The Standard Model of Cosmology

(history, status and some opinions of a card-carrying skeptic)

Douglas Scott


The Standard Model of Cosmology: A Skeptic's Guide

Douglas Scott(*)

arXiv:1804.01318v1 [astro-ph.CO] 4 Apr 2018

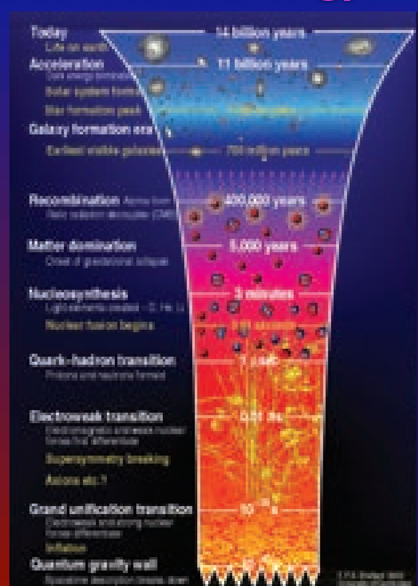
1. – What is the standard model of cosmology?

Further reading, based on lectures at 200th course of International School of Physics "Enrico Fermi", Varenna

Standard Model of Cosmology

GR
(simplest soln.)
+ expansion
+ CMB
+ simple I.Cs.
+ few components
→ Big Bang
(with spots)

a.k.a. ΛCDM



Basic Cosmology Equations

- GR, plus flat expanding space-time:

$$ds^2 = c^2dt^2 - a^2(t)\left\{dx^2 + dy^2 + dz^2\right\}$$

- Or in spherical coordinates

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

- Field equations

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

- + isotropy and homogeneity → Friedmann eqs.

Basic Cosmology Equations

- Scale factor $a(t) \equiv 1/(1+z)$:

$$H \equiv \dot{a}/a \quad \rho_{\rm crit} = 3H^2/8\pi G \quad \Omega = \rho/\rho_{\rm crit}$$

- Spatially flat:

$$\Omega_\gamma + \Omega_{\rm M} + \Omega_\Lambda = 1$$

- Friedmann equation:

$$H^2(z) = \left\{\Omega_\gamma(1+z)^4 + \Omega_{\rm M}(1+z)^3 + \Omega_\Lambda\right\} H_0^2$$

Early Universe

- Radiation domination implies

$$T \simeq 1.4\, g_{\rm eff}^{-1/4} \left(\frac{t}{\rm sec}\right)^{-1/2} \text{MeV}$$

- Where the effective number of relativistic degrees of freedom is

$$g_{\rm eff}(T) = \sum_{\rm Bosons} g_{\rm B} + \frac{7}{8} \sum_{\rm Fermions} g_{\rm F}$$

- Light elements made in about 3 minutes
- Inflation at $t \sim 10^{-3?}$ seconds; $t_{\rm Planck} \sim 10^{-43}$s

Perturbations

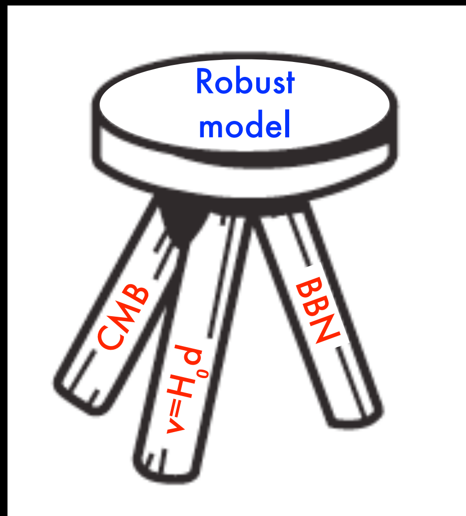
- Inflation (or something else) makes spectrum of density (scalar) perturbations:

$$P(k) \equiv |\delta_k|^2 = A_{\rm s} k_{\rm s}^n$$

- And also gravitational wave fluctuations of unknown amplitude, $A_{\rm t}$
- Density perturbations affect the CMB at $z \simeq 1000$ and galaxy clustering at $z \simeq 0$
- And make the Universe we know and love!

Assumptions underlying the SMC	
1	Physics is the same throughout the observable Universe.
2	General Relativity is an adequate description of gravity.
3	On large scales the Universe is statistically the same everywhere.
4	The Universe was once much hotter and denser and has been expanding.
5	There are five basic cosmological constituents:
5a	Dark energy behaves just like the energy density of the vacuum.
5b	Dark matter is pressureless (for the purposes of forming structure).
5c	Regular atomic matter behaves just like it does on Earth.
5d	Photons from the CMB permeate all of space.
5e	Neutrinos are effectively massless (again for structure formation).
6	The overall curvature of space is flat.
7	Variations in density were laid down everywhere at early times, proportionally in all constituents.

Testable and most have been tested!



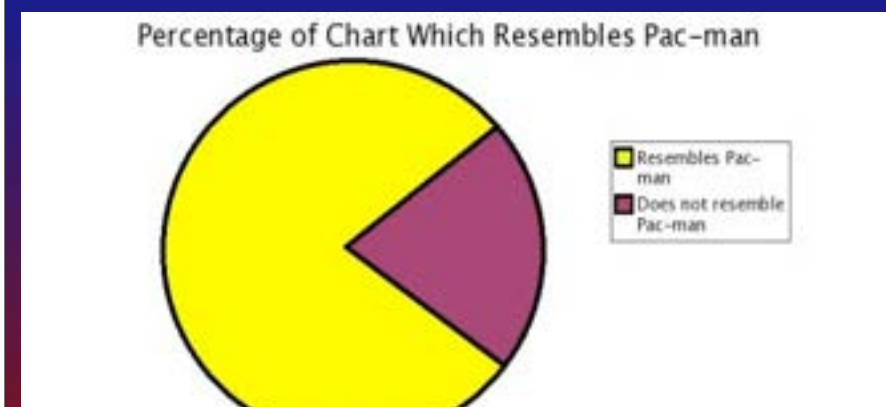
+ galaxy clustering and dynamics, CMB anisotropies,
+ lensing, absorption systems, ...

The Big Bang Theory

So well established it had its own TV show

But what kind of Big Bang model do we live in?

COSMIC CENSUS



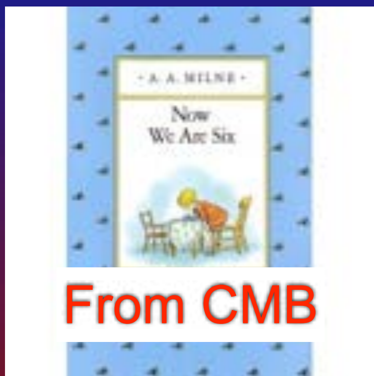
Funniest pie-chart

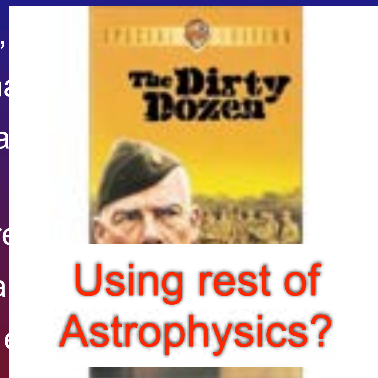
Standard Model of Cosmology

- ★ What kind of Big Bang model do we live in?
- ★ How many parameters do we need?
- ★ Will there be more parameters later?
- ★ Why do the parameters have these values?
- ★ What was the origin of the perturbations?
- ★ What's the dark matter and dark energy?
- ★ Is there evidence for new physics?

