– Dark Energy –

– Dark Energy –

Still bad for astronomy six years later?

Λ – an unwelcome guest?

NATURE · VOL 348 · 20/27 DECEMBER 1990

The cosmological constant and cold dark matter

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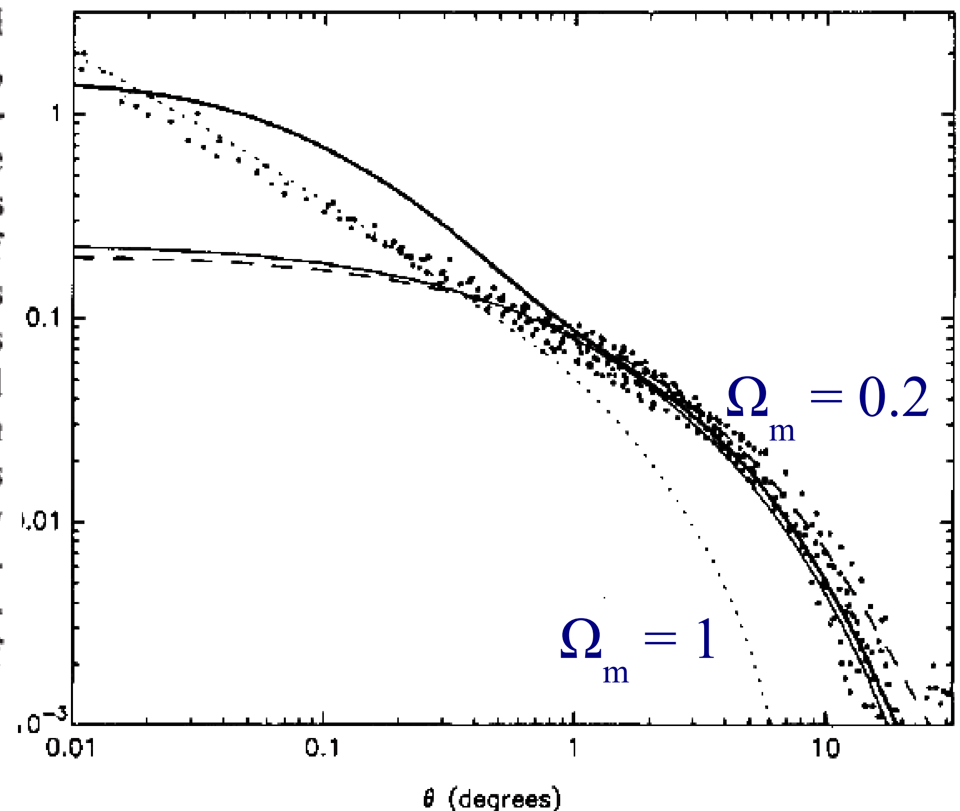
Department of Physics, University of Oxford, Oxford OX1 3RH, UK

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 $100\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$) 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.

Accept Λ rather than give up on inflation by accepting $\Omega_{tot} < 1$



Λ – an unwelcome guest?

NATURE · VOL 366 · 2 DECEMBER 1993

The baryon content of galaxy clusters: a challenge to cosmological orthodoxy

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‡ Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA

Baryonic matter constitutes a larger fraction of the total mass of rich galaxy clusters than is predicted by a combination of cosmic nucleosynthesis considerations (light-element formation during the Big Bang) and standard inflationary cosmology. This cannot be accounted for by gravitational and dissipative effects during cluster formation. Either the density of the Universe is less than that required for closure, or there is an error in the standard interpretation of element abundances.

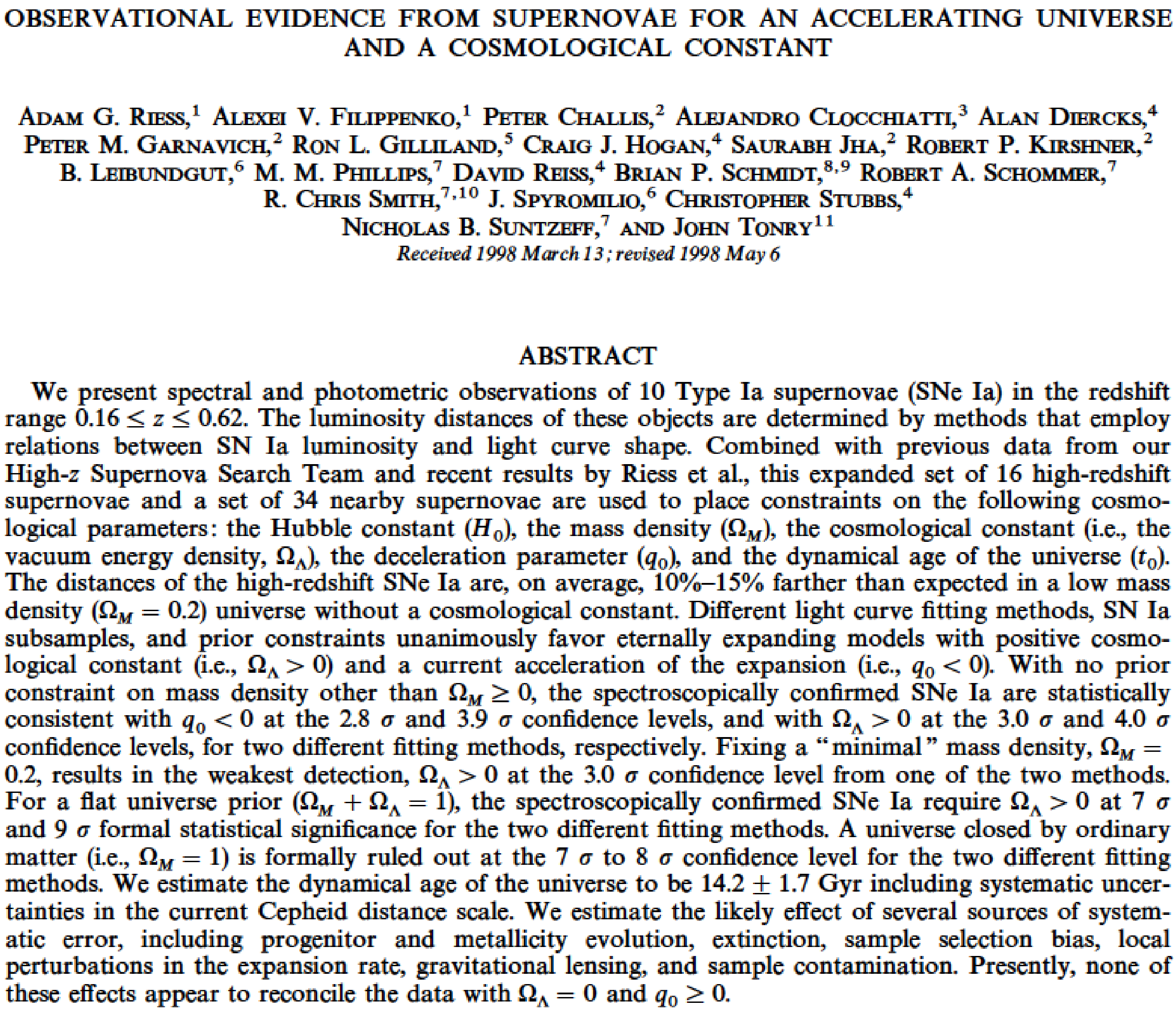
$$\Omega_0 = 0.16\, h^{-1/2}/(1 + 0.19\, h^{3/2}) \quad \sim 0.23 \qquad (8)$$

when the nucleosynthesis value is used for Ω_b. This may be too large as some of the unseen matter may be baryonic. The flat universe required by the inflation model can be rescued by a non-zero cosmological constant, a possibility which has other attractive features[41]

Accept Λ rather than give up inflation or Big Bang nucleosynthesis

Λ – an unwelcome guest?

...but there nonetheless!



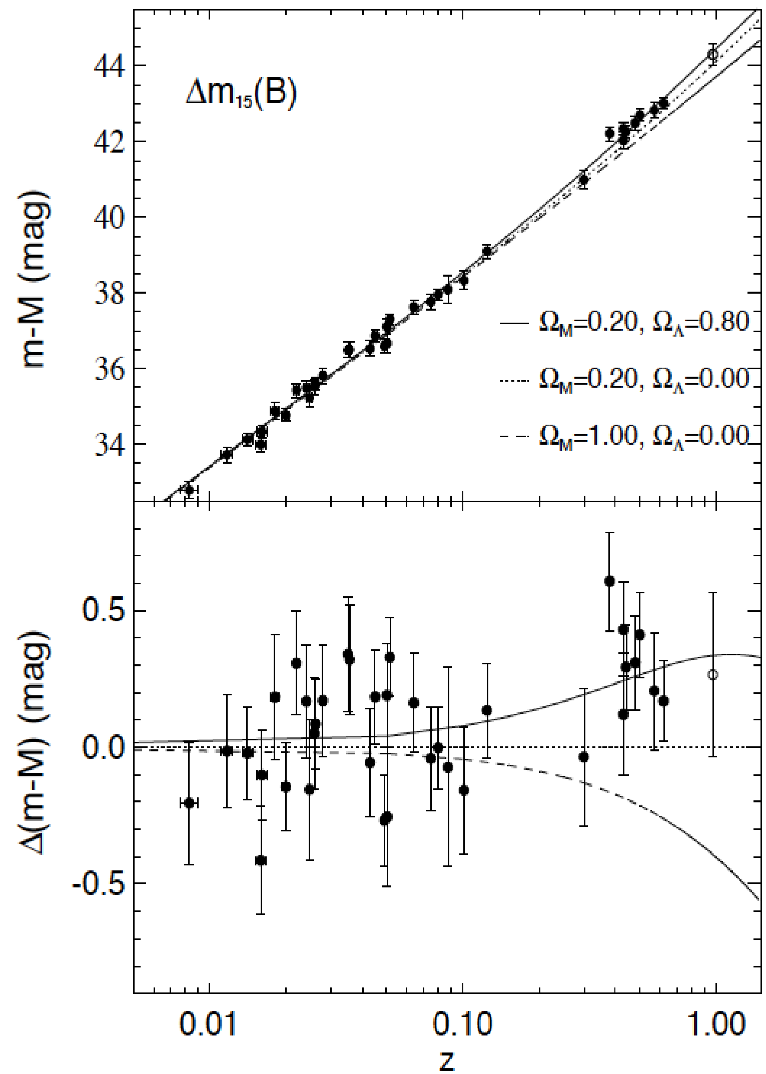
OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

Adam G. Riess,[1] Alexei V. Filippenko,[1] Peter Challis,[2] Alejandro Clocchiatti,[3] Alan Diercks,[4] Peter M. Garnavich,[2] Ron L. Gilliland,[5] Craig J. Hogan,[4] Saurabh Jha,[2] Robert P. Kirshner,[2] B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7] R. Chris Smith,[7,10] J. Spyromilio,[6] Christopher Stubbs,[4] Nicholas B. Suntzeff,[7] and John Tonry[11]

