Mass of the Coma Cluster

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Two Different Approaches

- Hughes 1989:
  - Fit to X-ray data from Einstein, EXOSAT, and Tenma
  - Model based on star cluster with and without extra dark matter term
- Kubo, Stebbins, Annis, Dell'Antonio, Lin, Khiabanian, and Frieman 2007
  - Fit to Sloan survey data
  - Fit to NFW galactic cluster model

Hughes’s Approach

- Assume the Coma cluster is spherical, with no subclumps
  - “I have chosen to ignore this complication”
- Assume a virial mass in hydrostatic equilibrium
- Find mass distribution
- Find temperature distribution
- Estimate mass

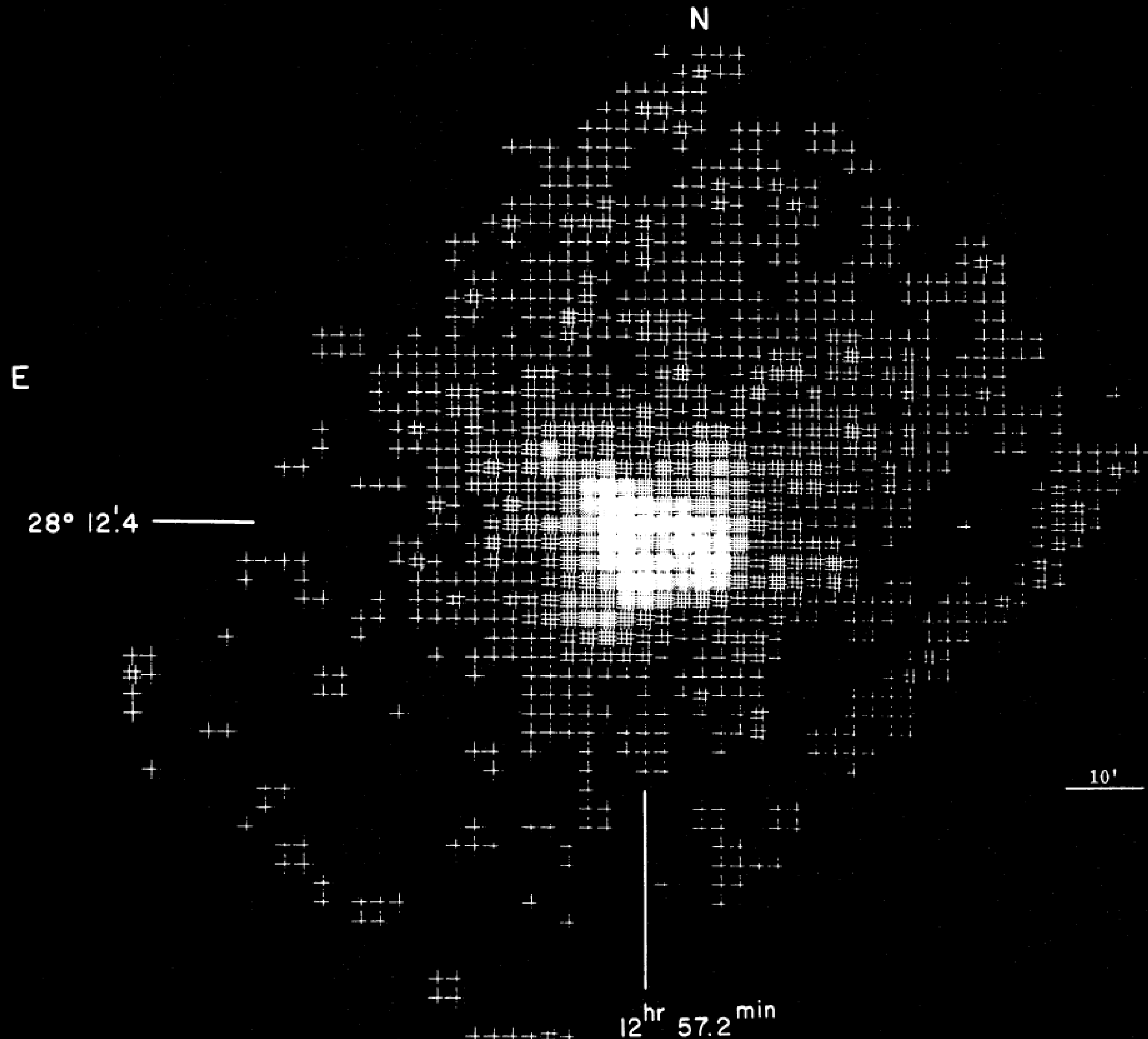
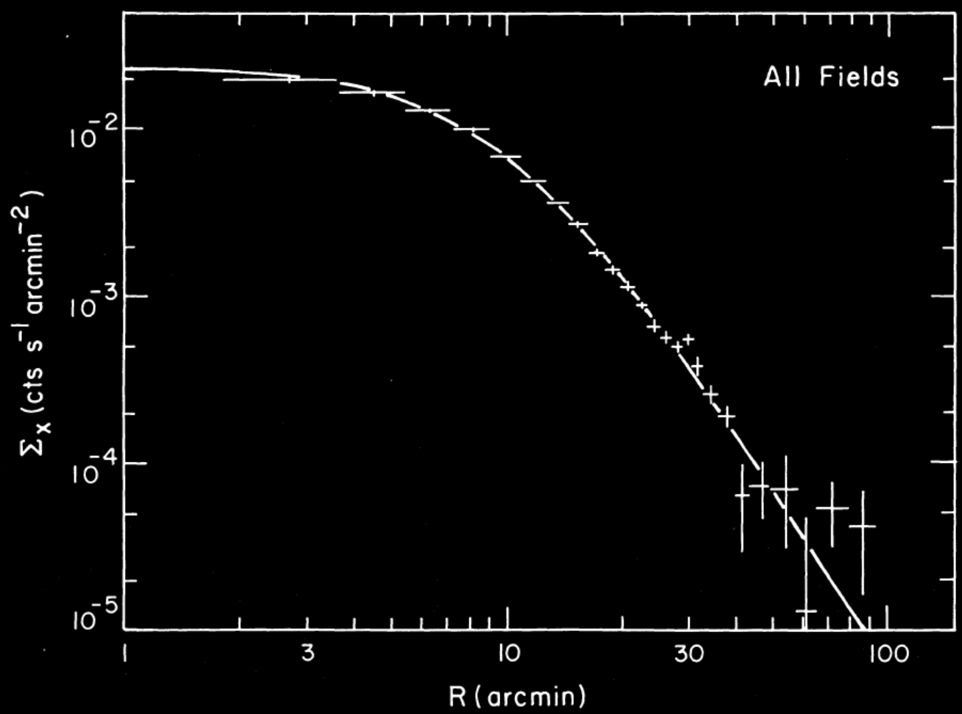


