Glimpsing the Big Bang?

Martin Hendry
University of Glasgow

Gravitational waves: have US scientists heard echoes of the big bang?

Discovery of gravitational waves by Bicep telescope at south pole could give scientists insights into how universe was born

Stuart Clark
The Guardian, Friday 14 March 2014 15.33 GMT

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Primordial gravitational waves would provide evidence of inflation in the moments after the big bang. Photograph: Alamy

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BICEP2 I: DETECTION OF B-mode POLARIZATION AT DEGREE ANGULAR SCALES

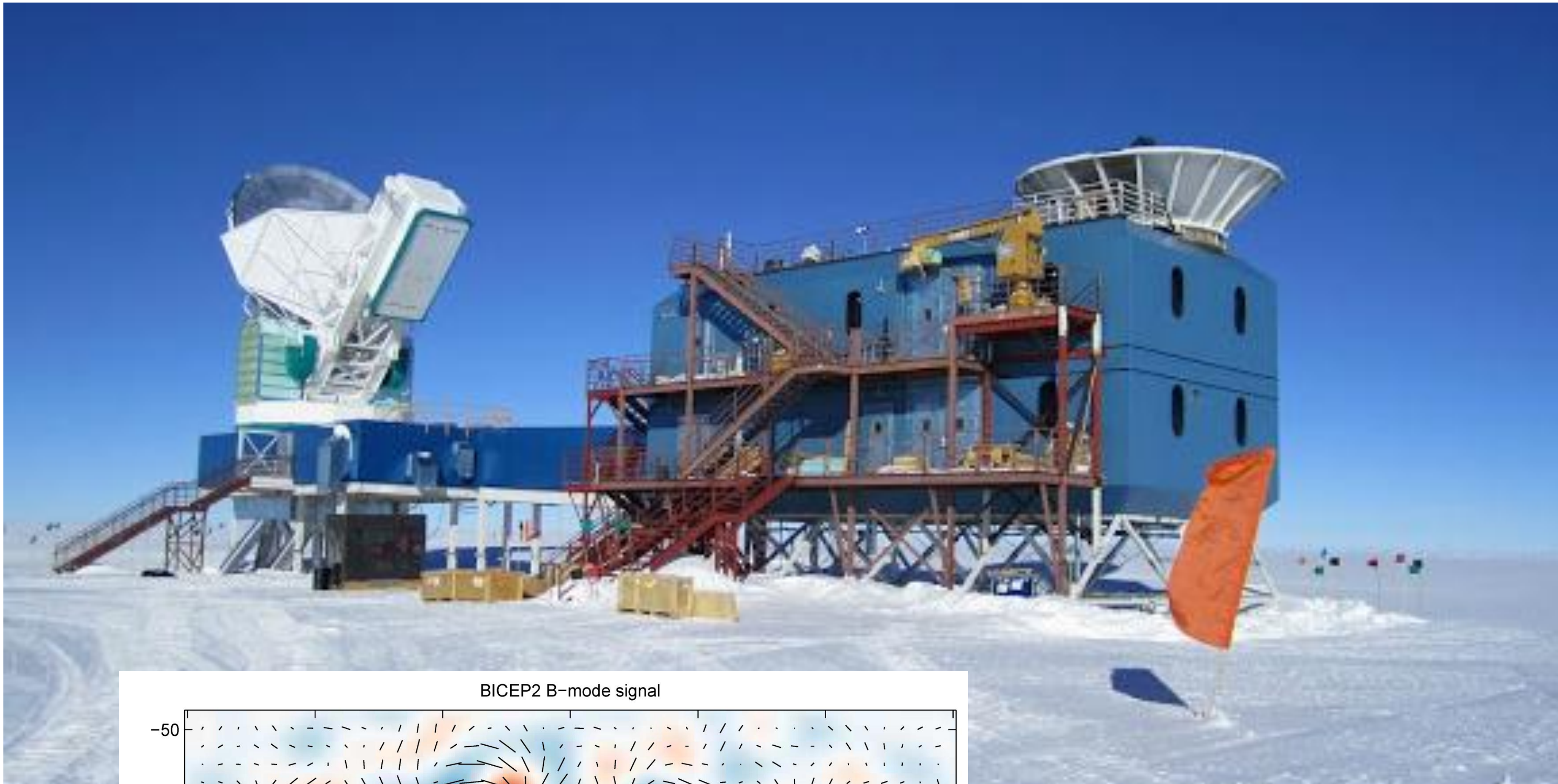
BICEP2 COLLABORATION - P. A. R. ADE[1], R. W. AIKIN[2], D. BARKATS[3], S. J. BENTON[4], C. A. BISCHOFF[5], J. J. BOCK[2,6], J. A. BREVIK[2], I. BUDER[5], E. BULLOCK[7], C. D. DOWELL[6], L. DUBAND[8], J. P. FILIPPINI[2], S. FLIESCHER[9], S. R. GOLWALA[2], M. HALPERN[10], M. HASSELFIELD[10], S. R. HILDEBRANDT[2,6], G. C. HILTON[11], V. V. HRISTOV[2], K. D. IRWIN[12,13,11], K. S. KARKARE[5], J. P. KAUFMAN[14], B. G. KEATING[14], S. A. KERNASOVSKIY[12], J. M. KOVAC[5,16], C. L. KUO[12,13], E. M. LEITCH[15], M. LUEKER[2], P. MASON[2], C. B. NETTERFIELD[4], H. T. NGUYEN[6], R. O'BRIENT[6], R. W. OGBURN IV[12,13], A. ORLANDO[14], C. PRYKE[9,7,16], C. D. REINTSEMA[11], S. RICHTER[5], R. SCHWARZ[9], C. D. SHEEHY[9,15], Z. K. STANISZEWSKI[2,6], R. V. SUDIWALA[1], G. P. TEPLY[2], J. E. TOLAN[12], A. D. TURNER[6], A. G. VIEREGG[5,15], C. L. WONG[5], AND K. W. YOON[12,13]

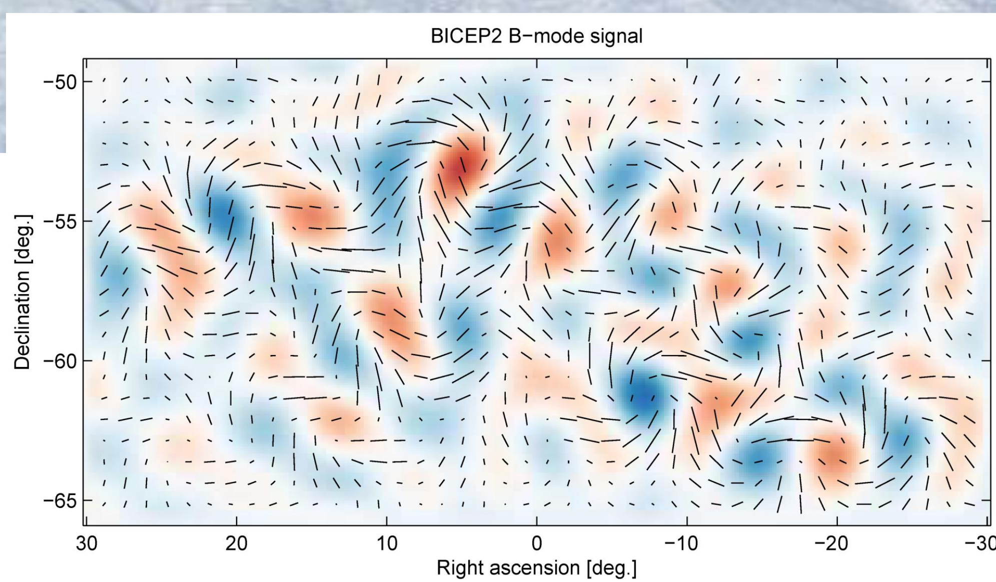
to be submitted to a journal TBD

ABSTRACT

We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the B-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300\ \mu\mathrm{K_{CMB}}\sqrt{\mathrm{s}}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of B-mode power over the base lensed-ΛCDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. We also estimate potential foreground signals and find that available models predict these to be considerably smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring synchrotron or dust at 2.3σ and 2.2σ, respectively. The observed B-mode power spectrum is well-fit by a lensed-ΛCDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.

Subject headings: cosmic background radiation — cosmology: observations — gravitational waves — inflation — polarization



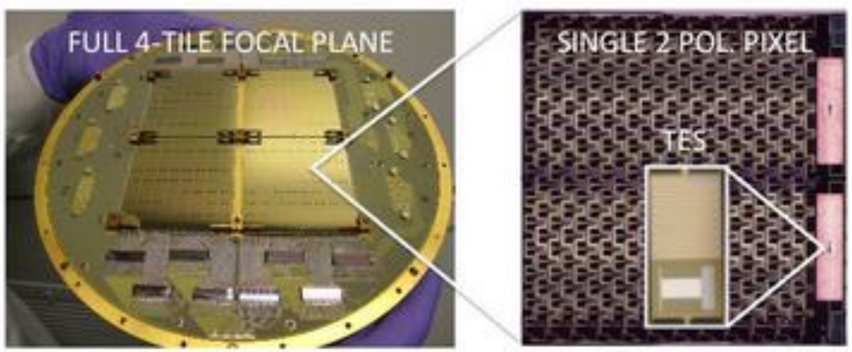


BICEP2 B−mode signal
Declination [deg.]
−50
−55
−60
−65
30
20
10
0
−10
−20
−30
Right ascension [deg.]

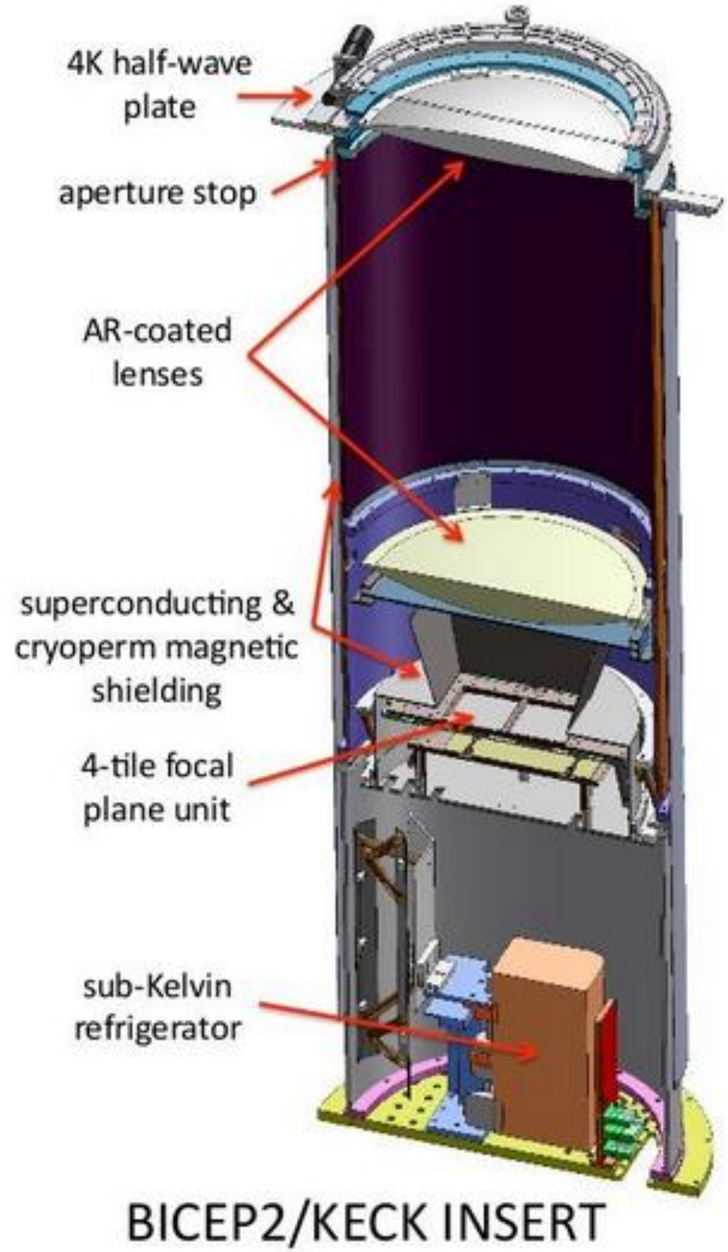
Instrumentation

BICEP2 observes on degree angular scales deep into the same patch of sky as BICEP1, employing cutting-edge technology to pack many more detectors onto the same size focal plane as BICEP1, thus dramatically increasing sensitivity. BICEP2 aims to measure the polarization of the cosmic microwave background (CMB) with better sensitivity than ever before.

The BICEP2 telescope is a small aperture, refracting telescope, allowing for precise control of systematic effects. The telescope optics are cooled to 4K. BICEP2 relies on the same principles as BICEP1, but with new detectors which allow for closer packing onto the focal plane. BICEP2 has 512 antenna-coupled TES bolometers in the focal plane. The focal plane is kept at 250 mK for CMB observations. Gaining detector sensitivity is critical in the search for "B-mode" polarization, and BICEP2 has an order of magnitude greater mapping speed than BICEP1.



The 512-detector BICEP2 focal plane and a zoom in of a dual polarization pixel with TES bolometer shown.



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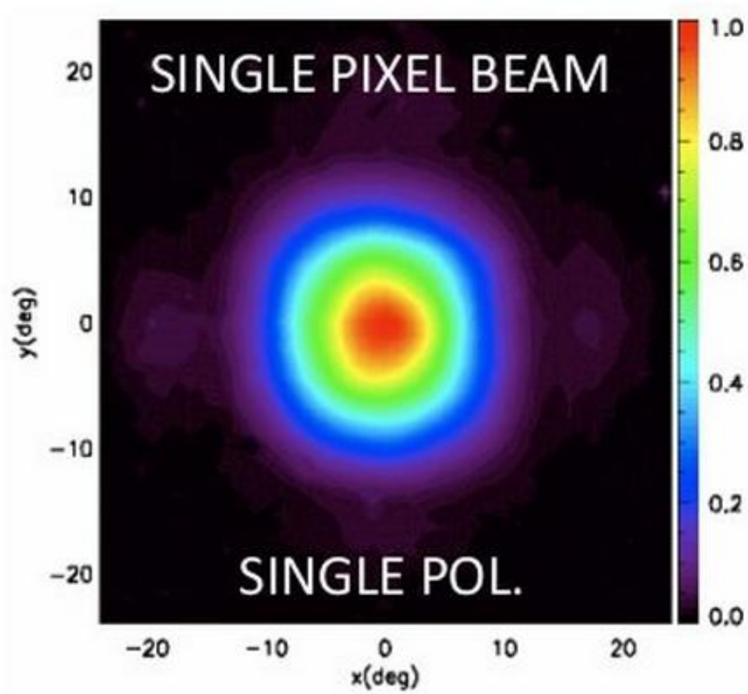

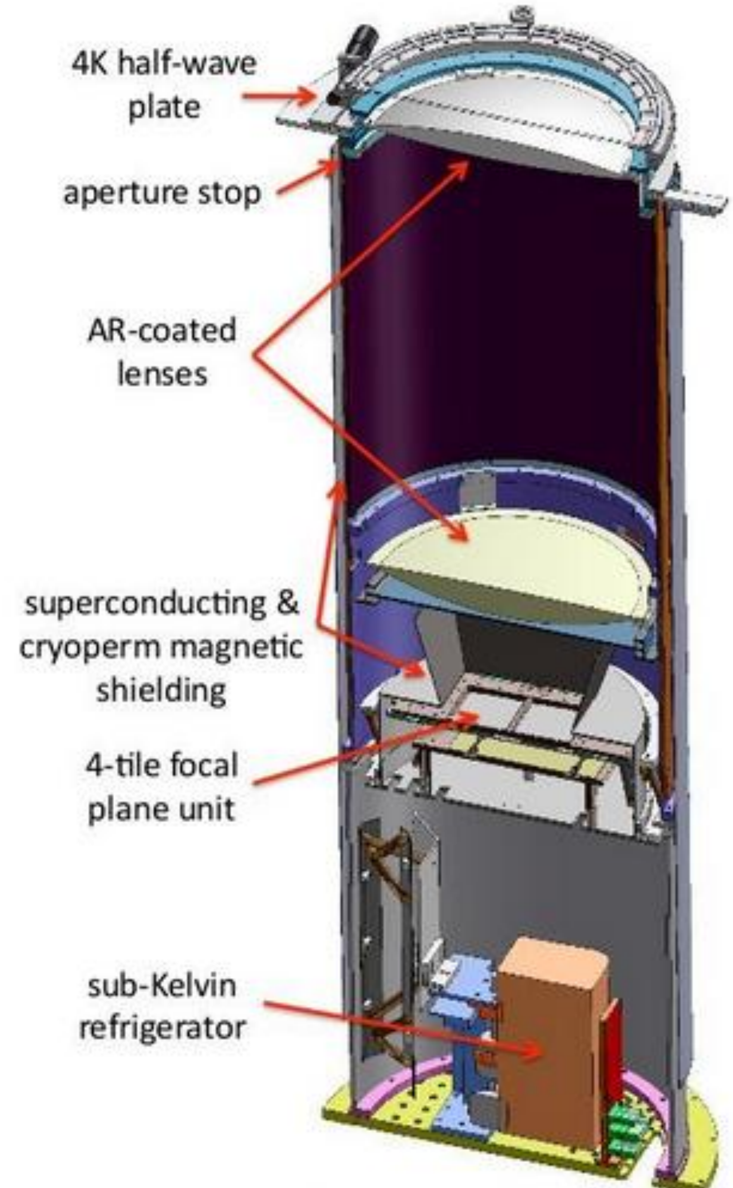

BICEP2/KECK INSERT

Primordial gravitational wave discovery heralds 'whole new era' in physics

Gravitational waves could help unite general relativity and quantum mechanics to reveal a 'theory of everything'

Stuart Clark
The Guardian, Monday 17 March 2014 18.08 GMT

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Scientists detected telltale signs of gravitational waves using the Bicep2 telescope (far left) at the south pole. Photograph: Keith Vanderlinde/NSF

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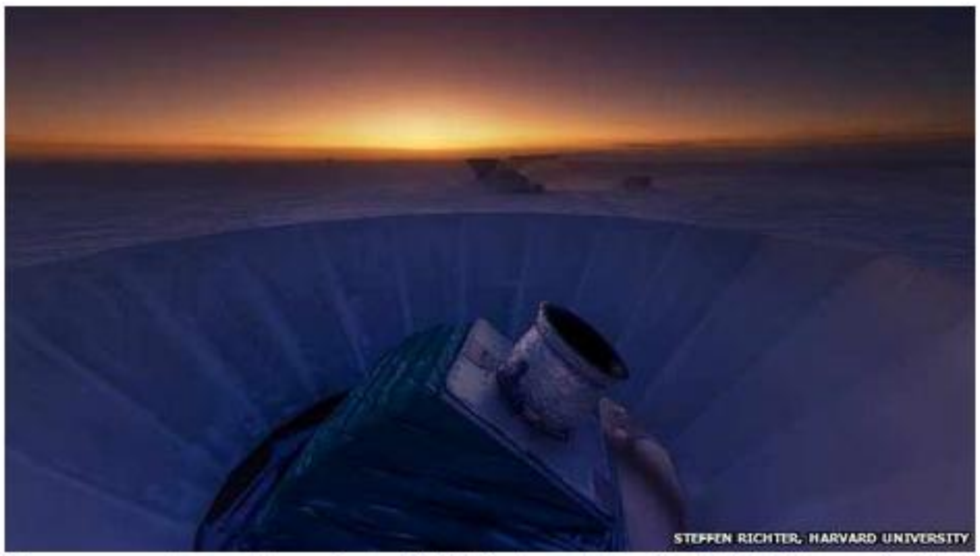
By Jonathan Amos
Science correspondent, BBC News



The measurements were taken using the BICEP2 instrument at the South Pole Telescope facility

Scientists say they have extraordinary new evidence to support a Big Bang Theory for the origin of the Universe.

