Dynamics of Elliptical Galaxies at Large Radii

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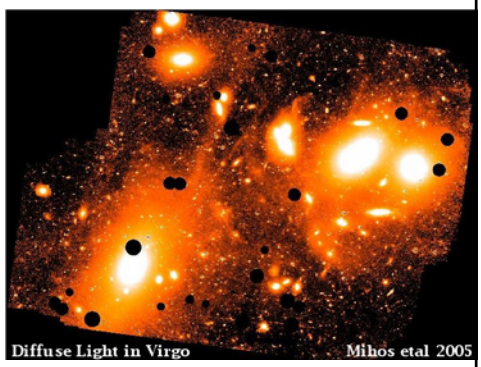
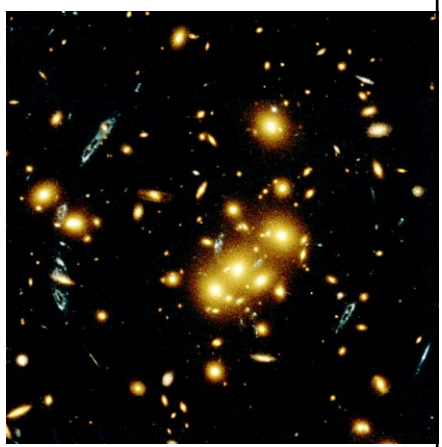


Core of the nearby Virgo cluster with luminous galaxies M87, M86, M84 and others

Outer Halos of Elliptical Galaxies –Dark and Luminous

- **Elliptical galaxies formed through merger and accretion processes, at different times and in different environments**
- **Expect different dark matter halo densities and orbit structure, as is indeed found**
  Gerhard+01, Thomas+09

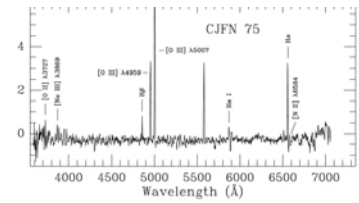
  Some ellipticals with apparently little or no dark matter Romanowsky+03
- **Orbit structure contains clue to formation history. Signatures of accretion should be best preserved in the outer halos where dynamical time-scales are long.**
- **But can only be determined together with dark matter potential – degeneracy known since**
  Binney & Mamon 82
- **Gravitational potential from**
  - **Modeling stellar kinematics**
  - **Hydrostatic equilibrium of X-ray gas**
    Humphrey+06, Churazov+08
- **Relation to environment: transition to the diffuse intracluster light**
  Doherty+09

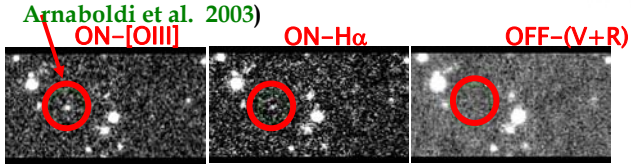


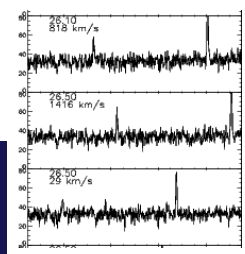
Dense galaxy cluster with several large elliptical galaxies

Planetary Nebulas (PNe) as Kinematic Tracers of Diffuse Light

- **PNe approximately trace light — α parameter, $\alpha_{1.0,B}$~(0.5-2)×10^{-8} PN/$L_{¤}$**
- **The [OIII] line emission at 5007Å is the strongest emission from a PN. Can use it for identification & measurement of its radial velocity.**
- **E.g., narrow-band photometry and follow-up spectroscopy (e.g., with FLAMES@VLT, Arnaboldi et al. 2003)**

