What do we know about the Universe?

Douglas Scott

February 2013

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→ The Standard Model of Cosmology

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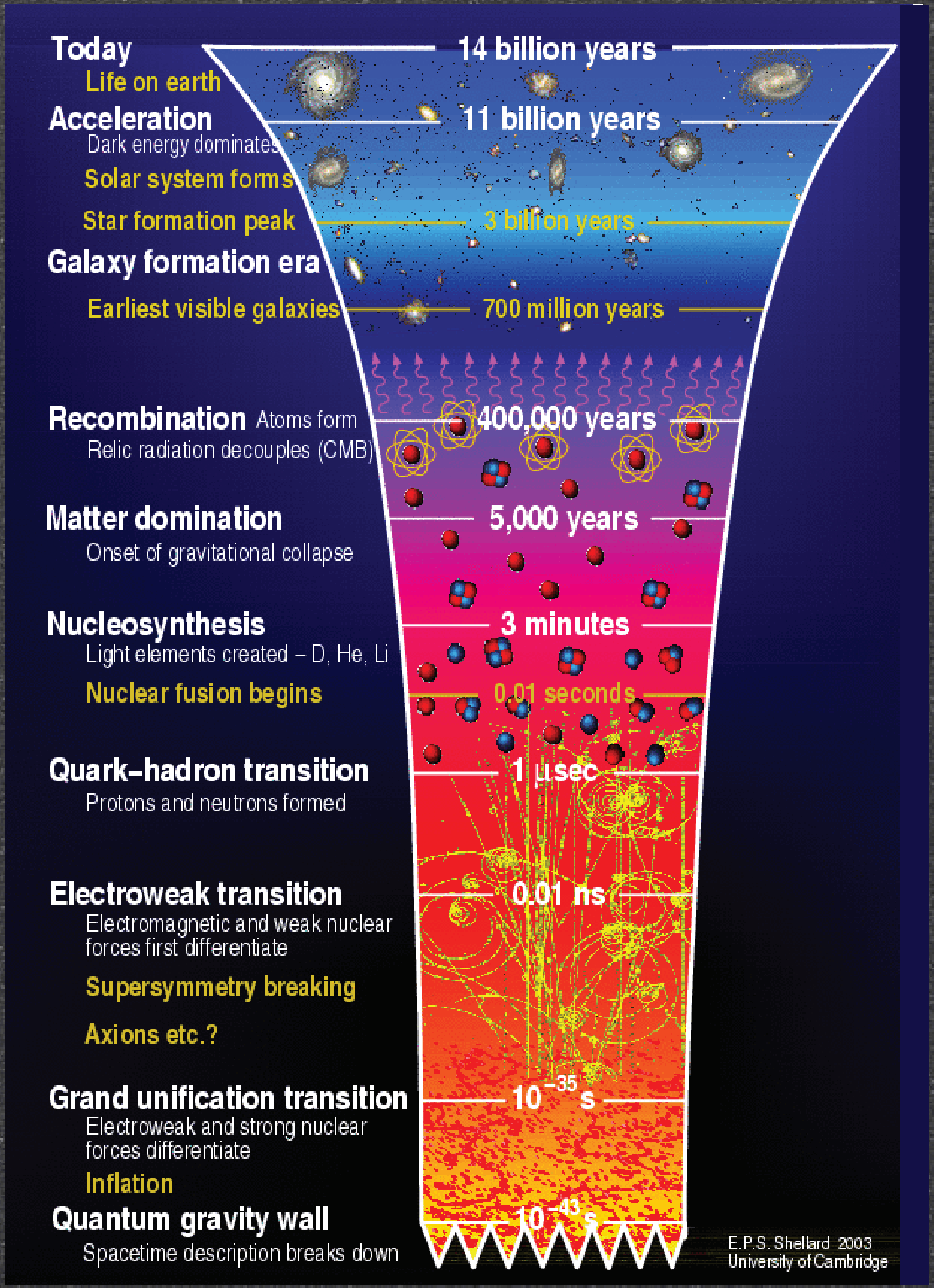
SUMMARY

GR
(easiest soln)
+ expansion
+ CMB
+ simple ICs
+ few components
→ Big Bang
(with spots)



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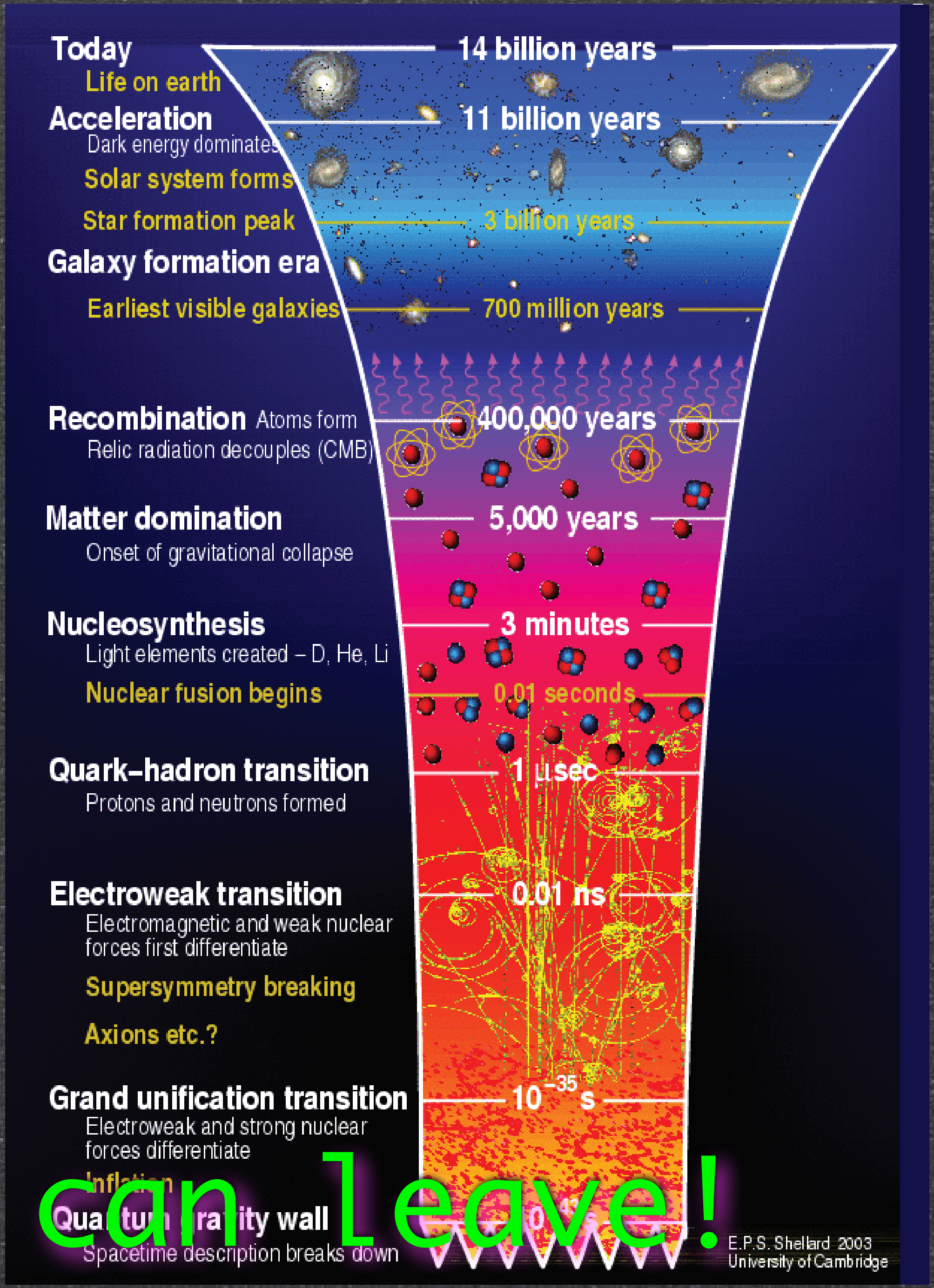
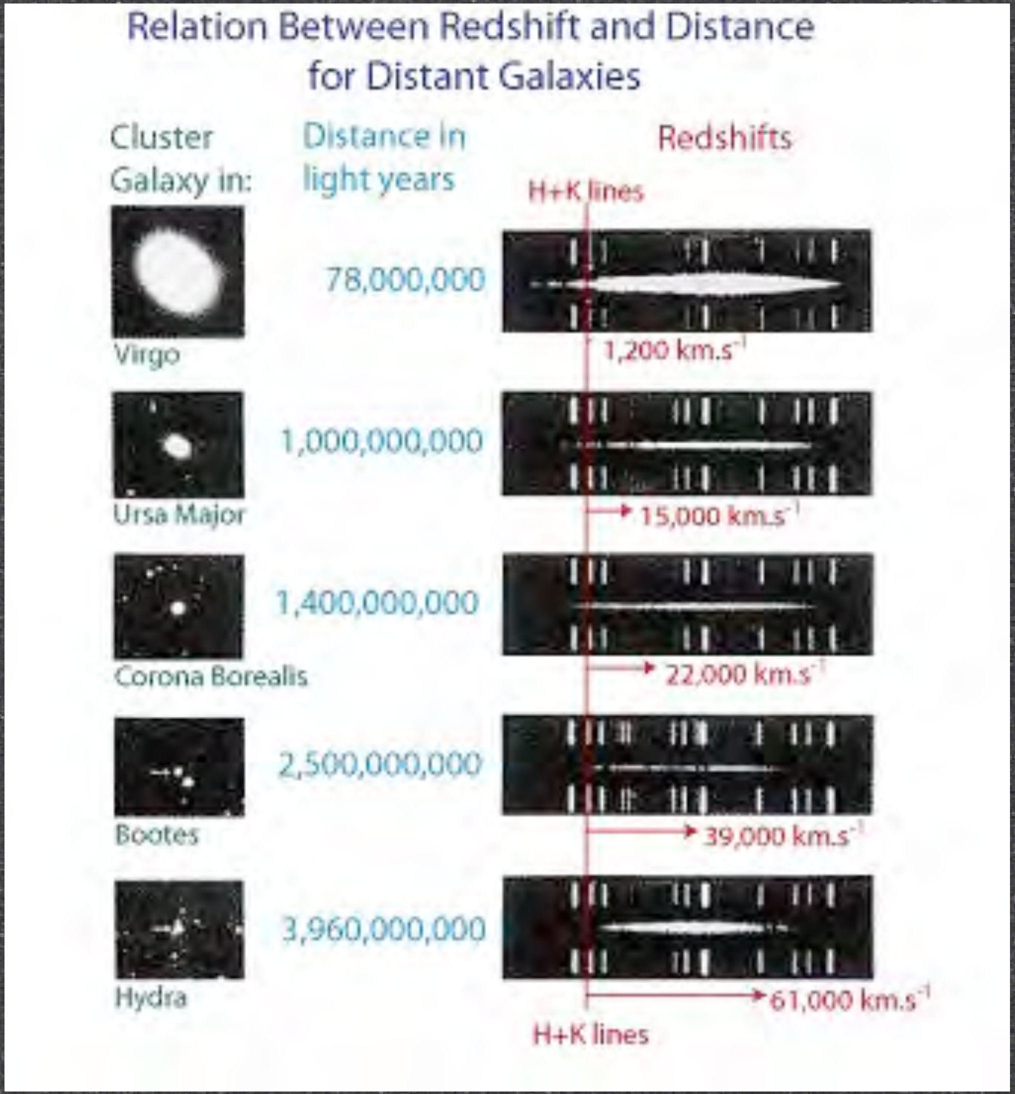
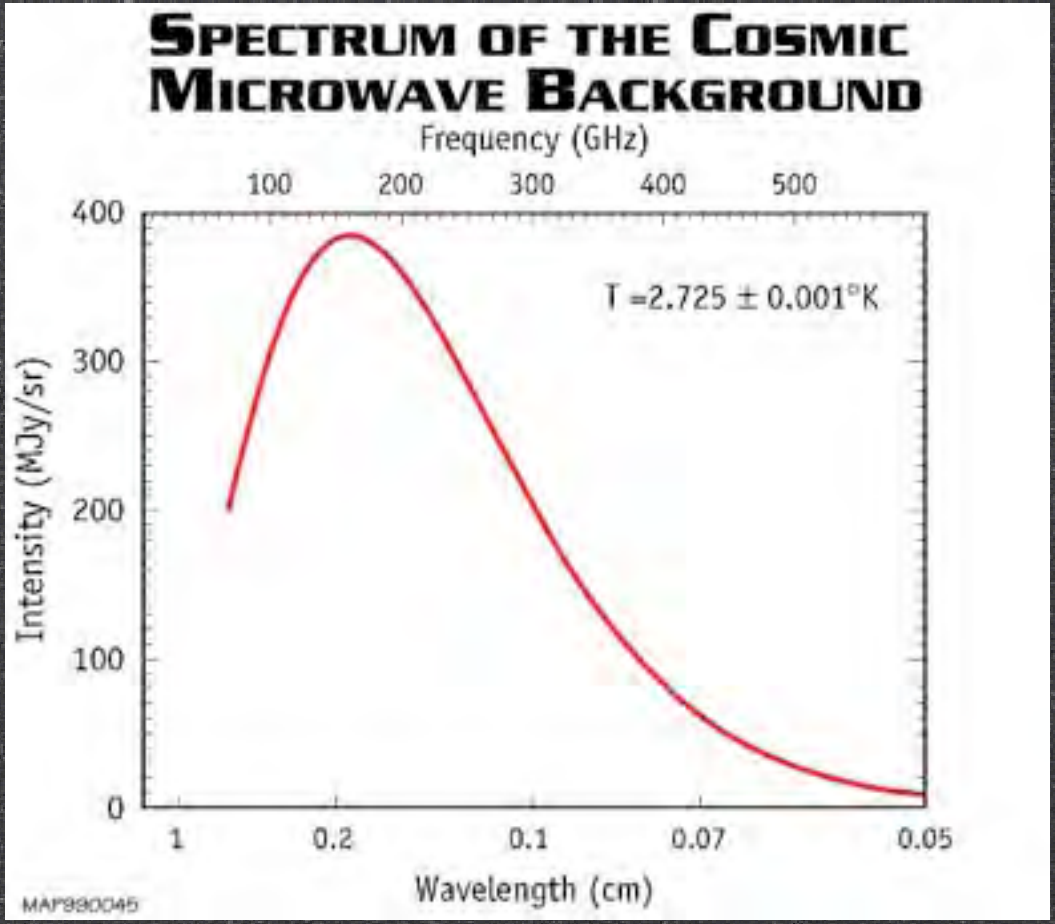


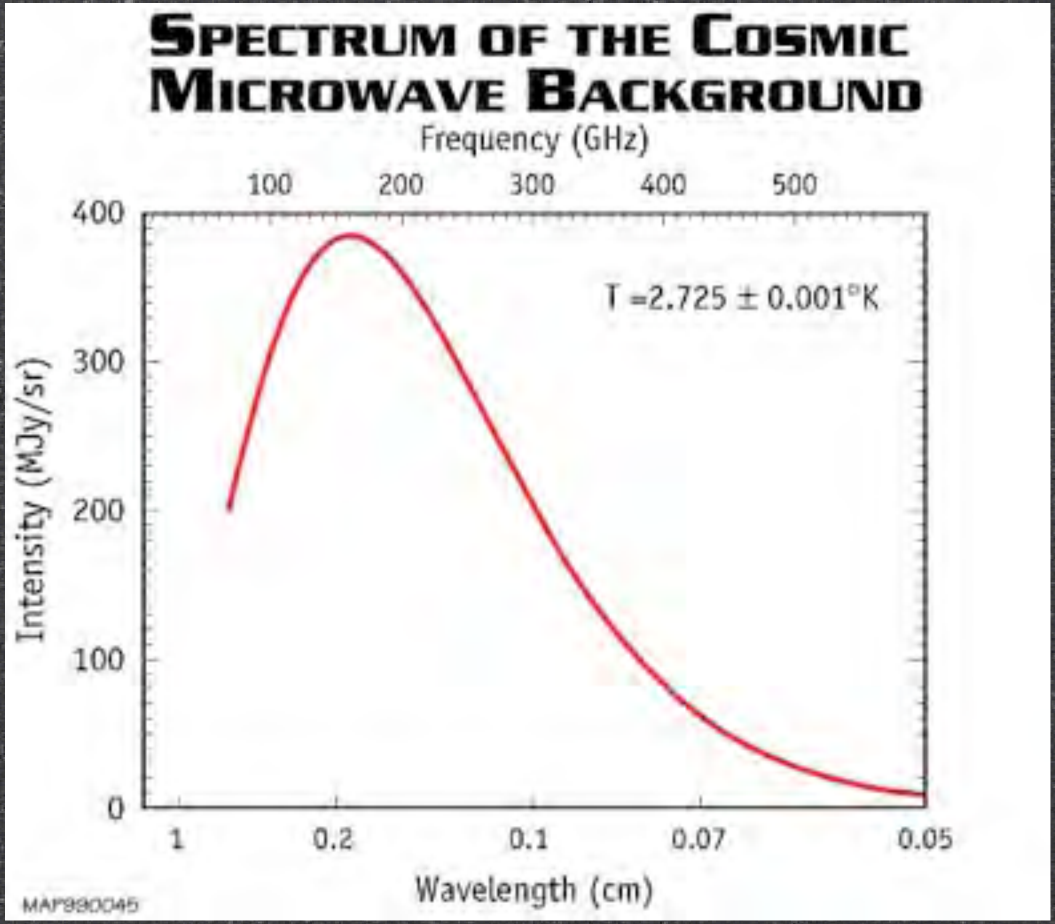
OK, now you can leave!





Expansion 1920s

Cosmic Microwave Background 1960s



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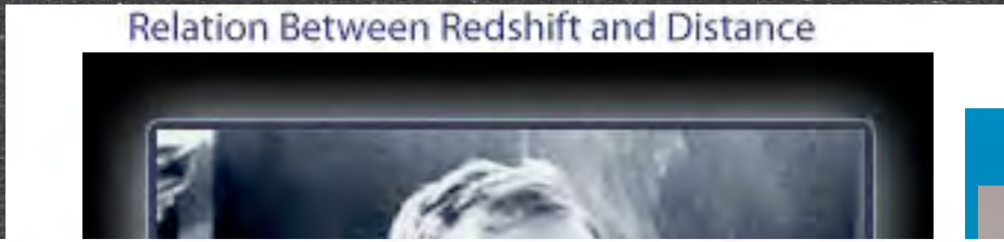


