Mass and stellar orbital distribution of Early-Type galaxy haloes

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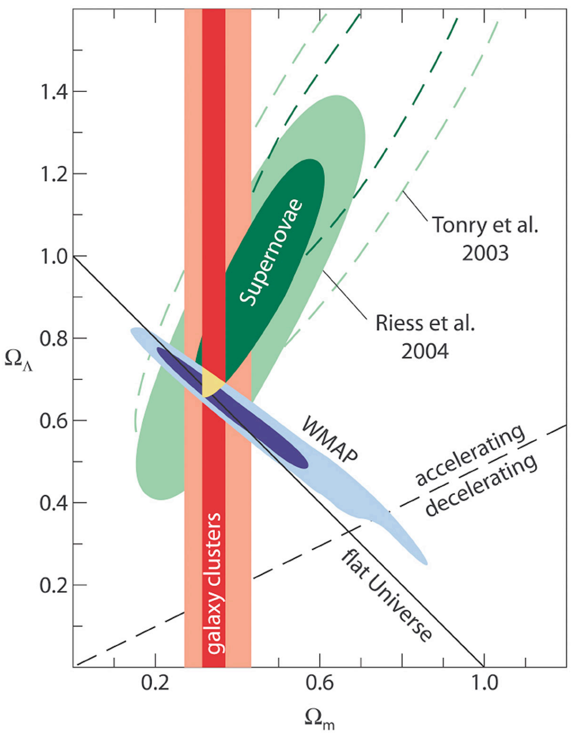
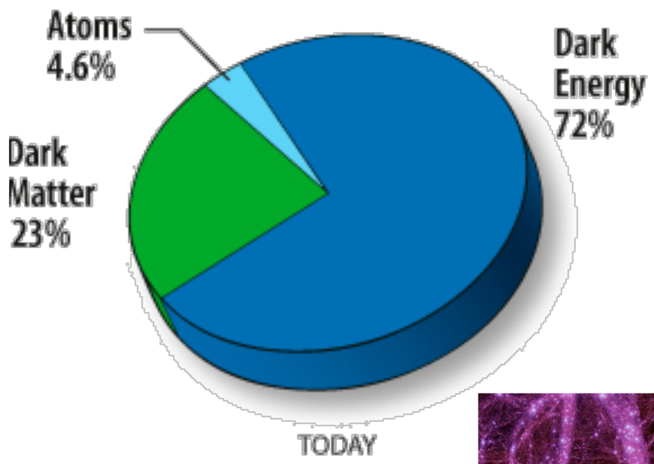
The stellar halos around galaxies – ESO/Garching, 23-27 February 2015

Outline

- simulation predictions
- planetary nebulae (and GCs) as dynamical tracers
- the dispersion-kurtosis Jeans analysis
- mass and anisotropy in galaxy haloes vs. simulations
- testing ΛCDM

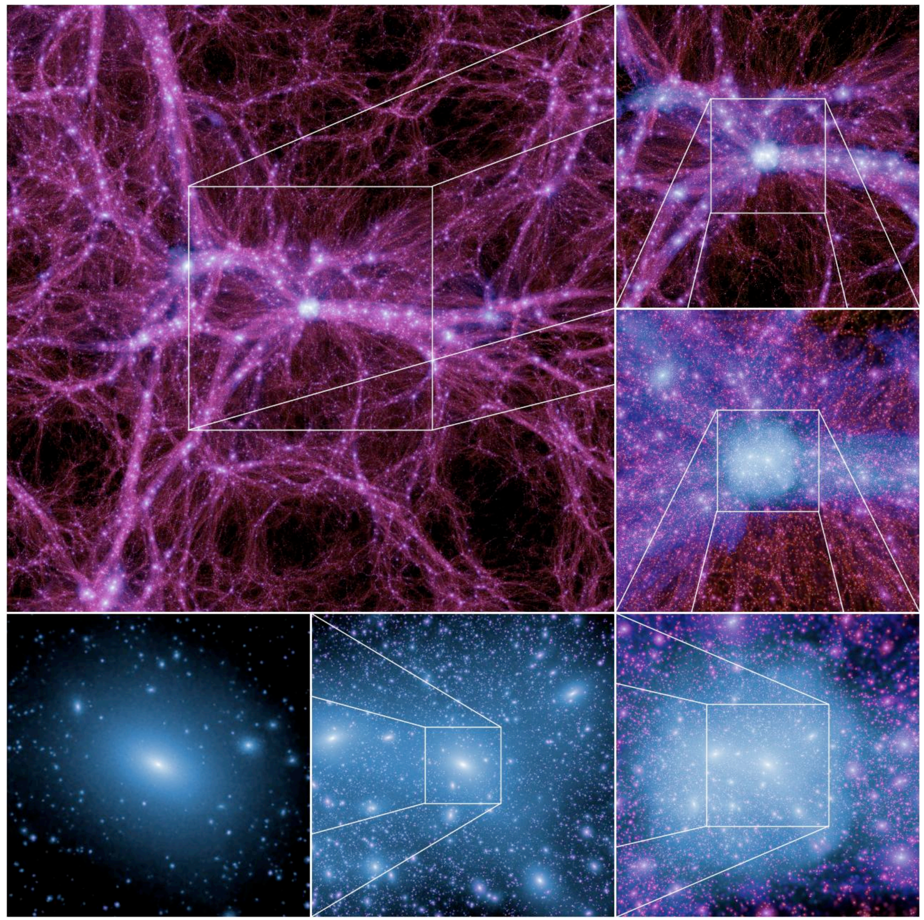
Simulation Prediction



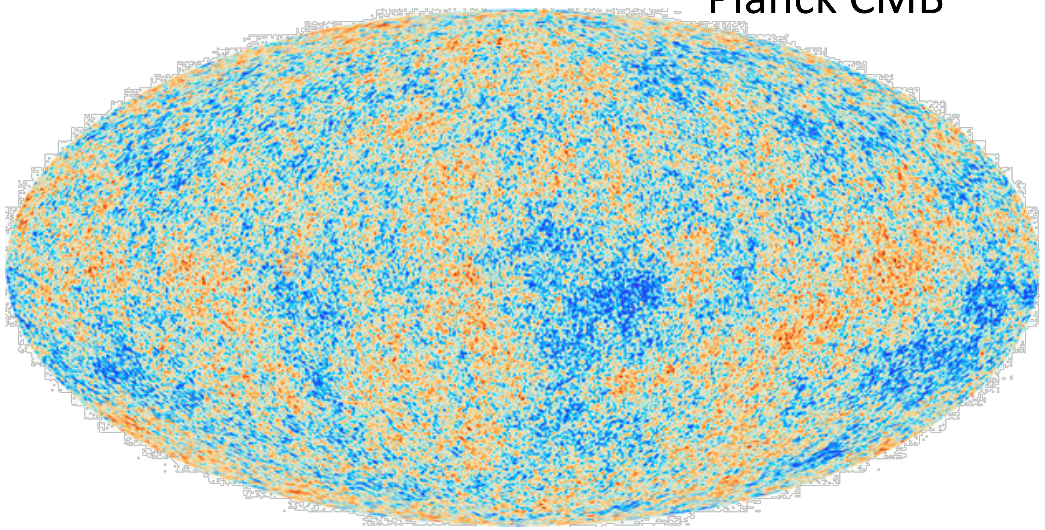


ΛCDM

Millennium Simulation

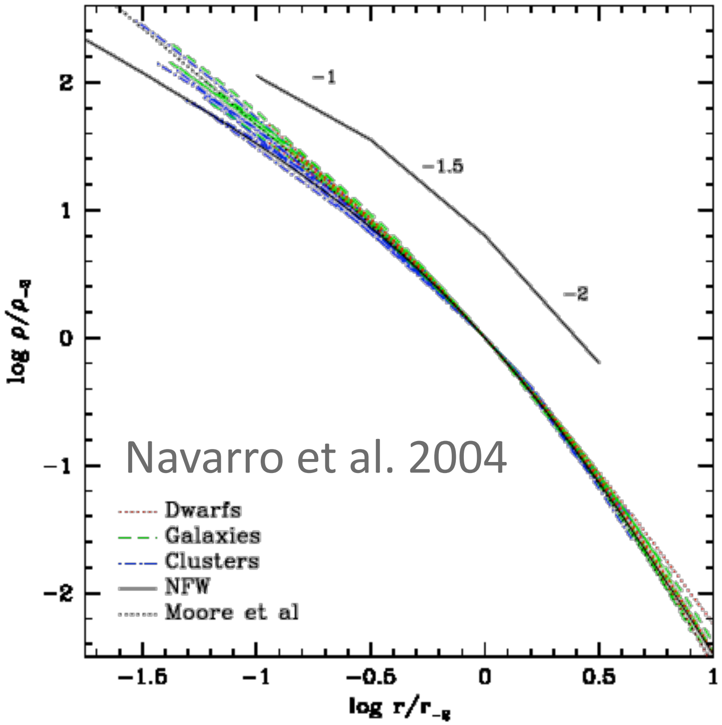


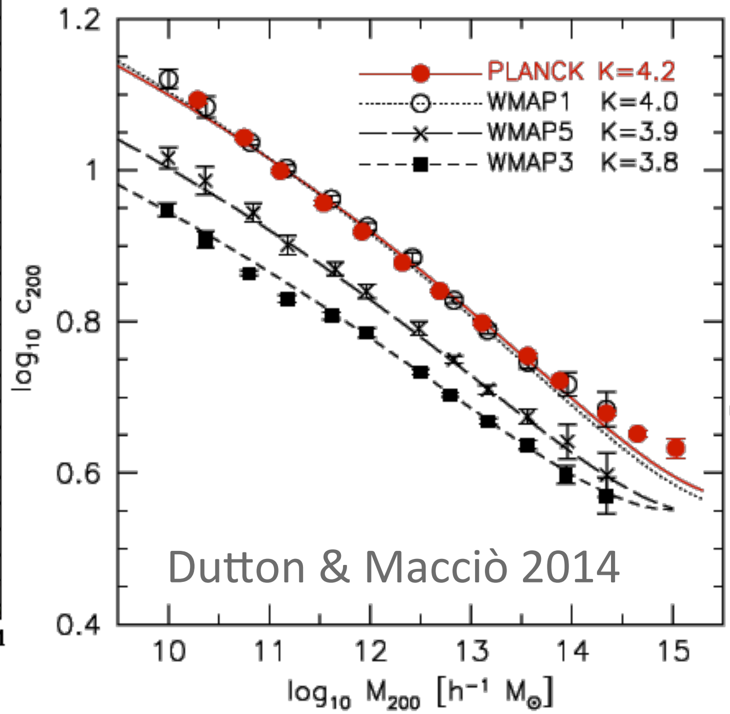
Planck CMB

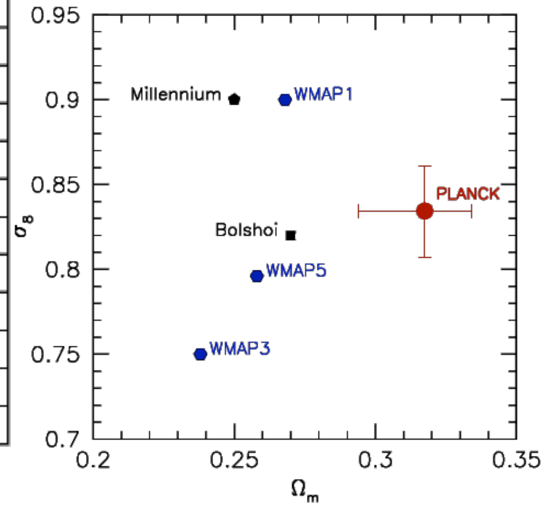


DM properties

(Cossisionless) Simulations







NFW

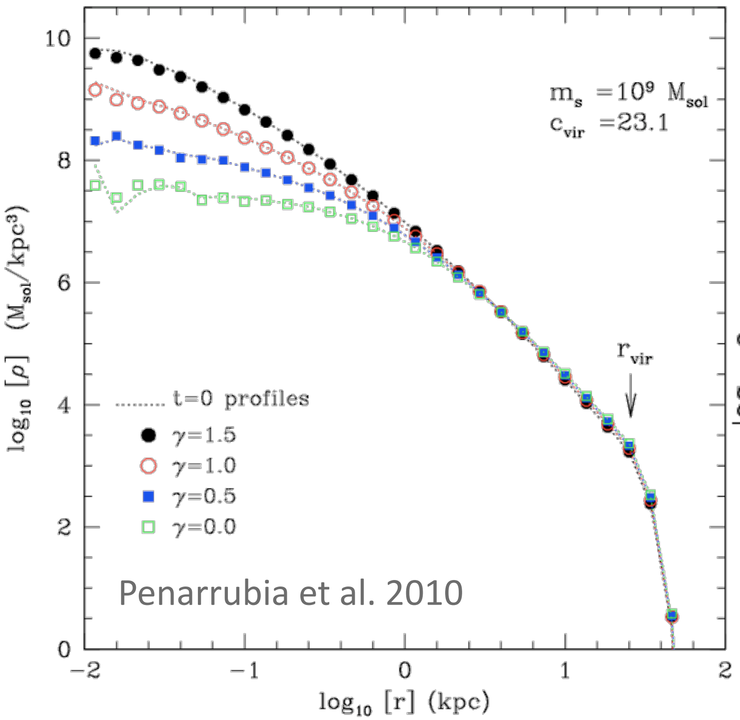
$$\rho(r) = \frac{\rho_s}{r/r_s(1 + r/r_s)^2}$$

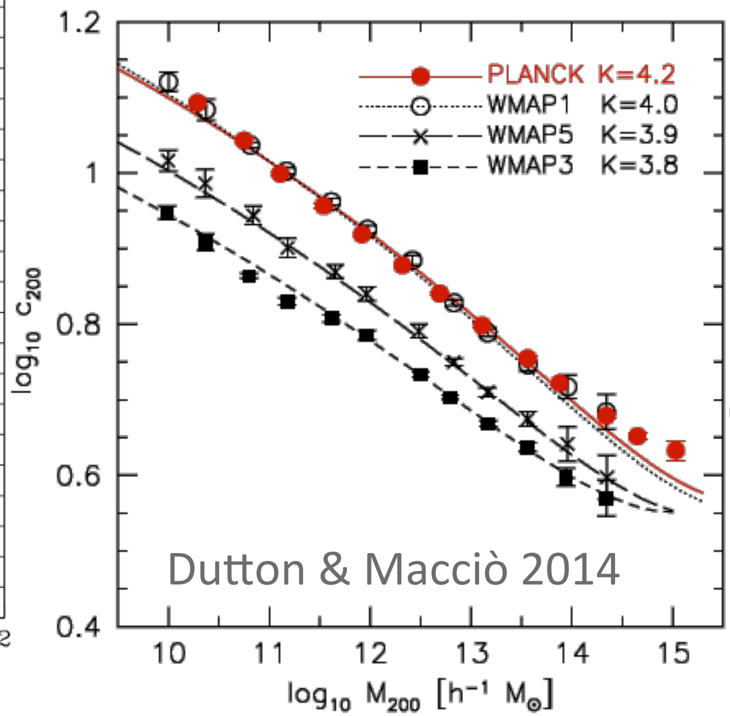
Concentration-Virial mass vs Cosmology

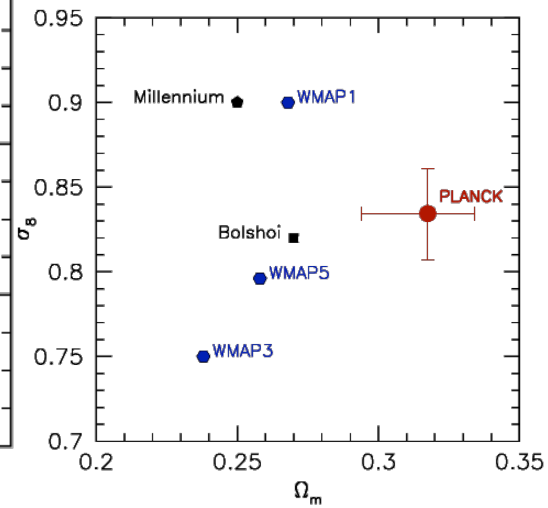
$$\log_{10} c_{vir} = 1.025 - 0.097 \log_{10}(M_{vir}/[10^{12} h^{-1} M_{\odot}])$$

