Simulations of dwarf galaxy formation in the ΛCDM model: from star formation to dark matter core formation and implications for environmental effects

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Outline

I. Cosmological simulations of field dwarfs: status overview

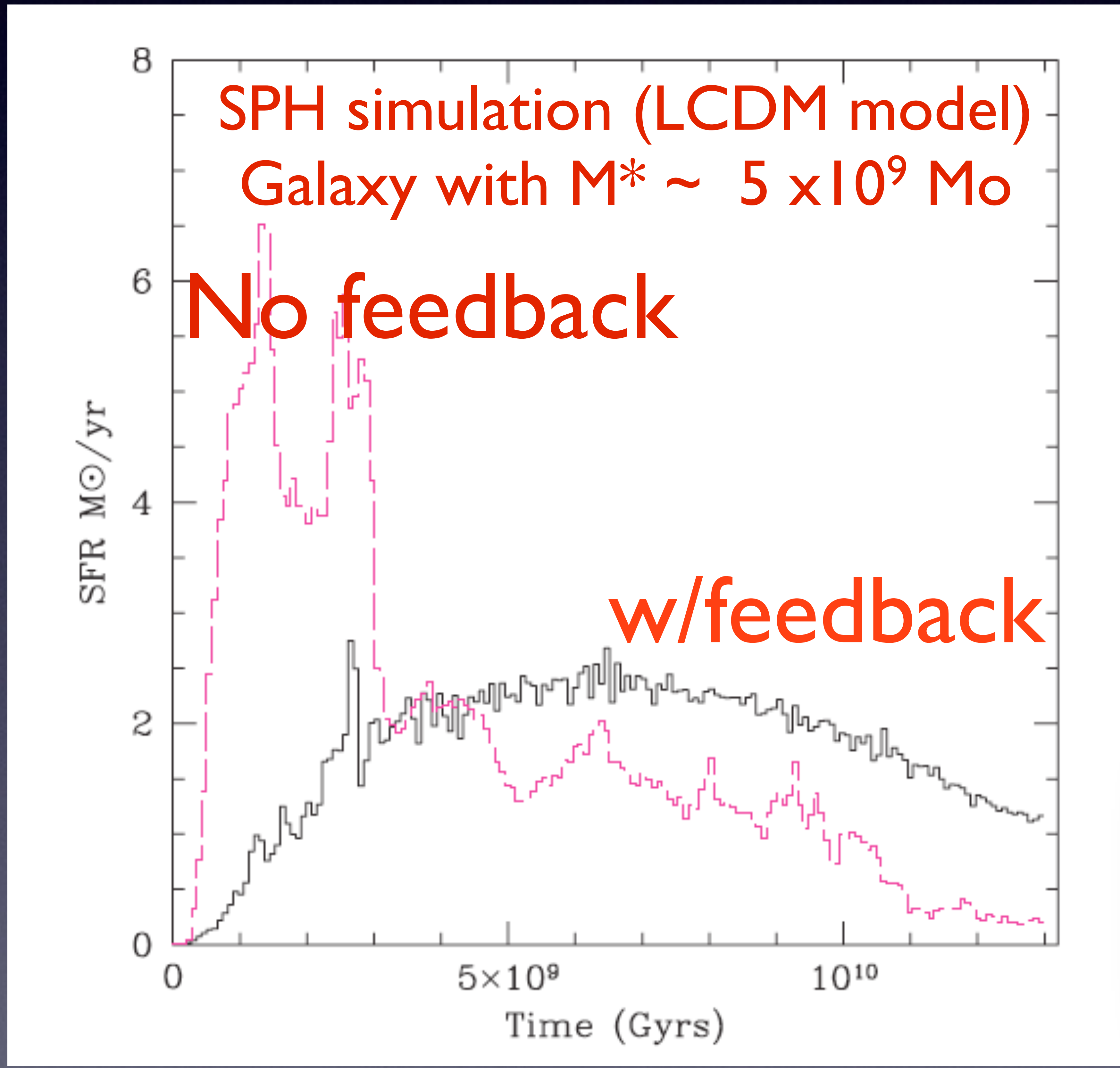
II. Dark matter core formation via baryonic outflows

III. Near-field cosmology with star formation histories and stellar population of dwarfs

IV. Implications of core formation on the origin of dSphs: from tidal stirring to the "too-big-to-fail" problem

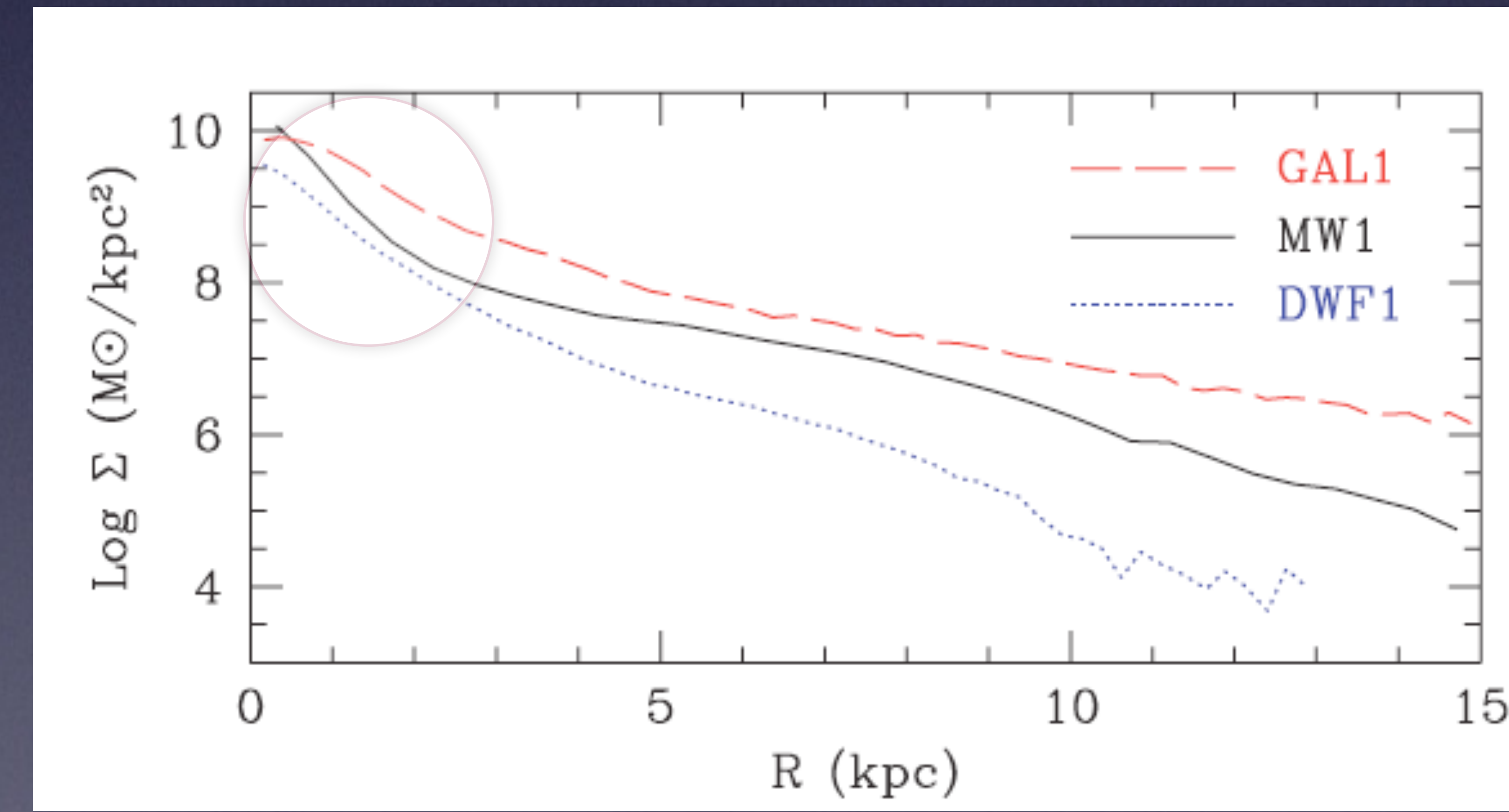
Cosmological simulations of (dwarf) galaxy formation have become sensible only in the last few years. *Before overcooling and angular momentum problem*

Increased numerical resolution (to avoid artifacts) + improvements of sub-grid models of star formation and feedback have been key



Governato, Willman, Mayer + 2007
Mayer, Governato & Kaufmann 2008

Before 2010 : resolution ~ 10^5 Mo, first sub-grid models of supernovae feedback capable of maintaining a hot gas phase and slow down SF (eg Stinson et al. 2006)
Without feedback only "red and dead" dwarfs at z=0 (purple curve on the left)



...But ubiquitous dense central stellar bulge while field dwarfs bulgeless!

THE STAR FORMATION DENSITY THRESHOLD

STARS FORM IN MOLECULAR CLOUDS, i.e. in gas at densities
in range 10-100 cm^{-2} (depends on metallicity, ambient UV flux)

TILL 2010 IN COSMOLOGICAL SIMULATIONS OF GALAXY FORMATION STARS
FORMED BASED ON A SCHMIDT LAW , $d\rho_{star}/dt \sim \varepsilon\rho_{gas}^{1.5}$ (ε=0.05-0.1)
AT GAS DENSITIES > 0.1 cm^{-3} (typical density of Warm Neutral Medium in Milky Way!)
(eg Abadi et al. 2003; Governato, Mayer+, 2004; Governato et al. 2007, Mayer+ 2008; Piontek & Steinmetz 2010; Scannapieco et al. 2010; Agertz et al. 2011; Naab et al. 2007)

TO CAPTURE COLD DENSE MOLECULAR PHASE:
FIRST STEP IS TO RESOLVE REGIONS OF CORRESPONDING DENSITY
IN SPH >~ 2 SPH kernels per Jeans mass ~ 10^6 Mo, eg Bate & Burkert 1997
required mass resolution 10^4 Mo ---> hi-res zoom-in cosmo sim

REVISIT FORMATION OF GAS-RICH DWARFS (10^8-10^{10} Mo)
WITH HIGH SF THRESHOLD PLUS "BLASTWAVE" SUPERNOVAE FEEDBACK (Stinson et al. 2006)
(Governato, Brook, Mayer et al., Nature, 2010, Governato et al. 2012; Shen et al. 2014)
"BLASTWAVE FEEDBACK": COOLING SHUT-OFF FOR 10-30 Myr NEAR SITES
OF SN II EXPLOSIONS (MIMICS ADIABATIC SEDOV-TAYLOR PLUS SNOWPLAUGH PHASE)

with SPH code GASOLINE (Wadsley et al. 2004)
and now with its successor code ChaNGa

“Clustered” Star Formation powers-up supernovae feedback

The K-S relation of each particle:

$$\frac{d\rho_*}{dt} = \frac{\epsilon_{\rm SF}\rho_{\rm gas}}{t_{\rm dyn}} \propto \rho_{\rm gas}^{1.5} \qquad \rho > \rho_{\rm \ thres}$$

SN feedback (blast-wave model):

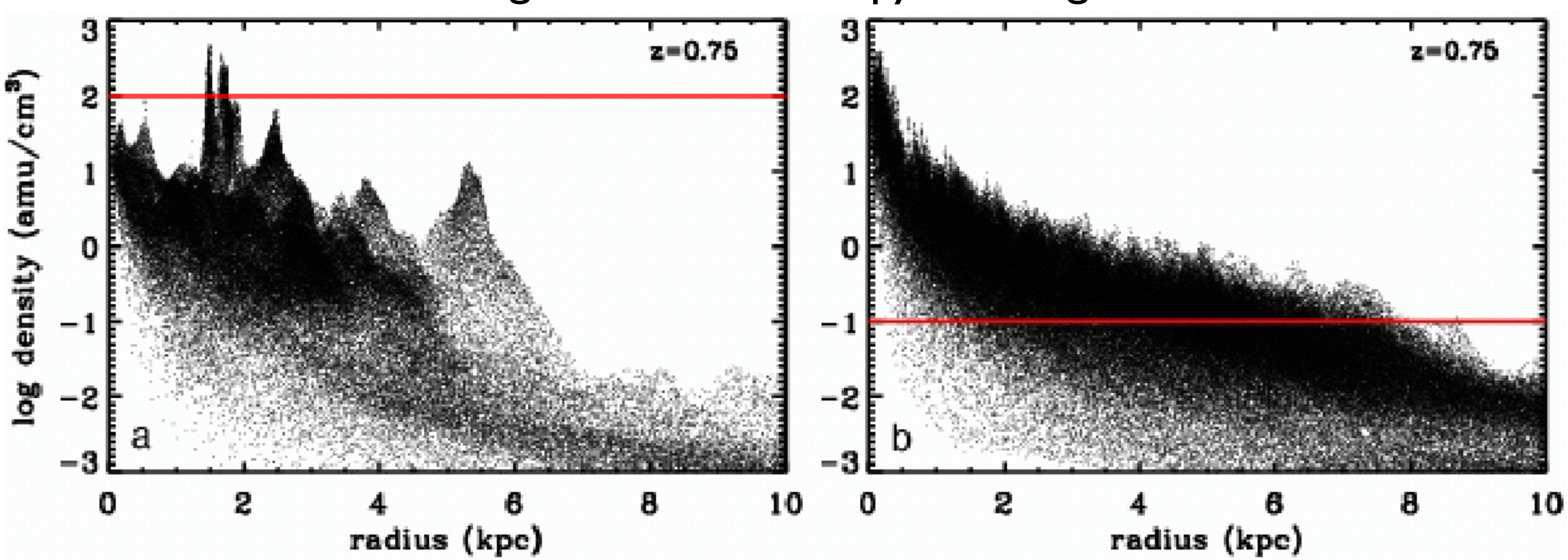
$$E_{\rm SN} = \epsilon_{SN} \times 10^{51}\,{\rm erg\,s^{-1}}$$

Radius of blastwave R_E set by local density/temperature/energy injection, ~ 30-50 pc in typical conditions

$$\frac{\rm N_{new*}}{\rm m_{gas}} \propto \sqrt{n_{\rm SF}} \longrightarrow$$

I - Higher supernovae rate per gas mass “unit” as SF density threshold rises, so *enhanced effect of feedback where stars can form*

II. Stronger local SN feedback further amplified by the fact that ISM becomes more inhomogeneous and clumpy with high SF threshold



Hi-res dwarf galaxy formation: blowing the wind

TWO Ics (DG1 and DG2, different mass assembly history)
Vvir ~ 50 km/s, Mvir ~ 10^{10} Mo (LMC-size)
NSPH ~ 2 x 10^6 particles
Ndm ~2 x 10^6 particles
Msph ~ 10^3 Mo
gravitational softening = 86 pc
WMAP5 cosmology

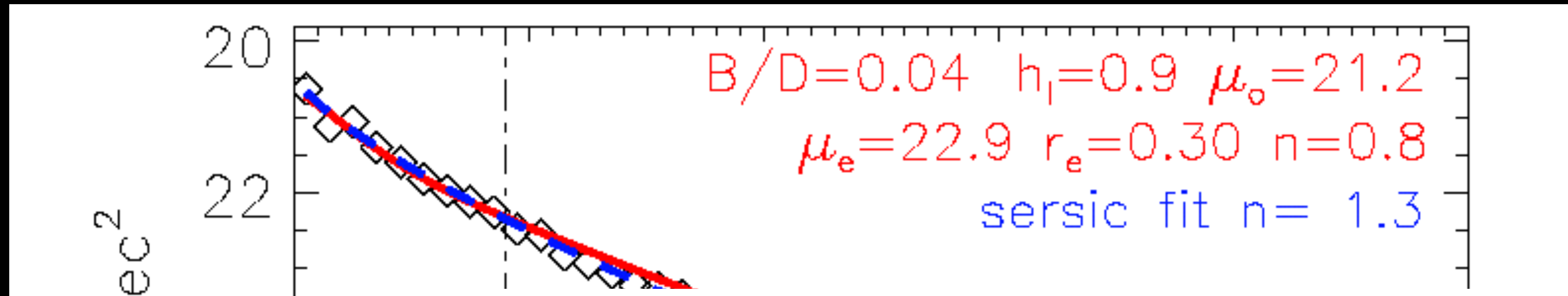
-Schmidt-law SF w/high density threshold of 100 atoms/cm^3
-Supernovae blastwave feedback model (Stinson et al. 2006)
-Cooling to 300 K owing to metal lines
-Heating/ionization by cosmic UV bg (Haardt & Madau 2006)

DWARF MOVIE

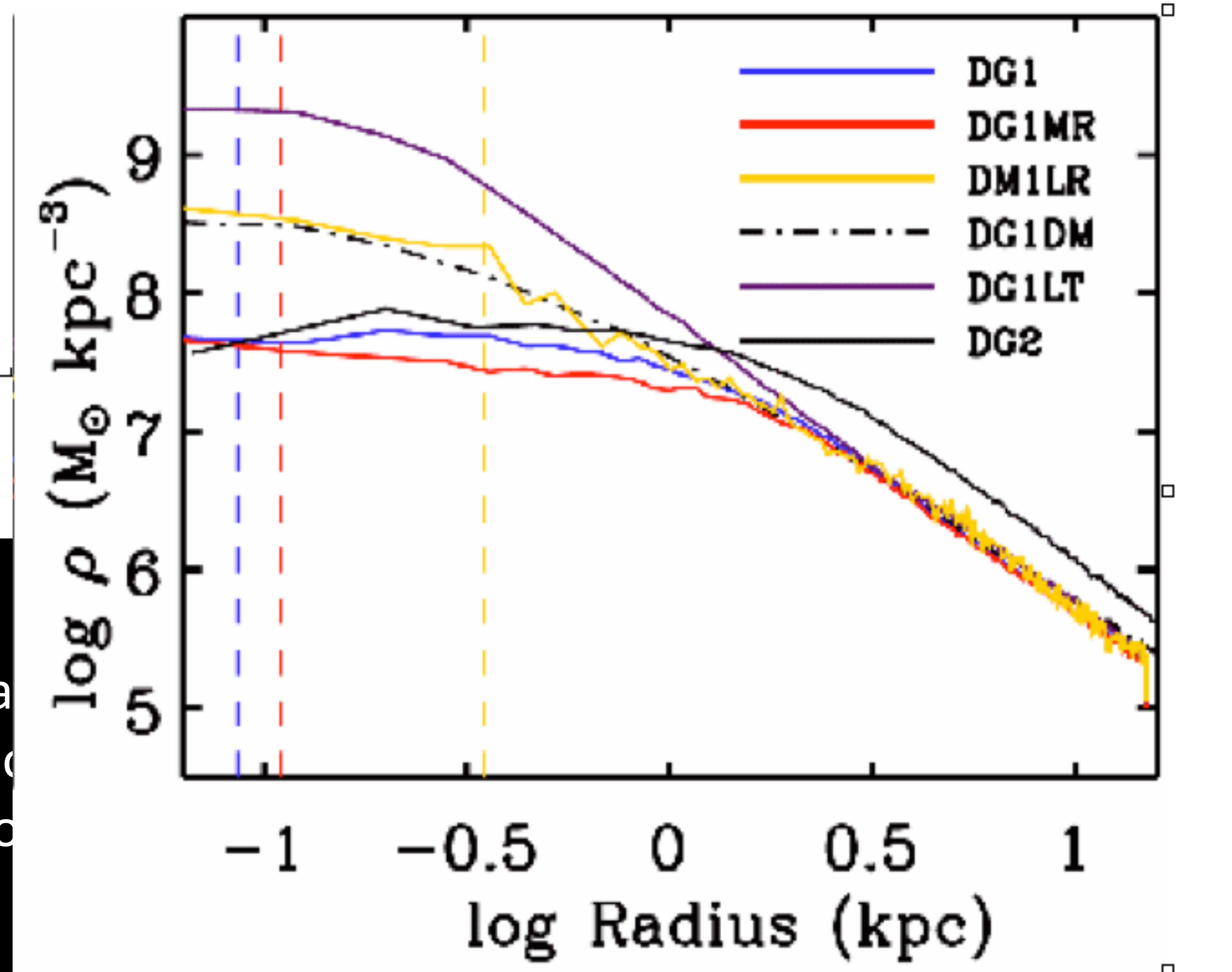
Frame = 15 kpc on a side: color-coded gas density of DG1 from z=100 to z=0

