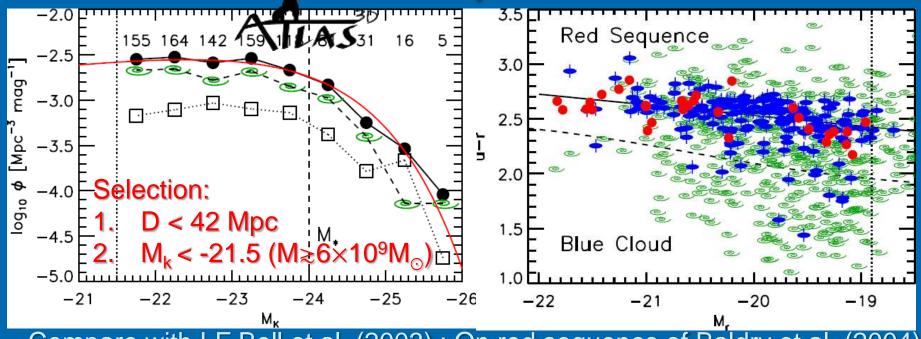
## Anisotropic Jeans models of 260 galaxies with MCMC

#### Michele Cappellari



# The 🐳 sample of ETGs



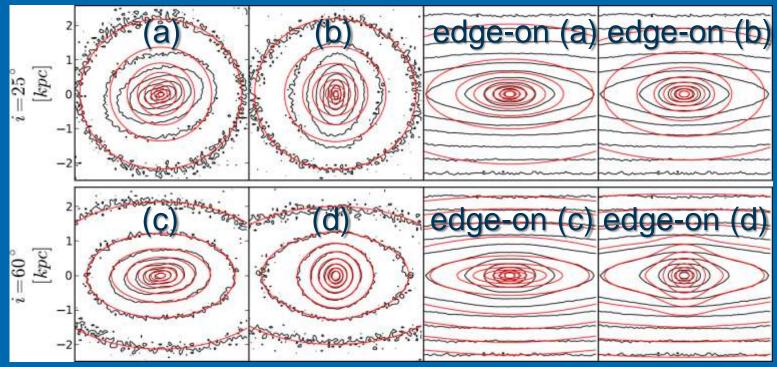
Compare with LF Bell et al. (2003) ; On red sequence of Baldry et al. (2004)

- Clean and simple volume-limited sample selection (Cappellari+11a [P1])
- Luminosity function representative of local Universe
- 260 ATLAS<sup>3D</sup> ETGs galaxies mostly on-red sequence (As in Strateva et al. 2001; Conselice 2006; van den Bergh 2007)

100560 103566 103676 102719 102782 101024 103631 10005448 10005474 1020502 1000509 1000516 1000524 50 50/6 50 50 50 50 50 50 50 50 50 50 50 50 50	
NGC0325 JGC0461 NGC05660 NGC0770 NGC0821 NGC0388 NGC1023 NGC1121 NGC1222 NGC1248 NGC1288 NGC1289 NGC1289 NGC1289 SO	
50/s 10 50 E 50/s 50 50 50 50 50 50 50 50 50 50 E 6 H0C2852 H0C2852 H0C2859 H0C2859 H0C2950 H0C2950 H0C2952 H0C3032 H0C3033 H0C3073 H0C3076 H0C3156 H0C3152 H0C3193	
50 56 50 50 50 50 50 50 50 50 50 50 50 50 50	
E 50 50 50 50 50/6 E 5 50 50 50 E 50 NGC3499 NGC3499 NGC3522 NGC3530 NGC3595 NGC3599 NGC3605 NGC3607 NGC3608 NGC3618 NGC3613 NGC3619 NGC6026	
50 50/0 E 50/0 50 50 E 50 E E 50 50 NGC3640 NGC3641 NGC3648 NGC3688 NGC3685 NGC3674 NGC3674 NGC37575 NGC3776 NGC3788 NGC3678 NGC3645	
50 E E 50 50 50 50 50 E 50 50 50 50 50 80 80 80/9 50/9 50/9 50 50 50 50 80 80/9 50/9 50 50 50 50 80/9 80/9 50 50 50 80/9 80/9 50 80/9 80/9 50 50 50 50 50 50 50 50 50 50 50 50 50	
NGC4233 NGC4239 NGC4239 NGC4239 NGC4239 NGC4239 NGC4239 NGC4239 NGC4236 NGC4236 NGC4236 NGC4237 NGC4239 NGC423	
E 50 E 50 50 50 50 50 50 E 50 E 50 50 50 50 50 50 50 50 50 50 50 50 50	
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NGC4624 NGC4636 NGC4638 NGC4638 NGC4649 NGC4660 NGC4680 NGC4680 NGC4697 NGC4710 NGC4733 NGC4753	
NGC4754 NGC4752 NGC4803 NGC5173 NGC5173 NGC5173 NGC5273 NGC5222 NGC5323 NGC5353 NGC5355 NGC5355 50 50 50 50/e 50/e E E 50 50 E 50 50 50 50 50 50 50 50 50 50 50 50 50	
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PCCD3-452 PCCD3-452 PCCD3-811+ PC20514-88 PCCD11531 PCC110172 UCC03980 UCCD4531 UCC24468 UCC0692 UCC09176 UCC09878 UCC09879	

