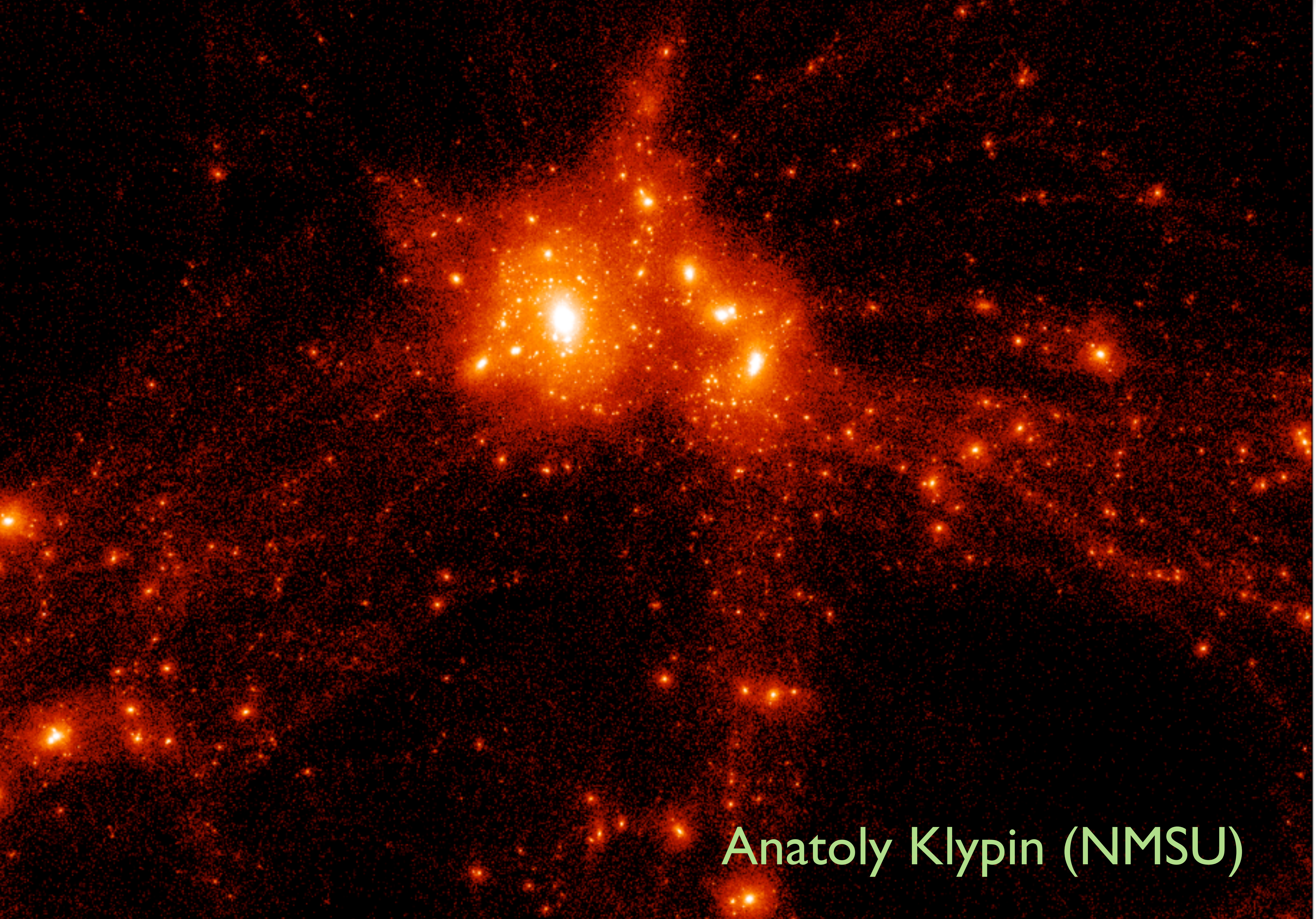
Nature of Dwarf Spheroidal Galaxies



Anatoly Klypin (NMSU)

- Properties of dSph
- Relation to dIrr
- Theory: abundances and structure of dSph

Dwarf Spheroidal Galaxies

40x40 arcmin B band image

Fornax Dwarf spheroidal

11x11 arcmin 2Mass JHK image

NGC 185 dE galaxy

8x8 arcmin 2Mass JHK image

M32 dE galaxy

Dwarf Spheroidals: strange beasts

The most abundant population of galaxies

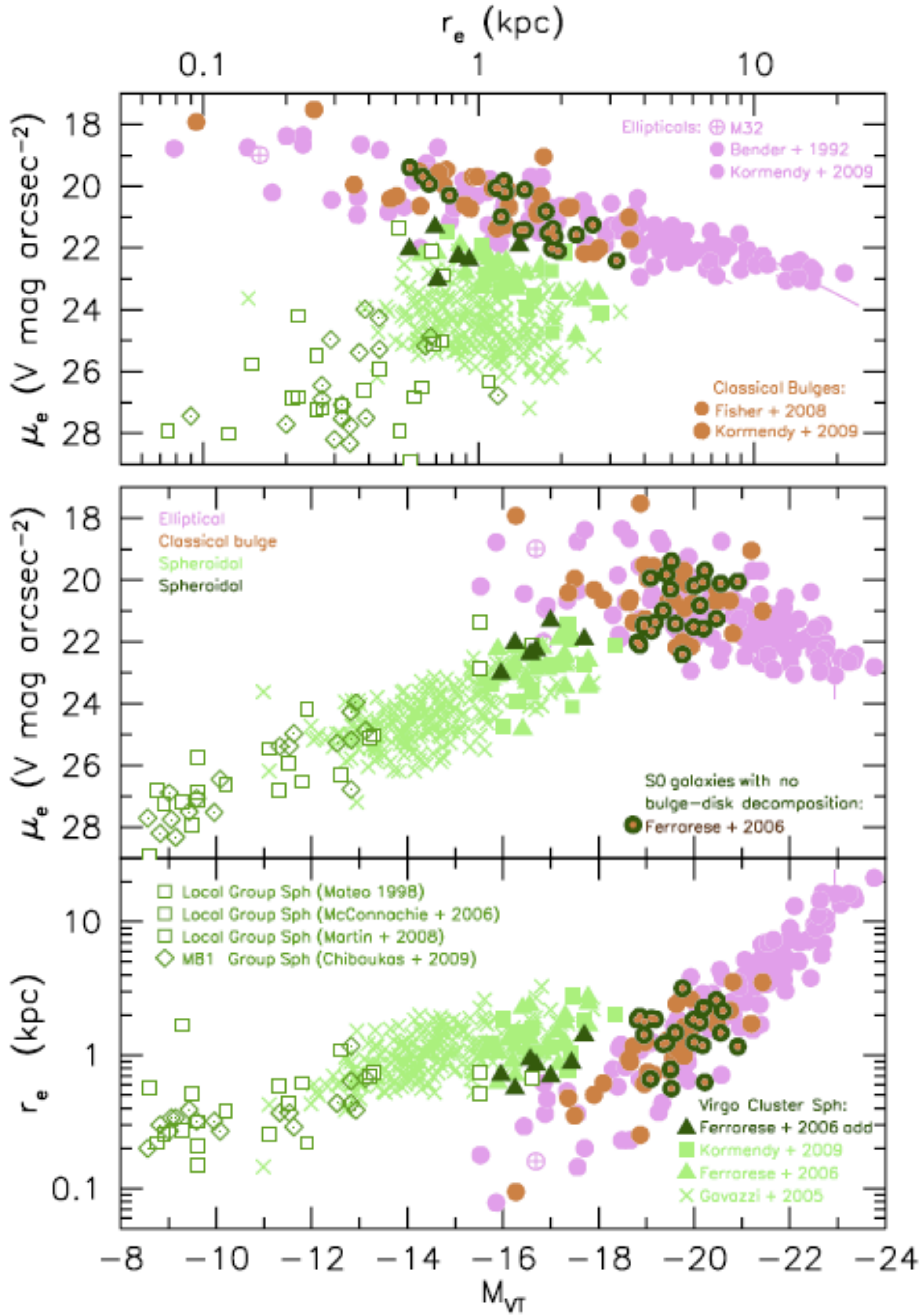
Not abundant enough: they are at the heart of the overabundance problem

Spheroidals, but not ellipticals

Strong environmental effects: exist only in groups. No isolated dSph

Dark matter dominated, but yet strong effects of normal matter

Spheroidals are not Ellipticals: a different population



Kormendy & Bender 2012

Mass at ~1 kpc radius. Overabundance problem

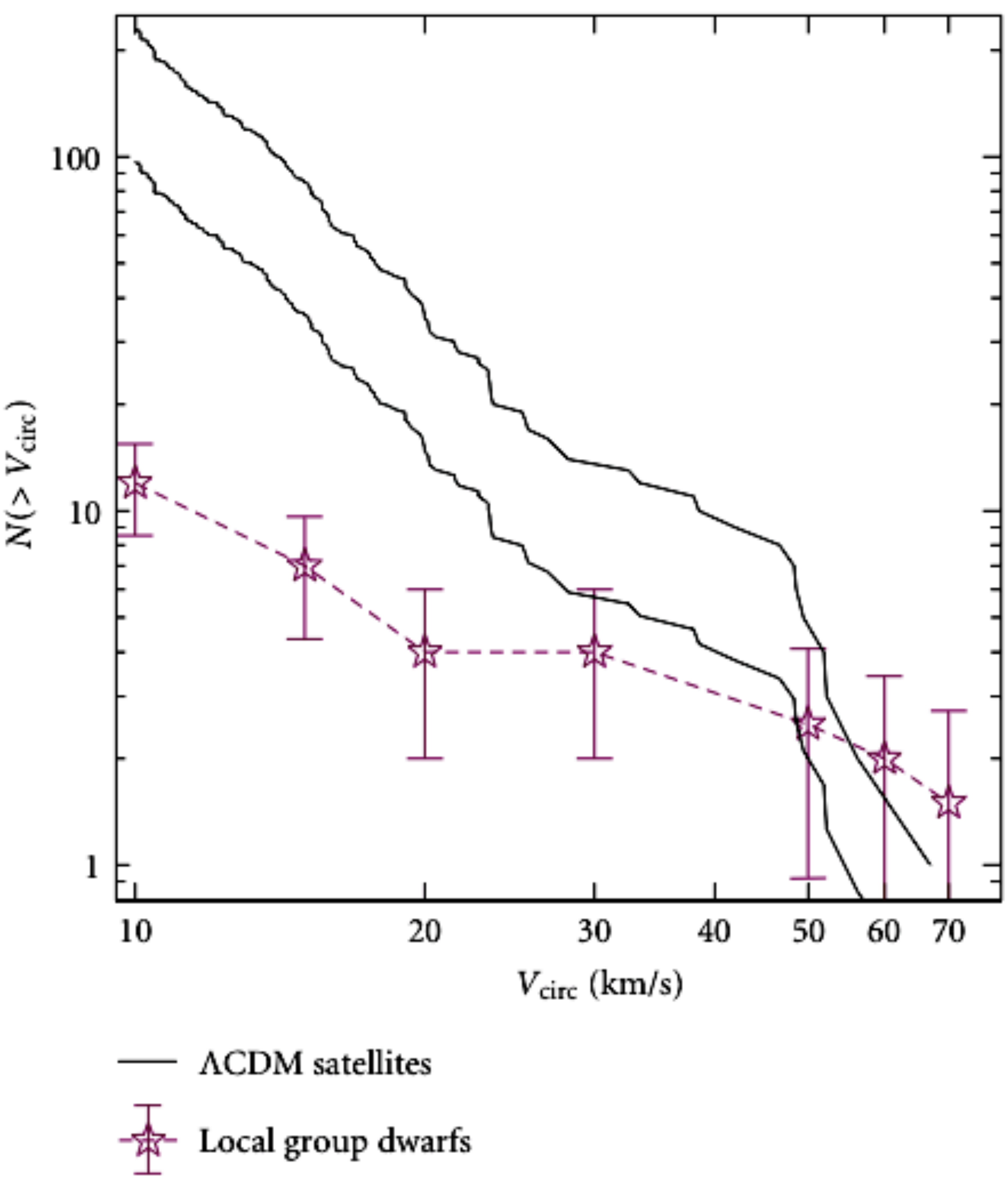
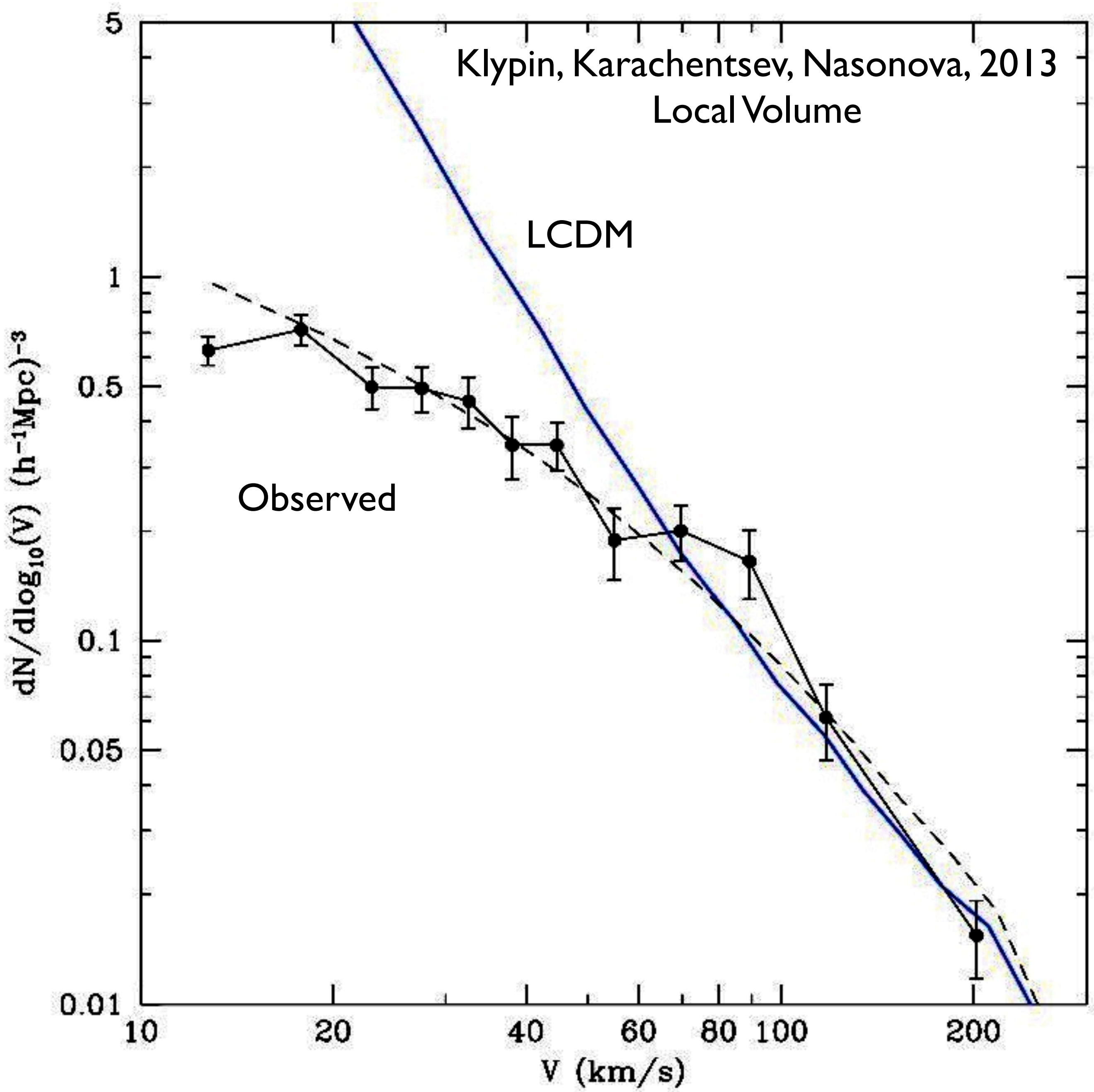