DM properties

(Cossisionless) Simulations







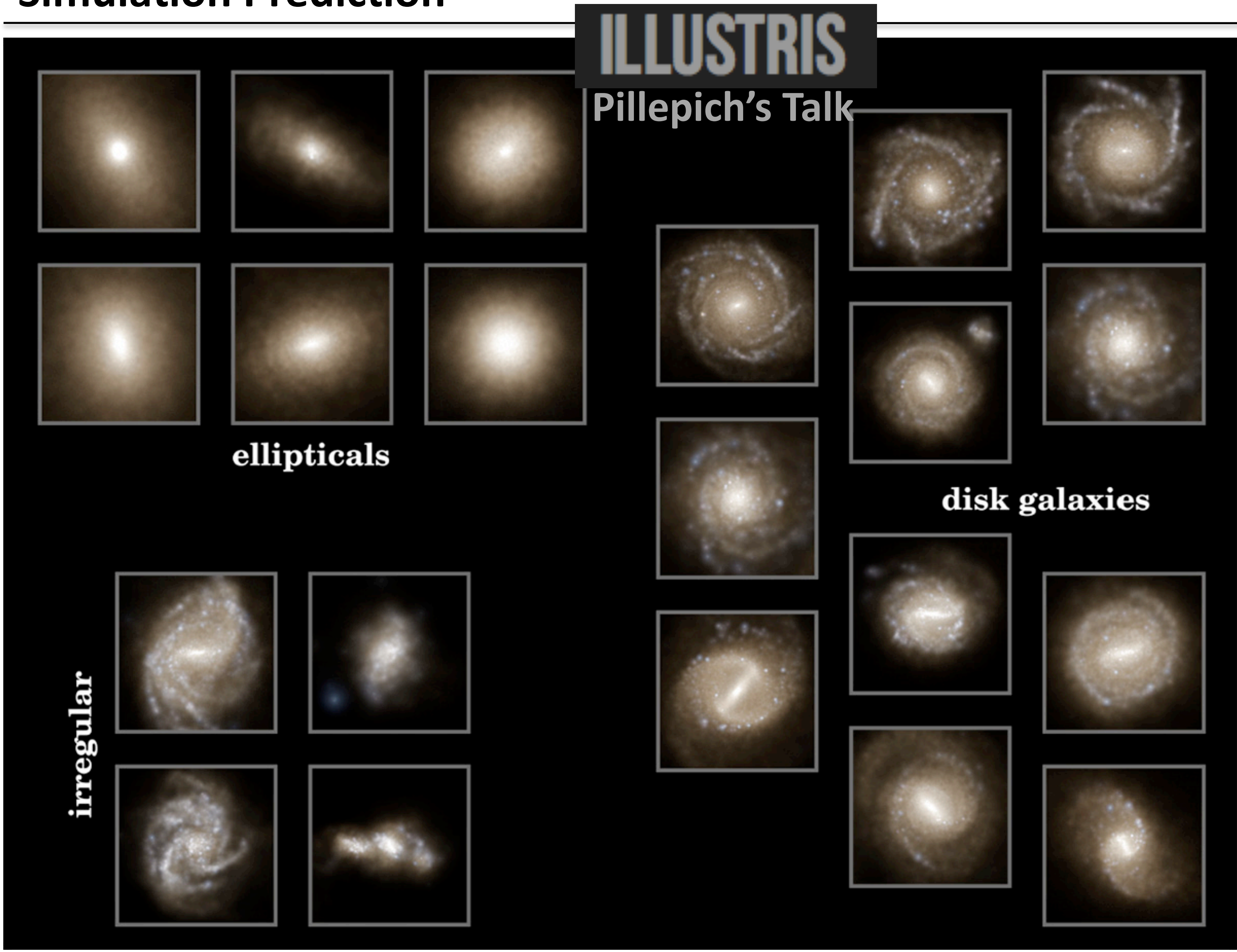
generalized NFW

$$\rho_d(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)\right]^{\gamma-3}$$

Concentration-Virial mass vs Cosmology

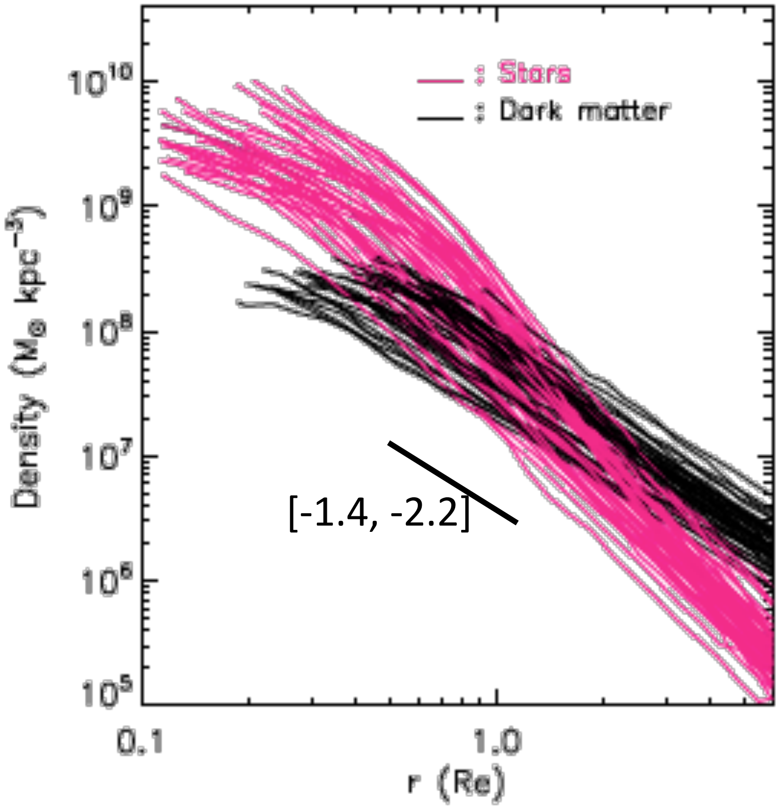
$$\log_{10} c_{vir} = 1.025 - 0.097 \log_{10}(M_{vir}/[10^{12} h^{-1} M_\odot])$$

Simulation Prediction

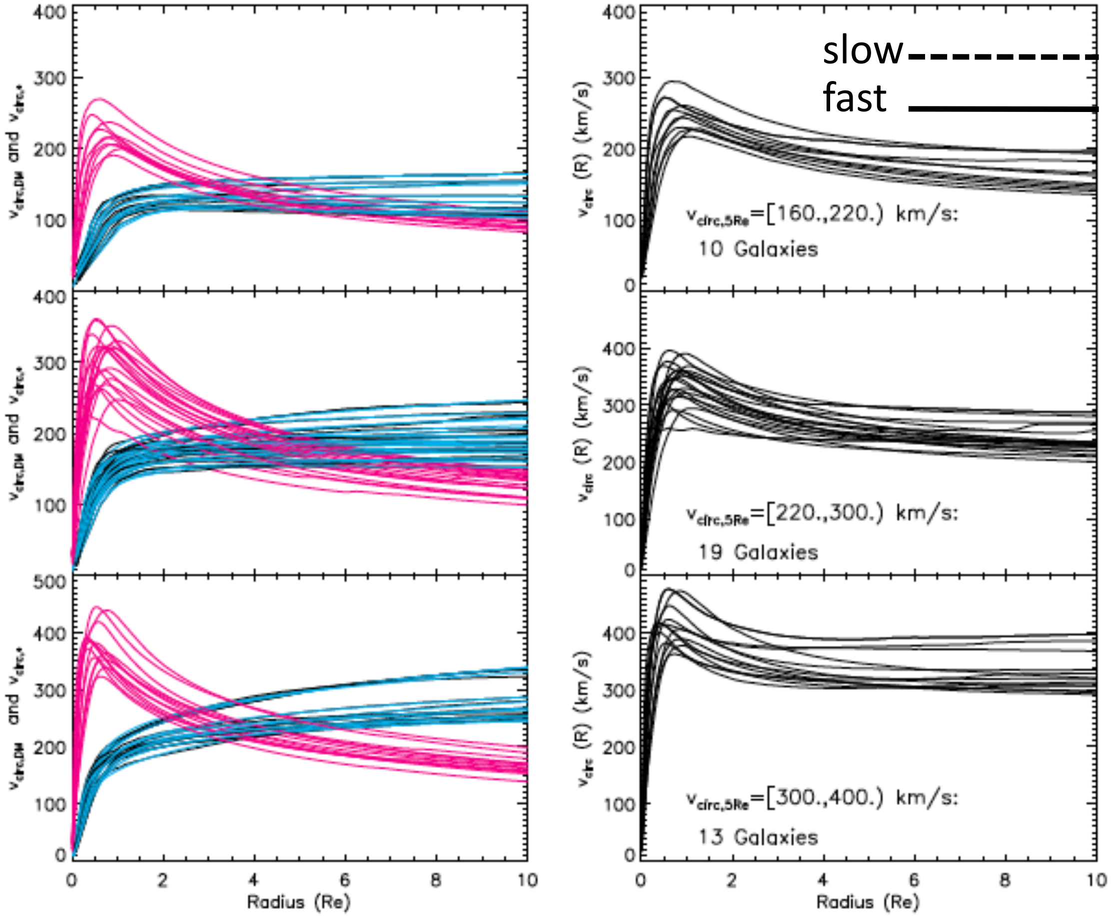


DM and Light properties – merging simulations

DM vs light densities



Circular velocity

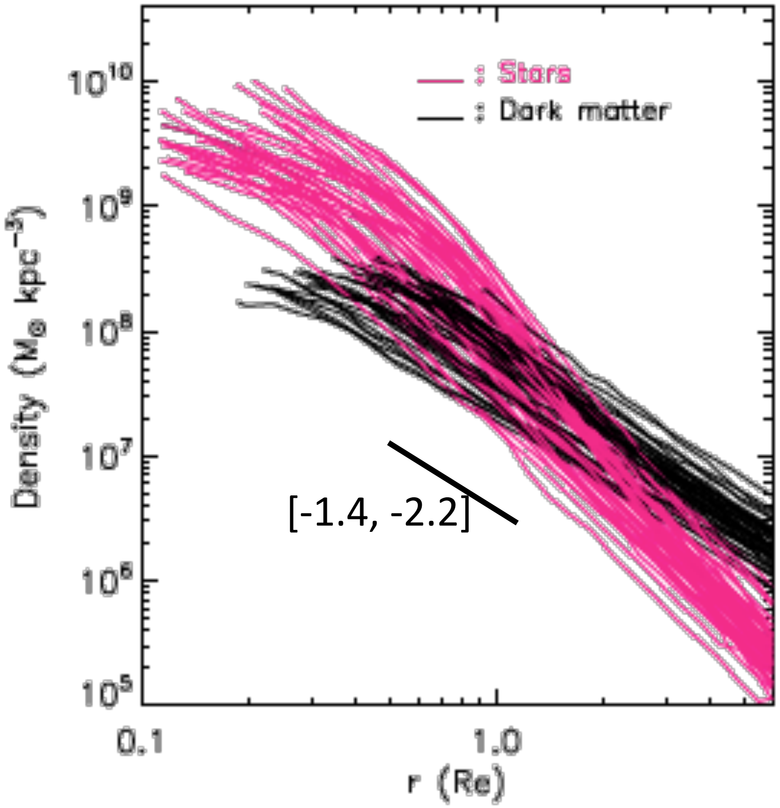


Wu et al. 2014

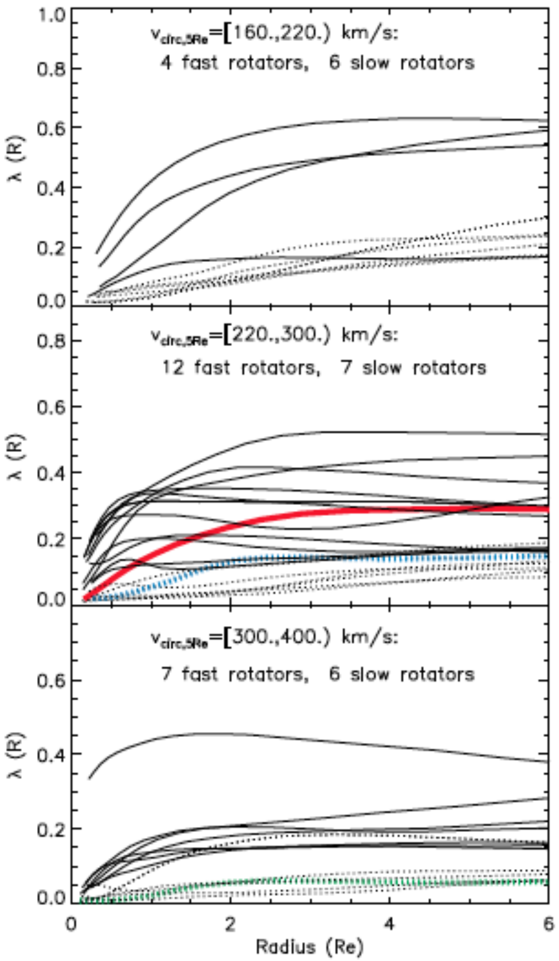
hydrodynamical re-simulation of DM only simulation