Images (Cappellari+11a [P1]) Stellar velocities (Krajnovic+11 [P2])

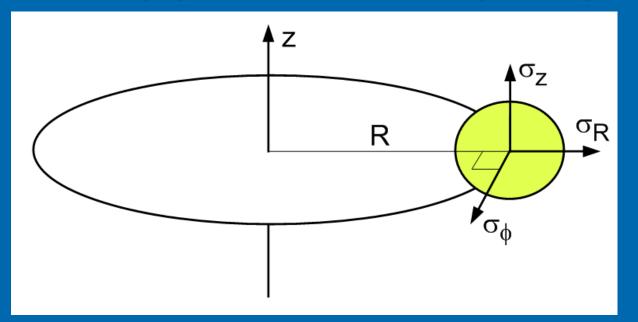
## Modelling problems



Simulations of barred galaxies (Lablanche+12 [P12])

- Deprojection non-unique (unless axisymmetric and edge-on) (Gerhard+Binney96, Romanowsky+Kochanek97, Magorrian99)
- 50% of our sample likely barred
- Deprojection is major obstacle for accurate models
- Range of data quality: only V and  $\sigma$  for 40% of the sample

## Anisotropy and velocity ellipsoid



• 
$$\beta = 1 - \frac{\sigma_z^2}{\sigma_R^2}; \gamma = 1 - \frac{\sigma_\phi^2}{\sigma_R^2}; \delta = 1 - \frac{2\sigma_z^2}{\sigma_R^2 + \sigma_\phi^2} = \frac{2\beta - \gamma}{2 - \gamma}$$

•  $\delta$  is measured by the (V/ $\sigma$ , $\varepsilon$ ) diagram (Binney78,05)

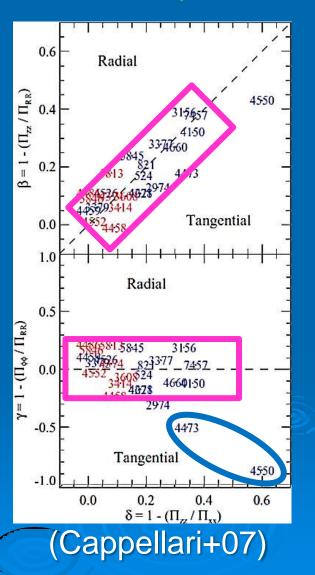
•  $\beta$ ,  $\gamma$  require dynamical models

