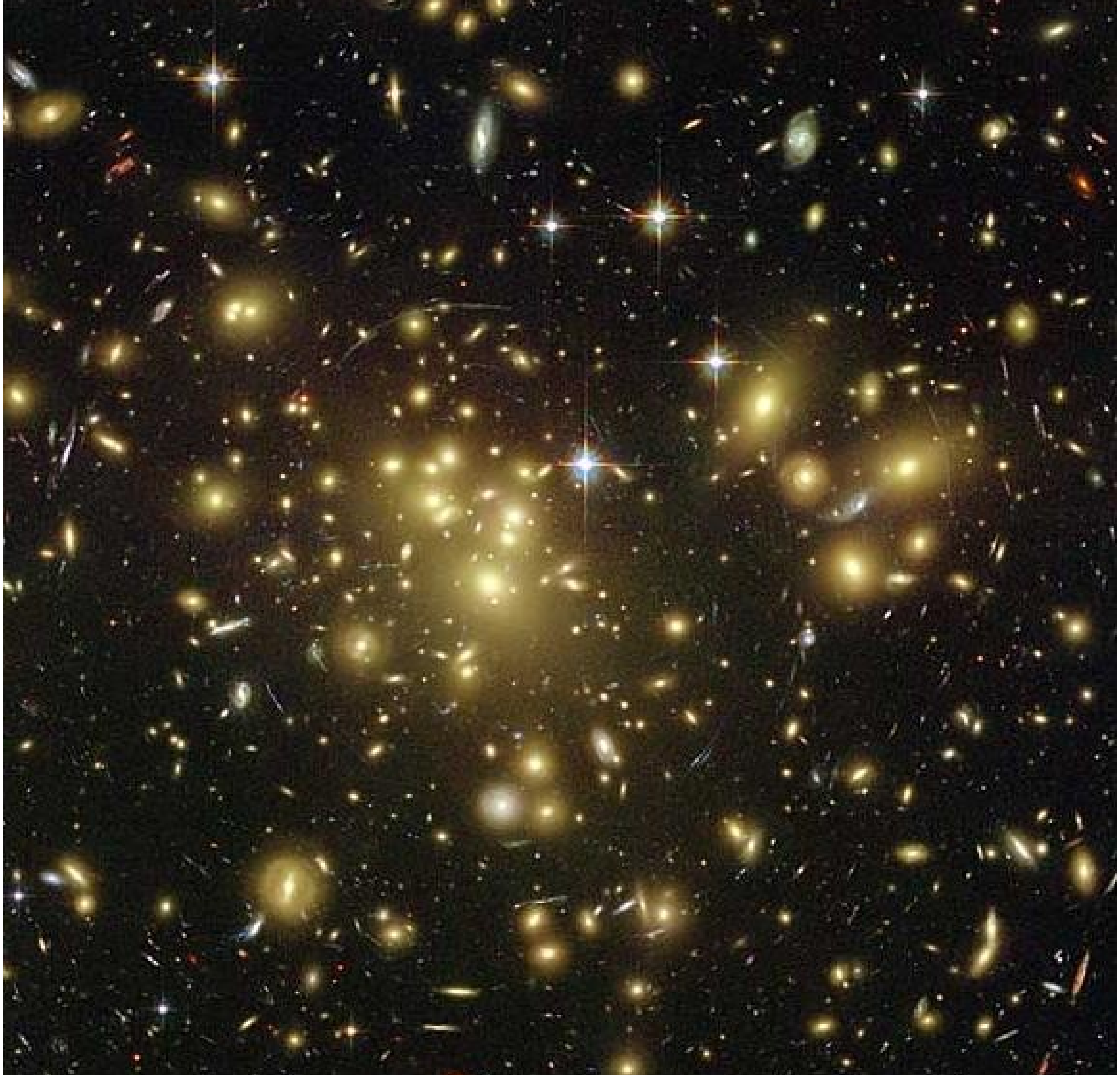
Galaxy Clusters, Dark Matter, and Cosmology

UC Davis

David Wittman
UC Davis

Coma
Cluster
(z=0.02)



Abell 1689
(z=0.19)
HST image

First Evidence for Dark Matter

Zwicky, 1930's:

steady-state virial theorem: $K = -W/2$

$\frac{1}{2} M\langle v^2\rangle = GM^2 / (2R)$
(Note: $\langle v^2\rangle = 3 \langle v_{los}^2\rangle$)

Measurements: $\langle v_{los}^2\rangle^{1/2} = 880$ km/s,
$R \sim 1.5$ Mpc

Result: $M = 2 \times 10^{15} M_\odot$

~250 times the mass in stars!

Difficulties with Zwicky's Method

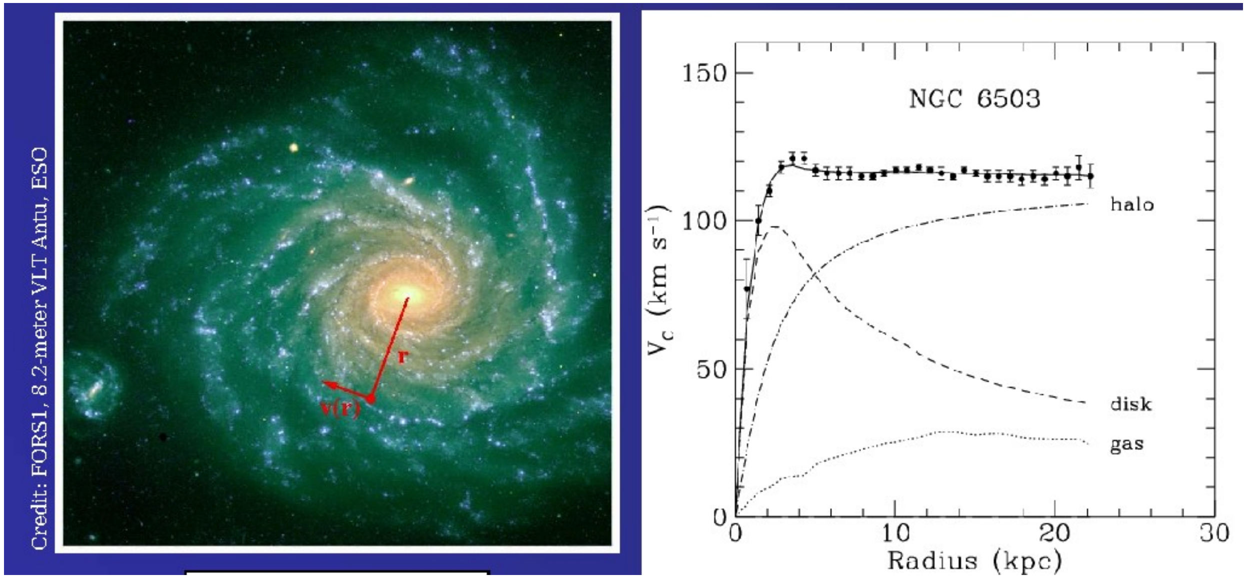
- cluster may not be in equilibrium as assumed
- measuring R is difficult: there is no clearly defined radius
- velocity dispersion can also be biased: upward by infalling galaxies, downward by tendency to target bright galaxies in core
- Zwicky had only a few clusters and very incomplete velocity measurements of each one

Despite these difficulties, the factor of 250 discrepancy is so large that we must take dark matter seriously!