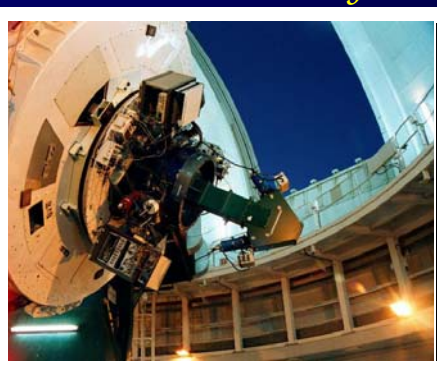


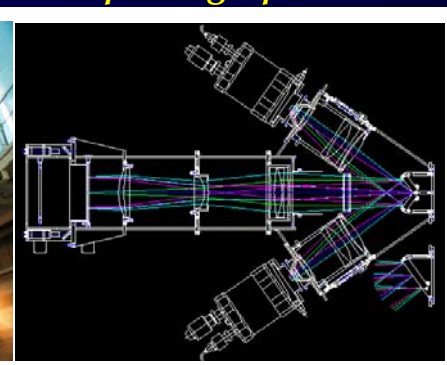




Can obtain PN number density distribution, 2D radial velocity fields, velocity dispersion, some LOSVD information in regions where the stellar surface brightness is too faint with respect to the night sky for absorption line spectroscopy (to μ_B=28.5 mag/□")

Slitless spectroscopy: Counterdispersed imaging (CDI) with the Planetary Nebula Spectrograph (PN.S)





- **Simultaneous CDI through two [OIII] arms; third Hα imaging arm**
- **Instrument mounted on Cassegrain focus at 4.2m WHT**
- **3 [O III] (5007 Å) filters covering (-1400 .. +3400) km/s; each FWHM = 36 Å = 2200 km/s**
- **Instrument efficiency = 72% ⇒ total system efficiency = 33% (~2x general purpose!)**
- **Field of view = 11.4' x 10.3' (50 x 50 kpc in Virgo Cluster)**
- **Built by Prime Optics, RSAA, ASTRON; see Douglas et al. 2002 PASP, 2007 MNRAS**

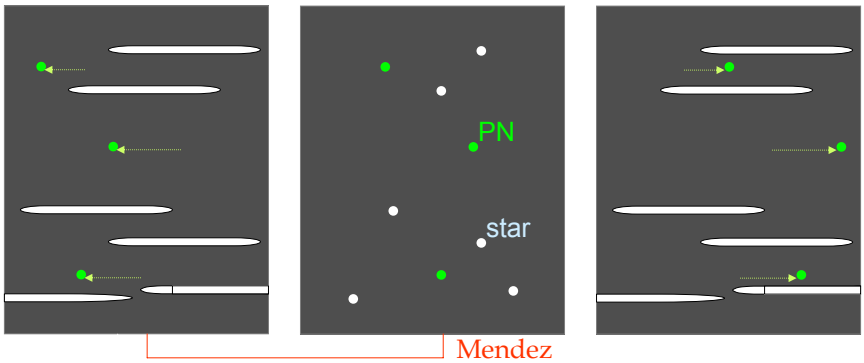
Slitless Spectroscopy (counter-dispersed imaging)

