Forming Bulgeless Disk Galaxies in a Cold Dark Matter Universe

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Overview

Some small scale problems with CDM

- ‘catastrophic’ loss of Angular Momentum
- inability to form bulgeless disk galaxies
- distribution of Angular Momentum
- peaked rotation curves
- Dark Matter profiles have ‘cusps’

Dwarf Galaxy simulations

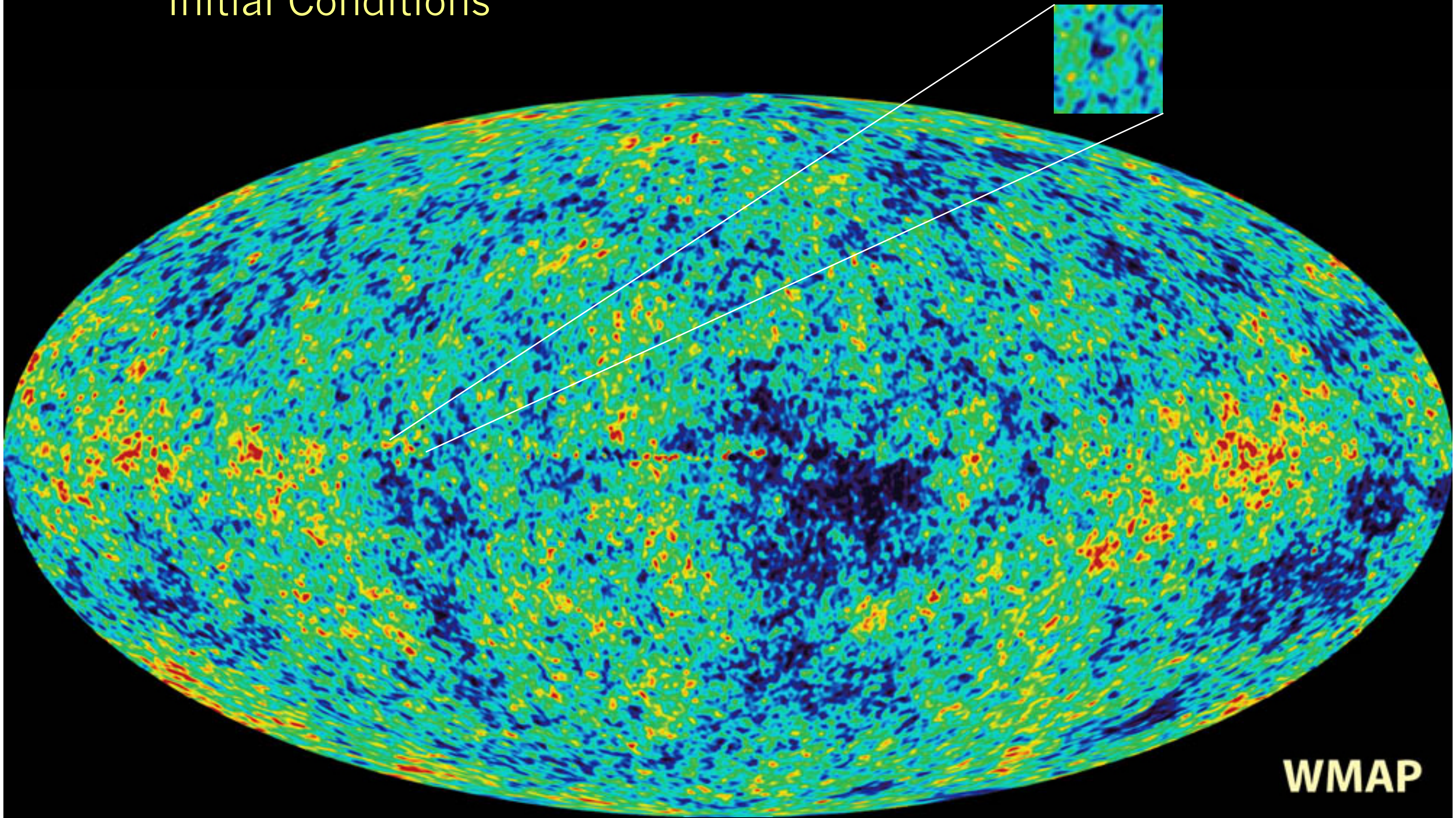
- “Resolving” star forming regions: inhomogeneous ISM
- gas blowout
- bulgeless disks
- Dark Matter cores

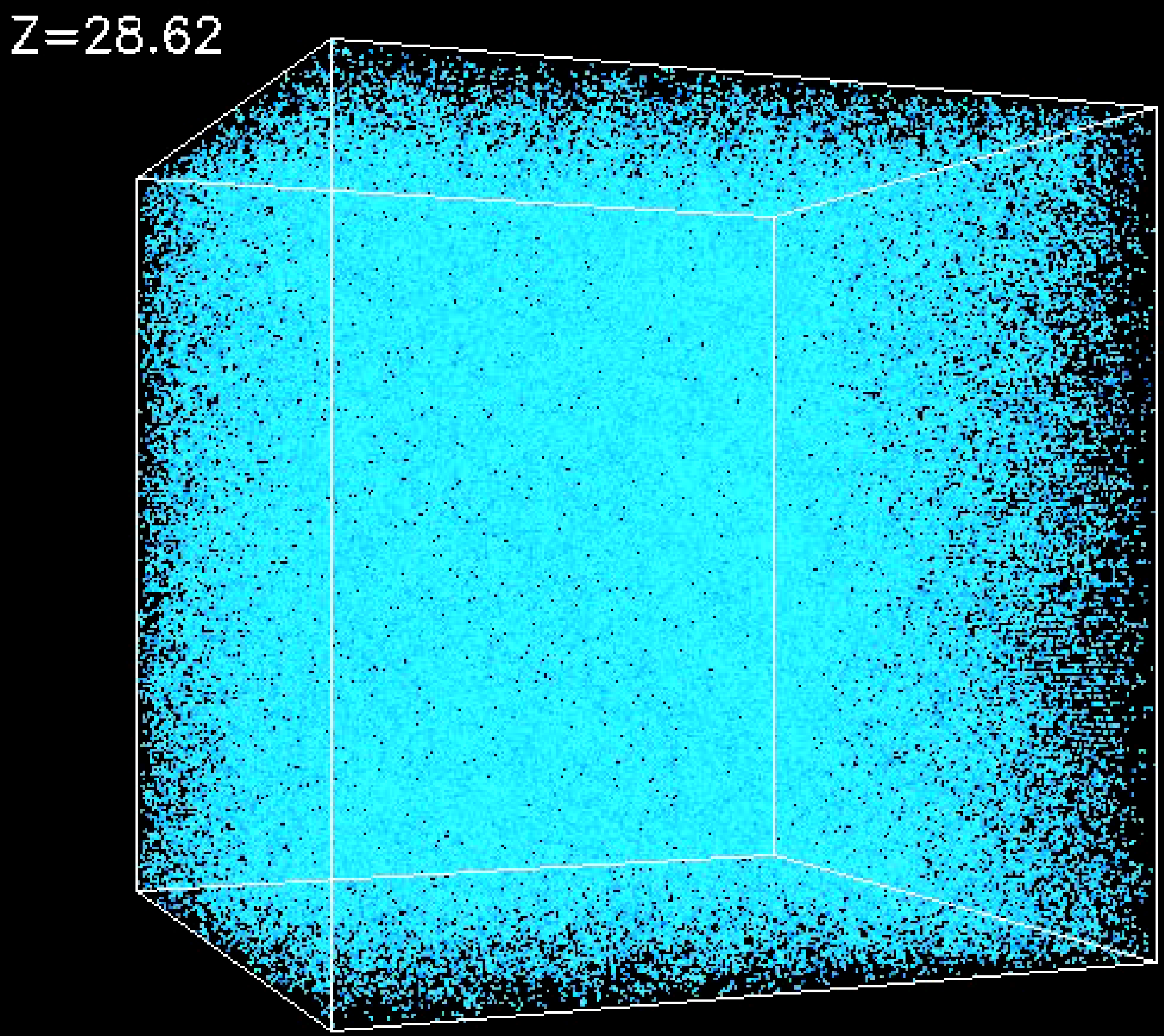
Details of the simulations

Gasoline: parallel chemo-dynamical galaxy evolution code (Wadsley et al. 2004)

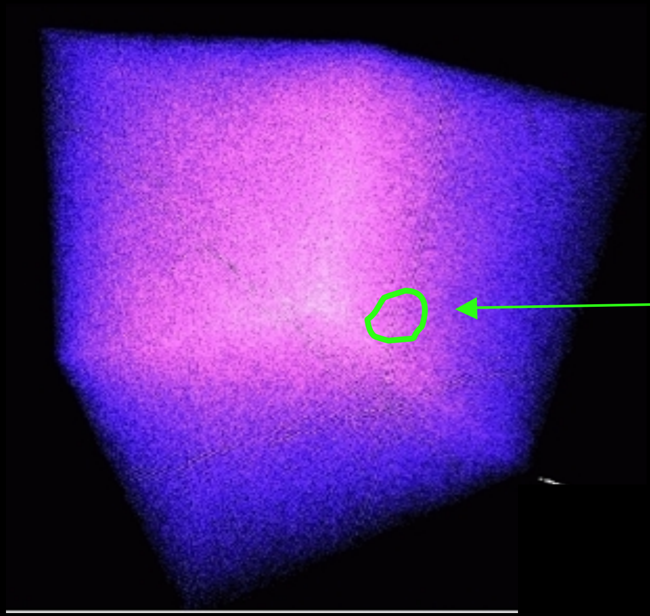
- Gravity: Tree N-body -DM & stars
- Hydrodynamics of gas: SPH
- Star Formation Rate $\propto \rho^{1.5}$
- UV background radiation (Haardt & Madau 96)
- Compton & radiative cooling
- Low temperature cooling ($<10^4$K, metal lines)
- Supernovae feedback II & Ia (Stinson et al. 2006)
- metal enrichment: H,He,O,Fe

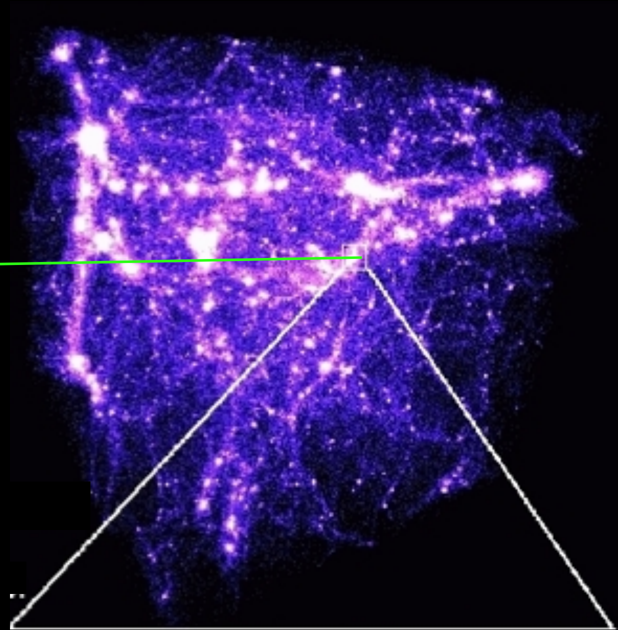
Initial Conditions





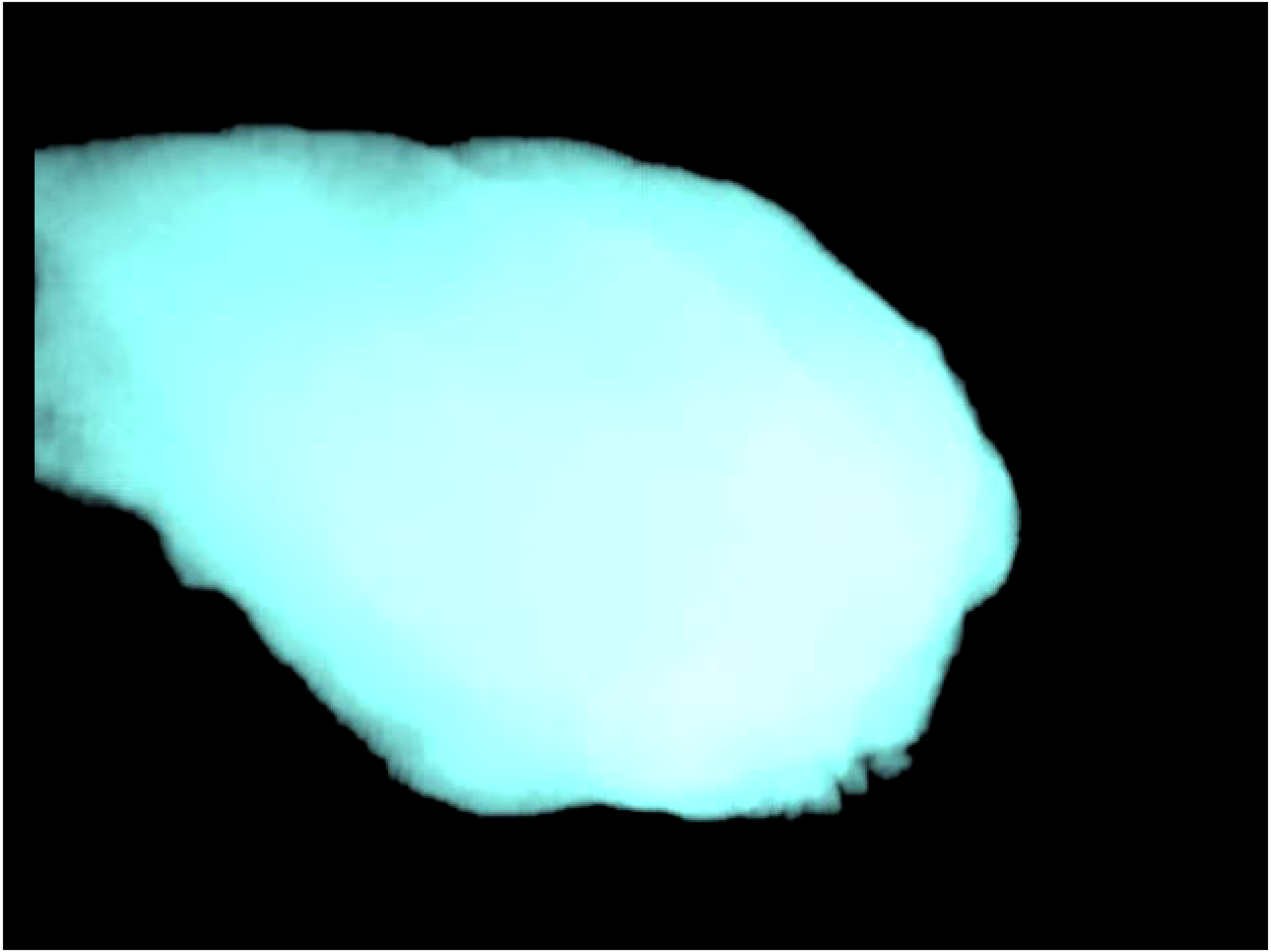
Structure formation driven by cosmologically relevant volume of dark matter.



