Redistributing matter in Dwarf Galaxies: Cusps and Cores

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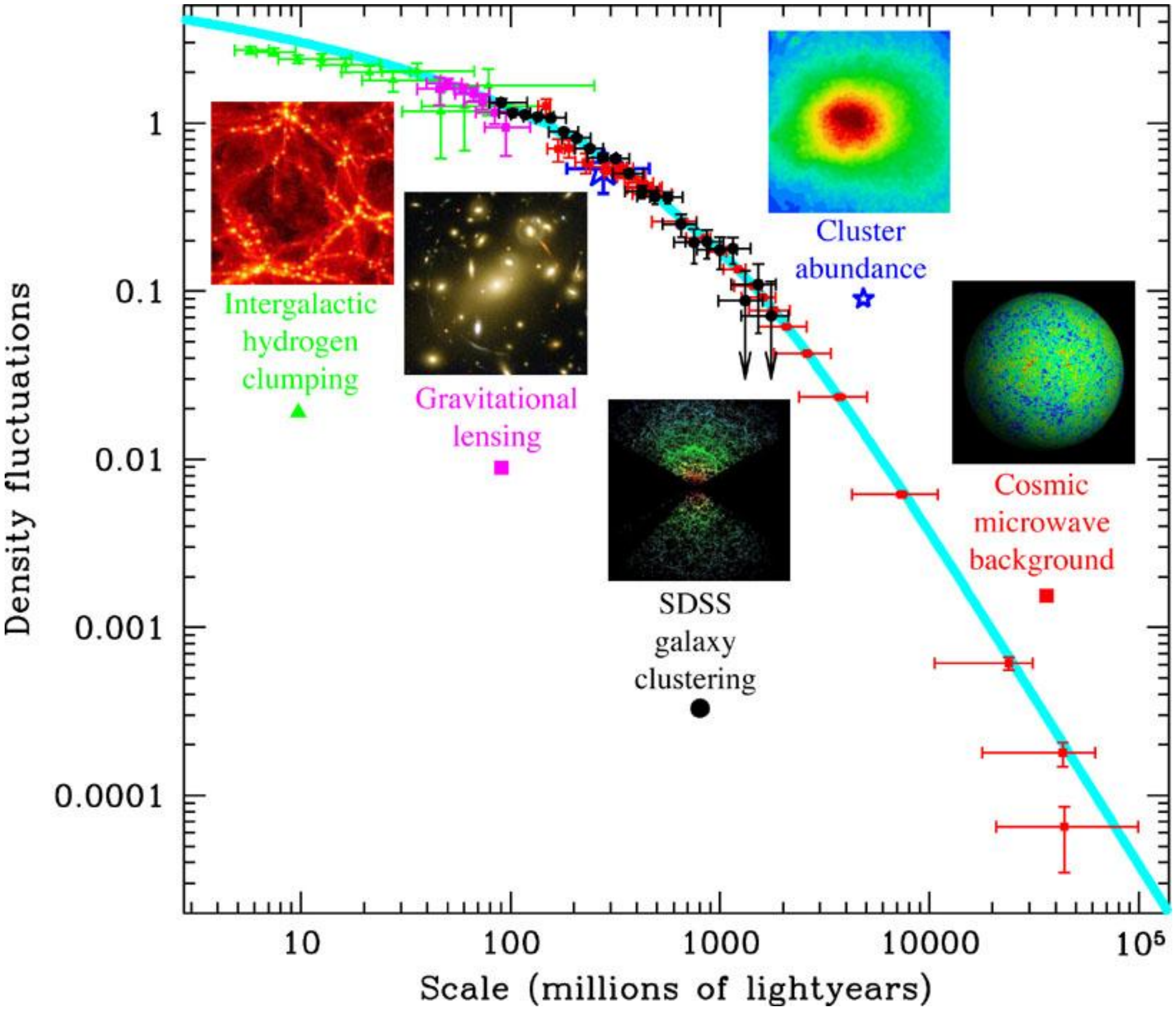
Santa Cruz Galaxy Workshop 2012

ΛCDM Cosmology Success Story
All's well at larger scales …



Tegmark, SDSS

Where Baryons are important: Problems for ΛCDM?

- Missing Satellites – Dark satellites vs. observed satellites: Not a problem

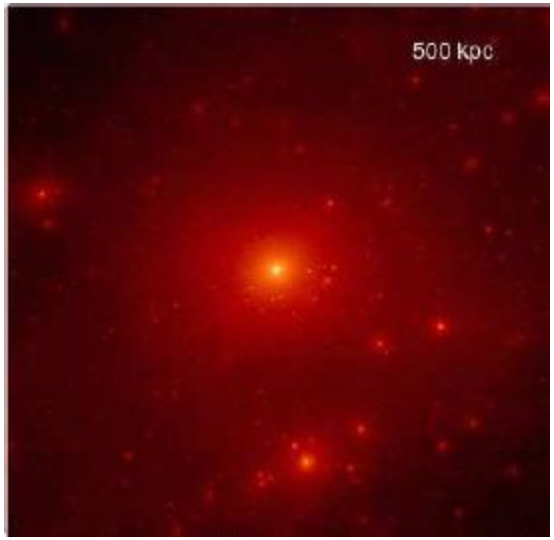
  See talks in this session, work by Zolotov, Brooks, etc …

- Too Many Baryons – Simulated Galaxies keep gas and eventually make too many stars

  Yet stronger feedback: See work by Stinson, Brook, Trujillo-Gomez, **Aquila Comparison**

- Dark Matter Profiles – Observed dwarf Galaxies vs. cuspy dark matter profiles

Aquila Comparison Project



- DM+Gas+Star Formation Simulations of a MW analogue halo
- Limitations: Same ΛCDM initial conditions but otherwise choose your favourite model

Scannapieco, Wadepuhl, Parry, Navarro ... Wadsley … et al. 2012

Groups/Codes

Table 1. Summary of code characteristics and sub-grid physics

Code	Reference	Type	UV background (z_{UV})	(spectrum)	Cooling	Feedback
G3 (GADGET3)	[1]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-BH	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH
G3-CR	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH, CR
G3-CS	[2]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
G3-TO	[3]	SPH	9	[11]	element-by-element [15]	SN (thermal+kinetic)
G3-GIMIC	[4]	SPH	9	[11]	element-by-element [15]	SN (kinetic)
G3-MM	[5]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-CK	[6]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
GAS (GASOLINE)	[7]	SPH	10	[12]	metal-dependent [16]	SN (thermal)
R (RAMSES)	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-LSFE	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-AGN	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal), BH
AREPO	[9]	Moving Mesh	6	[10]	primordial [13]	SN (thermal)

NOTE: [1] Springel et al. (2008); [2] Scannapieco et al. (2005); Scannapieco et al. (2006); [3] Okamoto et al. (2010); [4] Crain et al. (2009); [5] Murante et al. (2010); [6] Kobayashi et al. (2007); [7] Stinson et al. (2006); [8] Teyssier (2002); Rasera & Teyssier (2006); Dubois & Teyssier (2008); [9] Springel (2010a); [10] Haardt & Madau (1996); [11] Haardt & Madau (2001); [12] Haardt & Madau (2005, private communication); [13] Katz et al. (1996); [14] Sutherland & Dopita (1993); [15] Wiersma et al. (2009a); [16] Shen et al. (2010).

