Dynamic modelling of luminous and dark matter in 17 Coma early-type galaxies

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A Little Background

- Elliptical Galaxies
  - Numerous among bright galaxies
  - Harbor significant fraction of stellar mass in the Universe
- Key Parameters for Elliptical Galaxy Formation
  - Central dark matter density
  - Scaling radius of dark matter
  - Stellar mass-to-light ratio
  - Distribution of stellar orbits

Purpose of Dynamic Modelling

- Allows for reconstruction of mass structure and orbital state of galaxy
  - Requires high quality Line-of-Sight Velocity Distributions (LOSVDs) out to several Reff (1/2 light radius)
- What has been done:
  - Only large non-rotating Ellipticals have been probed with spherical models.
  - Authors will look at nonsymmetrical, rotating and nonrotating models.
    - Looking for evidence of dark matter
- Goal: Analyze the luminous and dark matter distributions and orbital structure of flattened Coma galaxies

Observations

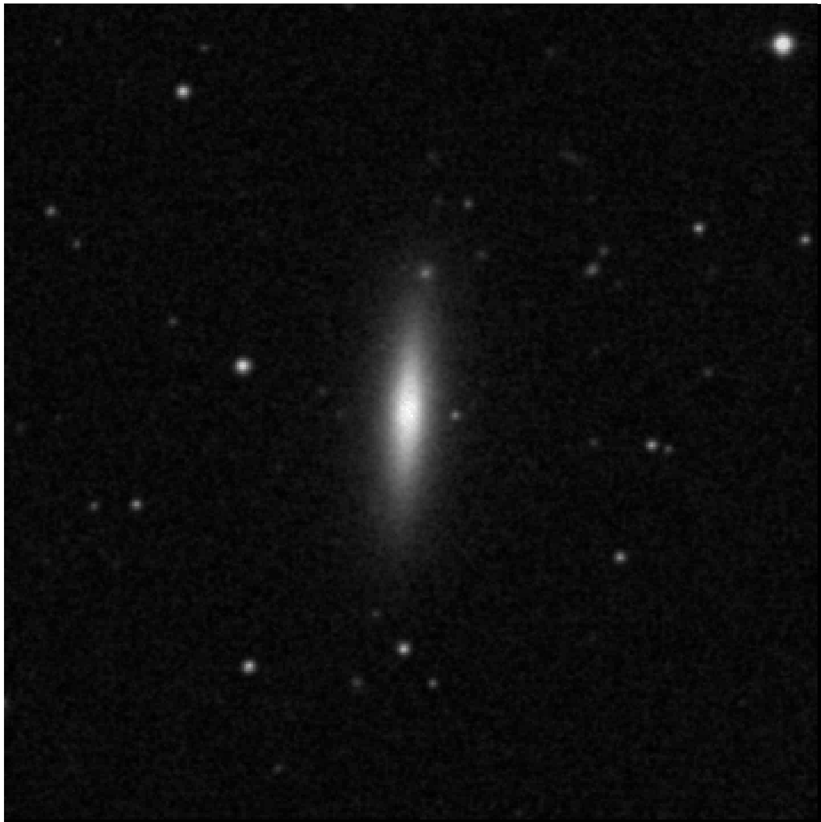
- Coma Sample: 17 early-type galaxies
  - 2 cD , 9 ordinary giant elliptical, and 6 lenticular galaxies
    - -20.30 < Mb < -22.56
    - H0 = 69 km/(s*Mpc)
    - 3.3 < reff < 18.4 (arcsec)
- Data obtained from HST (inner parts) and ground based (outer parts)
  - Data obtained along 2 position angles
    - Apparent Major and Minor Axes.

Table 1. Summary of observational data. Columns (1) and (2): galaxy ID (GMP from Godwin, Metcalfe & Peach 1983); column (3): morphological type (from Mehlert et al. 2000); columns (4) and (5): *HST* and ground-based photometry (L97 = *HST*/WFPC2 *R*-band data, Principal Investigator: John Lucey, Proposal ID: 5997; H98 = *HST*/WFPC2 *R*-band data, Principal Investigator: William Harris, Proposal ID: 6104; W07 = *HST*/WFPC2 *R*-band data, Principal Investigator: Gary Wegner, Proposal ID: 10884; M00 = Kron–Cousins R_C-band photometry from Mehlert et al. 2000; J94 = Gunn *r* photometry from Jørgensen & Franx 1994); column (6): absolute *B*-band magnitude (from Hyperleda; $H_0 = 69\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$); columns (7) and (8): effective radius $r_{\rm eff}$ and ellipticity $\epsilon_{\rm e}$ at $r_{\rm eff}$ from Mehlert et al. (2000); column (9): rms $\langle \mu_{\rm grd} - \mu_{HST} \rangle$ between shifted *HST* surface brightness μ_{HST} and corresponding ground-based $\mu_{\rm grd}$; columns (10)–(13): radius of the outermost kinematic data point along various slit positions: maj/min/dia = position angle of 0°/90°/45° relative to major axis; off = parallel to major axis (in case of GMP5568: two offset-slits). The offsets are quoted in the captions of Figs A1–A17.

Galaxy			Photometry						Kinematics			
id		type		Source	M_B	$r_{\rm eff}$	$\epsilon_{\rm e}$	rms $\langle \mu_{\rm grd} - \mu_{HST} \rangle$	maj	min	off	dia
GMP	NGC		*HST*	Ground-based	(mag)	(arcsec)		(mag)	($r_{\rm eff}$)	($r_{\rm eff}$)	($r_{\rm eff}$)	($r_{\rm eff}$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
0144	4957	E	L97	M00	−21.07	18.4	0.256	0.011	1.4	0.7	–	–
0282	4952	E	L97	M00	−20.69	14.1	0.315	0.009	1.7	0.5	–	–
0756	4944	S0	W07	M00	−21.77	11.7	0.657	0.010	3.0	0.4	2.5	–
1176	4931	S0	W07	M00	−20.32	7.4	0.552	0.080	4.7	0.8	3.7	–
1750	4926	E	L97	J94	−21.42	11.0	0.132	0.058	0.9	0.9	–	–
1990	IC 843	E/S0	W07	M00	−20.52	9.45	0.485	0.066	3.3	0.5	1.8	–
2417	4908	E/S0	L97	J94	−21.06	7.1	0.322	0.042	2.2	0.9	0.9	–
2440	IC 4045	E	W07	J94	−20.30	4.37	0.330	0.038	3.2	1.0	–	1.0
2921	4889	D	L97	J94	−22.56	33.9	0.360	0.028	0.7	0.3	–	–
3329	4874	D	H98	J94	−22.50	70.8	0.141	0.057	0.4	0.1	–	–
3510	4869	E	L97	J94	−20.40	7.6	0.112	0.033	2.0	1.1	–	–
3792	4860	E	L97	J94	−20.99	8.5	0.161	0.071	1.1	1.0	–	–
3958	IC 3947	E	L97	J94	−18.79	3.3	0.323	0.024	1.7	0.9	–	–
4928	4839	E/S0 (D)	L97	J94	−22.26	29.5	0.426	0.104	1.1	0.1	–	0.2
5279	4827	E	L97	M00	−21.36	13.6	0.205	0.019	1.6	0.7	–	–
5568	4816	S0	L97	M00	−21.53	55.7	0.284	0.075	0.5	0.1	0.1	–
5975	4807	E	L97	M00	−20.73	6.7	0.170	0.015	2.9	0.5	–	1.2