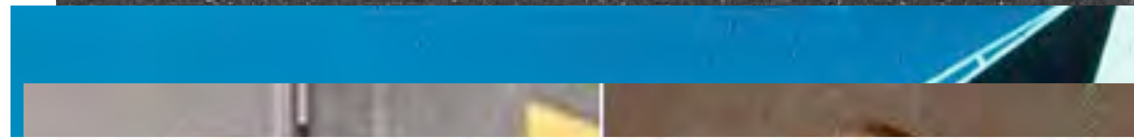


Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

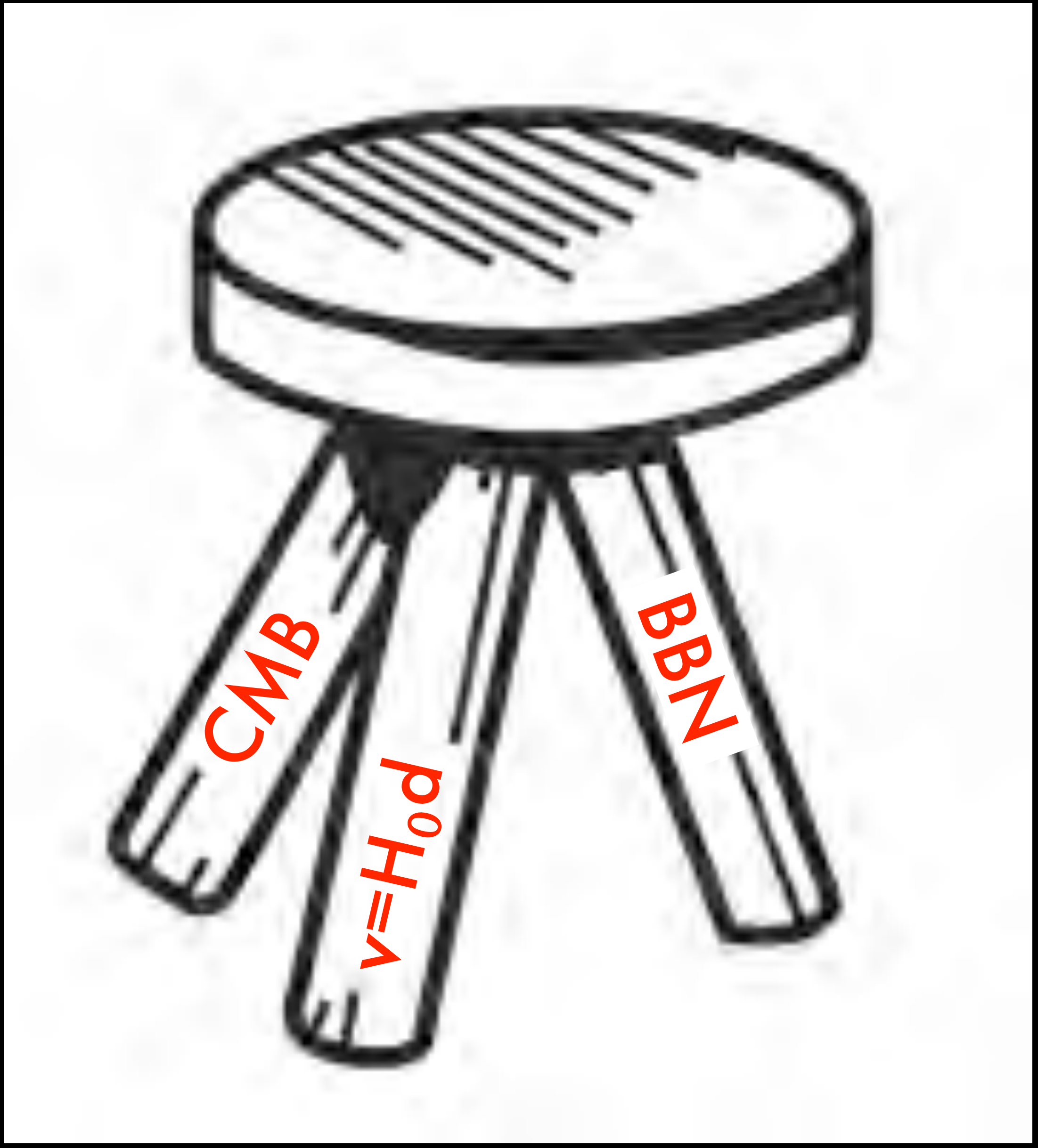
Photo: Homewood Photography

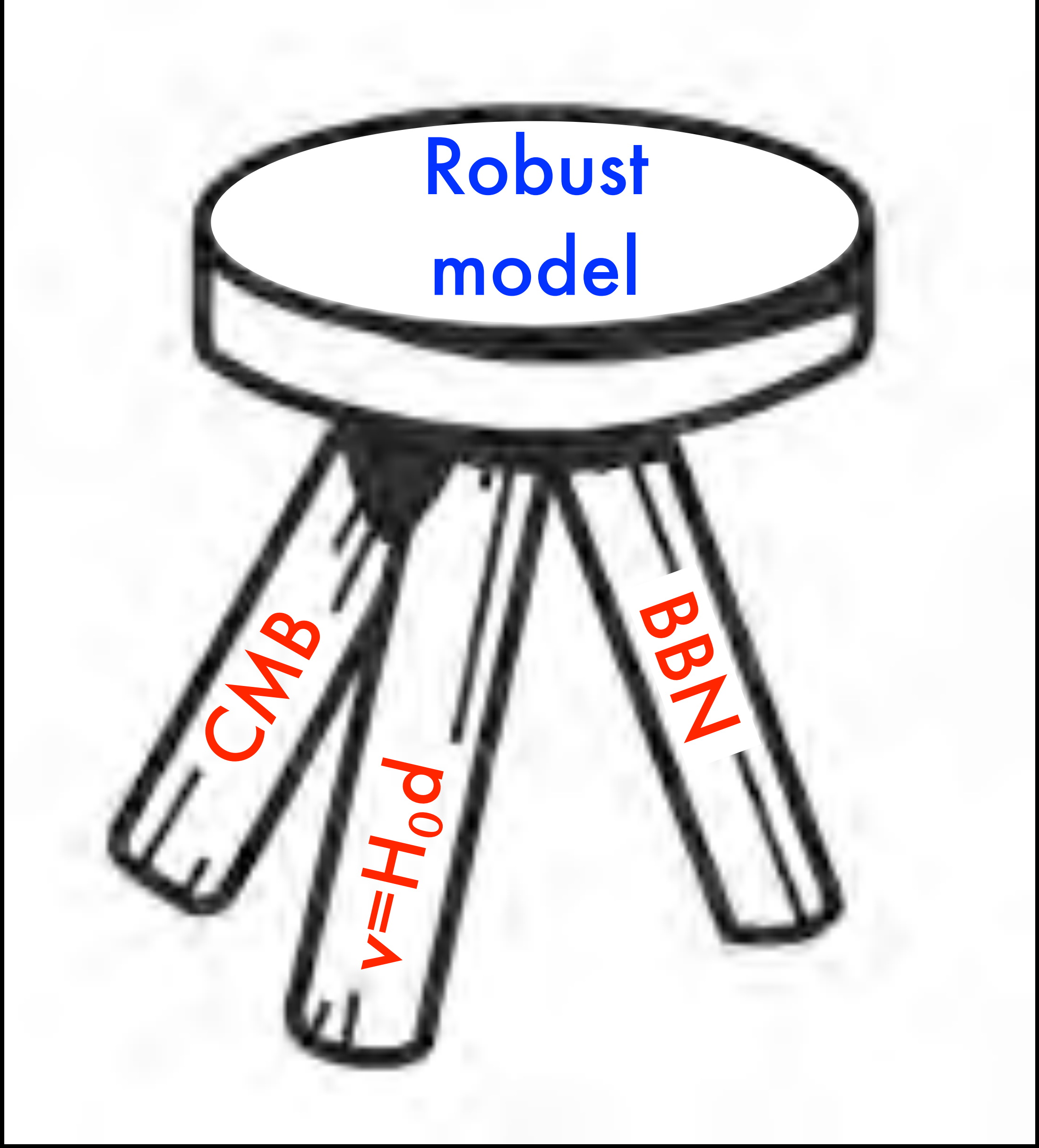
Adam G. Riess

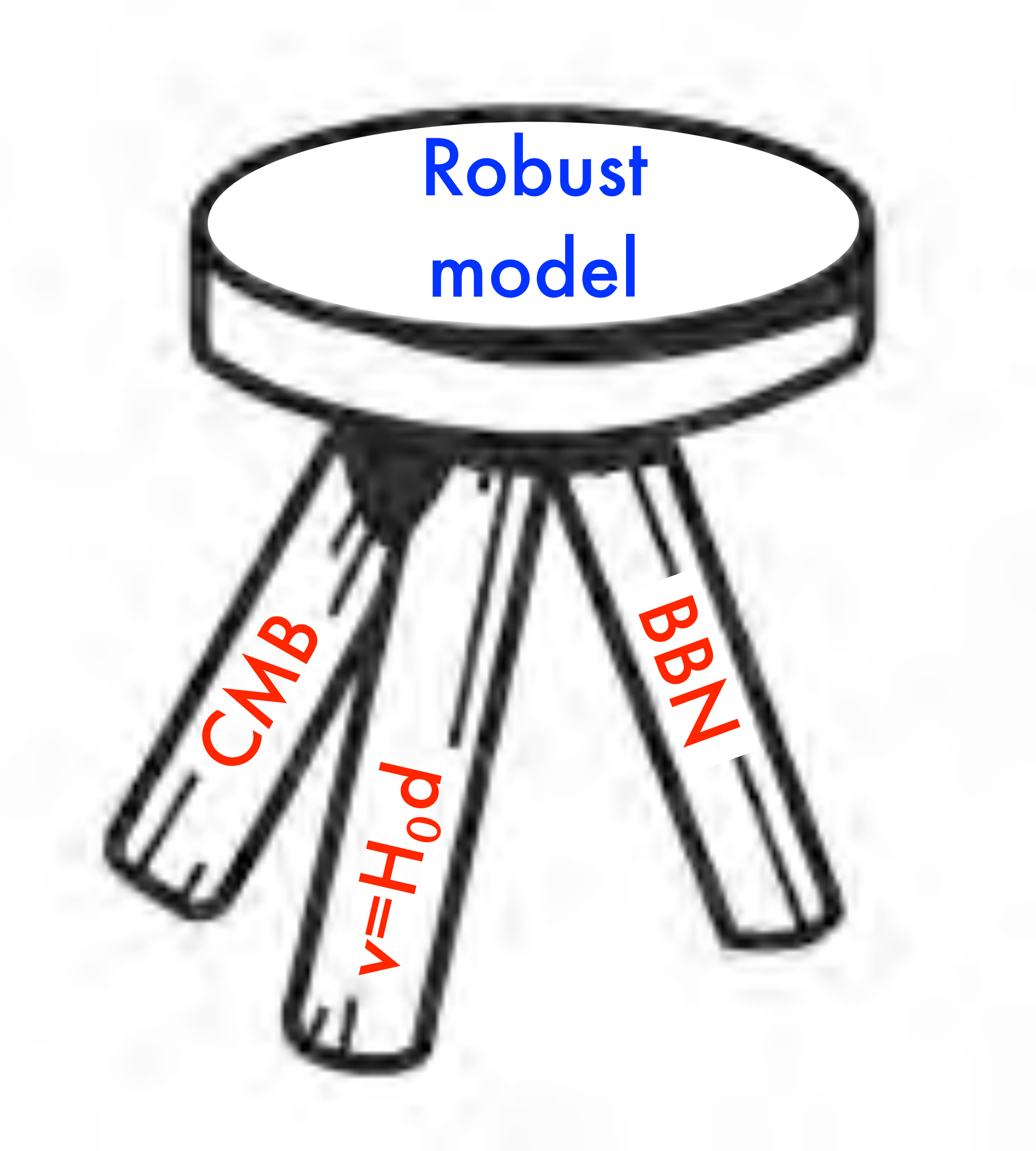
Acceleration late 1990s


CMB


CMB
v=H₀d


CMB
v=H$_0$d
BBN


Robust
model
CMB
v=H0d
BBN



+ acceleration + anisotropies + ...

The Big Bang Theory

The Big Bang Theory

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

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- ★ How many parameters do we need?

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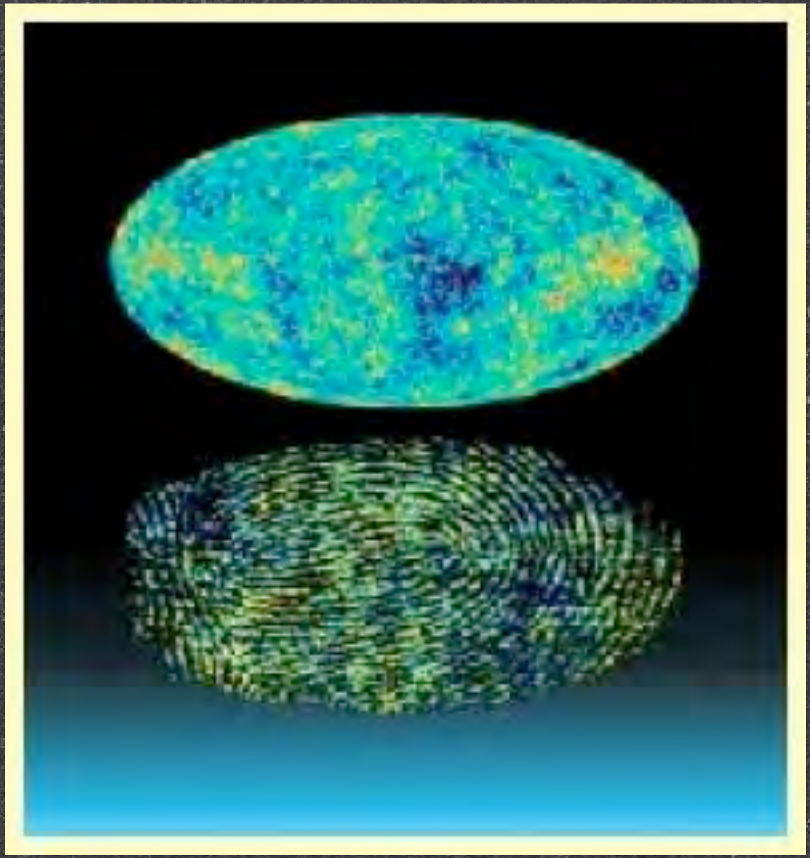
- ★ What kind of Big Bang model do we live in?
- ★ How many parameters do we need?
- ★ Why do the parameters have these values?
- ★ Is there evidence for new physics?

How do we know so much?

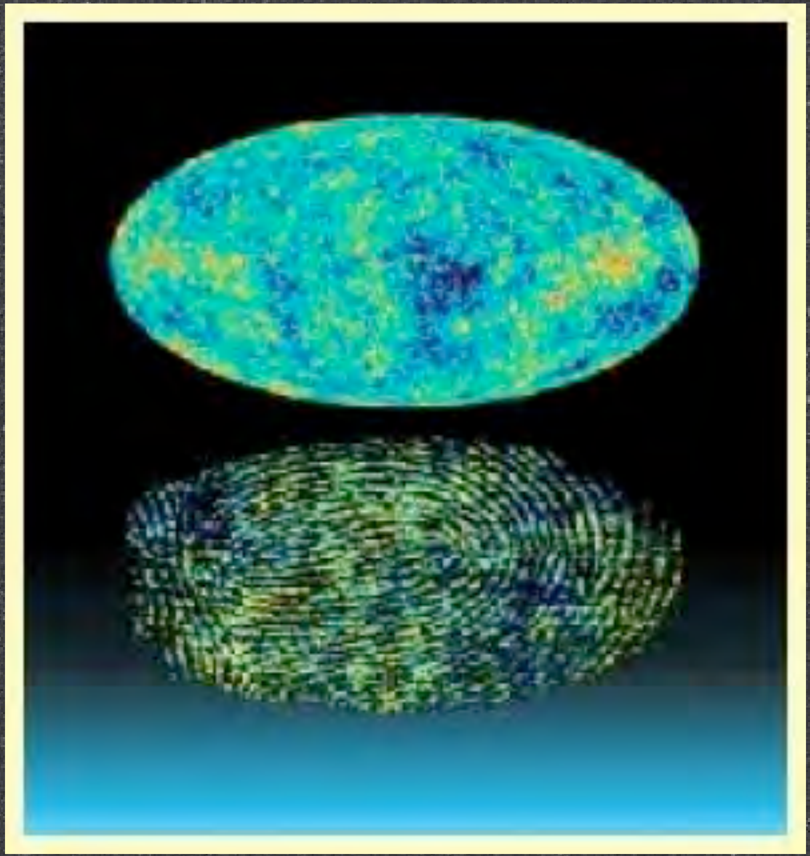


How do we know so much?

Cosmic Microwave Background:

remnant of radiation from the early Universe

variations on the sky (anisotropies) carry wealth of cosmological information



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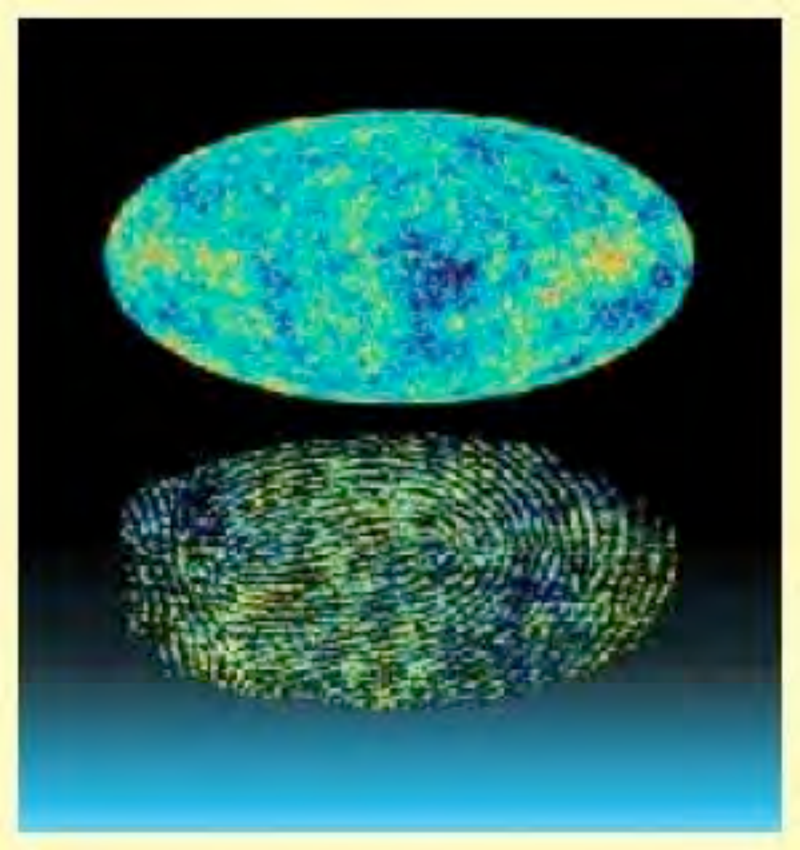
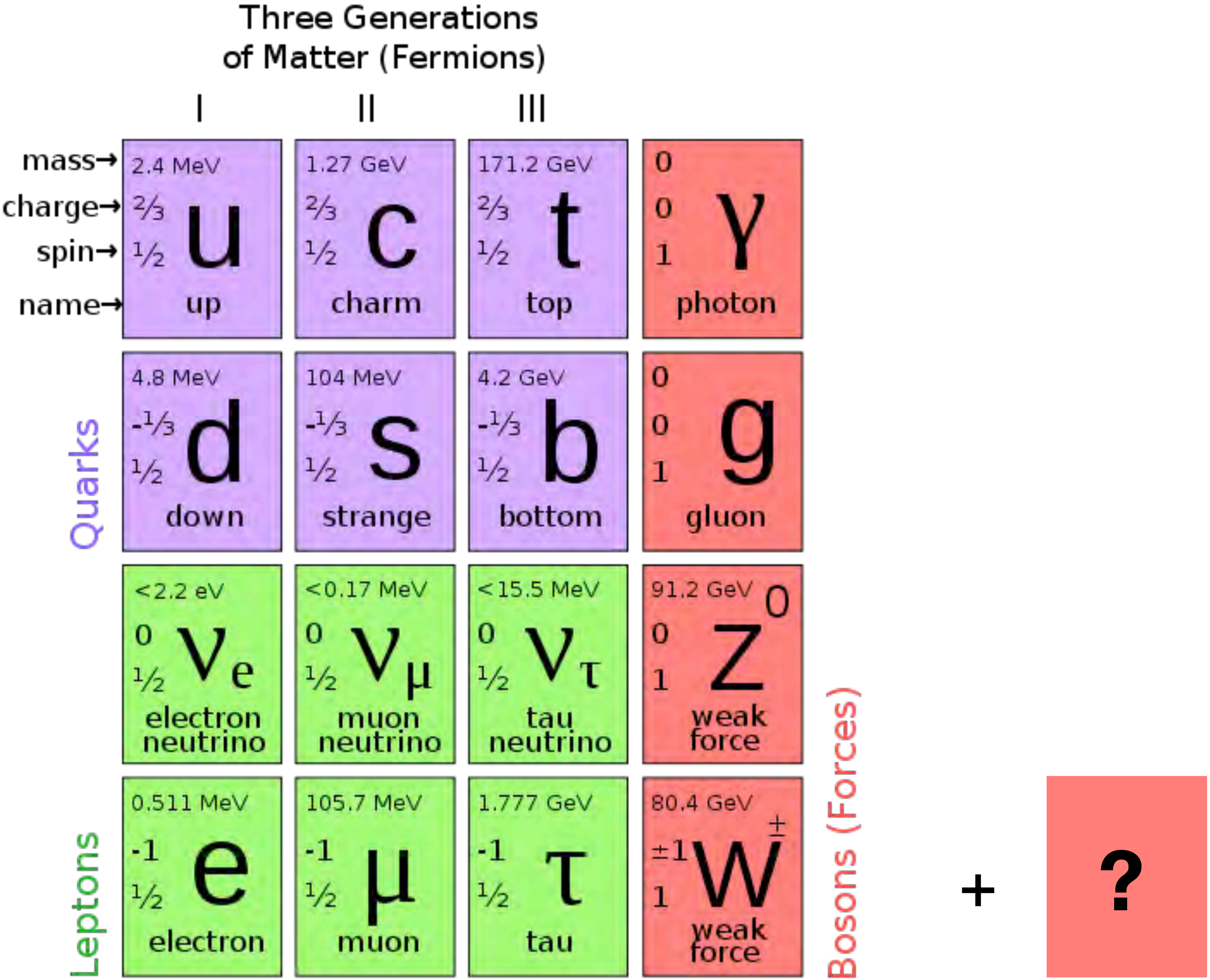
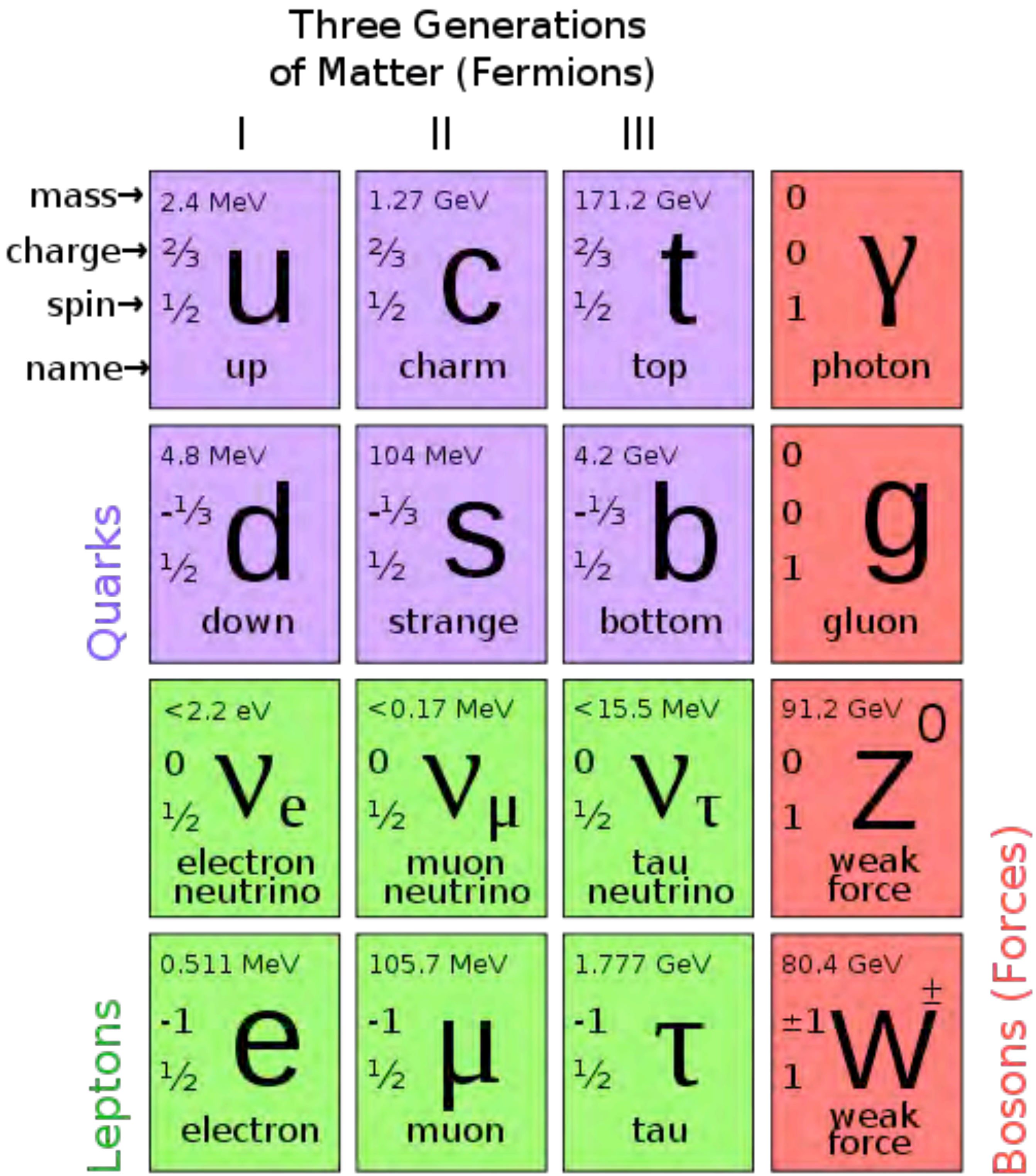


Plus consistency with the rest of Physics



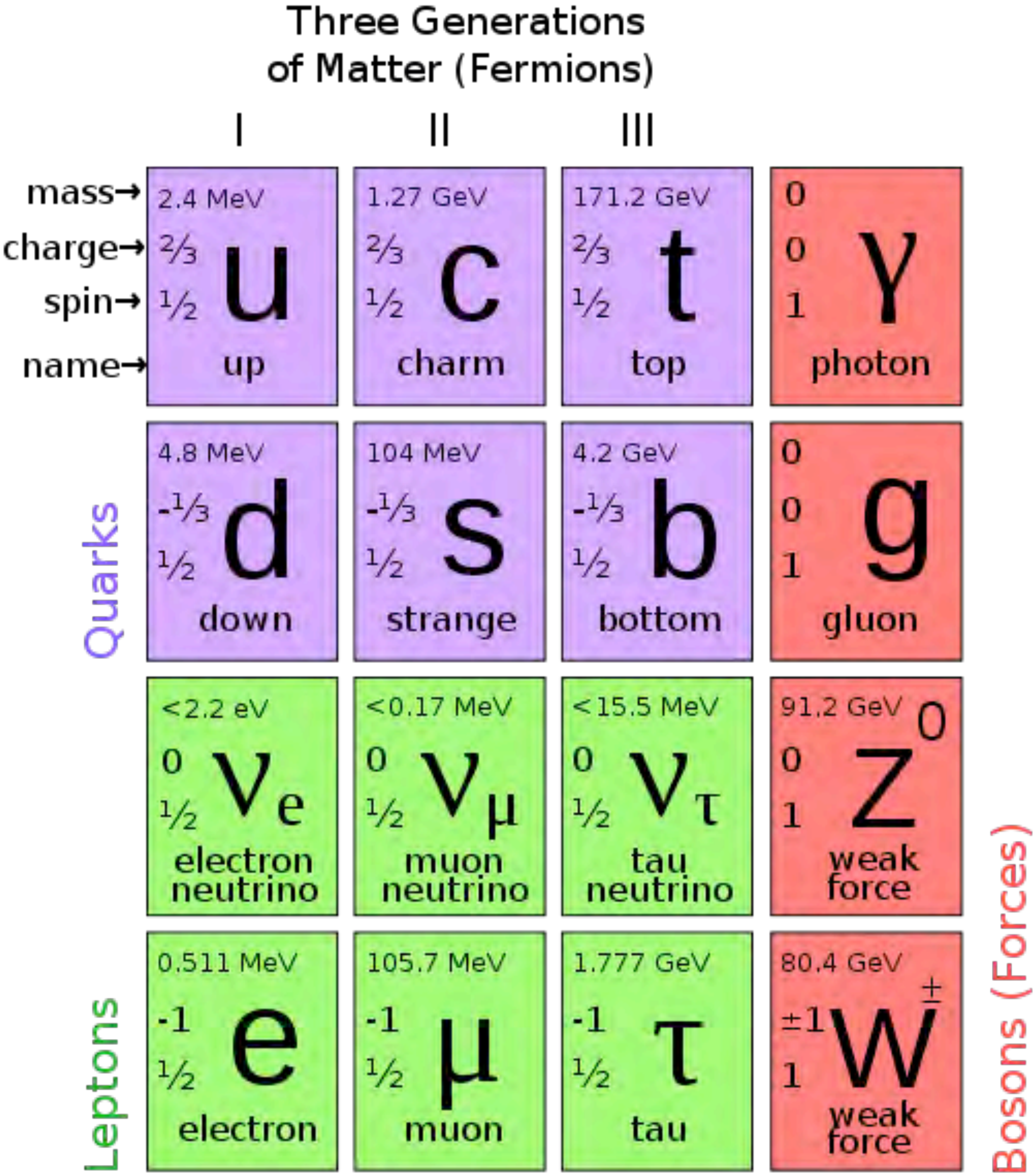
Three Generations
of Matter (Fermions)
I
II
III
mass→
charge→
spin→
name→
2.4 MeV
2/3
1/2
u
up
1.27 GeV
2/3
1/2
c
charm
171.2 GeV
2/3
1/2
t
top
0
0
1
γ
photon
Quarks
4.8 MeV
-1/3
1/2
d
down
104 MeV
-1/3
1/2
s
strange
4.2 GeV
-1/3
1/2
b
bottom
0
0
1
g
gluon
<2.2 eV
0
1/2
νe
electron neutrino
<0.17 MeV
0
1/2
νμ
muon neutrino
<15.5 MeV
0
1/2
ντ
tau neutrino
91.2 GeV
0
1
Z0
weak force
Leptons
0.511 MeV
-1
1/2
e
electron
105.7 MeV
-1
1/2
μ
muon
1.777 GeV
-1
1/2
τ
tau
80.4 GeV
±1
1
W±
weak force
Bosons (Forces)
+
?

The Standard Model of Particle Physics

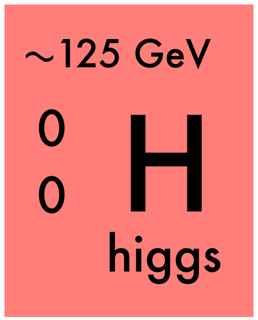


+ ?

The Standard Model of Particle Physics



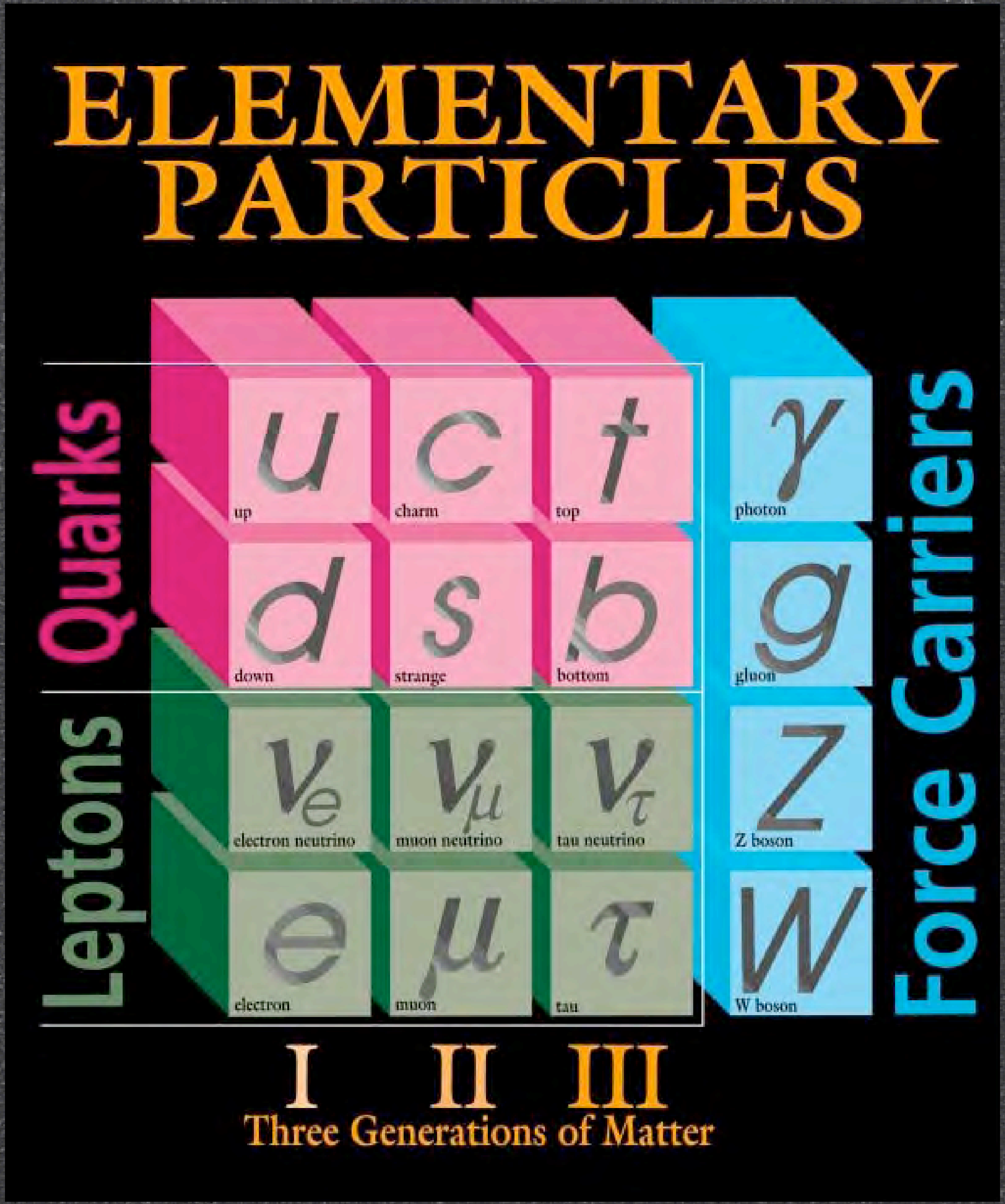
+



Higgs seen at the LHC

Higgs seen at the LHC

THE Standard Model (of Particle Physics)



Theory of Almost Everything!

