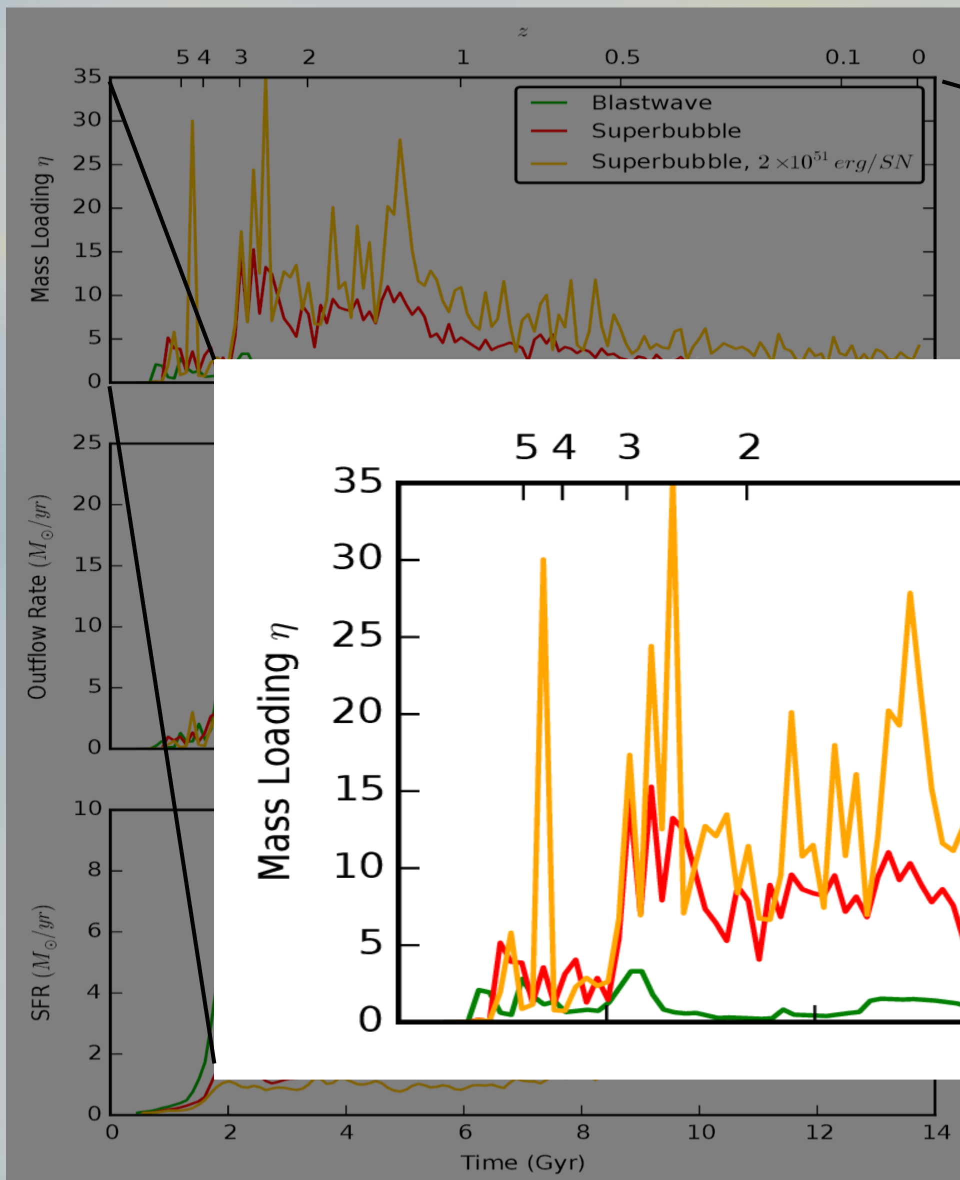
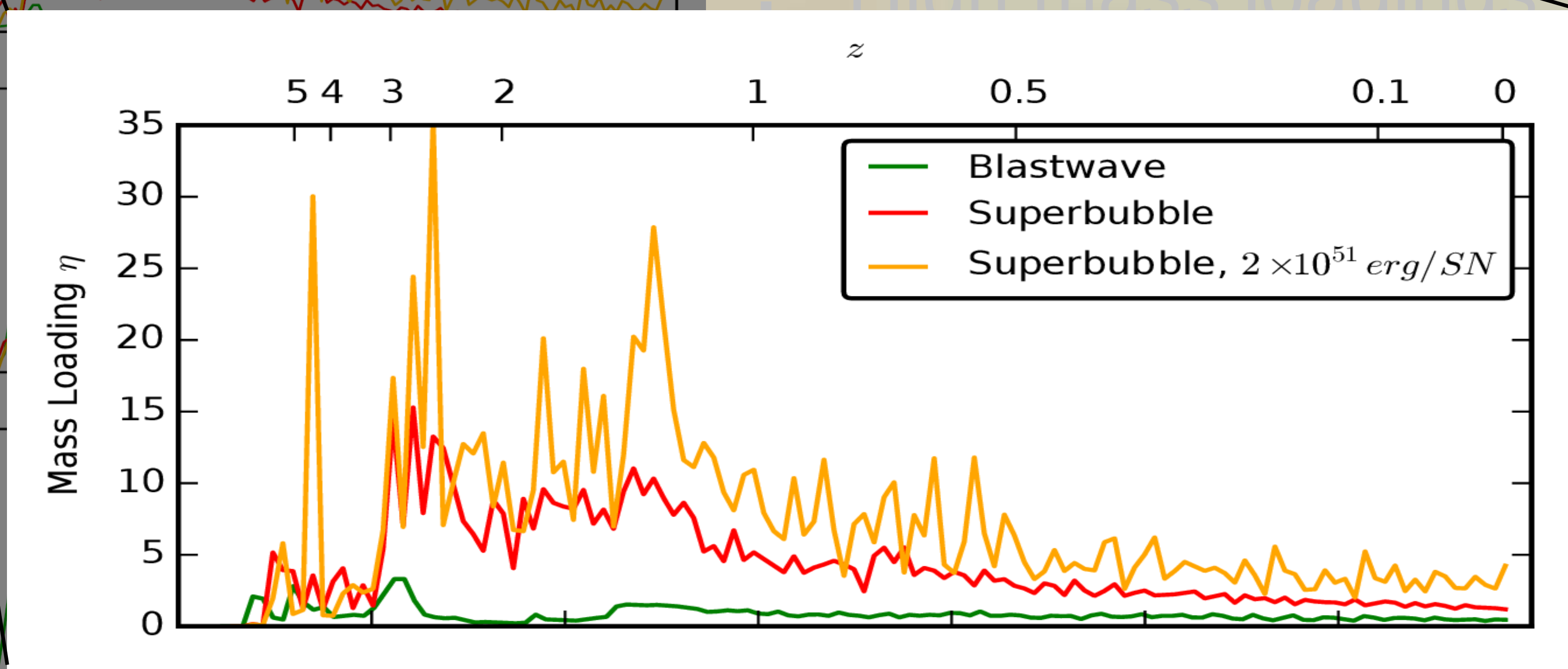
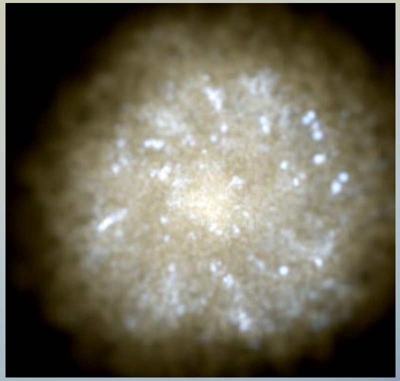
- High mass loadings:



# Conclusions

- Galactic outflows can be driven by thermal supernovae feedback alone if physics of superbubbles is included in simulation
- Strong outflows at high redshift remove gas that otherwise results in too many stars forming
- These outflows preferentially remove low angular momentum gas, preventing the formation of a massive bulge
- We can make a Milky Way ☺



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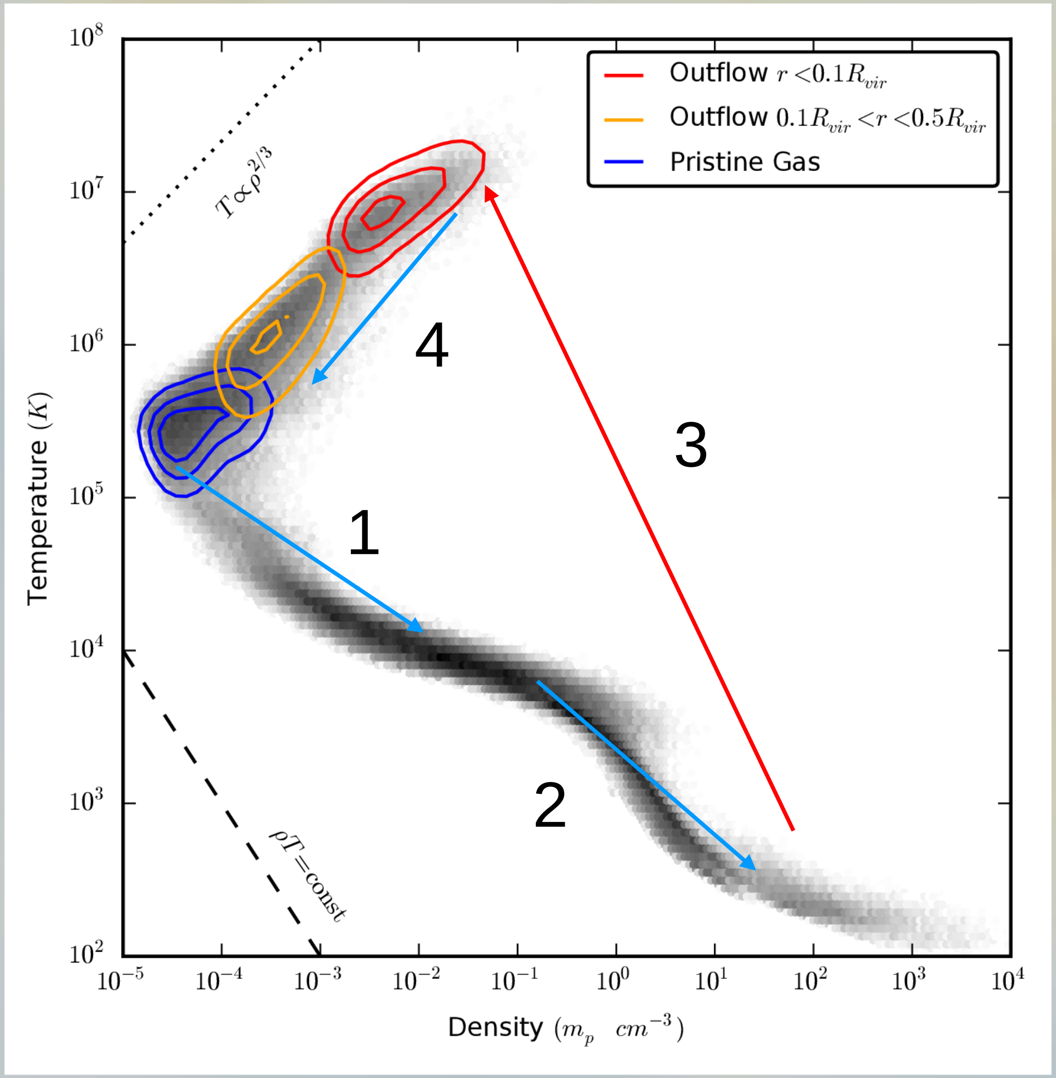
# Lifecycle of Gas




