Title: The long arc of cosmology

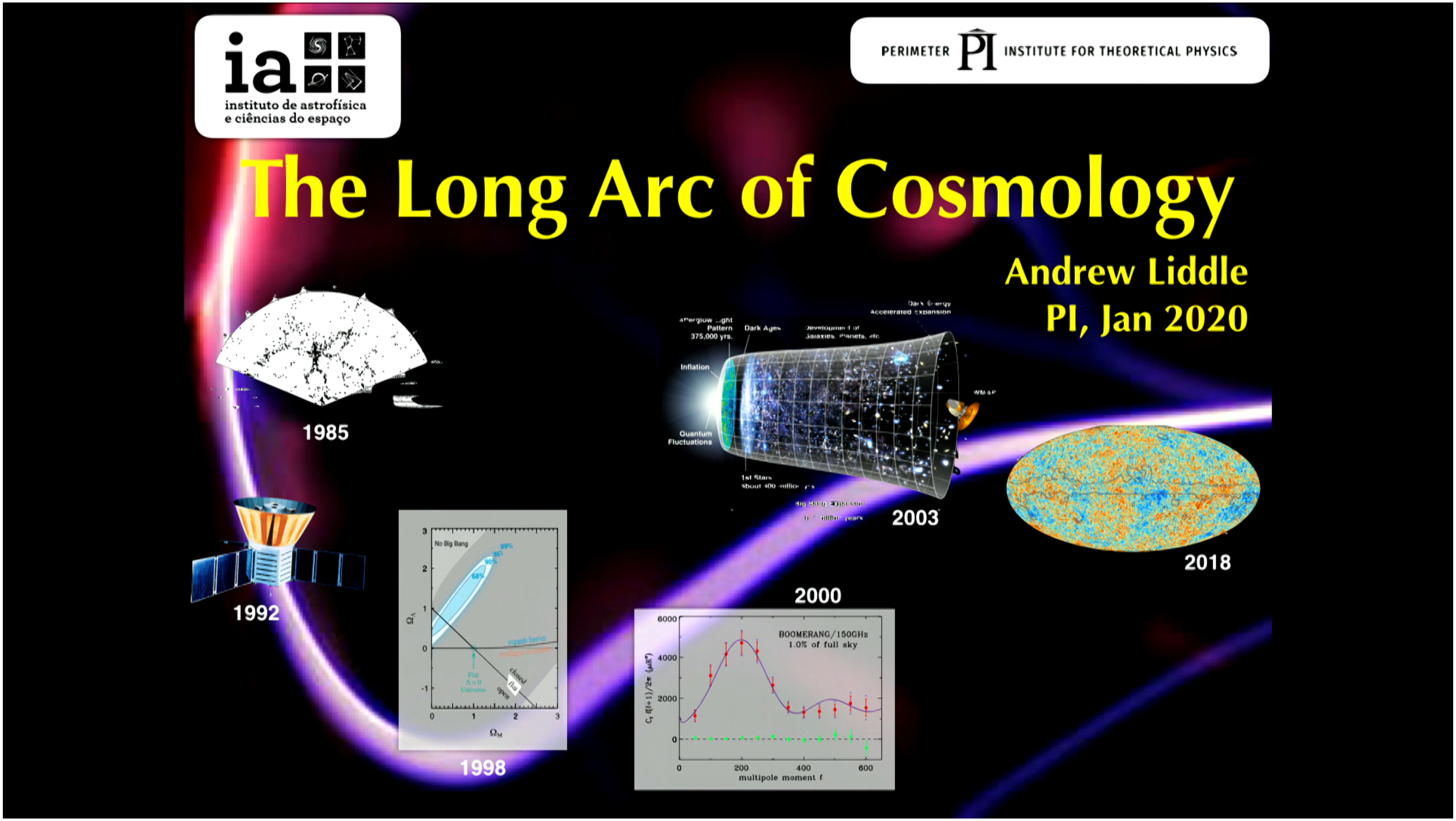
Speakers: Andrew Liddle

Series: Colloquium

Date: January 15, 2020 - 2:00 PM

URL: http://pirsa.org/20010025

Abstract: Our ability to model cosmological observations has reached an awesome level, a tour de force of observational innovation, sophisticated statistical inference, and delicate numerical computation. Thereâ€™s little doubt that the Standard Cosmological Model will stand the test of time. But what has it told us and what is still missing? What are the prospects for learning particle physics and condensed matter from cosmology? And what can the path weâ€™ve taken to reach this point tell us about where it might lead?


