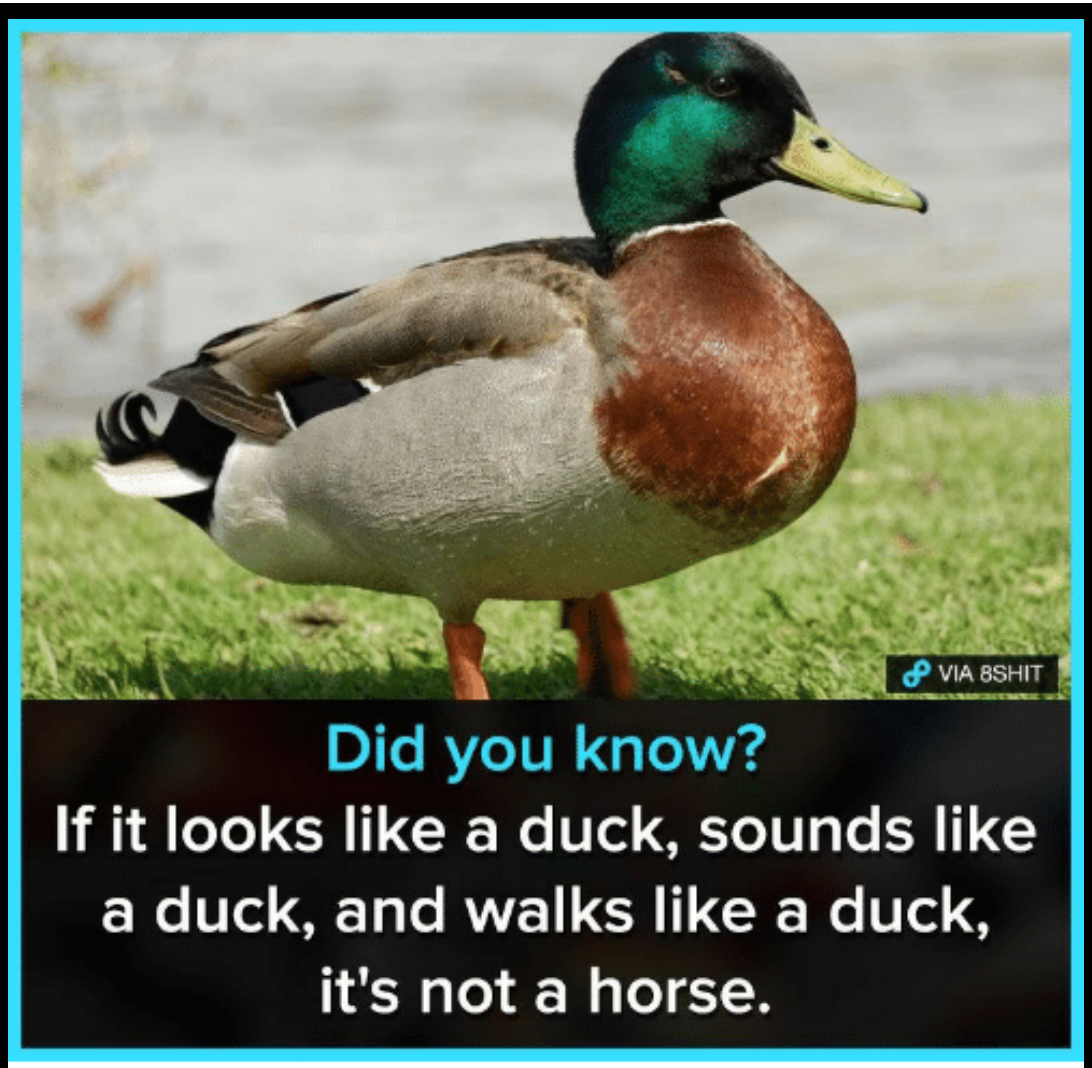
What is the price of abandoning dark matter?

Cosmological constraints on dark matter properties

David Spergel Feb 9, 2021

Cosmological measurements of dark matter

- CMB observations imply that there must be a dark matter component with an equation of state, w=0, and a sound speed, c_s=0. LCDM works on 0.01 -10 Gpc scale
- Measurements of CMB lensing show that there is a component that the Poisson equation is a good description on the Mpc to 100 Mpc scales LCDM works on 1-10 Mpc scale
- Galaxy-galaxy lensing and CMB-galaxy lensing shows that the lensing profiles around clusters are the predicted NFW profiles LCDM works on 0.1-10 Mpc scale
- Measurements of large-scale velocity fields show that there is a component that behaves like cold dark matter on the Mpc to 100 Mpc scales LCDM works on 10-100 Mpc scale
- On the kpc scale, MOND fails to fit the diversity of dwarf galaxies or the properties of clusters. CDM is consistent with the observations. LCDM works on 1-100 kpc scale

