Testing gravity and dark matter

in NGC 2419

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with:

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A. Mucciarelli (UniBo)

Testing MOND in star clusters

The basic idea:

If you consider the external region of the less dense clusters their stars should move in the deep MOND regime.

Given the same underlying mass and orbit distribution, these stars must display a larger velocity dispersion in MOND than what is expected in Newtonian gravity.

Testing MOND in star clusters

Scarpa et al. 2003,
Baumgardt et al. 2005,
Moffat & Toth 2008,
Haghi et al. 2009, 2011,
Jordi et al. 2009,
Lane et al. 2009, 2010,
Gentile et al. 2010,
etc.

However only clusters at large distances from the centre of the MW can be used since, independently of the “internal” acceleration, if the acceleration from the Galactic Potential is $\gtrsim a_0$, the cluster will NOT BE IN THE MOND REGIME.

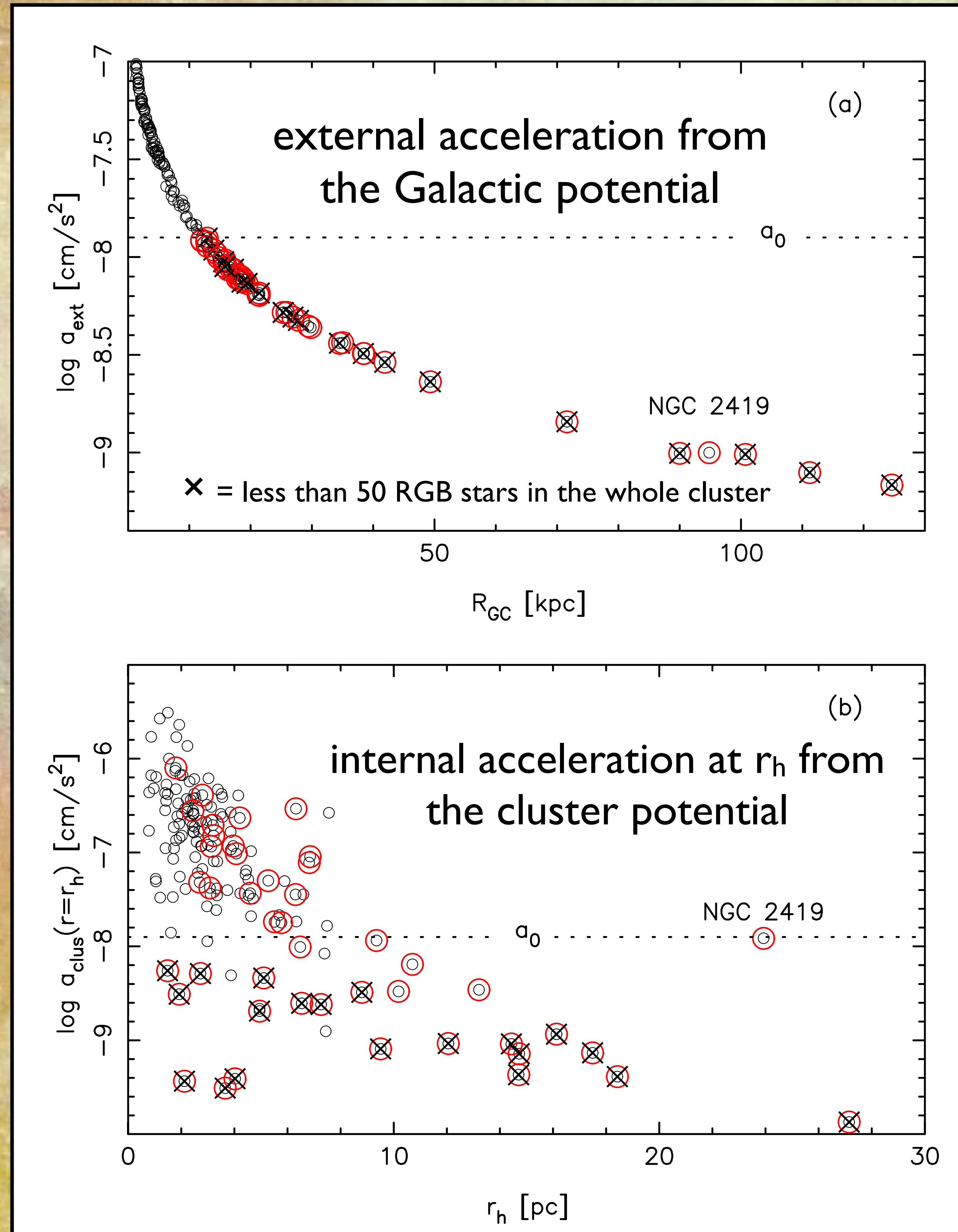
But in the MW the safely remote clusters are rare and very faint: only a handful of Red Giants are accessible to 8m class telescopes for accurate ($\leq$ 2 km/s) RV estimates ==> poor sampling of the σ profile

Milky Way globular clusters

Need clusters sufficiently remote that the acceleration from the gravitational field of the galaxy is significantly lower than a_0.
At R_{gc}> 50 kpc : six clusters, all very faint except NGC2419

A UNIQUE EXCEPTION:
NGC2419 at ~90 kpc with M_V=-9.5

half-mass relaxation time 43Gyr



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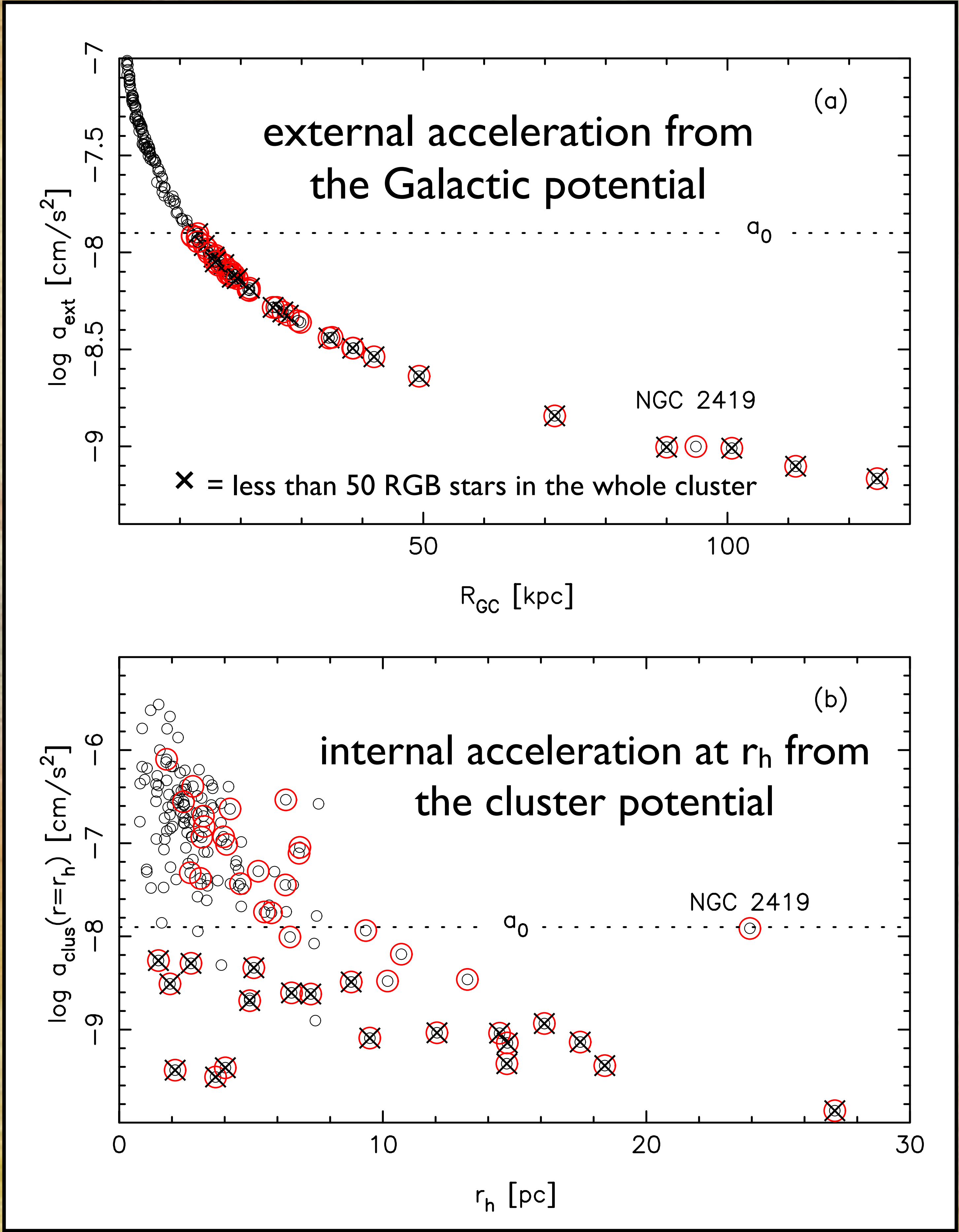
NGC 2419 stands out clearly as best globular cluster target to test MOND



NGC 2419

NGC2419: approximately at the same distance as Pal14 but 76 times brighter!!!
Studied by Baumgardt et al. 2009 and by us: Ibata et al. 2011a, b, 2012

Pal14: the best available study of the kinematics
for a MOND-testing cluster [Jordi et al. 2009]

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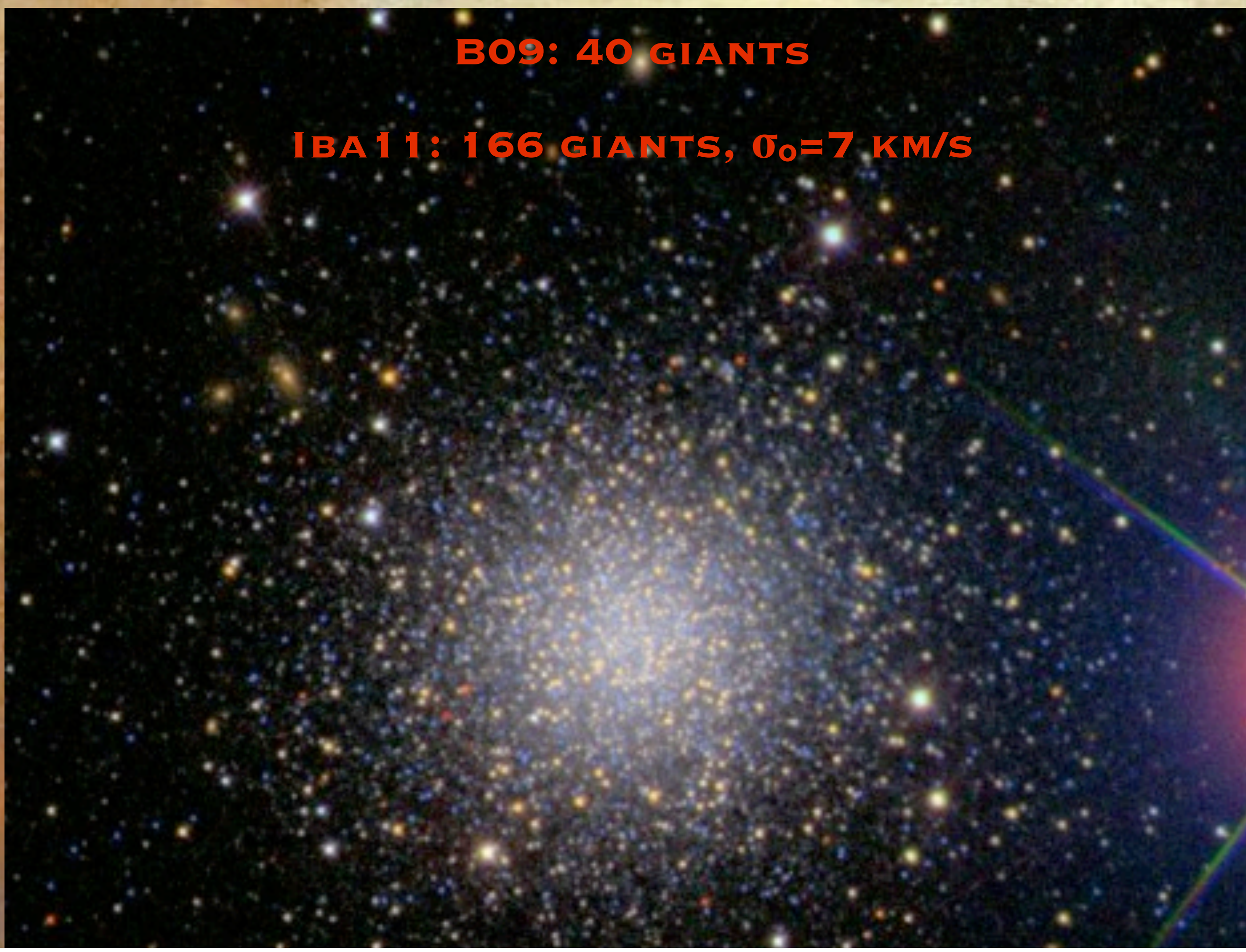

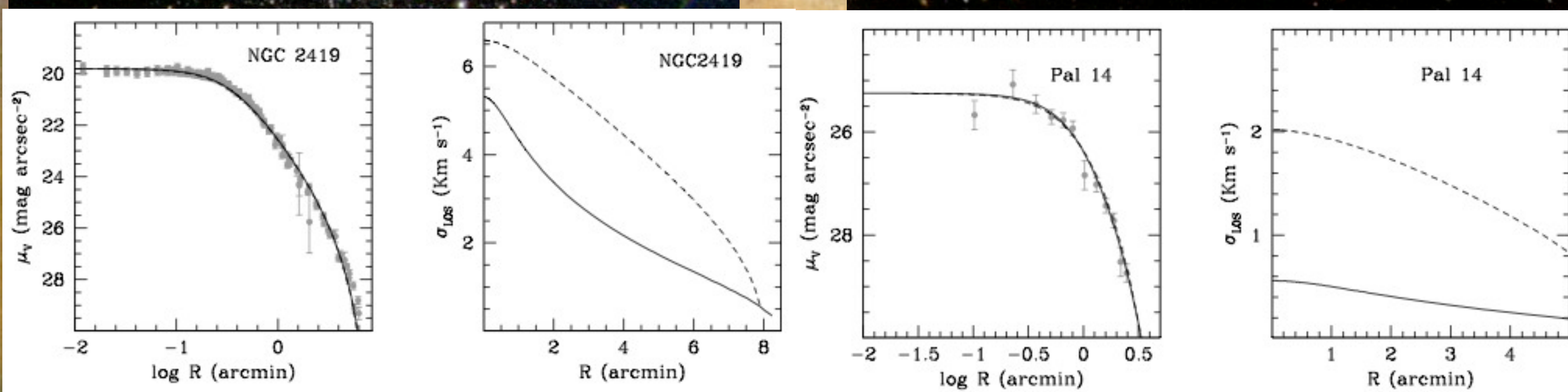

NGC 2419

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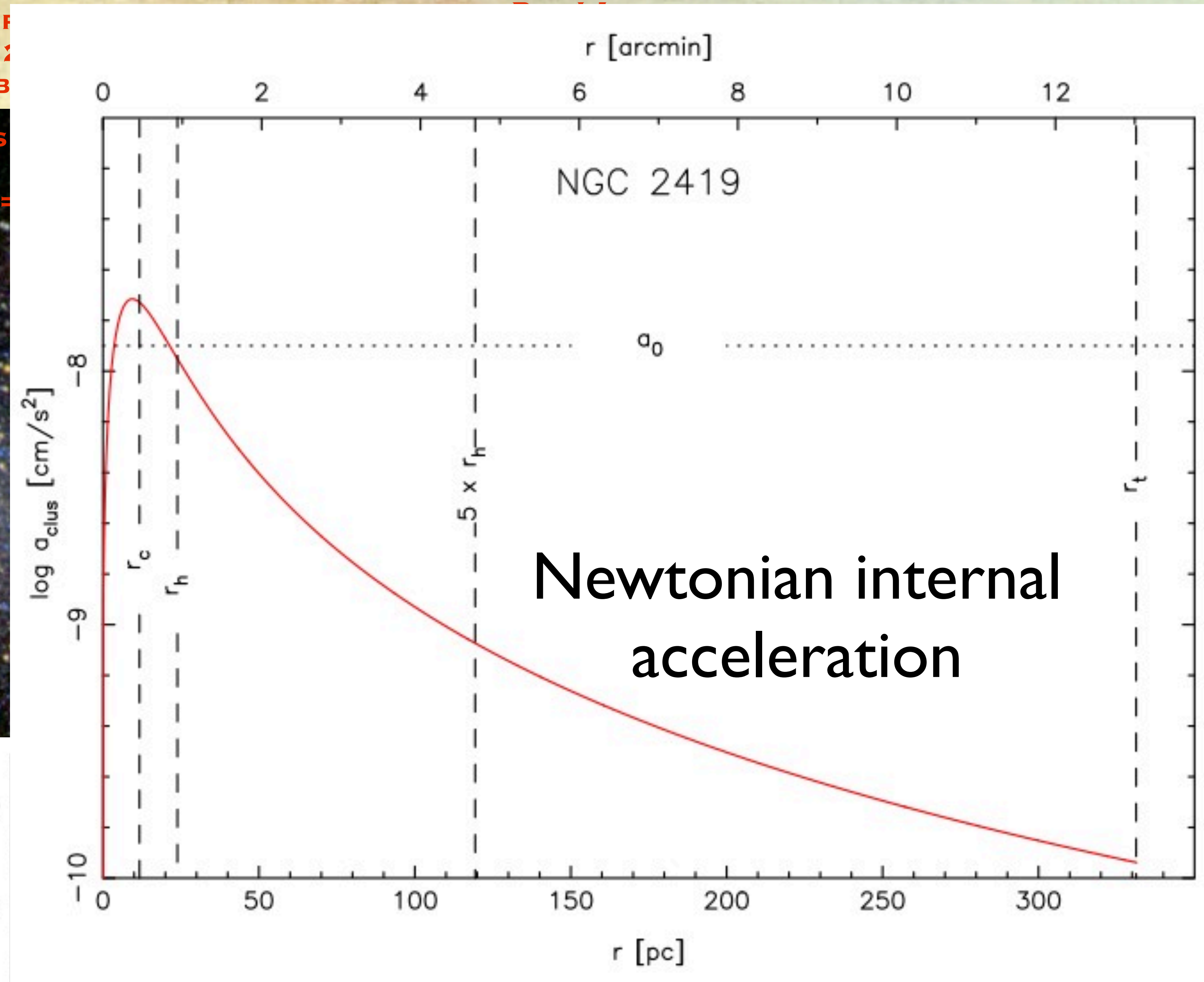
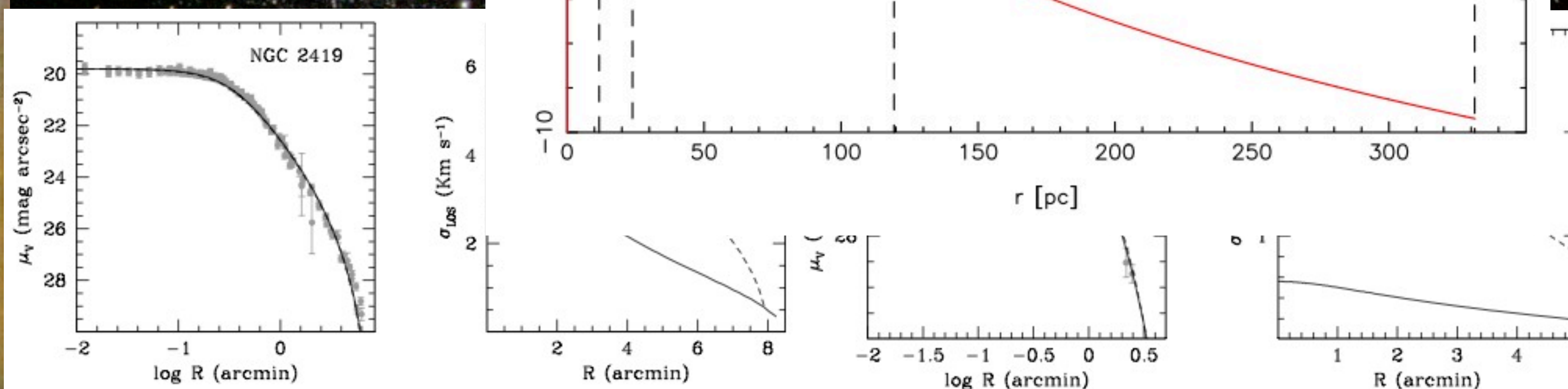
Studied by Baumgardt et al. 2…
Ibata et al. 2011a, b…

