Kinematic & dynamical modelling of elliptical galaxies: Do ellipticals bathe in dark matter halos?

with

Ewa ŁOKAS (*CAMK, Warsaw*)
Mamon & Łokas 05a, MNRAS, **362**, 95
Mamon & Łokas 05b, MNRAS, **363**, 705

and

Avishai DEKEL (*HU, Jerusalem*), Felix STOEHR (*IAP, Paris*),
TJ COX (*Harvard*), Greg NOVAK & Joel PRIMACK (*UC Santa Cruz*)
Dekel, Stoehr, Mamon et al. 05, Nature, **437**, 707, astro-ph/0501622

Vol 437 | 29 September 2005 | **doi:10.1038/nature03970** nature

LETTERS

Lost and found dark matter in elliptical galaxies

A. Dekel[1,2,3,4], F. Stoehr[2], G. A. Mamon[2,3], T. J. Cox[6], G. S. Novak[5] & J. R. Primack[4]

Outline

1) The need for DM halos

2) The Jeans formalism for kinematical modelling

3) Different methods to measure $M(r)$

4) Previous kinematical models of Elliptical Galaxies

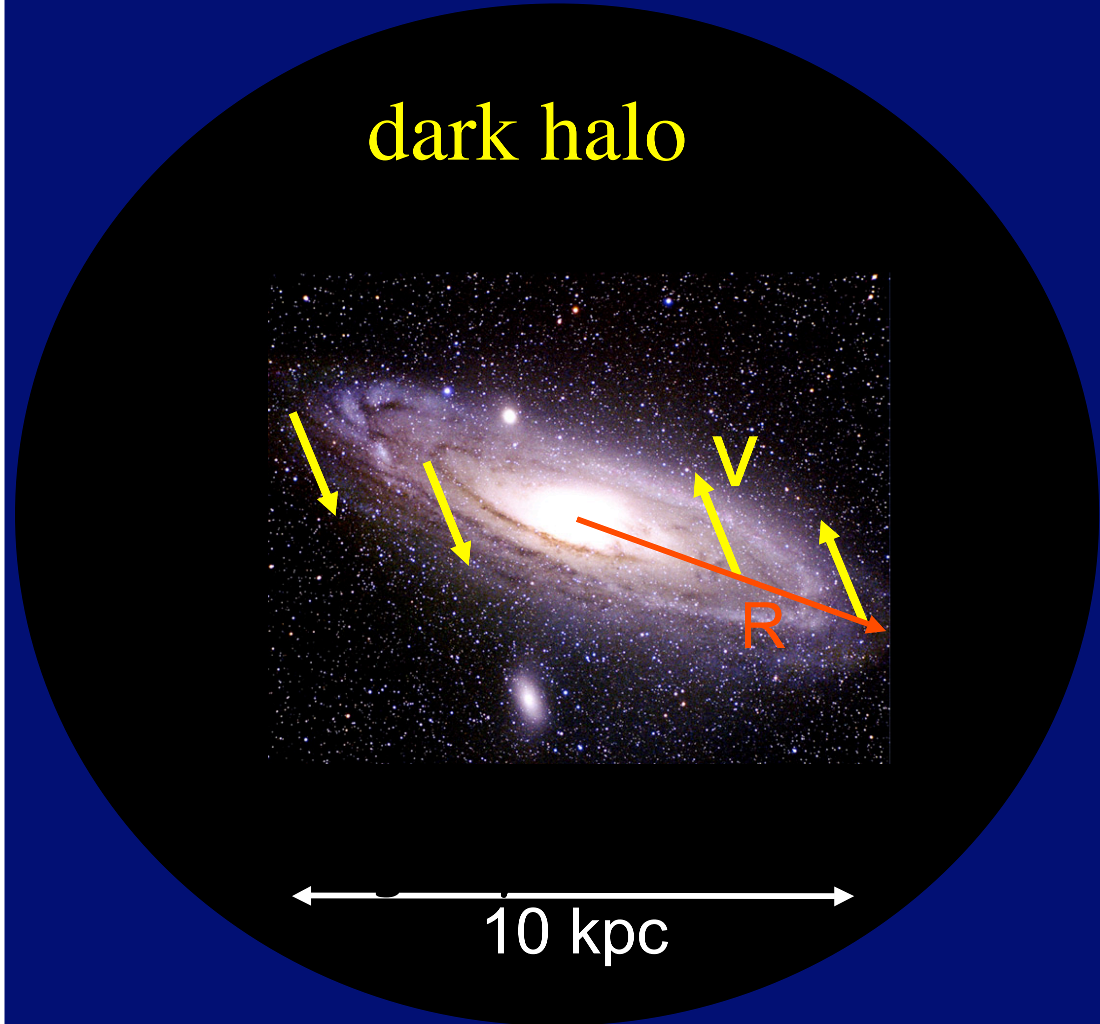
5) Our step-by-step kinematic modelling of Ellipticals

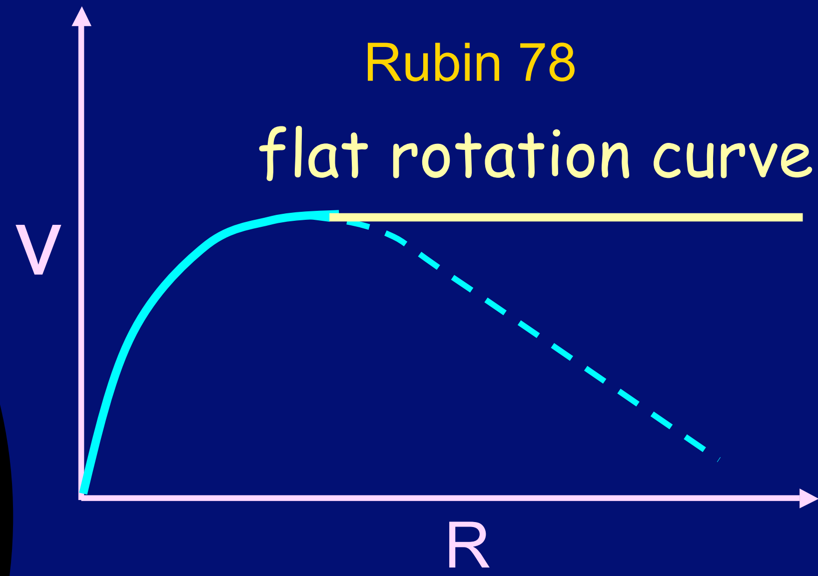
6) Dynamical modelling of Elliptical Galaxies

7) Are observed Planetary Nebulae young?

1) The need for DM halos

Spiral galaxies





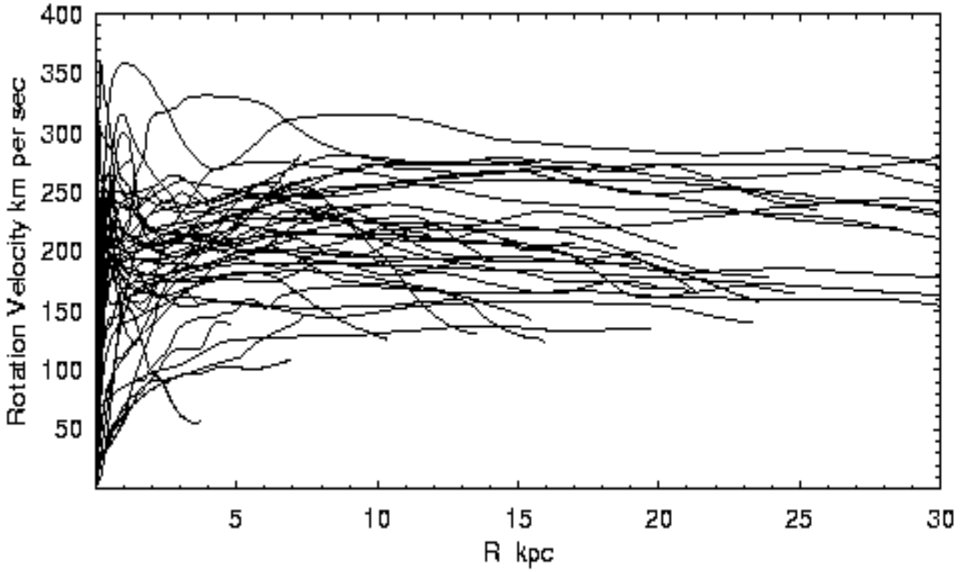
$$V^2 = \frac{GM(R)}{R} = \text{cst}$$

$$\rightarrow M(R) \propto R$$

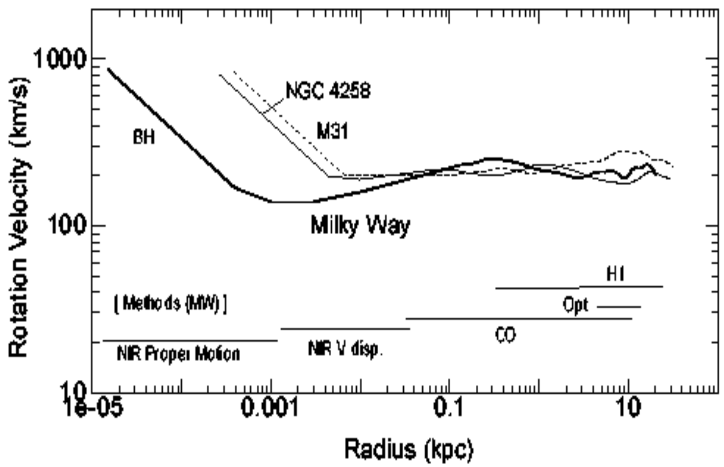
Ostriker, Peebles & Yahil 74; Einasto, Kaasik & Saar 74

Flat Rotation Curves: Extended Massive Dark-Matter Halos in Disk Galaxies

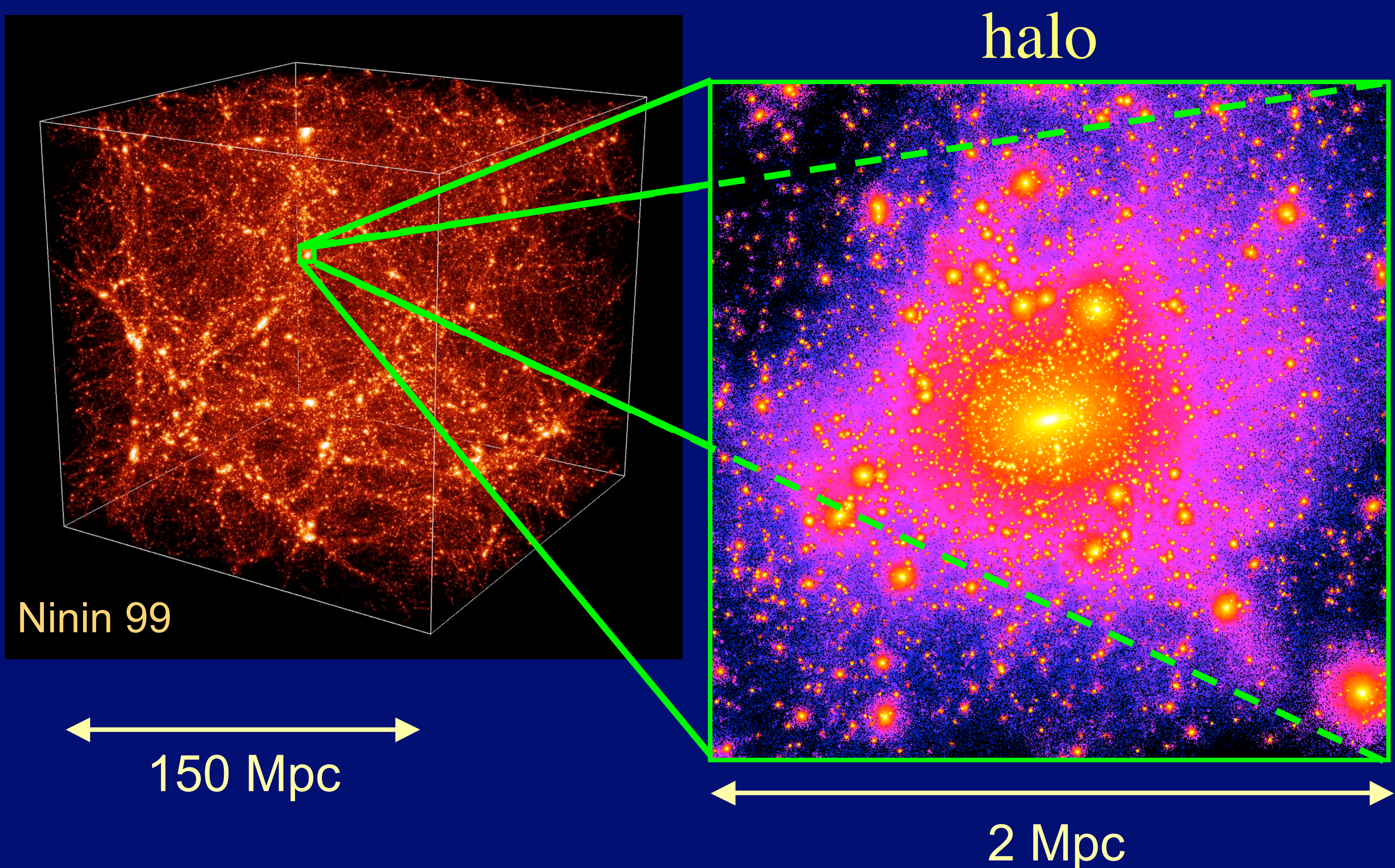
Sofue & Rubin 2001



Milky Way



Cosmological N-body simulations



Mass profiles from dissipationless cosmological simulations

$$\rho(r) \propto \frac{1}{\left(r/a_d\right)^{\alpha}\left[1+\left(r/a_d\right)^{\gamma}\right]^{(\eta-\alpha)/\gamma}}$$

$$\alpha = 1, \gamma = 1, \eta = 3 \quad \text{"NFW"}$$

Navarro, Frenk & White 95, 96, 97

$$\alpha = 3/2, \gamma = 3/2, \eta = 3$$

(Fukushige & Makino 98); Moore et al. 99

$$\alpha = 3/2, \gamma = 1, \eta = 3$$

Jing & Suto 00

$$\rho(r) = \rho(r_{-2}) \exp(2\mu) \exp\left[-2\mu\left(\frac{r}{r_{-2}}\right)^{1/\mu}\right]$$

=3D Sérsic!

Navarro et al. 04

$$\Sigma(R) \equiv \text{Sérsic} = \Sigma(0) \exp\left[-\left(\frac{R}{a}\right)^{1/m}\right]$$

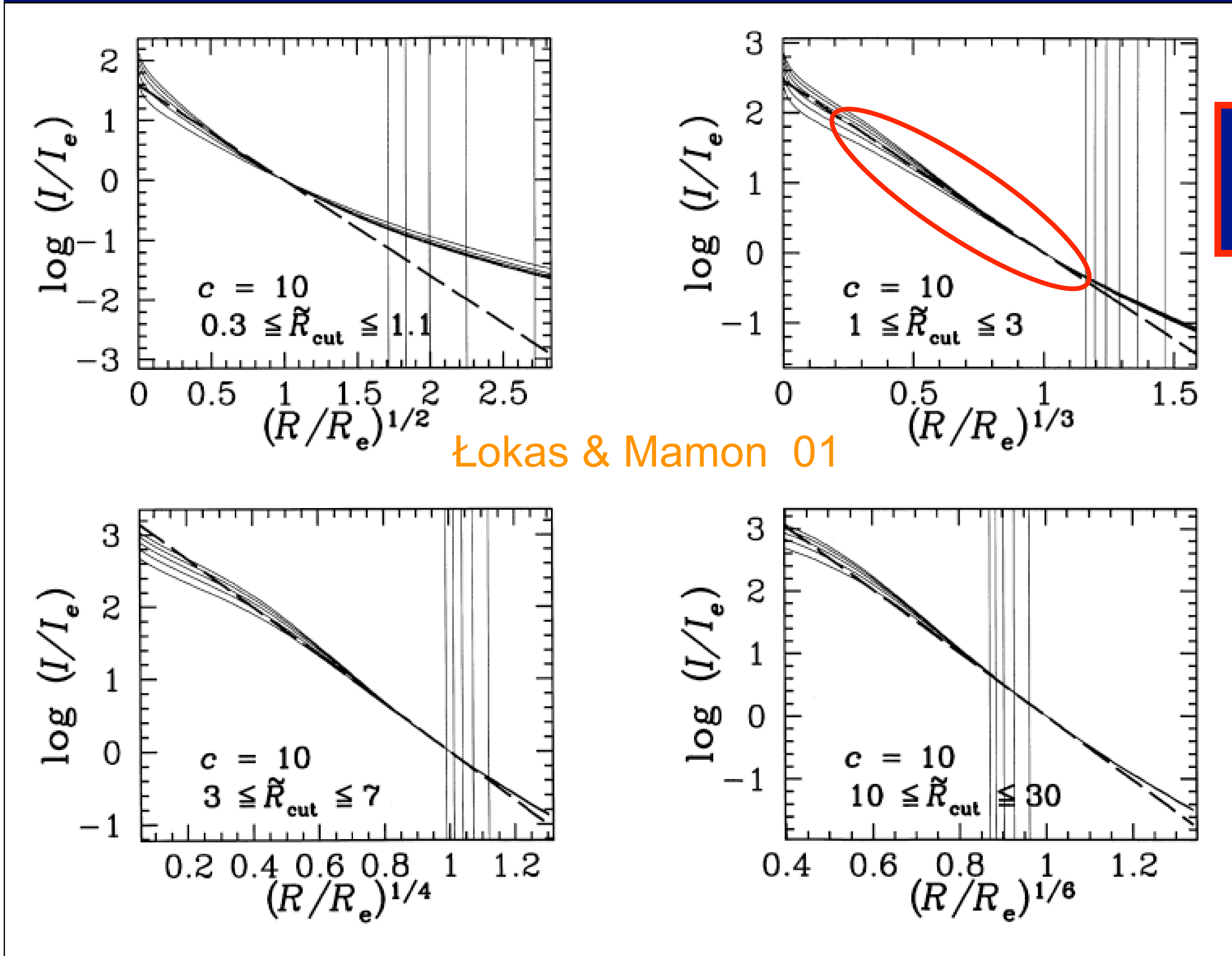
(m=3±0.5)

Merritt, Navarro et al. 05

Represents very well
surface brightness profiles
of elliptical galaxies (m=1-6)