FIGURE 7: Comparison of the cumulative circular velocity functions, $N(> V_{max})$, of subhalos and dwarf satellites of the Milky Way within the radius of 286 kpc (this radius is chosen to match the maximum distance to observed satellites in the sample and is smaller than the virial radius of the simulated halo, $R_{337} = 326$ kpc). The subhalo VFs are plotted for the host halos with maximum circular velocities of 160 km/s and 208 km/s that should bracket the V_{max} of the actual Milky Way halo. The VF for the observed satellites was constructed using circular velocities estimated from the line-of-sight velocity dispersions as $V_{max} = \sqrt{3}\sigma_r$ (see the discussion in the text for the uncertainties of this conversion).

Kravtsov 2009

Velocity function of galaxies



10 Mpc sphere centered on the Milky Way

Theory predicts correct abundance if galaxies with Vcirc> 50 km/s (Magellanic Clouds)

On small scales the disagreement is large. The discrepancy is due to a combination of photoionization heating at at the moment of re-ionization(z~10) and stellar feedback. Small halos do not host galaxies

Connection to dIrr galaxies

dSph are transformed dIrr:

as dIrr falls into parent halo,

its gas is ram pressure stripped

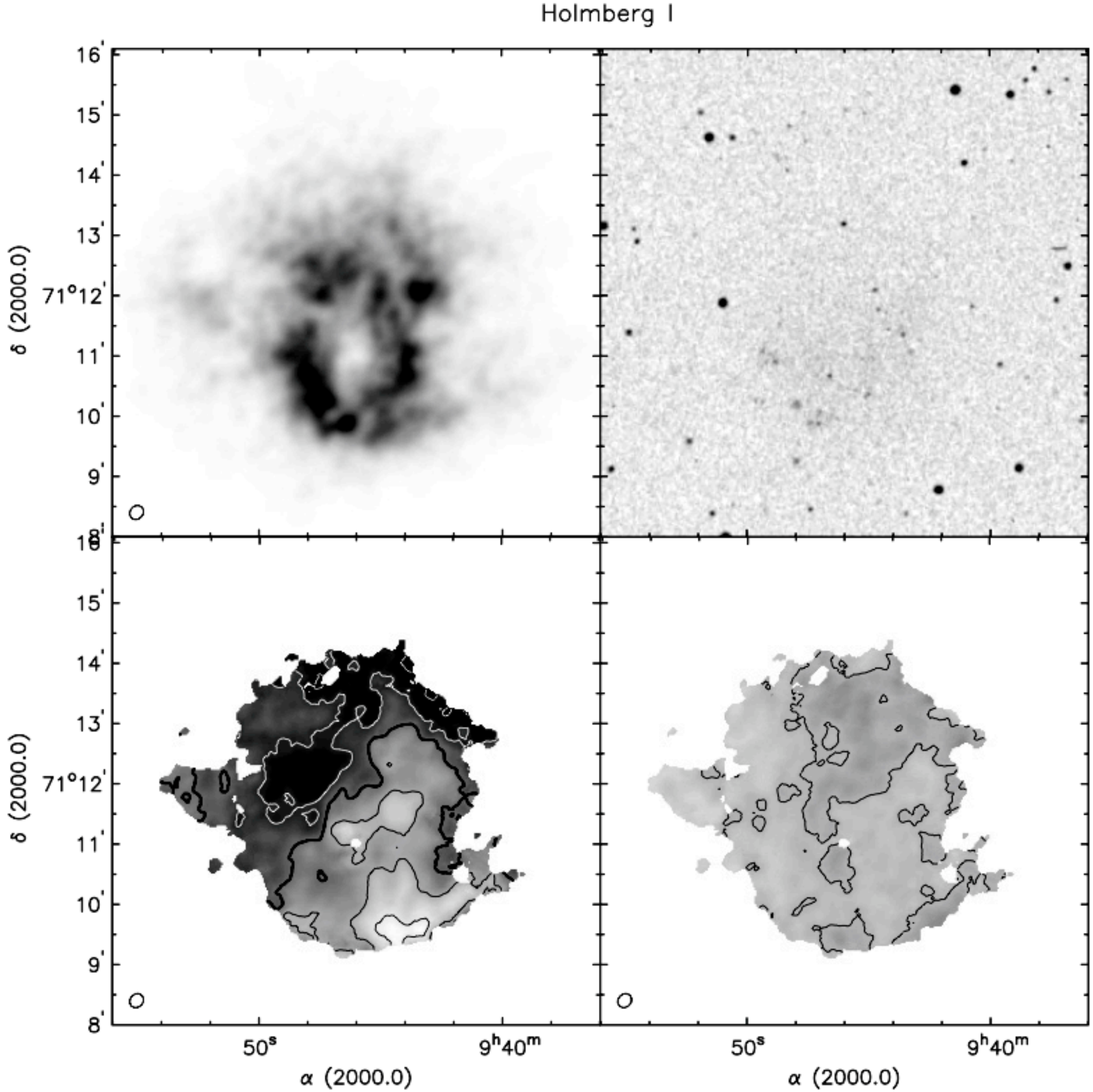
its disk tumbles

dSph (may) have the same issues as dIrr:

exponential stellar profiles

cored DM (not cusp)

We really do not know this: physics of tiny dIrr is poorly understood. Some should not exist, but they do.