DM and Light properties – merging simulations

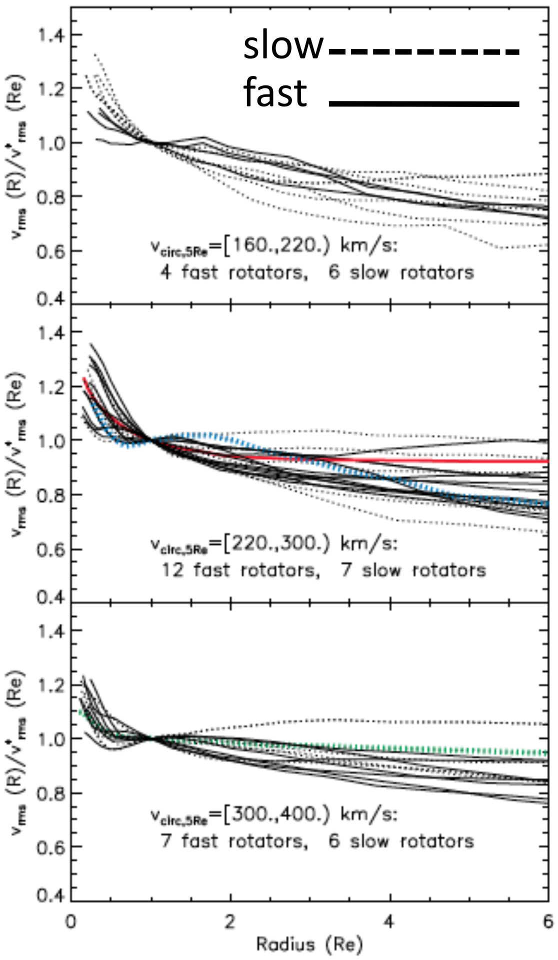
DM vs light densities



angular momentum



velocity dispersion



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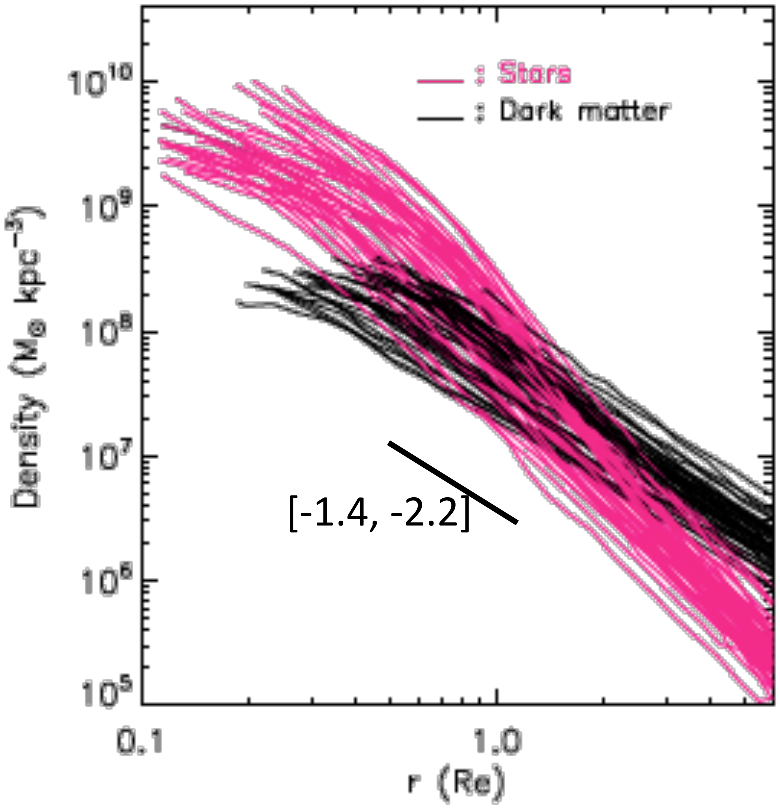
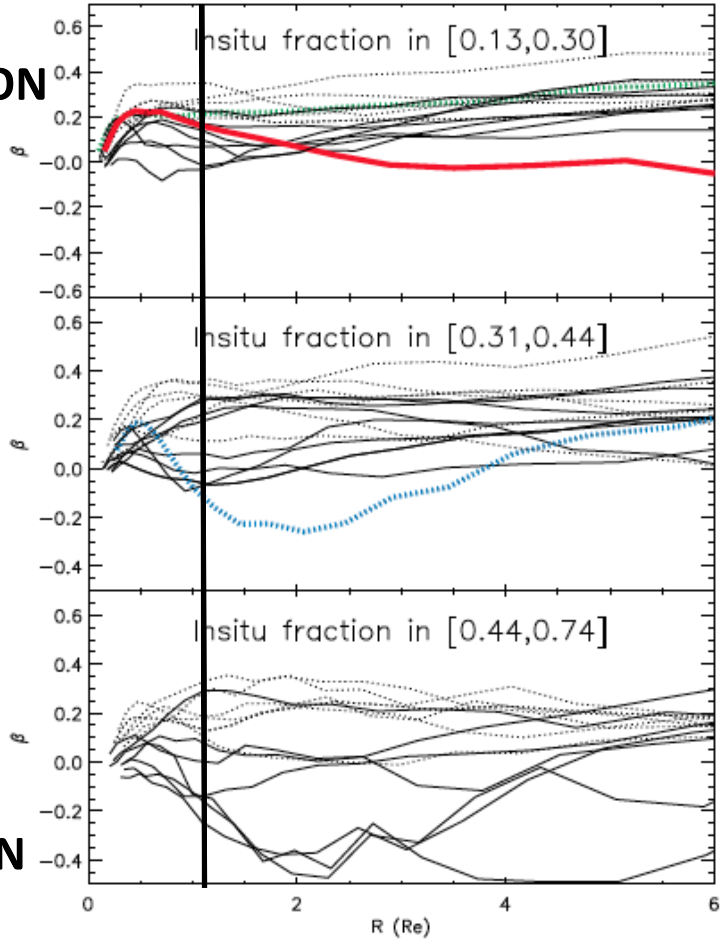


orbital anisotropy

HIGHER ACCRETION

LOWER ACCRETION



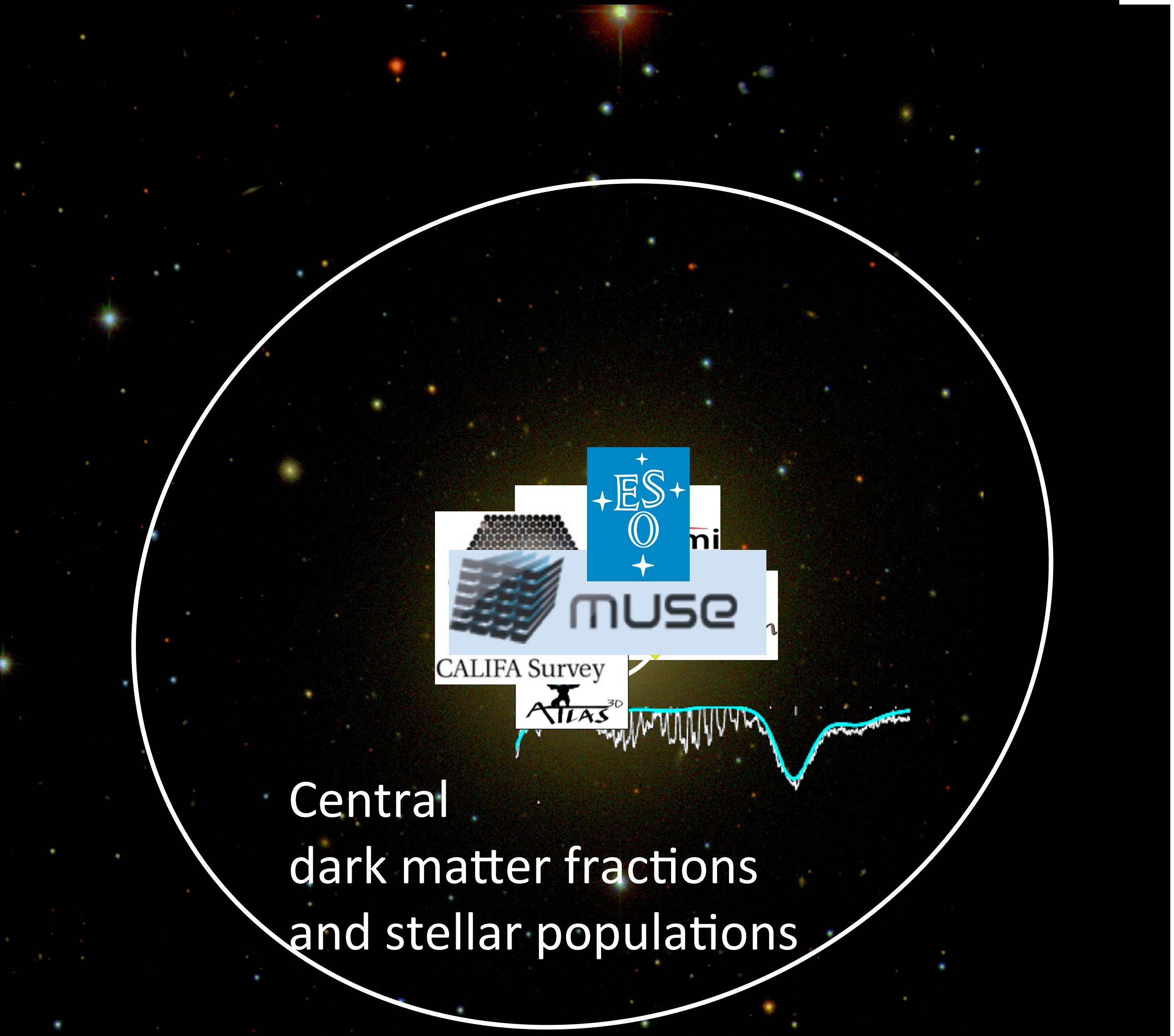
slow - - - - - - - -

fast ———

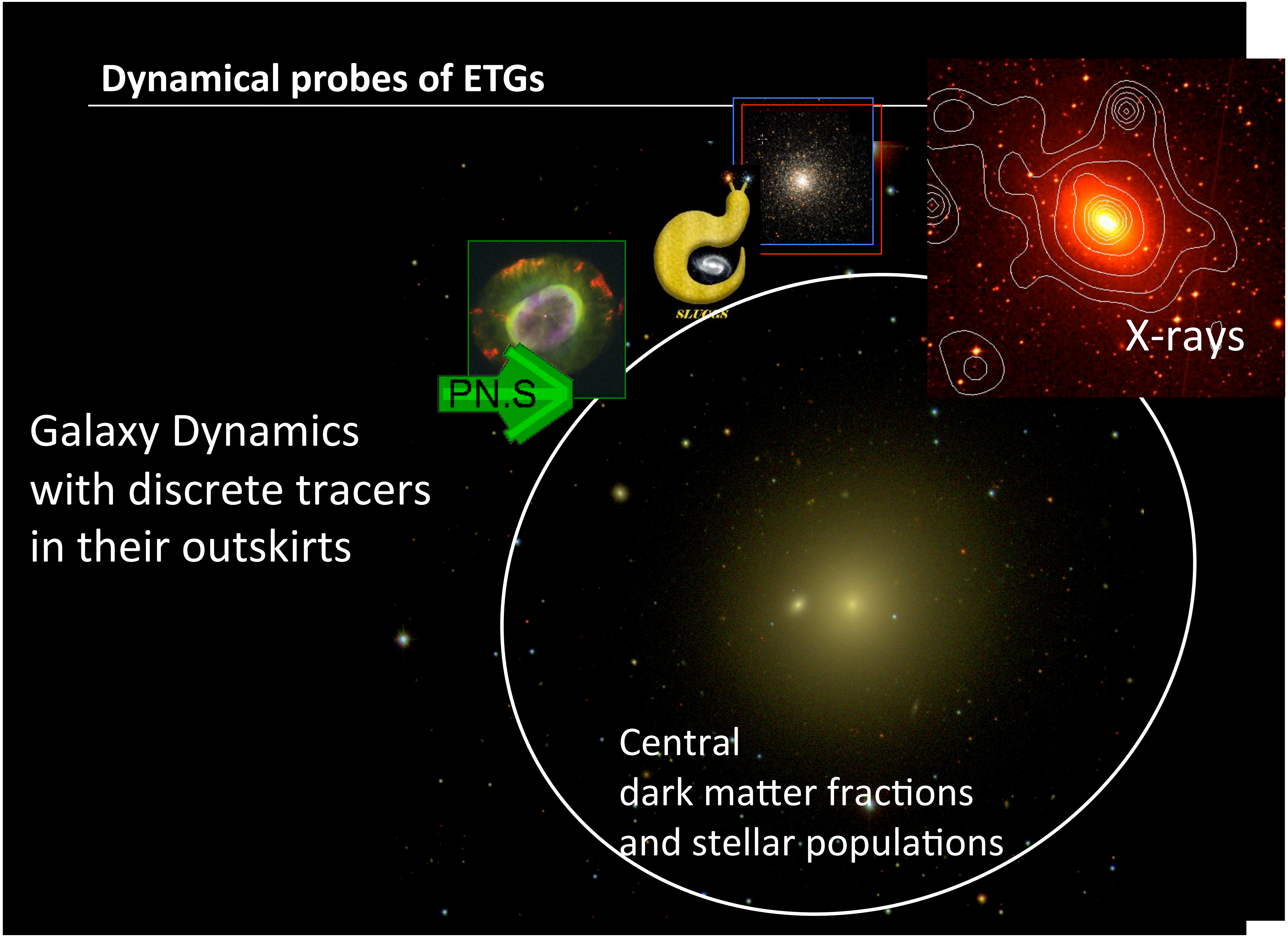
Wu et al. 2014

"**The accreted component is characterised by radially anisotropic** velocity dispersions (Abadi et al.2006; Hilz et al. 2012) because the merging satellites come in on predominantly radial orbits, and so many of the stars."

Dynamical probes of ETGs

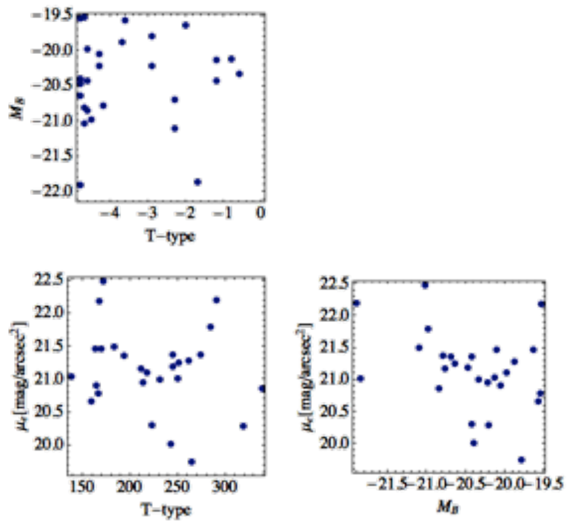
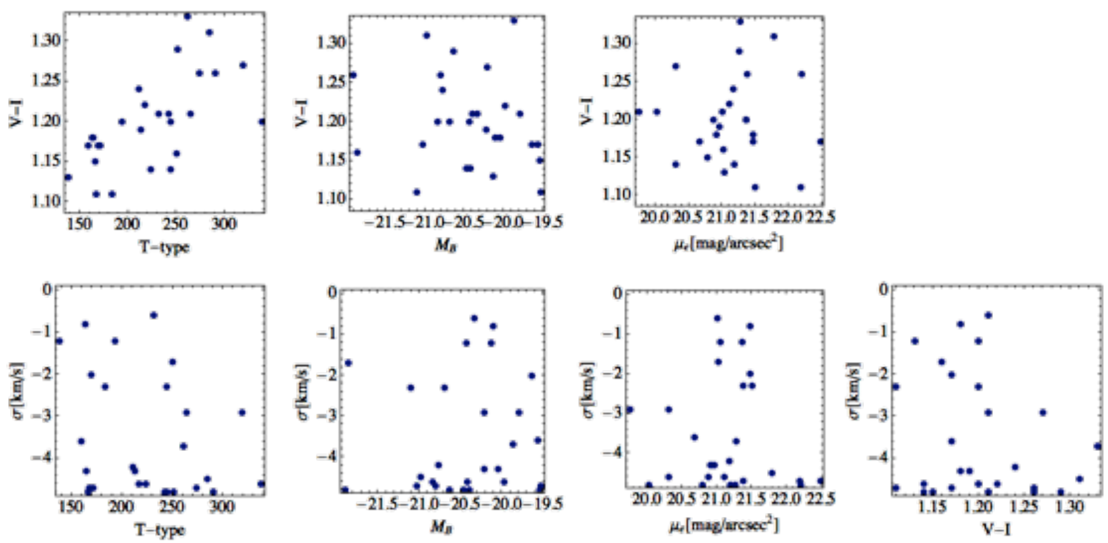


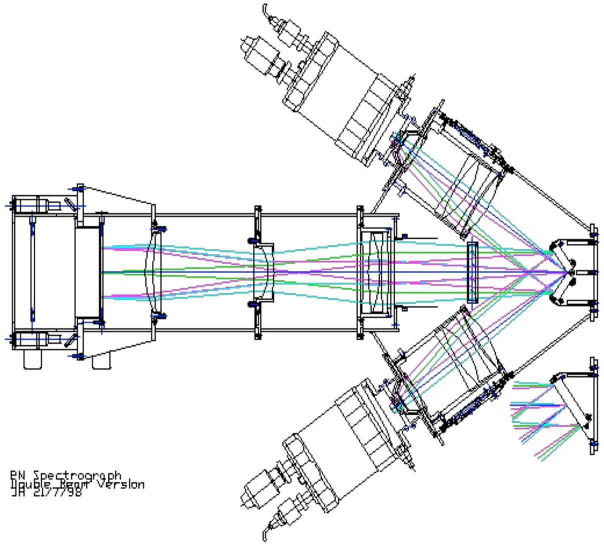
Central
dark matter fractions
and stellar populations

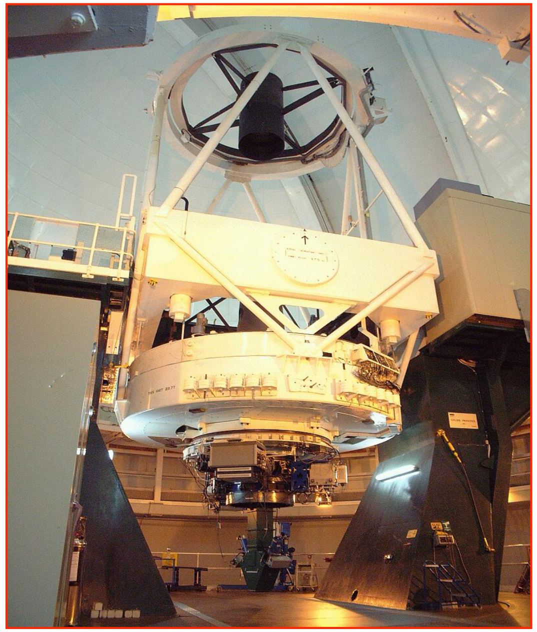

Dynamical probes of ETGs
PN.S
SLUGGS
X-rays
Galaxy Dynamics
with discrete tracers
in their outskirts
Central
dark matter fractions
and stellar populations