Similar Arguments, Other Contexts

•velocity dispersions of thermally supported galaxies (i.e., ellipticals): evidence for dark matter on galaxy scales

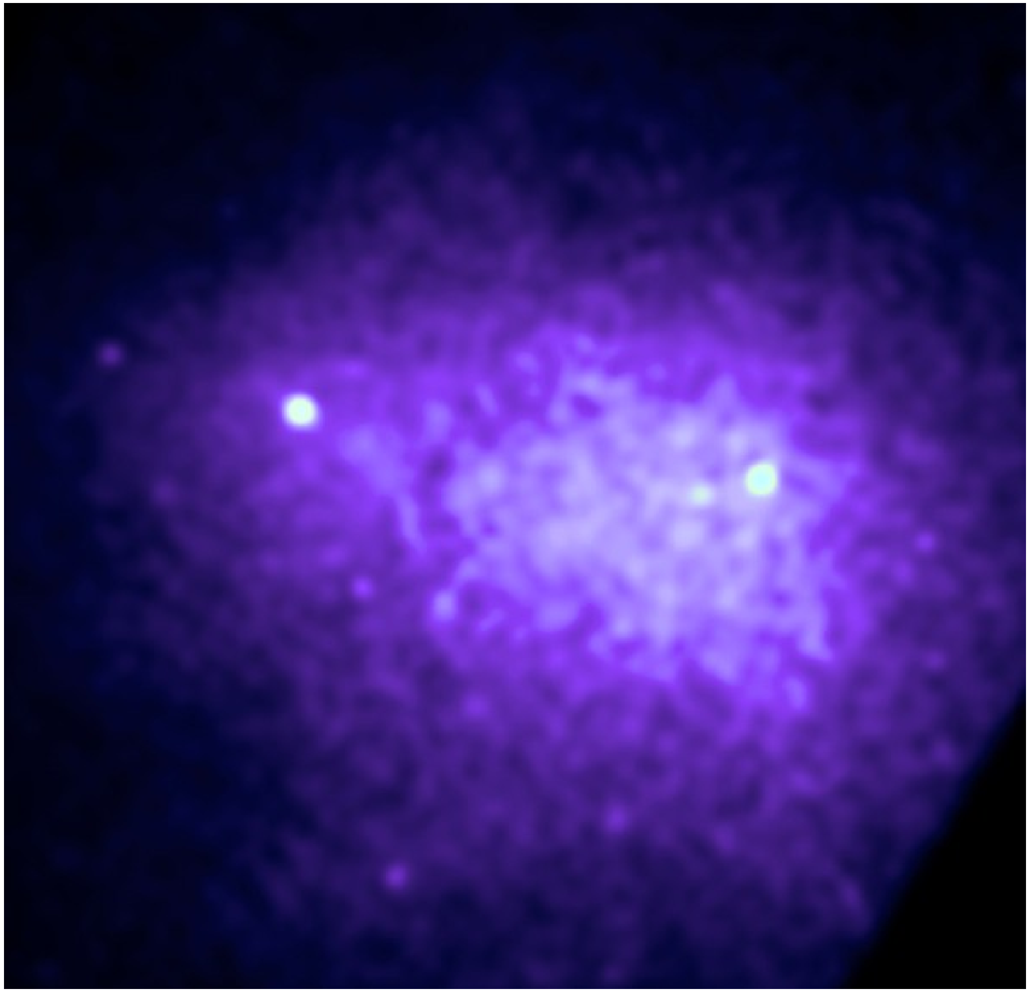
•for rotationally supported galaxies, $M(r) = v^2r/G$ also provides strong evidence



All these arguments assume equilibrium, usually considered a reasonable assumption (e.g. not many rotating galaxies are seen in the process of flying apart)

