Astrophysical evidence of Dark Matter

Simone Ferraro
(sferraro@lbl.gov, LBNL)

Some material from Uros Seljak and Risa Wechsler

Dark Matter: do we need it?

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

A Brief History of Dark Matter

1930s - Discovery that cluster $\sigma_V \sim 1000$ km/s

1970s - Discovery of flat galaxy rotation curves

1980s - Most astronomers are convinced that dark matter exists around galaxies and clusters

1980-84 - short life of Hot Dark Matter theory

1983-84 - Cold Dark Matter (CDM) theory proposed

1992 - COBE discovers CMB fluctuations as predicted by CDM; CHDM and ΛCDM are favored CDM variants

1998 - SN Ia and other evidence of Dark Energy

2000 - ΛCDM is the Standard Cosmological Model

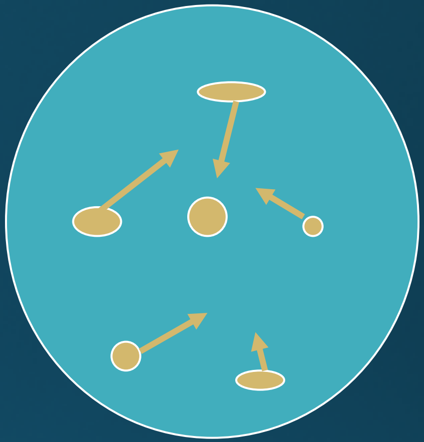
2003-12 - WMAP, Planck, and LSS confirm ΛCDM predictions

soon? Discovery of dark matter particles??

slide: J. Primack

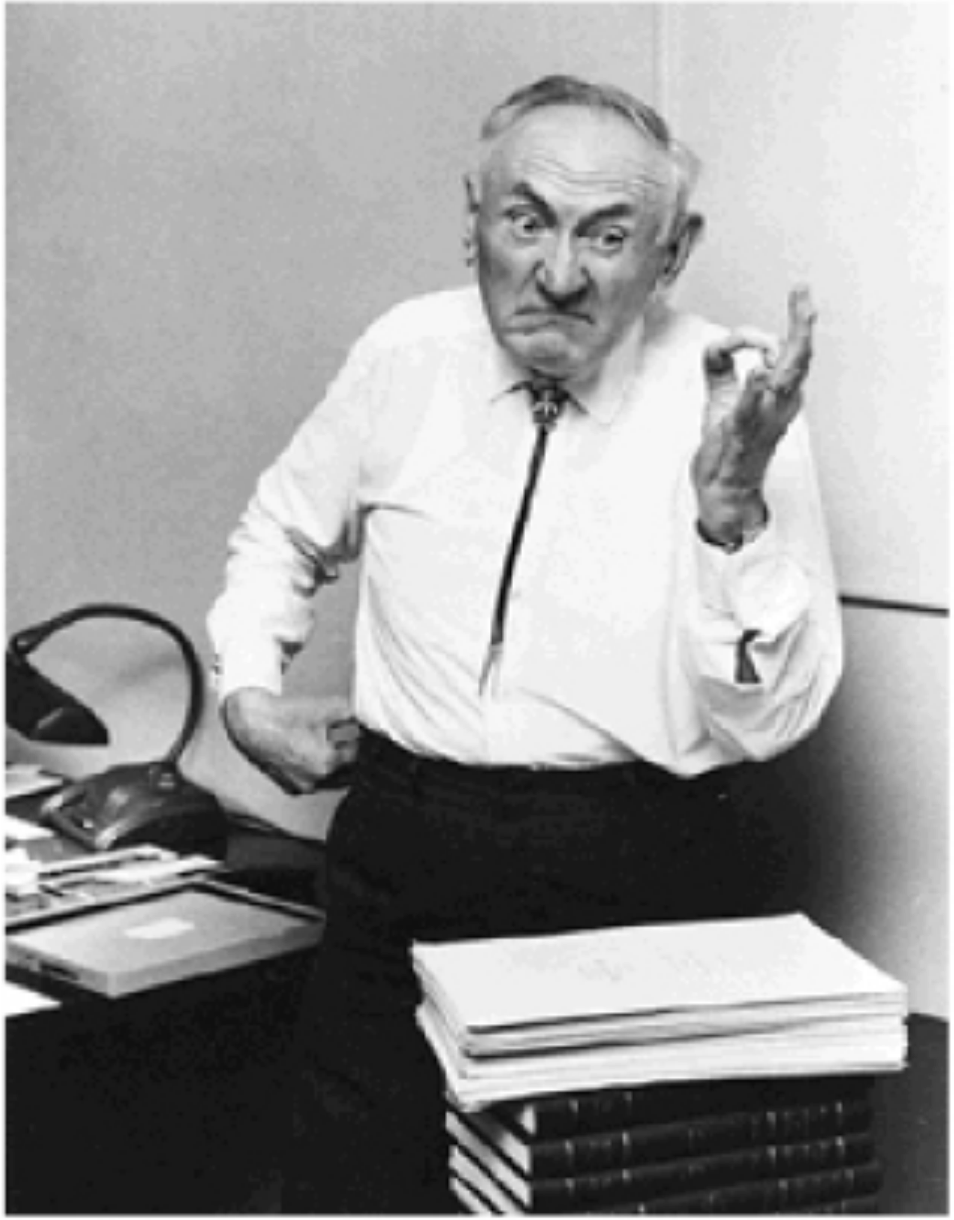
History: Dark Matter in clusters

- 1933: Fritz Zwicky measured the velocity dispersion of the Coma Cluster (~1000 galaxies)
- Virial theorem → mass > 400 x what is expected from luminous matter!

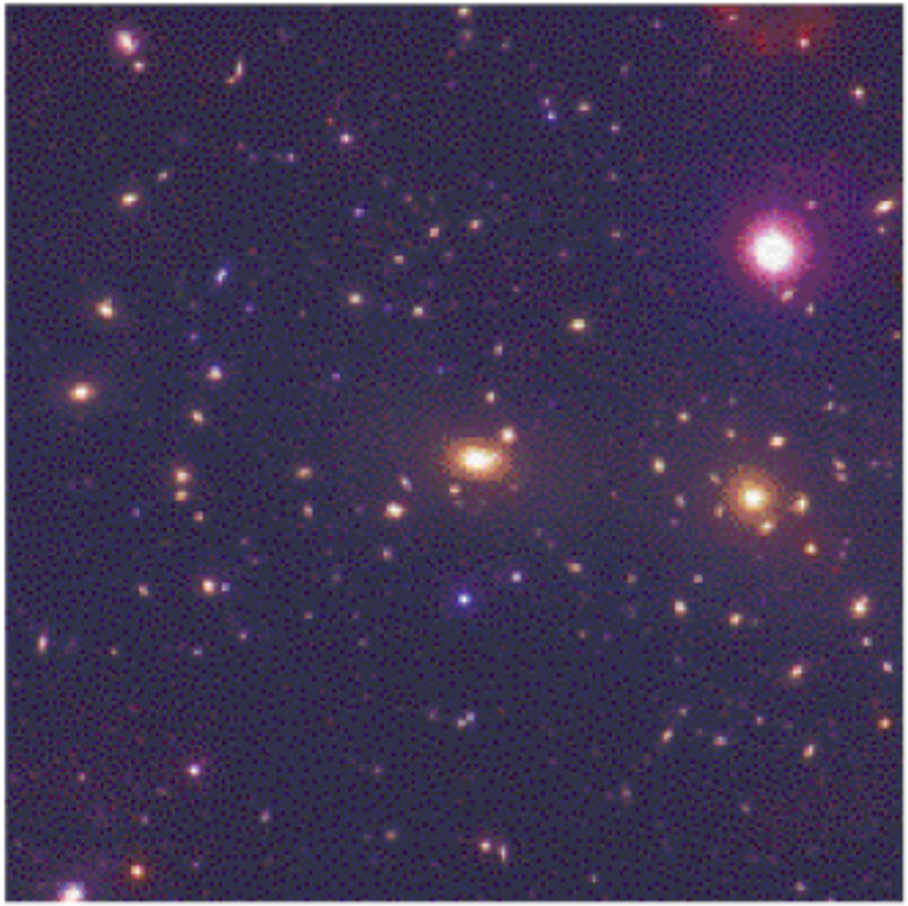


Coma cluster

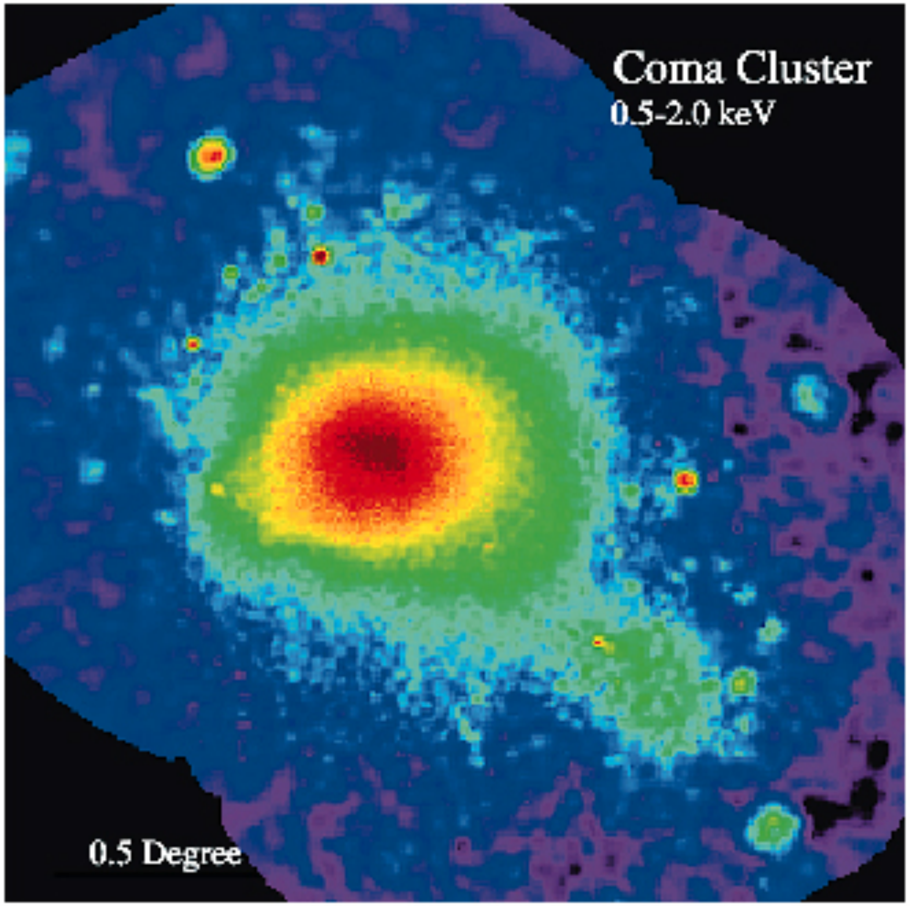
Fritz Zwicky



Clusters are full of hot gas



(a)



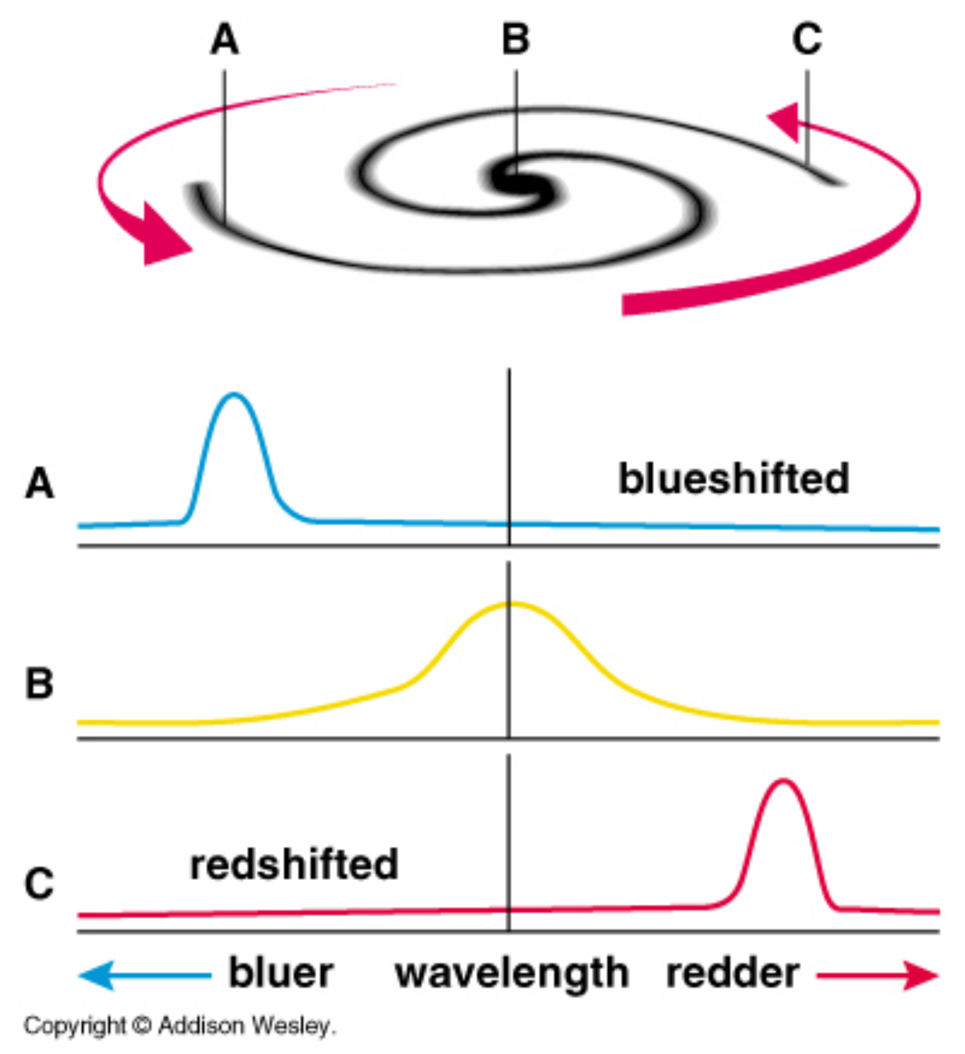
(b)

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
  - $M = (v^2 \times r)/G$

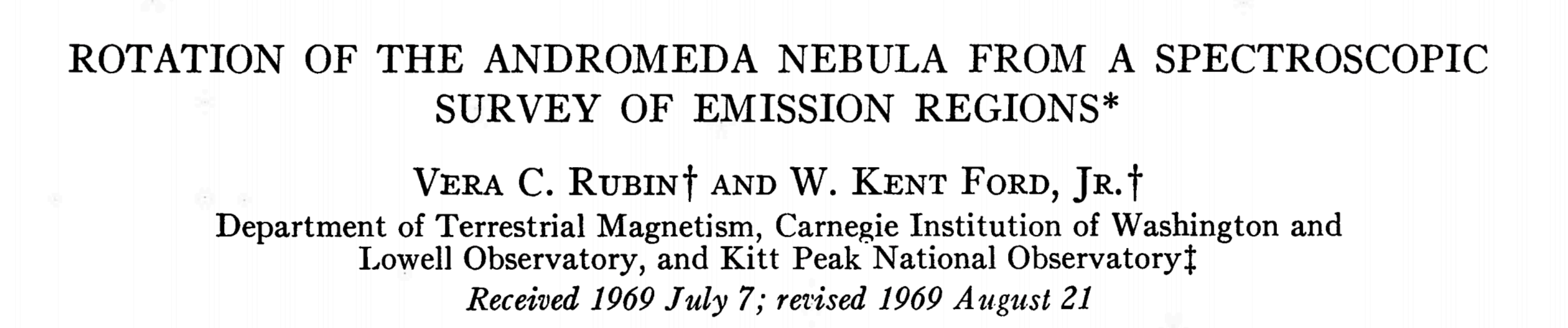
Evidence for dark matter in galaxies

Vera Rubin



Copyright © Addison Wesley.