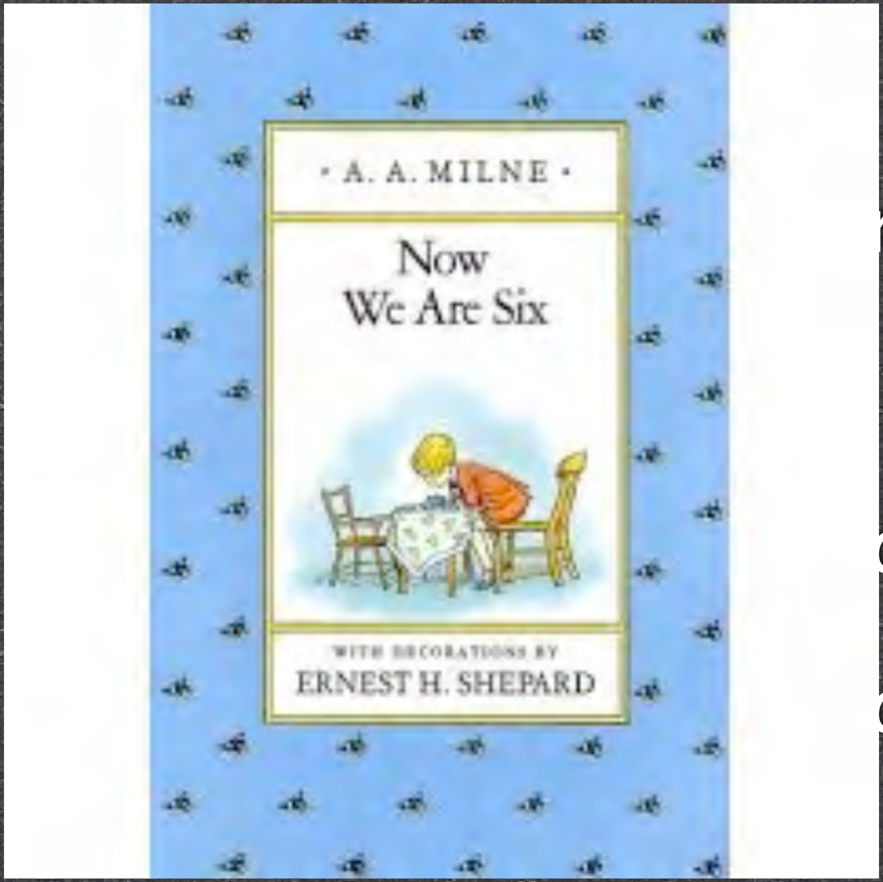
QFT

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

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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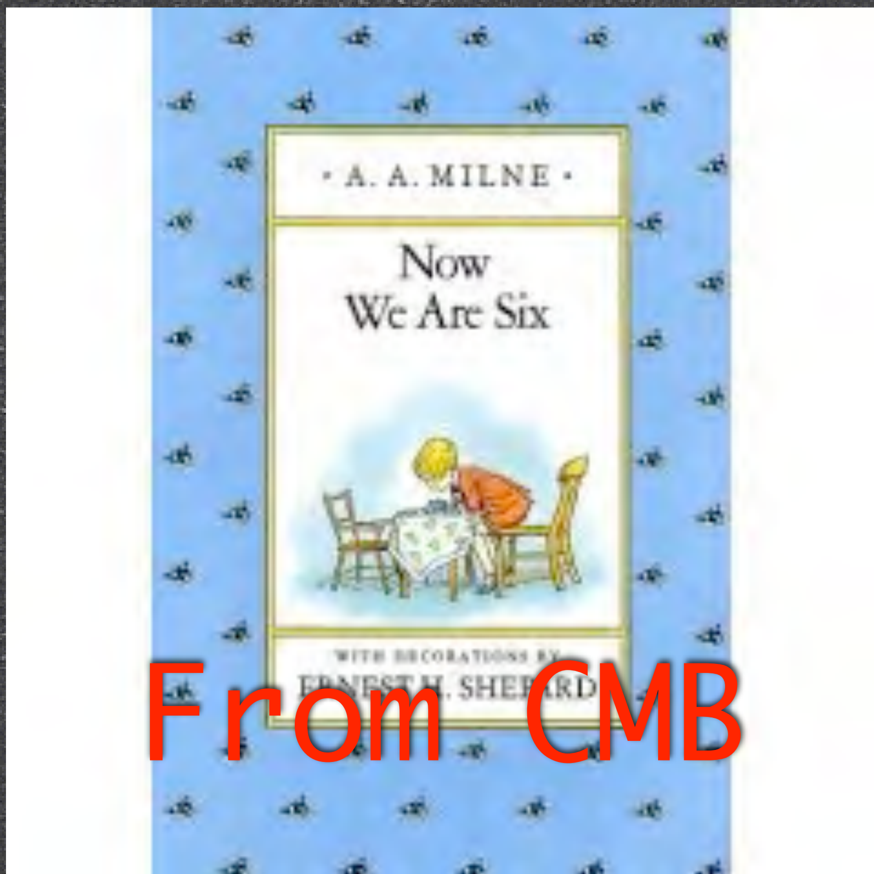
The Standard Model of Cosmology



From CMB

neous, expanding (FRW)

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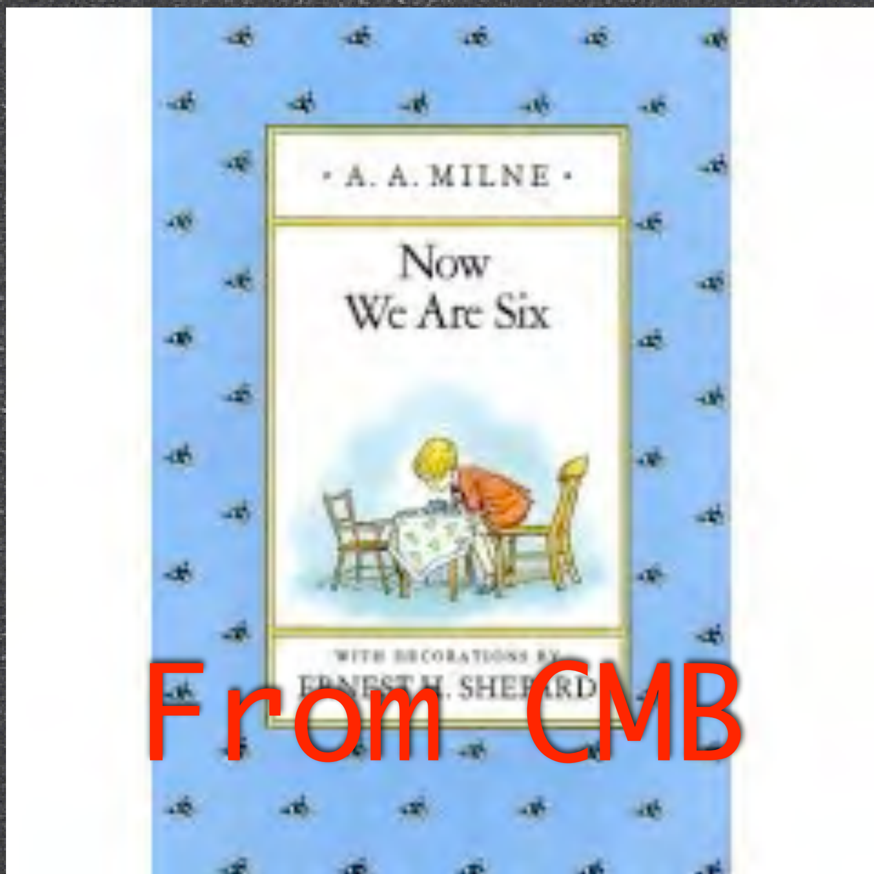
The Standard Model of Cosmology



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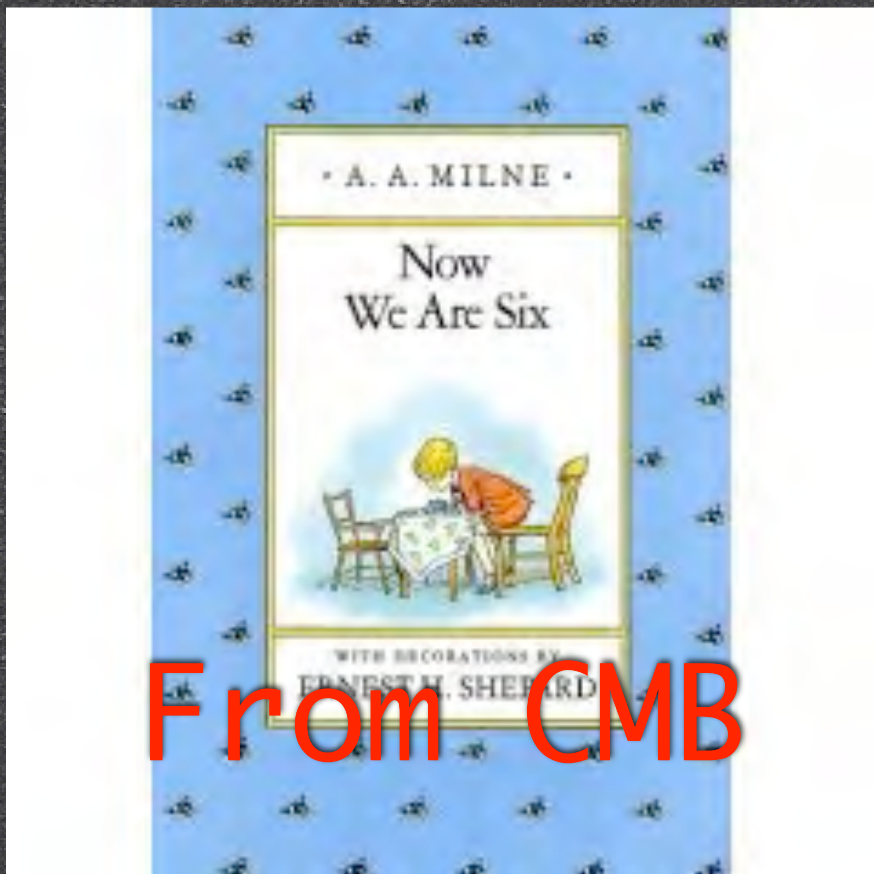
The Standard Model of Cosmology



- Determine parameters (~12 in all)

The Standard Model of Cosmology

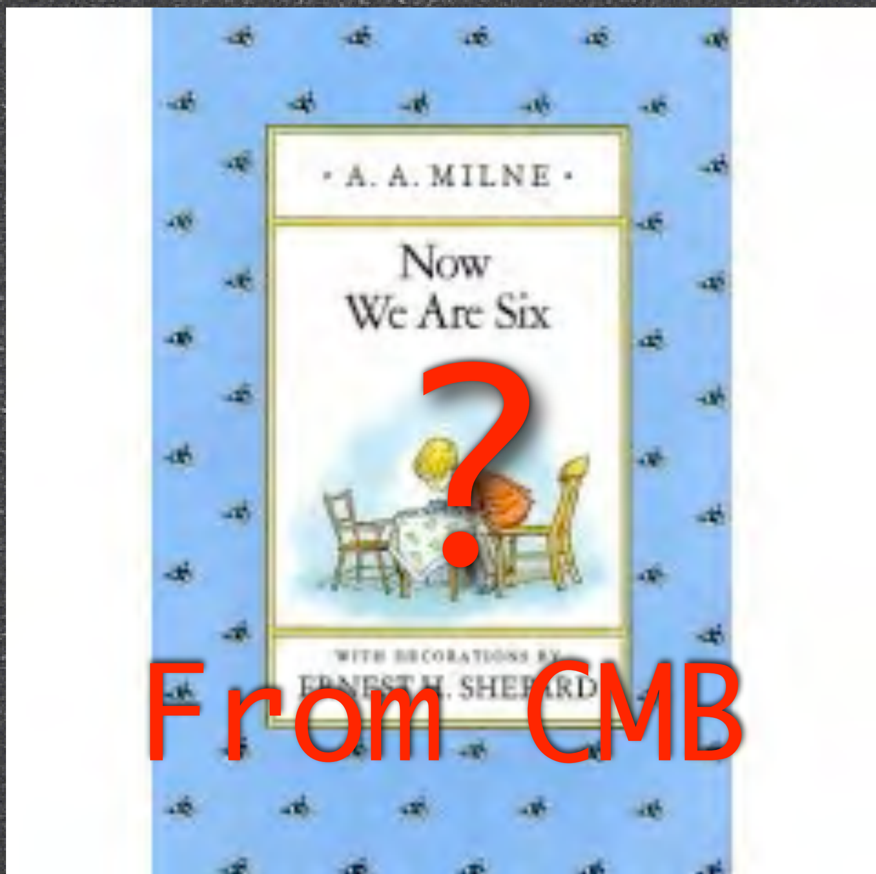
Rest of Astrophysics

- Determine parameters (~12 in all)

The Standard Model of Cosmology

- Determine parameters (~12 in all)

The Standard Model of Cosmology



nec

ark

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pe

- 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,
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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,
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Basic Cosmology Equations

- Scale factor a(t)≡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:

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

That described the "background" - now for the perturbations

- Write distribution function for each fluid: $f(p,\theta,\varphi,x)$
- Boltzmann equations: Df/Dt = collisions
- Perform linear perturbations
- Expand in k-modes (for space)
  + l-modes (for angles)
- → coupled hierarchy of Boltzmann equations
- Solve numerically for any (independent) k
- Evolve to obtain P(k) today
- Integrate (carefully) over k and integrate through line-of-sight for power spectra

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- → zmann equations
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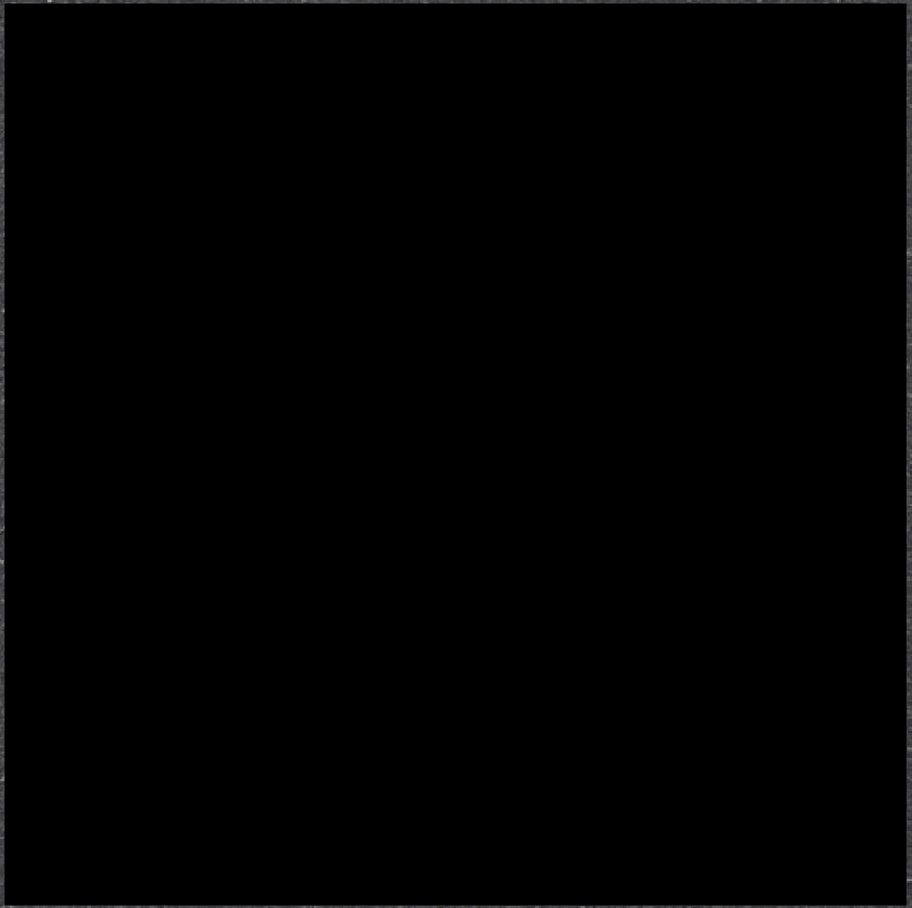
DONE!

Linear theory +
well understood physics
(gravity-driven sound waves)

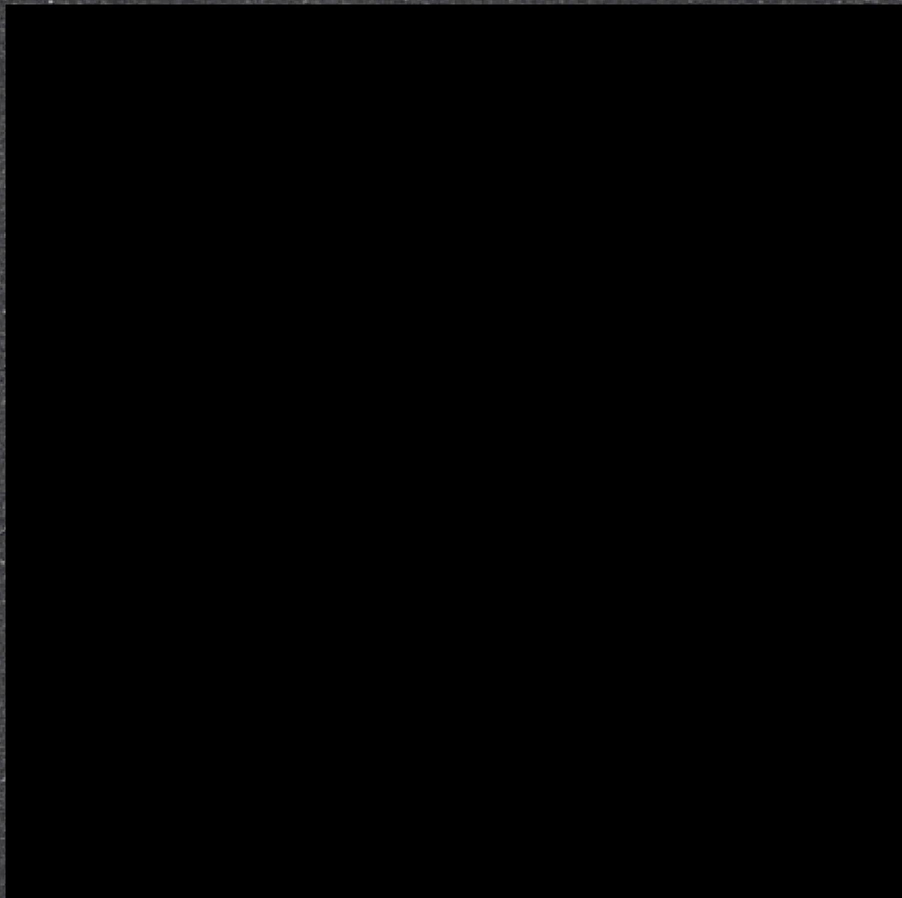
COMPONENTS

COMPONENTS

★ What's in the jar?

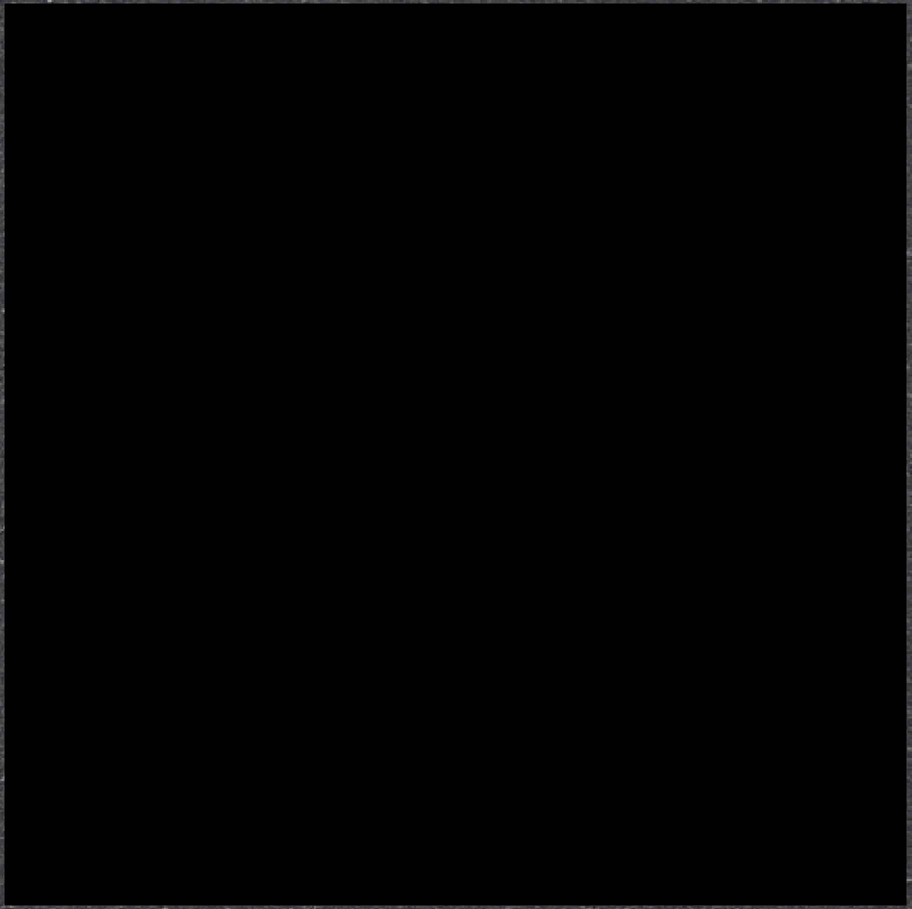


Dark Matter



Dark Matter

NOT Dark Matter



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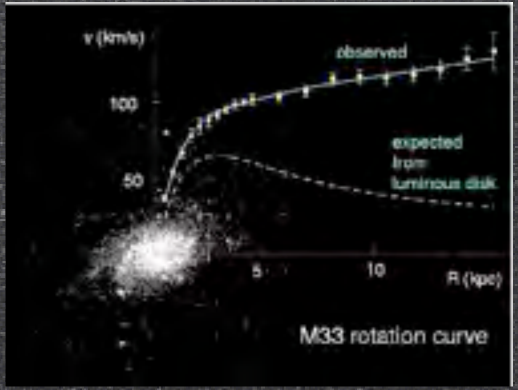

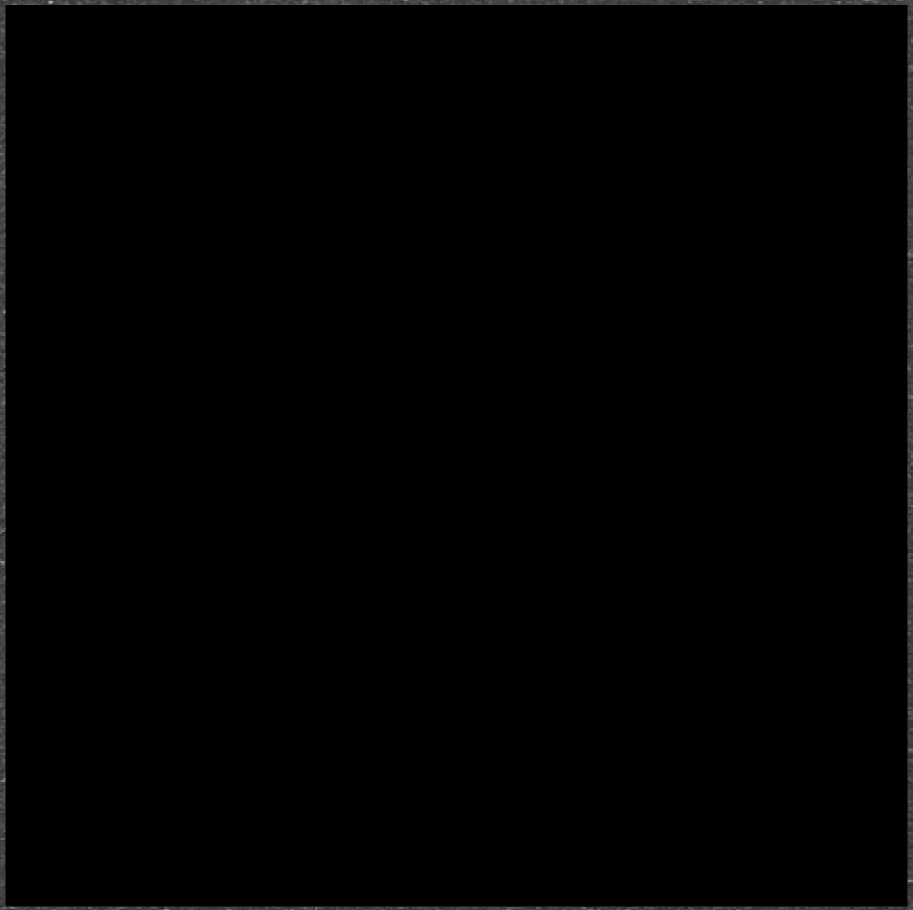

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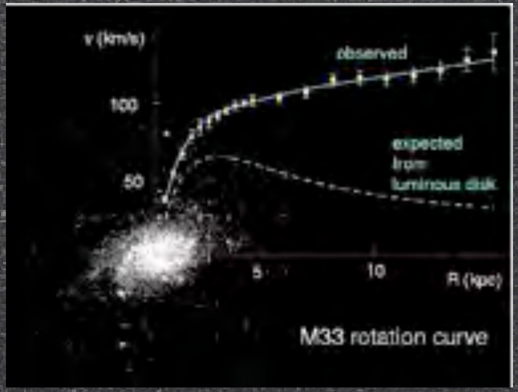

