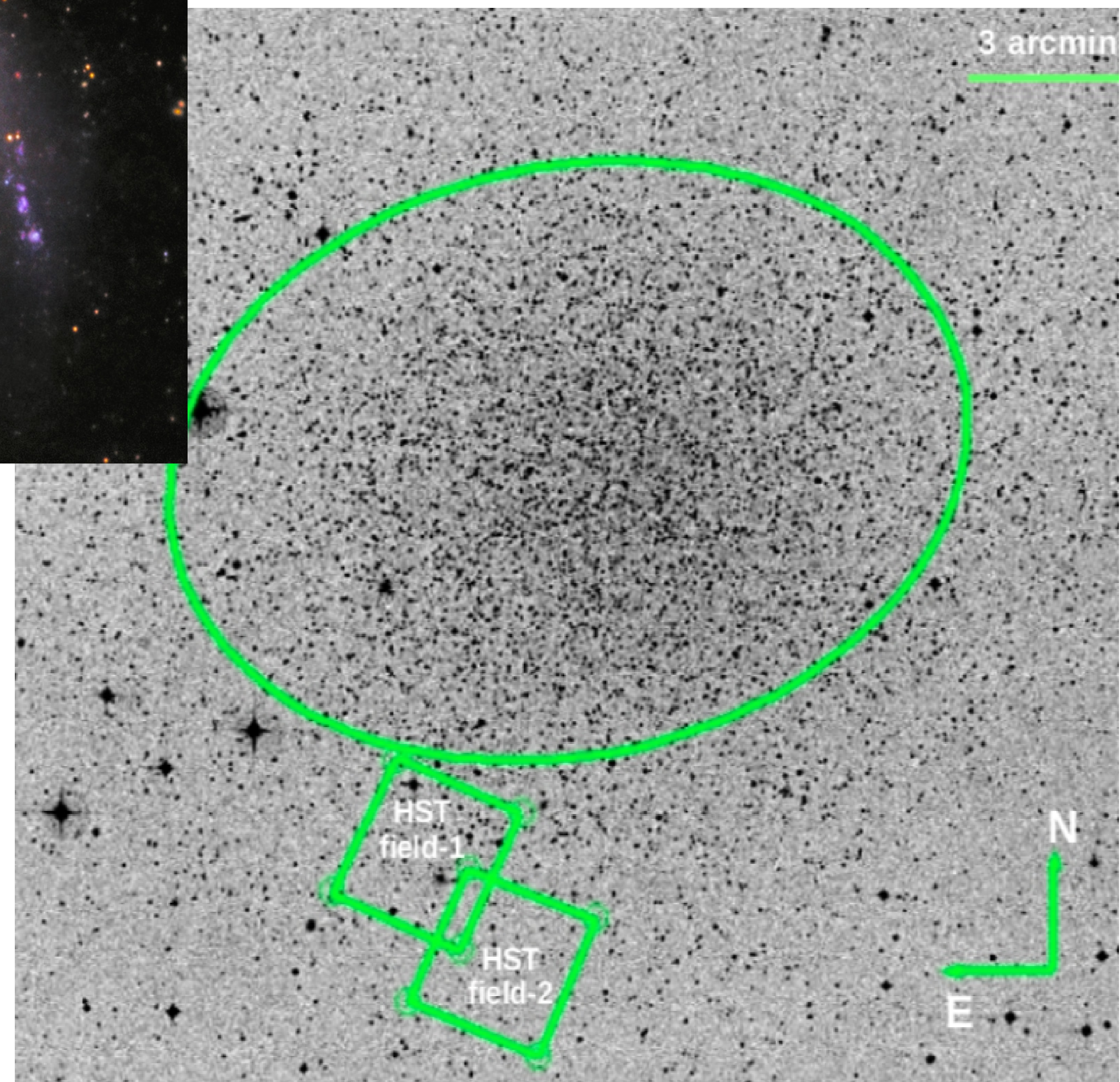
Geneva,
February 2018

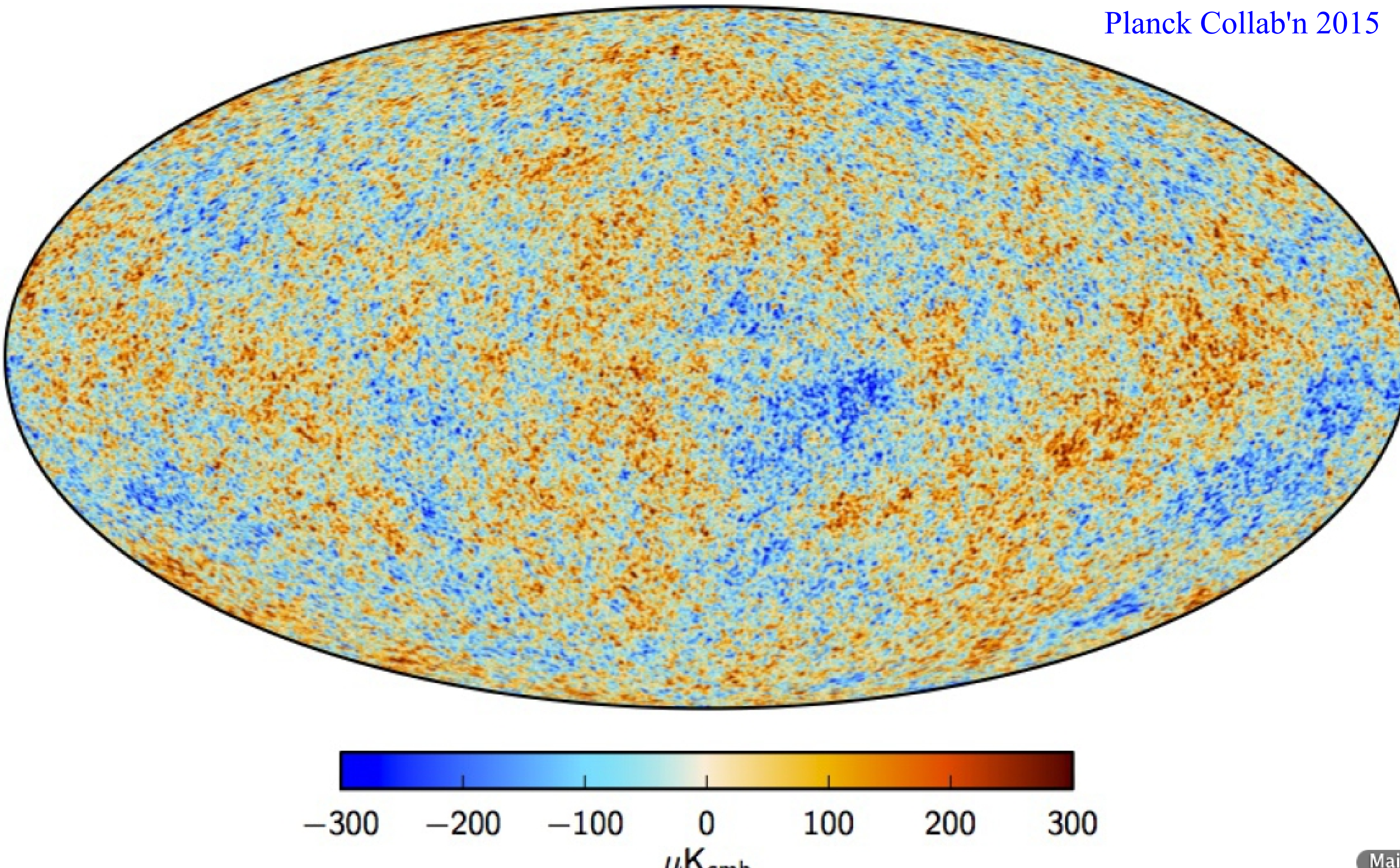


Cores or cusps in dwarf galaxies?

Simon White
Max Planck Institute for Astrophysics

CMB map from the full *Planck* mission

Planck Collab'n 2015



The six parameters of the base ΛCDM model

Planck Collab'n 2015

Parameter	TT+lowP 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04077 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.079 ± 0.017	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.094 ± 0.034	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049	0.9667 ± 0.0040

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80σ detection of nonbaryonic DM using *only* z ~1000 data!

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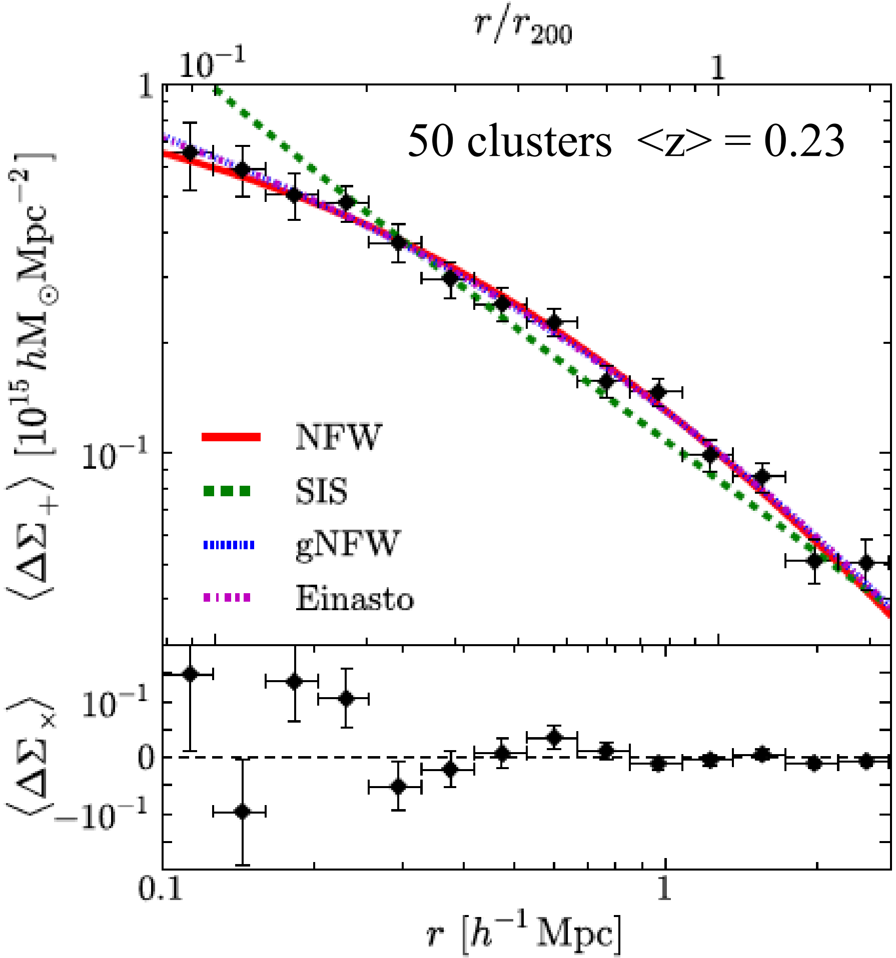
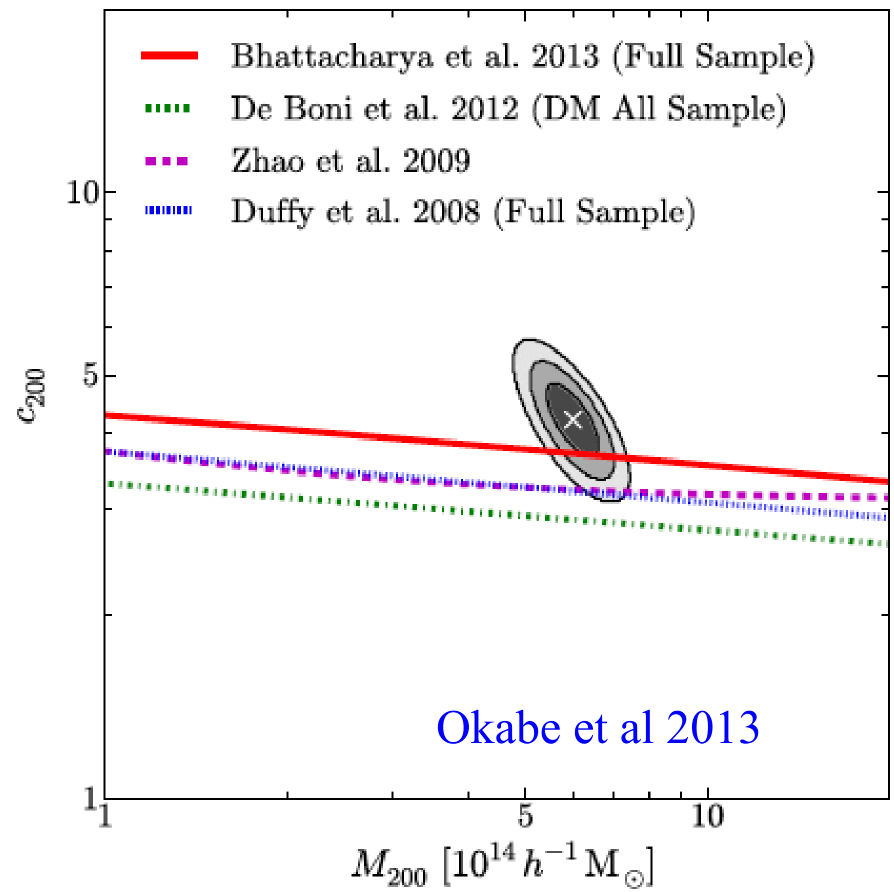
Total baryon density measured to 1%

80σ detection of nonbaryonic DM using *only* z ~1000 data!

