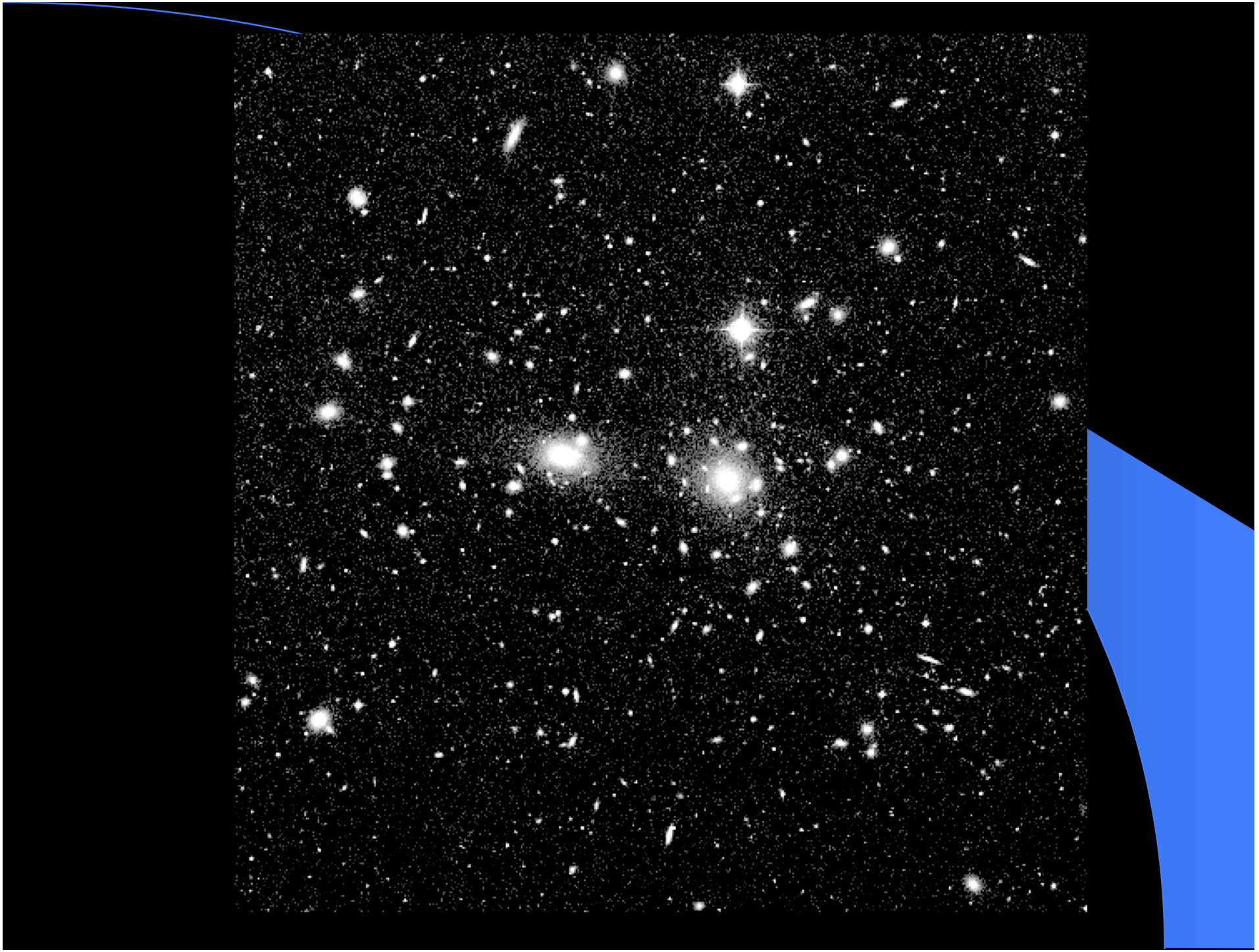
Masses of Nebulae and Clusters of Nebulae