ia
instituto de astrofísica
e ciências do espaço
PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS
The Long Arc of Cosmology
Andrew Liddle
PI, Jan 2020
1985
1992
1998
2000
2003
2018
Inflation
Dark Ages
Quantum Fluctuations
1st Stars
WMAP
No Big Bang
BOOMERANG/150GHz
1.0% of full sky
multipole moment ℓ

Things that did not exist when I started as a cosmologist

Hardware
Mobile phones.
Laptops.
Data projectors.
WiFi.

Information
The World Wide Web (hence google, amazon, facebook, …).
The arXiv.
LaTeX and PDF.

Collaboration tools
Skype.
DropBox.
Zoom, Slack, GitHub, GoogleDocs, …

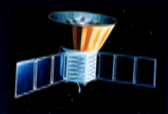
Software
Any public cosmology software, for anything.
Routine parallel computation.

Data
Observed cosmic microwave background anisotropies.
Observed high-redshift supernovae or baryon acoustic oscillations.
Observed weak gravitational lensing.

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

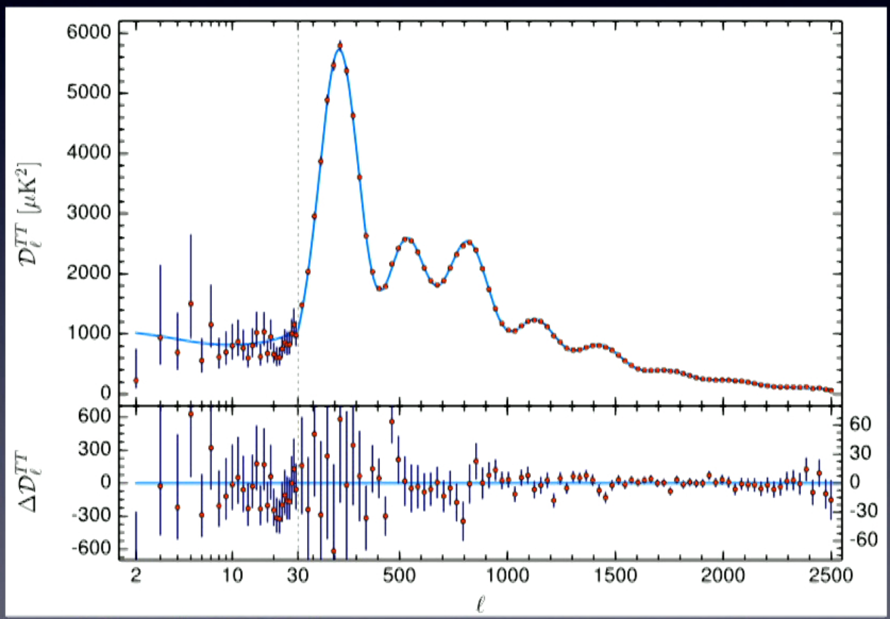
Overall, 2000 was much more like 2020 than like 1990.

The main story of the last thirty years of cosmology is the cosmic microwave background anisotropies.

	Mission	Launch	Key results	Outcome
	COBE (NASA)	1989	1992	First measurement of cosmic microwave anisotropies
	WMAP (NASA)	2001	2003/6	Establishes precision cosmology
	*Planck* (ESA)	2009	2013/18	Last word (?) on temperature anisotropies

The observational development was complemented by landmarks in theoretical model computation and statistical inference, especially CMBFAST (Seljak & Zaldarriaga 1996) and CosmoMC (Lewis & Bridle 2002).

Outcome: a standard six-parameter cosmological model that 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.

Parameters and models

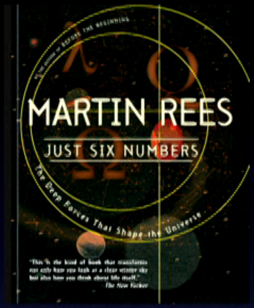
What is meant by a six-parameter model?