Governato, Brook, Mayer et al., Nature, 463, 203, 2010

-- Final baryonic mass fraction within Mvir = 0.3 x cosmic baryon fraction
-- Final stellar mass ~ 0.05 cosmic baryon fraction <~ 0.01 Mvir (see Oh et al. 2012 for comparison with dwarf galaxies in THINGS survey and other datasets)
-- Final gas/stars ratio in disk ~ 2.5



ulgeless exponential disk
nstead B/D ~ 0.3 in run
with conventional
w SF density threshold)



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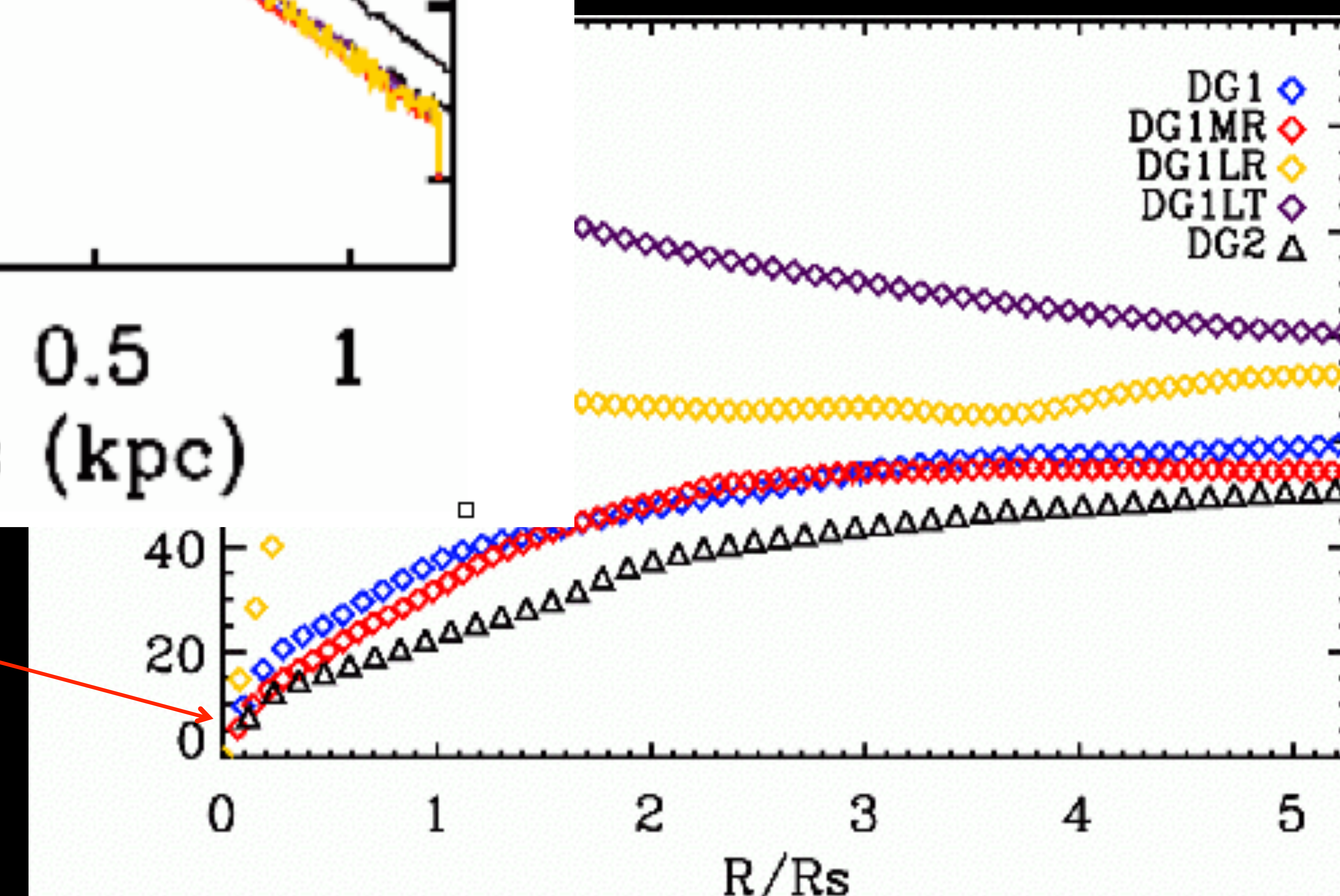
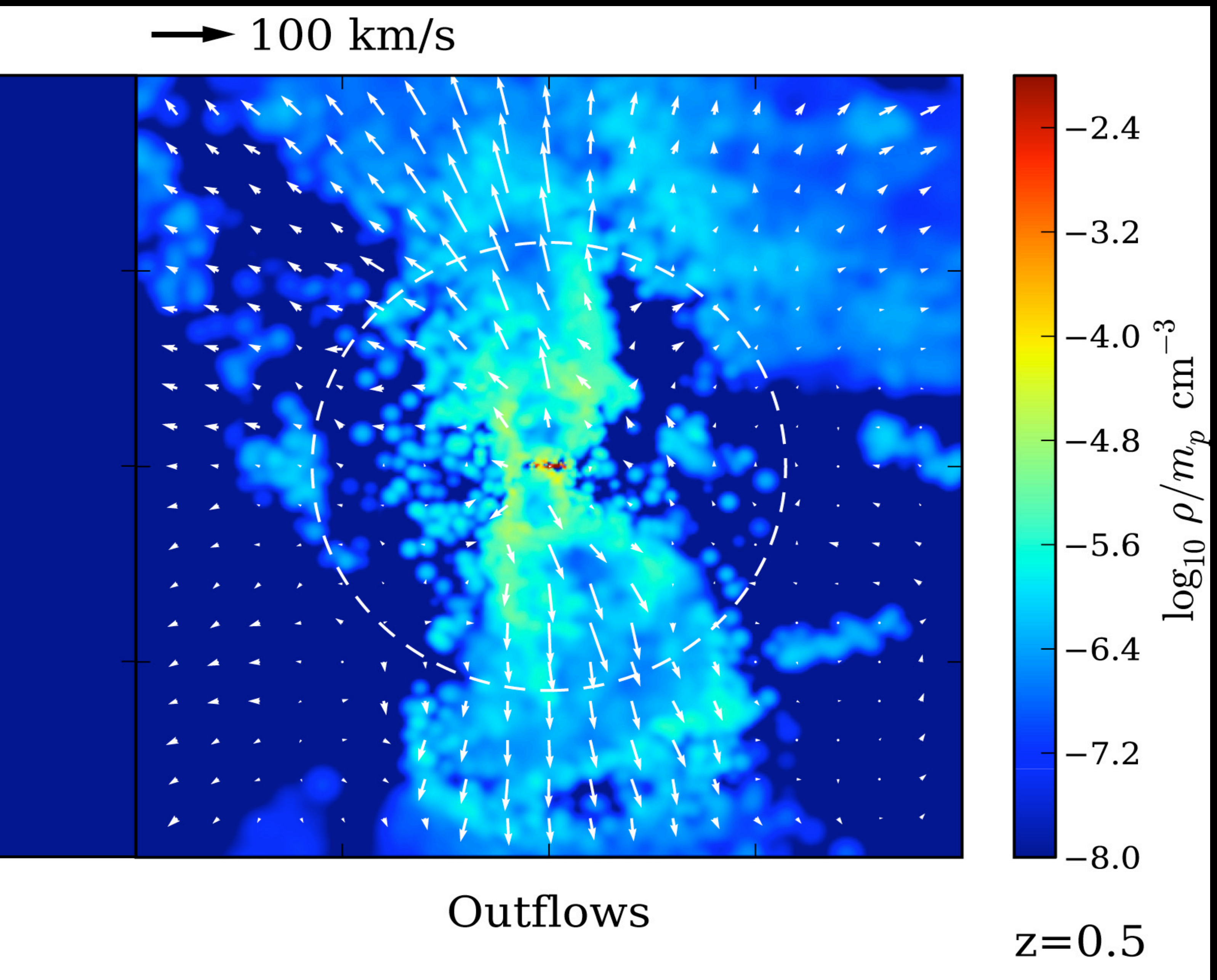
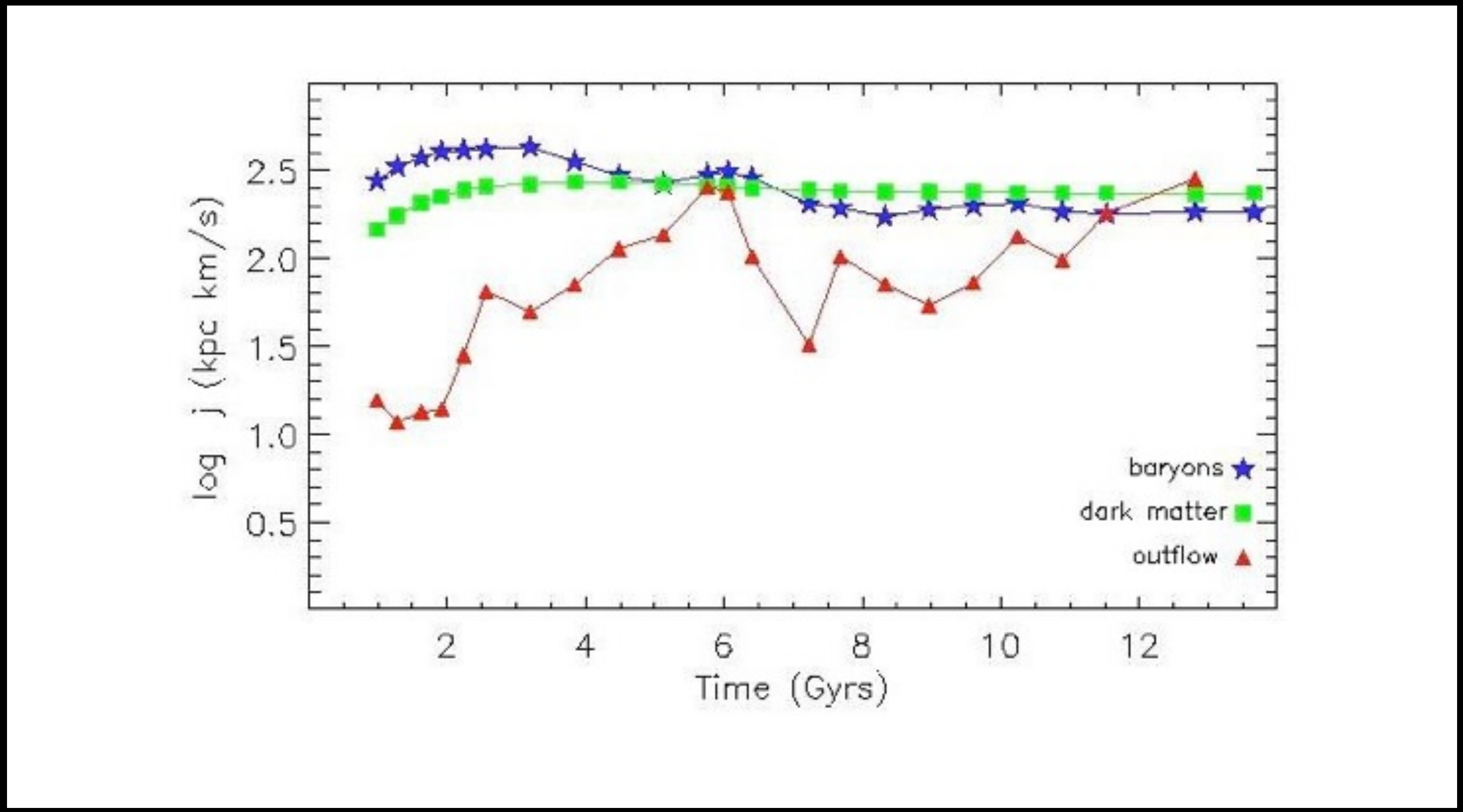


Inner dark matter profile flattened to $\sim r^{-0.6}$ by expansion following impulsive supernovae outflows producing potential fluctuations (Pontzen+Governato 2012 - see also Navarro, Frenk & Eke 1996; Read & Gilmore 2005; Maschenko et al. 2008)

Strong supernovae winds with high SF density threshold





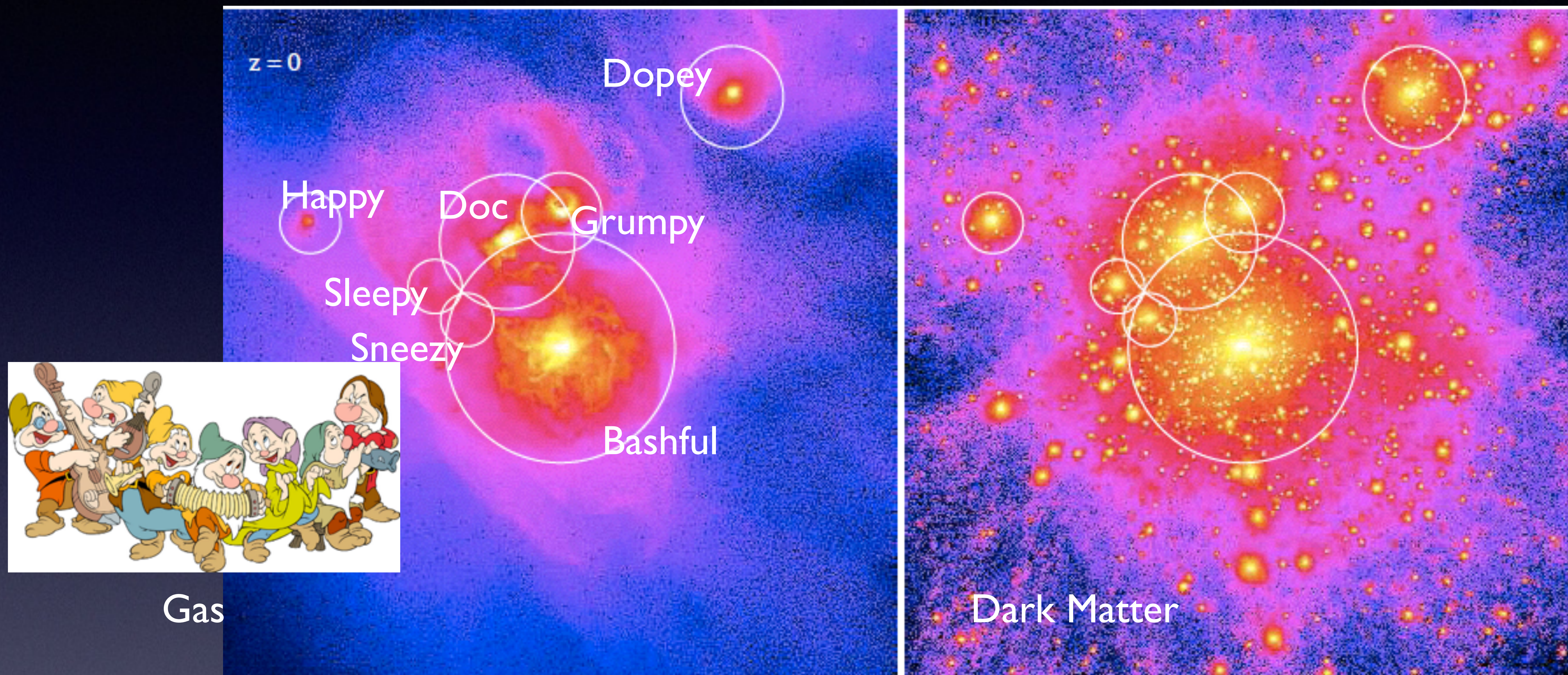
▪star formation CLUSTERED rather than DISTRIBUTED, mainly in high density peaks with scales ~ GMCs ---> stronger heating produces stronger gas outflows compared to runs with "standard" low SF density threshold (more gas heated at T > Tvir at z ~ 1-3, outflows at ~ 100km/s --> final baryonic fraction ~ 1/3 of cosmic)

•Outflows correlated with peaks of SFR, often correlated with mergers (hence occur preferentially at z > 1) – see Brook et al. (2010) for details

▪Outflows mostly from the center of galaxy where star forming density peaks higher ---> selective removal of lowest angular momentum material by winds
Confirms earlier prediction of Binney. Gerhard & Silk (2001)
---> suppress bulge formation and produce exponential profile

Formation of gas-rich field dwarfs in cosmological hydro simulations across a spectrum of mass scales (10^8 - 10^{10} Mvir)