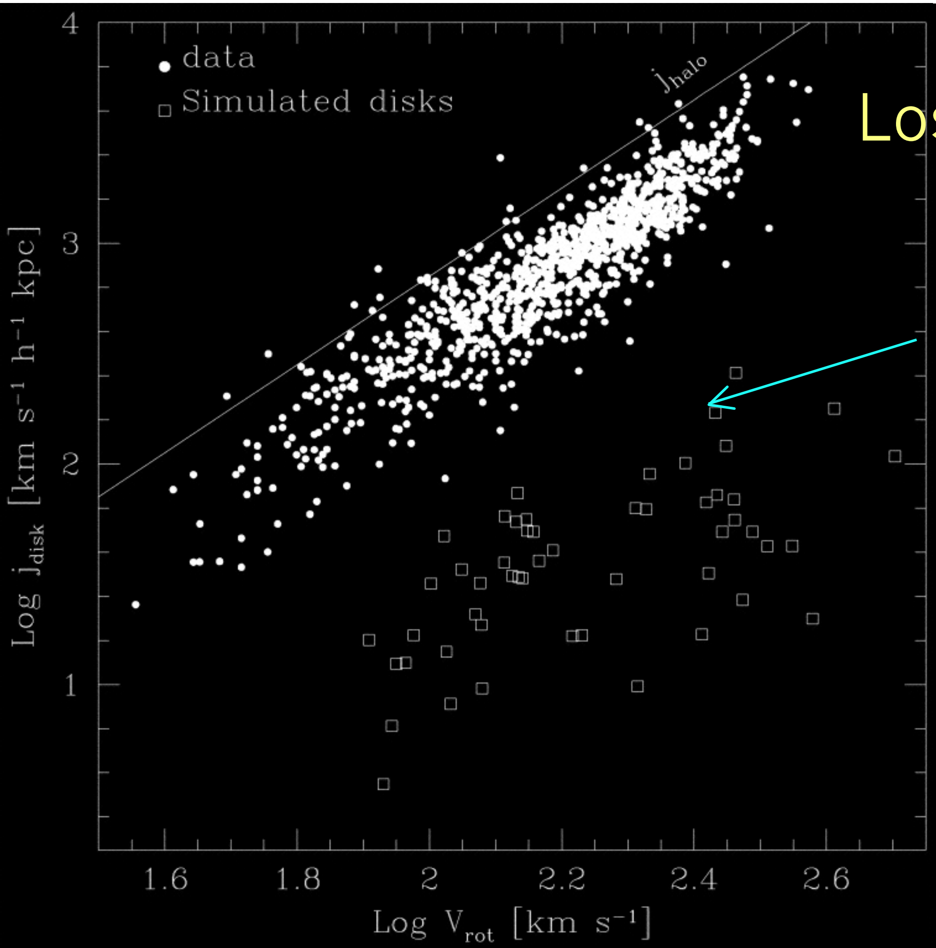


Select a galaxy sized dark matter halo

Identify those particles in initial conditions.... The whole box is then re-simulated with that region simulated in detail

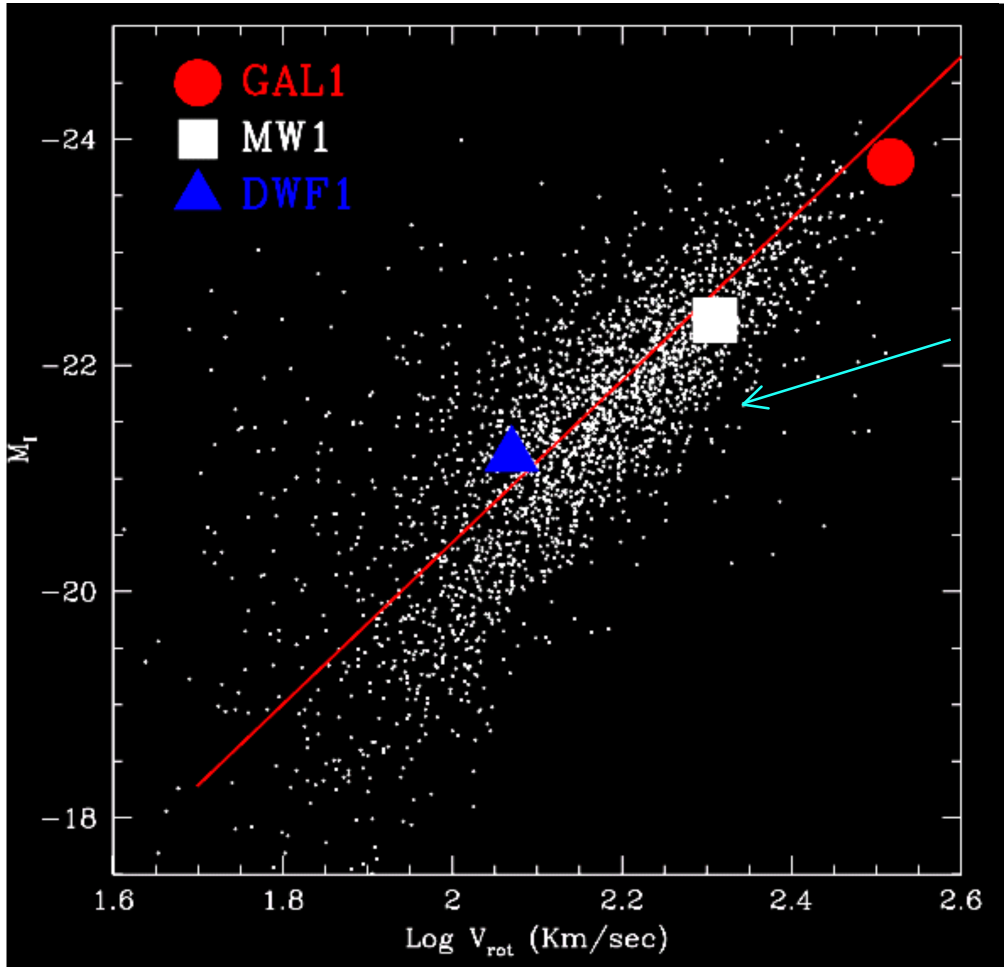


Loss of Angular Momentum



Simulations lost angular momentum

Navarro & Steinmetz 1999



Improvement in Angular Momentum Problem

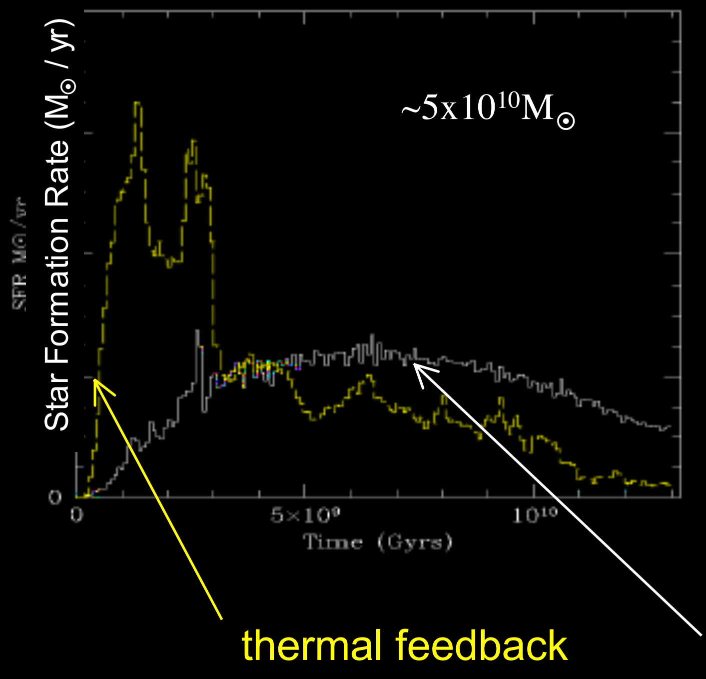
Governato 2006

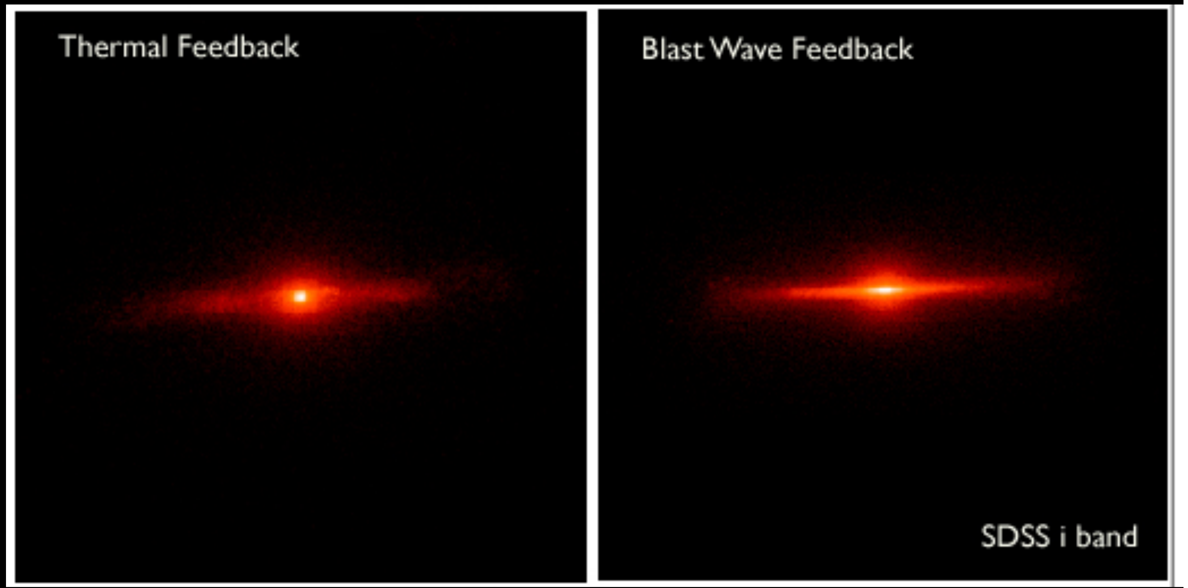
Solution?

feedback & regulation of star formation in proto-galaxies

White & Rees 1978, Thacker & Couchman 2001, Governato et al. 2006, 2008

Regulation of star formation has several other important consequences





- essential to forming low mass, low metallicity stellar halo

Brook, Kawata, Gibson, Flynn 2004
Bullock et al. 2005, Font et al. 2005, Moore et al. 2005

- early/low mass mergers are gas rich: implications for thick disk formation and the mass morphology relation

Brook, Kawata, Gibson, Freeman 2004, Robertson et al. 2006, Stewart et al. 2009

Where to next for Star Formation in simulations?

So far, star formation regions are not resolved

Star formation “averaged” over large regions

Star formation: density threshold is low

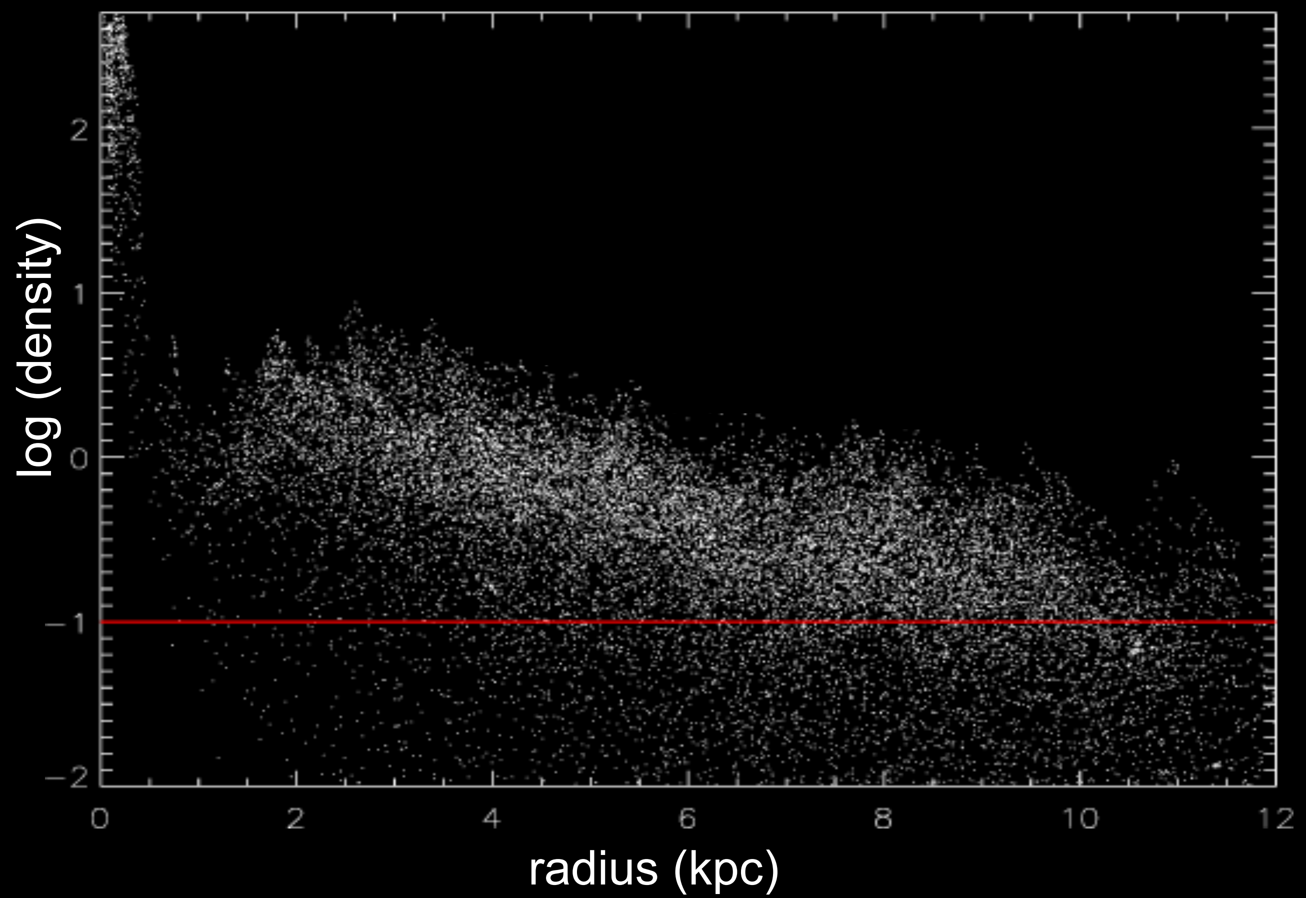
Parameters set to match Milky Way star formation rate

