A **simple** recipe for estimating masses of elliptical galaxies and clusters of galaxies

Quick and robust mass estimates

- for elliptical galaxies from optical data

(tested on simulated galaxies by Oser et al. 2010)

- for clusters of galaxies from optical data

(tested on simulated halos by Dolag et al. 2009)

N. Lyskova[1], E. Churazov[1], I. Zhuravleva[1], T. Naab[1], L. Oser[1], O. Gerhard[2], X. Wu[2]
(MNRAS, 2012)
[1] *Max Planck Institute for Astrophysics*
[2] *Max Planck Institute for Extraterrestrial Physics*

Looking for a *simple*, *fast* in implementation and *robust* method for estimating masses of ellipticals and clusters of galaxies...

Elliptical galaxies

Main problem:

degeneracy between the anisotropy of stellar orbits and the mass.

Options

- Virial theorem:

$V_c^2 = 3\sigma^2$ (isothermal potential, closed spherical, stationary system)

+: anisotropy does not matter

−: order of magnitude estimate

- Central velocity dispersion:

+: available for most galaxies

−: depends on the size of aperture, should work if orbits are isotropic

Can we do better?..

Churazov et al. 2010 → V_c estimate from *I(R)*, *σ(R)* and their slopes

Bolzman distribution

$$\Phi(r) = V_c^2 \ln r + const$$

$$j(r) = j_0 e^{-\frac{m\Phi}{kT}} = j_0 e^{-\frac{mV_c^2 \ln r}{kT}} = j_0 r^{-\frac{mV_c^2}{kT}}$$

$$j(r) \propto r^{-\frac{mV_c^2}{kT}} \rightarrow \frac{d \ln j(r)}{d \ln r} \propto -\frac{mV_c^2}{kT}$$

I(R)

σ(R)

V_c – estimate!

V_c primarily depends on ***I(R)***, ***σ(R)*** and their derivatives (slopes)

Churazov et al. 2010 → The method is based on the stationary non-streaming Jeans equations

$$\frac{d}{dr} j\sigma_r^2 + 2\frac{\beta}{r} j\sigma_r^2 = -j\frac{d\Phi}{dr} = -j\frac{V_c^2}{r}$$

j - stellar luminosity density,

$\sigma_r(r)$ - radial component of the velocity dispersion tensor (weighted by luminosity)

Assumption:

Gravitational potential

$$\Phi(r) = V_c^2 \ln r + const$$

Stellar anisotropy parameter

$$\beta(r) = 1 - \frac{\sigma_\theta^2}{\sigma_r^2}$$

Extreme types of stellar orbits:

- Isotropic → ***β = 0***
- Radial → ***β = 1***
- Circular → ***β = − ∞***

Observable quantities:
surface brightness ***I(R)*** &
LOS velocity dispersion ***σ(R)***

$$I(R) = 2\int_R^\infty \frac{j(r)r}{\sqrt{r^2 - R^2}} dr$$

$$\sigma^2(R) \cdot I(R) = 2\int_R^\infty j(r)\sigma_r^2(r)\left(1 - \frac{R^2}{r^2}\beta(r)\right)\frac{r}{\sqrt{r^2 - R^2}} dr$$

Algorithm for estimating V_c

1. Calculate ***α, γ, δ*** from observed ***I(R)*** and ***σ(R)*** profiles:

$$\alpha = -\frac{d\,\ln I(R)}{d\,\ln R}, \gamma = -\frac{d\ln\sigma^2}{d\ln R}, \delta = \frac{d^2\ln[I(R)\sigma^2]}{d(\ln R)^2}$$

2. Calculate V_c for the extreme types of stellar orbits

Full analysis

$$V_c^{iso} = \sigma(R)\cdot\sqrt{1+\alpha+\gamma}$$
$$V_c^{circ} = \sigma(R)\cdot\sqrt{(1+\alpha+\gamma)/\alpha}$$
$$V_c^{rad} = \sigma(R)\cdot\sqrt{(\alpha+\gamma)^2+\delta-1}$$

Simplified analysis

$$V_c^{iso} = \sigma(R)\cdot\sqrt{1+\alpha}$$
$$V_c^{circ} = \sigma(R)\cdot\sqrt{(1+\alpha)/\alpha}$$
$$V_c^{rad} = \sigma(R)\cdot\sqrt{\alpha^2-1}$$

3. Estimate V_c at a radius (sweet point R_{sweet}) where all three curves intersect each other. $V_c(R_{sweet})$ is <u>not</u> affected much by the anisotropy.

