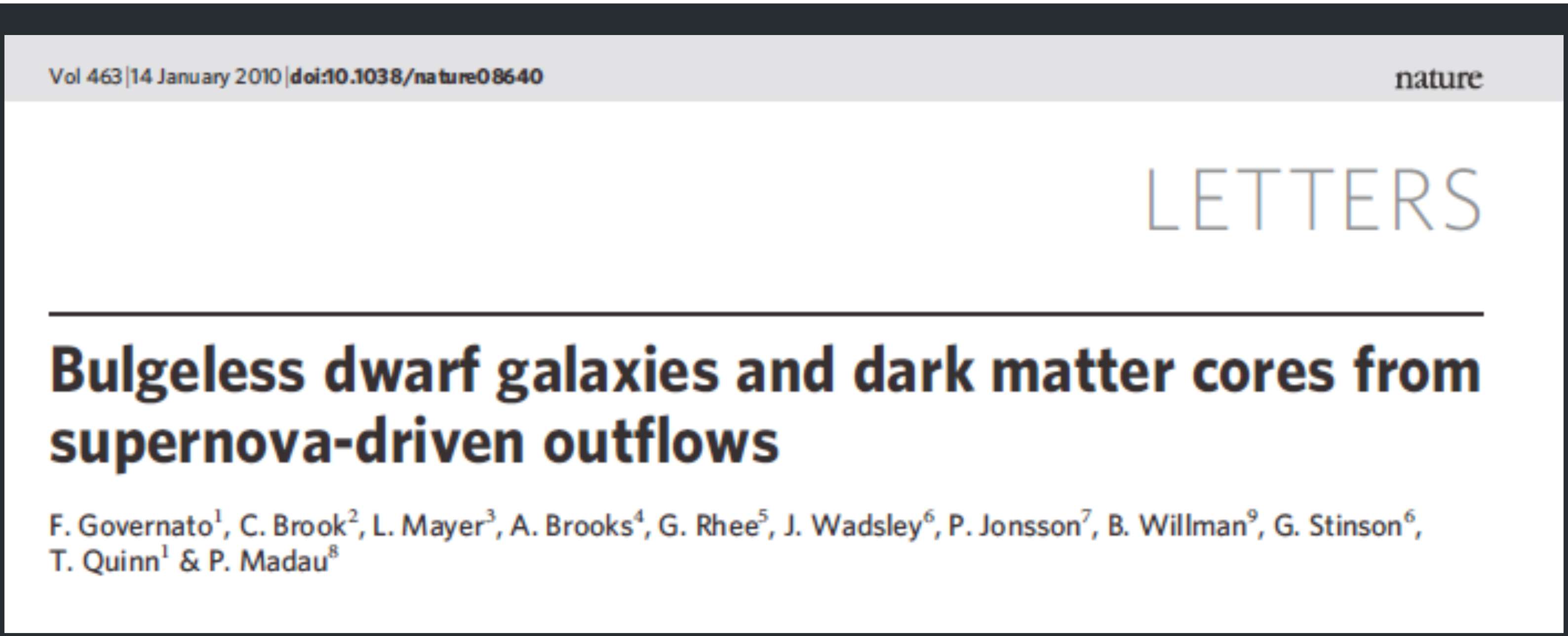
SC Summer '10

Bulgeless,Cored Disk Galaxies in a CDM Cosmology: Things you can do with GASOLINE and other SPH codes

F.Governato, T.Quinn, A.Brooks, C.Brook, L.Mayer, B.Willman, P.Madau ,G.Rhee, G.Stinson, A.Stilp. C.Christensen, Jillian Bellovary + Seon Oh (UCT) & Patrik Jonsson (UCSC)

And. . .

L.Pope, J. McCleary, F.Munshi and A.Zolotov



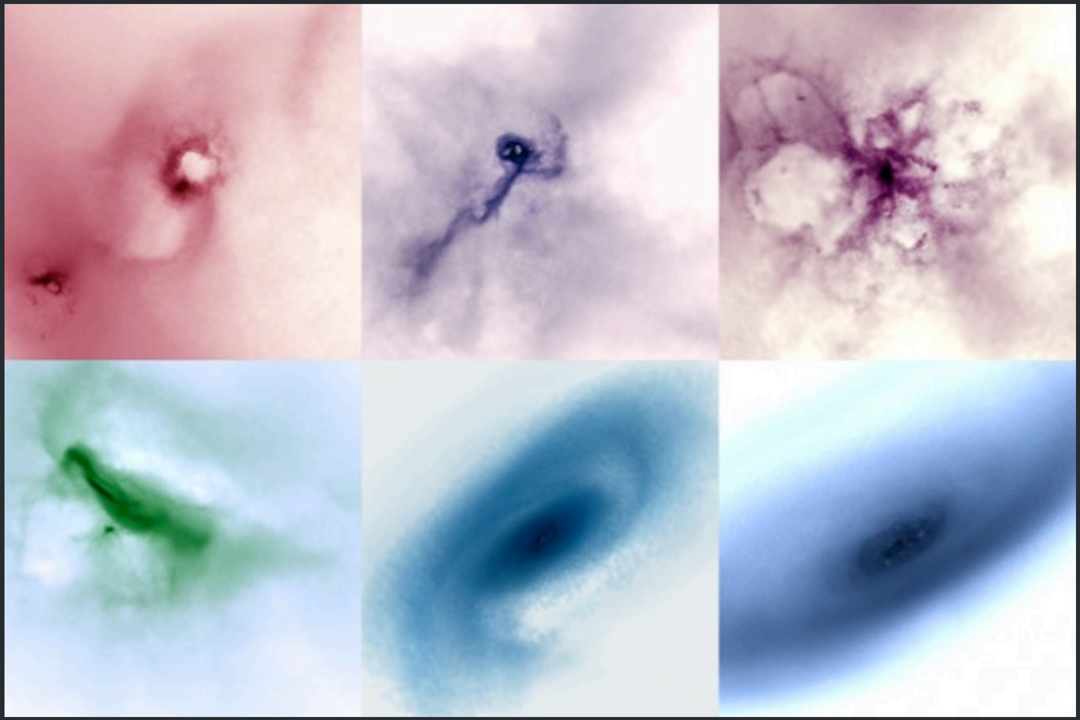
Vol 463 | 14 January 2010 | **doi:10.1038/nature08640**

nature

LETTERS

Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

F. Governato[1], C. Brook[2], L. Mayer[3], A. Brooks[4], G. Rhee[5], J. Wadsley[6], P. Jonsson[7], B. Willman[9], G. Stinson[6], T. Quinn[1] & P. Madau[8]



Science Drivers:

Physics: Processes affecting the Mass Distribution in Disk Galaxies

Robustness of Results: Comparing Simulations with Observations

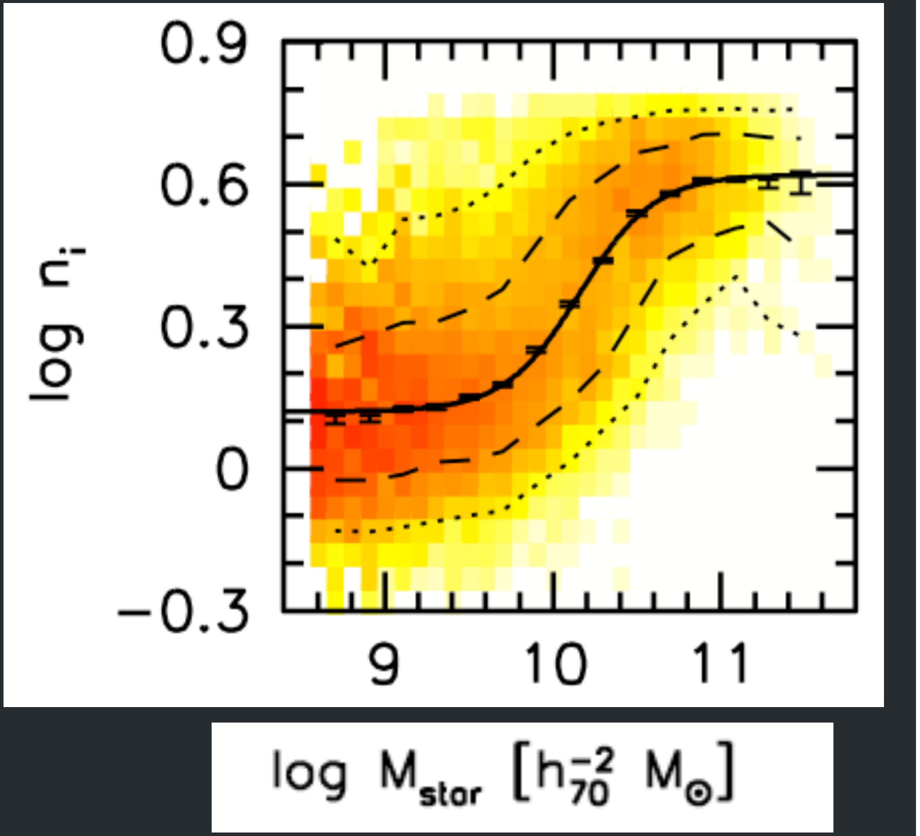
Think Big!: Solving the CDM Small Scales Crisis

Why Dwarf Galaxies?

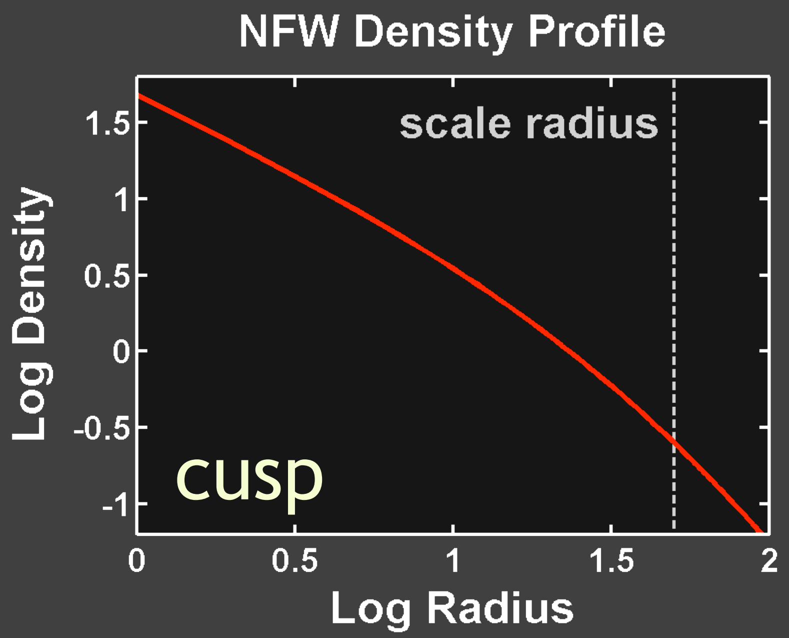
Observational Properties of Small galaxies I

- disk dominated (Sersic n =1)
- blue g-r < 0.6
- have DM cores of ~ 1kpc
- DM$_{core}$ rho < 10^8 M$_{sol}$ kpc-3

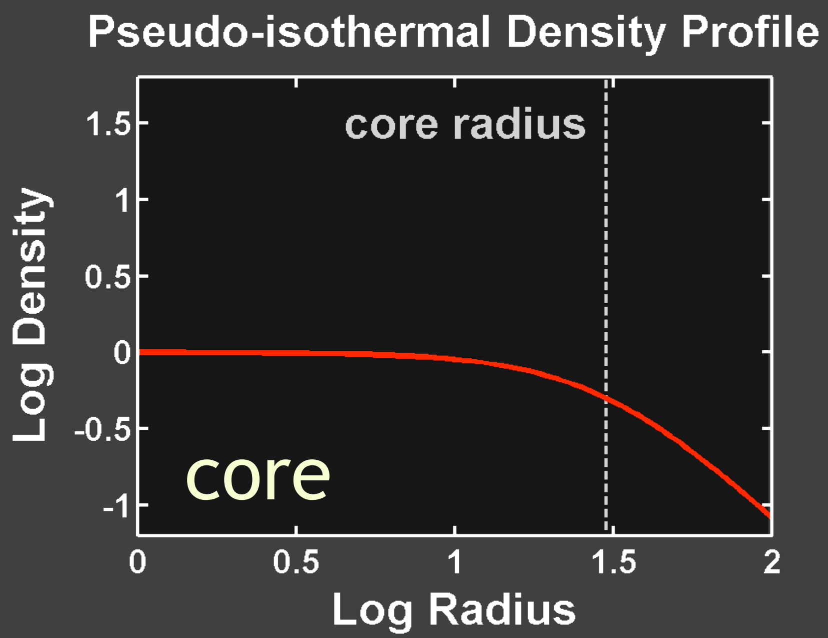
Dutton 08



The Cusp/Core Problem



NFW Density Profile



Pseudo-isothermal Density Profile

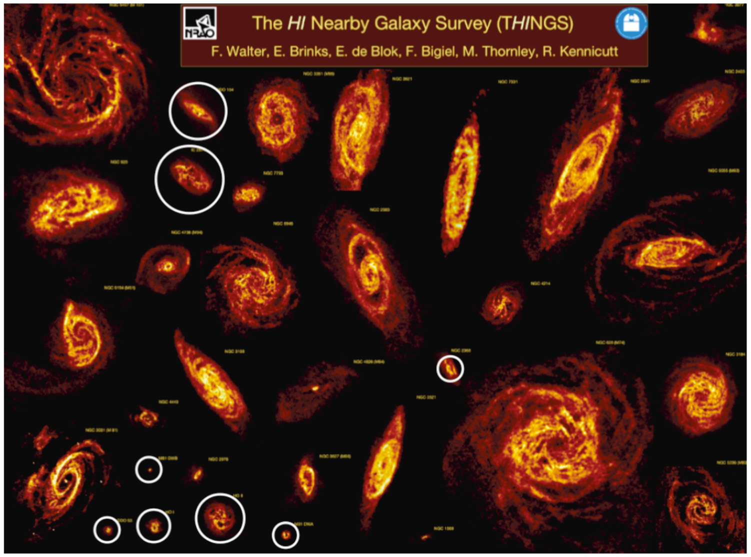
- Parametrize density profile as $\rho(r) \propto r^{-\alpha}$
  - Observations show $\alpha \sim 0$ (constant-density core)
  - Simulations predict $\alpha \sim 1$ (central cusp)

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

Recent progress on observations

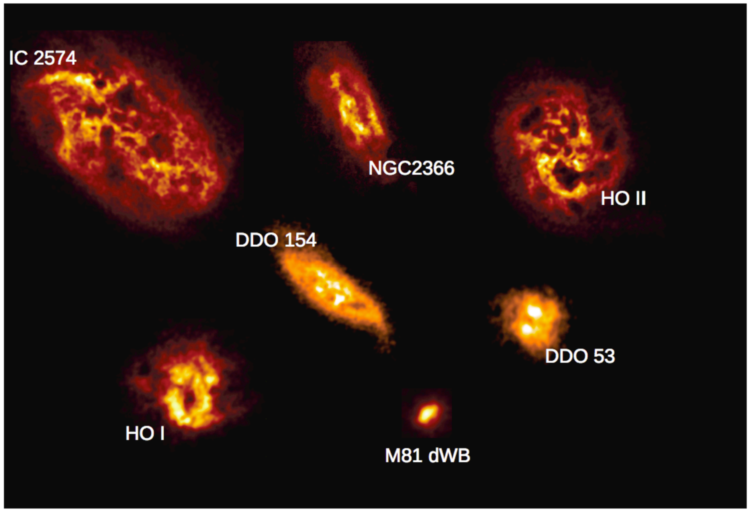
THINGS: The HI Nearby Galaxy Survey
(Walter et al. 2008)

- high angular (~6"; 100~300 pc) & spectral (2.5~5 km s^{-1}) resolution observations for 34 nearby (< 15 Mpc) galaxies
- complemented with multi-λ data (B, V, R, Spitzer SINGS 3.6 and 4.5 μm, CO, GALEX uv etc.)



7 THINGS dwarf galaxies

- dark matter dominated
- simple dynamical structure (no bulge and spirals)
- clear rotation pattern in the velocity field



Why Dwarf Galaxies?

It’s a well defined, long standing problem with a clear answer (most dwarfs are bulgeless and have cores).

We had software and computational resources to run simulations at much higher resolution than what had been done before.

New SF implementation that had not been tested in cosmological scenarios to z=0 (Ceverino, Dekel, Tasker…)

Field that had been neglected for a while. And feedback is more relevant in small halos as Vwinds> Escape velocity.

CDM Simulations had failed to form bulgeless dwarf galaxies…
why?

The Overcooling Catastrophe causes the formation of dense stellar spheroids.

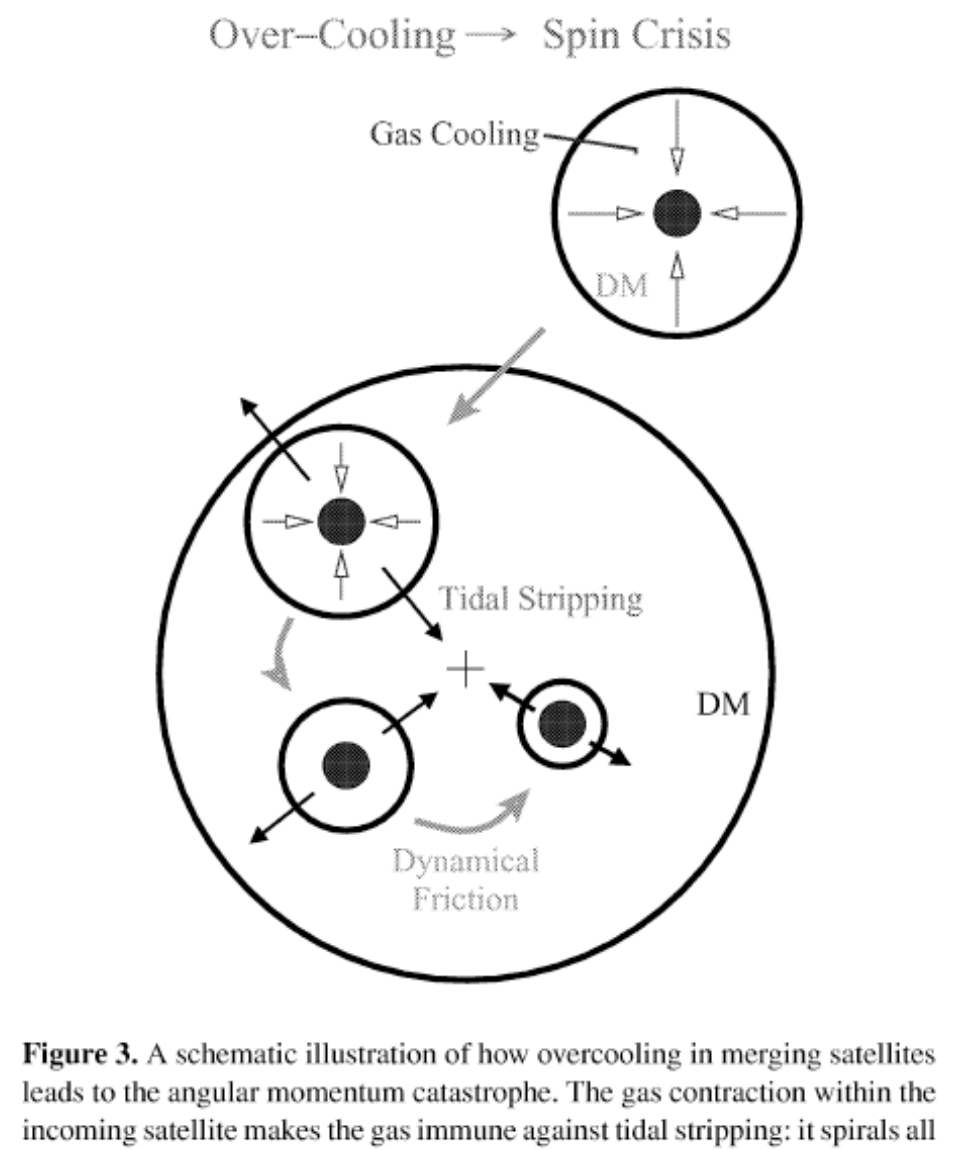


Figure 3. A schematic illustration of how overcooling in merging satellites leads to the angular momentum catastrophe. The gas contraction within the incoming satellite makes the gas immune against tidal stripping: it spirals all

Maller & Dekel 02

Disk Stars vs. DM halo
Angular Momentum Distribution.