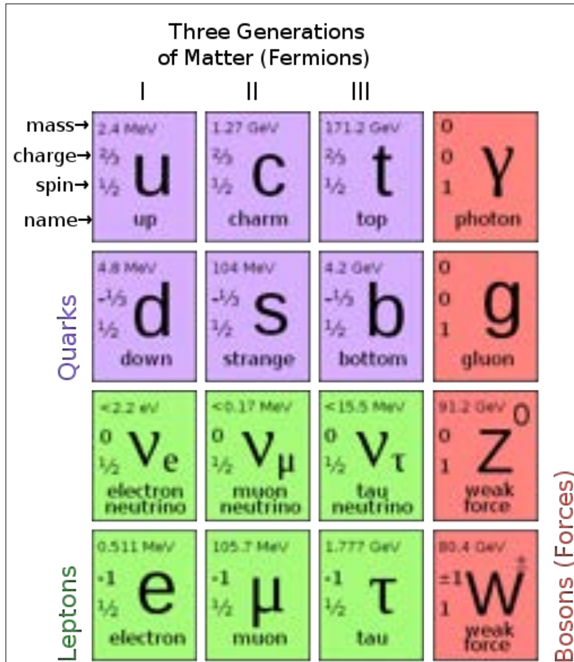
- ★ What about the other Standard Model?

The Standard Model of Cosmology





★ What about that other Standard Model?



Standard Model of Particle Physics

(the most precise and successful model in physics, maybe all science!)

\+

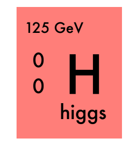


Table 1. The 26 Parameters of the Standard Model of Particle Physics.

6 quark masses:	m_u	m_d	m_s	m_c	m_t	m_b
4 quark mixing angles:	θ_{12}	θ_{23}	θ_{13}	δ		
6 lepton masses:	m_e	m_μ	m_τ	m_{ν_e}	m_{ν_μ}	m_{ν_τ}
4 lepton mixing angles:	θ'_{12}	θ'_{23}	θ'_{13}	δ'		
3 electroweak parameters:	α	G_F	M_Z			
1 Higgs mass:	m_H					
1 strong CP violating phase:	$\bar{\theta}$					
1 QCD coupling constant:	$\alpha_S(M_Z)$					
26 total parameters						

A,B,C,D,E,F,G,
H,I,J,K,L,M,N,
O,P,Q,R,S,T,U,
V,W,X,Y,Z

Table 2. The 12 Parameters of the Standard Model of Cosmology.

1 temperature:	T_0			
1 timescale:	H_0			
4 densities:	Ω_Λ	Ω_{CDM}	Ω_B	Ω_ν
1 pressure:	$w \equiv p/\rho$			
1 mean free path:	τ_{reion}			
4 fluctuation descriptors:	A	n	$n' \equiv dn/d\ln k$	$r \equiv T/S$
12 total parameters				

A,E,H,I,K,
L,M,N,O,P,
U,W

Vintage of the SMC?

arXiv:astro-ph/9504003 v1 3 Apr 1995

CWRU-P6-95
FERMILAB–Pub–95/063-A
astro-ph/9504003

THE COSMOLOGICAL CONSTANT IS BACK

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(submitted to *Gravity Research Foundation Essay Competition*)

SUMMARY

A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the wanted value for the cosmological constant corresponds to a very tiny vacuum energy density. We discuss future observational tests for a cosmological constant as well as the fundamental theoretical challenges—and opportunities—that this poses for particle physics and for extending our understanding of the evolution of the Universe back to the earliest moments.

arXiv:astro-ph/9505066 v1 16 May 1995

COSMIC CONCORDANCE

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Abstract

It is interesting, and perhaps surprising, that despite a growing diversity of independent astronomical and cosmological observations, there remains a substantial range of cosmological models consistent with all important observational constraints. The constraints guide one forcefully to examine models in which the matter density is substantially less than critical density. Particularly noteworthy are those which are consistent with inflation. For these models, microwave background anisotropy, large-scale structure measurements, direct measurements of the Hubble constant, H_0*, and the closure parameter,* $\Omega_{\rm Matter}$*, ages of stars and a host of more minor facts are all consistent with a spatially flat model having significant cosmological constant* $\Omega_\Lambda = 0.65 \pm 0.1$, $\Omega_{\rm Matter} = 1 - \Omega_\Lambda$ *(in the form of "cold dark matter") and a small tilt:* $0.8 < n < 1.2$.

Vintage of the SMC?

Nature **348**, 705 - 707 (27 December 1990); doi:10.1038/348705a0

The cosmological constant and cold dark matter

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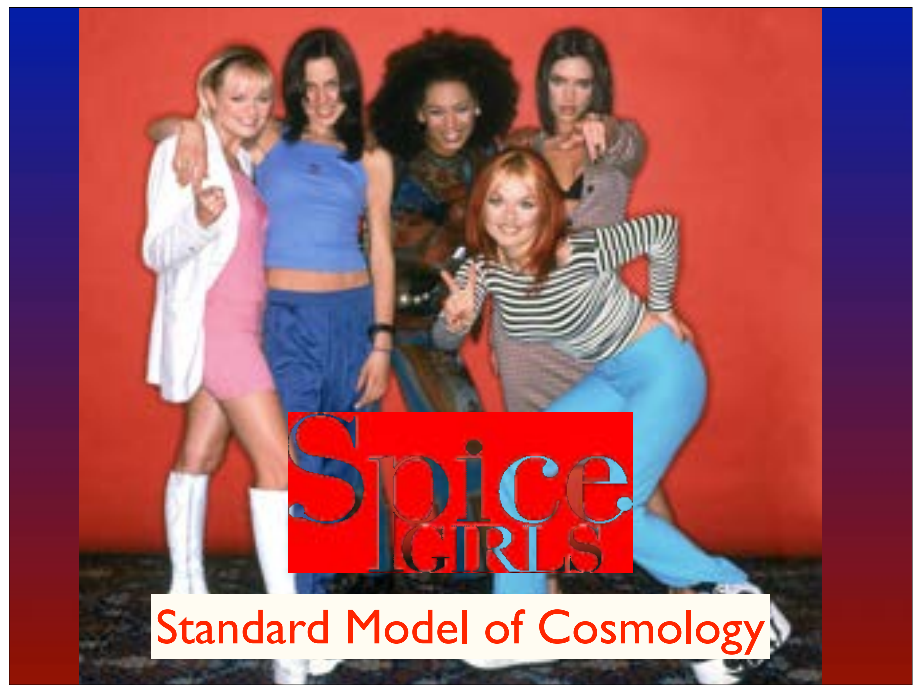
THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales (*l*> 10 *h* $^{-1}$ Mpc, where *h* is the Hubble constant H_0 in units of 100 km s^{-1} Mpc^{-1}) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

