International School of Astrophysics
Daniel Chalonge – Hector de Vega
June 23rd 2021

Maynooth University
National University of Ireland Maynooth

The State of the Universe

Peter Coles
(@telescoper)

Nature (2005), **433**, 248-255

year of physics **review articles**

The state of the Universe

Peter Coles

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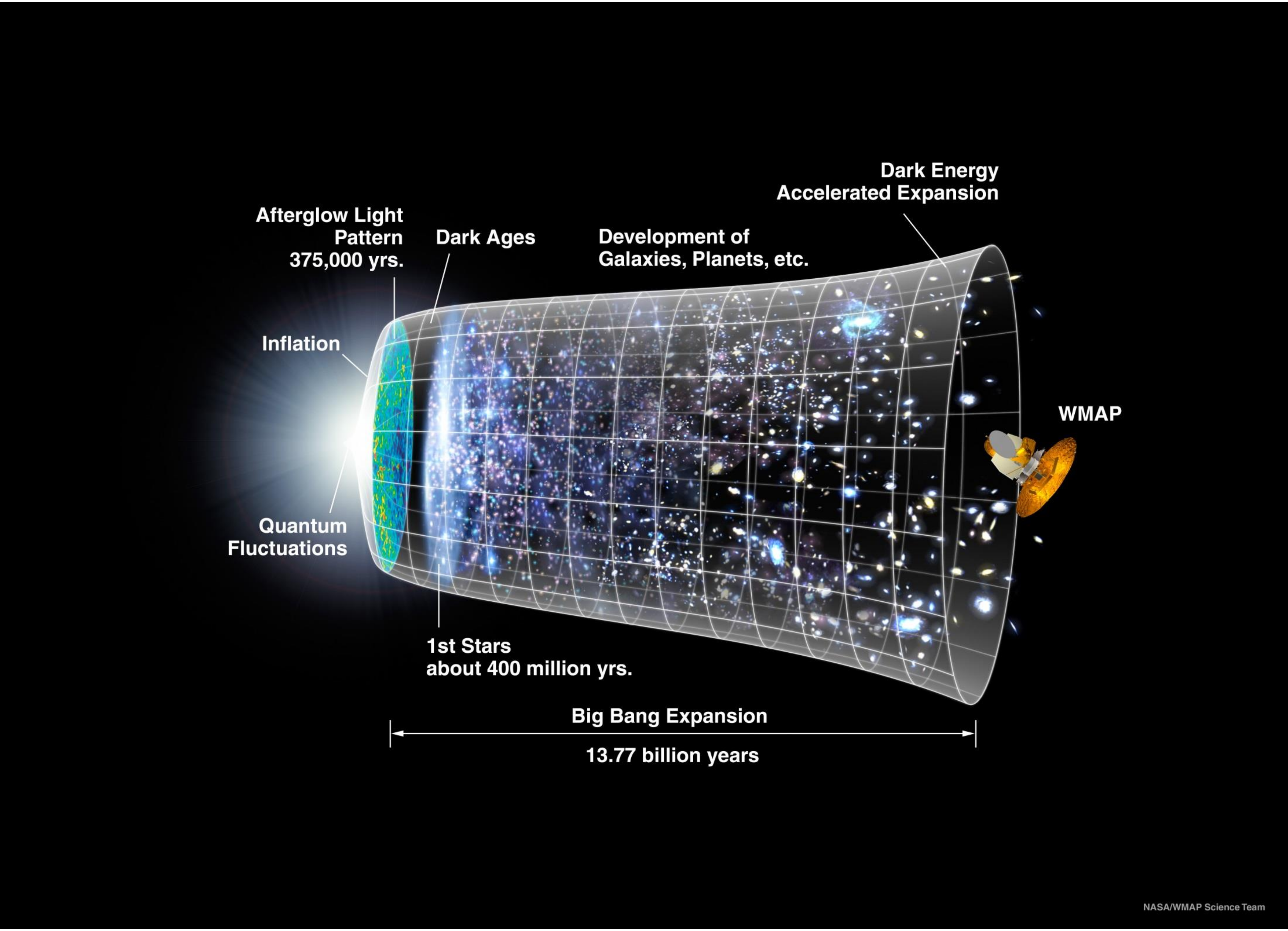
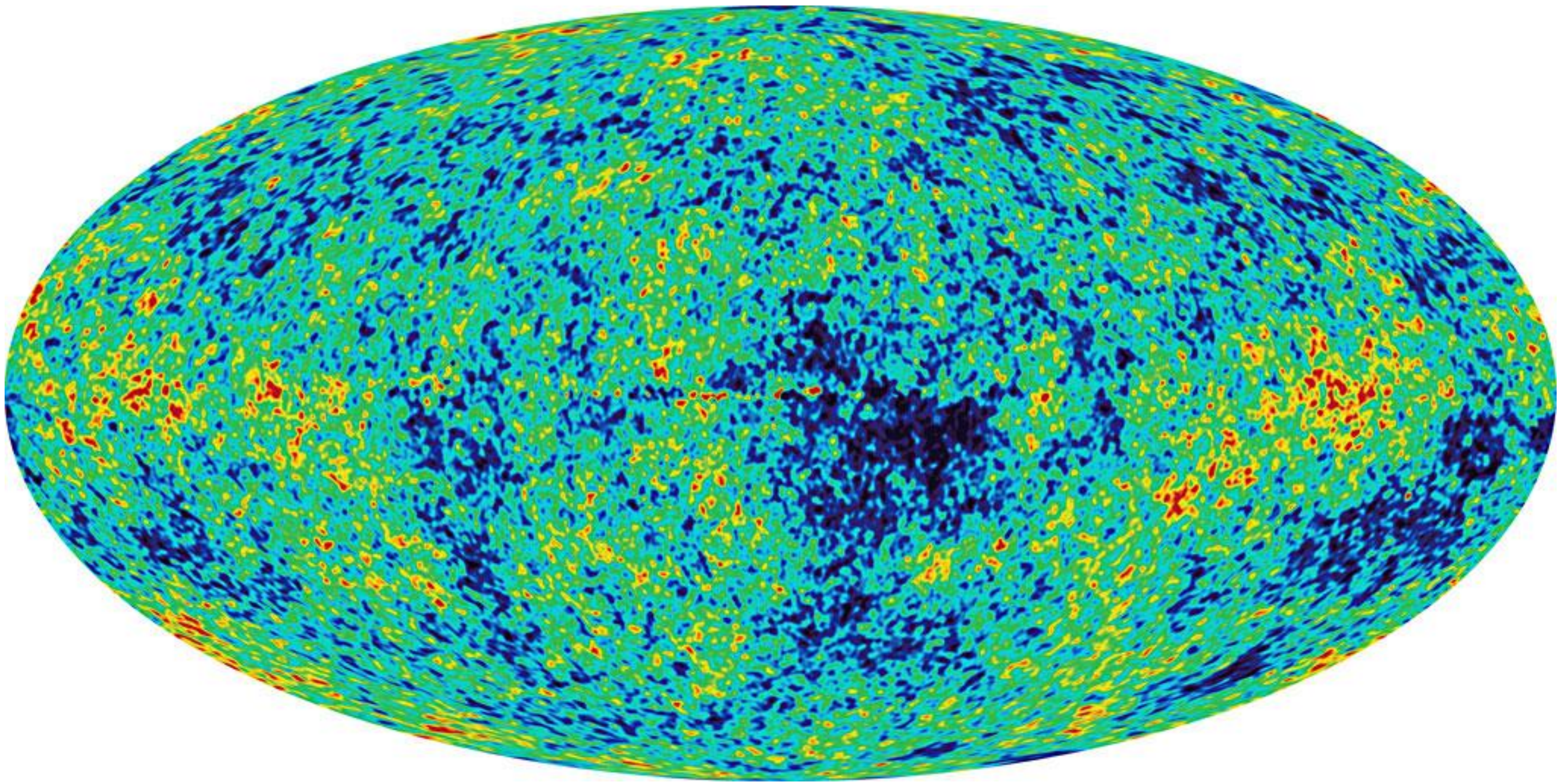
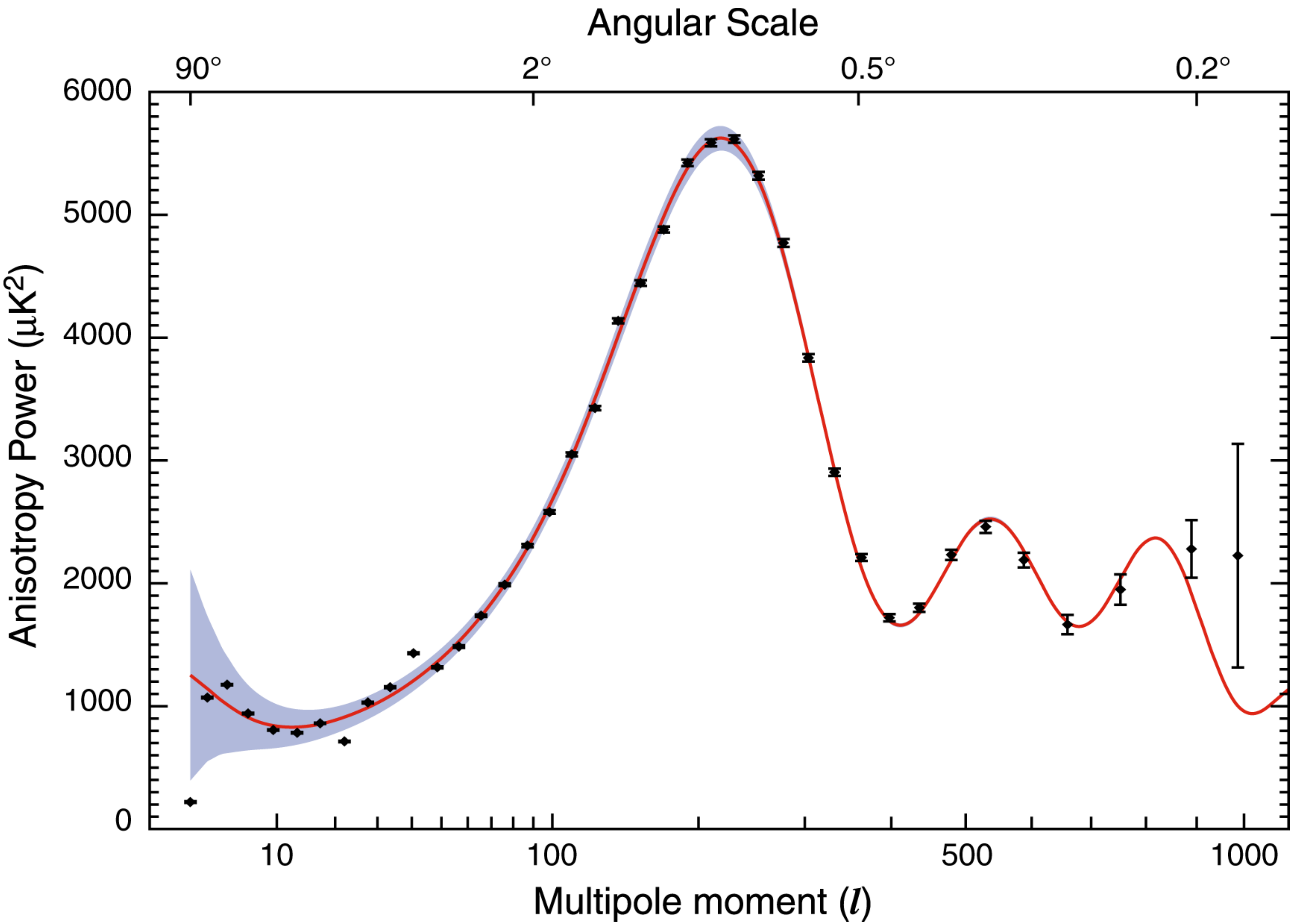
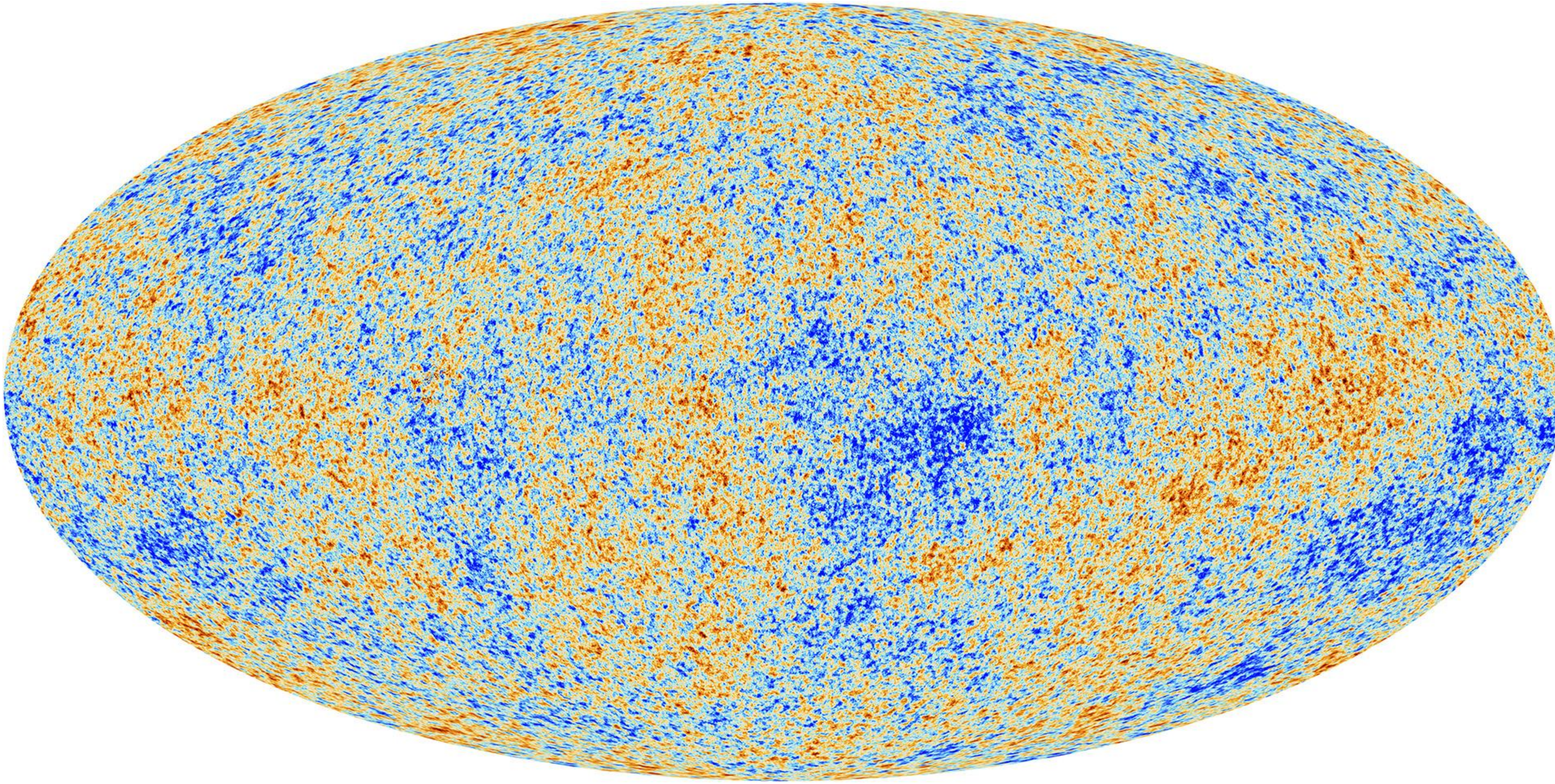
The past 20 years have seen dramatic advances in cosmology, mostly driven by observations from new telescopes and detectors. These instruments have allowed astronomers to map out the large-scale structure of the Universe and probe the very early stages of its evolution. We seem to have established the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