- results in positions & velocities simultaneously

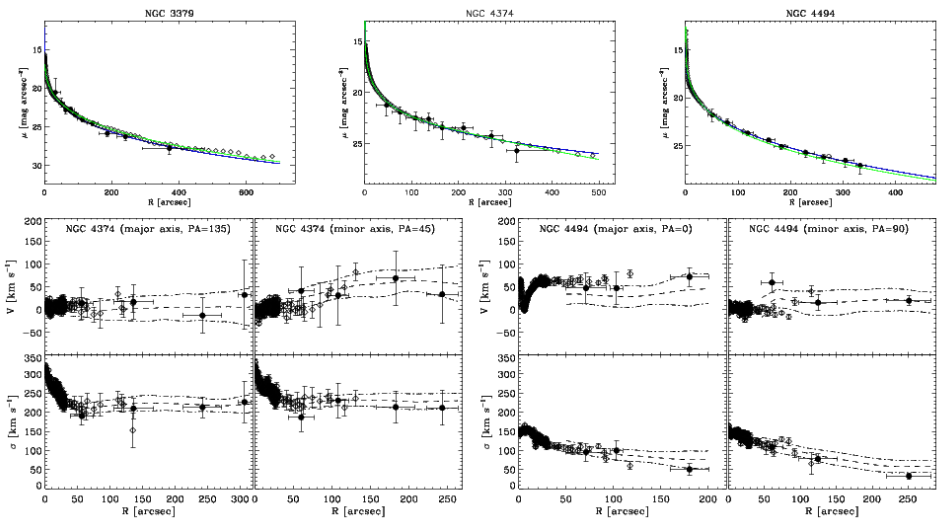
[O III] filter, slitless, dispersed 0°

undispersed field

[O III] filter, slitless, dispersed 180°



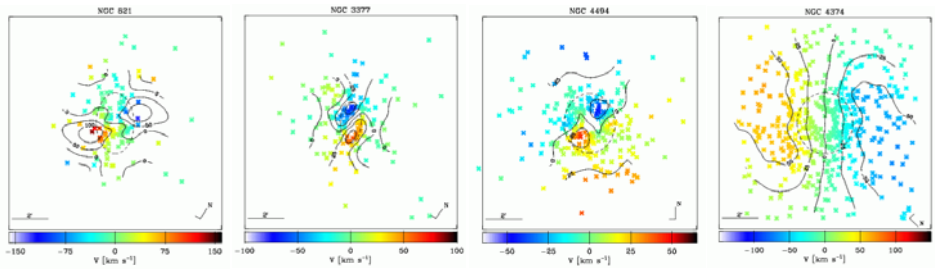
PNe trace stars

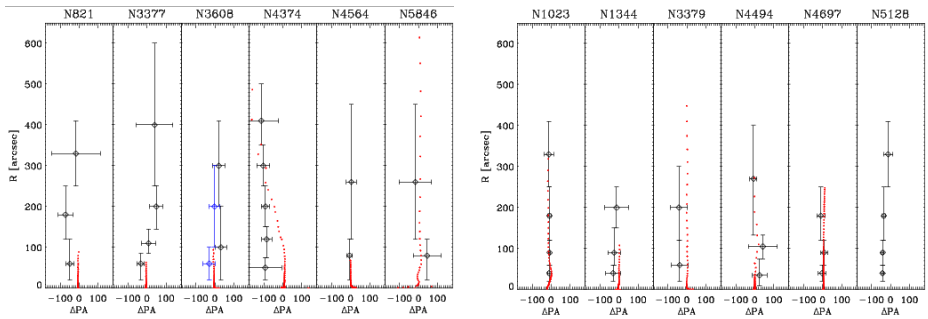


Coccato et al. 2009, MNRAS 394, 1249

See Poster L-P04 by Coccato et al.