Example:

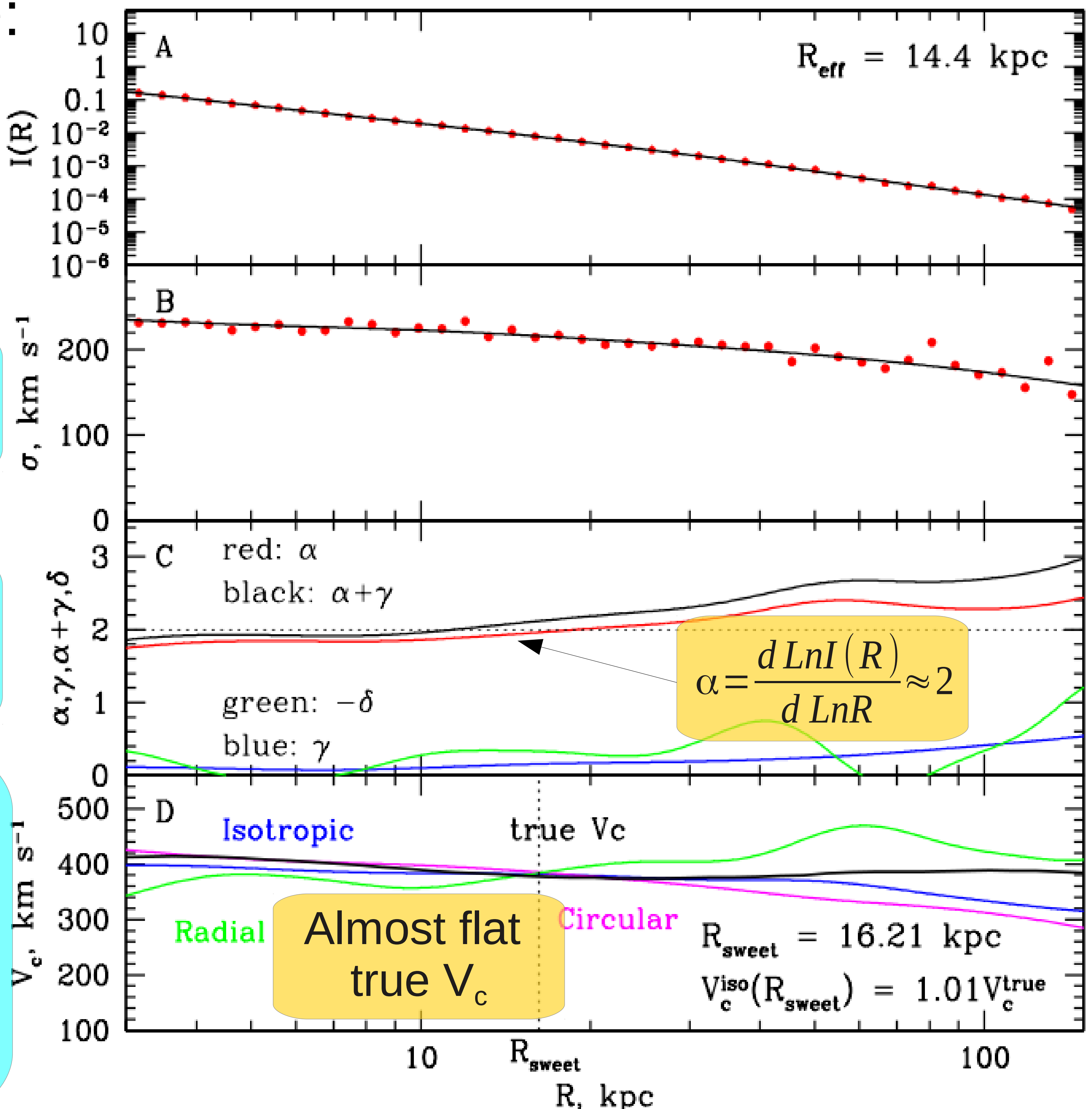
Surface brightness $I(R)$

LOS velocity dispersion $\sigma(R)$

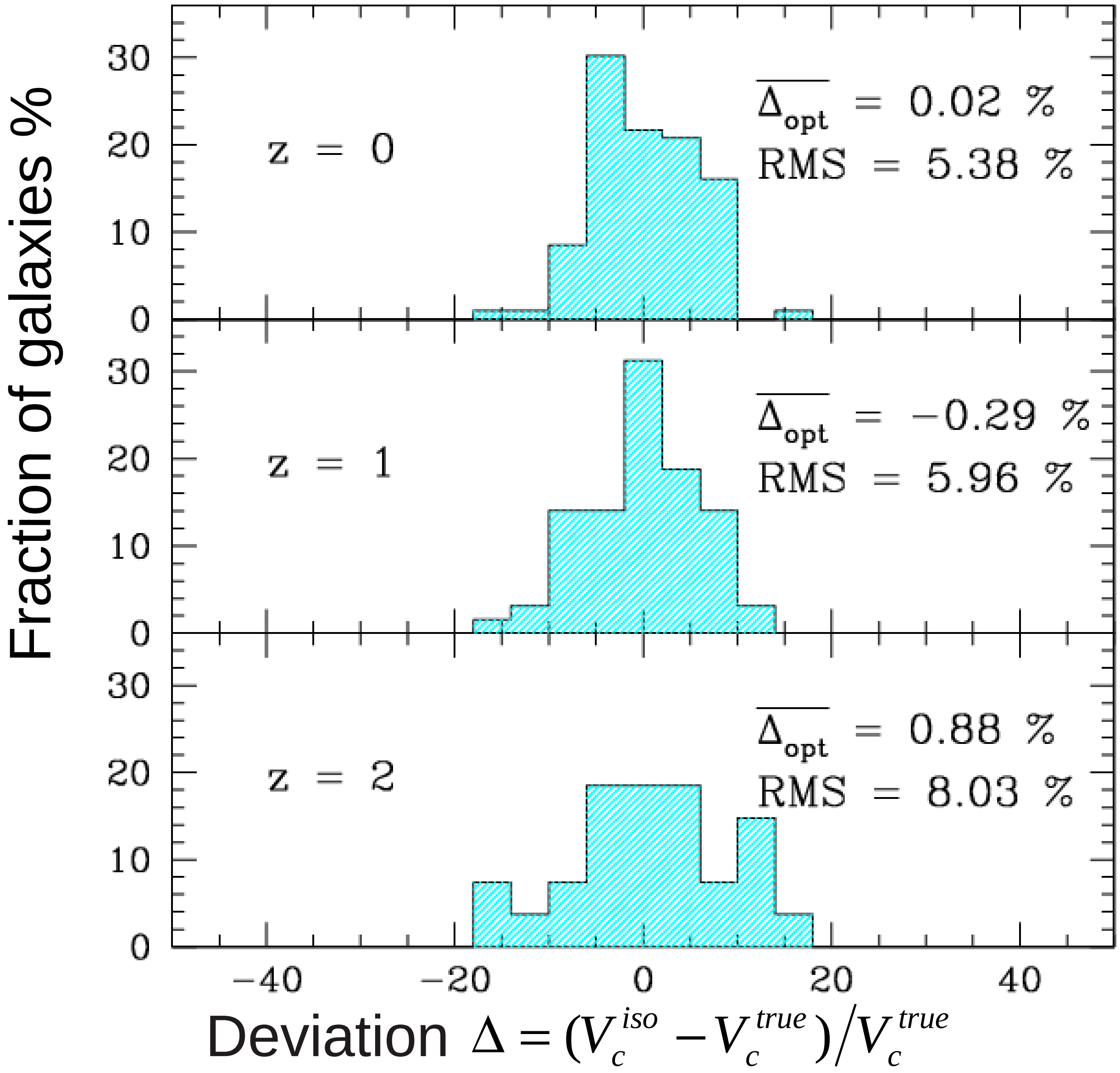
Logarithmic derivatives

Deviation of the estimated V_c from the true one

$$\Delta = \frac{V_c^{iso} - V_c^{true}}{V_c^{true}} \approx 1\%$$



Analysis of massive and slowly rotating galaxies at different redshifts at R_{sweet}



Almost unbiased estimate

+

Modest scatter even at high redshifts

Can be useful for galaxy surveys!

