Title: Not extending the standard cosmological model

Speakers: Andrew Liddle

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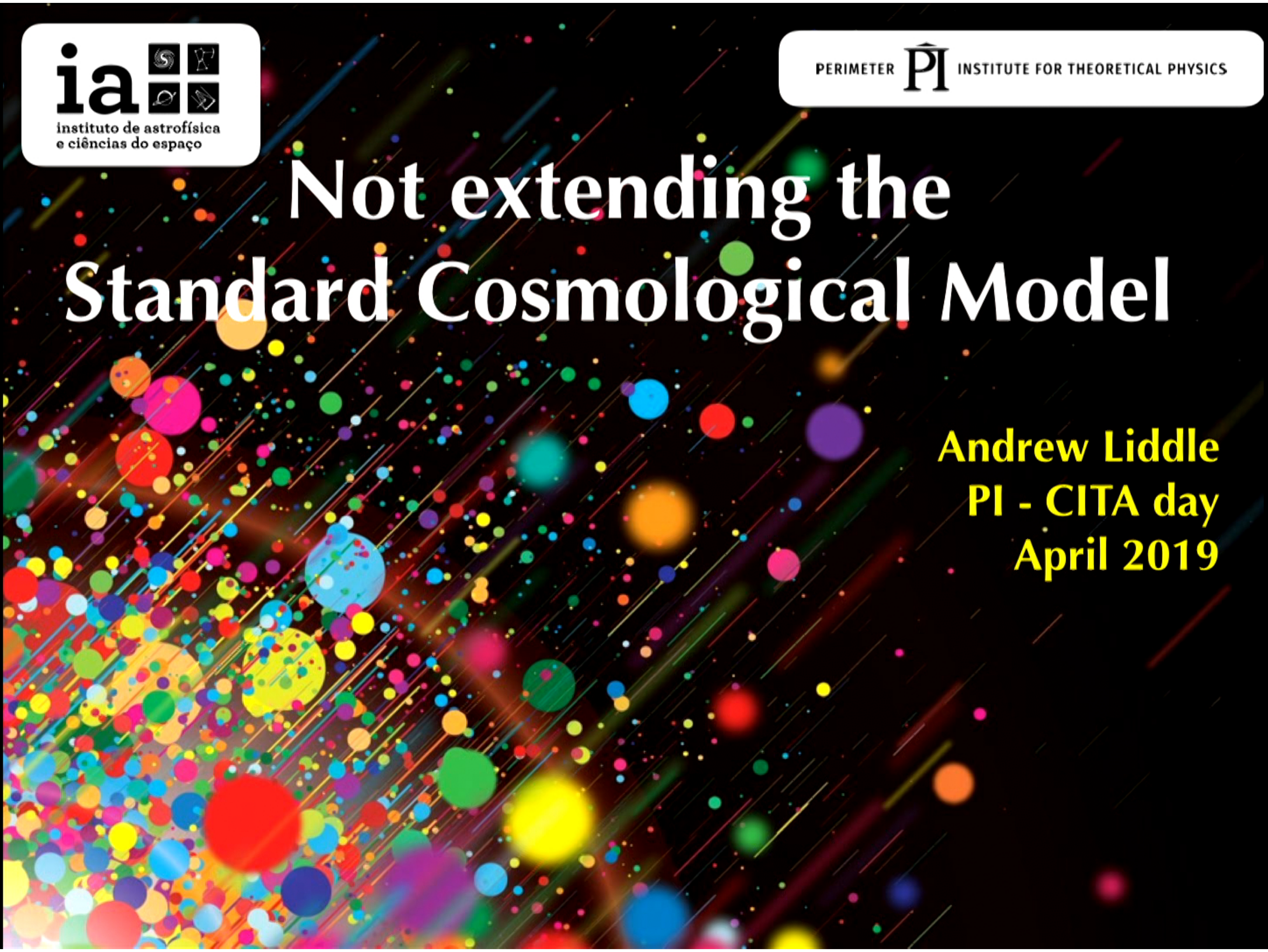
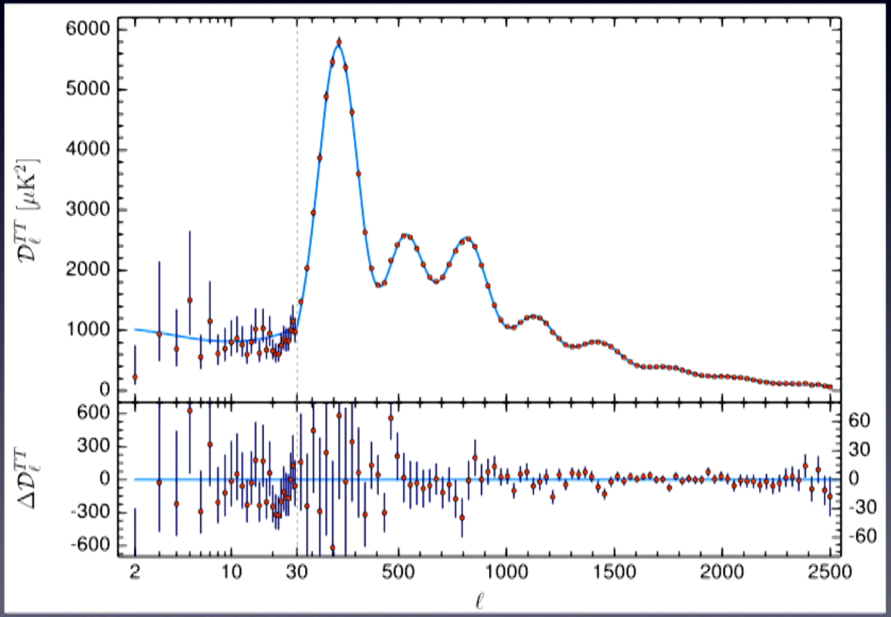
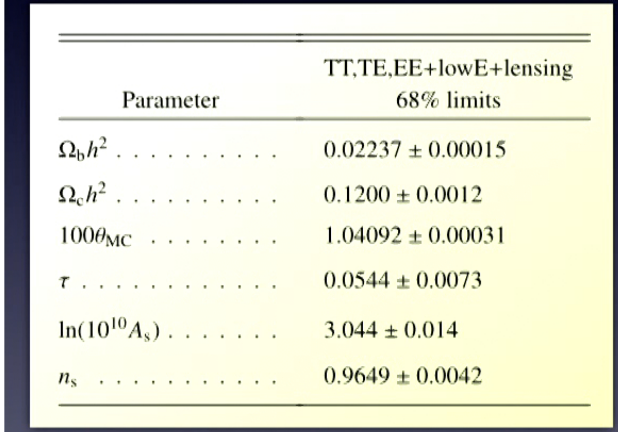


Not extending the Standard Cosmological Model

Andrew Liddle
PI - CITA day
April 2019

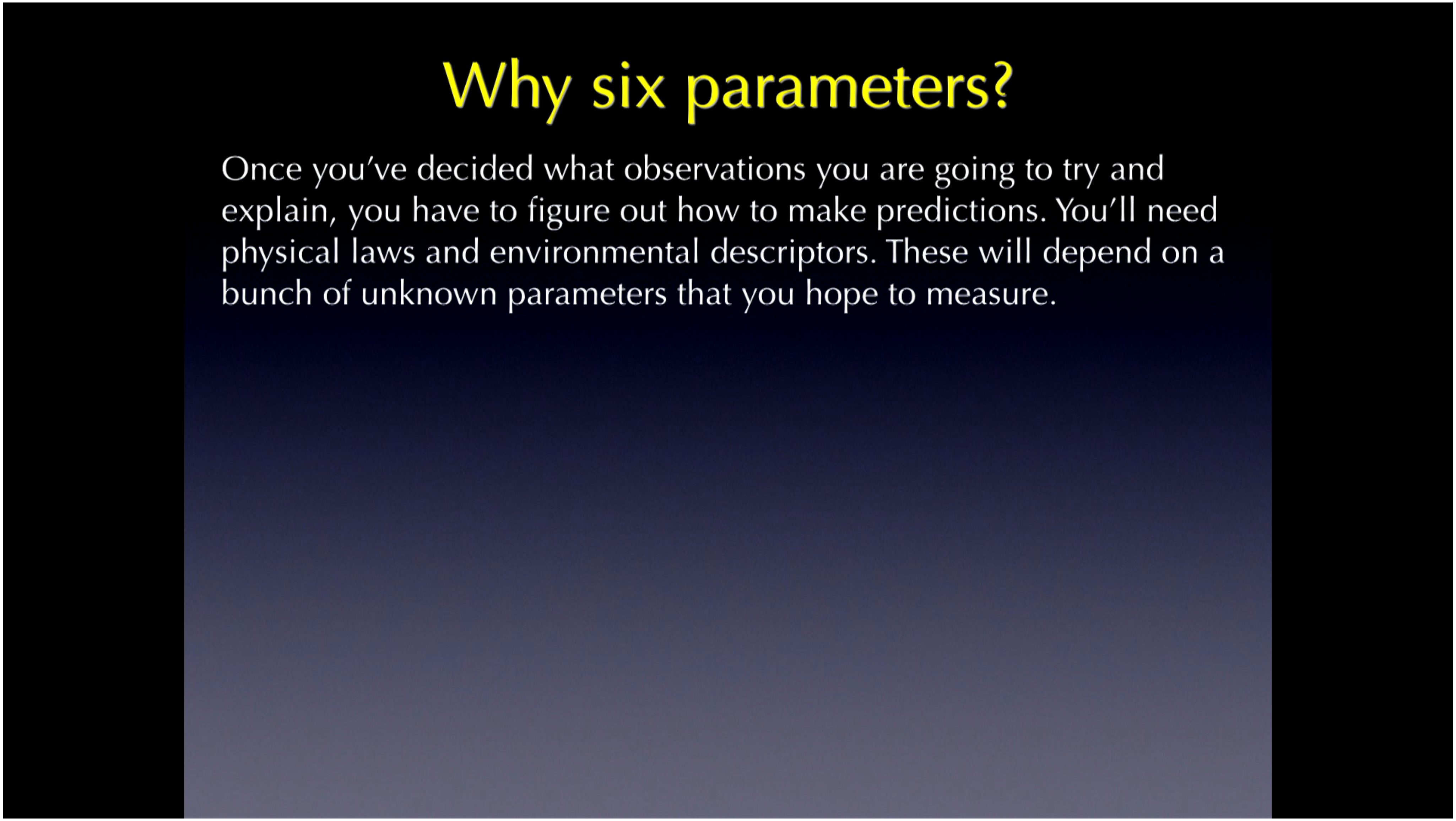
Starting point: the standard six-parameter cosmological model is extraordinarily successful and gives a precision description of our Universe.