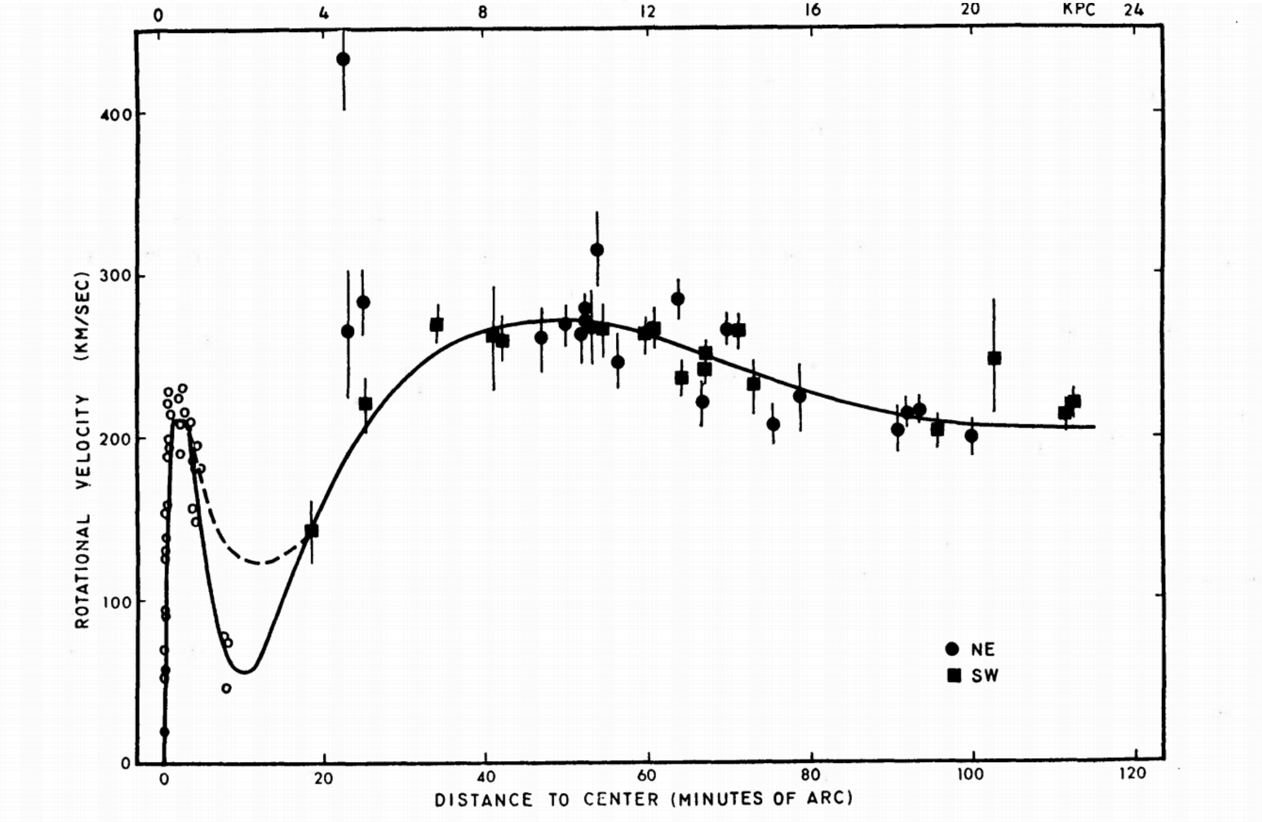
Rubin, Ford (1969)

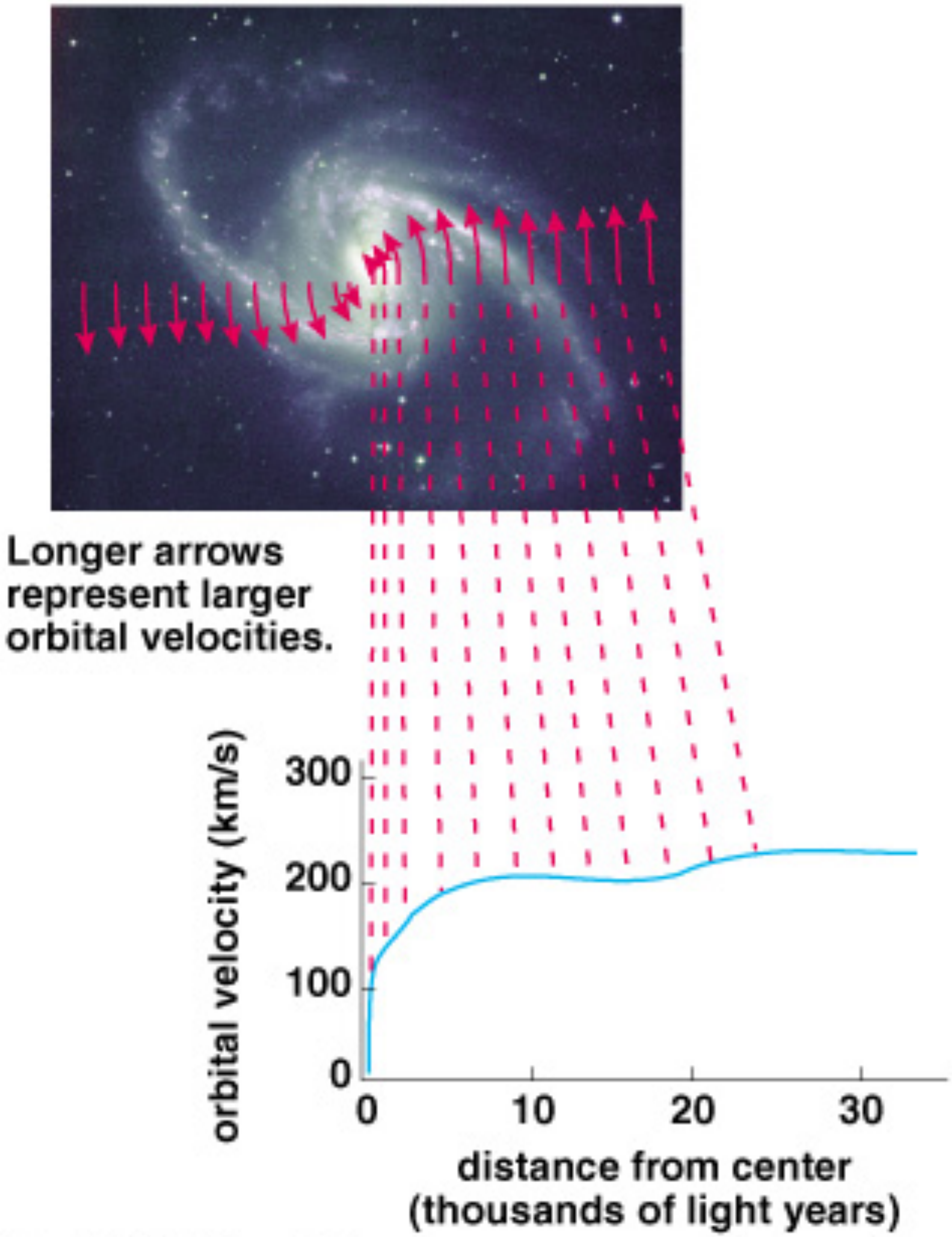


ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

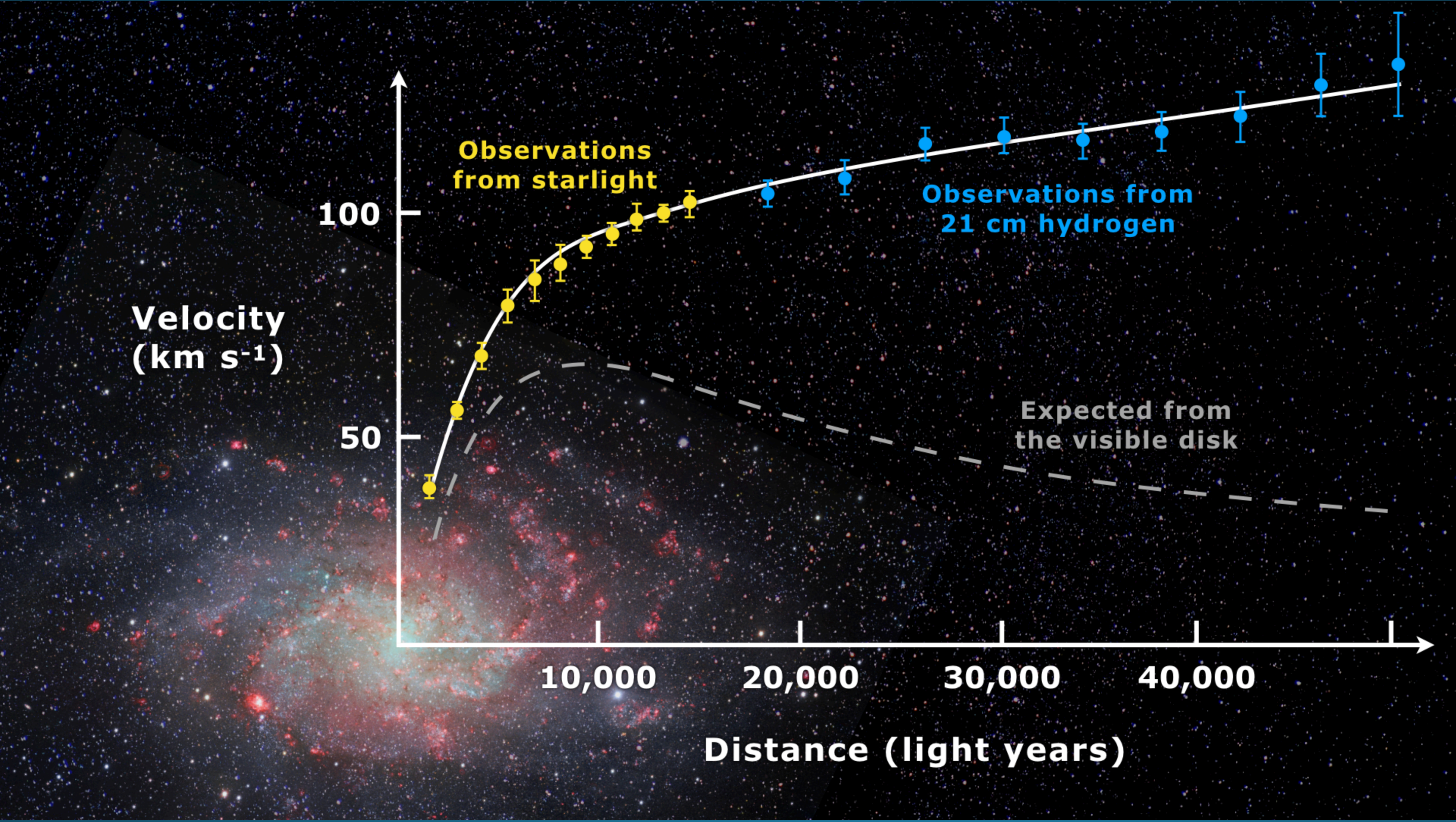
VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21




Longer arrows represent larger orbital velocities.
orbital velocity (km/s)
300
200
100
0
0
10
20
30
distance from center (thousands of light years)