Caon, Capaccioli & D'Onofrio 93

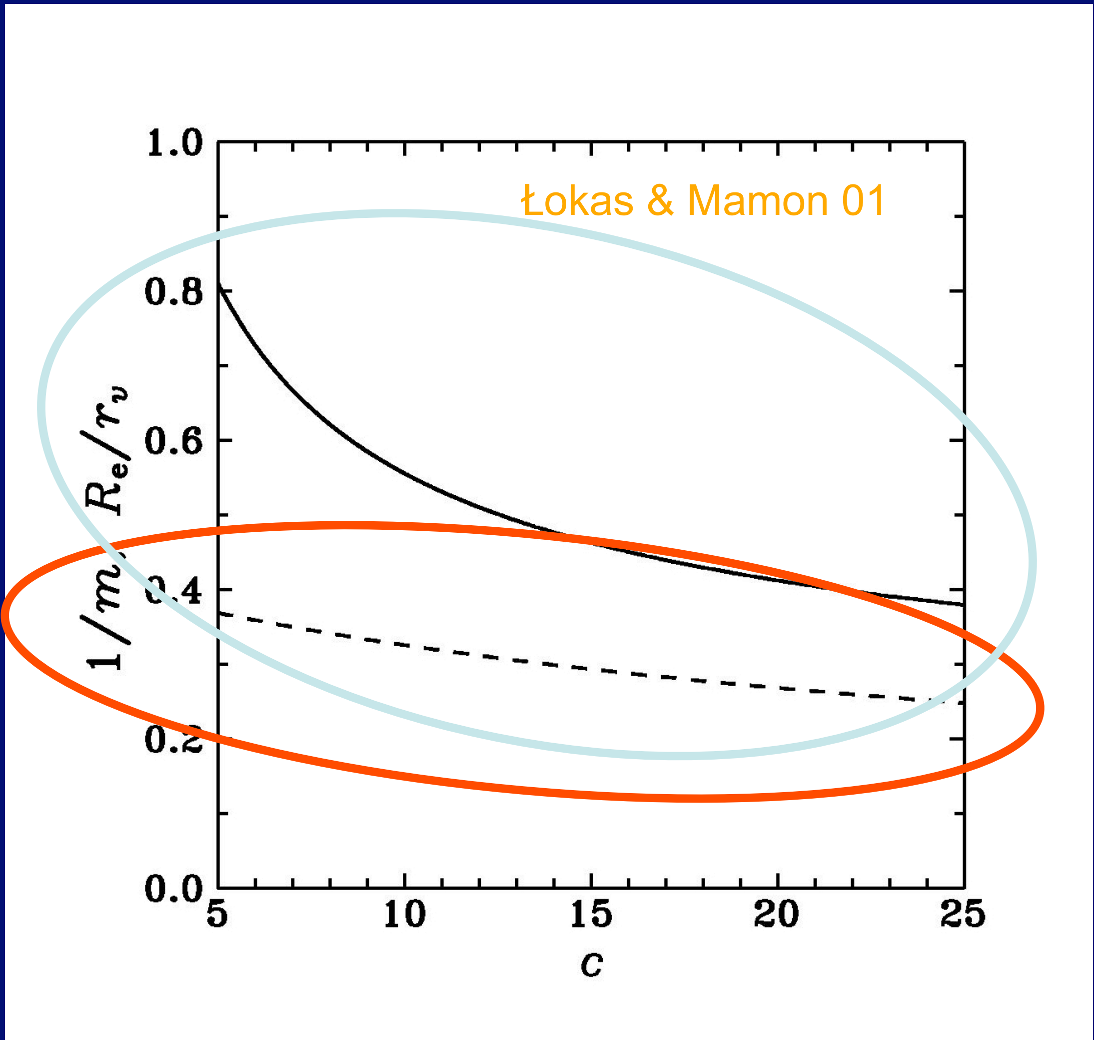
Do projected NFW halos resemble Sérsic Ellipticals?



Łokas & Mamon 01

excellent fit to $R^{1/3}$ law

Caveats for elliptical galaxies being NFW at cst M/L



NFW only fits m=3±1

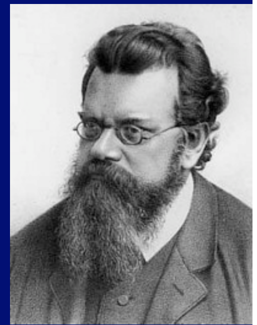
$r_v < 2R_e \Rightarrow M/L \ll 1$

$L\uparrow \rightarrow m\uparrow \rightarrow c\uparrow \rightarrow M\downarrow$

2) The Jeans formalism for kinematical modelling

From phase space to local space

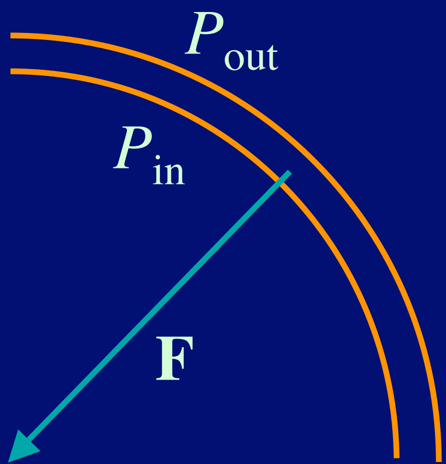
$f = f(r,v) \equiv$ distribution function=6D phase space density



Collisionless Boltzmann Equation

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f - \nabla\Phi\cdot\frac{\partial f}{\partial \mathbf{v}} = 0$$

$$\int v_j \,\mathrm{CBE}\, d^3\mathbf{v}$$



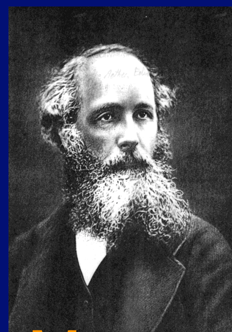
$\Delta r \to 0$

$$\nabla P = -\nu\,\nabla\Phi$$

Jeans Equation

tracer density

$$\Delta F_{\rm Pressure} = S\,\Delta P = -F = -\rho\, S\,\Delta r\,\frac{d\Phi}{dr}$$



Maxwell

Jeans

Spherical stationary Jeans equation

anisotropic dynamical pressure

$$\frac{d\left(\nu\sigma_r^2\right)}{dr} + 2\frac{\beta}{r}\nu\sigma_r^2 = -\nu\frac{GM}{r^2}$$

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

isotropic orbits: $\beta = 0$
radial orbits: $\beta = 1$
circular orbits: $\beta \to -\infty$

<u>mass / anisotropy degeneracy</u>

assume $\beta(r) \to M(r)$
or
assume $M(r) \to \beta(r)$

Binney & Mamon 82

Structural & kinematic projection & deprojection
(spherical symmetry)

2D density (surface brightness) → 3D density

$$\Sigma(R) = 2\int_R^\infty \nu(r) \frac{r\,dr}{\sqrt{r^2 - R^2}} \quad \Rightarrow \quad \nu(r) = -\frac{1}{\pi}\int_r^\infty \frac{d\Sigma}{dR}\frac{dR}{\sqrt{R^2 - r^2}}$$

2D "pressure" → 3D "pressure"
(isotropic models)

$$\Sigma(R)\,\sigma_{\rm los}^2(R) = 2\int_R^\infty \nu(r)\sigma^2(r) \frac{r\,dr}{\sqrt{r^2 - R^2}} \quad \Rightarrow \quad \nu(r)\sigma^2(r) = -\frac{1}{\pi}\int_r^\infty \frac{d(\Sigma\sigma_{\rm los}^2)}{dR}\frac{dR}{\sqrt{R^2 - r^2}}$$

(anisotropic models)

$$\Sigma(R)\,\sigma_{\rm los}^2(R) = 2\int_R^\infty \left[1 - \beta(r)\frac{R^2}{r^2}\right]\nu(r)\sigma_r^2(r) \frac{r\,dr}{\sqrt{r^2 - R^2}}$$

inversion is possible but complex

Binney & Mamon 82; (…); Dejonghe & Merritt 92

Projected velocity dispersions

line-of-sight velocity dispersion

for $\beta = 0$

$$I(R)\,\sigma^2_{\rm los}(R) = 2G\int_R^\infty \frac{\sqrt{r^2-R^2}}{r^2}\,\nu(r)M(r)\,dr$$

Prugniel & Simien 97

for some simple $\beta(r)$

$$I(R)\,\sigma^2_{\rm los}(R) = 2G\int_R^\infty K(r,R)\,\nu(r)M(r)\,dr$$

Mamon & Łokas 05b

aperture velocity dispersion

Mamon & Łokas 05a

$$\frac{3}{4\pi G}L_2(R)\,\sigma^2_{\rm ap}(R) = \int_0^\infty r\,\nu(r)M(r)\,dr - \int_R^\infty \frac{\left(r^2-R^2\right)^{3/2}}{r^2}\,\nu(r)M(r)\,dr$$

for $\beta = 0$

→ *isotropic* projected velocity dispersions easy to model

Power-law solutions to Jeans equations

Dekel, Stoehr, Mamon, et al. 05, *Nature*

Jeans eq. $$\frac{d\left(\nu\sigma_r^2\right)}{dr} + 2\frac{\beta}{r}\nu\sigma_r^2 = -\nu\frac{GM}{r^2} = -\nu\frac{v_{\rm circ}^2}{r}$$

$$\rho_{\rm tracer} \propto r^{-\alpha}$$
$$\rho_{\rm total} \propto r^{-\eta} \Rightarrow \sigma_r \propto v_{\rm circ} \propto r^{-\eta/2-1}$$

$$\Rightarrow \quad \sigma_r(r) = \frac{v_{\rm circ}(r)}{\sqrt{\alpha(r)+\eta(r)-2\beta-2}}$$

$$\beta\uparrow \Rightarrow \frac{\sigma_r}{v_{\rm circ}}\uparrow$$

anisotropic projection eq.

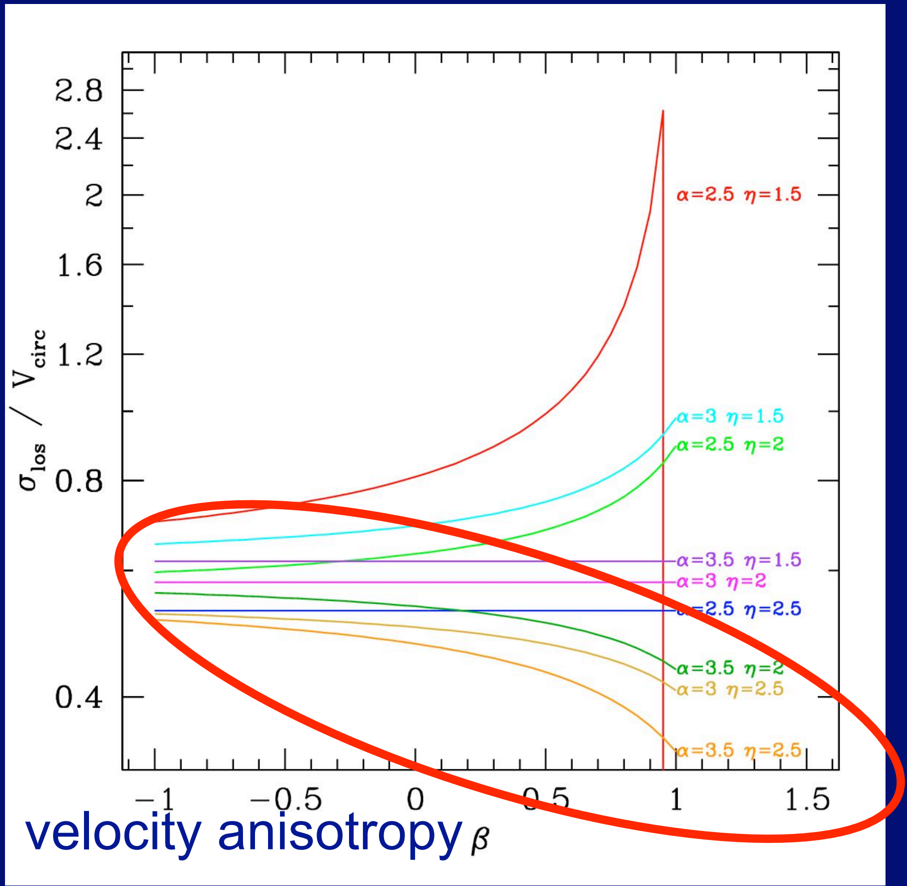
$$\Sigma(R)\,\sigma_{\rm los}^2(R) = 2\int_R^\infty \left[1-\beta(r)\frac{R^2}{r^2}\right]\nu(r)\sigma_r^2(r)\frac{r\,dr}{\sqrt{r^2-R^2}}$$

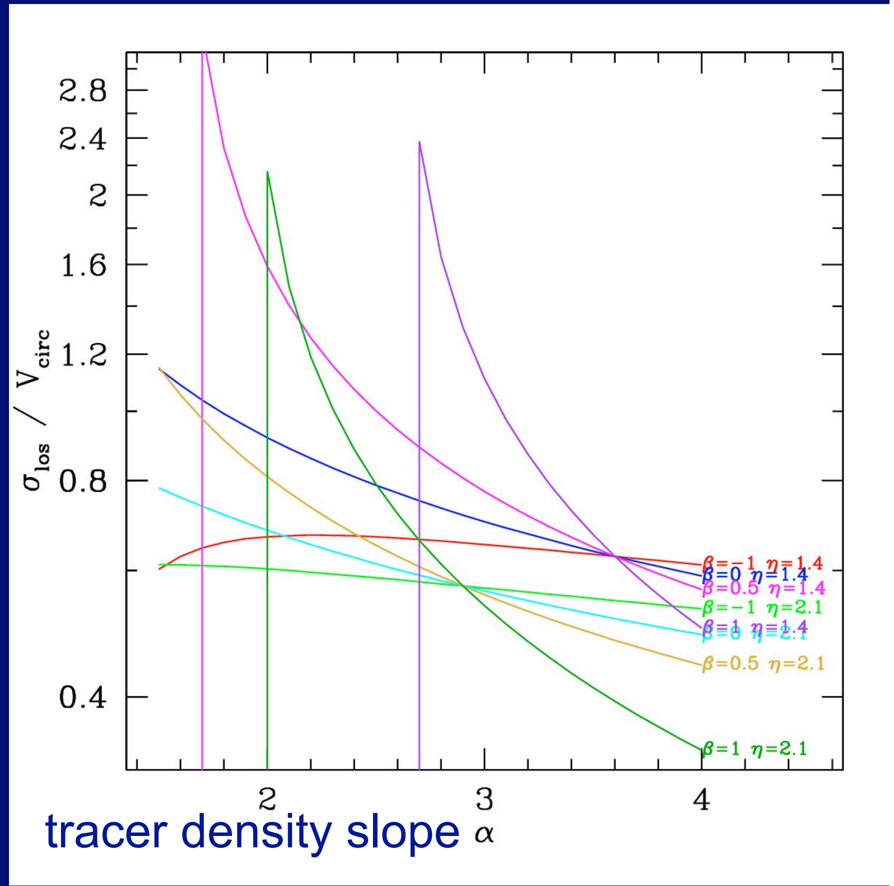
$$\frac{\sigma(r)}{v_{\rm circ}(r)} = A(\alpha,\eta)\sqrt{\frac{\alpha+\eta-2-(\alpha+\eta-3)\beta}{\alpha+\eta-2-2\beta}}$$

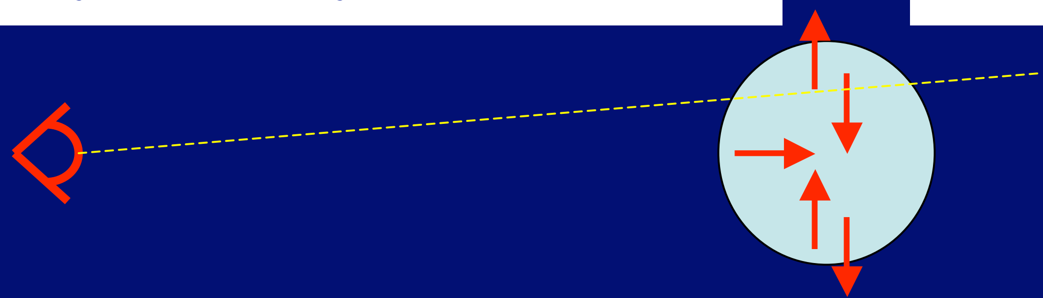
$$\Rightarrow \quad \alpha+\eta>5 \Leftrightarrow \frac{d\log\left(\sigma_{\rm los}/v_{\rm circ}\right)}{d\log\beta}<0$$

realistic slopes α & η $\longrightarrow$ $\alpha\uparrow$ or $\beta\uparrow \Rightarrow \sigma_{\rm los}\downarrow$

Power-law solutions to Jeans equations (2)







realistic outer slopes: $\alpha+\eta > 5$ ⟹ $\alpha\uparrow$ or $\beta\uparrow \Rightarrow \sigma_{\rm los}\downarrow$

3) Different methods to measure *M*(*r*)

a) quick & dirty: assume isotropy $\beta = 0$

$$M(r) = -\frac{r}{G}\,\frac{\int_r^\infty \frac{d^2\left(\Sigma\sigma_{\rm los}^2\right)}{dR^2}\,\frac{R\,dR}{\sqrt{R^2-r^2}}}{\int_r^\infty \frac{d\Sigma}{dR}\,\frac{dR}{\sqrt{R^2-r^2}}}$$

can be generalized to any assumed $\beta(r)$

Mamon & Boué 06, in prep

Gaussian $\{v\}$ → isotropy → $M(r)$ → $\beta(r)$ for other components

Merritt 87

Biviano & Katgert 05

but gaussian is not quite isotropic

Kazantzidis, Magorrian & Moore 04

Wojtak, Łokas, Gottlöber & Mamon 05

b) Orbit modelling

Schwarzschild 79

1) pick a gravitational potential $\Phi(\mathbf{r})$

2) throw orbit (E, $\mathbf{J}$)

3) project onto observable space

4) fit observations with positive linear combination of orbits

5) iterate on parameters of potential

c) Distribution function modelling

Density in projected phase space Dejonghe & Merritt 92

$$g(R, v_z) = 2\int_R^{\infty} \frac{r\,dr}{\sqrt{r^2 - R^2}} \int_{-\infty}^{+\infty} dv_R \int_{-\infty}^{+\infty} f\left[\frac{1}{2}v^2 + \Phi(r), \mathbf{J}\right] dv_\theta$$

1) pick a gravitational potential $\Phi(\mathbf{r})$

2) pick a set of elementary distribution functions $f_i(E, \mathrm{J})$

3) compute projected phase space density $g_i(R, v_z)$

4) fit observations with positive linear combination of $f_i(E, \mathrm{J})$

5) iterate on parameters of potential

Gerhard et al 98

d) 4th order Jeans equations

$$\frac{d\left(\nu\,\overline{v_r^4}\right)}{dr} + 2\frac{\beta}{r}\left(\nu\,\overline{v_r^4}\right) = -3\nu\,\sigma_r^2\,\frac{GM(r)}{r^2}$$