Received 1998 March 13; revised 1998 May 6

ABSTRACT

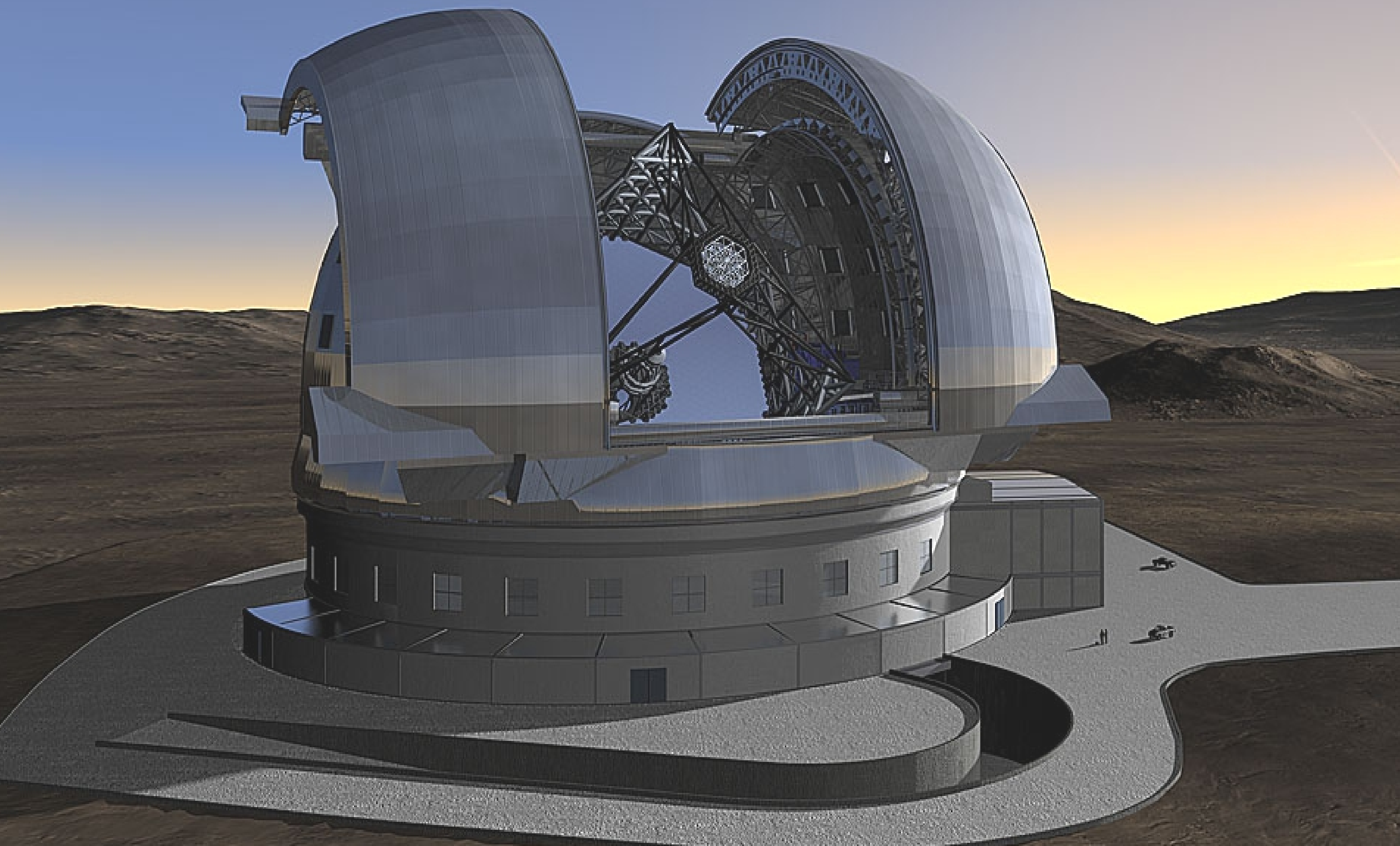
We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-*z* Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8 σ and 3.9 σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0 σ and 4.0 σ confidence levels, for two different fitting methods, respectively. Fixing a "minimal" mass density, $\Omega_M = 0.2$, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0 σ confidence level from one of the two methods. For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7 σ and 9 σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7 σ to 8 σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncertainties in the current Cepheid distance scale. We estimate the likely effect of several sources of systematic error, including progenitor and metallicity evolution, extinction, sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to reconcile the data with $\Omega_\Lambda = 0$ and $q_0 \geq 0$.



NB No mention of "Dark Energy" (yet)!

Creative thought in the era of Big Science

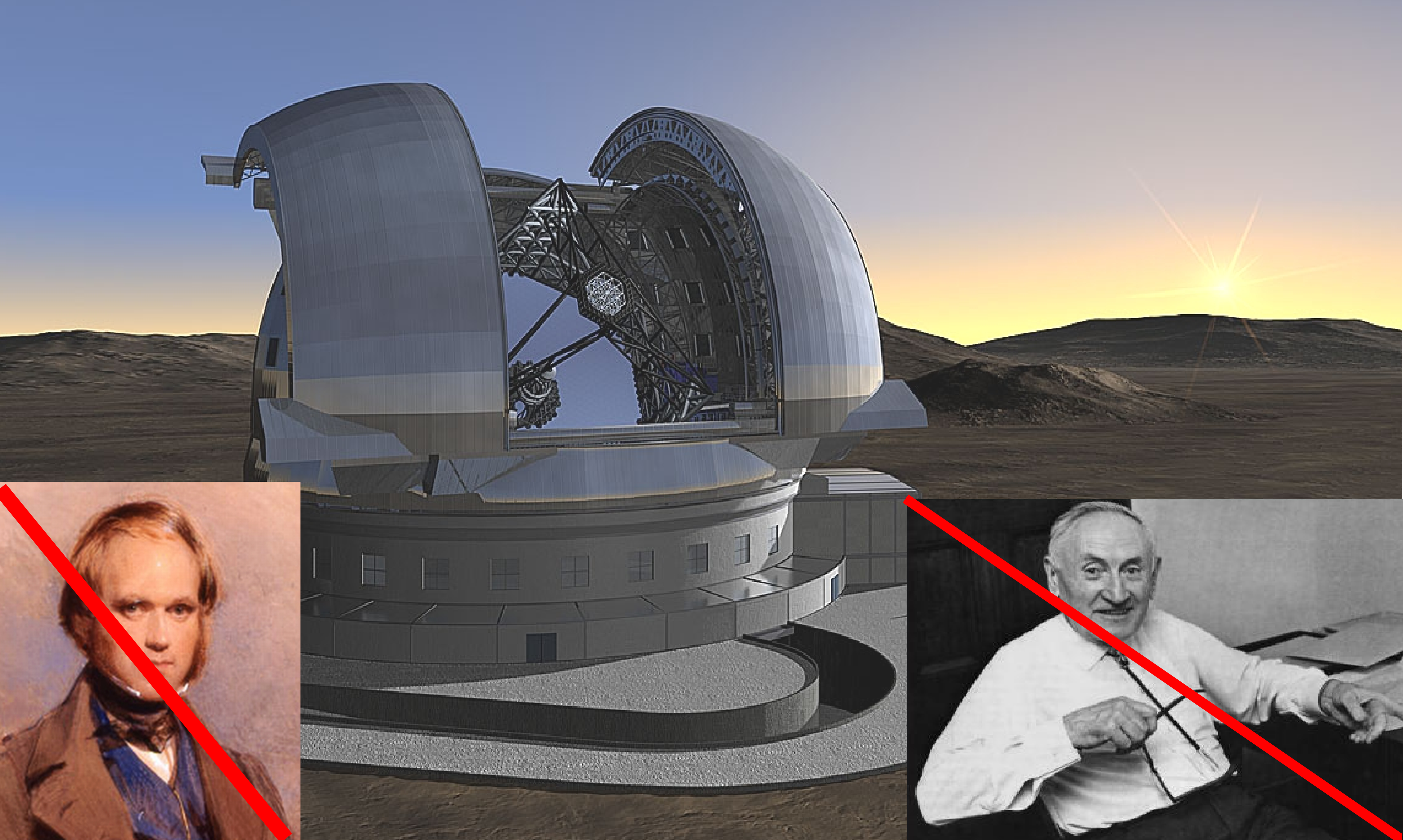
Simon White
Max Planck Institute for Astrophysics



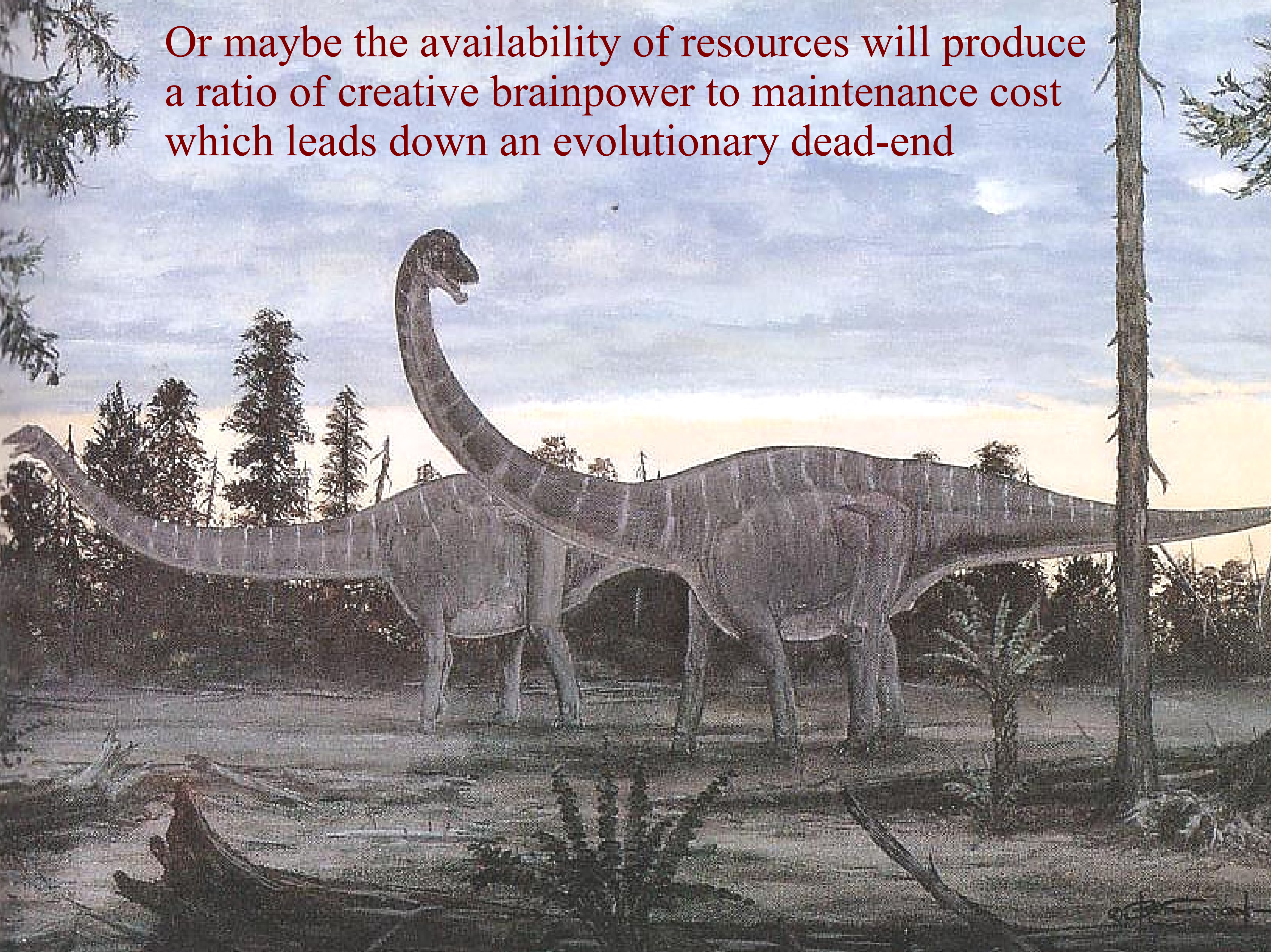
IAU General Assembly, Rio de Janeiro, 2009

In the XIXth and (most of) the XXth centuries scientific progress often came from brilliant individuals formulating and testing new hypotheses from data accumulated using relatively modest means

In the Big Science era such prima donna science is outmoded. Progress follows from large-scale, team-based implementation of forefront technology according to pre-agreed Road Maps.



