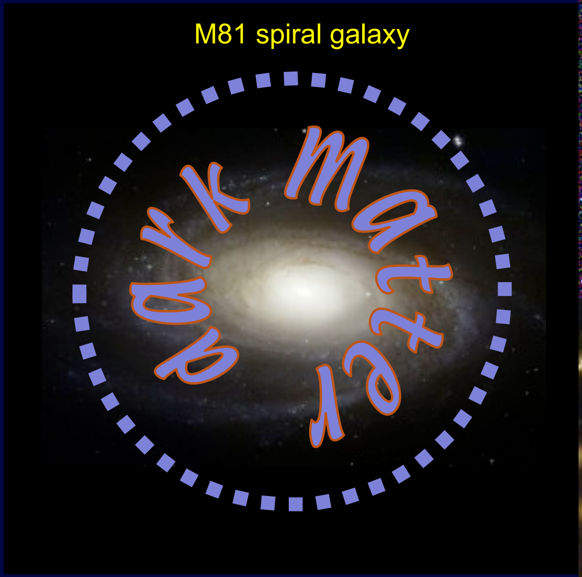
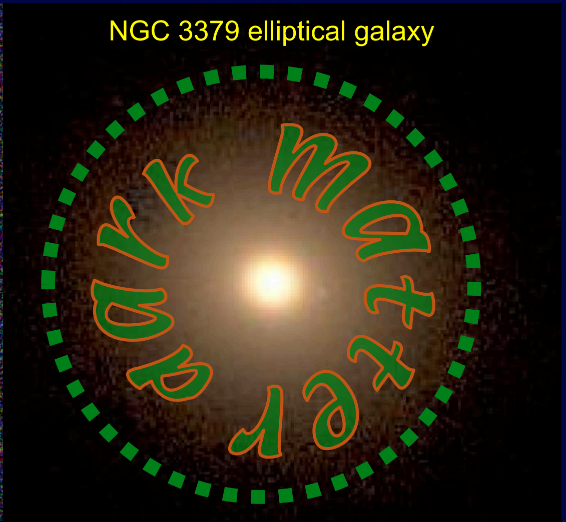
The distribution of dark matter in galaxies and clusters from internal motions


M81 spiral galaxy


Leo I dwarf spheroidal galaxy


NGC 3379 elliptical galaxy


Abell 1689 galaxy cluster


Seyfert Sextet galaxy group

Outline

1) The need for Dark Matter in the Universe

2) How to measure the radial distribution of Dark Matter

3) Dark Matter in Clusters of Galaxies

4) Dark Matter in Groups of Galaxies

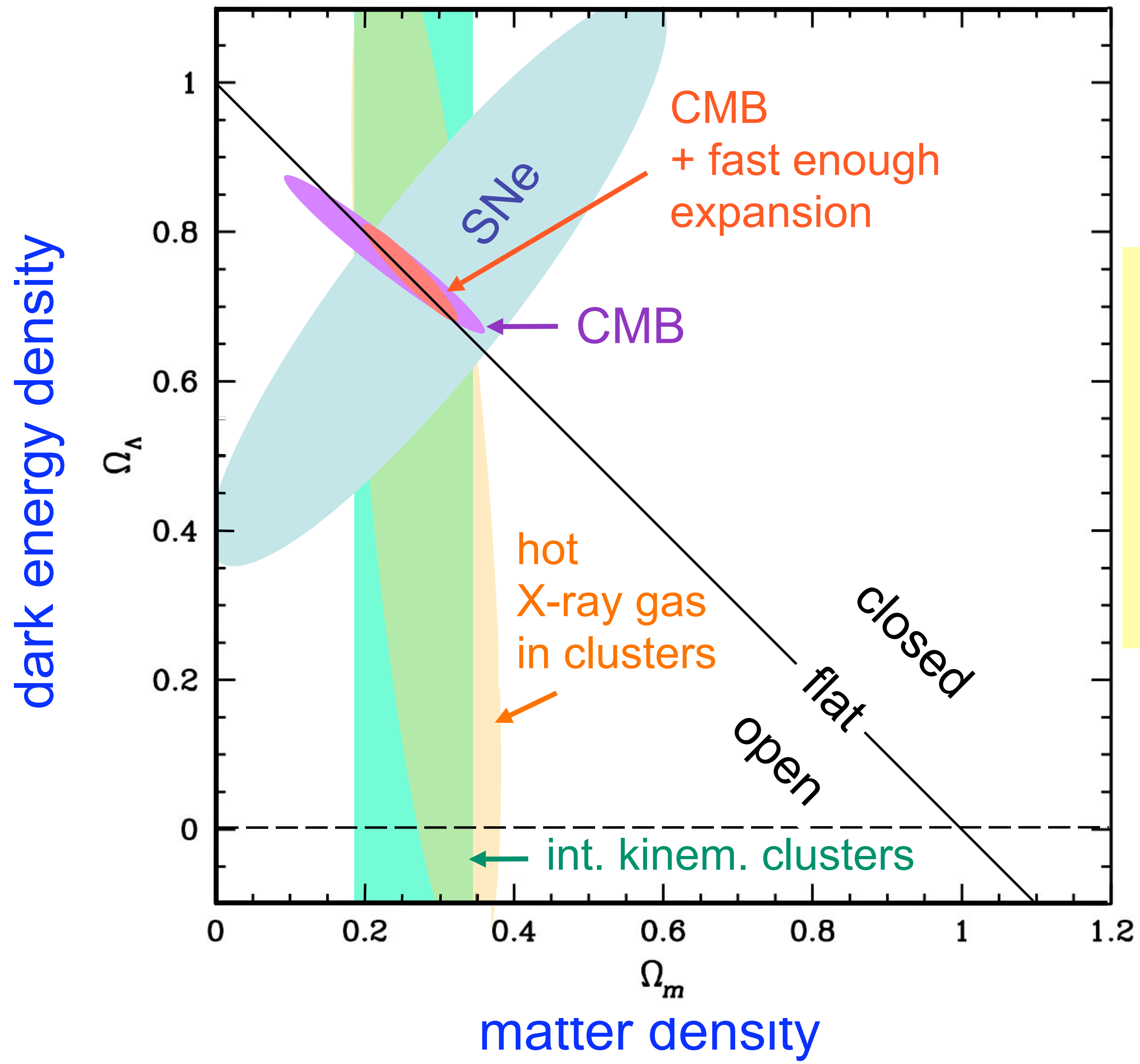
5) Do Spiral Galaxies have ΛCDM halos?

6) Do Elliptical Galaxies have Dark Matter halos?

7) Dark Matter in Dwarf Spheroidal Galaxies

1) The need for Dark Matter

Concordance model of the Universe



Ω_m=0.27

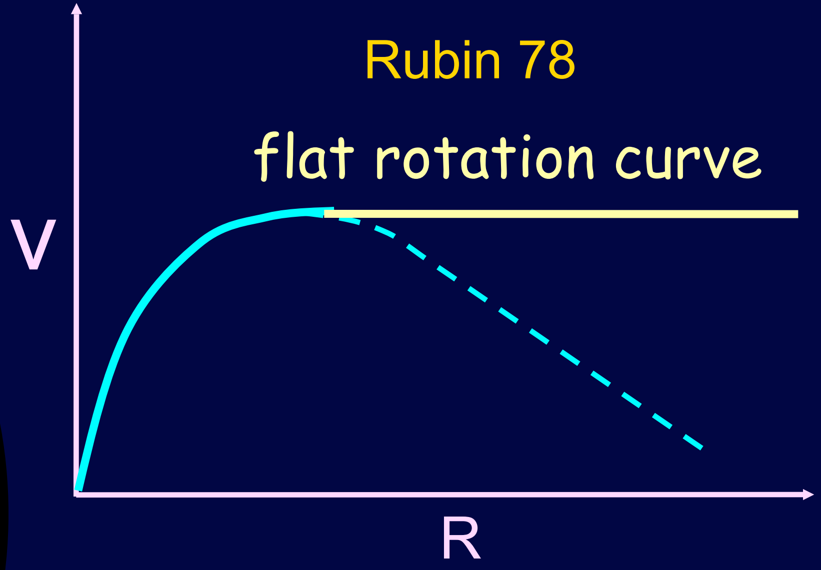
Ω_Λ=0.73

Ω_{baryons}=0.045

⇒Ω_{DM}=0.23

≈80% Ω_m

Spiral galaxies

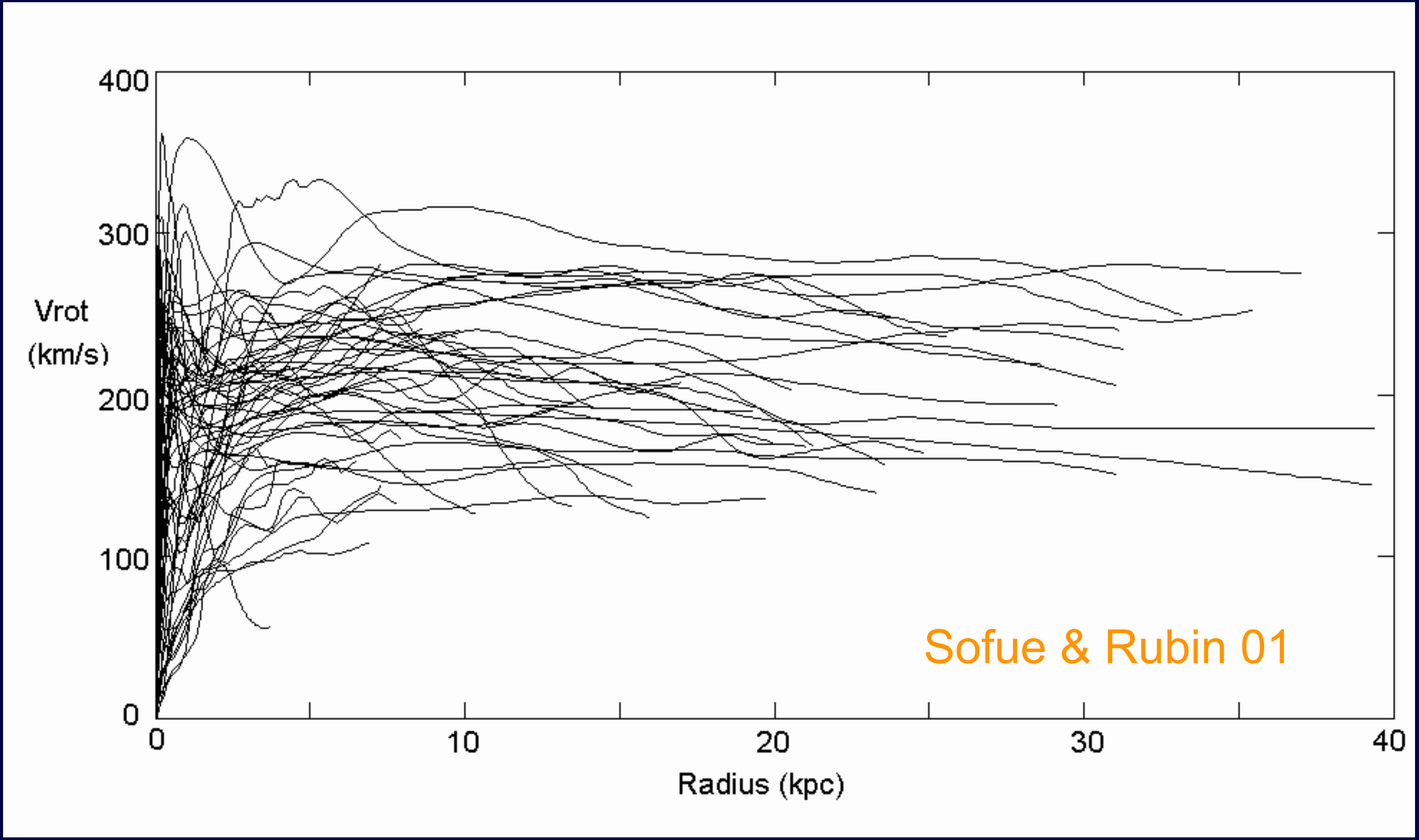


$$V^2 = \frac{GM(R)}{R} = \text{cst}$$

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

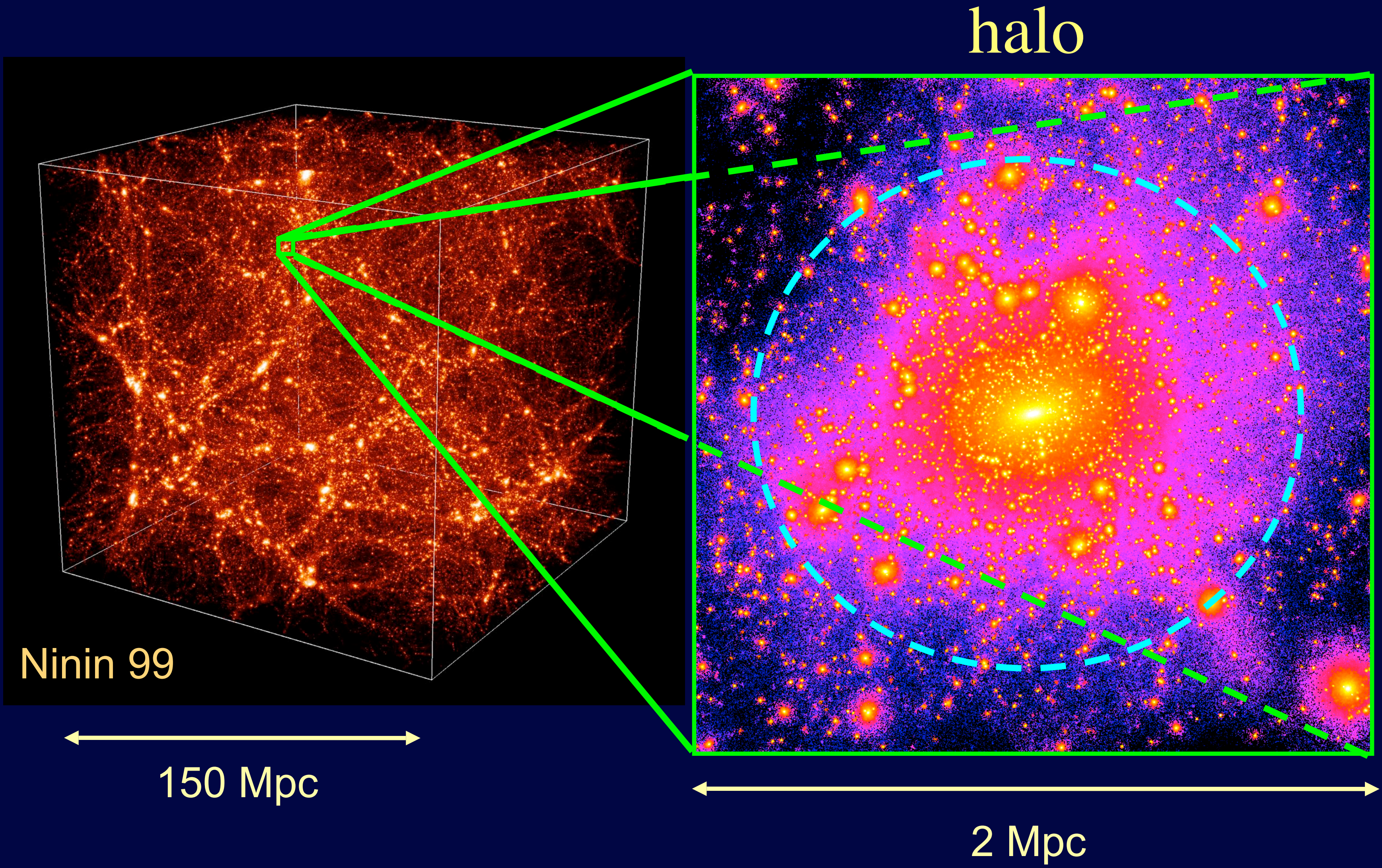
Ostriker, Peebles & Yahil 74; Einasto, Kaasik & Saar 74

Flat Rotation Curves in Spiral Galaxies



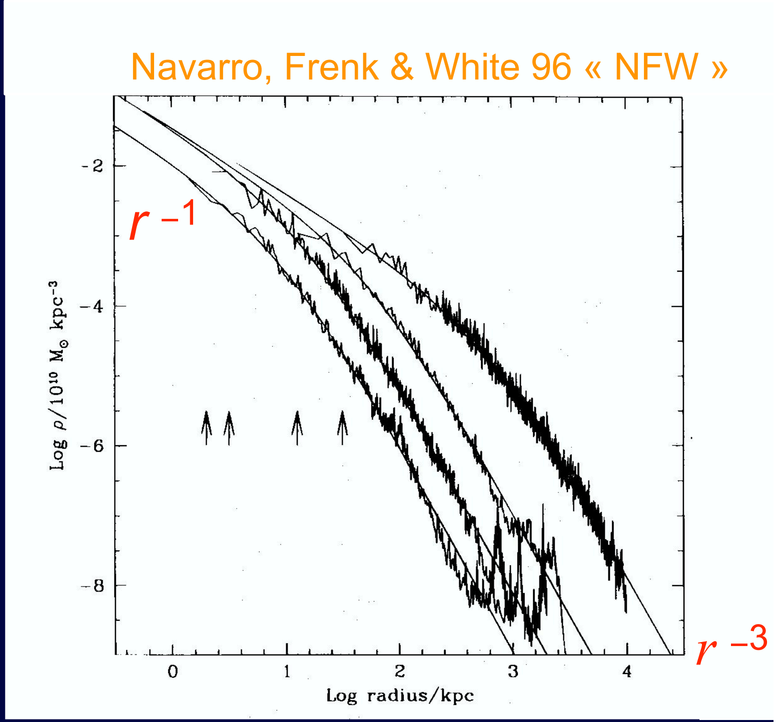
Sofue & Rubin 01

Cosmological N-body simulations



virial radius: mean density ≈ 100x critical density of Universe

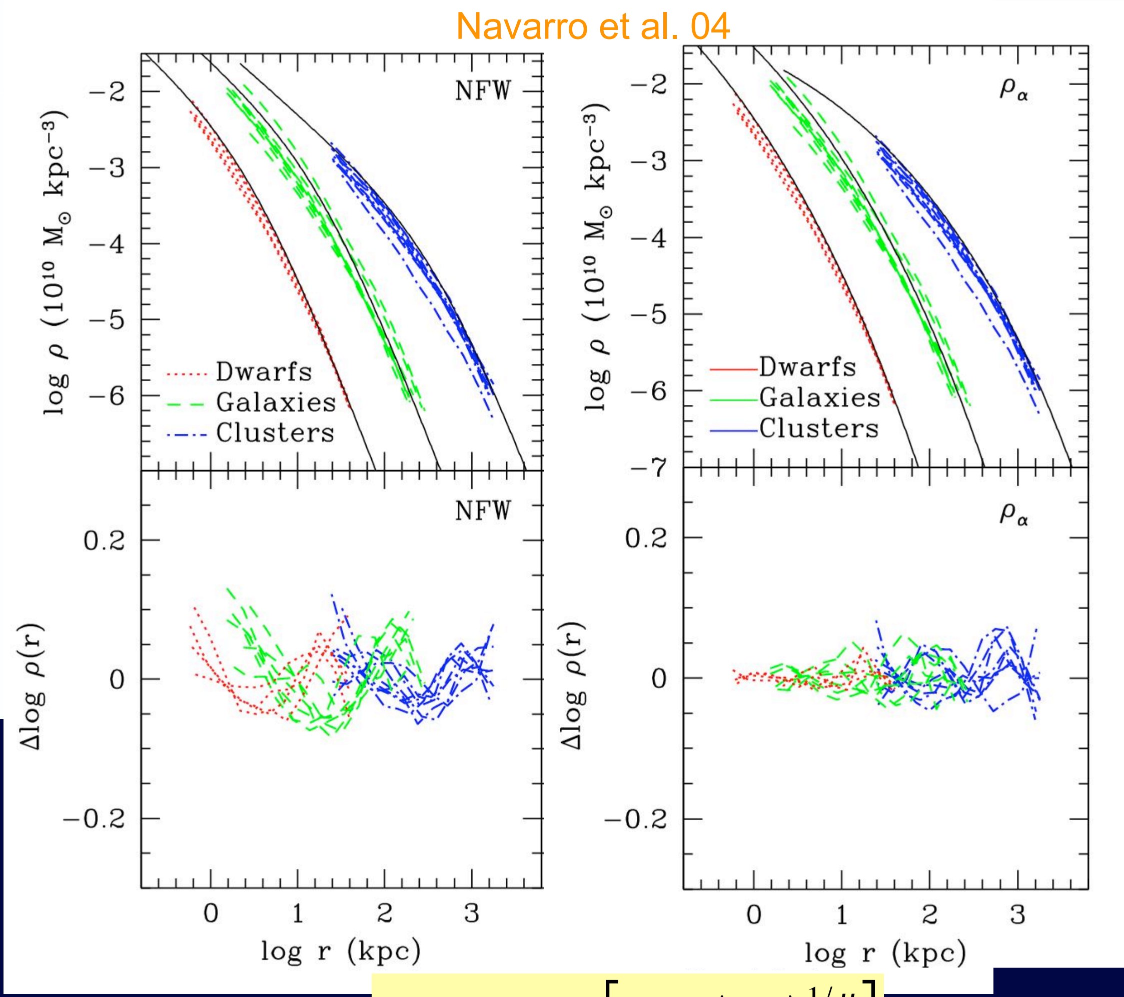
Density profiles in cosmological N body simulations