B09: 40 giants…

Iba11: 166 giants, σ_0=…



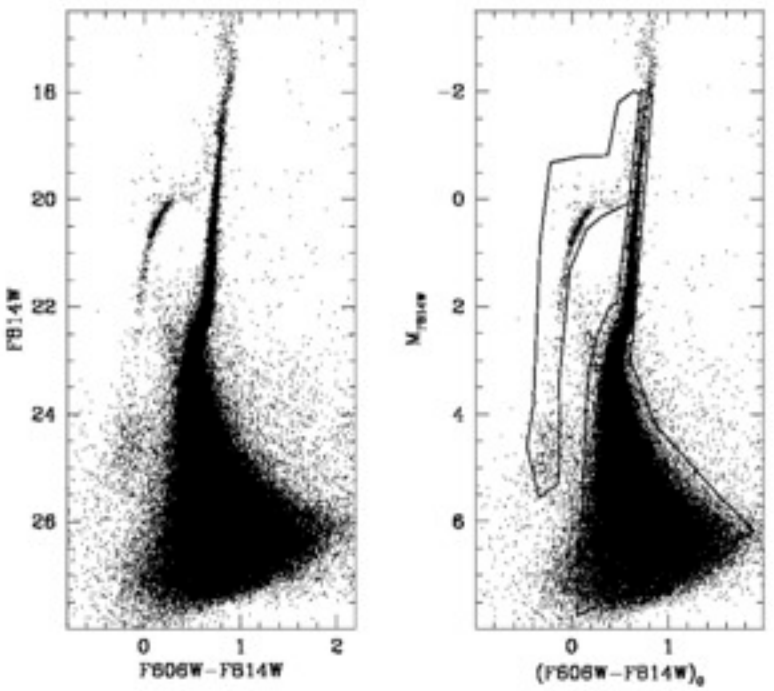


The Data Set

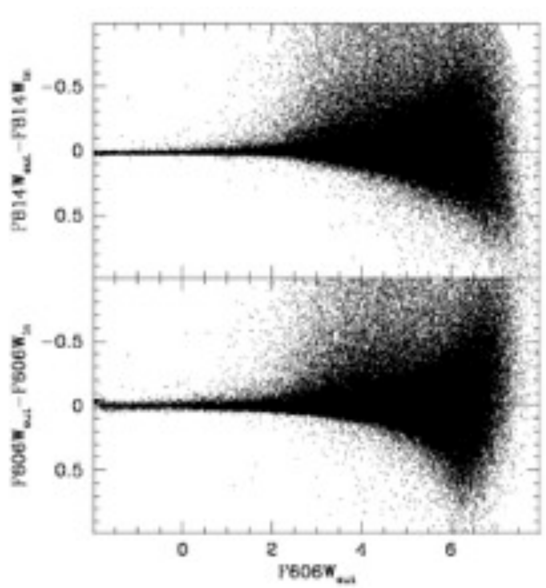
- Photometry:
  - Subaru imaging of the 0.5deg x 0.5deg field around the cluster
  - ACS deep imaging of the core (Dalessandro et al. 2008)
  - TNG imaging (Bellazzini 2007)
  - WFC3 deep imaging (Bellazzini et al. 2012)
- Spectroscopy:
  - HIRES: 40 stars (Baumgardt et al. 2009)
  - DEIMOS: 126 member stars

The stellar component of NGC 2419

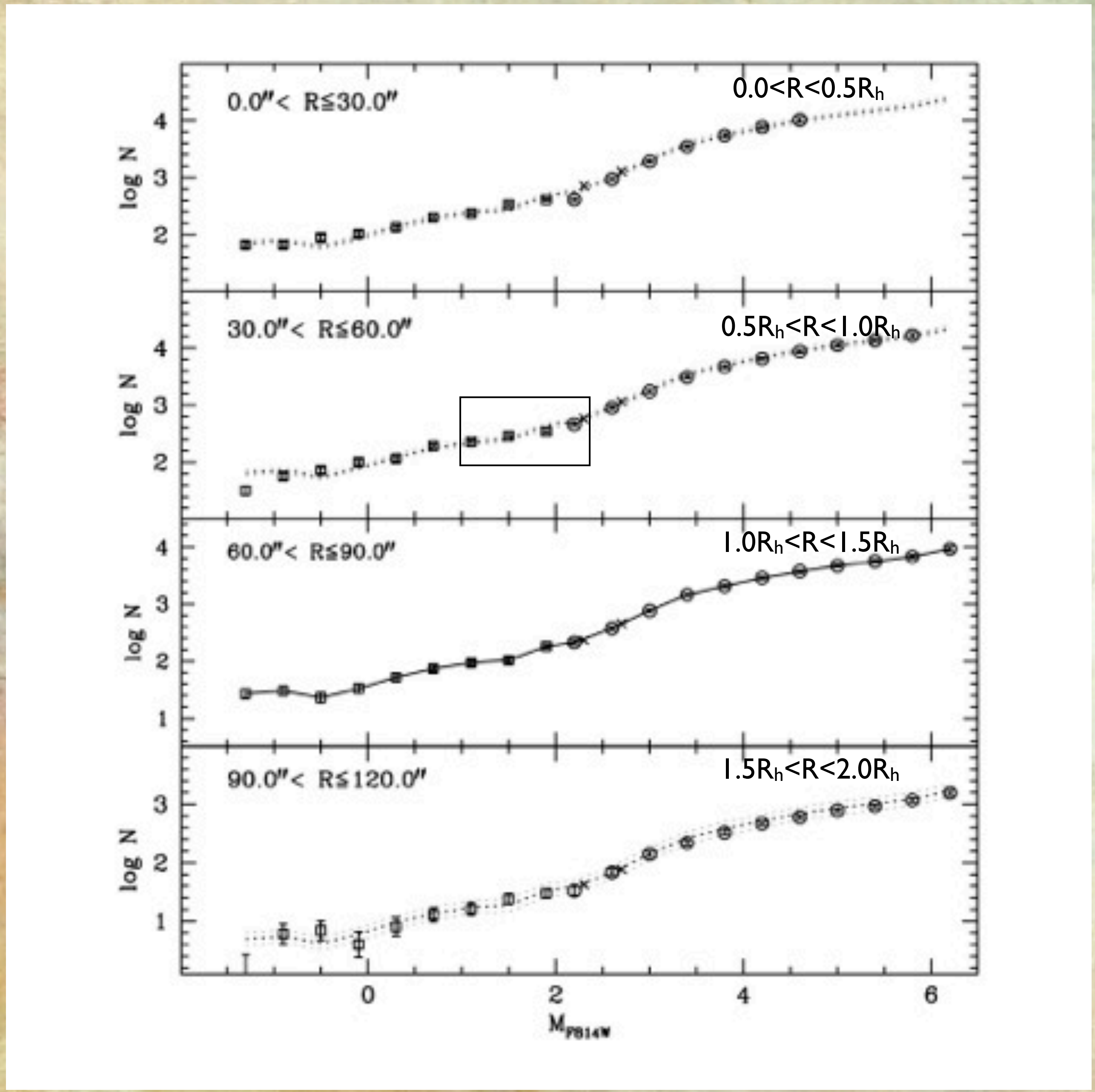
The deepest photometry from new HST WFC3-UVIS data



Extensive Artificial Stars Experiments



Bellazzini et al. 2012



Result: LF is constant with radius, so no sign of mass segregation

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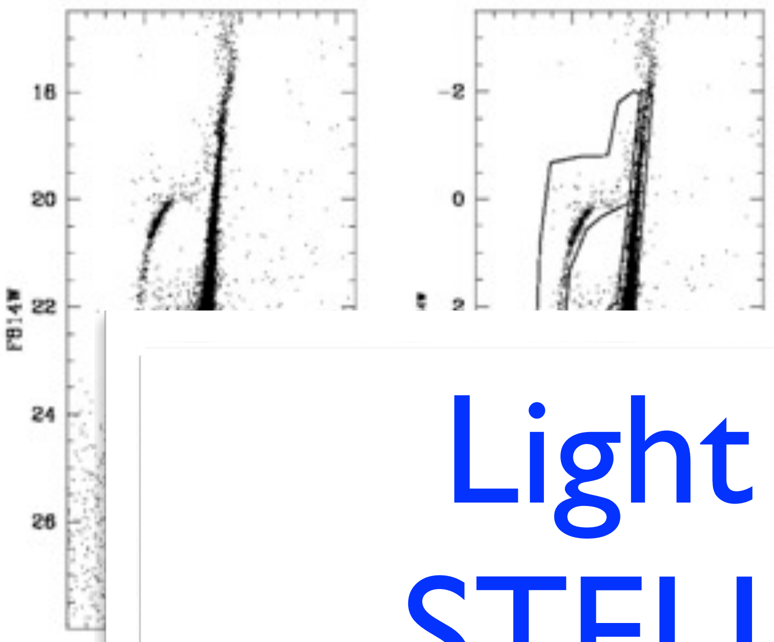

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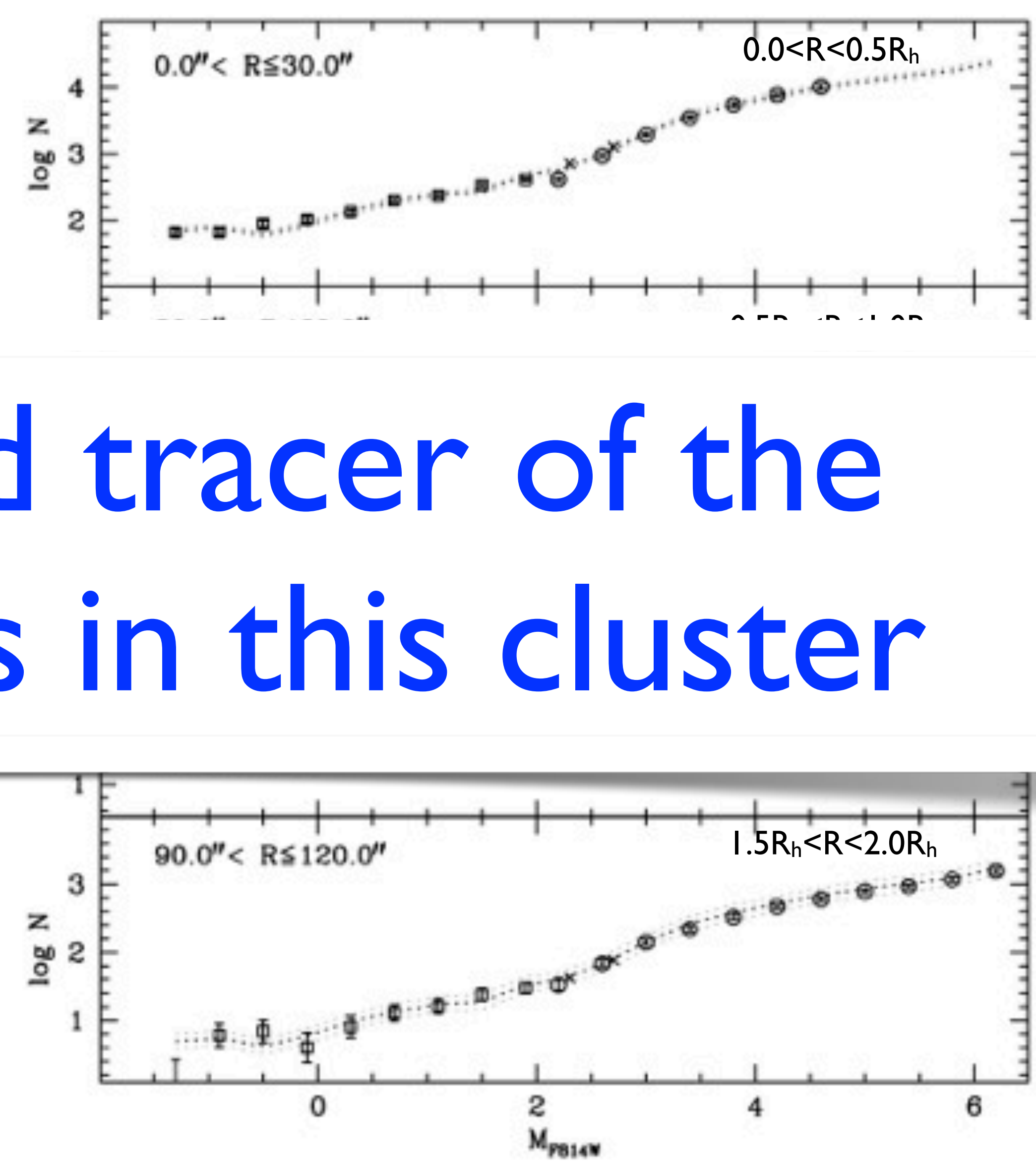

Light is a good tracer of the STELLAR mass in this cluster

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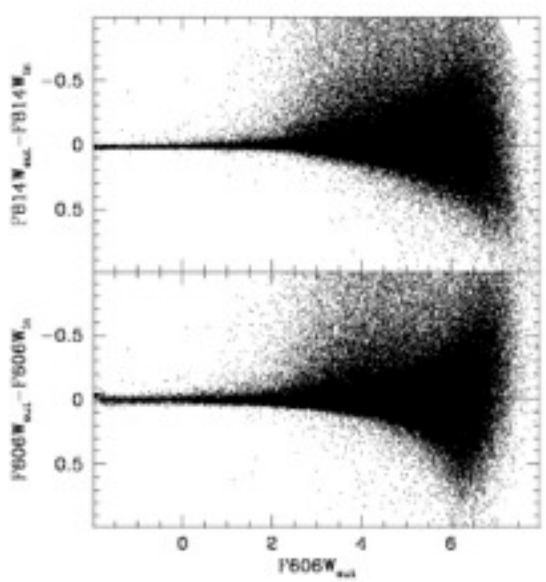

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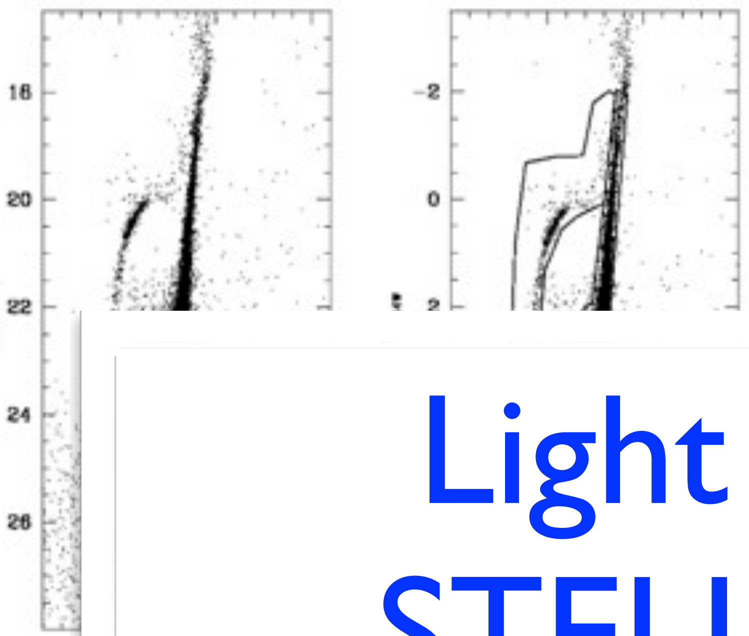

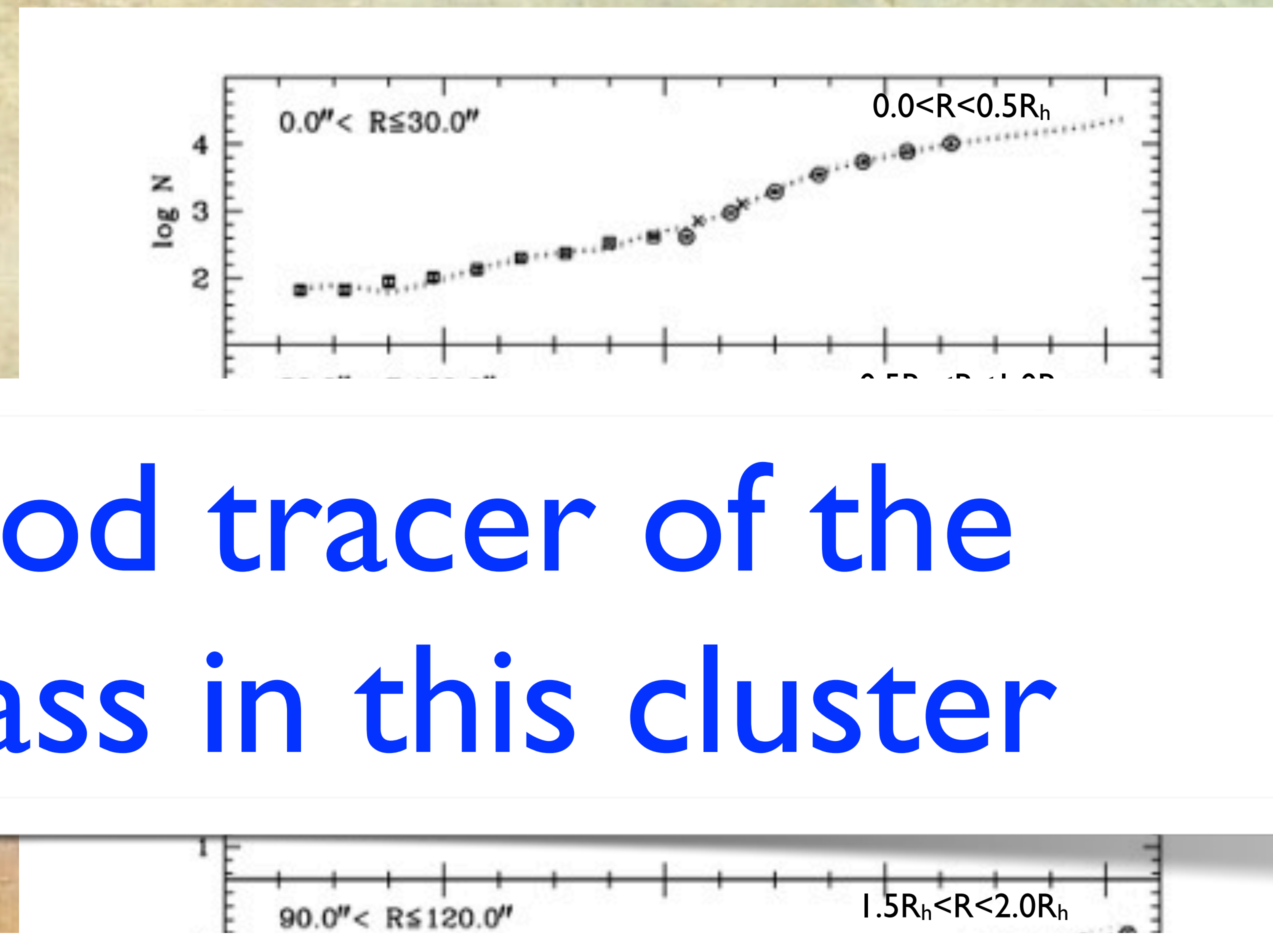

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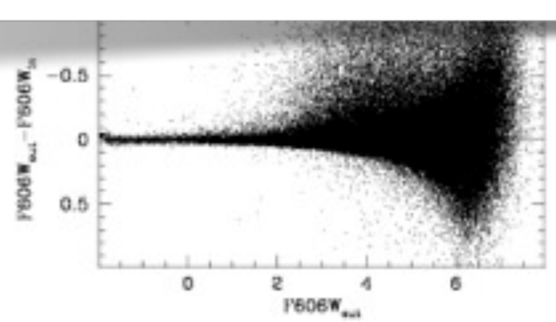