Or maybe the availability of resources will produce a ratio of creative brainpower to maintenance cost which leads down an evolutionary dead-end



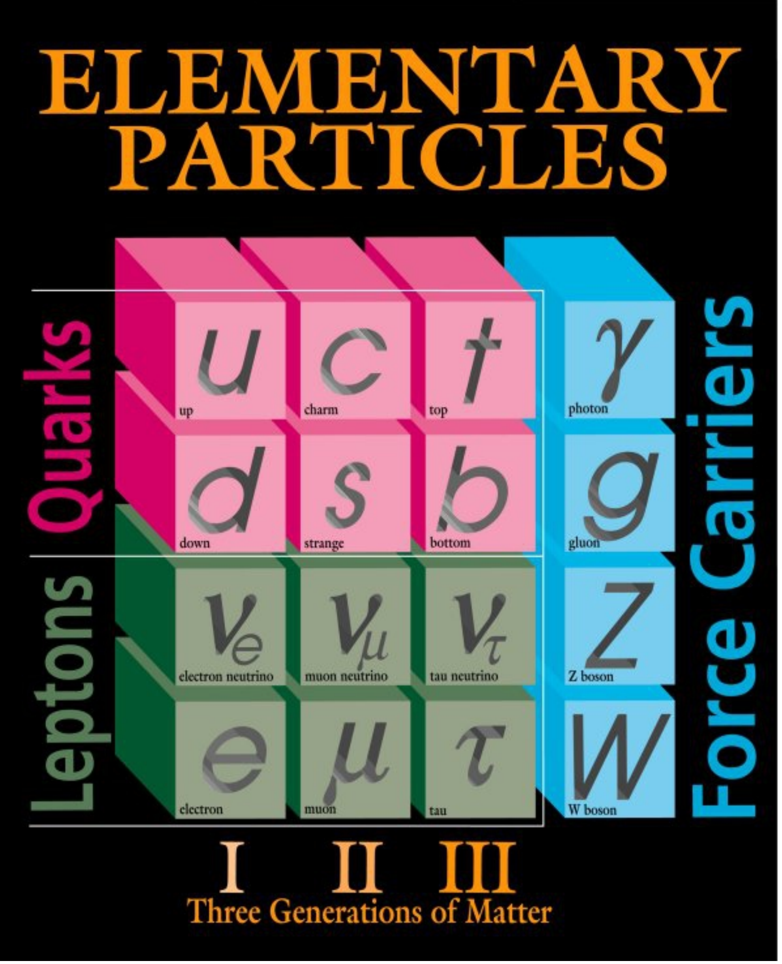
Fundamentalist physics: why Dark Energy is bad for Astronomy

Simon D.M. White

Max Planck Institute for Astrophysics, Garching bei München, Germany

Astronomers carry out observations to explore the diverse processes and objects which populate our Universe. High-energy physicists carry out experiments to approach the Fundamental Theory underlying space, time and matter. Dark Energy is a unique link between them, reflecting deep aspects of the Fundamental Theory, yet apparently accessible *only* through astronomical observation. Large sections of the two communities have therefore converged in support of astronomical projects to constrain Dark Energy. In this essay I argue that this convergence can be damaging for astronomy. The two communities have different methodologies and different scientific cultures. By uncritically adopting the values of an alien system, astronomers risk undermining the foundations of their own current success and endangering the future vitality of their field. Dark Energy is undeniably an interesting problem to attack through astronomical observation, but it is one of many and not necessarily the one where significant progress is most likely to follow a major investment of resources.

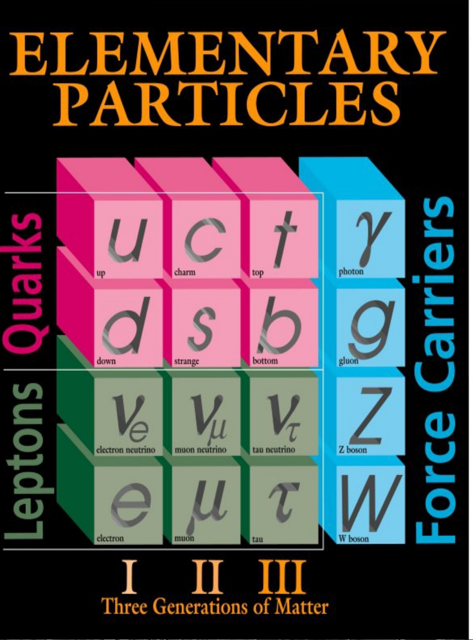
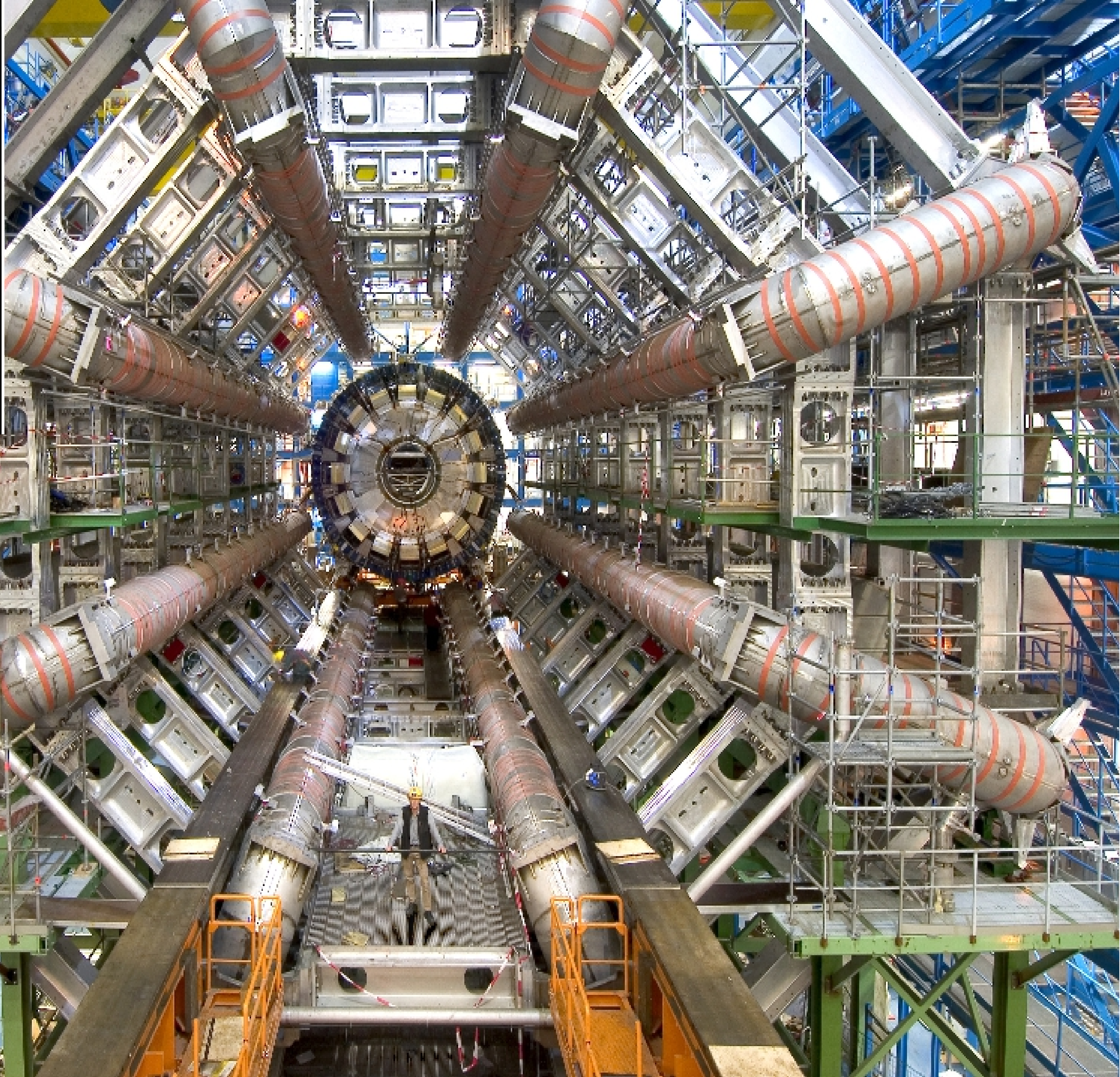
Rep.Prog.Phys. **70**, 883 (2007)