Navarro, Frenk & White 96 « NFW »

$$\rho(r) \propto \frac{1}{\left(r/r_{-2}\right)\left[1+\left(r/r_{-2}\right)\right]^2}$$

projected NFW ≈ *m*=3 Sérsic

Łokas & Mamon 01


Navarro et al. 04

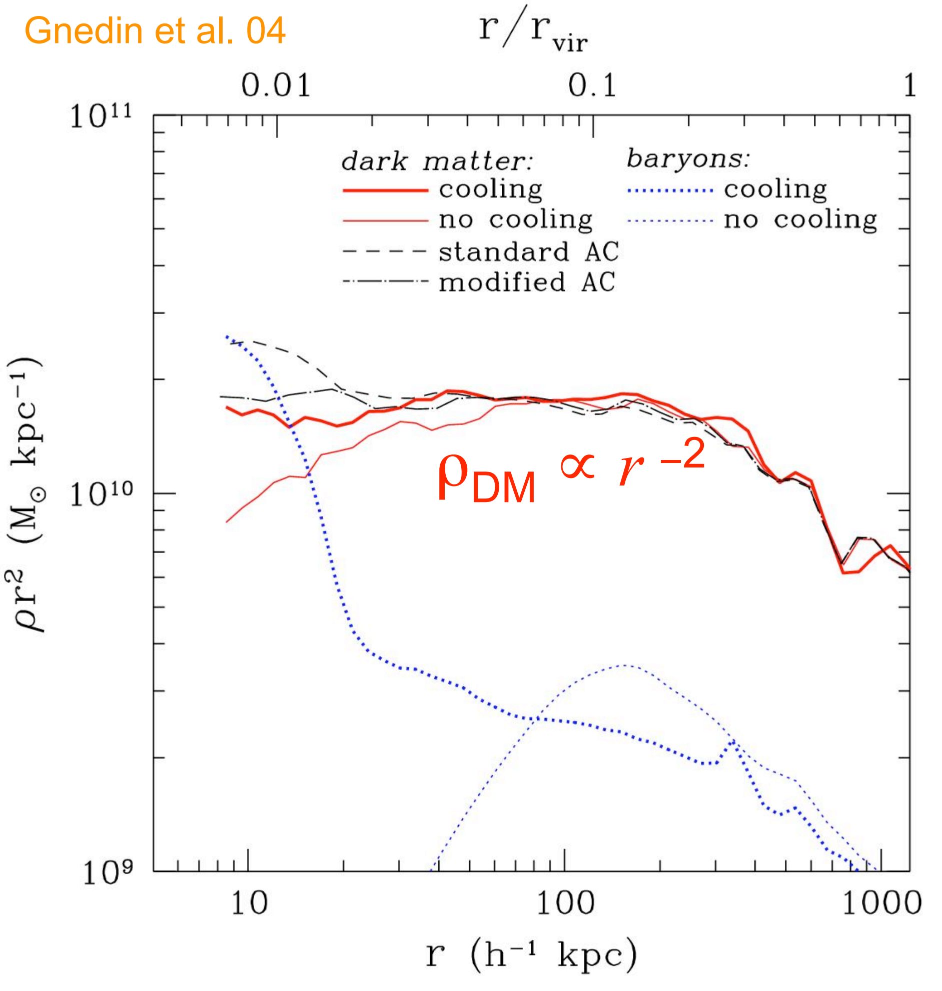
3D Sérsic

Einasto 65

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

Navarro et al. 04

Cosmological N-body simulations with gas



dark matter responds to the dominant baryons

effects of feedback?

Motivations

Nature of Dark Matter particles
Detectability of DM particles by γ rays from annihilation

Do galaxies have ΛCDM dark matter halos?

normalization

Is the dark matter (or total) density profile
as in cosmological simulations?

NFW? Einasto? $\propto r^{-2}$? *distribution*

Is concentration related to mass
as in cosmological simulations?
If not, what can we learn from the dissipative physics?

concentration

2) How to measure the radial distribution of dark matter

Dark Matter = Total Matter - Visible Matter

Mass Modeling Methods

Internal kinematics (motions)

BUT need to know orbital shapes (*velocity anisotropy*)

Hydrostatic equilibrium of hot diffuse X-ray emitting gas

Ellipticals: DM dominates $R > R_{\rm eff}$! Humphrey et al. 06

BUT
- no hot gas in dwarf spheroidals & low σ_v groups
- in ellipticals: often weak signal, confusion with stars

Weak gravitational lensing

BUT
- very weak signal (except in clusters): must stack
- requires distant objects

Weak lensing + internal kinematics

Ellipticals: $\rho_{\rm total} \propto r^{-2}$ out to $R_{\rm eff}$ Koopmans et al 06

BUT assume cst velocity anisotropy

Weak lensing + strong lensing

Ellipticals: out to 100 $R_{\rm eff}$! Gavazzi et al. 07

How to measure the radial distribution of total matter using internal motions

« Internal Kinematics »

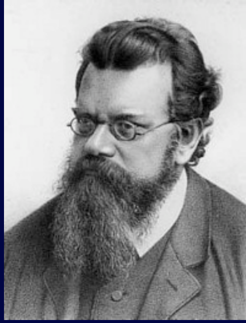
From phase space to local space

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

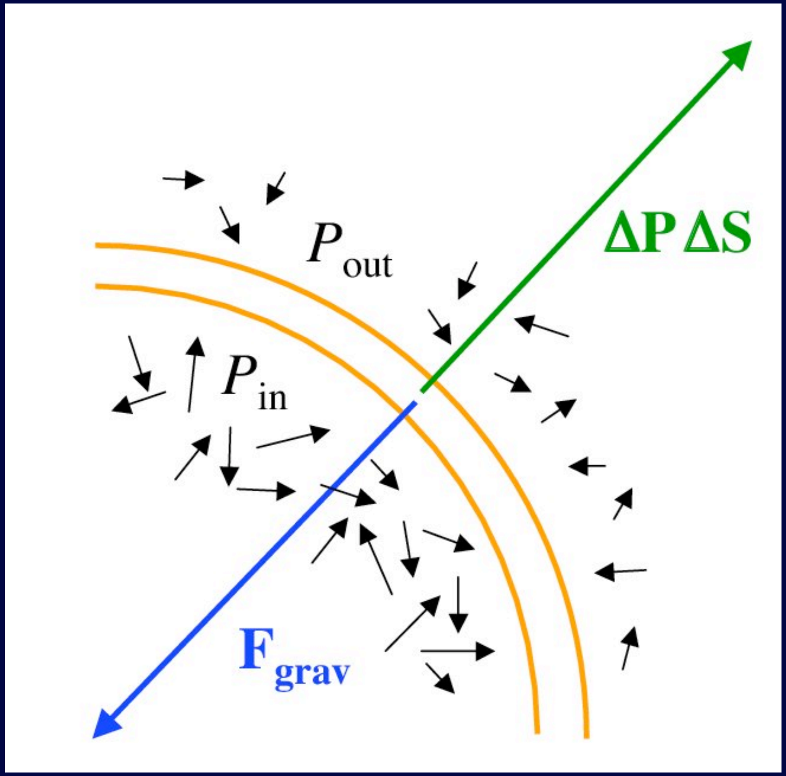
Collisionless Boltzmann Equation

incompressible 6D fluid

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



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

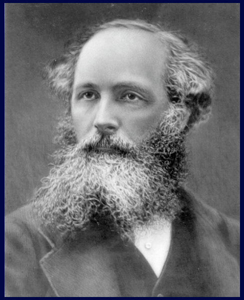


$$\nabla \bullet P = -\nu \nabla \Phi$$

Jeans Equation

tracer density

pressure (anisotropic)



Maxwell

Jeans

From local space to global properties

Jeans Equation

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

$$\int x_k \,\mathrm{Jeans}\, \mathrm{d}^3\mathbf{x}$$

Virial Equation

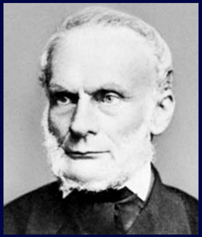
$$\cancel{\frac{1}{2}\frac{\mathrm{d}^2 I}{\mathrm{d}t^2}} + 2\,K + W = 0$$

moment of inertia

kinetic energy

potential energy

Virial Theorem



Clausius 1870

Chandrasekhar 53

Global kinematic analysis in Spherical Symmetry

Spherical, stationary, non-rotating:

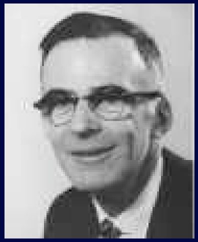
kinetic energy $\boxed{K = \frac{3}{2}\, M\, \sigma_{\rm v}^2}$

potential energy $\boxed{W = -\frac{G\, M^2}{r_{\rm G}}}$

gravitational radius ↑

$$\begin{aligned} M &= 3\, \frac{r_{\rm G}\, \sigma_v^2}{G} \\ &\simeq 7.5\, \frac{r_{1/2}\, \sigma_v^2}{G} \\ M(r_{1/2}) &\simeq 2.5\, \frac{R_{\rm eff}\, \sigma_{v,\rm ap}^2(R_{\rm eff})}{G} \\ M(r_{1/2}) &\simeq 4\, \frac{R_{\rm eff}\, \sigma_v^2}{G} \end{aligned}$$

Spitzer 69



Cappellari+06

Wolf+10

≈ independent of DM & β

Spherical stationary Jeans equation

tracer density

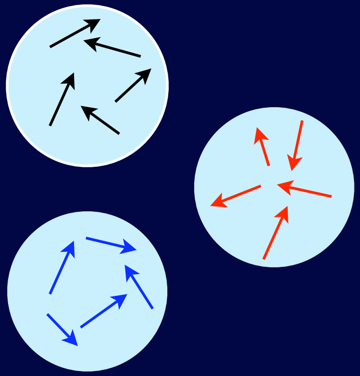
anisotropic dynamical pressure

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

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

= *velocity* anisotropy

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



⇨ Mass / Anisotropy Degeneracy

MAD

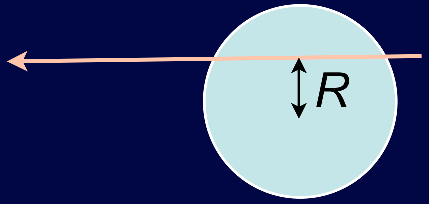
A) assume both $M(r)$ & $\beta(r)$ & fit the projected velocity dispersions

for $\beta = 0$

line-of-sight velocity dispersion

Tremaine et al. 94; Prugniel & Simien 97

surface density



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

kernels for other simple $\beta(r)$

Mamon & Łokas 05b

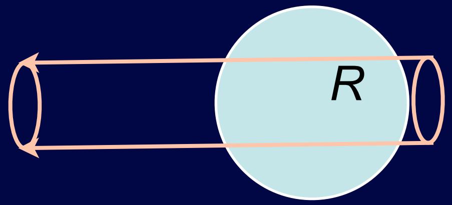
axisymmetric models

Cappellari 08

projected tracer mass

aperture velocity dispersion

Mamon & Łokas 05a



$$\frac{3}{4\pi G}M_2(R)\,\sigma^2_{\rm ap}(R) = \int_0^\infty r\,\nu\,M\,dr - \int_R^\infty \frac{\left(r^2-R^2\right)^{3/2}}{r^2}\,\nu\,M\,dr$$

B) assume either $M(r)$ or $\beta(r)$

given projected observations:

surface density $\Sigma(R)$

line of sight velocity dispersion $\sigma_{\rm los}(R)$

Anisotropy inversion

assume $M(r) \rightarrow \beta(r)$

Binney & Mamon 82
Tonry 83; Bicknell et al. 89
Solanes & Salvador-Solé 90
Dejonghe & Merritt 92

Mass inversion

assume $\beta(r) \rightarrow M(r)$

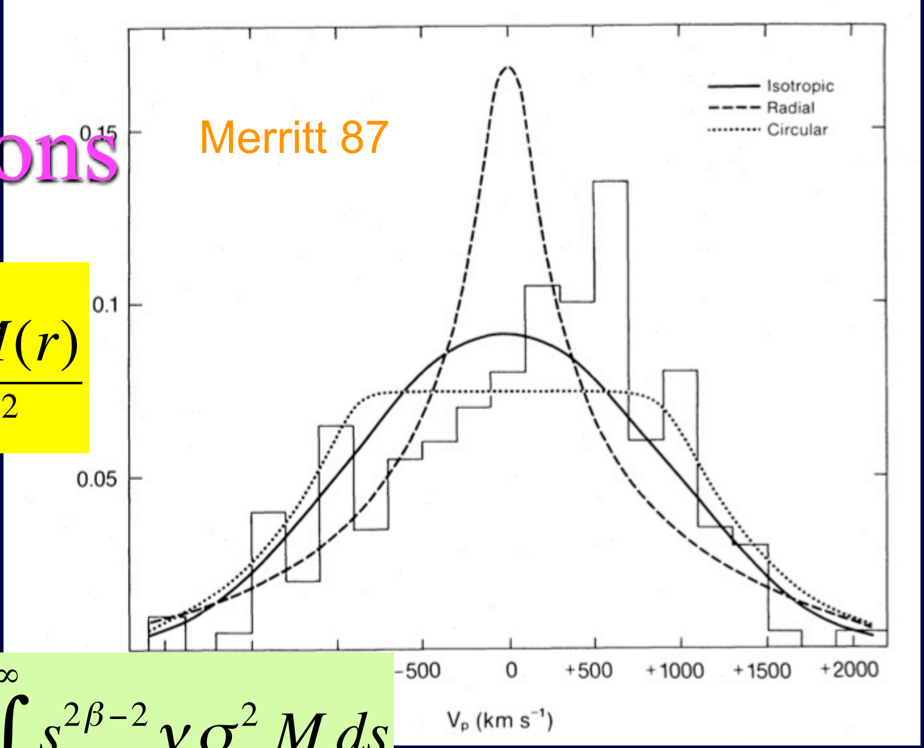
Mamon & Boué 10
Wolf et al. 10

C) combine dispersion & kurtosis assuming cst β

4th moment 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



Merritt 87

if β = cst

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

line of sight kurtosis

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

D) Fitting the distribution in projected phase space R, v_z

D1) Orbit modeling

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

continual updating of particle weights

Syer & Tremaine 94; de Lorenzi et al. 07

D2) distribution function modeling

Gerhard et al 98

Density in projected phase space Dejonghe & Merritt 92

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

what choice for $f(E,J)$?

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

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

Merritt & Saha 93

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

Three new methods

a) Mass inversion

Mamon & Boué 10; Wolf et al. 10

Kinematic deprojection & mass inversion
of spherical systems with known anisotropy

anisotropic kinematic projection

$$P(R) = 2\int_R^\infty \left(1-\beta\frac{R^2}{r^2}\right) p \frac{r\,dr}{\sqrt{r^2-R^2}}$$

deprojection

$$(1-\beta)\,p = \int_r^\infty K[\beta(s)] \int_s^\infty \frac{dP}{dR}\,\frac{R\,dR}{\sqrt{R^2-r^2}}$$

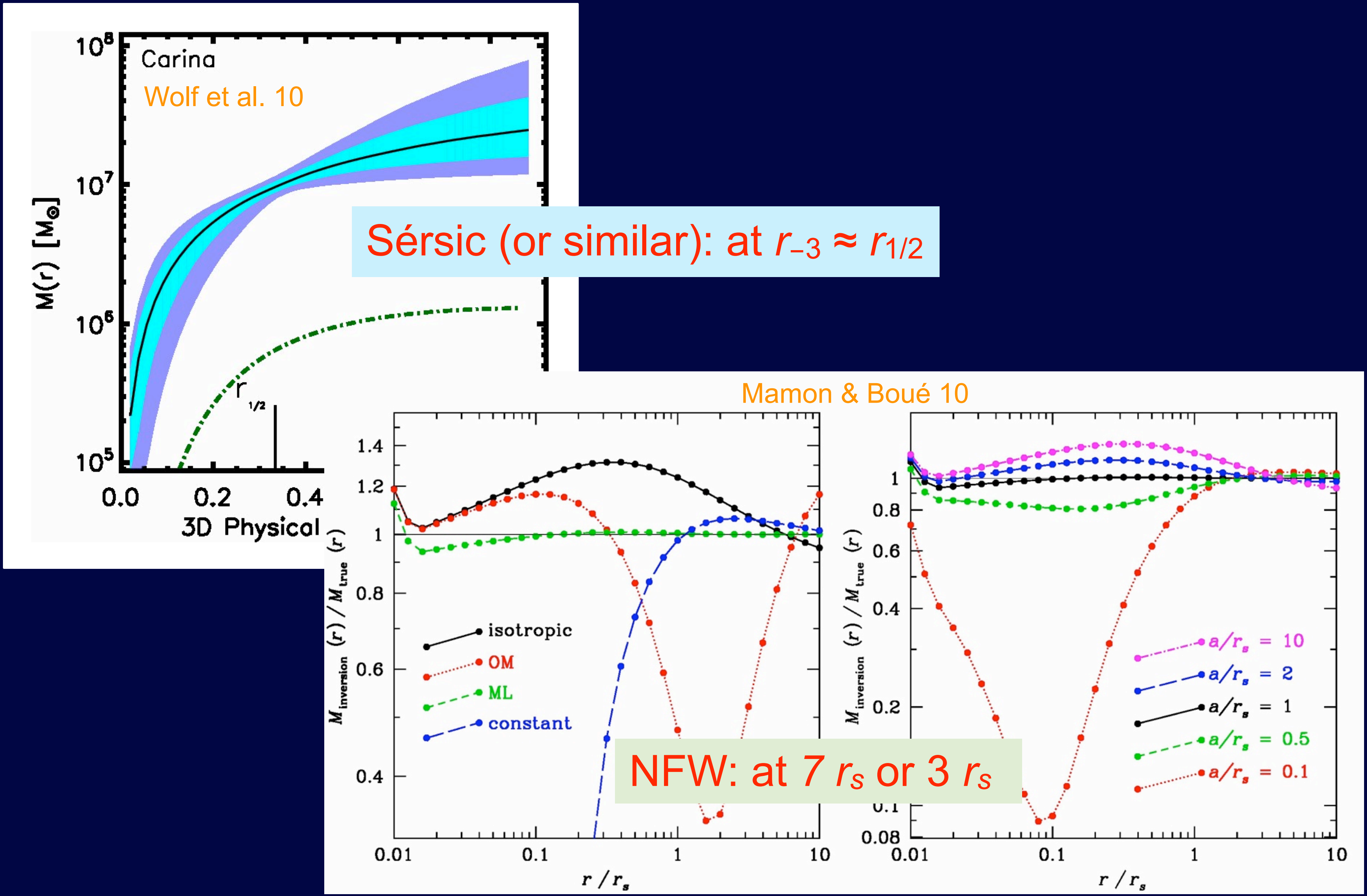
$P = \Sigma\, \sigma_{\rm los}^2$ = (observed) “projected pressure”

$p = \rho\, \sigma_r^2$ = dynamical pressure

$$\rho v_c^2 = -p' - 2\,\frac{\beta}{r}\,p$$

insert dynamical pressure into Jeans equation → mass profile

Radius where mass is independent of anisotropy



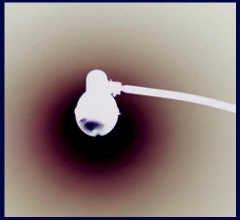
Wolf et al. 10

Mamon & Boué 10

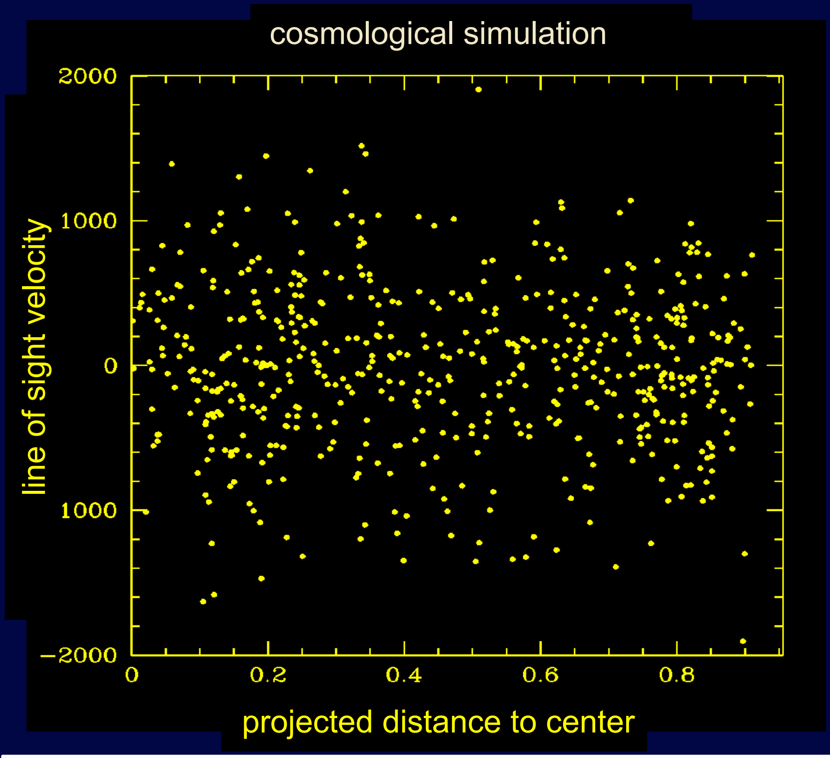
Sérsic (or similar): at $r_{-3} \approx r_{1/2}$

NFW: at 7 r_s or 3 r_s

b) [D3] MAMPOSSt: Modeling Anisotropy & Mass Profiles of Observed Spherical Systems



Mamon, Biviano & Boué, in prep.



assume radial profiles:

$M_{\mathrm{tot}}(r)$, $\nu(r)$, $\beta(r)$, $\{v\}(r)$

$$p(v_z|R) = \frac{\sqrt{2/\pi}}{\Sigma(R)} \int_R^\infty \frac{r\,\nu}{\sqrt{r^2-R^2}} \, \frac{(1-\beta R^2/r^2)^{-1/2}}{\sigma_r} \exp\left[-\frac{v_z^2}{2(1-\beta R^2/r^2)\,\sigma_r^2}\right] dr$$

$$\sigma_z^2(R,r) = \left[1-\beta\left(\frac{R}{r}\right)^2\right]\sigma_r^2(r)$$

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

dispersion-kurtosis
Sanchis, Łokas & Mamon 04

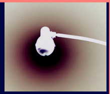
10 halos × 3 projections (400 pts / halo)

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

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

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

MAMPOSSt



Mamon, Biviano & Boué in prep.