Kinematic misalignments at large radii



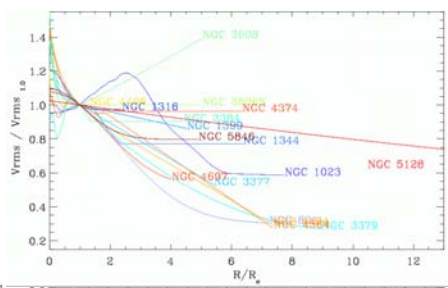


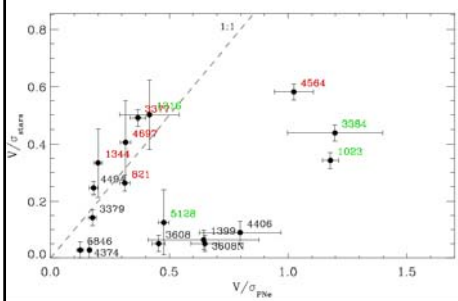
Coccato et al. 2009 MNRAS

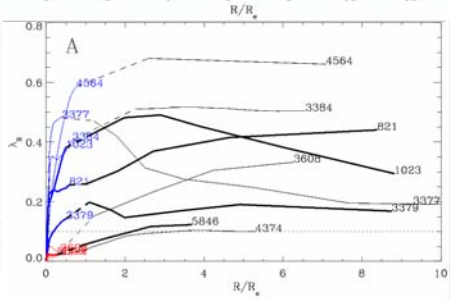
Outer Halo Kinematics from PNe

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

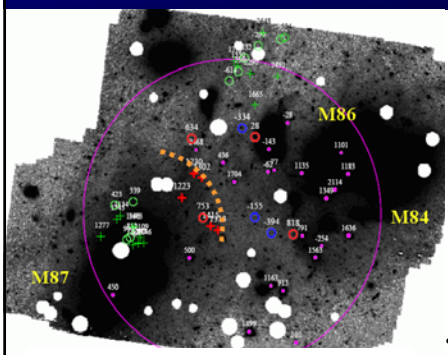
Coccato et al. 2009 & L-P04

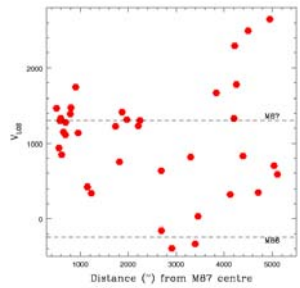


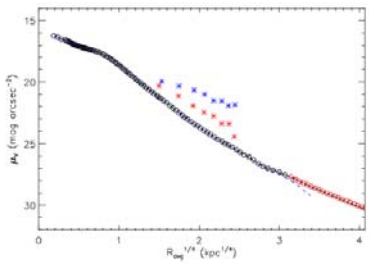




Extreme outer halo of Virgo-central galaxy M87

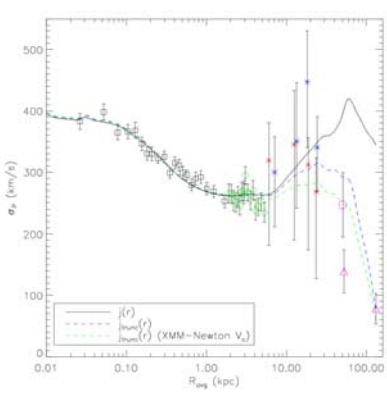






- **Very extended surface brightness profile (n=11.9, R_e=704"=51.2kpc, Kormendy+09)**
- **Surrounding diffuse ICL at μ_V=27.5**
- **PNe trace light (Coccato+09); GCs unclear**
- **PN velocities obtained down to μ_V=27.5 (Doherty+09, arxiv:0905.1958). Long slit data to ~24.0.**
- **PN with M87 v_{sys} only for R<160 kpc. At larger radii see ICL with M86 and other v's**

Truncation of the M87 halo



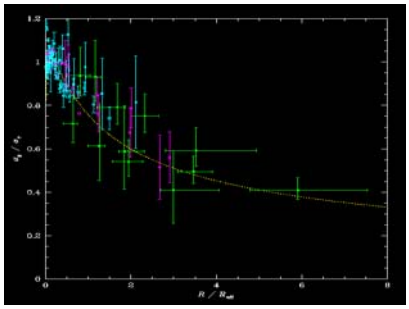
- Velocity dispersion falls to 78 ± 25 km/s at R_{avg}=140 kpc and 247 ± 50 km/s at R_{avg}=50 kpc.
- Jeans models in the X-ray potential (Nulsen & Boehringer 1995) can reproduce these low σ only if the stellar halo is trunctated at ~150kpc.
- Additionally, number density of PN with M87 velocities truncated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

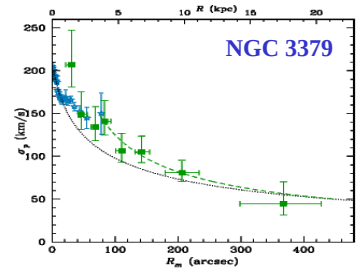
Doherty, Arnaboldi, Das, Gerhard et al. 2009, arxiv:0905.1958

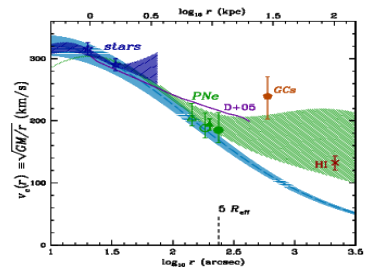
Possible origins of truncation: (i) earlier tidal effects by dark matter potential, (ii) AGN feedback stopping SF near R_{vir} through ram pressure stripping, (iii) cluster collapse onto M87 and adiabatic contraction.

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

Low density dark matter halos in elliptical galaxies?