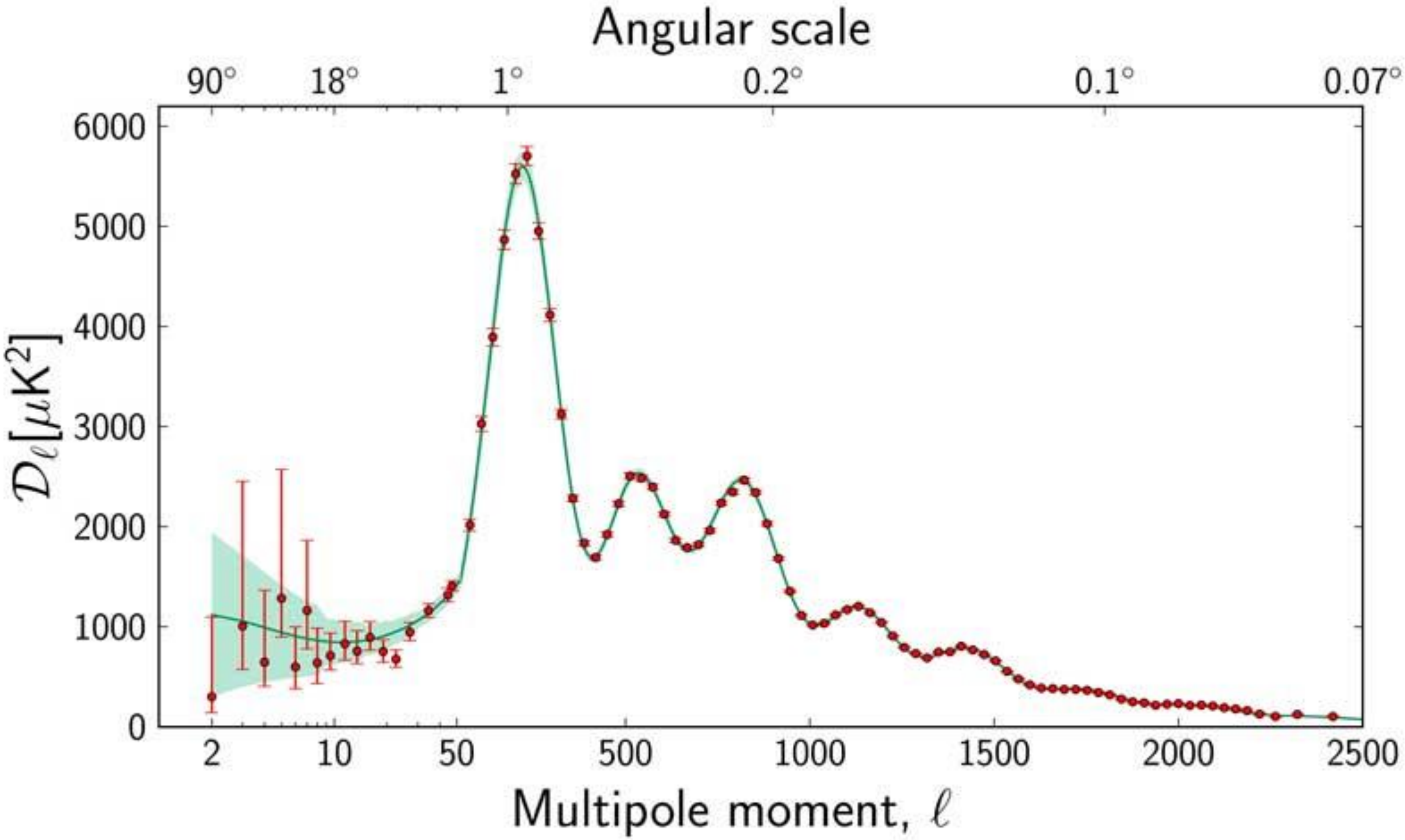

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team





Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
Anisotropy Power (μK²)
10
100
500
1000
Multipole moment (*l*)





Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

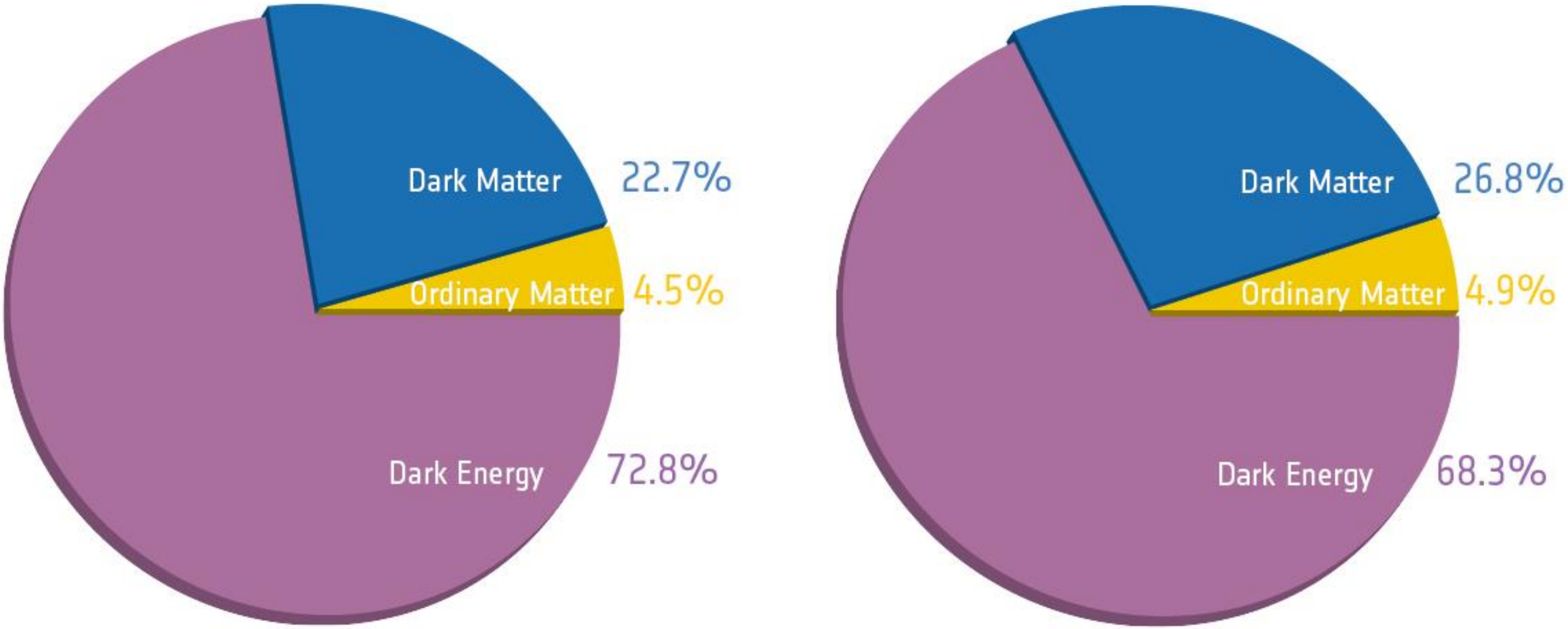
Planck results: cosmological parameters

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

	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$

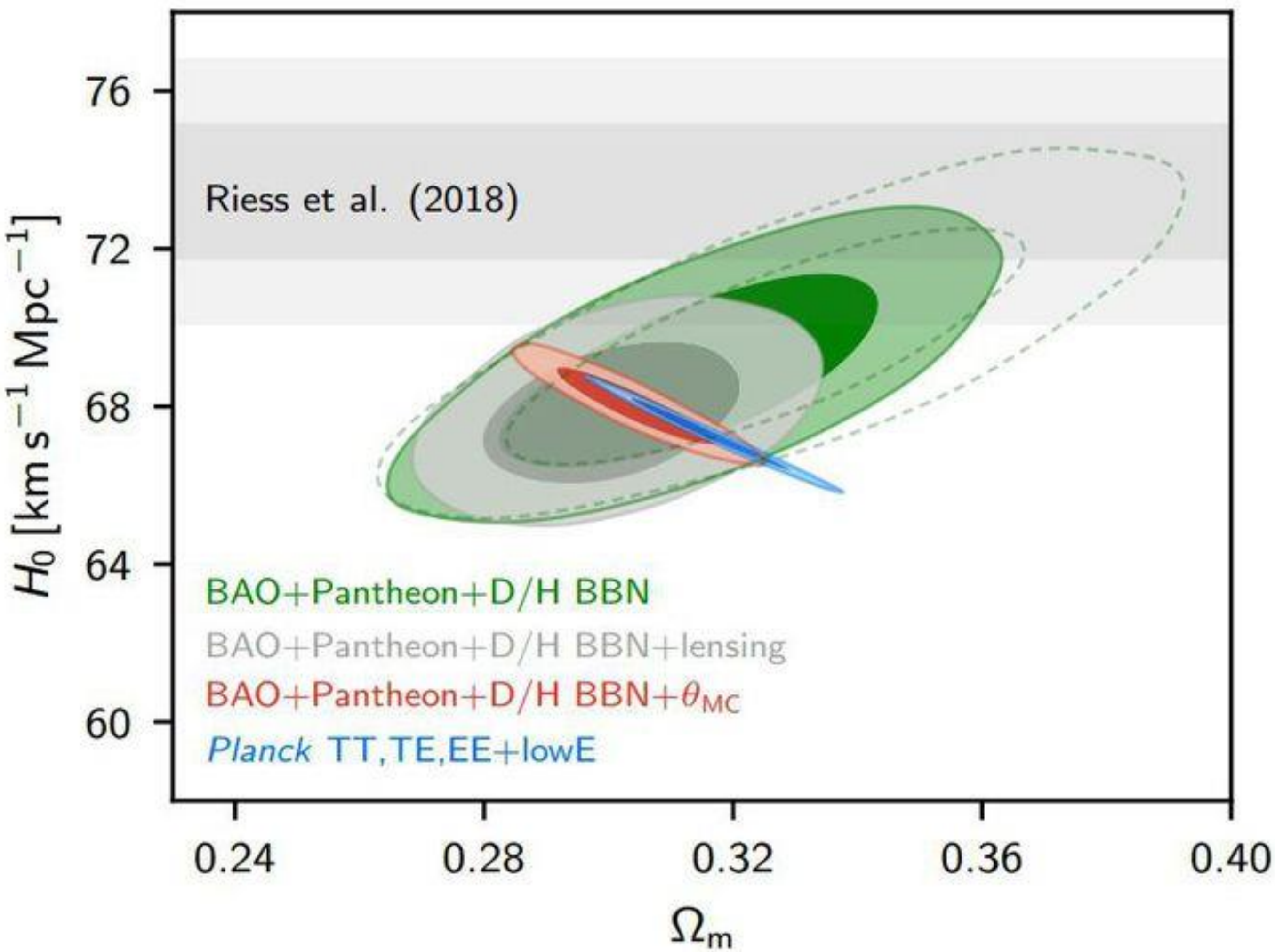
Some interesting derived numbers:

H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$



Before Planck

After Planck



Riess et al. (2018)
76
72
68
64
60
H_0 [km s^{-1} Mpc^{-1}]
0.24
0.28
0.32
0.36
0.40
Ω_m
BAO+Pantheon+D/H BBN
BAO+Pantheon+D/H BBN+lensing
BAO+Pantheon+D/H BBN+θ_{MC}
Planck TT,TE,EE+lowE


BJ AB JP PC VI PK
H0 40 35 65 75 60 70 60
Ω0 0.2 1 0.35 0.2 1 0.3 0.2
Λ0 0 0 0 0 0 0.7 0
k −1 0 −1 −1 0 0 −1
t0 15 14 >9 12 18 14 16

Hubble Tension?

Richard Ellis, Lectures on Observational Cosmology

SERC Summer School for new research students, 1985

Results : Sandage & Tammann $H_o = 55 \pm 5$ no infall found

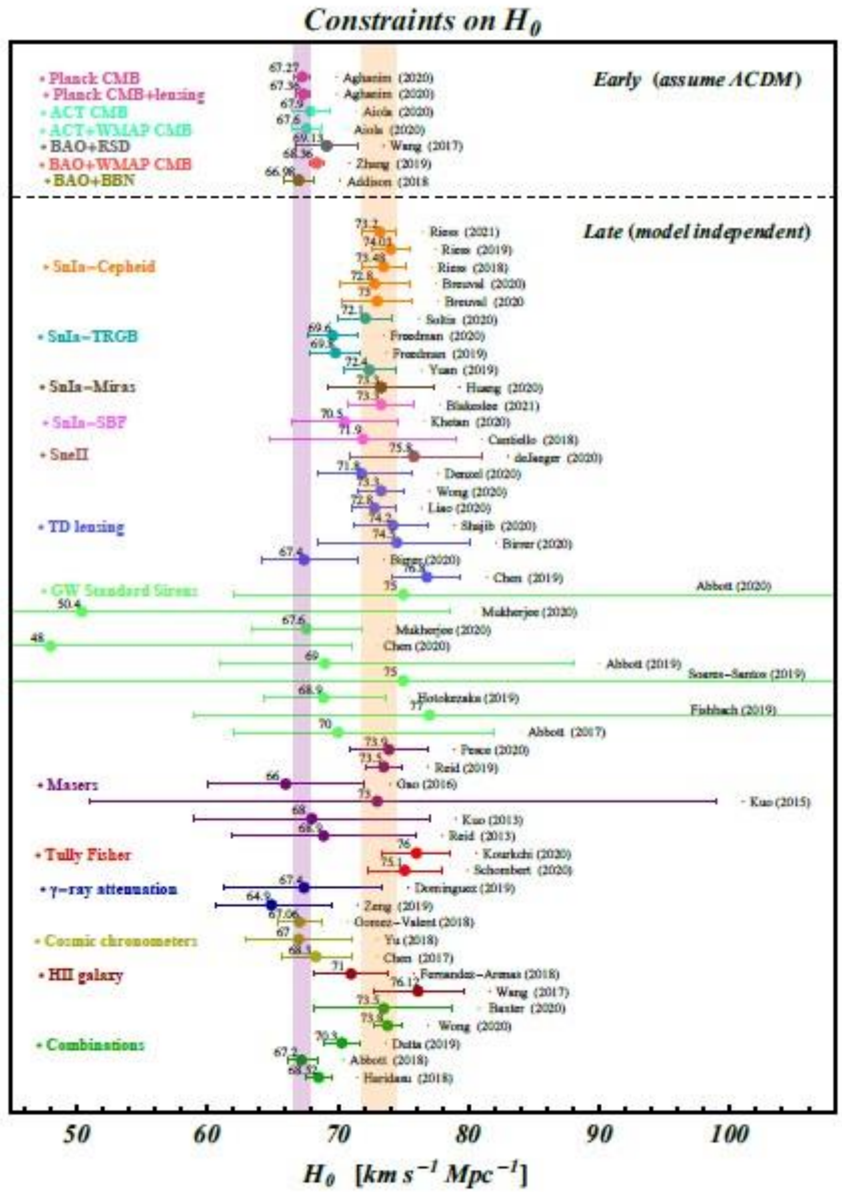
(corrected for infall $H_o \to 80$)

G. de Vaucouleurs $H_o = 100 \pm 10$ after infall correction

Tertiary indicators (i-r TF) $H_o \sim 60 - 100$

but dependent on infall model used

Perivolaropoulos & Skara
arXiv:2105.05208



The Robertson-Walker metric

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

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

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

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

The Etherington Reciprocity Theorem

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

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

which means that

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

since $1 + z = {}^{a_0}/_{a_e}$ defines the redshift z.

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

“CONCORDANCE”

Ingredients of the Standard Cosmology

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

Questionable Aspects of the Standard Cosmology

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

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\rho \qquad (1)$$

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

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

§ 1. Die Newtonsche Theorie.