FIG. 1.—X-ray map of the Coma cluster of galaxies, 0.15–2.0 keV, in 2′ × 2′ bins. Picture has been smoothed by averaging the observed number of counts in a given bin and that of three adjacent bins. Mirror vignettes by a factor of 2 at 38′ off-axis.

Gas Mass Distribution

- Assume isothermal, gas follows light
- Find a best fit to Einstein Observatory data

$$\rho_g = \rho_{g0}\left\{1 - \frac{6}{5}\beta\left[1 - (1 + y^2)^{-1/2}\right]\right\}^{2/3}$$



Hydrostatic Equilibrium

- Uniform density gas in equilibrium:

$$\nabla P = -\rho_g \nabla \Phi$$

- Assume spherically symmetric and ideal gas:

$$\frac{dT}{dR} = -\frac{1}{\rho_g}\frac{d\rho_g}{dR}T - \frac{4\pi\mu m_{\mathrm{H}} G}{k}\frac{1}{R^2}\int_0^R dr r^2 \rho_b(r)$$

Gas Pressure

Dark Matter/
Galactic Gravity

Binding Mass Distribution

- Assume either King (1966) model (star cluster) or dark matter power law (n=3,4,5):

$$\rho_b = \rho_{b0}[1 + (R/R_b)^2]^{-n/2}$$

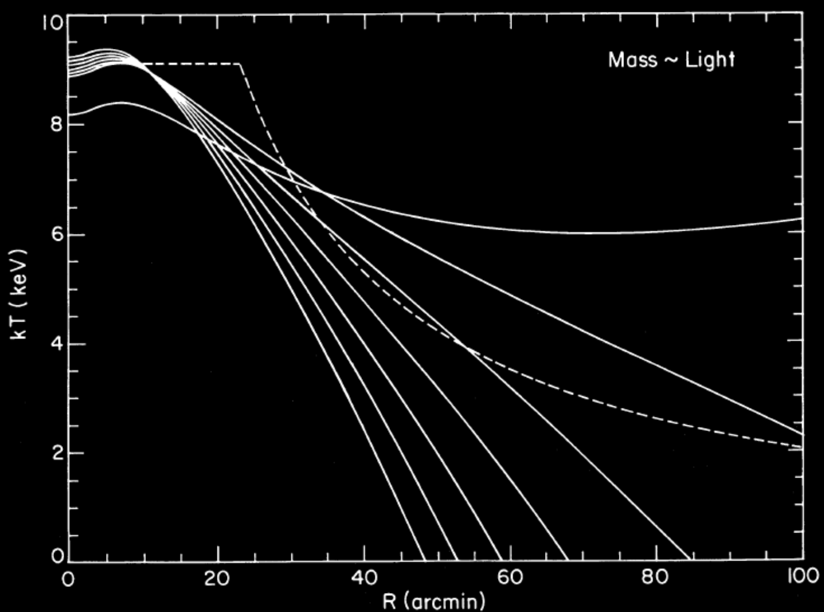
- Which results in:

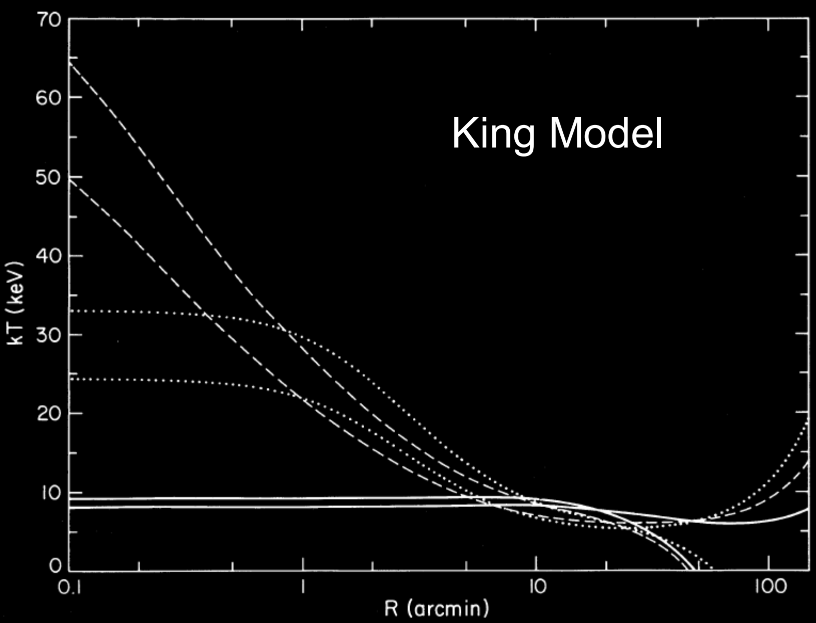
$$\frac{dt}{dy} = \frac{3\beta y}{1 + y^2}\, t - C\, \frac{1}{y^2}\, f_n\!\left(\frac{yR_c}{R_b}\right)$$

$$f_n(x) = (R_b/R_c)^3 \int_0^x du\, u^2 (1 + u^2)^{-n/2}$$

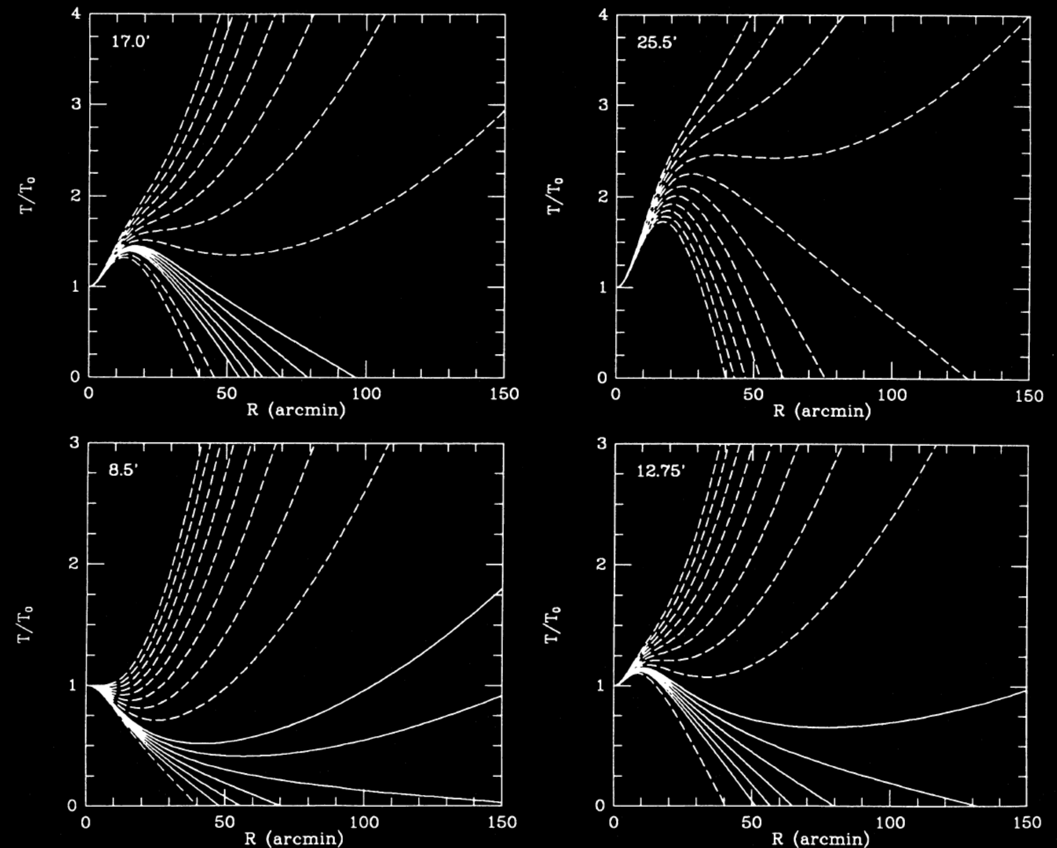
$$C = 5.92\left(\frac{\rho_{b0}\, h_{50}{}^2}{10^{-25}\ \mathrm{g\ cm}^{-2}}\right)\left(\frac{kT_0}{10\ \mathrm{keV}}\right)^{-1}\left(\frac{R_c h_{50}{}^{-1}}{8'.5}\right)^2$$