Clusters Also Emit X-Rays

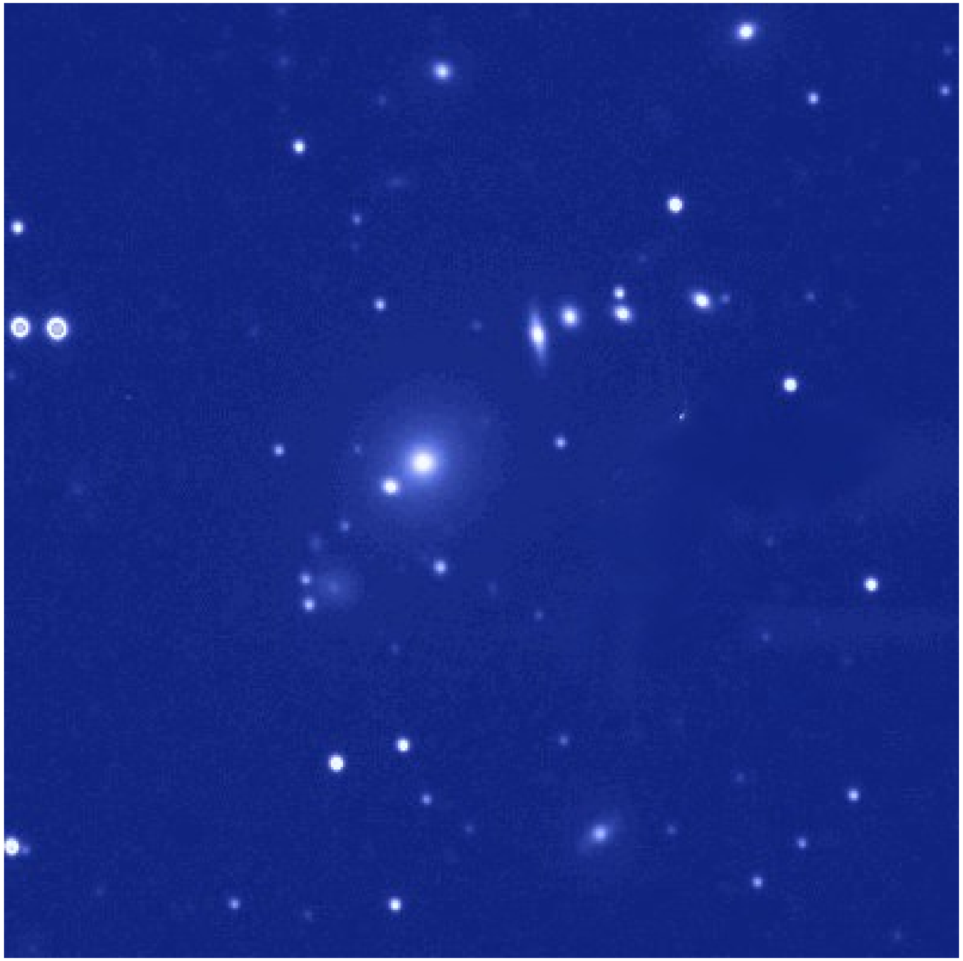
optical



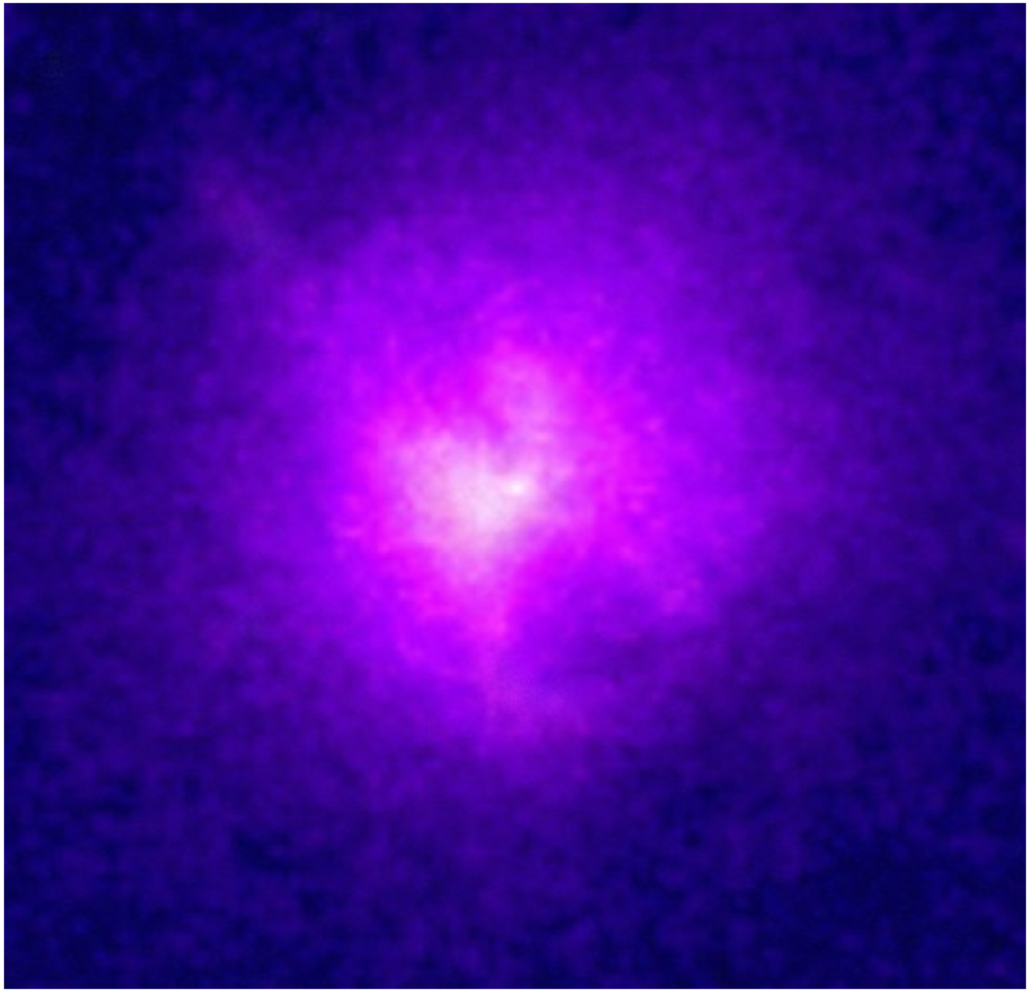
X-ray

Two views of the Coma cluster

Hydra A Cluster (z=0.05)



optical



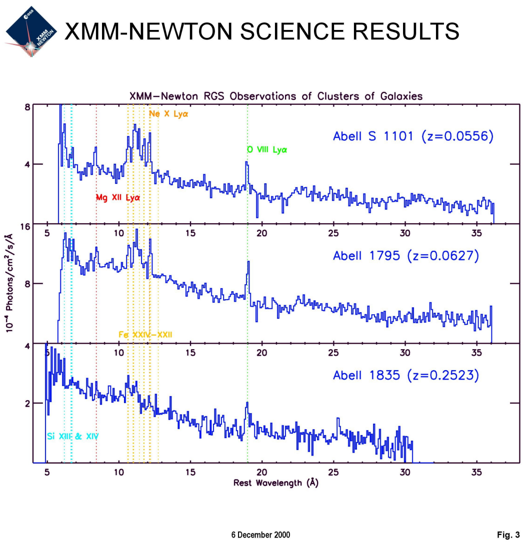
X-ray

X-Rays and Mass

X-rays are emitted by electrons in the hot ($10^7 – 10^8$ K), ionized gas we call the intracluster medium via thermal bremsstrahlung (“braking radiation”, also called free-free emission).

Assuming hydrostatic equilibrium: $dP/dr = -GM(r)r(r) / r2$

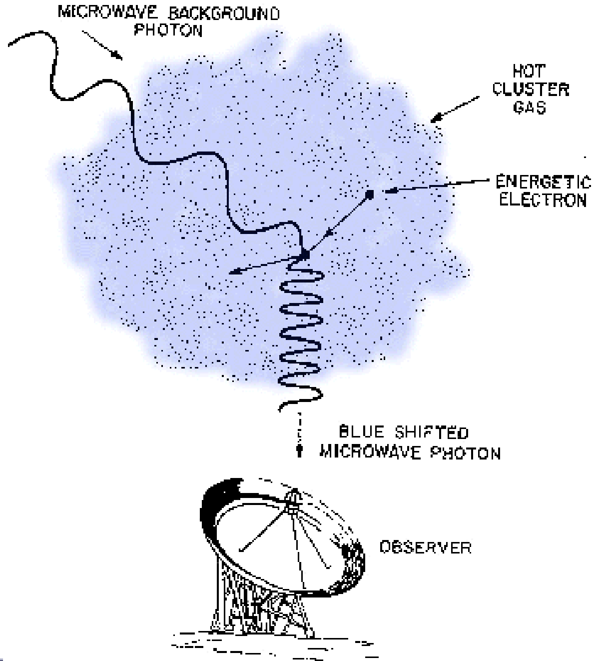
Combine with perfect gas law ($P=nkT$) to get $M(r)$ as function of n and T, which are extracted from the observed spectrum.



Result: 1-2 x 10^{15} $M_\odot$ for Coma

Again, hundreds of times the mass expected from the luminosity! And ~10 times the mass in the X-ray emitting gas!

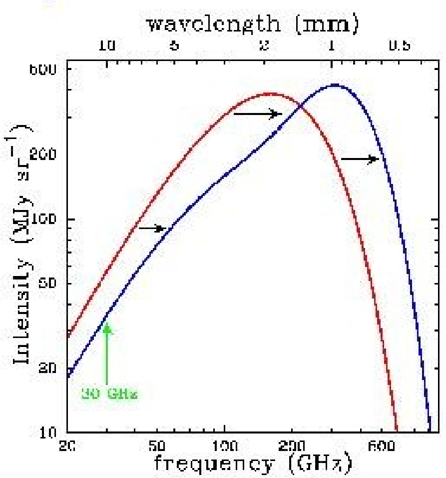
Sunyaev-Zel'dovich Effect

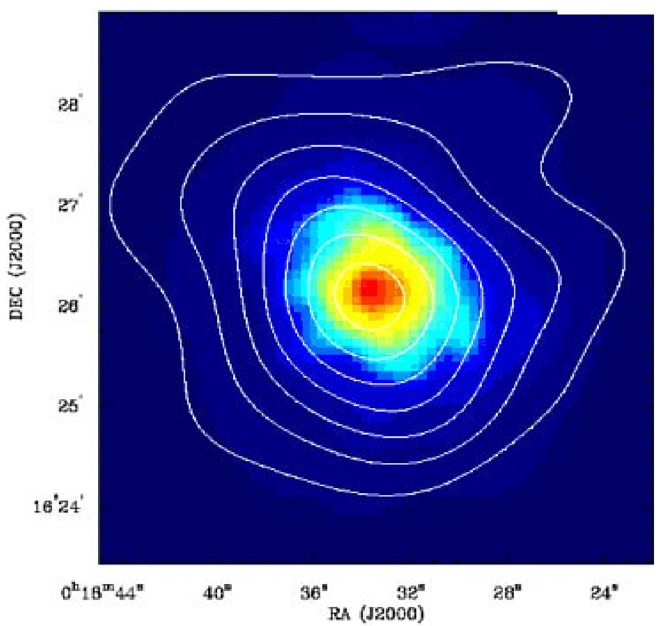


CMB photons are upscattered by the hot intracluster medium. The CMB is thus observed to be "hotter" in the direction of the cluster.