Results

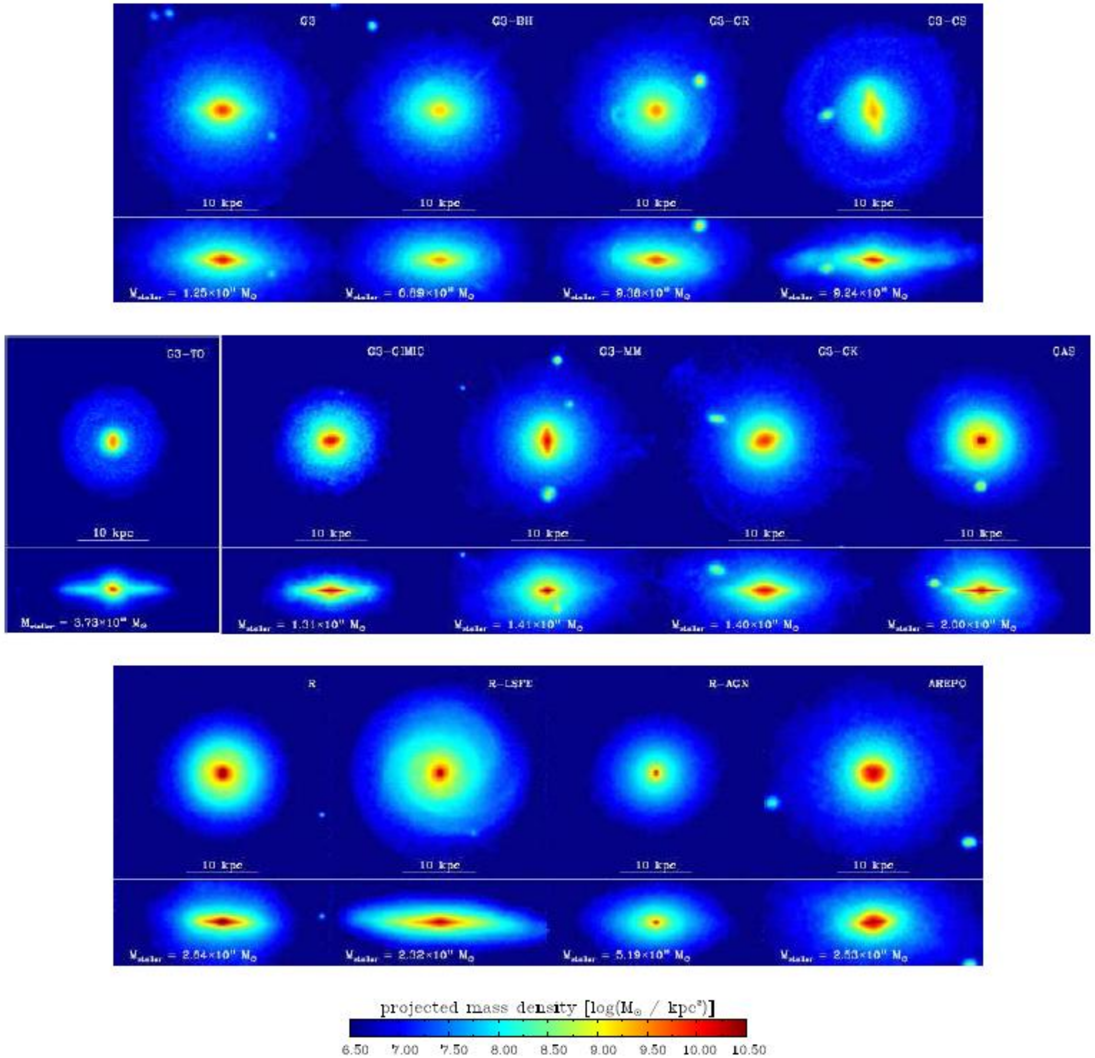


Figure: Stellar Mass Density at redshift z=0

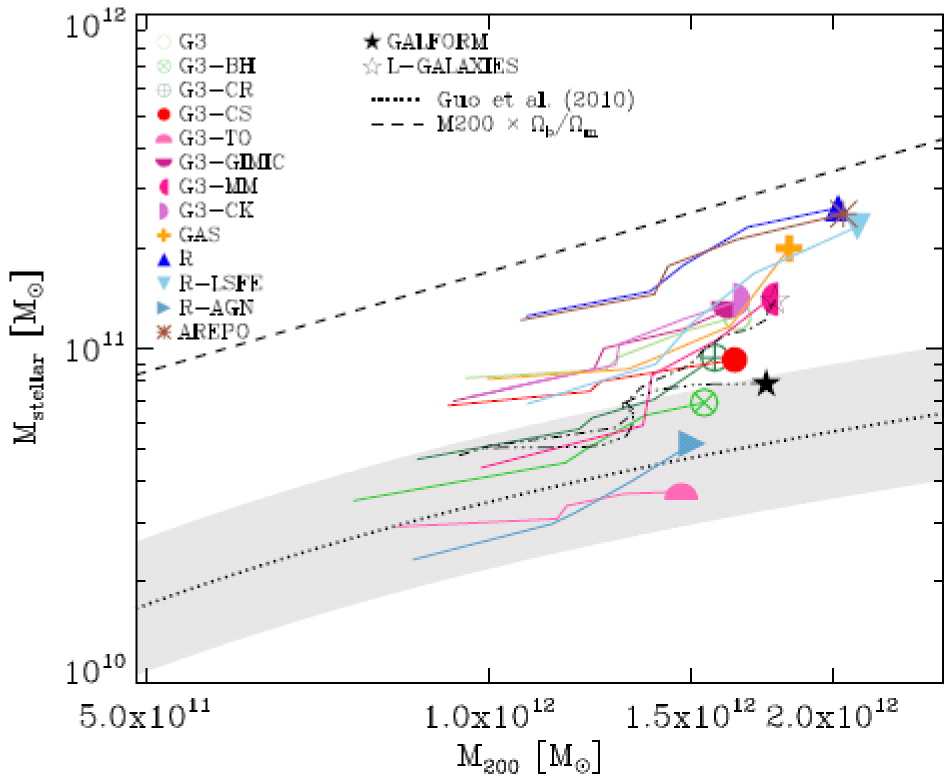
- Spheroidal → Spiral
- Stellar Mass variation: 1 order of magnitude

General Outcome

- Too many stars

(cf. Guo et al. 2010)

- Most star formation z > 3-4
- Too small, too rapidly rotating
- Primary solution: blow out the gas by hand



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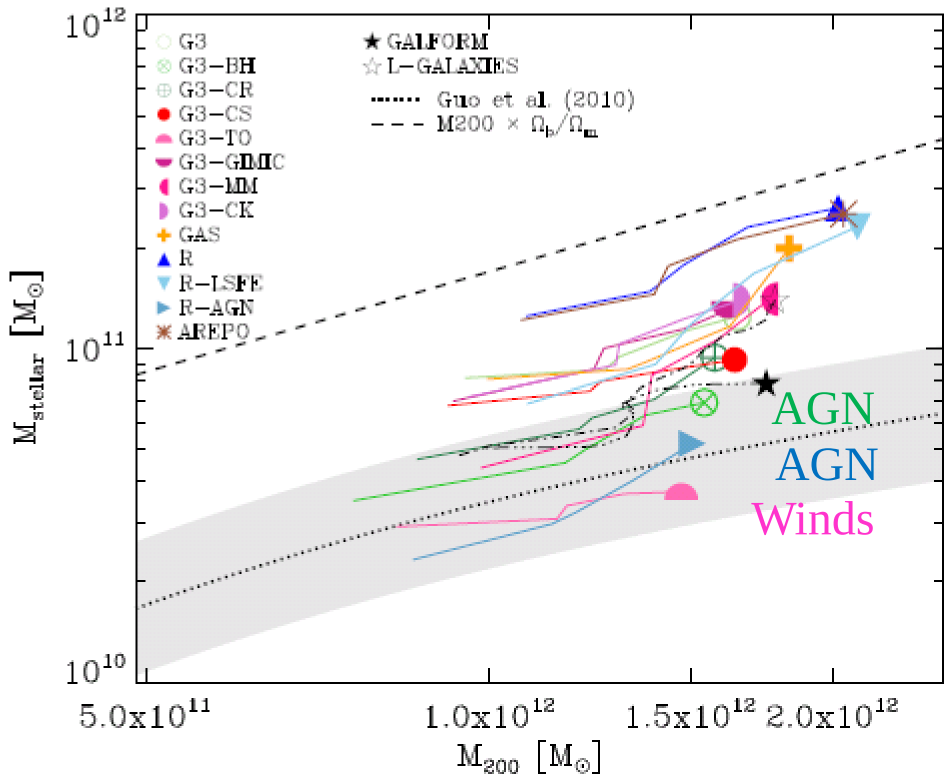
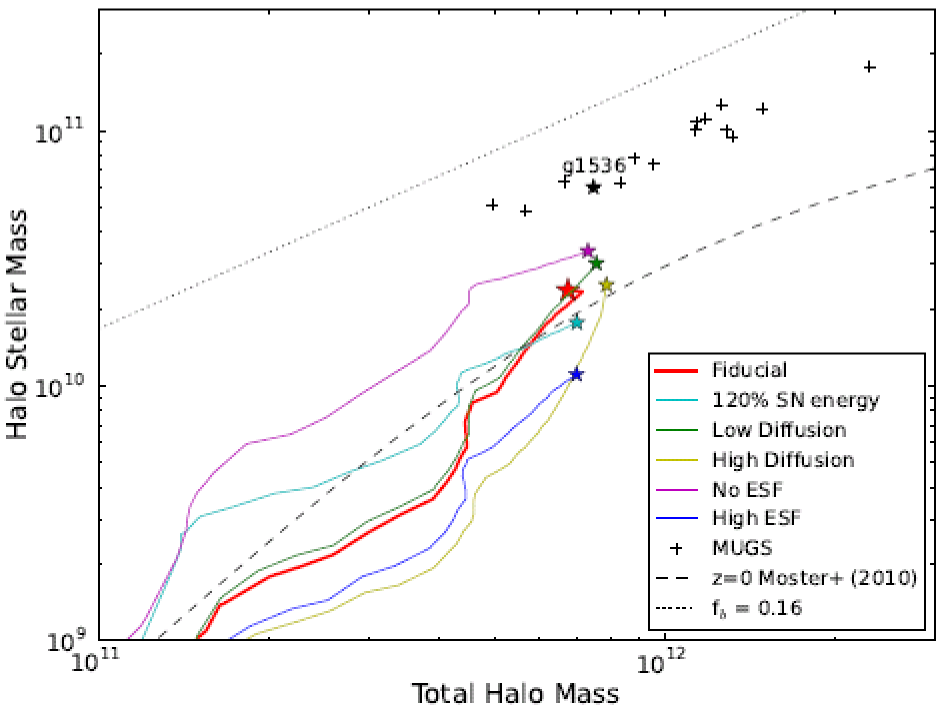


Alternate Solutions:
Early Stellar Feedback Models



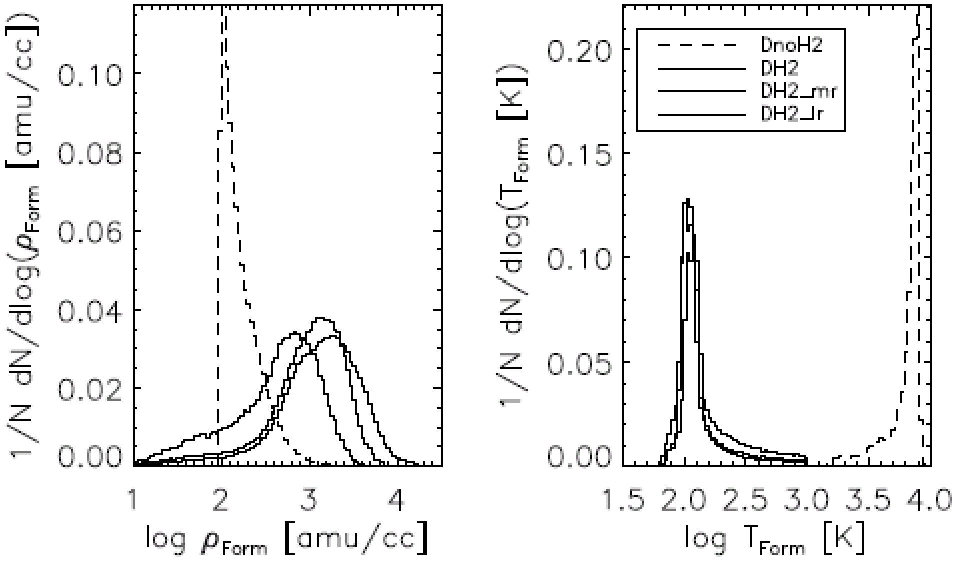
Stinson et al (2012)

Can match
Moster et al (2010)
stellar mass fractions
including SF history

Models mimic Stellar Winds, UV, Radiation Pressure , SN –
Lots of parameters -- getting like Semi-Analytic Models
Losing predictive power?

Avoiding Parameter Creep

- Ideally no imposed SF threshold: Just make the stars from H_2 (c.f. Gnedin)
- Gasoline implementation (Christensen et al. 2012)



Aquila Comparison and The State of Galaxy Formation

- Large code-to-code variation
- Sub-grid SF/Feedback models NOT mature, particularly for processes affecting larger galaxies
- Back-to-basics:

  Sub-grid models are unavoidable, we need to constrain them by understanding star formation on kpc scales and smaller

Structure of Dwarf Galaxies

Navarro, Frenk & White (1997) "Universal Dark Matter Profile"
with central density cusp doesn't match small galaxies

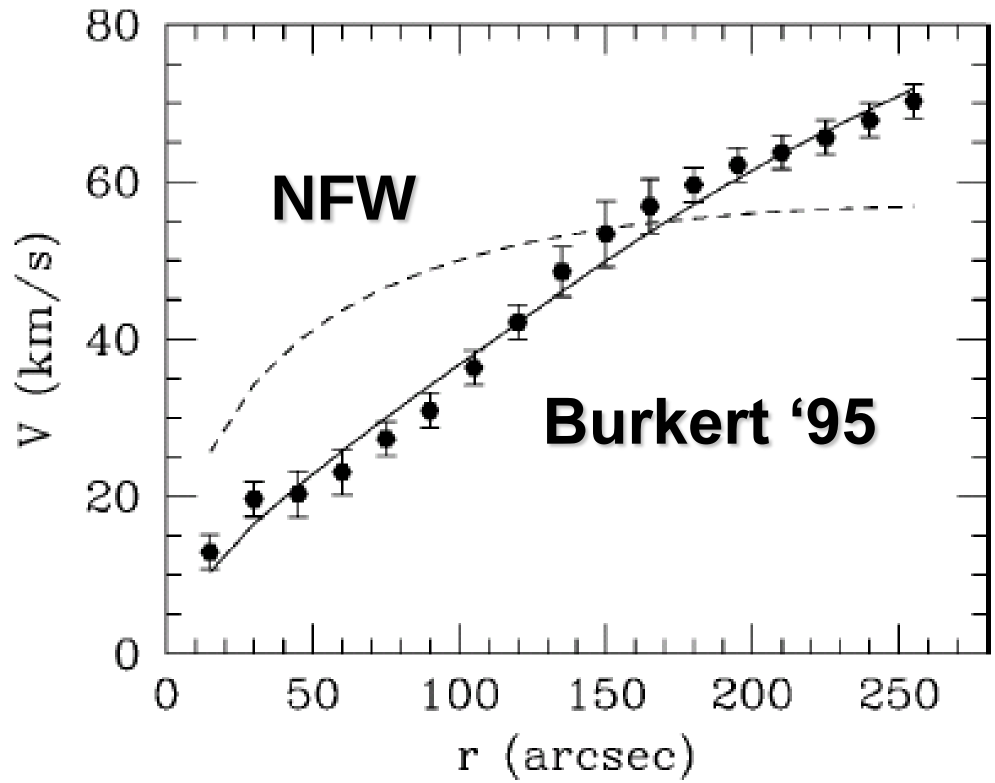


FIG. 2.—Mass models for DDO 47; the solid line is the best-fitting model with the Burkert halo, and the dashed line represents the best-fitting NFW model, with a virial mass $M_{vir} = 2.4 \times 10^{10}\ M_\odot$ (see text).

