Evidence for Dark Matter

ASTR 511

mjuric@astro.washington.edu

Some recent reviews and pedagogical introductions:

- Bertone & Hooper (2016): ***arXiv:1605.04909v2***
- Garrett & Duda (2011): ***arXiv:1006.2483v2***
- Massey, Kitching & Richard (2010) : ***arXiv:1001.1739***
- Famaey & McGaugh (2012): **arXiv:1112.3960**

Why Bother?

- "Dark Matter", here defined as matter that is detectable through its **gravitational interaction** with baryonic matter, yet **does not appear to emit or strongly interact electromagnetically**, has been a mainstay of astrophysics for (at least) half a century.

- Though we're yet to understand its nature, it is very tempting to take the existence of dark matter for granted – from your professor to late night TV, everyone tells you it's there… and that it's only a matter of time until we detected it directly!

- <u>**That would be unwise.**</u> History teaches us the value of being cautious, and continuously re-examining our assumptions and conclusions, doubly so in light of new data. **After all, *luminiferous aether,* was *known* to exist for nearly two centuries (Newton, 1718 – Einstein, 1905)!**

- We'll therefore (briefly) summarize various lines of evidence for dark matter, concentrating a bit more on those that have to do with the structure and evolution of galaxies. <u>***You'll hear more about this in ASTR 513 (Cosmology)!***</u>

Observations Inexplicable by Lumnous Matter Alone

- **Motions of galaxies in galaxy clusters (Zwicky 1930)**
- **Flat rotation curves (Rubin 1970)**
- **Stability of disk galaxies (Ostriker & Peebles 1973)**
- Dynamics of stars in galaxies
- **Dynamics of the Milky Way**
- Motions of globular clusters and dwarf satellites in potential wells of large galaxies
- **Internal dynamics of dwarf spheroidals**
- Observed temperature of hot gas in galaxy clusters
- Strong gravitational lensing
- Mass tomography from weak lensing
- **Observations of cluster collisions**
- Big-Bang nucleosynthesis
- Cosmic Microwave Background temperature and anisotropies
- **Local group timing argument**
- …

Galaxy Clusters

- **Fritz Zwicky** is usually credited with the first verifiable claim for dark matter, owing to a pair of papers (in 1933 and 1937) on the measurements velocity dispersions of galaxies in the Coma cluster.
- **Basic observation and line of reasoning:**
  - Galaxies in the Coma region exhibit a large velocity dispersion around the overall Hubble flow
  - We assume they're a part of a cluster, that has had enough time to *virialize*.
  - Apply the *virial theorem* to compute the mass of the cluster (and therefore the average mass of a galaxy)
  - Compute their *mass-to-light ratio*, and compare to M/L ratios of local stellar systems.

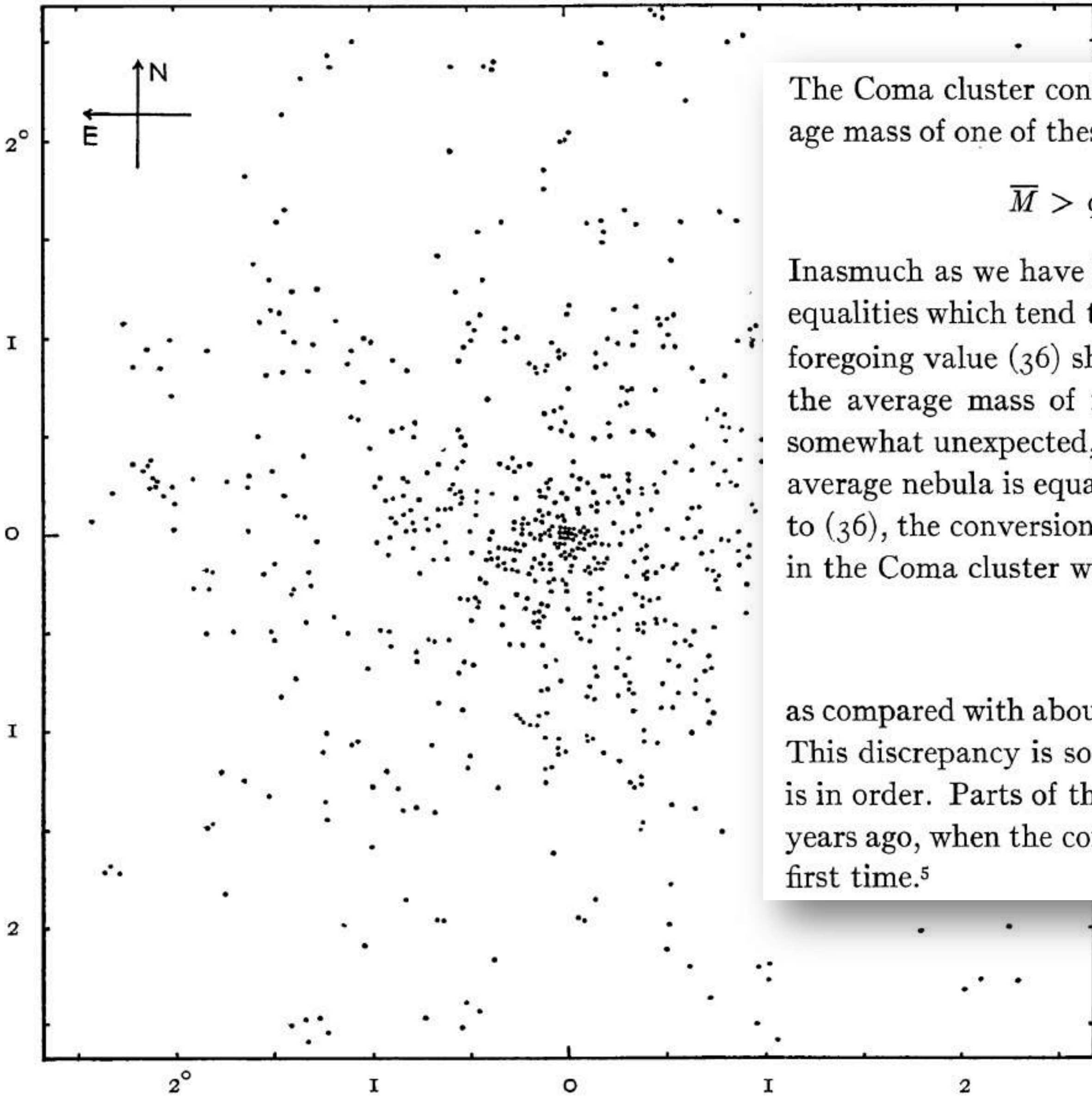


FIG. 3.—The Coma cluster of nebulae

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43}\ \text{gr} = 4.5 \times 10^{10}\ M_\odot\,. \qquad (36)$$

Inasmuch as we have introduced at every step of our argument inequalities which tend to depress the final value of the mass $\mathscr{M}$, the foregoing value (36) should be considered as the lowest estimate for the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns. According to (36), the conversion factor γ from luminosity to mass for nebulae in the Coma cluster would be of the order

$$\gamma = 500\,, \qquad (37)$$

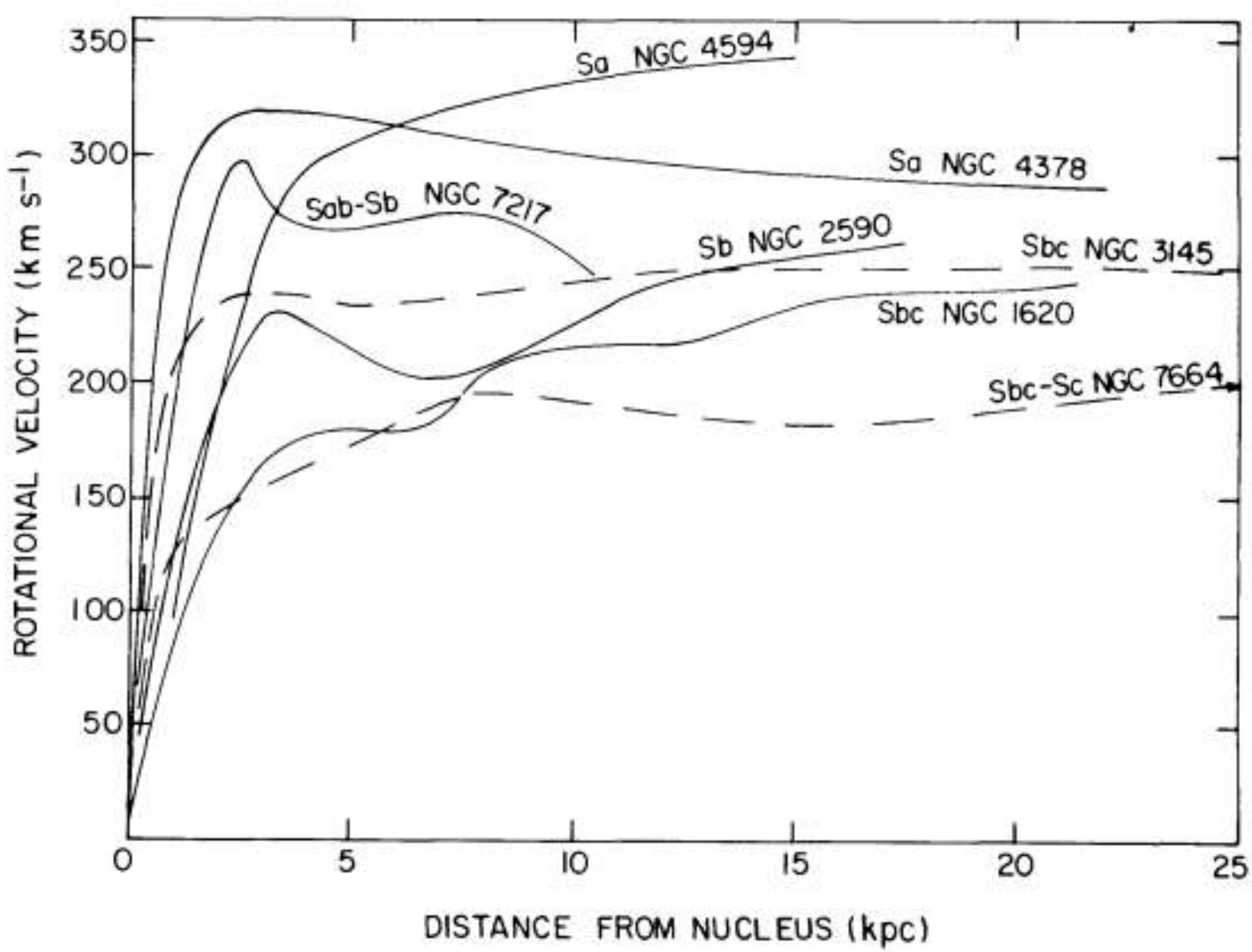
as compared with about $\gamma' = 3$ for the local Kapteyn stellar system. This discrepancy is so great that a further analysis of the problem is in order. Parts of the following discussion were published several years ago, when the conclusion expressed in (36) was reached for the first time.[5]

The details have changed (improved), but the basic conclusion has remained ever since Zwicky's initial observation: assuming clusters are in equilibrium and the physics is the same, an unseen gravitationally interacting component is required to explain the observed kinematics.

