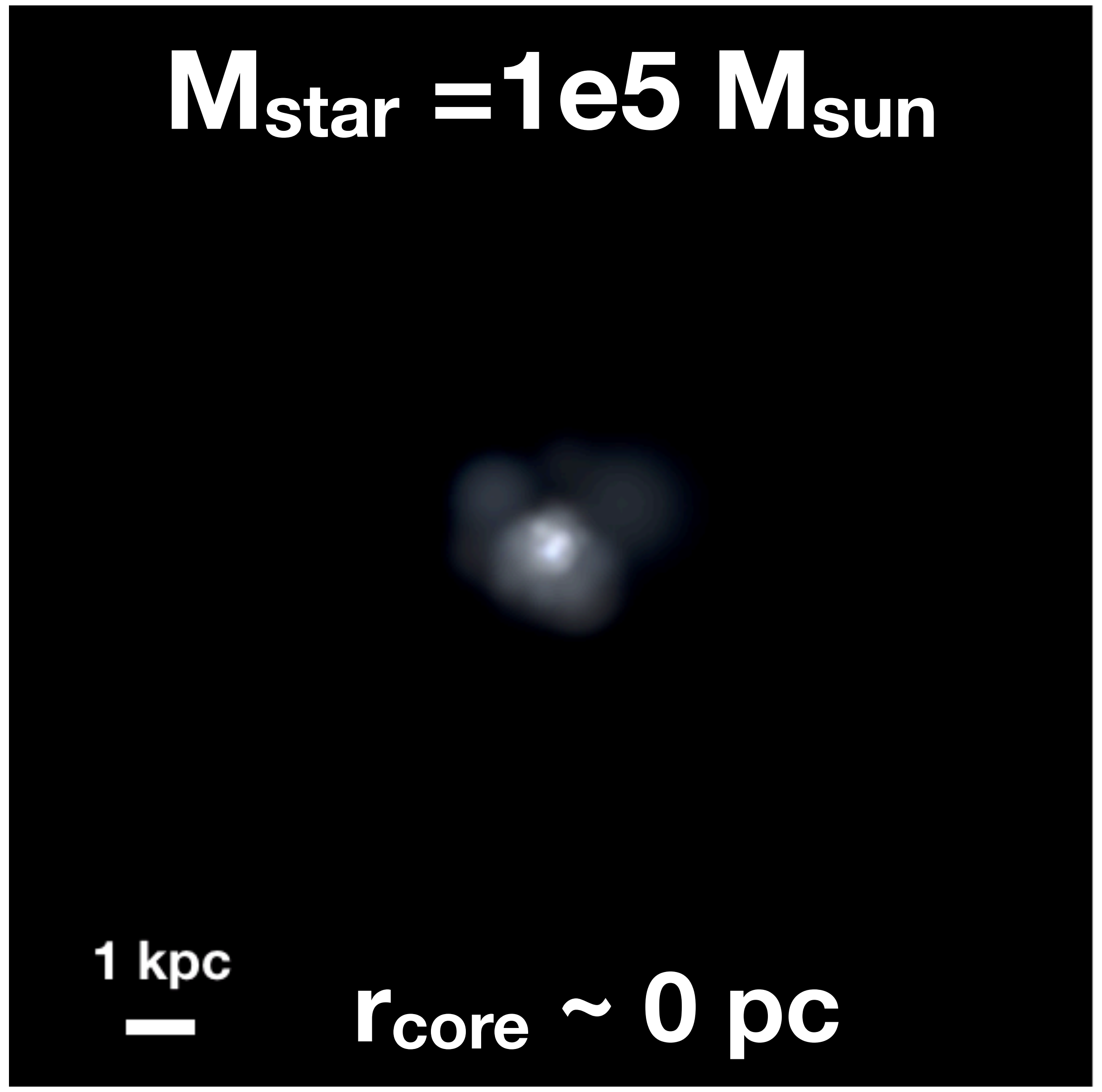
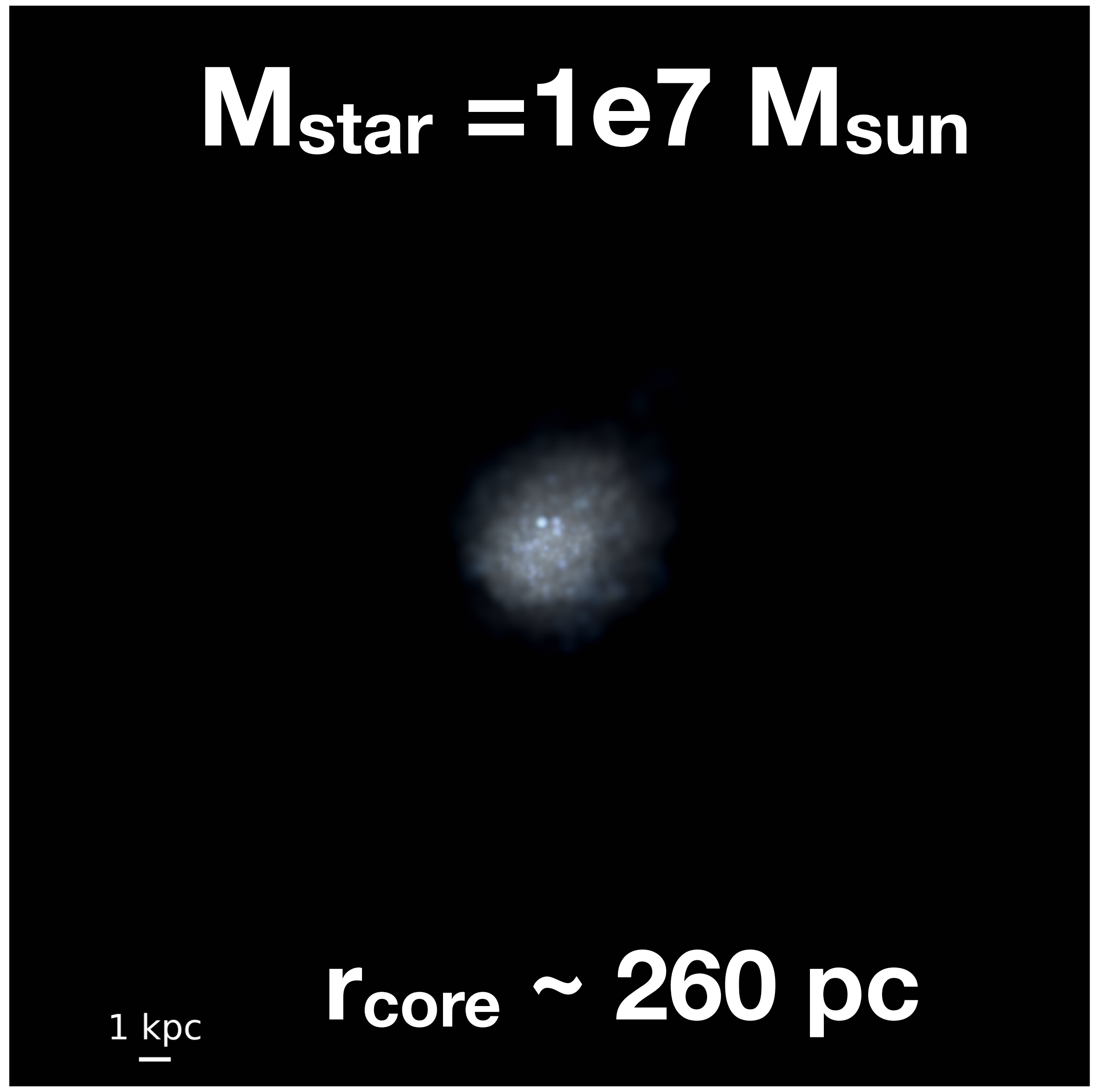
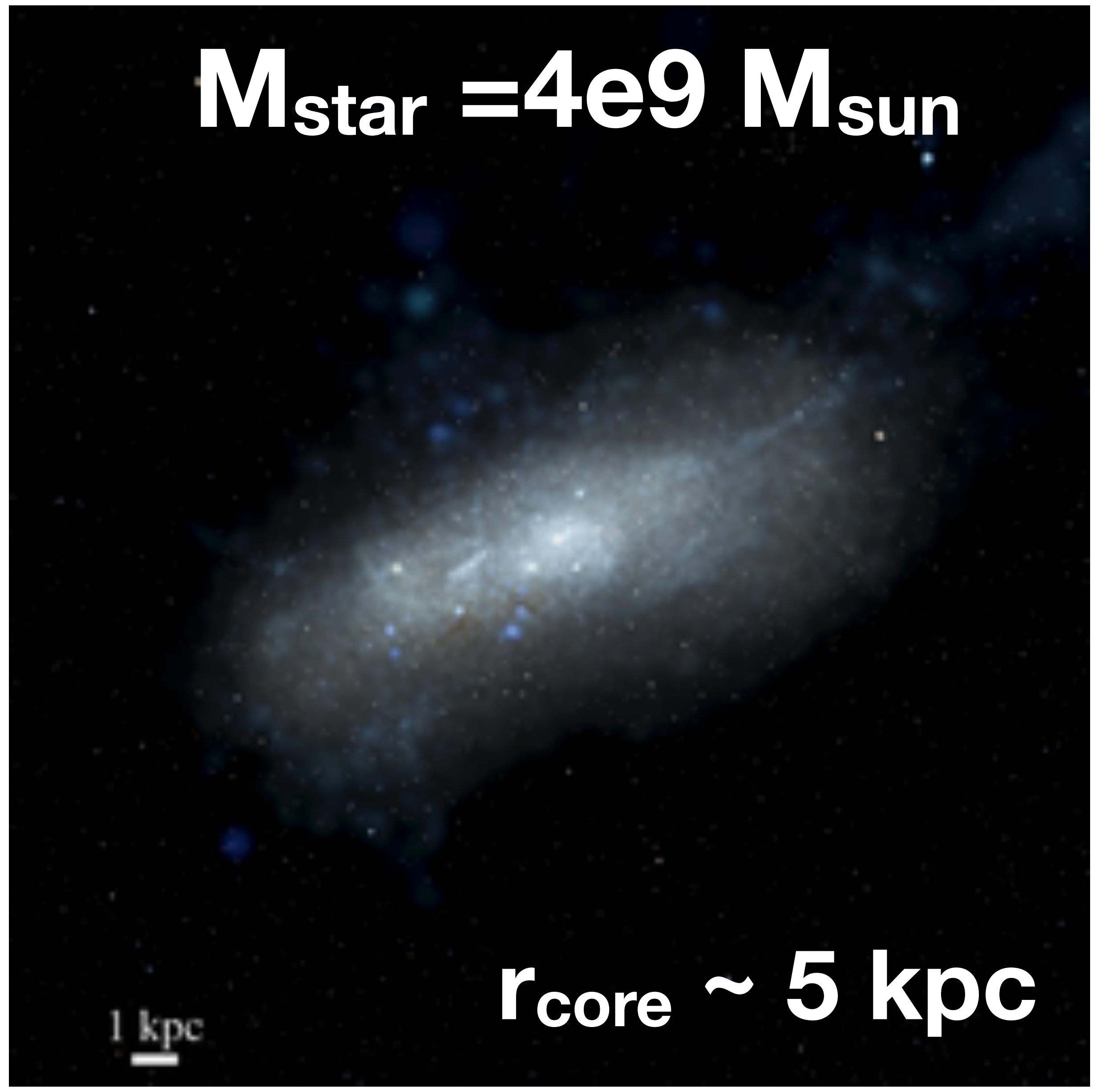
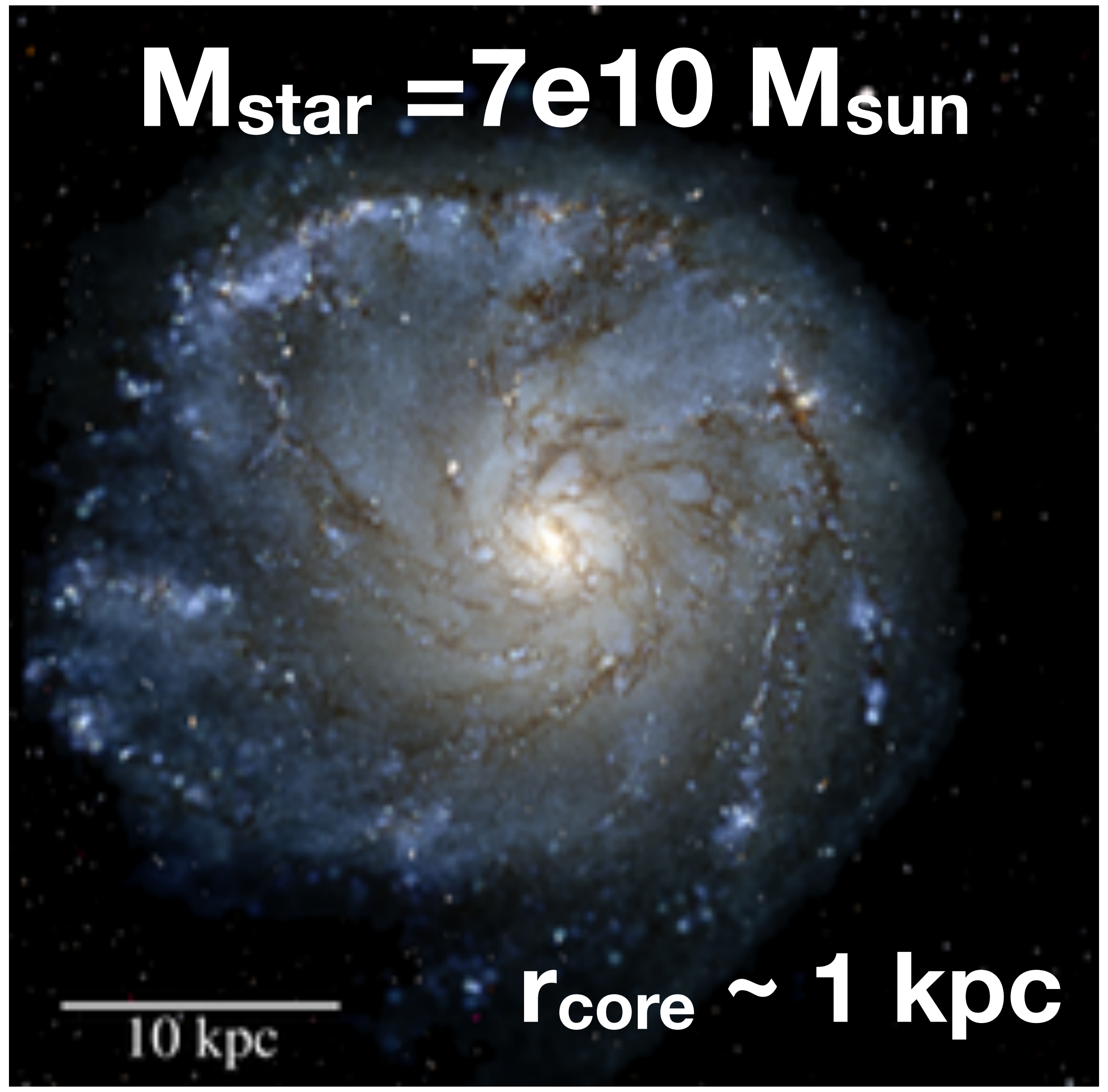
Dark Matter Profiles in Tiny Galaxies (and others too)