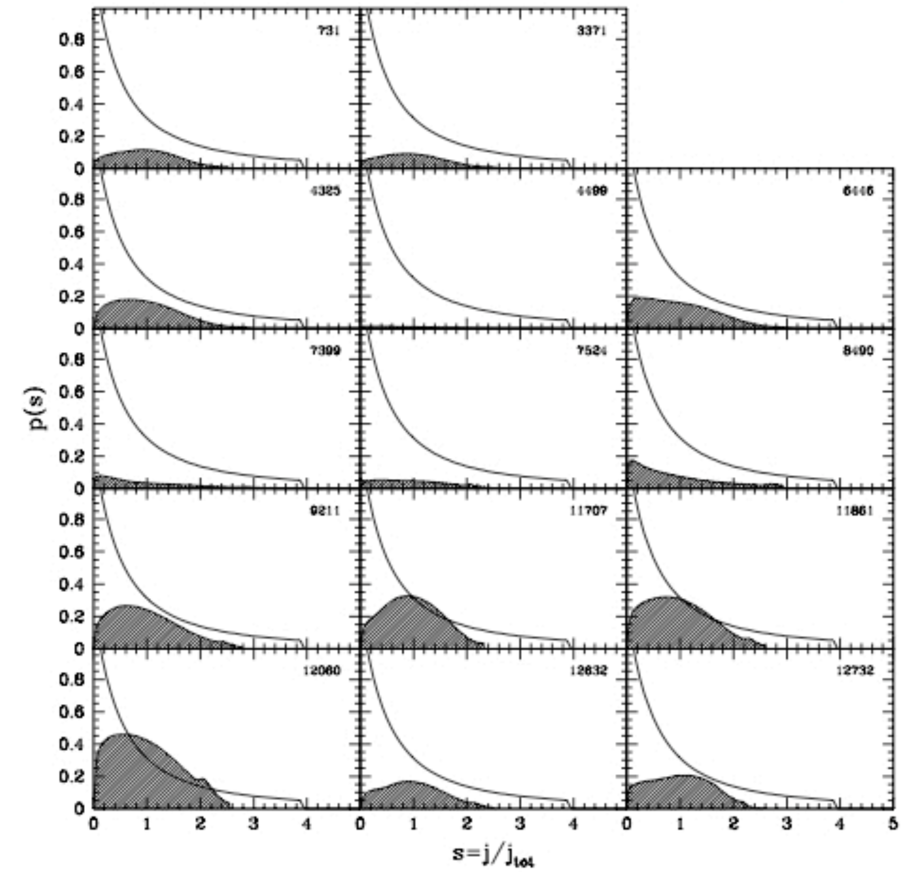


Figure 4. The shaded areas indicate the $p(s)$ of the AMDs for the 14 disc galaxies in our sample, normalized to $f_{\rm disc}/f_{\rm bar}$. For comparison we plot $p(s)$ of equation (11) with $\mu = 1.25$ (normalized to unity), and which represents the median of the AMDs of ΛCDM haloes. Under the standard assumption that baryons conserve their specific angular momentum the difference between the two distributions reflects the AMD of the baryonic matter that is not incorporated in the disc. Note that it is preferentially the baryonic matter with both the highest and the lowest angular momenta that is absent in the discs.

Where did the low J baryons go?

Van den Bosch et al 01
Bullock et al 01

Can we simulate dwarf galaxies that are

a) bulgeless

b) have a raising rotation curve

in a CDM cosmology?

Can the angular momentum problem be solved
without a major revision of the CDM model?
How do we create DM cores?

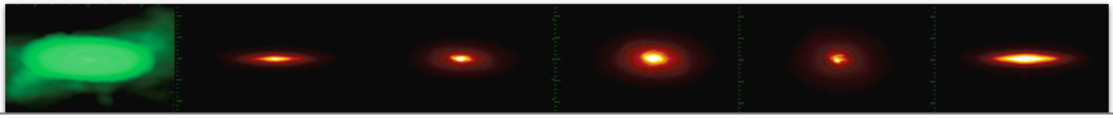
Baryons and DM
are too
concentrated…

Is it the end for
CDM?

New high-resolution SPH simulations of dwarf galaxies

(Governato et al. 2010, nature)

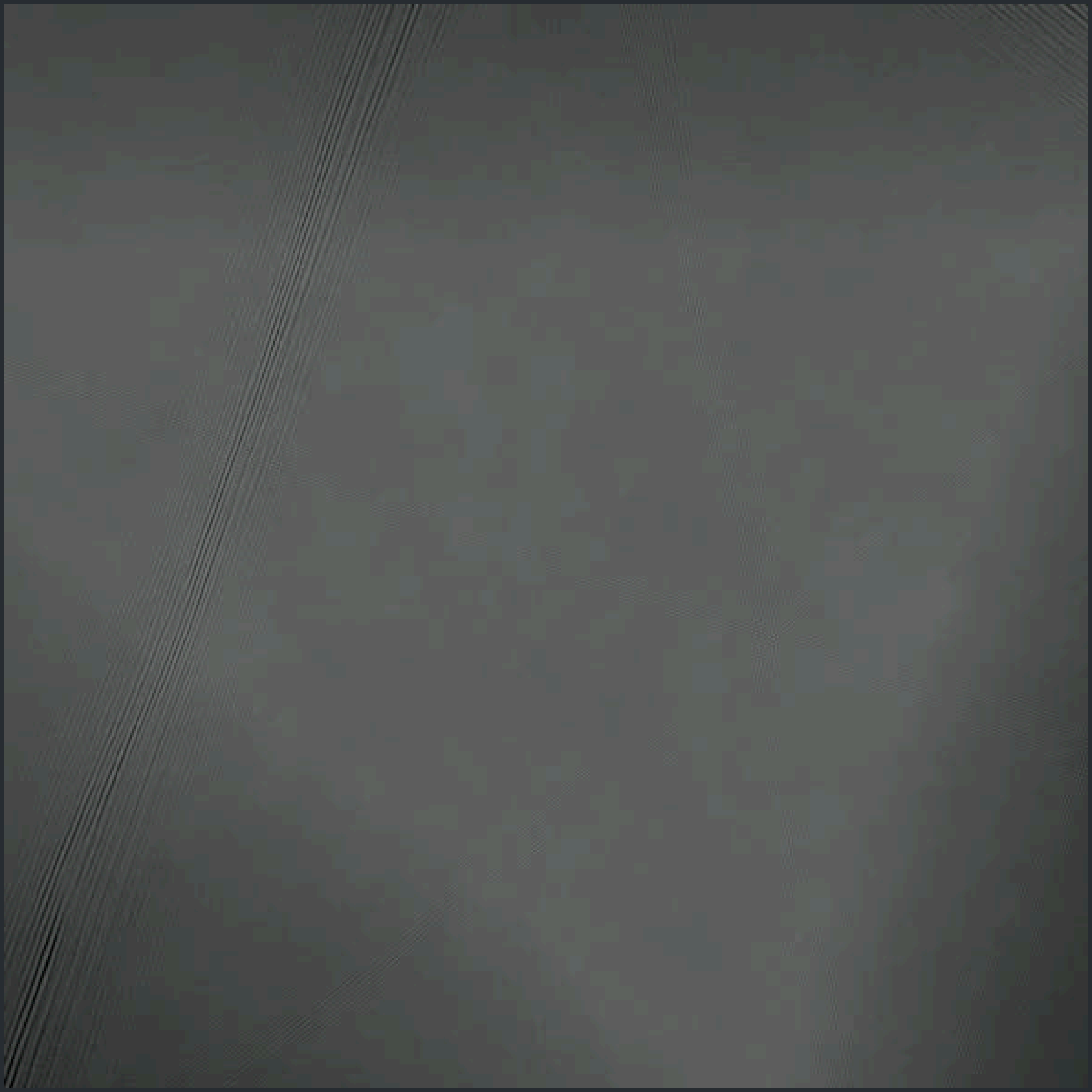
- N-body+SPH tree-code GASOLINE
- Flat Λ-dominated cosmology
- Baryonic processes are included such as,
  - gas cooling (v2.0 adds metal lines +H2 cooling)
  - cosmic UV field heating
  - star formation
  - SNe-driven gas heating
- There are ~3.3 million particles within the virial radius at $z = 0$.
- DM particle mass is $1.6\times10^4\ M_\odot$, and gas particle mass is $3.3\times10^3\ M_\odot$.
- The force resolution (gravitational softening) is 86 pc.



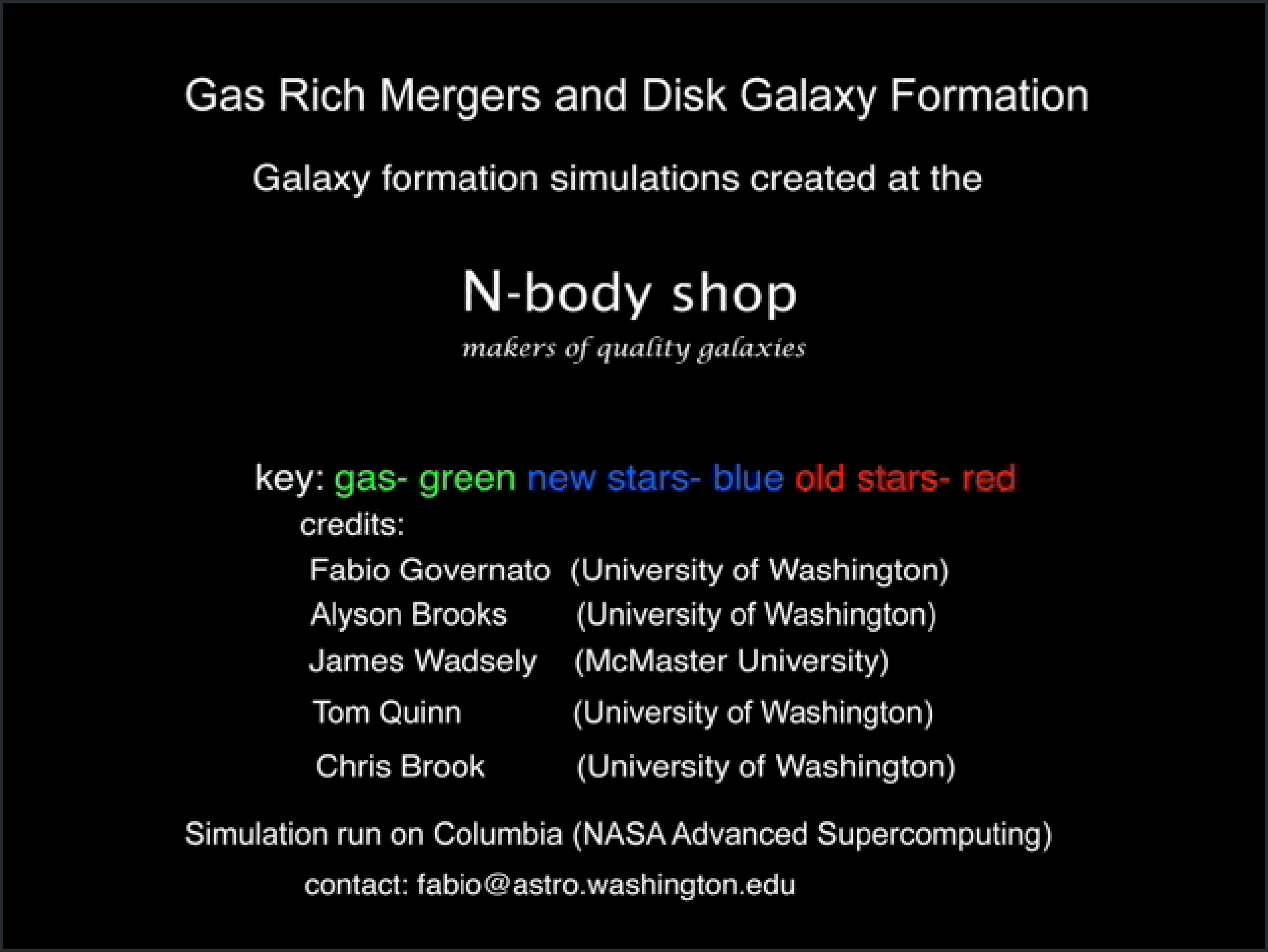
Treecode+SPH simulations are particle based.
Particles represent the mass distribution of dark matter, stars and gas in the region of interest. In each output the following information is available for each particle:

CodeOutput:	DM	gas	stars
Mass	x	x	x
x,y,z	x	x	x
vx,vy,vz	x	x	x
Rho		x	
Temperature		x	
Metal fraction		x	x
Oxygen,Iron		x	x
Time of formation			x
IMF			x
Trackable	x	x	x

1- Cosmological Volumes



Or ' Zoomed in' simulations?



Gas Rich Mergers and Disk Galaxy Formation

Galaxy formation simulations created at the

N-body shop

makers of quality galaxies

key: gas- green new stars- blue old stars- red

credits:

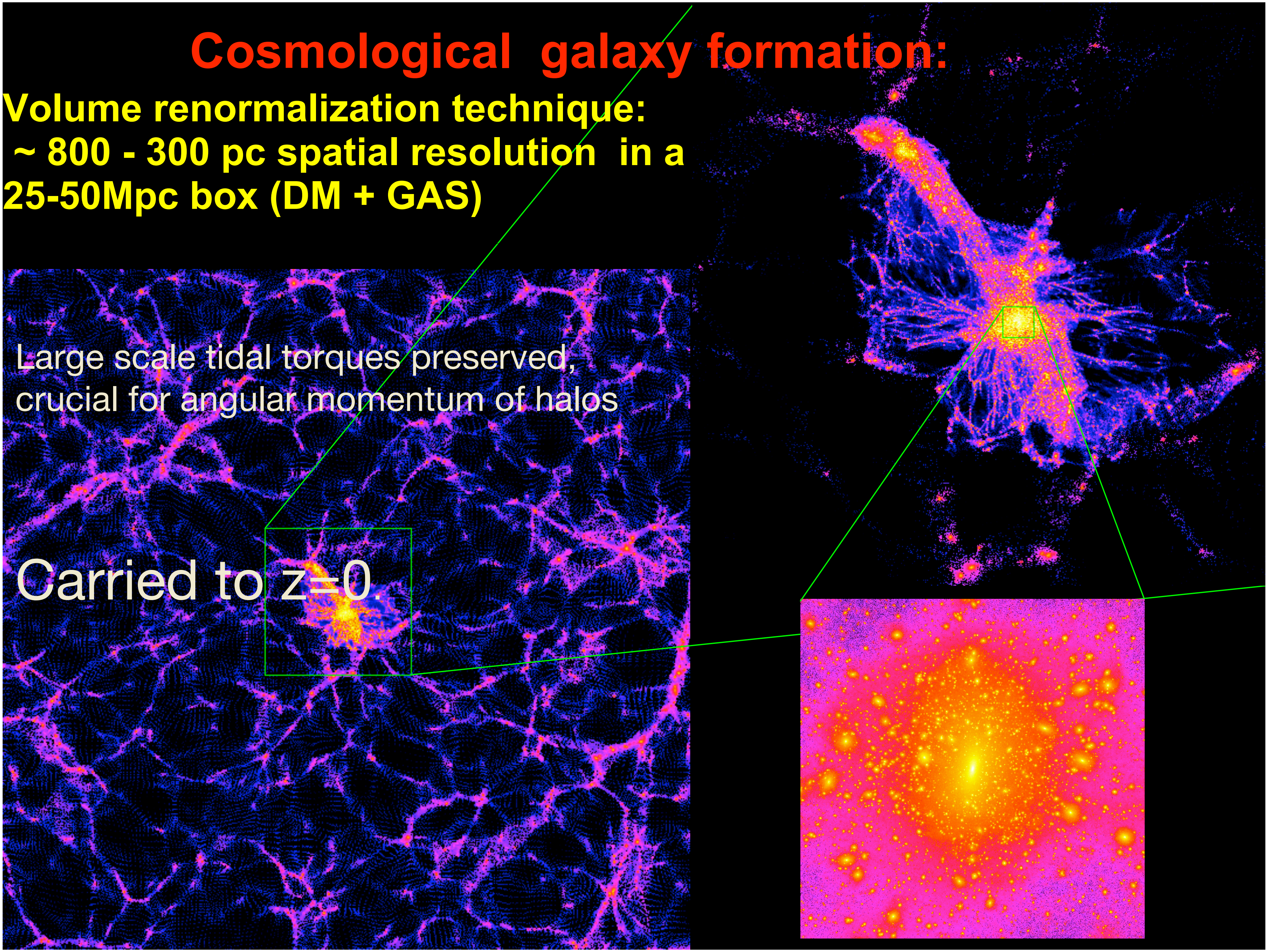
Fabio Governato	(University of Washington)
Alyson Brooks	(University of Washington)
James Wadsely	(McMaster University)
Tom Quinn	(University of Washington)
Chris Brook	(University of Washington)

Simulation run on Columbia (NASA Advanced Supercomputing)

contact: fabio@astro.washington.edu

Cosmological galaxy formation:

Volume renormalization technique:
~ 800 - 300 pc spatial resolution in a 25-50Mpc box (DM + GAS)



Large scale tidal torques preserved, crucial for angular momentum of halos

Carried to z=0.

Advantages of Cosmological Volumes vs ‘Zoomed-in’ simulations

- Larger Statistical sample
- Spatial distribution of objects
- Possibility of selecting different galaxy populations
- Can connect different galaxy populations through time.

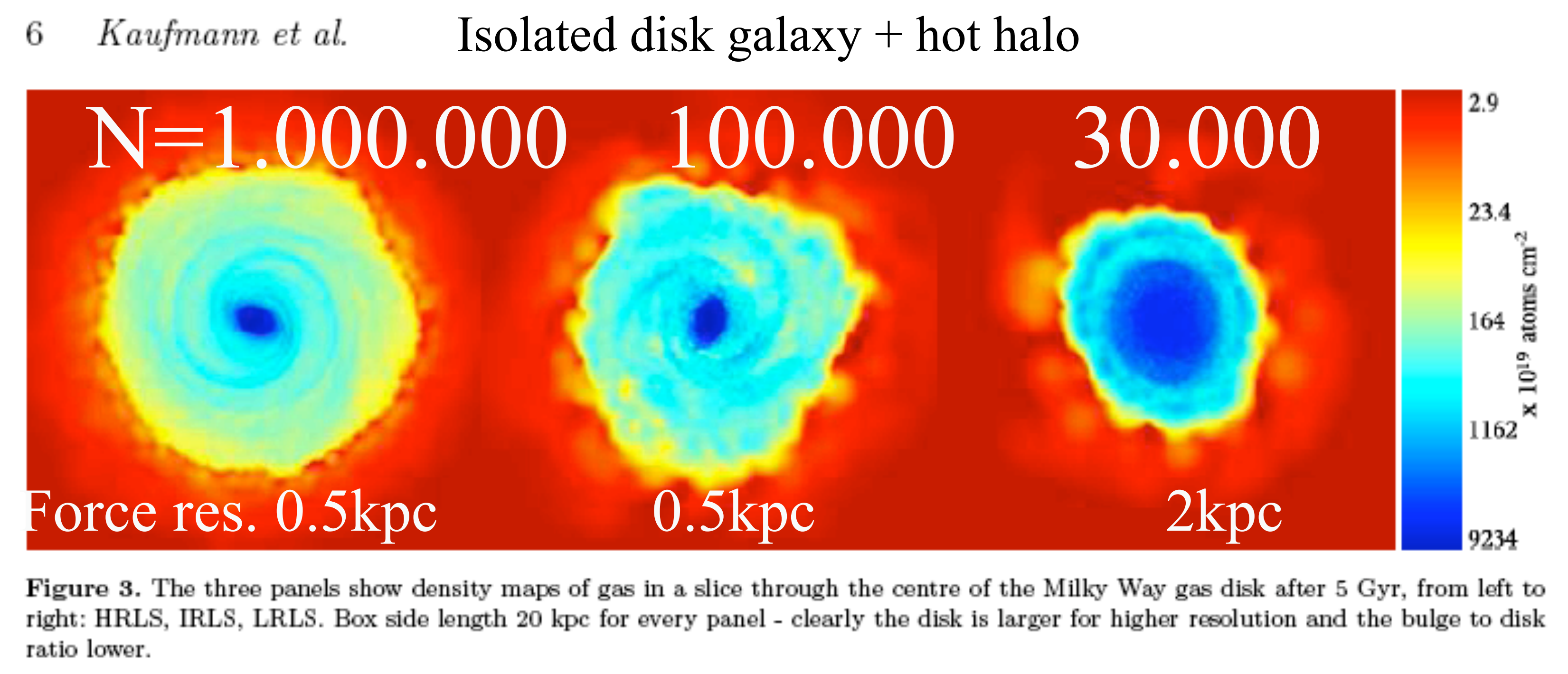
Advantages of ‘Zoomed-in’ simulations’ vs Cosmological Simulations.

- Numerical effects are greatly diminished and/or can be better evaluated.