BEST FIT $M/L_V=1.5\pm0.1$

ROBUST LOWER LIMIT $M/L_V>0.8$

Result: LF is constant with radius, so no sign of mass segregation

Spectroscopy and kinematics

previous work:
Baumgardt et al. (2009)
Keck/HIRES

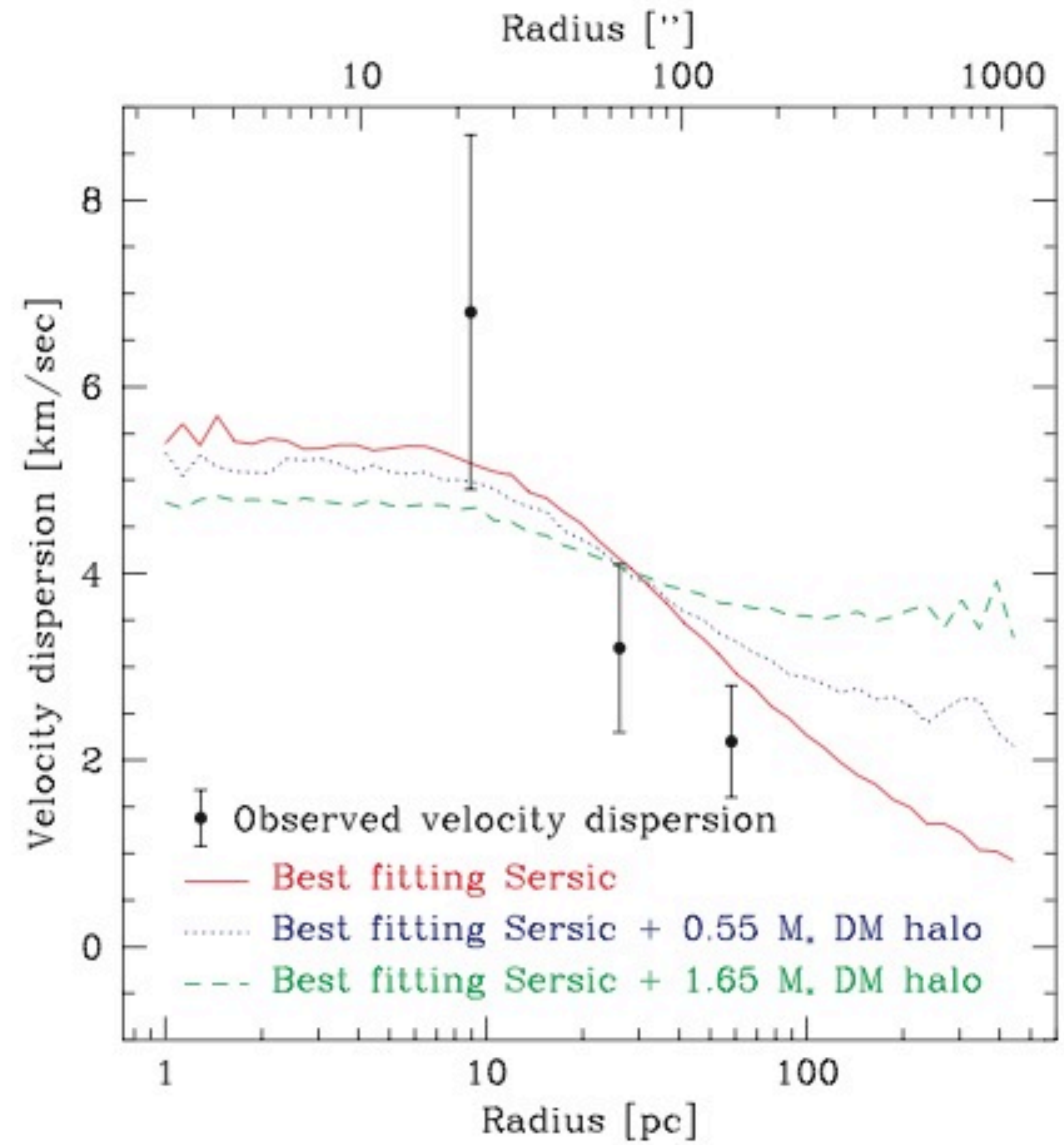

Figure 7. Observed velocity dispersion as a function of radius. The solid line shows our prediction based on the best-fitting cored Sérsic model. Dotted and dashed lines show the predicted velocity dispersion if we add NFW haloes with a scale radius of $R_S = 500\,\mathrm{pc}$ and masses of $M_{DM} = 4 \times 10^6$ and $10^7\,M_\odot$ inside R_S to this model. Models with additional DM haloes significantly overpredict the velocity dispersion in the outer parts, showing that NGC 2419 does not possess a dSph-like DM halo.

Spectroscopy and kinematics

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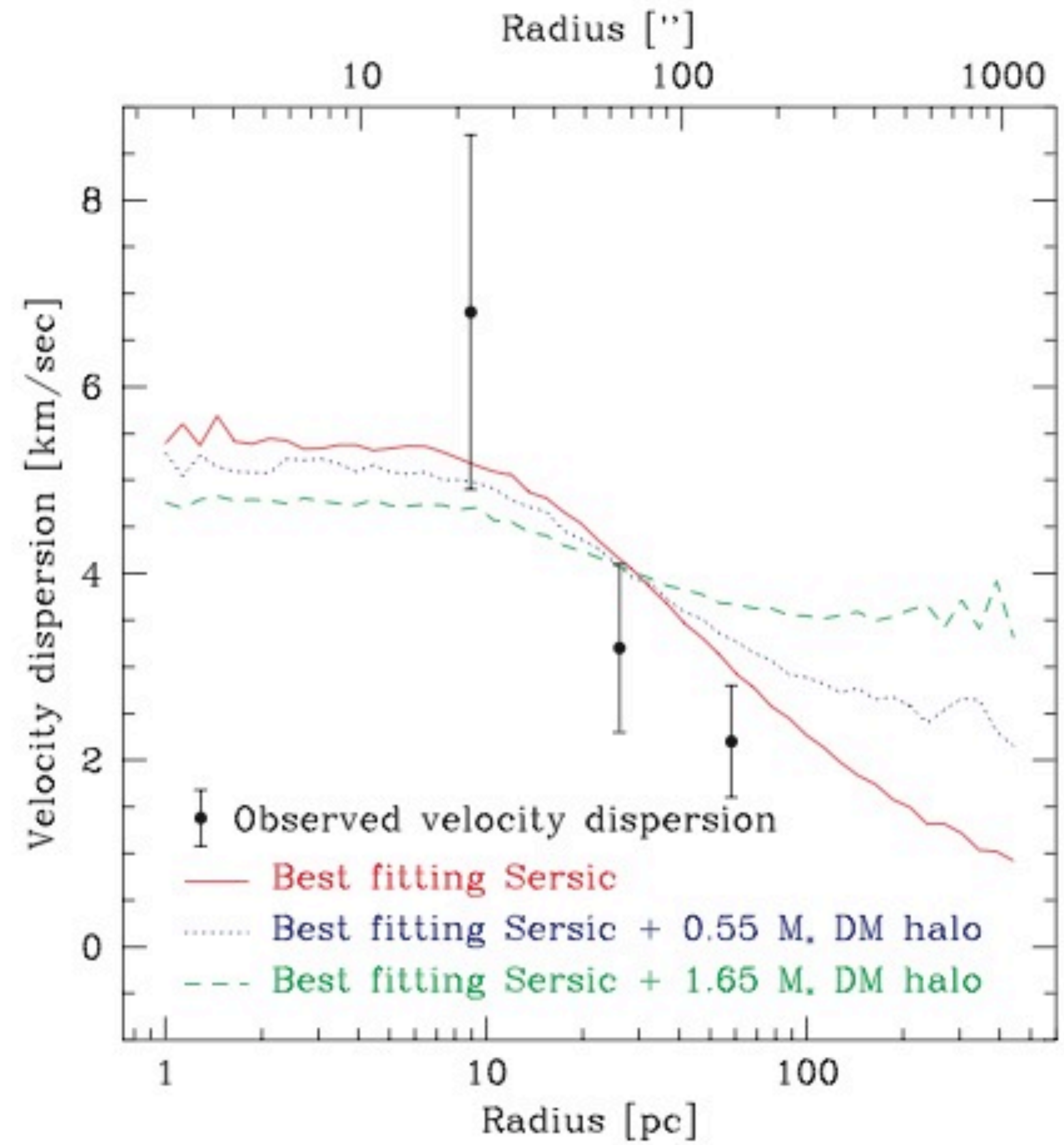
Can we do better than this?



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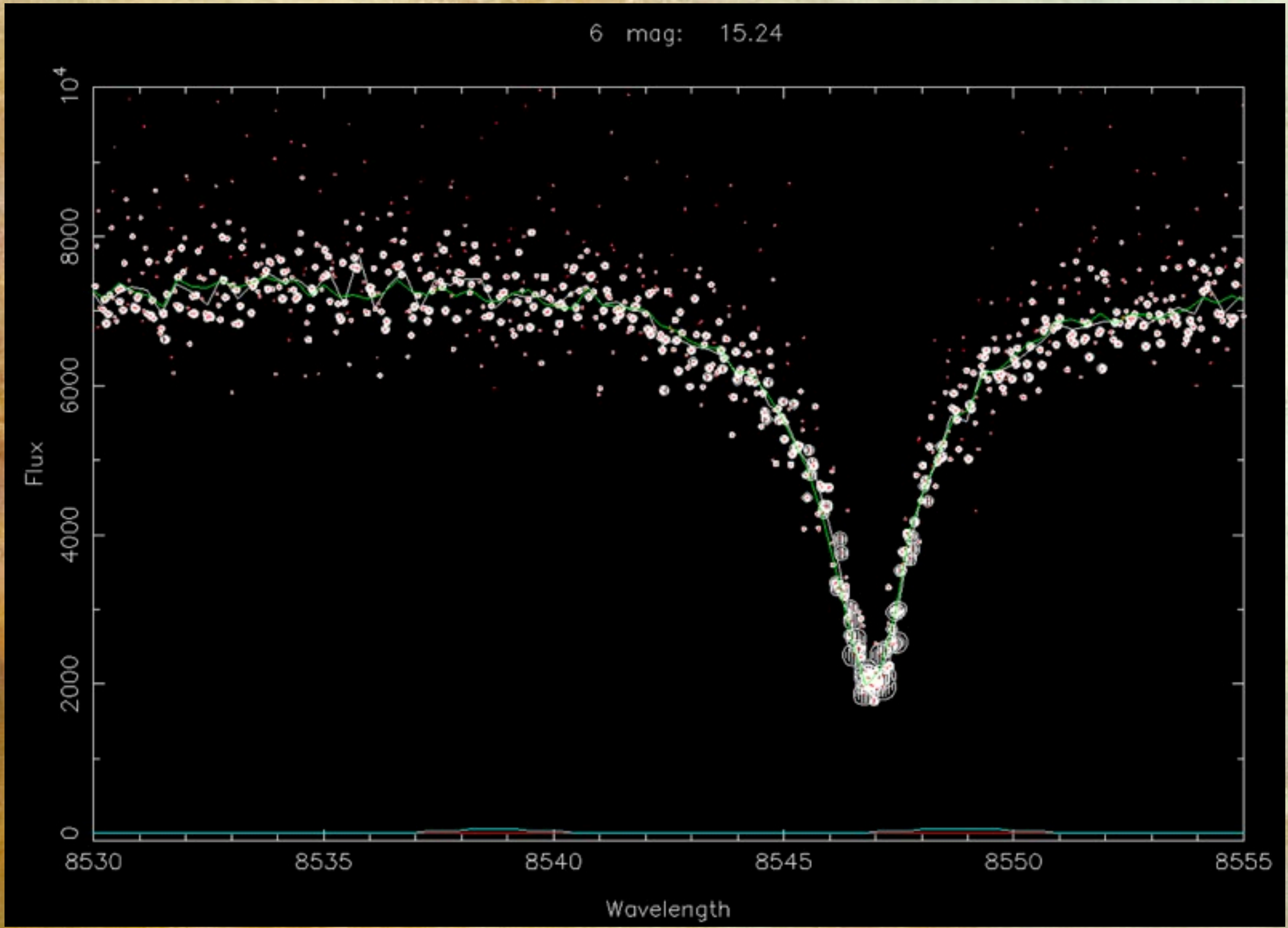
DEIMOS spectroscopy

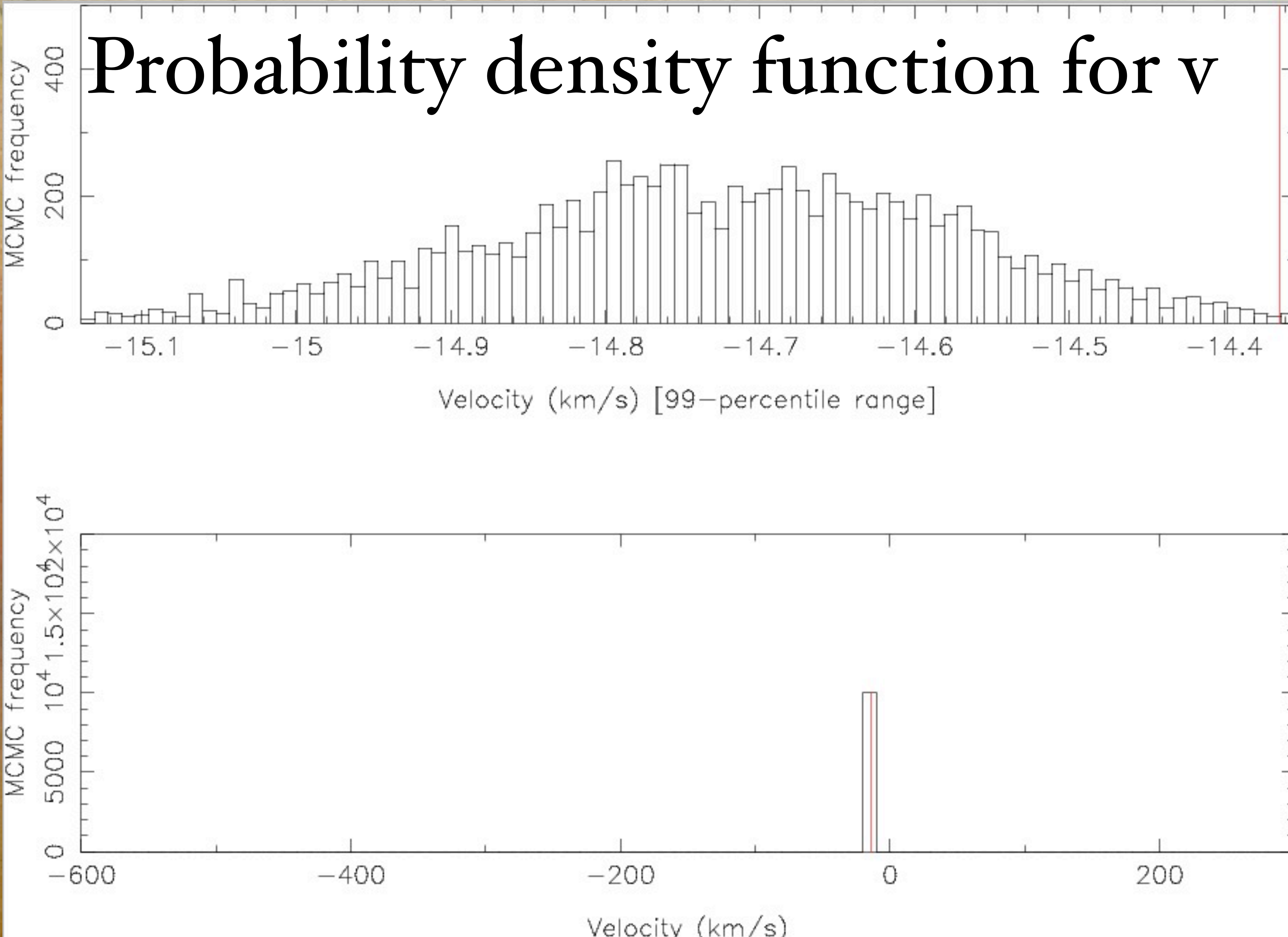
- State-of-the-art multi-object spectrograph on Keck2
- With 1200l/mm grating, one can realistically measure velocities at the sub-km/s level (though positioning issues)
- In 1hr integrations at 1Mpc : 5-10km/s for RGB tip
- 150-200 targets/field (normal) ; more with special modes
- For NGC2419 project: 2 masks with 3 x 1200 s exposures

New DEIMOS pipeline:
philosophy - leave the data alone!

- First-pass sky-subtract and extract
- Do 2-D sky-subtraction on non-resampled data (B-spline)
- Do optimal extraction with least-squares interpolating spline AND also just extract pixel table & uncertainties
- Velocities: weighted cross-correlation and maximum-likelihood fit to non-resampled data
- Measure also equivalent widths of CaII, NaI, and (Si/Mg)


6 mag: 15.24
10^4
8000
6000
4000
2000
0
Flux
8530
8535
8540
8545
8550
8555
Wavelength

Probability density function for v



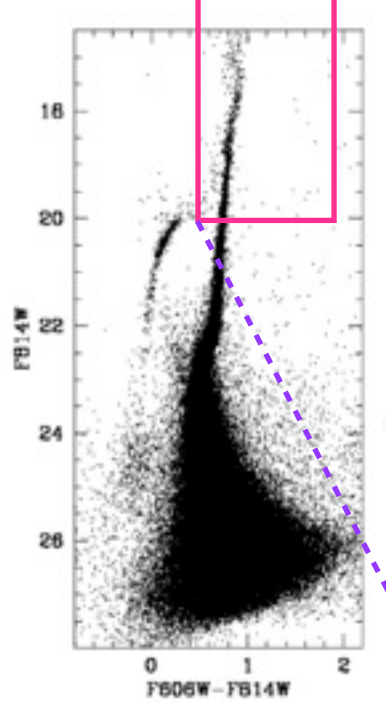
Advantages of new pipeline

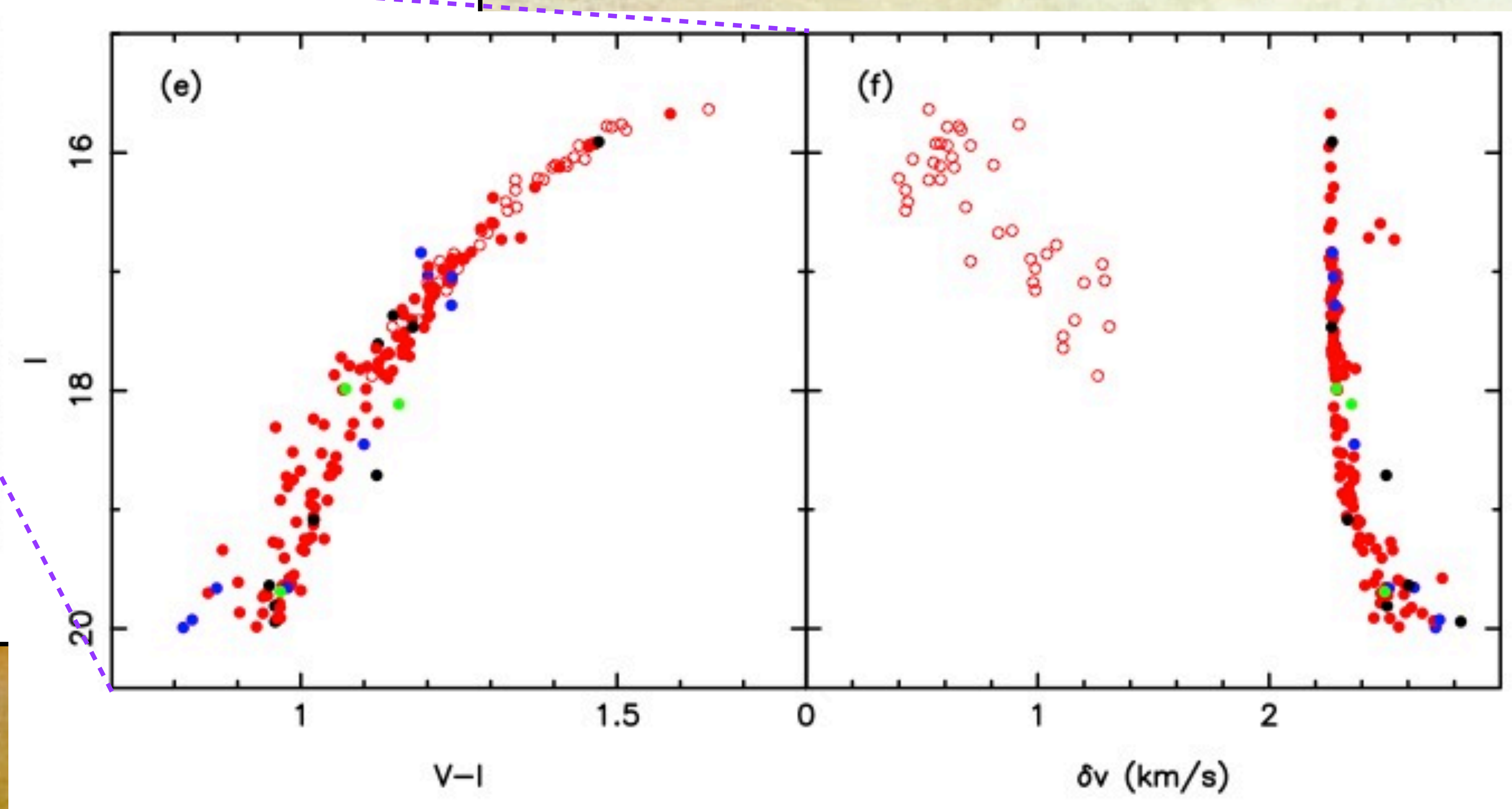
- Reduces data that DEEP2 cannot handle
  - normal masks; tightly-packed slits,
  - "Mega"-masks; "holes" masks
- Zero-resampling keeps maximum resolution
- Allows max-likelihood velocity measurements (and reliable uncertainties - which is key to what comes next)