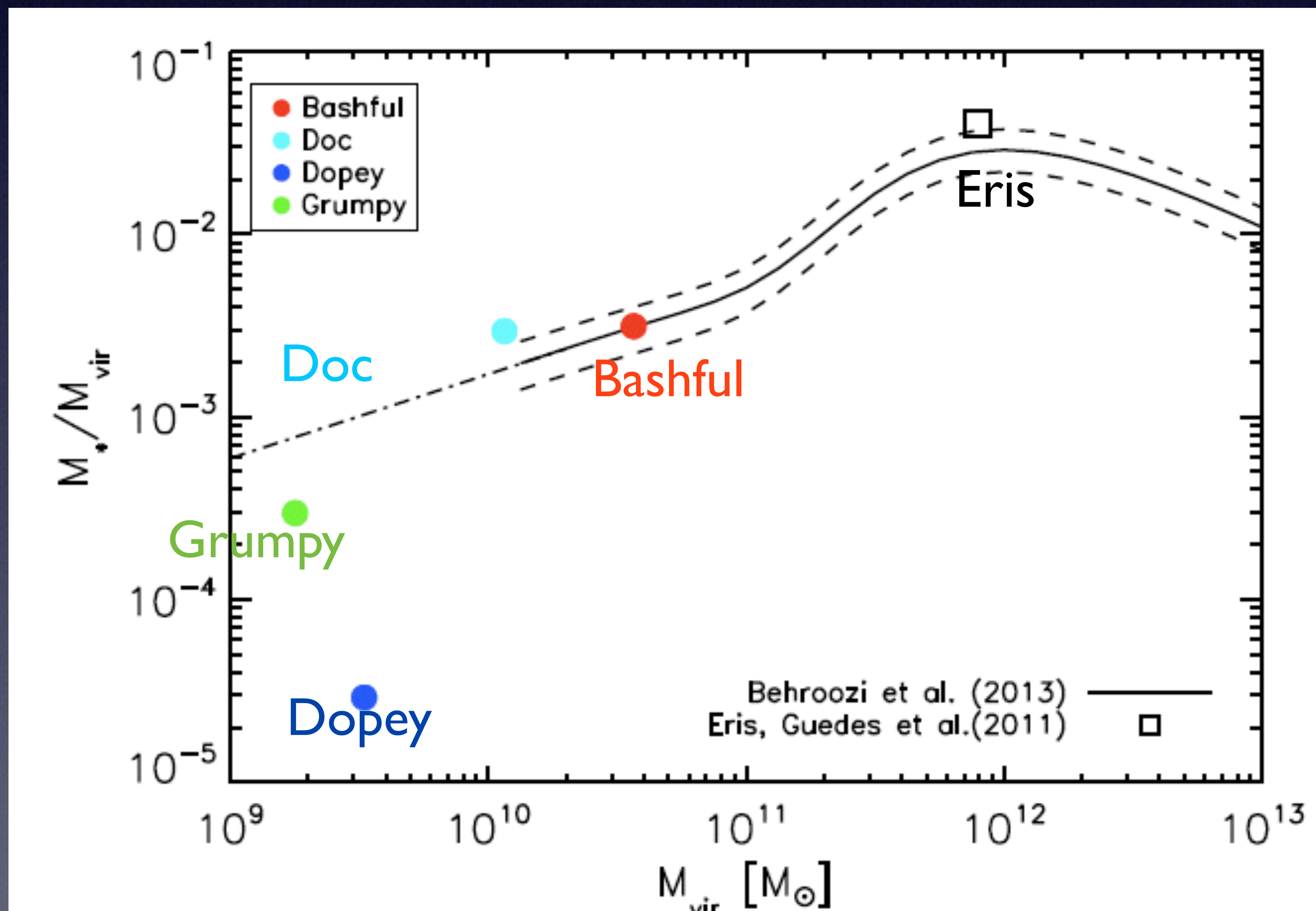
Sijing Shen, Charley Conroy, Piero Madau, Lucio Mayer, Fabio Governato, 2014 (ApJ)



- Resolution: DM 1.6×10^4 M_{sun}; Gas 3300 M_{sun}; Star 1000 M_{sun}; force resolution 86 pc
- "Field" dwarfs: nearest massive halo > 3 Mpc away
- Include metallicity-dependent cooling using CLOUDY, ionization equilibrium (but for H and He rates for non-equilibrium ionization), high SF density threshold of 100 cm^{-3}, blastwave feedback (Stinson et al. 2006), new UV background from stars and QSOs (Haardt & Madau 2013)
- 4 Luminous galaxies with stellar mass ranges from 10^5 to 10^8 M_{sun}, and halo mass ranges from 1.8×10^9 to 3.6×10^{10} M_{sun}
- 3 DARK DWARFS where gas accretion and SF are suppressed by the UVB (see also Kuhlen+13)

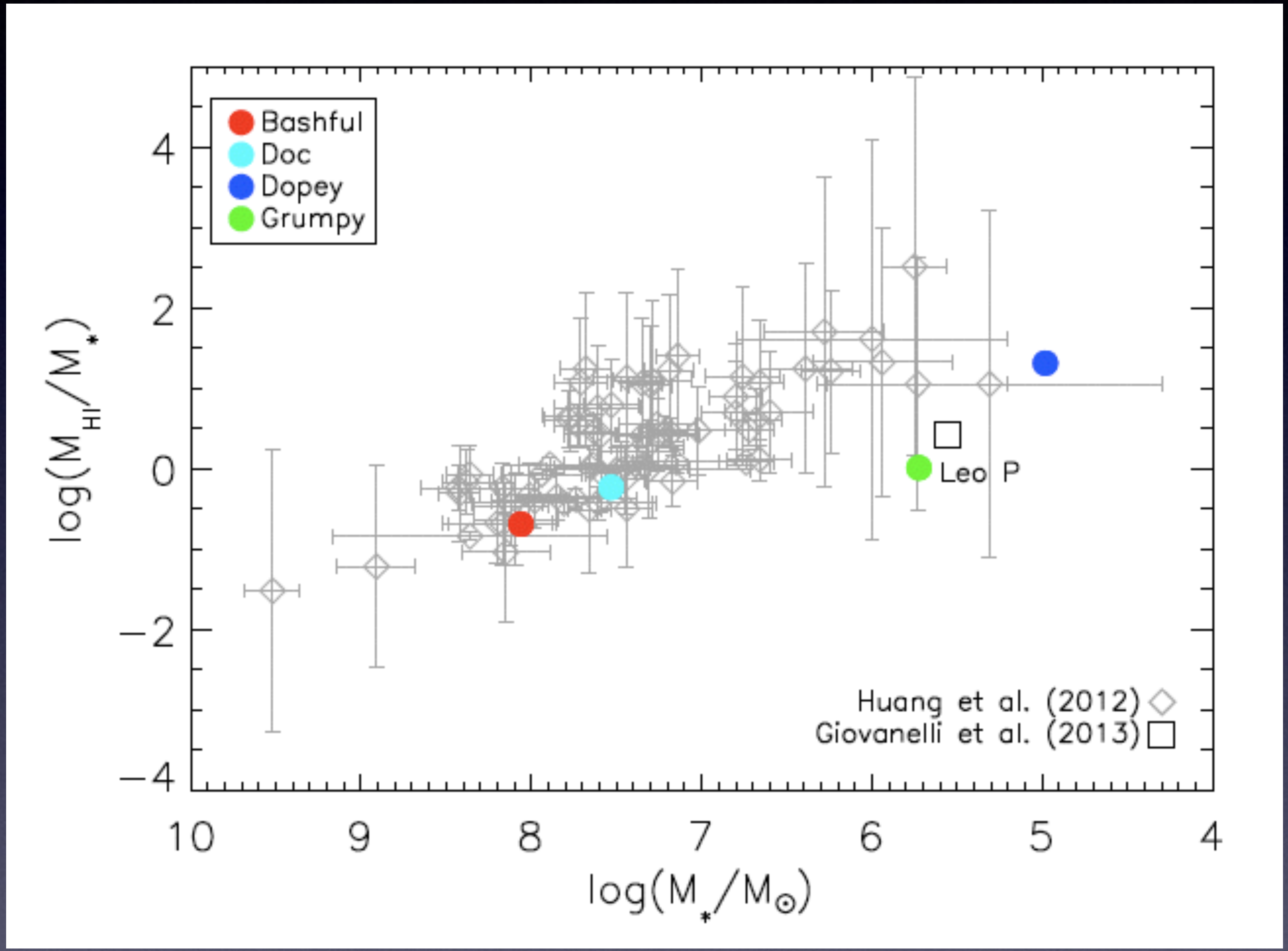
Stellar Mass of the Group of Seven (Shen et al. 2013)

Name	M_{vir} $[M_\odot]$	R_{vir} [kpc]	V_{max} $[km\,s^{-1}]$	$V_{1/2}$ $[km\,s^{-1}]$	M_* $[M_\odot]$	M_{gas} $[M_\odot]$	M_{HI} $[M_\odot]$	f_b	$\langle[Fe/H]\rangle$	M_V	$B-V$
Bashful	3.59×10^{10}	85.23	50.7	18.3	1.15×10^{8}	8.14×10^{8}	2.34×10^{7}	0.026	-0.96 ± 0.51	−15.5	0.3
Doc	1.16×10^{10}	50.52	38.2	21.6	3.40×10^{7}	1.74×10^{8}	1.98×10^{7}	0.018	-1.14 ± 0.44	−14.0	0.4
Dopey	3.30×10^{9}	38.45	22.9	4.44	9.60×10^{4}	4.47×10^{7}	1.96×10^{6}	0.014	-1.97 ± 0.44	−8.61	0.2
Grumpy	1.78×10^{9}	29.36	22.2	3.76	5.30×10^{5}	3.00×10^{7}	5.40×10^{5}	0.017	-1.52 ± 0.54	−11.0	0.0
Happy	6.60×10^{8}	22.49	15.6	—	—	2.54×10^{6}	—	0.004	—	—	—
Sleepy	4.45×10^{8}	19.71	14.8	—	—	—	—	—	—	—	—
Sneezy	4.38×10^{8}	19.62	13.2	—	—	1.64×10^{5}	—	0.0004	—	—	—



- 4 luminous dwarfs, with M* from 9.6×10^4 M_{sun} to 1.1×10^8 M_{sun}
- Bashful & Doc: M_*/M_h on abundance matching curve of Behroozi + (2013)
- Dopey & Grumpy: very small stellar fraction
- Dopey is very H I rich: $M_{HI} \sim 20\,M_*$

Cold Gas Fractions

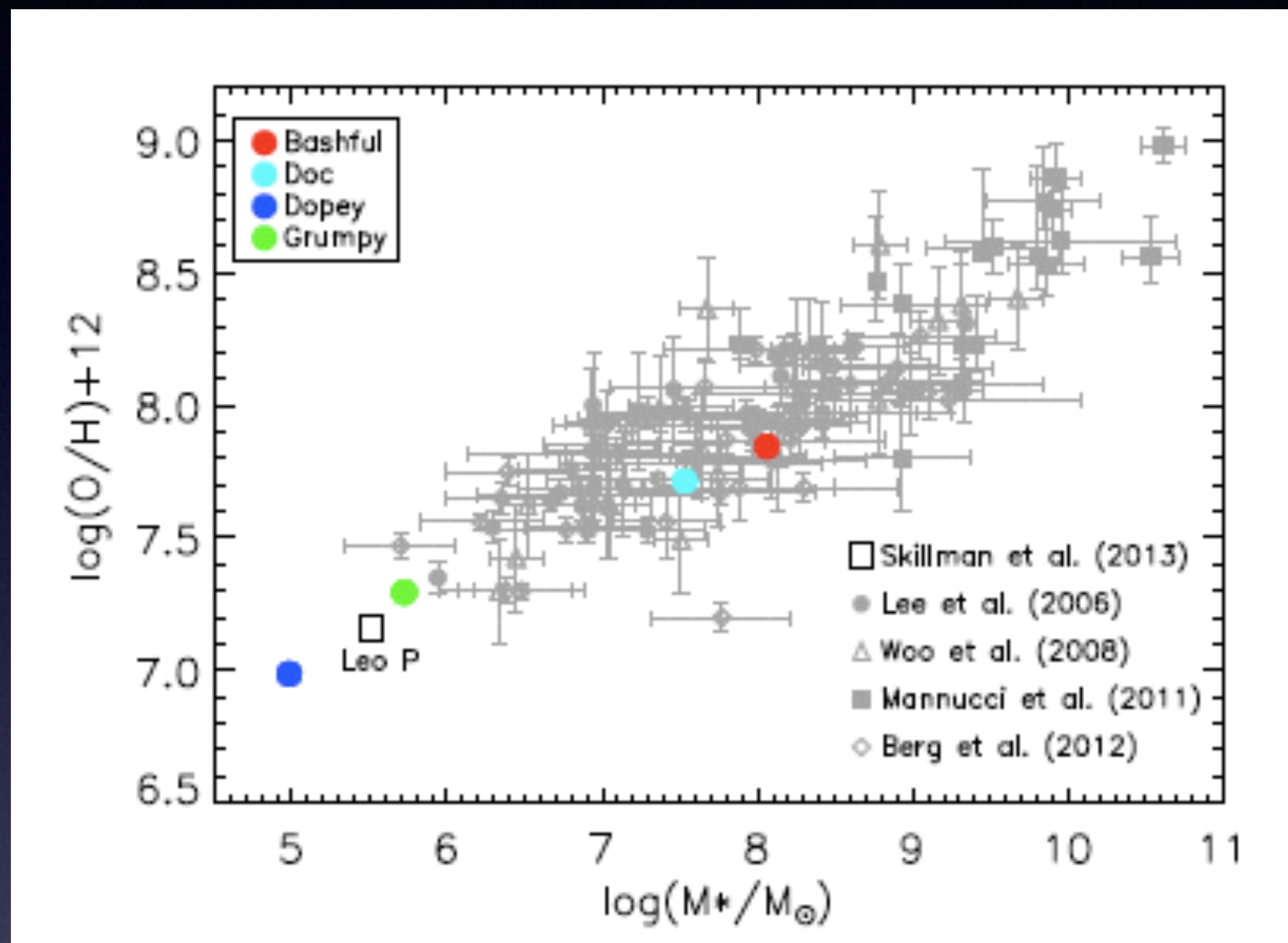


- Low stellar mass dwarfs in the ALFALFA sample are on average more HI gas rich (however here some gas is stripped due to dwarf-dwarf interactions)

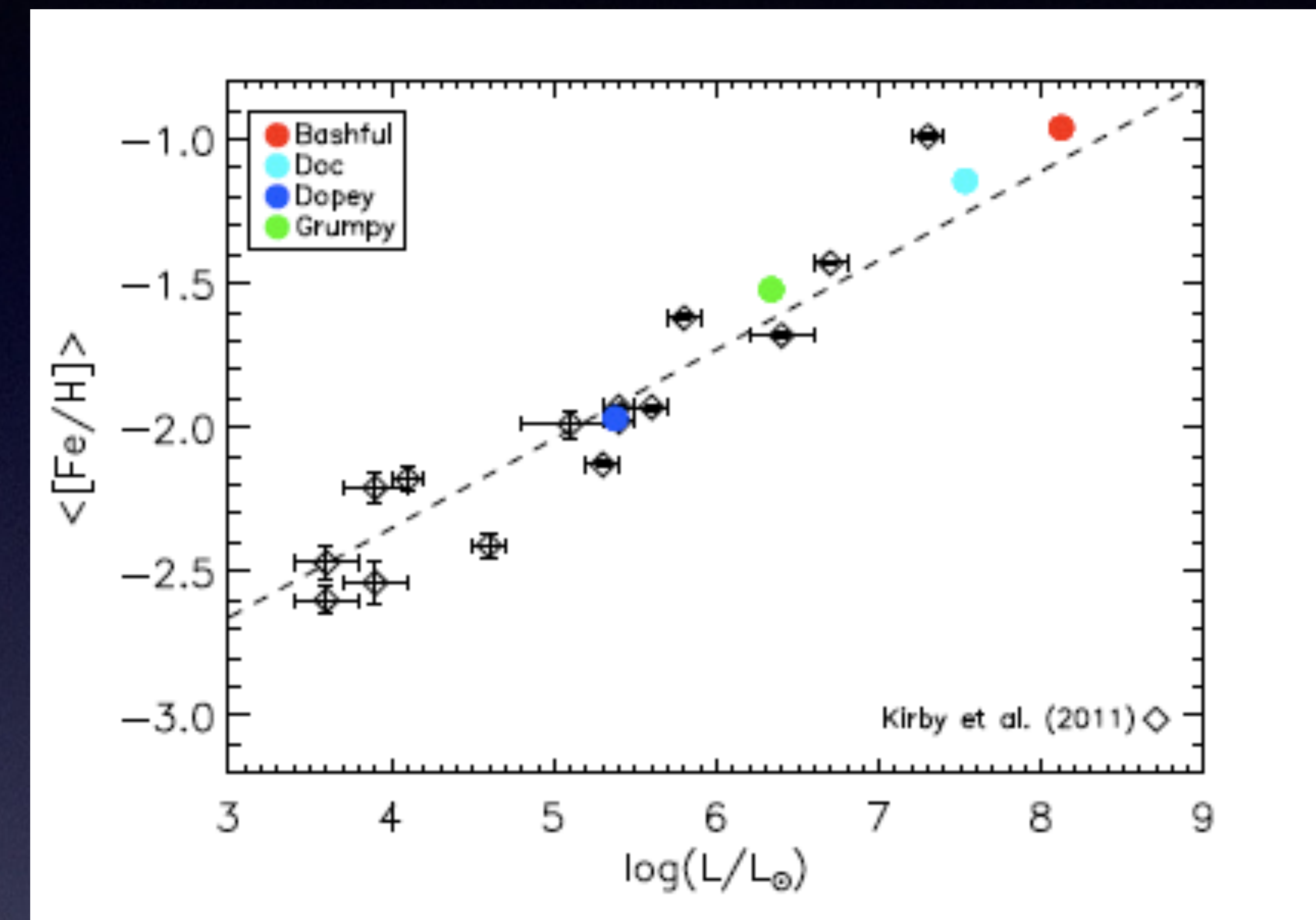
- SFR at z=0 in Bashful and Doc is low (0.01-0.02 Mo/yr) despite Bashful and Doc retain significant fraction of baryons ----> feedback regulates SF by allowing only a small fraction of the gas to be in a cold star forming phse

Mass(Luminosity)-Metallicity Relationship: an important constraint on the feedback model