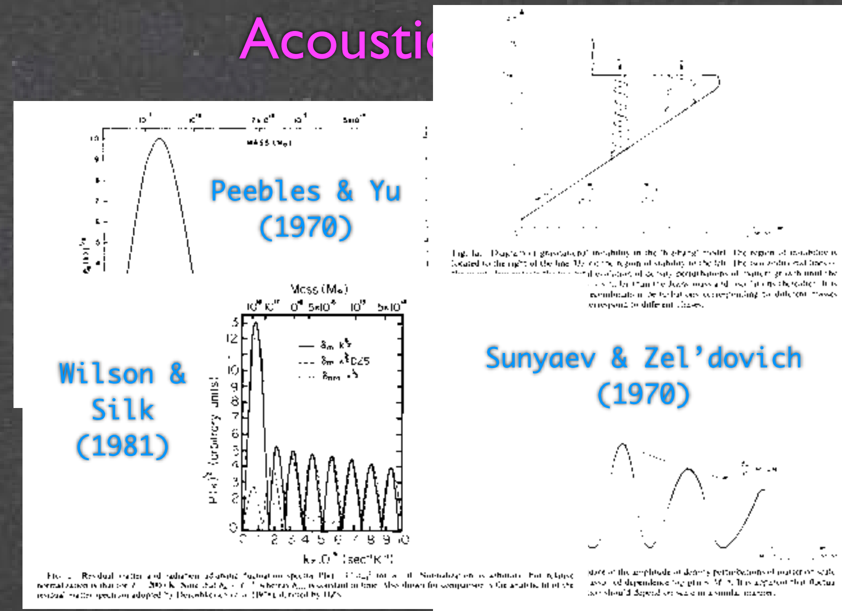


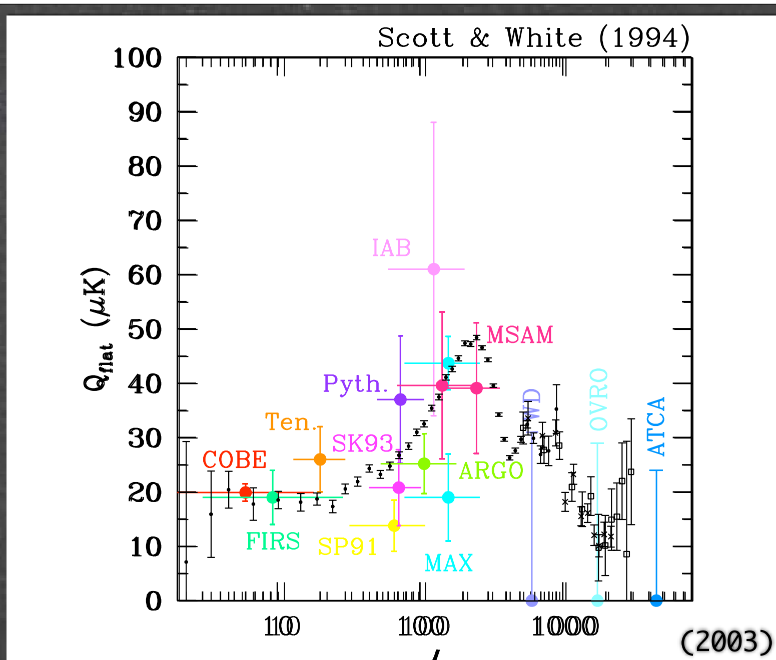
SMC Predictions

	Confirmation
CMB Acoustic Peaks	1994
Acceleration	1998
Cosmic Shear	2000
Cosmic Jerk	2001
CMB Polarization	2002
Baryon Acoustic Oscillations	2003
CMB(ISW)-LSS Correlation	2005
CMB-lensing Correlations	2007

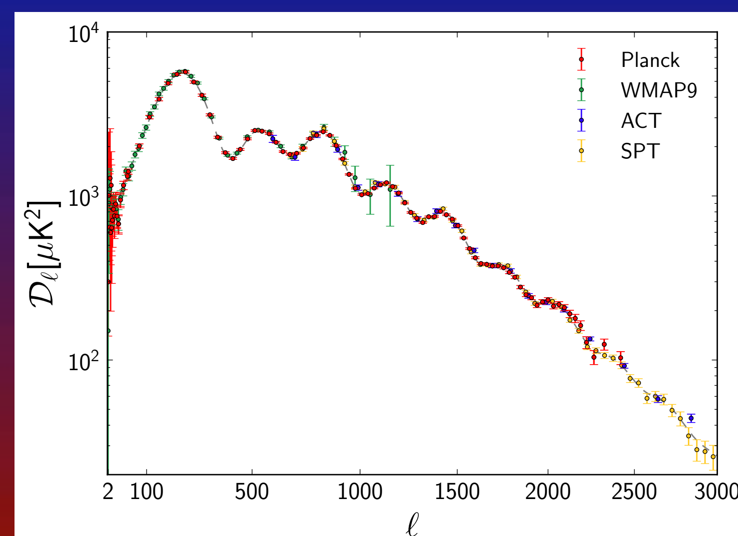
+ SZ power, CMB lensing convergence, ...

Acousti



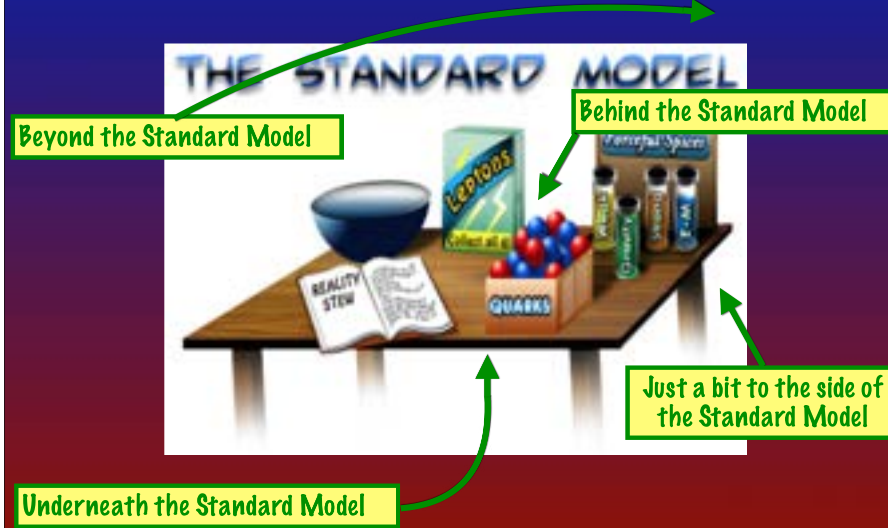


The "precision era" of CMBology
(dominated by Planck, but that will change soon)

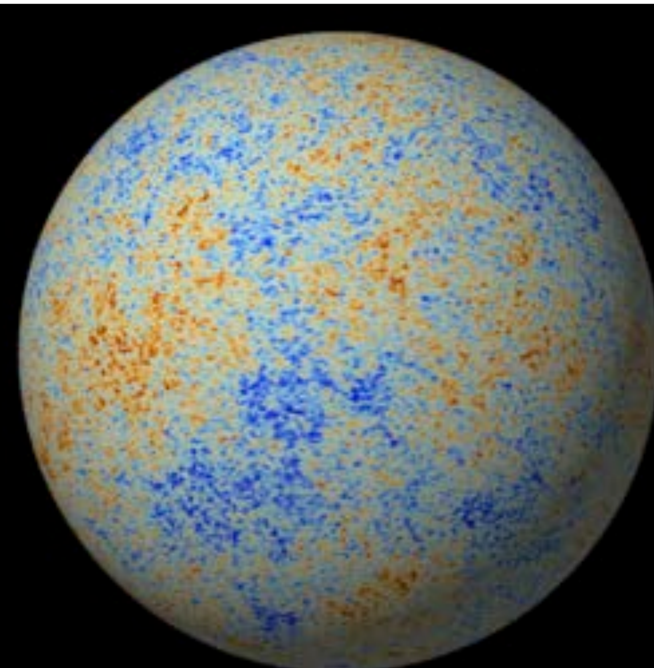


SMPP	SMC
Late 1960s / early 1970s	Early 1990s
Predicted:	Predicted:
• W,Z,c,t,g,Higgs	• many things!
Not fundamental	Not at all fundamental
Observer independent (not stochastic?)	Observer dependent (time + cosmic variance)
Very very precise	Getting very precise
What's next?	What's next?