James Bullock (University of California, Irvine)









FIRE
Feedback In Realistic Environments

Primarily work by Alexandres Lazar

Outline

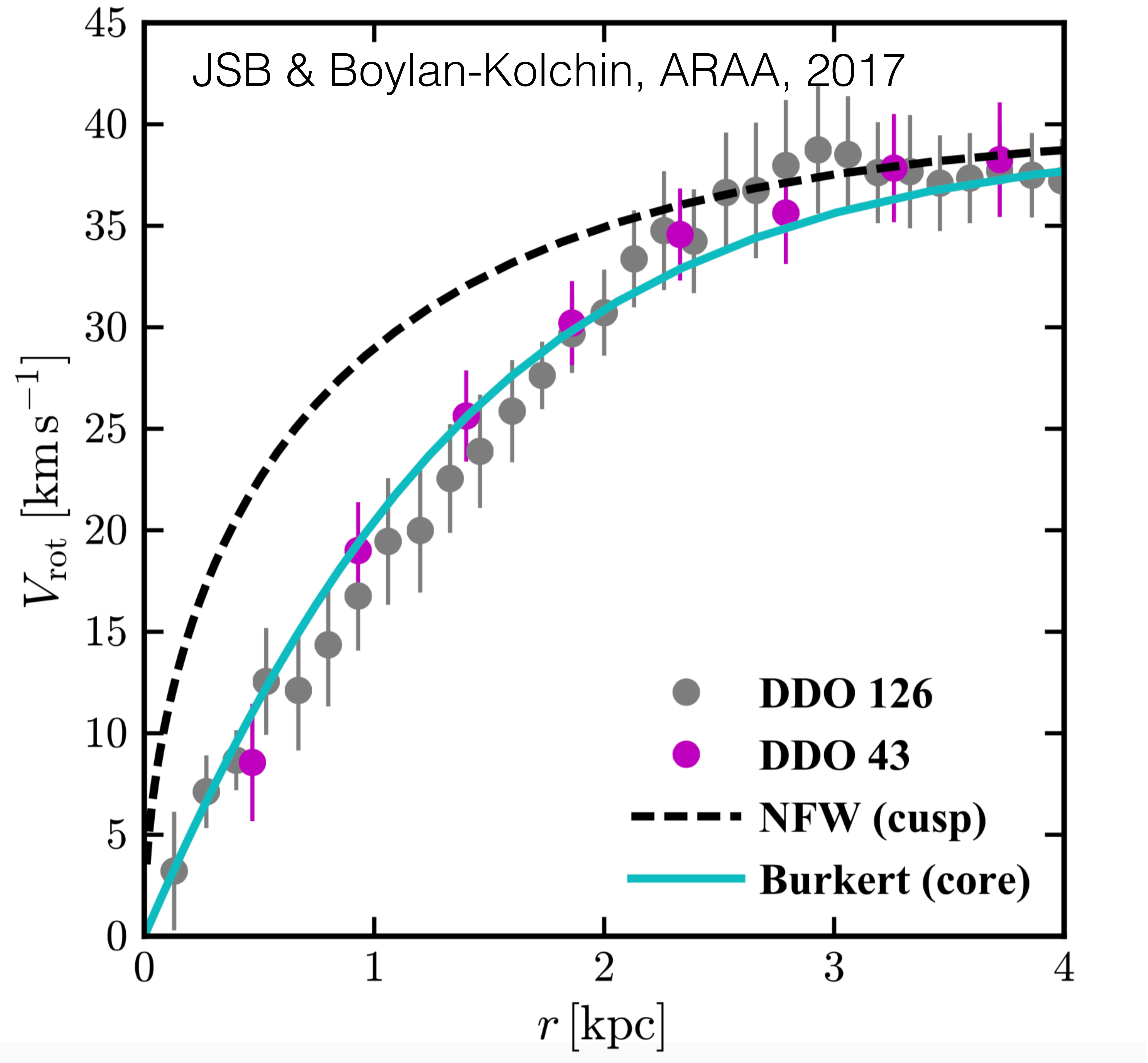
One: Dark Matter density profiles in FIRE-2 simulations

— A Universal “core-Einasto” profile from tiny dwarfs to the Milky Way.

Two: A new mass estimator for transverse velocity dispersions in spheroidal galaxies

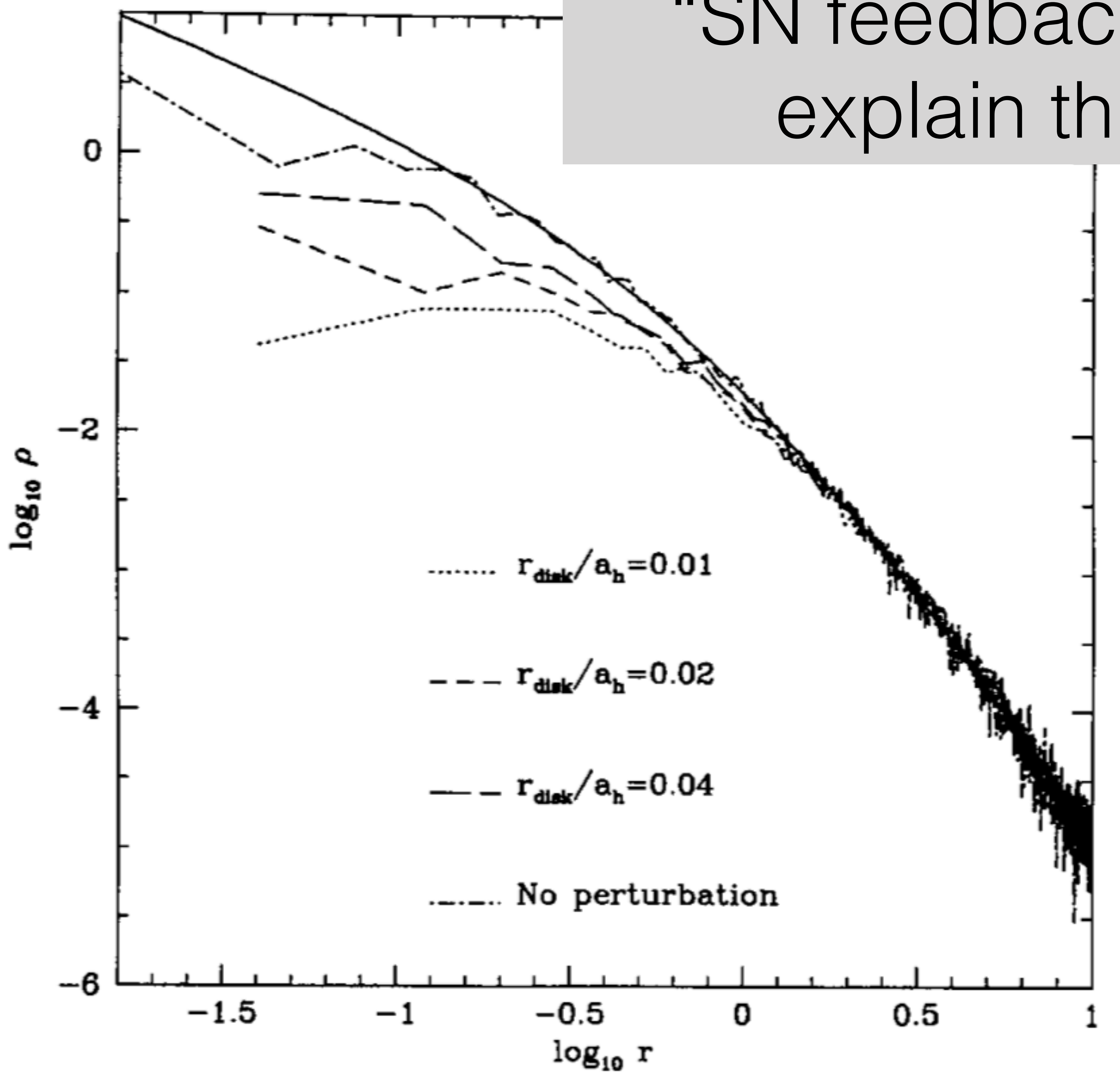
— Implication for profile slopes in Sculptor & Draco

Cusp/Core Problem



Flores & Primack 94; Moore 94

“SN feedback can explain this”



