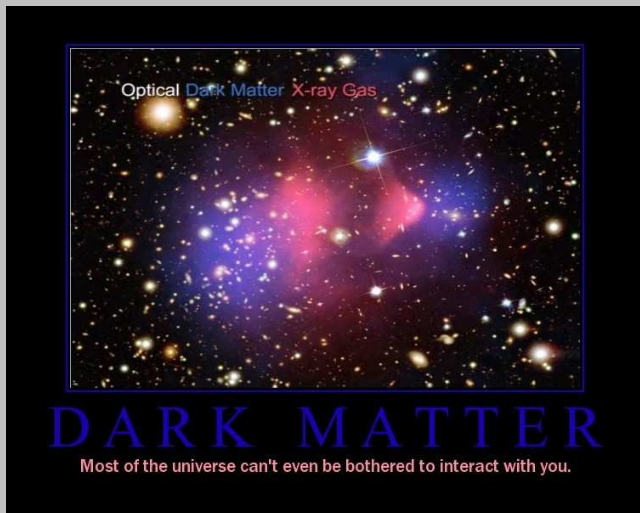
Why the new "Bullet Cluster" / Dark Matter results are important



Rob Knop
Astronomy Journal Club, 2006/08/31

Outline

I. Evidence for dark matter

II. Evidence for *non-baryonic* dark matter

III. Alternatives to dark matter (MOND)

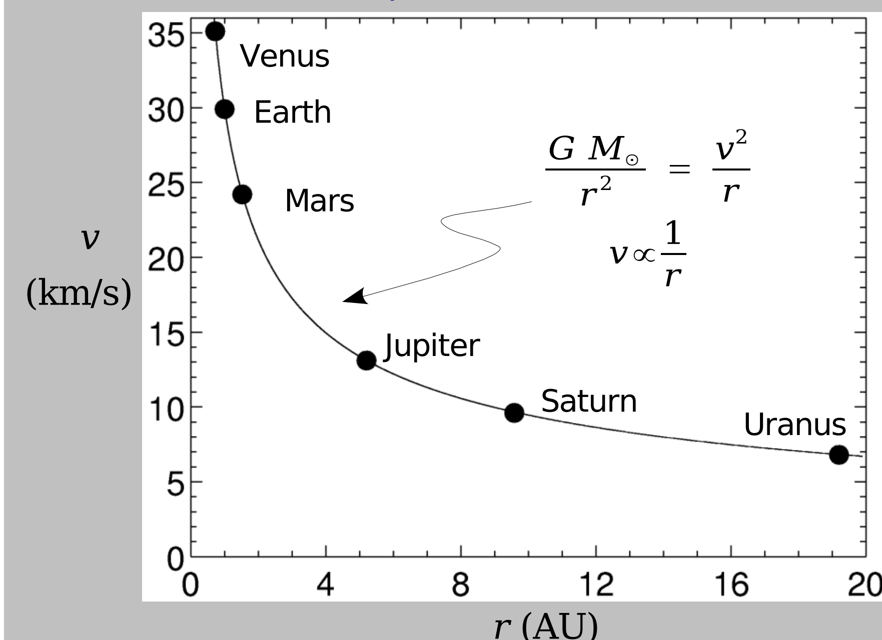
IV. Briefly about galaxy clusters...

V. The new results: ∃ Dark Matter

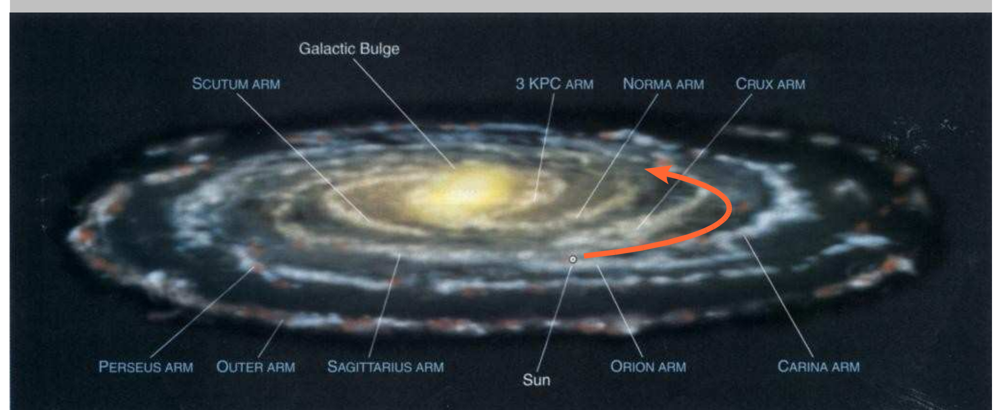
Paper

Clowe, *et al.*, 2006, "A direct empirical proof of the existence of dark matter," accepted to ApJL, astro-ph/0608407