Comparison with theory



credit: wikipedia

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

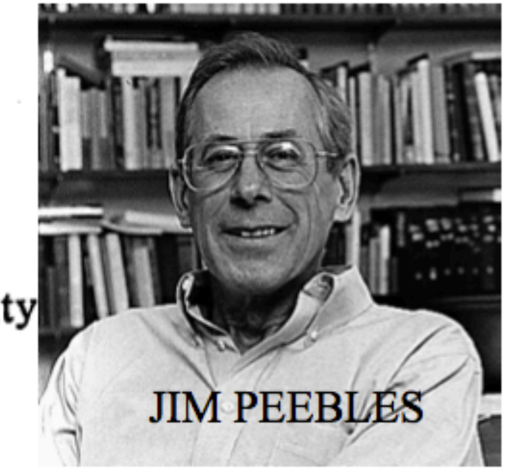

JERRY OSTRIKER

J. P. Ostriker
Princeton University Observatory

AND

P. J. E. Peebles
ph Henry Laboratories, Princeton University

Received 1973 May 29


JIM PEEBLES

ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

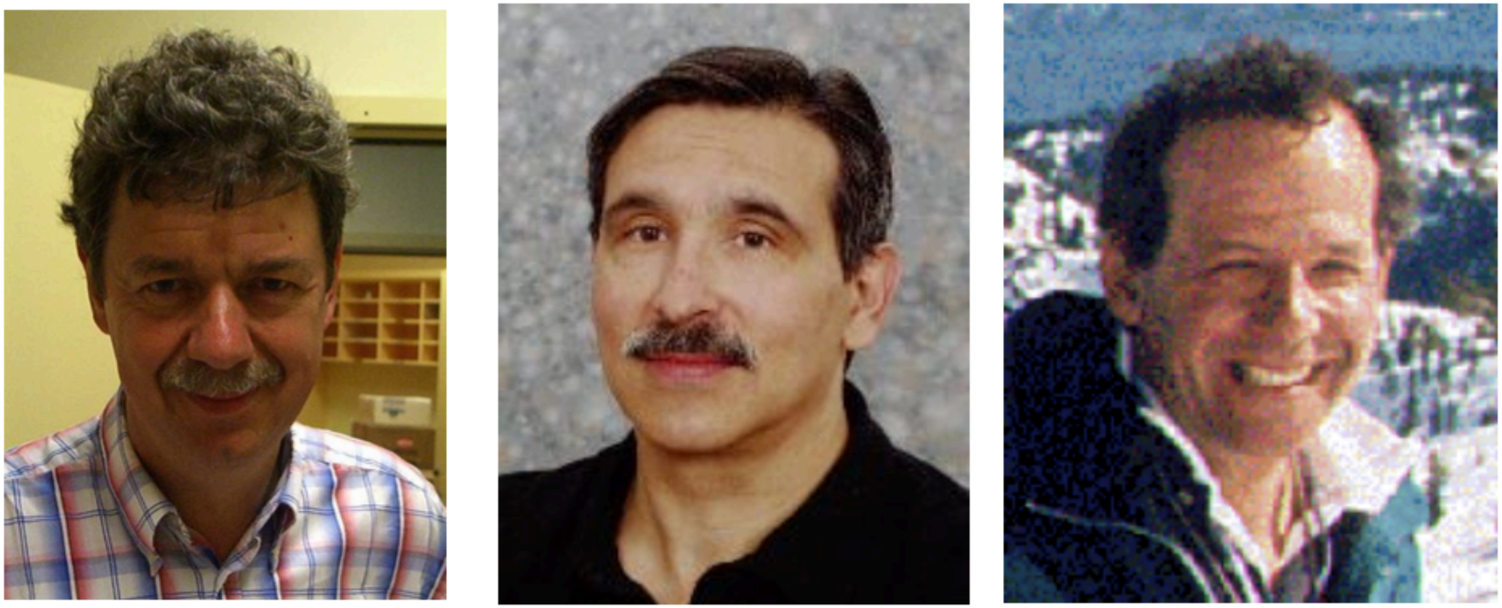
SIMON D. M. WHITE,[1,2] CARLOS S. FRENK,[1] AND MARC DAVIS[1,3]
University of California, Berkeley

Received 1983 June 17; accepted 1983 July 1

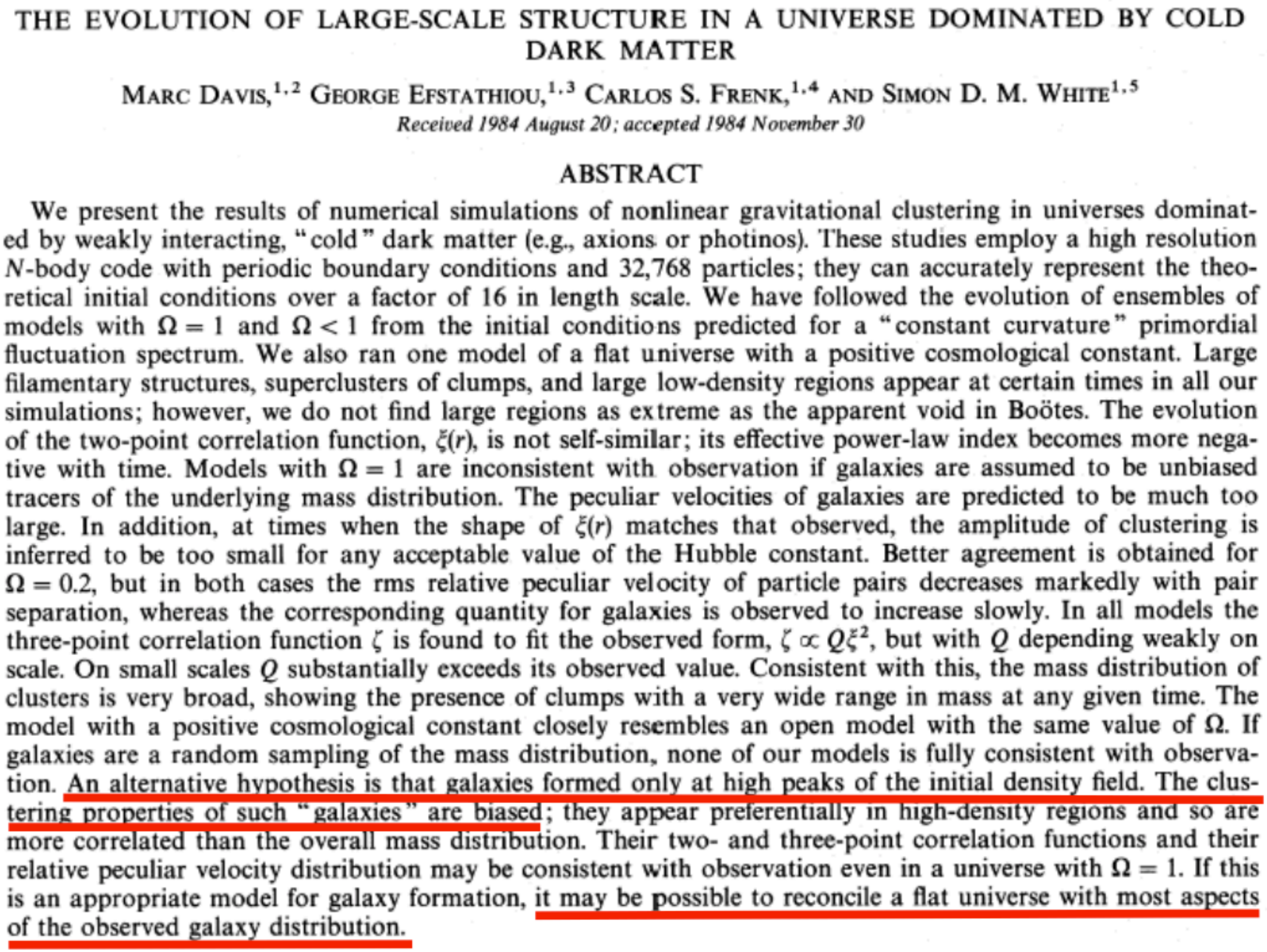
1983 ApJ 274, L1

ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.



1985 ApJ 292, 371



THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

MARC DAVIS,[1,2] GEORGE EFSTATHIOU,[1,3] CARLOS S. FRENK,[1,4] AND SIMON D. M. WHITE[1,5]

Received 1984 August 20; accepted 1984 November 30

ABSTRACT

We present the results of numerical simulations of nonlinear gravitational clustering in universes dominated by weakly interacting, "cold" dark matter (e.g., axions or photinos). These studies employ a high resolution N-body code with periodic boundary conditions and 32,768 particles; they can accurately represent the theoretical initial conditions over a factor of 16 in length scale. We have followed the evolution of ensembles of models with $\Omega = 1$ and $\Omega < 1$ from the initial conditions predicted for a "constant curvature" primordial fluctuation spectrum. We also ran one model of a flat universe with a positive cosmological constant. Large filamentary structures, superclusters of clumps, and large low-density regions appear at certain times in all our simulations; however, we do not find large regions as extreme as the apparent void in Boötes. The evolution of the two-point correlation function, $\xi(r)$, is not self-similar; its effective power-law index becomes more negative with time. Models with $\Omega = 1$ are inconsistent with observation if galaxies are assumed to be unbiased tracers of the underlying mass distribution. The peculiar velocities of galaxies are predicted to be much too large. In addition, at times when the shape of $\xi(r)$ matches that observed, the amplitude of clustering is inferred to be too small for any acceptable value of the Hubble constant. Better agreement is obtained for $\Omega = 0.2$, but in both cases the rms relative peculiar velocity of particle pairs decreases markedly with pair separation, whereas the corresponding quantity for galaxies is observed to increase slowly. In all models the three-point correlation function ζ is found to fit the observed form, $\zeta \propto Q\xi^2$, but with Q depending weakly on scale. On small scales Q substantially exceeds its observed value. Consistent with this, the mass distribution of clusters is very broad, showing the presence of clumps with a very wide range in mass at any given time. The model with a positive cosmological constant closely resembles an open model with the same value of Ω. If galaxies are a random sampling of the mass distribution, none of our models is fully consistent with observation. An alternative hypothesis is that galaxies formed only at high peaks of the initial density field. The clustering properties of such "galaxies" are biased; they appear preferentially in high-density regions and so are more correlated than the overall mass distribution. Their two- and three-point correlation functions and their relative peculiar velocity distribution may be consistent with observation even in a universe with $\Omega = 1$. If this is an appropriate model for galaxy formation, it may be possible to reconcile a flat universe with most aspects of the observed galaxy distribution.

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 9×10^{10} M_{sun}, and the luminosity is 1.5×10^{10} L_{sun}
  - → the mass-to-light ratio is 6 M_{sun}/L_{sun}.

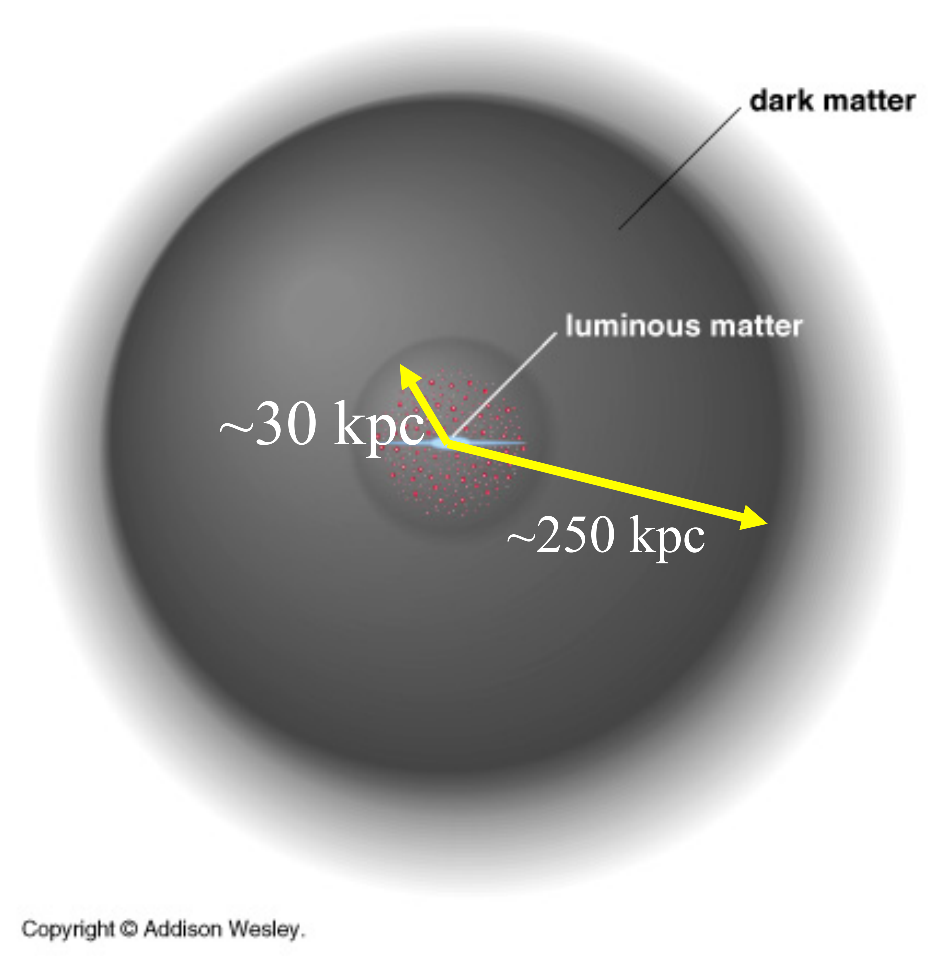
Mass-to-light ratio depends on radius

- 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 2×10^{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.

Cluster mass-to-light ratios

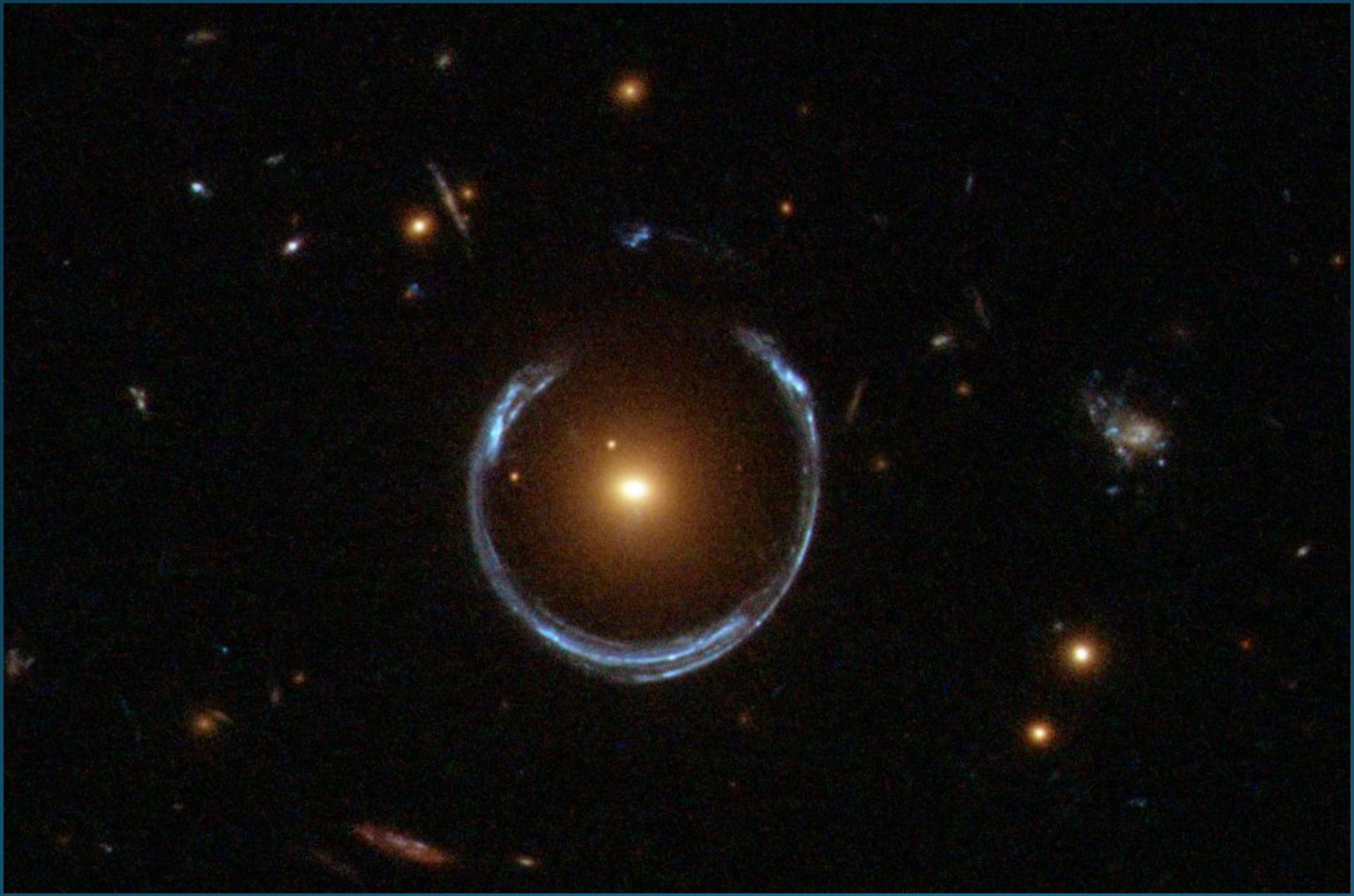
- all three methods (galaxy velocities, hot gas temperatures, and gravitational lensing) show that clusters have mass-to-light ratios of 100-500 M_{sun}/L_{sun}!

