What do we know about the Universe?

Douglas Scott

September 2016

What do we know about the Universe?

→ The Standard Model of Cosmology (SMC)

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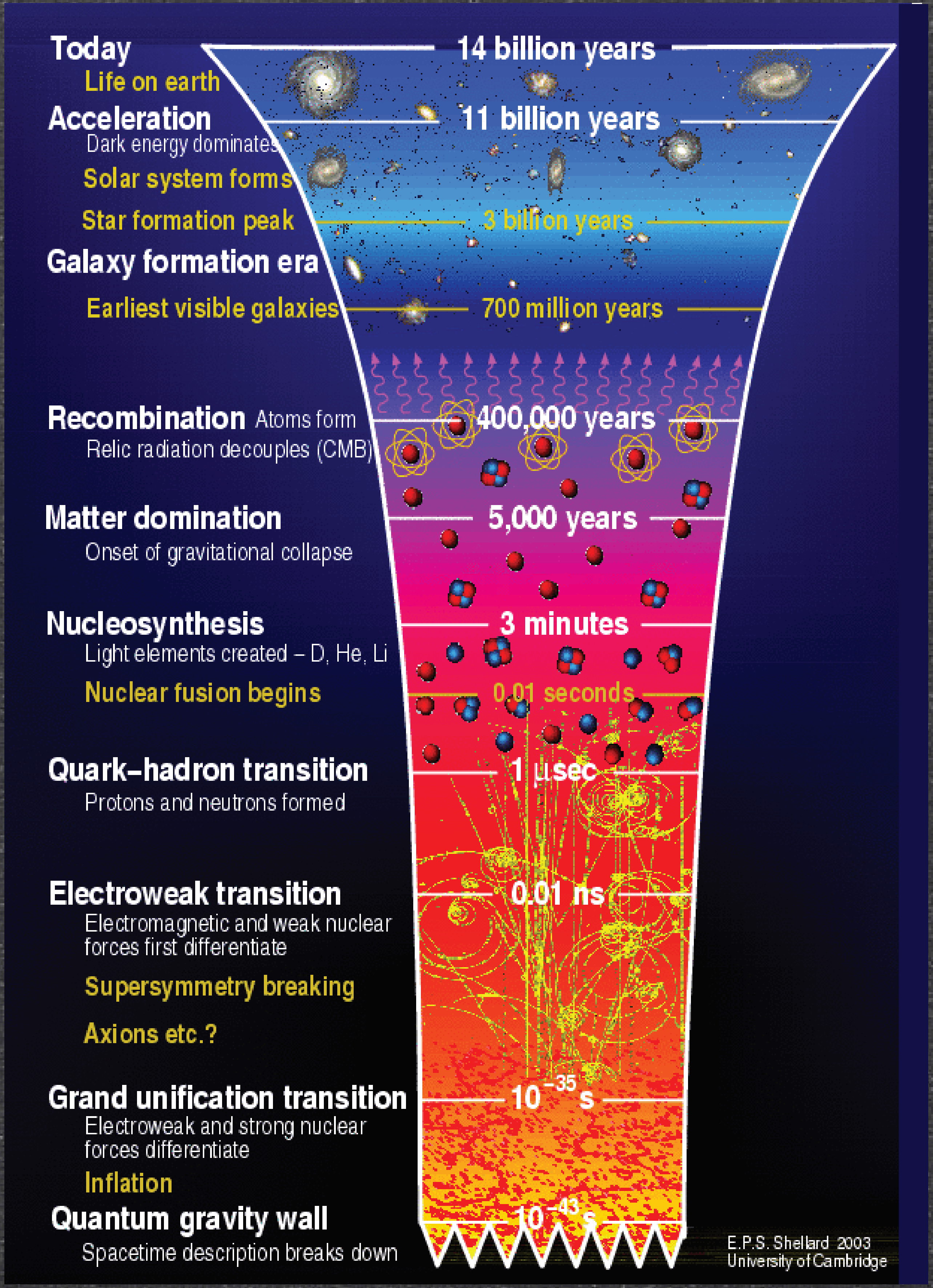
UBC

Basic picture of SMC

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

a.k.a. ΛCDM



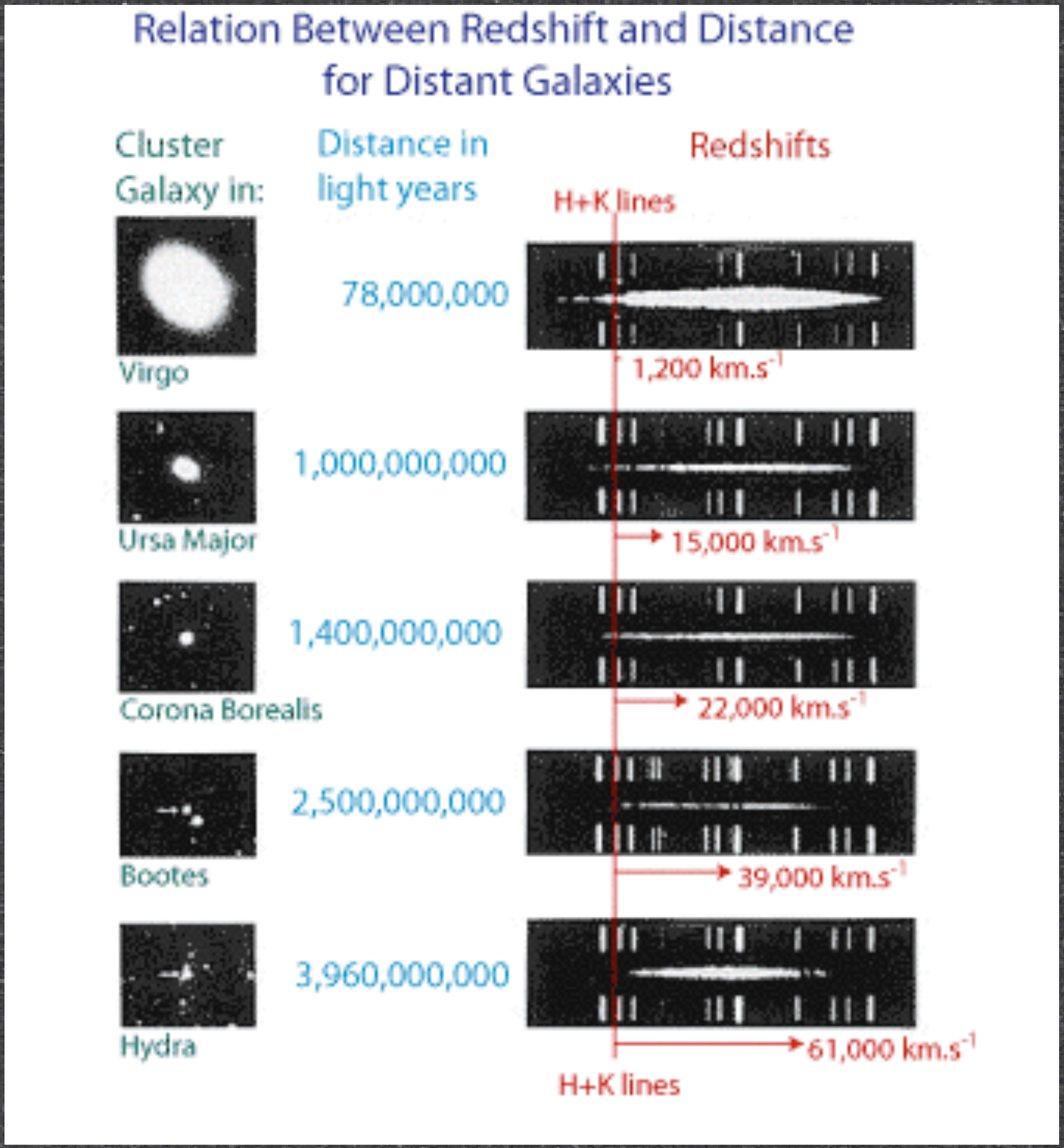
Assumptions underlying the SMC	
1	Physics is the same throughout the observable Universe.
2	General Relativity is an adequate description of gravity.
3	On large scales the Universe is statistically the same everywhere.
4	The Universe was once much hotter and denser and has been expanding.
5	There are 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!

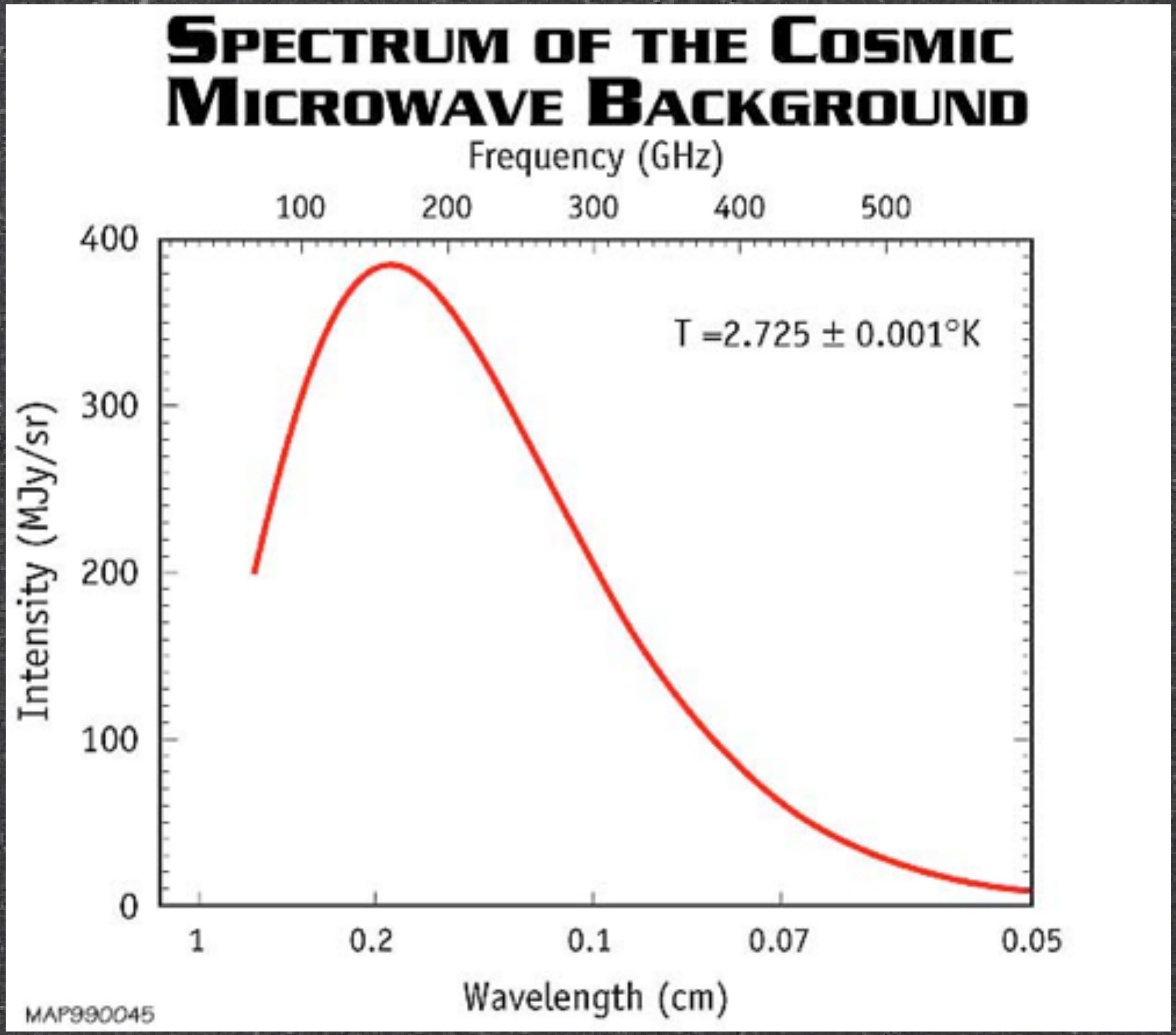
Underpinnings of SMC

Canonical hot big bang model
+ information about fluid components
+ perturbations

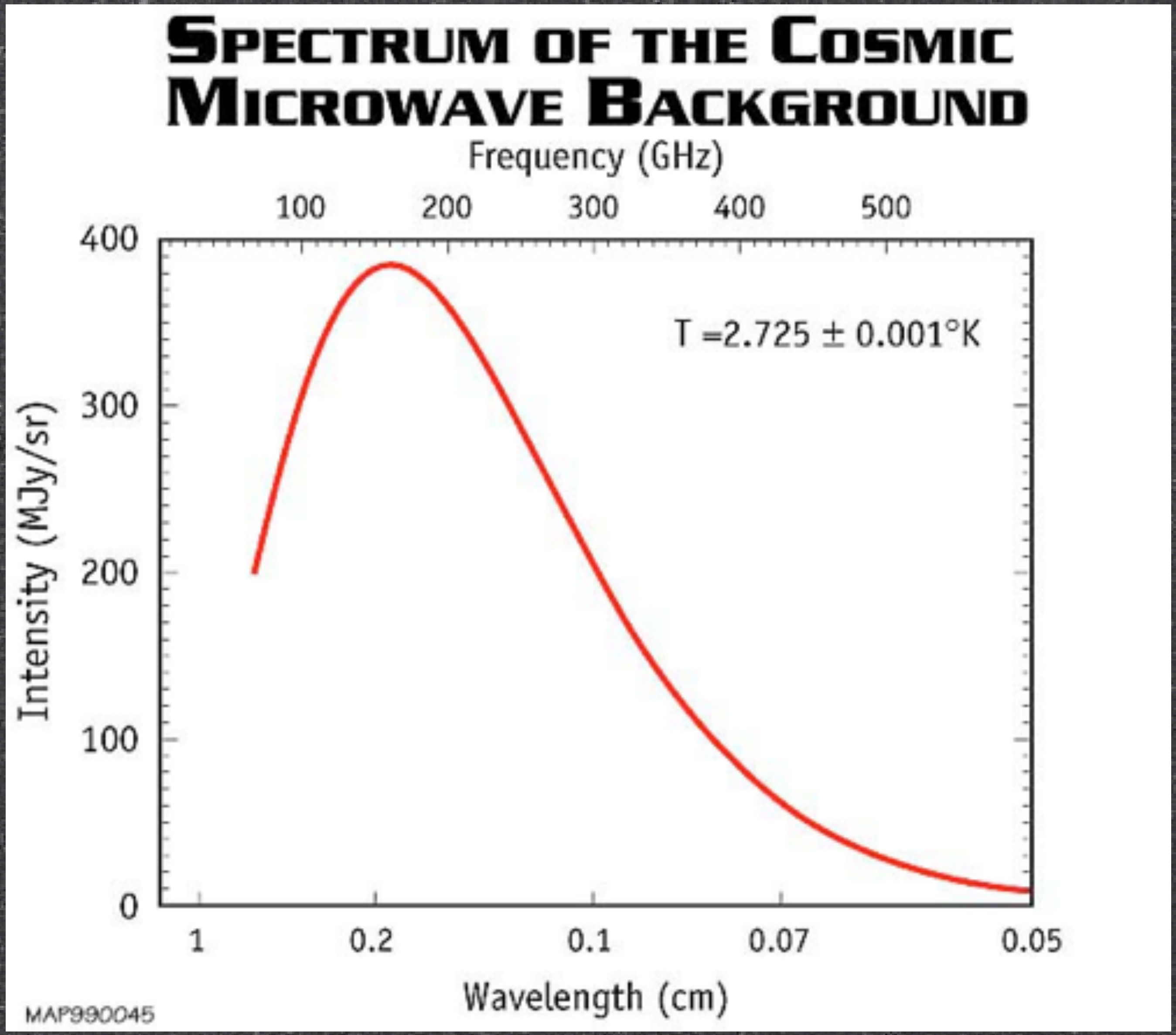
History?



Expansion 1920s



Cosmic Microwave Background 1960s



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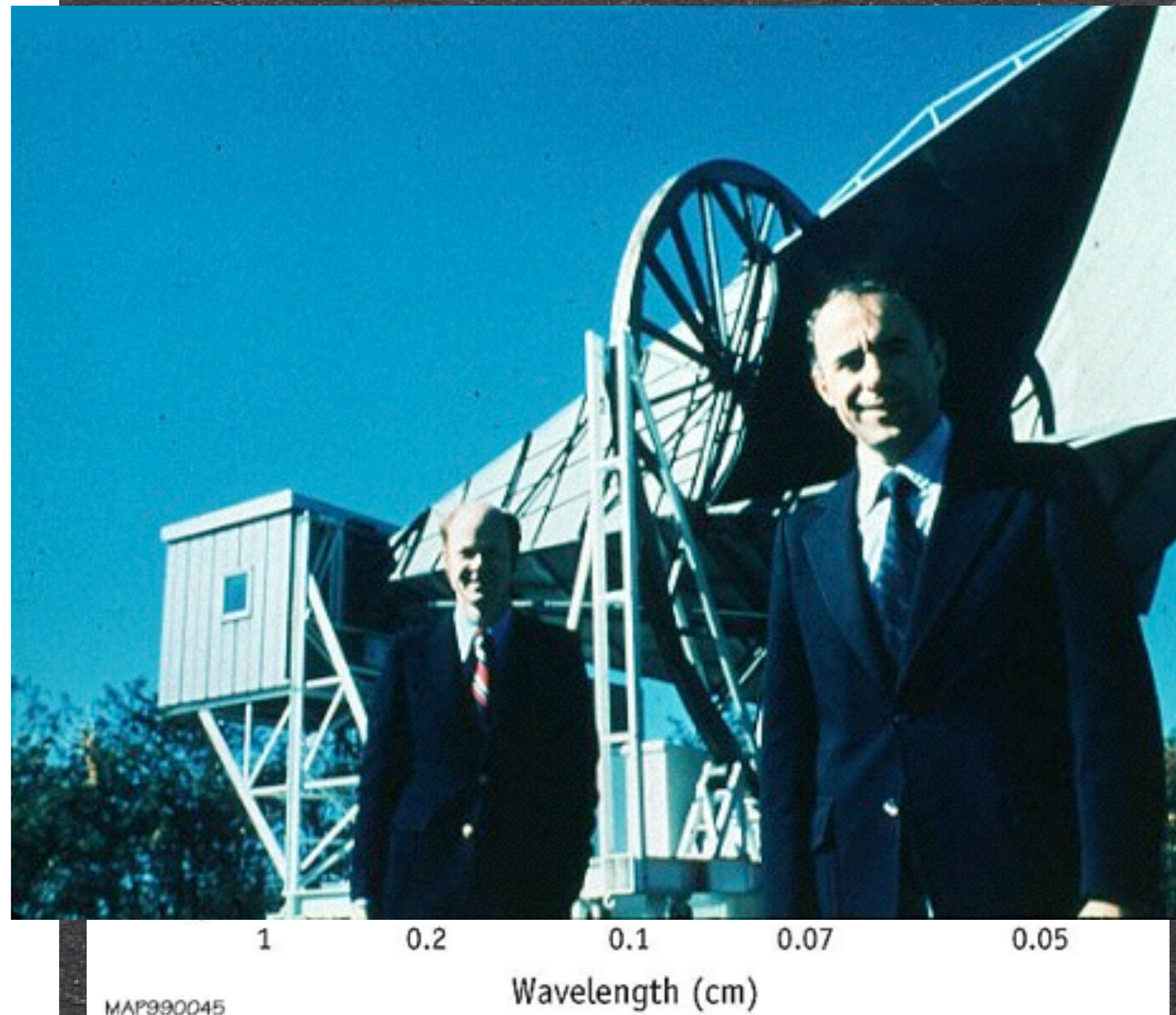

Cosmic Microwave Background 1960s

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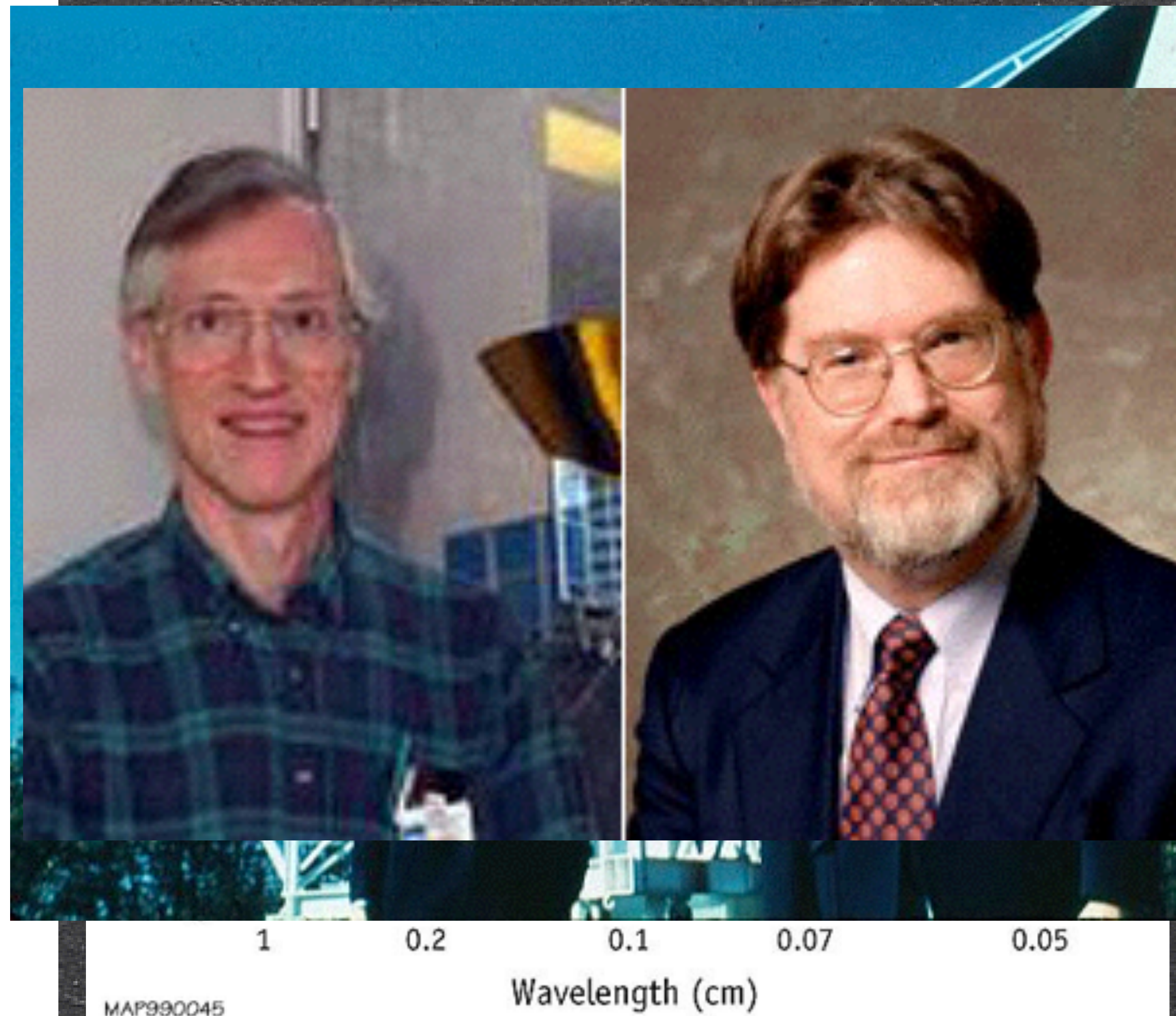


Cosmic Microwave Background 1960s

BBN 1960s to 80s

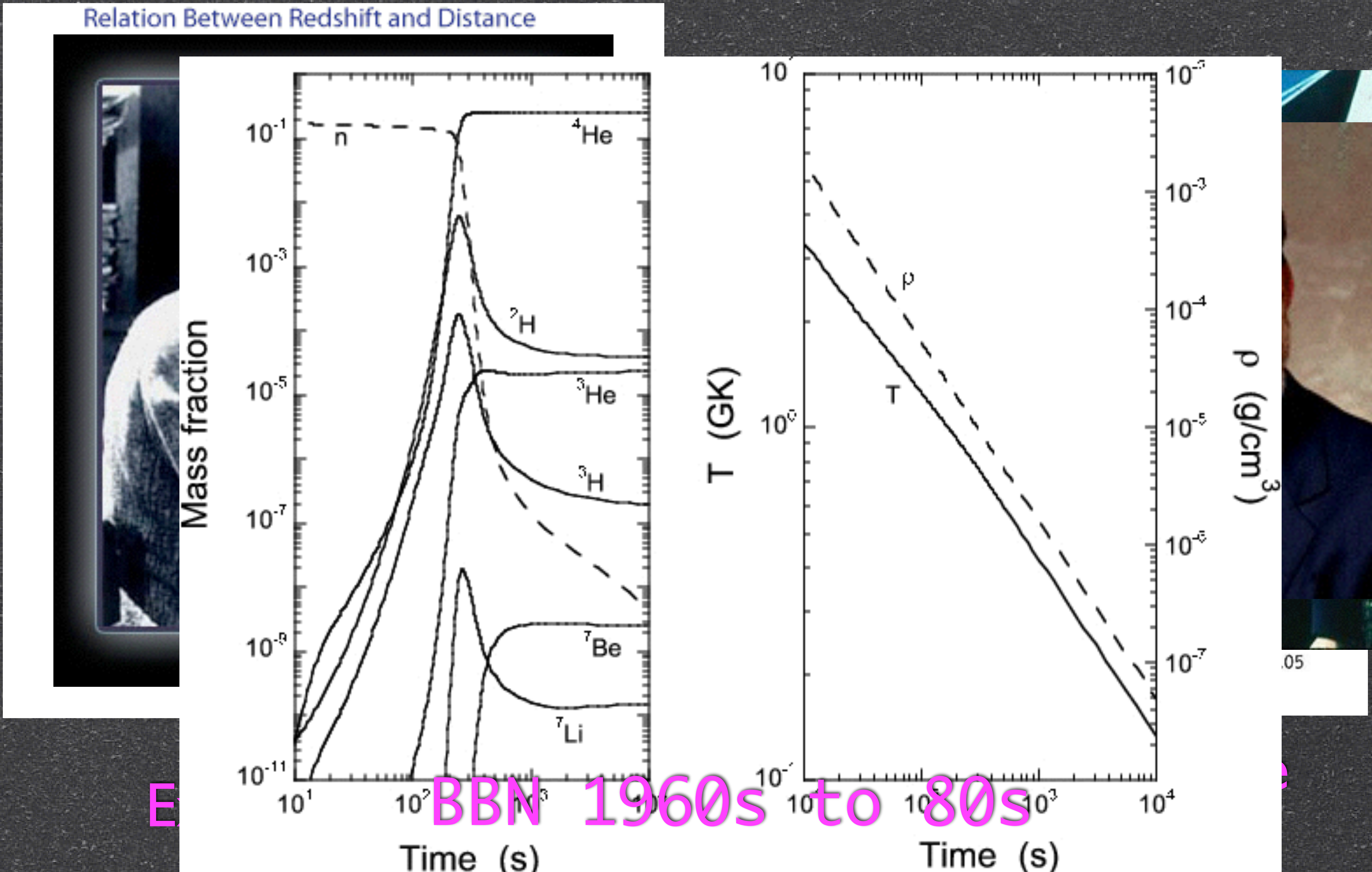


Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

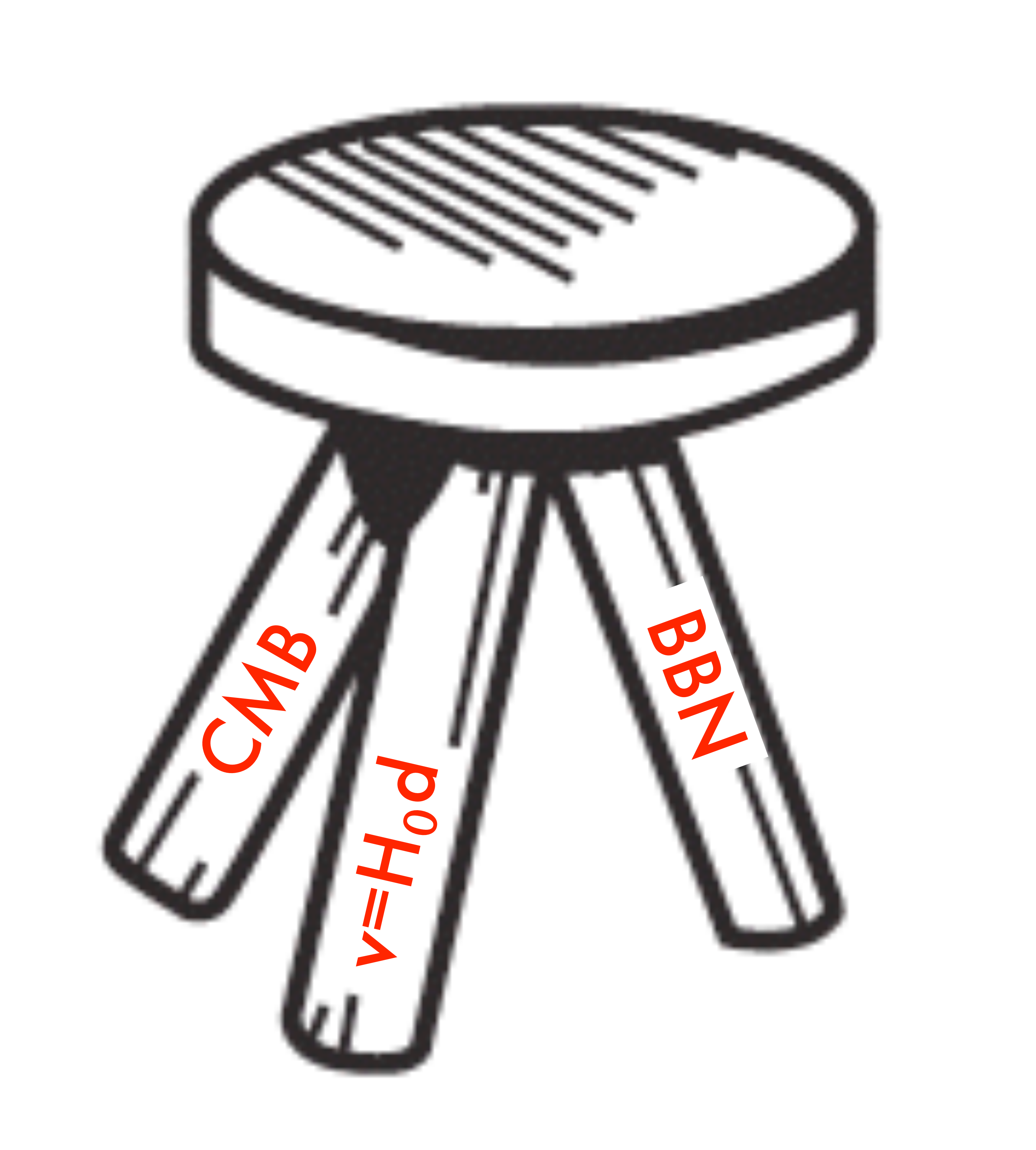
Photo: Belinda Pratten, Australian National University

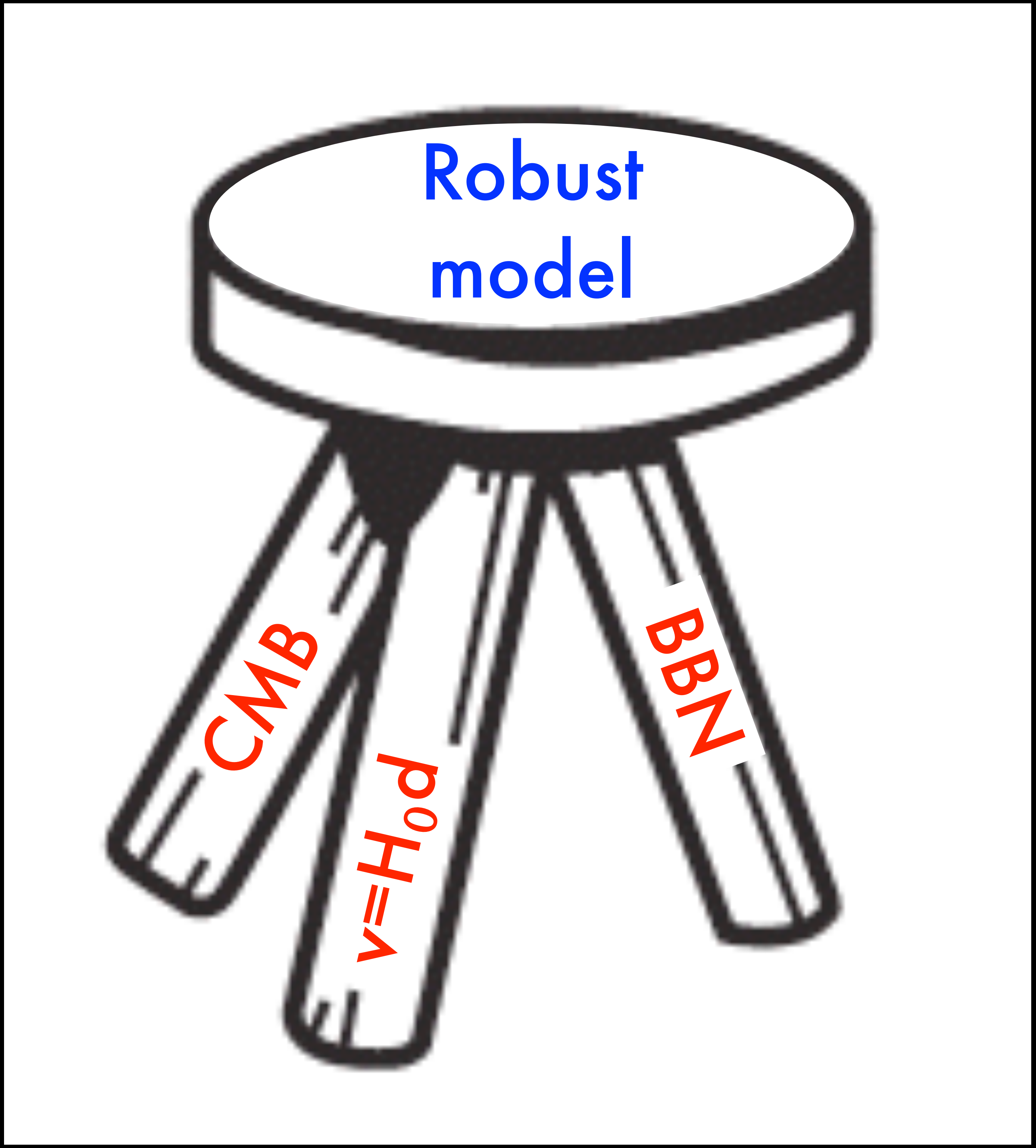
Brian P. Schmidt

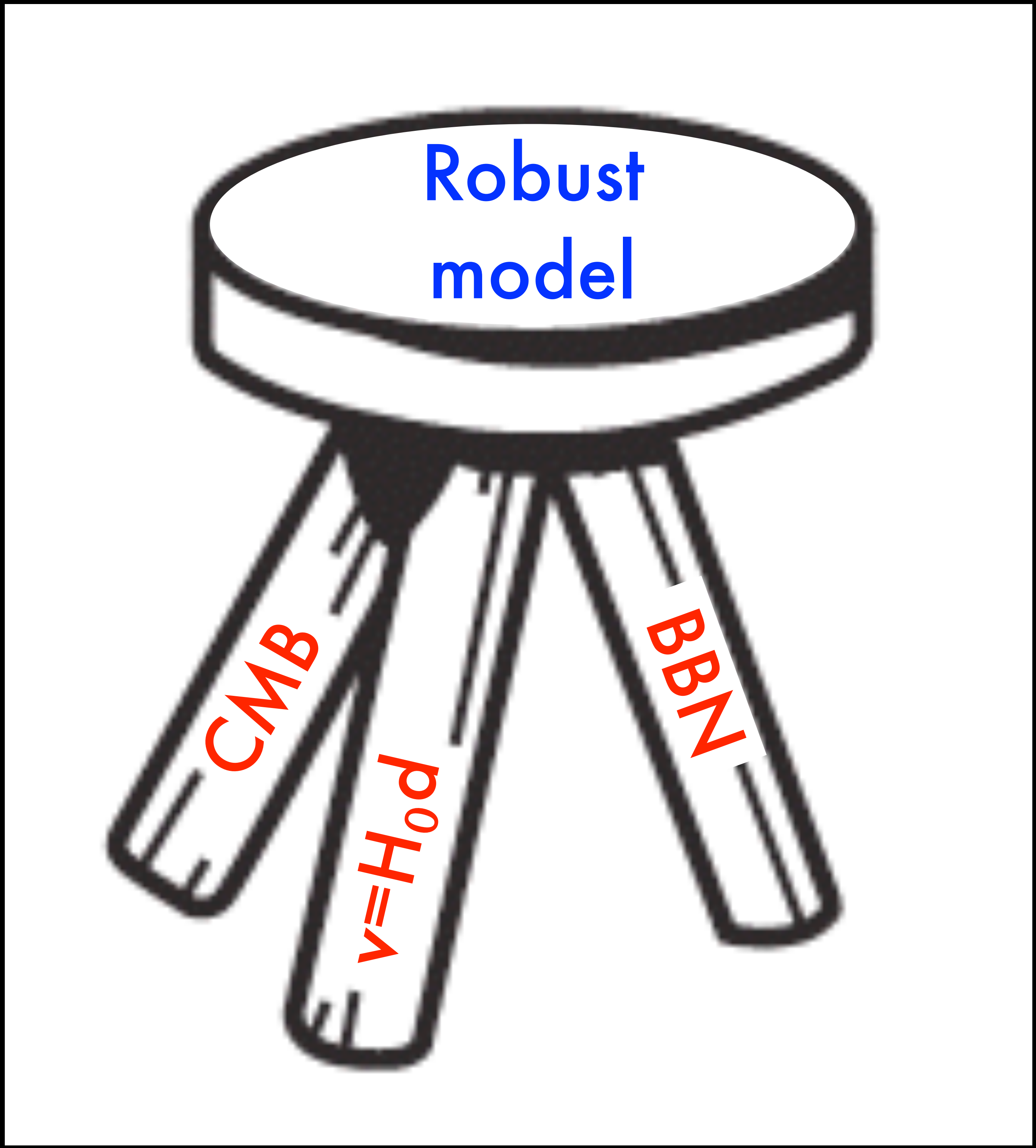
Photo: Homewood Photography

Adam G. Riess

Acceleration late 1990s


CMB
v=H₀d
BBN


Robust
model
CMB
$v=H_0d$
BBN



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

The Big Bang Theory

The Big Bang Theory

So well established it has its own TV show

The Big Bang Theory

The Big Bang Theory

★ What kind of Big Bang model do we live in?

