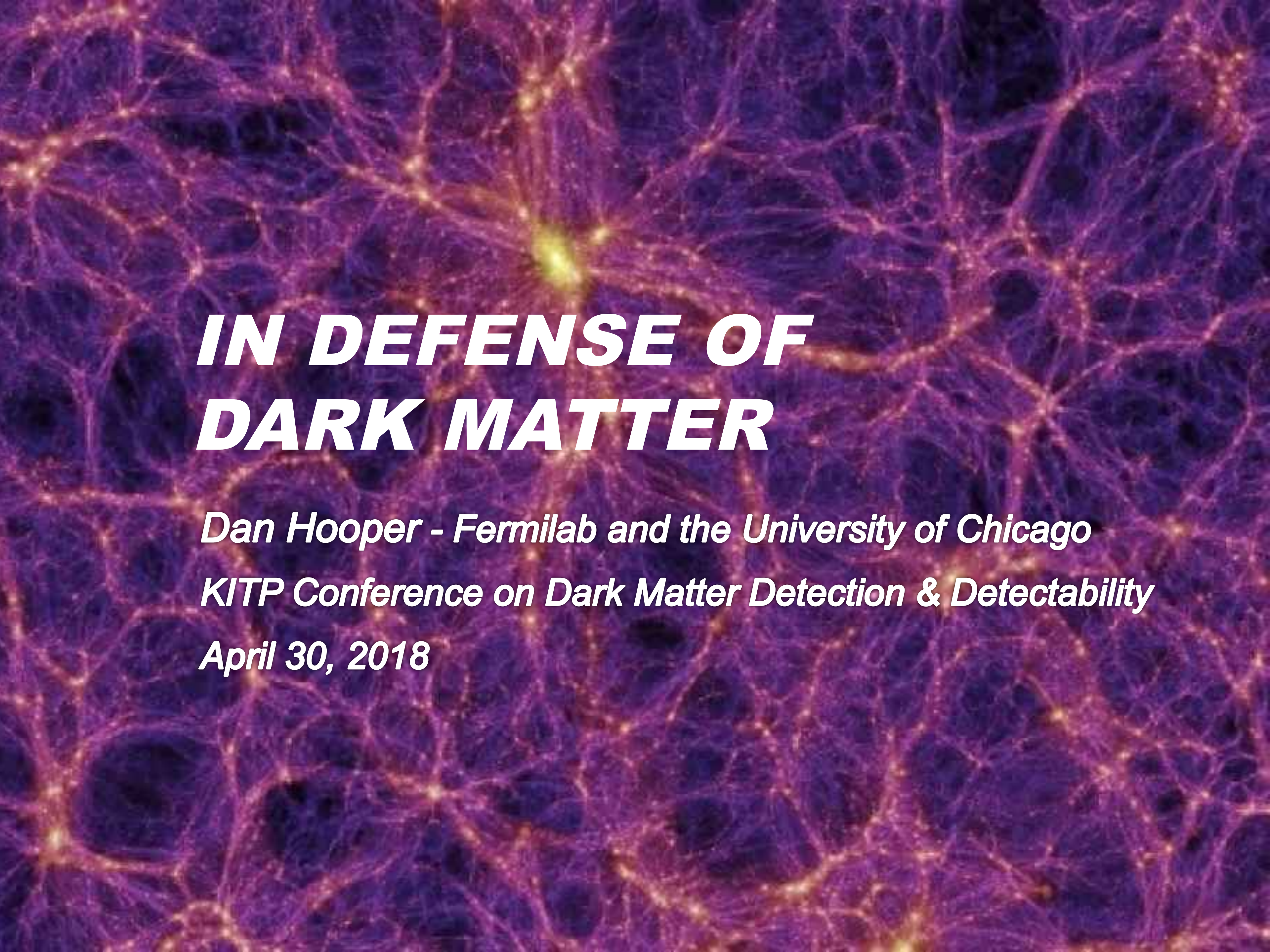


IN DEFENSE OF DARK MATTER

Dan Hooper - Fermilab and the University of Chicago

KITP Conference on Dark Matter Detection & Detectability

April 30, 2018

What I will try to argue in this talk

- The existence of dark matter is on extremely strong empirical footing
- Standard ΛCDM cosmology has been incredibly successful, explaining a large number and variety of precise cosmological observations
- We have “discovered” dark matter in a variety of different ways over the past several decades (although we do not yet have any unambiguous indications of dark matter’s particle nature)

- In contrast, no proposed version of MOND or other modification of general relativity has been able to explain the observed large scale structure of our universe, or the cosmic microwave background

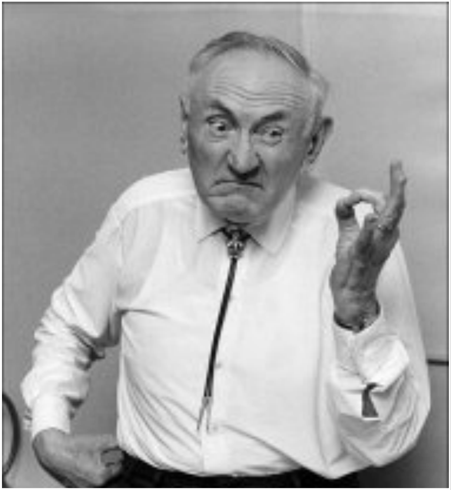
What I am *NOT* going to argue in this talk

- It is *entirely impossible* that the observations that we currently attribute to dark matter are actually somehow the consequence of some departure from general relativity – I will merely argue that this is highly unlikely

- No one should be working on MOND or other modifications of general relativity

These positions are strawmen

Myths and History



- I’ve seen hundreds of seminars, colloquia and conference talks which summarize the history of dark matter in terms of Fritz Zwicky (Coma 1933) and Vera Rubin (Andromeda 1970)

- This is more mythology than history

- Although Zwick and Rubin made important contributions, it was not the dynamics of galaxies or galaxy clusters that lead to the broad consensus that dark matter exists in large quantities
  (in fact, neither Zwicky nor Rubin was convinced that dark matter exists)

For a history of dark matter, see Bertone and DH (2016)

Myths and History

- Many of the papers that we now think of as the pioneering work on particle dark matter in fact make no reference to any missing mass or dark matter problem – the authors were, at the time, either unaware of or unconcerned with these issues
- Take, for example, Lee and Weinberg (1977): “Of course, if a stable heavy lepton were discovered with a mass of order 1-15 GeV, the gravitational field of these heavy neutrinos would provide a plausible mechanism for closing the universe.”
- Until the mid-1980s, most papers discussing cosmological constraints on particle physics models made no reference to the dark matter problem
- Many of the early papers on neutralinos and axions that we now think of as being about dark matter, in fact made no reference at all to the missing mass problem – the necessity of dark matter became a consensus view only later

For a history of dark matter, see Bertone and DH (2016)

What Lead to the Dark Matter Consensus?

For a history of dark matter, see Bertone and DH (2016)

What Lead to the Dark Matter Consensus?

1) **Large Scale Structure**: By the mid-80s, it was appreciated that the results of simulations matched galaxy surveys only if the universe contained large quantities of ***cold dark matter***

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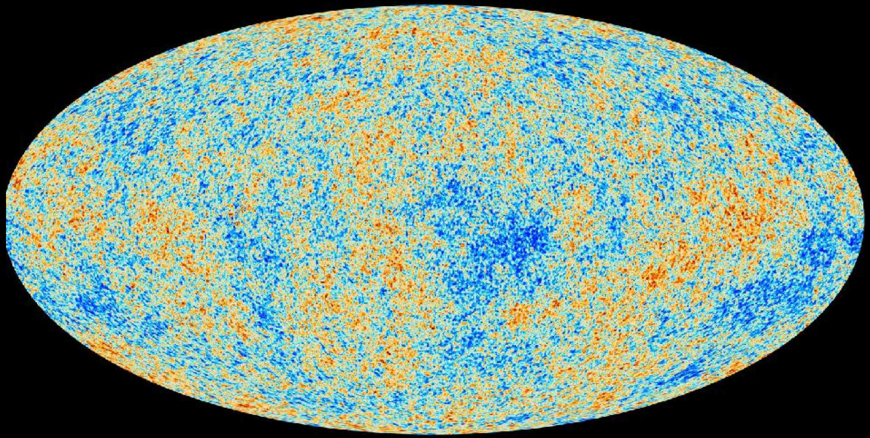
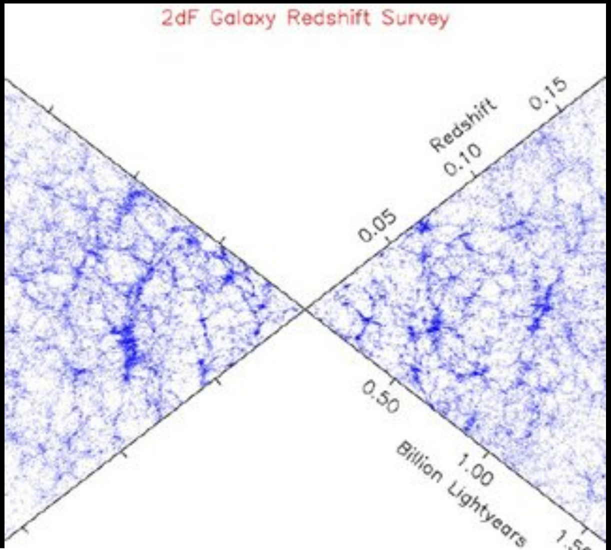
4) **The Tightening of the Baryon Budget**: In the 1970s, light element abundances required only $\Omega_b<0.1$; high precision deuterium measurements in the 1990s improved this to $\Omega_b h^2=0.020\pm0.002$