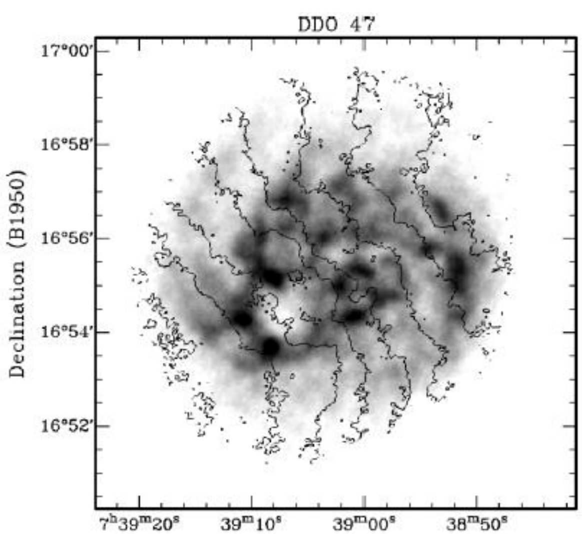
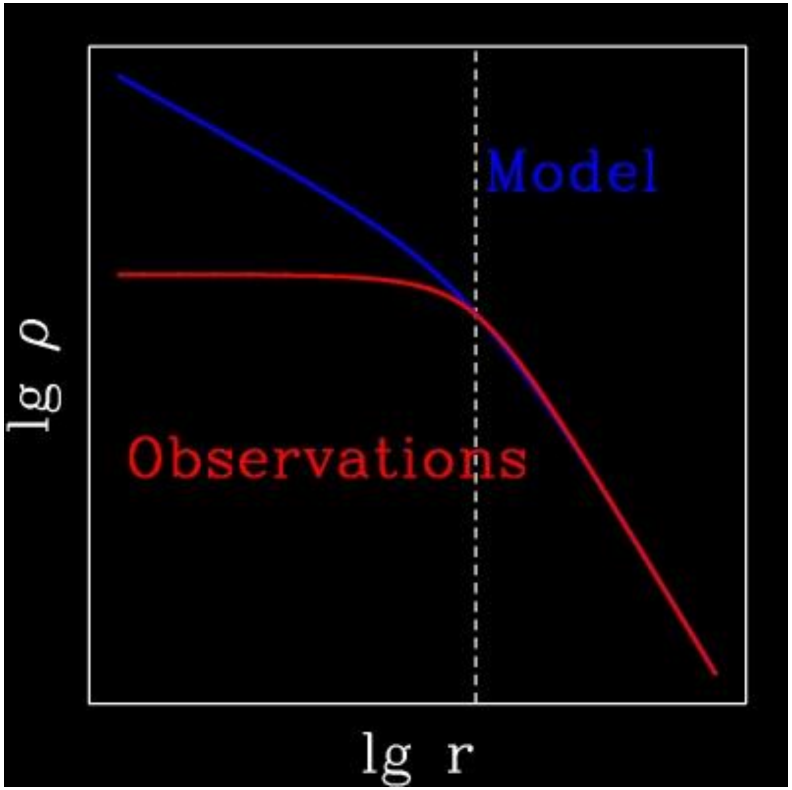


FIG. 1.—Velocity field of DDO 47 (*contours*) from the 15" resolution cube and its total H I map (*gray scale*). Contours are spaced by 10 km s^{-1}.

Gentile, Burkert, et al. 2005

Cusp/Core problem in ΛCDM



Walker & Peñarrubia (2011):
Fornax, Sculptor
Δlog M/ Δlog r ~ 2.61, 2.95
rule out NFW (cusp) at >~ 96%, 99%

Proposed solutions

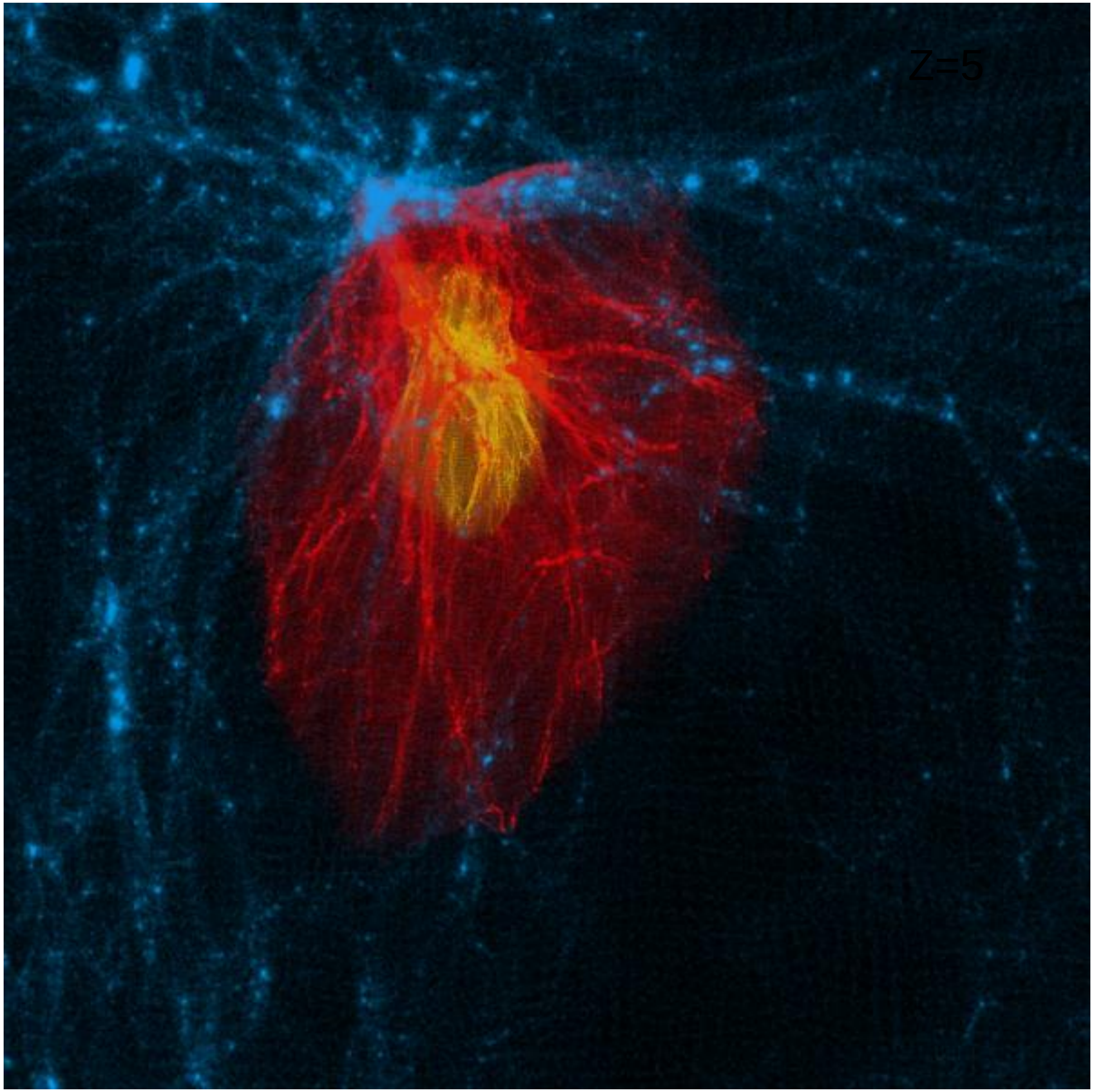
- New physics: WDM; self-interacting DM; MOND
- Solutions within standard ΛCDM require DM "heating", e.g.:
  - Rotating bar
  - Passive evolution of cold lumps (e.g., El Zant et al. 2001)
  - Recoiling black holes
  - AGN
  - "Maximal stellar feedback"/"blowout" (Read & Gilmore 2005, Navarro et al 1996)

A mechanism that is a natural consequence of structure formation:

- Bulk gas motions driven by supernovae and stellar winds cause potential fluctuations that "pump" the orbits of the collisionless components (Mashhchenko, Couchman & Wadsley 2006, Mashchenko, Wadsley & Couchman 2008, Pontzen & Governato 2012)
  - Must have been commonplace in early, gas-rich dwarfs
  - Observe bulk motions of cold gas in present-day dwarfs that are mildly supersonic, have scale ~ few 100pc and velocities ~10 km/s (similar to dark matter)

Fornax-like Dwarf galaxy simulation

4 Mpc (co-moving)



Constrained cosmological simulation

Evolution of isolated dwarf galaxy (~$10^9\ M_\odot$) over z=10…5.

