Thanks to L.Coccato, P. Das, F.de Lorenzi, E. McNeil, R.Saglia (MPE), M. Arnaboldi, M. Doherty (ESO), E. Churazov (MPA), R.Mendez Hawaii, V. Debattista (UK), PN.S team (AUS,D,IT,NL,UK)

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 — $\alpha$ parameter, $\alpha_{1.0,B} = (0.5-2) \times 10^{-8}$ PN/L$_\odot$

- The [OIII] line emission at 5007 Å 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 $\mu_B = 28.5$ mag/arcsec$^2$)

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

- Simultaneous CDI through two [OIII] arms; third H$_\alpha$ 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% $\Rightarrow$ 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, undispersed field

Mendez

[O III] filter, slitless, dispersed 180°

PNe trace stars


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 \( \mu_V = 27.5 \)
- PNe trace light (Coccato+09); GCs unclear
- PN velocities obtained down to \( \mu_V = 27.5 \) (Doherty+09, arxiv:0905.1958). Long slit data to \( \sim 24.0 \).
- 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 \( \sigma \) only if the stellar halo is truncated at \( \sim 150 \) kpc.
- Additionally, number density of PN with M87 velocities truncated at \( \sim 2\sigma \) significance (comparing light with PNe and using \( \alpha \) value determined from spectroscopically confirmed PNe).


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 Re (Douglas+07, Rom.+03)
- Different from other ellipticals which have ∼flat circular velocity curves and dense halos (Gerhard+01, Thomas+07)

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)
  - Silt kinematics (Statler & Smecker-Hane 99)
- **Discrete data**
  - PNe data (Douglas+07)

**Photometric data**
- Suraced brightness and luminosity density
  - Deprojection, e.g., axisymmetric (Magorrian 1999)

**Figure from Douglas+07**

---

**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
- \( \sigma \) = velocity dispersion of the stars
- \( h_n \) = higher order moments

**Lower left:** Initial \( \rightarrow \) 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

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)

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. 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 55° (black), 75° (red) and 90° (green), based on Sauron, slit & PNe data
- Note dispersions alone do not suffice; need likelihood of PN velocities
- Results favour $i=55°$ 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 (Milos & 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 $\mu_B=28.5$
• Kinematic misalignments are more frequent in the halos, presumably implying more triaxial shapes as a result of the last merger. Halo $\lambda$-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 $\Lambda$CDM simulation results. Larger sample and comparison with merger models in progress.