The kinematic sample

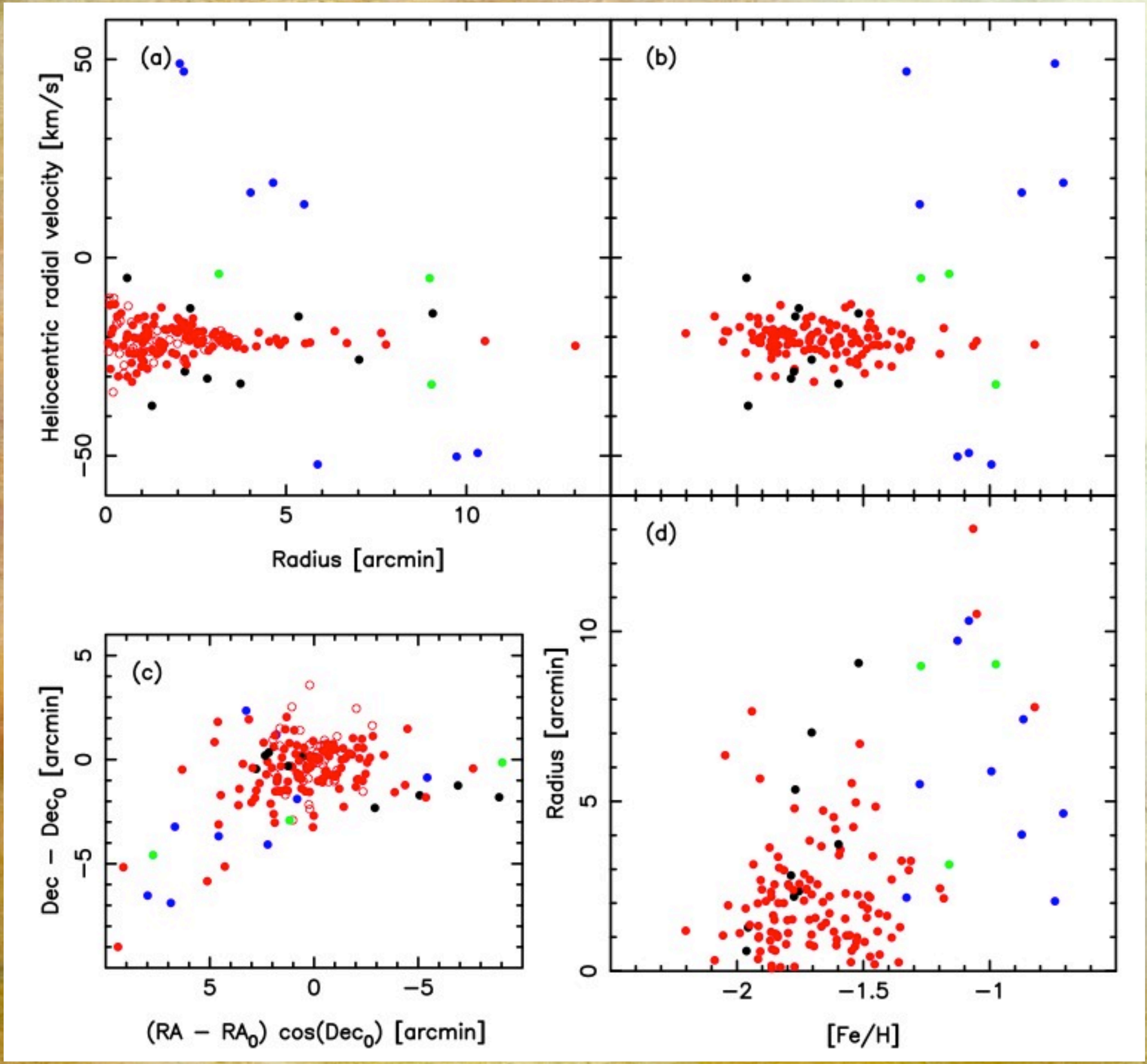
126 stars (DEIMOS)+ 40 stars (Baumgardt)

The deepest photometry from new HST WFC3-UVIS data

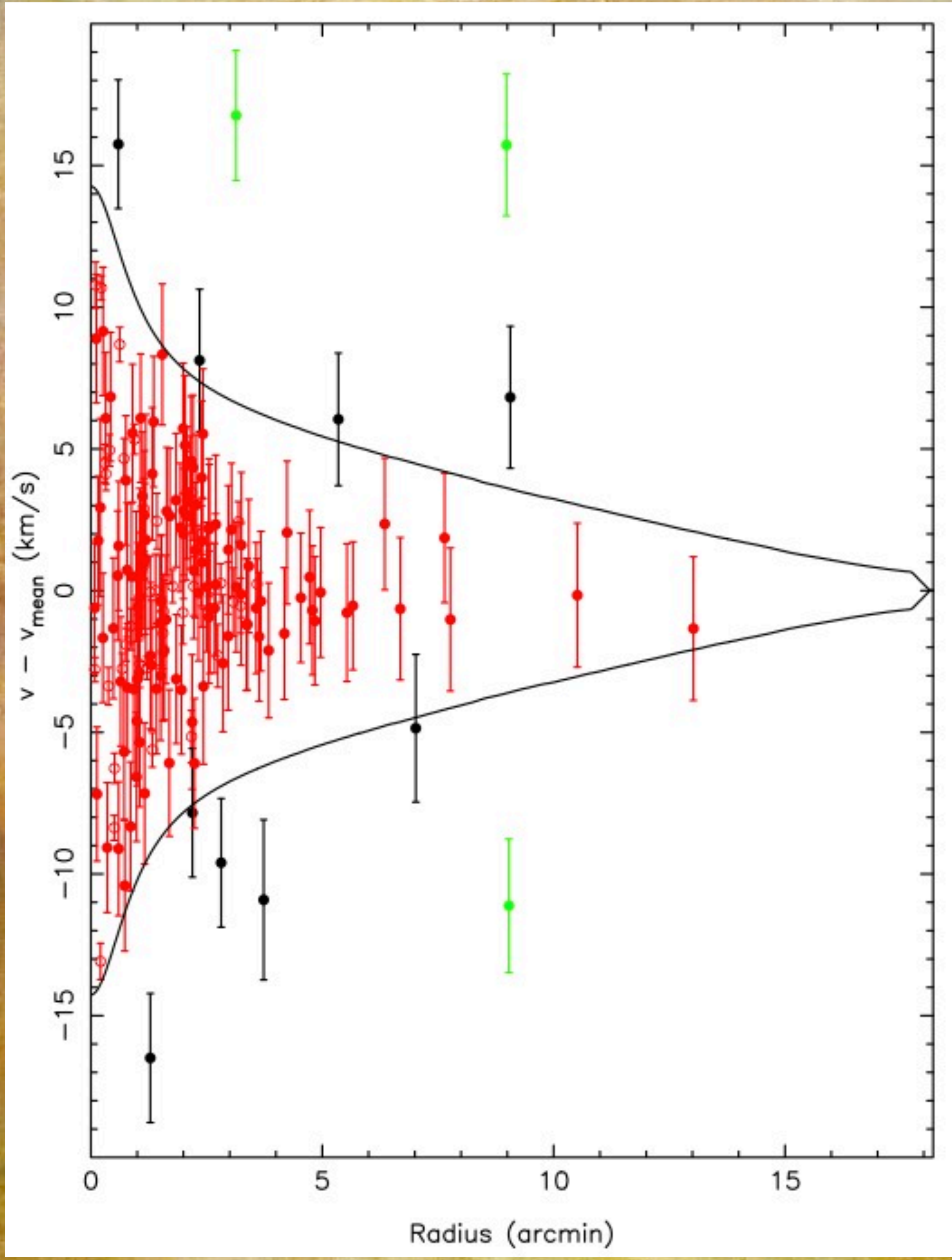




rms of repeats: 0.7 km/s



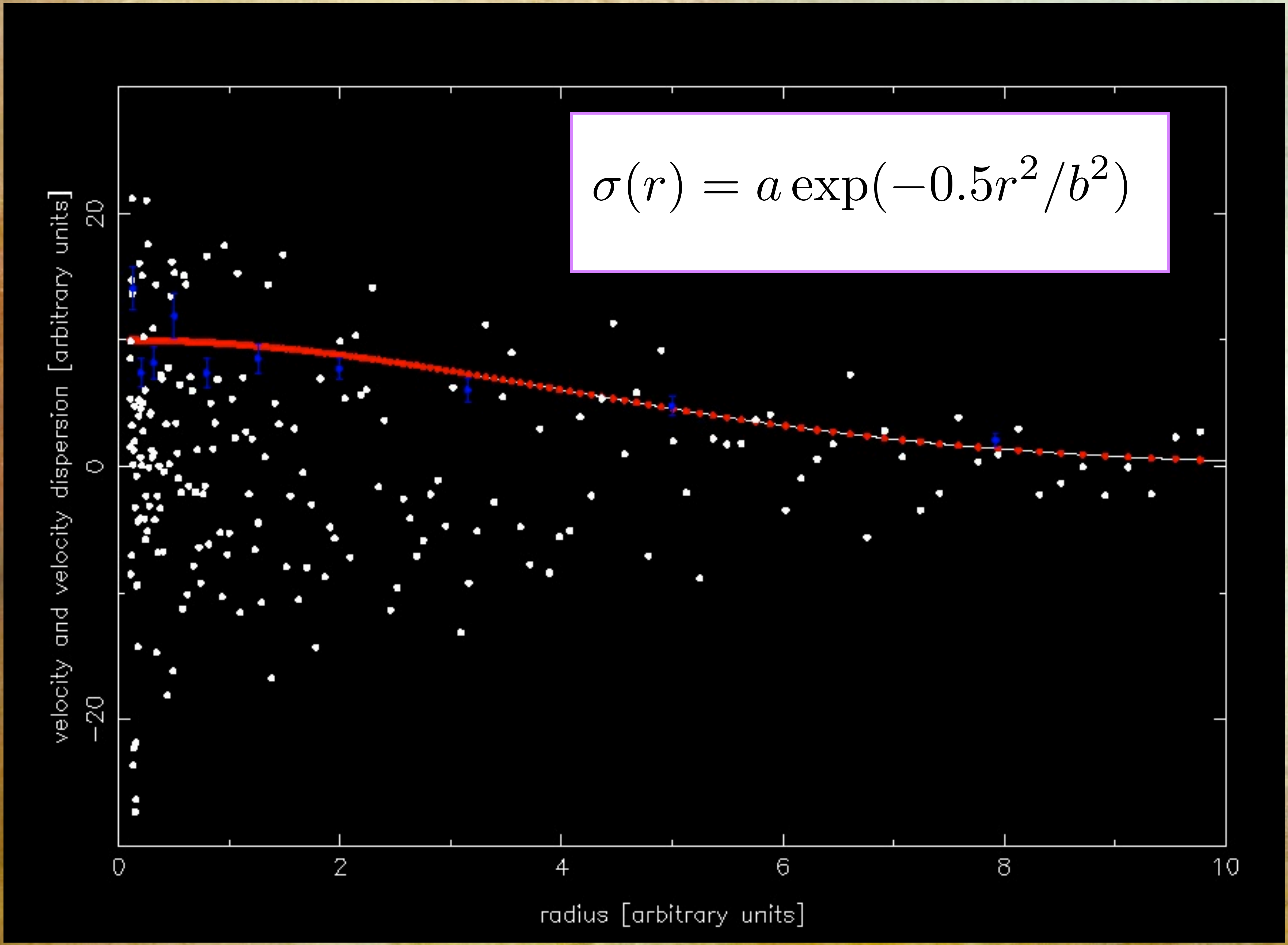
(a)
(b)
(c)
(d)
Heliocentric radial velocity [km/s]
Radius [arcmin]
Dec − Dec$_0$ [arcmin]
(RA − RA$_0$) cos(Dec$_0$) [arcmin]
Radius [arcmin]
[Fe/H]



Beautiful kinematic data!

must resist the temptation to take moments!!!

Model fitting - toy example



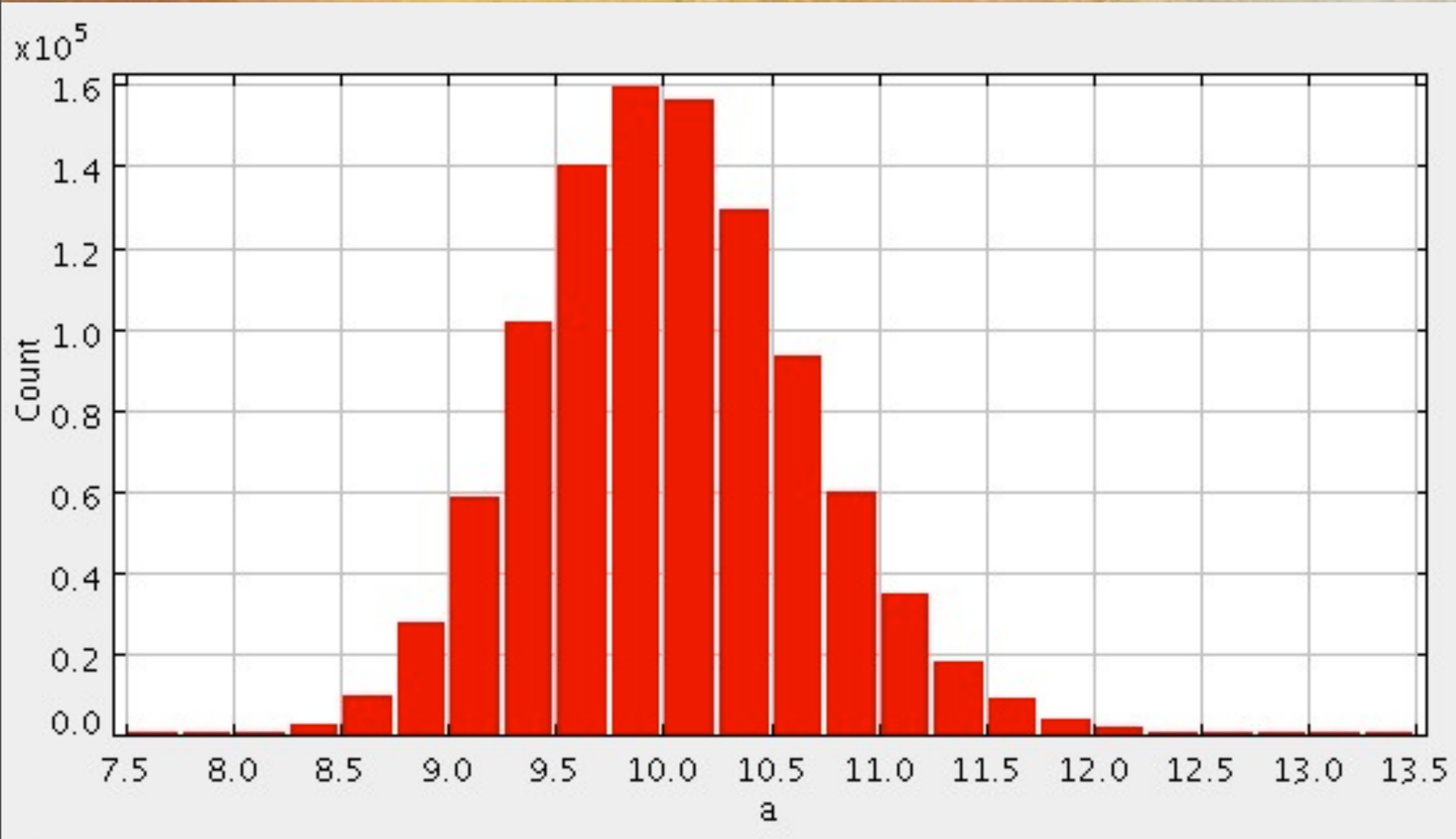
Thou shalt not take moments of data

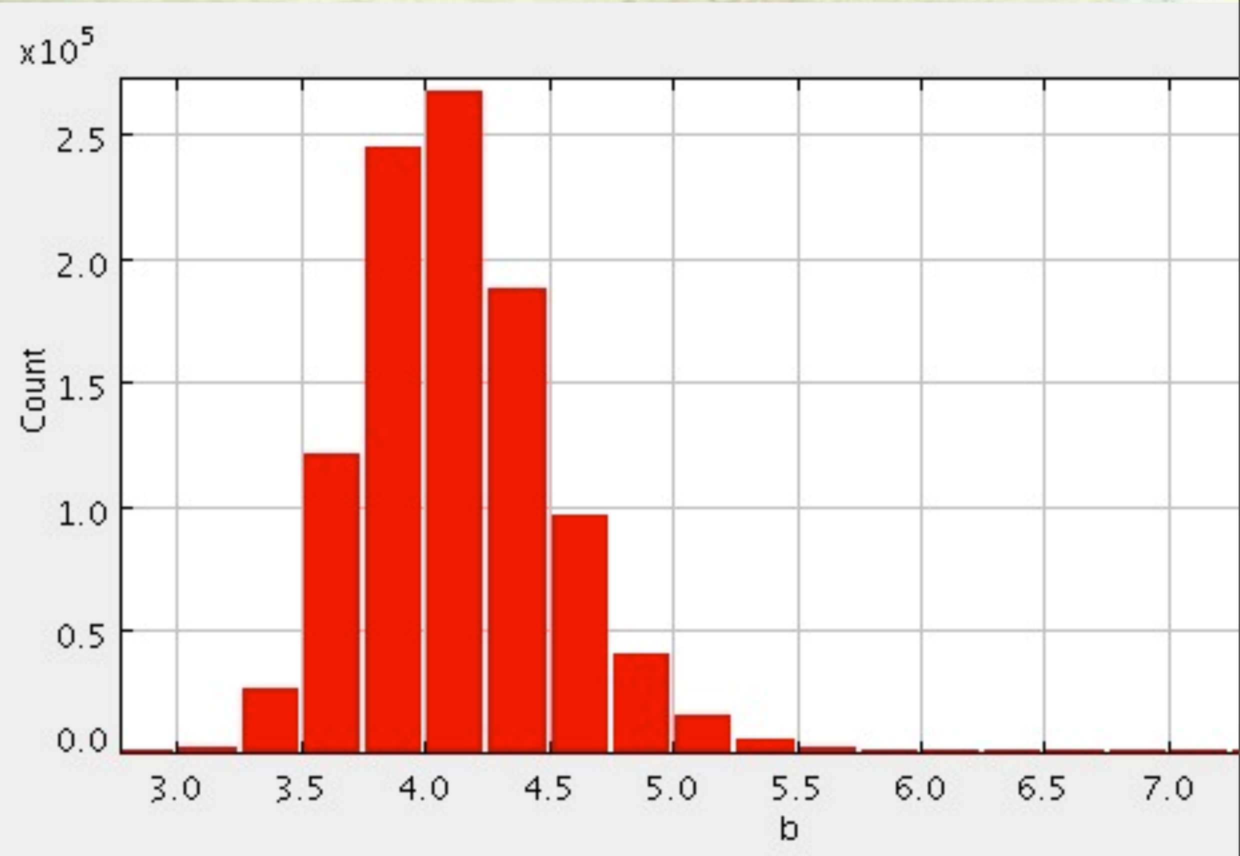
Toy model: $\sigma(r) = a\exp(-0.5r^2/b^2)$

choose a=10, b=4 (200 stars, velocity error 2 units)