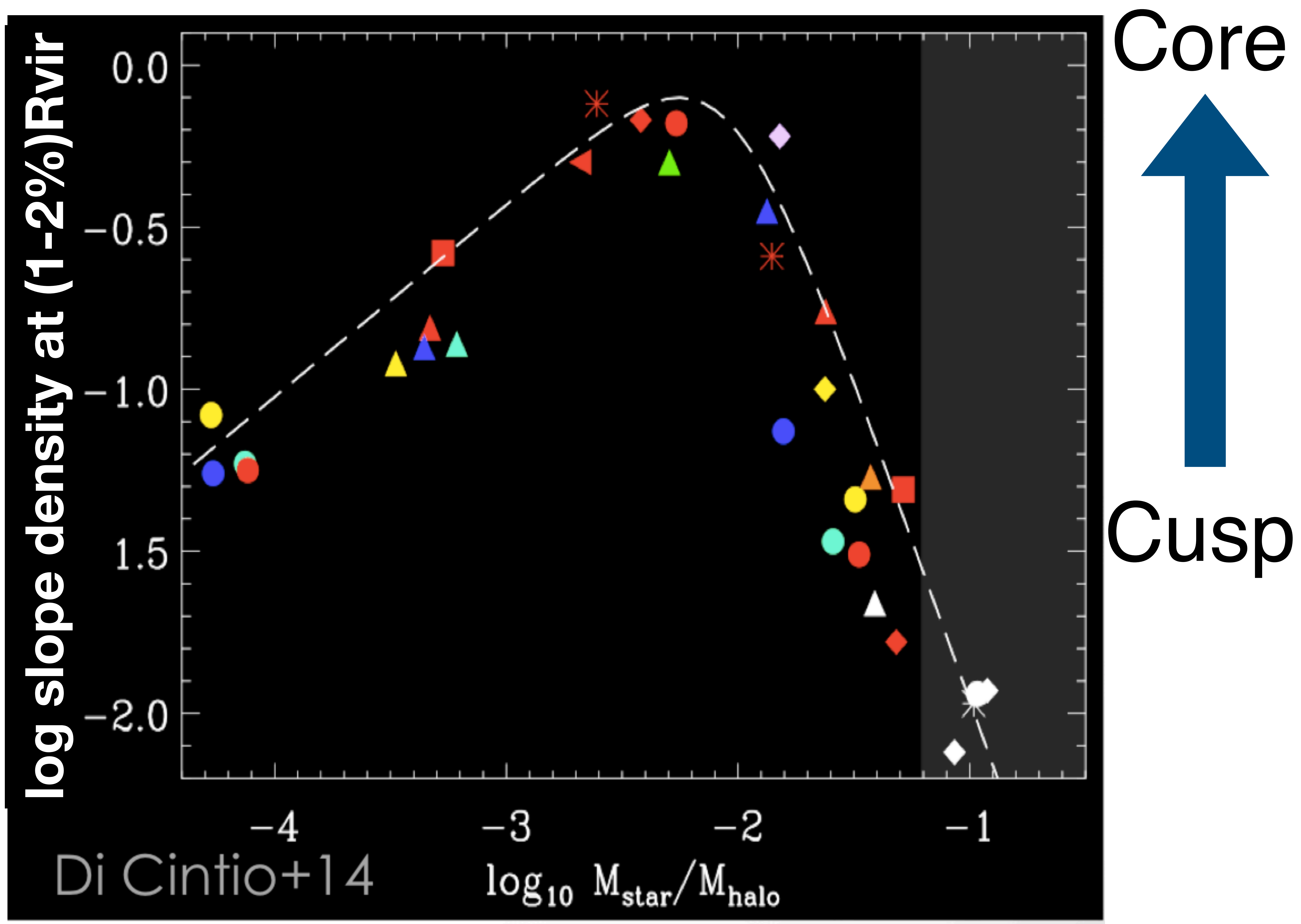
Navarro, Eke & Frenk 1996

Cusp/Core Problem

Predict “sweet spot” for core formation is bright dwarfs:

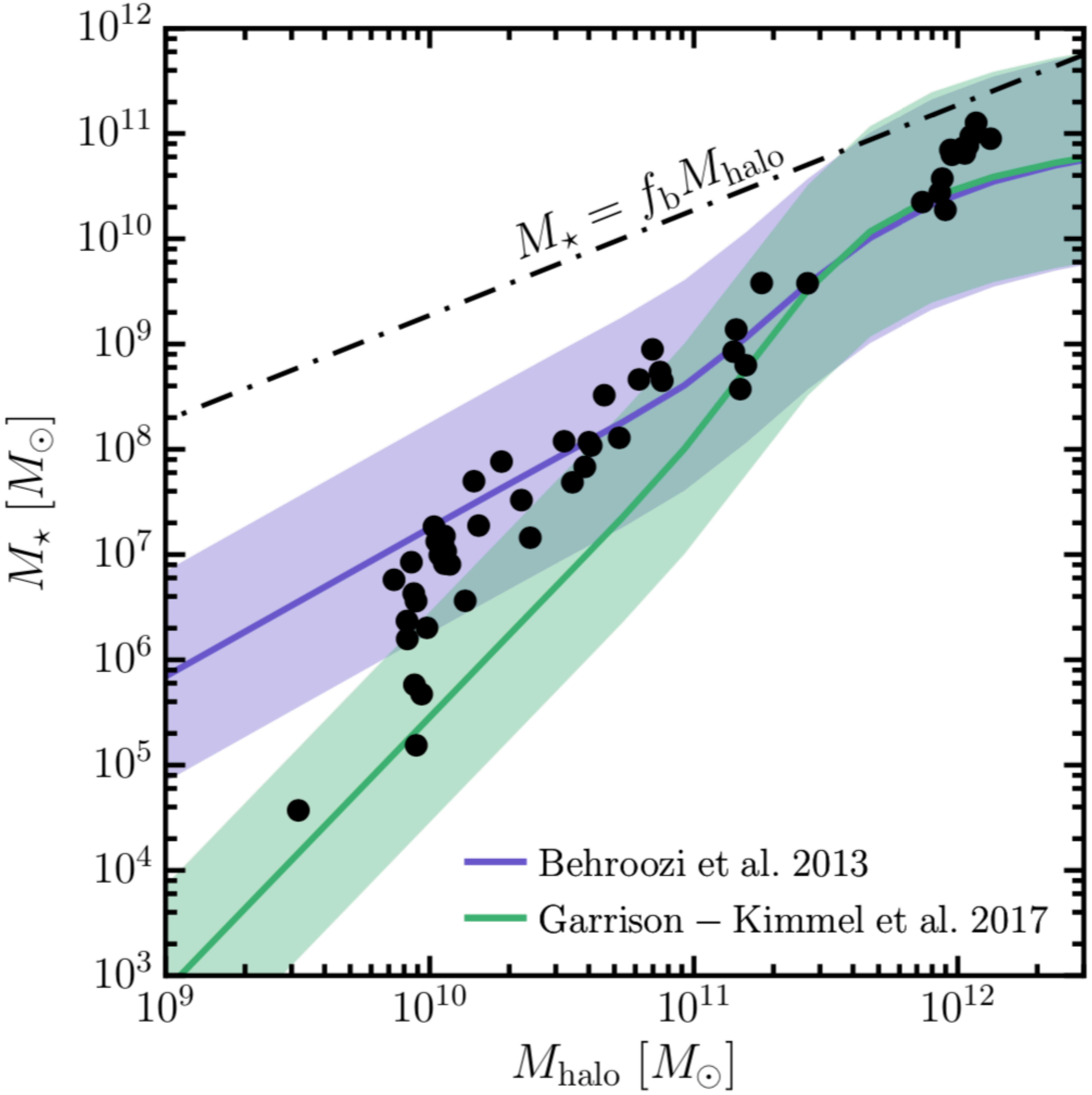
$$M_\star/M_{\rm halo} \simeq 0.005$$

Di Cintio + 2014



see also Governato+12,Brooks & Zolotov 12, Read+16, etc.

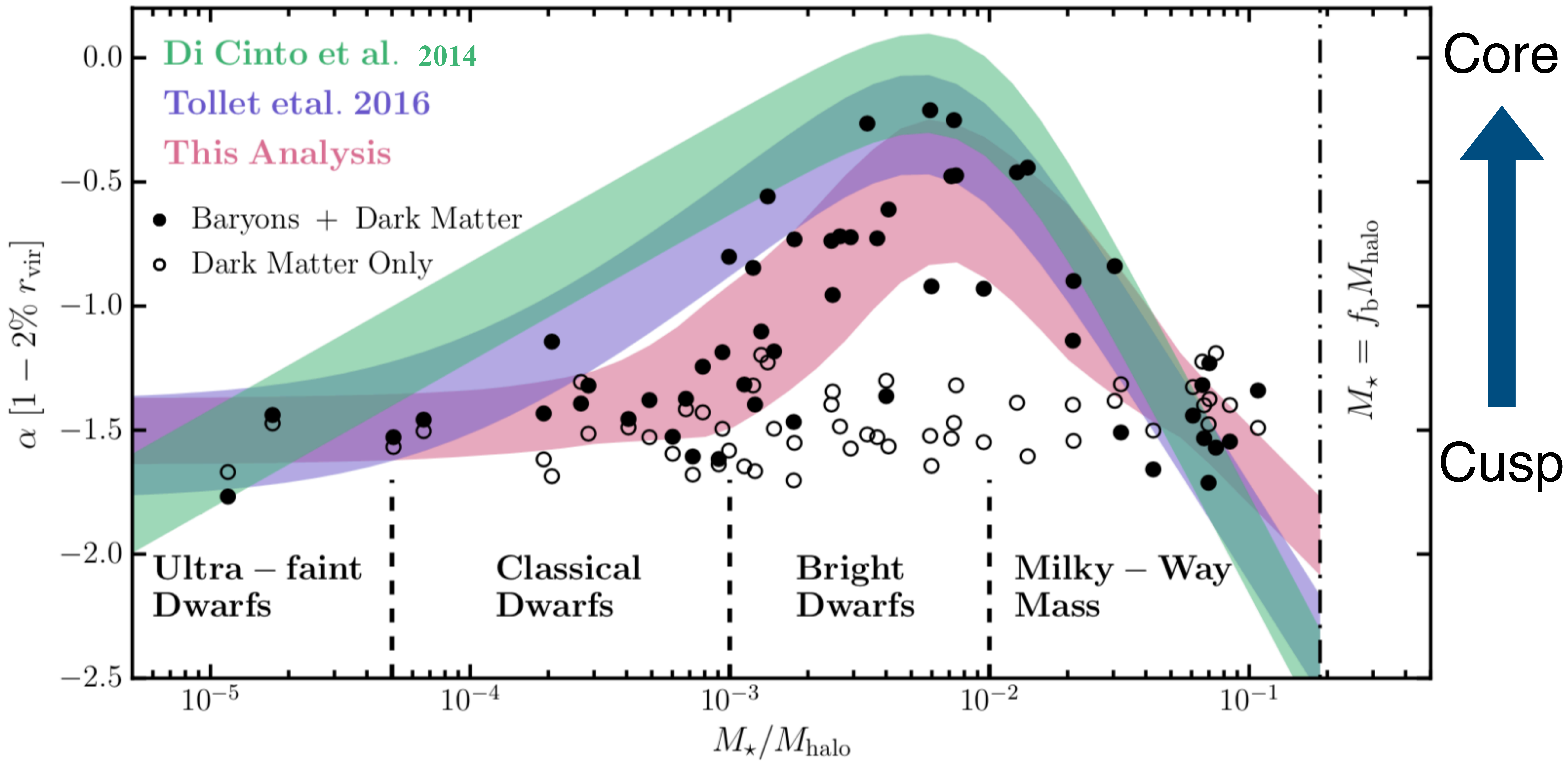
Simulations



See Hopkins+2018

53 galaxies simulated at high-resolution with FIRE2 physics.
- Each resolved to 0.5% of the virial radius

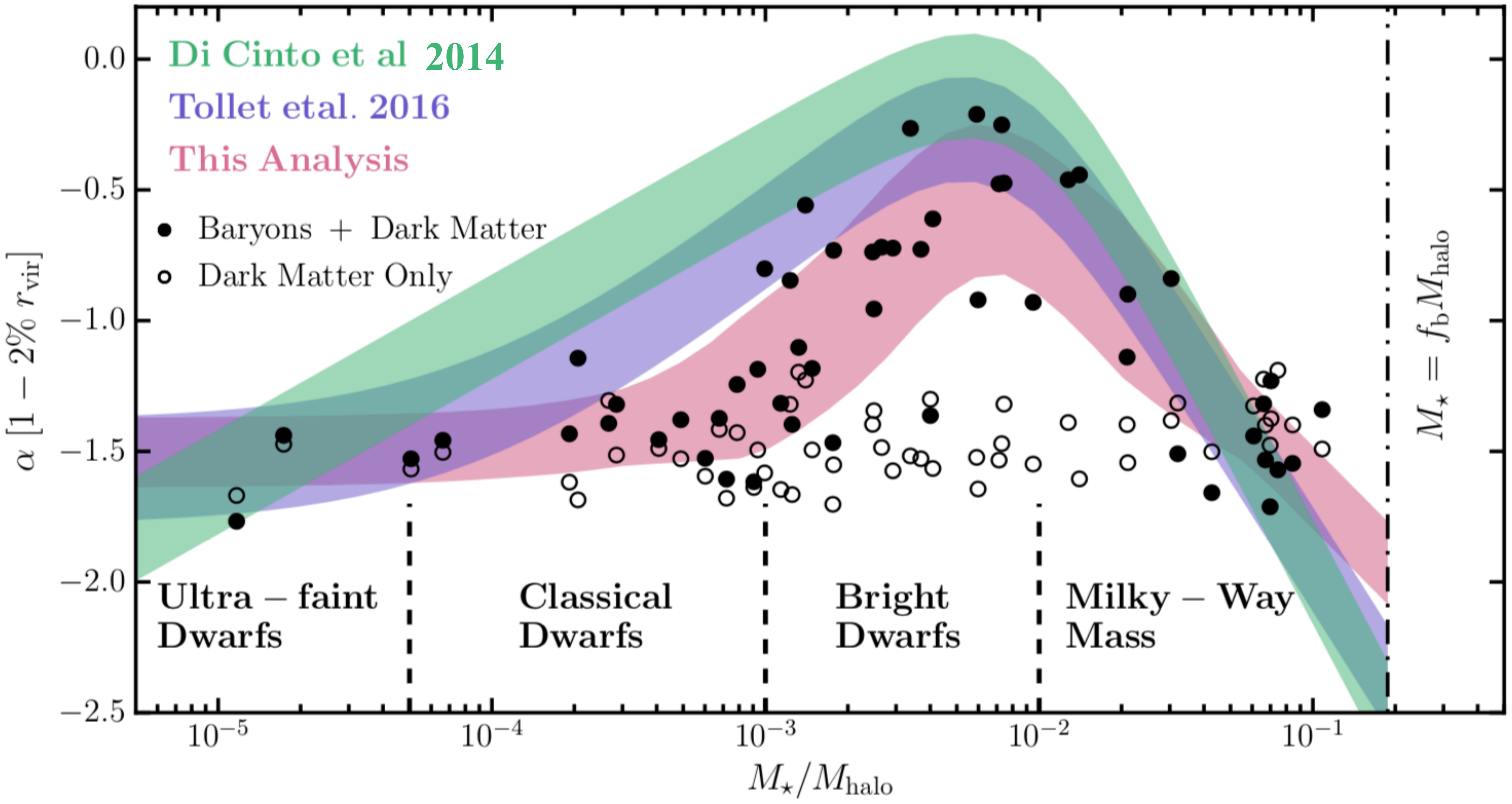
Lazar et al. 2019



Lazar et al. 2019

see also Governato+12,Brooks & Zolotov 12, Read+16, etc.