Gas

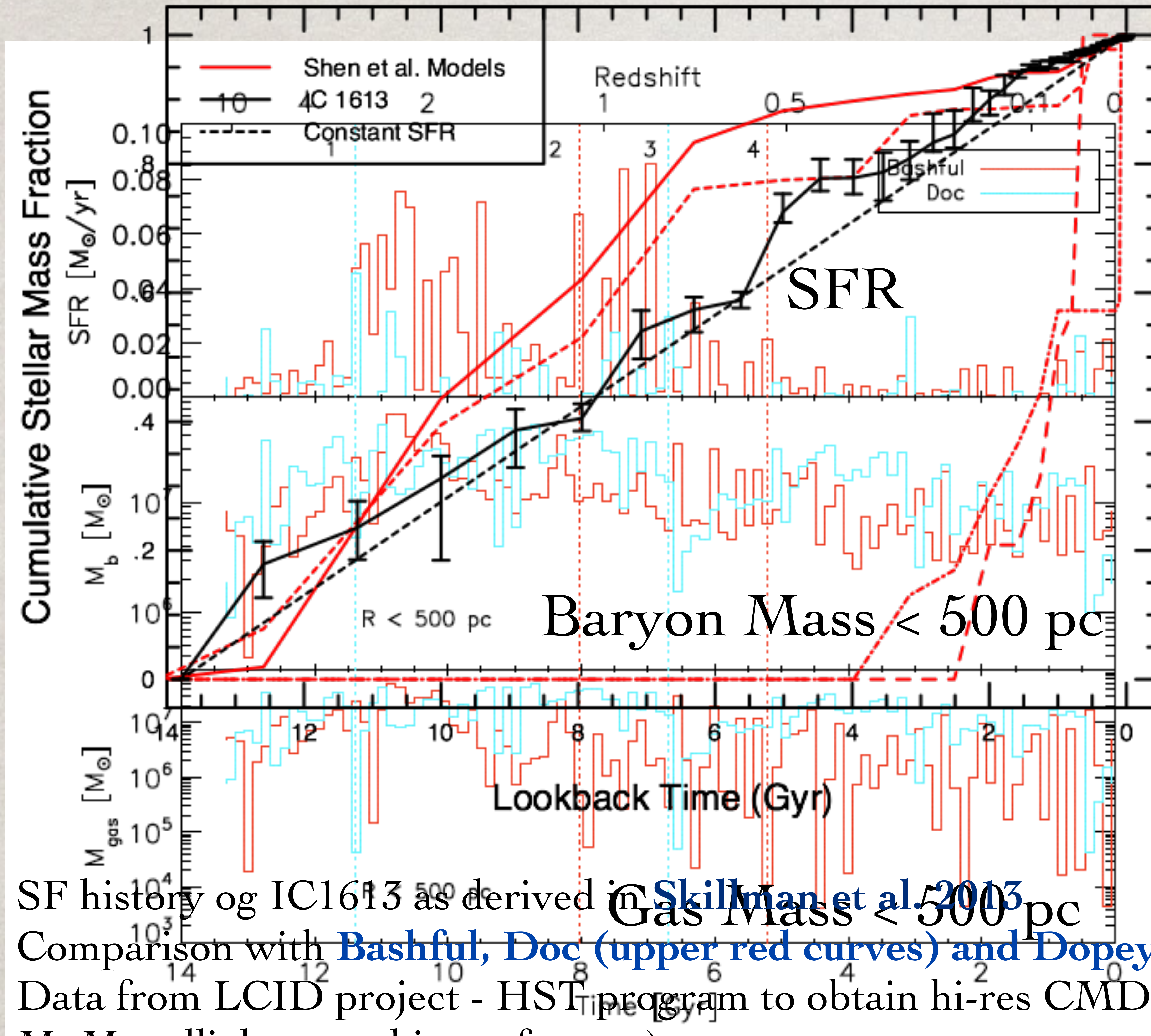


Stars



•Oxygen abundances in the ISM for the 4 dwarfs lie on the mass metallicity relationship and in good agreement with observations of LG dwarfs (Woo+2006), larger samples of nearby dwarf irregulars (Lee+2006), low luminosity galaxies in the local volume (Berg+2012)
•Dopey and Grumpy are extremely metal poor galaxies, but still on the MZR. Similar to a very recently discovered H I-rich dwarf, Leo P (Giovanelli+2013). They simply had too little SF to enrich the ISM significantly
•Stellar metallicity - V band luminosity relation consistent with Milky Way's dSphs from Kirby+(2011)

Bursty Star formation history



Bursty SF causes strong baryonic mass fluctuations near center

SF burst followed by decrease in M_b and M_{gas}

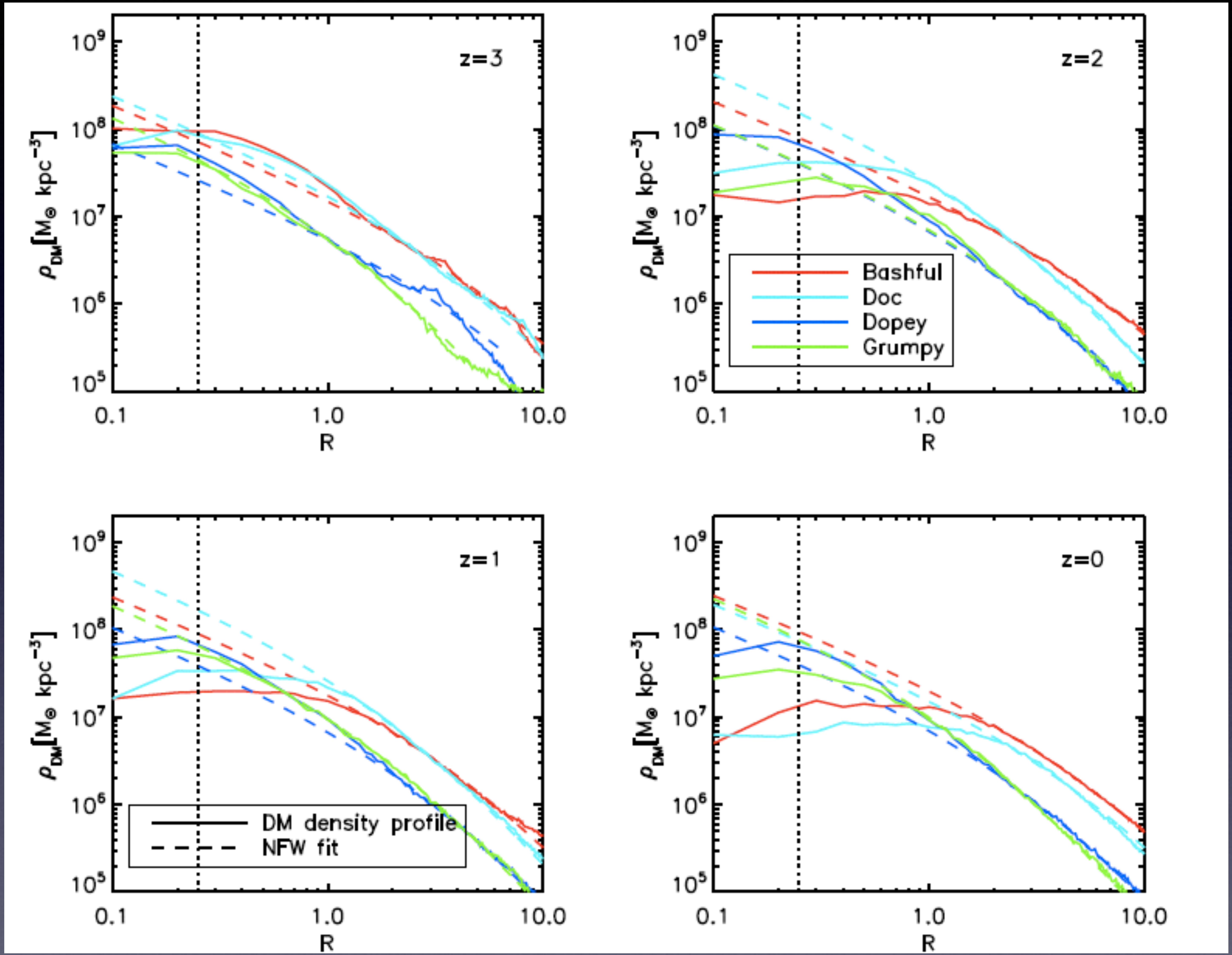
Rapid change of central potential, transfer energy into DM impulsively and generates long lasting-core cores (Pontzen & Governato 2012, Teyssier+ 2013)

SF history og IC1613 as derived in **Skillman et al. 2013**

Comparison with **Bashful, Doc (upper red curves) and Dopey, Grumpy (lower red curves)**

Data from LCID project - HST program to obtain hi-res CMD diagrams for nearby dwarfs (see M. Monelli later at this conference).

Cored Dark Matter Profiles in 3 of the 7 dwarfs



SF is not very efficient *TODAY* but DM profiles of Bashful and Doc have cores because SF more efficient early on. Grumpy has a smaller core (radii normalized) despite SF relatively late. Dopey has no core, not surprisingly is the only one with final M* < 10^5 Mo (lowest SF efficiency)

Possible contradiction:

To form cores we need strong bursts of SF.
Early on is more efficient since halo mass/potential well to "displace" is lower because progenitor has lower mass.

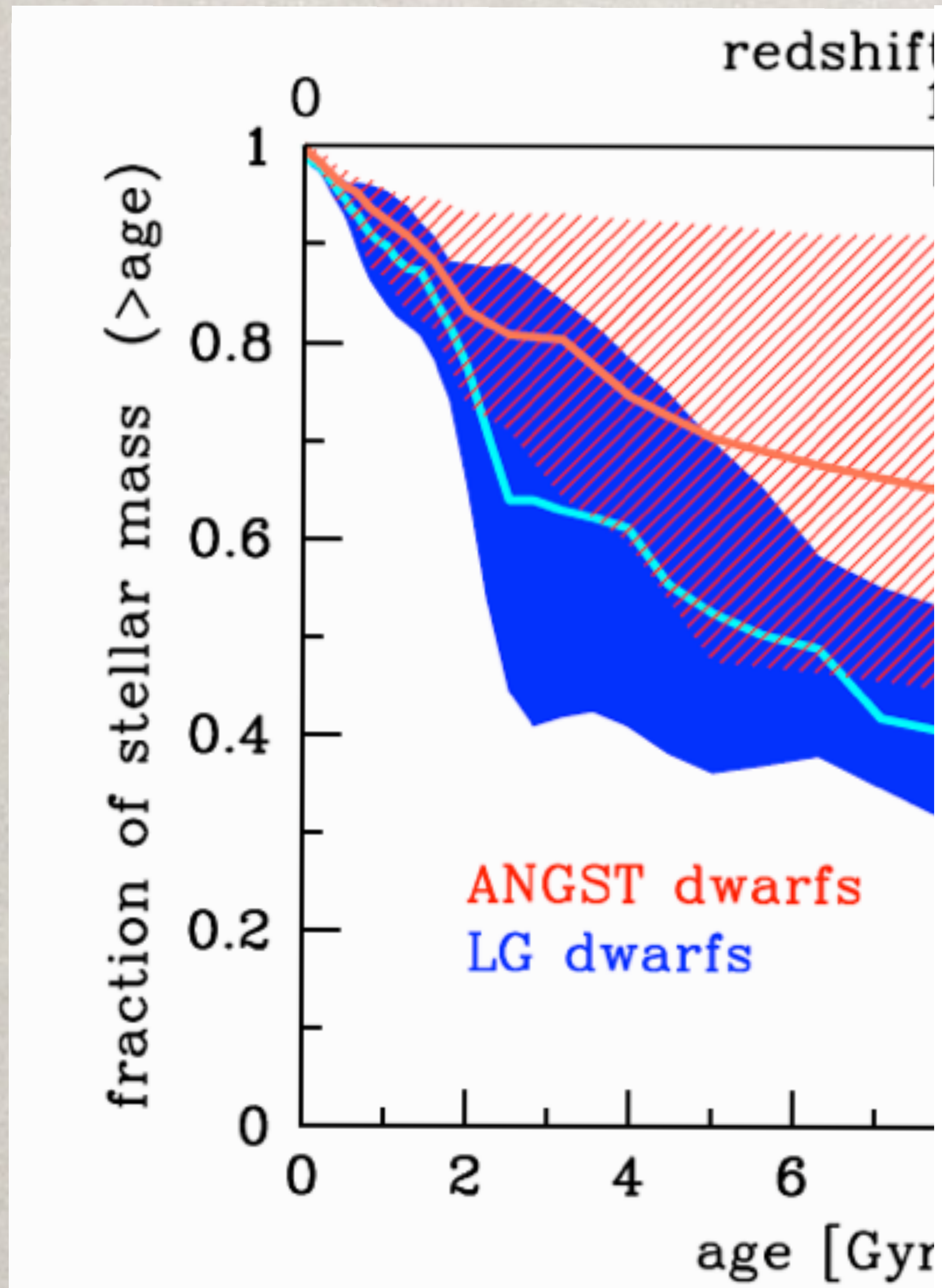
But isn't high SF rate early on at odds with the conventional notion that gas-rich dwarfs have "young" stellar populations and are still star forming today?

Not really... Majority of nearby dwarfs appears to have had higher SF efficiency (SFE) in the past than today (exceptions Leo A (Cole et al. 2006) and Aquarius (Cole et al. 2014))

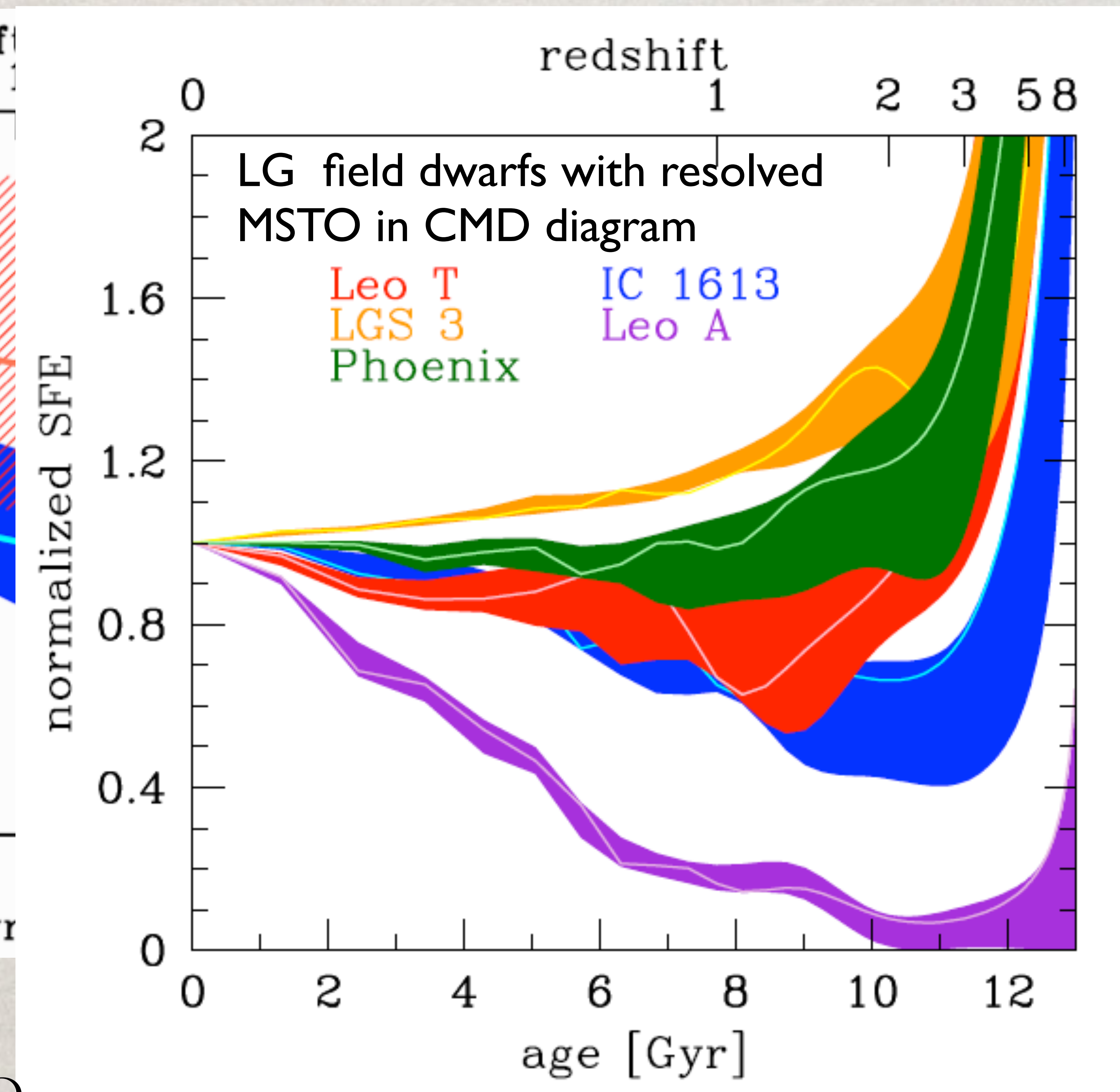
SFE = mean SF history / mean M(t) of halos in corresponding mass range

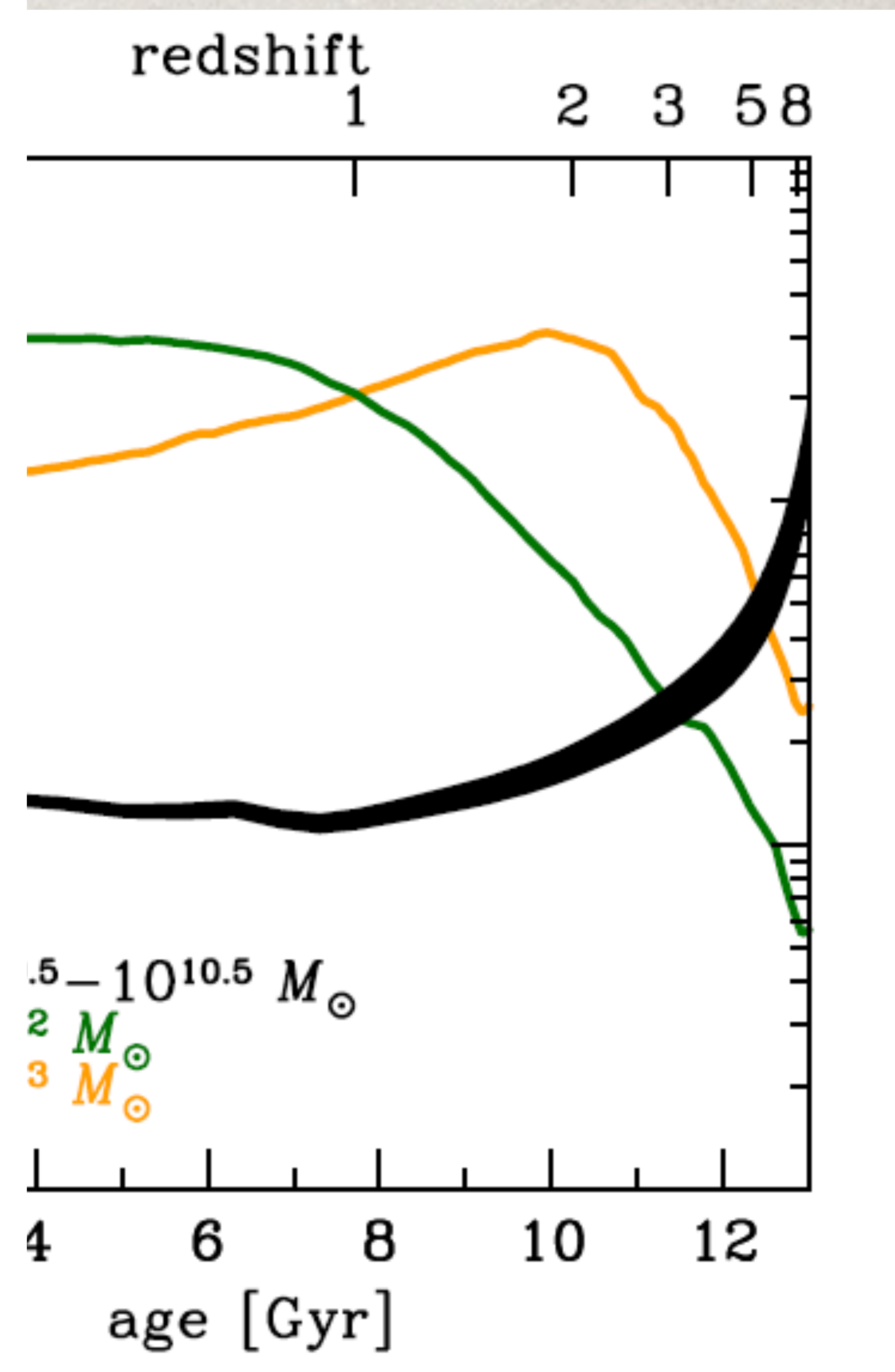
Implication: cases with very low SFE (eg Leo A) less likely to have cores.