11 halos × 3 projections (500 pts / halo)

$$\Delta \log M_{200} = 0.00 \pm 0.08$$

$$\Delta \log c = 0.06 \pm 0.19$$

$$\Delta \log \left(\frac{\sigma_r}{\sigma_\theta}\right) = -0.02 \pm 0.08$$

→ 18% accurate mass normalization, uncertain concentration

c) [D4] Distribution function modeling

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

Dejonghe & Merritt 92

ΛCDM halos:

$$f = f(E,J) = f_E(E)\, J^{2(\beta_\infty-\beta_0)} \left(1+\frac{J^2}{r_a^2 v_a^2}\right)^{-\beta_0}$$

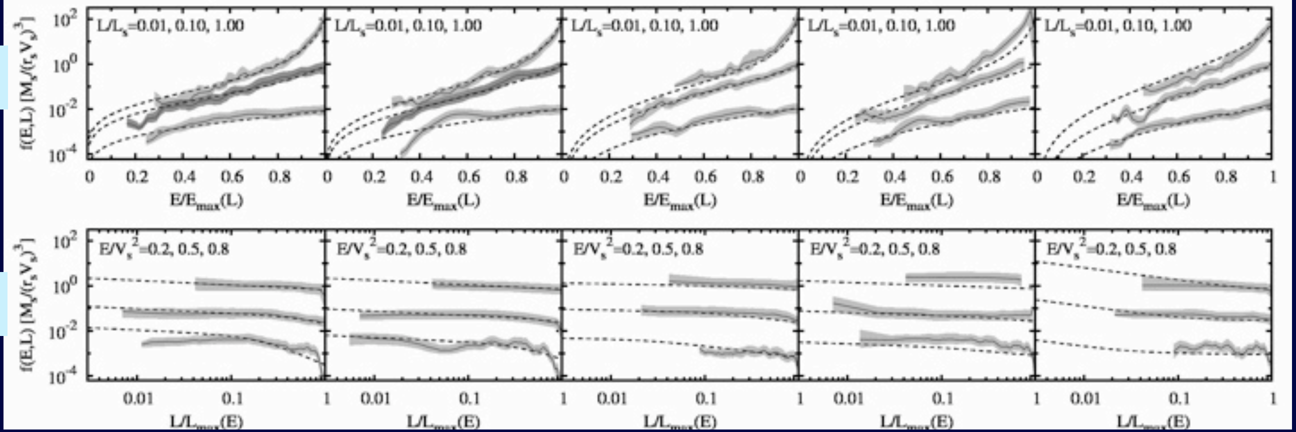
Wojtak, Łokas, Mamon, et al. 08

analysis in projection

Wojtak, Łokas, Mamon, et al. 09

5 ΛCDM halos

Wojtak, Łokas, Mamon, et al. 08



DF vs energy

DF vs angular momentum

5 ΛCDM halos

Wojtak, Łokas, Mamon, et al. 08

DF vs energy

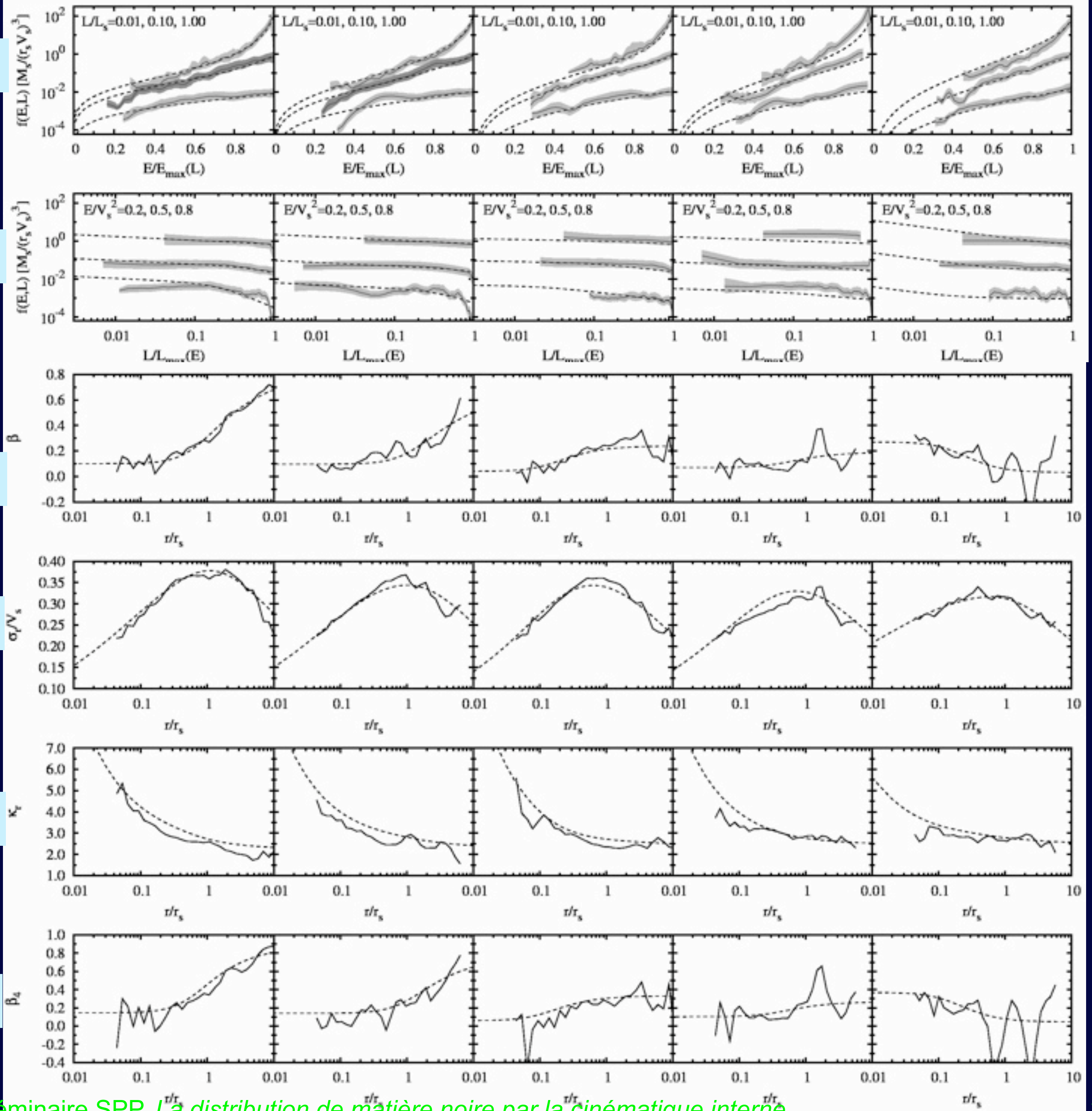
DF vs angular momentum

anisotropy

radial velocity dispersion

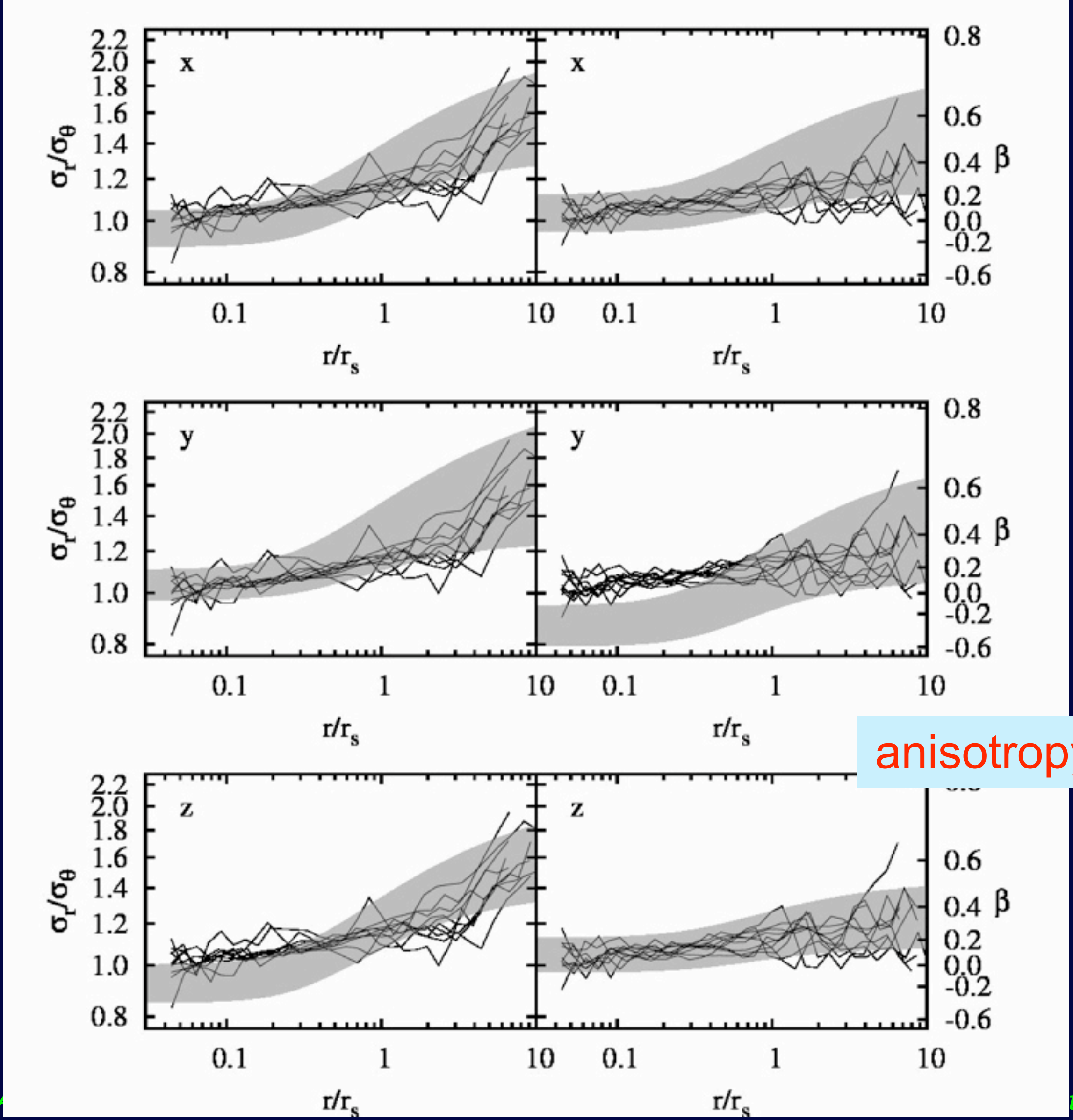
radial velocity kurtosis

4th order anisotropy



2D analysis:
Tests on 2 sets of 10 simulated clusters

Wojtak, Łokas, Mamon, et al. 09

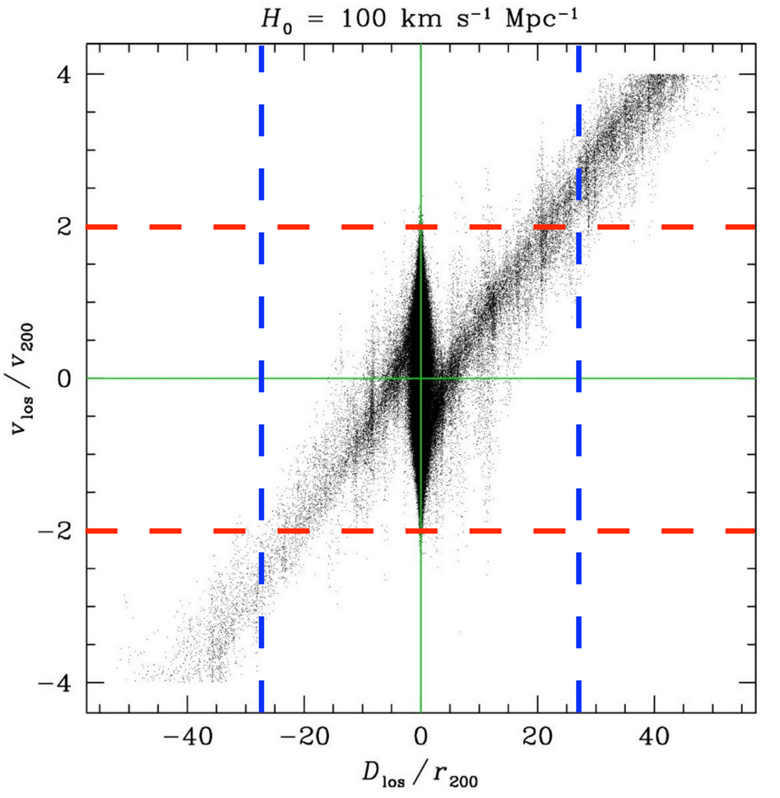


anisotropy profiles ≈ recovered

Does the Hubble Flow affect the kinematical mass modeling?

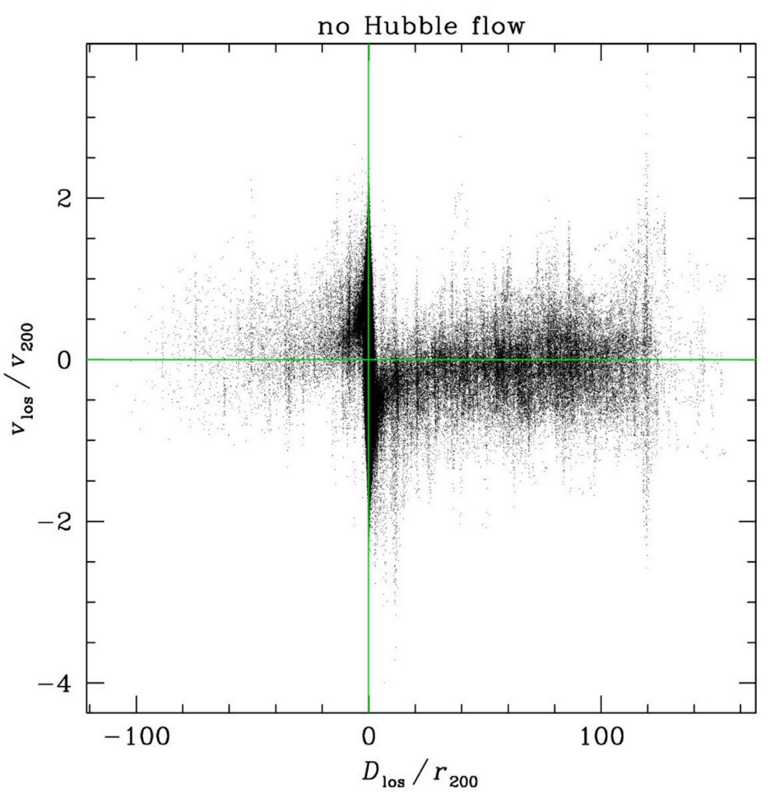
Mamon, Biviano & Murante 10, A&A in press

Hubble flow distortion



line-of-sight velocity

line-of-sight distance



line-of-sight velocity

line-of-sight distance

Hubble flow:

- $\pm 3\sigma_v$ cuts ~all particles beyond ~27 r_{200}
- what effect on projected phase space?

deprojection equations assume H_0=0!

Bias in cluster concentration?

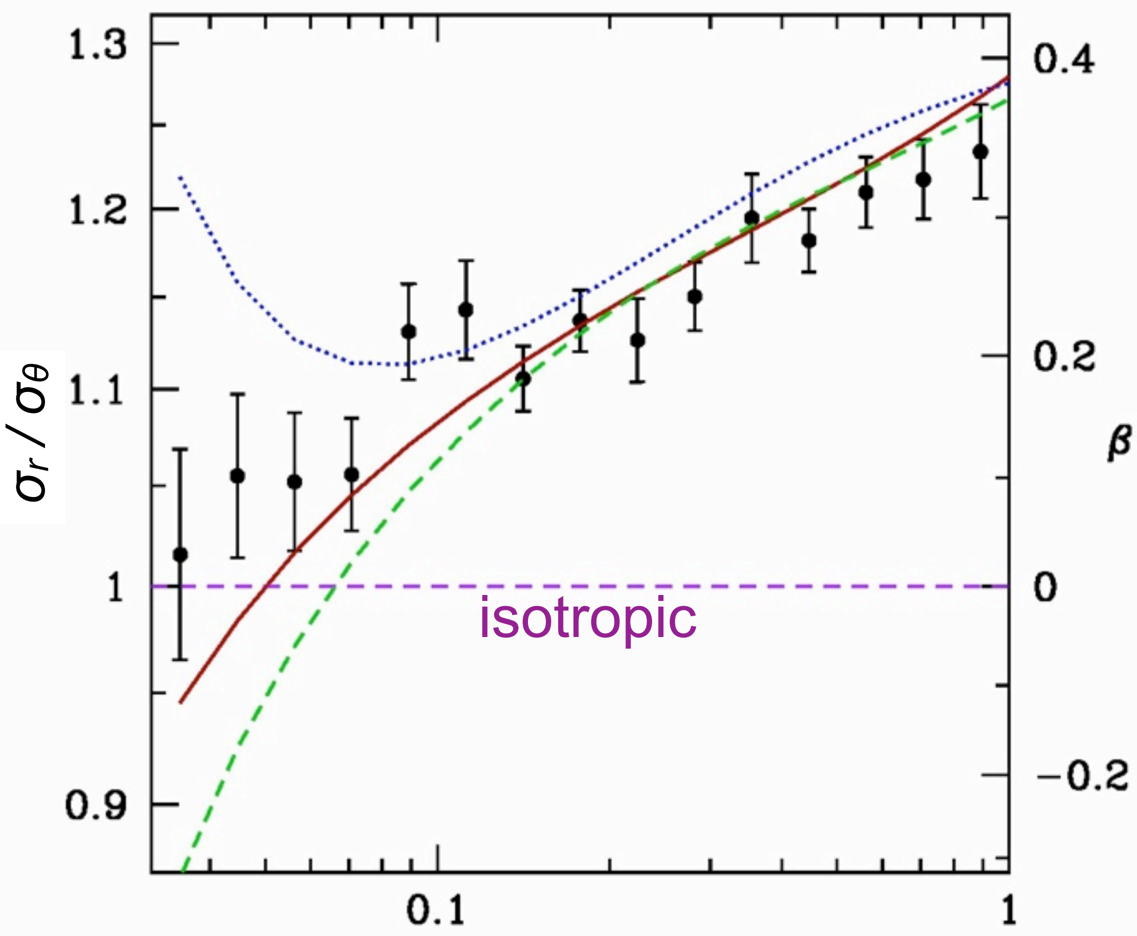
concentration from 2D fits from 0.03 to 1 r_{200}
in terms of best-3D-fit concentration
(both on stack of 93 clusters)

Model	no v-cut no bg	no v-cut with bg	v-cut no bg	v-cut with bg
NFW	0.86	1.00	0.96	1.02
m=5 Einasto	0.82	0.97	0.93	0.98
Einasto free *m*	0.84	0.96	0.95	0.97

Biases are negligible with velocity cut or background or both

Bias in velocity anisotropy?