Temperature Distribution





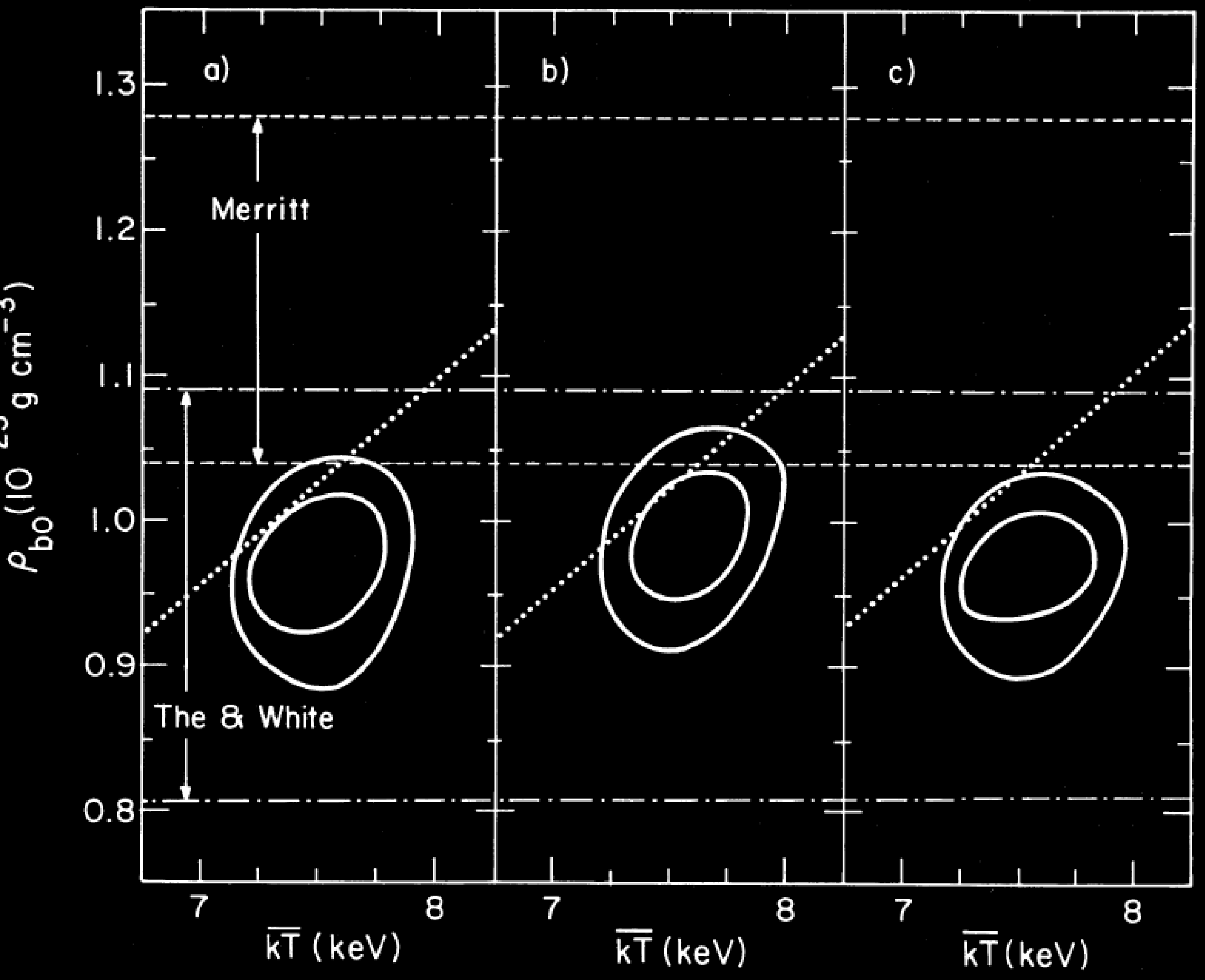
King Model



n=4 polynomial

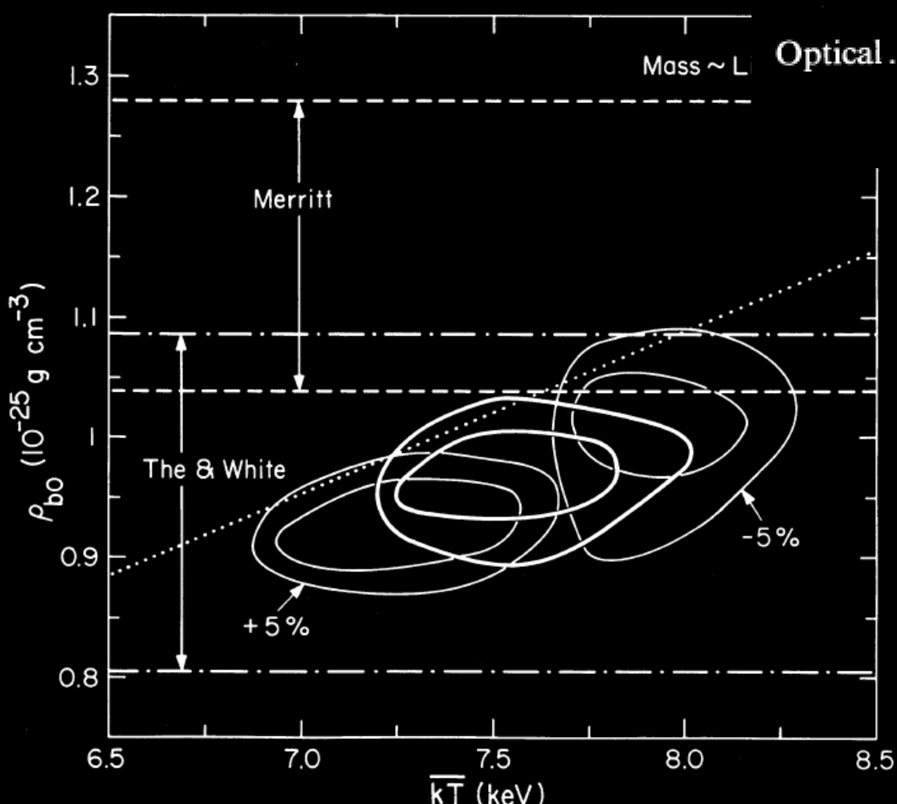
Mass Follows (X-Ray) Light

β=0.86,R_c=5.5'   β=0.76,R_c=9.8'   β=0.63 R_c=7.6'