Fritz Zwicky - 1937



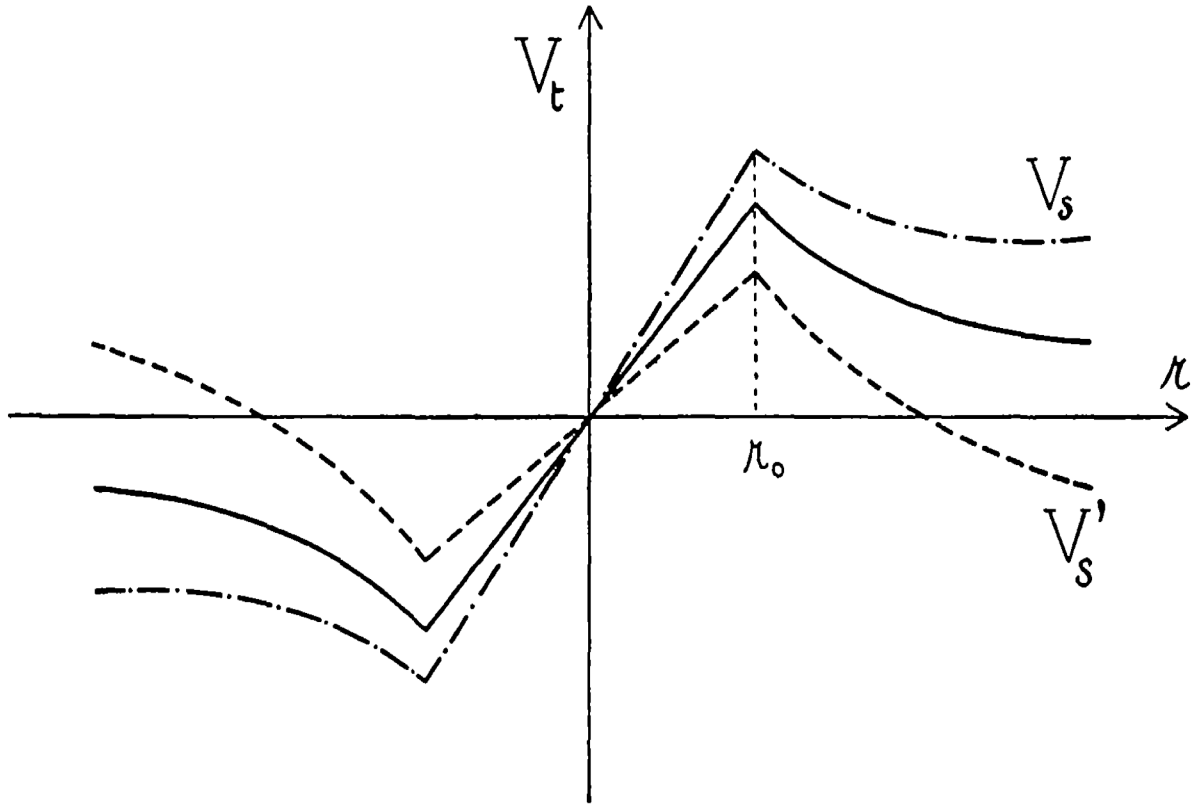
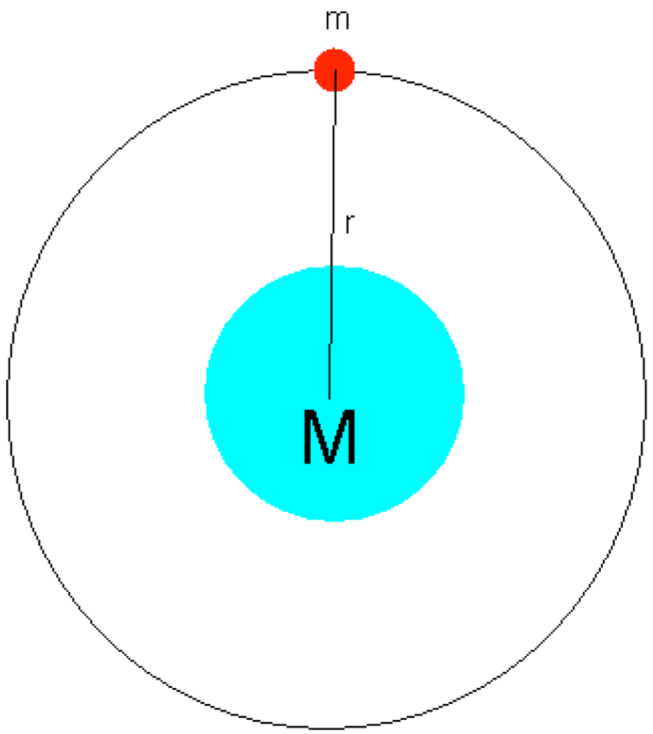


FIG. 1.—Velocity of rotation in nebulae

Virial Theorem For Nebulae



Basics

$$\sum F = ma = \frac{m v^2}{r} = \frac{G M m}{r^2}$$

$$v = \sqrt{\frac{G M}{r}}$$

$$U[r] = -\frac{G m M}{r}$$

$$T = \frac{m v^2}{2 r} = \frac{G M m}{2 r} = -\frac{U[r]}{2}$$

Deriving The Mass…

$$\overline{\overline{v^2}} = 3\overline{\overline{v_s^2}}\,.$$

$$\mathcal{M} > \frac{3R\overline{\overline{v_s^2}}}{5\Gamma}\,.$$

From the observations of the Coma cluster so far available we have, approximately,[5]

$$\overline{\overline{v_s^2}} = 5 \times 10^{15}\text{cm}^2\ \text{sec}^{-2}\,. \qquad (34)$$

$$\mathcal{M} > 9 \times 10^{46}\text{gr}\,.$$

$$\overline{M} > 9 \times 10^{43}\ \text{gr} = 4.5 \times 10^{10}\ M_\odot\,.$$

$$\gamma = 500$$

What do we expect the mass to light ratio to be???