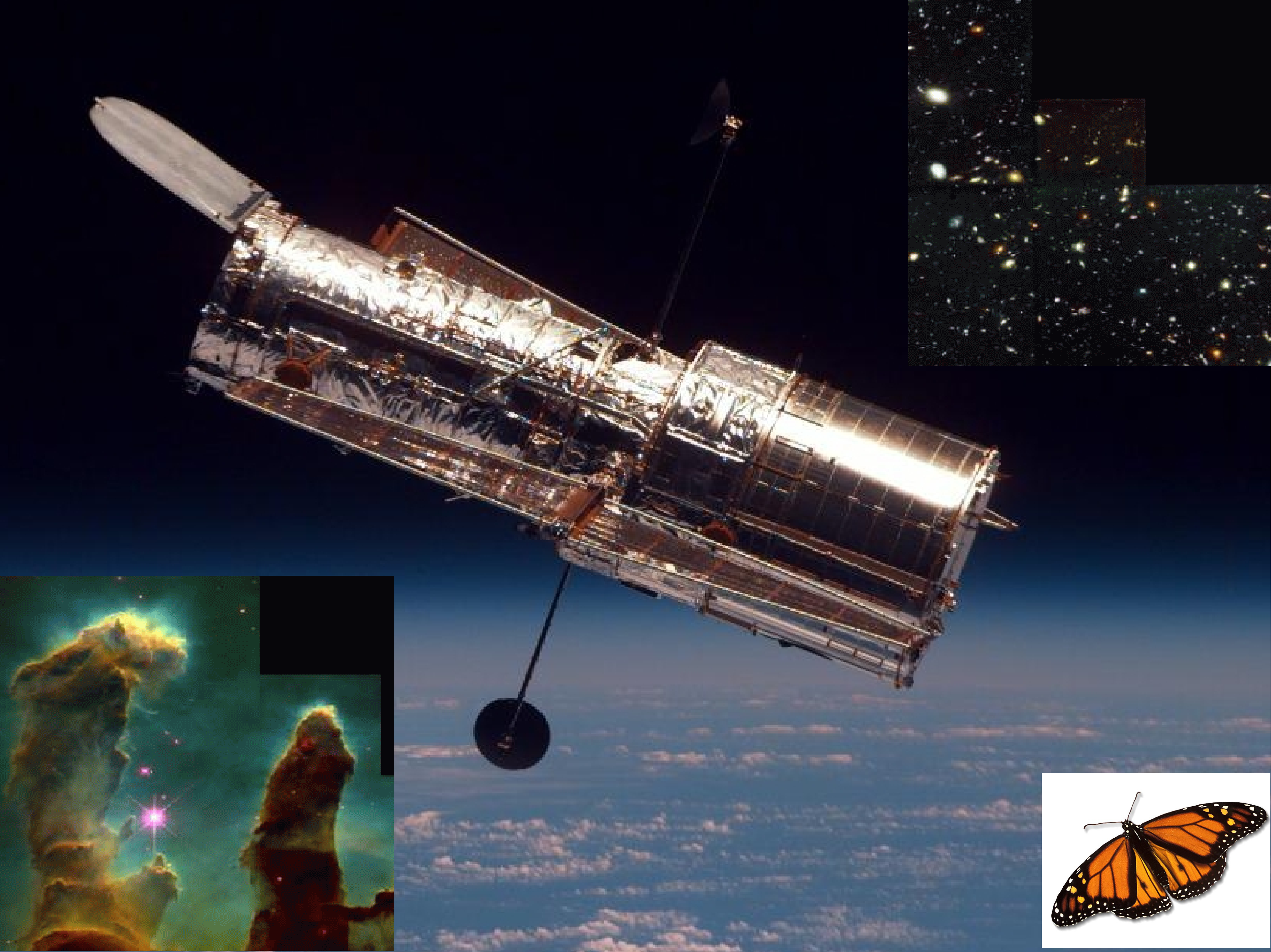


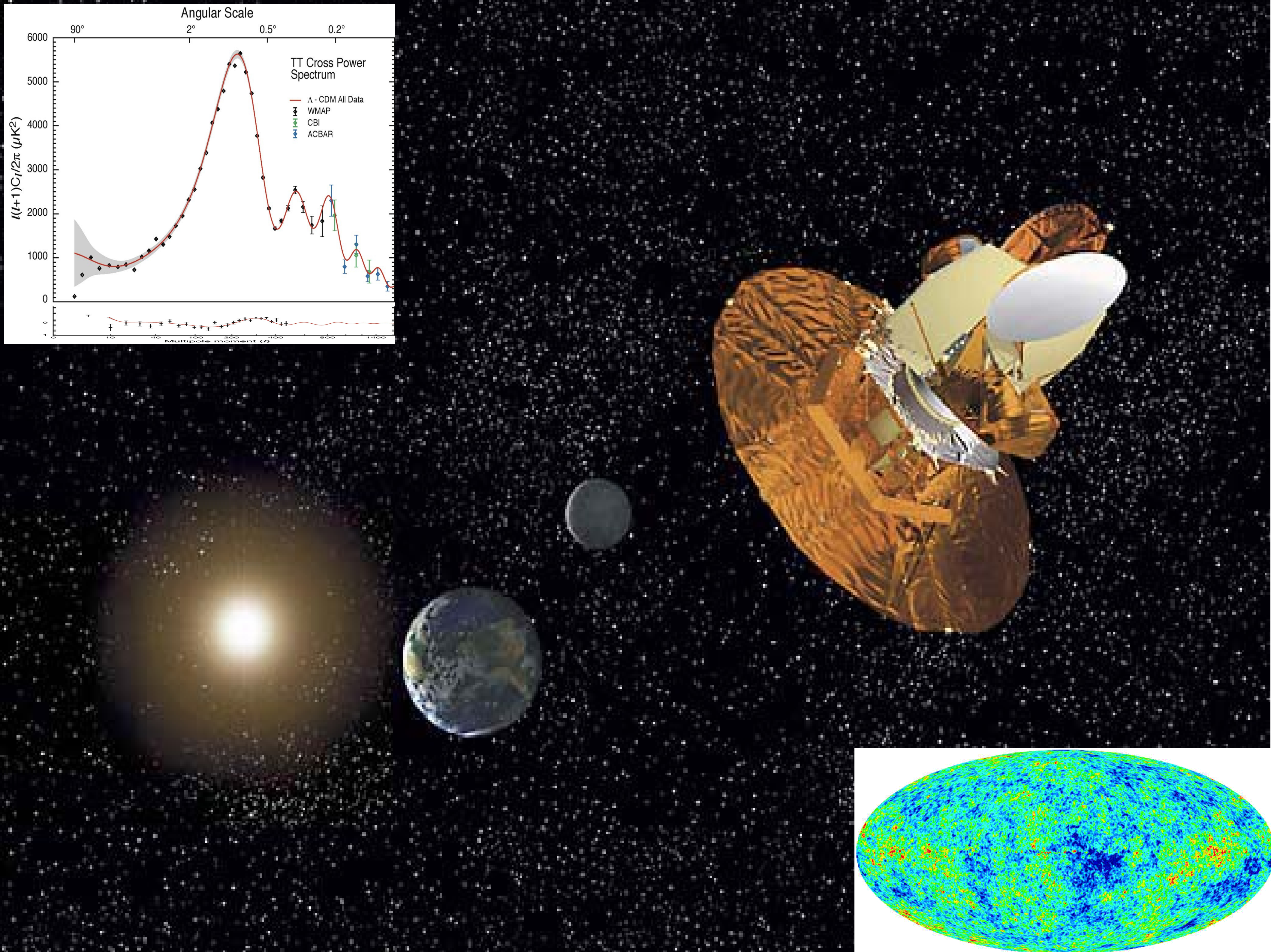
Fundamentalist physics

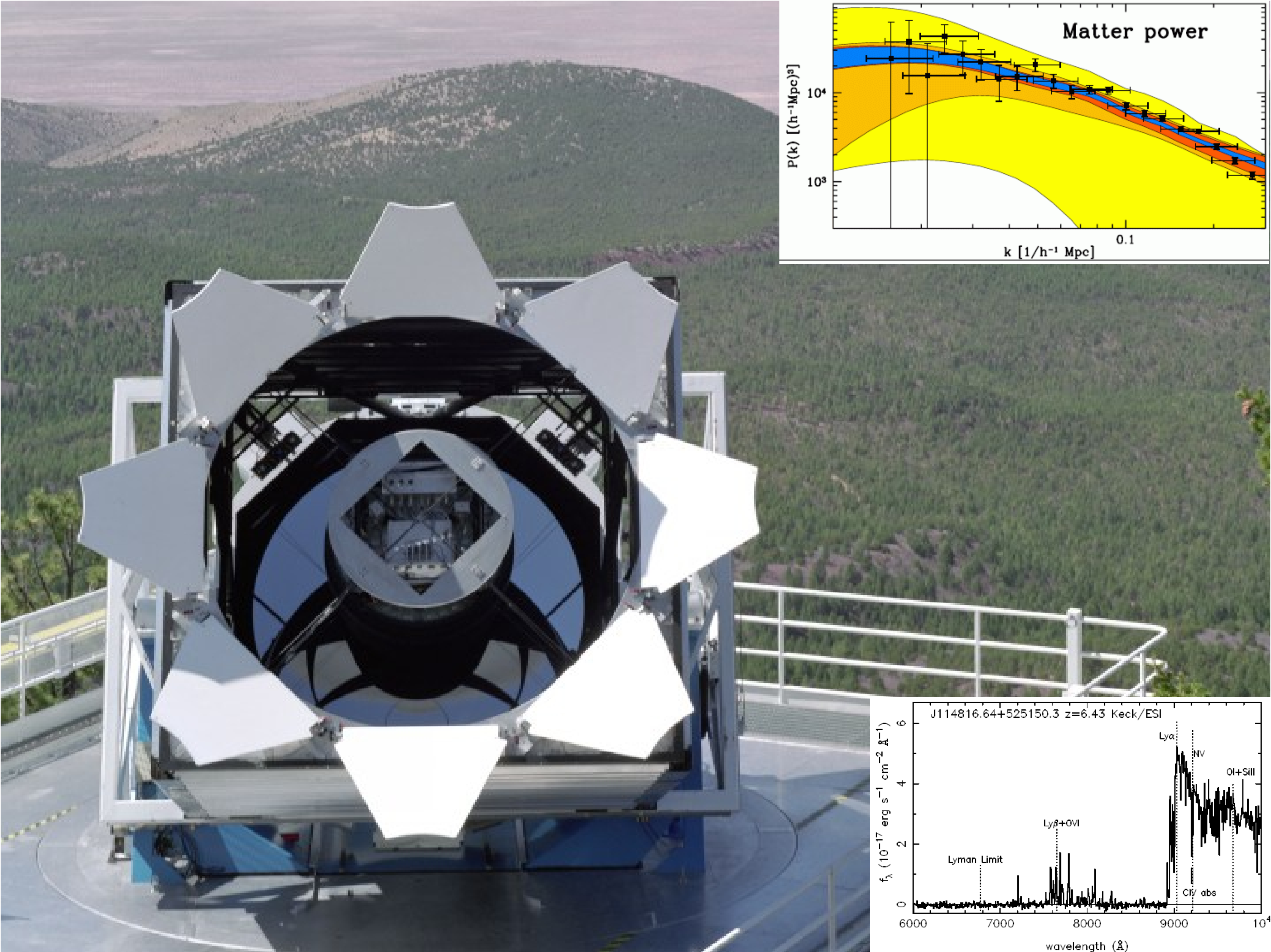
or..

Butterfly collecting


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I II III
Three Generations of Matter




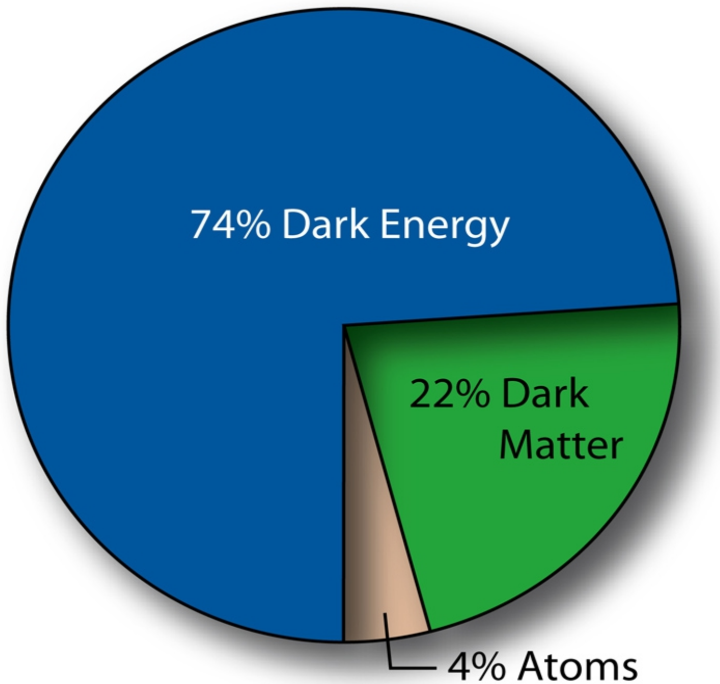

Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi\ (\mu K^2)$
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
0
-1
0
10
40
100
200
400
800
1400
Multipole moment (l)


Matter power
P(k) [(h⁻¹Mpc)³]
10⁴
10³
0.1
k [1/h⁻¹ Mpc]
J114816.64+525150.3 z=6.43 Keck/ESI
Lyα
NV
OI+SiII
Lyβ+OVI
Lyman Limit
CIV abs
fλ (10⁻¹⁷ erg s⁻¹ cm⁻² Å⁻¹)
0
2
4
6
6000
7000
8000
9000
10⁴
wavelength (Å)

Observatories vs Experiments

Observatories	Experiments
(HST or SDSS)	(ATLAS or WMAP)
Designed for general tasks	Optimised for a single task
Serves a diverse community	Serves a coherent community
Program built through proposals	Program set at design
Many teams of all sizes	A single team
Many results unanticipated	Main results “planned”
Synthetic/astrophysics skills	Analytic/data-process. skills
Public support as a facility	Public impact through results

Dark Matter and Dark Energy



<u>Both</u> are unknown

DM affects all aspects of cosmic structure formation and <u>may</u> be detectable directly, indirectly, or at accelerators

DE (apparently) affects only a(t) and g(t), both of which are already known to fairly high precision $\longrightarrow$ can be investigated only by "precision" astronomy

Dangers of Dark Energy

Inappropriate risk assessment

--- likelihood of an “uninteresting” result

--- likelihood of limitation by unanticipated systematics

Overly narrow investment strategy

--- optimisation for the primary “experimental” goal

$\rightarrow$ elimination of ability to address other issues

Undermining astronomy's cultural foundation

--- Division of labour/ role and power of “teams”

--- Allocation of scientific credit

--- Attraction for creative young scientists

--- Attraction for the general public

Other dangers of Big Science

Major emphasis on management

--- coordination of delivery from subprojects

--- maintenance of motivation/schedule throughout project

--- marketing to peers and resource providers

High value placed on loyalty to project/project members

--- required to maintain "momentum" and motivation

Corporate assessment structure

--- outsiders cannot judge individual's creative contributions

--- dependence on references from line managers

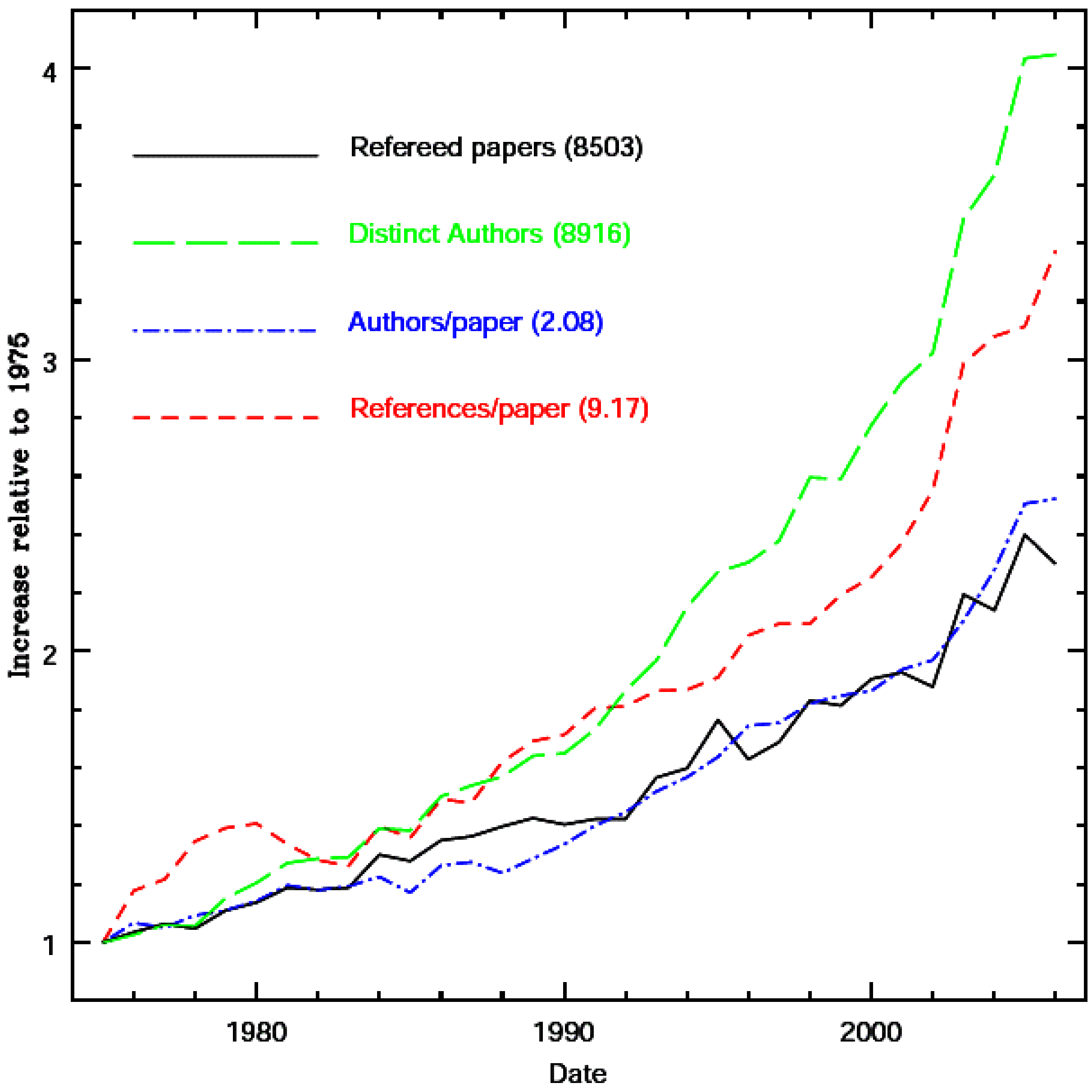
--- production of citation "clubs"

Long timescales

--- young scientists cannot obtain the independent scientific results needed to promote their own careers

--- advancement often based on functional contributions

Cultural shifts in astronomy publishing since 1975



What should be done?