Es ist wohlbekannt, daß die Newtonsche Grenzbedingung des konstanten Limes für ϕ im räumlich Unendlichen zu der Auffassung hinführt, daß die Dichte der Materie im Unendlichen zu null wird. Wir denken uns nämlich, es lasse sich ein Ort im Weltraum finden, um den herum das Gravitationsfeld der Materie, im großen betrachtet, Kugelsymmetrie besitzt (Mittelpunkt). Dann folgt aus der Poissonschen Gleichung, daß die mittlere Dichte ρ rascher als $\frac{1}{r^2}$ mit wachsender Entfernung r vom Mittelpunkt zu null herabsinken muß, damit ϕ im

Dark Energy:
A Cosmologist's Perspective

$$G = T$$

Gravity

Stuff

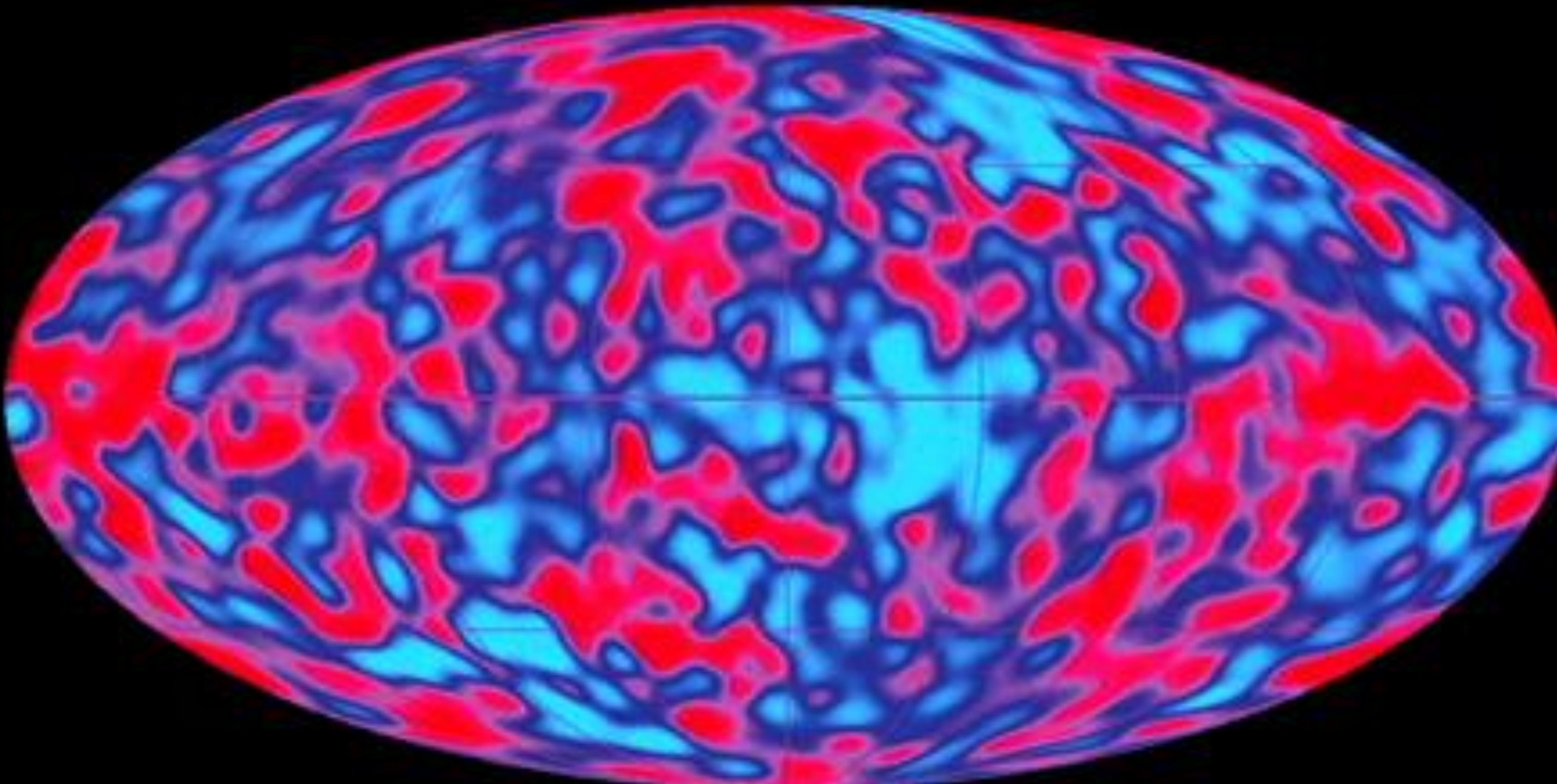
$$\boldsymbol{G} + ? = \boldsymbol{T}$$

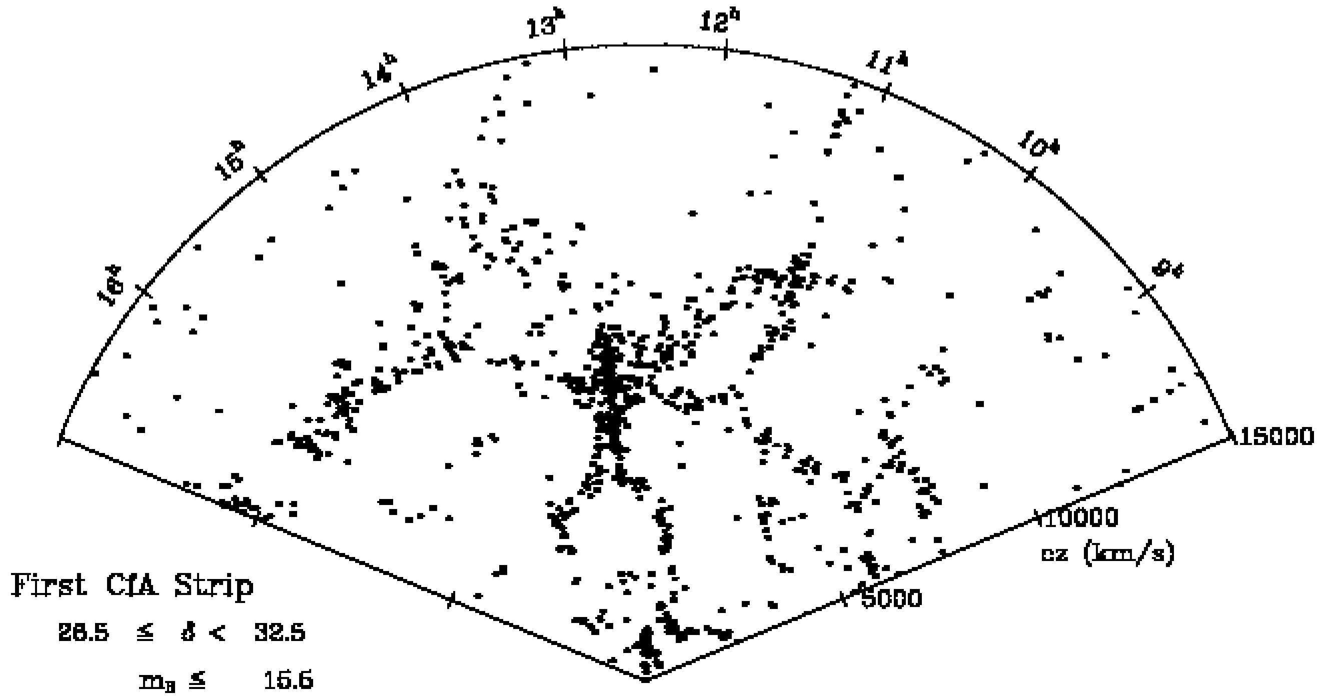
Dark Energy: A Physicist's Perspective

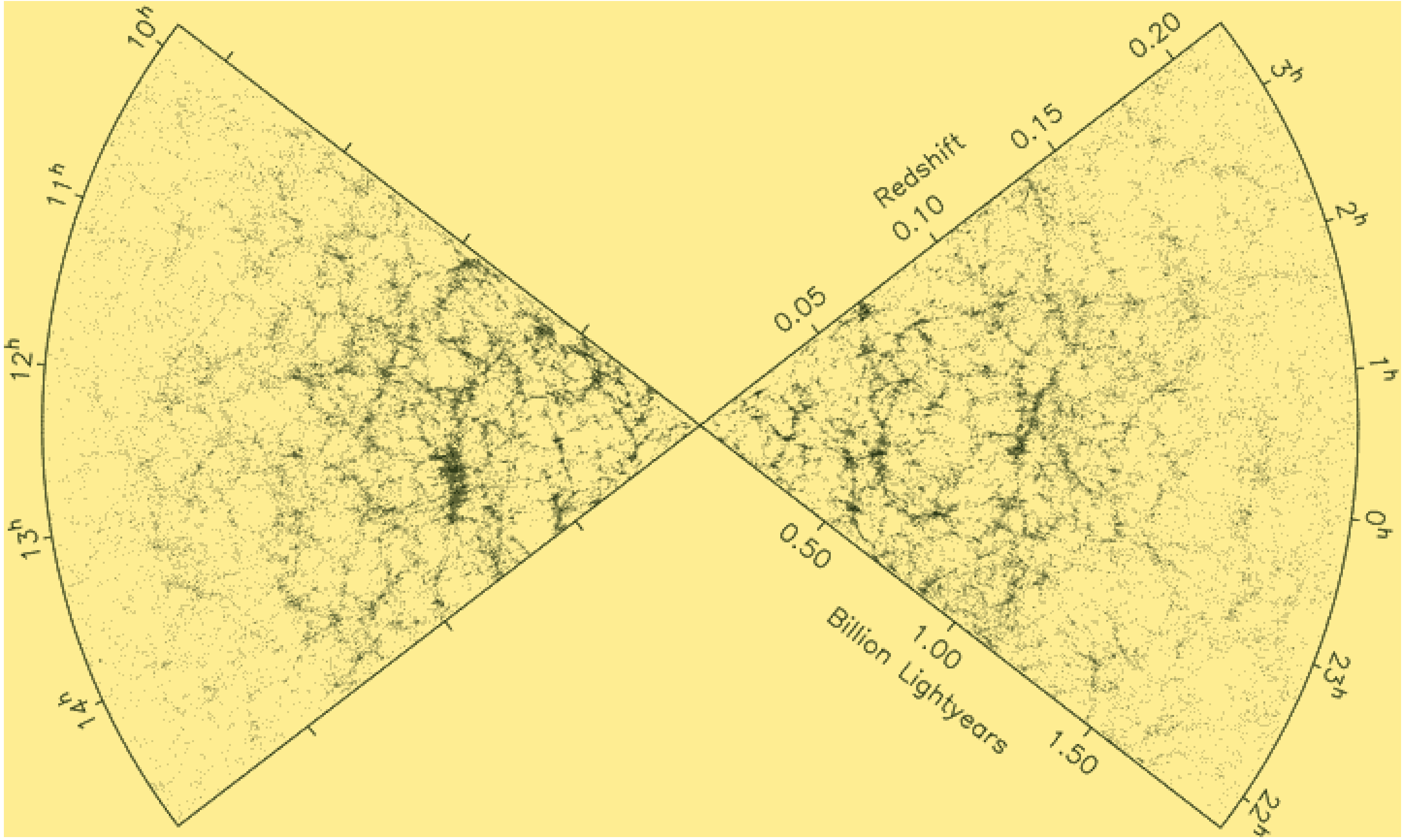
$$\boldsymbol{G} = \boldsymbol{T} + ?$$

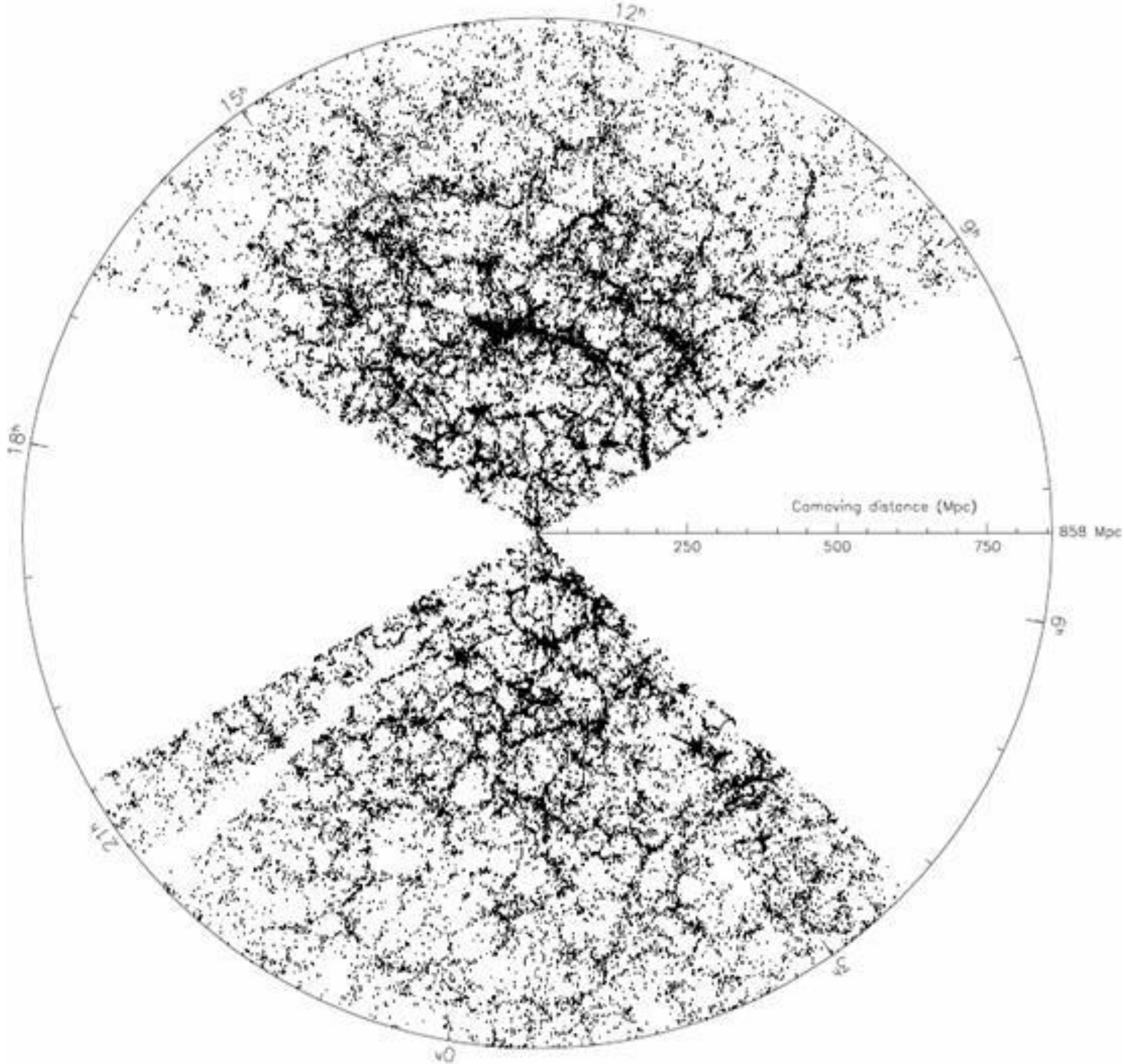
Whatever it is, Dark Energy is a *terrible* name for it…

