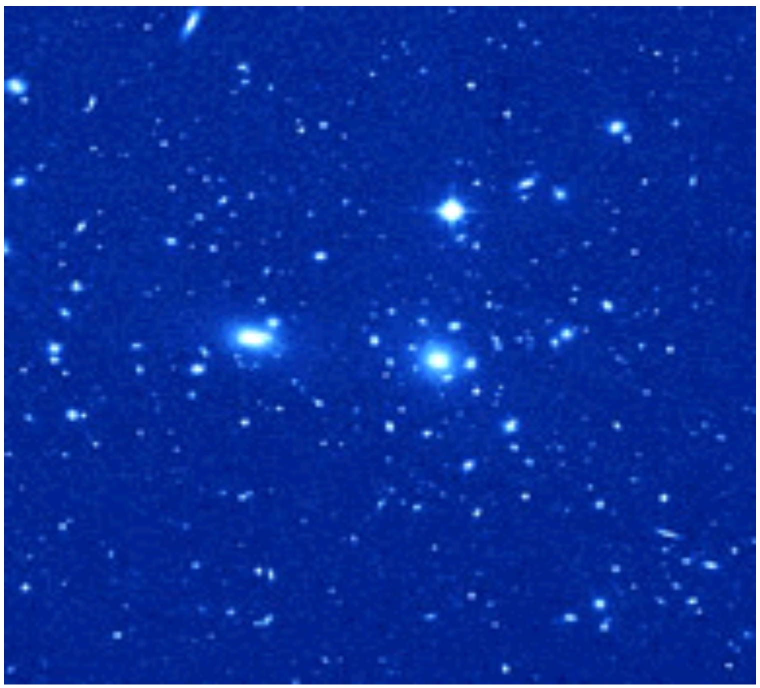
The Dark Matter

The Non-Baryonic Dark Matter

Discovered by Zwicky in 1937, by comparing the visible mass in galaxies in the Coma cluster (estimated $M_* \sim 10^{13}$ $M_\odot$), with the virial mass estimates ($M_{vir} \sim 5 \times 10^{14}$ $M_\odot$)



Confirmed by the modern measurements of galaxy dynamics, X-ray gas analysis, and masses derived from gravitational lensing

Virial Masses of Clusters:

Virial Theorem for a test particle (a galaxy, or a proton), moving in a cluster potential well:

$$E_k = E_p / 2 \quad \rightarrow \quad m_g \sigma^2 / 2 = G\, m_g\, M_{cl} / (2\, R_{cl})$$

where σ is the velocity dispersion

Thus the cluster mass is: $M_{cl} = \sigma^2 R_{cl} / G$

Typical values for clusters:

$\sigma \sim 500 - 1500$ km/s

$R_{cl} \sim 3 - 5$ Mpc

Thus, typical cluster masses are $\boldsymbol{M_{cl} \sim 10^{14} - 10^{15} M_\odot}$

The typical cluster luminosities (~ 100 - 1000 galaxies) are $L_{cl} \sim 10^{12} L_\odot$, and thus $(M/L) \sim 200 - 500$ in solar units

→ ***Lots of dark matter!***

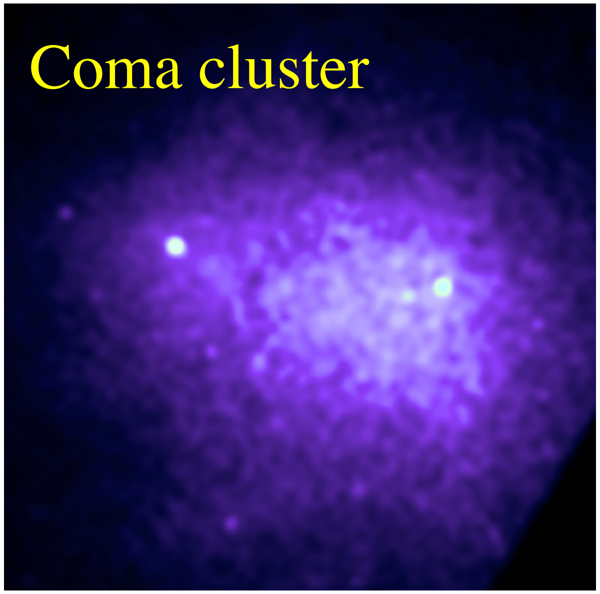
Masses of Clusters From X-ray Gas

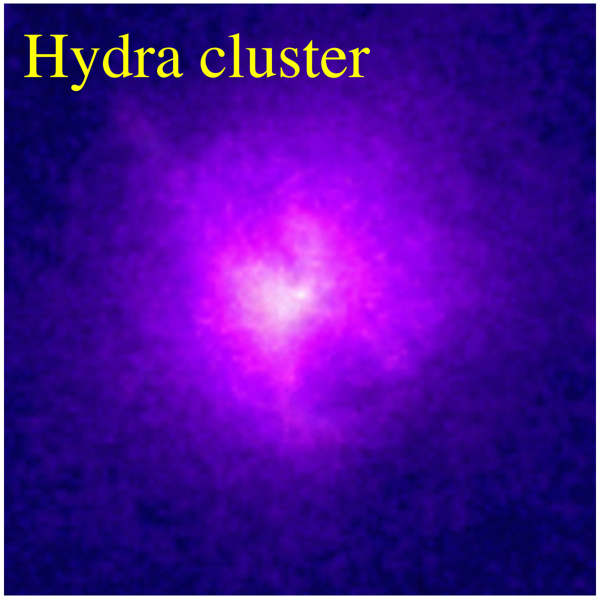
- Note that for a proton moving in the cluster potential well with a $\sigma \sim 10^3$ km/s, $E_k = m_p \sigma^2 / 2 = 5\,k\,T / 2 \sim$ few keV, and $T \sim$ few 10^7 °K → **X-ray gas**
- Hydrostatic equilibrium requires:

$$M(r) = - kT/\mu m_H G\,(d \ln \rho / d \ln r)\, r$$

- If the cluster is ~ spherically symmetric this can be derived from X-ray intensity and spectral observations
- Typical cluster mass components from X-rays:

  Total mass: 10^{14} to 10^{15} $M_\odot$
  Luminous mass: ~5%
  Gaseous mass: ~ 10%
  Dark matter: ~85%





Baryonic Mass Fraction in Clusters

- We can measure the baryonic fraction of galaxy cluster mass

$$f_B = f_{gas} + f_{gal} + f_{db} \qquad\qquad f_B > f_{gas} + f_{gal}$$

- Assume that this is universal, i.e., that clusters provide a fair sample of the Universe. Then taking the value of Ω_B from nucleosynthesis and CMB, we can estimate the total matter density parameter Ω_M :

$$f_U = \frac{\Omega_B}{\Omega_M} \qquad\qquad \text{if } f_U = f_B \text{ then } \Omega_M = \frac{\Omega_B}{f_B}$$

- Gas constitutes ~20% of the total mass in the most massive clusters. This gives a lower limit on f_B, and hard, upper limit on Ω_M:

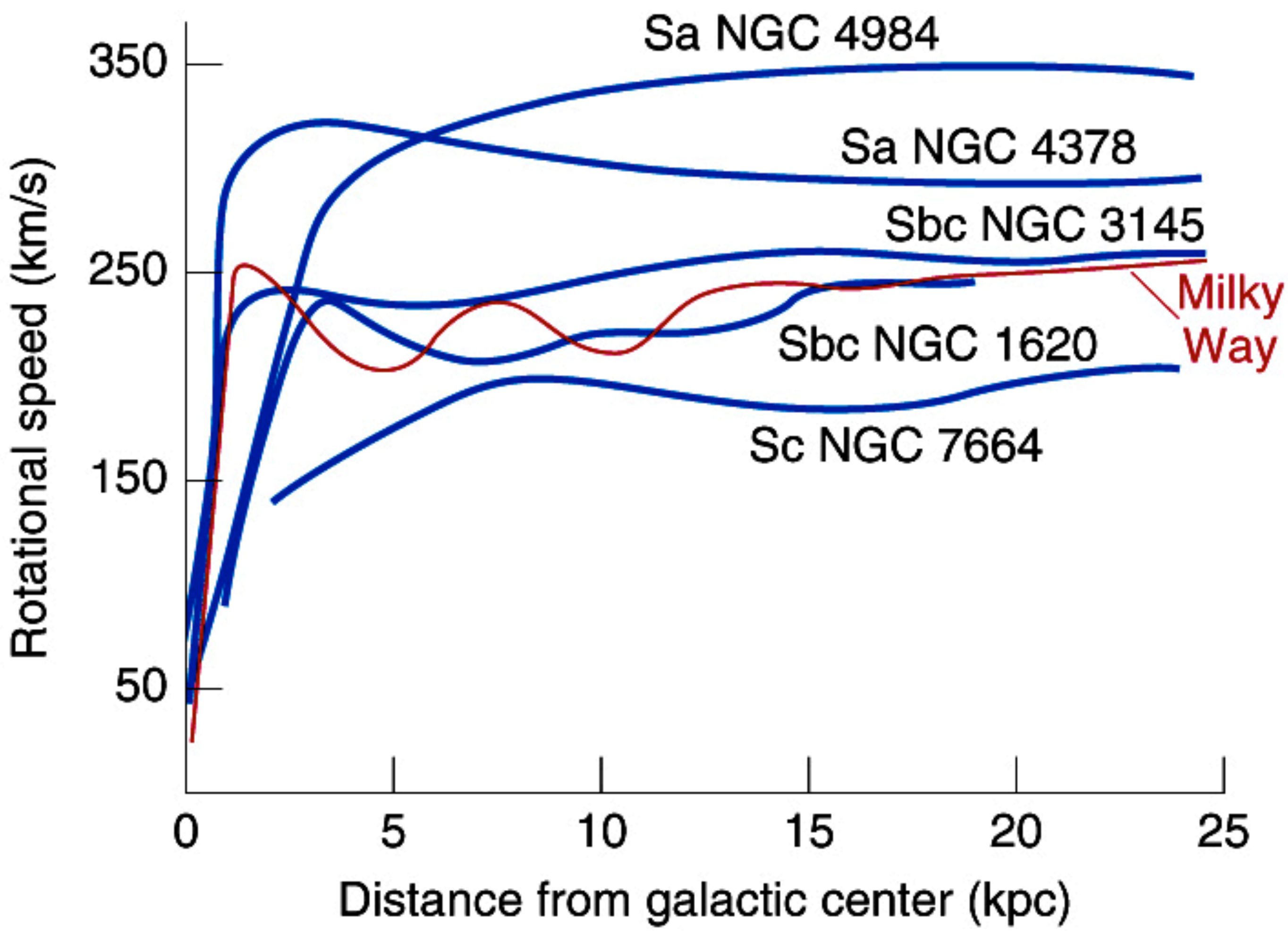
$$\text{because } f_{gas} < f_B \quad \Omega_M < \frac{\Omega_B}{f_{gas}} \qquad\qquad \Omega_M < 0.36 \pm 0.01$$

- Combined with measurements of the galaxy contribution to the cluster mass we get a best estimate of $\Omega_M \approx 0.25$

… in an excellent agreement with other methods!