Mamon, Biviano & Murante 10



slight tangential bias in outer regions

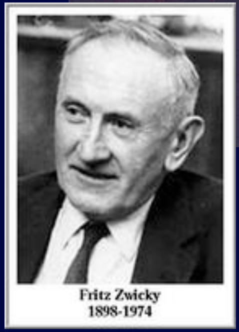
3) Dark matter in clusters of galaxies

Application to galaxy clusters

Coma cluster

Virgo cluster


© Anglo-Australian Observatory/ Royal Observatory, Edinburgh


Fritz Zwicky
1898-1974

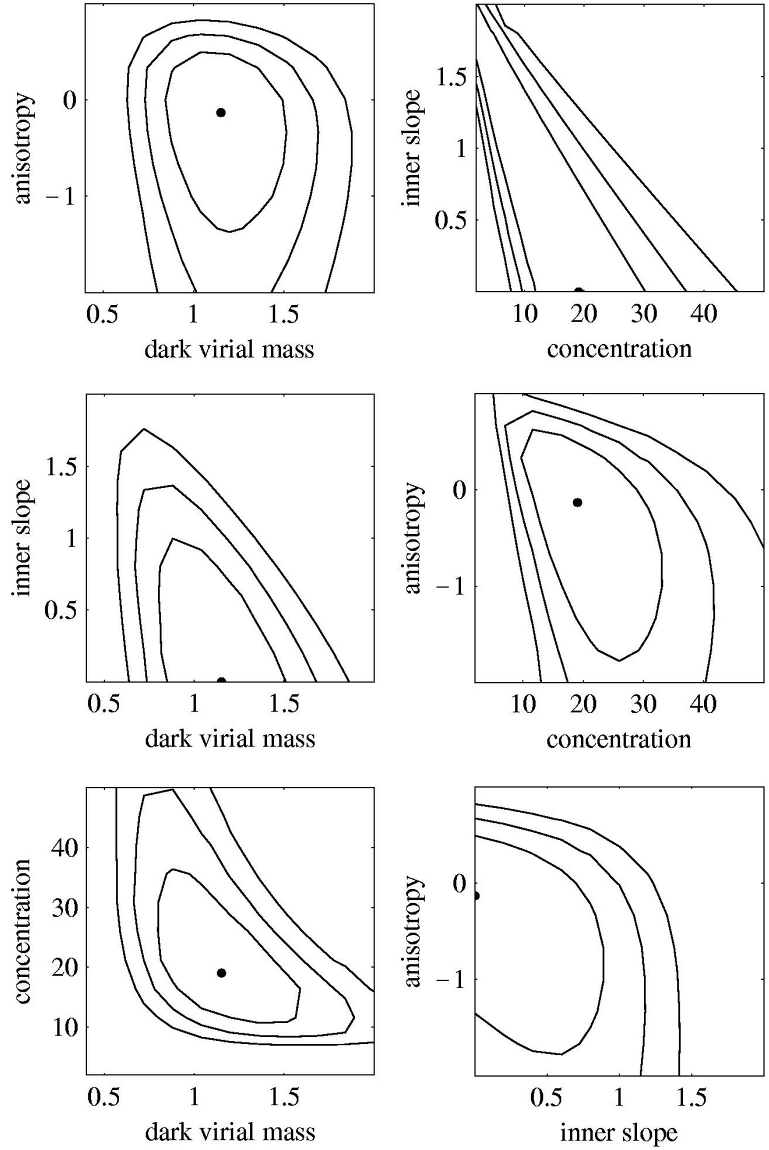
Zwicky 35

Smith 37

→ $$\boxed{\frac{M_{\mathrm{VT}}}{L} \gg \frac{M_{\mathrm{stars}}}{L}}$$ → dark matter!

Partially lifting the anisotropy / mass degeneracy: joint fits to velocity dispersion & kurtosis profiles

Łokas & Mamon 03



isotropic fits best!

cusp and core
both agree with data

NFW: $\boxed{c = \frac{r_{100}}{r_s} \approx 9.4}$

vs.

- $c = 6$ (cosmo sims) Bullock et al. 01
- $c = 5.5$ (stacked 2dFGRS)

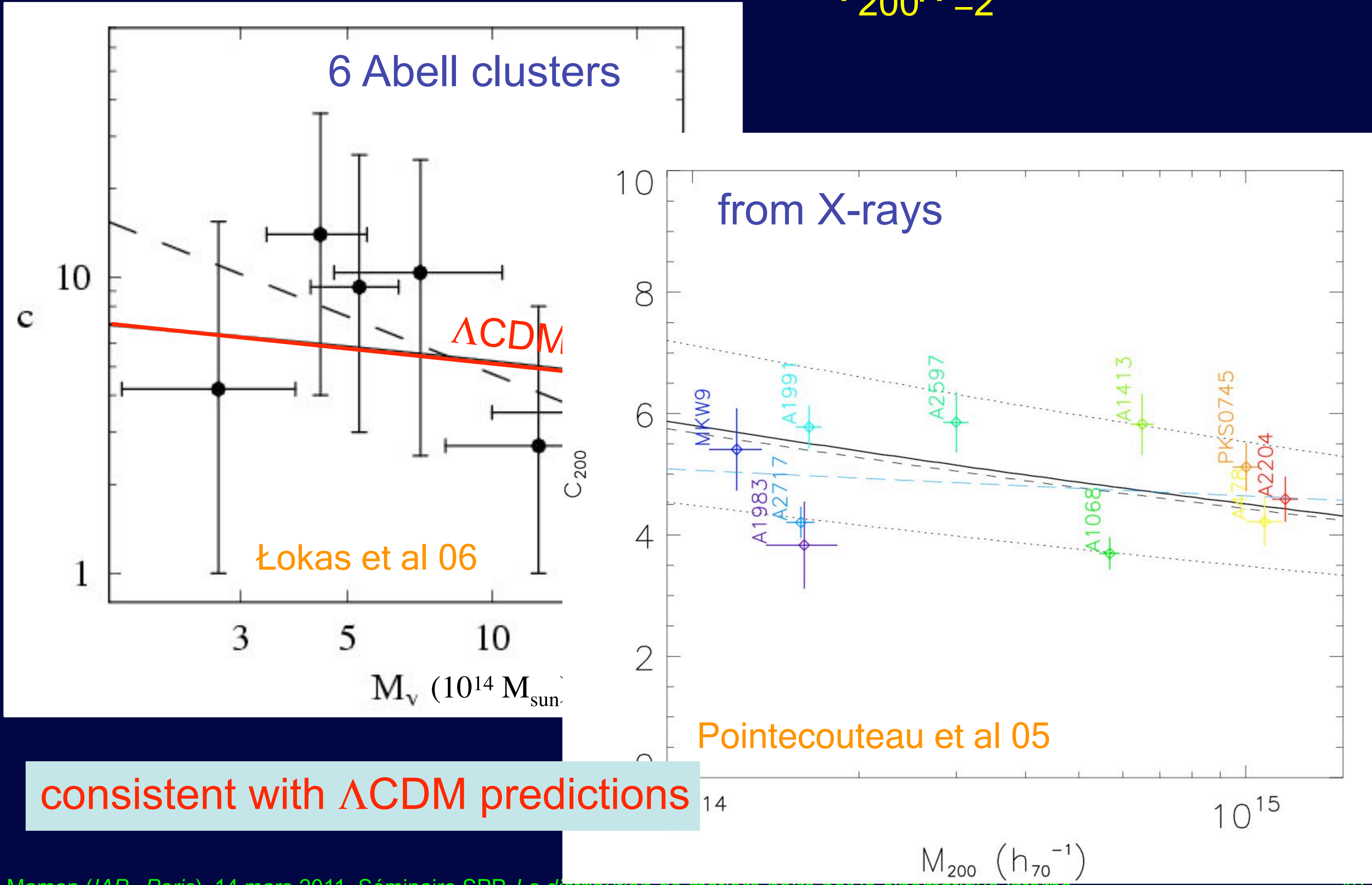
Biviano & Girardi 03

- $c = 4$ (stacked ENACS)

Katgert, Biviano & Mazure 04

Cluster concentration vs. mass

$= r_{200}/r_{-2}$

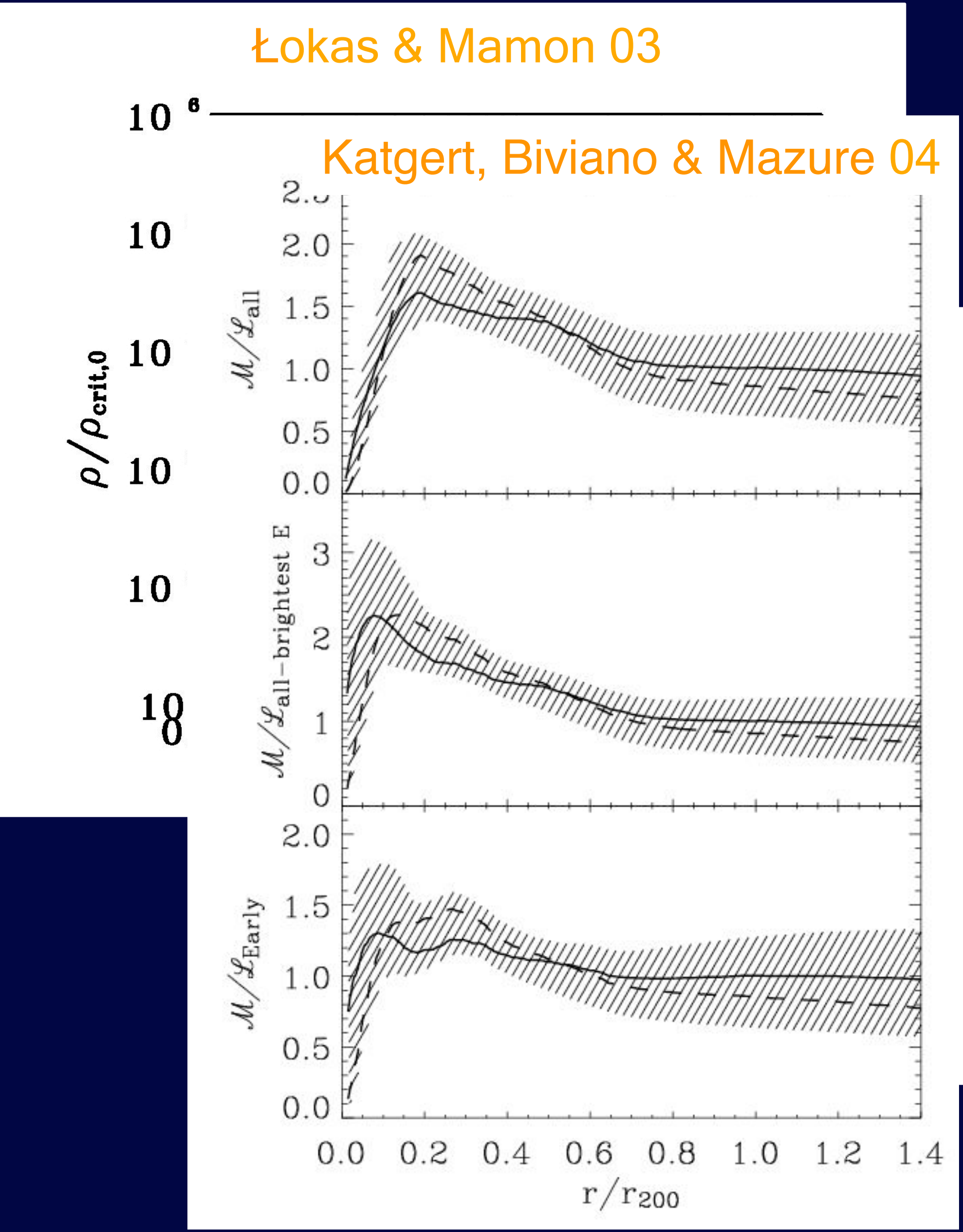


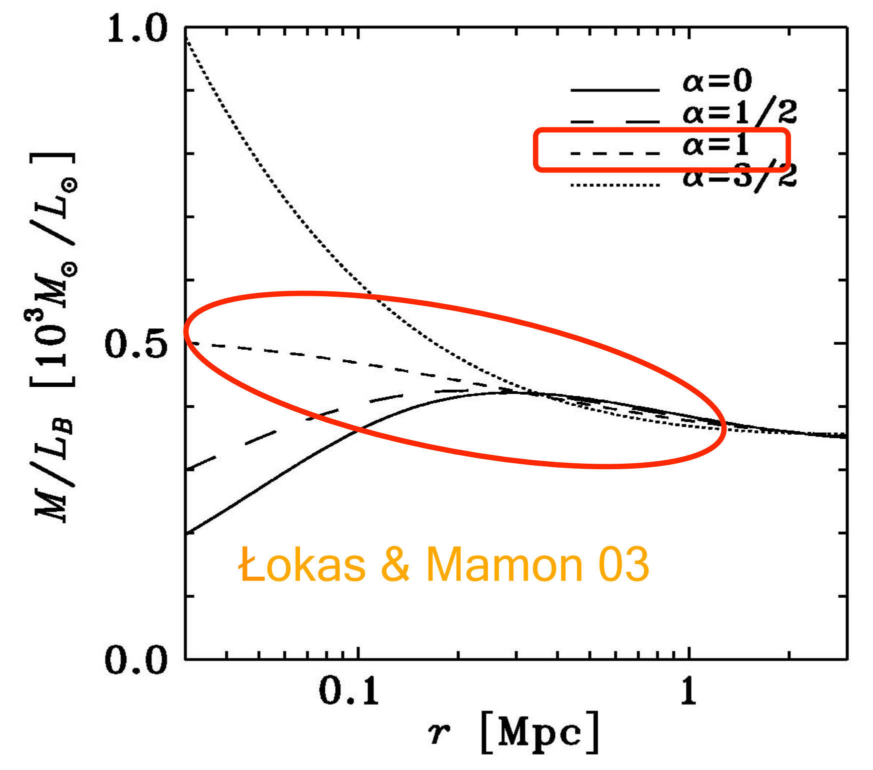
consistent with ΛCDM predictions

Best-fit density, mass & M/L profiles

Łokas & Mamon 03

Katgert, Biviano & Mazure 04

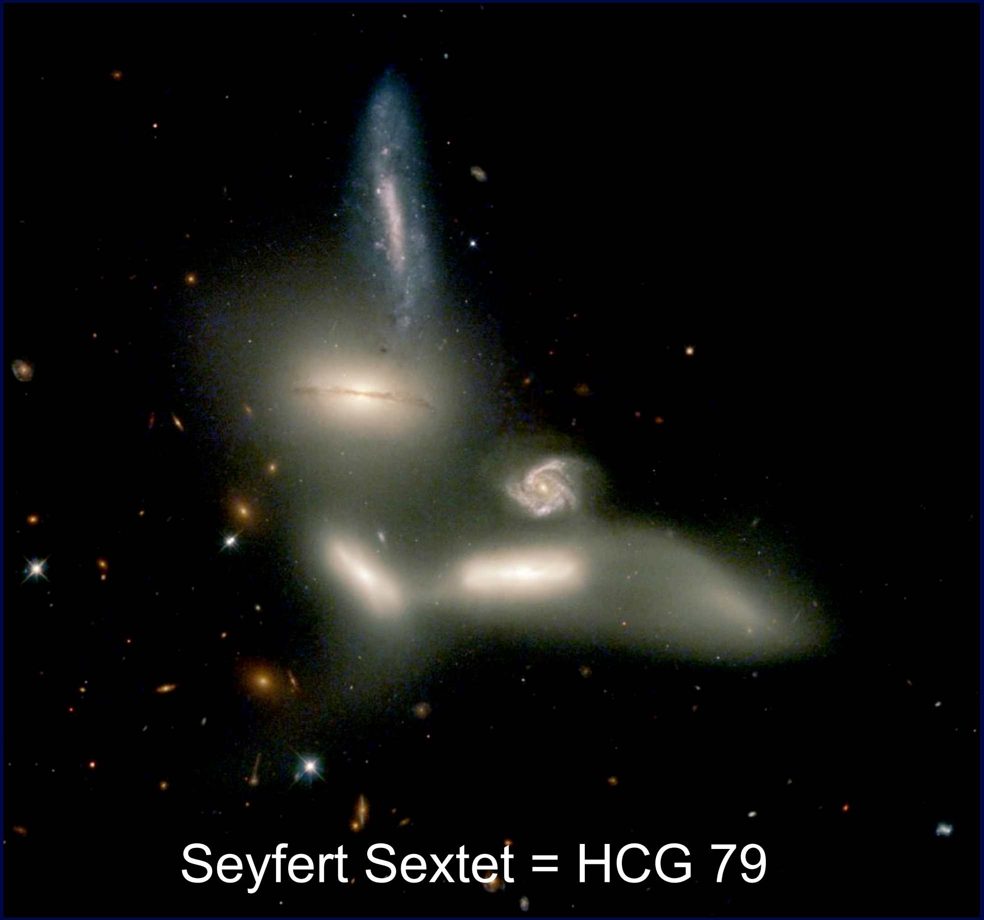




Łokas & Mamon 03

M/L ≈ cst

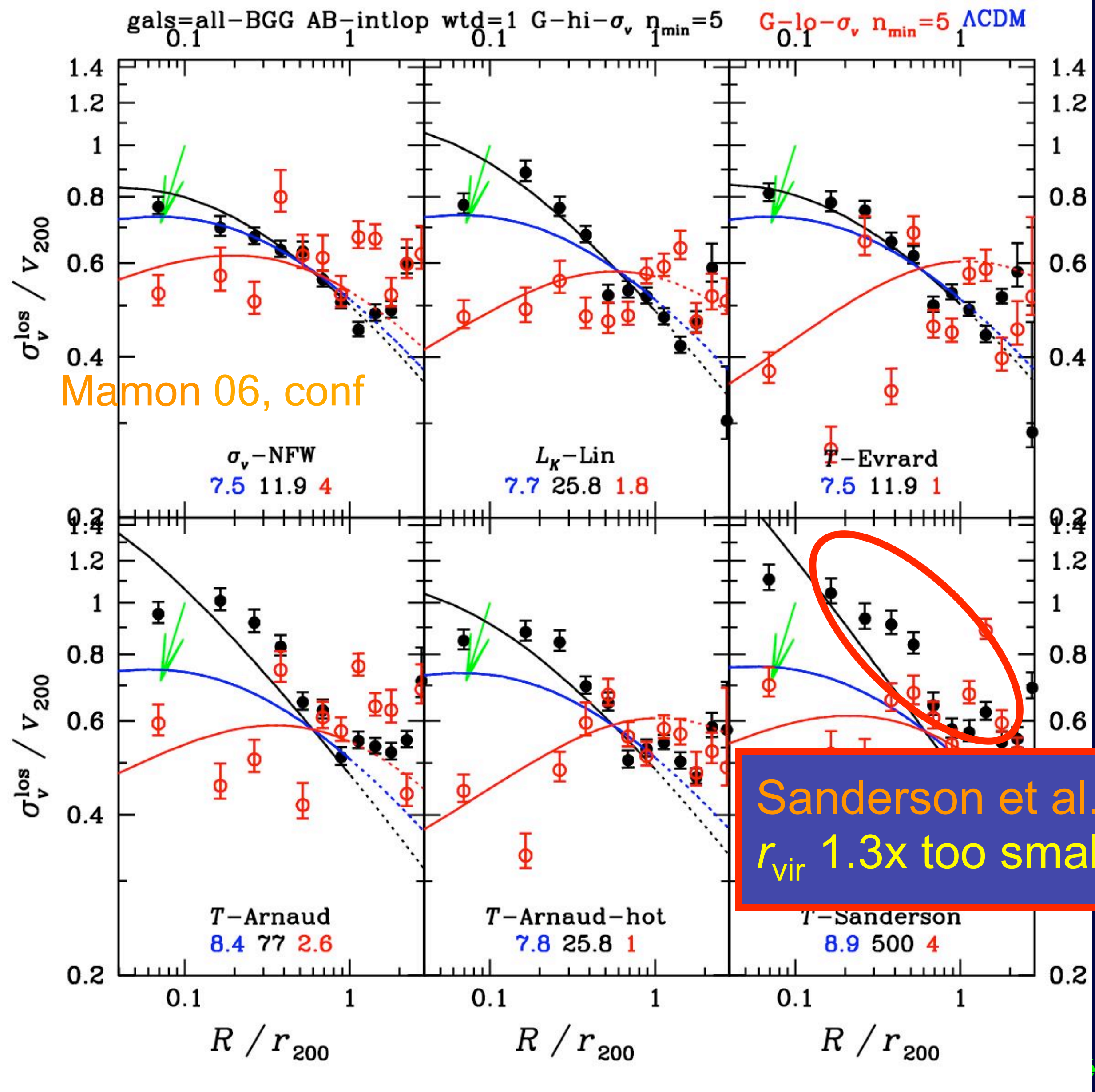
4) Dark Matter in Groups of Galaxies


Seyfert Sextet = HCG 79

X-ray selected groups

with Andrea BIVIANO (Trieste) &
Trevor PONMAN (Birmingham)