Researchers believe they have found the signal left in the sky by the super-rapid expansion of space that must have occurred just fractions of a second after everything came into being.

It takes the form of a distinctive twist in the oldest light detectable with telescopes.

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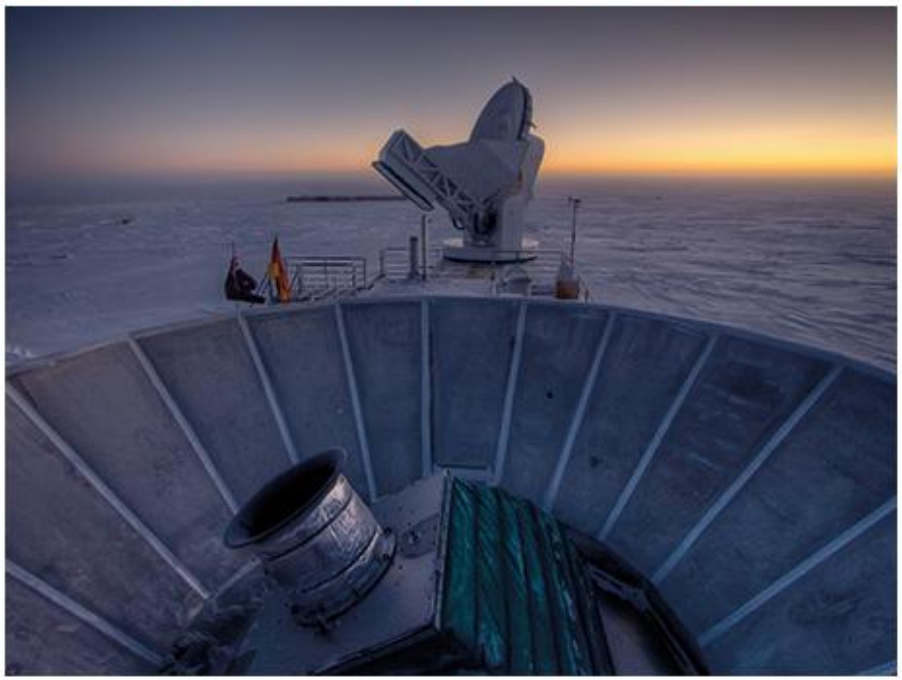

The first direct signs of a cosmic growth spurt that set space-time rippling means that we may live in just one of an infinite number of universes

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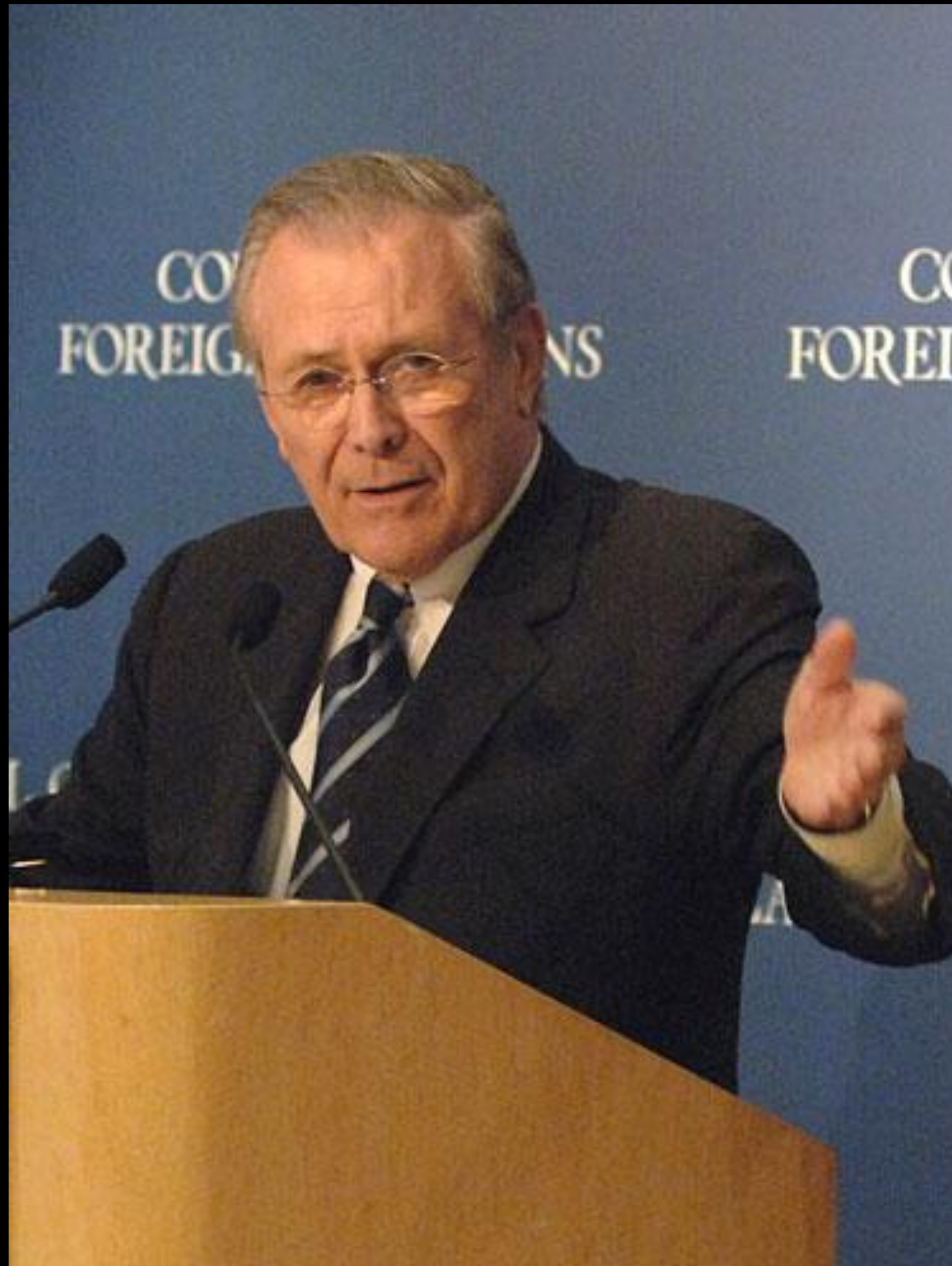
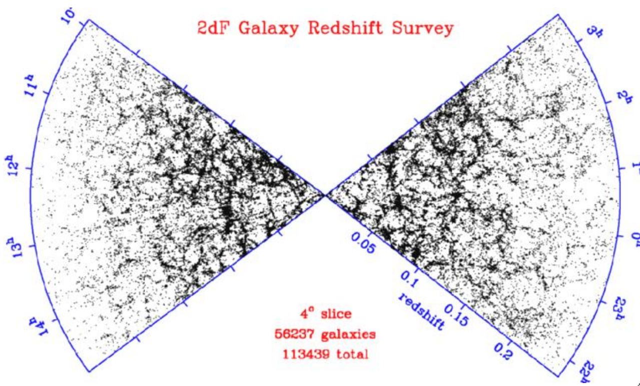


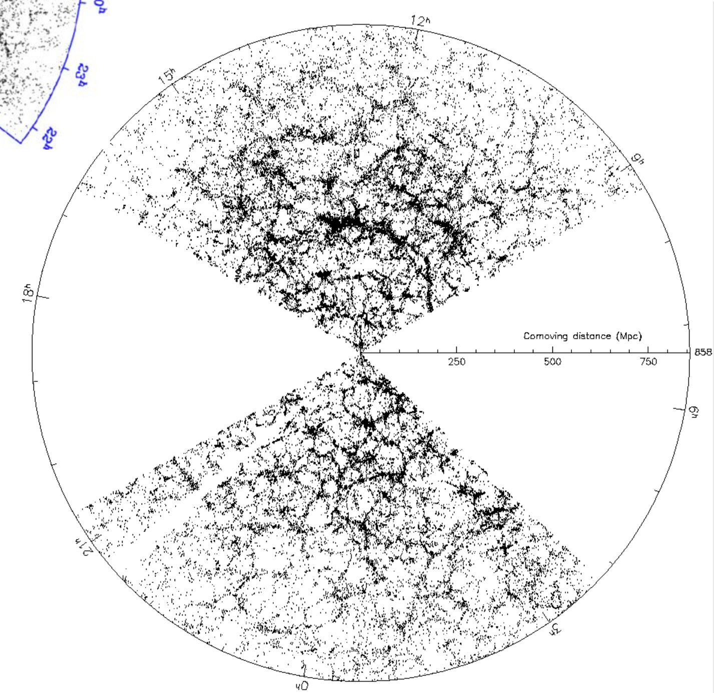
Modelling the Universe

Cosmological principle: universe is **homogeneous** and **isotropic** on large scales (> 100 - 300 Mpc).

Good evidence for this from:

- galaxy surveys
- isotropy of the CMBR





Modelling the Universe

Background cosmological model described by the Robertson-Walker metric

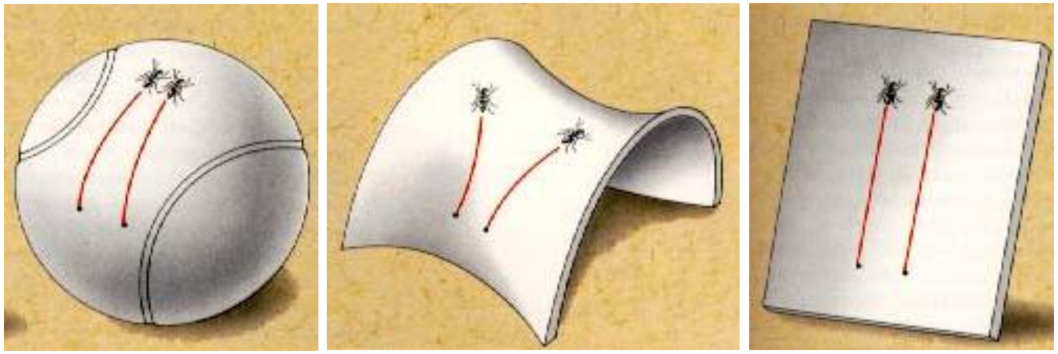
$$\boxed{ds^2 = -dt^2 + R(t)^2\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]}$$

$R(t) = \text{cosmic scale factor}$

$$k = \text{curvature constant} = \begin{cases} -1, & \text{open} \\ 0, & \text{flat} \\ +1, & \text{closed} \end{cases}$$

$$\frac{R(t)}{R_0} = \frac{1}{1+z}$$

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} = \text{redshift}$$



Closed **Open** **Flat**

Friedmann's Equations:

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{k}{R^2}$$

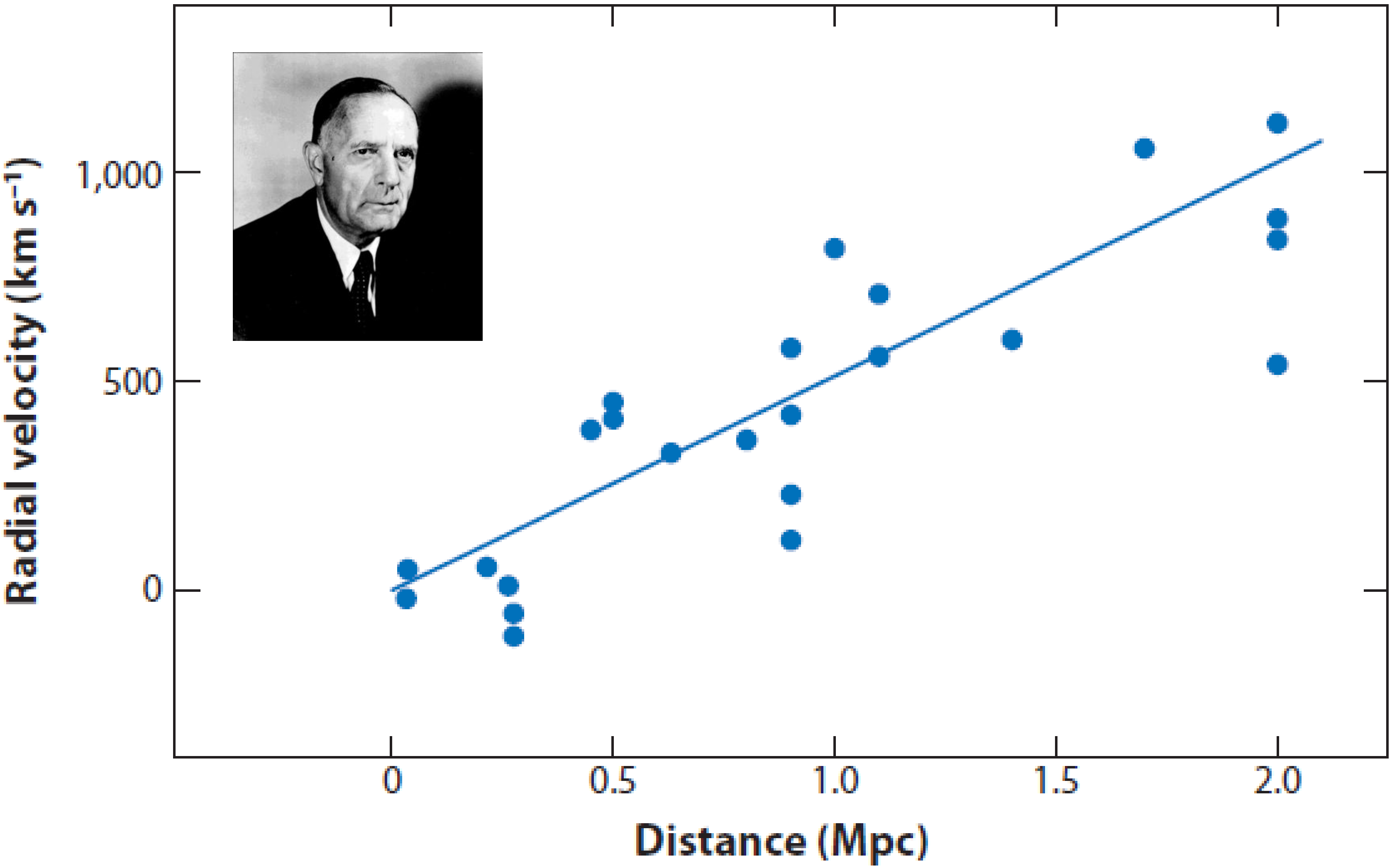
$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

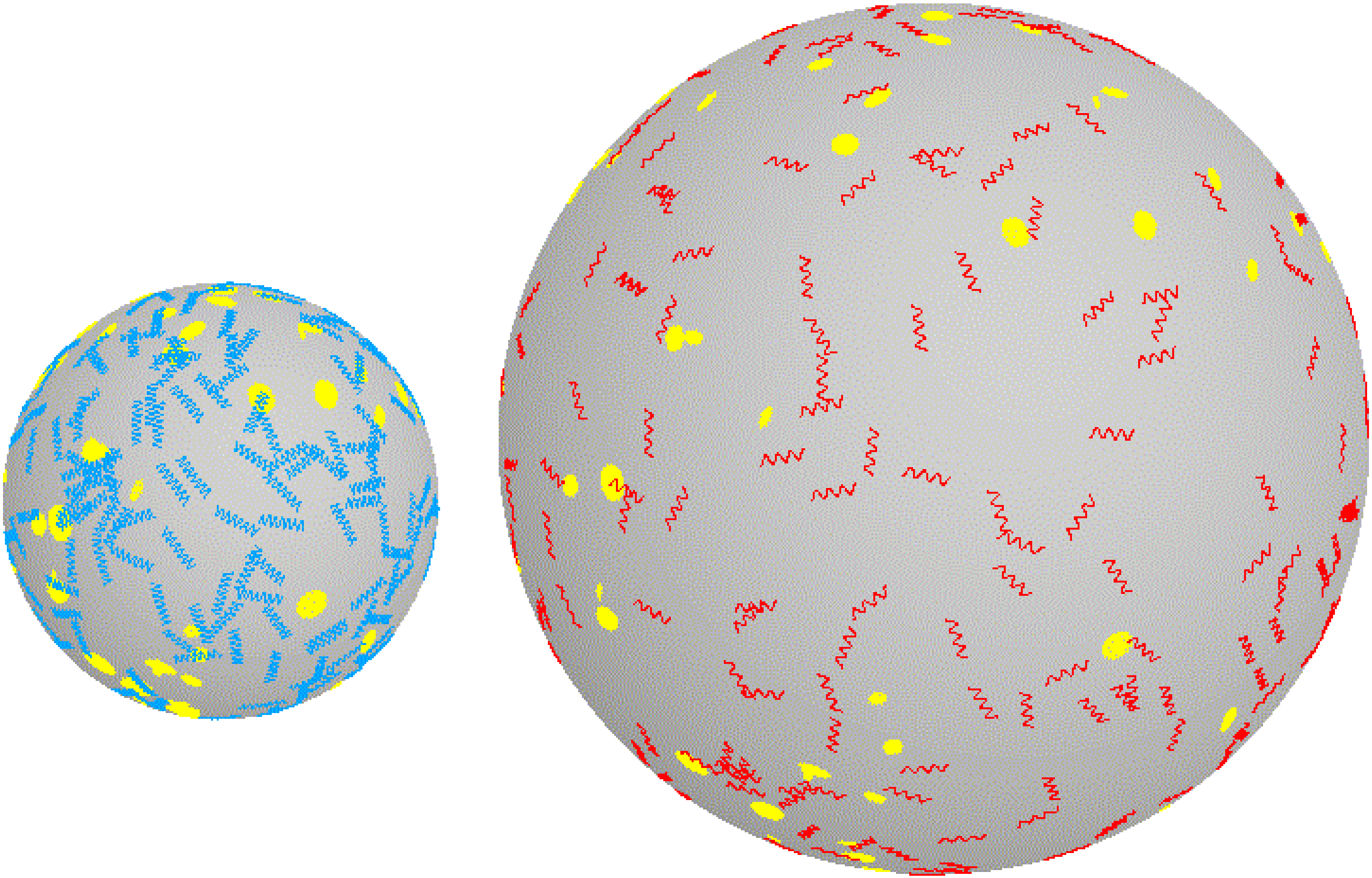
Can tune Λ to give $\dot{R} = 0$ for all t but *unstable*

(and *Hubble expansion* made idea redundant)

But Lambda term could still be non-zero anyway !