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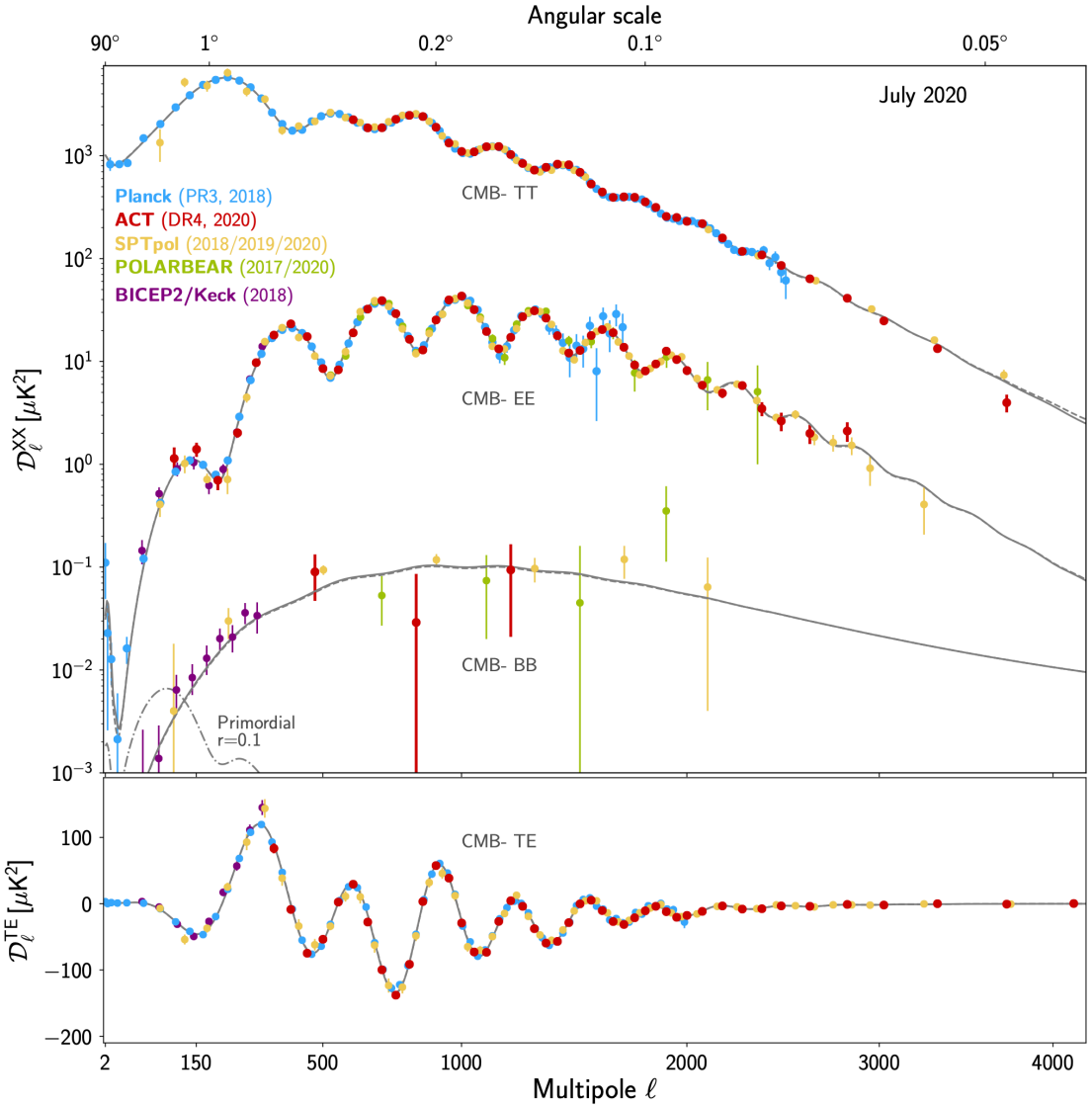
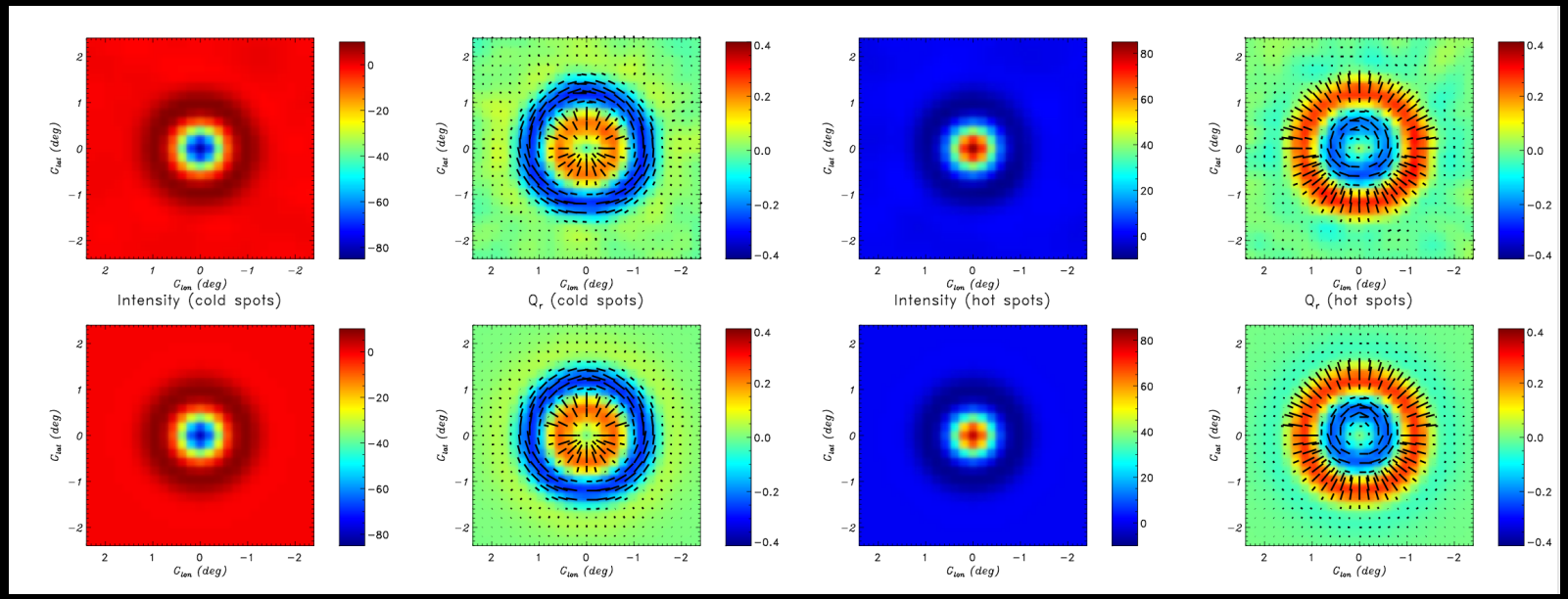
    it.swimStyle == SwimStyle.duck &&
    it.quackStyle == QuackStyle.duck) {
        return it is Duck
}
```

whiletruetypecode.tumblr.com

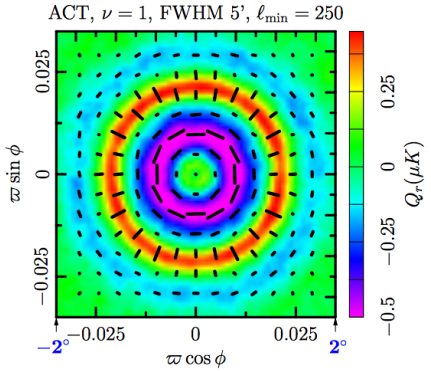

Angular scale
90°
1°
0.2°
0.1°
0.05°
July 2020
Planck (PR3, 2018)
ACT (DR4, 2020)
SPTpol (2018/2019/2020)
POLARBEAR (2017/2020)
BICEP2/Keck (2018)
CMB- TT
CMB- EE
CMB- BB
Primordial
r=0.1
CMB- TE
$\mathcal{D}_\ell^{XX}\,[\mu K^2]$
$\mathcal{D}_\ell^{TE}\,[\mu K^2]$
Multipole ℓ

Acoustic Fluctuations

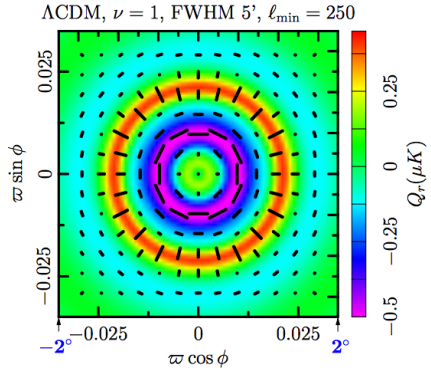


Planck Paper 1 (2013)

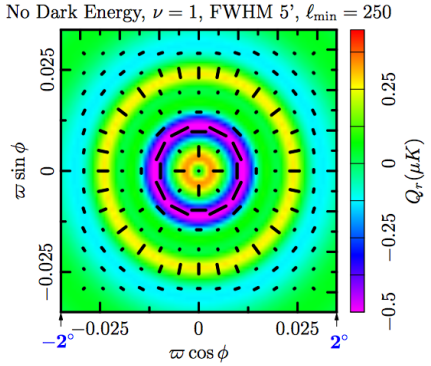
ACT data



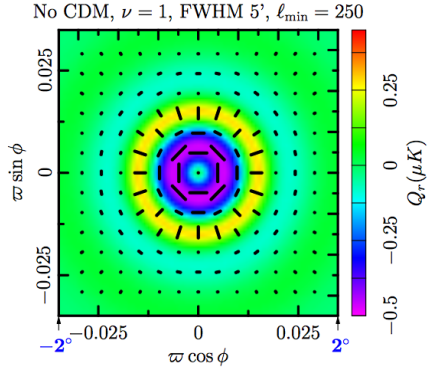
ΛCDM



No DE



No CDM

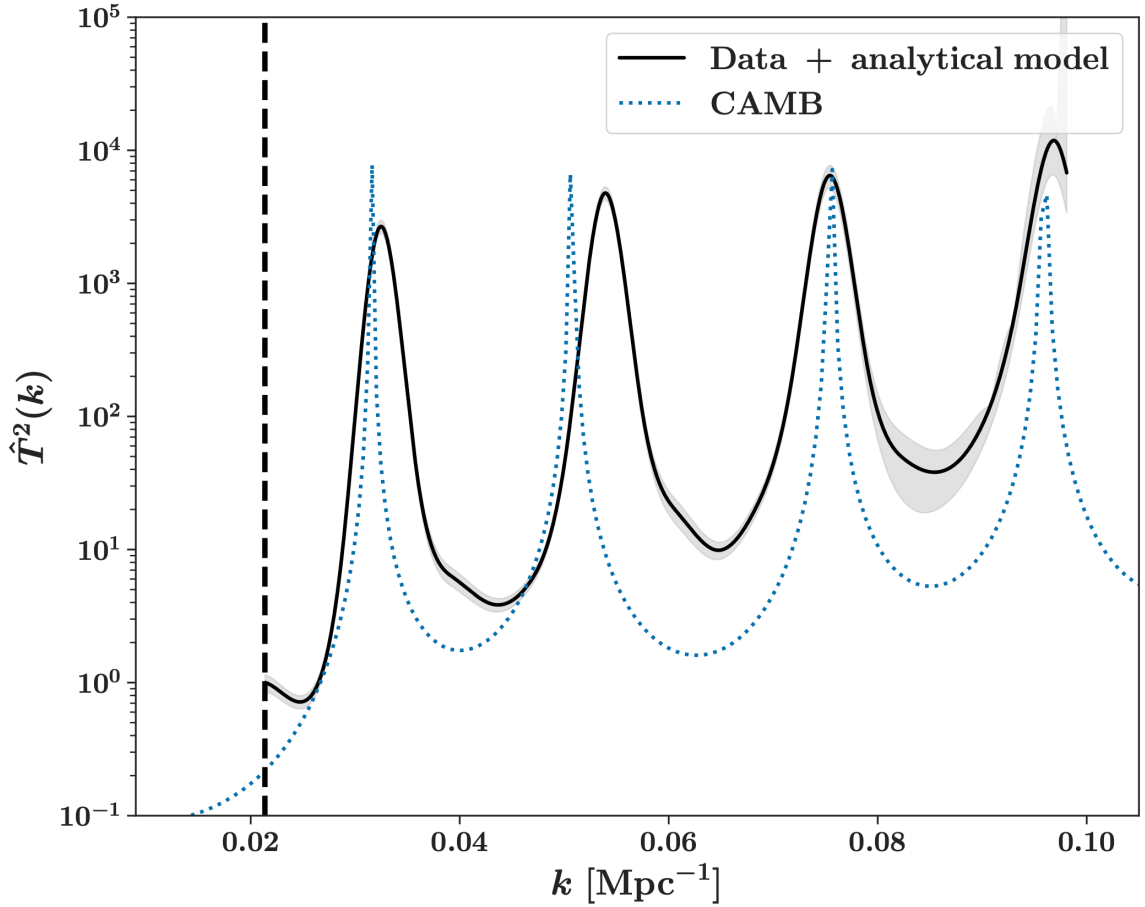


ACT Map Stacking (1.5% sky)

On Planck T hot pixels (reduce systematics)
No DE: $\Omega_\Lambda = 0$, $\Omega_c = 1 - \Omega_b - \Omega_\nu$.