Łokas 02; Łokas & Mamon 03

if $\beta = \mathrm{cst}$ ⇒

$$\overline{v_r^4}(r) = \frac{3\,r^{-2\beta}}{\nu(r)}\int_r^\infty s^{2\beta-2}\,\nu\sigma_r^2\,GM(s)\,ds$$

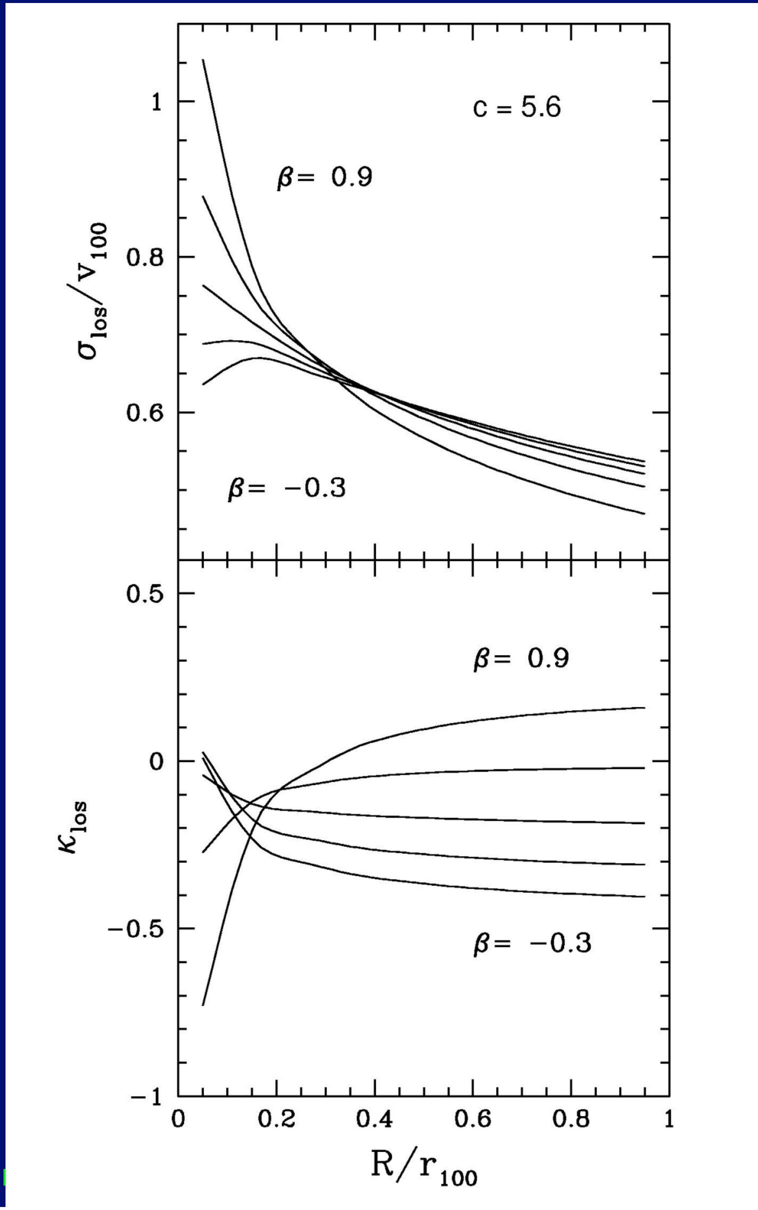
line of sight kurtosis excess

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

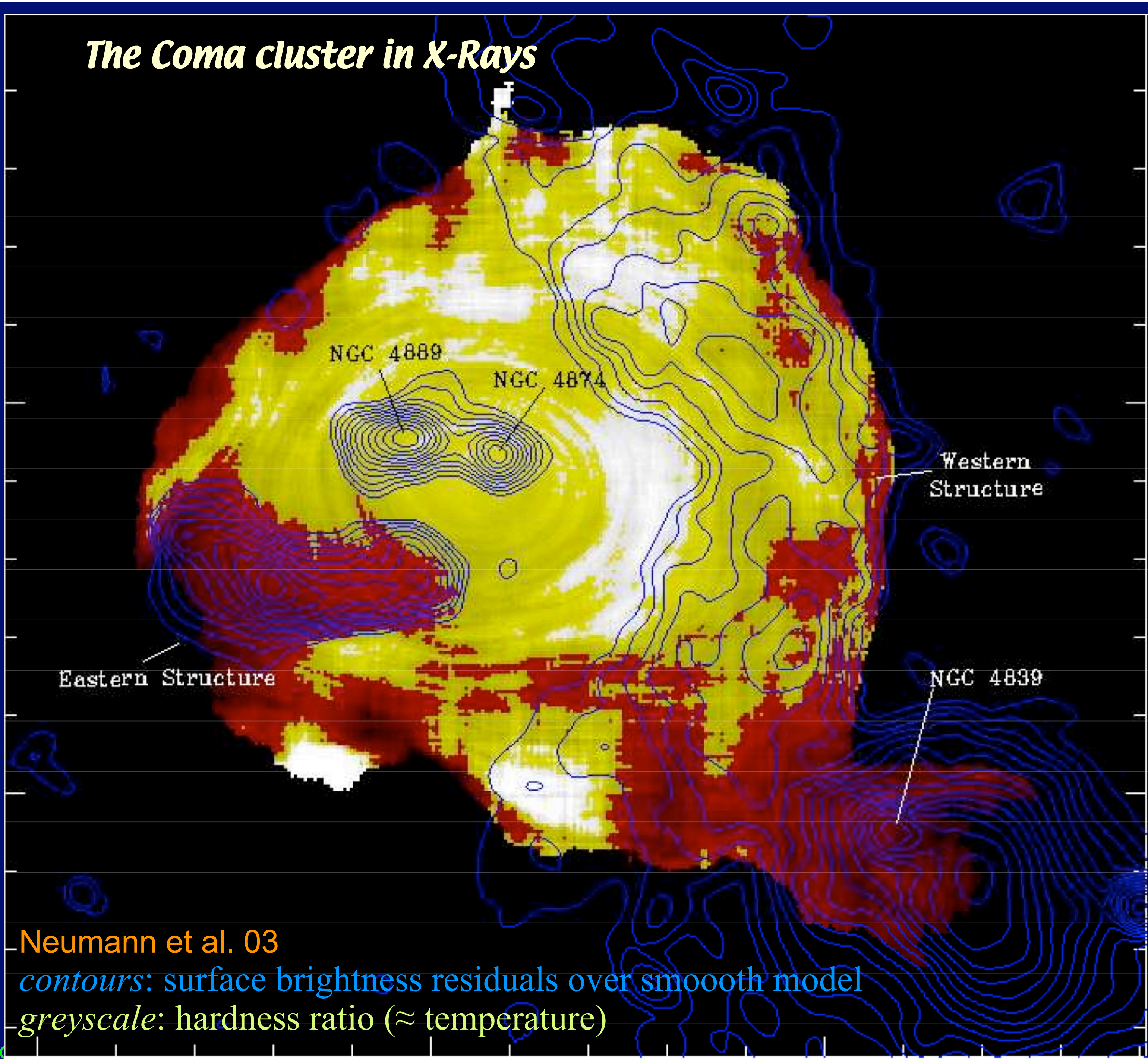
Effect of anisotropy on dispersion & kurtosis

Sanchis, Łokas & Mamon 04

pure NFW model



⇨ joint constraints


The Coma cluster in X-Rays
NGC 4889
NGC 4874
Western Structure
Eastern Structure
NGC 4839
Neumann et al. 03
contours: surface brightness residuals over smoooth model
greyscale: hardness ratio (≈ temperature)

What are the kinematical effects of:
non-sphericity?
projected infalling filaments?
substructure?
streaming motions (infall, rebound)?

test with halos from cosmological *N*-body simulations:
measure in 3D & reestimate in 2D

10 halos × 3 projections:

$$\Delta \log M_{100} = -0.07 \pm 0.10$$

$$\Delta \log c = 0.08 \pm 0.24$$

$$\Delta \log\left(\frac{\sigma_r}{\sigma_\theta}\right) = -0.04 \pm 0.11$$

Sanchis, Łokas & Mamon 04

→ 3D density profile recovered quite well!

Other methods

Hydrostatic equilibrium of hot diffuse X-ray emitting gas

⇒ difficult to remove X-ray emission from stars

Weak gravitational lensing

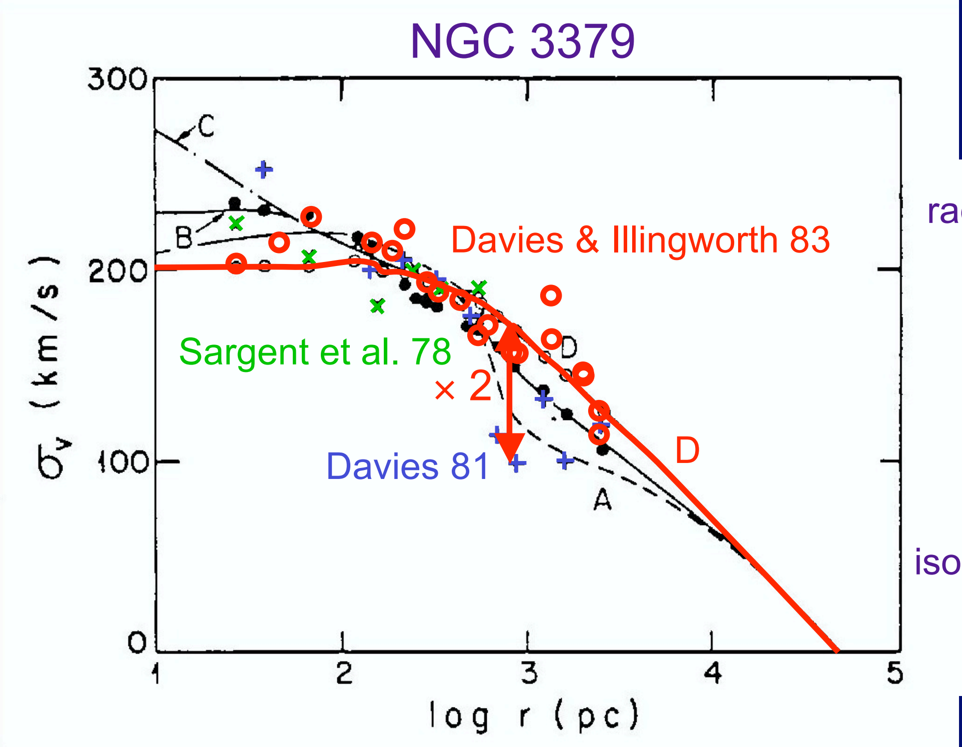
⇒ very weak signal: must stack; require distant objects

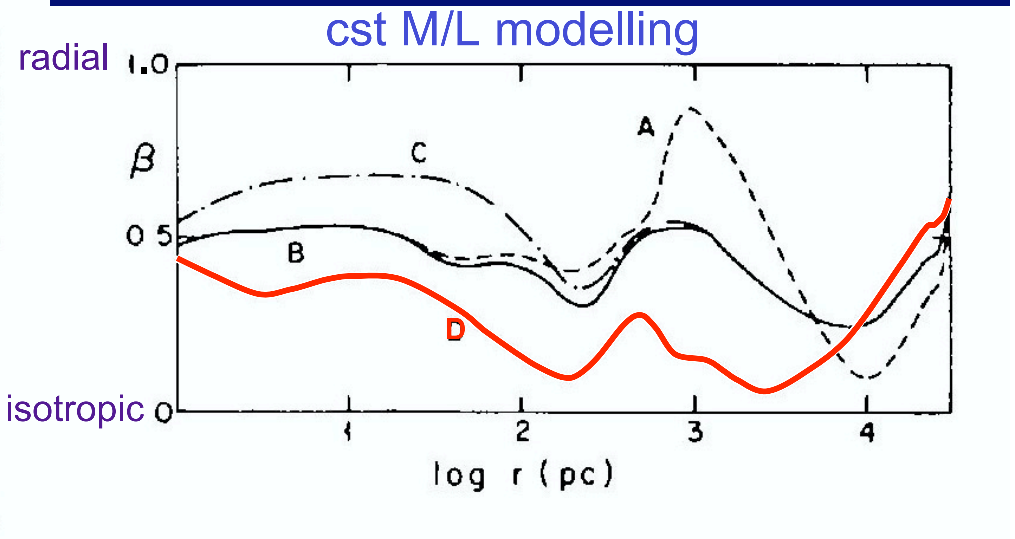
Joint analyses (internal kinematics & weak gravitational lensing)

4) Previous kinematical modelling of Elliptical Galaxies

Old Jeans modelling

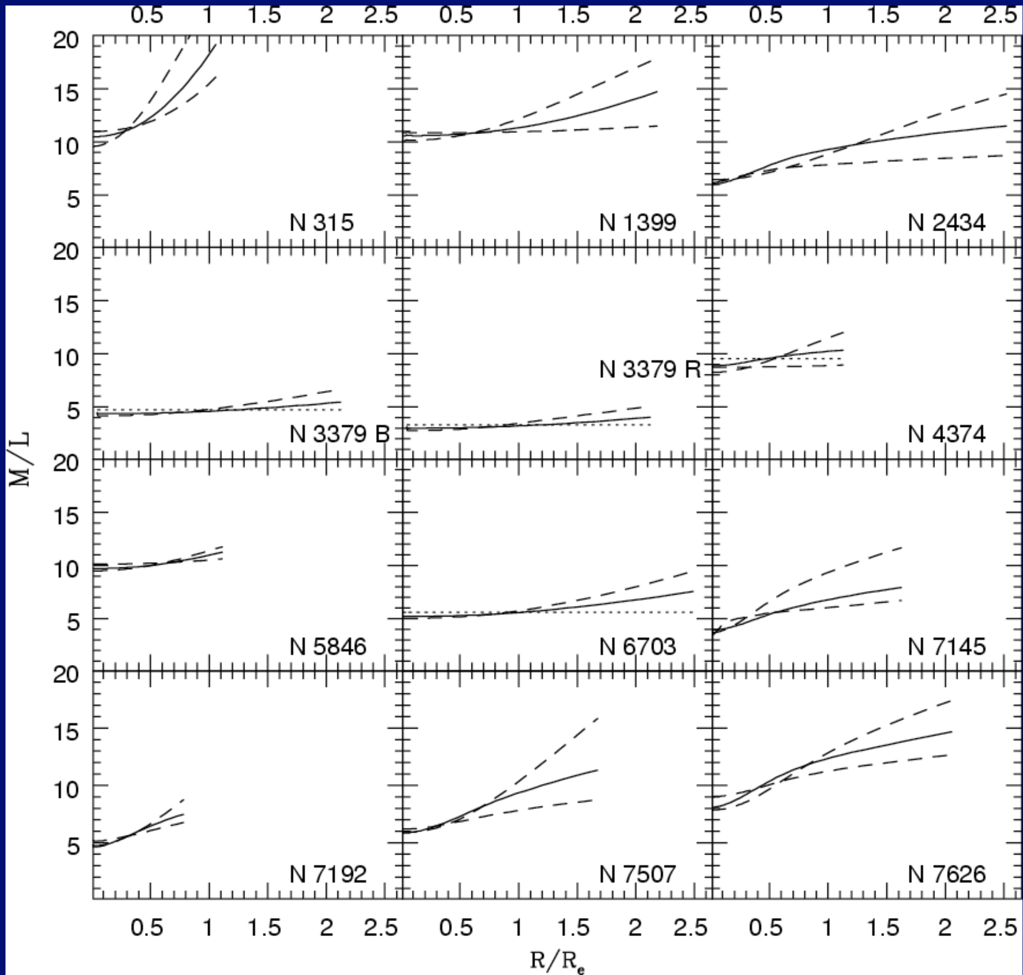
Mamon 83 (Besançon, IAU Symp. Aug 82)





radial or nearly isotropic?

Orbit modelling of ellipticals

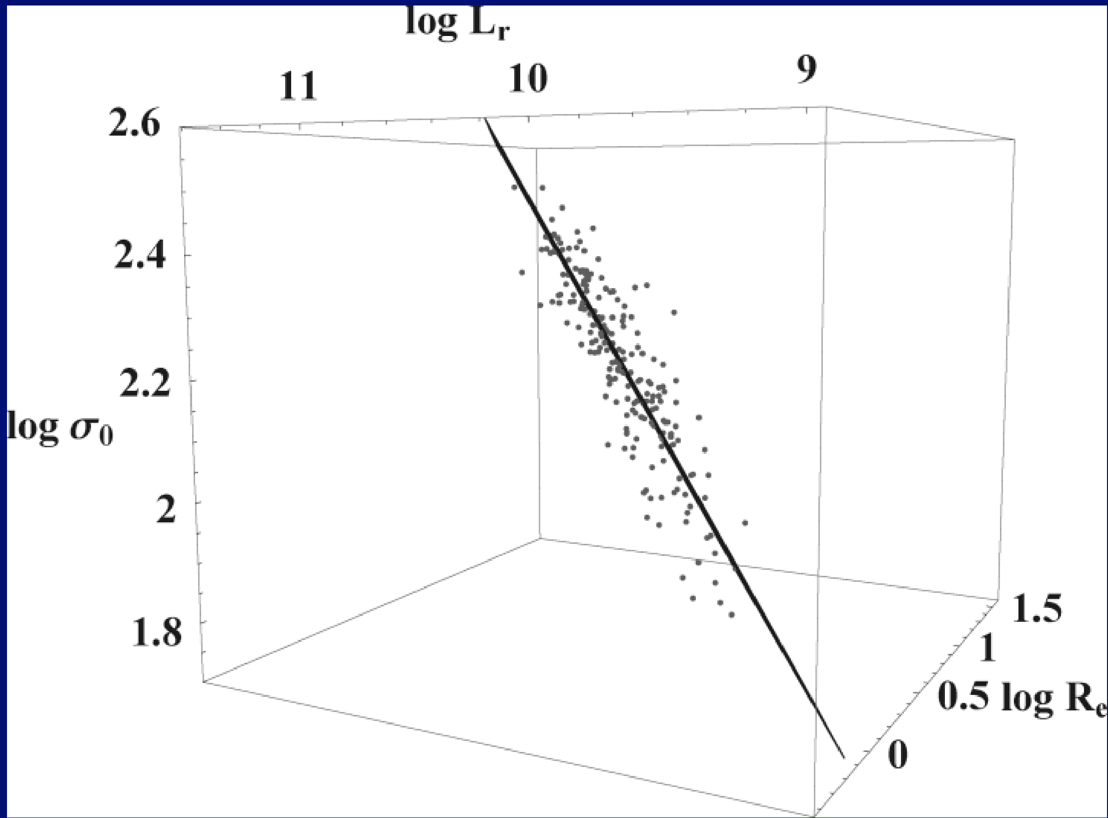


Kronawitter et al. 00

some galaxies show DM
some show instead cst M/L

but bad $\Phi(r)$!