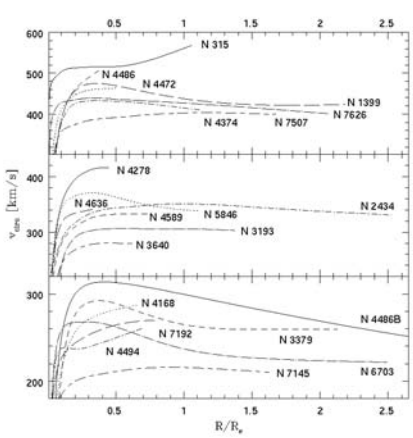


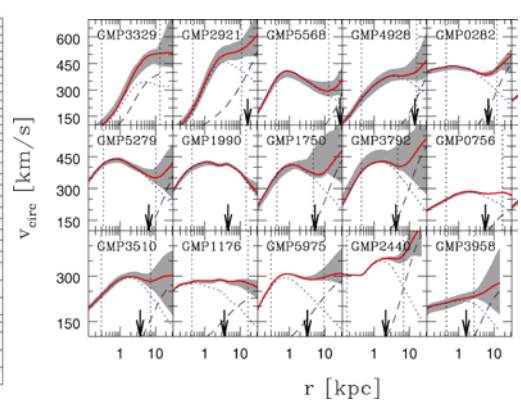


- Velocity dispersion profiles of 4 intermed. luminosity E's falling (Méndez+01, Romanowsky+03); Jeans and orbit models suggest little extra dark matter inside several R_e (Douglas+07, Rom.+03)
- Different from other ellipiticals which have ~flat circular velocity curves and dense halos (Gerhard+01, Thomas+07)

Douglas+07, PN.S project

Circular Velocity Curves from Stellar Kinematics





Round galaxies, derived from non-parametric spherical DF models
Gerhard et al. (2001)

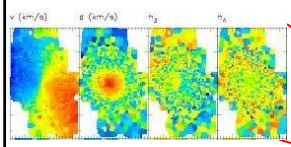
Flattened Coma ellipticals, derived from axisymmetric Schwarzschild models
Thomas et al. (2007)

Observables (NGC 3379)

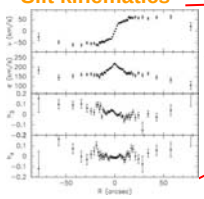
Kinematic data

luminosity weighted Gauss-Hermite moments of the LOSVD

- **SAURON data** (Shapiro+06)



- **Slit kinematics**



(Statler & Smecker-Hane 99)

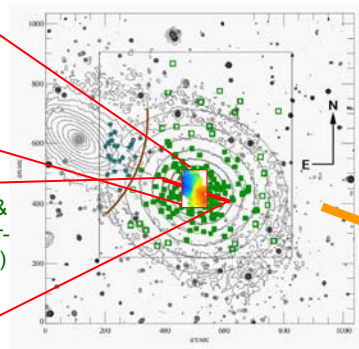


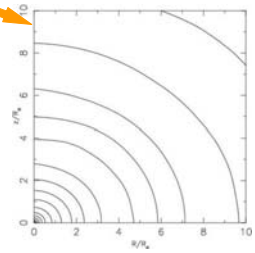
Figure from Douglas+07

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

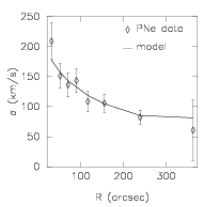
Photometric data

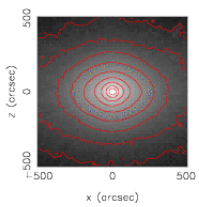
Surfaced brightness and luminosity density

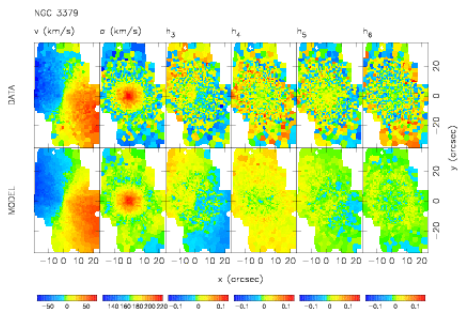
Deprojection, e.g., axisymmetric Magorrian 1999)



NMAGIC – A New Way of Modeling Galaxies







(final model instead of film)

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

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

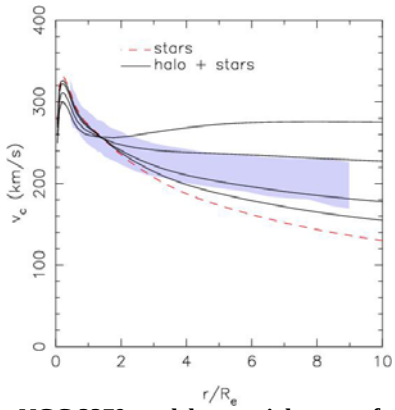
Top right: Light distribution (observer sees ~spherical image from top)
Top left: radial profile of stellar velocity dispersion