We now have ability to resolve star forming regions and to form clusters of stars in dwarf galaxy simulations

High density threshold: observations suggest that stars form where molecular gas exists

Particle mass resolution ~ a few 10^3 $M_\odot$

Gravitational Softening 86pc



Low star formation threshold allows stars to form in the disk

The density of gas used to determine the star formation rate is averaged over large volumes

Difficulties exist in mimicking the effects of feedback on these scales

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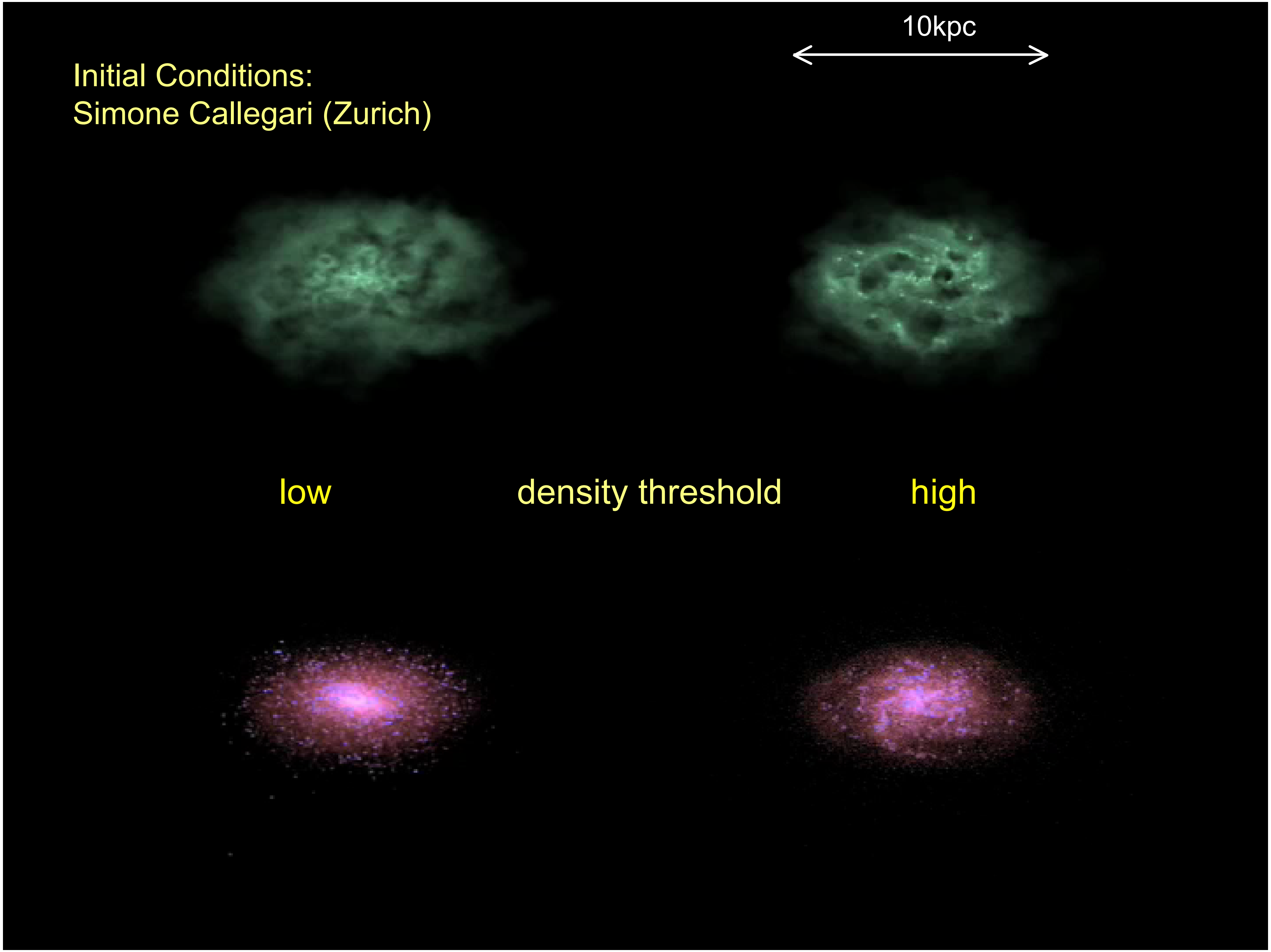
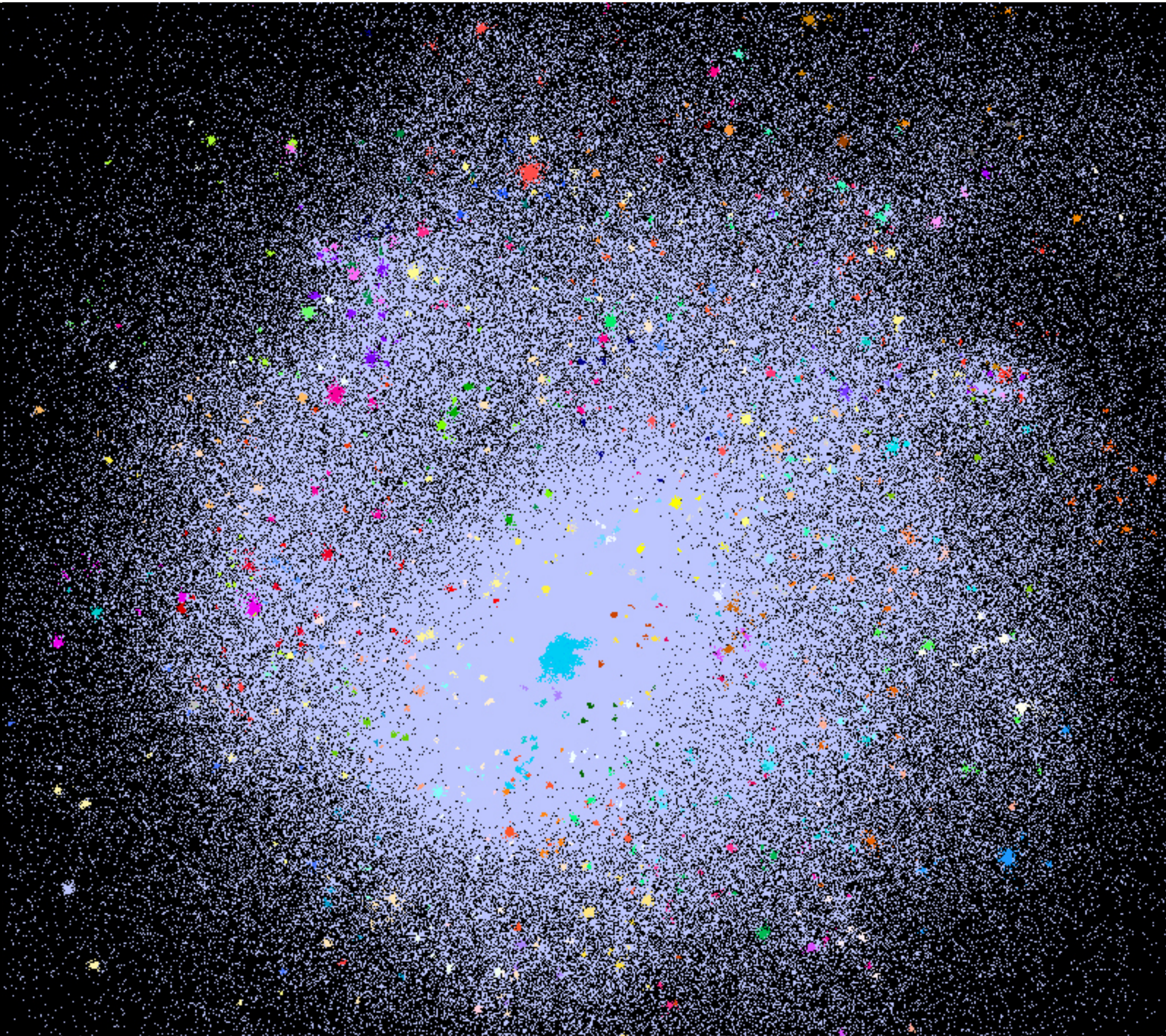
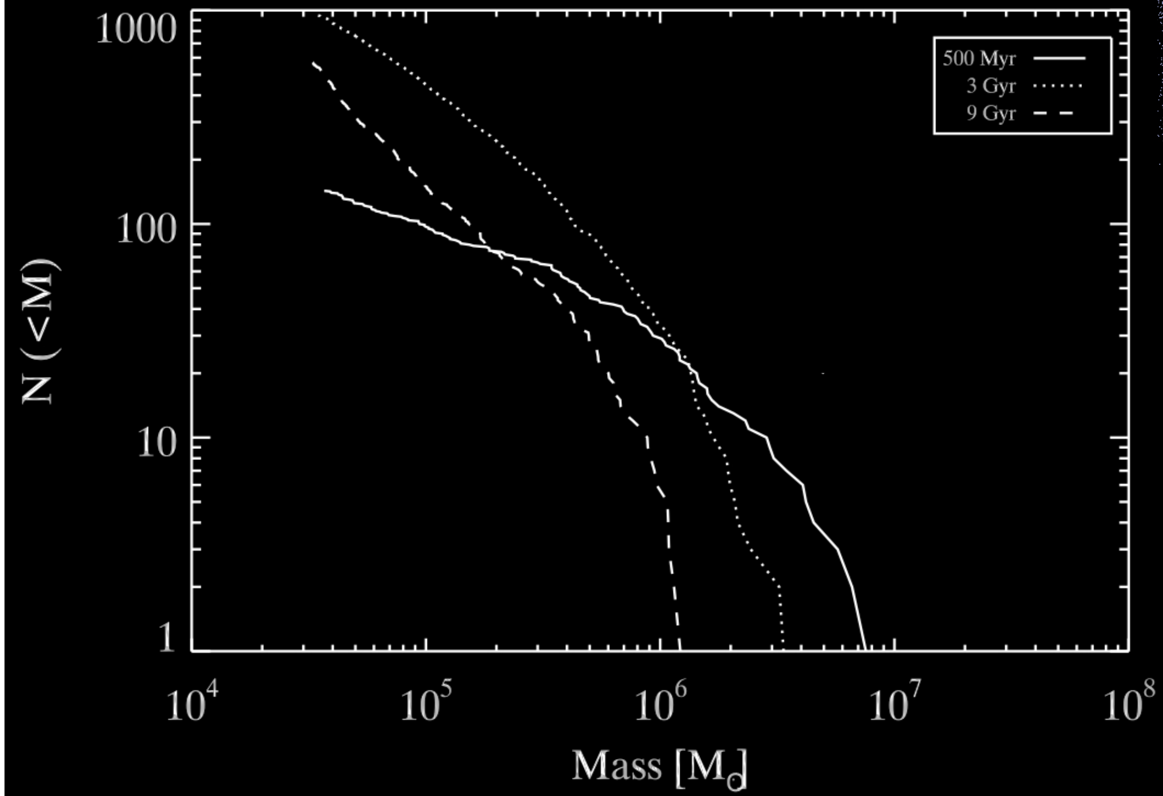
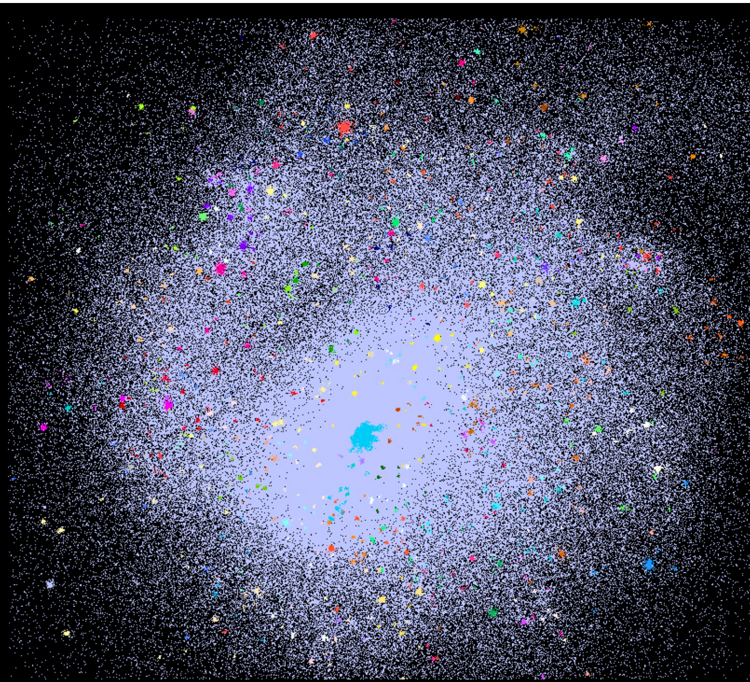

10kpc
Initial Conditions:
Simone Callegari (Zurich)
low
density threshold
high



Note: Different simulation with mass of LMC

Evolution of the Cluster Mass Function





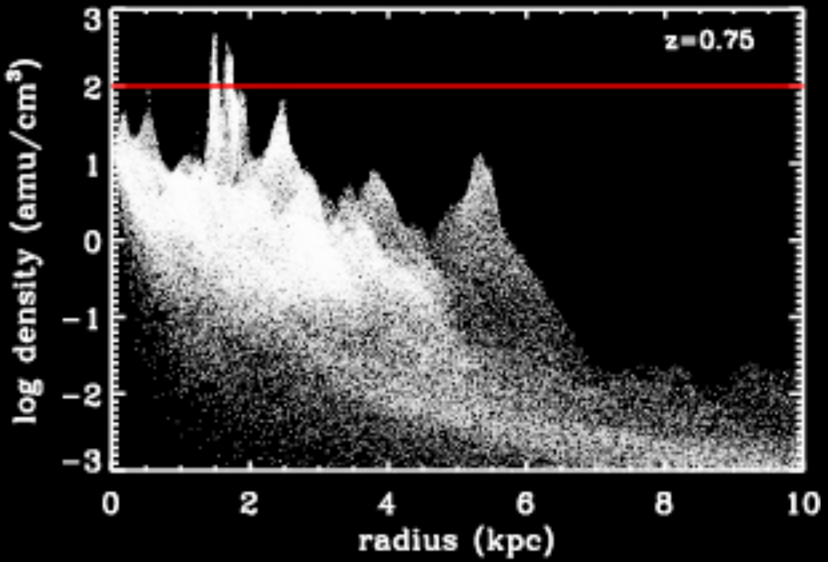
Greg Stinson UCLan

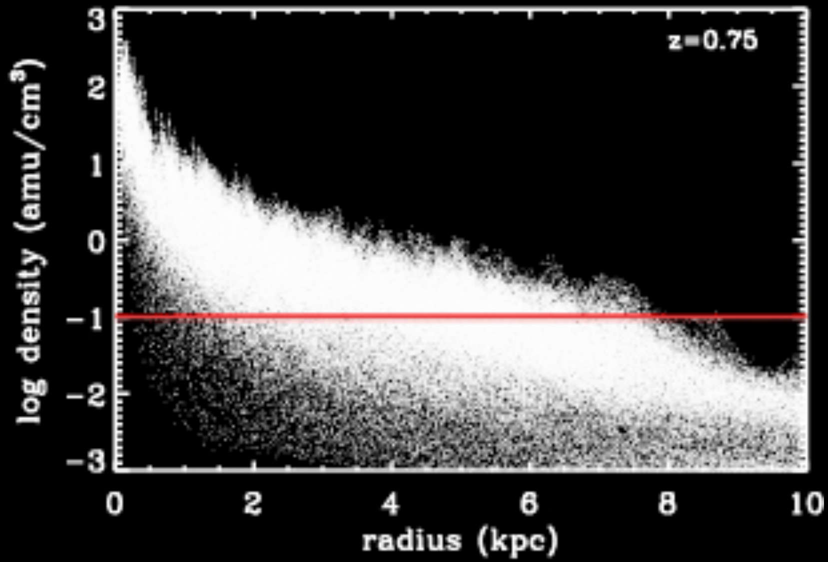
THE FORMATION OF A BULGELESS GALAXY WITH A SHALLOW DARK MATTER CORE

Fabio Governato (University of Washington)
Chris Brook (University of Central Lancashire)
Lucio Mayer (ETH and University of Zurich)
and the N-Body Shop

KEY: Blue: gas density map. The brighter regions represent gas that is actively forming stars. The clock shows the time from the Big Bang. The frame is 50,000 light years across.