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- Uh…1-3.

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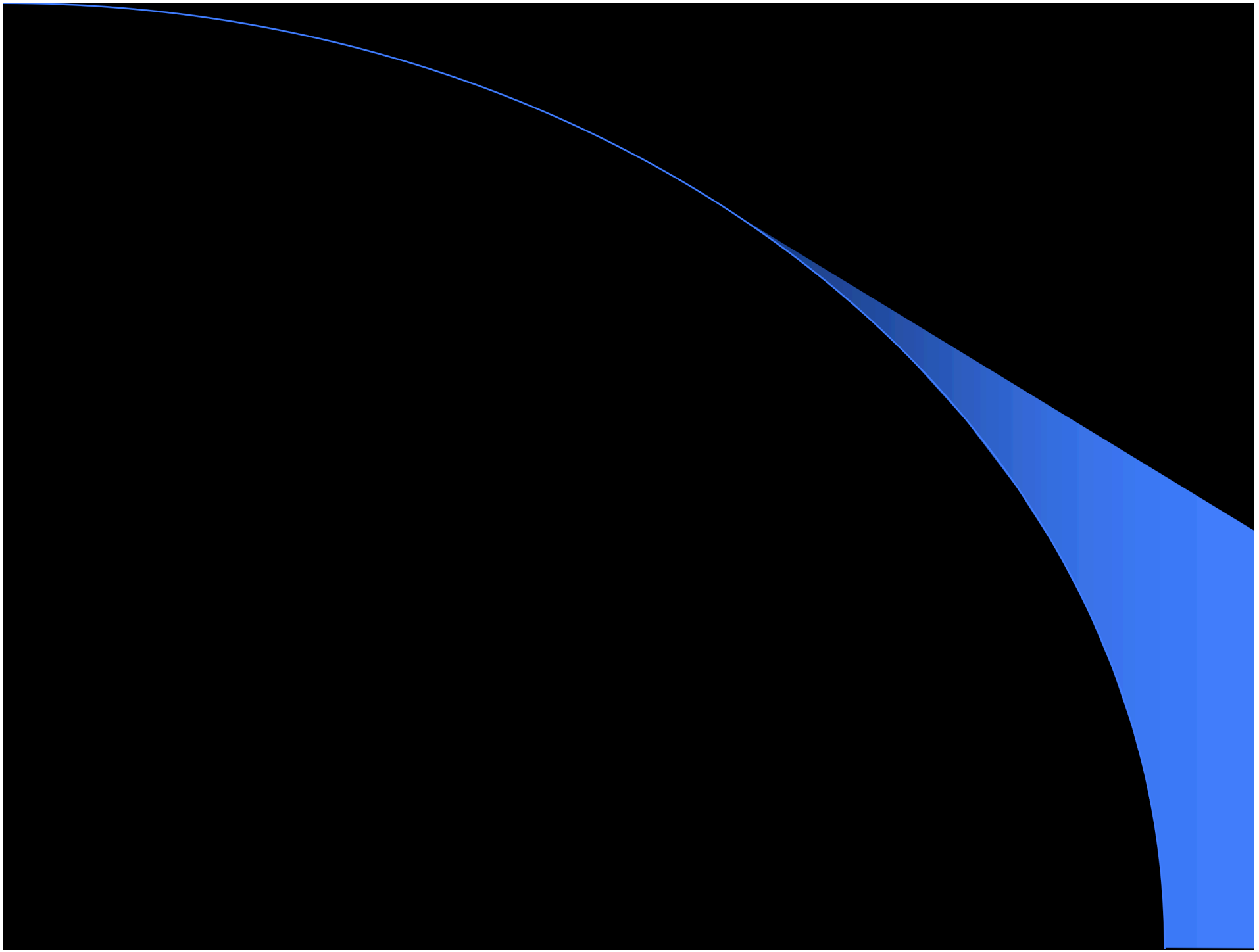
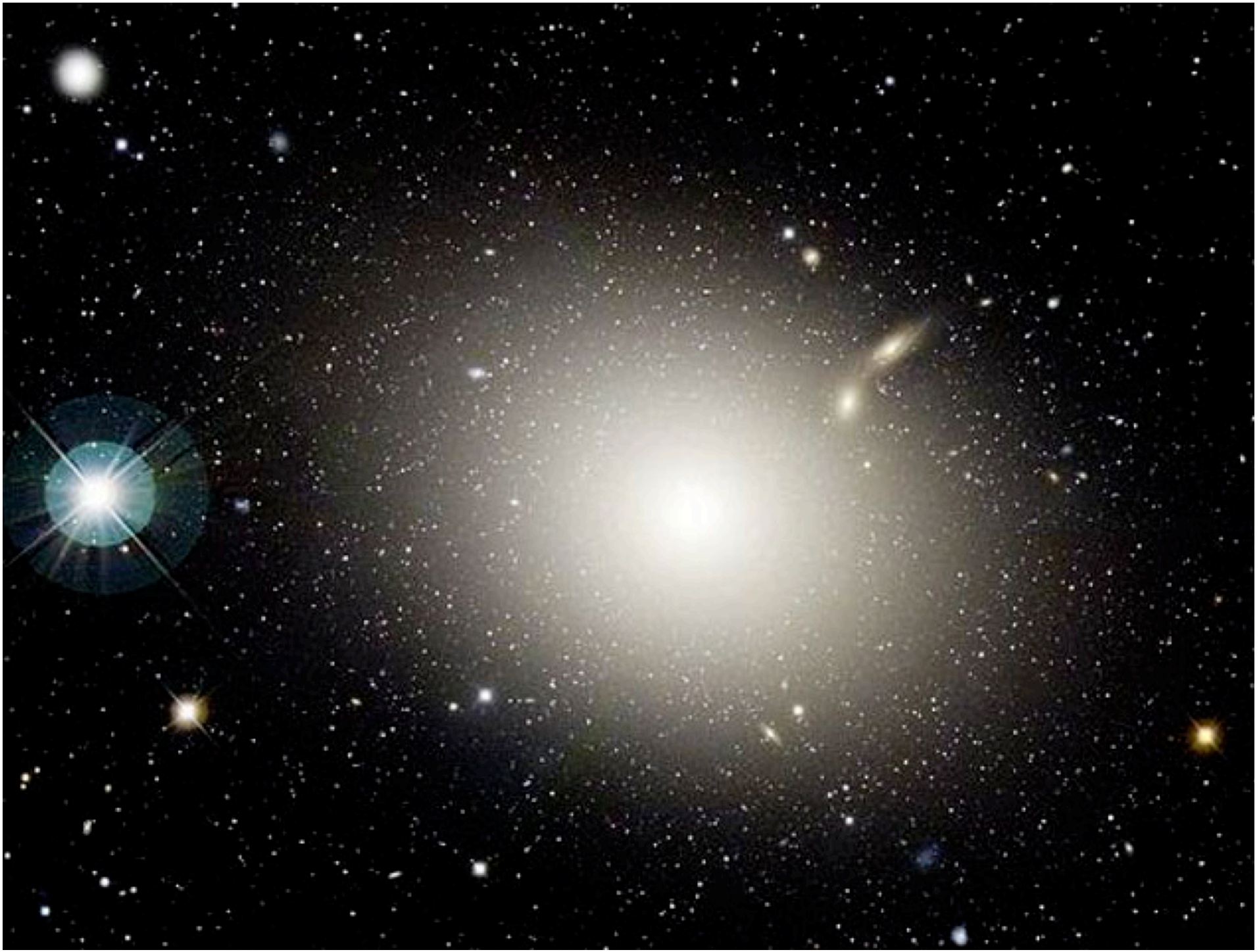
- Uh…1-3.
- What could this non-luminous material possibly be???