No CDM: $\Omega_c = 0$, $\Omega_\Lambda = 1 - \Omega_b - \Omega_\nu$.

$\langle \Delta T^2 \rangle$ normalized by adjusting A_s.

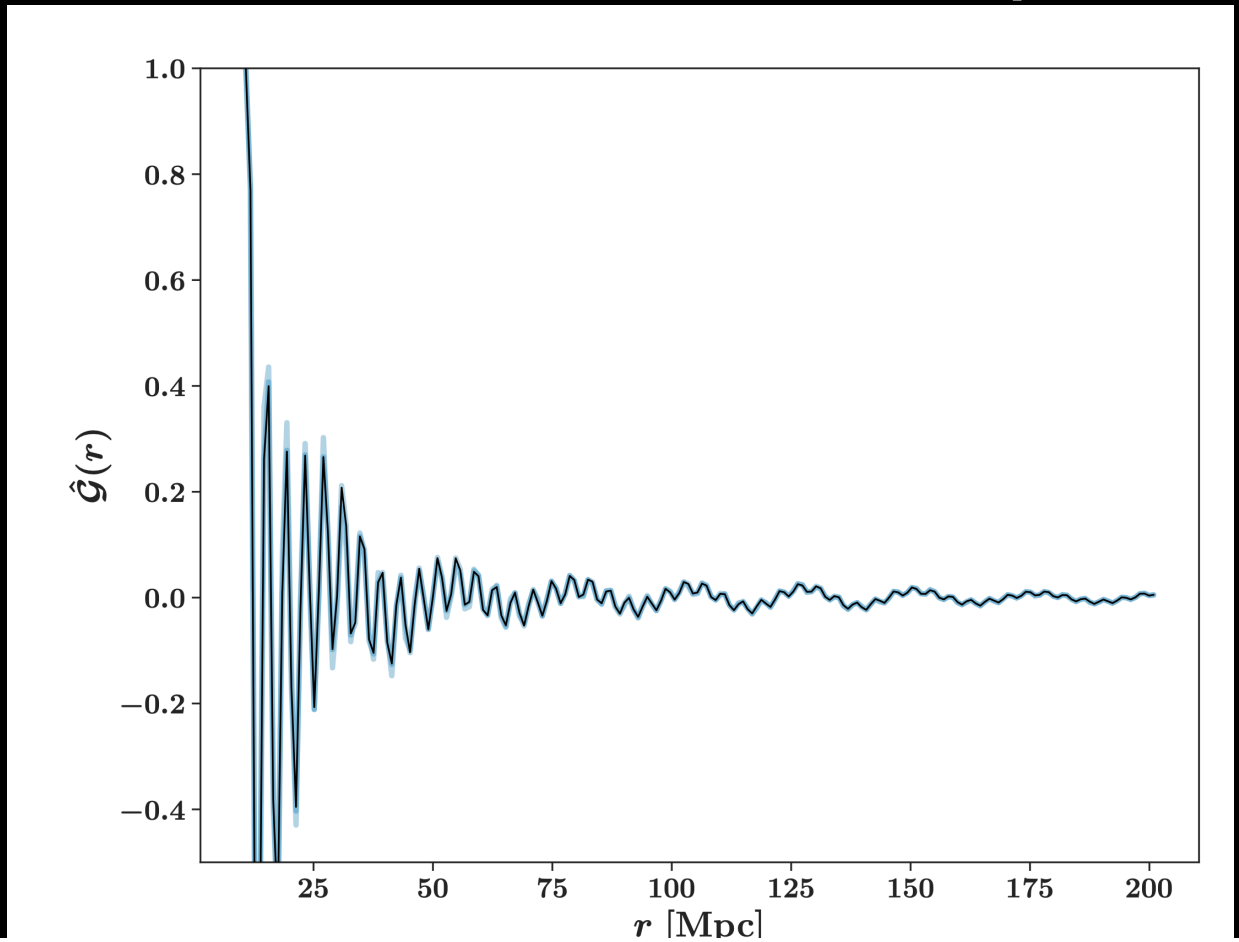
Baryon-Transfer Function



Without a component that is behaving like cold dark matter on cosmological scales, it is very difficult to connect the CMB to large-scale structure

Pardo & Spergel (2020)

Green's Function for a Cosmology without a cold dark matter component



Linear Theory Observations (CMB at z = 1100 and P(k) at z = 0.3) require that there is a component that behaves is described by GR linear perturbation theory and has the same sound speed and equation of state as CDM

RMOND + CMB

- RMOND posits a field that on cosmological scales has a sound speed and equation of state consistent with CDM. The field has a very complex non-renormalizable Lagrangian but at the end of the day is another non-interacting field:

$$\dot{\delta} = 3H\left(w\delta - \Pi\right) + (1+w)\left(3\dot{\Phi} - \frac{k^2}{a^2}\theta\right)$$

$$\dot{\theta} = 3c_{\rm ad}^2 H\theta + \frac{\Pi}{1+w} + \Psi$$

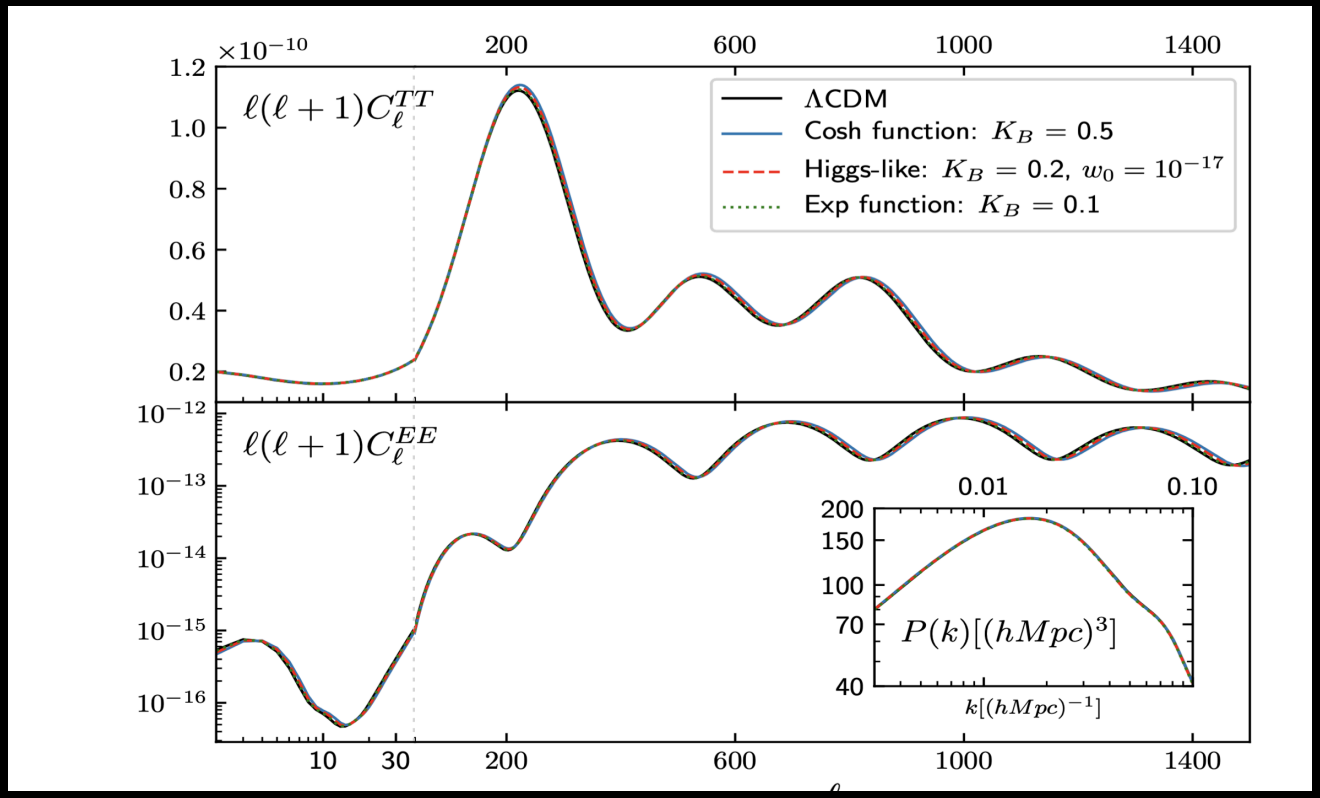
but with non-standard pressure contrast:

$$\Pi = c_{\rm ad}^2\delta - \frac{c_{\rm ad}^2}{8\pi G a^2\bar{\rho}}\vec{\nabla}^2\left[K_{\rm B}E + (2-K_{\rm B})\,\chi\right] \qquad (16)$$

$$S = \int d^4x \frac{\sqrt{-g}}{16\pi\tilde{G}}\Big[R - \frac{K_{\rm B}}{2}\hat{F}^{\mu\nu}\hat{F}_{\mu\nu} + 2(2-K_{\rm B})\hat{J}^\mu\nabla_\mu\phi$$
$$- (2-K_{\rm B})\mathcal{Y} - \mathcal{F}(\mathcal{Y},\mathcal{Q}) - \lambda(\hat{A}^\mu\hat{A}_\mu + 1)\Big] + S_m[g] \qquad (10)$$

Skordis and Zlosnik 2007.00082

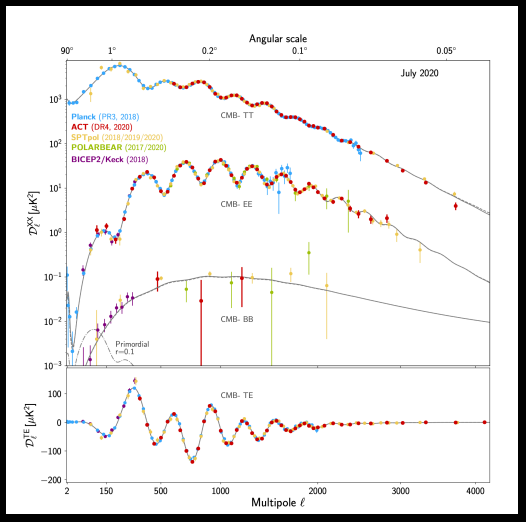
Does this anisotropic pressure change the CMB spectrum?



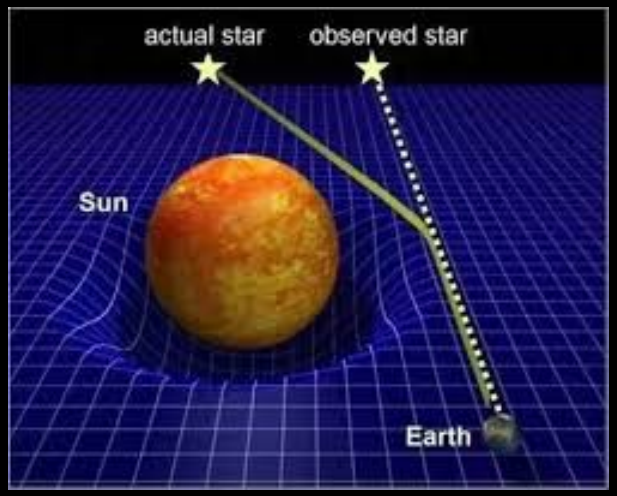
