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The State of the Universe

Peter Coles (@telescoper)

year of physics review articles

The state of the Universe

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The past 20 years have seen dramatic advances in cosmology, mostly driven by observations from new telescopes and detectors. These instruments have allowed astronomers to map out the large-scale structure of the Universe and probe the very early stages of its evolution. We seem to have established the basic parameters describing the behaviour of our expanding Universe, thereby putting cosmology on a firm empirical footing. But the emerging 'standard' model leaves many details of galaxy formation still to be worked out, and new ideas are emerging that challenge the theoretical framework on which the structure of the Big Bang is based. There is still a great deal left to explore in cosmology.











Planck results: cosmological parameters

Main result: the standard 6-parameter Λ CDM model remains a good fit to CMB data.

Parameter	Planck		Planck+lensing		Planck+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\overline{\Omega_{\mathrm{b}}h^2}$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_{\rm c}h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
100θ _{MC}	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
<i>n</i> _s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10}A_{\rm s})$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$

Some interesting derived numbers:

H_0	67.1 <mark>1</mark>	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
Ω_{Λ}	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
$\Omega_{\rm m}$	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$



Before Planck

After Planck





Hubble Tension?

Richard Ellis, Lectures on Observational Cosmology SERC Summer School for new research students, 1985

Perivolaropoulos & Skara arXiv:2105.05208



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The Robertson-Walker metric

In cosmology it is most useful to use spherical polar coordinates rather than a Cartesian system. In this system the only metric that describes space-times compatible with the cosmological principle is the Robertson-Walker metric:

$$ds^{2} = c^{2}dt^{2} - a^{2}(t)\left[\frac{dr^{2}}{1 - kr^{2}} + r^{2}(d\theta^{2} + sin^{2}\theta d\phi^{2})\right]$$

$$ds^{2} = c^{2}dt^{2} - a^{2}(t)\left[\frac{dr^{2}}{1 - kr^{2}} + r^{2}d\Omega^{2}\right]$$

Here k is the spatial curvature and (r, θ, ϕ) are comoving coordinates; the cosmic scale factor is a(t). The time coordinate is *cosmological proper time*.

The Etherington Reciprocity Theorem

Putting the two results for angular diameter distance and luminosity distance together we have that

$$D_A = a_e r$$
$$D_L = a_o^2 \frac{r}{a_e}$$

which means that

$$\frac{D_L}{D_A} = \frac{a_0^2}{a_e^2} = (1+z)^2$$

since $1 + z = \frac{a_0}{a_e}$ defines the redshift z.

This is a general result for any Riemannian space-time for which Maxwell's equations hold.

"CONCORDANCE"





Ingredients of the Standard Cosmology

- General Relativity
- Cold Dark Matter
- Cosmological Constant
- Cosmological Principle
- Primordial fluctuations (adiabatic, scaleinvariant, Gaussian).
- Inflation
- Baryons
- Neutrinos
- Radiation...

Questionable Aspects of the Standard Cosmology

- General Relativity
- Cold Dark Matter
- Cosmological Constant
- Cosmological Principle
- •Primordial fluctuations (adiabatic, scaleinvariant, Gaussian).
- Inflation
- Baryons
- Neutrinos
- Radiation...

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. EINSTEIN.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$\Delta \phi = 4\pi K \rho$

(1)

in Verbindung mit der Bewegungsgleichung des materiellen Punktes die Newronsche Fernwirkungstheorie noch nicht vollständig ersetzt. Es muß noch die Bedingung hinzutreten, daß im räumlich Unendlichen das Potential ϕ einem festen Grenzwerte zustrebt. Analog verhält es sich bei der Gravitationstheorie der allgemeinen Relativität; auch hier müssen zu den Differentialgleichungen Grenzbedingungen hinzutreten für das räumlich Unendliche, falls man die Welt wirklich als räumlich unendlich ausgedehnt anzusehen hat.

Bei der Behandlung des Planetenproblems habe ich diese Grenzbedingungen in Gestalt folgender Annahme gewählt: Es ist möglich, ein Bezugssystem so zu wählen, daß sämtliche Gravitationspotentiale g_{ω} im räumlich Unendlichen konstant werden. Es ist aber a priori durchaus nicht evident, daß man dieselben Grenzbedingungen ansetzen darf, wenn man größere Partien der Körperwelt ins Auge fassen will. Im folgenden sollen die Überlegungen angegeben werden, welche ich bisher über diese prinzipiel wichtige Frage angestellt habe.

§ 1. Die Newronsche Theorie.