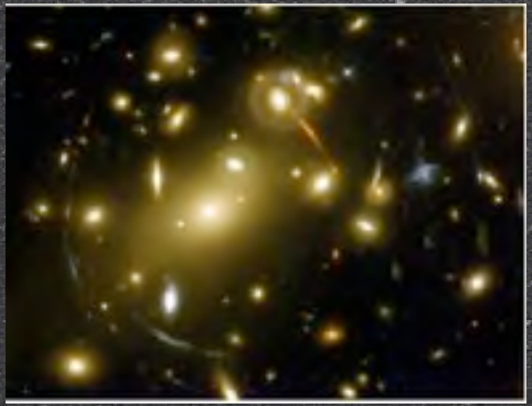

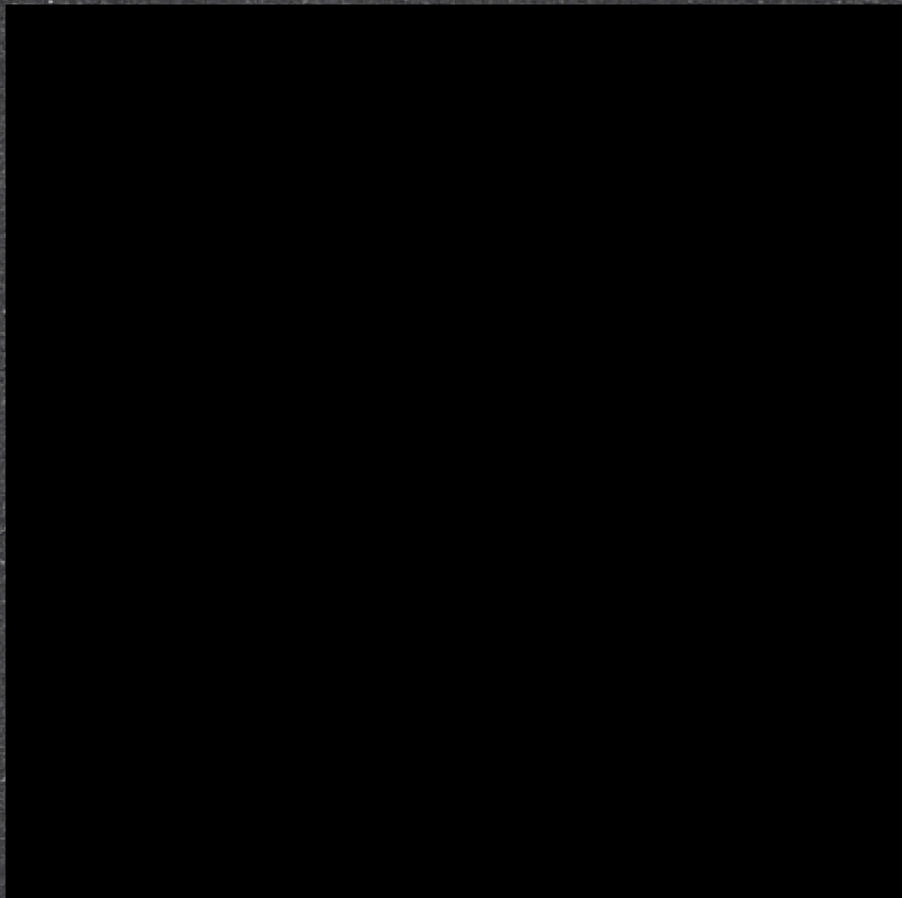

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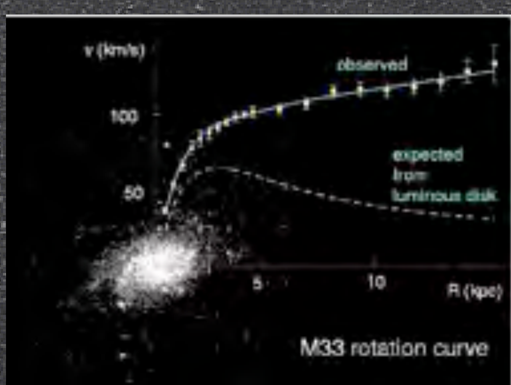
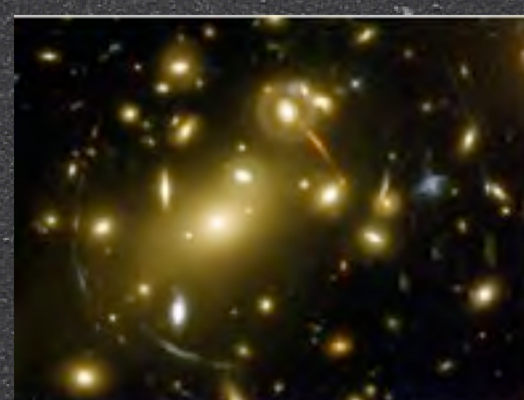




COSMIC CENSUS

$DE \approx 73\%$

$DM \approx 23\%$

$B \approx 4\%$

$\nu \approx 0.1\%$

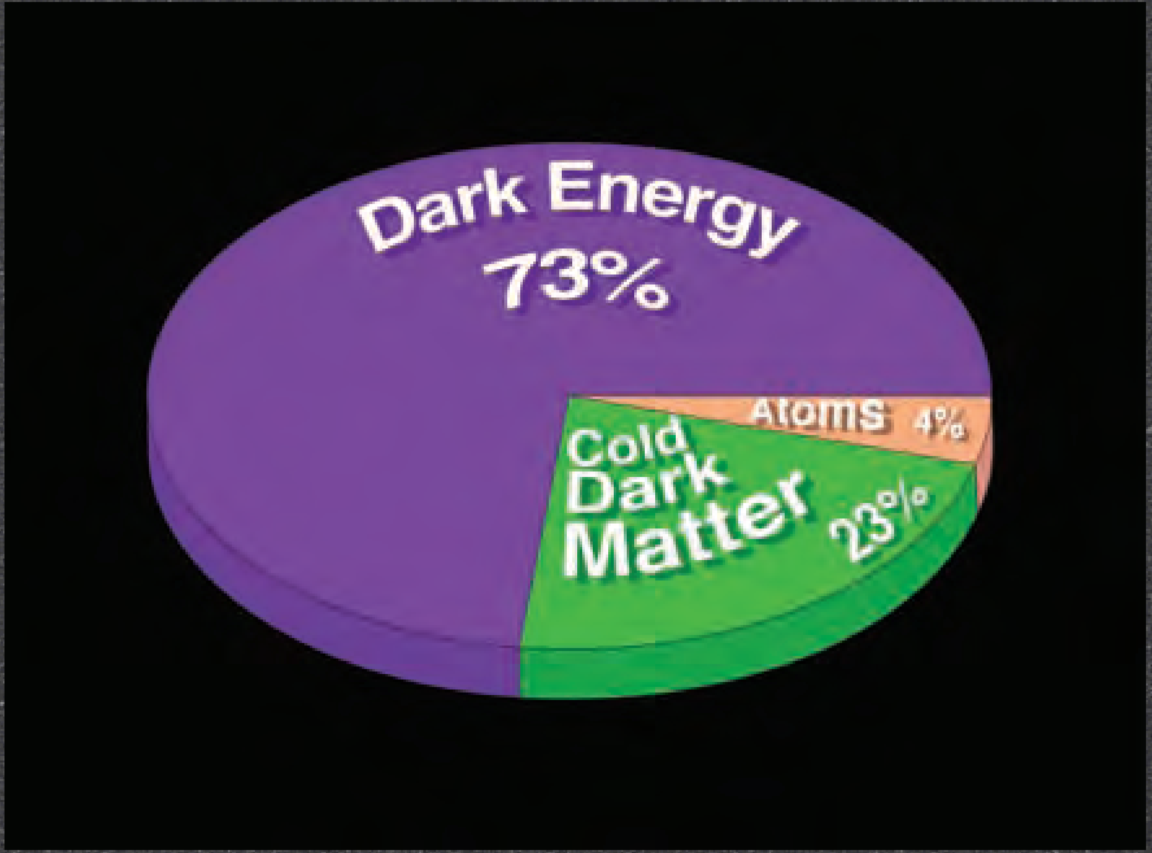
$\gamma \approx 0.05\%$

$GW \approx 0\%$

$\Sigma = 100\%$

COSMIC CENSUS

DE≈73%
DM≈23%
B≈4%
ν≈0.1%
γ≈0.05%
GW≈0%
______
Σ=100%



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——————
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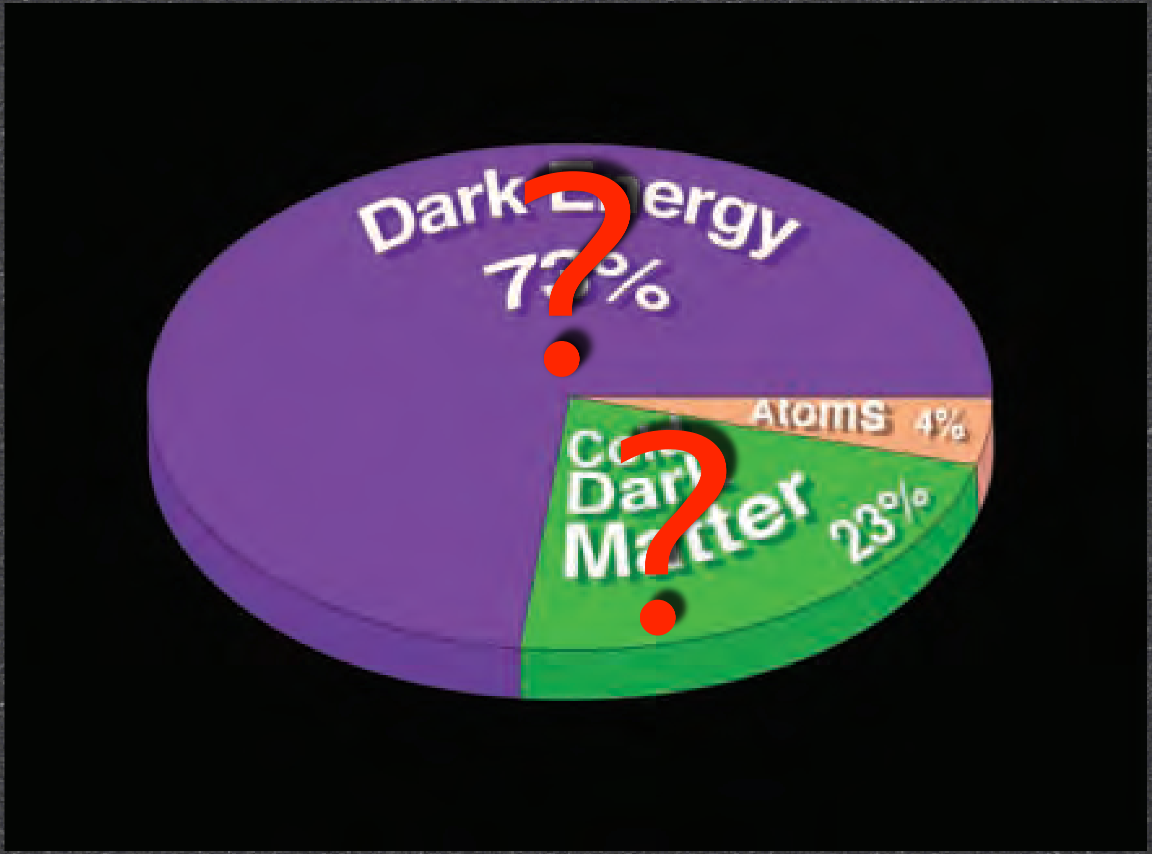

Least informative pie-chart

COSMIC CENSUS

DE≈73%

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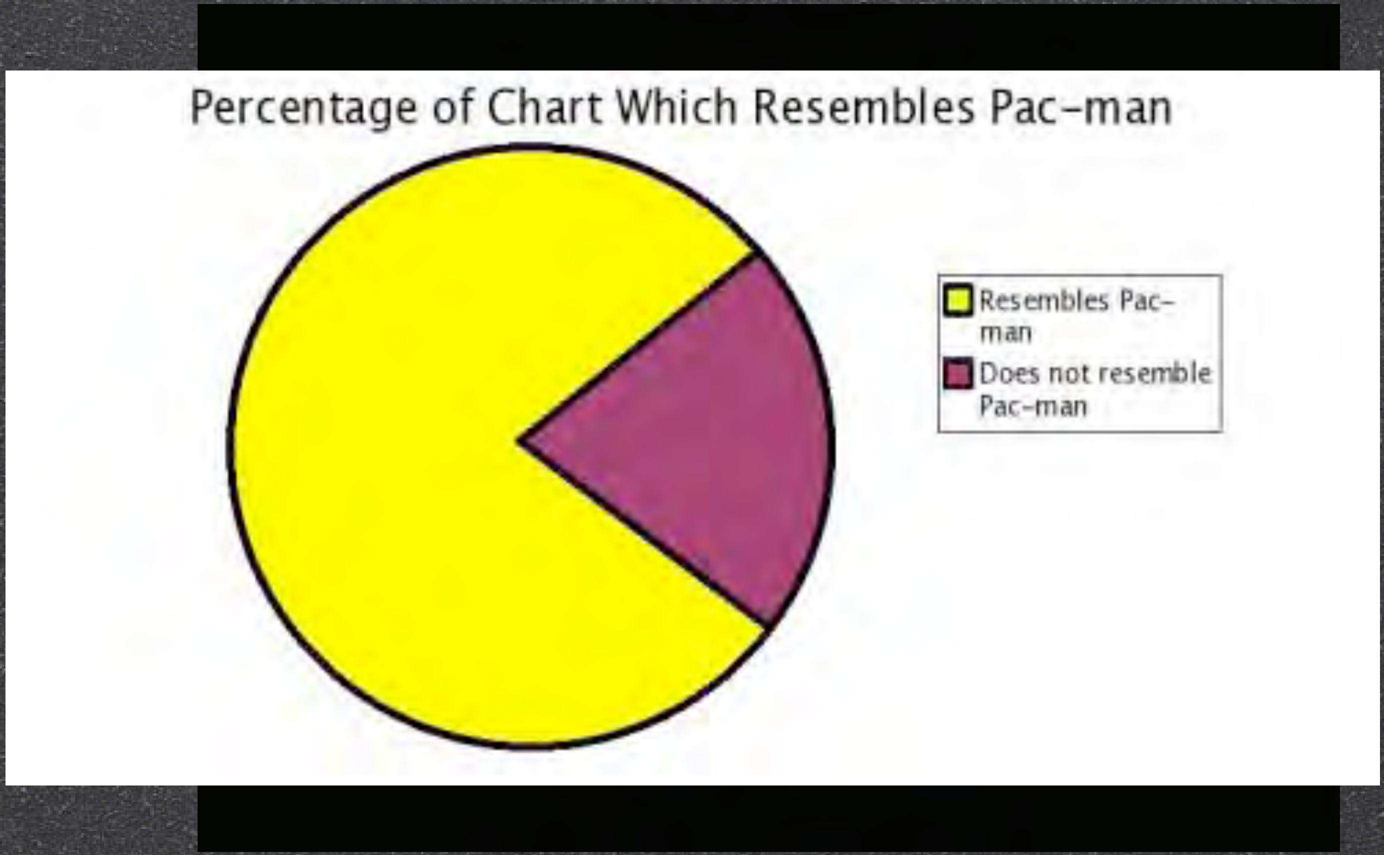
γ≈0.05%

GW≈0%

______

Σ=100%



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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Case Western Reserve University
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?

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.

Acoustic Peaks

Acoustic Peaks

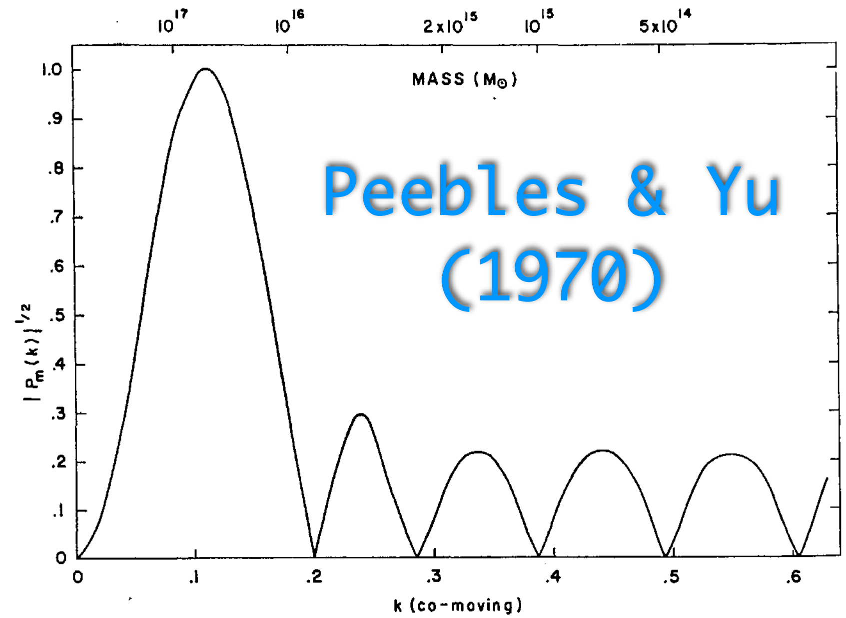


FIG. 5.—Same as Fig. 4 for the cosmologically flat general-relativity model, $\rho_0 = \rho_c$. The normalization is fixed to peak value unity.

Acoustic

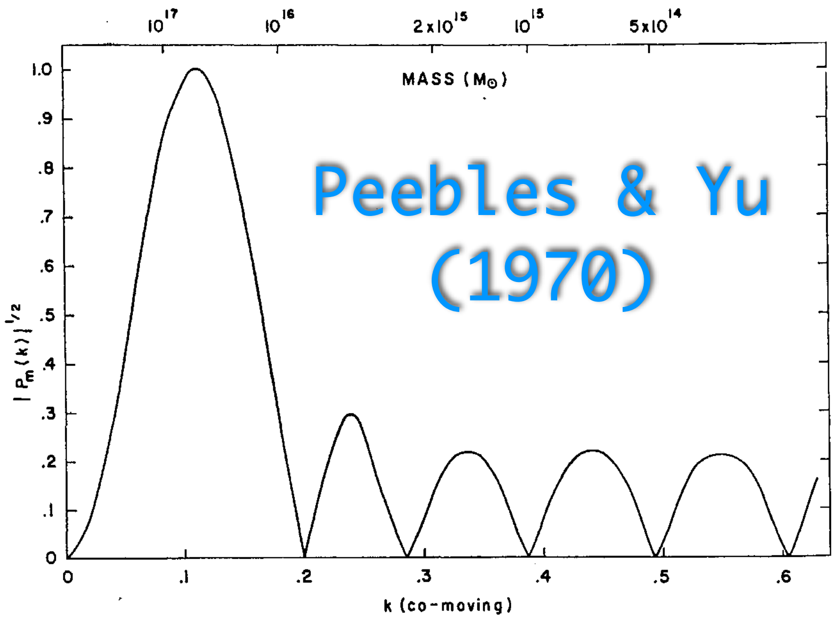


FIG. 5.—Same as Fig. 4 for the cosmologically flat general-relativity model, $\rho_0 = \rho_c$. The r
is fixed to peak value unity.

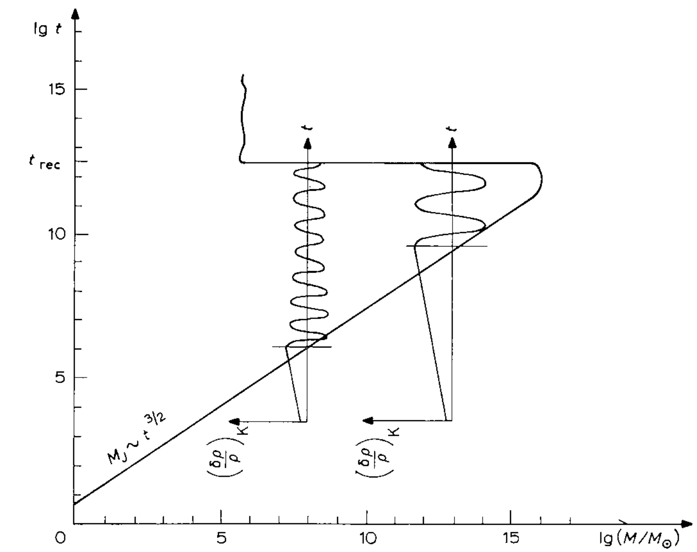


Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until 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.

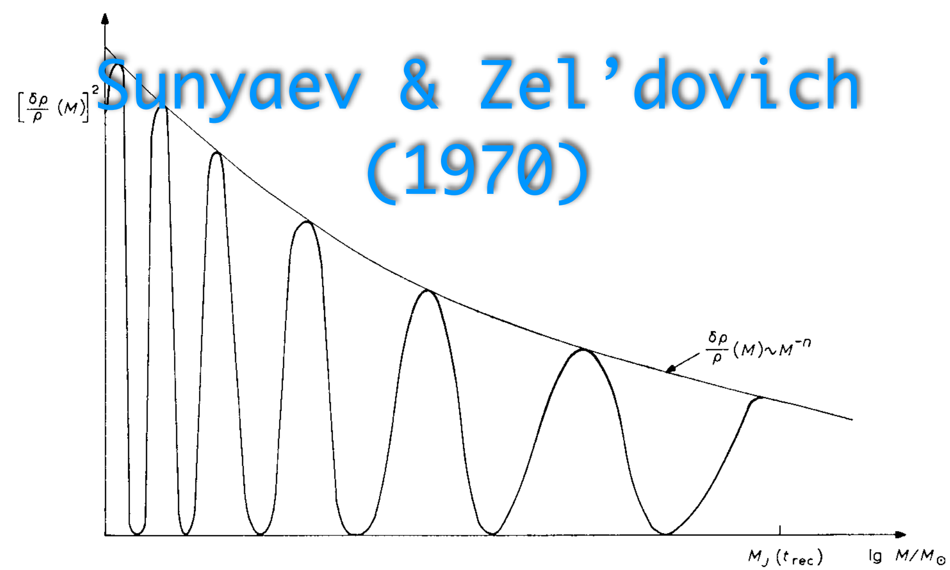
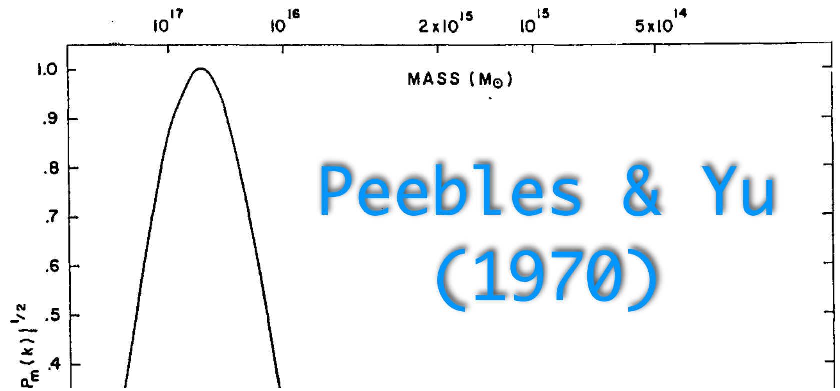
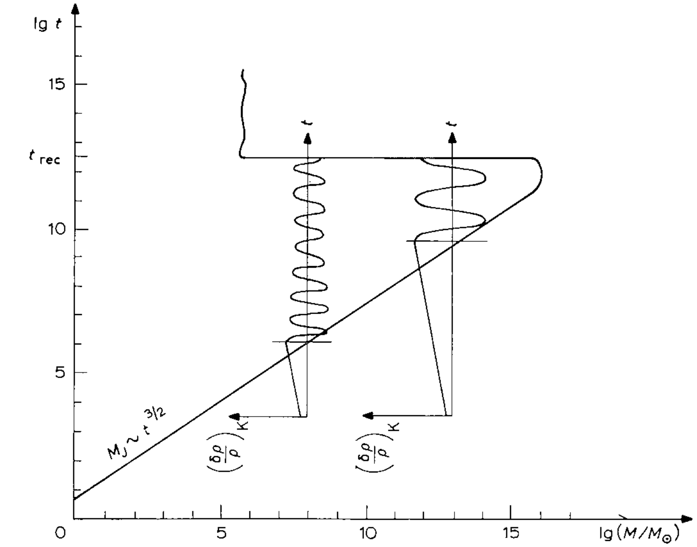


Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

Acoustic



Peebles & Yu (1970)



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Wilson & Silk (1981)

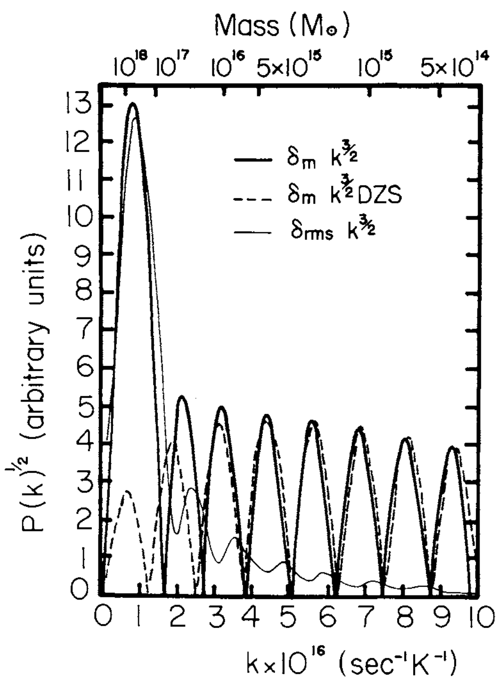
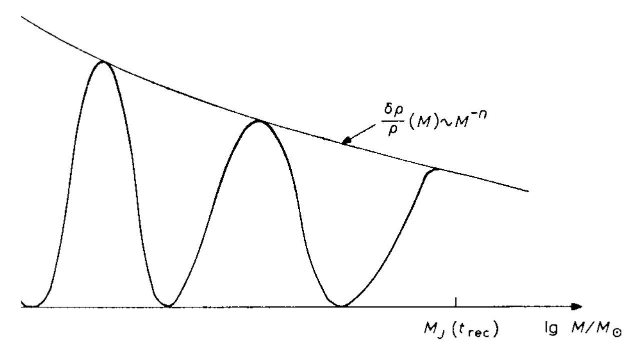