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

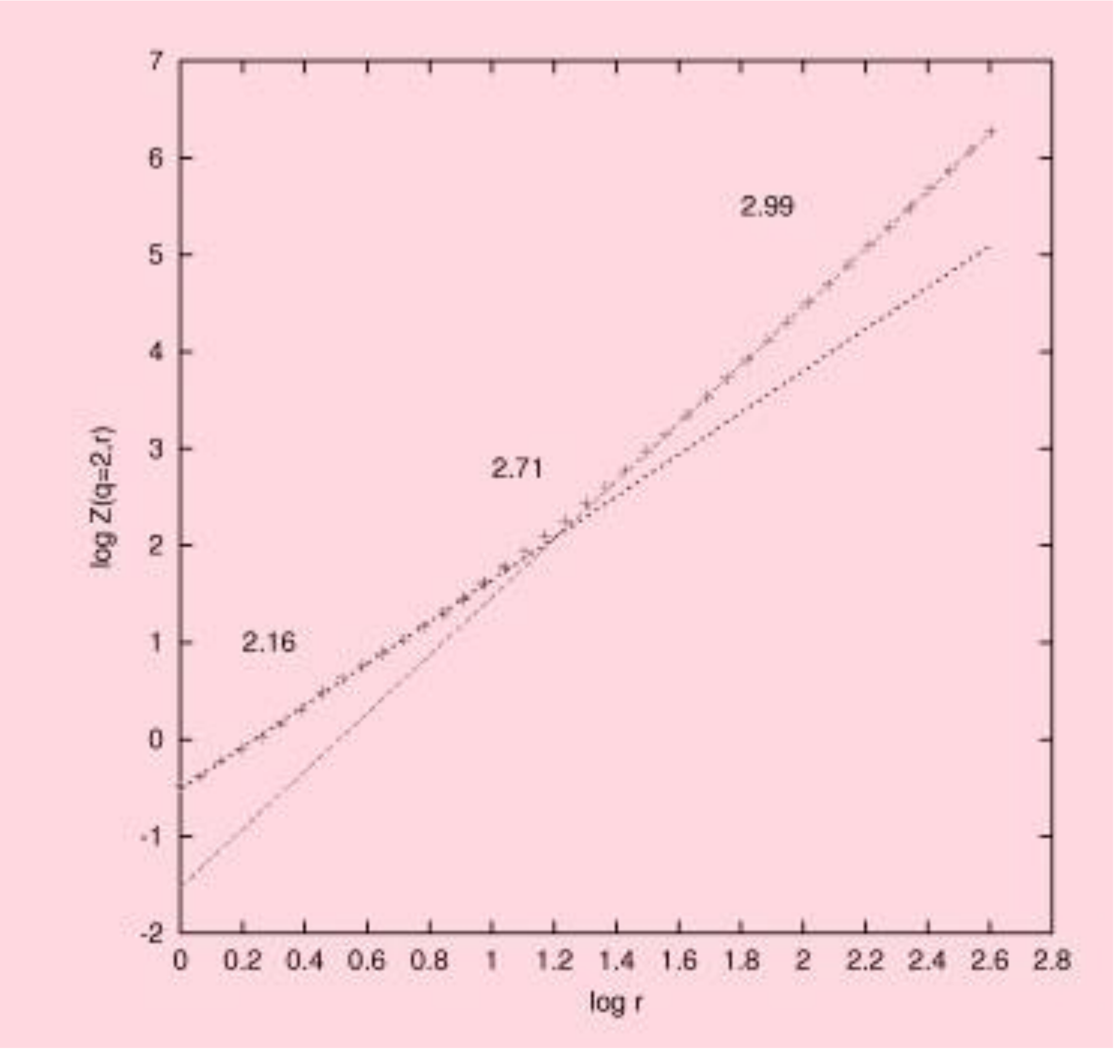


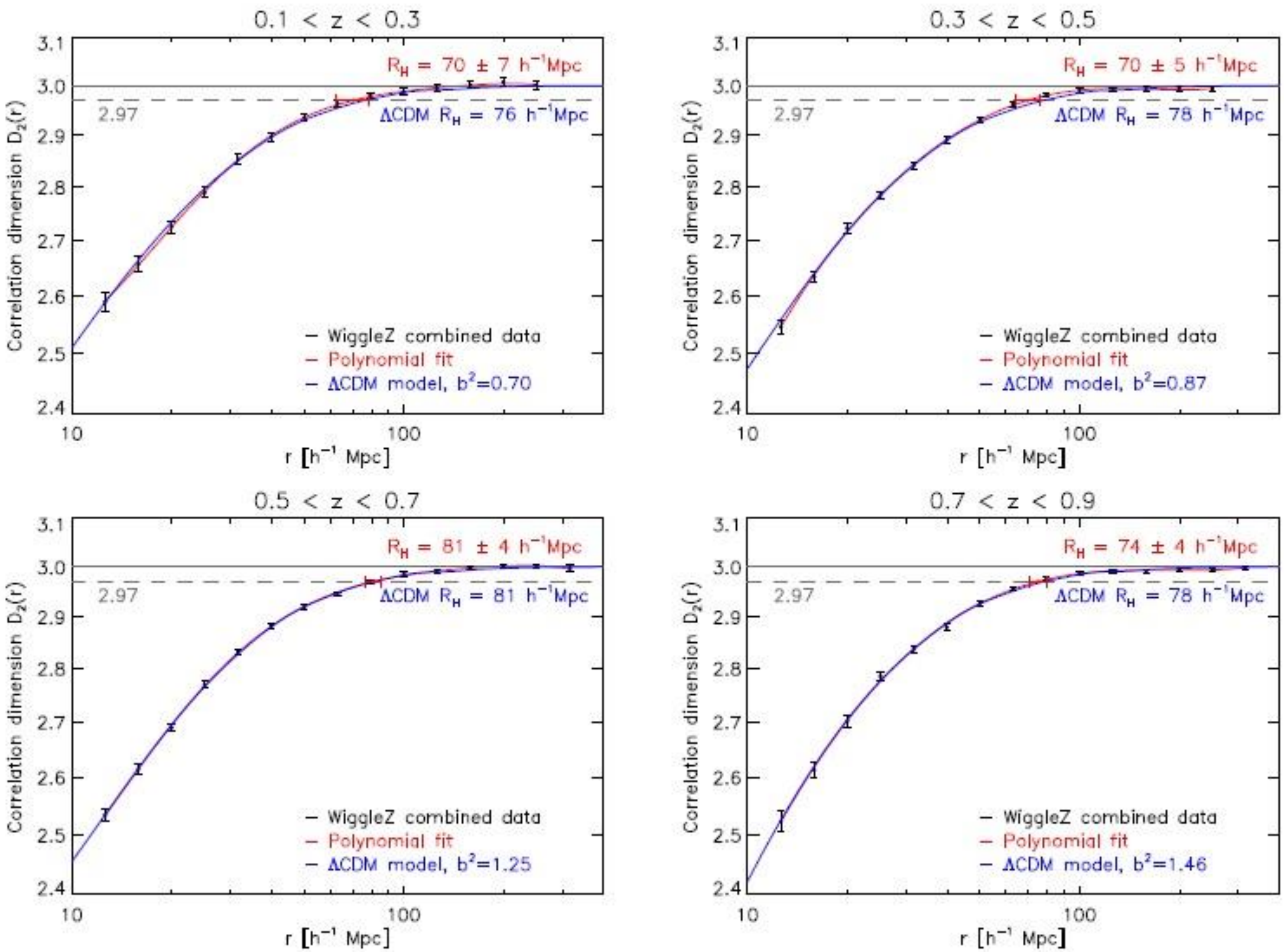

13h
12h
11h
10h
9h
14h
15h
16h
15000
10000
cz (km/s)
5000
First CfA Strip
26.5 ≤ δ < 32.5
m_B ≤ 15.6


10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50


12h
15h
9h
18h
6h
21h
3h
0h
Comoving distance (Mpc)
250
500
750
858 Mpc

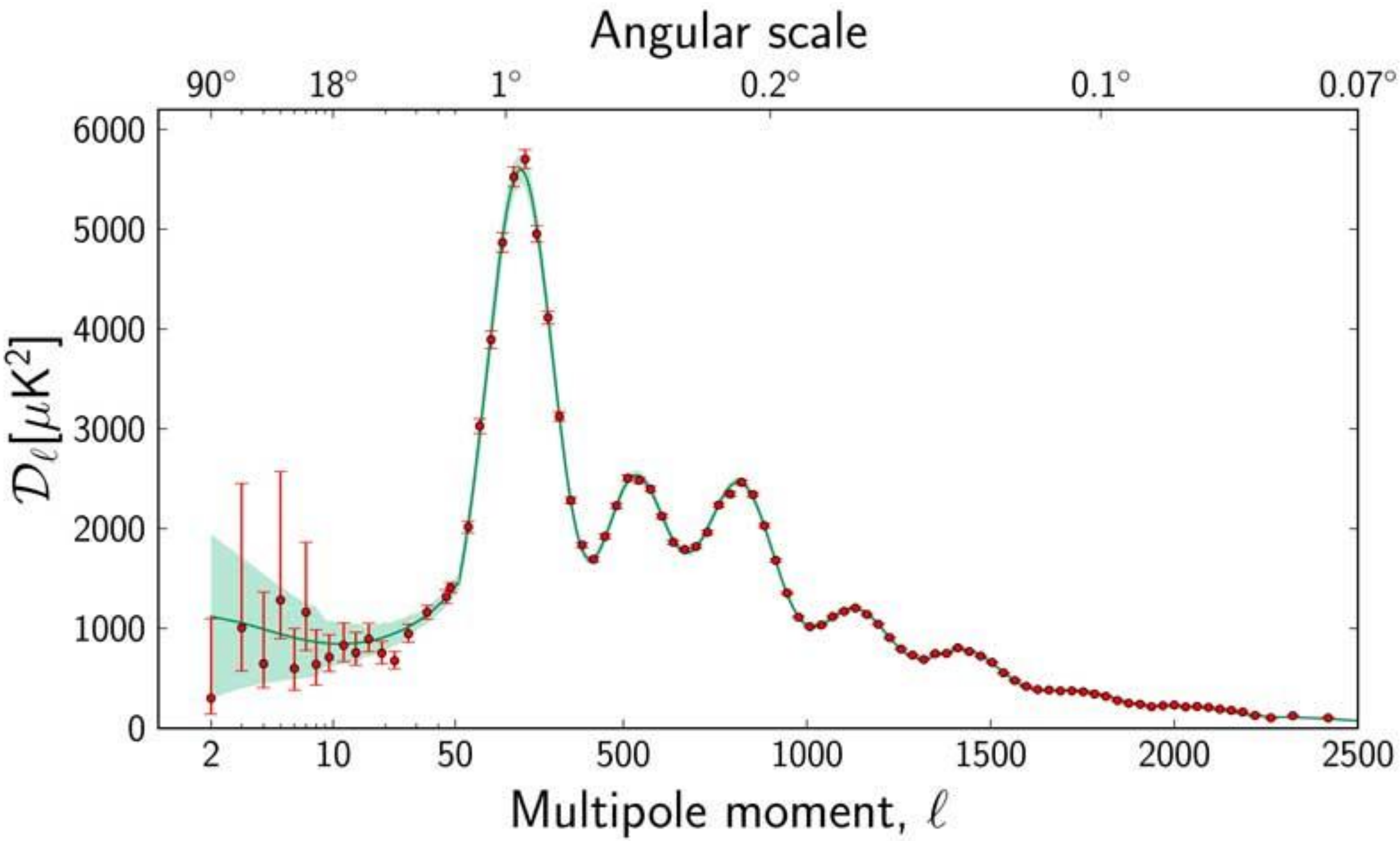
Pan & Coles, 2000, MNRAS, 318, L51




0.1 < z < 0.3
R_H = 70 ± 7 h^{-1}Mpc
2.97
ΛCDM R_H = 76 h^{-1}Mpc
WiggleZ combined data
Polynomial fit
ΛCDM model, b^2=0.70
0.3 < z < 0.5
R_H = 70 ± 5 h^{-1}Mpc
2.97
ΛCDM R_H = 78 h^{-1}Mpc
WiggleZ combined data
Polynomial fit
ΛCDM model, b^2=0.87
0.5 < z < 0.7
R_H = 81 ± 4 h^{-1}Mpc
2.97
ΛCDM R_H = 81 h^{-1}Mpc
WiggleZ combined data
Polynomial fit
ΛCDM model, b^2=1.25
0.7 < z < 0.9
R_H = 74 ± 4 h^{-1}Mpc
2.97
ΛCDM R_H = 78 h^{-1}Mpc
WiggleZ combined data
Polynomial fit
ΛCDM model, b^2=1.46
Correlation dimension $D_2(r)$
r [h^{-1} Mpc]
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
10
100

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

…it’s 10^{-5} all the way up!

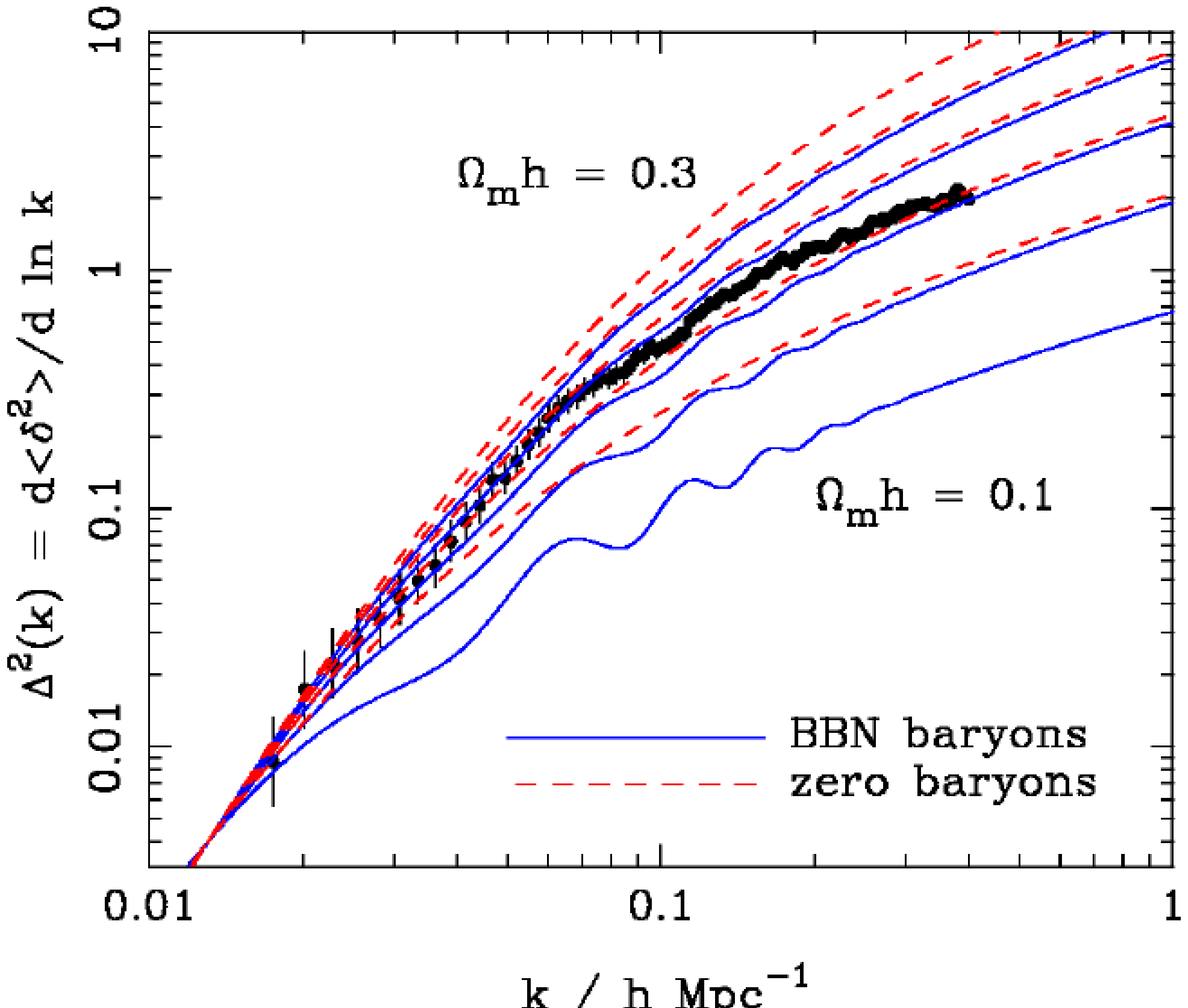


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

2dFGRS power spectrum: small BAO proves DM

Dimensionless power:

d (fractional variance in density) / d ln k



Percival et al. MNRAS 327, 1279 (2001)

Why Should The Dark Sector Be Simple?