Rotation curve for Keplerian Orbits (all mass @ center)

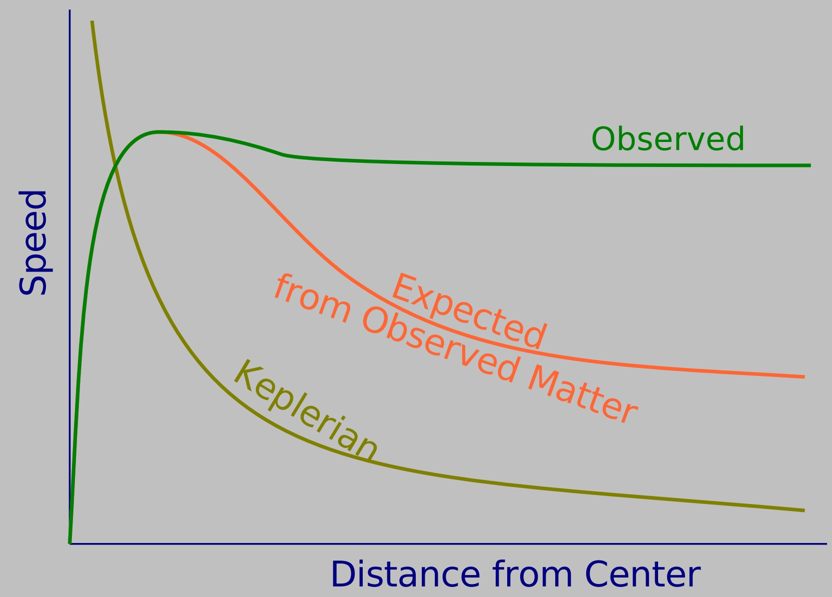


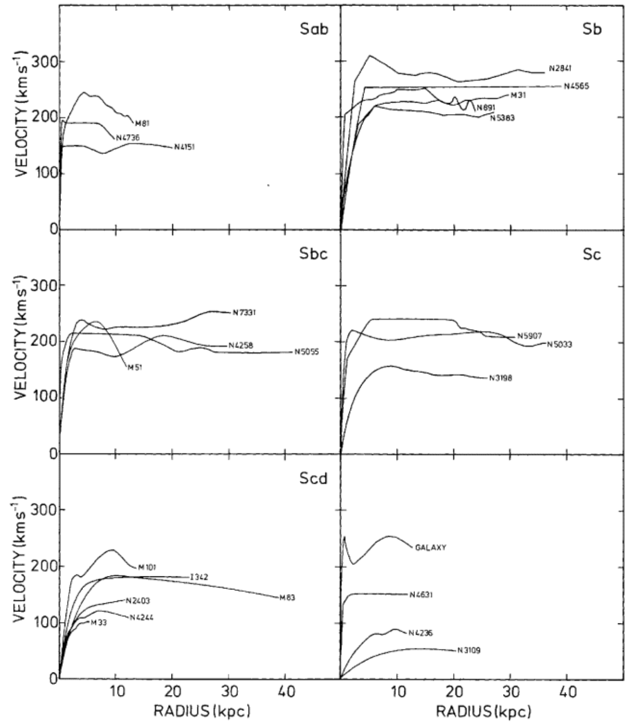
Spiral Galaxy Rotation Curves
(Can be measured from Doppler shifts)



(Artist's Conception of the Milky Way, from, I think, Hester et al., "21st Century Astronomy")

