"Certain situations should be taken in a comic way"

— *Ofer Lahav*


AN

Wiener reconstruction of density, velocity and potential fields from all-sky galaxy redshift surveys

K. B. Fisher,[1] O. Lahav,[1] Y. Hoffman,[2] D. Lynden-Bell[1] and S. Zaroubi[2]

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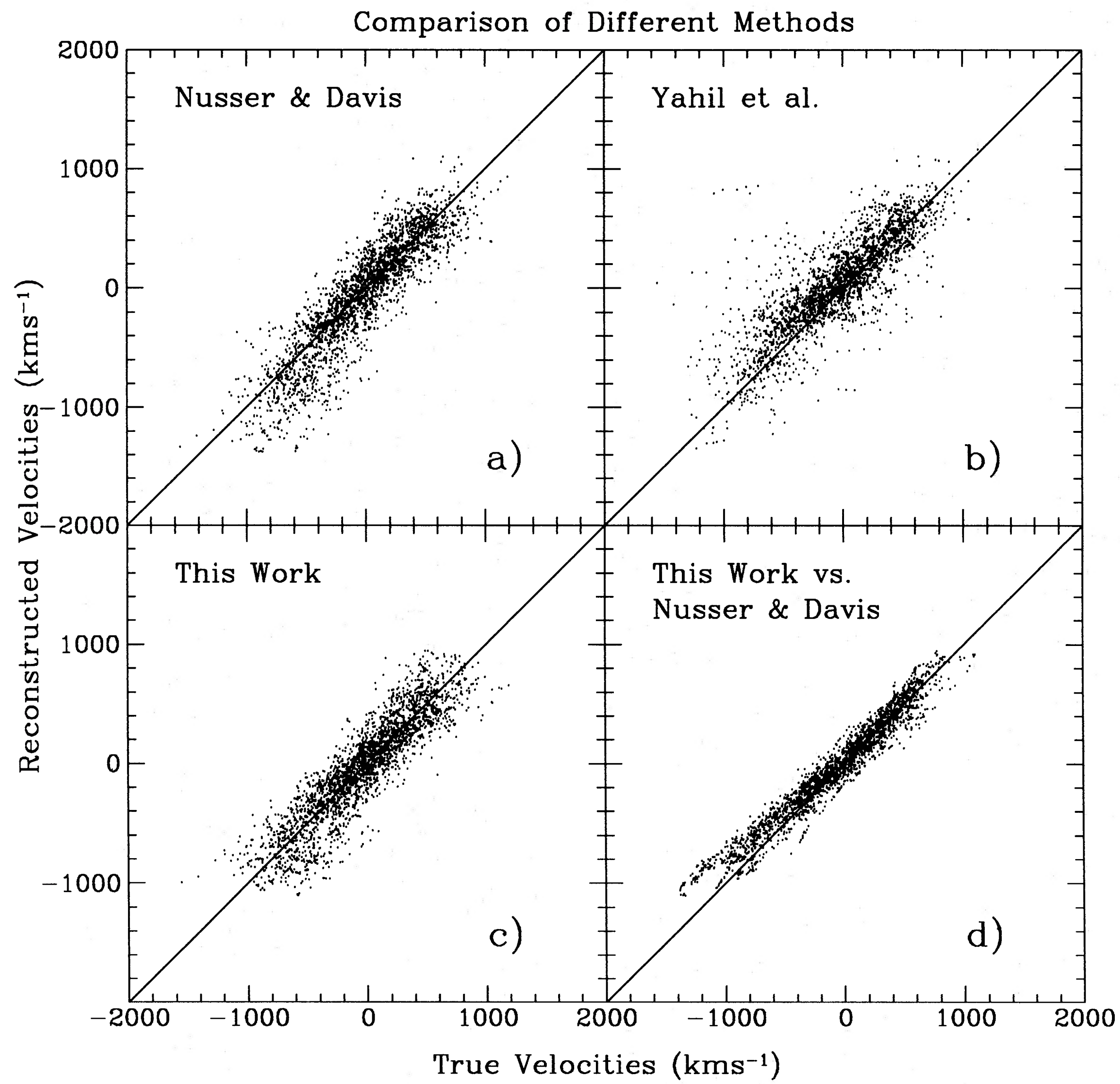

This result can be combined with equation (D13) for the distortion term to express equation (D7) in a way which clearly shows the coupling of the radial modes in redshift space. Let

$$\delta^{\mathrm{S}}_{lmn} = \sum_{n'} (\mathbf{Z}_l)_{nn'} \delta^{\mathrm{R}}_{lmn'}, \qquad \text{(D16)}$$

A challenge for Ofer: find the typo

where we have defined the coupling matrix, for a given l and $\phi(r)\, w(r) = 1$, as

$$(\mathbf{Z}_l)_{nn'} = \delta^{\mathrm{K}}_{nn'} - \beta C_{ln} \int_0^R \mathrm{d}r\, r^2 j_l(k_n r) \left\{ j_l''(k_{n'} r) + \left[\frac{j_l'(k_{n'} r)}{k_{n'} r} - \frac{\delta^{\mathrm{K}}_{l1}}{3} \frac{1}{r} \int_0^R \mathrm{d}x\, j_l(k_{n'} x) \right] \left[2 + \frac{\mathrm{d} \ln \phi(r)}{\mathrm{d} \ln r} \right] \right\}. \qquad \text{(D17)}$$

One dwarf with little dark matter!?

A galaxy lacking dark matter

Pieter van Dokkum[1], Shany Danieli[1], Yotam Cohen[1], Allison Merritt[1,2], Aaron J. Romanowsky[3,4], Roberto Abraham[5], Jean Brodie[4], Charlie Conroy[6], Deborah Lokhorst[5], Lamiya Mowla[1], Ewan O'Sullivan[6], Jielai Zhang[5]

- ``Towards a higher mass for NGC 1054-DF2," AN, 2019, MNRAS
- ``Orbital decay of globular clusters in the galaxy with little dark matter," AN, 2018, MNRAS

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Science 2003

A Dearth of Dark Matter in Ordinary Elliptical Galaxies

Aaron J. Romanowsky,[1,2*] Nigel G. Douglas,[2]
Magda Arnaboldi,[3,4] Konrad Kuijken,[5,2] Michael R. Merrifield,[1]
Nicola R. Napolitano,[2] Massimo Capaccioli,[3,6] Kenneth C. Freeman[7]

The kinematics of the outer parts of three intermediate-luminosity elliptical galaxies were studied with the Planetary Nebula Spectrograph. The galaxies' velocity-dispersion profiles were found to decline with the radius, and dynamical modeling of the data indicates the presence of little if any dark matter in these galaxies' halos. This unexpected result conflicts with findings in other galaxy types and poses a challenge to current galaxy formation theories.

