Early-type Galaxies: Dark Matter and Dynamics

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Inventory of DM in galaxies

Detailed observational constraints:
• Test $\Lambda$CDM paradigm
• Constrain nature of DM
• Probe galaxy formation

Unique properties of CDM halos:
• $dN/dM_{\text{vir}}$
• central density cusp: $\rho(r) \sim r^{-\alpha}$, $\alpha \sim 1-1.5$
• mass-density relation reflecting $z_{\text{collapse}}$


"Via Lactea 2" simulation
(Diemand et al. 2008)
Late-type galaxies: mass from gas

Rotation curve (circular velocity):
\[ v_c(r) \equiv \sqrt{ra_r} = \sqrt{GM(<r)/r} \]
Keplerian: \[ v_c(r) \sim r^{-1/2} \]
Spiral halos: \[ v_c(r) \sim \text{const} \]
\[ \Rightarrow M(<r) \propto r : \text{dark matter!} \]

radio emission of cold gas: 21cm HI spin-flip transition (1970s)
Disk/halo degeneracy

$L^*$ spirals

HI rotation curve:

$$v_c(r) = \sqrt{GM/r}$$

constant at large $r$

(Persic et al. 1996)

But shape of inner halo profile dependent on disk M/L

NGC 6503

(Bottema 1997)
DM puzzles from late-type galaxies

- LSBs: cusps not seen
- $L^*$ galaxies: low DM density

\[ c_{\text{vir}} \equiv \frac{r_{\text{vir}}}{r_{-2}} \]

(Kassin et al. 2006; McGaugh et al. 2007; Dutton et al. 2007; Gnedin et al. 2007)
DM probes in early-type galaxies

• kinematics
  – resolved stars (TMT!)
  – integrated stellar light
  – planetary nebulae (PNe)
  – globular clusters (GCs)

• X-ray emission

• gas disks & rings (HI & Hα)

• strong gravitational lensing

• weak gravitational lensing

• satellite dynamics

\{ \text{ideal probes} \}

\{ \text{selection effects} \}

\{ \text{statistical only} \}
DM in early-types: weak+strong lensing

22 bright E/S0s at $z \sim 0.2$ (SLACS: Gavazzi et al. 2007)

- halo concentration, inner slope not constrained
- $\sigma_c < 200 \text{ km/s}$ (fast rotators) not well constrained
Kinematical tracers in early-type galaxies

- field stars *(integrated light)*
- planetary nebulae
- globular clusters
Theory testing

• Data
  ⇒ fit (parametrized) models
  ⇒ compare to theory

  E.g. kinematics
  ⇒ mass, orbit profiles
  ⇒ compare ΛCDM

Questions about model assumptions: geometry, equilibrium, uniqueness, oversimplification…

• Theory
  ⇒ “observe” (parametrized)
  ⇒ compare to data

  E.g. simulated galaxies
  ⇒ luminosity, velocity profiles
  ⇒ compare to data

Need large data sample + suitable parameters incl. correlations…
Kinematics → Dynamics → Mass

**Distribution Function (6-D position-velocity phase space)**

\[
\int d^3x d^3v f(x, v, t) = 1 \quad \text{separate for subpopulations (metallicity, age…)}
\]

\[
\nu(x) \equiv \int d^3v f(x, v) \quad \text{spatial density}
\]

\[
\frac{df}{dt} = 0 \quad \text{incompressible fluid (collisionless)}
\]

\[
\frac{\partial f}{\partial t} + v \cdot \frac{\partial f}{\partial x} - \nabla \Phi \cdot \frac{\partial f}{\partial v} = 0 \quad \text{Boltzmann equation: connect to grav. potential}
\]

**Jeans theorem:** DF described by "integrals of motion" \( I_i \): conserved quantities along orbit (spherical: energy, angular momentum)

\[
\frac{d}{dt} I[x(t), v(t)] = 0
\]
Dynamical modeling approaches

- **Projected mass estimators**
  - small # discrete velocities; based on Virial Theorem \( W = -2K \)
- **Jeans equations**
  - moments of DF; assume equilibrium
- **Direct DF construction**
  - numerical superposition of DF basis functions
- **Orbit models** (“Schwarzschild’s method”)
  - numerical superposition of stationary orbits
- **Particle models** (“made-to-measure”)
  - numerical superposition of evolving orbits
Dynamical modeling challenges