The Big Bang Theory

- ★ What kind of Big Bang model do we live in?
- ★ How many parameters do we need?

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★ Why do the parameters have these values?

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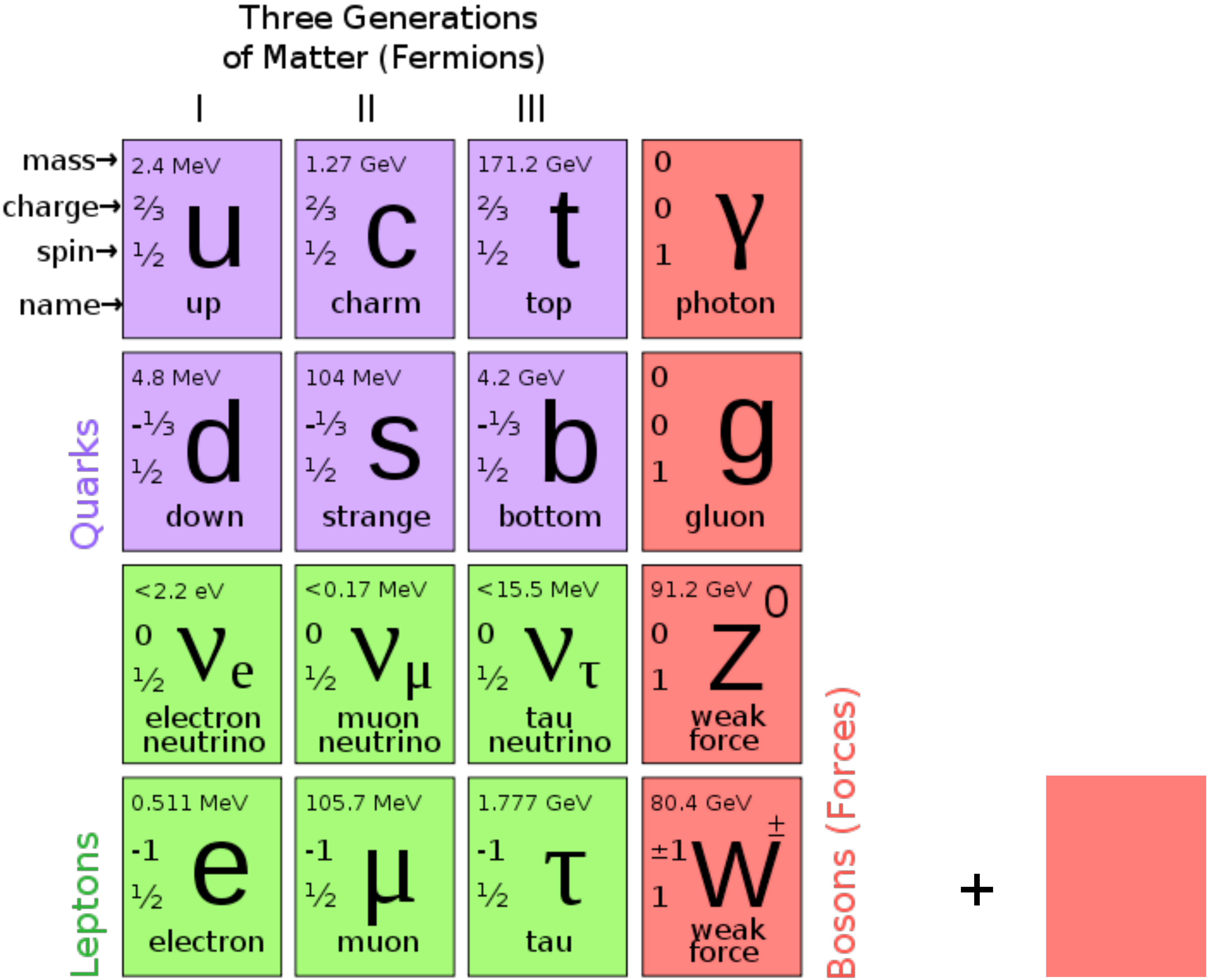
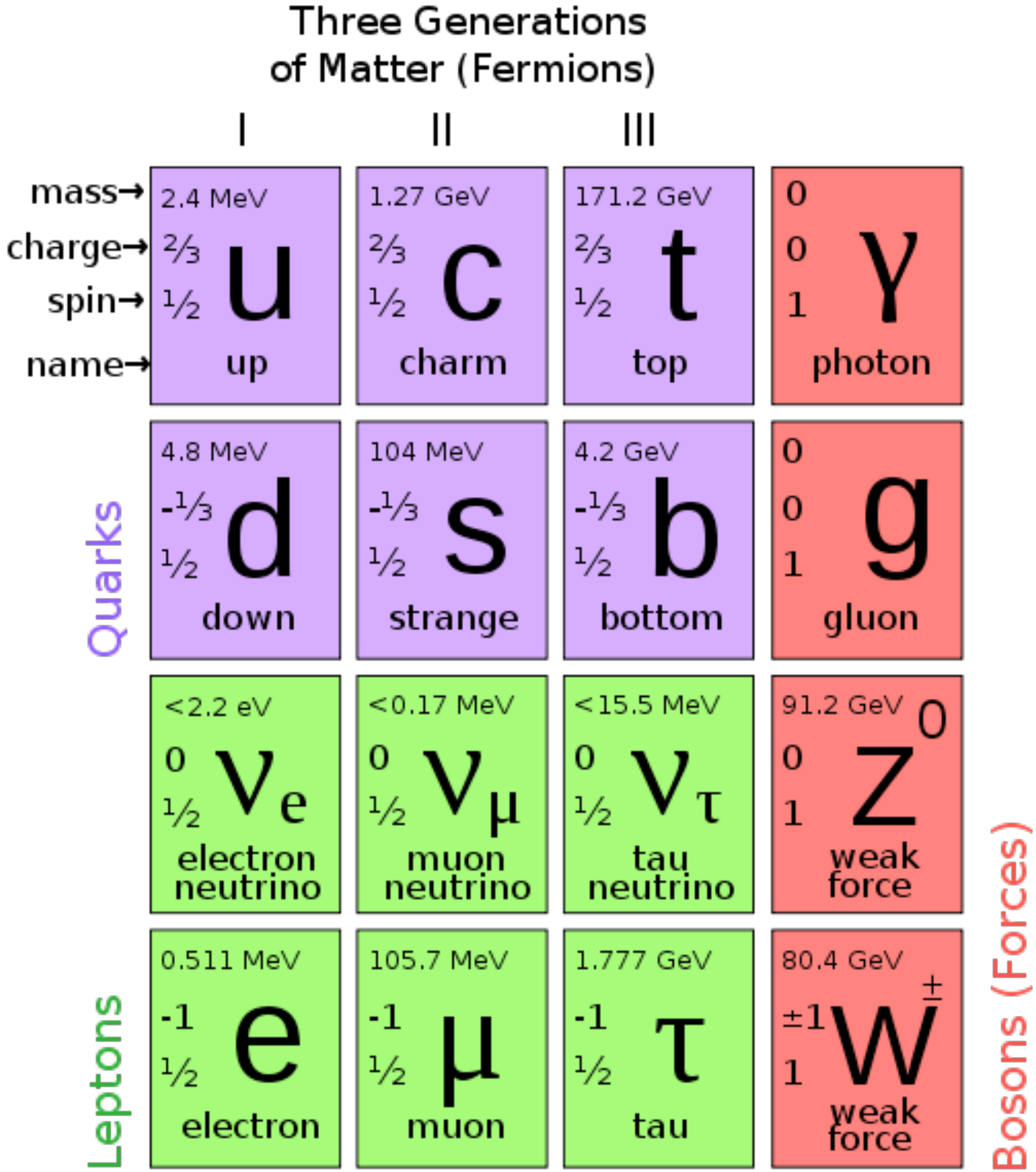
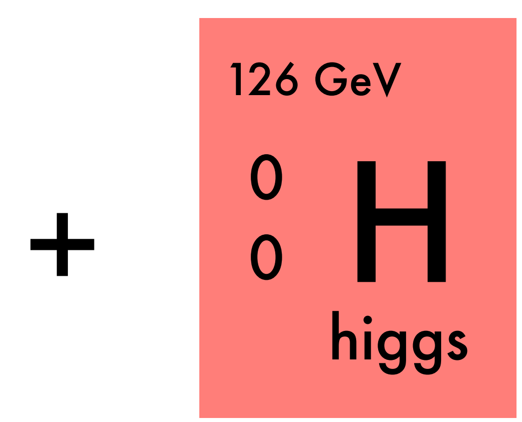
- ★ Is there evidence for new physics?

- ★ What about the other Standard Model?

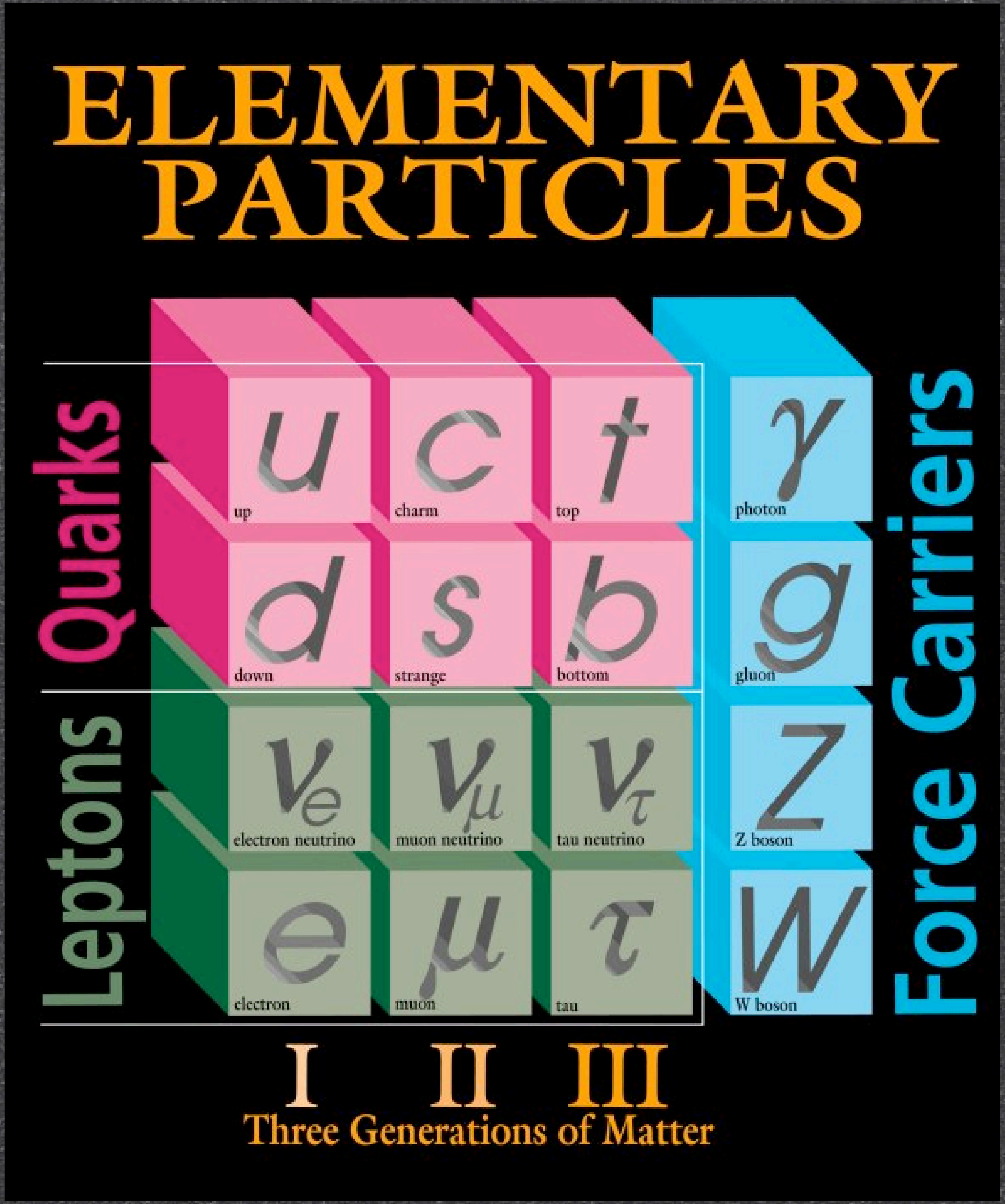

Three Generations
of Matter (Fermions)
I
II
III
mass→
charge→
spin→
name→
2.4 MeV
⅔
½
u
up
1.27 GeV
⅔
½
c
charm
171.2 GeV
⅔
½
t
top
0
0
1
γ
photon
4.8 MeV
-⅓
½
d
down
104 MeV
-⅓
½
s
strange
4.2 GeV
-⅓
½
b
bottom
0
0
1
g
gluon
<2.2 eV
0
½
νe
electron neutrino
<0.17 MeV
0
½
νμ
muon neutrino
<15.5 MeV
0
½
ντ
tau neutrino
91.2 GeV
0
1
Z0
weak force
0.511 MeV
-1
½
e
electron
105.7 MeV
-1
½
μ
muon
1.777 GeV
-1
½
τ
tau
80.4 GeV
±1
1
W±
weak force
Quarks
Leptons
Bosons (Forces)
+



The Standard Model of Particle Physics



THE Standard Model (of Particle Physics) → SMPP



Theory of Almost Everything!

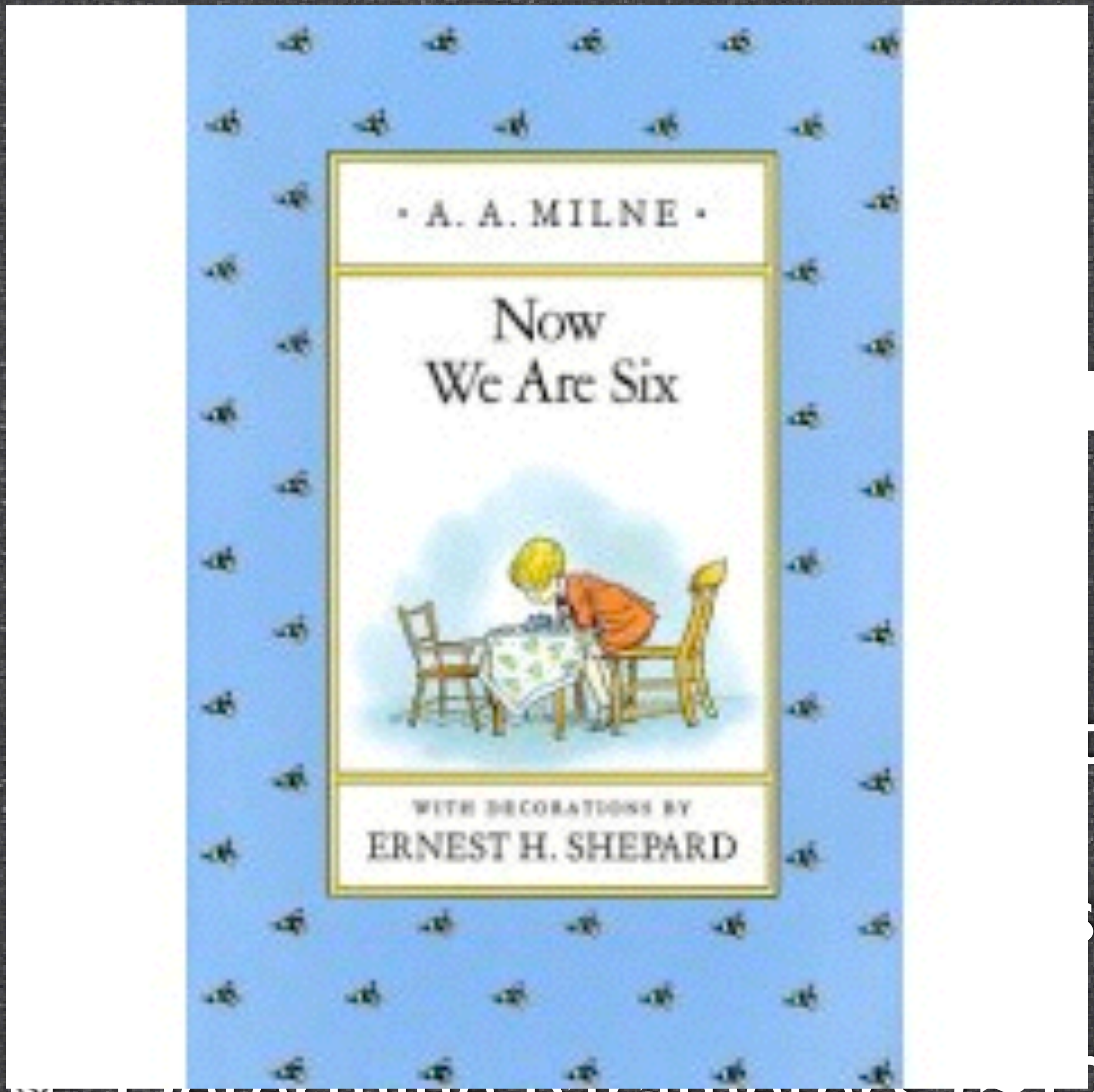
QFT

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

The Standard Model of Cosmology

- Isotropic, homogeneous, expanding (FRW)
- Spatially flat
- Dark Energy and Dark Matter dominated
- Adiabatic, Gaussian, nearly scale-invariant initial perturbations
- Determine parameters (~12 in all)

The Standard Model of Cosmology



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- ter dominated
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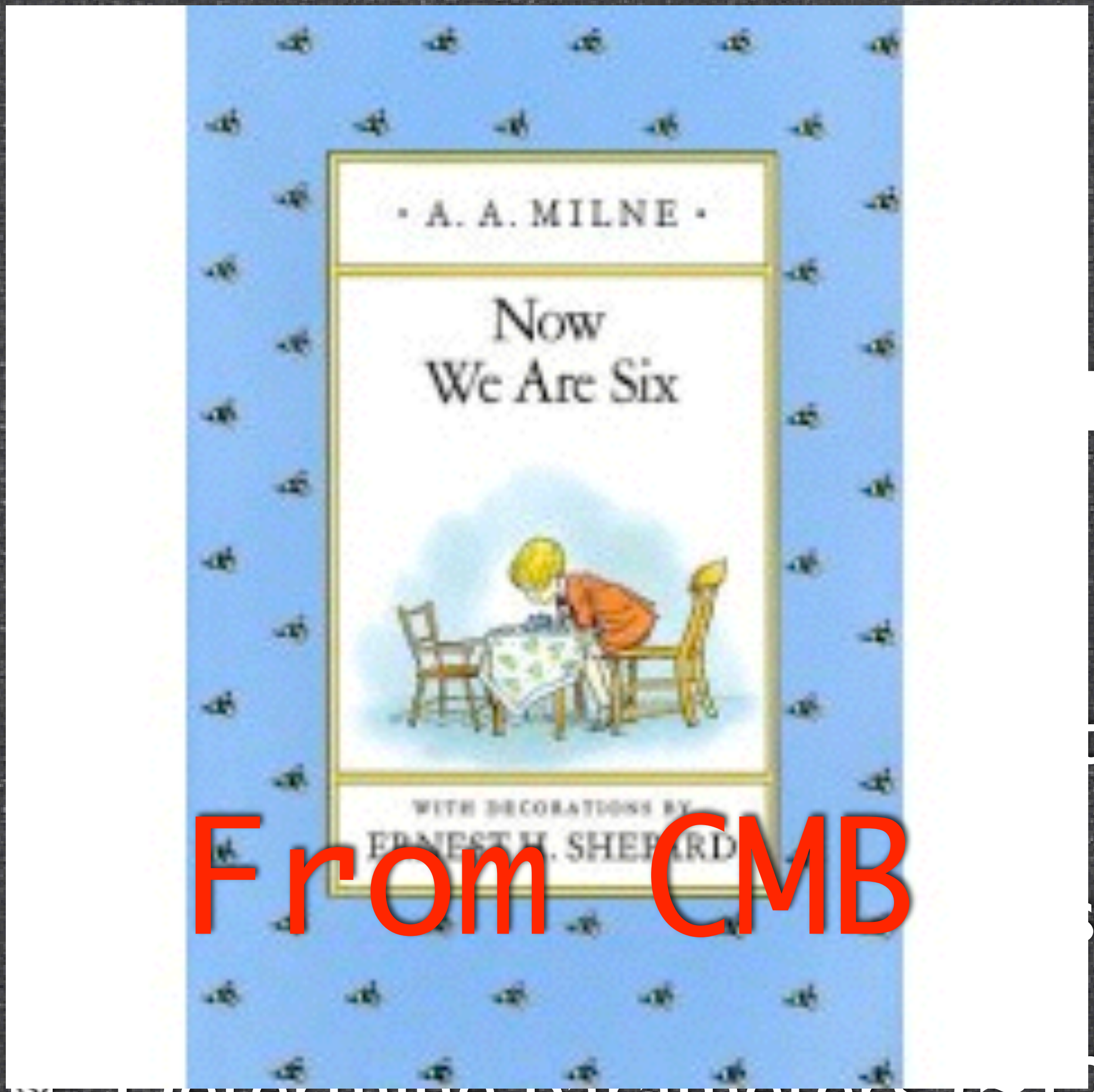
The Standard Model of Cosmology



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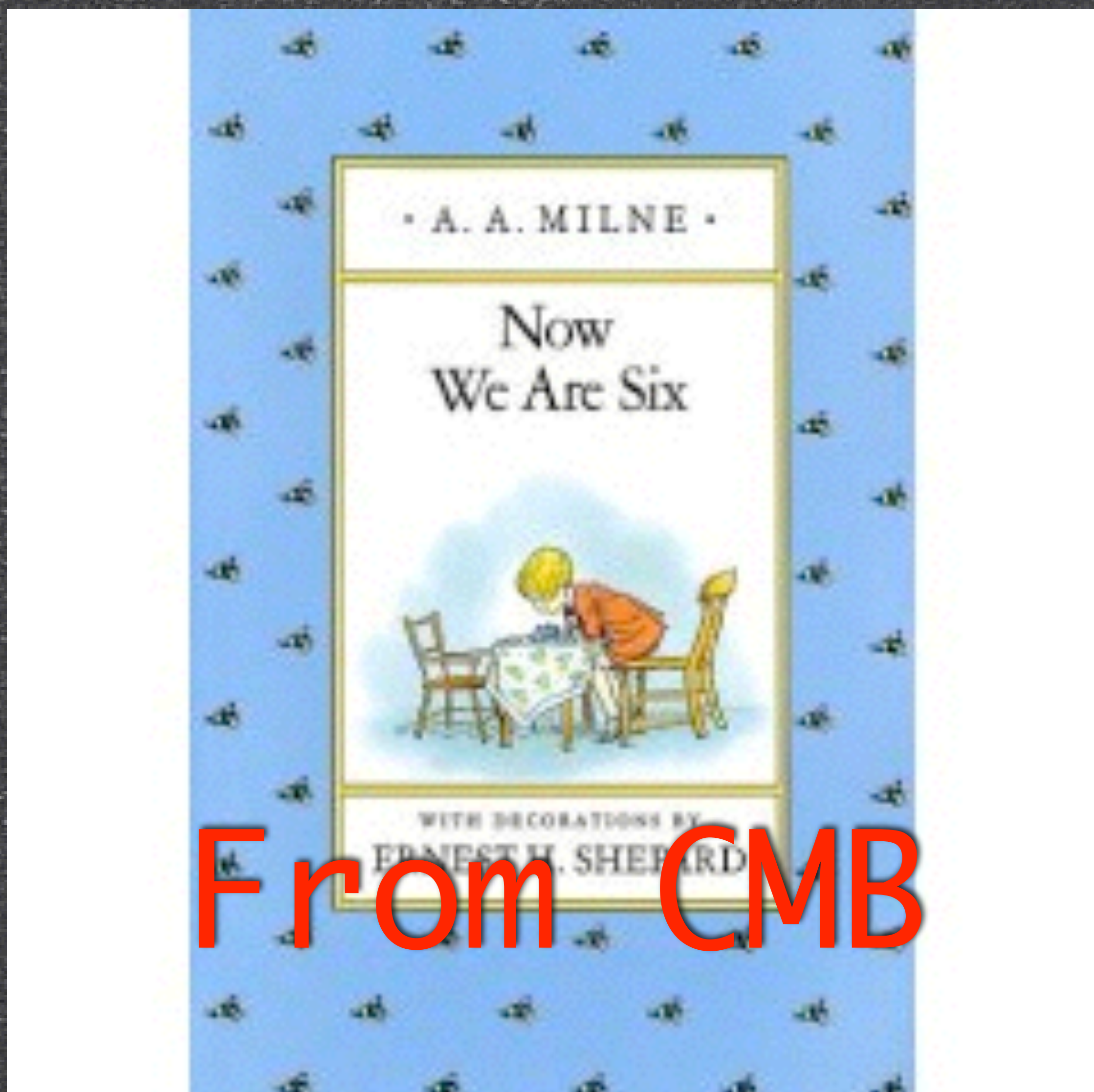
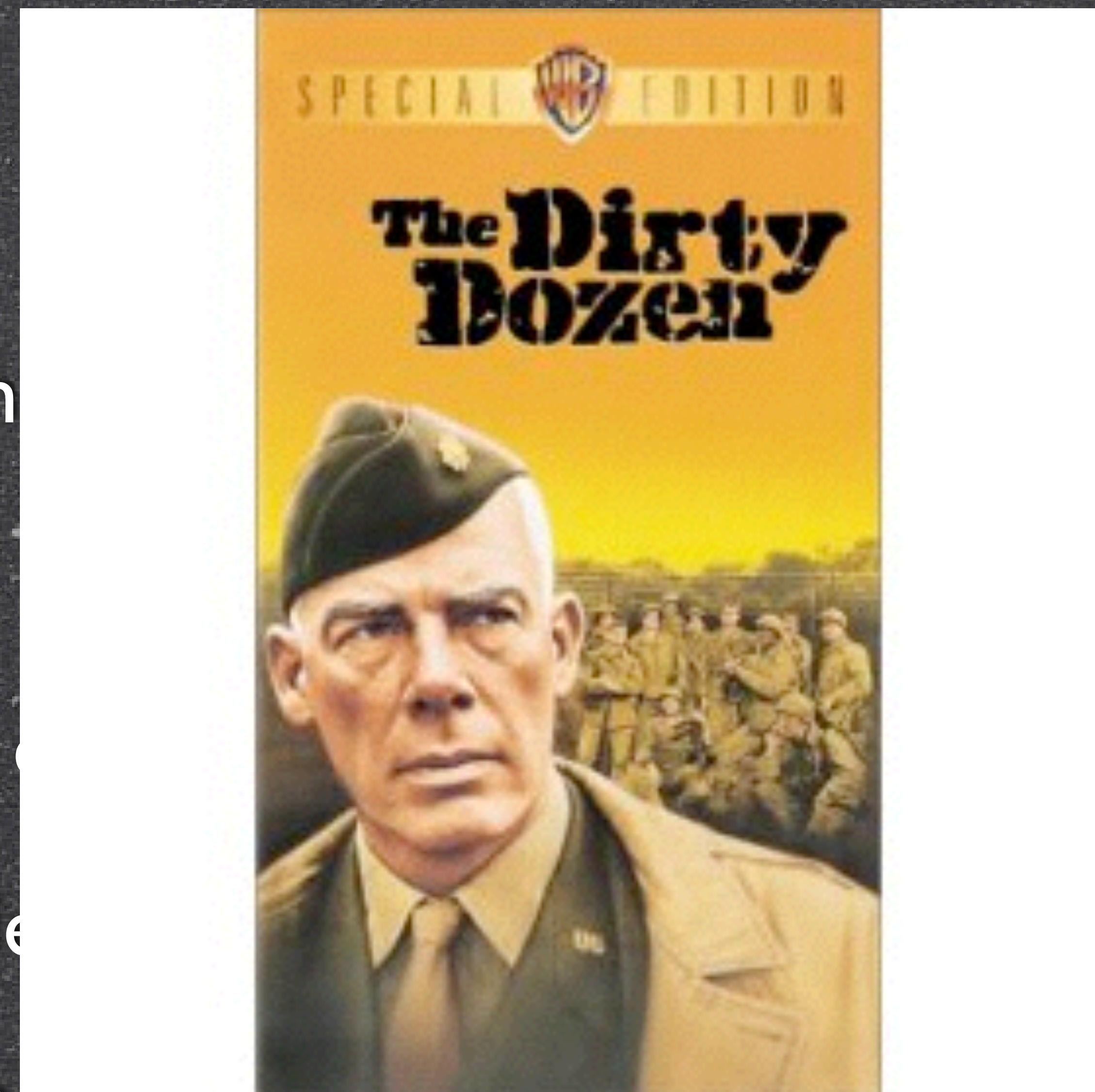
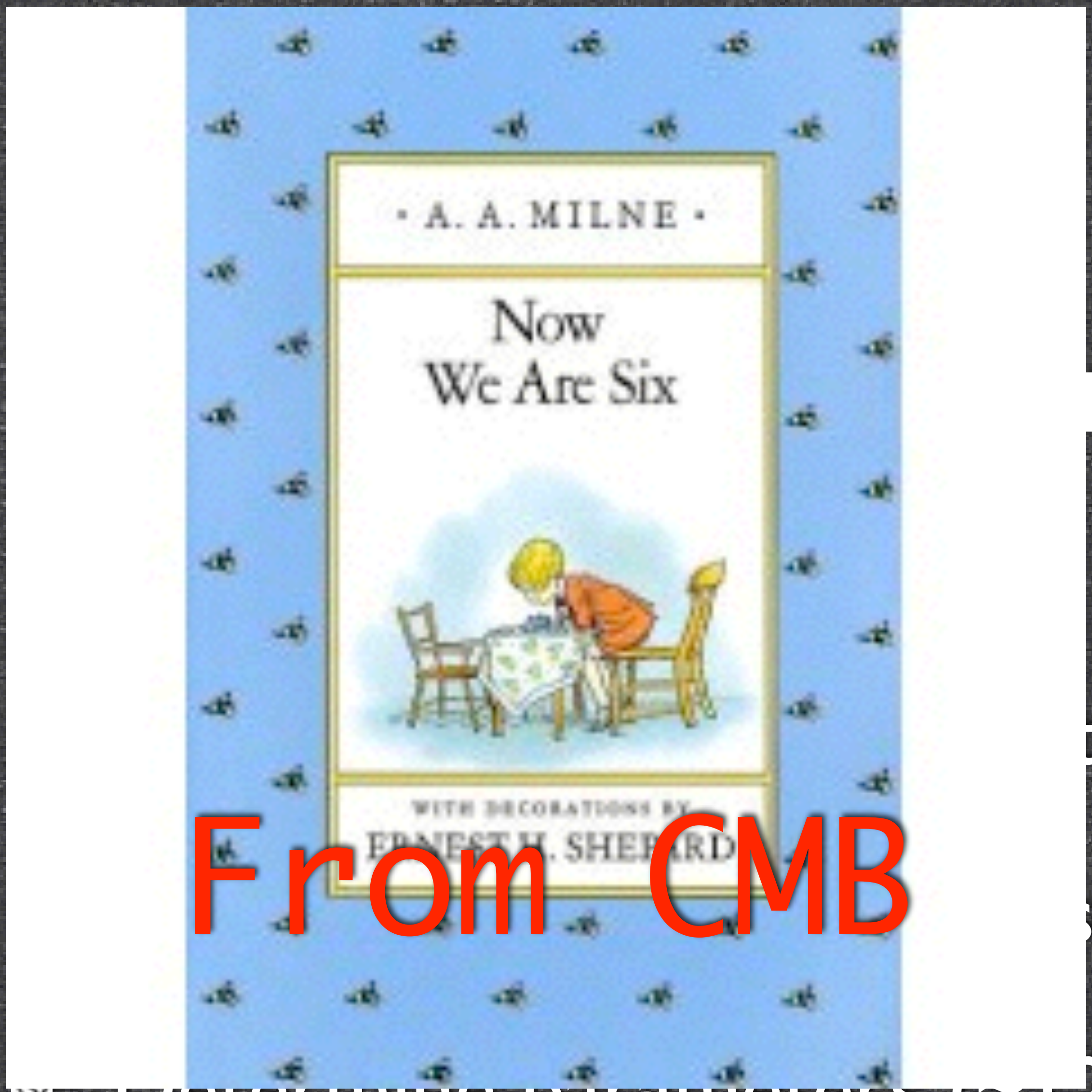
The Standard Model of Cosmology