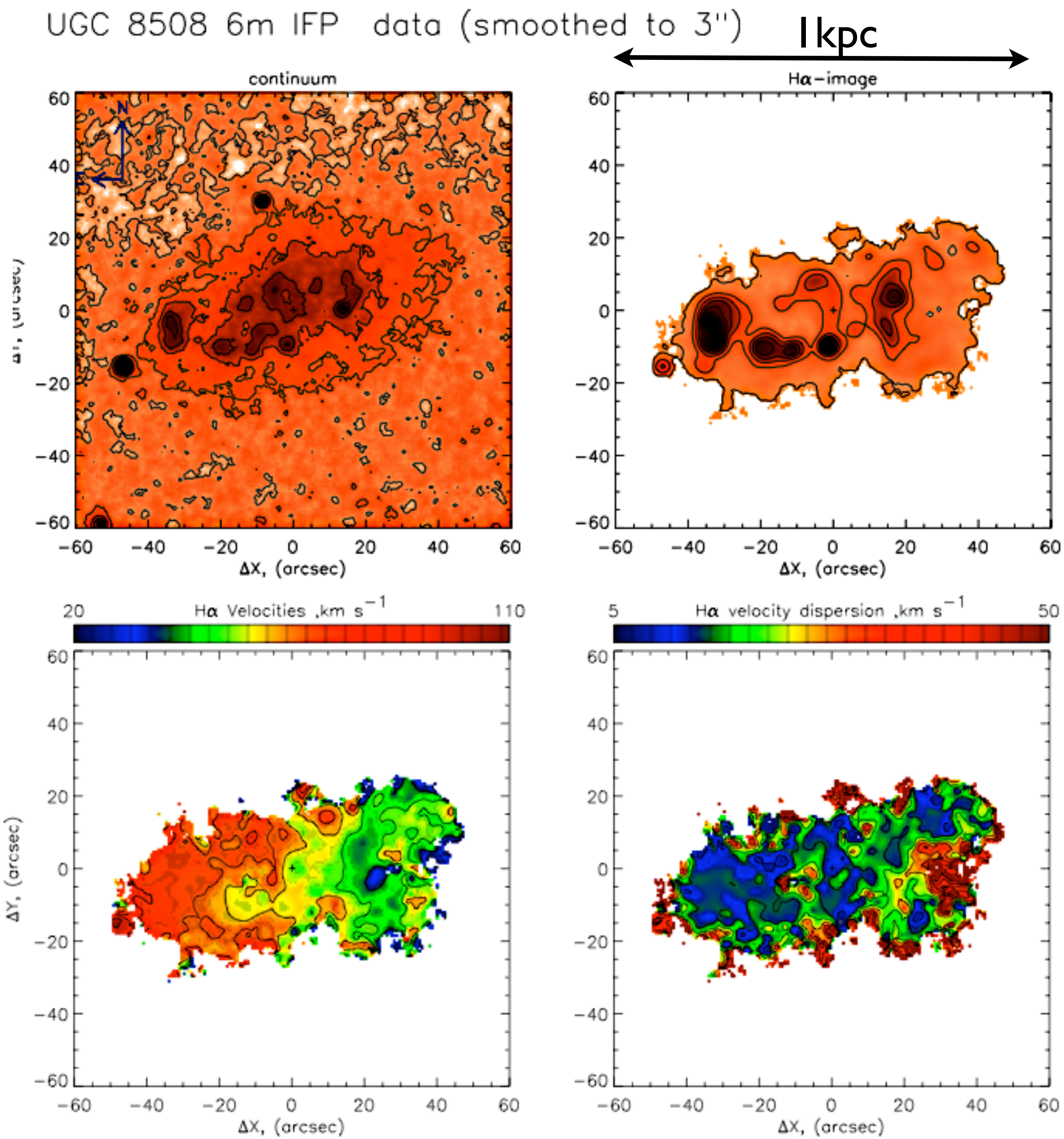


M_B =-14.8 inclination =12deg

Example: UGC8508

Distance 2.5 Mpc

M_B =-12.9

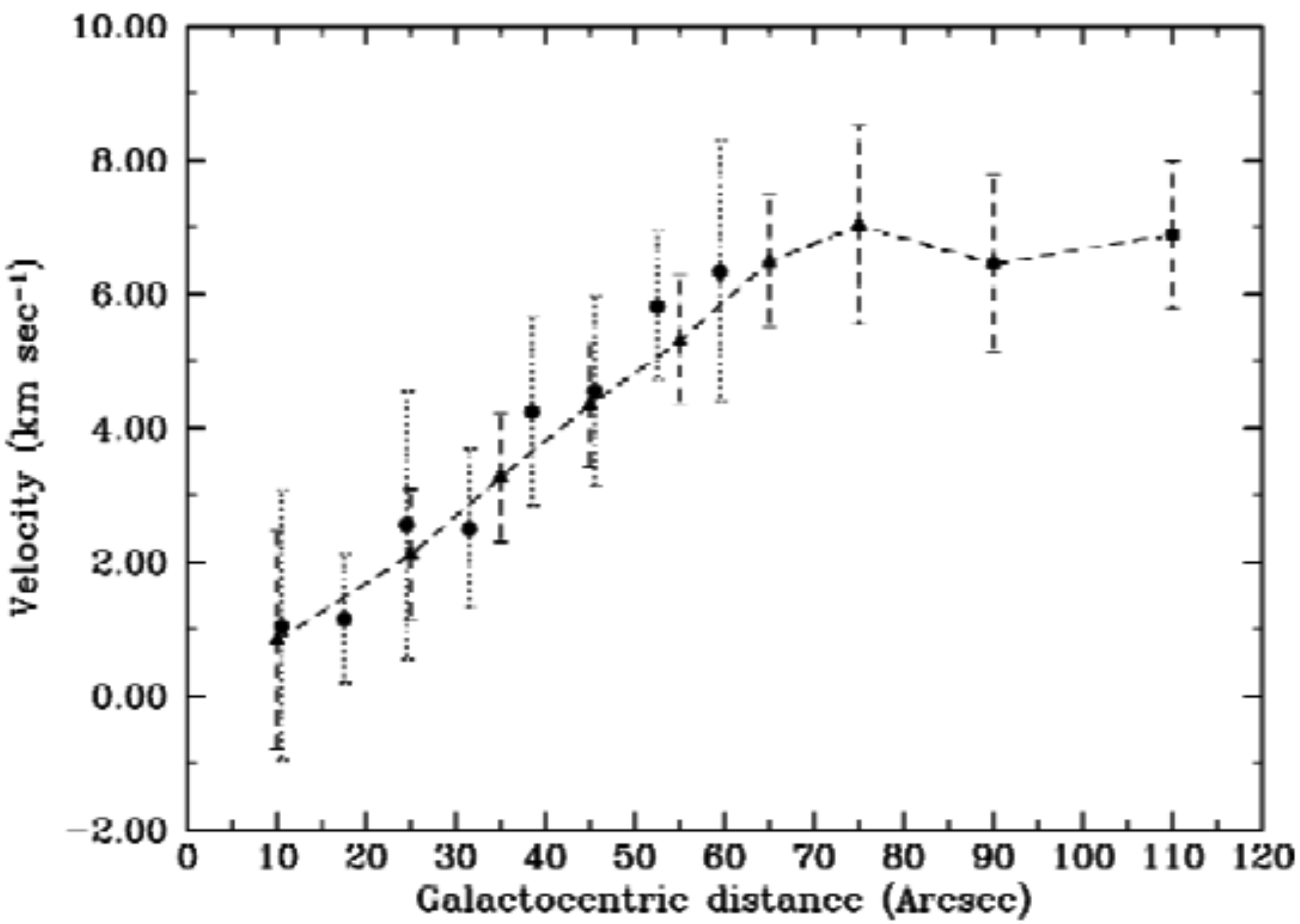


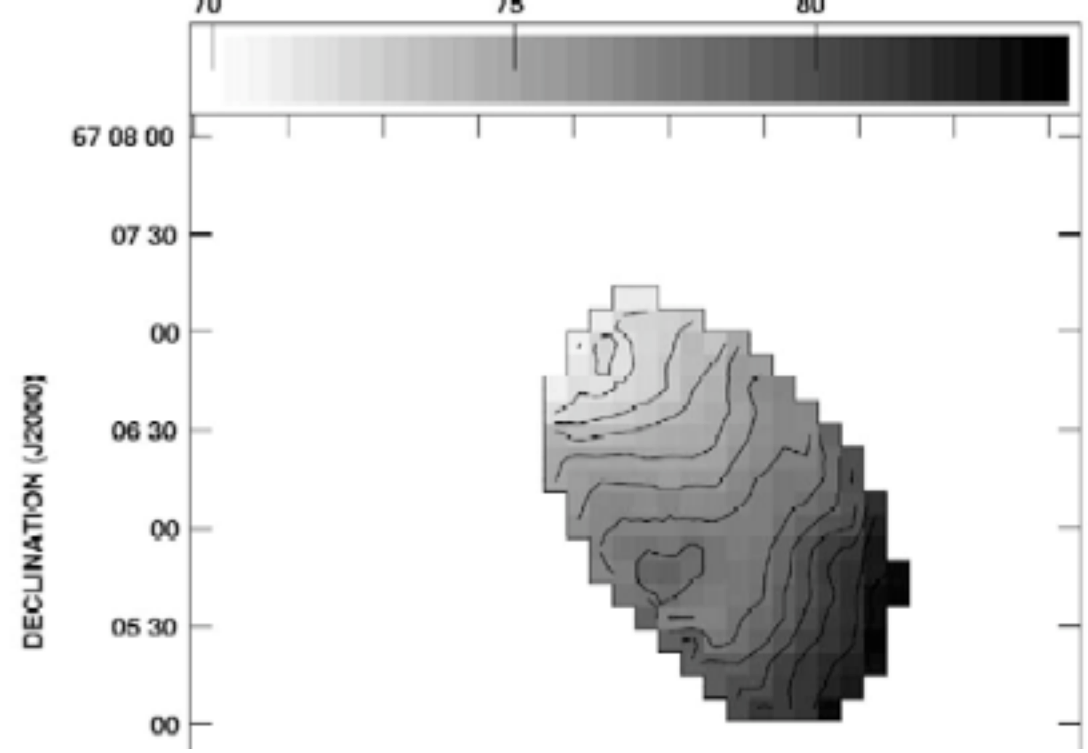
Russian 6m telescope

Galaxy, which should not exist:

Cam B (Begum et al 2003)

$V_{rot+rms}$ = 10km/s
M_B = -12.3
D = 3.5 Mpc





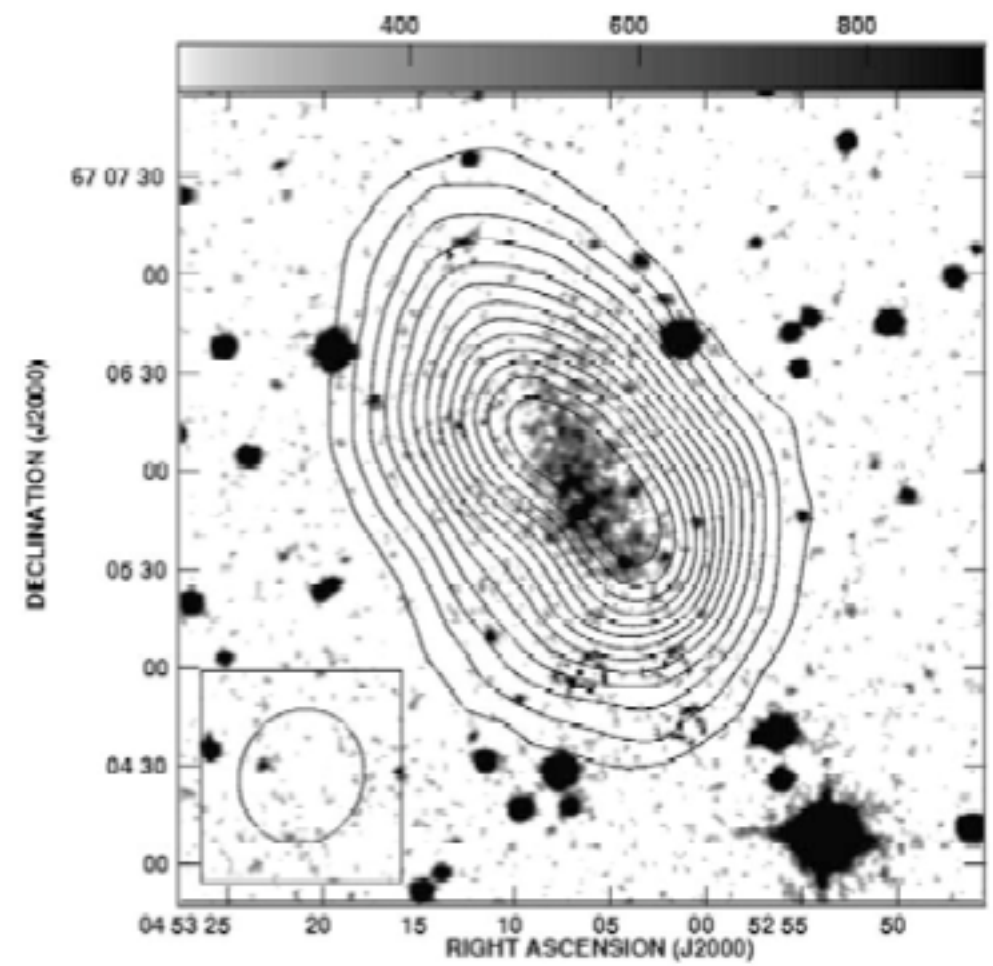
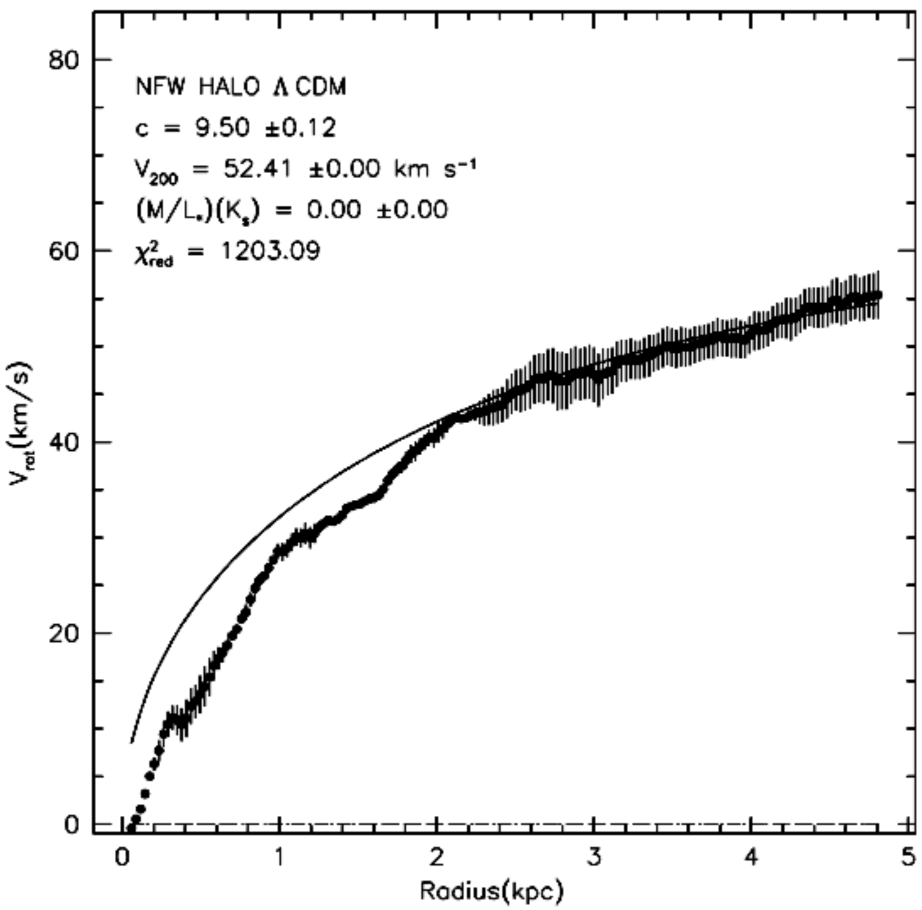


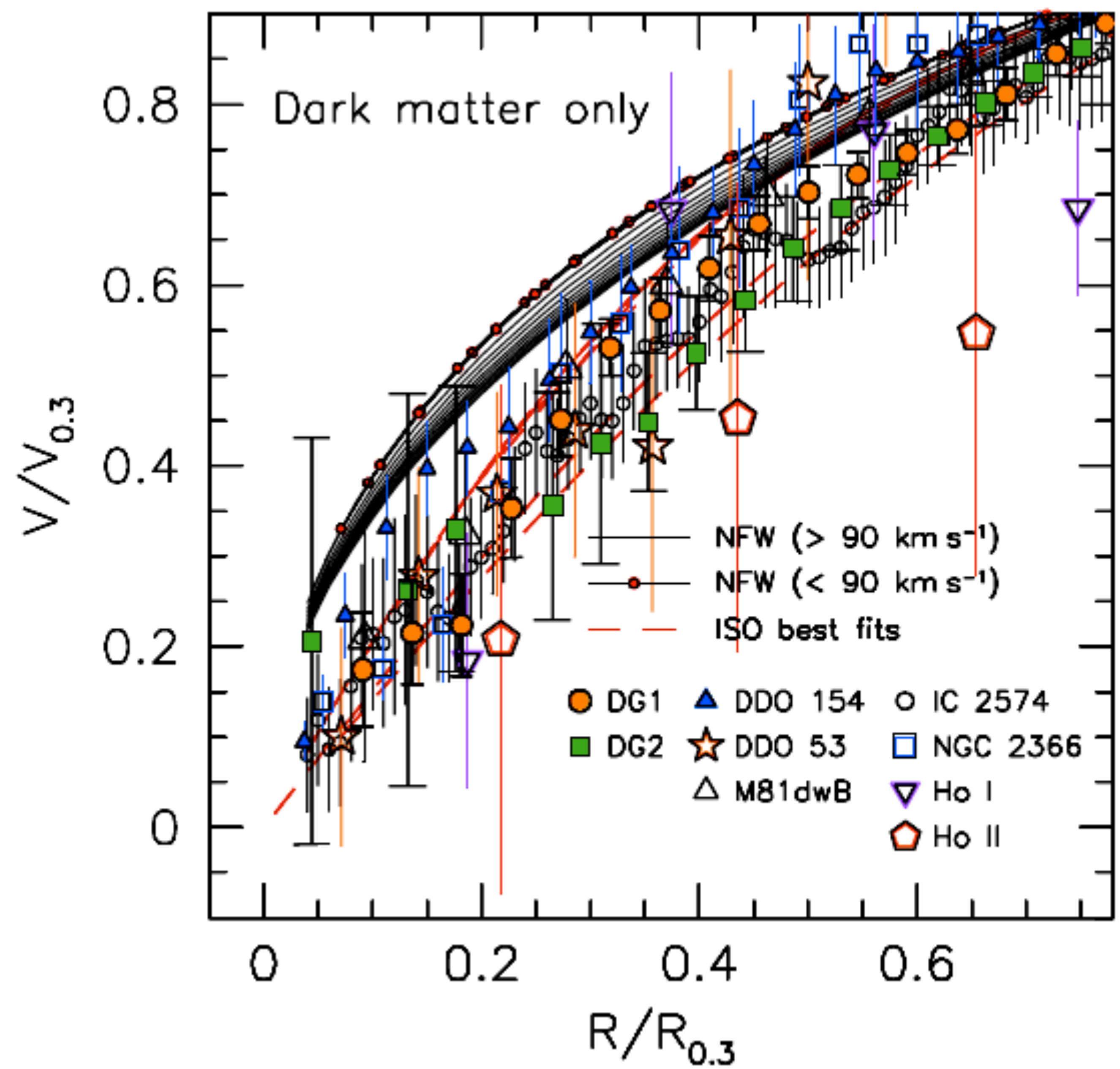
Fig. 3. The digitized Palomar Sky Survey image of Cam B with the GMRT 40″×38″ resolution integrated HI emission (moment 0) map overlayed. The contour levels are 3.7, 8.8, 19.1, 24.3, 29.4, 34.6, 39.8, 44.9, 50.1, 55.2, 60.4, 65.5 and 70.7×10^{19} atoms cm^{-2}.