- **Unbiased tracers of DF for space + velocity**
- **Information loss in projection:**
  - konus (luminosity) degeneracy
    (Rybicki 1987; Gerhard & Binney 1996; Kochanek & Rybicki 1996; Romanowsky & Kochanek 1997)
  - mass-anisotropy degeneracy
- In spherical system, complete info on projected DF $f(R_p, v_p)$ in known $\Phi(r)$ determines true DF
- Constraining $\Phi + DF$ unclear
  (Dejonghe & Merritt 1992)
Mass-anisotropy degeneracy

- **Radial orbits**
  - at large $R$, most of the motion in plane of sky
  - lowered velocity dispersion
  - peaked velocity distributions

- **Tangential orbits**
  - at large $R$, much of the motion in line of sight
  - higher velocity dispersion
  - flat velocity distributions
**Jeans equations**

\[
\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{x}} - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} = 0 \quad \text{take moments of Boltzmann eqn (Jeans 1919)}
\]

\[
v_c^2 = \frac{GM(r)}{r} = -\sigma_r^2 \left( \frac{d \ln \nu}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right) \quad \text{spherical non-rotating Jeans eqn}
\]

\(\nu: \text{tracer density}\)

\(\sigma_r: \text{radial velocity dispersion}\)

\(\beta(r) \equiv 1 - \sigma_\theta^2 / \sigma_r^2: \text{velocity dispersion anisotropy}\)

\(\beta > 0: \text{radial}\)

\(\beta = 0: \text{isotropic}\)

\(\beta < 0: \text{tangential}\)

\[
\nu \sigma_r^2 = \int_r^\infty dr' \nu \frac{d\Phi}{dr'} \int_r^{r'} 2\beta \left( \frac{r''}{r'} \right) dr''
\]

\[
\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left( 1 - \beta \frac{R^2}{r^2} \right) \frac{\nu \sigma_r^2 r}{\sqrt{r^2 - R^2}} dr
\]

- physical DF not guaranteed
- \(\nu, \sigma, \beta\) often parameterized
- higher-order moments tricky

solve for known \(\beta(r)\)

projection to observables
Breaking the mass-anisotropy degeneracy

$$k_p \sim \frac{\langle v_p^4 \rangle}{\langle v_p^2 \rangle^2} - 3$$

kurtosis

$h_4, k_p$ measure shape of line-of-sight velocity distribution (LOSVD)

$h_4, k_p = 0$: Gaussian;

*isotropic orbits*

$h_4, k_p > 0$: “peaked”;

*radial orbits*

$h_4, k_p < 0$: “flat-topped”;

*tangential orbits*

$v_p = \left( v_p - \hat{v}_p \right) / \sigma_p$

$\hat{v}_p = \frac{\sqrt{2\gamma_0}}{\hat{\gamma}_p} \int_{-\infty}^{\infty} \frac{dL}{dv_p} (v_p) e^{-\frac{\hat{w}^2}{2}} H_l(\hat{w}) dv_p$

van der Marel & Franx (1993)
Higher-order Jeans equations

Assume \( f(E,L) = f_0(E)L^{-2\beta} \rightarrow \beta \) constant

\[
\frac{d}{dr} \left( \nu \left\langle v_r^4 \right\rangle \right) + \frac{2\beta}{r} \nu \left\langle v_r^4 \right\rangle + 3\nu \sigma_r^2 \frac{d\Phi}{dr} = 0
\]

\[
\nu \left\langle v_r^4 \right\rangle = 3r^{-2\beta} \int_r^\infty r'^{2\beta} \nu \sigma_r^2 \frac{d\Phi}{dr'} dr'
\]

\[
\left\langle v_p^4 \right\rangle (R) = \frac{2}{I(R)} \int_R^\infty \left[ 1 - 2\beta \frac{R^2}{r^2} + \frac{\beta(1 + \beta)}{2} \frac{R^4}{r^4} \right] \frac{\nu \left\langle v_r^4 \right\rangle r}{\sqrt{r^2 - R^2}} dr
\]

\[
\kappa_p = \left( \frac{\left\langle v_p^4 \right\rangle}{\left\langle v_p^2 \right\rangle^2} \right)^2 - 3
\]

\[
\kappa_p = 3 \left( \frac{I_0I_4}{I_2^2} - 1 \right)
\]

