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

with

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Mamon & Łokas 05a, MNRAS, 362, 95

and

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Dekel, Stoehr, Mamon et al. 05, Nature, 437, 707, astro-ph/0501622
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**

- 10 kpc
- Dark halo
- Flat rotation curve
- Rubin 78

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

\[ \rightarrow M(R) \propto R \]

Ostriker, Peebles & Yahil 74; Einasto, Kaasik & Saar 74
Flat Rotation Curves: Extended Massive Dark-Matter Halos in Disk Galaxies

Sofue & Rubin 2001
**Cosmological N-body simulations**

Ninin 99

150 Mpc

halo

2 Mpc
Mass profiles from dissipationless cosmological simulations

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

\[ \rho(r) = \rho(r_2) \exp(2\mu) \exp\left[ -2\mu \left( \frac{r}{r_2} \right)^{1/\mu} \right] \]

\( = 3D \text{ Sérsic!} \)

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

\( (m=3\pm0.5) \)

\( \alpha = 1, \gamma = 1, \eta = 3 \) "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

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

Caon, Capaccioli & D’Onofrio 93

Merritt, Navarro et al. 05
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

Łokas & Mamon 01

NFW only fits $m=3\pm1$

$v < 2R_e \Rightarrow M/L << 1$

$L \uparrow \Rightarrow m \uparrow \Rightarrow c \uparrow \Rightarrow M \downarrow$
2) The Jeans formalism for kinematical modelling
From phase space to local space

\[ f = f(r, v) \equiv \text{distribution function=6D phase space density} \]

Collisionless Boltzmann Equation

\[ \frac{\partial f}{\partial t} + v \cdot \nabla f - \nabla \Phi \cdot \frac{\partial f}{\partial v} = 0 \]

\[ \int v_j \maxwell \, d^3v \]

\[ \nabla P = -\nu \nabla \Phi \]

\[ \Delta F_{\text{Pressure}} = S \Delta P = -F = -\rho S \Delta r \frac{d\Phi}{dr} \]

Maxwell

Jeans

Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste
**Spherical stationary Jeans equation**

\[
\frac{d(v\sigma_r^2)}{dr} + 2 \beta \frac{\beta}{r} v\sigma_r^2 = -v \frac{GM}{r^2}
\]

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

= velocity anisotropy

isotropic orbits: \( \beta = 0 \)
radial orbits: \( \beta = 1 \)
circular orbits: \( \beta \rightarrow -\infty \)

mass / anisotropy degeneracy

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

Binney & Mamon 82
Structural & kinematic projection & deprojection (spherical symmetry)

2D density (surface brightness) $\rightarrow$ 3D density

$$\Sigma(R) = 2 \int_{R}^{\infty} \nu(r) \frac{r \, dr}{\sqrt{r^2 - R^2}} \rightarrow \nu(r) = -\frac{1}{\pi} \int_{r}^{\infty} \frac{d\Sigma}{dR} \frac{dR}{\sqrt{R^2 - r^2}}$$

2D “pressure” $\rightarrow$ 3D “pressure” (isotropic models)

$$\Sigma(R) \sigma_{los}^2(R) = 2 \int_{R}^{\infty} \nu(r) \sigma^2(r) \frac{r \, dr}{\sqrt{r^2 - R^2}} \rightarrow \nu(r)\sigma^2(r) = -\frac{1}{\pi} \int_{r}^{\infty} \frac{d(\Sigma\sigma_{los}^2)}{dR} \frac{dR}{\sqrt{R^2 - r^2}}$$

(anisotropic models)

$$\Sigma(R) \sigma_{los}^2(R) = 2 \int_{R}^{\infty} \left[1 - \beta(r) \frac{R^2}{r^2}\right] \nu(r) \sigma_r^2(r) \frac{r \, dr}{\sqrt{r^2 - R^2}} \quad \text{inversion is possible but complex}$$

Binney & Mamon 82; (...) Dejonghe & Merritt 92
Projected velocity dispersions

line-of-sight velocity dispersion

for $\beta = 0$

$$I(R) \sigma_{los}^2 (R) = 2G \int_{R}^{\infty} \frac{\sqrt{r^2 - R^2}}{r^2} \nu(r) M(r) dr$$