Adapted from Hubble (1929)





Evolution of scale factor given by Friedmann's equation

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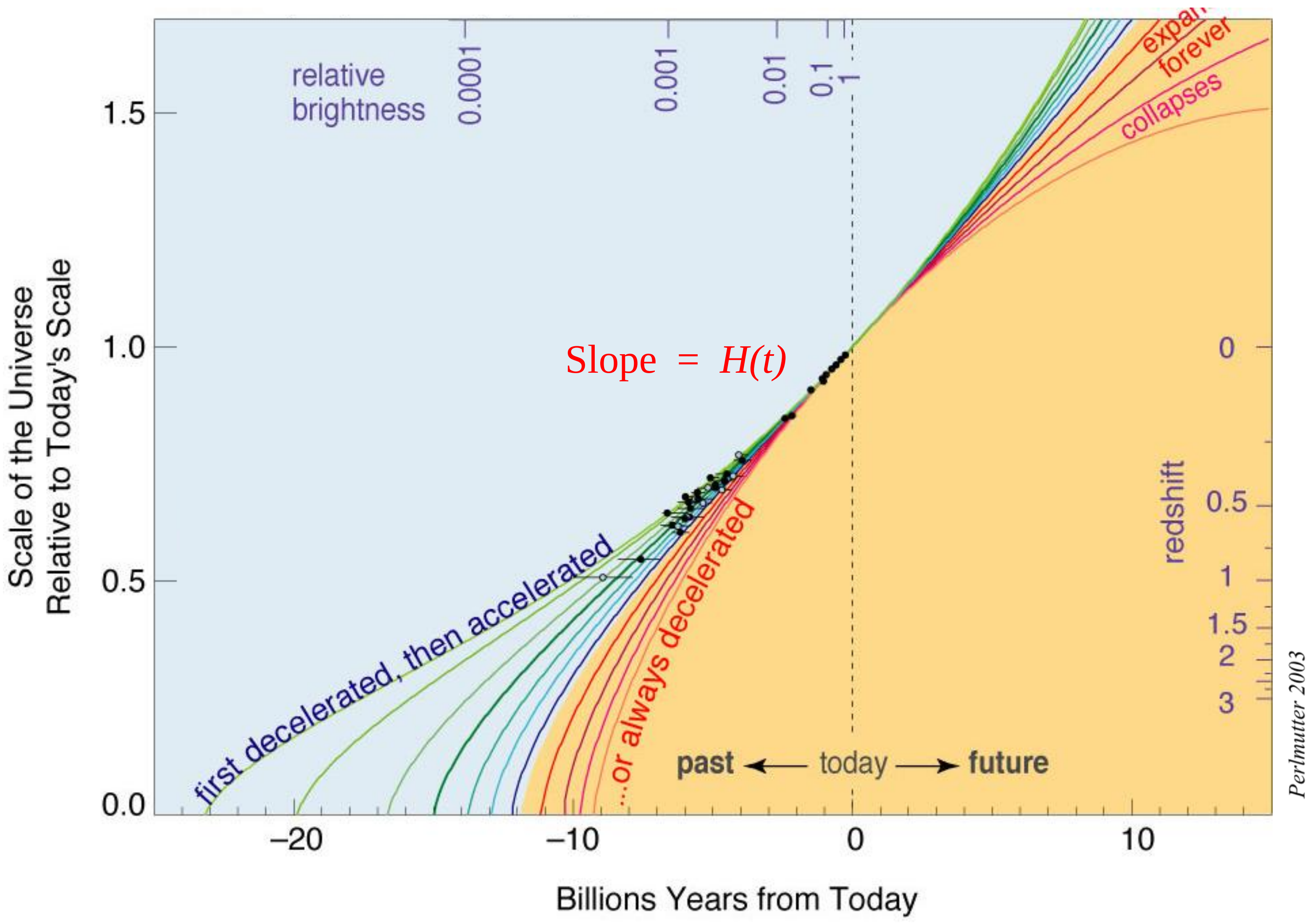

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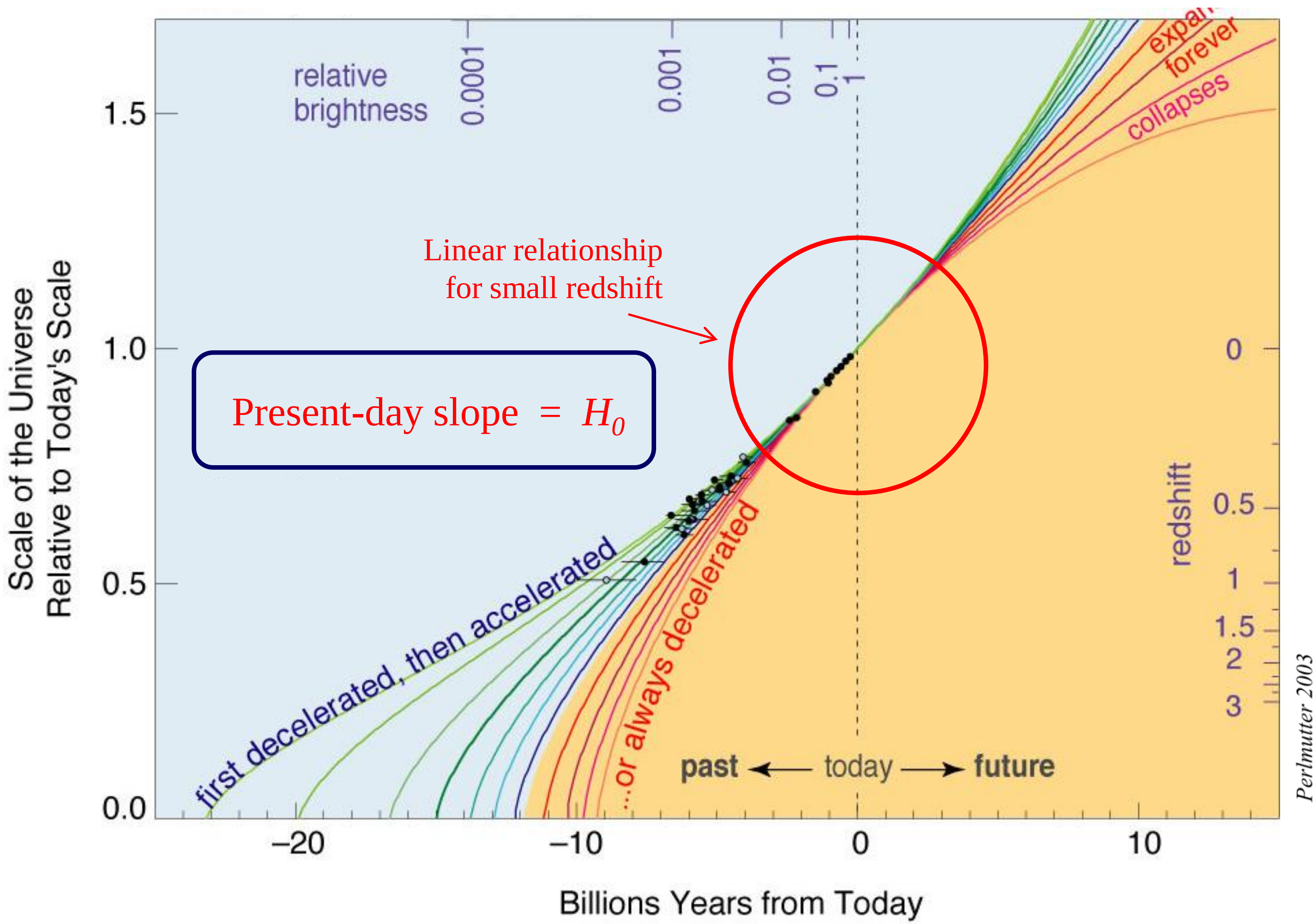


Re-expressing Friedmann's Equations

For $\Lambda = 0$

$$H^2 = \frac{8\pi G\rho}{3} - \frac{k}{R^2} \quad \Rightarrow \quad k = 0 \Leftrightarrow \rho = \left[\frac{8\pi G}{3H^2}\right]^{-1} = \rho_{\mathrm{crit}}$$

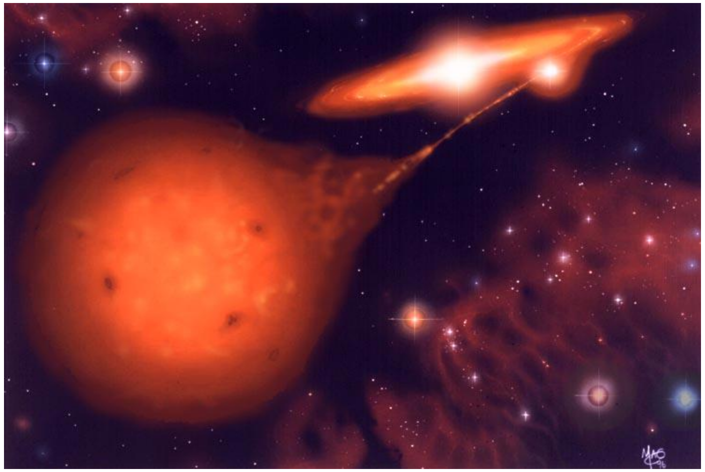
Define

$$\Omega_m = \rho \big/ \rho_{crit} = \frac{8\pi G\rho}{3H^2} \qquad \Omega_\Lambda = \frac{\Lambda}{3H^2} \qquad \Omega_k = -\frac{k}{R^2 H^2}$$

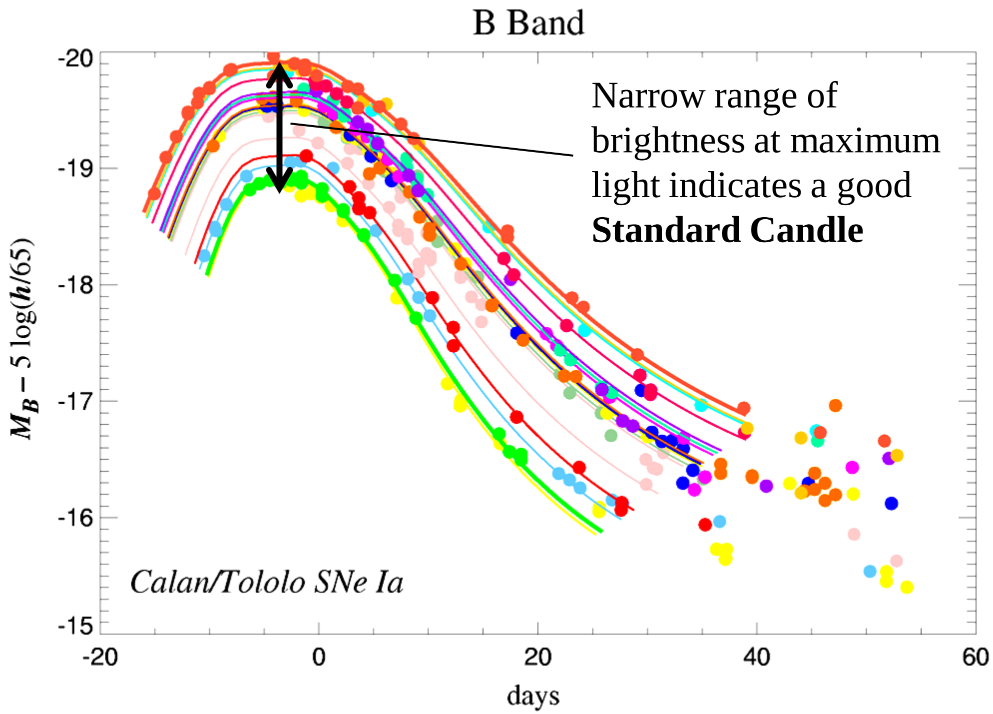
It follows that, at *any time*

$$\boxed{\Omega_m + \Omega_\Lambda + \Omega_k = 1}$$

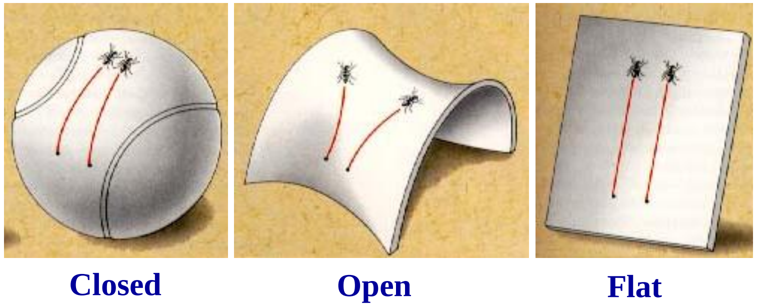
Is the Universe speeding up or slowing down?



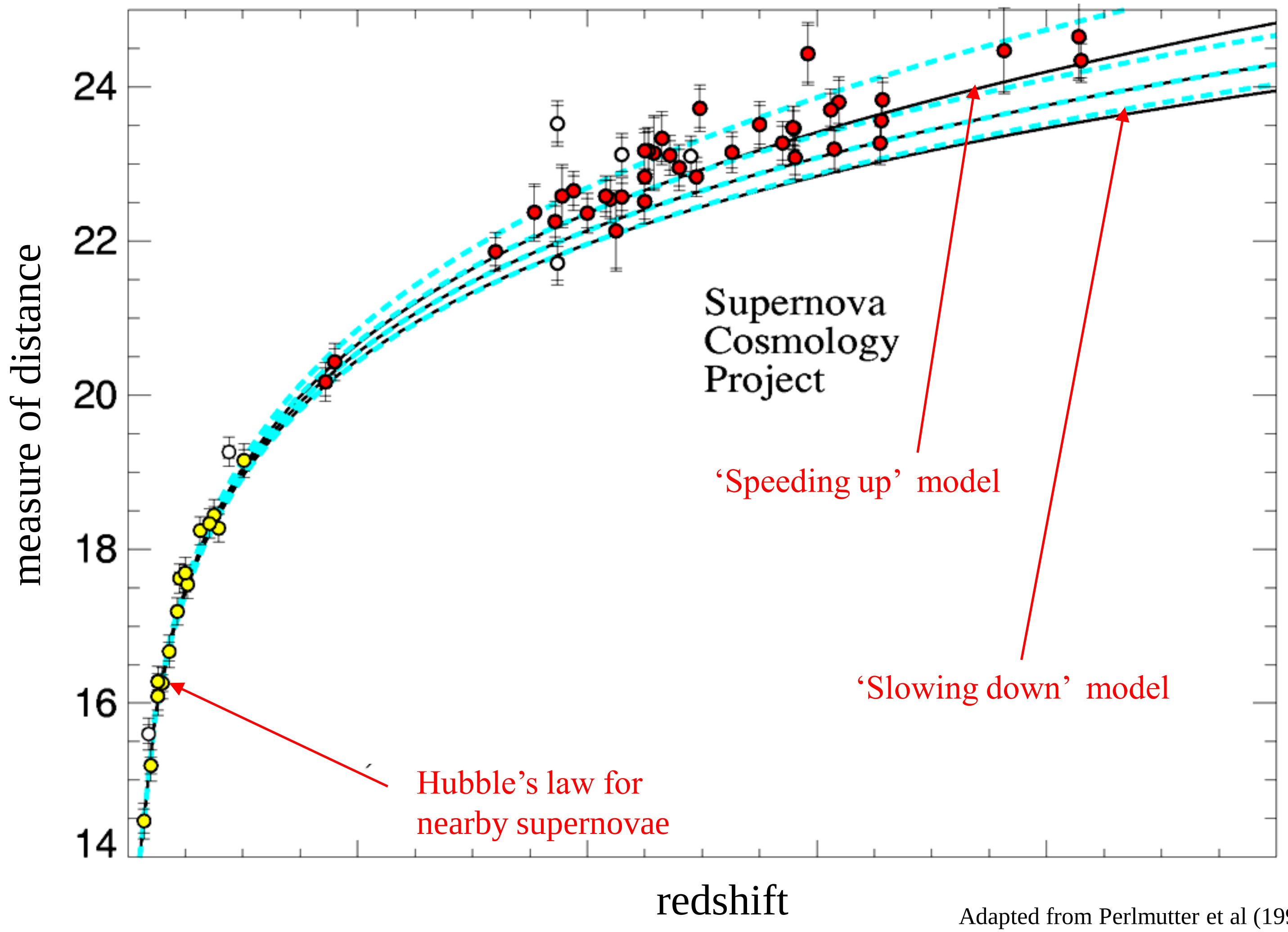
We can answer this question using **type Ia supernovae**