Once you have decided all the physical processes, principles and symmetries that you are going to include in your attempt to explain the observations, the parameters are those quantities that are still undetermined. They are then fit from the data.

A *model* is the choice of *set* of parameters. Usually questions about models are much more interesting than those about parameters.

The usual goal is to find the *simplest* model that can explain the data, by eliminating extraneous parameters. But `simplest' means different things to different people.

How might this look in cosmology?

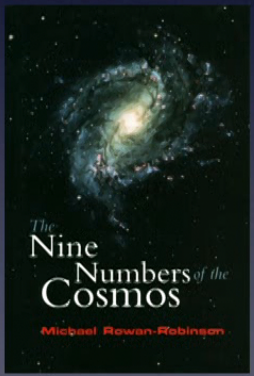


In *Just Six Numbers* (1999), Martin Rees selects

1) Fine-structure constant.
2) Ratio of gravitational and electromagnetic interaction strengths.
3&4) Density parameter and cosmological constant.
5) Amplitude of primordial density perturbations.
6) Spatial dimensions of the Universe.

while Michael Rowan-Robinson's *The Nine Numbers of the Cosmos* (1999), plumps for

1-3) Densities of baryons, cold dark matter, and hot dark matter.
4) The cosmological constant.
5&6) The age and expansion rate.
7) The temperature of the microwave background.
8) Amplitude of primordial density perturbations.
9) The star formation history of the Universe.



How might this look in cosmology?

In this talk I adopt a more modern version:

The parameters are the *interesting subset* of those quantities varied in the likelihood of the *simplest* model capable of fitting the data being considered.

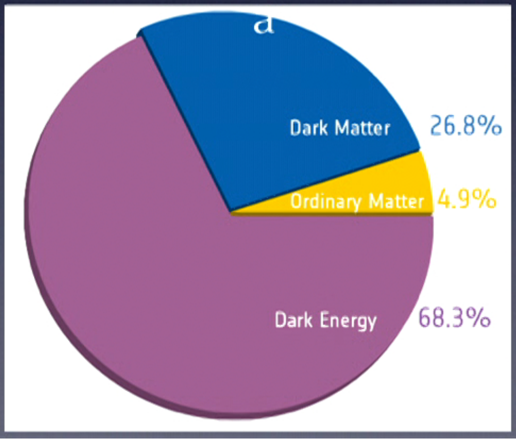
Cosmological parameters 2020

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

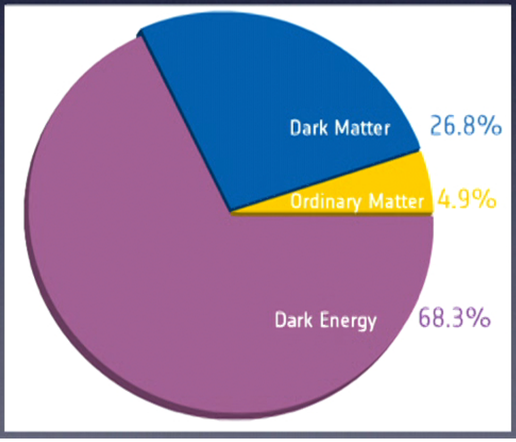
Status of observational cosmology

- 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.
- 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.



What would make a satisfactory theoretical explanation?

We would like to state a number of satisfying underlying principles that dictate how the Universe operates, whose consequences match what is observed.

Prevailing ideas in fundamental physics describe physical laws through imposition of symmetries in the context of quantum field theories, which themselves might be embedded in a more fundamental structure of extra dimensions and quantum dynamics of extended objects.

In cosmology this probably entails the writing of a low-energy effective field theory action. Ideally this would be part of some grander action explaining other aspects of fundamental physics including the Standard Model of Particle Physics plus some preferred extension of it to higher and lower energies.

Option 1

The chosen principles prove so powerful that they select a unique description compatible with all we know about the Universe.

In the heady days of the `first superstring revolution' (the 1984 Green & Schwarz anomaly cancellation), many people believed this outcome was just round the corner.

It wasn't.

Option 2

There are several consistent descriptions, one of which is observed and presumed to have been picked by chance.

Compare with:

Question: Why does our Solar System have 8 planets?