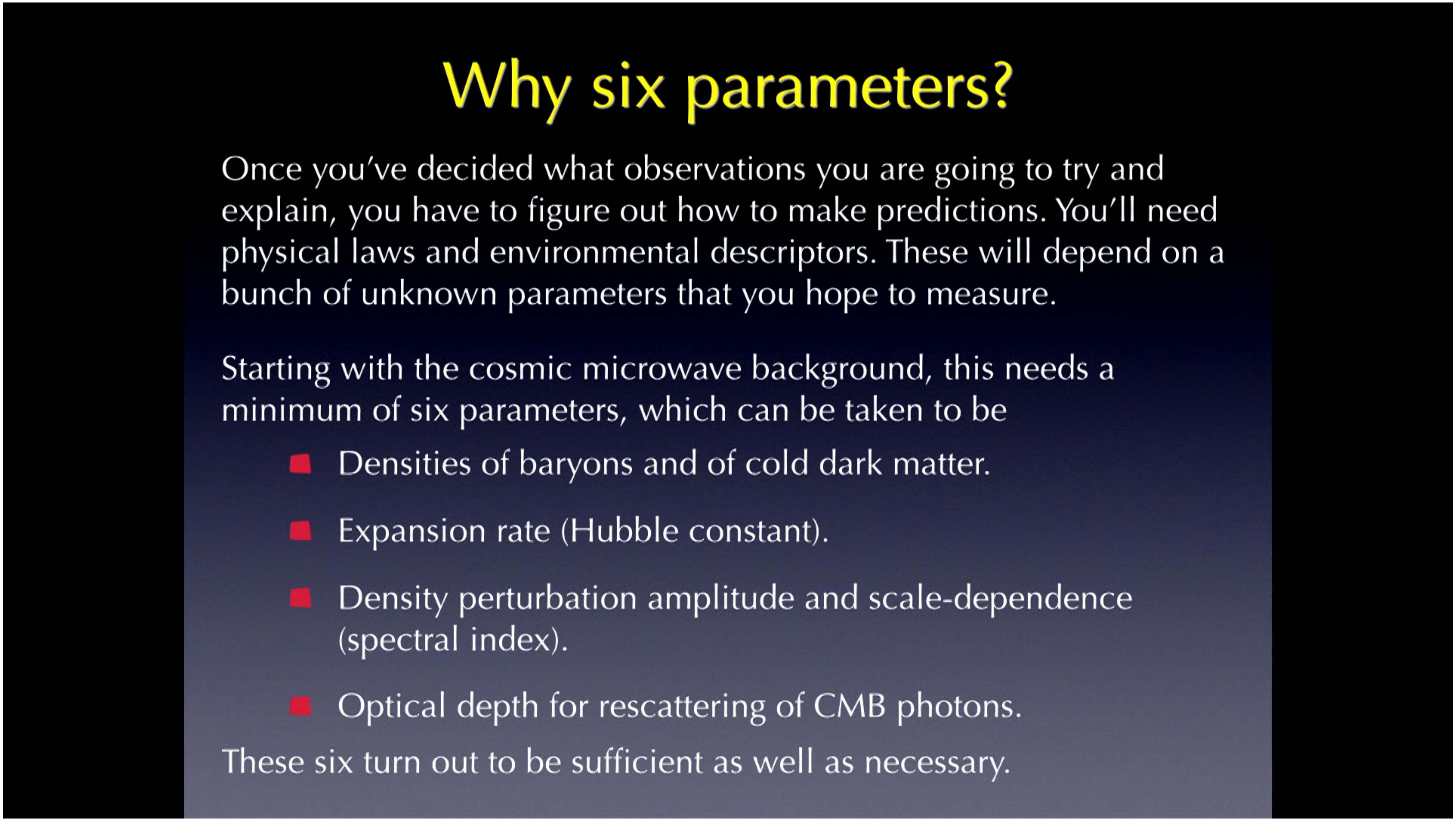
Parameter	TT,TE,EE+lowE+lensing 68% limits
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042

Planck 2018 temperature power spectrum .... and parameter constraints.



Why six parameters?

Once you've decided what observations you are going to try and explain, you have to figure out how to make predictions. You'll need physical laws and environmental descriptors. These will depend on a bunch of unknown parameters that you hope to measure.



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Starting with the cosmic microwave background, this needs a minimum of six parameters, which can be taken to be

- Densities of baryons and of cold dark matter.
- Expansion rate (Hubble constant).
- Density perturbation amplitude and scale-dependence (spectral index).
- Optical depth for rescattering of CMB photons.

These six turn out to be sufficient as well as necessary.

Why six parameters?

There might also be any number of so-called `nuisance’ parameters to model various effects (eg subtraction of uncertain foreground contaminants from CMB maps, or intrinsic alignment of galaxies from weak lensing surveys).

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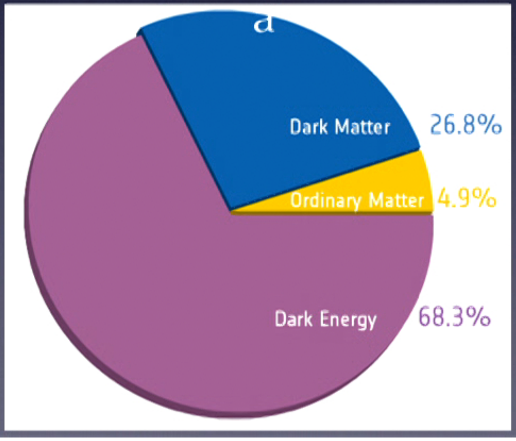
Of course, one person’s nuisance may be another person’s signal.

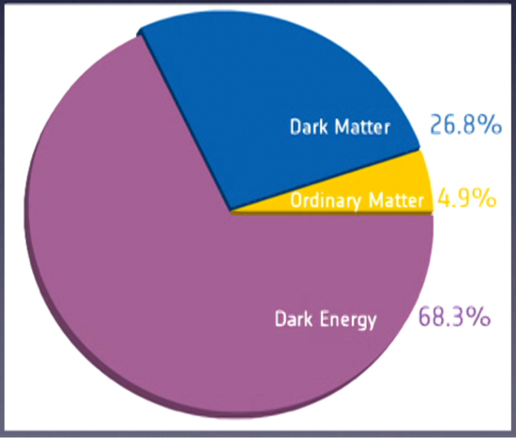
Status of observational cosmology

- We can make precision measurements, especially of the cosmic microwave background.
- A simple model, with just six parameters, is sufficient to explain all the major datasets.
- The composition of the Universe is accurately measured. It contains substantial amounts of dark matter and dark energy.
- There are strong indications that period of inflation took place in the very young Universe.