If \( \sigma(r) \) const (isothermal),

simple expression relating kurtosis, anisotropy, luminosity:
Integrated light stellar kinematics

Long-slit data: cross-correlate template and object spectra → v, σ, h as function of radius

currently viable to ~ 2 $R_{\text{eff}}$

(De Lorenzi et al. 2008)
Integral field spectroscopy

False colour: mean velocity
Contours: surface brightness

currently viable to $\sim 1 \, R_{\text{eff}}$

(de Zeeuw et al. 2002)
Case study: Jeans eqns + stellar kinematics

335 nearby early-type galaxies observed by Prugniel & Simien (1996)
Observables: surface brightness profile $I(R)$, aperture velocity dispersion $\sigma_{Ap}(R)$
Assume mass profile $\rho(r) \sim r^{-2}$, solve Jeans equations to solve for dynamical mass $< R_{\text{eff}}$

Model spectral energy distribution $UBVRI$ using stellar populations model (Bruzual & Charlot 2003) with star formation history $e^{-t/\tau}$
Adopt Kroupa IMF, calculate stellar mass

$\text{Subtract stellar mass from dynamical mass to get dark mass...}$

$M/L_{\text{dyn}} \sim L^{0.21}$, $M/L_* \sim L^{0.06}$
→ most of Fundamental Plane “tilt” driven by DM!
Central dark matter fractions (cont’d)

$f_{DM} \equiv 1 - \frac{\Upsilon_*}{\Upsilon_{dyn}}$

$f_{DM}$ increases with luminosity, no clear dependence on galaxy sub-type (cf. Cappellari et al. 2006)

Central DM density roughly follows $\Lambda$CDM expectations, modulo uncertain concentrations and virial masses

(Tortora et al. 2009)
Global dark matter fractions

Virial $M/L$ can be rephrased as star formation efficiency $\varepsilon_{\text{SF}} \equiv M_*/(f_b M_{\text{vir}})$.

**U-shaped curve observed:**
- “directly” with weak-lensing,
- indirectly by correlating $dN/dL$ with theoretical DM halo $dN/dM$.

$\varepsilon_{\text{SF}}$ maximum near $L^*$:
- lower mass galaxies can’t hold gas
- higher mass galaxies can’t cool gas

(fr. van den Bosch et al.)

(Mandelbaum et al. 2006)

(Mandelbaum et al. 2006)
Linking dark matter and star formation

(Tortora et al. 2008 → Napolitano et al. 2009b)

$f_{\text{DM}}$ in early-types decreases with stellar age
Mass assembly histories would predict opposite trend
(more DM than stars accreted at later times)

$\rightarrow \epsilon_{\text{SF}}$ decreases with time
$\rightarrow$ “DM upsizing”

Orbit weights \( w_k \) project to observables

- physical DF (stability unknown)
- fully non-parametric DF (not \( \Phi \))
- higher-order LOSVD easy
Model fits to data

Minimize goodness-of-fit:

\[ \chi^2 = \sum_i \left( \frac{y_i^m - y_i^d}{\Delta y_i} \right)^2 \]

68% one-parameter confidence interval:

\[ \Delta \chi^2 = 1 \]

\[ N_{\text{dof}} \equiv N_{\text{data}} - N_{\text{param}} < 0 \]

Regularization:

\[ f(w) \equiv \frac{1}{2} \chi^2 + \lambda S \]

e.g. maximum entropy:

\[ S = \sum_k w_k^2 \ln w_k^2 \]

M87 stellar data
(Romanowsky & Kochanek 2001)

\[ \mu(R) \]

\[ \sigma_p(R) \]

\[ \lambda \text{ increasing} \rightarrow \] (Rix et al. 1997)
Model accuracy

Comparing $M/L$ to 3-l axisymmetric orbit models (Cappellari et al. 2006)

- **Virial estimator**
  - $M_* \propto R_{\text{eff}} \sigma_{\text{eff}}^2/(GL)$
  - good to 11%

- **Jeans models** good to 6%

with IFU data!