PN as dynamical probles of the galaxy outer haloes

PN.S Planetary Nebula Spectrograph Galaxy Survey





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M. Capaccioli	Univ. Naples
L. Coccato	ESO - Garching
A. Cortesi	Univ. Sau Paulo
N.Douglas	Kapteyn Institute, Groningen
K. Freeman	Mt. Stromlo
O. Gerhard	MPE – Garching
K. Kuijken	Un. Leiden
M. Merrifield	Un. Nottingham
N. R. Napolitano	INAF – Capodimonte
A. Romanowsky	San José/Sta Cruz (USA)

PN as dynamical probles of the galaxy outer haloes

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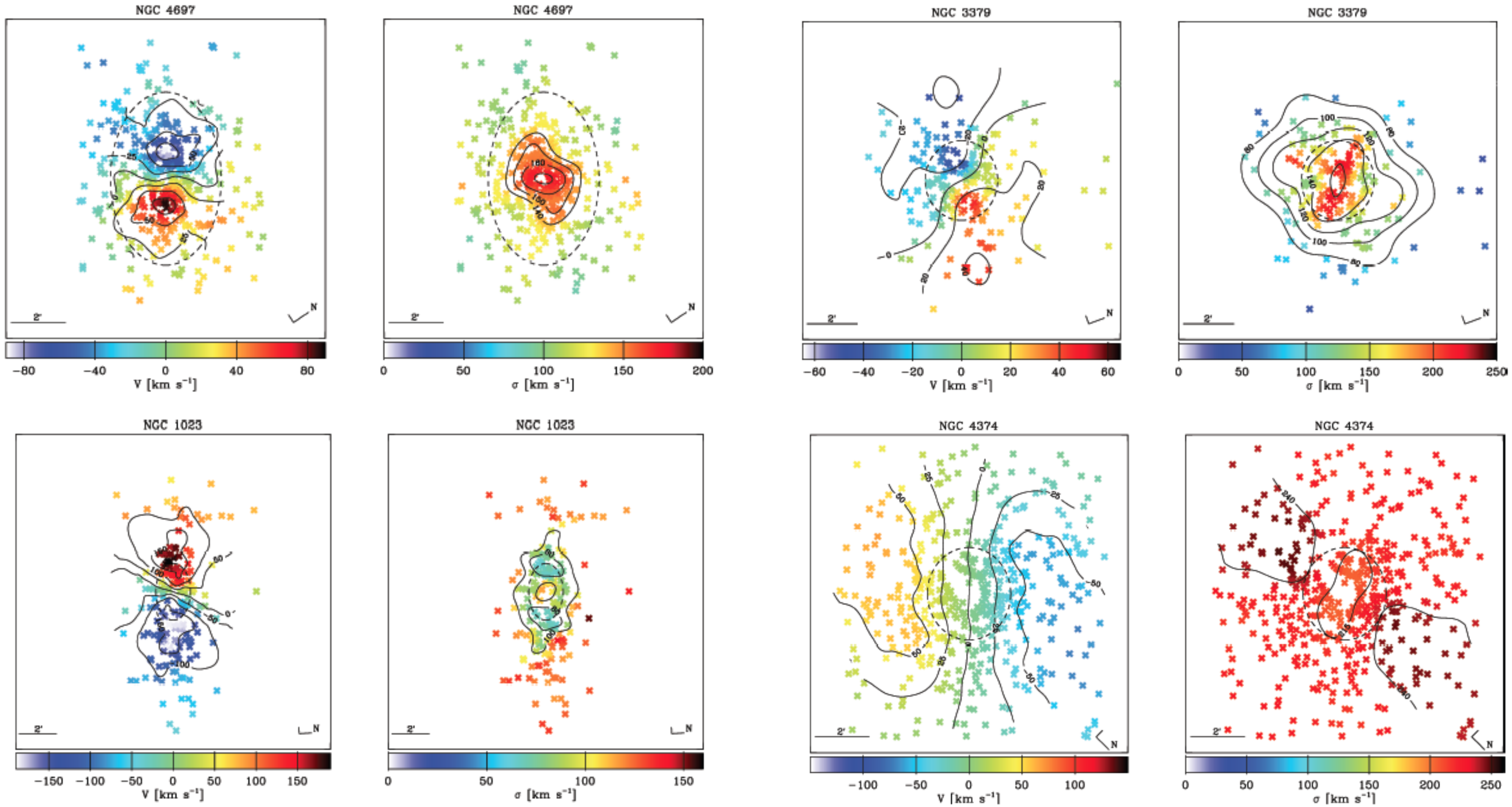
Planetary Nebula Spectrograph Galaxy Survey

Coccato et al. 2009



PN as dynamical probles of the galaxy outer haloes

PN.S Planetary Nebula Spectrograph Galaxy Survey

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A Dearth of Dark Matter in Ordinary Elliptical Galaxies

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

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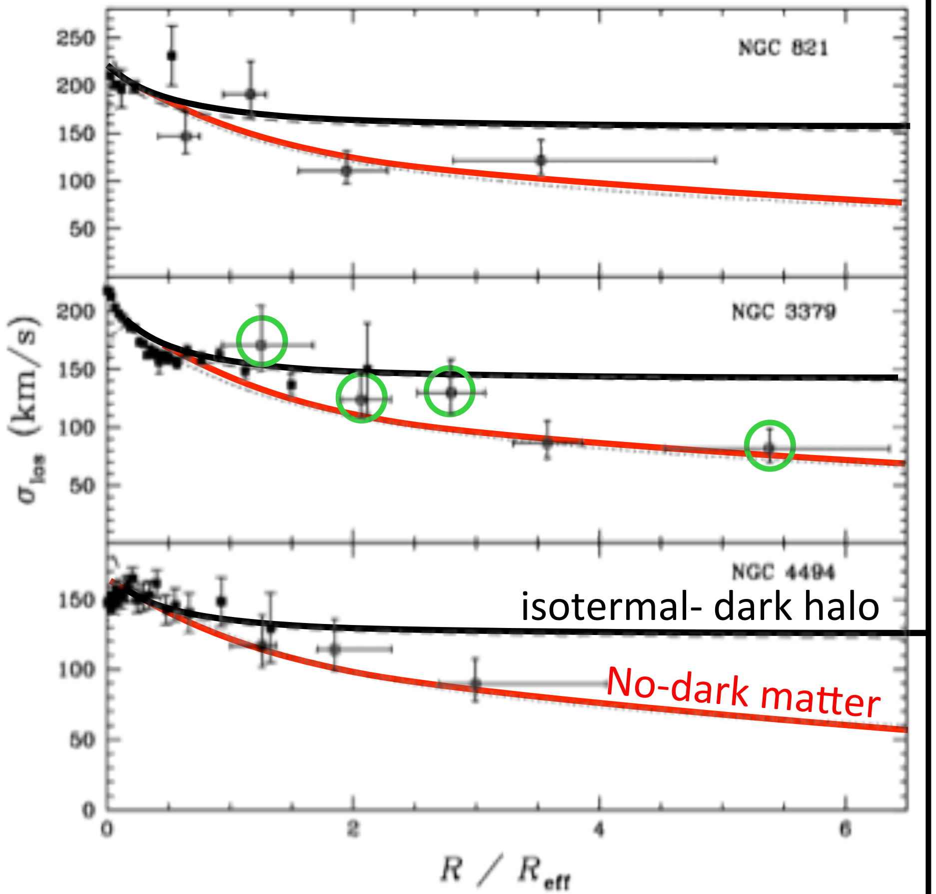
The kinematics of the outer parts of three intermediate-luminosity elliptical galaxies have been studied using the Planetary Nebula Spectrograph. The galaxies' velocity dispersion profiles are found to decline with radius; dynamical modeling of the data indicate the presence of little if any dark matter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

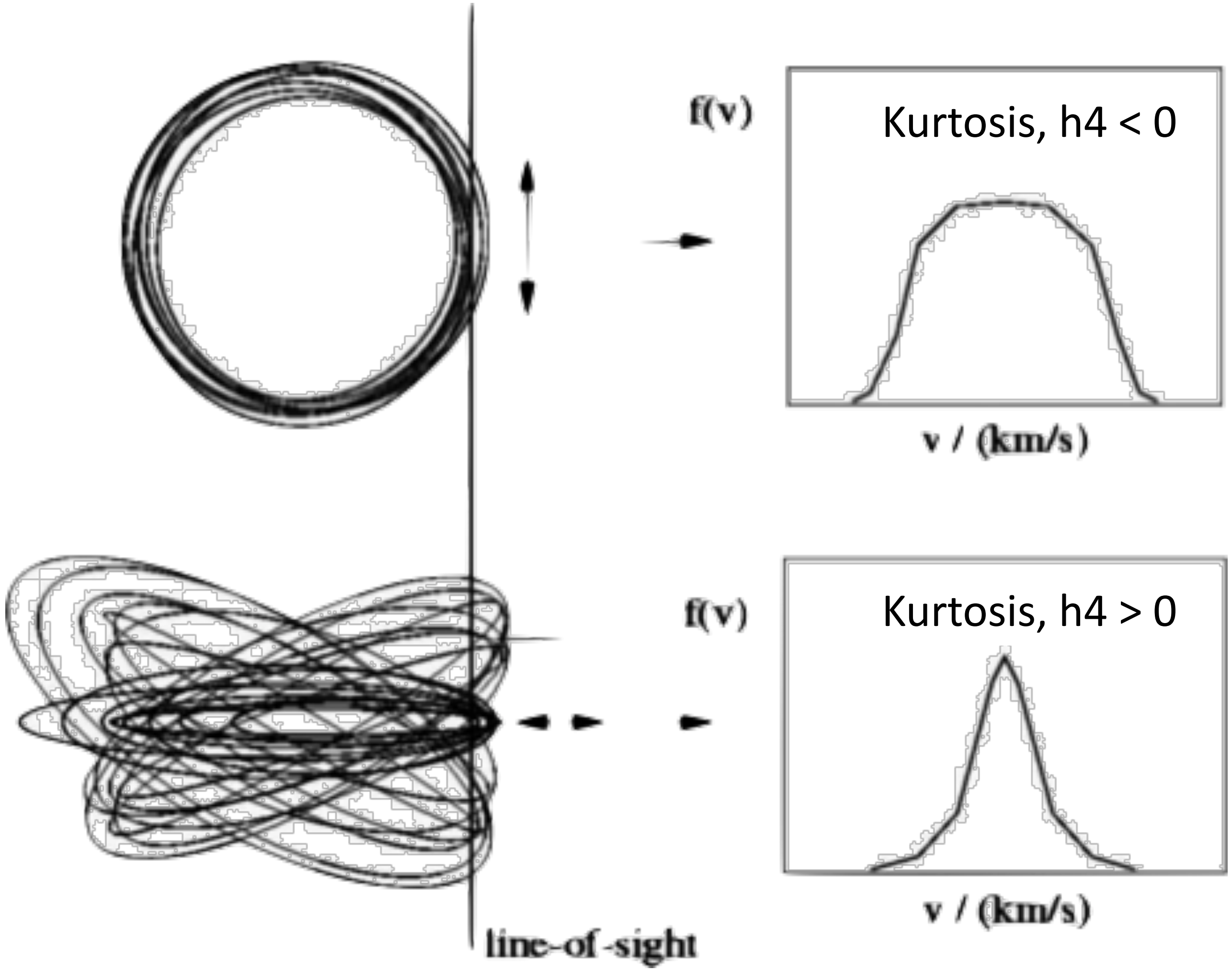
Romanowsky et al. 2003



The effect of the orbital anisotropy

Tangential orbits

Radial orbits



$$\mathrm{v}_c^2 = \frac{GM(r)}{r} = -\sigma_r^2\left(\frac{d\ln v}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

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

Jeans analysis of E systems

2[nd] moment Jeans Equation (spherical non rotating systems)

$$\frac{\mathrm{d}}{\mathrm{d}r}(j\sigma_r^2) + \frac{2\beta}{r} j\sigma_r^2 = -j\frac{\mathrm{d}\Phi}{\mathrm{d}r} \qquad \beta = 1 - \frac{\sigma_\theta^{\ 2}}{\sigma_r^{\ 2}}$$

(e.g. Lokas 2002)

$$j_*\sigma_r^2(\beta = \text{const}) = r^{-2\beta}\int_r^\infty r'^{2\beta} j_* \frac{\mathrm{d}\Phi}{\mathrm{d}r'}\,\mathrm{d}r'$$

$$f(E,L) = f_0(E)L^{-2\beta}$$

where $$\Phi(r) = -\frac{GM(r)}{r} = -\frac{GM_{star}(r) + M_{DM}(r)}{r}$$

$$\sigma_{\rm los}^2(R) = \frac{2}{I(R)}\int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right)\frac{j_*\,\sigma_r^2\, r}{\sqrt{r^2 - R^2}}\,\mathrm{d}r$$

$$M(r) = -\frac{\sigma_r^2\, r}{G}\left(\frac{d\ln j_*}{d\ln r} + \frac{d\ln \sigma_r^2}{d\ln r} + 2\beta\right)$$

Jeans analysis of E systems

4th moment Jeans Equation

$$\frac{\mathrm{d}}{\mathrm{d}r}(j_* \overline{v_r^4}) + \frac{2\beta}{r} j_* \overline{v_r^4} + 3 j_* \sigma_r^2 \frac{\mathrm{d}\Phi}{\mathrm{d}r} = 0$$

$$j_* \overline{v_r^4} = 3 r^{-2\beta} \int_r^\infty r'^{2\beta} j_* \sigma_r^2 \frac{\mathrm{d}\Phi}{\mathrm{d}r'} \, \mathrm{d}r'$$

$$\overline{v_{\mathrm{los}}^4}(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - 2\beta \frac{R^2}{r^2} + \frac{\beta(1+\beta)}{2} \frac{R^4}{r^4}\right) \frac{j_* \, \overline{v_r^4} \, r}{\sqrt{r^2 - R^2}} \, \mathrm{d}r$$

$$\kappa_{\mathrm{los}}(R) = \frac{\overline{v_{\mathrm{los}}^4}(R)}{\sigma_{\mathrm{los}}^4(R)} - 3$$

Jeans analysis of E systems

4th moment Jeans Equation

$$\frac{\mathrm{d}}{\mathrm{d}r}(j_*\overline{v_r^4}) + \frac{2\beta}{r} j_*\overline{v_r^4} + 3j_*\sigma_r^2\frac{\mathrm{d}\Phi}{\mathrm{d}r} = 0$$

$$j_*\overline{v_r^4} = 3r^{-2\beta}\int_r^\infty r'^{2\beta} j_*\sigma_r^2\frac{\mathrm{d}\Phi}{\mathrm{d}r'}\ \mathrm{d}r'$$

$$\Sigma\overline{v_{los}^4}(R) = 2\int_R^\infty g(\beta,r,R)\frac{\nu\overline{v_r^4}r}{\sqrt{r^2-R^2}}dr$$

$$g(\beta,r,R) = 1 - 2\beta\frac{R^2}{r^2} + \frac{\beta(1+\beta)}{2}\frac{R^4}{r^4} - \frac{R^4}{4r^3}\frac{d\beta}{dr}$$

$$\kappa_{\mathrm{los}}(R) = \frac{\overline{v_{\mathrm{los}}^4}(R)}{\sigma_{\mathrm{los}}^4(R)} - 3$$