Zwicky (1937)

Galactic Rotation Curves

- Similar observations can be made in galaxies.
- **Vera Rubin** and **Kent Ford** begun to precisely measure rotation curves of galaxies, starting with M31 in 1970 and continuing through the 1970-ies.
- Their observations led to a surprising discovery: **the rotation curves were not falling, as would be expected of Keplerian motion, but were instead (roughly) flat (constant).**
- ***The inferred M/L ratios were on order of a ~100***
  - Compare this to M/L of ~1-10 for purely stellar systems



Measurements like this are routine today (and remain consistent with Rubin's original observations).

Rubin et al. (1978)

Flat Rotation Curves

- In many ways, this discovery was more powerful than Zwicky's; nearby galaxies were much more familiar systems than clusters:
  - they were definitely in (approximate) equilibrium, and
  - their stellar populations were reasonably well understood.
- This led to a conclusion that either:
  - Newton's gravity requires modifications, or
  - **an additional, unseen, component needs to be added to explain the kinematic observations.**
- Also: Galactic disks are inherently unstable to small perturbations; however, a large, massive, "dark halo" would stabilize them (Ostriker & Peebles 1973)

Rotation Curve of the Milky Way

- The same effect is seen in Milky Way using observations of a variety of tracers MW's disk

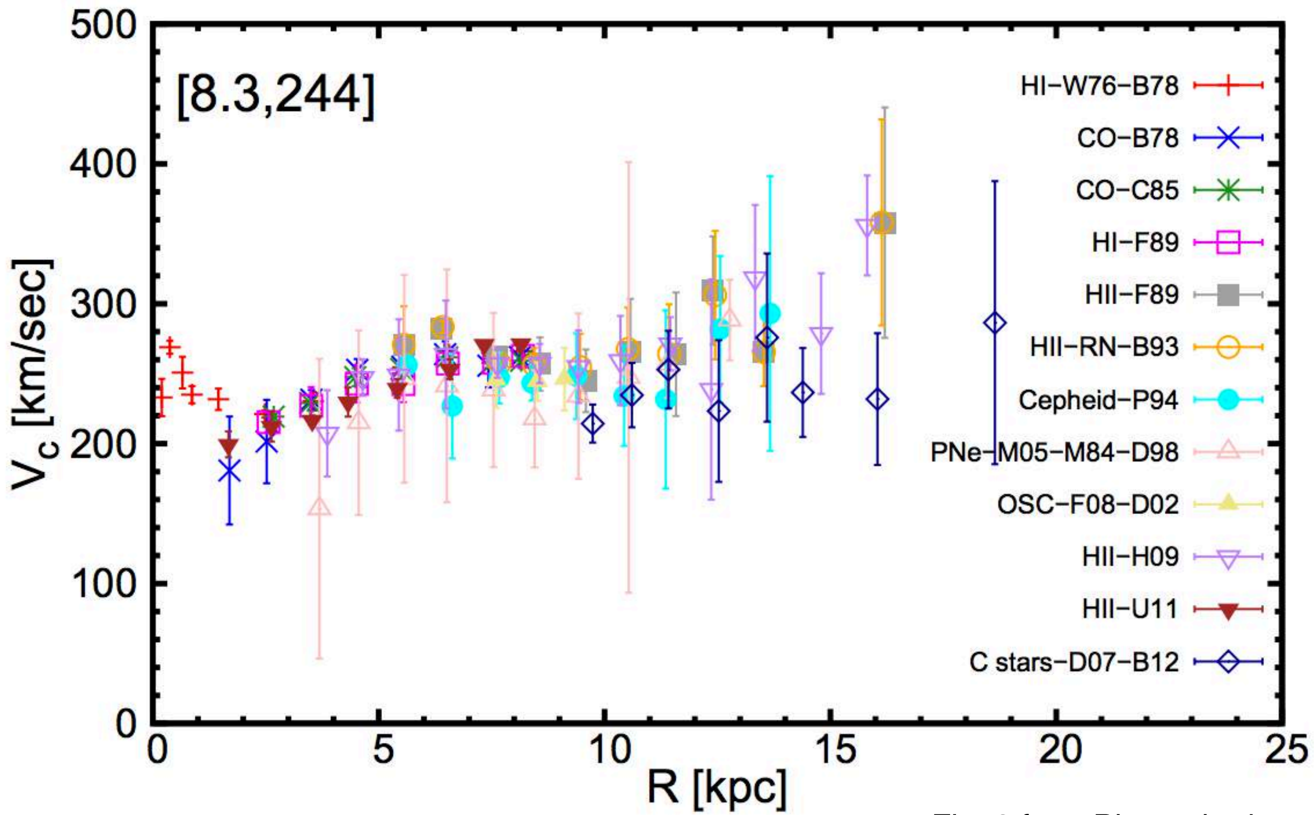


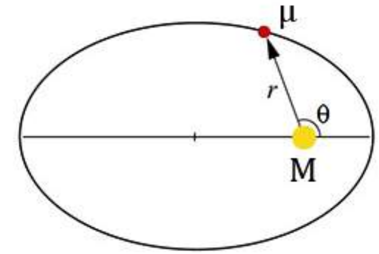
Fig. 2 from Bhattacharjee, Chaudhury and Kundu (2013)

The Timing Argument

- Another simple argument points to a need for an unseen component in our Milky Way: the ***"timing argument"***
  - We observe that the MW and M31 are on a collision course
  - Assuming Big Bang holds, they have started close by (everything was close at $t=0$!) and receded from each other until their mutual gravitational attraction overcame the initial kick imparted by the Big Bang.
  - When that happens will depend on the total mass of the MW and the M31.

E.g., see Withagen (2009) for a nice exposition.

The Timing Argument



$$r = a\,(1 - e\cos\theta)$$

Equation of a Keplerian ellipse

$$t = \left(\frac{a^3}{GM_{\rm tot}}\right)^{\frac{1}{2}}(\theta - e\sin\theta)$$

The Kepler Equation

$$v = \frac{dr}{dt} = \frac{dr}{d\theta}\Big/\frac{dt}{d\theta} = \left(\frac{GM}{a}\right)^{\frac{1}{2}}\left(\frac{sin\theta}{1 - sin\theta}\right)$$

$$v = \frac{r\sin\theta(\theta - \sin\theta)}{t(1 - \cos\theta)^2}$$

Assuming e=1 (radial infall)

Left: all measurable (estimable) quantities

$$\frac{vt}{r} = \frac{\sin\theta(\theta - \sin\theta)}{(1 - \cos\theta)^2}.$$

Right: a function of theta.

The Timing Argument

- Age of the universe: ***t ~ 15* Gyr**
- Distance to M31: ***~700* kpc**
- Relative velocity: ***-130* km/s**
- Assume M31 is on its first approach to MW

- Solving for θ, then total mass, we obtain ***~3.5 x 10^{12} M_o***
- Even if just a third of that is due to the Milky Way, ***the inferred M/L ratio is on the order of a ~100***.

Dark Matter in Elliptical Galaxies

- In the central part of elliptical galaxies there is no evidence for dark matter (mass-to-light ratio 5 to 10 in solar units – typical for old stellar populations). In the outer parts it is harder to find such evidence because there is no gas on circular orbit as is the case for spiral galaxies.

- Nevertheless, there are several methods that indicate the presence of dark matter in elliptical galaxies
  - **Analysis of stellar kinematics** (detailed models of motion in gravitational potential) can be made to work by introducing a dark matter component
  - **Gravitational lensing** of massive ellipticals requires more mass than explicable by stars only
  - **X-ray halos** (by application of virial theorem)

Dwarf Spheroidal Galaxies

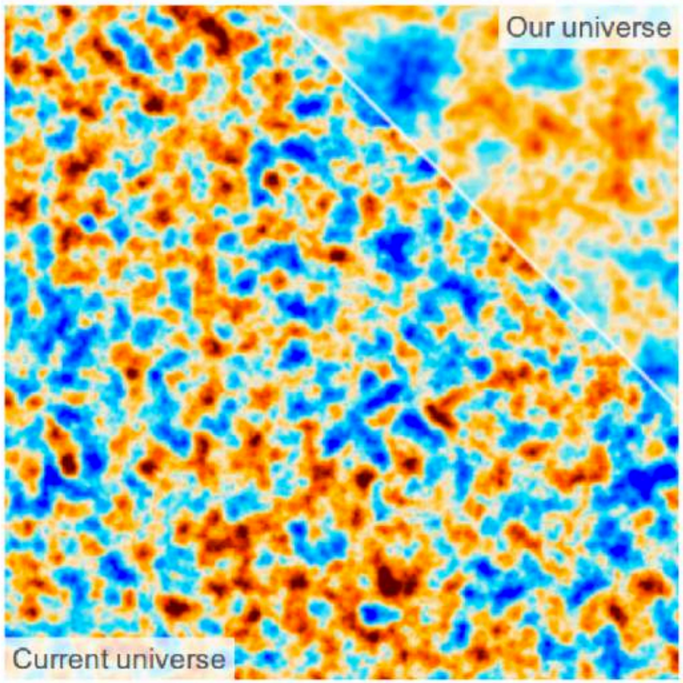
Fornax (NASA)