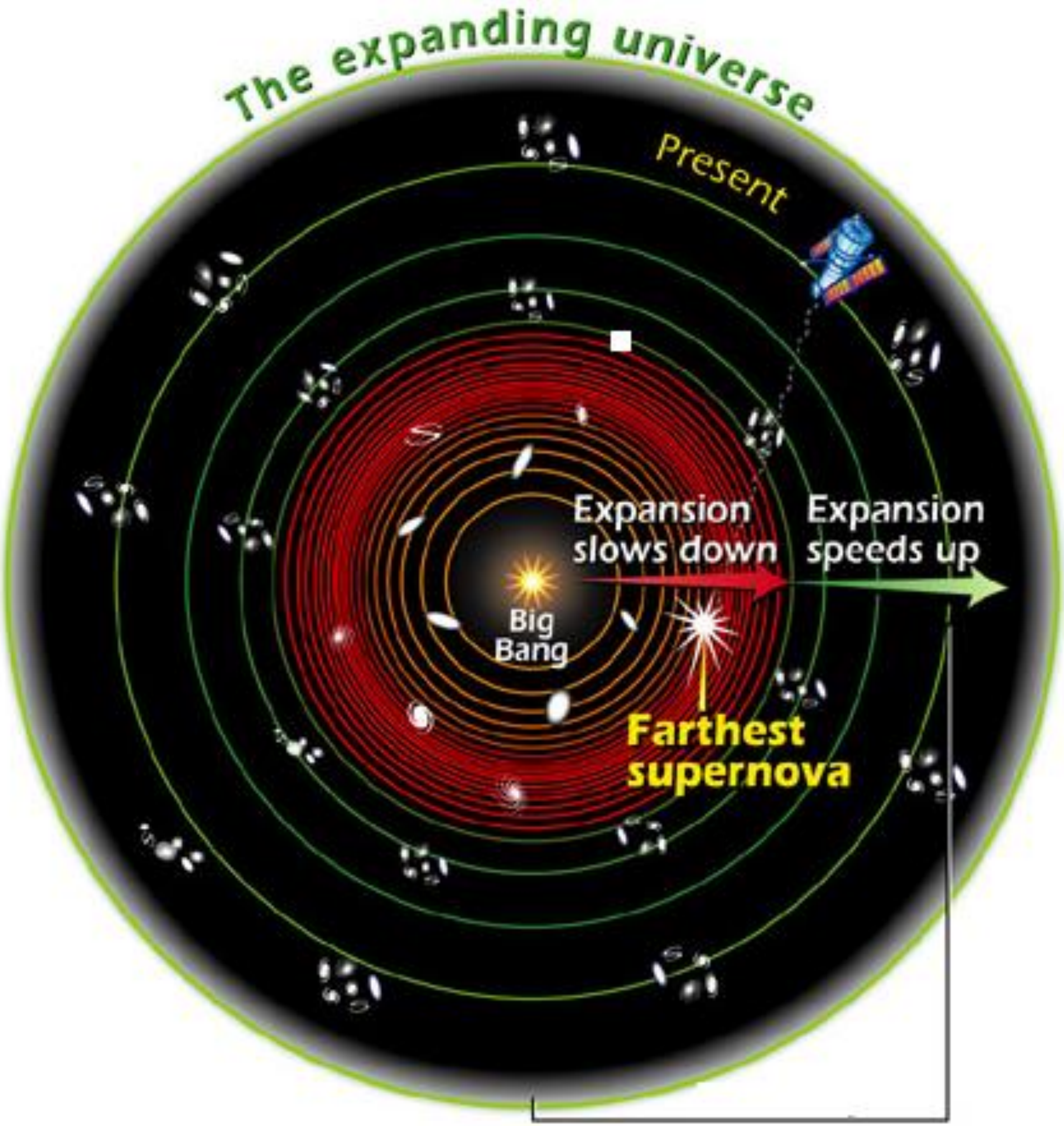
Geometry of the universe affects the relationship between redshift and luminosity distance of distant supernovae

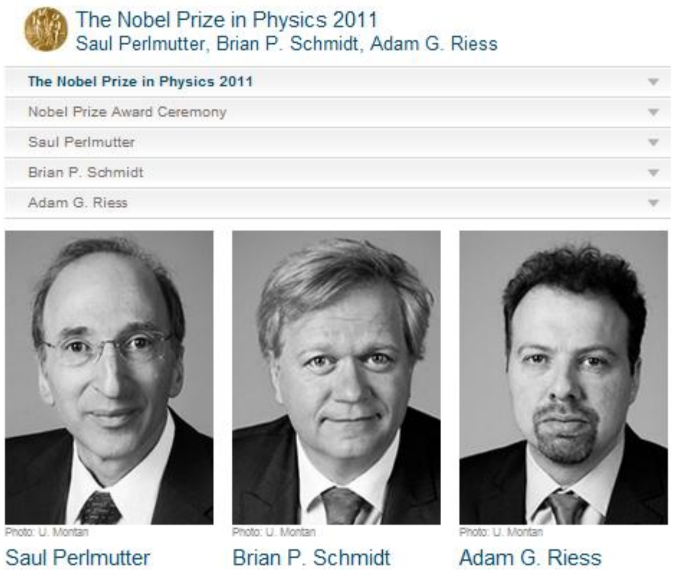


Hubble diagram of distant supernovae



Adapted from Perlmutter et al (1998)





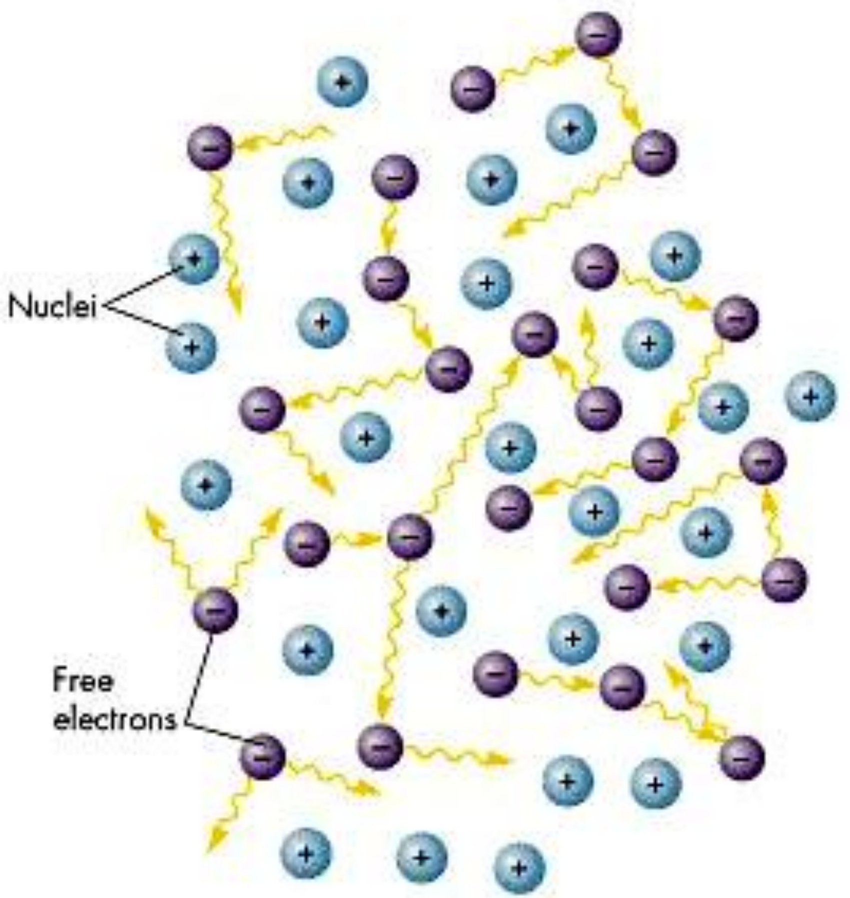
Dark Energy

Dark Energy

Image from wikipedia

Early Universe too hot for neutral atoms to exist

Free electrons scatter light (as in a fog)



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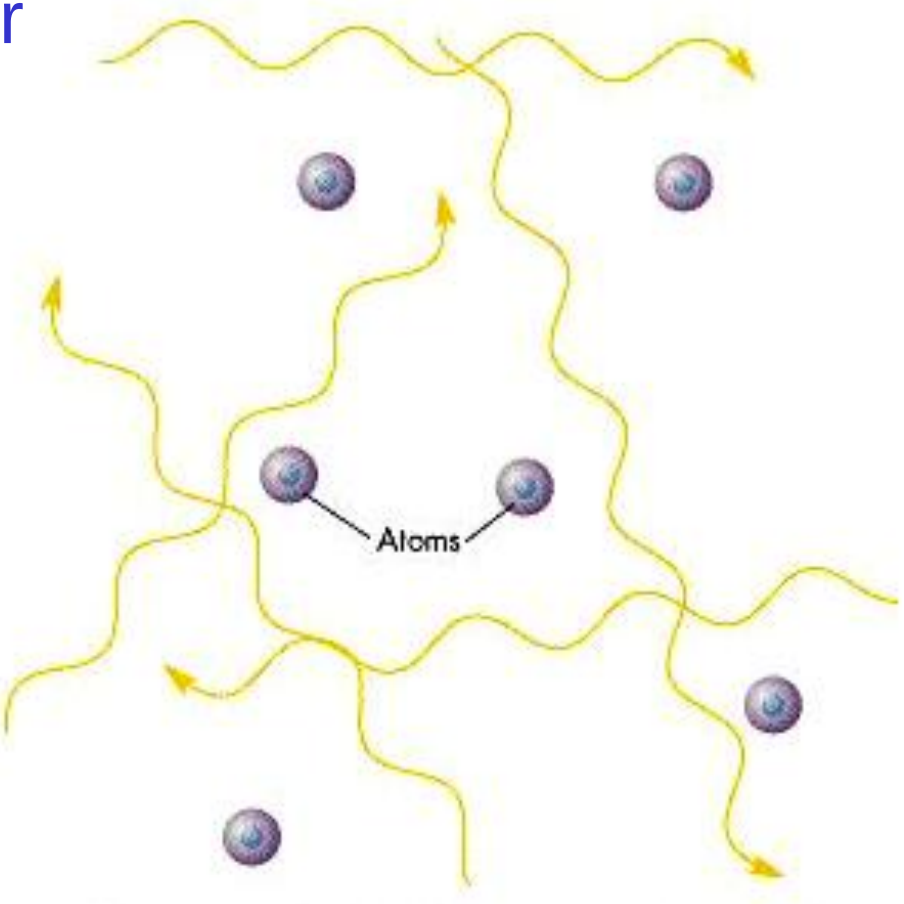
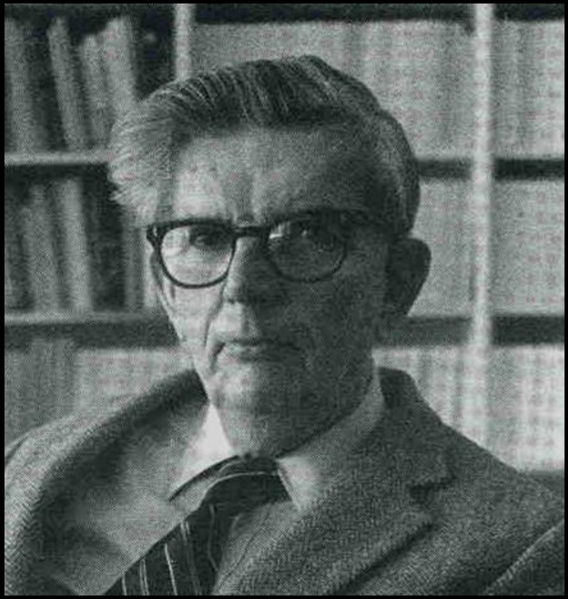


After ~380,000 years, Universe cool enough for neutral hydrogen to form: the fog clears!

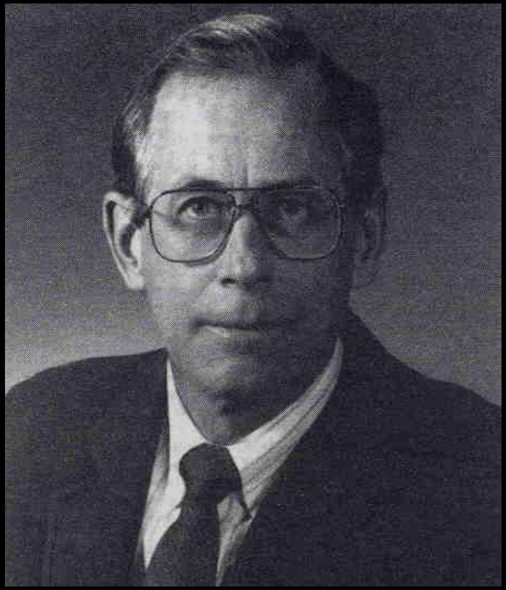
Background radiation predicted in 1950s and 1960s by Gamov, Dicke, Peebles.