An independent way to observe n and T for a cluster. A new, (almost) redshift-independent way to *find* clusters.

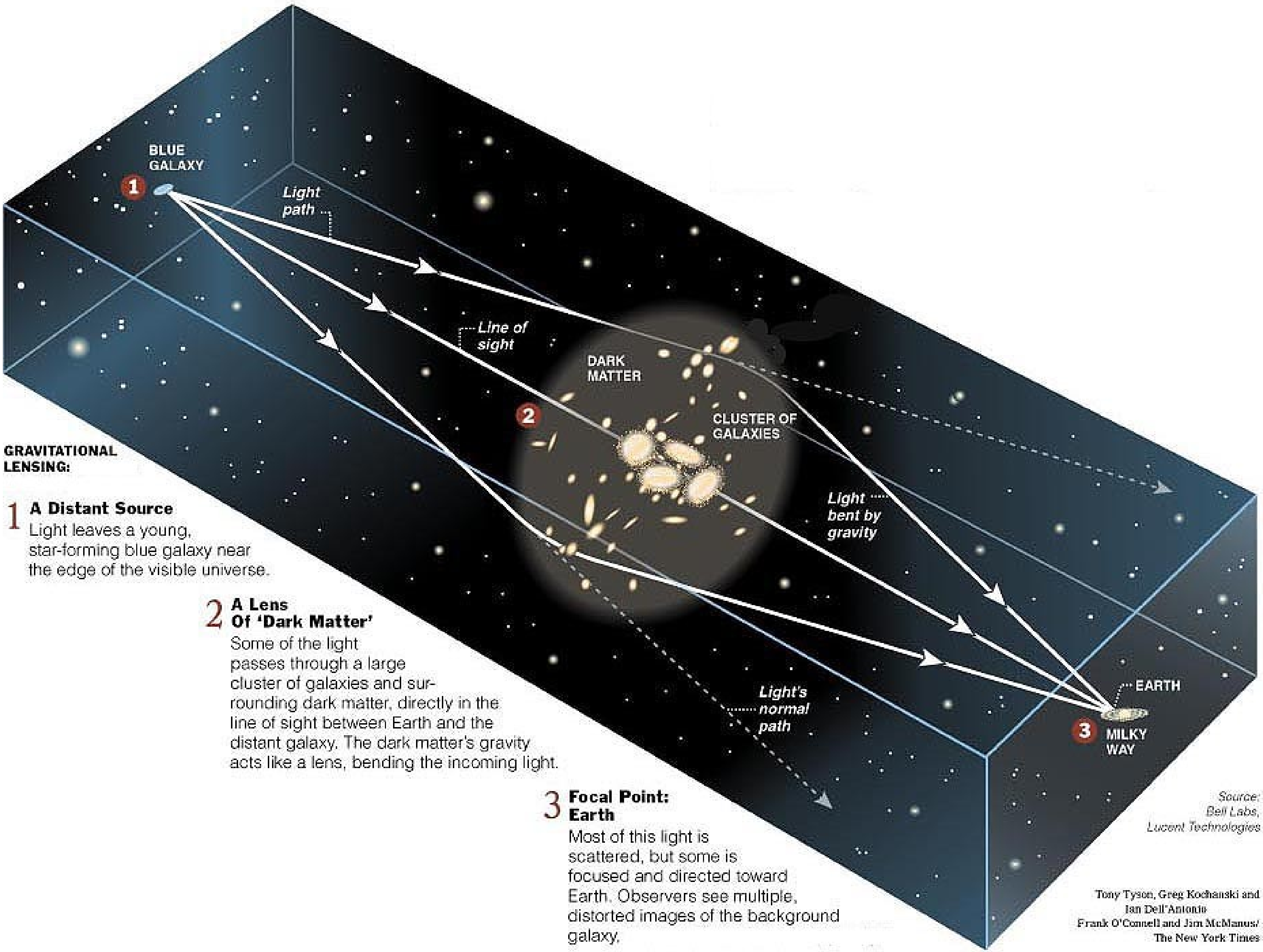
The Sunyaev-Zel'dovich Effect





Gravitational Lensing:

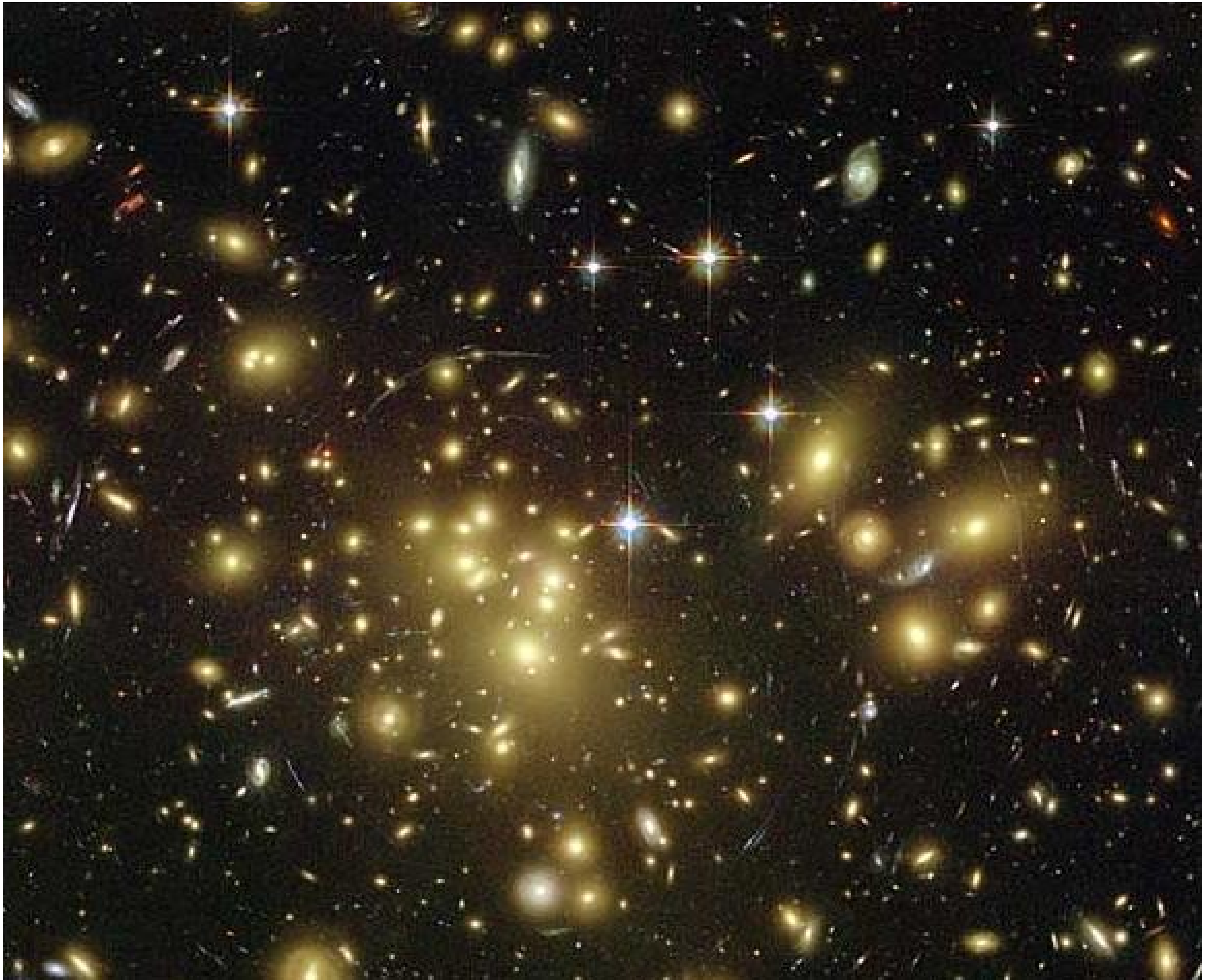
Third Line of Evidence for Dark Matter in Clusters