The modern view



1 parsec (pc) = 3.26 light-years

Gravitational lensing



NASA

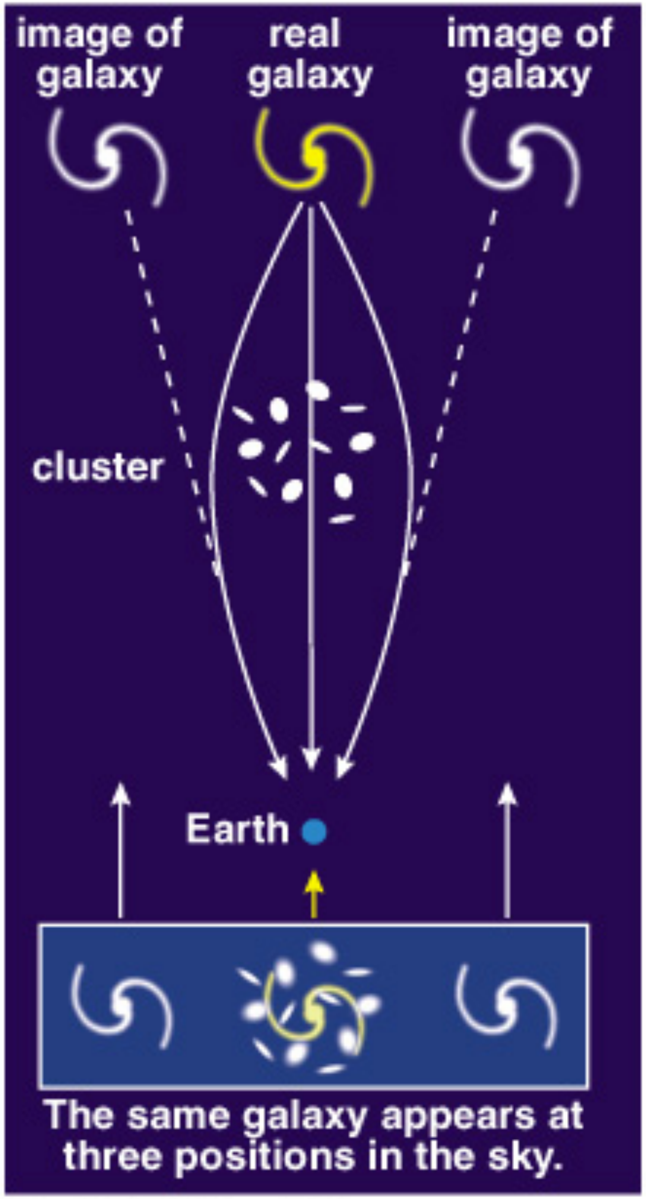
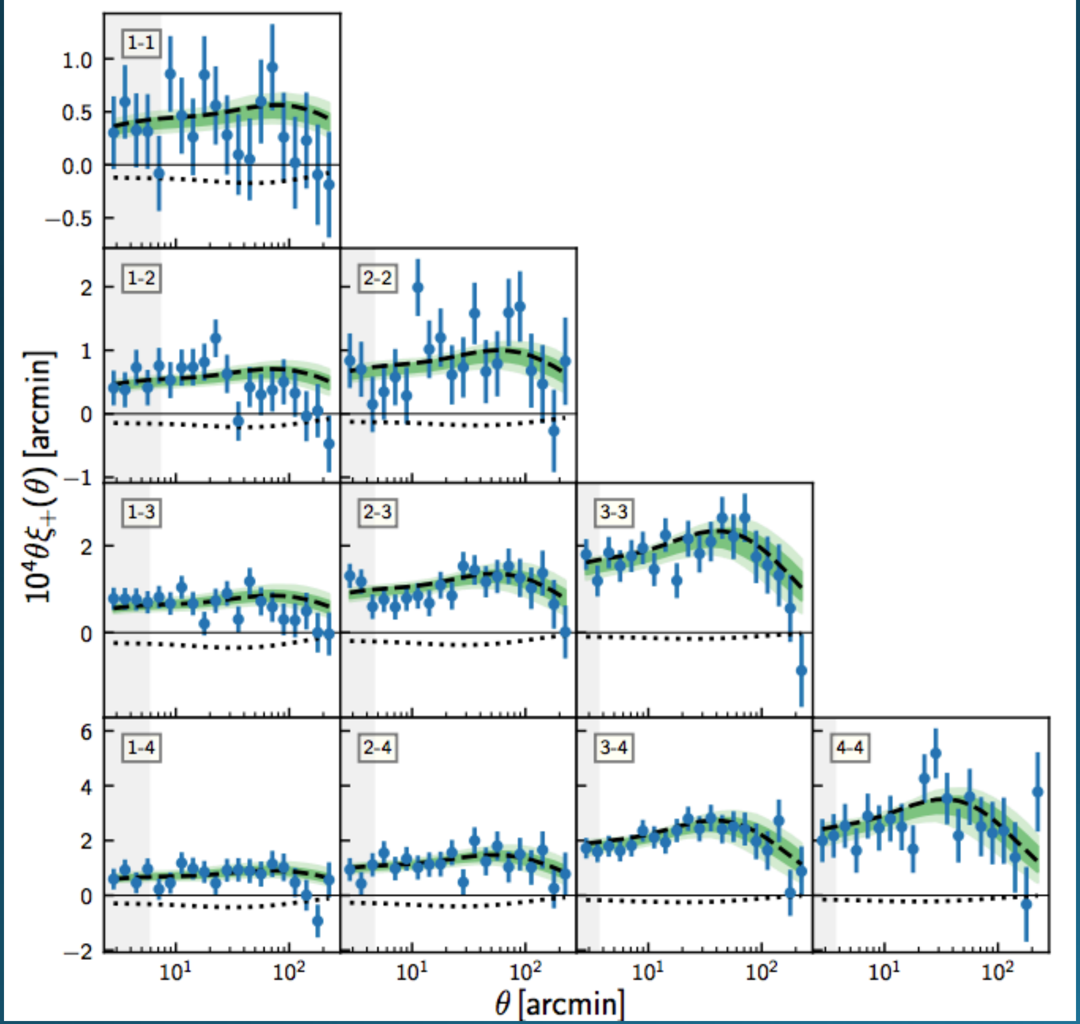
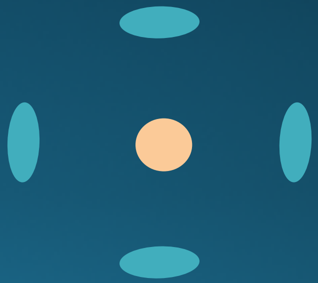


image of galaxy
real galaxy
image of galaxy
cluster
Earth
The same galaxy appears at three positions in the sky.

Weak Galaxy gravitational lensing



- Dark matter around galaxies induces tangential distortion of background galaxies: extremely small, 0.1%
- Signal as a function of galaxy luminosity, type…

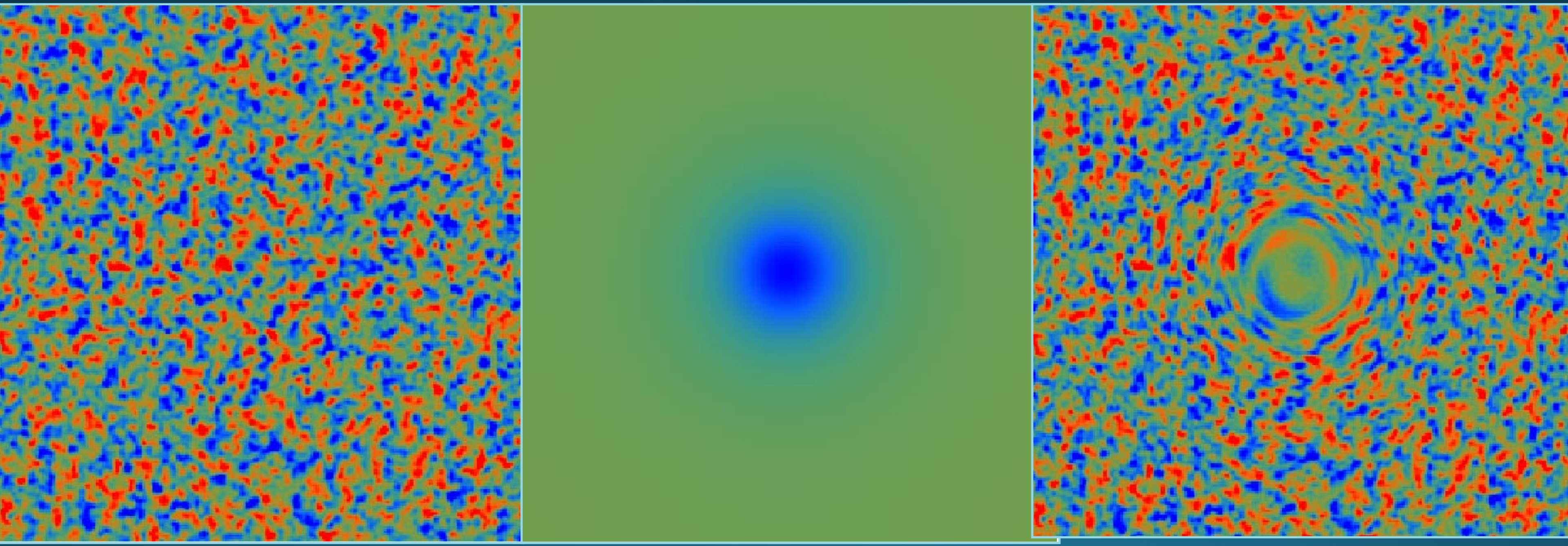


DES Y1 (Dark Energy Survey)

Effect of gravitational lensing on CMB

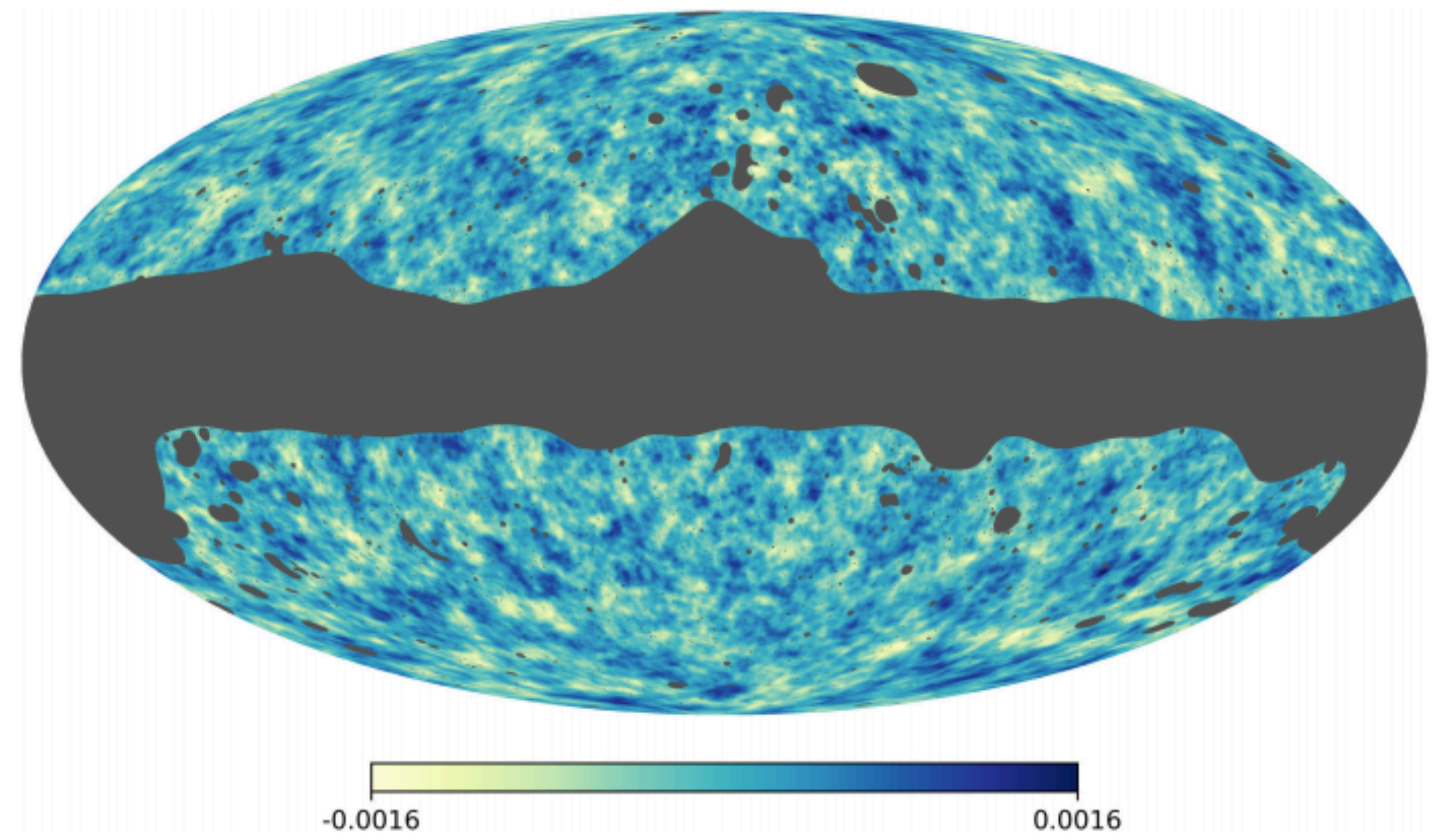
$$T_{lensed}(\vec{\mathbf{n}}) = T_{unlensed}(\vec{\mathbf{n}}+\vec{\mathbf{d}}) \qquad \vec{\mathbf{d}} = -2\vec{\nabla}\nabla^{-2}\kappa$$