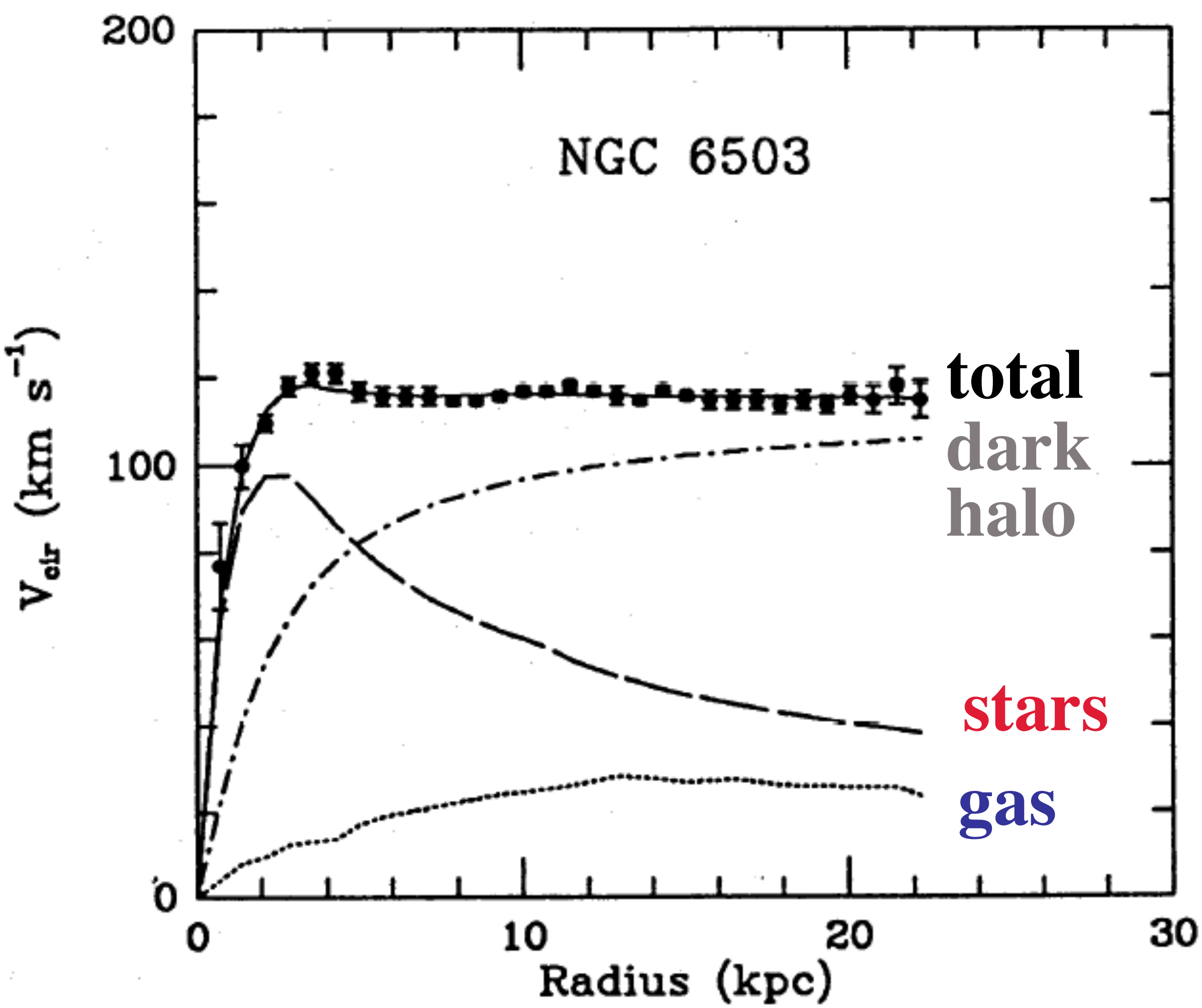
Flat Rotation Curves of Disk Galaxies:

The Other Key Piece of Evidence for the Existence of Dark Matter



Noted early by Jan Oort and others, but really appreciated since 1970's, due to the work by Rubin, Ford, and others

Disk Galaxy Rotation Curves: Mass Component Contributions



Dark Matter dominates at large radii

It cannot be concentrated in the disk, as it would make the velocity dispersion of stars too high

Interpreting the Rotation Curve

Motions of the stars and gas in the disk of a spiral galaxy are approximately circular (V_R and $V_Z << V_R$).