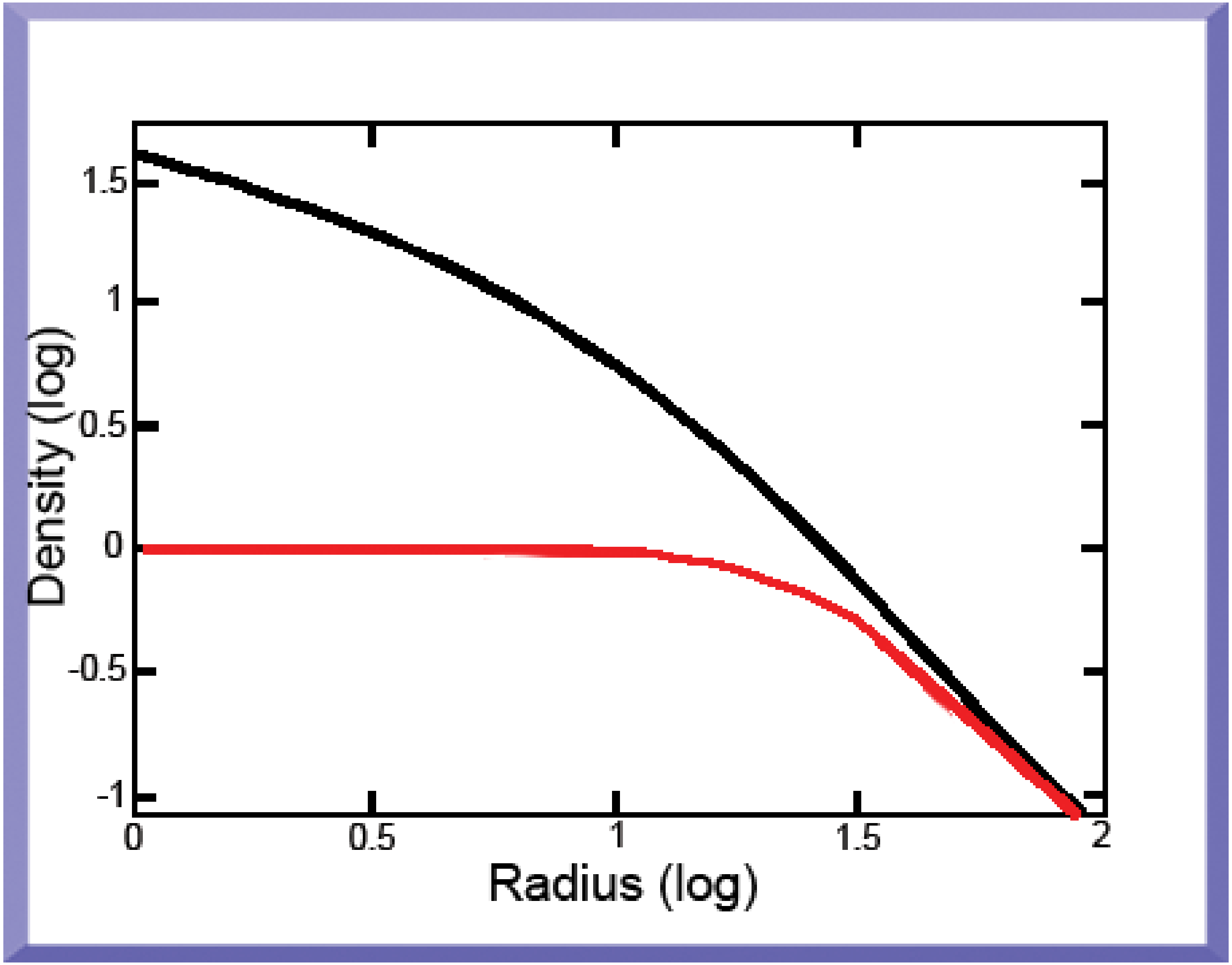
Problems with Cold Dark Matter

Astrophysics:

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

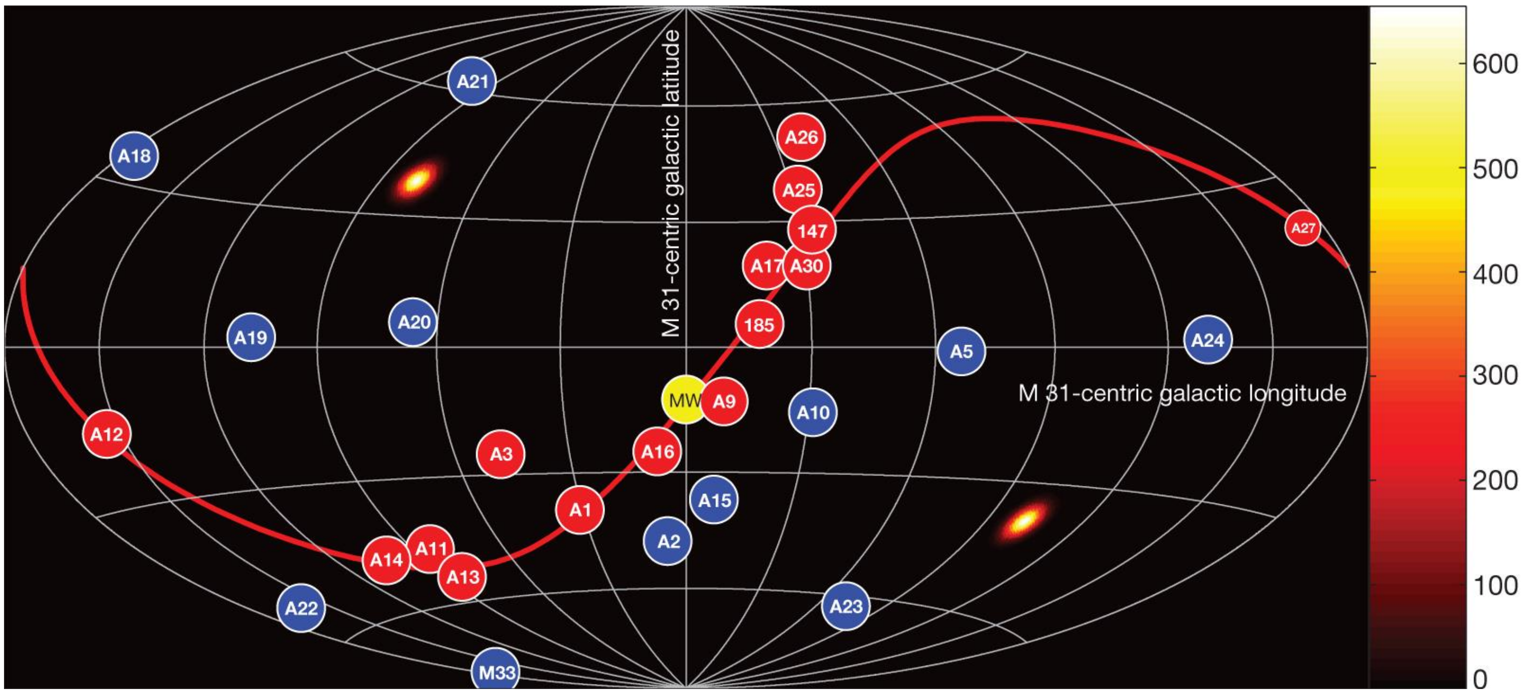
Particle Physics

- No Evidence for Supersymmetry
- No evidence from Direct Searches
- …

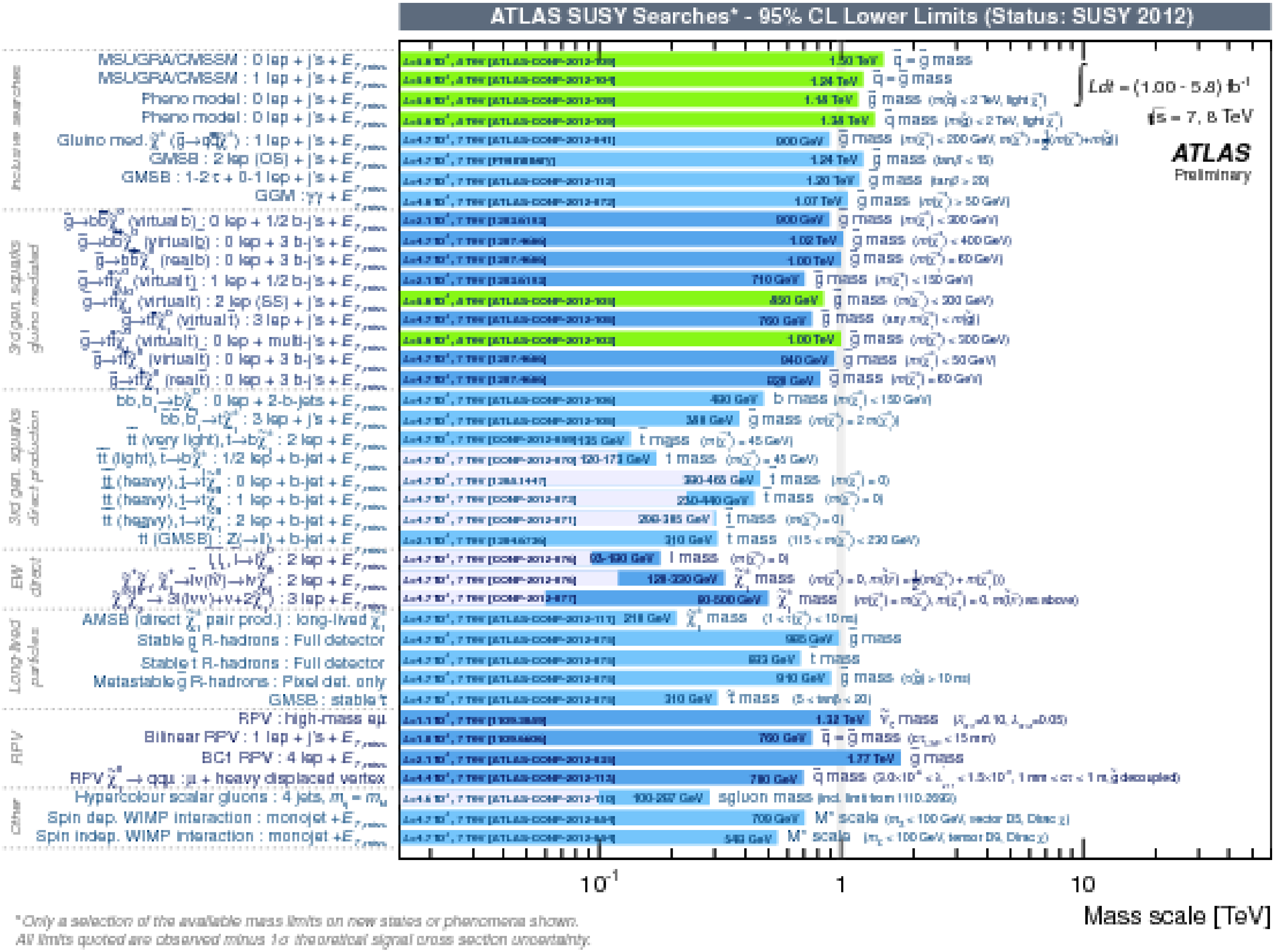


Density (log)
1.5
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
Radius (log)

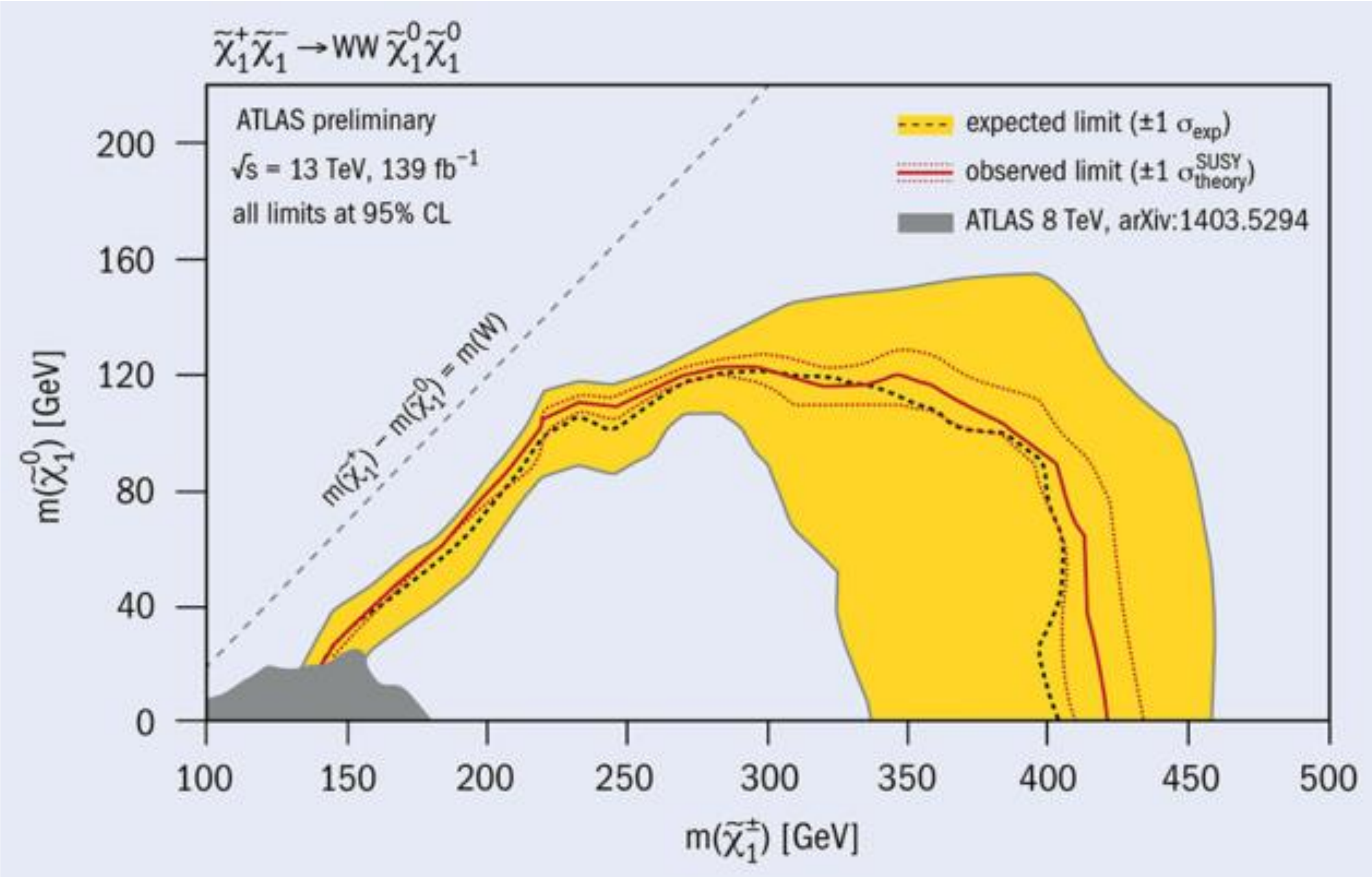
Satellite galaxy positions as viewed from Andromeda.



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



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: SUSY 2012)
ATLAS
Preliminary
$\sqrt{s}$ = 7, 8 TeV
Inclusive searches
3rd gen. squarks gluino mediated
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
GMSB : 2 lep (OS) + j's + $E_{T,miss}$
GGM : γγ + $E_{T,miss}$
AMSB (direct $\tilde{\chi}_1^{\pm}$ pair prod.) : long-lived $\tilde{\chi}_1^{\pm}$
Stable $\tilde{g}$ R-hadrons : Full detector
Stable $\tilde{t}$ R-hadrons : Full detector
Metastable $\tilde{g}$ R-hadrons : Pixel det. only
GMSB : stable $\tilde{\tau}$
RPV : high-mass eμ
Bilinear RPV : 1 lep + j's + $E_{T,miss}$
BC1 RPV : 4 lep + $E_{T,miss}$
Hypercolour scalar gluons : 4 jets, $m_{ij} \approx m_{kl}$
Spin dep. WIMP interaction : monojet + $E_{T,miss}$
Spin indep. WIMP interaction : monojet + $E_{T,miss}$
1.50 TeV
1.24 TeV
1.18 TeV
1.38 TeV
900 GeV
1.24 TeV
1.20 TeV
1.07 TeV
900 GeV
1.02 TeV
1.00 TeV
710 GeV
850 GeV
760 GeV
1.00 TeV
940 GeV
820 GeV
480 GeV
380 GeV
135 GeV
120-173 GeV
380-465 GeV
230-440 GeV
310 GeV
140-295 GeV
128-230 GeV
210 GeV
985 GeV
683 GeV
910 GeV
310 GeV
1.32 TeV
760 GeV
1.77 TeV
700 GeV
100-287 GeV
700 GeV
540 GeV
$\tilde{q} = \tilde{g}$ mass
$\tilde{g}$ mass
$\tilde{q}$ mass
$\tilde{b}$ mass
$\tilde{t}$ mass
$\tilde{l}$ mass
$\tilde{\chi}_1^{\pm}$ mass
$\tilde{\tau}$ mass
$\tilde{\nu}_\tau$ mass
sgluon mass
M* scale
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



$\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow WW\,\tilde{\chi}_1^0\tilde{\chi}_1^0$
ATLAS preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
all limits at 95% CL
expected limit ($\pm 1\ \sigma_{exp}$)
observed limit ($\pm 1\ \sigma_{theory}^{SUSY}$)
ATLAS 8 TeV, arXiv:1403.5294
$m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = m(W)$
$m(\tilde{\chi}_1^0)$ [GeV]
$m(\tilde{\chi}_1^\pm)$ [GeV]