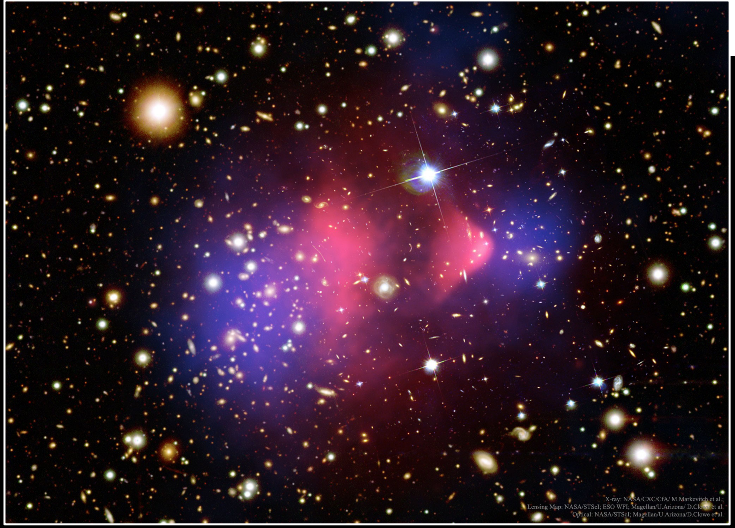
Galactic dynamics had little to do with the rise of particle dark matter
Cosmological considerations played a very important role

For a history of dark matter, see Bertone and DH (2016)

The Spectacular Success of ΛCDM in the Age of Precision Cosmology







X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
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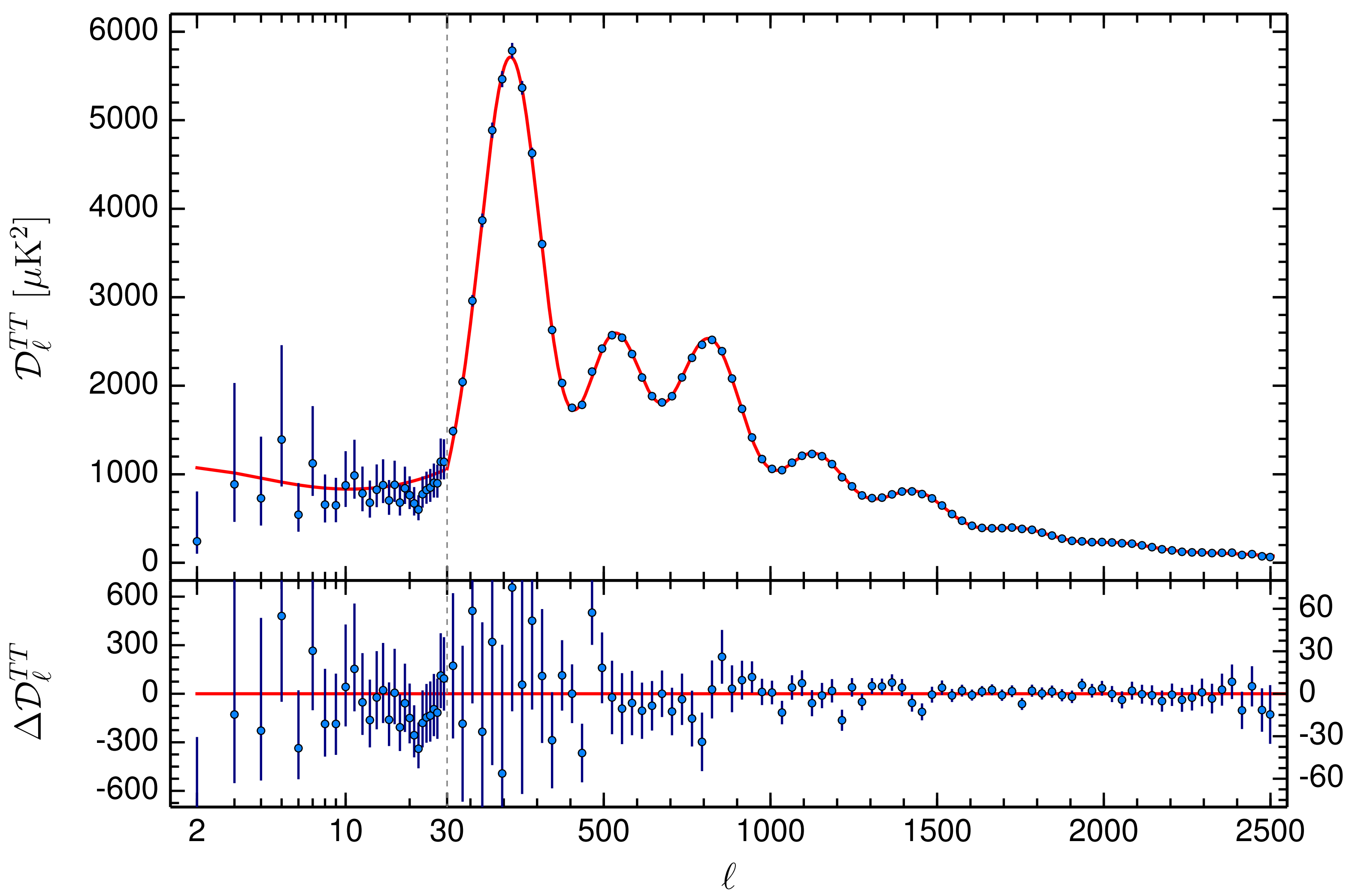
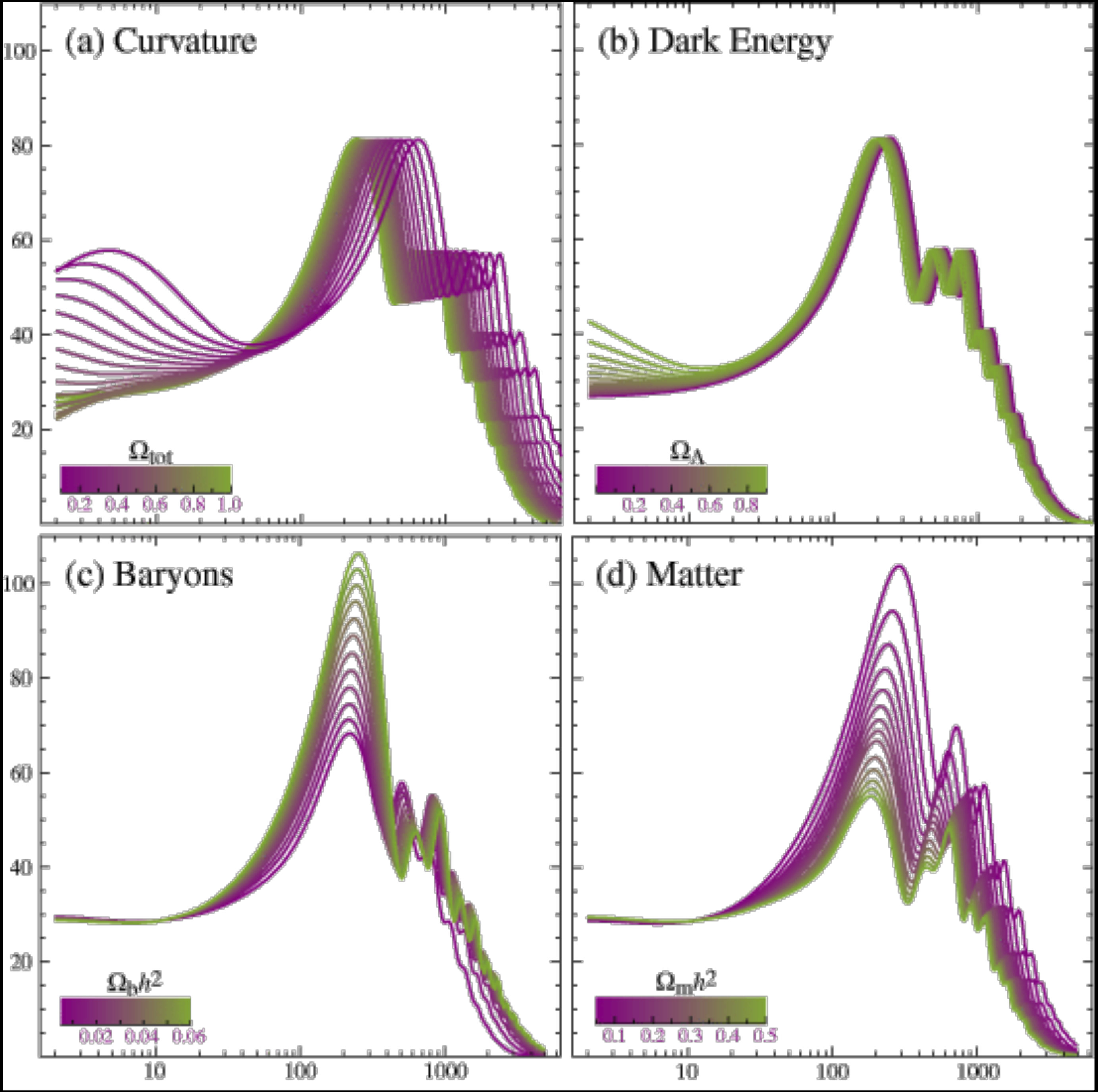
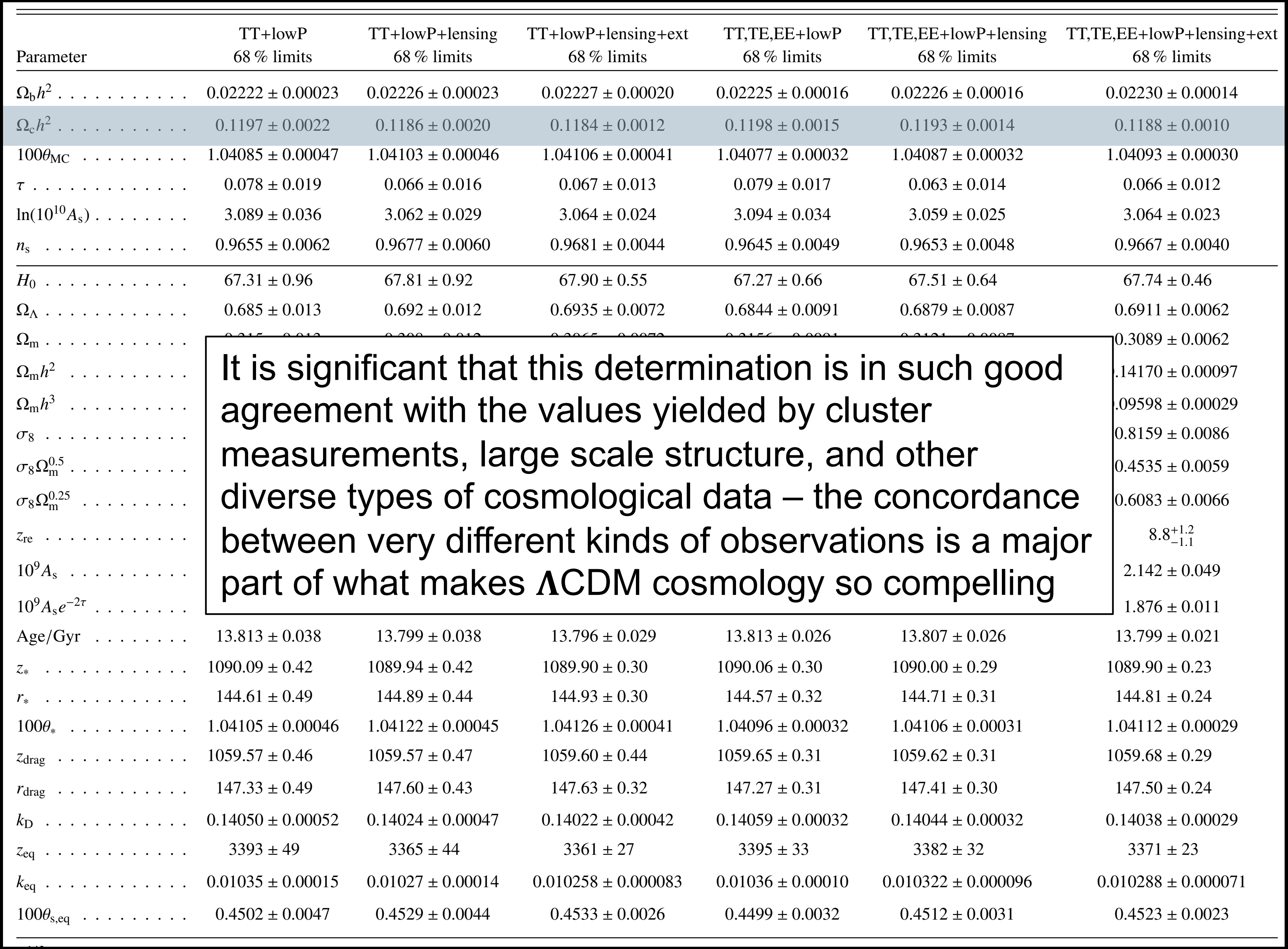