Richardson & Fairbairn 2014

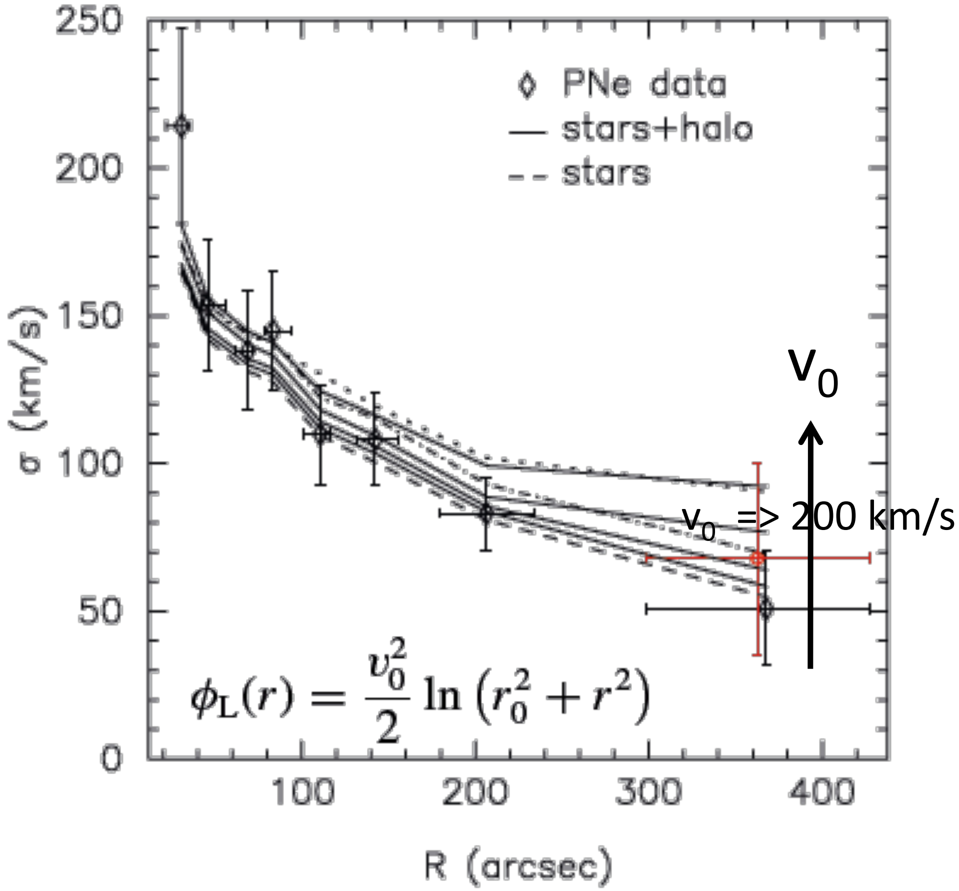
generalize for β(r)

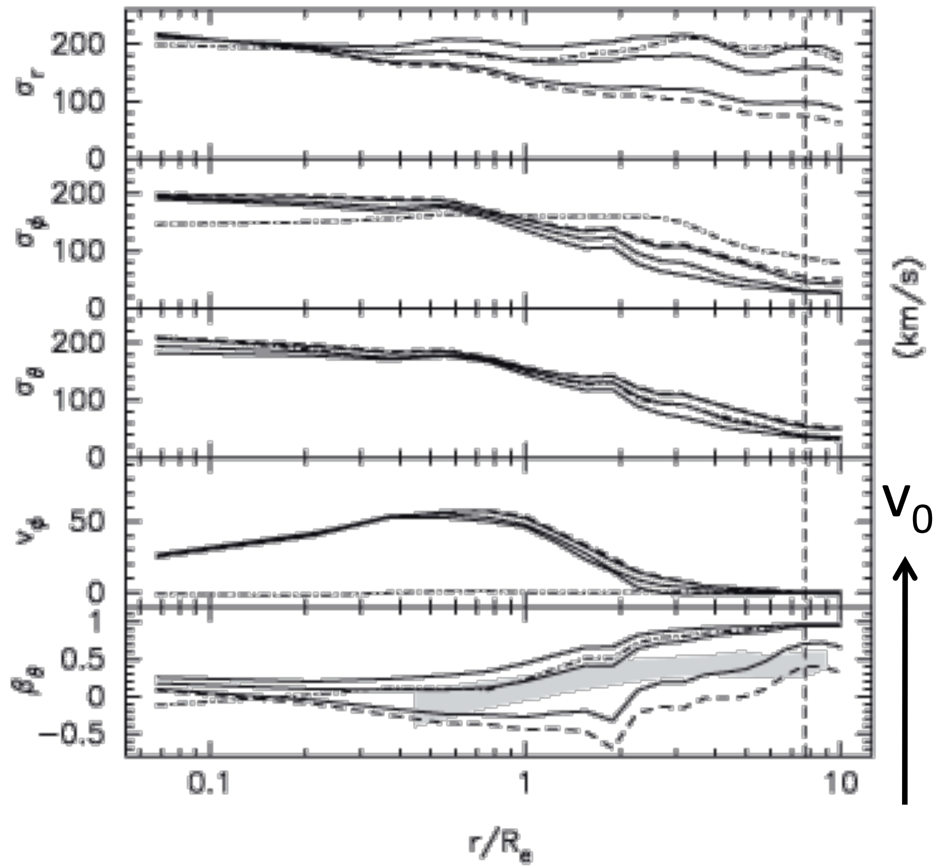
for separable augmented density

$$\beta(r) = \frac{\beta_2 r^c + \beta_1 r_a^c}{r^c + r_a^c}$$

Churazov et a. 2010

Jeans analysis vs. more sophisticated dynamics





De Lorenzi et al. 2008; 2009

NMAGIC: χ^2 made-to- measure particle method
(see Gerhard's talk)

Dearth of dark matter or massive dark halo? Mass-shape-anisotropy degeneracies revealed by NMAGIC dynamical models of the elliptical galaxy NGC 3379

F. De Lorenzi,[1,2★] O. Gerhard,[2] L. Coccato,[2,3] M. Arnaboldi,[4,5] M. Capaccioli,[6] N. G. Douglas,[3] K. C. Freeman,[7] K. Kuijken,[8] M. R. Merrifield,[9] N. R. Napolitano,[6] E. Noordermeer,[9] A. J. Romanowsky[3,9,10] and V. P. Debattista[11]

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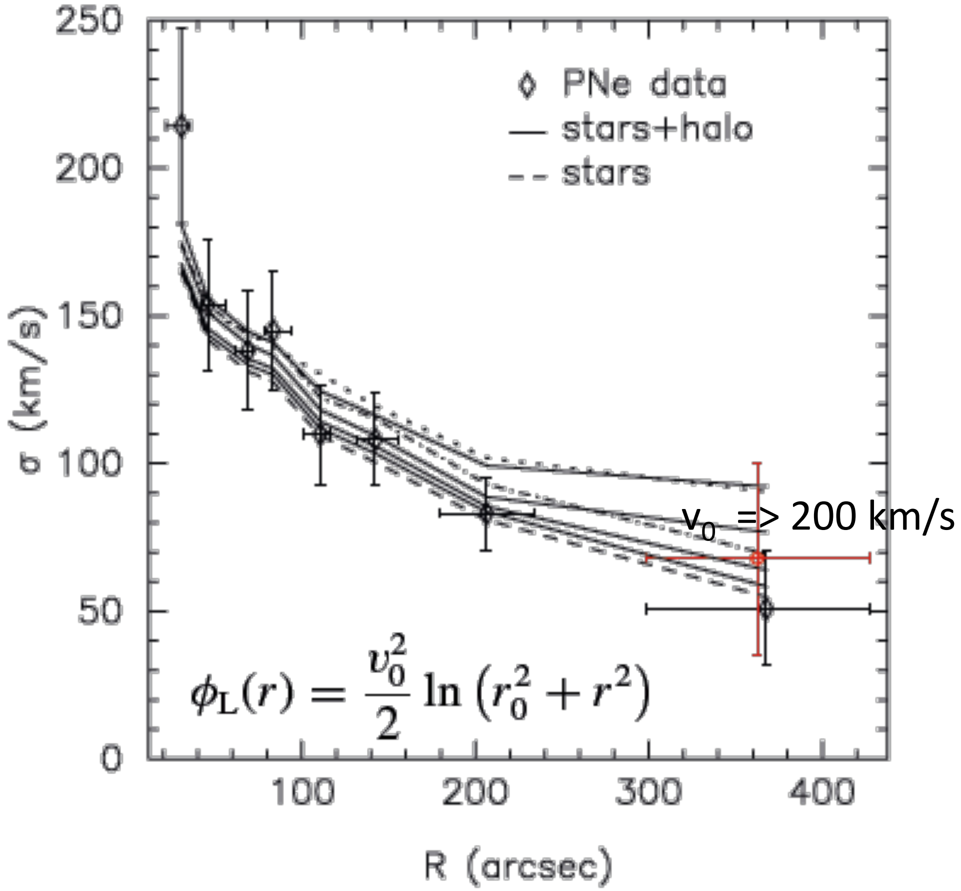