But perhaps most important indicator is mean value of SF rate, hence final M*/Mhalo



For LG dwarfs well resolved HST CMD diagrams, for ANGST dwarfs wider field but coarse CMD





Madau, Weisz & Conroy 2014

Consistent with **Rapid early stellar mass assembly**

---> feedback ----> DM core formation via baryonic outflows

Models now reaching maturity.

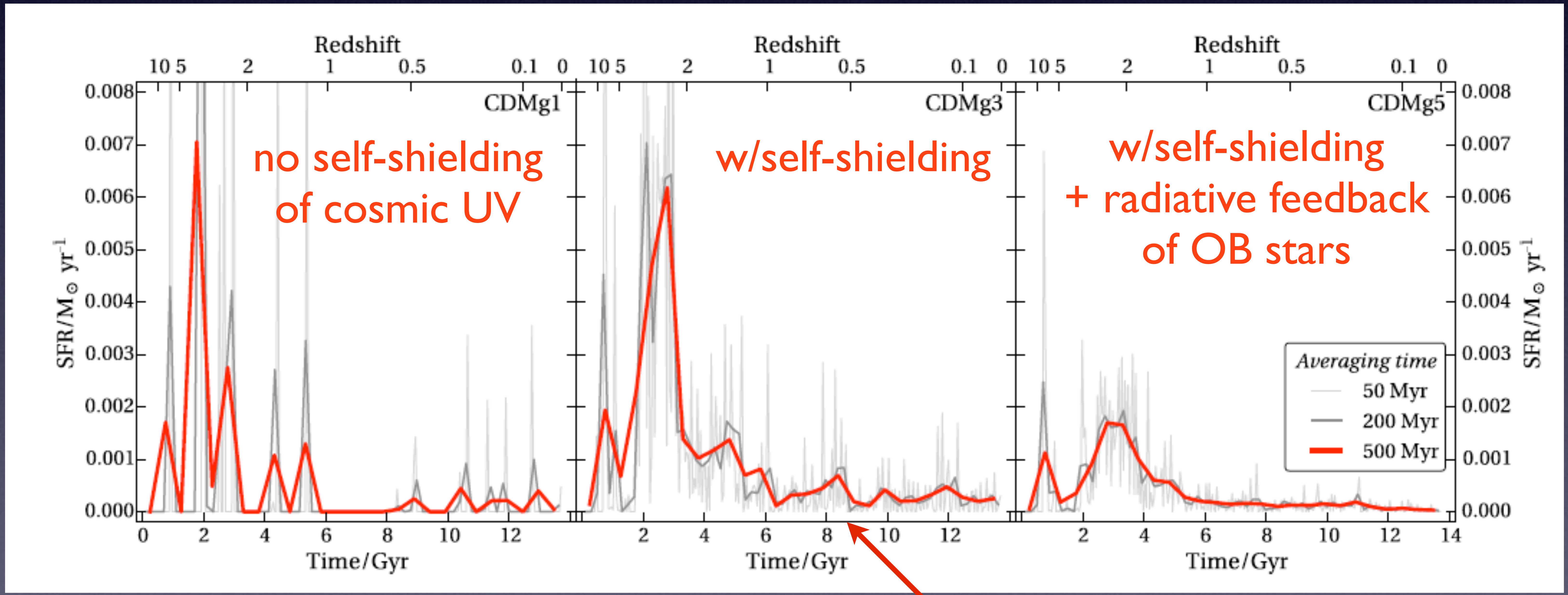
Details of sub-grid recipes begin to matter for eg amplitude and duration of SF bursts with implications for:

(a) comparison with observed SF histories, metallicities etc..

(b) predictions for core formation.

....a theorist's nightmare?

Sensitivity on sub-grid SF parameters (self-shielding, extra feedback mode)



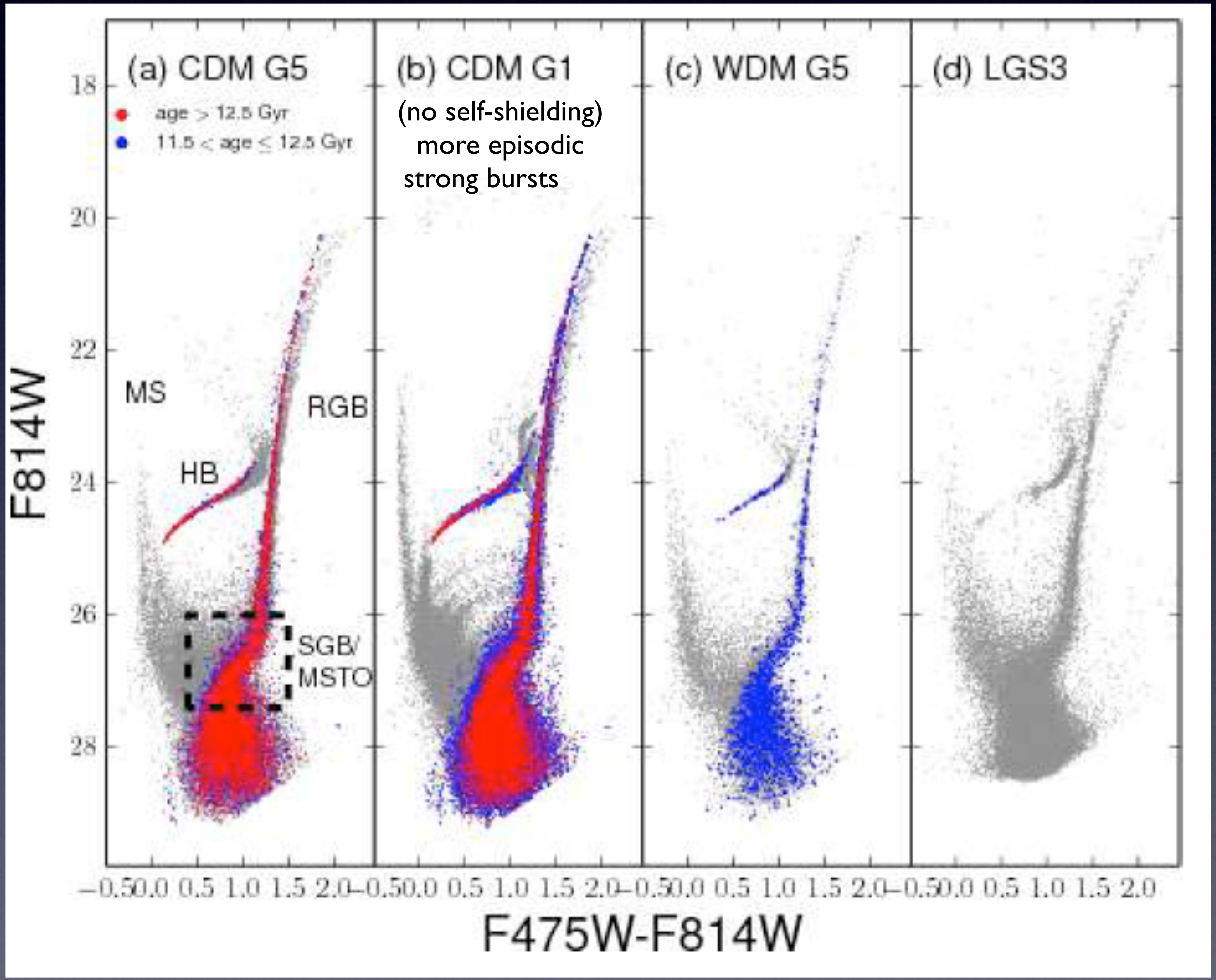
Governato et al. 2014

High frequency burst pattern closer to observed SF history in gas-rich dwarfs?

The next level of analysis

Mock CMD diagrams of simulated dwarfs againts observed CMD diagrams for LG dwarfs

We consider also alternative Lambda- Warm Dark Matter (LWDM) cosmology (2 keV particle, mass scale of truncated power spectrum in simulation)



Governato et al. 2014

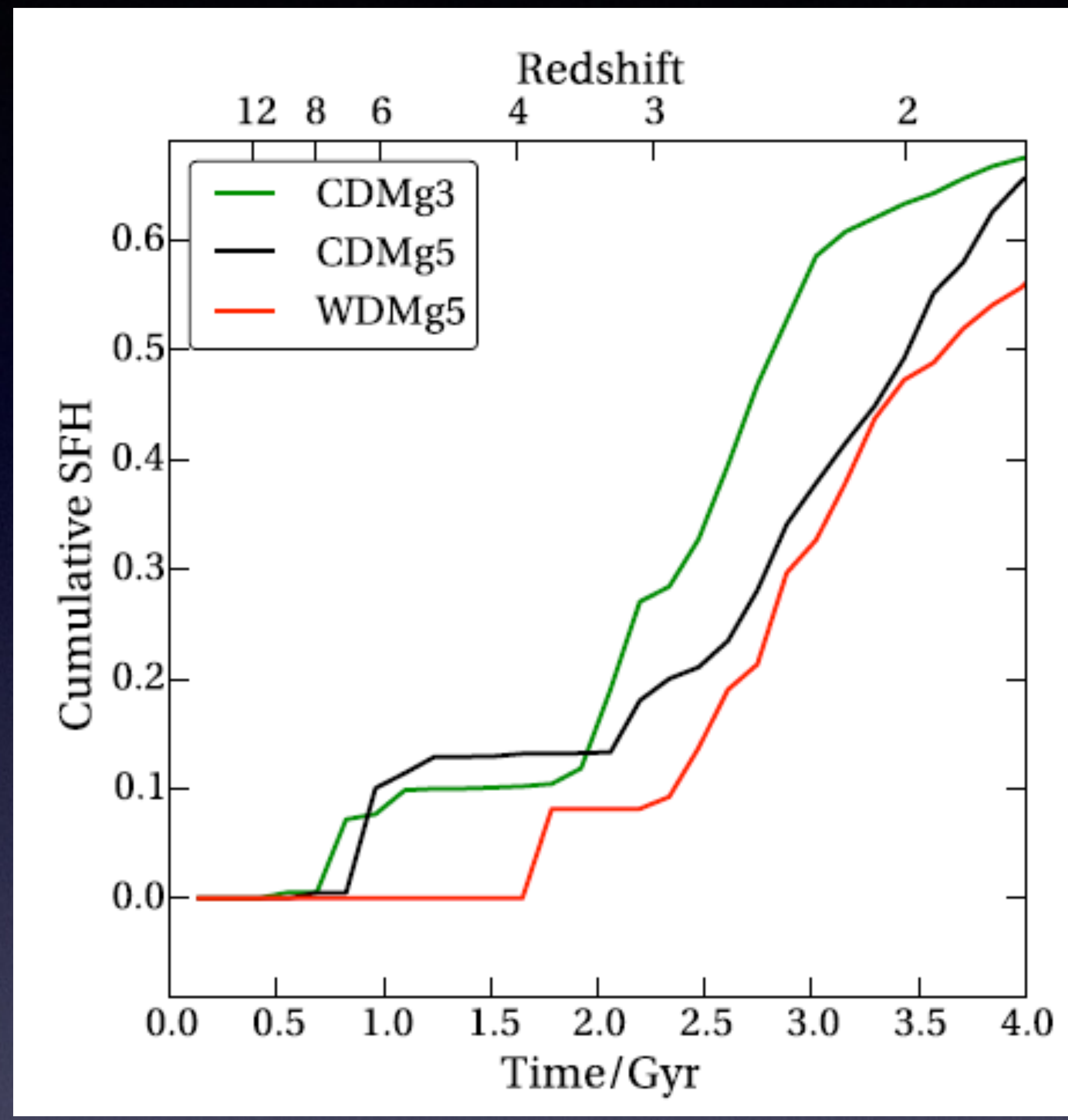
Main points:

- the two CDM dwarfs (differ for sub-grid feedback parameters) are qualitatively consistent with LGS3 (Hidalgo et al. 2011).

- their WDM dwarf analog is deficient of old stars relative to LGS3

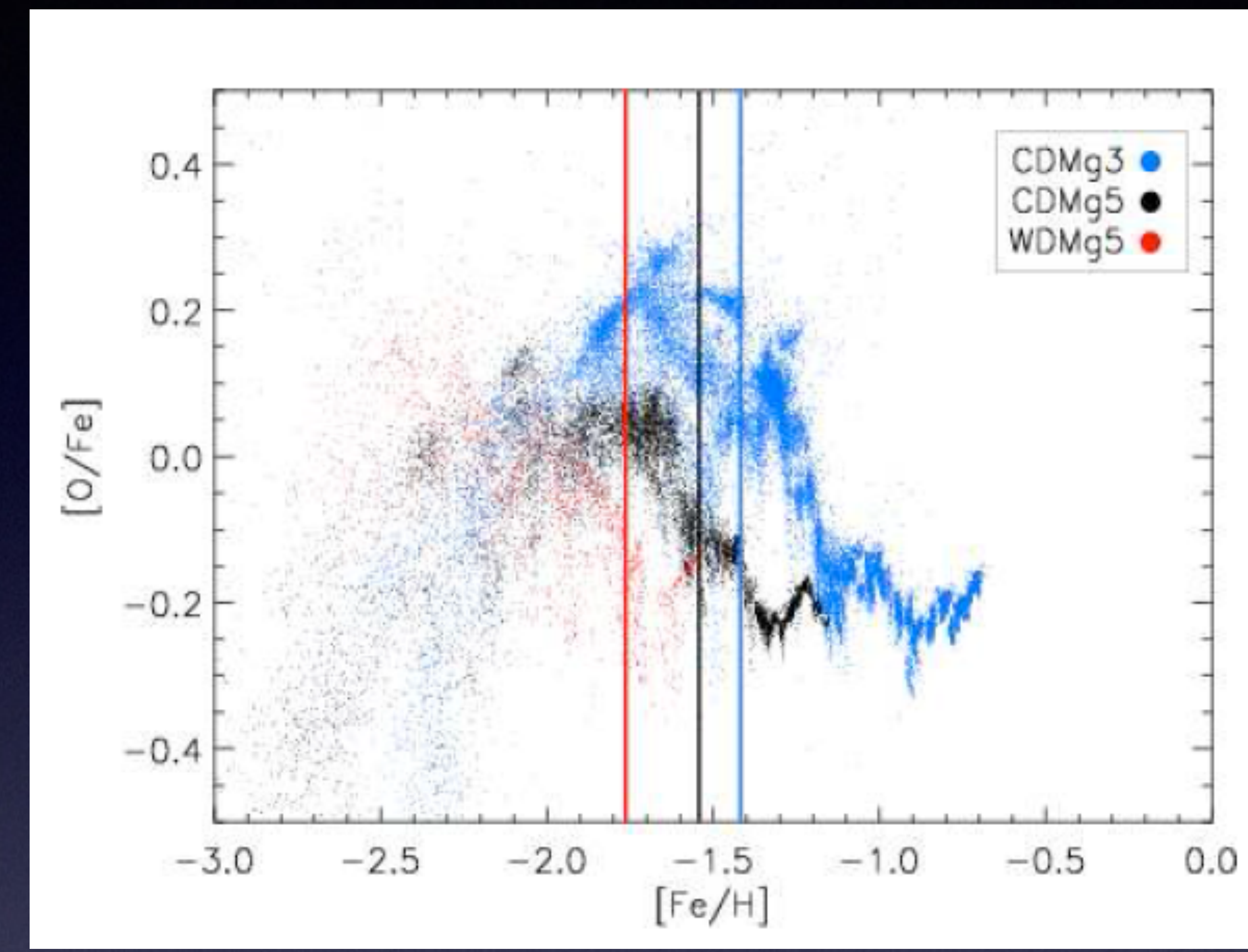
Of course need to this for more objects, but remarkable is sensitivity of star formation history to structure formation model

WDM vs. CDM: once again key diagnostic is the SF efficiency



SF delayed more in WDM model
Here it is equivalent to lower SF efficiency
at high z since halo mass is the same
in three cases

Lower average SF rates explain lower
metallicity and dearth of old stars
in CMD diagram of WDM dwarf (see previous slide)



Top: Abundance ratios
for different versions of
the same dwarf simulation
Vertical lines show mean metallicity
for nearby dwarfs with similar stellar
mass to simulated dwarfs
(Kirby et al. 2007)

So far we focused on field dwarfs
Now some implications of dark matter "core" formation on dwarf galaxy satellites