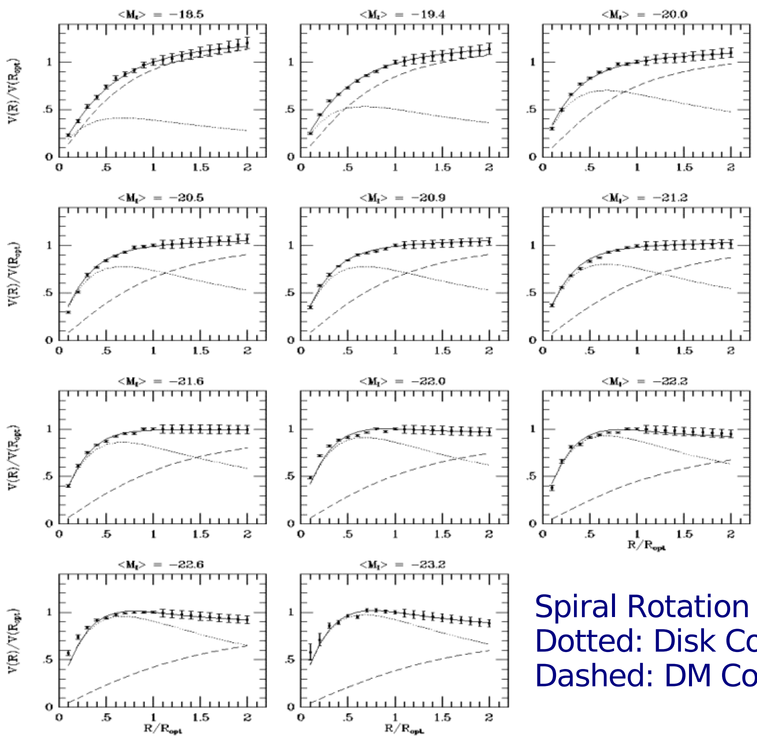
Galaxy Rotation Curve – Expected and Observed





Rotation curves of several spiral galaxies.

Faber & Gallagher, 1979, after Bosma, A., 1978, PhD Thesis



Salucci & Persic, 1997, astro-ph/9703027

Spiral Rotation Curves
Dotted: Disk Contrib.
Dashed: DM Contrib.

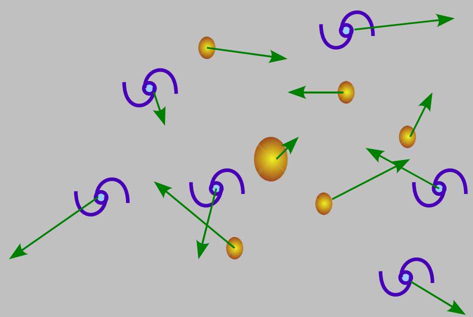
"After reviewing all the evidence, it is our opinion that the case for invisible mass in the Universe is very strong and getting stronger."

Faber & Gallagher, 1979, ARA&A, 17, 135

Even before that...

Zwicky, F., 1933, *Helvetica Physica Acta,* 6, 110

Clusters of galaxies should be flying apart given their velocity dispersions; 10-100 times the mass is *missing* (i.e. not in the Galaxies)