Recognise (and exploit) astro./H.E. cultural differences

Design instruments to address a wide spectrum of issues

Prioritise based on broad impact as well as primary goal

Promote creative “secondary” science within large projects

Assign students such science projects, not functional work

Assign <u>scientific</u> credit based on <u>intellectual</u> contribution

Assign credit separately for infrastructure work

Ensure “astro” projects enhance <u>creativity</u> in astrophysics

Make high value data usefully available to all

Give scientists, especially young ones, time to think

How have things changed by 2013?

How have things changed by 2013?

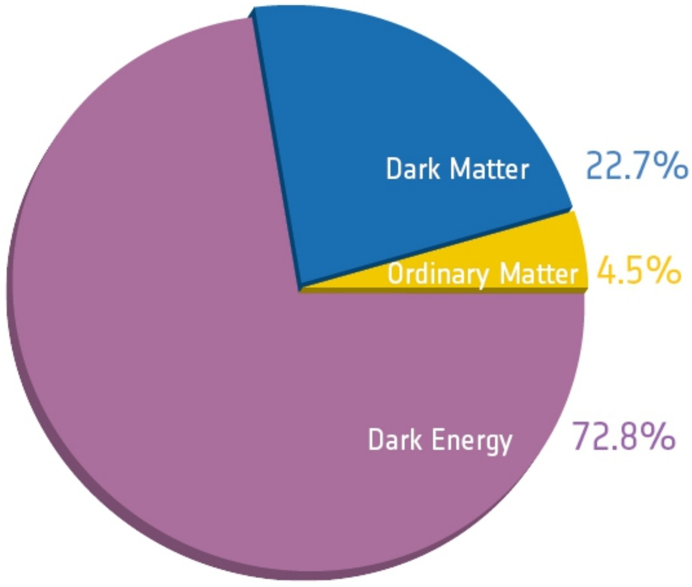
- The preferred model has not changed significantly

How have things changed by 2013?

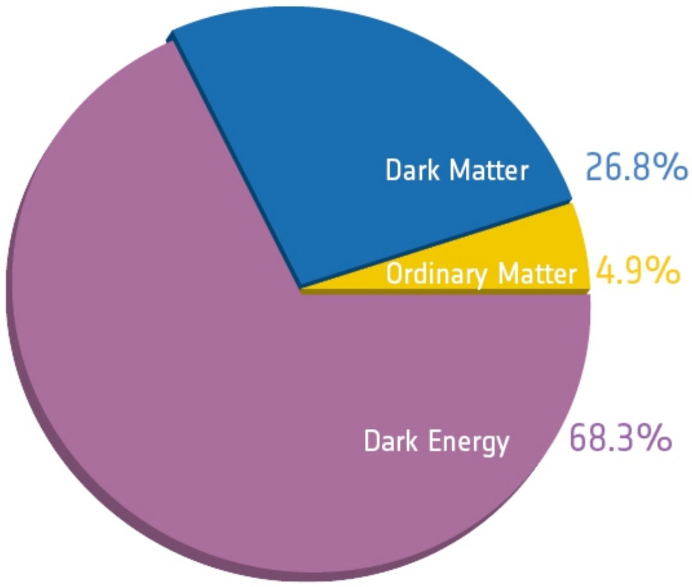
- The preferred model has not changed significantly
- ..but it is now established as the “standard model”

How have things changed by 2013?

- The preferred model has not changed significantly
- ..but it is now established as the "standard model"
- ..and it is better tested and has more precise parameters



Before Planck



After Planck

Planck 2013 results. XVI. Cosmological parameters

Planck Collaboration: P. A. R. Ade[90], N. Aghanim[63], C. Armitage-Caplan[96], M. Arnaud[77], M. Ashdown[74,6], F. Atrio-Barandela[19], J. Aumont[63], C. Baccigalupi[89], A. J. Banday[99,10], R. B. Barreiro[70], J. G. Bartlett[1,72], E. Battaner[102], K. Benabed[64,98], A. Benoît[61], A. Benoit-Lévy[26,64,98], J.-P. Bernard[10], M. Bersanelli[37,53], P. Bielewicz[99,10,89], J. Bobin[77], J. J. Bock[72,11], A. Bonaldi[73], J. R. Bond[9], J. Borrill[14,93], F. R. Bouchet[64,98], M. Bridges[74,6,67], M. Bucher[1], C. Burigana[52,35], R. C. Butler[52], E. Calabrese[96], B. Cappellini[53], J.-F. Cardoso[78,1,64], A. Catalano[79,76], A. Challinor[67,74,12], A. Chamballu[77,16,63], R.-R. Chary[60], X. Chen[60], L.-Y Chiang[66], H. C. Chiang[29,7], P. R. Christensen[85,40], S. Church[95], D. L. Clements[59], S. Colombi[64,98], L. P. L. Colombo[25,72], F. Couchot[75], A. Coulais[76], B. P. Crill[72,86], A. Curto[6,70], F. Cuttaia[52], L. Danese[89], R. D. Davies[73], R. J. Davis[73], P. de Bernardis[36], A. de Rosa[52], G. de Zotti[49,89], J. Delabrouille[1], J.-M. Delouis[64,98], F.-X. Désert[56], C. Dickinson[73], J. M. Diego[70], K. Dolag[101,82], H. Dole[63,62], S. Donzelli[53], O. Doré[72,11], M. Douspis[63], J. Dunkley[96], X. Dupac[43], G. Efstathiou[67*], F. Elsner[64,98], T. A. Enßlin[82], H. K. Eriksen[68], F. Finelli[52,54], O. Forni[99,10], M. Frailis[51], A. A. Fraisse[29], E. Franceschi[52], T. C. Gaier[72], S. Galeotta[51], S. Galli[64], K. Ganga[1], M. Giard[99,10], G. Giardino[44], Y. Giraud-Héraud[1], E. Gjerløw[68], J. González-Nuevo[70,89], K. M. Górski[72,104], S. Gratton[74,67], A. Gregorio[38,51], A. Gruppuso[52], J. E. Gudmundsson[29], J. Haissinski[75], J. Hamann[97], F. K. Hansen[68], D. Hanson[83,72,9], D. Harrison[67,74], S. Henrot-Versillé[75], C. Hernández-Monteagudo[13,82], D. Herranz[70], S. R. Hildebrandt[11], E. Hivon[64,98], M. Hobson[6], W. A. Holmes[72], A. Hornstrup[17], Z. Hou[31], W. Hovest[82], K. M. Huffenberger[103], T. R. Jaffe[99,10], A. H. Jaffe[59], J. Jewell[72], W. C. Jones[29], M. Juvela[28], E. Keihänen[28], R. Keskitalo[23,14], T. S. Kisner[81], R. Kneissl[42,8], J. Knoche[82], L. Knox[31], M. Kunz[18,63,3], H. Kurki-Suonio[28,47], G. Lagache[63], A. Lähteenmäki[2,47], J.-M. Lamarre[76], A. Lasenby[6,74], M. Lattanzi[35], R. J. Laureijs[44], C. R. Lawrence[72], S. Leach[89], J. P. Leahy[73], R. Leonardi[43], J. León-Tavares[45,2], J. Lesgourgues[97,88], A. Lewis[27], M. Liguori[34], P. B. Lilje[68], M. Linden-Vørnle[17], M. López-Caniego[70], P. M. Lubin[32], J. F. Macías-Pérez[79], B. Maffei[73], D. Maino[37,53], N. Mandolesi[52,5,35], M. Maris[51], D. J. Marshall[77], P. G. Martin[9], E. Martínez-González[70], S. Masi[36], S. Matarrese[34], F. Matthai[82], P. Mazzotta[39], P. R. Meinhold[32], A. Melchiorri[36,55], J.-B. Melin[16], L. Mendes[43], E. Menegoni[36], A. Mennella[37,53], M. Migliaccio[67,74], M. Millea[31], S. Mitra[58,72], M.-A. Miville-Deschênes[63,9], A. Moneti[64], L. Montier[99,10], G. Morgante[52], D. Mortlock[59], A. Moss[91], D. Munshi[90], P. Naselsky[85,40], F. Nati[36], P. Natoli[35,4,52], C. B. Netterfield[21], H. U. Nørgaard-Nielsen[17], F. Noviello[73], D. Novikov[59], I. Novikov[85], I. J. O'Dwyer[72], S. Osborne[95], C. A. Oxborrow[17], F. Paci[89], L. Pagano[36,55], F. Pajot[63], D. Paoletti[52,54], B. Partridge[46], F. Pasian[51], G. Patanchon[1], D. Pearson[72], T. J. Pearson[11,60], H. V. Peiris[26], O. Perdereau[75], L. Perotto[79], F. Perrotta[89], V. Pettorino[18], F. Piacentini[36], M. Piat[1], E. Pierpaoli[25], D. Pietrobon[72], S. Plaszczynski[75], P. Platania[71], E. Pointecouteau[99,10], G. Polenta[4,50], N. Ponthieu[63,56], L. Popa[65], T. Poutanen[47,28,2], G. W. Pratt[77], G. Prézeau[11,72], S. Prunet[64,98], J.-L. Puget[63], J. P. Rachen[22,82], W. T. Reach[100], R. Rebolo[69,15,41], M. Reinecke[82], M. Remazeilles[63,1], C. Renault[79], S. Ricciardi[52], T. Riller[82], I. Ristorcelli[99,10], G. Rocha[72,11], C. Rosset[1], G. Roudier[1,76,72], M. Rowan-Robinson[59], J. A. Rubiño-Martín[69,41], B. Rusholme[60], M. Sandri[52], D. Santos[79], M. Savelainen[28,47], G. Savini[87], D. Scott[24], M. D. Seiffert[72,11], E. P. S. Shellard[12], L. D. Spencer[90], J.-L. Starck[77], V. Stolyarov[6,74,94], R. Stompor[1], R. Sudiwala[90], R. Sunyaev[82,92], F. Sureau[77], D. Sutton[67,74], A.-S. Suur-Uski[28,47], J.-F. Sygnet[64], J. A. Tauber[44], D. Tavagnacco[51,38], L. Terenzi[52], L. Toffolatti[20,70], M. Tomasi[53], M. Tristram[75], M. Tucci[18,75], J. Tuovinen[84], M. Türler[57], G. Umana[48], L. Valenziano[52], J. Valiviita[47,28,68], B. Van Tent[80], P. Vielva[70], F. Villa[52], N. Vittorio[39], L. A. Wade[72], B. D. Wandelt[64,98,33], I. K. Wehus[72], M. White[30], S. D. M. White[82], A. Wilkinson[73], D. Yvon[16], A. Zacchei[51], and A. Zonca[32]

(Affiliations can be found after the references)