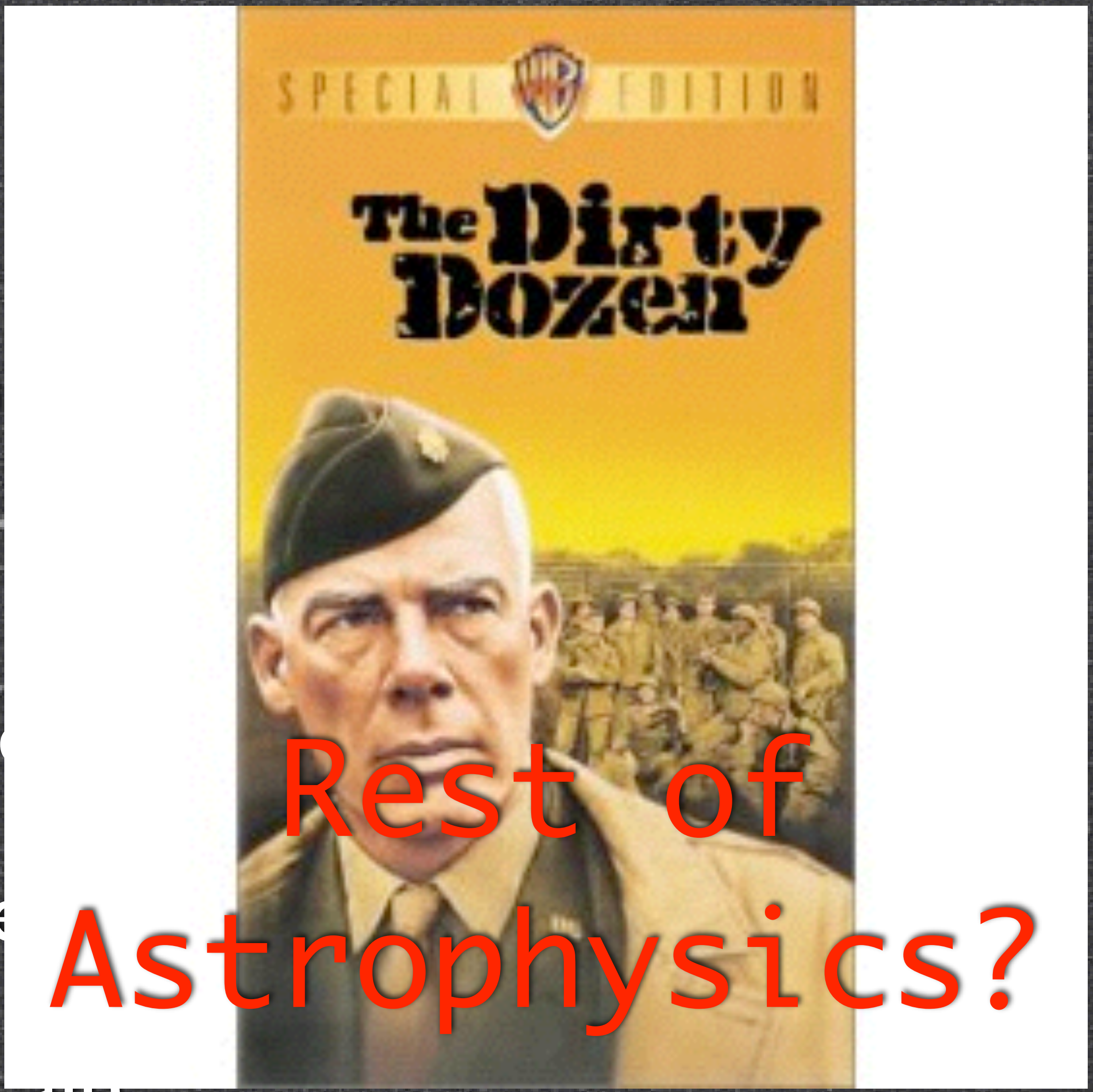




- ☑ Determine parameters (~12 in all)

The Standard Model of Cosmology





- Determine parameters (~12 in all)

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:	$\alpha_{\mathrm{S}}(M_Z)$					
26 total parameters						

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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

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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	$\Omega_{\rm CDM}$	$\Omega_{\rm B}$	Ω_ν
1 pressure:	$w \equiv p/\rho$			
1 mean free path:	$\tau_{\rm reion}$			
4 fluctuation descriptors:	A	n	$n' \equiv dn/d\ln k$	$r \equiv T/S$
12 total parameters				

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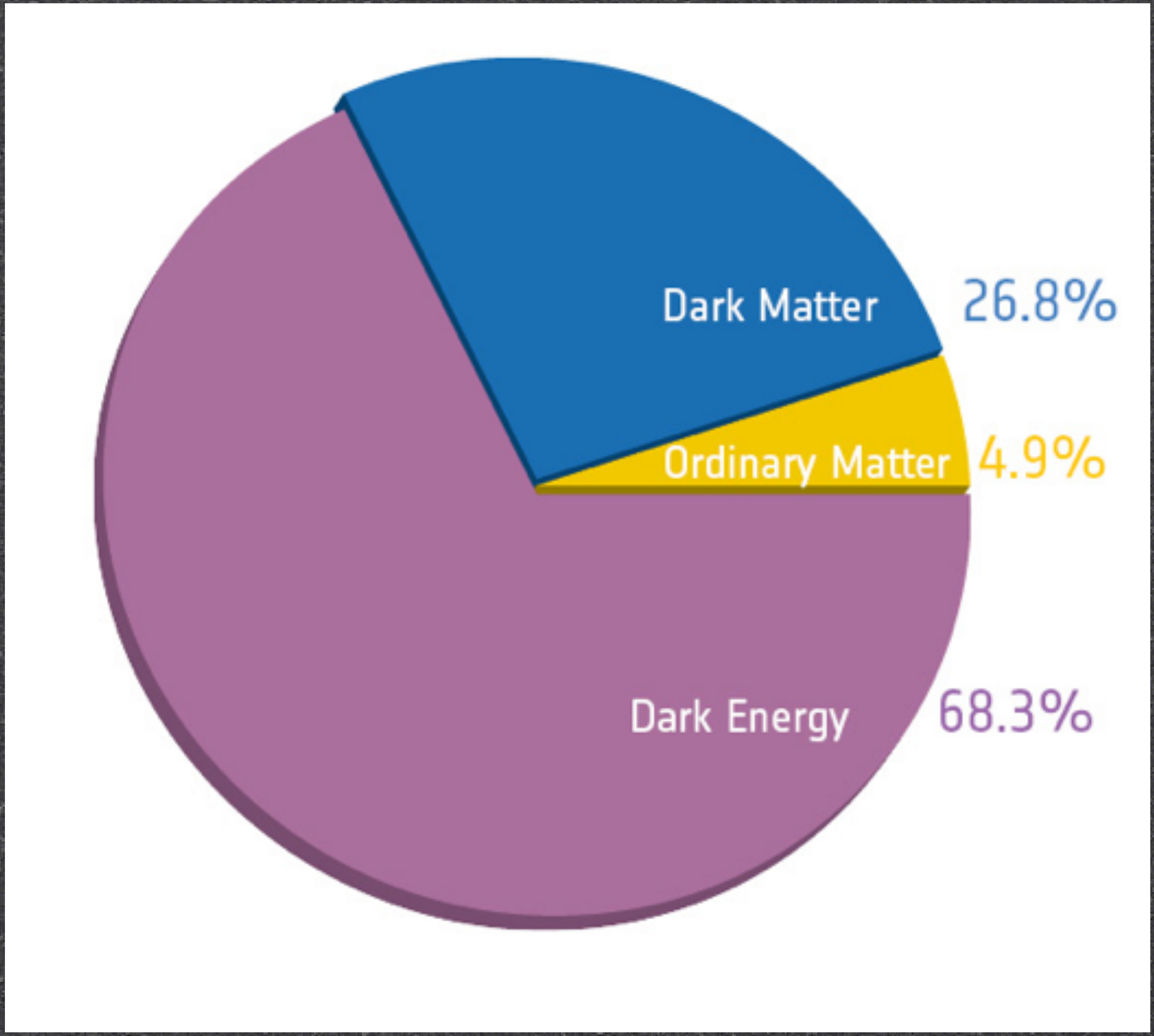
A, E, H, I, K,
L, M, N, O, P,
U, W

COSMIC CENSUS

DE≈68%
DM≈27%
B≈5%
ν≈0.1%
γ≈0.05%
GW≈0%

Σ=100%



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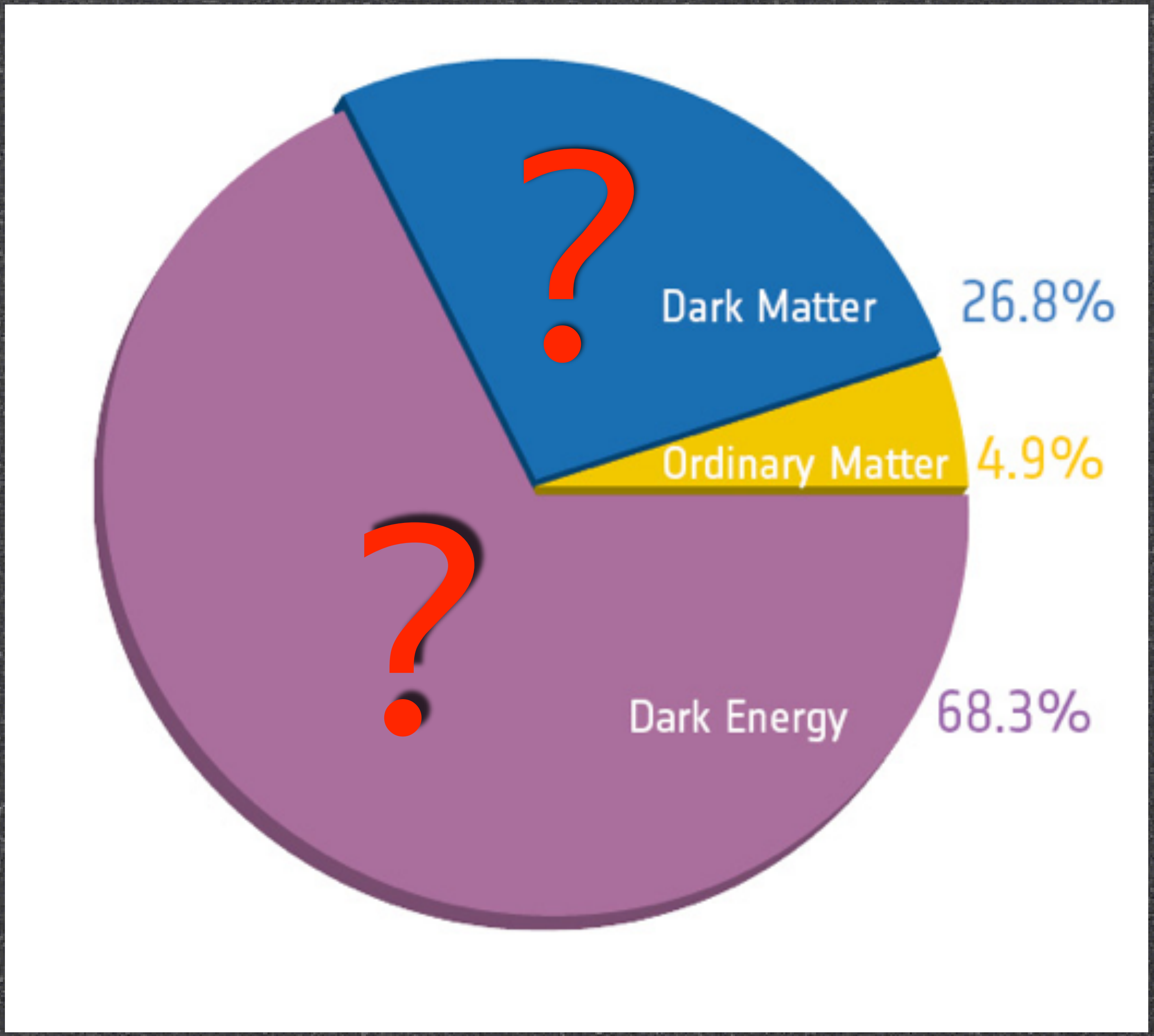
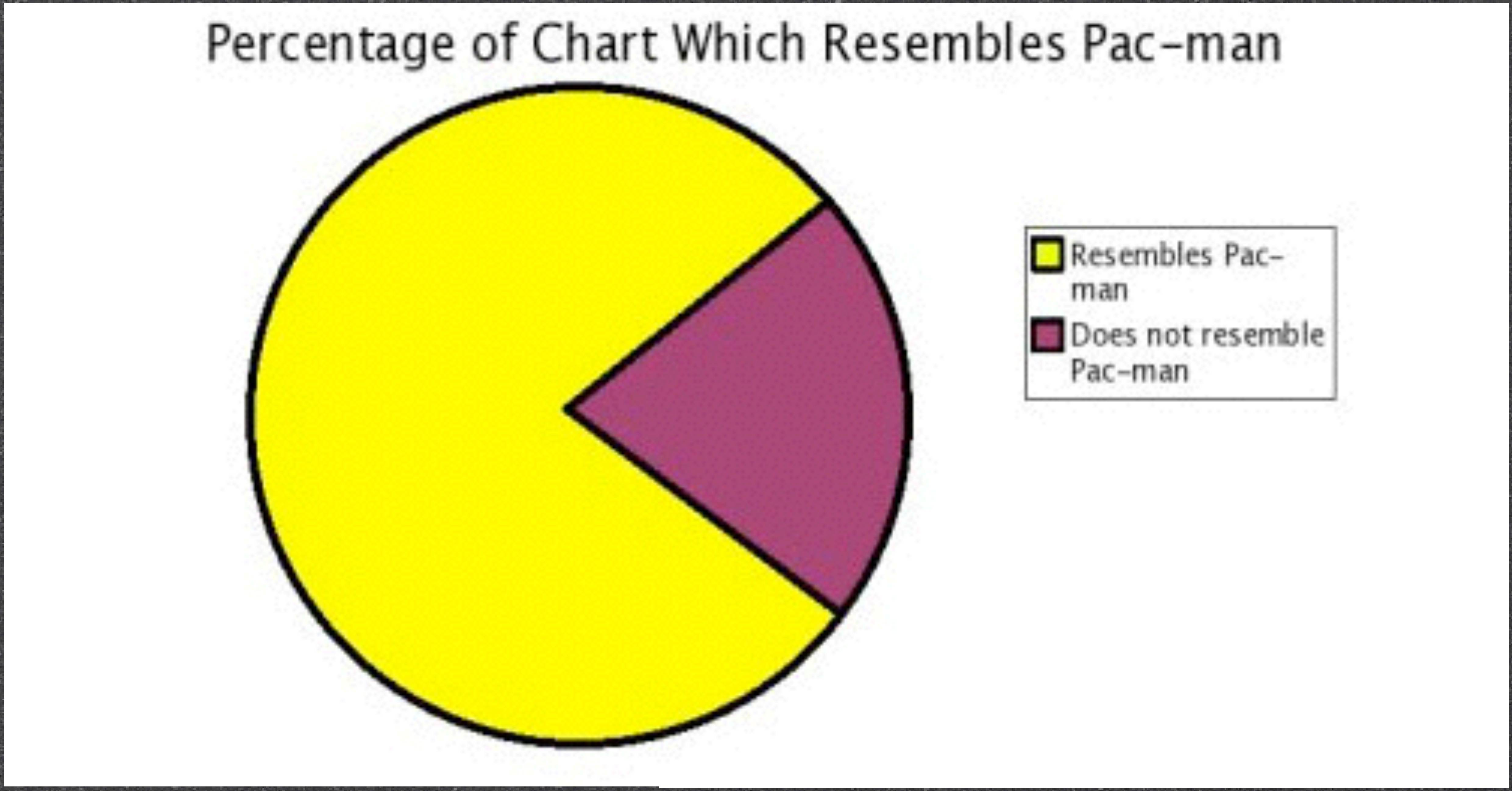


Least informative pie-chart

COSMIC CENSUS



Funniest pie-chart

Vintage of the SMC?

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

THE COSMOLOGICAL CONSTANT IS BACK

Lawrence M. Krauss[1] and Michael S. Turner[2,3]

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Cleveland, OH 44106-7079

[2]*Departments of Physics and of Astronomy & Astrophysics*
Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637-1433

[3]*NASA/Fermilab Astrophysics Center*
Fermi National Accelerator Laboratory, Batavia, IL 60510-0500

(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.

COSMIC CONCORDANCE

J. P. Ostriker

Department of Astrophysical Sciences

Princeton University

Princeton, N.J. 08544 USA

Paul J. Steinhardt

Department of Physics and Astronomy

University of Pennsylvania

Philadelphia, Pennsylvania 19104 USA

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?

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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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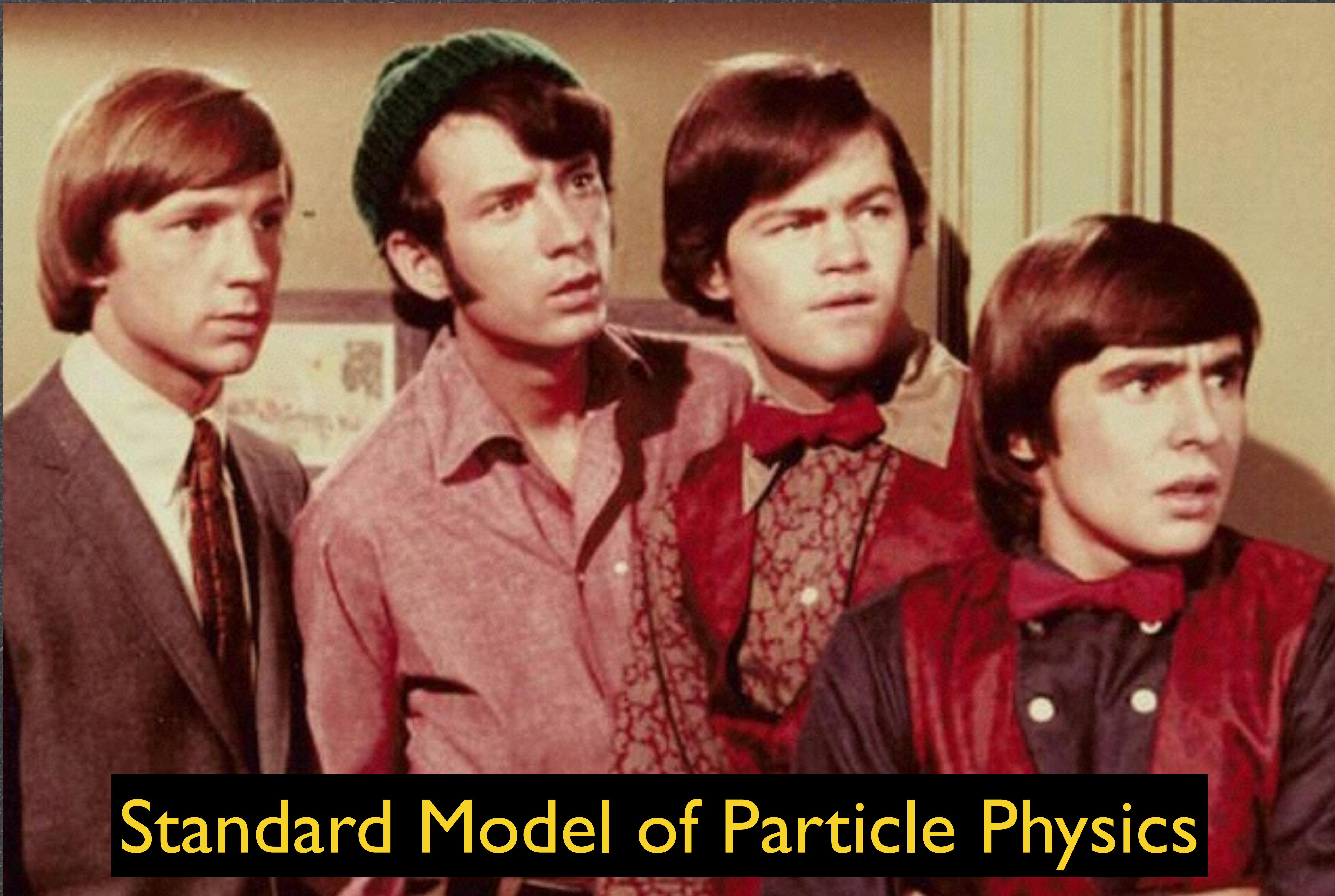
Department of Physics, University of Oxford, Oxford 0X1 3RH, UK

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.

What's about a half century old?


Standard Model of Particle Physics

What’s about a quarter century old?

Standard Model of Cosmology

SMC Predictions

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

+ SZ power, CMB lensing convergence, ...

Acoustic Peaks

Acoustic Peaks

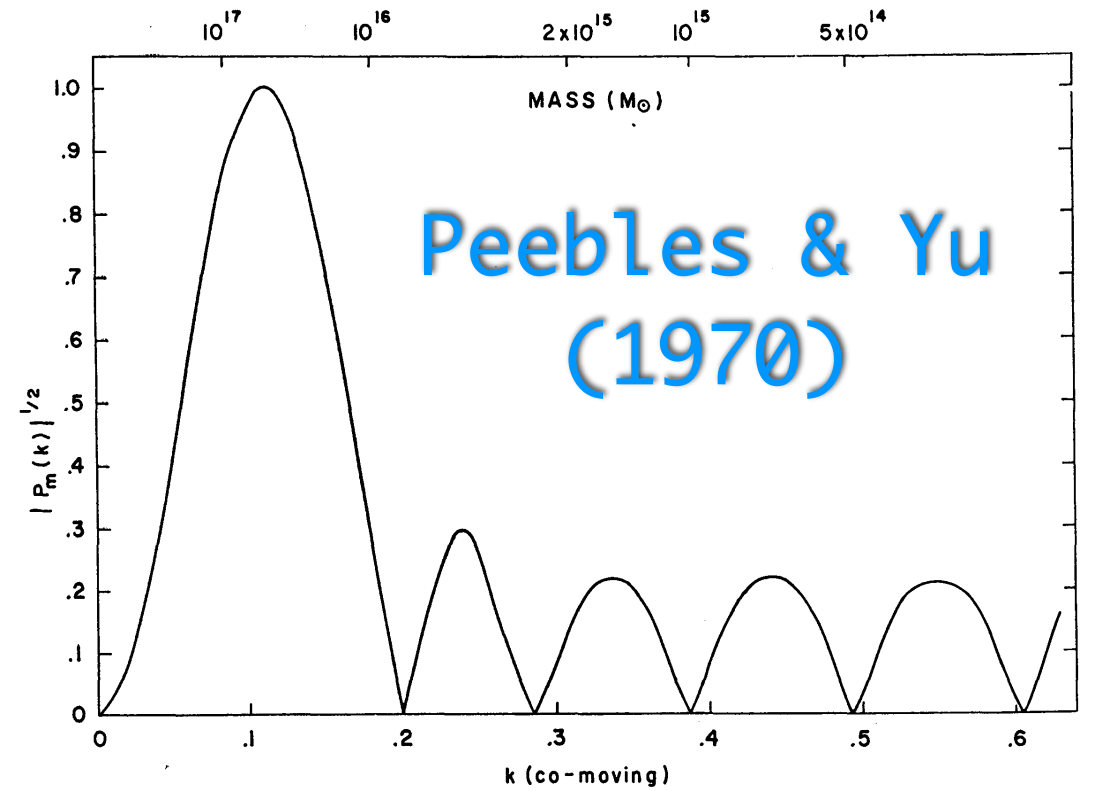
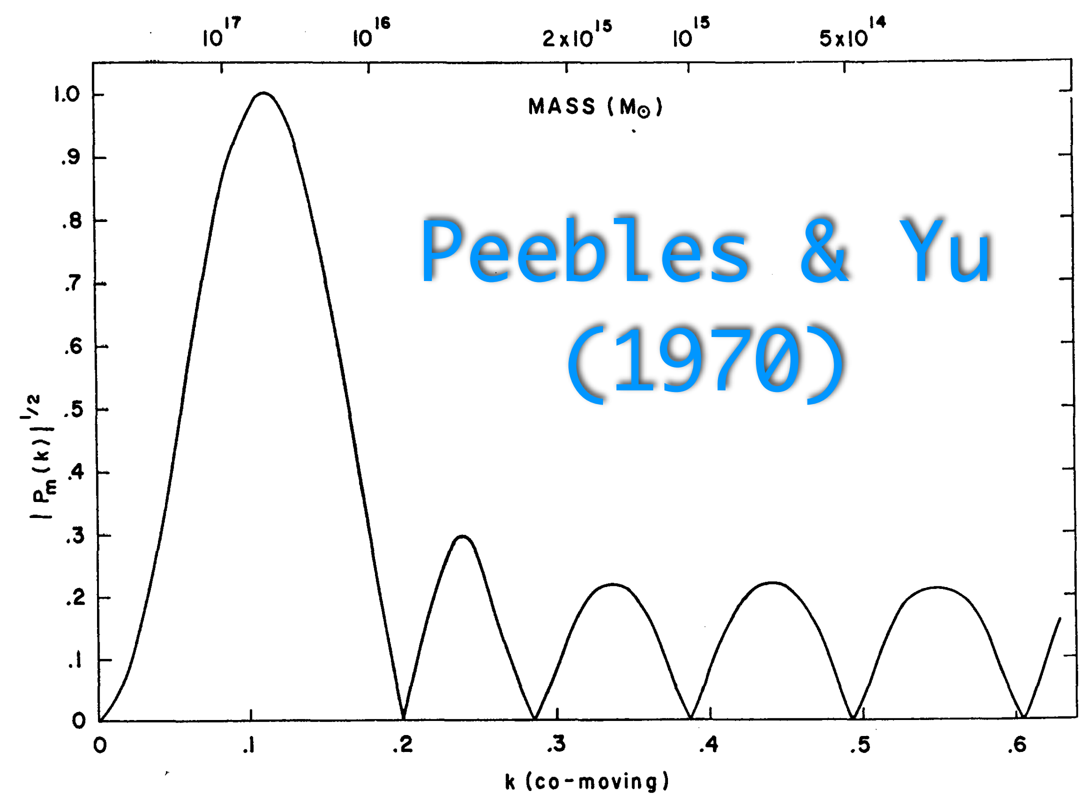


FIG. 5.—Same as Fig. 4 for the cosmologically flat general-relativity model, $\rho_0 = \rho_c$. The normalization is fixed to peak value unity.

Acousti

Peebles & Yu (1970)



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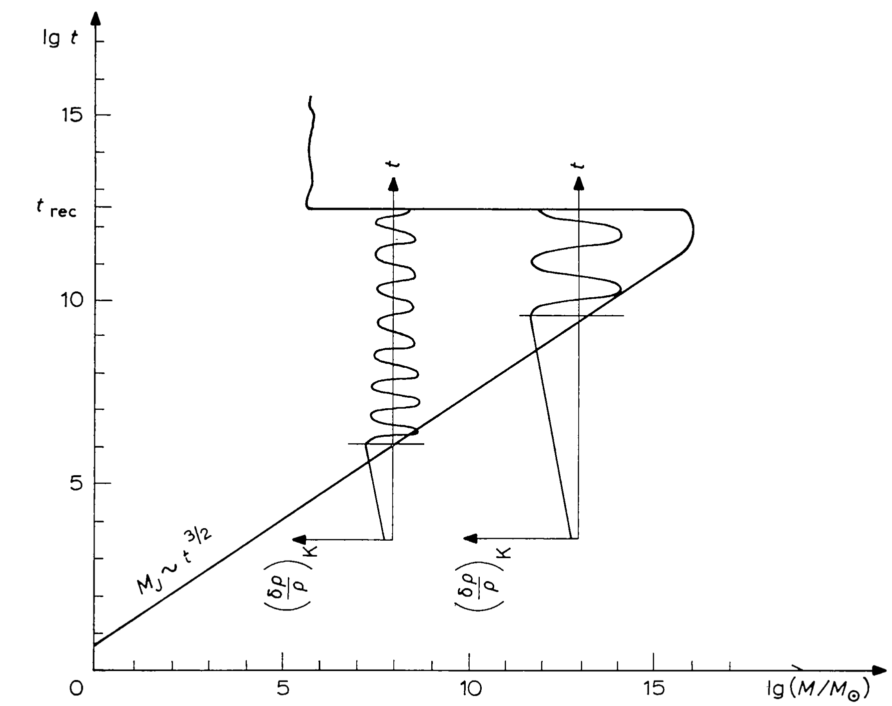


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.