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

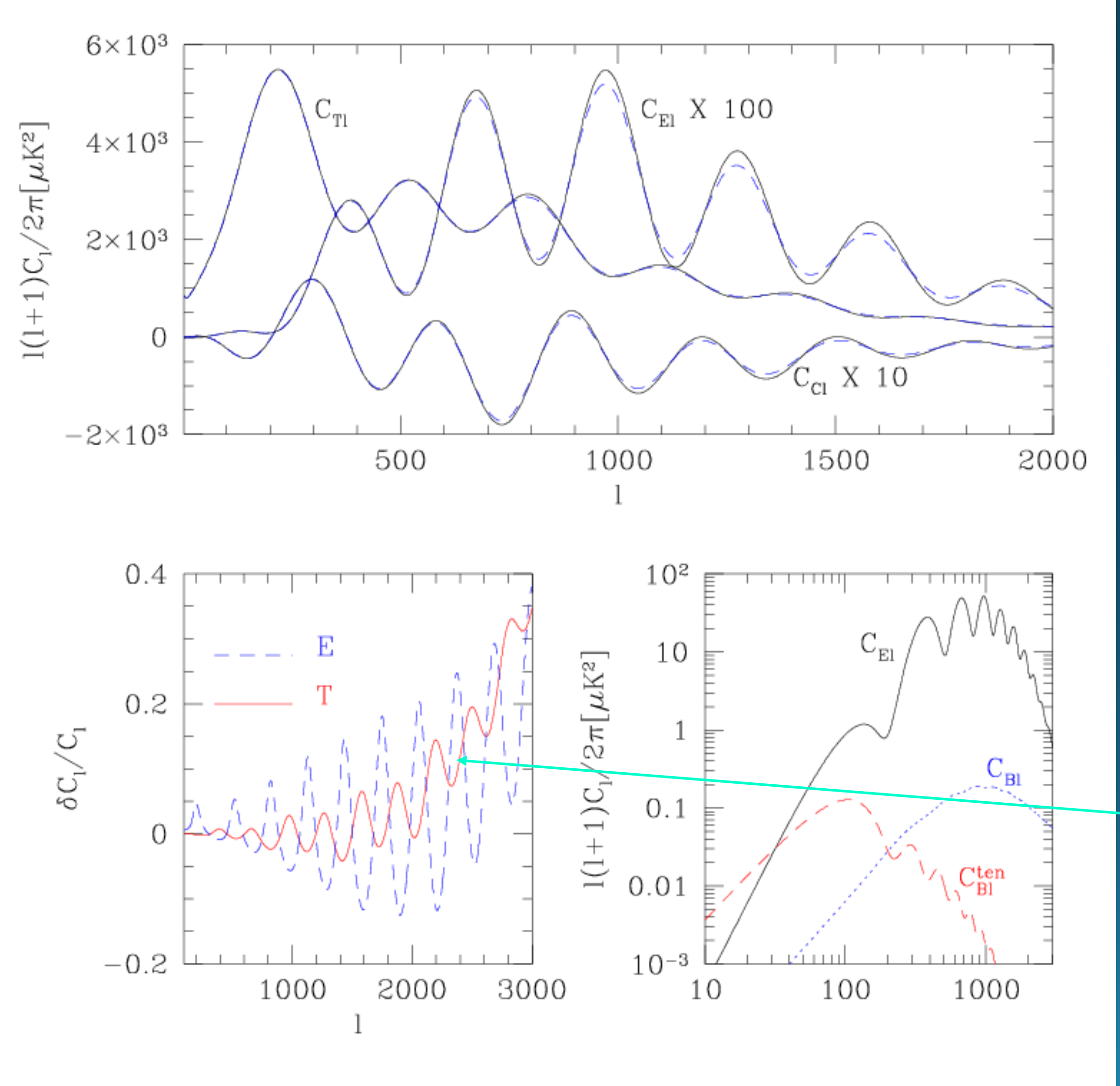


Okamoto and Hu 2002

CMB lensing: Planck 2018



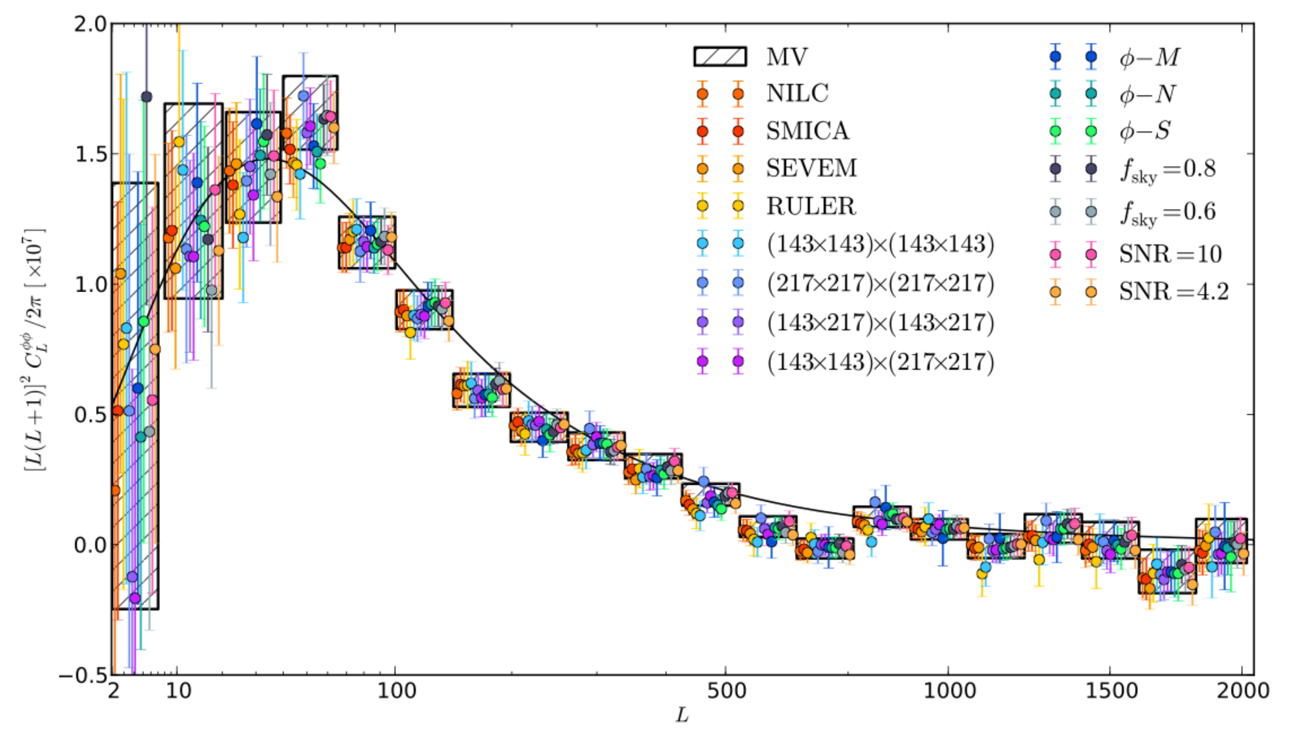
Lensing effect on CMB power spectra



Smoothing and power transfer

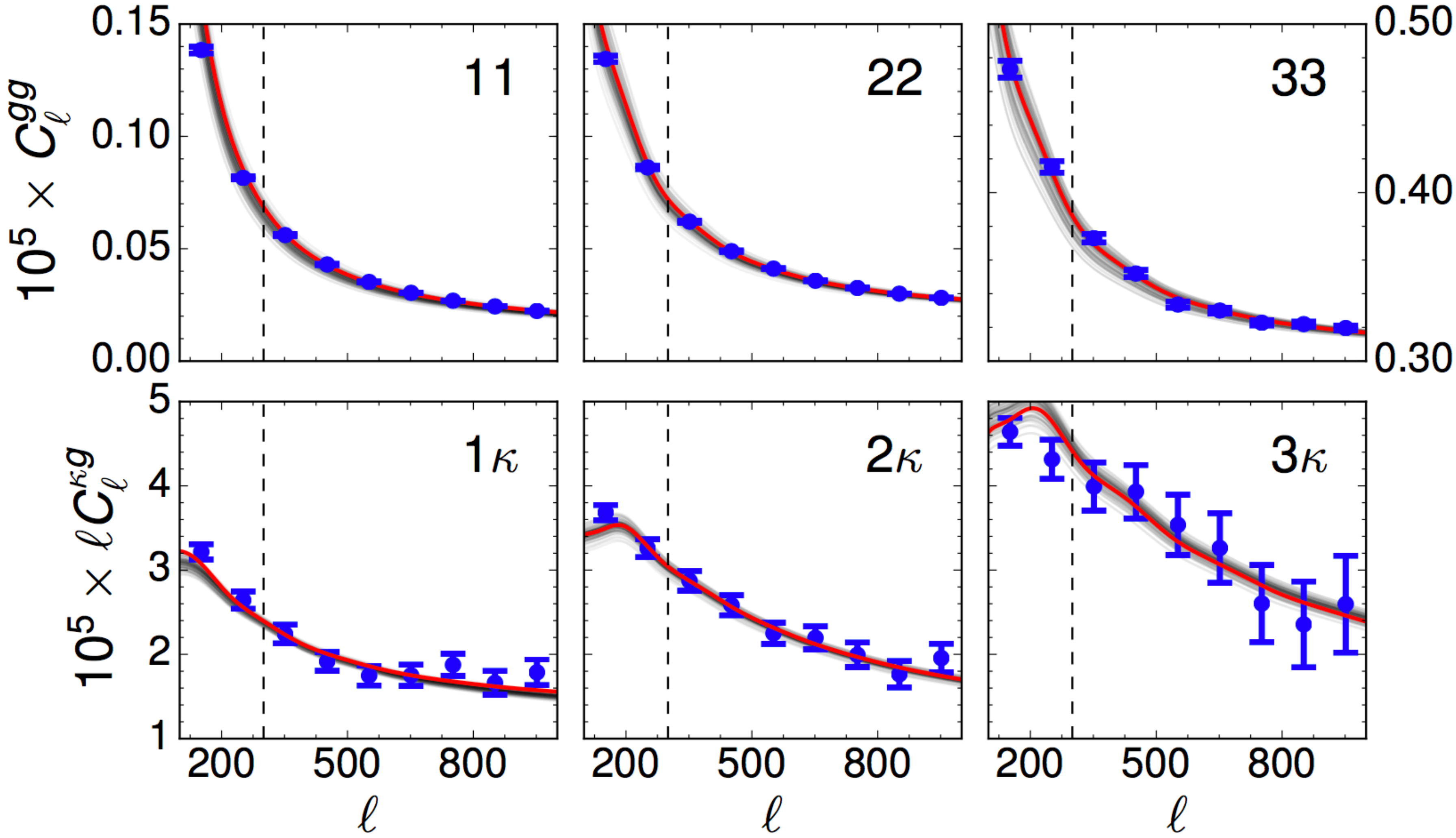
State of the art in CMB lensing: Planck

40 sigma in Planck 2015



Future CMB experiments (stage 3 and 4): 400+ sigma

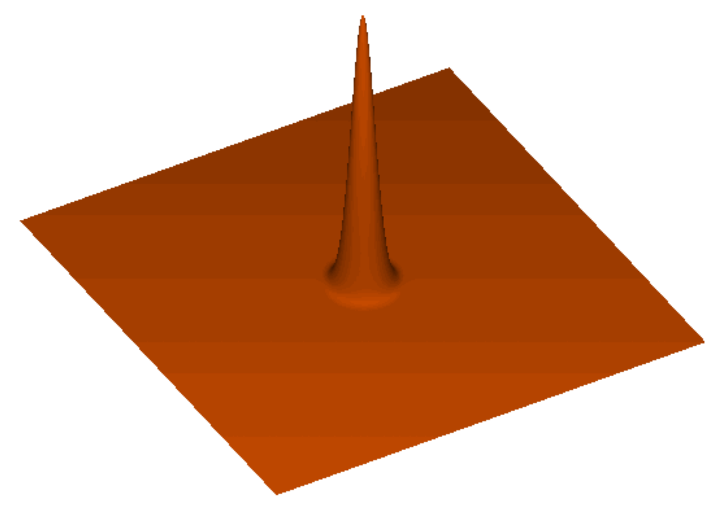
Cross-correlations



WISE galaxies x Planck CMB lensing
(Krolewski, SF, Schlafly, White, in prep)

Baryonic Acoustic Oscillations

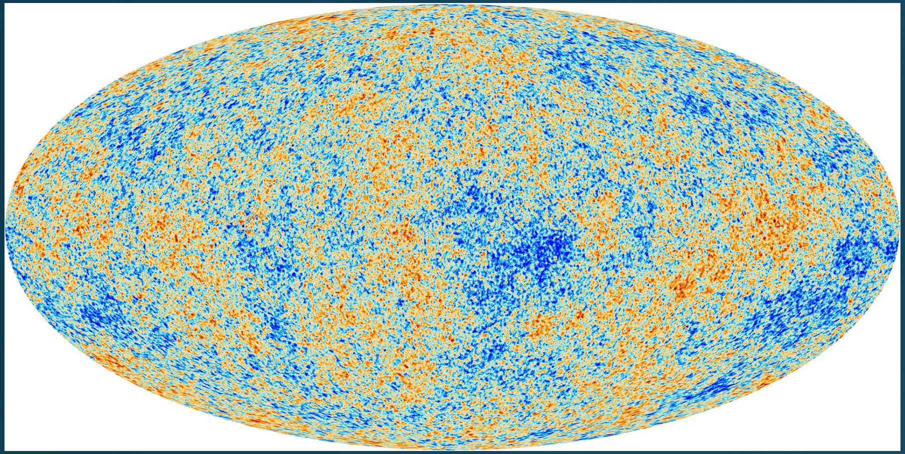
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 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.