Triaxial orbit models (van de Ven et al. 2008)
Case study: orbit models + stellar kinematics

3I axisymmetric models of 19 early-types in Coma cluster

Similar results to Gerhard et al. (2001)

DM halos of early-types follow common scaling laws, ~10x denser than spirals → higher $z_{\text{collapse}}$ (~2 vs ~1)

Halo densities ~2× higher than in Millennium Sim ($\sigma_8 = 0.9$) → baryonic contraction? (spirals ~2× lower than sims)

(Thomas et al. 2007, 2008)
The future of stellar kinematics

Existence and properties of DM halos still at low statistical significance

Need 2-D coverage to $R_{\text{eff}}$

Traditional long-slit spectroscopy lacks efficiency and homogeneity → need new generation of wide-field IFU or new techniques

(Statler & Smecker-Hane 1999)
2-D stellar kinematics with Keck

Use leftover slit light from DEIMOS GC spectra to probe galaxy kinematics to \(~3\ R_{\text{eff}}\) \((\text{poor person’s IFU})\)

Proctor et al. (2009)
Globular clusters as halo mass tracers

GCs: $\sim 10^6$ stars

(Huchra & Brodie 1987)

GLOBULAR CLUSTERS

X-RAY GAS

GALAXY BULGE

© Anglo-Australian Observatory
$D=19\ \text{Mpc},\ M_B=-21.1$

Fornax central E1

VLT+FORS2/MXU, Gemini-S+GMOS: 656 velocities to 80 kpc
(largest data set in any galaxy)
$\Delta v = 20-100\ \text{km/s}$
(Richtler et al. 2004, 2008; Schuberth et al. 2009)
SAGES Legacy Unifying Globulars and Galaxies Survey

- NSF funded (2008-2010)
- 25 representative early-type galaxies:
  - spread of luminosities, environments, photometric and kinematical properties
- Global properties, with focus on halo tracers:
  - field stars, planetary nebulae, globular clusters
  - photometry, kinematics, metallicities
  - Subaru/Suprime-Cam, Keck/DEIMOS
    (high-quality, deep wide-field imaging + spectroscopy)

SLUGGS
Extragalactic GC spectra for kinematics

M31-B19 (Perrett et al. 2002)

Typical wavelength range 4800-5400 Å
(Keck/LRIS, VLT/FORS2, Gemini/GMOS, etc.)

NIR Ca II triplet: highly efficient with Keck/DEIMOS
GC dynamics in NGC 1407

E1, $M_B = -21.0$, Group central galaxy (GCG), $D = 21$ Mpc

172 GC velocities from LRIS, DEIMOS to 60 kpc ($10 R_{\text{eff}}$) (Cenarro et al. 2007; Romanowsky et al. 2009) + ~150 new velocities to be analyzed…
GC dynamics of group-central Es

Fairly flat dispersions out to very large radii imply increasing circular velocities and group-scale DM halos

(Romanowsky & Kochanek 2001; Côté et al. 2003; Schuberth et al. 2006; Bergond et al. 2006; Woodley et al. 2007; Richtler et al. 2008; Hwang et al. 2008; Romanowsky et al. 2009)
Modeling discrete velocities

Binning (in $R, v$) loses information

Likelihood fcn

$$\mathcal{L}_i(v_i, R_i | w) \propto \int_{-\infty}^{\infty} \frac{dL}{dv_p}(v_p, R_i) e^{-\frac{(v_i-v_p)^2}{2(\Delta v_i)^2}} dv_p$$

$$\chi^2 = -2 \ln \mathcal{L}$$

~1000 velocities needed to break mass-anisotropy degeneracy in axisymmetric const-$M/L$ system

Chanamé et al. (2008)
Orbit modeling with discrete velocities

Schwarzschild orbit model fit of stellar + GC kinematics in M87
(Romanowsky & Kochanek 2001)

Unbinned LOSVD fitting, shown in radial bins:
• model
• data
• simulated from data