Circular speed from X-ray data

Spherical symmetry + hydrostatic equilibrium of gas:

$$-\frac{1}{\rho}\frac{dP}{dr} = \frac{d\Phi}{dr} = \frac{V_c^2}{r} = \frac{GM}{r^2}$$

Gas pressure $P = nkT$

Gas density $\rho = \mu m_p n$

n – gas number density,

m_p – proton mass,

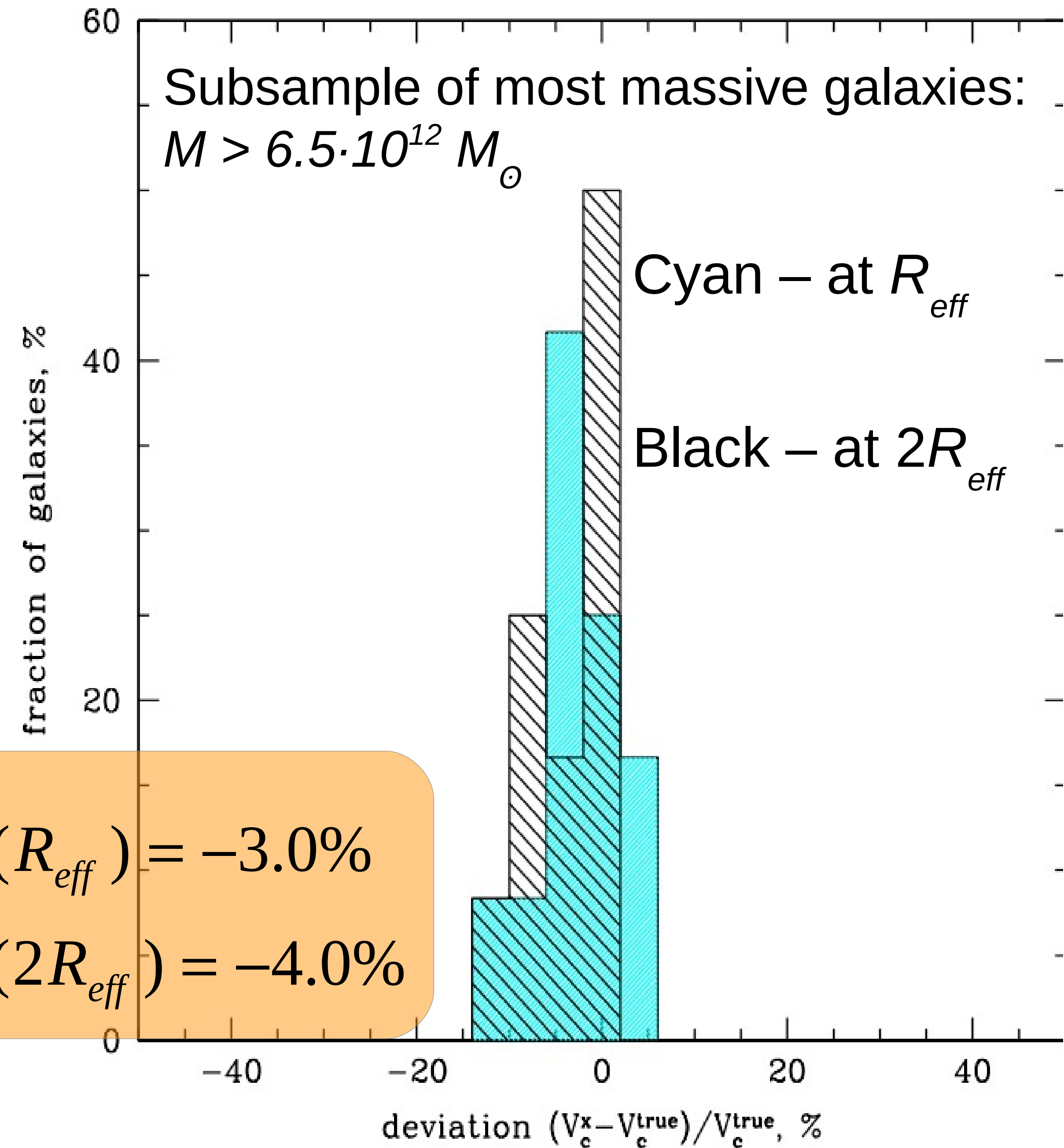
μ - mean atomic weight,

T - temperature

Gas motions

!