Deprojection and inclination

- Surface photometry is deprojected to form 3D luminosity function (ν)
- Inclinations
  - 3 different inclinations are used
    - I = 90º (edge on)
    - A minimum inclination that is found by requiring the deprojection to be as flattened as an E7
    - Intermediate inclination for which the deprojection looks like an E5
  - In many galaxies, inclination is poorly constrained




Mass Model

$$\rho = \Upsilon \nu + \rho_{\mathrm{DM}}$$

$$\rho_{\mathrm{NFW}}(r, r_{\mathrm{s}}, c) \propto \frac{1}{(r/r_{\mathrm{s}})(1 + r/r_{\mathrm{s}})^2}$$

$$\rho_{\mathrm{LOG}}(r) \propto v_{\mathrm{c}}^2 \frac{3r_{\mathrm{c}}^2 + r^2}{\left(r_{\mathrm{c}}^2 + r^2\right)^2}$$

$$r_{\mathrm{s}}^3 \propto 10^{(A - \log c)/B} \left(200 \frac{4\pi}{3} c^3\right)^{-1}$$

$$r \rightarrow r\sqrt{\cos^2(\vartheta) + \sin^2(\vartheta)/q^2}$$

$$A = 1.05 \text{ and } B = 0.15$$

- Trial mass density, combination of stellar mass to light ratio and dark matter density.

- Two different density functions are used to fit the kinematic data. NFW distribution and a LOG distribution

Orbital Superposition

$$\hat{S} \equiv S - \alpha\, \chi^2_{\mathrm{LOSVD}} \rightarrow \max.$$

$$S \equiv -\int f \ln(f)\, \mathrm{d}^3r\, \mathrm{d}^3v = -\sum_i w_i \ln\left(\frac{w_i}{V_i}\right)$$

$$\beta_\vartheta \equiv 1 - \frac{\sigma_\vartheta^2}{\sigma_r^2}$$

$$f_i \equiv \frac{w_i}{V_i}$$

$$\chi^2_{\mathrm{LOSVD}} \equiv \sum_{j=1}^{N_{\mathcal{L}}} \sum_{k=1}^{N_{\mathrm{vel}}} \left(\frac{\mathcal{L}^{jk}_{\mathrm{mod}} - \mathcal{L}^{jk}_{\mathrm{dat}}}{\Delta \mathcal{L}^{jk}_{\mathrm{dat}}} \right)^2$$

$$\beta_\varphi \equiv 1 - \frac{\sigma_\varphi^2}{\sigma_r^2}$$

- S -> Boltzmann entropy
- f -> phase-space distribution function
- Wi -> total amount of light on the orbit
- Vi -> orbital phase-space volume
- α -> regularization
- χ^2_{LOSVD} -> deviations between data and mode
- Betas -> Anisotrophy

What is this α?

- Controls the relative weight of data fit and entropy maximization.
- The higher α the better the fit, but noisier the DF becomes.
- α = 0.02 for all modelling

Goodness-of-fit

$$\chi^2_{\rm GH} \equiv \sum_{j=1}^{N_{\mathcal{L}}} \left[\left(\frac{v^j_{\rm mod} - v^j_{\rm dat}}{\Delta v^j_{\rm dat}} \right)^2 + \left(\frac{\sigma^j_{\rm mod} - \sigma^j_{\rm dat}}{\Delta \sigma^j_{\rm dat}} \right)^2 + \left(\frac{H^j_{3,\rm mod} - H^j_{3,\rm dat}}{\Delta H^j_{3,\rm dat}} \right)^2 + \left(\frac{H^j_{4,\rm mod} - H^j_{4,\rm dat}}{\Delta H^j_{4,\rm dat}} \right)^2 \right]$$

- Best fit is determined by above eqn

$$\chi^2_{\rm SC} \equiv \min\left\{\chi^2_{\rm GH}(\Upsilon, i)/N_{\rm data}\right\},$$

$$\chi^2_{\rm LOG} \equiv \min\left\{\chi^2_{\rm GH}(r_{\rm c}, v_{\rm c}, \Upsilon, i)/N_{\rm data}\right\}$$

and

$$\chi^2_{\rm NFW} \equiv \min\left\{\chi^2_{\rm GH}(c, q, \Upsilon, i)/N_{\rm data}\right\}$$

$$\chi^2_{\rm min} \equiv \min\left\{\chi^2_{\rm LOG}, \chi^2_{\rm NFW}, \chi^2_{\rm SC}\right\}$$

- Most fits are better than $\chi^2_{\rm min}$ <0.1

Table 2. Summary of modelling results. Column (1): galaxy id (cf. Table 1); columns (2) and (3): best-fitting stellar $\Upsilon_{\rm SC}$ [$M_\odot/L_\odot$] (R_C-band) and achieved goodness-of-fit $\chi^2_{\rm SC}$ (per data point) without dark matter; columns (4)–(7): the same as columns (2) and (3), but for LOG haloes with parameters r_c (kpc) and v_c (km s^{-1}); columns (8)–(11): the same as columns (2) and (3), but for NFW haloes with concentration c and flattening q; columns (12) and (13): best-fitting halo profile with significance $\Delta\chi^2_{\rm halo} = (\chi^2_{\rm NFW} - \chi^2_{\rm LOG}) \times N_{\rm data}$; column (14): evidence for dark matter $\Delta\chi^2_{\rm DM} = (\chi^2_{\rm SC} - \chi^2_{\rm min}) \times N_{\rm data}$; column (15): inclination of best fit with minimum and maximum in the 68 per cent confidence region of calculated models (where no range is quoted, only edge-on models were calculated).