Prugniel & Simien 97

for some simple $\beta(r)$

$$I(R) \sigma_{los}^2 (R) = 2G \int_{R}^{\infty} K(r,R) \nu(r) M(r) dr$$

Mamon & Łokas 05b

aperture velocity dispersion

$$\frac{3}{4\pi G} L_2(R) \sigma_{ap}^2 (R) = \int_{0}^{\infty} r \nu(r) M(r) dr - \int_{R}^{\infty} \left( \frac{r^2 - R^2}{r^2} \right)^{3/2} \nu(r) M(r) dr$$

Mamon & Łokas 05a

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.

\[
\frac{d}{dr} \left( \nu \sigma_r^2 \right) + 2 \beta \frac{\nu \sigma_r^2}{r} = -\nu \frac{GM}{r^2} = -\nu \frac{v_{\text{circ}}^2}{r}
\]

\[
\sigma_r(r) = \frac{v_{\text{circ}}(r)}{\sqrt{\alpha(r) + \eta(r) - 2\beta - 2}}
\]

\[
\beta \uparrow \Rightarrow \frac{\sigma_r}{v_{\text{circ}}} \uparrow
\]

### Anisotropic projection eq.

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

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

\[
\alpha + \eta > 5 \Leftrightarrow \frac{d \log \left( \frac{\sigma_{\text{los}}}{v_{\text{circ}}} \right)}{d \log \beta} < 0
\]

### Realistic slopes \(\alpha\) & \(\eta\)

\[
\alpha \uparrow \text{ or } \beta \uparrow \Rightarrow \sigma_{\text{los}} \downarrow
\]
Power-law solutions to Jeans equations (2)

realistic outer slopes: $\alpha + \eta > 5$  

$\alpha \uparrow$ or $\beta \uparrow \Rightarrow \sigma_{\text{los}} \downarrow$
3) Different methods to measure $M(r)$
a) **quick & dirty: assume isotropy $\beta = 0$**

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

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

Mamon & Boué 06, in prep

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

Merritt 87

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 $\Phi(r)$

2) throw orbit $(E, J)$

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  

\[ g(R, v_z) = 2 \int_{R}^{\infty} \frac{r \, dr}{\sqrt{r^2 - R^2}} \int d\nu_R \int f \left[ \frac{1}{2} \nu^2 + \Phi(r), J \right] d\nu_\theta \]

1) pick a gravitational potential \( \Phi(r) \)

2) pick a set of elementary distribution functions \( f_i(E, J) \)

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

4) fit observations with positive linear combination of \( f_i(E, J) \)

5) iterate on parameters of potential

Dejonghe & Merritt 92

Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste
**d) 4\textsuperscript{th} order Jeans equations**

\[
\frac{d}{dr} \left( \bar{v} \bar{v}_r^4 \right) + 2 \frac{\beta}{r} \left( \bar{v} \bar{v}_r^4 \right) = -3 \nu \sigma_r^2 \frac{GM(r)}{r^2}
\]

Łokas 02; Łokas & Mamon 03

if $\beta = \text{cst}$

\[
\bar{v}_r^4(r) = \frac{3 r^{-2\beta}}{\nu(r)} \int_r^\infty s^{2\beta - 2} \nu \sigma_r^2 GM(s) ds
\]

line of sight kurtosis excess

\[
\kappa_{\text{los}}(R) = \frac{\bar{v}_{\text{los}}^4(R)}{\sigma_{\text{los}}^4(R)} - 3
\]
Effect of anisotropy on dispersion & kurtosis

Sanchis, Łokas & Mamon 04

pure NFW model

joint constraints
The Coma cluster in X-Rays

Neumann et al. 03
contours: surface brightness residuals over smooth 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:  
\[
\begin{align*}
\Delta \log M_{100} &= -0.07 \pm 0.10 \\
\Delta \log c &= 0.08 \pm 0.24 \\
\Delta \log \left( \frac{\sigma_r}{\sigma_\theta} \right) &= -0.04 \pm 0.11 
\end{align*}
\]

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)

NGC 3379

radial or nearly isotropic?

Gary Mamon, 2 December 2005, IAP
Orbit modelling of ellipticals

some galaxies show DM
some show instead cst M/L
but bad $\Phi(r)$!