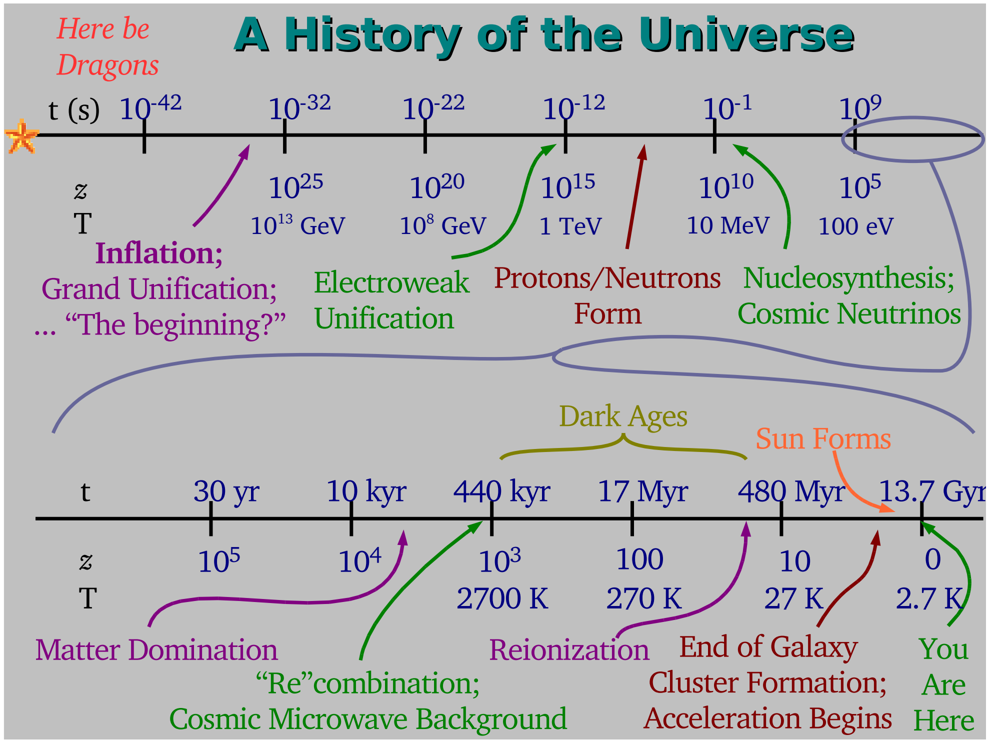


(Of course, Zwicky was a strong personality and everybody hated him, so nobody listened.)

OK, so dark matter seems to exist. From looking at the dynamics of galaxies and clusters, we need $\Omega_M \simeq 0.2$ (the mass of the Universe is about 20% of the critical density).

...but what is it?

A History of the Universe



Big-Bang Nucleosynthesis

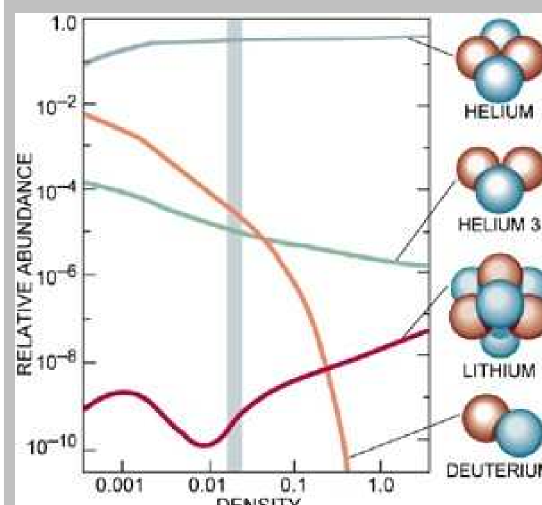


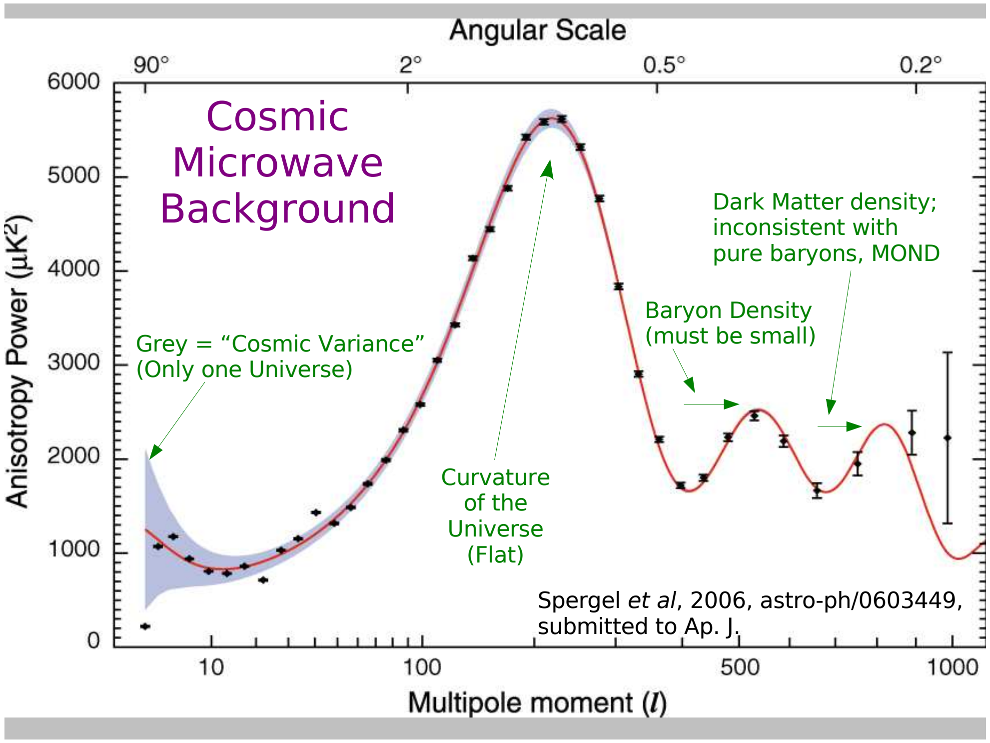
Image stolen from Martin White's website at UC Berkeley