	No dark matter		LOG haloes				NFW haloes							
GMP	$\Upsilon_{\rm SC}$	$\chi^2_{\rm SC}$	$\Upsilon_{\rm LOG}$	r_c	v_c	$\chi^2_{\rm LOG}$	$\Upsilon_{\rm NFW}$	c	q	$\chi^2_{\rm NFW}$	Halo	$\Delta\chi^2_{\rm halo}$	$\Delta\chi^2_{\rm DM}$	i
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
0144	7.0	0.400	5.0	4.4	212	0.383	4.5	17.17	0.7	0.336	NFW	−2.45	3.3	50^{50}_{50}
0282	6.5	0.436	5.0	17.0	502	0.244	4.5	11.24	0.7	0.256	LOG	1.01	16.9	60^{70}_{60}
0756	3.0	1.253	2.6	12.7	215	0.930	2.2	20.2	0.7	0.942	LOG	1.57	41.3	90
1176	2.5	1.353	2.0	3.4	200	0.724	2.0	18.0	1.0	0.707	NFW	−1.8	67.2	90
1750	7.0	0.540	6.0	18.7	500	0.452	6.0	12.5	1.0	0.469	LOG	0.81	4.2	65^{90}_{65}
1990	10.0	0.301	10.0	13.1	105	0.291	9.0	24.0	1.0	0.298	LOG	0.72	1.0	90
2417	8.5	0.244	8.0	23.8	500	0.206	7.0	14.76	0.7	0.216	LOG	0.46	1.8	90
2440	7.0	0.579	6.5	10.9	482	0.453	6.5	16.47	0.7	0.475	LOG	1.69	9.6	60^{60}_{60}
2921	9.0	0.112	6.5	8.2	425	0.073	6.5	9.2	0.7	0.067	NFW	−0.47	3.3	90^{90}_{60}
3329	12.0	0.325	7.0	3.6	400	0.307	9.0	10.85	0.7	0.309	LOG	0.22	1.4	90^{90}_{45}
3510	6.0	0.425	5.5	11.6	287	0.398	5.0	16.12	0.7	0.398	LOG	0.67	2.5	90^{90}_{60}
3792	9.0	0.370	8.0	15.3	550	0.339	8.0	10.0	1.0	0.349	LOG	0.54	1.7	60^{90}_{40}
3958	6.0	0.229	5.0	6.8	274	0.162	4.0	14.7	1.0	0.174	LOG	0.42	2.4	90^{90}_{70}
4928	10.0	0.232	8.5	29.1	507	0.109	7.0	12.7	1.0	0.122	LOG	0.66	6.4	90^{90}_{70}
5279	7.0	0.132	6.5	28.4	482	0.099	6.0	15.9	0.7	0.109	LOG	0.71	2.3	90^{90}_{90}
5568	7.0	0.162	6.0	66.7	650	0.103	5.0	17.2	0.7	0.104	LOG	0.12	5.2	90^{90}_{50}
5975	4.0	0.580	3.0	1.7	200	0.333	3.0	15.0	0.7	0.314	NFW	−1.37	19.1	90

Model Inclinations

- Most of the best fits are edge on
  - Does this mean there is a bias in model?
- Possible biases
  - Using the same α for all galaxies
  - For face on galaxies, noise in kinematics
  - Non random inclinations
  - Bias due to extreme cases

Model Inclinations 2

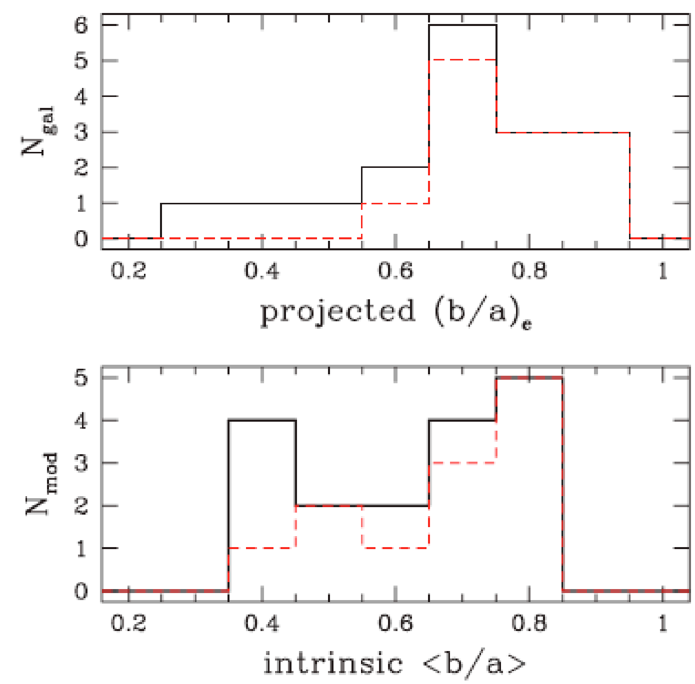


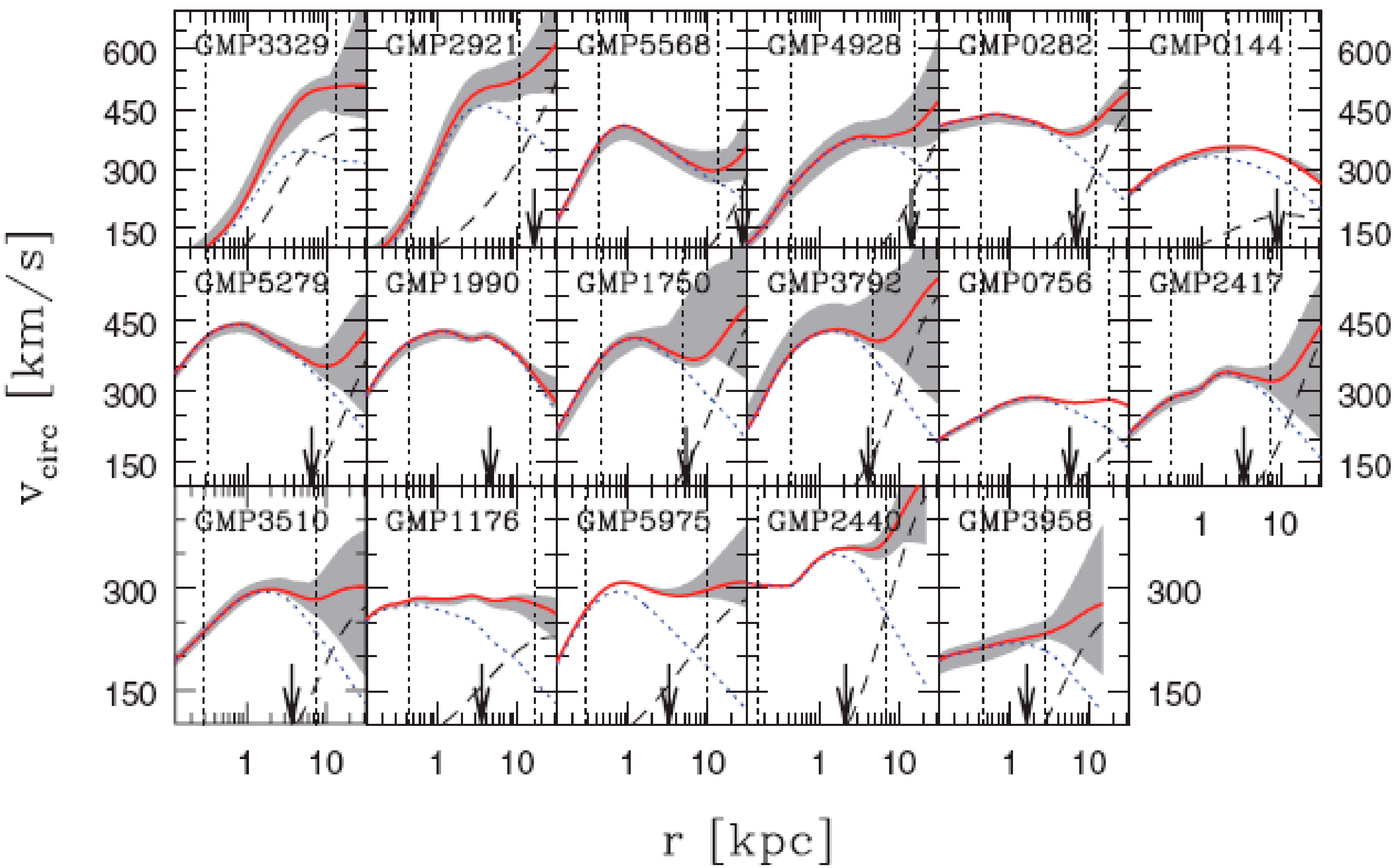
Figure 3. Top panel: histogram of apparent short-to-long axial ratios at $r_{\rm eff}$. Bottom panel: intrinsic best-fitting short-to-long axial ratio $\langle b/a \rangle$ (averaged over $r/r_{\rm eff} \in [0.5, 2.5]$). Black/solid line: whole sample; red/dashed line: without S0s.

