Dark matter: astrophysical evidence

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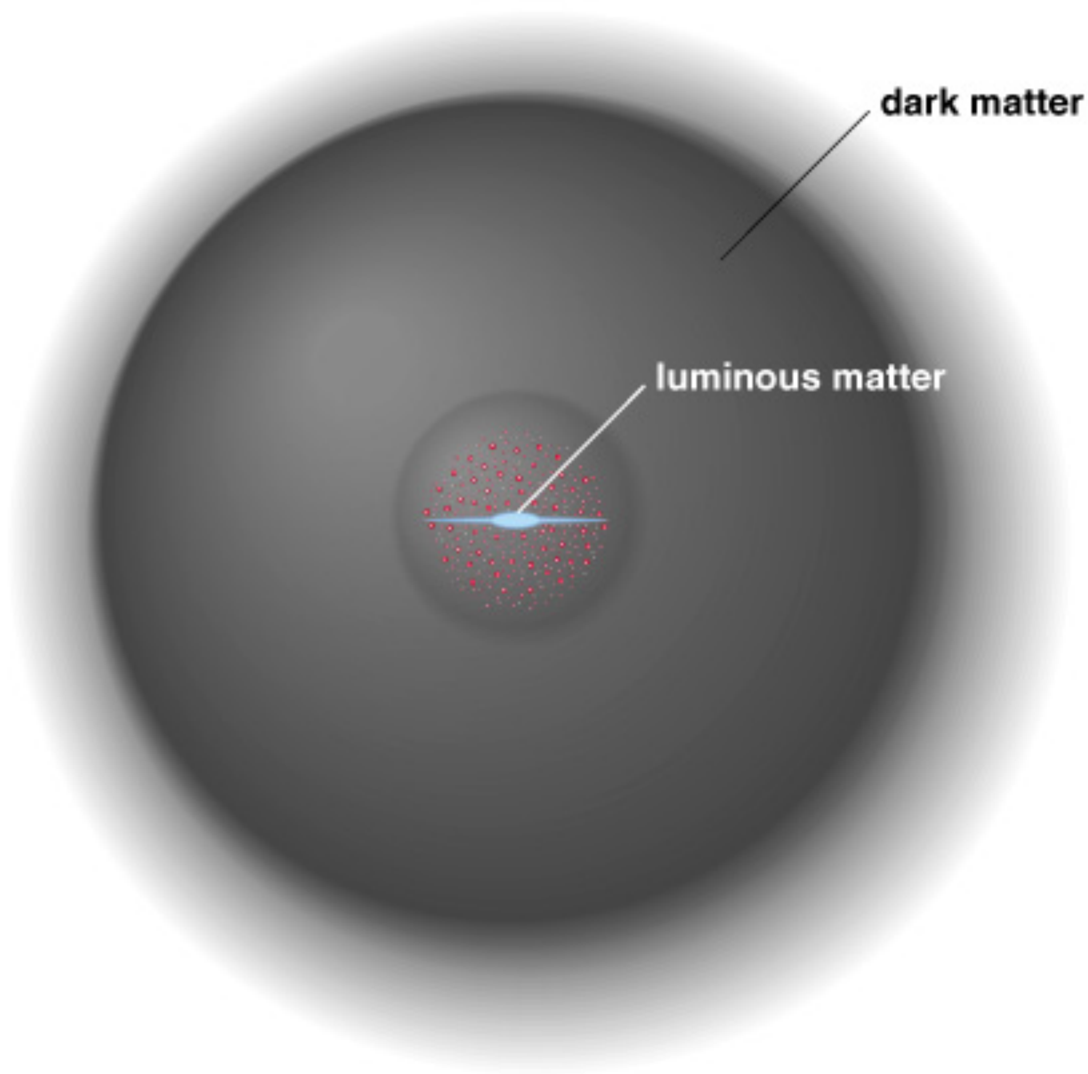
Slides from Risa Wechsler

dark matter: do we need it?

- motions of stars/gas within galaxies show that there is 'dark matter' *within galaxies*
- motions of galaxies within groups and clusters show that there is dark matter *between* galaxies as well
- *gravitational lensing* also provides a different sort of evidence for the existence of dark matter
- CMB+BAO: best constraints



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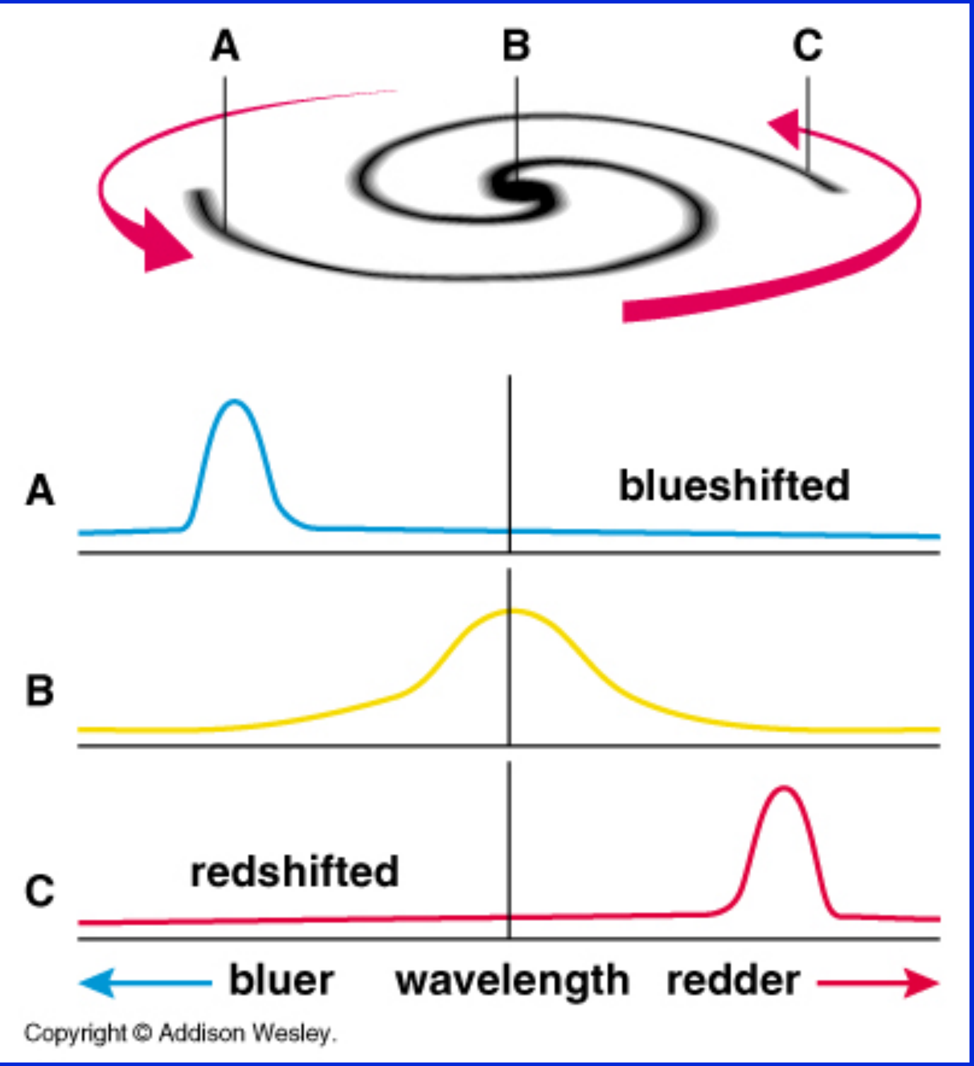
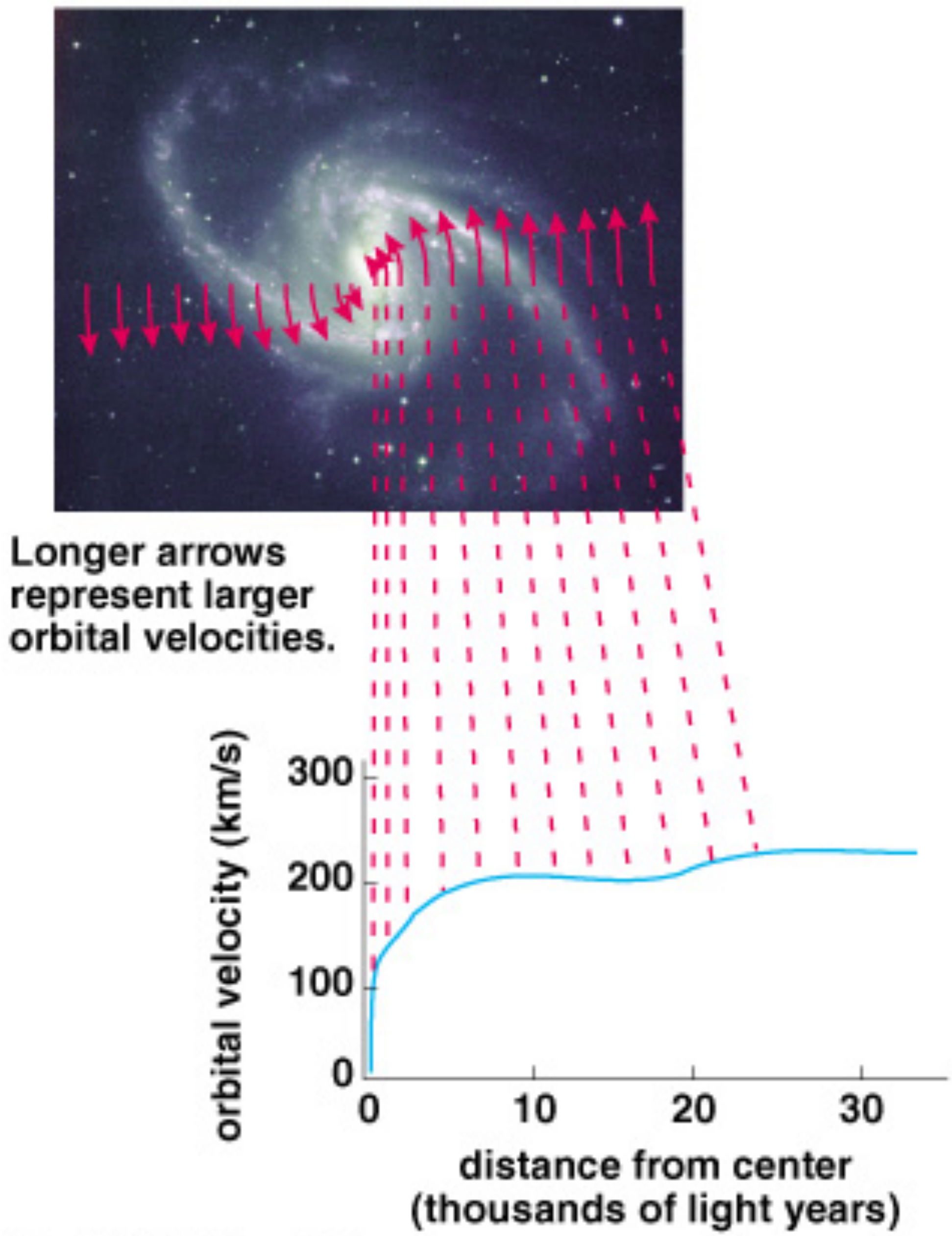
Evidence for dark matter in galaxies





