The Role of Gas in the Formation of Disk Galaxies

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Caltech

In collaboration with the University of Washington's N-body Shop™

makers of quality galaxies

Motivating Questions

1) What drives star formation as a function of mass, and the resulting star formation density of the Universe?

2) What role does feedback (supernovae, AGN) have in galaxy formation as a function of mass?

3) How does baryonic physics affect the dark matter distribution as a function of mass?

Image by C. Brook, using Sunrise, courtesy P. Jonsson.

Pre-Conclusions (aka Mythbusting)

1) Cosmological simulations CAN make realistic galaxy disks (due to feedback and resolution; yes, we can!)

(Only some of these galaxies are simulated. Can you tell which?)

2) The existence of bulgeless disk galaxies and dark matter cores is NOT at odds with CDM

3) Galaxies do NOT grow primarily through mergers (but rather predominantly through smooth accretion)

4) Mergers do NOT necessarily destroy disks (and merging two disk galaxies does NOT necessarily form an elliptical)

Image by C. Brook, using Sunrise, courtesy P. Jonsson.

Outline

I. Simulating Realistic Disk Galaxies

The Role of Resolution and Feedback

II. The Effect of Resolution on Feedback

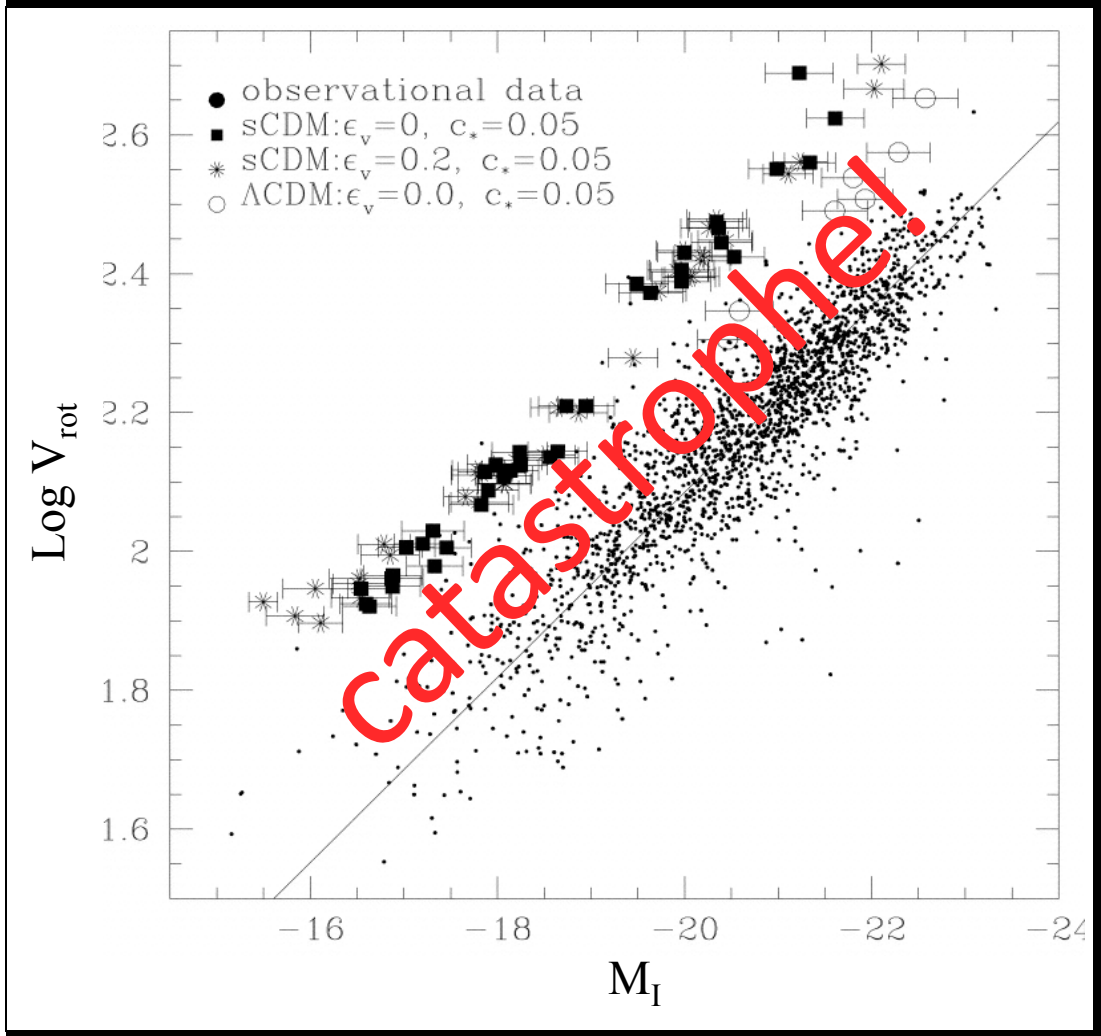
Gas Loss: The Formation of Bulgeless Disk Galaxies

III. Gas Accretion

Cold Flows and the Growth of Stellar Disks

III. The Future of Galaxy Simulations

The CDM Angular Momentum Problem



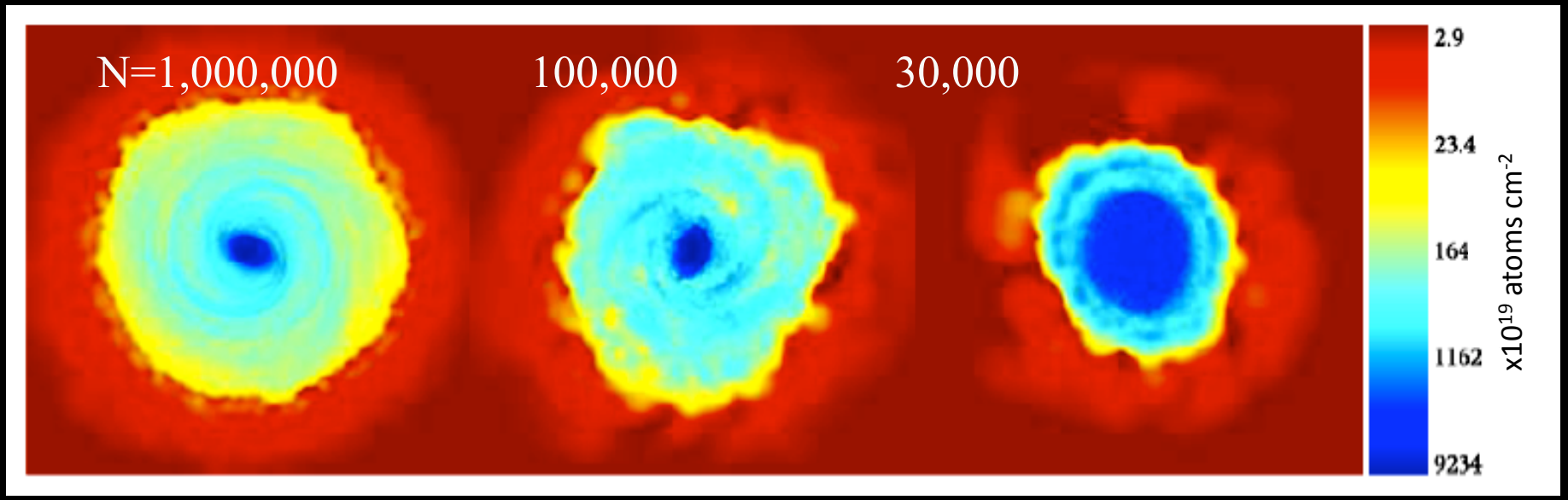
Disks rotate too fast at a given luminosity

Mass (dark and luminous) is too concentrated

Disks are too small at a given rotation speed

Navarro & Steinmetz (2000)

What is the role of *resolution* in forming realistic disk galaxies?



20 kpc 20 kpc 20 kpc

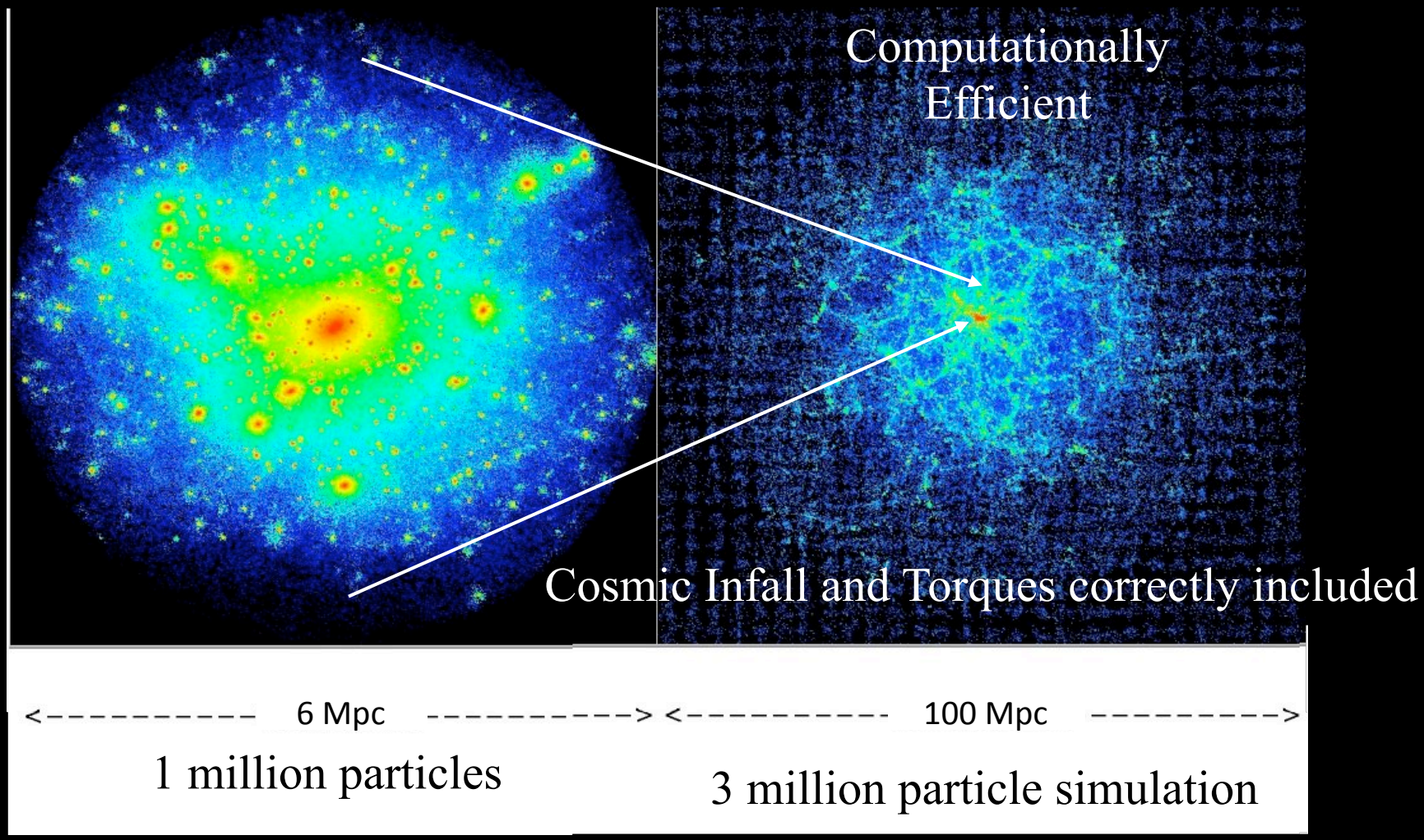
- Isolated (non-cosmological) galaxy simulation
- MW mass halo after 5 Gyr

Low resolution: disks heat and lose angular momentum to halo

Kaufmann et al. (2007)

“Zoom in” technique:

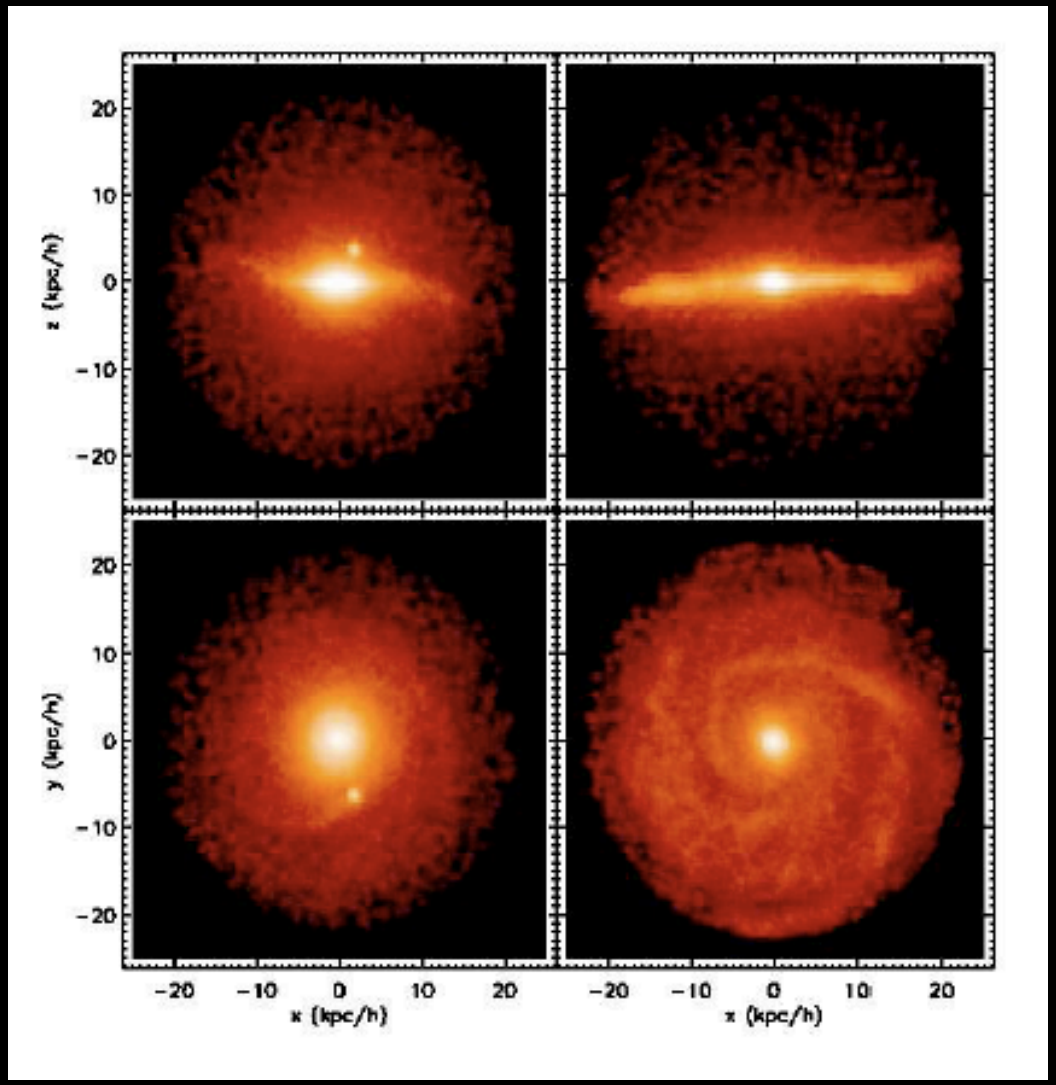
high resolution halo surrounded by low resolution region



Katz & White (1993)

What is the role of *feedback* in forming realistic disk galaxies?