Nature 2005

Lost & found dark matter in elliptical galaxies

A. Dekel[1,2,3], F. Stoehr[2], G.A. Mamon[2], T.J. Cox[4], G.S. Novak[5], & J.R. Primack[3]

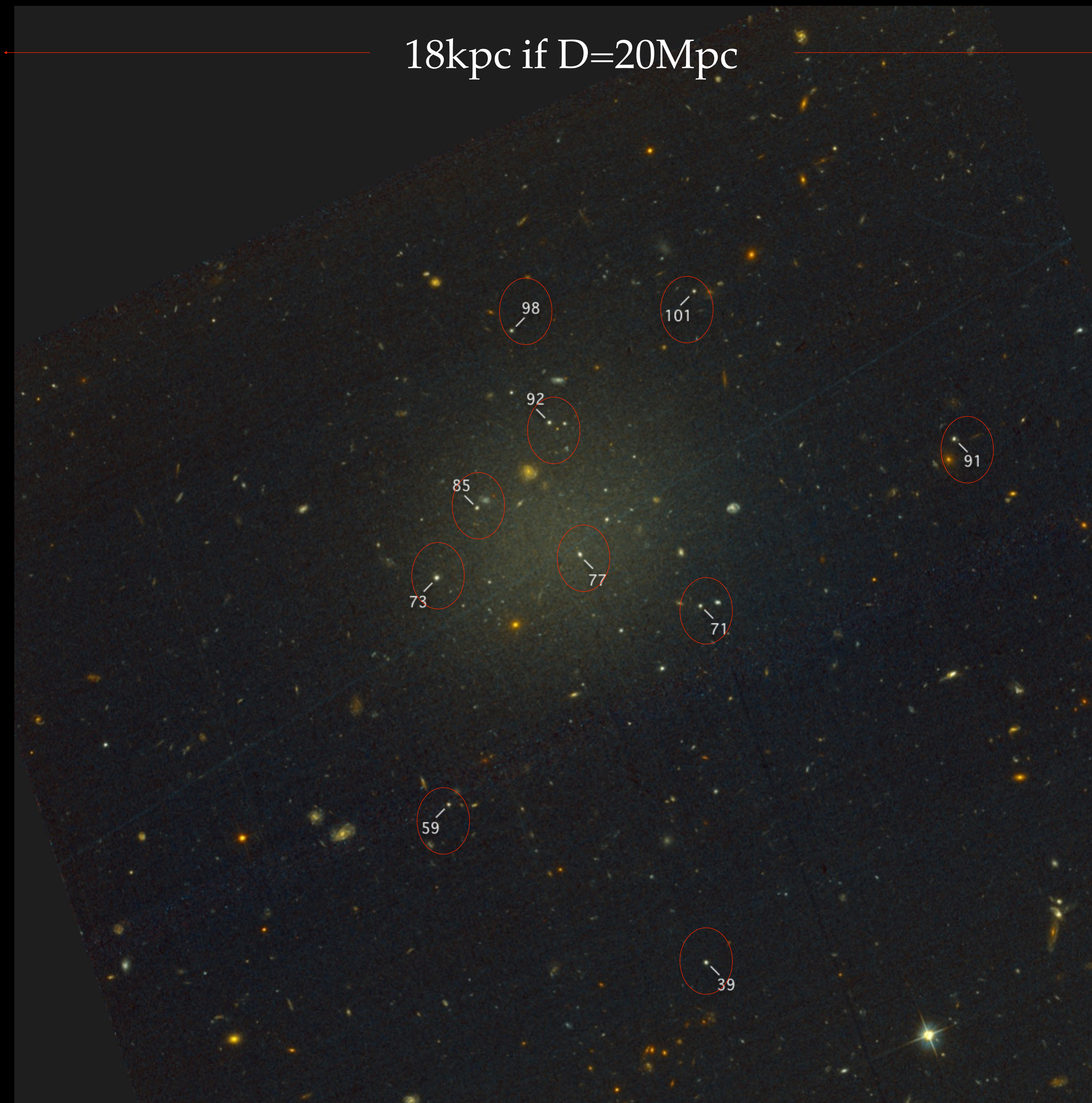
There is strong evidence that the mass in the Universe is dominated by dark matter, which exerts gravitational attraction but whose exact nature is unknown. In particular, all galaxies are believed to be embedded in massive haloes of dark matter.[1,2] This view has recently been challenged by surprisingly low random stellar velocities in the outskirts of ordinary elliptical galaxies, which were interpreted as indicating a lack of dark matter.[3,4] Here we show that the low velocities are in fact compatible with galaxy formation in dark-matter haloes. Using numerical simulations of disc-galaxy mergers,[5,6] we find that the stellar orbits in the outer regions of the resulting ellipticals are very elongated. These stars were torn by tidal forces from their original galaxies during the first close passage and put on outgoing trajectories. The elongated orbits, combined with the steeply falling density profile of the observed tracers, explain the observed low velocities even in the presence of large amounts of dark matter. Projection effects when viewing a triaxial elliptical can lead to even lower observed velocities along certain lines of sight.

A galaxy lacking dark matter

Pieter van Dokkum[1], Shany Danieli[1], Yotam Cohen[1], Allison Merritt[1,2], Aaron J. Romanowsky[3,4], Roberto Abraham[5], Jean Brodie[4], Charlie Conroy[6], Deborah Lokhorst[5], Lamiya Mowla[1], Ewan O'Sullivan[6], Jielai Zhang[5]

10 star clusters as mass tracers:

σ_u <~10km/s



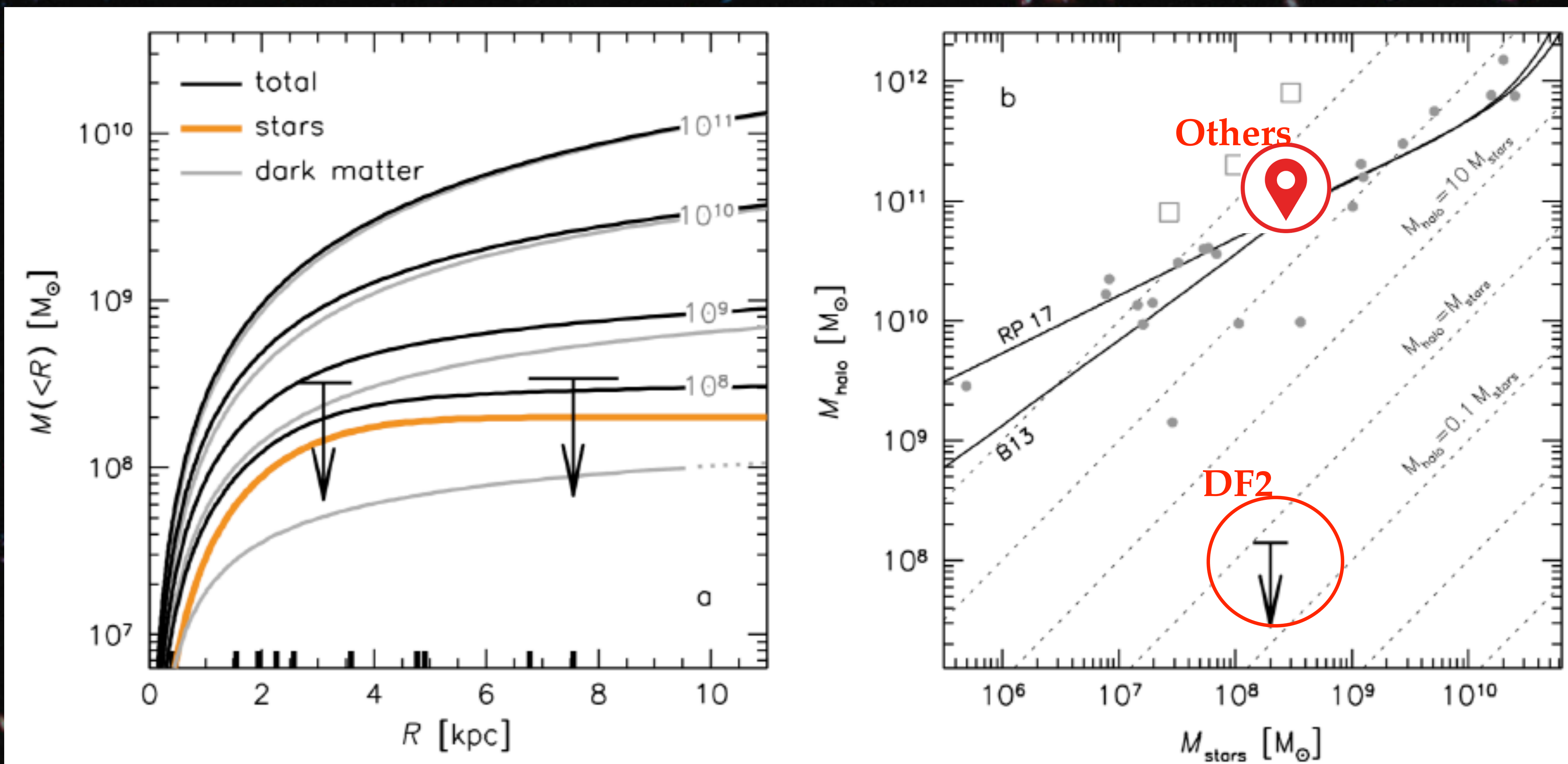
size of a big galaxy but M* ~10^8 solar masses

UDFs are just at the tail of the N(SB)

σ_u <10km/s: M_{dyn} close to M_{stars}!