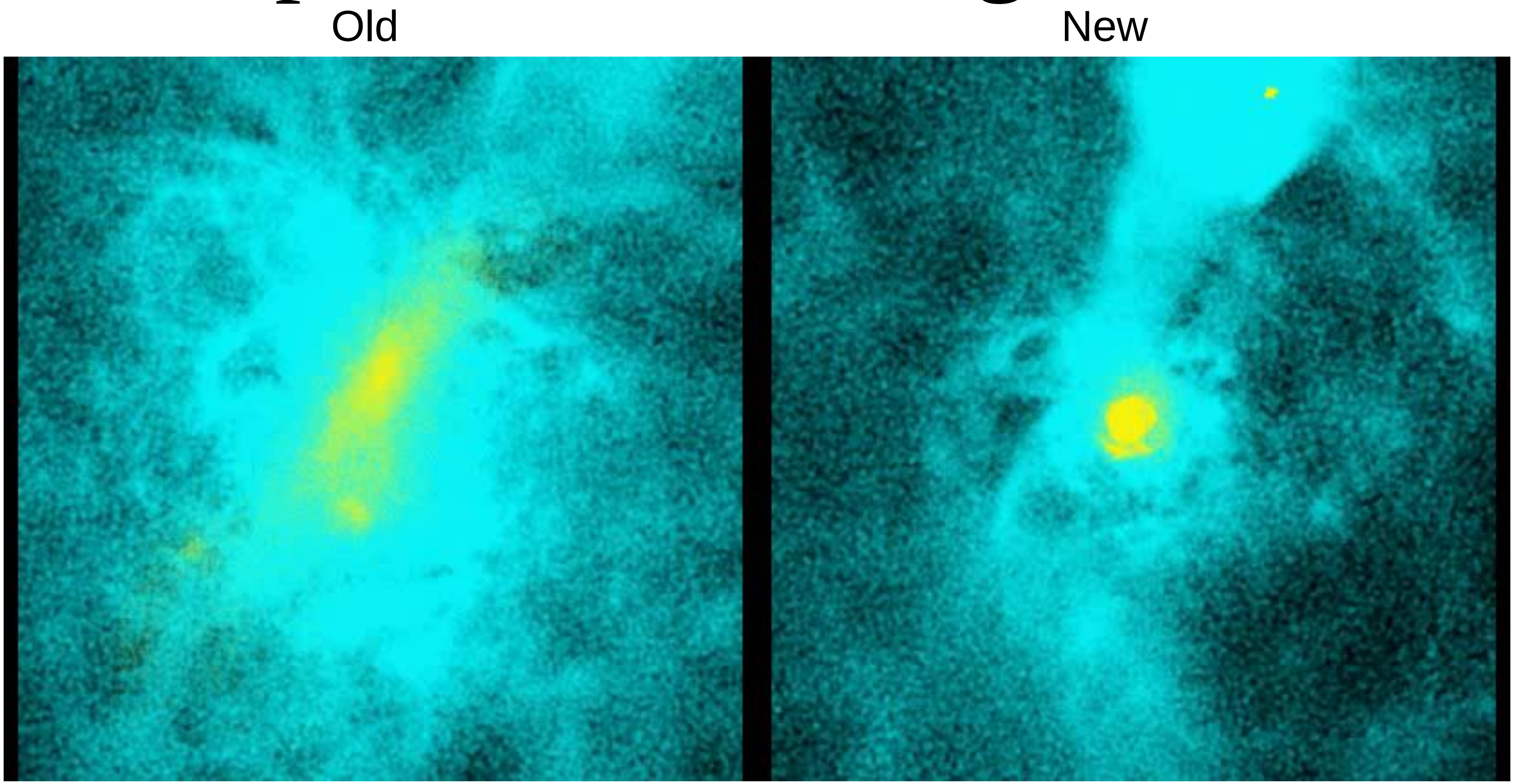
15 million particles (10 million hi-res).

m_{DM}= 1900 $M_\odot$
m_{gas}= 370 $M_\odot$
m_{star}= 120 $M_\odot$

ε = 12pc

1.1 10^7 dark
4.5 10^6 gas
4.5 10^5 star

Improved modelling of ISM



Need low temperature cooling and a high density threshold for "clustered star formation".

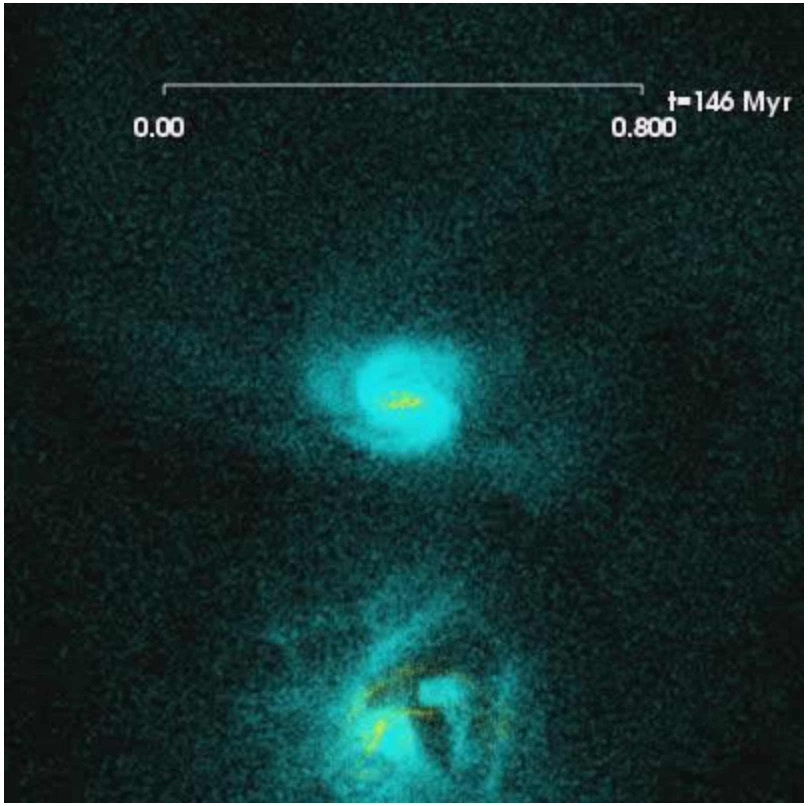
Model supernovae as point explosions.

Cosmological simulation with gas dynamics, clustered star formation and stellar feedback.

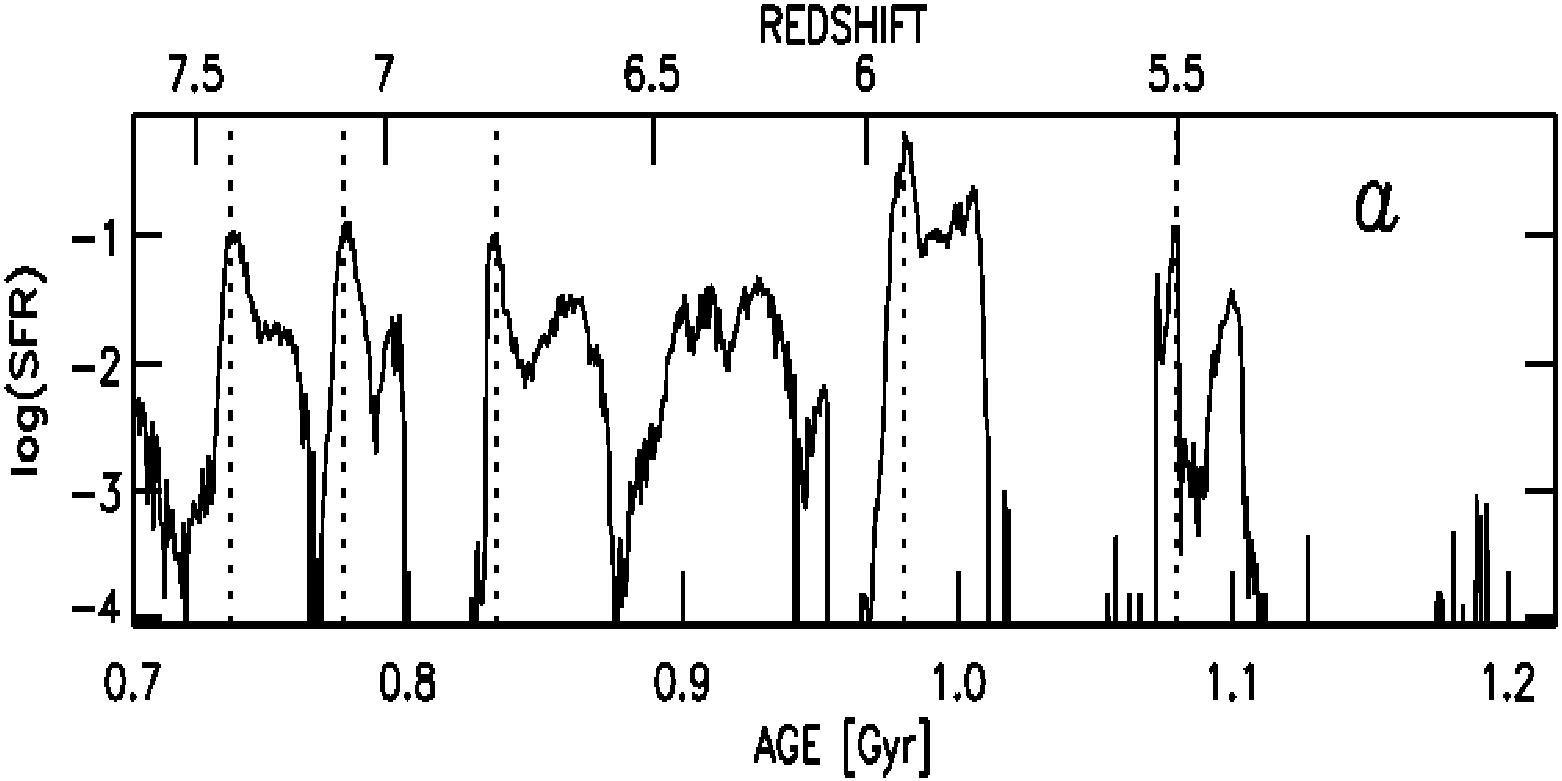
Central 1.3 kpc of a forming dwarf galaxy.