Simulations were run on Columbia (NASA Advanced Supercomputing Center) and at ARSC



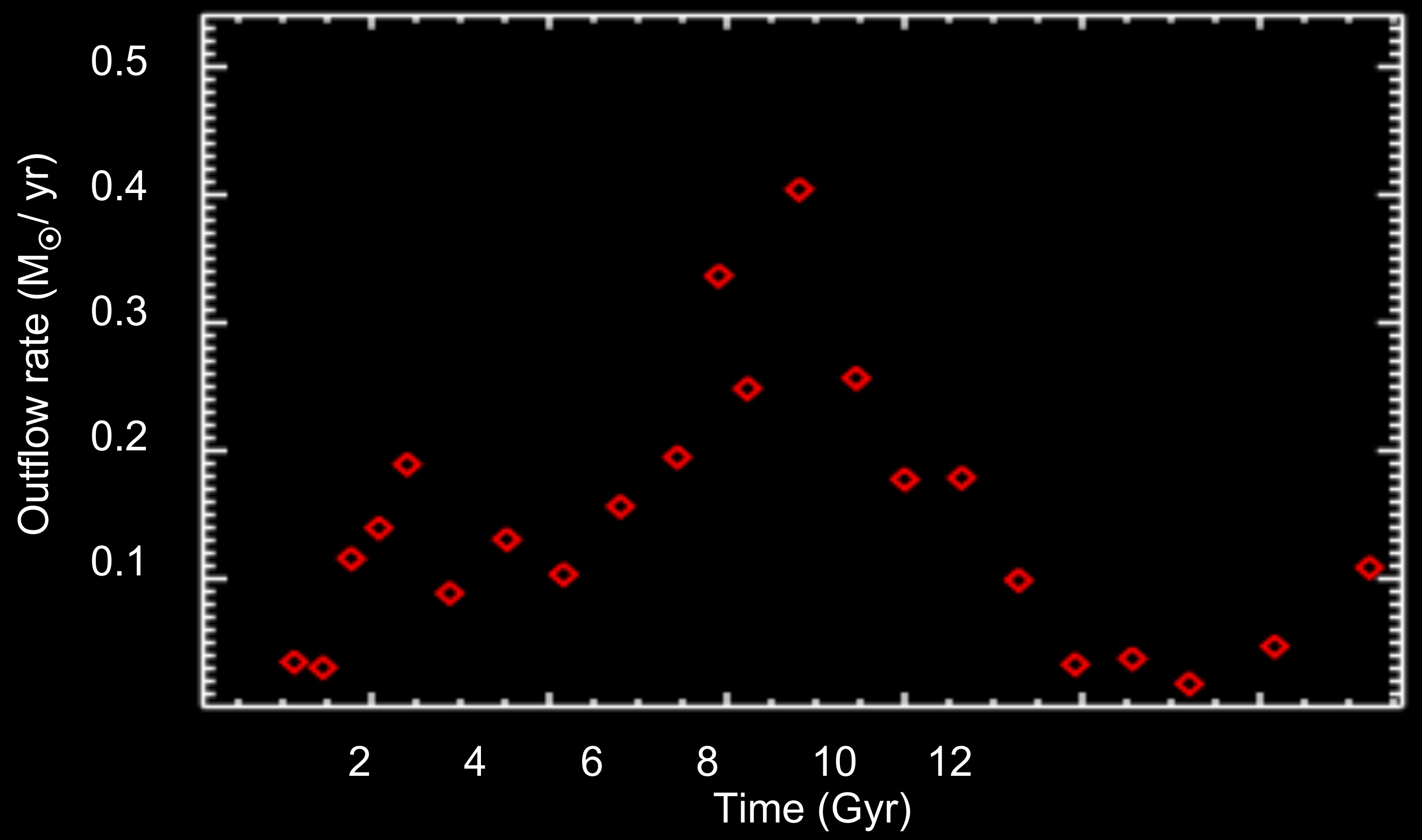


High threshold

Low threshold

Create inhomogeneous Inter Stellar Medium

Feedback from dense areas more efficient



significant gas outflow from central galaxy when star forming regions resolved

Code Essentials: Supernovae Feedback

-Energy = $\varepsilon 10^{51}$/SN ergs, $\varepsilon<1$

-energy release rate tied to star formation time/IMF

-stars within the blast wave radius have cooling turned off

- cooling shut off time proportional to the Sedov solution of the blast wave equation

- considers local density and temperature as well as Energy (Chevalier 1972, McKee & Ostriker 1977)

see Stinson et al. 2006

How we test/constrain our feedback

Measure shells/bubbles from overlapping supernovae

Compare to observed shells in local galaxies (e.g. THINGS)

Turbulence of gas

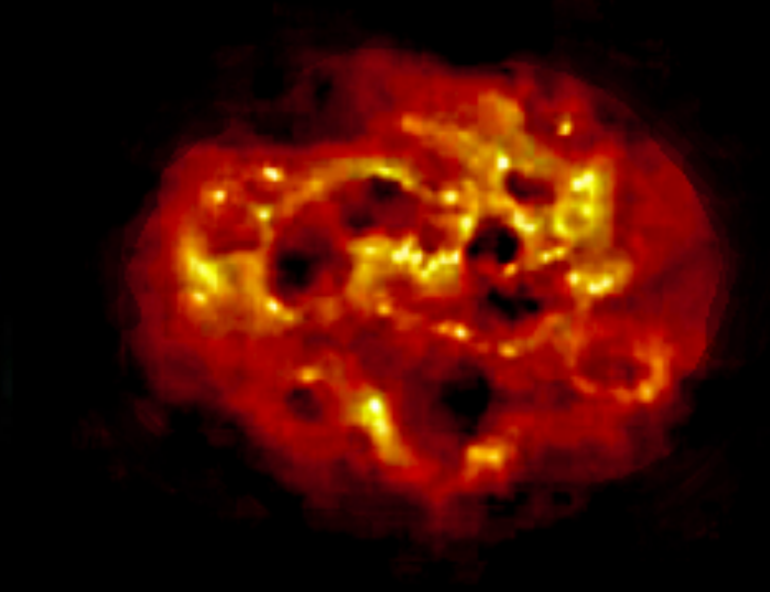
Star formation rates/histories

Mass loading

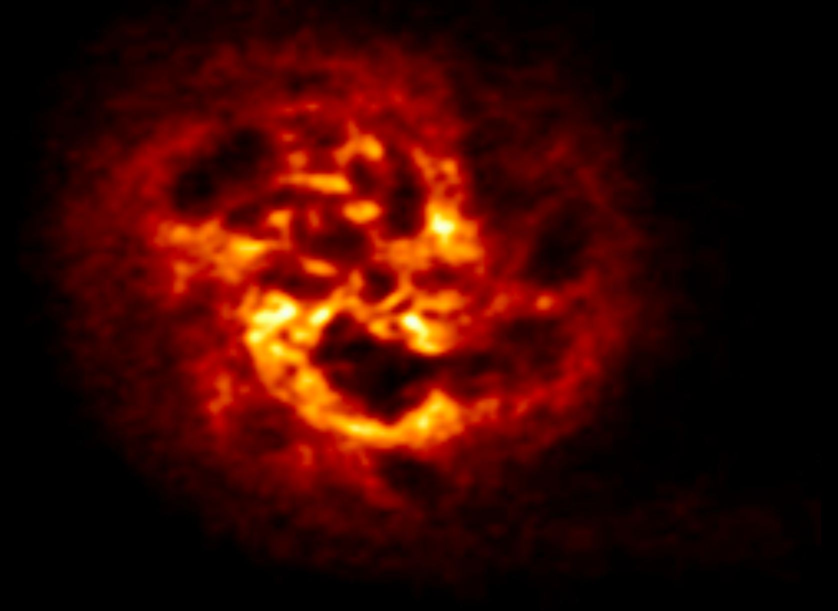
Baryon fraction (mass to light, Tully Fisher)

Gas fraction

How we test/constrain our feedback



Simulated Dwarf Galaxy



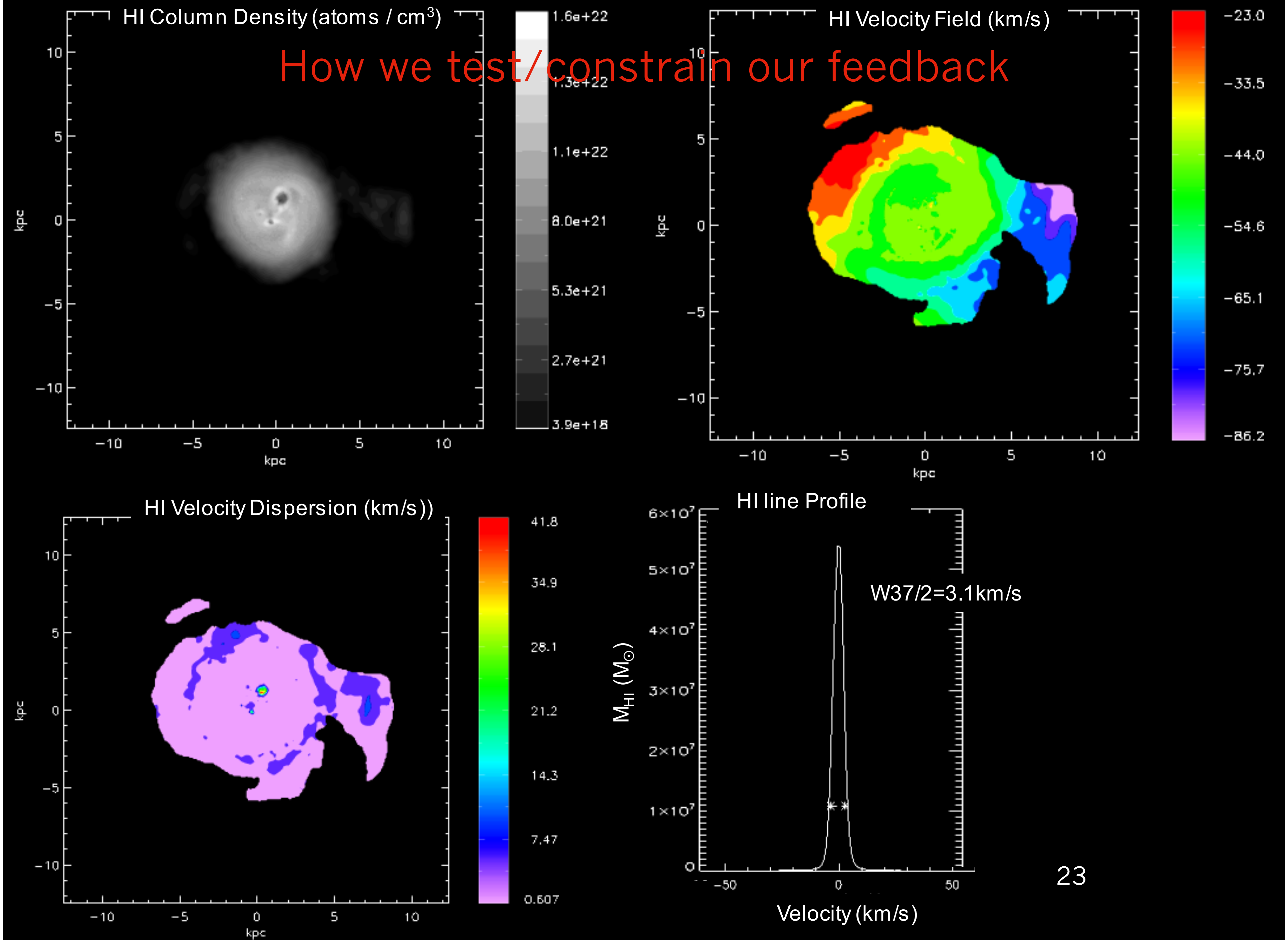
Holmberg II

Compare shell properties to those observed- match size and distribution properties of shells (Pilkington et al. in prep)