Density Profiles: Mass at ~1 kpc radius. Core-cusp problem



NGC 6822, de Blok etal 2007

Oh et al 2011



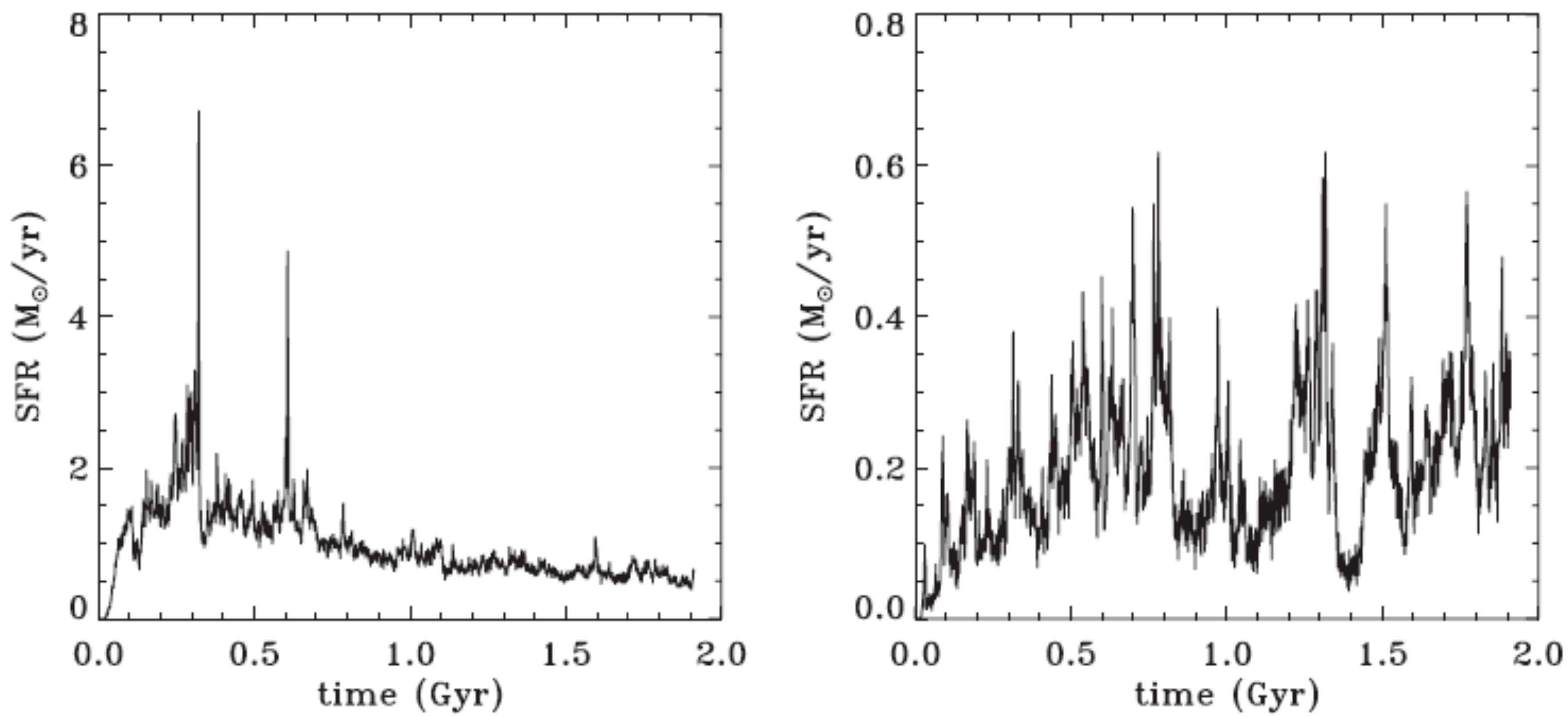


Figure 3. Star formation history in the runs without (left-hand plot) and with (right-hand plot) feedback.

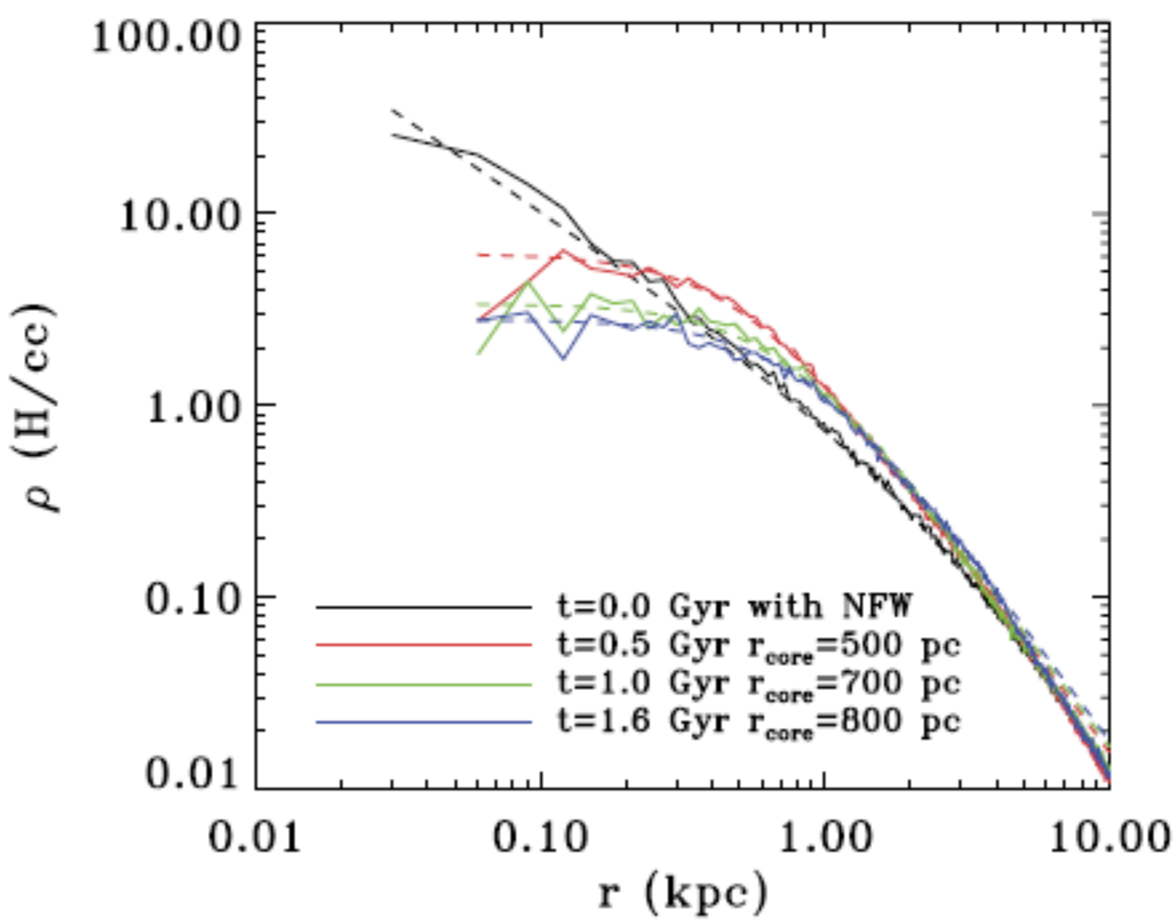
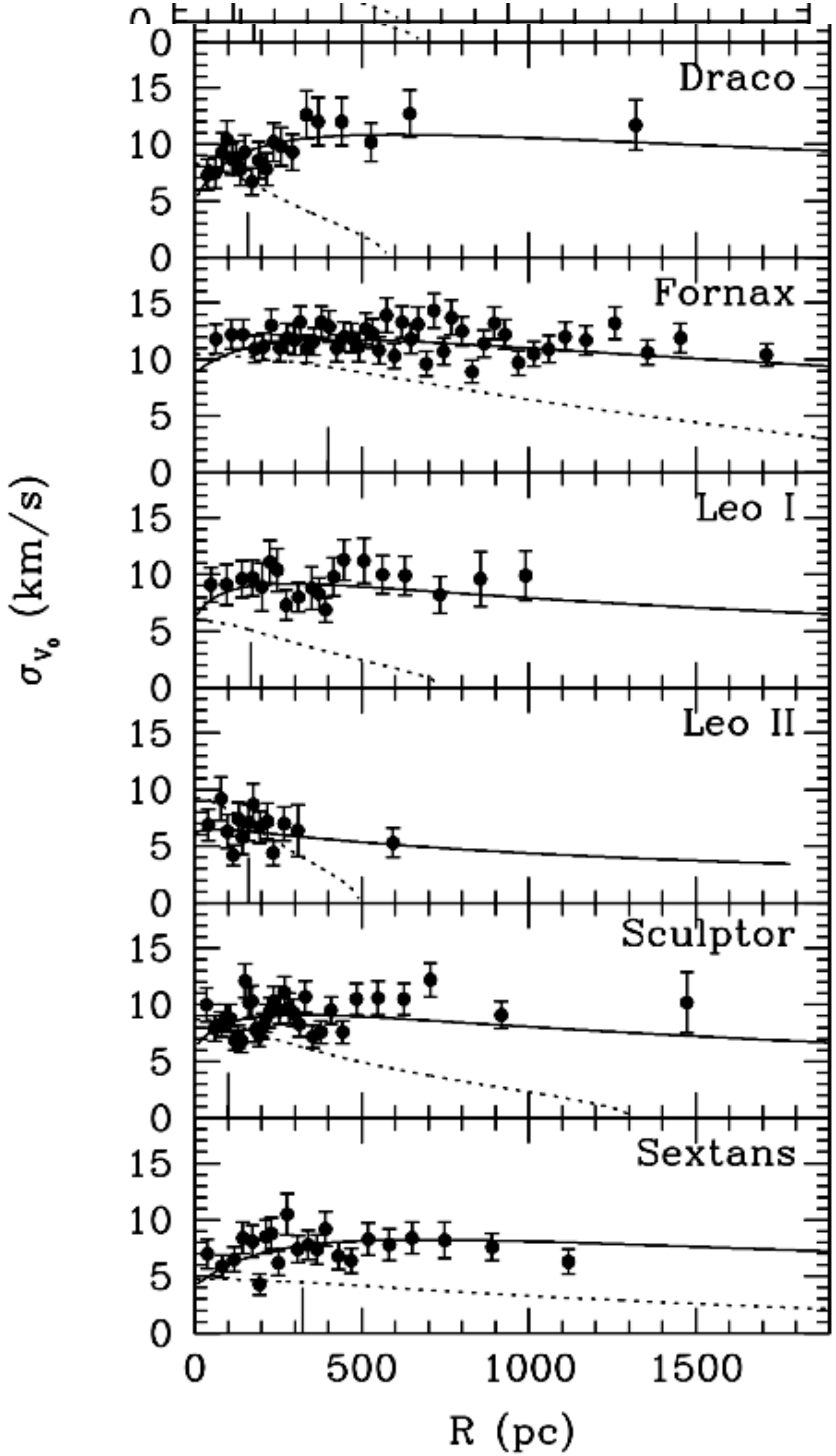


Figure 5. Evolution of the dark matter density profile over the 2Gyr of evolution for the control run with cooling, star formation and stellar feedback. We see the formation of a large core. We also show for comparison the analytical fit (dashed line) based on a pseudo-isothermal profile.

Romain Teyssier, Andrew Pontzen, Yohan Dubois and Justin I. Read 2013

Too Big To Fail

Is the structure of dwarf spheroidal galaxies consistent with the LCDM?

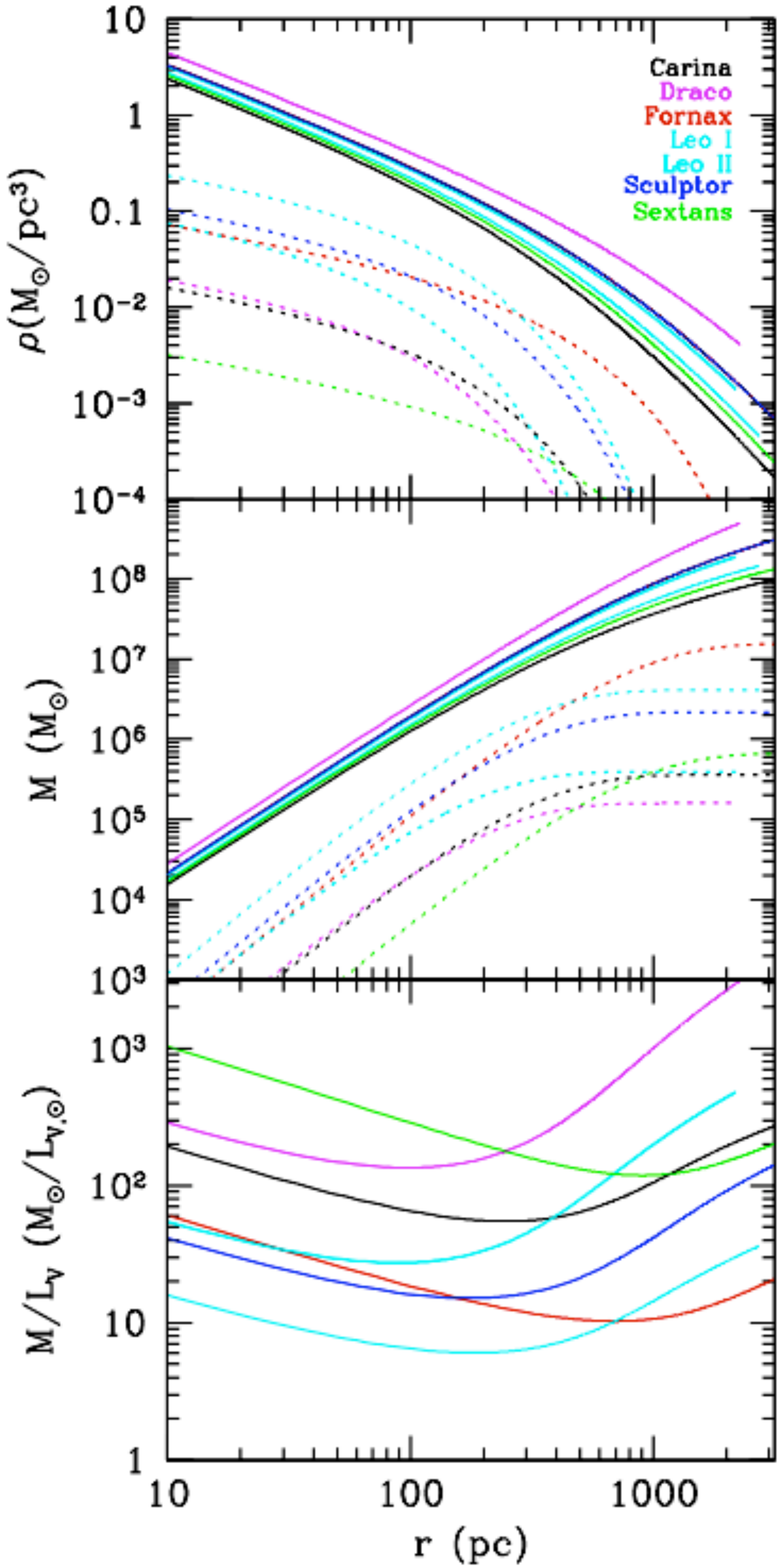


Projected velocity dispersion profiles for six Milky Way dSph satell
Overplotted are profiles corresponding to mass-follows light (King
1962) models (dashed lines; these fall to zero at the nominal "edge
stellar distribution), and best-fitting NFW profiles that assume cons
velocity anisotropy. Short, vertical lines indicate luminous core radi
Distance moduli are adopted from Mateo (1998)

Walker et al 20

Solid lines represent density, mass and M/L profiles corresponding to best-fitting NFW profiles.