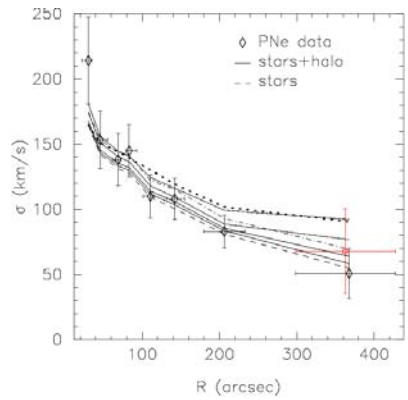
Left: Projected kinematics of NGC 3379 (SAURON data)
v=mean line-of-sight velocity
σ=velocity dispersion of the stars
hn= higher order moments

Lower left: Initial → Final model fit

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

Spherical Models for NGC 3379 in Different Potentials





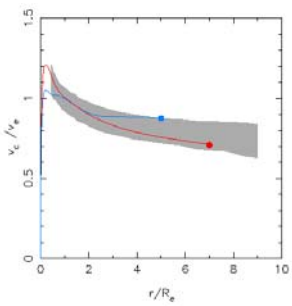
- **NGC 3379 model potentials range from stars only (- -. Model A), to stars plus dark halo models (—, B-E). Models A, E (weakly) ruled out by likelihood analysis**
- **shaded range is from Dekel et al. (2005) star-forming merger simulations on orbits from ΛCDM cosmology**

de Lorenzi et al. 2009 & Poster L-P09

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

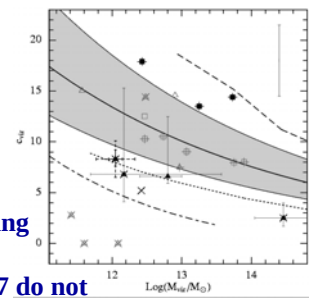
►Baryons centrally concentrated, but no contradiction to ΛCDM

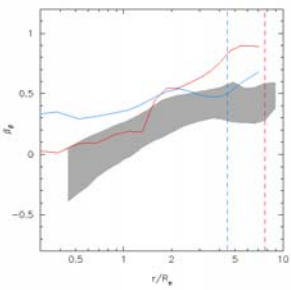
Halo Dynamics in NGC 3379 & NGC 4697



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, Poster L-P09)

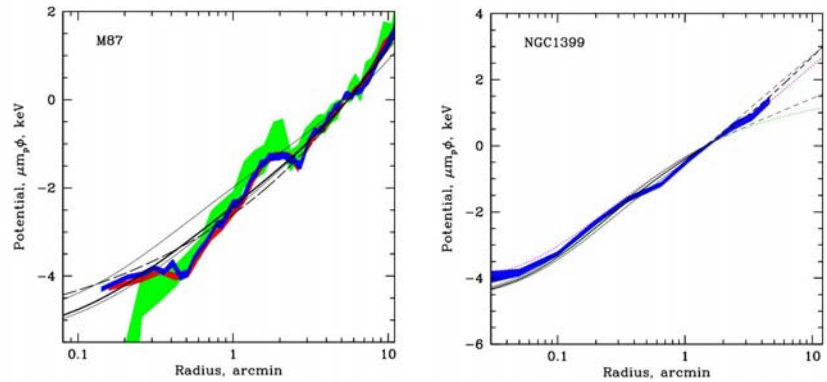
Fig. from Napolitano et al. 2009 shows virial masses and concentrations from fitted NFW models & compares with LCDM 1sigma range from Bullock et al. 2001