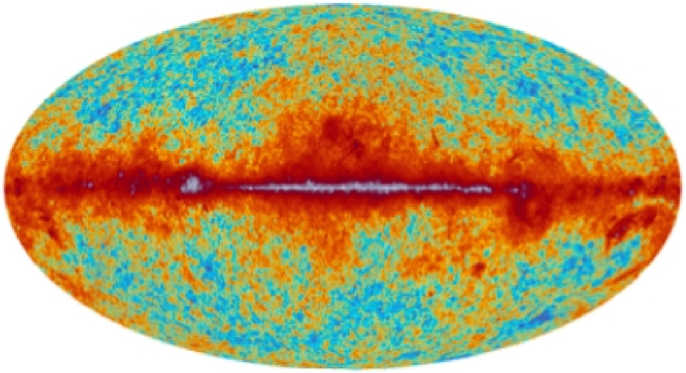
21 March 2013

261 authors

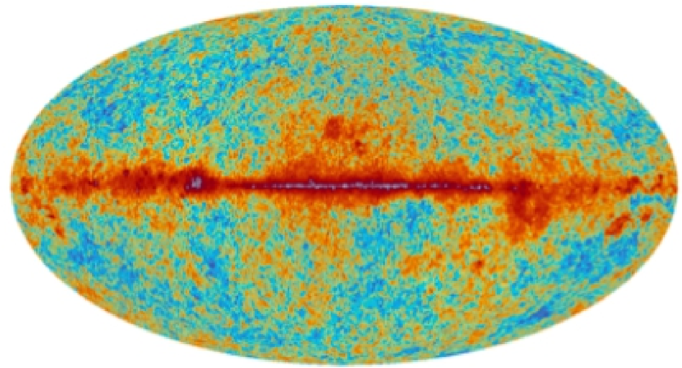
737 citations (to 13/10/2013)