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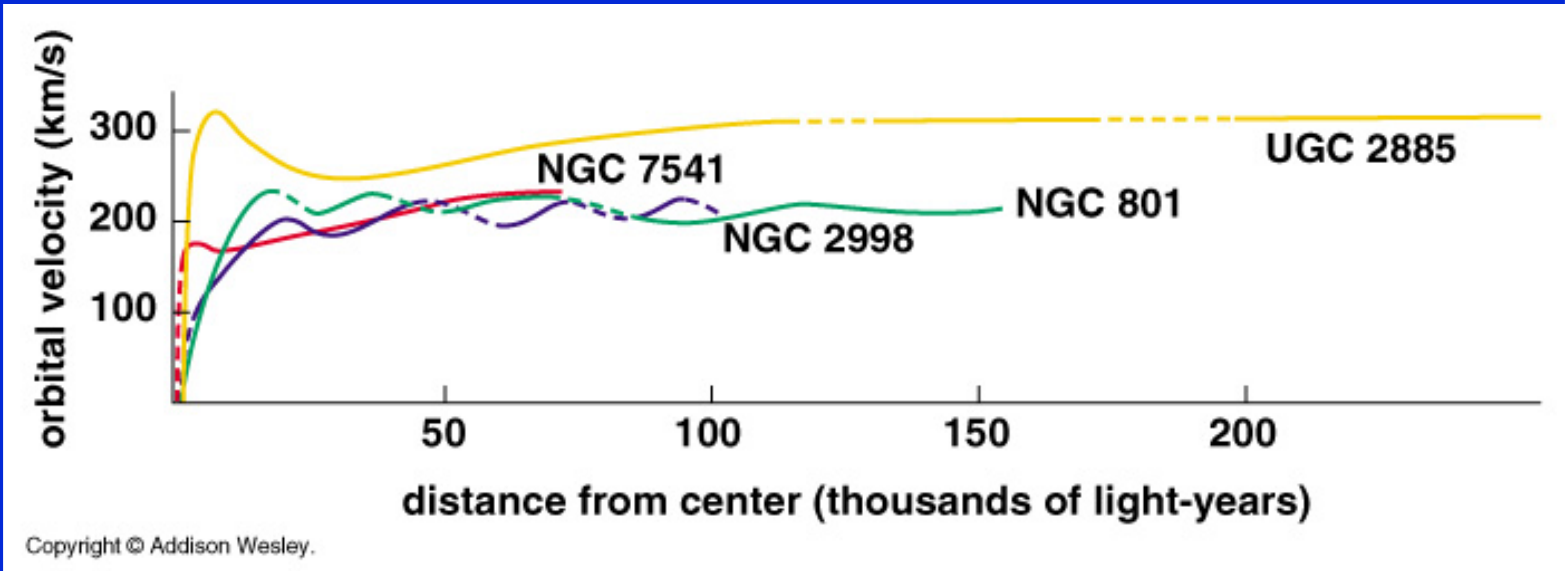
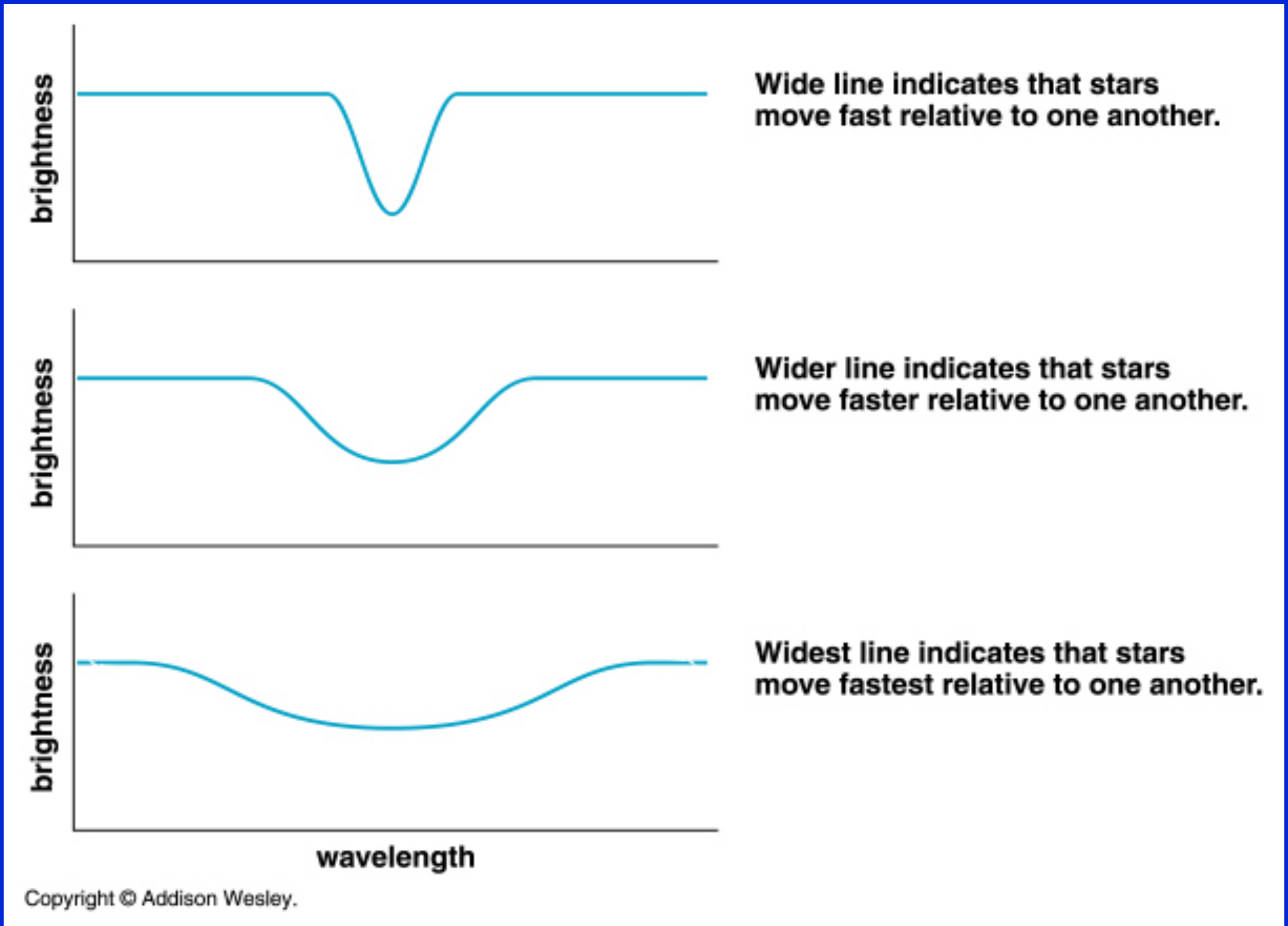
rotation curves of four typical spiral galaxies



elliptical galaxies: absorption line broadening



mass-to-light ratio

- the mass-to-light ratio is defined as the total mass in solar masses divided by the luminosity in solar luminosities
- for example: the mass of the Milky Way within the Solar radius is about $9 \times 10^{10}\ M_{sun}$, and the luminosity is $1.5 \times 10^{10}\ L_{sun}$

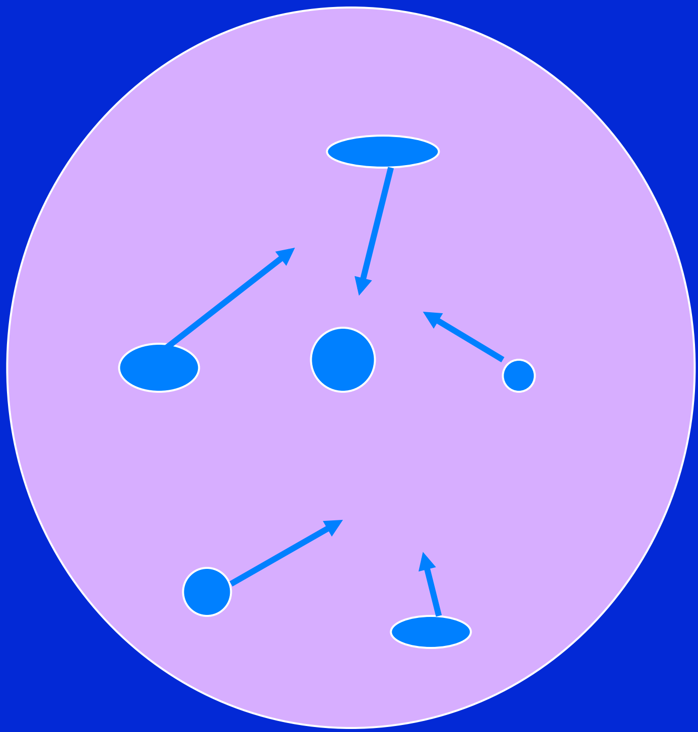
  → the mass-to-light ratio is 6 M_{sun}/L_{sun}.

mass-to-light ratio depends on radius

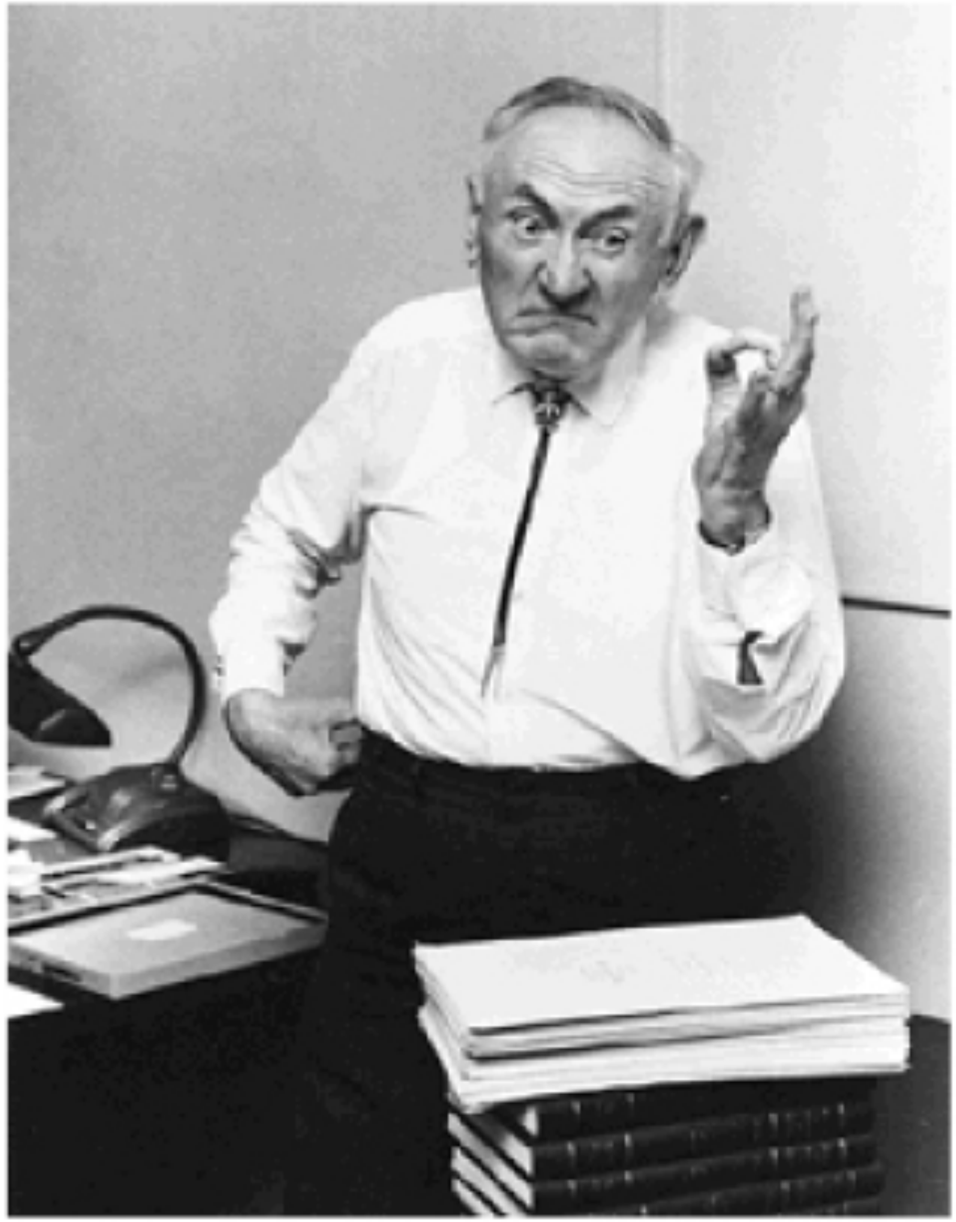
- the motions of satellite galaxies around the Milky Way show that the mass within 100 kpc is about 10^{12} M_{sun}.
- the total luminosity within this radius is about $2x10^{10}$ L_{sun}, so the mass-to-light ratio is about 50 M_{sun}/L_{sun}!
- about 90% of the mass within 100 kpc is dark matter.