z = 9…5

Gas is in blue, stars are in yellow

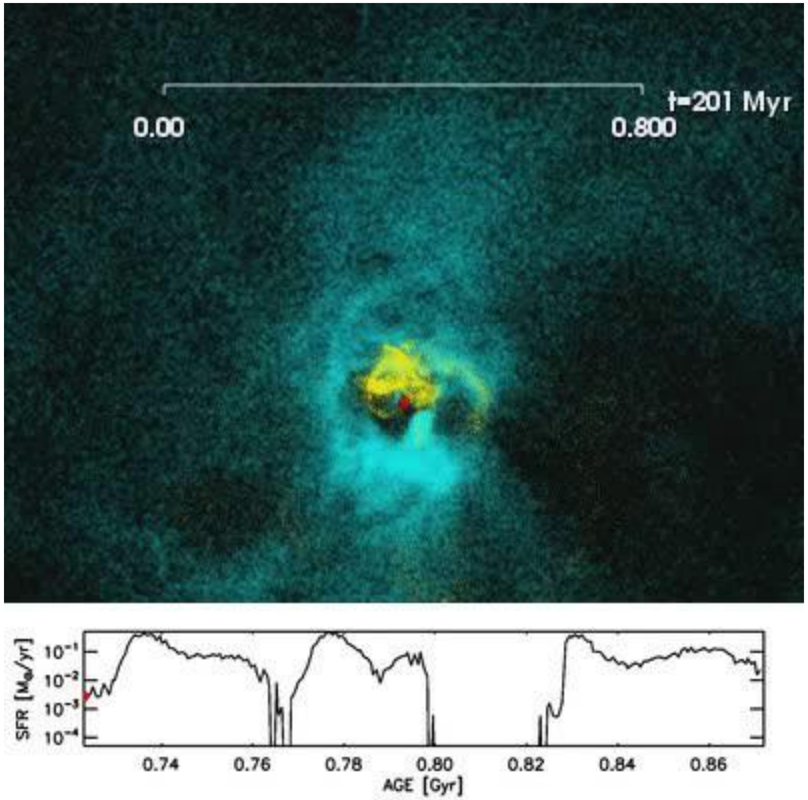


Episodic, clustered star formation



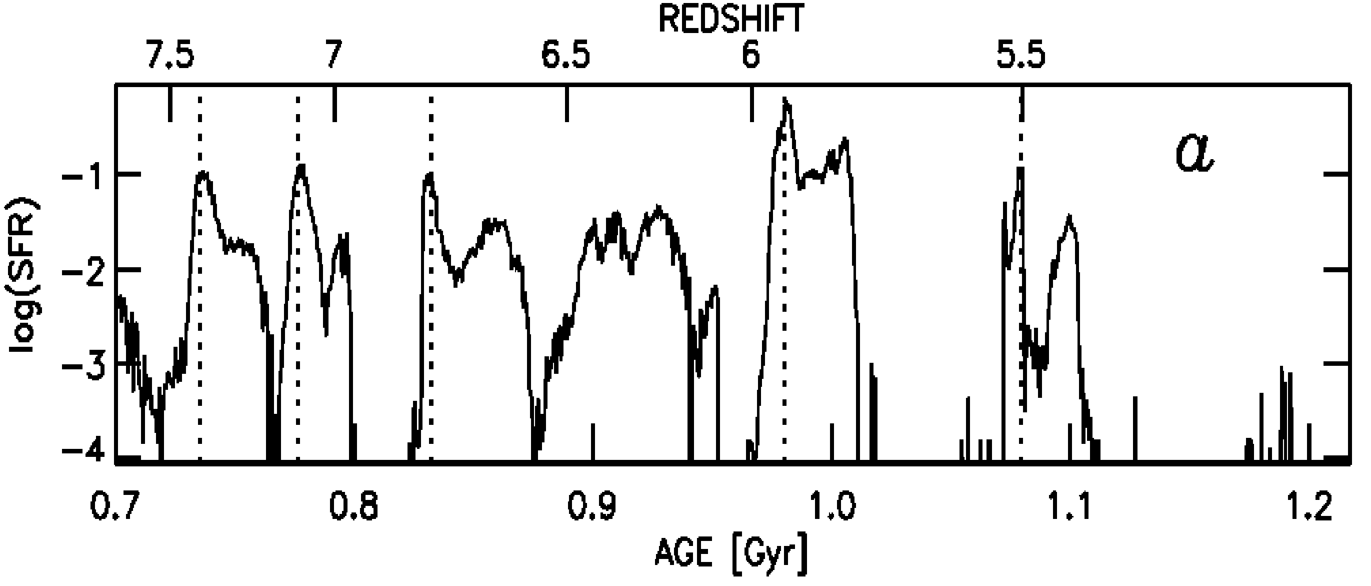
Maxwell, Wadsley, Couchman & Mashchenko (2012)

Star formation and feedback close up



Orbit pumping: how it works

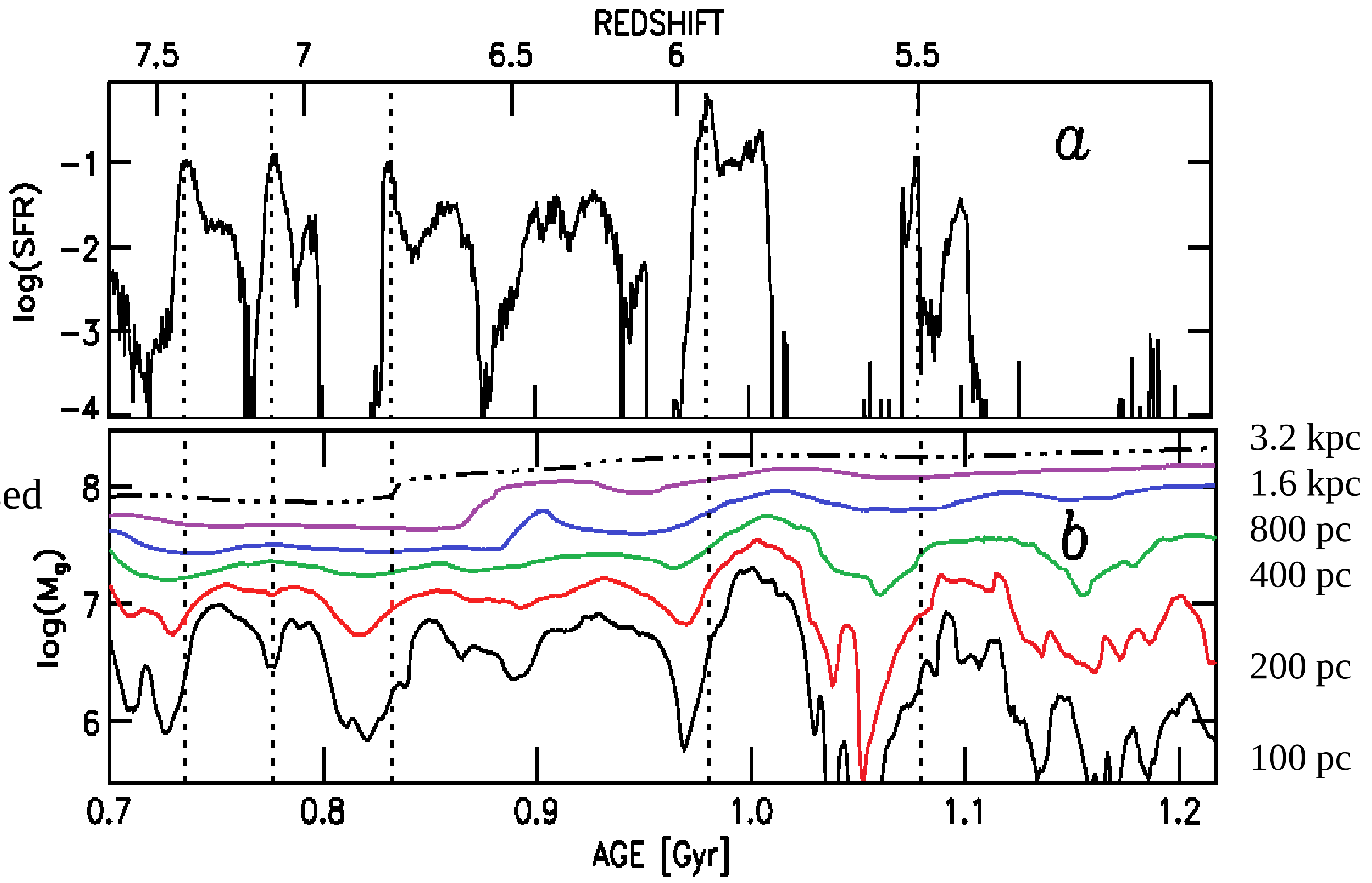
Star
Formation
Rate



Maxwell, Wadsley, Couchman & Mashchenko (2012)

Orbit pumping: how it works

Enclosed
Gas
Mass



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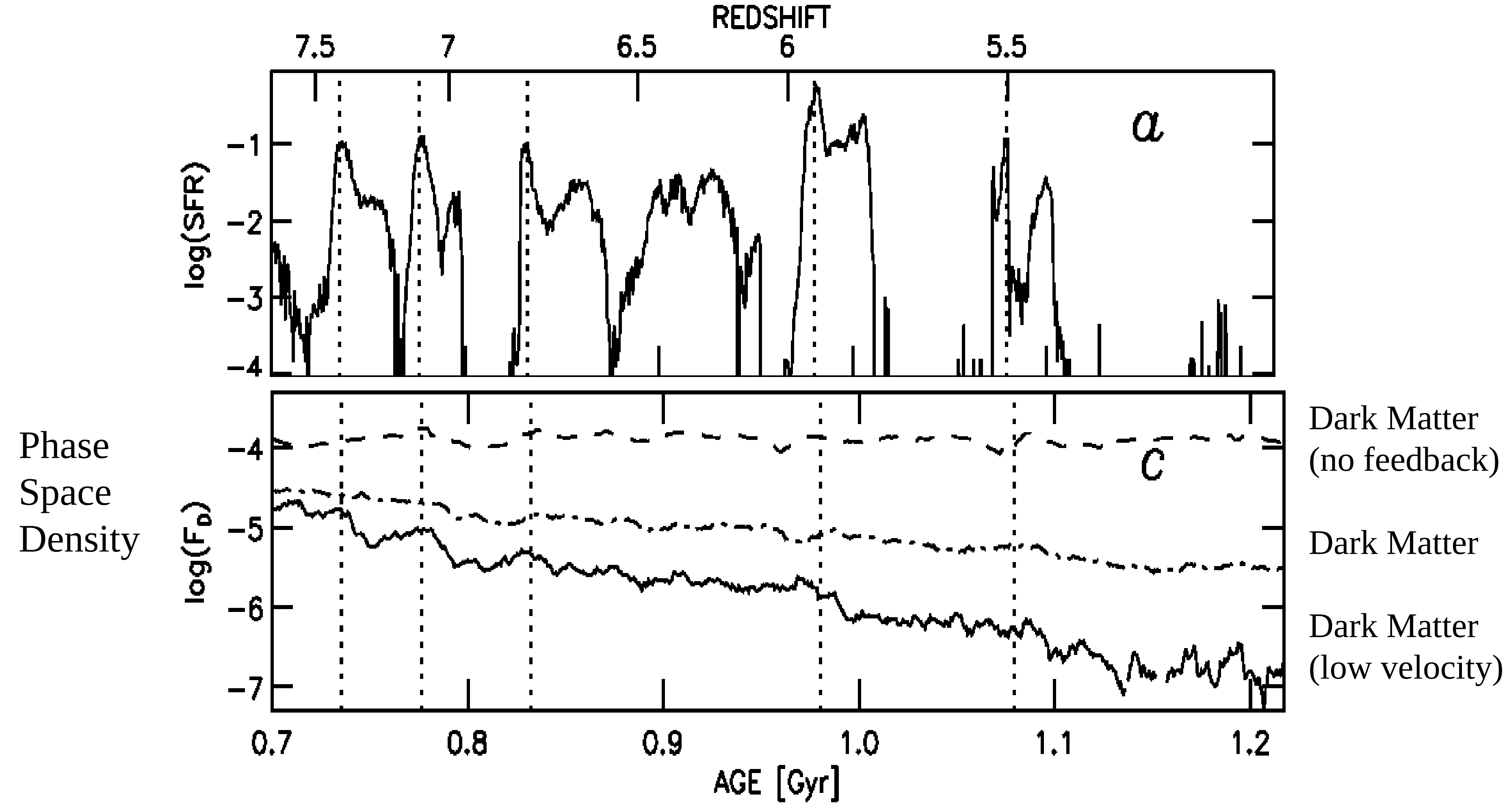
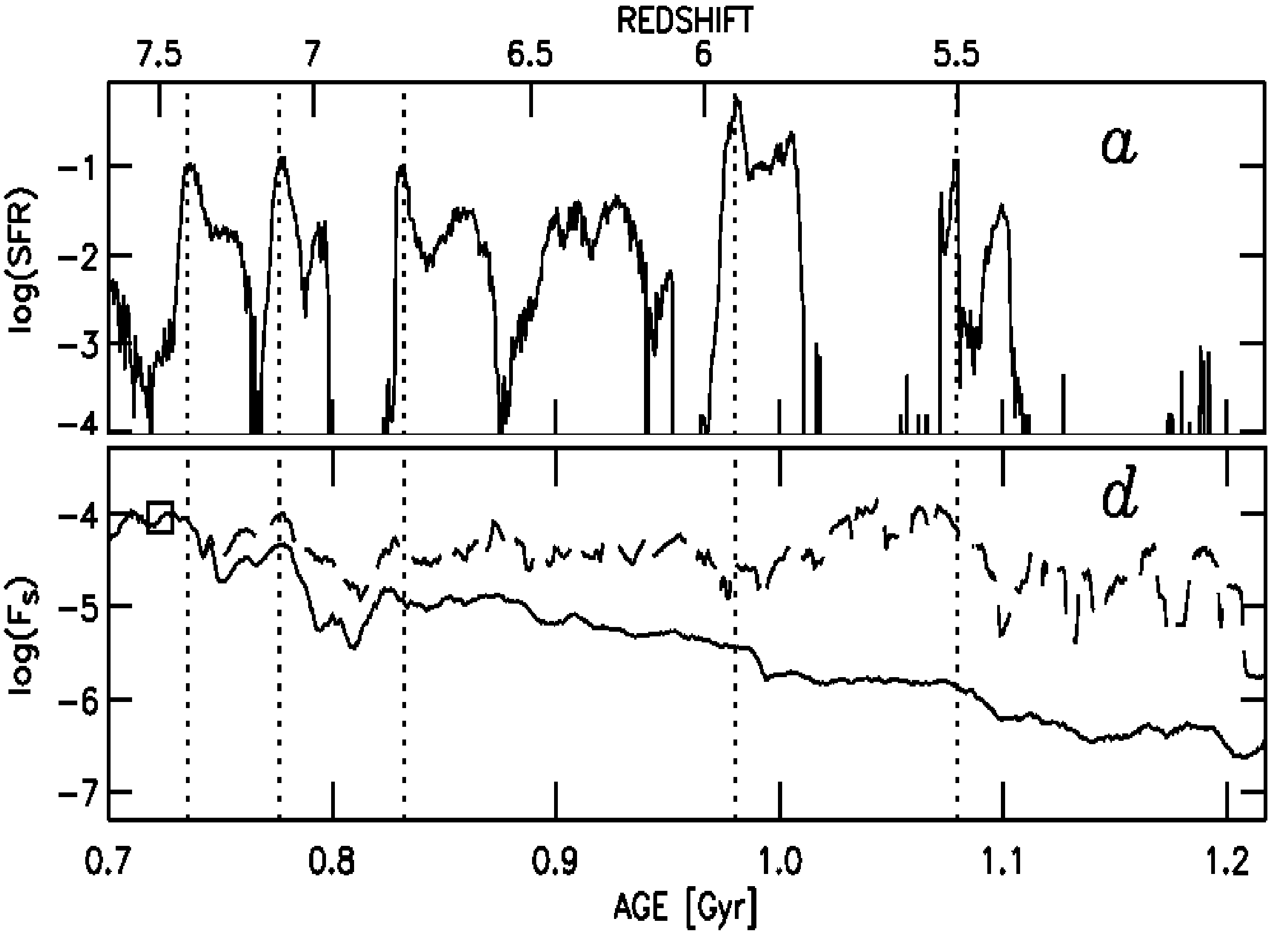