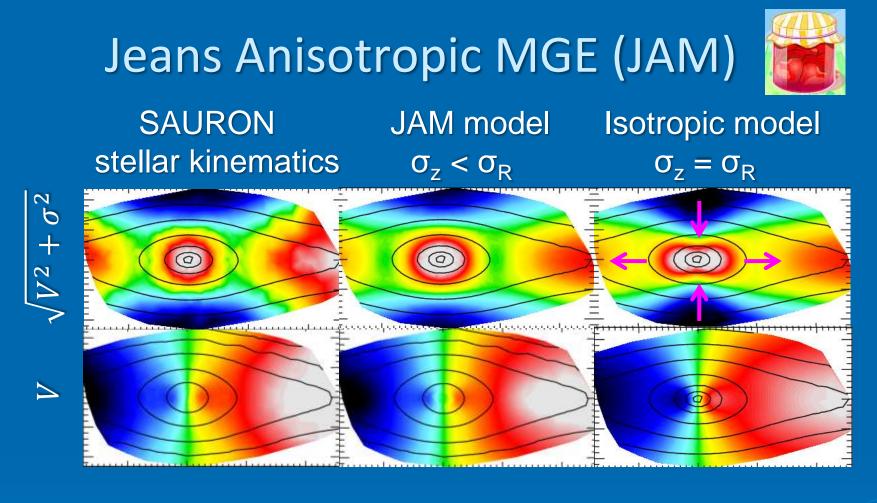
•  $\sigma_R = \sigma_{\phi} \rightarrow (\delta = \beta; \gamma = 0)$ : Oblate velocity ellipsoid

## Anisotropy of flattened ETGs



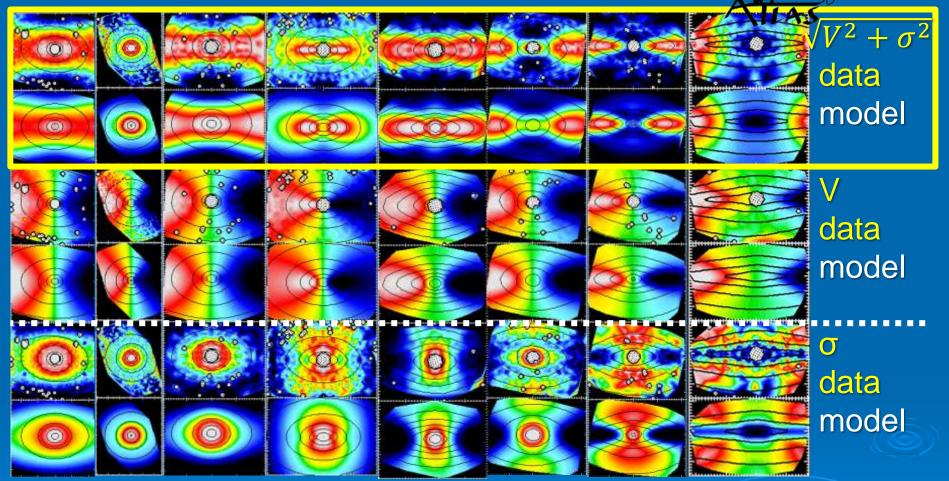
- SAURON integral-field data
- Schwarzschild's axisymmetric models
- 24 galaxies (Cappellari+07)
- Global anisotropy approximation
- $\rightarrow \delta \approx \beta \text{ and } \gamma \approx 0$ 
  - (2 important exceptions)
- → Oblate velocity ellipsoid!
- Independently confirmed in Coma (Thomas+09)





- Use Multi-Gaussian Expansion to fit images (Emsellem+94)
- Efficient anisotropic Jeans solution with  $\sigma_z < \sigma_R$  (Cappellari 08)
- Just two parameters (i,  $\sigma_z/\sigma_R$ ) fit shape of both V<sub>rms</sub> and V! (http://purl.org/cappellari/idl)

## Sample JAM models for

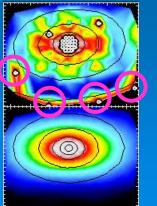


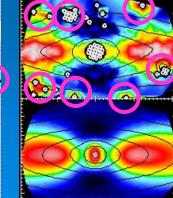
- Large variations in observed kinematics
- Kinematics shape well 'predicted' by JAM (i,  $\sigma_z/\sigma_R$ )
- Caveat: JAM not accurate for slow rotators (10% sample)