dark matter in clusters

- we can find the mass of a cluster using the velocities of galaxies relative to the central galaxy



Fritz Zwicky



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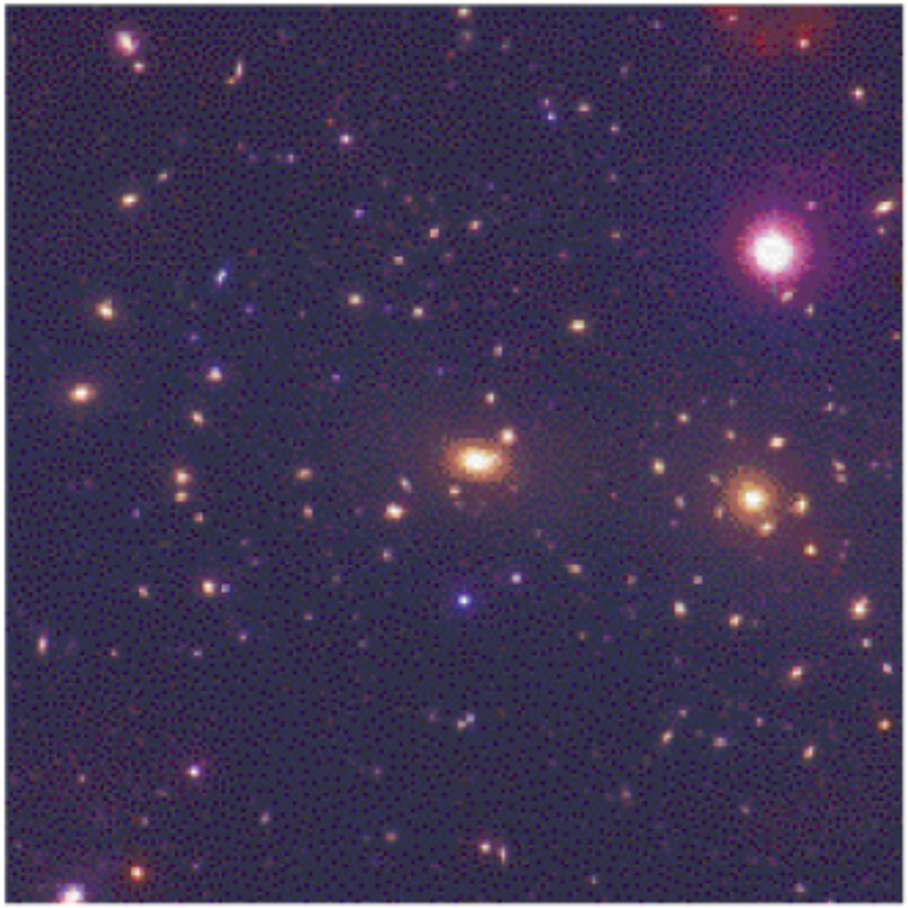
clusters are full of hot gas



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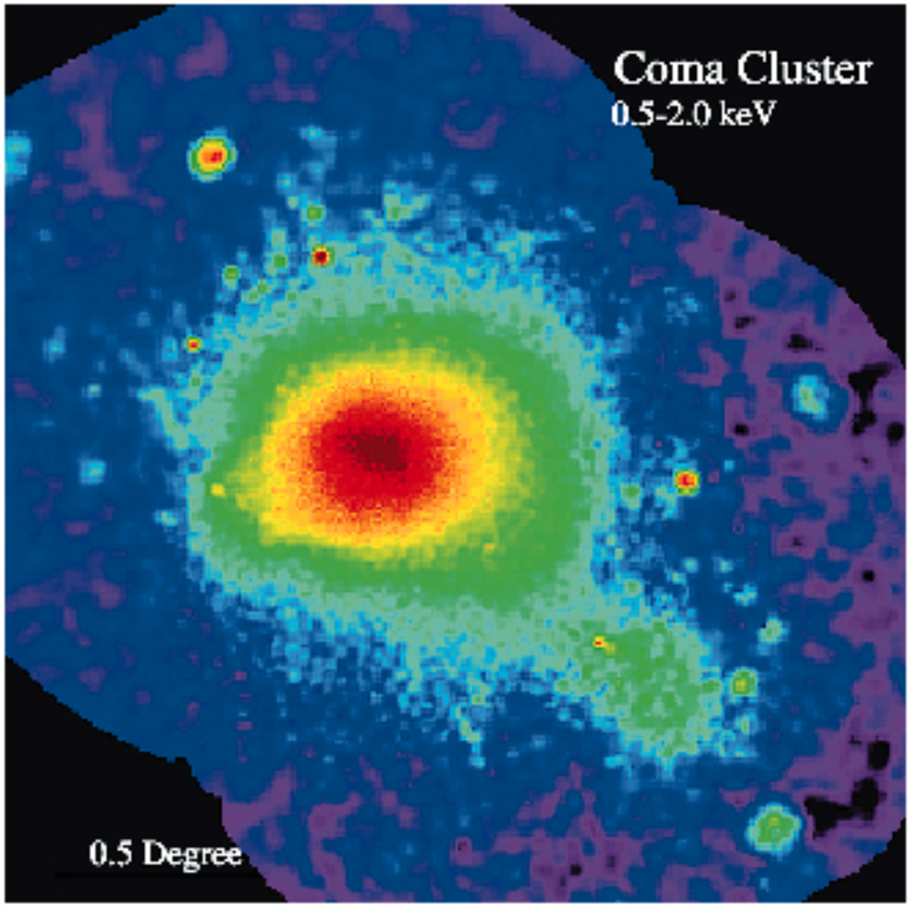

(b)

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another way to weigh a cluster

- assuming that the hot gas in clusters is in gravitational equilibrium, we can use the *temperature* of the gas to estimate the mass of the cluster
- $v = (0.1\ \text{km/s}) \times (T/\text{Kelvin})^{1/2}$
- then use v in the usual formula
  - $M = (v^2 \times r)/G$

Example: the Coma cluster

The galaxies in the Coma cluster have an average orbital velocity of 1200 km/s within a radius of 1.5 Mpc. The hot gas has an average temperature of 10^8 K. Find the mass of the Coma cluster using both methods. Do they agree?

a third way: gravitational lensing

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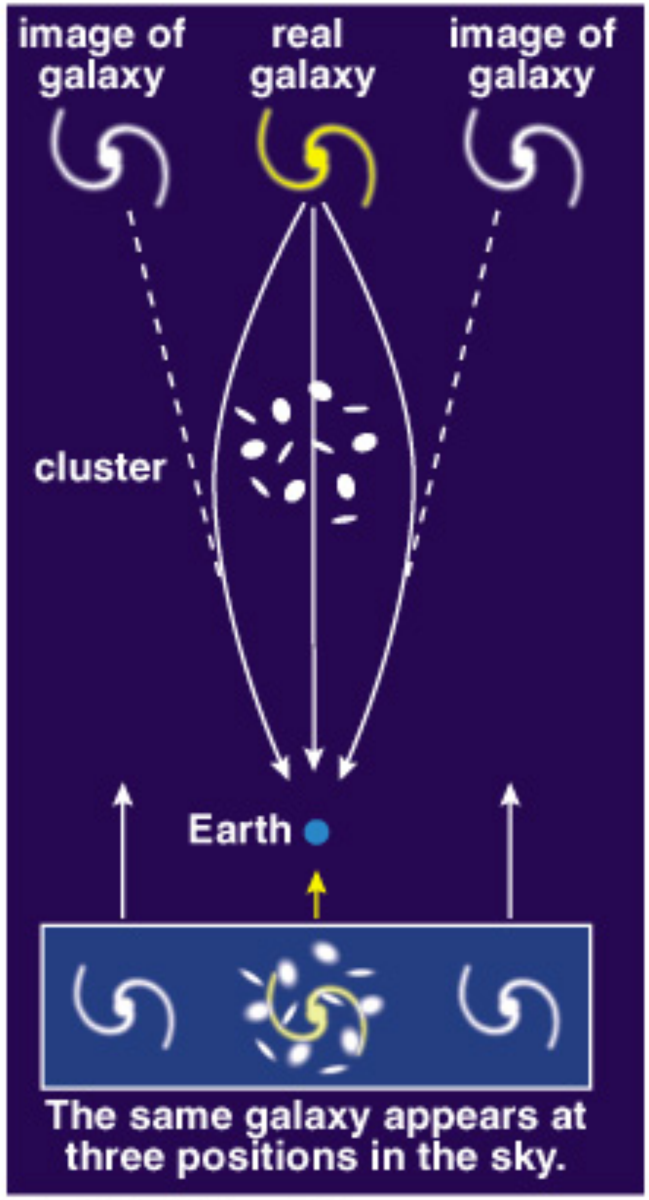