FIG. 1.—Residual matter and radiation adiabatic fluctuation spectra $P(k) = k^3|\delta_m|^2$ for $n = 0$. Normalization is arbitrary, but relative normalization is that for $T = 2000$ K. Note that $\delta_m \propto T^{-1}$, whereas δ_{rms} is constant in time. Also shown for comparison is the analytic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

Sunyaev & Zel'dovich (1970)



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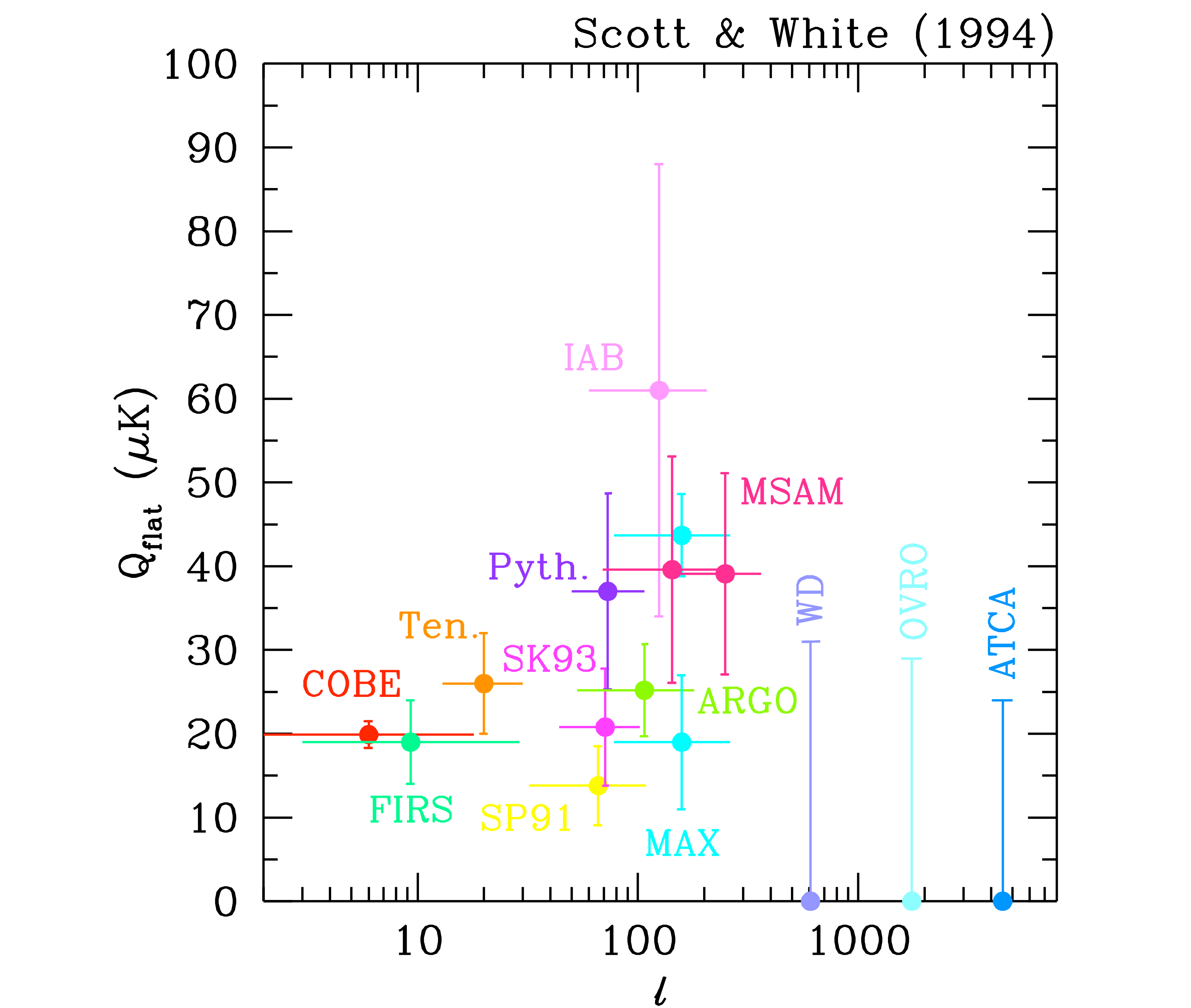
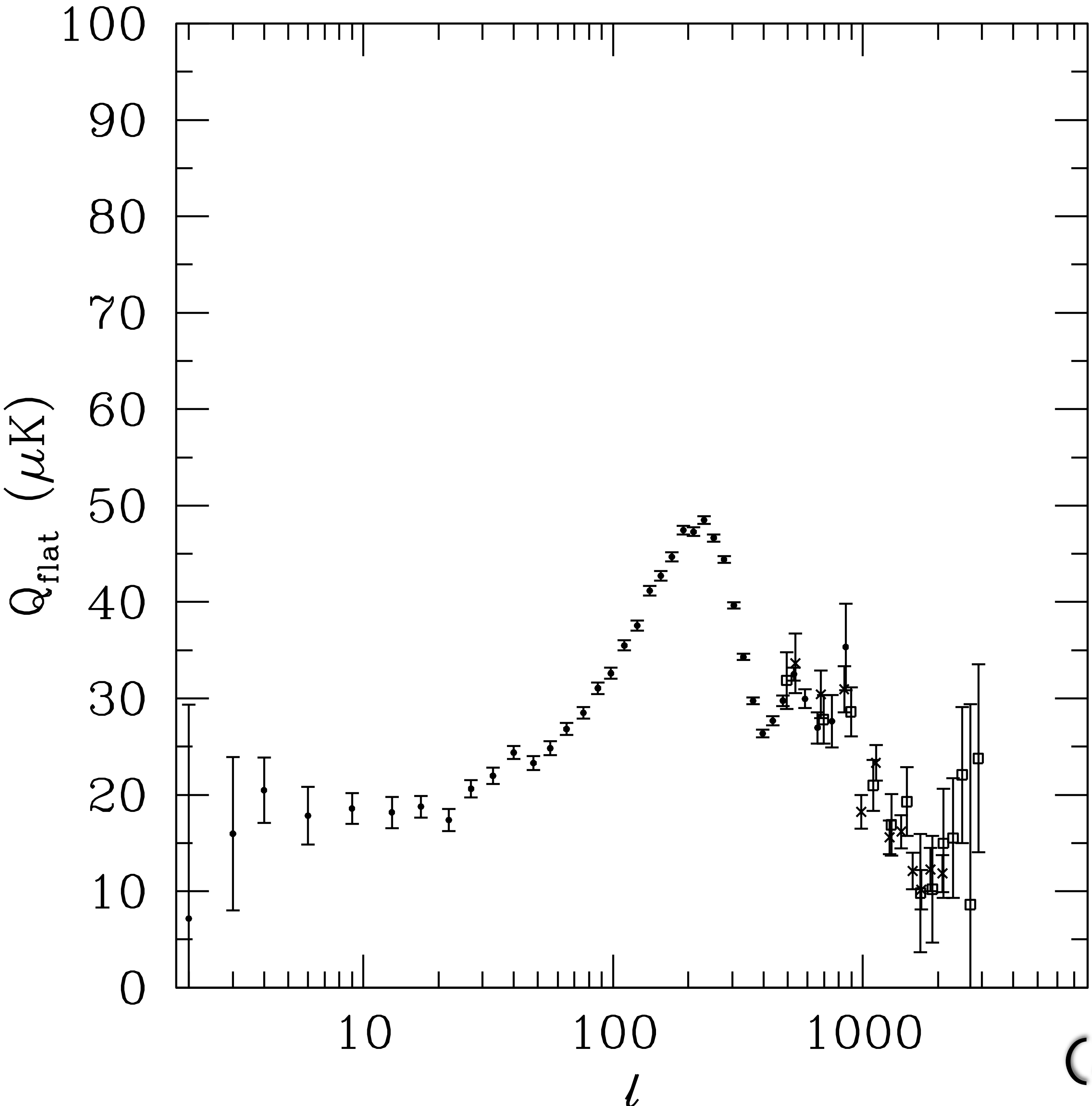
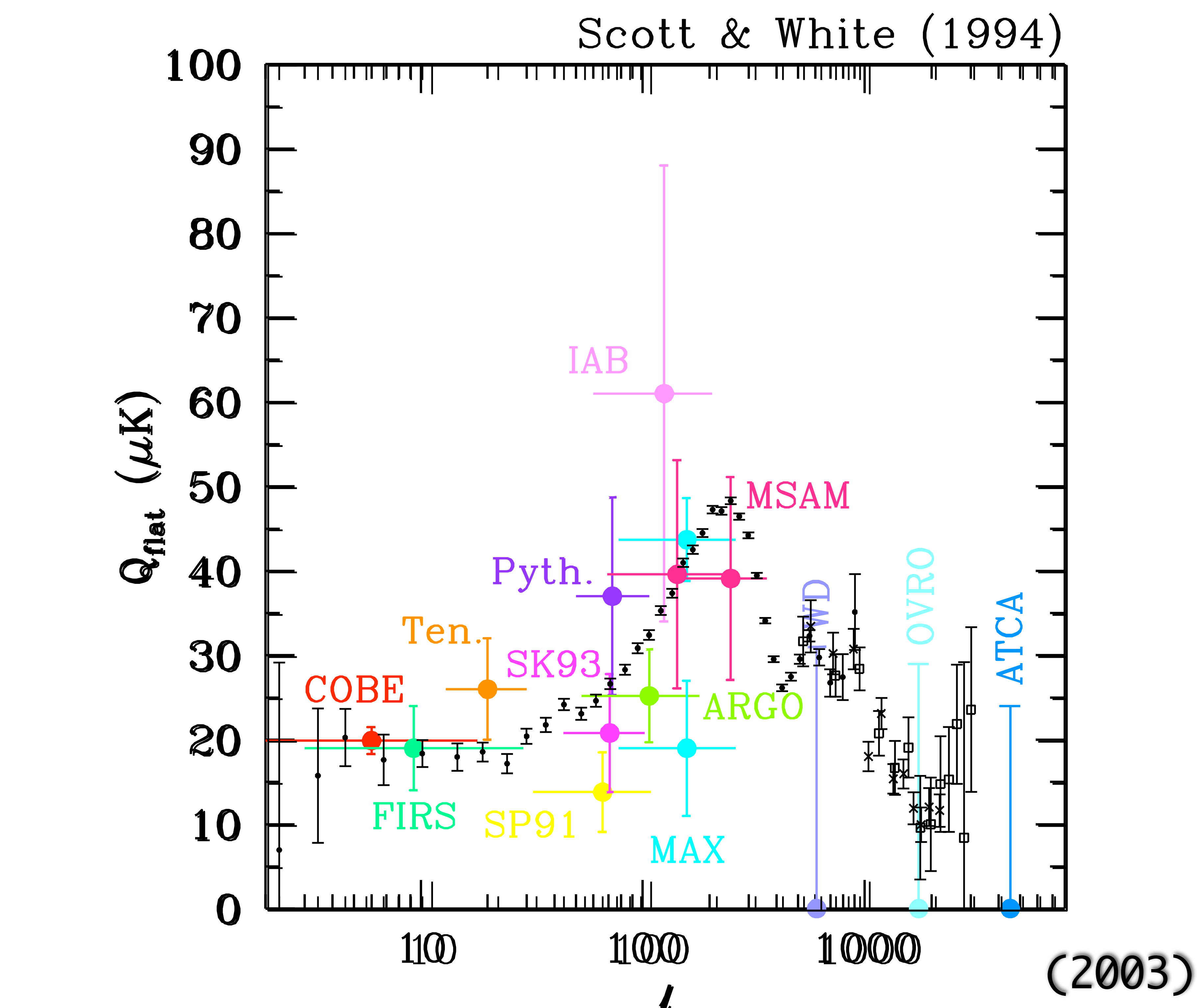


Scott & White (1994)
Q_{flat} (μK)
ℓ
100
90
80
70
60
50
40
30
20
10
0
10
100
1000
IAB
MSAM
Pyth.
Ten.
SK93
COBE
ARGO
FIRS
SP91
MAX
WD
OVRO
ATCA



(2003)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(2003)

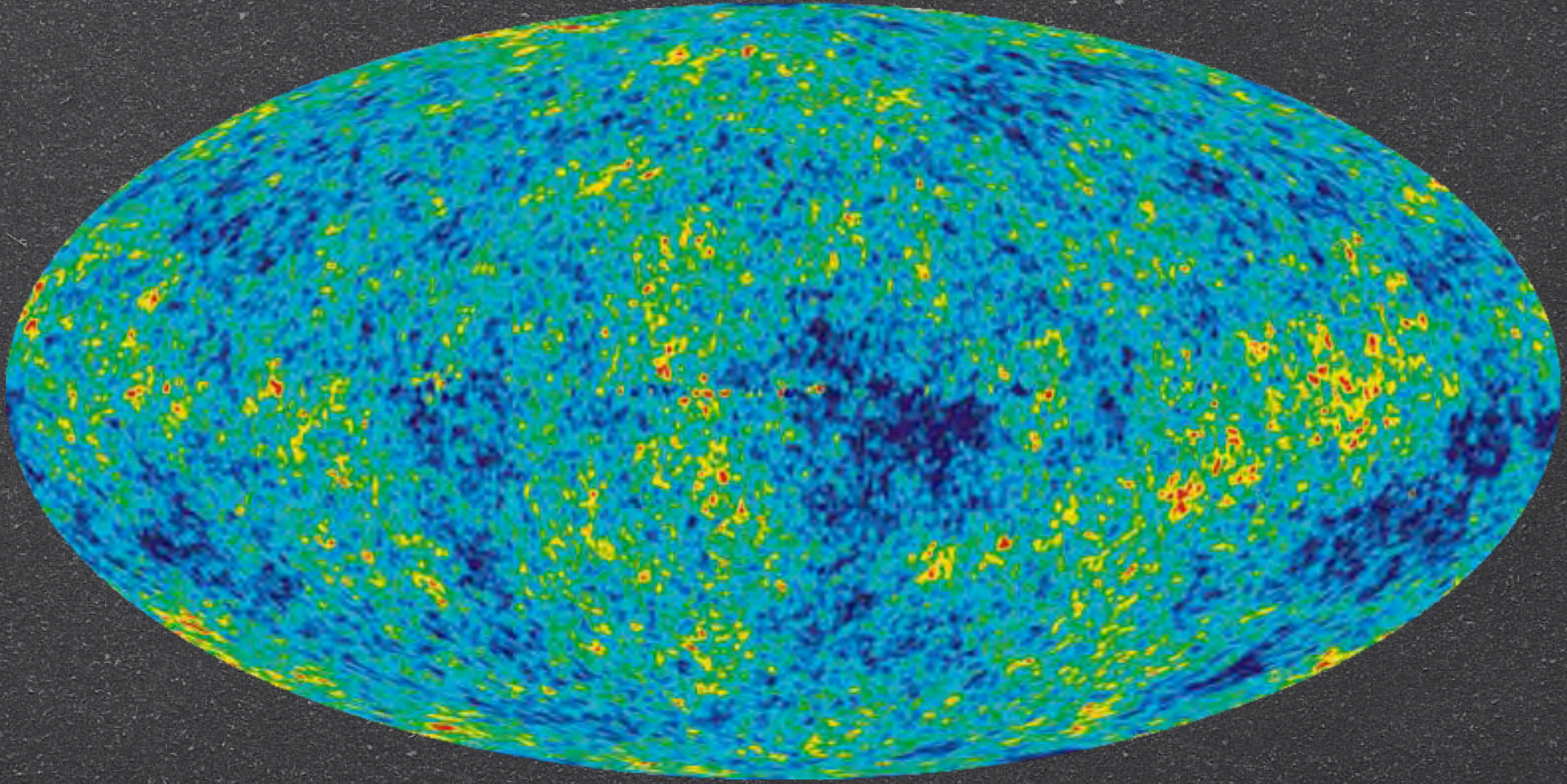
SMC Predictions

	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

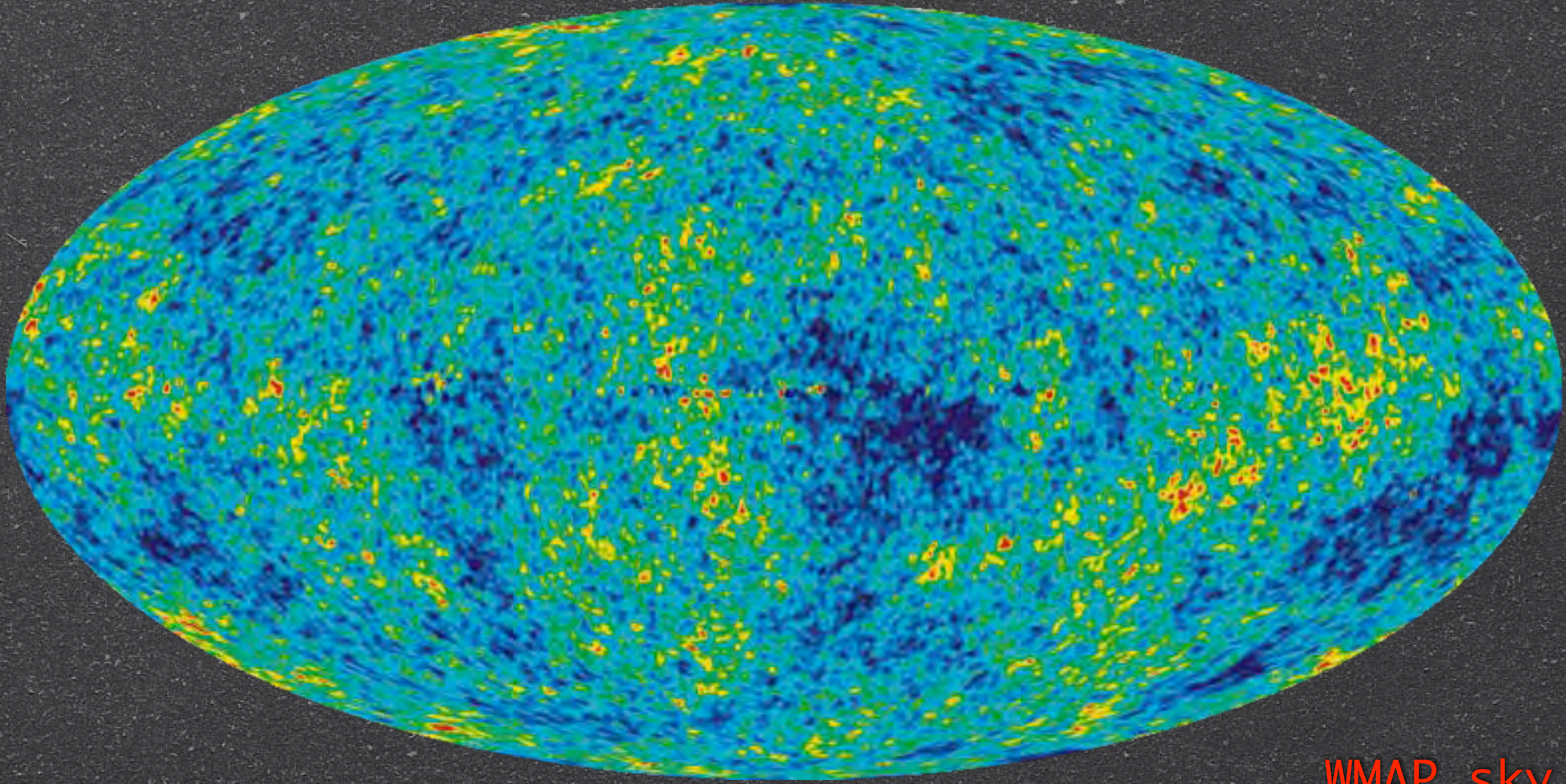
+ SZ power, CMB lensing convergence, ...

CMB sky

(Wilkinson Microwave Anisotropy Probe
all-sky temperature map)

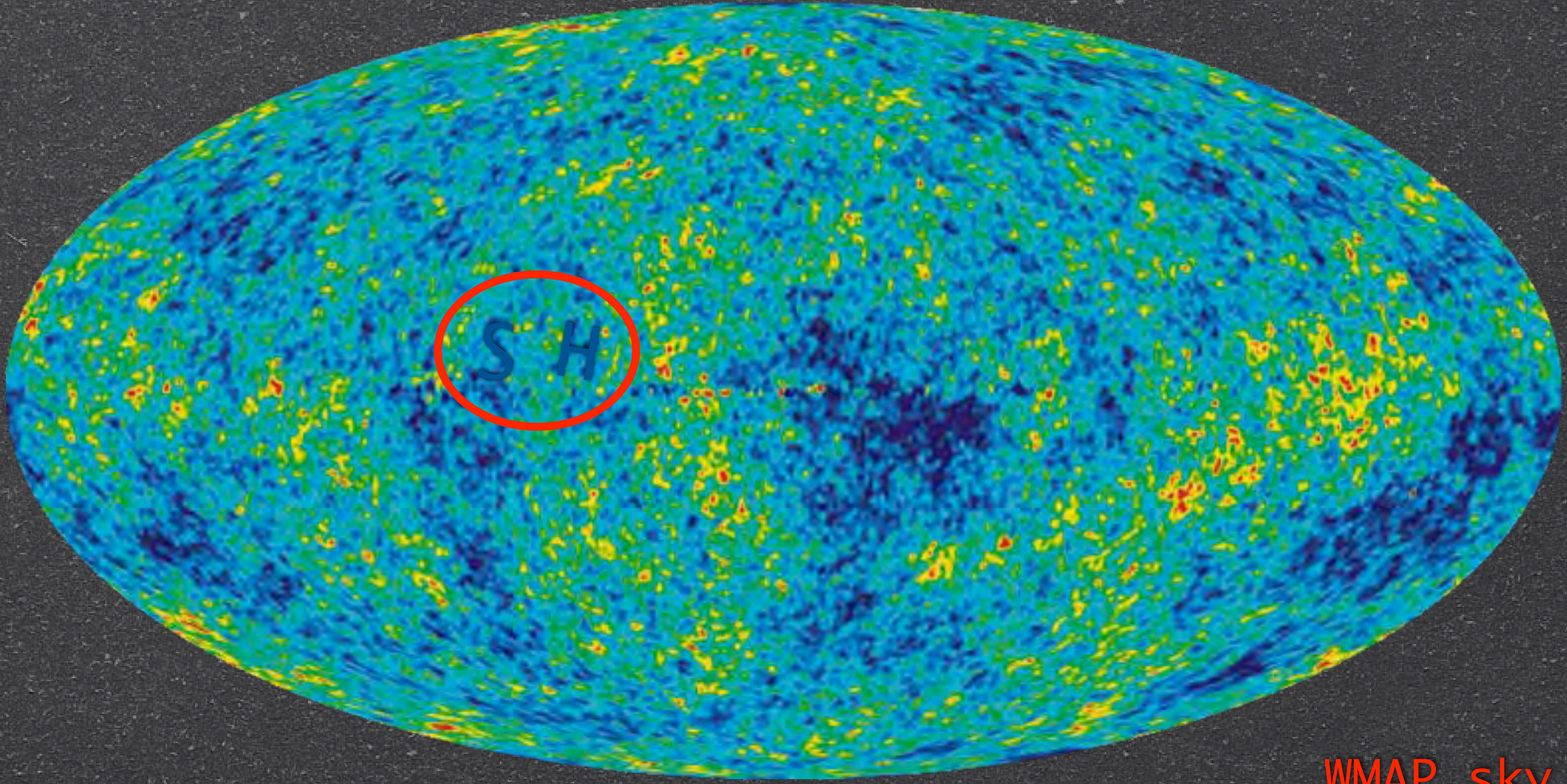


CMB anomalies?



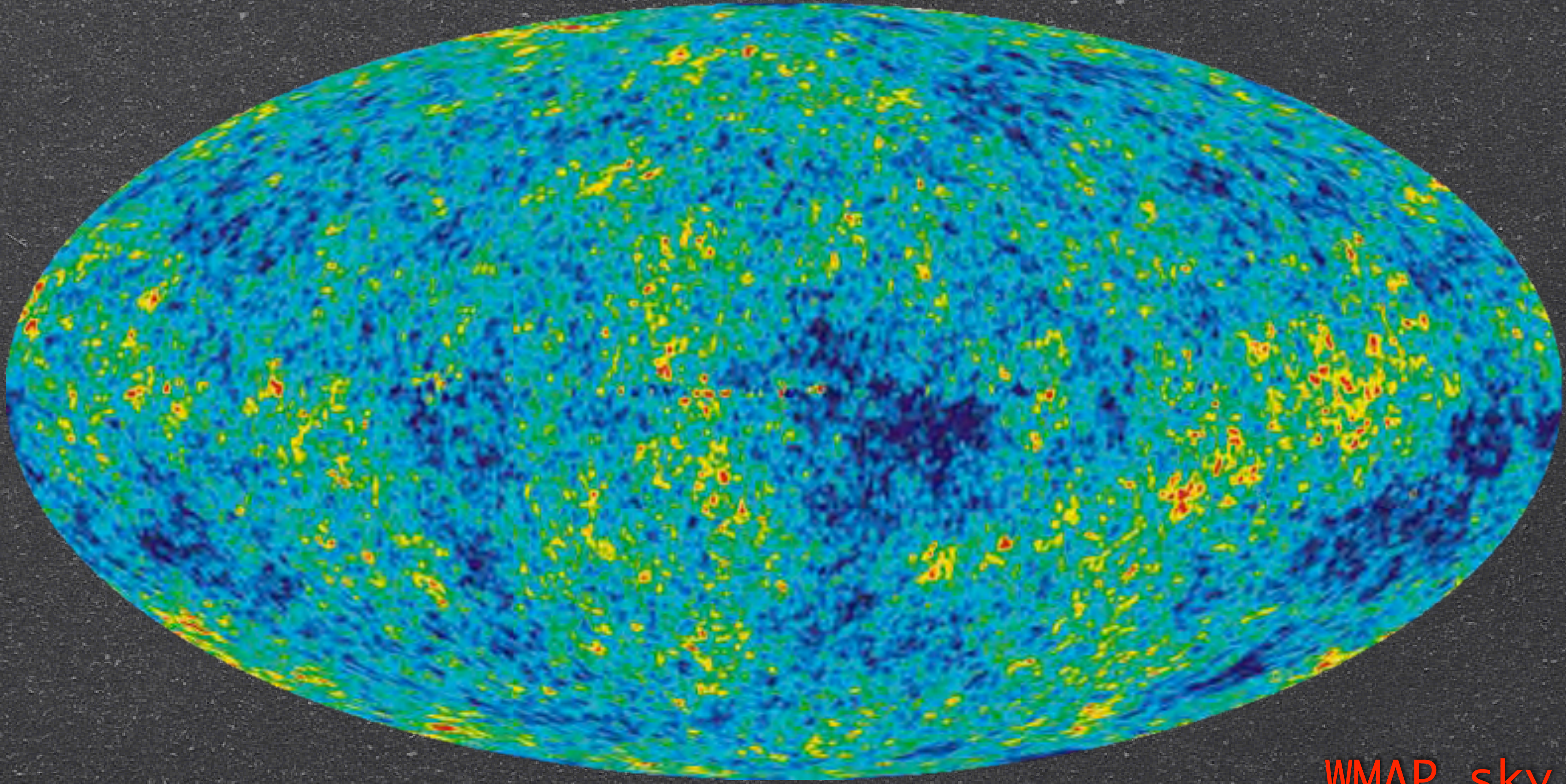
WMAP sky

CMB anomalies?