Lensing: *independent of* **dynamics, baryon content, star formation history**

Strong lensing: **on axis, high resolution,** ***densest*** **regions of universe**

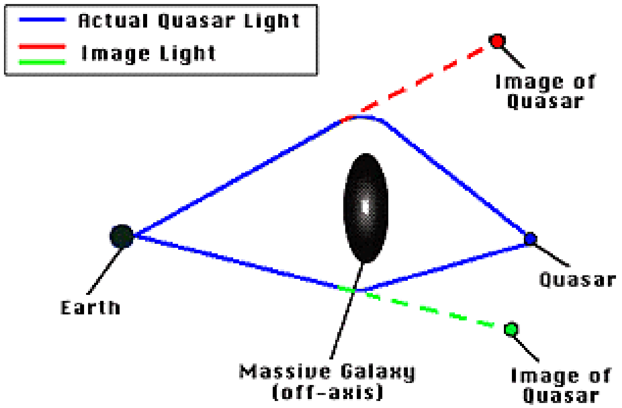
Weak lensing: **off axis, low resolution,** ***all*** **regions of universe, statistical**



Abell 1689 (z=0.19) HST image

Abell 2218 as Seen by HST

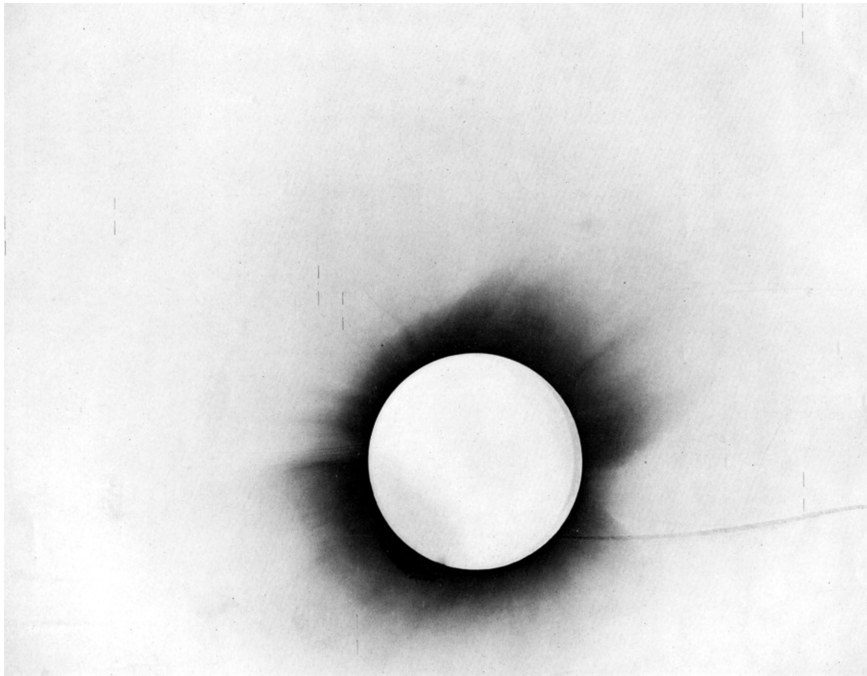
Lensing Basics



Newtonian expression for deflection angle:
$\alpha = 2GM / (v^2 r)$ (Cavendish 1784)

GR expression: $4GM / (c^2 r)$ for weak fields
("Quasi-Newtonian approximation")

Eddington



1919 eclipse

Lensing Basics ctd

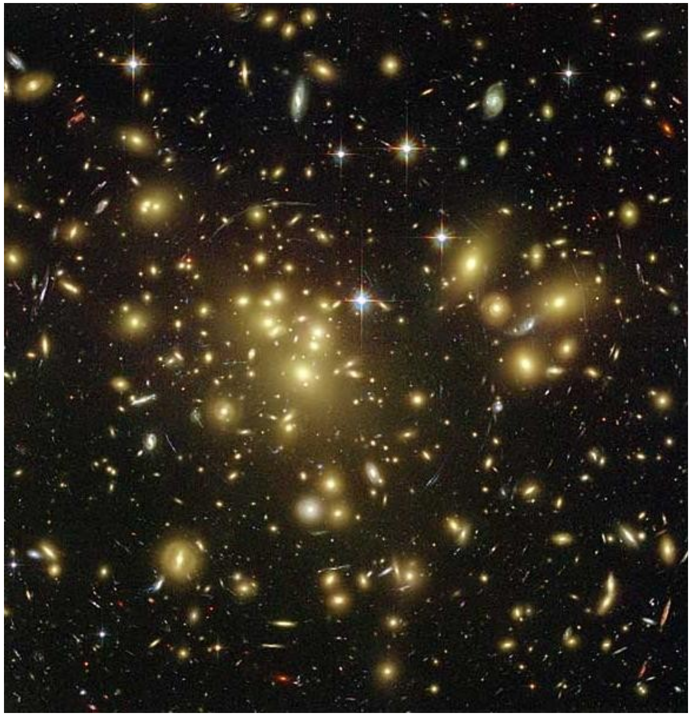
All masses deflect light from background sources, but it is measurable only for masses as large as galaxy clusters ($\sim 10^{14}$ M⊙ and up).*

Above a critical (2-d) density

$\Sigma crit = c^2 / (4\pi G) \times D_S / (D_L D_{LS})$

a single background source produces multiple observed images (strong lensing).

$\Sigma crit \sim 1$ gm cm^{-2} so this happens only along the densest lines of sight in the universe!



"There is no great chance of observing this phenomenon."