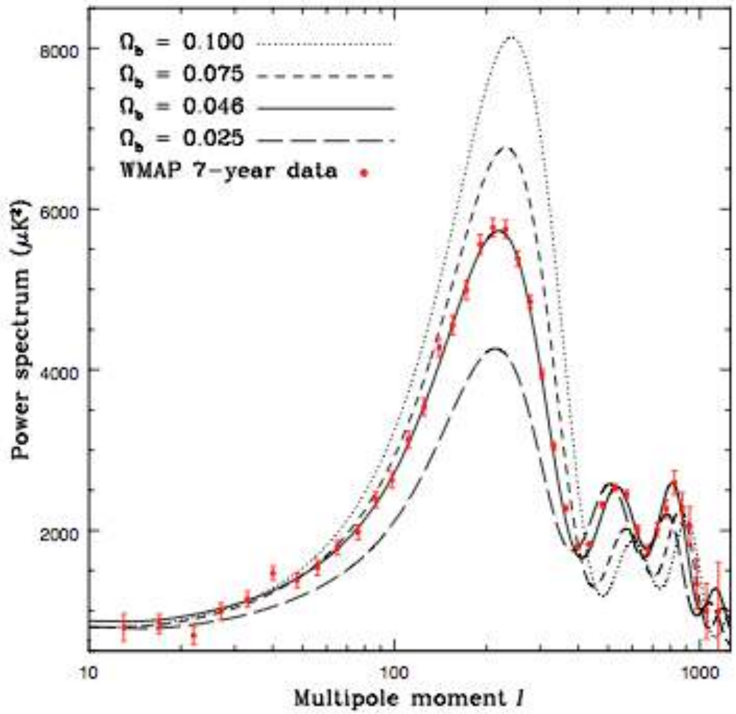
SEGUE 1 (SDSS/M. Geha)

Kinematics of stars in dwarf spheroidals shows motions consistent with
M/L ratios of ~500, approaching 1000 in extreme cases (ultra-faint dwarf spheroidals).

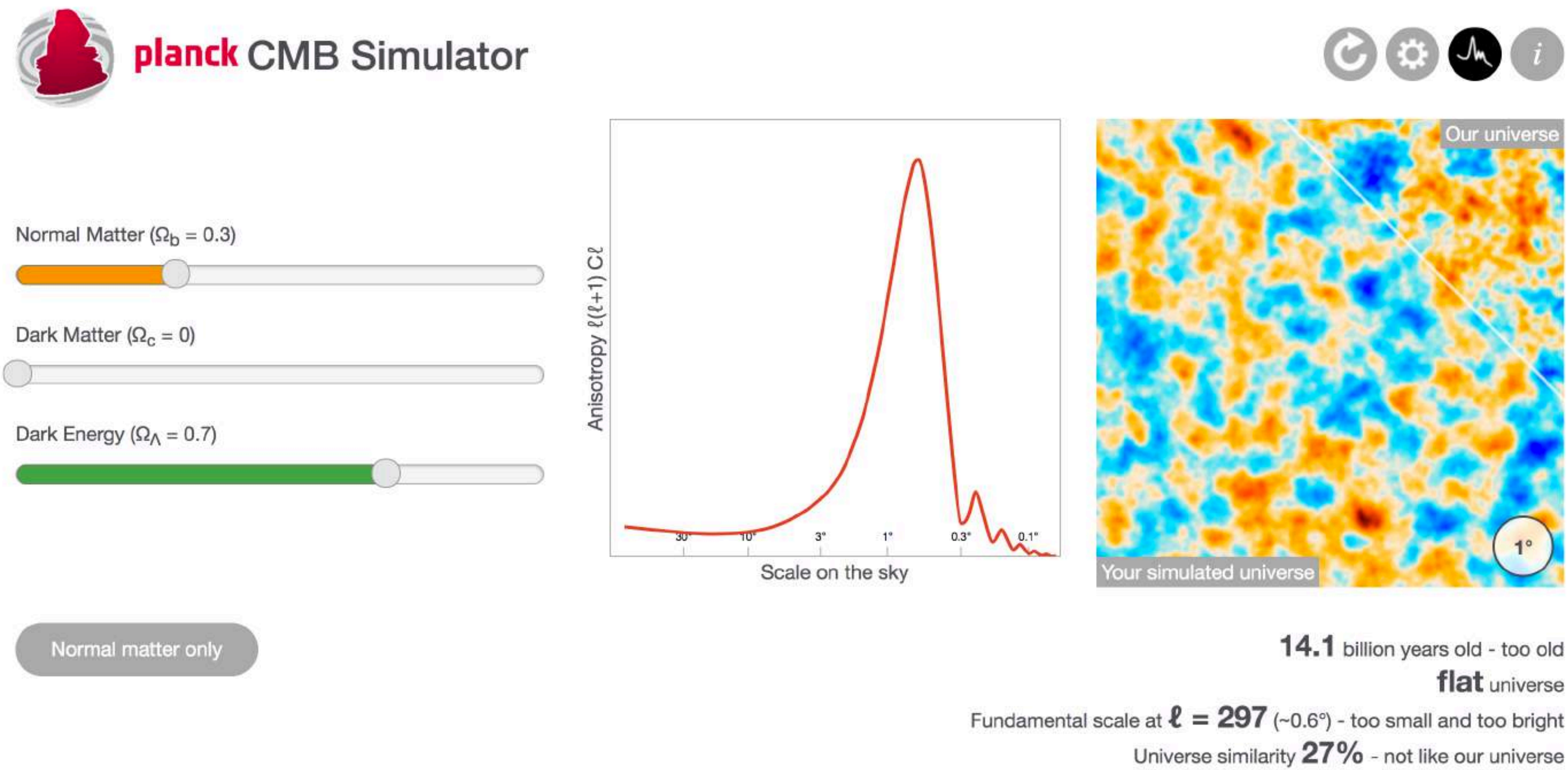
Note: We're assuming these are ***virialized systems***.

Cosmological Evidence



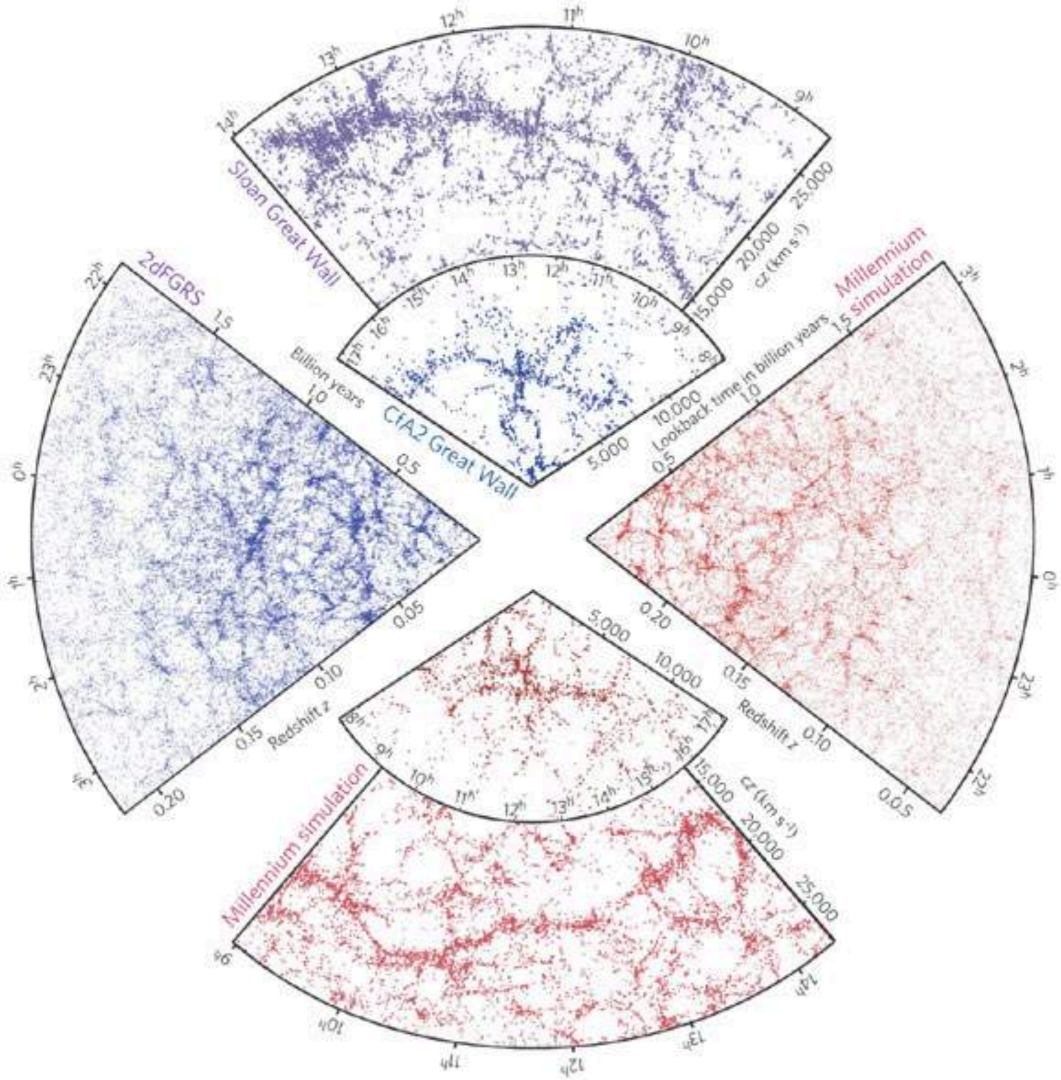


The amplitude of the first acoustic peak in the CMB is sensitive to the baryon content of the universe. The observations of the CMB power spectrum require a massive, weakly interacting, component to be successfully modeled.