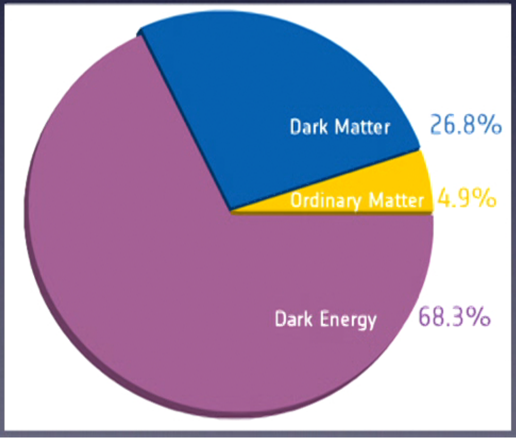
Status of theoretical cosmology

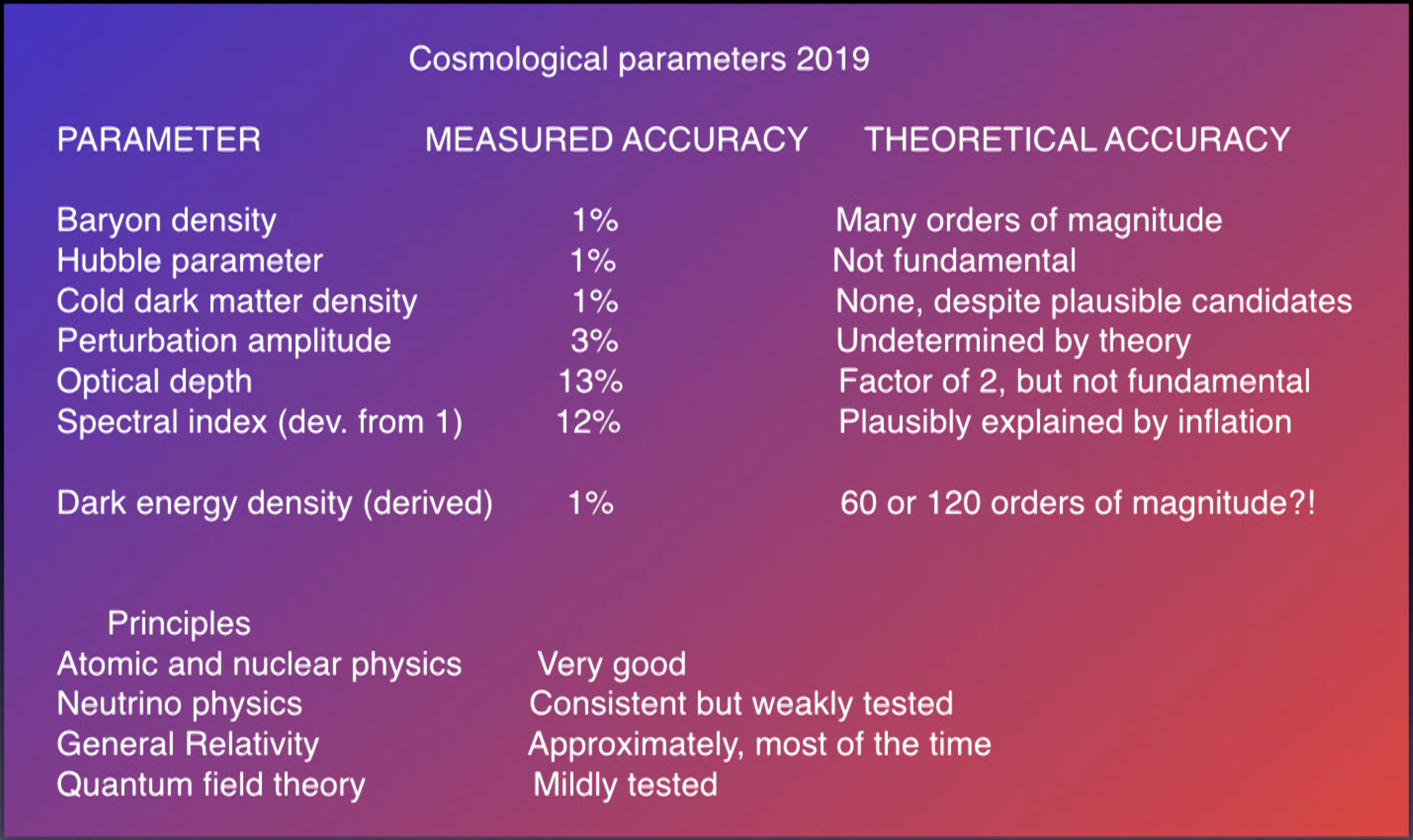
- We don't know why the Universe is all matter and no anti-matter.



Status of theoretical cosmology

- We don’t know why the Universe is all matter and no anti-matter.
- We don’t know what the dark matter is.
- We don’t know what the dark energy is.
- We don't know how inflation took place.





Cosmological parameters 2019

PARAMETER	MEASURED ACCURACY	THEORETICAL ACCURACY
Baryon density	1%	Many orders of magnitude
Hubble parameter	1%	Not fundamental
Cold dark matter density	1%	None, despite plausible candidates
Perturbation amplitude	3%	Undetermined by theory
Optical depth	13%	Factor of 2, but not fundamental
Spectral index (dev. from 1)	12%	Plausibly explained by inflation
Dark energy density (derived)	1%	60 or 120 orders of magnitude?!

Principles	
Atomic and nuclear physics	Very good
Neutrino physics	Consistent but weakly tested
General Relativity	Approximately, most of the time
Quantum field theory	Mildly tested

Changing the six

The ideal outcome of any observational programme is to ***break*** the standard cosmological model.

New parameter

=

New physics to learn about!

Instead, we've been constraining the same six parameters better and better for over a decade.

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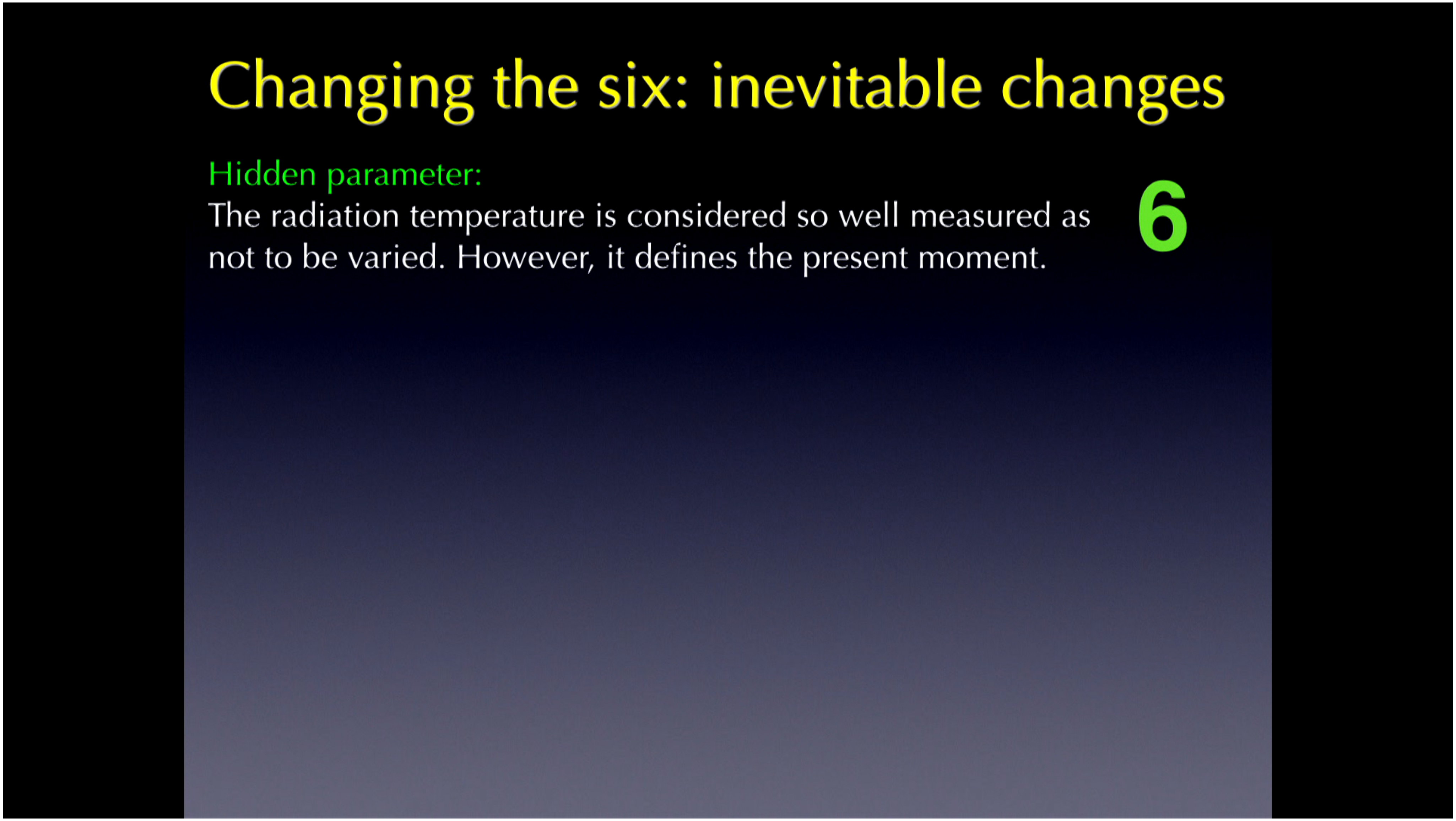
Instead, we've been constraining the same six parameters better and better for over a decade.