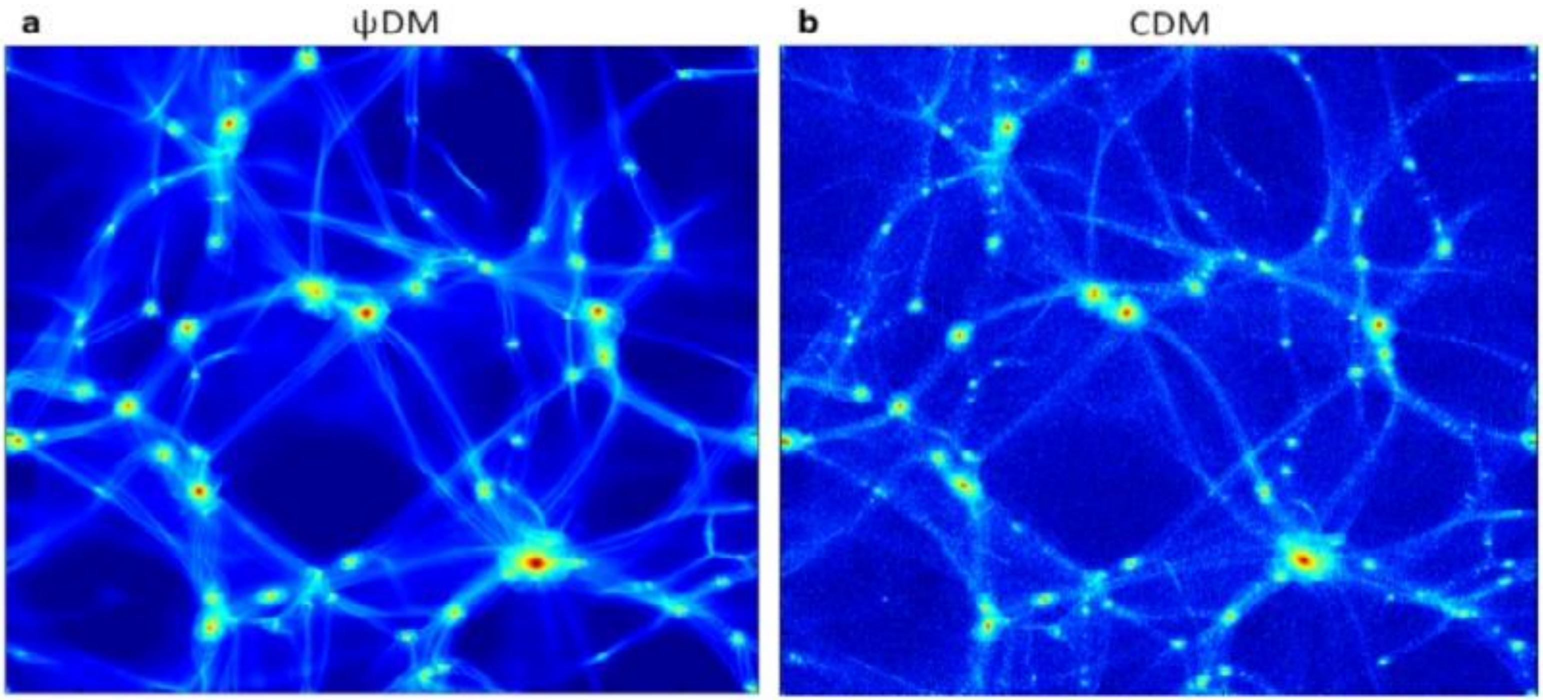
Alternatives (not exhaustive)

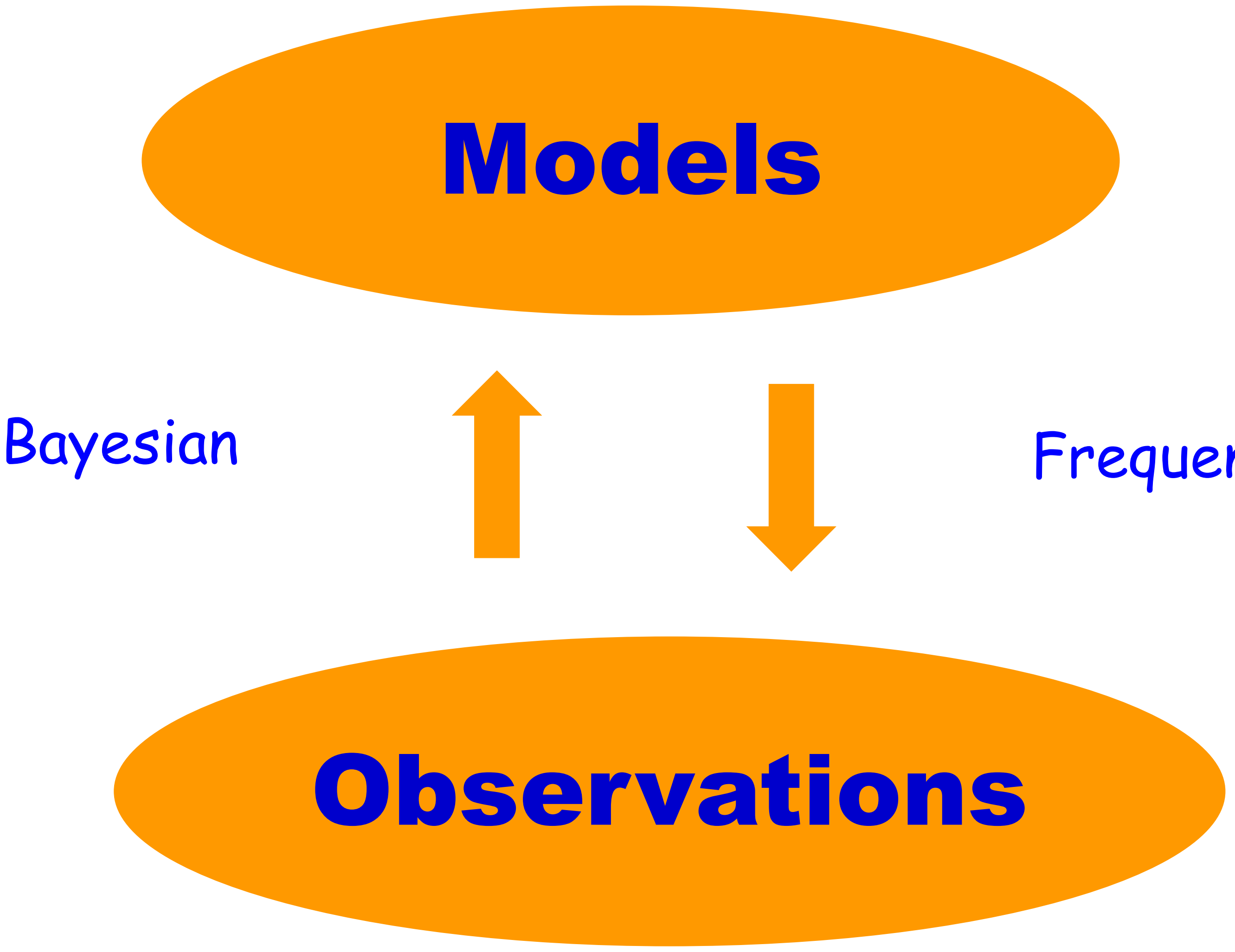
- HDM (historical; see also CHDM)
- WDM
- SIDM
- SADM
- Axions
- Fuzzy DM
- ……
- Modified Gravity (e.g. MOND)

Might dark matter be quantum-mechanical?

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

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



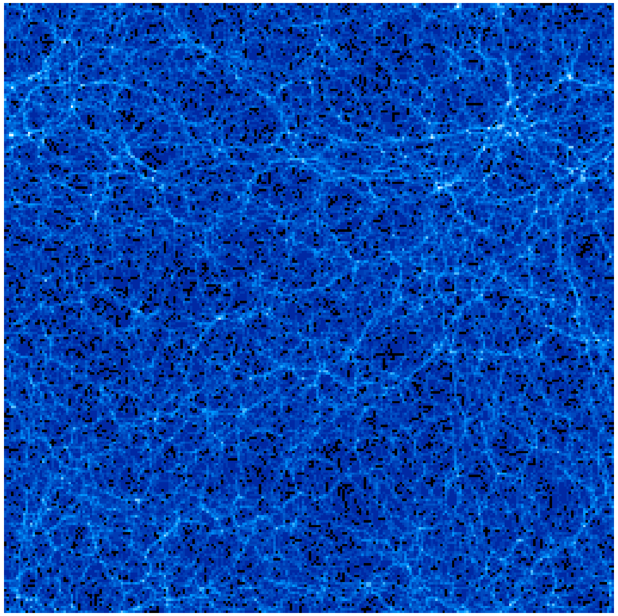

Models
Bayesian
Frequentist
Observations

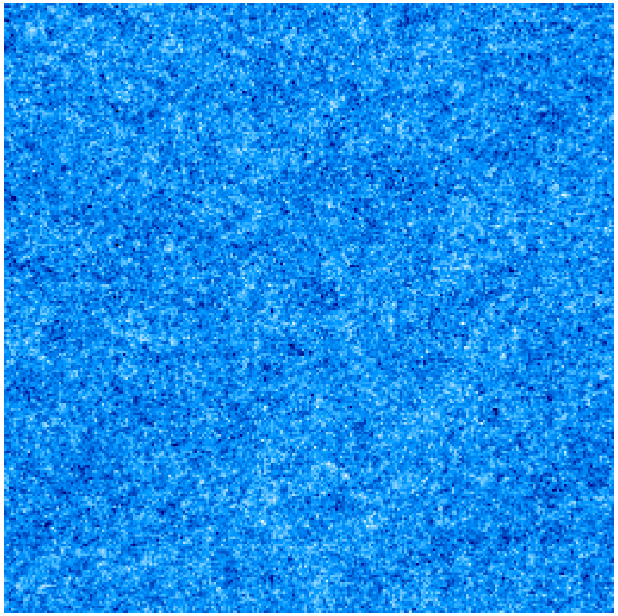
Cosmology is a massive exercise in data compression...

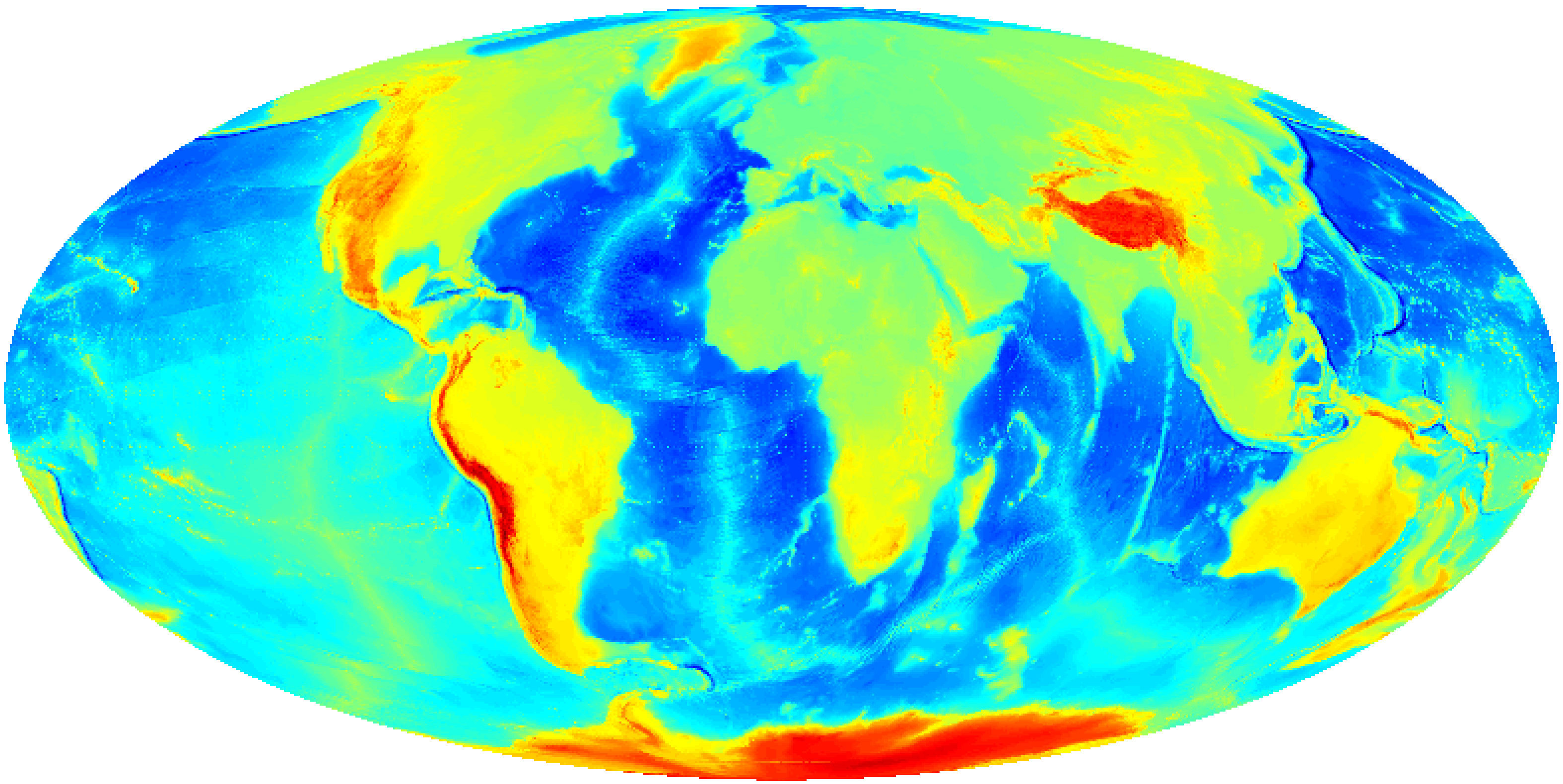
….but it is worth looking at the information that has been thrown away to check that it makes sense!