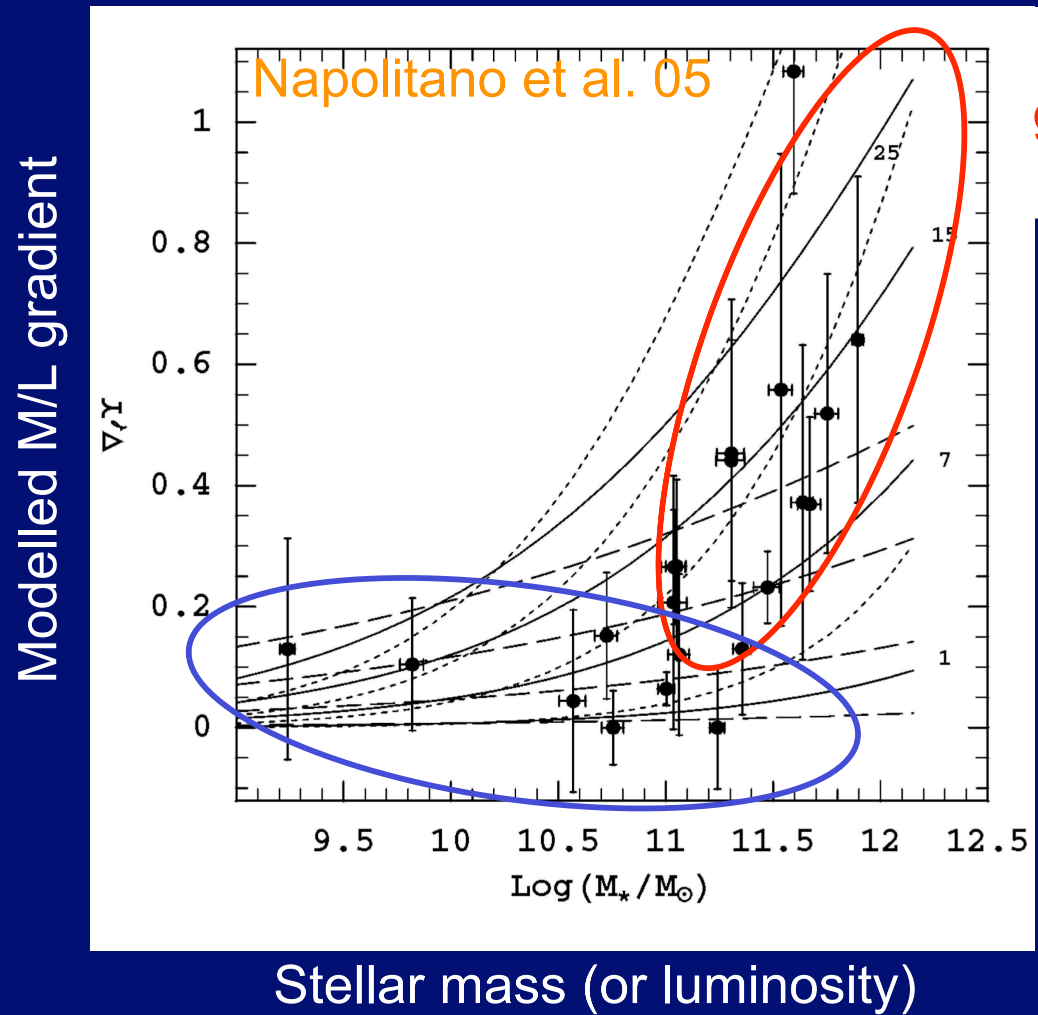
Fitting Fundamental Plane of Elliptical Galaxies



Recover flat FP ⇒ NFW halos must have *low concentration*

Borriello, Salucci & Danese 03

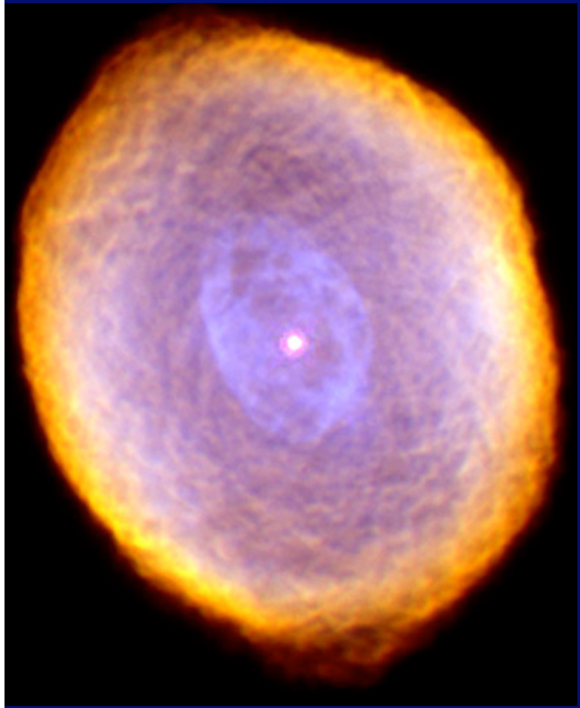
M/L gradients



brightest group/cluster members

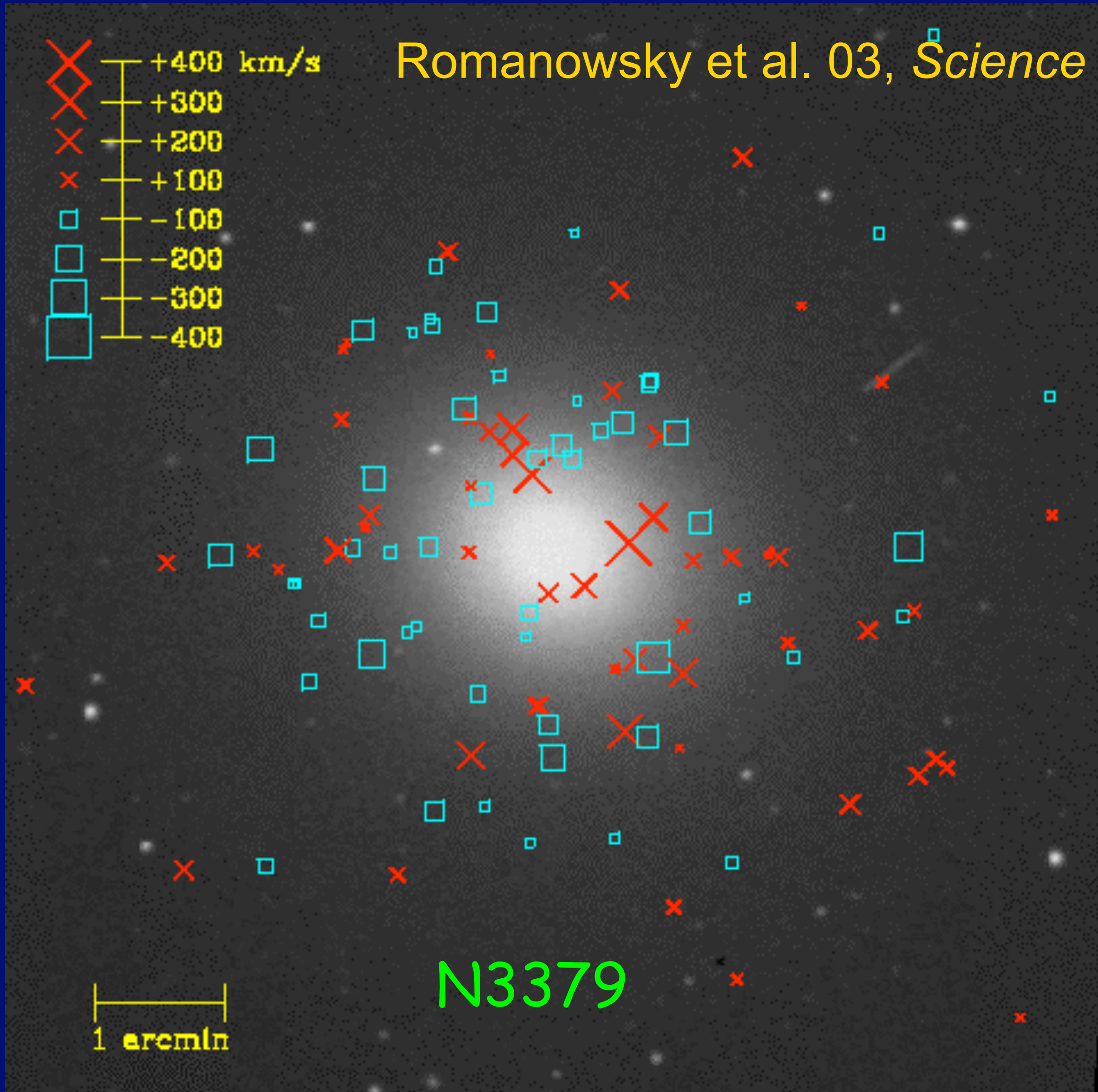
low & intermediate luminosity ellipticals:
almost no DM
OR
very low DM concentration

Planetary Nebulae: Tracers at 1-3R_{eff}



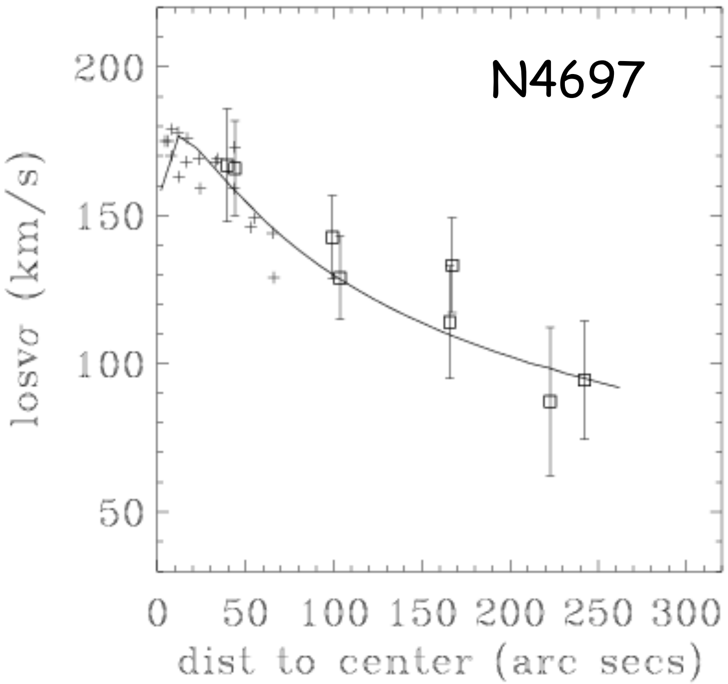
[OIII]

5007 A

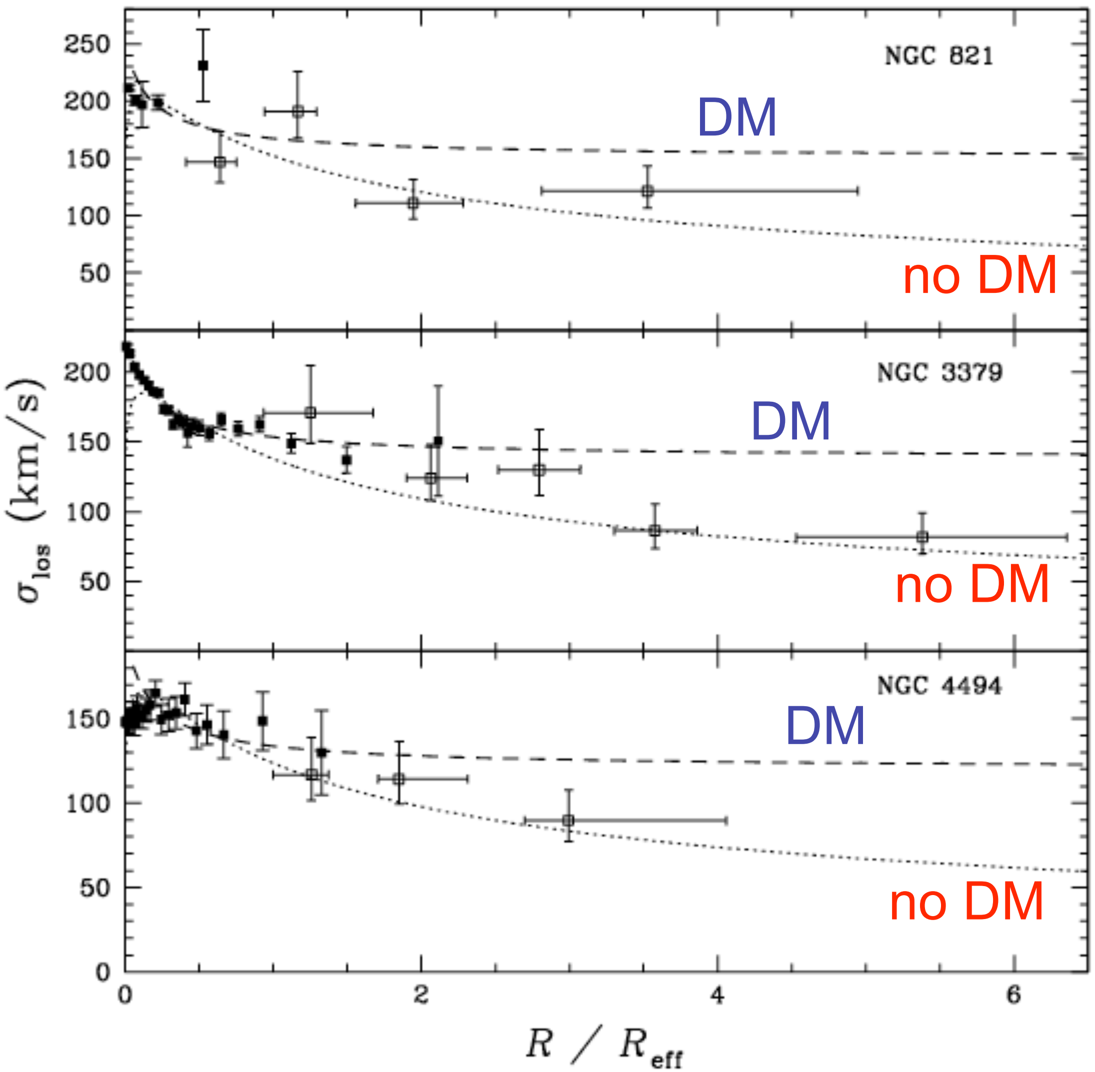


PN velocity dispersions are low

Mendez et al. 01



Romanowsky et al. 03

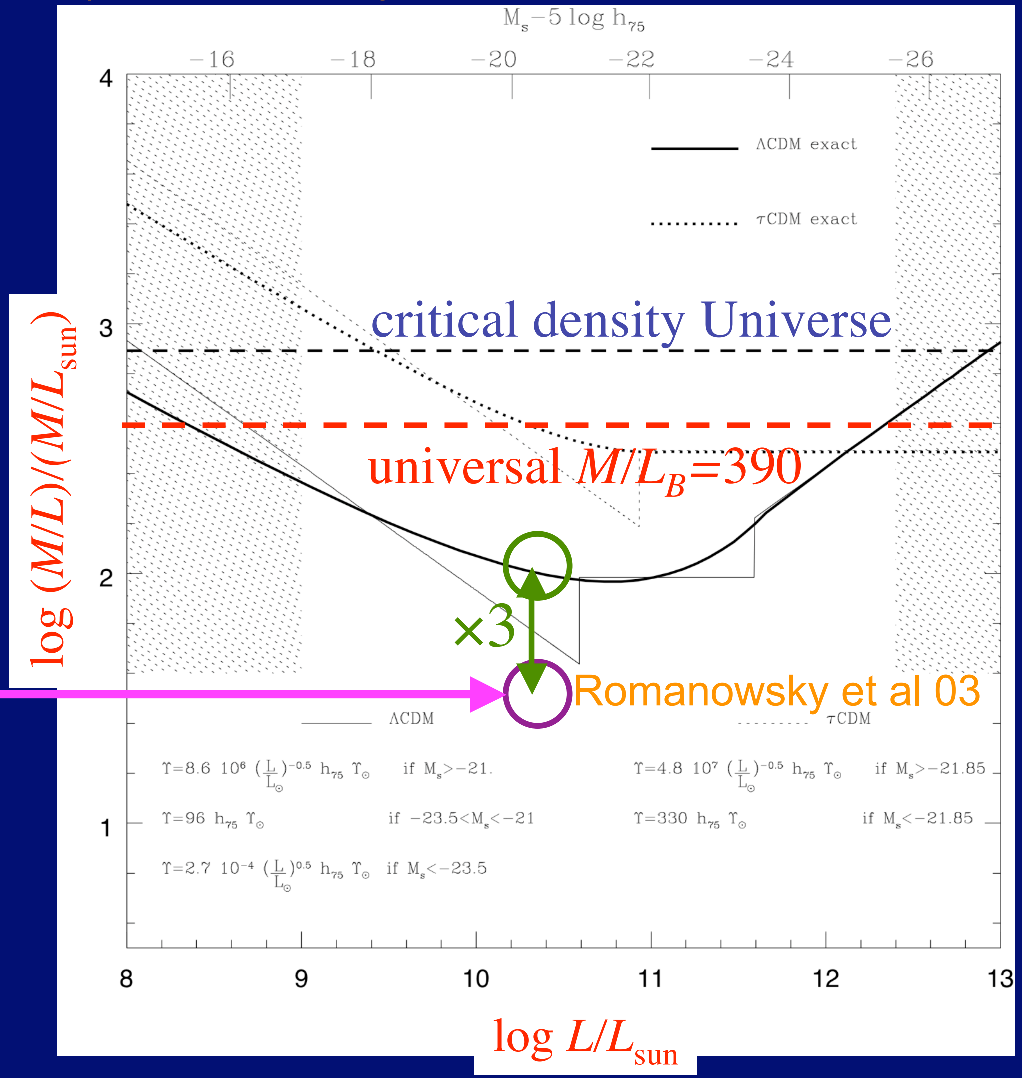


are Ellipticals naked?

Predicted & observed M/L

Marinoni & Hudson 02
(see also Yang, Mo & van den Bosch 03; Eke et al. 05)

M/L = 33?