Define the circular velocity at radius r in the galaxy as $V(r)$. Acceleration of the star moving in a circular orbit must be balanced by gravitational force:

$$\frac{V^2(r)}{r} = -F_r(r)$$

To calculate $F_r(r)$, must in principle sum up gravitational force from bulge, disk and halo. If the mass enclosed within radius r is $M(r)$, gravitational force is:

$$F_r = -\frac{GM(r)}{r^2}$$

Thus, from observed $V(r)$, we can infer $M(r)$

Interpreting the Observed Rotation Curves

Simple model accounting for the luminous mass only predicts the rotation curve of the Milky Way ought to look like:

$$v \approx \sqrt{\frac{GM_{galaxy}}{R}} = 210 \left(\frac{M_{galaxy}}{8 \times 10^{10} M_{sun}} \right)^{1/2} \left(\frac{R}{8\ \mathrm{kpc}} \right)^{-1/2} \mathrm{km\ s^{-1}}$$

This number is about right - Sun's rotation velocity is around 200 km s^{-1}.

Scaling of velocity with $R^{-1/2}$ is not right - actual rotation velocity is roughly constant with radius.

This implies:

- Gravity of visible stars and gas largely explains the rotation velocity of the Sun about the Galactic center
- *Flat rotation curve requires extra matter at larger radii, in addition to the visible components* ➔ **Dark Matter**

Mass Distribution and Rotation Curve

If the density $\rho = const.$, then: $$M(r) = \frac{4}{3}\pi r^3 \rho$$

Implied rotation curve rises linearly with radius; this is about right for central regions of spirals, but fails at the larger radii where $V(r) \sim const.$

$$V(r) = \sqrt{\frac{4\pi G\rho}{3}}\, r$$

Consider instead a power law density profile: $$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\alpha}$$

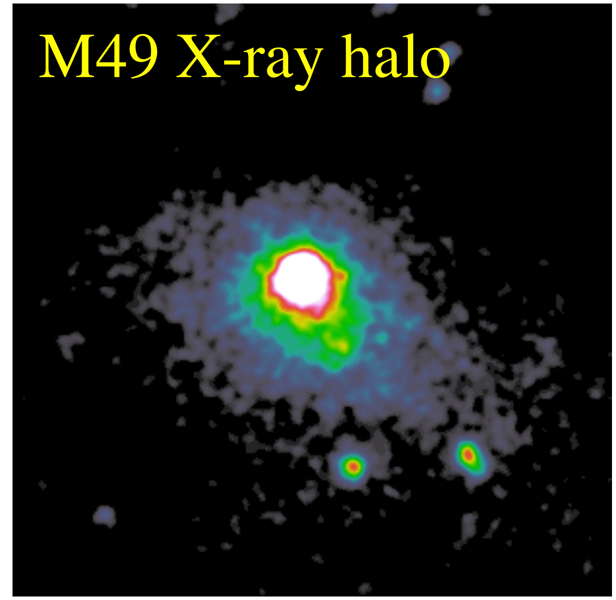
with $\alpha < 3$, the rotation curve is:

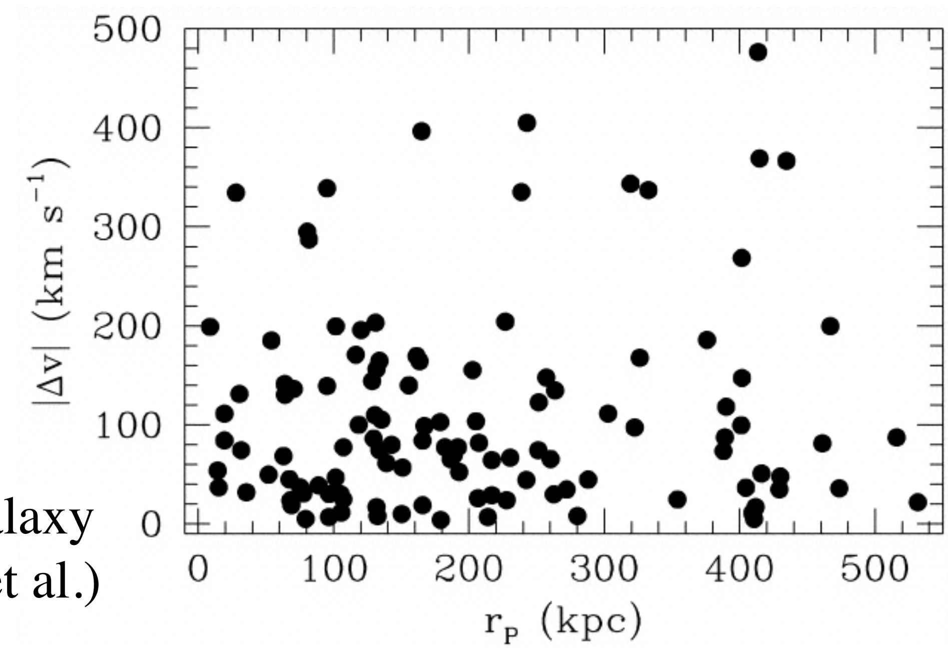
$$V(r) = \sqrt{\frac{4\pi G\rho_0 r_0^{\alpha}}{3-\alpha}}\, r^{1-\alpha/2}$$

$V(r) = const.$ then implies $\rho(r) \sim r^{-2}$. This profile is called a *singular isothermal sphere*. Note that the enclosed mass increases linearly with radius, $M(r) \sim r$! (Where does it stop?)