Mass bias

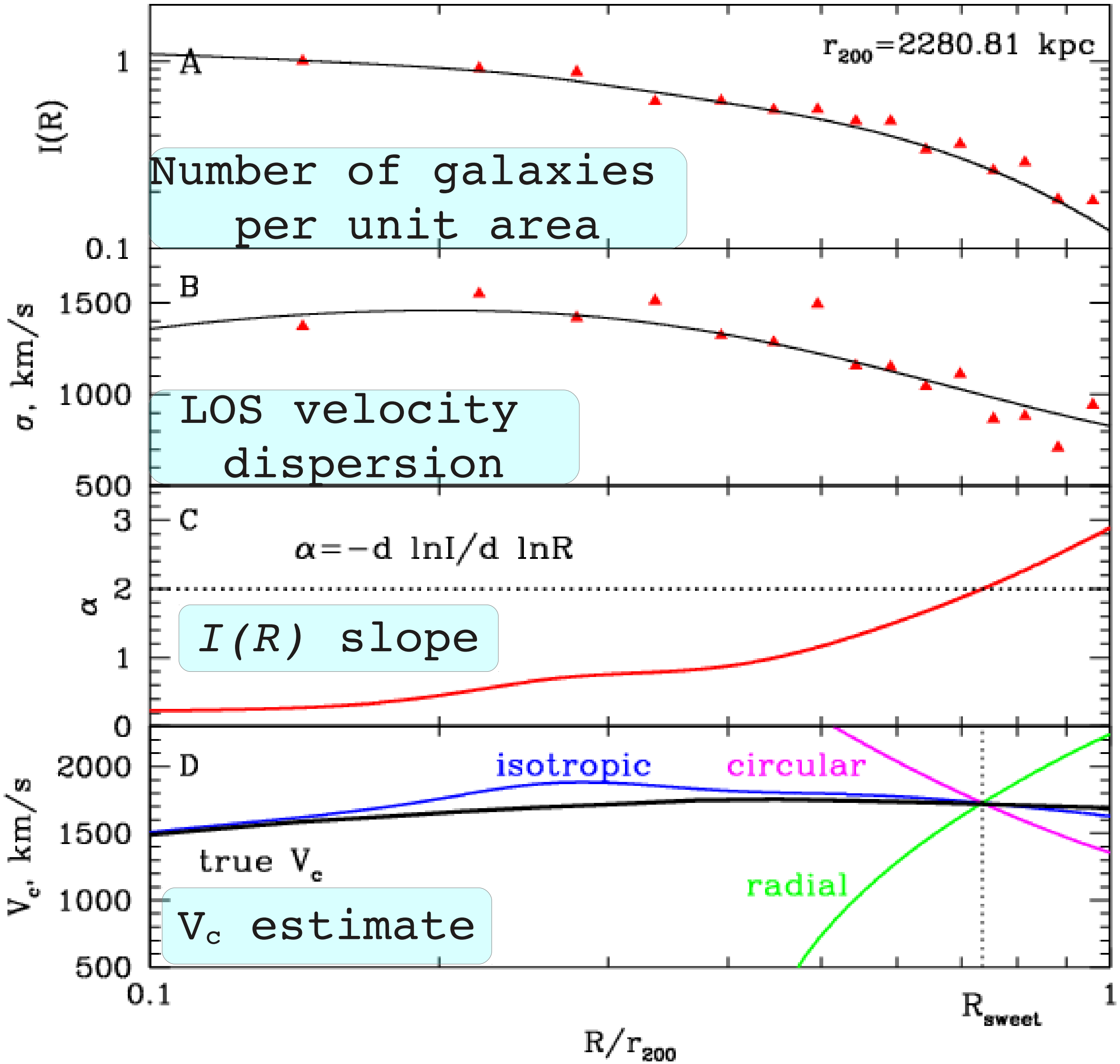


$$\bar{\Delta}_X(R_{eff}) = -3.0\%$$

$$\bar{\Delta}_X(2R_{eff}) = -4.0\%$$

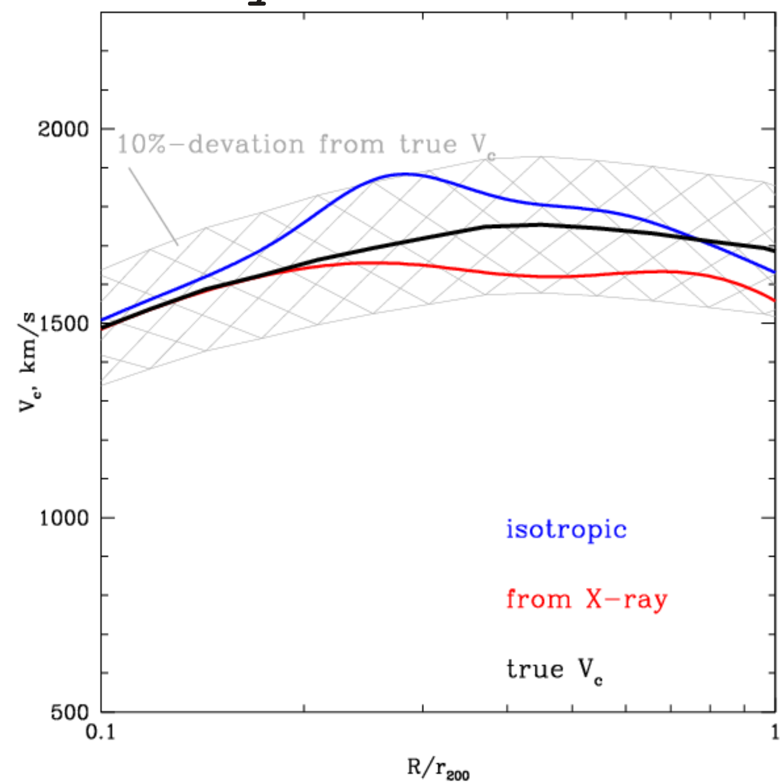