NO or Very Little DM

van Dokkum et al: very little dark matter



Note:

A distance of 13 Mpc resolves the claimed anomalies of the galaxy lacking dark matter

Ignacio Trujillo,[1,2★†] Michael A. Beasley,[1,2] Alejandro Borlaff,[1,2] Eleazar R. Carrasco,[3] Arianna Di Cintio,[1,2] Mercedes Filho,[4,5] Matteo Monelli,[1,2] Mireia Montes,[6] Javier Román,[1,2] Tomás Ruiz-Lara,[1,2] Jorge Sánchez Almeida,[1,2] David Valls-Gabaud,[7] and Alexandre Vazdekis[1,2]

But this implies a very large peculiar velocity!

AN ENIGMATIC POPULATION OF LUMINOUS GLOBULAR CLUSTERS IN A GALAXY LACKING DARK MATTER

Pieter van Dokkum[1], Yotam Cohen[1], Shany Danieli[1], J. M. Diederik Kruijssen[2], Aaron J. Romanowsky[3,4], Allison Merritt[5], Roberto Abraham[6], Jean Brodie[3], Charlie Conroy[7], Deborah Lokhorst[6], Lamiya Mowla[1], Ewan O'Sullivan[7], Jielai Zhang[6]

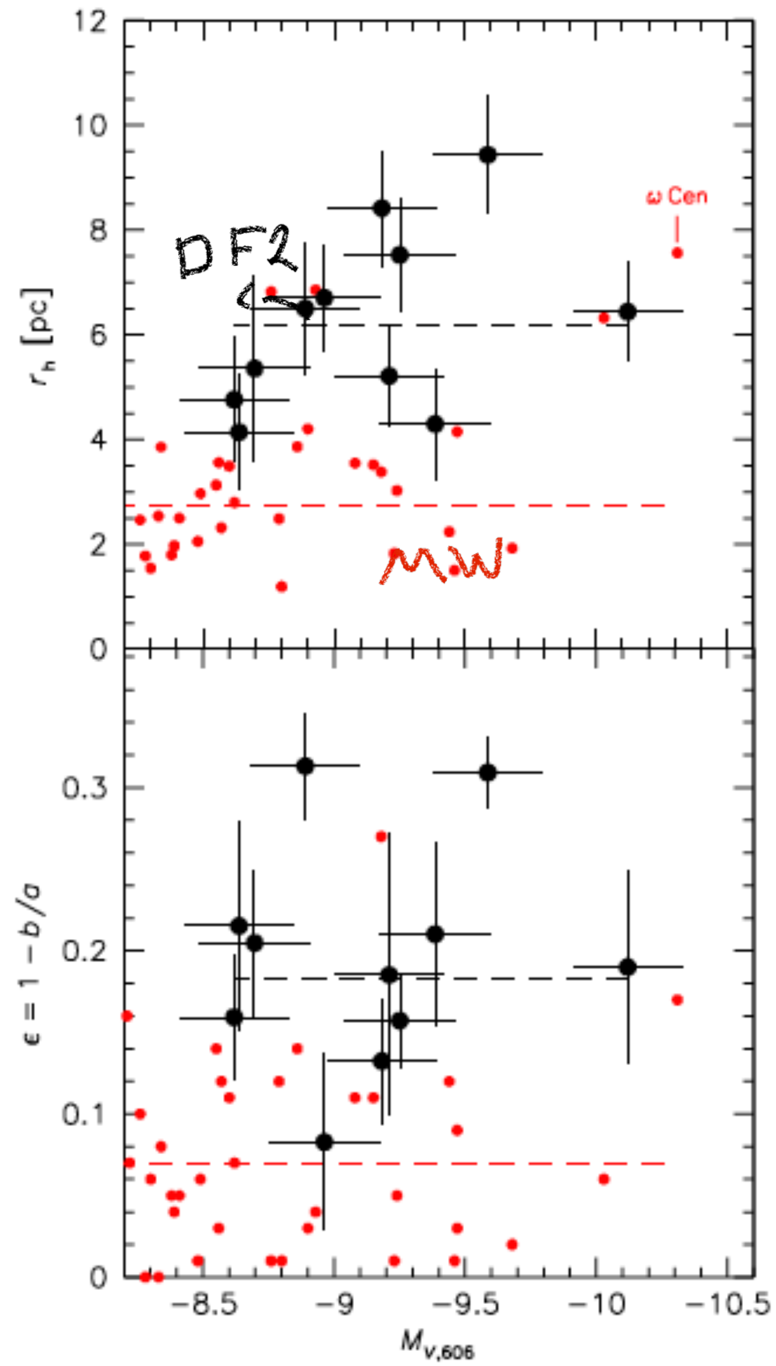
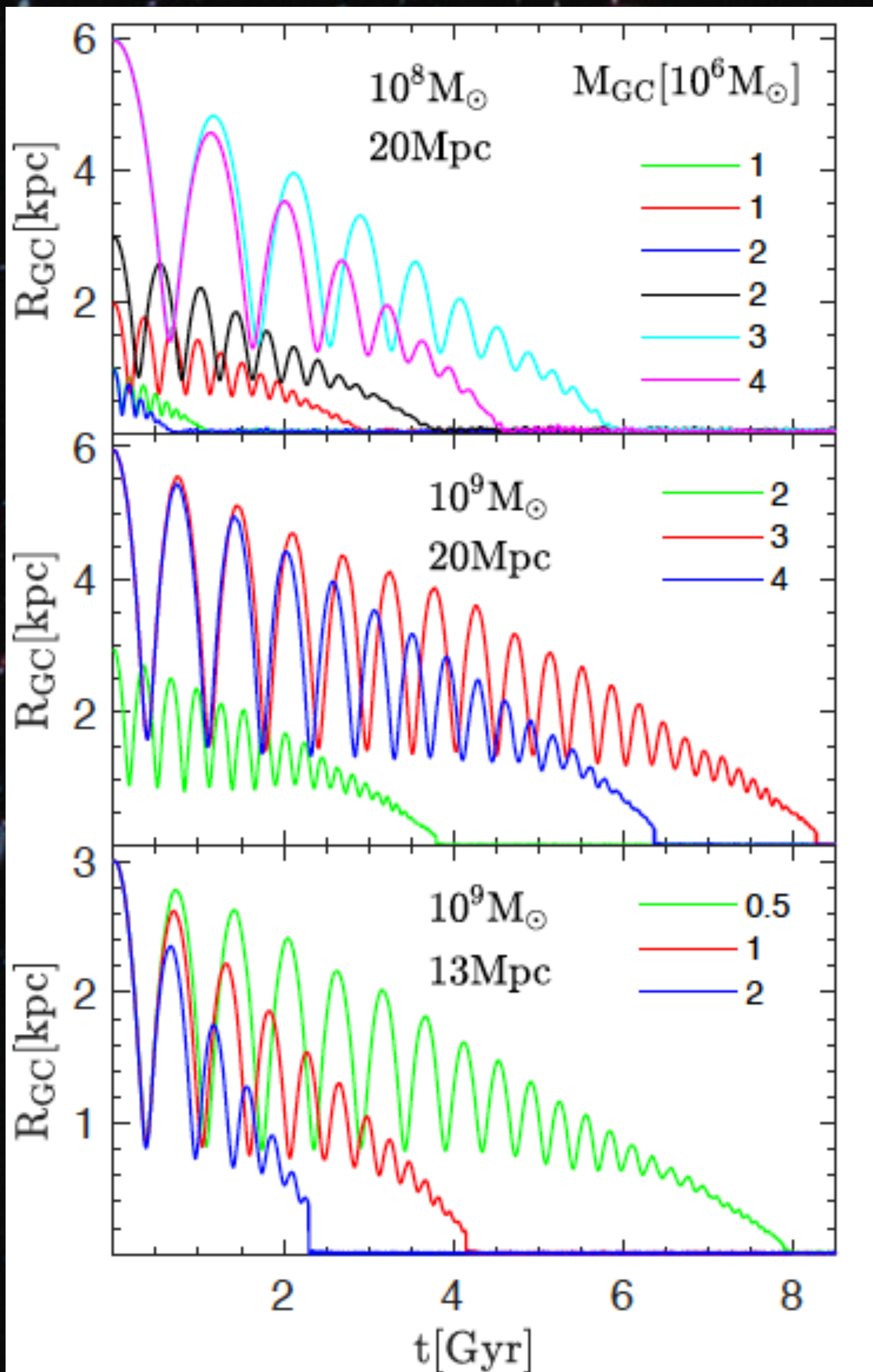