Kronawitter et al. 00
Recover flat FP $\Rightarrow$ NFW halos must have *low concentration*

Borriello, Salucci & Danese 03
M/L gradients

Stellar mass (or luminosity)

Napolitano et al. 05

brightest group/cluster members

low & intermediate luminosity ellipticals: almost no DM
OR
very low DM concentration
Planetary Nebulae: Tracers at $1-3R_{\text{eff}}$

$[\text{O}_{\text{III}}]$ 5007 Å

Romanowsky et al. 03, *Science*

N3379
PN velocity dispersions are low

Mendez et al. 01

N4697

Romanowsky et al. 03

are Ellipticals naked?
Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste

Predicted & observed M/L

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

\[ \log \left( \frac{M}{L} \right)_{\text{predicted}} \]

\[ \log \left( \frac{M}{L} \right)_{\text{sun}} \]

\[ \log \left( \frac{L}{L_{\text{sun}}} \right) \]

Critical density Universe

Universal \( \frac{M}{L_B} = 390 \)

\( \times 3 \)

Romanowsky et al 03

\( M/L = 33? \)
5) Step by step kinematical modelling
Is the total mass profile NFW-like?

Mamon & Łokas 05a, MNRAS

aperture velocity dispersion for $\beta = 0$

$$\frac{3}{4\pi G} L_2(R) \sigma_{ap}^2(R) = \int_0^\infty rv(r)M(r)dr - \int_R^\infty \frac{(r^2 - R^2)^{3/2}}{r^2} v(r)M(r)dr$$

$M(r_{\text{vir}}/L_B) = 39, 390, 3900$

local $M/L$ lower than stellar!

central aperture velocity dispersions lower than observed!

Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste
4-component model of elliptical galaxies

- Sérsic stars
- NFW-like dark matter
- $\beta$-model hot gas
- central supermassive black hole
X-rays

Humphrey et al. 06

Stars dominate inside

→ few $R_e$

Mamon & Łokas 05b

Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste
Velocity Anisotropy in cosmological simulations

\[ \beta = \frac{1}{2} \frac{r}{r + a} \]

Mamon & Łokas 05b

Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste
Velocity dispersion vs anisotropy & dark halo model

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

\[ \frac{M}{L_B}(r_{\text{vir}}) \propto \left[ \sigma_{\text{los}}(5R_e) \right]^8 \]
Effects on M/L at virial radius

Mamon & Łokas 05b

\[ \frac{\sigma_{\text{los}}}{\sigma_{\text{NFW,iso}}} \]

100 110 120 130 140 150

\( \sigma_{\text{los}} \) (km s\(^{-1}\))

5\(R_e\)

2\(R_e\)

Nav04 - 0.18

Nav04 - iso

Nav04 - 0.018

NFW - 0.18
6) Dynamical modelling of Elliptical Galaxies
Major merger simulation

Sbc201a–n4
Zsolar–imf2.35
 urz color

Disk
Bulge
Gas
Dark halo
TREE-SPH
GADGET
Springel 01

Cox 04,
PhD Thesis
Stars: old and new (face-on view)

Cox 04, PhD thesis
**Surface Density: like typical Es!**

\[
\frac{\Sigma}{\Sigma_{\text{eff}}} = \begin{cases} 
10^1 & \text{for } N4697 \\
10^0 & \text{for } N3379 \\
10^{-1} & \text{for de Vaucouleurs}
\end{cases}
\]

Dekel et al. 05, *Nature*
Line-of-sight Velocity Dispersions: low!

Dekel et al. 05, *Nature*

Romanowsky et al. 03 w DM

Romanowsky et al. 03 w/o DM

dark matter

all stars

young stars
Velocity Anisotropy

stars on much more radial orbits than dark matter!

Dekel et al. 05, Nature

\[ \beta \equiv 1 - \frac{\sigma_\theta^2}{\sigma_r^2} \]

Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste
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

Cox 04, PhD thesis
Effects of triaxiality

One merger remnant: Sbc+Sbc

edge-on

face-on

20%
Time evolution

late times

late times
Jeans equilibrium

\[ M_{\text{Jeans}}(r) = \frac{r \langle v_r^2 \rangle}{G} (\alpha + \gamma - 2\beta) \]

\[ \gamma = -\frac{d \ln \langle v_r^2 \rangle}{d \ln r} \]

good equilibrium to 8 \( R_e \)!

small time-dependence effects

Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste
Minor mergers: 3:1 all particles

1:1 mergers

3:1 G-G mergers

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Minor mergers:
secondary particles

β

10:1 3:1 1:1

r/R_{eff}

σ_{p}/σ_{p,\text{eff}}

10:1 3:1 1:1

r_{p}/R_{eff}
even more radial orbits!

Gary Mamon (IAP), 22 February 2006, Osserv. Astr. di Trieste
Effects of gas dynamics

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

Mamon & Lokas 05b

value in Romanowsky et al. 03

Bullock et al. 01
Napolitano et al. 05

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 $\Lambda$CDM 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