Planck Collaboration, 2015


(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
100
80
60
40
20
10
100
1000
$\Omega_{\rm tot}$
0.2 0.4 0.6 0.8 1.0
Ω_Λ
0.2 0.4 0.6 0.8
$\Omega_{\rm b}h^2$
0.02 0.04 0.06
$\Omega_{\rm m}h^2$
0.1 0.2 0.3 0.4 0.5

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_\mathrm{b} h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_\mathrm{c} h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_\mathrm{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_\mathrm{s})$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_\mathrm{m} h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_\mathrm{m} h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_\mathrm{m}^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_\mathrm{m}^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_re	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_\mathrm{s}$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_\mathrm{s} e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_drag	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_drag	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_eq	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_eq	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_\mathrm{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023



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It is significant that this determination is in such good agreement with the values yielded by cluster measurements, large scale structure, and other diverse types of cosmological data – the concordance between very different kinds of observations is a major part of what makes **Λ**CDM cosmology so compelling

What The CMB Really Tells Us About Dark Matter and Modified Gravity

- The CMB tells us that inhomogeneities in the photon-baryon plasma were at a level of one part in ~10^4 at the time of recombination
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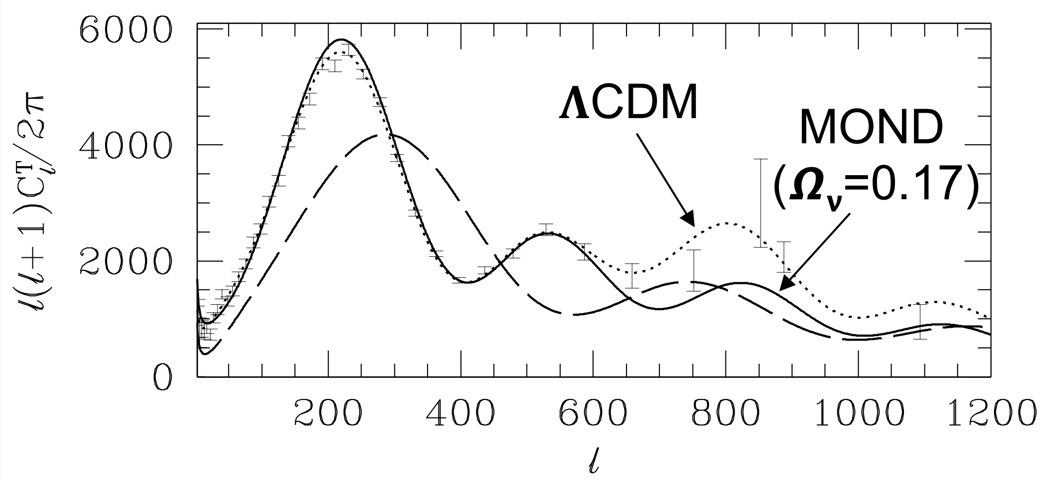
- Although the ratio of the first and second peaks is roughly consistent with no dark matter, the third peak would have been much smaller without dark matter

What The CMB Really Tells Us About Dark Matter and Modified Gravity

- Here is an example, (as calculated within TeVeS), Skordis et al. (2005)



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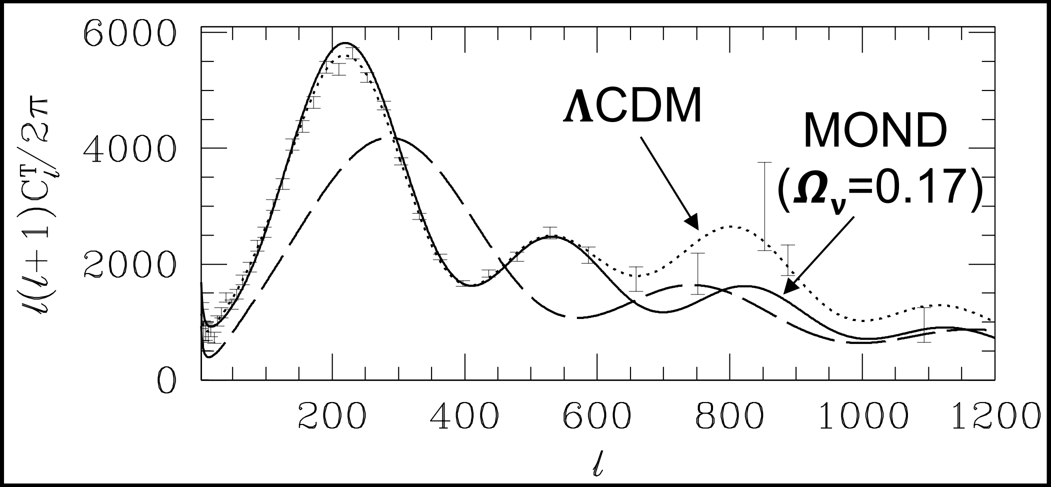