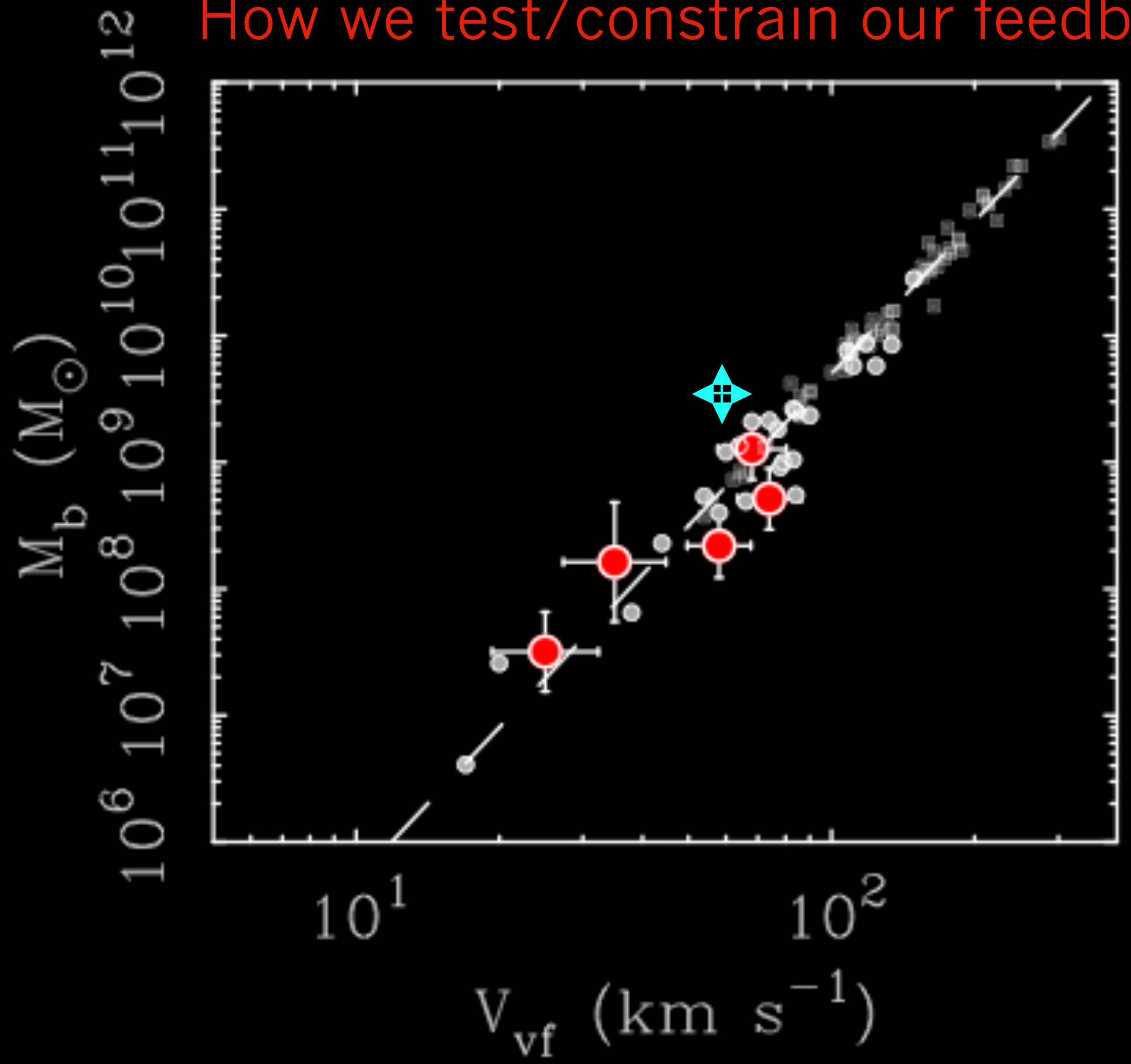
Important constraint on our feedback on the scales of multiple (~50-100) overlapping Supernovae, which our simulations resolve.

These are the scales that the THINGS survey in particular provide a wealth of information.

How we test/constrain our feedback

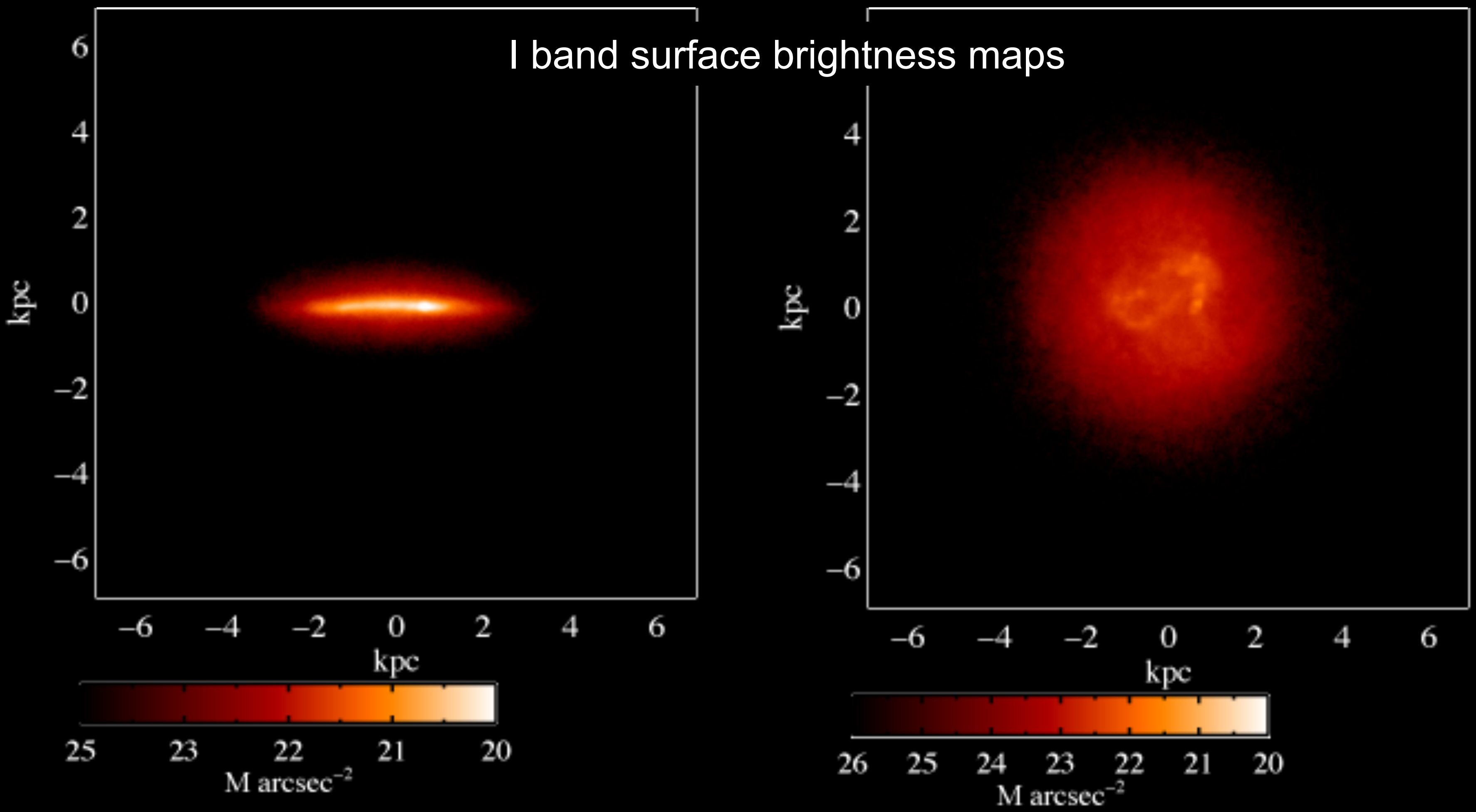


How we test/constrain our feedback



Trachternach et al. 2009

I band surface brightness maps



M_I= -17.4

MHI/L_B=1.1

Vrot~55km/s

g-r = 0.5

Baryon Fraction ~0.067

Some small scale problems with Cold Dark Matter

Catastrophic loss of Angular Momentum

Inability to form bulgeless disk galaxies

Distribution of Angular Momentum

Peaked rotation curves

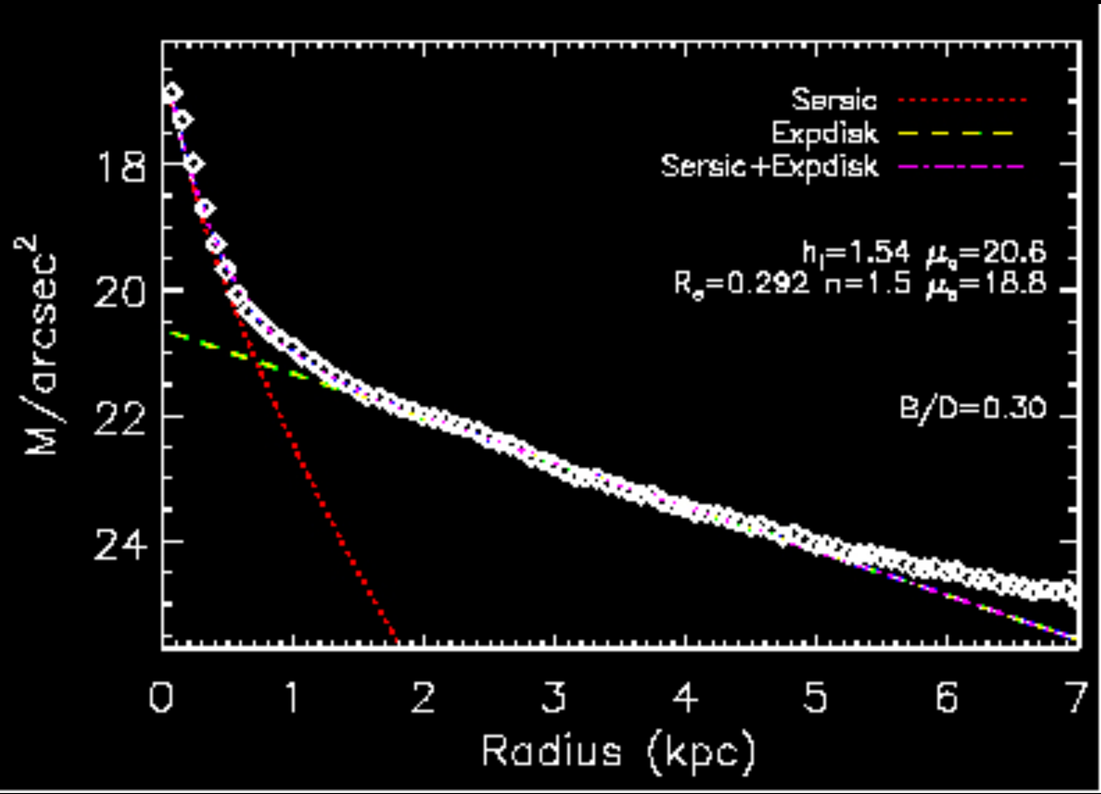
Dark Matter profiles have cusps

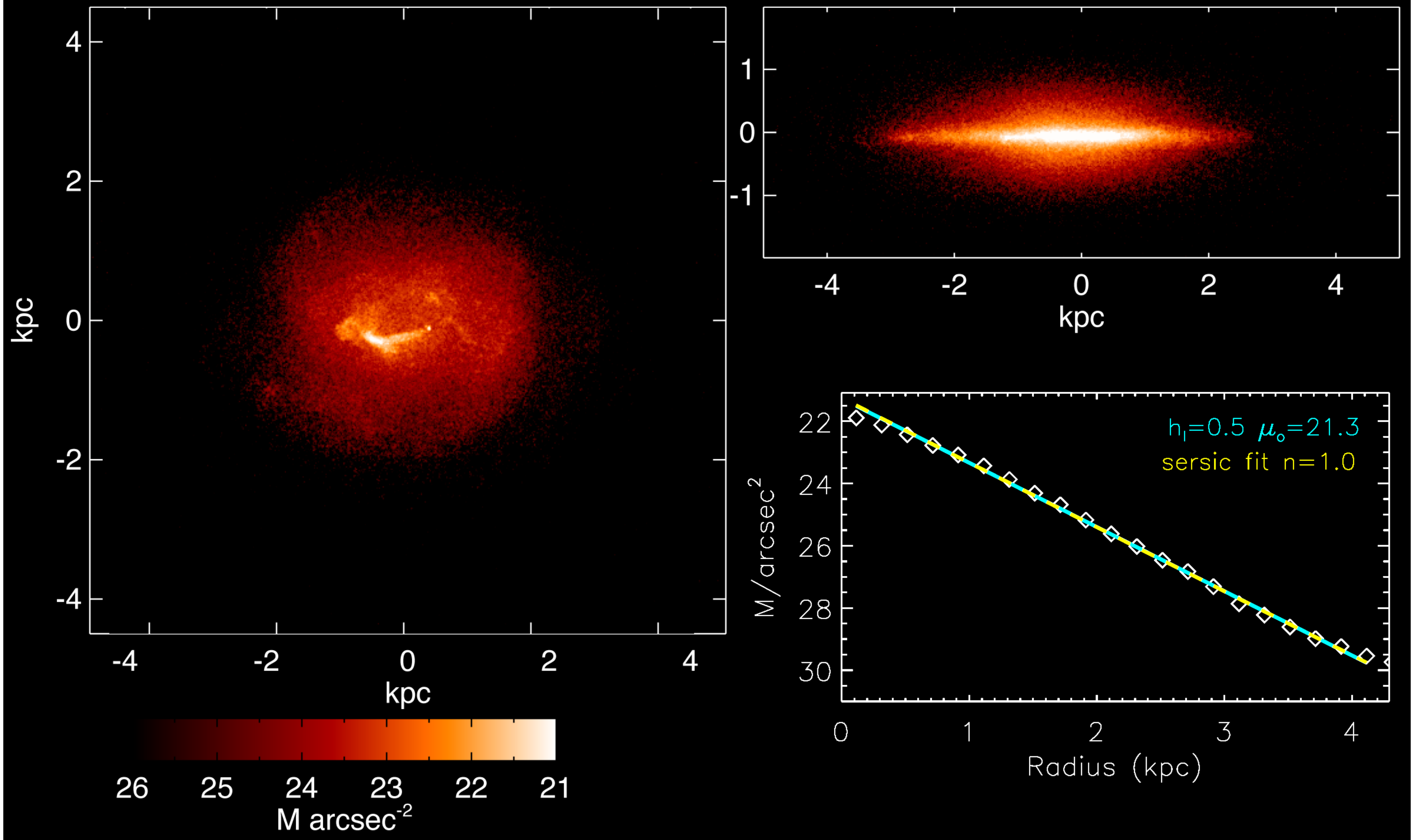
Bulgless Disks

Observed dwarf galaxies typically have no bulge

Simulated dwarfs invariably have bulges

Typical radial surface brightness profile of a simulated disk galaxy





kpc
4
2
0
-2
-4
-4
-2
0
2
4
kpc
26
25
24
23
22
21
M arcsec-2
1
0
-1
-4
-2
0
2
4
kpc
22
24
26
28
30
M/arcsec2
h_l=0.5 μ_o=21.3
sersic fit n=1.0
0
1
2
3
4
Radius (kpc)

No bulge!