Dark Matter in Elliptical Galaxies

- Similar to spirals, but using X-ray gas, planetary nebulae, globular clusters, or companion galaxies as test particles to map the velocity field at large radii
- X-ray gas gives the strongest evidence for DM in ellipticals, but mass density in the visible parts is dominated by baryons
- Most of the motions are random, rather than circular, so one can speak of a flat velocity dispersion curve



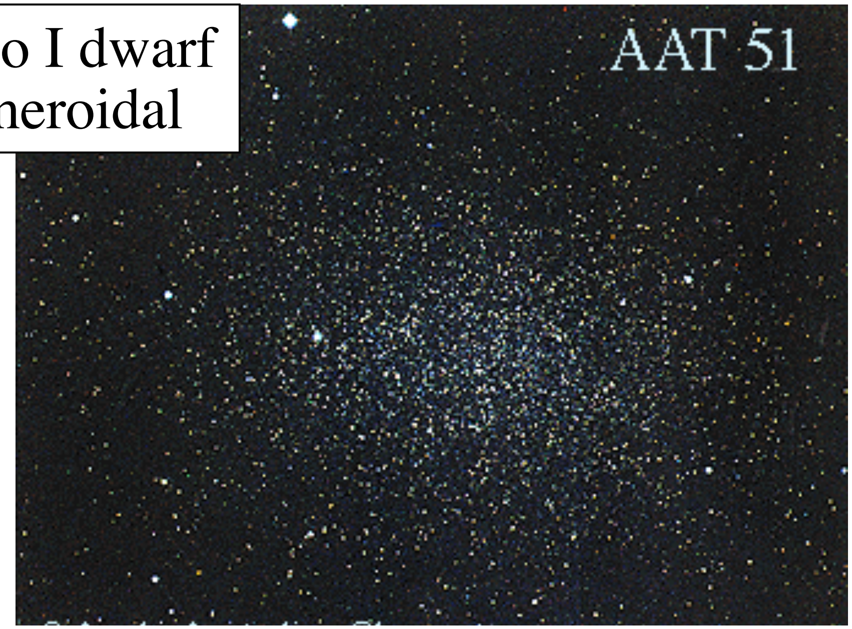


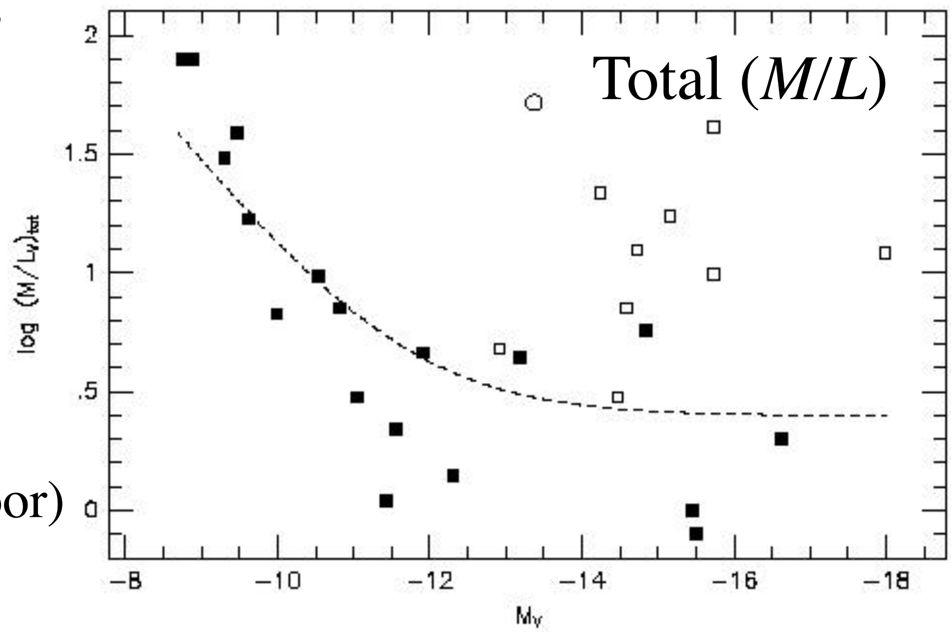
Relative velocities of dwarf galaxy companions of E's (Zaritsky et al.)

Dark Matter in Dwarf Galaxies

- Kinematics of dwarf galaxies suggests copious amounts of DM, especially in the lowest luminosity systems (the smallest systems are the darkest), with (*M*/*L*) ratios reaching ~ 100!
- One theory is that baryons have been expelled by galactic winds in their early star forming stages, while the DM remained