Lazar et al. 2019



Agreement with past work:

"Sweet spot" for core formation is bright dwarfs:

$M_\star / M_{halo} \simeq 0.005 \qquad M_\star \simeq 10^9 M_\odot$

Smallest dwarfs remain cuspy

Differences:

FIRE-2 simulations have **more diversity** / scatter in core properties

Threshold for core formation is somewhat higher

$M_\star \lesssim 10^6 M_\odot$ ← remain cuspy

A Universal Density Profile for Galaxy-Occupied Dark Matter Halos

Einasto:

(Navarro 2004)

$$\rho_{\rm Ein}(r) = \rho_{-2} \exp\left\{-\frac{2}{\hat{\alpha}}\left[\left(\frac{r}{r_{-2}}\right)^{\hat{\alpha}} - 1\right]\right\}$$

$\hat{\alpha} = 0.16$

Great for Dark Matter Only

2 parameters, better than NFW

Core Radius

Core-Einasto:

$$\rho_{\rm cEin}(r) = \tilde{\rho}_s \exp\left\{-\frac{2}{\hat{\alpha}}\left[\left(\frac{r + r_c}{\tilde{r}_s}\right)^{\hat{\alpha}} - 1\right]\right\}$$

$\hat{\alpha} = 0.16$

Great for our hydro runs

3 parameters, better than cNFW, Burkert, etc.

Lazar et al. 2019

Core-Einasto: Excellent fit to DM in hydro simulations

$M_{star} = 2.10^5\ M_{sun}$ | $M_{star} = 5.10^6\ M_{sun}$ | $M_{star} = 5.10^9\ M_{sun}$ | $M_{star} = 8.10^{10}\ M_{sun}$

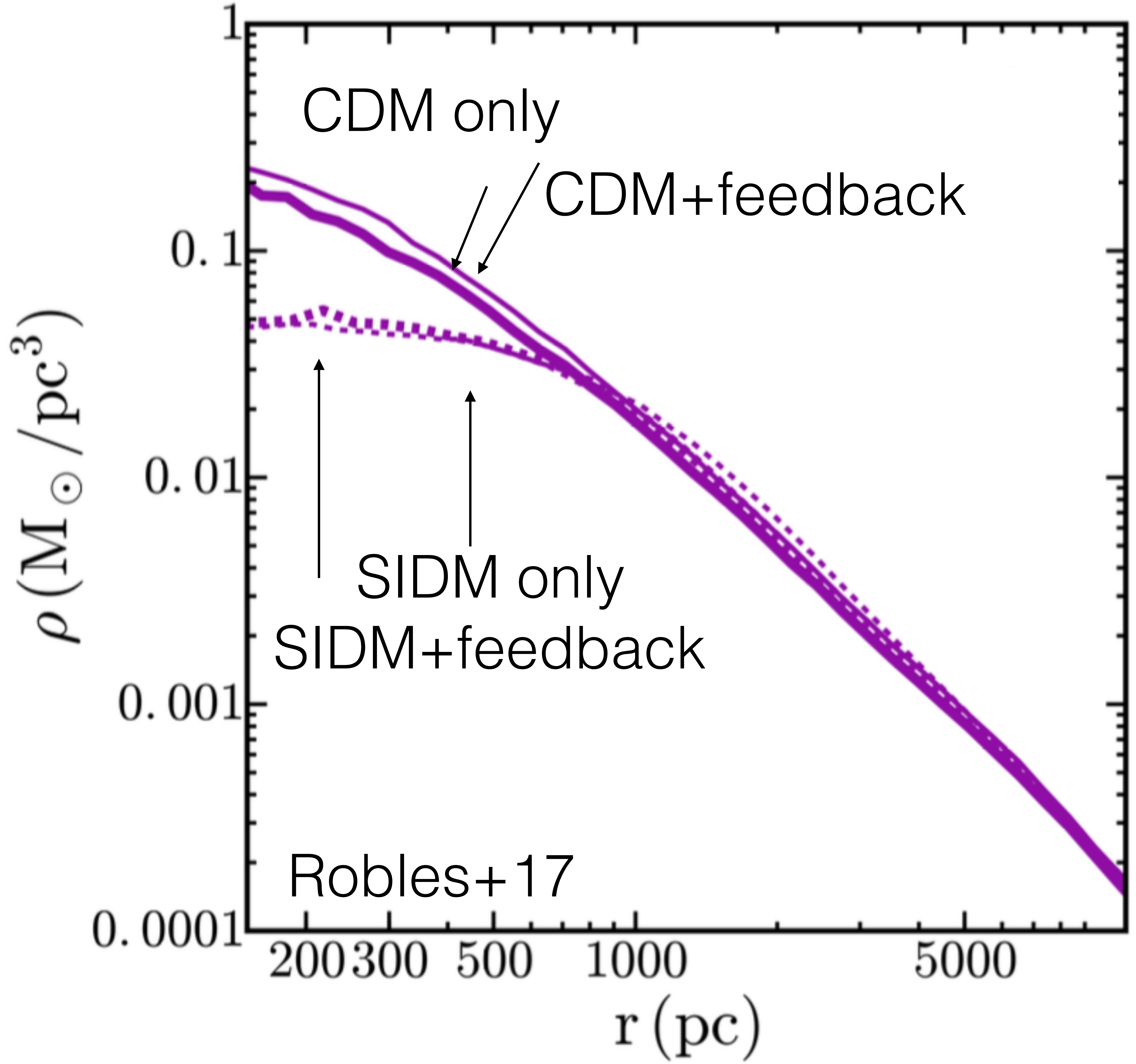
- Baryons + Dark Matter
- Dark Matter Only
- cEinasto
- Einasto

$$\rho_{\rm cEin}(r) = \tilde{\rho}_s \exp\left\{-\frac{2}{\hat{\alpha}}\left[\left(\frac{r+r_c}{\tilde{r}_s}\right)^{\hat{\alpha}} - 1\right]\right\}$$

$\hat{\alpha} = 0.16$

Lazar et al. 2019

Tiny Galaxies: Perfect place to test CDM

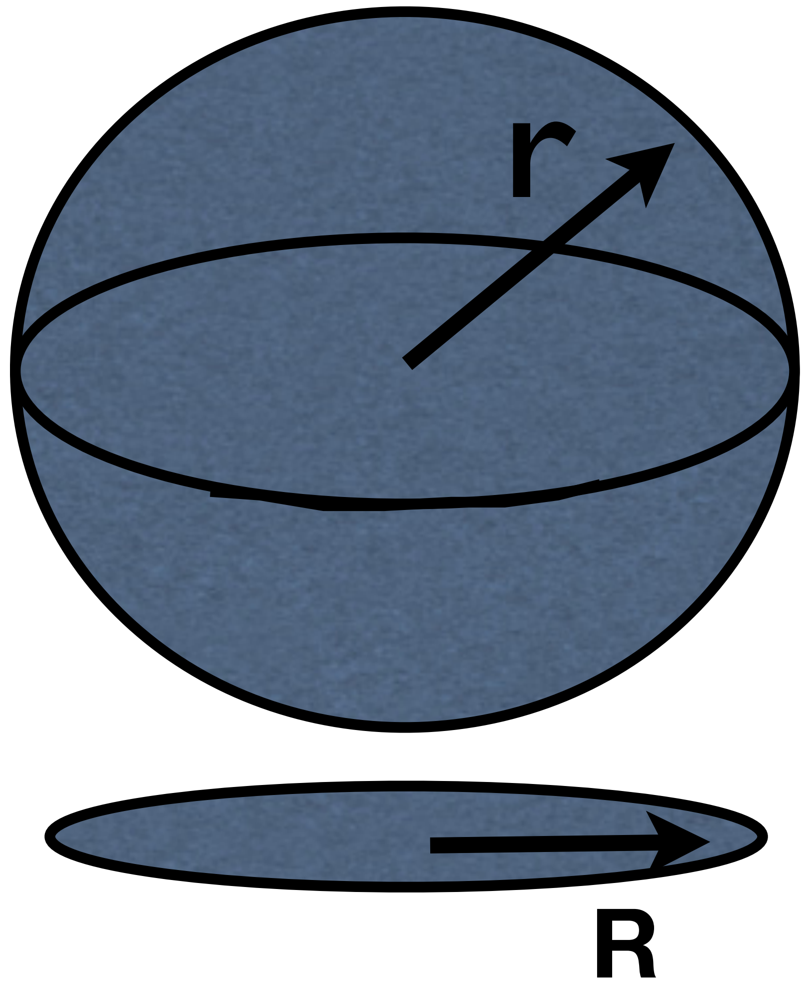


$M_* = 1.e6\ M_{sun}$

SIDM makes cores where CDM retains cusps.

Problem: these tiny galaxies are dispersion supported. Hard to extract density profiles.

Density profiles notoriously hard to deconstruct from 1D velocity dispersions



$$\sigma_{los}(R)$$

$$\Sigma_\star \sigma^2_{\rm los}(R) = \int_{R^2}^{\infty} \frac{dr^2}{\sqrt{r^2 - R^2}} \left[1 - \frac{R^2}{r^2}\beta(r)\right] n_\star \sigma_r^2(r)\,.$$