Dotted lines in the top and middle panels are baryonic density and mass profiles, respectively, following from the assumption that the stellar component (assumed to have M/L=1) has exponentially falling density



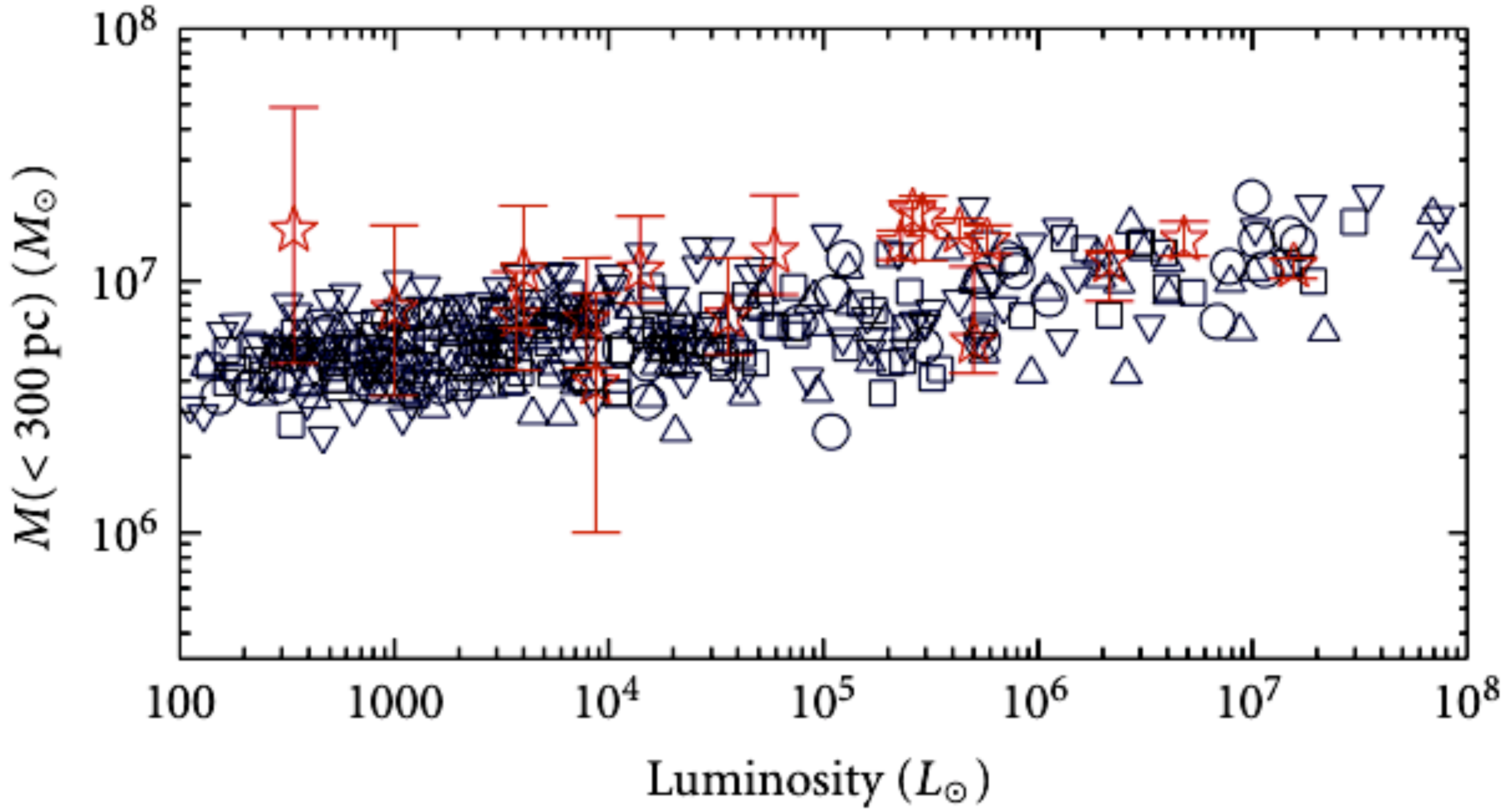


FIGURE 10: The mass within the central 300 pc versus luminosity for the dwarf satellites of the Milky Way (stars with error bars, see [88]). The open symbols of different types show the expected relation for subhalos in three different Milky Way-sized halos formed in the simulations of the concordance ΛCDM cosmology if the luminosity of the subhalos is related to their virial mass at accretion epoch as $L = 5 \times 10^3 L_\odot (M_{\rm vir,acc}/10^9 M_\odot)^{2.5}$ (see text for discussion).

Kravtsov 2009

Cusp or core

Accurate masses for dispersion-supported galaxies, J.Wolf et al MN, 406,1220, 2010

$$M_{1/2} \equiv M(r_{1/2}) \simeq 3G^{-1}\langle\sigma_{\rm los}^2\rangle\, r_{1/2},$$
$$\simeq 4G^{-1},\langle\sigma_{\rm los}^2\rangle R_{\rm e}\,,$$
$$\simeq 930\left(\frac{\langle\sigma_{\rm los}^2\rangle}{\rm km^2\,s^{-2}}\right)\left(\frac{R_{\rm e}}{\rm pc}\right)\,\mathrm{M}_\odot\,.$$

In the second line, we have used $R_{\rm e} \simeq (3/4)\,r_{1/2}$ for the two-dimensional (2D) projected half-light radius. This approximation is accurate to better than 2 per cent for exponential, Gaussian, King, Plummer and Sérsic profiles (see Appendix B for useful fitting formulae).

$$-n_\star\frac{{\rm d}\Phi}{{\rm d}r} = \frac{{\rm d}(n_\star\sigma_{\rm r}^2)}{{\rm d}r} + 2\frac{\beta\, n_\star\sigma_{\rm r}^2}{r}.$$

Here $\sigma_{\rm r}(r)$ is the radial velocity dispersion of the stars/tracers and $\beta(r) \equiv 1 - \sigma_{\rm t}^2/\sigma_{\rm r}^2$ is a measure of the velocity anisotropy, where the tangential velocity dispersion $\sigma_{\rm t} = \sigma_\theta = \sigma_\phi$. It is informative to rewrite the implied total mass profile as

$$M(r) = \frac{r\sigma_{\rm r}^2}{G}\,(\gamma_\star + \gamma_\sigma - 2\beta)\,, \qquad (9)$$

where $\gamma_\star \equiv -{\rm d}\ln n_\star/{\rm d}\ln r$ and $\gamma_\sigma \equiv -{\rm d}\ln\sigma_{\rm r}^2/{\rm d}\ln r$. Without the

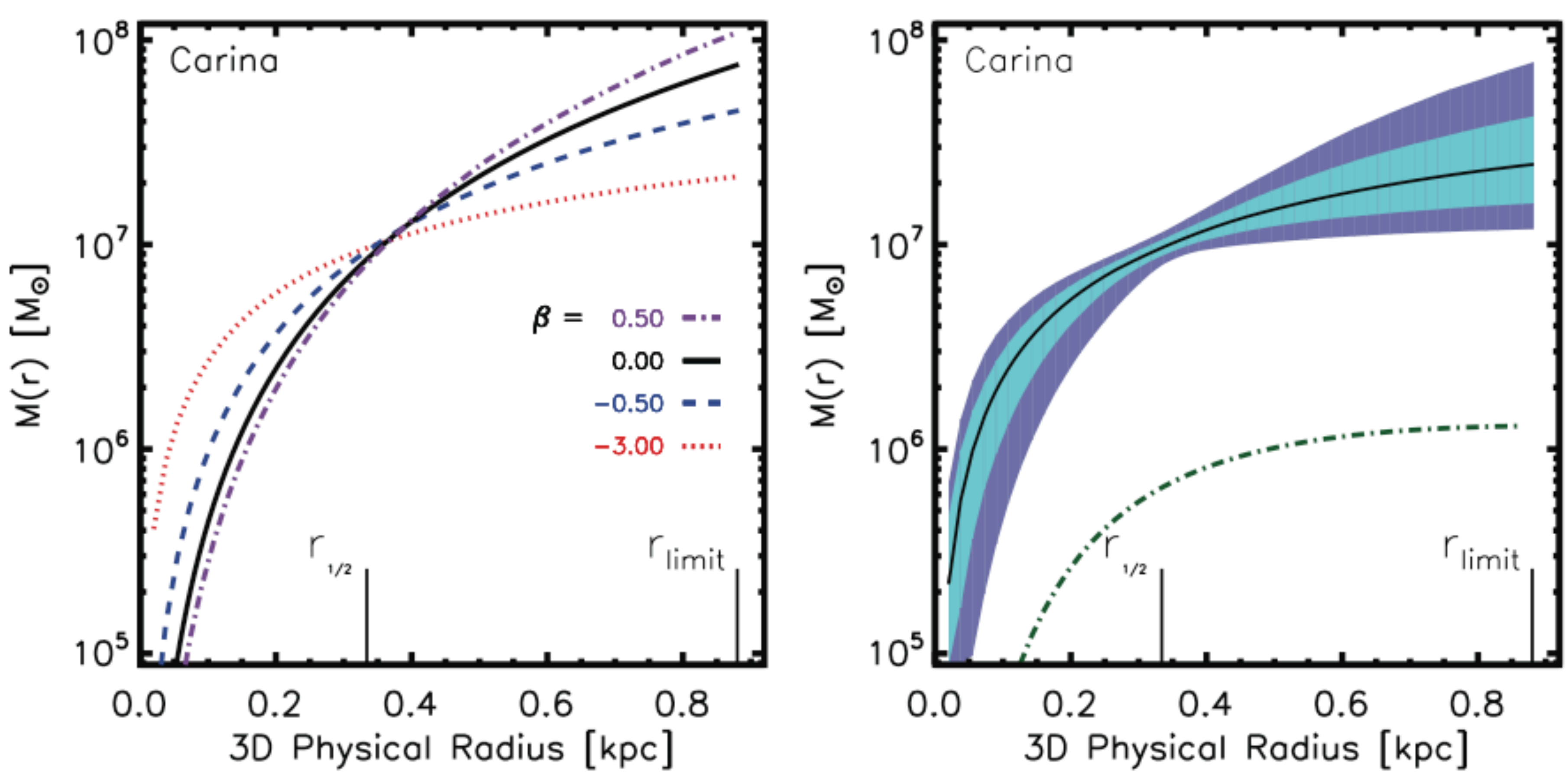


Figure 1. *Left:* the cumulative mass profile generated by analysing the Carina dSph using four different constant velocity dispersion anisotropies. The lines

M. Boylan-Kolchin, J. S. Bullock, and M. Kaplinghat ApJ 2012

Too Big To Fail

Is the structure of large dwarf spheroidal galaxies consistent with the LCDM?