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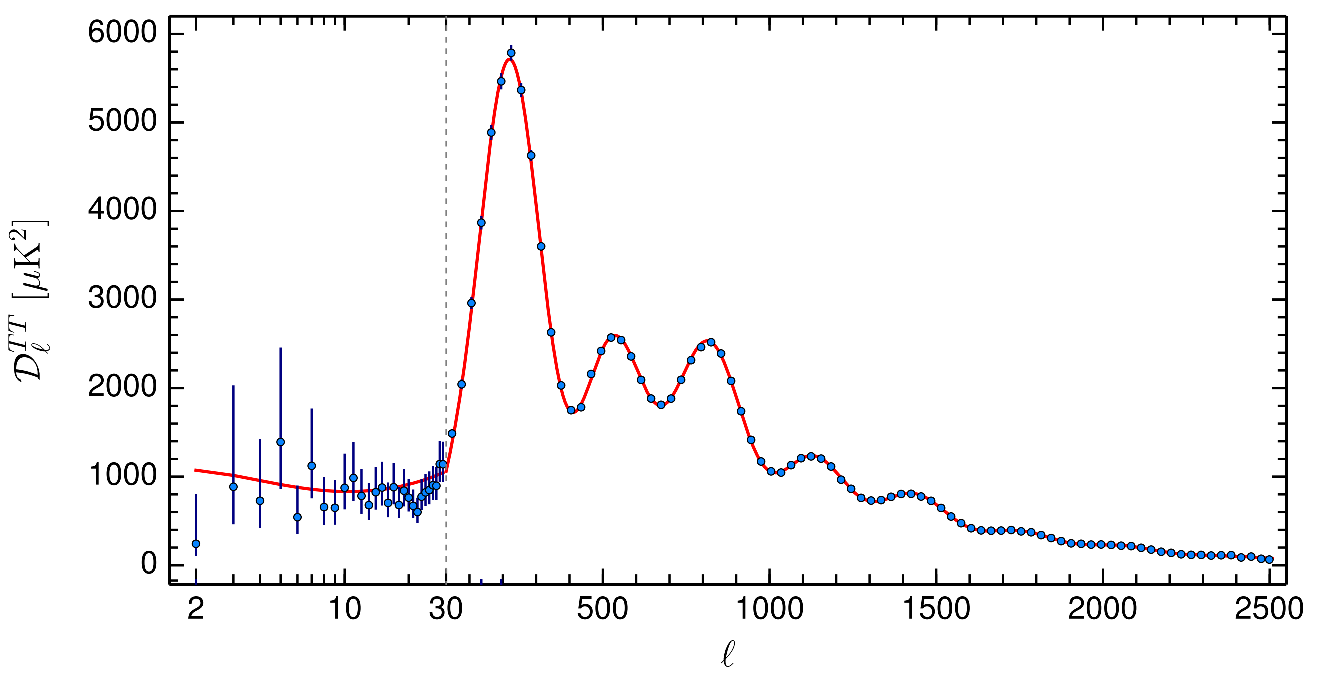

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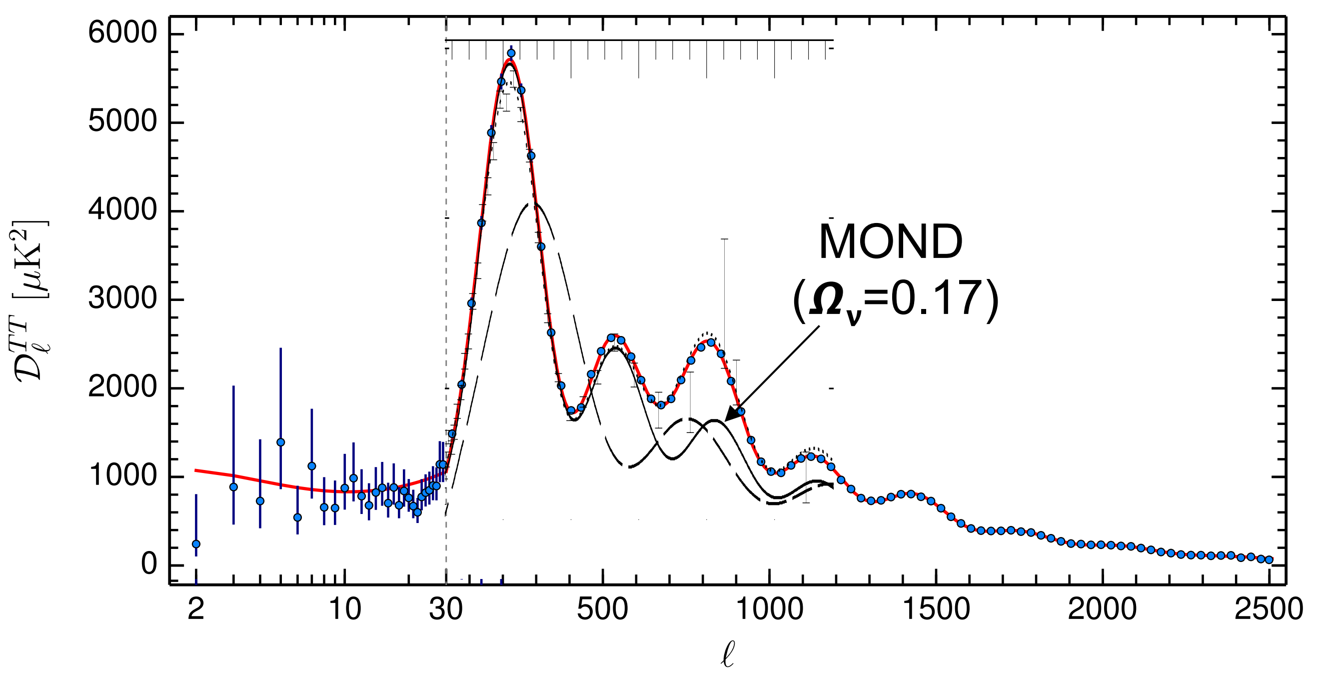
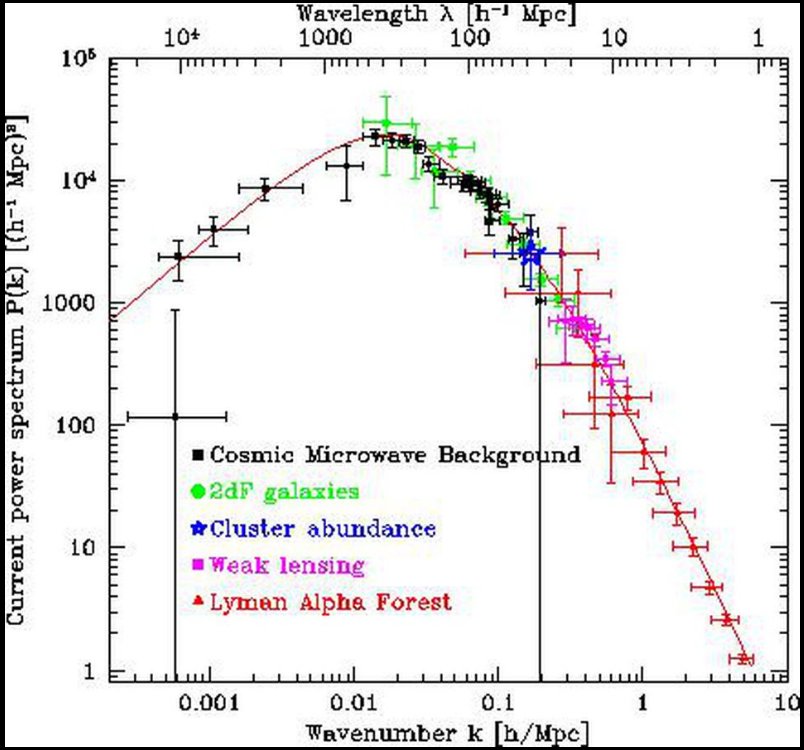


The Biggest Problem For MOND – The Matter Power Spectrum

- The matter power spectrum has been measured from scales as large as the cosmic horizon (~10 Gpc), down to those of galaxies (~1 Mpc)
- These observations are in fantastic agreement with the predictions of standard ΛCDM cosmology



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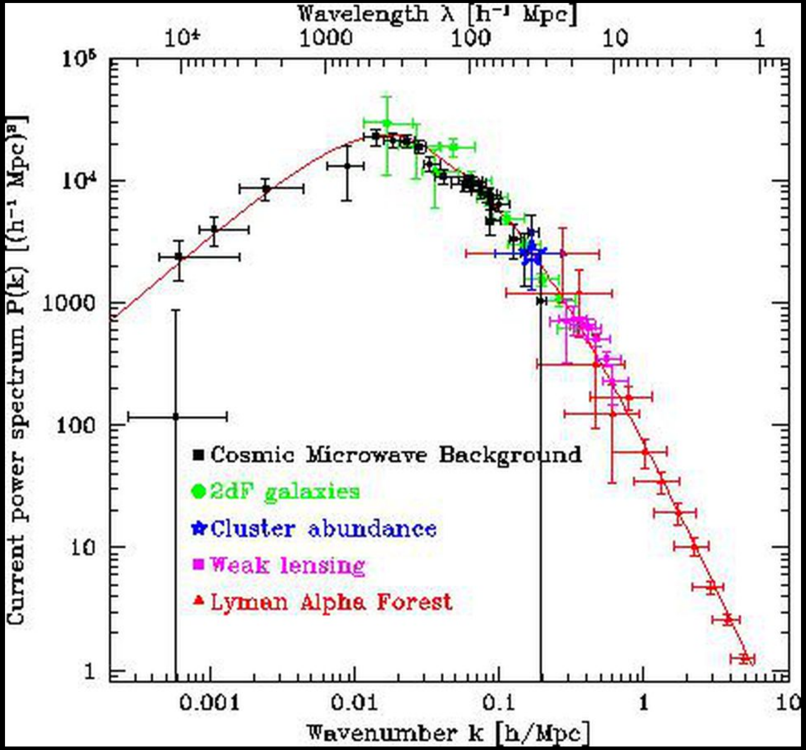
- If you look closely, you can see small wiggles in the matter power spectrum, resulting from baryon acoustic oscillations (BAO)
- These BAO are small in standard ΛCDM cosmology, because they are suppressed as baryons fall into the potential wells formed by dark matter – only a few percent of the primordial oscillations survive