1. Virialized halo gas cools to form disk ISM

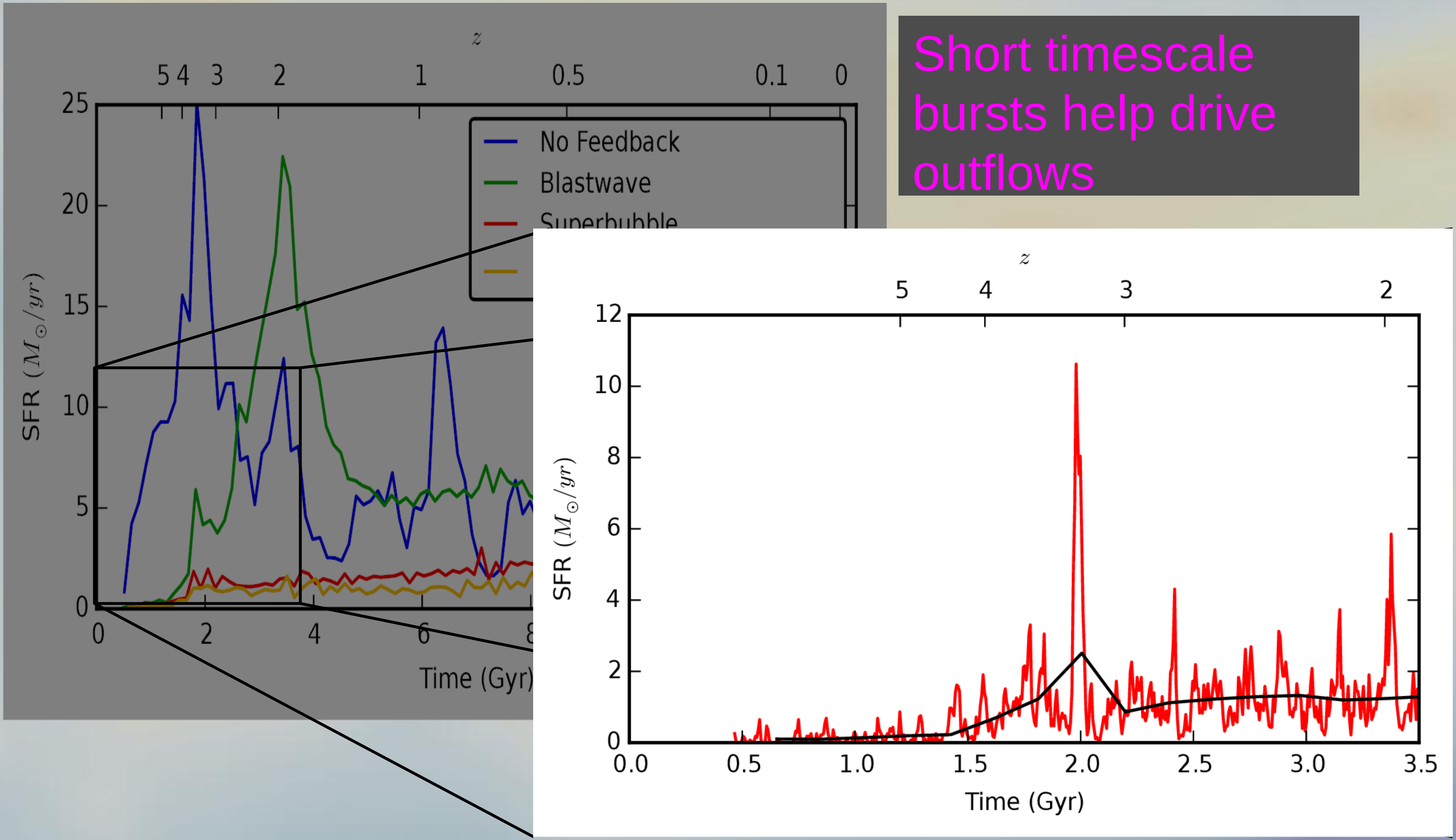
2. Disk ISM cools, forming stars

3. SNII heats gas to form superbubbles

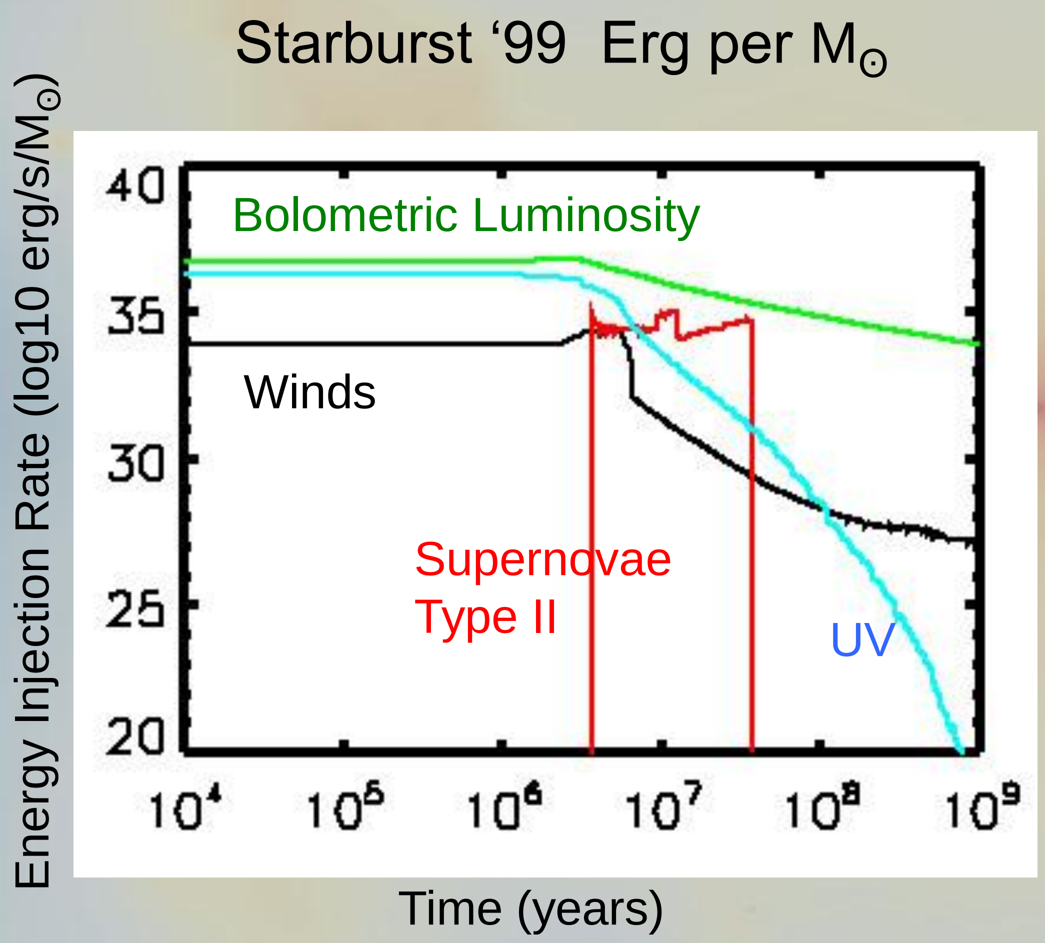
4. Superbubbles rise buoyantly out of disk, cooling adiabatically & mixing with pristine gas

# Bursty Star formation

Short timescale bursts help drive outflows



# Stellar Feedback Budget




- UV & Radiation pressure disrupt dense clouds
  - Denser gas ($>10^4$ H/cc) dispersed, star formation cut off
- $SN_{II}$ and stellar winds

  Steady $10^{34}$ erg/s/$M_\odot$

  for ~ 40 Myr