VLII movie

Via Lactea II: hi-res cosmological simulation of Milky Way-sized dark matter halo (Diemand et al. 2007)

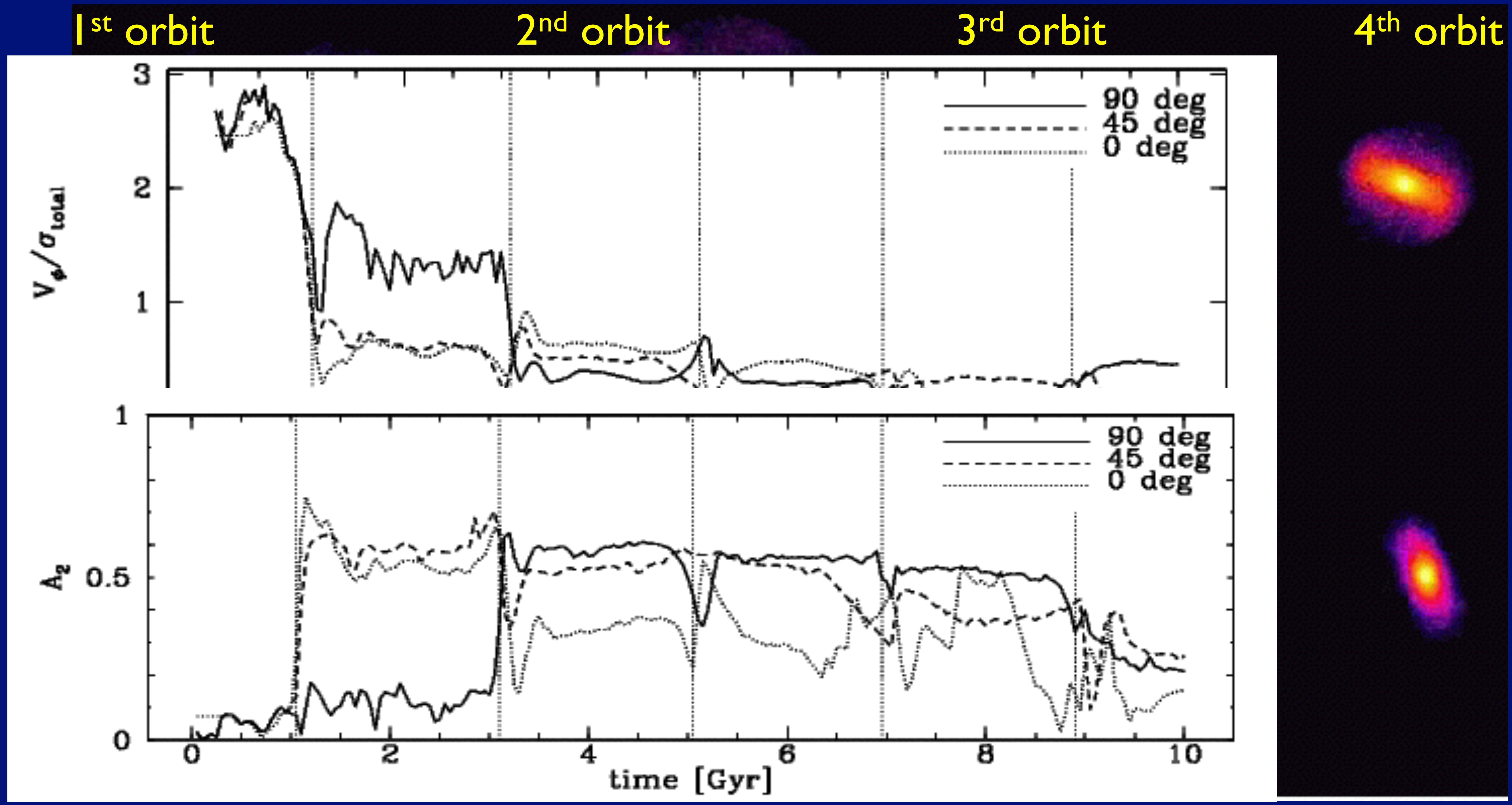
Tidal stirring of disky dwarfs orbiting inside massive hosts

Tidal stirring = repeated tidal shocks at pericenters with primary galaxy (Weinberg 1994; Gnedin, Hernquist & Ostriker 1999) turn rotationally supported late-type dwarf ($v/\sigma >> 1$) into faint spheroidals with low $v/\sigma < 0.5$ (Mayer et al. 2001, 2002; 2007; Klimentowski et al. 2008,2009)

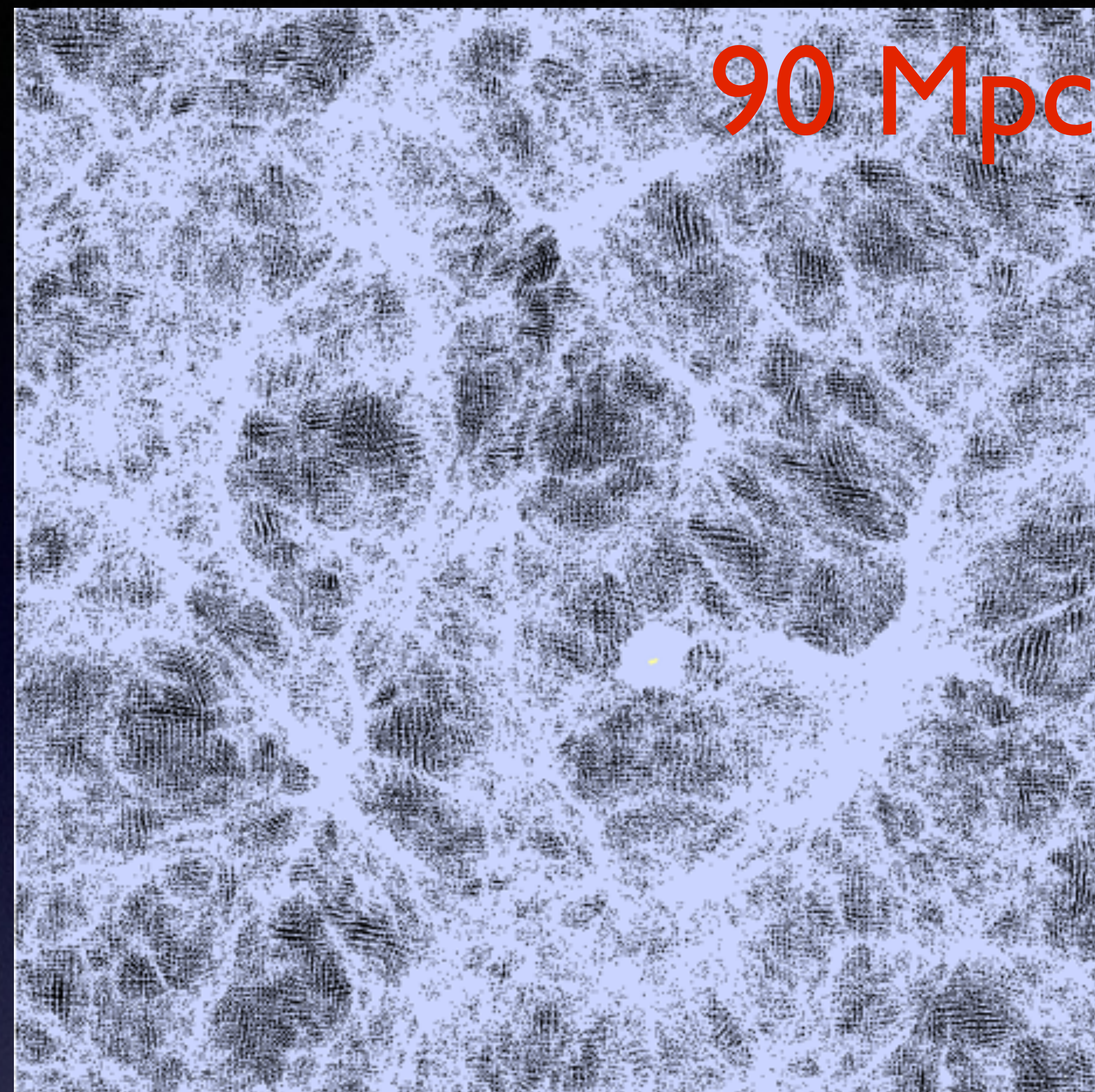
NATURAL SCENARIO FOR FORMATION OF dSPHs/dEs IN HIERARCHICAL UNIVERSE

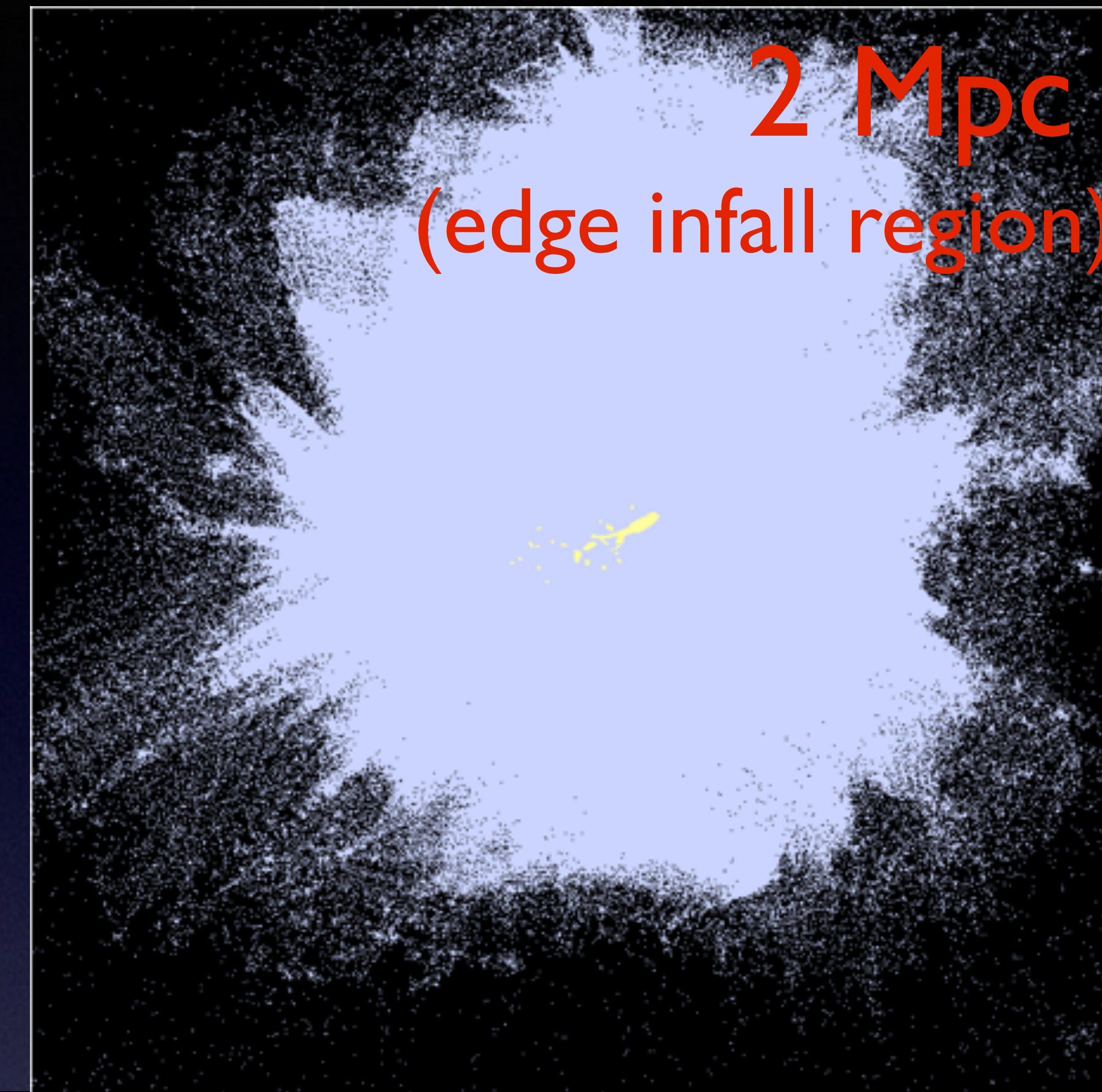
EXAMPLE below: N-BODY DISK+HALO SATELLITE MODEL PLACED ON 5:1 COSMOLOGICAL ORBIT (apo = 150 kpc, peri = 30 kpc), satellite with initial Mvir ~ 10^9 Mo

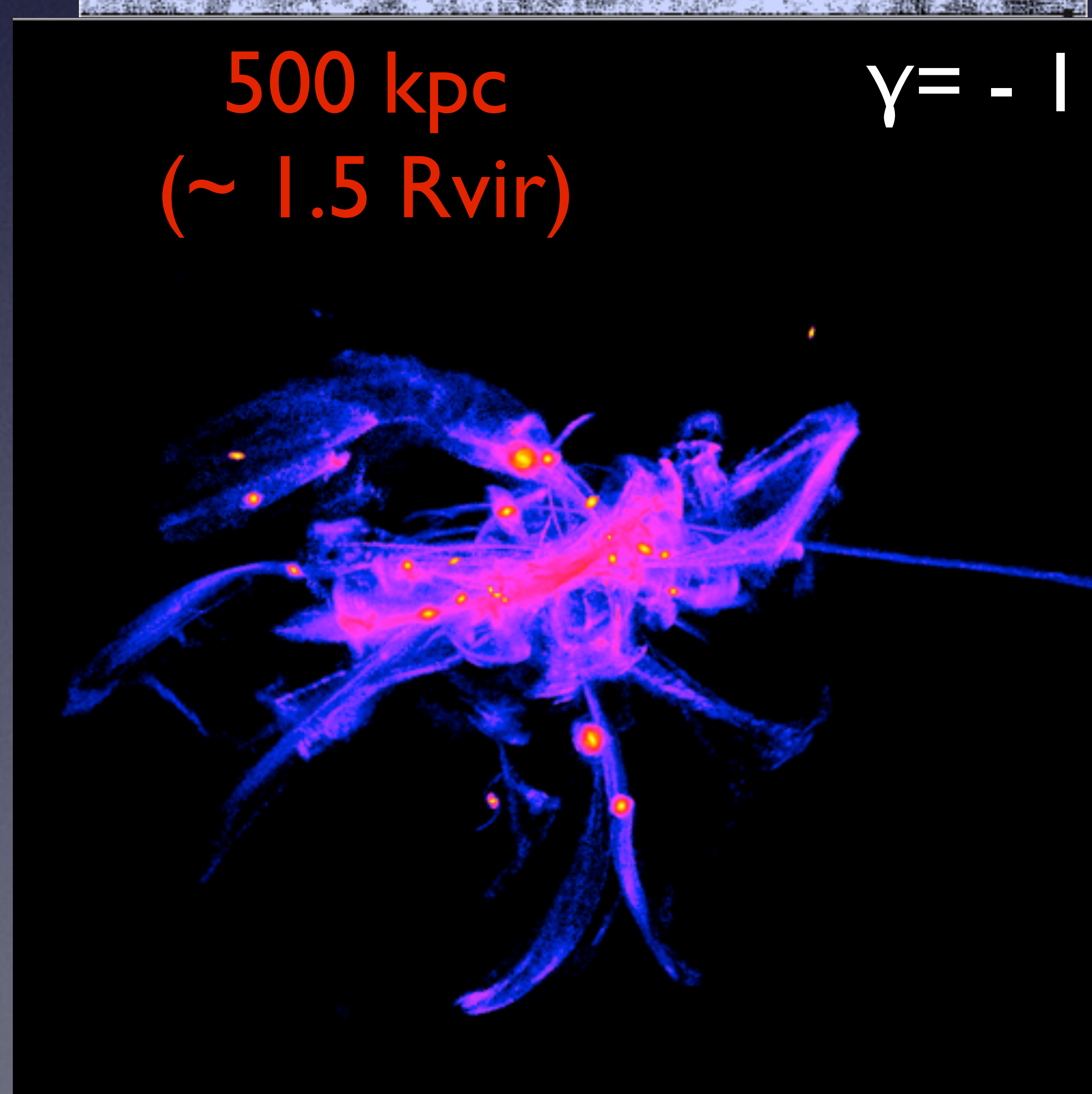
- Tidal heating/stripping of stars + bar/buckling instabilities.