GCS roughly isotropic overall, possibly tangential toward center

cf. Côté et al. (2001);
Wu & Tremaine (2006)
More breaks in the mass-anisotropy degeneracy

Metal-poor and metal-rich GC subsystems require consistent solution (Kumar et al. in prep)

Stars or GCs alone do not rule out $\rho(r) \sim r^{-2}$ but used jointly they do…
→ multiple independent mass tracers!
Dynamical uniformity of tracers

- Bright GCs show flat-tops / double-peaks in almost all cases! (significant in ~3 cases)
  - DF changes with luminosity: $v(r)$ from faint GCs may not be valid

(Romanowsky et al., in prep.)
Mass in early-types: X-ray gas

\[ v_C^2(r) = -\frac{k_B T_X(r)}{\mu m_p} \left( \frac{d \ln n_g}{d \ln r} + \frac{d \ln T_X}{d \ln r} \right) \]

The equation of hydrostatic equilibrium: (ideal) gas pressure balances gravity.

\( n_g \): gas density
\( T_X \): gas temperature

\( \sim 10^7 \) K, 1 keV  
(Fabricant et al. 1980)

thermalized hot gas fills halo potential well and emits X-rays

\( M_\text{HALO} \sim r \)

M87 (Fabricant et al. 1980)
Mass cross-checks: GCs + X-rays in NGC 1407

Chandra/ACIS-S3, 49 ksec

Deproject temperature in coarse radial bins, density in fine bins

Model unresolved point-sources as power-law component

Hydrostatic equilibrium equation:

\[ v_c^2(r) = -\frac{k_B T_X(r)}{\mu m_p} \times \left( \frac{d \ln \rho}{d \ln r} + \frac{d \ln T_X}{d \ln r} \right) \]
NGC 1407 mass profile: X-rays vs GCs

GC kinematics from DEIMOS, X-ray mass from Chandra

discrepant at 2 $\sigma$ (cf. high-$c_{\text{vir}}$, low $\Upsilon^*$ found by Humphrey et al. 2006)

What $\beta(r)$ for GCs required for consistency?
Cross-check: X-rays & dynamics in M87

**Orbit modeling**
of stars + 234 GCs with non-parametric $\beta(r)$
(Cohen & Ryzhov 1997; Romanowsky & Kochanek 2001; Wu & Tremaine 2006)

**XMM-Newton**
(Matsushita et al. 2002)

⇒ good agreement except inside 2 kpc

**Chandra**: unphysical mass wiggles from shocks(?) but broad agreement
(Churazov et al. 2008)
More X-ray/GC cross checks

NGC 4636
(Johnson et al. 2009)

M60
(Bridges et al. 2006)

GCs
stars
β model
general model

(Jones et al. 2002)
(Diehl & Statler 2008)

(Bridges et al. 2006)
Chandra study implies extensive DM halos
(Humphrey et al. 2006)

“shoulders” seen in mass profiles (e.g. Zhang et al. 2007)
→ lack of hydrostatic equilibrium?

ΛCDM halo fits to X-ray data require:
• low stellar $M/L$ and
• high halo concentrations (indirect inconsistency)

A few dynamics cross-checks:
X-ray mass too low in centers
non-thermal pressure support?

X-rays not useful for mass profiles until gas physics understood?
Extragalactic planetary nebulae

dying stars casting off outer layers of ionized gas

10% of the energy comes out at 500.7 nm “forbidden” O$^{++}$ line
(“nebulium”: Huggins & Miller 1864; 3P-1D transition)
Counter-dispersed imaging

(Douglas & Taylor 1999)
Counter-dispersed imaging

- Central wavelength: 5007 Å
- Star
- Planetary nebula
Counter-dispersed imaging

- Narrow band [O III] filter
- Planetary nebula
- Star
Counter-dispersed imaging
Counter-dispersed imaging

- Narrow band [O III] filter
- Star
- Planetary nebula
Counter-dispersed imaging

positions & velocities in one go!
Planetary Nebula Spectrograph (PN.S)

- Cassegrain mount at 4.2m WHT
- 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