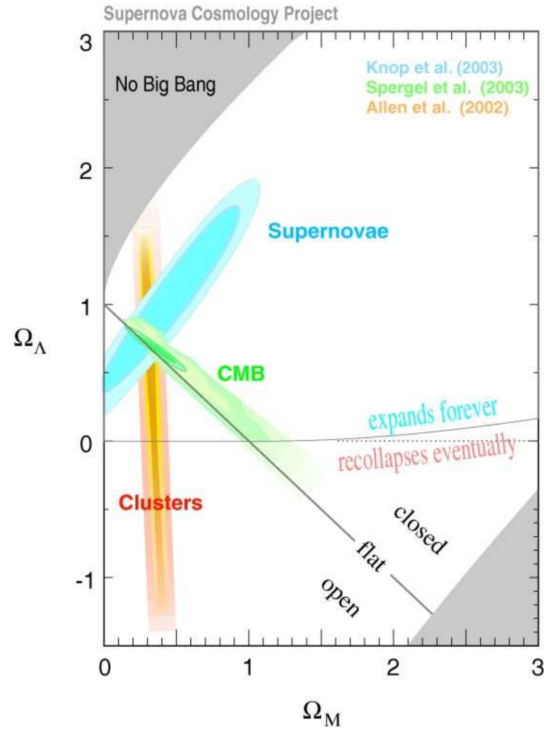
Burles, Nollett, & Turner, 2001, ApJL, 552, 1

$\mathbf{\Omega_b = 0.040 \pm 0.004}$

(for H_0 = 71 km s^{-1} Mpc^{-1})

The baryonic mass in the Universe is something like a *fifth* of the mass we need for galaxy and cluster dynamics....!!!!





And, of course, there's always this old chestnut... (which doesn't comment on Ω_b)

Conclusion so far:

$$\Omega_M = 0.25$$
$$\Omega_b = 0.04$$

(with 10%ish uncertainty)

So let's be curmudgeons...

You cosmologists and your dark matter! That's a bloody *tooth fairy*! You're making all of this up! Cosmology is the *worst* sort of astronomy!

You sound just like the late 19th-century physicists with their luminiferous aether! You've got this invisible, pervasive substance that's spread thinly through galaxies but which we can't see!

Harumph!

Oops, gotta go, have a dinner date with Arp...

Can we get by without dark matter?

Milgrom, 1983, *ApJ*, 270, 365 : “A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis”

(Plus two more bloody papers in the same issue... way to pad the publication and citation counts, dude!)

Basic idea : $1/r^2$ and F=ma and all that is well tested in the lab and in the Solar System, but galaxies represent huge extrapolations in scale from these regimes.

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

a_0 = “acceleration constant”

$\mu(x) \to 1$ for $x \gg 1$ “old” law for “high” accel.