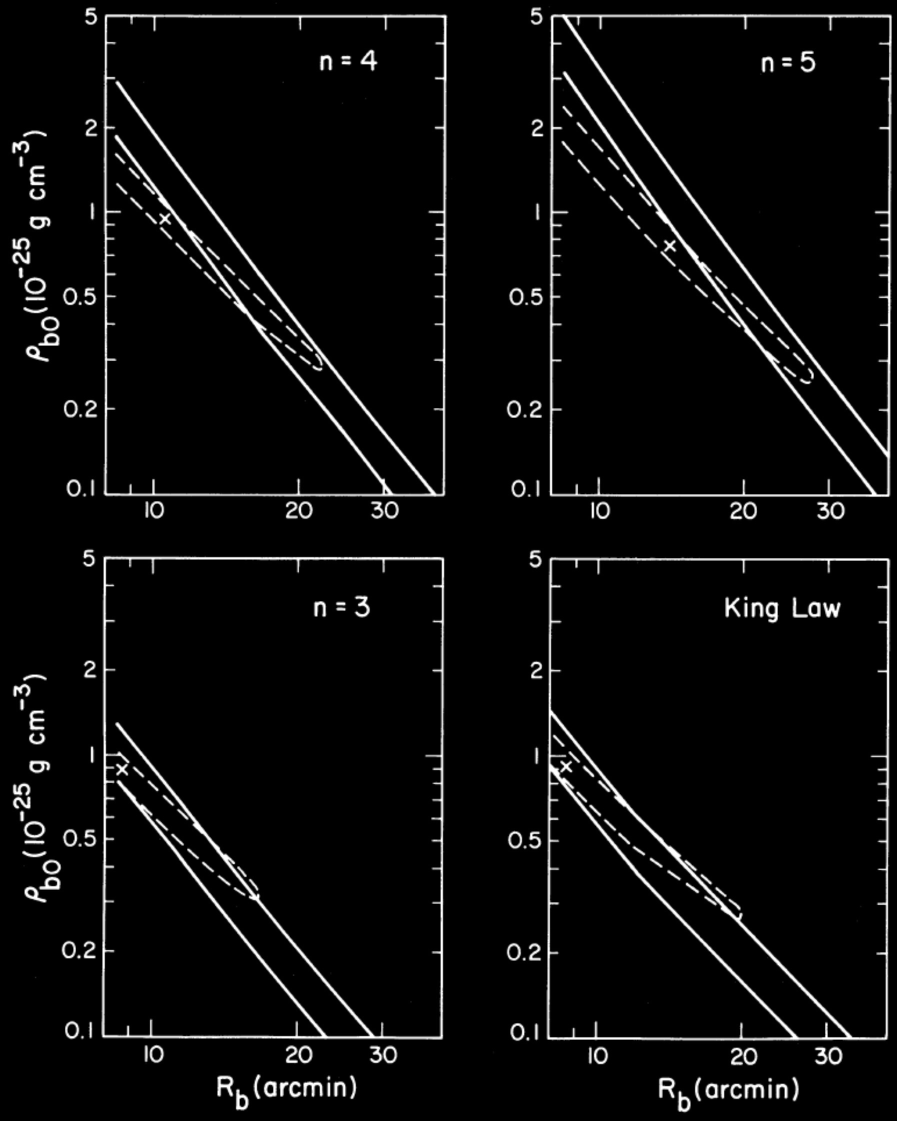
Mass Follows (X-Ray) Light

Band	Model	ρ_{b0} $(10^{-25} h_{50}{}^{2}$ g cm$^{-3})$	χ^{2} [a]
X-Ray	$\beta = 0.86$, $R_c = 5\rlap{.}'5$ (truncated)	$0.98^{+0.021}_{-0.022}$ [b]	70.7
	$\beta = 0.76$, $R_c = 9\rlap{.}'8$	$0.99^{+0.017}_{-0.020}$ [b]	75.2
	$\beta = 0.63$, $R_c = 7\rlap{.}'6$	$0.97^{0.013}_{-0.014}$ [b]	68.8
	Tenma efficiencies +5%	0.93 ± 0.020 [b]	71.3
	Tenma efficiencies −5%	1.01 ± 0.018 [b]	69.0
Optical	Merritt	1.16 ± 0.12	...
	The and White	0.94 ± 0.14	...
	Kent and Gunn	1.14	...



Not much difference due to calibration
of Tenma space telescope

Binding Mass Distribution



- Dashed line = 99% confidence
- All intersect 1x10^{-25}
- Not much difference between King and n=3

Mass Results

Model	$M(R < 1h_{50}{}^{-1}$ Mpc) $(10^{14}h_{50}{}^{-1}\ M_\odot)$	$M(R < 5h_{50}{}^{-1}$ Mpc) $(10^{15}h_{50}{}^{-1}\ M_\odot)$
Mass ~ Light	5.2–6.7	1.6–2.1
$n = 3$	5.3–7.1	1.3–3.0
$n = 4$	5.9–7.0	1.2–2.6
$n = 5$	6.2–7.2	1.1–2.3
King: $W_0 = 12$	3.9–5.2	1.6–2.4
King: $W_0 = 18$	4.1–5.8	1.6–2.2