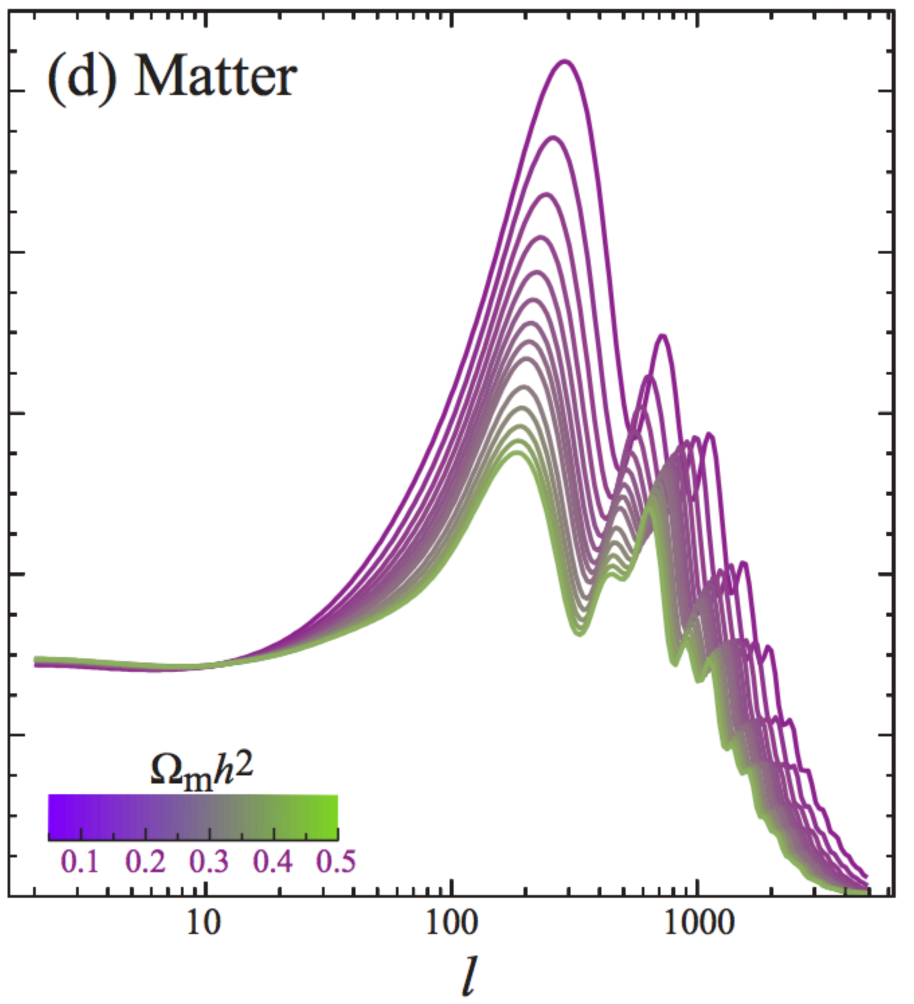
Sound horizon at drag epoch (from Planck) : $r_d = 147.49 \pm 0.59\ \mathrm{Mpc}$

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

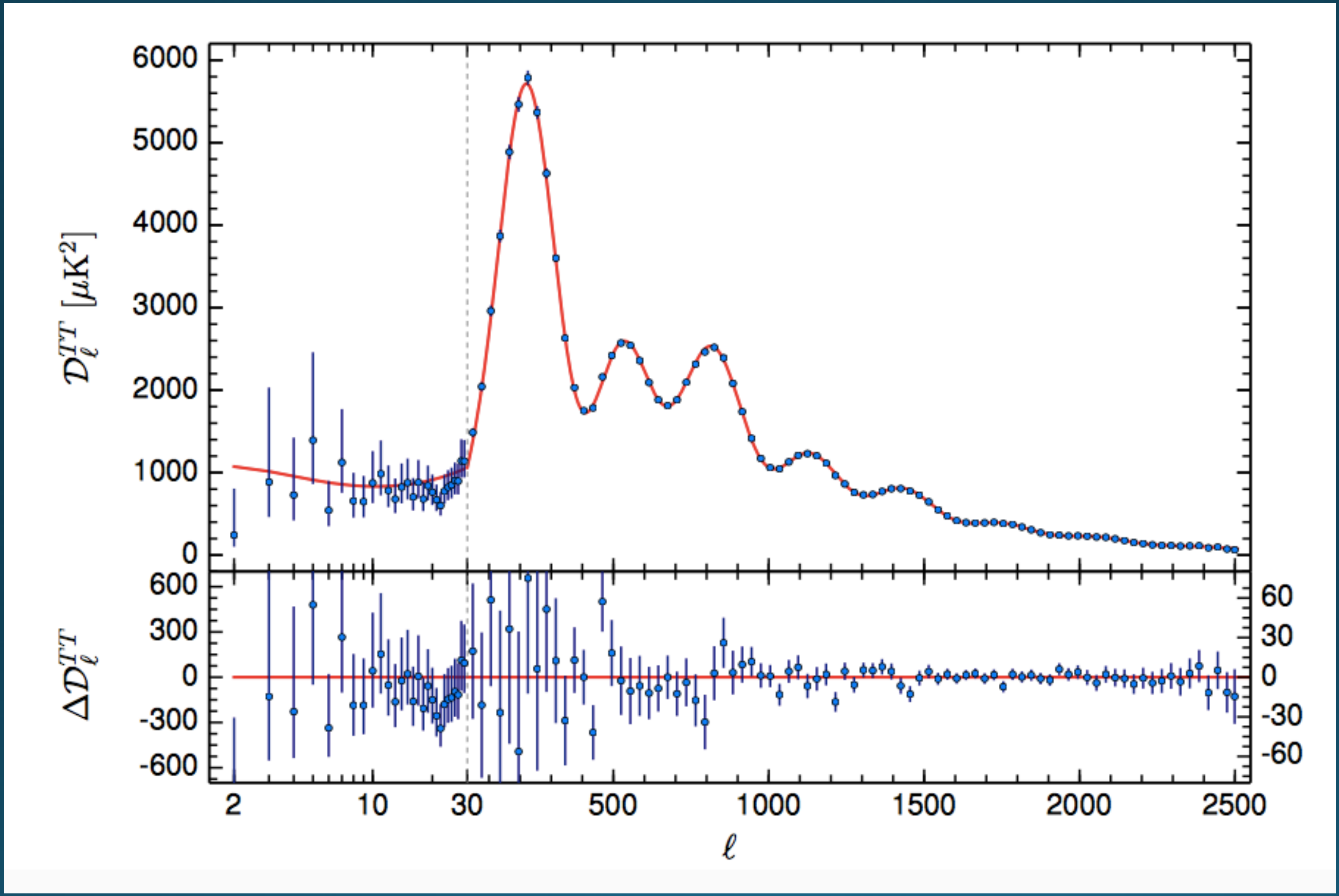
The CMB: sensitivity to matter



Planck satellite



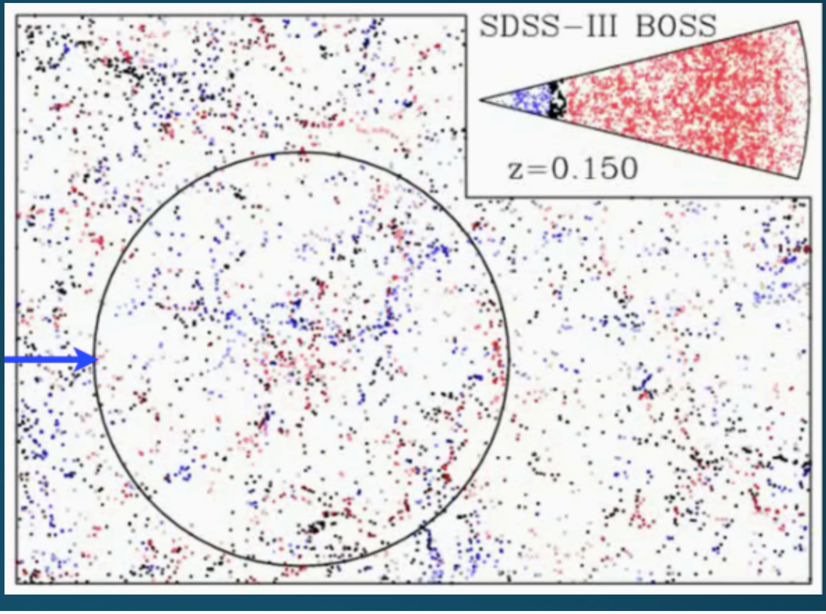
Planck: state of the art in CMB

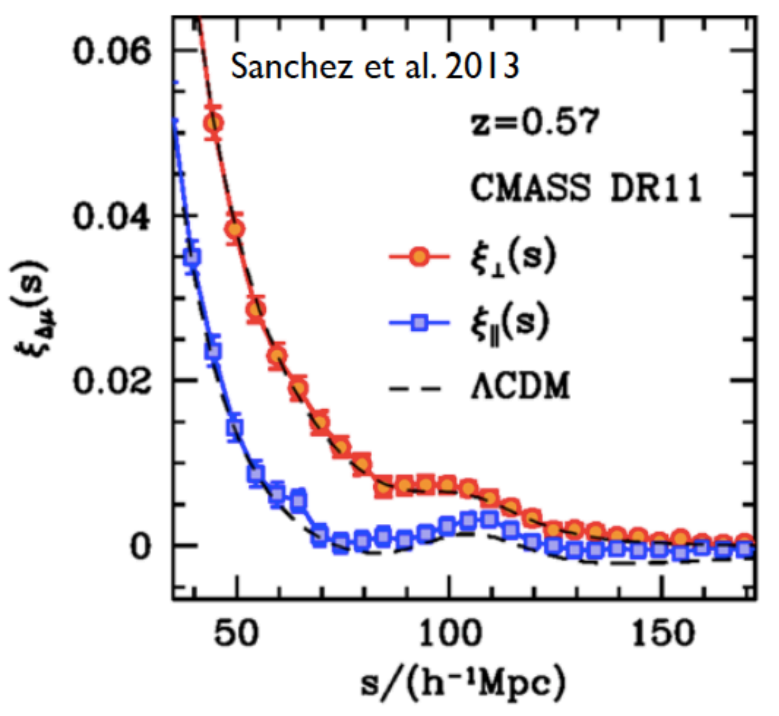


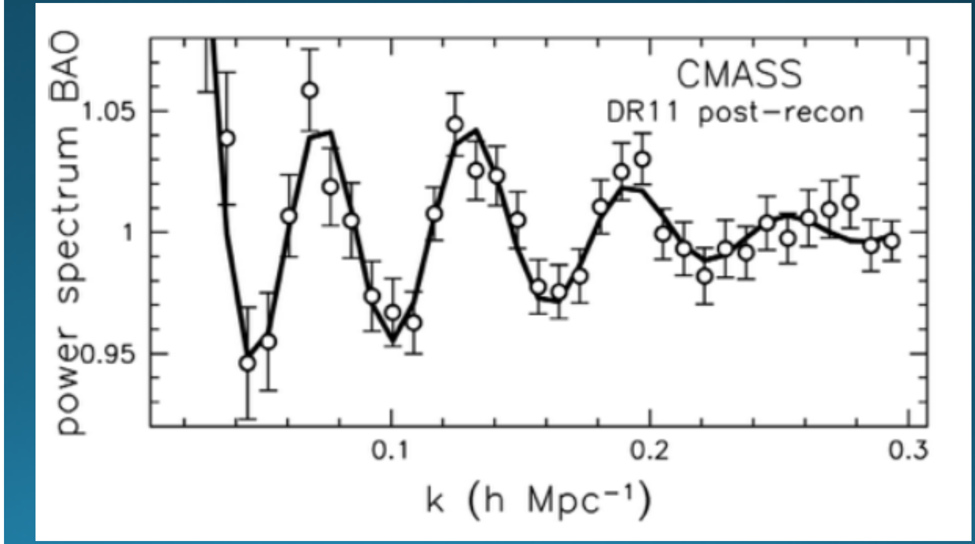
Planck 2018

See https://map.gsfc.nasa.gov/resources/camb_tool/index.html

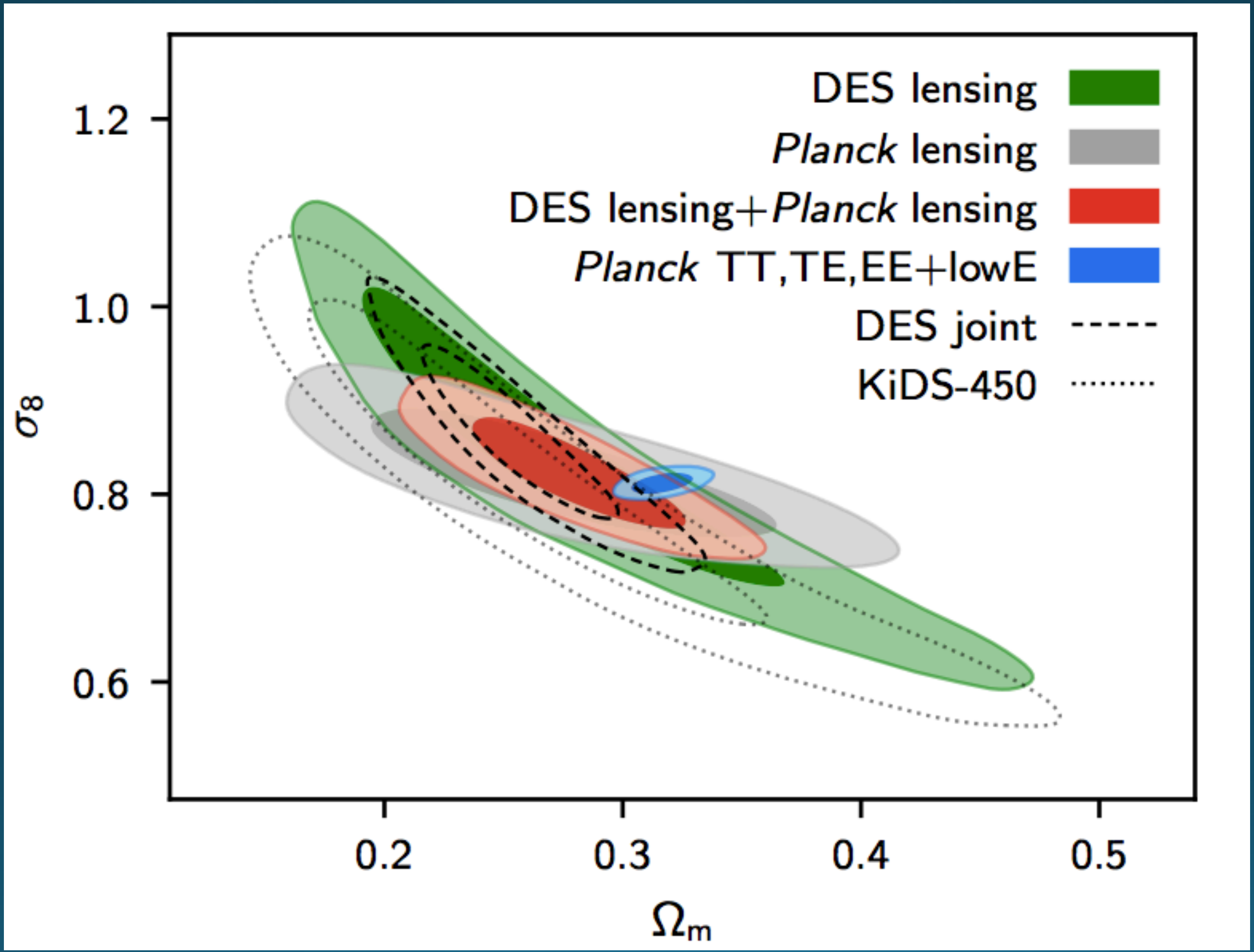
Hunting for BAO in BOSS: correlation function and power spectrum