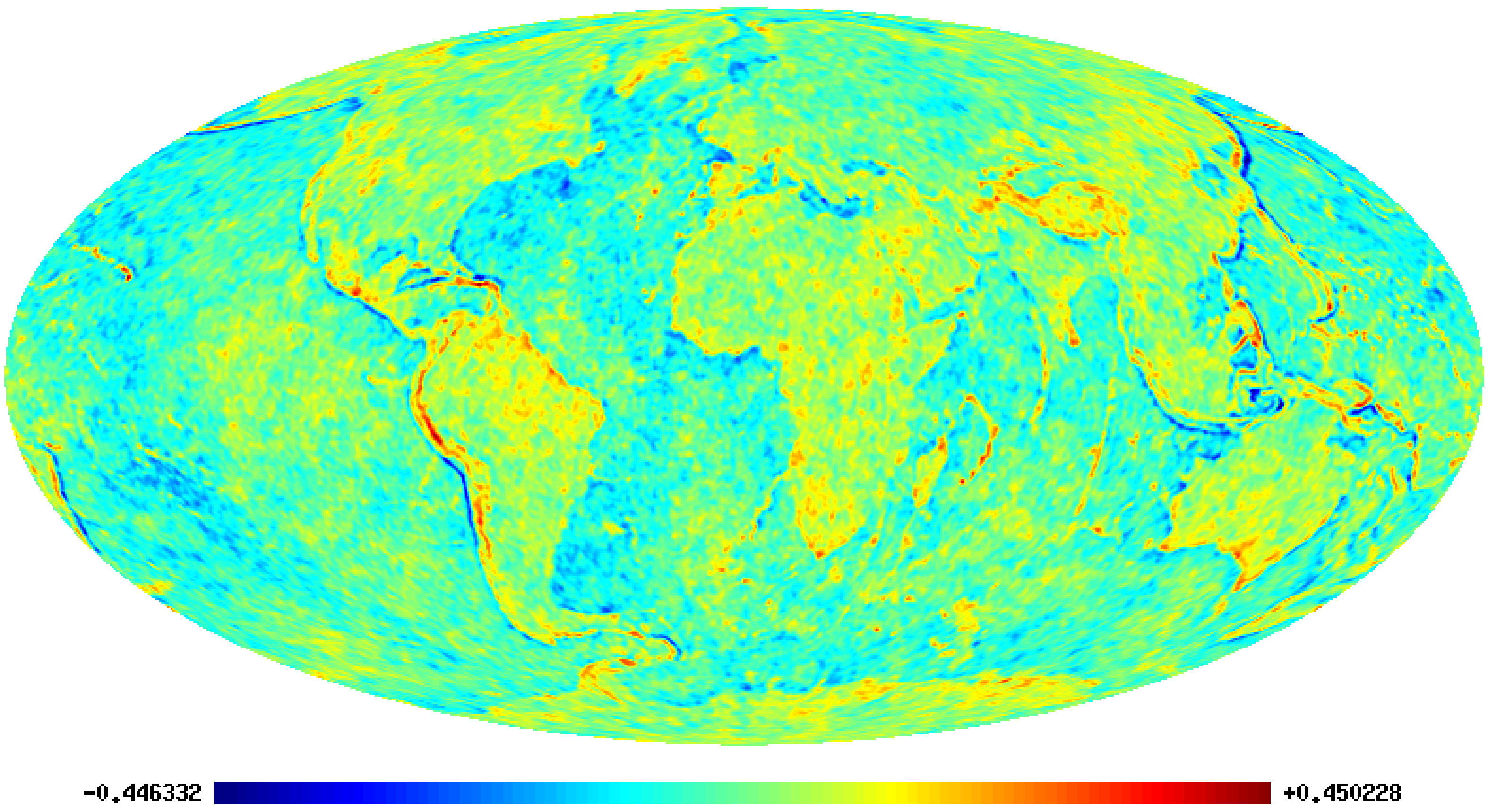
Beyond the Power Spectrum

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

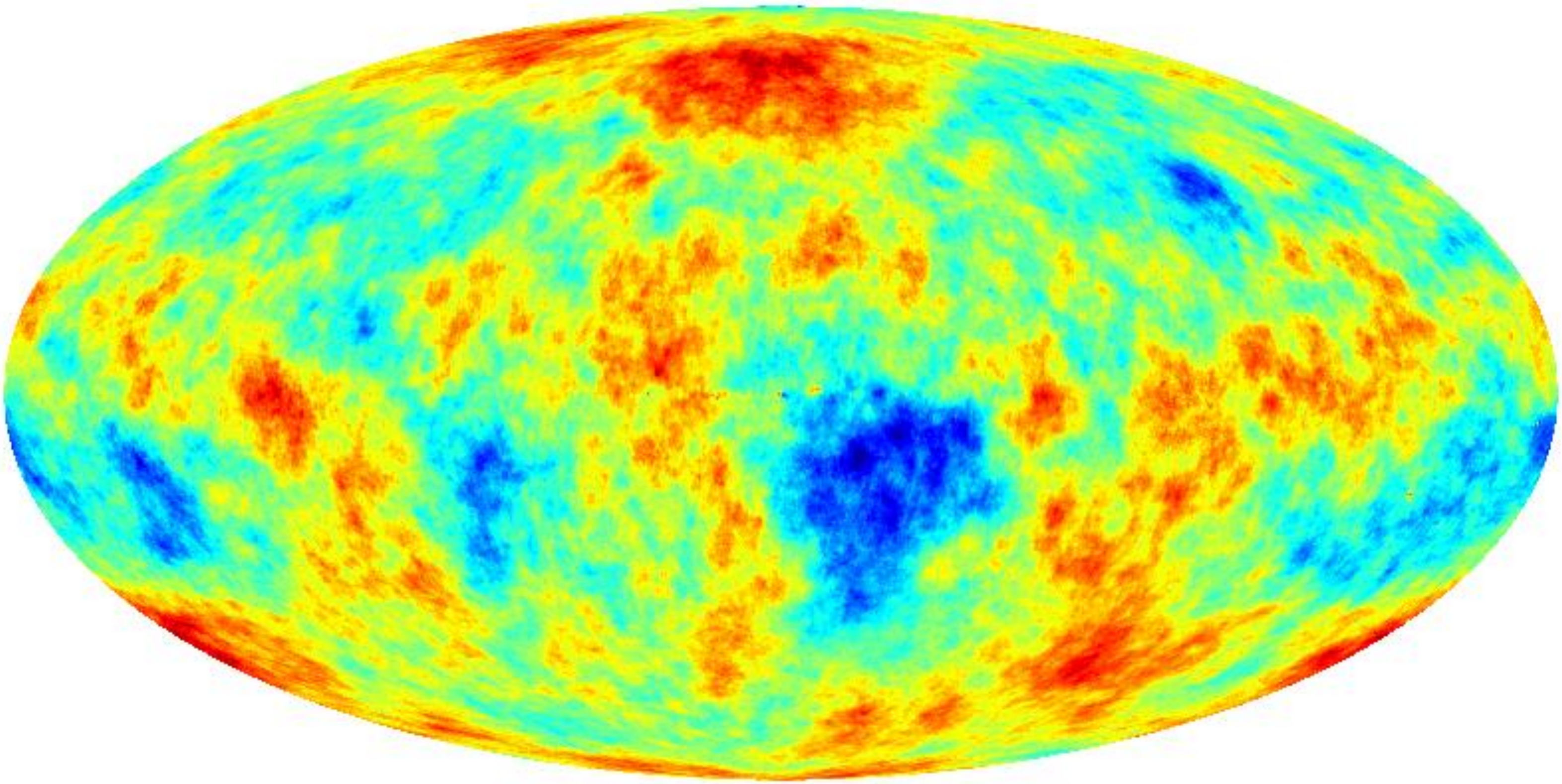


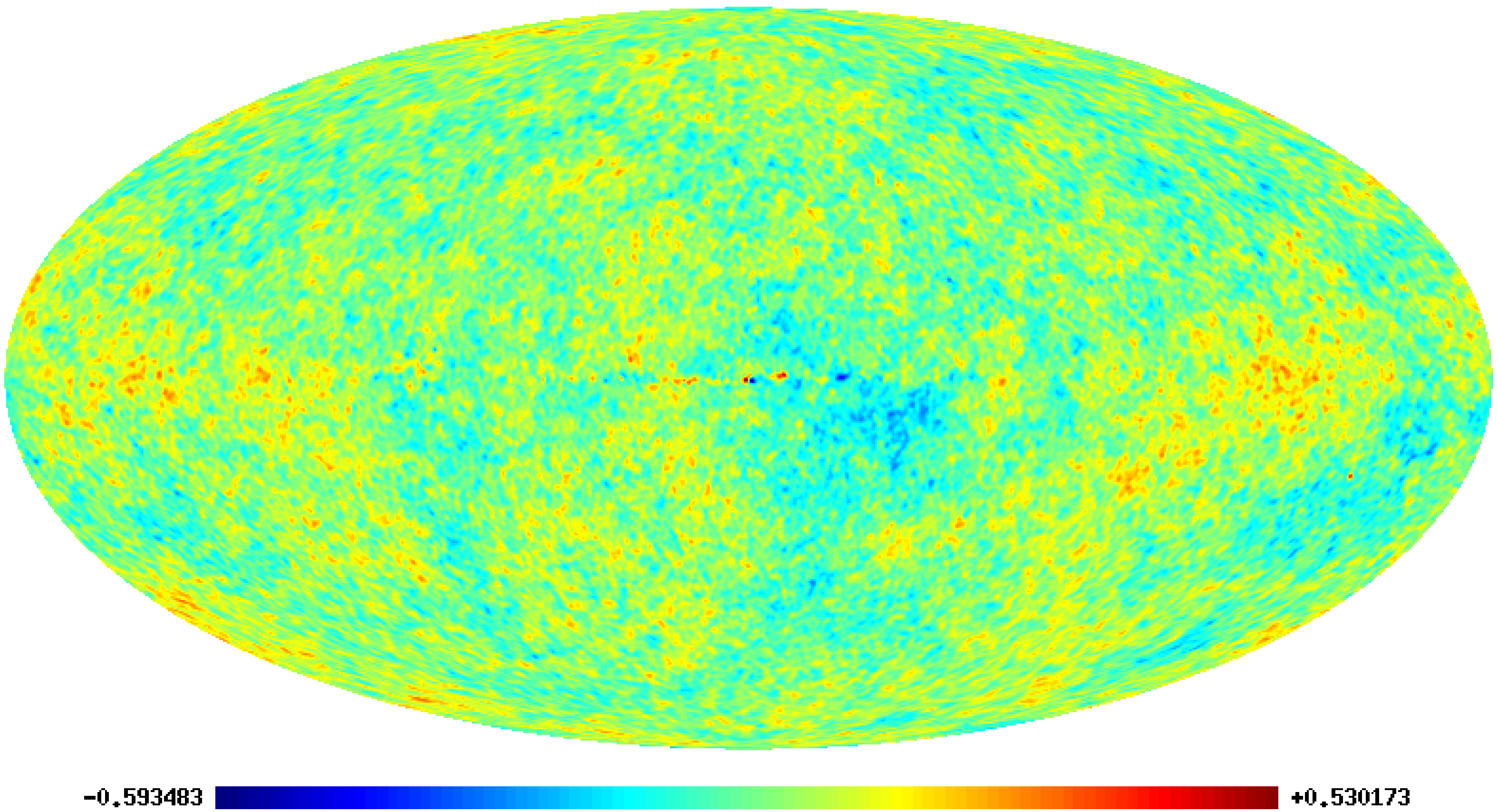


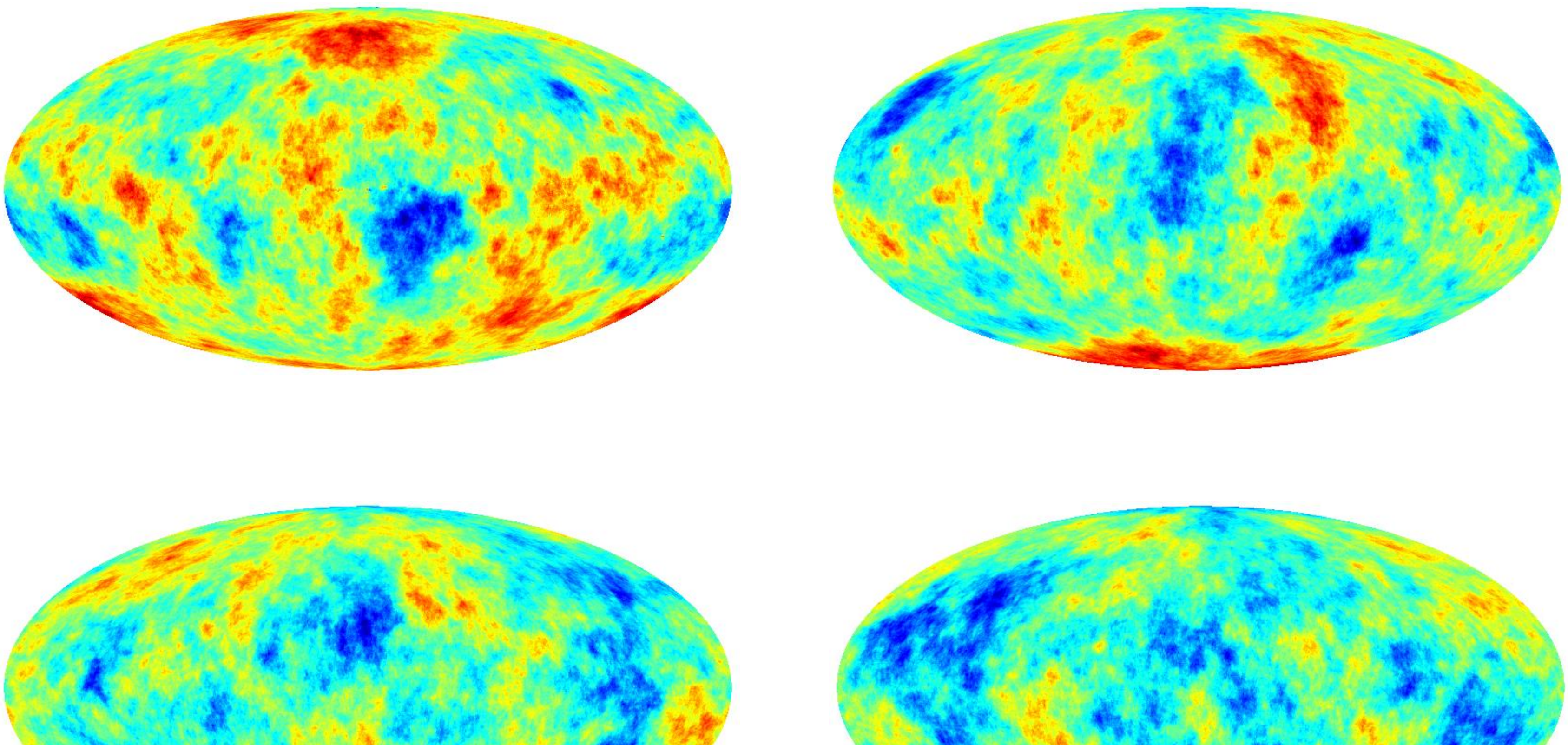




-0.446332
+0.450228




-0.593483
+0.530173



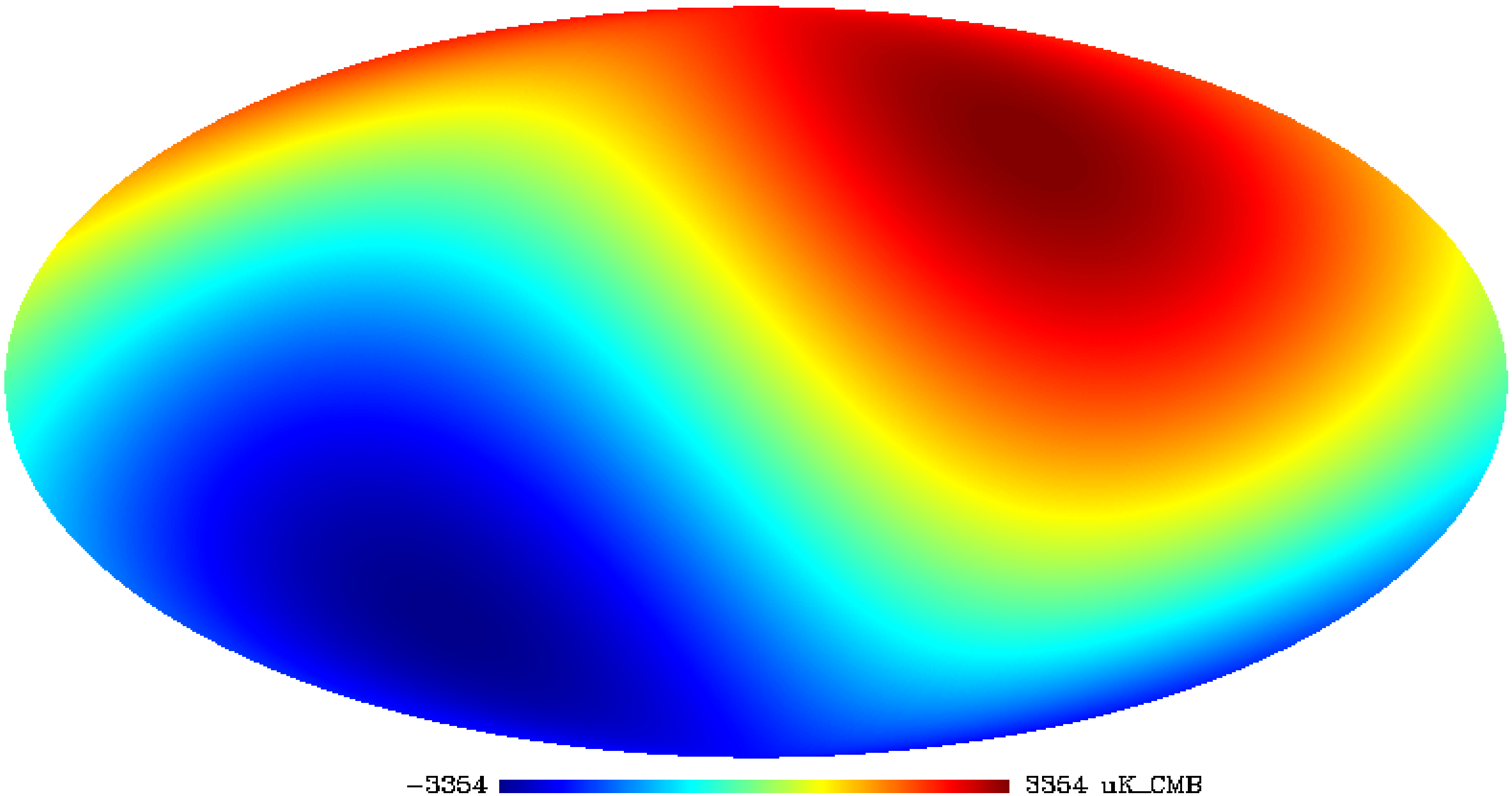
"If tortured sufficiently, data will confess to almost anything"