Physics beyond the SMC?



How do we know the parameters of the SMC so well?



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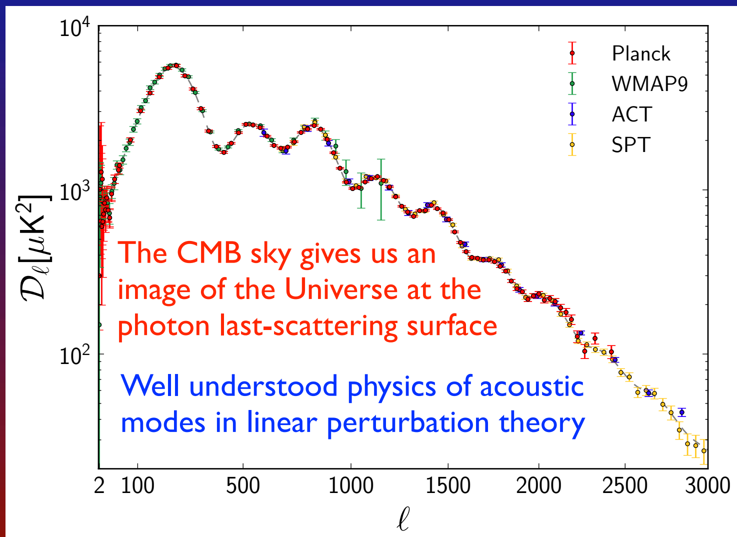
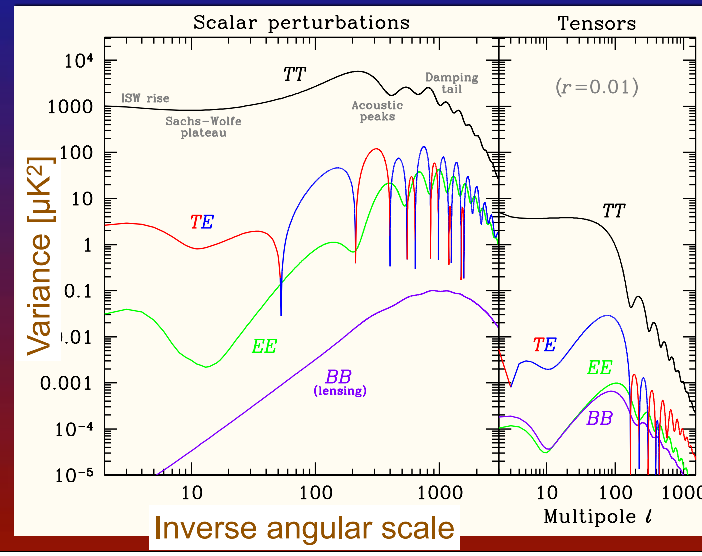


Can precisely calculate 4 power spectra (given a set of parameters)



Scott & Smoot 2022 RPP

Planck data compression

- Trillions of bits of data
- Billions of measurements at 9 frequencies
- 50 million pixel map of whole sky
- 2 million harmonic modes measured
- ~2000σ detection of CMB anisotropy power
- Fit with just 6 parameters!
- With no significant evidence for a 7th

So what are these 6 parameters?

The 6 parameters

("Planck" here means Planck TT+TE+EE+lensing)

There are somewhat different constraints for Planck + other data

	Parameter	*Planck* alone	*Planck* + BAO
Physical baryon density / Amount of atoms	$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
Physical CDM density / Amount of dark stuff	$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
Sound horizon/angular dist. / Stretch factor for wiggles	$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
Reionization optical depth / Fraction of recent scattering	τ	0.0544 ± 0.0073	0.0561 ± 0.0071
Amplitude of initial P(k) / Strength of lumpiness	$\ln(10^{10}A_s)$	3.044 ± 0.014	3.047 ± 0.014
Slope of initial P(k) / Scale variation in clumpiness	n_s	0.9649 ± 0.0042	0.9665 ± 0.0038

(CMB temperature already so well determined it's usually not thought of as a parameter)

And some derived parameters
(+ t_0 + σ_8 + ...)

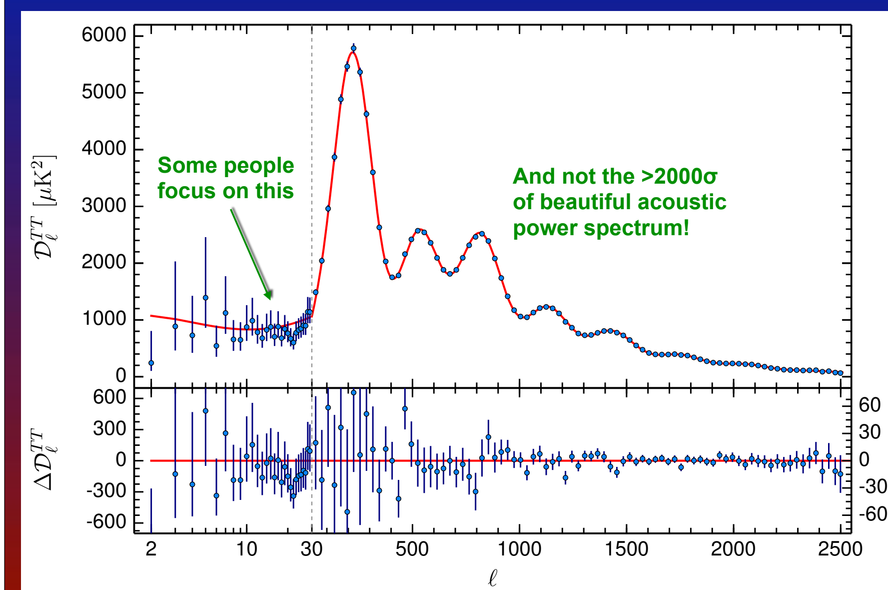
	H_0	67.36 ± 0.54	67.66 ± 0.42
	Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
	Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056

- The 6-parameter ΛCDM model is so good that focus turns to “tensions”
  - -Planck vs WMAP ?
  - -Discrepancy with distance-ladder H_0 ?
  - -CMB vs lensing and clustering σ_8 ?
  - -Preference for A_L>1 ?
- Plus large-scale “anomalies”
  - -particularly the “low low-ℓs” ?
  - -dipole modulation/hemispheric asymmetry
  - -cold spot
  - -etc.

If today’s SMC status was an episode of Sesame Street, it would be ...