http://chrisnorth.github.io/planckapps/Simulator/#

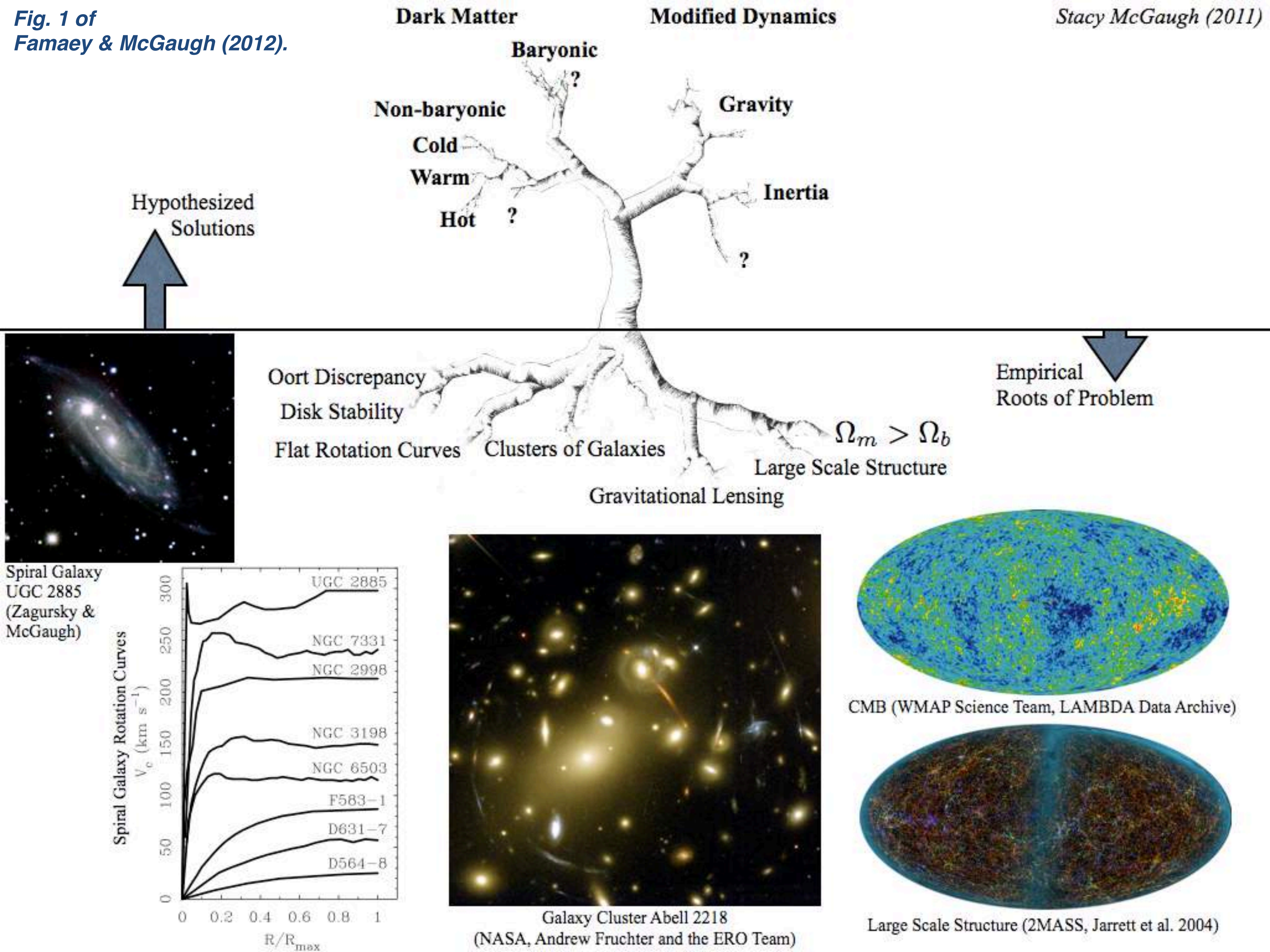
Large Scale Structure



The observed large scale structure of galaxies in the universe requires an unseen, gravitationally interacting, component to be reproduced by simulations.

Left: Fig 1. from Springel, Frenk & White (2006).

Fig. 1 of Famaey & McGaugh (2012).



Candidates for an Explanation

- Dark Matter Theories:
  - Non-luminous macroscopic objects consisting of "normal" matter (including neutron stars and stellar-mass black holes); MACHOs (Massive Compact Objects)
  - One or more flavors of unknown, **w**eakly **i**nteractive, **m**assive elementary **p**articles; **"WIMPS"**.
    - The favored explanation
    - Nearly all common extensions of the Standard Model predict the existence of such particles

- Modified Gravity/Dynamics Theories
  - Theories where either Newton's 2nd law or Newton's gravity are modified for small accelerations.

Dark Matter vs. Modified Dynamics/Gravity?

Is there a different explanation that fits all observational facts and does not involve introducing an unseen form of matter?

Milgrom (1983) offered one such solution, one of a class of ***MOdified Newtonian Dynamics (MOND)*** theories.

Milgrom's (quite reasonable) observation was that all (then known) pieces of **evidence for Dark Matter relied on *kinematics*** that was observed to be inconsistent with the luminosity distribution and Newtonian gravity. Instead of introducing a new component to explain the extra mass, why not modify Newtonian gravity?

$$F_N = m \cdot \gamma\left(\frac{a}{a_0}\right) \cdot a$$

where $\gamma(x)$ is some function that reduces to 1 if $a >> a_0$ and a when $a << a_0$. This modification to gravity can explain the flat rotation curves of galaxies.

Table 2: Observational tests of MOND.

Observational Test	Successful	Promising	Unclear	Problematic
Rotating Systems				
solar system			X	
galaxy rotation curve shapes	X			
surface brightness $\propto \Sigma \propto a^2$	X			
galaxy rotation curve fits	X			
fitted M_*/L	X			
Tully–Fisher Relation				
baryon based	X			
slope	X			
normalization	X			
no size nor Σ dependence	X			
no intrinsic scatter	X			
Galaxy Disk Stability				
maximum surface density	X			
spiral structure in LSBGs	X			
thin & bulgeless disks		X		
Interacting Galaxies				
tidal tail morphology		X		
dynamical friction			X	
tidal dwarfs	X			
Spheroidal Systems				
star clusters			X	
ultrafaint dwarfs			X	
dwarf Spheroidals	X			
ellipticals	X			
Faber-Jackson relation	X			
Clusters of Galaxies				
dynamical mass				X
mass–temperature slope	X			
velocity (bulk & collisional)		X		
Gravitational Lensing				
strong lensing	X			
weak lensing (clusters & LSS)			X	
Cosmology				
expansion history			X	
geometry			X	
big bang nucleosynthesis	X			
Structure Formation				
galaxy power spectrum			X	
empty voids		X		
early structure		X		
Background Radiation				
first:second acoustic peak	X			
second:third acoustic peak				X
detailed fit				X
early re-ionization	X			

Dark Matter vs. Modified Dynamics/Gravity?

Flat rotation curves in MOND:

$$a \ll a_0 : F_N = m \cdot a^2 / a_0$$

$$\frac{GMm}{r^2} = m\frac{(v^2/r)^2}{a_0} \Rightarrow v^4 = GMa_0$$

Issues:

- Dynamical masses and colliding globular clusters
- Explaining the locations and amplitudes of higher-order peaks in the Cosmic Microwave Background
- Various cosmological observations (large scale structure, galaxy power spectrum, structure evolution, …)

In general, MOND is more successful in explaining galaxy-scale observations, but has difficulties in forming a basis for a coherent theory that simultaneously explains observations at all scales.

Left: Famaey & McGaugh, arXiv:1112.3960

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Cosmology				
expansion history			X	
geometry			X	
big bang nucleosynthesis	X			
Structure Formation				
galaxy power spectrum			X	
empty voids		X		
early structure		X		
Background Radiation				
first:second acoustic peak	X			
second:third acoustic peak				X
detailed fit				X
early re-ionization	X			

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER *

DOUGLAS CLOWE[1], MARUŠA BRADAČ[2], ANTHONY H. GONZALEZ[3], MAXIM MARKEVITCH[4,5], SCOTT W. RANDALL[4],
CHRISTINE JONES[4], AND DENNIS ZARITSKY[1]