Key degeneracy with Anisotropy parameter

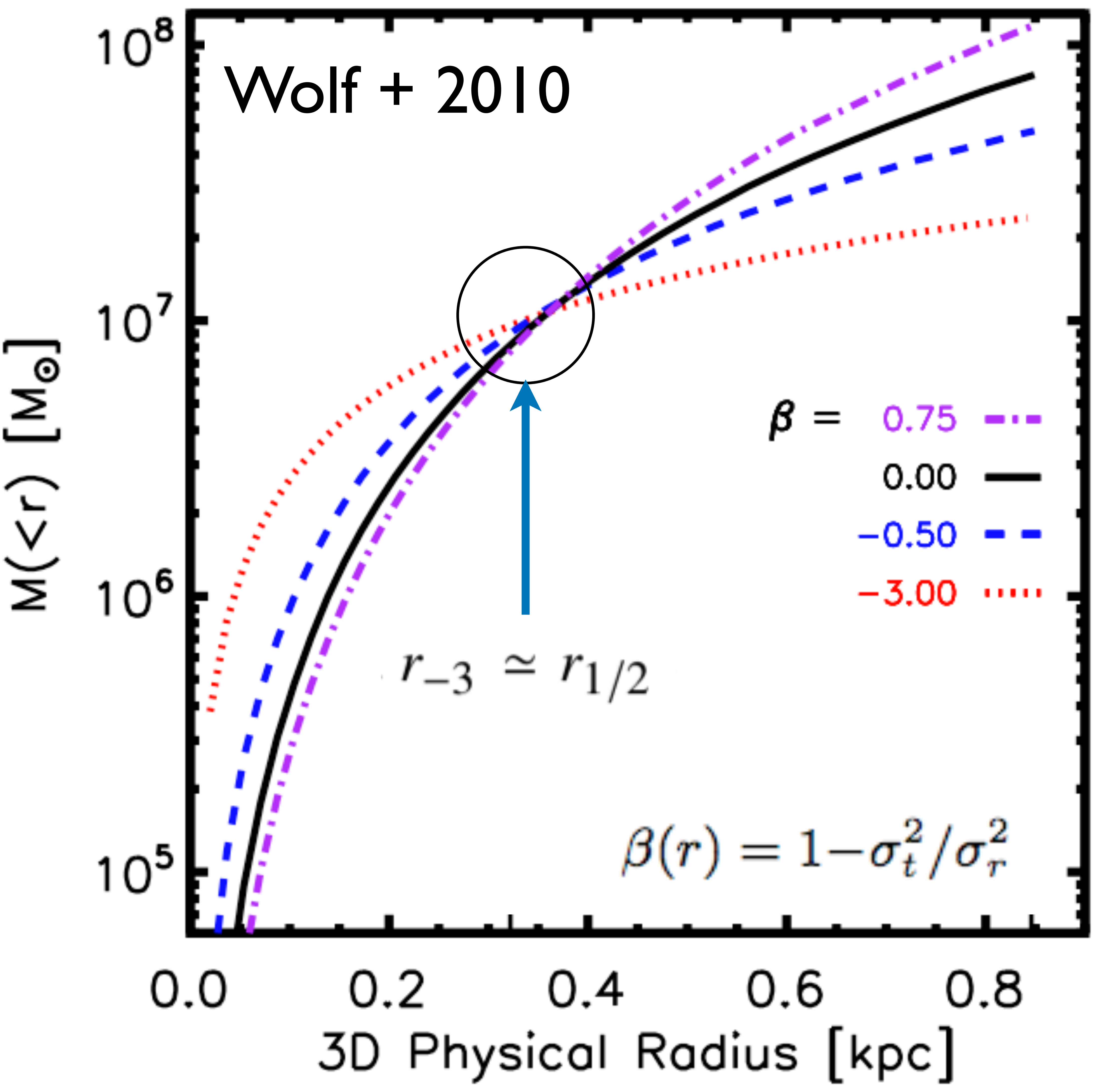
$$\beta(r) = 1 - \sigma_t^2/\sigma_r^2$$

$$M(r|\beta) = \frac{r\sigma_r^2(r)}{G}\left[\gamma_\star + \gamma_\sigma - 2\beta(r)\right]$$

$$\gamma_\star := -d\log n_\star / d\log r$$

$$\gamma_\sigma := -d\log \sigma_r^2 / d\log r\,.$$

A single radius where mass is accurately known from LOS velocities!



Can show that if you fix LOS observables

$$M(r|\beta) - M(r|\beta = 0) \simeq \frac{r\sigma_r^2\beta}{G}(\gamma_\star - 3)$$

$$\gamma_\star := -d\log n_\star / d\log r$$

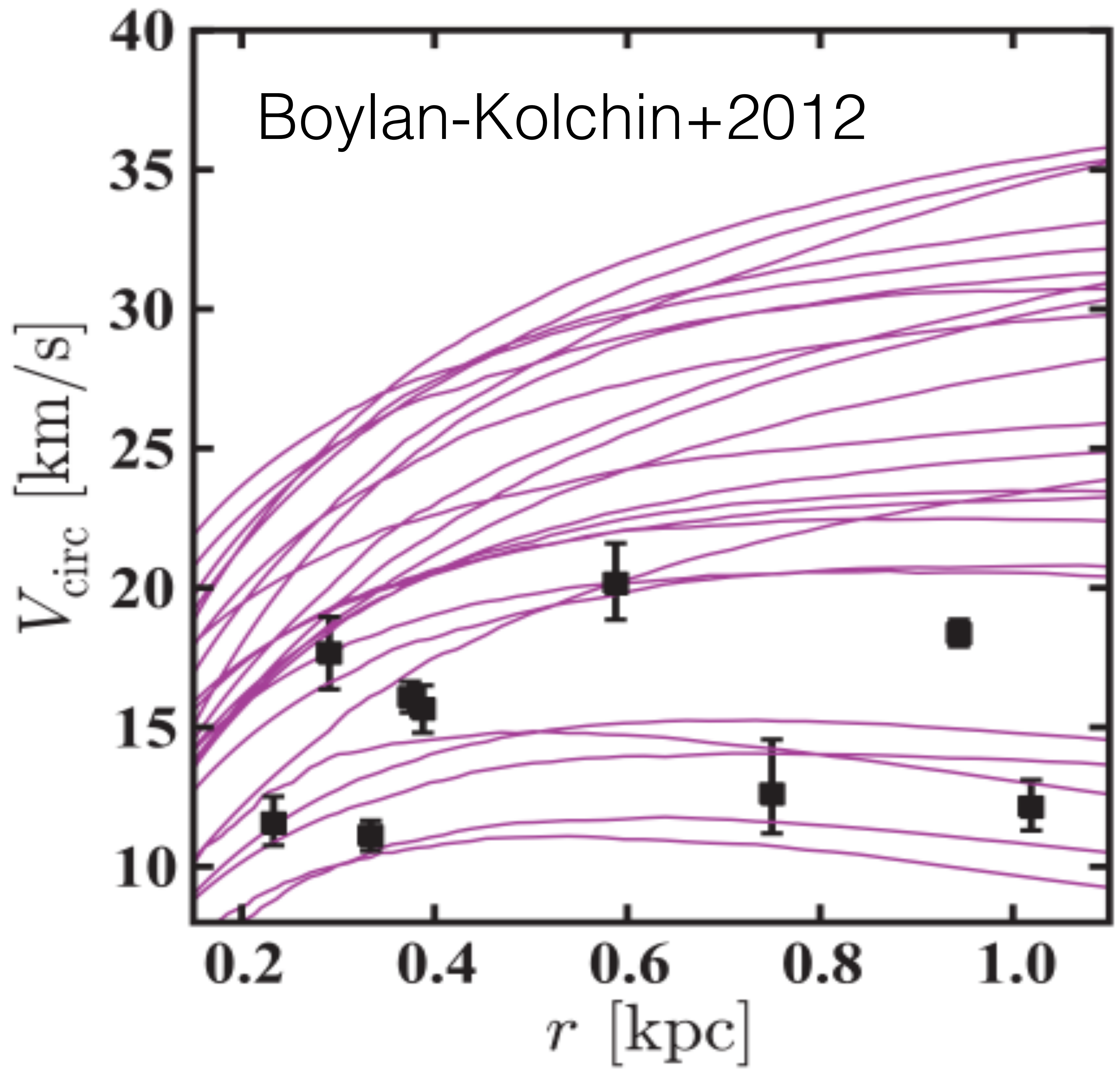
Mass is independent of anisotropy at radius where log-slope of tracer profile is -3

$$M(r_{-3}) = \frac{3\langle\sigma_{\rm los}^2\rangle r_{-3}}{G}$$

$$r_{-3} \simeq r_{1/2} \simeq 4R_e/3$$

See Walker+2009 for a related result

M_{-3} is mass estimator used in TBTF comparisons



$$V_{\rm circ}(r_{-3}) = \sqrt{3\langle\sigma^2_{\rm los}\rangle}$$

$$r_{-3} \simeq r_{1/2} \simeq 4R_e/3$$

Velocity dispersion in the plane of the sky

nature astronomy

Letter | Published: 27 November 2017

Three-dimensional motions in the Sculptor dwarf galaxy as a glimpse of a new era

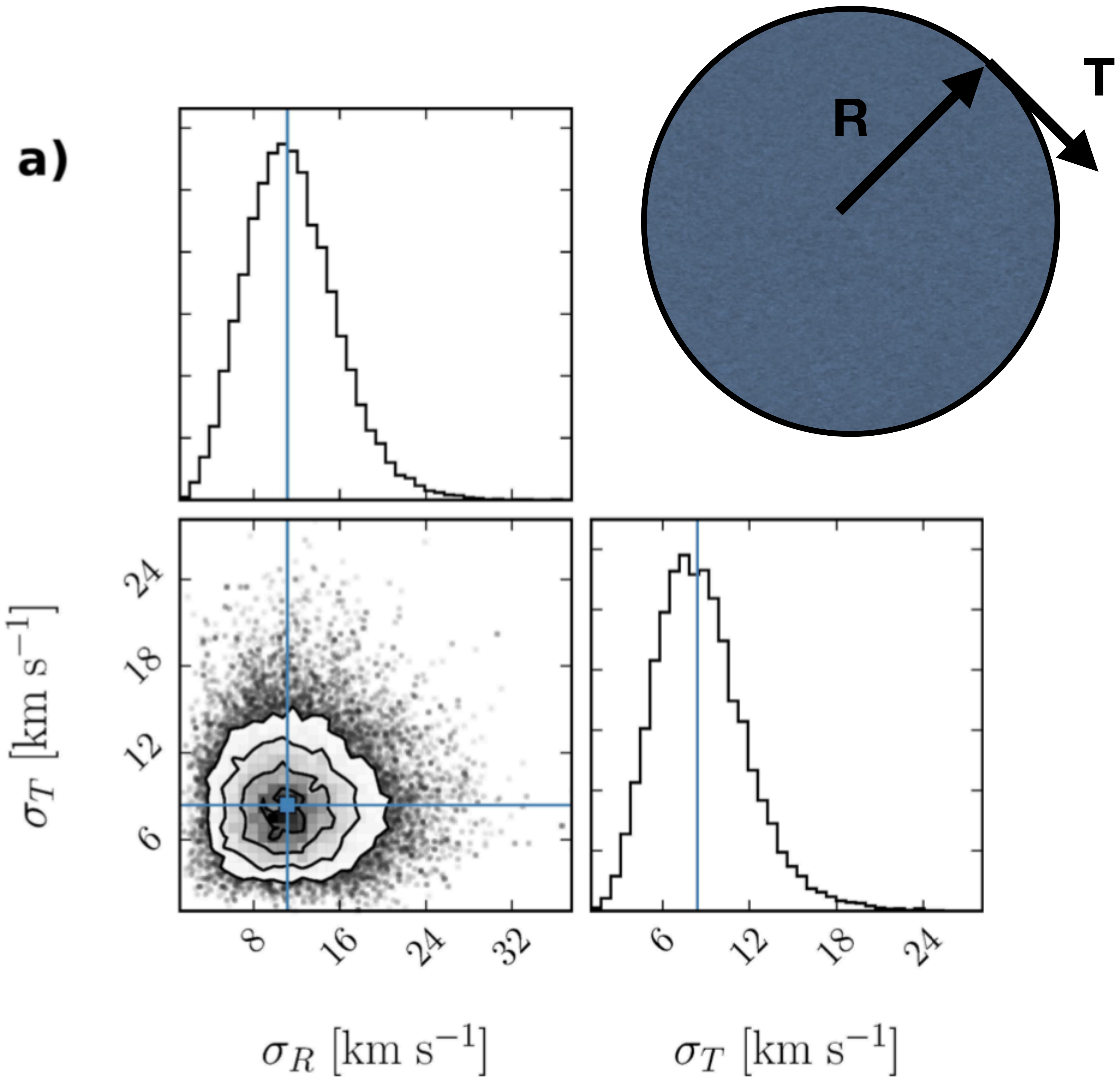
D. Massari, M. A. Breddels, A. Helmi, L. Posti, A. G. A. Brown & E. Tolstoy