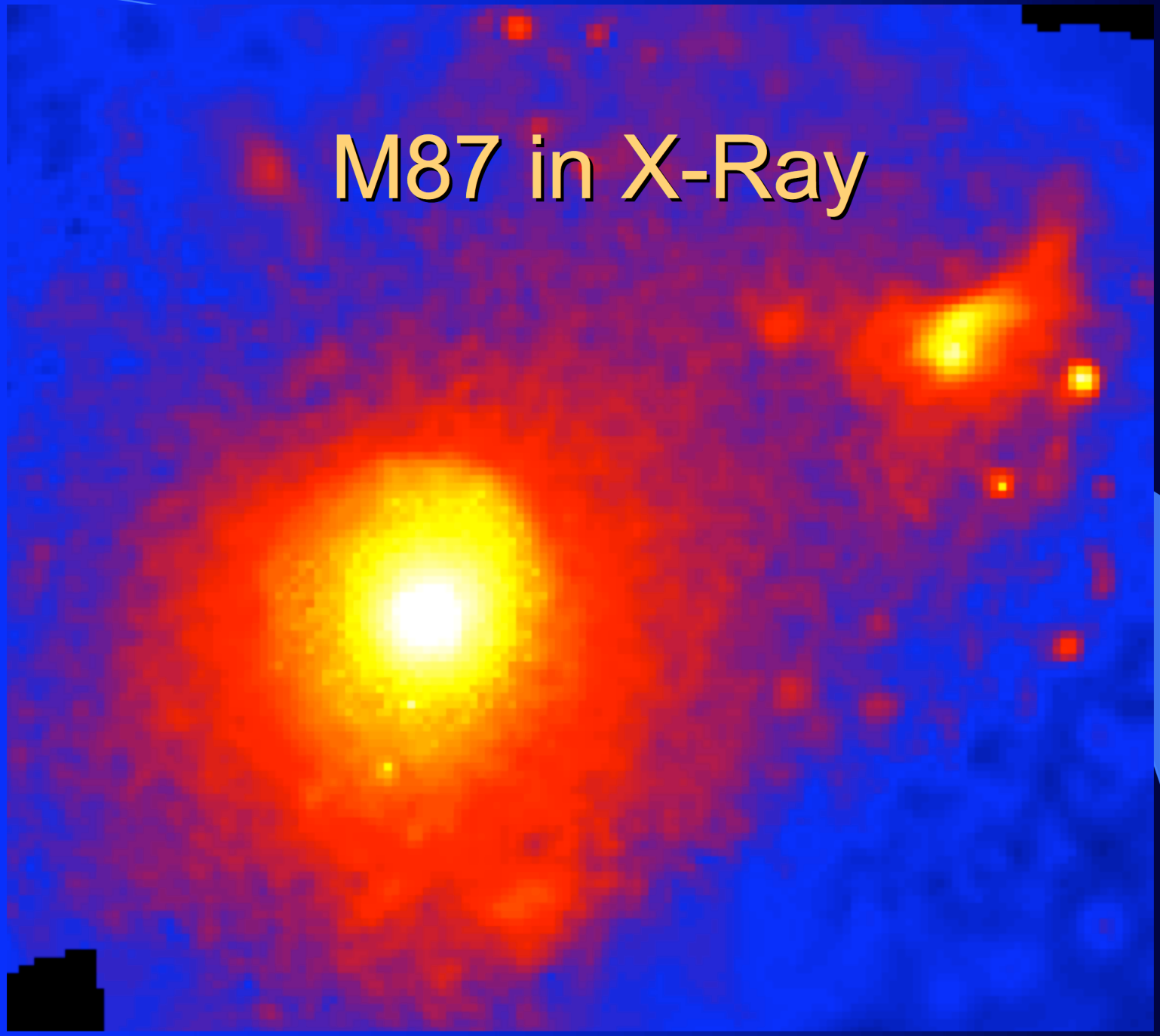
Dark Matter!