Sunyaev & Zel'dovich (1970)

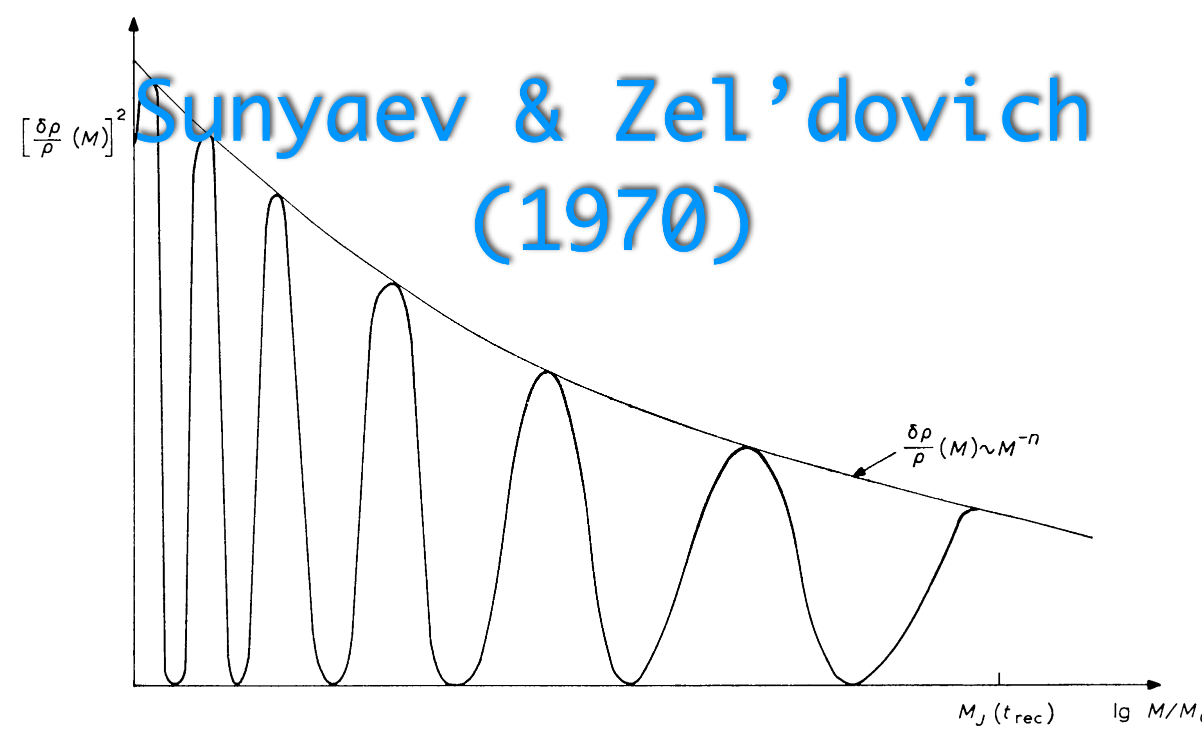
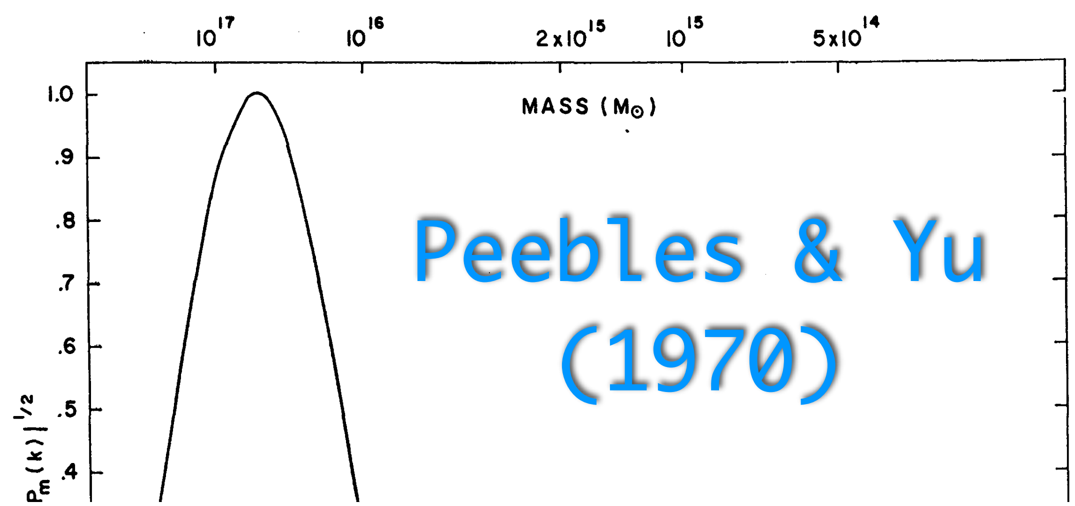
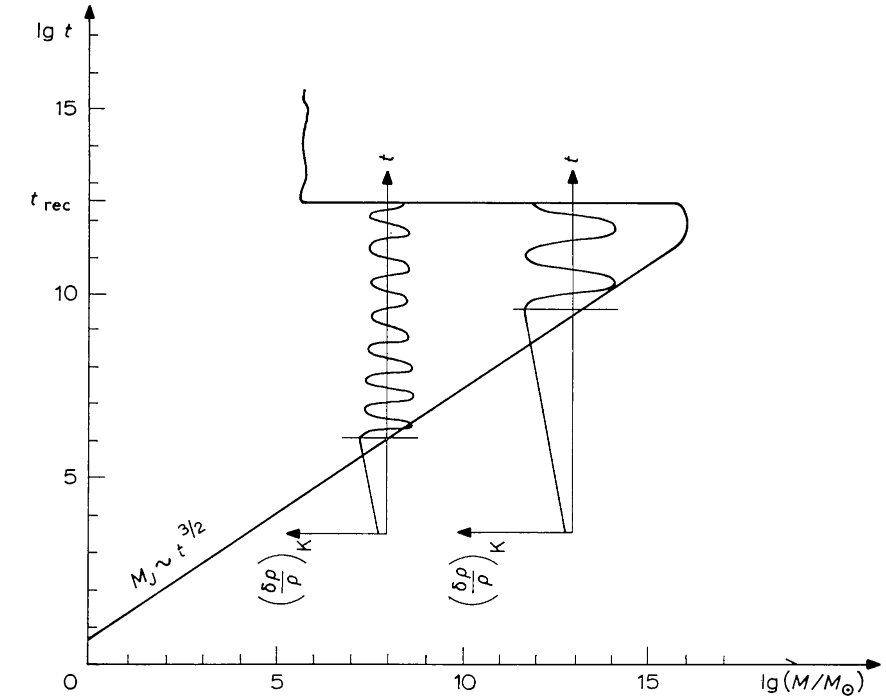


Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

Acousti



Peebles & Yu (1970)



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Wilson & Silk (1981)

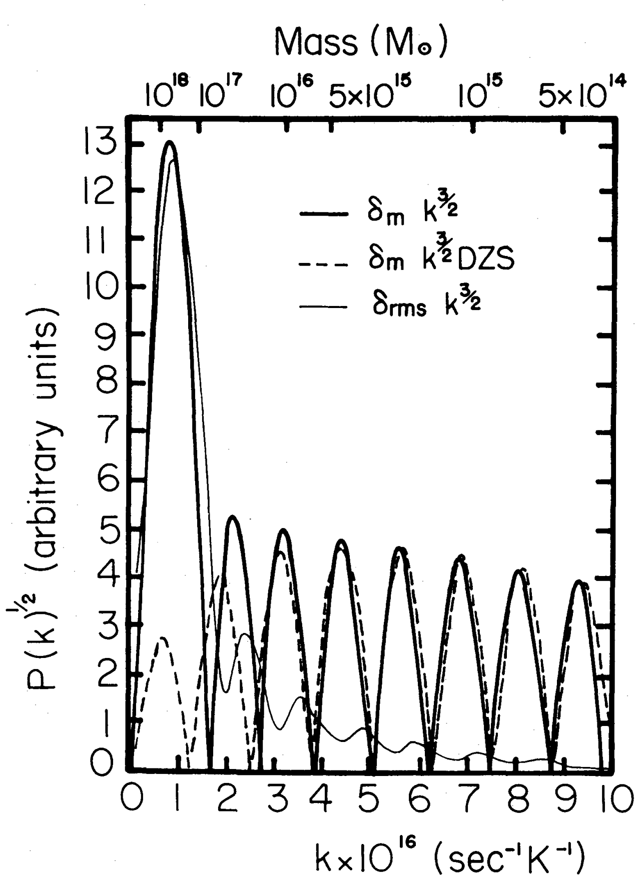
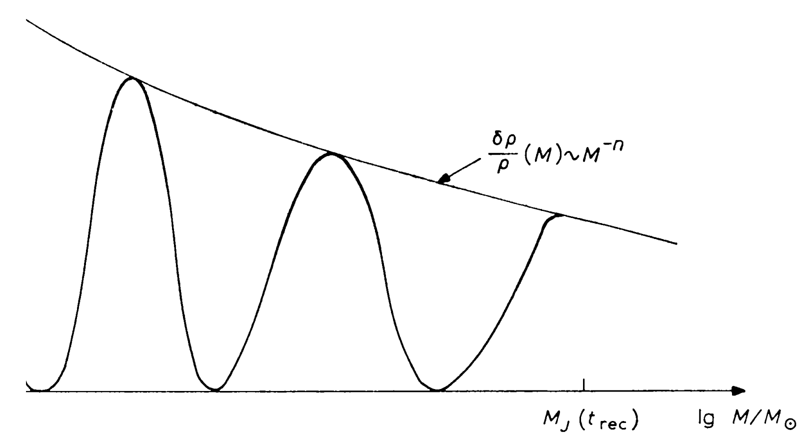
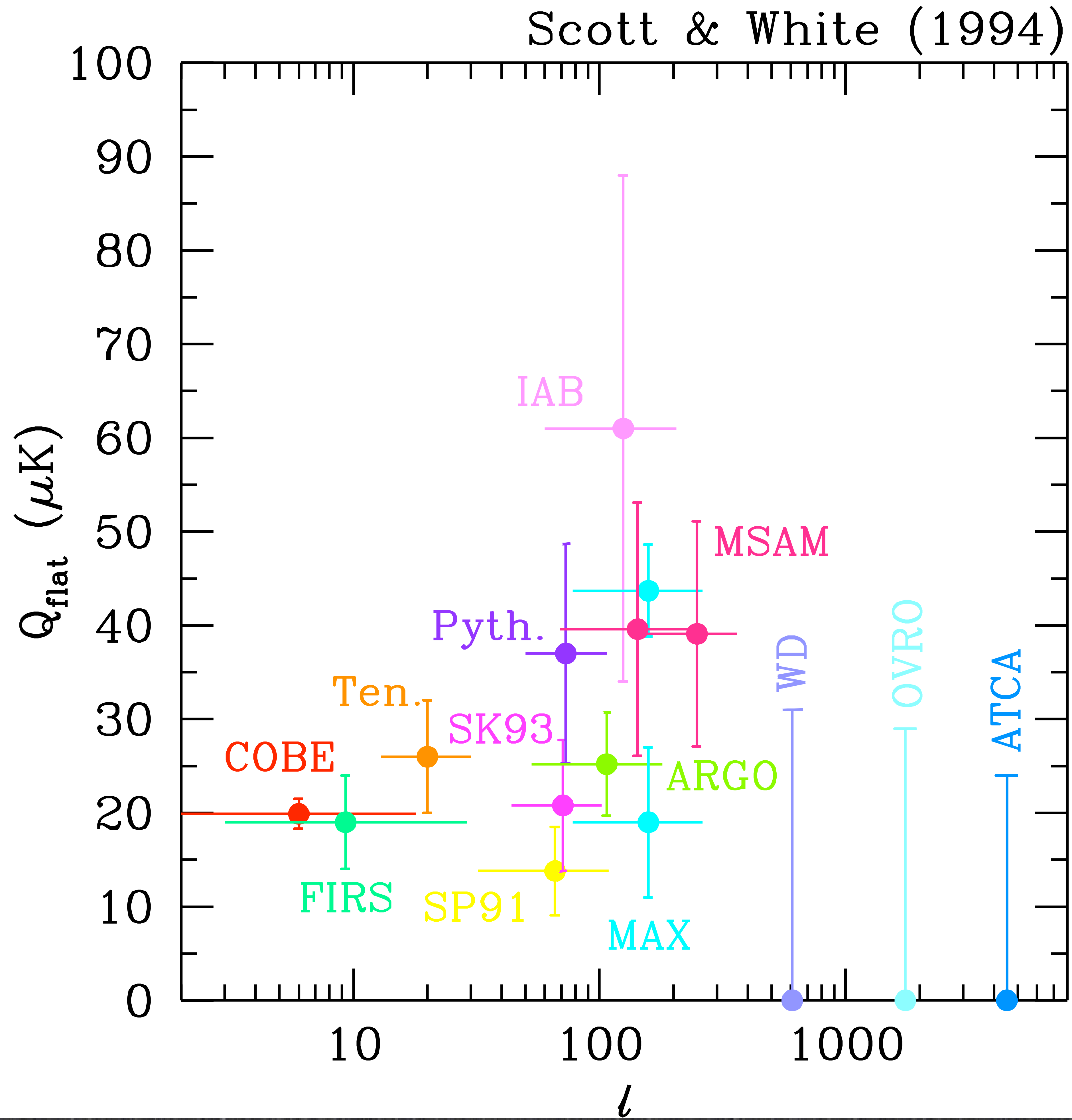


FIG. 1.—Residual matter and radiation adiabatic fluctuation spectra $P(k) = k^3|\delta_m|^2$ for $n = 0$. Normalization is arbitrary, but relative normalization is that for $T = 2000$ K. Note that $\delta_m \propto T^{-1}$, whereas δ_{rms} is constant in time. Also shown for comparison is the analytic fit of the residual matter spectrum adopted by Doroshkevich *et al.* (1978), denoted by DZS.

Sunyaev & Zel'dovich (1970)



...uare of the amplitude of density perturbations of matter on scale. ... assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuation should depend on scale in a similar manner.


Scott & White (1994)
Q_{flat} (μK)
100
90
80
70
60
50
40
30
20
10
0
10
100
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l
IAB
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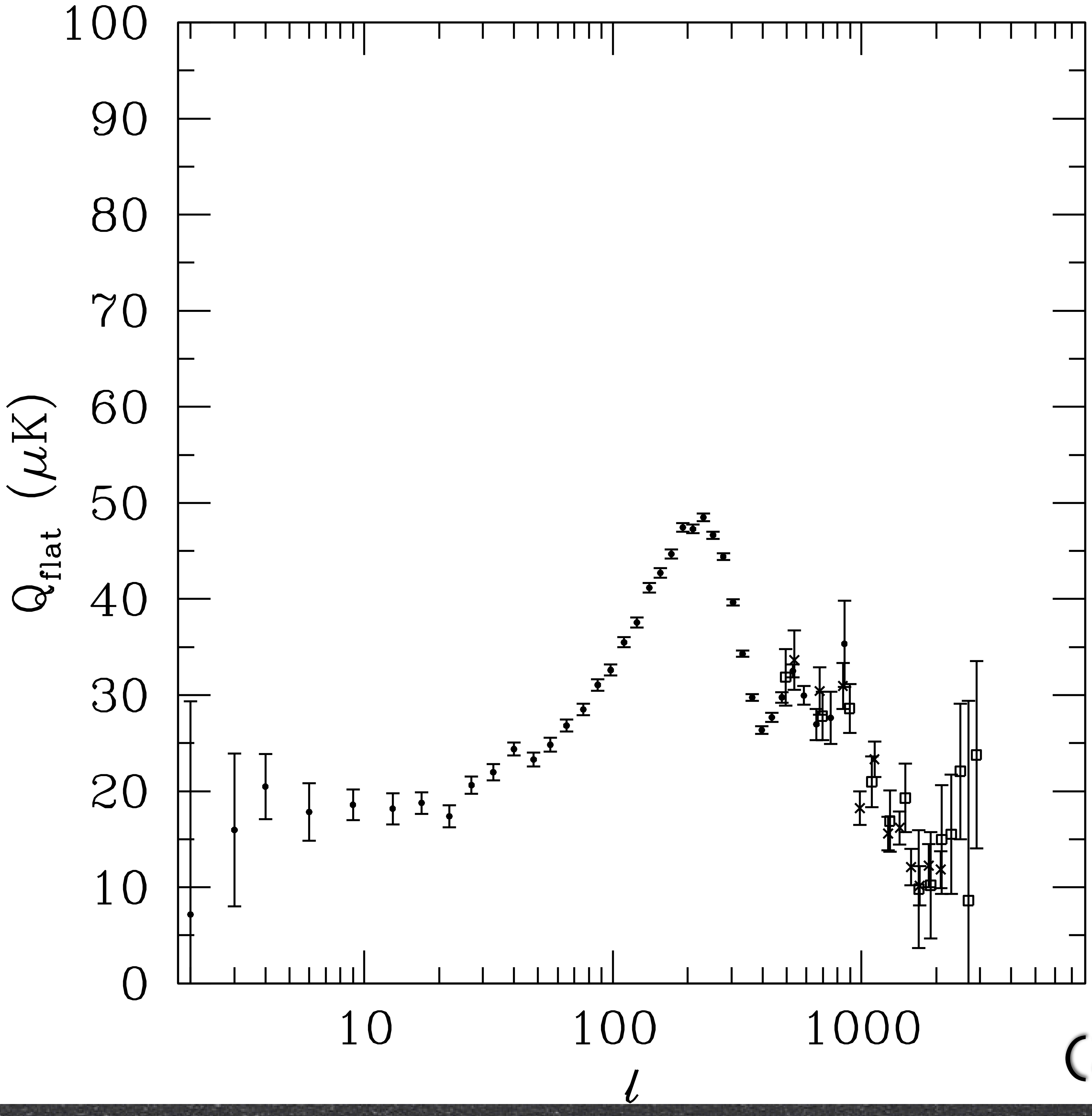
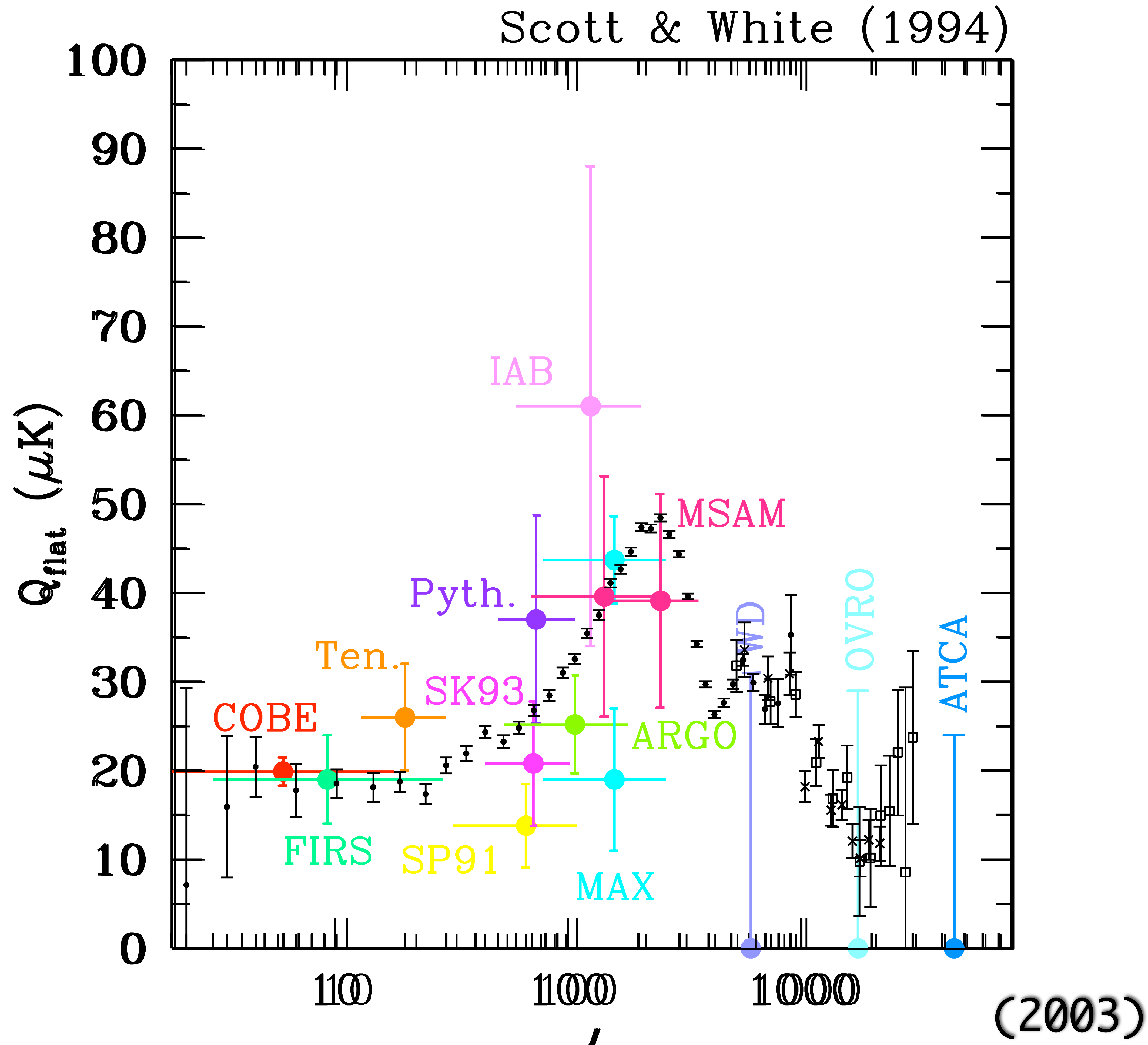
Pyth.
Ten.
SK93
COBE
ARGO
FIRS
SP91
MAX
WD
OVRO
ATCA



(2003)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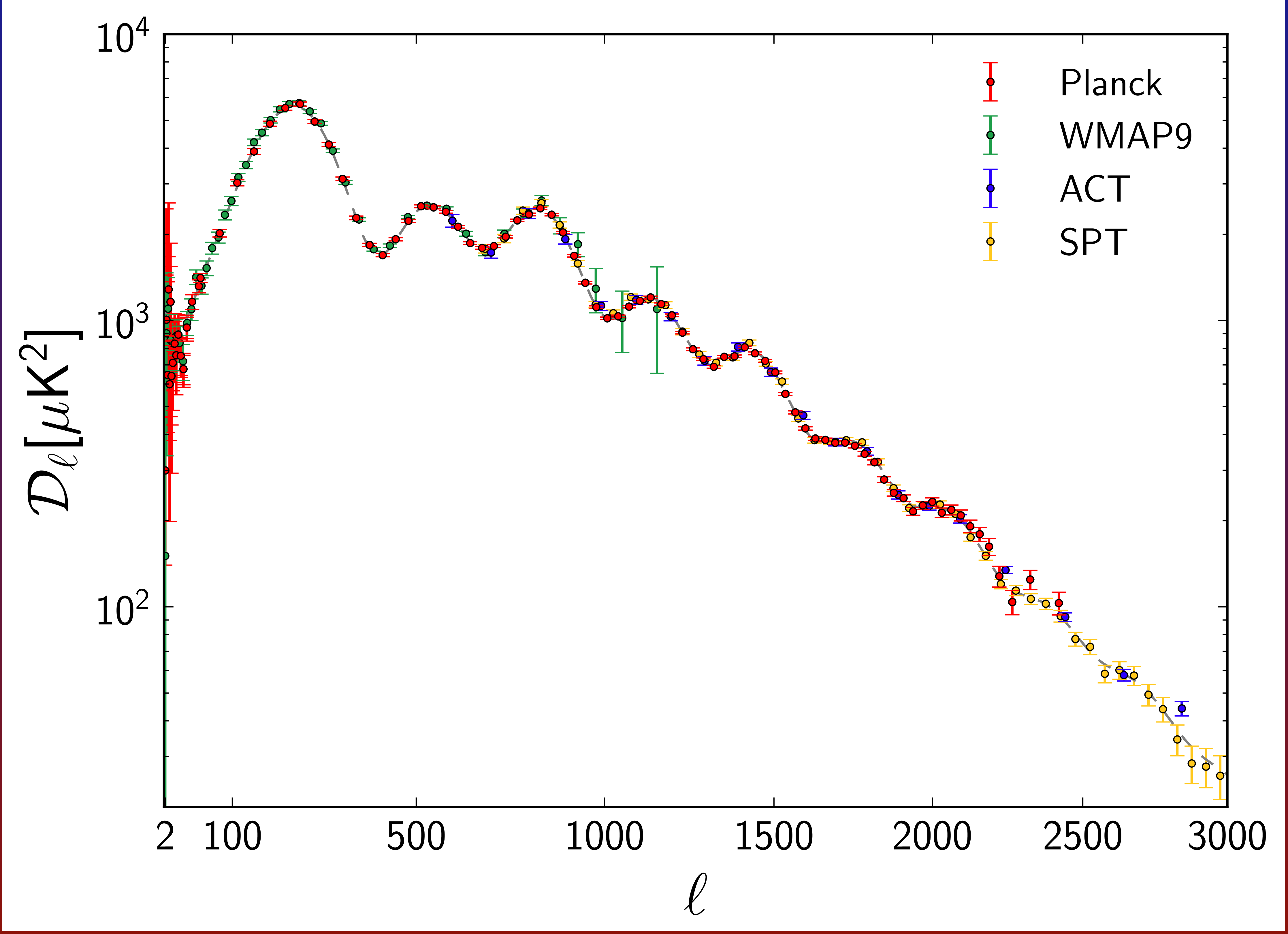
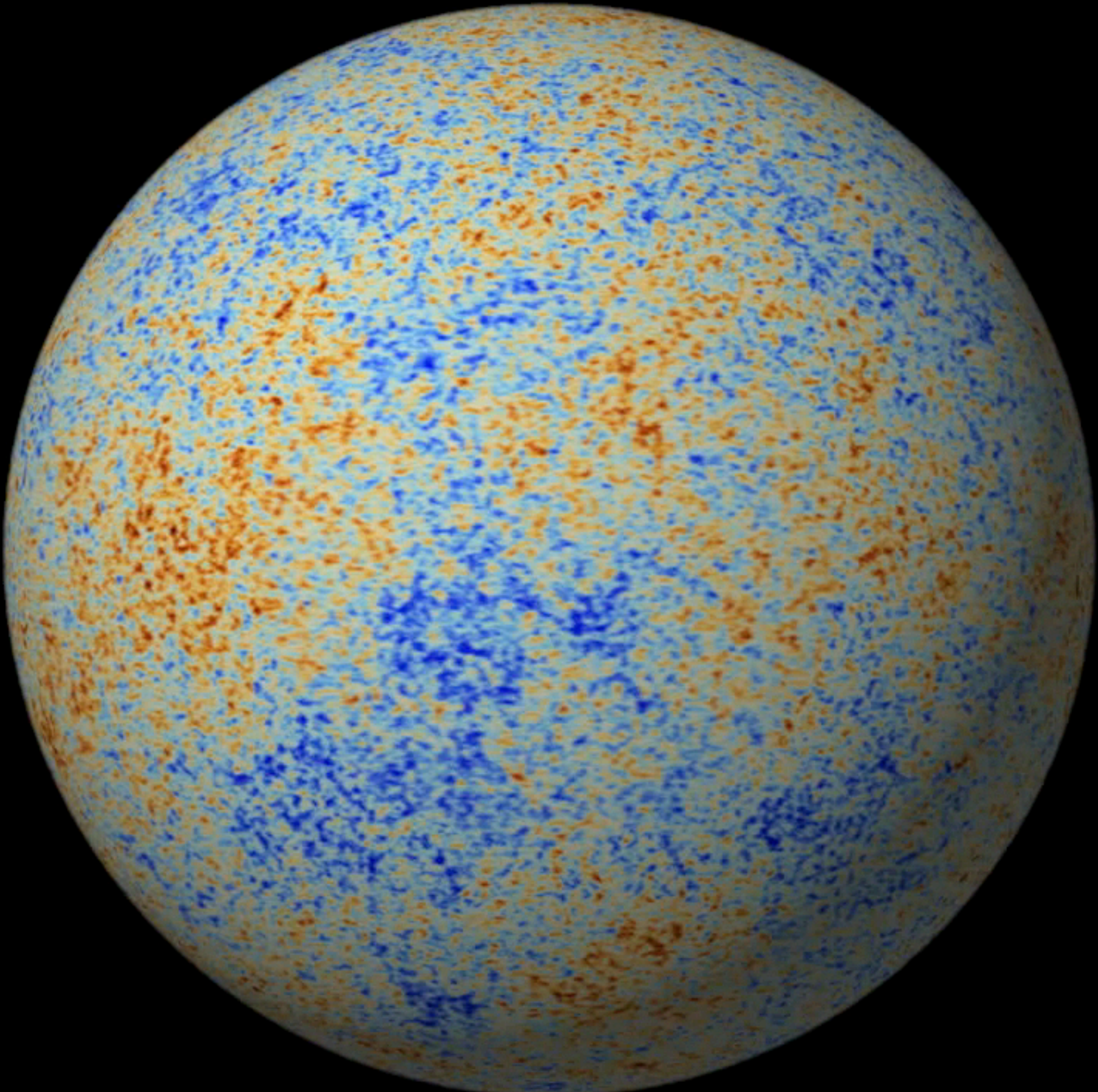
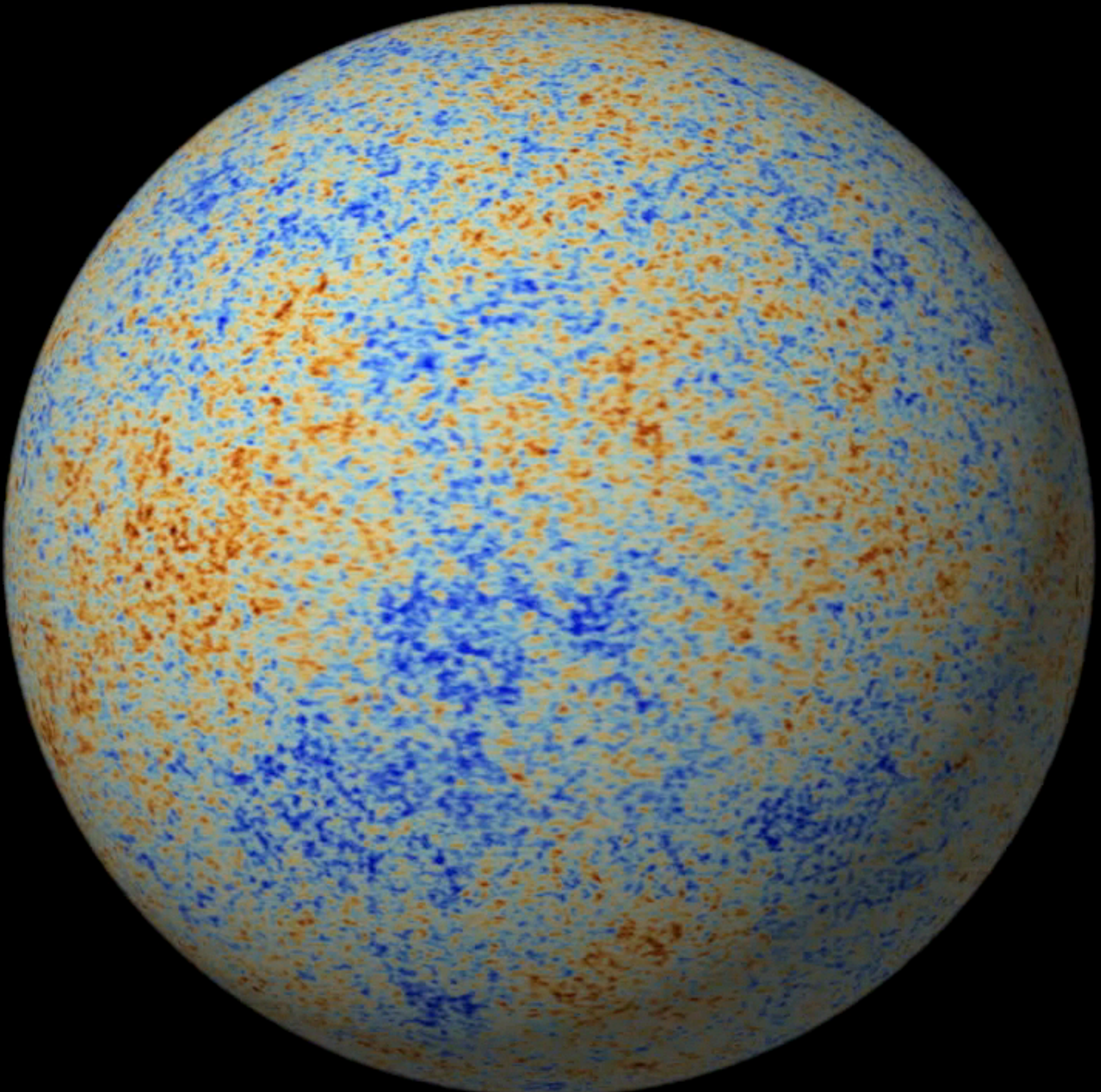
OVRO
ATCA
10
100
1000
ℓ
(2003)

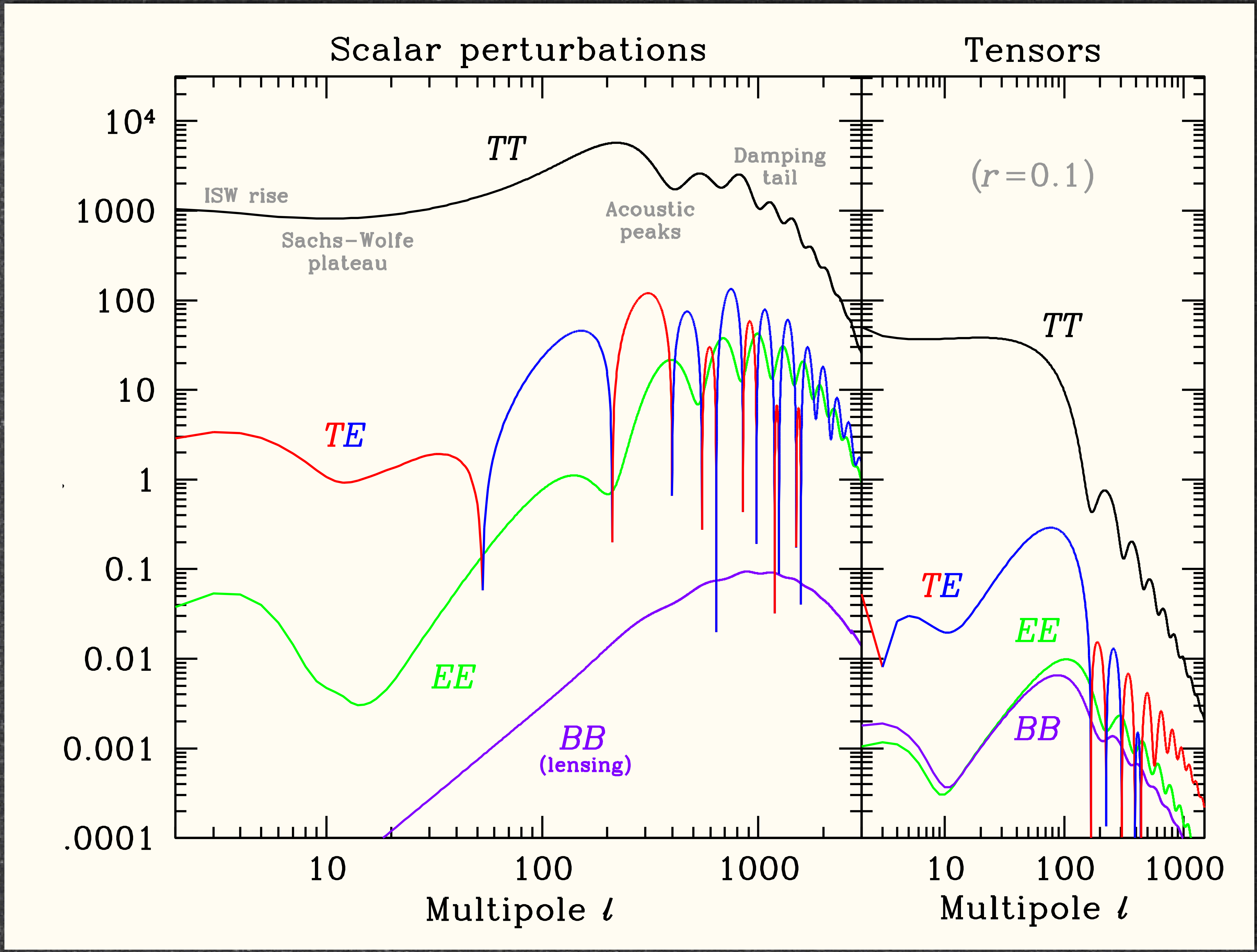
The "precision era" of CMBology
(dominated by Planck, but that will change soon)