- $h_{50}{}^{-1} = 2\,h^{-1}$
- Range: 0.6-1.5 x 10^{15} h^{-1}

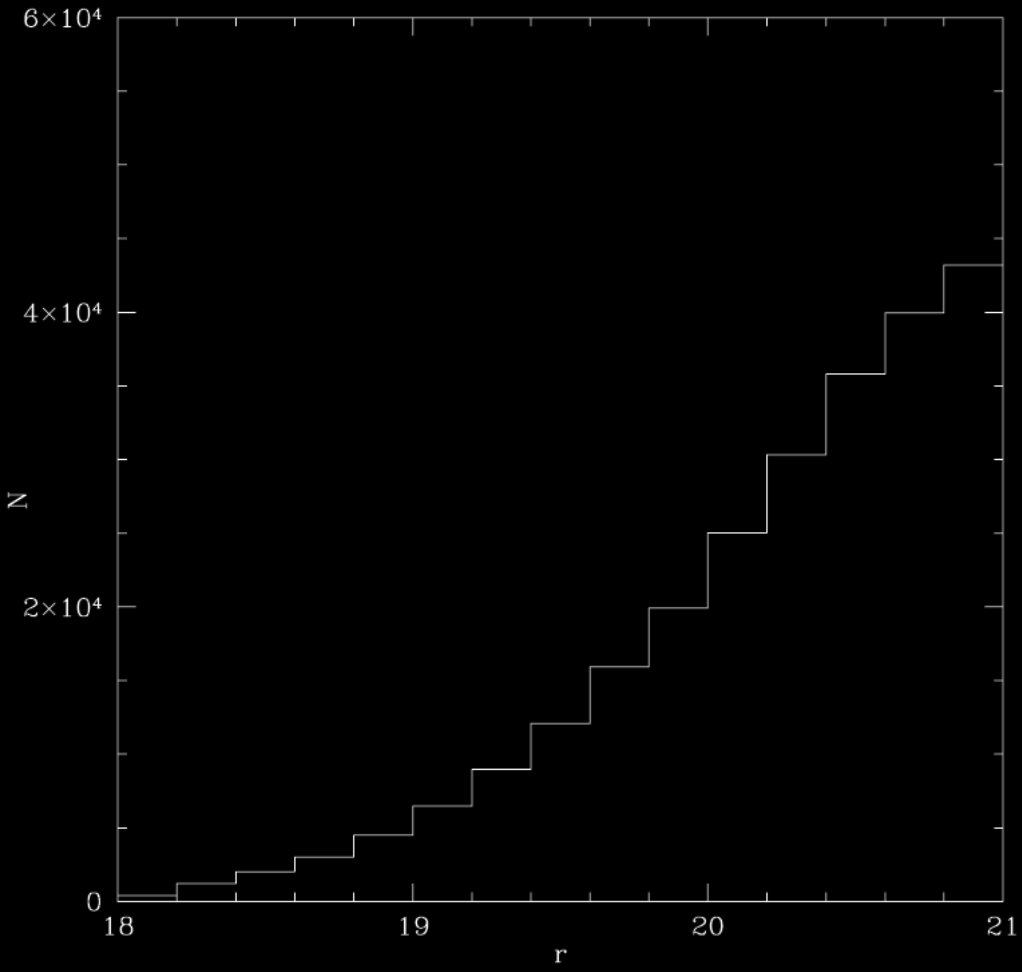
Kubo et al.'s Approach

- Select a set of galaxies from SDSS
- Measure tangential shear across those galaxies
- Convert tangential shear to a surface density
- Fit that density to a Navarro, Frenk, and White (NFW) profile
- Convert the density profile to a virial mass

Observations

- Galactic data from the Sloan Digital Sky Survey Data Release 5 (SDSS DR5)
- Used PHOTO pipeline to do object detection and shape measurement
- 200 deg^2 region of the sky centered at NGC 4889 ($13^h02^m0.2^s$, 27°41’26.6’’, J2000)

Sample Selection



- Only objects PHOTO identified as galaxies
- Also cut ones with bad PSF
- ~270,000 galaxies total