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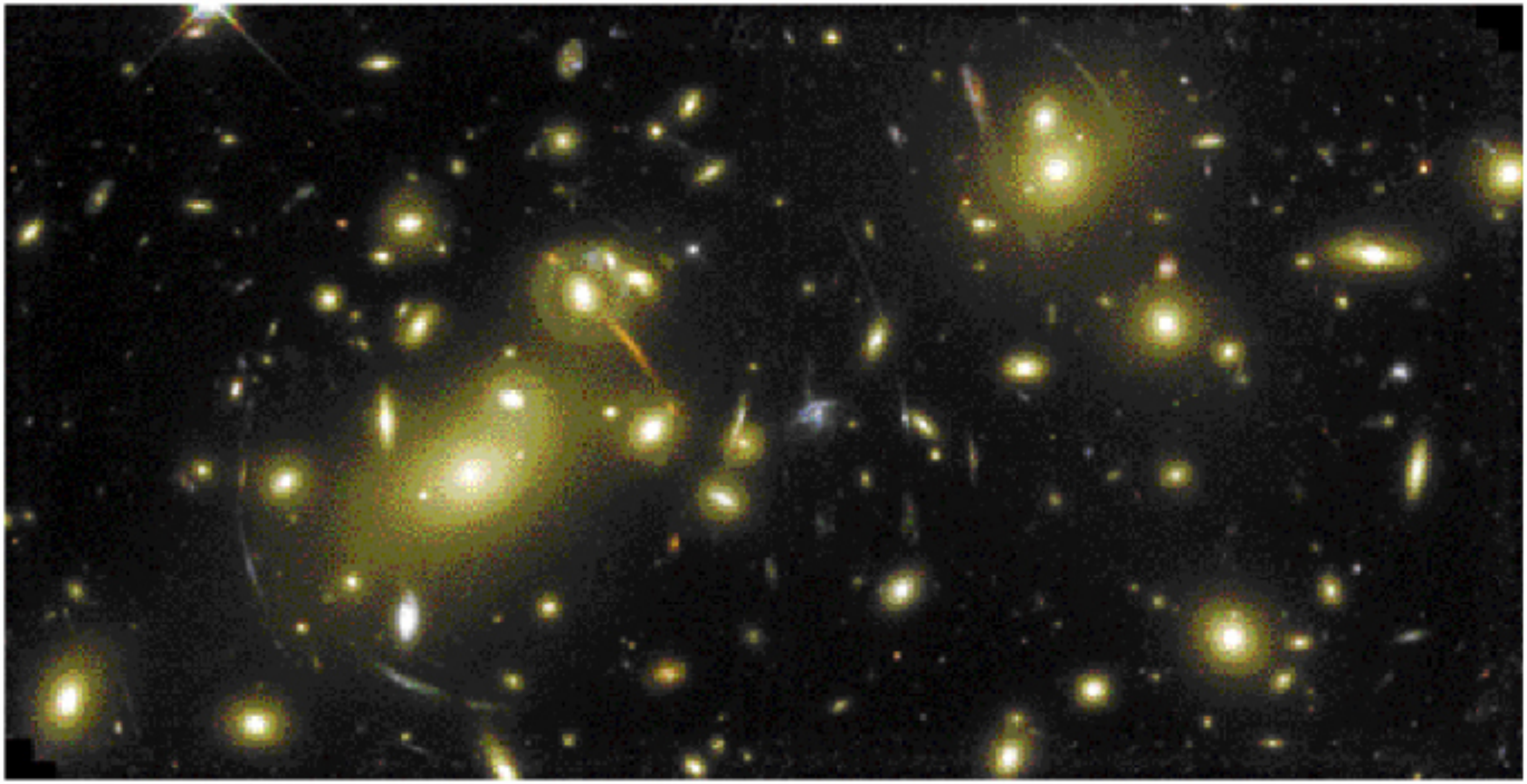
Abell 2218



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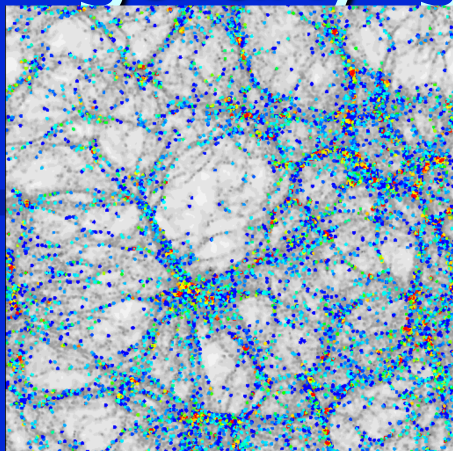
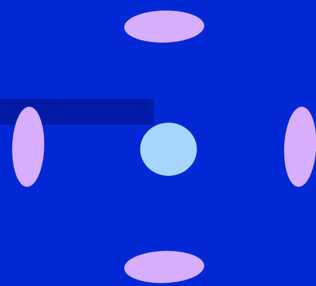
cluster mass-to-light ratios

- all three methods (galaxy velocities, hot gas temperatures, and gravitational lensing) show that clusters have mass-to-light ratios of 100-500 M_{sun}/L_{sun}!

galaxy-galaxy lensing





$$R = r_L \Theta$$

$$\gamma_T = \frac{\Delta\Sigma(R)}{\Sigma_{\rm crit}}$$

$$\Delta\Sigma(R) = \bar{\Sigma}(R) - \Sigma(R)$$

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G} \frac{r_S}{(1+z_L) r_L r_{LS}}$$

- dark matter around galaxies induces tangential distortion of background galaxies: extremely small, 0.1%

♦Useful to have redshifts of foreground galaxies: SDSS Express signal in terms of projected surface density and transverse r

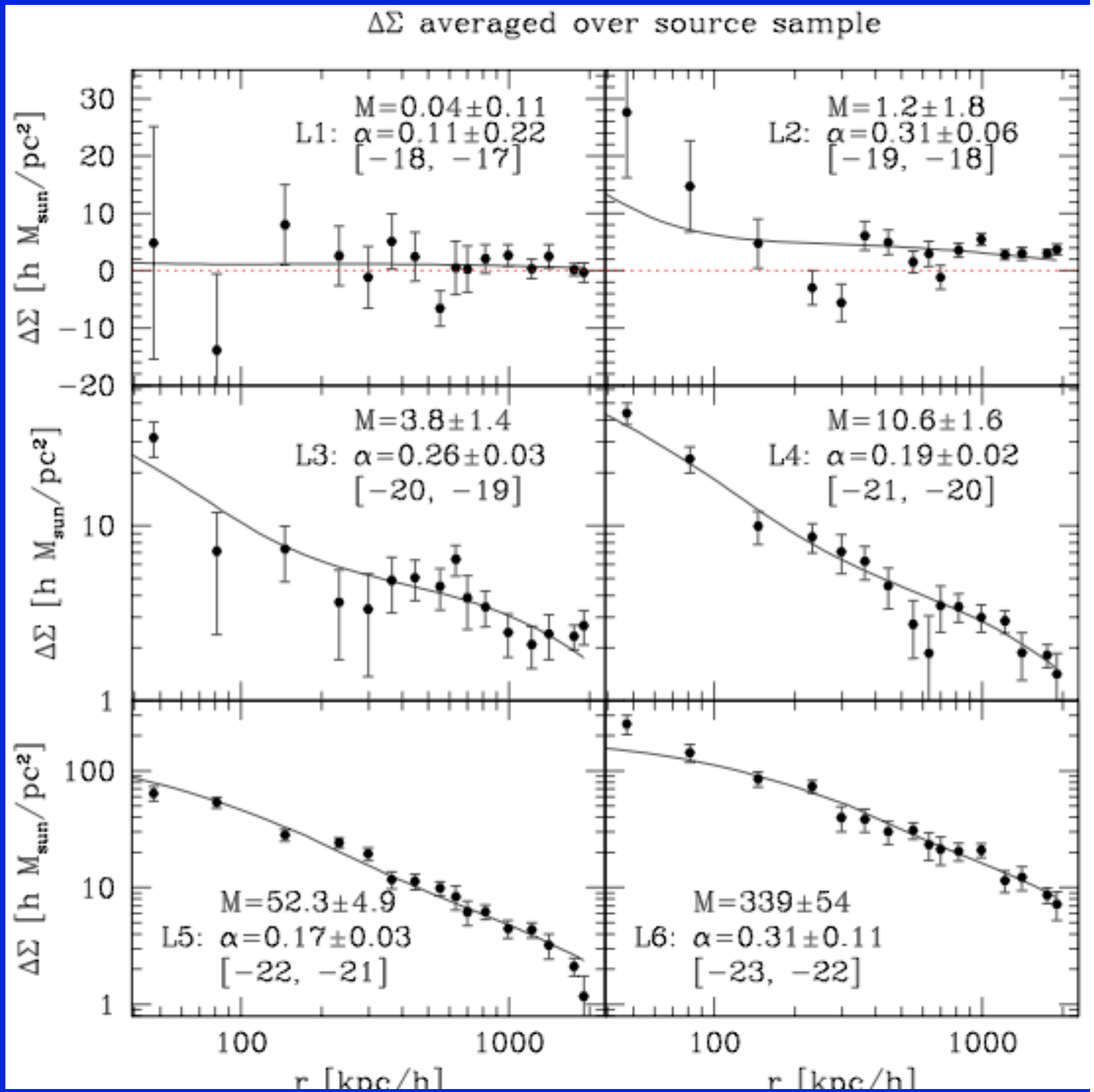
♦Signal as a function of galaxy luminosity, type…

Galaxy-galaxy lensing measures galaxy-dark matter correlations

Goal: lensing determines dark matter masses

Halo mass increases with galaxy luminosity

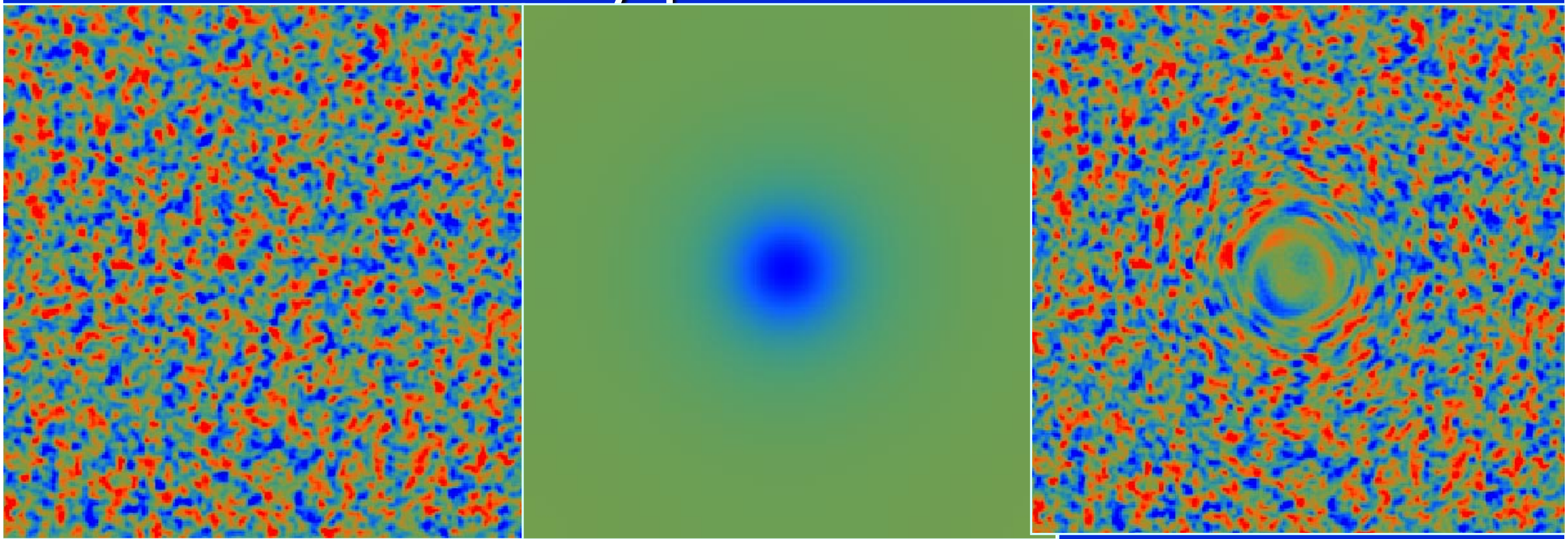
SDSS gg: 300,000 foreground galaxies, 20 million background