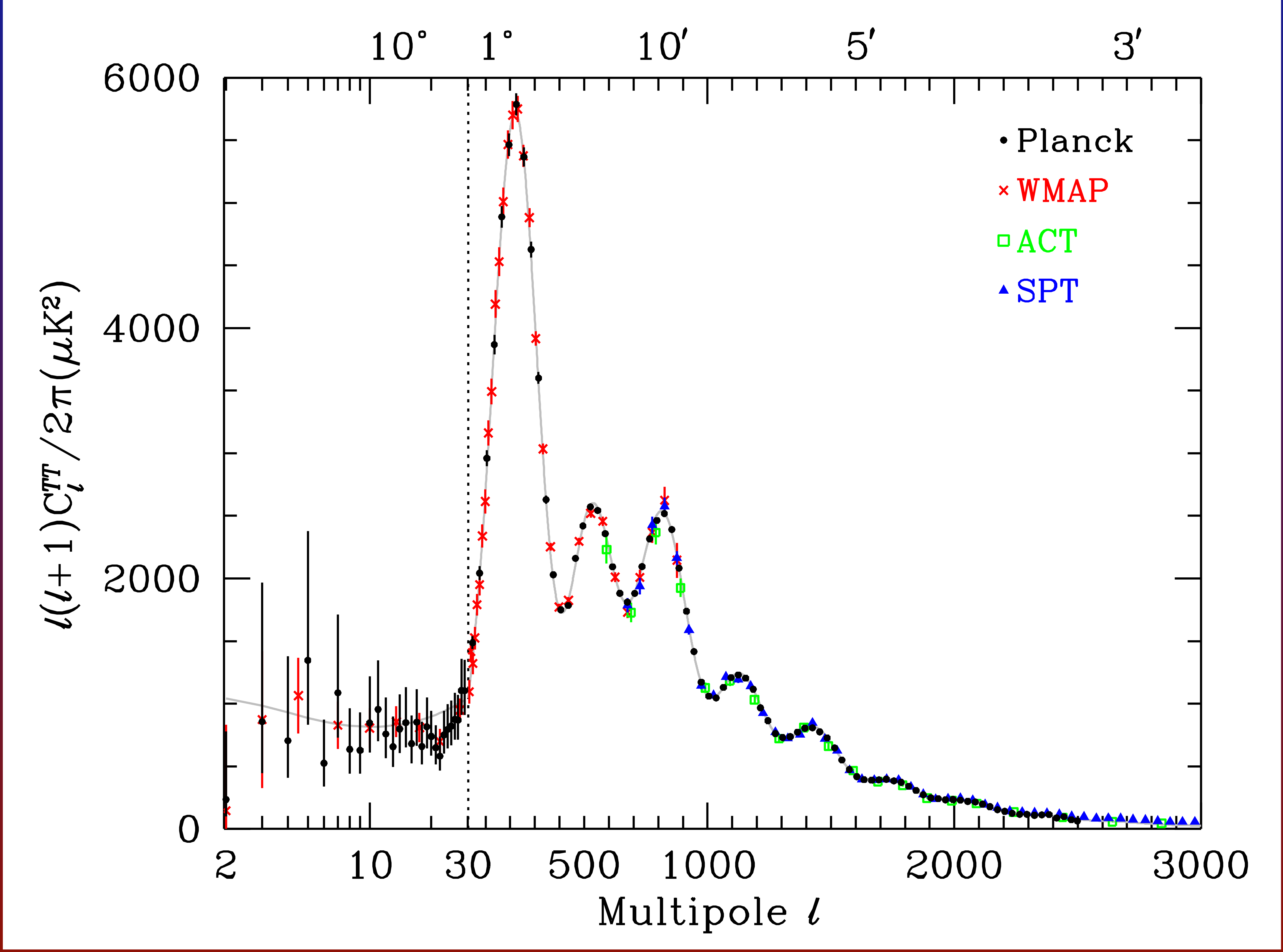


Can precisely calculate 4 power spectra (given a set of parameters)



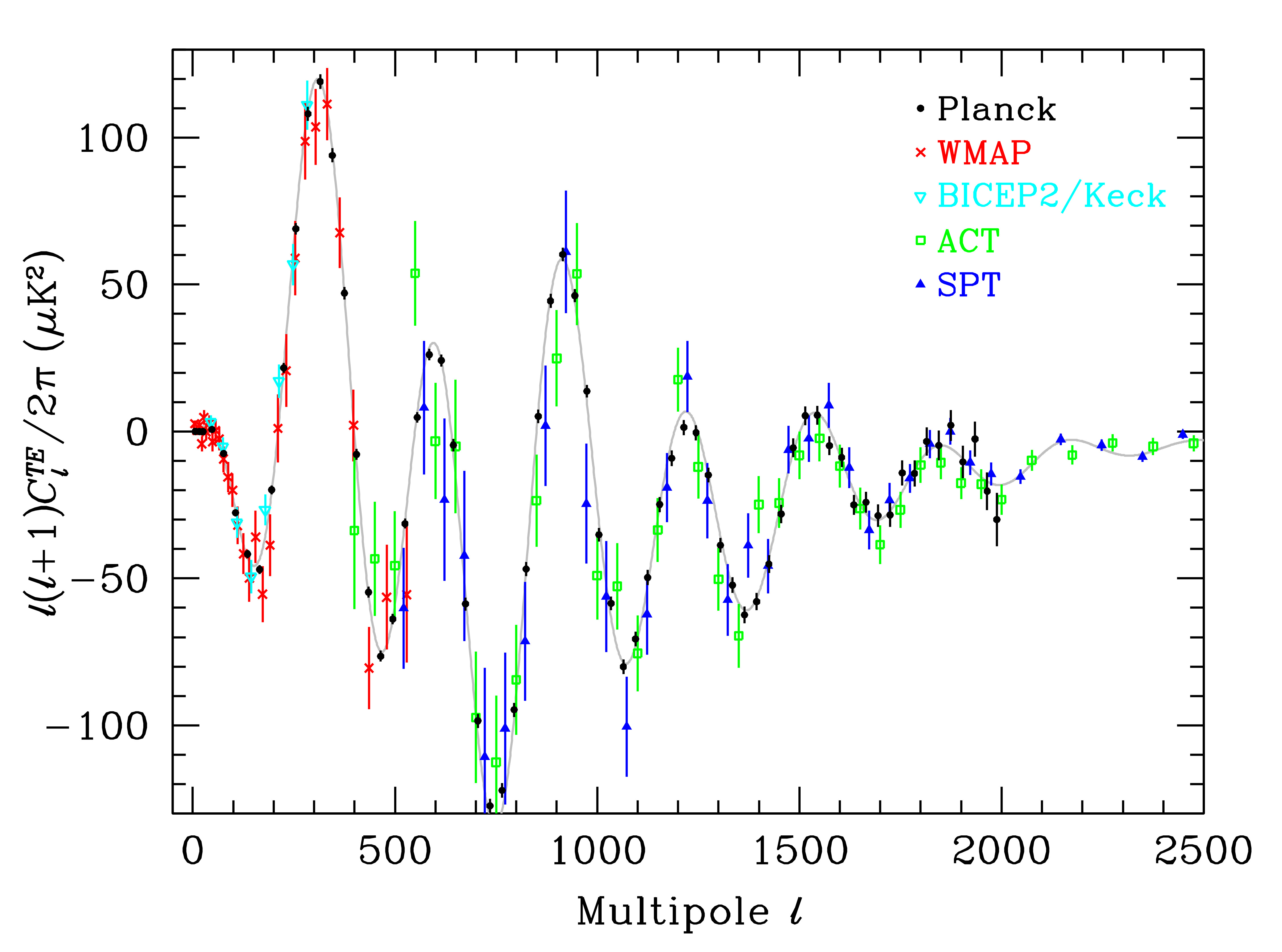
Scott & Smoot 2016 RPP

"Precision era" of cosmology



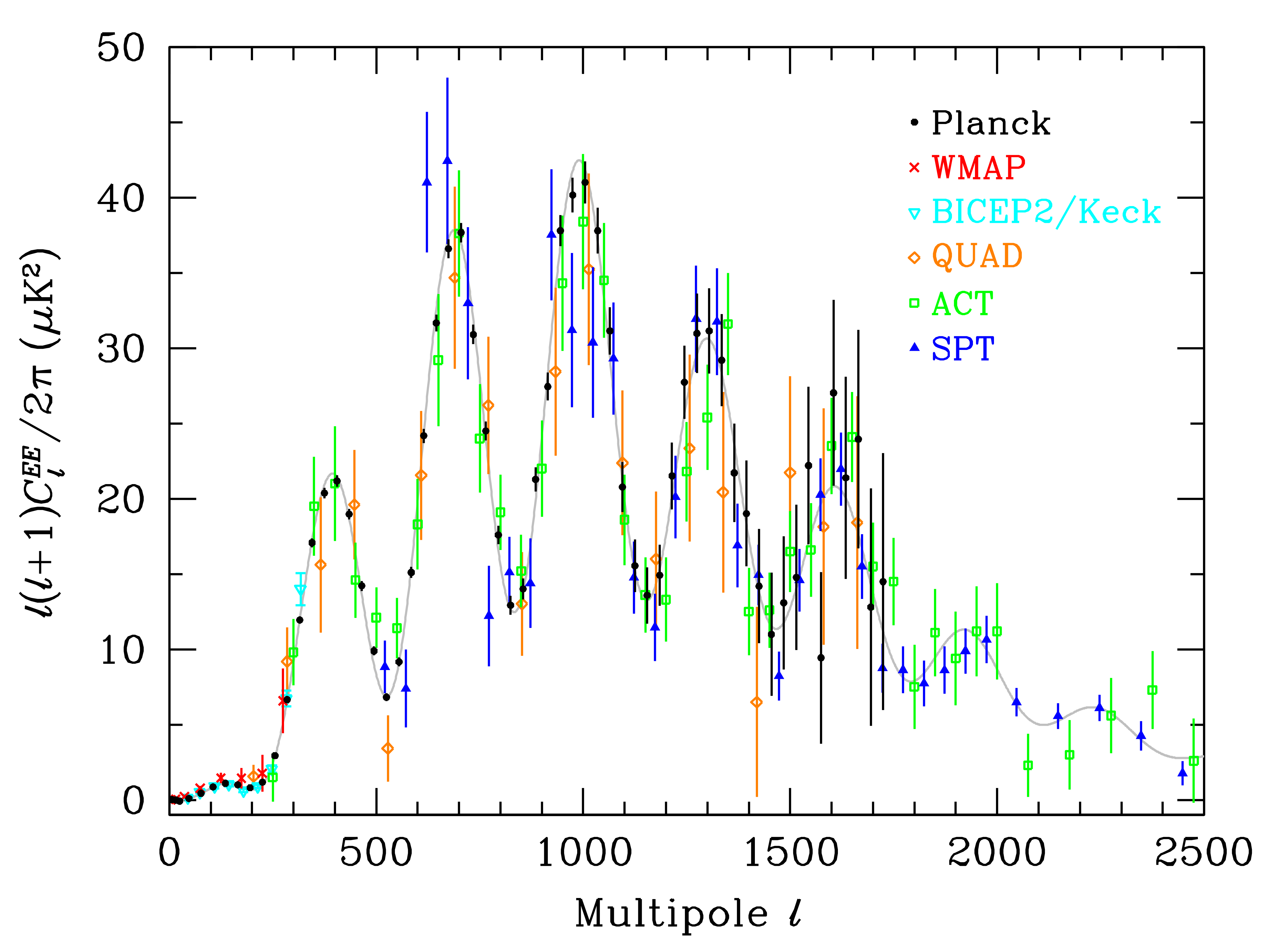
Scott & Smoot 2016 RPP

TE



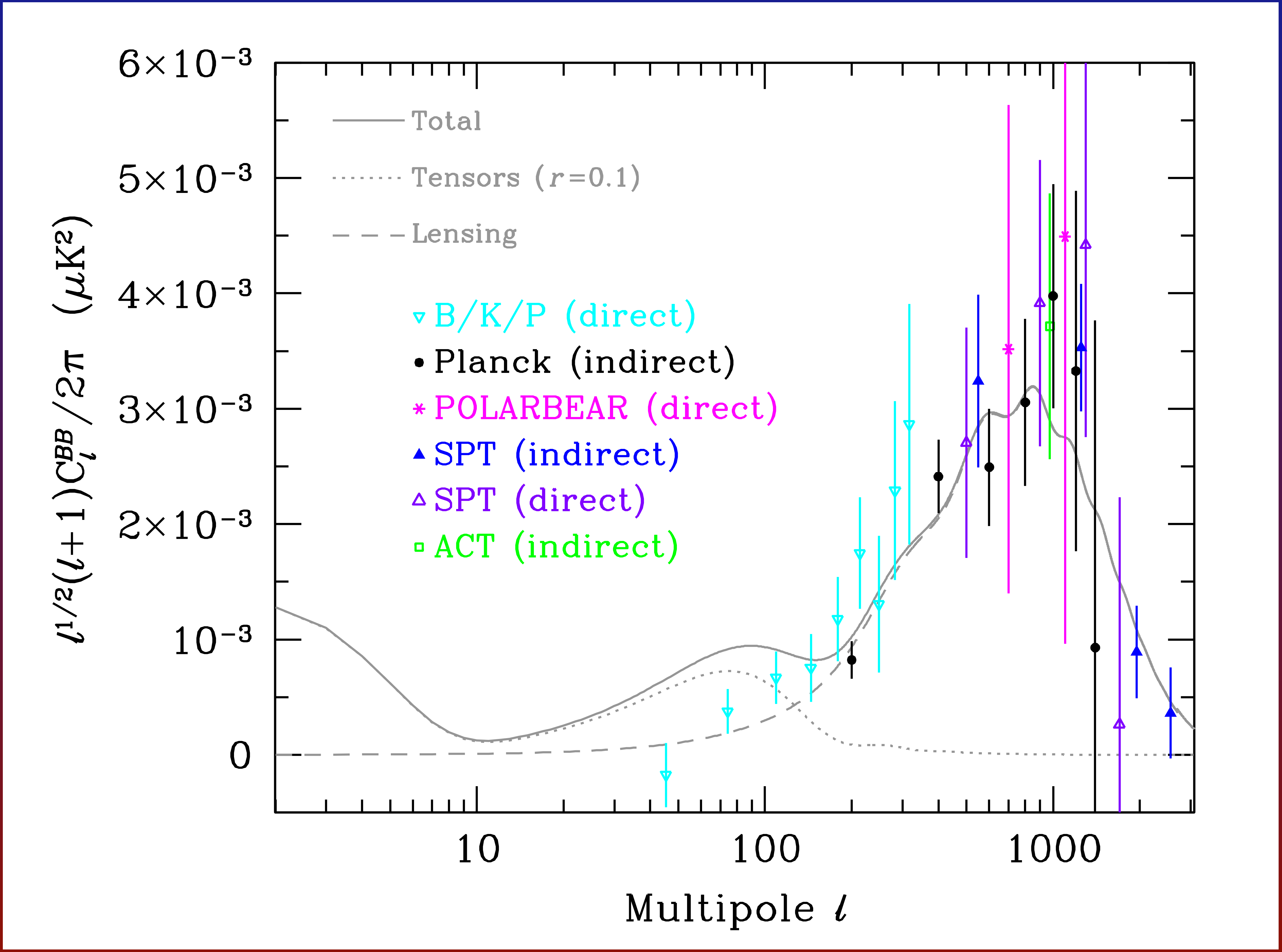
Scott & Smoot 2016 RPP

EE



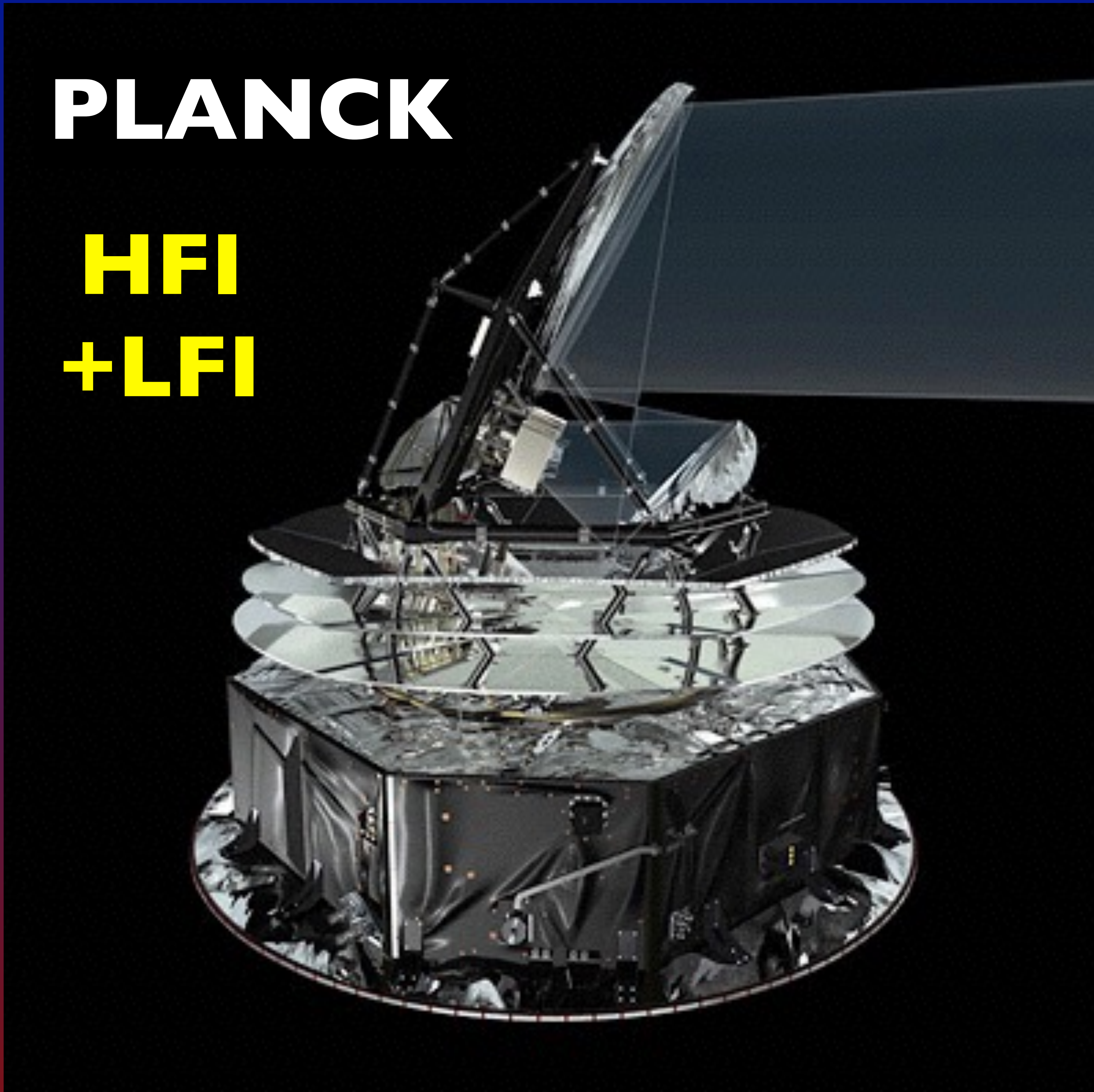
Scott & Smoot 2016 RPP

BB



Scott & Smoot 2016 RPP

2 instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI) in a shared focal plane containing 74 channels (in 9 separate frequencies) and covering 8 degrees on the sky.



2 instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI) in a shared focal plane containing 74 channels (in 9 separate frequencies) and covering 8 degrees on the sky.

ESA Mission (+ European national agencies +NASA +CSA)

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

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So what are these 6 parameters?

The 6 parameters

(Planck 2015 results alone here)

There are somewhat different constraints for Planck + other data

	Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits
Physical baryon density	$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023
Physical CDM density	$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020
Sound hor./ang.diam.dist.	$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046
Reionization optical depth	τ	0.078 ± 0.019	0.066 ± 0.016
Amplitude of initial P(k)	$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029
Slope of initial P(k)	n_s	0.9655 ± 0.0062	0.9677 ± 0.0060

The 6 parameters

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	Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits
Amount of atoms	$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023
Amount of dark stuff	$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020
Stretch factor for wiggles	$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046
Fraction of recent scattering	τ	0.078 ± 0.019	0.066 ± 0.016
Strength of lumpiness	$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029
Scale variation of lumpiness	n_s	0.9655 ± 0.0062	0.9677 ± 0.0060

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

H_0	67.31 ± 0.96	67.81 ± 0.92
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012
Ω_m	0.315 ± 0.013	0.308 ± 0.012

Planck papers

- "Planck pre-launch status"
  - 14 papers
- "Planck early results"
  - 26 papers
- "Planck intermediate papers"
  - 51 papers (so far)
- "Planck 2013 results"
  - 32 papers
- "Planck 2015 results"
  - 28 papers so far!
- "BICEP + Planck"
- "Planck final results" soon

Instrumentation
Cosmic rays
Zodiacal emission
Component separation
Interstellar medium
All-sky optical depth
Galactic cold clumps
Anomalous microwave emission
Polarized dust radiation
All-sky CO map
Nearby galaxies
High-z extragalactic sources
Cosmic infrared background
CMB power spectra
Cosmological parameters
Gravitational lensing
Dipole & boosting effects
Integrated Sachs-Wolfe effect
SZ cluster cosmology
Cluster physics
Peculiar velocities
Constraints on inflation
Topological defects
Non-Gaussianity
Isotropy & statistics
Geometry & topology
Dark energy & modified gravity
Primordial magnetic fields
Reionization
Parity & birefringence
...

- But people mostly just care about parameters!
- The 6-parameter ΛCDM model is so good that focus turns to “tensions”:
  - -Planck vs WMAP ?
  - -Discrepancy with direct H_0 ?
  - -CMB vs lensing and cluster σ_8 ?
  - -Preference for $A_L>1$?
  - -Large-angle anomalies

    particularly the “low low-ℓs” ?
- (results may change with final 2017 release of Planck data)

If today's CMB status was an episode of Sesame Street, it would be ...

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Brought to you
by the words
"tensions"
and
"anomalies"

By the way here's a real anomaly!

SpaceX said "an anomaly" had occurred while the rocket was being loaded with fuel.

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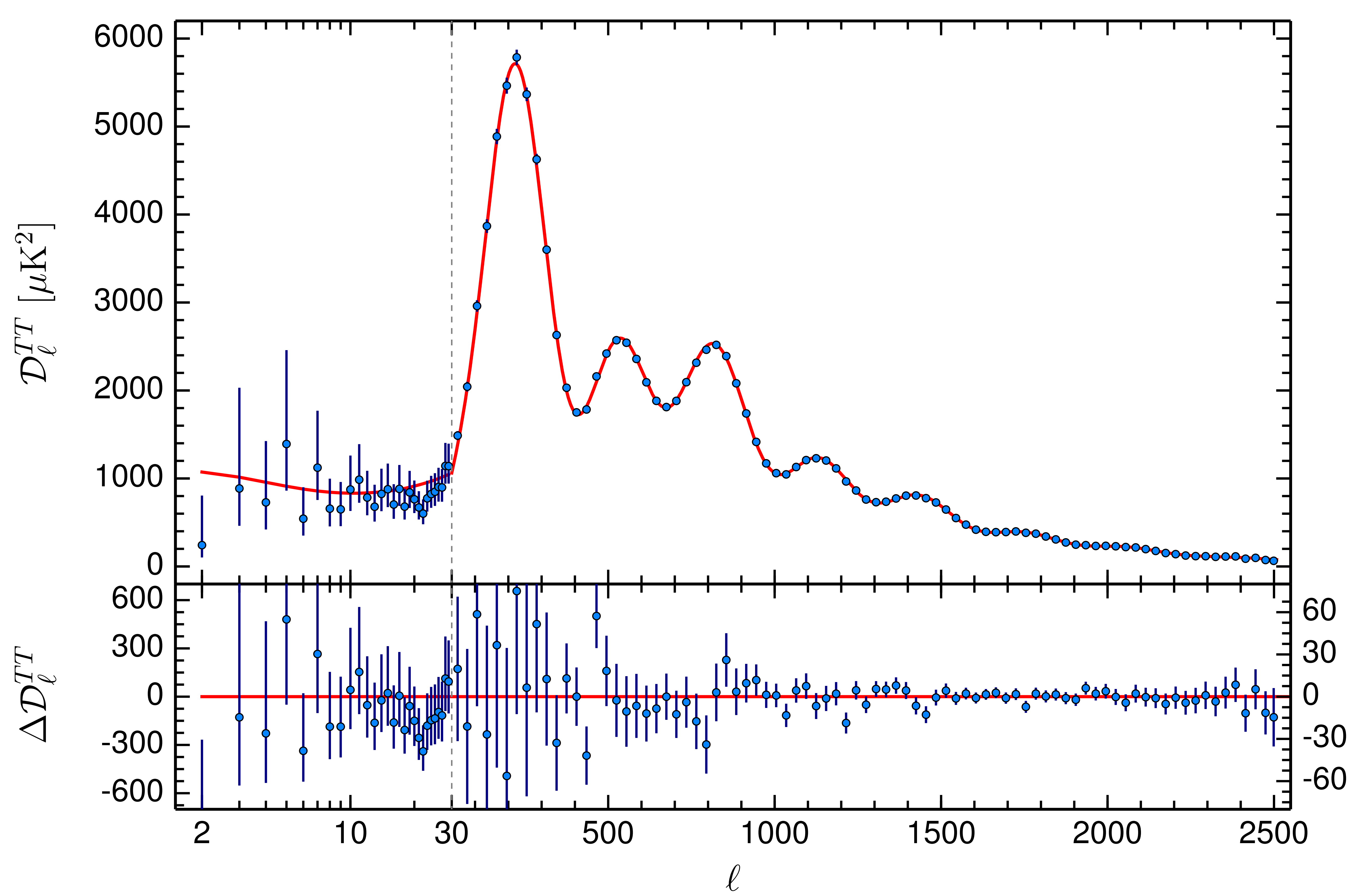
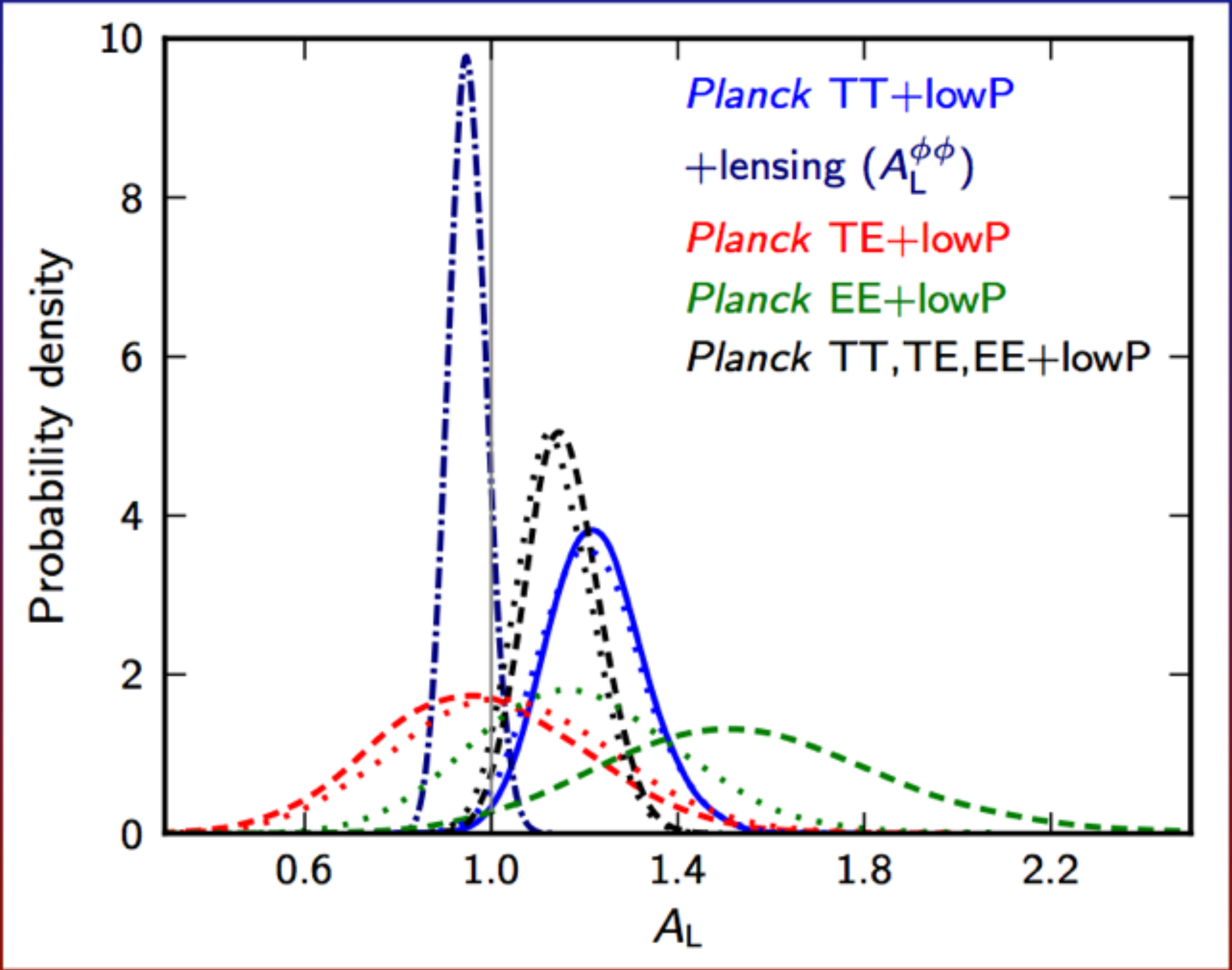
Planck 2015 TT power spectrum



Effect of "low low-ℓs"

- Lack of power at low multipoles is real
- But not very significant (when marginalizing)
- It's composed of a "dip" at about ℓ=20-30 and a general deficit to low multipoles
- Since it's at the end, it affects parameters more than if it was elsewhere
- Because WMAP doesn't have higher multipoles, <u>the parameters are biased more than for Planck</u>

Lensing anomaly?