No feedback

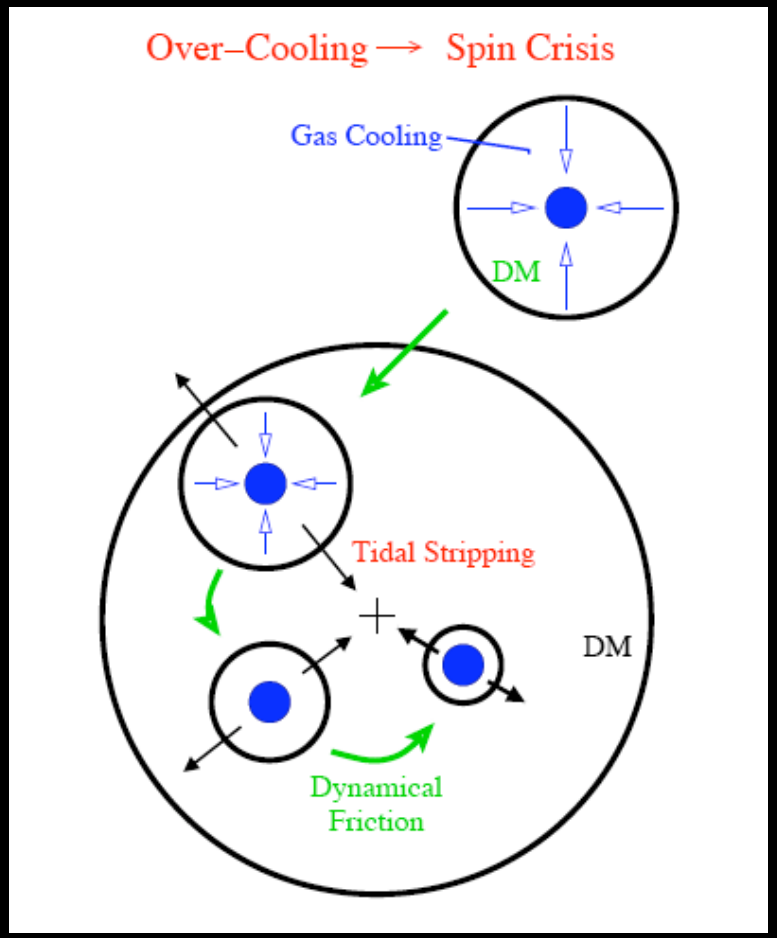


feedback

Zavala et al. (2008)
Scannapieco et al. (2008)

What is the role of *feedback* in forming realistic disk galaxies?

"Over-cooling" leads to loss of angular momentum similar to low resolution



Maller & Dekel (2002)

Gasoline

- PKDGRAV: Parallel N-body Tree Code
- Gasoline: PKDGRAV+gas using smoothed particle hydrodynamics (SPH)
- Physics: Gravity, Hydrodynamics, Shocks, Radiative Heating +Cooling, UV field
- Sub-grid Physics: Star Formation, Supernova Feedback, Stellar Winds, Metal Enrichment

Stadel (2001)
Wadsley *et al.* (2004)

Sub-grid physics & Blastwave Feedback Model

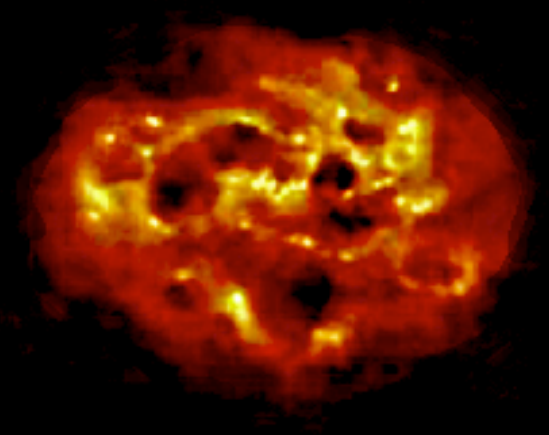
- Star Formation: reproduces the Kennicutt-Schmidt Law; each star particle a SSP with Kroupa IMF

- Energy from SNII deposited into the ISM as thermal energy based on McKee & Ostriker (1977)

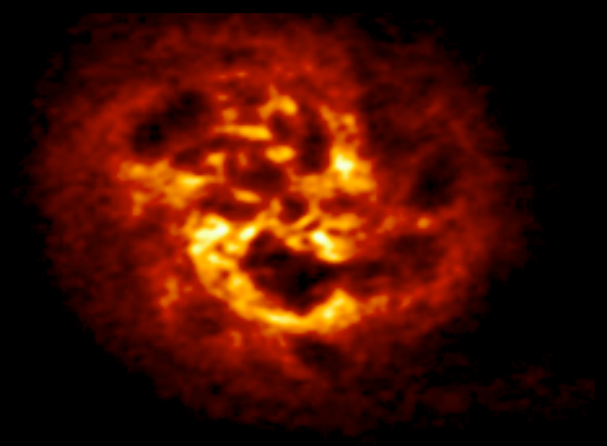
- Radiative cooling disabled to describe adiabatic expansion phase of SNe (Sedov-Taylor phase); ~20Myr (blastwave model)

- Only Free Parameters: SN & Star Formation efficiencies

HI Map



Simulated Dwarf Galaxy



Holmberg II

Stinson *et al*. (2006), Governato *et al*. (2007)

The Formation of a Bulgeless Dwarf Galaxy

$M_{vir} = 2x10^{10}\ M_{\odot}$
$M_{*} = 1.2x10^{8}\ M_{\odot}$

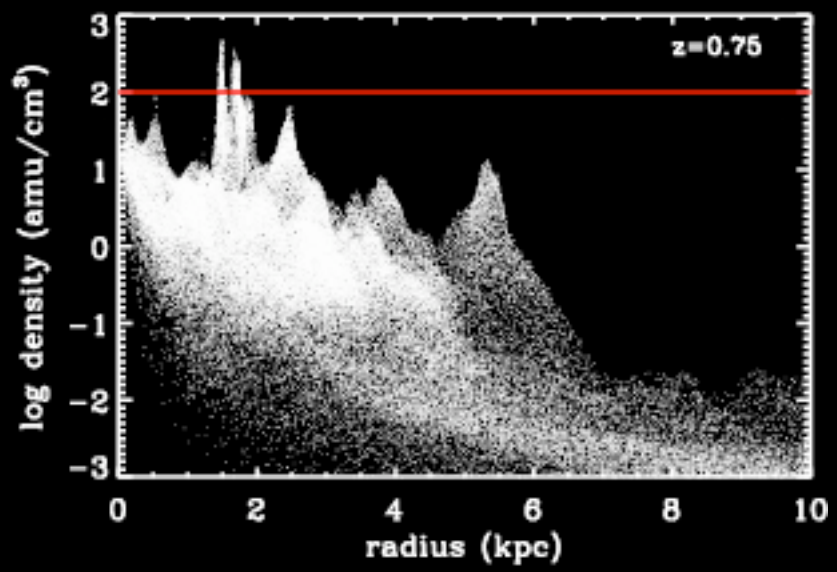
15 kpc on a side

Green = gas

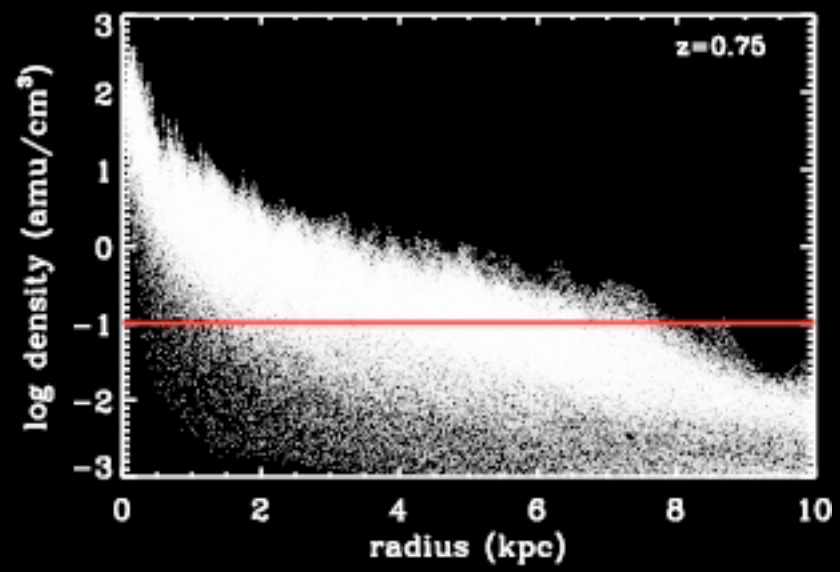
Blue/Red = age/metallicity weighted stars

What is the effect of
resolution on *feedback*?

“Resolving” Star Formation Regions



High threshold



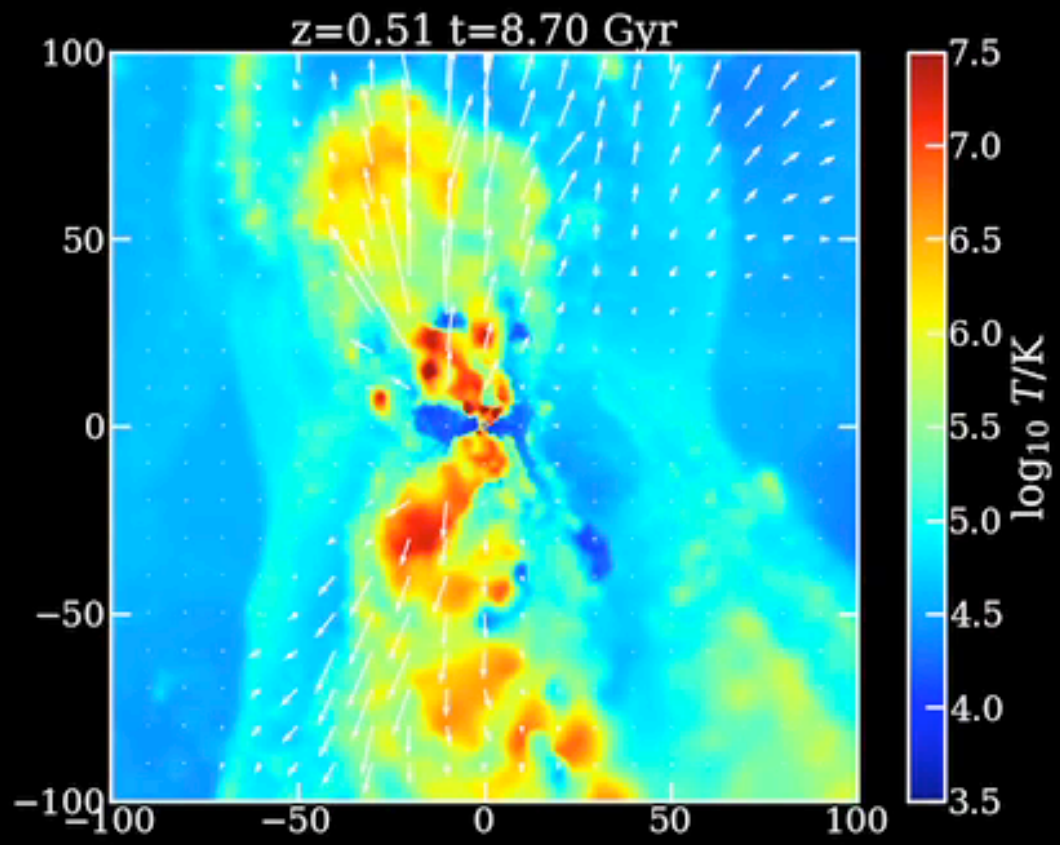
Low threshold

Feedback becomes more efficient

(more outflows per unit mass of stars formed)

See also: Ceverino & Klypin (2008)
Robertson & Kravtsov (2008)
Tasker & Bryan (2008)

Outflows!

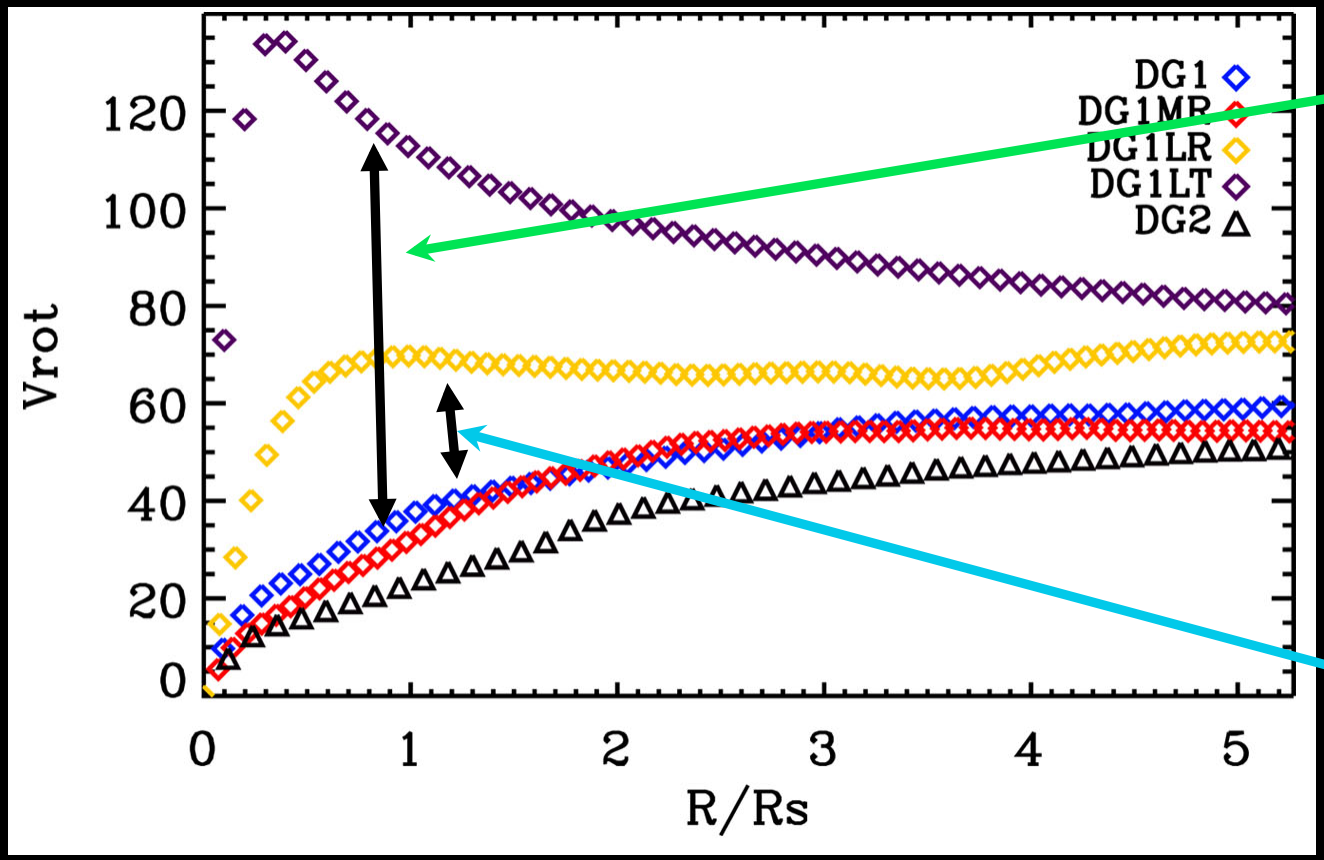


Edge on disk orientation

(arrows are velocity vectors)