Effect of gravitational lensing on CMB

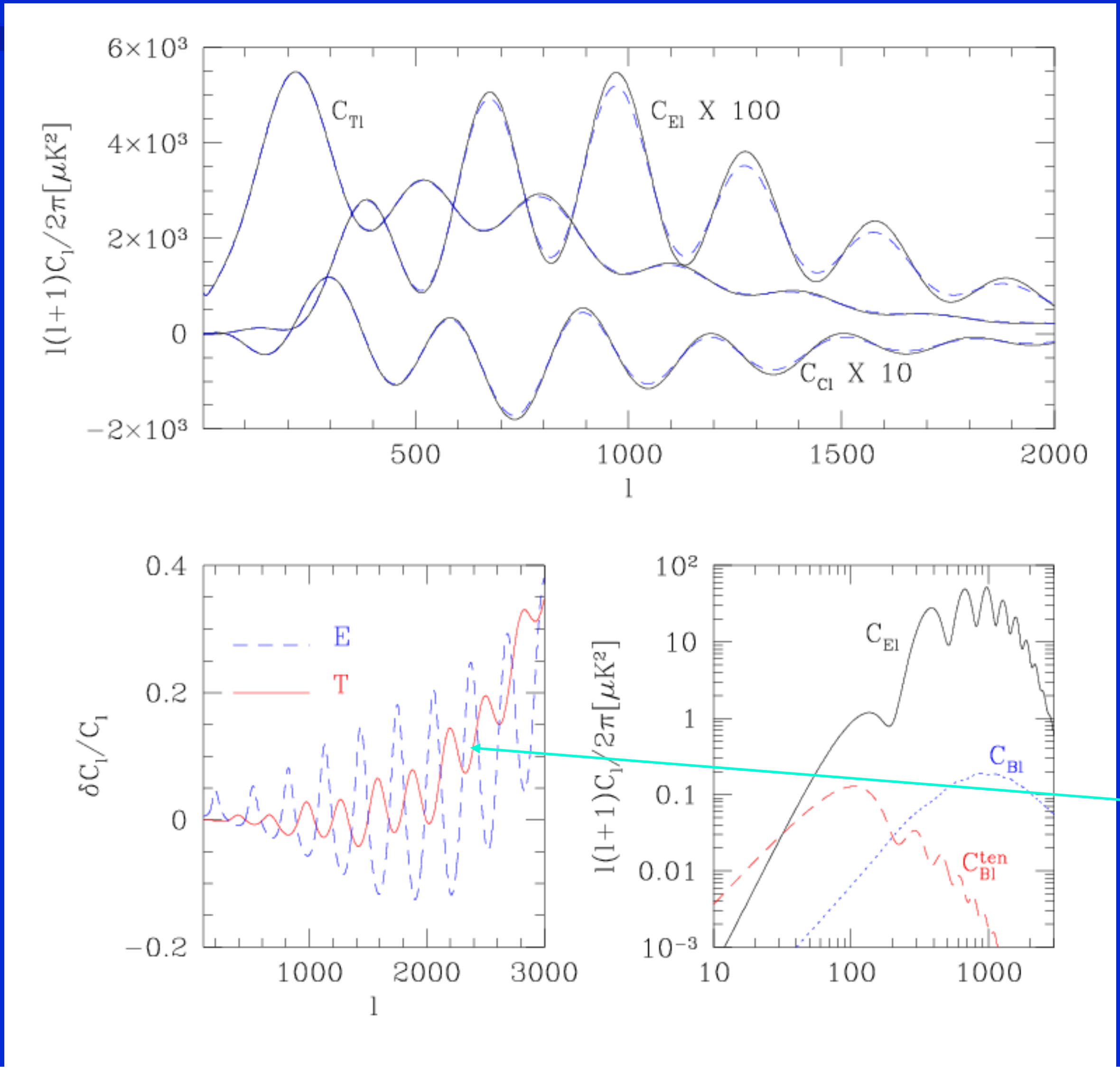
$$T_{lensed}(\vec{\mathbf{n}}) = T_{unlensed}(\vec{\mathbf{n}} + \vec{\mathbf{d}}) \qquad \vec{\mathbf{d}} = -2\vec{\nabla}\nabla^{-2}\kappa$$

- Here κ is the convergence and is a projection of the matter density perturbation.



Okamoto and Hu 2002

Lensing effect on CMB power spectra

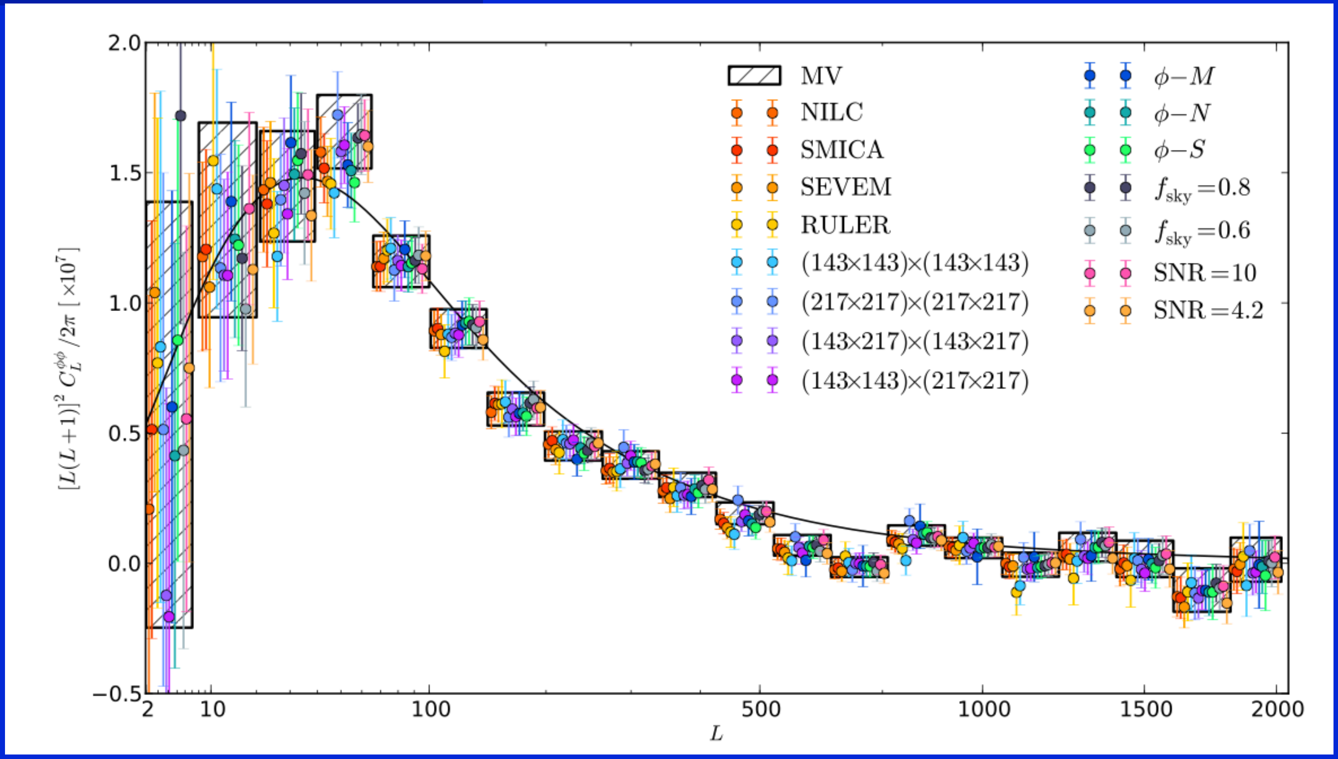


Smoothing and power transfer

Detected by several sigma in Planck

State of the art in CMB lensing: Planck

40 sigma in Planck 2015



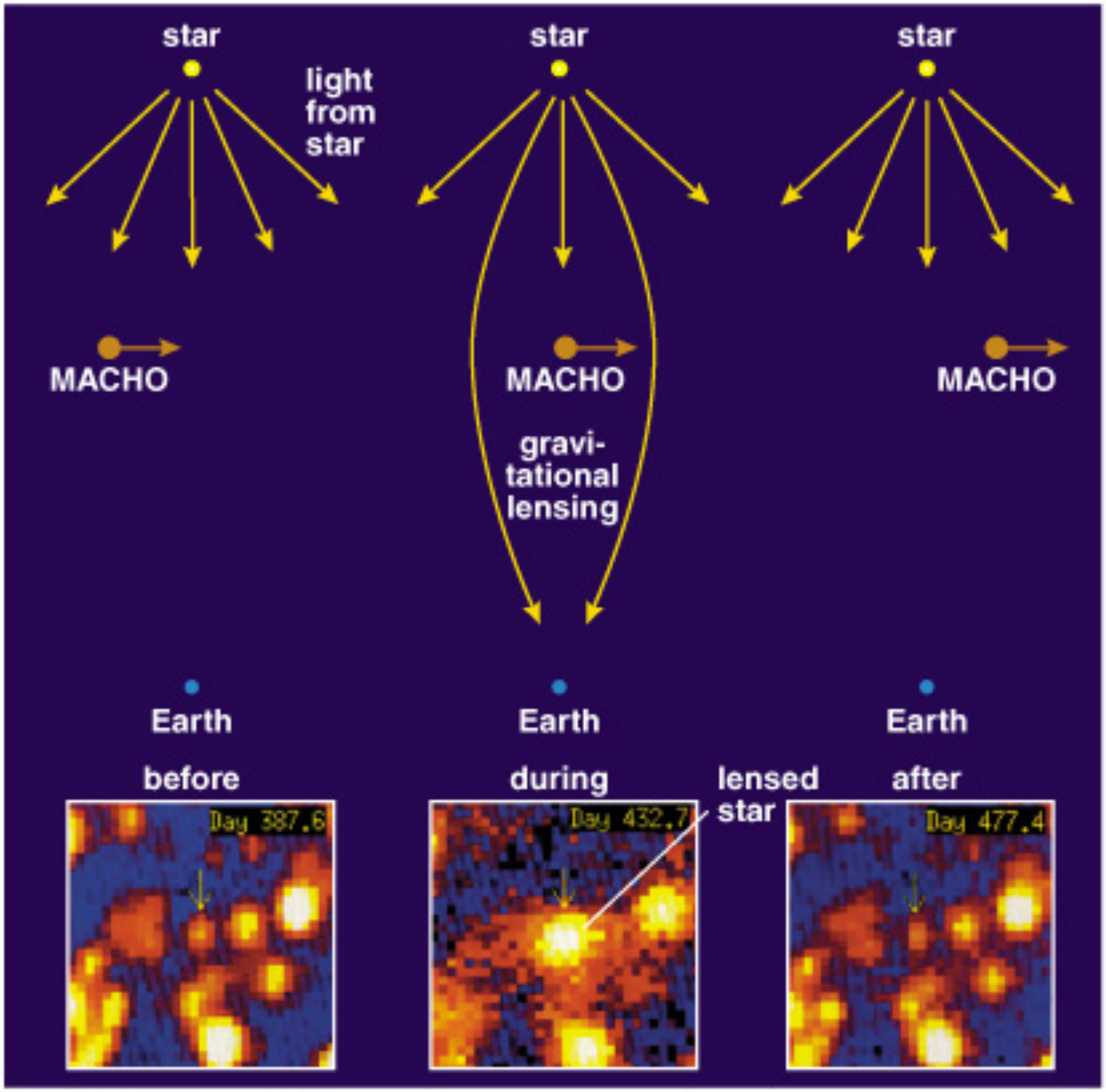
Future CMB experiments (stage 3 and 4): 200+ sigma

dark matter: what is it?