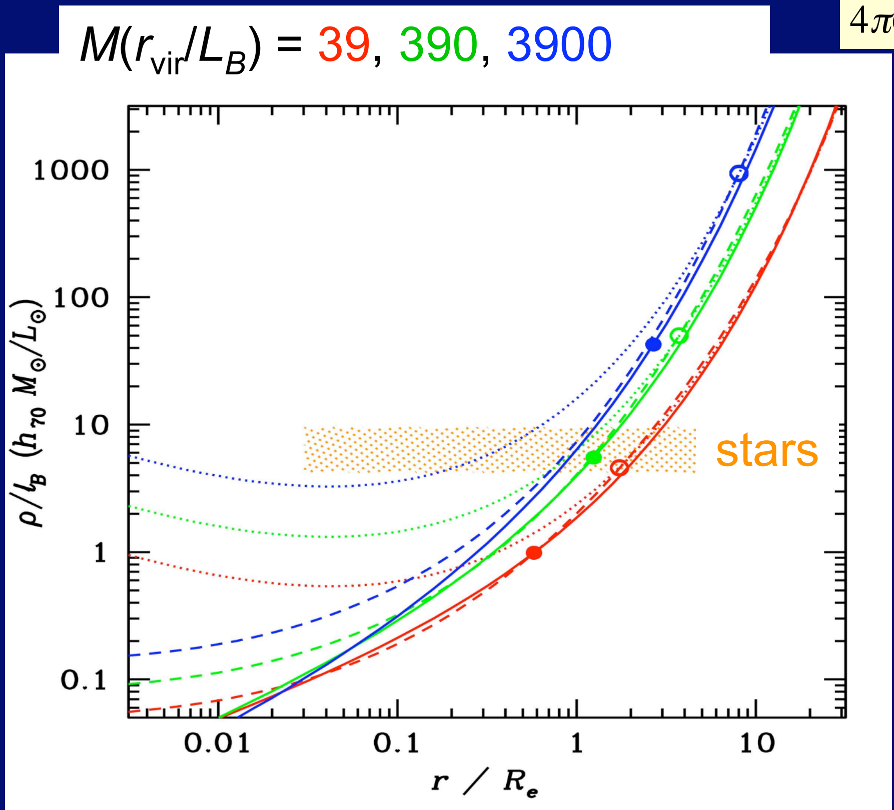
5) Step by step kinematical modelling

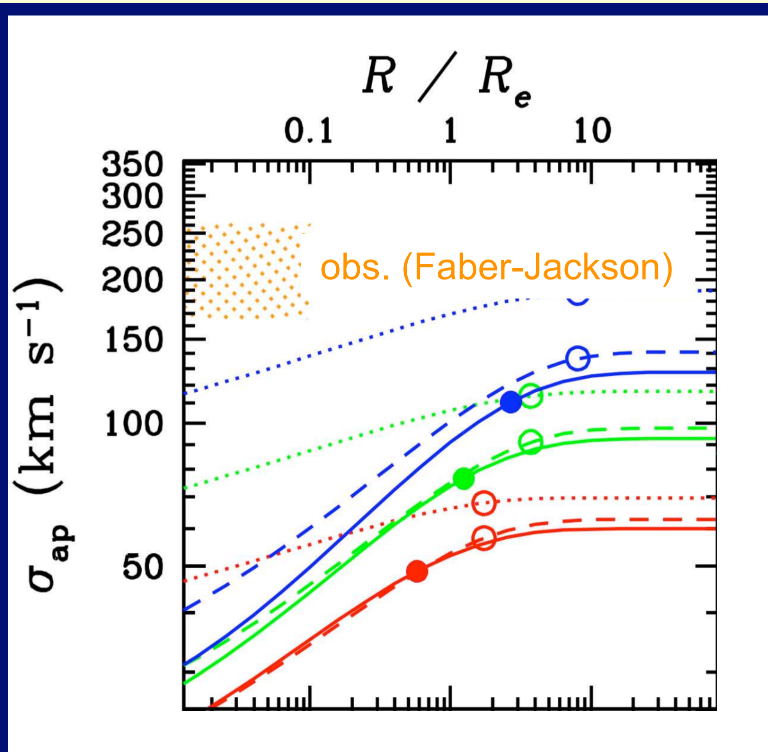
Is the total mass profile NFW-like?

Mamon & Łokas 05a, *MNRAS*

aperture velocity dispersion for $\beta = 0$

$$\frac{3}{4\pi G} L_2(R)\,\sigma_{\rm ap}^2(R) = \int_0^\infty r\nu(r)M(r)\,dr - \int_R^\infty \frac{\left(r^2-R^2\right)^{3/2}}{r^2}\nu(r)M(r)\,dr$$



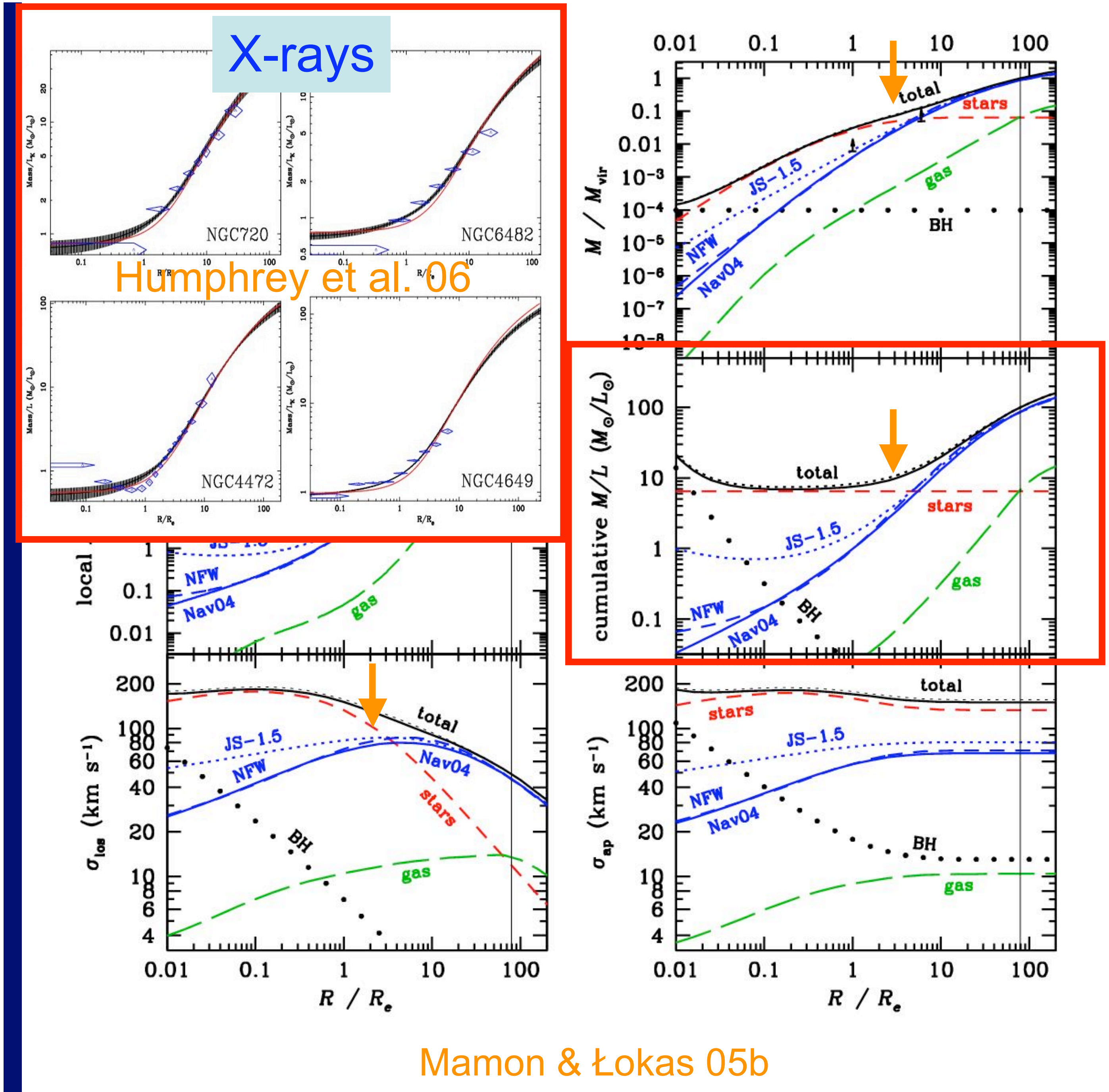


local M/L lower than stellar!

central aperture velocity dispersions lower than observed!

4-component model of elliptical galaxies

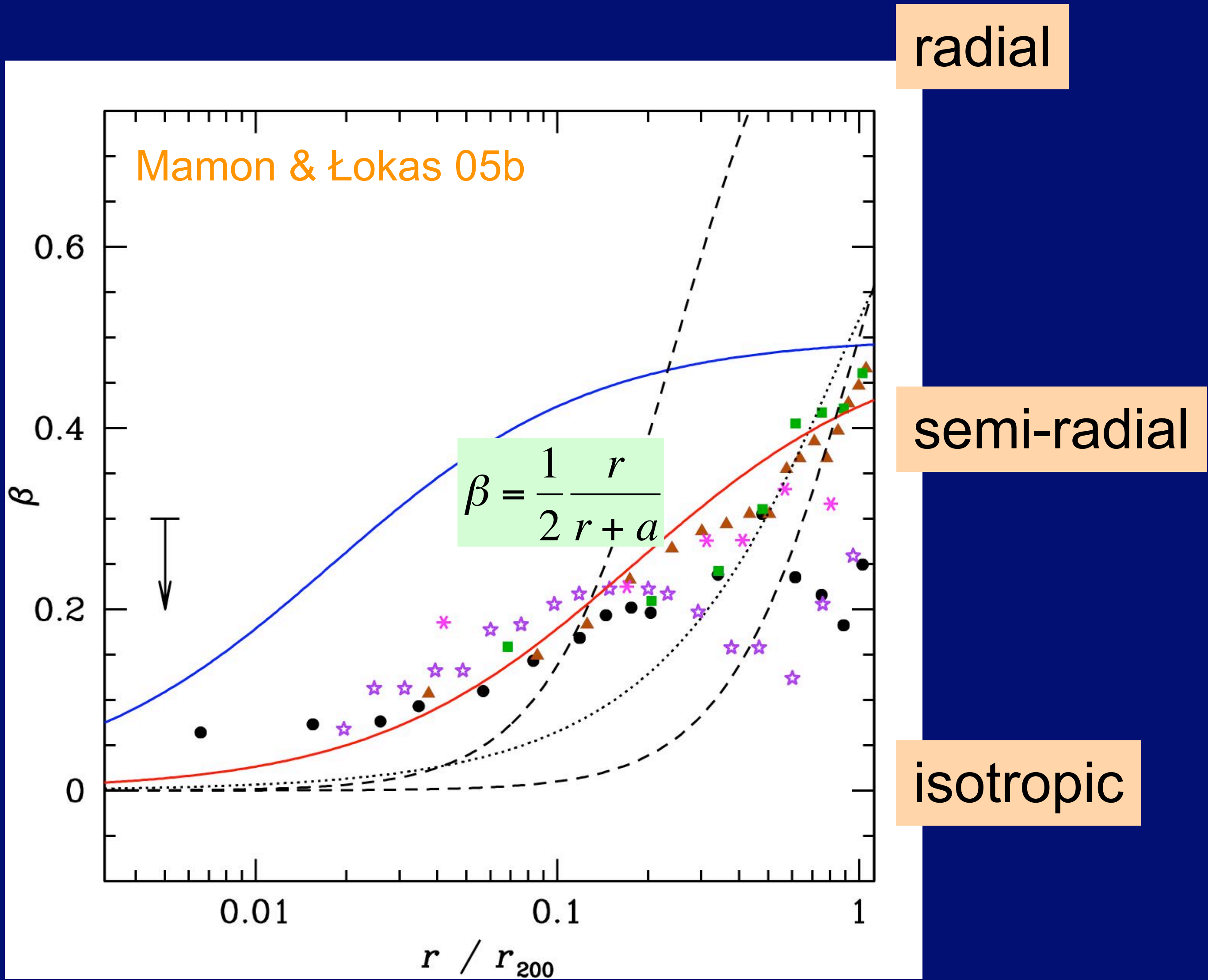
- Sérsic stars
- NFW-like dark matter
- β-model hot gas
- central supermasssive black hole



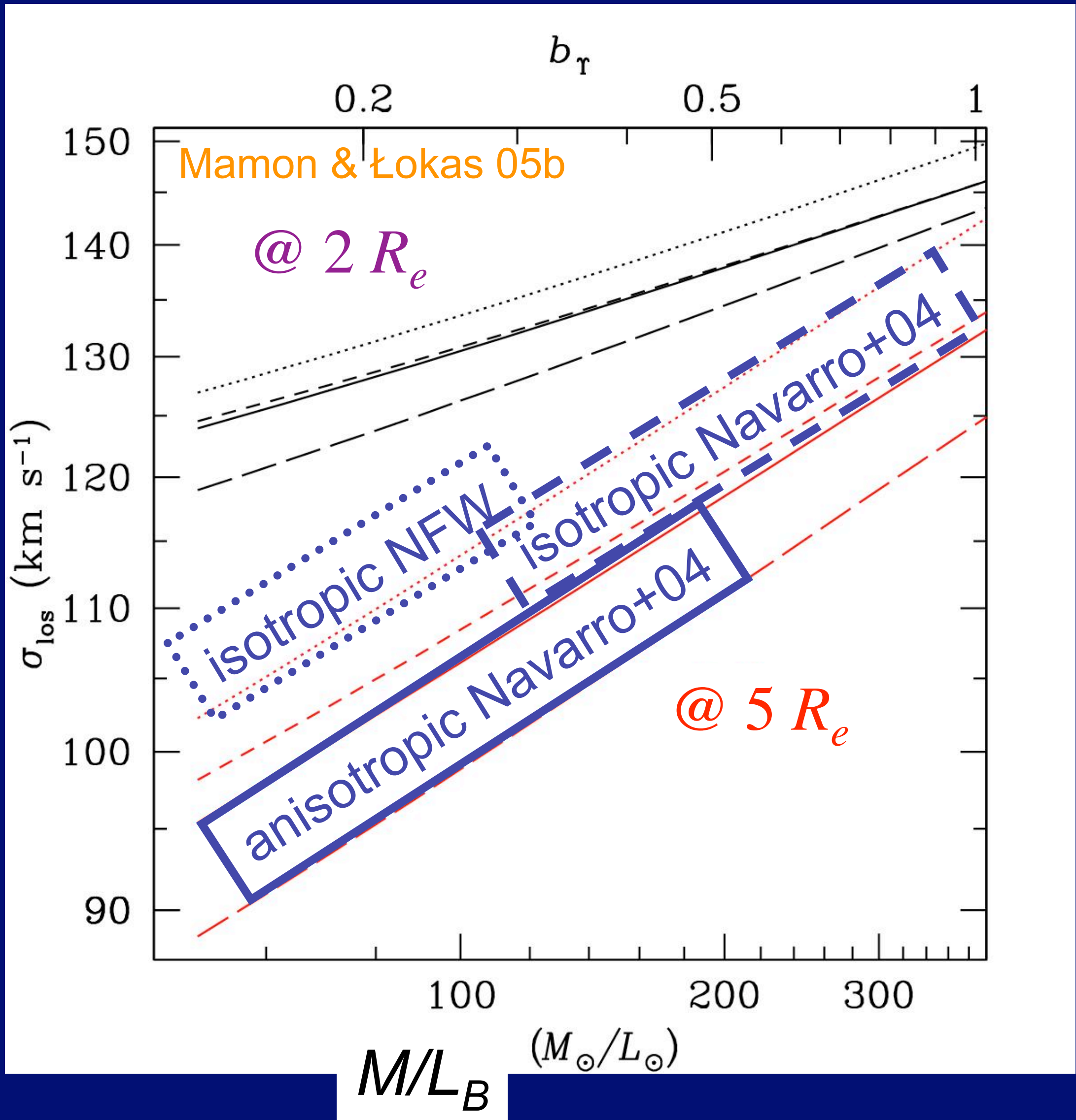
Stars dominate inside

→ few R_e

Velocity Anisotropy
in cosmological simulations



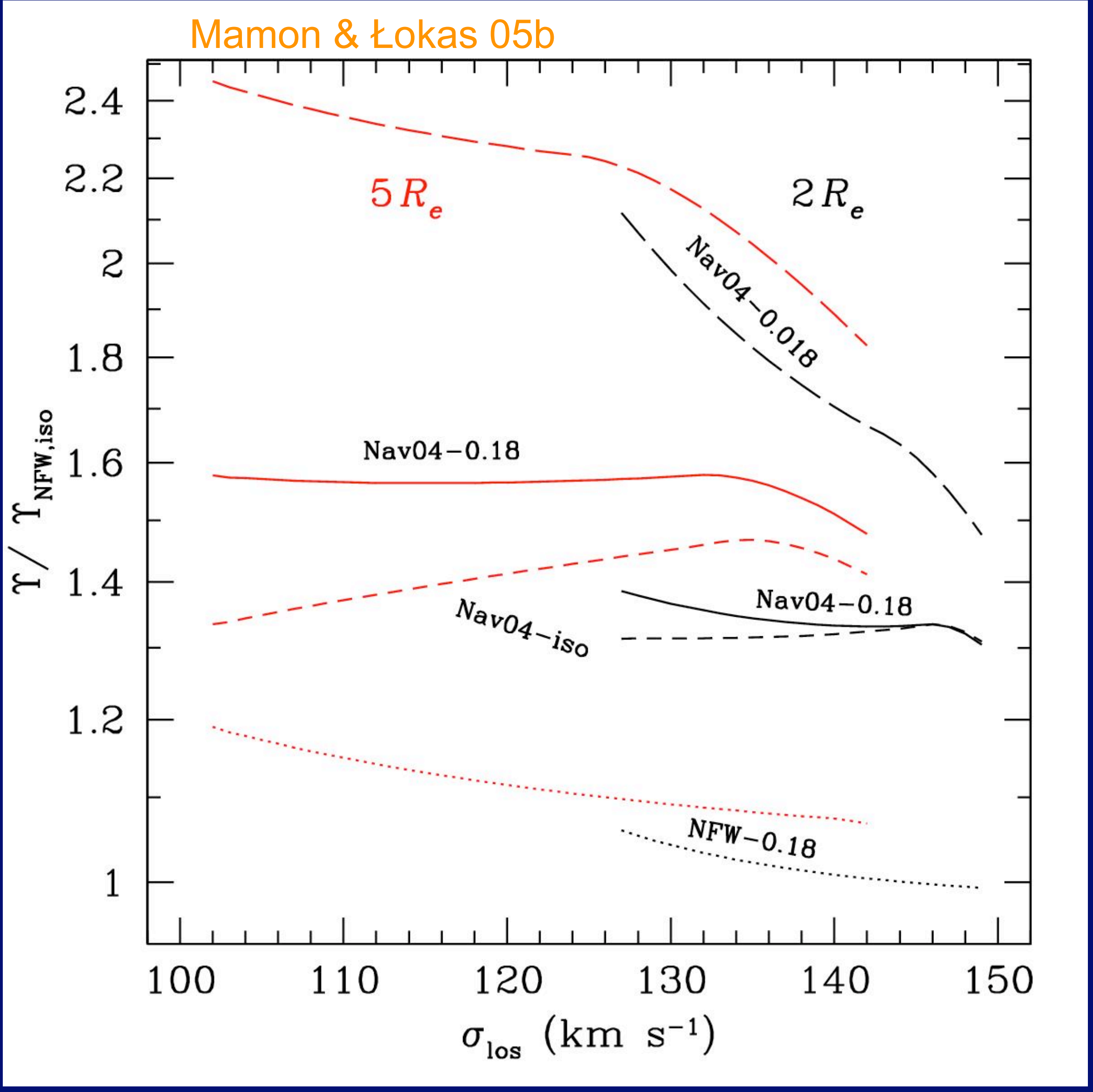
Velocity dispersion vs anisotropy & dark halo model