But they were already measured far better than current theory demands.

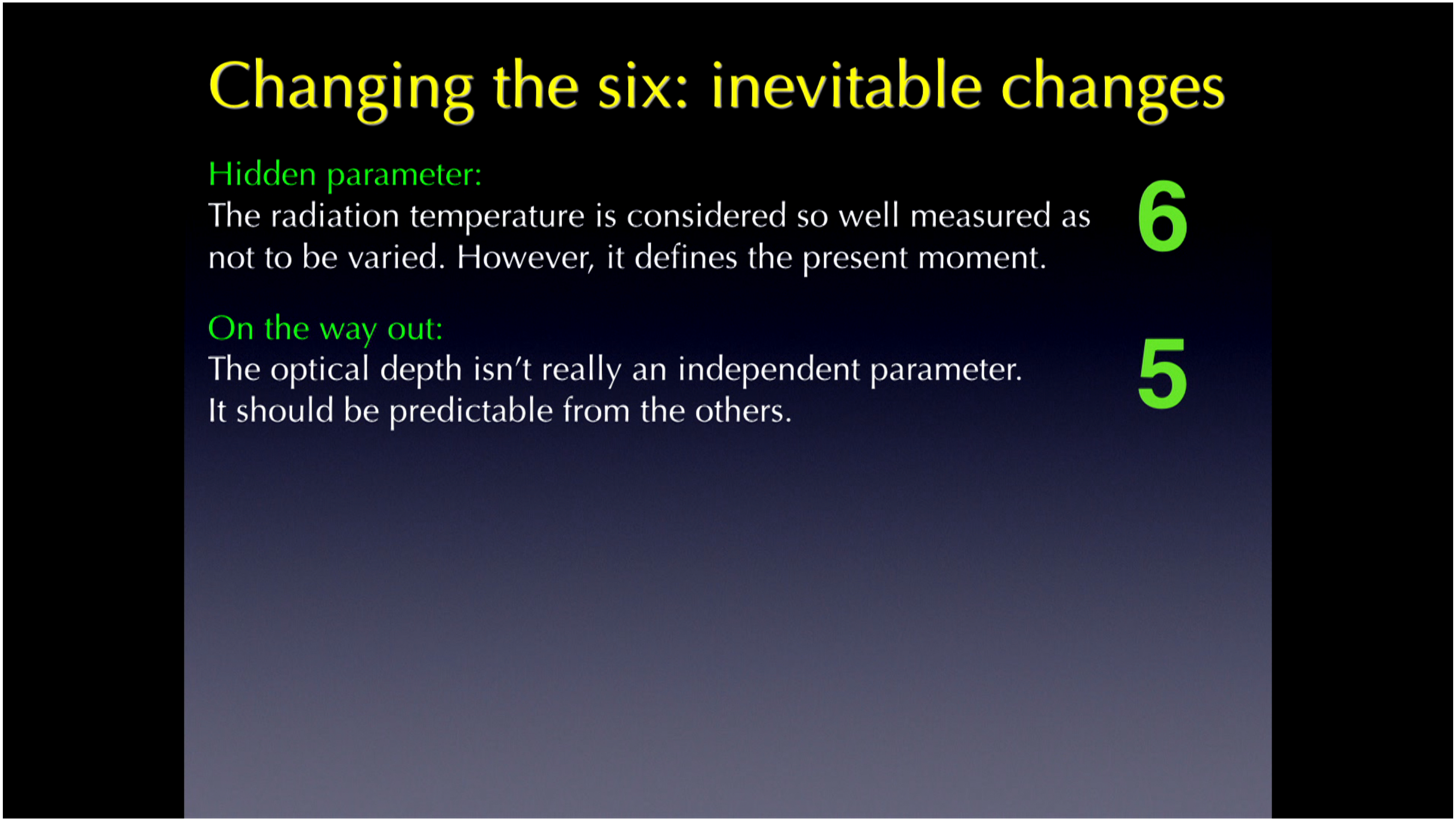


Changing the six: inevitable changes

Hidden parameter:

The radiation temperature is considered so well measured as not to be varied. However, it defines the present moment.

6



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On the way out:

The optical depth isn't really an independent parameter. It should be predictable from the others.

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Coming soon:
Neutrino mass(es) is on the verge of inevitable detection.

6+

Much more interesting is what *might* happen in the future.

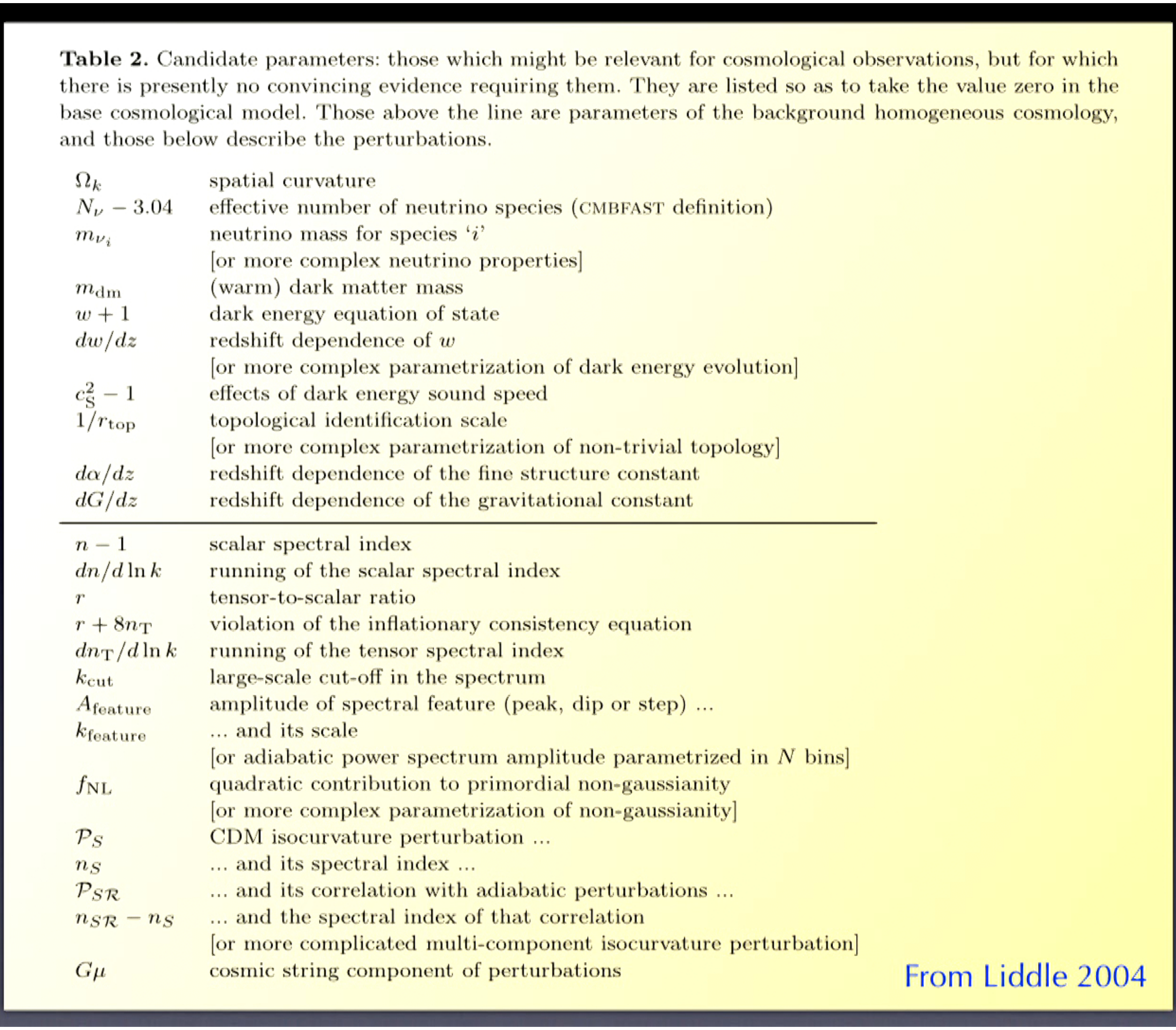

Table 2. Candidate parameters: those which might be relevant for cosmological observations, but for which there is presently no convincing evidence requiring them. They are listed so as to take the value zero in the base cosmological model. Those above the line are parameters of the background homogeneous cosmology, and those below describe the perturbations.