ApJ Letters in press

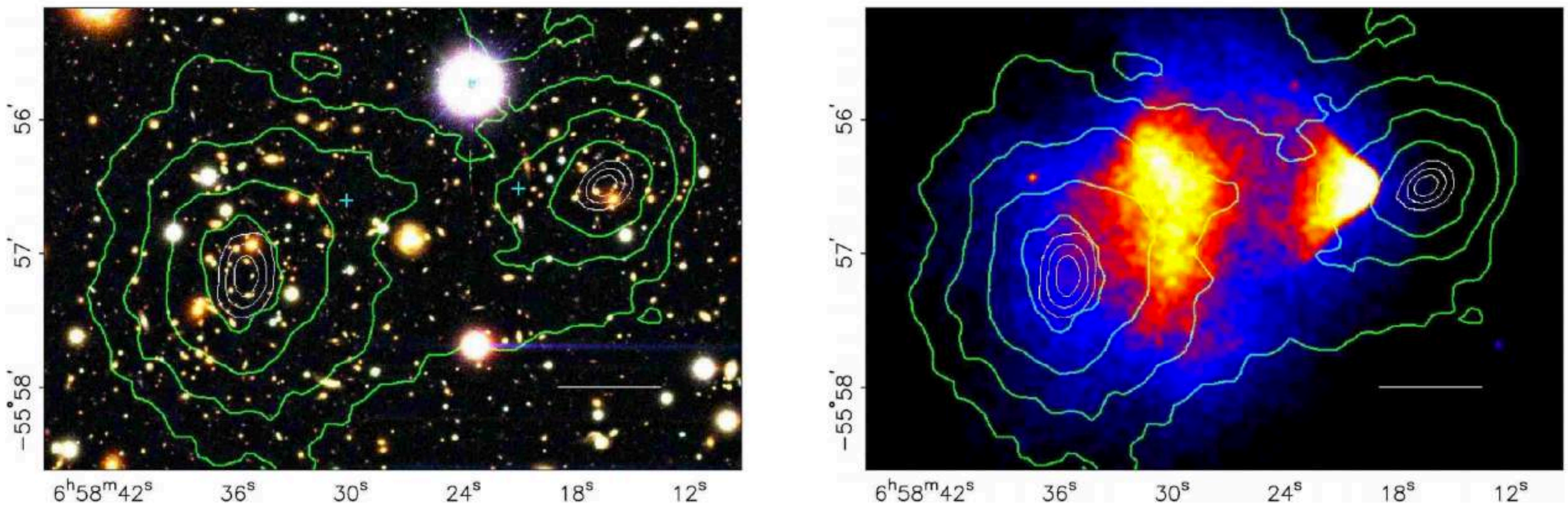
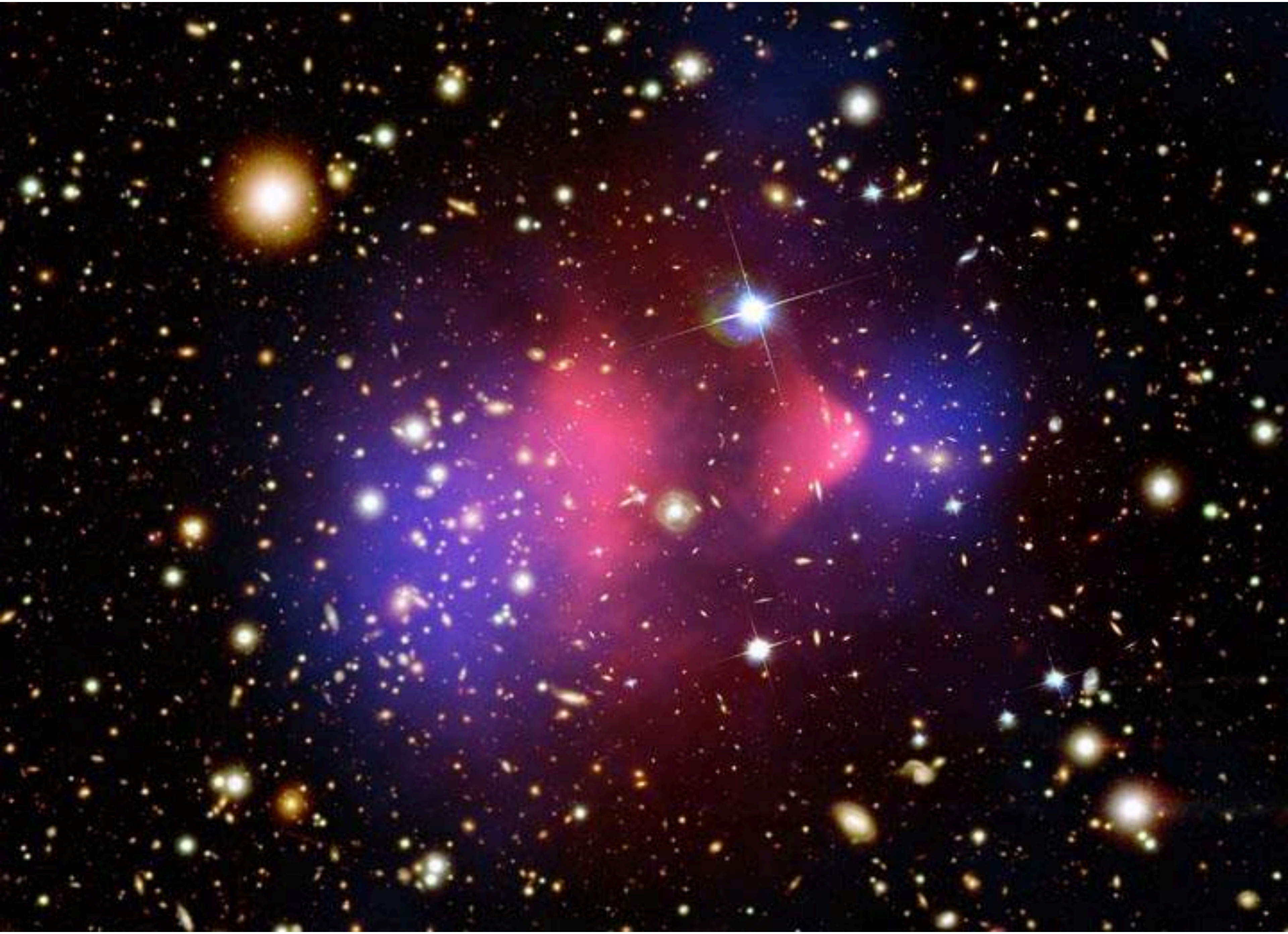
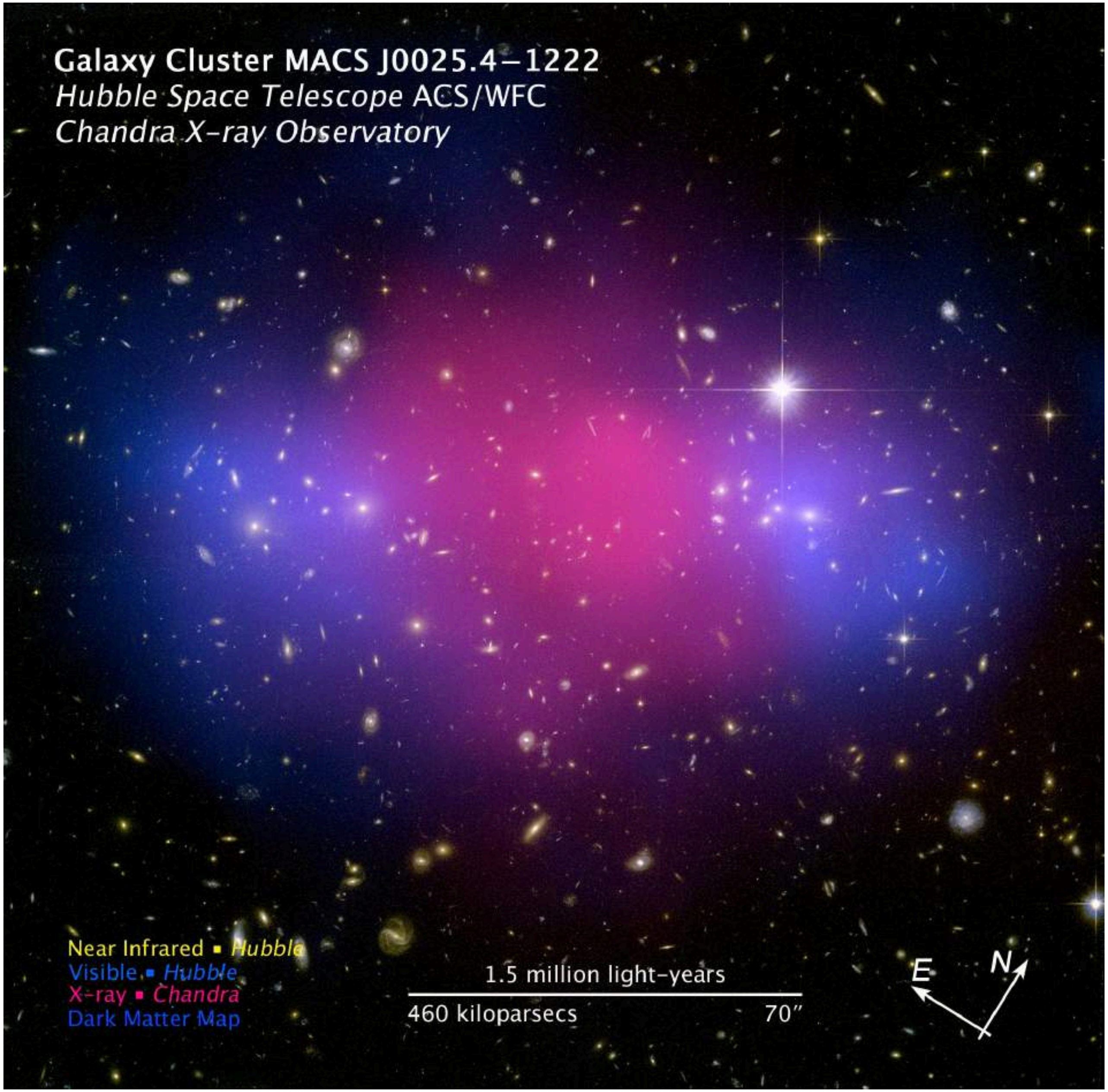


FIG. 1.— Shown above in the top panel is a color image from the Magellan images of the merging cluster 1E0657−558, with the white bar indicating 200 kpc at the distance of the cluster. In the bottom panel is a 500 ks Chandra image of the cluster. Shown in green contours in both panels are the weak lensing κ reconstruction with the outer contour level at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue +s show the location of the centers used to measure the masses of the plasma clouds in Table 2.

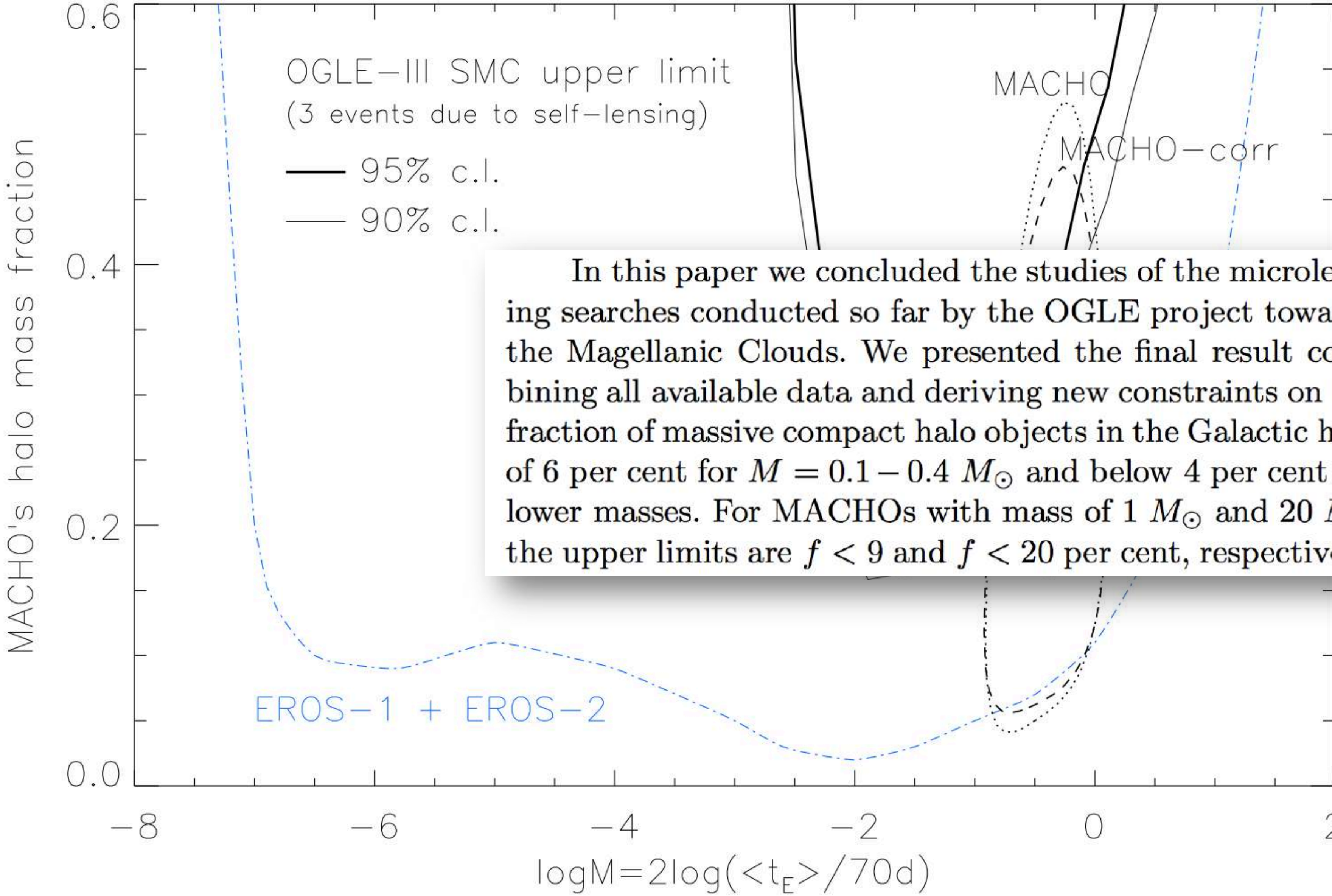
Clowe et al. (2006)