Leo I dwarf spheroidal

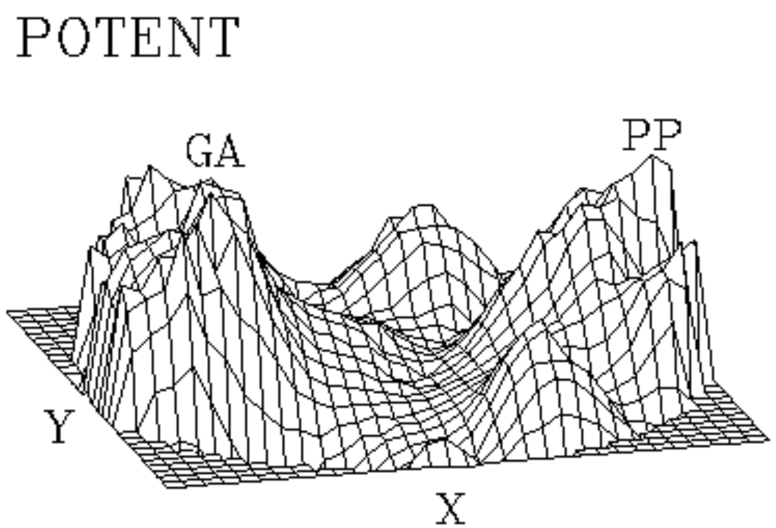




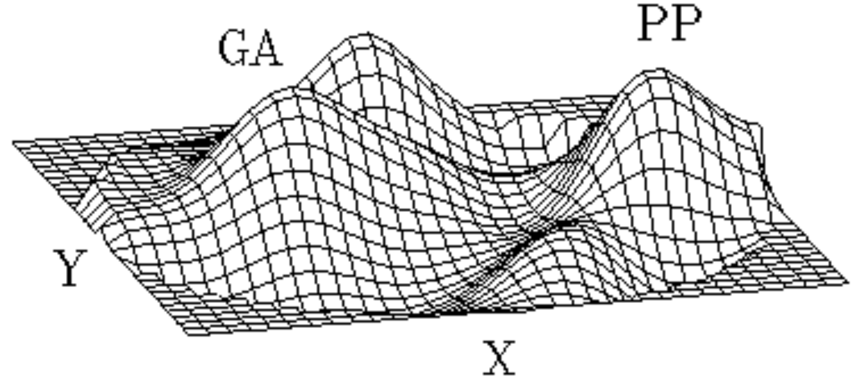
Filled squares = dSph (gas poor)
Open squares= dIrr (gas rich)

Mass Density From Peculiar Velocities

- Assume that the measured galaxy peculiar velocities are generated from nearby large mass concentrations; derive the implied gravitational potential, which implies the mass distribution
- Compare the observed velocity field to a density field (derived from a galaxy redshift survey) and derive the matter density distribution
- Most results favor $\Omega_m < 0.3$



IRAS



Density contours from POTENT (peculiar velocity analysis) and IRAS redshift survey

Non-Baryonic DM Candidates

- **Massive neutrinos** ← The *only* DM constituent actually known to exist!
  - Known to exist and to have mass, but how much?
- **Weakly Interacting Massive Particles (WIMPs)**
  - Not known to exist, but possible
  - A generic category, e.g., the neutralino = the least massive SUSY particle; also inlcude gravitinos, photinos, and higgsino
  - Thermal relics from the Big Bang
  - Possible masses > 10 GeV
  - WIMPzillas: $10^{10} \times$ mass of WIMPS, would have been created just after the Big Bang, and might explain ultra-high-energy cosmic rays
- **Axions**
  - Predicted in some versions of quantum chromodynamics
  - Originate in non-thermal processes
  - Could interact electromagnetically
  - Possible masses 10^{-12} eV to 1 MeV
- **Many (many!) other speculative possibilities …**

Some Proposed DM Constituents:

(from Trimble 1987)

Note the range of masses ~ 10^{80} !

Table 3 Summary of nonbaryonic dark matter candidates[a]

Candidate/particle	Approximate mass	Predicted by	Astrophysical effects
$G(R)$	—	Non-Newtonian gravitation	Mimics DM on large scales
Λ (cosmological constant)	—	General relativity	Provides $\Omega = 1$ without DM
Axion, majoron, goldstone boson	10^{-5} eV	QCD; PQ symmetry breaking	Cold DM
Ordinary neutrino	10–100 eV	GUTs	Hot DM
Light higgsino, photino, gravitino, axino, sneutrino[b]	10–100 eV	SUSY/SUGR	Hot DM
Para-photon	20–400 eV	Modified QED	Hot/warm DM
Right-handed neutrino	500 eV	Superweak interaction	Warm DM
Gravitino, etc.[b]	500 eV	SUSY/SUGR	Warm DM
Photino, gravitino, axino, mirror particle, simpson neutrino[b]	keV	SUSY/SUGR	Warm/cold DM
Photino, sneutrino, higgsino, gluino, heavy neutrino[b]	MeV	SUSY/SUGR	Cold DM
Shadow matter	MeV	SUSY/SUGR	Hot/cold (like baryons)
Preon	20–200 TeV	Composite models	Cold DM
Monopoles	10^{16} GeV	GUTs	Cold DM
Pyrgon, maximon, perry pole, newtorites, Schwarzschild	10^{19} GeV	Higher-dimension theories	Cold DM
Supersymmetric strings	10^{19} GeV	SUSY/SUGR	Cold DM
Quark nuggets, nuclearites	10^{15} g	QCD, GUTs	Cold DM
Primordial black holes	10^{15-30} g	General relativity	Cold DM
Cosmic strings, domain walls	$10^{8-10}\ M_\odot$	GUTs	Promote galaxy formation, but cannot contribute much to Ω

[a] Abbreviations: DM, dark matter; QCD, quantum chromodynamics; PQ, Peccei & Quinn; GUTs, grand unified theories; SUSY, supersymmetric theories; SUGR, supergravity; QED, quantum electrodynamics.