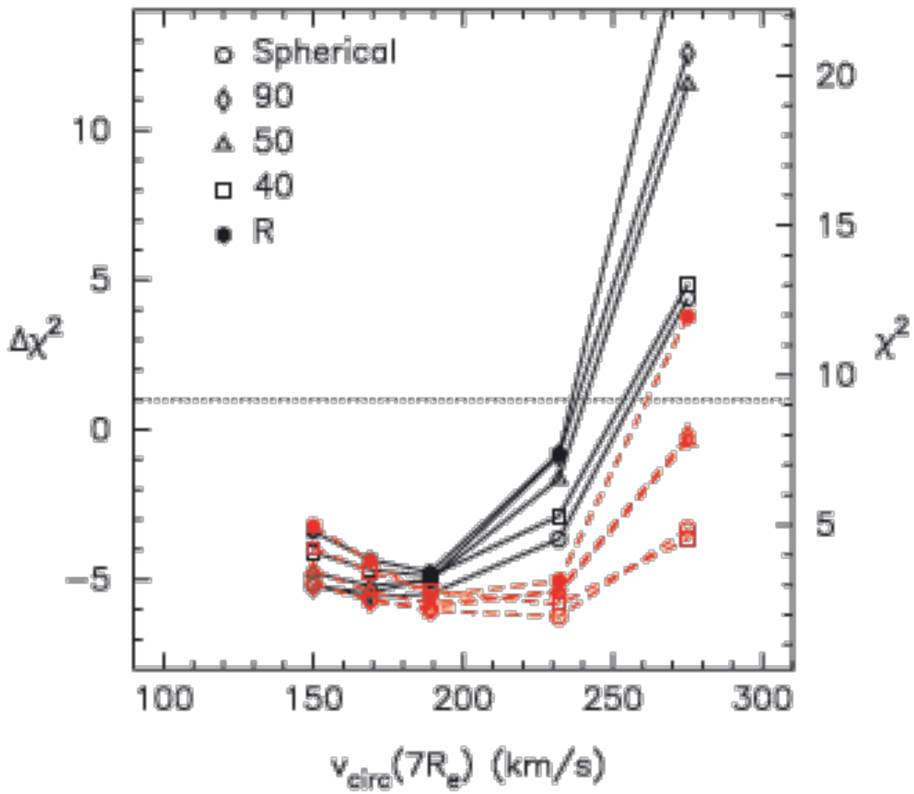

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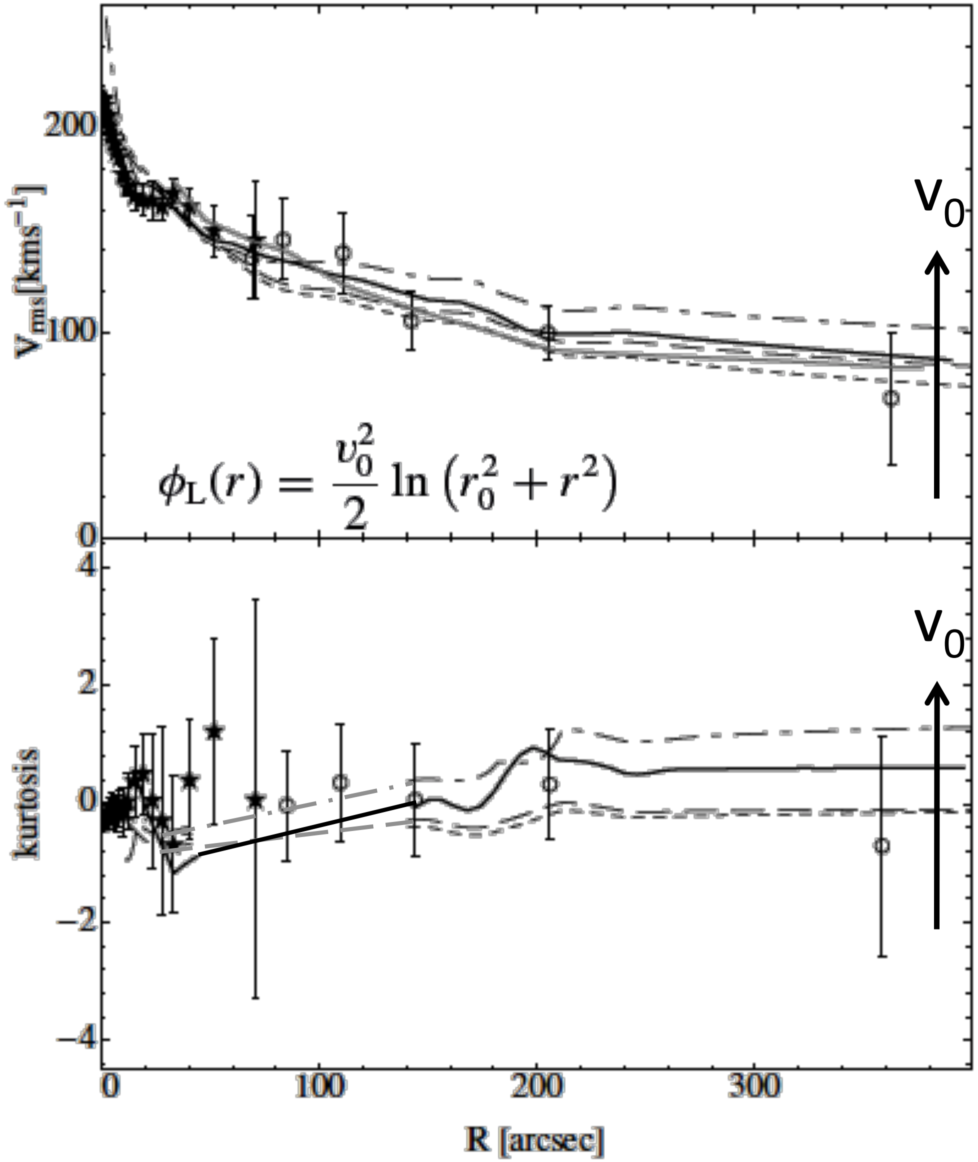
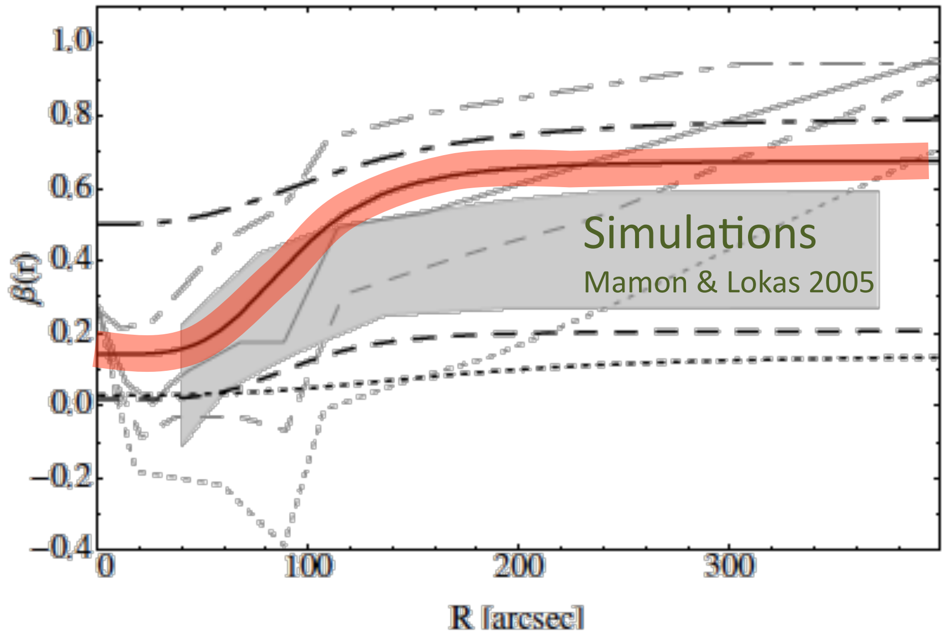
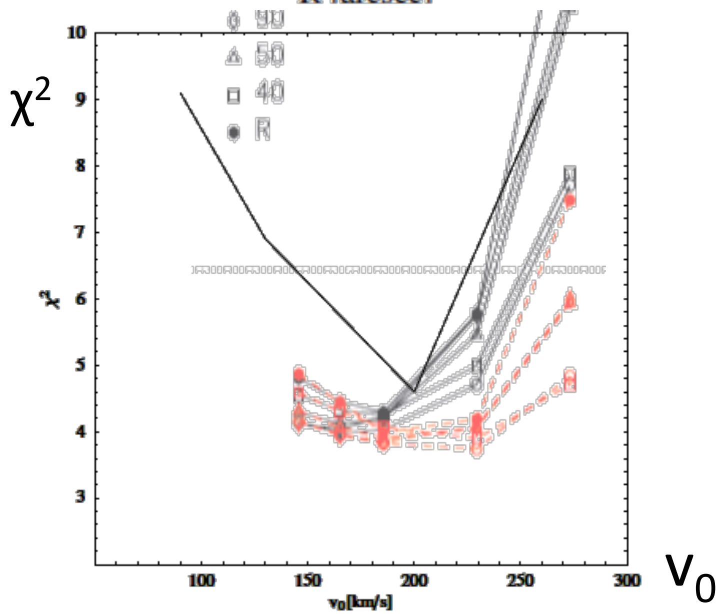
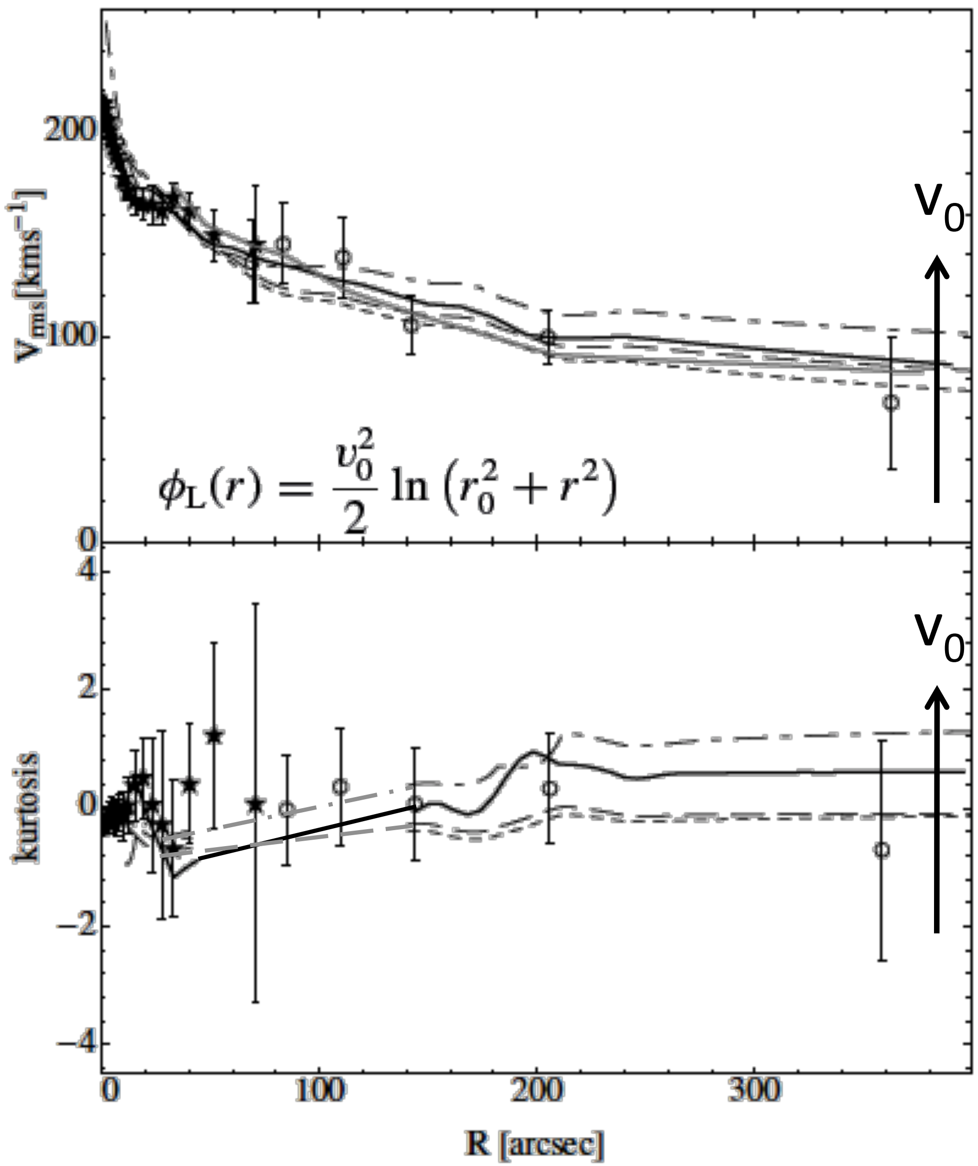
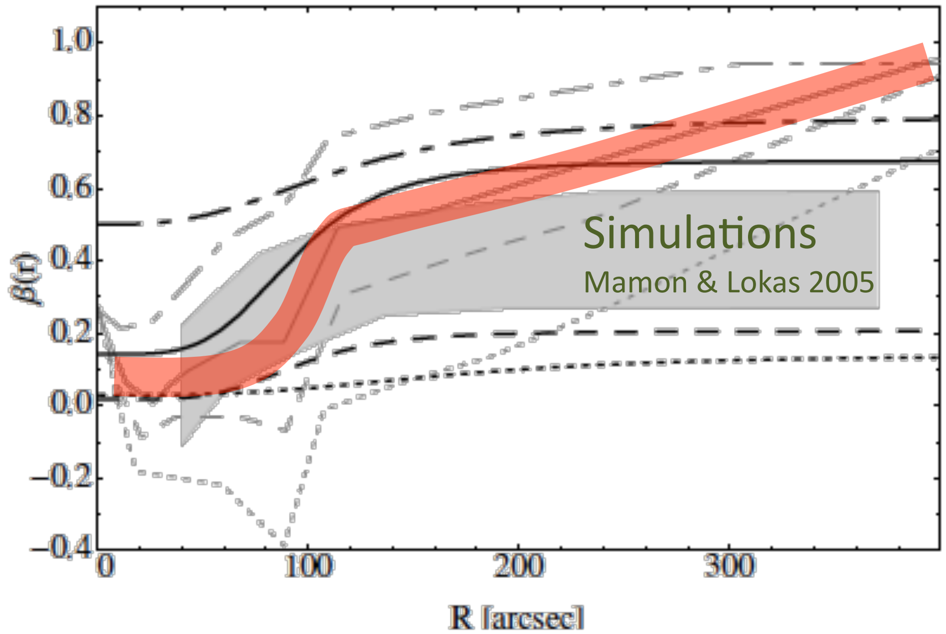


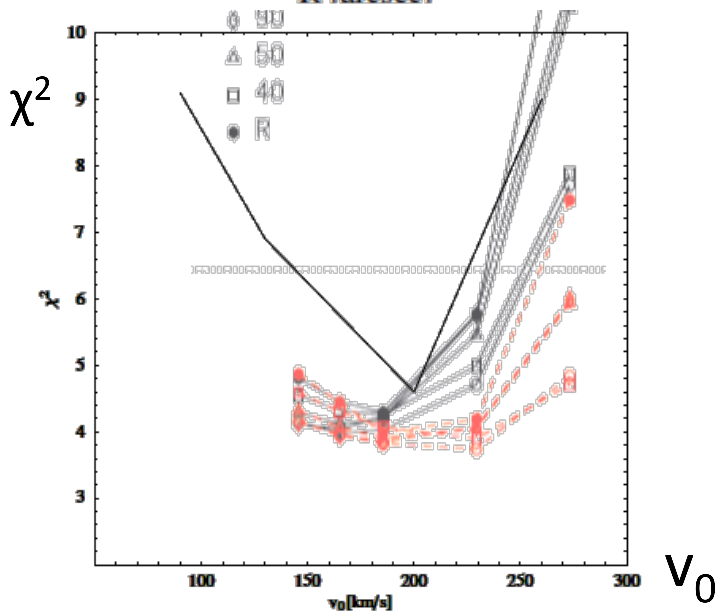




Jeans analysis vs. more sophisticated dynamics







The effect of the orbital anisotropy

Use the higher order velocity moments to (somehow) break the mass-anisotropy degeneracy (Merrifield & Kent 1998, Lokas 2002, Lokas & Mamon 2003).

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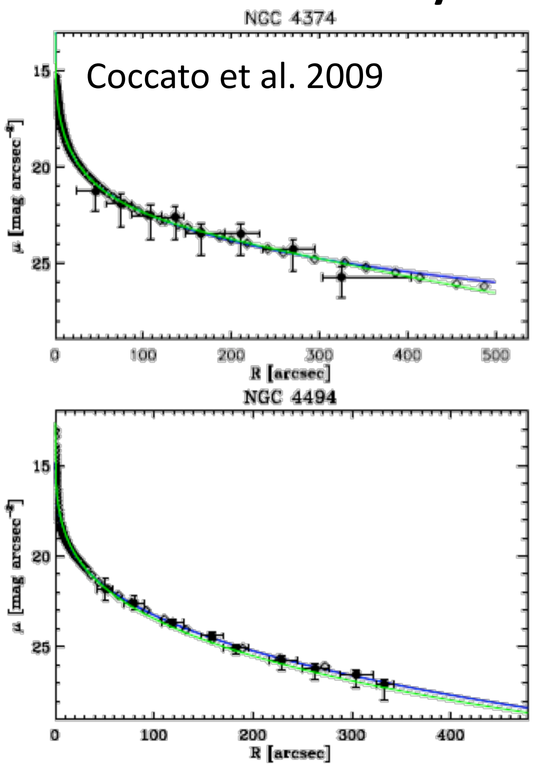
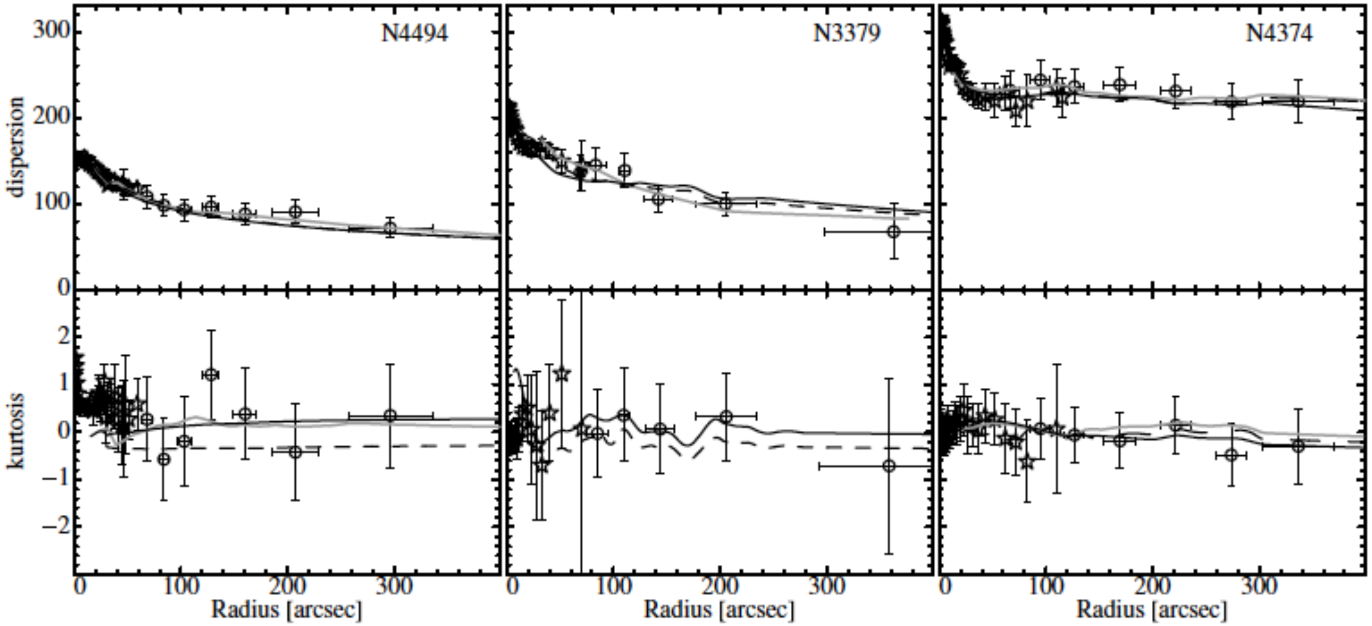
Surface Density



Velocity Dispersion and kurtosis



NRN+, 2009, 2011, 2012

$$f(E,L) = f_0 L^{-2\beta}$$

$$\frac{\mathrm{d}}{\mathrm{d}r}(j\sigma_r^2) + \frac{2\beta}{r} j\sigma_r^2 = -j\frac{\mathrm{d}\Phi}{\mathrm{d}r}$$

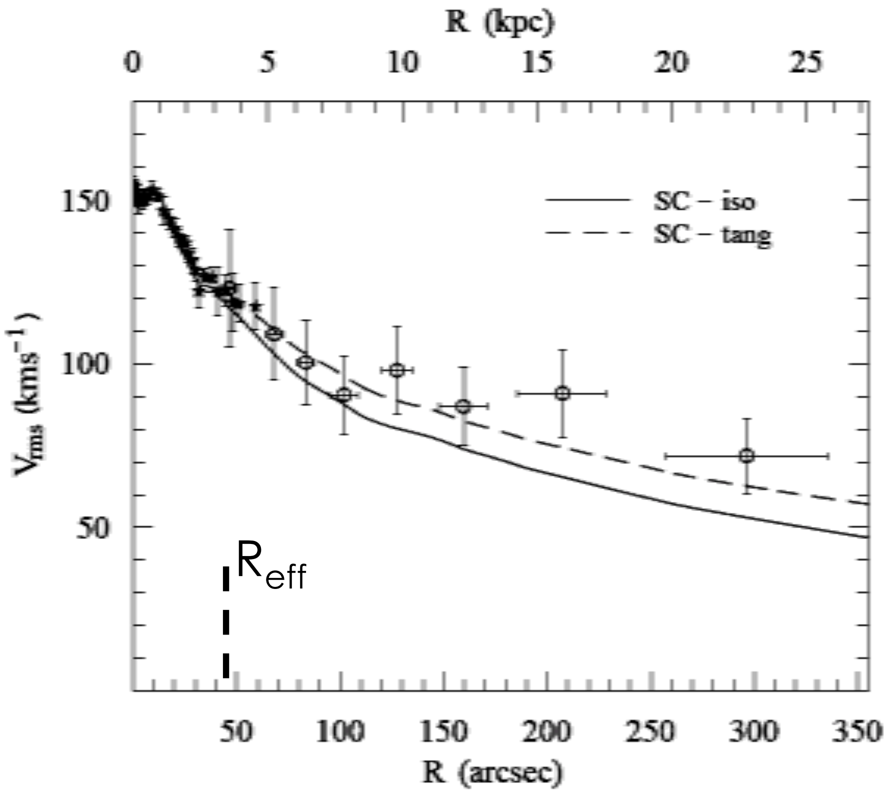
$$\beta(r) = \frac{\beta_2 r^c + \beta_1 r_a^c}{r^c + r_a^c}$$

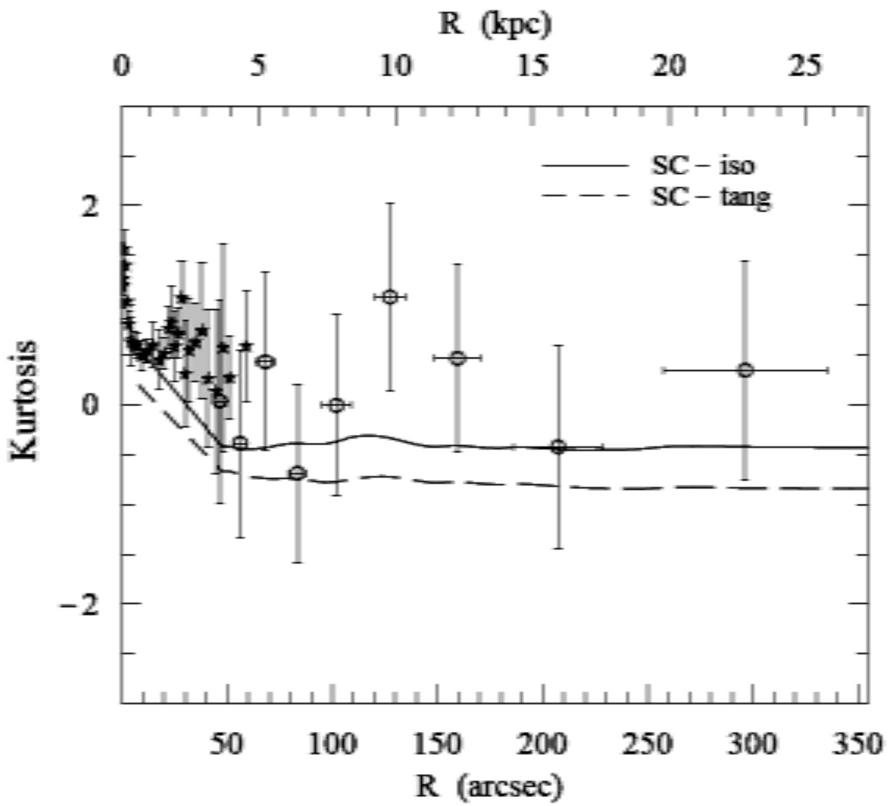
dispersion-kurtosis Jeans analysis

$$\frac{\mathrm{d}}{\mathrm{d}r}(j_* \overline{v_r^4}) + \frac{2\beta}{r} j_* \overline{v_r^4} + 3 j_* \sigma_r^2 \frac{\mathrm{d}\Phi}{\mathrm{d}r} = 0$$

Does this work to break the mass-anisotropy degeneracy?