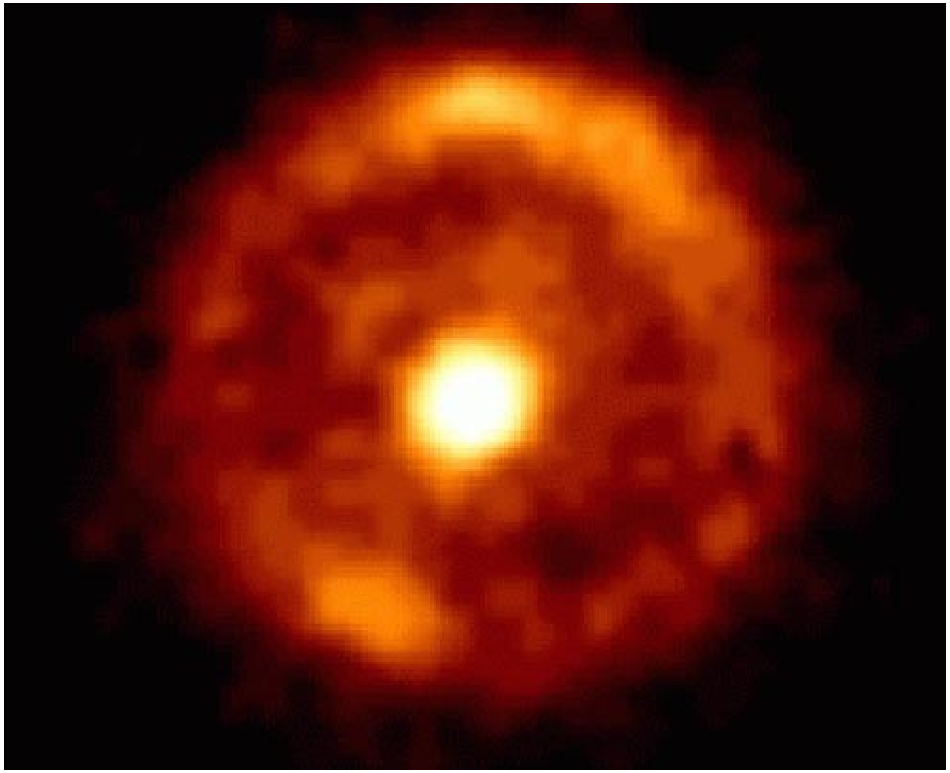
Einstein (1936)
Re: strong lensing

*Galaxies can be measured by "stacking" them; results agree with other methods.

Lensing Basics ctd

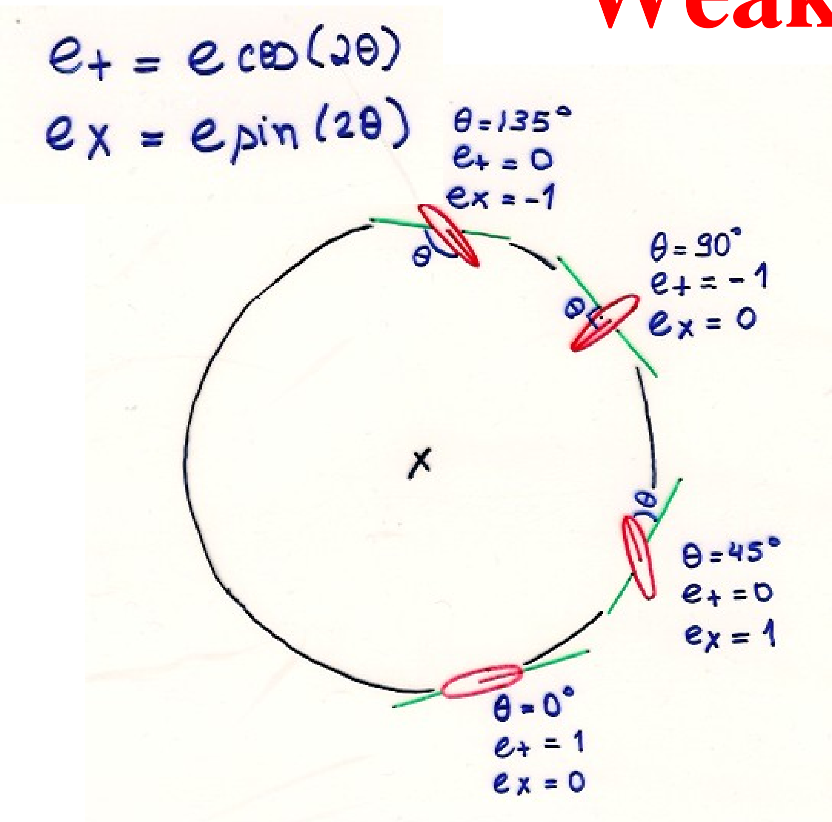
If observer, lens, and source are perfectly aligned, by symmetry the observer must see a ring ("Einstein ring"). (Also requires a perfectly axisymmetric lens!)

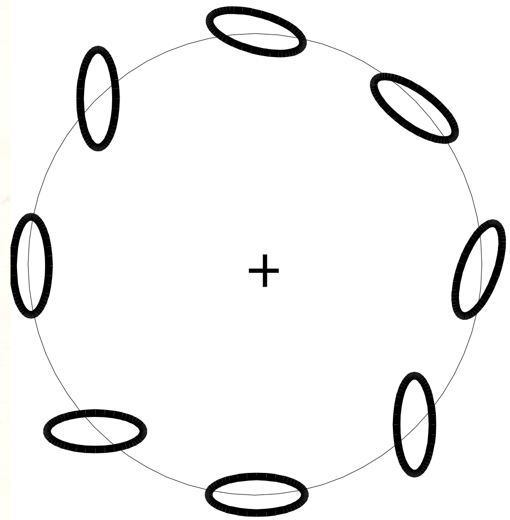
Radius of ring is related to enclosed mass: $M = \theta^2 c^2 D_L / (4G)$ or $(\theta / 0.09'')^2 (D_L / pc)$ in $M_\odot$