Possible answer: Solar Systems tend to have a handful of planets and ours just happens to have 8.

Certainly at the moment we are faced with multiple ways of generating the same observational outcome, e.g. different dark matter candidates or models of inflation. More generally the answers to some questions may be probability distributions.

Option 3

There are so many consistent descriptions as to require additional considerations to explain why ours has been chosen.

Compare with:

Question: Why is our Moon proportionally so large?

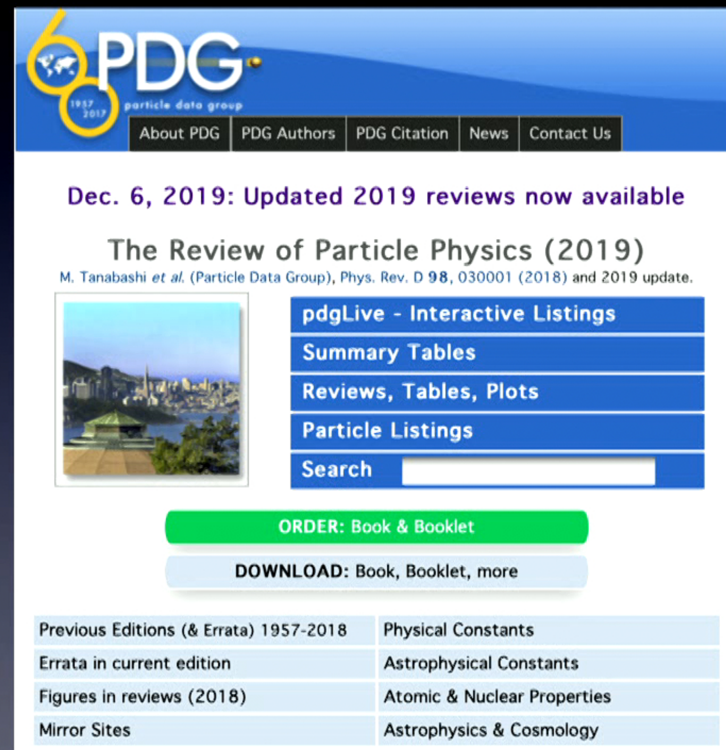
Possible answer: Moons come in all sorts of sizes, but only huge ones stabilise the rotation axis of their host planet, easing the development of life that can observe them.

Modern superstring/M-theory with its 10^{500} possible vacuum states fits this bill.

The unnerving stability of the Standard Cosmological Model

Since 2003, Ofer Lahav and I have written a biannual article on `Cosmological Parameters' for the Review of Particle Physics (a.k.a. the Particle Data Group).

These articles span the period from the first WMAP satellite release up to the final *Planck* satellite Legacy release.