(Douglas et al. 2002)
PNe: slitless spectroscopy

5' x 2' (1 kpc x 0.5 kpc) field in M31 (Merrett et al. 2006)
Sb, $M_B = -21.2$

$D = 0.8$ Mpc

WHT+PN.S, WYFFOS:
9 nights:

2615 PN velocities over 7 deg$^2$

(Halliday et al. 2006; Merrett et al. 2006)

X : approaching
X : receding
PN-based rotation curves in spirals

PN circular velocity curves agree with HI, CO (modulo asymmetric drift)

*Rules out magnetic field explanation for flat curves*

(Merrett et al. 2006)
Best-studied early-type galaxy:
E2/S0 merger remnant
$D = 4$ Mpc
$M_B = -20.7$

780 PN velocities with
AAT, CTIO
(Peng et al. 2004)
E1, $M_B = -19.9 \ (\sim L^*)$
$D = 10 \text{ Mpc}$
Leo I central
“ordinary” elliptical, fast rotator

WHT+PN.S:
186 PN velocities
to $8 \ R_{\text{eff}}$
$\Delta v = 20 \text{ km/s}$

Douglas et al. (2007)
Extended stellar/PN dispersion profiles

Bimodality of flat / declining dispersion profiles in ordinary early-type galaxies?

Coccato et al. (2009)
Stellar + PN data: Jeans models

Fourth-order Jeans equations
(\(\beta\) simplifications)

Lower-density halo than \(\Lambda\)CDM at 1-\(\sigma\) (\(\sigma_8=0.9\))
Particle-based models ("made-to-measure")


Similar to orbit models but "live"density and potential evolve (not separate orbit library + fitting stages)

\[
\frac{dw_i(t)}{dt} = \varepsilon w_i(t) \left( \mu \frac{\partial S}{\partial w_i} - \sum_j \frac{K_j [z_i(t)]}{\sigma(Y_j)} \Delta_j(t) \right)
\]

\[
\Delta_j(t) = (y_j - Y_j) / \sigma(Y_j)
\]

Spherical, axisymmetric, triaxial versions
Stellar + PN data: particle models

NGC 3379

• Rotation field rules out face-on geometry
• DM required but not a lot

SAURON data
quasi-triaxial model

(De Lorenzi et al. 2009)

long-slit kinematics
PN dispersion

Stellar + PN data: particle models

SAURON data
quasi-triaxial model

(De Lorenzi et al. 2009)

long-slit kinematics
PN dispersion

• Rotation field rules out face-on geometry
• DM required but not a lot
Issues in mass estimates from PNe

- Foreground/background contamination
- PN-stellar population link?

Left/right asymmetry of bright PNe: unmixed young population?

But no systematic differences evident between stars and PNe in surface densities, kinematics in large galaxy sample...
Probes of halo kinematics

**Planetary nebulae:**
- feasible to 25 Mpc
- more reliable velocities
- well-known spatial distribution
- not affected by dust
- contiguous constraints with central stellar kinematics
- less contamination problem
- more abundant in fainter galaxies
- detection & spectra in one go

**Globular clusters:**
- feasible to 40 Mpc
- larger radius
- disk less likely
- not affected by dust
  (Baes & Dejonghe 2001)
Lost & Found: Gemini Finds “Lost” Dark Matter in NGC 3379

Gemini, 16 Feb 2006

Follows: Romanowsky et al. 2003, Science, 301, 1696
NGC 3379 : GCS dispersion profile

Weakly declining dispersion:

$$\sigma_p(R) \propto R^\gamma ,$$

$$\gamma = -0.13 \pm 0.12$$

Due largely to different $N(R) , \beta(r)$

(Puzia et al. 2004; Pierce et al. 2006; Bergond et al. 2006)
NGC 3379: HI gas ring

Mass measurement

N3379 + N3384:

\[ \frac{M}{L_B} \text{ (100 kpc)} = 27 \pm 5 \]

(Schneider 1985)

Not consistent with group-mass halo
Difficulty harmonizing both GC, HI constraints

Nearby companion (NGC 3384) → halo not in equilibrium?
Comparing PN + GC dispersions

5 cases with fairly similar dispersions, 2 discrepant
Independent mass results in NGC 4697

\[ \beta(r) = 0.7 \frac{r}{r + 6.3 \text{ kpc}} \]

Crude spherical model gives same results as sophisticated flattened model!