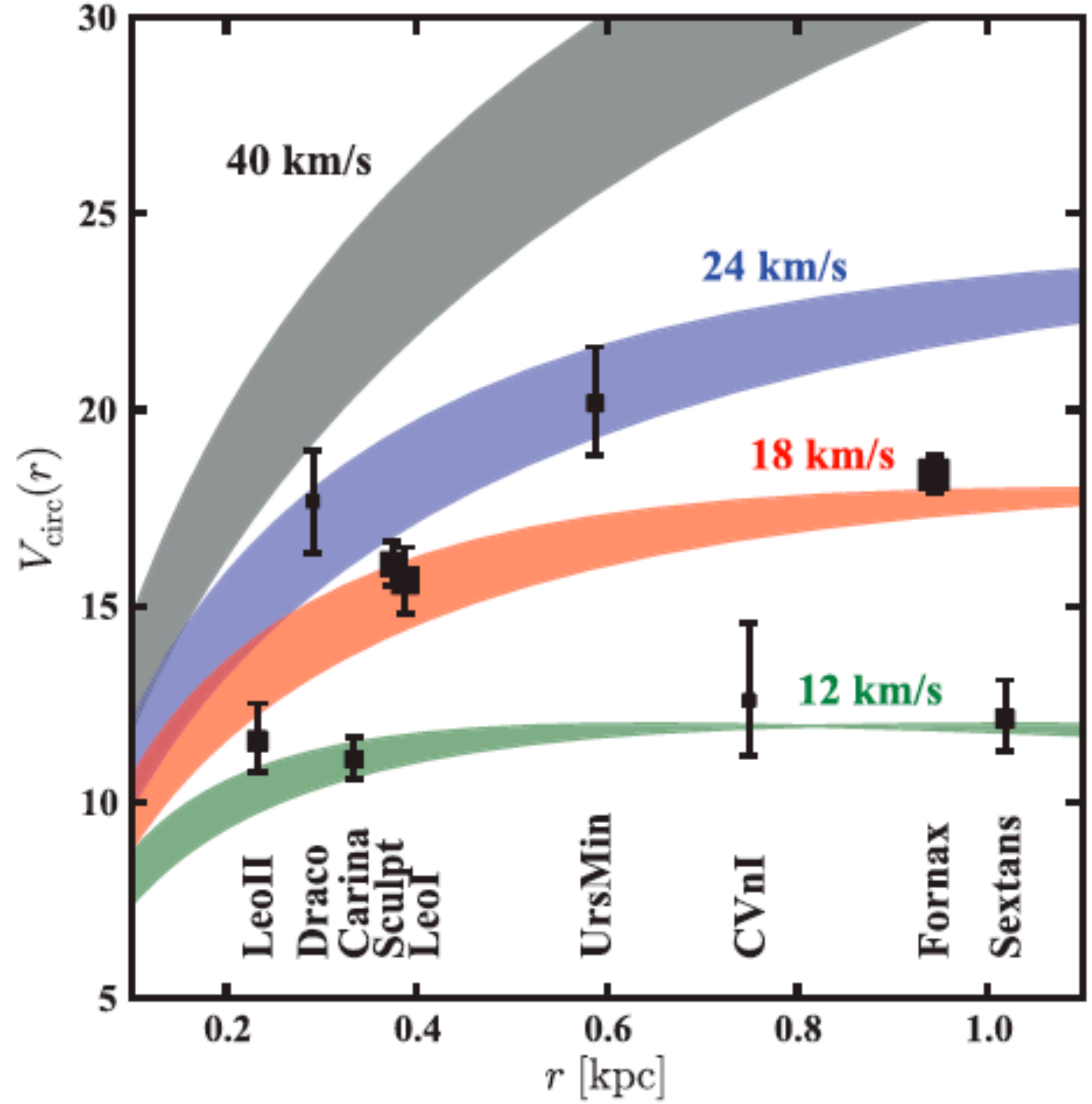
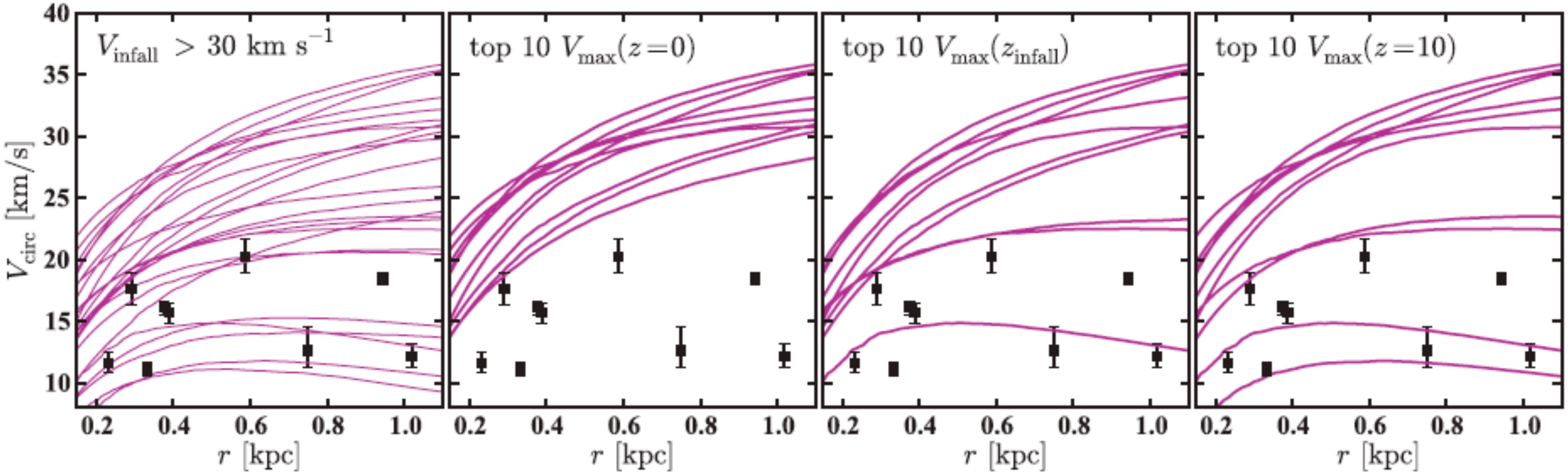


Figure 1. Observed $V_{\rm circ}$ values of the nine bright dSphs (symbols, with sizes proportional to log L_V), along with rotation curves corresponding to NFW subhaloes with $V_{\rm max} = (12, 18, 24, 40)\,{\rm km\,s^{-1}}$. The shading indicates the 1σ scatter in $r_{\rm max}$ at fixed $V_{\rm max}$ taken from the Aquarius simulations. All of the bright dSphs are consistent with subhaloes having $V_{\rm max} \leq 24\,{\rm km\,s^{-1}}$, and most require $V_{\rm max} \lesssim 18\,{\rm km\,s^{-1}}$. Only Draco, the least luminous dSph in our sample, is consistent (within 2σ) with a massive CDM subhalo of $\approx 40\,{\rm km\,s^{-1}}$ at $z = 0$.



Circular velocity profiles at redshift zero for subhaloes of the Aquarius halo ($M_{vir} = 1.4 \times 10^{12}$ M) that have $V_{infall} > 30$ km s^{-1} and $V_{max}(z = 0) > 10$ km s^{-1} (excluding Magellanic Clouds candidates).

Measured $V_{circ}(r1/2)$ values for the MW dSphs are plotted as data points with error bars. Each subsequent panel shows redshift-zero rotation curves for subhaloes from the left-hand panel with the 10 highest values of $V_{max}(z = 0)$ (second panel), V_{infall} (third panel) or $V_{max}(z = 10)$ (fourth panel). In none of the three scenarios are the most massive subhaloes dynamically consistent with the bright MW dSphs: there are always several subhaloes more massive than all of the MW dSphs. (Analogous results are found for the other four haloes.)

Arraki etal 2013: Effects of removal of baryons

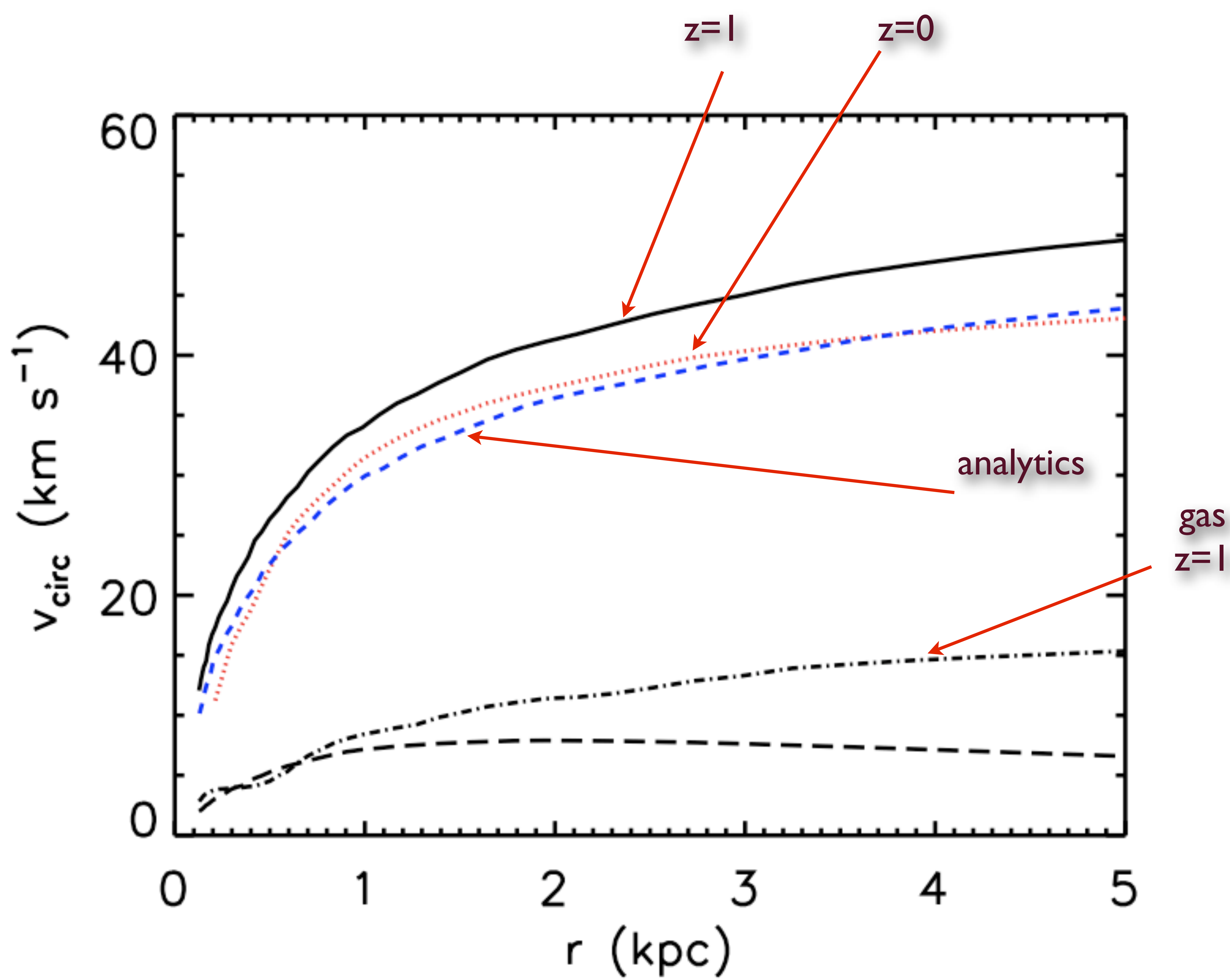
- Cosmological hydro simulations with and without baryons removal
- Evolution of isolated NFW halo with baryons removed:
    - slow
    - fast
- Evolution of NFW satellite as it orbits around the Milky Way

Effects of removal of baryons

- Cosmological N-body simulations are wrong because baryons are assumed to follow dark matter, which is not a good approximation for dwarf spheroidals

  - There is not much of baryons (stars, gas) at present in dSphs
  - Significant gas mass should have been removed by ram pressure when dIrr (progenitor of dSph) fell into halo of its parent
  - This removal of 20% of mass resulted in expansion of dark matter

hydro simulation: testing analytics



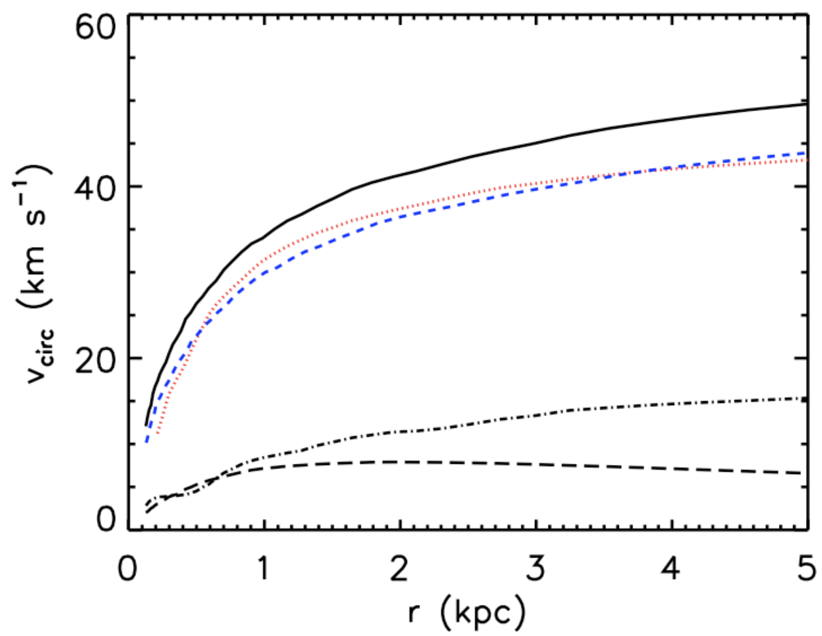
Simple analytics

$$V_{\rm circ} = \sqrt{GM(r)/r}$$

conservation of angular momentum:

$$r_{\rm f} = \frac{r_{\rm i}}{\alpha(r_{\rm i})},$$

$$V_f(r_{\rm f}) = \alpha(r_{\rm i})\, V_i(r_{\rm i}) = \alpha(\alpha\, r_{\rm f})\, V_i(\alpha\, r_{\rm f}).$$



$\alpha(r_{\rm i})$ is the fraction of mass that remains inside $r_{\rm i}$ after the removal

$$\rho(r) = \rho_0 \Psi\left(\frac{r}{r_0}\right) \qquad \rho_{0,\mathrm{f}} = \alpha_0^4\, \rho_{0,\mathrm{i}}, \quad r_{0,\mathrm{f}} = \frac{r_{0,\mathrm{i}}}{\alpha_0}$$

$1 - f_b \approx 0.8$, which leads to a drop in density of $\rho_{0,\mathrm{f}}/\rho_{0,\mathrm{i}} \approx 0.4$