Bradac et al. (2008)

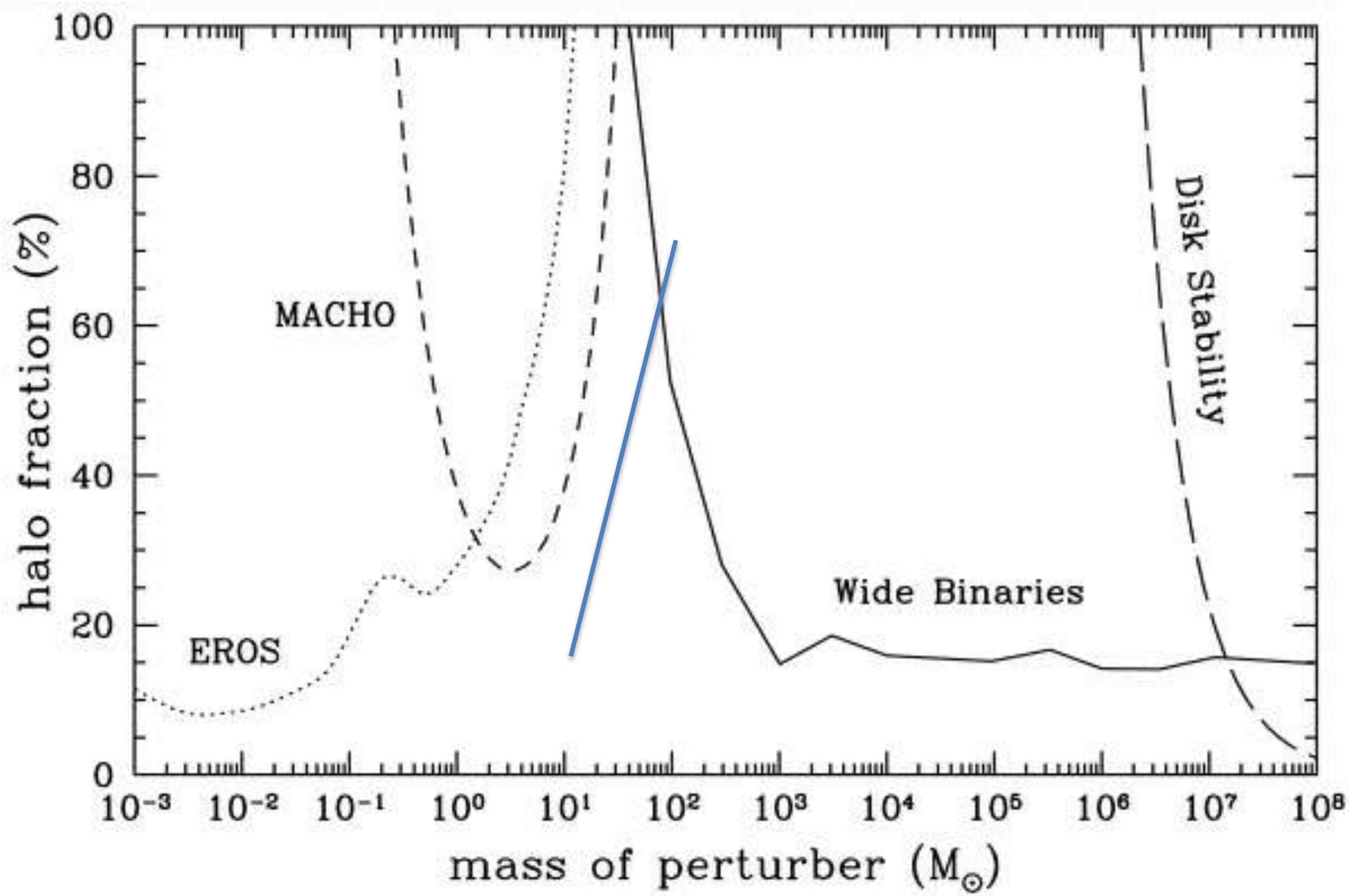
Could it be planets, white dwarfs, or neutron stars?



In this paper we concluded the studies of the microlensing searches conducted so far by the OGLE project towards the Magellanic Clouds. We presented the final result combining all available data and deriving new constraints on the fraction of massive compact halo objects in the Galactic halo of 6 per cent for $M = 0.1 - 0.4\ M_{\odot}$ and below 4 per cent for lower masses. For MACHOs with mass of 1 $M_{\odot}$ and 20 $M_{\odot}$ the upper limits are $f < 9$ and $f < 20$ per cent, respectively.

Wyrzykowski et al. (2012)

OK, so it's not planets or WDs… Massive black holes?

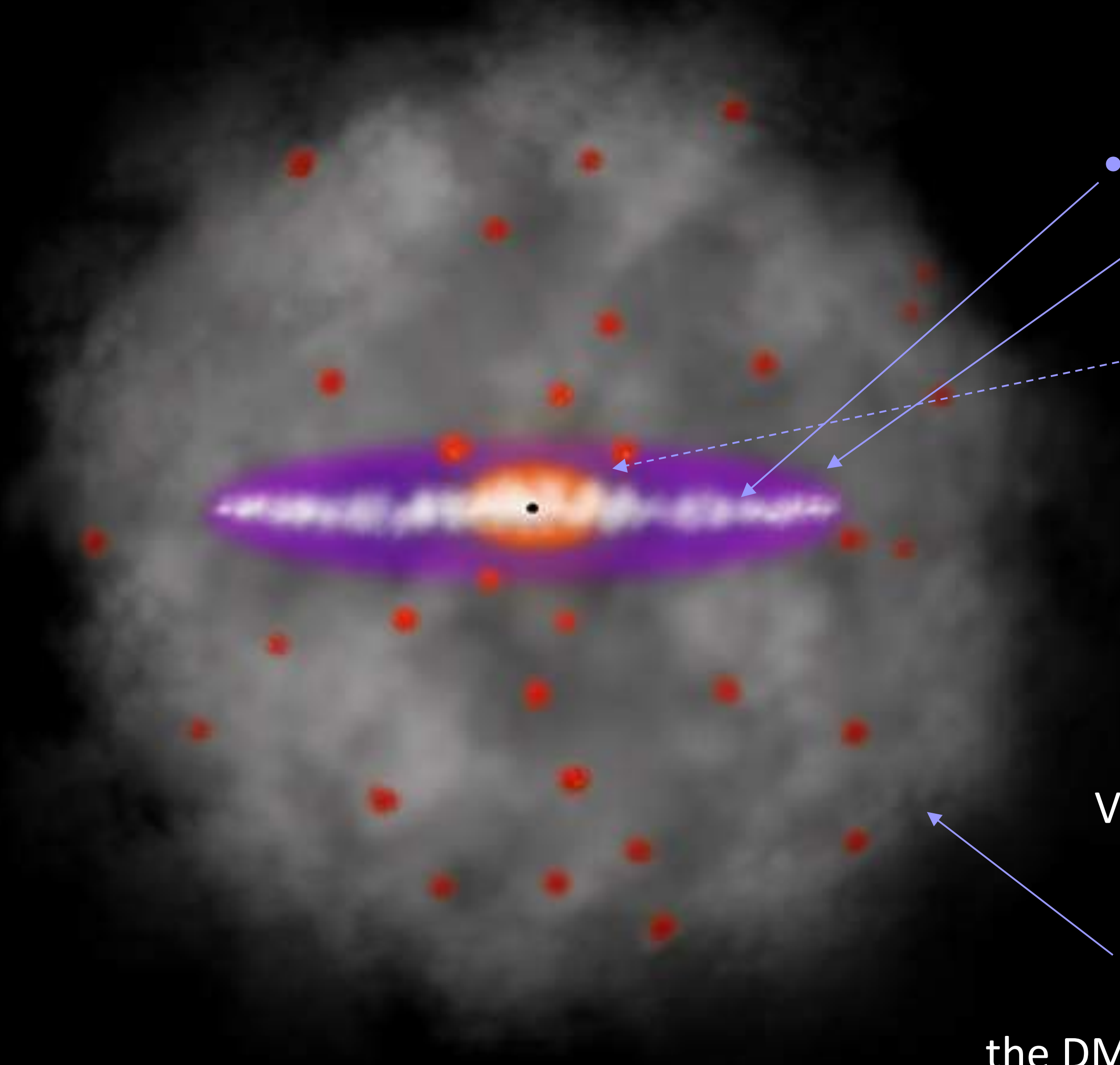


Yoo, Chaname & Gould (2003)

Penny et al. (2009)