Brought to you by the words “tensions” and “anomalies”

Planck TT power spectrum

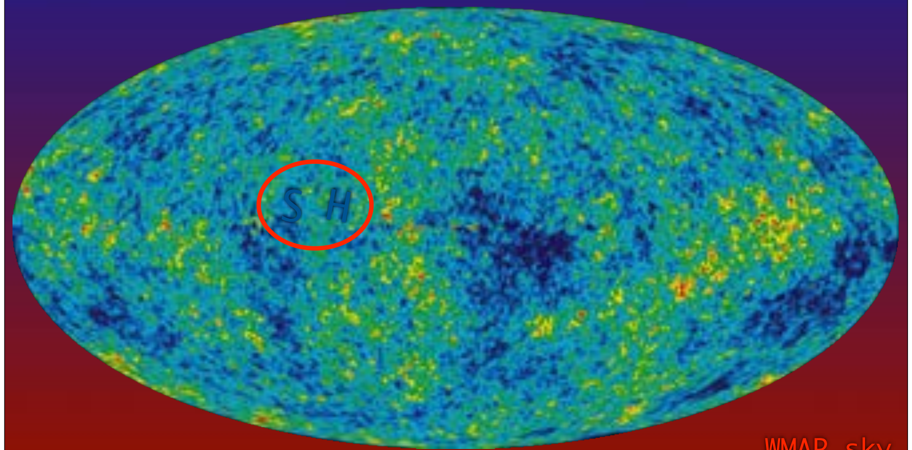


Anomalies?

- WMAP large-scale anomalies persist in Planck
- But are still of fairly low significance
- Are any of them telling us something?

- Low quadrupole
- “Cold Spot”
- “Hemispheric Asymmetry”
- First ~30 multipoles seem low
- Alignment of low multipoles
- Odd/even multipole asymmetry
- ...

CMB anomalies: here’s a famous example



See this paper for details!

Pi in the Sky

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(Dated: 1st April 2016)

Deviations of the observed cosmic microwave background (CMB) from the standard model, known as ‘anomalies’, are obviously highly significant and deserve to be pursued more aggressively in order to discover the physical phenomena underlying them. Through intensive investigation we have discovered that there are equally surprising features in the digits of the number π, and moreover there is a remarkable correspondence between each type of peculiarity in the digits of π and the anomalies in the CMB. Putting aside the unreasonable possibility that these are just the sort of flukes that appear when one looks hard enough, the only conceivable conclusion is that, however the CMB anomalies were created, a similar process imprinted patterns in the digits of π.

Cold Spot?

CMB sky | Digits of π

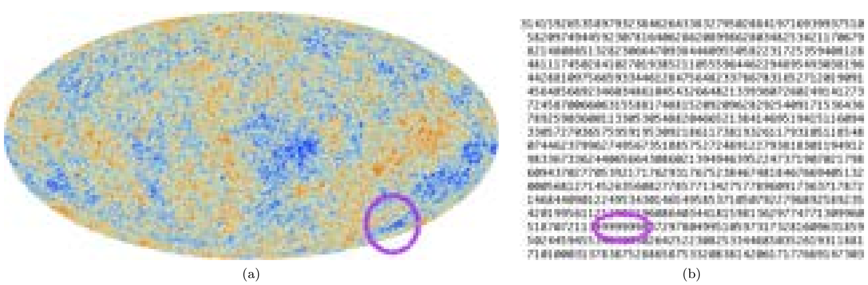


FIG. 1: (a) Map of the CMB sky from the *Planck* satellite [5]. It seems hardly necessary to mark the position of the Cold Spot, since it stands out so clearly. (b) The first 900 digits of π, showing the early ‘hot spot’, also known as the Feynman point.

Low-ell deficit

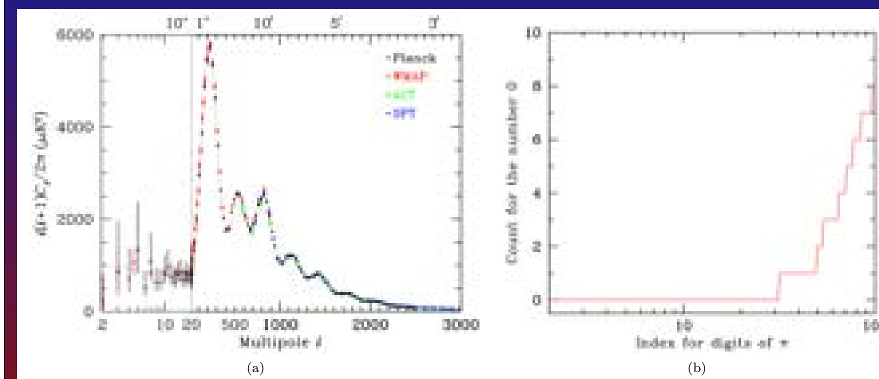


FIG. 3: (a) Compilation of CMB power spectrum data from *Planck*, *WMAP*, Atacama Cosmology Telescope [29] and South Pole Telescope [30]. As has become conventional, the lowest multipole part is plotted logarithmically and the rest on a linear scale. One can see that over the wide range of multipoles that have now been well measured, the deficit of power at $\ell = 20$–30 really stands out. (b). For π we focus on the lowest integer, i.e. ‘0’, and find that there is a deficit in its abundance in the first digits. In fact the number 0 does not occur at all until the 33rd digit.

Hemispheric asymmetry

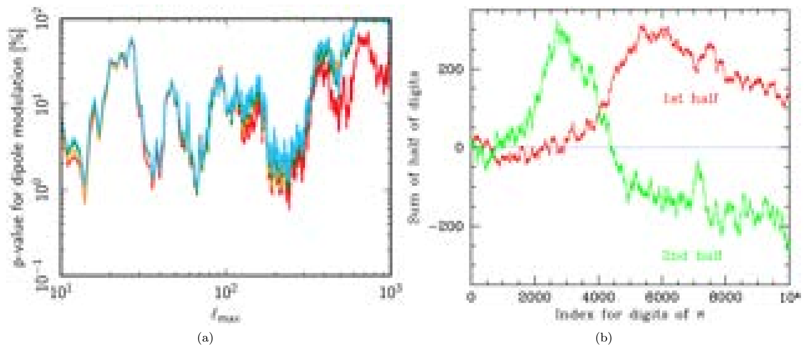


FIG. 4: (a) On large angular scales the CMB sky has more power in one hemisphere than the other, which can also be thought of as dipole modulation of the sky. Here (taken from Ref. [10], and plotted for four different foreground-separated CMB maps) we show how the significance of this modulation varies with the maximum multipole considered. It is clear that the spike at $\ell \simeq 65$ stands out compared with all other scales. The amplitude of the dipole modulation at this scale is only found in about 1 % of random simulations. (b) If we take the digits of π out to some maximum digit and separately add the first half and second half (after removing the average), we obtain the red and green lines, respectively. It is clear that the two halves of the digits behave in a remarkably different way.

Alignment

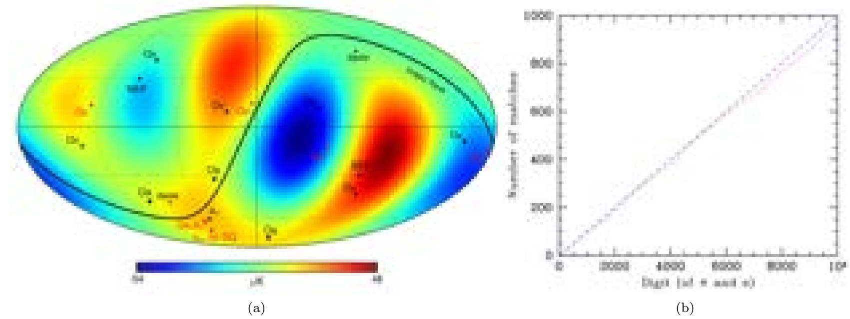


FIG. 5: (a) Alignment of the dipole (D), quadrupole (Q) and octupole (O) directions, taken from Ref. [12]. Since the dots all appear in one small part of the sky, one can see that these special directions are remarkably well aligned. (b) Anti-alignment of the digits of π and e. If one compares these two numbers, digit by digit, it becomes apparent that the fraction of matches found falls systematically short of expectations for essentially all the digits investigated.

