NMAGIC Made-to-Measure Modeling of Elliptical Galaxies

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I. Made-to-measure dynamical modeling with NMAGIC

II Elliptical galaxy halo kinematics with planetary nebulae

III Dark matter in elliptical galaxies from NMAGIC modeling

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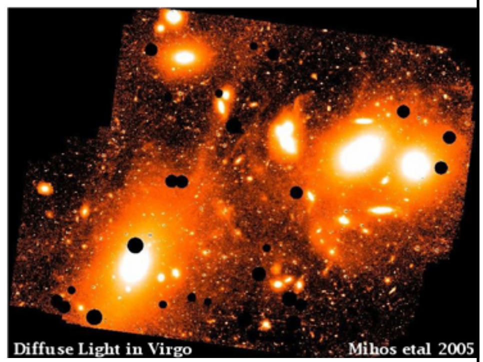


Core of the nearby Virgo cluster with luminous galaxies M87, M86, M84 and others

NMAGIC - χ^2M2M

De Lorenzi, Debattista, Gerhard & Sambhus, 2007

- **Made-to-Measure (M2M) Syer & Tremaine 1996**
  - **N-particle system with adjustable weights**
  - **Change particle weights according to force-of-change equation until the particle system has evolved towards specified target system**
- **χ^2M2M extends M2M to take into account observational errors $\sigma(Y_j)$ for target observables Y_j. Measure deviation from target observables by**

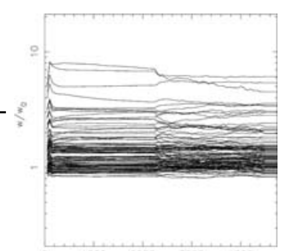
$$\chi^2 = \sum_j \Delta_j^2 \qquad \Delta_j = \frac{y_j - Y_j}{\sigma(Y_j)}$$

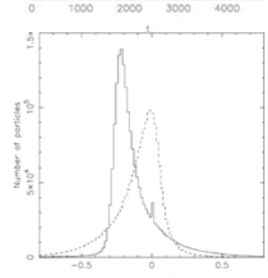
- **The FOC is** $$\frac{dw_i}{dt} = \varepsilon w_i \left(\mu \frac{\partial S}{\partial w_i} - \sum_j \frac{K_{ji}}{\sigma(Y_j)} \Delta_j \right)$$

then the w_i will have converged once F = μS - ½ χ^2 is maximized.

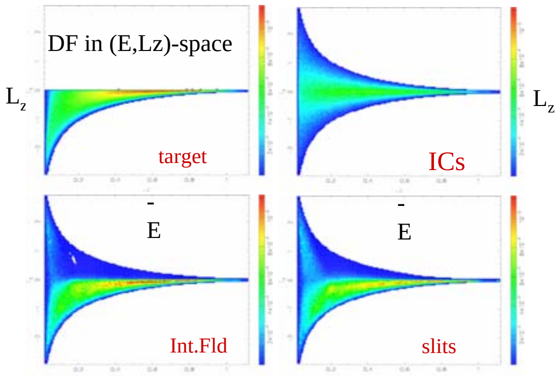
- **Likelihood term in the FOC to take into account constraints from individual velocities**

De Lorenzi et al. 2008

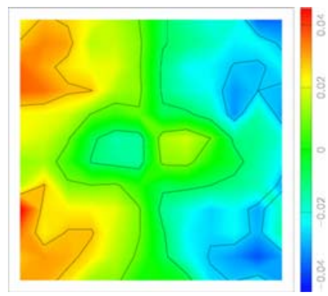




Tests: Recovering Maximally Rotating Oblate System
Setting up a Rotating Triaxial System