Skordis and Zlosnik 2007.00082

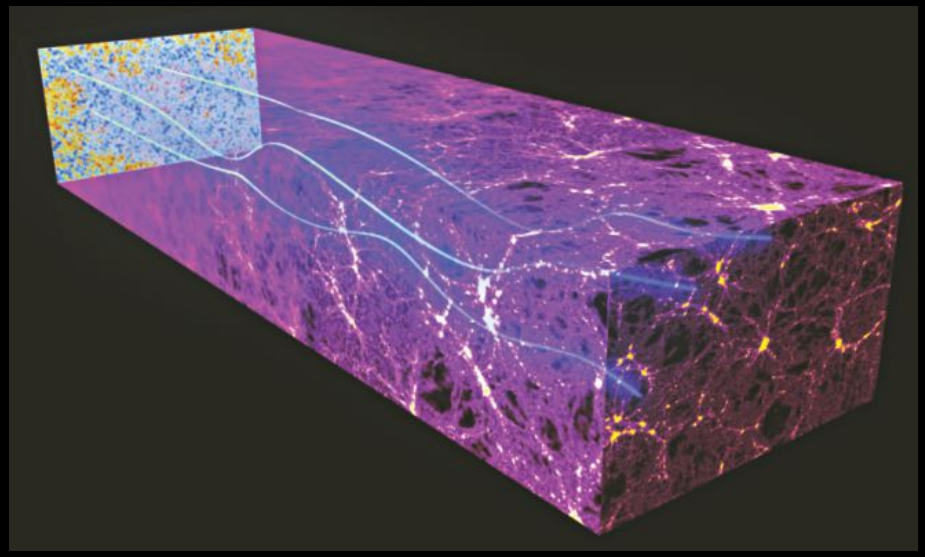
As shown, these curves actually don't fit the Planck data
Probably due to anisotropic pressure

There likely are fits, but need to check whether they are consistent with BBN, etc.

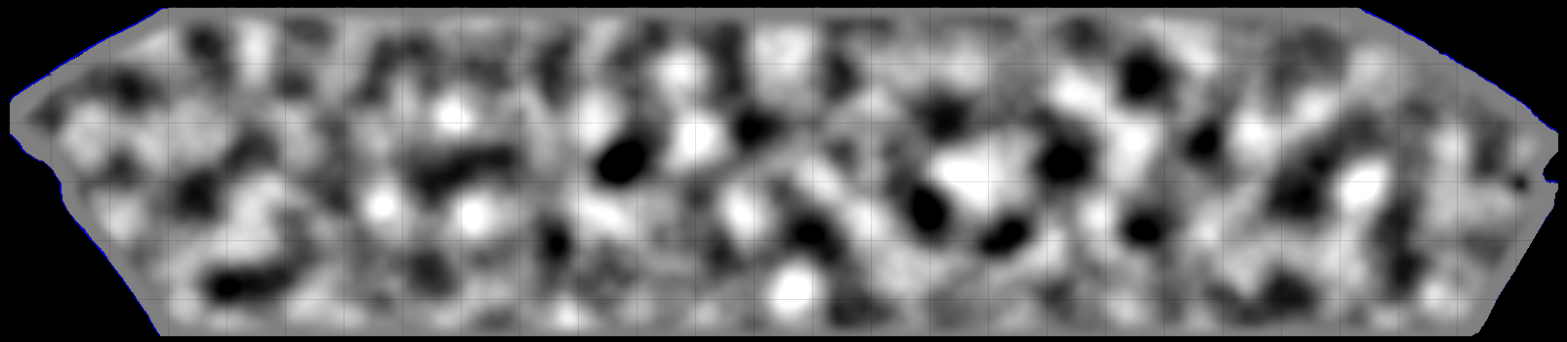


Mapping Universe's Mass

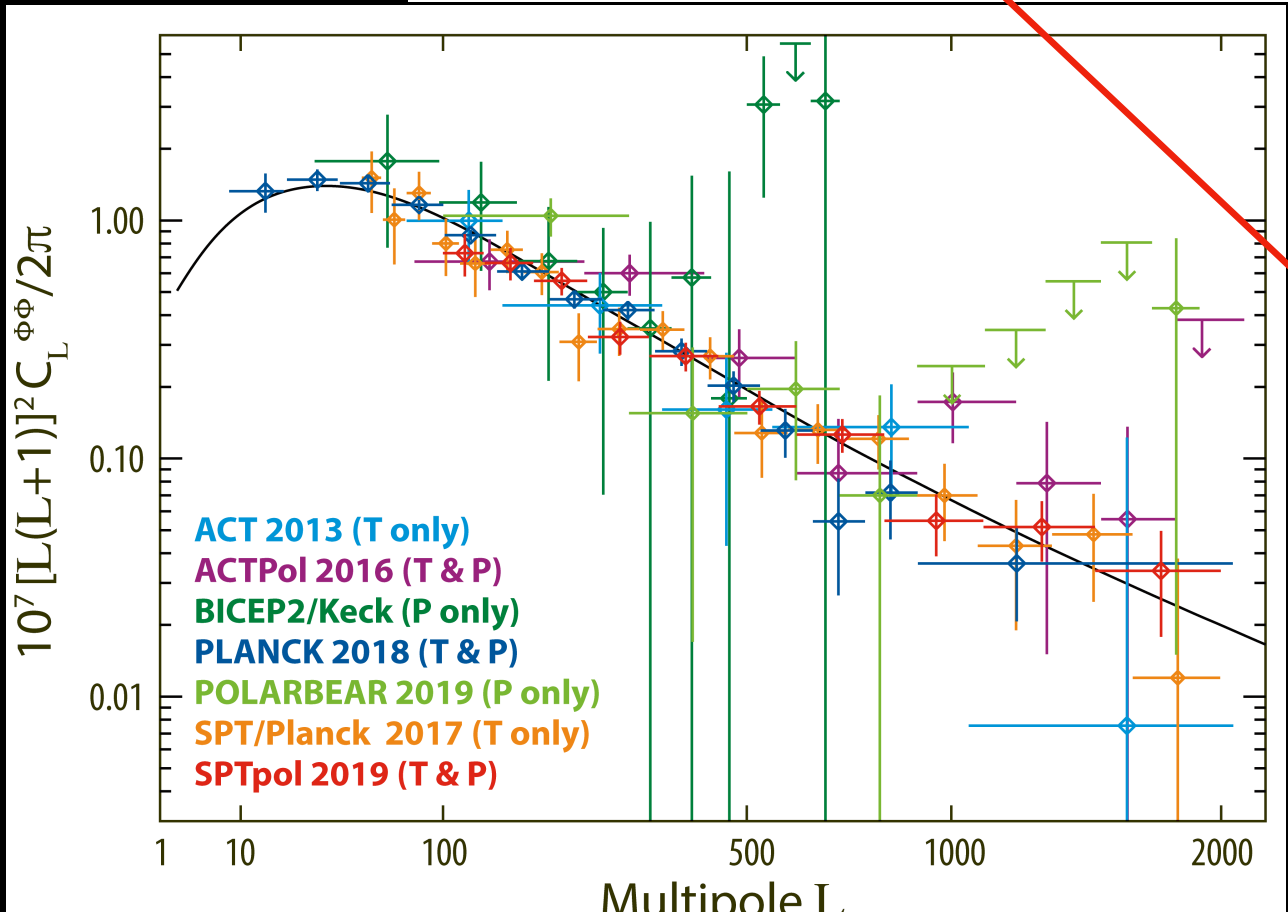




Mapping the Distribution of Mass

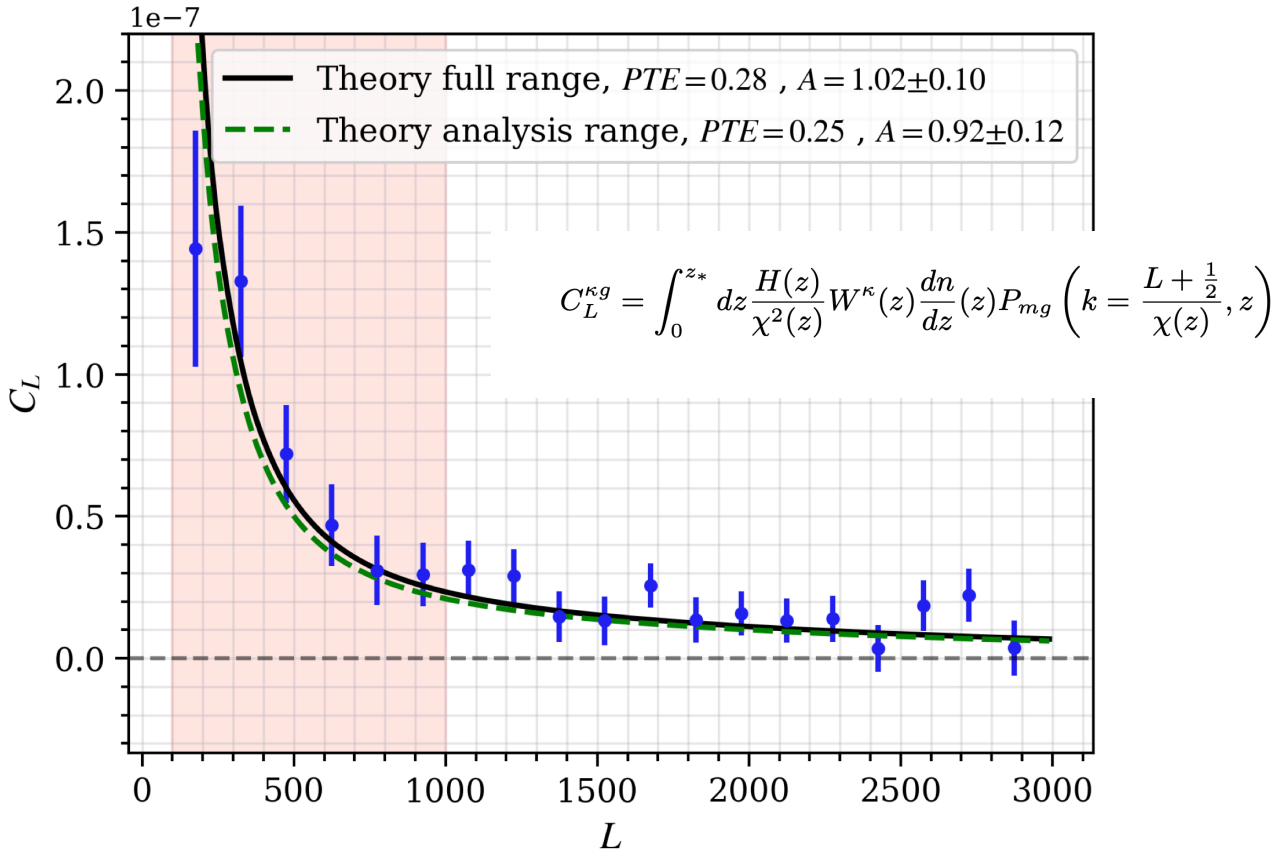


$$C_L^{\phi\phi} = \frac{9\Omega_{m0}^2 H_0^4}{c^4} \int_0^{\chi_s} d\chi \left(\frac{\chi_s - \chi}{\chi^2 \chi_s}\right)^2 \frac{(1+z)^2 P_m(k, z(\chi))}{k^4} \quad (5)$$



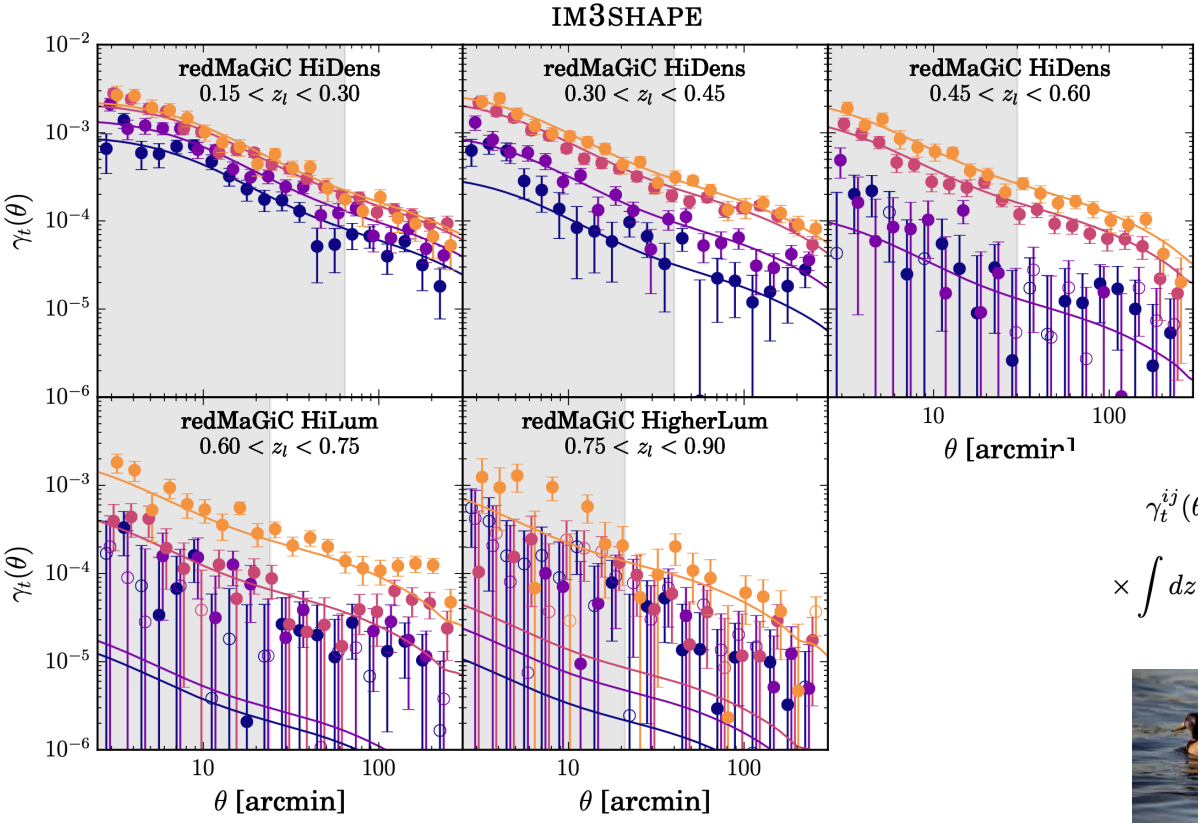
1/r gravitational potential

matter density

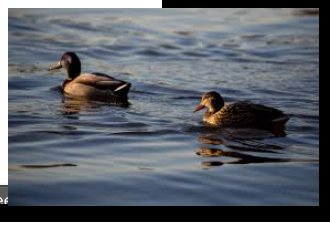

1e−7
Theory full range, $PTE = 0.28$, $A = 1.02 \pm 0.10$
Theory analysis range, $PTE = 0.25$, $A = 0.92 \pm 0.12$