- Top: Axial ratio from data (apparently)
- Bottom: Axial ratio from models
- If biased, we would see most galaxies at 1.

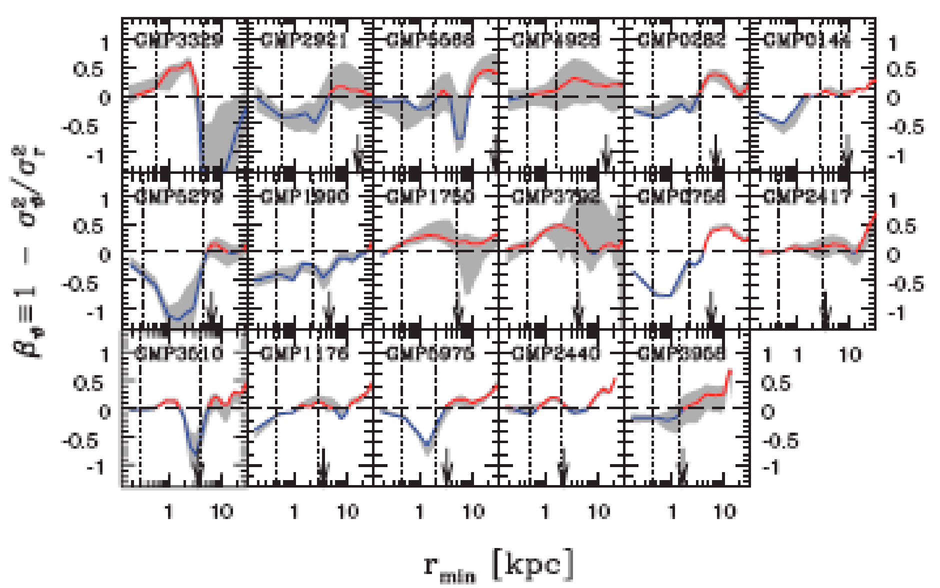
Luminous and Dark Matter

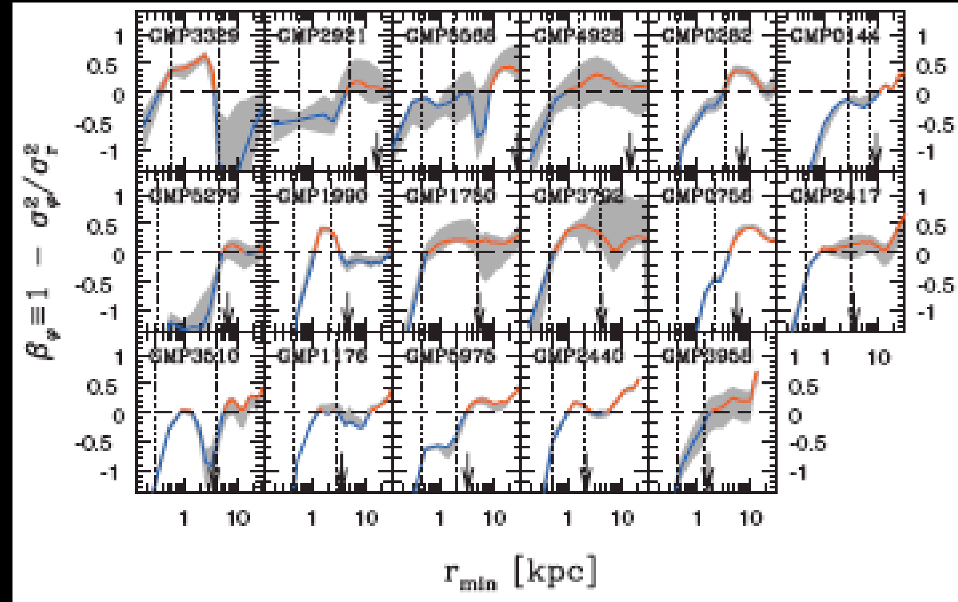
- Does mass follow light?
  - Best fitting models include a dark matter halo.
- All galaxies fall into 3 categories
  - Inconsistent with a constant mass to light ratio (8/17)
  - Models with and without dark matter differ but, evidence for DM is less than 2σ (5/17)
  - Evidence for DM is generally weak (4/17)