Discovered in 1965 by Penzias and Wilson

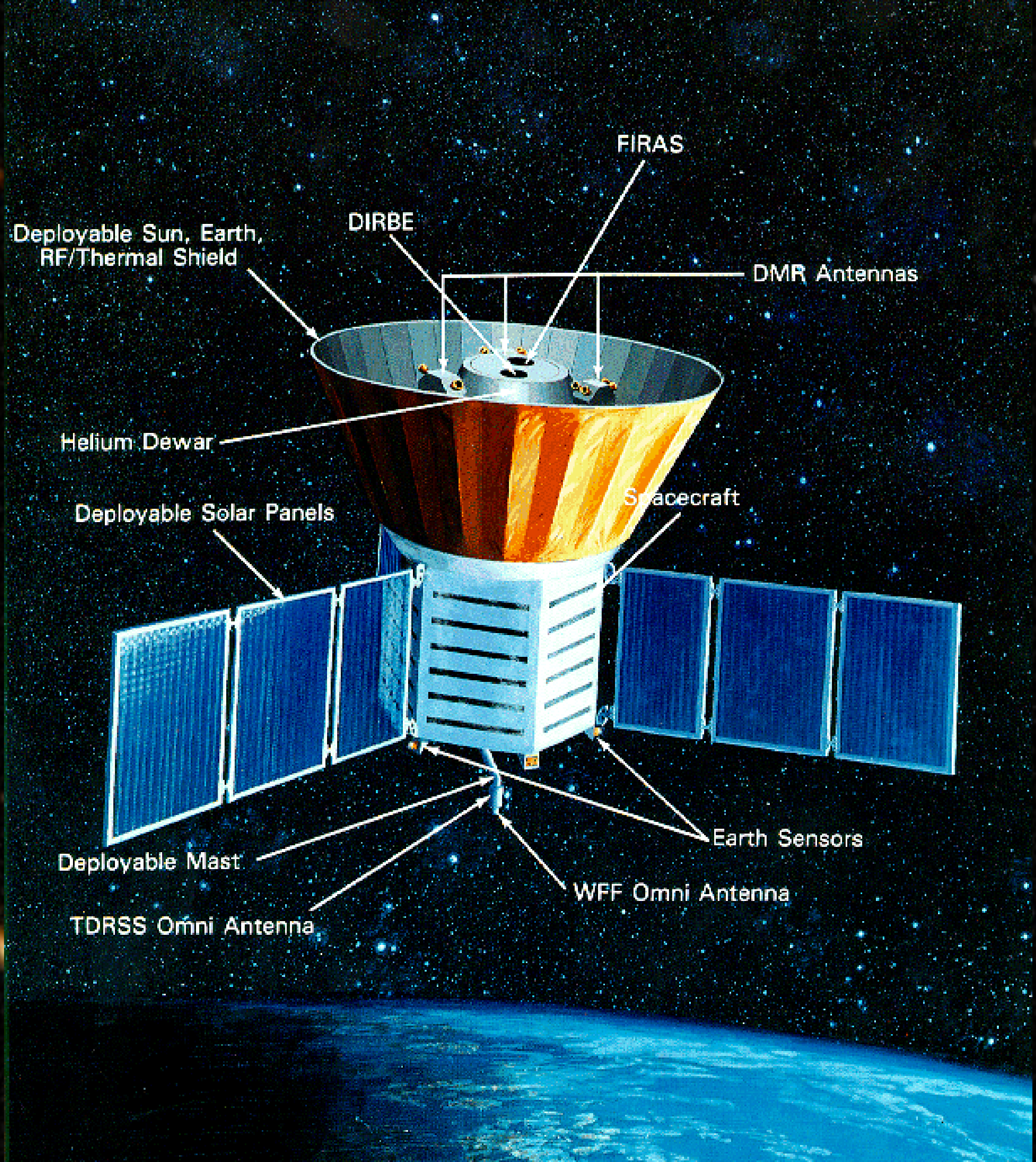


Robert Dicke

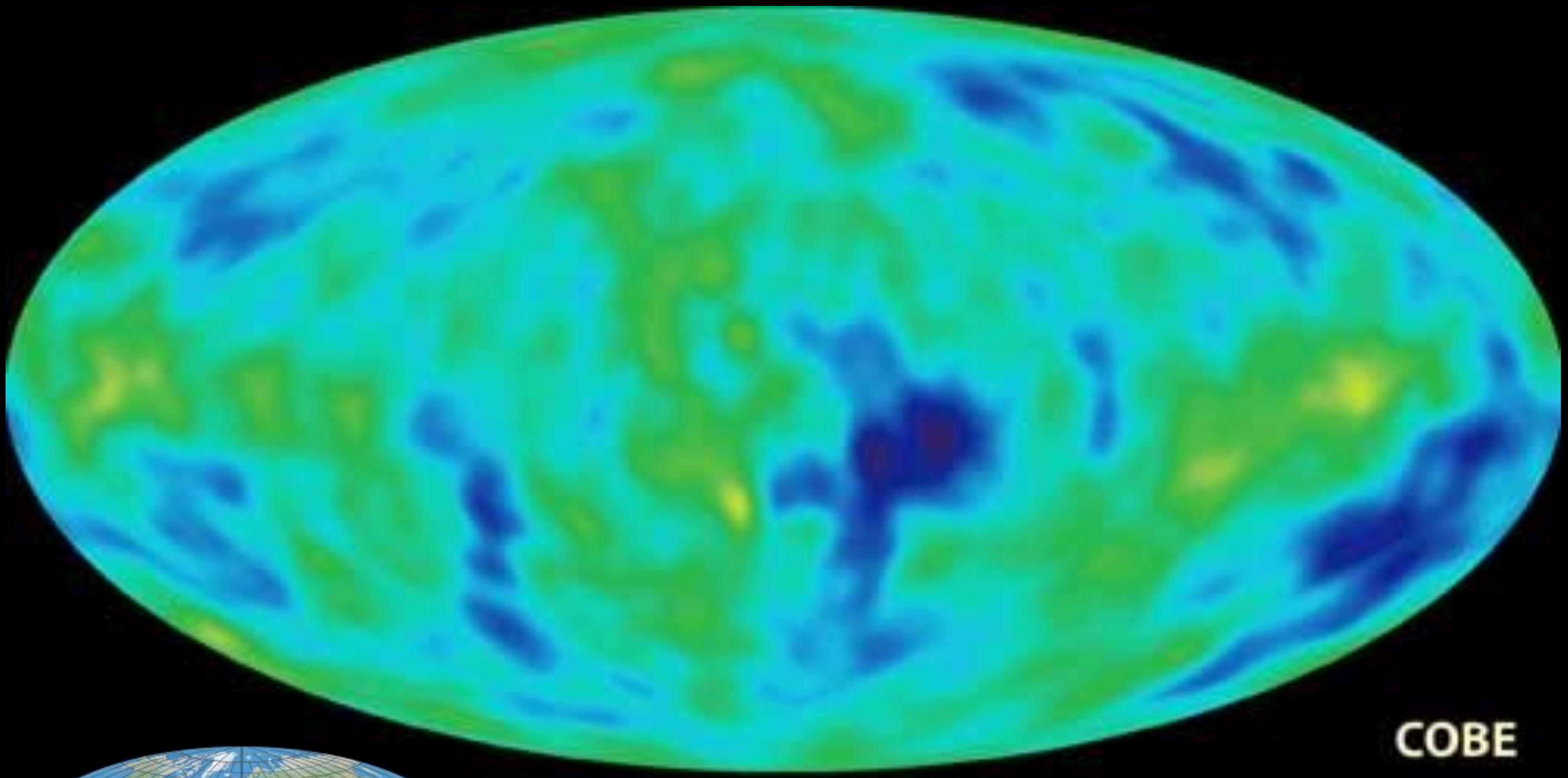
Arno Penzias and Robert Wilson



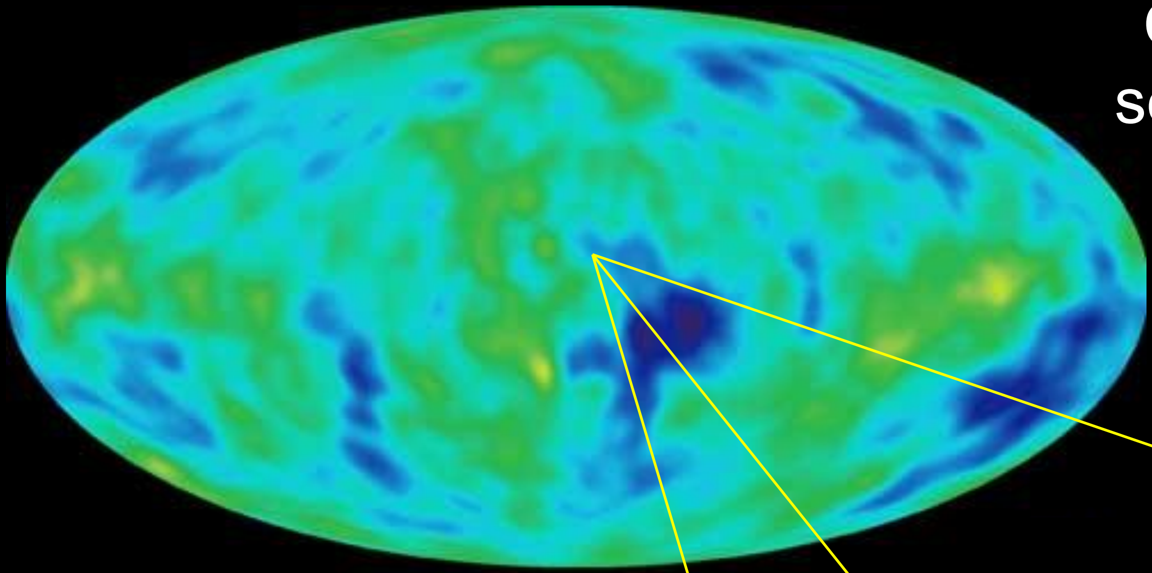
Jim Peebles

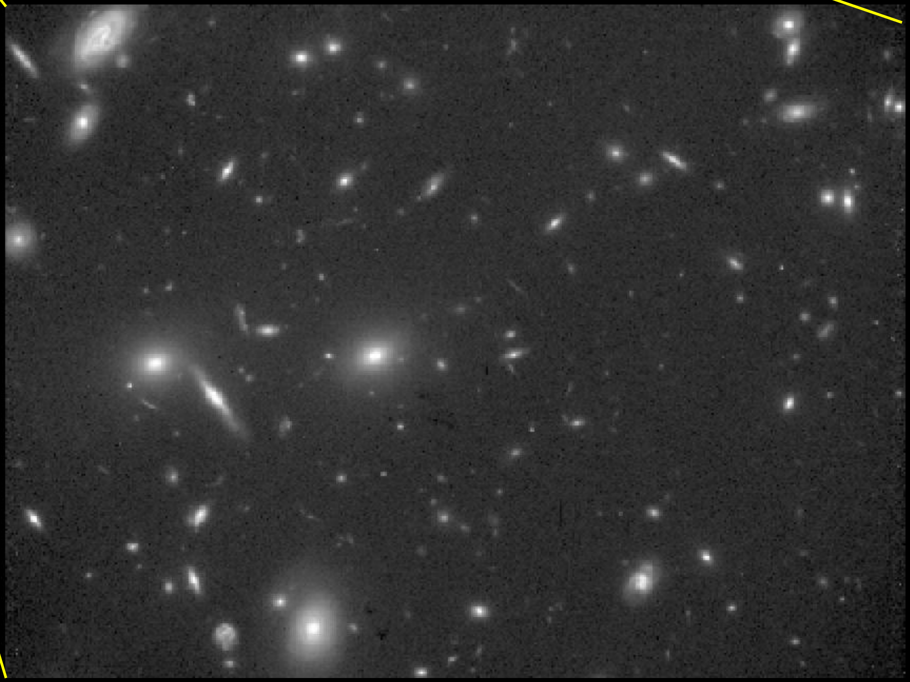

FIRAS
DIRBE
Deployable Sun, Earth, RF/Thermal Shield
DMR Antennas
Helium Dewar
Spacecraft
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna

COBE map of temperature across the sky

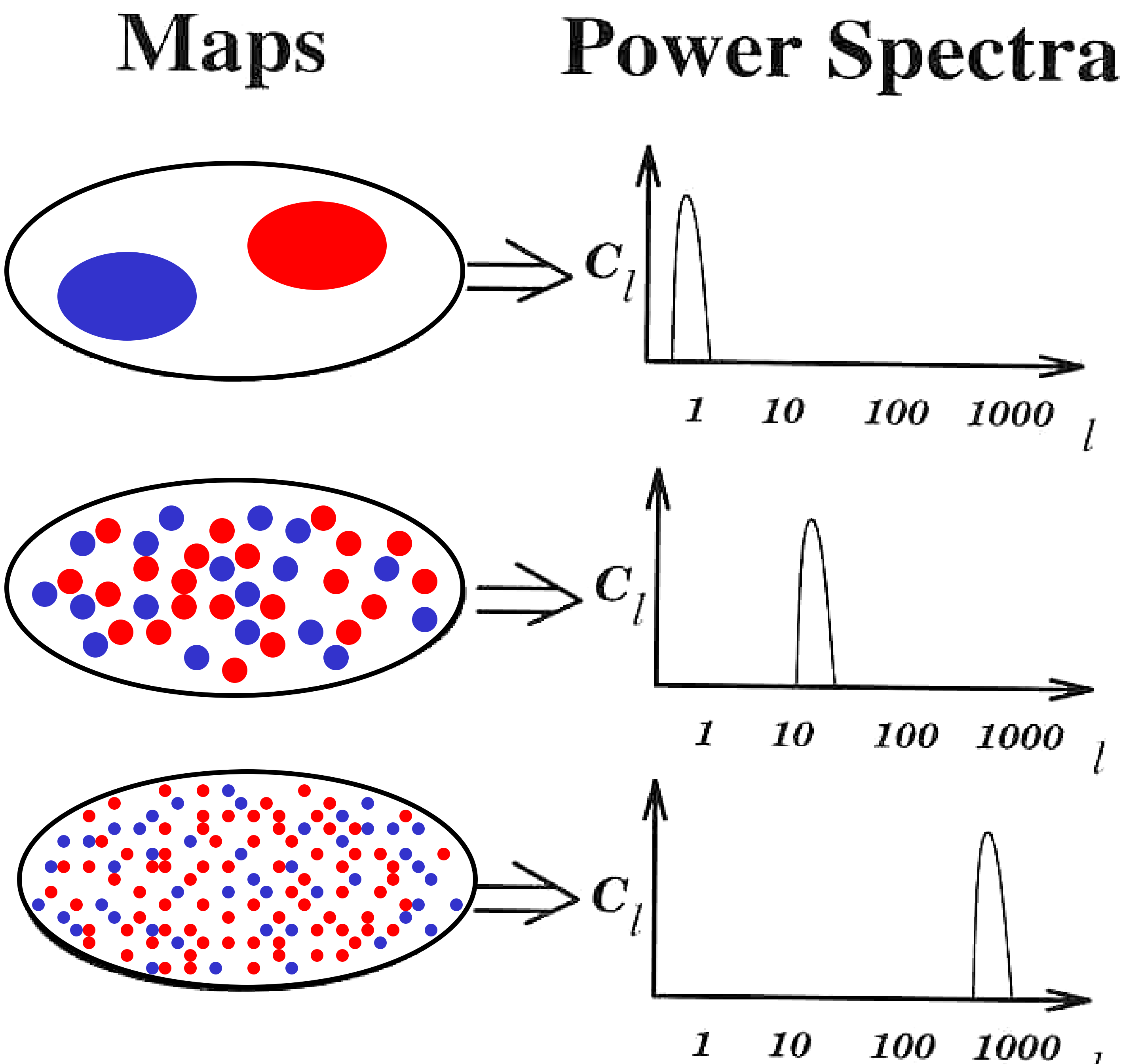


CMBR ‘ripples’ are the seeds of today’s galaxies

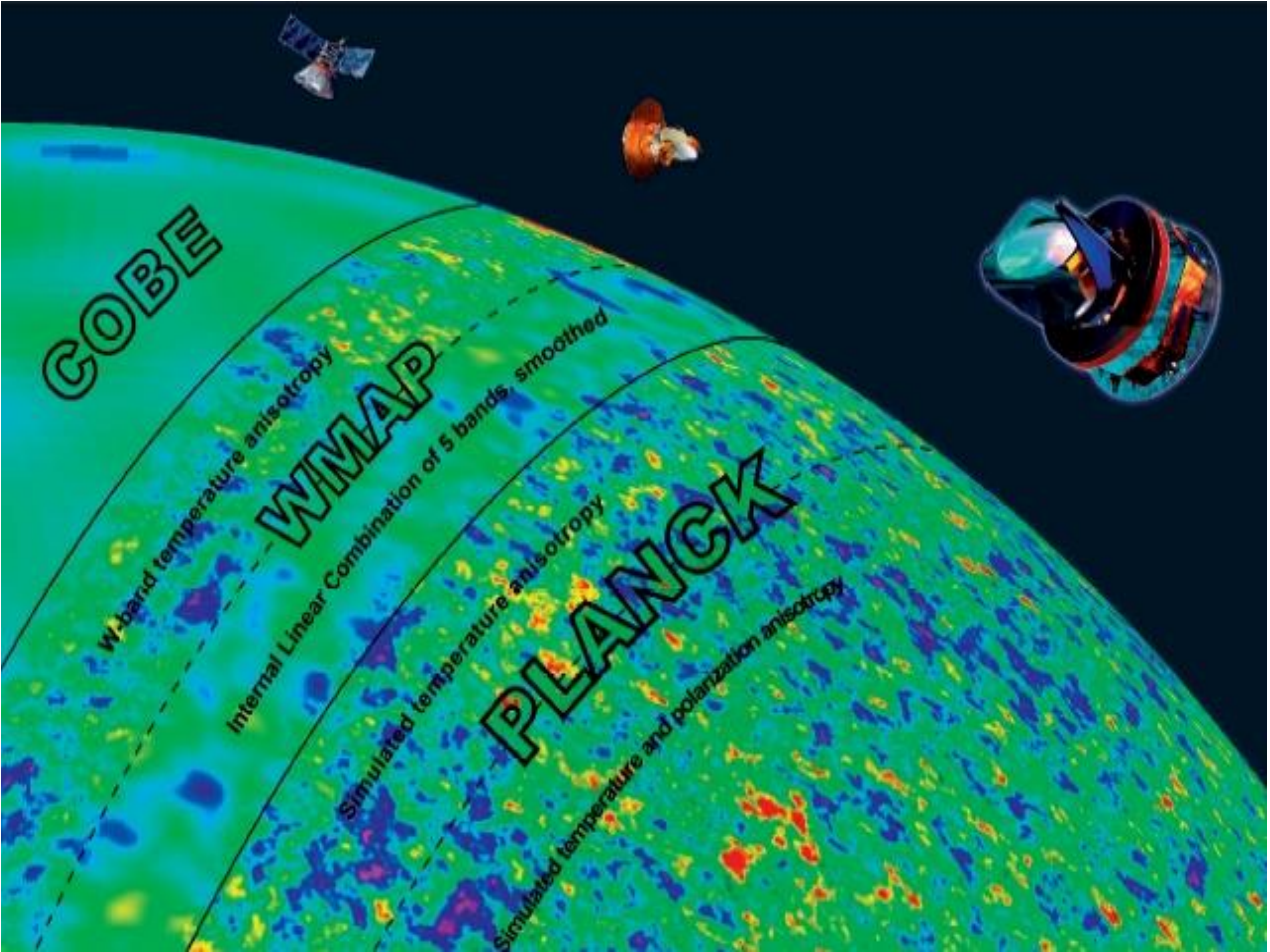




Galaxy formation is highly sensitive to the pattern of CMBR temperature

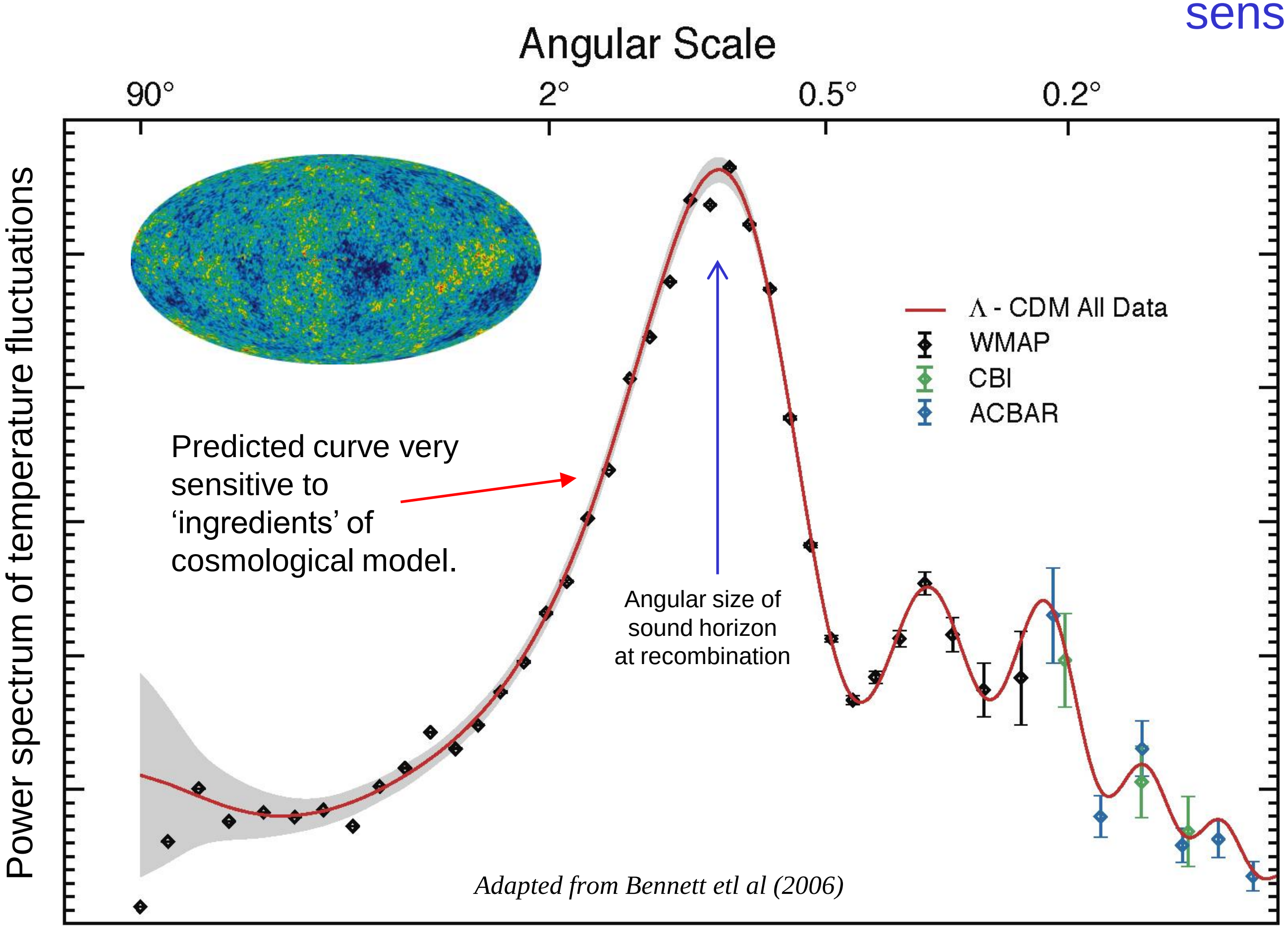


Adapted from Lineweaver (1997)