The mass profiles of massive galaxy clusters

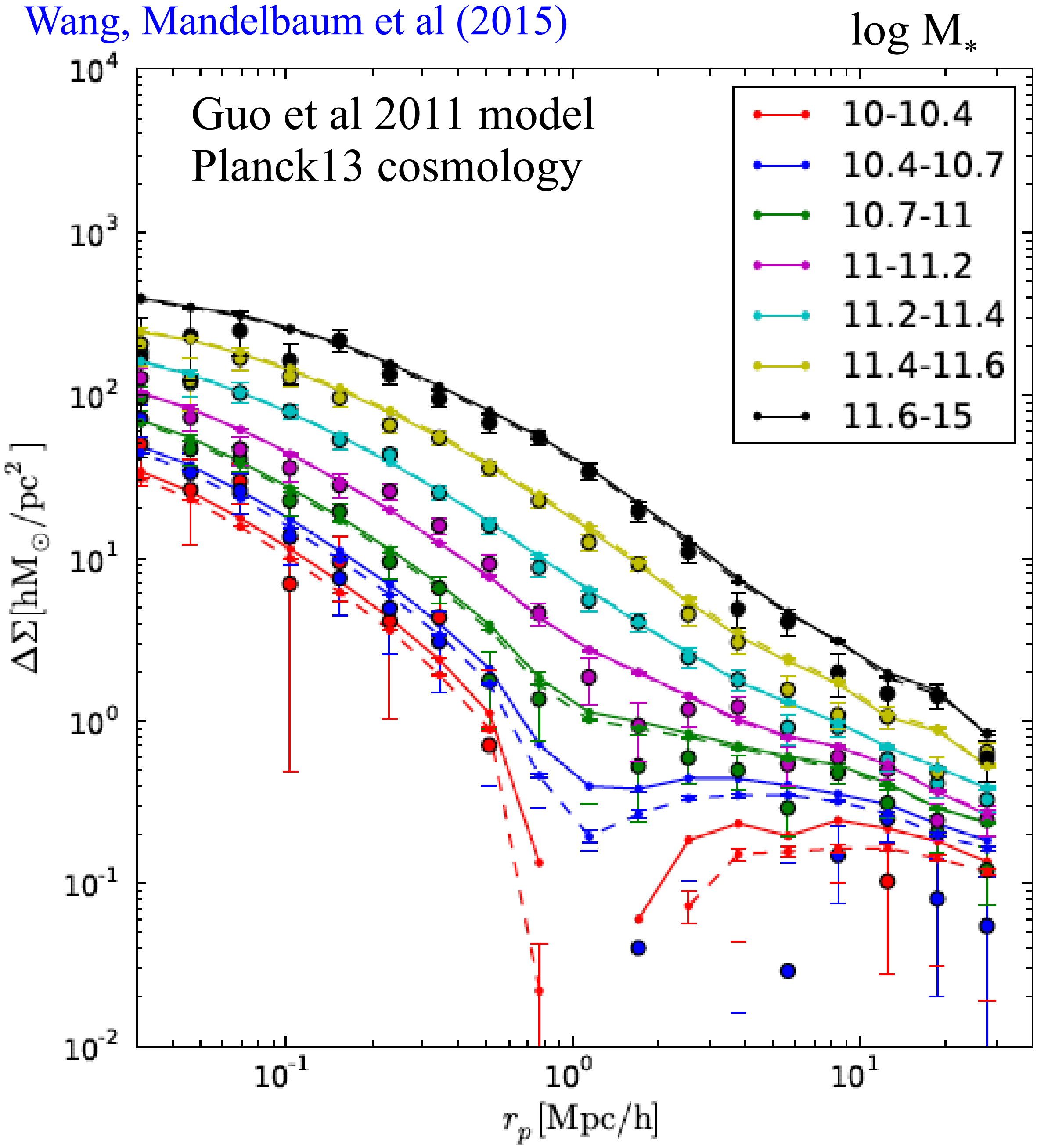




- The mean density profile of rich clusters has the predicted ΛCDM shape
- This is effectively a one-parameter fit (the mean cluster mass)

Stacked weak lensing profiles for LBG's

Wang, Mandelbaum et al (2015)



LBG's are SDSS/DR7 galaxies brighter than any neighbor with $\Delta r_p <$ 1 Mpc, $\Delta v <$ 1000 km/s

These are predominantly (>83%) centred in their halos

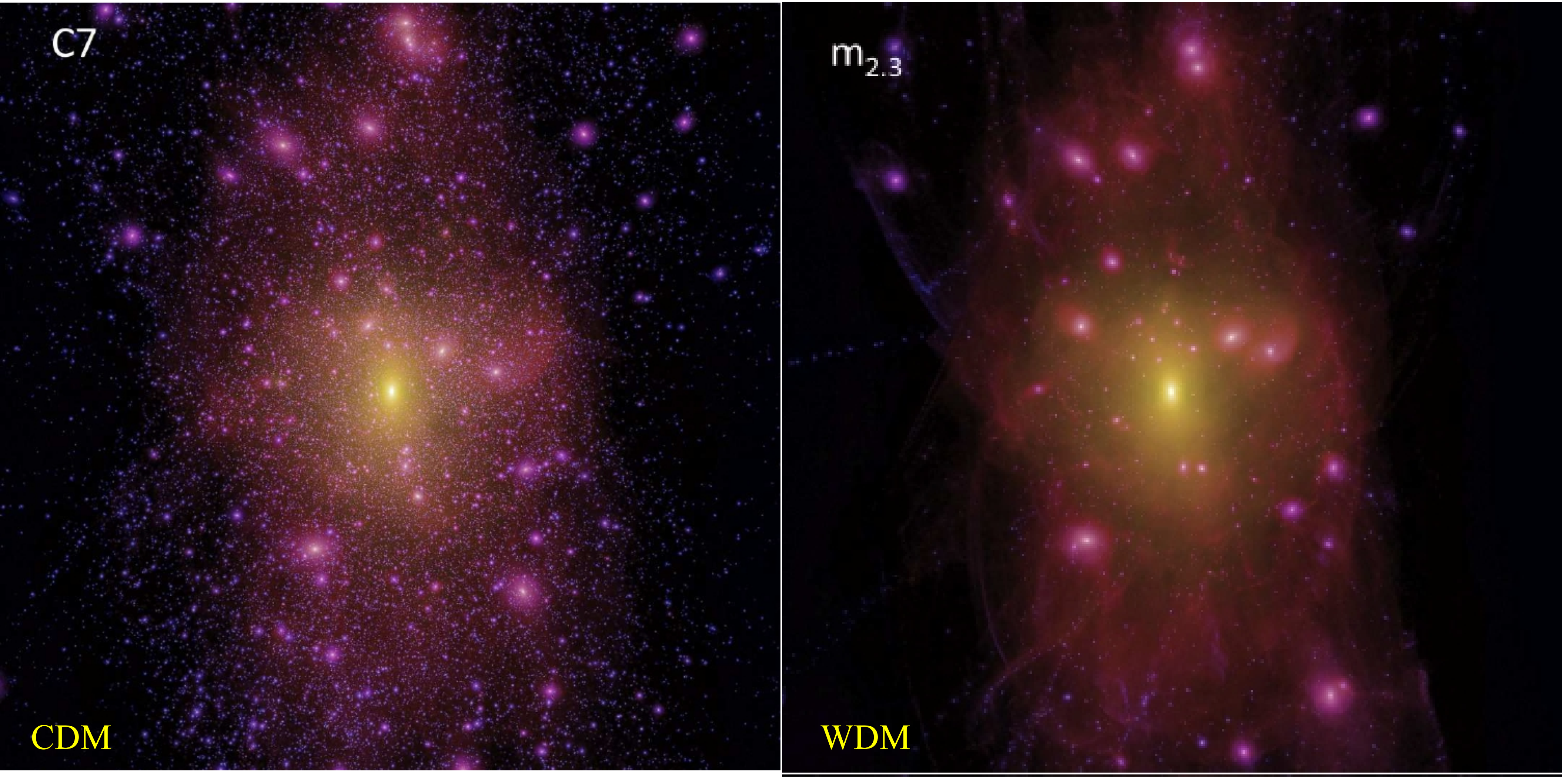
Symbols are observed results stacked in bins of log M_*

Predictions are from a simulation in Planck cosmology tuned to fit the observed stellar mass function

No parameters were adjusted to fit the lensing data

Dark matter effects on galaxy formation?

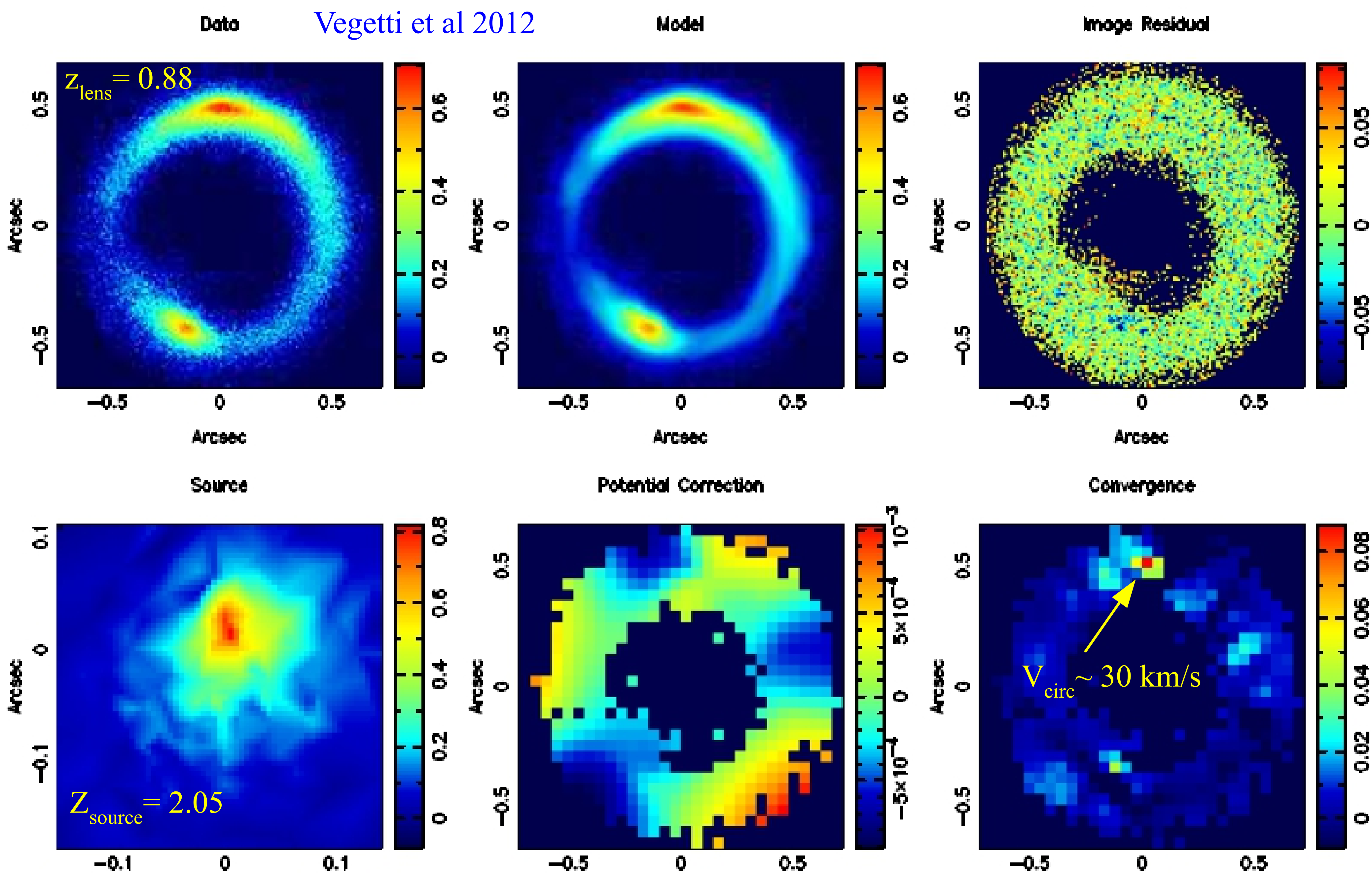
Lovell et al 2014.



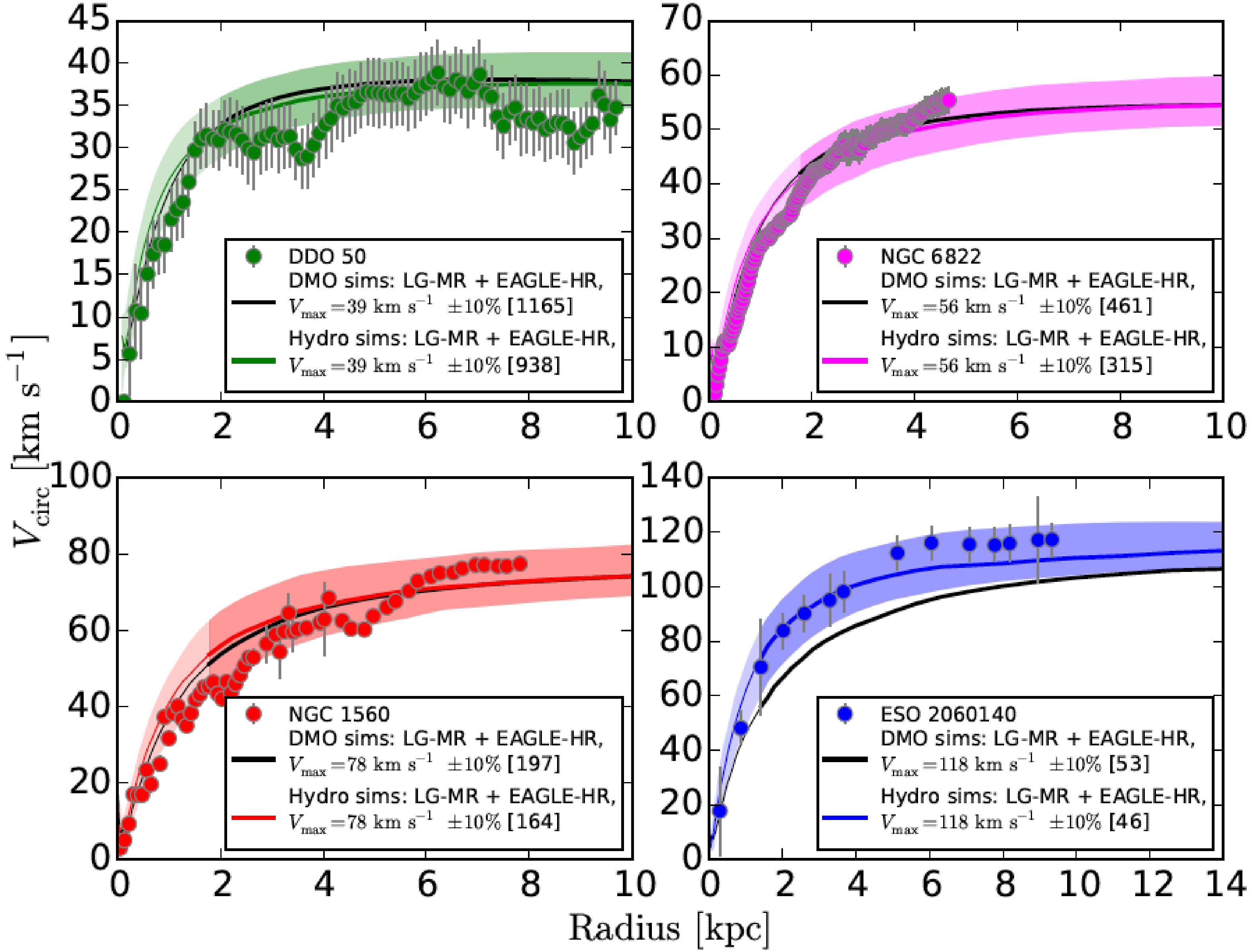
"Milky Way" halos in CDM and WDM. Note, the Ly α forest 2σ lower limit gives a limiting halo mass 6.5 times *smaller* than assumed here.

→ real IC's are ~ΛCDM on essentially all scales relevant to galaxies

Detecting substructures with no stars...