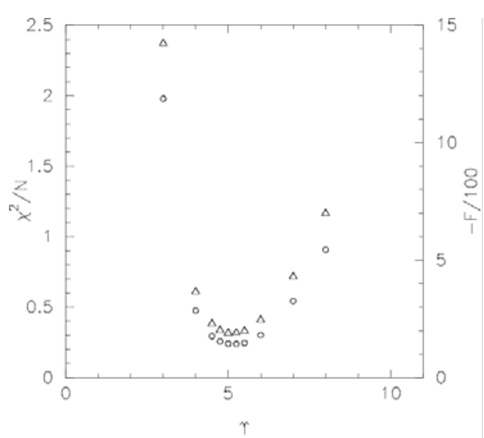
De Lorenzi et al. 2007

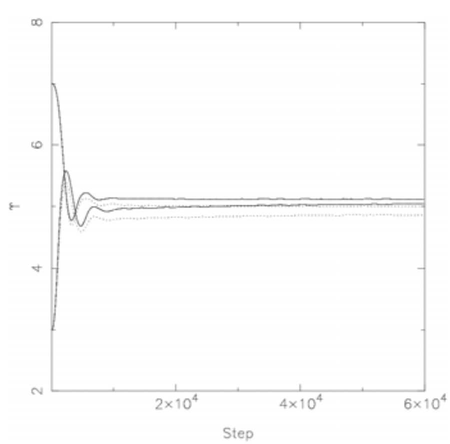


- Squeeze spherical model
- Keep in self-consistent equilibrium, using NMAGIC
- + Gradually set in figure rotation, corotation 10 R_e
- + Again use NMAGIC to keep in dynamical equilibrium

los velocity field ⇒ in $[-R_e,R_e] \times [-R_e,R_e]$

Tests of M/L fits





χ^2 of models with different M/L

Convergence of fitted M/L; true value always M/L=5

Observables (NGC 3379)

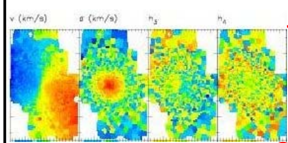
Kinematic data

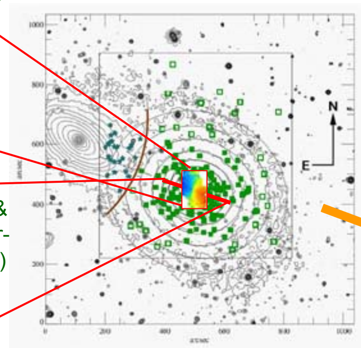
luminosity weighted Gauss-Hermite moments of the LOSVD

Photometric data

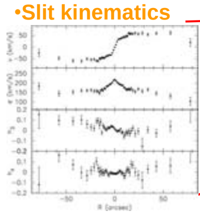
Surfaced brightness and luminosity density

•**SAURON data** (Shapiro+06)





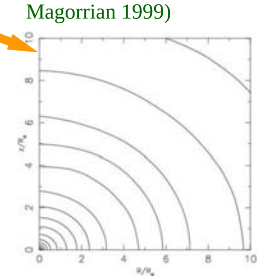
•**Slit kinematics**



(Statler & Smecker-Hane 99)

Figure from Douglas+07

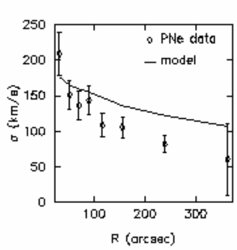
Deprojection, e.g., axisymmetric Magorrian 1999)

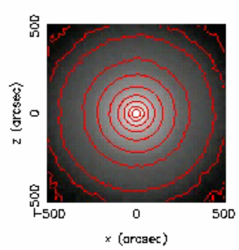


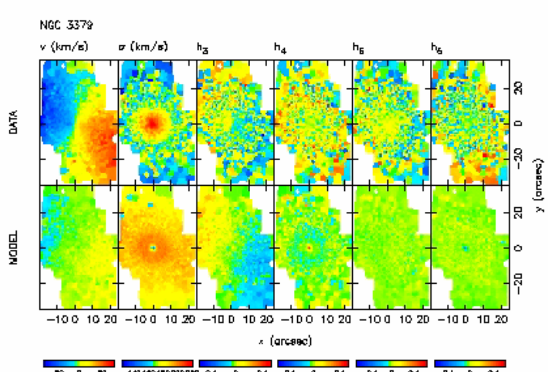
•**Discrete data**

- **PNe data** (Douglas+07) either binned or as discrete velocities

NMAGIC – A New Way of Modeling Galaxies







Developed @ Basel&MPE 2002-2007
De Lorenzi, Gerhard etal., MNRAS

N-particle model approaches target data for elliptical galaxy NGC 3379

Top right: Light distribution (observer sees ~spherical image from top)