Ω_k	spatial curvature
$N_\nu - 3.04$	effective number of neutrino species (CMBFAST definition)
m_{ν_i}	neutrino mass for species 'i' [or more complex neutrino properties]
$m_{\rm dm}$	(warm) dark matter mass
$w + 1$	dark energy equation of state
dw/dz	redshift dependence of w [or more complex parametrization of dark energy evolution]
$c_{\rm S}^2 - 1$	effects of dark energy sound speed
$1/r_{\rm top}$	topological identification scale [or more complex parametrization of non-trivial topology]
$d\alpha/dz$	redshift dependence of the fine structure constant
dG/dz	redshift dependence of the gravitational constant

$n - 1$	scalar spectral index
$dn/d\ln k$	running of the scalar spectral index
r	tensor-to-scalar ratio
$r + 8n_{\rm T}$	violation of the inflationary consistency equation
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$k_{\rm cut}$	large-scale cut-off in the spectrum
$A_{\rm feature}$	amplitude of spectral feature (peak, dip or step) ...
$k_{\rm feature}$	... and its scale [or adiabatic power spectrum amplitude parametrized in N bins]
$f_{\rm NL}$	quadratic contribution to primordial non-gaussianity [or more complex parametrization of non-gaussianity]
$\mathcal{P}_S$	CDM isocurvature perturbation ...
n_S	... and its spectral index ...
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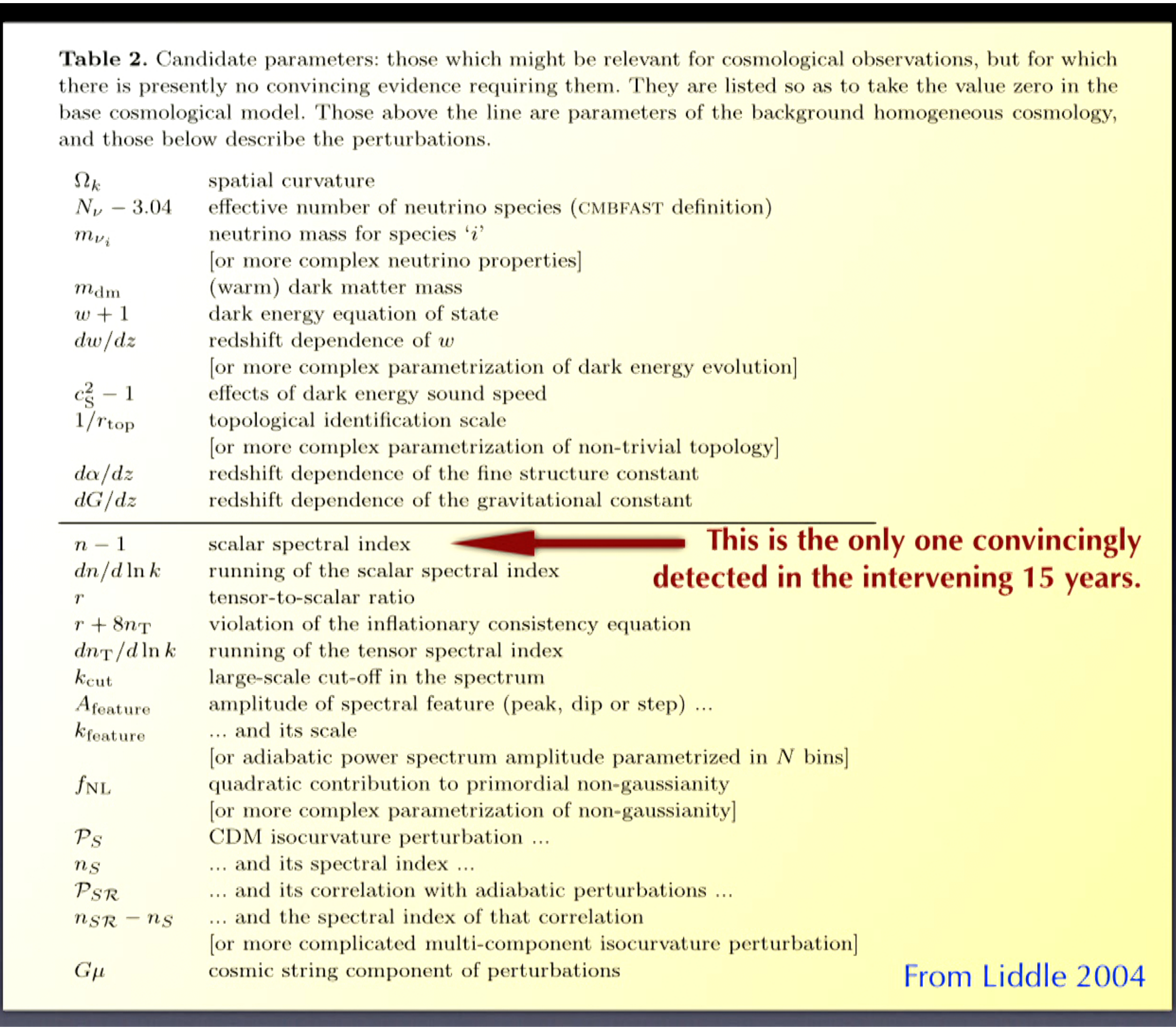
$n_{S\mathcal{R}} - n_S$	... and the spectral index of that correlation [or more complicated multi-component isocurvature perturbation]
$G\mu$	cosmic string component of perturbations

From Liddle 2004



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This is the only one convincingly detected in the intervening 15 years.

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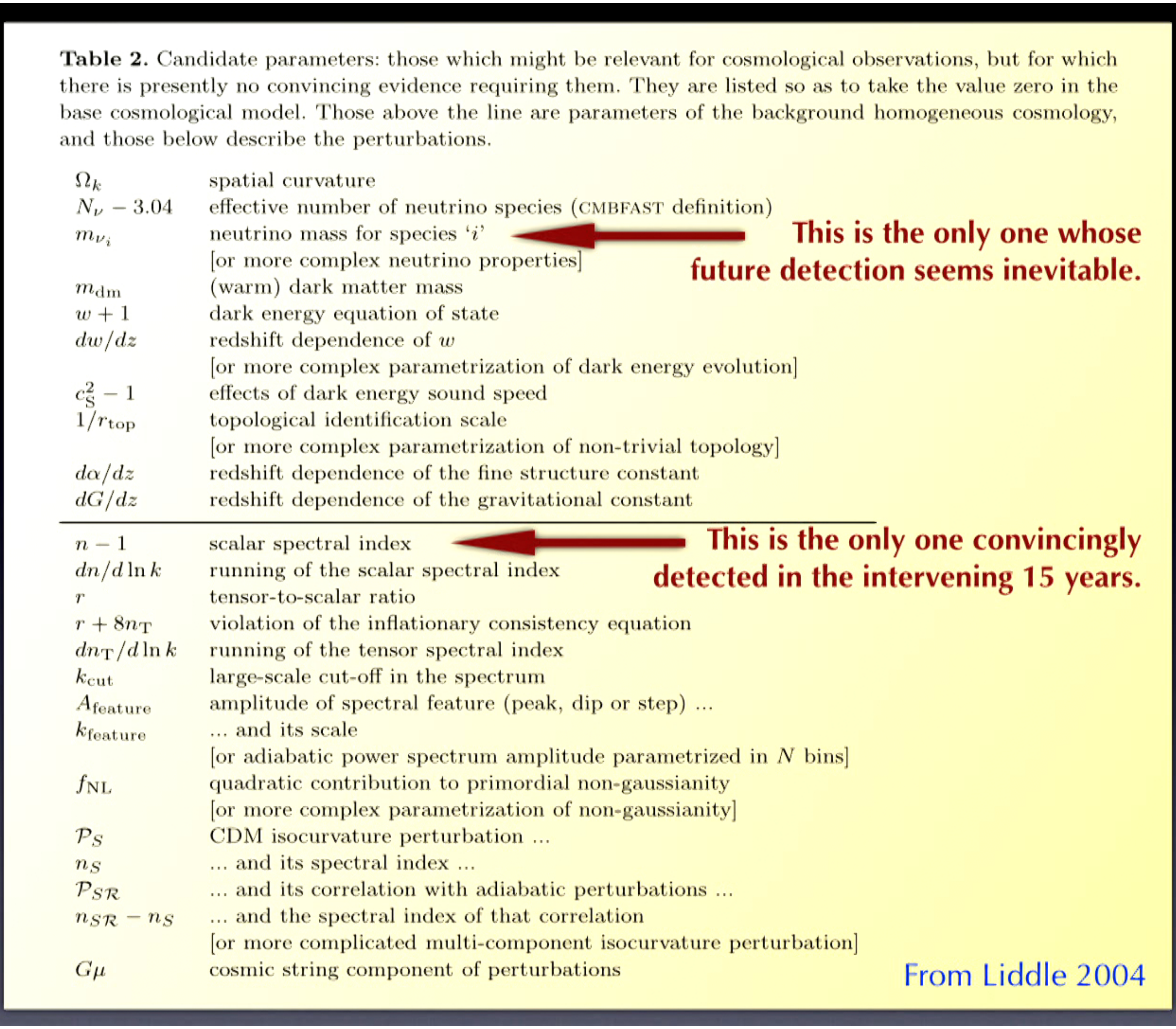