GCs more sensitive than PNe to halo mass because more radially extended

Lower-mass DM halo from NMAGIC solutions preferred
Mass from X-rays: NGC 4697

NASA/CXC/UVa/C.Sarazin et al.

R. Johnson et al., in prep.
Matching observations to simulations

Simulations of “wet” galaxy mergers naturally produce declining dispersions

- primarily from radial anisotropy in halo
Mass profile decompositions

Simulations including baryon physics
(Dekel et al. 2005; Naab et al. 2007; Oñorbe et al. 2007)

Systematic central dark matter difference between simulations and observations (modeled including radial anisotropy)

partial stellar $M/L$ degeneracy as in spirals

5 $R_{\text{eff}}$
Bimodality of early-type galaxies

Fast rotators = E/S0s?
- optically faint
- low velocity dispersion
- disky isophotes
- rapid rotators
- cuspy cores
- low X-ray luminosity
- weak radio sources

Slow rotators = true Es?
- optically luminous
- high velocity dispersion
- boxy isophotes
- slow rotators
- flat cores
- high X-ray luminosity
- strong radio sources

(Kormendy & Bender 1996; Faber et al. 1997; Emsellem et al. 2007)
Dynamical bimodality of ellipticals

Isotropic, round, slow rotators (Cappellari et al. 2007)

Anisotropic, flattened, fast rotators

Early wet multiple mergers (Burkert et al. 2008)

Wet/dry pair major mergers
Early-type halo velocity dispersions

- **Bimodality in PN velocity dispersions**
  
  (Méndez et al. 2008; Coccato et al. 2009; Douglas et al. in prep.)

- **GCs similar but less dramatic**
Early-type circular velocity profiles

Slow rotators: flat/rising $v_c$

Fast rotators: declining $v_c$

Romanowsky et al. (2003); Douglas et al. (2007); De Lorenzi et al. (2008, 2009); Napolitano et al. (2009)

GC cross-checks support PN results in most cases
DM trends of early-type galaxies

“concentration” $c_{\text{vir}}$ parameterizes DM density, relates to collapse redshift (Bullock et al. 2001)

**systematic difference:**
slow, fast rotators
(opposite DM, stellar concentrations)

$\Lambda$CDM prediction is “forbidden region”!
(Napolitano et al. 2009)

Low-$c$ early-types from strong lensing, FP:
(Keeton 2001; Borriello et al. 2003)
Dark matter bimodality

Fast/slow rotator dichotomy not explainable via:
- smooth scalings with luminosity
- biasing with formation redshift
- biasing with angular momentum
- anti-hierarchical/downsizing DM (WDM, etc.?)
- dynamical modeling systematics (geometry/orbit structure)
- selection effects
- alternative gravitational dynamics (MOND, etc.)
- stellar populations modeling systematics

Could be due to:
- baryonic physics (cooling, feedback, merger dynamics, etc.)
- environment (all slow rotators are group central?)

Further clues from halo rotation, orbits, GC properties
Baryonic effects on halo concentration

Baryonic dissipation produces adiabatic contraction of halo
→ *increases* central $\rho_{DM}$
(Blumenthal et al. 1986; Gnedin et al. 2004)
→ slow rotators?

Baryonic feedback expands halo ??
(Mo & Mao 2004)
→ spirals, fast rotators?

(U. Seljak)
Baryonic effects on DM profile

DM bimodality from coupled merger histories + baryonic physics?

Fast rotators from $z < 1$ quenching and wet mergers (Faber et al. 2007) with substantial feedback to lower $\rho_{\text{DM}}$
– *lenticulars included, or 3rd family?*

Slow rotators from $z > 1$ quasi-monolithic collapse in high-overdensity regions with dissipation to raise $\rho_{\text{DM}}$
(later dry merging also helps):
Blumenthal et al. (1984); Burkert et al. (2008);
  but see Kang et al. (2007)
– *did all slow rotators form in group-mass halos?*

→ Why two distinct episodes for early-type galaxy formation?
Data are improving…
Models are improving…
Theory is improving…
Stay tuned for stronger constraints on dark matter!