WMAP sky

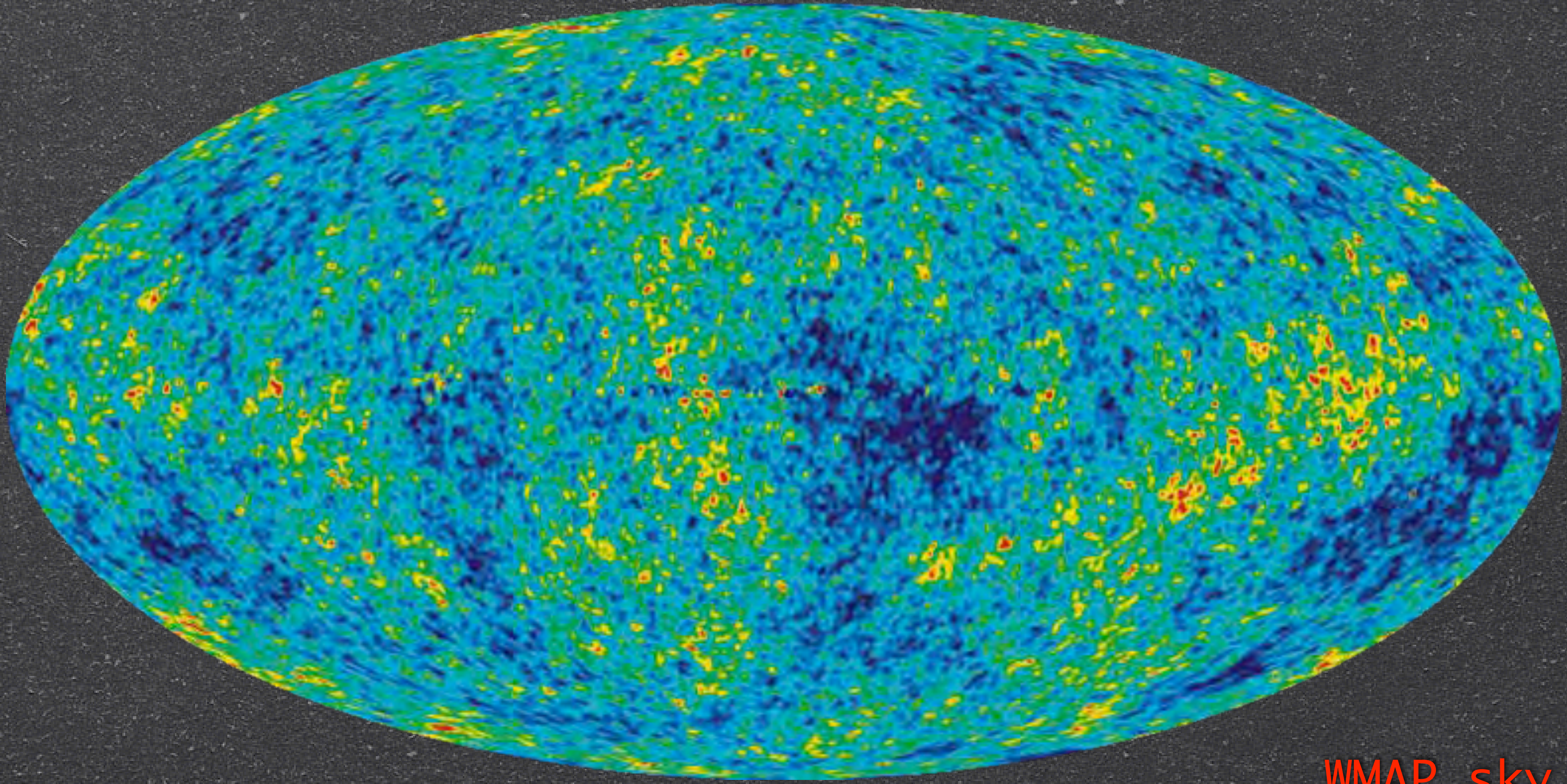
CMB anomalies?



WMAP sky

CMB anomalies?

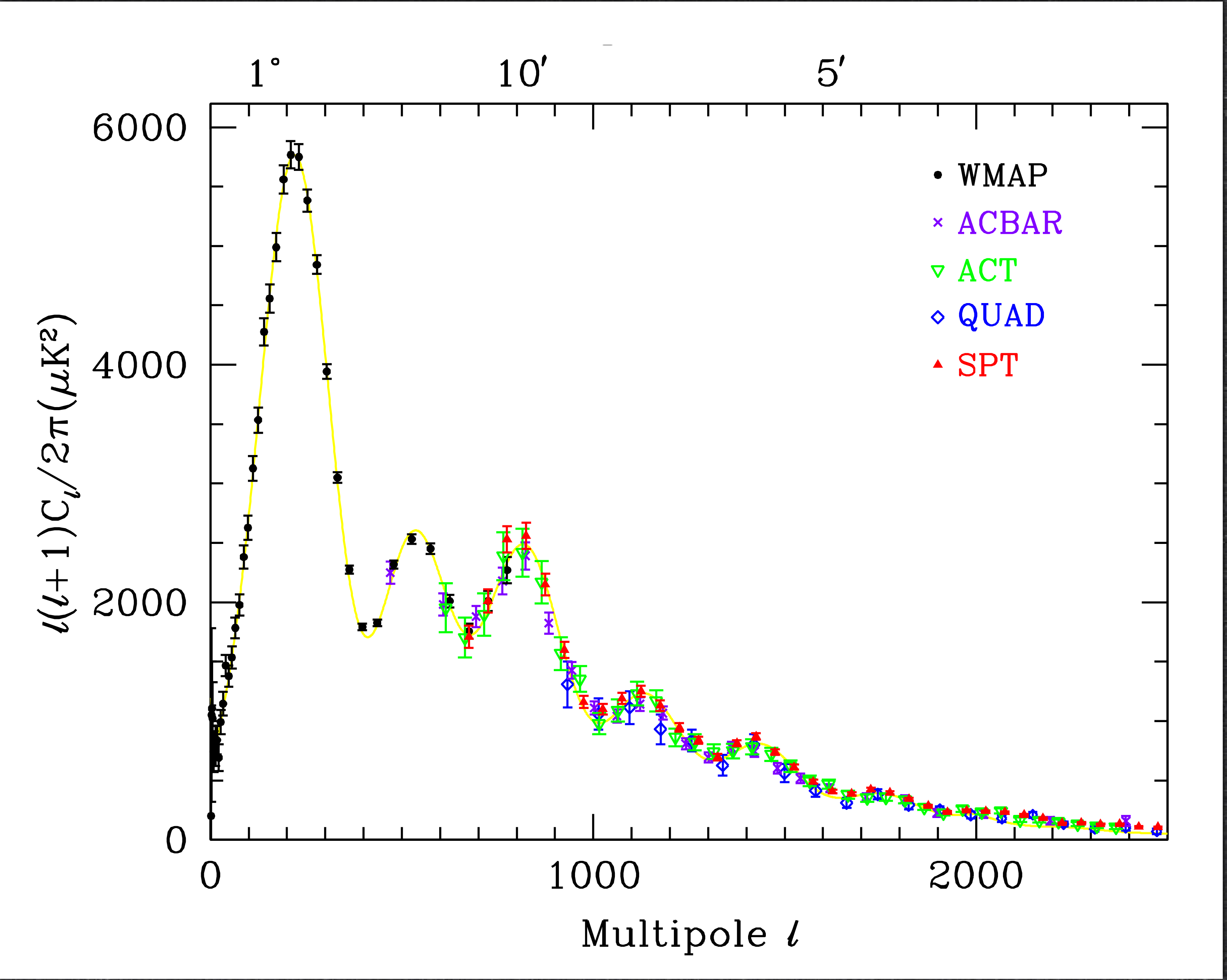
Not really - almost all information is contained in the power spectrum



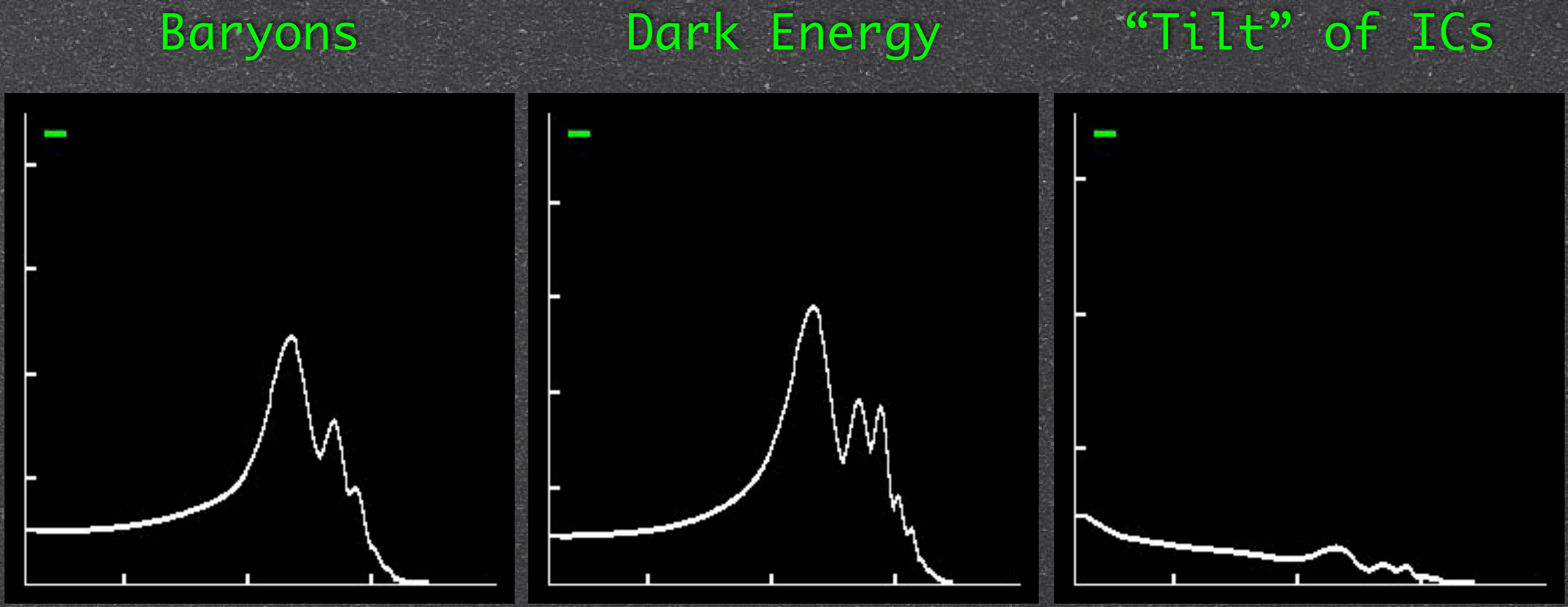
WMAP sky

- Individual hot/cold spots are just the particular realisation of our sky
- Actually anisotropies look very Gaussian (i.e. maximally random)
- This is what is expected from inflation
- Gaussian ⇒ all info. in variance (or power spectrum)
- Shape of power spectrum varies with cosmological parameters

Acoustic Peaks

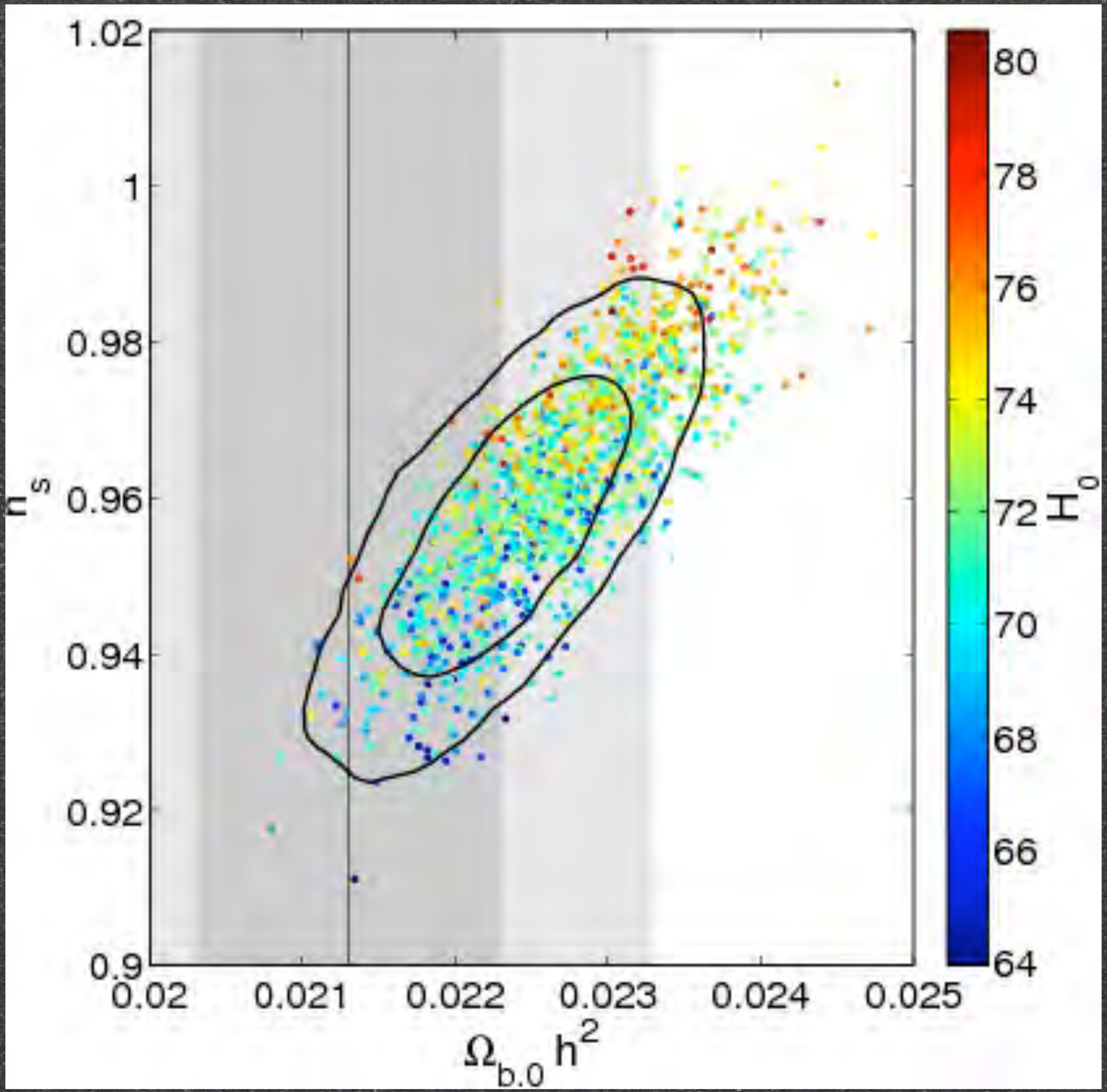


Parameters affect peak structure in different ways



Movies from Martin White

Markov Chain Monte Carlo



COSMOMC

WMAP+SPT+ACT

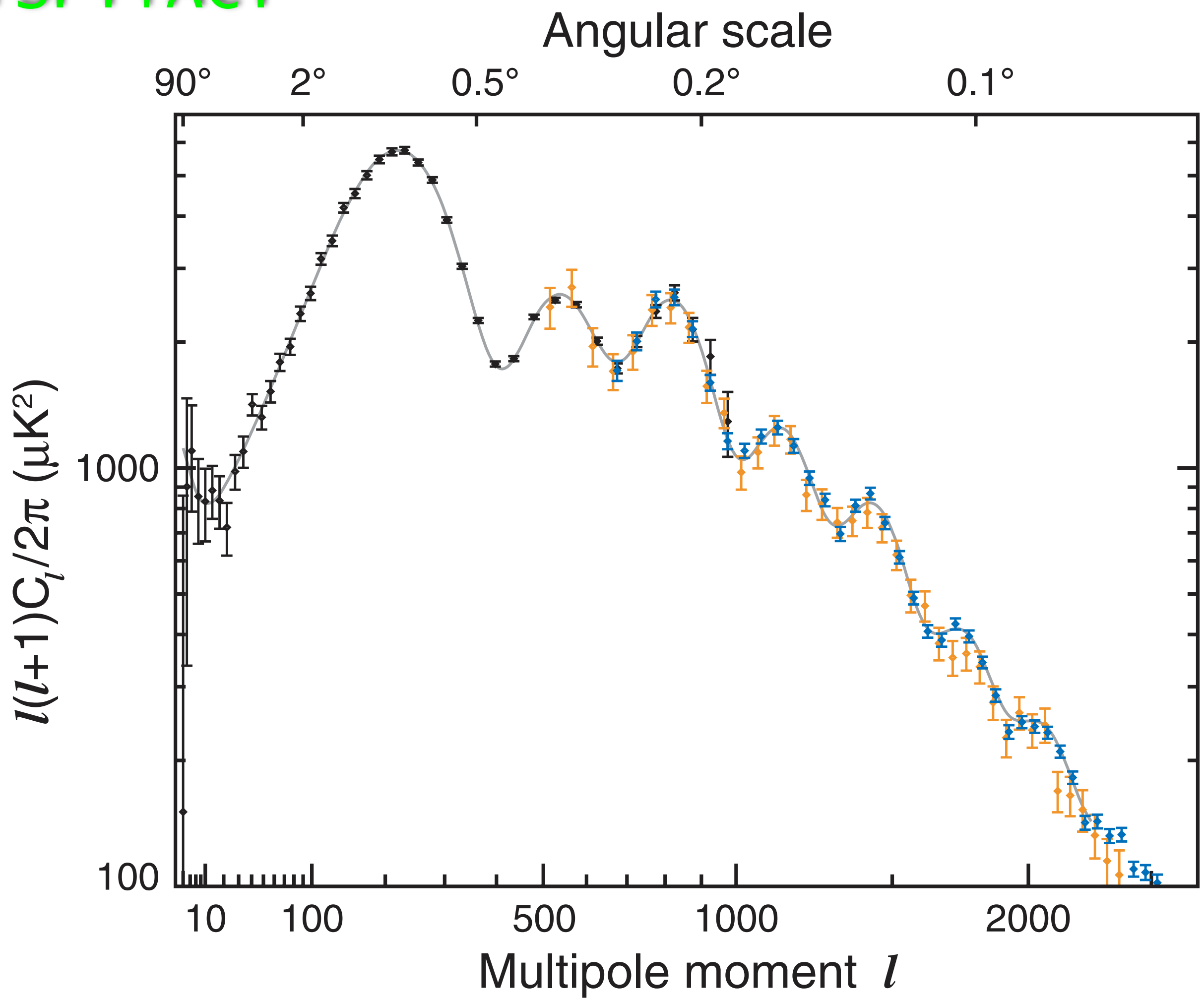


FIG. 1.— A compilation of the CMB data used in the nine-year *WMAP* analysis. The *WMAP* data are shown in black, the extended CMB data set – denoted 'eCMB' throughout – includes SPT data in blue (Keisler et al. 2011), and ACT data in orange, (Das et al. 2011). We also incorporate constraints from CMB lensing published by the SPT and ACT groups (not shown). The ΛCDM model fit to the *WMAP* data alone (shown in grey) successfully predicts the higher-resolution data.

Hinshaw et al. 2012

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+ SZ power, CMB lensing convergence, ...