Circular velocity curves



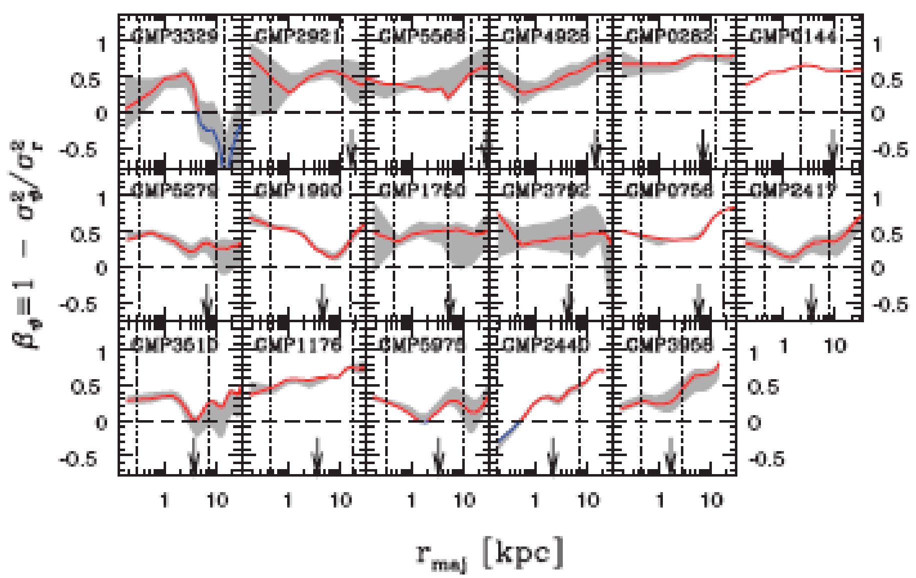
Velocity Anisotropy

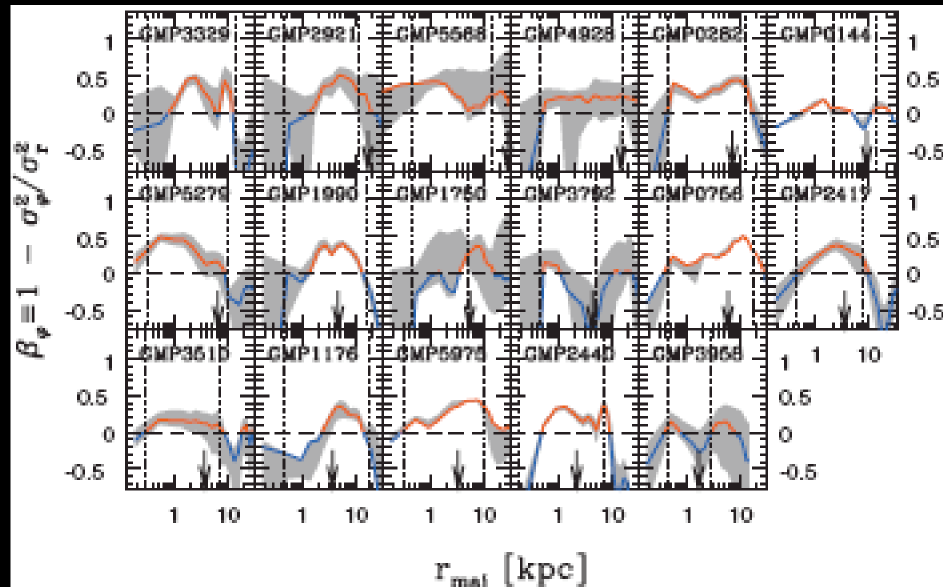




- Polar region
  - $\beta_\upsilon = \beta_\varphi$ due to axial symmetry
  - Center is not constrained
  - Galaxies differ in amount of anisotropy

Velocity Anisotropy



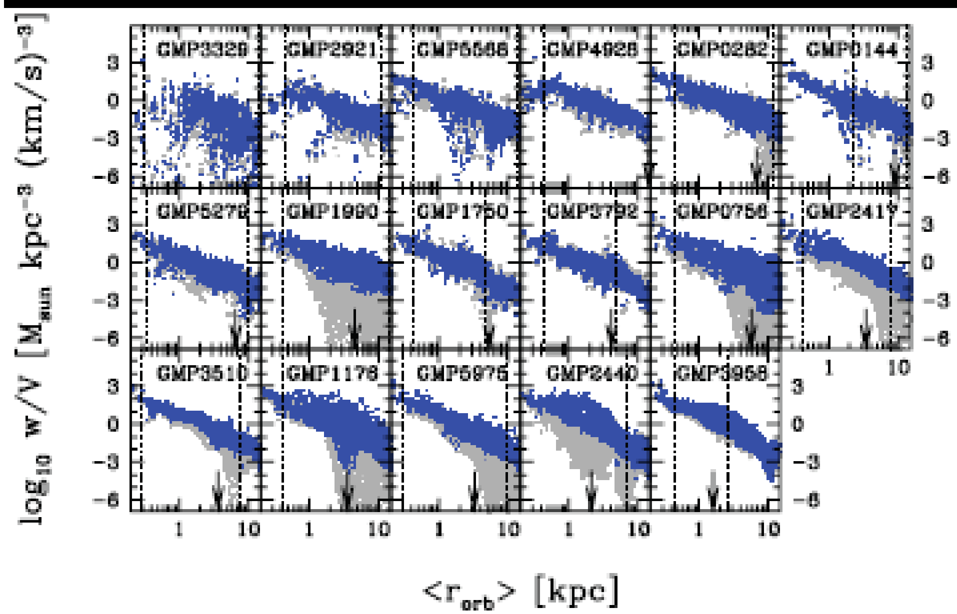


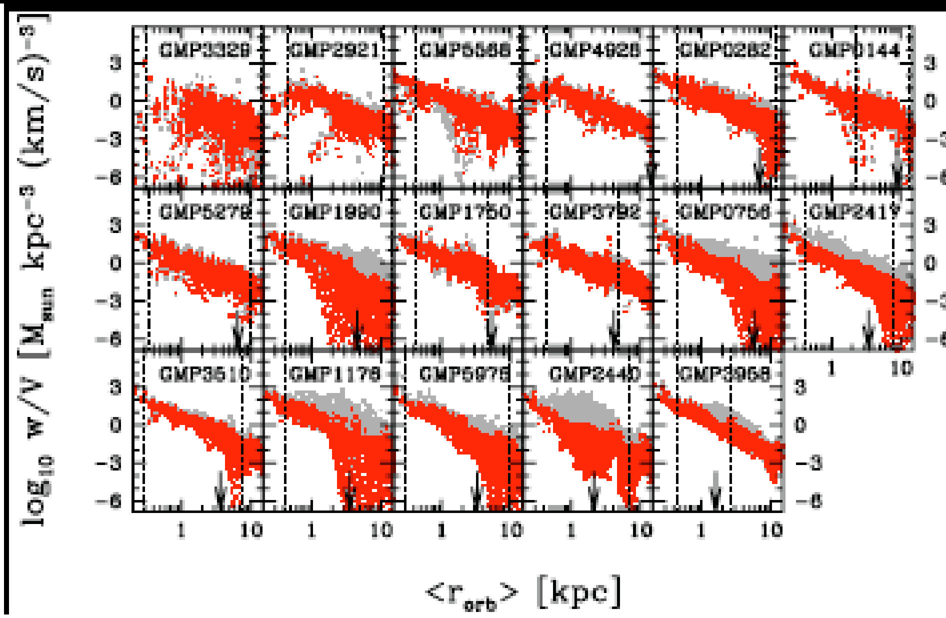
- Equatorial Plane
  - Meridional
    - All have $\beta\nu$ >0 over sampled range.
    - Average $\beta\nu$ is related to flattening of galaxy
    - Poorly constrained
  - Azimuthal
    - Much more diverse than Meridional