Nature Astronomy **2**, 156–161 (2018) | Download Citation

Astronomy & Astrophysics manuscript no. draco_arxiv ©ESO 2019
April 9, 2019

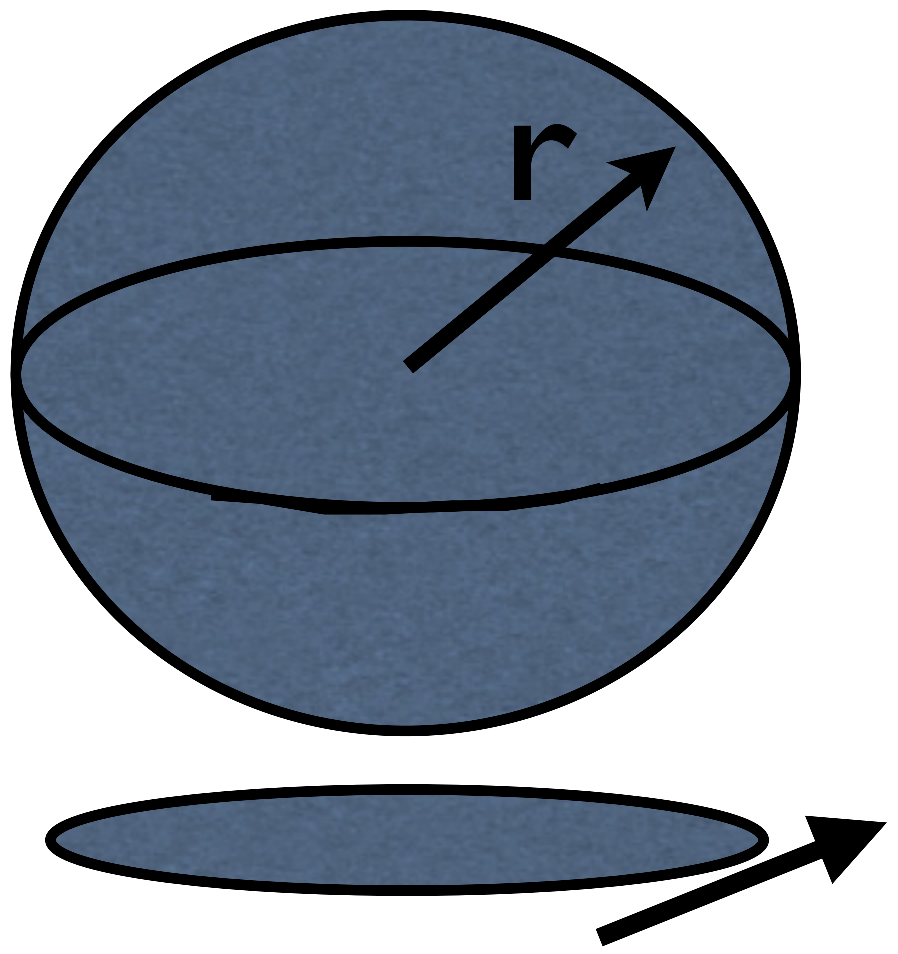
Stellar 3-D kinematics in the Draco dwarf spheroidal galaxy

D. Massari[1], A. Helmi[1], A. Mucciarelli[2,3], L. V. Sales[4], L. Spina[5], and E. Tolstoy[1]



Massari + 2017; 2019

Tangential Velocity Dispersion



$\sigma_{\mathcal{T}}(R)$

$$\Sigma_\star \sigma_{\mathcal{T}}^2(R) = \int_{R^2}^{\infty} \frac{dr^2}{\sqrt{r^2 - R^2}} [1 - \beta(r)]\, n_\star \sigma_r^2(r)$$

Fix observables **Can show**

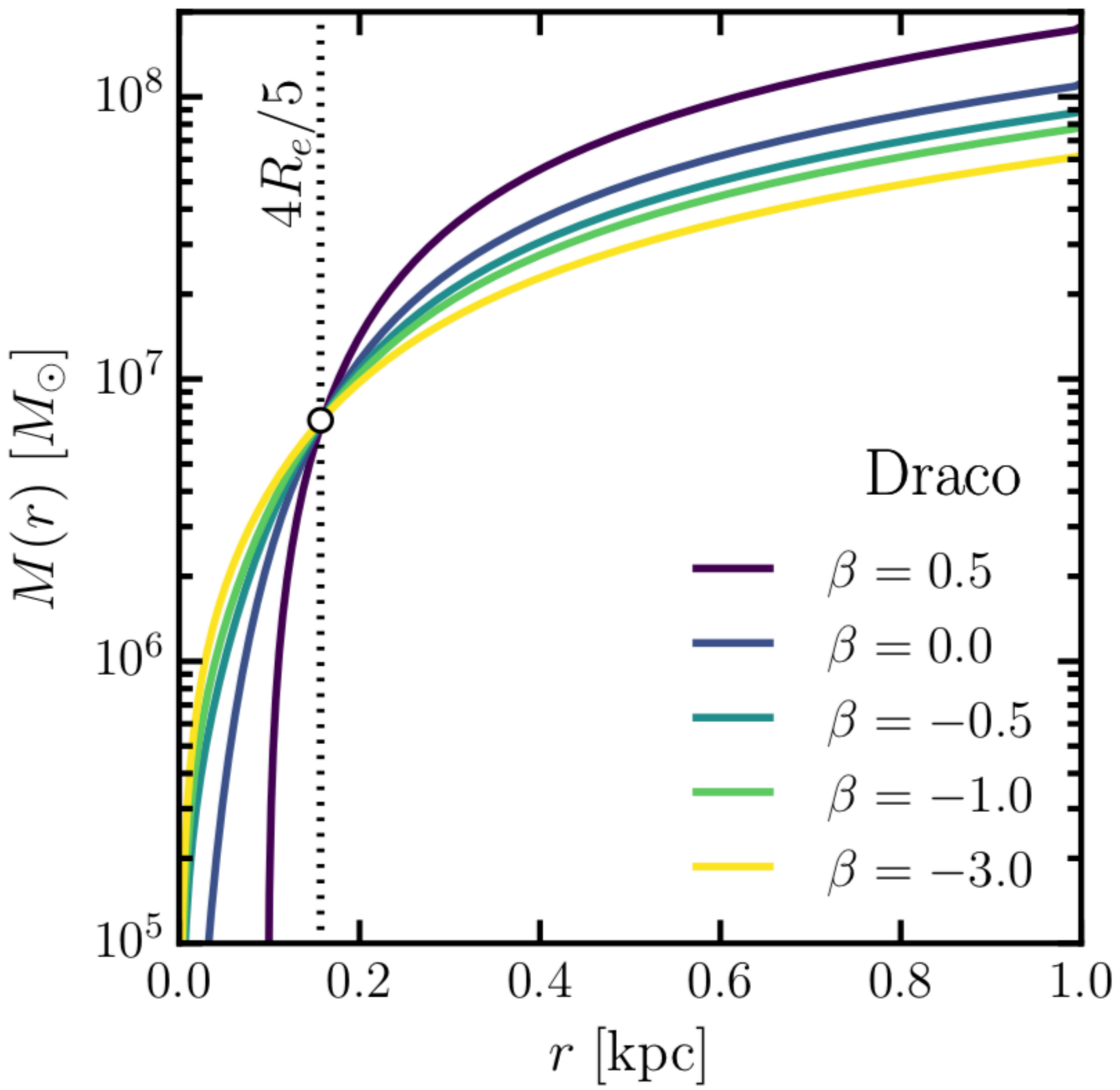
$$M(r|\beta) - M(r|\beta = 0) \simeq \frac{r\sigma_r^2 \beta}{G} (\gamma_\star - 2)$$

$$\gamma_\star := -d \log n_\star / d \log r$$

Mass is independent of anisotropy at radius where log-slope of tracer profile is -2

Lazar & JSB 2019

Tangential velocity dispersion from Massari+2019



Accurate mass from tangential velocity dispersion

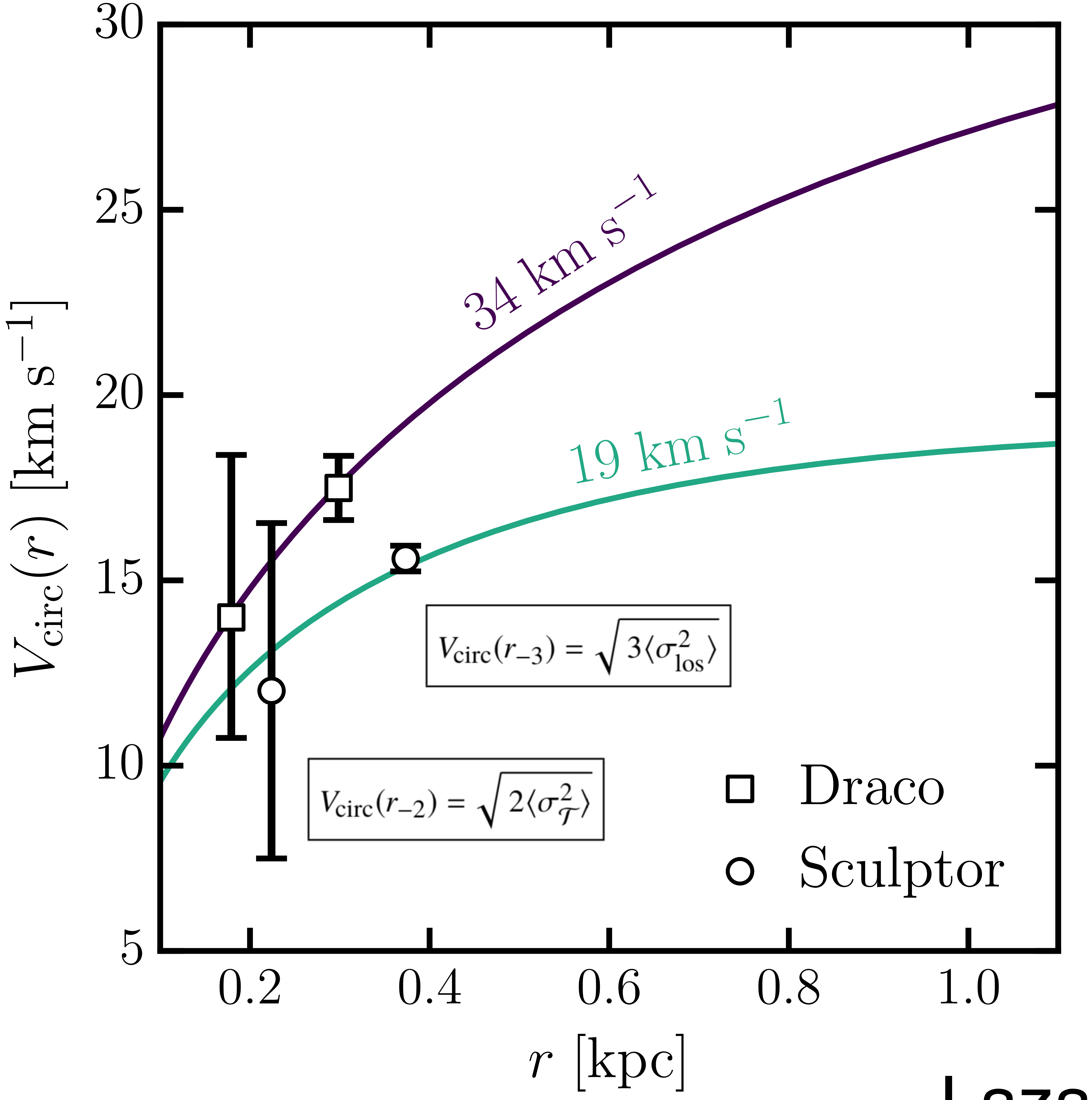
$$M(r_{-2}) = \frac{2\langle\sigma_{\mathcal{T}}^2\rangle r_{-2}}{G}$$