[b] Of these various supersymmetric particles predicted by assorted versions of supersymmetric theories and supergravity, only one, the lightest, can be stable and contribute to Ω, but the theories do not at present tell us which one it will be or the mass to be expected.

The Types of Non-Baryonic Dark Matter

- DM dominates the density field and thus governs the structure formation in the universe
- **Hot (HDM):** matter is relativistic, so low-mass particles such as neutrinos
  - Their streaming erases the small-scale density fluctuations, so big structures form first, then later fragment. This is "top-down" structure formation
- **Cold (CDM):** matter moves more slowly; includes exotic as yet unknown particles such as axions, WIMPs, etc.
  - Density fluctuations at all scales survive. Small fluctuations collapse first, then larger ones (pulling in the littler ones along the way). This is "bottom-up" structure formation and this is the best match to what we observe
- There is probably a little bit of HDM and a lot of CDM

Laboratory Detection of Dark Matter Particles?

Now pursued by many groups. Usually involves inelastic scattering of a DM particle in an ultracold crystal, and measurement of the deposited kinetic energy.

No convincing results yet.

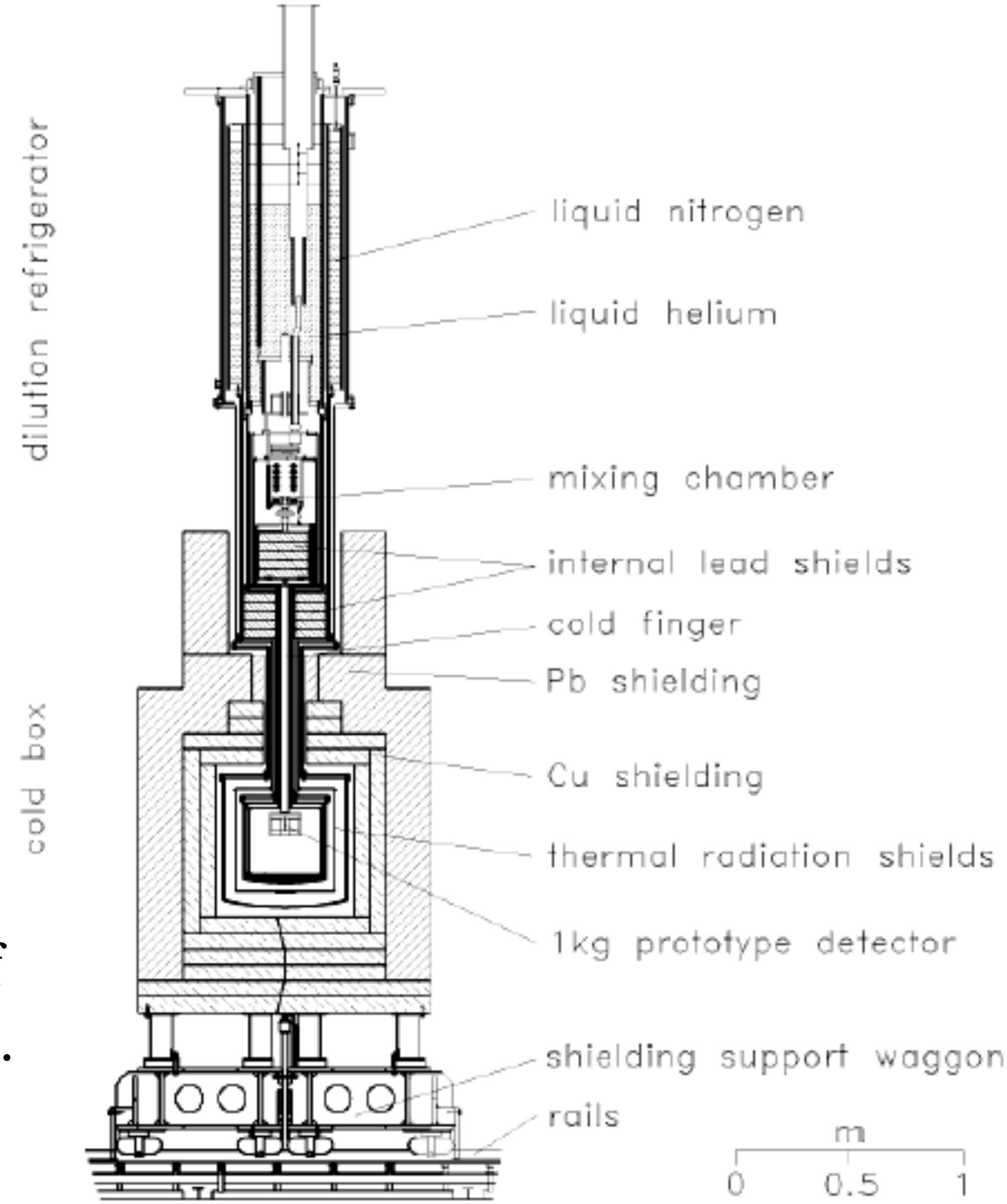


Figure 5. Schematic view of the experimental setup of CRESST, located in the Gran Sasso underground laboratory near Rome (Italy), as an example for a cryogenic dark-matter experiment.