Top left: radial profile of stellar velocity dispersion

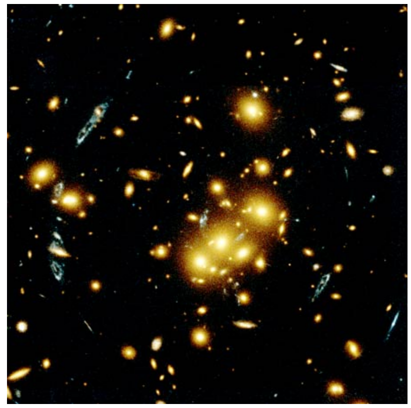
Left: Projected kinematics of NGC 3379 (SAURON data)
v=mean line-of-sight velocity
σ=velocity dispersion of the stars
hn= higher order moments

Lower left: Initial → Final model fit

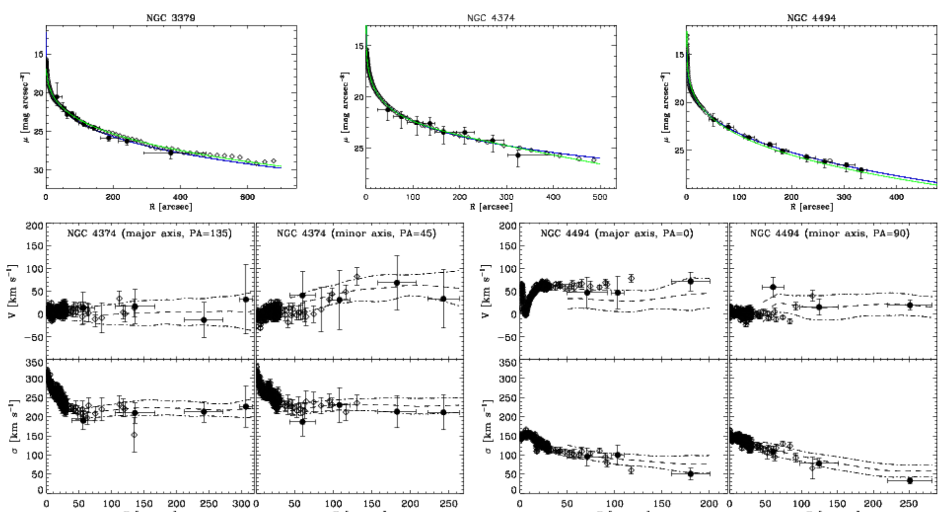
Applications: black hole masses, dark matter halos, galactic nuclei, star clusters, also in Galactic Center

Outer Halos of Elliptical Galaxies – Kinematics with Planetary Nebulae

- PNe trace the stellar light and kinematics
- Especially useful to constrain the dark matter and orbit distribution at large radii
- PNe can be used to trace the transition to the intracluster light