Maxwell, Wadsley, Couchman & Mashchenko (2012)

Orbit pumping: how it works

Phase Space Density

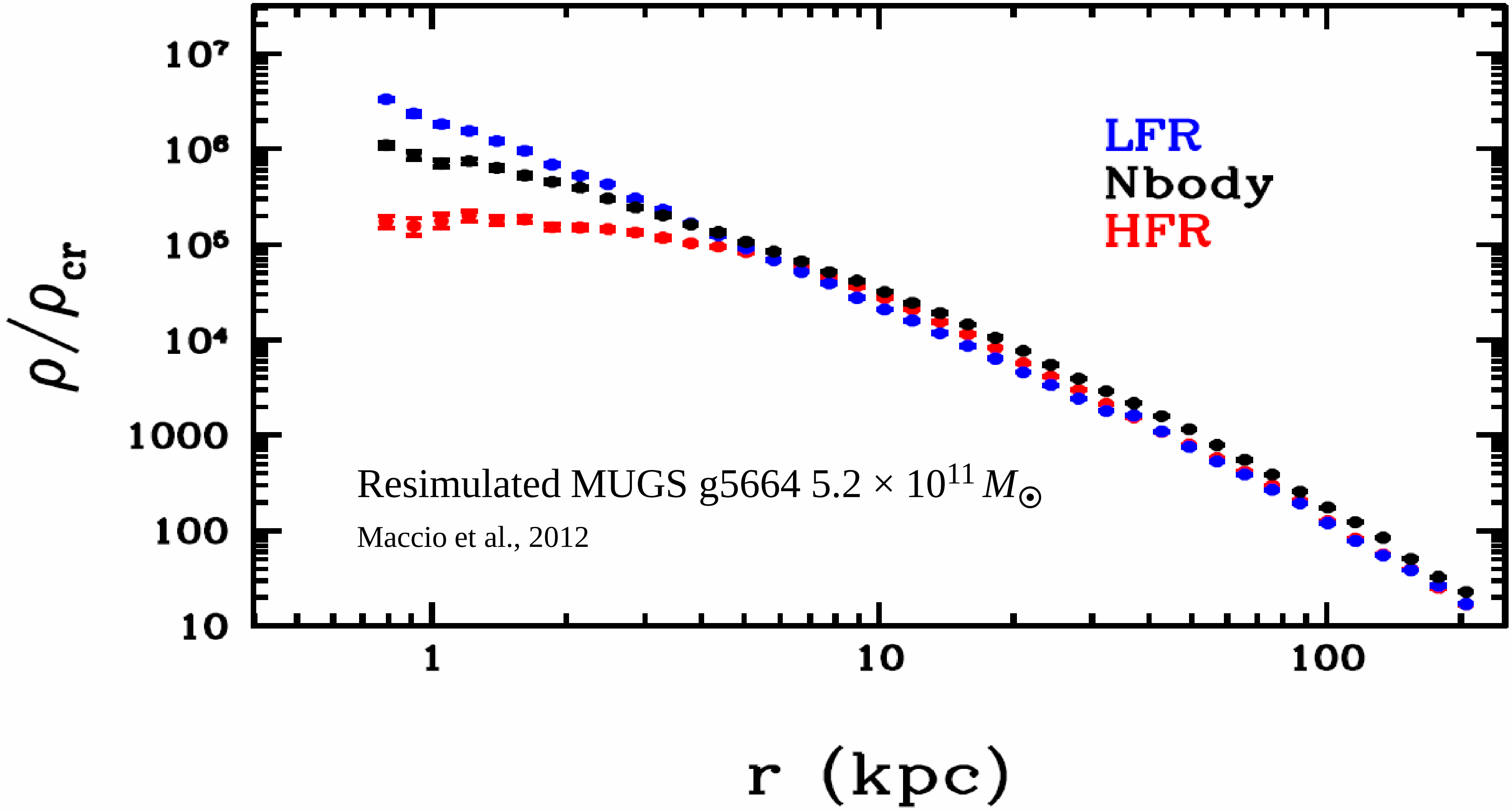


All Stars

Old Stars (formed at z = 7.5)

Maxwell, Wadsley, Couchman & Mashchenko (2012)

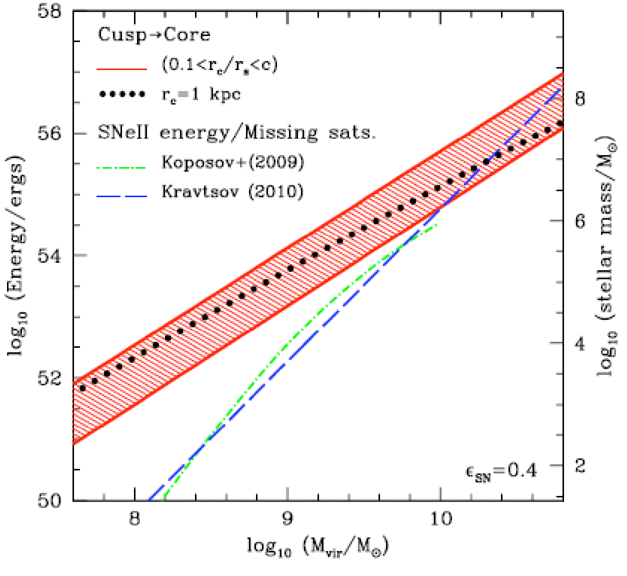
Radial profiles



Mashchenko et al., Science 2008 (Governato et al 2010; Pontzen & Governato 2011)

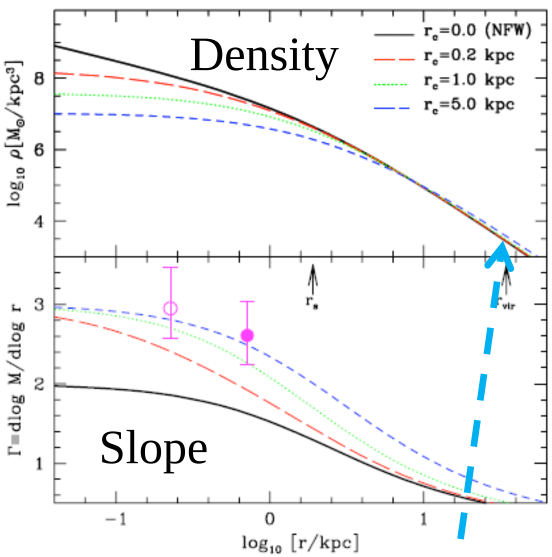
Energy costs to form a core

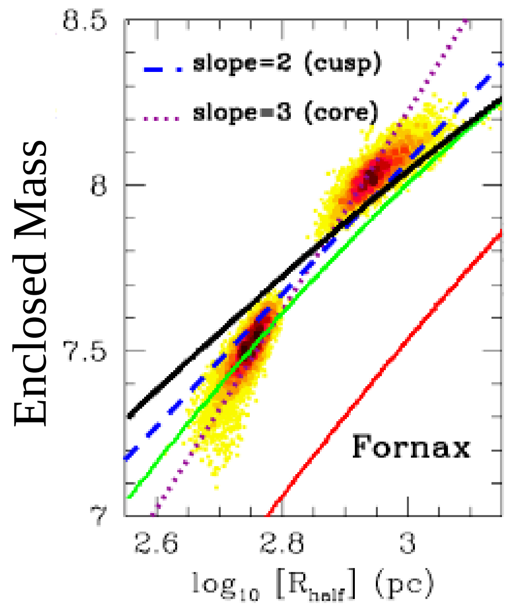
- Blowout is less effective and energetically more expensive than Orbit pumping
- Even with orbit pumping: Does forming cores require too many SN in dwarf galaxies?