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

Cosmological parameters from the CMBR

Amplitude of Doppler peaks sensitive to density of matter



Friedmann equation

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{k}{R^2}$$

For $\Lambda = 0$

$$k = 0 \Leftrightarrow \rho = \left[\frac{8\pi G}{3H^2}\right]^{-1} = \rho_{\text{crit}}$$

$$\Omega_m = \rho / \rho_{crit} = \frac{8\pi G\rho}{3H^2}$$

i.e. $\rho \propto H^2$

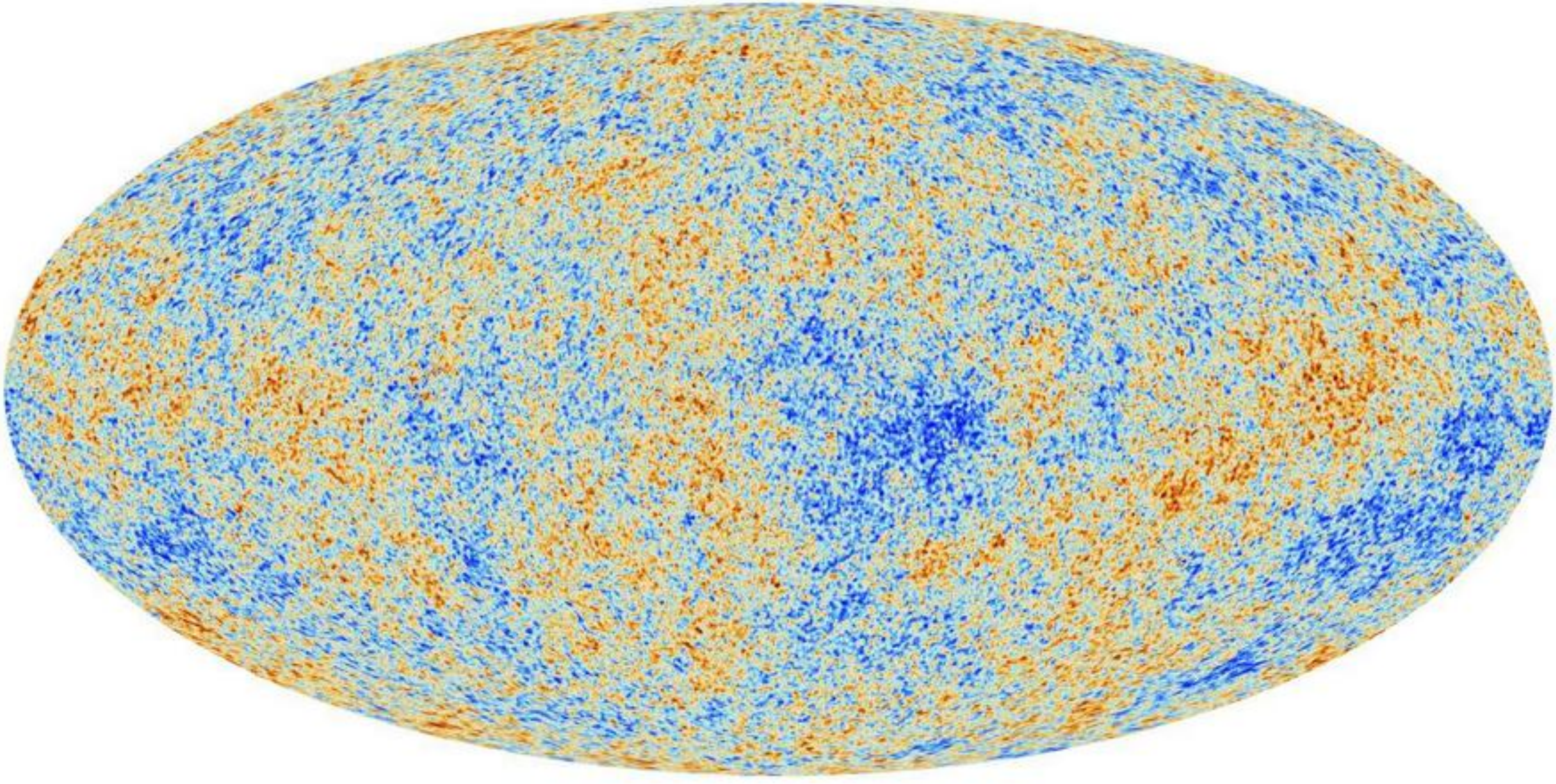
CMBR spectrum tightly constrained but H_0 degenerate with other parameters

21 March 2013 Last updated at 10:00

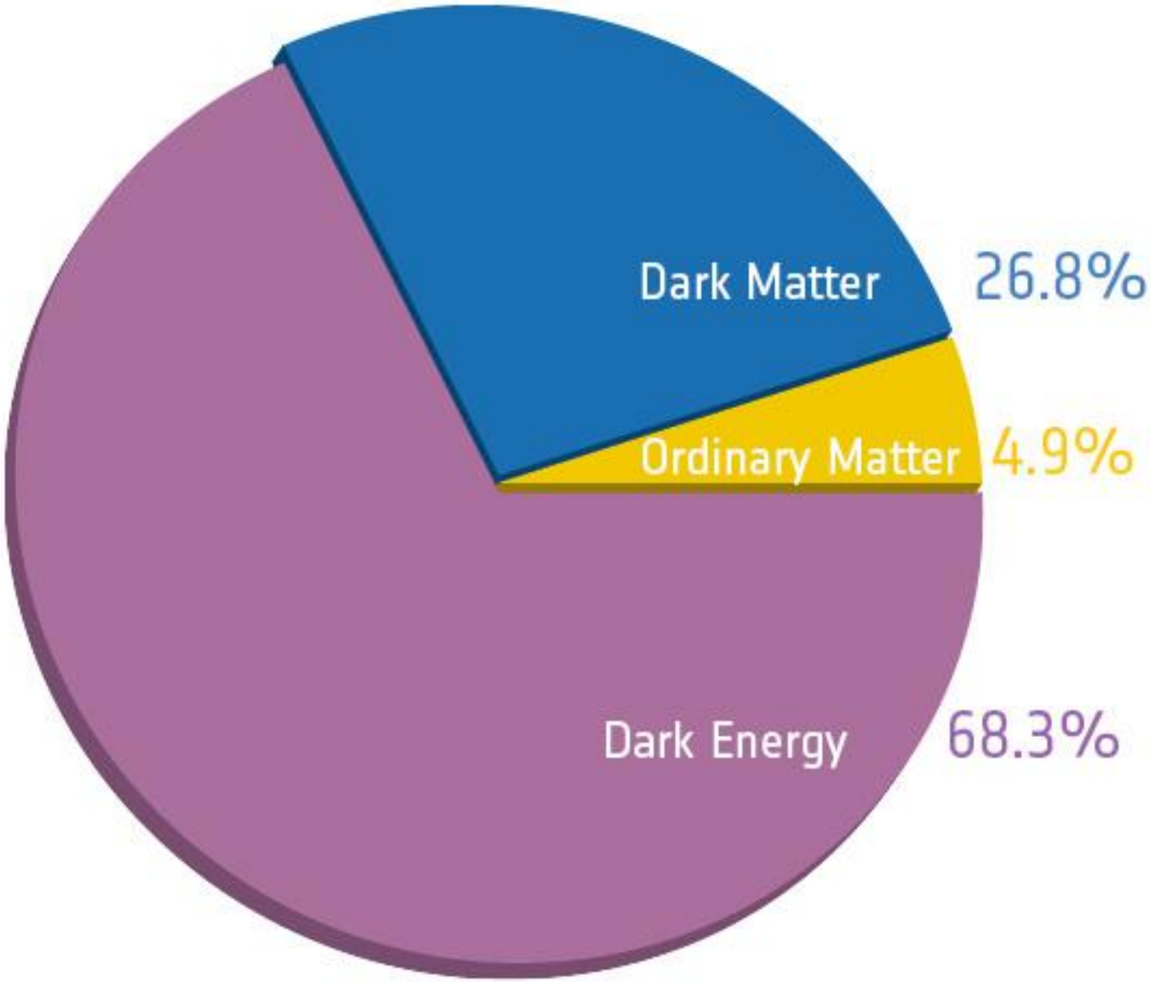
Share

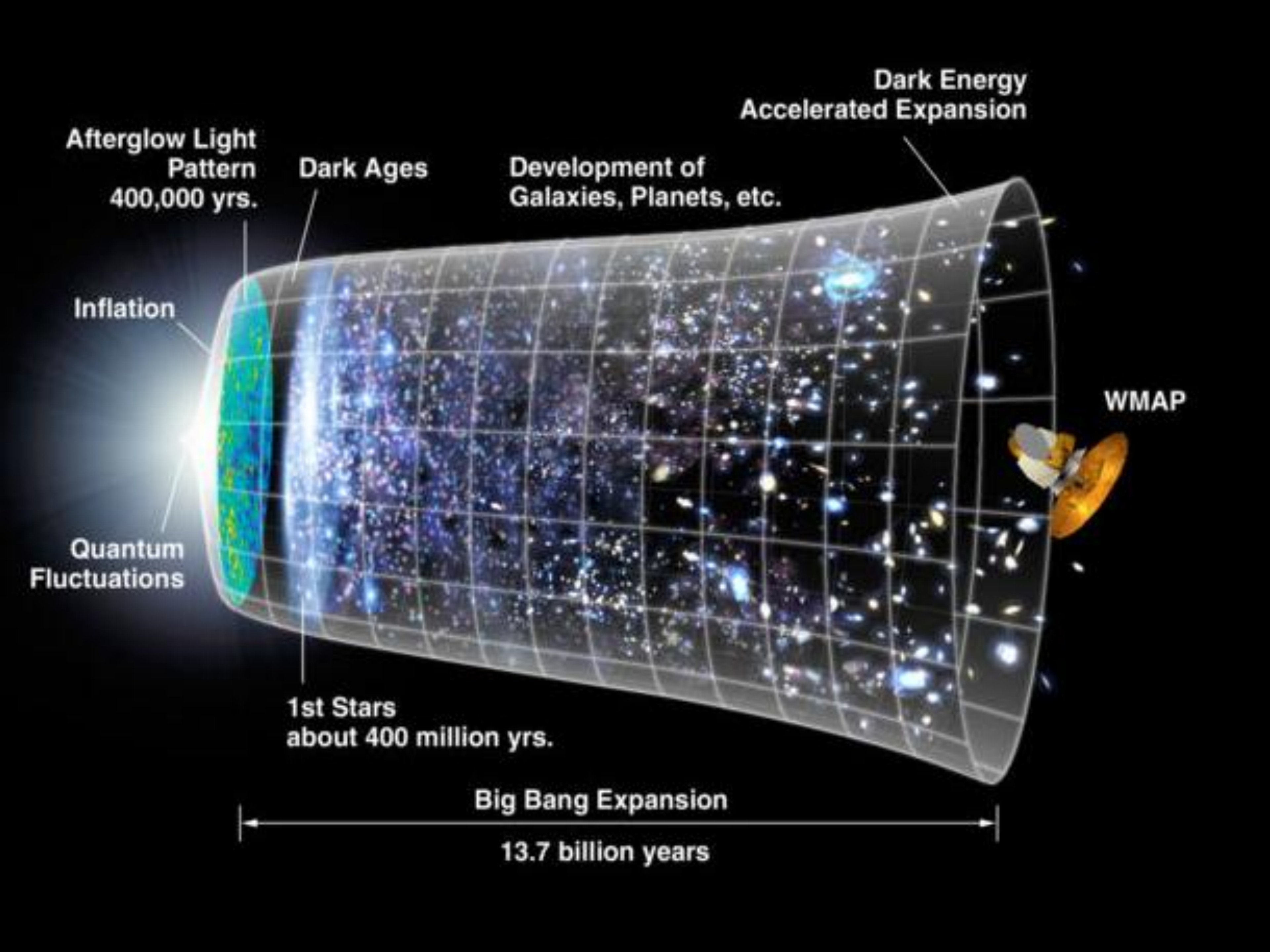
Planck satellite: Maps detail Universe's ancient light

A map tracing the "oldest light" in the sky has been produced by Europe's Planck Surveyor satellite. Its pattern confirms the Big Bang theory for the origin of the Universe but subtle, unexpected details will require scientists to adjust some of their ideas.



State of the Universe: Mar 2013

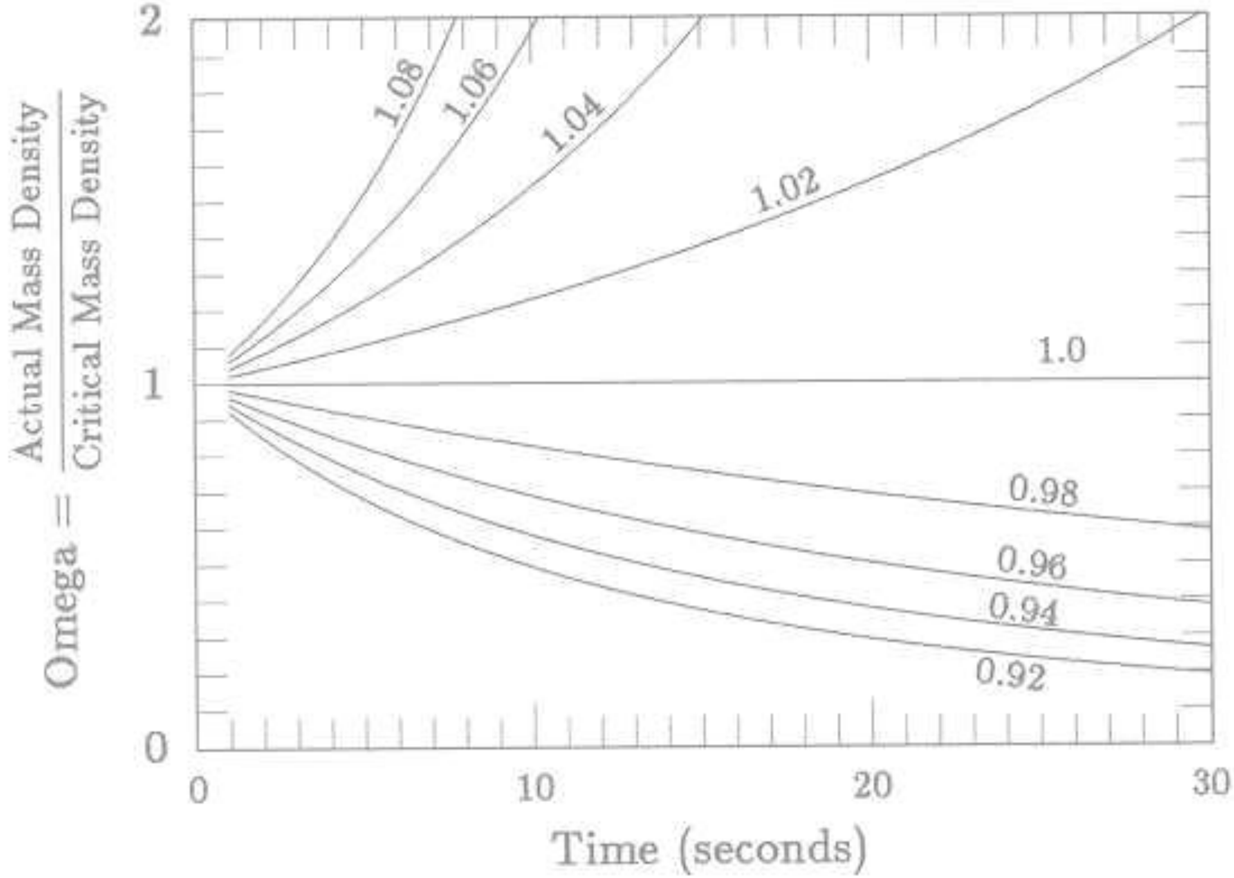




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Inflation for astronomers

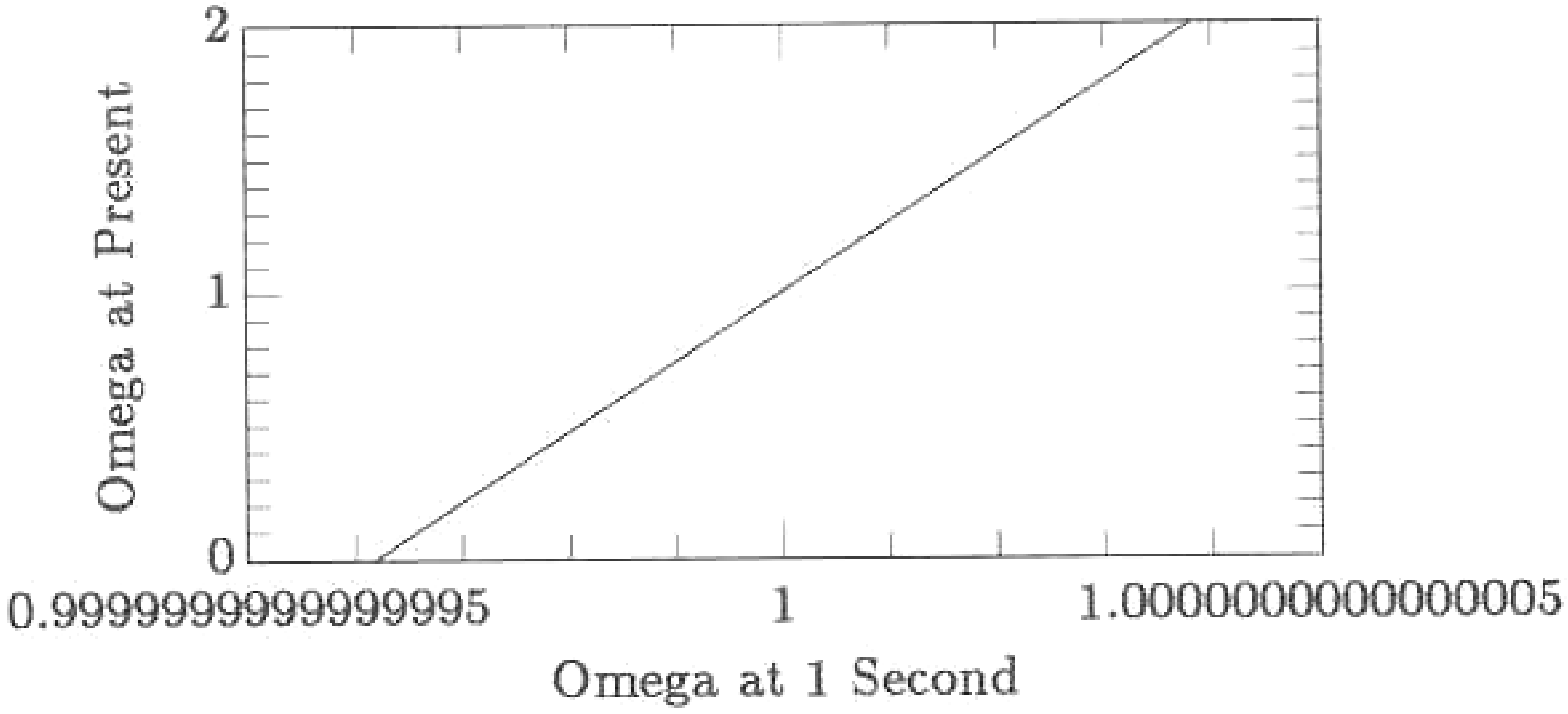
We have been considering $\Omega_{k0} = 0$ but suppose that in the past $\Omega_k \neq 0$. From the Friedmann equations it would then be very difficult to explain why it is so close to zero today.