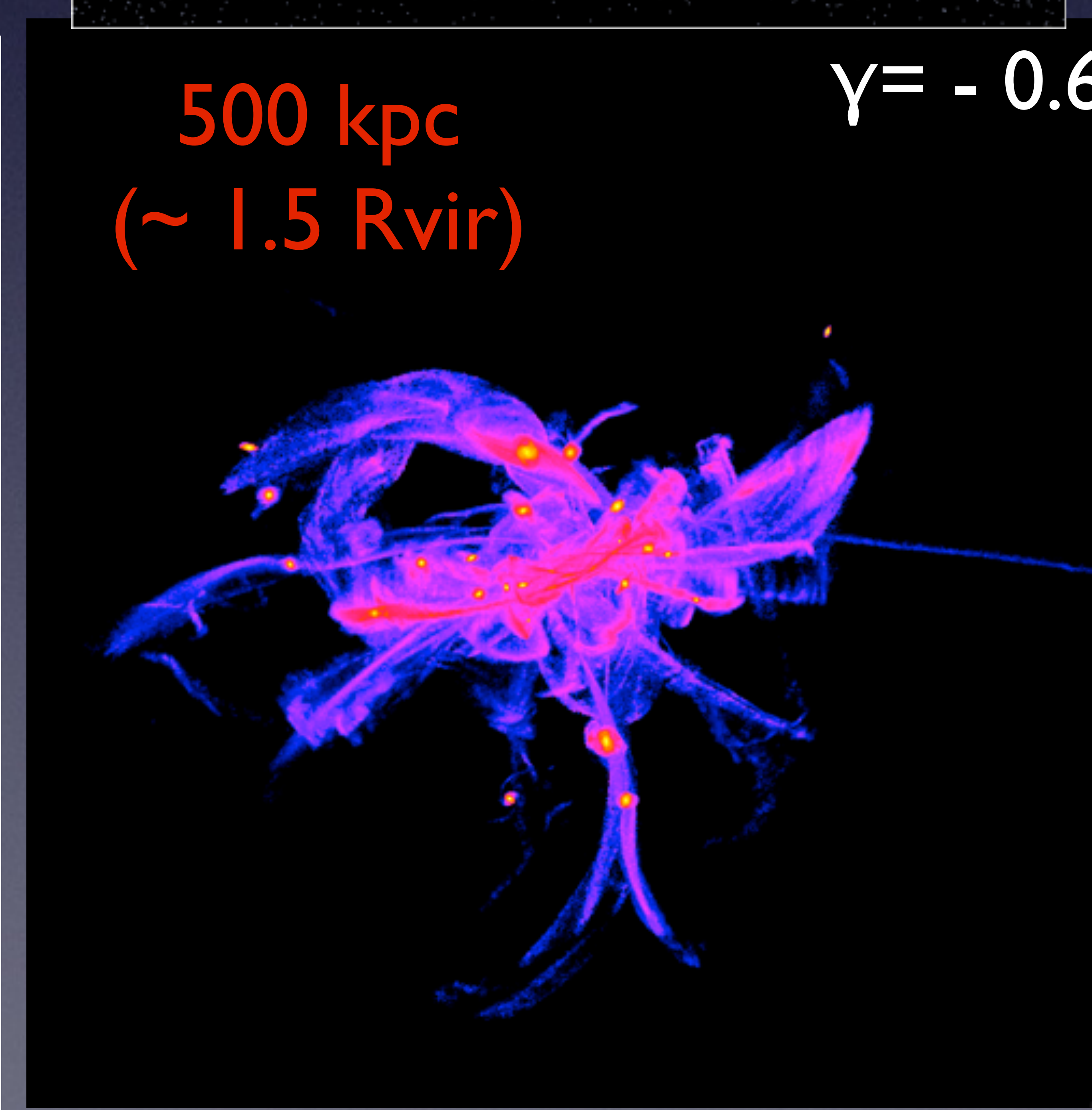


Effect of core formation on tidal stirring of dwarf satellites



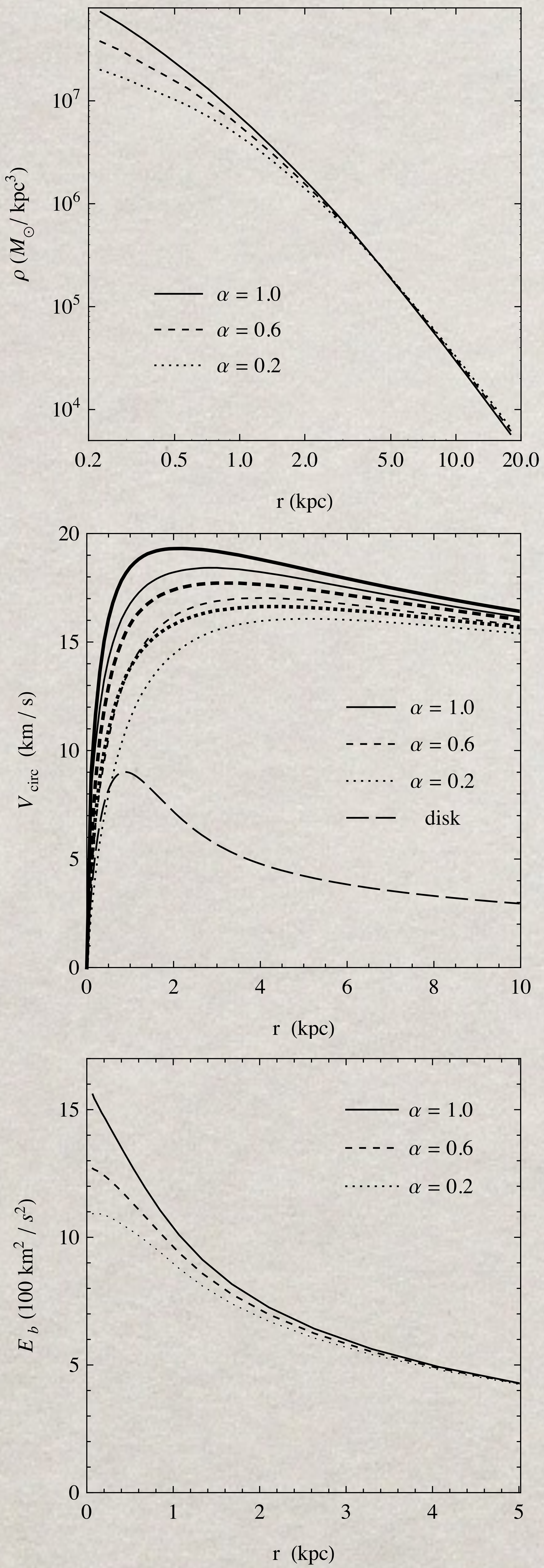






ErisDark zoom-in cosmological simulation of Milky Way-sized halo + hi-res N-body models of dwarfs to replace subhalos at infall (Tomozeiu, Mayer et al. , in prep. - technique previously used by Mastropietro et al. 2005 for galaxies in clusters)

Models: Vc ~20-60 km/s, with stellar disk and NFW or “cored” (γ=-0.6) halo M*/Mhalo satisfy abundance matching constraints for stellar vs. halo mass. Resolution 30 pc and 300 Mo



Kazantzidis, Lokas & Mayer (2013)

Predecessor work using non-cosmological tidal interaction simulations using dwarf N-Body models orbit inside primary galaxy (live disk+bulge+halo model of the Milky Way)

Initial dwarf models (stellar disk+halo, no gas) with virial mass 10^9 (Vmax ~ 20 kms) or 2 x 10^{10} Mo (Vmax ~ 50 km/s) , DM slope -0.2,**-0.6** or -1 (NFW).

Note: Vmax ~ 50 km/s roughly corresponds to massive satellites of MW-halos at infall time giving rise "too big-to fail problem" in the Aquarius simulations at z=0 (Boylan-Kolchin et al. 2012) --> see next slides

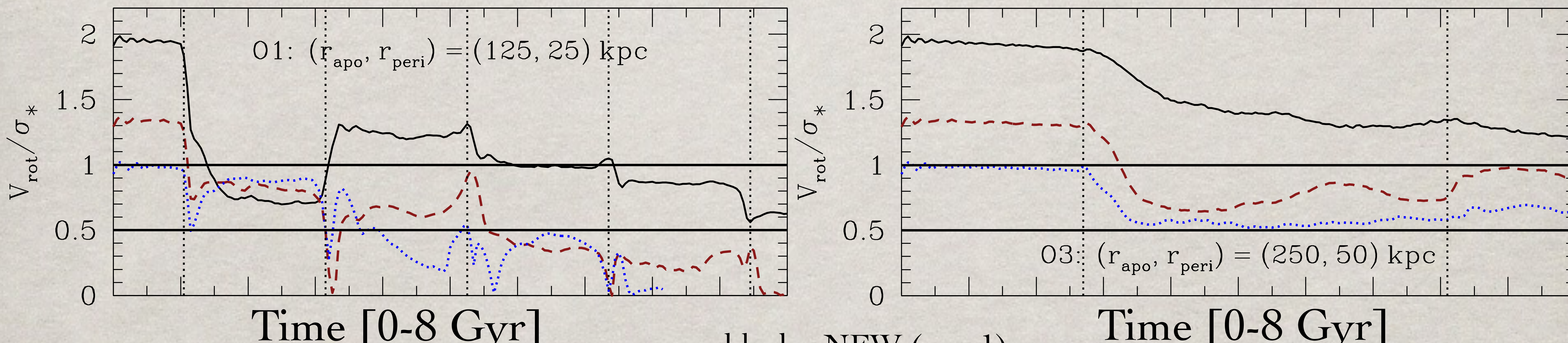
“Cores” enhance transformation dIrr->> dSph

Kazantzidis, Lokas & Mayer 2013

Due to lower internal binding energy of stars they respond more impulsively to tidal shocks with a shallow halo profile (γ < 1) than with a cuspy halo (see also Penarrubia et al. 2010)

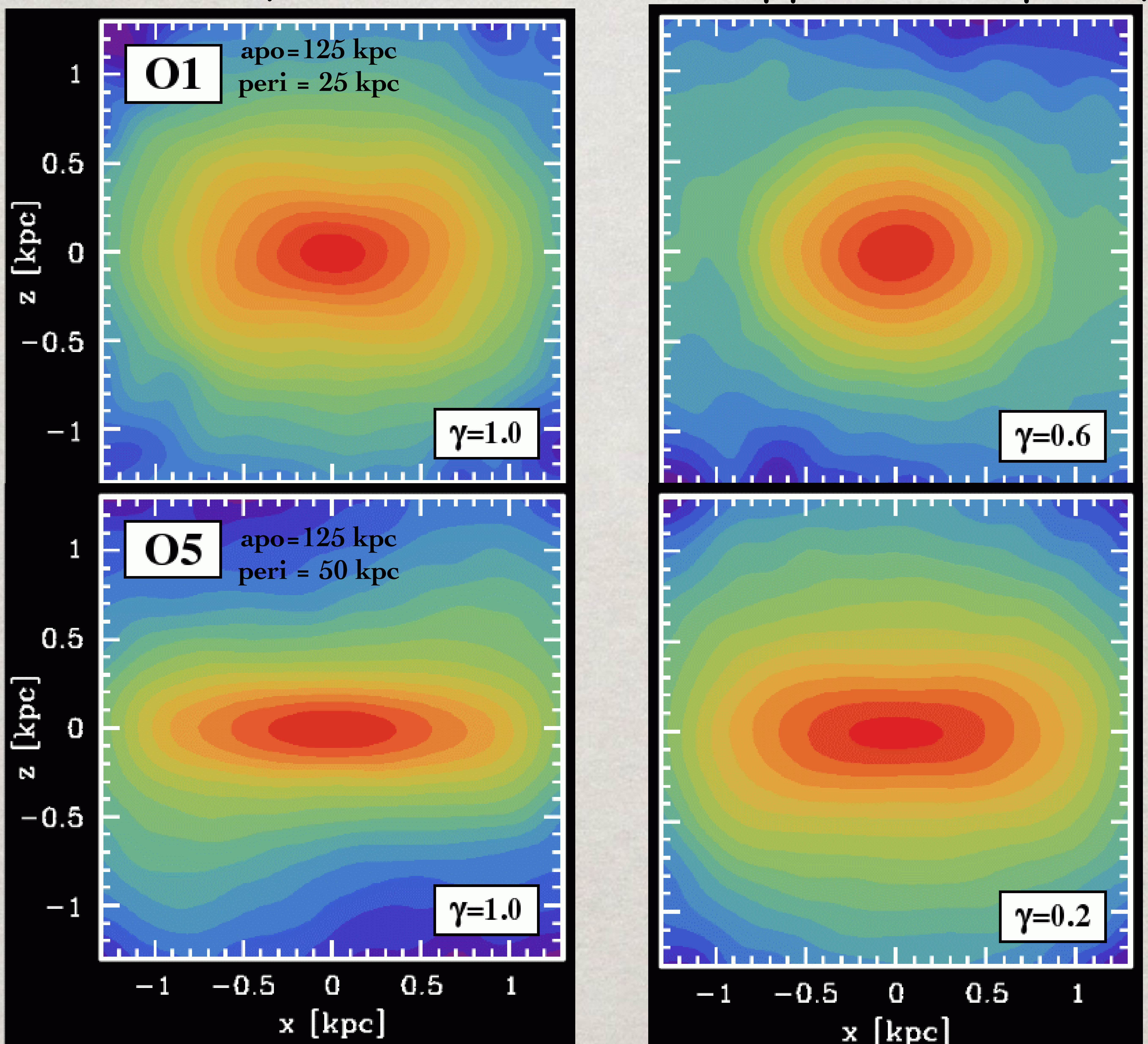
---> **Transformation faster and more effective with shallow DM profiles** (significantly lower final vrot/sigma and higher c/a for any initial condition tried), **in some cases even complete disruption**

----> **Transformation into dSphs happens even for nearly circular orbits as well as orbits with large pericenters** (Leo I easier to accomodate, Cetus/Tucana still predicted to have v_{rot}/σ~ 1 unless orbit nearly radial (apo/peri ~ 10:1).



black - NFW (γ =- 1)
red (γ=- 0.6)
blue (γ=- 0.2, tidally destroyed)

Effect on the shape: shown is projected isodensity countours for projection that yields the HIGHEST apparent ellipticity



Impact on “too-big-to-fail problem”: proof-of-concept

Mayer, Kazantzidis, Tomozeiu et al. in prep.

Tidal evolution of most massive satellites with initial Vmax ~ 50 km/s

In cosmological simulations satellites with Vmax ~ 50 km.s *at infall* are too dense and massive to host dSph satellites of the Milky Way, (“massive failures” - eg Boylan-Kolchin et al. 2012)

Infall on different orbits (peri 12-50 kpc, apo 125-250 kpc, consistent with VL2), MW halo with M ~ 10^{12} Mo (see Lokas et al. 2011), 4 representative cases shown here.

Results after ~ 9 Gyr

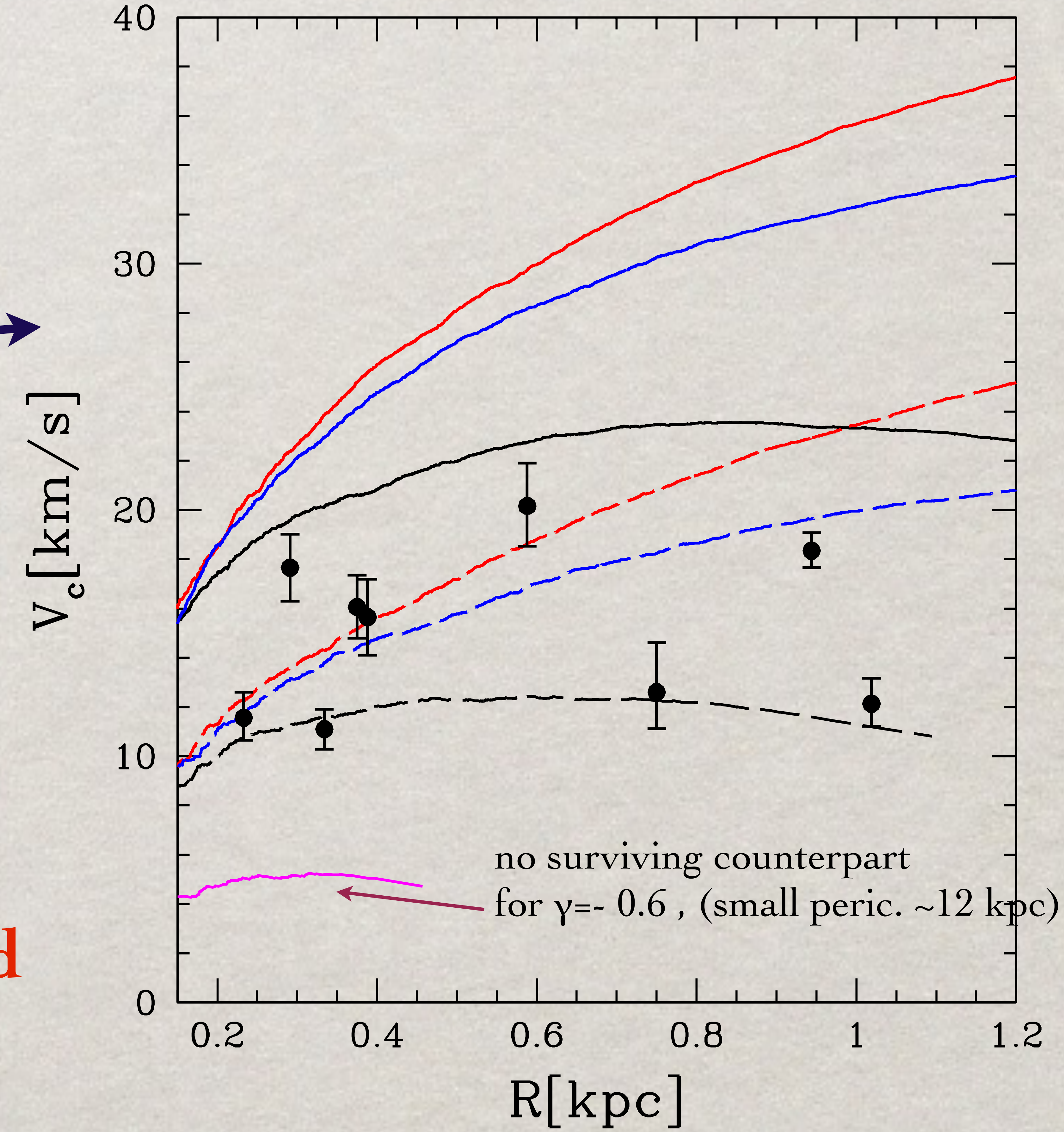
(corresponds to infall at z ~ 1, average infall time of z=0 satellites in cosmological sims).