The nine *Planck* maps

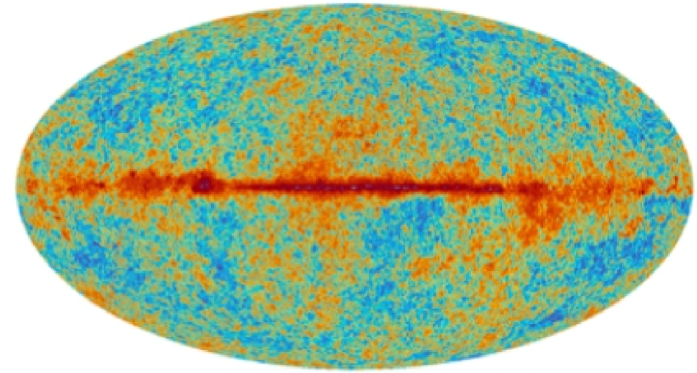
30 GHz



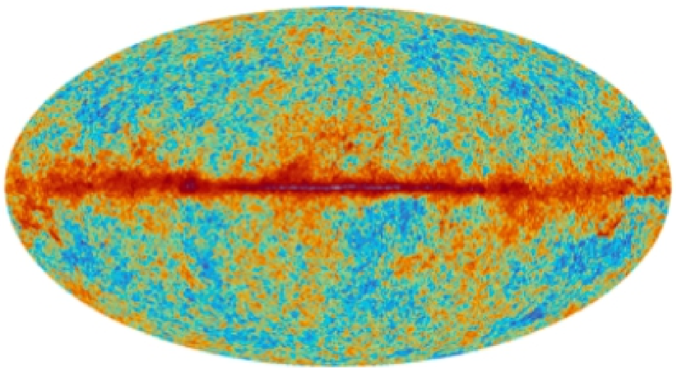
44 GHz



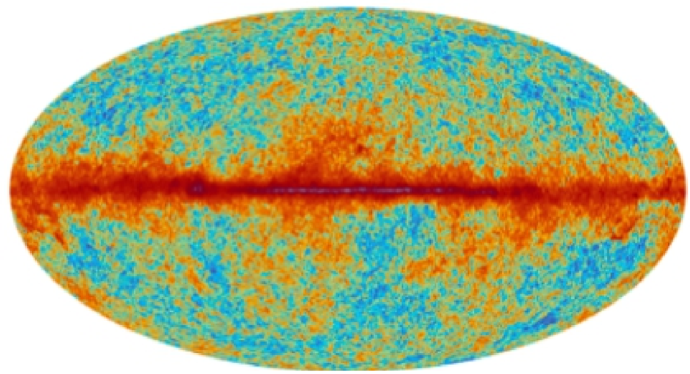
70 GHz



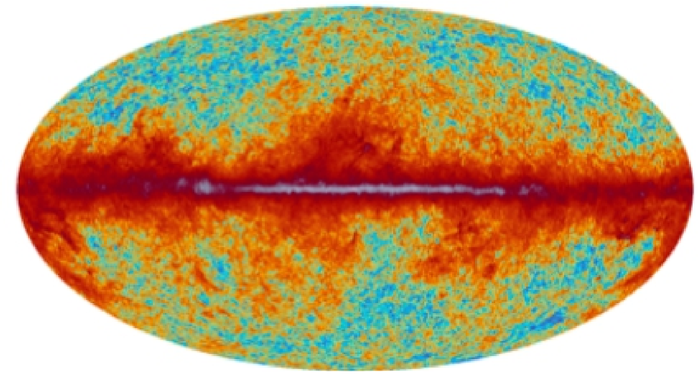
100 GHz



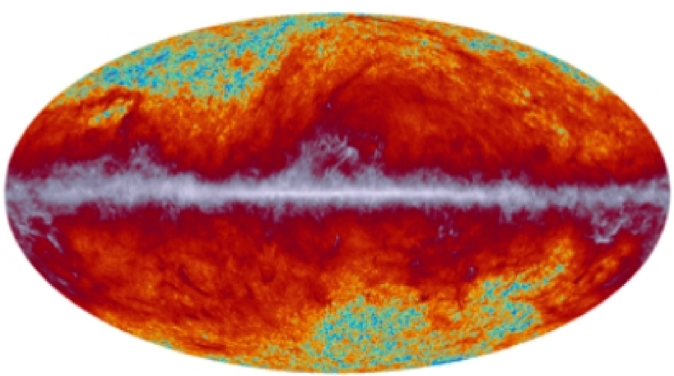
143 GHz



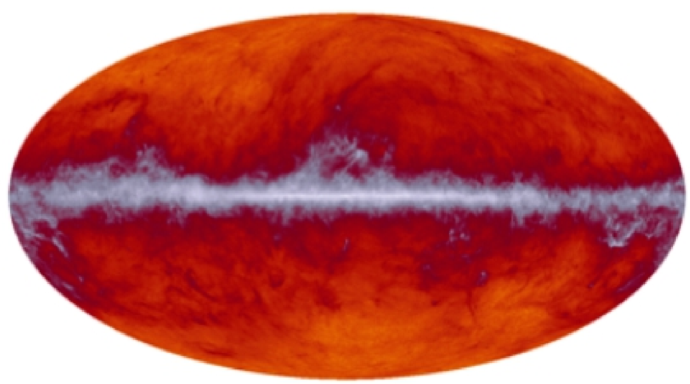
217 GHz



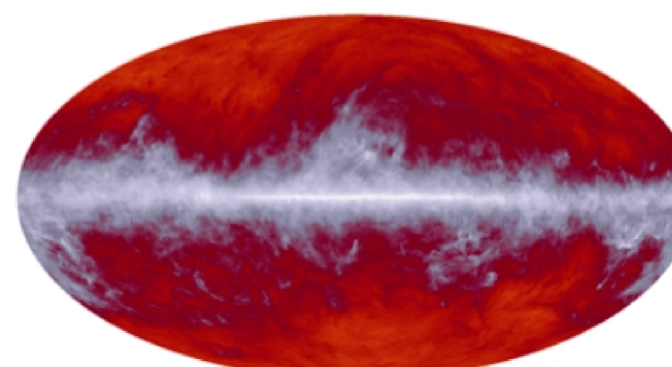
353 GHz



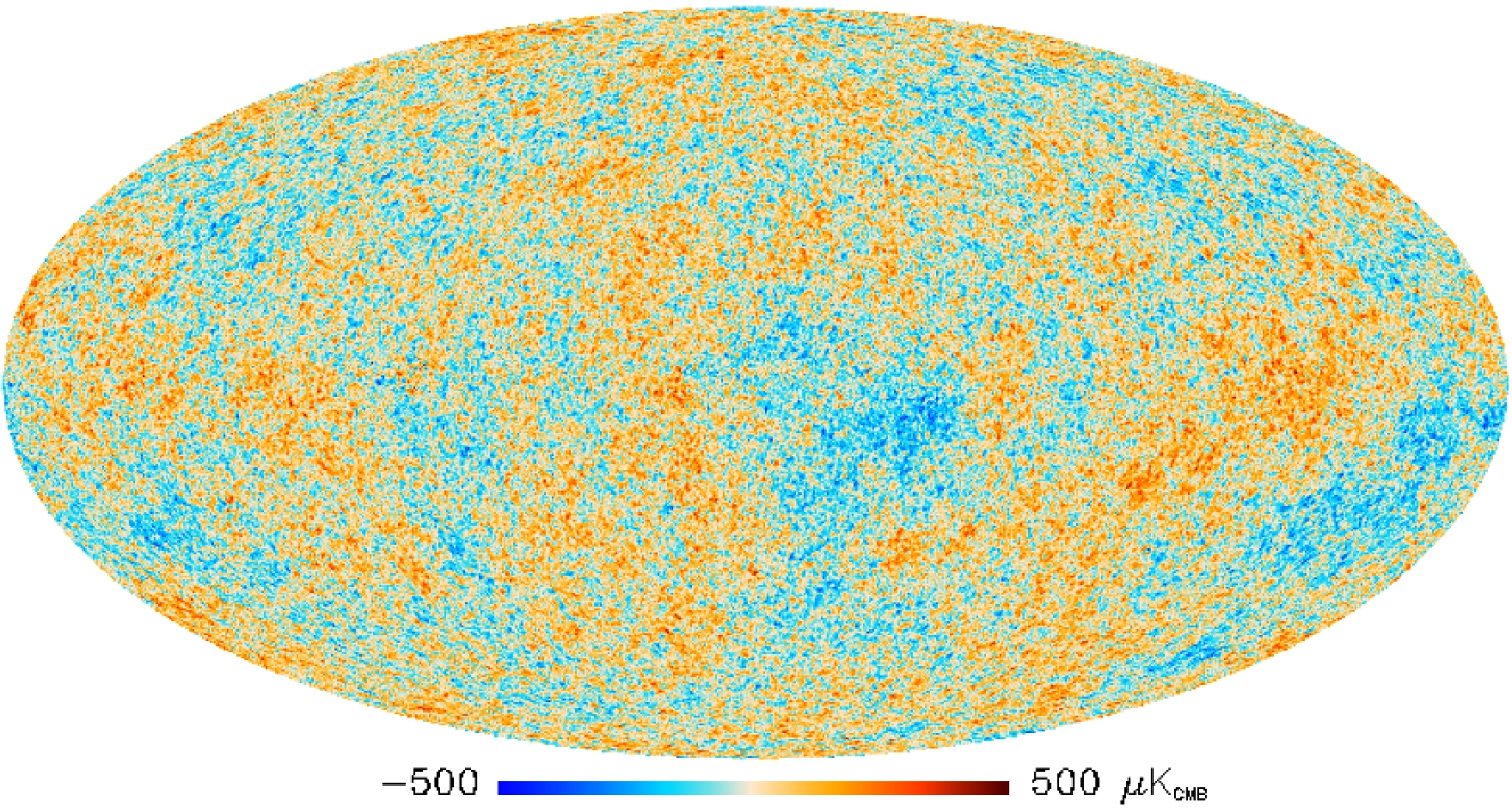
545 GHz

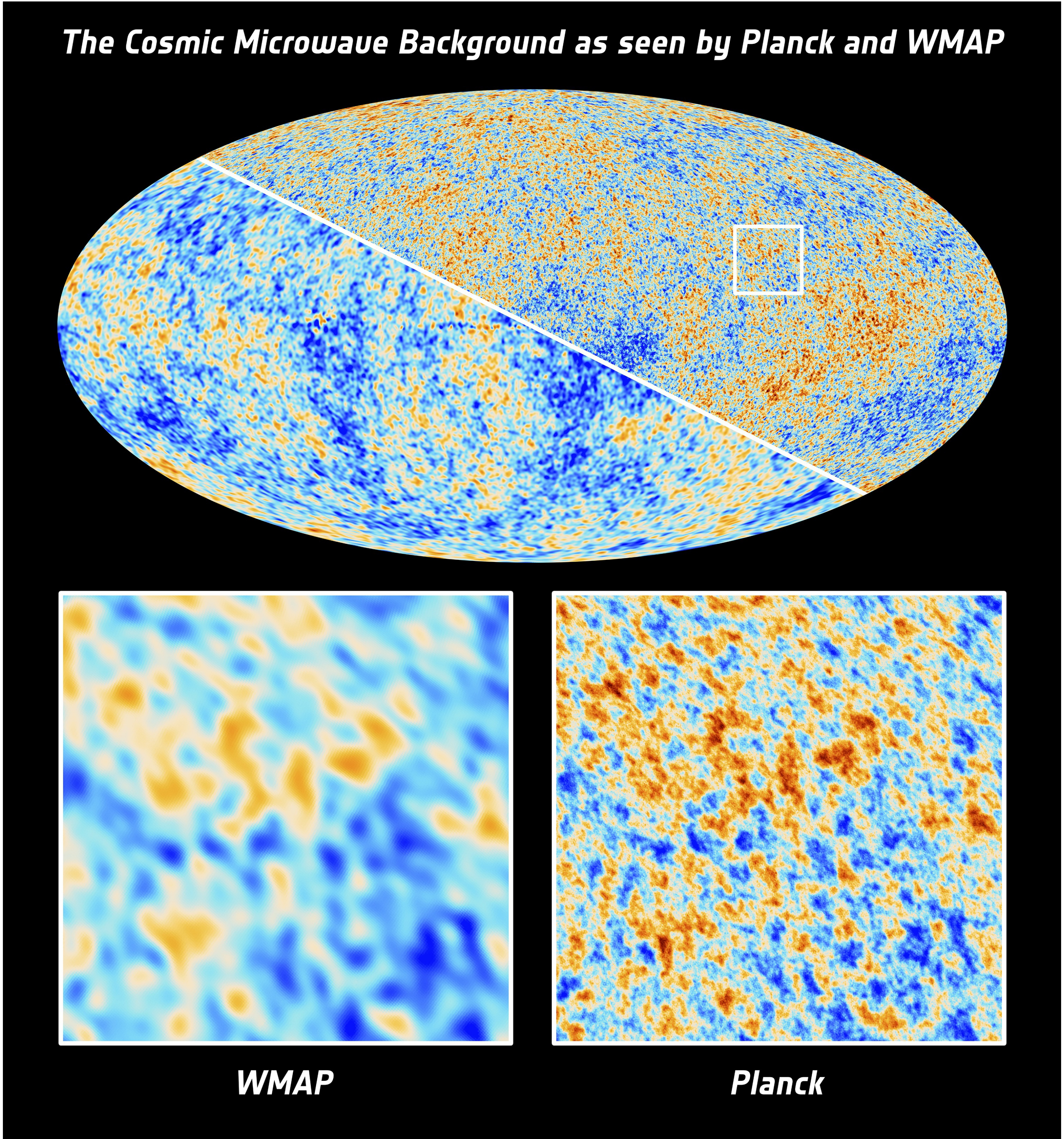


857 GHz



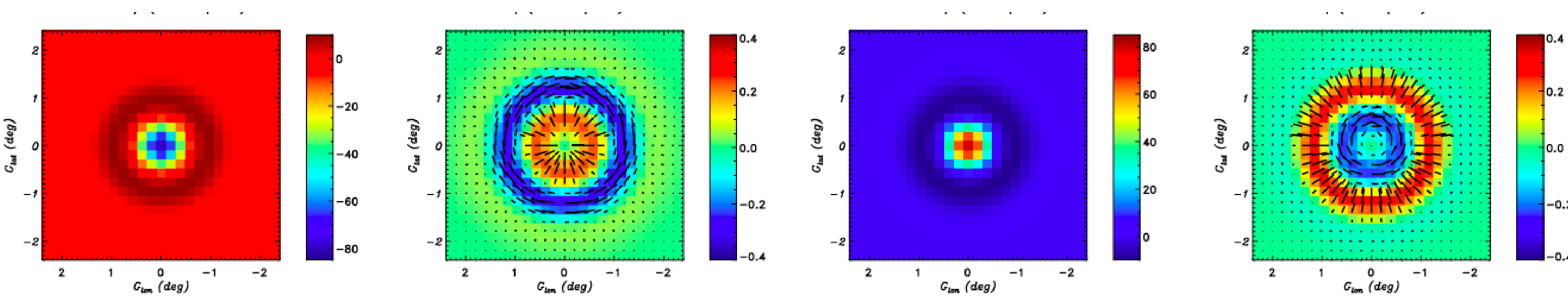
CMB map after the first 2.5 surveys




The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

Stacked temperature and polarisation maps

Predictions for standard recombination in a ΛCDM universe



intensity polarisation intensity polarisation

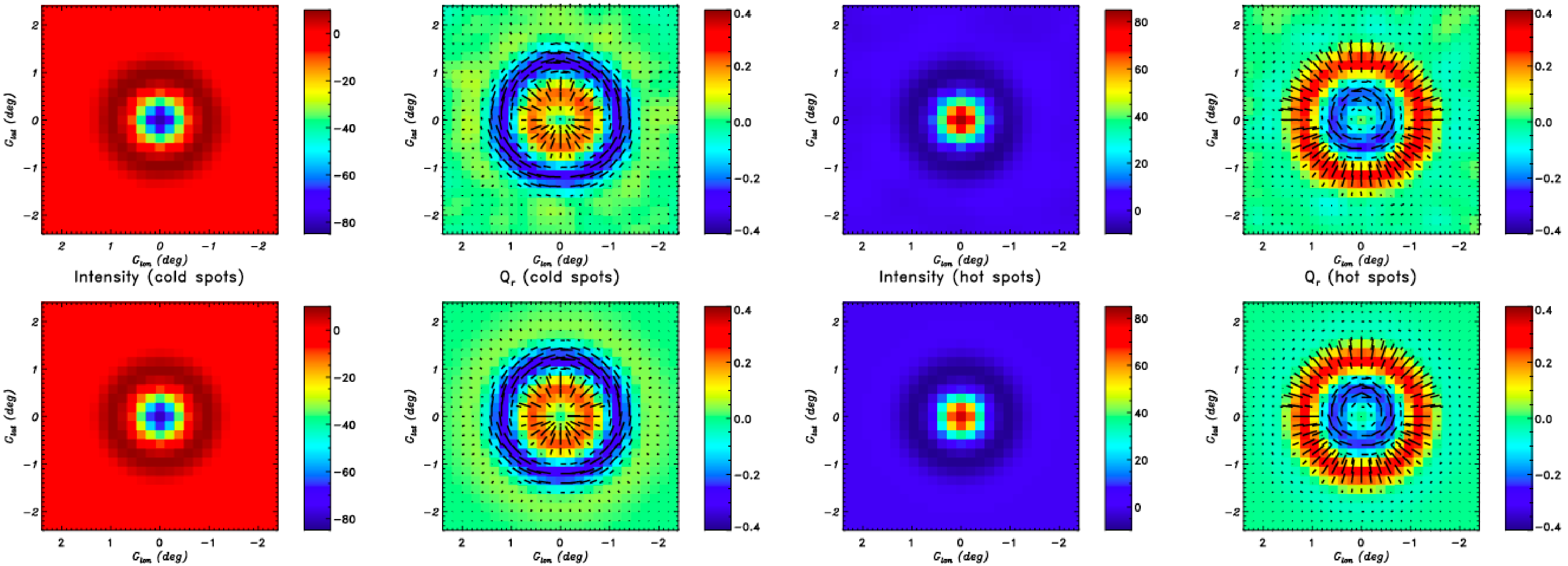
Temperature minima Temperature maxima

Thomson scattering in the last scattering surface is expected to induce characteristic polarisation patterns around extrema of the temperature field.