Brook et al., arXiv:1010.1004

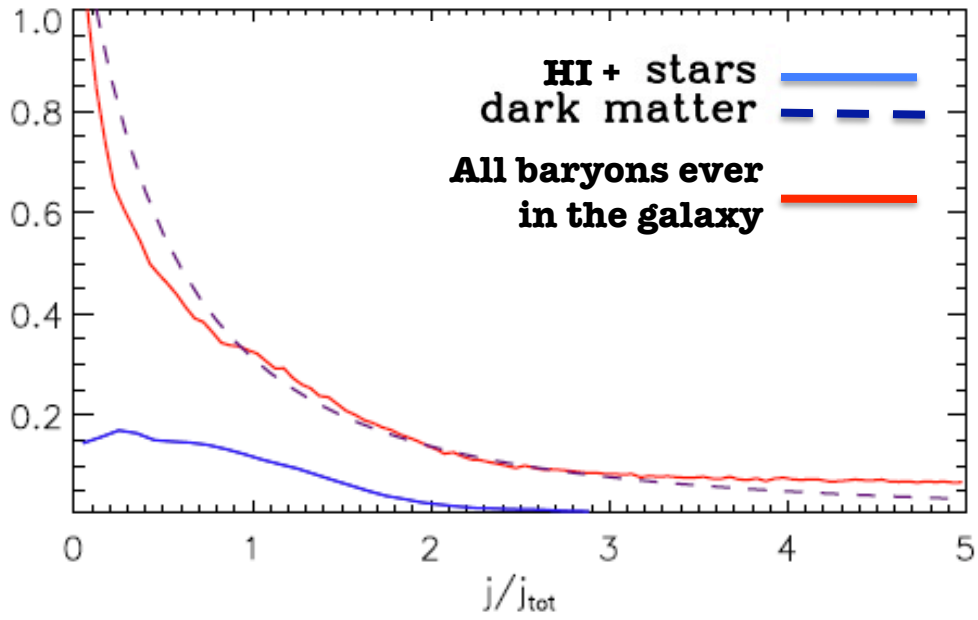
Resolving Star Forming Complexes



The effect of altering the SF density threshold

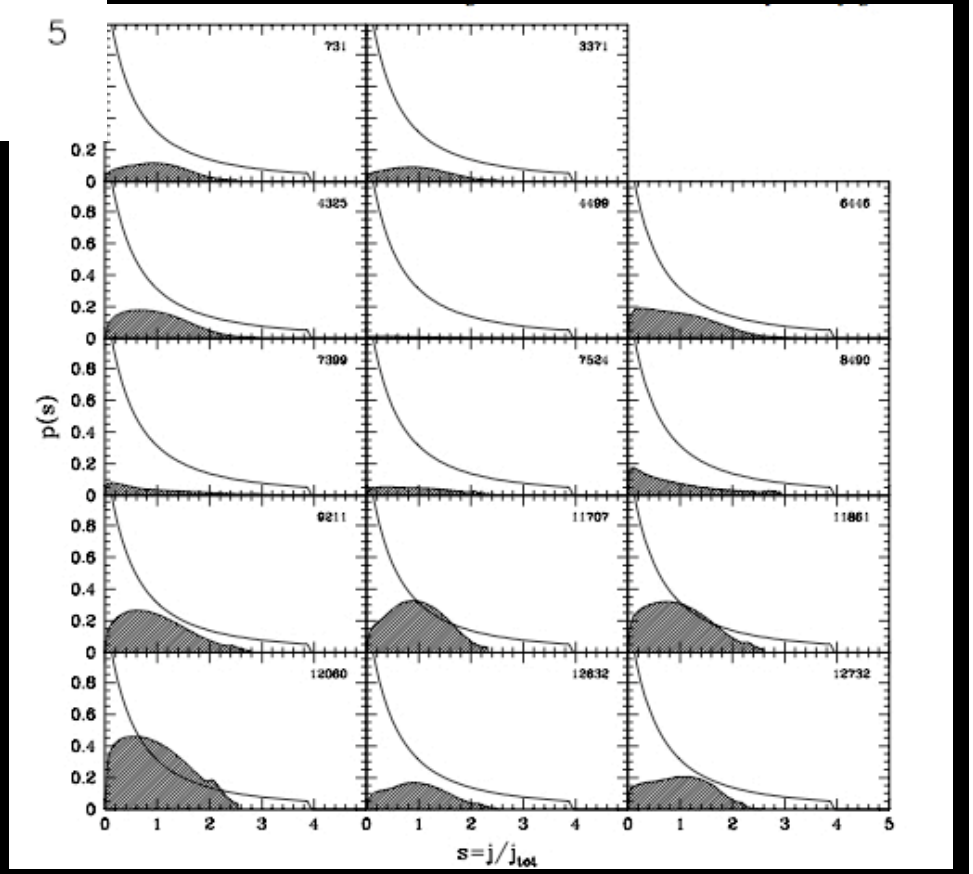
The effect of altering resolution

Governato et al., 2009, Nature, 463, 203
arXiv:0911.2237



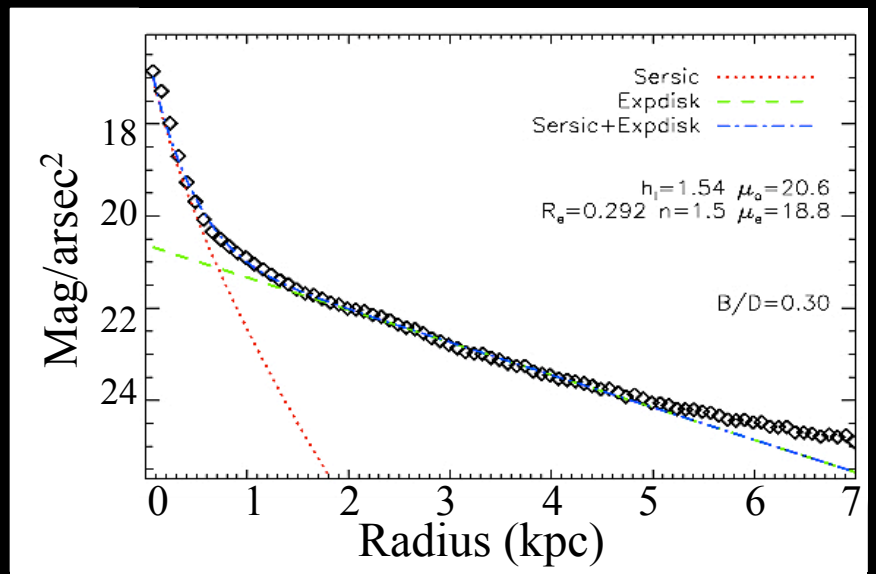
Brook et al., arXiv:1010.1004

van den Bosch et al. (2001)

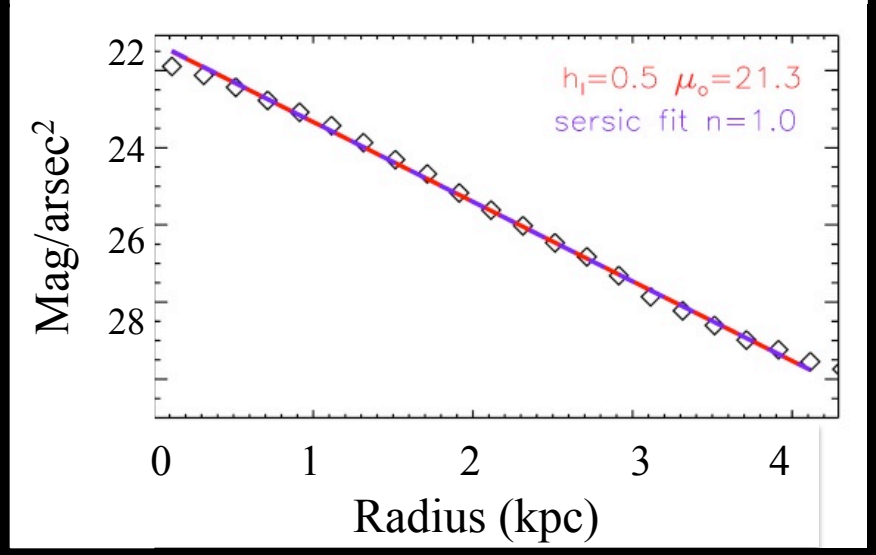


The Angular Momentum Distribution of baryons must be altered to match observed galaxies

"Observed" Surface Brightness Profile



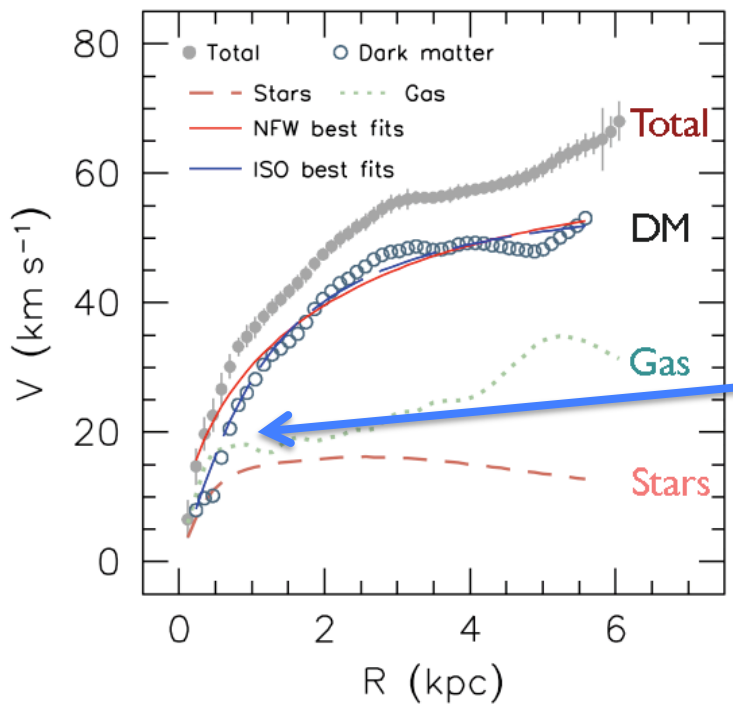
Diffuse Star Formation



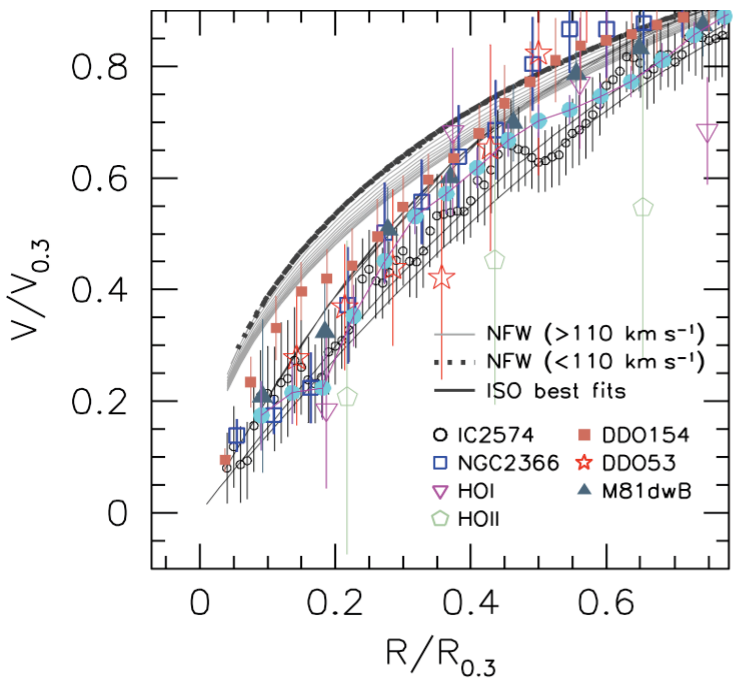
"Resolved" Star Formation

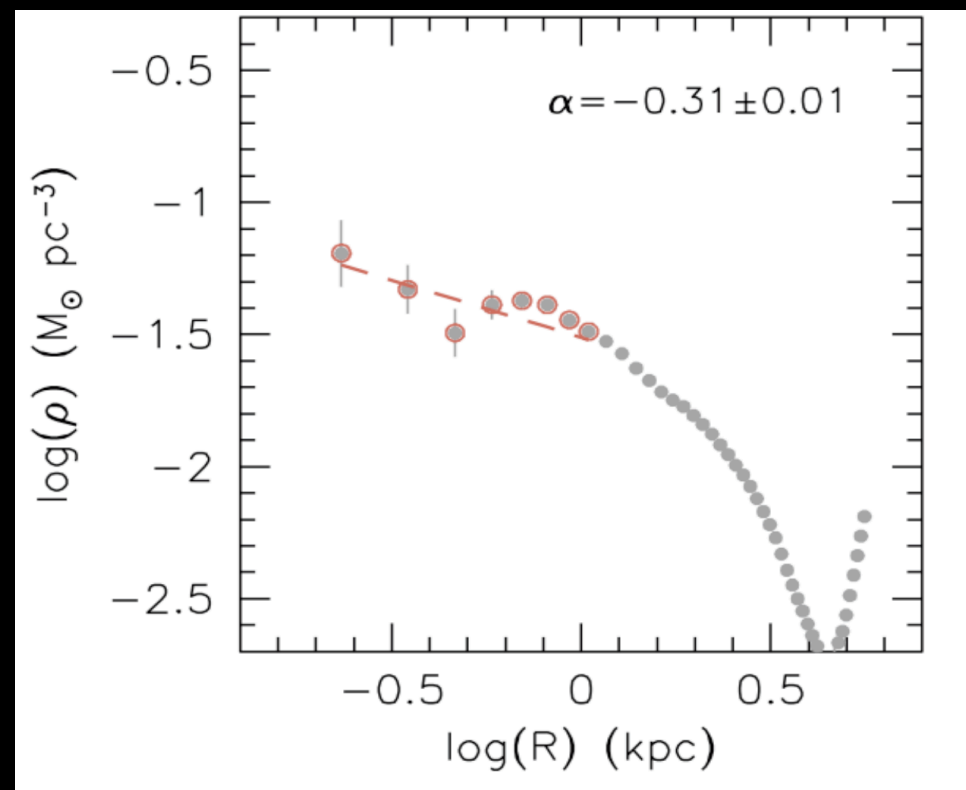
Governato et al., 2009, Nature, 463, 203, arXiv:0911.2237