$\mu(x) \to x$ for $x \ll 1$

MOND

Sanders & McGaugh, 2002, *ARA&A*, 40, 263

It may be argued that [MOND] is a speculative topic for review in this series. In our opinion, the subject of dark matter (Trimble 1987) is, in the absence of its direct detection, no less speculative, particularly considering that the standard model of particle physics does not predict the existence of candidate dark matter particles with the necessary properties.

$$m_g\, \mu(a/a_0)\, a \;=\; F$$

$$\mu(x)\to 1 \quad \text{for } x \gg 1$$
$$\mu(x)\to x \quad \text{for } x \ll 1$$

$$a_0 \;\approx\; 10^{-8}\,\mathrm{cm/s^2} \;\approx\; \frac{c\,H_0}{6}$$

MOND predicts many things as well as does dark matter

Merrifield, 2004, "Dark Matter on Galactic Scales (or the Lack Thereof)", astro-ph/0412059

Issue : MOND is ad-hoc empirical

Bekenstein, 2004, PhRvD, 70, 8, 083509

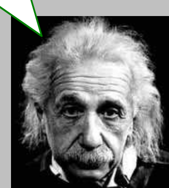
...claims to have a relativistic field theory that reduces to MOND in the appropriate limit....

(I haven't taken the time to try to understand this.)

Will no one rid me of this meddlesome MOND?!?

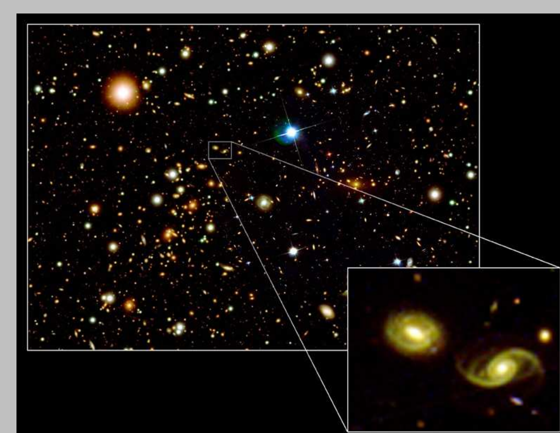
King Henry II

Don't look at me... I'm done mucking about with Sir Isaac's gravity!



Galaxy Clusters

- 10^2 – 10^3 galaxies in 1-10 Mpc diameter
- 10-15% of the *baryonic* mass is stellar (i.e. in galaxies)
- most of the baryonic mass is in X-ray emitting intracluster plasma
- Using standard Newtonian gravity, the gas accounts for 5-15% of the total mass of the cluster (Vikhlinin *et al.*, 2006, ApJ, 445, 578)



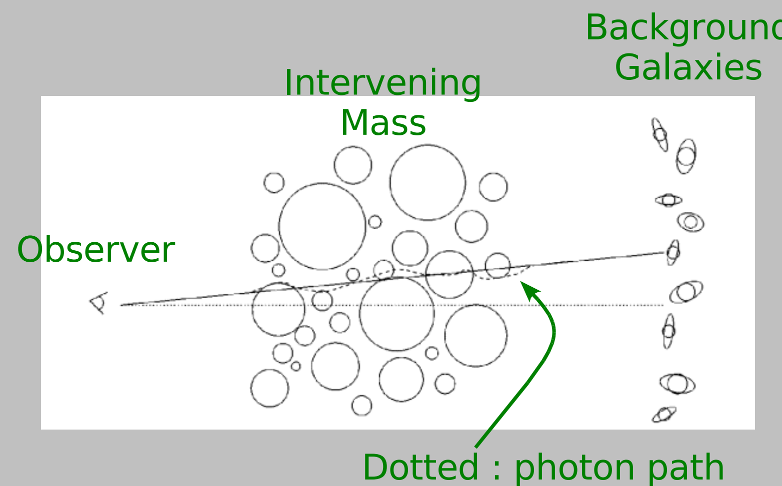
Merging Galaxy Clusters

- Galaxies are (mostly) *collisionless*-- they pass through each other, dissipation is only via. dynamical friction
- The intra-cluster gas does interact via. fluid stuff when clusters collide
- if there is non-baryonic, weakly interacting dark matter, it will also be collisionless

How can we measure where the *mass* really is?

Weak gravitational lensing – it measures the total mass, regardless of what it is.

Refregier, 2003, ARA&A, 41, 645



Result : systematic shearing of galaxy images at few % level

The mass (blue, from weak lensing) is not where the baryons (pink, X-ray gas) are! The mass must be mostly made up of a weakly interacting component that is non-baryonic!

Dark Matter Exists!

By the Sanders & McGaugh (MOND advocates) criterion, MOND is now *more speculative* than dark matter. Har!!!