These four dwarf galaxies are part of a census of small galaxies near the center of the nearby Perseus galaxy cluster. **The galaxies appear smooth and symmetrical,** suggesting that they have **not been tidally disrupted** in the dense cluster environment. ***Larger galaxies around them, however, are being ripped apart by the gravitational tug of other galaxies!***

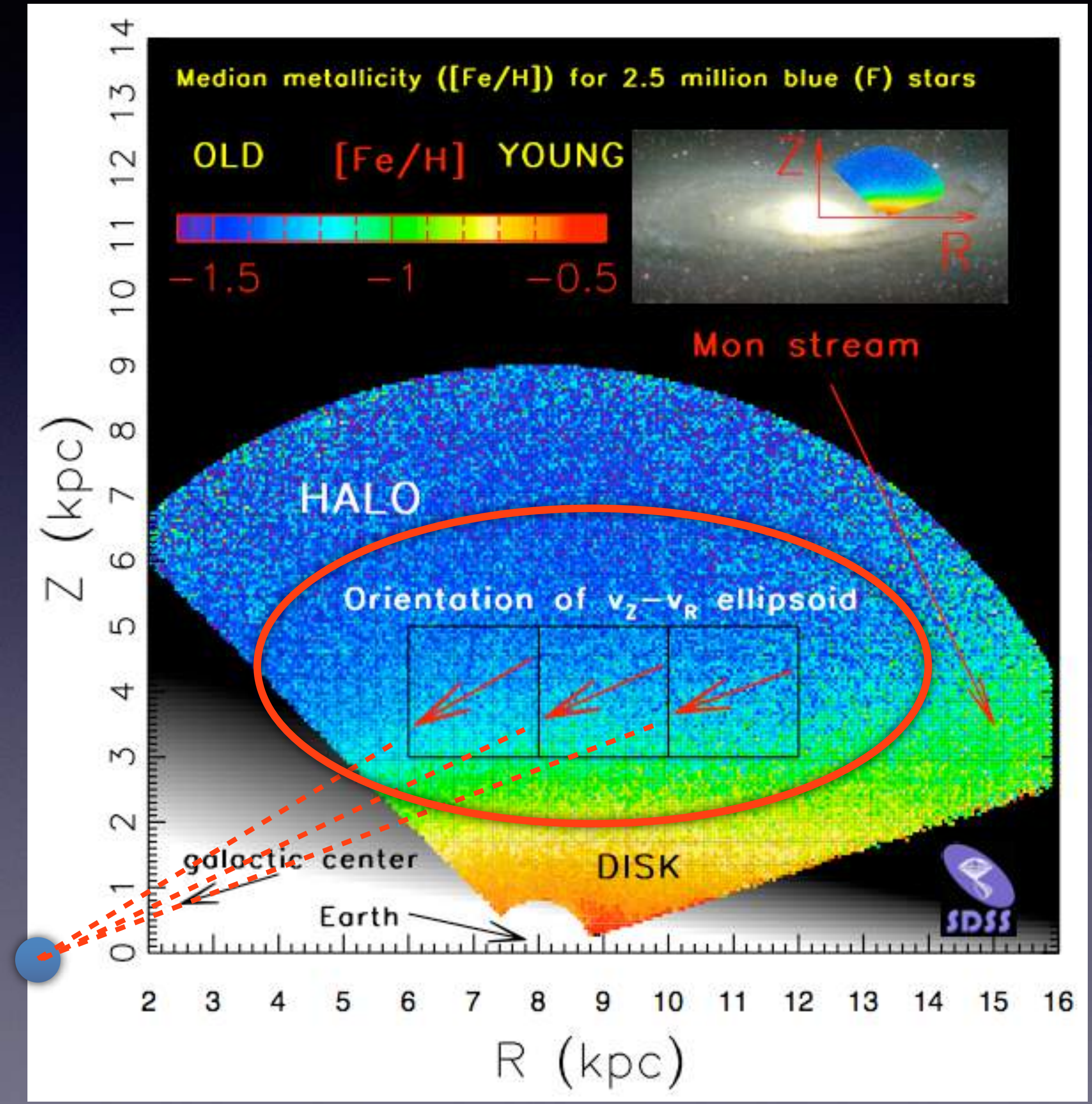
Classical Decomposition of the Milky Way



- Thin disk
- Thick disk
- Bulge/Bar
- Stellar halo

- Exponential or sech^2 disk models
- Power laws or de Vaucouleurs profiles for the halo
- Components trace the DM dominated potential

Velocity distribution for (nearby) halo stars



Kinematics of halo stars based on SDSS-POSS proper motions:

velocity ellipsoid is nearly invariant in spherical coordinate system

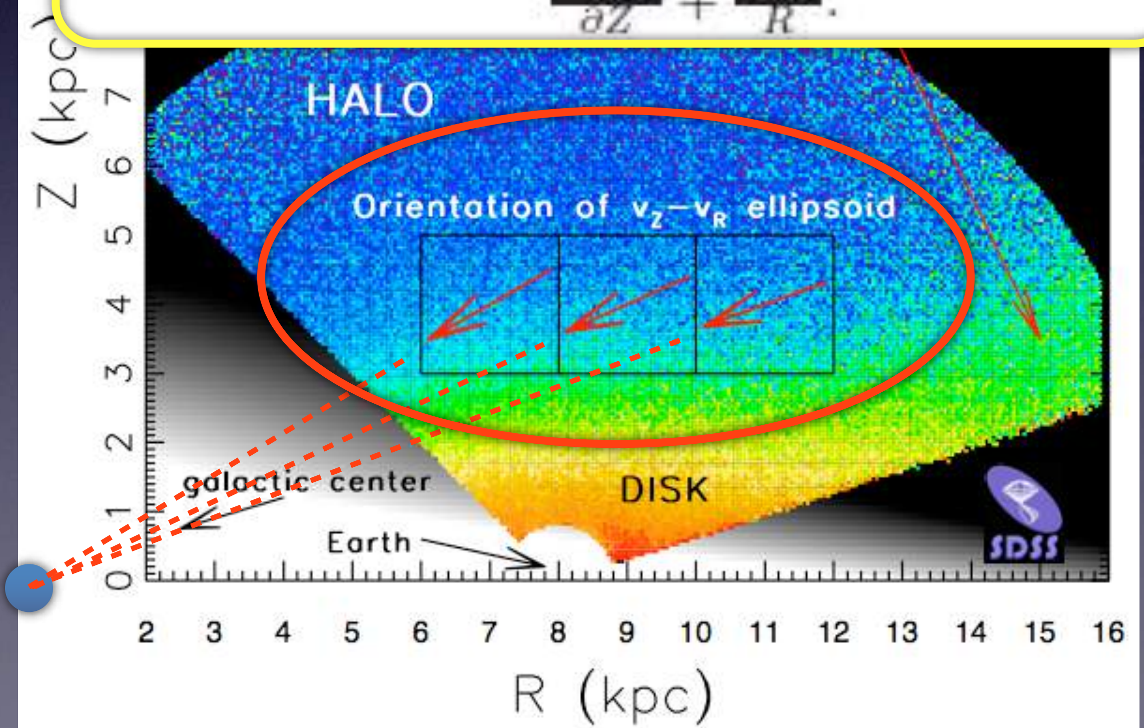
Bond et al. (2010, ApJ, 716, 1)

Velocity distribution for (nearby) halo stars

Kinematic data constrain dark matter via Jeans equations

$$a_R = \sigma^2_{RR} \times \frac{\partial(\ln\nu)}{\partial R} + \frac{\partial\sigma^2_{RR}}{\partial R} + \sigma^2_{RZ} \times \frac{\partial(\ln\nu)}{\partial Z} + \frac{\partial\sigma^2_{RZ}}{\partial Z} + \frac{\sigma^2_{RR}}{R} - \frac{\sigma^2_{\phi\phi}}{R} - \frac{\overline{v_\phi}^2}{R},$$

$$a_Z = \sigma^2_{RZ} \times \frac{\partial(\ln\nu)}{\partial R} + \frac{\partial\sigma^2_{RZ}}{\partial R} + \sigma^2_{ZZ} \times \frac{\partial(\ln\nu)}{\partial Z} + \frac{\partial\sigma^2_{ZZ}}{\partial Z} + \frac{\sigma^2_{RZ}}{R}.$$



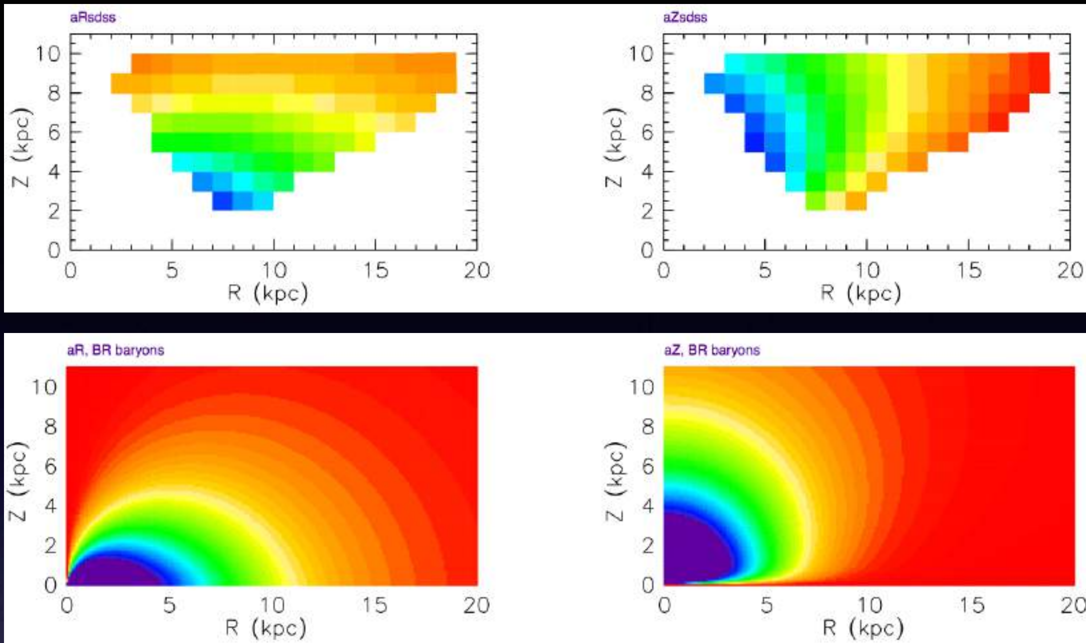
Kinematics of halo stars based on SDSS-POSS proper motions:

velocity ellipsoid is nearly invariant in spherical coordinate system

Bond et al. (2010, ApJ, 716, 1)