Odd/even asymmetry

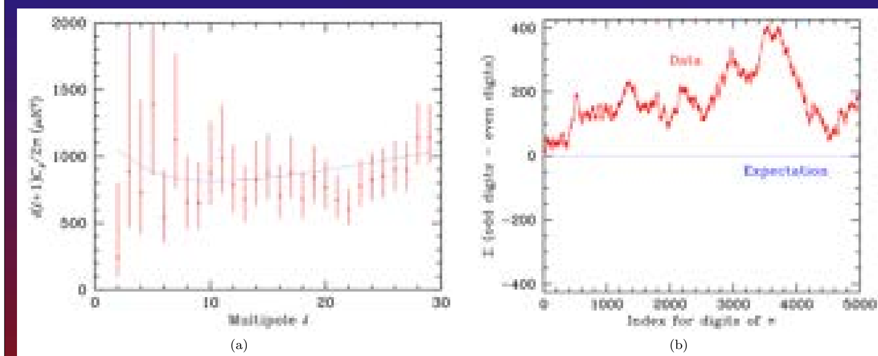


FIG. 6: (a) Power spectrum from *Planck* data, showing the first 30 multipoles. The 'parity asymmetry' is evident here, with a striking 'saw-tooth' pattern of odd versus even multipoles. (b) If we examine the digits of π we find that the odd digits are systematically higher than the even digits – shown here by plotting the cumulant of the sum of odd digits minus the sum of even digits.

Words

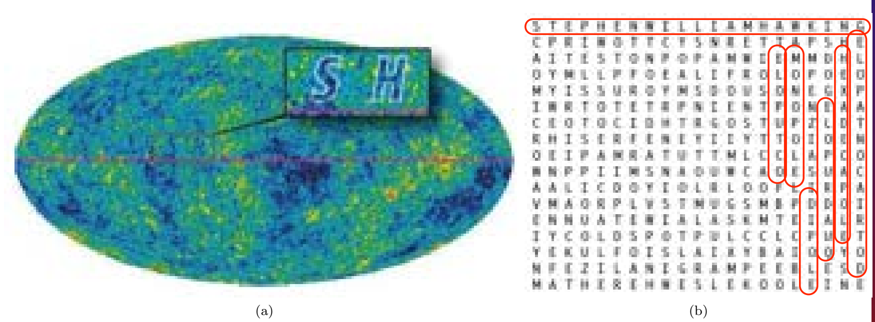
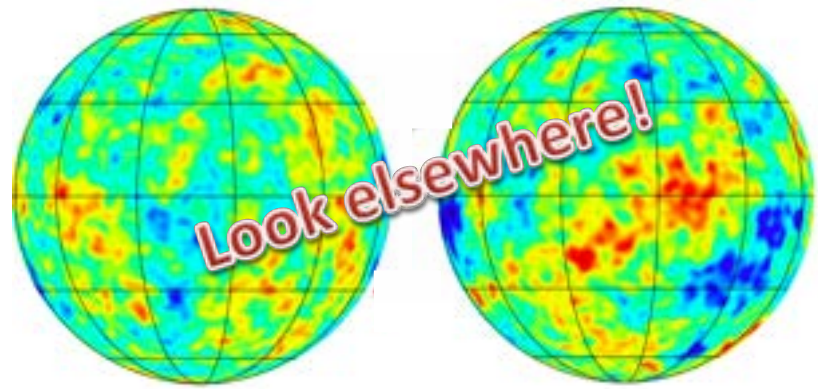


FIG. 7: (a) Indication of the initials 'S.H.' that appear on the CMB sky (taken from Ref. [9]). (b) When we translate the digits of π into letters, we can start to see messages that are more unusual than mere initials.

But seriously folks...

Large Angle Anomalies



Also known as "multiplicity of tests"

What to think of anomalies?

- Remember there's only one observable Universe!
- These measurements are "cosmic variance" limited
- So we can't do better just by re-measuring them

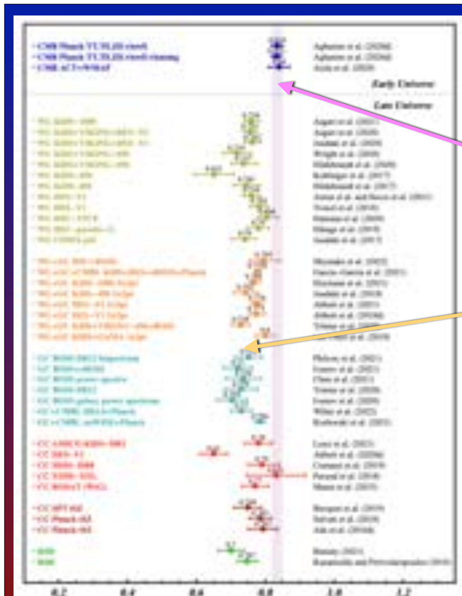
- We have to be cautious about "a posteriori" claims
- But, these are special and important modes
- So we should continue to look for "explanations"
- And look in independent data, e.g. polarization
- One of the things that LiteBIRD can do with *E* modes

A Hubble patch

Many Hubble patches

What about tensions?

S_8 tension



$$S_8 \equiv \sigma_8 \, (\Omega_{\rm m}/0.3)^{0.5}$$

CMB-related estimates

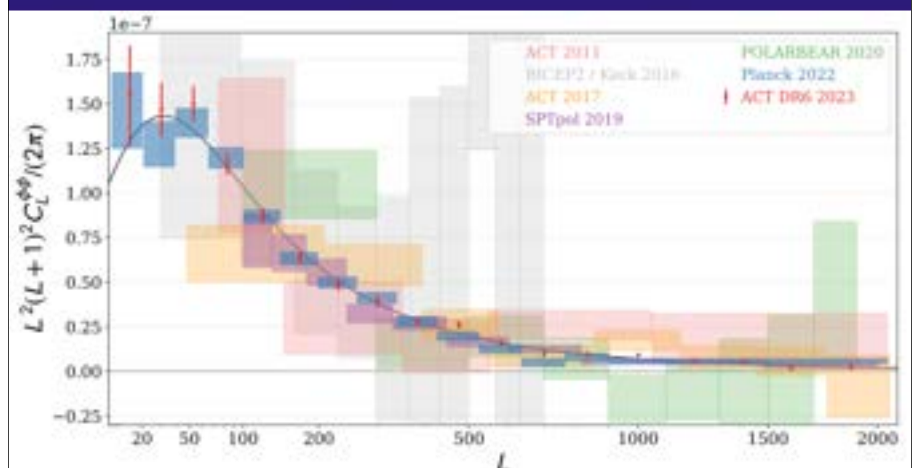
Galaxy-based estimates

These differ by >2σ

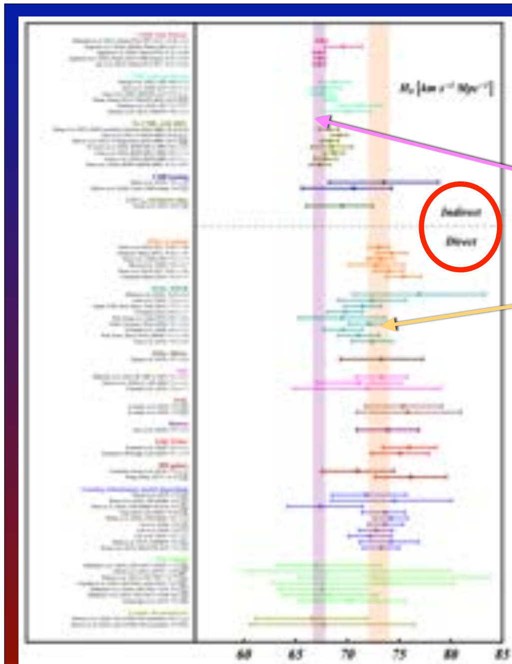
From Abdallah et al. (2022)