Figure 4. Morphological parameters of the GCs. The top panel shows the circularized half-light radii versus the absolute magnitude, for NGC1052–DF2 (black points with error bars) and the Milky Way (red). Errors in $M_{V,606}$ and r_h include a 10% uncertainty in the distance (see vD18). The bottom panel shows the ellipticity. Means are indicated with dashed lines.

$M_{\rm GC} \sim 10^6 M_\odot$ ***in a*** $M_{\rm halo} \sim 10^8 - 10^9 M_\odot$

DYNAMICAL FRICTION

Dynamical friction in NGC1052-DF2 using simulations



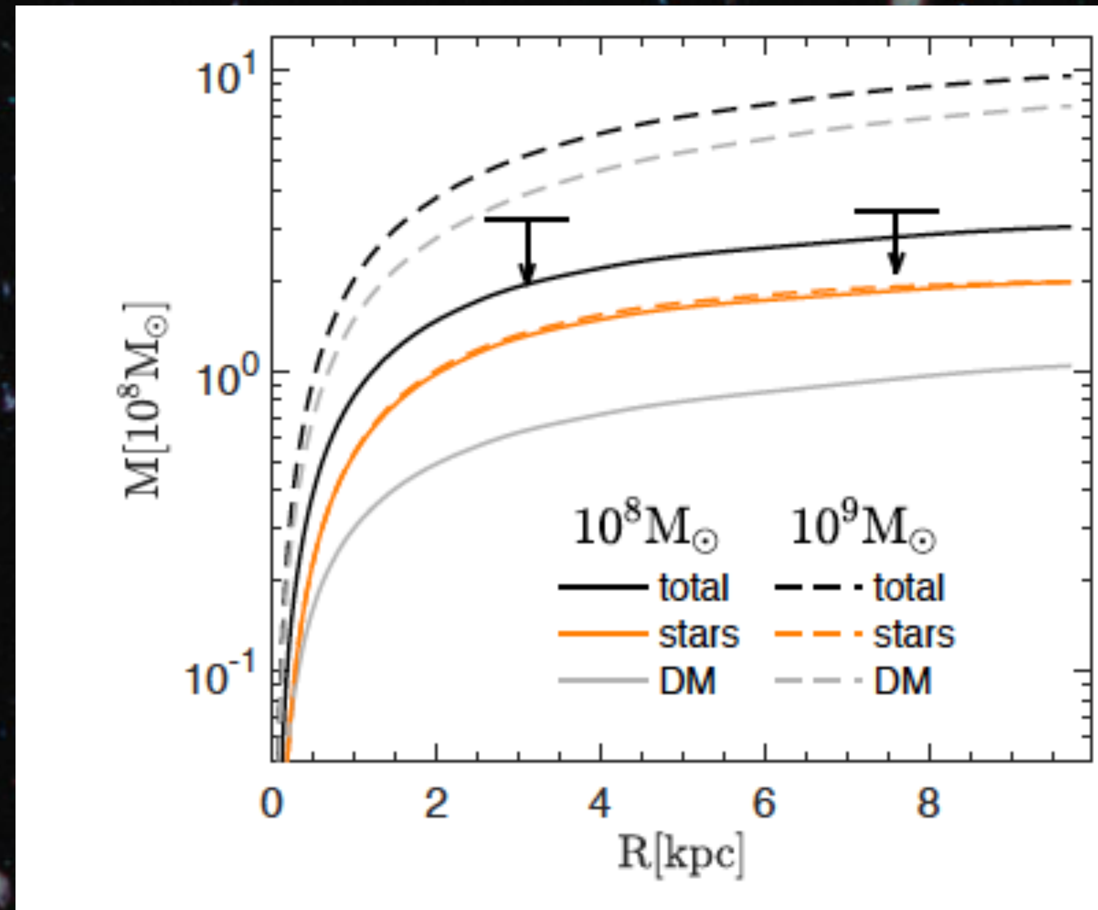


Figure 1. Mass profiles from the simulations run without GCs at an output time $t = 1.5$Gyr. The lower curve represents a low mass galaxy close to the observed 90% mass limits as indicated by the arrows. The upper curve is obtained from a simulation with 4 times the mass in the lower curve.

From a simulation:
Treecode, 2.4×10^5 particles

Could it be like Fornax?

The Fornax conundrum

Fornax is the most massive MW satellite.
Looks very relaxed.
Distance ~ 130 kpc.
Unlike other MW dwarf satellites, it has (5+1) GCs.

Puzzle: none of the GCs has settled to the center by dynamical friction.

Possible solutions:

a. it has a core of constant density at r<1.5kpc (e.g. Cole et al 2012). Core suppressed dynamical friction!?

b. **Special initial configuration for GCs** (Angus & Diaferio 09, Cole et al 12, Boldirini, Mohayaee & Silk 19).