Is There Really a Dark Matter …
… Or is Newtonian Gravity Wrong?

- Milgrom (1983) proposed a modification to Newtonian gravity, Modified Newtonian Dynamics (MOND), in which

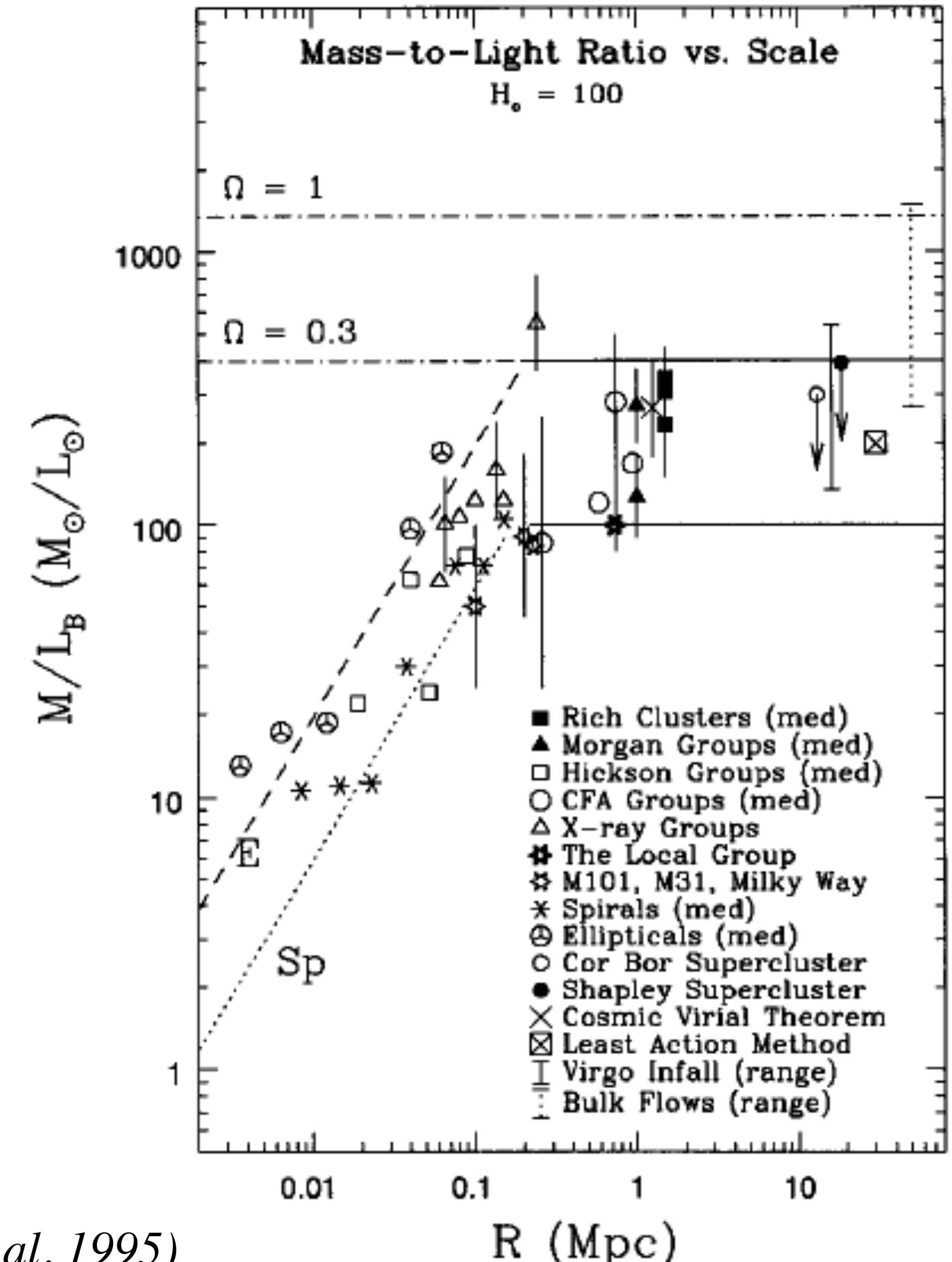
$$F = m\,\mu\,(a/a_0)\,a$$

where $\mu\,(x >> 1) = 1$ (normal gravity), and $\mu\,(x << 1) \sim x$, so MOND would only kick in at low accelerations (what we generally see in galaxy dynamics) $a_0 \sim 10^{-8}$ cm/s^2

- For $a << a_0$, $a = (a_0\, g_N)^{1/2}$ there is more acceleration than expected from Newtonian gravity at slow acceleration scales
- MOND *may* explain flat rotation curves and the Tully-Fisher relation, but can't explain extra mass in the cores of big clusters (acceleration scales too big); probably not dwarf galaxies
- It is an *ad hoc* model - no clear physical motivation other than to get rid of the DM - and no other testable predictions
- It could be made consistent with GR, but it is awkward…

Dark Matter Distribution

Dynamical measurements indicate that the (*M*/*L*) ratio increases with the scale, from galaxies to clusters, implying that the DM is distributed more diffusely than light, but then it saturates with a value corresponding to $\Omega_{0,m} \sim 0.25$



(Bahcall et al. 1995)


Next:
Gravitational Lensing