Some small scale problems with Cold Dark Matter

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Distribution of Angular Momentum

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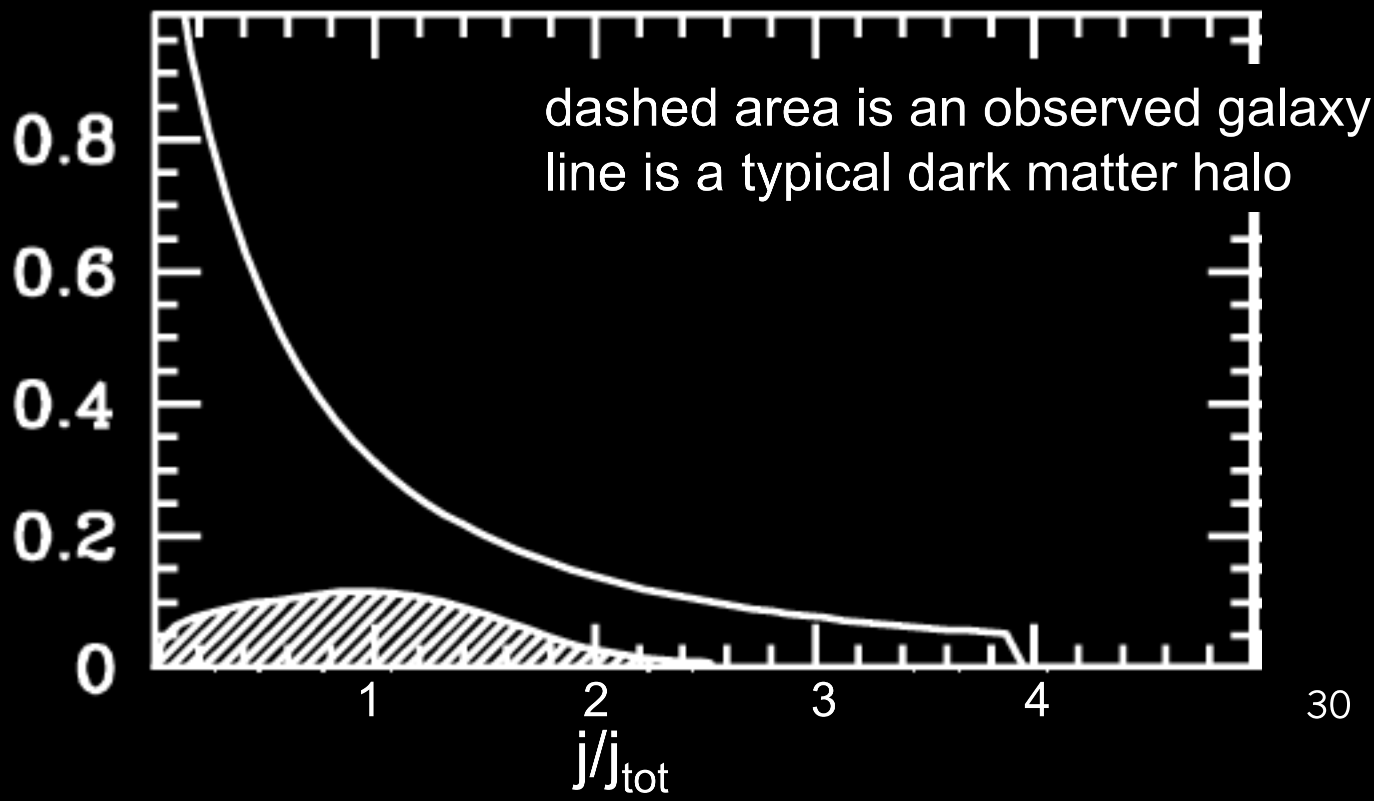
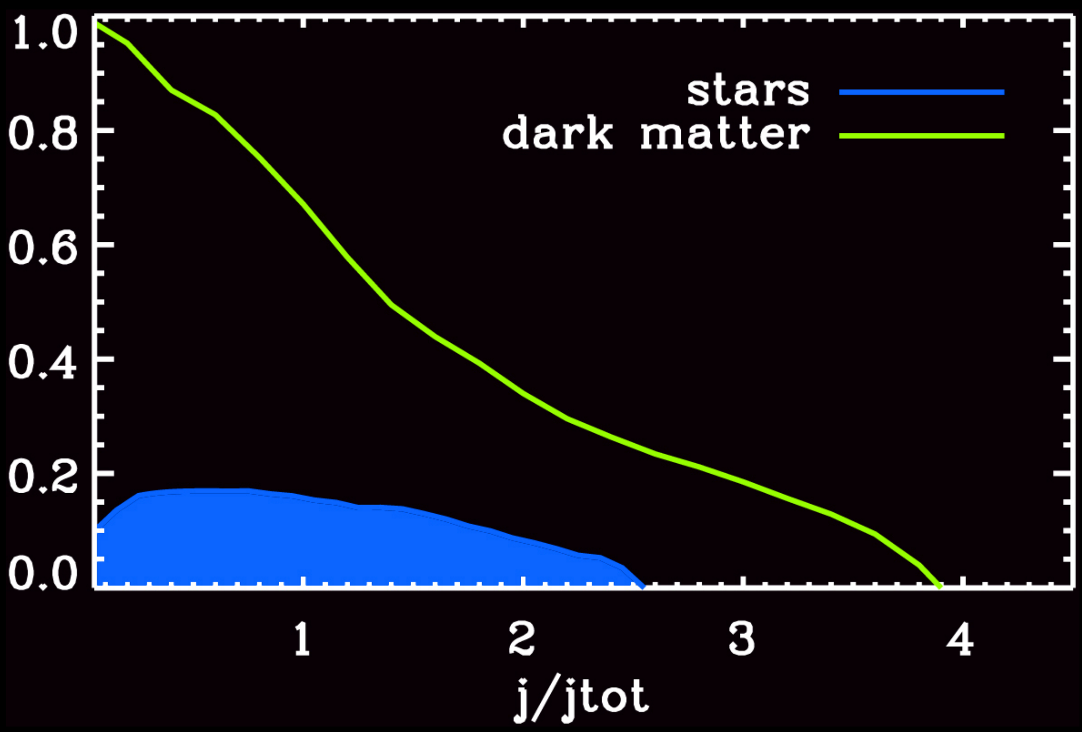
Angular Momentum Distribution

Cold dark matter halos have a lot of low angular momentum material (van den Bosch Burkert & Swaters 2001)
Regardless of mass
Interpreted as associated with bulges
(SAMs galaxies have bulge problem Dutton et al. 2009)



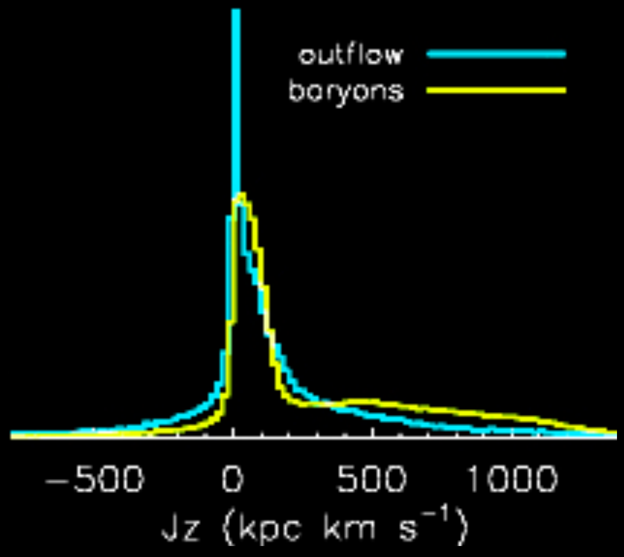
Angular Momentum Distribution

Angular momentum distribution of stars in simulated dwarf



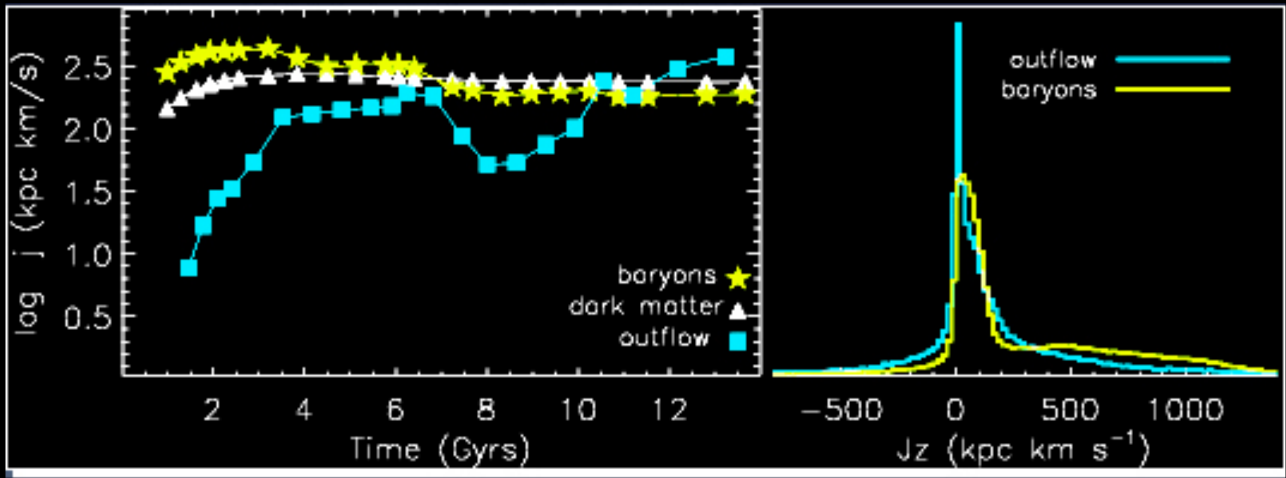
Preferentially blow out low angular momentum material

1. Low angular momentum material is accreted first
2. Low potential well at early times
3. Extended HI disk is a repository for high angular momentum material
4. Outflows perpendicular to the disk
5. Merger induced outflows

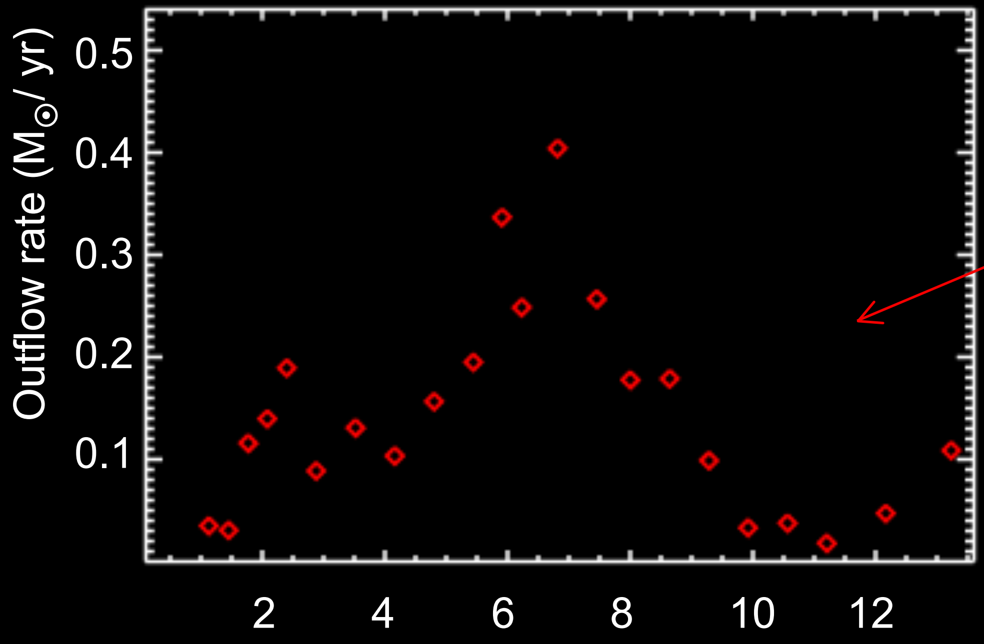


Brook et al. (in prep)

Preferentially blow out low angular momentum material

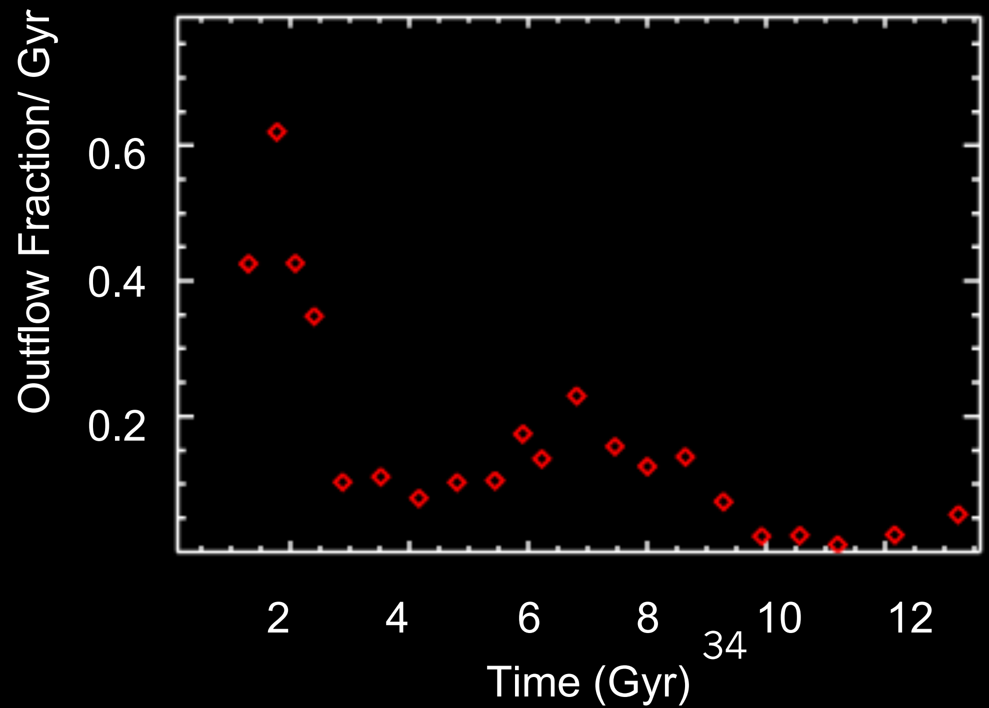


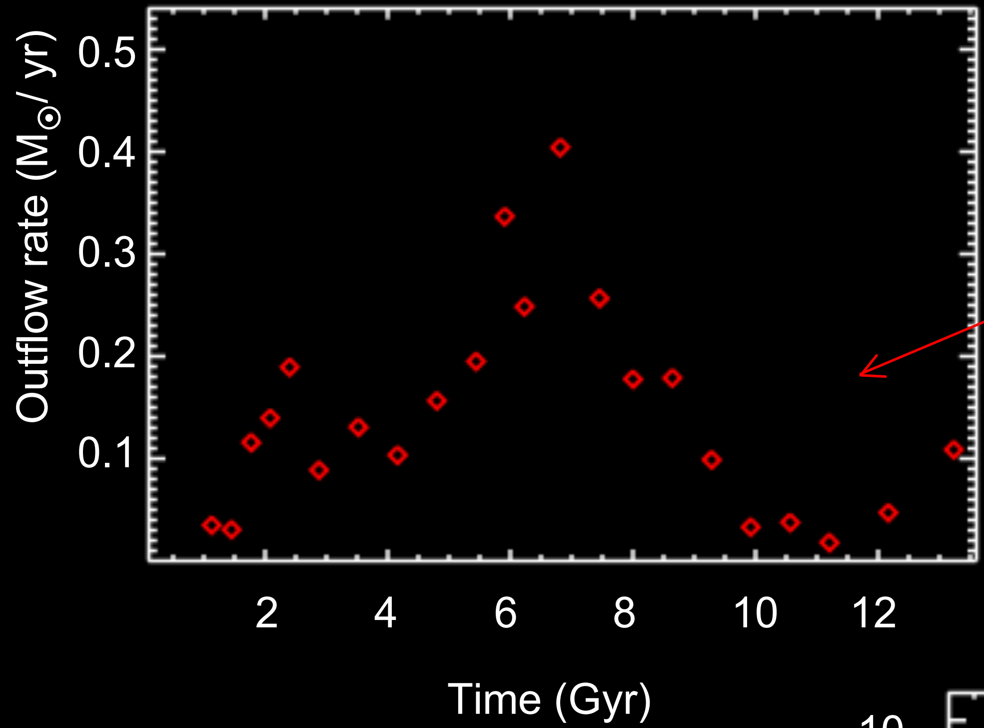
- Early accreted material is torqued less, has lower angular momentum
- To be expelled, the gas first needs to be in the galaxy.
- In absence of star formation, this creates a strong bias for low angular momentum to be expelled.
- Low star formation rates and high mass loading in low mass galaxies ensure that this effect is significant