Phase-Space Distribution Function of the Stars

- Stationary systems
  - DF is function of the isolating integrals
  - Constant along an orbit
    - Look at: Energy, Lz, 3rd integral, be positive
  - Since the Schwarzschild model exists, it ensures that the luminous component of the model is stationary and physically meaningful

$$\langle r_{\rm orb}\rangle_i \equiv \sum_k \frac{\Delta t_i^k}{T_i} r_i^k ,$$



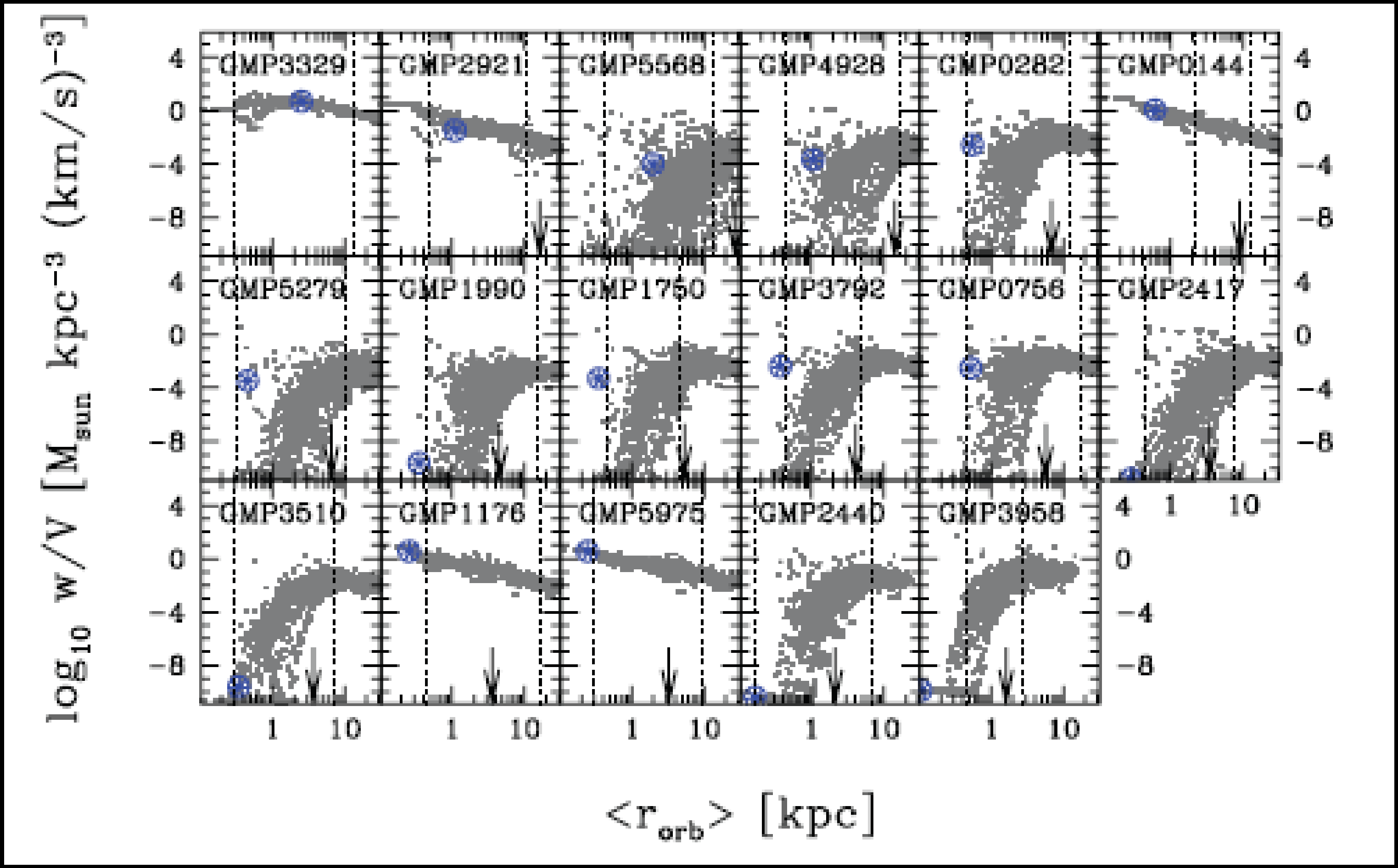


Phase Space Distribution Function of Dark Matter

- Without baryons, DF's for halo profiles are known. But with baryons it is not so.
- To find DM DF, solve: $\hat{S} \equiv S - \alpha\, \chi^2_{\mathrm{LOSVD}} \rightarrow \max$
- But, with alpha = 0
- Use dark matter profile as boundary condition
- Turns out that there does exist a DF for the DM.