Tensions

- Won’t discuss the external tensions here (since that’s a complicated and endless discussion!)
- But the internal tensions in Planck data are in this paper:

Tensions

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- But the <u>internal</u> tensions in Planck data are in this paper:

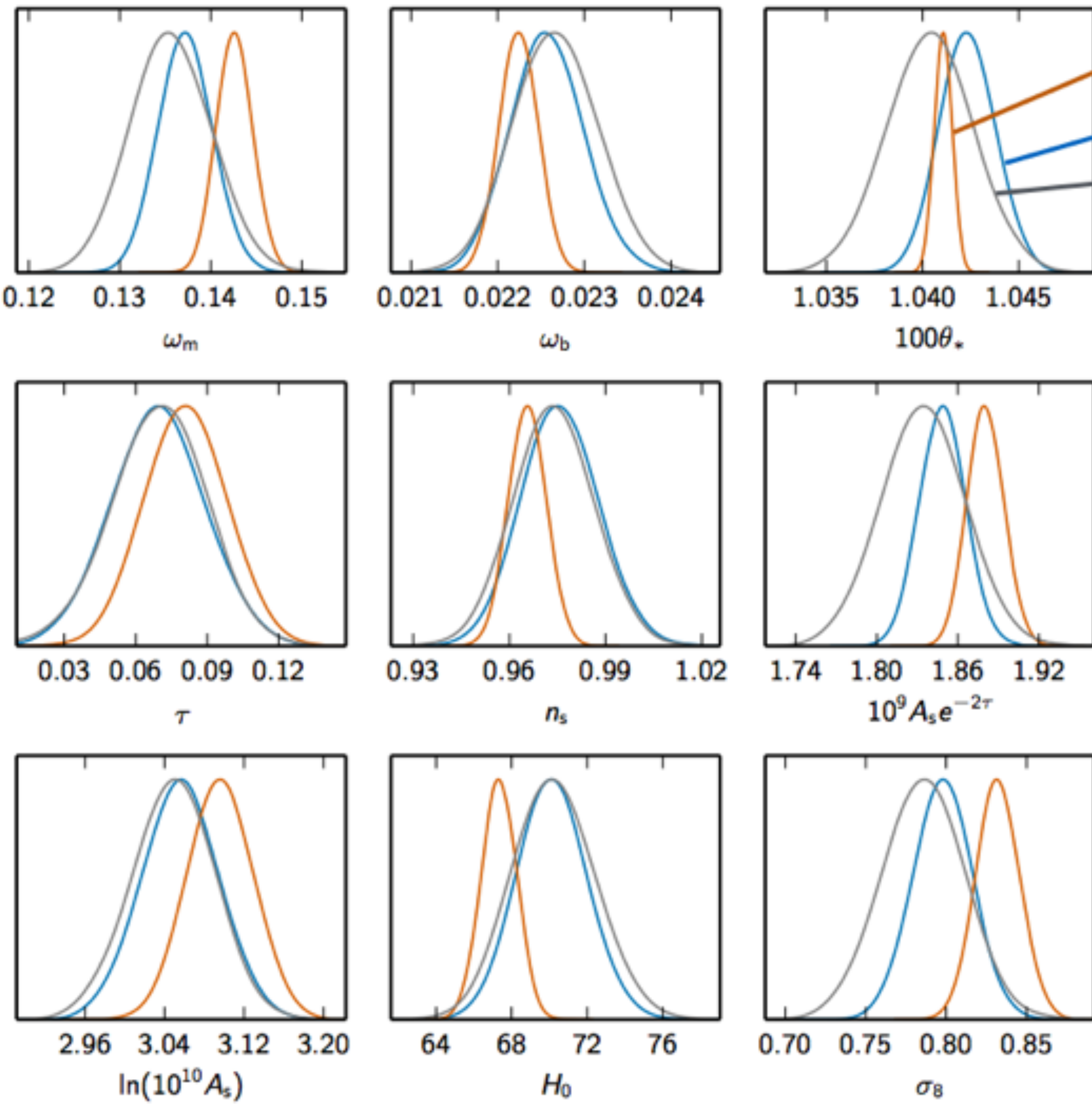
Planck 2016 intermediate results. LI. Features in the cosmic microwave background temperature power spectrum and shifts in cosmological parameters

Planck Collaboration: N. Aghanim[51], Y. Akrami[54,85], M. Ashdown[61,5], J. Aumont[51], M. Ballardini[28,43,46], A. J. Banday[83,8], R. B. Barreiro[56], N. Bartolo[27,57], S. Basak[72], K. Benabed[52,82], M. Bersanelli[31,44], P. Bielewicz[70,8,72], A. Bonaldi[59], L. Bonavera[15], J. R. Bond[7], J. Borrill[11,79], F. R. Bouchet[52,77], C. Burigana[43,29,46], E. Calabrese[80], J.-F. Cardoso[64,1,52], A. Challinor[53,61,10], H. C. Chiang[22,6], L. P. L. Colombo[18,58], C. Combet[65], B. P. Crill[58,9], A. Curto[56,5,61], F. Cuttaia[43], P. de Bernardis[30], A. de Rosa[43], G. de Zotti[40,72], J. Delabrouille[1], E. Di Valentino[52,77], C. Dickinson[59], J. M. Diego[56], O. Doré[58,9], A. Ducout[52,50], X. Dupac[35], S. Dusini[57], G. Efstathiou[61,53], F. Elsner[19,52,82], T. A. Enßlin[68], H. K. Eriksen[54], Y. Fantaye[34,2], F. Finelli[43,46], F. Forastieri[29,47], M. Frailis[42], E. Franceschi[43], A. Frolov[76], S. Galeotta[42], S. Galli[60,52*], K. Ganga[1], R. T. Génova-Santos[55,14], M. Gerbino[81,71,30], J. González-Nuevo[15,56], K. M. Górski[58,86], A. Gruppuso[43,46], J. E. Gudmundsson[81,71,22], D. Herranz[56], E. Hivon[52,82], Z. Huang[74], A. H. Jaffe[50], W. C. Jones[22], E. Keihänen[21], R. Keskitalo[11], K. Kiiveri[21,39], J. Kim[68], T. S. Kisner[67], L. Knox[24], N. Krachmalnicoff[31], M. Kunz[13,51,2], H. Kurki-Suonio[21,39], G. Lagache[4,51], J.-M. Lamarre[63], A. Lasenby[5,61], M. Lattanzi[29,47], C. R. Lawrence[58], M. Le Jeune[1], F. Levrier[63], A. Lewis[20], P. B. Lilje[54], M. Lilley[52,77], V. Lindholm[21,39], M. López-Caniego[35], P. M. Lubin[25], Y.-Z. Ma[59,73], J. F. Macías-Pérez[65], G. Maggio[42], D. Maino[31,44], N. Mandolesi[43,29], A. Mangilli[51,62], M. Maris[42], P. G. Martin[7], E. Martínez-González[56], S. Matarrese[27,57,37], N. Mauri[46], J. D. McEwen[69], P. R. Meinhold[25], A. Mennella[31,44], M. Migliaccio[53,61], M. Millea[24,78,52†], M.-A. Miville-Deschênes[51,7], D. Molinari[29,43,47], A. Moneti[52], L. Montier[83,8], G. Morgante[43], A. Moss[75], A. Narimani[17], P. Natoli[29,3,47], C. A. Oxborrow[12], L. Pagano[30,48], D. Paoletti[43,46], G. Patanchon[1], L. Patrizii[46], V. Pettorino[38], F. Piacentini[30], L. Polastri[29,47], G. Polenta[3,41], J.-L. Puget[51], J. P. Rachen[16,68], B. Racine[54], M. Reinecke[68], M. Remazeilles[59,51,1], A. Renzi[34,49], M. Rossetti[31,44], G. Roudier[1,63,58], J. A. Rubiño-Martín[55,14], B. Ruiz-Granados[84], L. Salvati[30], M. Sandri[43], M. Savelainen[21,39], D. Scott[17], C. Sirignano[27,57], G. Sirri[46], L. Stanco[57], A.-S. Suur-Uski[21,39], J. A. Tauber[36], D. Tavagnacco[42,32], M. Tenti[45], L. Toffolatti[15,56,43], M. Tomasi[31,44], M. Tristram[62], T. Trombetti[43,29], J. Valiviita[21,39], F. Van Tent[66], P. Vielva[56], F. Villa[43], N. Vittorio[33], B. D. Wandelt[52,82,26], I. K. Wehus[58,54], M. White[23], A. Zacchei[42], and A. Zonca[25]

arXiv:1608.02487

New "parameter shifts" paper

- Paper has been worked on for ~2 years!
- Motivation is to study apparent parameter shifts within subsets of Planck data
- Not a response to Addison et al. (or other papers) - but partly addresses similar ground
- Specific focus is Planck full-ℓ versus low-ℓ (<800)
- Basic story is that shifts are not as significant as claimed - but has required a lot of work!
- Lower τ makes parameter shifts worse, but only by about 0.3σ



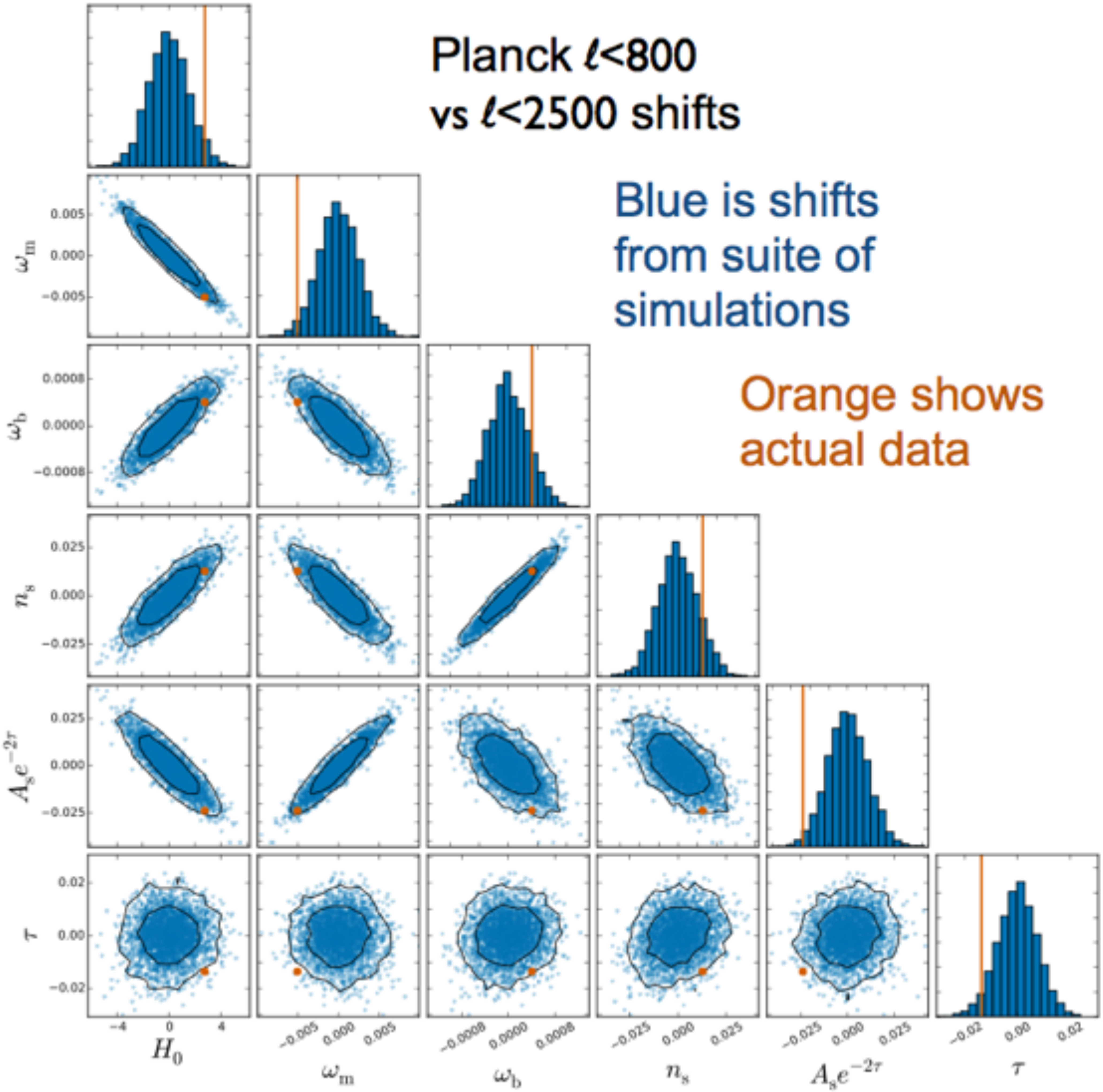
Planck low ℓ and WMAP agree well (although Planck is still better!)

But for Planck full ℓ, the parameters seem to shift

Are these shifts bigger than expected?

And what causes the shifts?

($\tau=0.07\pm0.02$ prior used here)



Planck $\ell<800$ vs $\ell<2500$ shifts

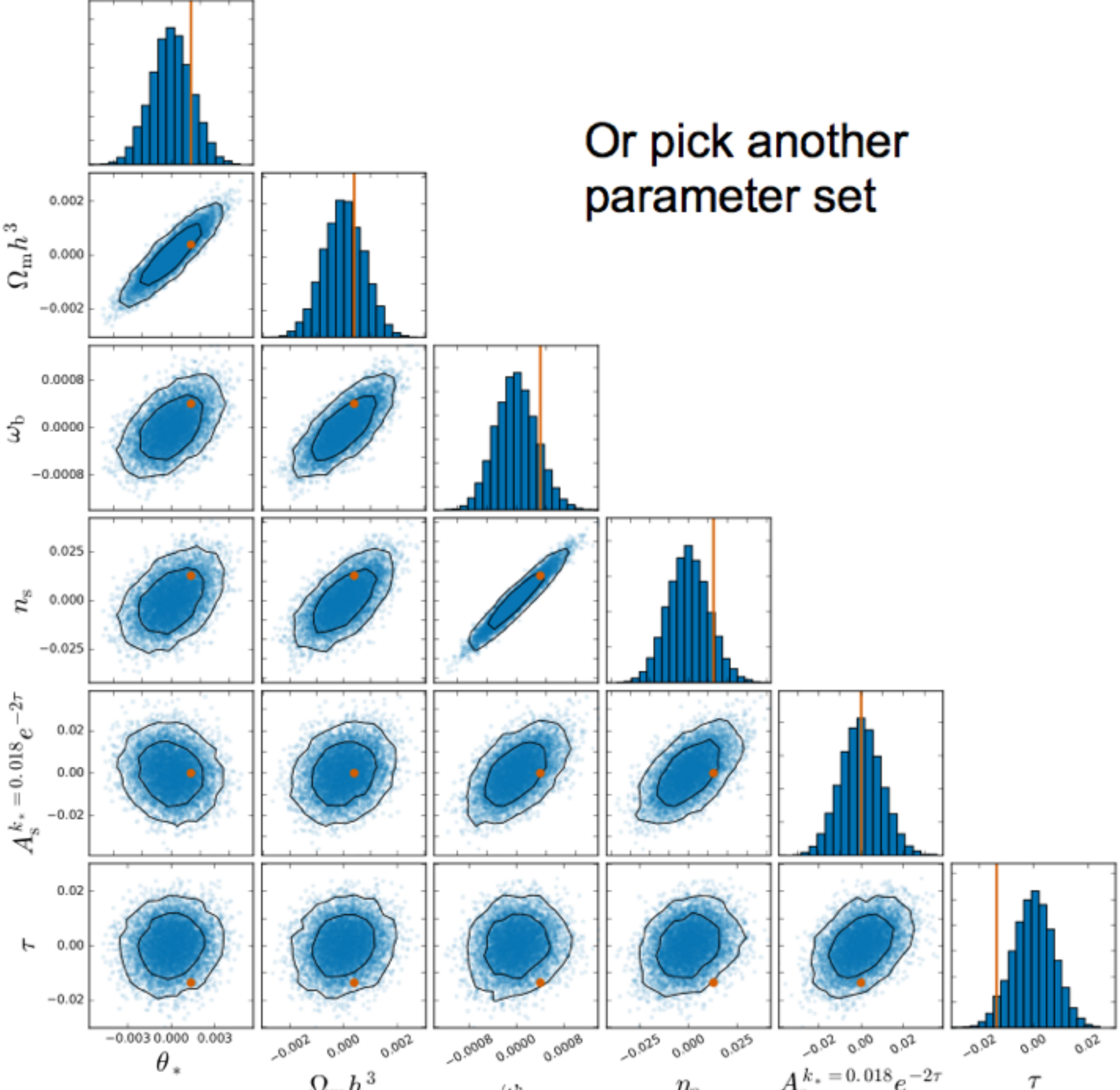
Blue is shifts from suite of simulations

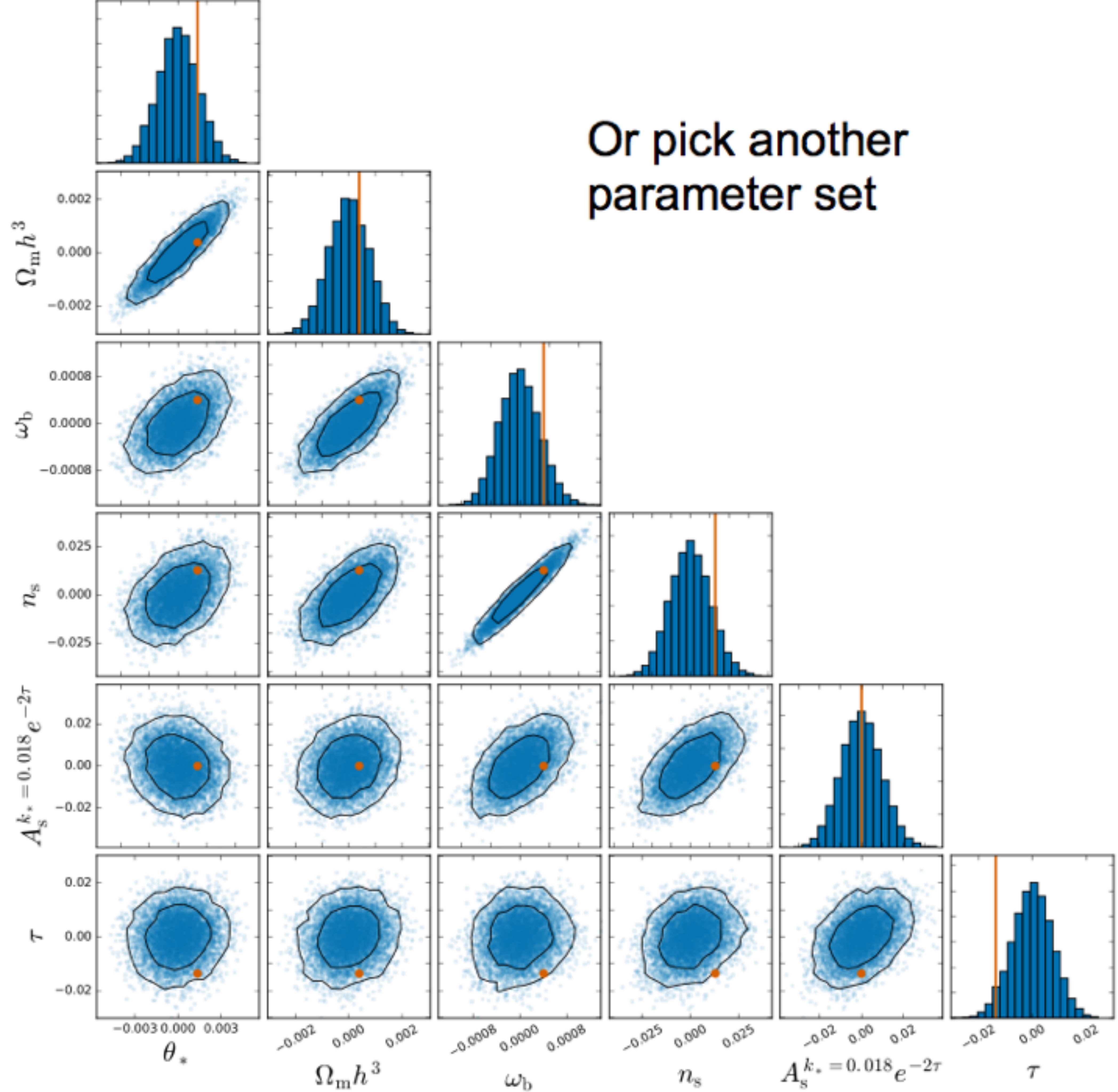
Orange shows actual data

Are these shifts bigger than you'd expect?

Hard to do "chi-by-eye" because of correlations

Or pick another parameter set



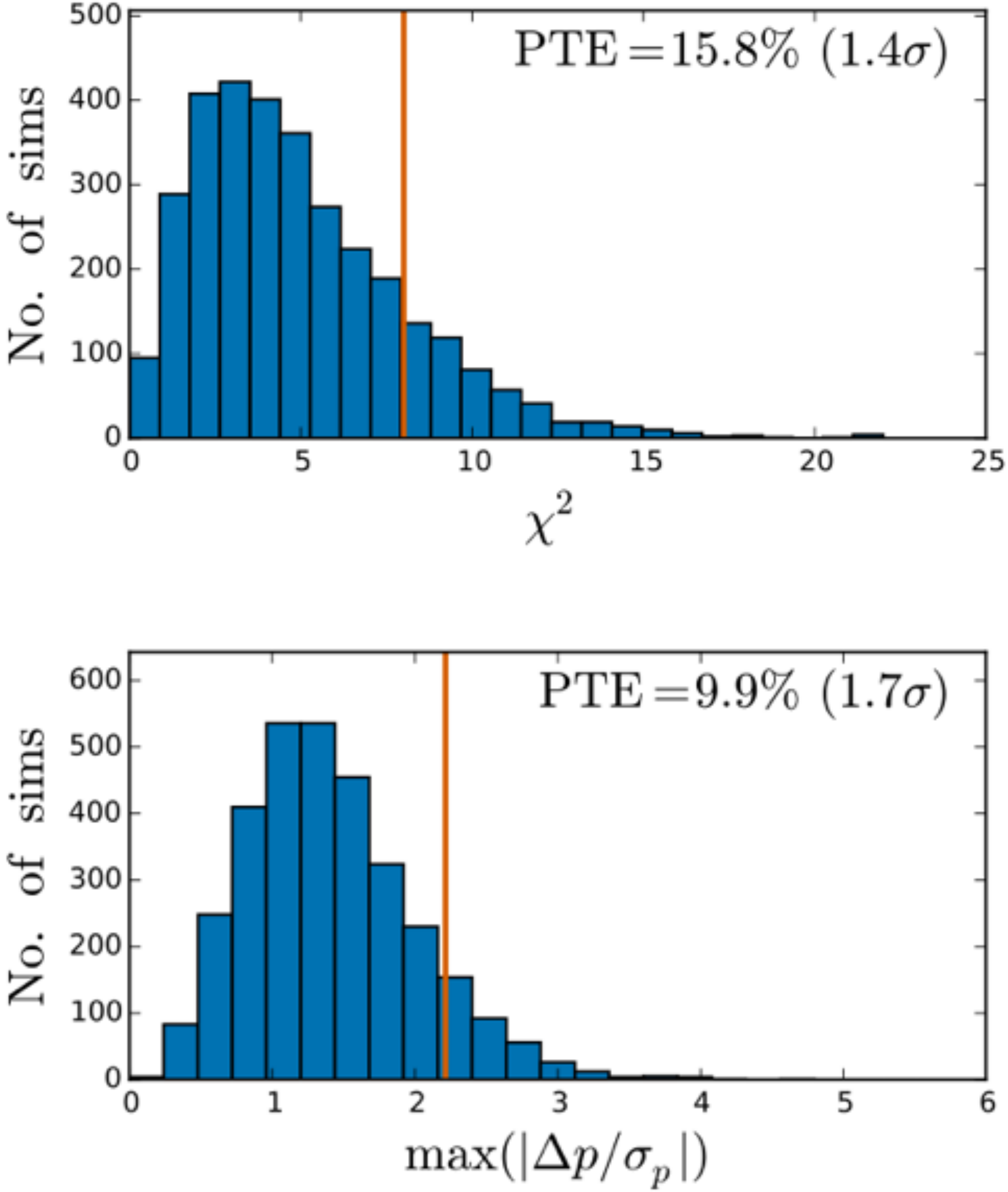


Or pick another parameter set

Now you can see that overall it's not bad

So how big are shifts overall?

Need a statistic that assesses the whole set of parameters



Examine two specific statistics

Overall shift not dramatic

Focusing on biggest parameter shift is misleading (unless you marginalize)

Tensions within CMB

Tensions within CMB

- Overall ℓ>800 versus ℓ<800 gives parameter shifts that are <2σ (if you take into account the set of parameters)
- An apparent excursion at low ℓ (<30) "explains" some of the parameter shifts
- An oscillatory-like power excursion around ~1000 gives much of the remaining shifts (and "explains" A_L>1)
- This "oscillation" doesn't look like a foreground effect

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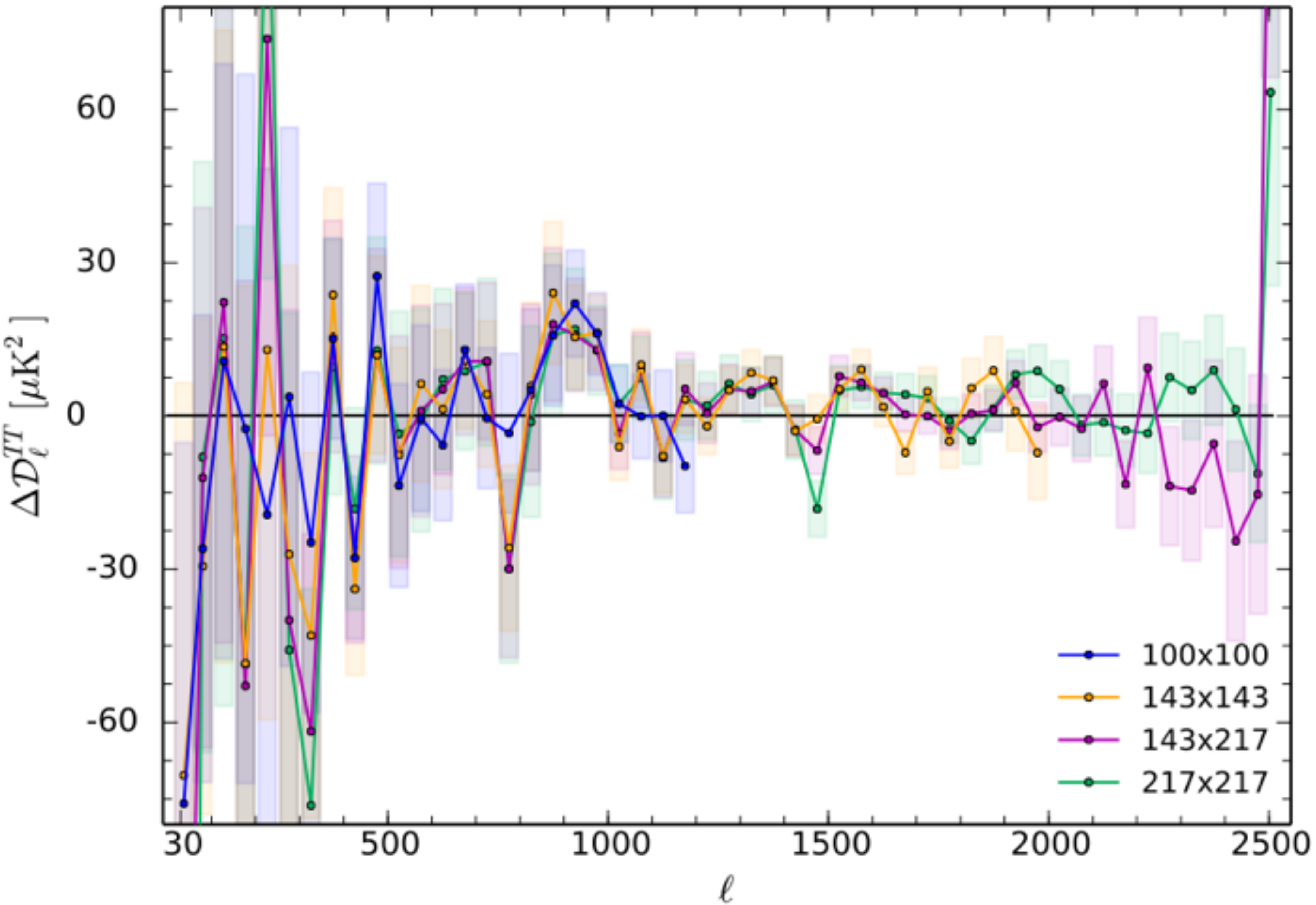
No tensions within CMB!

Residuals don't look like foregrounds



Anomalies?

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

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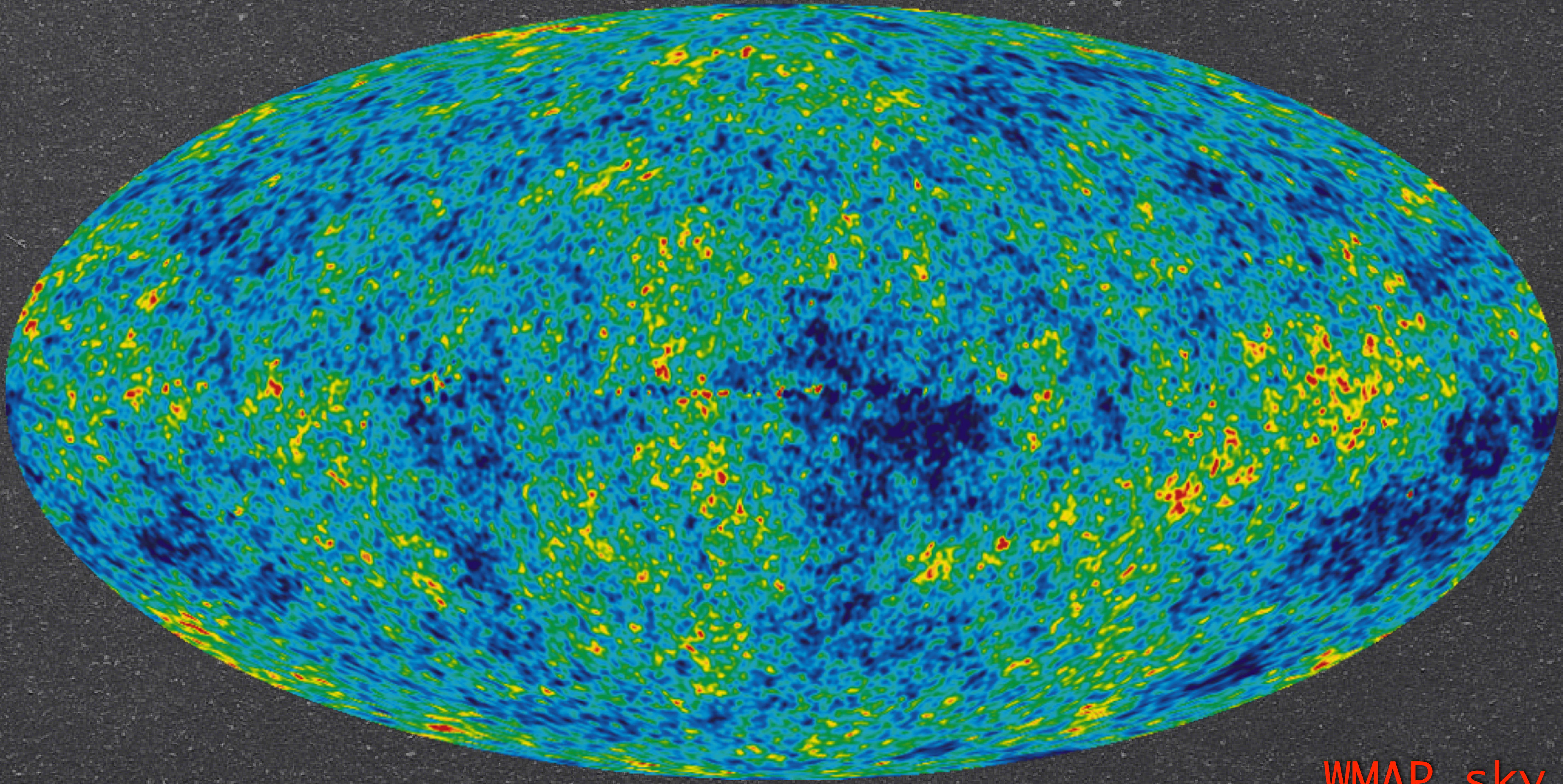
- WMAP large-scale anomalies persist
- But are still of fairly low significance
- Are any of them telling us something?

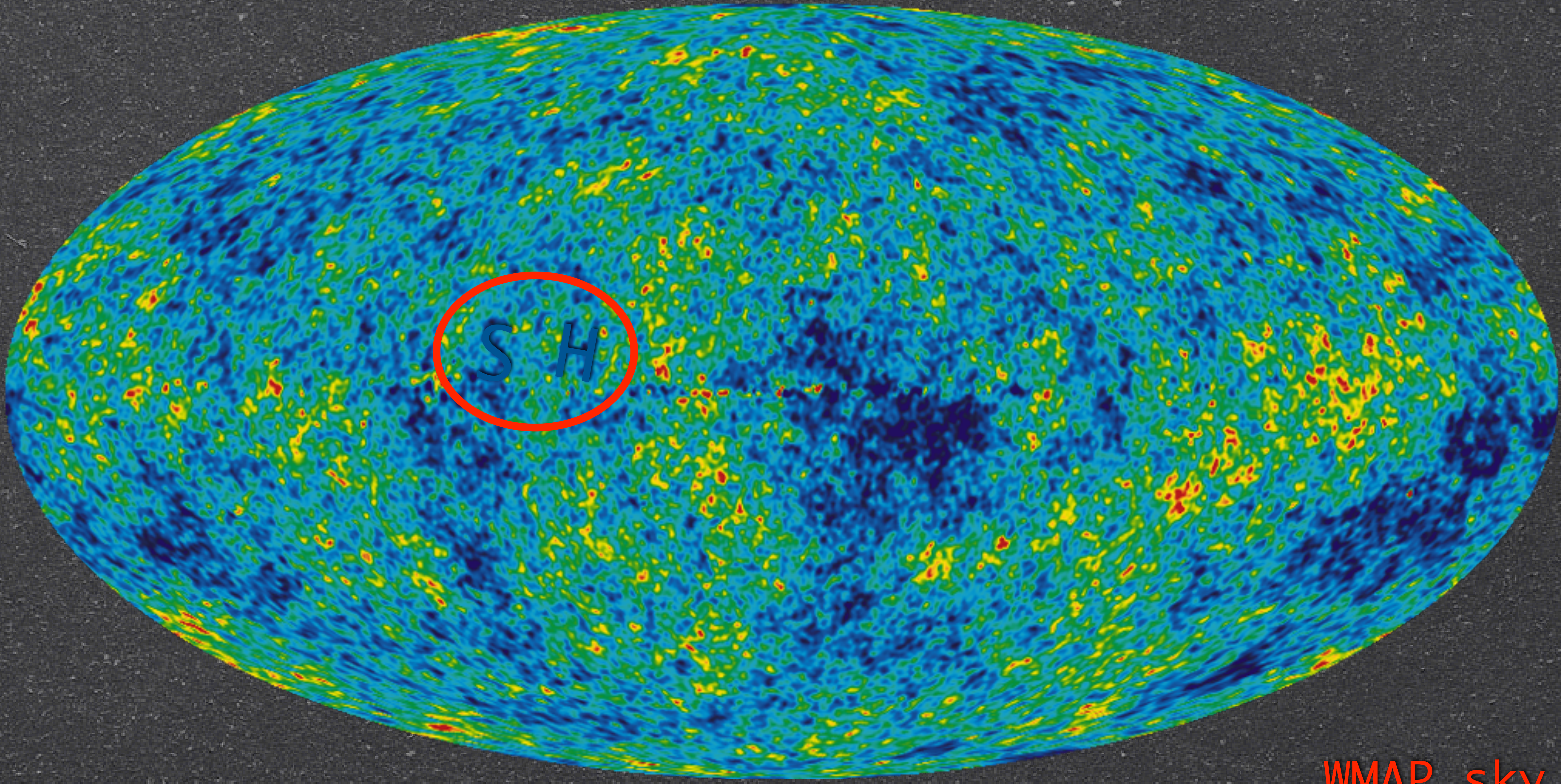
- Low quadrupole
- “Cold Spot”
- “Hemispheric Asymmetry”
- First ~30 multipoles seem low
- Low multipole alignment
- Odd/even multipole asymmetry
- ...

CMB anomalies?



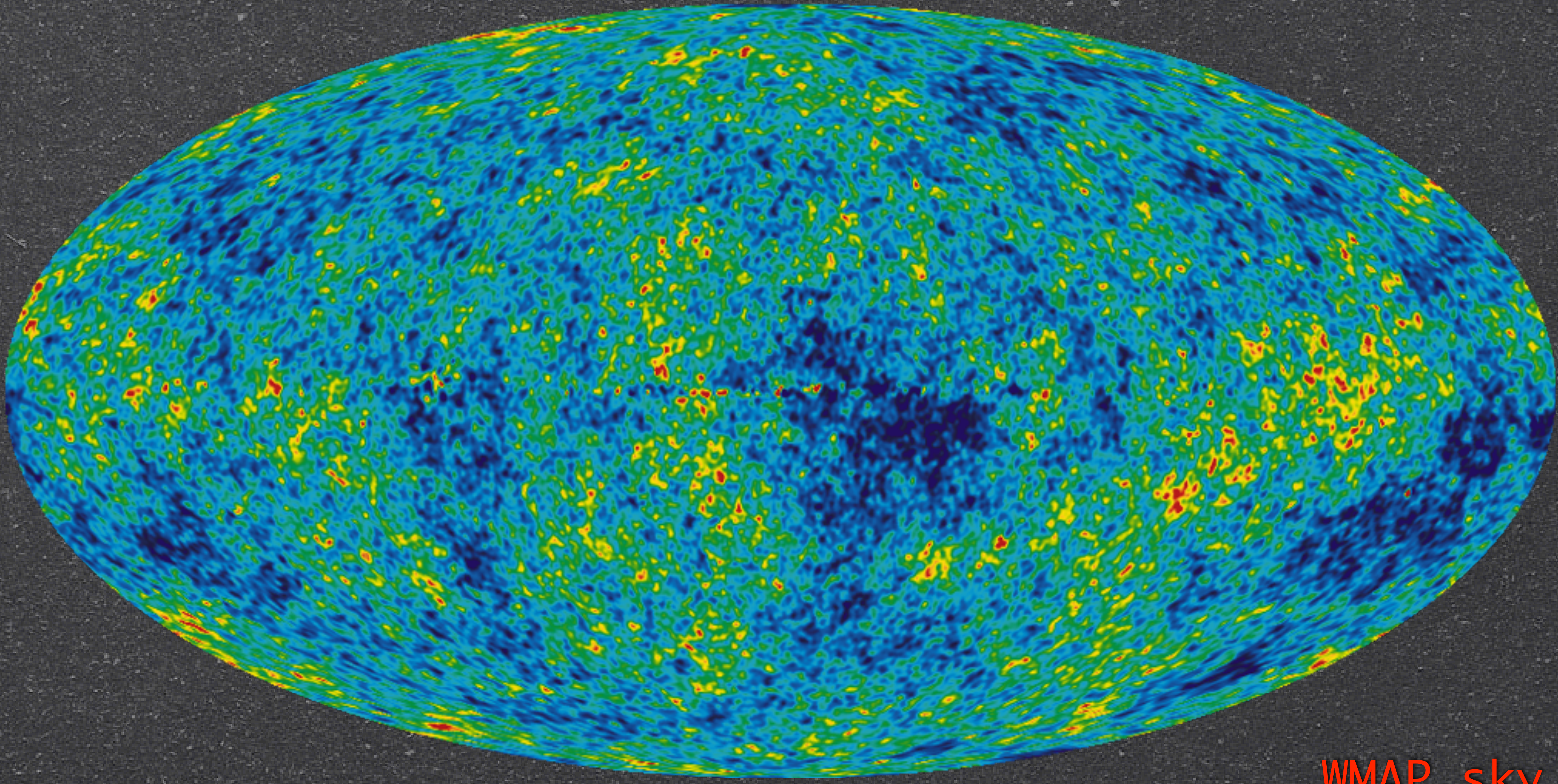
WMAP sky

CMB anomalies?