- there are two basic possibilities:
  1. *baryonic dark matter* – ‘ordinary matter’ (i.e. protons, neutrons, electrons, etc.) perhaps faint stars, brown dwarfs, planets, gas?
  2. *non-baryonic dark matter* – a new kind of particle that we have never seen directly

the search for MACHOs

- perhaps the dark “halo” of our Galaxy is made up of normal material (like faint stars or brown dwarfs)
- these are called Massive Compact Halo Objects (MACHOs).
- they might be detected by *microlensing*
- *Microlensing has been detected, but likely originates from faint stars (and a few planets)*



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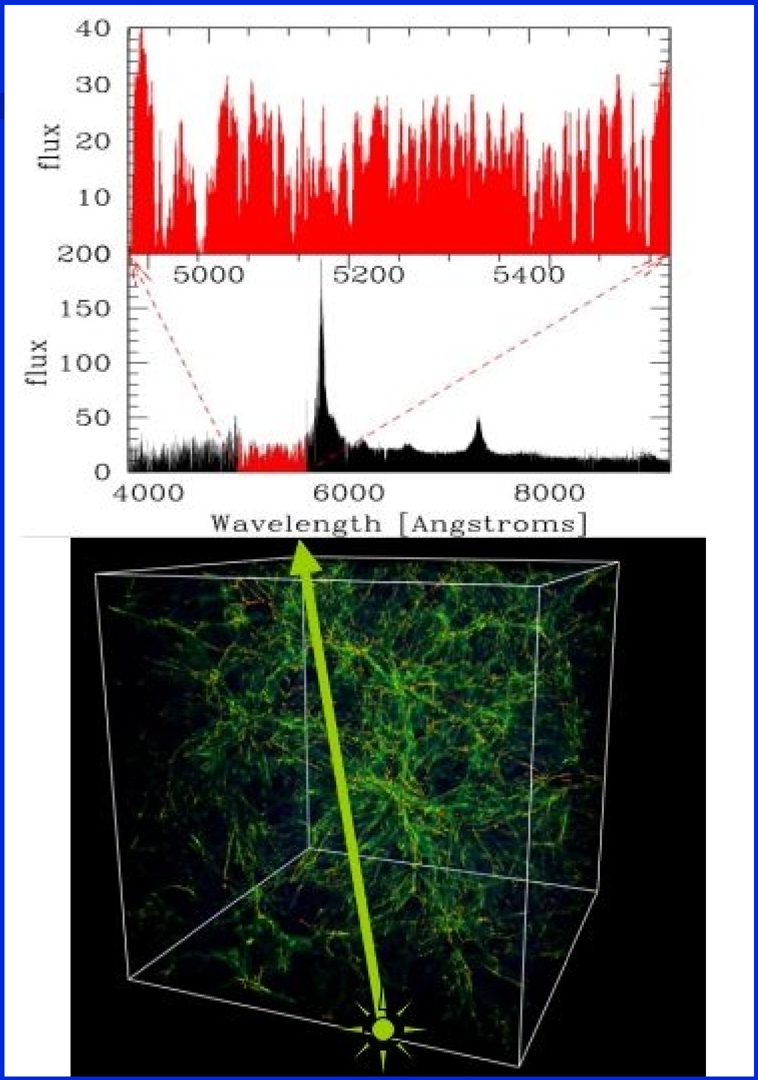
Hot, warm and cold dark matter

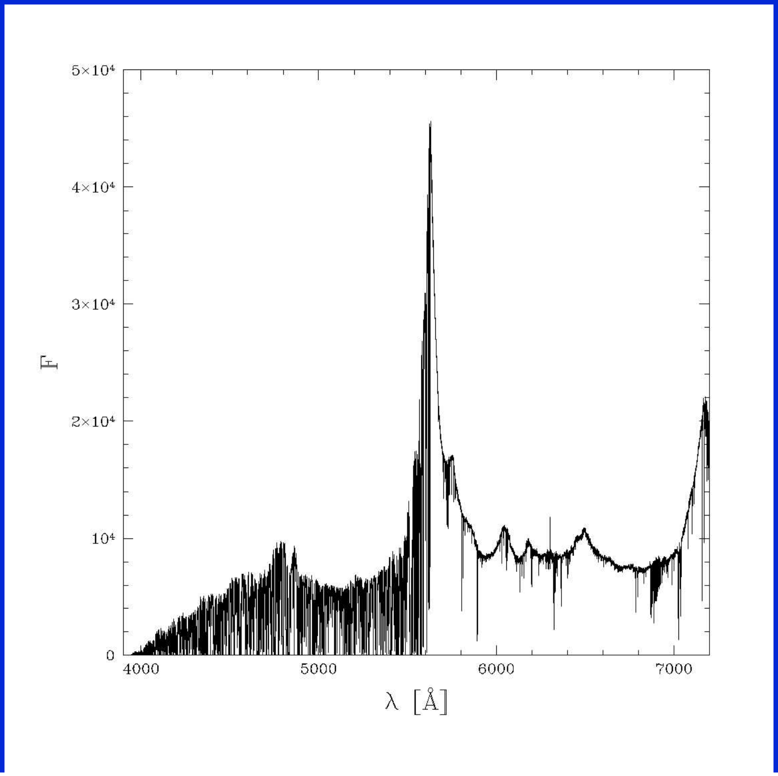
- *hot* dark matter is made of particles that move very close to the speed of light (such as neutrinos)
- *cold* dark matter is made of particles that move much slower than the speed of light
- we now think most of the dark matter must be cold or warm

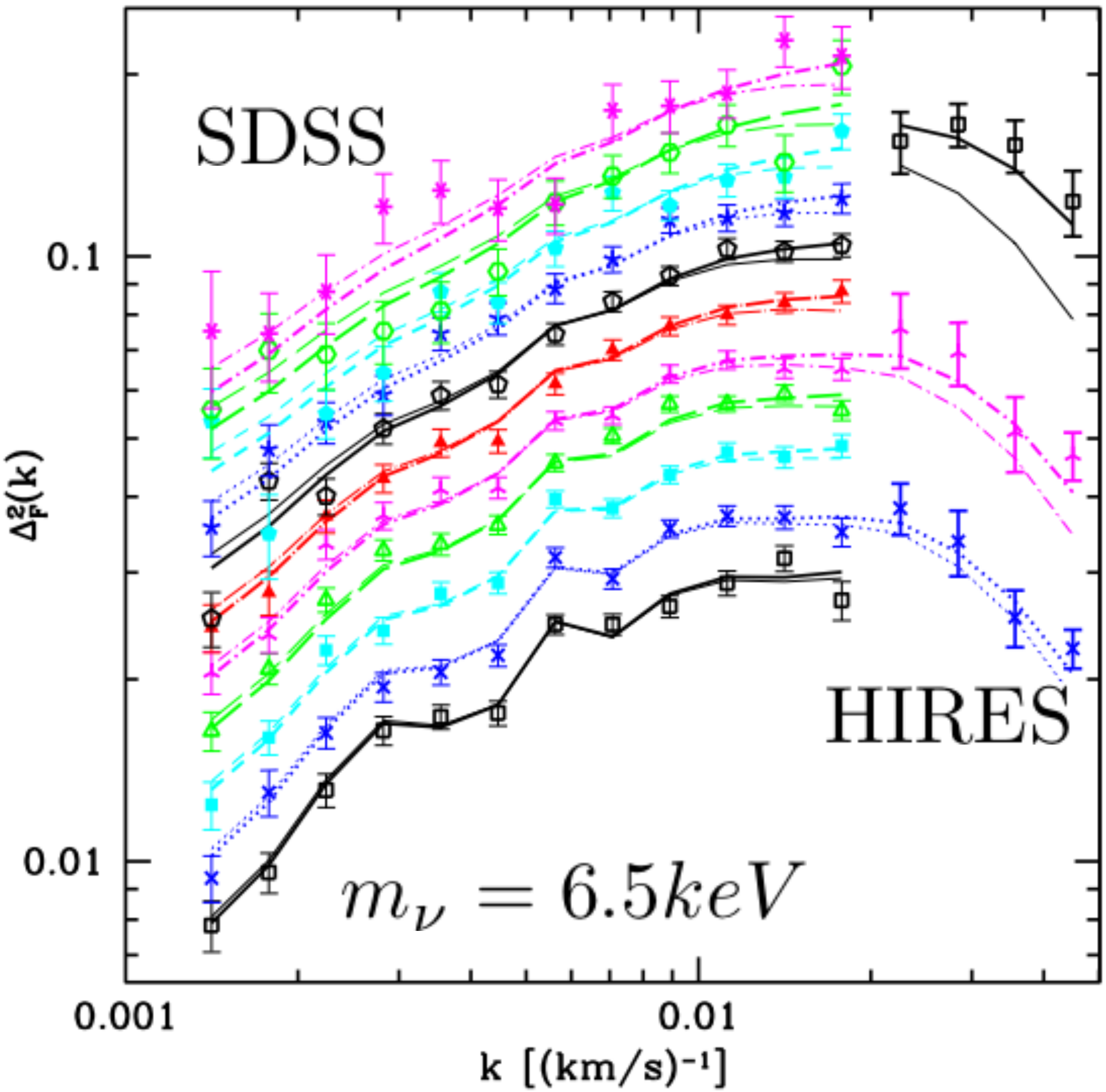
Ly-alpha forest: basics



SDSS Quasar Spectrum

- Neutral hydrogen leads to Lyman-α absorption at $\lambda < 1216\ (1+z_q)$ Å; it traces baryons, which in turn trace dark matter





WDM is a worse fit to the data

Neoclassical tests

- We wish to test Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8}{3}\pi G\bar{\rho} - Ka^{-2}$$

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

$$\bar{\rho} = \rho_m a^{-3} + \rho_{\rm de} a^{-3(1+w)} + \rho_\gamma a^{-4} + \rho_\nu F(a)$$