significant gas outflow from central galaxy when star forming regions resolved

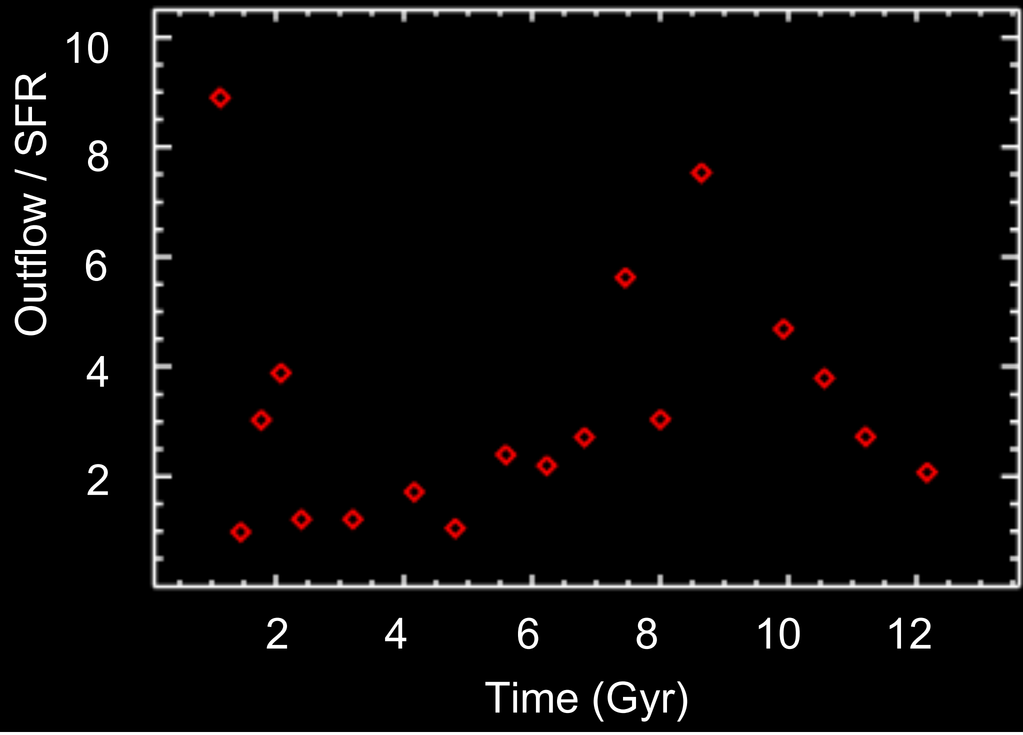
Fraction of mass lost to outflows is highest at high z ie in low mass progenitors

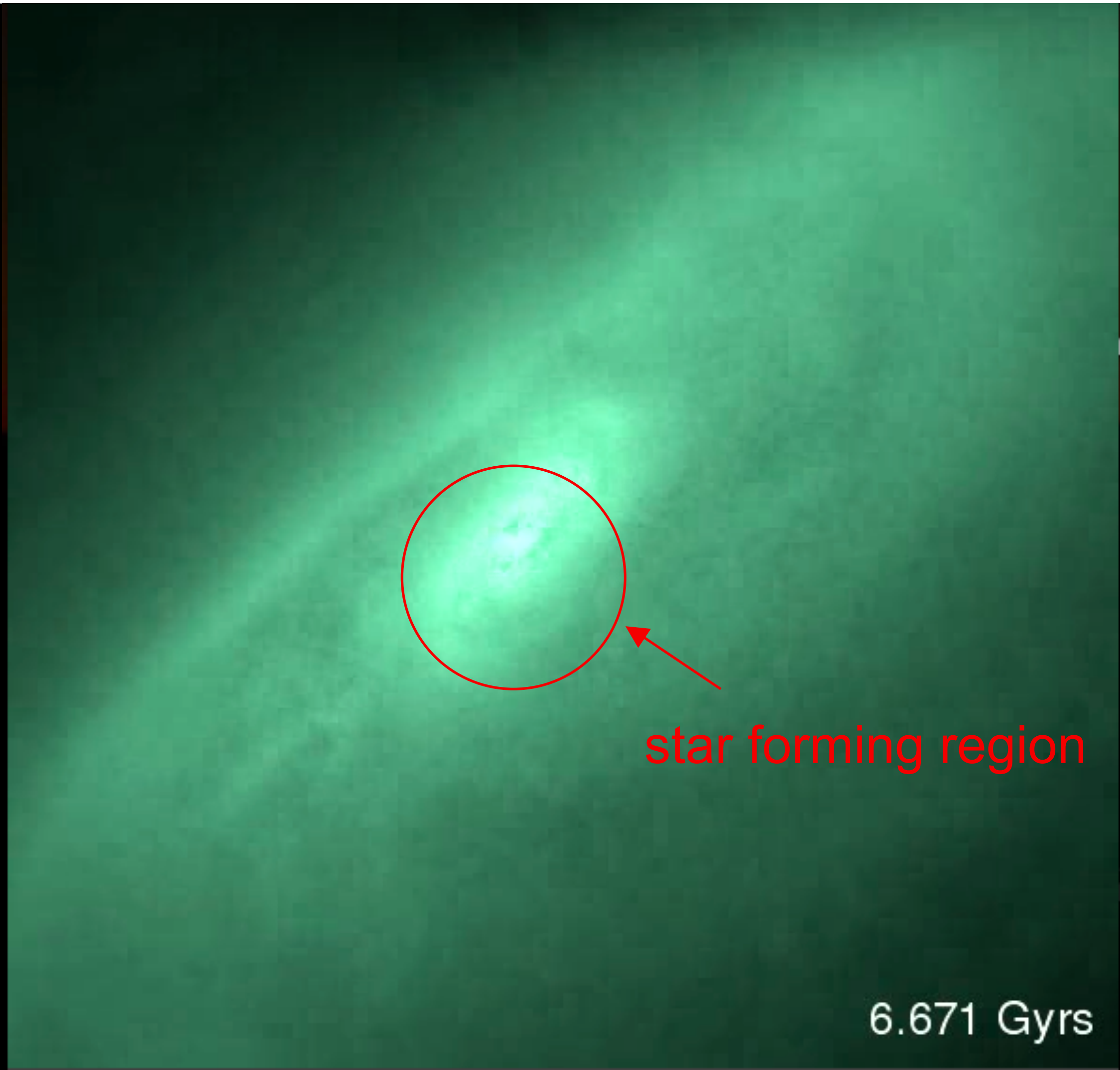




significant gas outflow from central galaxy when star forming regions resolved

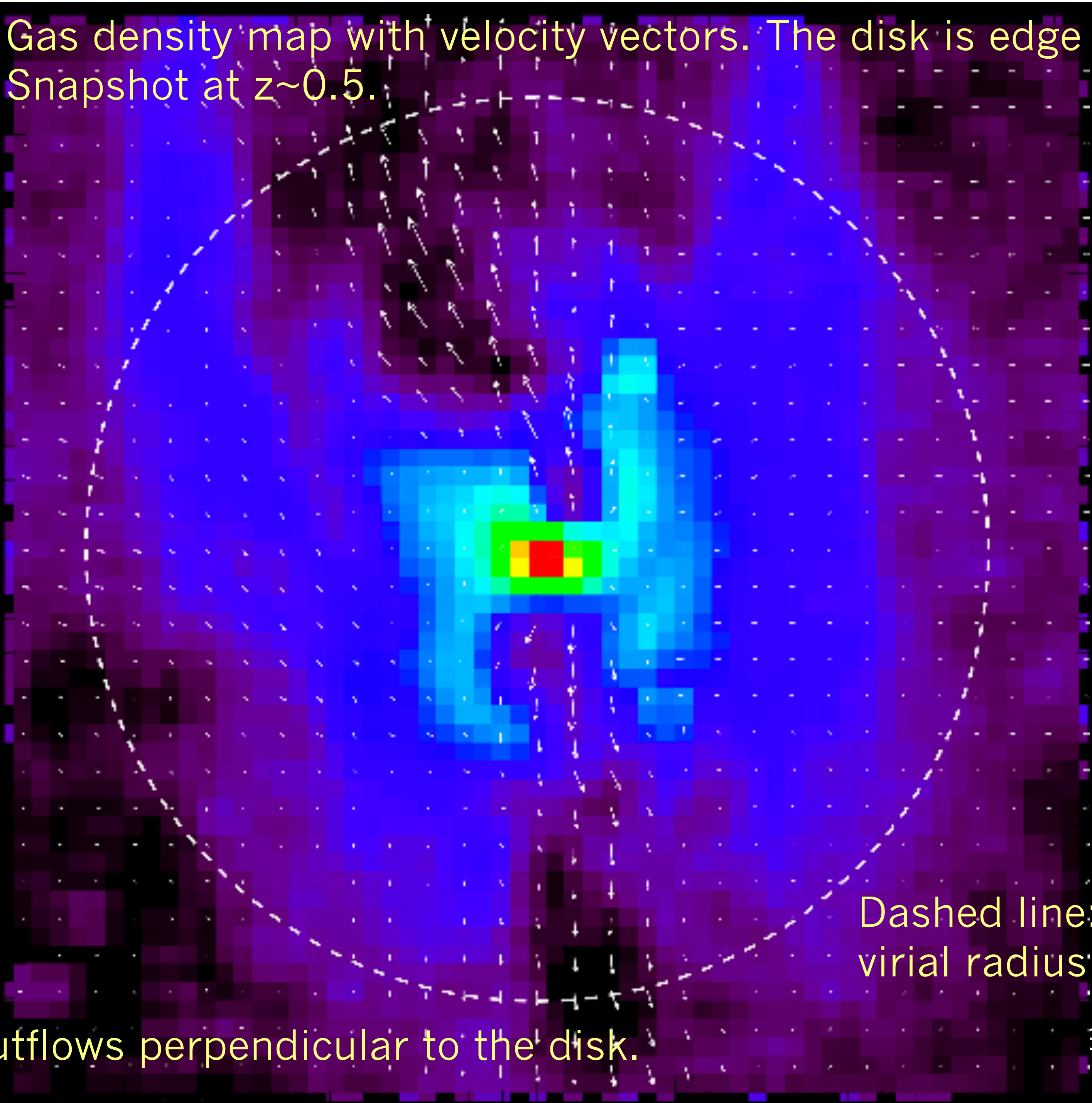
mass loading





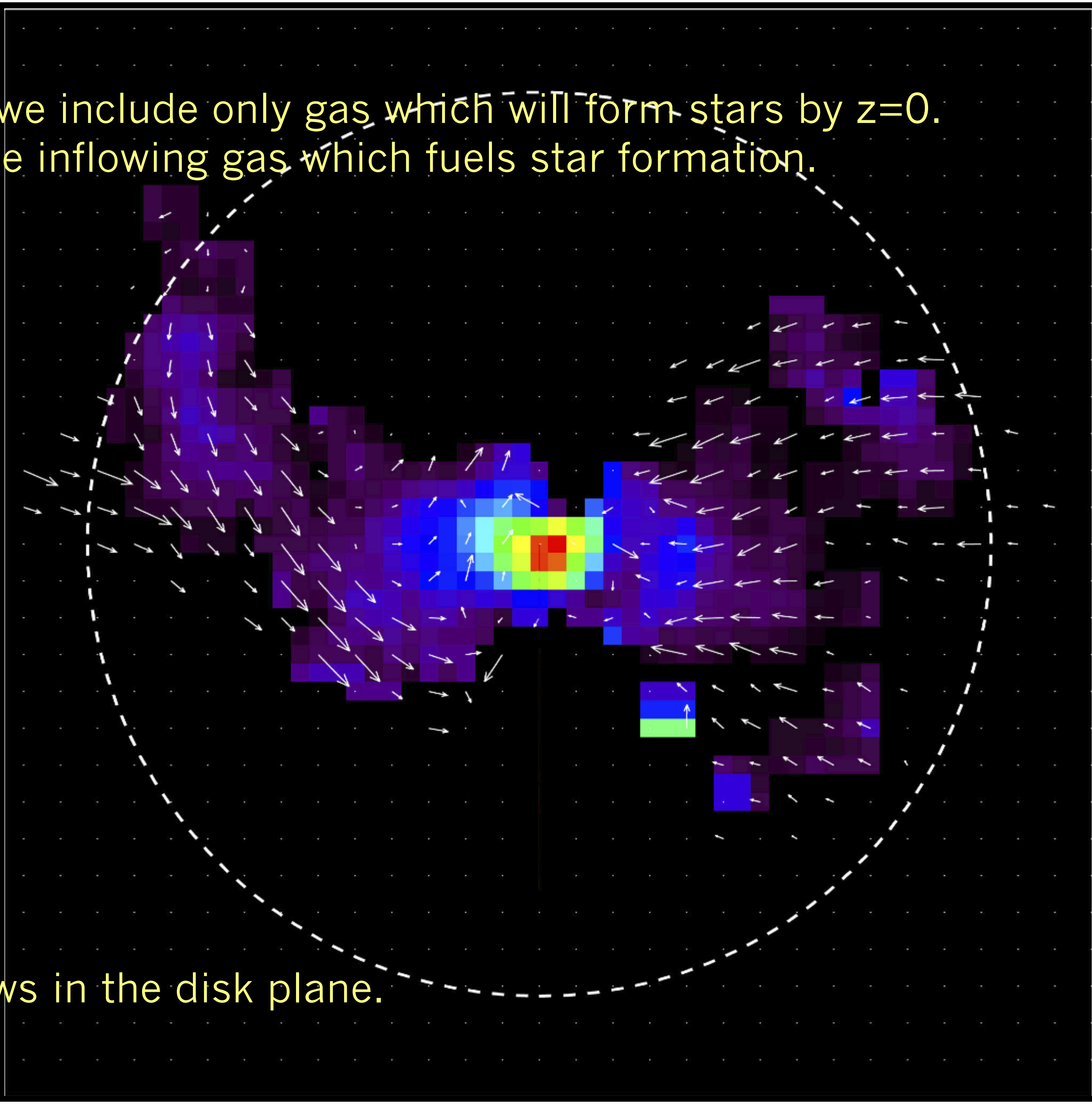
Outflows come from inner regions where star formation occurs and where angular momentum is relatively low. Extended HI gas disks found around isolated low mass galaxies (Broeils & Rhee 1997). These act as reservoirs of high angular momentum material

Gas density map with velocity vectors. The disk is edge on.
Snapshot at z~0.5.