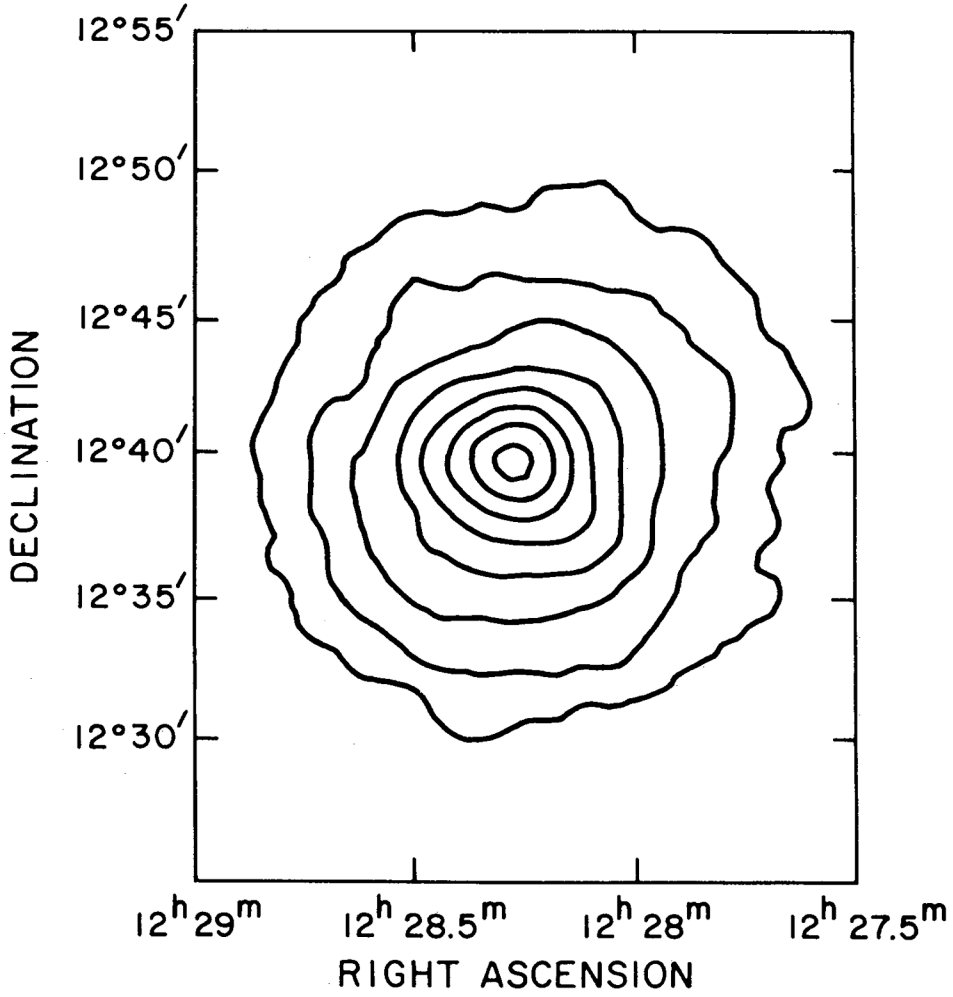
X-ray measurements on the mass of M-87

- Written by D. fabricant, M. Lecar and P. Gorenstein.