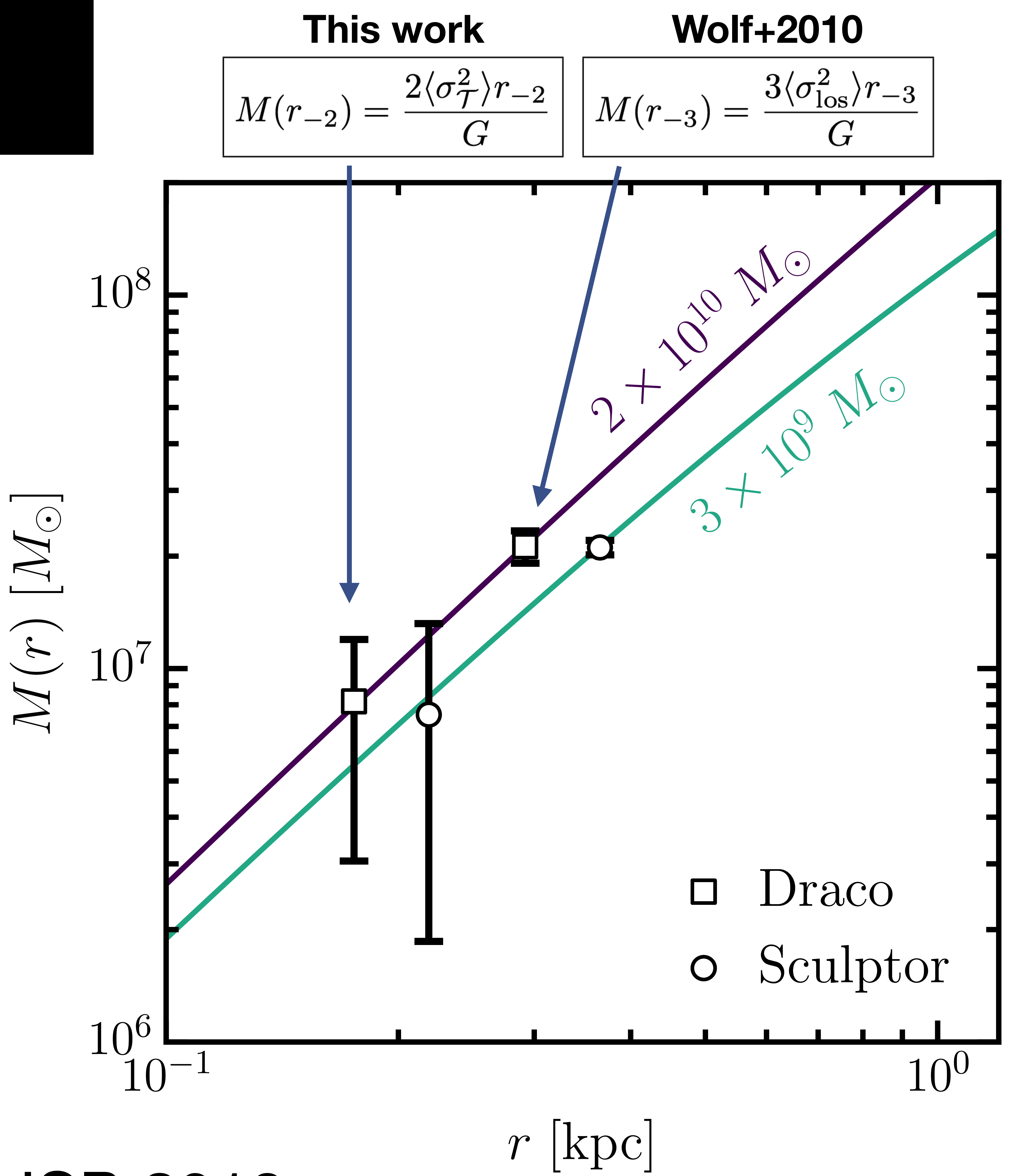
$$r_{-2} \simeq 4R_e/5 \simeq 3r_{1/2}/5$$

$$V_{\rm circ}(r_{-2}) = \sqrt{2\langle\sigma_{\mathcal{T}}^2\rangle}$$

Lazar & JSB 2019

Draco & Sculptor both consistent with NFW halos

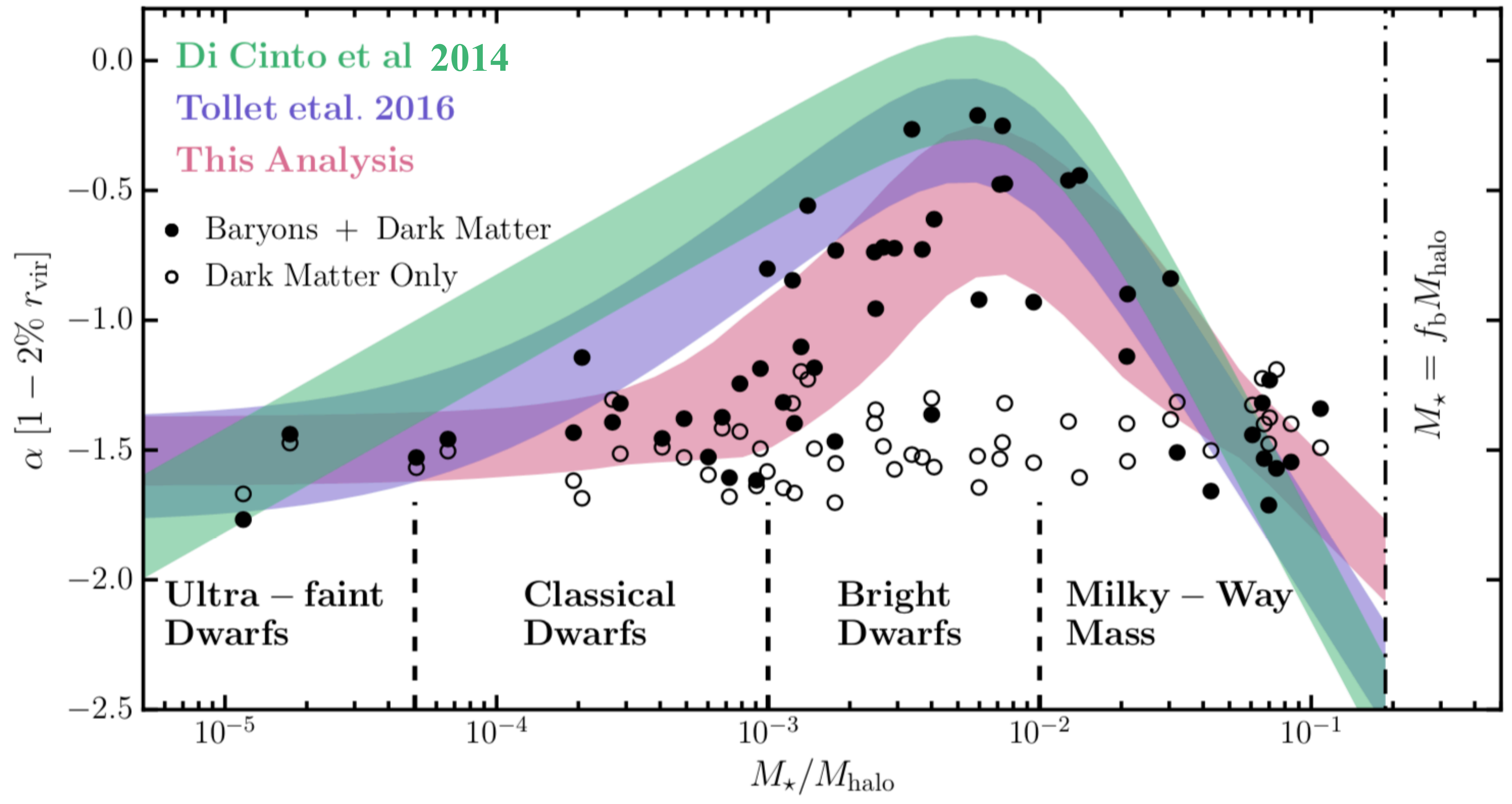




Lazar & JSB 2019

Summary 1: FIRE-2 DM density profiles

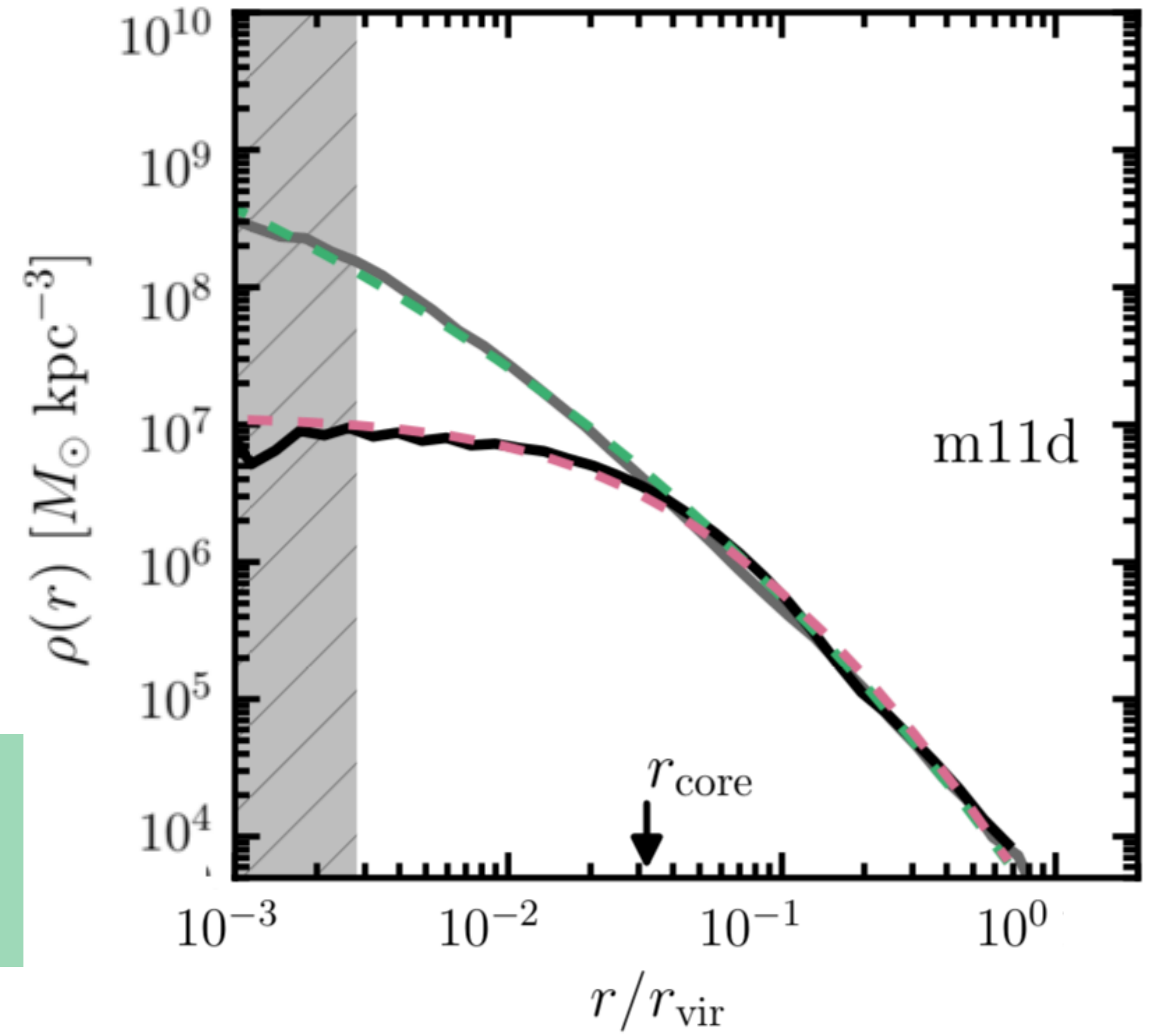
Lazar et al. 2019



All profiles well fit by 3 parameter "core-Einasto"

$$\rho_{cEin}(r) = \tilde{\rho}_s \exp\left\{-\frac{2}{\hat{\alpha}}\left[\left(\frac{r + r_c}{\tilde{r}_s}\right)^{\hat{\alpha}} - 1\right]\right\}$$