CMB lensing provides additional information

ACT agrees with Planck



H_0 tension



CMB-related estimates

Distance-ladder type estimates

These differ by >4σ

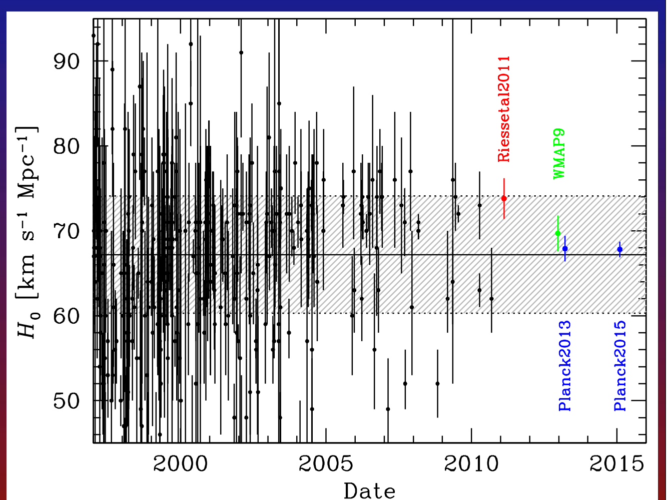
From Abdallah et al. (2022)

From wikipedia

Historic Hubble "tension"

>20 years of H_0 estimates

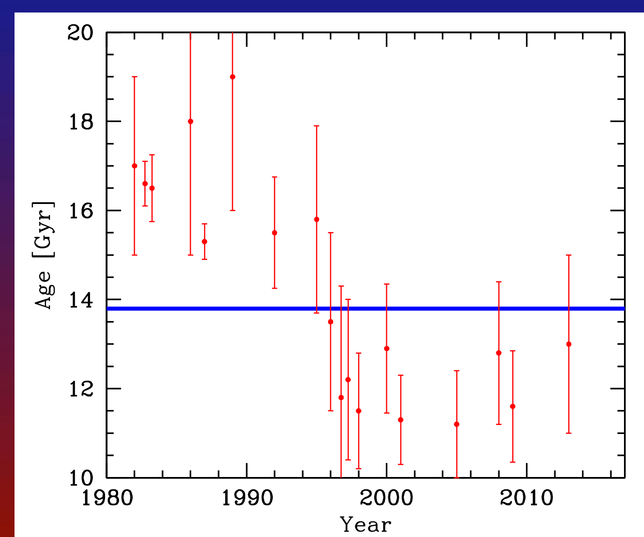
Is this evidence for new physics?



See "Cosmology for skeptics" arXiv:1804.01318

Example of historical "tension"

Ages of oldest globular clusters (once > age of Universe!)



Exciting solutions

- Early dark energy
- Decaying dark matter
- Interacting DE/DM
- Modified gravity
- Variation of fundamental constants
- …

Boring solution

- Underestimated or underappreciated systematic effects

(But mostly people don’t want the really dull explanation!)

Guy finds a ring and his nephew returns it to the factory

But the future is bright!

- H_0 from new methods, such as standard sirens
- Improved optical/NIR galaxy surveys, Euclid, DESI, Rubin, Roman, etc.

 →Dramatic improvement in WL, BAO, RSD, etc.

- Better CMB polarisation measurements, complementing temperature (including LiteBIRD)

→Can we probe the physics of inflation?

Inflation scorecard

Prediction	Measurement
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.002} < 0.07$
which are Gaussian	$f_{NL} = 2.5 \pm 5.7$
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$

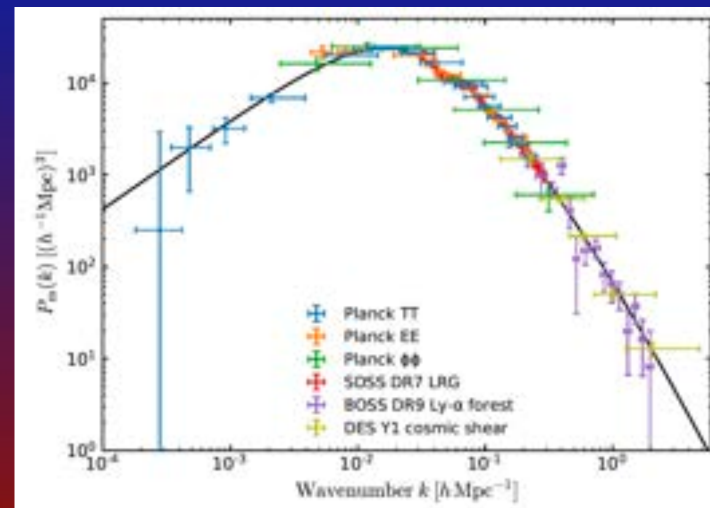
Planck 2018 Paper I

Status of inflation:

“Something like inflation is something like proven”

r~0.001 is a well-motivated target, and there’s more to cosmology…

Amazing consistency!



But is there room for something new?

Beyond the SMC?

- Constrain parameters better?
- Which of ~12 have null values?
- Will Ω_ν be next to be measured?
- Will there be genuine surprises?
- Are $1+w$ and *B*-modes detectable?
- Did inflation happen or something else?
- Will the SMC get as boringly successful as the SMPP?

Big questions for theorists

- Why Λ ?
- Why is $\Omega_{CDM}/\Omega_B \simeq 5$?
- Are some parameters stochastic?
- Alternatives to inflation?
- Naturally explain any anomalies?
- Predict something new: non-Gauss., isocurvature, defects, PMFs, PBHs, MG ?

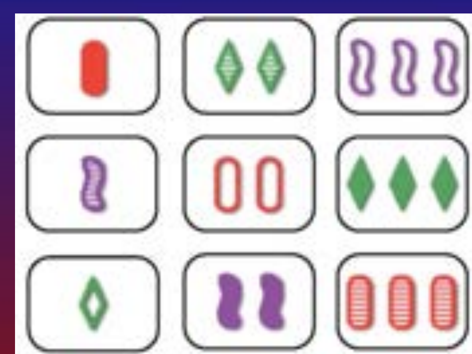
Either the best time or worst time to be a theorist in cosmology!

Now the future is lunch!

Thanks!

Extra slides

Our sky might look like this deal from the game “Set”



You should only get excited if it looks like this!

Standard model works well

- So if there are no strong tensions or anomalies, what are theorists meant to do?!
- The trick is to wisely pick the 2 to 3σ effects that grow into 5σ effects
- A 6 parameter model continues to fit!
- With only some simple (and testable) assumptions
- We appear to have a fairly precise model for the Universe on the largest scales
- But: Where did the parameters come from?
- Will further precision uncover more parameters?
- Could any of the basic assumptions turn out to be wrong?