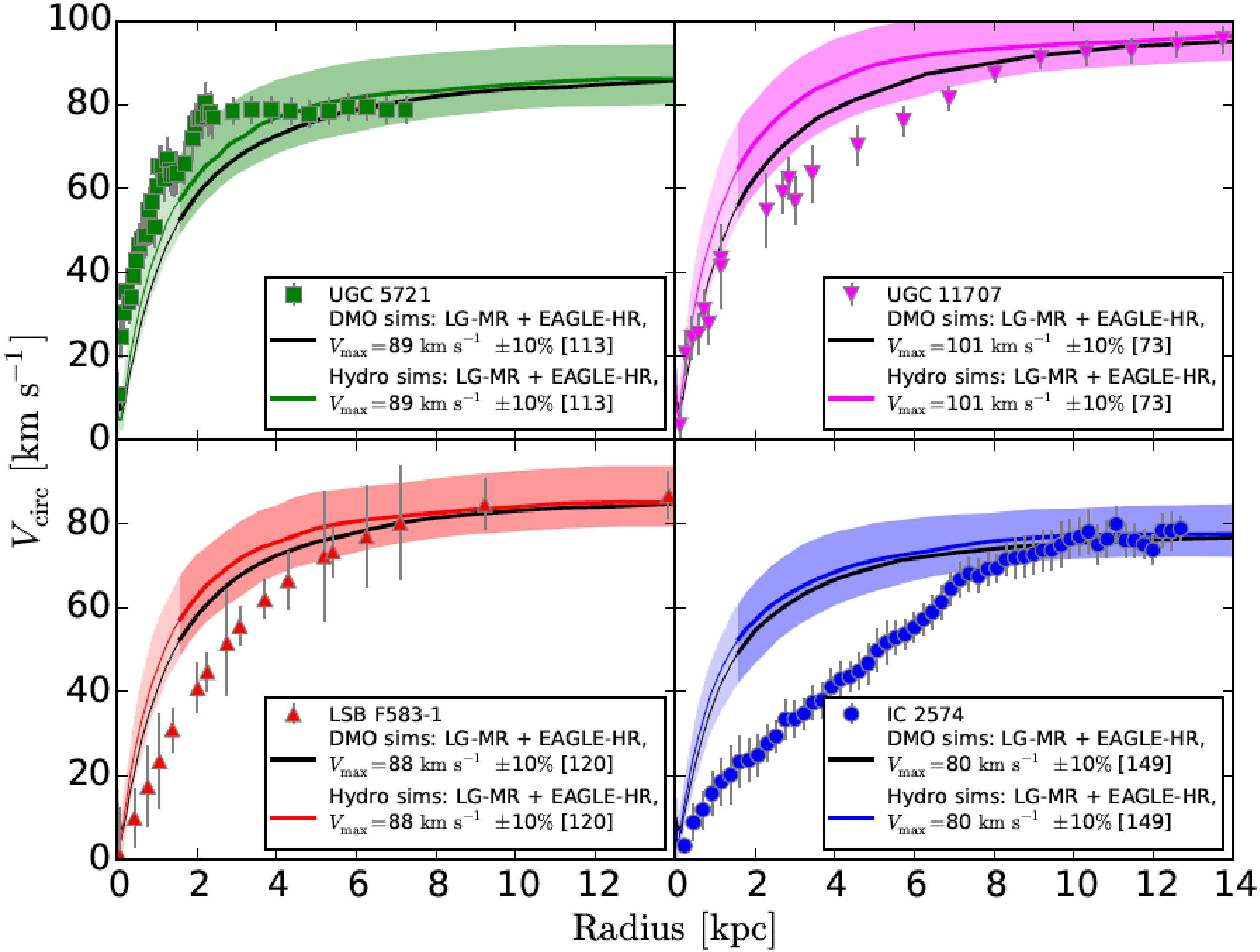


Dwarf galaxy rotation curves: cusps vs cores



Many dwarf galaxies have rotation curves that fit ΛCDM predictions well

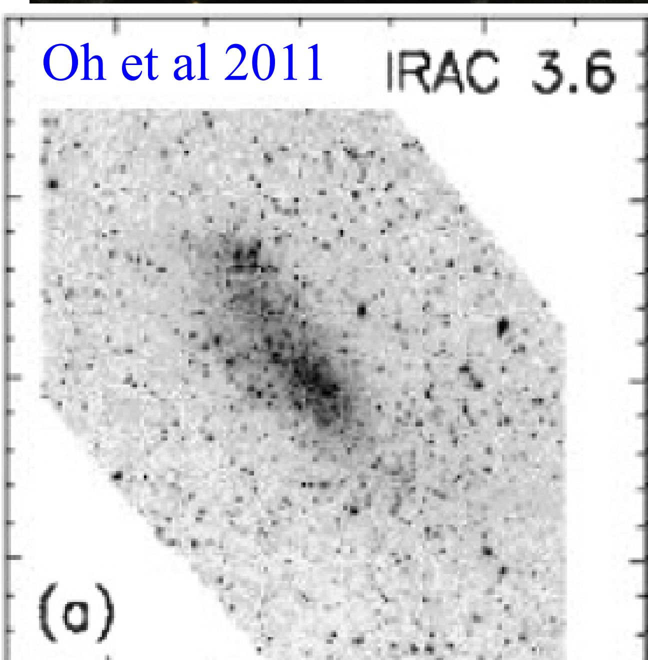
Dwarf galaxy rotation curves: cusps vs cores

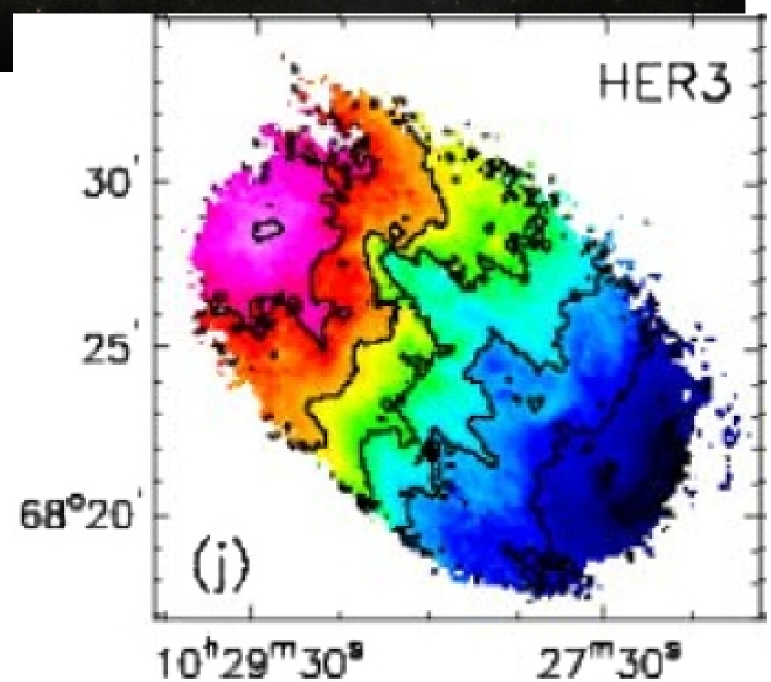


Many others fail dramatically to fit ΛCDM predictions.

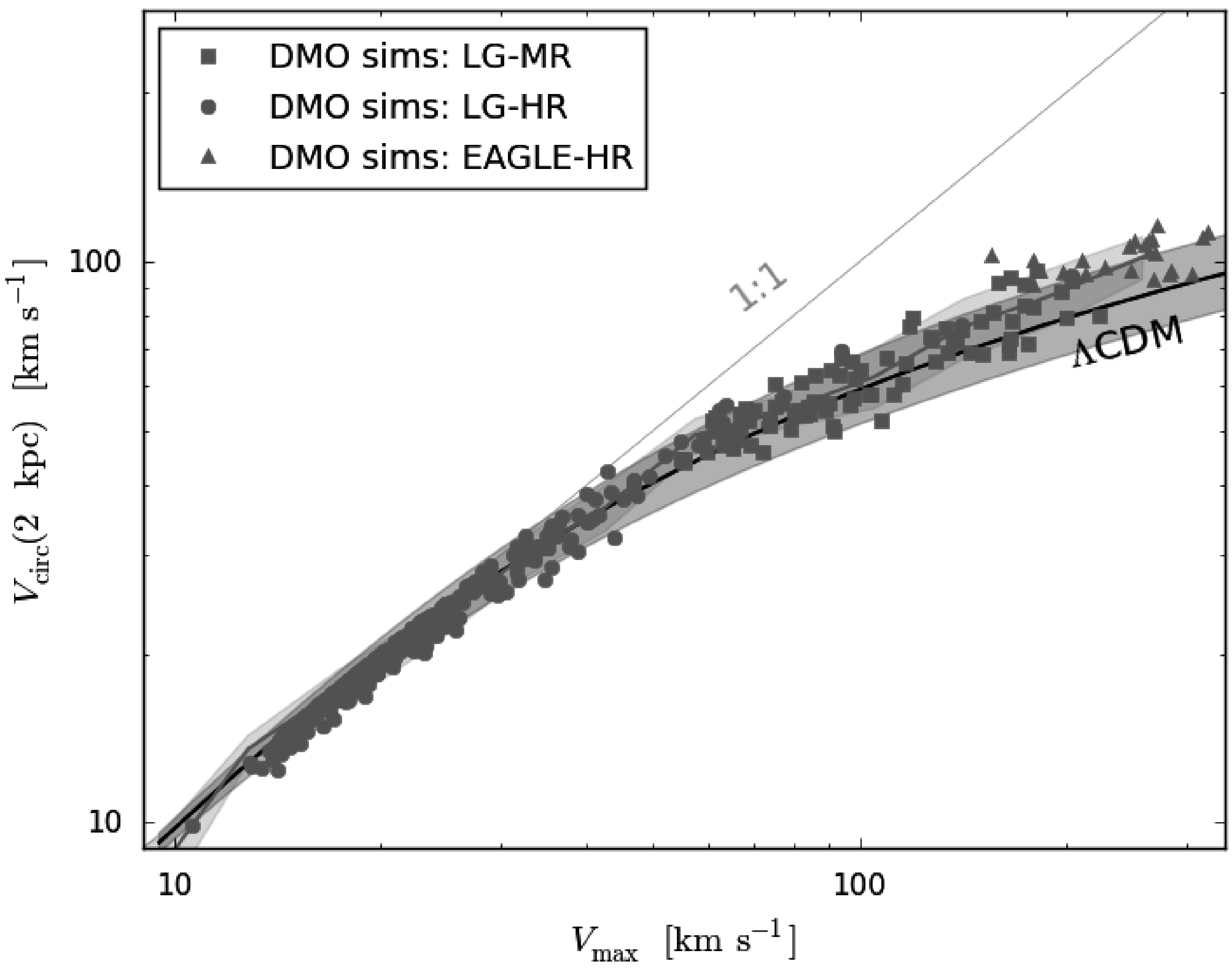
“Cores” from: (i) DM properties? (ii) Baryon effects? (iii) Incorrect modelling?


IC 2574


Oh et al 2011
IRAC 3.6
(a)