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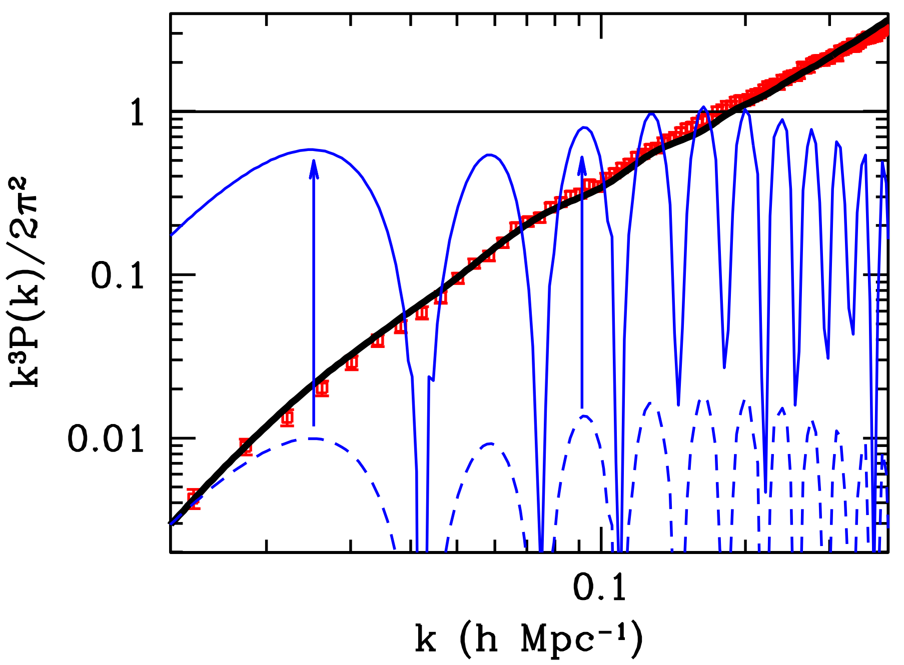
- In a universe without dark matter, however, these oscillations should be *much* larger
- Even if structure growth is somehow enhanced through modifications of gravity, without dark matter, BAO should be ~30 times larger than observed



Dodelson (2011)

The Bullet Cluster (and its cousins)

X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
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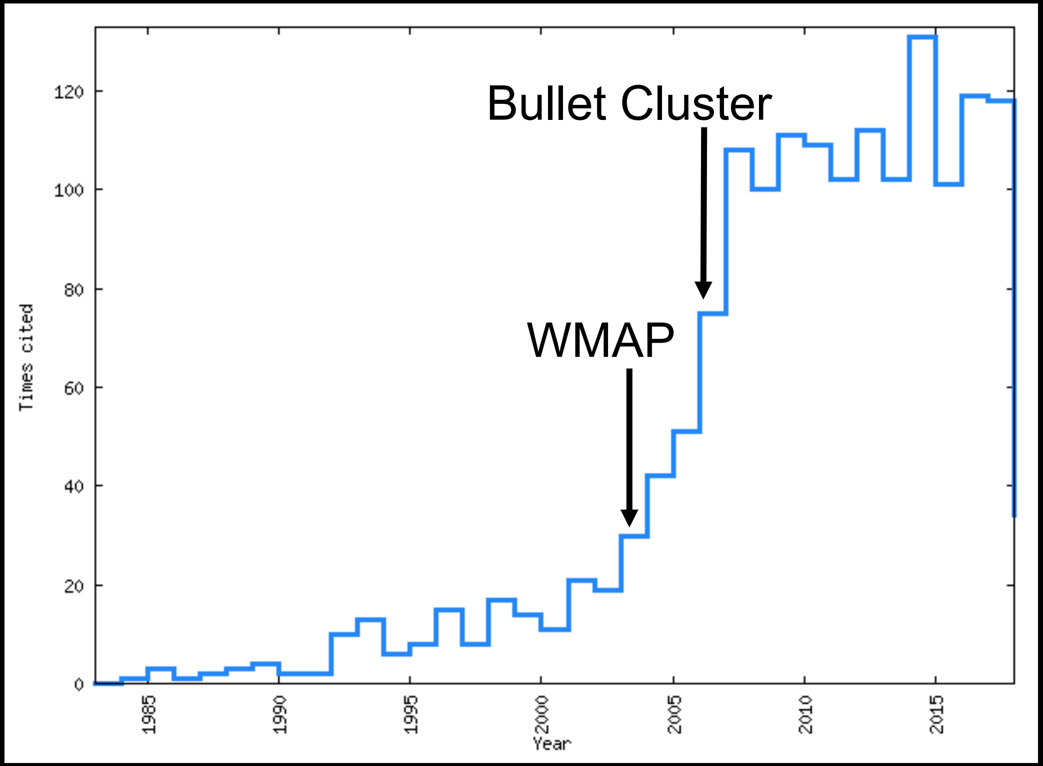

The citation rate of Milgrom’s 1984 paper, “A Modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis”

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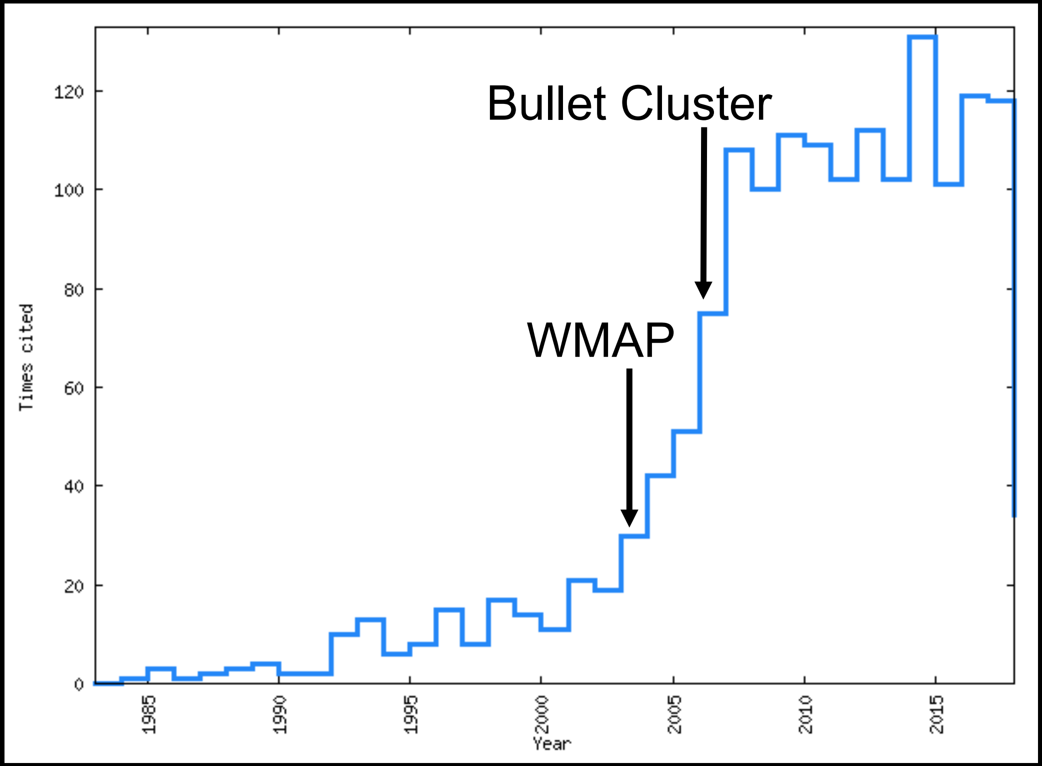

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What has driven this dramatic surge in interest in MOND?!?

Small Scale Structure Problems for CDM

The So-Called “Missing Satellites Problem”

- In the late 90s, its was pointed out that dark matter-only simulations predicted many more Milky Way satellite galaxies (~10^2-10^3) than had been observed at the time (~10) (Klypin *et al*., Moore *et al*. 1999)
- Since that time, SDSS, DES and other surveys have lead to the discovery of ~50 such satellites, and many more are expected from LSST
- Even more important has been the progress made in understanding how baryonic physics impacts such systems; it is now clear that most subhalos lighter than ~10^9 $M_\odot$ do not efficiently form stars

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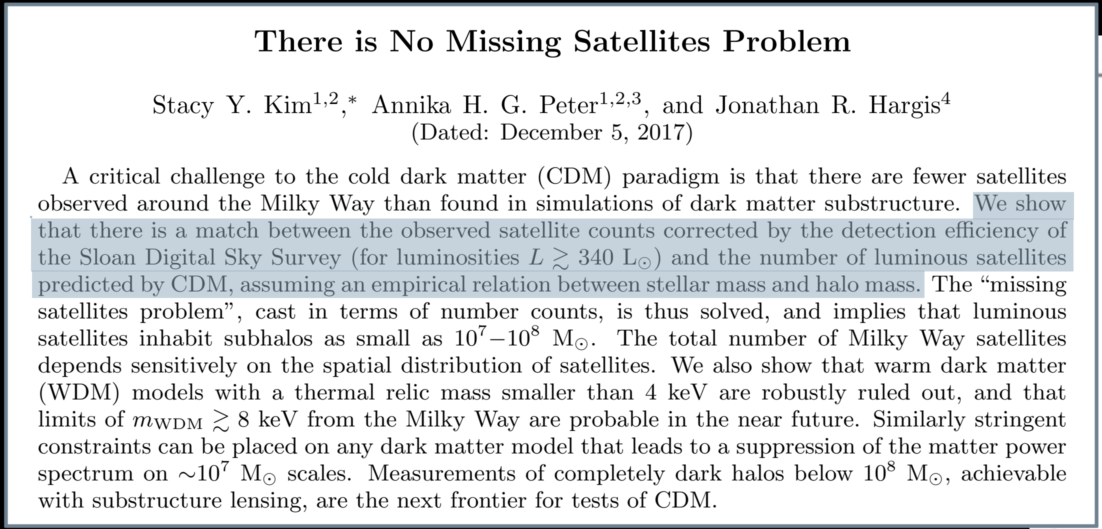
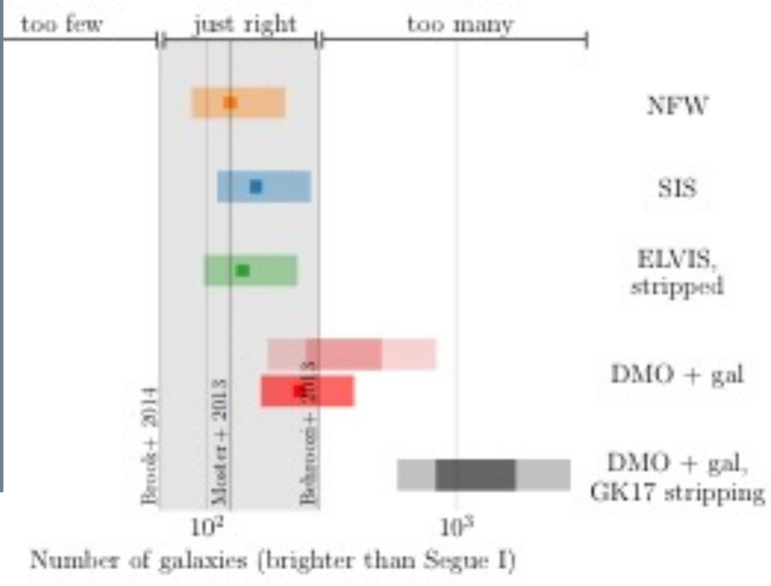
- Since that time, SDSS, DES and other surveys have lead to the discovery of ~50 such satellites, and many more are expected from LSST
- Even more important has been the progress made in understanding how baryonic physics impacts such systems; it is now clear that most subhalos lighter than ~10^9 $M_\odot$ do not efficiently form stars