WMAP sky

CMB anomalies?



WMAP sky

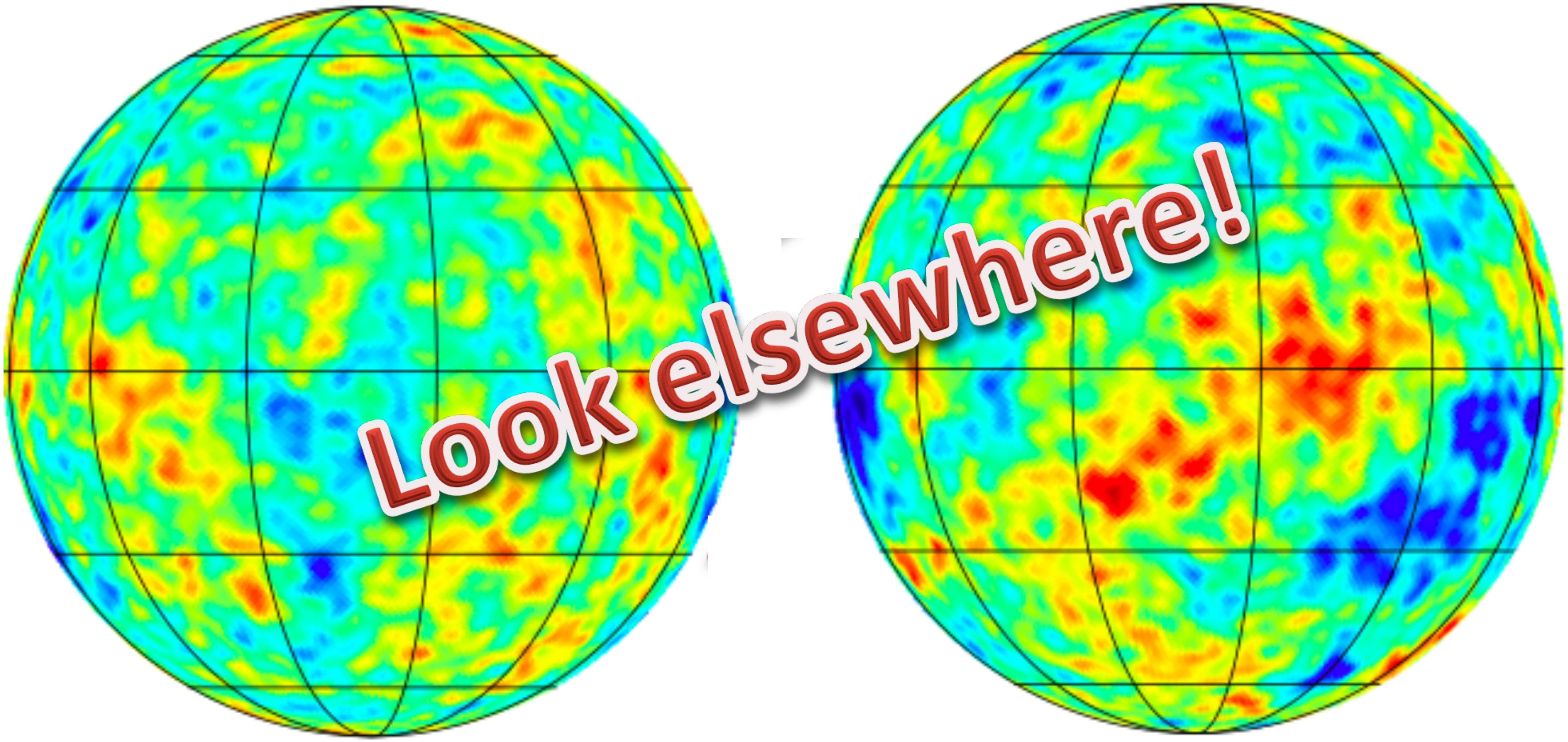
See this paper for details!

Pi in the Sky

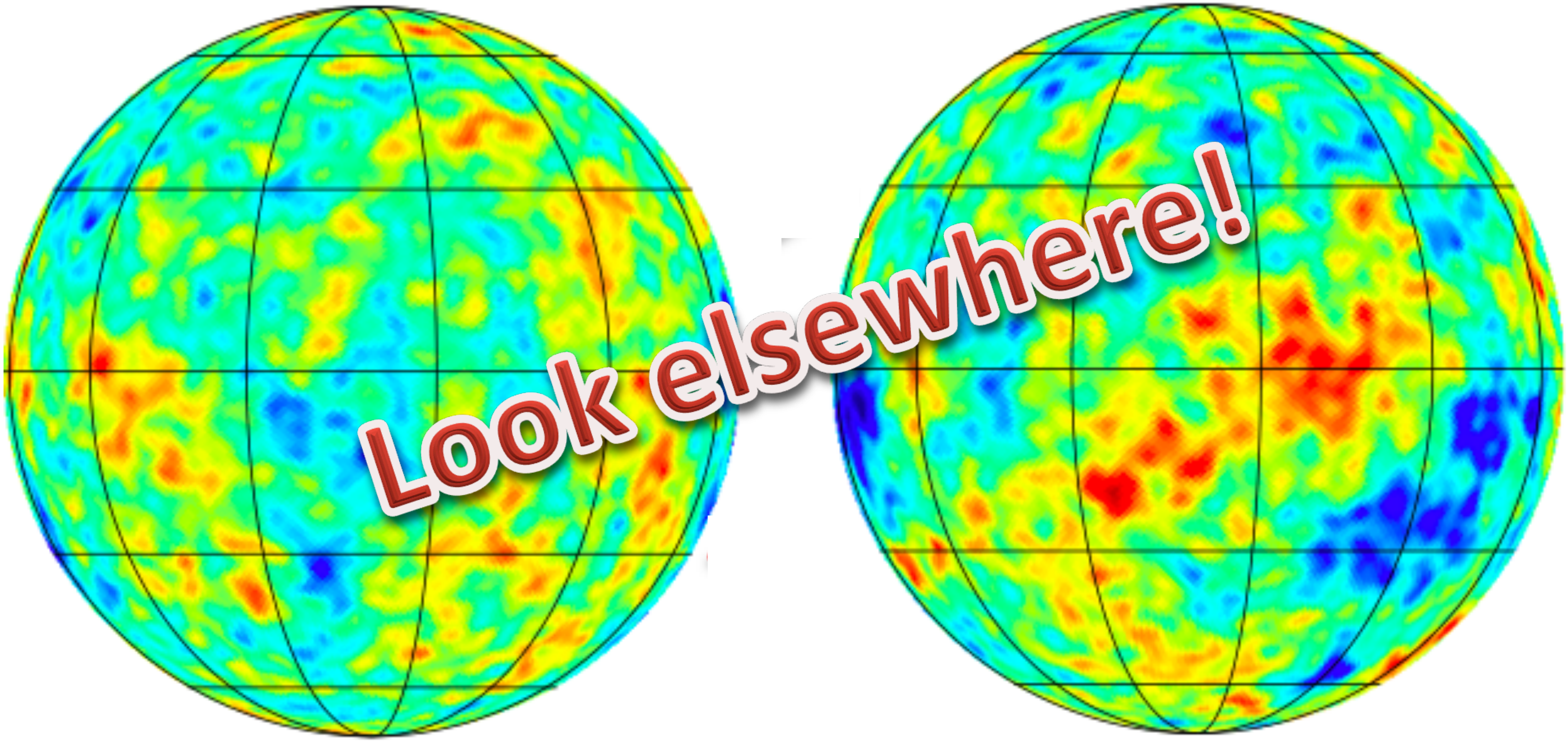
Ali Frolop* and Douglas Scott†
Dept. of Physics & Astronomy, University of British Columbia, Vancouver, Canada
(Dated: 1st April 2016)

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.

Large Angle Anomalies

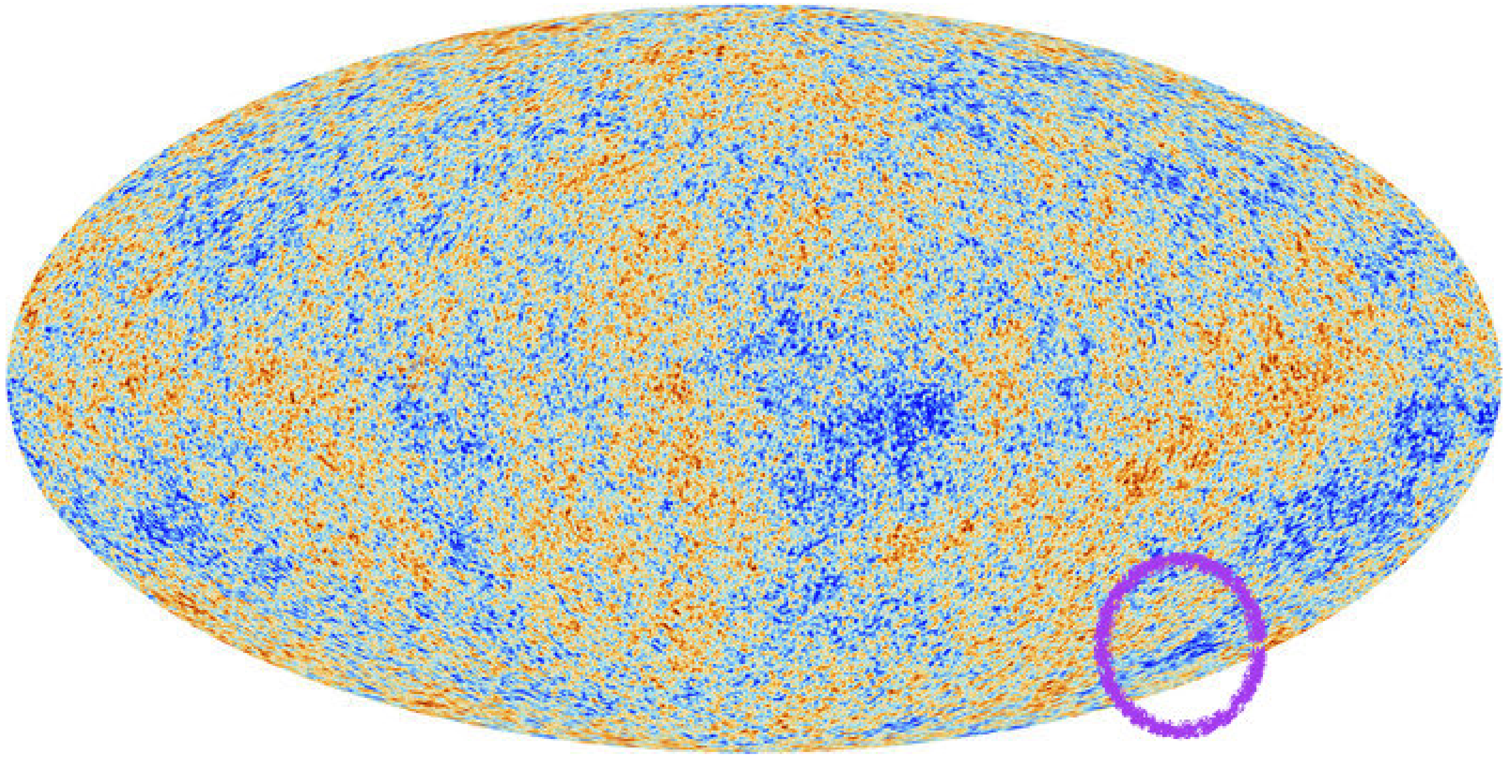


Large Angle Anomalies



Also known as "multiplicity of tests"

Cold Spot



(a)