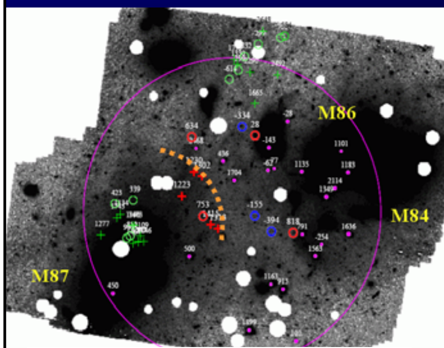


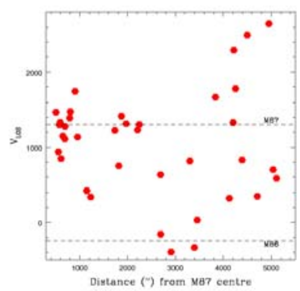
PNe trace stars

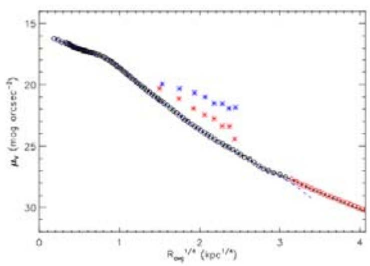


Coccato et al. 2009, MNRAS 394, 1249

Extreme outer halo of Virgo-central galaxy M87

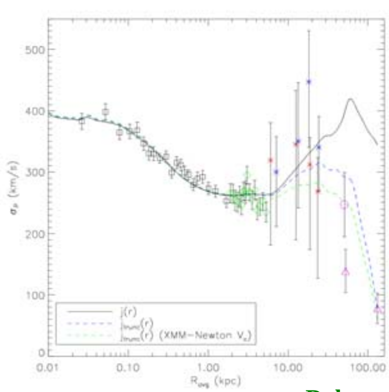






- **Very extended surface brightness profile (n=11.9, R_e=704"=51.2kpc, Kormendy+09)**
- **Surrounding diffuse ICL at μ_V=27.5**
- **PNe trace light (Coccato+09); GCs unclear**
- **PN velocities obtained down to μ_V=27.5 (Doherty+09). Long slit data to ~24.0.**
- **PN with M87 v_{sys} only for R<160 kpc. At larger radii see ICL with M86 and other v's**

Truncation of the M87 halo



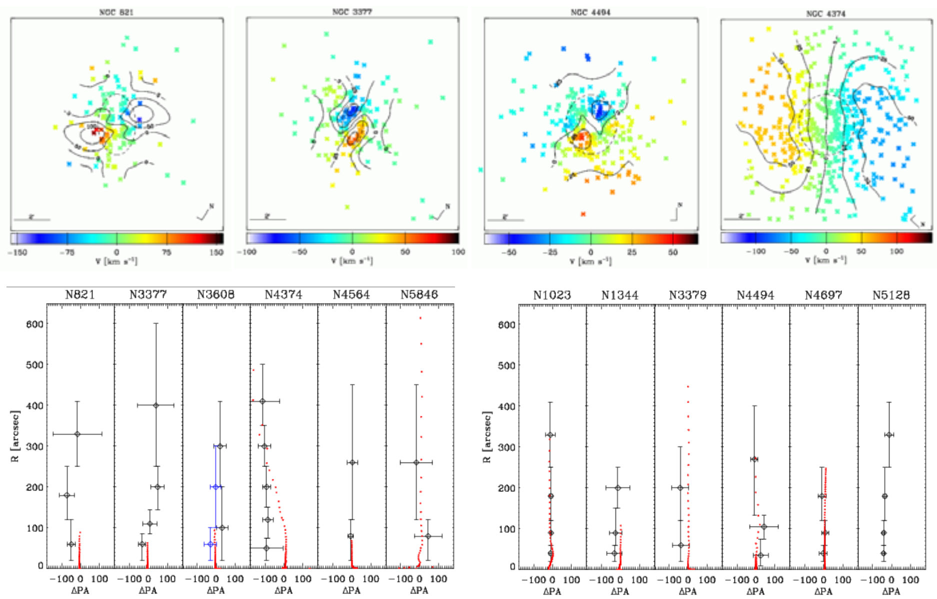
- Velocity dispersion falls to 78 ± 25 km/s at R_{avg}=140 kpc and 247 ± 50 km/s at R_{avg}=50 kpc.
- Jeans models in the X-ray potential (Nulsen & Boehringer 1995) can reproduce these low σ only if the stellar halo is tructated at ~150kpc.
- Additionally, number density of PN with M87 velocities truncated at ~2σ significance (comparing light with PNe and using α value determined from spectroscopically confirmed PNe).

Doherty, Arnaboldi, Das, Gerhard et al., arXiv 0905.1958

Possible origins of truncation: (i) earlier tidal effects by dark matter potential, (ii) AGN feedback stopping SF near R_{vir} through ram pressure stripping, (iii) cluster collapse onto M87 and adiabatic contraction.

Nb: Tidal truncation observed in dense cluster cores (weak/strong lensing observations).