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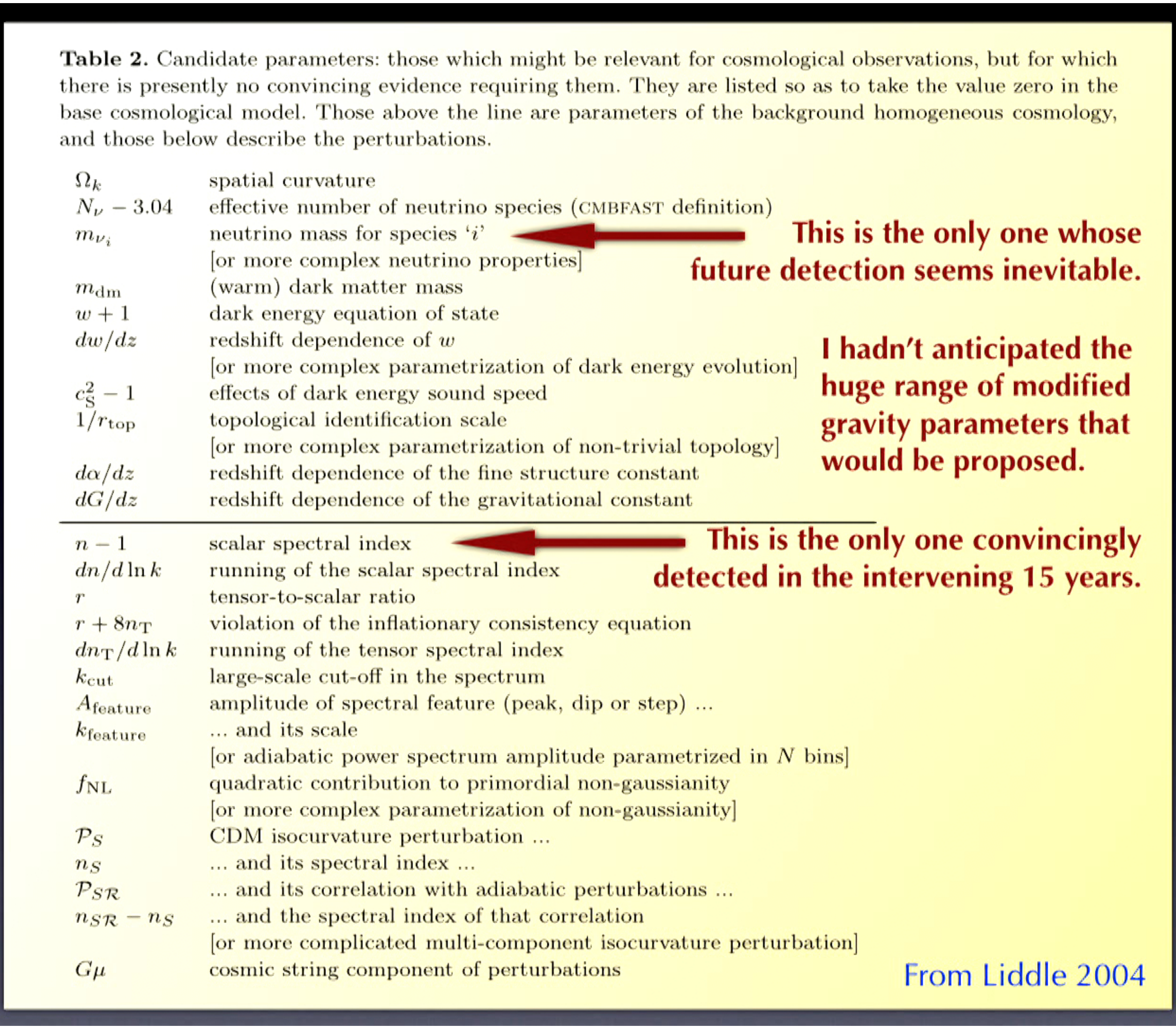

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I hadn't anticipated the huge range of modified gravity parameters that would be proposed.

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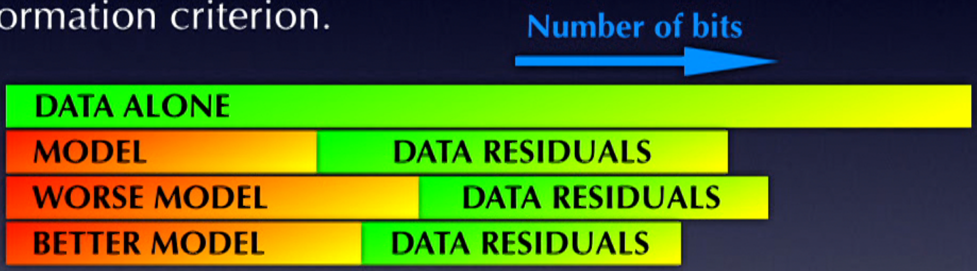

Number of bits

DATA ALONE

MODEL | DATA RESIDUALS

WORSE MODEL | DATA RESIDUALS

BETTER MODEL | DATA RESIDUALS

- Bayesian methods.
  These assign probabilities to all quantities of interest and update when new data comes in. For model selection we assign a probability to each *set* of parameters as well as to the parameter values.
  Archetype: Bayesian evidence (aka Bayes factor).

Dataset comparison

An interesting recent use of the Bayesian evidence is to test compatibility of two datasets D_1 and D_2. We compare the evidences of a single-model fit with one assuming that each dataset measures independent parameters within the model:

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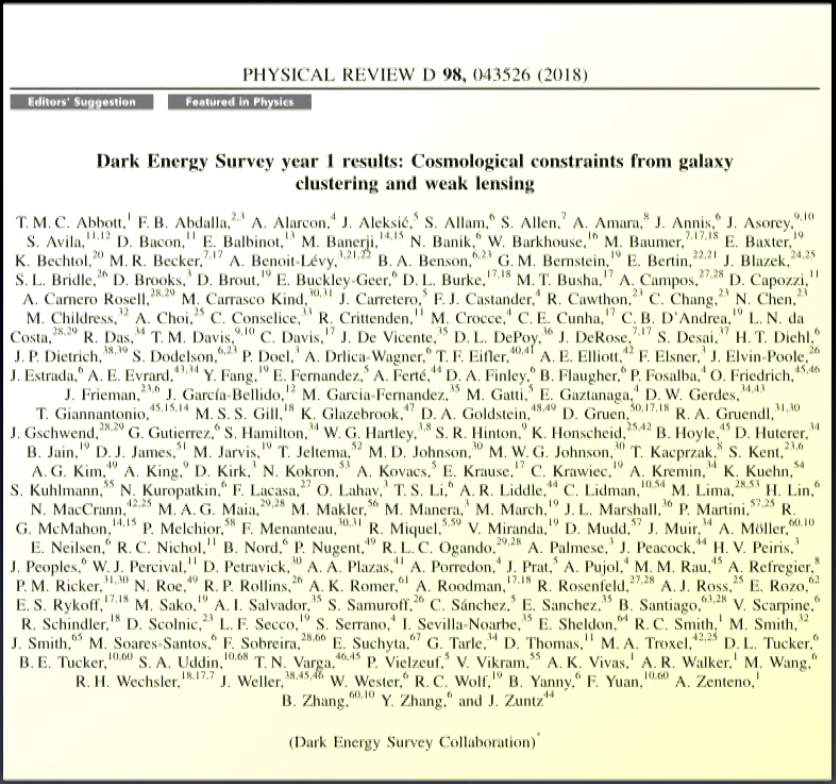
Note that dataset consistency depends on the chosen model.