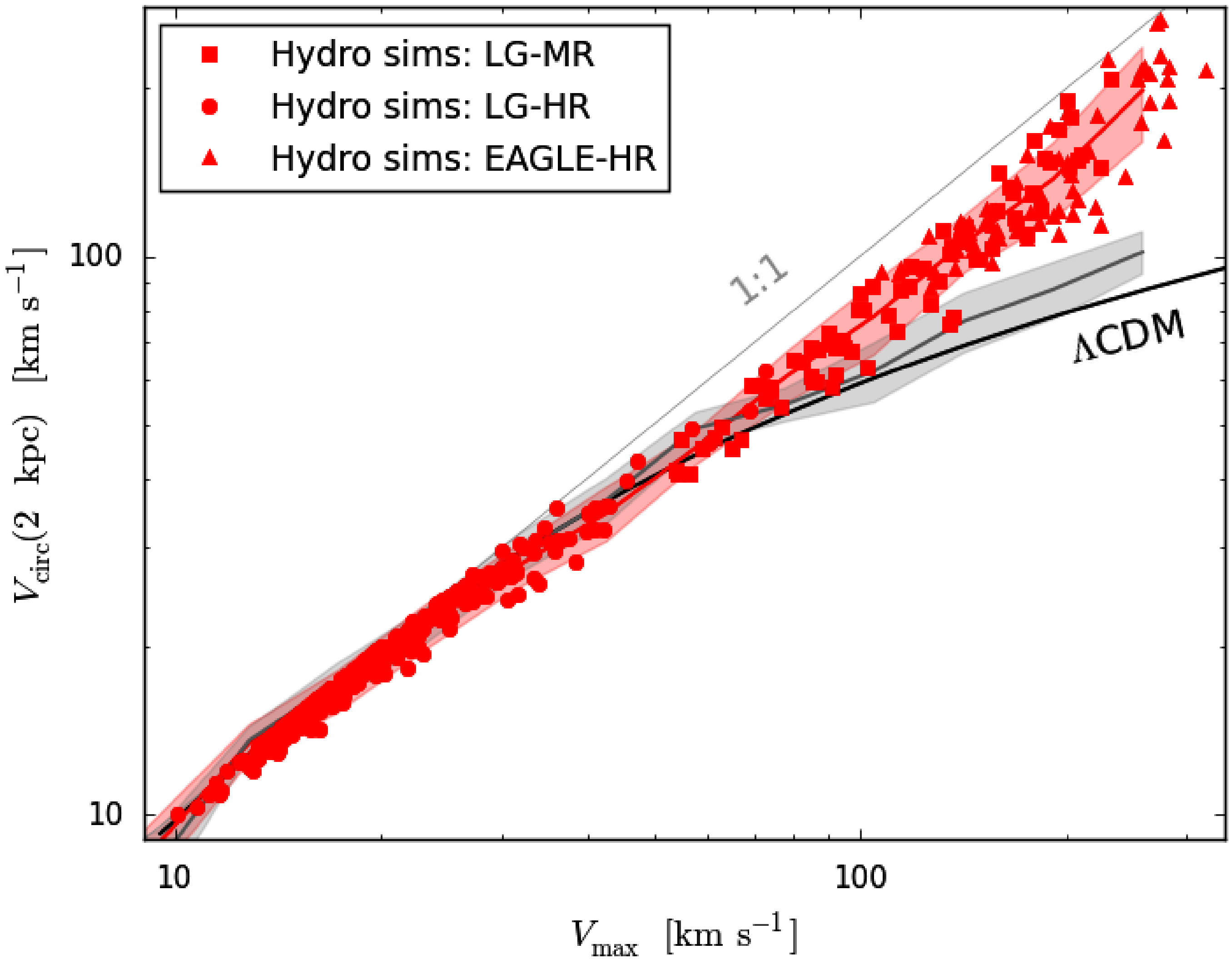

HER3
30'
25'
68°20'
(j)
10h29m30s
27m30s

V_{circ}(2 kpc) versus V_{max} for ΛCDM halos



Oman et al 2015

V_{circ}(2 kpc) versus V_{max} for ΛCDM galaxies



Oman et al 2015

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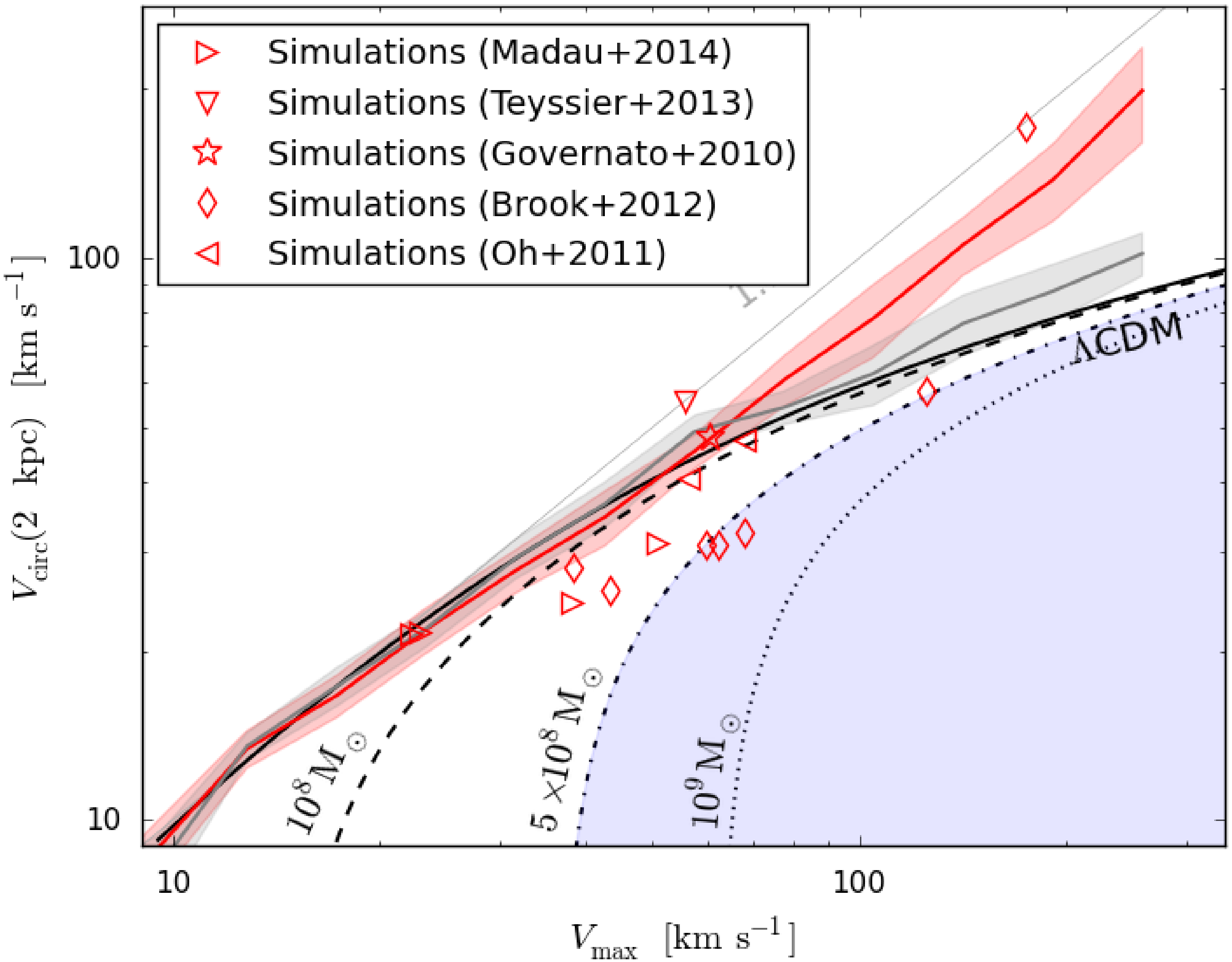
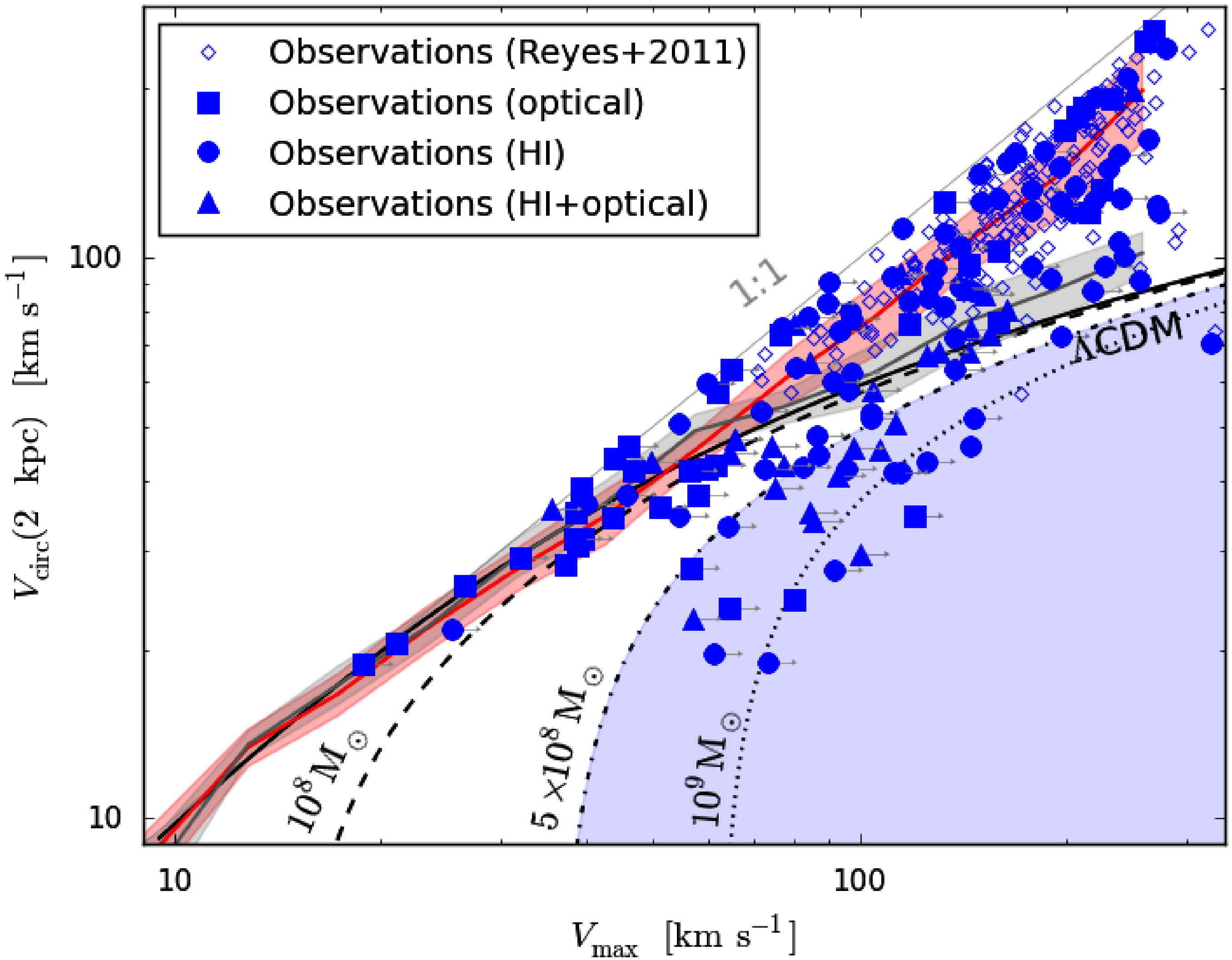


Simulations with high SF thresholds and strong feedback → cusps expand into cores

Oman et al 2015

V_{circ}(2 kpc) versus V_{max} for observed dwarfs



Enormous apparent <u>diversity:</u>

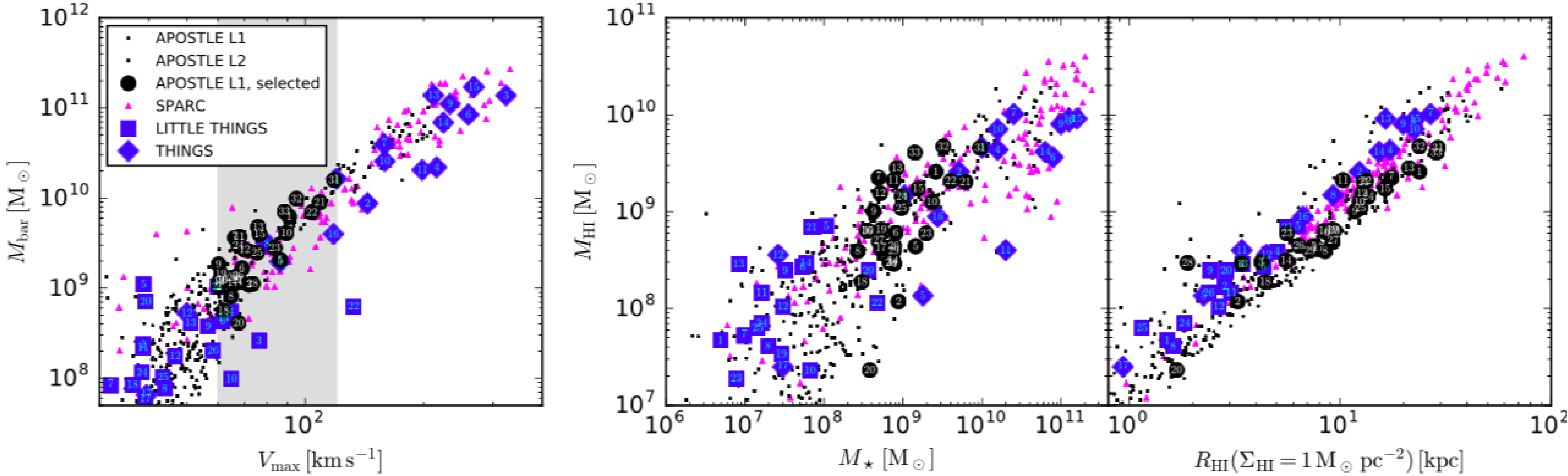
Too large for baryon effects proposed so far?

Too large to reflect DM properties alone?

Oman et al 2015

Analysing mock observations of simulated dwarfs

Oman et al 2017

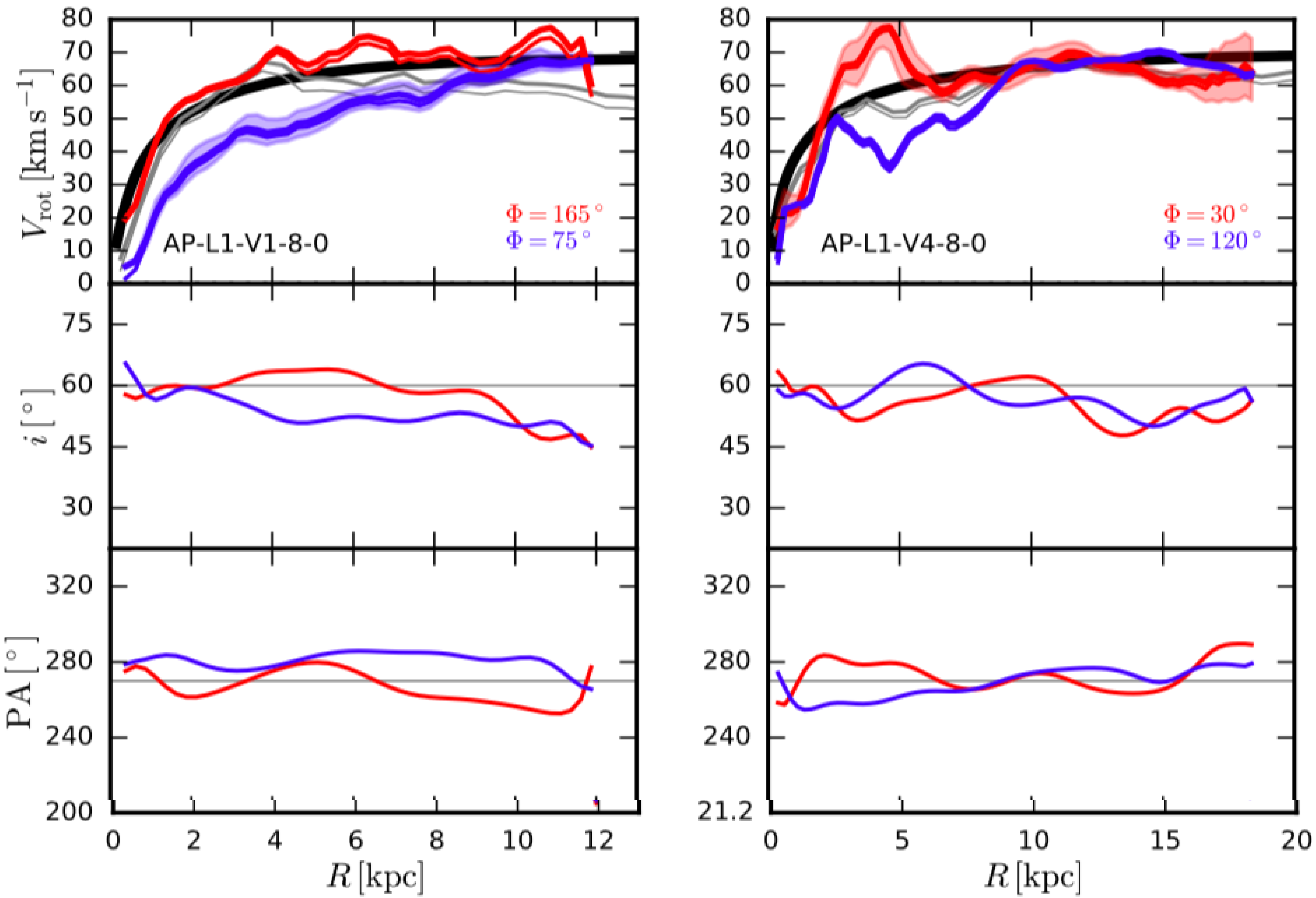


"Field" dwarfs are chosen from the Apostle suite of zoom simulations of Local Group like volumes with 60 km/s < $V_{circ,max}$ < 120 km/s

Their global properties are a relatively good match to observation.