Towards a high mass for NGC1052-DF2

A Deficit of Dark Matter from Jeans Modeling of the Ultra-diffuse Galaxy NGC 1052-DF2

Asher Wasserman,[1] Aaron J. Romanowsky,[2,3] Jean Brodie,[1,3] Pieter van Dokkum,[4] Charlie Conroy,[5] Roberto Abraham,[6] Yotam Cohen,[4] and Shany Danieli[4]

relation are in tension with the data and also require a large central density core. Better fits are obtained when the halo mass is left free, even after accounting for increased model complexity. The dynamical mass-to-light ratio for our model with a weak prior on the halo mass is $1.7^{+0.7}_{-0.5}\ M_\odot/L_{\odot,V}$, consistent with the stellar population estimate for DF2. We use tidal analysis to find that the low-mass

Mhalo~10^9M$_{sun}$

I will challenge that conclusion

NGC 1052-DF2 is associated with a larger galaxy, NGC 1052, at a projected distance of ~75 kpc

$$V_{\rm rel} = |V_{\rm DF2} - V_{1052}| \approx 293 kms^{-1}$$

$$\sigma_{1052}^{\rm los} \approx 110 kms^{-1}, \quad V_{\rm c}^{HI} \sim 200 kms^{-1}$$

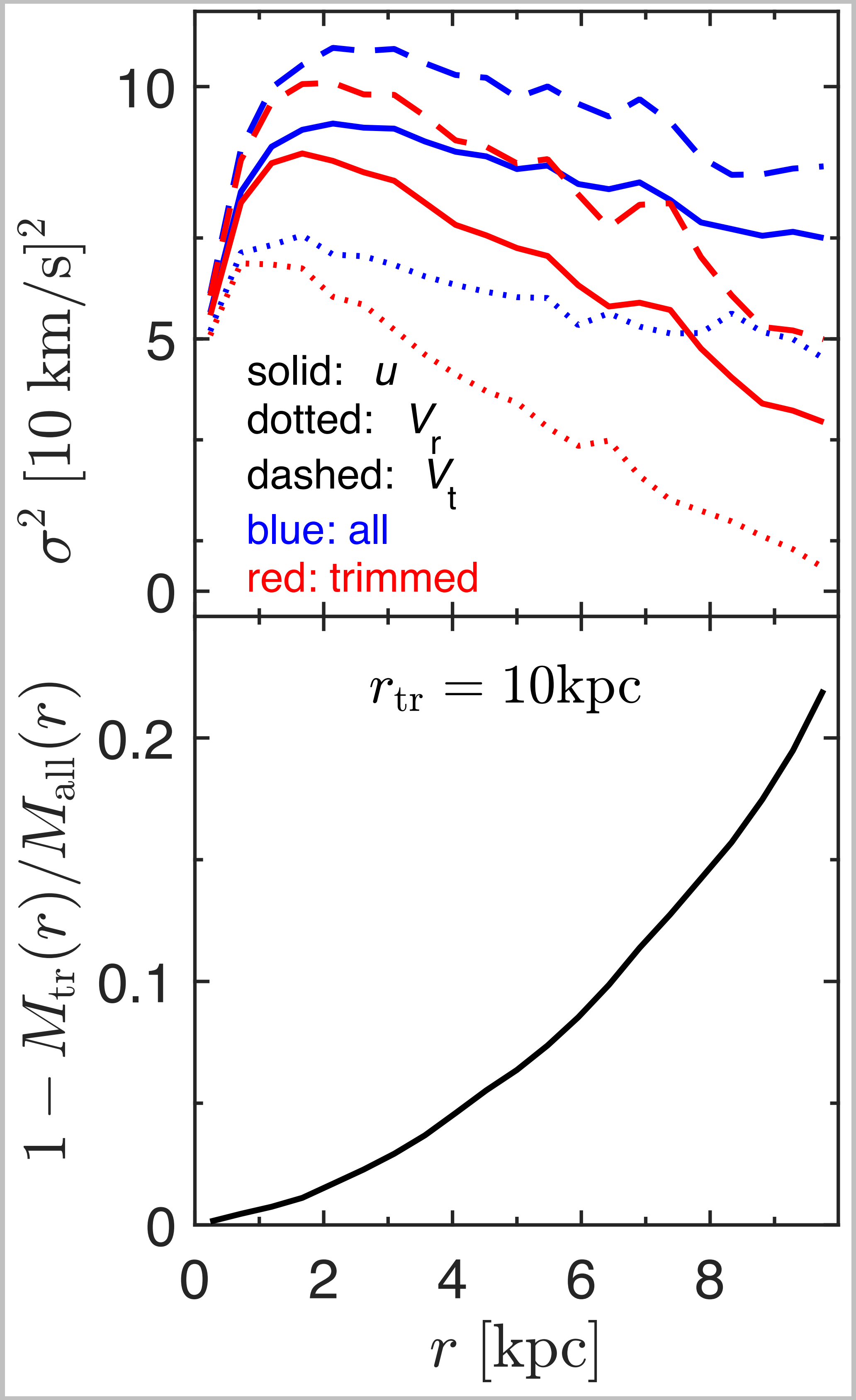
$$So \quad V_{\rm rel} \sim V_{\rm esc}!!!$$

But SHMR implies larger mass for NGC 1052

Perhaps it was tidally stripped by the larger galaxy!?

Tidal stripping reduces the velocity dispersion by eliminating high velocity particles.

From a simulation: tidal stripping and velocity dispersion



Observables

10 star clusters- could be Globular Clusters with unusual properties

observed

$$R_{0i} = R_i$$

true projected

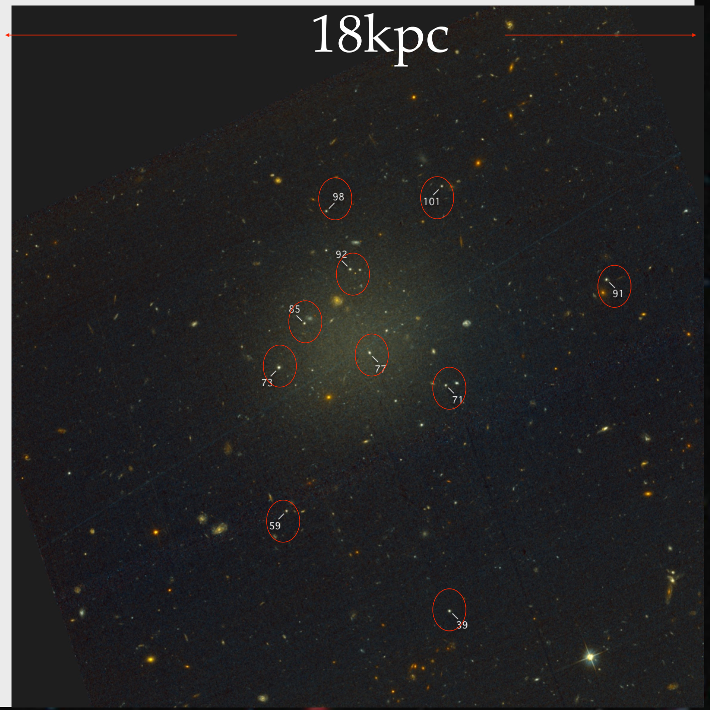
$$u_{0i} = u_i + u_{\rm sys} + \delta u_i$$

error in vel.

observed velocity

true vel.

unknown systemic vel.
to within 5km/s



Analysis

Maximum likelihood for the observed quantities given a mass model

$$\mathcal{L} = \int \mathrm{d}u_{\mathrm{sys}} P(u_{\mathrm{sys}}) \prod_i \int \mathrm{d}u_i G(u_{0i}|u_i + u_{\mathrm{sys}}) \boxed{F(u_i, R_{0i})\ .}$$

measurement errors

physical model

$$F(u, R) = \int \mathrm{d}z f_u(u, r = \sqrt{R^2 + z^2})$$

3D to 1D

$$f_u(u, r) = 2\pi \int_0^{\mathcal{E}_{\mathrm{m}}} \mathrm{d}\mathcal{E} f(\mathcal{E})$$

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2} \frac{\mathrm{d}}{\mathrm{d}\mathcal{E}} \int_0^{\mathcal{E}} \frac{\mathrm{d}\Psi}{\sqrt{\mathcal{E}-\Psi}} \frac{\mathrm{d}\nu}{\mathrm{d}\Psi}$$