NGC 4494



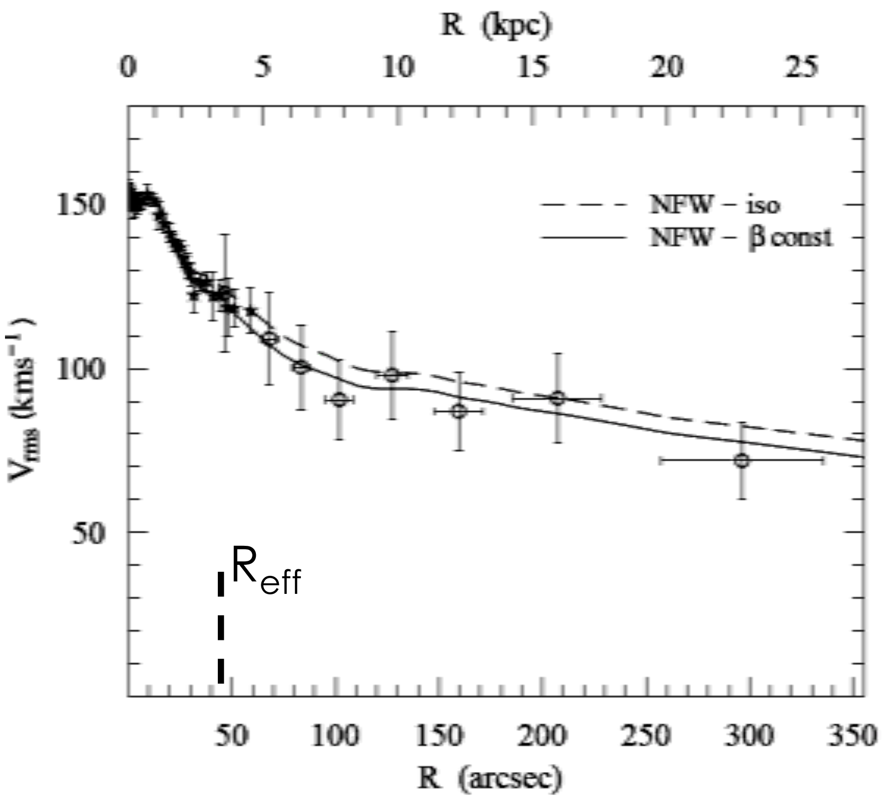


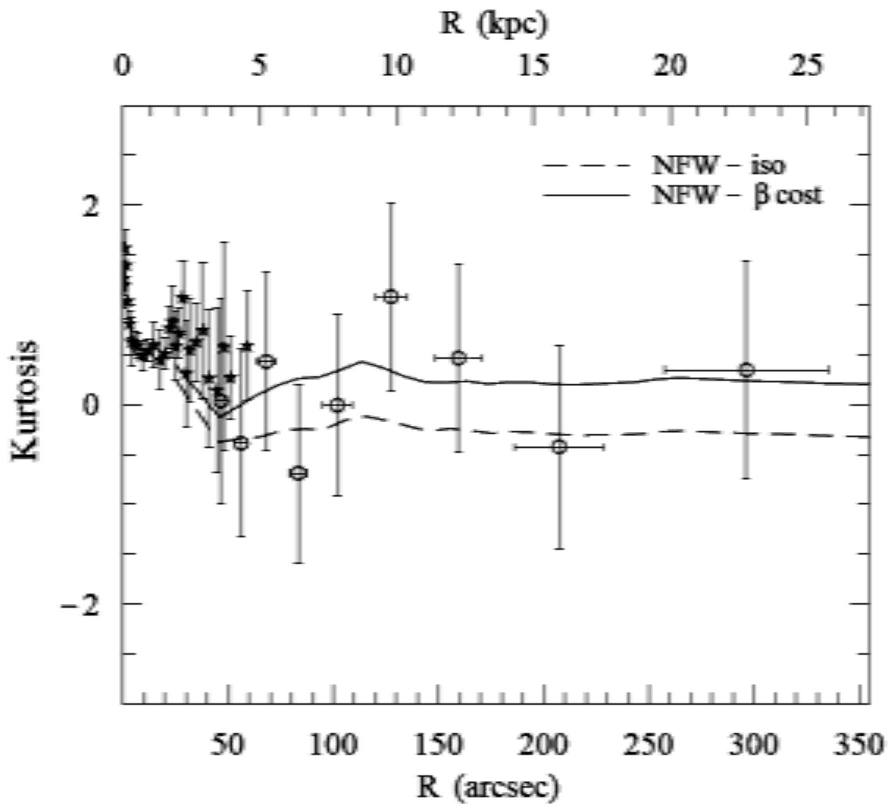
NO-DM

M/L_B=const=5

Does this work to break the mass-anisotropy degeneracy?

NGC 4494





NFW+ anisotropy
M/L_B=4.3

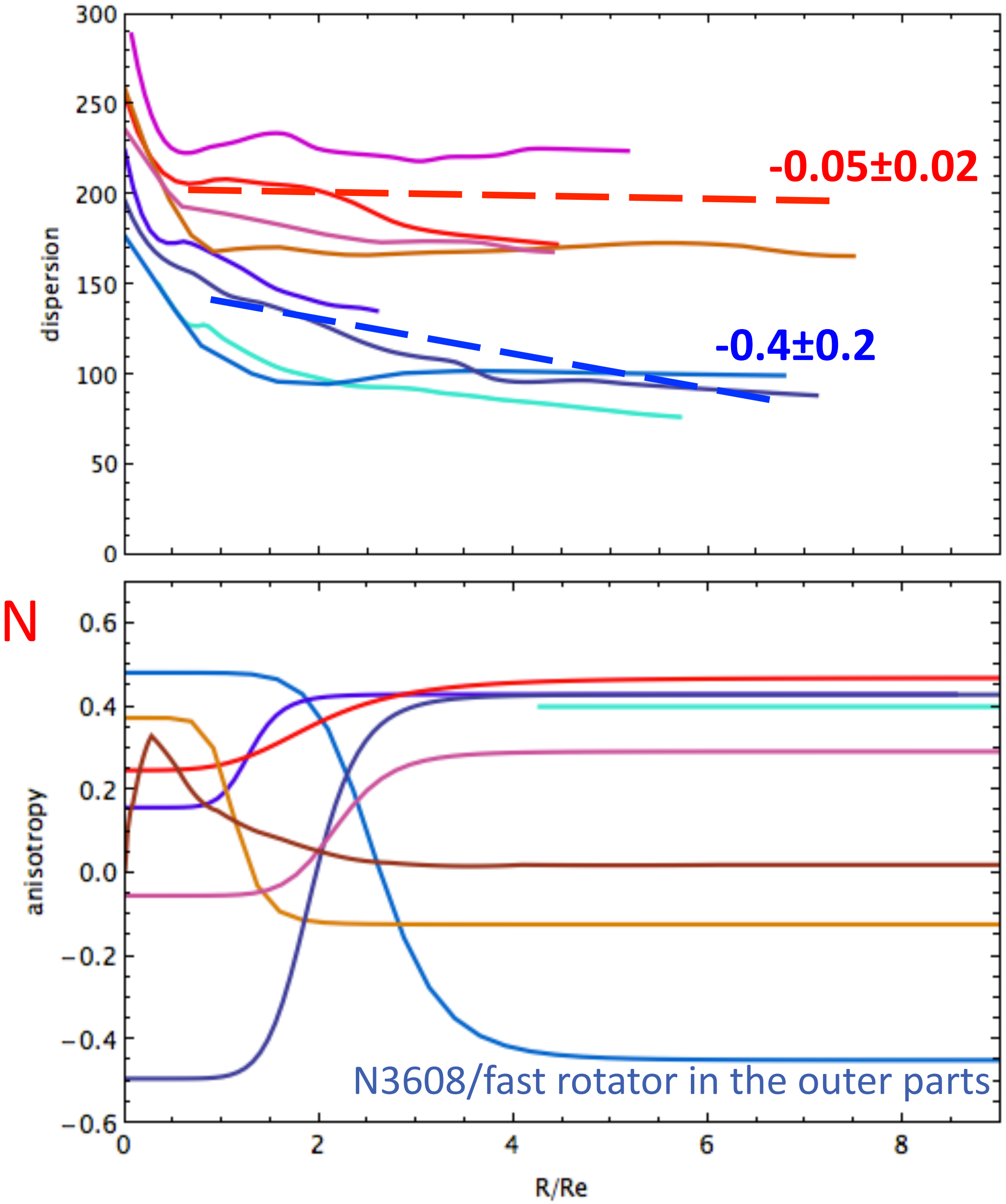
β~ 0.4-0.5 (radial orbits) in the outer regions