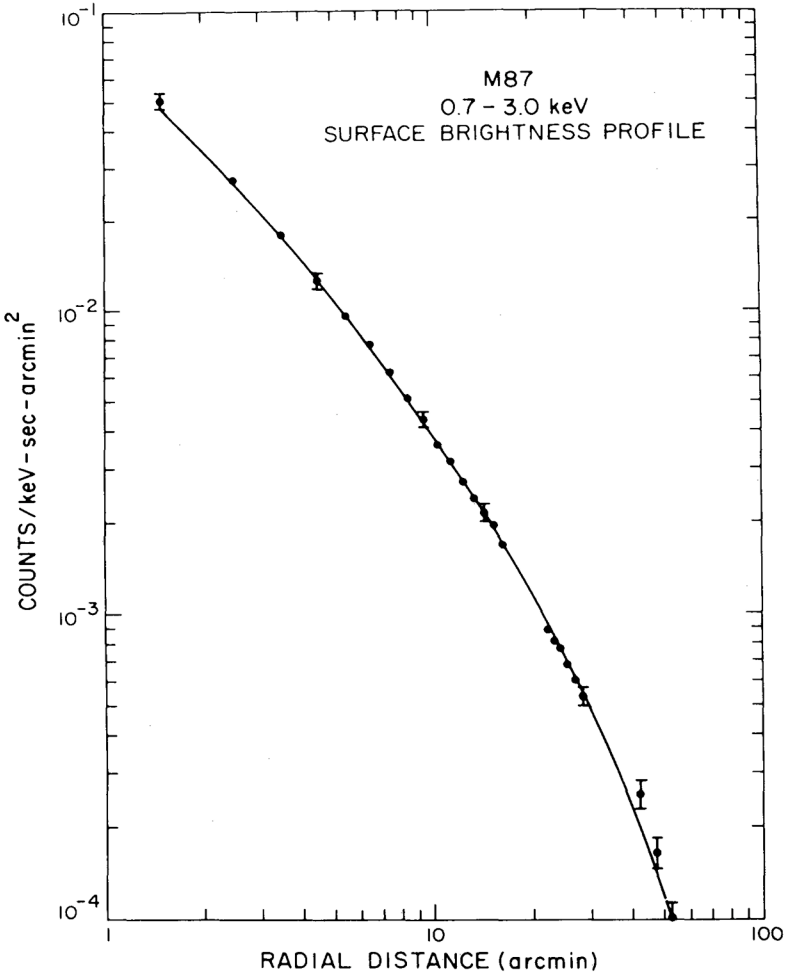


M87 in X-Ray




12°55′
12°50′
12°45′
12°40′
12°35′
12°30′
DECLINATION
12h29m
12h28.5m
12h28m
12h27.5m
RIGHT ASCENSION