Comparison to THINGS: the HI Nearby Galaxy Survey



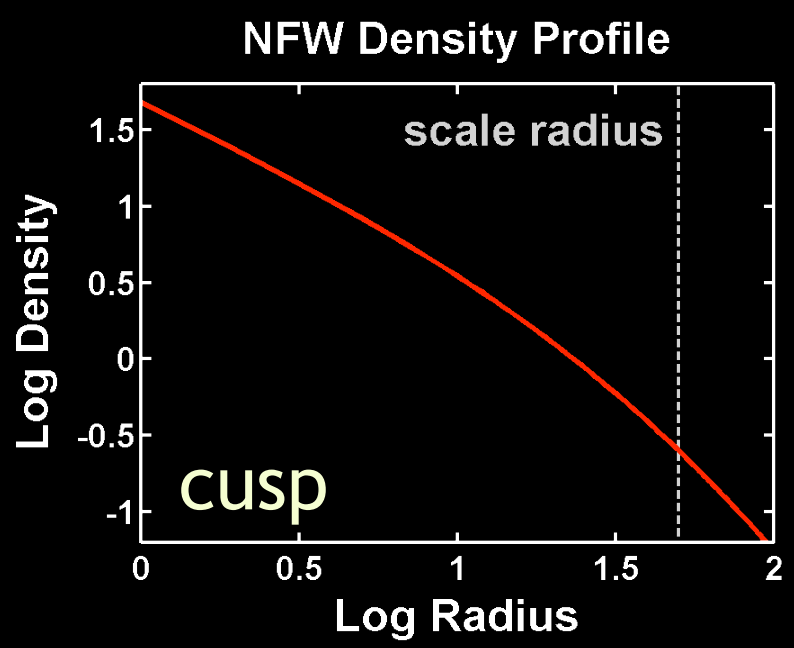
Rotation curve rises too slowly to match cuspy NFW profile

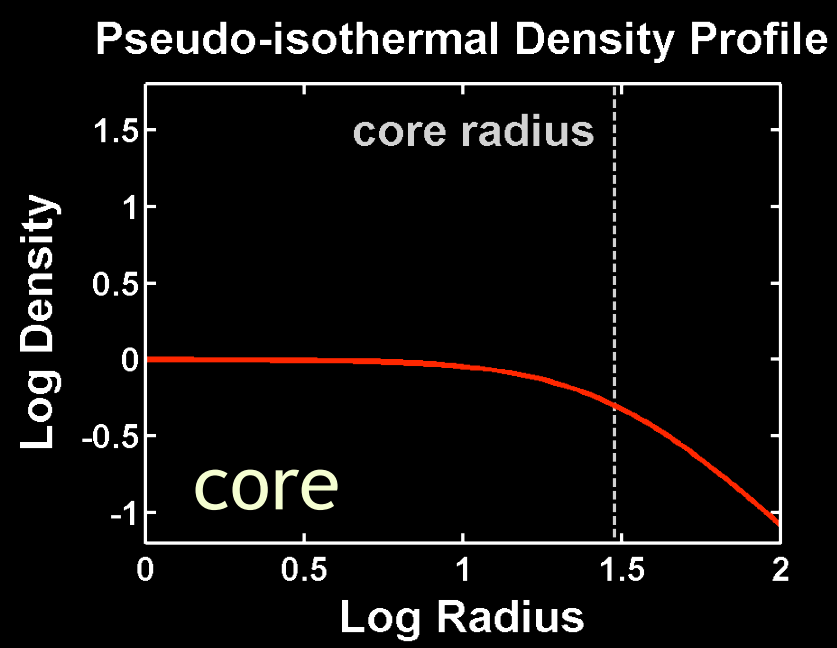




Walter et al. (2008); Oh et al., arXiv:1011.2777

The Cusp/Core Problem

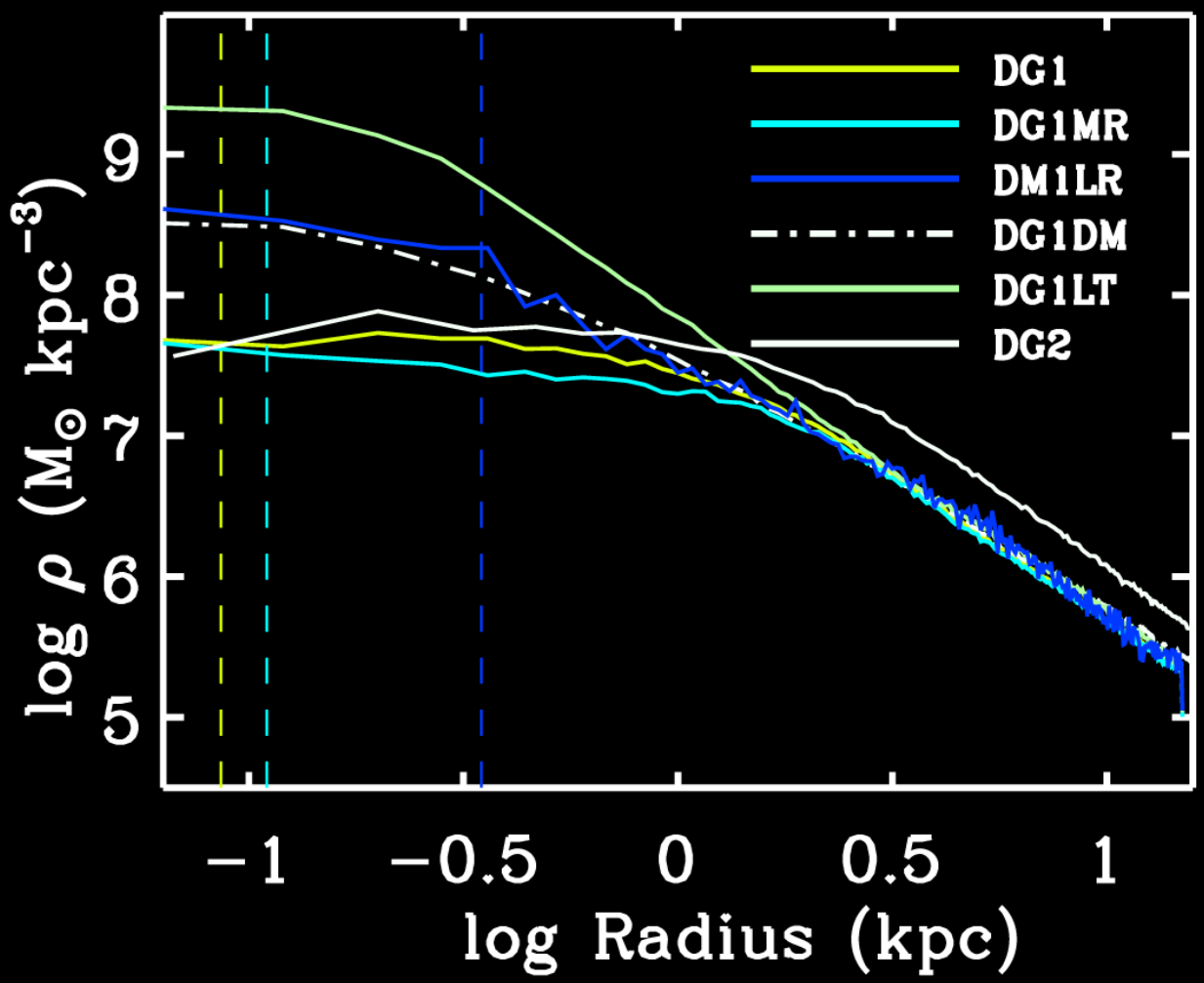




- Parameterize density profile as $\rho(r) \propto r^{-\alpha}$
  - Observations show $\alpha \sim 0$ (constant-density core)
  - Simulations predict $\alpha \sim 1$ (central cusp)

de Blok et al. (2008)
Simon et al. (2005)
Diemand et al. (2004)
Swaters et al. (2003)

Dark Matter with a Central Core



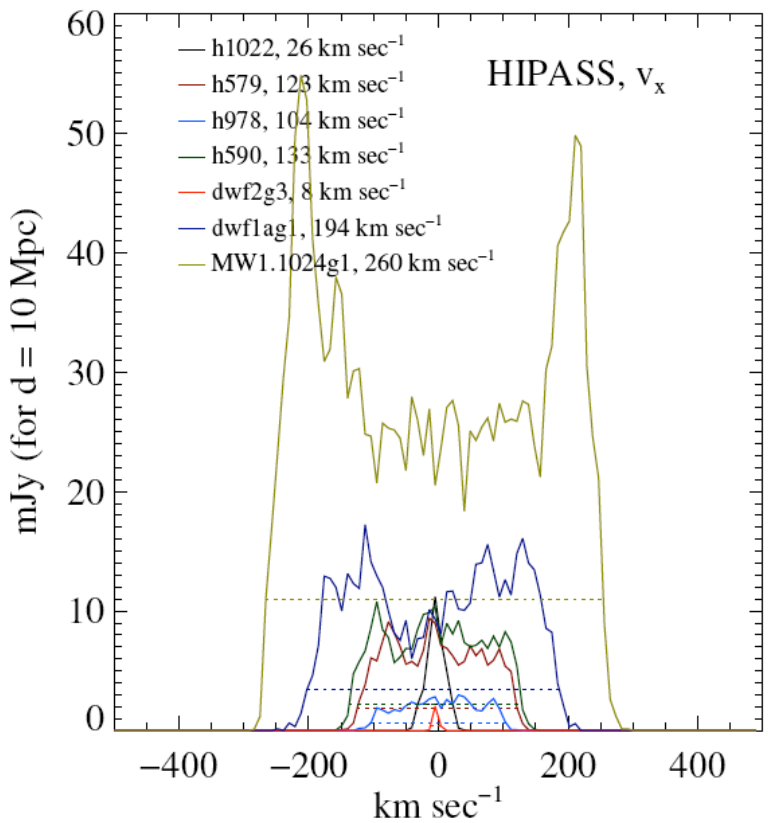
Clumpy Gas transfers energy to DM

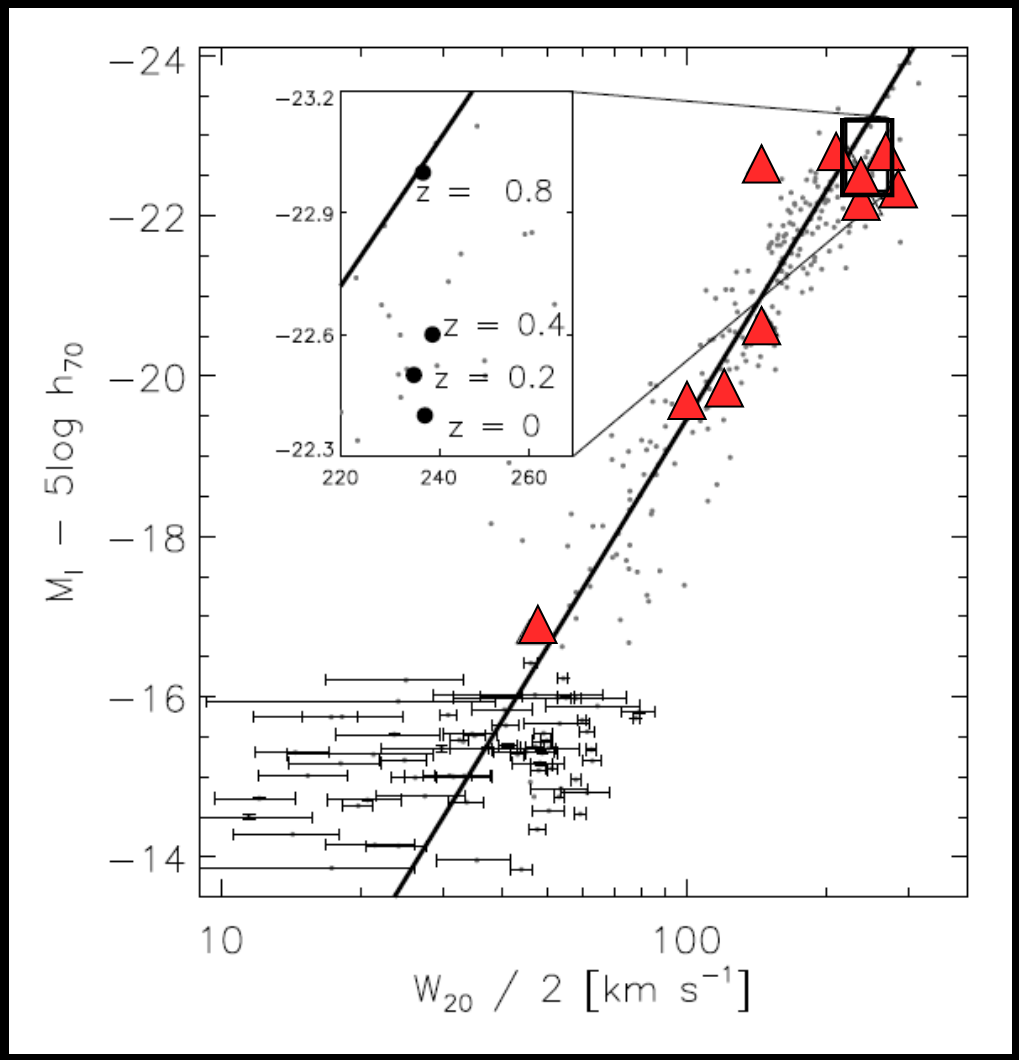
DM expands as gas is rapidly removed

e.g., Mashchenko et al. (2007, 2008); El-Zant et al. (2004); Navarro et al. (1996); Mo & Mao (2004); Tonini et al. (2006)

baryonic
Tully-Fisher relation

(magnitudes from Sunrise)

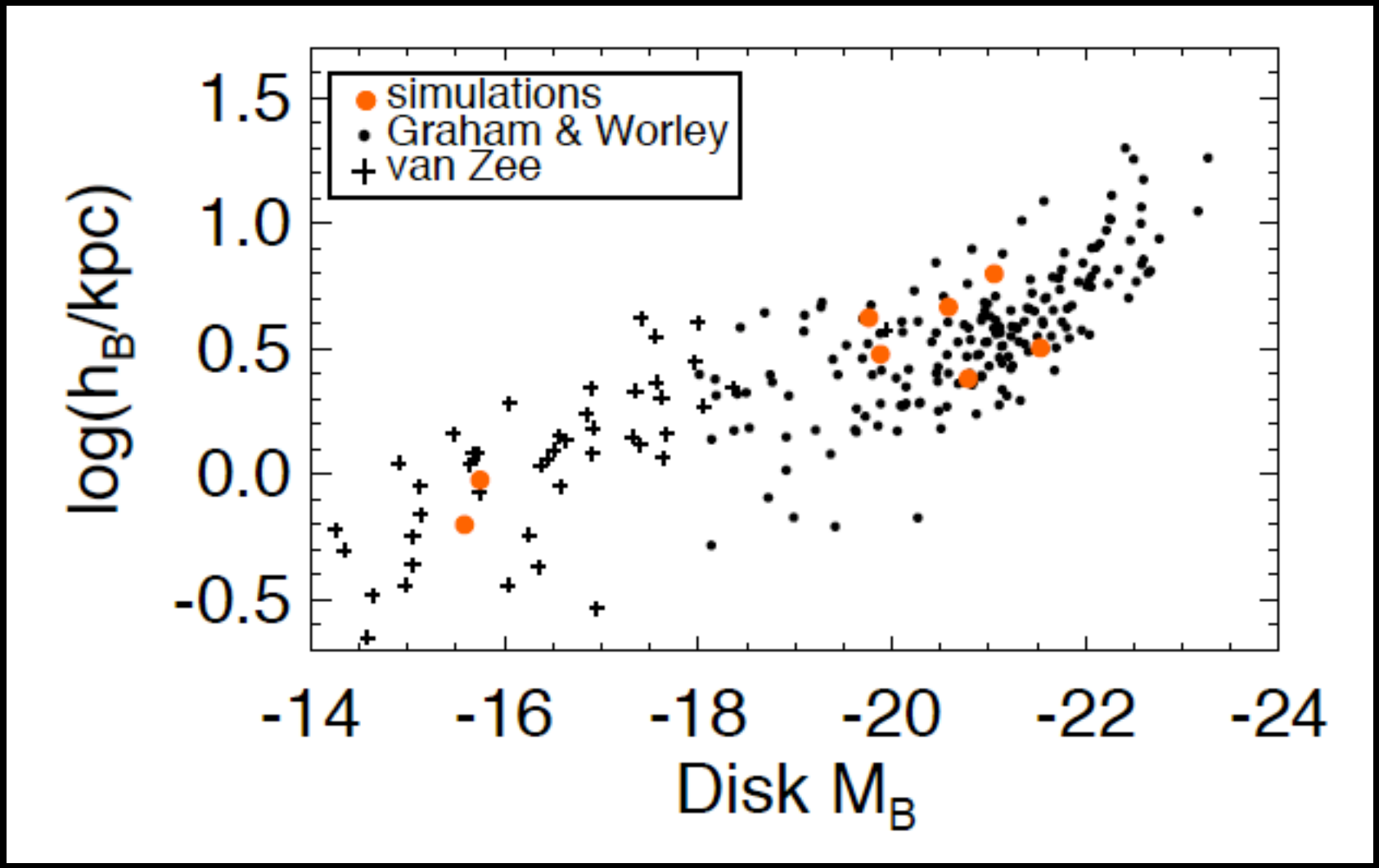




HI W20/2
velocity widths = V_{max}

Geha et al. (2006)
Governato et al. (2008, 2009)