Kinematic misalignments at large radii



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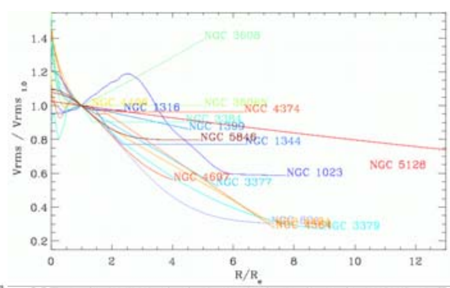
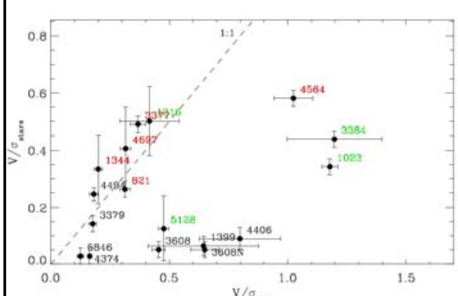
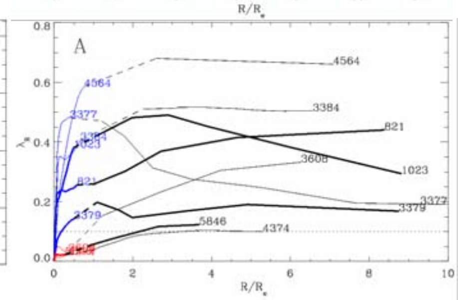
Outer Halo Kinematics from PNe

- **2 types of slowly falling and rapidly falling kinematic profiles**
- **Slow/fast rotator division more complicated in the outer halos**

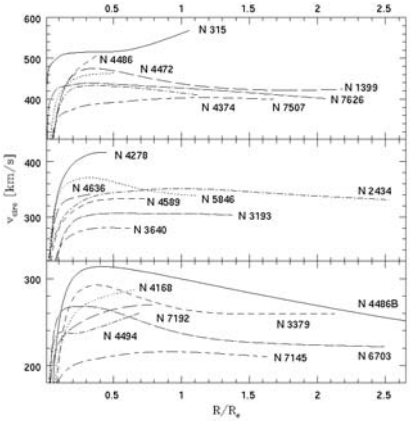
Coccato et al. 2009



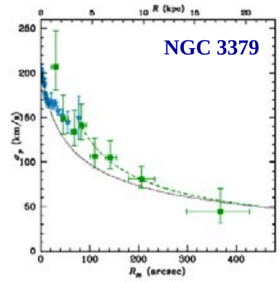


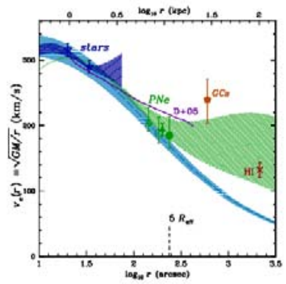


Dark Halos Circular Velocity Curves from Stellar Kinematics



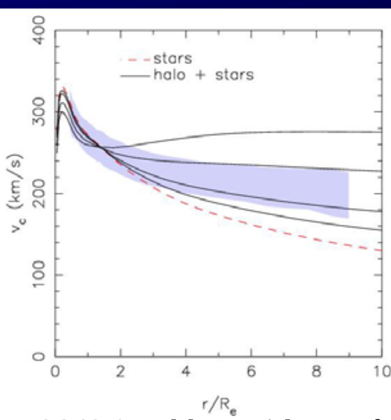
Round galaxies, derived from non-parametric spherical DF models Gerhard et al. (2001). Similar results for flattened Coma ellipticals, derived from axisymmetric Schwarzschild models Thomas et al. (2007)



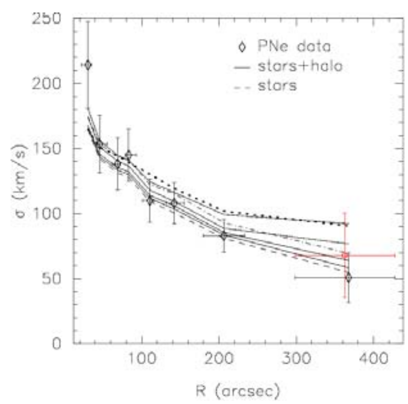


Steeply falling dispersion profile in NGC 3379 is consistent with little dark matter if the galaxy is isotropic Romanowsky+03 Douglas+07