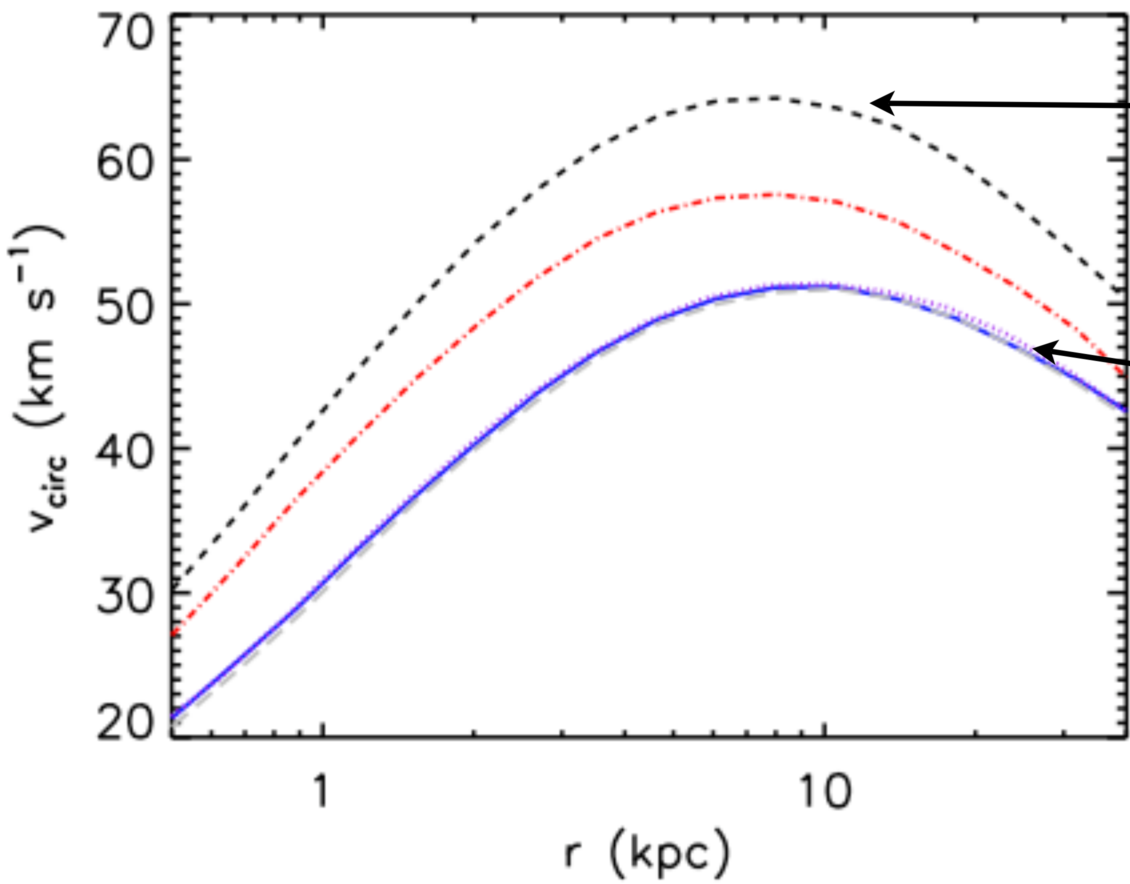
$$\frac{\rho_\mathrm{f}(r)}{\rho_\mathrm{i}(r)} = \alpha_0^4 \frac{\Psi\left(\frac{r}{r_{0,\mathrm{f}}}\right)}{\Psi\left(\frac{r}{\alpha_0 r_{0,\mathrm{f}}}\right)}.$$

If the function Ψ is the power law $\Psi \propto x^{-\beta}$, then

$$\frac{\rho_\mathrm{f}(r)}{\rho_\mathrm{i}(r)} = \alpha_0^{4-\beta}.$$

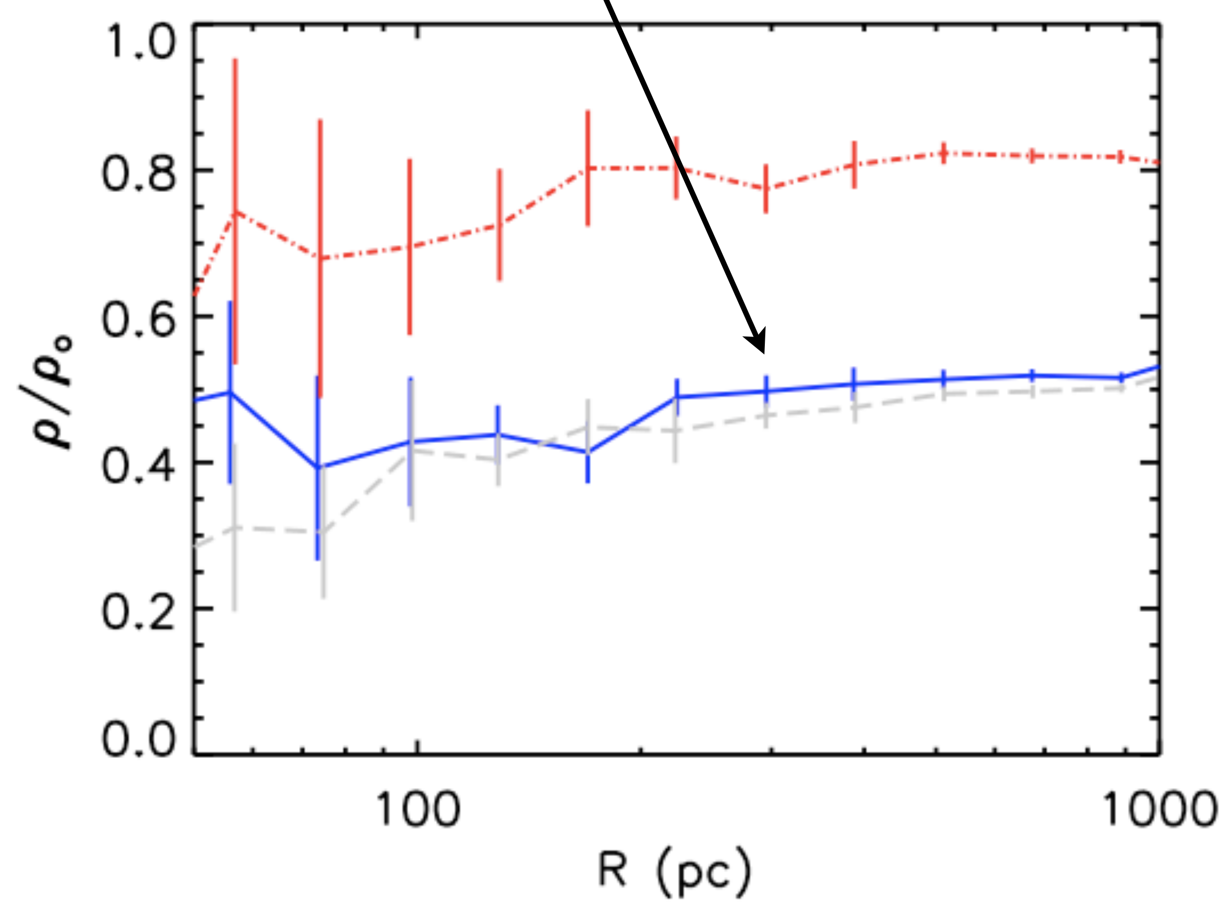
For the NFW profile, the central cusp has slope $\beta = 1$ and the density declines by large factor $\rho_\mathrm{f}/\rho_\mathrm{i} = \alpha_0^3 \approx 0.5$, again assuming that $\alpha_0 \approx 0.8$. The change in the outer region is much smaller as $\beta = 3$, so $\rho_\mathrm{f}/\rho_\mathrm{i} = \alpha_0 \approx 0.8$. It is interesting to note that a density profile with a central core ($\beta = 0$) experiences the largest decline in density, $\rho_\mathrm{f}/\rho_\mathrm{i} = \alpha_0^4$.

K. Arraki et al ApJ 2012



NFW profile of normal satellite in N-body simulations
Baryons are locked with dark matter

DM profile once baryons are removed

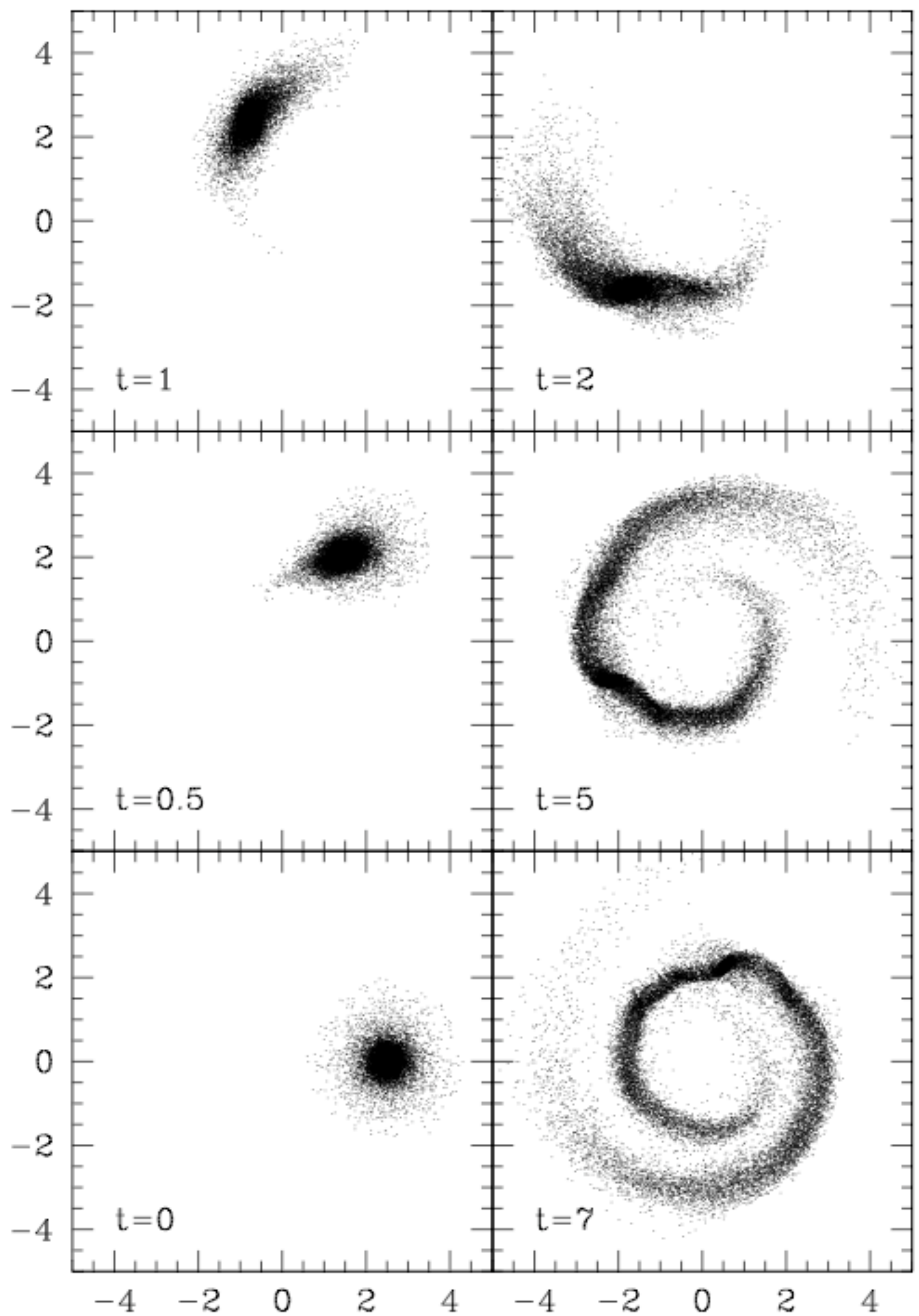


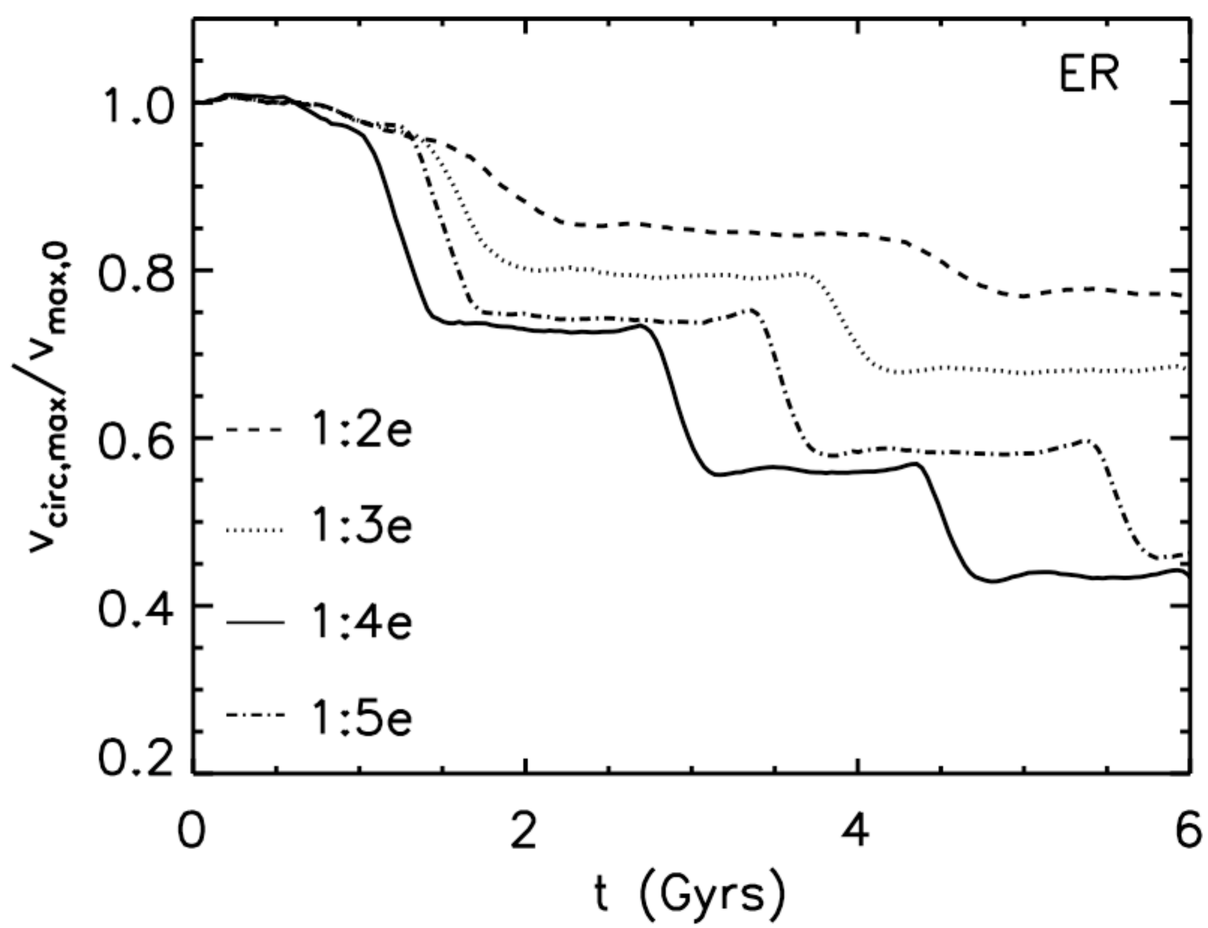
Removal of a small fraction of mass (20%) from isolated NFW cuspy profile:

Fast or slow give the same result
Analytics works very well

K. Arraki et al ApJ 2012

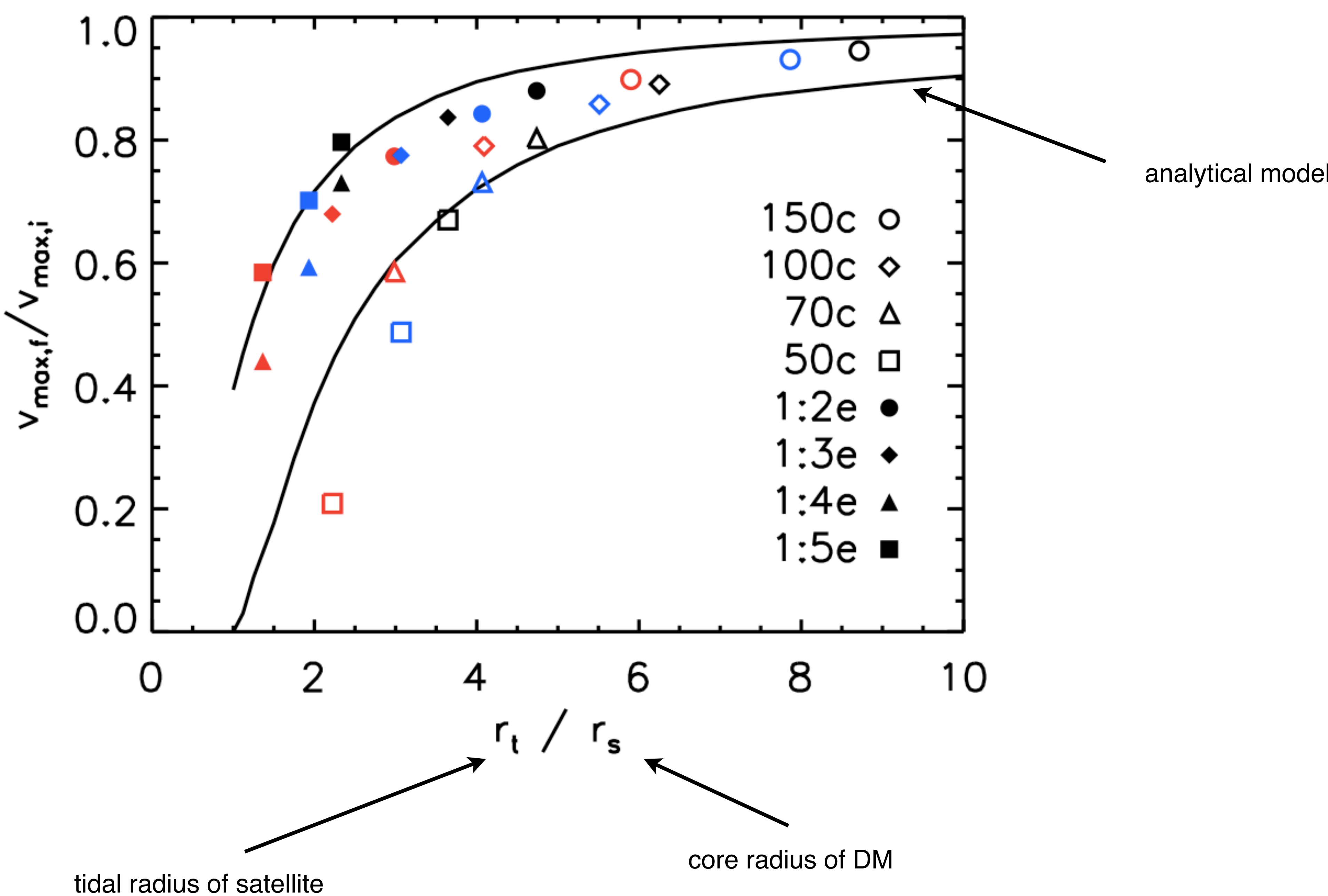
Tidal stripping of satellite orbiting Milky Way

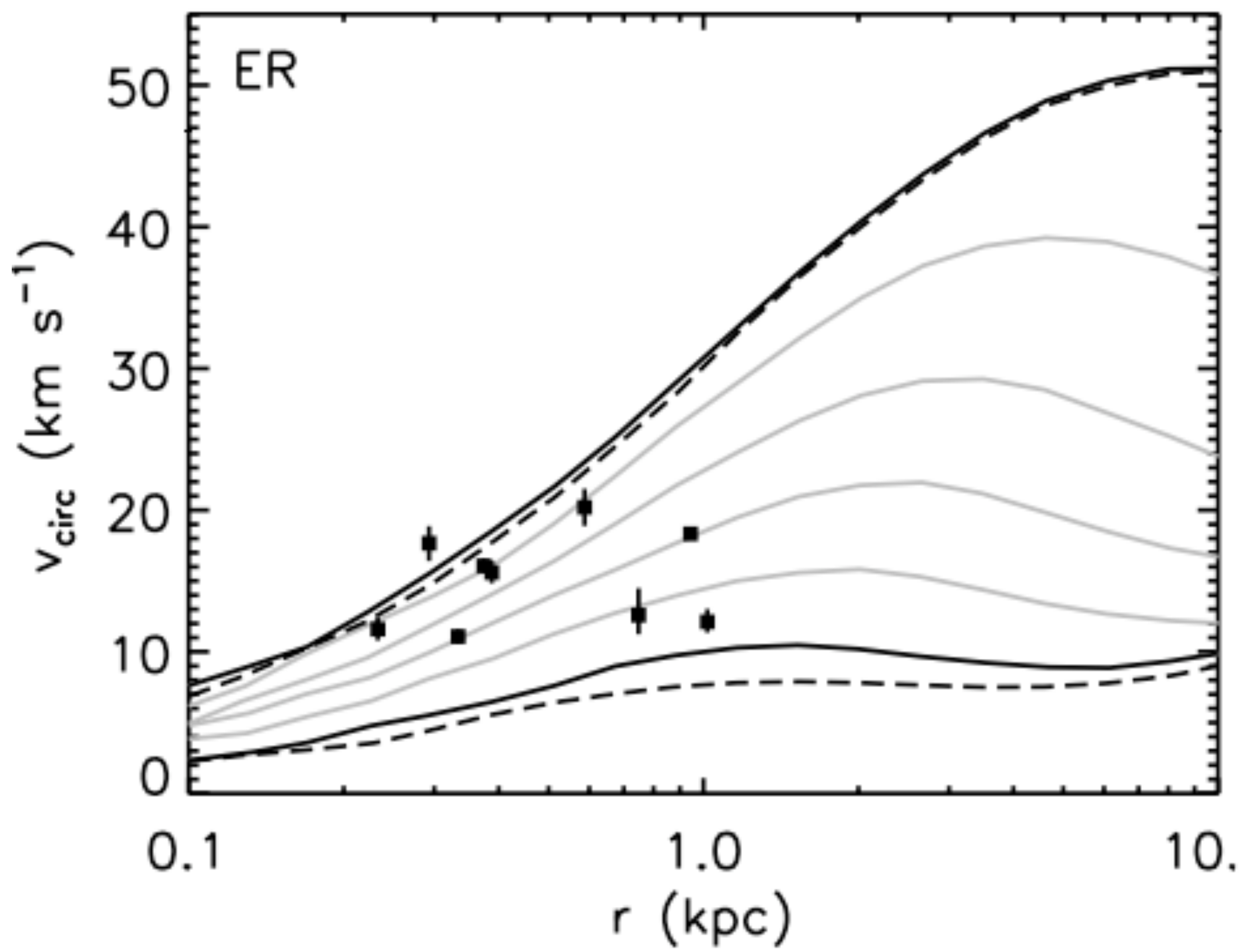




Tidal stripping of satellite orbiting Milky Way

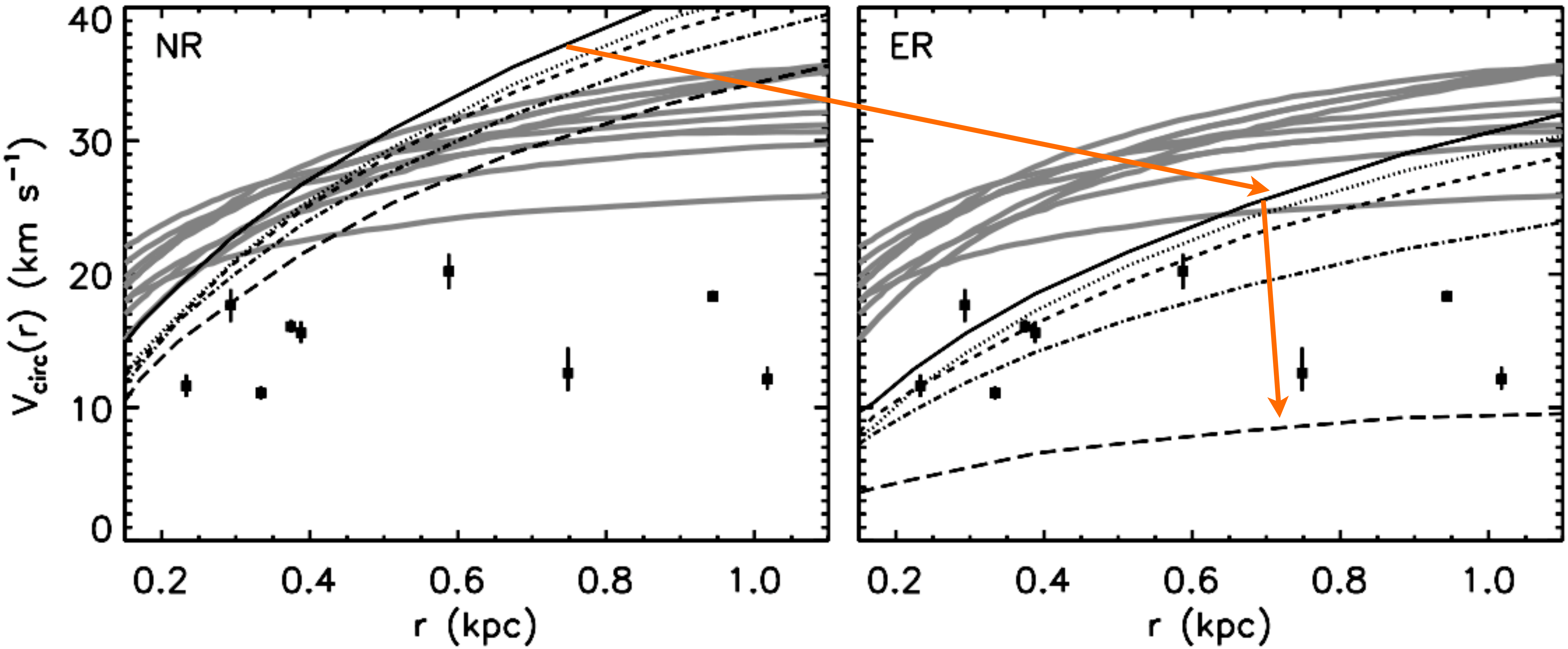
Once tidal radius is less than 2 core radii of the density profile, results are very sensitive to small changes in parameters.





Enhanced tidal stripping

- removal of gas from a dwarf makes it more vulnerable for tides
- infall of baryons to the primary makes tides stronger



Comparison of circular orbits to observations of the MW satellites (black squares) and the Aquarius E halo's "massive failures" from the analysis of Boylan-Kolchin et al. (2012) (thick grey lines). Left: The circular velocity profiles of the no mass removal case (NR). This profile does not agree with the MW dSph population and was created to mimic the Aquarius cosmological simulations. Right: The circular velocity profiles of the exponential mass removal case (ER). These profiles span a much larger range of parameter space and are in agreement with observed MW dwarfs due to their inclusion of baryonic effects. Both panels show the initial isolated profile as a solid black line. The circular orbits after 5 Gyrs of evolution are shown from top to bottom as:

150 kpc (dotted), 100 kpc (short-dashed), 70 kpc (dash-dotted), and 50 kpc (long-dashed).

K. Arraki et al ApJ 2012

Scenario for evolution of dSph

- Dwarf irregular galaxy at high redshifts
  - depending on mass, re-inization may be important or not
  - if mass is large enough and star formation is bursty, core forms
  - fraction of mass in gas is ~cosmological

- Transition stage: gas is removed by ram pressure
  - disk tumbles, angular momentum is lost, heating
  - can the stripping happen outside of parent galaxy? Filament
  - dark matter expands in the central region

- Stripping of satellite as it orbits inside 'parent'
  - very dependent on ellipticity and initial moment (radius)
  - some DM satellites are totally destroyed - not a bit survives.