Ergodic (isotropic vel. dispersion) phase space DF

$$\mathcal{E} = \Psi - v^2/2 \quad \text{and} \quad \Psi = -\Phi$$

potential from mass model

$$\nu \propto r^{-\gamma}$$

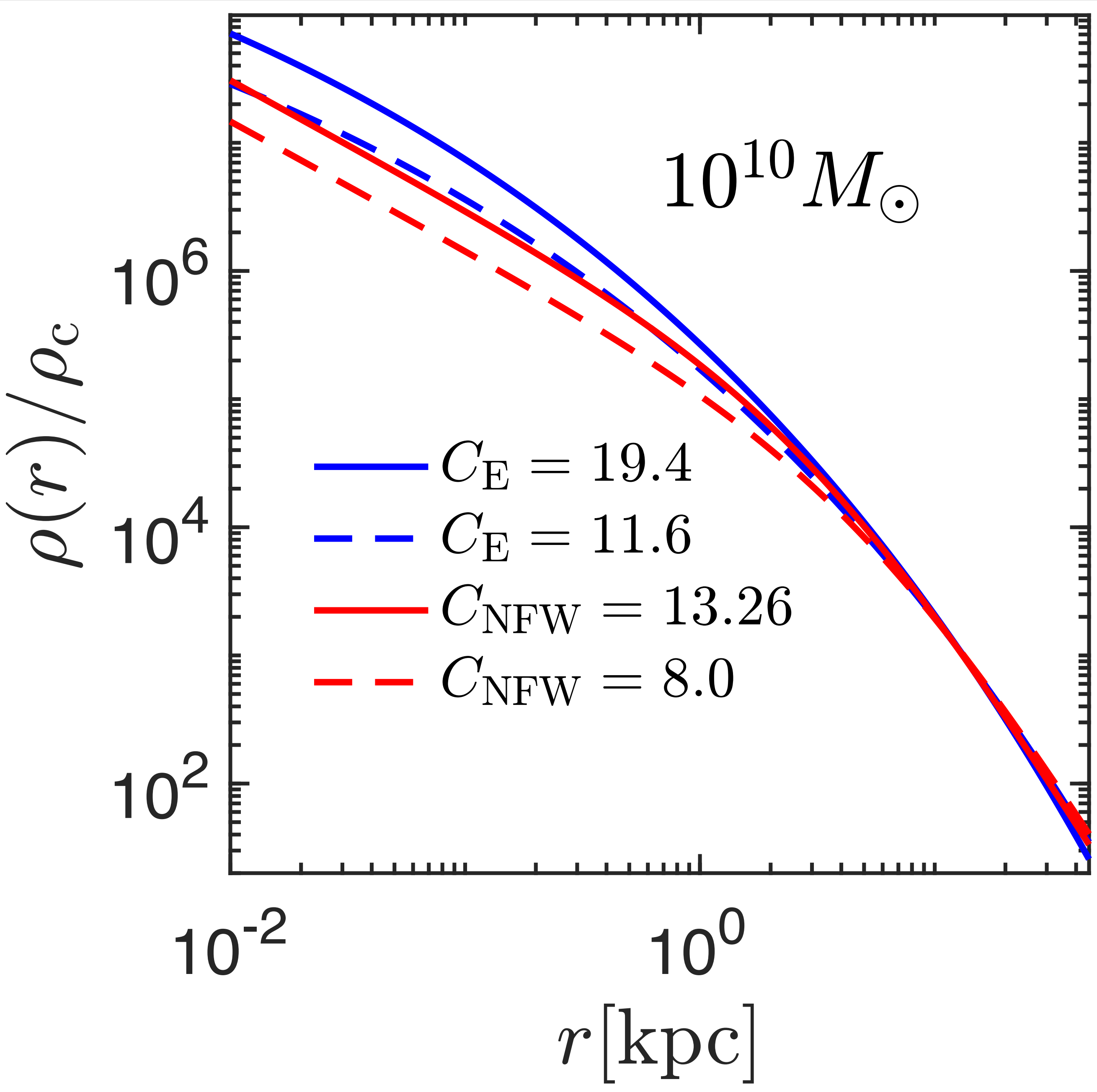
distribution of tracers

Mass Model

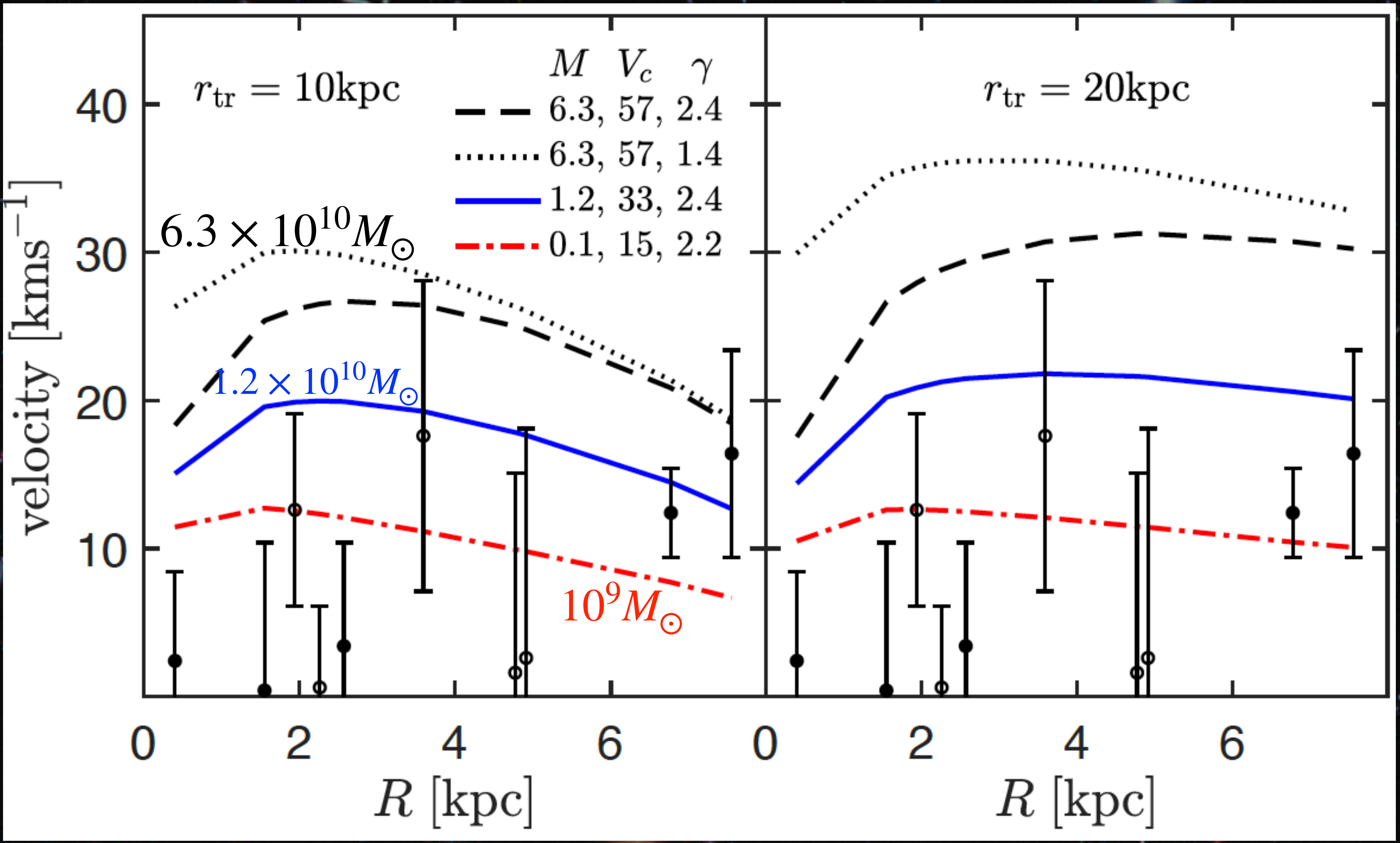
We compute $\mathcal{L}$ as a function of **virial mass** for **NFW** and **Einasto profiles**