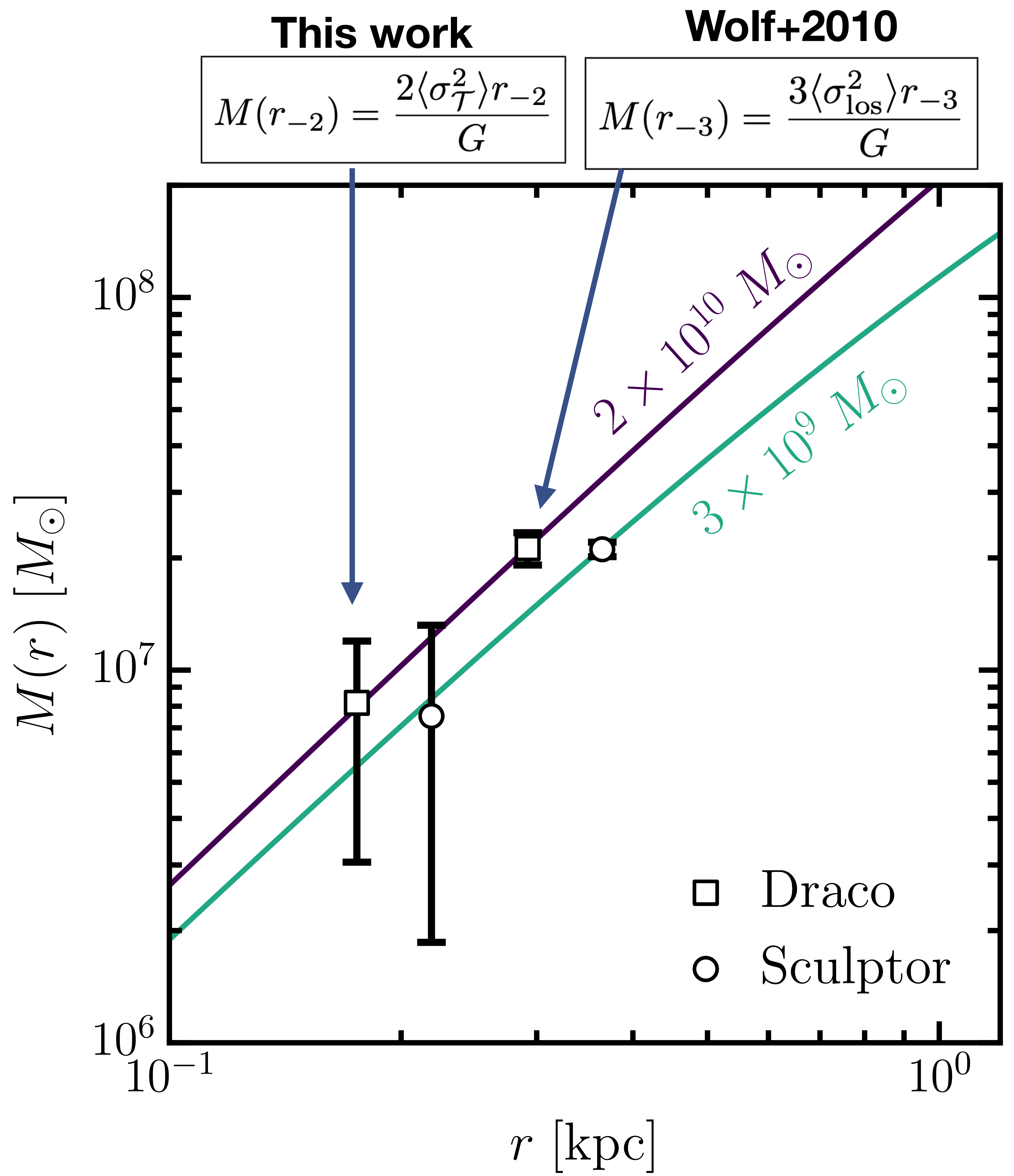
$\hat{\alpha} = 0.16$



No core formation in tiny dwarfs $M_{star} < 10^6$ M_{sun}

Significant **diversity** in core sizes/ densities at scale of bright dwarfs

Summary 2: New Mass Estimator



Accurate mass from tangential velocity dispersion

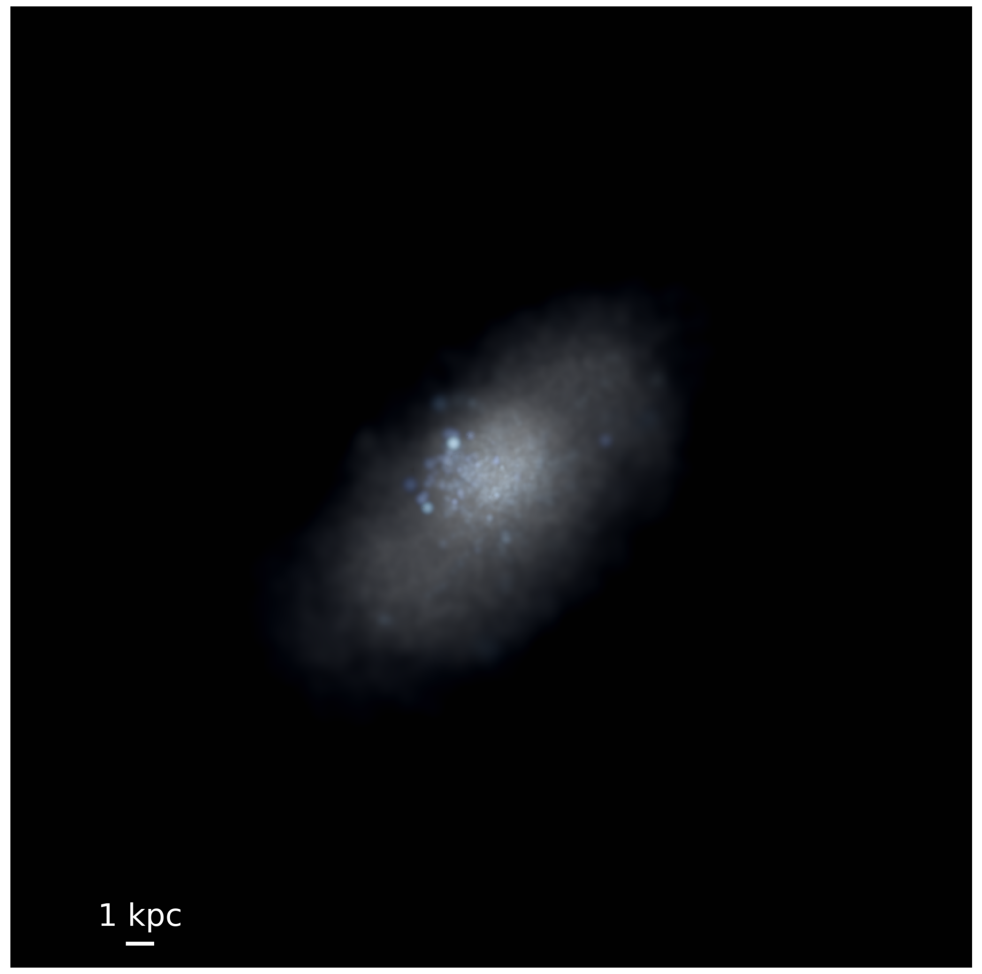
$$M(r_{-2}) = \frac{2\langle\sigma_T^2\rangle r_{-2}}{G}$$

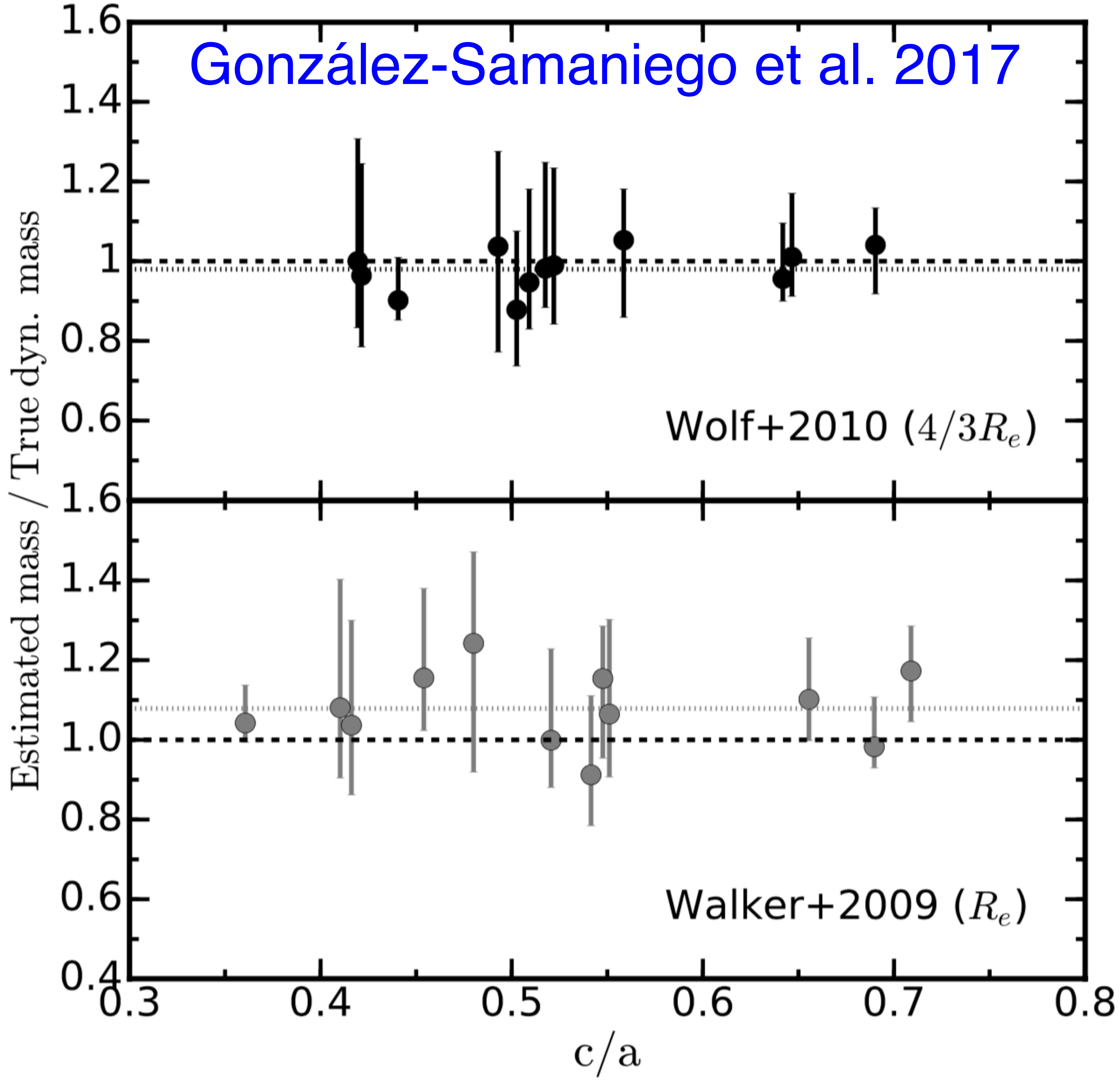
$$r_{-2} \simeq 4R_e/5 \simeq 3r_{1/2}/5$$

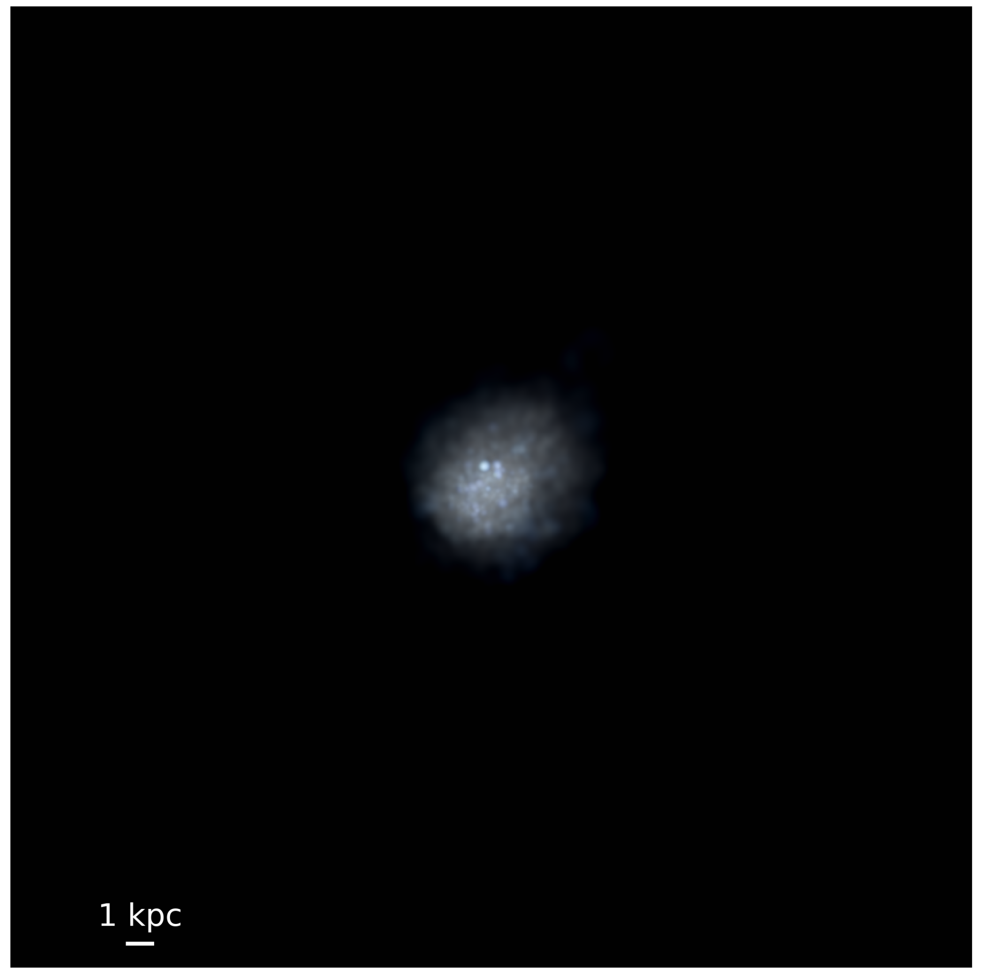
Draco & Sculptor both consistent with NFW halos; more data required to provide tighter constraints

Lazar & JSB 2019

Single-radius estimator good to <20% when compared to cosmological simulations







Also Campbell et al. 2017