- Redshift-distance relation has come a long way since the days of Hubble

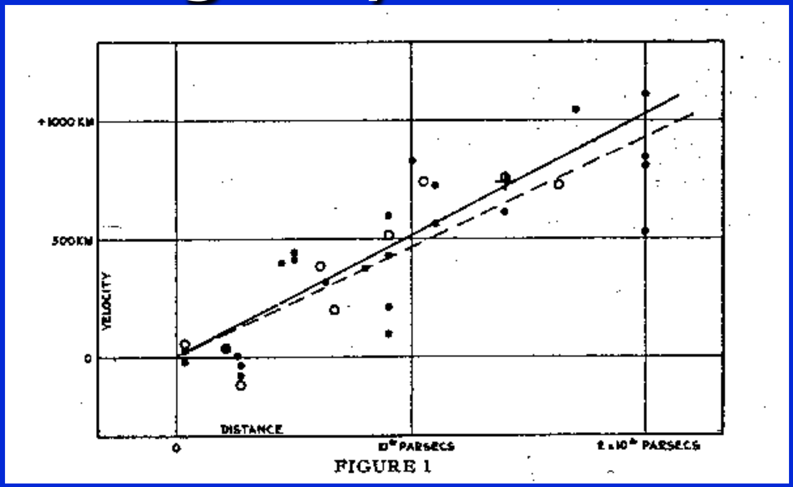
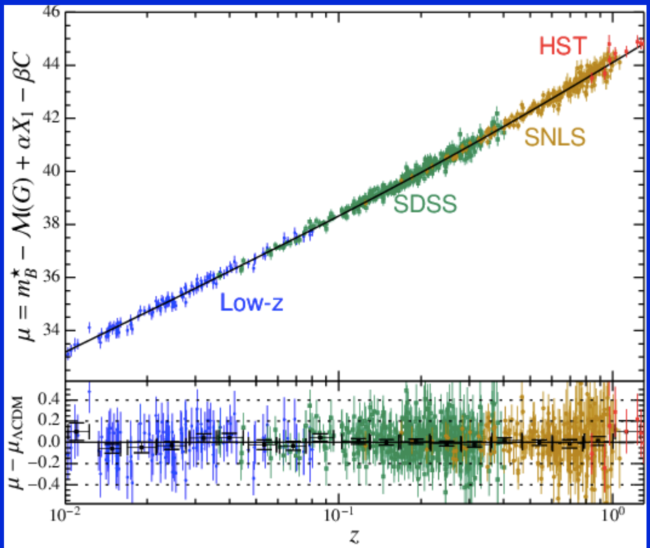
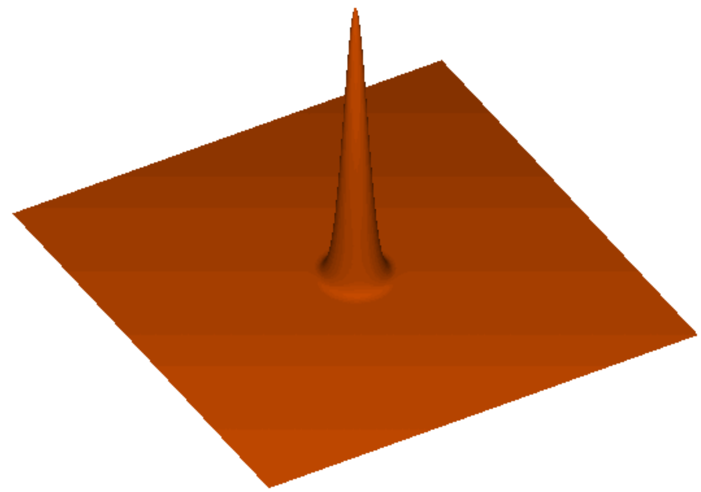


FIGURE 1



Baryonic Acoustic Oscillations

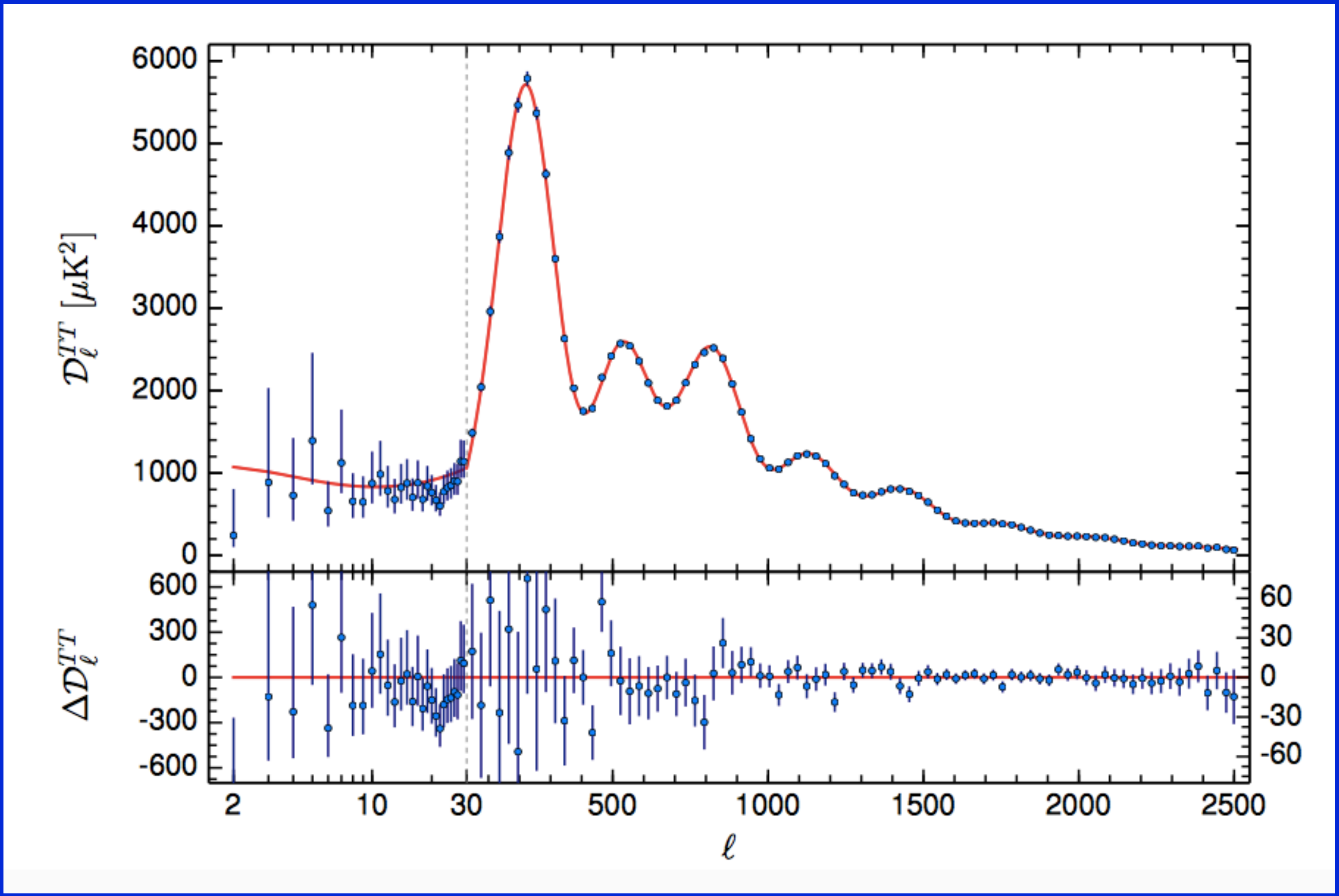
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 147 Mpc.
- Seen in CMB as acoustic peaks
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 147 Mpc.



Sound horizon at drag epoch (from Planck) : $r_d = 147.49 \pm 0.59 \text{ Mpc}$

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \qquad c_s(z) = 3^{-1/2} c \left[1 + \tfrac{3}{4}\rho_b(z)/\rho_\gamma(z)\right]^{-1/2}$$

Planck: state of the art in CMB



A Standard Ruler

- The acoustic oscillation scale depends on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$)

$$r_d \approx \frac{56.067 \exp\left[-49.7(\omega_\nu + 0.002)^2\right]}{\omega_{cb}^{0.2436}\, \omega_b^{0.128876}\, [1 + (N_{\rm eff} - 3.046)/30.60]} \ \text{Mpc}$$

- The CMB anisotropies measure these and fix the oscillation scale to <1%.
- In a redshift survey, we can measure this along and across the line of sight:
- BAO along los
- BAO tranverse
- Yields H(z) and $D_M(z)$

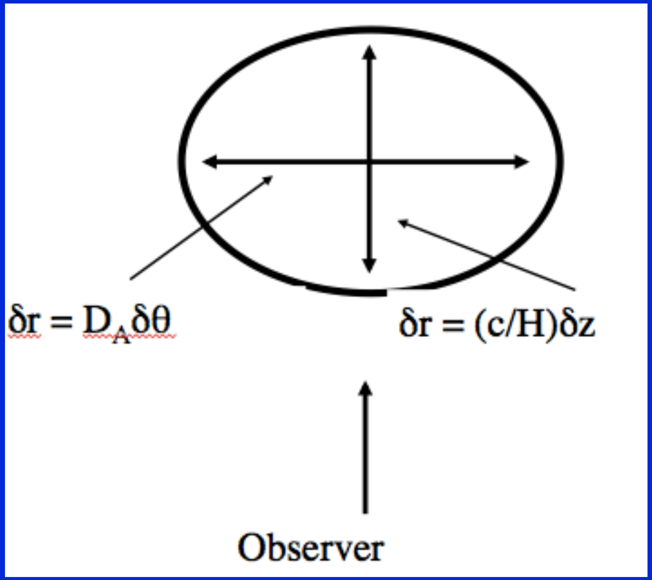
$$\Delta v_{BAO} = \frac{r_d}{1+z} H(z)$$

$$\Delta\theta_{BAO} = \frac{r_d}{1+z} \frac{1}{D_A(z)}$$

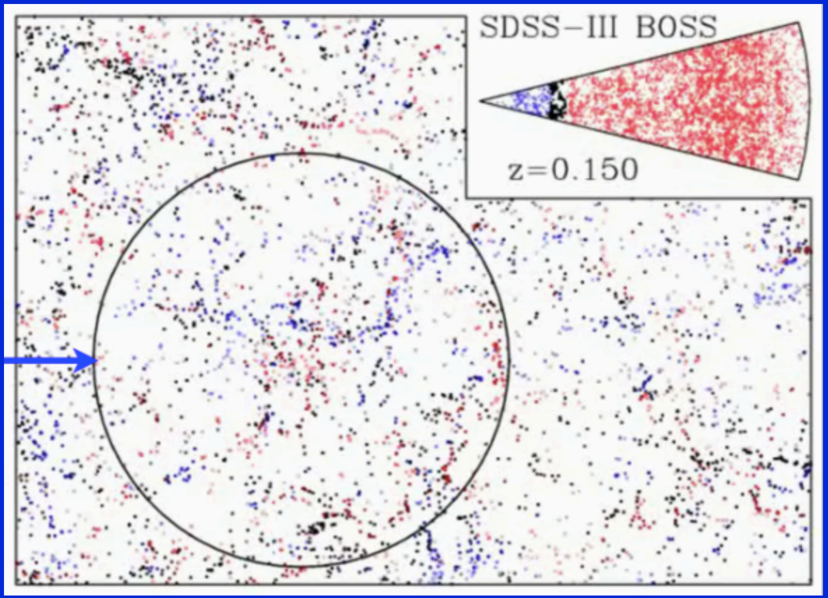
$$D_M(z) = \frac{c}{H_0} S_k\left(\frac{D_C(z)}{c/H_0}\right)$$