See review by L. Mayer, F. Governato & T.Kaufmann 08

Increased resolution reduces artificial angular momentum loss in gaseous disks

(loss is caused by artificial viscosity and torques)

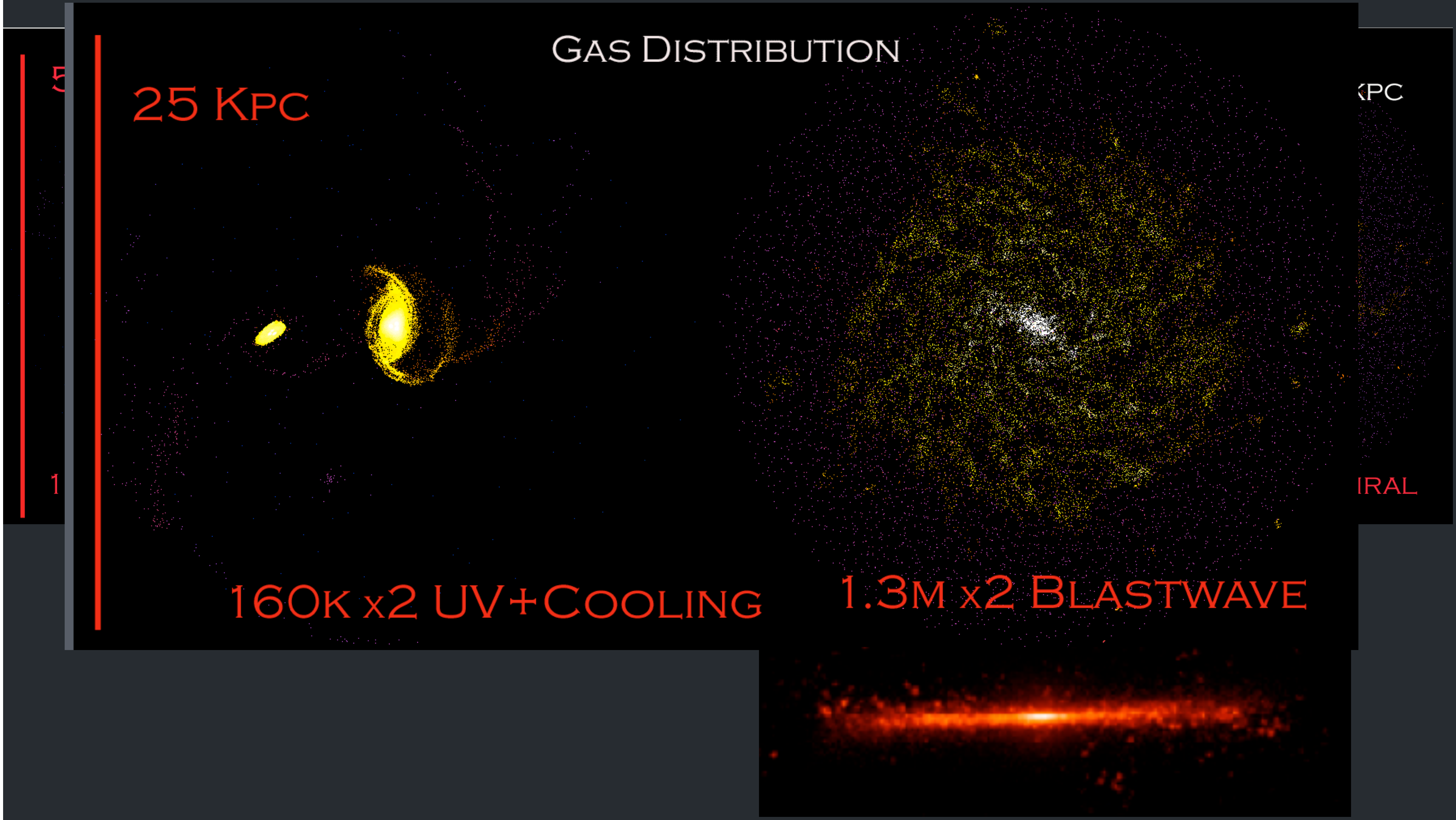


6 *Kaufmann et al.*

Isolated disk galaxy + hot halo

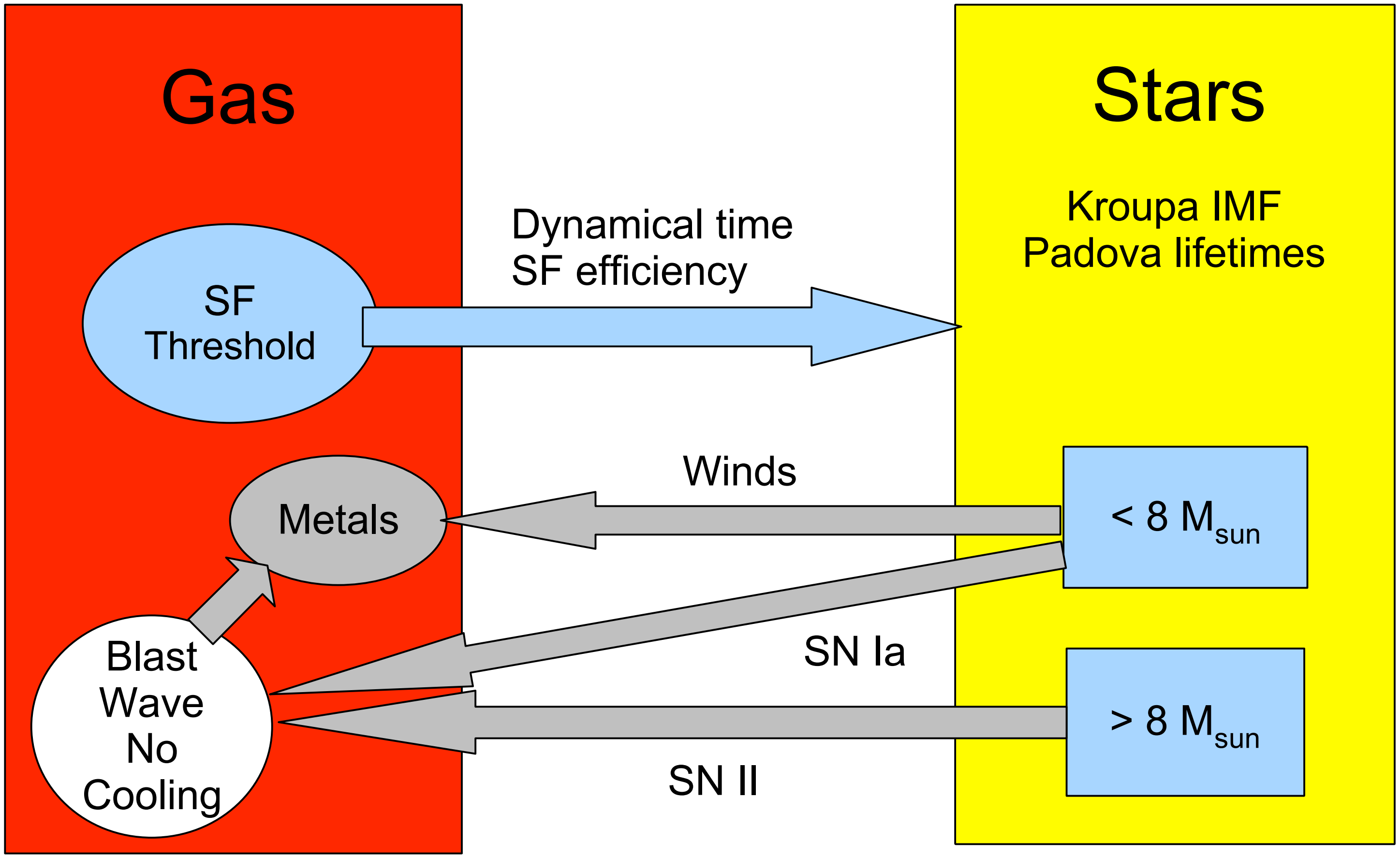
Figure 3. The three panels show density maps of gas in a slice through the centre of the Milky Way gas disk after 5 Gyr, from left to right: HRLS, IRLS, LRLS. Box side length 20 kpc for every panel - clearly the disk is larger for higher resolution and the bulge to disk ratio lower.

Size of Disks: Cold gas



Feedback reduces physical angular momentum loss during the build up of disks.

Star Formation/Feedback



Gas

SF Threshold

Metals

Blast Wave No Cooling

Dynamical time
SF efficiency

Winds

SN Ia

SN II

Stars

Kroupa IMF
Padova lifetimes

$< 8\ M_{sun}$

$> 8\ M_{sun}$

Stinson et al 2006

2 free parameters: C*, eSN

Star Formation and feedback scheme gives a physically motivated description of *the effects of SN feedback at unresolved scales*.

Only two free parameters:

- star formation efficiency (0.05 - 0.1)
- fraction of SN energy coupled with ISM (0.4-1)

Governato et al 07,09,10, Brooks 07 Stinson et al 07.

Requirement to properly create outflows:

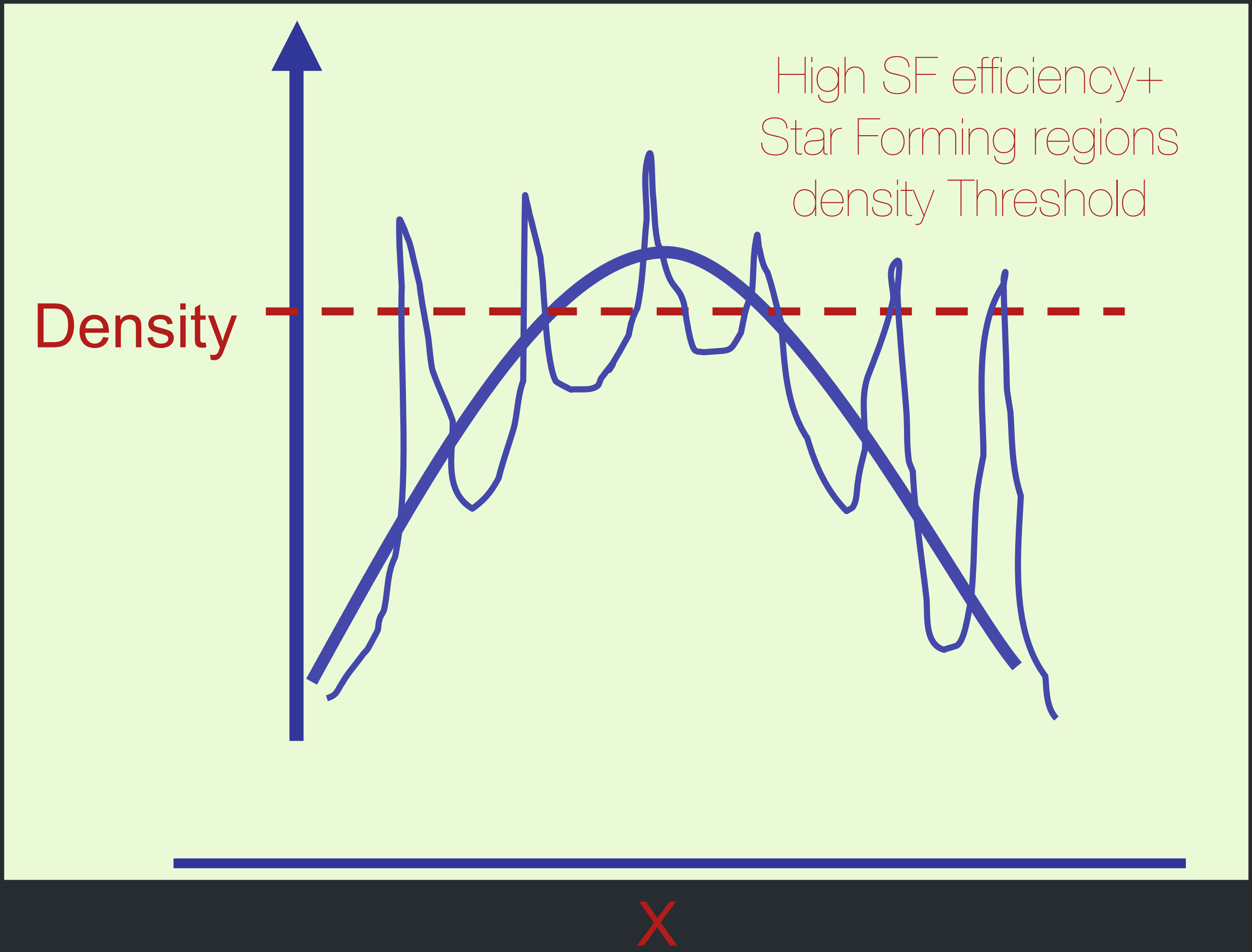
resolve IGM structure “enough”
to resolve individual star forming regions.

In practice: resolve regions with density
higher 100 amu/cm^3
where HII would be dominant.

spatial density < 150 pc
gas particle mass < 10^4 M_{sol}

(Ceverino+ 07, Tasker+ 08, Robertson & Kravtsov 08)

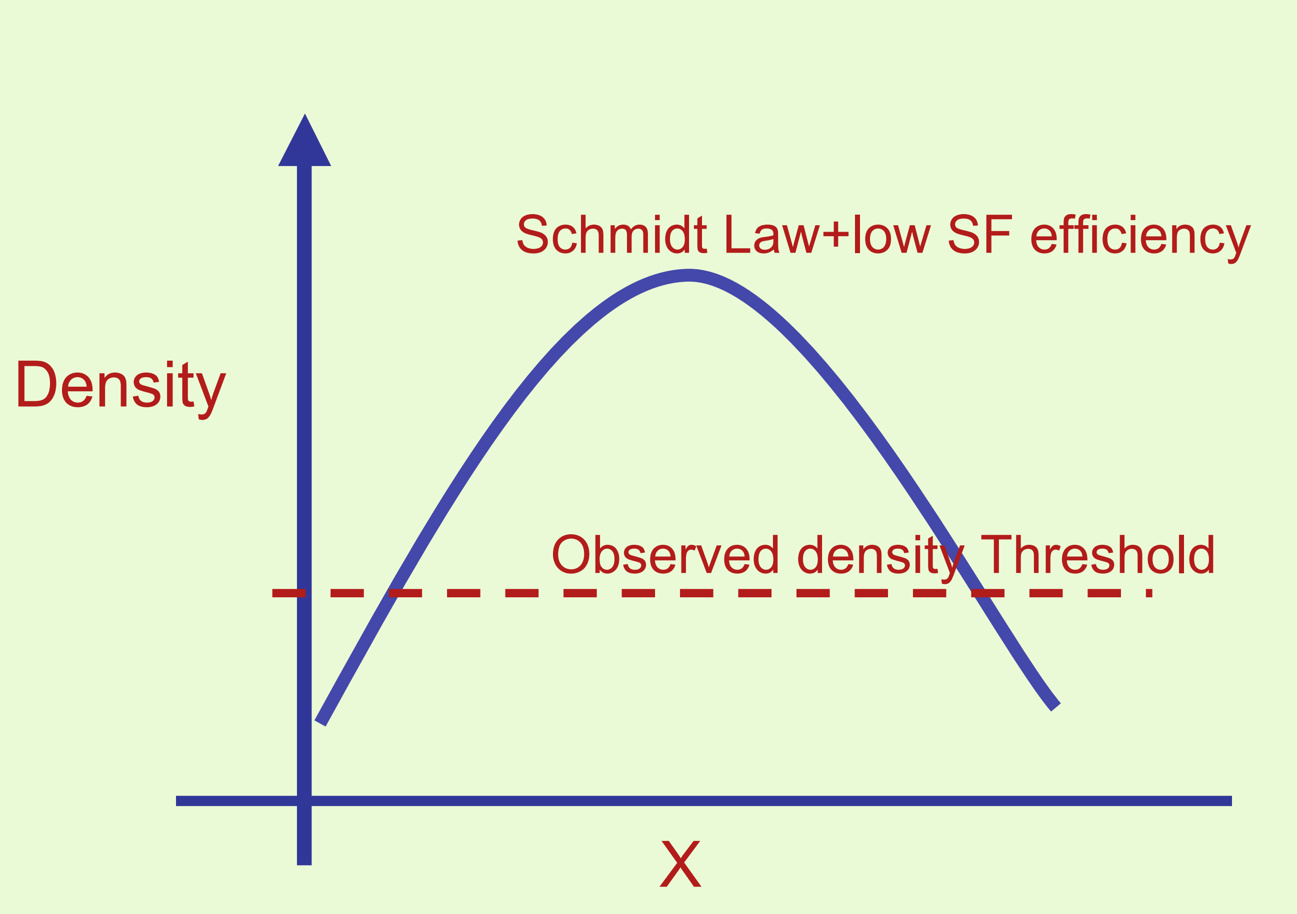
High vs Low Resolution SF



Feedback becomes more efficient.

(more outflows per unit mass of stars formed)

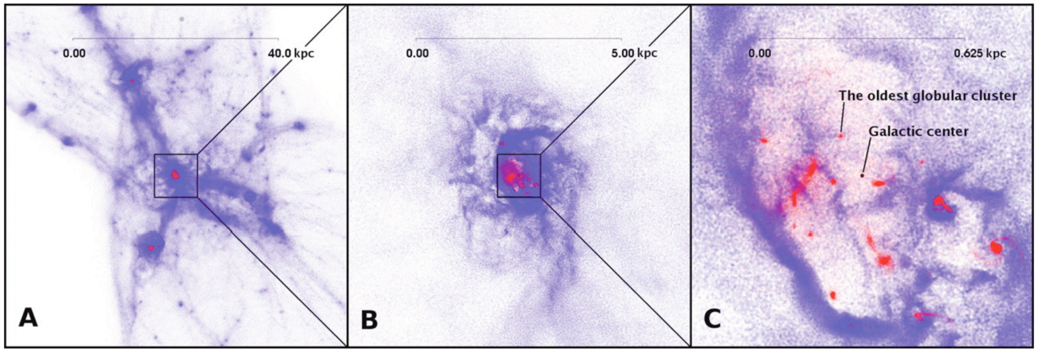
But where should we form stars?
High vs Low Resolution SF



Baryonic feedback on the central cusps

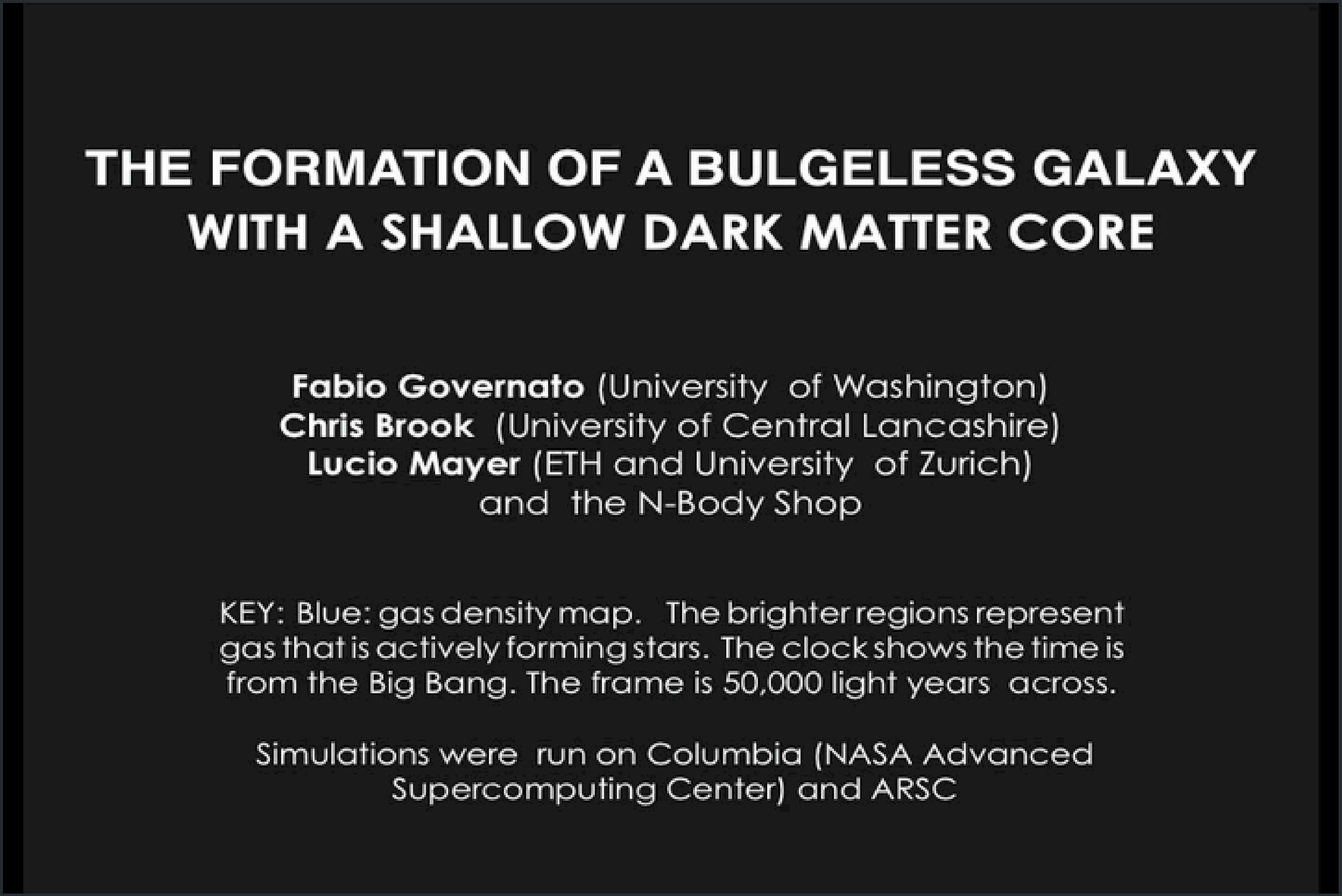
- Gas winds created by SNe explosions are efficient to remove (selectively) low-angular-momentum baryons from the galaxy centres (e.g., Binney et al. 2001).
- Orbital energy loss of gas clouds due to dynamical friction can transfer energy to the galaxy centres (e.g., Mo et al. 2004).
- For these, modelling the formation of a highly inhomogeneous multi-phase ISM is critical (e.g., Robertson & Kravtsov 2008).
- These schemes have been applied to high-z (z=5.0) protogalaxies (Mashchenko et al. 2008)

Mashchenko et al. (2008)



Does it really work?

Simulations of dwarf galaxies in a cosmological context.