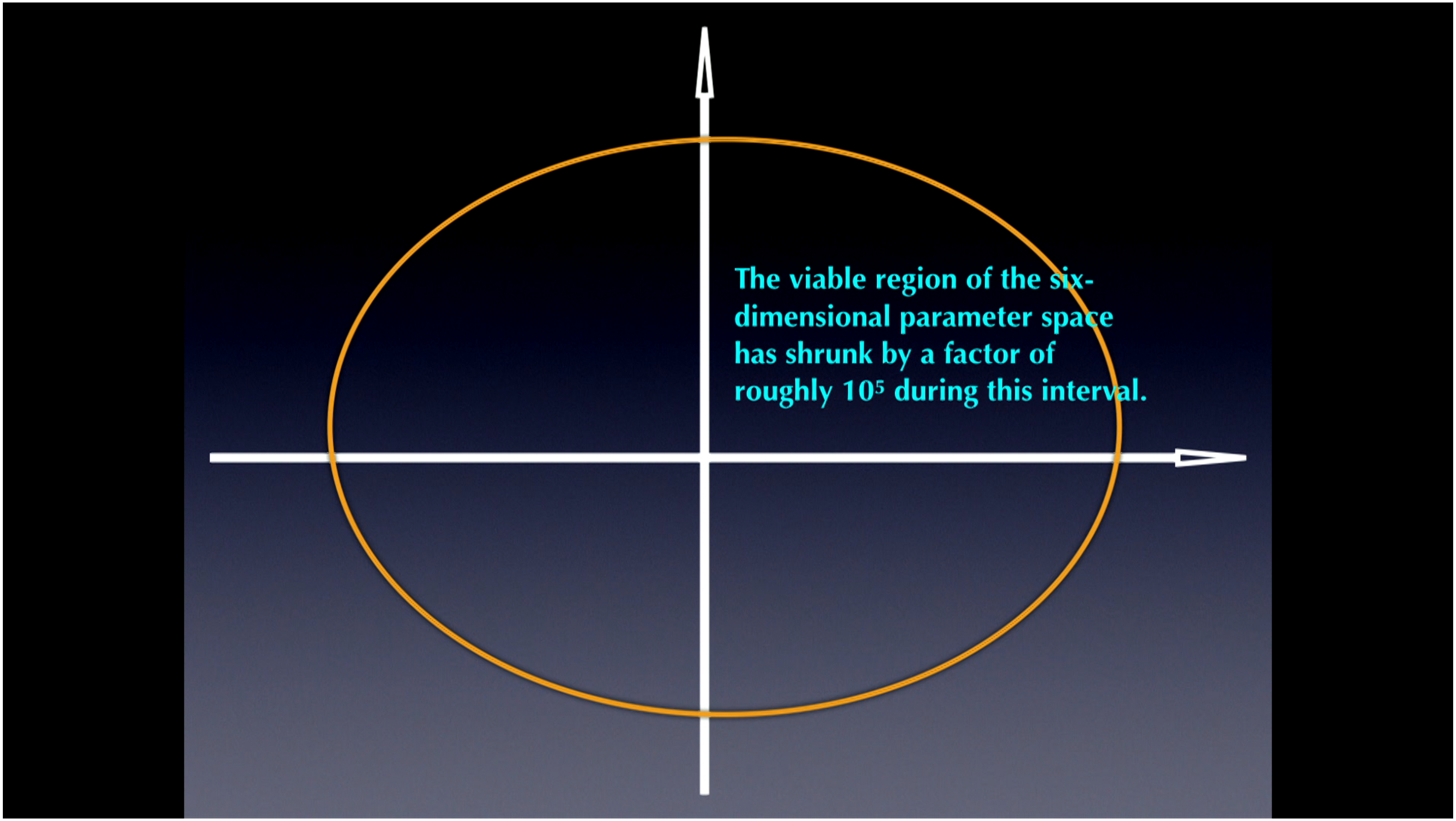


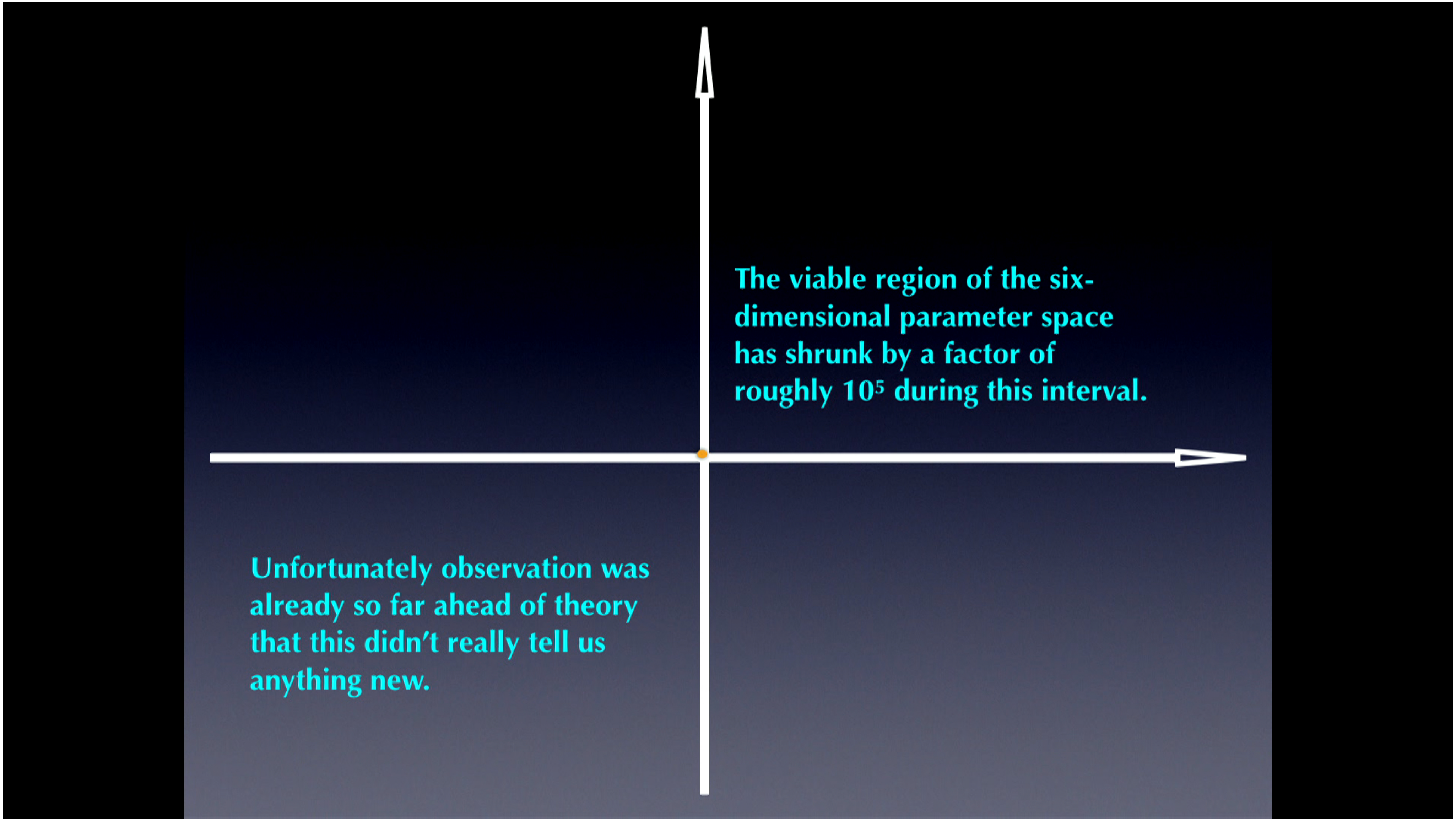
The 21st century cosmological arc

	2003 *WMAP* + 2dFGRS	2019 *Planck* TT,TE,EE +lowE+lensing	Improvement (*WMAP* → *Planck*)	Shift (in *WMAP* σ)
$\Omega_b h^2$	0.023 ± 0.001	0.02237 ± 0.00015	$\times 7$	0.6
$\Omega_c h^2$	0.111 ± 0.006	0.1200 ± 0.0012	$\times 4$	1.5
h	0.73 ± 0.03	0.674 ± 0.005	$\times 6$	1.9
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.16 ± 0.13	3.044 ± 0.014	$\times 9$	0.9
n_s	0.97 ± 0.03	0.965 ± 0.004	$\times 8$	0.2
τ	0.15 ± 0.07	0.054 ± 0.007	$\times 10$	1.4

Typically the uncertainty has shifted along to the next digit. But the actual values from *Planck* are completely consistent with what WMAP told us.

And the content of our article has hardly changed at all.


The viable region of the six-dimensional parameter space has shrunk by a factor of roughly 10^5 during this interval.