Fred Menger

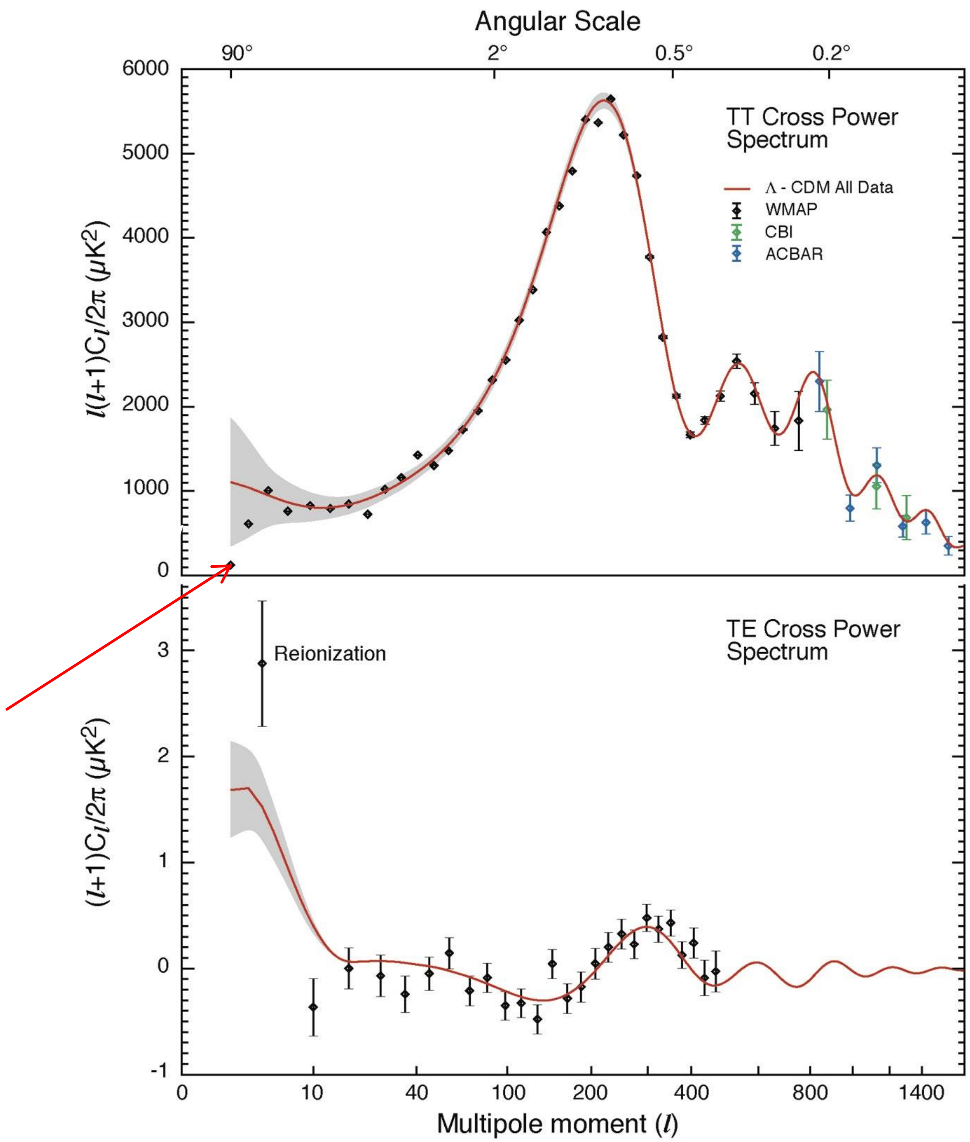
CMB Anomalies

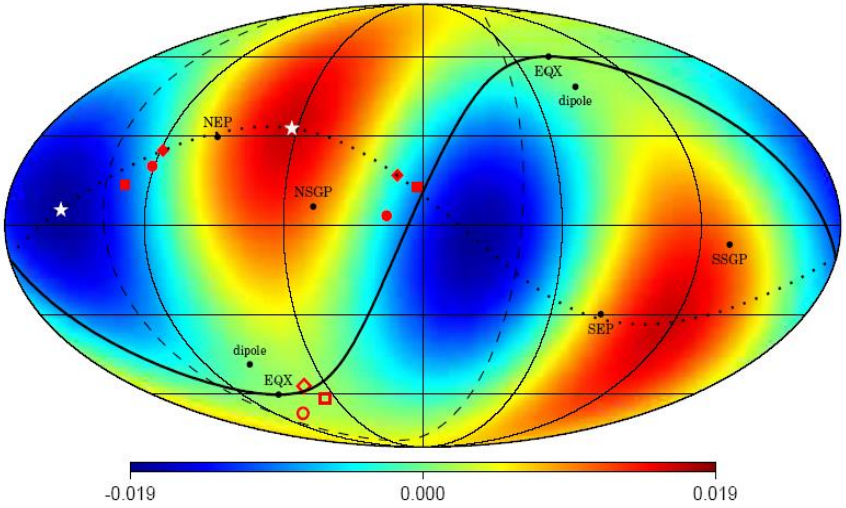
- Type I – obvious problems with data (e.g. foregrounds)
- Type II – anisotropies and alignments (North-South, Axis of Evil..)
- Type III – localized features, e.g. “The Cold Spot”
- Type IV – Something else (even/odd multipoles, magnetic fields, ?)

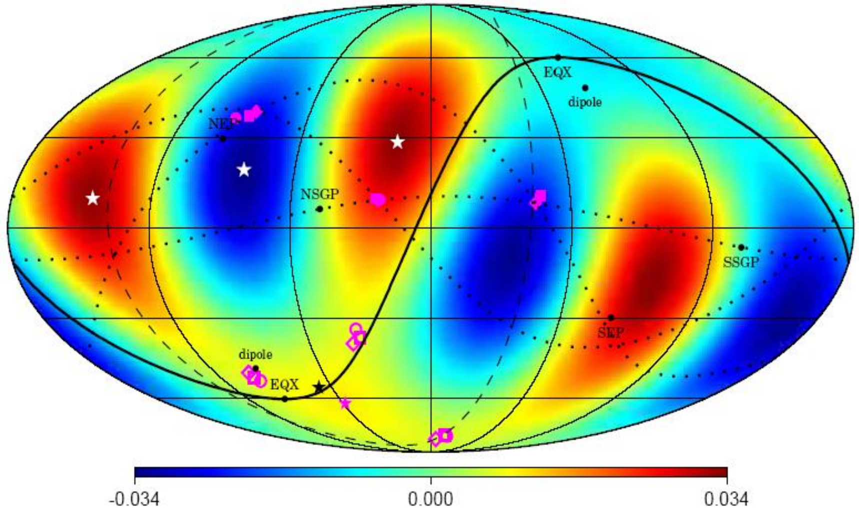
CMB dipole



Low Quadrupole?

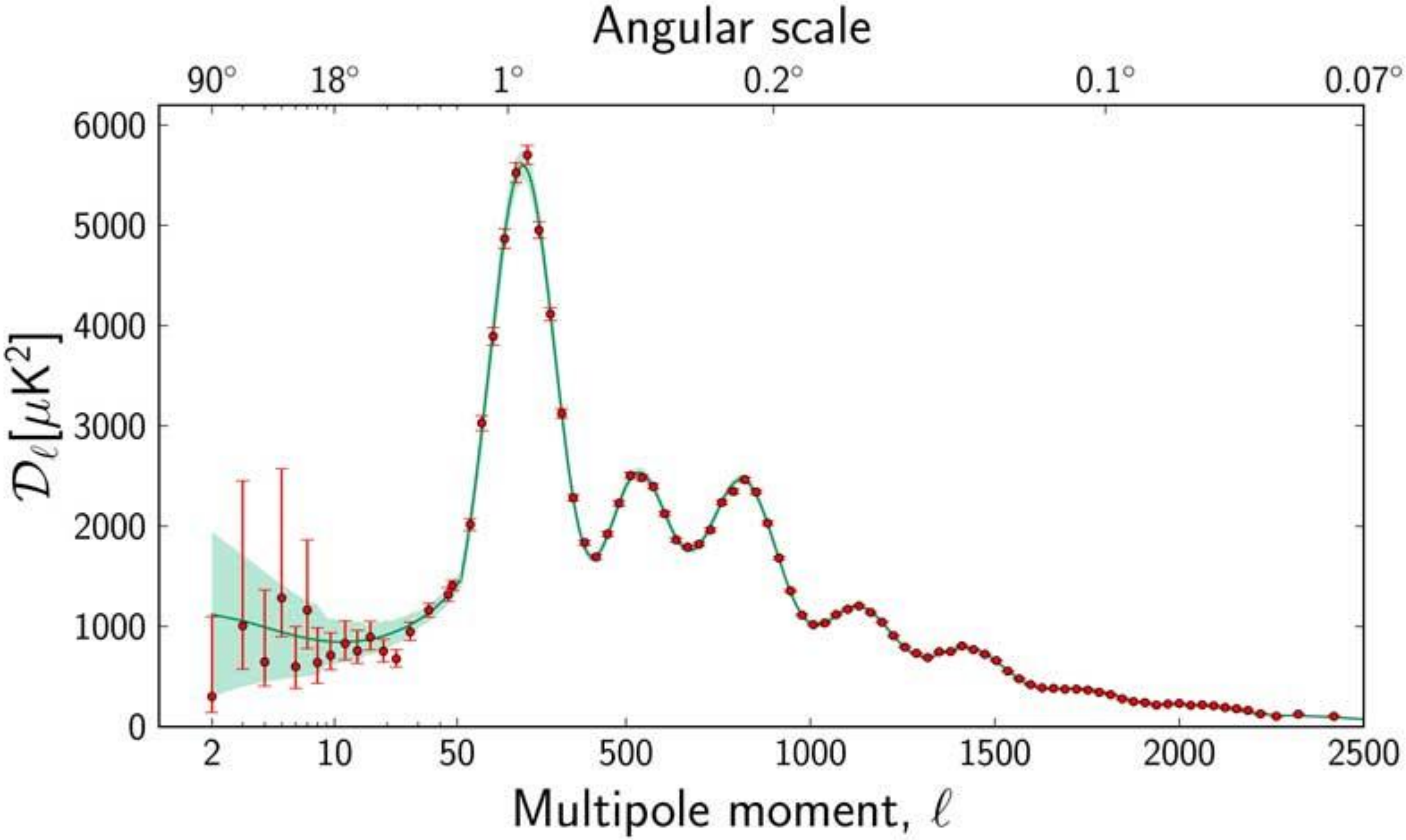




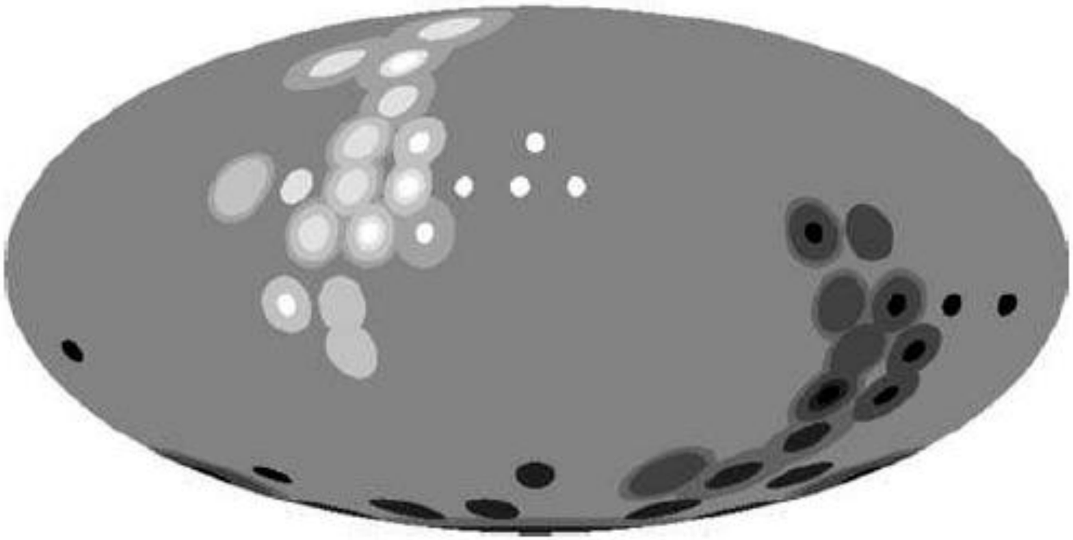


(from Copi et al. 2005)

Parity Violation?

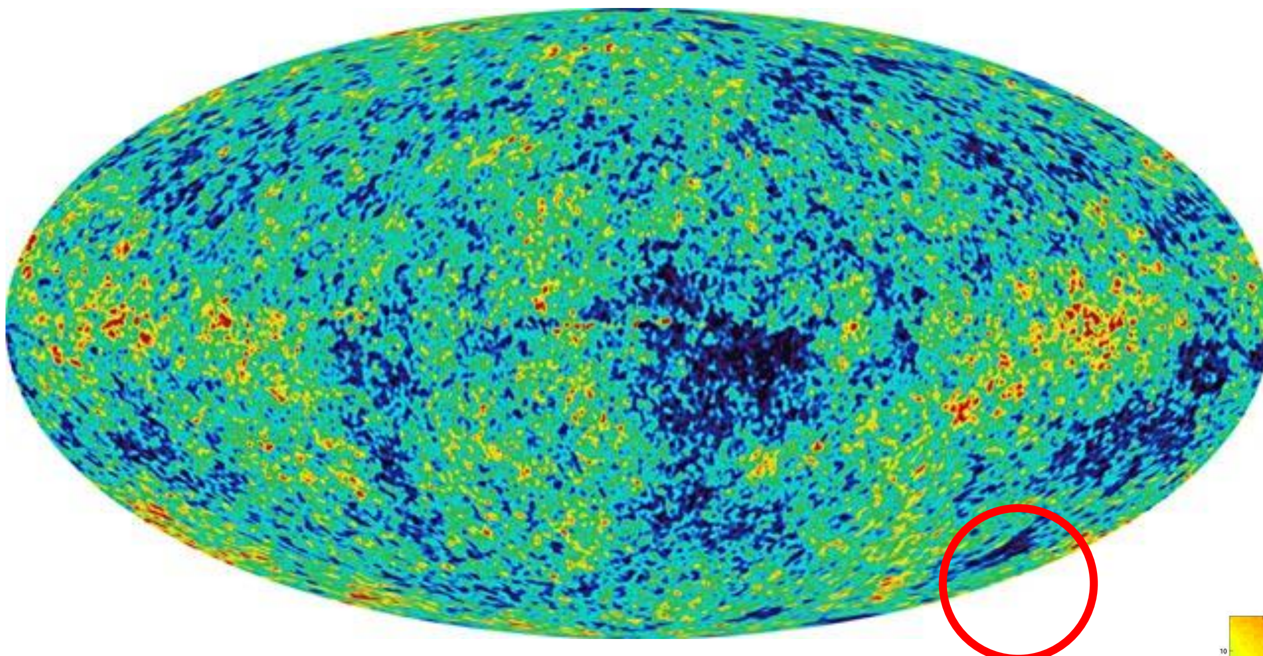


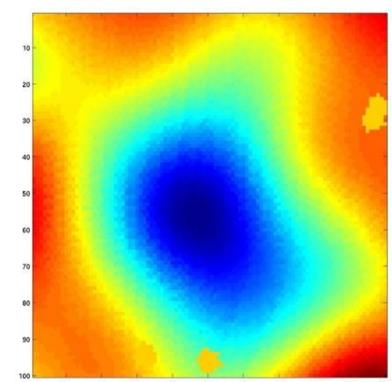
Maximum asymmetry positions



(from Hansen et al. 2004)

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




10 20 30 40 50 60 70 80 90 100
10 20 30 40 50 60 70 80 90 100

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The hottest hotspot on the microwave sky

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

1 Introduction

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

Beware the Prosecutor's Fallacy!

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

A. There’s no problem at all with ΛCDM…

B. There are interesting indications…

C. There’s definitely evidence of new physics

Is ΛCDM the "Maximally Boring Universe"?

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