Two values of halo **concentrations**: ***C(M)*** and ***0.6C(M)***

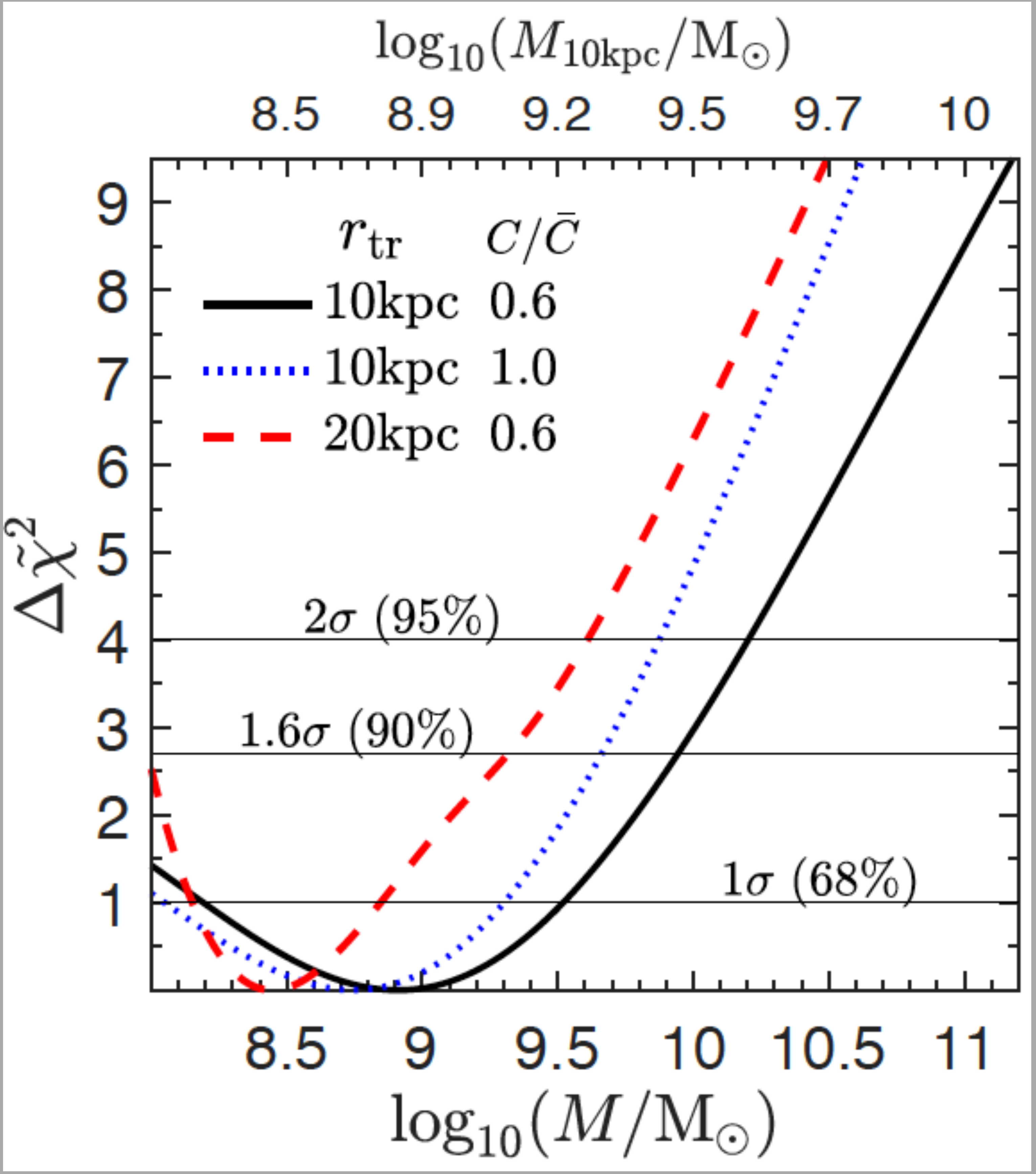
Tidal stripping radius is fixed at ***10kpc***