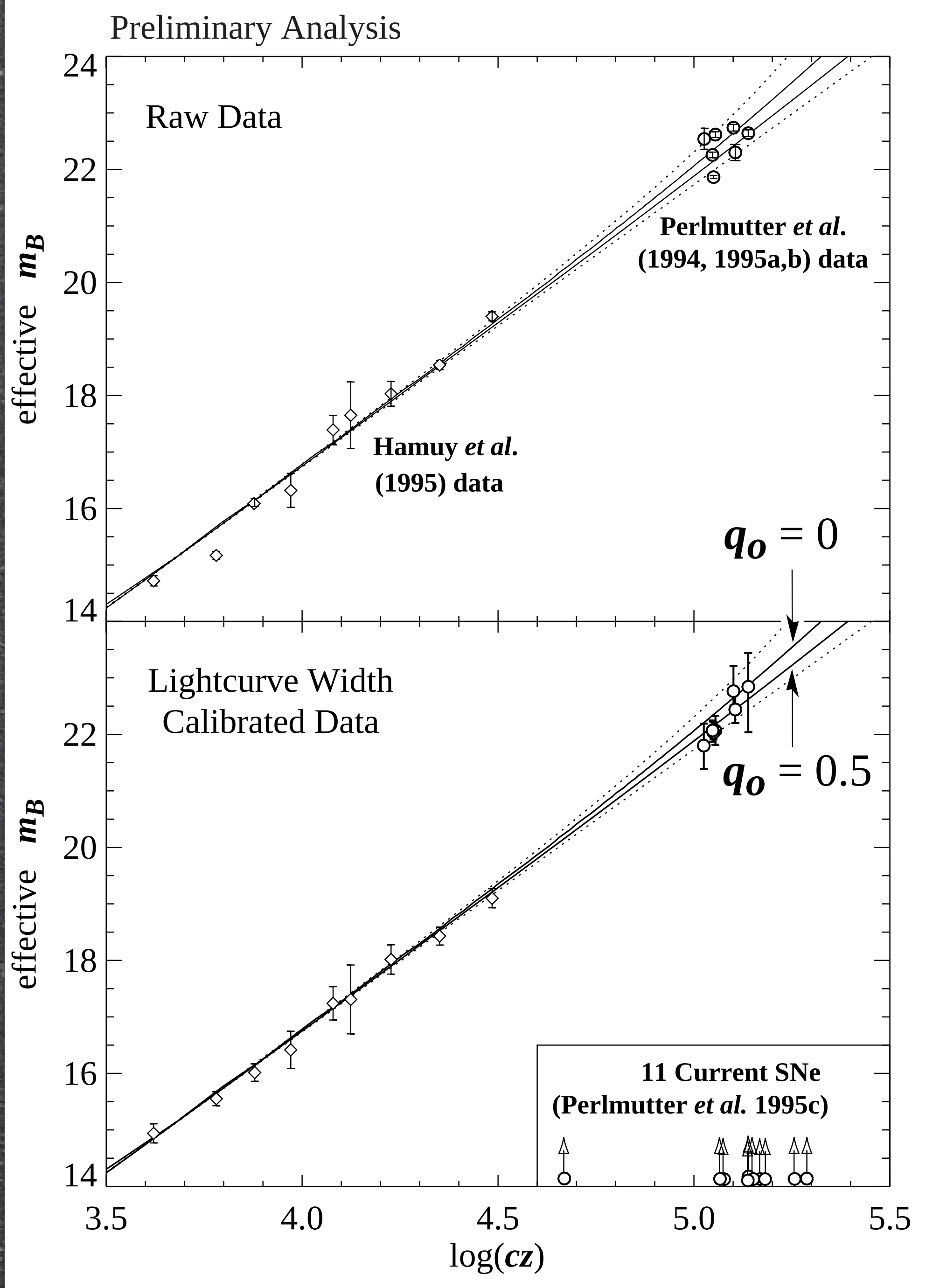
Acceleration

$$\ddot{a} > 0$$

using d_{L}

in distant SNe

Acceleration

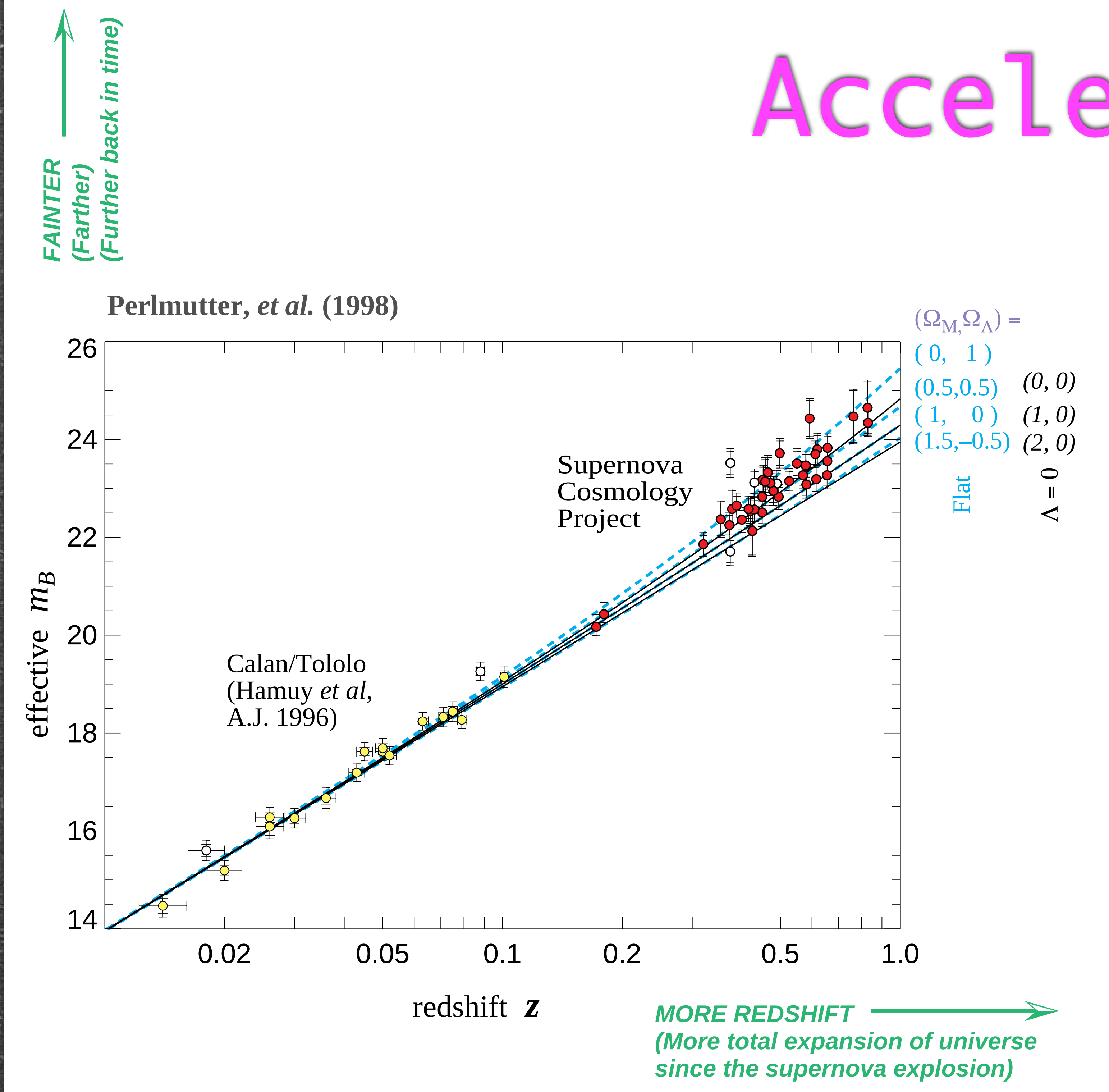


$\ddot{a} > 0$

using d_L

in distant SNe

Acceleration

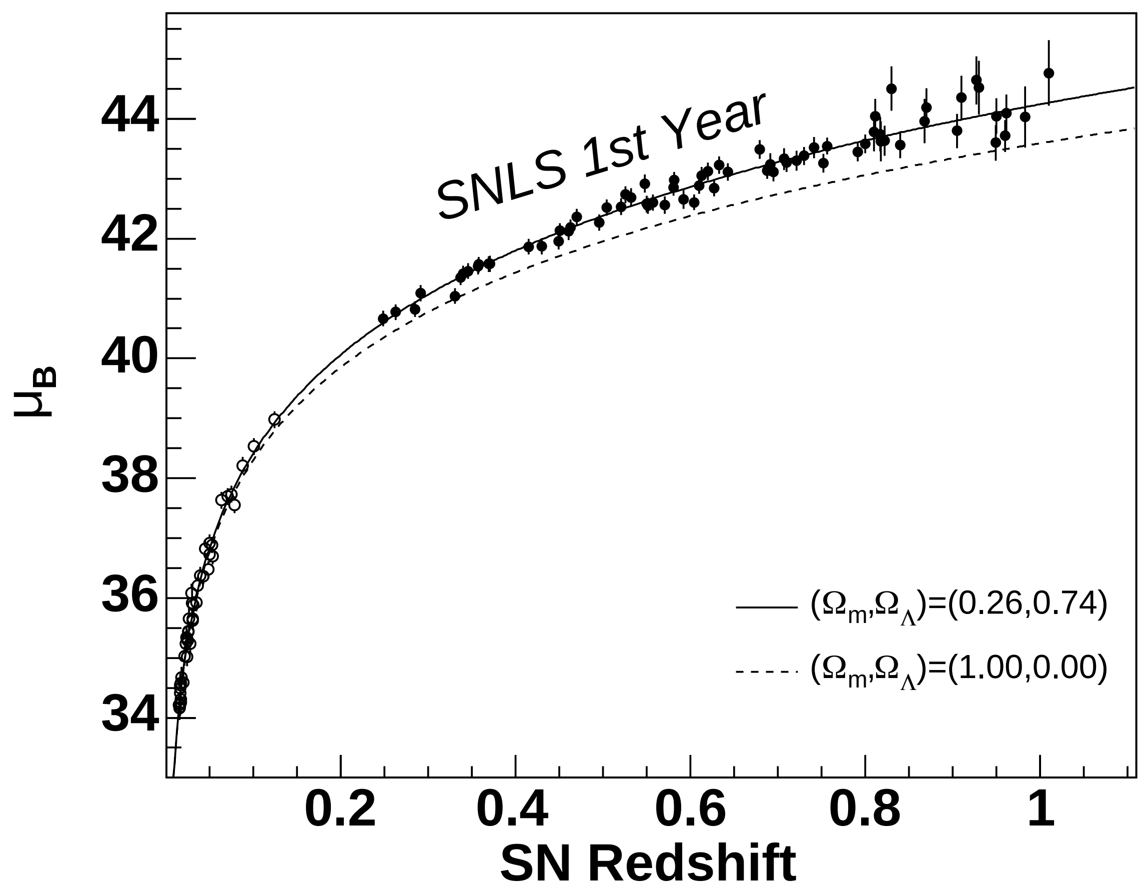


$\ddot{a} > 0$

using d_L

in distant SNe

Acceleration

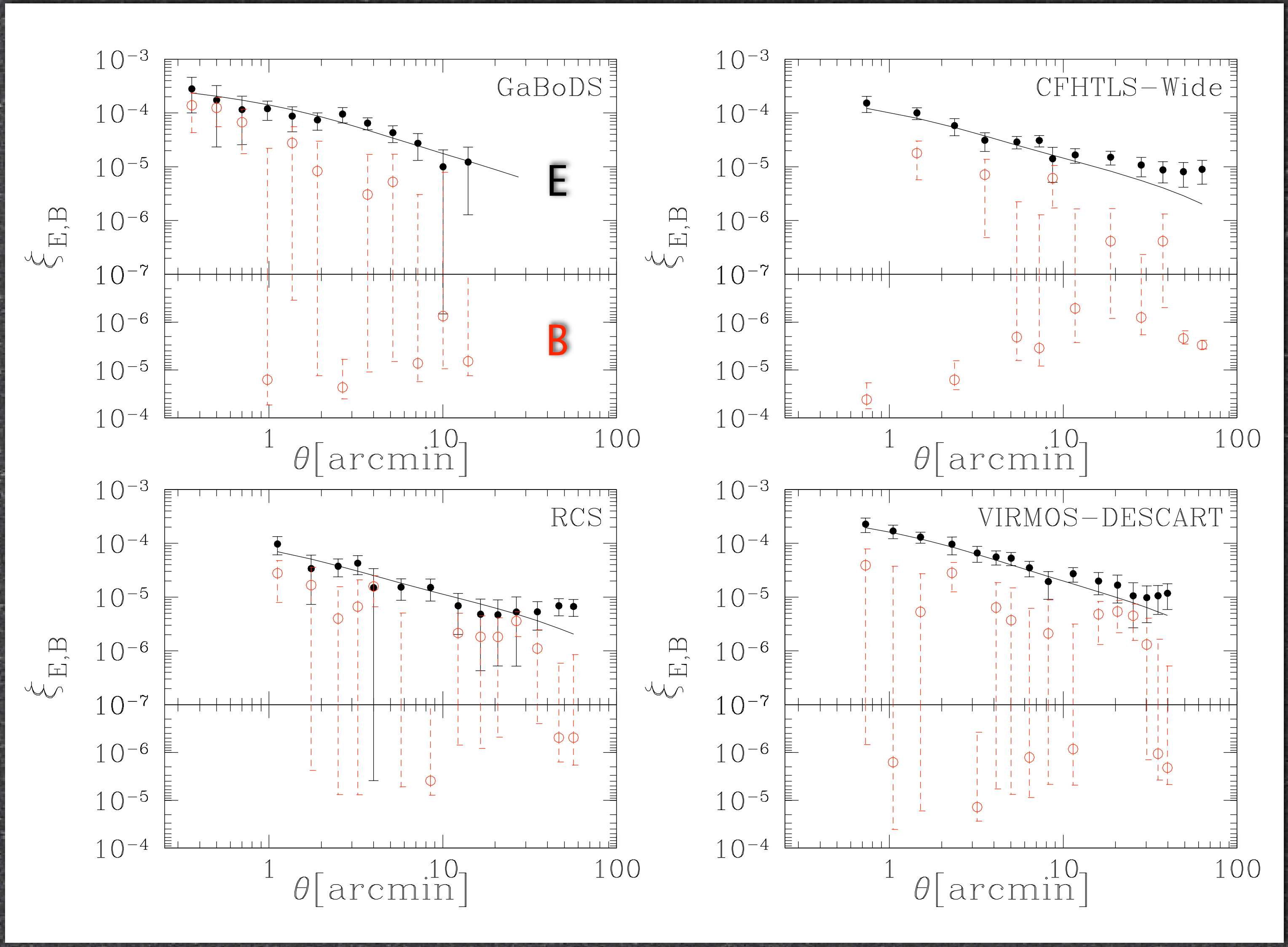


$\ddot{a} > 0$

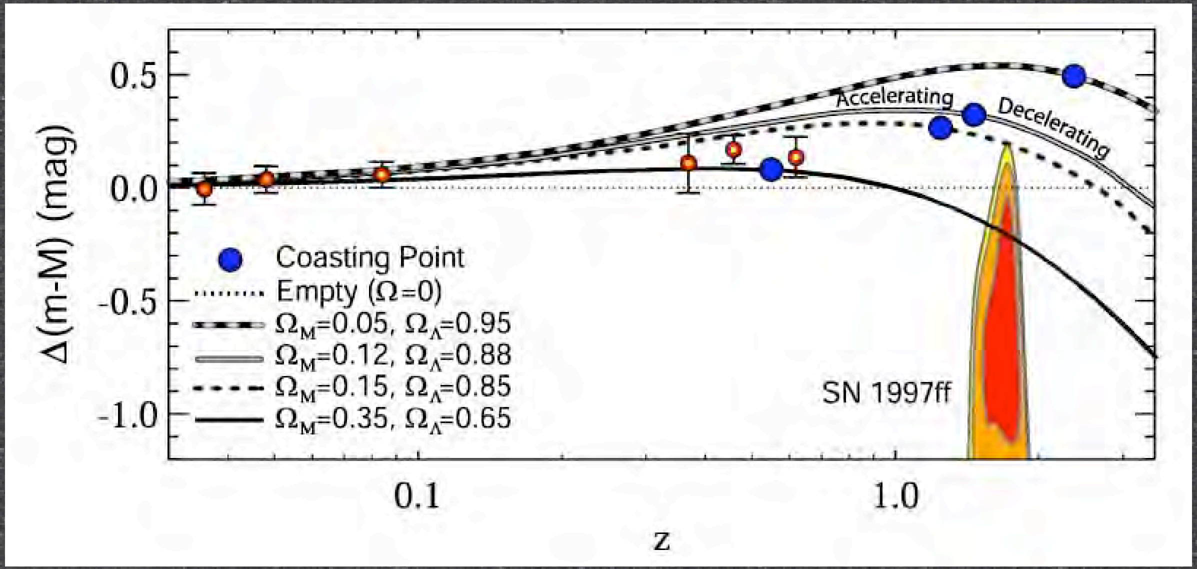
using d_L

in distant SNe

Cosmic Shear



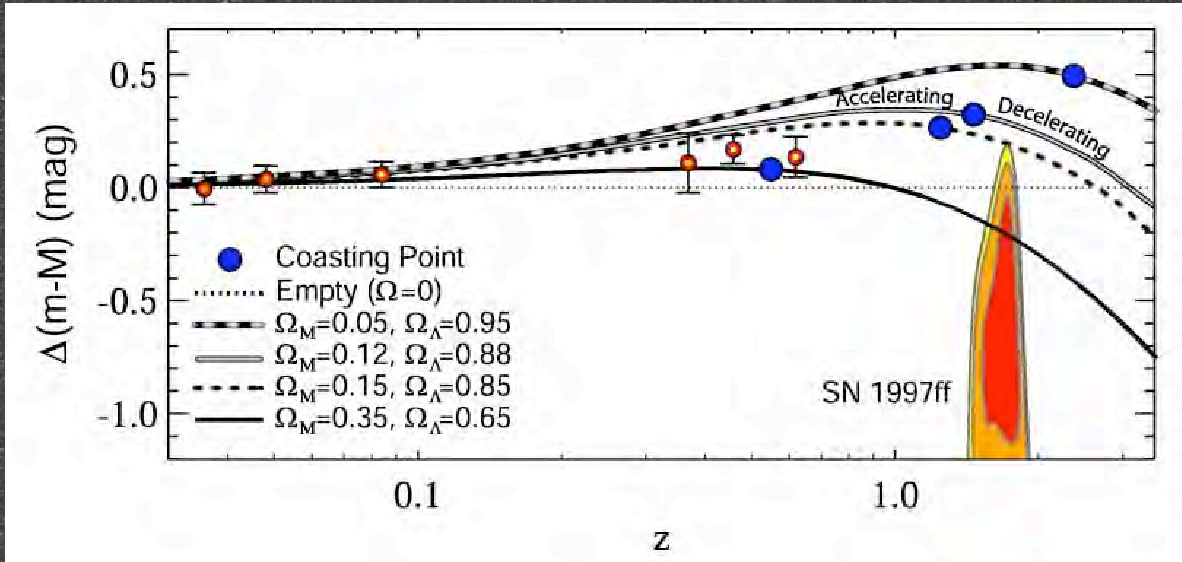
Benjamin et al. (2007)



Cosmic Jerk

$$\ddot{a} = 0$$

at $\simeq 0.5$



THE NEW YORK TIMES NATI

A 'Cosmic Jerk' That Reversed the Universe

By DENNIS OVERBYE

CLEVELAND, Oct. 10 — Astronomers said on Friday that they had determined the time in cosmic history when a mysterious force, "dark energy," began to wrench the universe apart.

Five billion years ago, said Dr. Adam Riess, an astronomer at the Space Telescope Science Institute in Baltimore, the universe experienced a "cosmic jerk." Before then, Dr. Riess said, the combined gravity of the galaxies and everything else in the cosmos was resisting the expansion, slowing it down. Since the jerk, though, the universe has been speeding up.

The results were based on observations by a multinational team of astronomers who used the Hubble Space Telescope to search exploding stars known as Type 1a supernovas, reaching back in time three-quarters of the way to the Big Bang, in which the universe was born. The results should help quell remaining doubts that the expansion of the universe is

Marty Katz for The New York Times

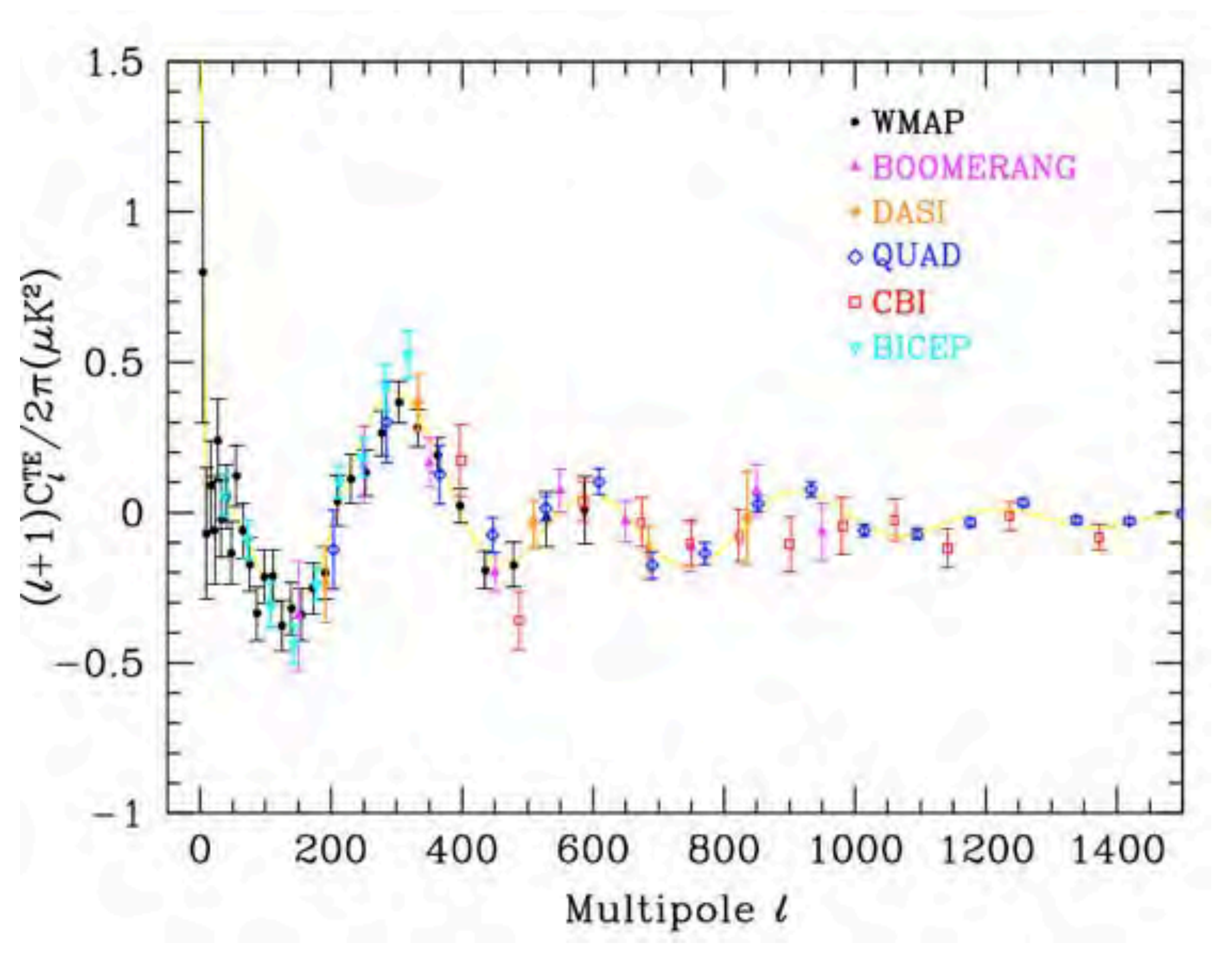
Dr. Adam Riess, who reported yesterday on the speeding and expanding universe, at the Space Telescope Science Institute in Baltimore.

Cosmic Jerk

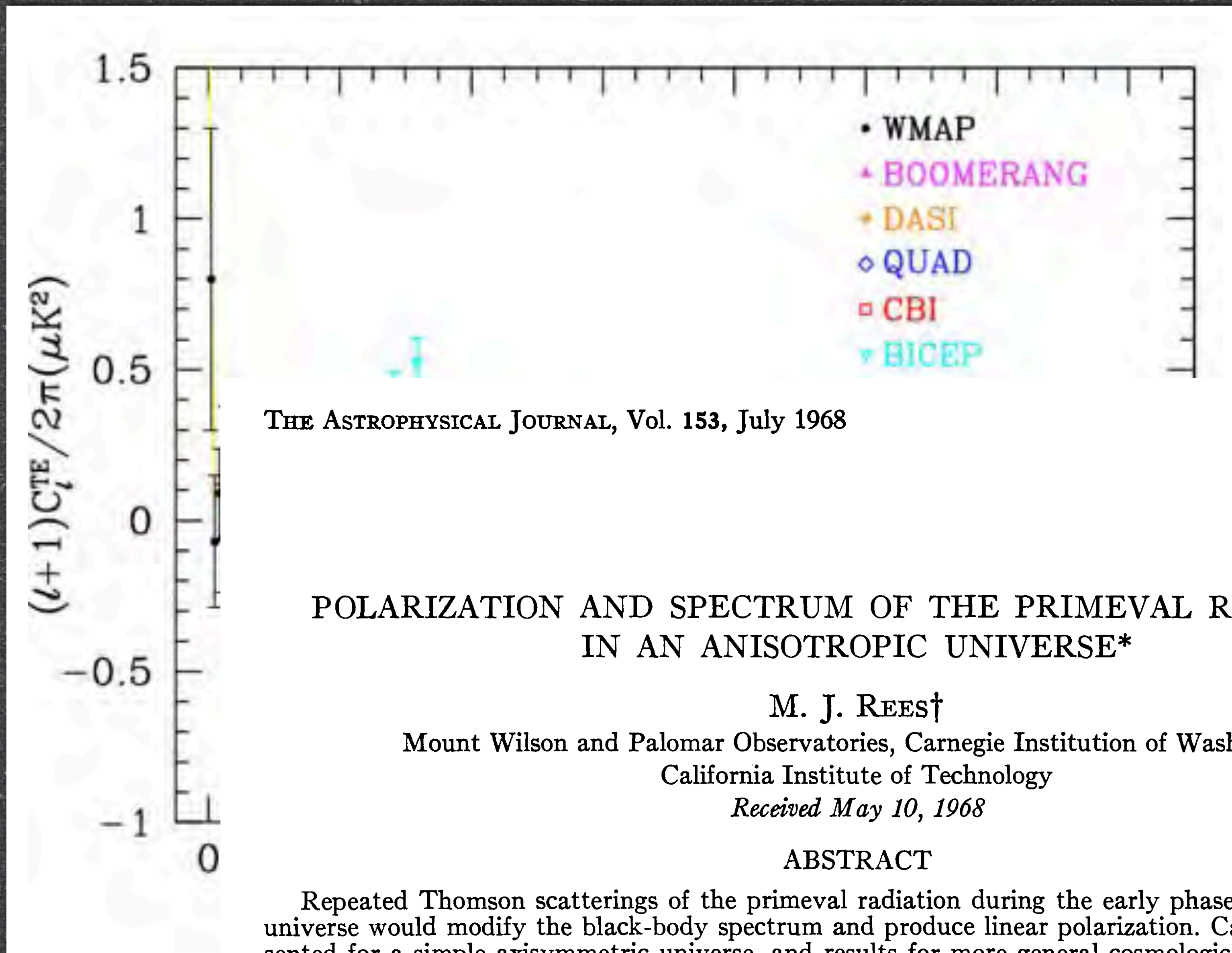
$$\ddot{a} = 0$$

at $\simeq 0.5$

CMB Polarization



CMB Polarization



THE ASTROPHYSICAL JOURNAL, Vol. 153, July 1968

POLARIZATION AND SPECTRUM OF THE PRIMEVAL RADIATION IN AN ANISOTROPIC UNIVERSE*

M. J. REES†

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington

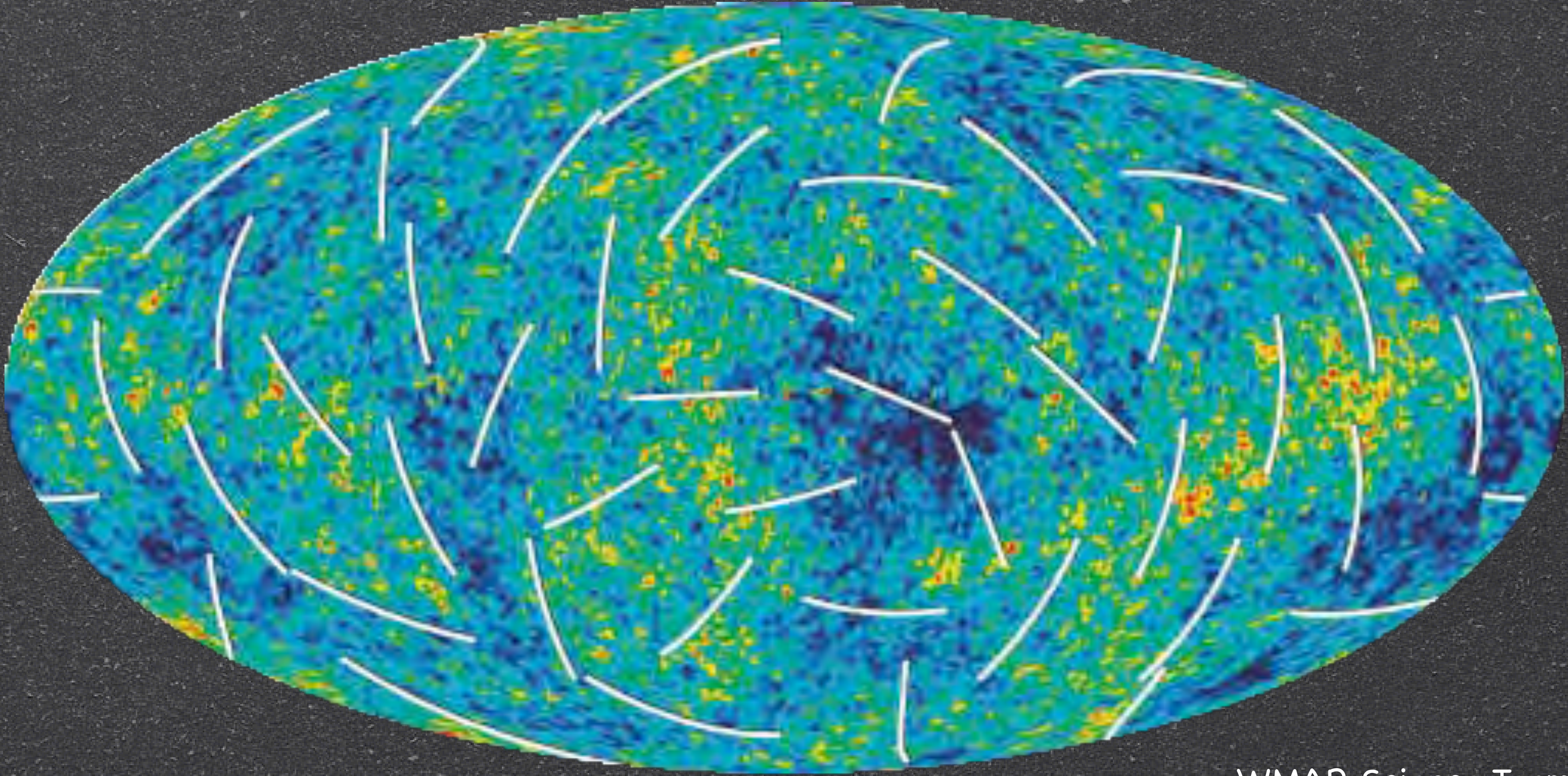
California Institute of Technology

Received May 10, 1968

ABSTRACT

Repeated Thomson scatterings of the primeval radiation during the early phases of an anisotropic universe would modify the black-body spectrum and produce linear polarization. Calculations are presented for a simple axisymmetric universe, and results for more general cosmological models are summarized. These effects are potentially observable.