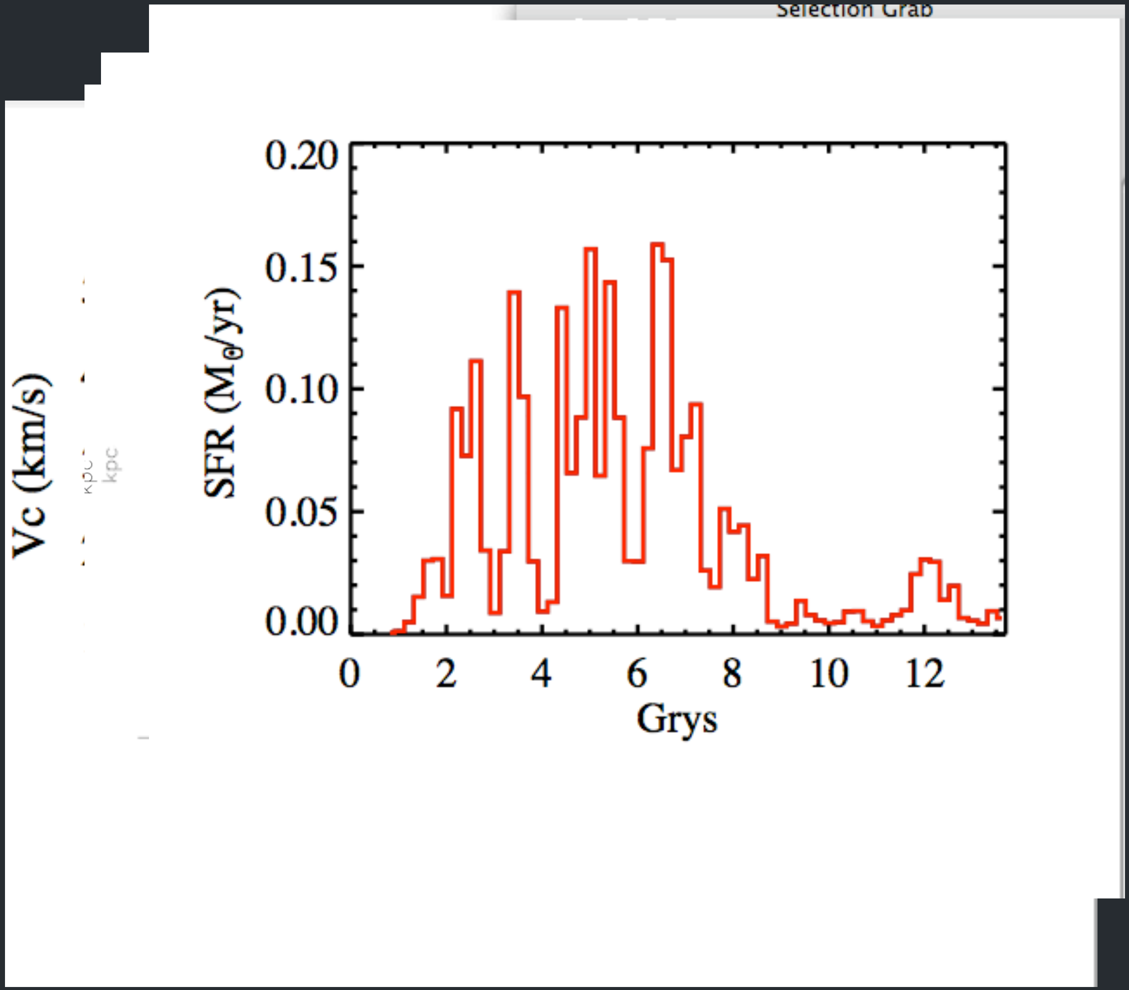
THE FORMATION OF A BULGELESS GALAXY WITH A SHALLOW DARK MATTER CORE

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 is from the Big Bang. The frame is 50,000 light years across.

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

Dwarf Galaxy Properties



Bursty SF

Holes in HI distribution

HI turbulence 5-10 km/sec

Raising Rotation Curve.

Less than 10% of gas turned into stars.Baryons only 30% of cosmic abundance at z=0

Theoretical predictions must be compared with real data by creating “artificial observations”. I.e. going from the mass distribution to “light distribution”

This is more robust than doing the opposite: noisy data, observational biases, uncertainty in going “from light to mass”

How to compare with real galaxies?

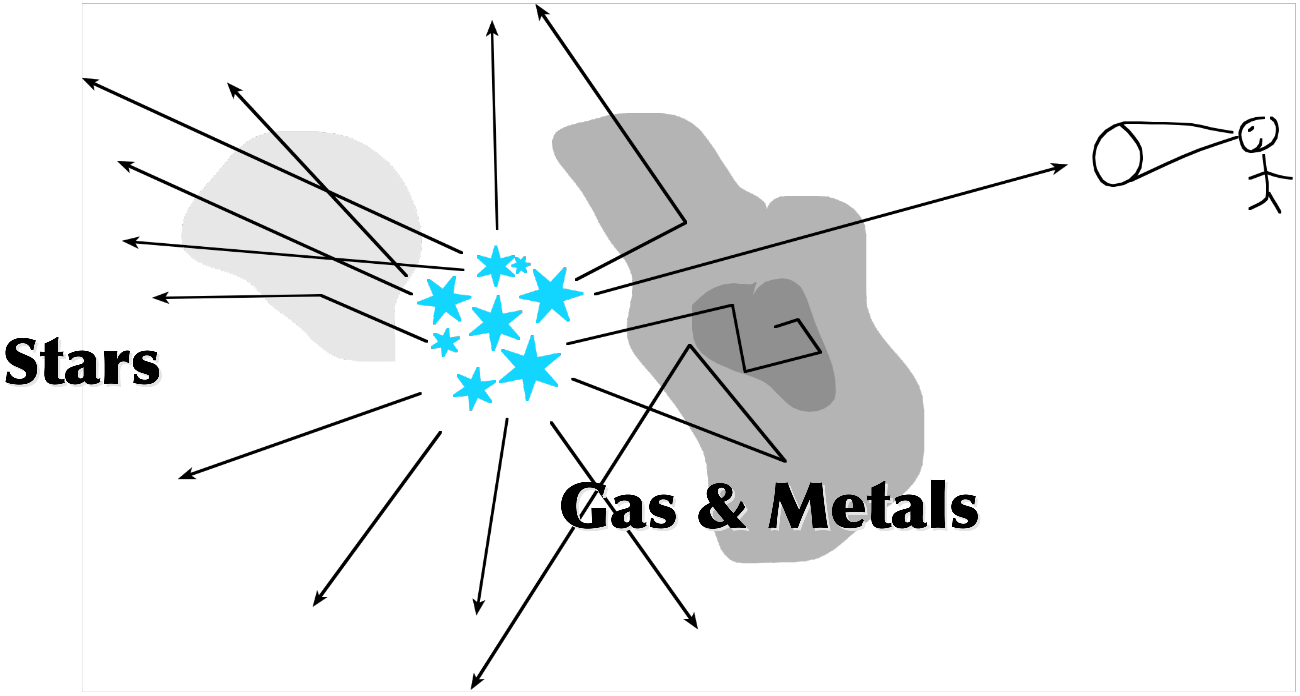
Enters 'SUNRISE',
a set of programs that
create artificial images of
galaxies, including the
effects of
dust absorption.

(courtesy of P. Jonsson)

Using Sunrise...

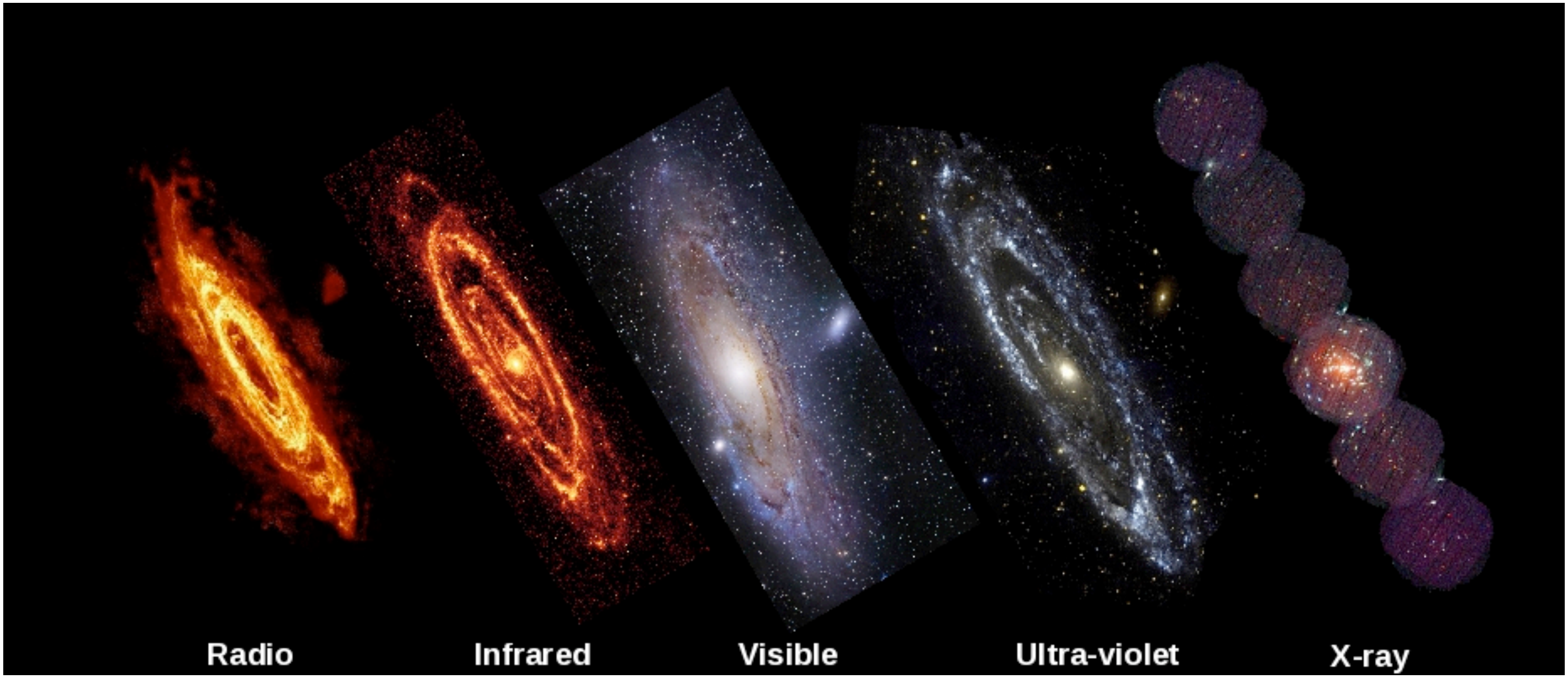
Monte-Carlo method

“Photons” are emitted and scattered/absorbed stochastically
(courtesy Patrik Jonsson)
http://www.ucolick.org/~patrik/sunrise/



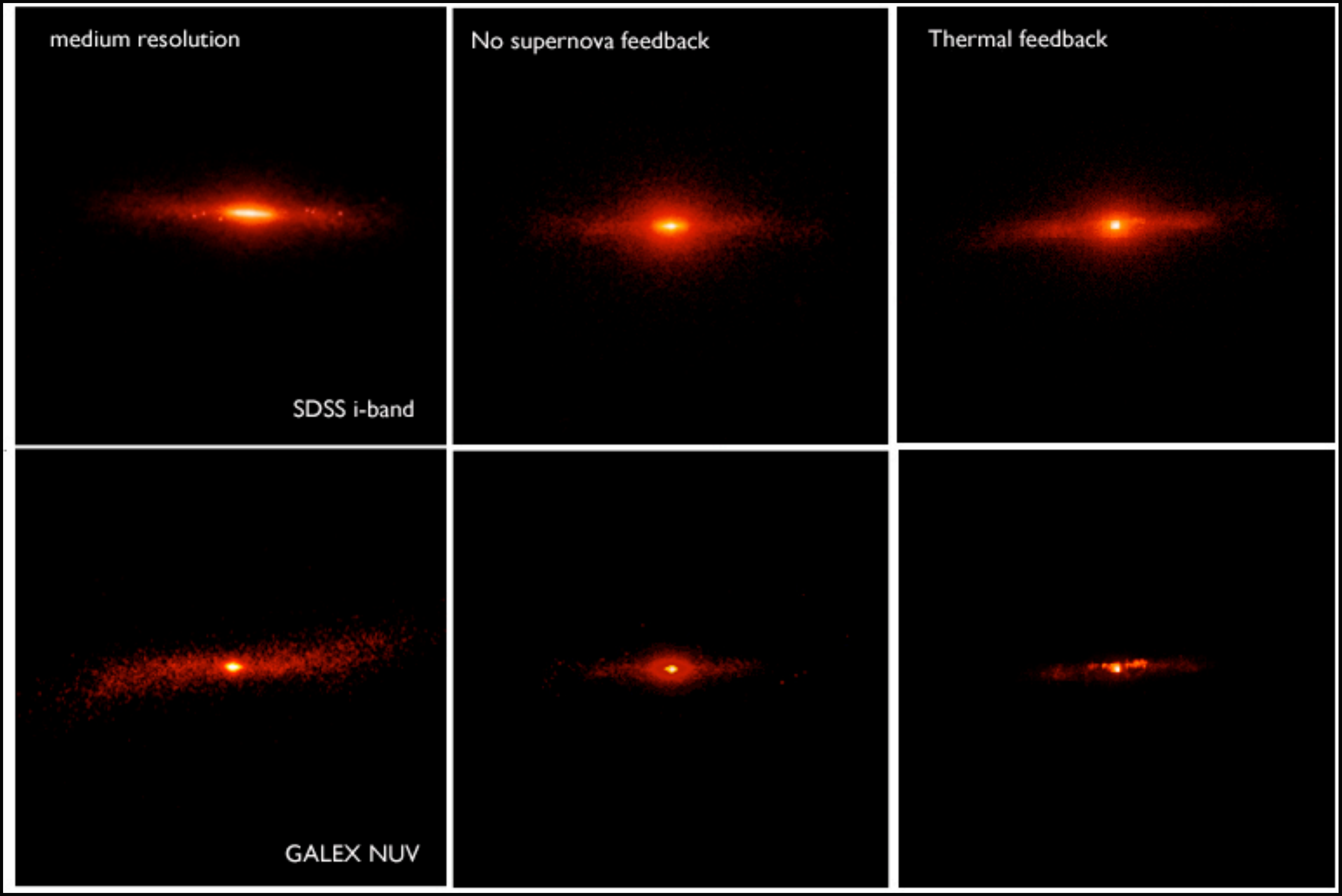
Dust follows the metal distribution of the gas component

See also codes by Narayanan and Chakrabarti



ESA - Planck

(Blastwave) Feedback makes larger disks

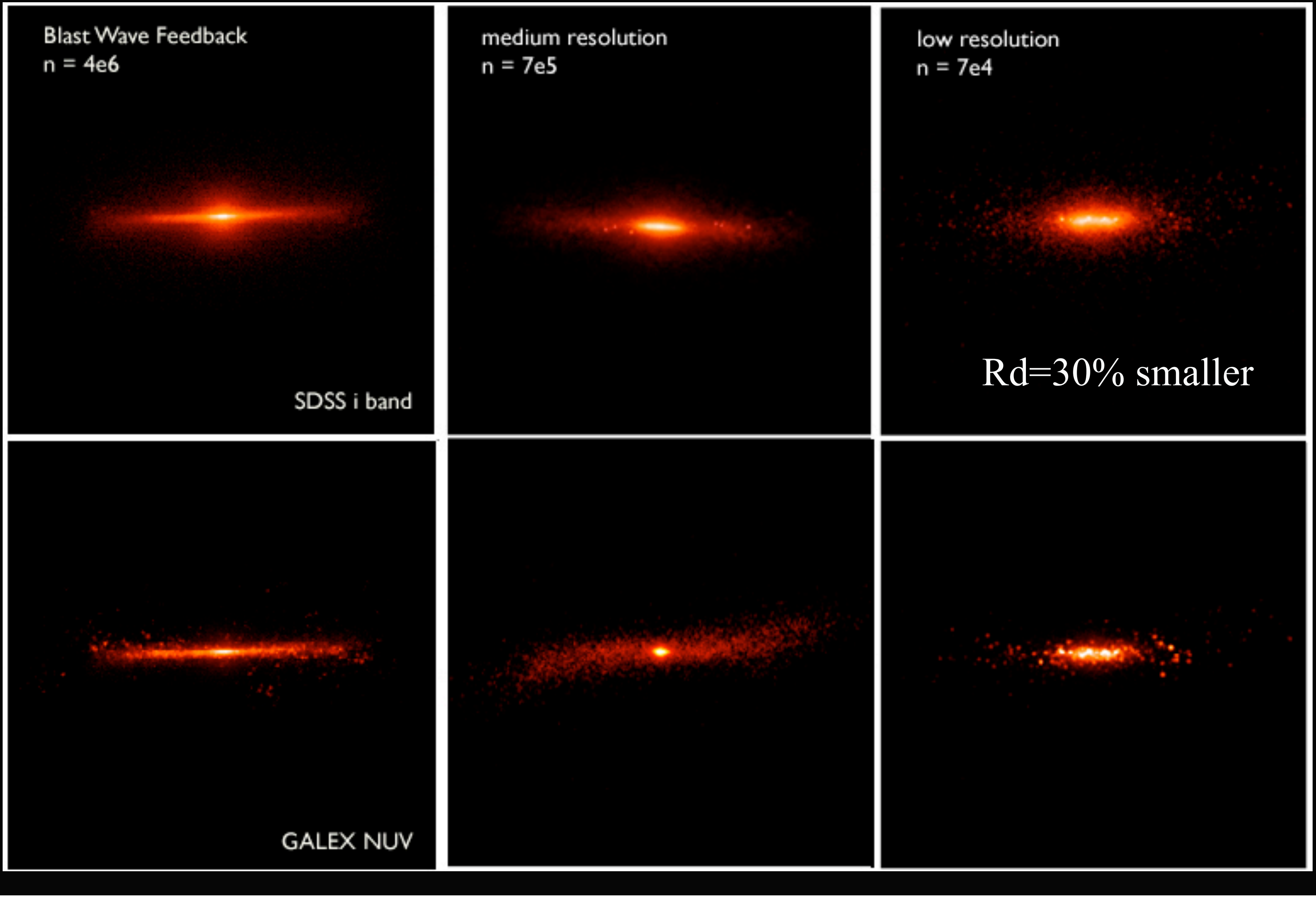


..and so does resolution

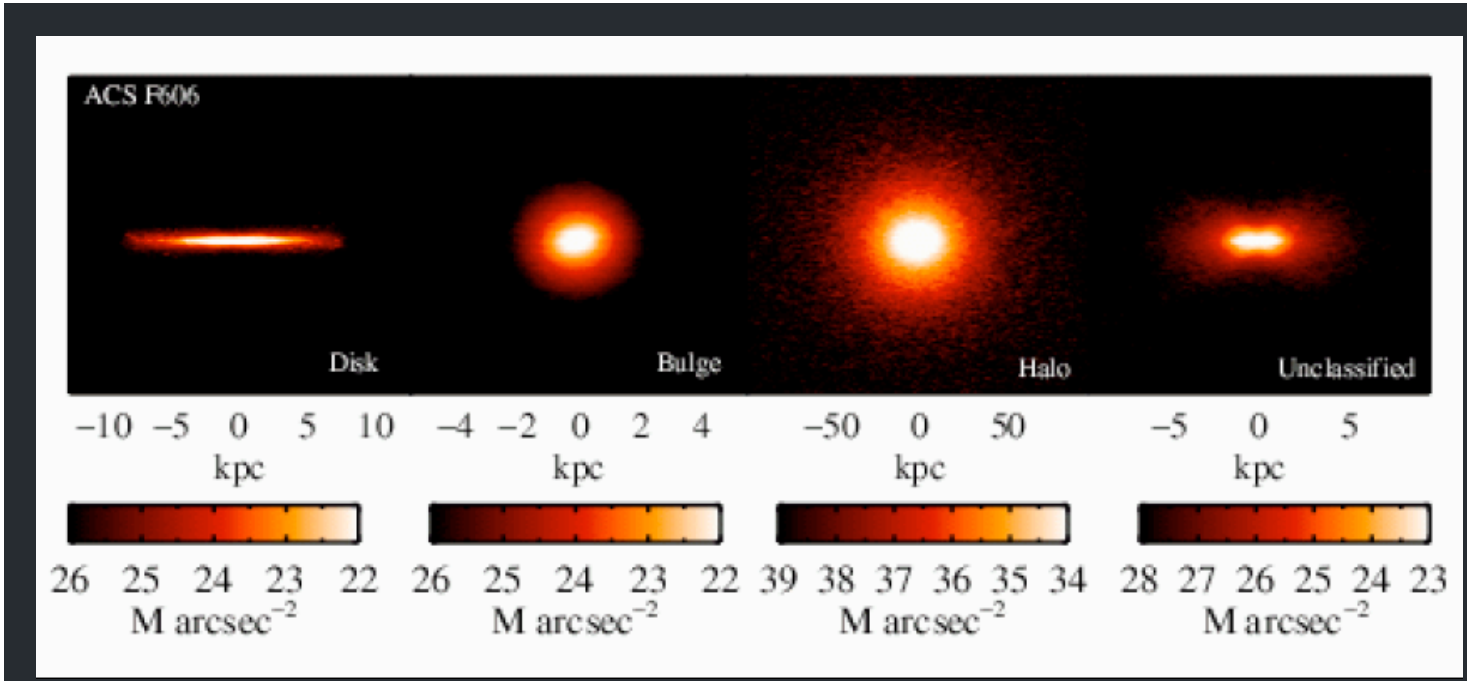
MW-sized galaxy (halo has ~10^{12} Mo, λ ~ 0.05)