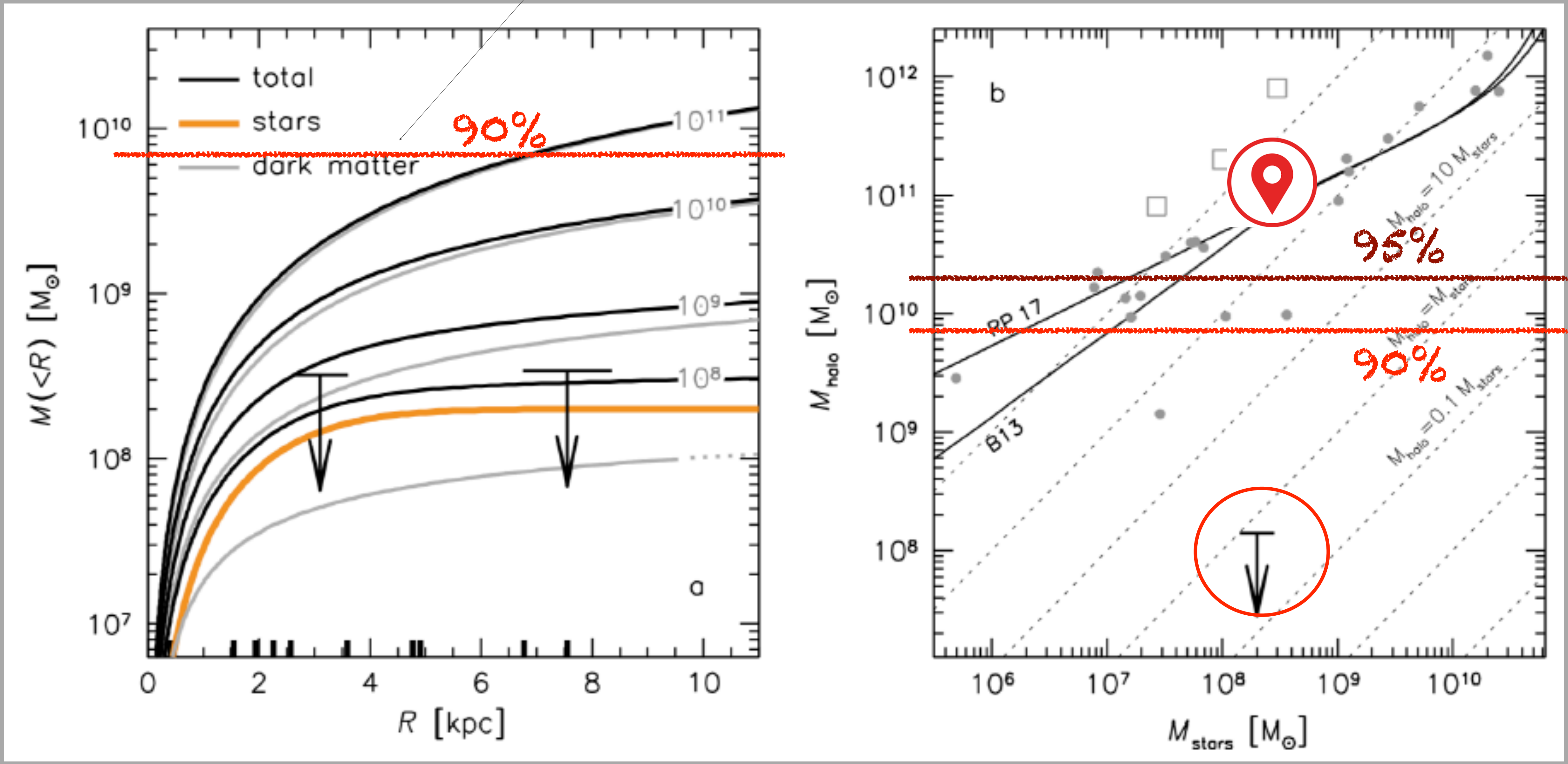
M in $10^{10}\ M_{sun}$ V_C in km/s



$-2\log\mathcal{L}/\mathcal{L}_{min}$ vs Mass only



This talk



total
stars
dark matter
90%
10^{11}
10^{10}
10^{9}
10^{8}
a
$M(<R)$ [$M_\odot$]
R [kpc]
b
95%
90%
RP 17
B13
$M_{halo}=10\,M_{stars}$
$M_{halo}=M_{stars}$
$M_{halo}=0.1\,M_{stars}$
M_{halo} [$M_\odot$]
M_{stars} [$M_\odot$]

The ultra-diffuse galaxy NGC 1052-DF2 with MUSE: I. Kinematics of the stellar body*

Eric Emsellem[1,2], Remco F. J. van der Burg[1], Jérémy Fensch[1], Tereza Jerabkova[1,3,4], Anita Zanella[1], Adriano Agnello[1,5], Michael Hilker[1], Oliver Mller[6], Marina Rejkuba[1], Pierre-Alain Duc[6], Patrick Durrell[7], Rebecca Habas[8], Federico Lelli[1], Sungsoon Lim[9], Francine R. Marleau[8], Eric Peng[10,11], Rubén Sánchez-Janssen[12]

rotator. We estimate a velocity dispersion from the clusters and PNe of $\sigma_{\rm int} = 10.6^{+3.9}_{-2.3}$ km s^{-1}. The velocity dispersion $\sigma_{\rm DF2\star}(R_{\rm e})$ for the stellar body within one effective radius is $10.8^{-4.0}_{+3.2}$ km s^{-1}. Considering various sources of systemic uncertainties, this central value varies between 5 and 13 km s^{-1}, and we conservatively report a 95% confidence upper limit to the dispersion within one $R_{\rm e}$ of 21 km s^{-1}. We provide updated mass estimates based on these dispersions corresponding to the different distances to NGC 1052-DF2 that have been reported in the recent literature.

BUT,

We expect stellar velocity dispersions for the UDG and clusters typically between 5 and 35 km s^{-1}, which thus represent a substantial fraction of the spectral resolution of the MUSE datacube (σ_{inst} going from $\sim$ 35 to 80 km s^{-1}). To estimate the velocity

And THEN,

Still Missing Dark Matter: KCWI High-Resolution Stellar Kinematics of NGC1052-DF2

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ABSTRACT

The velocity dispersion of the ultra diffuse galaxy NGC1052-DF2 was found to be $\sigma_{\rm gc} = 7.8^{+5.2}_{-2.2}\,{\rm km\,s^{-1}}$, much lower than expected from the stellar mass – halo mass relation and nearly identical to the expected value from the stellar mass alone. This result was based on the radial velocities of ten luminous globular clusters that were assumed to be associated with the galaxy. A more precise measurement is possible from high resolution spectroscopy of the diffuse stellar light. Here we present an integrated spectrum of the diffuse light of NGC1052-DF2 obtained with the Keck Cosmic Web Imager, with an instrumental resolution of $\sigma_{\rm instr} \approx 12\,{\rm km\,s^{-1}}$. The systemic velocity of the galaxy is $v_{\rm sys} = 1805 \pm 1.1\,{\rm km\,s^{-1}}$, in very good agreement with the average velocity of the globular clusters ($\langle v_{\rm gc} \rangle = 1803 \pm 2\,{\rm km\,s^{-1}}$). There is no evidence for rotation within the KCWI field of view. We find a stellar velocity dispersion of $\boxed{\sigma_{\rm stars} = 8.4 \pm 2.1\,{\rm km\,s^{-1}}}$, consistent with the dispersion that was derived from the globular clusters. The implied dynamical mass within the half-light radius $r_{1/2} = 2.7\,{\rm kpc}$ is $M_{\rm dyn} = (1.3 \pm 0.8) \times 10^8\,{\rm M}_\odot$, similar to the stellar mass within that radius ($M_{\rm stars} = (1.0 \pm 0.2) \times 10^8\,{\rm M}_\odot$). With this confirmation of the low velocity dispersion of NGC1052-DF2, the most urgent question is whether this "missing dark matter problem" is unique to this galaxy or applies more widely.

A SECOND GALAXY MISSING DARK MATTER IN THE NGC 1052 GROUP

PIETER VAN DOKKUM[1], SHANY DANIELI[1], ROBERTO ABRAHAM[2], CHARLIE CONROY[3], AARON J. ROMANOWSKY[4,5]

The ultra-diffuse galaxy NGC1052-DF2 has a very low velocity dispersion, indicating that it has little or no dark matter. Here we report the discovery of a second galaxy in this class, residing in the same group. NGC1052-DF4 closely resembles NGC1052-DF2 in terms of its size, surface brightness, and morphology; has a similar distance of $D_{\rm sbf} = 19.9 \pm 2.8$ Mpc; and also has a population of luminous globular clusters extending out to ≥ 7 kpc from the center of the galaxy. Accurate radial velocities of the diffuse galaxy light and seven of the globular clusters were obtained with the Low Resolution Imaging Spectrograph on the Keck I telescope. The velocity of the diffuse light is identical to the median velocity of the clusters, $v_{\rm sys} = \langle v_{\rm gc} \rangle = 1445\,{\rm km\,s^{-1}}$, and close to the central velocity of the NGC1052 group. The rms spread of the globular cluster velocities is very small at $\sigma_{\rm obs} = 5.8\,{\rm km\,s^{-1}}$. Taking observational uncertainties into account we determine an intrinsic velocity dispersion of $\boxed{\sigma_{\rm intr} = 4.2^{+4.4}_{-2.2}\,{\rm km\,s^{-1}}}$, consistent with the expected value from the stars alone ($\sigma_{\rm stars} \approx 7\,{\rm km\,s^{-1}}$) and lower than expected from a standard NFW halo ($\sigma_{\rm halo} \sim 30\,{\rm km\,s^{-1}}$). We conclude that NGC1052-DF2 is not an isolated case but that a class of such objects exists. The origin of these large, faint galaxies with an excess of luminous globular clusters and an apparent lack of dark matter is, at present, not understood.

For simplicity we assume that $\beta = 0$ and that the globular clusters trace the potential, so that $\gamma = \alpha + 2$. If all the mass is in stars the potential is similar to that of a point mass for most of the globular clusters; hence we use $\alpha = 1$ and $\gamma = 3$.

Some thoughts:

- Criticism of Wasserman et al and van Dokkum et al based on bias in v-disp from GCs is largely unjustified.
- **Similarity to Fornax! Maybe not too similar.**
- **Could DF2 have a core of constant density for R<2.4kpc ?** A core could greatly suppress dynamical friction, but there is a caveat.
- Stellar velocity dispersion?
- **Is DF2 really affected by strong tides?**
- **Suppose the galaxy has no DM at all.** *Is it a problem? What does it mean?*