Clusters of galaxies

Tracers = individual galaxies



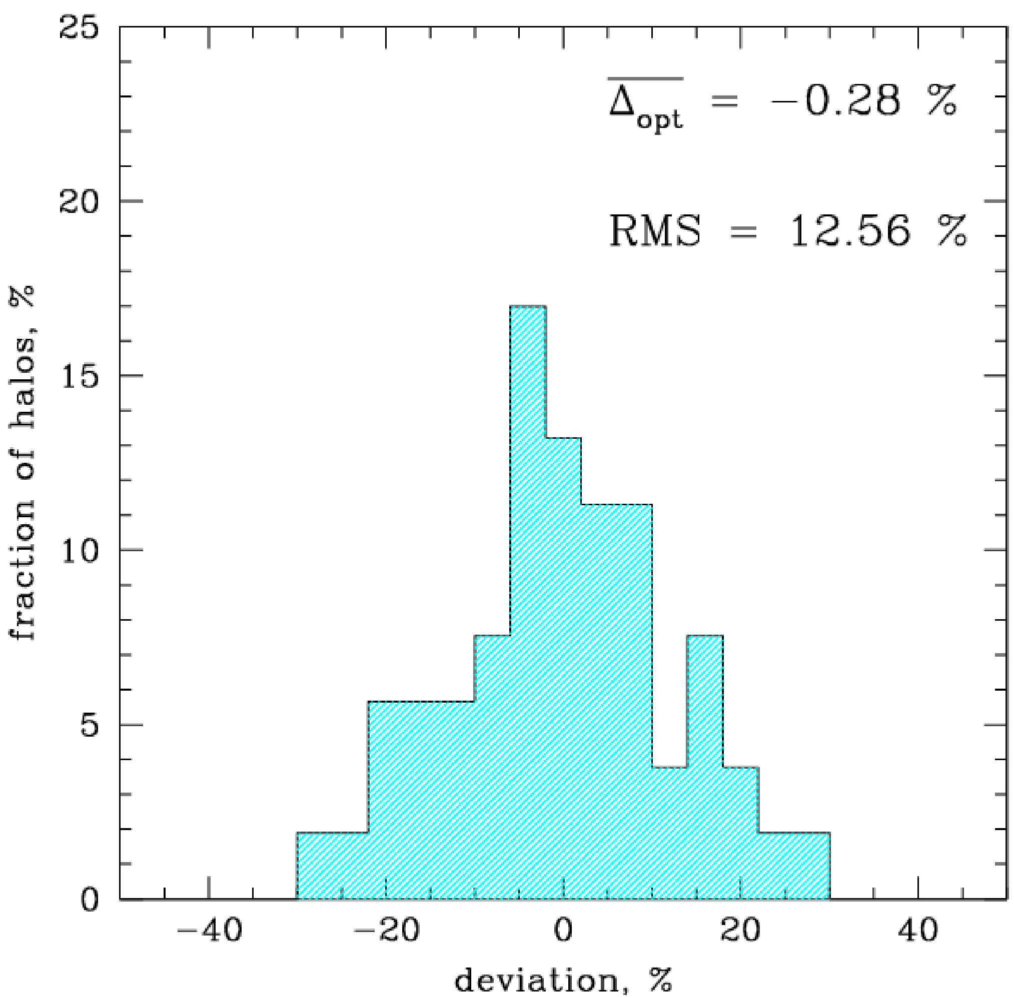
Noisy profiles ⇒ simplified analysis!