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 71010003137838752886587533208381420617177669147303
```

(b)

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.

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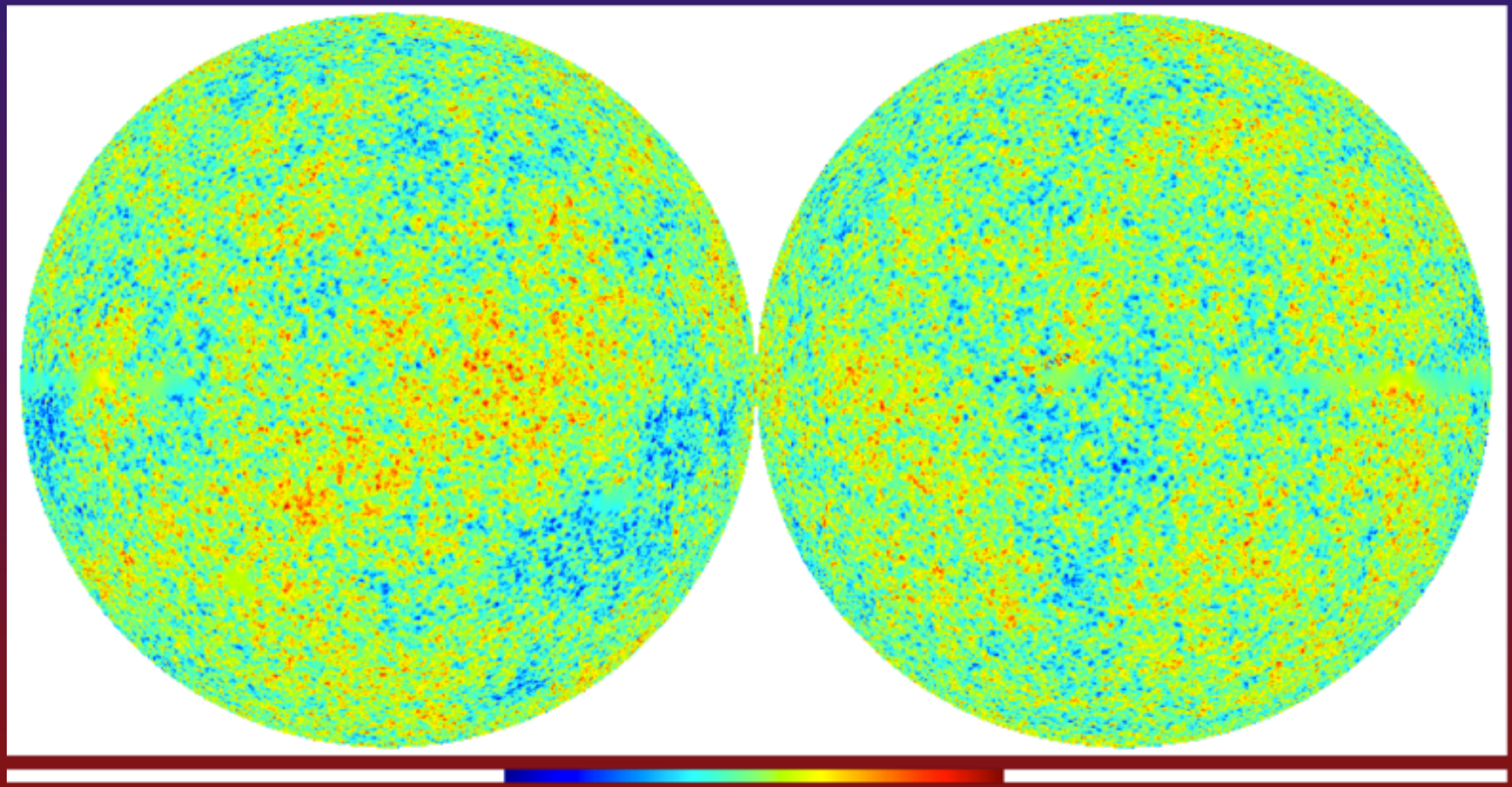
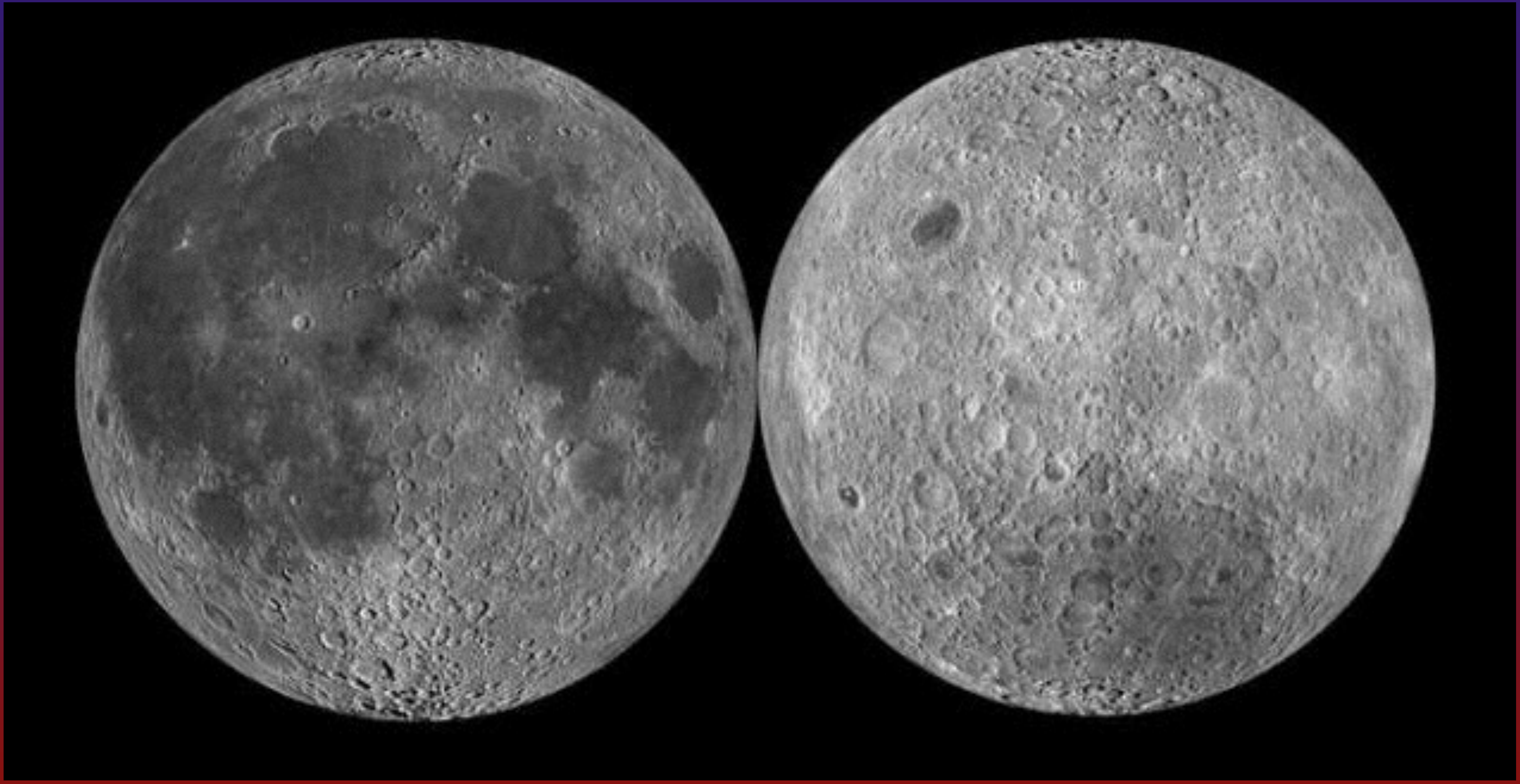
- We have to be cautious about "a posteriori" claims
- <u>But</u>, these are special and important modes
- So we should continue to look for "explanations"
- <u>And</u> look in independent data, e.g. polarization

(this is being done for next Planck I&S paper)

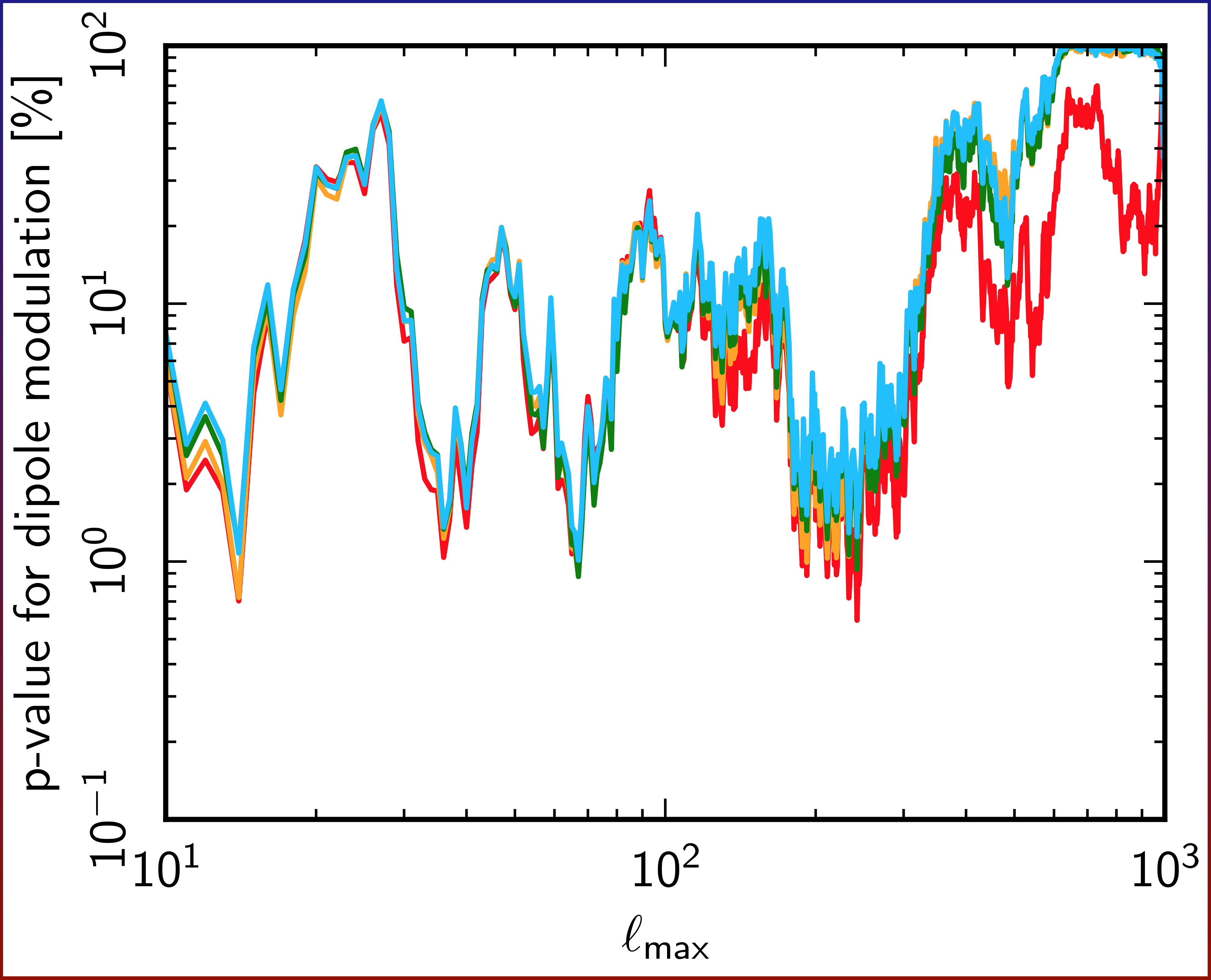
Do the 2 sides of the CMB sky look alike?



Do the 2 sides of the Moon look alike?



Probability of dipole modulation



- Some dipole modulation (or hemispheric asymmetry) is <u>expected</u>
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- Then when we find some low-p modulation, we have to marginalise over effects of similar p for other ℓ_{max}
- In other words, ask how often you find such apparently unlikely modulations in simulations

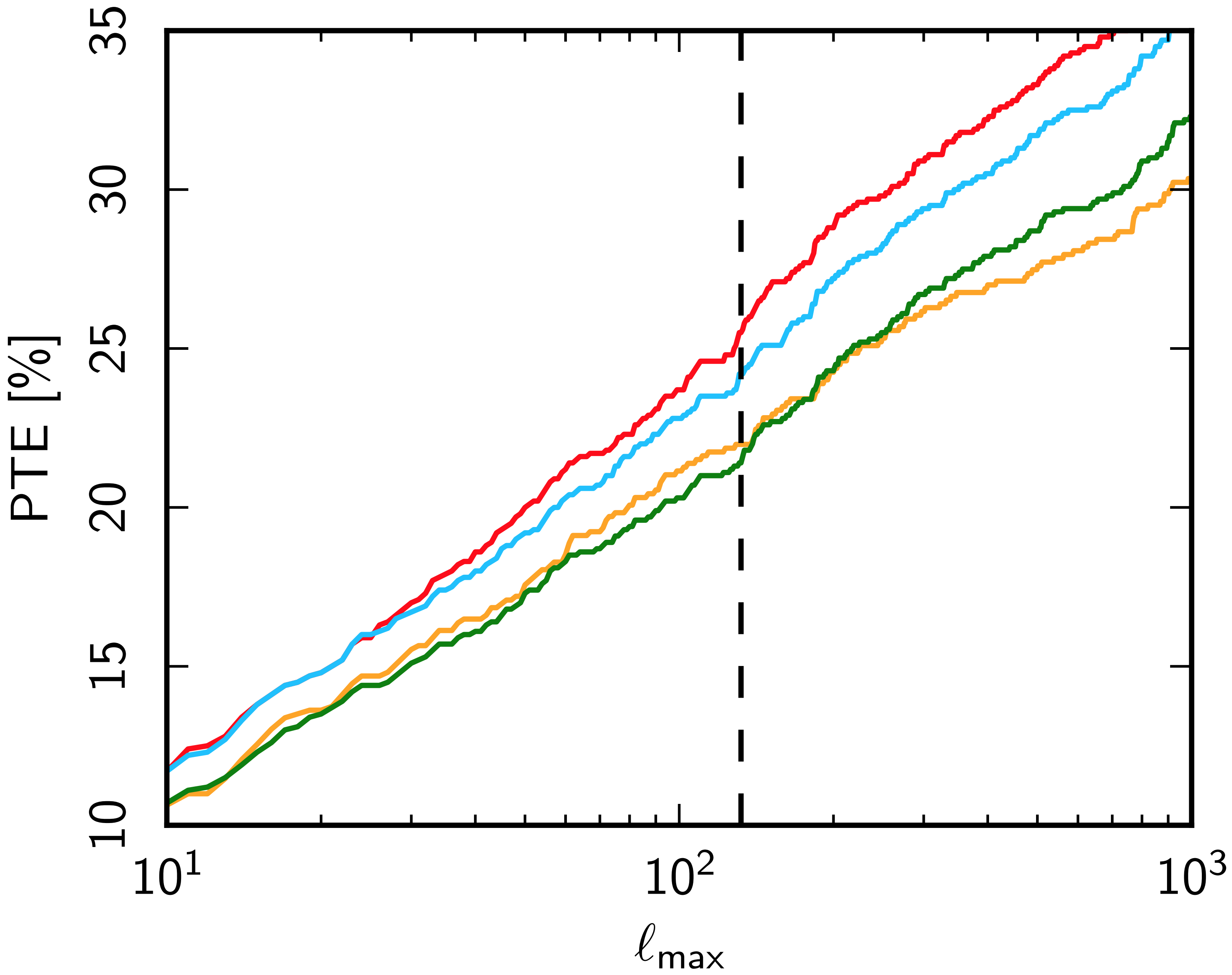
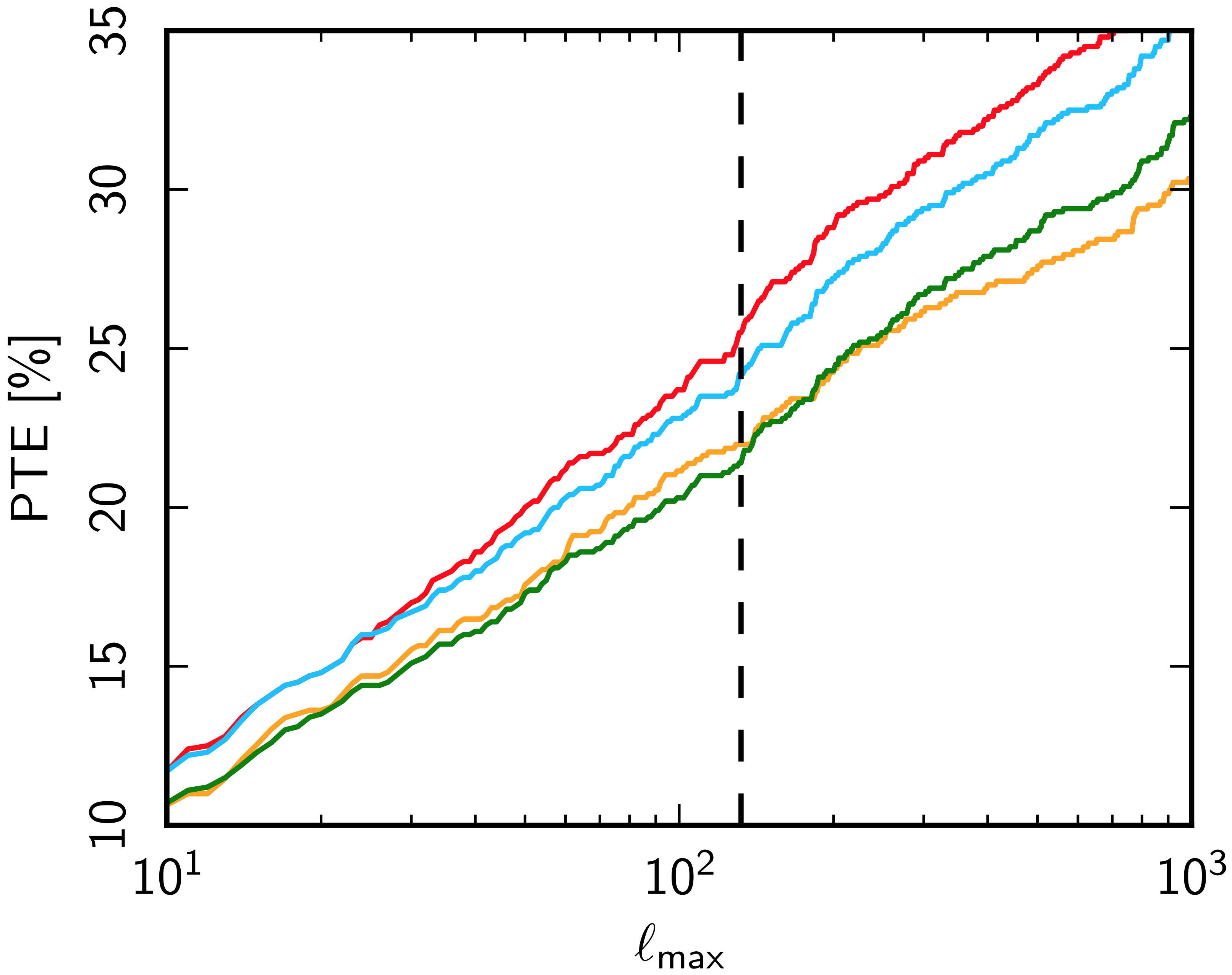


Fig. 31. Probability determined from the QML analysis for obtaining a dipole modulation amplitude at least as anomalous as the `Commander` (red), `NILC` (orange), `SEVEM` (green), and `SMICA` (blue) data sets, for the range $\ell \in [10, \ell_{max}]$. The vertical line corresponds to $\ell_{max} = 132$ which was used as the search limit in Bennett et al. (2011). The probability grows approximately logarithmically with ℓ_{max}. This means that the adopted probability to exceed is fortunately not very sensitive to ℓ_{max}, and for any reasonable choice is above 10 %.



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Marginalising over values of $\ell_{\rm max}$ (i.e. looking for modulations with equal *p*-values in the simulated data sets) shows that the "probability to exceed" is <u>not</u> small

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- We appear to have a fairly precise model for the Universe on the largest scales
- But: Where did the parameters come from?
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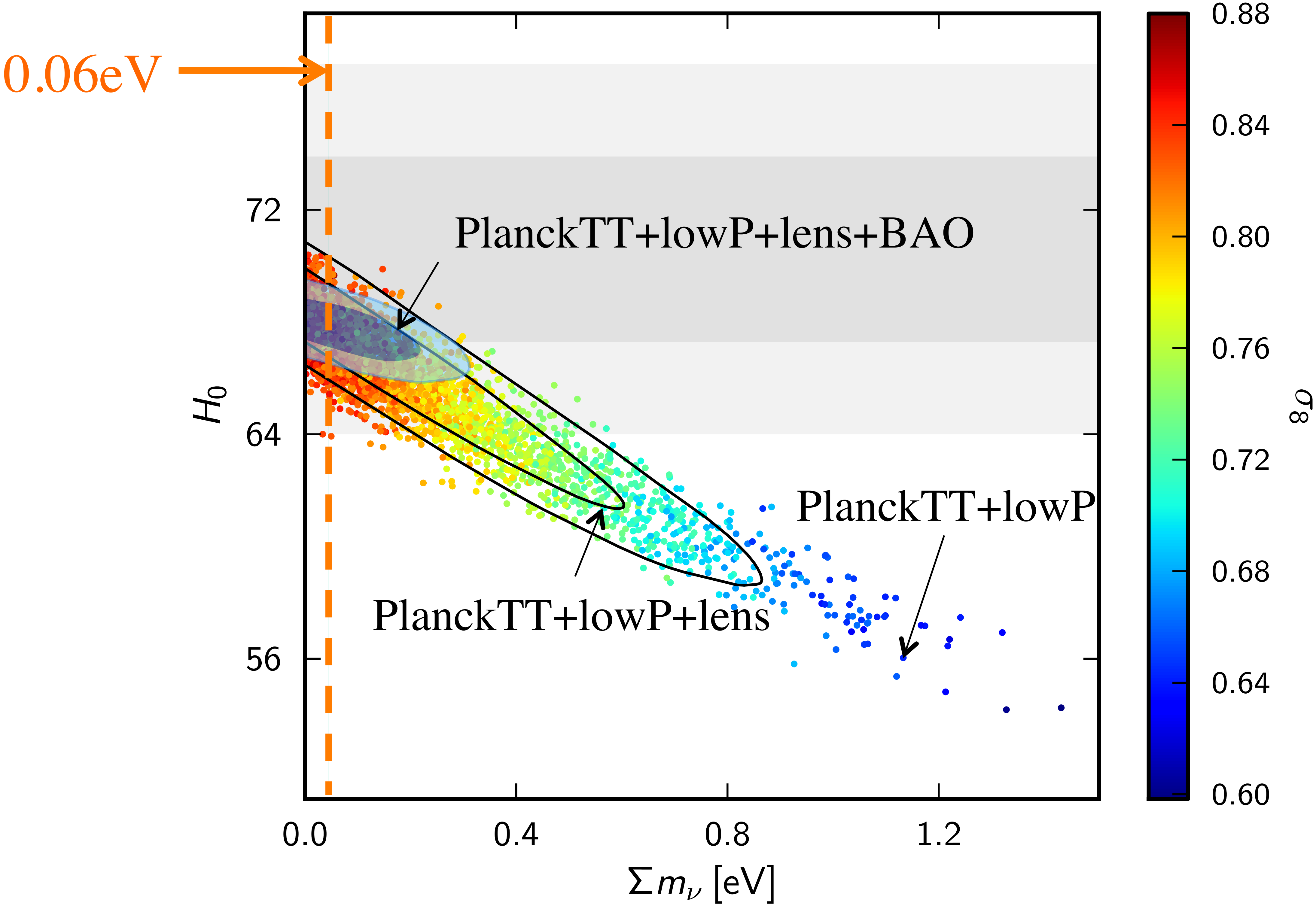
- Could any of the basic assumptions turn out to be wrong?

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?

Constraints on neutrinos now tighter



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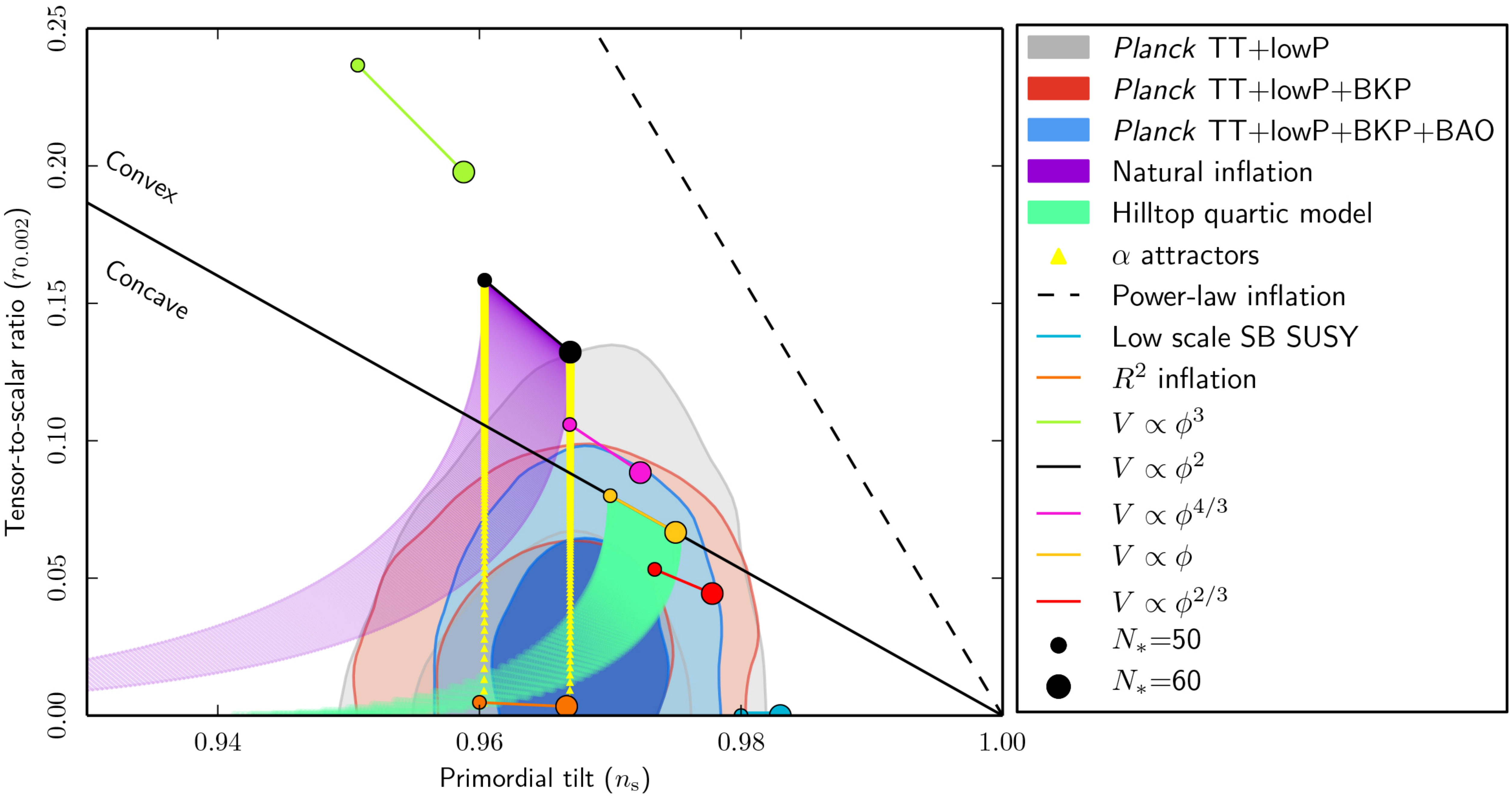
Planck 2015 and inflation

- Ω_K=0.000±0.005 (95%CL)
- n_s=0.968±0.006
- $dn_s/d\ln k$=−0.003±0.007
- no features required in fits
- r<0.11 (*Planck TT+TE+EE*)
- r<0.12 (BICEP2+Keck Array+*Planck BB*)
- r<0.08 (combined)
- f_{NL}(local)=2±6; f_{NL}(equil)=0±40; f_{NL}(ortho)=−26±21
- isocurvature < few% (depending on mode)
- no evidence of cosmic defects

Planck 2015 and inflation



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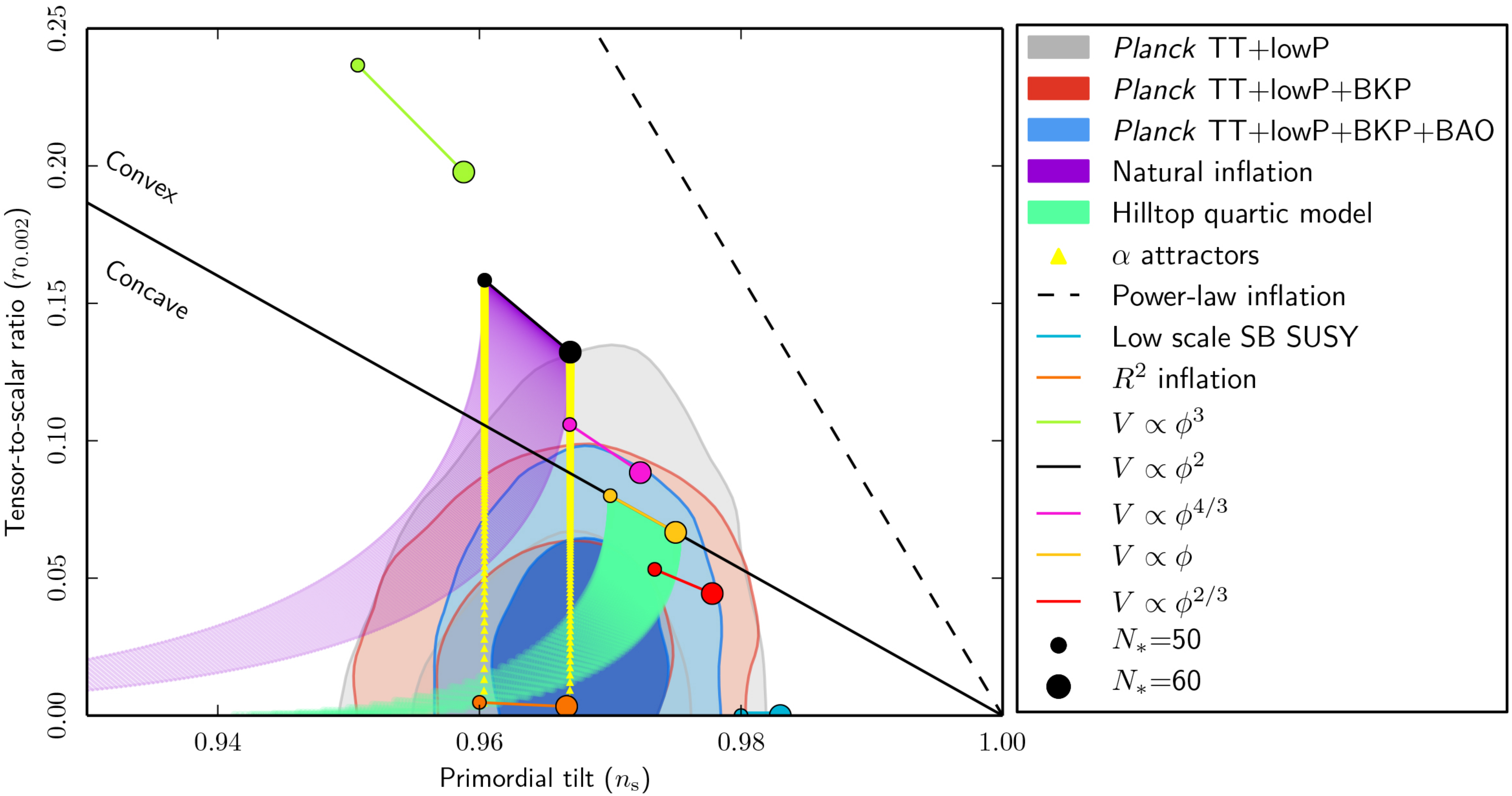
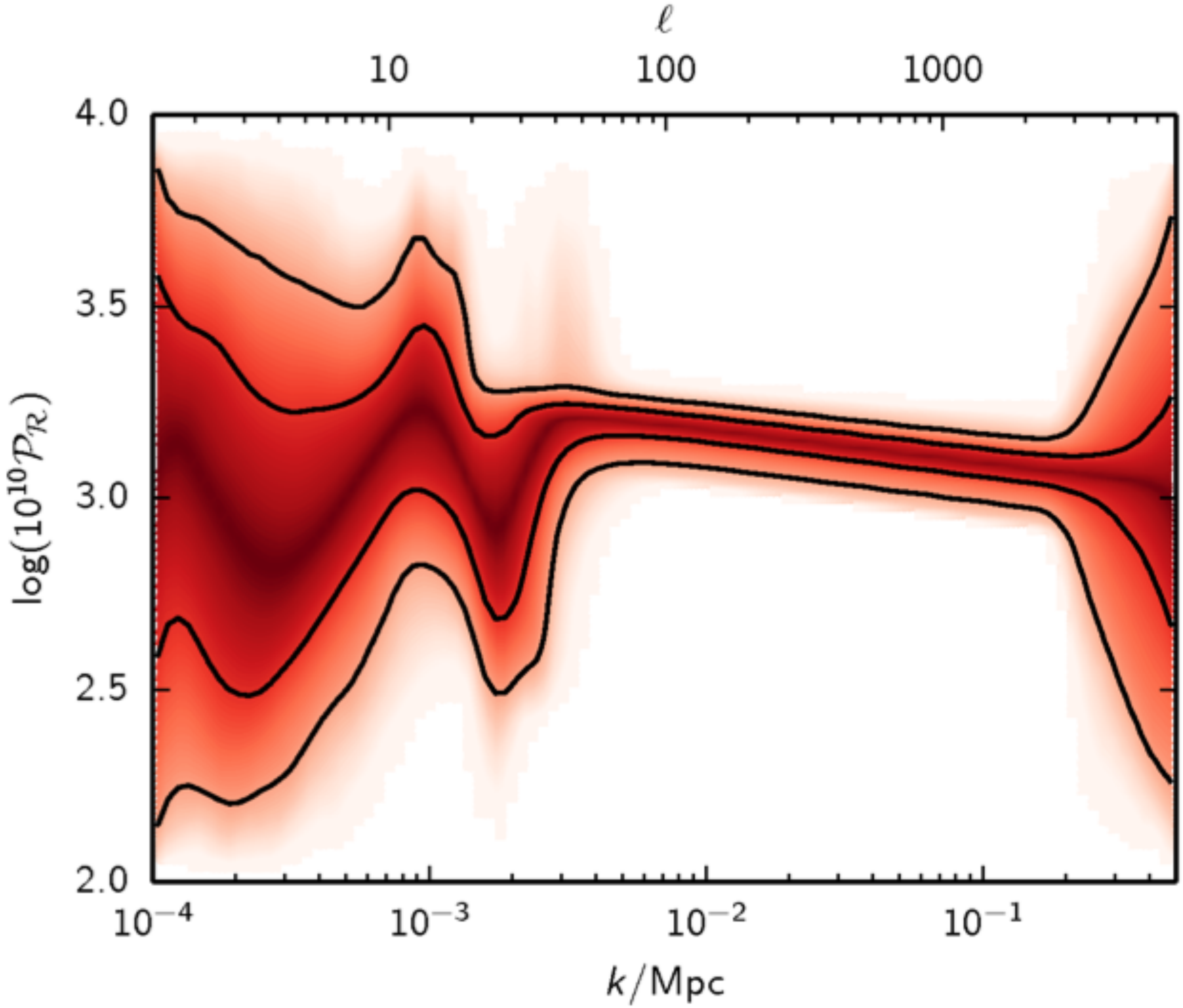


V ∝ φ^2 now disfavoured by data

Power spectrum reconstruction (typical example)



Clearly we've learned <u>something</u>, but what?

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This is my best attempt:

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This is my best attempt:

"Something like inflation
is something like proven"

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 ?

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

Dark Energy Theories

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
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- Dark fluid
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- 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

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(Did someone say the "A" word?)

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SMPP

- Late 1960s / early 1970s
- Predicted:
  - W,Z,c,t,g,Higgs
- Not fundamental
- Observer independent (not stochastic?)
- Very very precise
- What's next?

SMC

- Early 1990s
- Predicted:
  - many things!
- Not fundamental
- Observer dependent (time + cosmic variance)
- Getting very precise
- What's next?

What about non-standard models?

- Global anisotropy, rotation, topology
- Isocurvature or defect contribution
- Primodial magnetic fields
- We live in the centre of a void
- Interacting Dark Matter
- Modifications to Gravity
- Variable fundamental constants

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BUT NEED STRONGER MOTIVATION TO THROW OUT EVERYTHING!

A new model of the Universe

Anon

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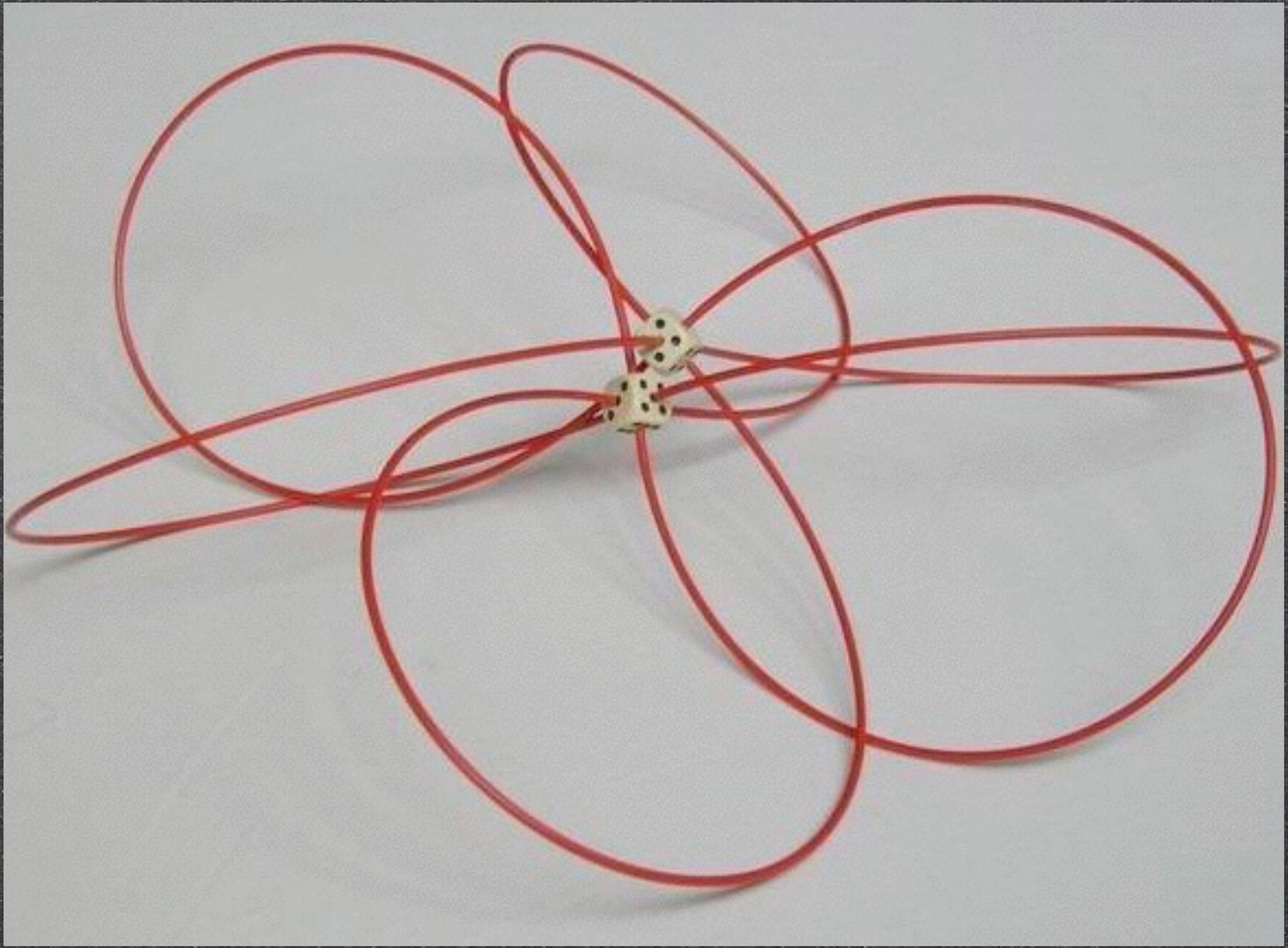
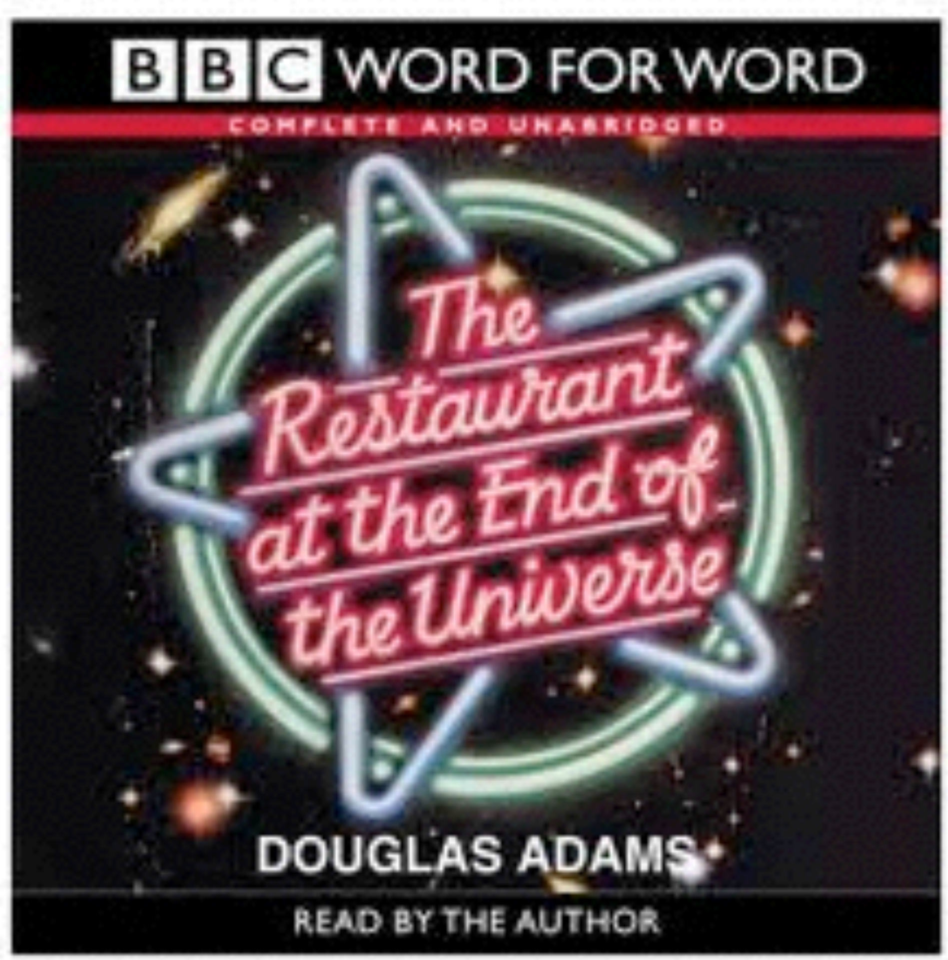


Anon

Douglas Adams

The Restaurant at the End of the Universe



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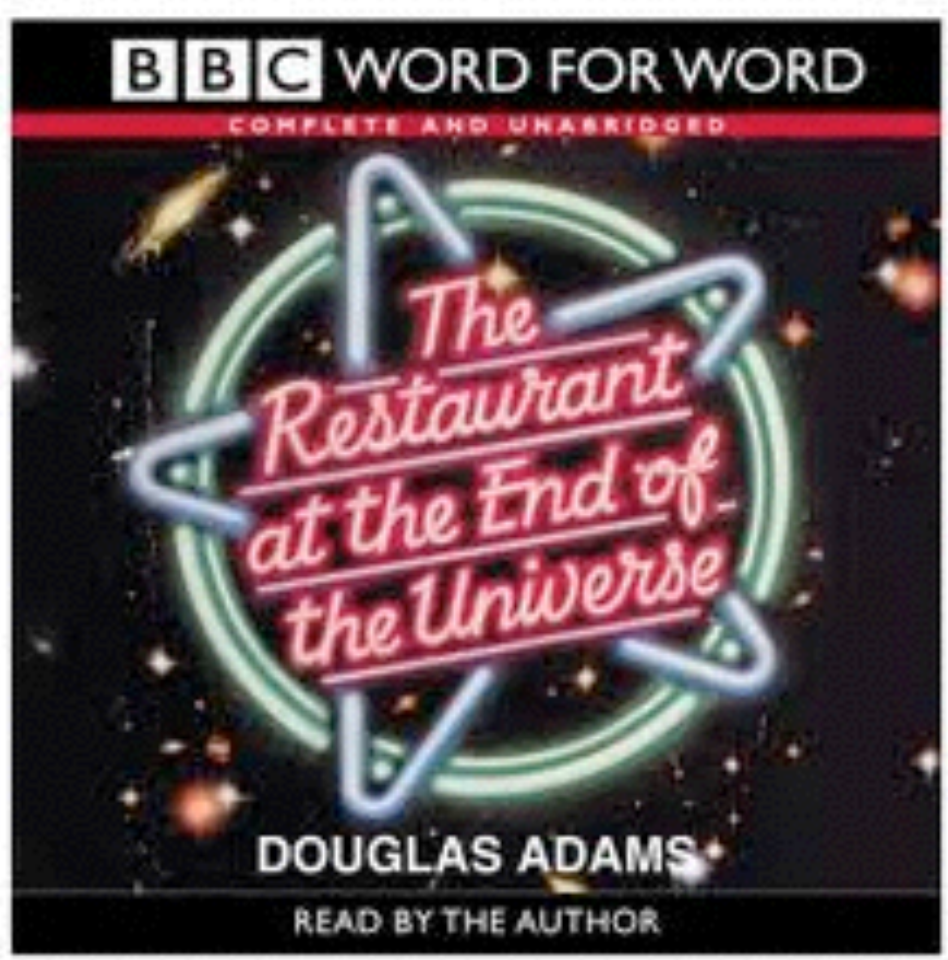

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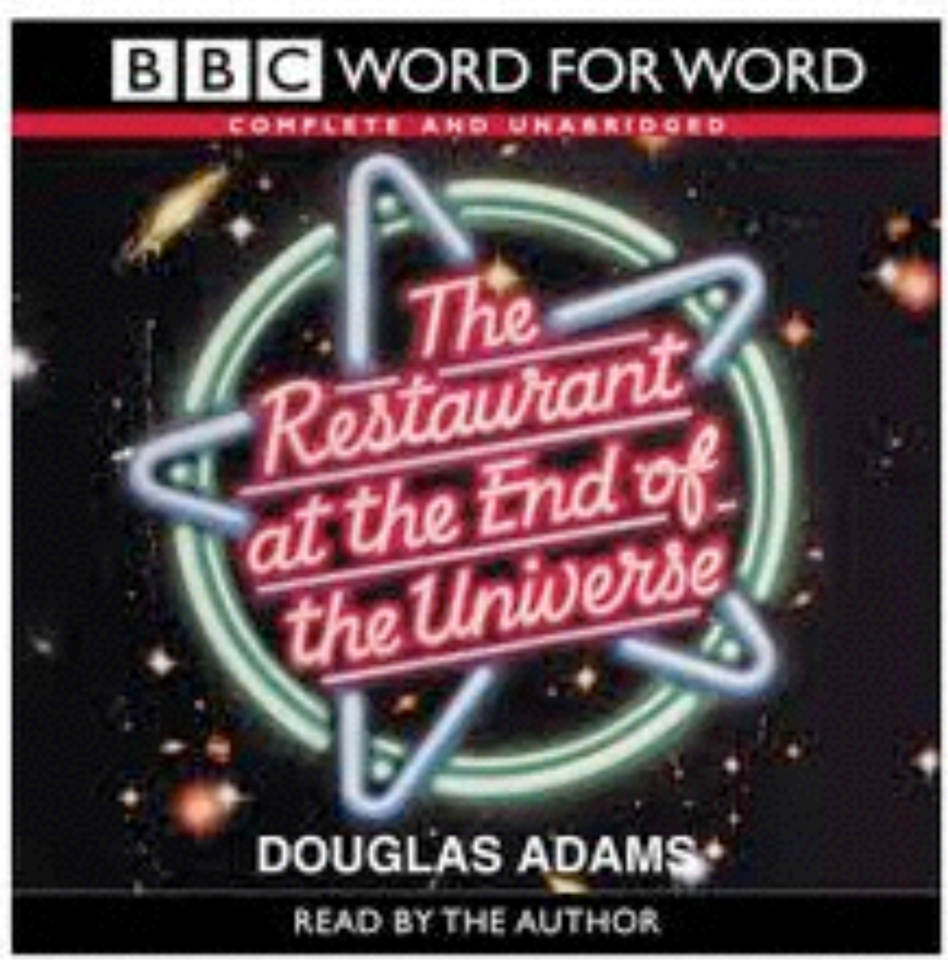

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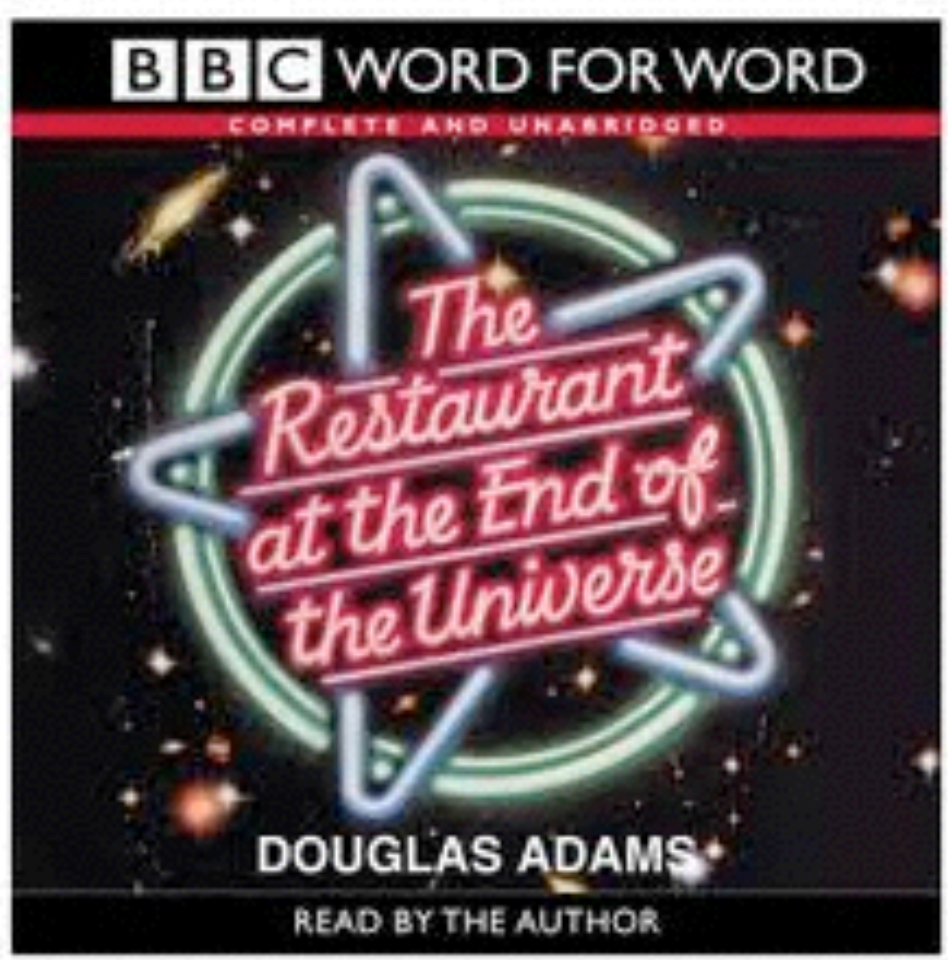

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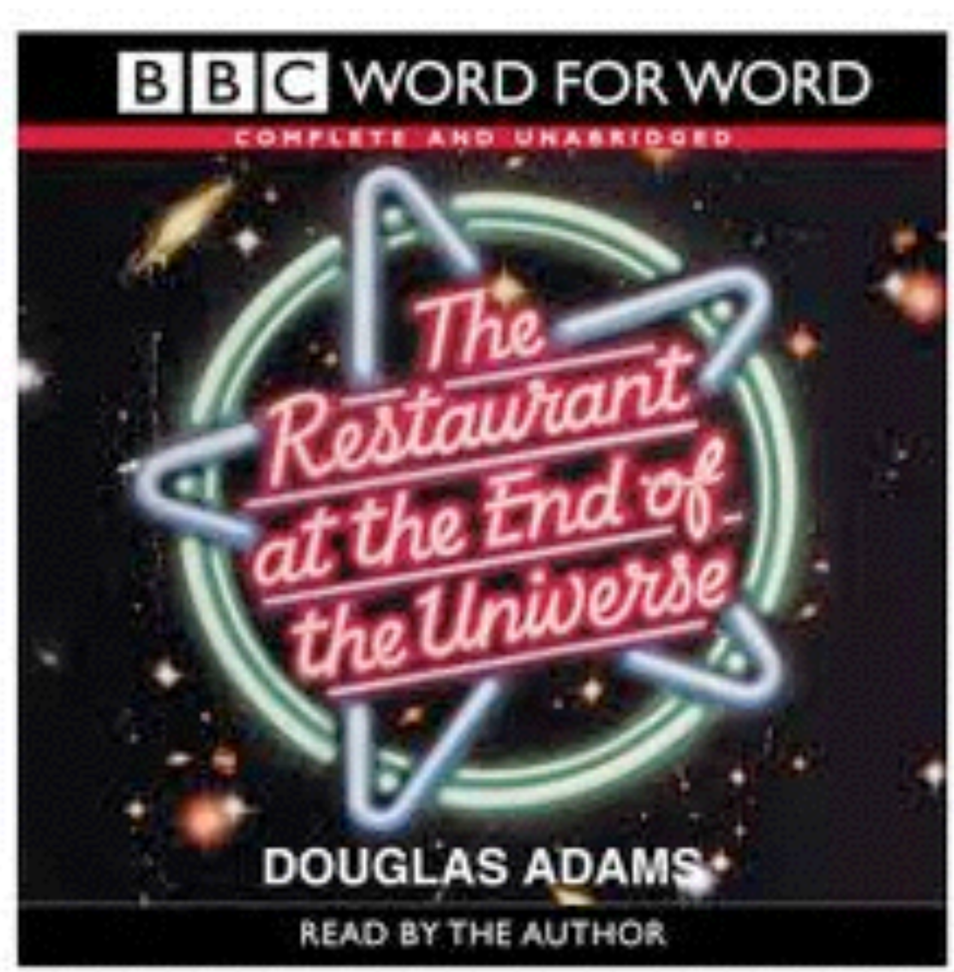

Cosmic Mnemonics

With Ali Narimani + Don Page (+Jim Zibin) arXiv:1309.2381, Phys. in Canada

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  - $H(t \to \infty) = (56.4 \pm 1.1)$km/s/Mpc

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- Growth factor today: g=0.784±0.006
- Reionization: fraction of CMB scattered = 8.8%
- Scaling of acoustic peaks = 0.6° (=Sun or Moon)
- $\Omega_m/\Omega_b = 2\Omega_\Lambda/\Omega_m$ (=5.4)
- $\Omega_\gamma = 5.4\times10^{-5} = \alpha^{-2}$
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$\theta_\star = r_S/d_A$

Measured to >2000σ

We call this the Planck Scale!

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Lose some of the detailed slides in the middle of the talk (examples of proofs of SMC + some of math parts?)