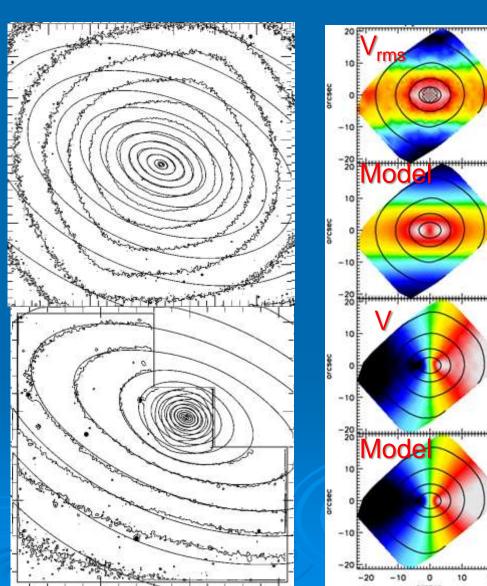
## Uncovering modelling problems

- JAM approximates inner dynamics of disk galaxies
- Useful reference to uncover exceptions
- Most JAM fits problems
  - hidden bars
  - low inclination
  - interactions

#### JAM can flag bad kinematics bins



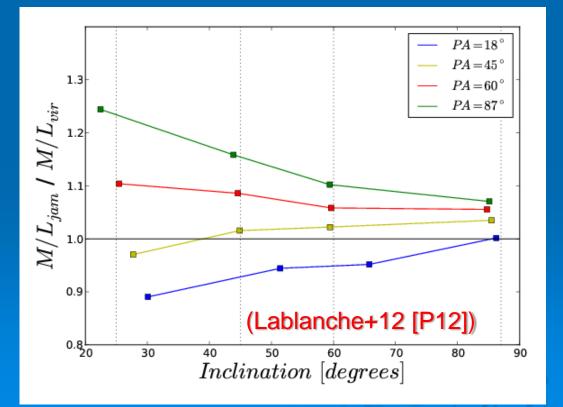


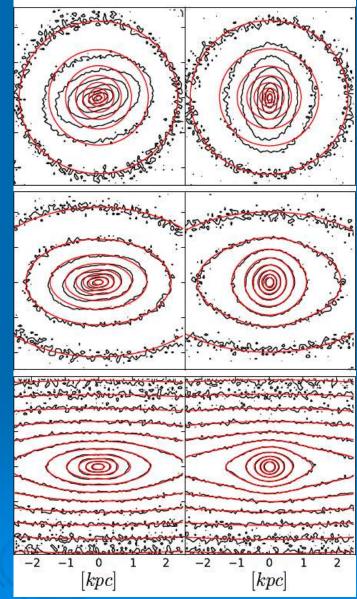


# (Scott, MC, et al. 2009)

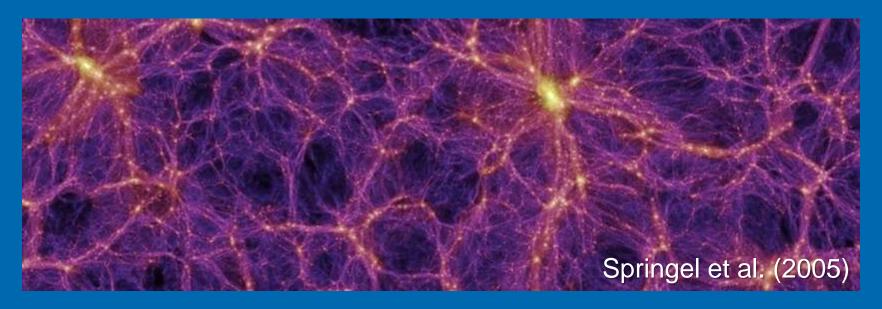
## Impact of bars on M/L

- MGE models of barred fast rotators
  - Trying to recover M/L
  - For various inclinations and bar PAs
  - M/L error < 15% for i > 40





### But where is dark matter?



#### JAM 'predicts' kinematics from galaxy images

- Accurate photometric model essential
- Global anisotropy remarkably homogeneous