Stacked temperature and polarisation maps

Stacked Planck data, 30' smoothing

11,396 cold spots 10,468 hot spots



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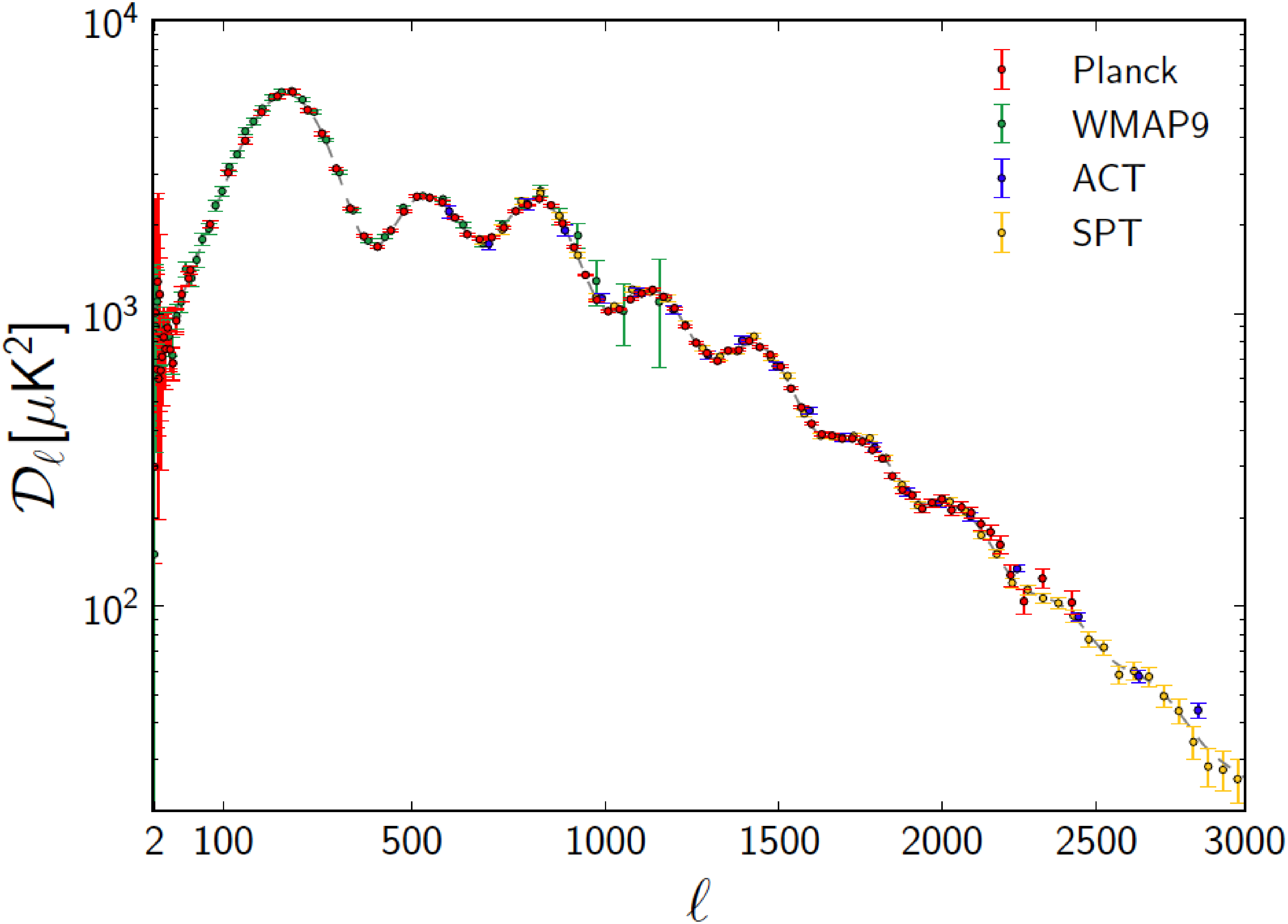
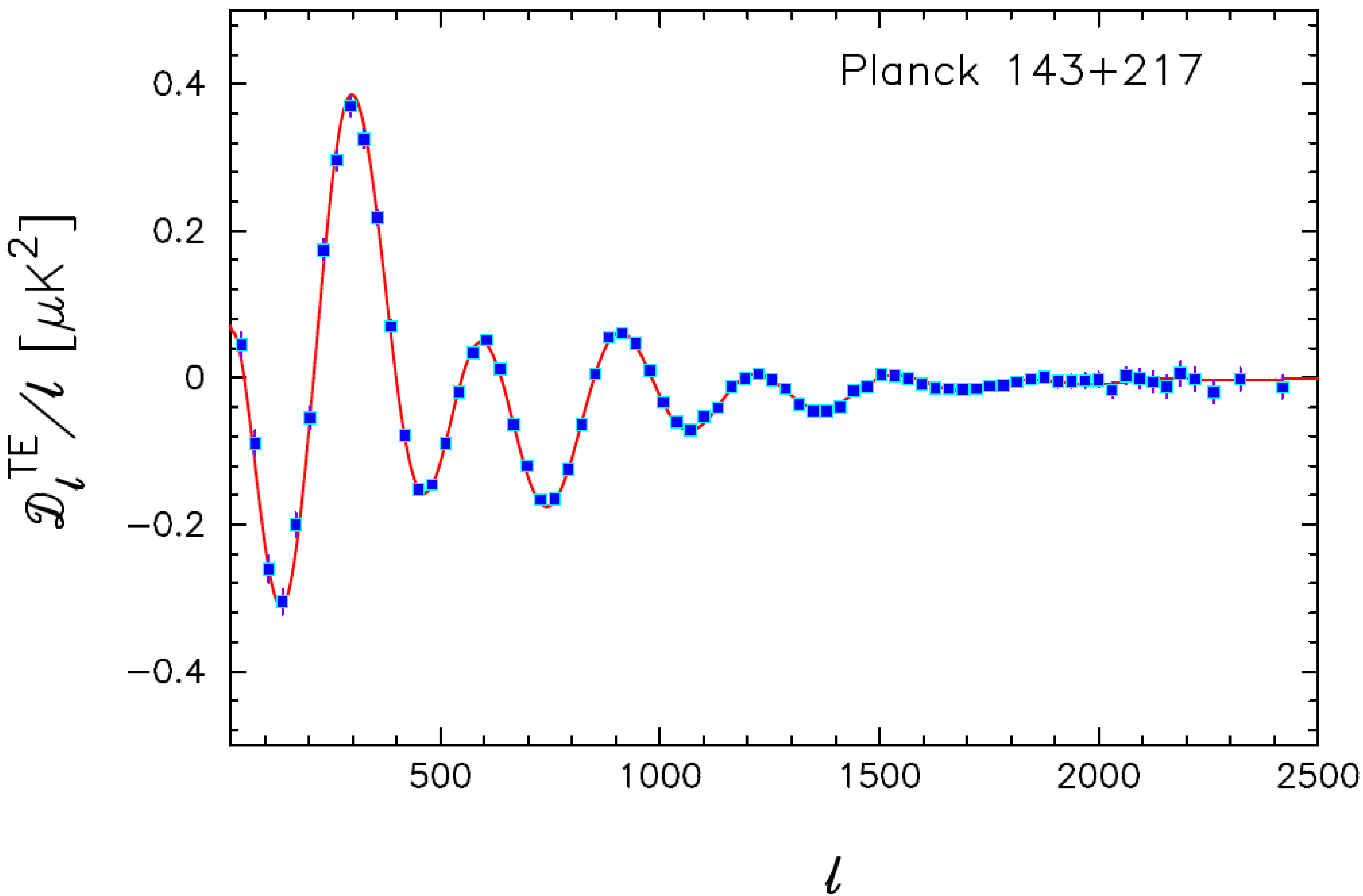
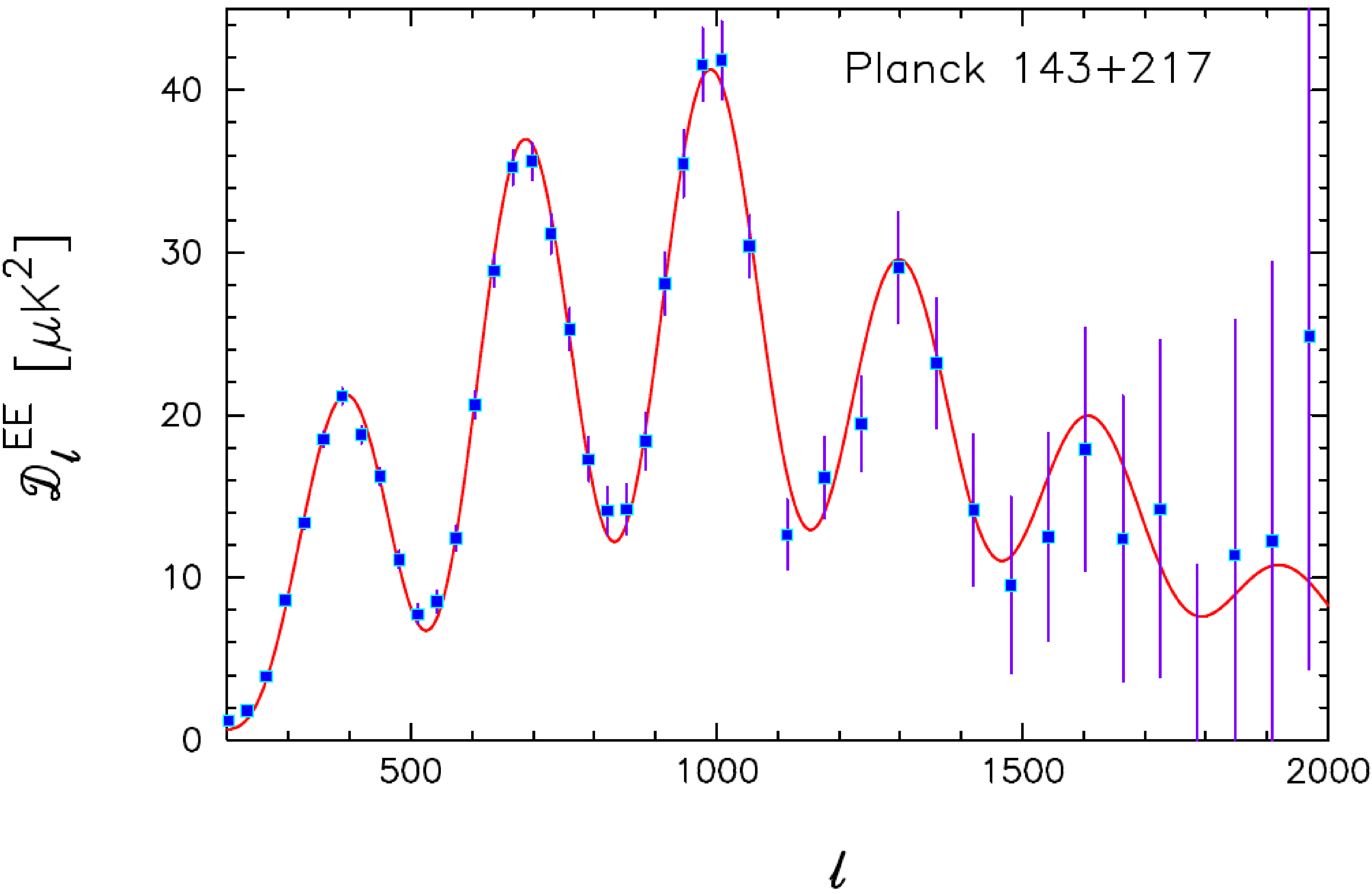
Planck CMB power spectrum from 2.5 surveys



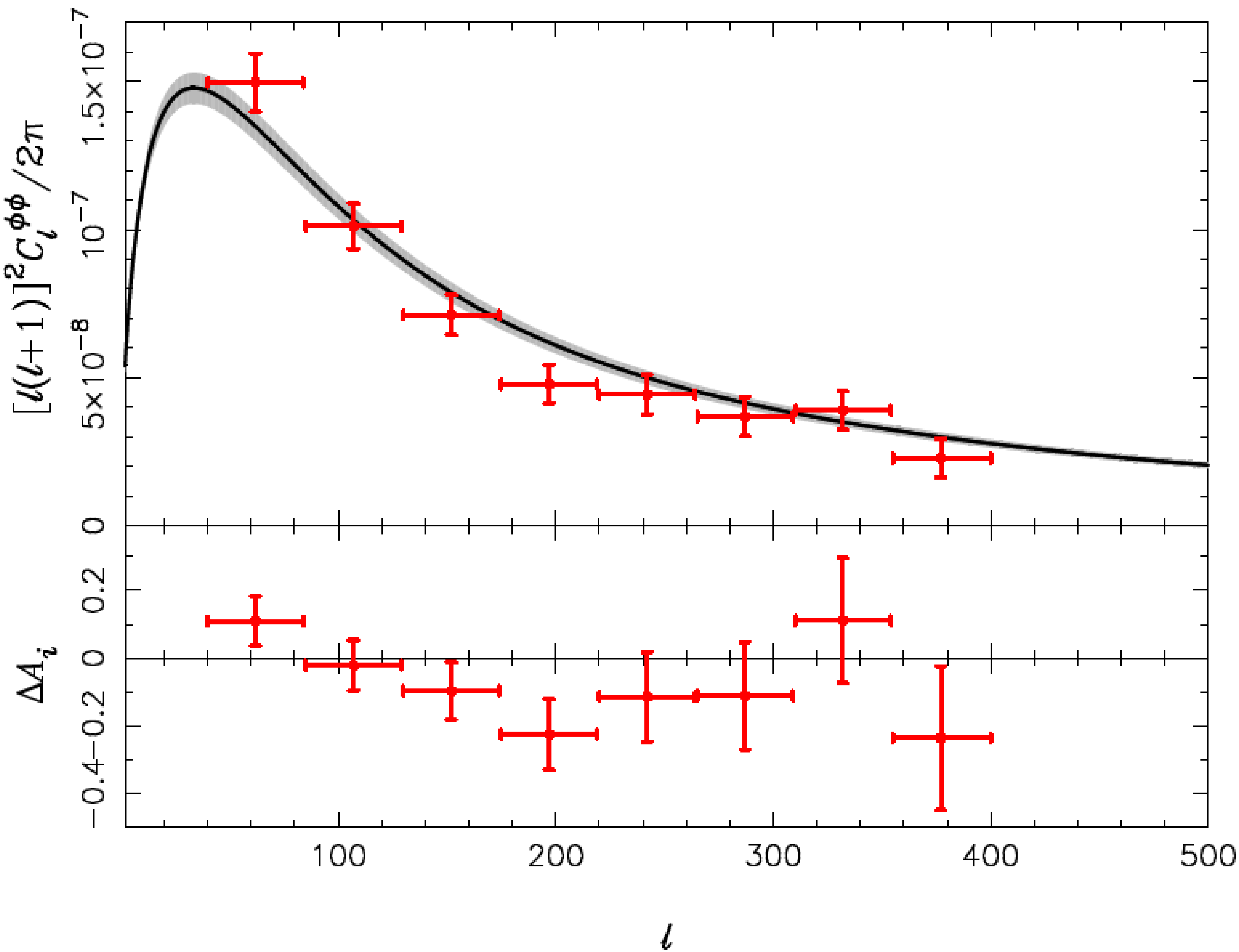
Planck TE power spectrum from 2.5 surveys



Planck EE power spectrum from 2.5 surveys



Planck gravitational lensing power spectrum



The six parameters of the base ΛCDM model

Parameter	*Planck*+WP	
	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

The six parameters of the base ΛCDM model

	Planck+WP	
Derived parameter	Best fit	68% limits
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$
σ_8	0.8347	0.829 ± 0.012
$z_{\rm re}$	11.37	11.1 ± 1.1
H_0	67.04	67.3 ± 1.2
Age/Gyr	13.8242	13.817 ± 0.048

One parameter extensions of the base ΛCDM model

Parameter	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 95% limits
Ω_K	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.000	< 0.230
N_{eff}	3.22	$3.30^{+0.54}_{-0.51}$
Y_{P}	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\mathrm{s}}/d\ln k$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.111
w	-1.109	$-1.13^{+0.23}_{-0.25}$

Planck results bearing on models of inflation

Parameter values

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Non-Gaussianity constraints

f_{NL}

	Independent KSW	**ISW-lensing subtracted** KSW
SMICA		
Local	9.8 ± 5.8	$\mathbf{2.7} \pm \mathbf{5.8}$
Equilateral	-37 ± 75	$\mathbf{-42} \pm \mathbf{75}$
Orthogonal	-46 ± 39	$\mathbf{-25} \pm \mathbf{39}$

How have things changed by 2013?

- The preferred model has not changed significantly
- ..but it is now established as the "standard model"
- Planck finds no strong evidence of departures
  - All CMB and lensing spectra consistent with the base model
  - Inflationary expectation for *n* confirmed
  - Non-gaussianity limits pushed down by a substantial factor

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- No agreed evidence for DM from direct/indirect detection exp'ts
  - but DAMA/LIBRA, CoGeNT, CRESST, etc., still unexplained...?

How have things changed by 2013?

Sociological aspects

- The particle-astrophysics-cosmology community developed at a dramatic rate (e.g. the growth of JCAP)

- The trend towards involvement in large long-term projects has also continued (e.g. Euclid)

- Many new DE projects include breadth of impact/auxiliary science among the design drivers (but c.f. WiggleZ, HETDEX)

- Problems of encouraging creativity, recognising individual intellectual contributions, and maintaining scientific motivation in 10 to 20 year "Big Science" projects remain to be solved

  Further "division of labour" needed?

- The communities may now diverge again: Quo vadis, JCAP?