$$\sigma_{\rm los}(5\,R_e) \propto \left[\frac{M}{L_B}(r_{\rm vir})\right]^{1/8}$$

$$\frac{M}{L_B}(r_{\rm vir}) \propto \left[\sigma_{\rm los}(5\,R_e)\right]^{8}$$

Effects on M/L at virial radius



6) Dynamical modelling of Elliptical Galaxies

Major merger simulation

Disk

Bulge

Gas

Dark halo

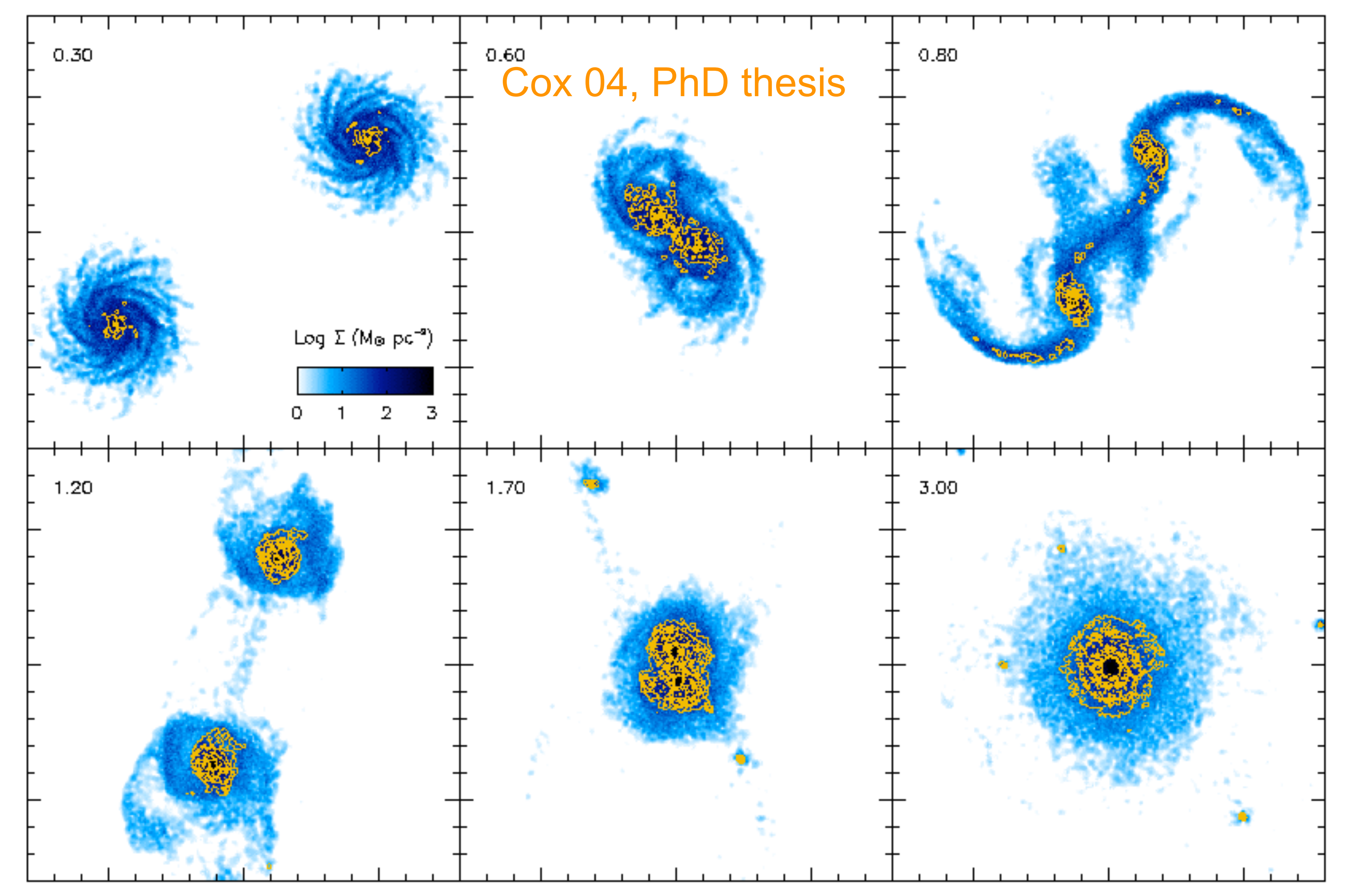
TREE-SPH

GADGET

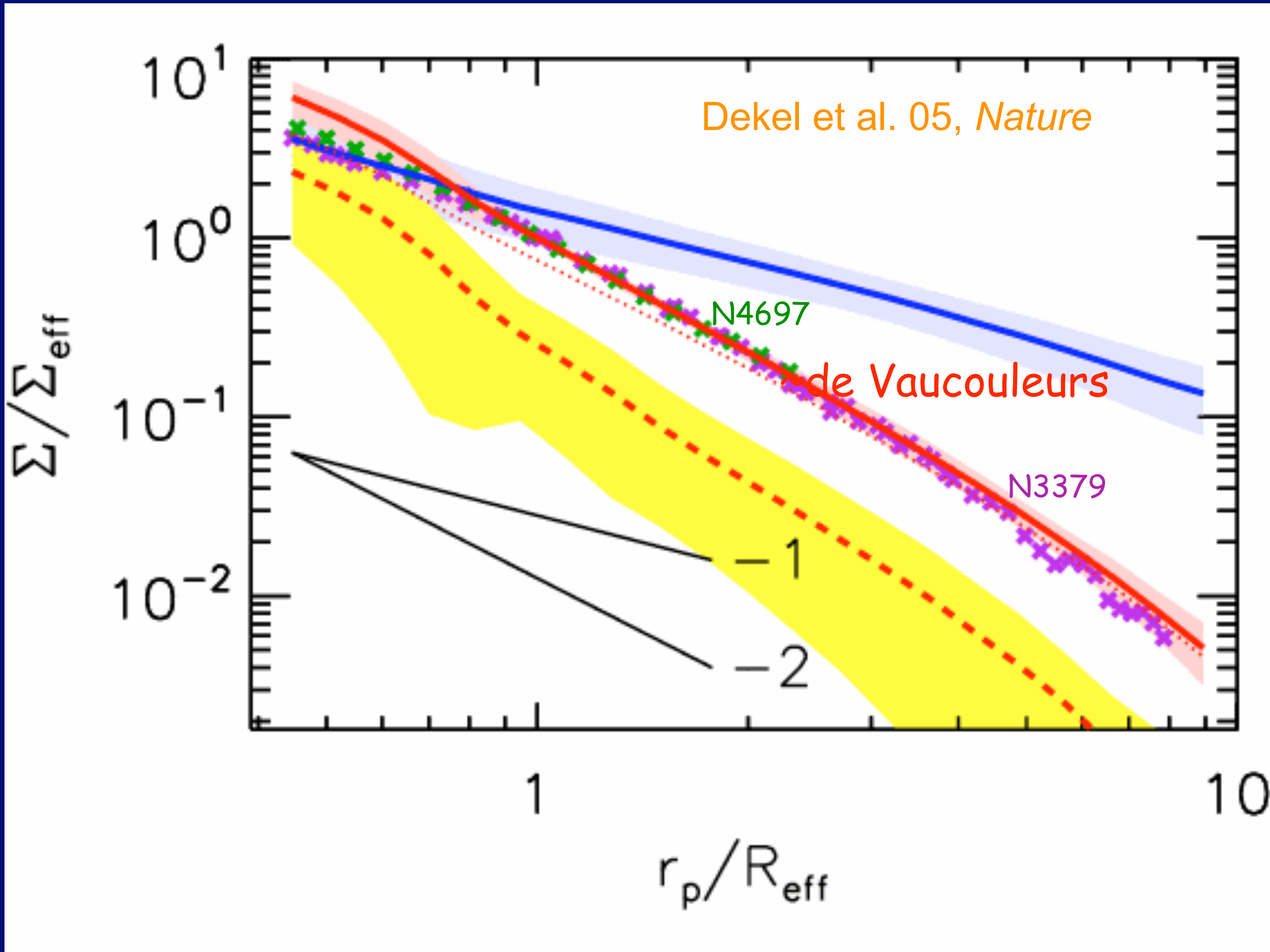
Springel 01

Cox 04,
PhD Thesis

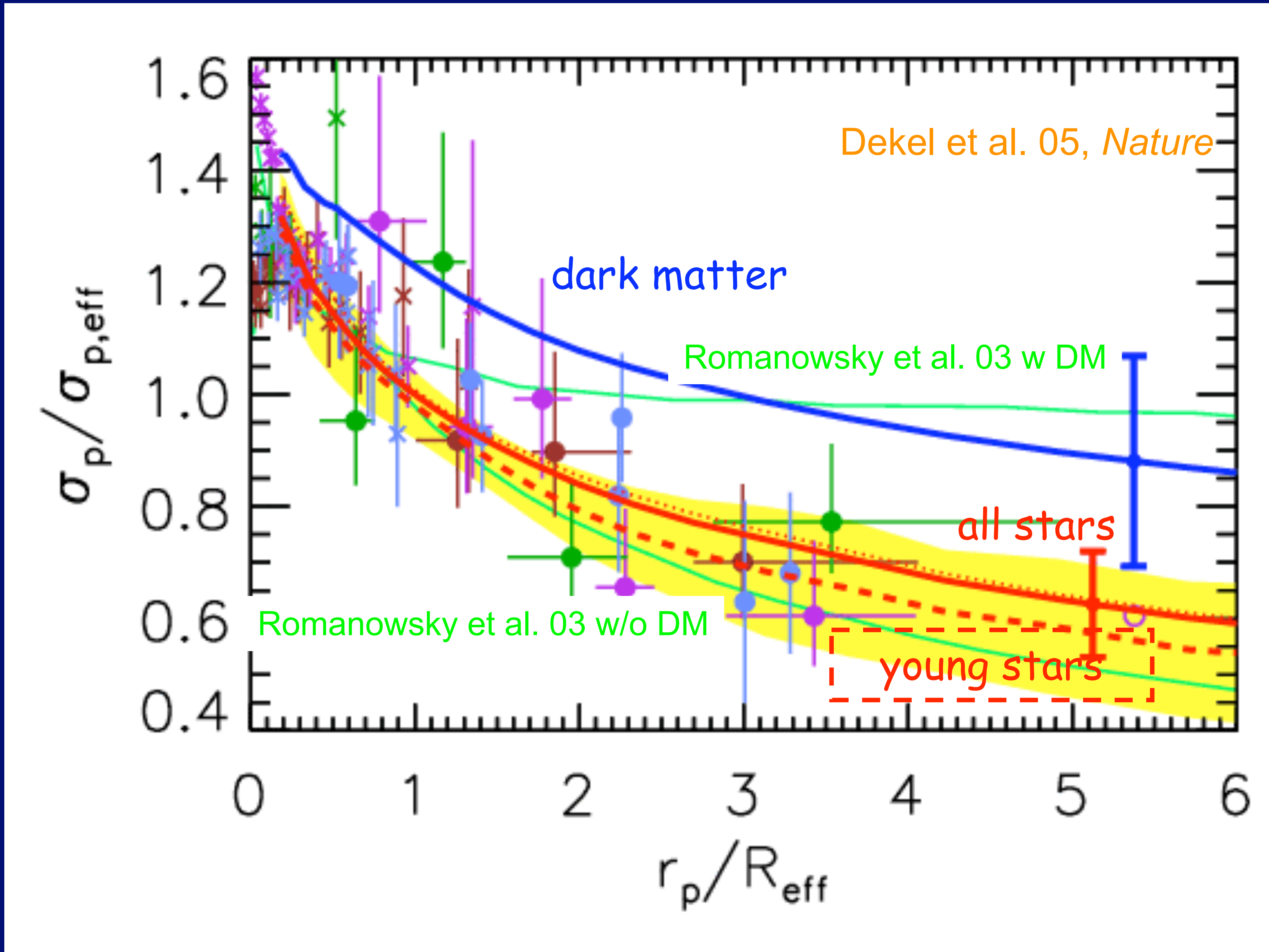
Stars: old and new (face-on view)



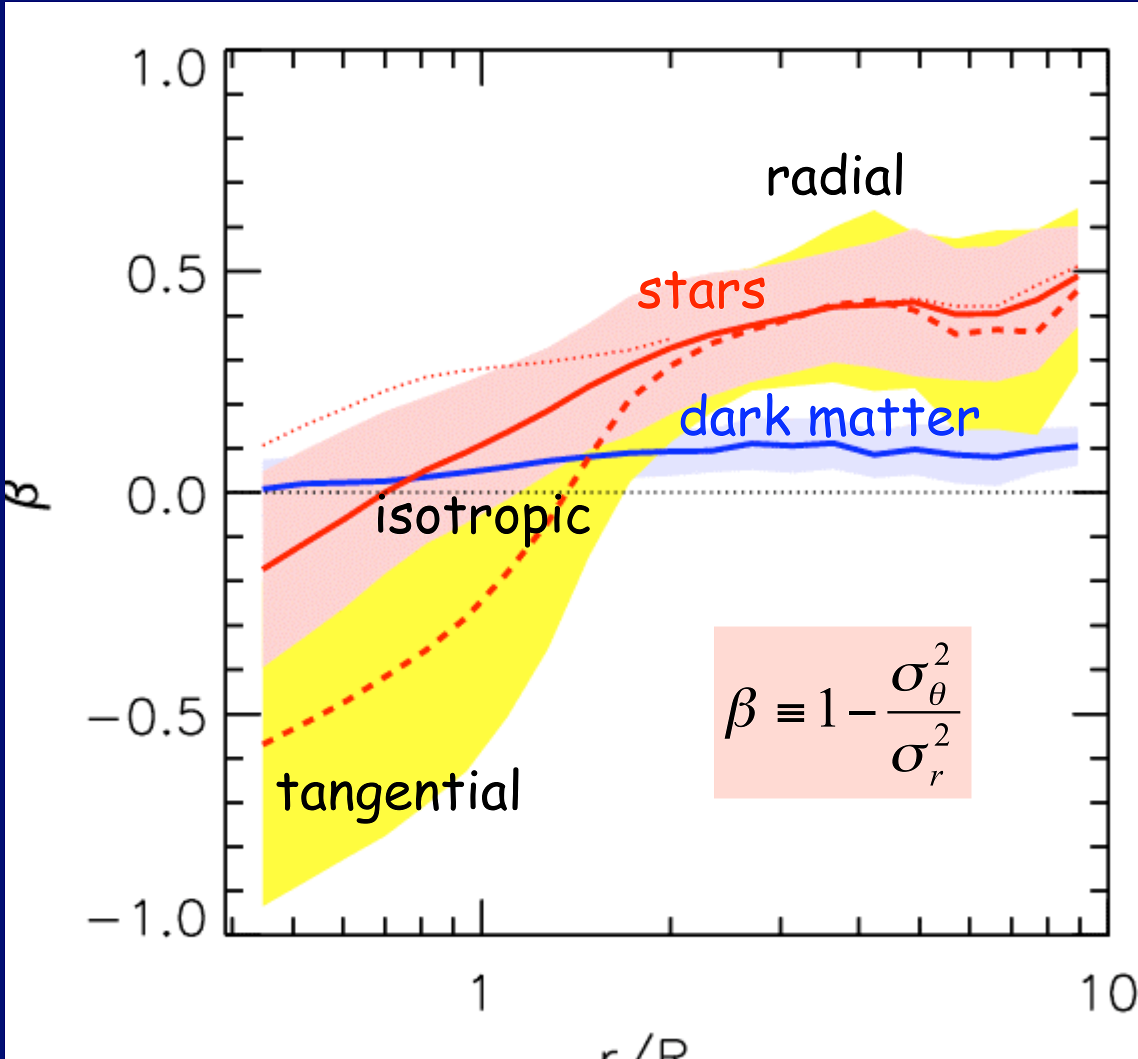
Surface Density: like typical Es!



Line-of-sight Velocity Dispersions: low!