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



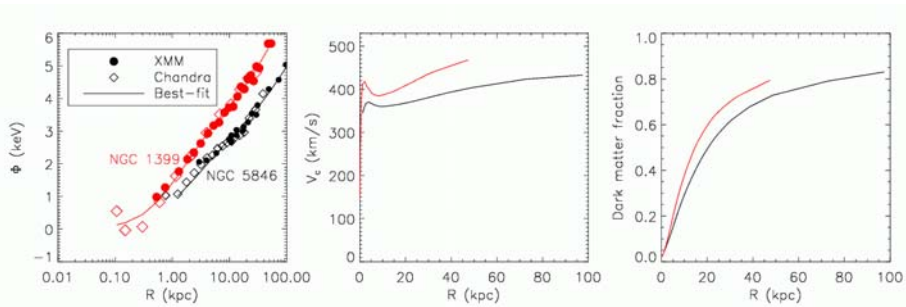
- **Potential from Chandra X-ray emission for M87, NGC 1399 (hot gas dominates, but point sources subtracted, different energy bands), agrees with potential determined from optical data (M87: Romanowsky & Kochanek 2001, Wu & Tremaine 2006; NGC 1399: Saglia et al. 2000, Kronawitter et al. 2000) to within 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 $\Rightarrow$ NGC 1399: $(M/L)_V$=9.1
  NGC 5846: $(M/L)_V$=6.1

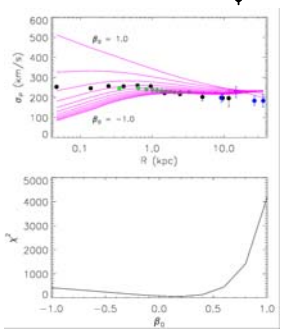
  Dark matter accounts for 70-80% of total mass at 50 kpc.

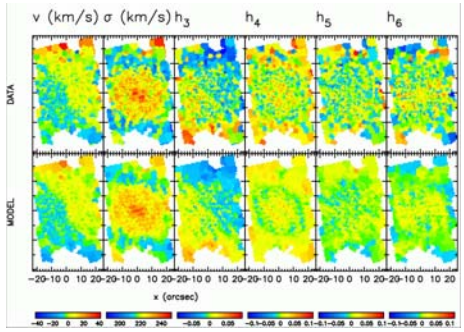
  . **Das et al. in prep.; see Posters L-P07 by P. Das, L-P14 E. McNeil**

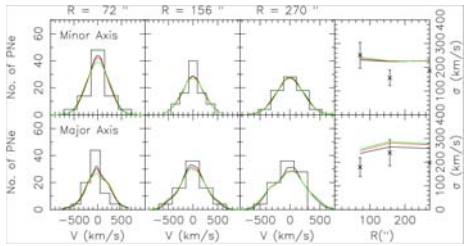


Orbital Structure of NGC 5846

- **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; need likelihood of PN velocities**
- **Results favour i=55º and $\sigma_\phi >\sim \sigma_r > \sigma_\theta$**







Das et al. 2009 in prep.

Galaxy Mergers

- **First suggestion that merging is a major process in transforming galaxies, by Toomre & Toomre (1972) and Toomre (1977).**
- **Simulations in the 1980's showed that major mergers can morphologically transform disks to spheroids (Gerhard 1981, Farouki & Shapiro 1982, Negroponte & White 1983).**
- **Barnes (1992), Barnes & Hernquist (1992) fully realized the importance of the dark halos in reducing the merging time-scales.**
- **First gas-rich merger simulations demonstrated angular momentum loss and concentration of the gas in centre (Mihos & Hernquist 1994, 1996)**
- **Equal-mass mergers are generally triaxial and slowly rotating, and have boxy or disky isophotes, while unequal mass mergers are more supported by rotation and have disky isophotes (Naab et al. 1999, Naab & Burkert 2003, Bournaud et al. 2005). Gas accumulating at the center creates a steep cusp and more axisymmetric central shape (Barnes & Hernquist 1996, Naab et al. 2006).**
- **Binary mergers provide reasonable models for intermediate mass ellipticals, while the most massive, boxy Es may be remnants collisionless early-type galaxy mergers (Naab & Burkert 2003, Naab et al. 2006). Multiple mergers may be important for forming BCGs in groups and clusters (Weil & Hernquist 1996).**
- **Merger models with gas inflow regulated by black hole feedback explain the observed relation between spheroid stellar velocity dispersion and black hole mass (Di Matteo et al. 2005, Johansson et al. 2007).**

These models provide predictions for the morphology, dynamical structure, and mass distribution of elliptical galaxies, which can be compared with the observed structure of nearby ellipticals.

Conclusions

- **Planetary nebulae are good tracers of outer halo and diffuse ICL kinematics 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.**
- **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.**
- **Evidence increasing that the outer halos of ellipticals are dark matter dominated and radially anisotropic, consistent with ΛCDM simulation results. Larger sample and comparison with merger models in progress.**