Line-of-sight velocity dispersion profiles of groups: effect of global velocity dispersion



Mamon 06, conf

low σ_v (< 300 km/s) groups:

shallower $\rho(r)$

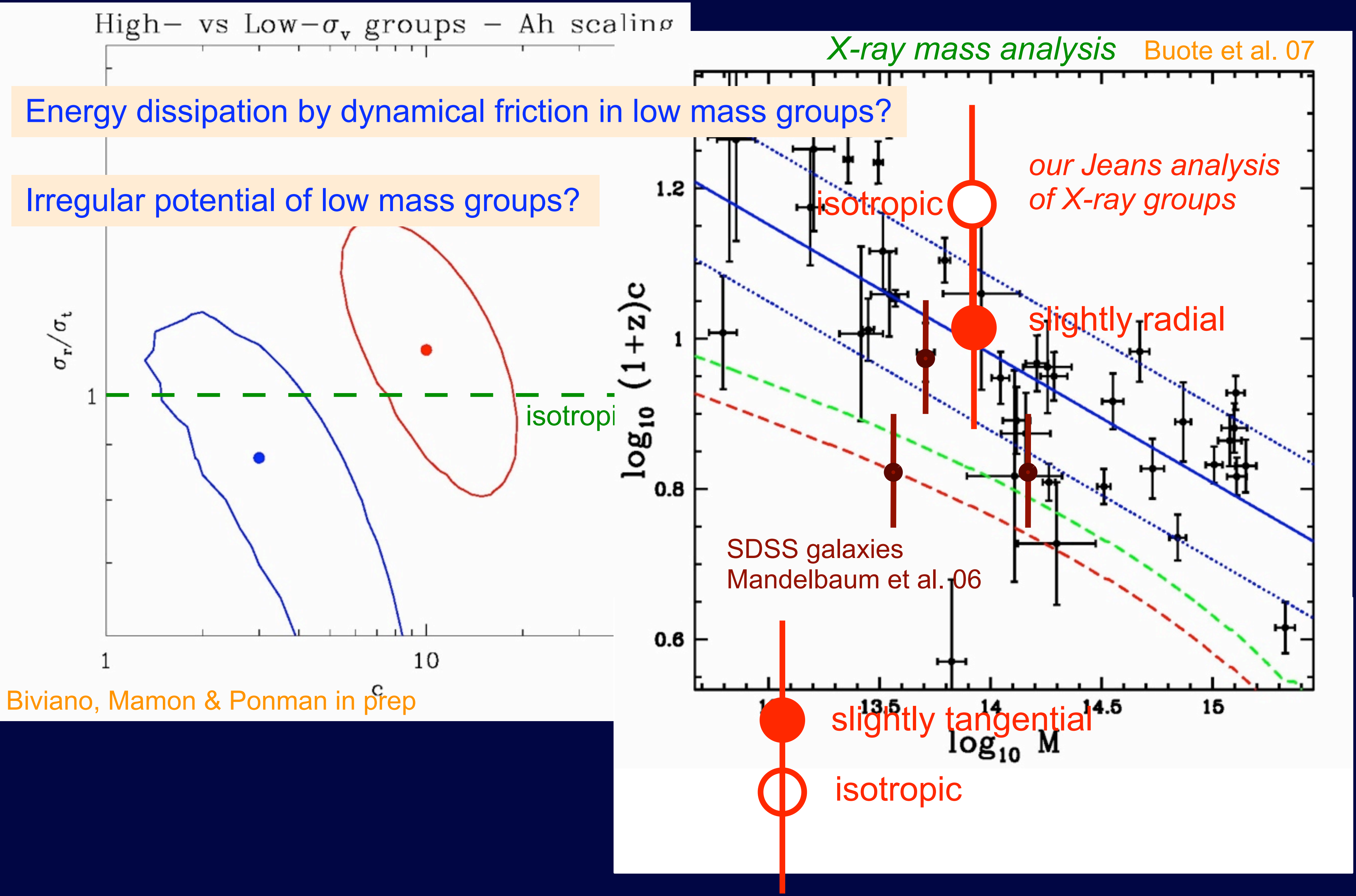
OR

tangential orbits

Sanderson et al.:

r_{vir} 1.3x too small $\Rightarrow$ M_{vir} 2x too small

Concentration vs. Mass



Energy dissipation by dynamical friction in low mass groups?

Irregular potential of low mass groups?

Biviano, Mamon & Ponman in prep

X-ray mass analysis Buote et al. 07

our Jeans analysis of X-ray groups

isotropic

slightly radial

SDSS galaxies
Mandelbaum et al. 06

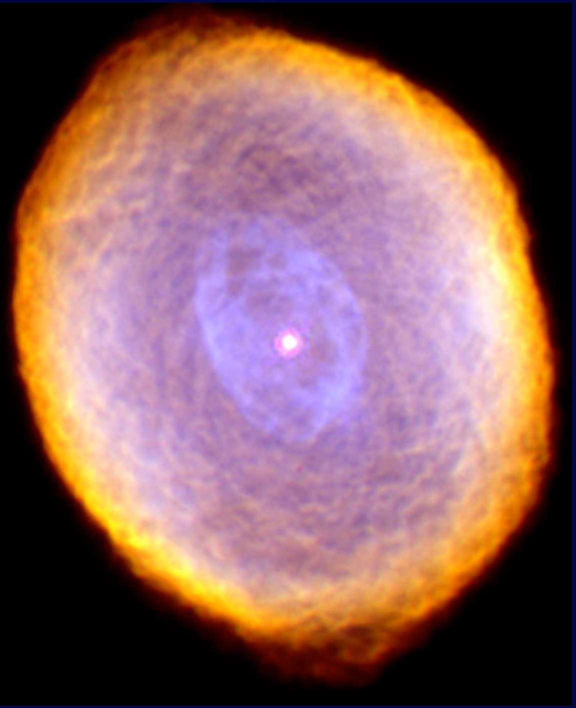
slightly tangential

isotropic

5) Do Elliptical Galaxies have dark matter halos?

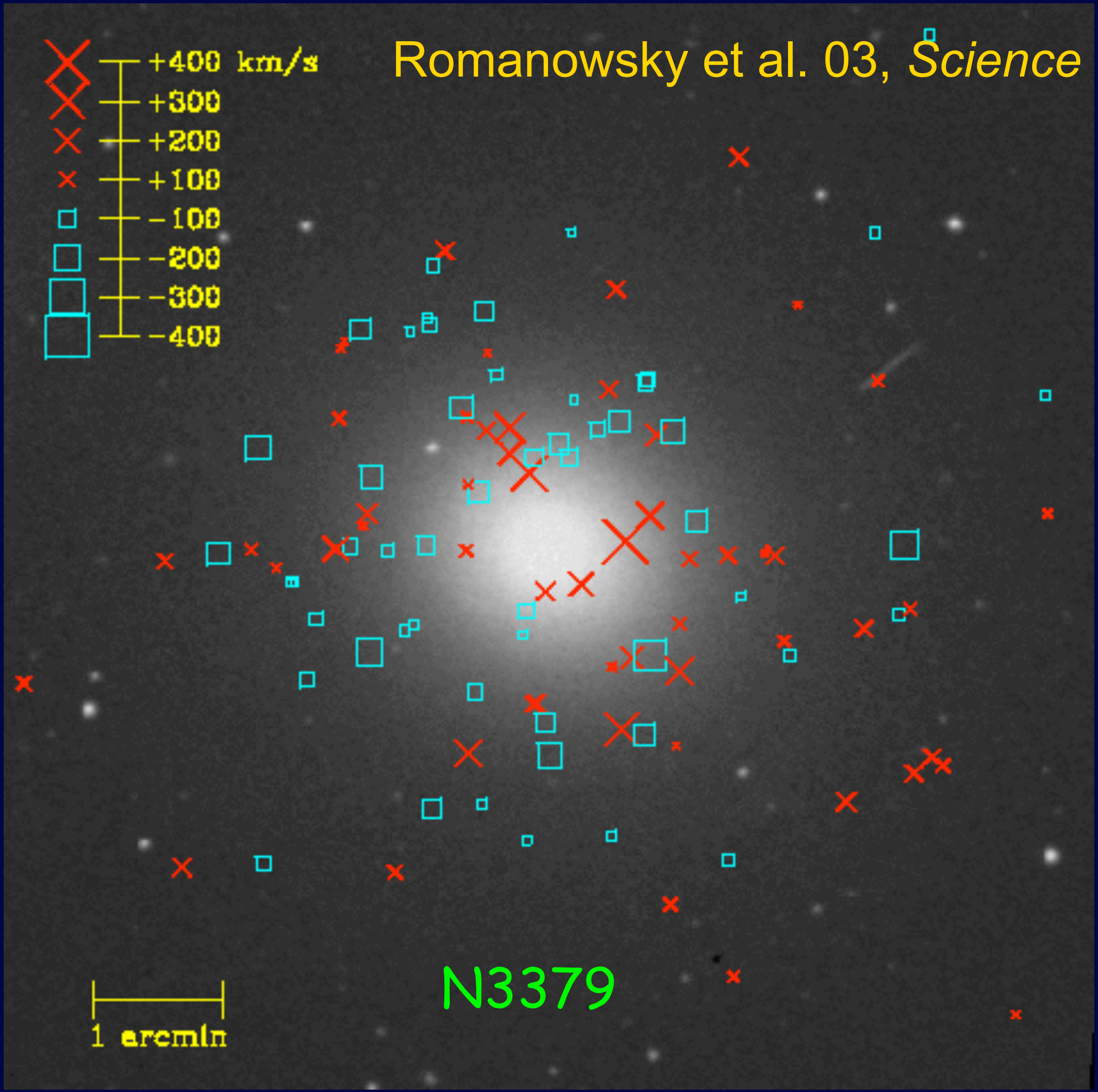
NGC 3379 = M105

Planetary Nebulae: Tracers at 1-4R_{eff}



[OIII]

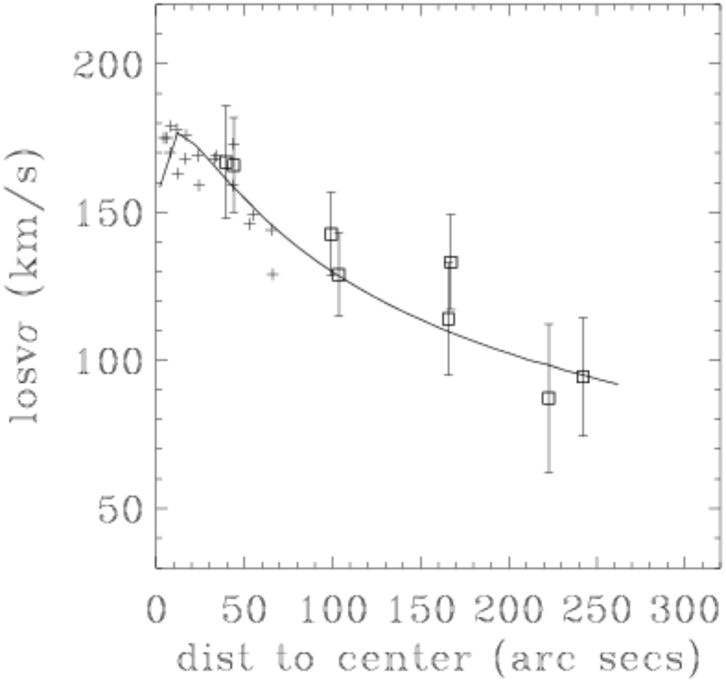
5007 A



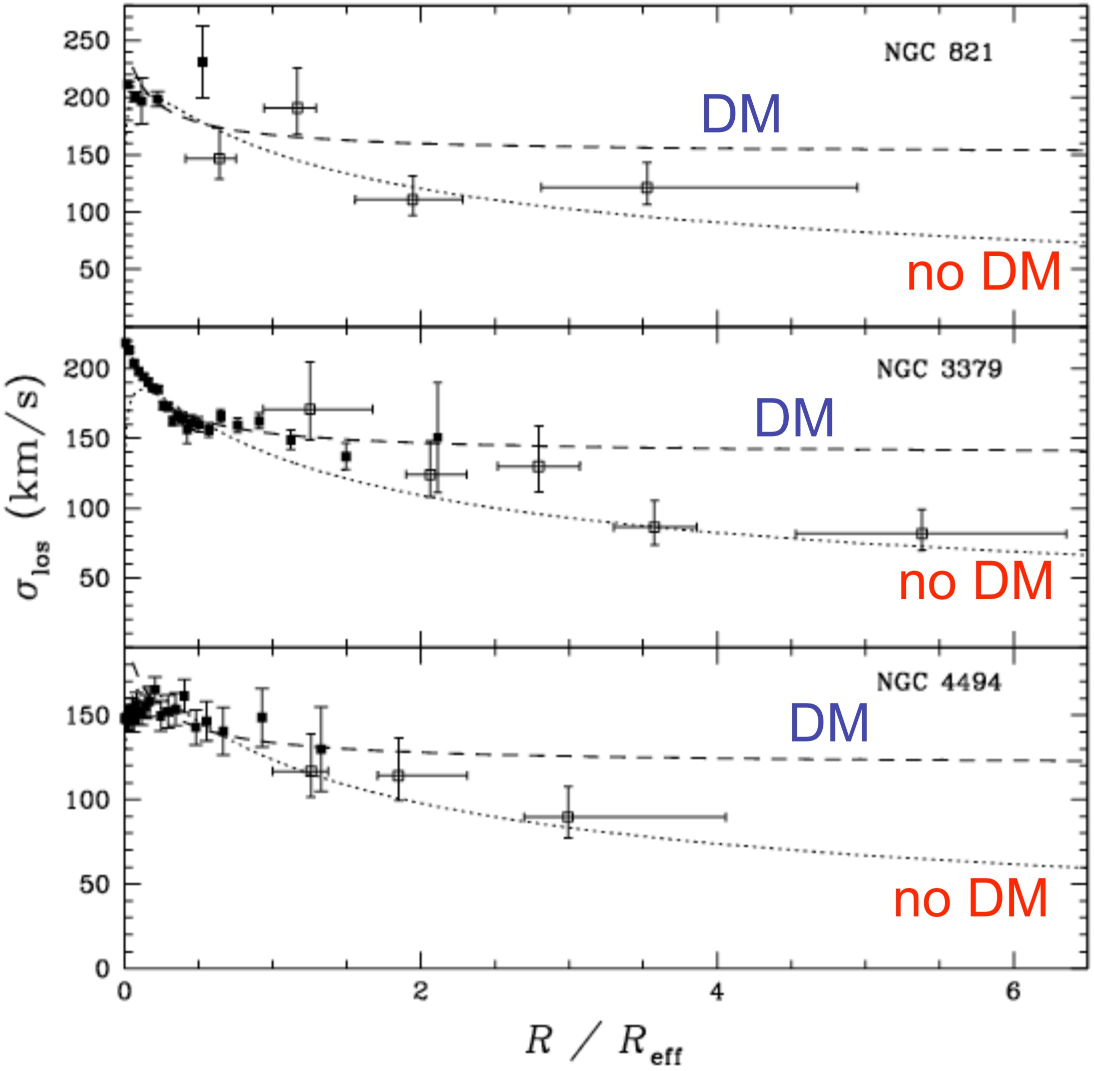
Romanowsky et al. 03, *Science*

PN velocity dispersions are low

Mendez et al. 01



Romanowsky et al. 03



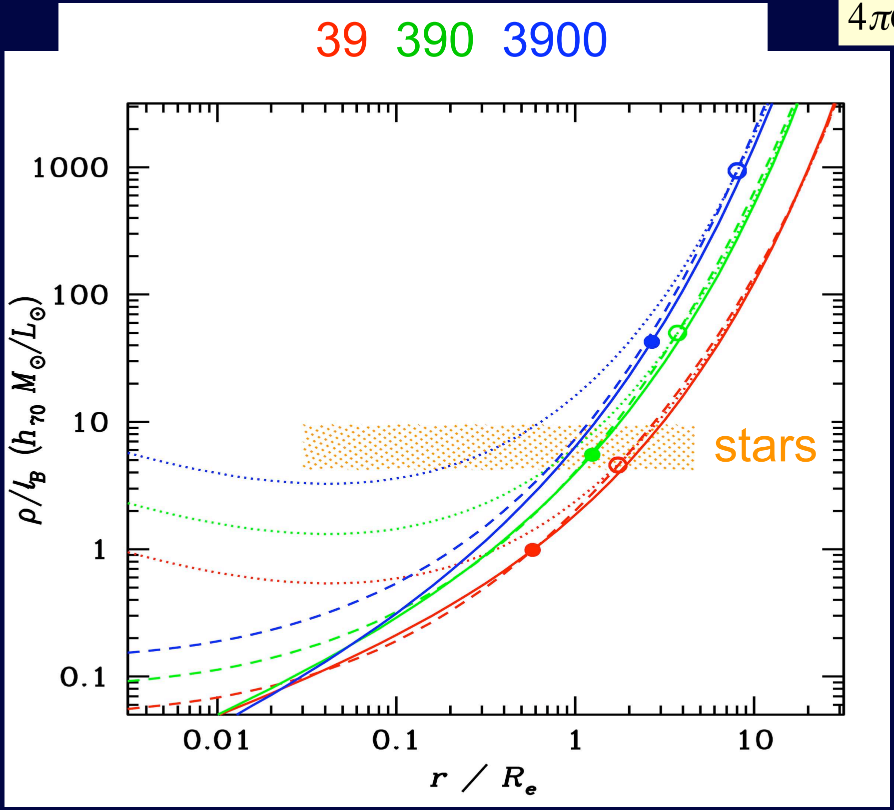
are Ellipticals naked?

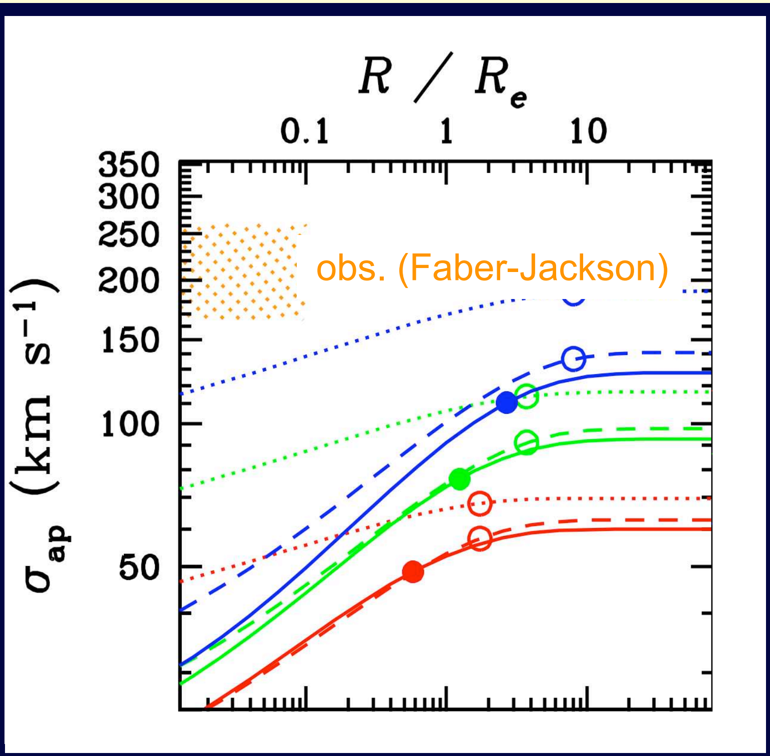
Is the total mass profile NFW-like?