CMB+lensing+BAO, state of the art



$\Omega_m = 0.3147 \pm 0.0074$ Planck 2018

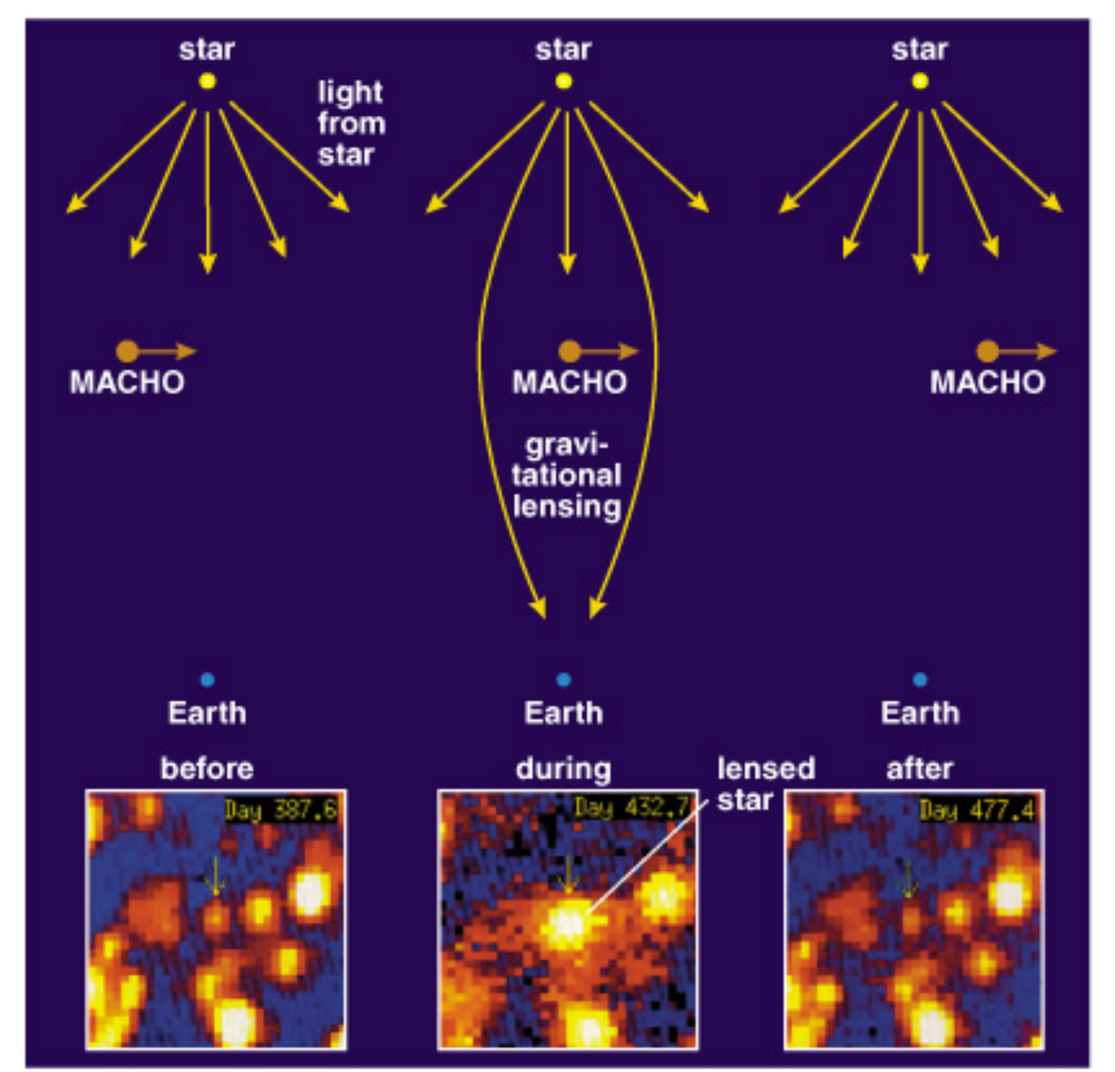
Dark matter: what is it?

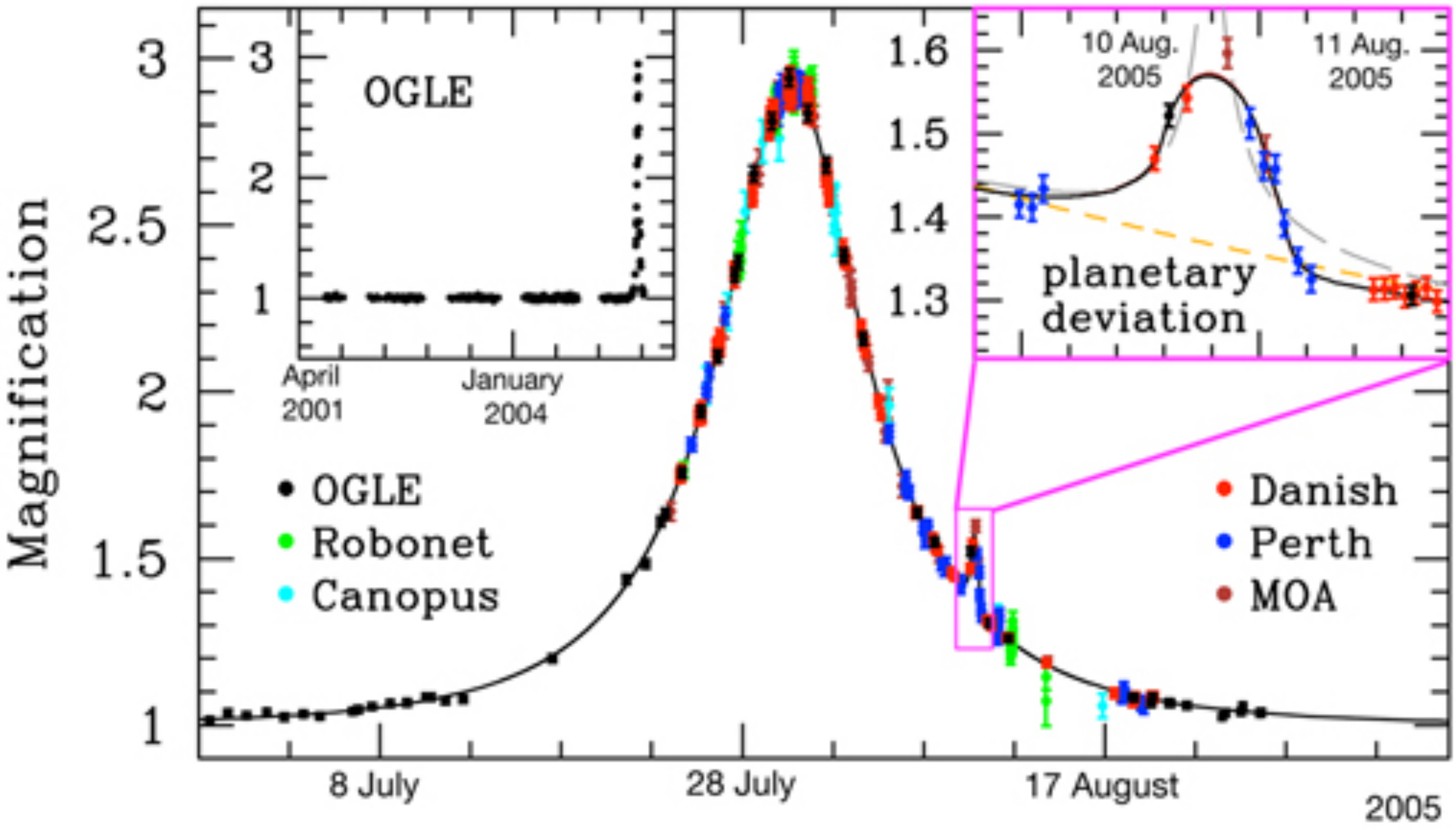
- there are two basic possibilities:
  1. *baryonic dark matter* – ‘ordinary matter’ (i.e. protons, neutrons, electrons, etc.) perhaps faint stars, brown dwarfs, planets, black holes?
  2. *non-baryonic dark matter* – a new kind of particle that we have never seen directly

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)*

“Micro”lensing

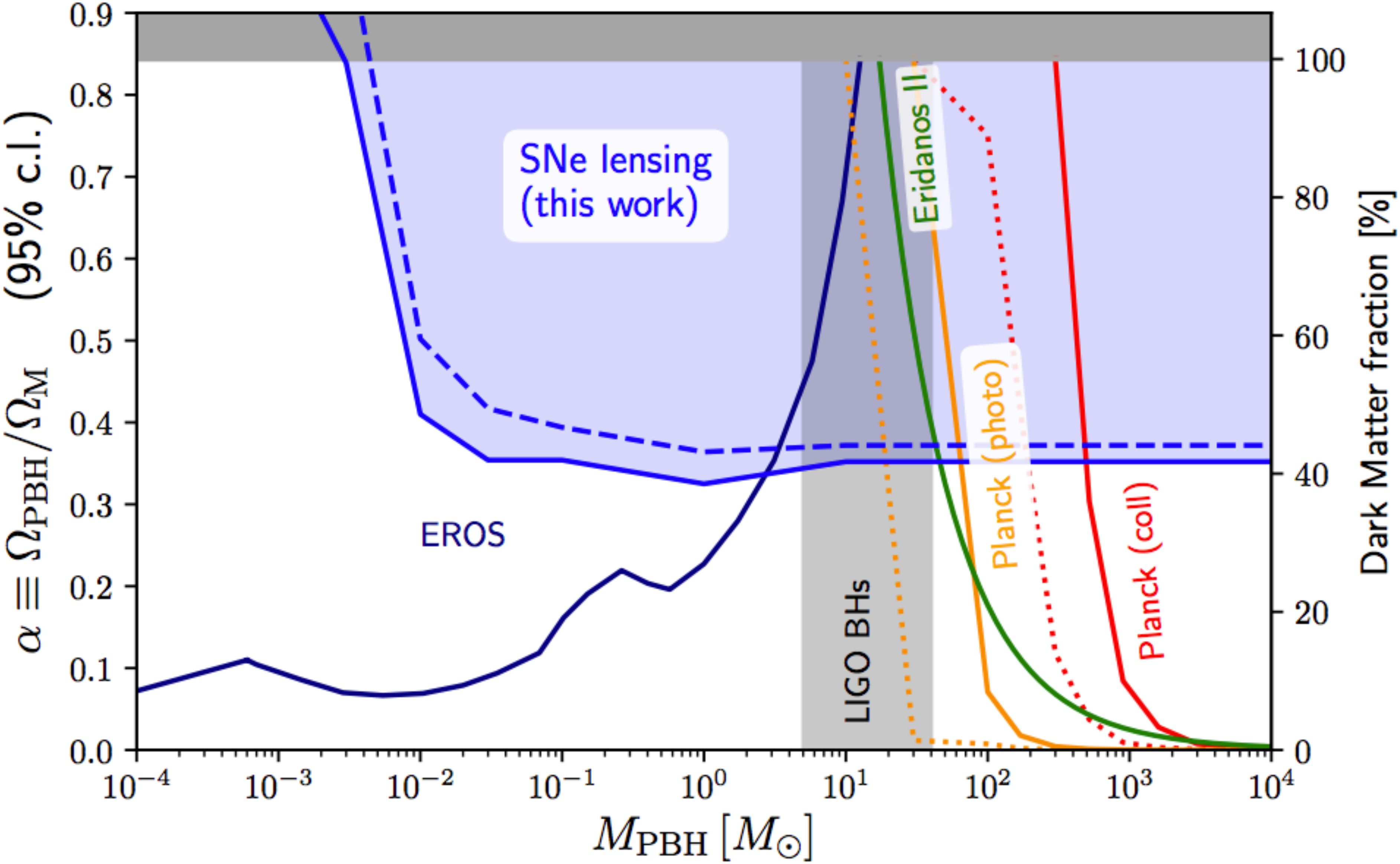




Light Curve of OGLE-2005-BLG-390

ESO PR Photo 03b/06 (January 25, 2006)