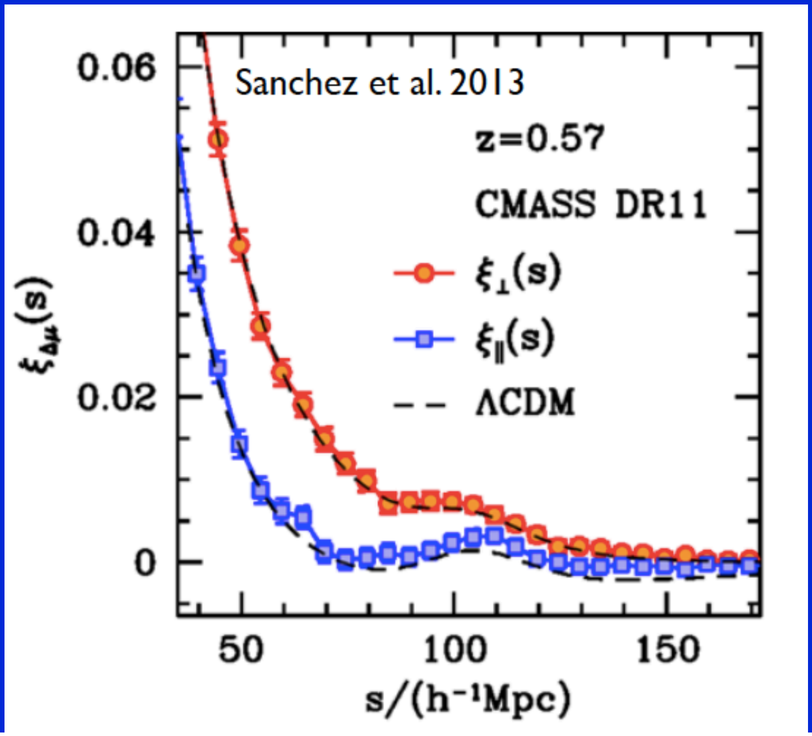
$$D_H(z) = c/H(z)$$

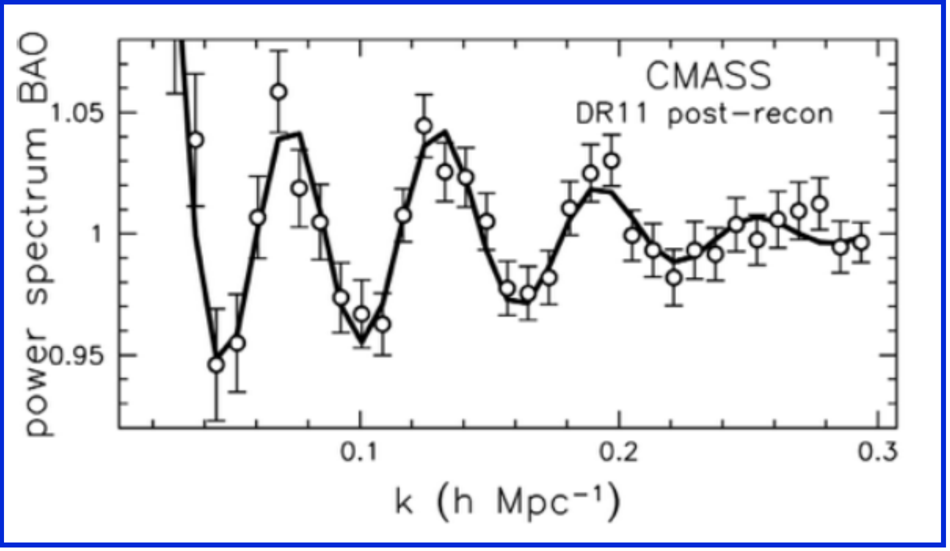
$$D_V(z) = \left[z D_H(z) D_M^2(z)\right]^{1/3}$$



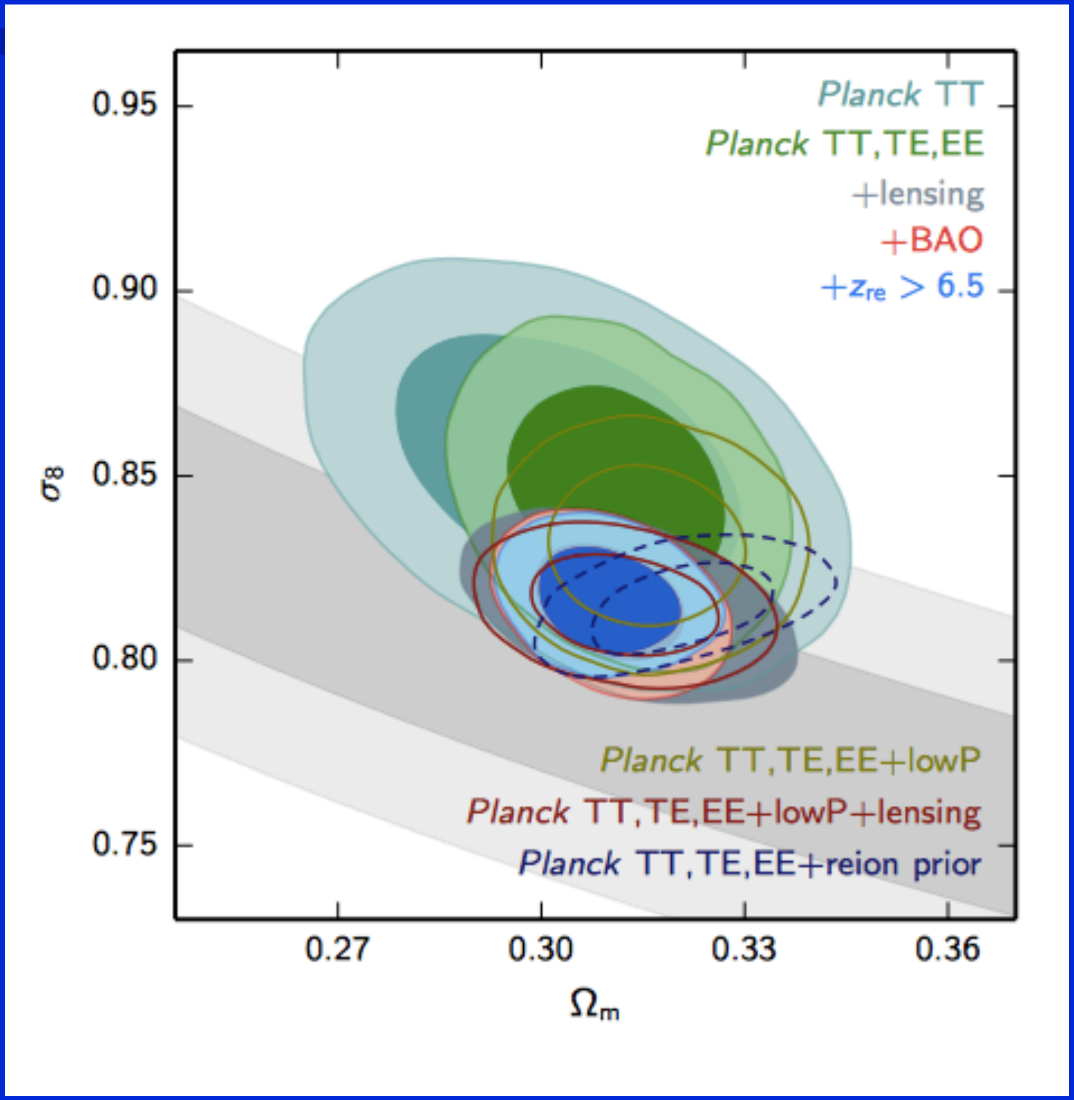
Hunting for BAO in BOSS: correlation function and power spectrum





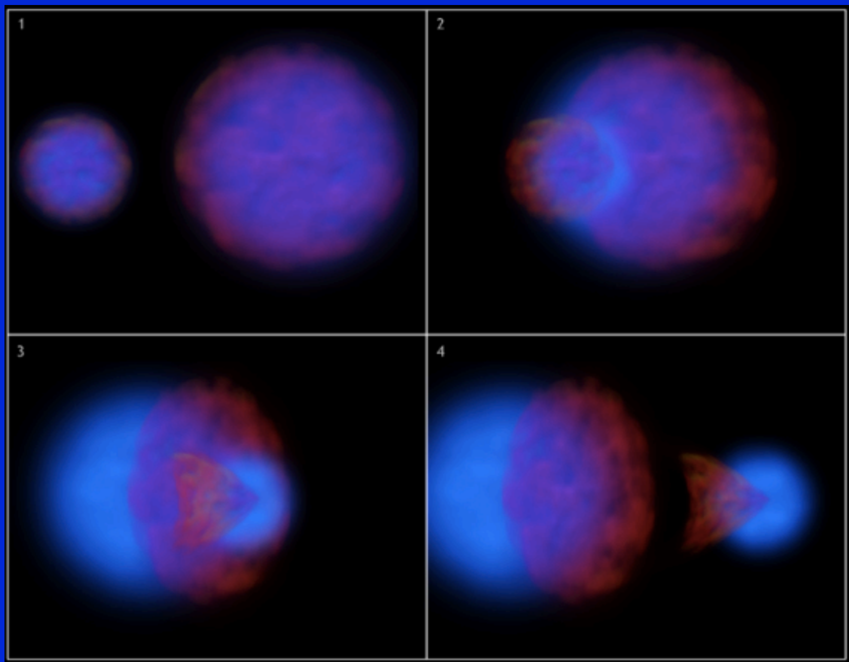


CMB+lensing+BAO



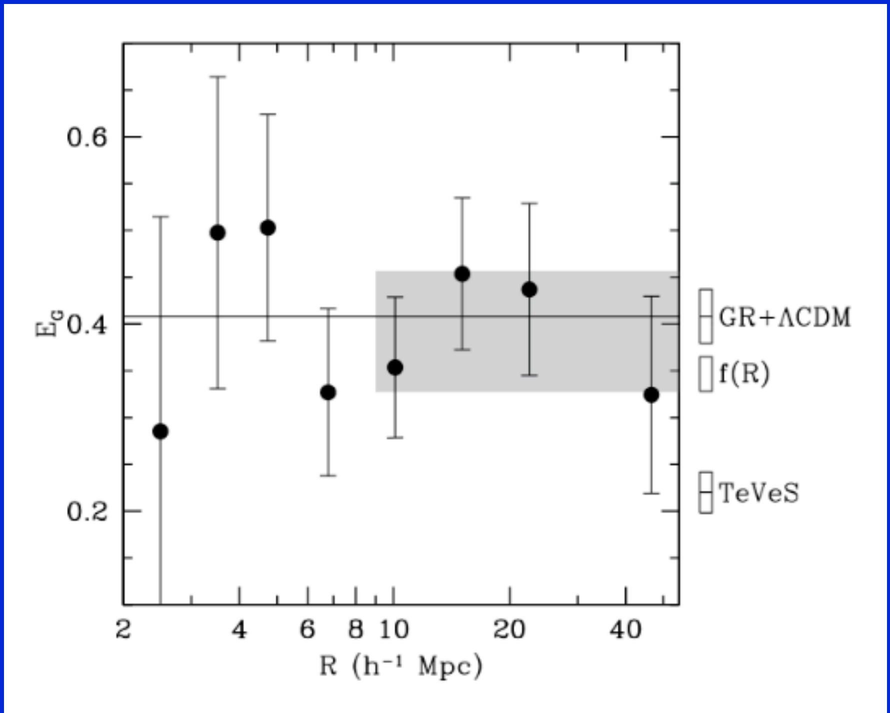
Alternatives? MOND

- Bullet cluster argues against MOND



Alternatives: TeVeS

- Lensing versus velocities modified in these models versus GR



Conclusions

- The case for dark matter is overwhelming
- It consists of 25% of critical density
- Data point to cold, non-interacting
- Possible topics: dark matter physics in CMB, LSS, self-interacting dark matter, warm dark matter, massive neutrinos as dark matter…