Spherical Models for NGC 3379 in Different Potentials



- **NGC 3379 model potentials range from stars only (- -. Model A), to stars plus dark halo models (—, B-E). Models A, E (weakly) ruled out by likelihood analysis**
- **shaded range is from Dekel et al. (2005) star-forming merger simulations on orbits from ΛCDM cosmology**

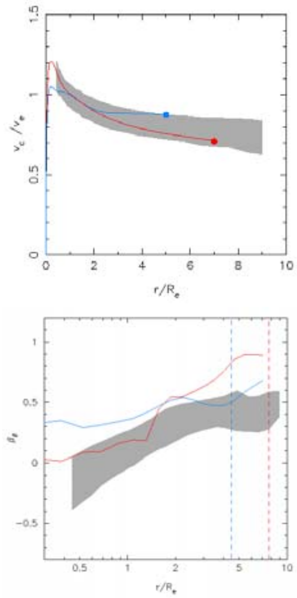


de Lorenzi et al. 2009

►Falling PN velocity dispersion profile can be reproduced in A-D

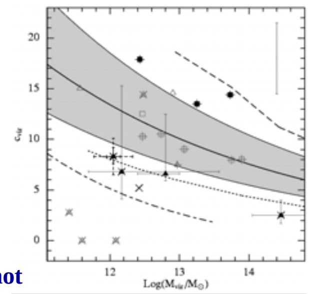
►Baryons centrally concentrated, but no contradiction to ΛCDM

Halo Dynamics in NGC 3379 & NGC 4697



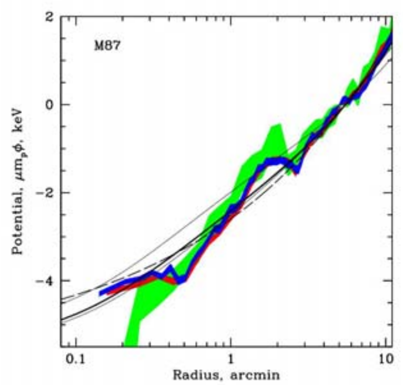
Best axisymmetric models for NGC 3379 (red) and N4697 (blue) have moderately falling circular velocity curves and radially anisotropic halos (de Lorenzi et al. 2008, 2009)

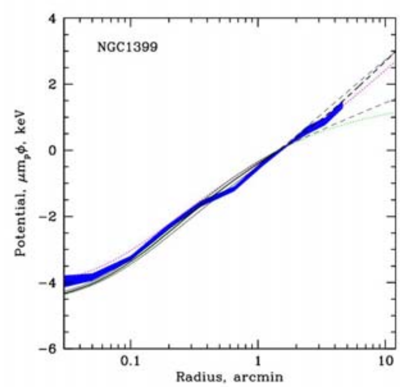
Fig. from Napolitano et al. 2009 shows virial masses and concentrations from fitted NFW models & compares with LCDM 1sigma range from Bullock et al. 2001



Strongly radially falling dispersion profiles in NGC 3379, NGC 4697 do not necessarily imply non-standard diffuse halos, but may be consistent with predicted scatter.

Gravitational Potential: X-ray vs. Optical





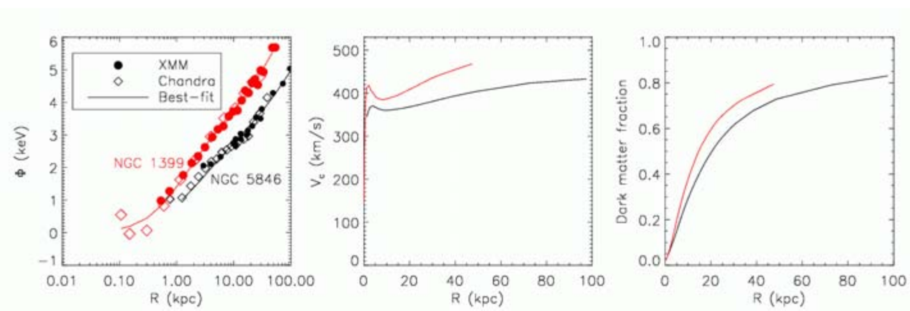
- **Potential from Chandra X-ray emission for M87, NGC 1399 (hot gas dominates, but point sources subtracted, different energy bands), agrees with potential determined from optical data (M87: Romanowsky & Kochanek 2001, Wu & Tremaine 2006; NGC 1399: Saglia et al. 2000, Kronawitter et al. 2000) to within 10-20% resp. 7%. This is the level of non-thermal contributions to the pressure. In M87, characteristic signature of an outgoing shock wave (Churazov et al. 2008).**
- **Work is being extended to a larger galaxy sample – potentials are near-isothermal.**
- **Can use X-ray potential as input for dynamical modeling.**