Mamon & Łokas 05a

aperture velocity dispersion for β = 0

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

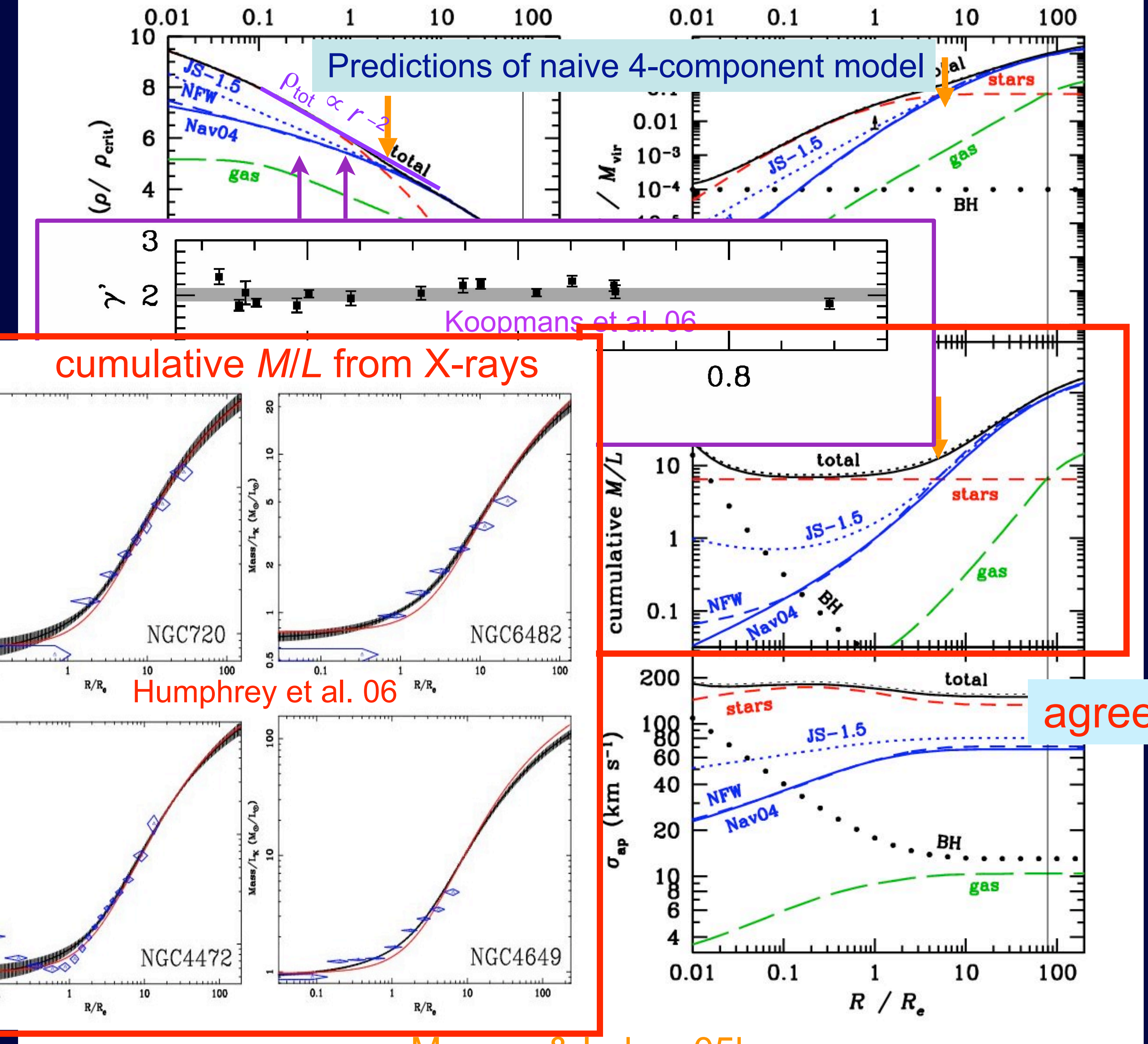




local *M*/*L* lower than stellar!

central aperture velocity dispersions lower than observed!

Stars dominate inside



Predictions of naive 4-component model

Koopmans et al. 06

cumulative *M*/*L* from X-rays

Humphrey et al. 06

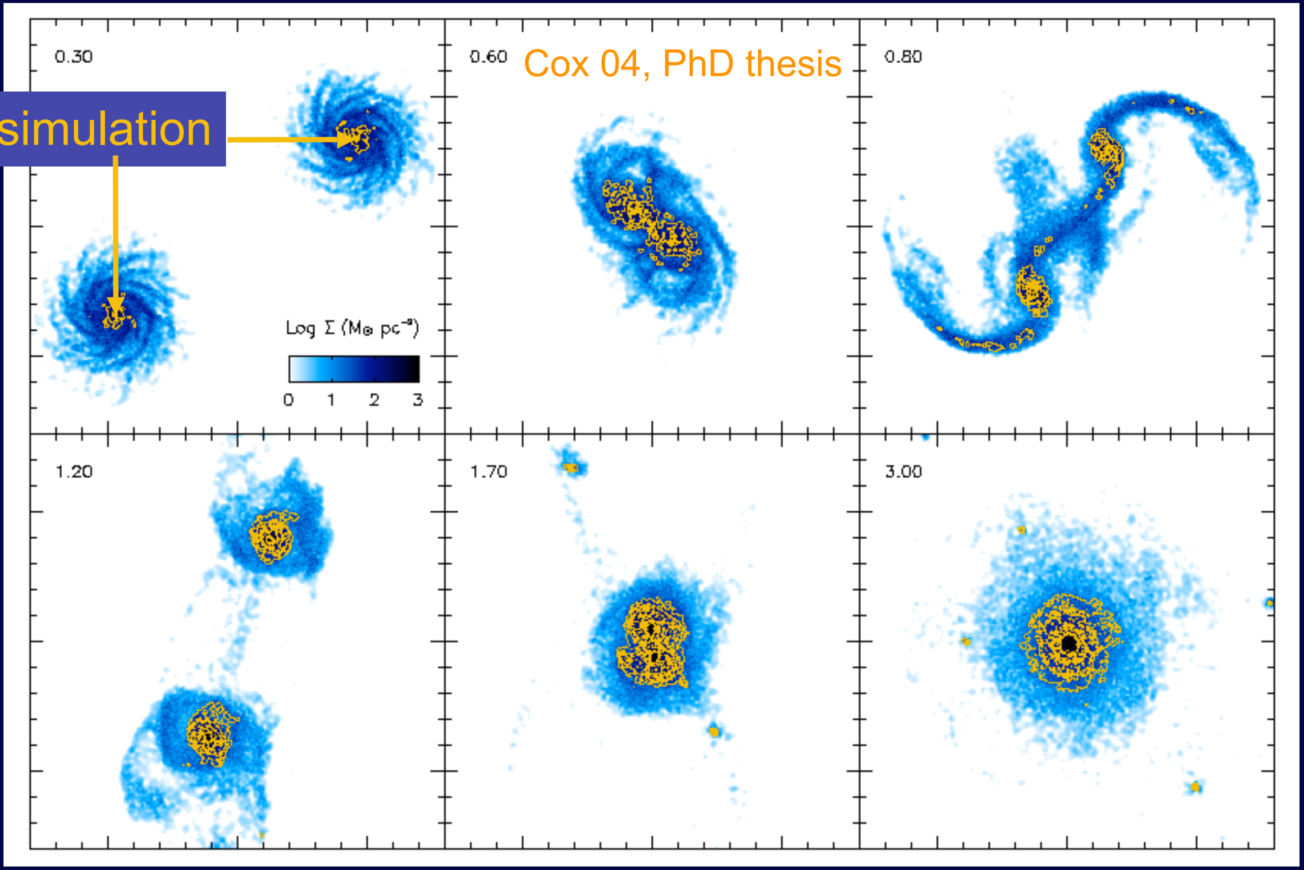
Mamon & Łokas 05b

→ few R_e

slope of *total* density profile = -2.0

agreement with X-rays

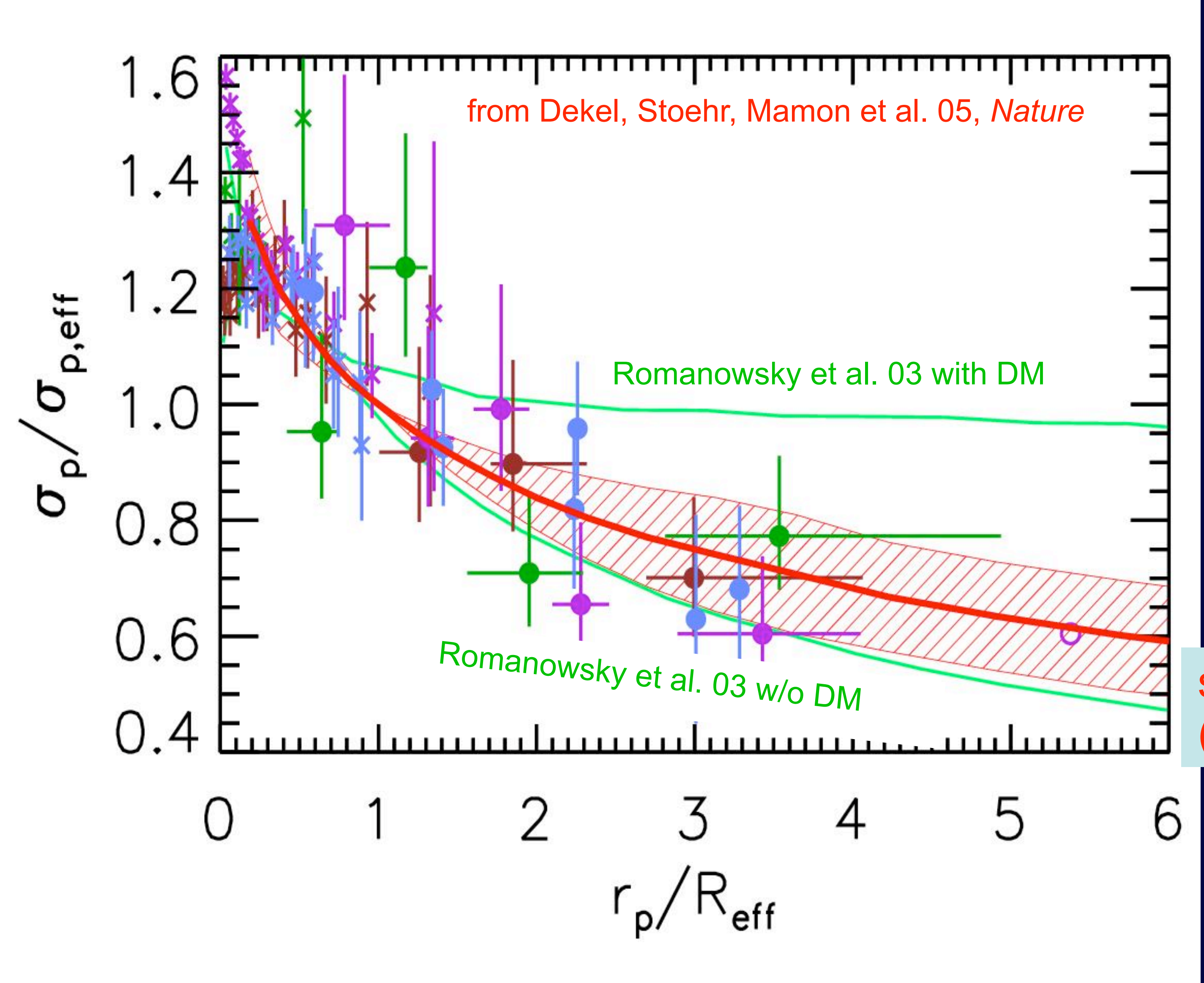
Merger simulation: old & young stars



Cox 04, PhD thesis

stars born during simulation

Line-of-sight Velocity Dispersions



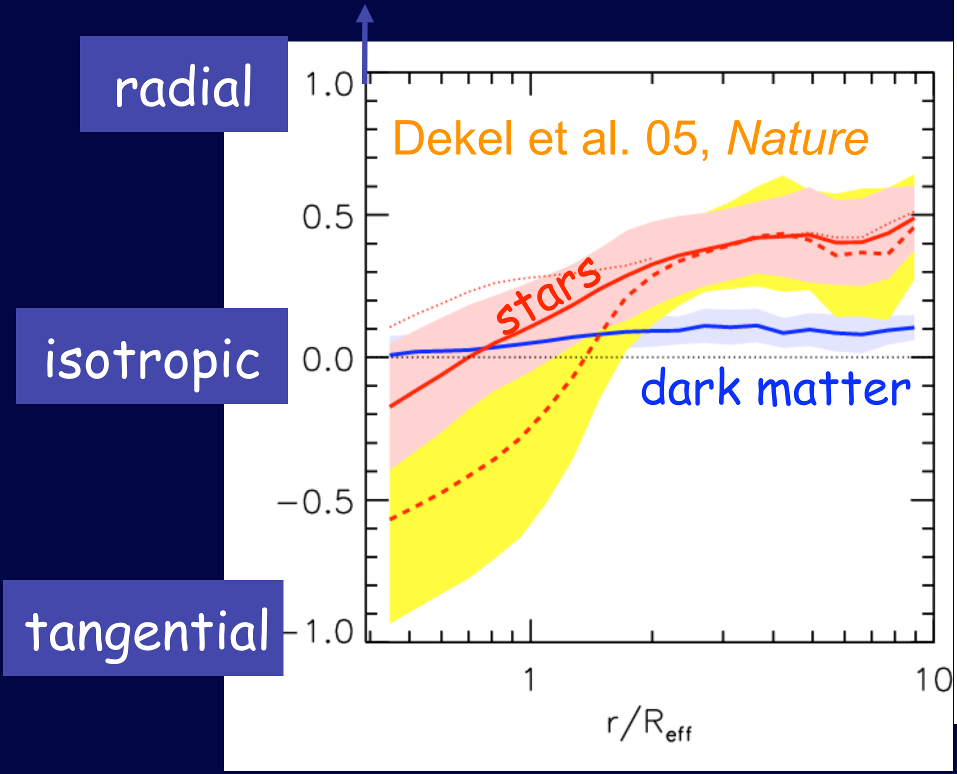
from Dekel, Stoehr, Mamon et al. 05, *Nature*

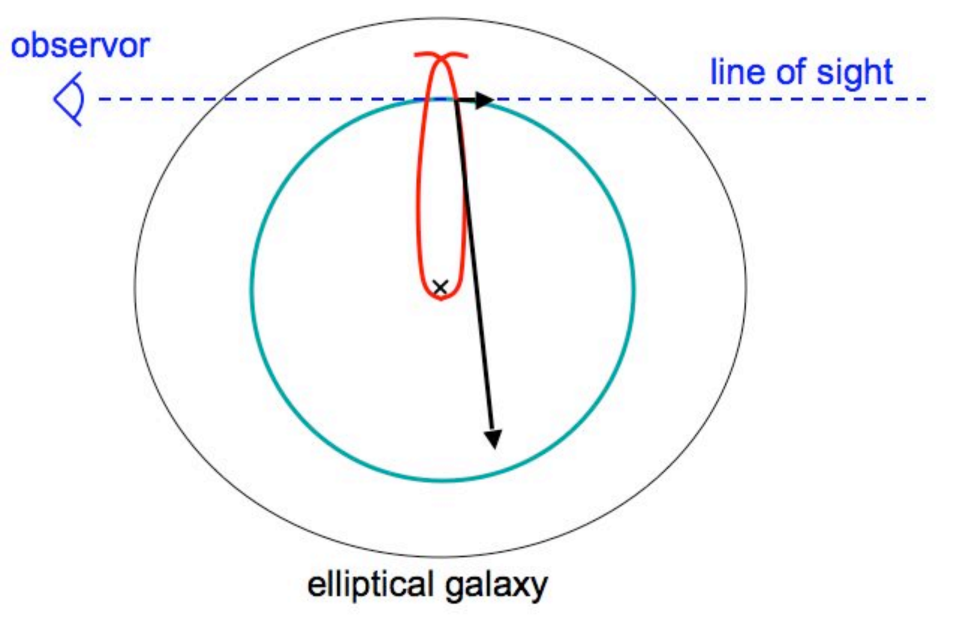
simulations (with DM)

simulations with DM reproduce low velocity dispersions!