All-sky Cosmic Polarization



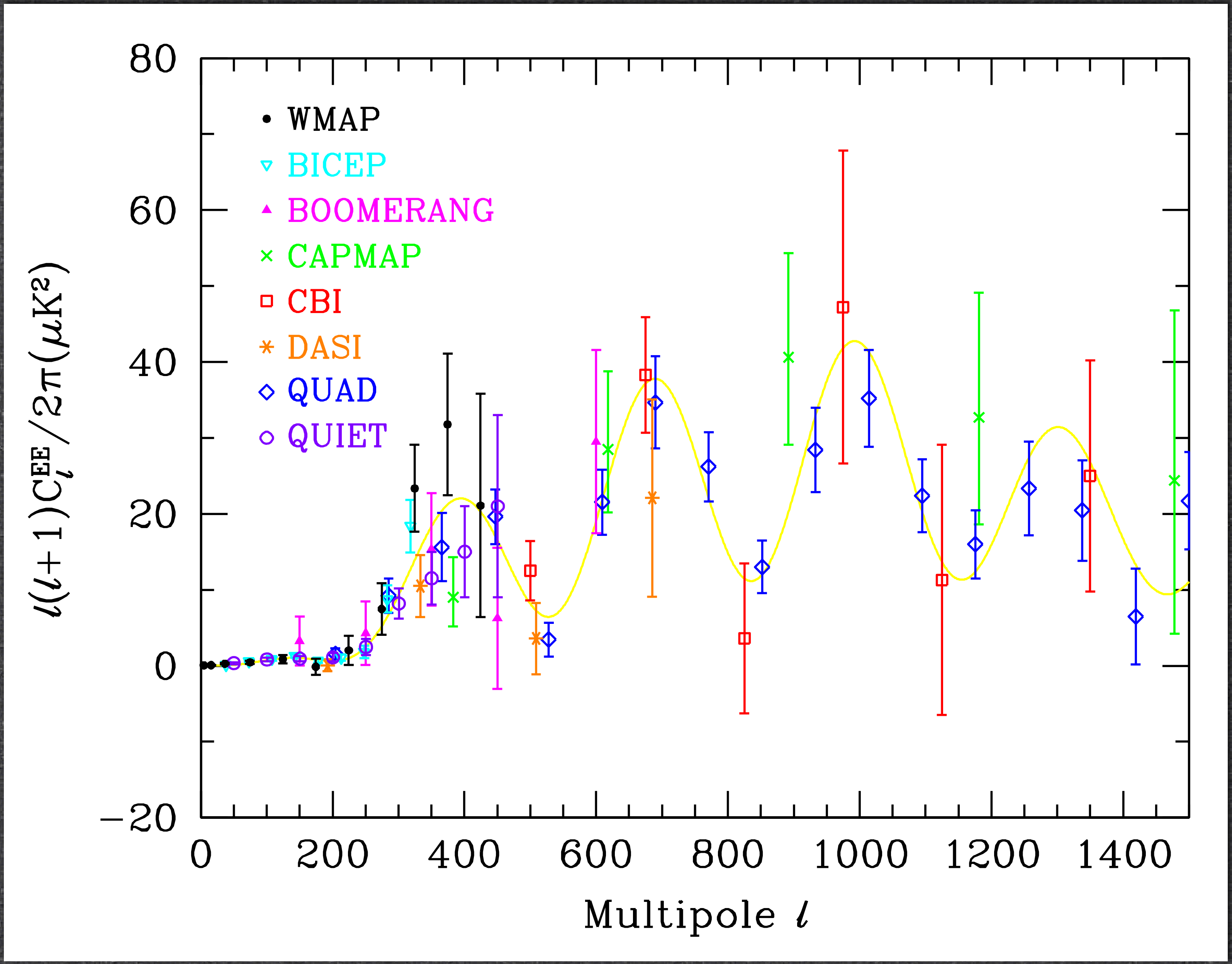
WMAP Science Team

Information in the CMB

- CMB partially polarized
- 2 numbers for each pixel (as well as T)
  → call these "E" and "B"
- 4 correlations to measure: TT, TE, EE, BB
  → 4 different power spectra
- (TB and EB are zero)
- plus "non-Gaussian" signatures

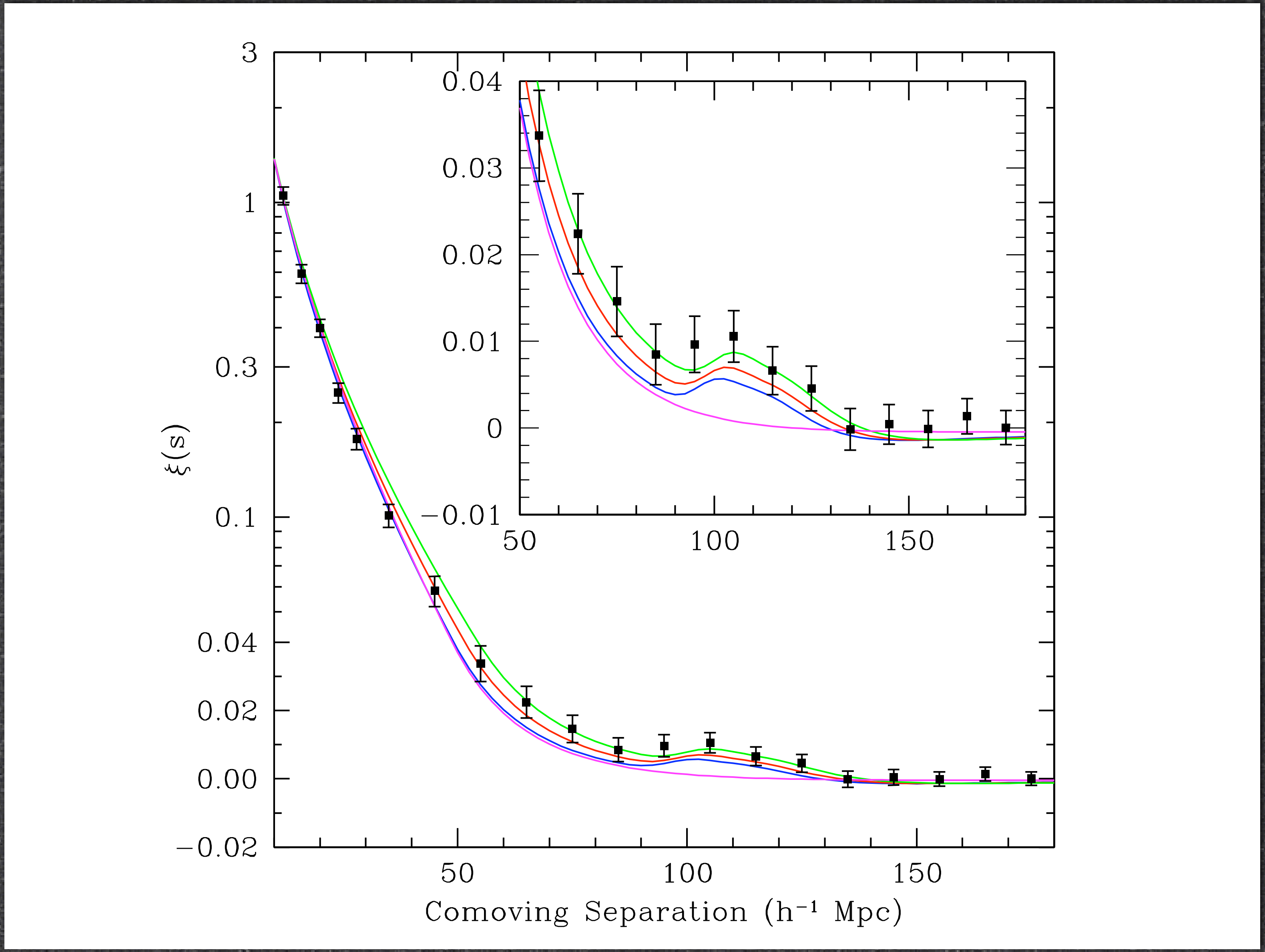
B-modes probe inflation?

Acoustic Peaks



Baryon Acoustic Oscillations

(not Beijing Astronomical Observatory)



Eisenstein et al. (2005)

ISW-LSS Correlation

- Predicted Crittenden & Turok (1996)
- 1st limit Boughn & Crittenden (2002)
- Flurry of low significance results
- Convincing by ~2005
- But hard to get a constraining detection

CMB lensing

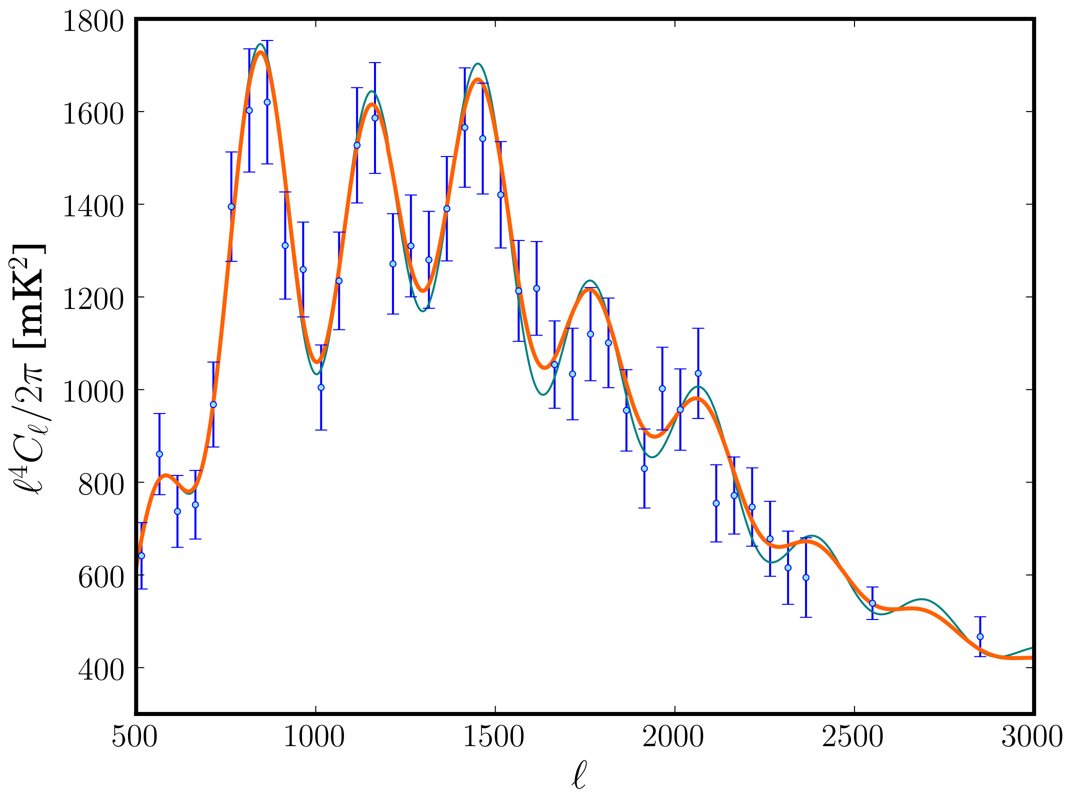


FIG. 12.— Lensing of the CMB smooths out the acoustic peaks in the CMB power spectrum. The best fit model with lensed CMB, secondaries, and point sources is shown as the thick orange curve, while the same with no lensing is shown with the thin green curve.

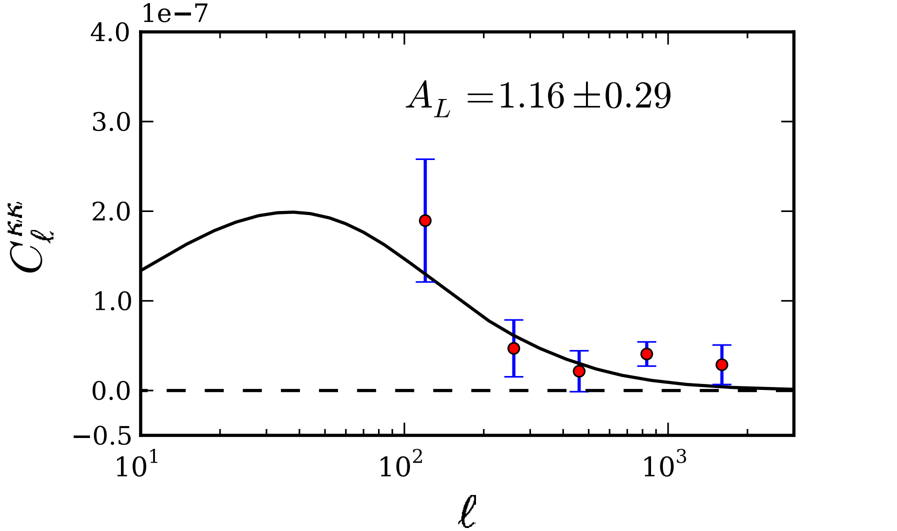


FIG. 2. Convergence power spectrum (red points) measured from ACT equatorial sky patches. The solid line is the power spectrum from the best-fit WMAP+ACT cosmological model with amplitude $A_L = 1$, which is consistent with the measured points. The error bars are from the Monte Carlo simulation results displayed in Fig. 1. The best-fit lensing power spectrum amplitude to our data is $A_L = 1.16 \pm 0.29$

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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6 parameters have values measured to 1 or 2 digits

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1 mean free path:	τ_{reion}			
4 fluctuation descriptors:	A	n	$n' \equiv dn/d\ln k$	$r \equiv T/S$
12 total parameters				

6 parameters have values measured to 1 or 2 digits

Is that really it?!

Beyond the SMC?

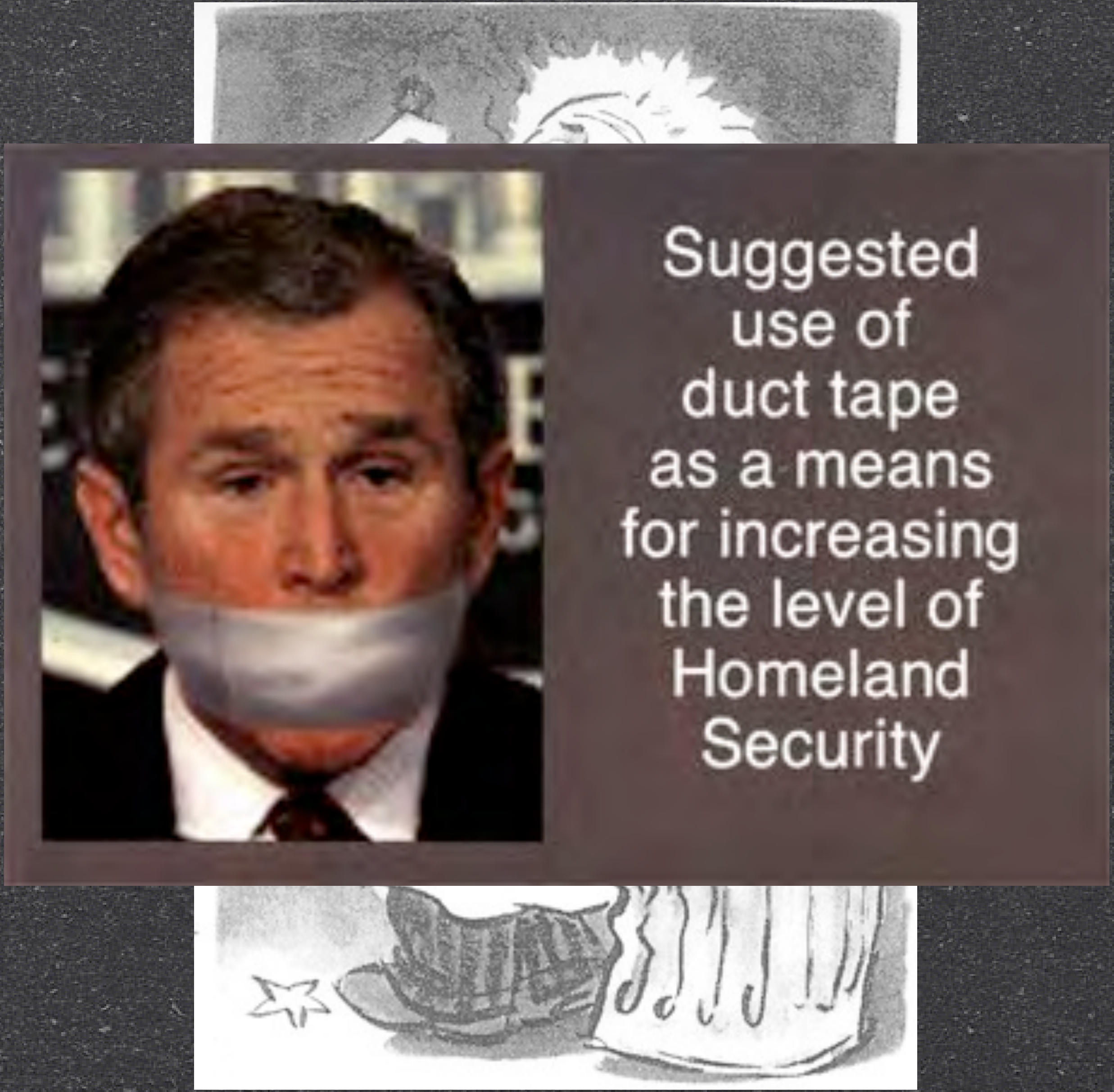
- Constrain parameters better?
- Which of others have null values?
- 1+w and B-modes measurable?
- Damping of high multipoles?
- Will it get as boringly successful as the SMPP?
- Something we haven't thought of?

Constraining "w"

$w=p/\rho$
for DE

Constraining “w”

$w = p/\rho$
for DE



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
- Elastic Dark Energy
- Holographic Dark Energy
- Natural Dark Energy

Good Dark Energy Theories

SMPP	SMC
Early 1970s	Early 1990s
Predicted:	Predicted:
• W,Z,c,t,g,Higgs	• ~6 things (later)
Not fundamental	Not fundamental
Observer independent	Observer dependent (time + Cosmic Var.)

Where did the parameters come from?

Connection with fundamental physics theory?

Are some parameters stochastic?

(Did someone say the "A" word?)

Are some parameters stochastic?

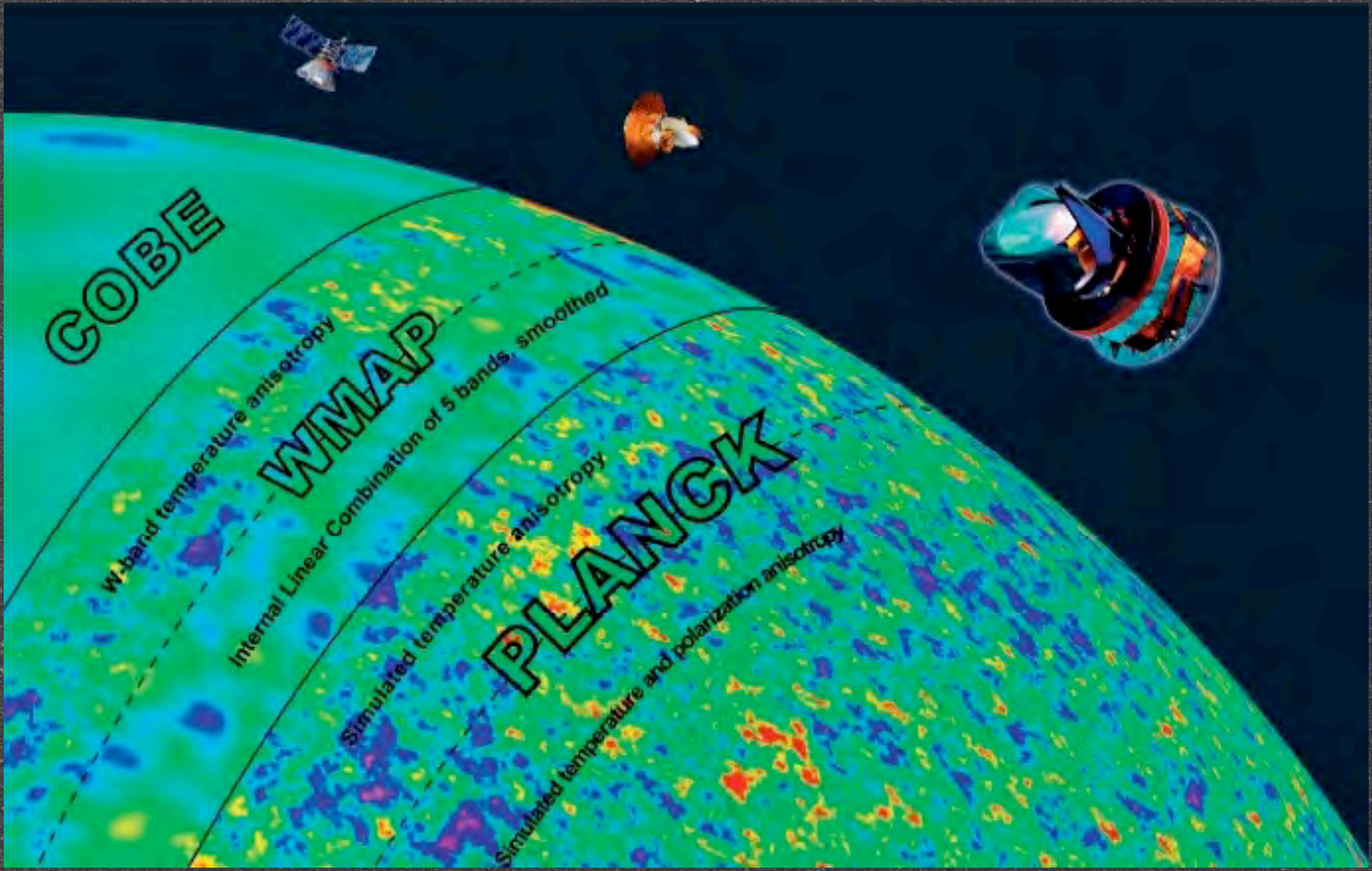
(Did someone say the "A" word?)

3rd CMB satellite

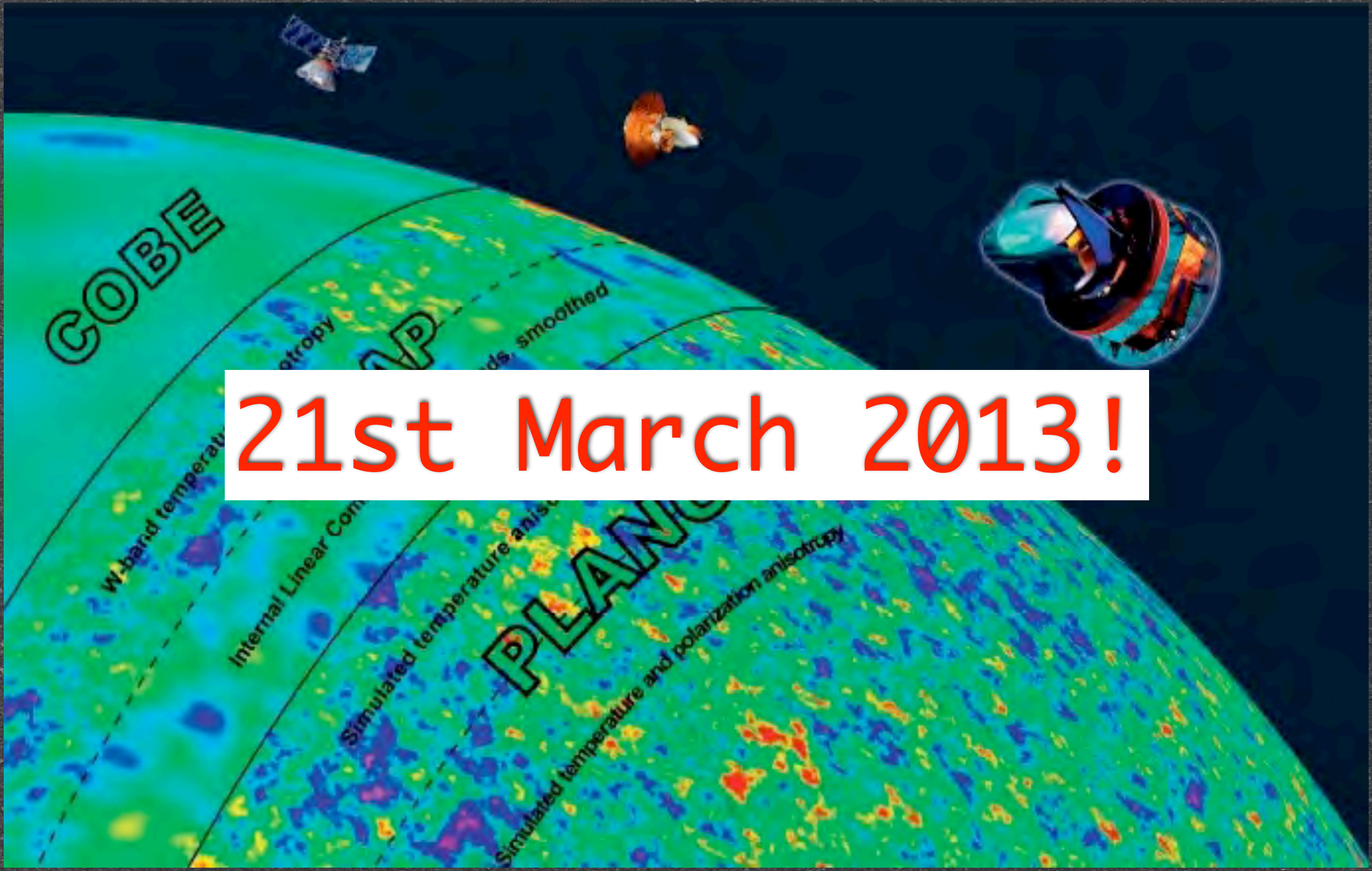
All sky 5′ resoln.

9 bands: 30-860GHz (LFI & HFI)

Launched May 2009


COBE
W-band temperature anisotropy
WMAP
Internal Linear Combination of 5 bands, smoothed
Simulated temperature anisotropy
PLANCK
Simulated temperature and polarization anisotropy

21st March 2013!



Looking towards the future ...


Looking towards the future ...
...20 years later it’s the same SMC!