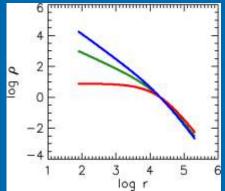
• Total density closely follow stellar one (within  $1R_e$ )

 $\rightarrow$  little DM (within a sphere of radius  $\approx R_e$ )

## Measuring Stellar M/L

Generalized NFW halo profile

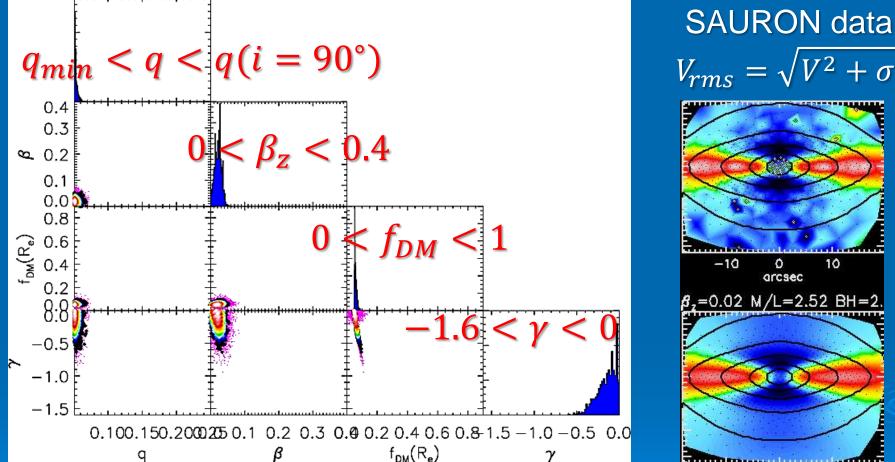
• 
$$\rho_{DM}(r) = \rho_s \left(\frac{r}{r_s}\right)^{\gamma} \left(\frac{1}{2} + \frac{1}{2}\frac{r}{r_s}\right)^{-\gamma-2}$$



Sample (i, β<sub>z</sub>, <sup>M</sup>/<sub>L</sub>, f<sub>DM</sub>, γ) via Markov chain Monte Carlo
Outer halo profile nearly irrelevant (use fixed break radius r<sub>s</sub>)
P(model | data) ∝ P(data | model) P(model)
P(data |model) ∝ exp(-<sup>1</sup>/<sub>2</sub> χ<sup>2</sup>) (→ Gaussian errors)
noninformative (constant) priors (but -1.6 < γ < 0)</li>
10,000 sampled points (=model run) per galaxy

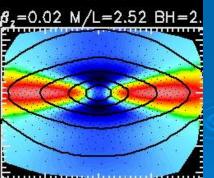
Adaptive Metropolis method (Haario+01)