N=DM+Gas+stars

Images with SUNRISE

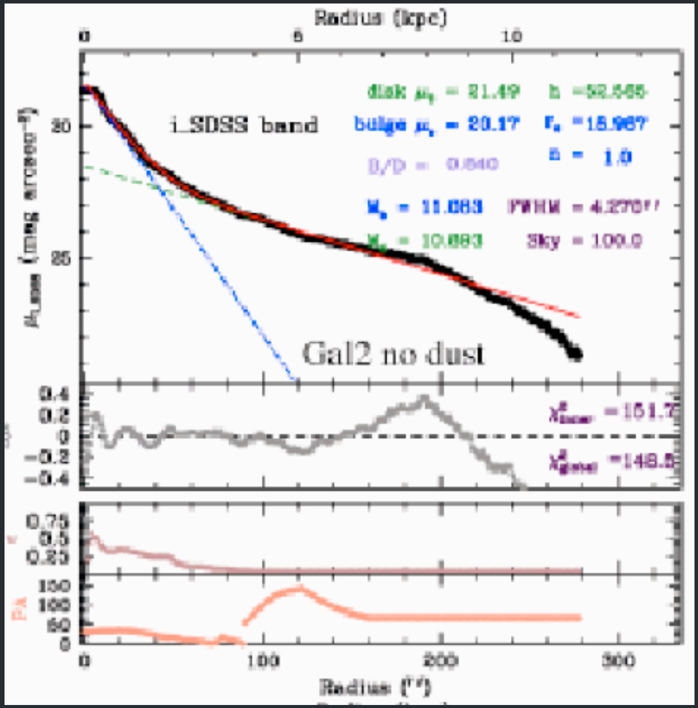


Rd=30% smaller



Theory vs Observations

Kinematic vs Photometric Decompositions

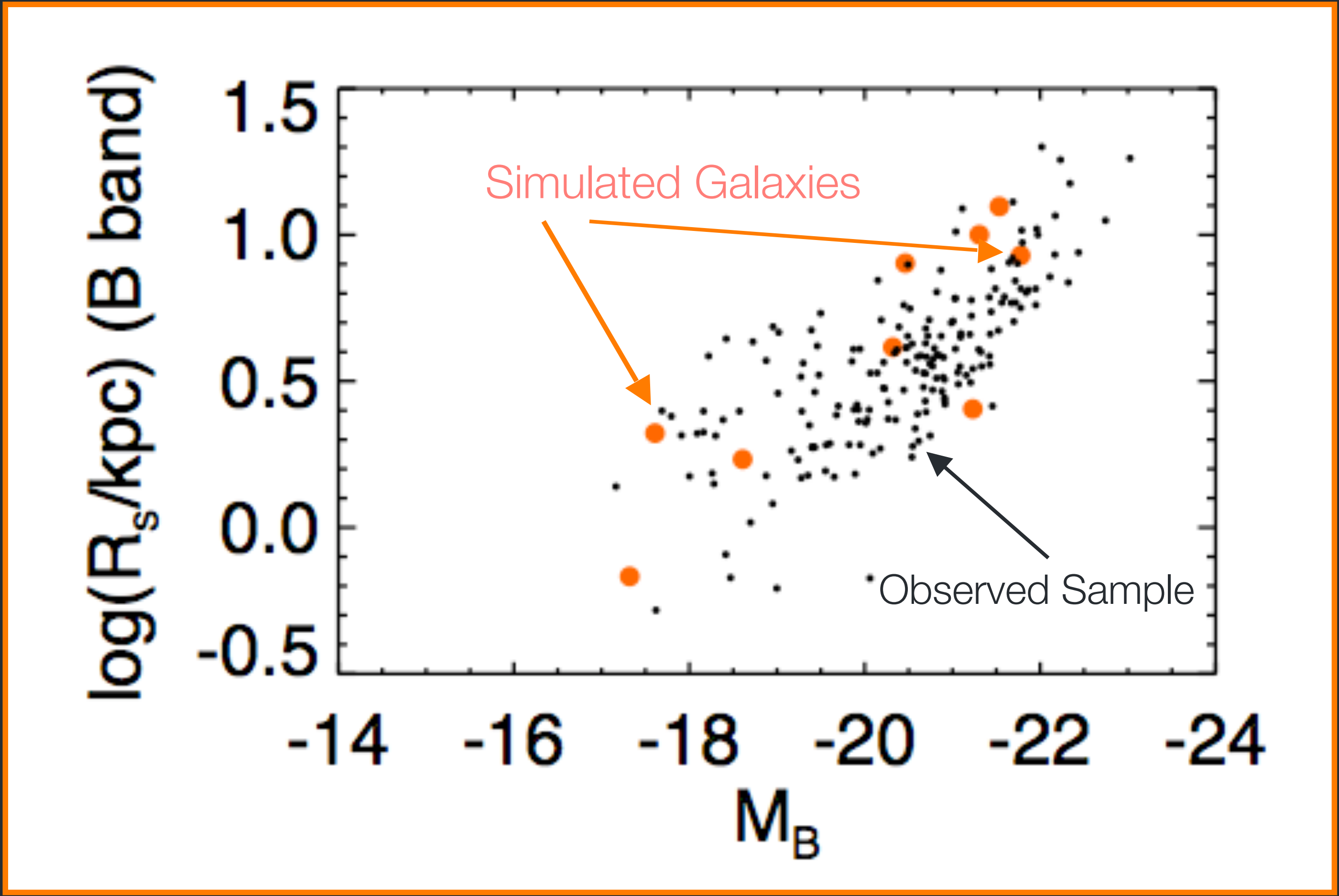


News & Views Geha, M.

Figure 1 | Which is the real galaxy? Governato and colleagues' numerical simulations[1] produce galaxies that seem identical to images of real galaxies. (Real galaxy (right) and background image courtesy of the Sloan Digital Sky Survey Collaboration (www.sdss.org); simulated galaxy (left) and composite image courtesy of C. Brook, F. Governato and P. Jonsson.)

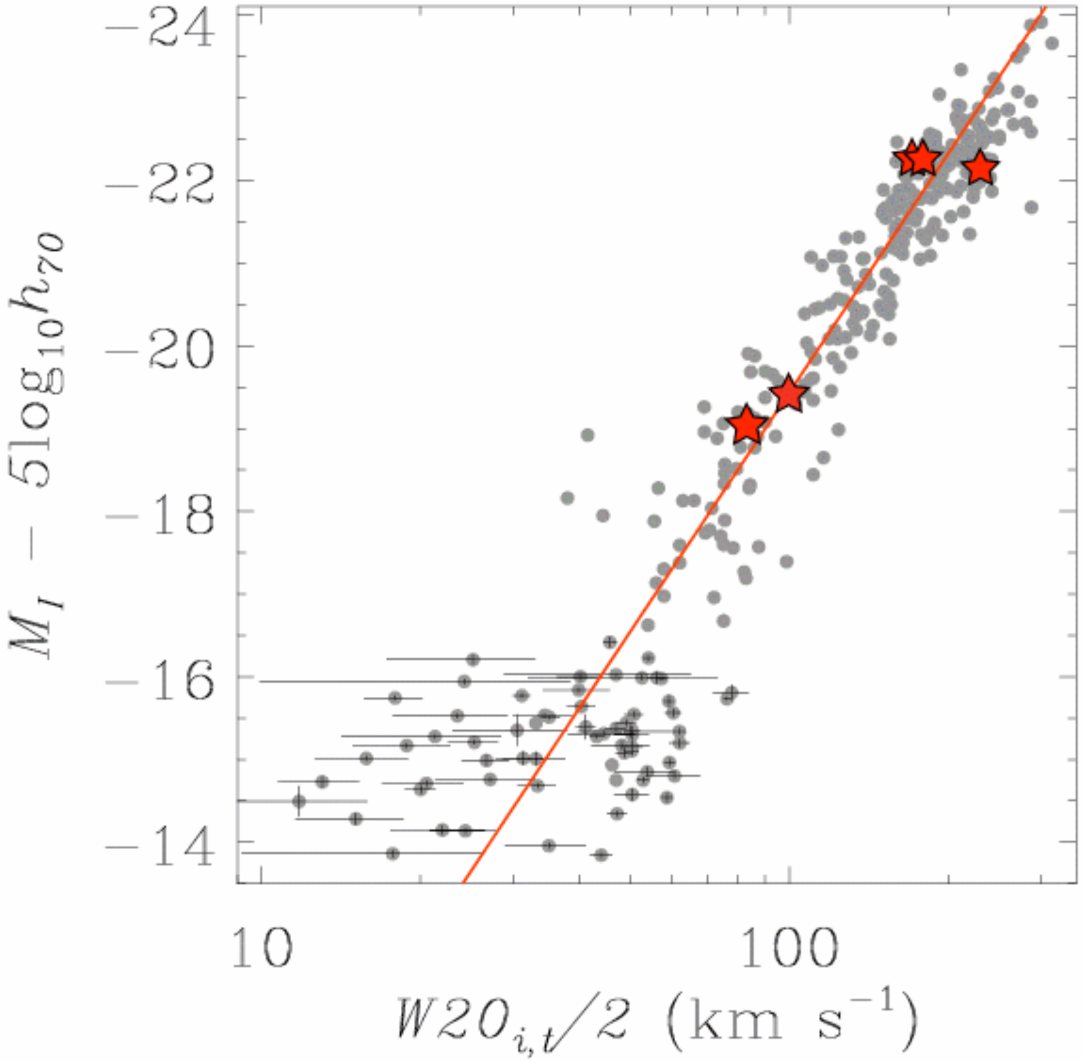
A Multi Color, Dust reddened Milky Way like Galaxy formed in a cosmological simulation.

Size - Luminosity Relation



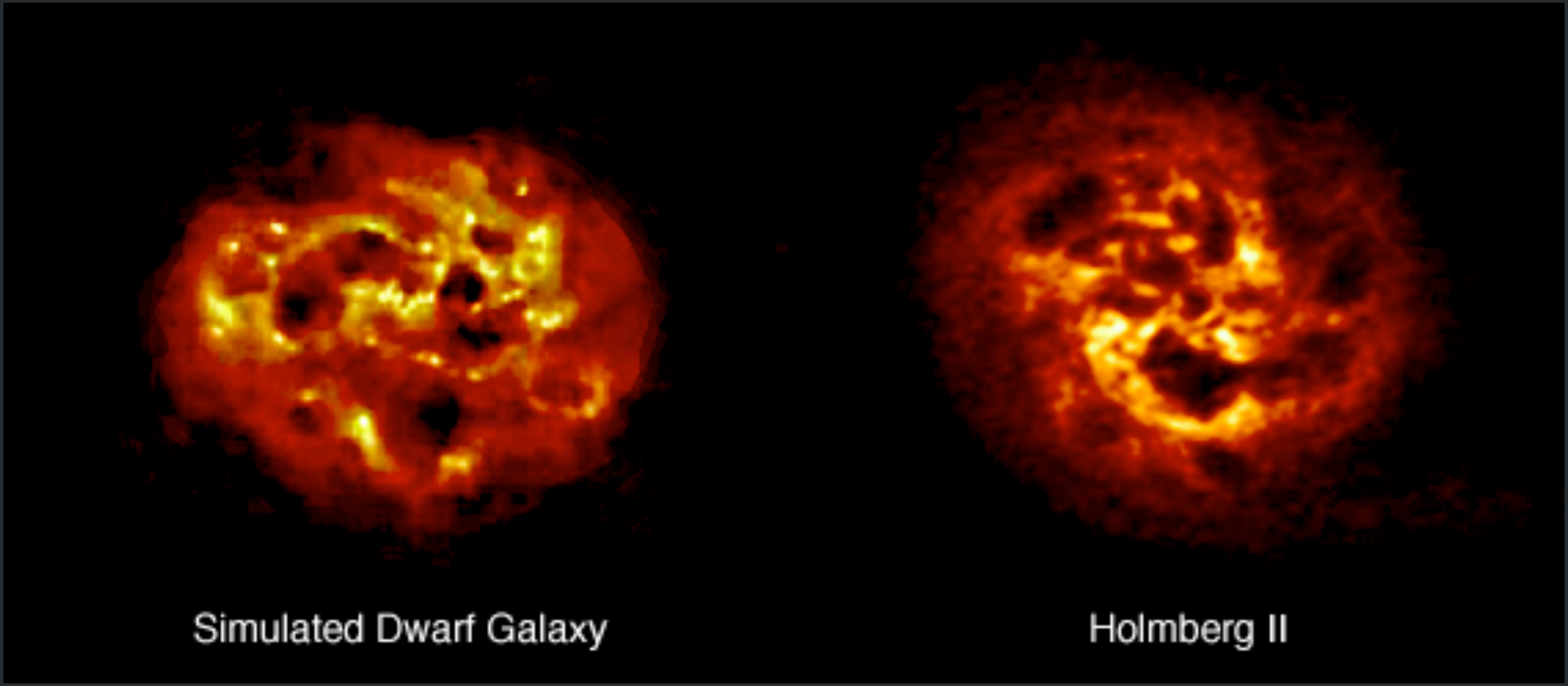
Simulated disk galaxies have the correct size.

Alyson Brooks in prep.
Data from **Graham & Worley, 2008**



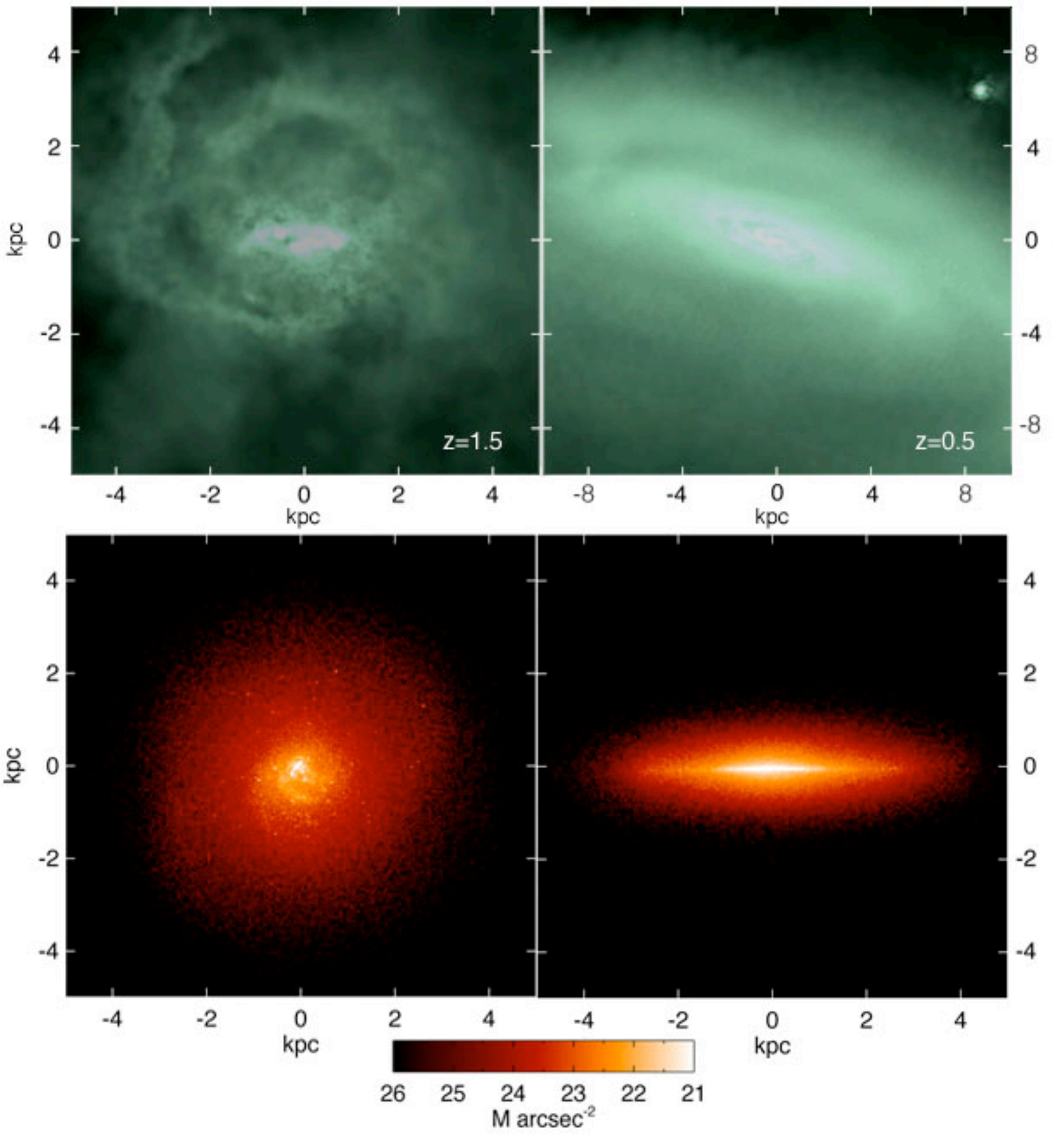
The Tully-Fisher Relation

The **simulated halos** (stars) on a plot of the Tully-Fisher relation from Geha et al. (2006), using measured HI widths and I-band magnitudes. The grey background points are from a variety of sources as cited in Geha et al. (2006).



z=0 HI map (A.Stilp and C.Brook)

Gas Density Map



I band surface density map

At z = 0

Stellar mass = 2-5^8 Msol

Mi =-16.8

g-r 0.52

Rd = 1kpc

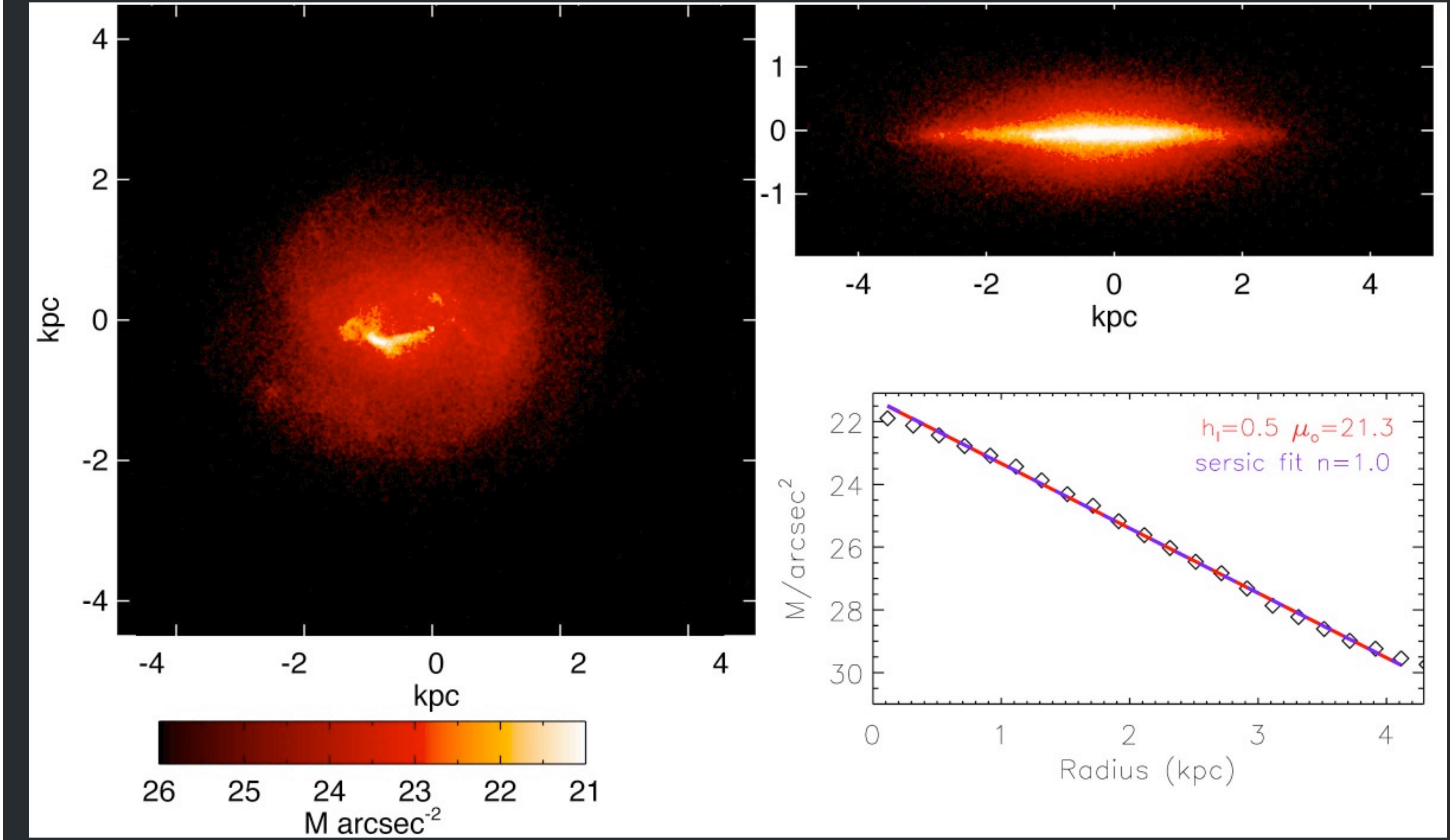
Vrot = 55 km/sec

MHI/Mstar=2.5

Baryons within Rvir 20-30% of cosmic Fraction.