Dark Halo Potential from X-rays: NGC 1399 & 5846

- Temperature, density profiles from Chandra + XMM X-ray spectra; potential and circular velocity curves from hydrostatic equilibrium for NGC 1399 to ~500" and NGC 5846 to ~800"
- Stellar component + NFW dark matter fit ⇒ NGC 1399: $(M/L)_V$=9.1
NGC 5846: $(M/L)_V$=6.1

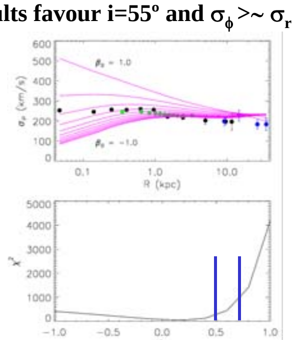
Dark matter accounts for 70-80% of total mass at 50 kpc.

. **Das et al. 2009 in prep.**

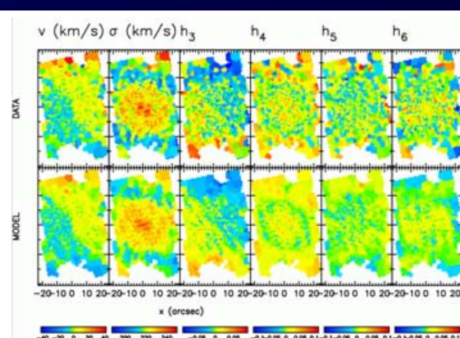


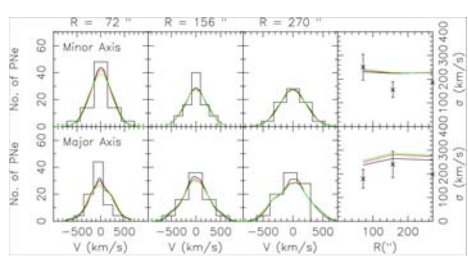
Orbital Structure of NGC 5846

- **Best-fit oblate NMAGIC models for inclinations 55º (black), 75º (red) and 90º (green), based on Sauron, slit & PNe data**
- **Note dispersions alone do not suffice for these densities (see Gerhard 1993); need likelihood of PN velocities**
- **Results favour i=55º and σ_ϕ >~ σ_r > σ_θ**



Likelihood constraint R>2Re





Das et al. 2009 in prep.

Conclusions

- **Made-to-measure dynamical modeling with NMAGIC new, competitive method**
  - **No symmetry assumption & orbit gridding, includes Φ evolution & stability**
  - **Still slower and not routine; issues with convergence, initial conditions dependence when non-unique – working on those**
- **Outer halo kinematics from PNe (down to μ_B=28.5)**
  - **Kinematic misalignments are more frequent in the halos, presumably implying more triaxial shapes as a result of the last merger. Halo λ-profiles are more diverse, dispersion profiles either slightly, or strongly falling.**
  - **Outer halo of M87 truncated and anisotropic; beyond 150 kpc we see only encroaching stars of M86 and other galaxies, probably prior to substantial dry merger.**
- **Evidence increasing that the outer halos of ellipticals are dark matter dominated and radially anisotropic, consistent with ΛCDM simulation results.**
  - **Strongly radially falling dispersion profiles in NGC 3379, NGC 4697 do not necessarily imply non-standard diffuse halos; these may be halos on the low density side of the predicted scatter.**
  - **Non-thermal pressure sources in X-ray bright E's at level of 10-20%; data imply high-density halos with near-isothermal potentials.**

  Dynamical analysis of several galaxies on-going.