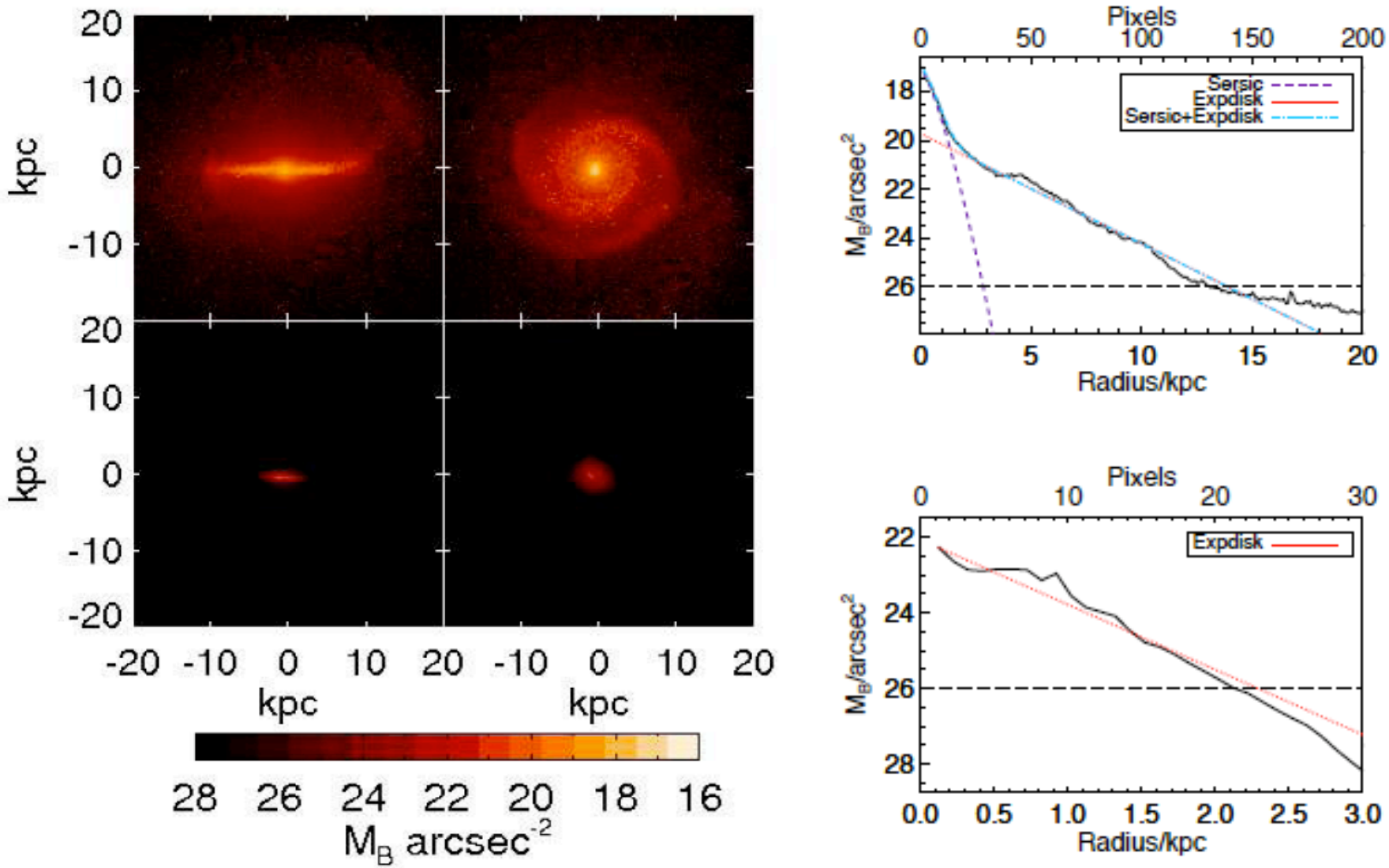
Size - Luminosity Relation



Brooks et al., submitted

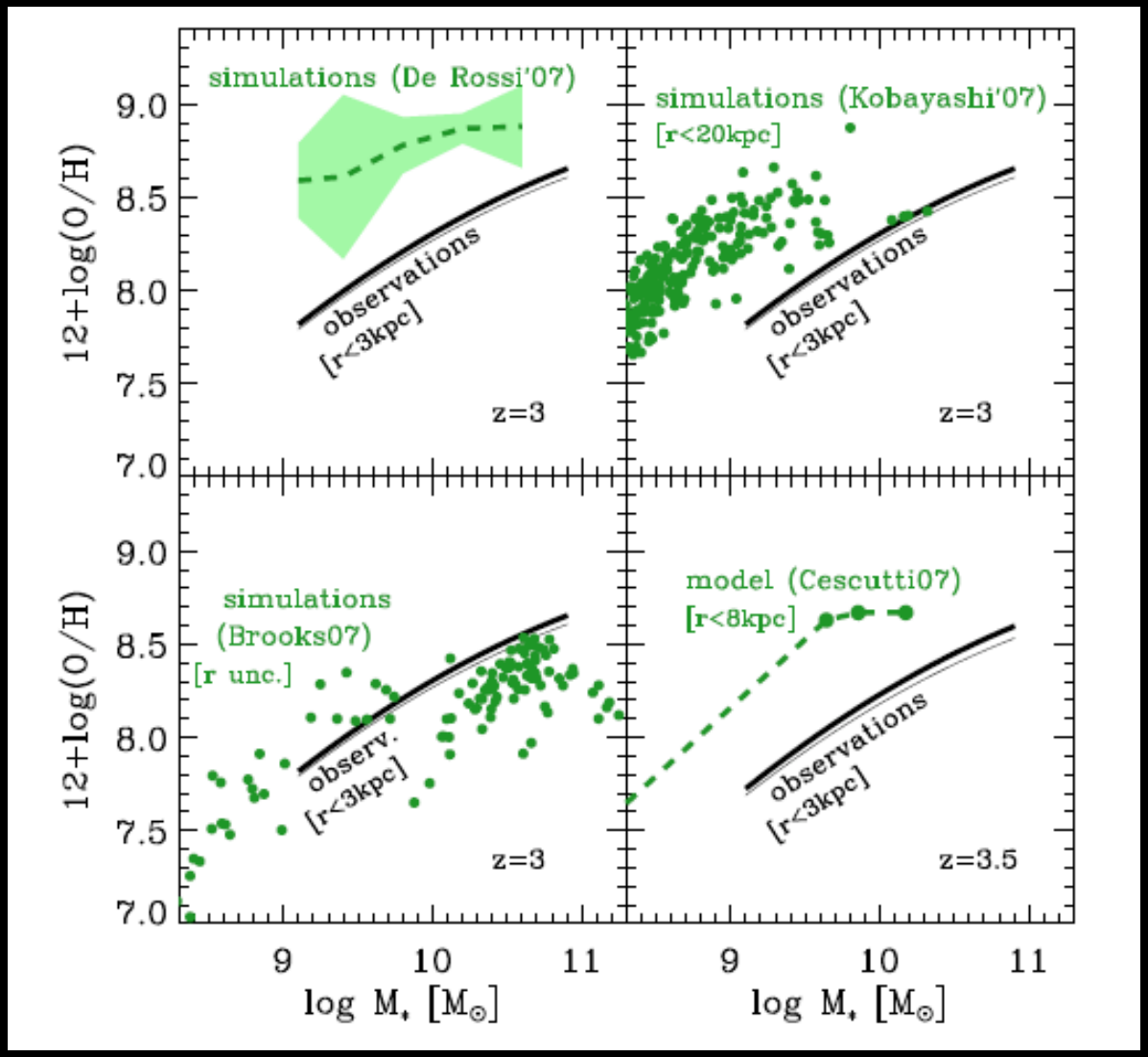
Data from Graham & Worley, 2008; van Zee 2000

Measure sizes as Observers do!



Jonsson (2006), Jonsson et al. (2010)

The Mass-Metallicity Relationship for Galaxies



Brooks et al. (2007)
Maiolino et al. (2008)

Outline

I. Simulating Realistic Disk Galaxies

The Role of Resolution and Feedback

II. The Effect of Resolution on Feedback

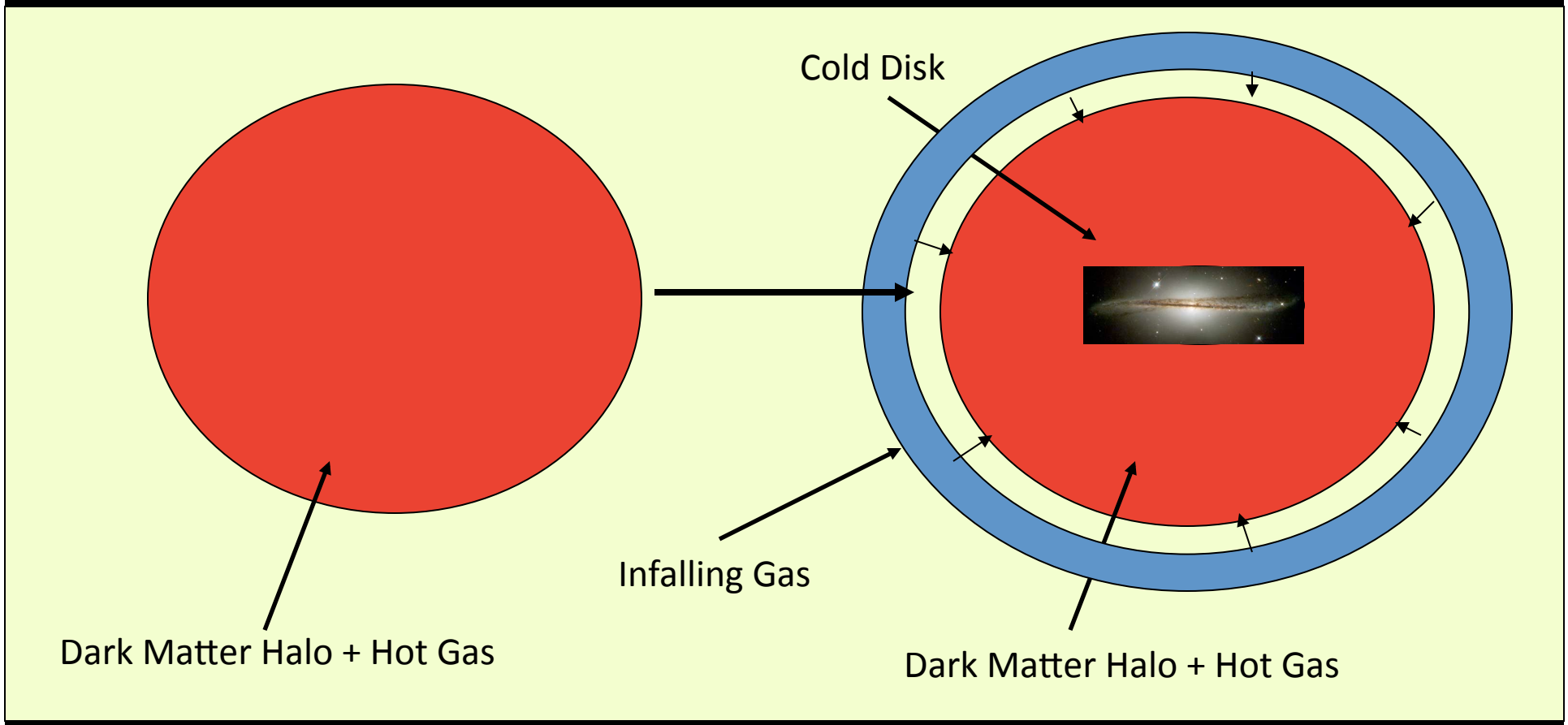
Gas Loss: The Formation of Bulgeless Disk Galaxies

III. Gas Accretion

Cold Flows and the Growth of Stellar Disks

III. The Future of Galaxy Simulations

How Do Galaxies Get Their Gas?