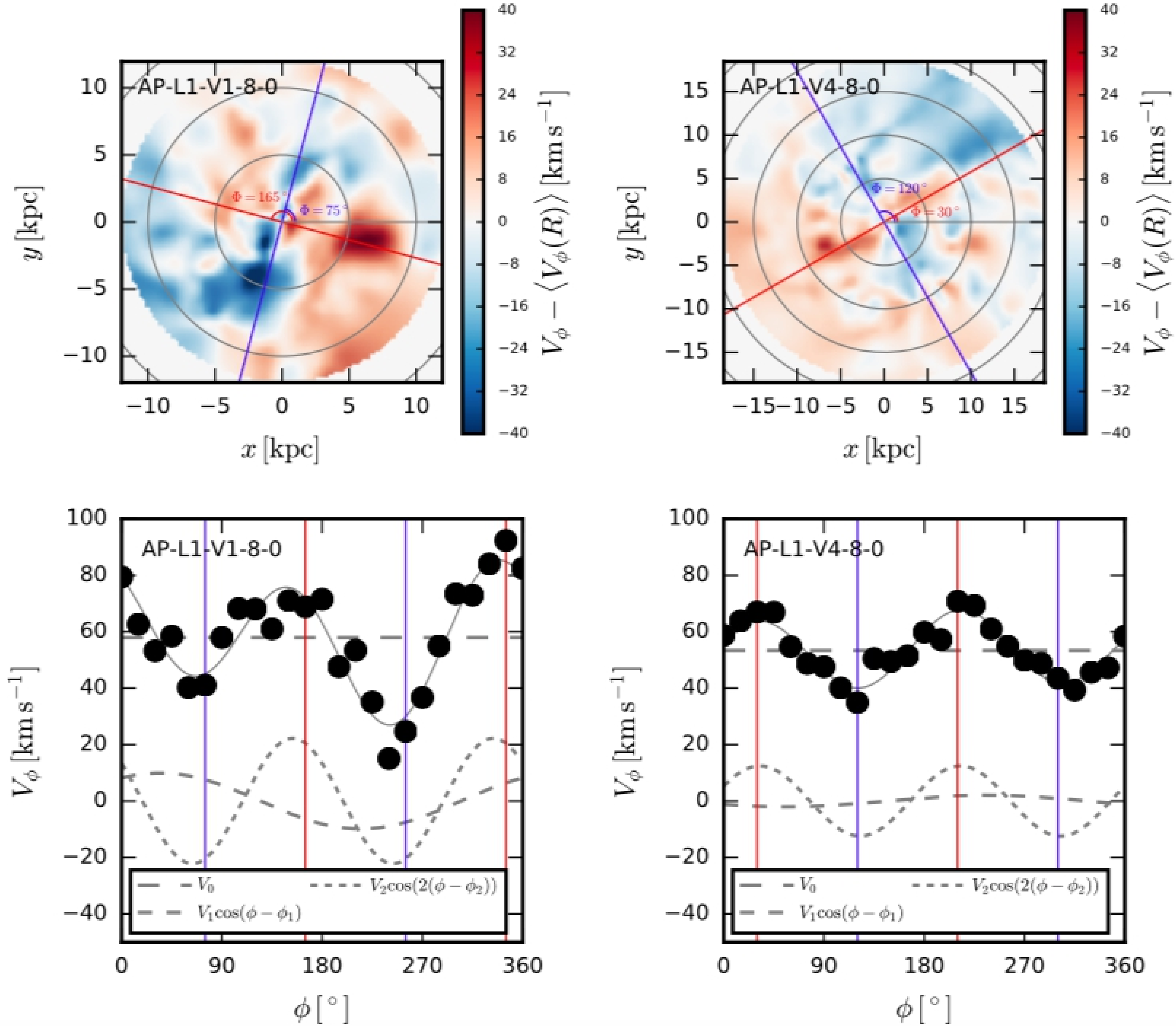
Analysing mock observations of simulated dwarfs

Oman et al 2017



“Observational” data cubes constructed by projecting a given simulated galaxy can lead to very different inferred rotation curves when analysed using the state-of-the-art tilted ring code, Barolo (Di Teodoro & Fraternali 2015)

Analysing mock observations of simulated dwarfs

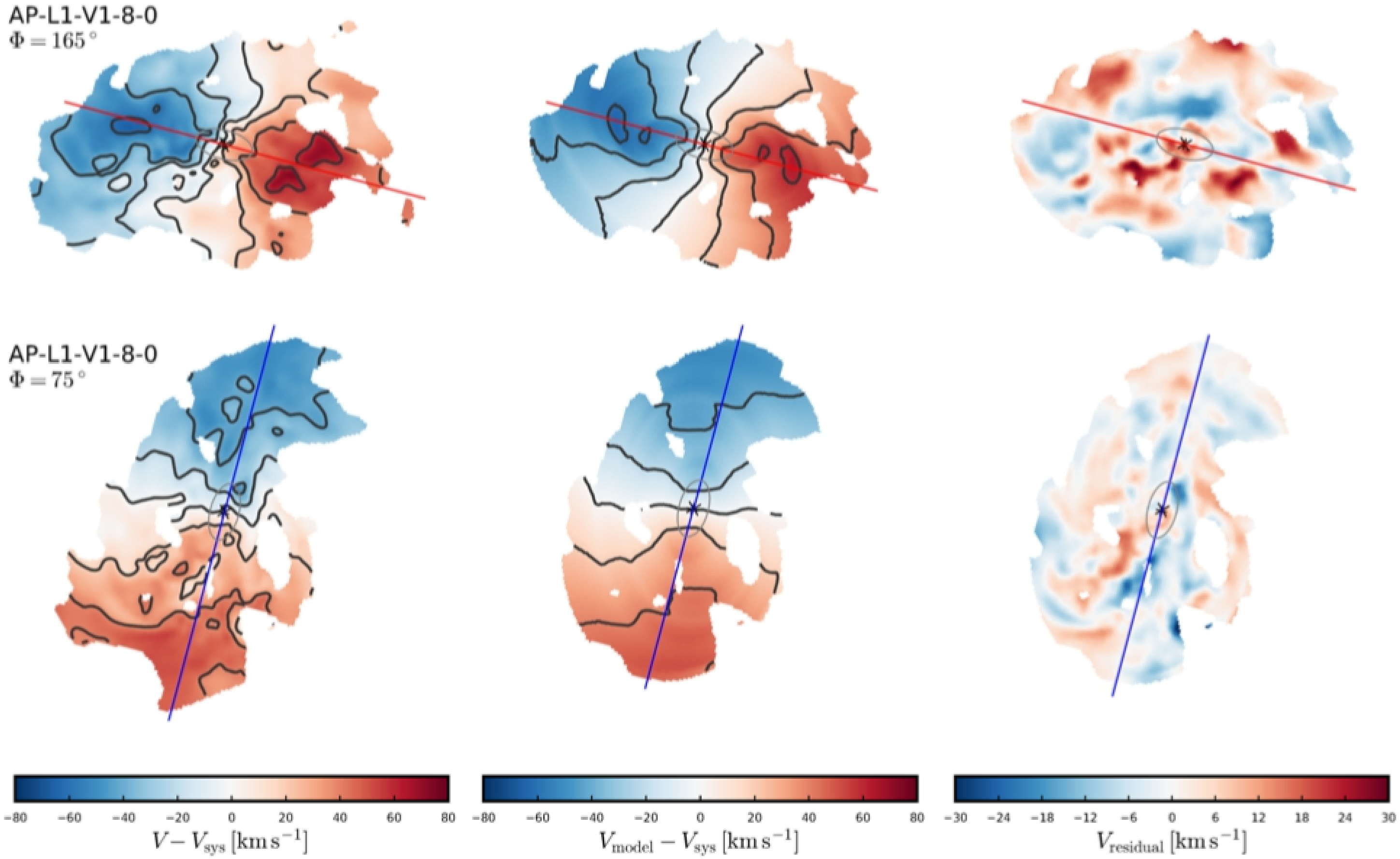


Oman et al 2017

"Observational" data cubes constructed by projecting a given simulated galaxy can lead to very different inferred rotation curves when analysed using the state-of-the-art tilted ring code, Barolo (Di Teodoro & Fraternali 2015)
These reflect systematic m=2 residuals from circular motion

Analysing mock observations of simulated dwarfs

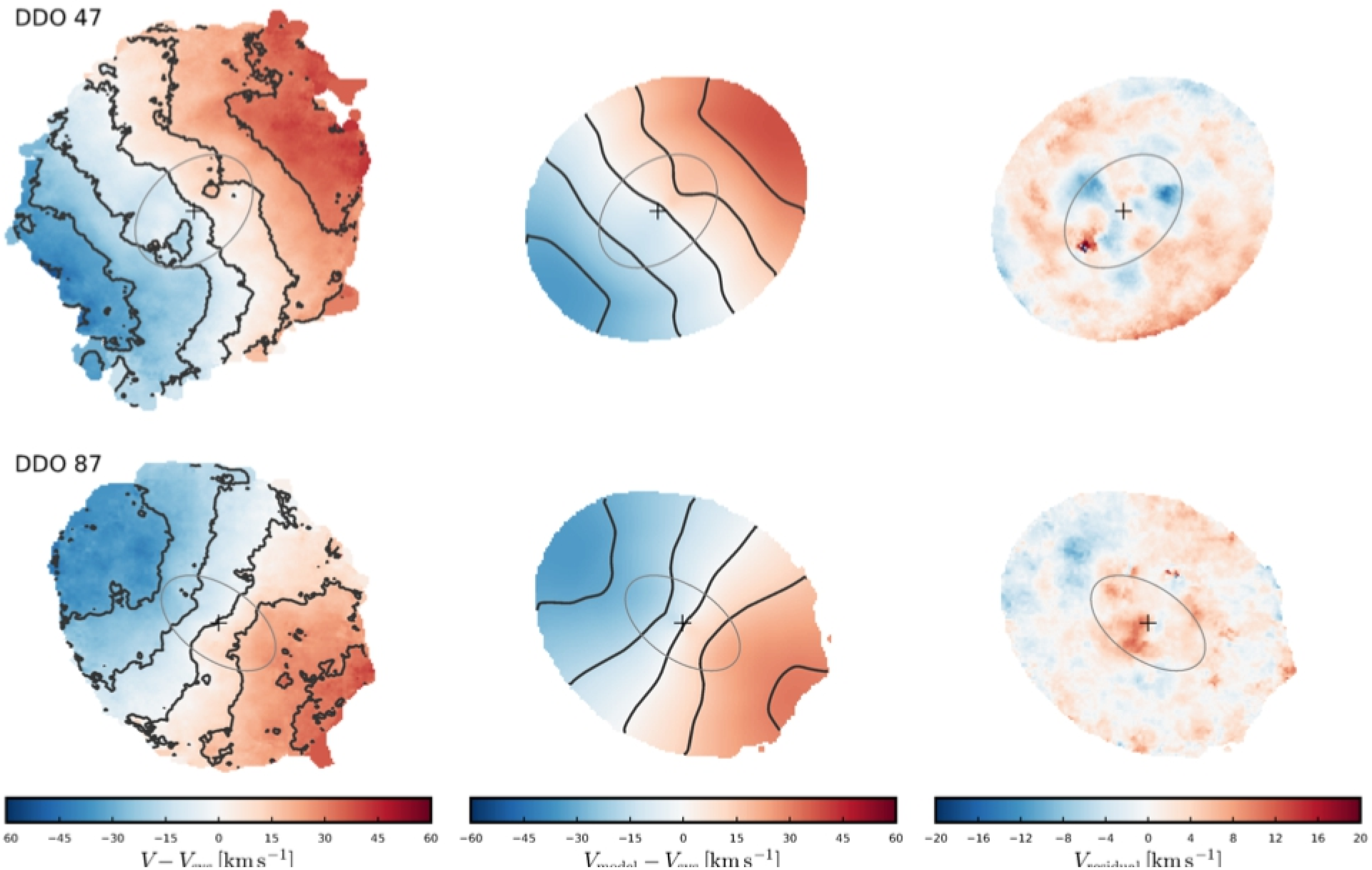
Oman et al 2017



"Observational" data cubes constructed by projecting a given simulated galaxy can lead to very different inferred rotation curves when analysed using the state-of-the-art tilted ring code, Barolo (Di Teodoro & Fraternali 2015)
The corresponding residuals in "observed" maps are m=3