Es ist wohlbekannt, daß die Newronsche Grenzbedingung des konstanten Limes für ϕ im räumlich Unendlichen zu der Auffassung hinführt, daß die Dichte der Materie im Unendlichen zu null wird. Wir denken uns nämlich, es lasse sich ein Ort im Weltraum finden, um den herum das Gravitationsfeld der Materie, im großen betrachtet, Kugelsymmetrie besitzt (Mittelpunkt). Dann folgt aus der Poissonschen Gleichung, daß die mittlere Dichte ρ rascher als $\frac{1}{r^*}$ mit wachsender Entfernung r vom Mittelpunkt zu null herabsinken muß, damit ϕ im

Dark Energy: A Cosmologist's Perspective



G+?=T

Dark Energy: A Physicist's Perspective

G = T + ?

Whatever it is, Dark Energy is a *terrible* name for it...

- What is important is not so much the *energy*, but the *pressure*...
- Dark Energy has to act like something with negative pressure (or tension)
- It also has to be smoothly distributed throughout space





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With scale-invariant fluctuations the Universe is never *exactly* homogeneous...

... it's 10⁻⁵ all the way up!



2dFGRS power spectrum: small BAO proves DM

Dimensionless power: d (fractional variance in density) / d ln k



Percival et al. MNRAS 327, 1279 (2001)

Why Should The Dark Sector Be Simple?

Problems with Cold Dark Matter

Astrophysics:

- Cuspy Halo Problem
- Missing Satellite Problem
- Planar Structures
- Galaxy Morphology
- ...

Particle Physics

- No Evidence for Supersymmetry
- No evidence from Direct Searches





Satellite galaxy positions as viewed from Andromeda.



RA Ibata et al. Nature 493, 62-65 (2013) doi:10.1038/nature11717



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: SUSY 2012)

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10 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena shown. All limits quoted are observed minus 1 or theoretical signal cross section uncertainty.



Alternatives (not exhaustive)

- •HDM (historical; see also CHDM)
- •WDM
- •SIDM
- •SADM
- Axions
- •Fuzzy DM
- •
- Modified Gravity (e.g. MOND)

Might dark matter be quantummechanical?

- Simple idea): DM is a (very) light particle (m~ 10⁻²² eV) then the de Broglie wavelength can be a galactic scale.
- Something like `warm' dark matter arises (actually `fuzzy' dark matter), but with *quantum pressure.*
- Sometimes called *Fuzzy Dark Matter*

From Schive et al., arXiv: 1406.6586 (also published in Nature)





Cosmology is a massive exercise in data compression...

....but it is worth looking at the information that has been thrown away to check that it makes sense!

Beyond the Power Spectrum

- So far what we have discovered is largely based on second-order statistics...
- This is fine as long as we don't throw away important clues...
- ..ie if the fluctuations are statistically homogeneous and istropic, and Gaussian..















"If tortured sufficiently, data will confess to almost anything"

Fred Menger

CMB Anomalies

- •Type I obvious problems with data (e.g. foregrounds)
- •Type II anisotropies and alignments (North-South, Axis of Evil..)
- •Type III localized features, e.g. "The Cold Spot"
- •Type IV Something else (even/odd multipoles, magnetic fields, ?)





Low Quadrupole?





(from Copi et al. 2005)

Parity Violation?





Figure 24. The discs show the positions of the hemispheres with the 10 highest (black discs) and 10 lowest (white discs) bin values. The power-spectrum bins considered were $\ell = 2-40$ (large discs), $\ell = 8-40$ (second-largest discs), $\ell = 5-16$ (second-smallest discs) and $\ell = 29-40$ (smallest discs).





The hottest hotspot on the microwave sky

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Summary. Approximate confidence limits on the temperature of the hottest hotspot expected on the microwave sky are derived under the condition that the coherence angle of the temperature fluctuations is a very small fraction of the total sky. We apply the result to temperature anisotropies expected in galaxy formation models where the universe is dominated by cold dark matter and discuss its possible use for discriminating between high peaks in system noise and true sky fluctuations.

1 Introduction

Anisotropies of the cosmic microwave background provide one of the few direct tests of theories of galaxy formation. Theoreticians have predicted the rms amplitudes and covariance functions of the fluctuations produced by various models (Bond & Efstathiou 1984, Bond, Efstathiou & Silk 1981; Wilson & Silk 1980) and more recently, using techniques developed for the study of biased galaxy formation, have examined more detailed statistical properties of temperature fluctuations (Sazhin 1985; Zabotin & Nasel'skii 1985; Bond & Efstathiou 1987; Vittorio & Juszkiewicz 1987; Coles & Barrow 1987; Coles 1987, in preparation). For the most part, these analyses concentrate on *local* properties of the microwave sky such as the mean number density

Beware the Prosecutor's Fallacy!

$P(A|M) \neq P(M|A)$

A. There's no problem at all with $\Lambda CDM...$

B. There are interesting indications...

C. There's definitely evidence of new physics

Is ΛCDM the "Maximally Boring Universe"?

- There are many unanswered theoretical questions!
- So far the questions we've asked have been the "easy" ones
- Now that this "boring" stuff is out of the way, cosmology will start to get interesting!
- Because we now have a better idea what to ask!