DES collaboration, arXiv:1708.01530, PRD

Dark Energy Survey on *w*



PHYSICAL REVIEW D **98,** 043526 (2018)

Editors' Suggestion

Featured in Physics

Dark Energy Survey year 1 results: Cosmological constraints from galaxy clustering and weak lensing

T. M. C. Abbott,[1] F. B. Abdalla,[2,3] A. Alarcon,[4] J. Aleksić,[5] S. Allam,[6] S. Allen,[7] A. Amara,[8] J. Annis,[6] J. Asorey,[9,10] S. Avila,[11,12] D. Bacon,[11] E. Balbinot,[13] M. Banerji,[14,15] N. Banik,[6] W. Barkhouse,[16] M. Baumer,[7,17,18] E. Baxter,[19] K. Bechtol,[20] M. R. Becker,[7,17] A. Benoit-Lévy,[3,21,22] B. A. Benson,[6,23] G. M. Bernstein,[19] E. Bertin,[22,21] J. Blazek,[24,25] S. L. Bridle,[26] D. Brooks,[3] D. Brout,[19] E. Buckley-Geer,[6] D. L. Burke,[17,18] M. T. Busha,[17] A. Campos,[27,28] D. Capozzi,[11] A. Carnero Rosell,[28,29] M. Carrasco Kind,[30,31] J. Carretero,[5] F. J. Castander,[4] R. Cawthon,[23] C. Chang,[23] N. Chen,[23] M. Childress,[32] A. Choi,[25] C. Conselice,[33] R. Crittenden,[11] M. Crocce,[4] C. E. Cunha,[17] C. B. D'Andrea,[19] L. N. da Costa,[28,29] R. Das,[34] T. M. Davis,[9,10] C. Davis,[17] J. De Vicente,[35] D. L. DePoy,[36] J. DeRose,[7,17] S. Desai,[37] H. T. Diehl,[6] J. P. Dietrich,[38,39] S. Dodelson,[6,23] P. Doel,[3] A. Drlica-Wagner,[6] T. F. Eifler,[40,41] A. E. Elliott,[42] F. Elsner,[3] J. Elvin-Poole,[26] J. Estrada,[6] A. E. Evrard,[43,34] Y. Fang,[19] E. Fernandez,[5] A. Ferté,[44] D. A. Finley,[6] B. Flaugher,[6] P. Fosalba,[4] O. Friedrich,[45,46] J. Frieman,[23,6] J. García-Bellido,[12] M. Garcia-Fernandez,[35] M. Gatti,[5] E. Gaztanaga,[4] D. W. Gerdes,[34,43] T. Giannantonio,[45,15,14] M. S. S. Gill,[18] K. Glazebrook,[47] D. A. Goldstein,[48,49] D. Gruen,[50,17,18] R. A. Gruendl,[31,30] J. Gschwend,[28,29] G. Gutierrez,[6] S. Hamilton,[34] W. G. Hartley,[3,8] S. R. Hinton,[9] K. Honscheid,[25,42] B. Hoyle,[45] D. Huterer,[34] B. Jain,[19] D. J. James,[51] M. Jarvis,[19] T. Jeltema,[52] M. D. Johnson,[30] M. W. G. Johnson,[30] T. Kacprzak,[8] S. Kent,[23,6] A. G. Kim,[49] A. King,[9] D. Kirk,[3] N. Kokron,[53] A. Kovacs,[5] E. Krause,[17] C. Krawiec,[19] A. Kremin,[34] K. Kuehn,[54] S. Kuhlmann,[55] N. Kuropatkin,[6] F. Lacasa,[27] O. Lahav,[3] T. S. Li,[6] A. R. Liddle,[44] C. Lidman,[10,54] M. Lima,[28,53] H. Lin,[6] N. MacCrann,[42,25] M. A. G. Maia,[29,28] M. Makler,[56] M. Manera,[3] M. March,[19] J. L. Marshall,[36] P. Martini,[57,25] R. G. McMahon,[14,15] P. Melchior,[58] F. Menanteau,[30,31] R. Miquel,[5,59] V. Miranda,[19] D. Mudd,[57] J. Muir,[34] A. Möller,[60,10] E. Neilsen,[6] R. C. Nichol,[11] B. Nord,[6] P. Nugent,[49] R. L. C. Ogando,[29,28] A. Palmese,[3] J. Peacock,[44] H. V. Peiris,[3] J. Peoples,[6] W. J. Percival,[11] D. Petravick,[30] A. A. Plazas,[41] A. Porredon,[4] J. Prat,[5] A. Pujol,[4] M. M. Rau,[45] A. Refregier,[8] P. M. Ricker,[31,30] N. Roe,[49] R. P. Rollins,[26] A. K. Romer,[61] A. Roodman,[17,18] R. Rosenfeld,[27,28] A. J. Ross,[25] E. Rozo,[62] E. S. Rykoff,[17,18] M. Sako,[19] A. I. Salvador,[35] S. Samuroff,[26] C. Sánchez,[5] E. Sanchez,[35] B. Santiago,[63,28] V. Scarpine,[6] R. Schindler,[18] D. Scolnic,[23] L. F. Secco,[19] S. Serrano,[4] I. Sevilla-Noarbe,[35] E. Sheldon,[64] R. C. Smith,[1] M. Smith,[32] J. Smith,[65] M. Soares-Santos,[6] F. Sobreira,[28,66] E. Suchyta,[67] G. Tarle,[34] D. Thomas,[11] M. A. Troxel,[42,25] D. L. Tucker,[6] B. E. Tucker,[10,60] S. A. Uddin,[10,68] T. N. Varga,[46,45] P. Vielzeuf,[5] V. Vikram,[55] A. K. Vivas,[1] A. R. Walker,[1] M. Wang,[6] R. H. Wechsler,[18,17,7] J. Weller,[38,45,46] W. Wester,[6] R. C. Wolf,[19] B. Yanny,[6] F. Yuan,[10,60] A. Zenteno,[1] B. Zhang,[60,10] Y. Zhang,[6] and J. Zuntz[44]

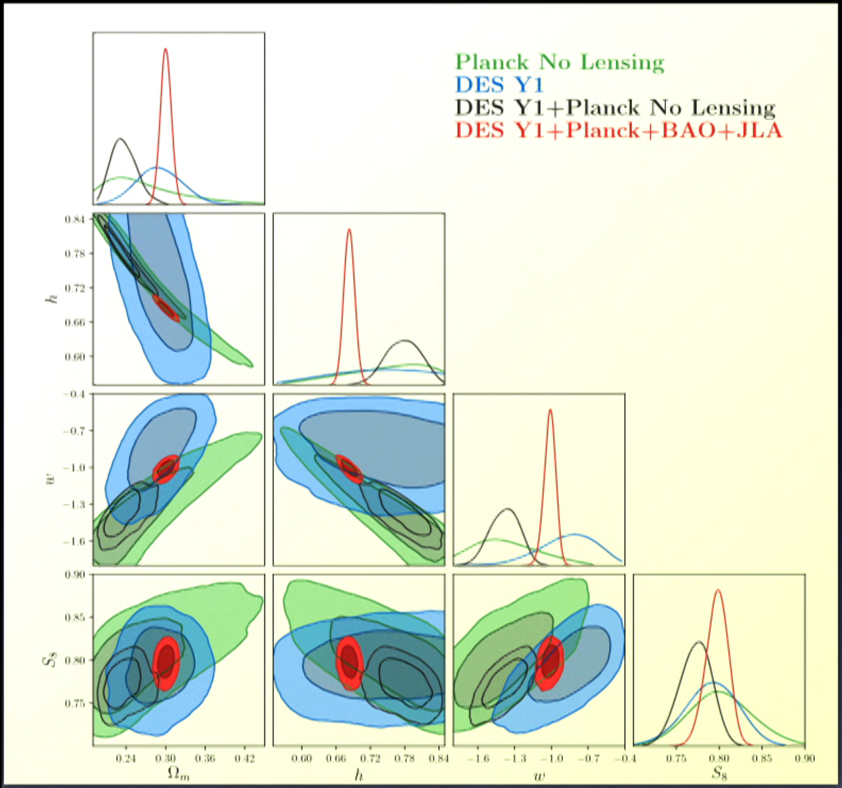
(Dark Energy Survey Collaboration)[*]

We used the first-year dataset from the Dark Energy Survey to constrain the equation of state *w*, through combination with *Planck* and other data. We found

$$w = -1.00^{+0.05}_{-0.04}$$

DES collaboration, arXiv:1708.01530, PRD

Dark Energy Survey on *w*



We used the first-year dataset from the Dark Energy Survey to constrain the equation of state *w*, through combination with *Planck* and other data. We found

$$w = -1.00^{+0.05}_{-0.04}$$

Clearly this does not indicate against the cosmological constant case $w = -1$.

This is borne out by the Bayesian evidence ratio $R_w = 0.1$.

Here are the combined constraints on the modified potentials.

Taking CFHTlens as our fiducial lensing dataset we have

$$\Sigma_0 = +0.05^{+0.05}_{-0.07}$$
$$\mu_0 = -0.10^{+0.20}_{-0.16}$$

Clearly there is no evidence here against GR / ΛCDM.