Tangential Shear

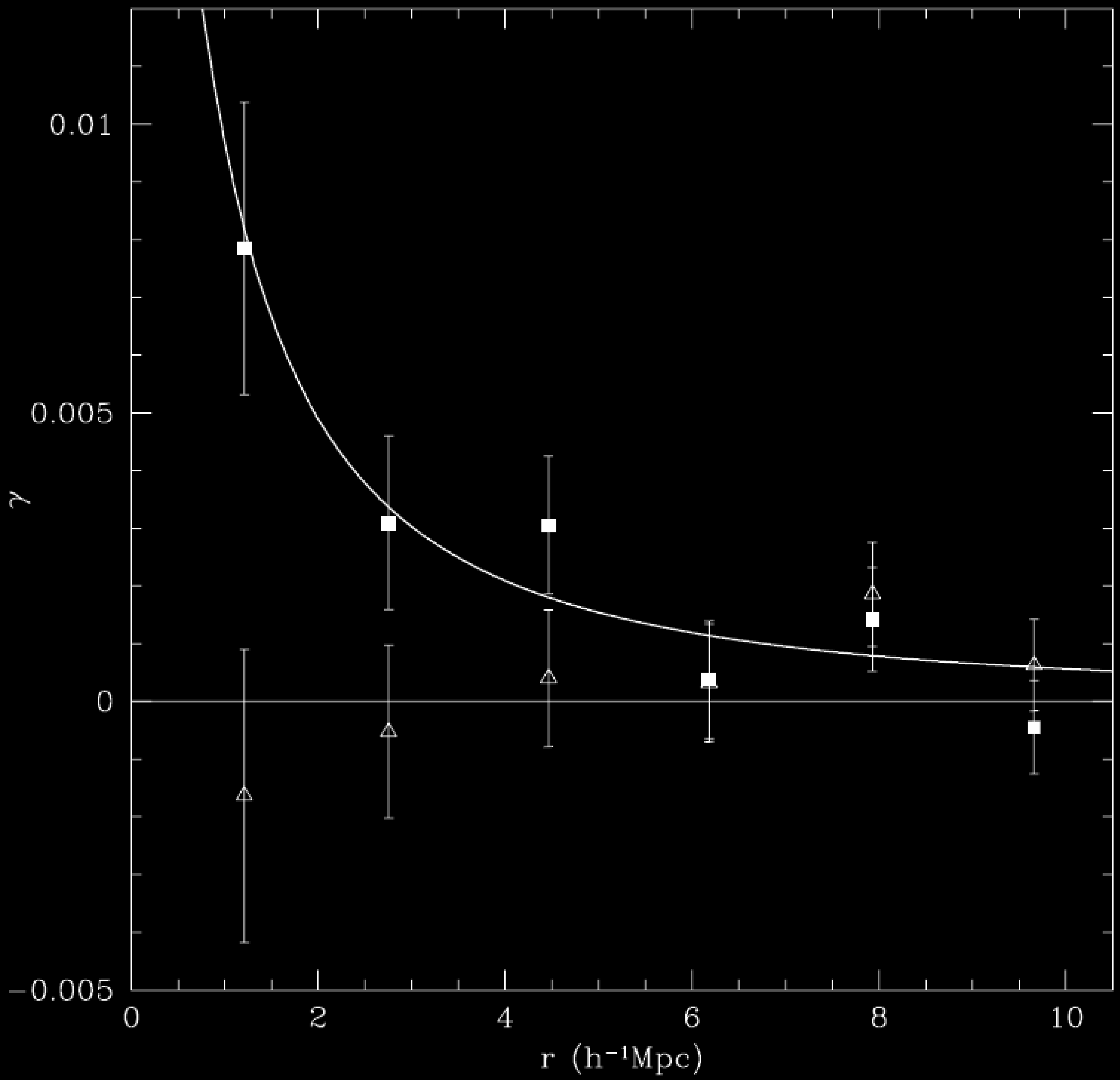
- Break into radial bins from 0.05-10.5 h^{-1} Mpc
- Use 1-D shear based on Castro et al. (2005):

$$\gamma_t = \frac{1}{2\mathcal{R}} \frac{\sum e_t}{N}$$

- γ_t = tangential shear for bin, e_t = tangential ellipticity of bin, N = number in bin

$$\mathcal{R} = 1 - \sigma_{\rm SN}^2$$

Tangential Shear



- Squares = γ_t with 1 σ error
- Triangles = 45° shear
- Total χ^2 = 23.33

Surface Density

- Tangential shear relates to surface density:

$$\gamma_t = \frac{\bar{\Sigma}(\leq r) - \Sigma(r)}{\Sigma_{\rm crit}}$$

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_s}{D_l D_{ls}}$$

- D_s, D_l angular diameter distance to source or lens; D_{ls} angular distance from lens to source

NFW Profile

- Fit to profile from Navarro, Frenk, and White:

$$\rho(r) = \frac{\delta_c \rho_c}{(r/r_s)(1 + r/r_s)^2}$$

$$\delta_c = \frac{200}{3} \frac{c^3}{\ln(1 + c) - c/(1 + c)}$$

$$\rho_c = 3H^2(z)/8\pi G$$

- The two parameters, r_s and c can constrained by setting the virial radius $r_{200} = c\, r_s$:

$$M_{200} = \frac{800\pi}{3} \rho_c r_{200}^3$$

Results!

- Fitting the profile:

$$r_{200} = 1.99^{+0.21}_{-0.22}\ h^{-1}\ \mathrm{Mpc}$$

$$c = 3.84^{+13.16}_{-1.84}$$

- With $\chi^2 = 3.87$ for 4 degrees of freedom

- For a mass of:

$$M_{200} = 1.88^{+0.65}_{-0.56} \times 10^{15}\ h^{-1}\ M_{\odot}$$

Cross-Comparison

Virial Radius (h^{-1} Mpc)	Mass ($10^{15}\ h^{-1}\ M_{\odot}$)	Reference
$1.99^{+0.21}_{-0.22}$	$1.88^{+0.65}_{-0.56}$	1[a]
1.5..	0.8	2[a]
2.5..	0.93 ± 0.12	3
2.7..	0.95 ± 0.15	4

1. Kubo et al. 2007
2. Geller et al. 1999

1. Hughes 1989
2. The & White 1986

Questions?