Classical chi-squared non-linear least squares fitting: a=8.7±2.4 b=4.5±3.3

likelihood analysis: a=10.03±0.62 b=4.13±0.38





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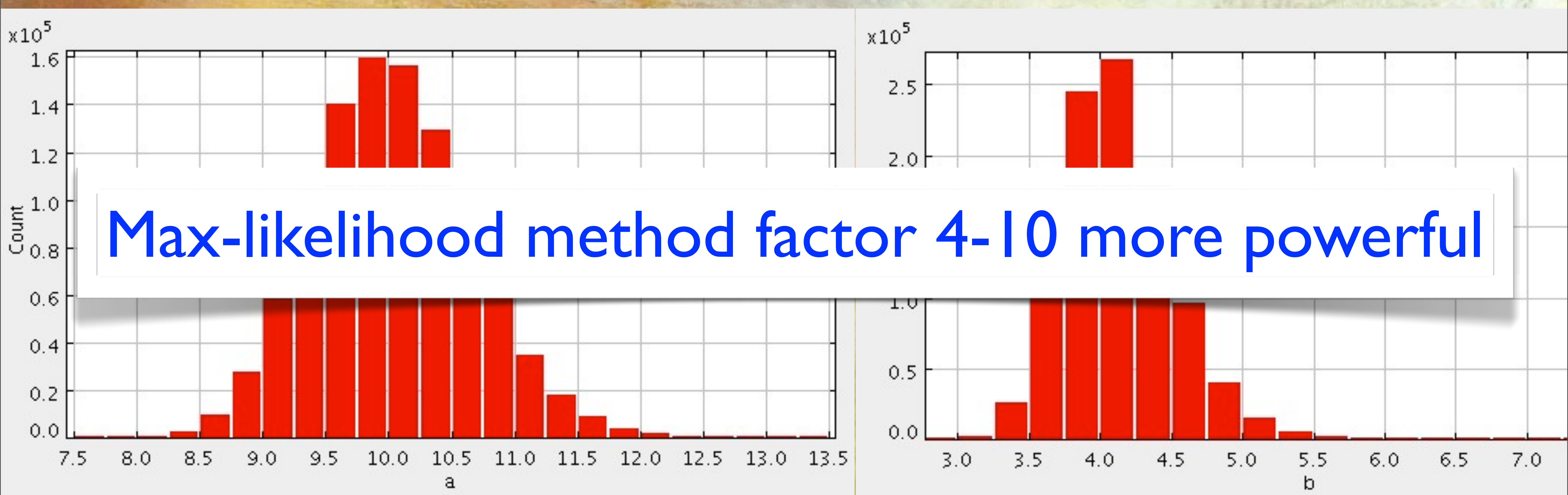


Max-likelihood method factor 4-10 more powerful

Spherical distribution functions

$\varepsilon = \Psi - \frac{1}{2}v^2$ Choose ε, Ψ so $f(\varepsilon) = 0$ for $\varepsilon < 0$

isothermal sphere $f(\varepsilon) = \frac{\rho_1}{(2\pi\sigma^2)^{3/2}} \exp(\varepsilon/\sigma^2)$

King model $f_K(\varepsilon) = \frac{\rho_1}{(2\pi\sigma^2)^{3/2}} \left[\exp(\varepsilon/\sigma^2) - 1\right]$

Michie (1963):

$$f_M(\varepsilon, L) = \frac{\rho_1}{(2\pi\sigma^2)^{3/2}} \left[\exp(\varepsilon/\sigma^2) - 1\right] \exp(-L^2/(2r_a^2\sigma^2))$$

(r_a = anisotropy radius)

Model evaluation

Integrate numerically the Poisson equation

$$\nabla^2 \varphi_N = 4\pi G \rho \qquad \vec{\nabla} \cdot \left[\mu\left(\frac{|\vec{\nabla}\varphi|}{a_0} \right) \vec{\nabla}\varphi \right] = 4\pi G \rho$$

Newton MOND

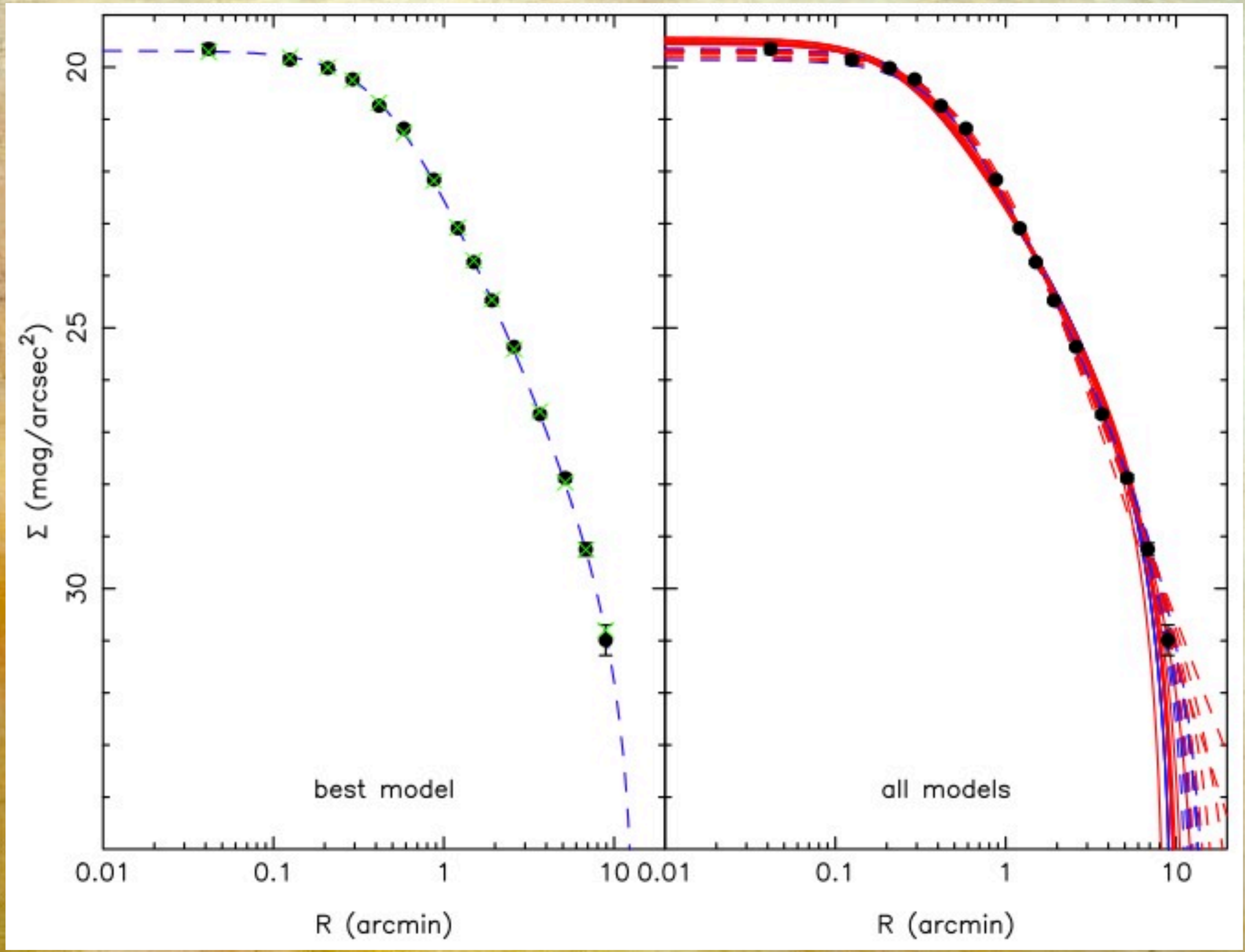
and project onto the line of sight

Calculate likelihood of projected distributions given data

Fit to surface brightness and kinematics

Michie models for Newton and MOND

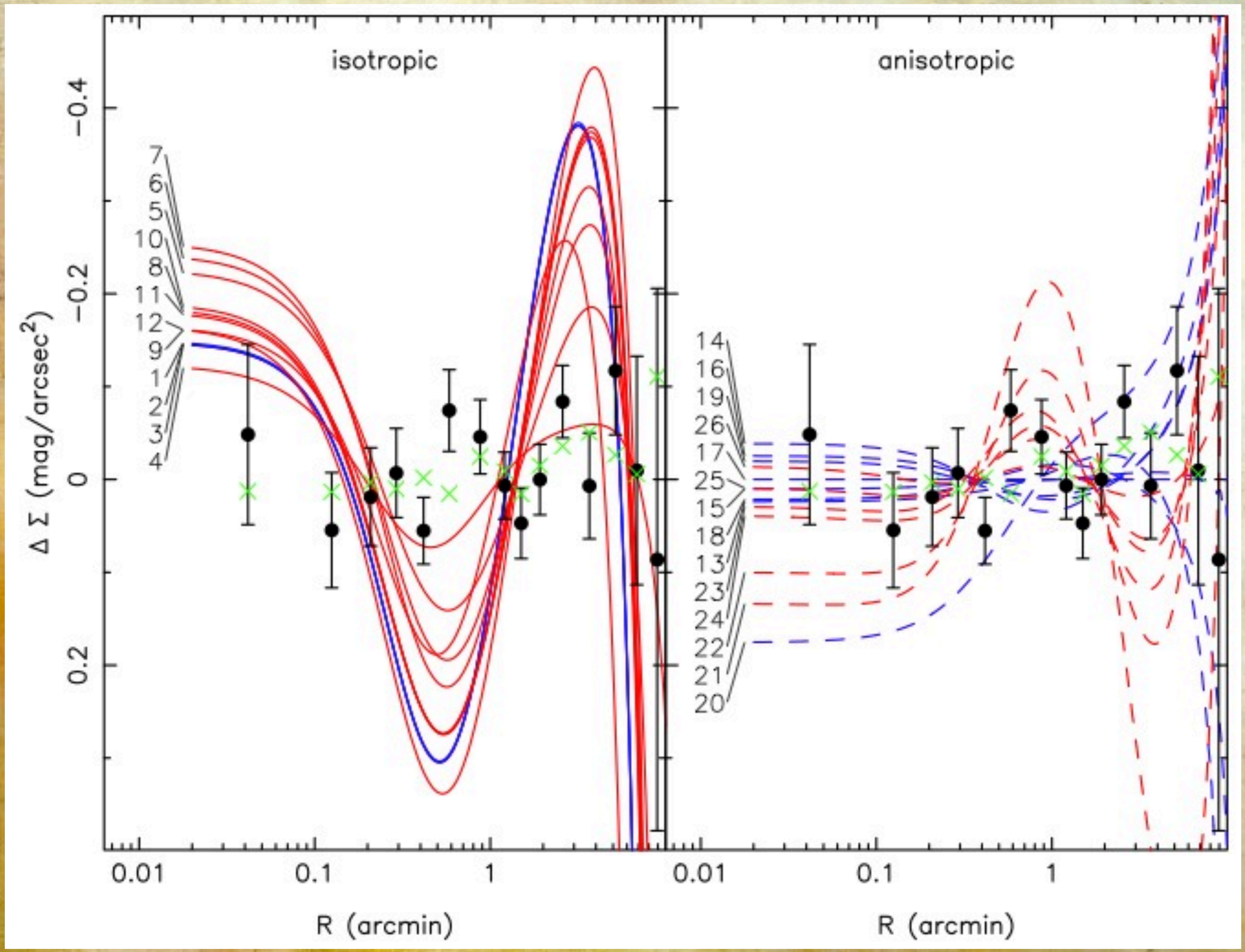
Surface brightness



Fit to surface brightness and kinematics

Michie models for Newton and MOND

Surface brightness residuals



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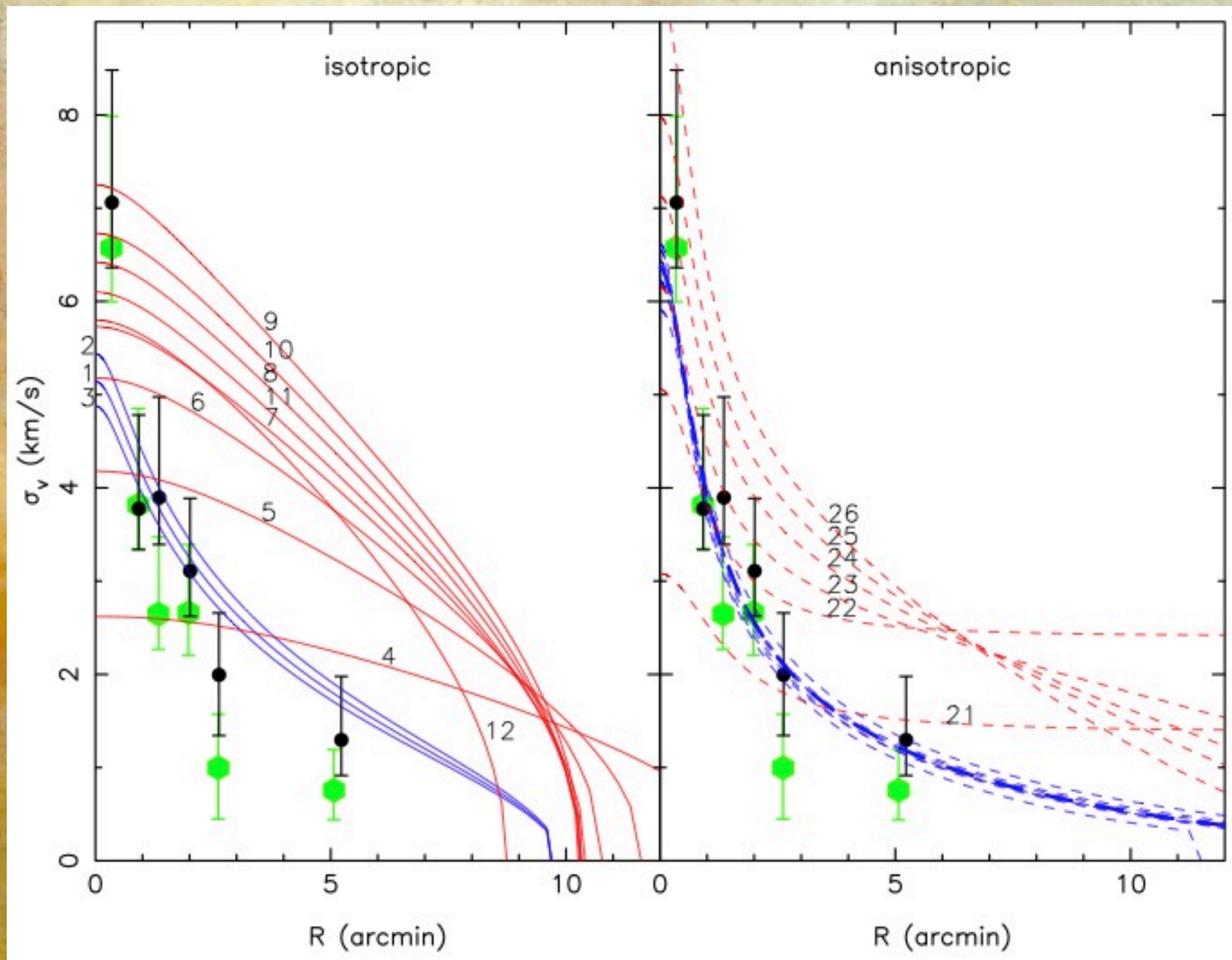
velocity dispersion



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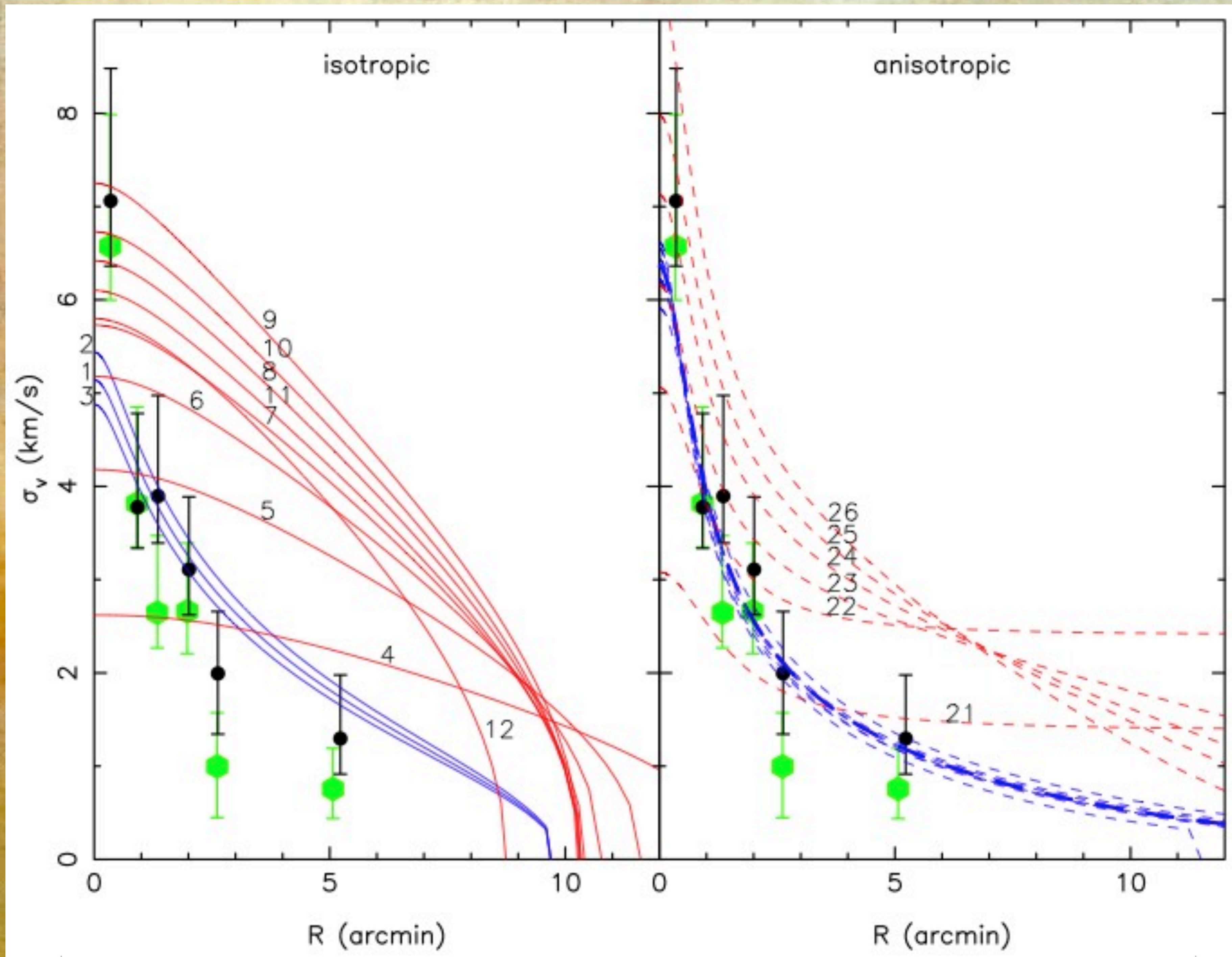