Analysing mock observations of simulated dwarfs

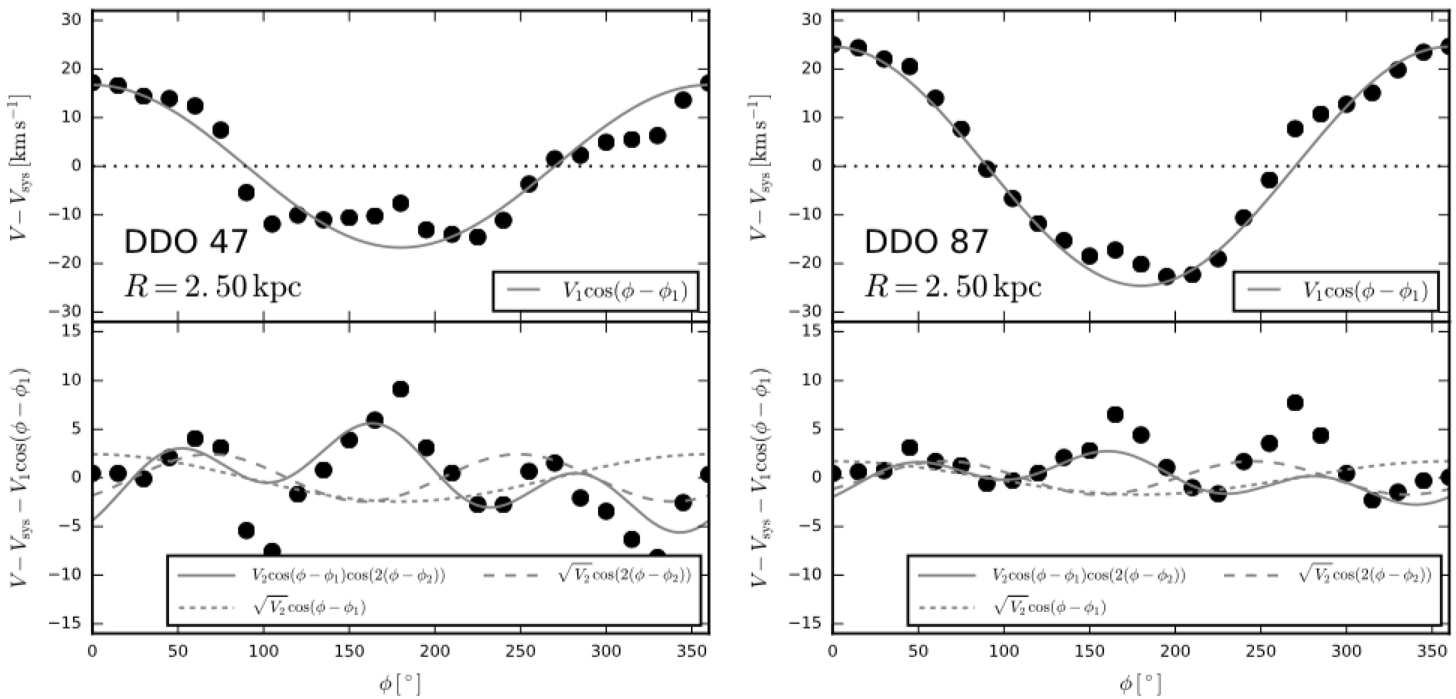
Oman et al 2017



Real dwarfs show residual patterns with similar m=3 morphology

Analysing mock observations of simulated dwarfs

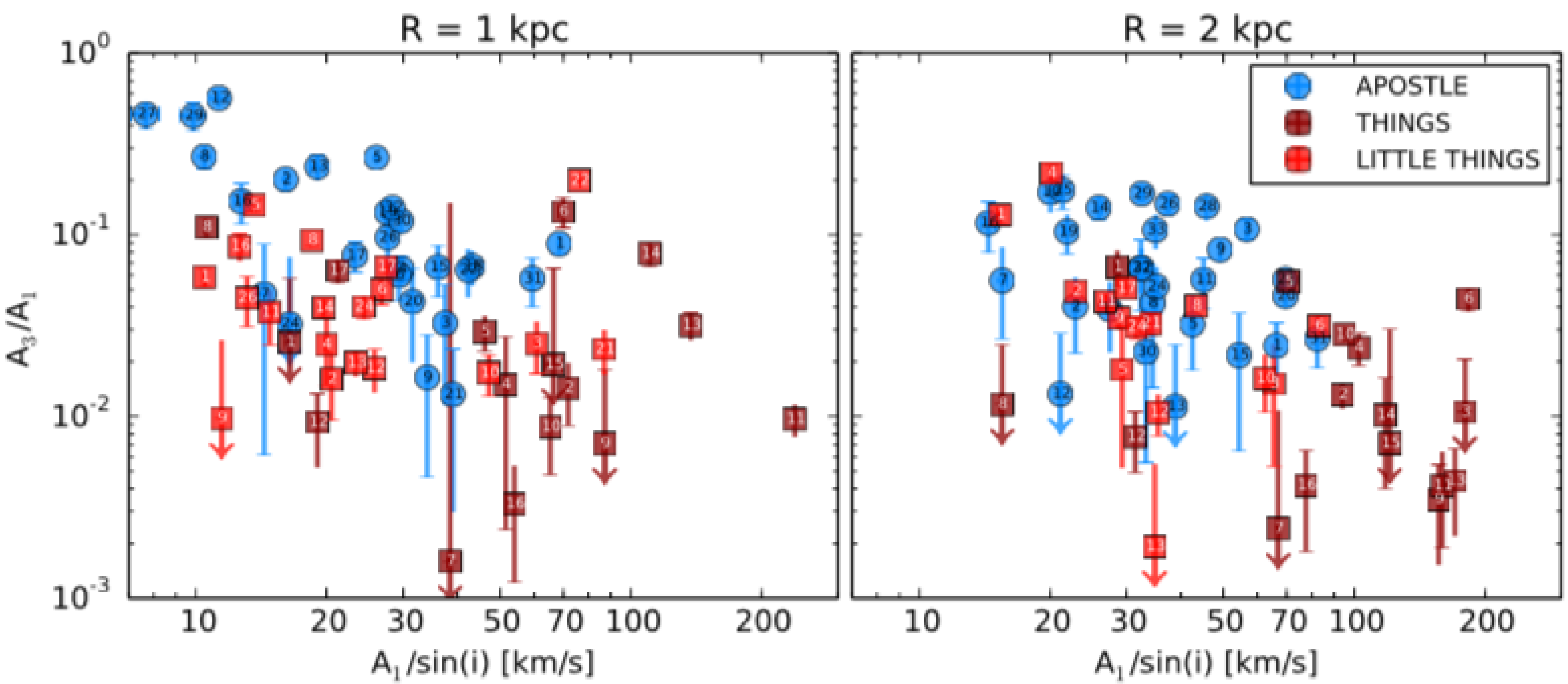
Oman et al 2017



Real dwarfs show residual patterns with similar m=3 morphology

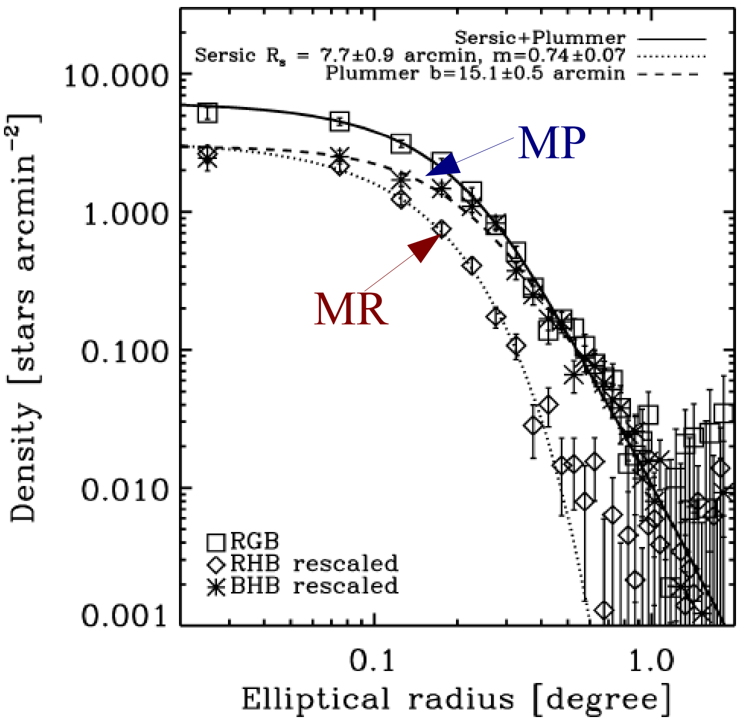
Analysing mock observations of simulated dwarfs

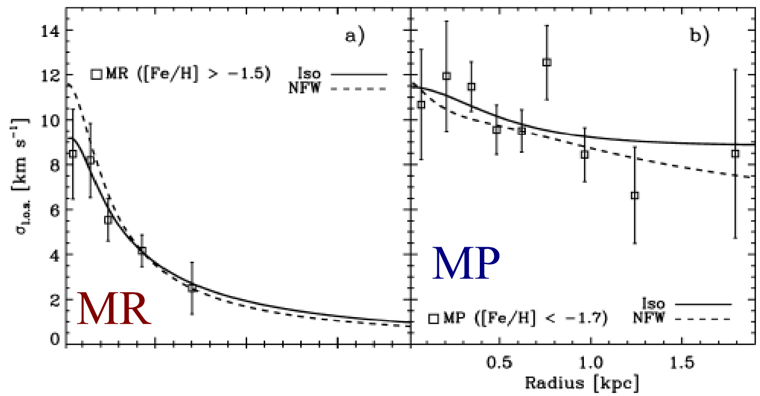
Marasco et al 2018



However, the m=3 amplitudes in real dwarfs seem smaller than in the simulated dwarfs.

A core in the Sculptor dwarf spheroidal?

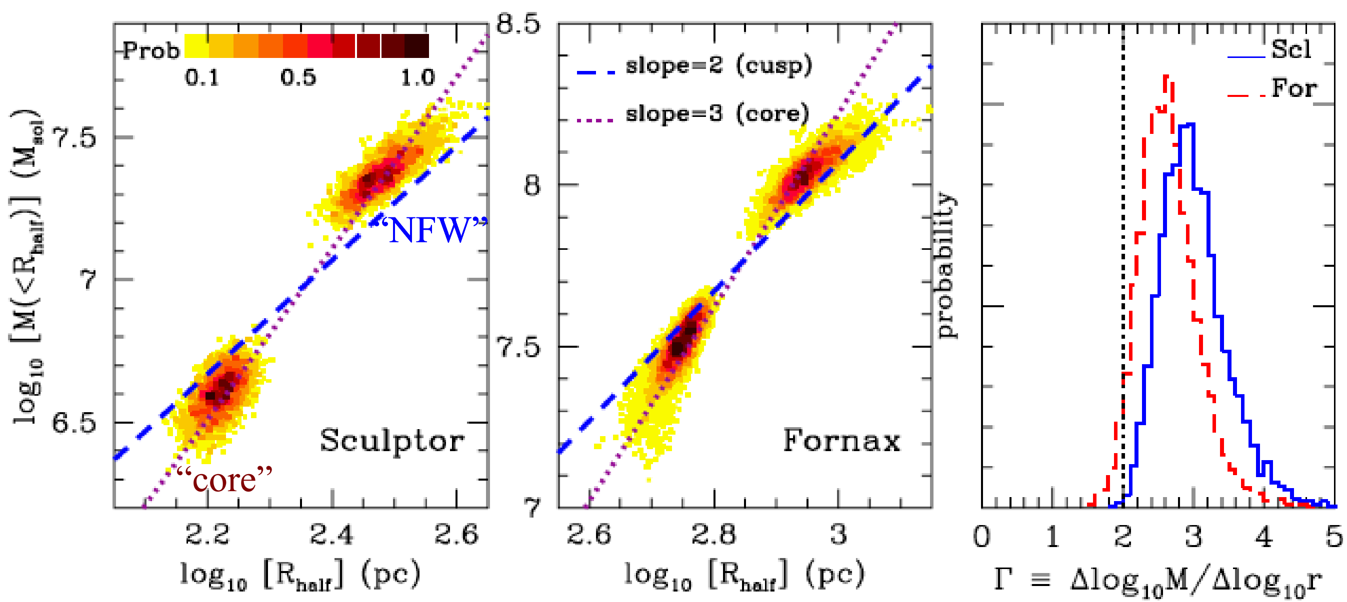




Battaglia et al 2008
~500 stars

NFW
"core"

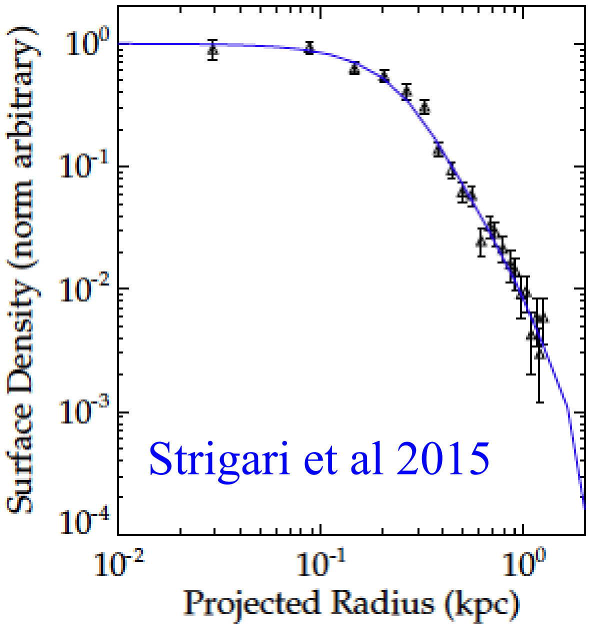
- Sculptor has 2 populations
- Counts for both show cores
- MR stars less extended and cooler than MP
- Both cusped and cored potentials can fit

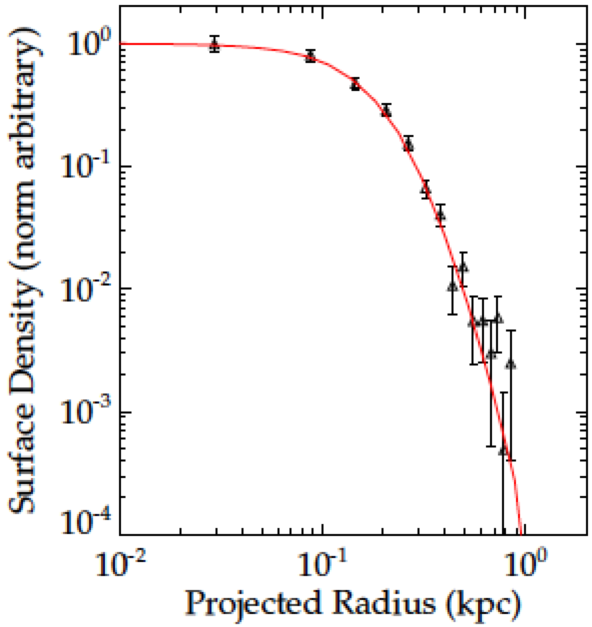


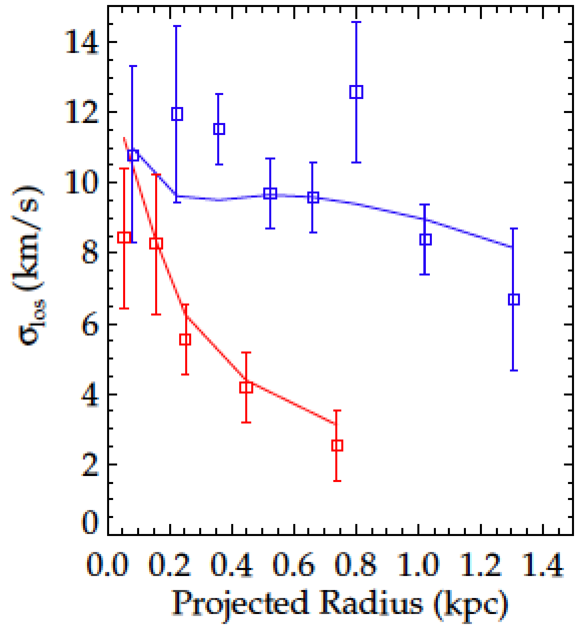
Walker & Penarrubia 2011
~1500 stars

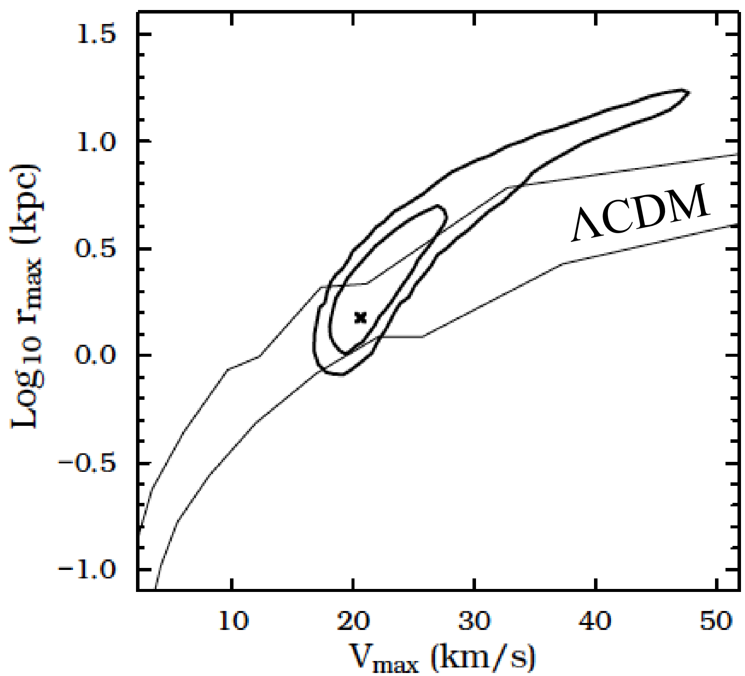
Two populations separated statistically. $r_{1/2}$, $M(r_{1/2})$ estimated for each. An NFW potential is excluded

A core in the Sculptor dwarf spheroidal?