Velocity Anisotropy

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

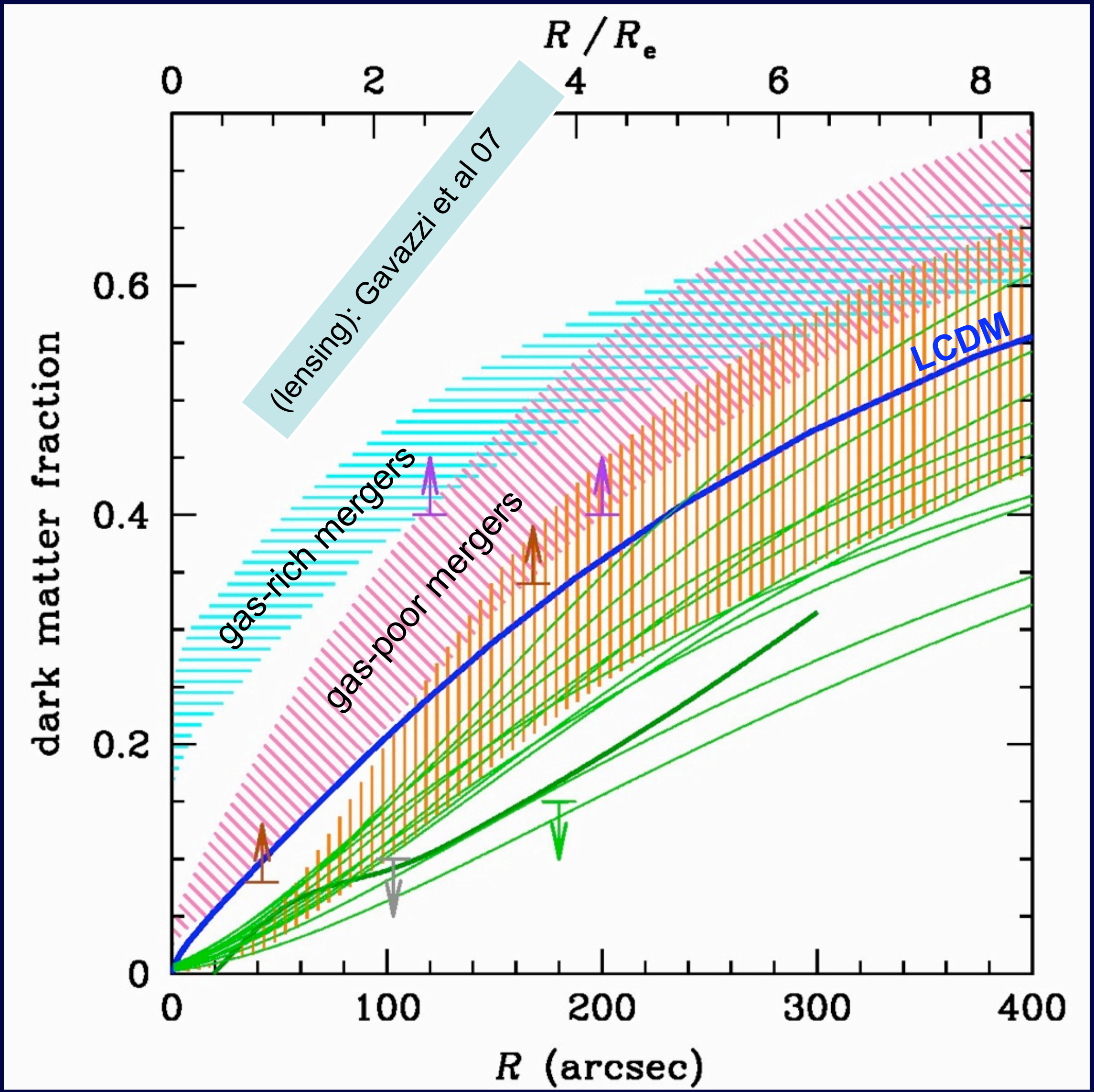




→ low line-of-sight velocity dispersion

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

New analyses of NGC 3379



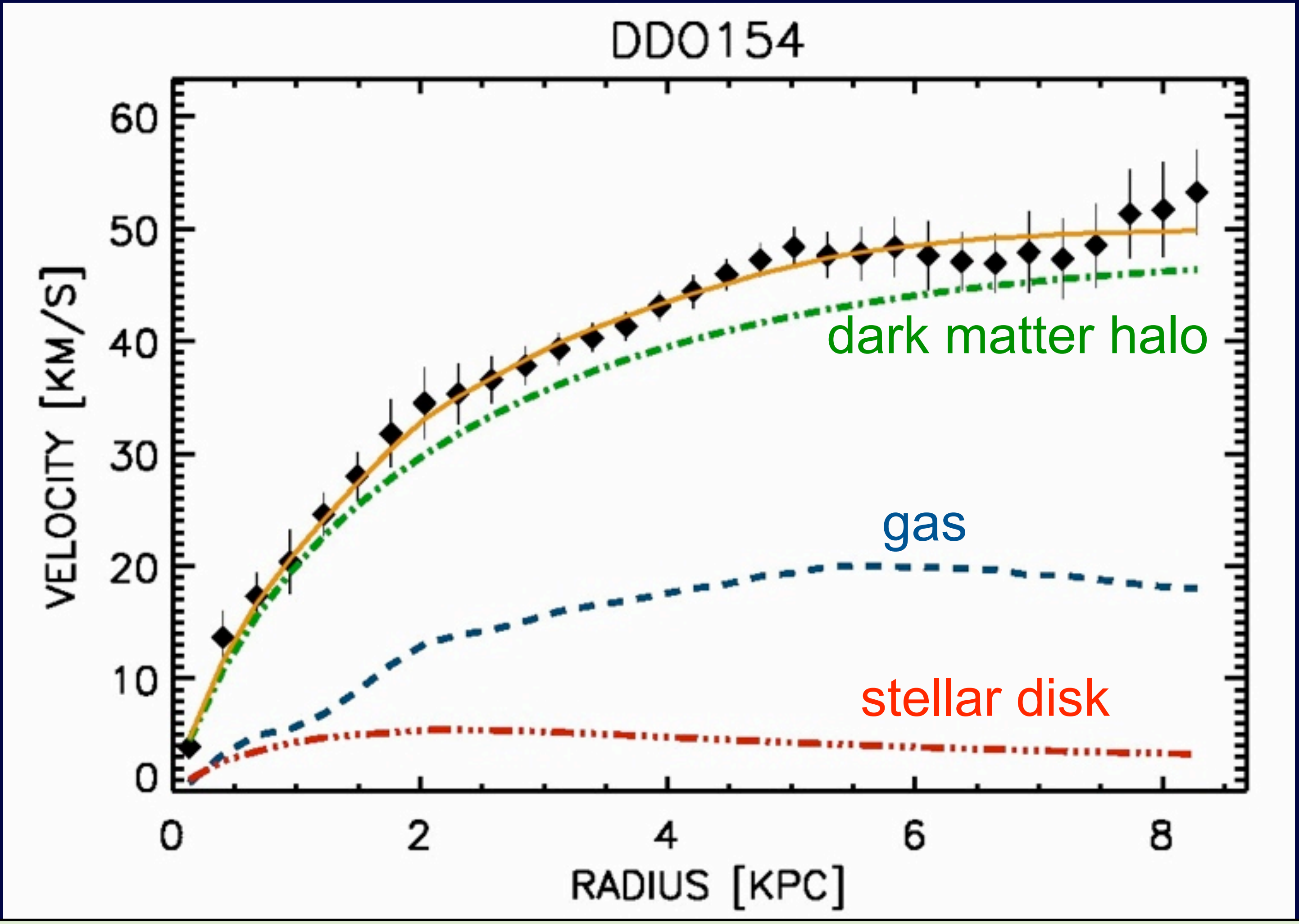
	Tracer	Method	Ref.
↓	Stars	Orbits	Kronawitter+00
↓	PN	Jeans	Romanowsky+03
╱	PN	Orbits	Romanowsky +03
╱	Stars +PN	Jeans	Douglas+07
▥	Stars +PN	Orbits	De Lorenzi+09
↑	GCs	Jeans	Pierce+06
↑	Stars	Orbits	Weijmans+09

dark matter content @ 4 R_e still very uncertain!

6) LCDM in Spiral Galaxies?

Rotation curves

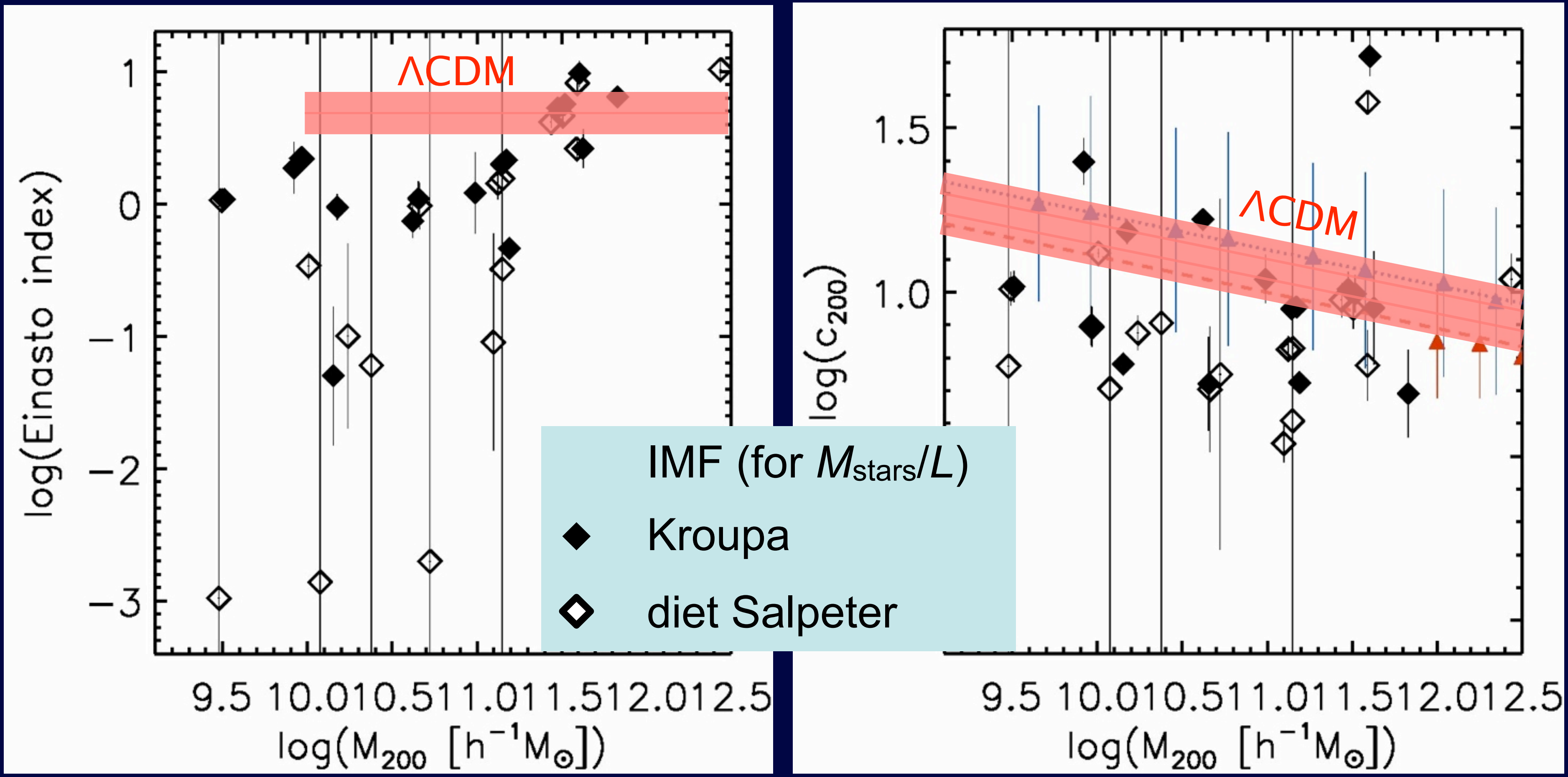
(cuspy) NFW often fails at low R... does (cored) Einasto fit better?



Yes! (fits are significantly better even with extra parameter)

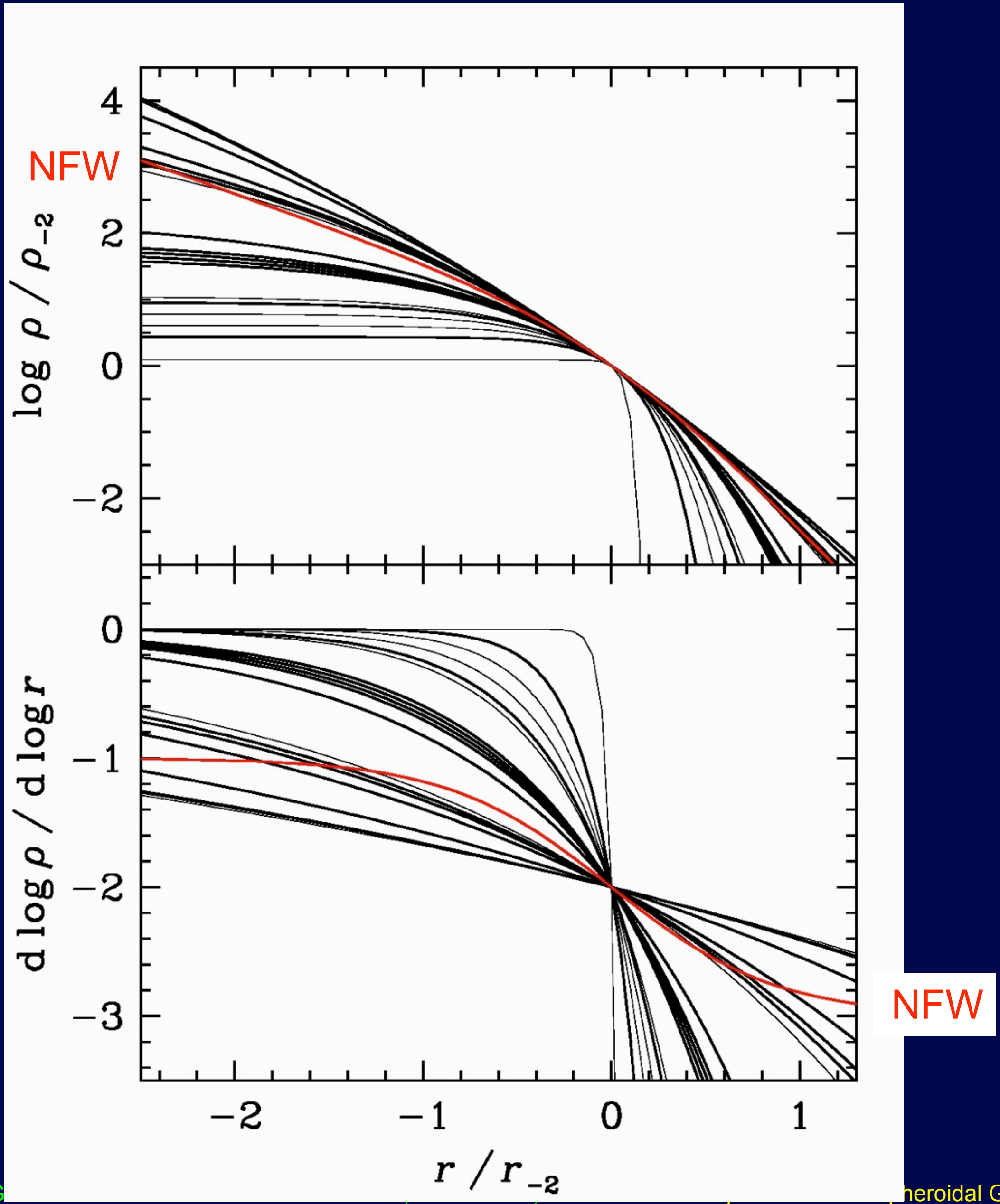
Halo Index & Concentration

Chemin, de Blok & Mamon 11, in prep.