Isotropic models provide very poor fit

Fit to surface brightness and kinematics

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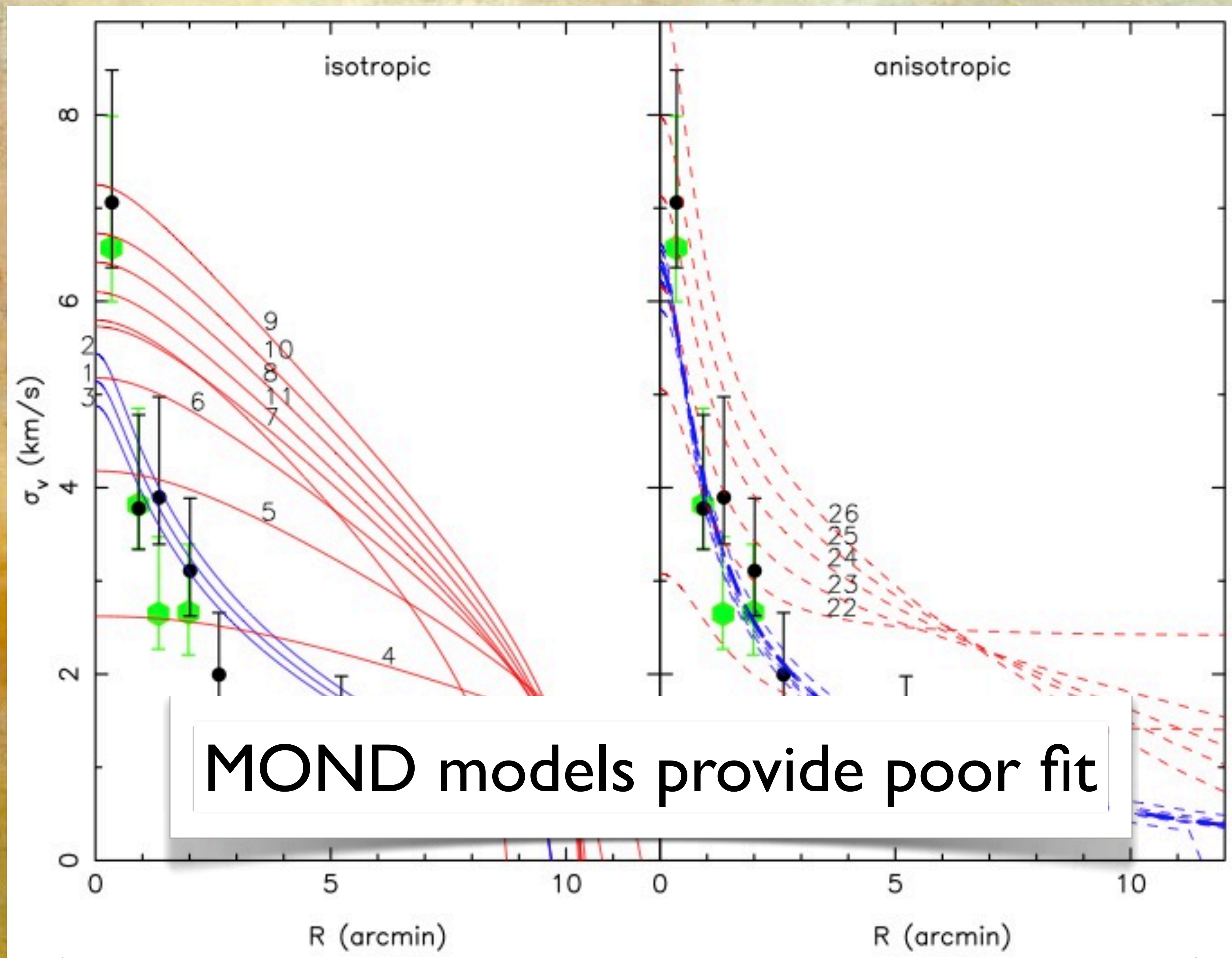

MOND models provide poor fit

Isotropic models provide very poor fit

Max-likelihood model comparison with density profile + individual velocities

Model	type	M/L	r_a/r_c	d (kpc)	r_c (pc)	r_h (pc)	r_t (pc)	σ_0 ($\mathrm{km\,s^{-1}}$)	μ^{-1}	L_1	L_2
1	Newton	(1.903)	∞	87.5	6.88	28.62	245.80	5.14	—	129.9	129.1
2	Newton	(1.903)	∞	96.25	7.57	31.49	270.46	5.44	—	141.6	140.8
3	Newton	(1.903)	∞	78.75	6.20	25.79	221.51	4.88	—	119.0	118.2
4	MOND	0.100	∞	87.5	15.42	24.67	350.01	2.62	$1+x$	21.4	11.4
5	MOND	0.500	∞	87.5	10.03	24.97	294.65	4.18	$1+x$	31.6	31.1
6	MOND	1.000	∞	87.5	8.65	25.86	273.54	5.18	$1+x$	47.7	48.6
7	MOND	1.346	∞	87.5	8.09	26.28	264.21	5.73	$1+x$	64.0	66.1
8	MOND	1.903	∞	87.5	7.86	27.60	261.47	6.42	$1+x$	232.2	236.3
9	MOND	2.691	∞	87.5	7.37	28.88	262.10	7.25	$1+x$	887.7	894.8
10	MOND	1.903	∞	96.25	8.62	30.26	286.75	6.73	$1+x$	268.8	274.1
11	MOND	1.903	∞	78.75	7.09	24.88	235.86	6.10	$1+x$	195.0	198.0
12	MOND	1.903	∞	87.5	7.45	26.46	221.90	5.80	$\sqrt{1+x^2}$	80.4	82.2
13	Newton	(1.903)	0.9	87.5	13.70	24.11	292.23	6.62	—	9.3	9.2
14	Newton	(1.903)	1.1	87.5	12.31	23.88	359.96	6.55	—	1.7	1.7
15	Newton	(1.903)	1.3	87.5	12.20	23.91	327.61	6.37	—	8.2	8.0
16	Newton	(1.903)	1.4	87.5	11.66	23.79	361.16	6.43	—	1.0	1.0
17	Newton	(1.903)	1.5	87.5	11.70	23.87	331.27	6.36	—	0.0	0.0
18	Newton	(1.903)	1.6	87.5	11.70	23.87	314.19	6.22	—	9.1	8.9
19	Newton	(1.903)	1.7	87.5	11.13	23.93	364.33	6.20	—	1.1	1.0
20	Newton	(1.903)	2.0	87.5	11.67	26.02	378.50	5.91	—	12.3	12.1
21	MOND	0.100	1.4	87.5	23.33	24.50	23330.00	3.08	$1+x$	59.8	53.9
22	MOND	0.500	1.4	87.5	17.05	24.55	17050.00	5.06	$1+x$	14.2	13.3
23	MOND	0.861	1.4	87.5	14.95	23.92	587.00	6.16	$1+x$	7.5	6.7
24	MOND	1.346	1.5	87.5	13.95	23.99	460.87	7.13	$1+x$	5.7	5.3
25	MOND	1.903	1.6	87.5	13.02	23.83	403.28	7.98	$1+x$	5.3	5.8
26	MOND	2.691	1.5	87.5	12.48	23.84	346.91	9.30	$1+x$	4.6	6.7

Models tested for stability using N-body simulations

best Newton

best MOND

Max-likelihood model comparison with density profile + individual velocities

Model	type	M/L	r_a/r_c	d (kpc)	r_c (pc)	r_h (pc)	r_t (pc)	σ_0 (km s^{-1})	μ^{-1}	L_1	L_2
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15	Newton	(1.903)	1.3	87.5	12.20	23.91	327.61	6.37	—	8.2	8.0
16	Newton	(1.903)	1.4	87.5	11.66	23.79	361.16	6.43	—	1.0	1.0
17	Newton	(1.903)	1.5	87.5	11.70	23.87	331.27	6.36	—	0.0	0.0
18	Newton	(1.903)	1.6	87.5	11.70	23.87	314.19	6.22	—	9.1	8.9
19	Newton	(1.903)	1.7	87.5	11.13	23.93	364.33	6.20	—	1.1	1.0
20	Newton	(1.903)	2.0	87.5	11.67	26.02	378.50	5.91	—	12.3	12.1
21	MOND	0.100	1.4	87.5	23.33	24.50	23330.00	3.08	$1+x$	59.8	53.9
22	MOND	0.500	1.4	87.5	17.05	24.55	17050.00	5.06	$1+x$	14.2	13.3
23	MOND	0.861	1.4	87.5	14.95	23.92	587.00	6.16	$1+x$	7.5	6.7
24	MOND	1.346	1.5	87.5	13.95	23.99	460.87	7.13	$1+x$	5.7	5.3
25	MOND	1.903	1.6	87.5	13.02	23.83	403.28	7.98	$1+x$	5.3	5.8
26	MOND	2.691	1.5	87.5	12.48	23.84	346.91	9.30	$1+x$	4.6	6.7

Models tested for stability using N-body simulations

best Newton

best MOND

- Best model is anisotropic Newtonian Michie model with M/L=1.9, r_a/r_c=1.5, which is an excellent description of the data
- Isotropic Michie models completely ruled out
- Best anisotropic MOND Michie model 40000 times less likely than best Newtonian model

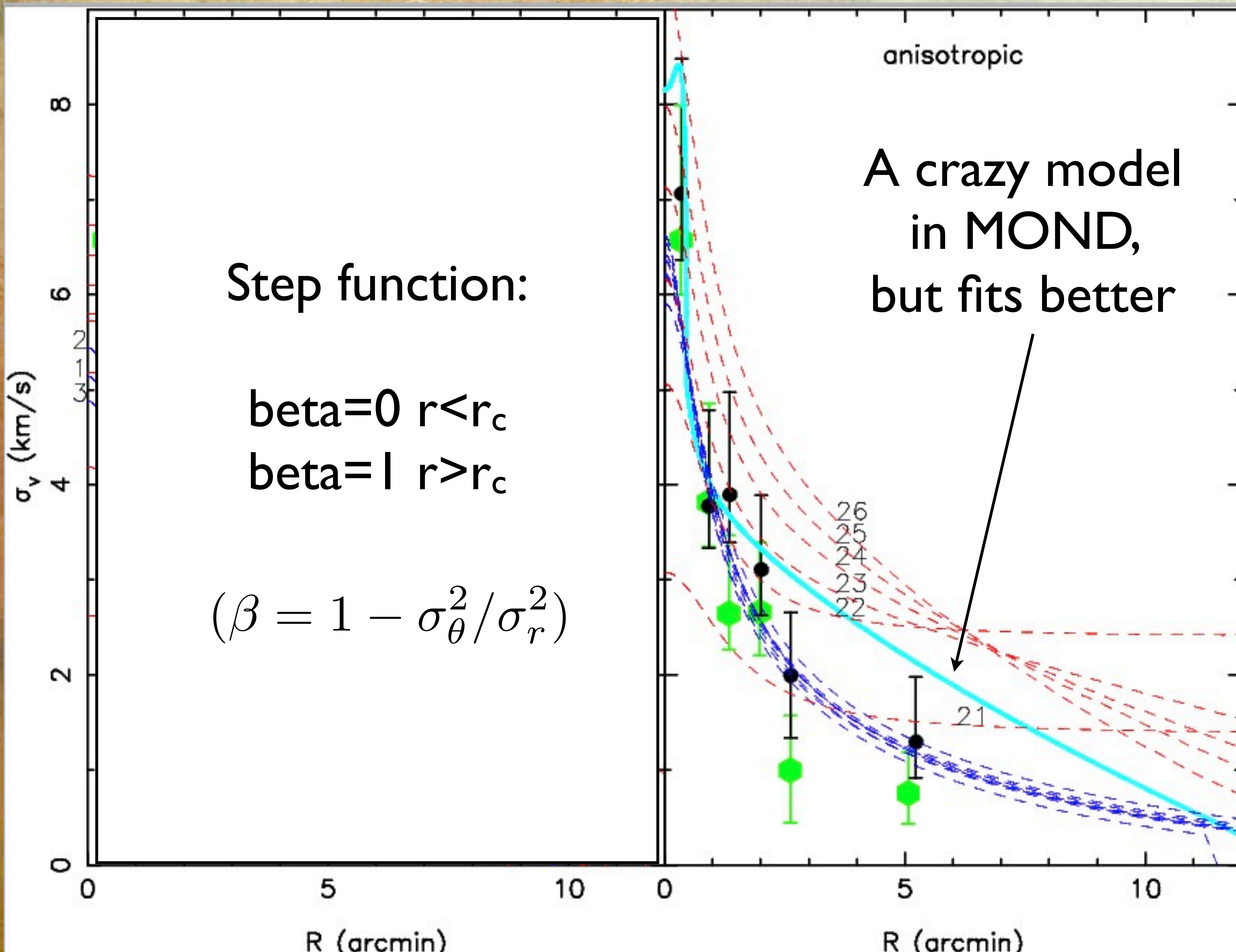
Step function:

beta=0 r<r_c

beta=1 r>r_c

$$(\beta = 1 - \sigma_\theta^2/\sigma_r^2)$$

A crazy model in MOND, but fits better



More general models in MOND

Adopt the best Michie model density profile, choose M/L, and use a cubic spline to define $\sigma_r(r)$

Solve the spherical Jeans equation

$$\frac{GM(r)}{r} = -\overline{v_r^2}\left[\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln\overline{v_r^2}}{\mathrm{d}\ln r} + 2\left(1 - \frac{\overline{v_\theta^2}}{\overline{v_r^2}}\right)\right],$$

via Markov-Chain Monte Carlo to get $\sigma_\theta(r)$

Set some physical priors:

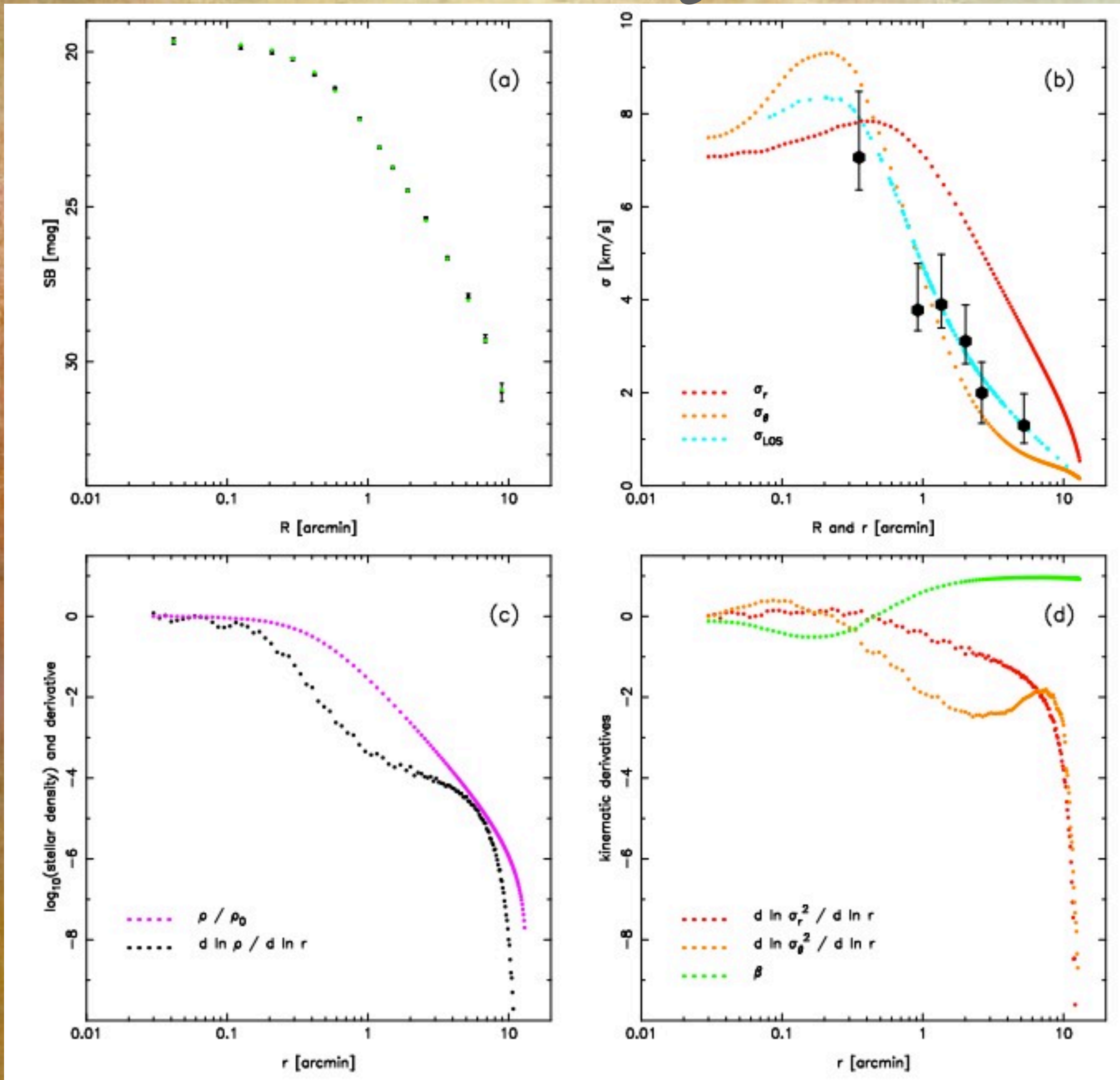
+ve $\sigma_\theta(r)$

Global density-slope inequality (consistency)

Polyachenko parameter (stability)

sensible density profile

MCMC Jeans solutions



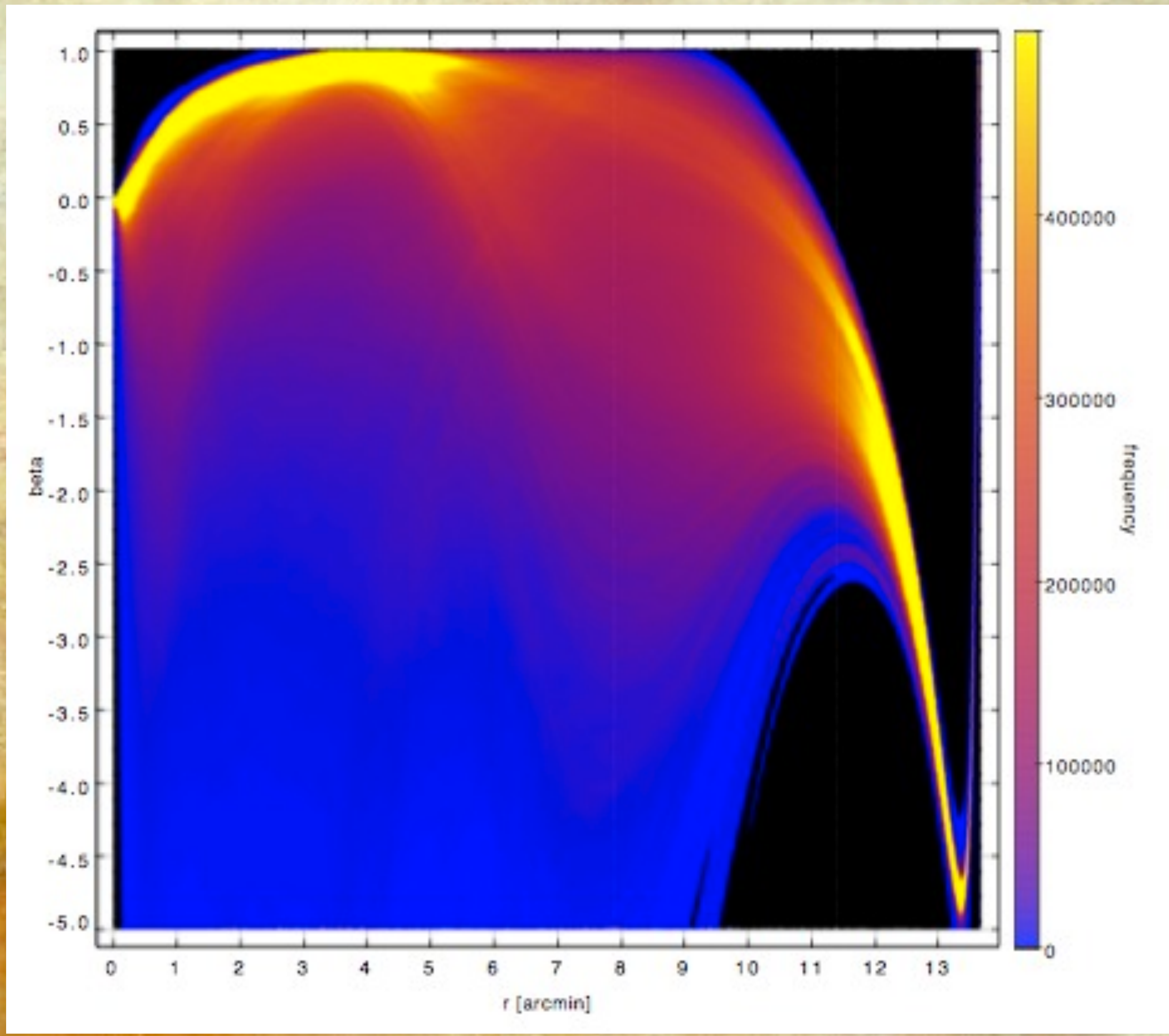
parameters:
sigma(0)
stellar M
stellar M/L
+129 per profile