Current bounds on MACHOs

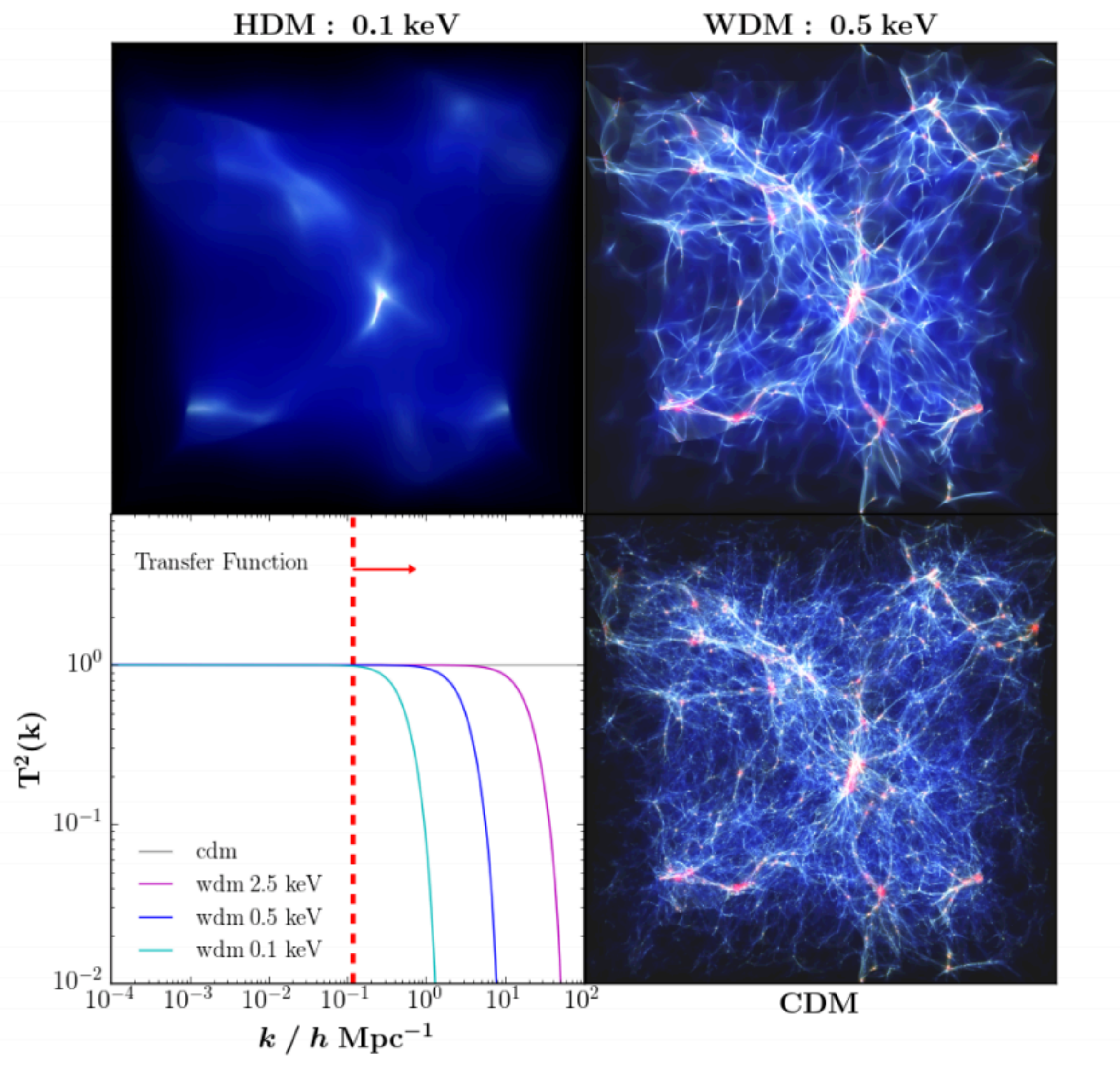


Zumalacarregui, Seljak (2018)

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

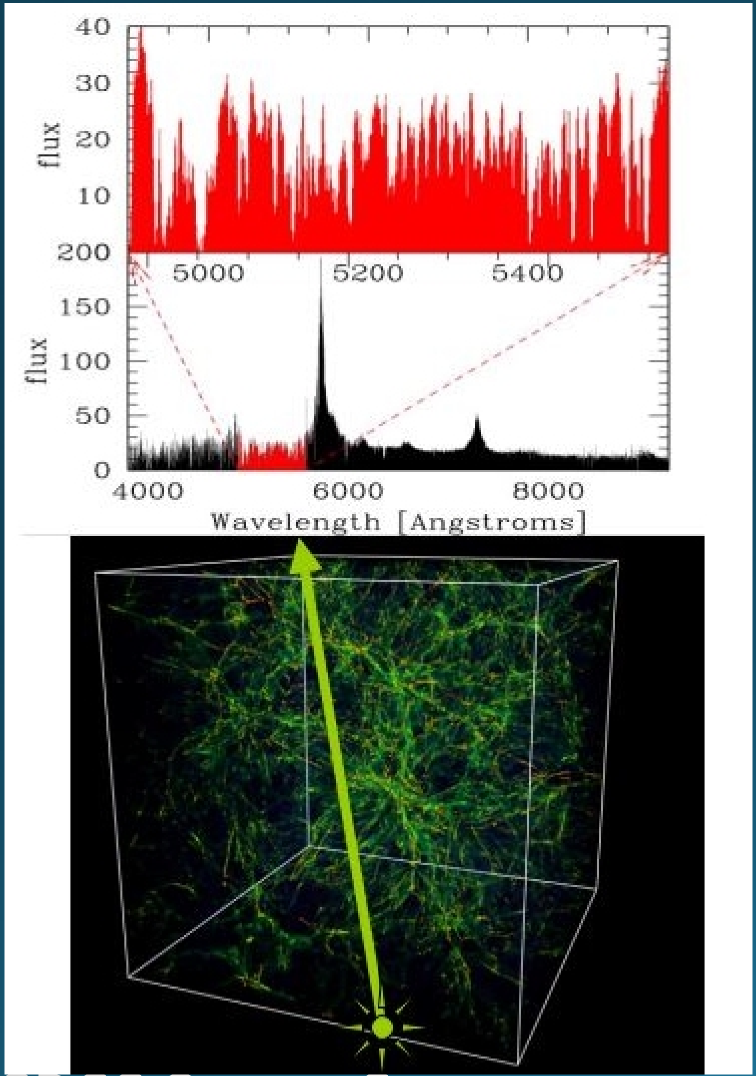
Structure formation with warm DM



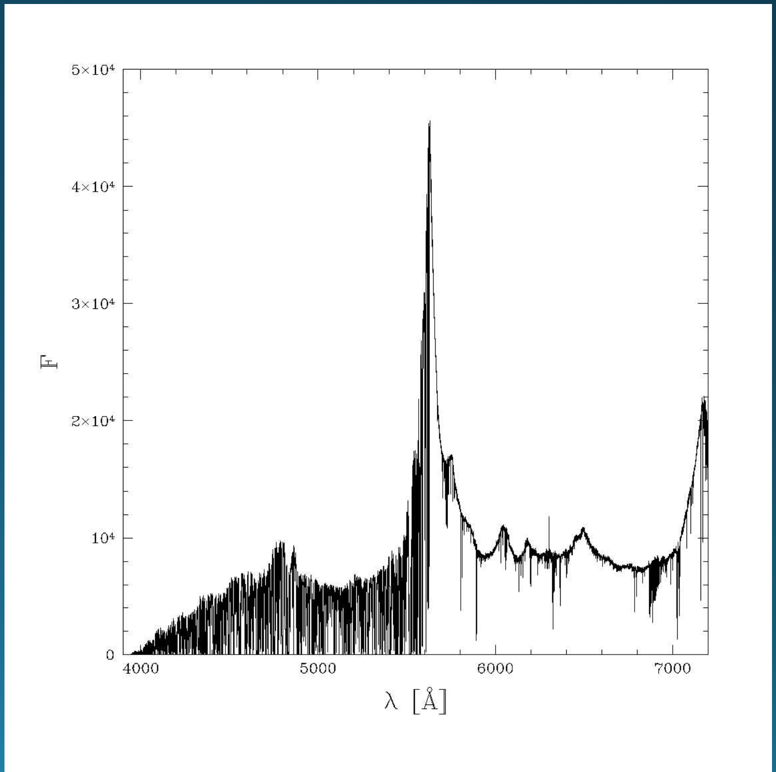
Baur et al arXiv:1512.01981

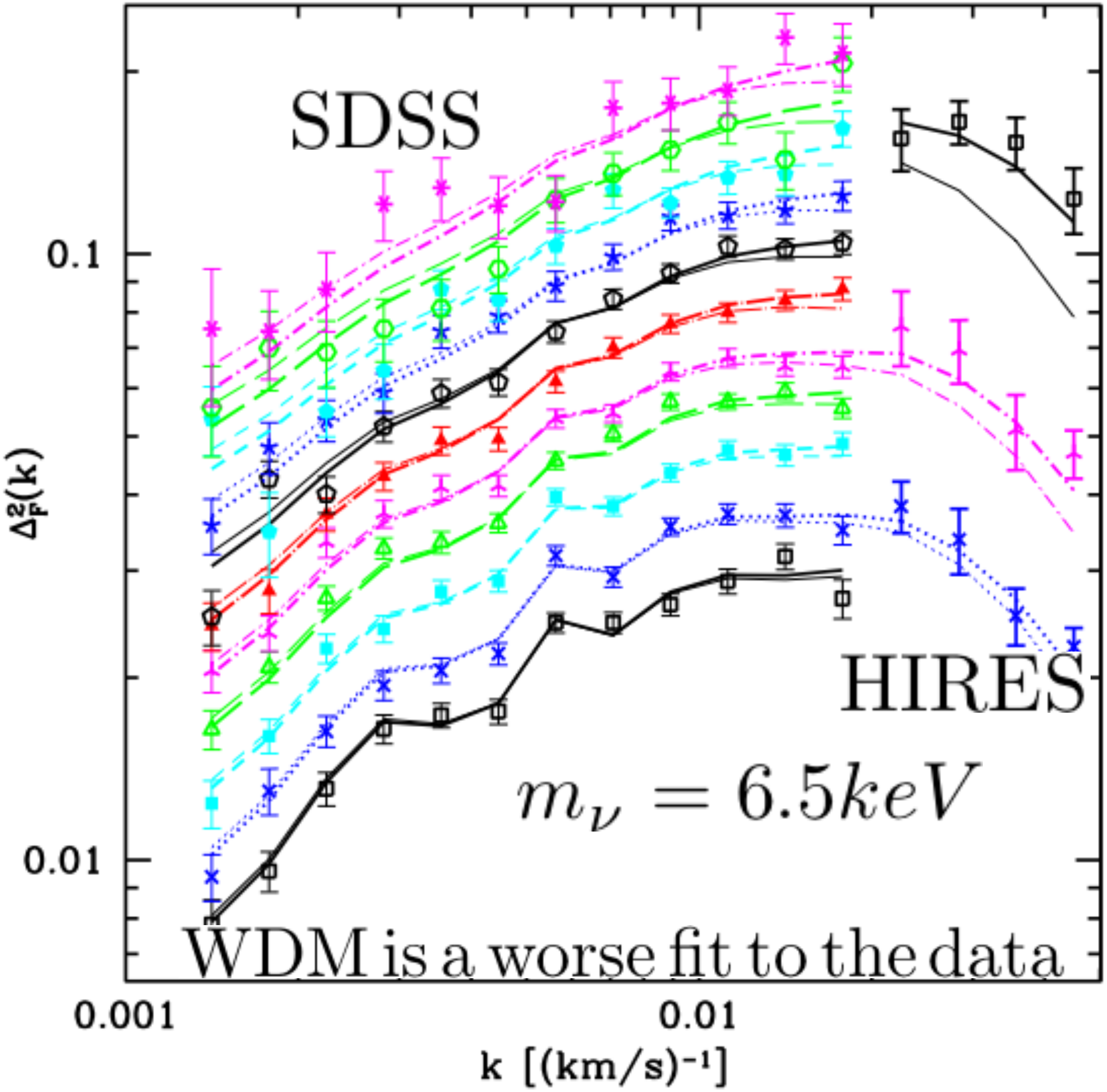
Ly-alpha forest: basics

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



SDSS Quasar Spectrum





$m_\nu = 6.5keV$

WDM is a worse fit to the data

Best bound to date: $m_{DM} > 3$ keV

Alternatives? MOND

- Modify Newton's law: $F_N = m\mu\left(\frac{a}{a_0}\right)a$

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

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

Bullet cluster argues against it:

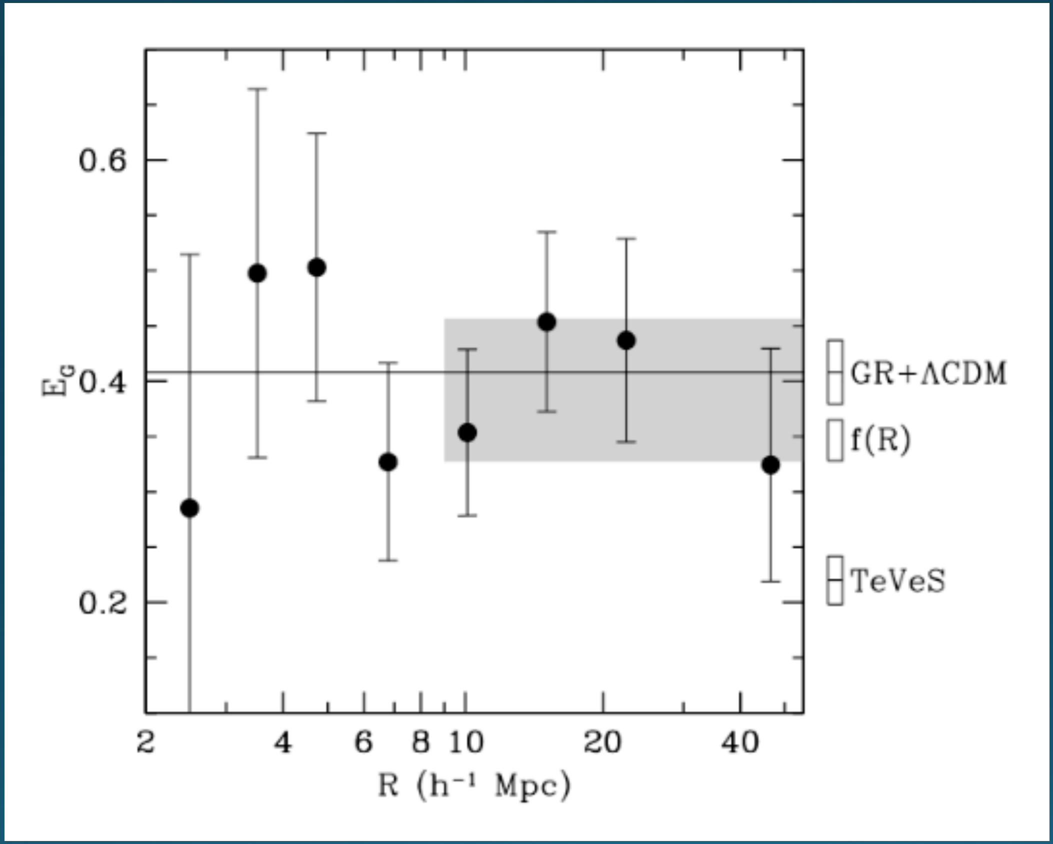
RED: **hot gas** (X-ray),
BLUE: **total mass** (lensing)

also, bound on DM self-interaction

$$\sigma/m < 0.47\,\mathrm{cm}^2\,\mathrm{g}^{-1}$$

Relativistic generalization: TeVeS

- Lensing versus velocities modified in these models versus GR



See also: S. Dodelson "The Real Problem with MOND" (2011)

Conclusions

- The case for dark matter is overwhelming
- It consists of ~25% of total energy 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…