LOG vs NFW

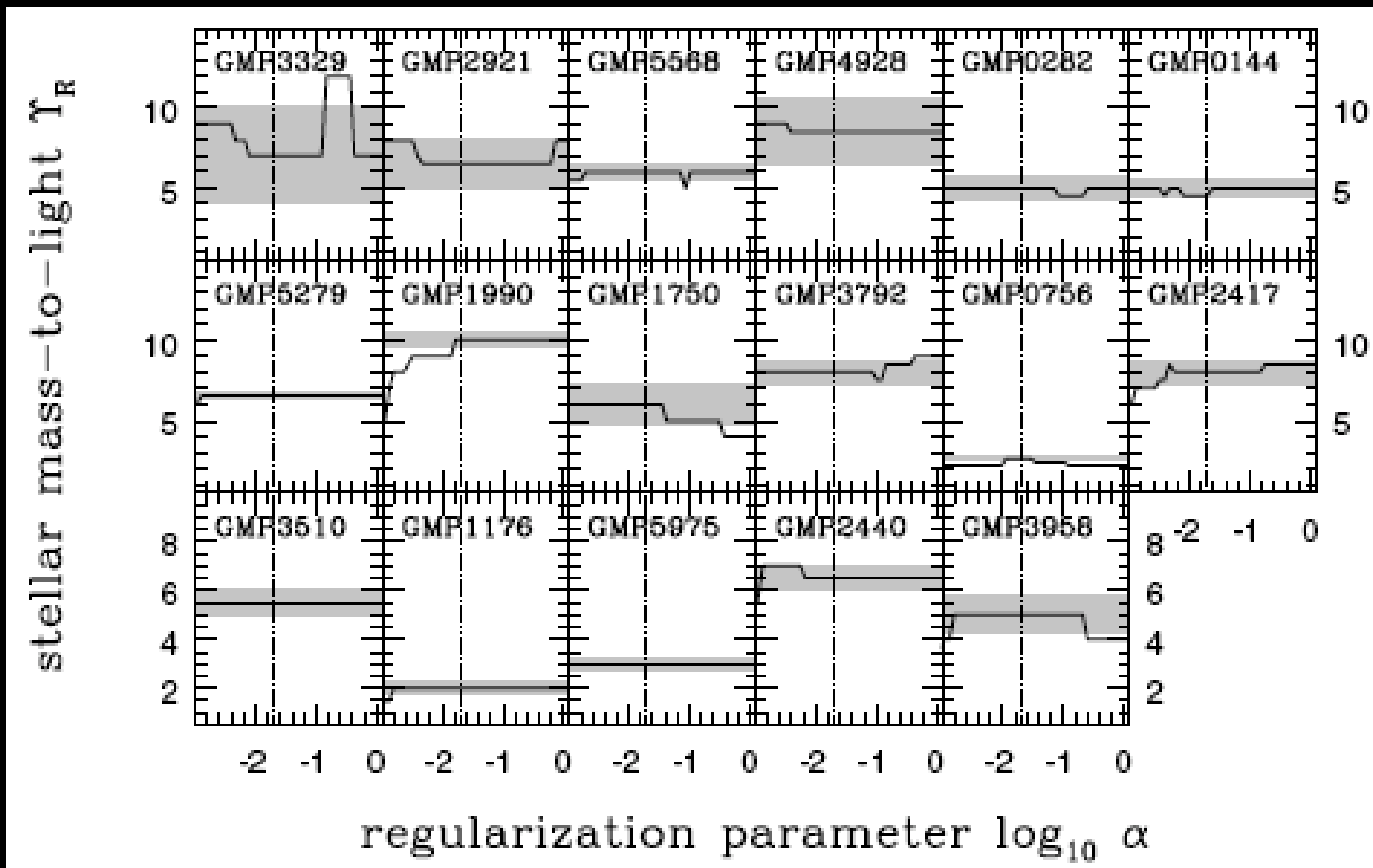
- 13 of 17 best fit haloes are LOG
- Significance of fit between profiles is low. No clear distinction can be made.
- With kinematic data, one or the other halo type cannot be rules out.
- Shape and structure of LOG halo DFs do make them unlikely

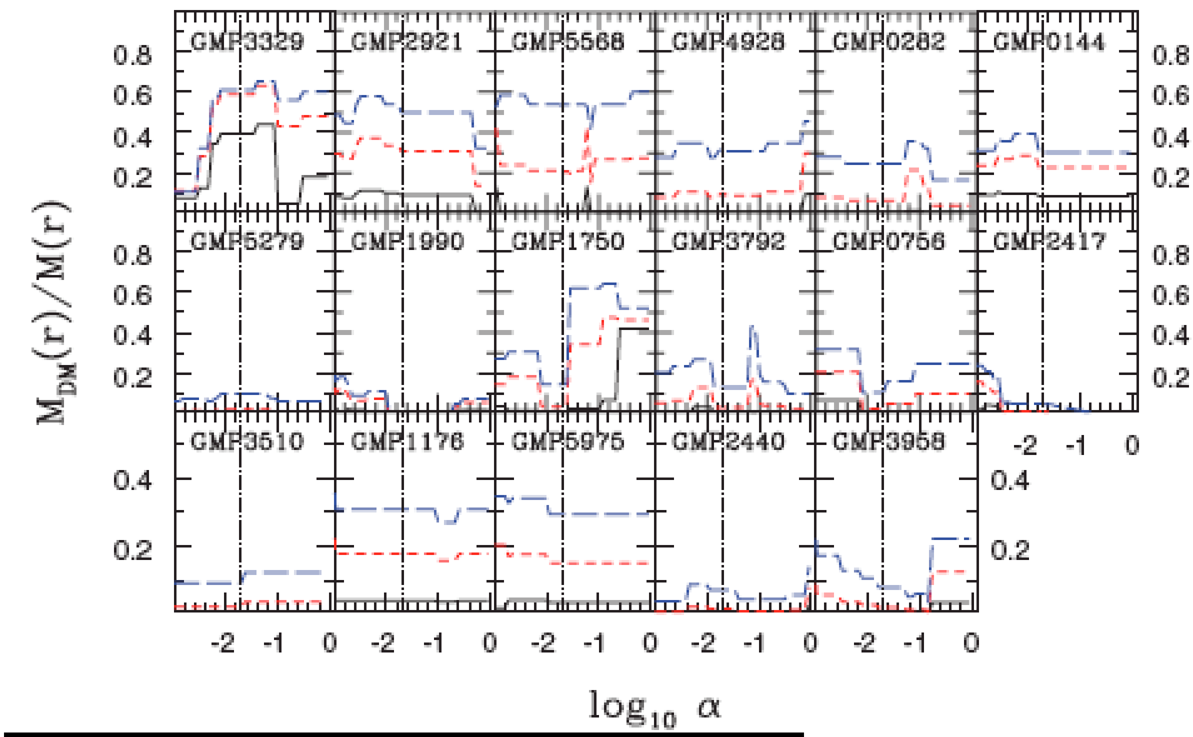


- Dark Matter phase space densities

Regularization

- α = 0.02 was chosen for all Coma Galaxies.