Zoom in: only isotropic V_c + V_c from hydrostatics

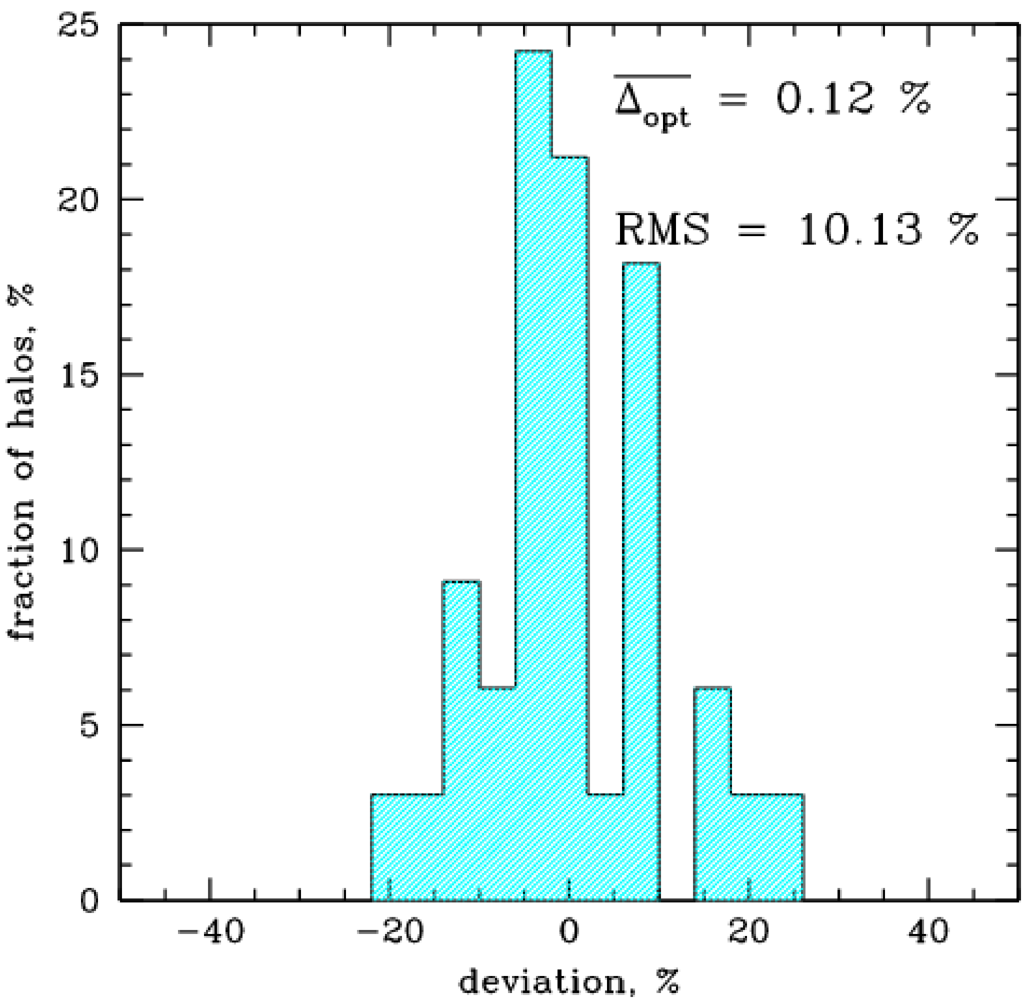


V_c estimates of simulated halos

Number of tracers > 50
N = 53 objects



Number of tracers > 100
N = 33 objects



To conclude:

Part I. Elliptical galaxies.

1. Full analysis → unbiased estimate of V_c (⇔ total M) and modest scatter (RMS = 5-8%) even for high-redshift galaxies. May be useful for galaxy surveys.

2. X-ray + hydrostatic equilibrium → estimate of V_c is biased low (what can be traced to the presence of gas motions).

Part II. Clusters.

1. Simplified analysis → unbiased estimate of V_c. May be useful for calibration other mass determination methods (hydrostatics, weak lensing, etc)