Outflows perpendicular to the disk.

Here we include only gas which will form stars by z=0.
i.e. the inflowing gas which fuels star formation.

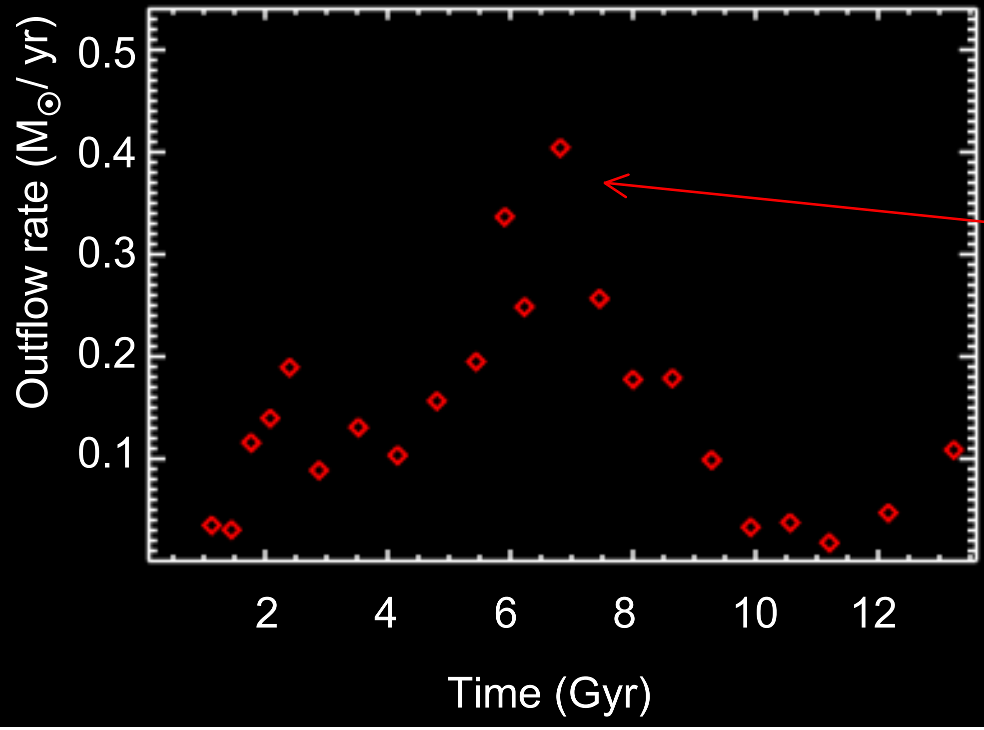


Inflows in the disk plane.

Why don't bulges form during mergers?

Our results are not reliant on chosing quiescent galaxies

The simulation analysed in this talk has a rich merger history



Merger induced star burst triggers outflows

This is the very material which has lost angular momentum during the merger

Some small scale problems with Cold Dark Matter

Catastrophic loss of Angular Momentum

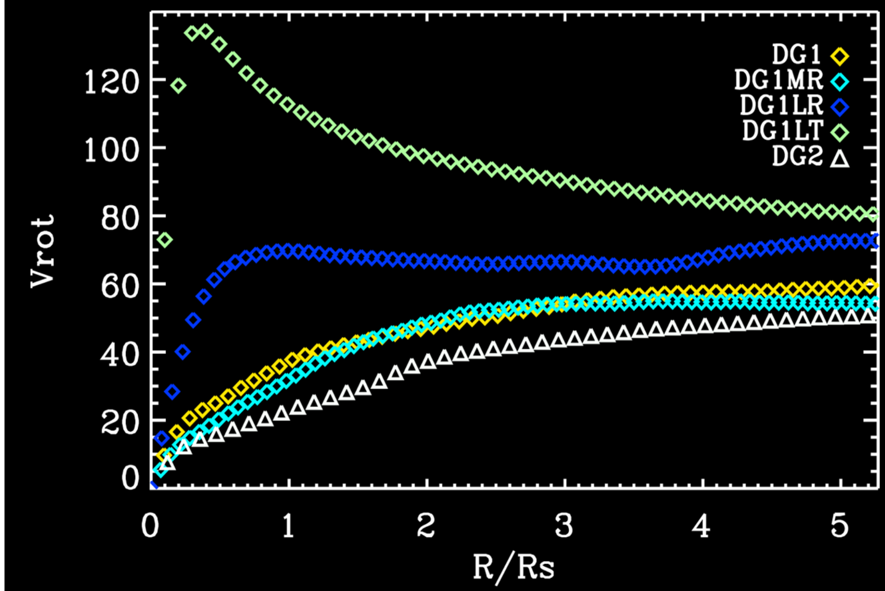
Inability to form bulgeless disk galaxies

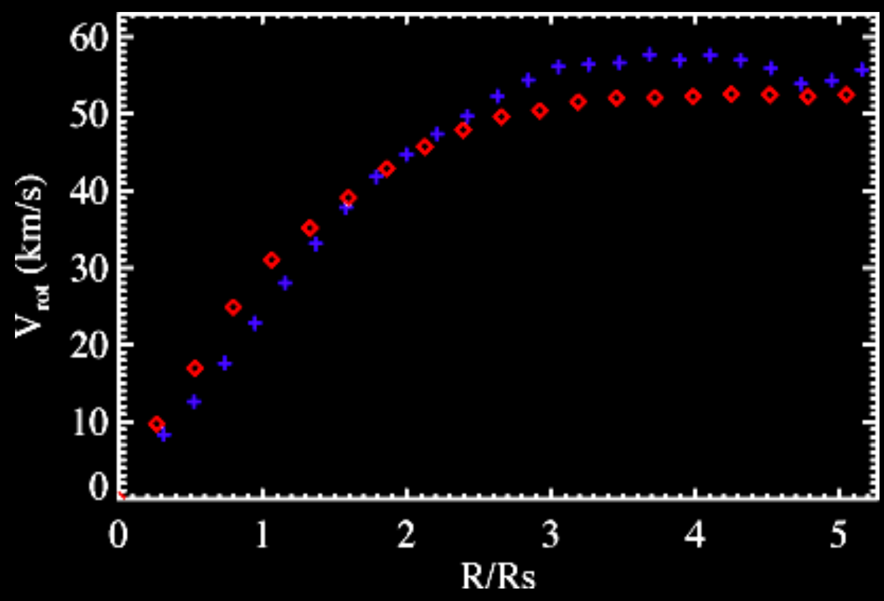
Distribution of Angular Momentum

Peaked rotation curves

Dark Matter profiles have cusps

Linearly Rising/Flat Rotation Curves





DG1	softening 84pc
DG1MR	110pc
DG1LR	436pc
DG1LT	low threshold, medium res
DG2	softening 84pc quiet merger history

◇ theoretical

\+ Tilted ring model

(using cold gas: George Rhee)

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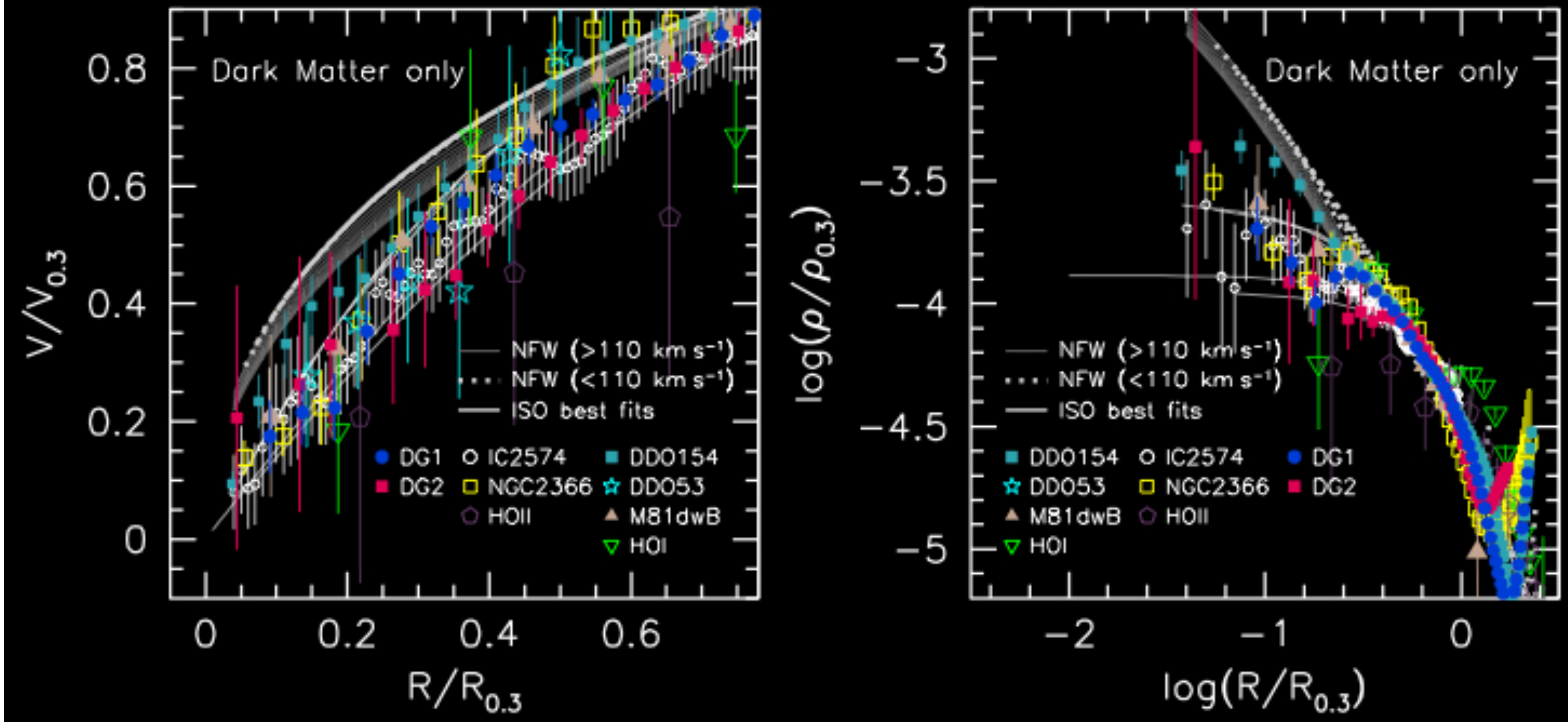
Linearly Rising and dark Matter Cores



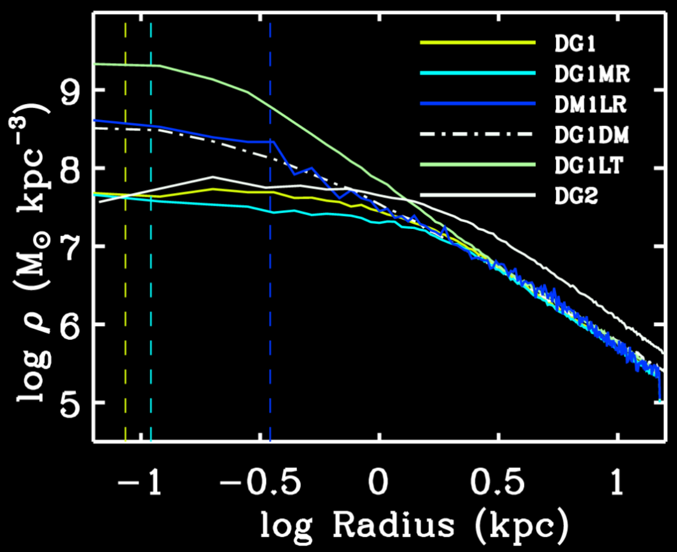
Oh, Brook et al. (in prep)

Dark Matter Cores

interactions/mergers trigger disk instabilities
→ star bursts → baryonic outflows
baryon density within ~1 kpc decreases repeatedly
timescales < than the local dynamical timescale
this reduces DM binding energy → expands.

inhomogeneous ISM → baryons and DM are spatially decoupled
→ local torques transfer energy from the baryons to the DM.

See also Navarro et al. 1996, Read et al. 2005, Tonini et al. 2006, Mashchenko et al 2008



DG1	86pc
DG1MR	110pc
DG1LR	436pc
DG1LT	low threshold, 110pc
DG2	86pc quiet merger history

Conclusions

Resolving star forming regions is the next step

Gas blowout arises naturally with our supernova recipes

Eject low angular momentum gas from high redshift cold flows

Simultaneous results on several outstanding problems:

- bulgeless disk galaxies
- linearly rising/flat rotation curves
- dark matter cores
- angular momentum distribution of baryons

Governato, Brook, Mayer et al. 2010 Nature
Brook et al 2010 (submitted very soon!)
Oh, Brook, Governato, Brinks, Mayer, De Bloc (submitted very soon!)

SDSS low z galaxies.