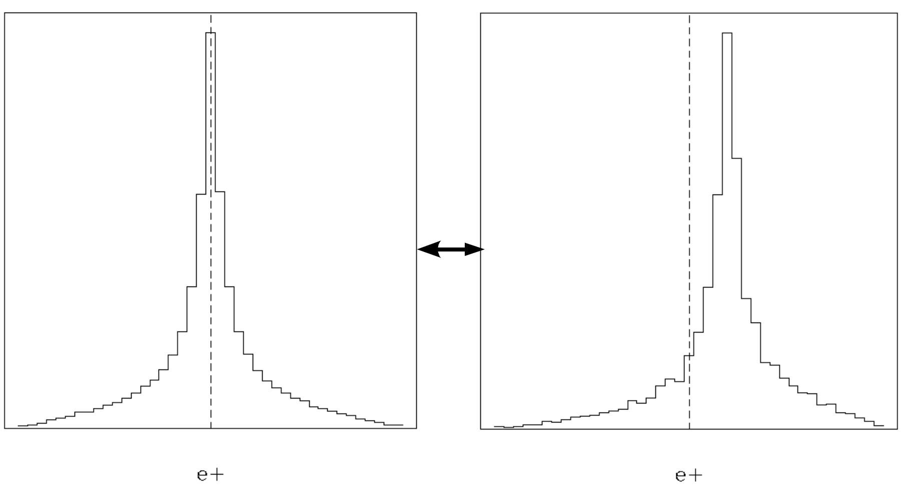


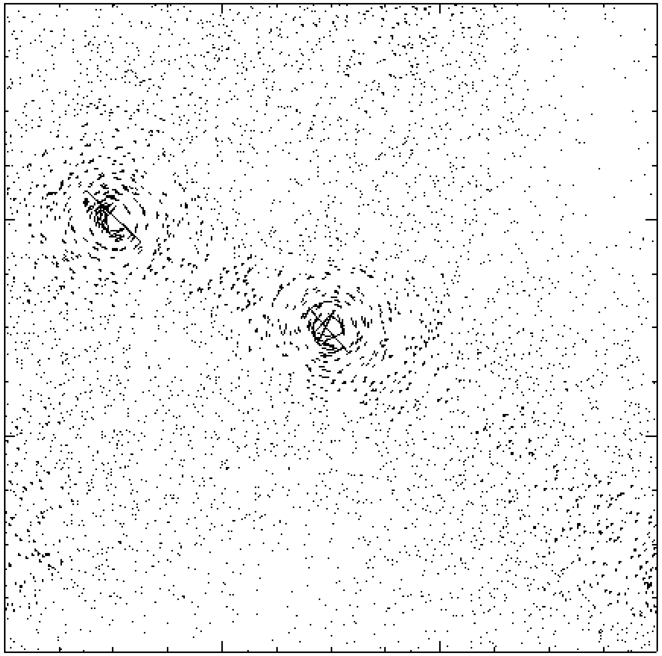
B1938+666 (APOD, March 31, 1998)
(lens is a galaxy, not a cluster)

Weak Lensing







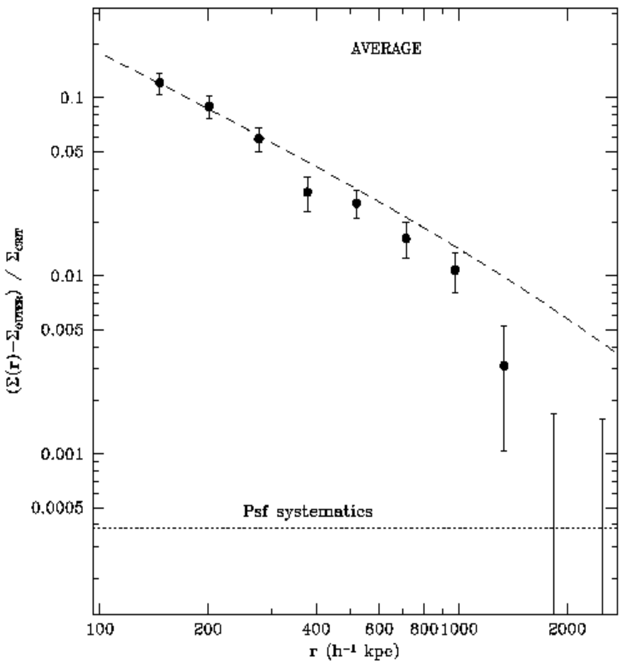


simulated noiseless
ellipticity field

Cluster Masses from Lensing

There is compelling evidence for dark matter from both strong lensing (near cluster center) and weak lensing (cluster outskirts).

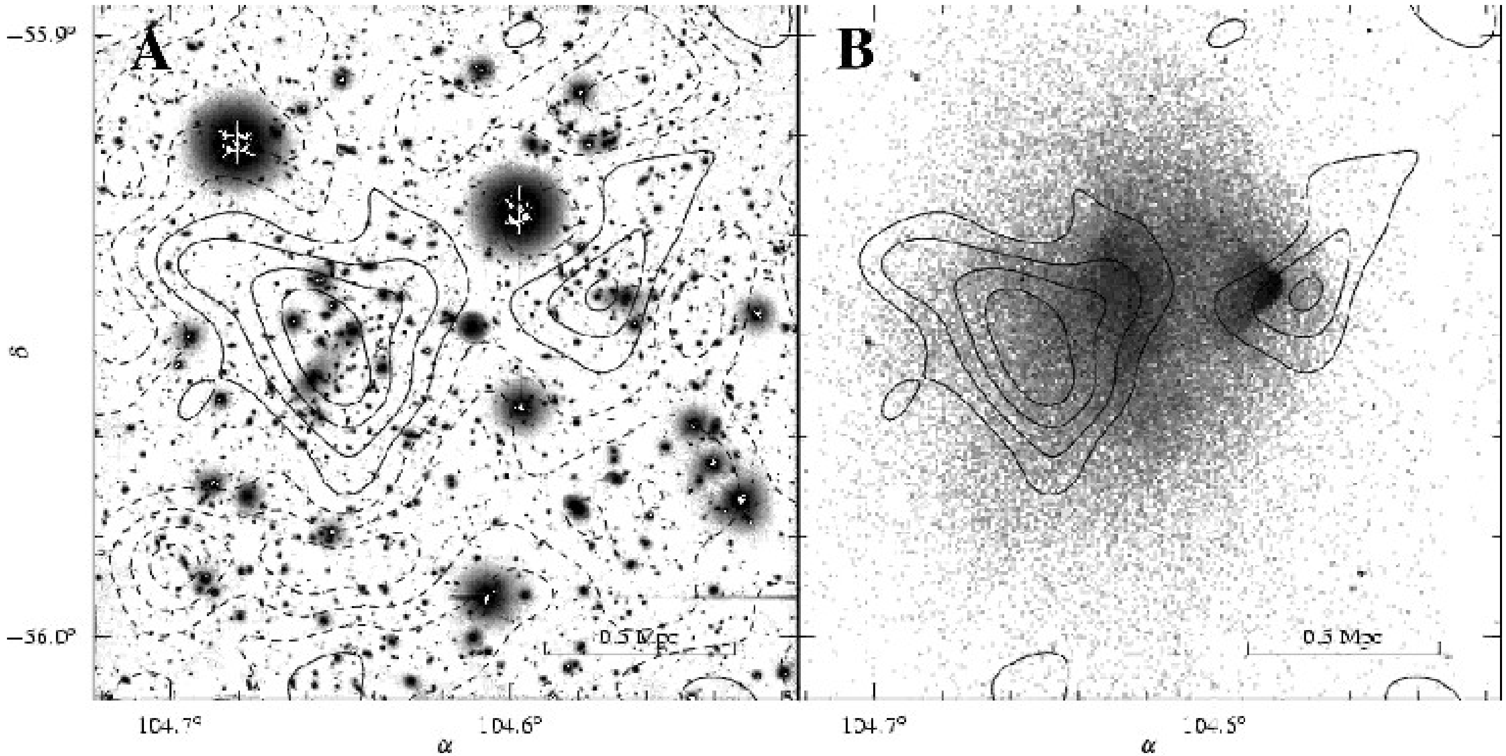
Strong and weak lensing operate in very different regimes of density, acceleration, and radius, making it unlikely that the discrepancy between total mass and luminous mass could be an artifact of some misunderstanding of cluster physics or of modified gravity.