- The Battaglia count and velocity dispersion data can be well fit by a distribution function f(E,J) in an NFW potential Φ(r)
- The characteristic parameters of Φ(r) are consistent with the expected ΛCDM relation
- A "cored" potential fits equally well but not significantly better

Nature, November 2017

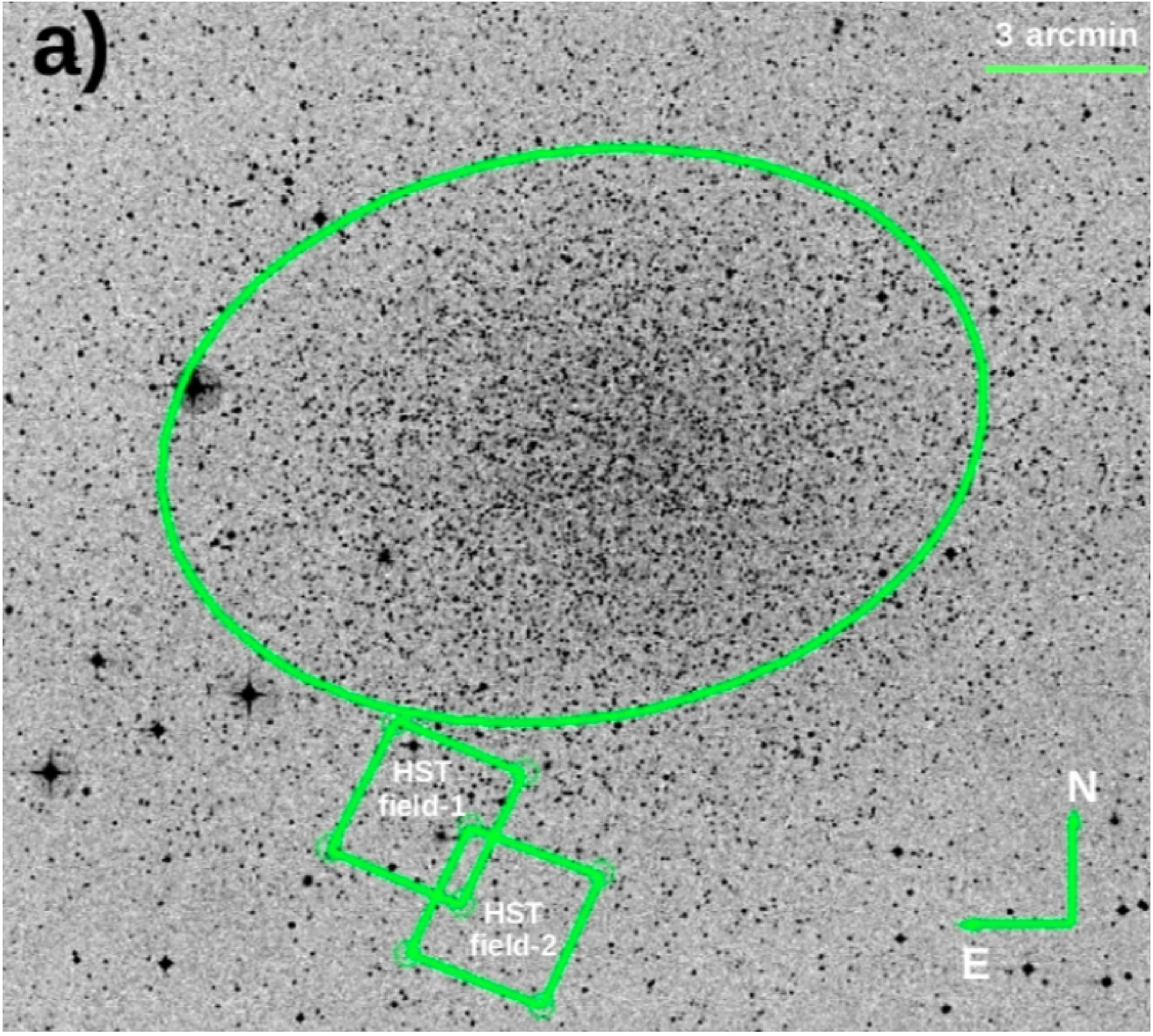
3D motions in the Sculptor dwarf galaxy as a glimpse of a new era

D. Massari[1,2,*], M. A. Breddels[1], A. Helmi[1], L. Posti[1], A. G. A. Brown[2], E. Tolstoy[1]

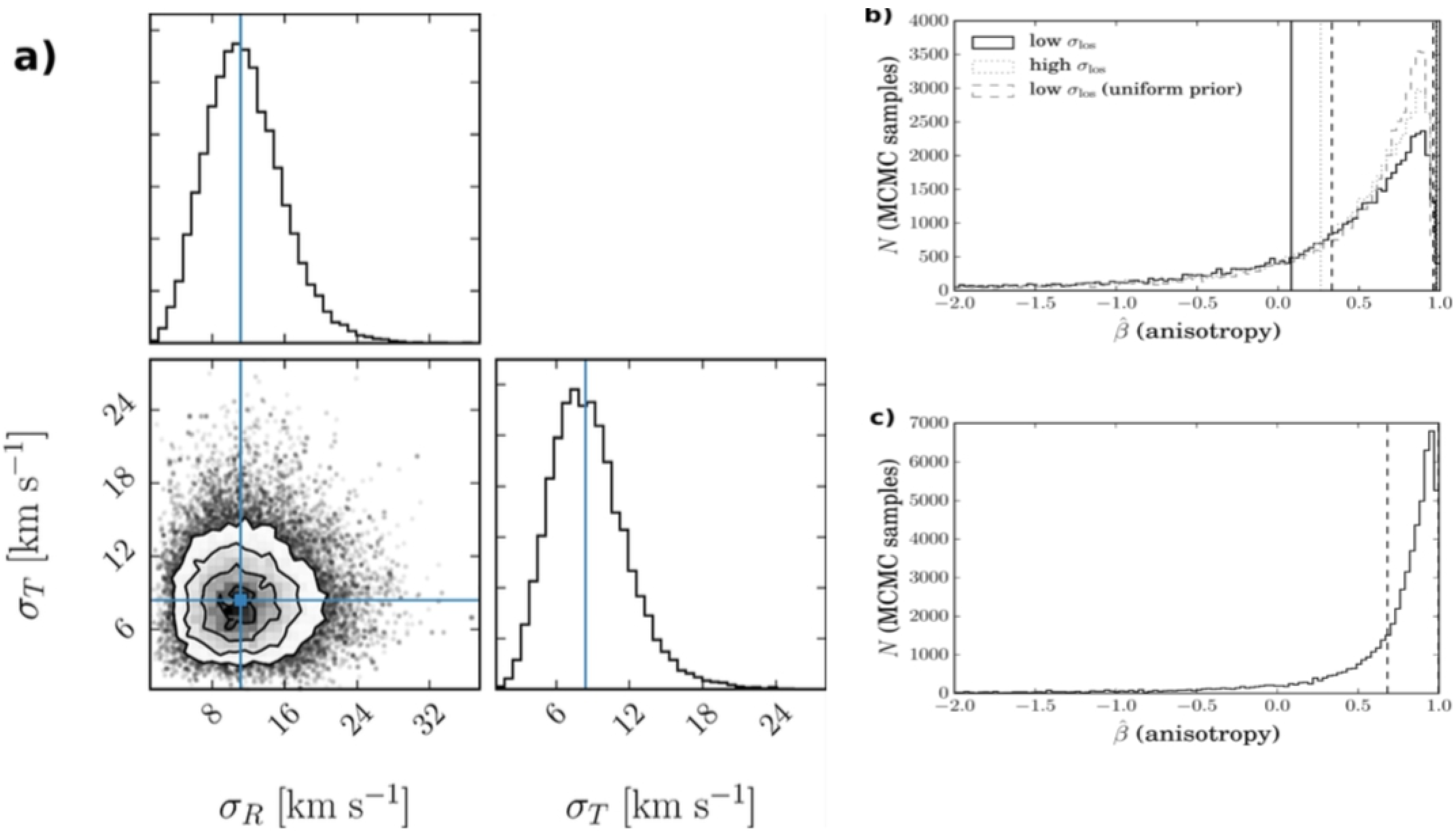
[1] *Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands*

[2] *Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands*

Here we report, based on data from the *Gaia* space mission[8] and the *Hubble Space Telescope*, a new precise measurement of Sculptor's mean proper motion. From this we deduce that Sculptor is currently at its closest approach to the Milky Way and moving on an elongated high-inclination orbit that takes it much farther away than previously thought. For the first time we are also able to measure the internal motions of stars in Sculptor. We find $\sigma_R = 11.5 \pm 4.3\ \mathrm{km\,s^{-1}}$ and $\sigma_T = 8.5 \pm 3.2\ \mathrm{km\,s^{-1}}$ along the projected radial and tangential directions, implying that the stars in our sample move preferentially on radial orbits as quantified by the anisotropy parameter, which we find to be $\beta \sim 0.86^{+0.12}_{-0.83}$ at a location beyond the core radius. Taken at face value such a high radial anisotropy requires abandoning conventional models[9] for the mass distribution in Sculptor. Our sample is dominated by metal-rich stars


a)
3 arcmin
HST
field-1
HST
field-2
N
E

Massari et al 2017



$$\hat{\beta} = 1 - \frac{\sigma_T^2}{\sigma_{\rm los}^2 + \sigma_R^2 - \sigma_T^2}.$$

with the transverse dispersions estimated from 15 stars and the l.o.s. dispersion from just 10 stars!

Models for a stellar population in a given potential

Strigari et al 2017

$$\rho(r) = \frac{\rho_s}{x(1+x)^2},$$

with corresponding gravitational potential

$$\Phi(r) = \Phi_s \left[1 - \frac{\ln(1+x)}{x}\right],$$

where we define $\Phi_s = 4\pi G \rho_s r_s^2$ and $x = r/r_s$.

N.B. these are spherical models in equilibrium

$$f(E, J) = g(J)h(E),$$

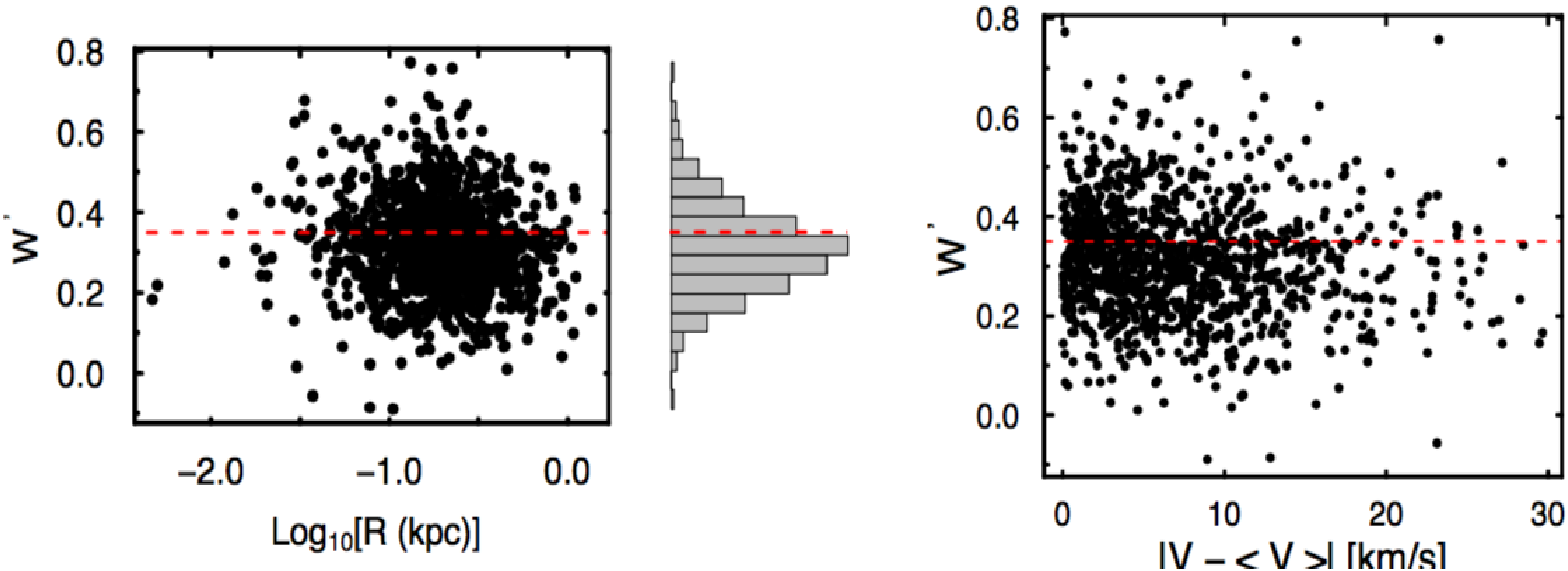
$$g(J) = \left[\left(\frac{J}{J_\beta}\right)^{\frac{b_0}{\alpha}} + \left(\frac{J}{J_\beta}\right)^{\frac{b_1}{\alpha}}\right]^\alpha,$$

$$h(E) = \begin{cases} NE^a(E^q + E_c^q)^{d/q}(\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for } E \geq \Phi_{lim}, \end{cases}$$

Two parameters for the potential and eleven for *each* stellar population can be varied using MCMC to find acceptable fits to the observational data.

Two stellar populations in Sculptor?

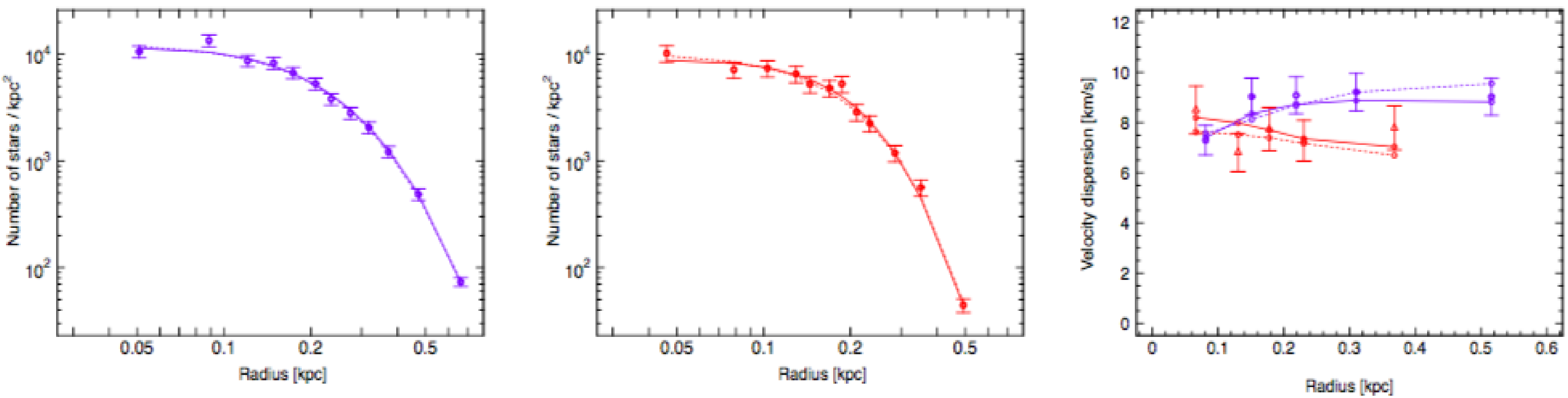
Strigari et al 2017



Data from Walker & Penarrubia (2011).
W is the directly measured indicator of metallicity.
The red line is the split which maximizes the difference in radial distribution between "metal-rich" ($W > 0.35$) and "metal-poor" ($W < 0.35$) stars