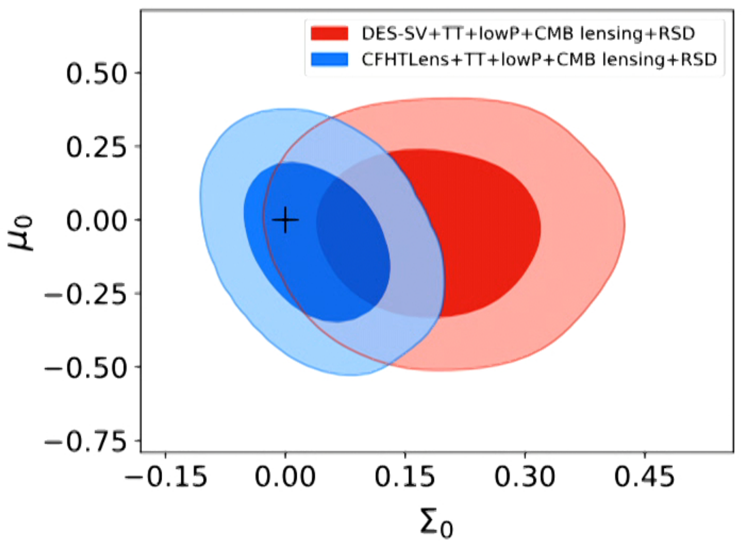
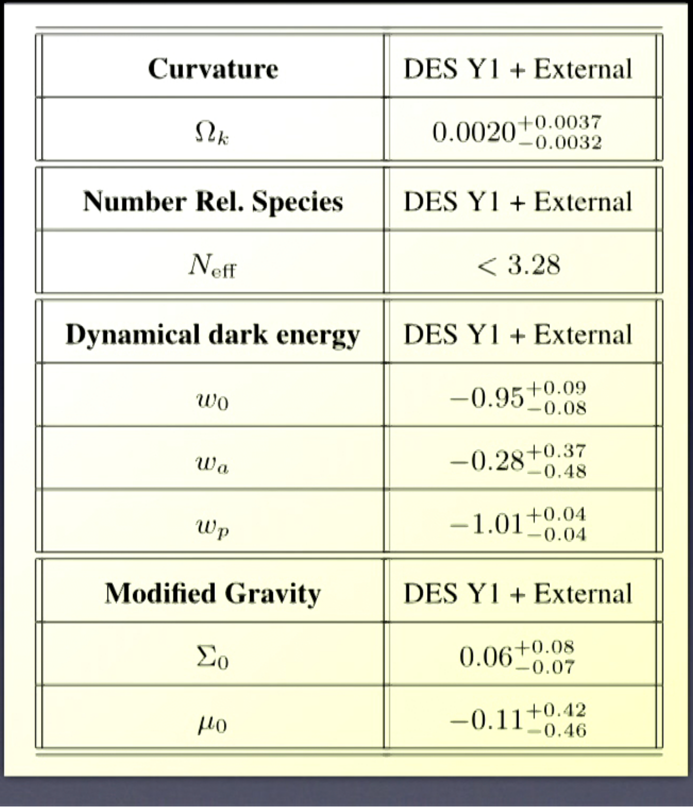


FIG. 8. 68% and 95% confidence contours on Σ_0 and μ_0 combining RSD data (BOSS DR12 + 6dFGS), CMB data (TT+lowP+CMB lensing from *Planck*) and cosmic shear data (CFHTLenS in blue and DES-SV in red).

DES collaboration, arXiv:1810.02499

Dark Energy Survey extensions paper

In this paper we used the Y1 DES data alongside the others to test for various extensions to the standard cosmological model.



Curvature	DES Y1 + External
Ω_k	$0.0020^{+0.0037}_{-0.0032}$
Number Rel. Species	DES Y1 + External
$N_{\rm eff}$	< 3.28
Dynamical dark energy	DES Y1 + External
w_0	$-0.95^{+0.09}_{-0.08}$
w_a	$-0.28^{+0.37}_{-0.48}$
w_p	$-1.01^{+0.04}_{-0.04}$
Modified Gravity	DES Y1 + External
Σ_0	$0.06^{+0.08}_{-0.07}$
μ_0	$-0.11^{+0.42}_{-0.46}$

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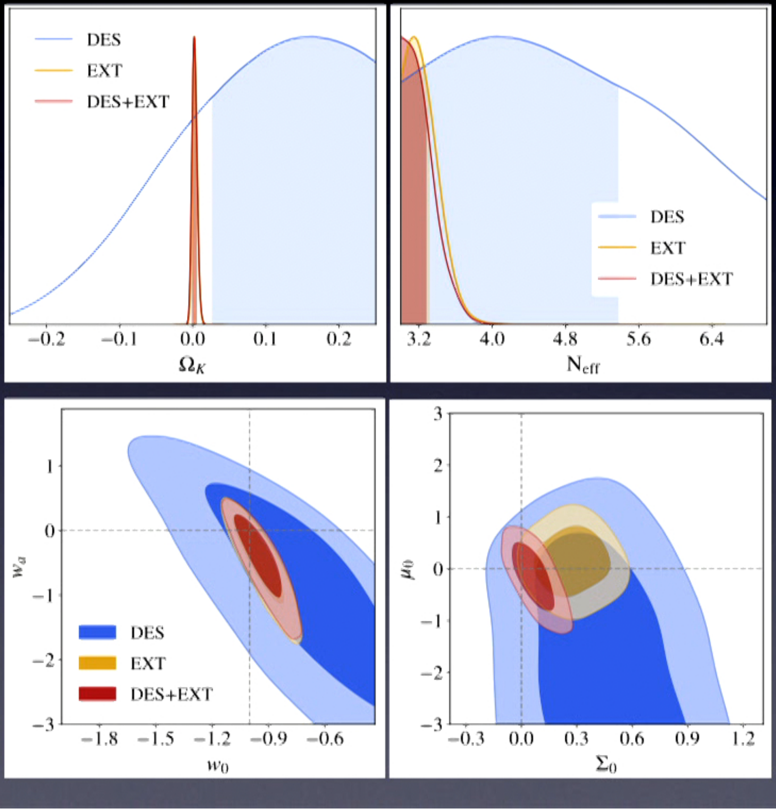

DES collaboration, arXiv:1810.02499

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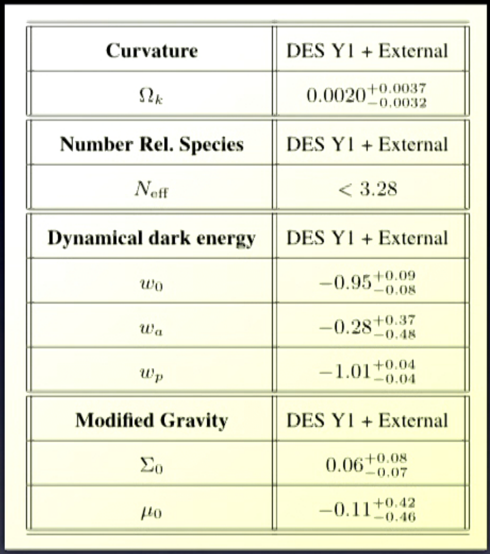

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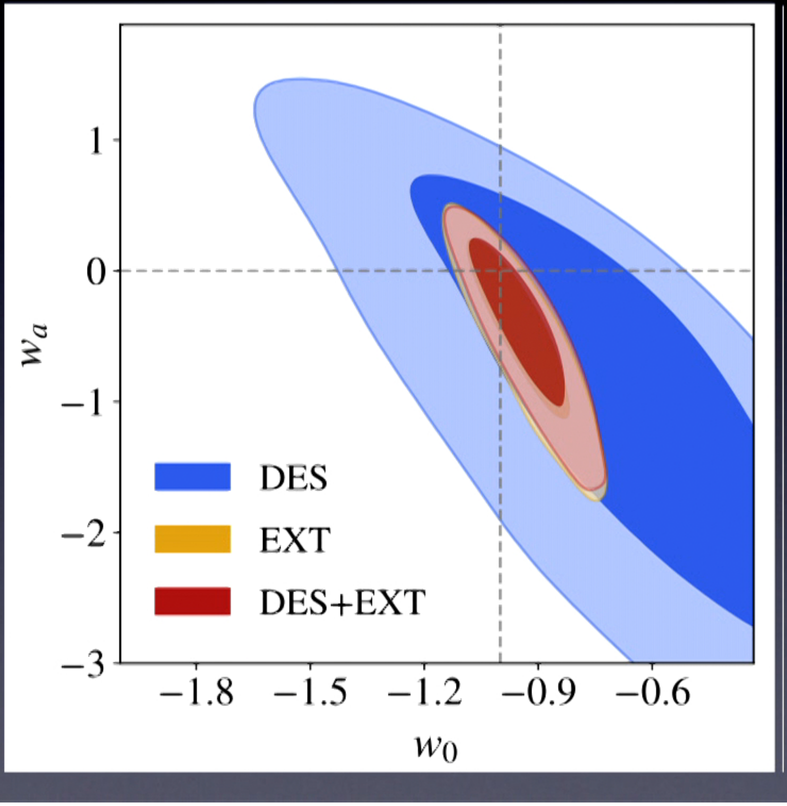
$R_{w_a w_0} = 0.006$! Less than 1% chance of dynamical dark energy being right!



Conclusion

- The Universe is doing very well at resisting our attempts to find any interesting new physics beyond ΛCDM.