The viable region of the six-dimensional parameter space has shrunk by a factor of roughly 10^5 during this interval.
Unfortunately observation was already so far ahead of theory that this didn't really tell us anything new.

We seek to destroy what we create

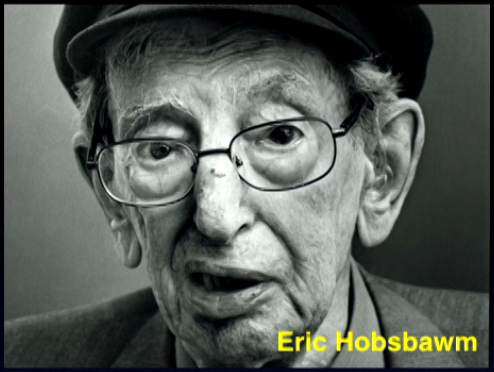
" The urge to destroy is also a creative urge. "

Mikhail Bakunin, 1850s

Girl with balloon / Love is in the bin

Banksy 2006/2018

The Short Cosmological Century (1915 to 2003)



The Short Cosmological Century (1915 to 2003)

Quantitative cosmology began in 1915 with the formulation of GR. It initiated an era of great discoveries in cosmology, including

- The Universe is expanding (1920s).
- The Universe was once hot (1940s).
- The Universe contains dark matter (1970s).
- The Universe is accelerating (1990s).
- The Universe has an (almost) flat geometry (2000s).
- The Universe was initially, or later became, perturbed on scales beyond its Hubble radius (2000s).