$C_L^{\kappa g} = \int_0^{z_*} dz \frac{H(z)}{\chi^2(z)} W^{\kappa}(z) \frac{dn}{dz}(z) P_{mg}\left(k = \frac{L+\frac{1}{2}}{\chi(z)}, z\right)$
C_L
2.0
1.5
1.0
0.5
0.0
0
500
1000
1500
2000
2500
3000
L

Galaxy-galaxy lensing

DES yr1 data (Prat et al. 2018)

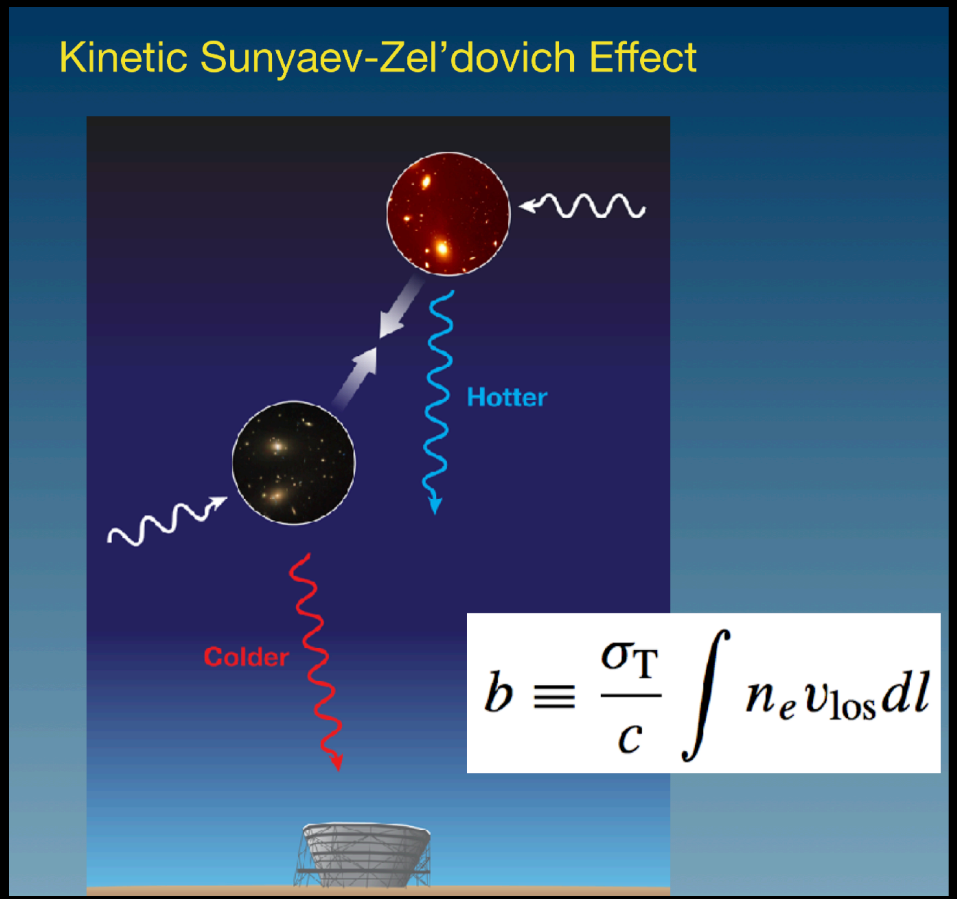


$$\gamma_t^{ij}(\theta) = b^i \frac{3}{2}\Omega_m \left(\frac{H_0}{c}\right)^2 \int \frac{d\ell}{2\pi}\, \ell\, J_2(\theta\ell) \times$$
$$\times \int dz \left[\frac{g^j(z)\, n_l^i(z)}{a(z)\,\chi(z)}\, P_{\delta\delta}\left(k = \frac{\ell}{\chi(z)}, \chi(z)\right)\right], \quad (1)$$



Large-scale velocity fields

CMB-galaxy cross-correlations of KSZ effect

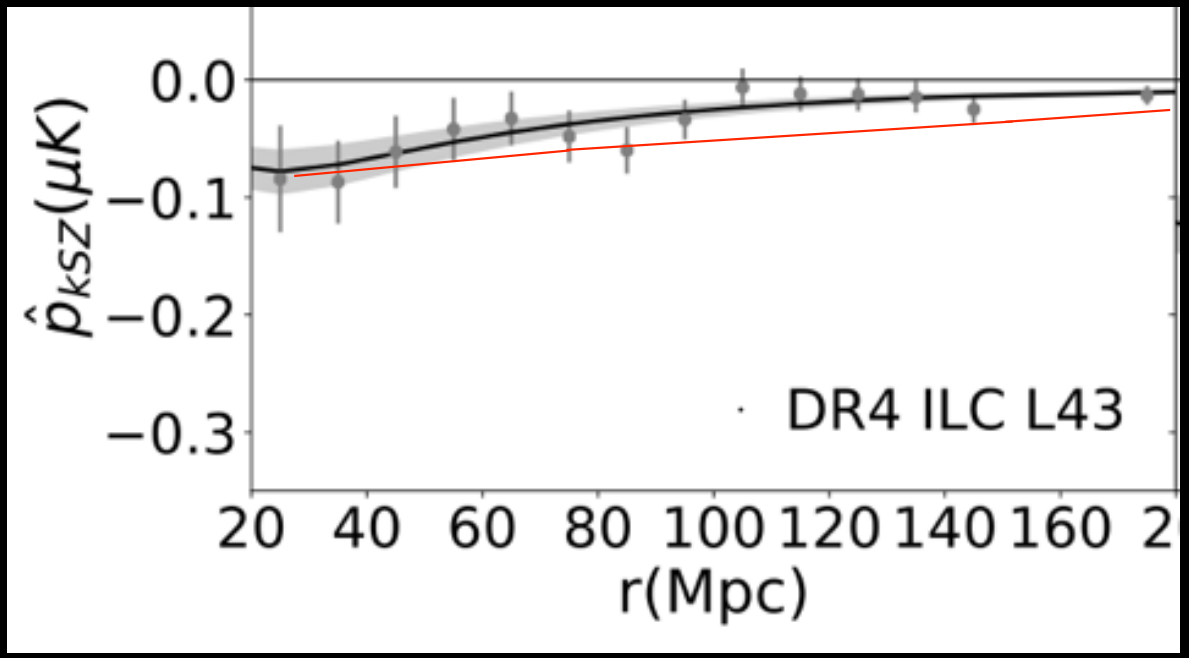


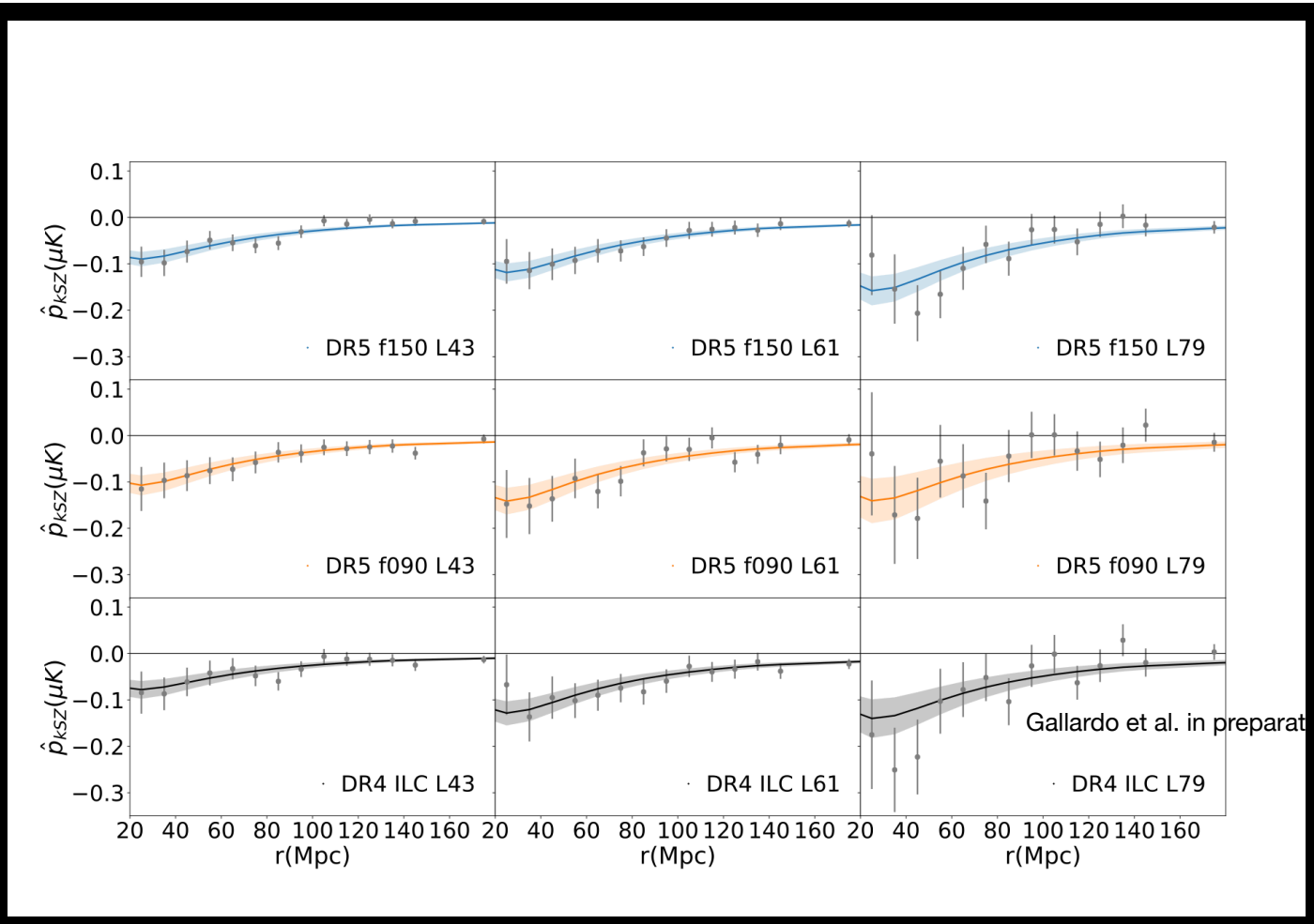
In Newtonian theory on the 10-100 Mpc scale, we can compute the expected gravitational acceleration from the matter correlation function, which scales roughly as $(R/R_0)^{-1.8}$:

$$a_N = \frac{4\rho_0}{R^2}\int \xi(r) r^2 dr = \frac{5\Omega_m H_0^2 R_0^{1.8}}{4R^{0.8}} \tag{1}$$

While MOND predicts

$$a_{MOND} = (a_N a_0)^{1/2} = \frac{a_0\sqrt{5\Omega_b H_0^2} R_0^{0.9}}{2R^{0.4}} \tag{2}$$

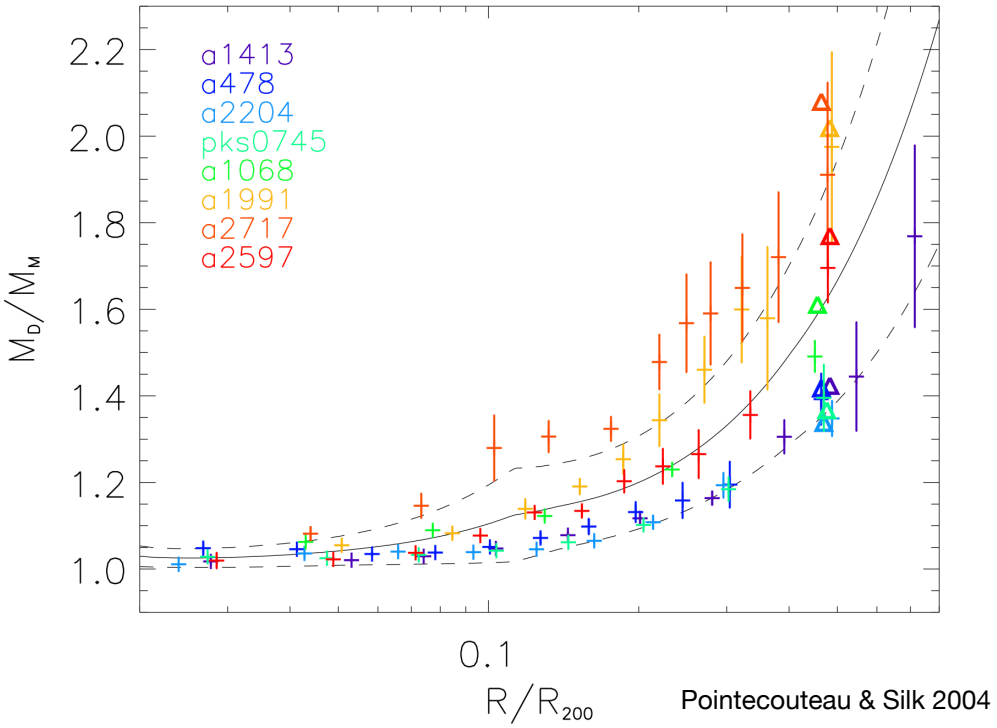




Calafut et al. 2101.08374

Not a horse….

MOND failures in clusters



Pointecouteau & Silk 2004

MOND apologists have shown that a 11 eV sterile neutrino could fit the cluster profiles with MOND (see e.g., Angus et al. 2013)

11 eV sterile neutrinos are a form of dark matter… hot dark matter

On galactic scales, data favors GR over MOND

Lisanti, Moschella, Outmezguine, Slone 1812.08169

comparison of vertical acceleration to radial acceleration favors GR by 2 sigma

Upcoming GAIA data should improve the significance of this test

Wasn't a horse 30 years ago.....