## **Posterior distribution**



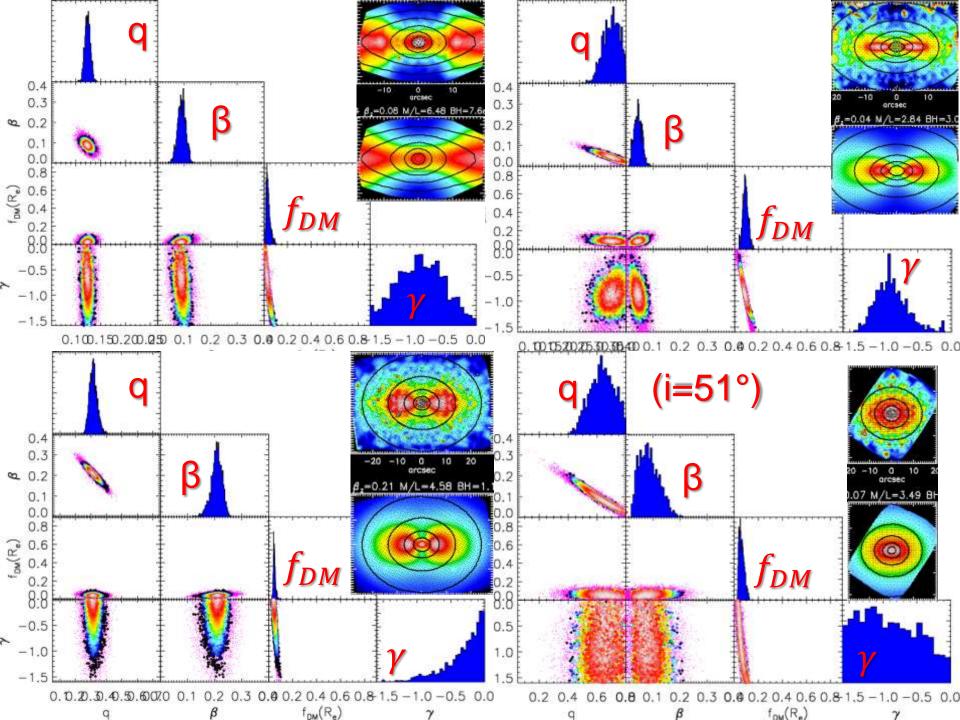
0 10 arcsec

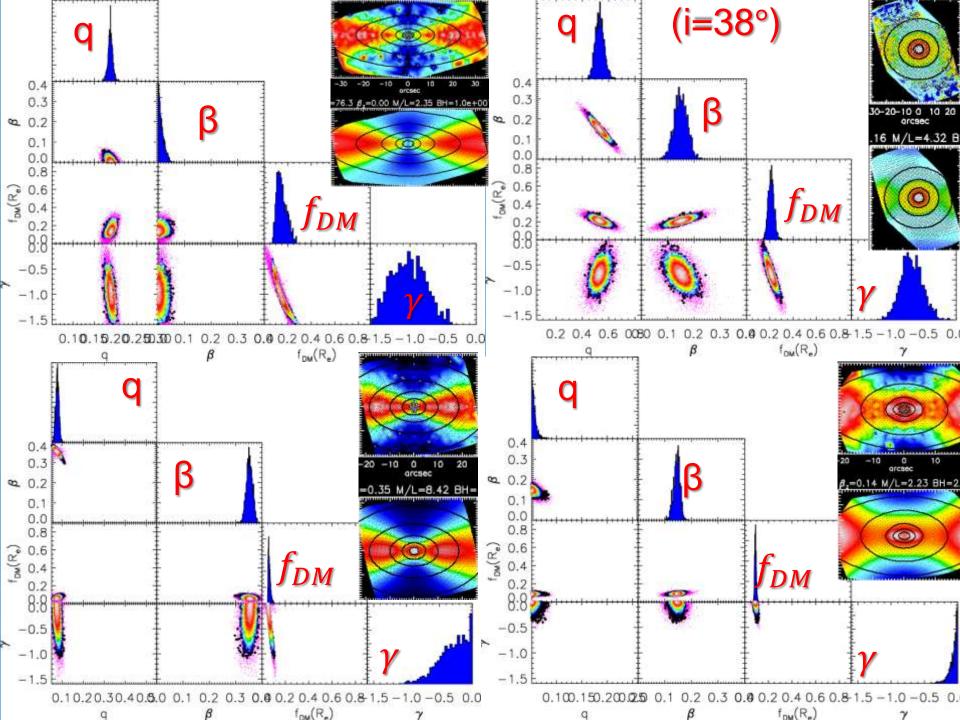
 $V^2 + \sigma^2$ 



Posterior distribution of model parameters: Marginalized 2-dim and 1-dim histograms (see also Barnabé+12)

JAM best fit  $f_{DM}(R_{e}) = 5\%$ 





## Conclusions

- Modelling large galaxy samples
- Deprojection is major uncertainty in models
- Most early-type galaxies have simple dynamics
- Kinematics 'predicted' by detailed photometry
- Useful reference to flag exceptions / problems
- Accurate constraints on  $M/L_{stars}$  and  $f_{DM}(R_e)$
- Useful for galaxy surveys (e.g. MaNGA)
- See tomorrow slides for IMF results