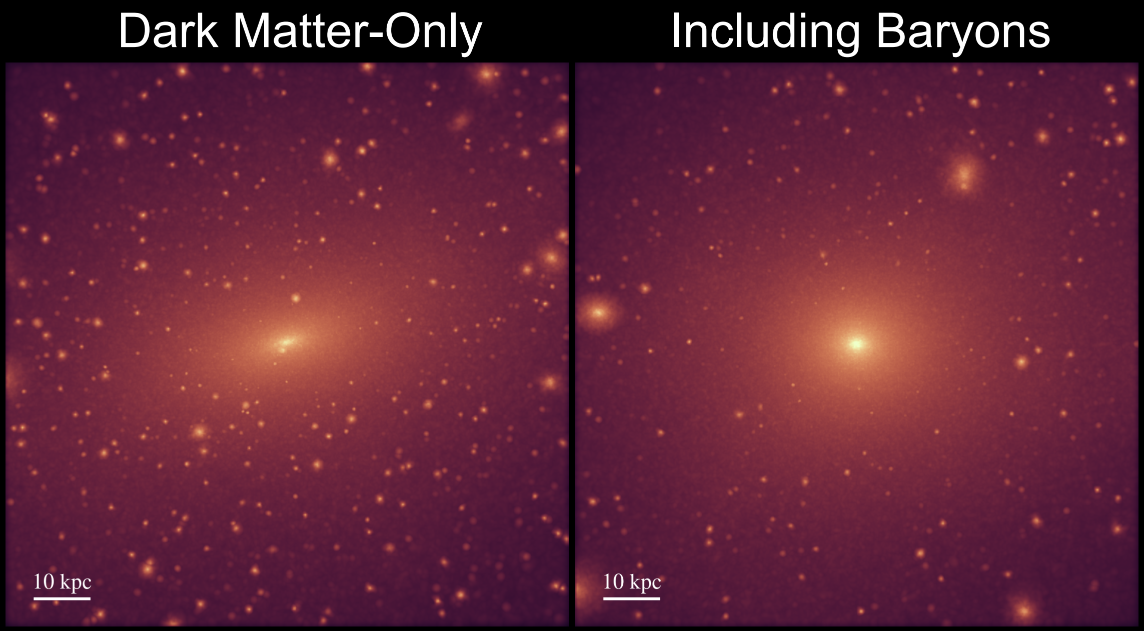


There is No Missing Satellites Problem

Stacy Y. Kim[1,2,*] Annika H. G. Peter[1,2,3], and Jonathan R. Hargis[4]
(Dated: December 5, 2017)

A critical challenge to the cold dark matter (CDM) paradigm is that there are fewer satellites observed around the Milky Way than found in simulations of dark matter substructure. We show that there is a match between the observed satellite counts corrected by the detection efficiency of the Sloan Digital Sky Survey (for luminosities $L \gtrsim 340$ $L_\odot$) and the number of luminous satellites predicted by CDM, assuming an empirical relation between stellar mass and halo mass. The “missing satellites problem”, cast in terms of number counts, is thus solved, and implies that luminous satellites inhabit subhalos as small as 10^7–10^8 $M_\odot$. The total number of Milky Way satellites depends sensitively on the spatial distribution of satellites. We also show that warm dark matter (WDM) models with a thermal relic mass smaller than 4 keV are robustly ruled out, and that limits of $m_{\mathrm{WDM}} \gtrsim 8$ keV from the Milky Way are probable in the near future. Similarly stringent constraints can be placed on any dark matter model that leads to a suppression of the matter power spectrum on $\sim 10^7$ $M_\odot$ scales. Measurements of completely dark halos below 10^8 $M_\odot$, achievable with substructure lensing, are the next frontier for tests of CDM.





Here’s an example, from Garisson-Kimmel et al. 2017, comparing the results of a dark matter-only simulation to a hydro-simulation (FIRE)

Too Big To Fail?

- In 2011, Boylan-Kolchin, Bullock and Kaplinghat pointed out that ΛCDM simulations predict more very massive ($\sim 10^{10}$ $M_\odot$) satellite galaxies than are observed
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- If the mass of the Milky Way is on the low side of current estimates, it is not clear that this is really a problem (perhaps just a mild outlier);
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- Baryonic effects can also reconcile simulations with observations (Brooks and Zolotov 2014, Brooks et al. 2013, Zolotov et al. 2012, Di Cintio et al. 2013, Arraki et al. 2014)
- Baryons can cool, moving mass toward the center of the parent halo and creating stronger tidal forces and greater tidal striping of satellites
- The presence of the Galactic Disk alone (which doesn't exist in DM only simulations), will destroy roughly a third of the most massive satellites

Cores and Cusps

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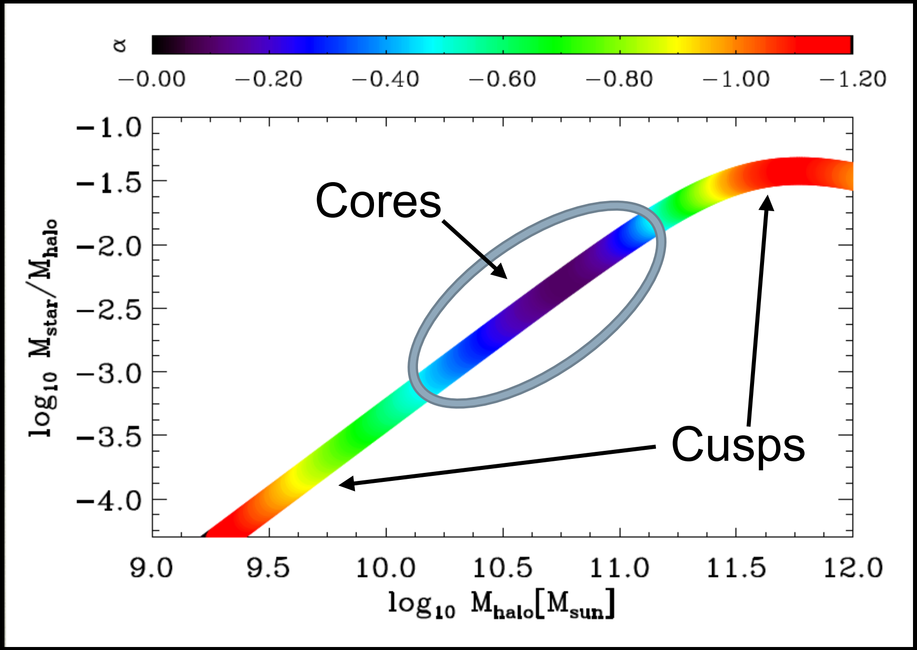
- More recent work has shown that stellar feedback can lead to repeated fluctuations in the gravitational potentials of such systems, removing dark matter from the central ~kpc (Pontzen and Governato 2012, Teyssier et al. 2013, Di Cintio et al. 2014, Pontzen and Governato 2014)



Di Cintio et al. (2014)

What To Make of the Small Scale Structure Problems?