What about the `Hubble tension'?

One of the most discussed topics in cosmology is the supposed tension between low and high redshift probes of the expansion rate.

Incorrect results, or new physics?

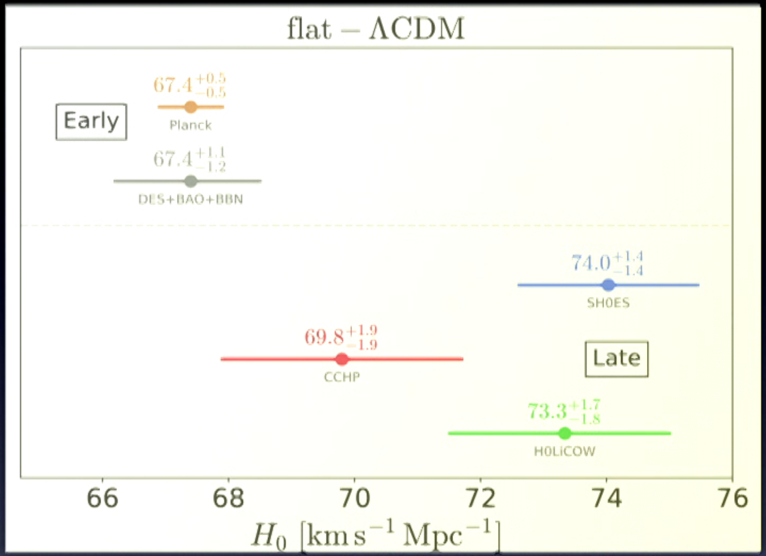


Figure by Vivien Bonvin and Martin Millon

Maybe, but …

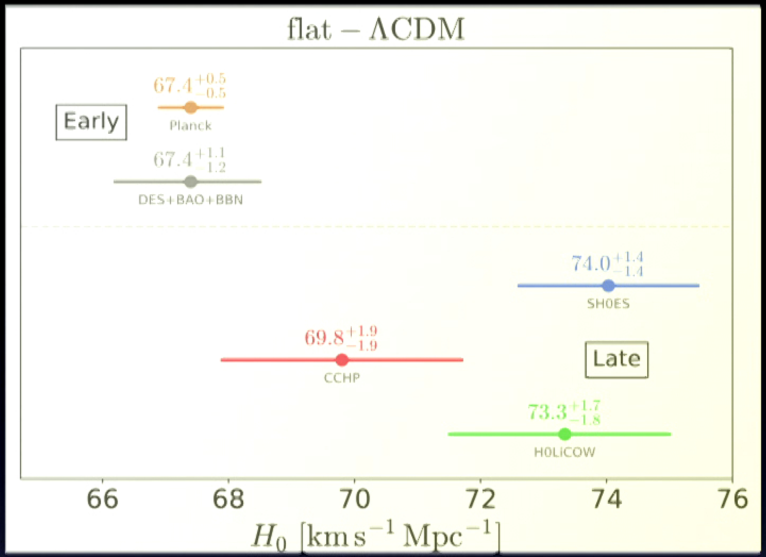


Figure by Vivien Bonvin and Martin Millon

- None of the many parameters considered to date help explain this on their own.
- The CMB data has vastly more statistical power than the direct measurements. It's a big coincidence for new physics to be invisible to the CMB+ data on its own, yet powerfully revealed when that is combined with the direct measurement.

Far-future cosmology

One day the very last significant cosmological observation will be made.

The latest this can happen is when the cosmic variance limit eclipses the last available observational strategy.

Theory might be ahead or behind observation at that point.

Might that day already be in the past ?!?!?!