PNe: latest news

velocity dispersion

NO EVIDENT CORRELATION WITH…

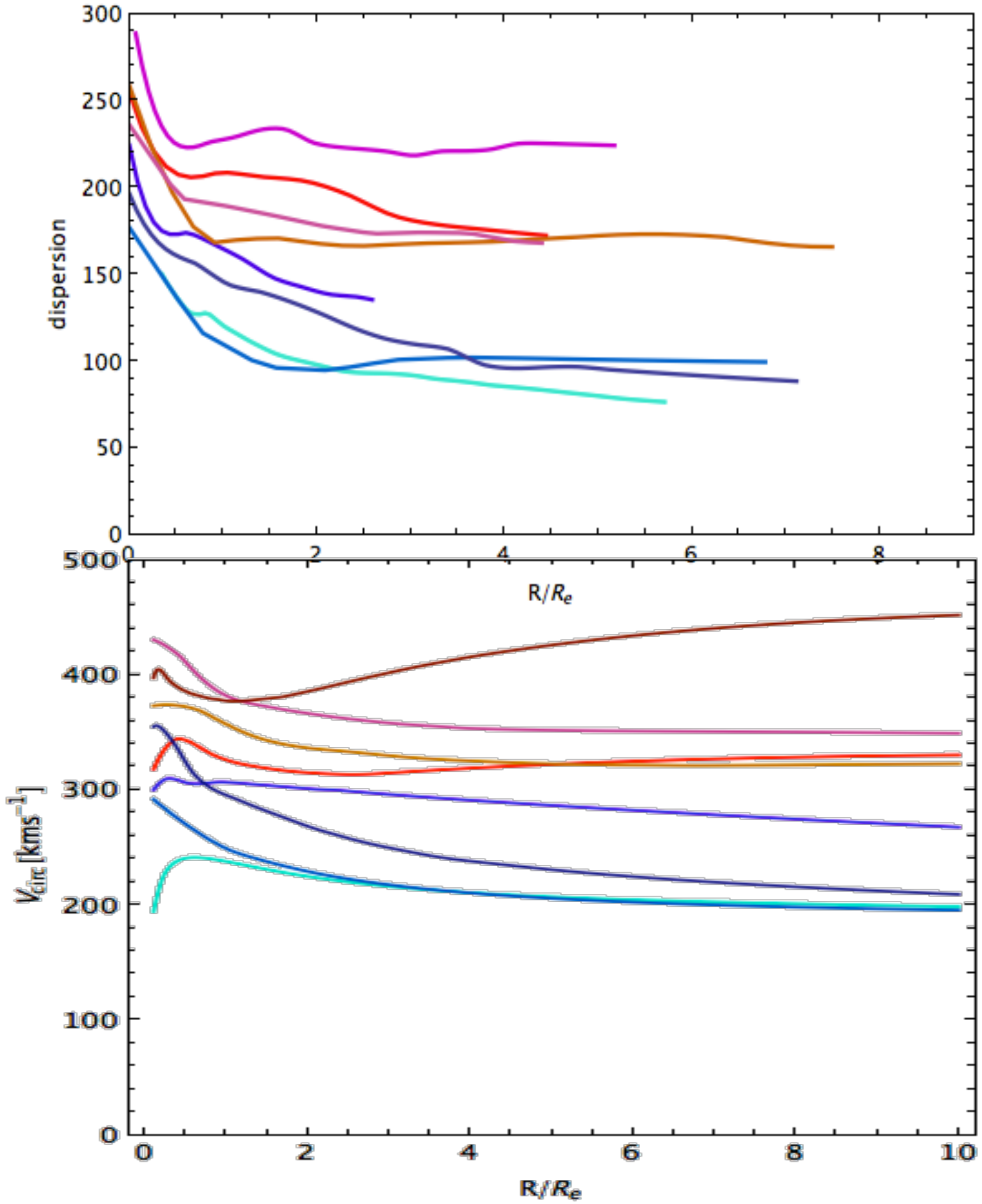
anisotropy



PNe: latest news

velocity dispersion

clearer correlation with circular velocity

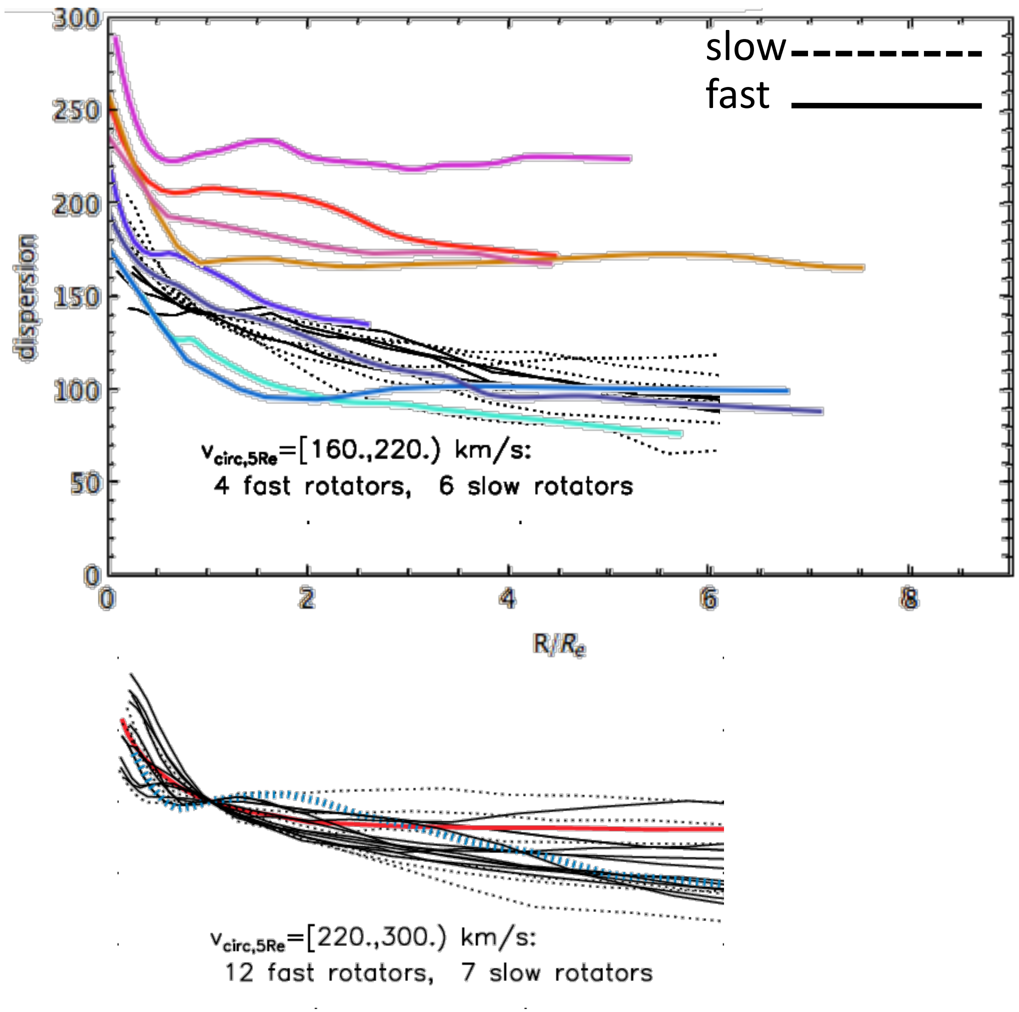


PNe: latest news

velocity dispersion

comparison with merging simulations

Wu et al. 2014

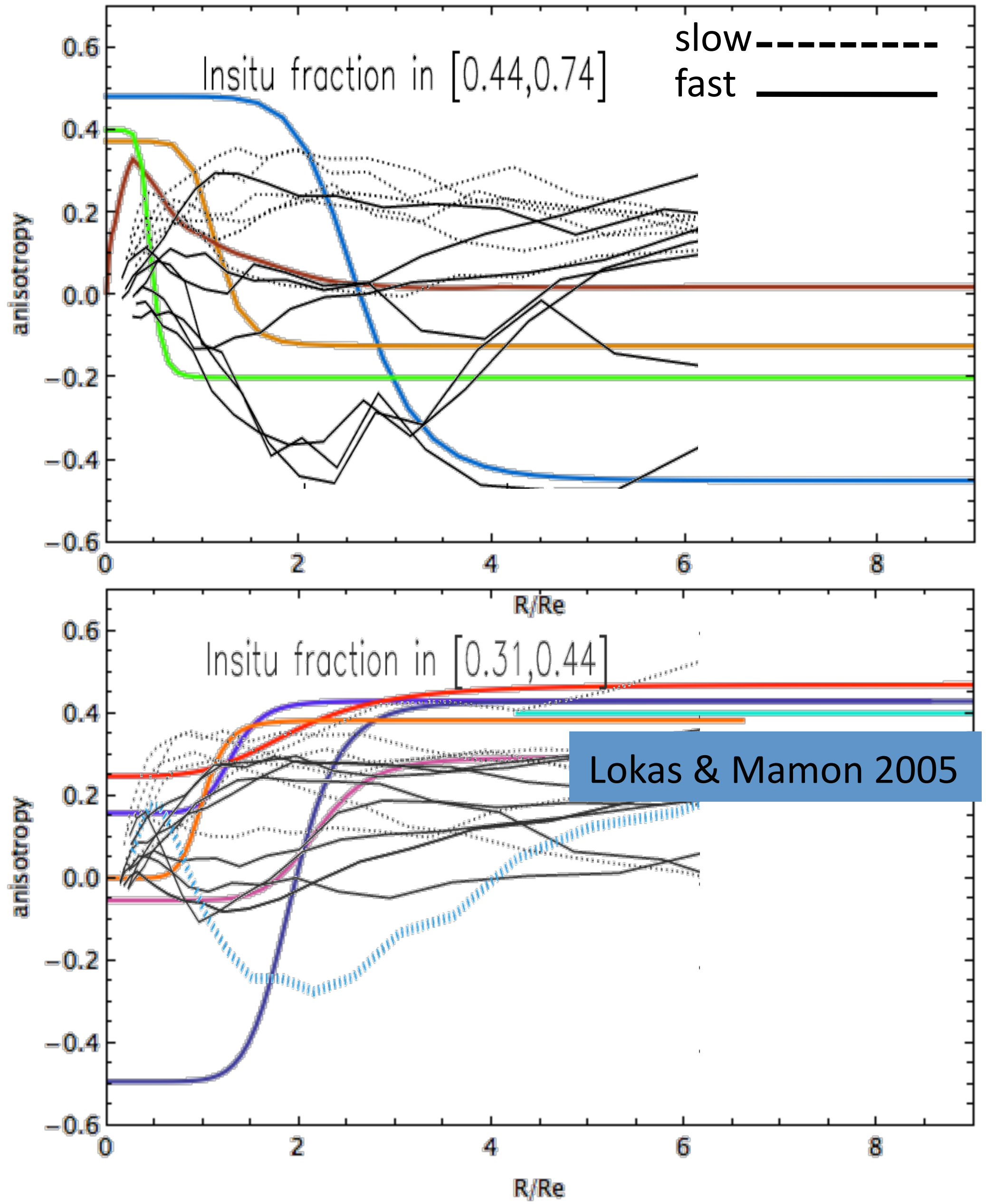


PNe: latest news

anisotropy

comparison with merging simulations

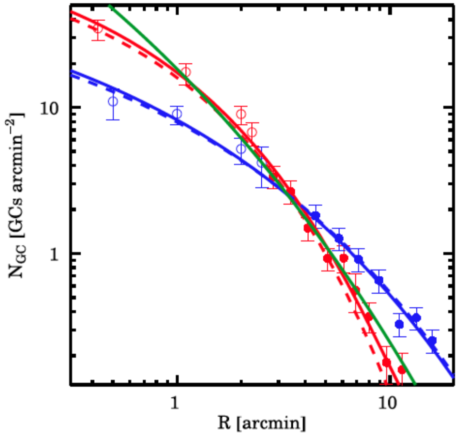
Wu et al. 2014

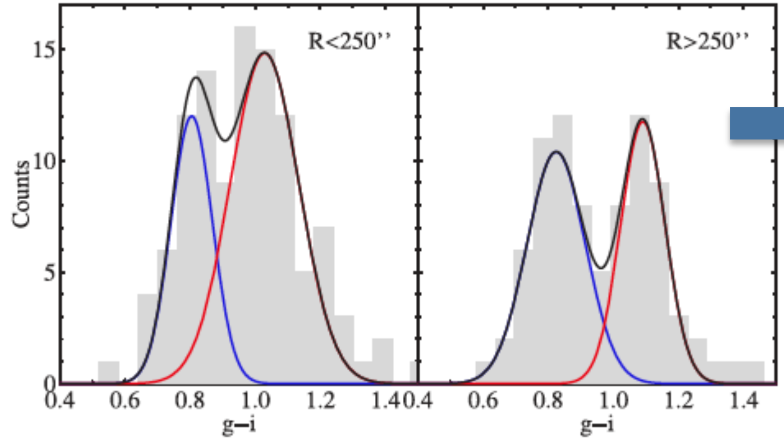


and finally something from the globular clusters

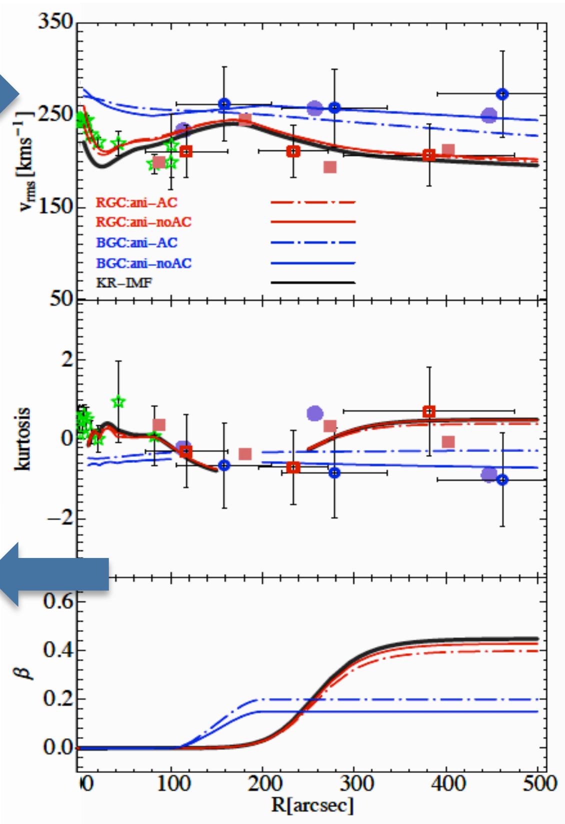
SLUGGS Collaboration (Brodie, Romanowsky, Forbes, Pota, Foster)

RGCs et BGCs``decoupled´´ in the phase space

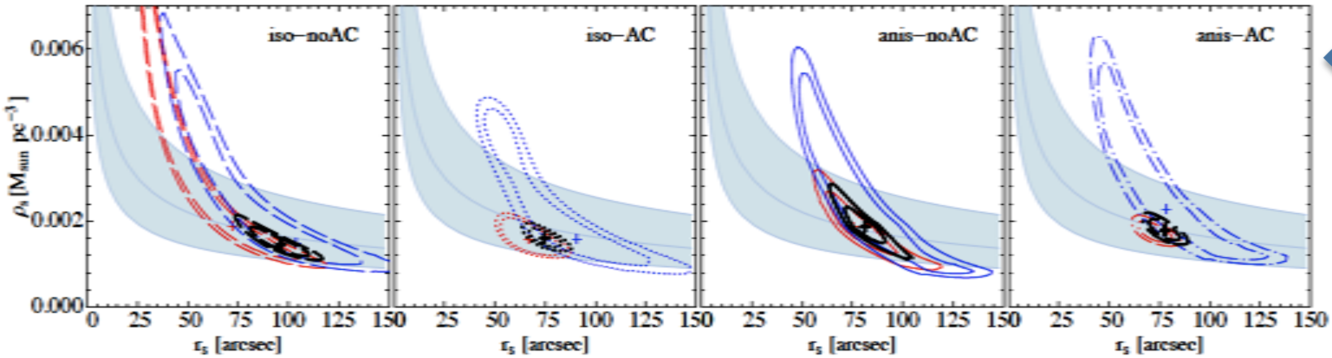




...means different velocity dispersiona and orbits

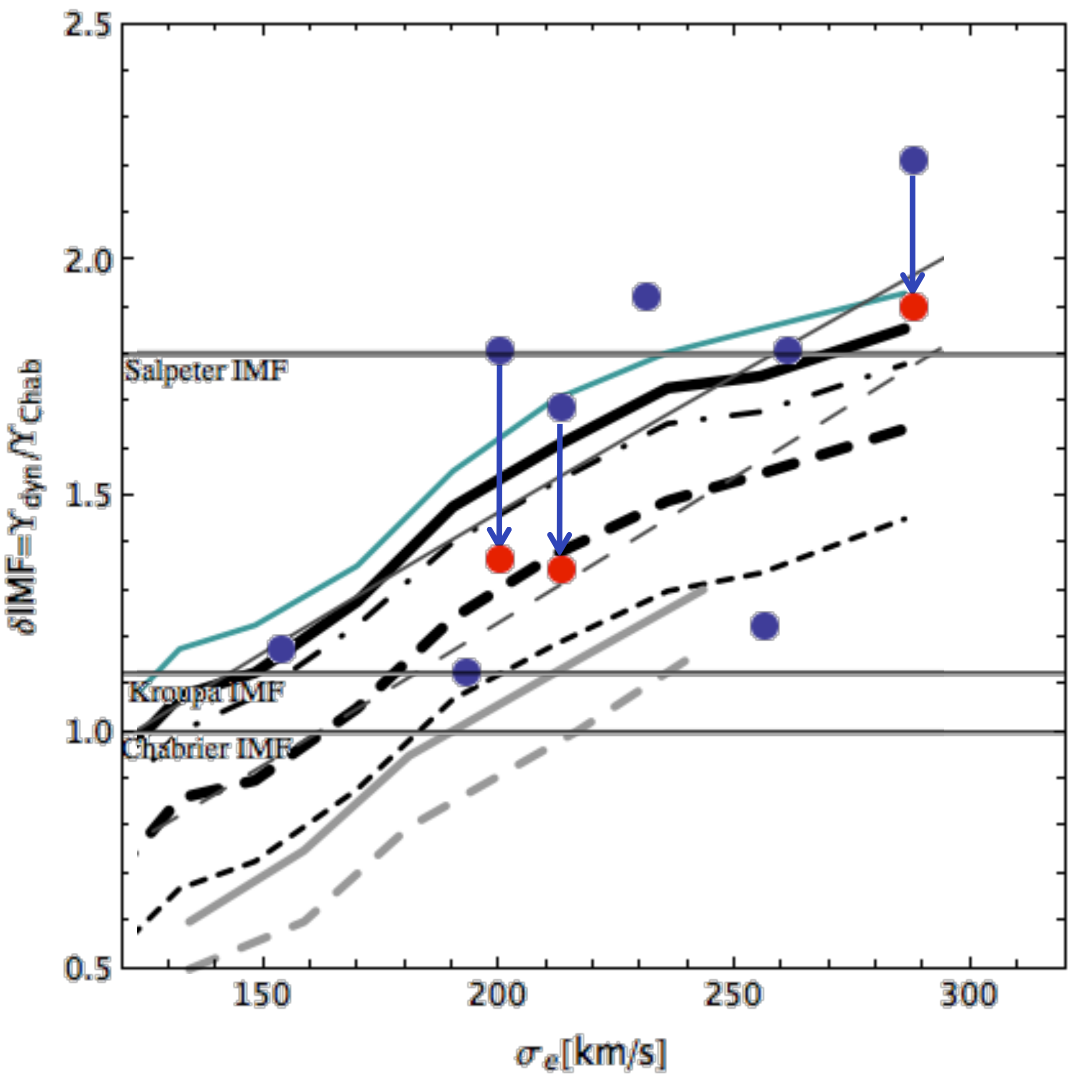


...but a common dark matter halo



NRN+2014

IMF variation with σ



Tortora et al. 2013

- M_{vir}–M_* (M+10)
- M_{vir}–M_* (M+10) + AC (G+04)
- M_{vir}–M_* (M+10) + AC (A+10)
- M_{vir}–M_* (M+10) + AC (B+86)
- M_{vir}–M_* (M+10) – high Σ_*
- M_{vir}–M_* (M+10) + AC (G+04) – high Σ_*
- no DM

PN.S sample

Napolitano et al. (in preparation)

- NFW no AC
- NFW G+04 AC

Conclusions

1) Planetary nebulae (and globular clusters) are excellent probes to investigate the outer galaxy haloes both from the kinematical (V/sigma, angular momentum) and from the **dynamical point of view (mass and anisotropy);**

2) The velocity dispersion profiles of **(mostly) slow-totator ETG from PNe are statistically overlapping with the ones from recent models of (merging) galaxy formation**

3) Anisotropy (preliminary) constraints on a sample of 8 ETGs from the Planetary Spectrograph (+2 external) elliptical galaxy survey show **a variety of β(r) profile which are generally consistent with a moderate (30-40%) to large (40-70%) fraction of "in situ" star formation**, but there are also some highly tangential orbits (fast rotator, merging?).

4) Mass distribution: **concentrations and virial masses are consistent with the expectations from collisionless simulations with Plank cosmological parameters.**