- Personally, I think it’s likely that baryonic physics will ultimately resolve all of the small-scale problems currently being discussed
- Many very smart and informed experts hold other opinions, however, and no consensus exists
- But even if these problems are not the result of baryons, departures from cold, collisionless dark matter could very plausibly resolve the issues at hand, without resorting to modifications of general relativity

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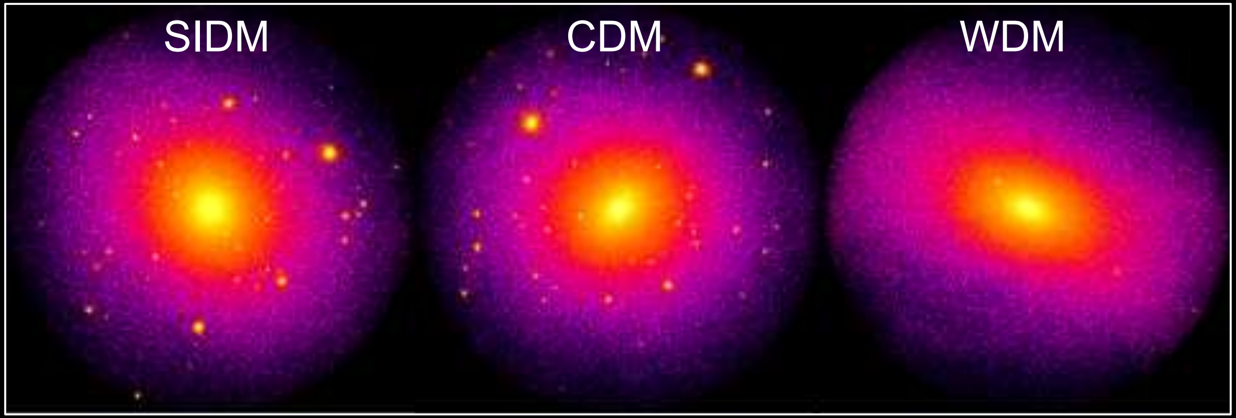
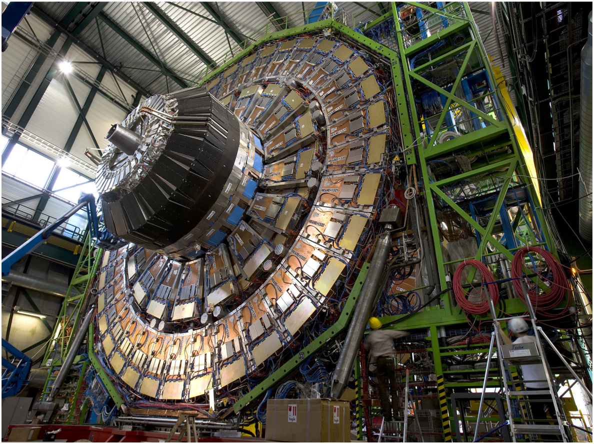
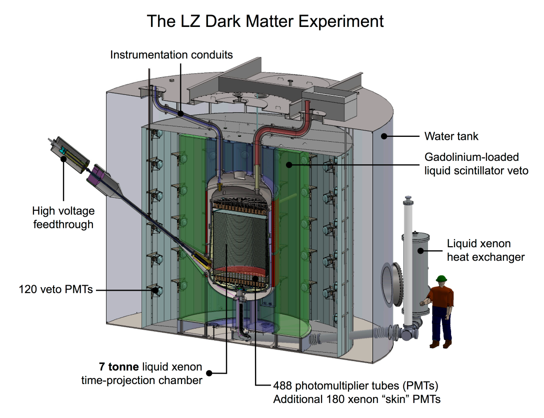
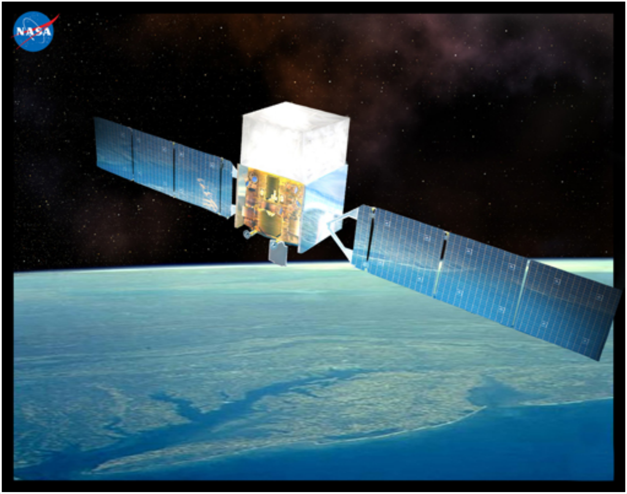


- Here's an example from Brooks et al. (2014) of a series of dark matter-only simulations of a 10^{10} $M_\odot$ halo, for self-interacting dark matter (2 cm^2/g), cold and collisionless dark matter, and warm dark matter (2 keV)

If dark matter exists, how surprised should we be that we haven't observed it non-gravitationally?







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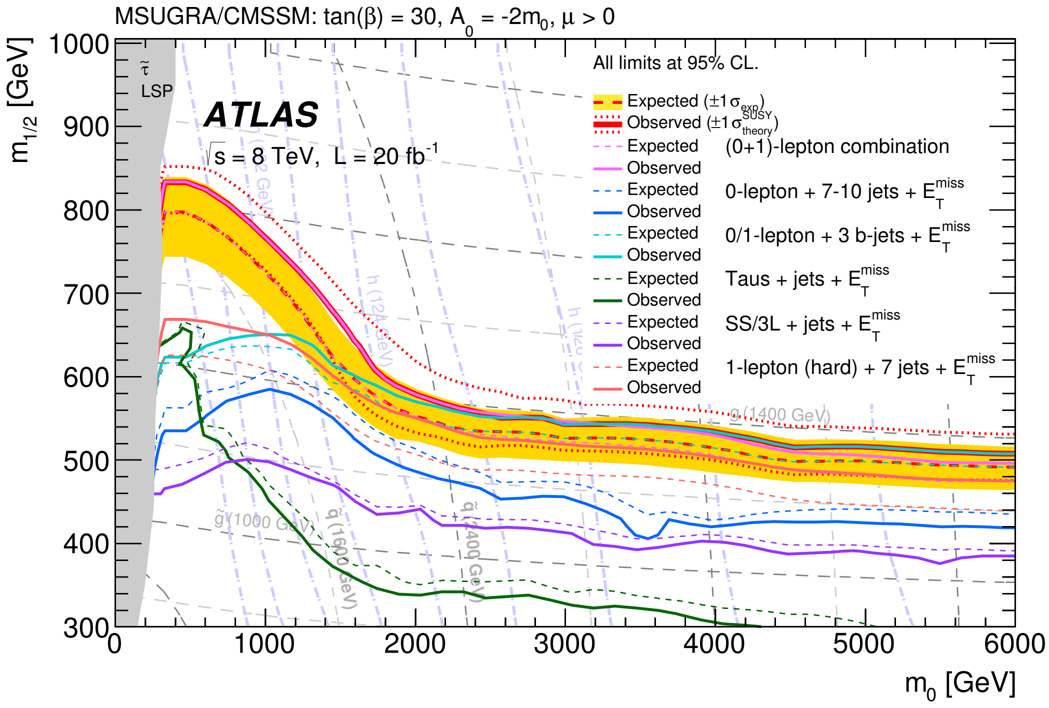
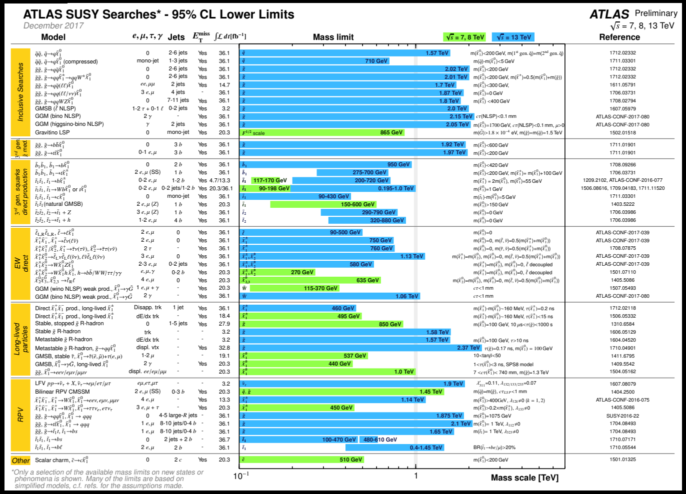
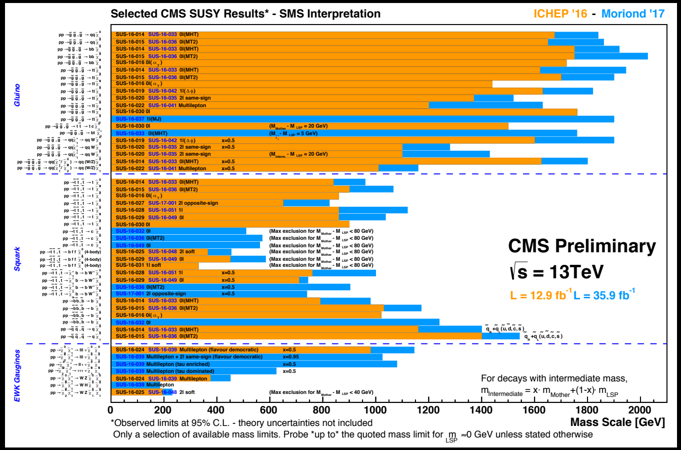
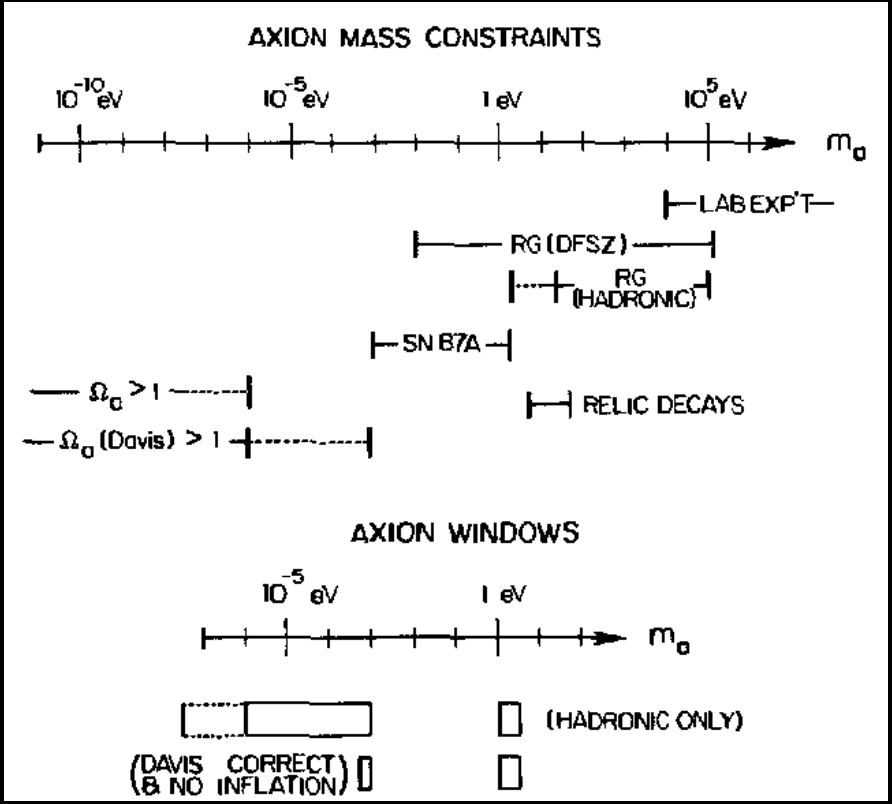
Constraints on Supersymmetry