From Guth (1997)

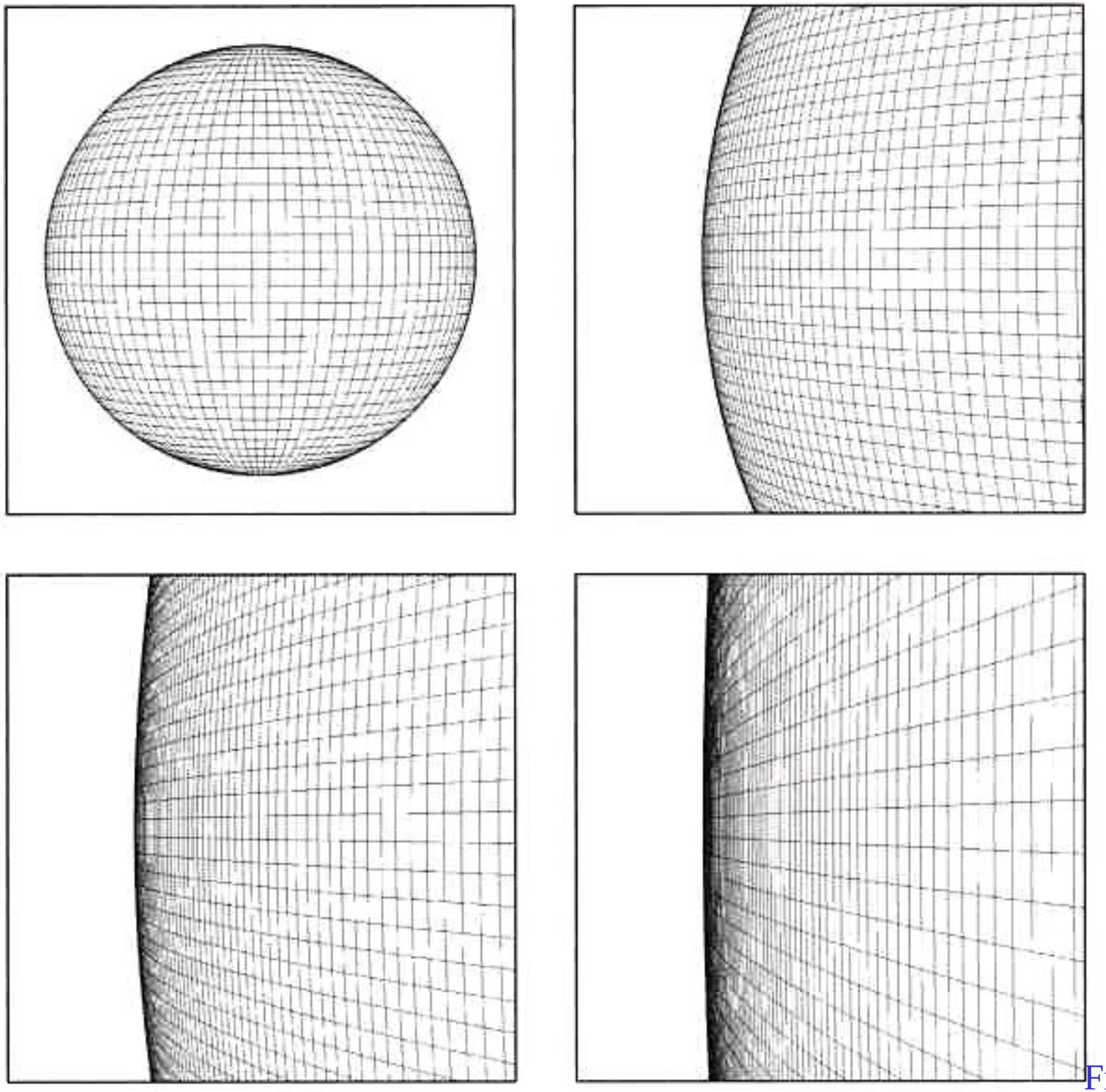
Present day ‘closeness’ of matter density to the critical density appears to require an incredible degree of ‘fine tuning’ in the very early Universe.

FLATNESS PROBLEM



From Guth (1997)

Inflationary solution to the Flatness Problem



From Guth (1997)

How do we explain the isotropy of the CMBR, when opposite sides of the sky were 'causally disconnected' when the CMBR photons were emitted?

HORIZON PROBLEM

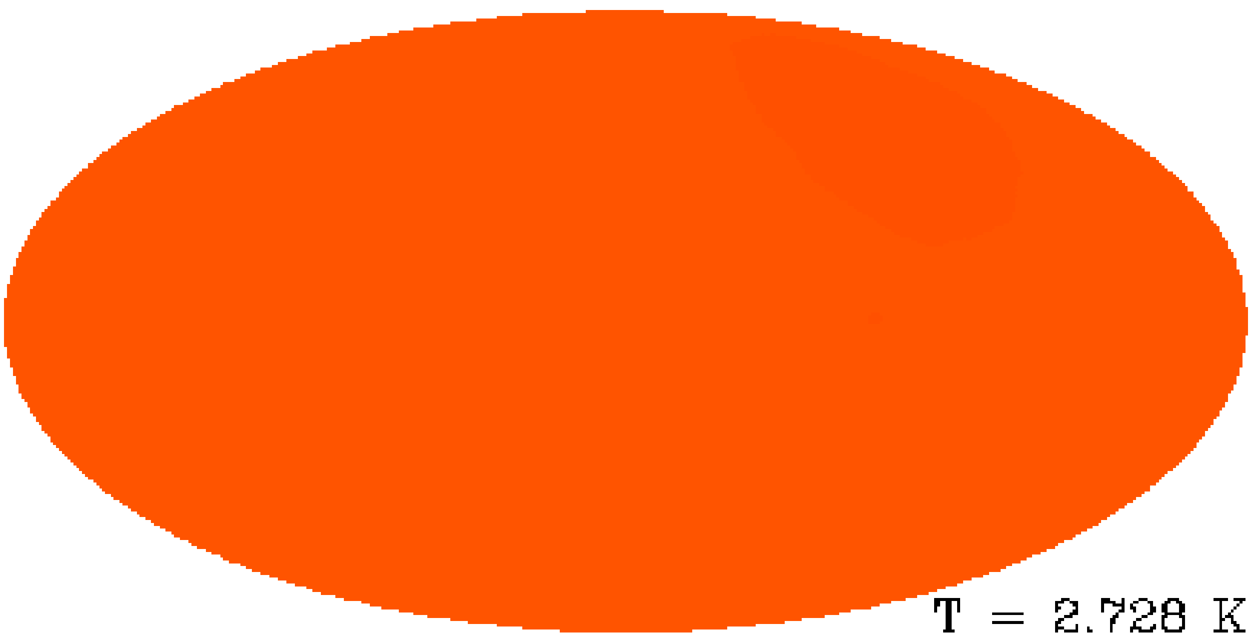
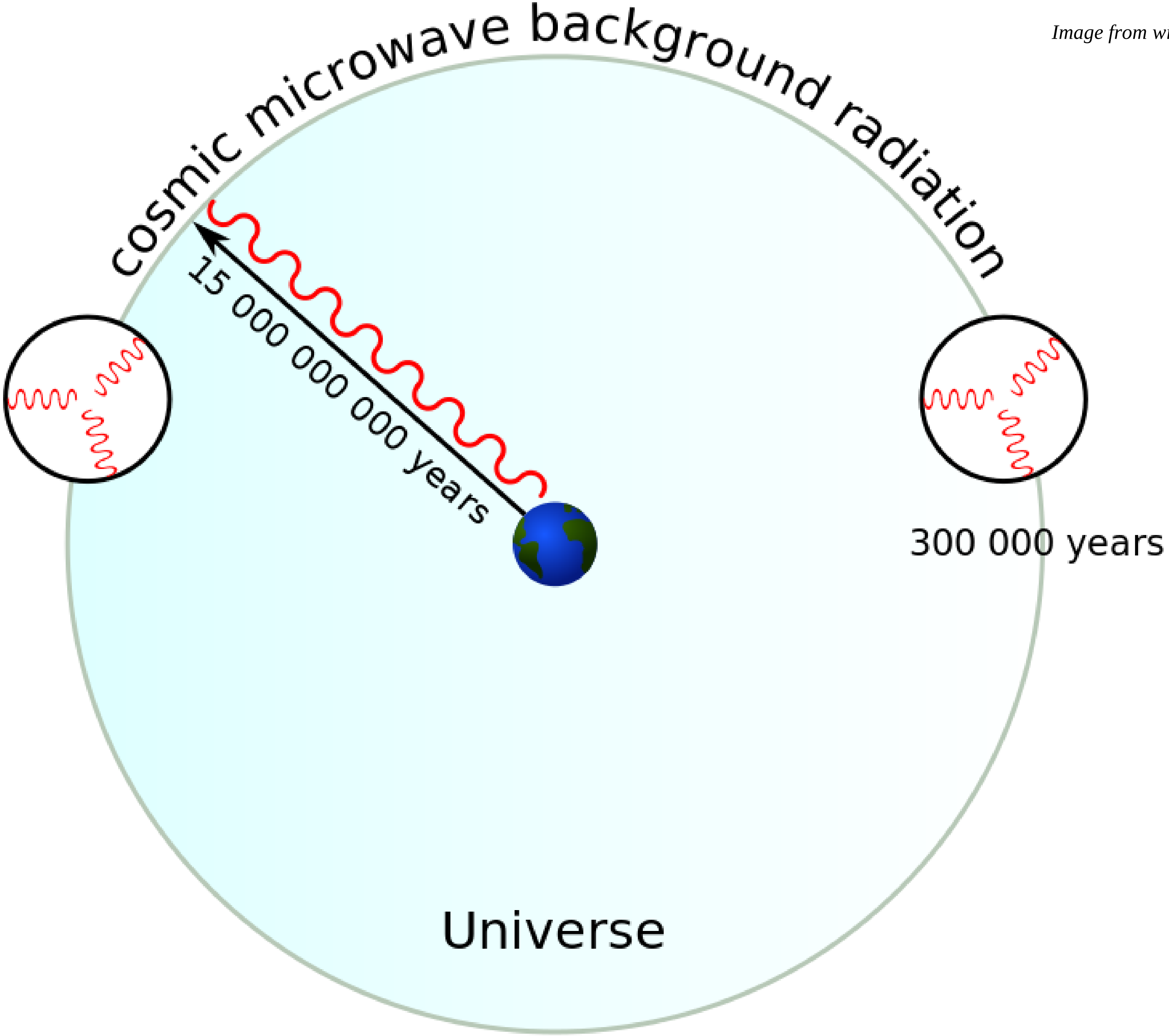
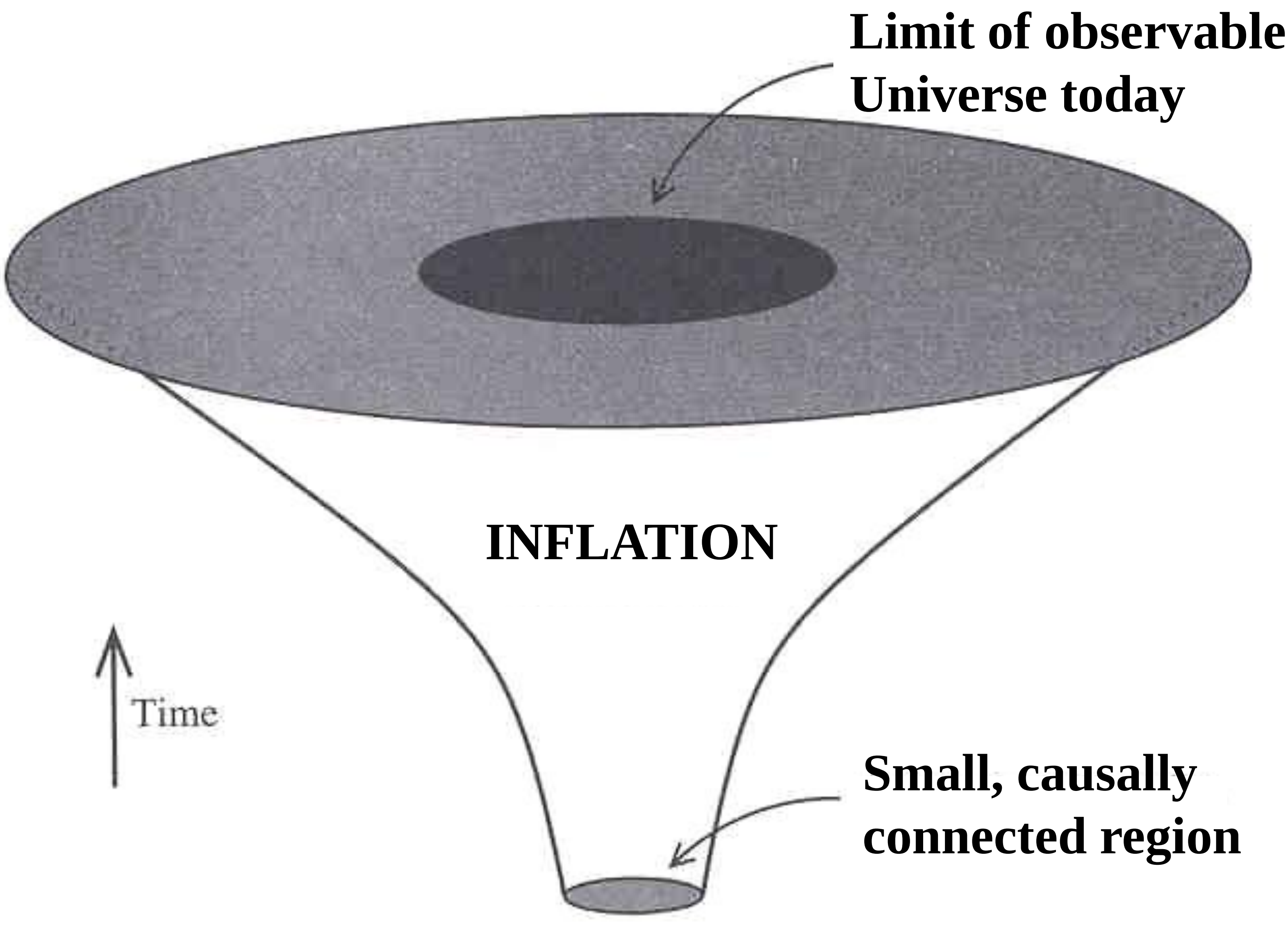


Image from wikipedia

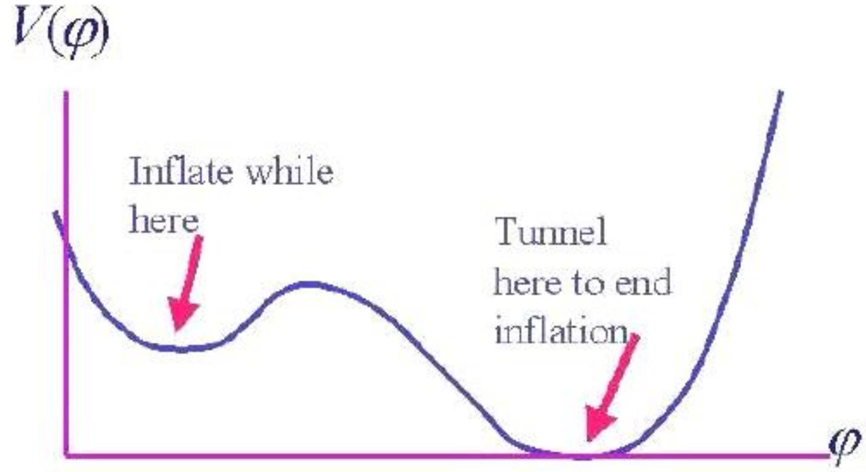


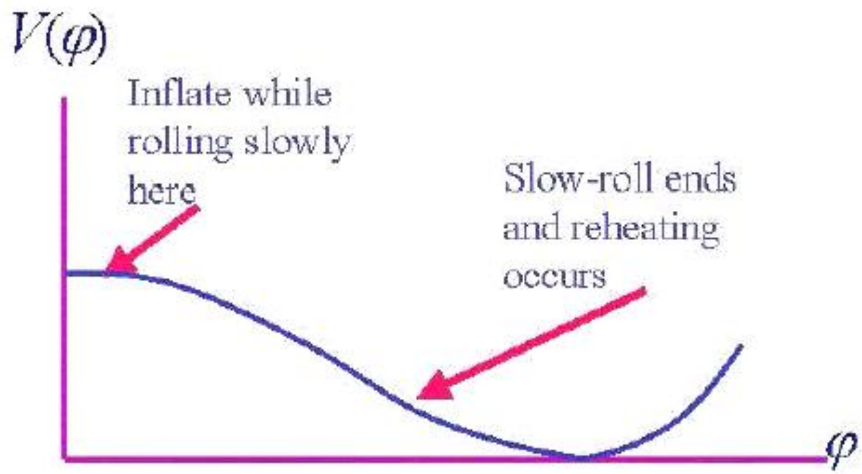
Inflationary solution to the Horizon Problem



From Guth (1997)