Velocity Anisotropy



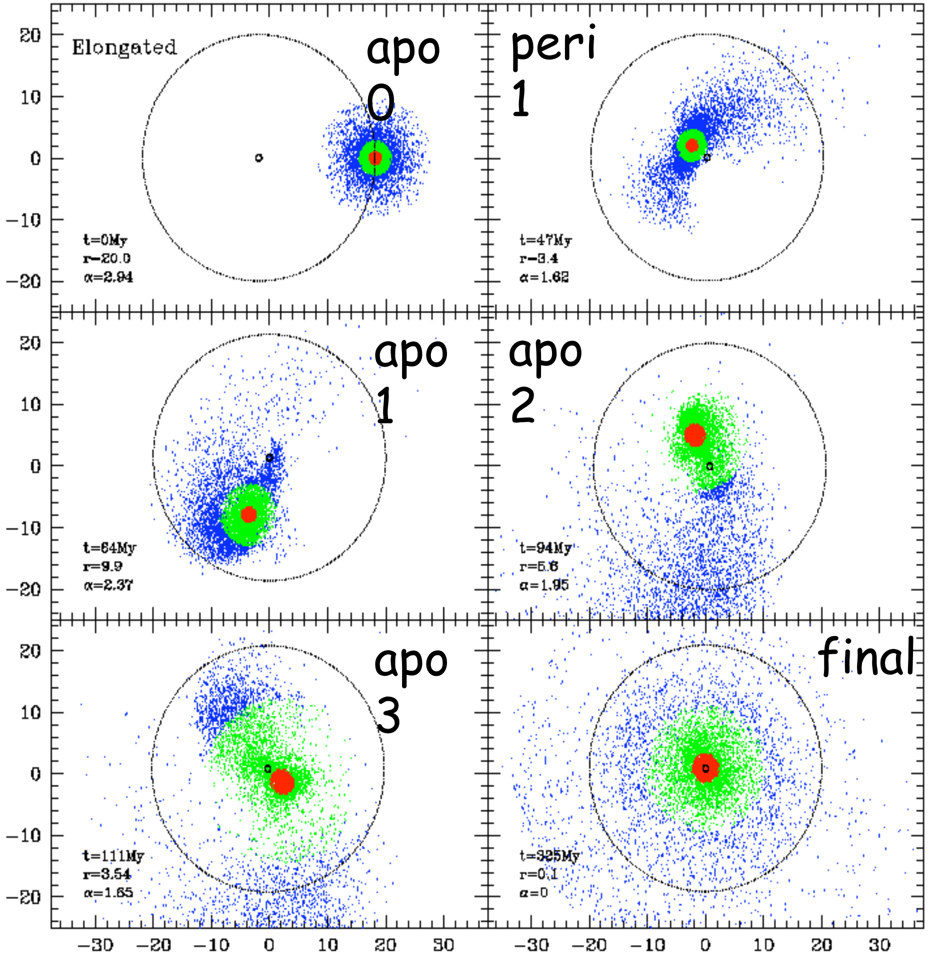
Dekel et al. 05, *Nature*

stars on much more radial orbits than *dark matter*!

Why do stars have radial orbits while dark matter particles don't?

A 10:1 Minor Merger

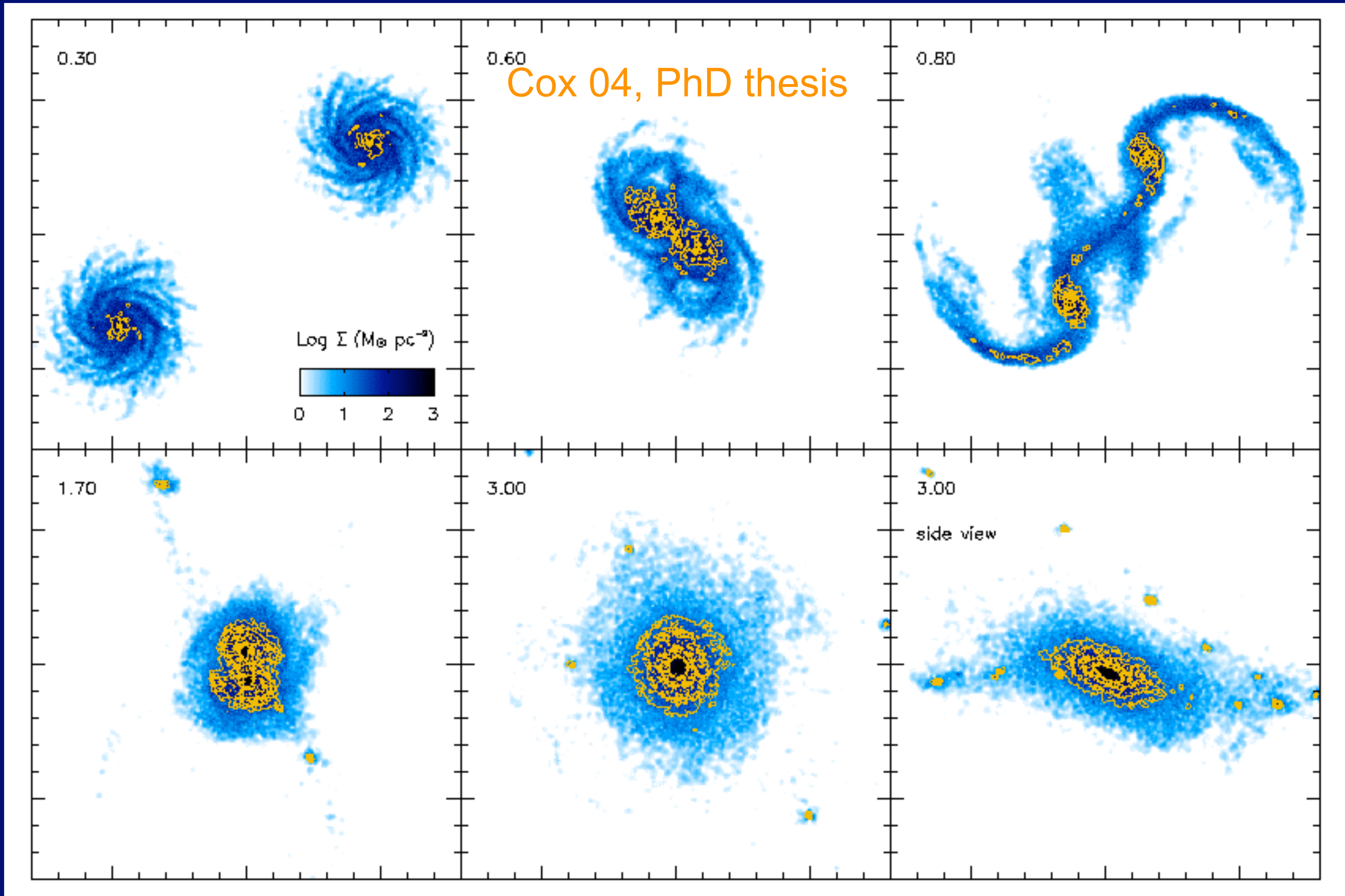
Dekel, Devor & Hetzroni 03



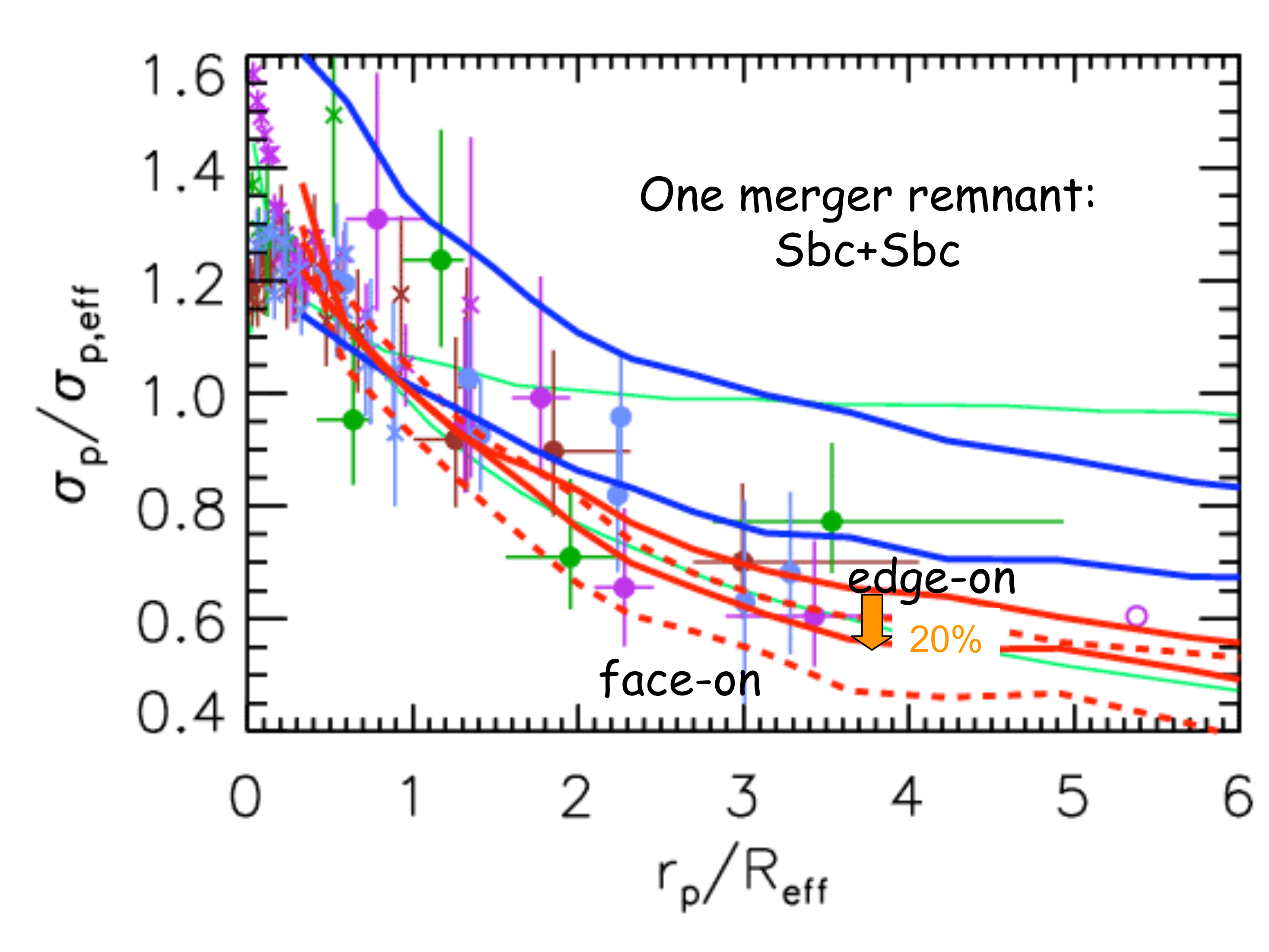
central particles in secondary end up in center of remnant

outer *stars* originate from central regions
outer *dark matter* particles come from outer regions

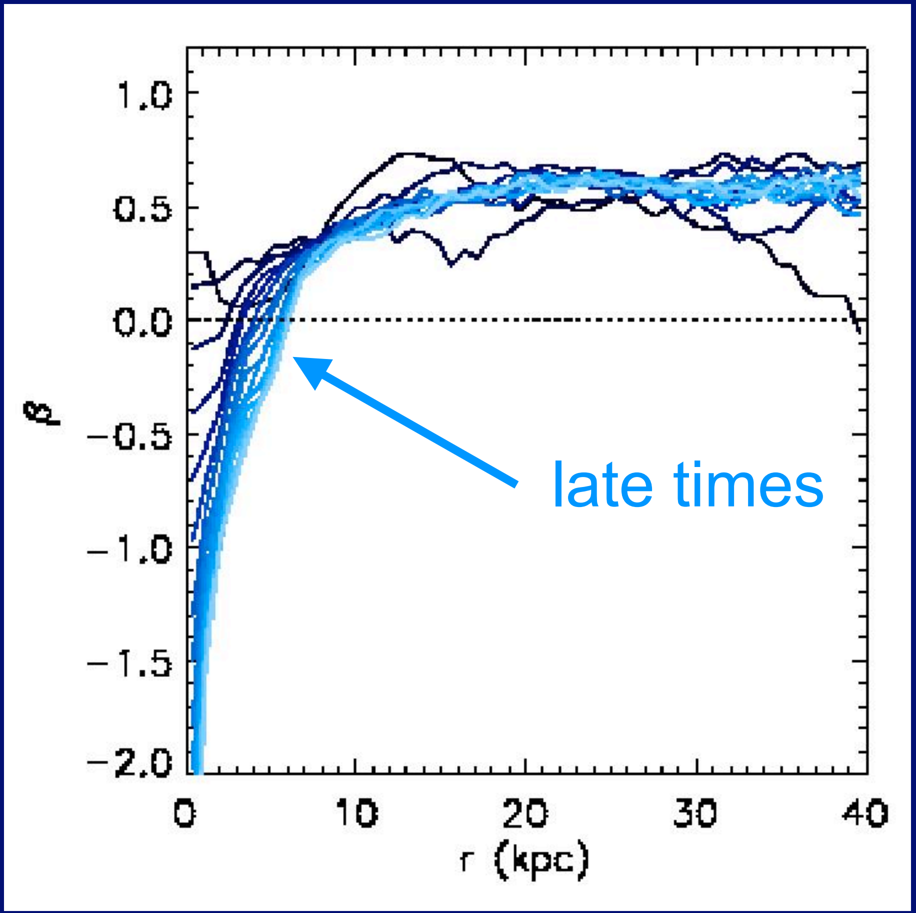
Triaxiality

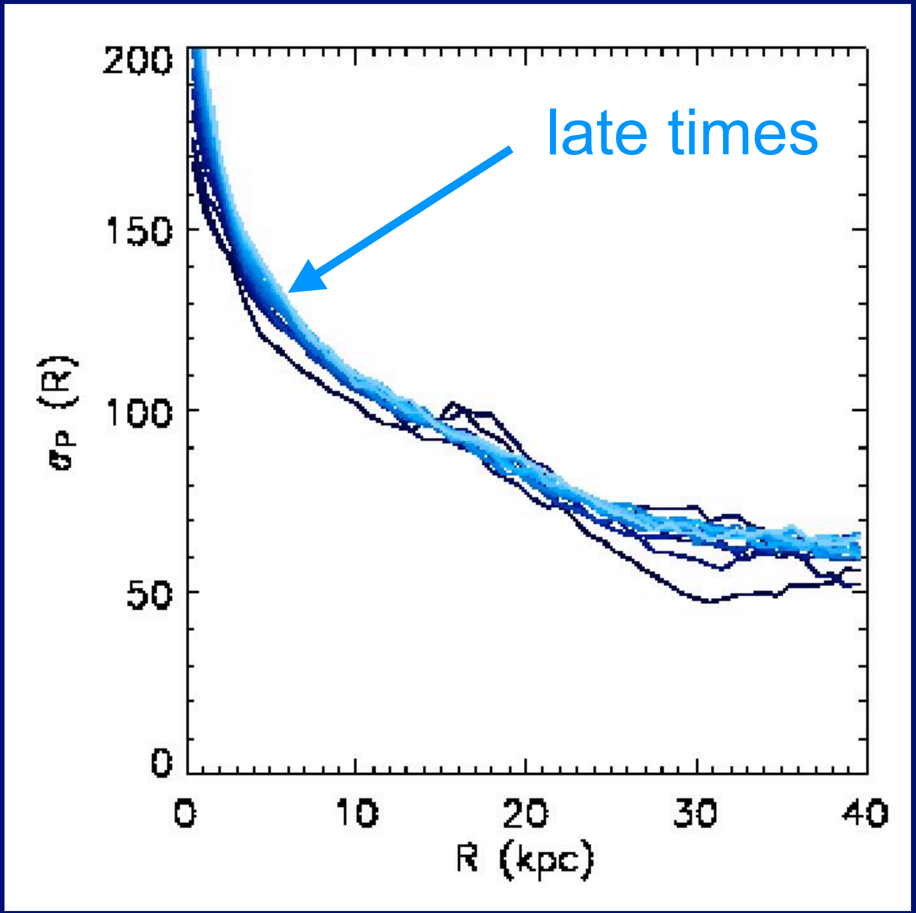


Effects of triaxiality



Time evolution





Jeans equilibrium

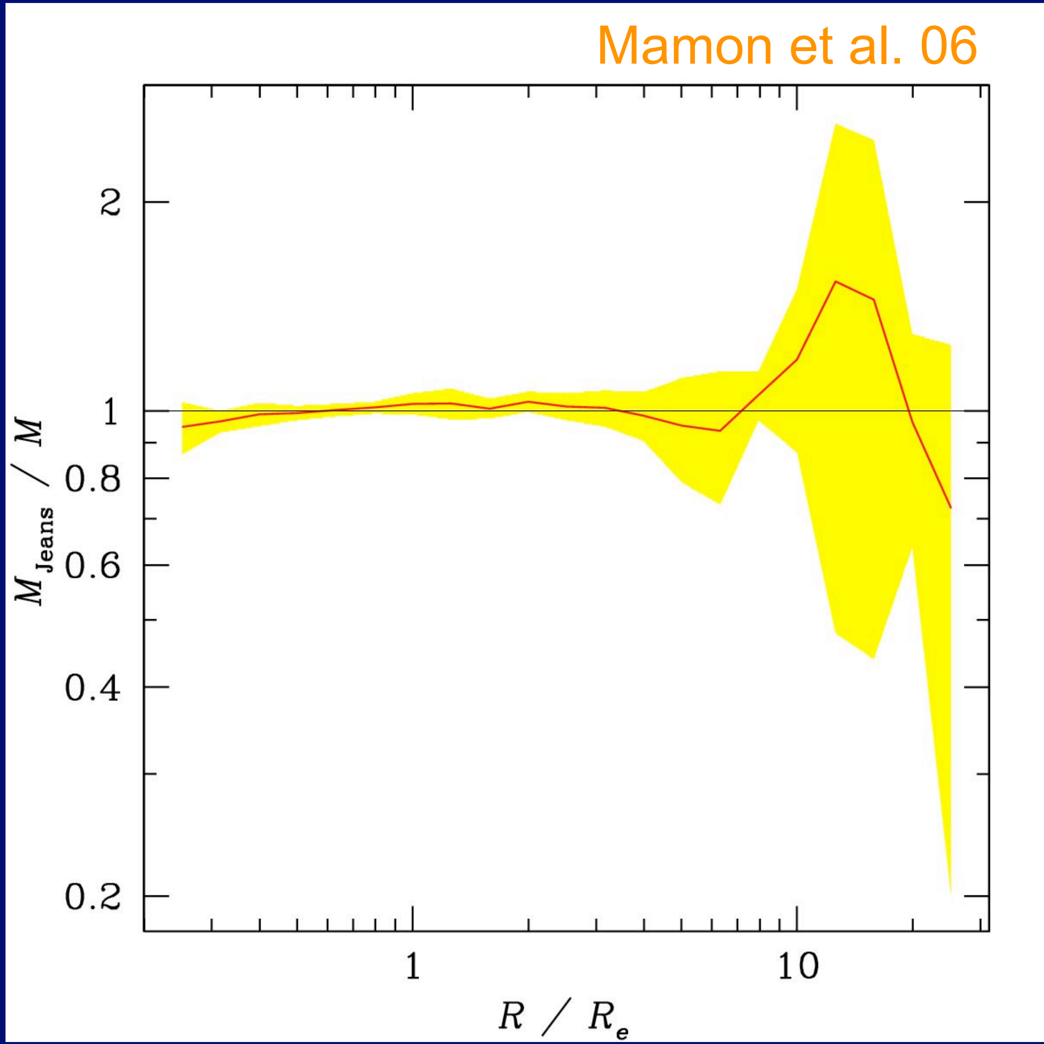
$$M_{\rm Jeans}(r) = \frac{r\left\langle v_r^2\right\rangle}{G}\left(\alpha+\gamma-2\beta\right)$$