Constraints on the QCD Axion



Kolb and Turner (1989)

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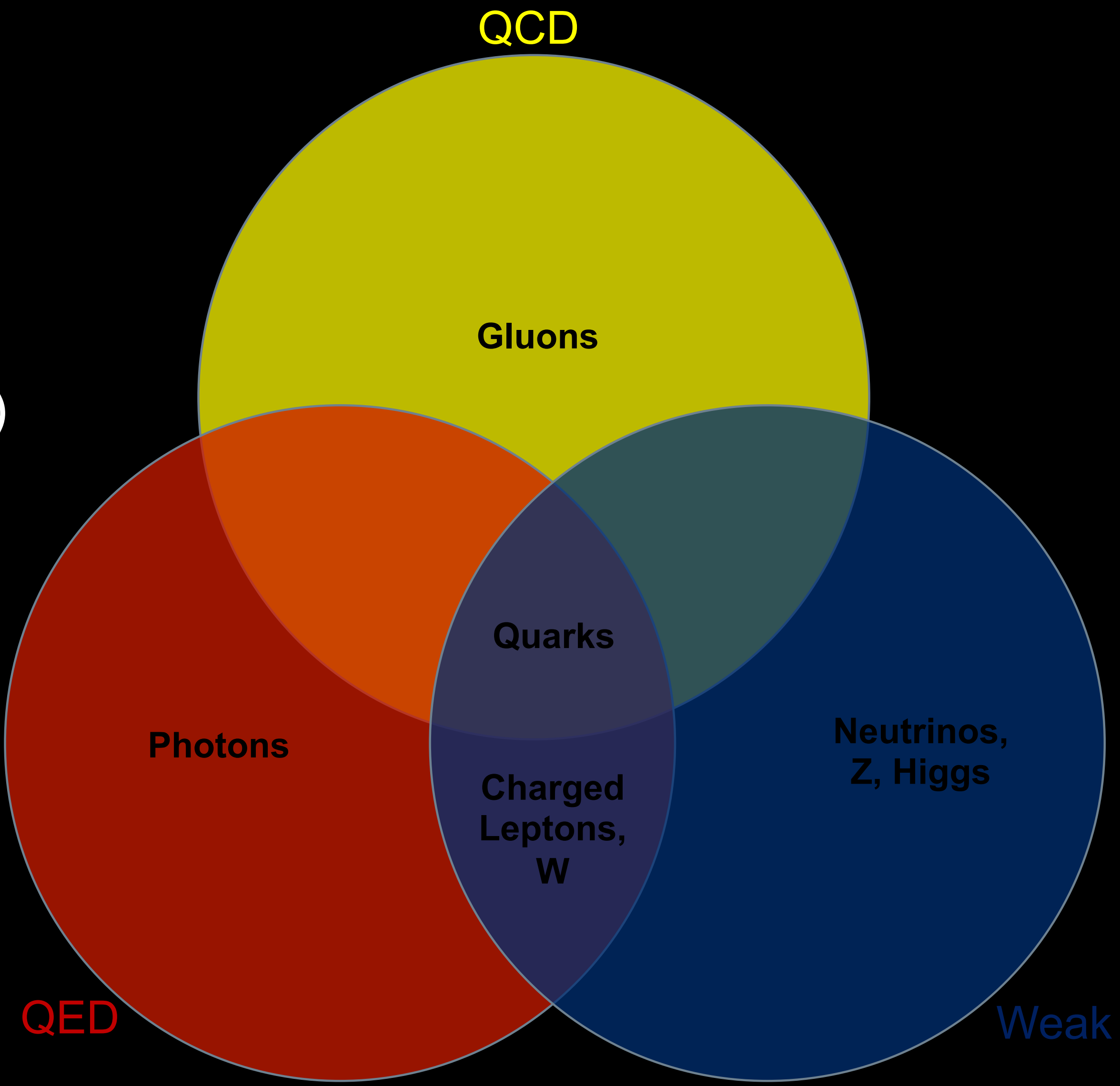
- Example II (bottom-up phenomenologist):
  - -Motivated by “WIMP Miracle”, among other possibilities
  - -Viable models often (but not always) invoke features such as resonances, coannihilations, low-masses, etc.
  - -Hidden sector WIMPs are essentially unconstrained (as one of many possible examples)

From among the 17 particle species contained in the Standard Model:

7/17 carry QCD color

11/17 carry (or couple to) electric charge

15/17 carry weak charge



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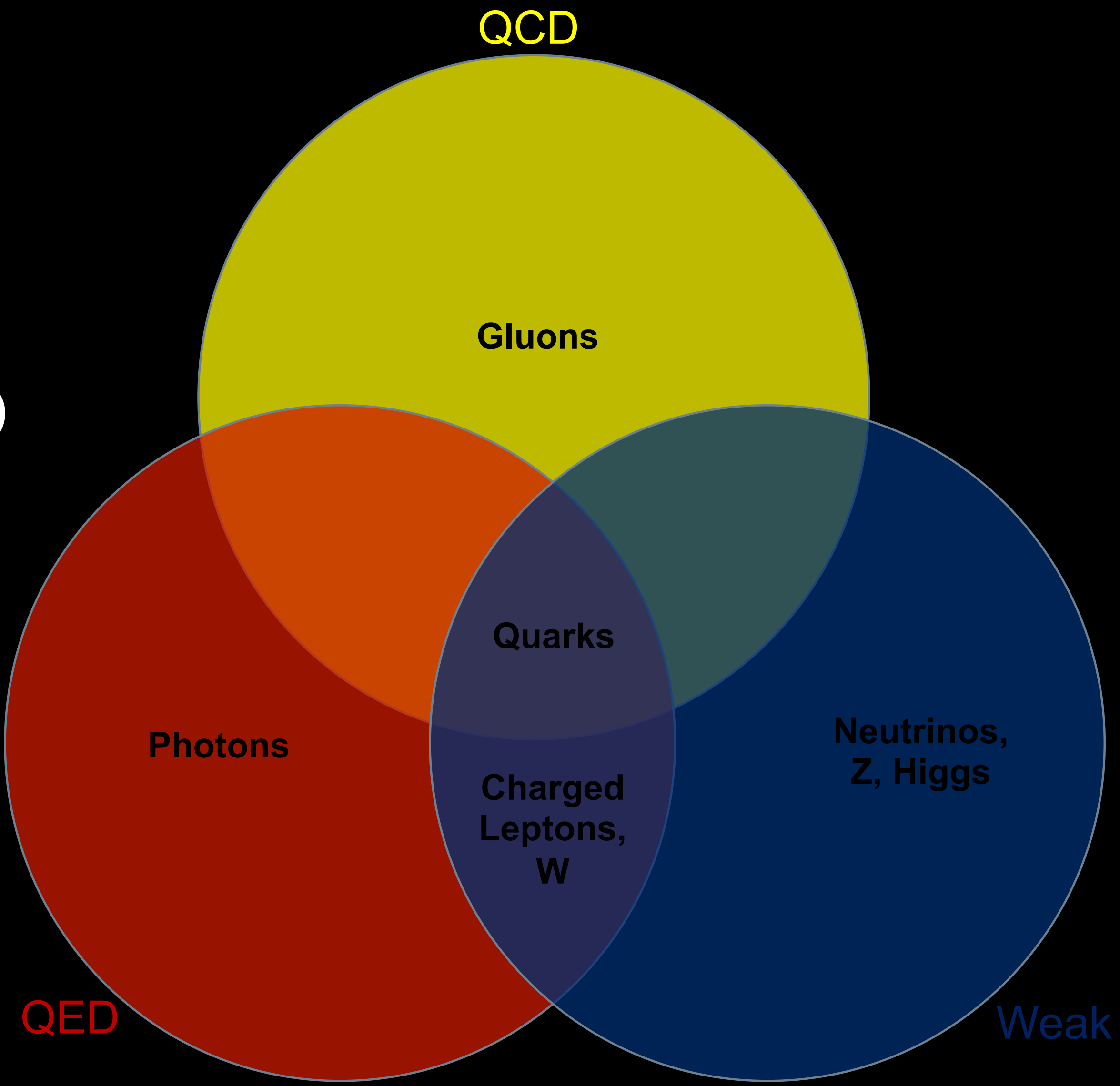
How many particles exist that aren't charged under the Standard Model?



If dark matter exists, how surprised should we be that we haven’t observed it non-gravitationally?

- The answer to this question clearly depends on one’s Bayesian priors
- I would argue that for essentially any reasonable set of priors, one should not be all that surprised

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- For either of these cases – and for essentially any reasonable set of priors – the Bayes Factor against dark matter is of order unity; the fact that we have not yet observed dark matter should thus have relatively little impact on our posterior

Urbi et Orbi