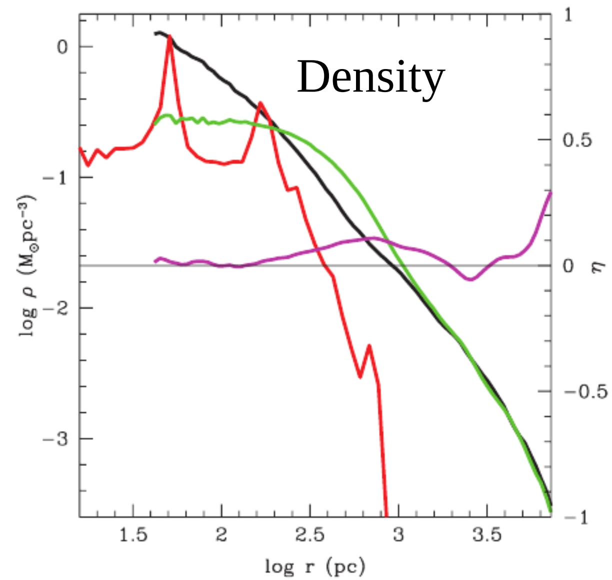


Peñarrubia, Pontzen, Walker & Koposov (2012)
Estimate that small galaxy star formation rates inconsistent with energy requirements to form a core

Energy costs to form a core





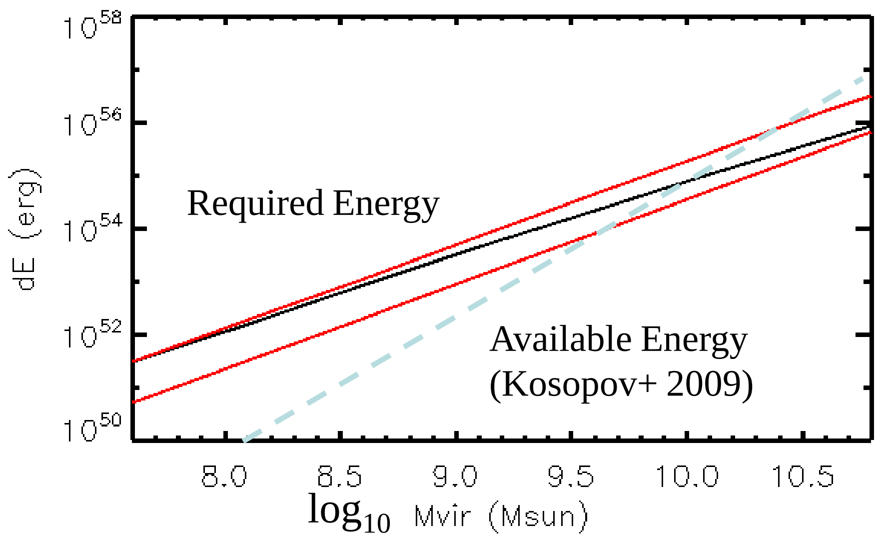


Peñarrubia et al. assumed large smooth cores (1-5 kpc) and redistribute mass out to virial radius

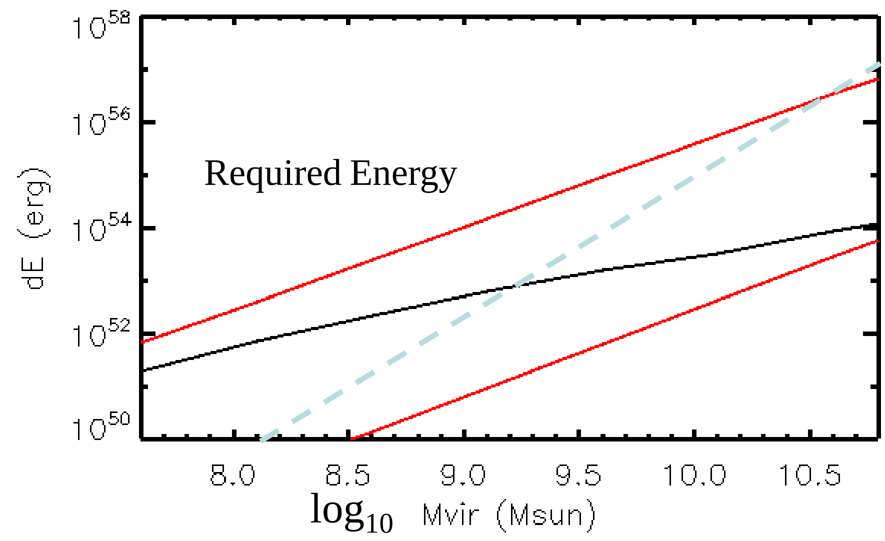
5 kpc core (red) may fit slope but does not fit enclosed mass! (data from Walker & Penarrubia 2011)

Simulations – core is smaller, very flat and distributes mass to roughly twice core radius (black to green line)

Energy costs to form a core



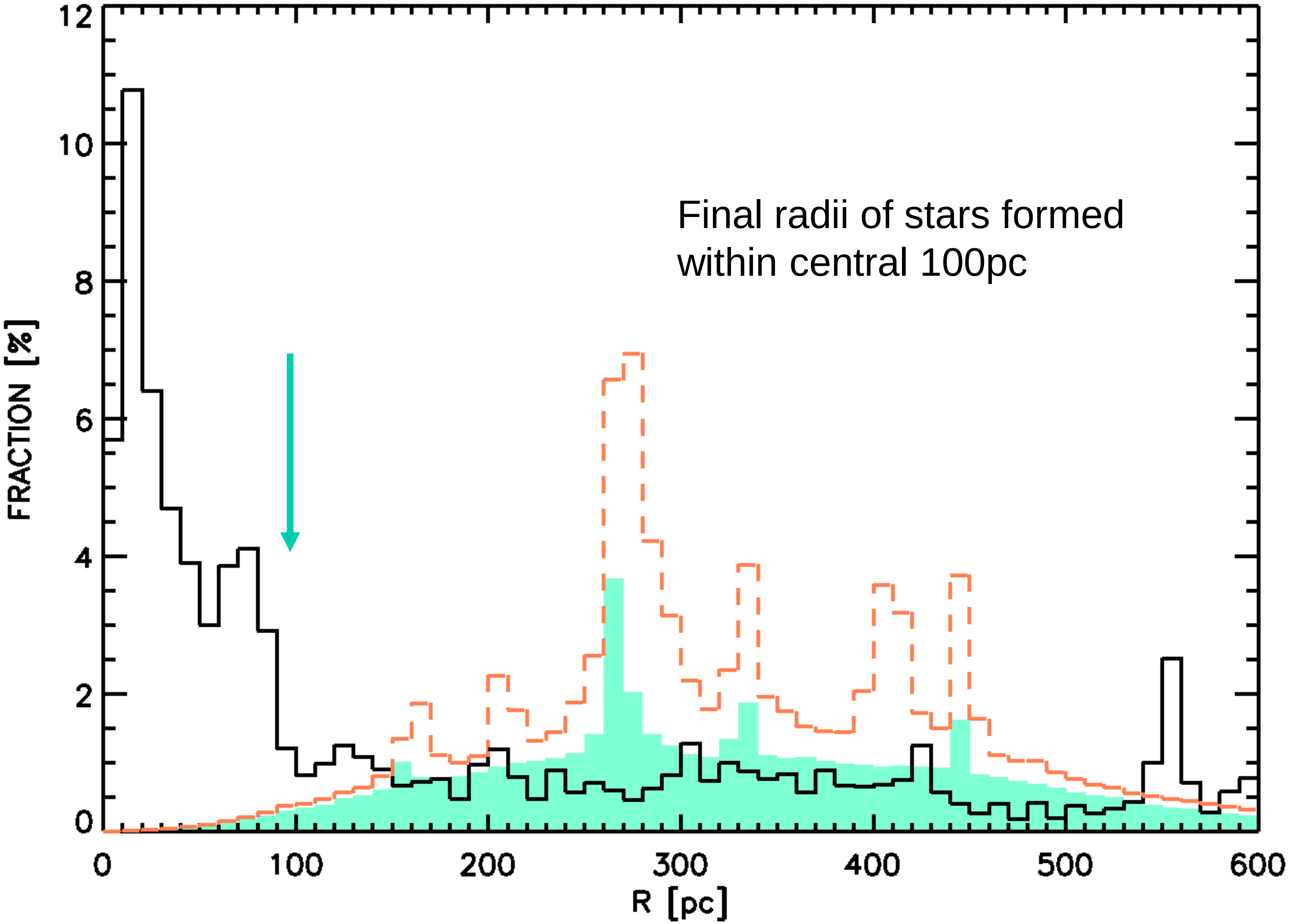
Peñarrubia et al estimate – move matter to virial radius



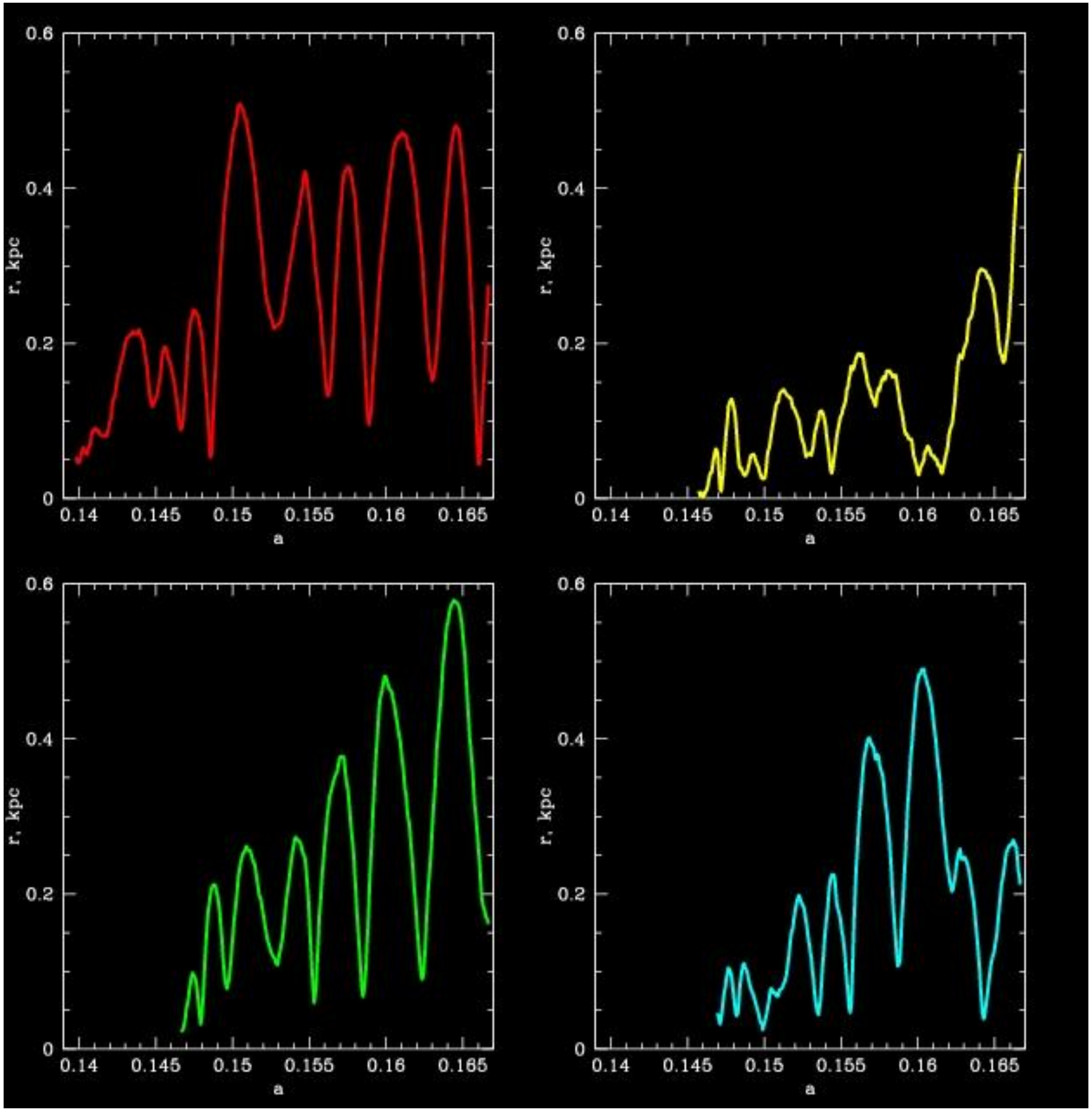
Estimate moving matter to 2 x core radius
Wadsley et al, in prep