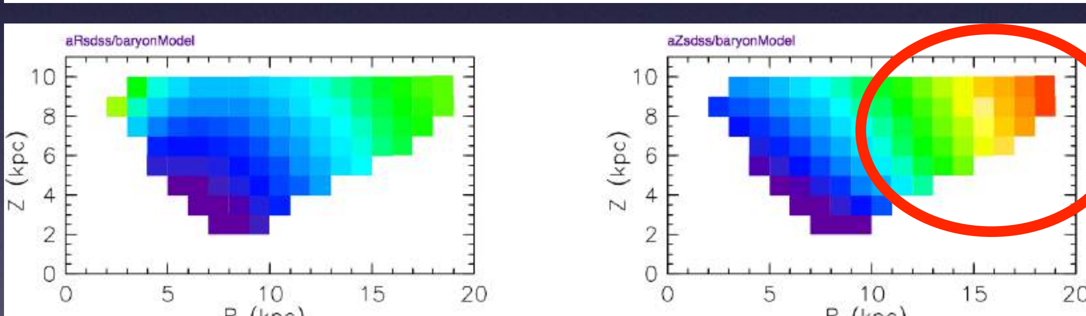
Given stellar distribution from Juric+2008 and stellar kinematics from Bond+2010, we can apply **Jeans equations** and infer the gravitational potential, and ultimately the distribution of dark matter!

aR aZ



SDSS, halo, total
(Loebman et al. 2012)

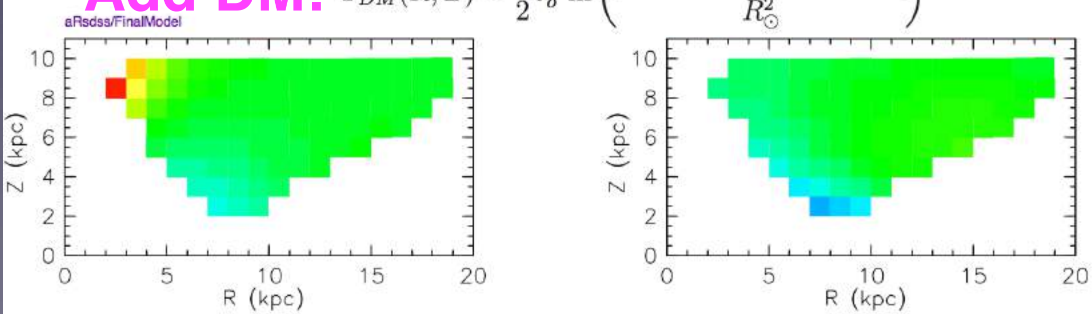
Baryons (SDSS, disk)
(Bovy & Rix, 2013)



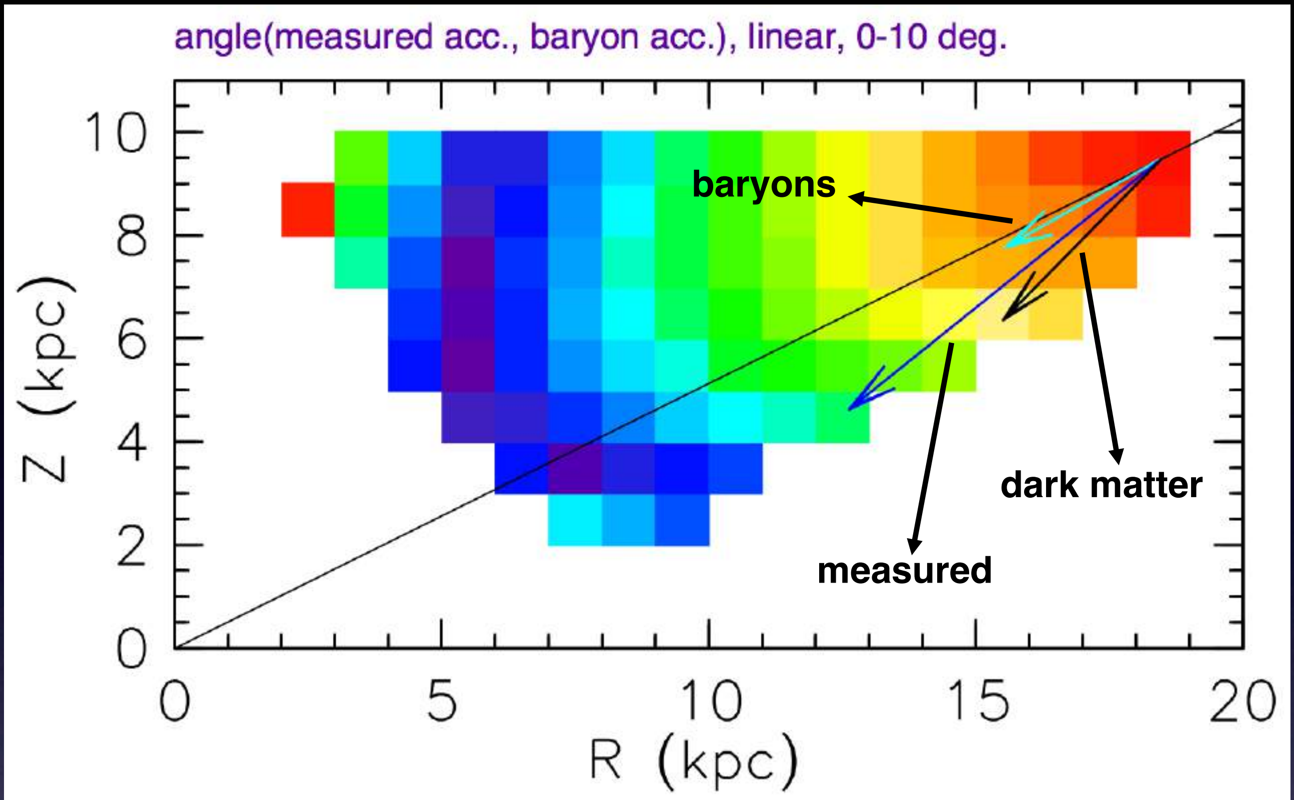
Up to 3 times stronger acc.!

SDSS measured over baryon model

Add DM: $\Phi_{DM}(R,Z) = \frac{1}{2} v_o^2 \ln\left(\frac{R^2 + (Z/q_{DM})^2 + R_{core}^2}{R_\odot^2}\right)$

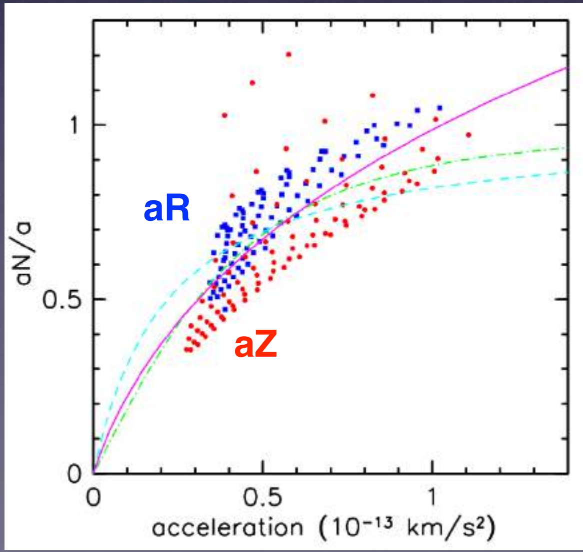


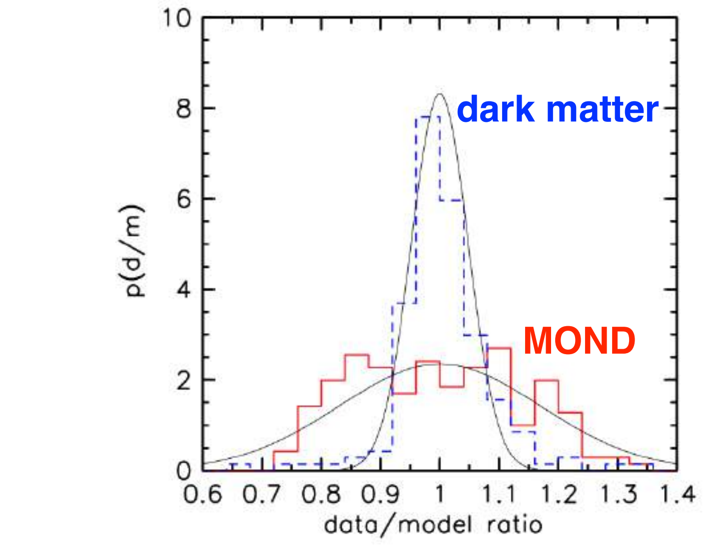
DM halo is oblate!
qPot=0.7±0.1
qRho=0.4±0.1
(Loebman et al. 2014)



Acceler. due to baryons and measured acc. don’t point in the same direction:

1) DM halo can’t be spherical





2) MOND does not work

Strong constraints because of 2D acceleration measurements

MOND vs. Dark Matter

- Strongest evidence against MOND comes from cosmology
- ΛCDM cosmological models have been tremendously successful explaining a variety of ***high precision*** observations over a large range of spatial and temporal scales **while requiring one assumption: the existence of (a) weakly interacting particle(s)**
  - CMB fluctuations (spectrum and higher-order statistics)
  - D/H ratios from BBN (as well as other element ratios)
  - Galactic P(k), as a function of time
  - N.b.: Both MOND and CDM need dark energy.
- Predictions of MOND are not able to ***quantitatively*** explain modern cosmological data to the same level.
  - E.g., see compare Fig 1. in Dodelson et al (arXiv:1112.1320) with the rebuttal in Famaey & McGaugh (arXiv:1112.3960).
- Combined with other pieces of evidence seemingly contradicting MOND, Dark Matter appears as the more likely solution.

- ***NOTE: This is not to say that alternative explanations do not exist; it's just that no alternative has been been shown to explain the data to the level of precision and accuracy we see with ΛCDM. This matter will only be closed when the putative WIMP is directly detected.***