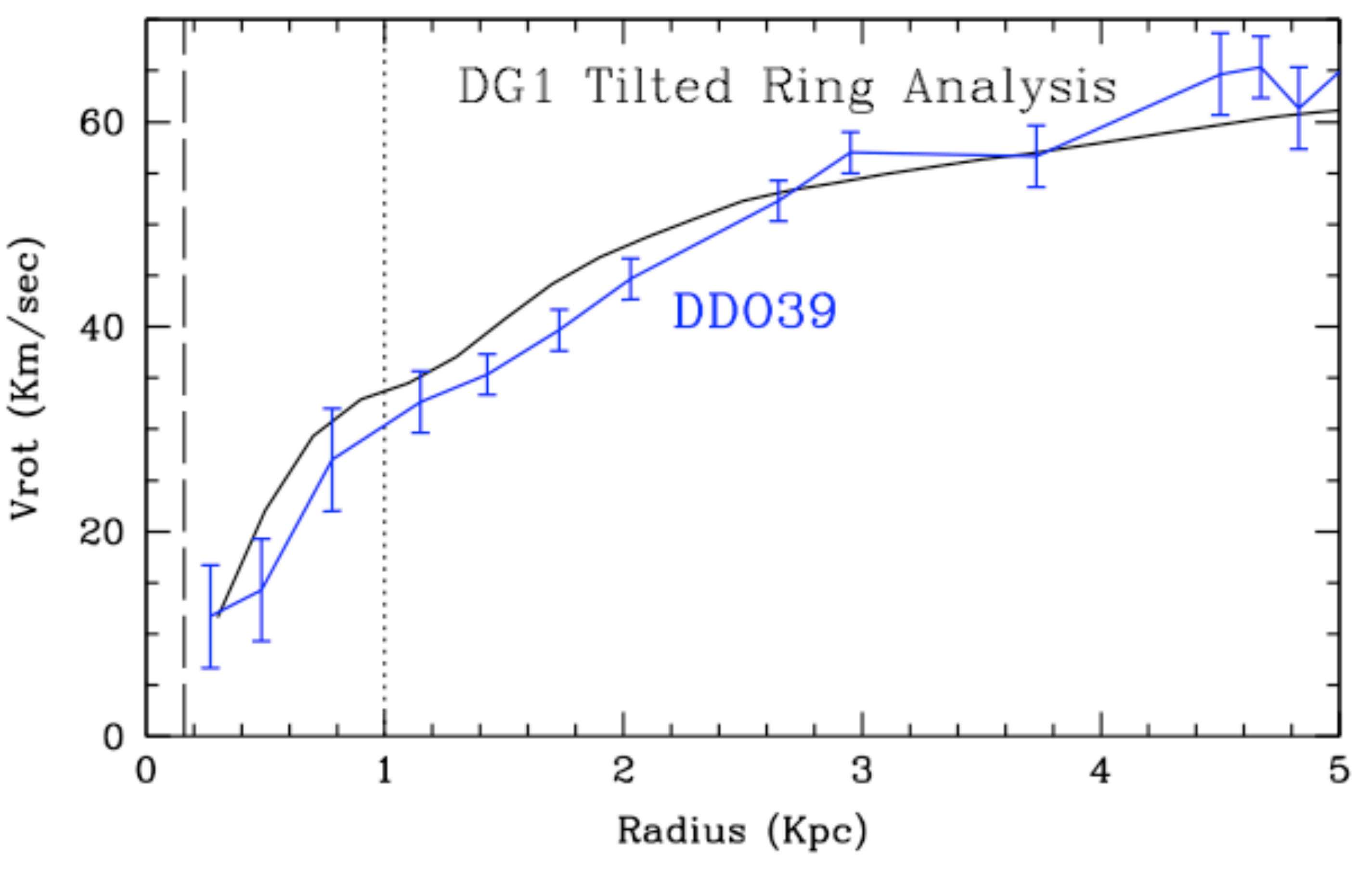
Only a few % converted Into stars.

Sunrise Images



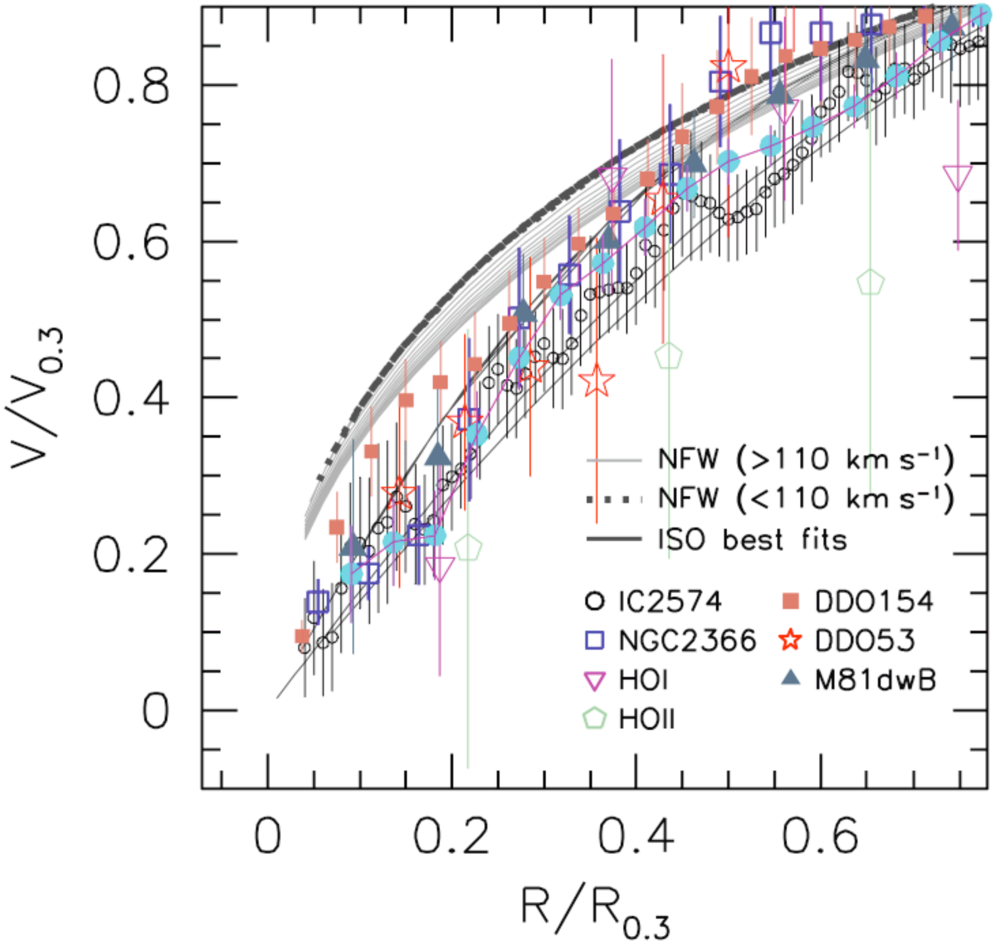
Stellar light profile is a pure exponential in all optical to near IR bands

Rotation Curve of a simulated CDM dwarf



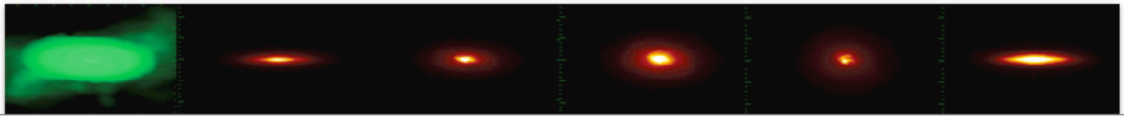
Comparison with the THINGS dwarfs :

I. Rotation curve shape



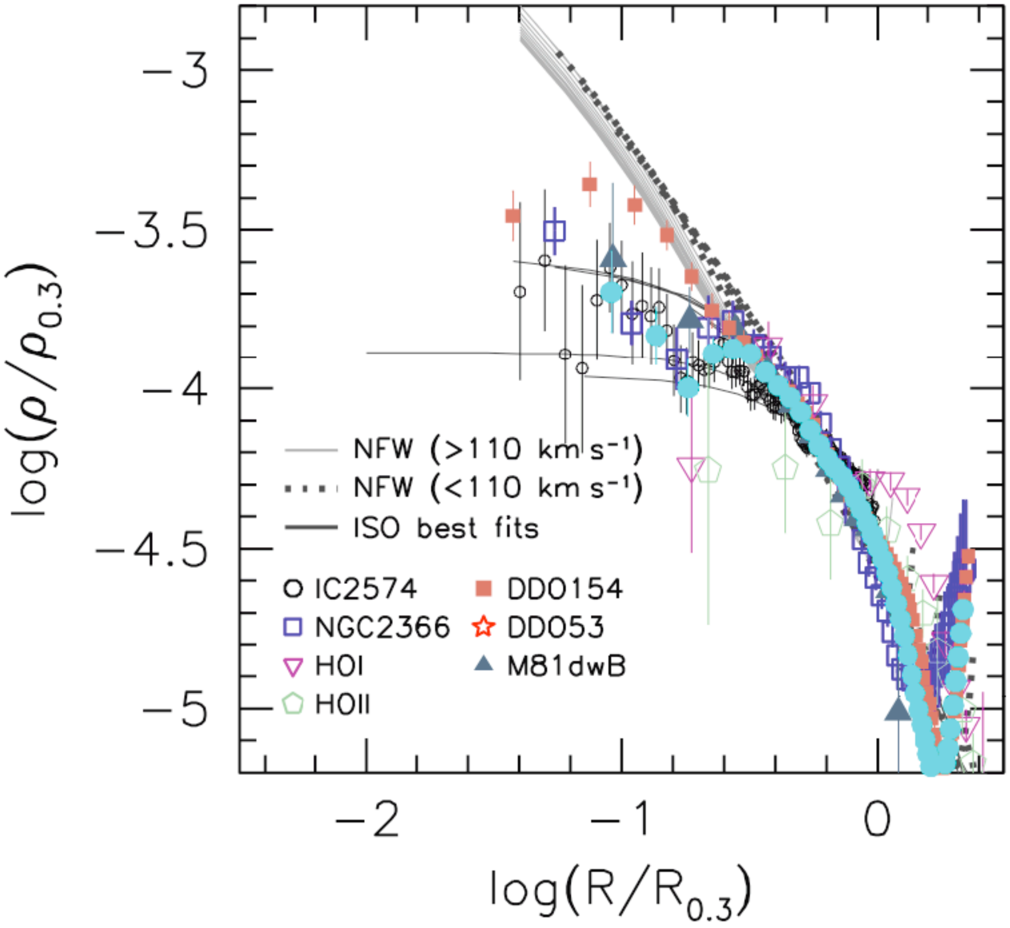
The scaled rotation curve rises too slowly to match the cuspy CDM halos, and is consistent with those of the THINGS dwarfs.

Oh et al. (2010b) in prep.



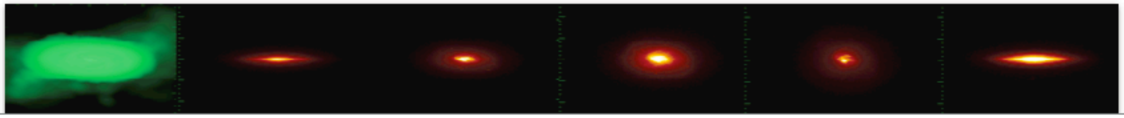
Comparison with the THINGS dwarfs :

II. Mass density profiles

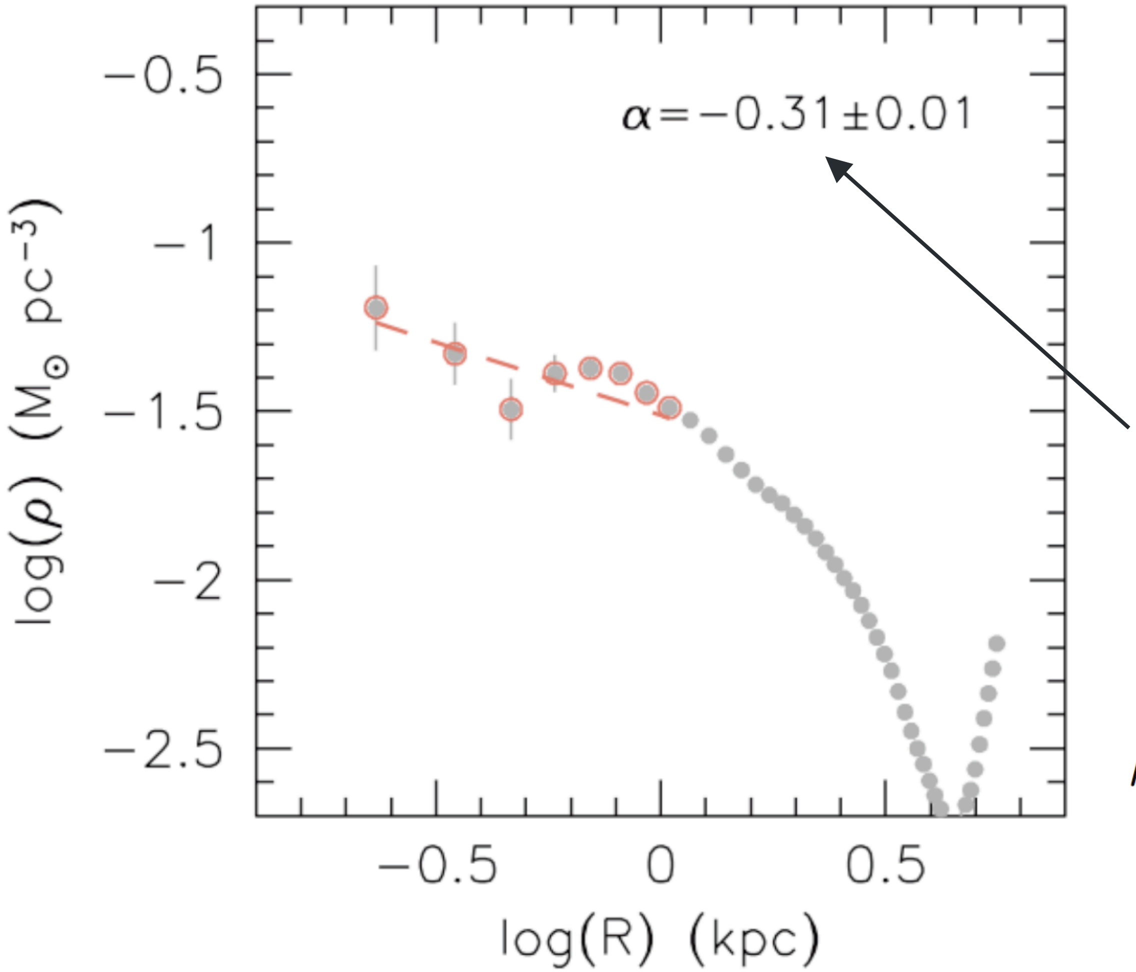


The dark matter density profile of the simulated dwarf galaxy DG1 is much shallower than -1, and consistent with those of the THINGS dwarfs.

Oh et al. (2010b) in prep.



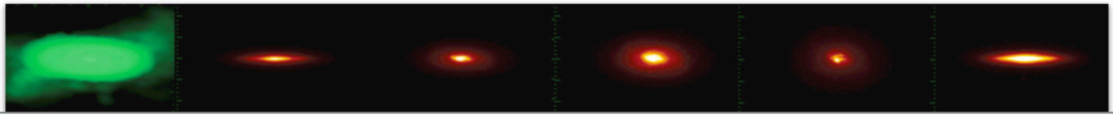
III. Mass density profiles



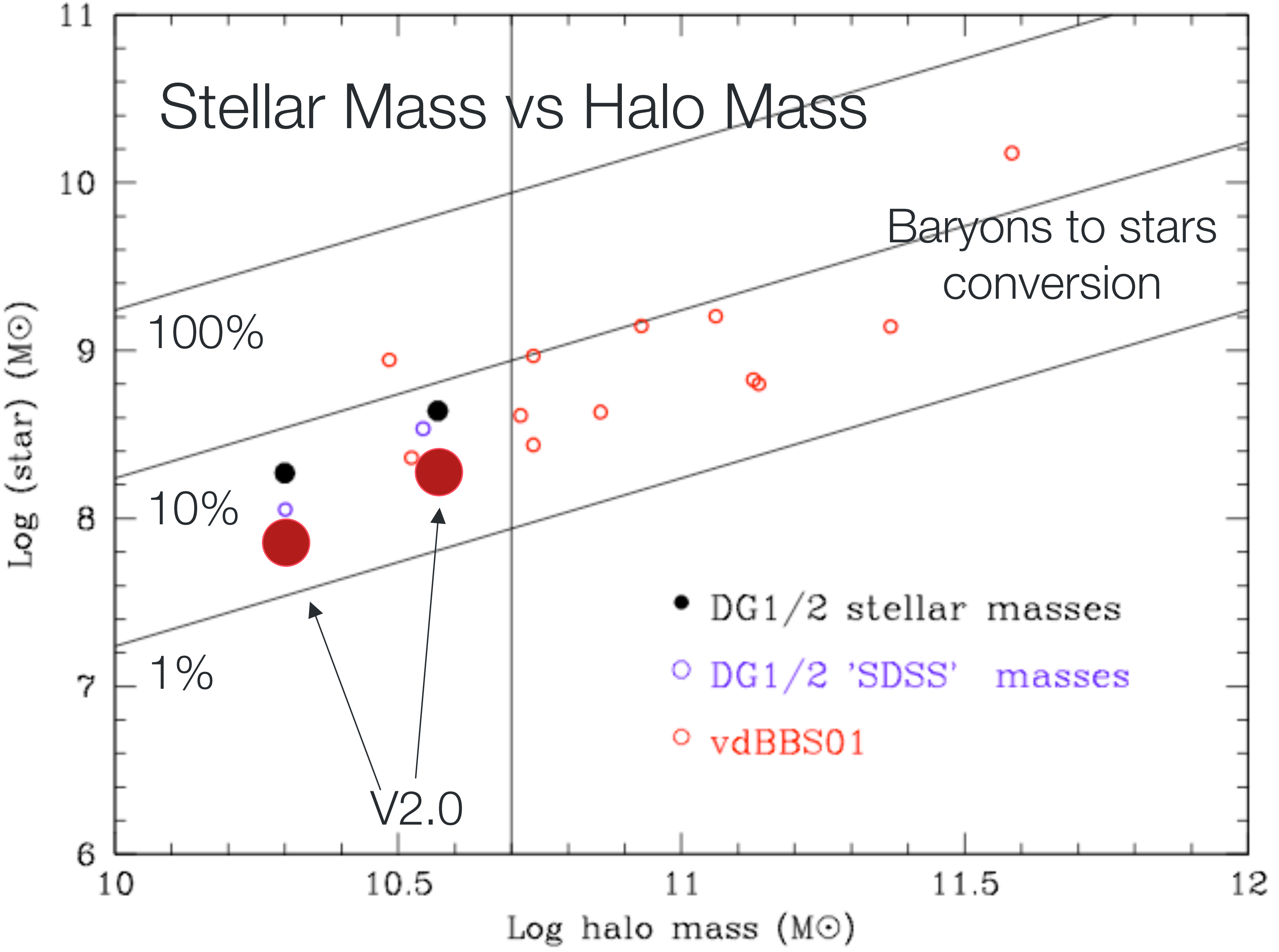
The inner density slope α= −0.31 is consistent with those of the THINGS dwarfs (α= −0.29 ± 0.07).