More general models in MOND

(from solving Jeans equation via MCMC)

posterior distribution for beta

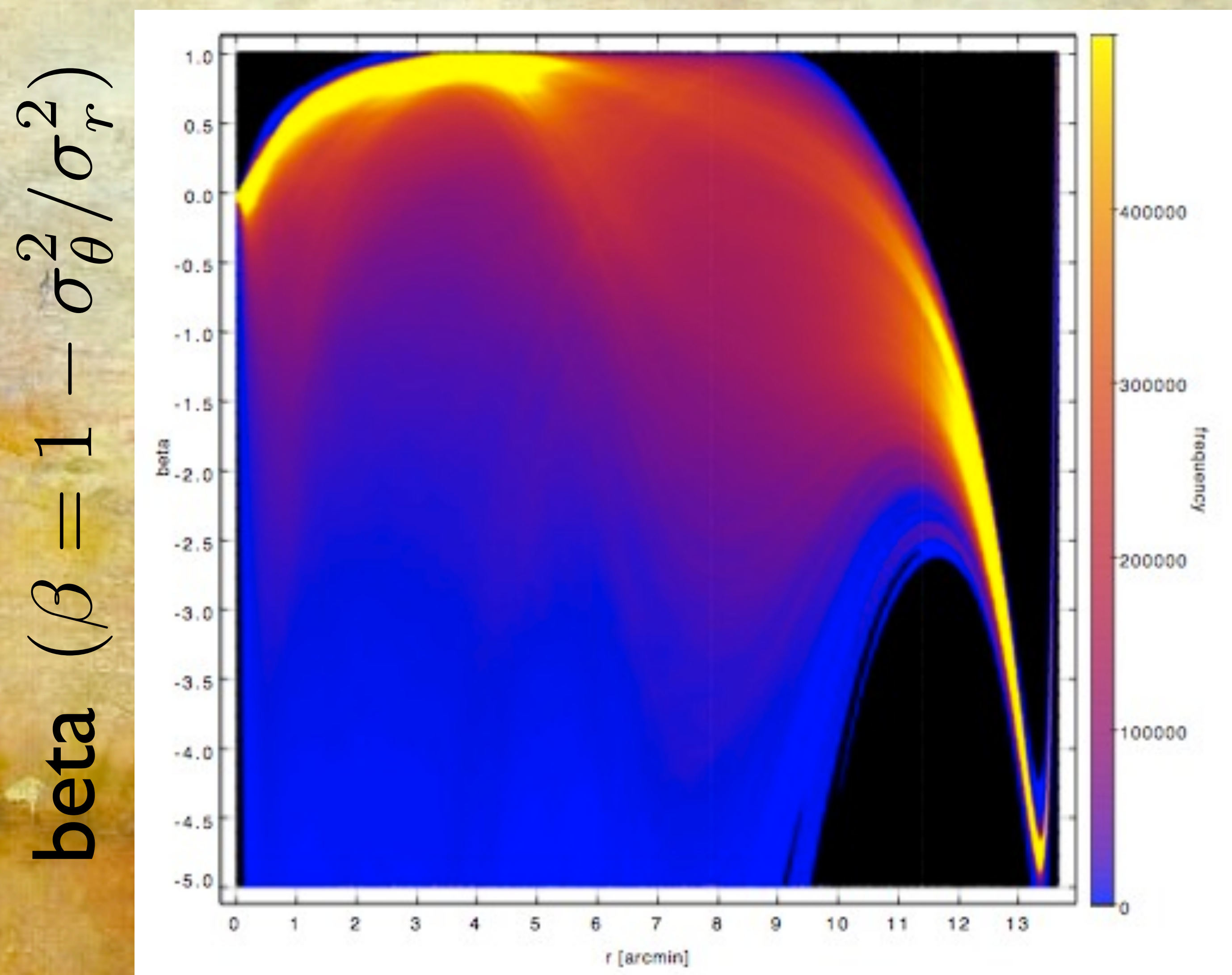
beta $(\beta = 1 - \sigma_\theta^2/\sigma_r^2)$



More general models in MOND

(from solving Jeans equation via MCMC)

posterior distribution for beta



Even with the greatly increased freedom, best MOND model is 350 times less likely than best Newtonian model

Caveats

- Cluster assumed to be spherical (could be elongated along LOS)
- assumed to be non-rotating (but no evidence for rotation)
- assumed to be isolated (part of a stream?)
- assumed to be static (but short time to reach equilibrium)

- Sanders (2011a,b) criticises our conclusions, suggesting that other models (polytropes) are possible. In Ibata et al. 2012b we show that his proposed models are extremely unlikely.

Dark Matter in NGC2419?

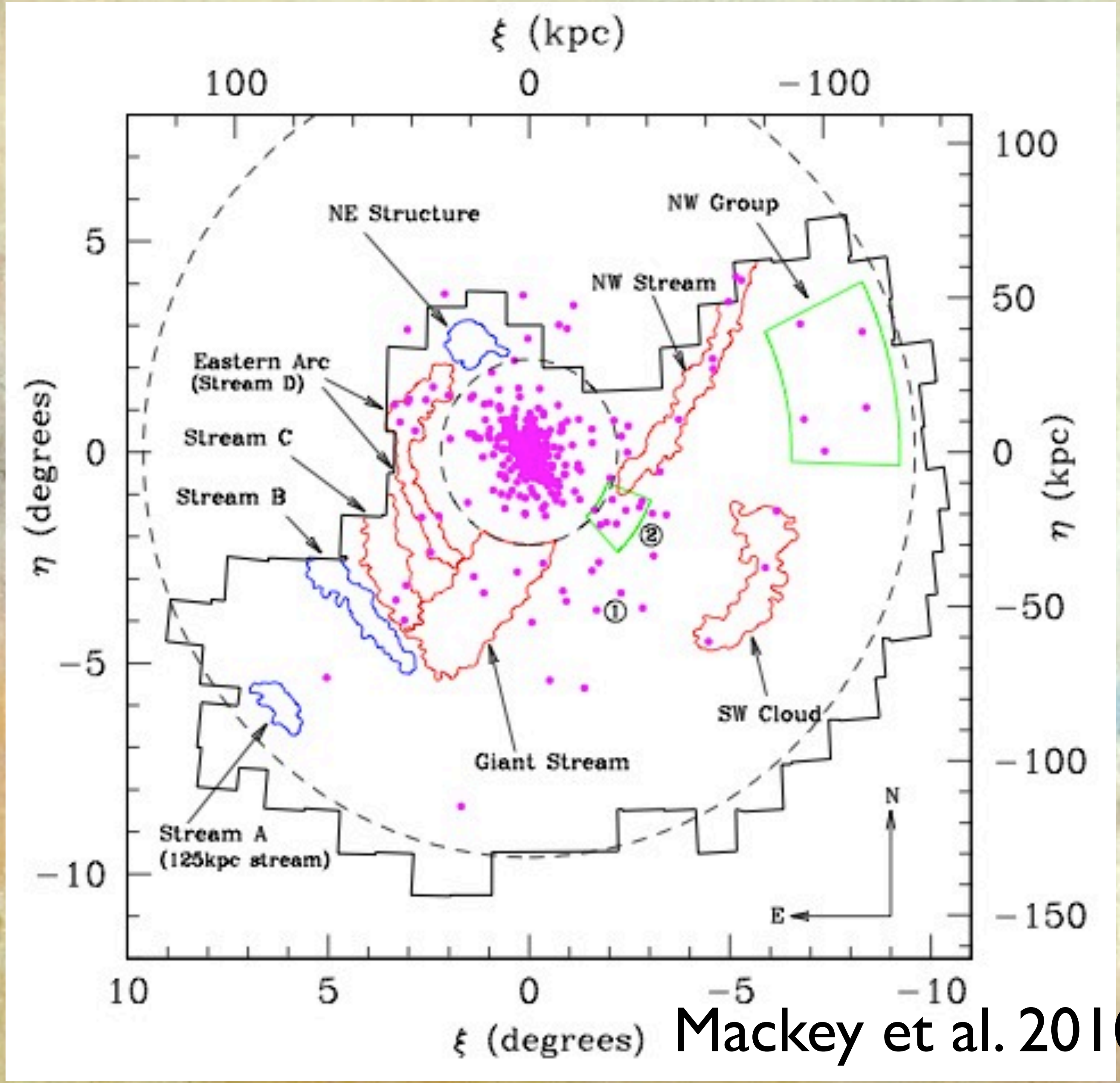
Can globular clusters harbour dark matter?

Clear evidence that (some?) halo globulars arrive with accreting dwarf galaxies

Massive clusters will sink to dwarf galaxy's DM centre prior to dissolution of host (e.g. M54 in Sgr dSph)

Some DM could stay bound to cluster

Place to look: outer halo!



Mackey et al. 2010

A flexible dynamical model

Construct composite model:

Dark matter: $$\rho_{\rm dm}(r) = \frac{\rho_{\rm dm,0}}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\frac{r}{r_s}\right)^{\delta-\gamma}},$$

+

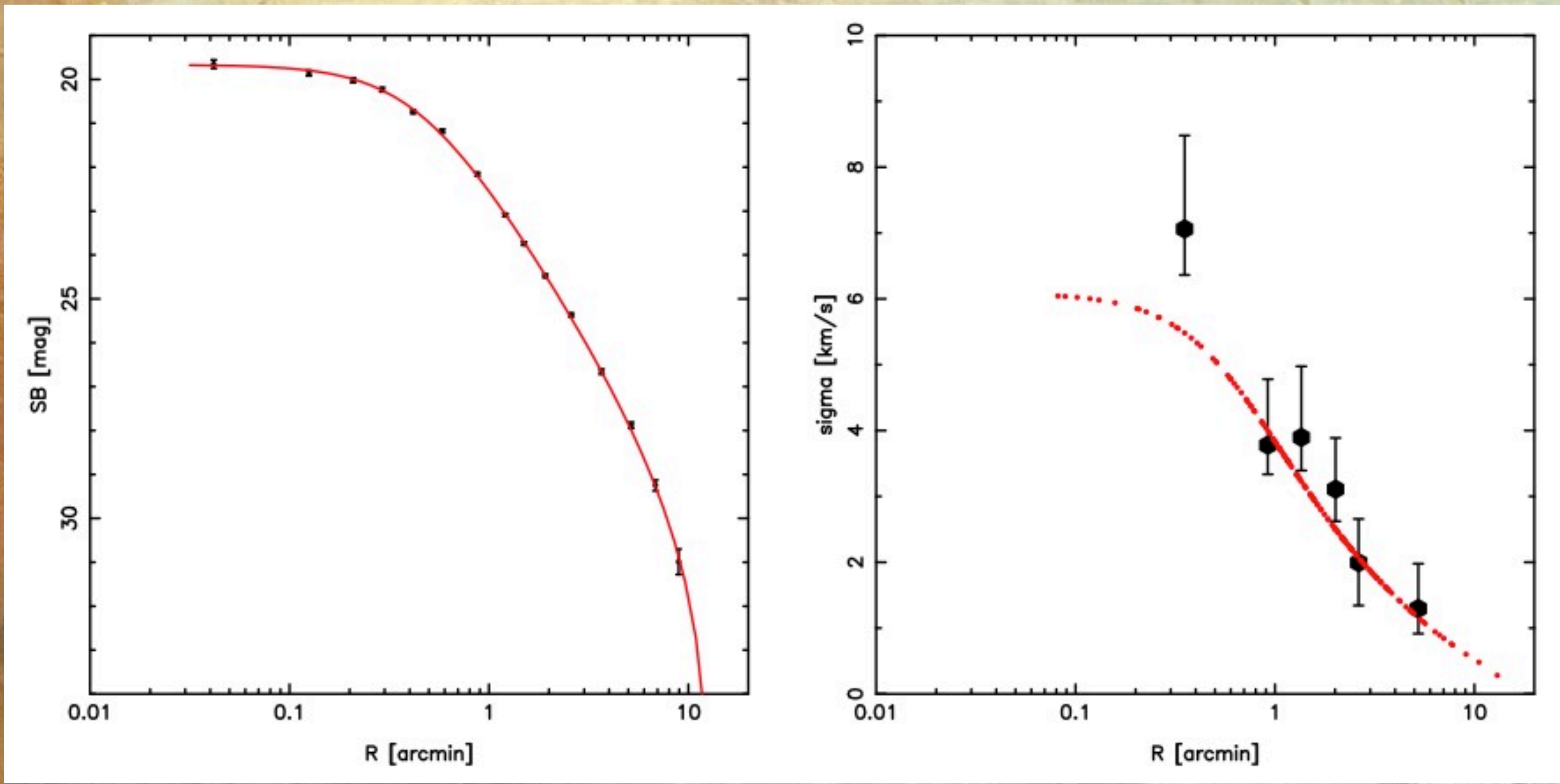
Stars: Michie

Solve system by using the Poisson equation
project density and velocity distributions onto line of sight

and compare against data

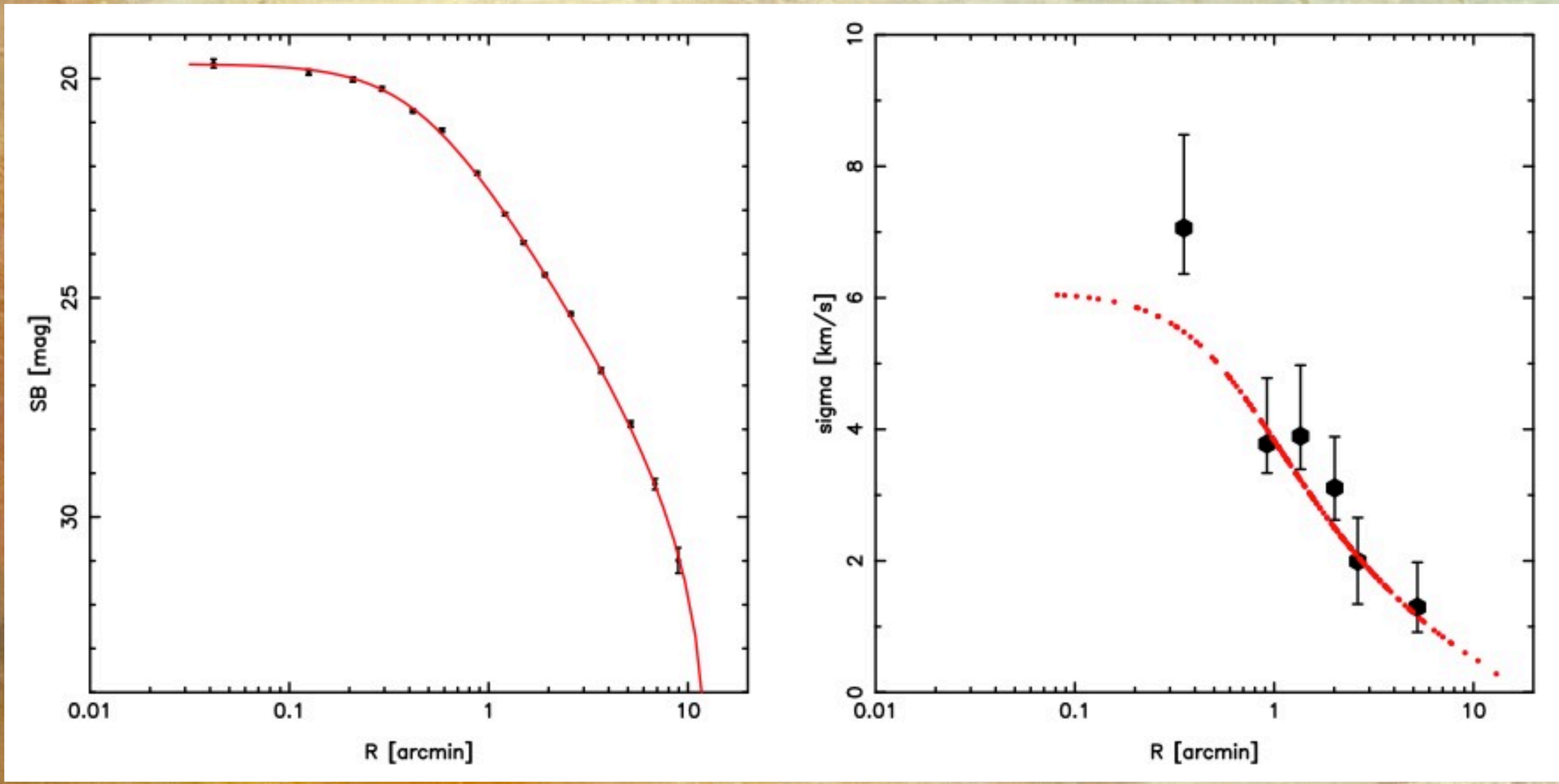
explore parameter (5+4+1) space using MCMC

Best dark matter solution:



Excellent fit, but M_{DM}=4.1x10^4 M_0

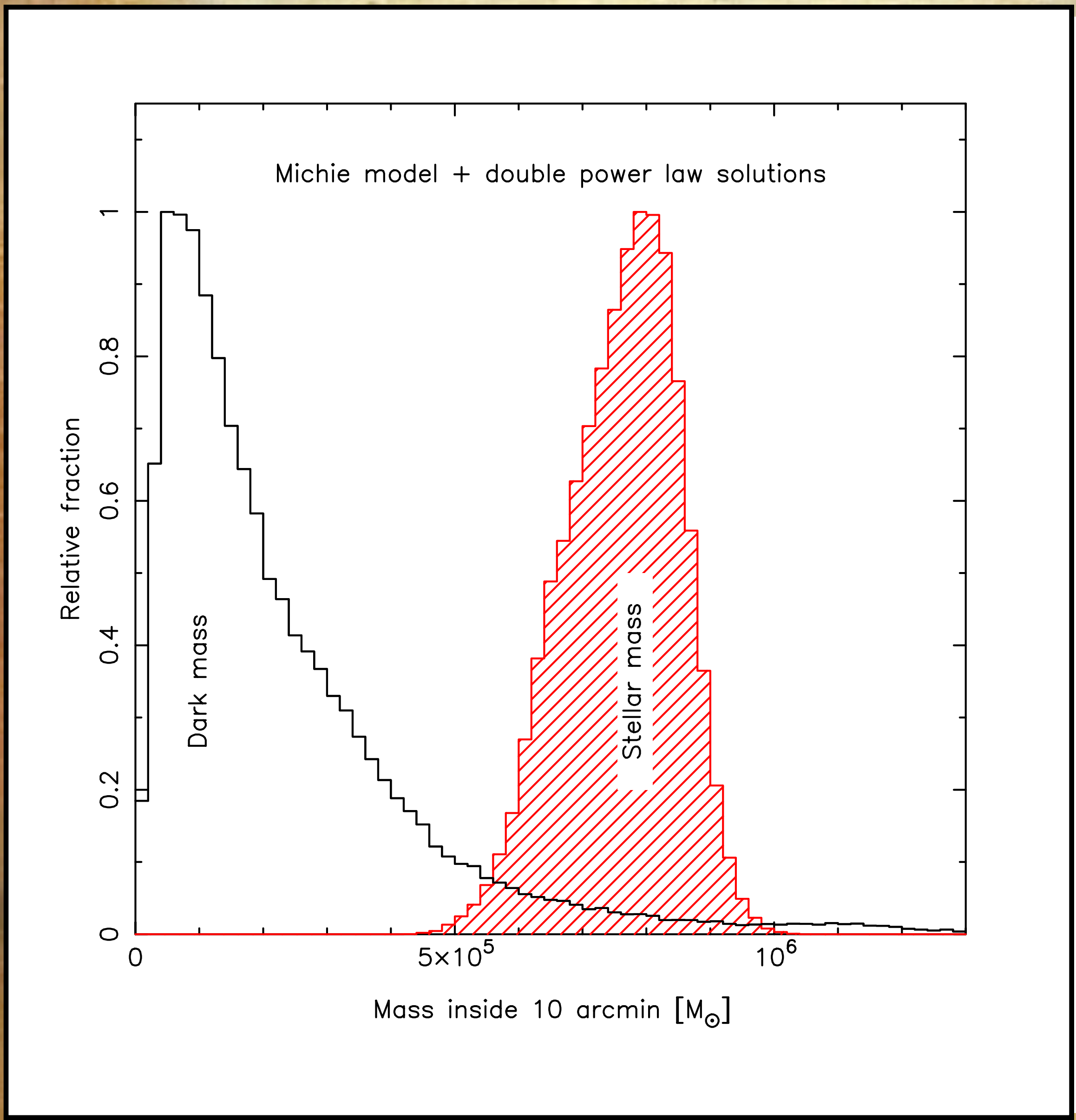
Best dark matter solution:

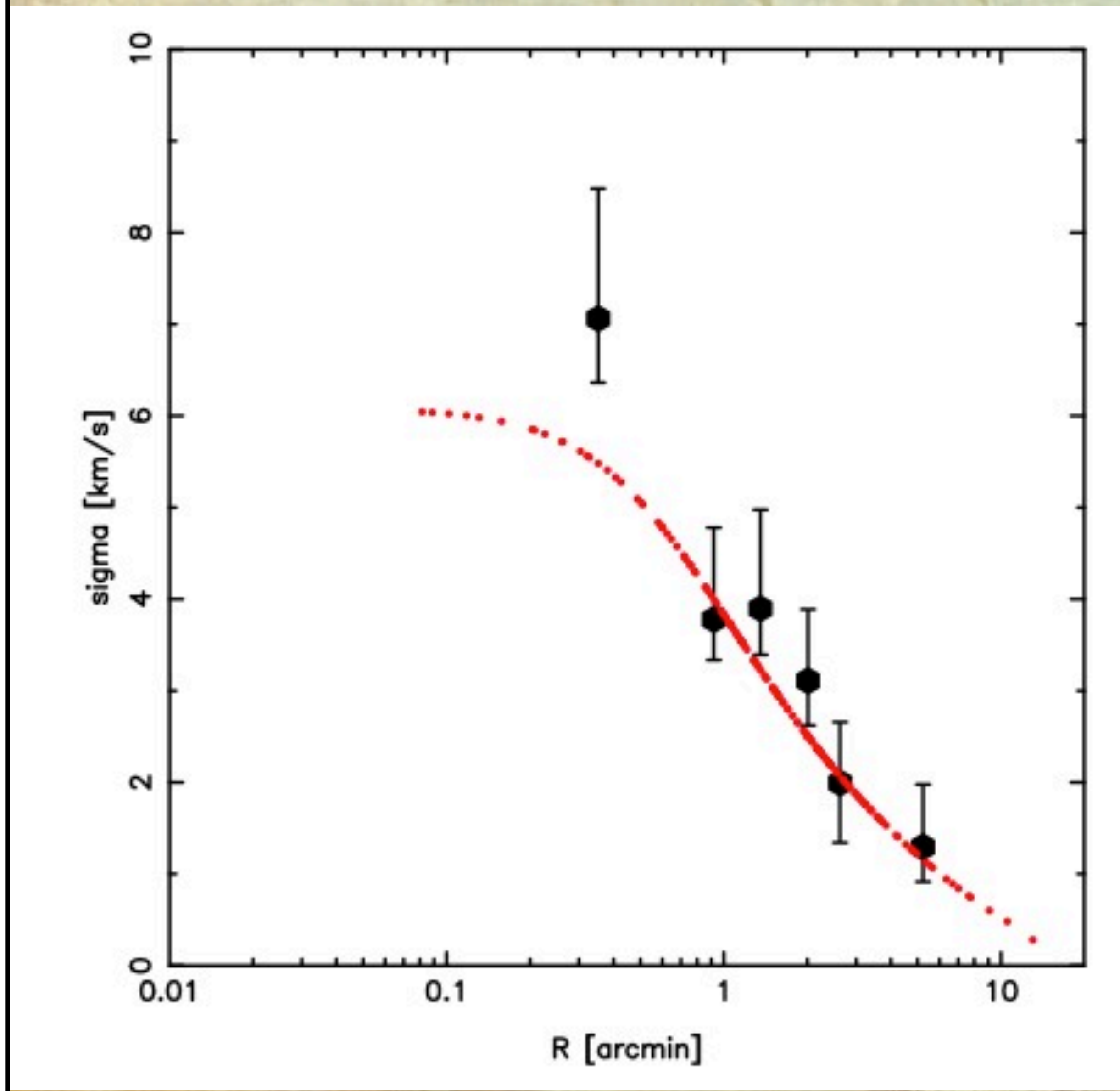


Excellent fit, but $M_{DM}=4.1\times10^4\ M_0$

Essentially dark matter free!

Best dark matter solution:



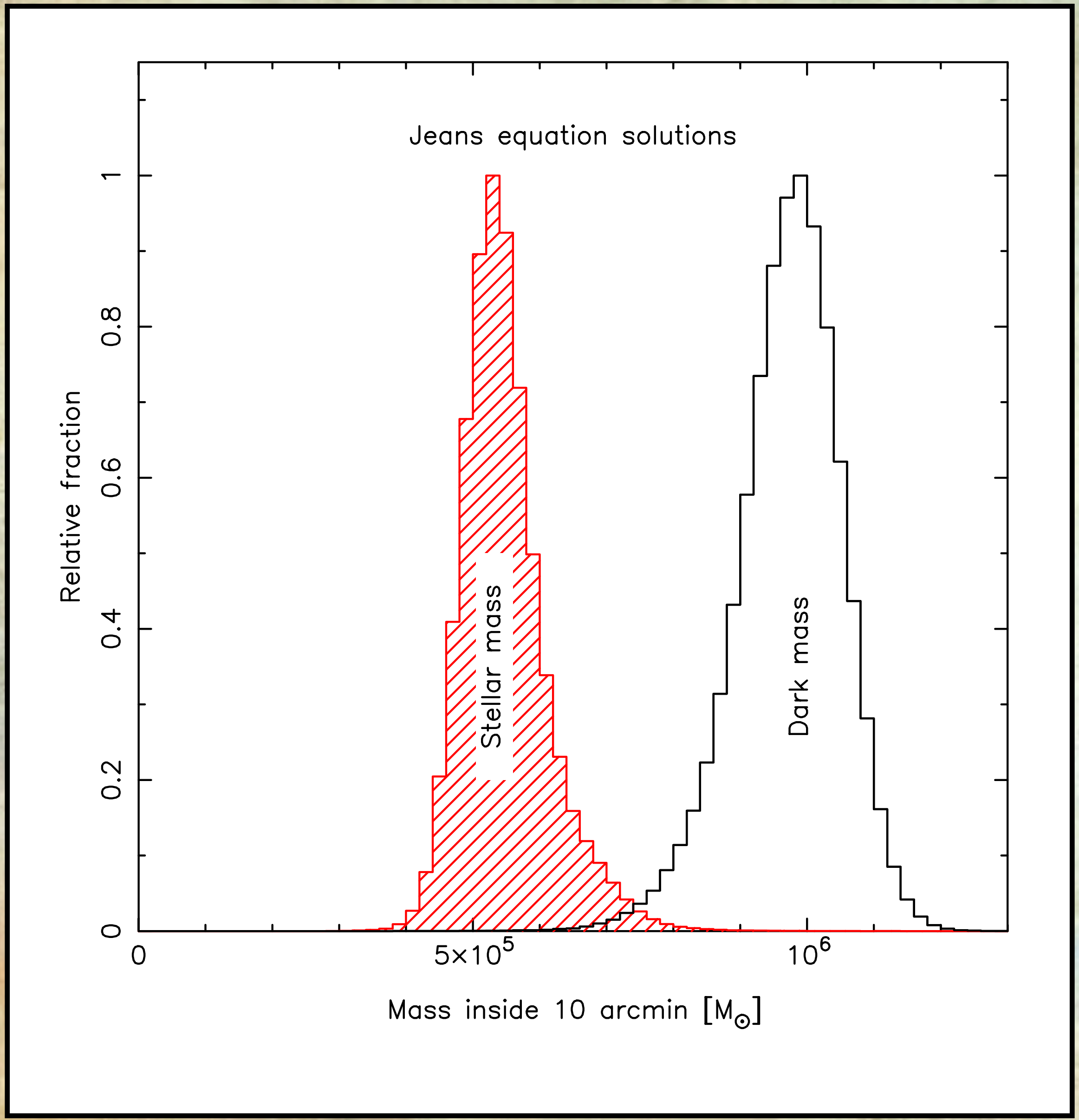


Excellent fit, but $M_{DM}=4.1\times10^4\ M_0$

Essentially dark matter free!

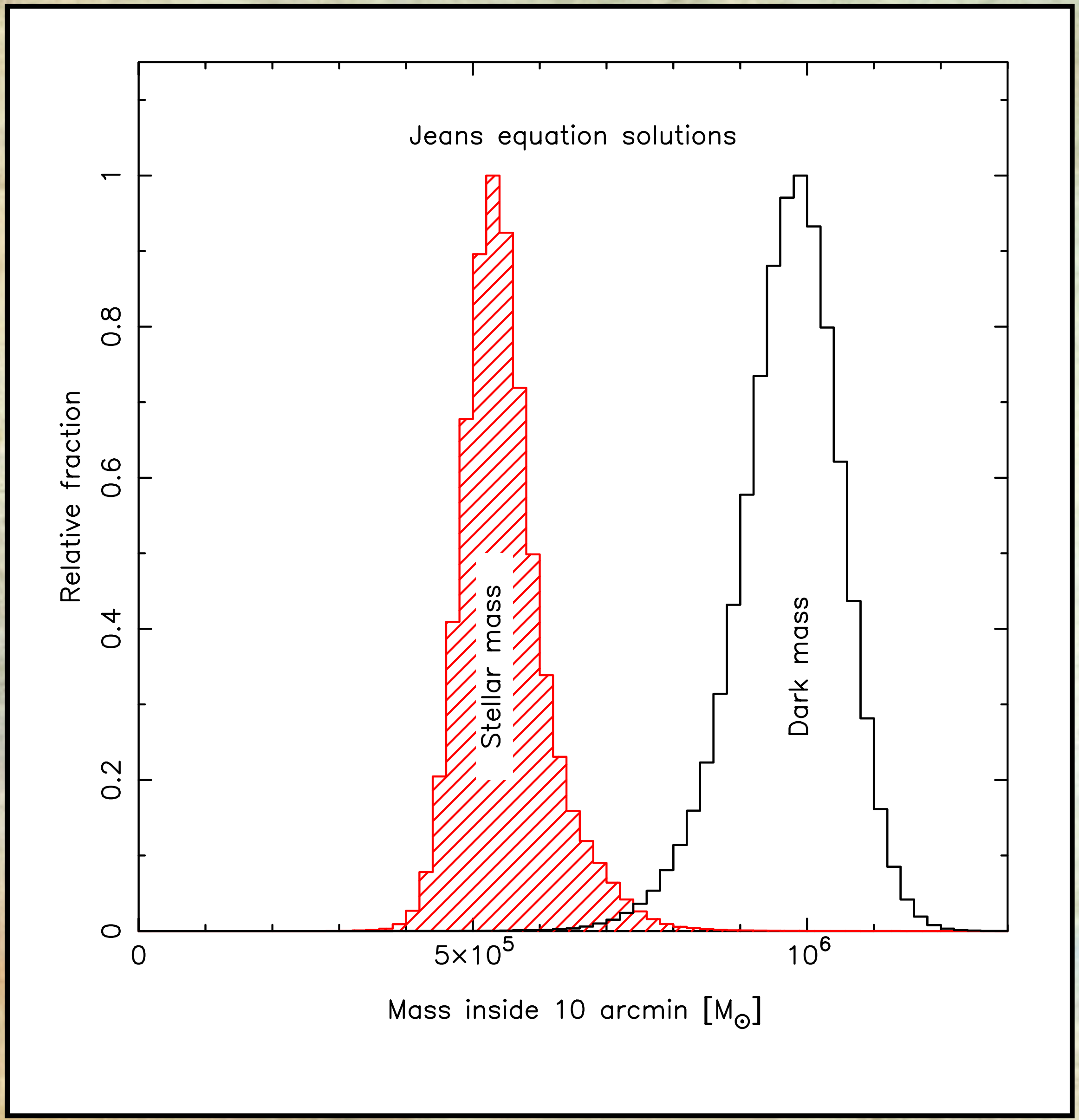
But life is not so simple...

Solving the Jeans equation with an MCMC scheme as before (now with Newtonian gravity):



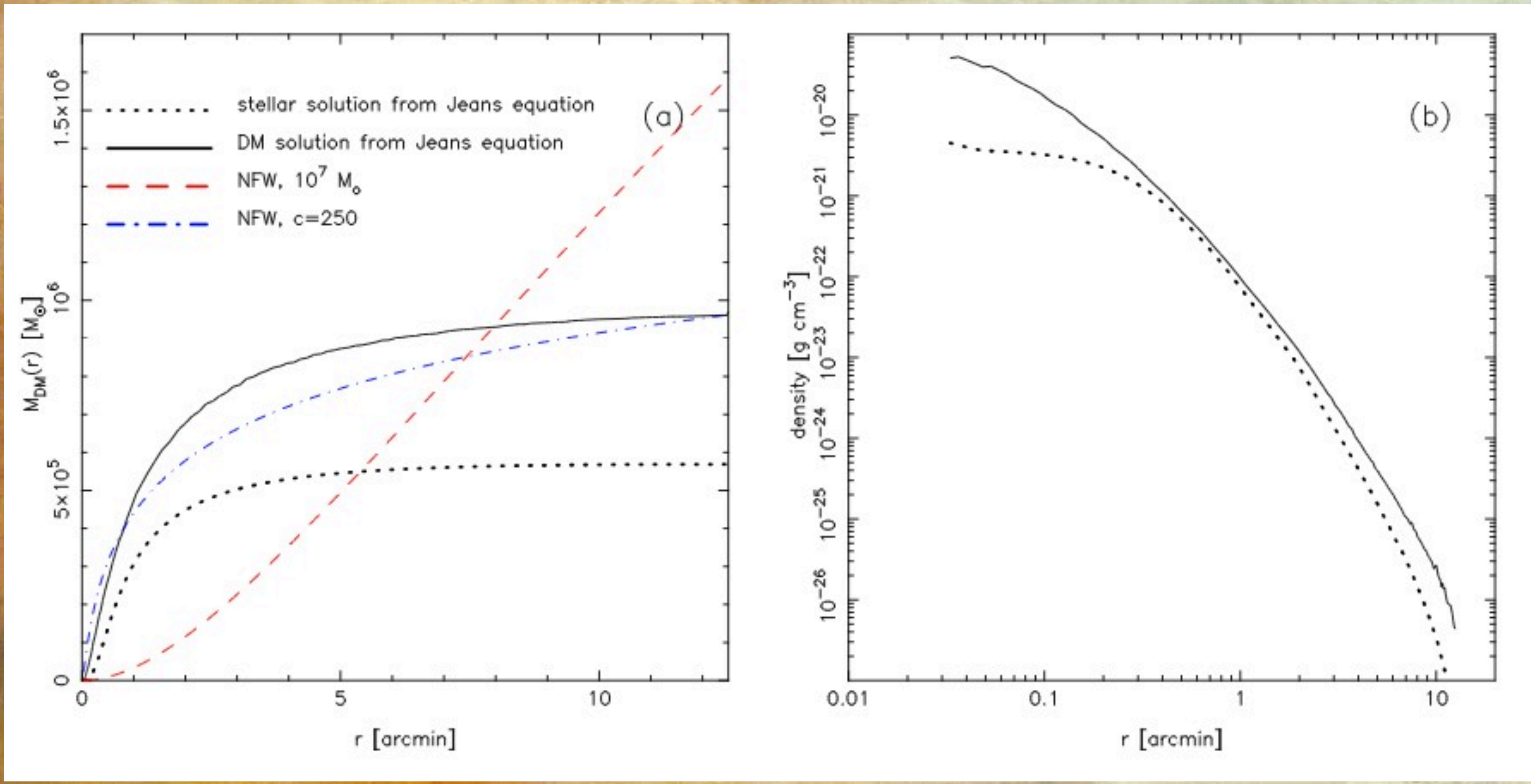
But life is not so simple...

Solving the Jeans equation with an MCMC scheme as before (now with Newtonian gravity):

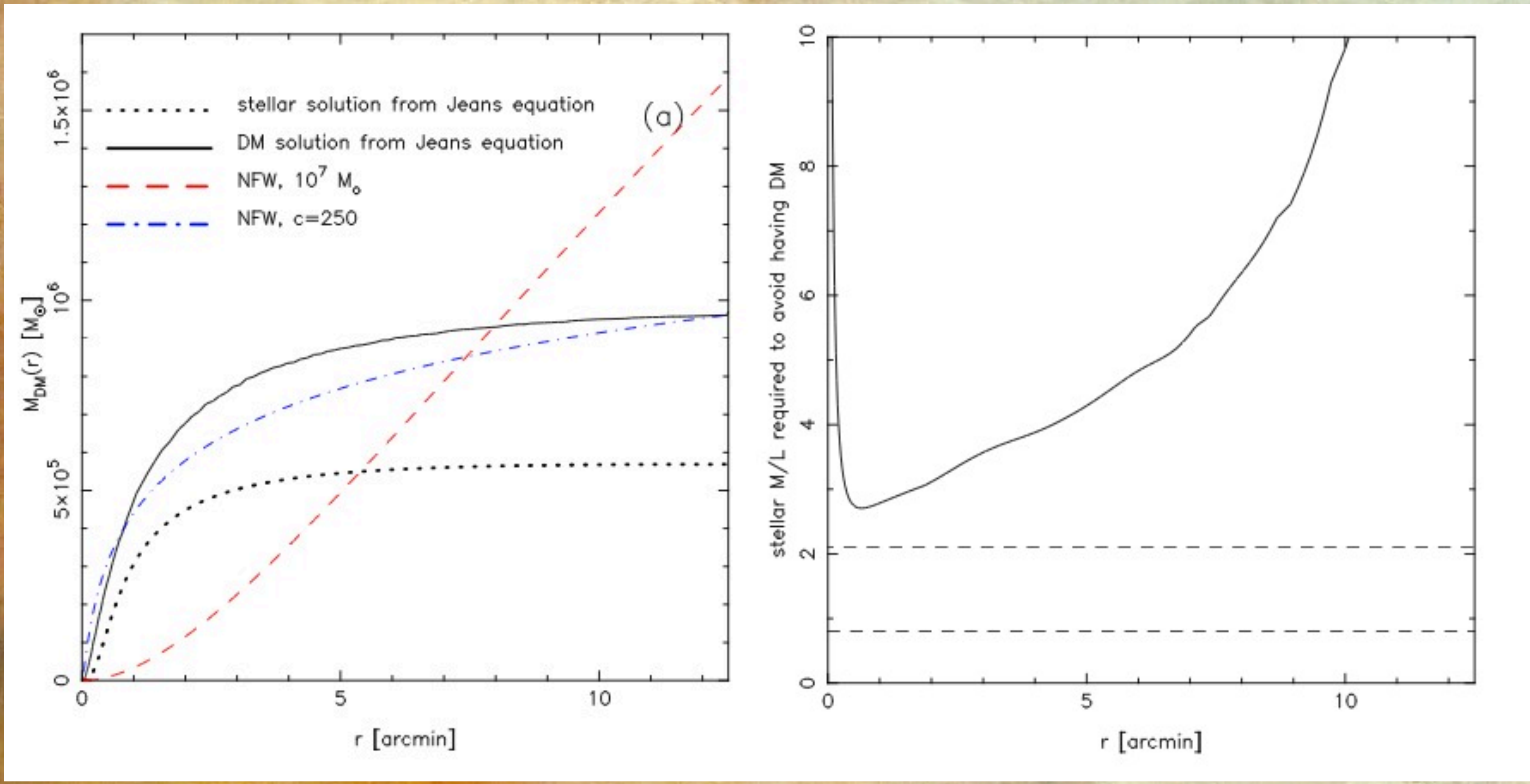


Lots of dark matter possible!

best Jeans solution



best Jeans solution



Conclusions & Prospects

- NGC2419 is by far the best globular cluster to test MOND, also interesting for DM
- With new reduction software, Keck/DEIMOS is capable of measuring hundreds of radial velocities to ~1km/s accuracy. Reliable uncertainties are derived.
- We confirm that NGC2419 shows no sign of mass segregation: the hypothesis that the stellar M/L is constant over the whole extension of the cluster has robust observational basis
- The stellar M/L_V from direct integration of the model that best-fits the observed LF is $M/L_V = 1.5 \pm 0.1$, with a robust lower limit $M/L_V > 0.8$
- Isotropic models are completely ruled out
- A Newtonian anisotropic Michie model gives best fit to unbinned kinematics for N2419
- MOND Michie models are disfavoured wrt Newton (factor of 40000 less likely)
- Adopting polytopes (suggestion Sanders 2011) does not make the case better for MOND
- The case for dark matter is perplexing - models appear to rule out much dark matter but (kinematic) Jeans analysis appears to leave plenty of leeway for DM.

- Need to wait for ELT to get much larger samples on this object :-(
- Status of NGC2419 project: dynamical analysis of models with Dark Matter: ongoing (Nipoti et al.); abundance analysis of the high S/N subset of our spectra: ongoing (Mucciarelli et al.)