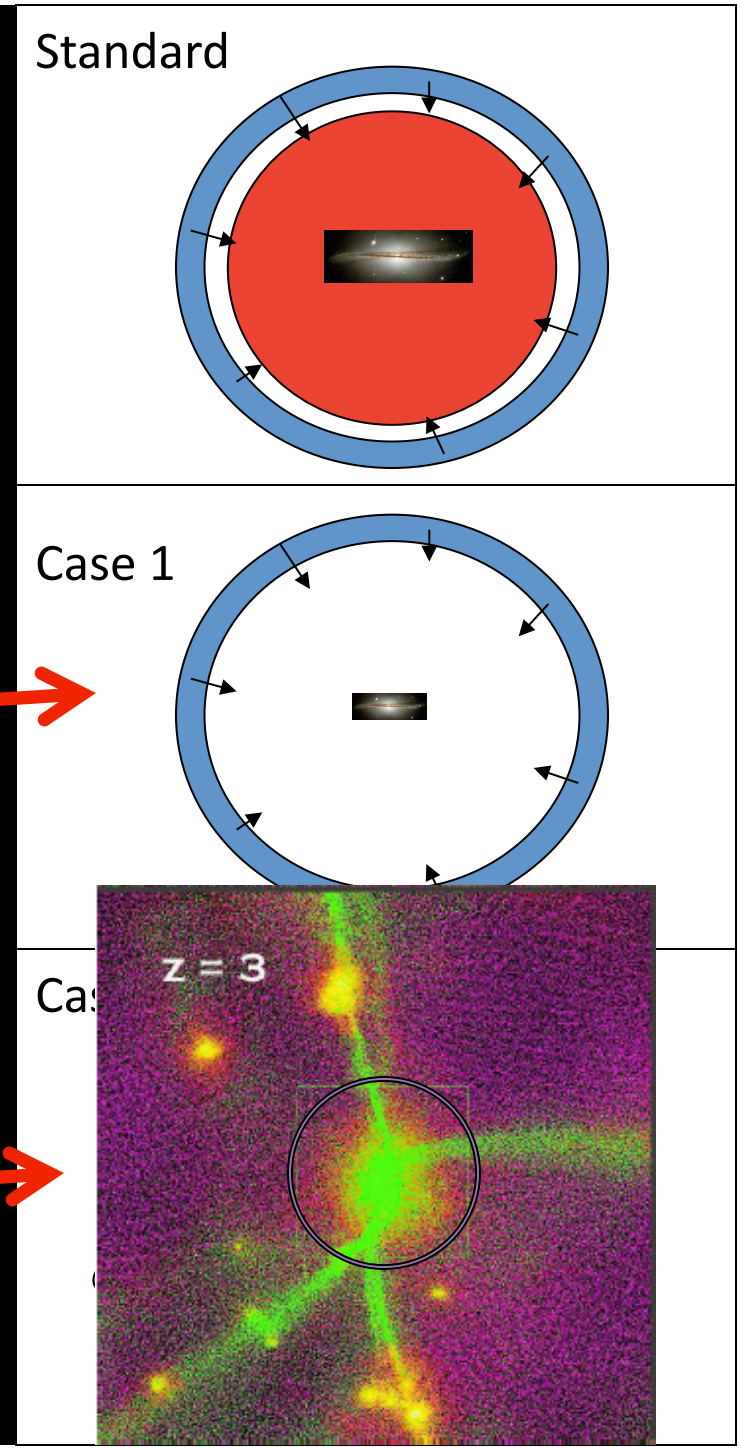


e.g., Peebles (1969), Rees & Ostriker (1977), Silk (1977), Binney (1977), White & Rees (1978), Fall & Efstathiou (1980), Somerville & Primack (1999)

- Not all gas is shock heated!
- Fraction of shocked gas is a strong function of galaxy mass
- Cold flow gas acc
  1. Mass thresh
  2. Even after shock develops, there can be cold gas accretion at high z in dense filaments

This is already in the SAMs.

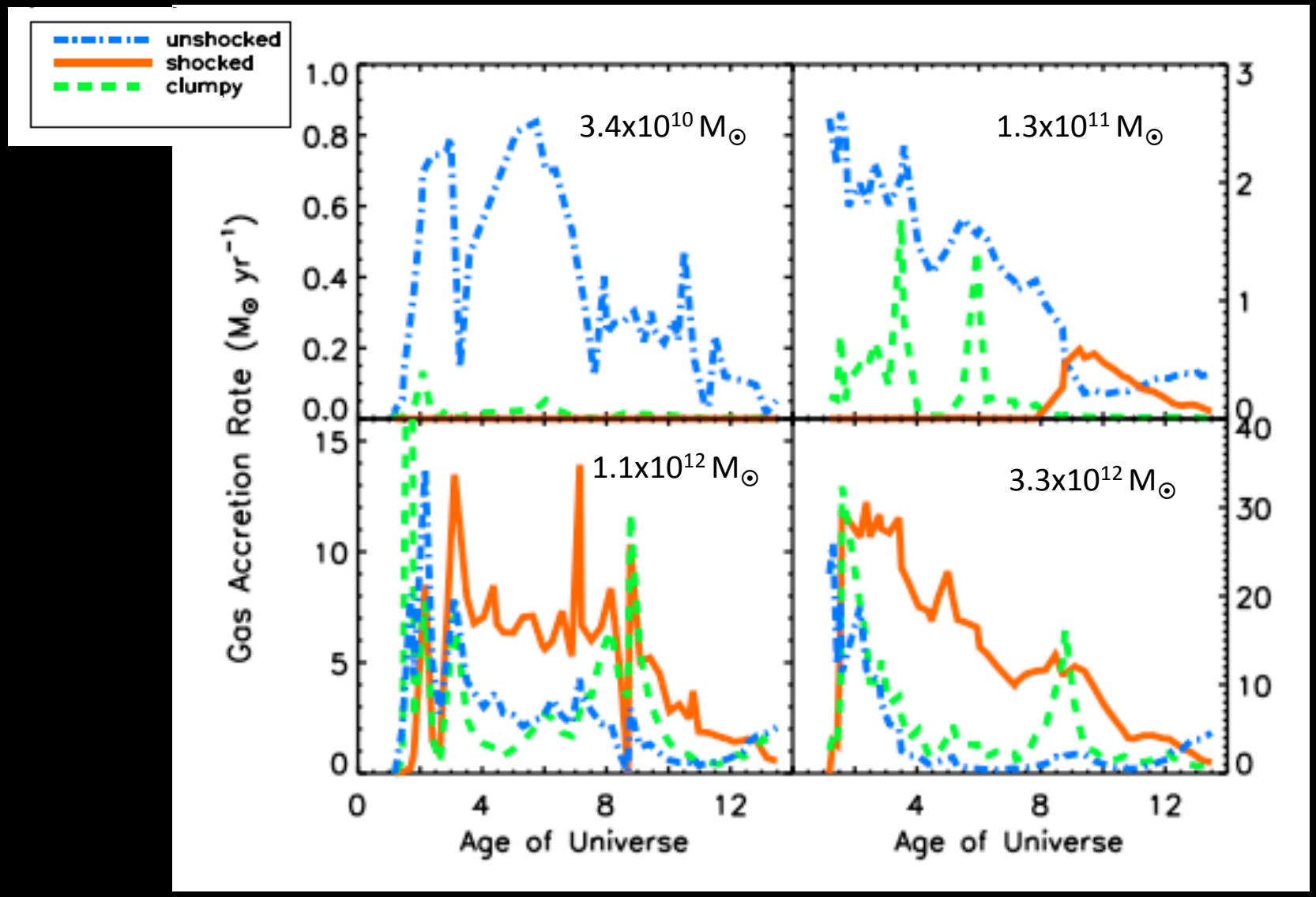
This is not.



Keres et al. (2005), Dekel & Birnboim (2006), Ocvirk et al. (2008), Agertz et al. (2009), Dekel et al. (2009)

What is the effect of *cold flow* gas accretion on the growth of *galaxy disks*?

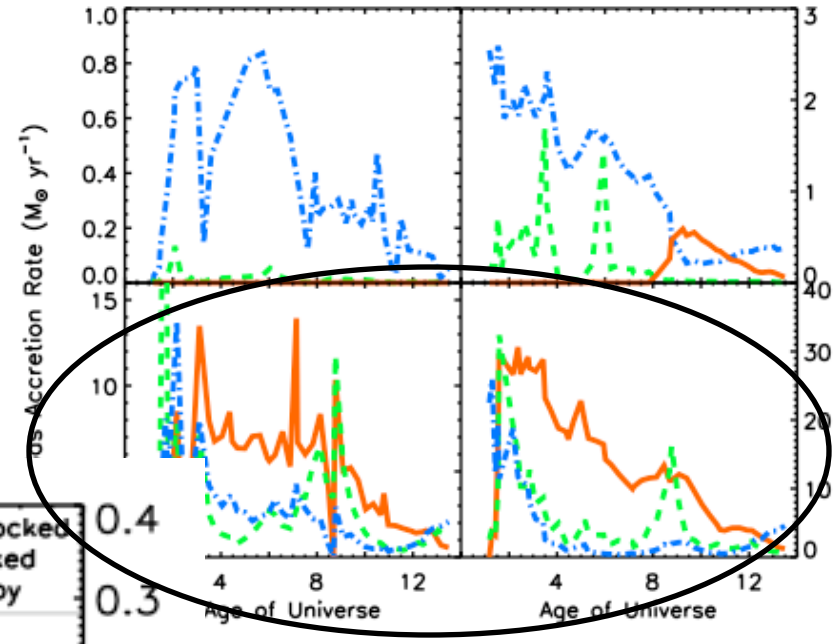
Gas Accretion Rates at the Virial Radius

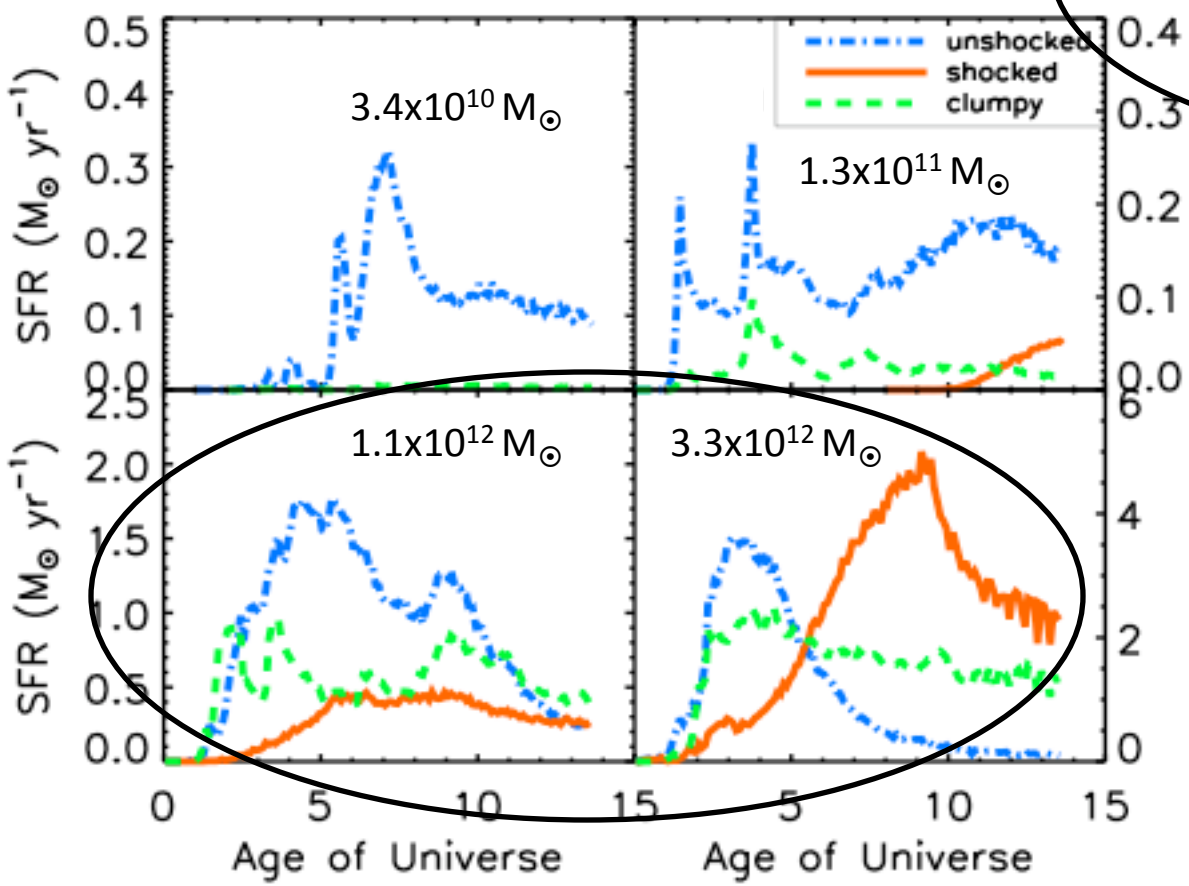


Brooks et al. (2009)

Gas Accretion Rates

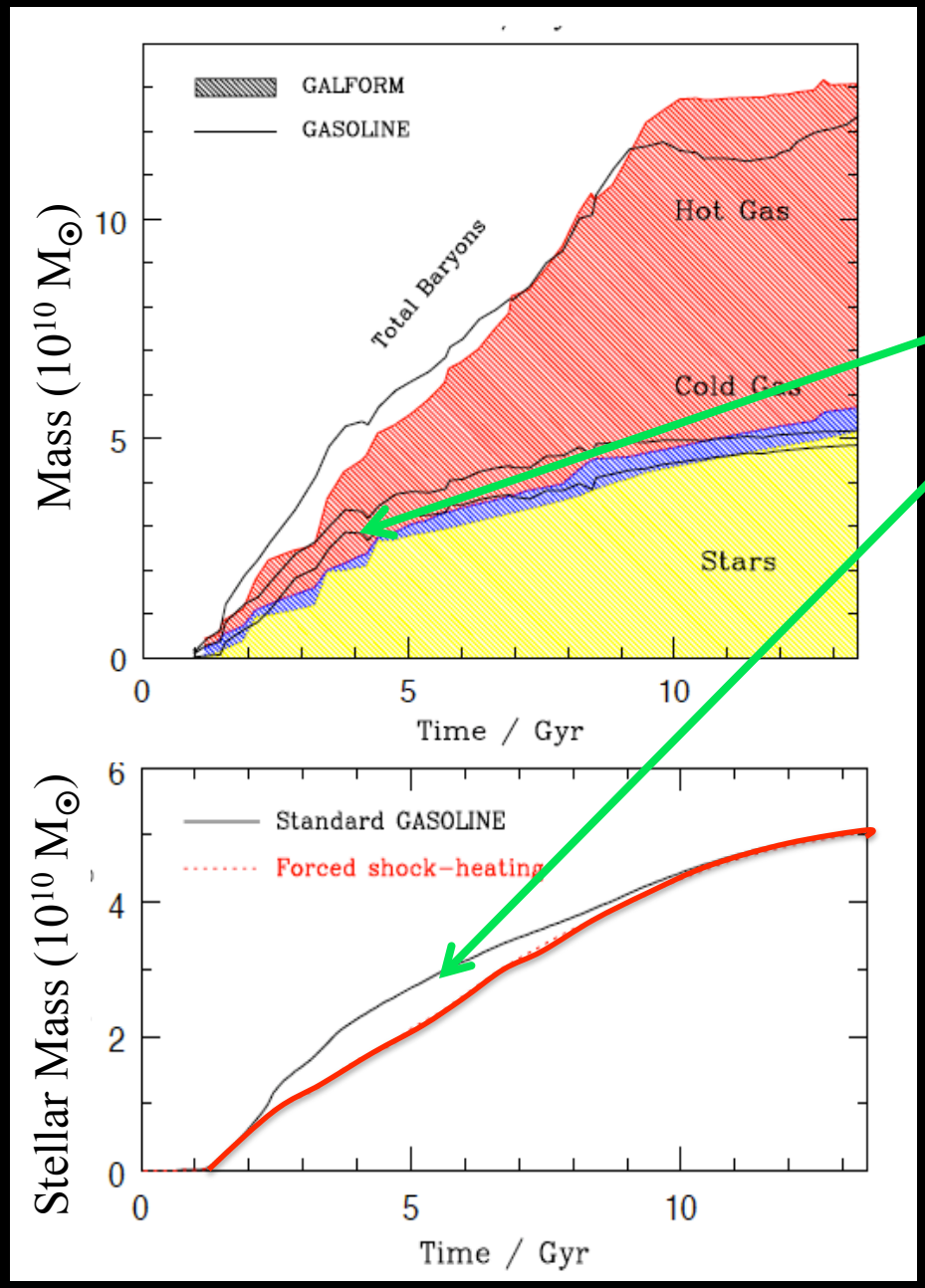
Disk Star Formation Rates





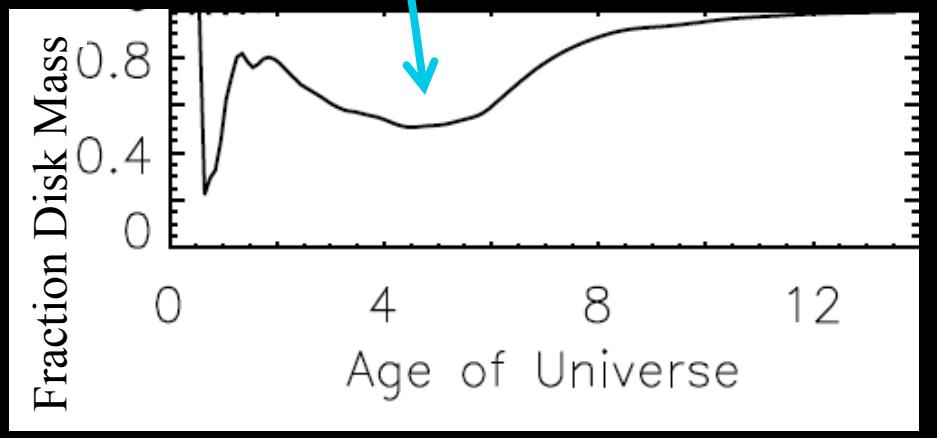
Brooks et al. (2009)