Weak lensing mass profile

Interacting Clusters: Proof of Dark Matter

optical (contours=DM) X-ray

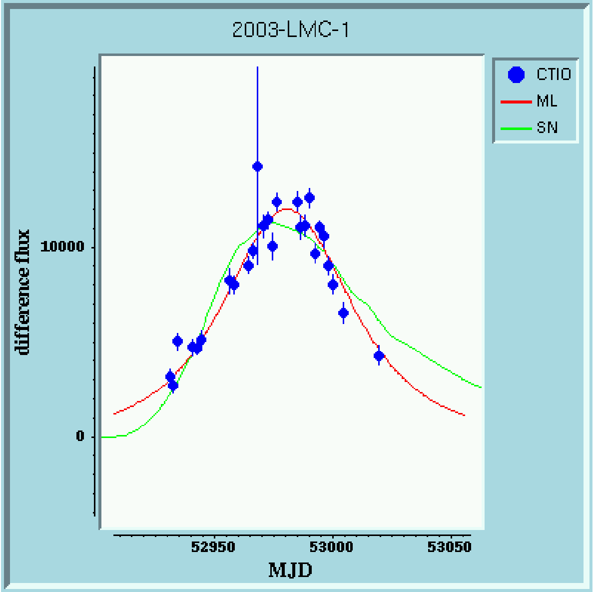


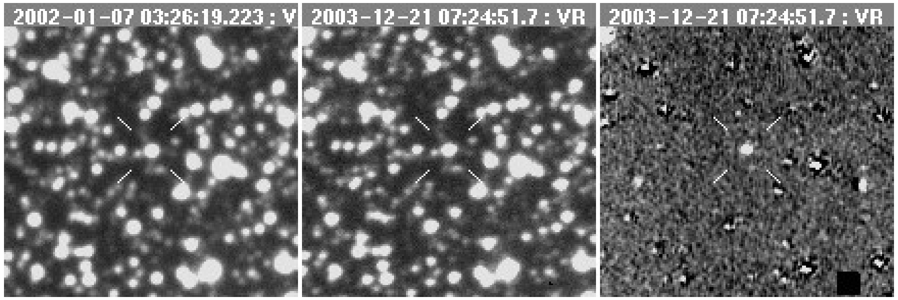
galaxies: collisionless
dark matter: collisionless
gas: collisional

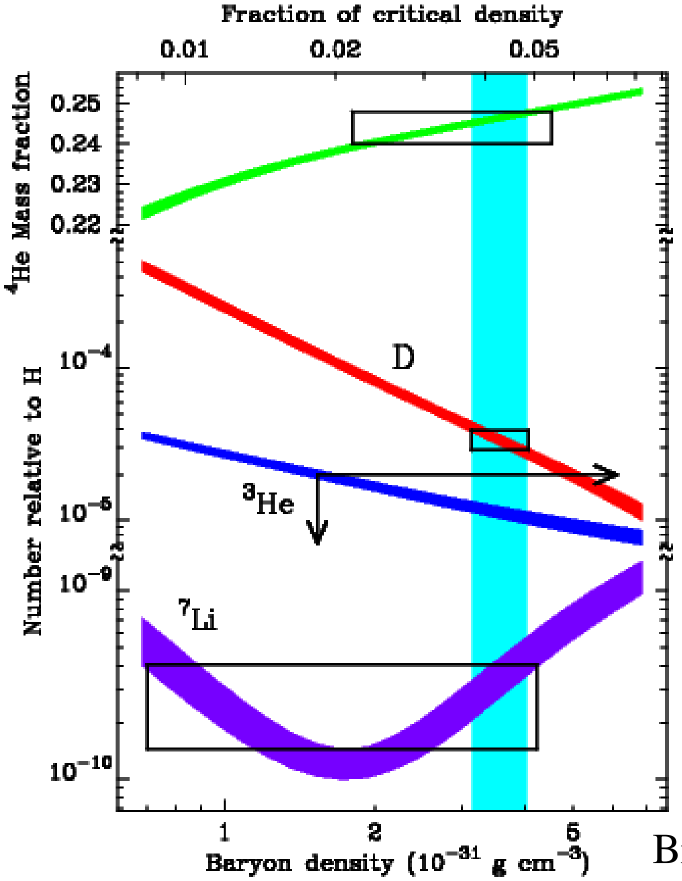
What Dark Matter Is Not

- •dead stars, black holes: ruled out by microlensing
- •planets, junk mail: ruled out by Big Bang nucleosynthesis
- •charged: electromagnetic interactions would be easy to detect

microlensing event





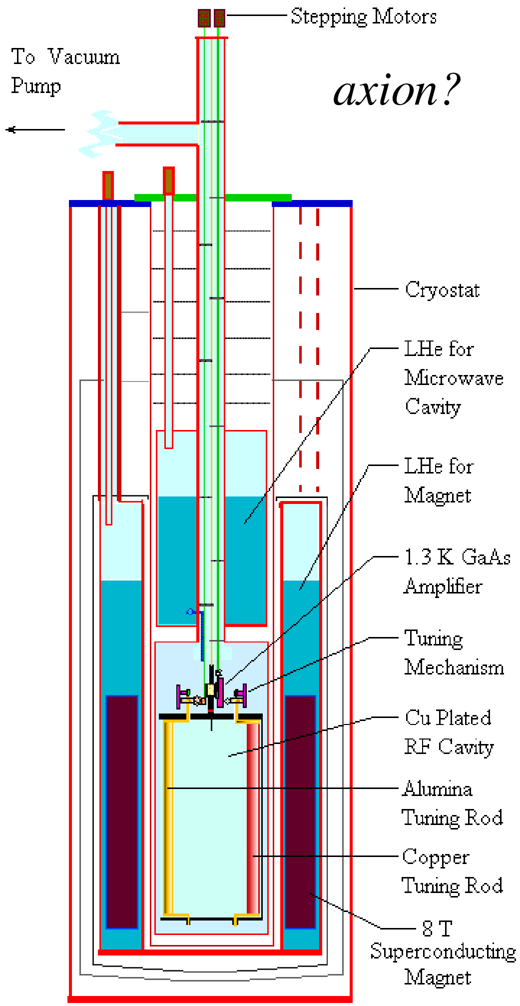


Big Bang nucleosynthesis

What Dark Matter Is

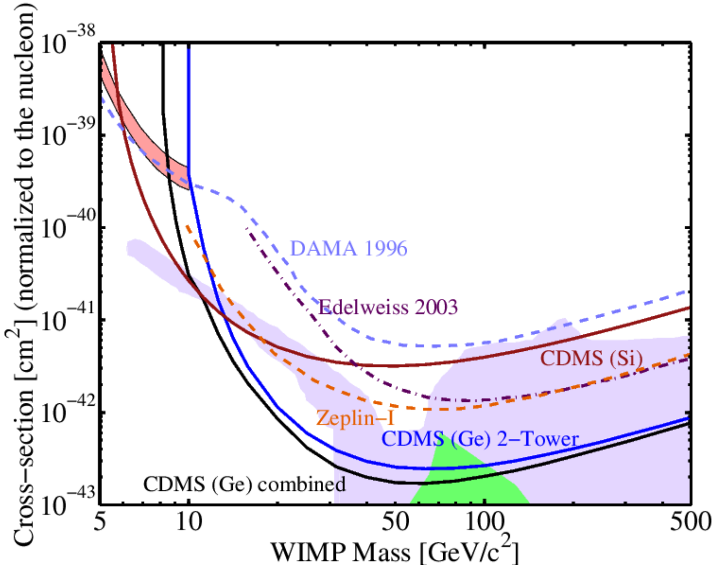
•stable over a Hubble time
•"cold" (nonrelativistic): can collapse to form small structures
•interacts only weakly, both with ordinary matter (we would have found it already) and with itself (would form puffy structures)

axion?



Livermore axion search

WIMP? (weakly interacting massive particle)



CDMS

indirect searches

Veritas

+accelerator experiments...