Flux of .7 – 3.0 keV X-Rays



Temperature Profile of M-87

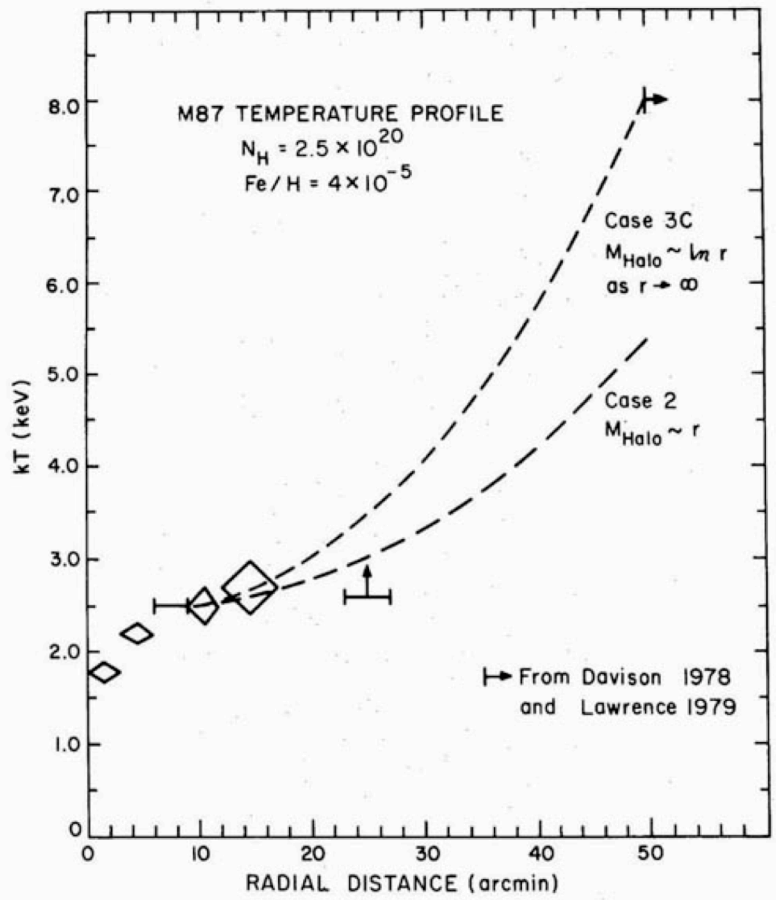
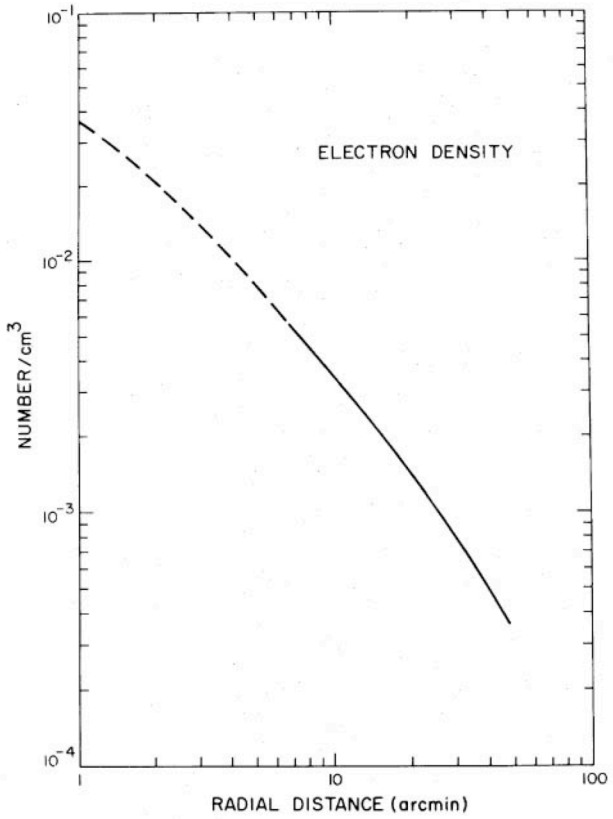
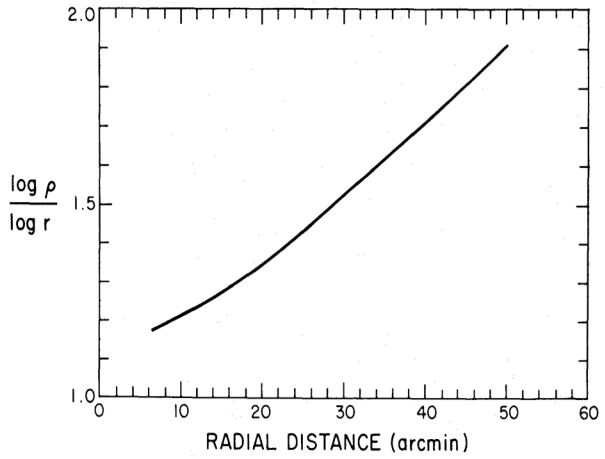


FIG. 3.—The temperature profile of M87 derived by fits to the spectral data. N_H has been fixed at 2.5×10^{20} and the ratio of iron

Electron Density





Equation of State for M87

$$\frac{dP_{\rm gas}}{dr} = \frac{-G\mathfrak{M}_*(r)\rho_{\rm gas}}{r^2}$$

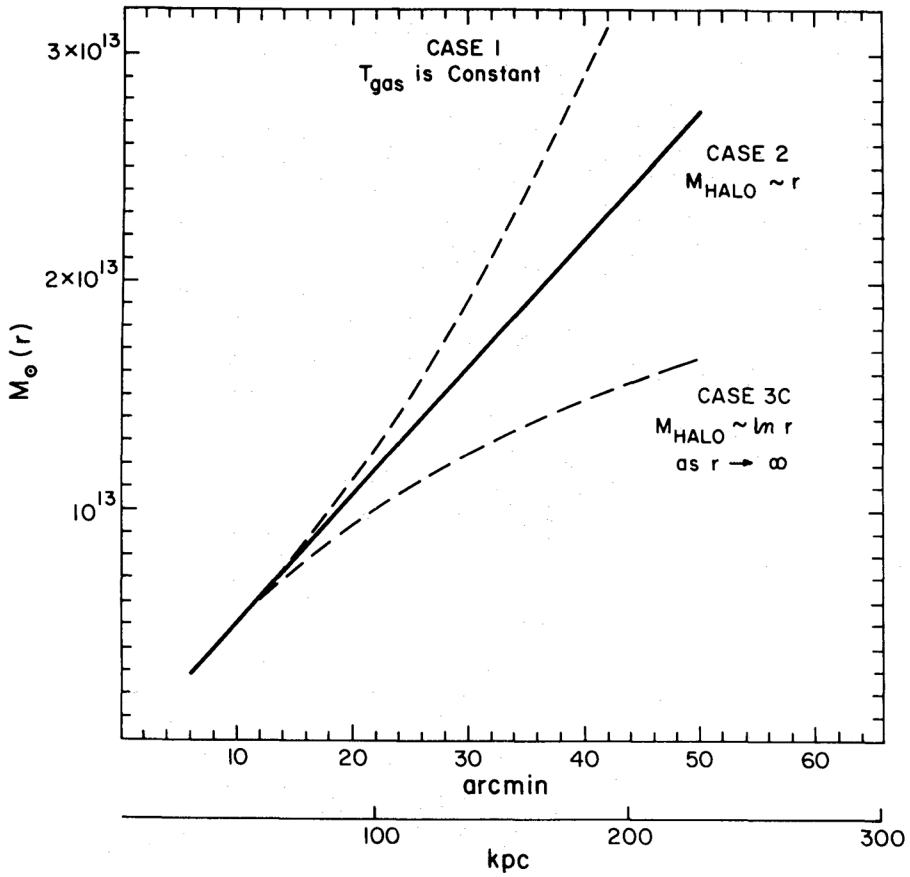
$$P_{\rm gas} = \frac{\rho_{\rm gas} K T_{\rm gas}}{\mu \mathfrak{M}_{\rm H}}$$