THE ASTROPHYSICAL JOURNAL, 397:38–43, 1992 September 20

DWARF SPHEROIDAL GALAXIES AND NON-NEWTONIAN GRAVITY

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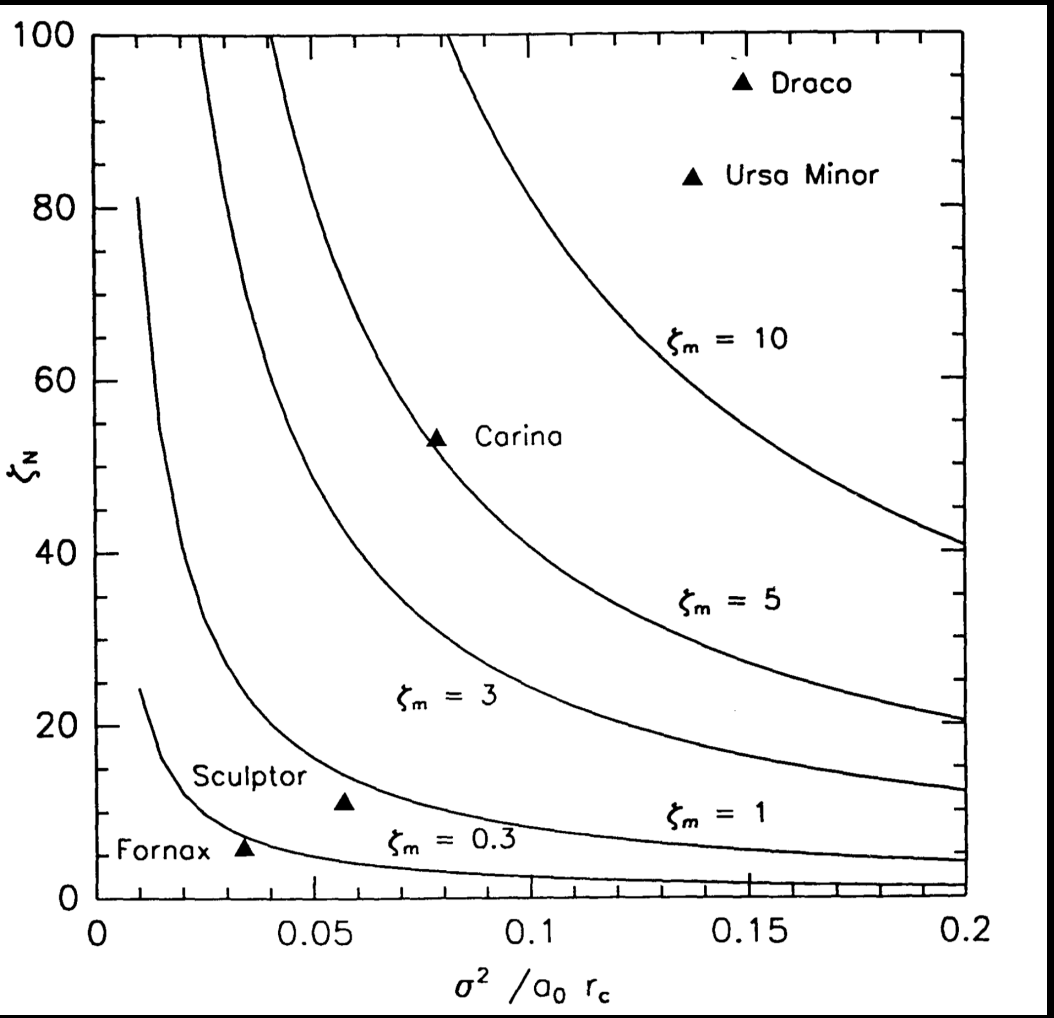
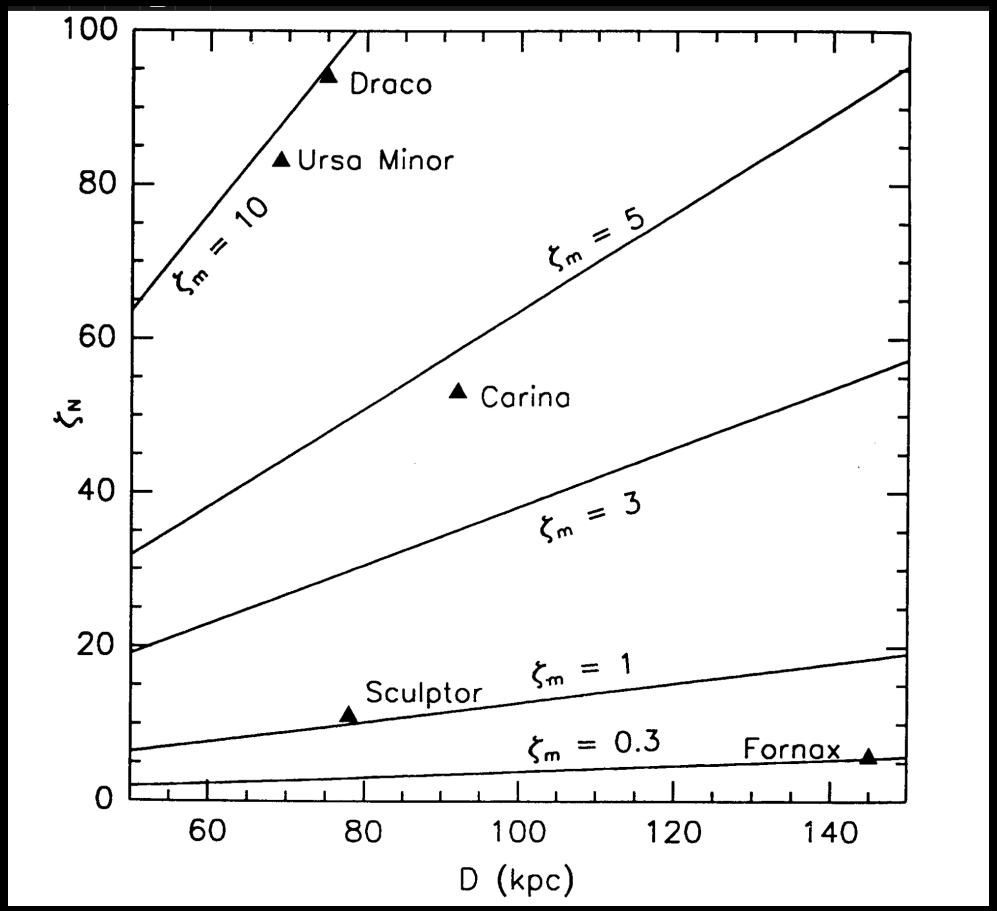
ABSTRACT

We derive a virial theorem and an analog for King's formula in modified Newtonian dynamics (MOND; Milgrom 1983) and use these to estimate the mass-to-light ratios (M/Ls) in MOND of the dwarf spheroidal galaxies in the Local Group. We find that the low-velocity dispersion observed in the Fornax dwarf galaxy implies low values for its M/L in MOND: 0.3–1. In particular the derived value in the core of Fornax (0.3) is much lower than expected for a normal old stellar population. Conversely, the velocity-dispersion measurements in Draco and Ursa Minor appear to still require dark matter in MOND. We show that M/L must vary between the dwarf spheroidals around the Galaxy by a factor of order at least 20, even in MOND.

Subject headings: dark matter — galaxies: elliptical and lenticular, cD — galaxies: kinematics and dynamics — gravitation



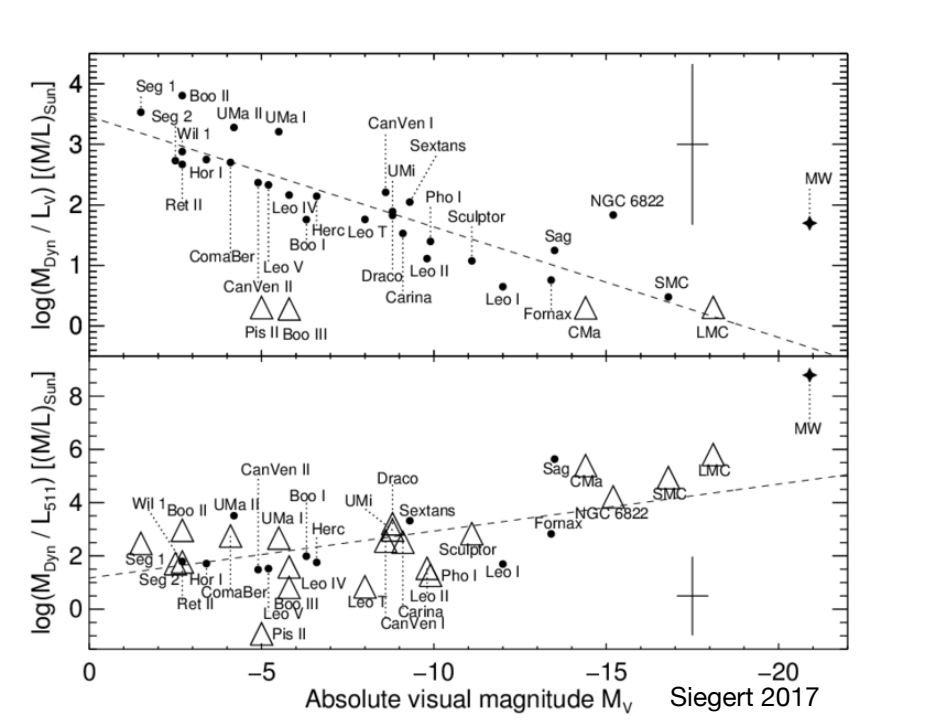
M/L ratios: Treating Dwarfs as Isolated System



M/L ratios: Including MW gravity

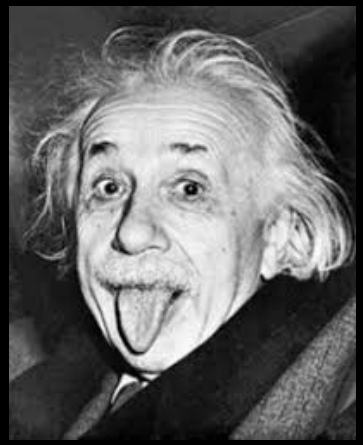
Still not a horse…..

MOND failures in dwarf galaxies



Siegert 2017

Sorry, Moti—- these aren’t all being tidally disrupted!



Conclusions

Alternative theories can fit CMB observations, lensing observations, large-scale flow measurements, and cluster observations as long as the model behaves like linear GR on the kpc to Gpc scale and has a sound speed and equation of state close to 0.