Note: the ‘true’ DM slope is -0.6

$$\rho(R) = \frac{1}{4\pi G}\left[2\frac{V}{R}\frac{\partial V}{\partial R} + \left(\frac{V}{R}\right)^2\right]$$



Stellar Mass vs Halo Mass



Baryons to stars conversion

100%

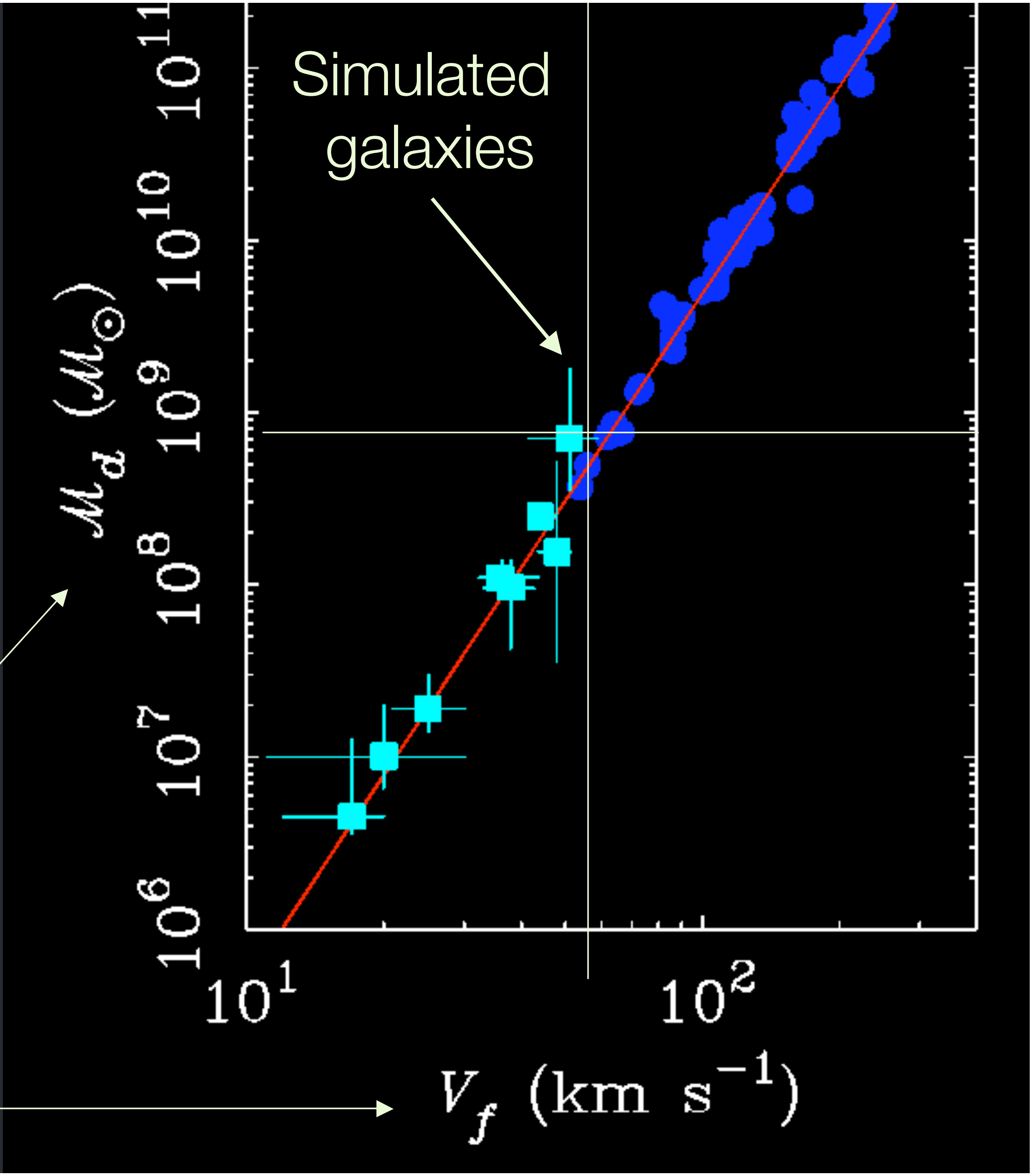
10%

1%

V2.0

Baryonic
Tully Fisher

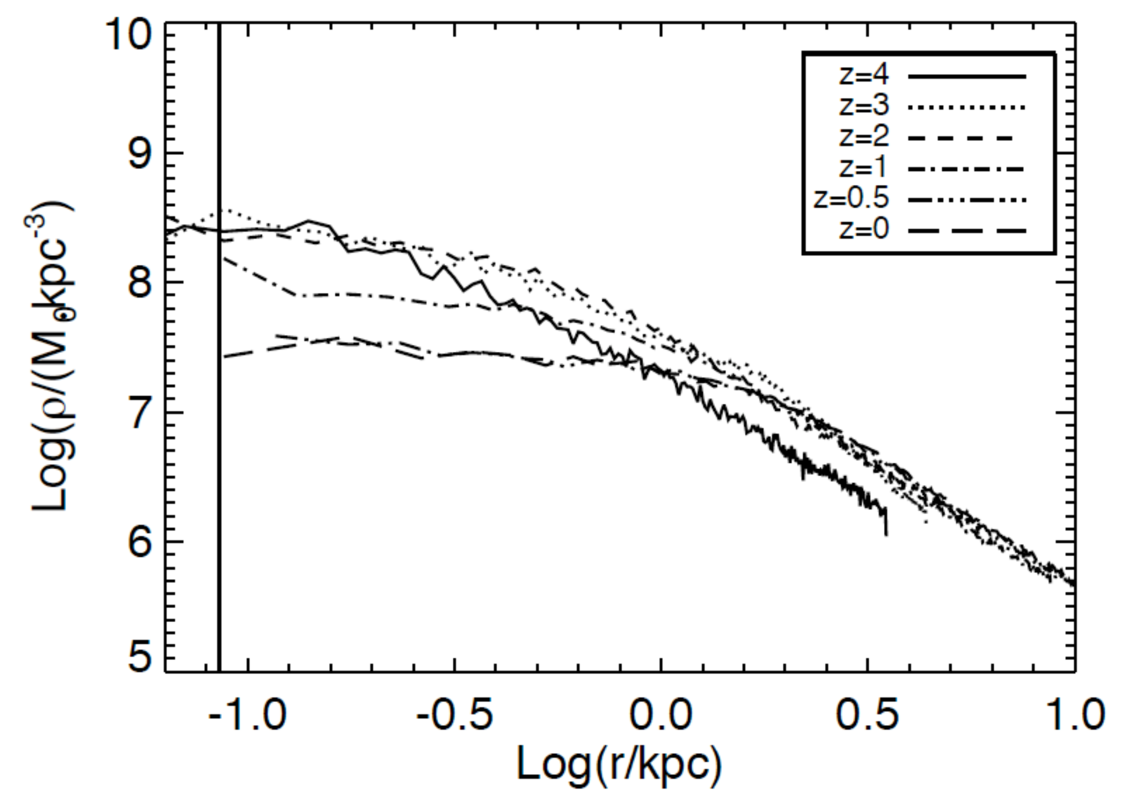
MacGaugh
2009,10



HI+stars
In disks

Peak Velocity

Central Core Evolution



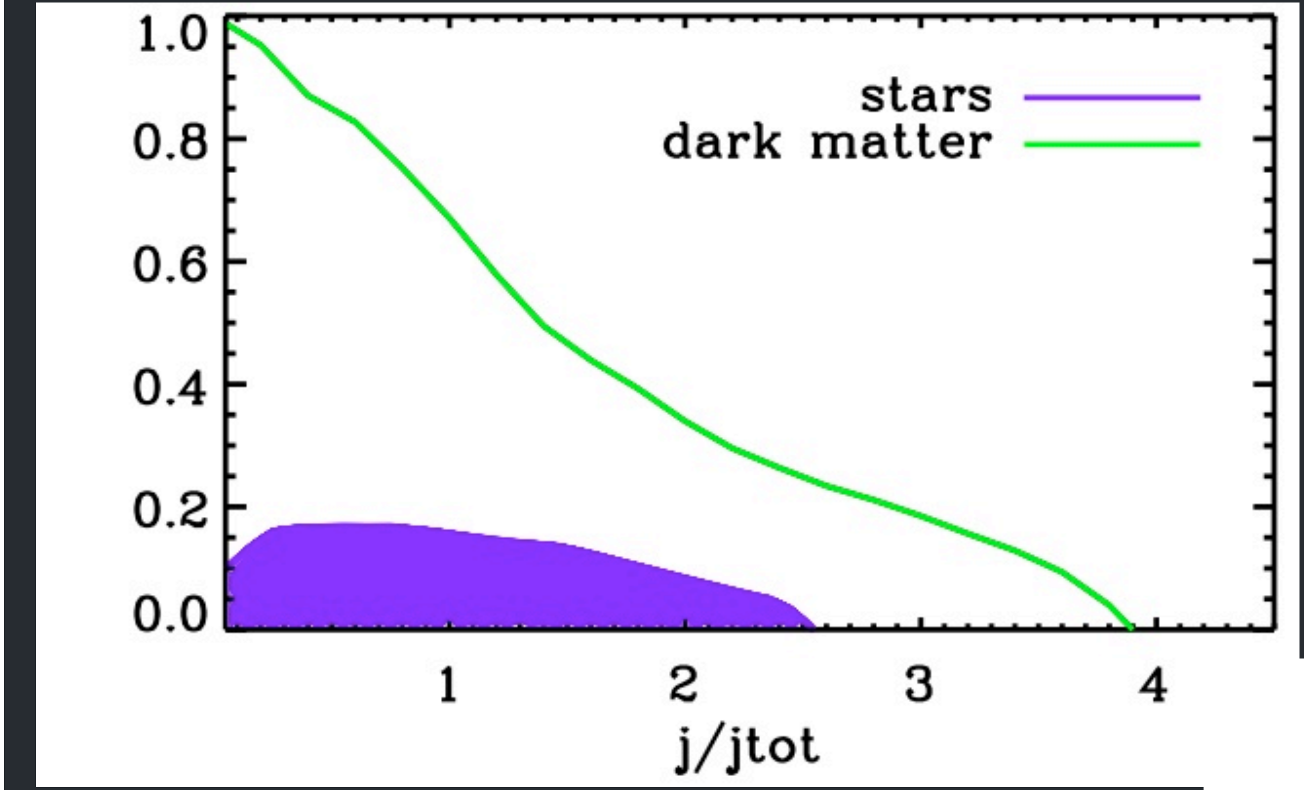
Clumpy Gas transfers energy to DM.

DM contracts adiabatically.

BUT.

DM expands as gas is rapidly removed!

Angular Momentum of Stellar Disk vs DM halo



Outflows
preferentially
remove
Low angular
momentum
baryons

Our simulation

Van den Bosch 01
Bullock 01

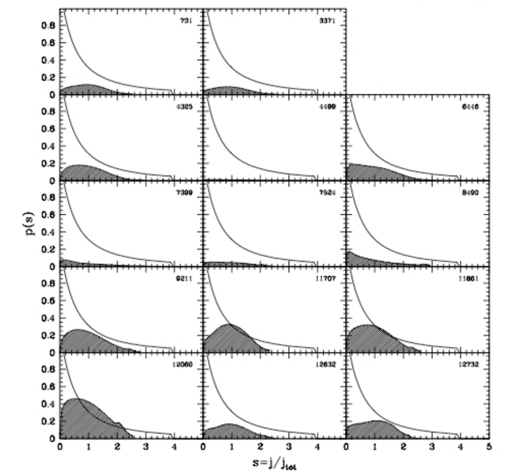


Figure 4. The shaded areas indicate the $p(s)$ of the AMDs for the 14 disc galaxies in our sample, normalized to f_{disc}/f_{bar}. For comparison we plot $p(s)$ of equation (11) with $\mu = 1.25$ (normalized to unity), and which represents the median of the AMDs of ΛCDM haloes. Under the standard assumption that baryons conserve their specific angular momentum the difference between the two distributions reflects the AMD of the baryonic matter that is not incorporated in the disc. Note that it is preferentially the baryonic matter with both the highest and the lowest angular momenta that is absent in the discs.

Summary

- The central dark matter distribution of the 7 THINGS dwarf galaxies from high-quality multi-λ observations is cored.
- The mean of their inner density slopes is $\alpha = -0.29 \pm 0.07$, which significantly deviates from −1 predicted from ΛCDM simulations.
- New high-resolution N-body+SPH simulations including baryonic feedback processes is able to make bulgeless dwarf galaxies with shallow inner mass density profiles.
- The rotation curve shape and inner mass density slopes of real and simulated dwarf galaxies are very close to each other.
- The baryonic feedback process (e.g., gas outflows by SNe explosions or merging etc.) in the early universe is able to not only remove low-angular momentum baryons but also make the initial cusps shallower.

The case for feedback has always been weak.
Galaxies outside of clusters are primarily rotationally supported disks; their final structure has clearly been set by their angular momentum rather than by a struggle between gravity and winds. The strongest starbursts seen in nearby dwarf galaxies lift the gas out of their disks, but the energy input is insufficient to expel the gas and reshape the galaxy.

(Moore…Quinn, Governato et al 1998)

Simulations and software available

/home/hipacc-29 (Fabio Governato)

/COSMO 50 Mpc volume completed
/DWARFS z=0 outputs with different SF and feedback
/MOVIES: animations from this talk
/papers a few papers on galaxy formation
/GALAXY initial conditions of MW-like galaxies

/ANALYSIS:
GALFIT: B/D photometric decomposition
Decomposition: B/D kinematic decomposition
IDLMags: magnitude of simulated galaxies
1DFIT: simple B/D photometric decomposition

DM core density: simulation versus THINGS data

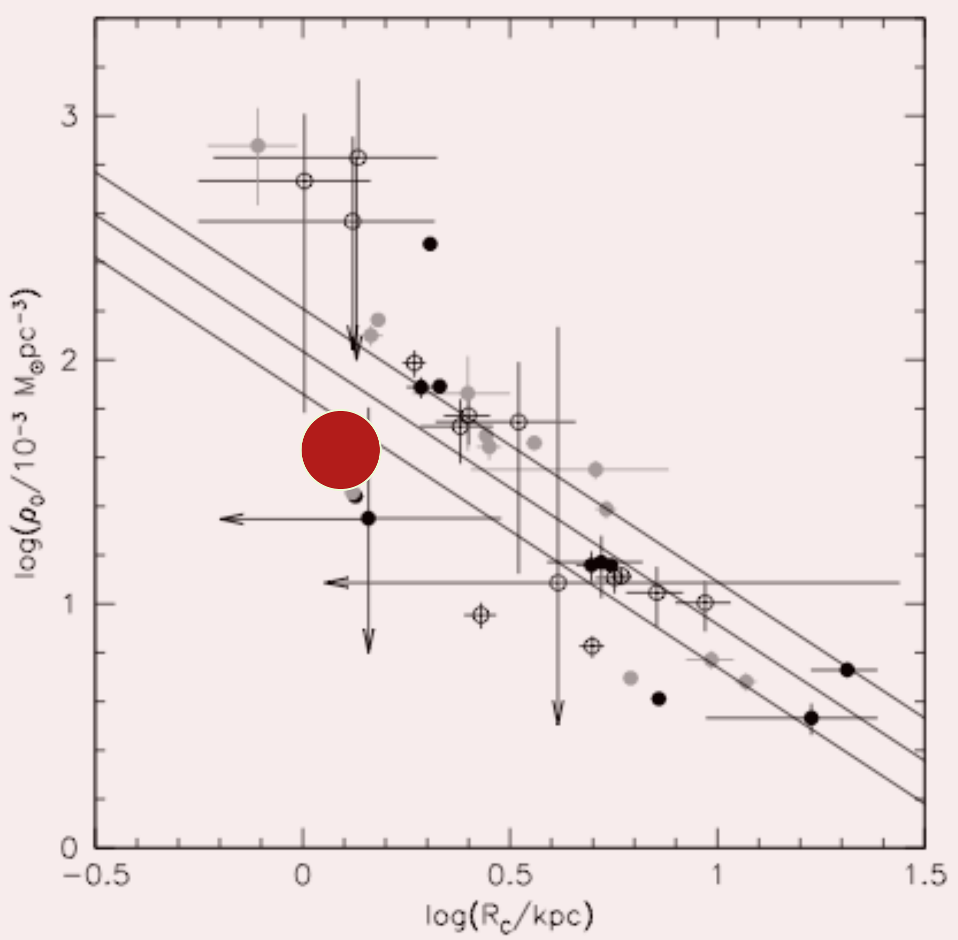


FIG. 66.— Left: Distribution of core density ρ of the ISO halo against core radius R_C. Filled circles show the results derived assuming fixed $\Upsilon_\star^{3.6}$ values, with black symbols assuming a diet-Salpeter IMF and grey circles assuming a Kroupa IMF. Open circles show the results derived using free $\Upsilon_\star^{3.6}$ values. The full lines show the relation derived in Kormendy & Freeman (2004) along with the 1σ scatter.

deBlok 08

Observational Properties of Small galaxies III

- disk dominated (Sersic n =1)
- blue g-r < 0.6
- have DM cores of ~1kpc
- $\mathrm{DM_{core}}$ rho < 10^8 $\mathrm{M_{sol}}$ kpc-3

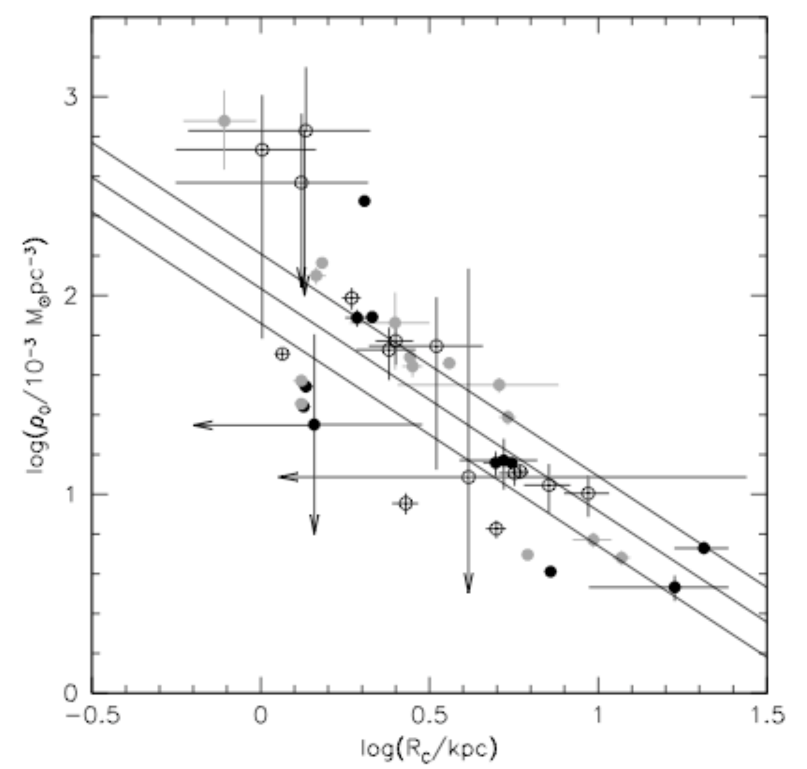
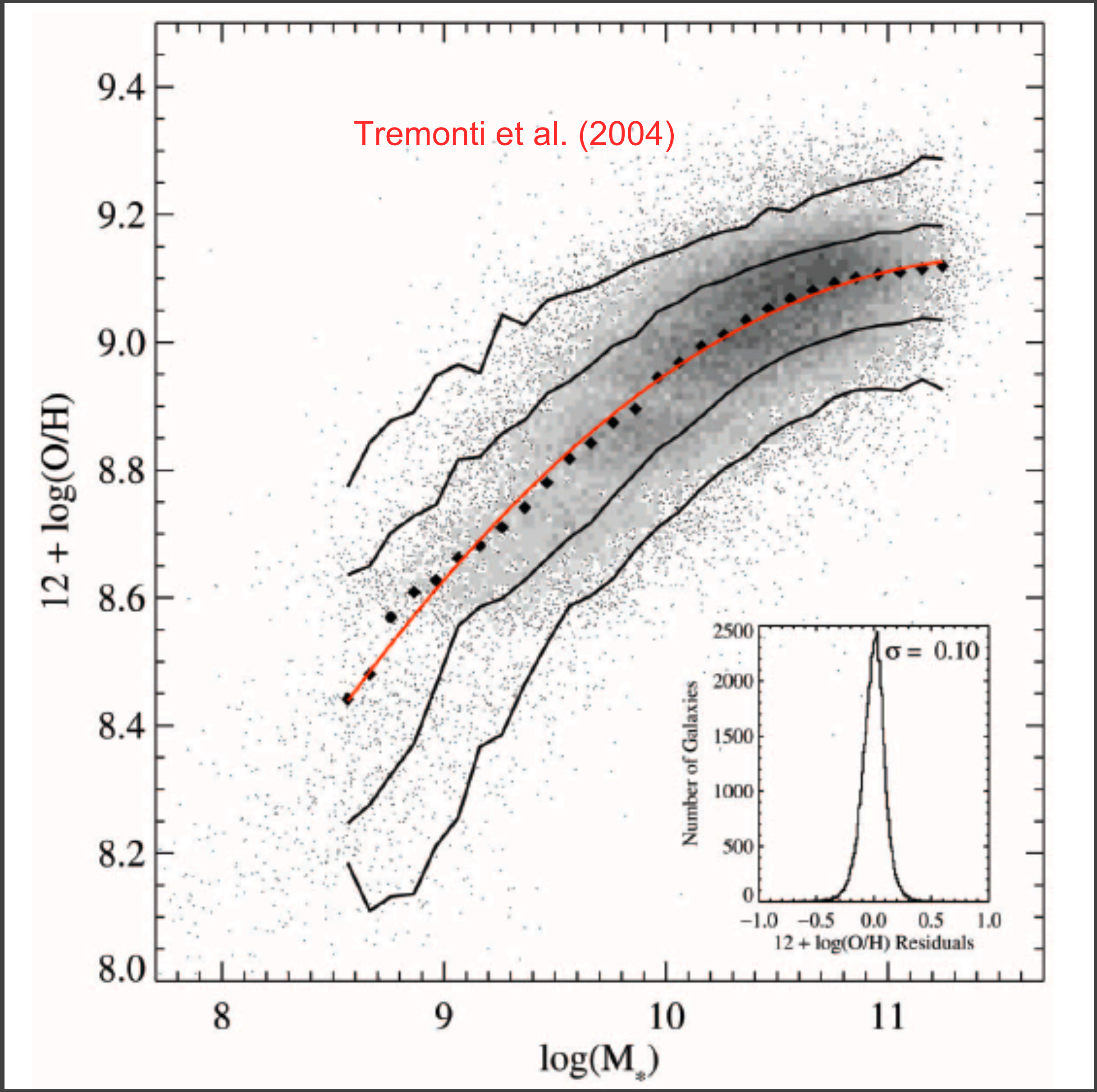


FIG. 66.— Left: Distribution of core density ρ of the ISO halo against core radius R_C. Filled circles show the results derived assuming fixed $\Upsilon_*^{3.6}$ values, with black symbols assuming a diet-Salpeter IMF and grey circles assuming a Kroupa IMF. Open circles show the results derived using free $\Upsilon_*^{3.6}$ values. The full lines show the relation derived in Kormendy & Freeman (2004) along with the 1σ scatter.