Direct Comparison to GALFORM semi-analytic model



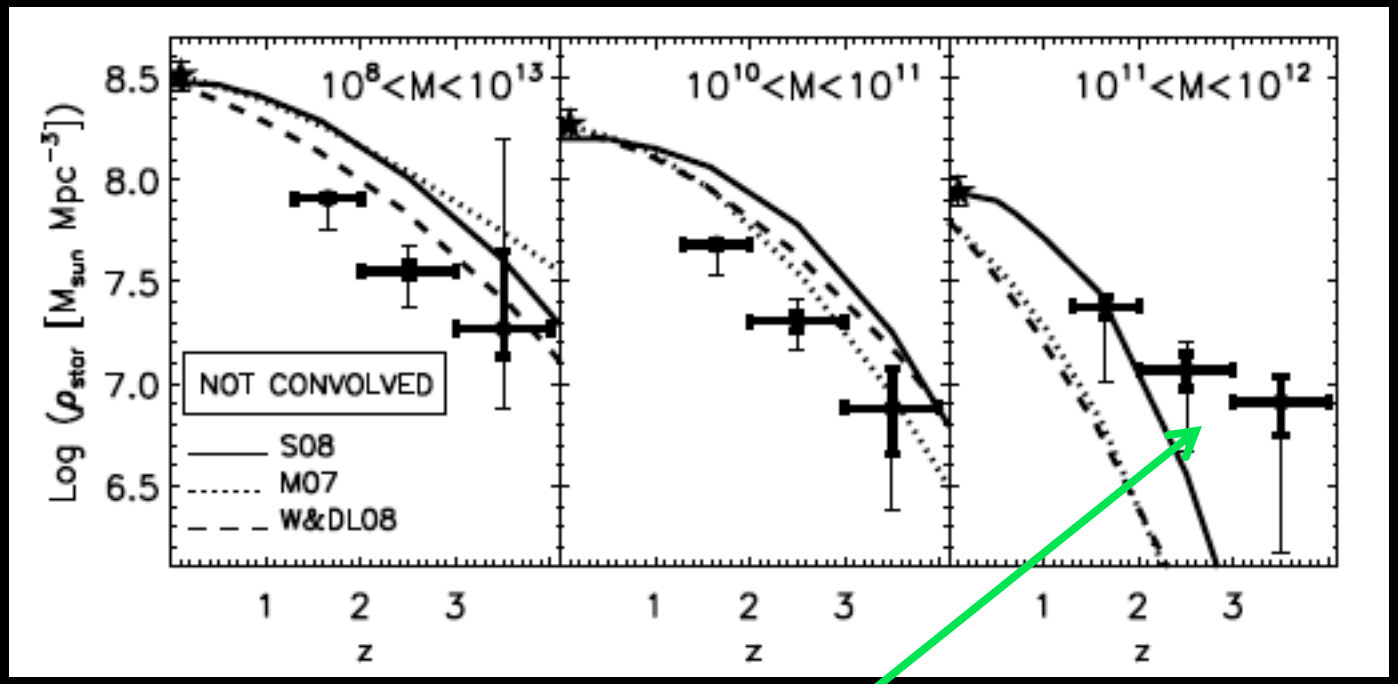
SAMs under-predict stellar mass at z > 1

50% less stars in the disk at z > 1 if gas is shock heated



Stringer, Brooks et al. (2010)

Cold Flows are Building the Stellar Component of Massive Galaxies at higher z than previously predicted



SAMs under-predict stellar mass at z > 3

Marchesini et al. (2009)

A case study:

The Formation of a Large Galaxy Disk in a Low z Major Merger

Mergers or Smooth Gas Accretion?

CDM → mergers

Mergers destroy or thicken

NO GAS

e.g., Toth & , Kazantzidis et al. 200 . 2008, Purcell et al. 2

Therefore, disk galaxies must grow rather quiescently

Mergers or Smooth Gas Accretion?

CDM → mergers

Mergers destroy or thicken

NO GAS

e.g., Toth & , Kazantzidis et al. 200 . 2008, Purcell et al. 2

Therefore, disk galaxies must grow rather quiescently

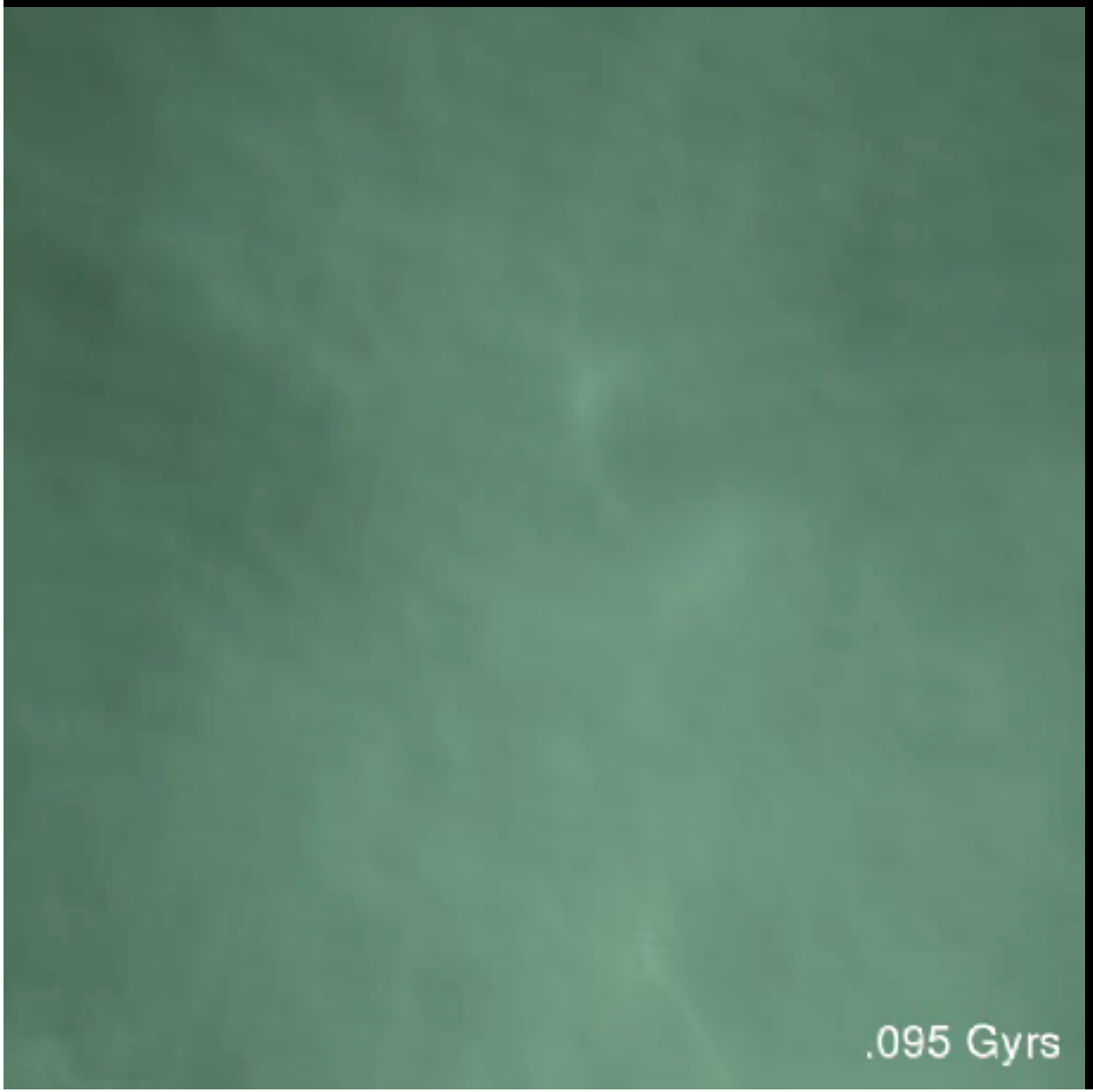
Or do they?

NO GAS ACCRETION

Baugh et al. 1996 Navarro 2002, Roberts Hopkins et al. 2008, R ock 2008

N are gas rich (f_{gas} > 50%)