Big questions for theorists

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Primordial magnetic fields
Primordial black holes
Modified gravity

Dark Energy Theories

- Quintessence with perturbations
- Rolling scalar field
- Generalized Chaplygin gas
- k-essence
- Cuscuton cosmology
- Tracker fields
- Phantom Energy
- Cardassian Dark Energy
- Interacting Dark Matter-Dark Energy
- DGP brane cosmology
- f(R) gravity
- Gauss-Bonnet gravity
- Scalar-tensor theories
- Tensor-Vector-Scalar theory
- Lorentz-violating Dark Energy
- Tolman-Bondi cosmology
- Back-reaction effects
- Elastic Dark Energy
- Holographic Dark Energy
- Natural Dark Energy
- Dark monodromies
- Vacuum energy
- Dark fluid
- Effective Field Theory
- Horndeski models
- Post-Friedman parameterization
- Massive gravity
- Vainshtein screening
- Chameleon models
- Galileo theory
- Multi-metric gravity
- K-mouflage
- Teleparallel Dark Energy
- Warped brane-worlds
- Pilgrim Dark Energy
- Machine strings
- Condensate-induced Dark Energy
- 3-form Dark Energy
- Ricci Dark Energy
- Einstein-Cartan torsion
- Tachyon Dark Energy
- Quintom Dark Energy
- Emergent gravity
- Cosmological constant

Good Dark Energy Theories

Big questions for theorists

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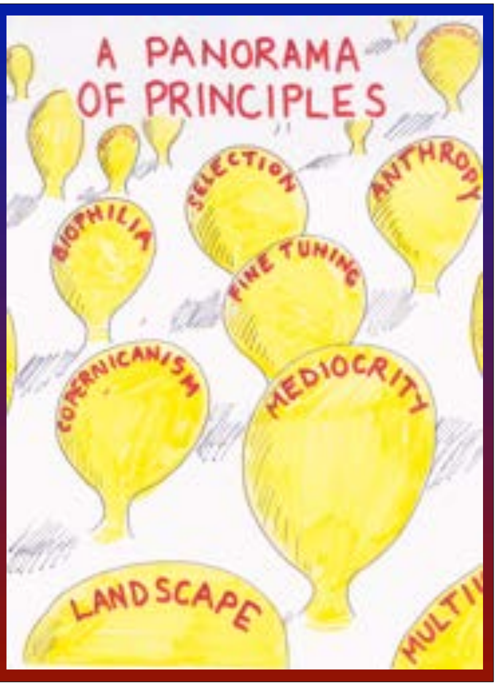
- Predict something new: non-Gauss., isocurvature, defects, PMFs, PBHs, MG ?

Either the best time or worst time to be a theorist in cosmology!

Are some parameters stochastic?

(Did someone say the "A" word?)



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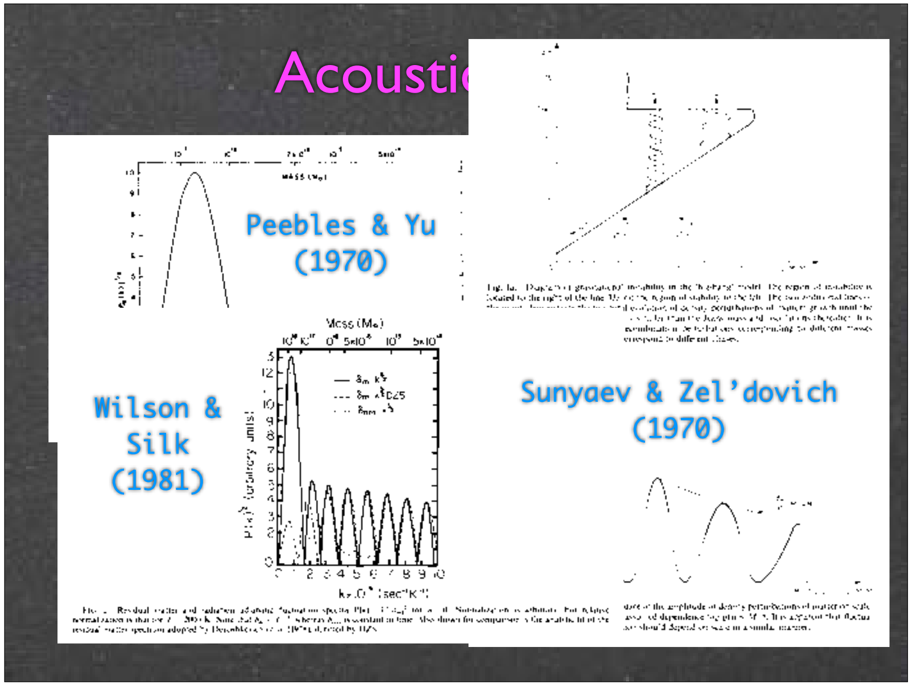
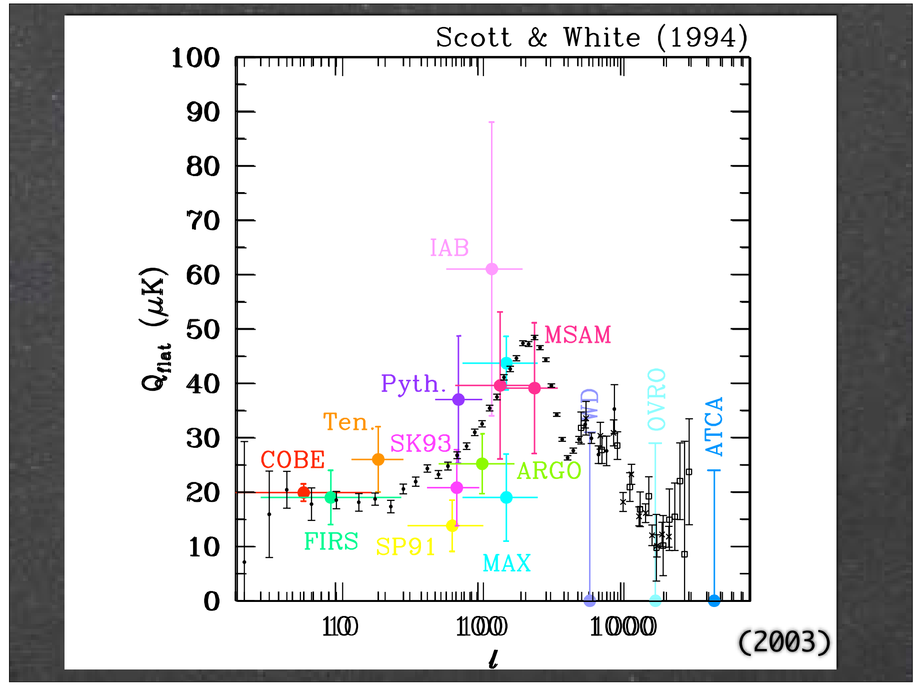
SMC Predictions

	Confirmation
CMB Acoustic Peaks	1994
Acceleration	1998
Cosmic Shear	2000
Cosmic Jerk	2001
CMB Polarization	2002
Baryon Acoustic Oscillations	2003
CMB(ISW)-LSS Correlation	2005
CMB-lensing Correlations	2007

+ SZ power, CMB lensing convergence, ...


Acousti
Peebles & Yu
(1970)
Wilson &
Silk
(1981)
Sunyaev & Zel'dovich
(1970)


Scott & White (1994)
(2003)
IAB
MSAM
Pyth.
Ten.
SK93
COBE
ARGO
FIRS
SP91
MAX
OVRO
ATCA


BEYOND
The Standard Model of Cosmology