- Energetics of core formation <u>are</u> consistent with satellite SFR (e.g. Kosopov et al 2009)

Orbit pumping of the stellar component



Orbits of “Globular Clusters”



Long-lived star clusters

Distance from galactic centre:

- At birth (z~6.2): σ_r = 37 pc
- After 200 Myr: σ_r = 280 pc

- Stellar feedback also acts on GCs, and
- Impact of dynamical friction reduced by flat core (*e.g., Fornax*)

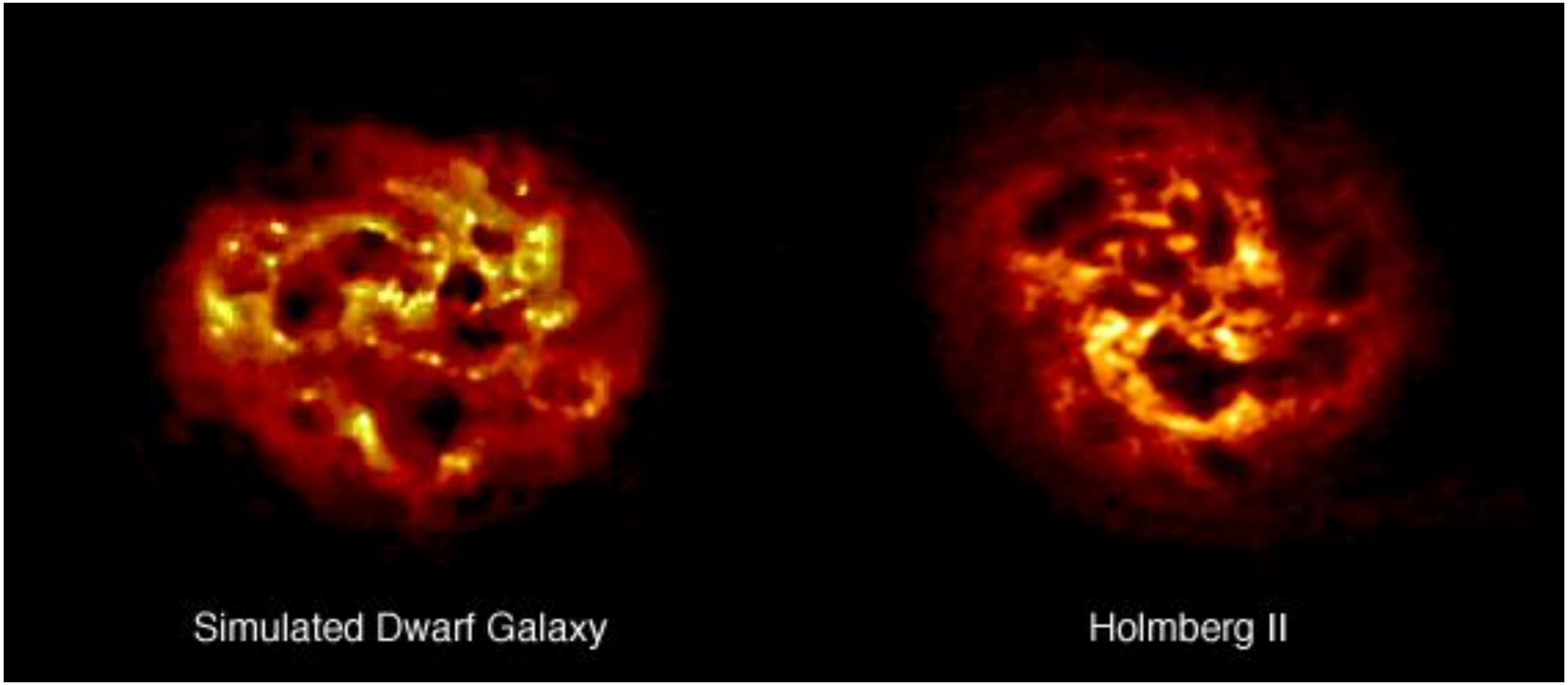
Clusters formed near centre, “kicked” out to large radii

Conclusions: Implications of Orbit pumping for Stars

- Leads to a decreasing gradient of stellar metallicity with radius; redistribution stops when vigorous star formation stops
- Central stellar density roughly constant as migrating stars replenished
- “Globular clusters” form in ISM (no DM) and migrate outwards over several orbits; may form multiple generations (c.f. D’Ercole et al. 2010) from enriched gas in nucleus (lose access to this gas as orbits grow)
- GCs protected from tidal disruption as orbits grow and cusp erased
- Mergers and tidal stripping will deposit the GCs and loosely bound stars into haloes of later generations of larger galaxies; could be source of current GCs in all galaxies

Maxwell, Wadsley, Couchman & Mashchenko (2012)

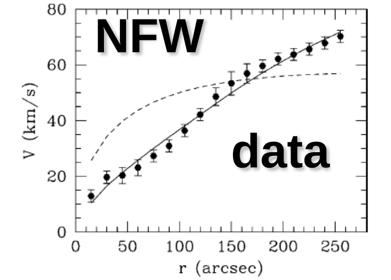
Dwarf Galaxy (DG1)

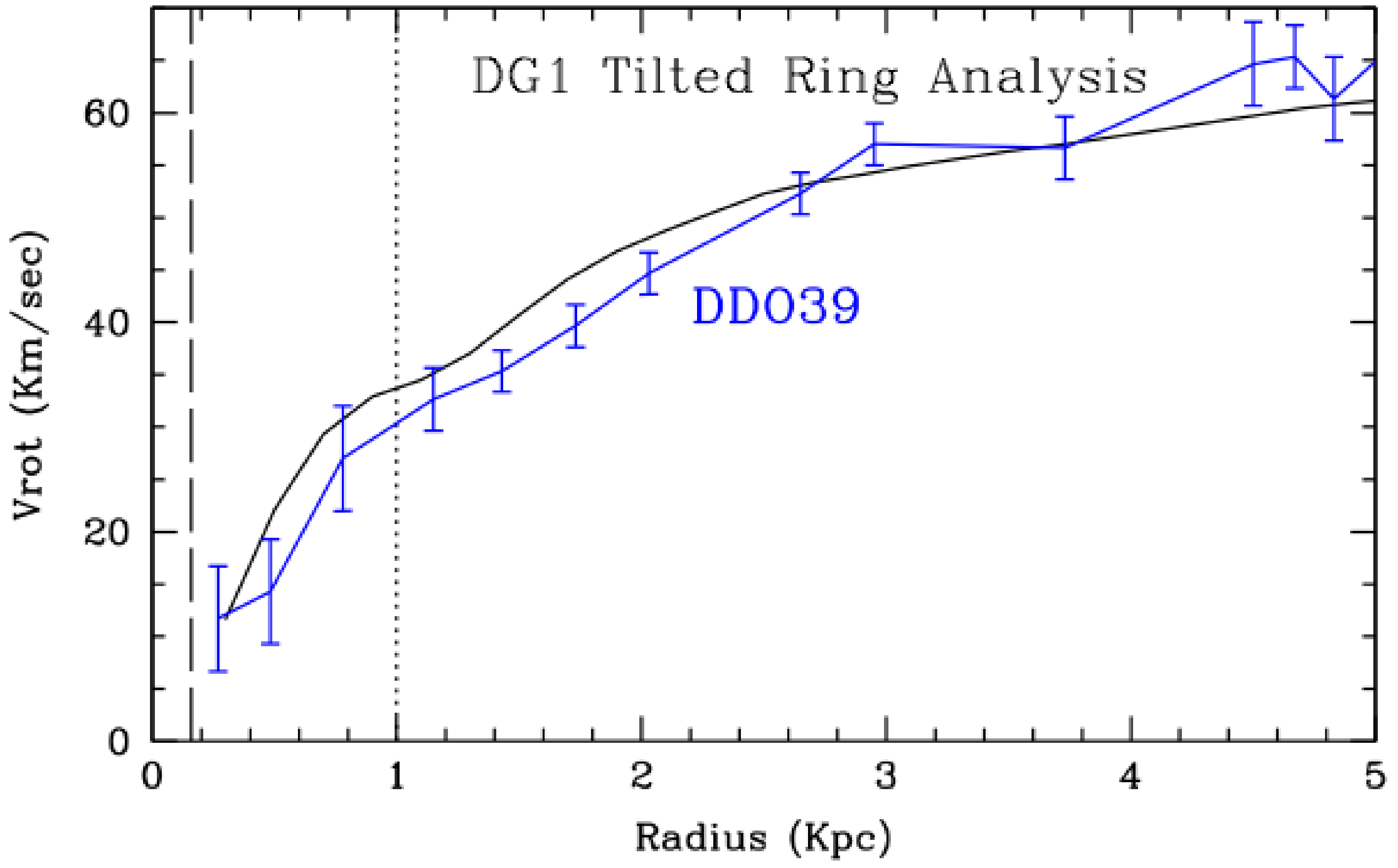


Simulation (Governato .. JW et al. 2010)

- ~ 10^9 M_{SUN} Halo
- ~80 pc resolution, mass resolution < 10^4 M_{SUN}
- "Zoomed" Cosmological IC: 50 Mpc box

DG1 Rotation Curve





Cored galaxy property maintained for analogues of nearby dwarfs (Governato .. JW et al 2010)