good fitting w Kroupa IMF: most have low index & concentration

Wide variety of halo profile shapes

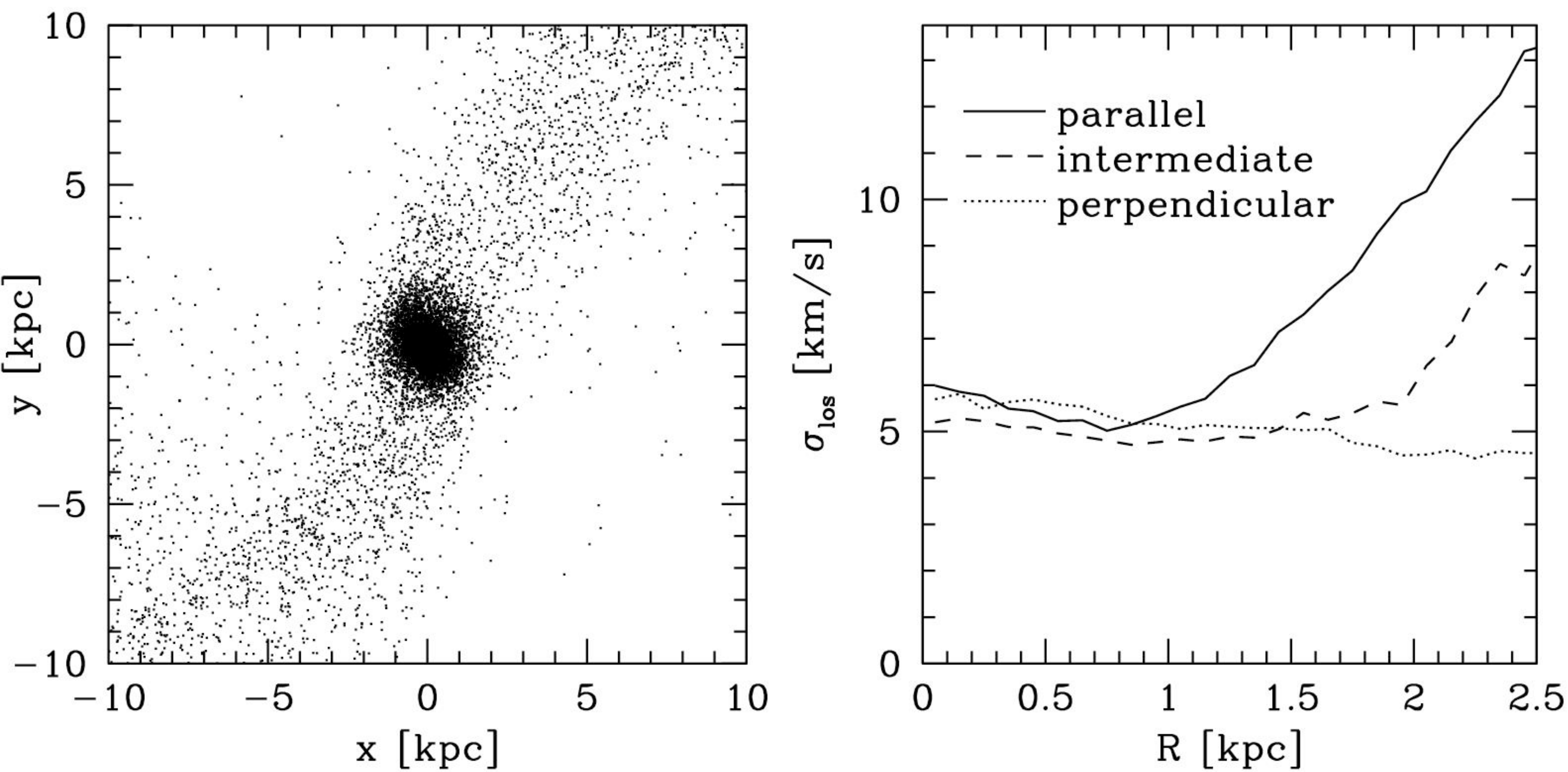


7) Dark Matter in Dwarf Spheroidal Galaxies

Leo I Dwarf Spheroidal

Tidal tails in dwarf spheroidal galaxies

Klimentowski et al 07



kinematical modeling depends on viewing angle

Fornax data

2633 velocities
2278 Fornax members

$L_V = 1.9 \times 10^7 L_{sun}$

Irwin & Hatzimiditriou 95

x2 discrepancy

$L_V = 0.9 \times 10^7 L_{sun}$

Walcher et al. 03

$m = 0.7$ Sersic distribution

Walcher et al. 03;
Battaglia et al. 06

ellipticity: 0.21 → 0.36
Battaglia et al. 06

main starburst: age = 5.4 Gyr

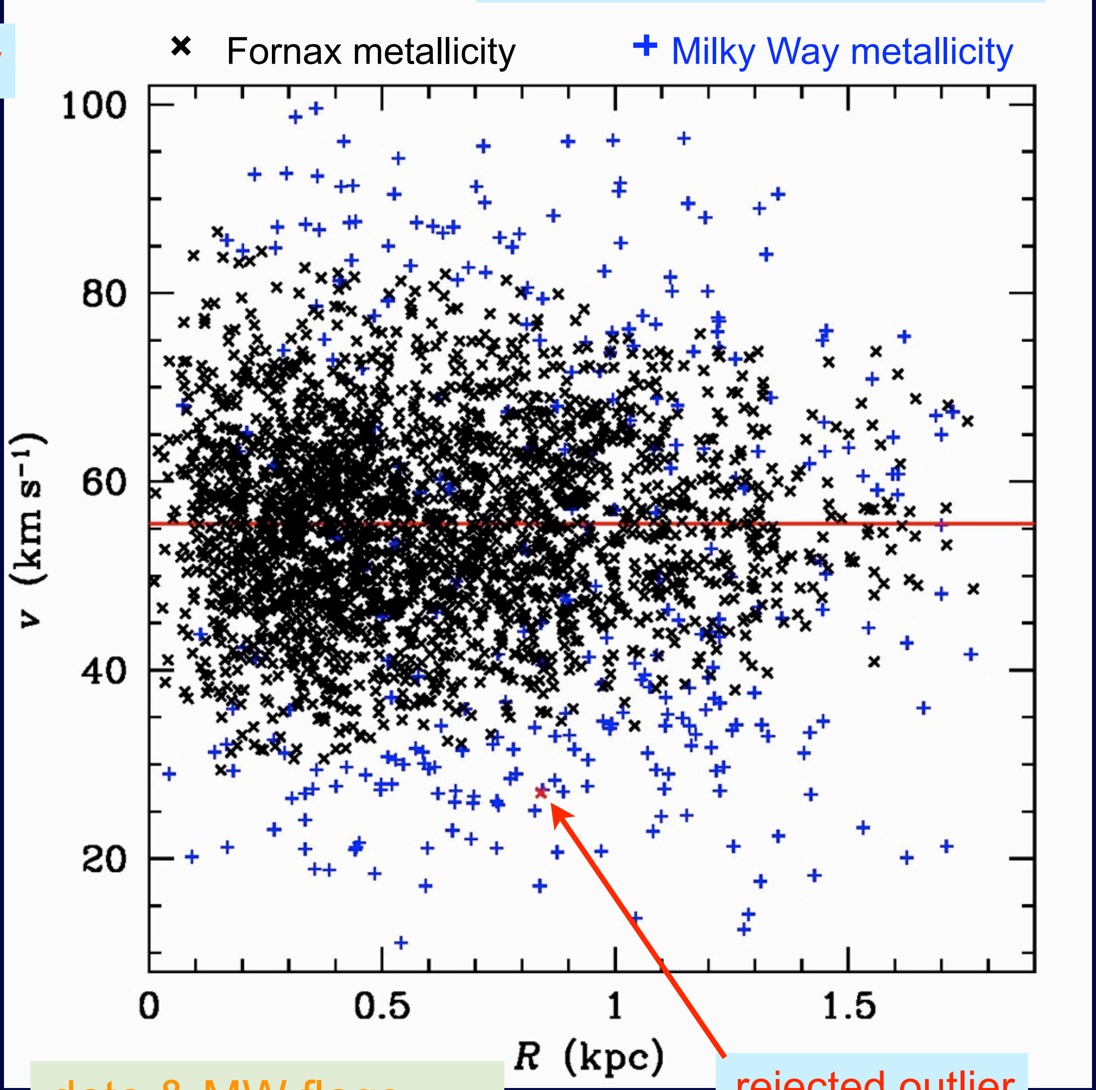
Saviane et al. 00

⬇

$M_{stars}/L_V = 4.8$

Walcher et al. 03

(uncertain) center:
Battaglia et al. 06



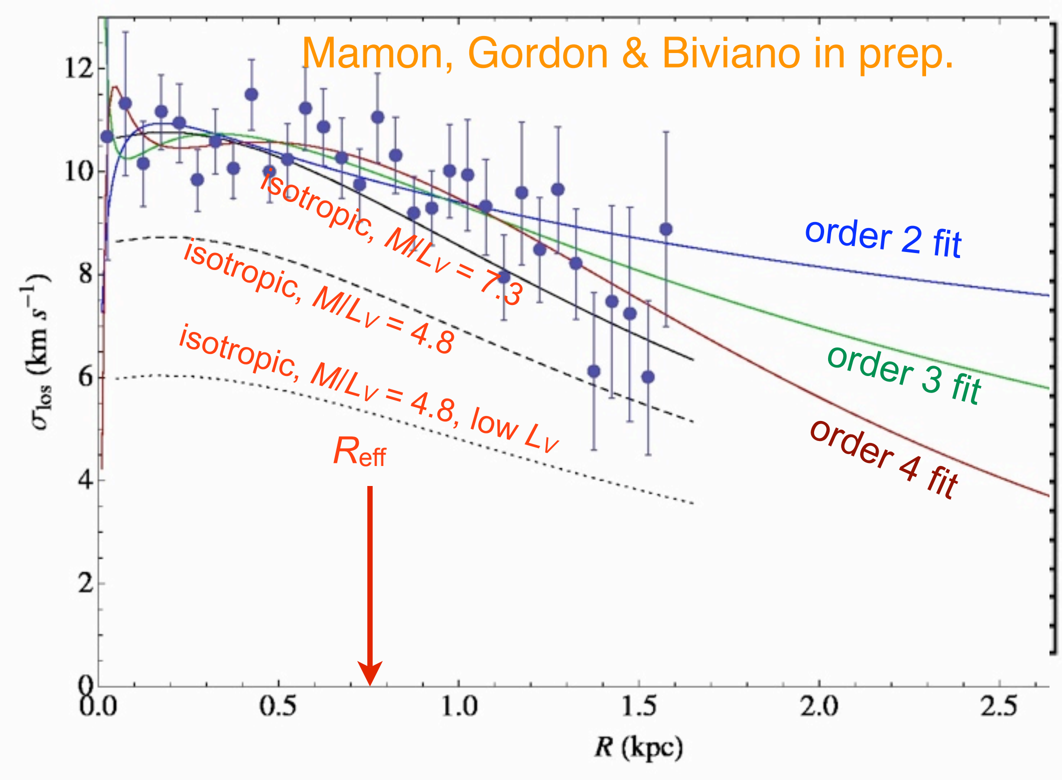
rejected outlier

data & MW flags
from Walker et al. 09

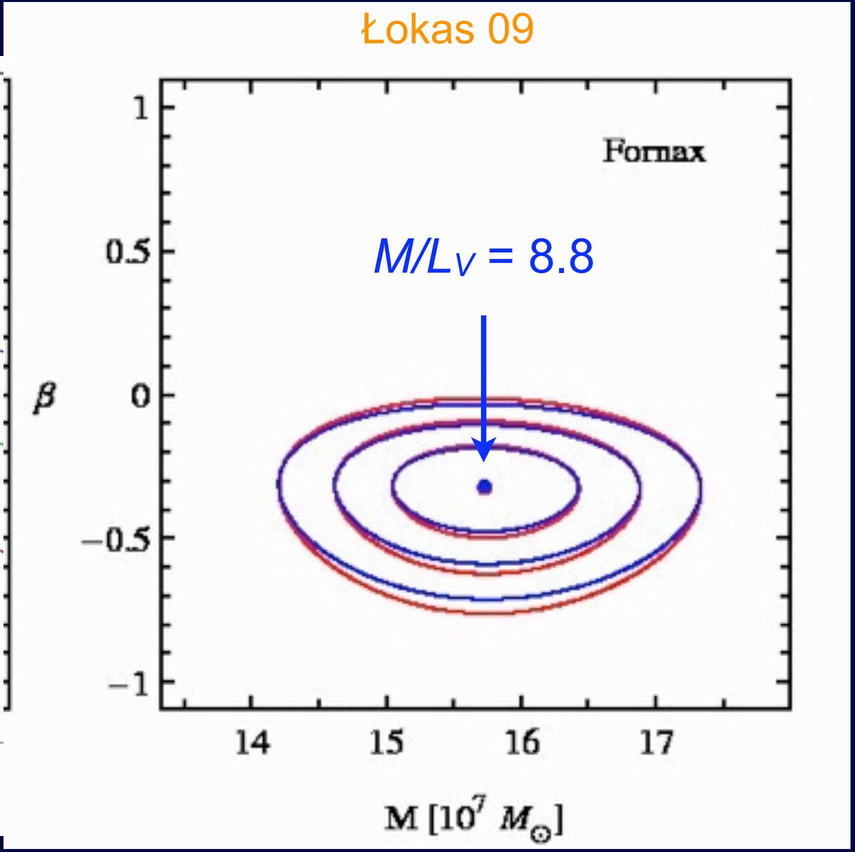
Fornax: 2300 member velocities

out to 2 $R_{\rm eff}$

Walker et al. 08



Mamon, Gordon & Biviano in prep.

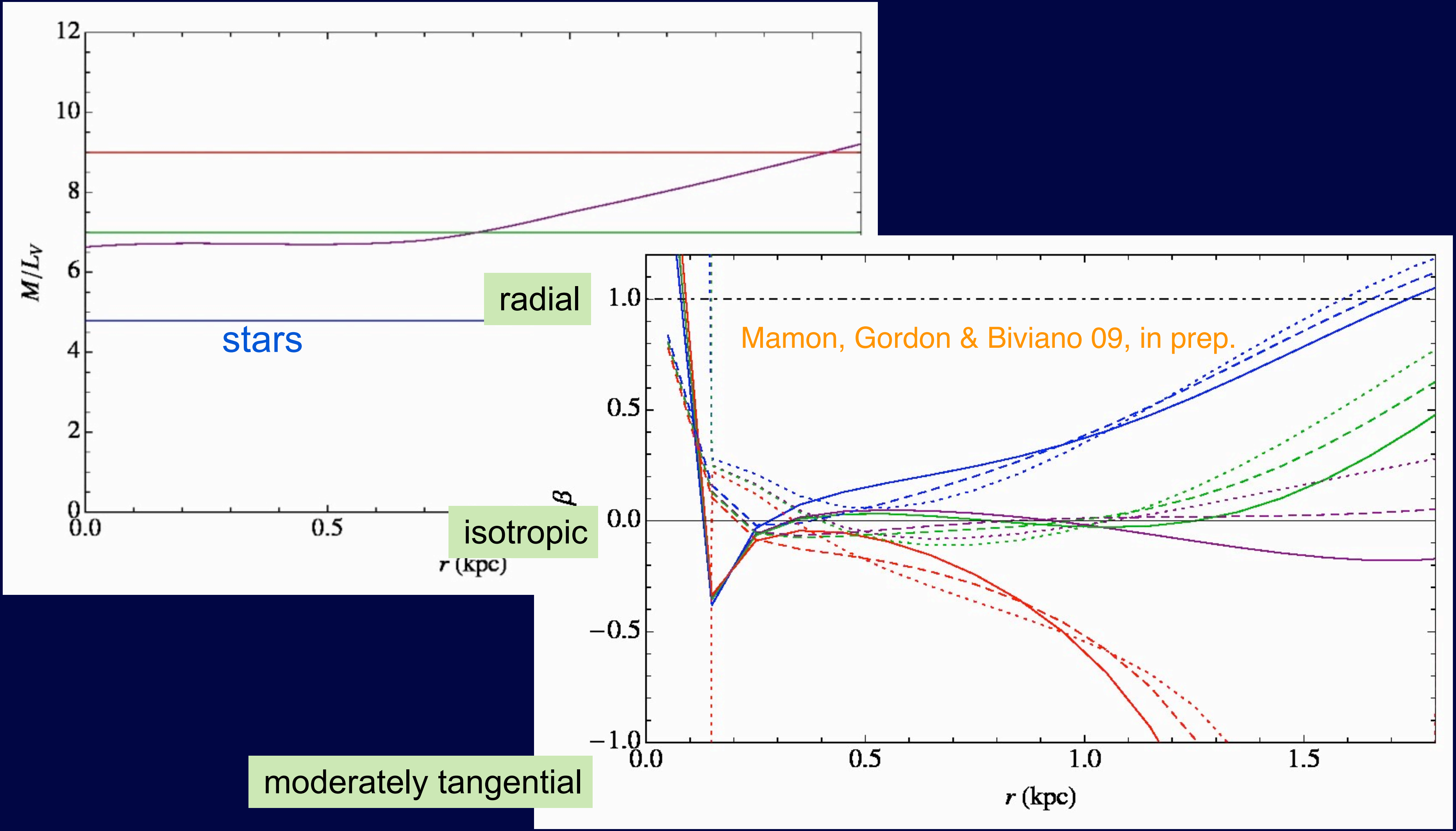


Łokas 09

1/3 fraction of dark matter in inner regions? OR L_V underestimated by 40%?

M/*L* increases outwards? OR tangential outer orbits?

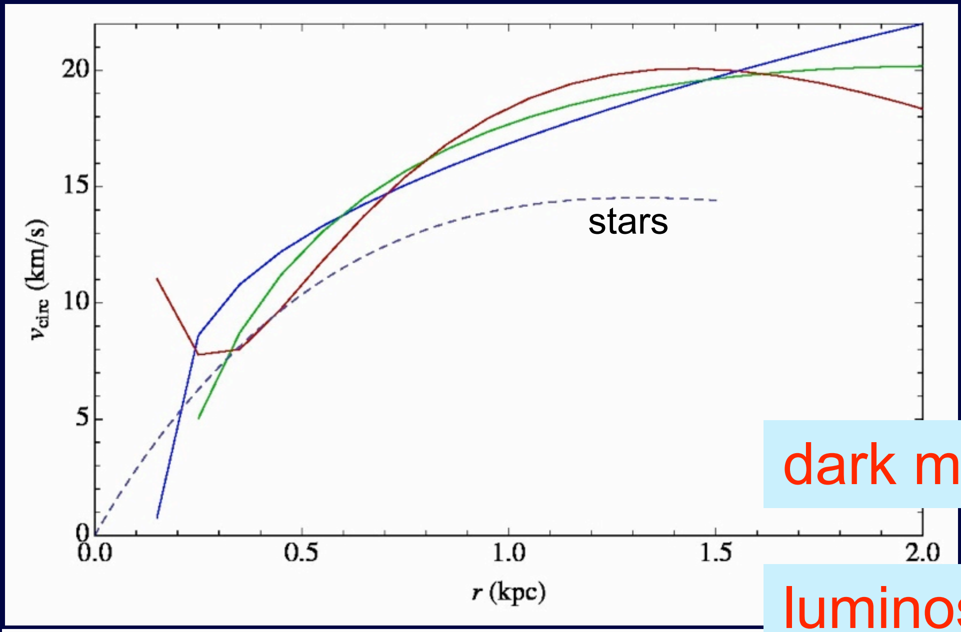
Fornax: anisotropy inversion



Mamon, Gordon & Biviano 09, in prep.

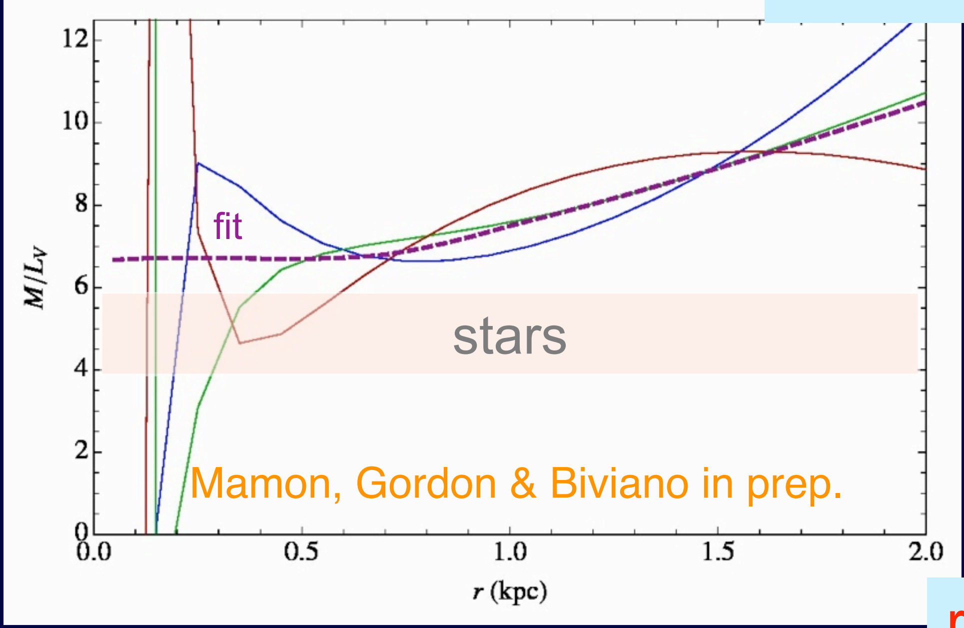
cst *M*/*L* → radial (low *M*/*L*) or tangential (high *M*/*L*) orbits

Fornax: isotropic mass inversion

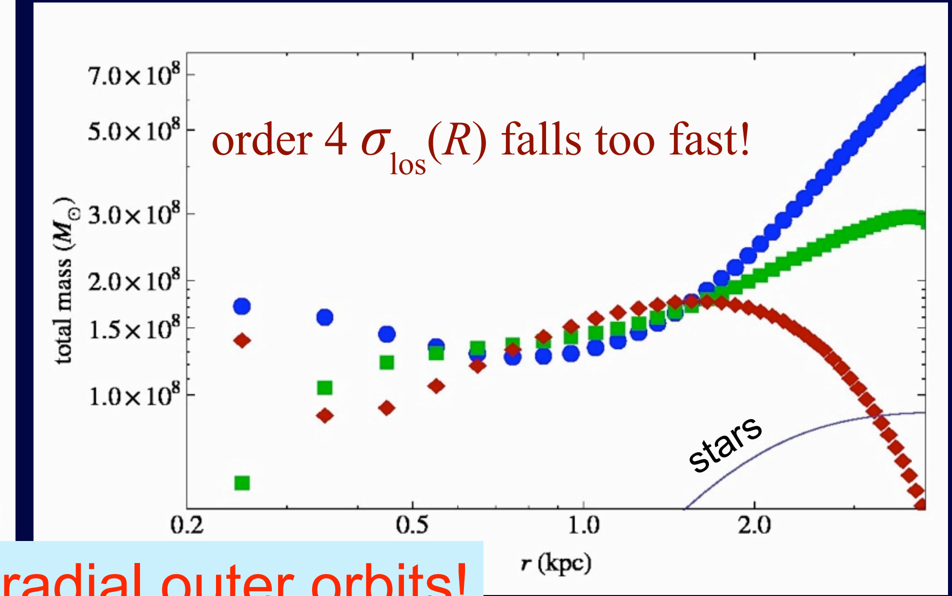


dark matter, even in inner regions?

luminosity and/or $M_{\rm stars}/L$ too low?



Mamon, Gordon & Biviano in prep.



order 4 $\sigma_{\rm los}(R)$ falls too fast!

radial outer orbits!

Mamon, Gordon & Biviano in prep.

Fornax with MAMPOSSt

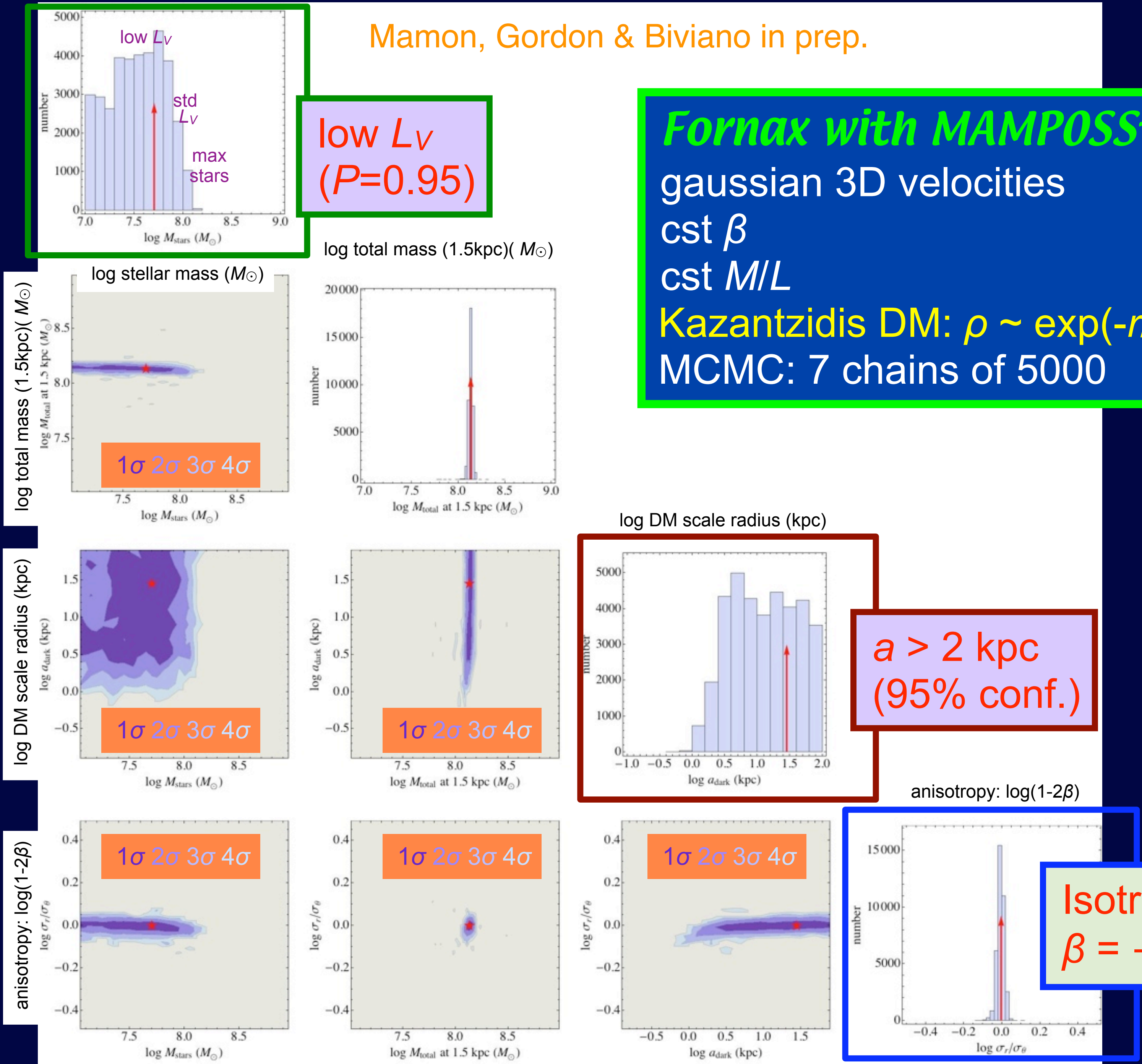
gaussian 3D velocities

cst β

cst M/L

Kazantzidis DM: $\rho \sim \exp(-r/a) / r$

MCMC: 7 chains of 5000



low L_V (P=0.95)

a > 2 kpc (95% conf.)

Isotropic orbits!

$\beta = -0.03 \pm 0.09$

Conclusions

Kinematical modeling of spherical systems is difficult
new techniques & joint (X or lensing) modeling are promising

Interlopers (tidal tails, [Hubble flow]) plague the modeling

ΛCDM DM halos consistent with all observations
except:

giant Es: flat v_{circ} curves

X-ray groups:

dynamically cold X-ray groups appear less concentrated than ΛCDM halos:
signature of energy dissipation by dynamical friction? or irregular potential?

Spiral galaxies: Einasto halos fit well, but low index & concentration in 2/3
reponse of DM to dissipative baryons (collapse, feedback from SN & AGN)?

Future: astrometric surveys (GAIA...) → proper motions → 2 more dimensions