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GMP2921
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GMP0144
GMP5279
GMP1990
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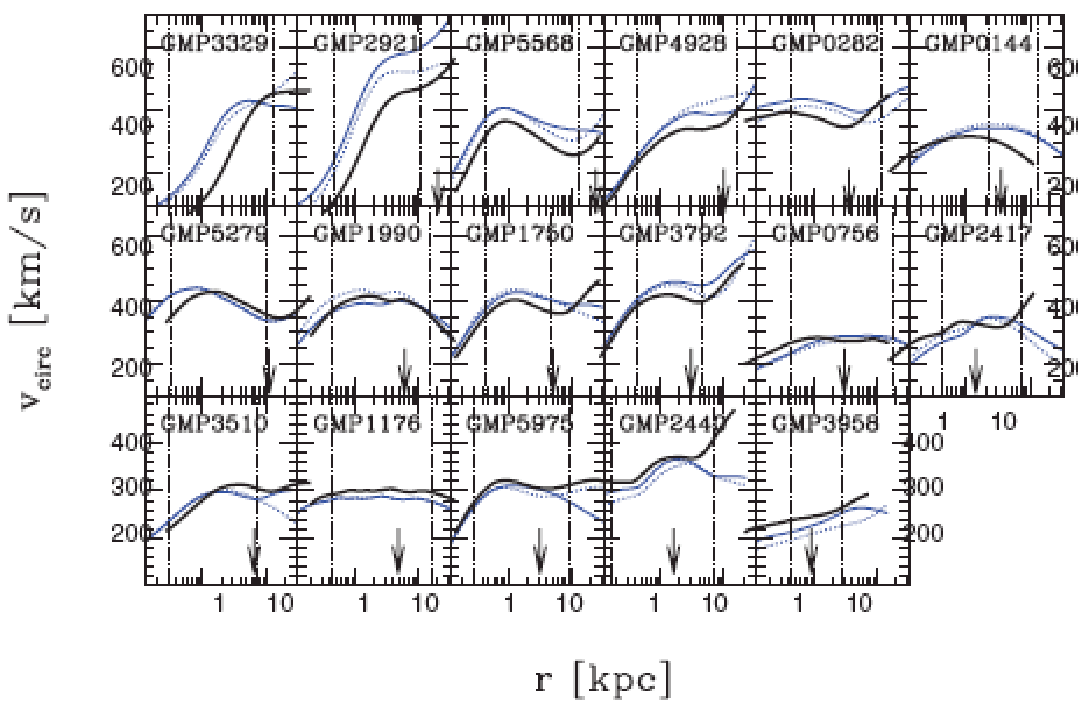
GMP5975
GMP2440
GMP3958
$M_{DM}(r)/M(r)$
$\log_{10} \alpha$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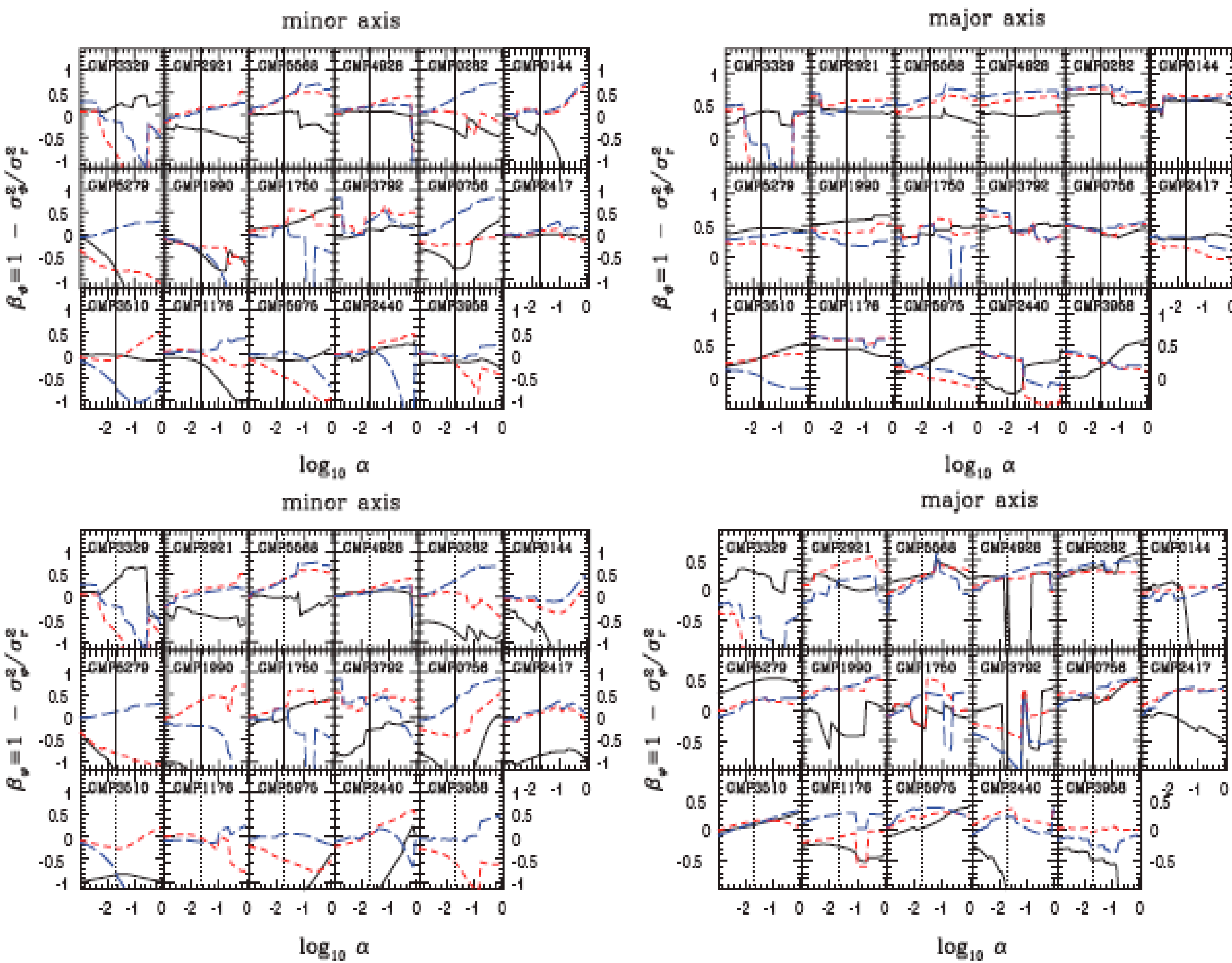
GMP3510
GMP1176
GMP5975
GMP2440
GMP3958
v_{circ} [km/s]
r [kpc]

α Influence on Model Kinematics

- Minor Axis
  - Max entropy fits (α->0) yield isotropy
  - Lowering the weights (w) increases anisotropy
- Major Axis
  - No trend as seen in minor axis
  - Variations in intrinsic velocity anisotropies with alpha are weaker than along minor axis
- Bottom Line: No clear trend of velocity anisotropies with α is notable


minor axis
major axis
minor axis
major axis
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GMP3792
GMP0756
GMP2417
GMP3510
GMP1176
GMP5975
GMP2440
GMP3958
$\beta_\vartheta = 1 - \sigma_\vartheta^2/\sigma_r^2$
$\beta_\varphi = 1 - \sigma_\varphi^2/\sigma_r^2$
$\log_{10} \alpha$

Summary I

- 17 Coma Early-type galaxies surveyed
  - Axisymmetric Schwarzschild models used to fit LOSVDs out to 1-4 Reff.
  - 2 Different profiles used
  - Models regularized towards maximum entropy

Summary II

- Models with dark matter fit better than those without.
- NFW haloes fit 4/17 best
- LOG haloes fit 13/17 best
- Central Dark matter densities are at least 1-2 orders of magnitude lower than mass densities
- Between 10-50 % of mass inside Reff is dark matter
- Circular velocities is fairly constant over observed region
- All dark haloes are supported by al least 1 phase space DF

Summary III

- Rotation comes from overpopulation of prograde orbits and underpopulation of retrograde orbits
- Strong tangential anisotropy along minor axis
- α does not matter!

Ok. Now I am done.

- Questions? Comments? Rude Remarks?

- Thanks!