Solid lines: γ= - 1 models dashed lines: γ=- 0.6 models, data points for MW dSphs (Boylan-Kolchin et al. 2012; Wolf et al. 2010)

Surviving satellites have a lower circular velocity, by a factor of 1.5-2, in shallow vs. cuspy halos

----> with γ=- 0.6 no “massive failures” expected

(Some satellites are completely destroyed)



Conclusions

I. Cosmological simulations of dwarf galaxy formation are finally yielding qualitative sensible results owing to combination of increased resolution in the ISM component and improved models of SN +stellar feedback.
No more overcooling and angular momentum problem, instead bulgeless exponential disks

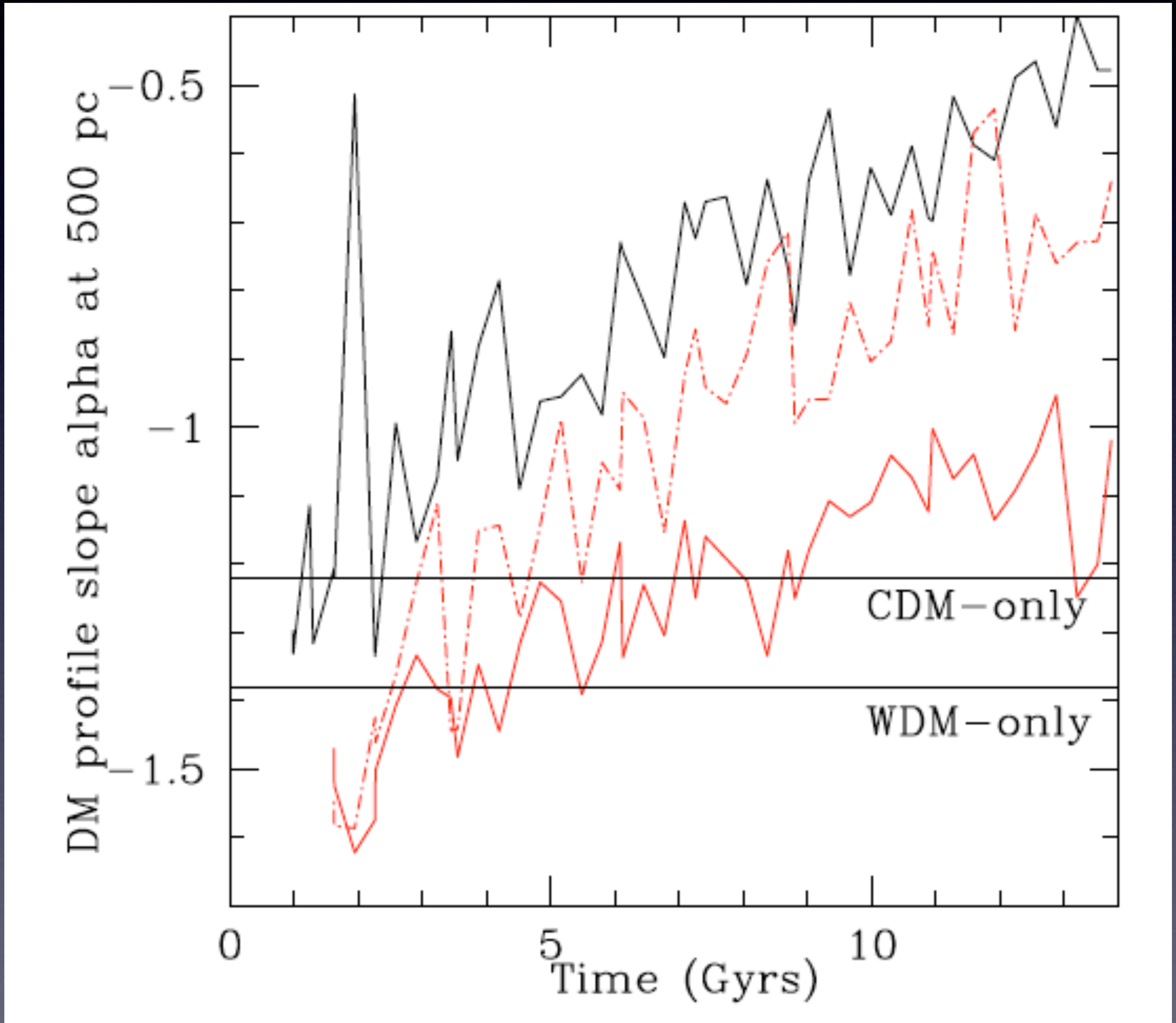
II. For some fundamental observables, such as stellar-to-halo mass ratio, gas content, present-day SF rate and mean metallicity models match observations quantitatively

III. An unexpected prediction of the new simulations is the formation of DM cores, which seems unavoidable if powerful baryonic outflows at early times are the reason why dwarfs end up faint, bulgeless and dark matter dominated. Core formation also aids tidal stirring of dIrrs into dSphs and possibly solves "too-big-to-fail" problem.

IV. The SF histories in the models are not yet quantitatively robust and are sensitive to the details of the sub-grid star formation and feedback implementation. However a general robust prediction is that dwarfs with stellar mass > 10^6 Mo had much higher SF efficiencies in the past than today, at variance with massive galaxies. This conclusion is supported by HST-derived SF histories of nearby/LG dwarfs

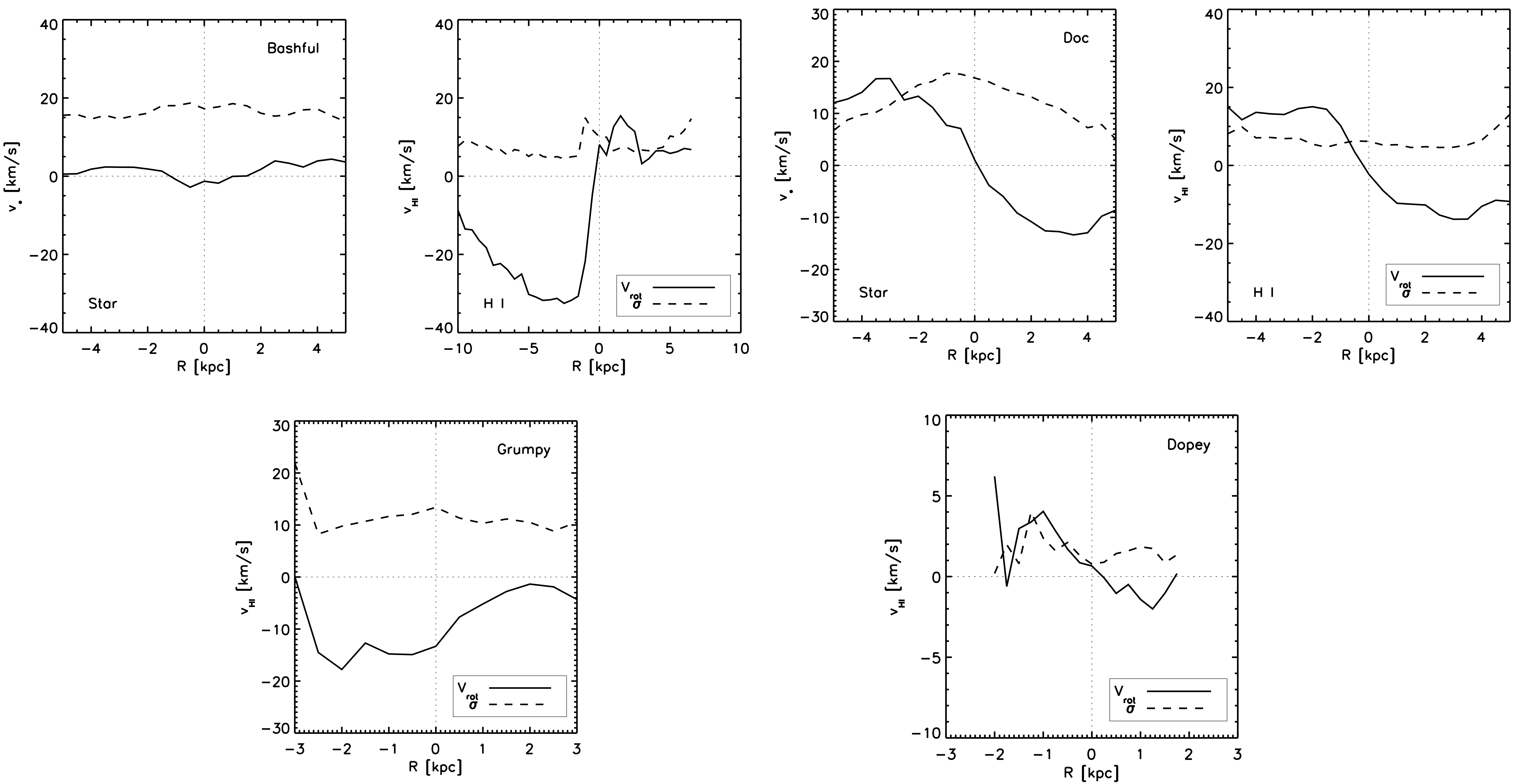
V. Mock CMD diagrams and detailed elemental abundances for gas and stars will take the comparison with observations to new quantitative level, perhaps breaking degeneracies such as those between feedback parametrization and DM model (eg CDM vs. WDM)

Core formation: DM model vs. feedback mode
Suggests degeneracy



Solid lines: CDM and WDM cases with same SF efficiency, dash-dotted line is WDM case with higher SF efficiency

Gas and stellar kinematics of the 4 luminous dwarfs

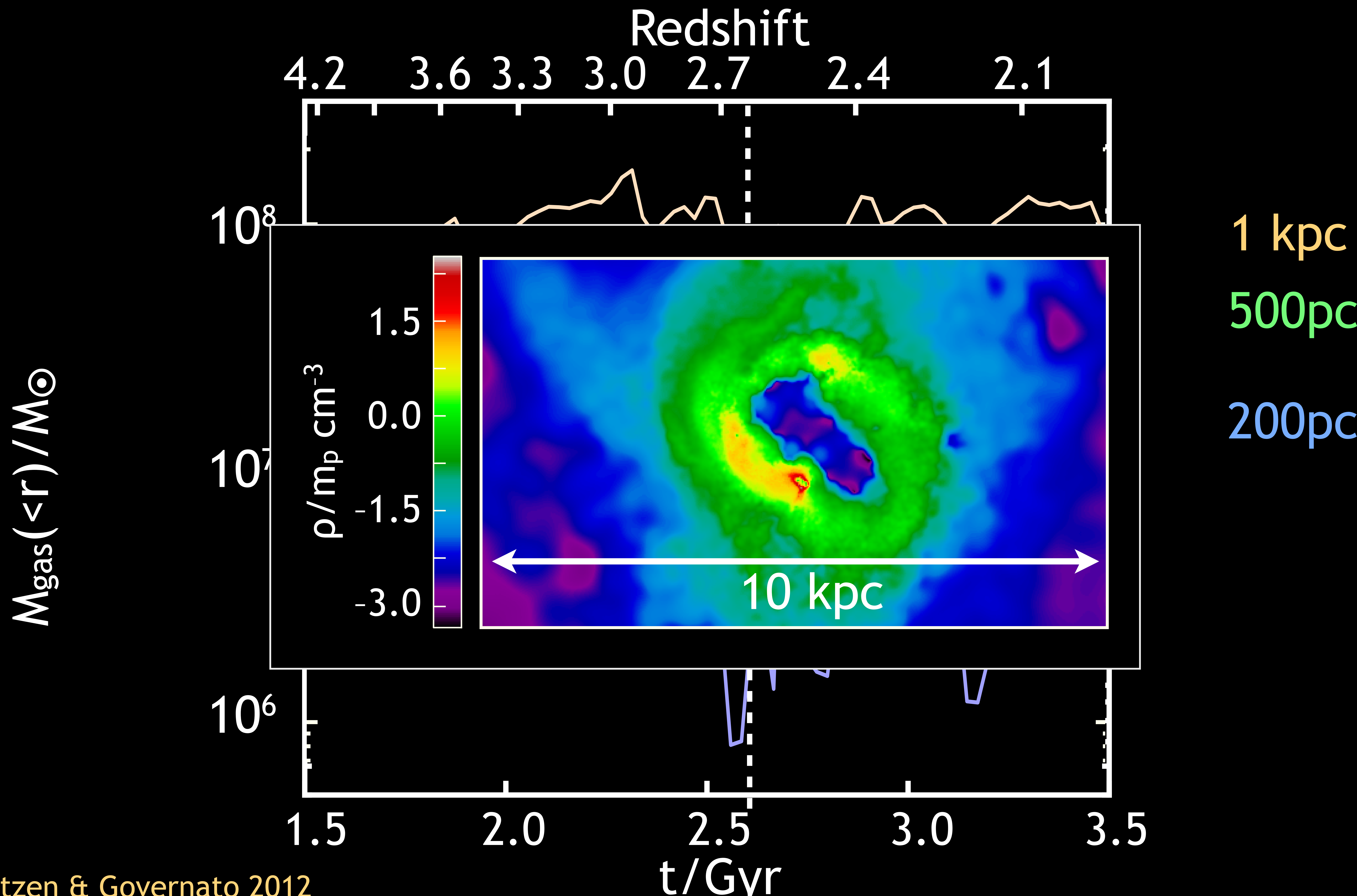


ERIS: The Basics

✳ Eris is a product of **GASOLINE.**
✳ Follows the formation of a light Milky Way galaxy of mass
$M_{vir} = 8 \times 10^{11}\ M_{sun}$
✳ Selected to have a quiet merger history. No mergers larger than 1:10 after z=3.
✳High mass and spatial resolution: 18.6 million particles within the virial radius. ε_G=120 pc

✳ Physics: metal dependent gas cooling (only for T <~ 10^4K,) UVB heating, SN Type Ia and Type II (blastwave) thermal feedback.
✳ High SF gas density threshold:
nSF=5 atoms $cm^{-3,}$ + control run ErisLT with low SF threshold (n_{SF} = 0.1 atoms cm^{-3}) and other runs with lower resolution or lower SF efficiency
✳ Expensive: 9 months per single run at NASA Pleiades and "Rosa" Cray at Swiss National Supercomputing Center using up to1024 cores.

What is missing: High Temperature metal cooling, H_2 cooling, metal and thermal diffusion diffusion, radiative feedback from stars, AGN feedback.....(see Eris2 runs later)



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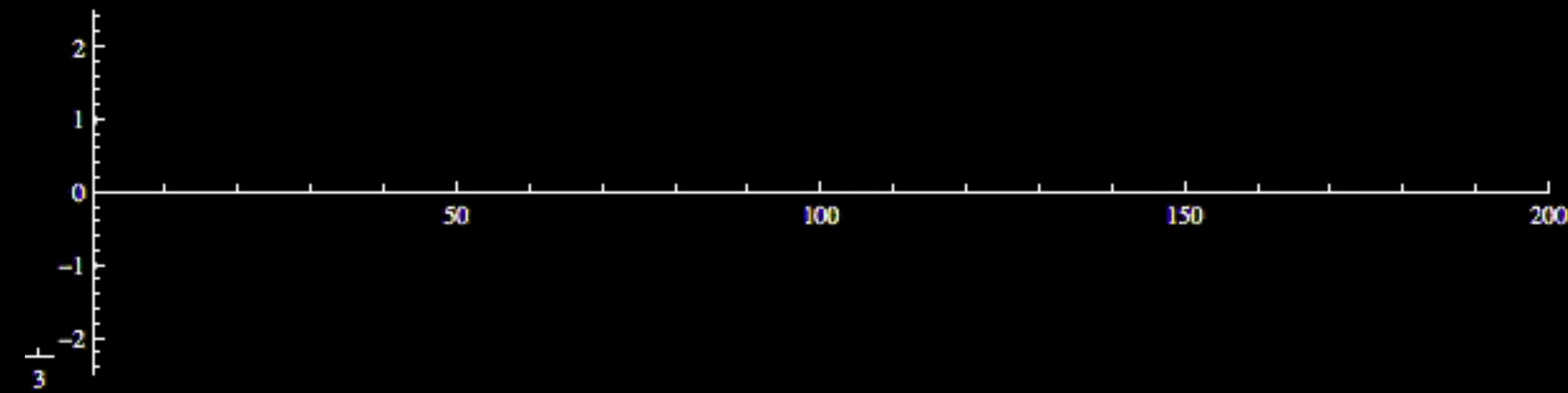
Adiabatic

$$E_f = E_i$$

Gnedin & Zhao 2002



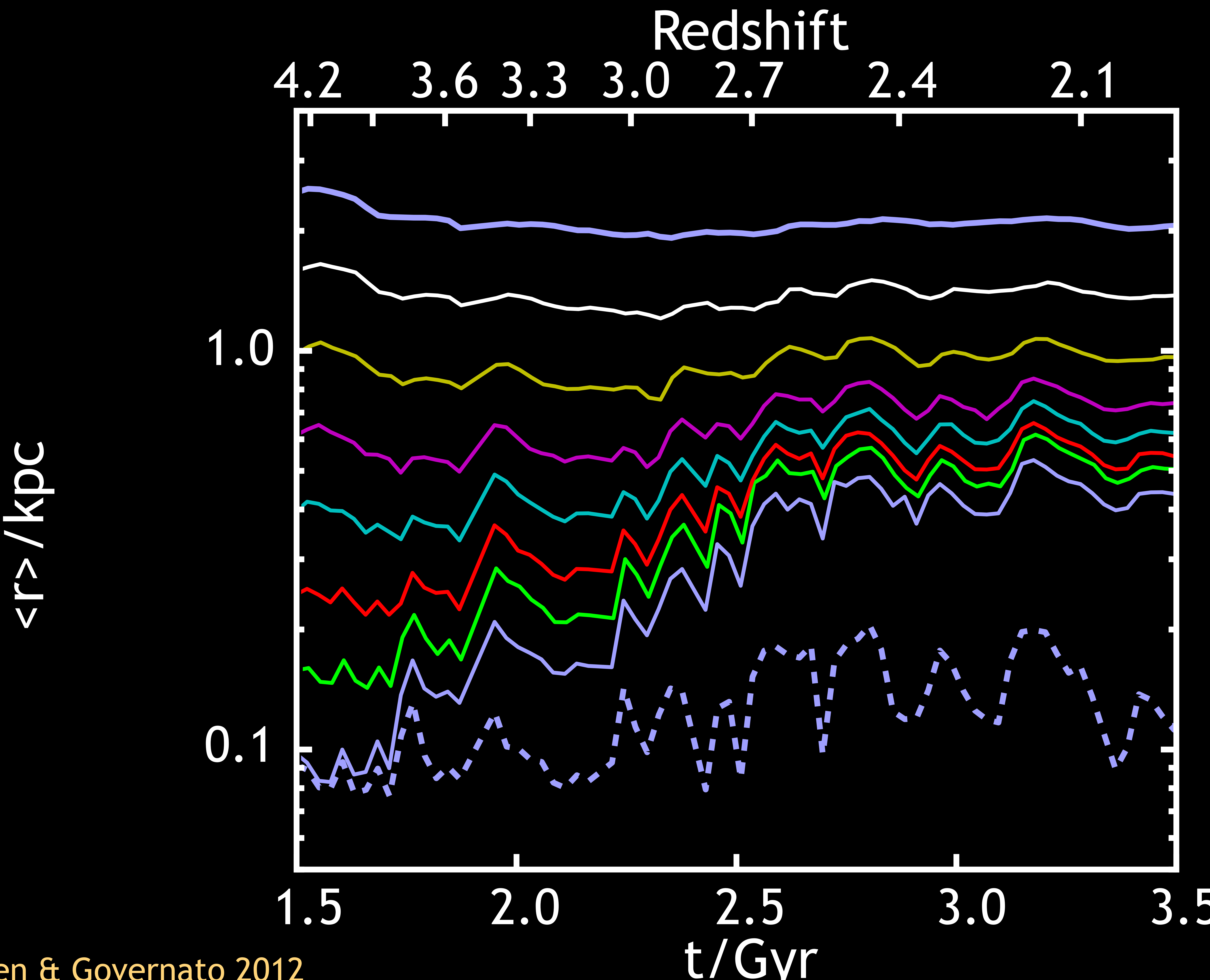
Sudden, then adiabatic

$$\frac{\langle E_f \rangle}{E_i} = \frac{1}{2}\left(\frac{\omega_1}{\omega_0} + \frac{\omega_0}{\omega_1}\right)$$

Generalization:

$$\Delta E = \Delta E(\Phi(t), E_0, j)$$

Pontzen & Governato 2012



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