The Mass-Metallicity Relationship for Galaxies


Tremonti et al. (2004)

Two main theories for origin of MZR:

1) Preferential metal loss from low mass galaxies

2) Low SFR in low mass galaxies

Savaglio et al. (2005)
Lee et al. (2006)
Erb et al. (2006)

Star Formation and Feedback (Stinson et al. 2006 for details) with GASOLINE (Wadlsey et al 04)

- A local Schmidt Law is assumed
- O and Fe yields from SN I & II
- Kroupa IMF
- Mass/metals loss from stellar winds included.
- Star Particles formed from cold, dense gas
- Uniform, time-dependent cosmic UV bg from Haardt & Madau

▪**Supernovae Feedback with Blastwave model**

- based on multiphase ISM model of McKee & Ostriker (1977)

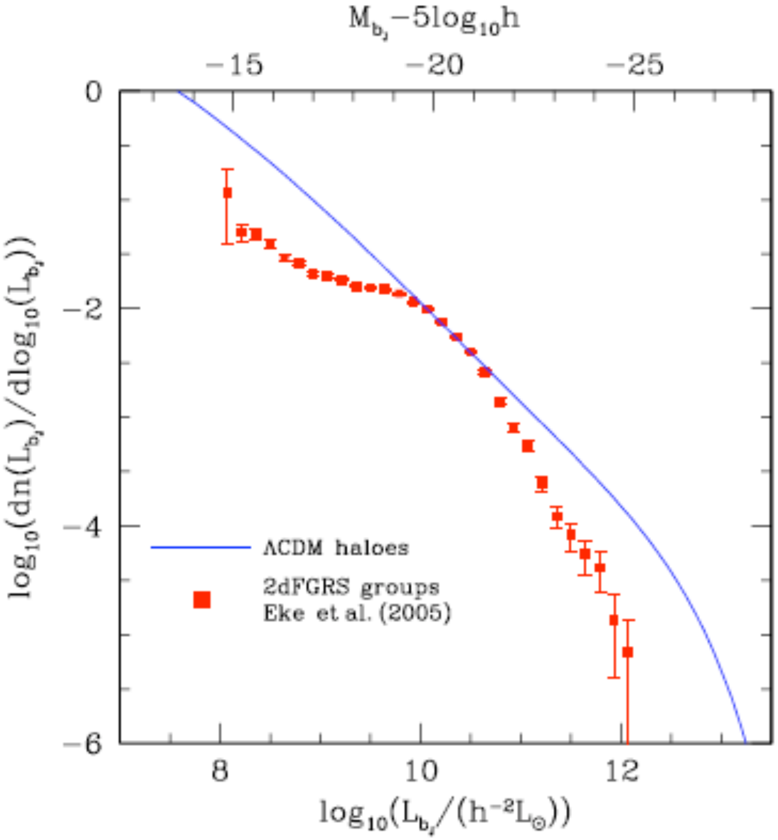
- cooling stopped during adiabatic expansion phase of supernova blast wave (Sedov-Taylor phase) ~ 2 x 10^6 years + gas volume encompassed by blastwave self-consistently calculated

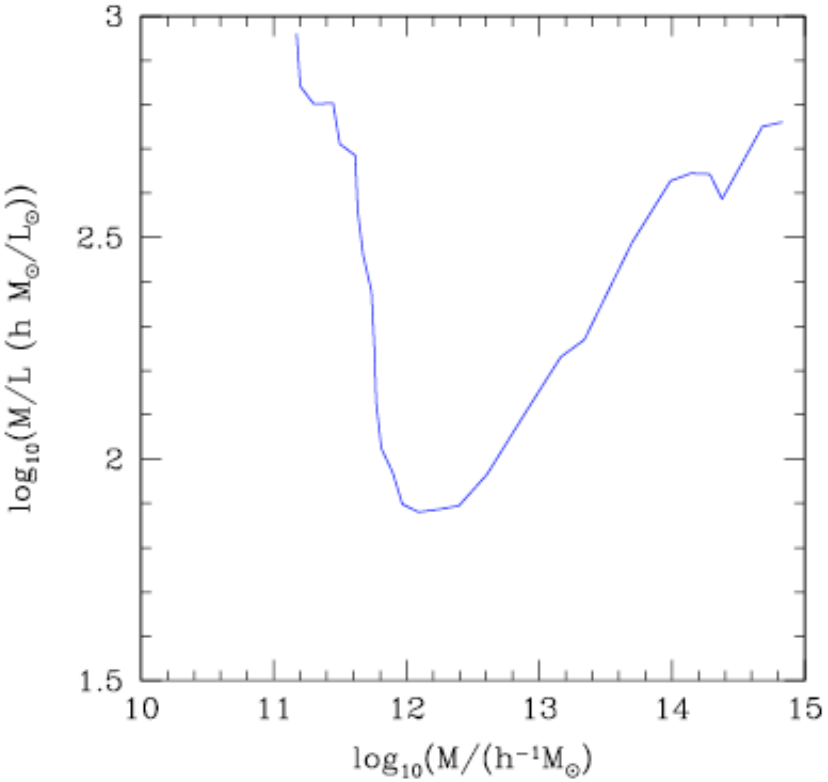
Result: no outflows but star formation quenched.

Only two Free Parameters:

SF efficiency & fraction of SN energy coupled to ISM

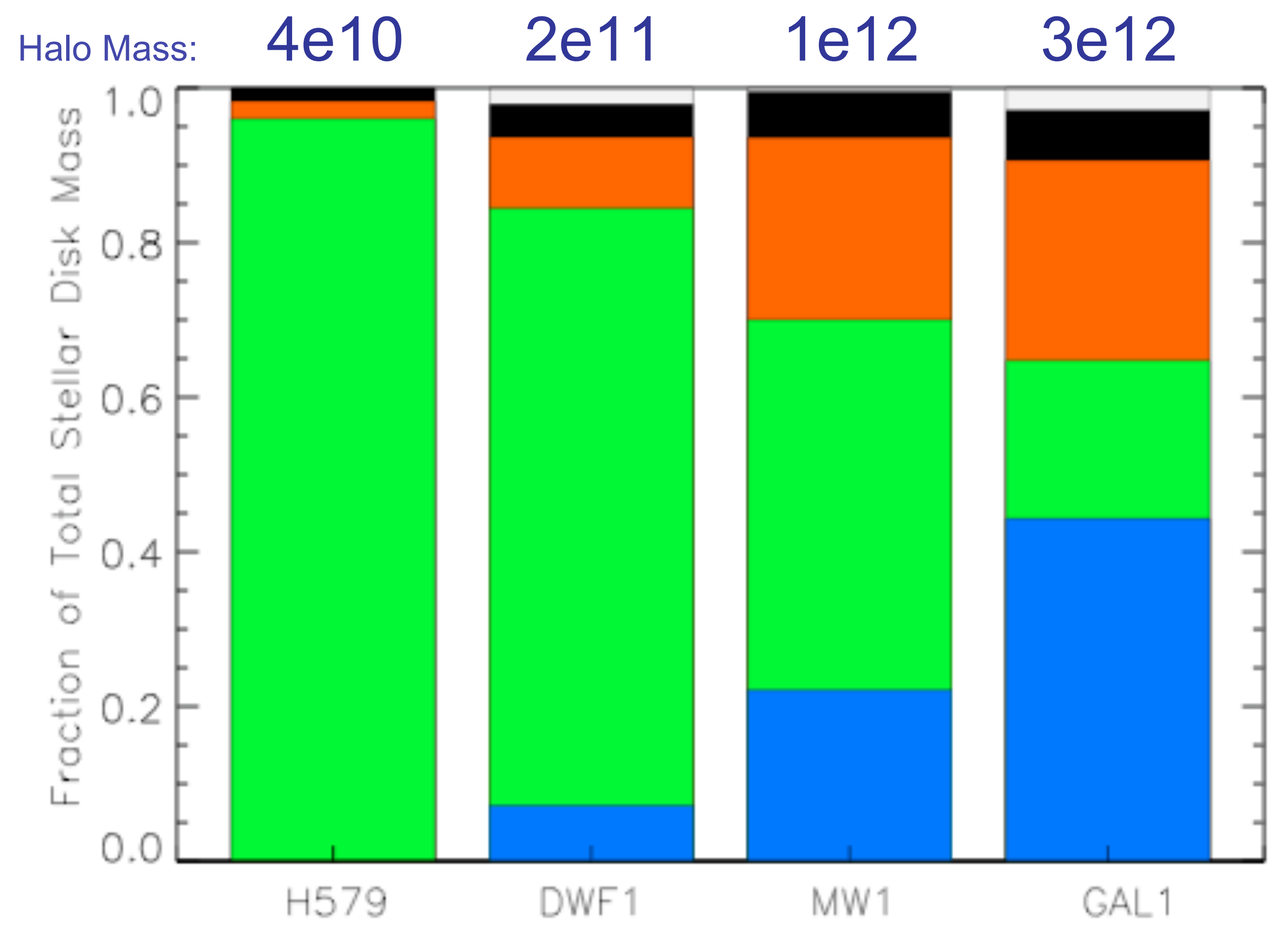
SN Feedback: important at M< L*





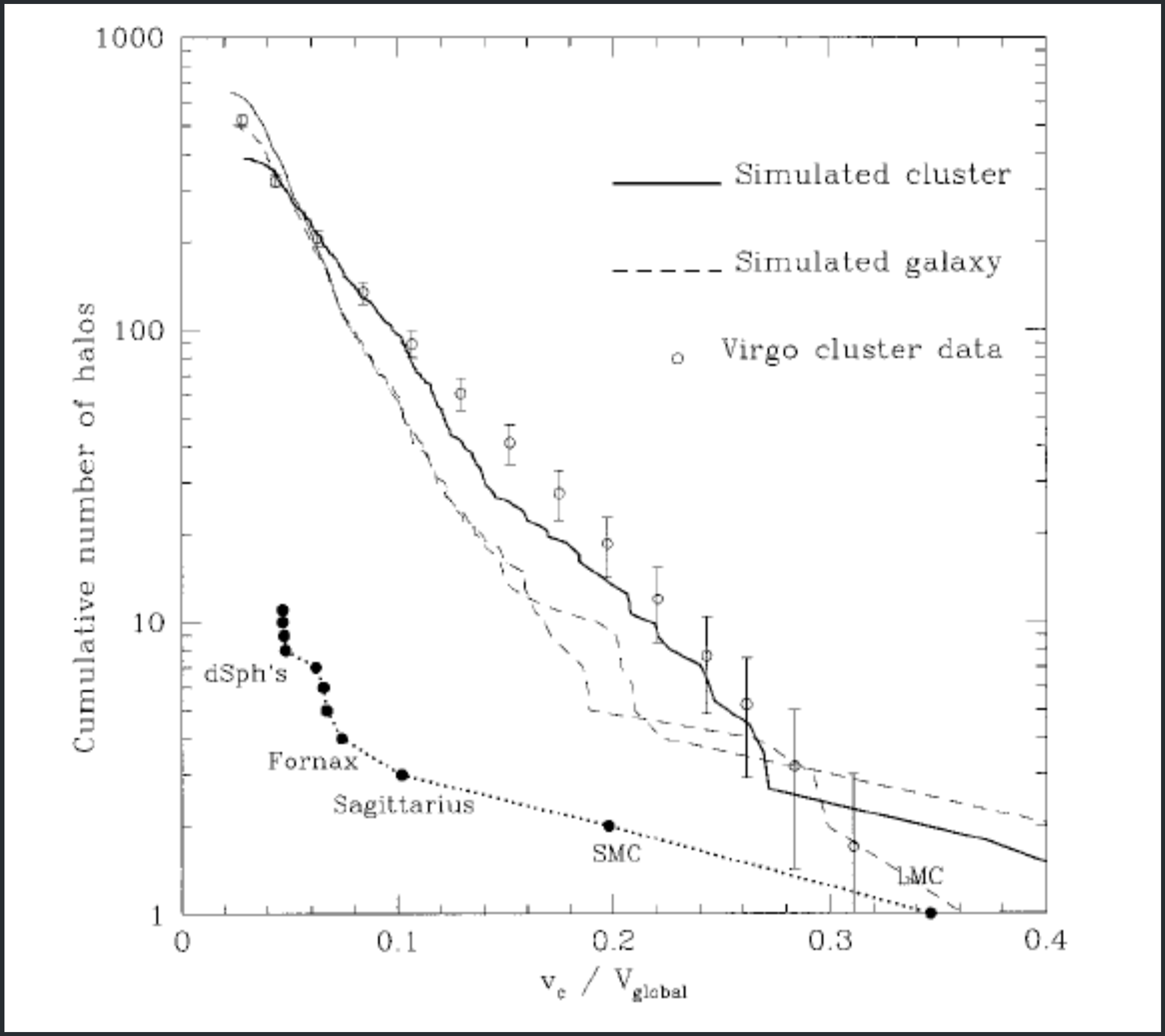
Gas Accretion I: disk stars @ z=0

clumpy cold flows shocked



Brooks et al in prep.

The CDM Substructure Problem



Moore,…,Quinn, Governato et al 1998

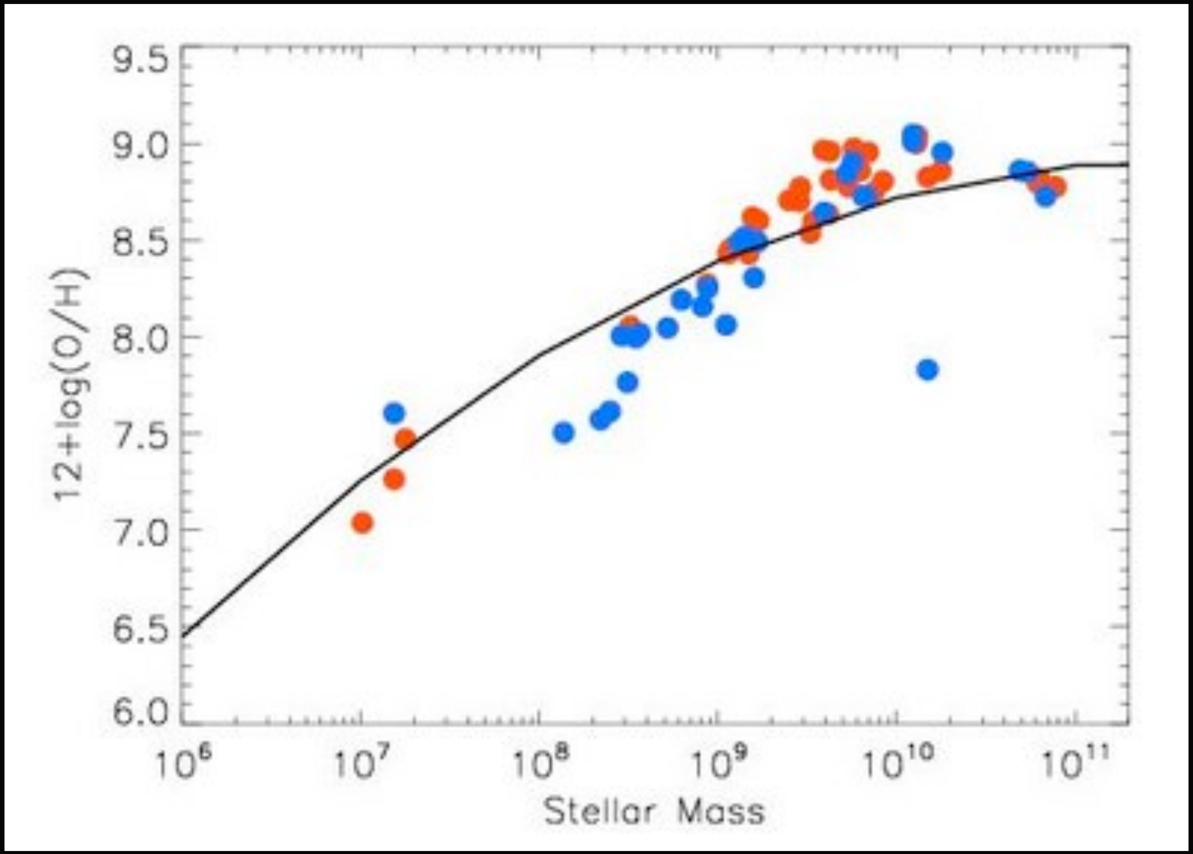
Processes affecting the Baryon Distribution in Galaxies

Numerical Resolution

Angular momentum Loss

Removal of Low Angular Momentum Gas

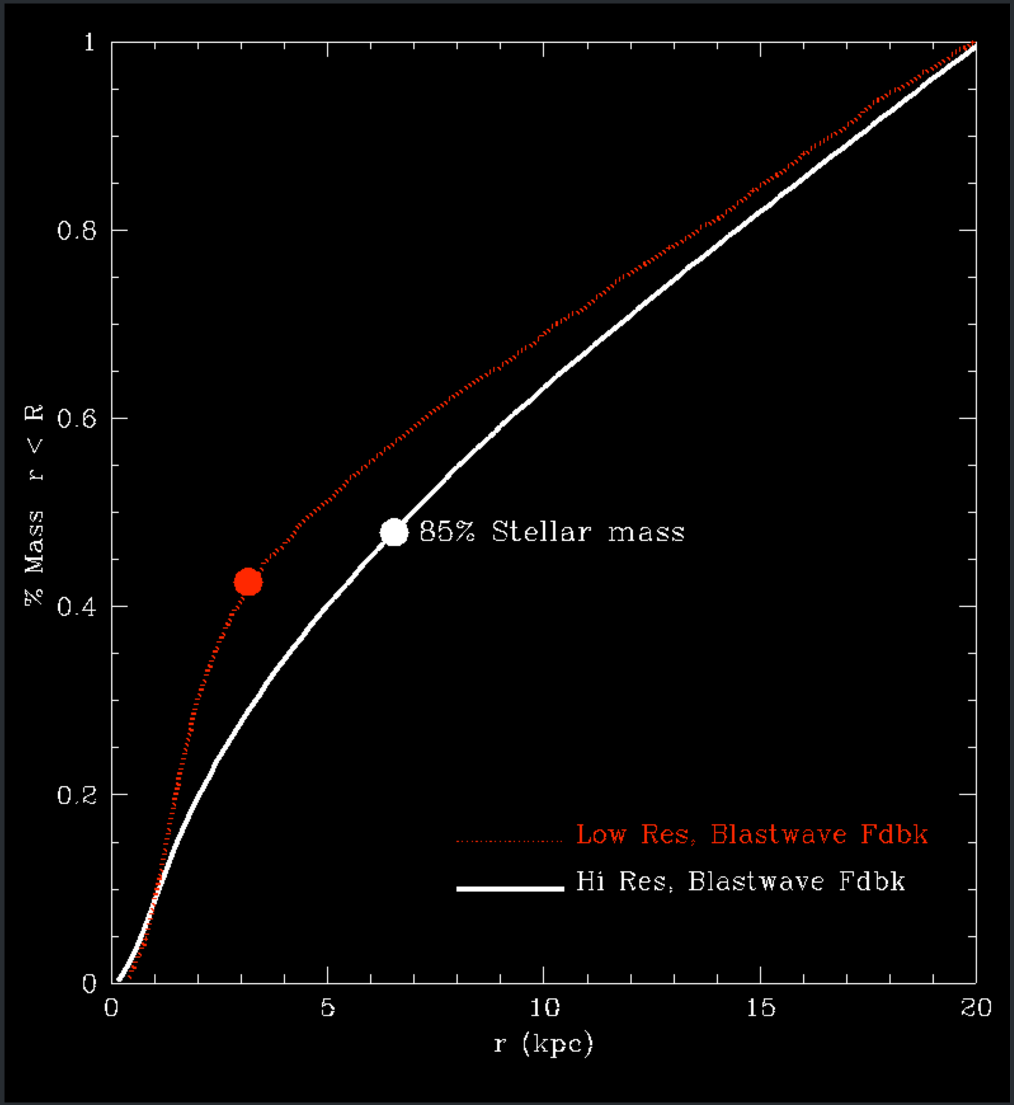
The Stellar Mass - Metallicity Relation
(Brooks et al. 07).



Data from Tremonti et al 04, z=0

Star Formation less efficient
In small galaxies due to feedback
and UV background.

Cumulative Mass Distribution



Have Simulations of Galaxy Formation improved over the past few years?

-Algorithms + CPU Power (N: 10k to 3-5 million)

-Description of “Baryon Physics” Processes