The Formation of a Milky Way-Mass Galaxy to z=0

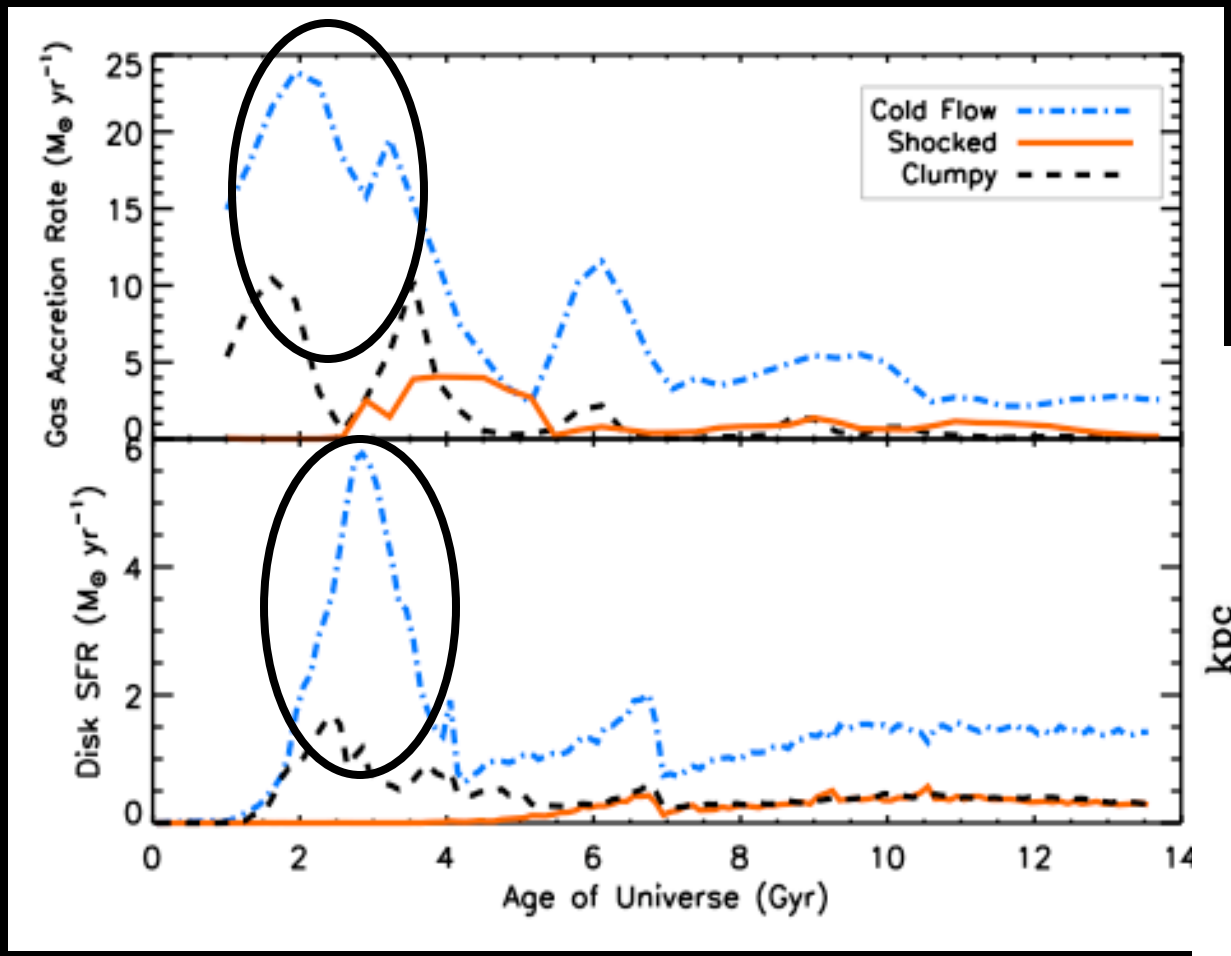


30 kpc on a side

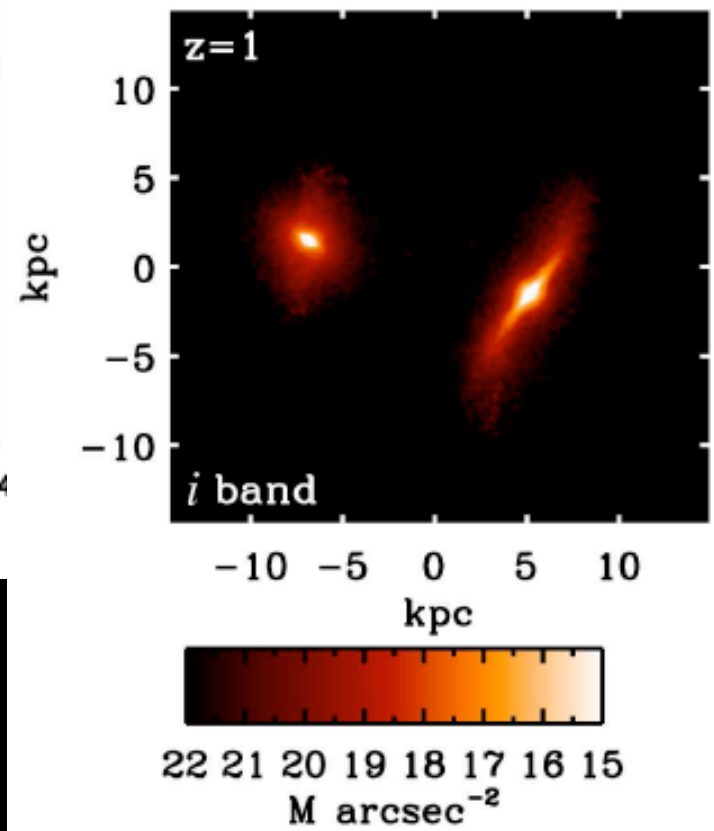
Green = gas

Blue/Red = age/metallicity weighted stars

The Role of Cold Flows

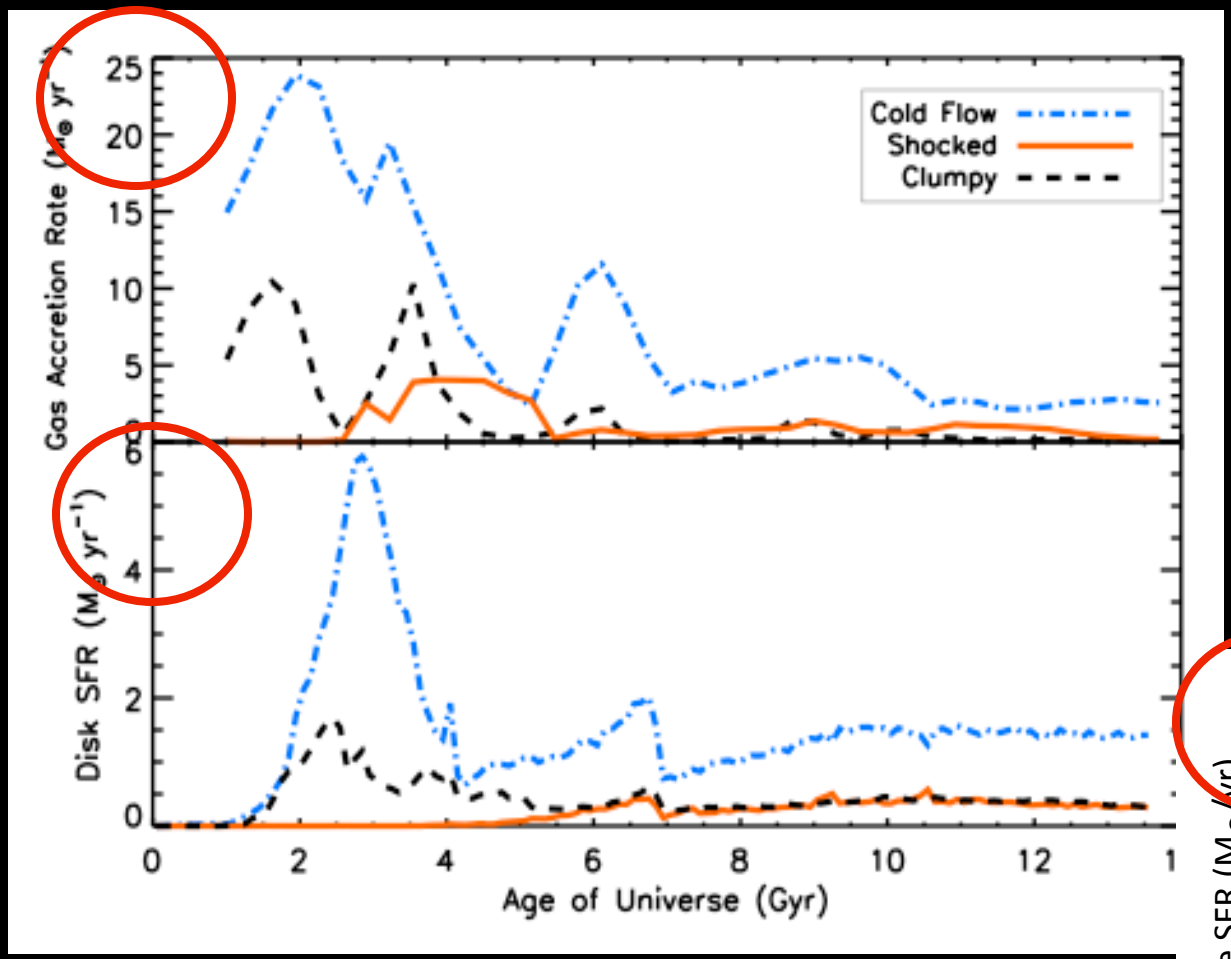


Disk growth prior to z=1 due to cold flows

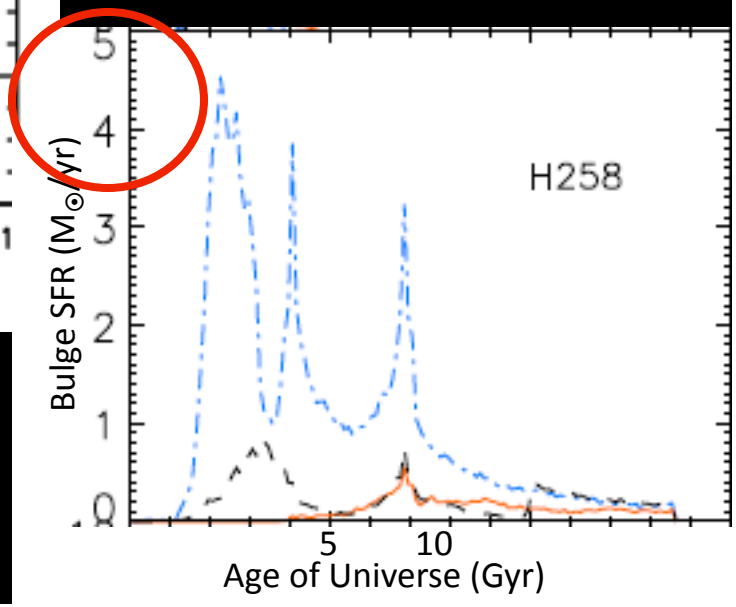


Brooks et al. (2009), Governato et al. (2009)
Keres et al. (2008), Ocvirk et al. (2008),
Agertz et al. (2009), Dekel et al. (2009),
Bournaud & Elmegreen (2009)

The Role of Feedback

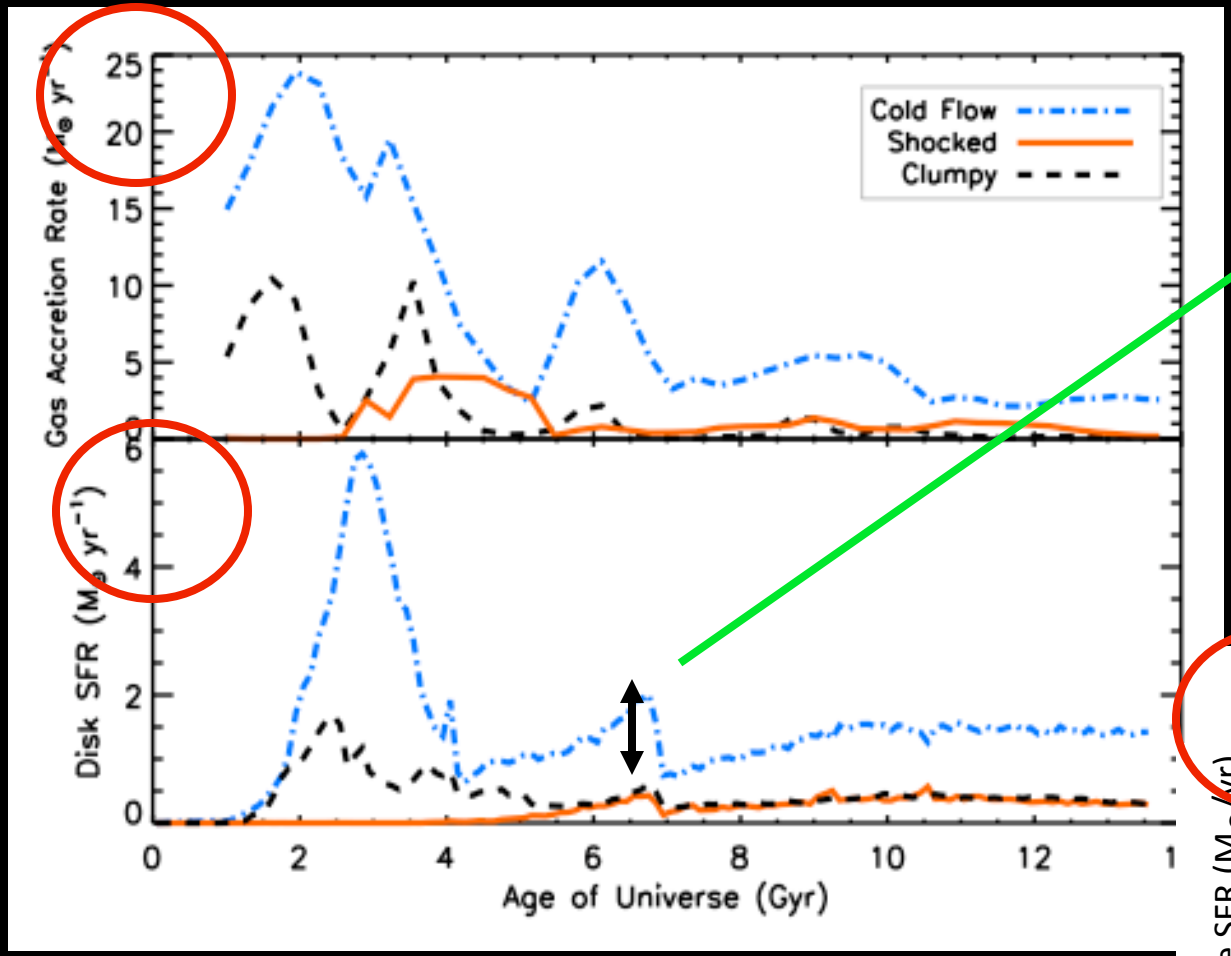


Develop a gas reservoir, yet f_{gas} never > 25%

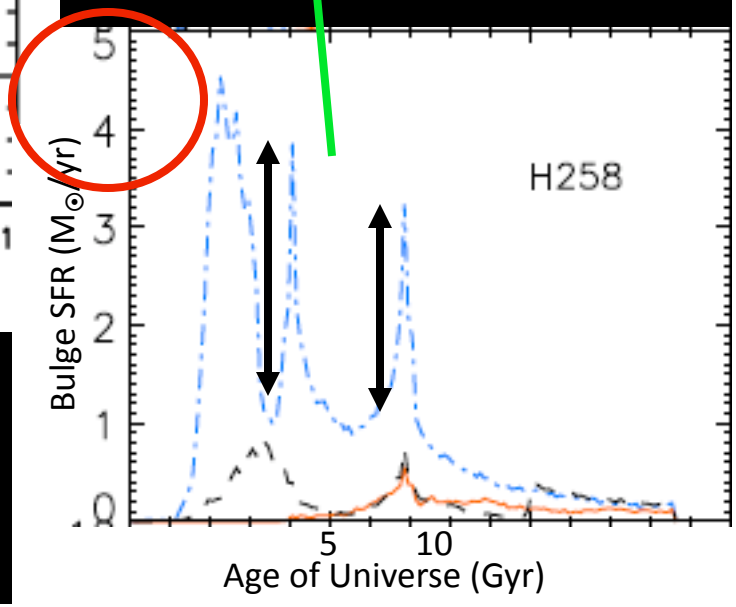


Brooks et al. (2009), Governato et al. (2009)

The Role of Feedback

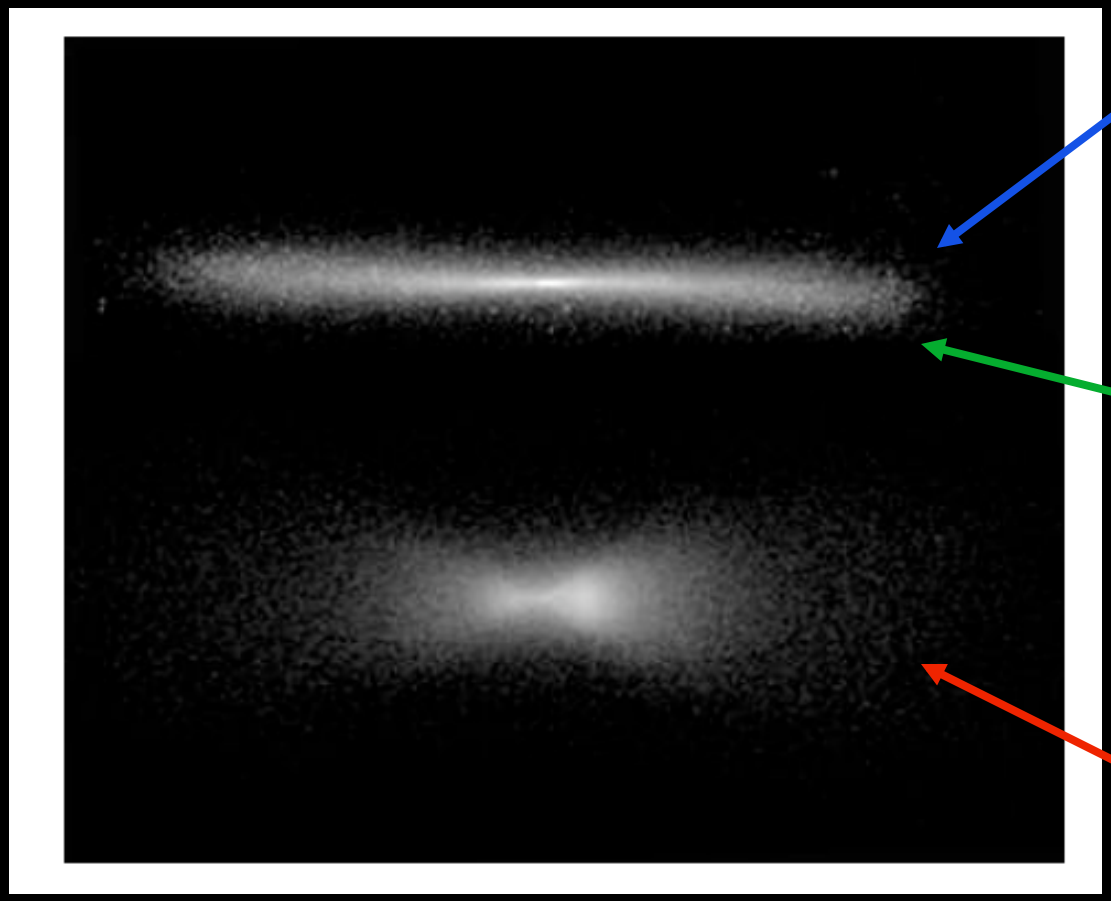


SFR increases by ~2-3x in mergers



Jogee et al. (2008), Stewart et al. (2008), di Matteo et al. (2008), Hopkins et al. (2008), Cox et al. (2008), Daddi et al. (2007), Bell et al. (2005), Bergvall et al. (2003), Georgakakis et al. (2000)

Disk Regrowth



Brightness not to scale!

Young stellar disk, formed after last major merger ($z < 0.8$);
30% of $z=0$ disk mass (but dominates the light)

~30 % due to cold gas accreted prior to lmm;
~35% due to cold gas accreted after lmm;
~30% due to hot gas accretion

Old stellar disk, formed prior to last major merger ($z > 0.8$);
70% of $z=0$ stellar disk mass

Conclusions

- Strong gas outflows can selectively remove low angular momentum gas (but force resolution < 100pc is required)
- Cold gas accretion leads to the building of disks at higher z than predicted by standard models
- Feedback regulates SFR in galaxies, building a gas reservoir and limiting gas consumption in mergers
- Do not require f_{gas} > 50% to rebuild disks, due to subsequent gas accretion and cooling from hot halo
- Although mergers are expected to be common in CDM, this is not at odds with the existence of disks

What's Next?

Milky Way mass (and above) galaxies at sub-100pc resolution

The role of AGN feedback, the evolution of the M-σ relation

Realistic dwarf galaxies!

- Origin of DM cores
- The role of metals in SF
- Creation of the stellar component