Two population fits to the MP11 data for Sculptor

Strigari et al 2017

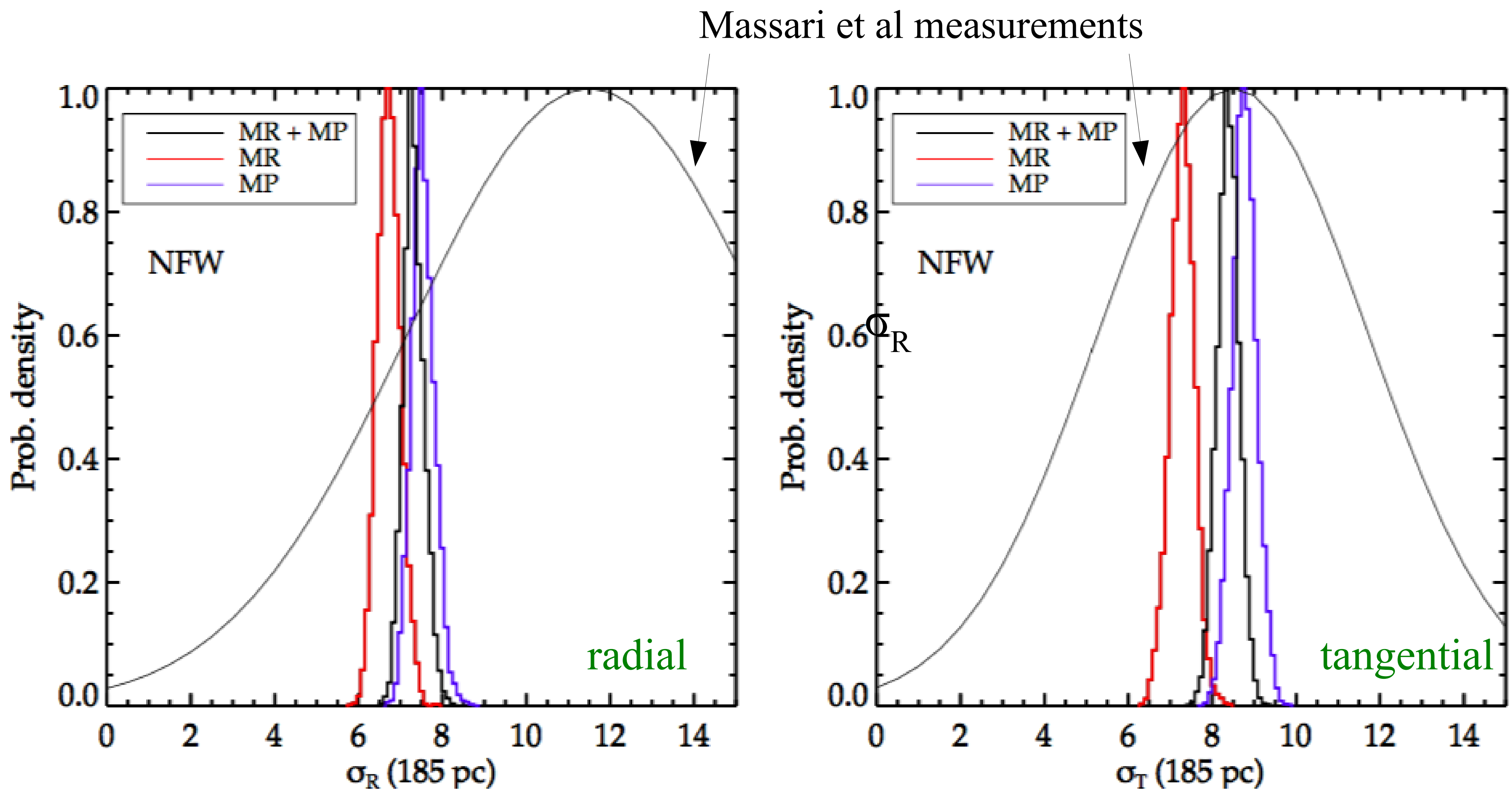


Good simultaneous fits can be found to the star count and velocity dispersion data from WP11 for both MR and MP stars

The fits for cored (Burkert) and cusped (NFW) potentials are equally good

The parameters found for NFW profiles are consistent with those expected from simulations of the standard ΛCDM model

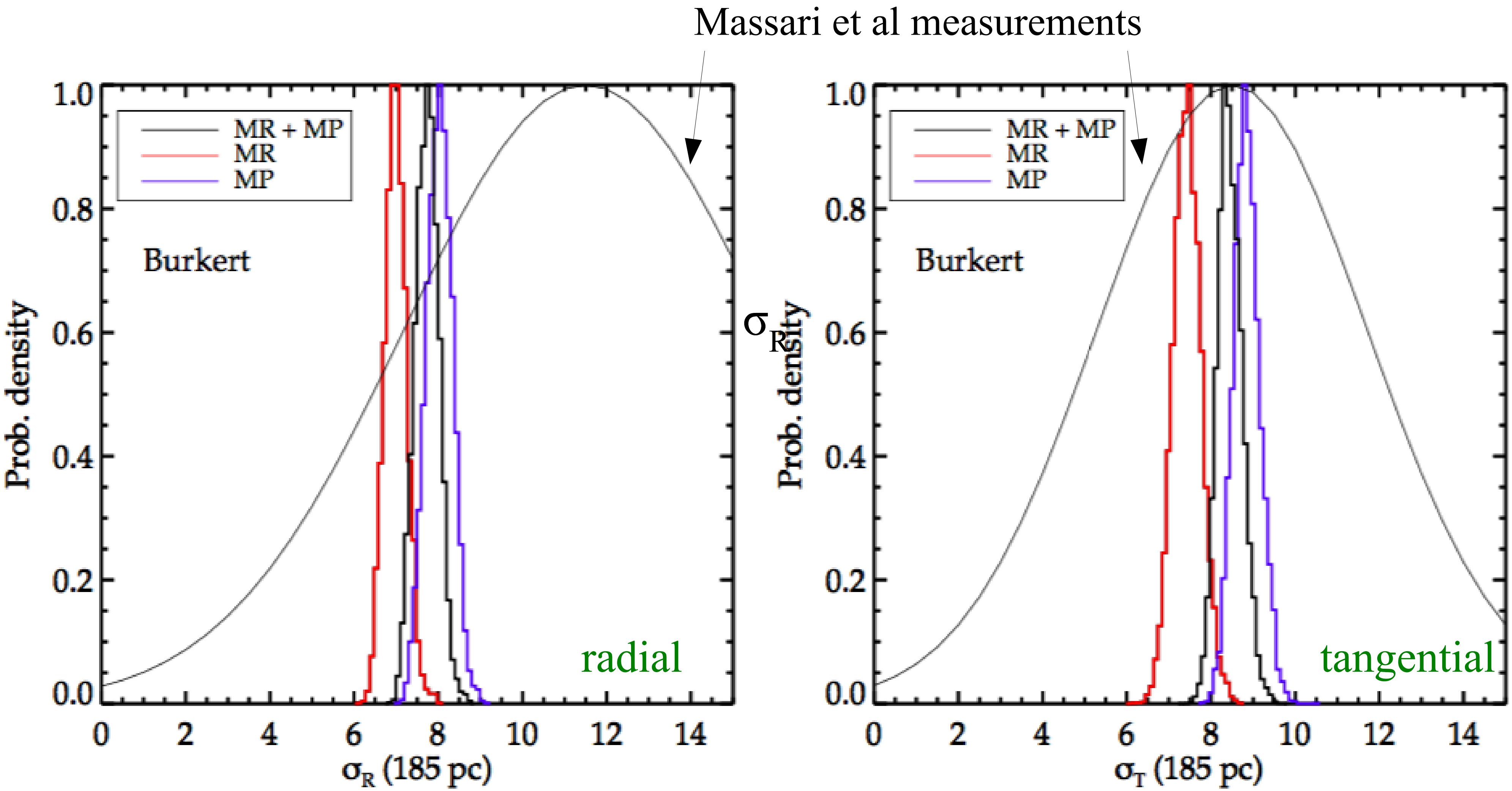
Transverse dispersions predicted in the HST fields by models fit to the WP11 data



Strigari et al 2018

The models predict $\sigma_R < \sigma_T$!

Transverse dispersions predicted in the HST fields by models fit to the WP11 data



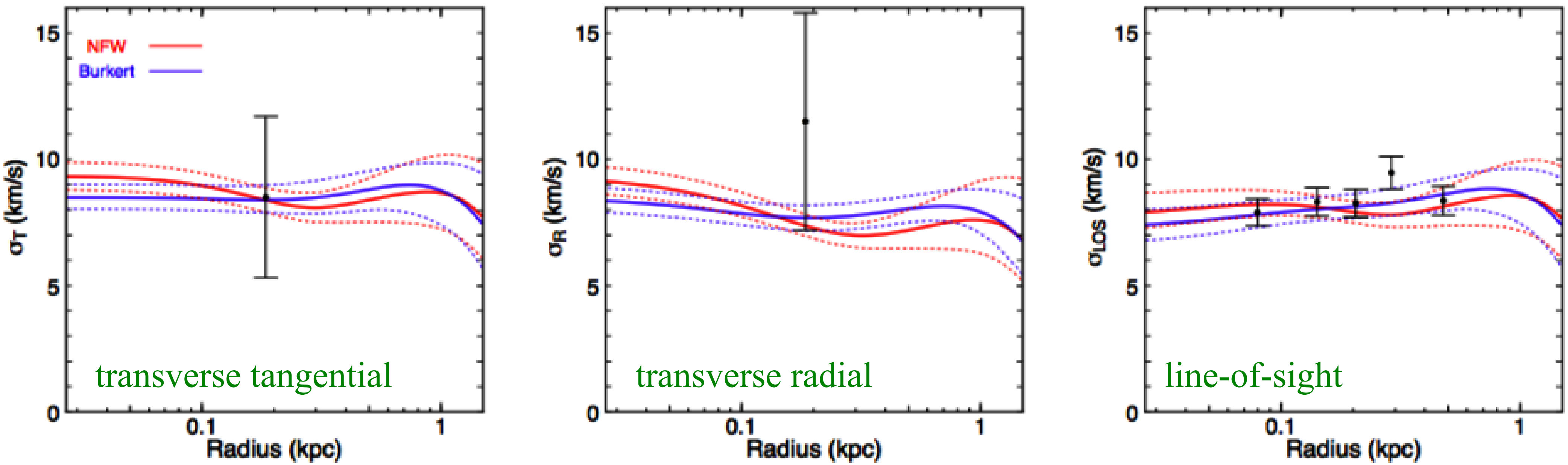
Strigari et al 2018

The models predict $\sigma_R < \sigma_T$!

Transverse and l.o.s. dispersion profiles predicted by models fit to the WP11 data

Strigari et al 2018

All stars



The dispersion profiles predicted for cored and cusped potentials differ little

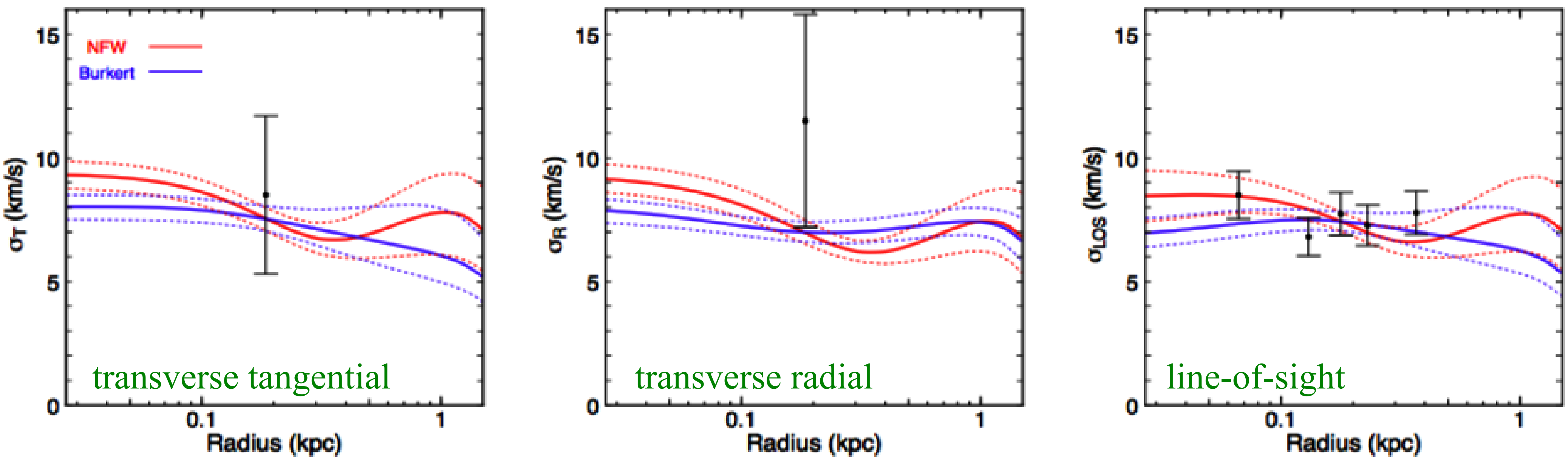
Differences are small at the radius of the HST fields and largest at small radii

Transverse dispersions are no more discriminating than l.o.s. dispersions

Transverse and l.o.s. dispersion profiles predicted by models fit to the WP11 data

Strigari et al 2018

MR stars



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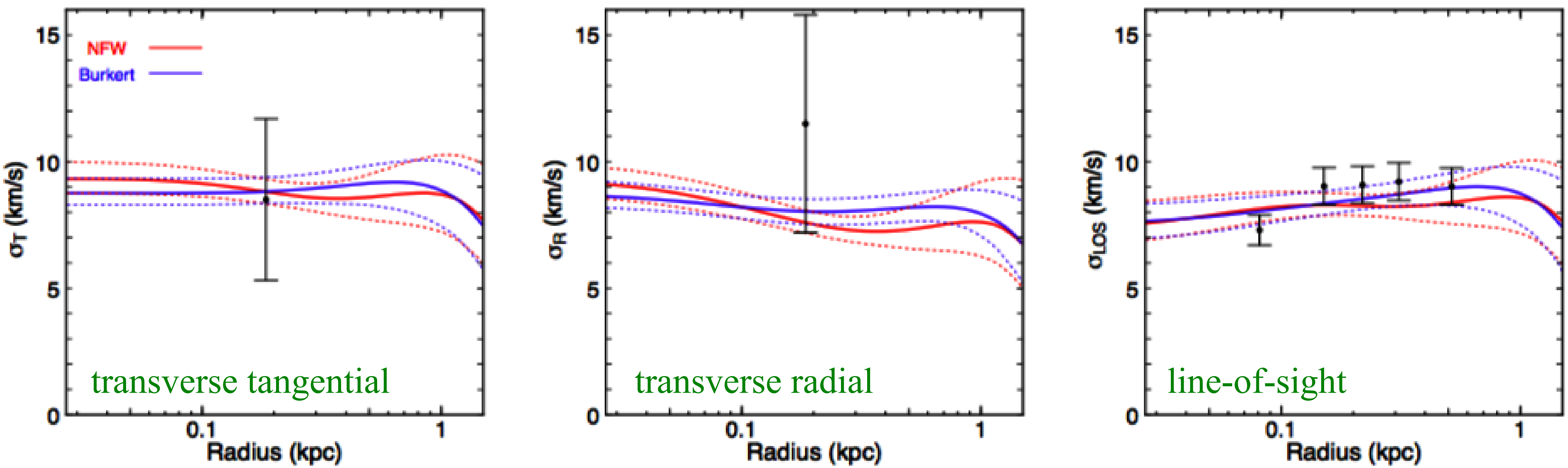
Transverse and l.o.s. dispersion profiles predicted by models fit to the WP11 data

Strigari et al 2018

MP stars



The dispersion profiles predicted for cored and cusped potentials differ little

Differences are small at the radius of the HST fields and largest at small radii

Transverse dispersions are no more discriminating than l.o.s. dispersions

Conclusions?

- Apparent cores in dwarfs may in many cases be due to non-circular motions caused by non-axisymmetric halos
- Simulations and observations show deviations from circular motion of similar morphology but different amplitude
- Current data on Sculptor cannot distinguish between an (NFW) cusp and a (Burkert) core, even including PMs
- It may be possible to tell the difference with dispersion profile measures over a broad range in radii and with an accuracy for individual points of 0.5 km/s or less
- This will require measurement of $\sim 10^4$ radial velocities and/or proper motions with high individual accuracy
- Good data in the inner regions (<100pc) are particularly important