$$\gamma = -\frac{d\ln\left\langle v_r^2\right\rangle}{d\ln r}$$

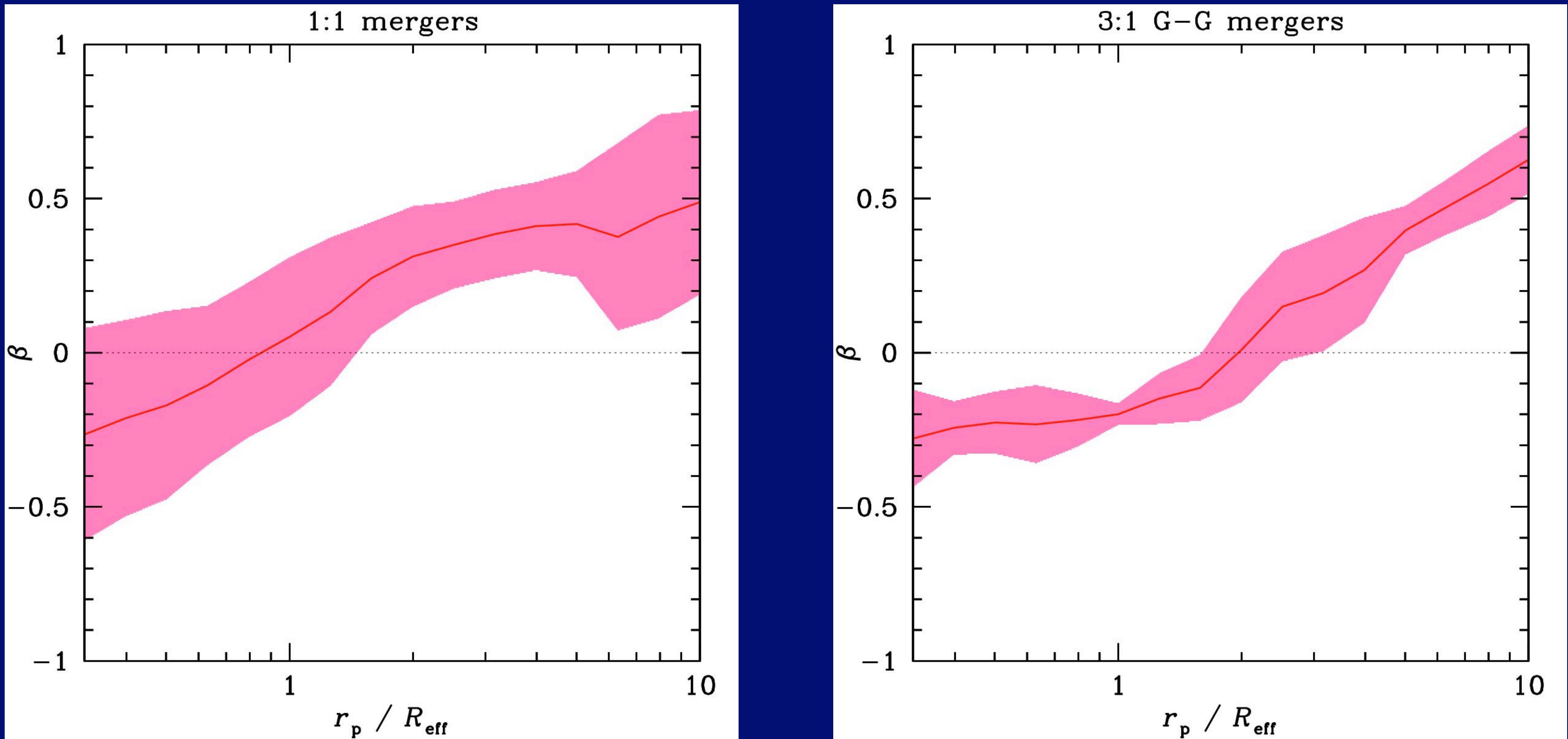
good equilibrium to 8 R_e!

⇓

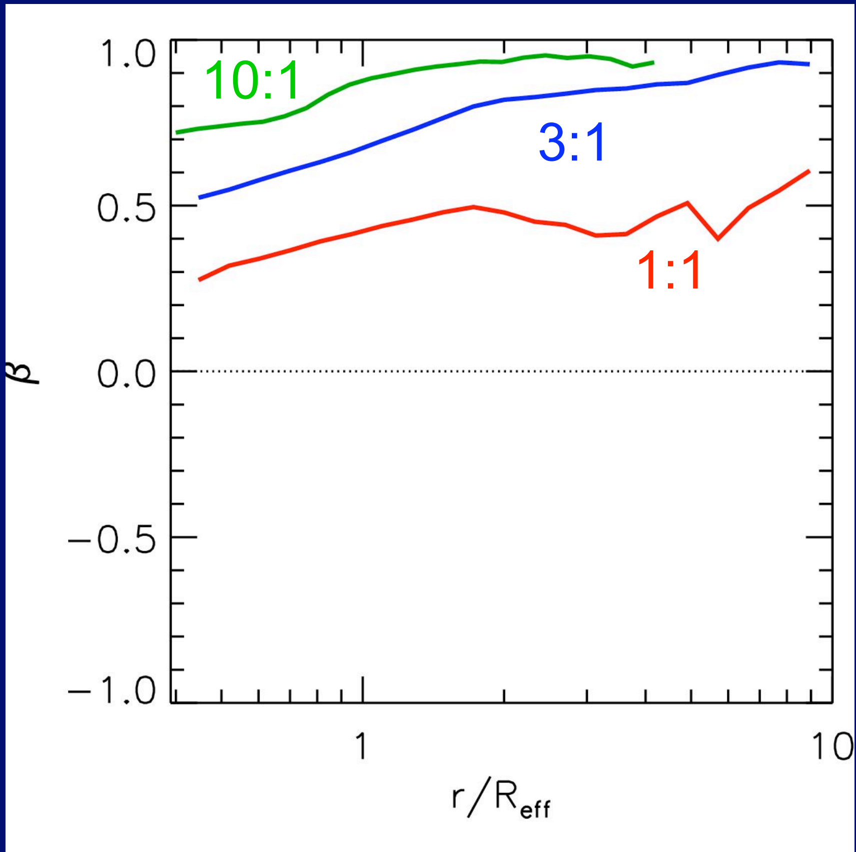
small time-dependence effects

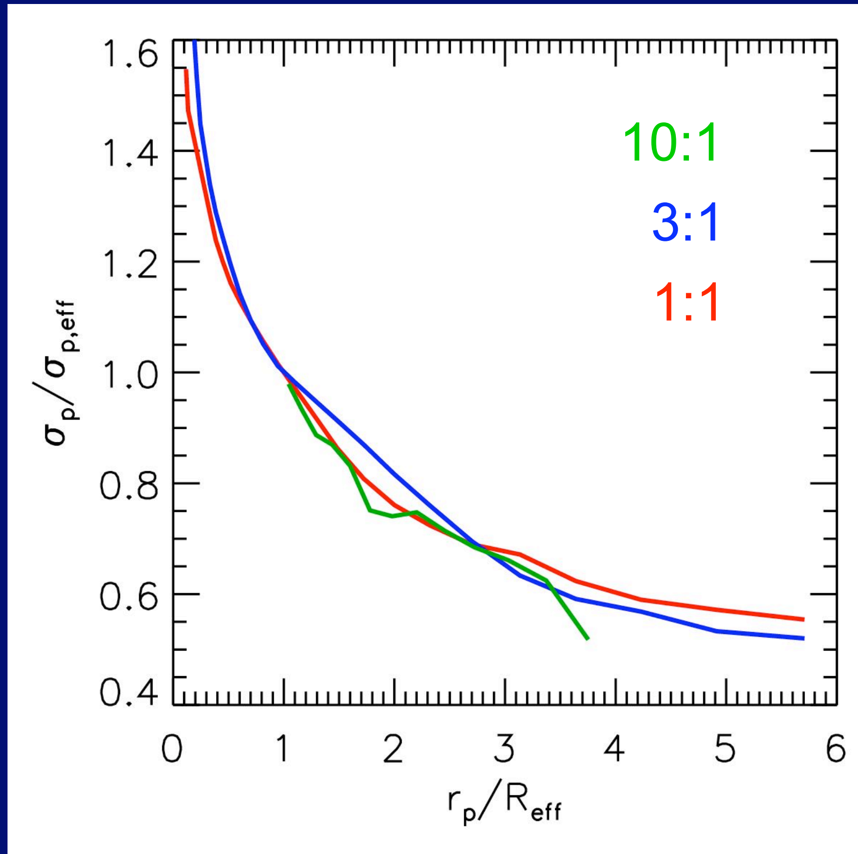


Minor mergers: 3:1 all particles



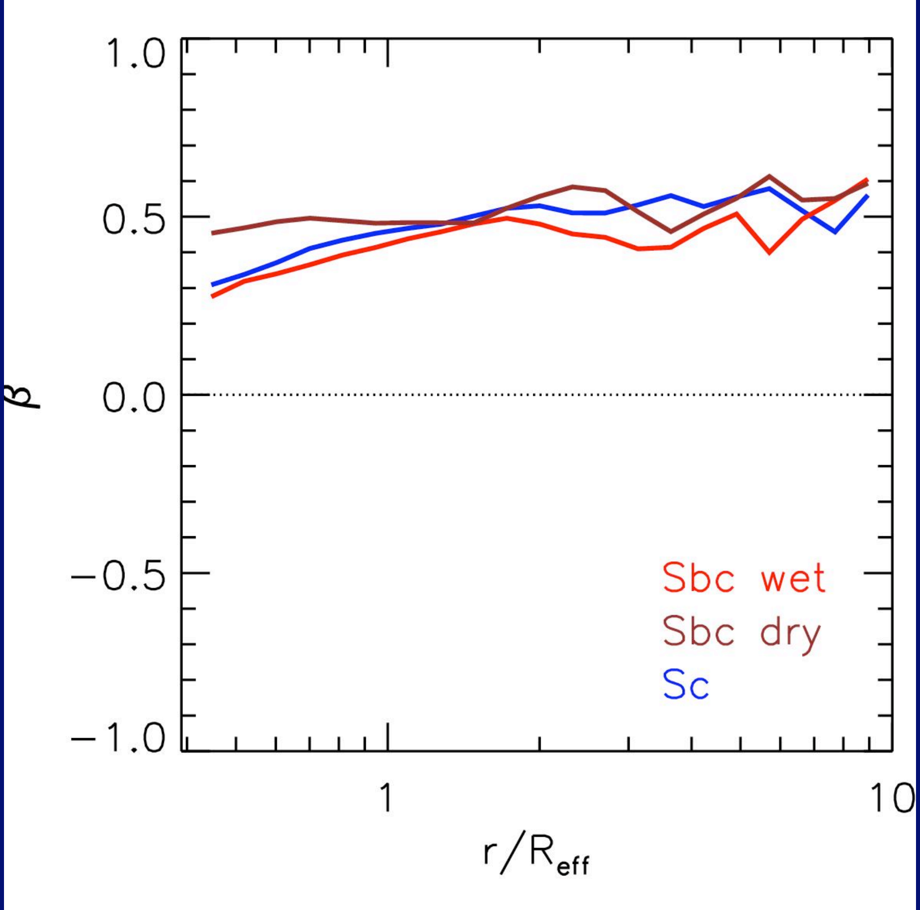
Minor mergers: secondary particles

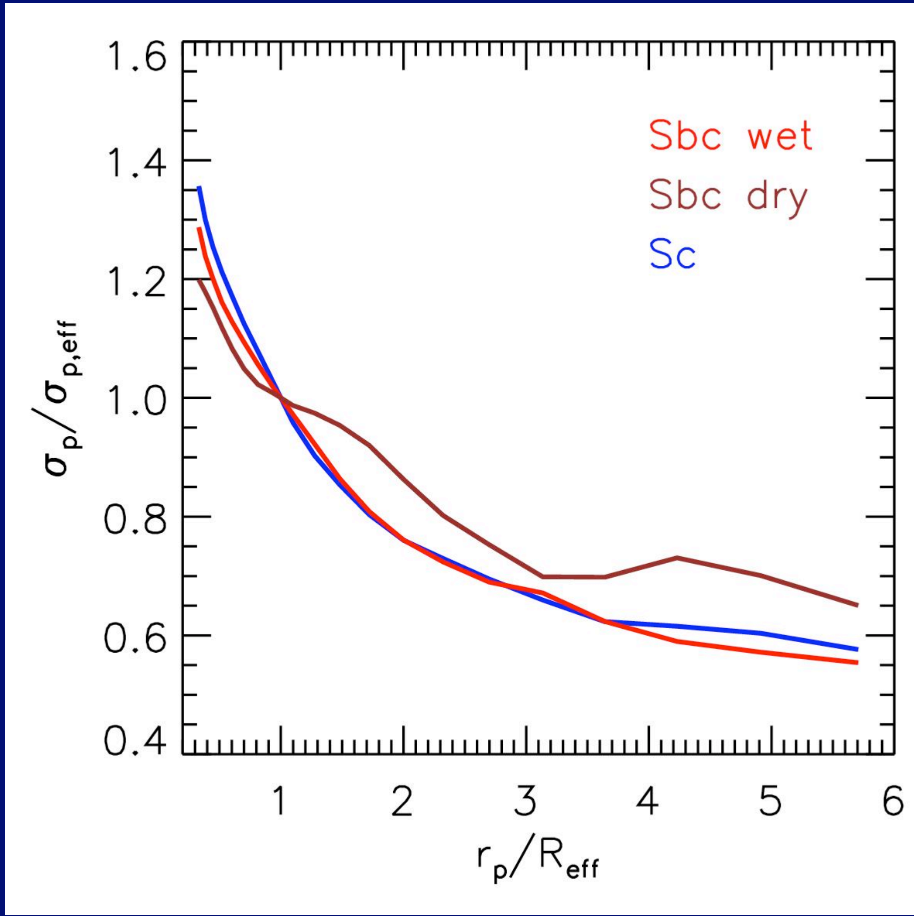




→ even more radial orbits!

Effects of gas dynamics

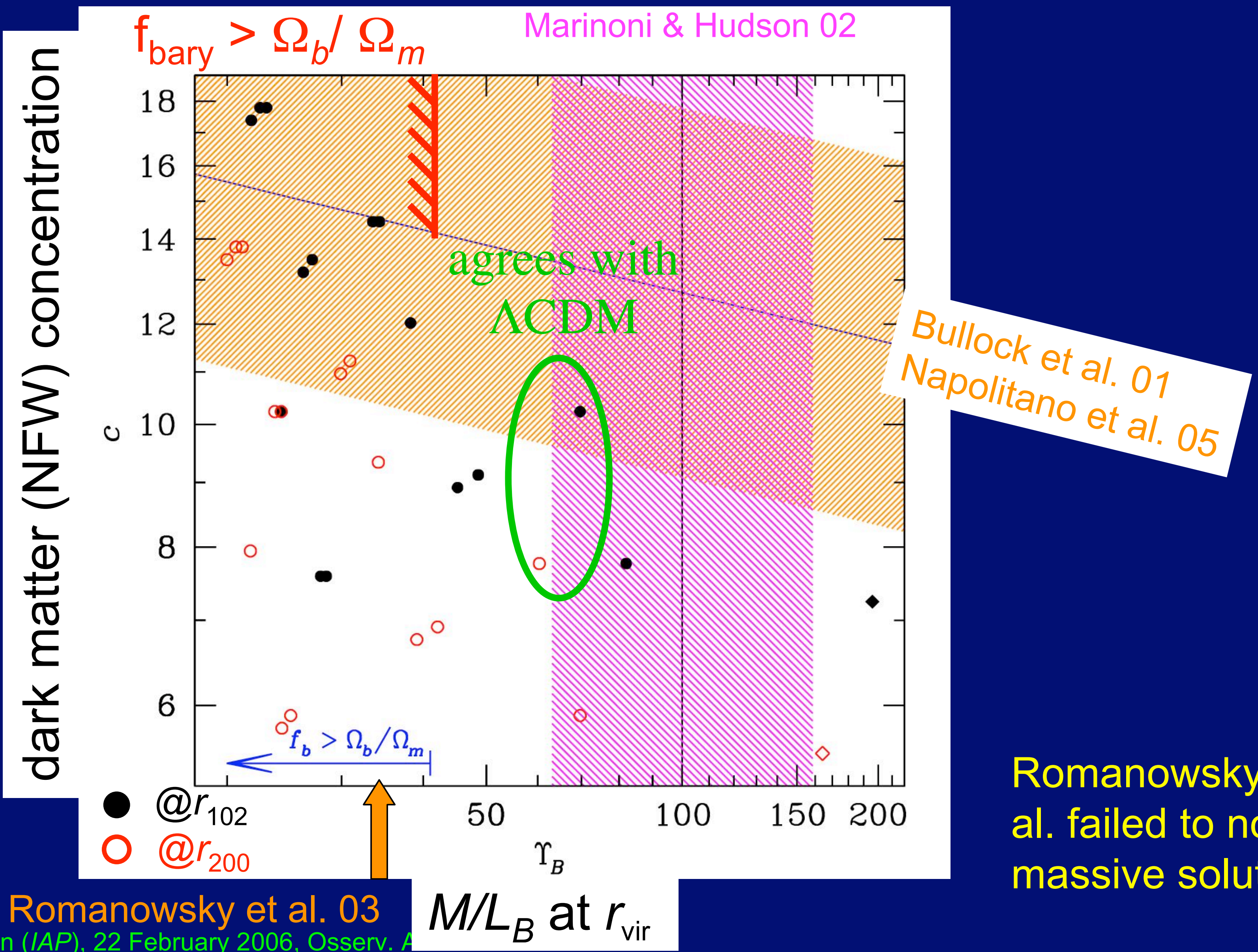




→ small effect!

What M/Ls were found by Romanowsky et al. 03?

Mamon & Lokas 05b



Romanowsky et al. failed to notice massive solutions

Conclusions

Elliptical galaxies not compatible with NFW-like total *M*(*r*)

➡ stars dominate to a few R_e

Merger simulations of spirals embedded in DM:

→ remnants that reproduce low PN vel. dispersions

➡ consistent with ΛCDM scenario

Low velocity dispersion produced by:

- not assuming NFW density profile
- radial anisotropy
- steep tracer density
- viewing oblate ellipticals face-on

Spherical kinematical modelling is difficult!

but Romanowsky et al. failed to notice their massive solutions!

Indications that bright PNe in ellipticals have young progenitors