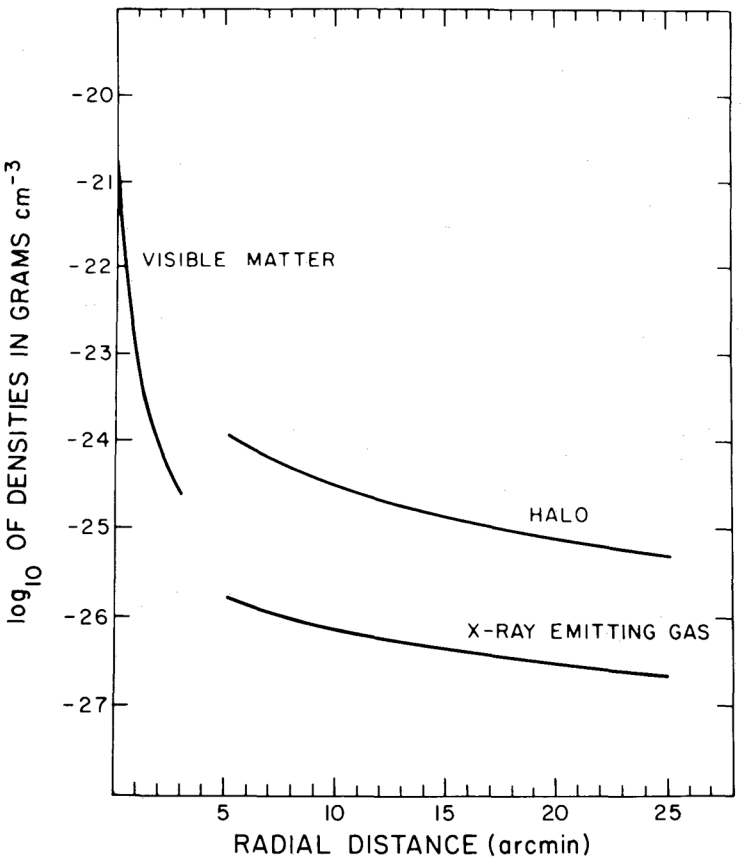
$$-\frac{KT_{\rm gas}}{G\mu\mathfrak{M}_{\rm H}}\left(\frac{d\log\rho_{\rm gas}}{d\log r}+\frac{d\log T_{\rm gas}}{d\log r}\right)r=\mathfrak{M}_*(r)$$

If $T_{\rm gas}$ is a constant, this simplifies to:

$$-\frac{KT_{\rm gas}}{G\mu\mathfrak{M}_{\rm H}}\left(\frac{d\log\rho_{\rm gas}}{d\log r}\right)r=\mathfrak{M}_*(r).$$

Results!


CASE 1
T_{gas} is Constant
CASE 2
$M_{HALO} \sim r$
CASE 3C
$M_{HALO} \sim \ln r$
as $r \to \infty$
3×10^{13}
2×10^{13}
10^{13}
$M_\odot(r)$
10
20
30
40
50
60
arcmin
100
200
300
kpc


VISIBLE MATTER
HALO
X-RAY EMITTING GAS
$\log_{10}$ OF DENSITIES IN GRAMS cm^{-3}
-20
-21
-22
-23
-24
-25
-26
-27
5
10
15
20
25
RADIAL DISTANCE (arcmin)

Conclusions

- Halo mass lies within a range of 1.7 * 10^13-4*10^13 Solar masses.
- Halo extends to a minimum extent of 50’ to 60’.
- Dark matter comprises over 99% of M87’s mass!