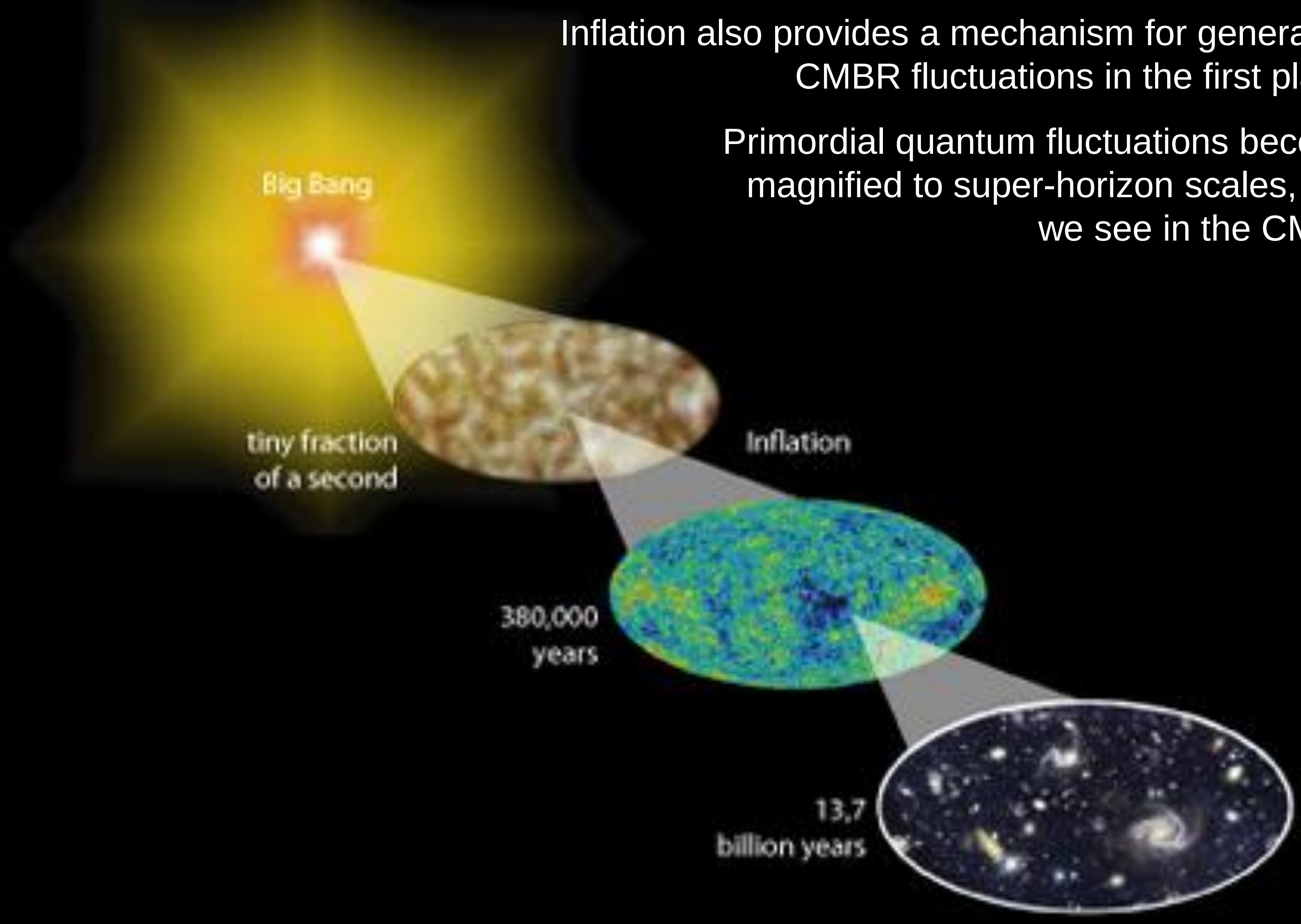
Following Albrecht (2000)



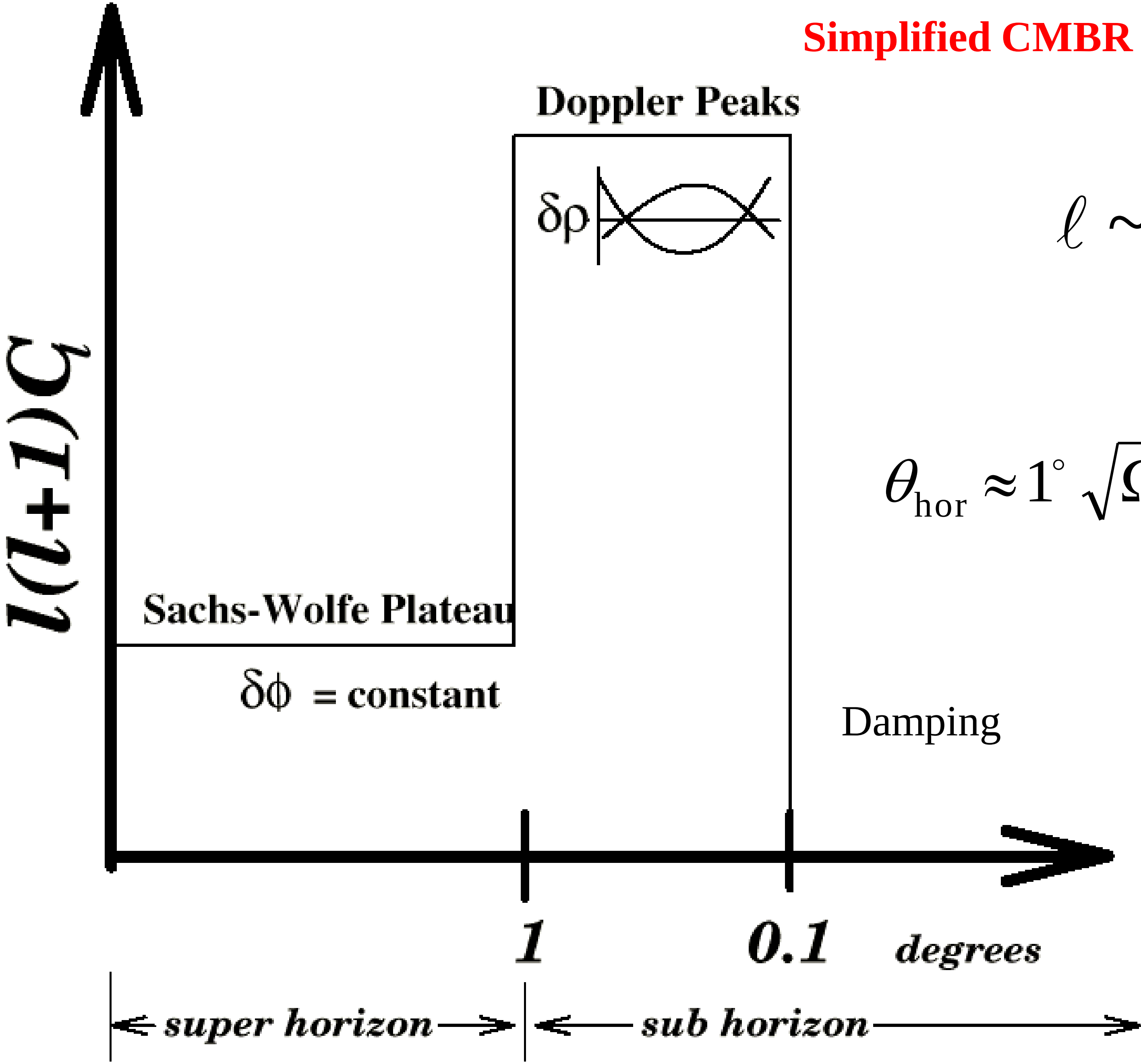


Inflation also provides a mechanism for generating CMBR fluctuations in the first place.

Primordial quantum fluctuations become magnified to super-horizon scales, that we see in the CMBR



Simplified CMBR Power Spectrum



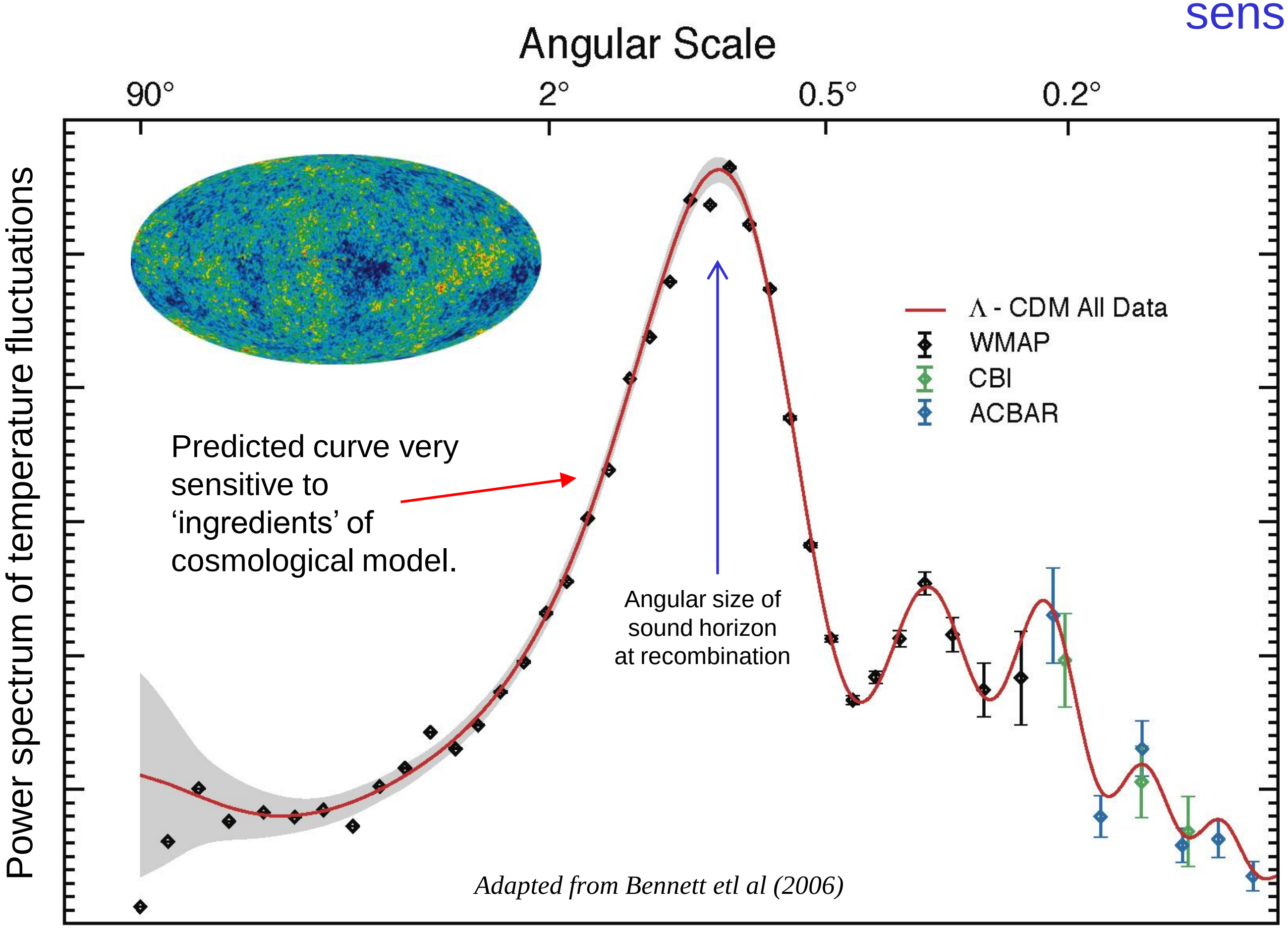
$$\ell \sim \frac{100}{\theta^\circ}$$

$$\theta_{\rm hor} \approx 1^\circ \sqrt{\Omega_{m0}} \left(\frac{z_{\rm LSS}}{1000} \right)^{-1/2}$$

Adapted from Lineweaver (1997)

Cosmological parameters from the CMBR

Amplitude of Doppler peaks sensitive to density of matter



Friedmann equation

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda}{3} - \frac{k}{R^2}$$

For $\Lambda = 0$

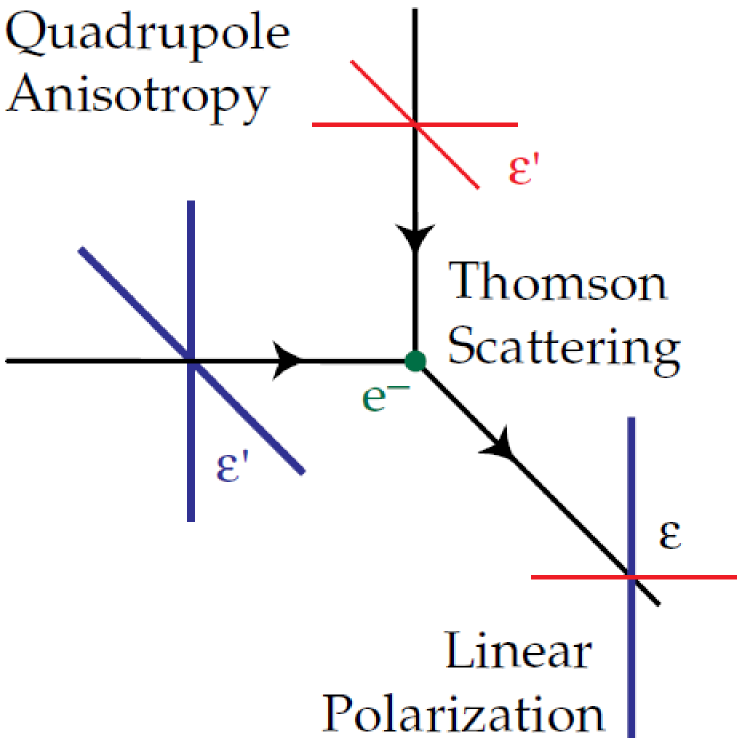
$$k = 0 \Leftrightarrow \rho = \left[\frac{8\pi G}{3H^2}\right]^{-1} = \rho_{\mathrm{crit}}$$

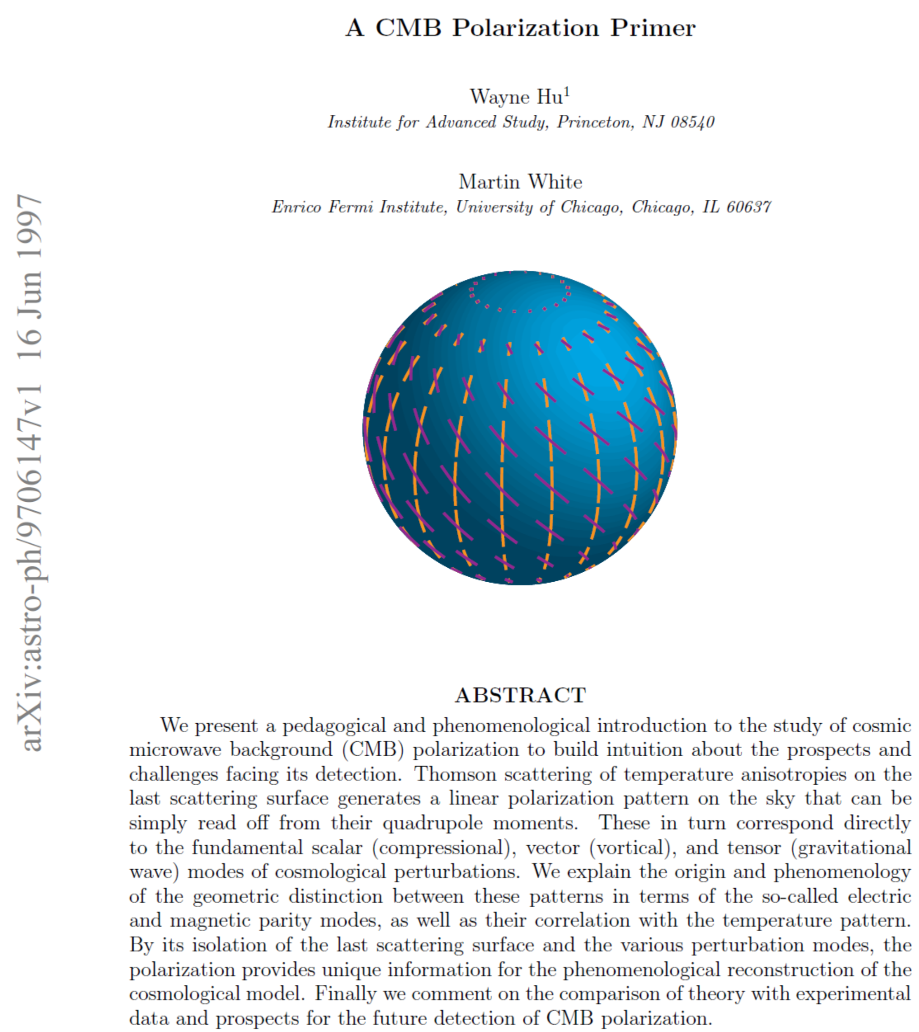
$$\Omega_m = \rho \Big/ \rho_{crit} = \frac{8\pi G\rho}{3H^2}$$

i.e. $\rho \propto H^2$

CMBR spectrum tightly constrained but H_0 degenerate with other parameters

We can obtain information from the CMBR **polarisation** as well as temperature maps.





arXiv:astro-ph/9706147v1 16 Jun 1997

A CMB Polarization Primer

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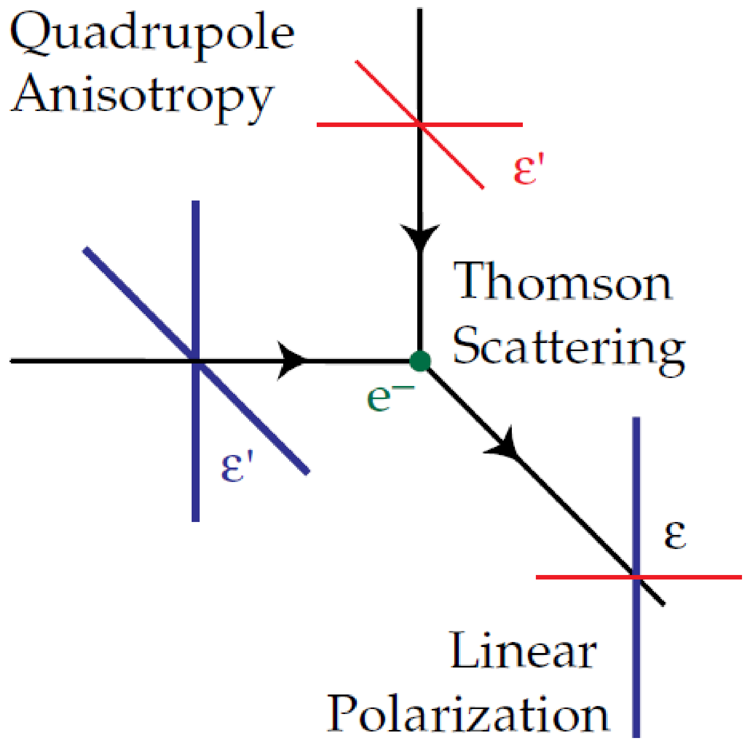
Institute for Advanced Study, Princeton, NJ 08540

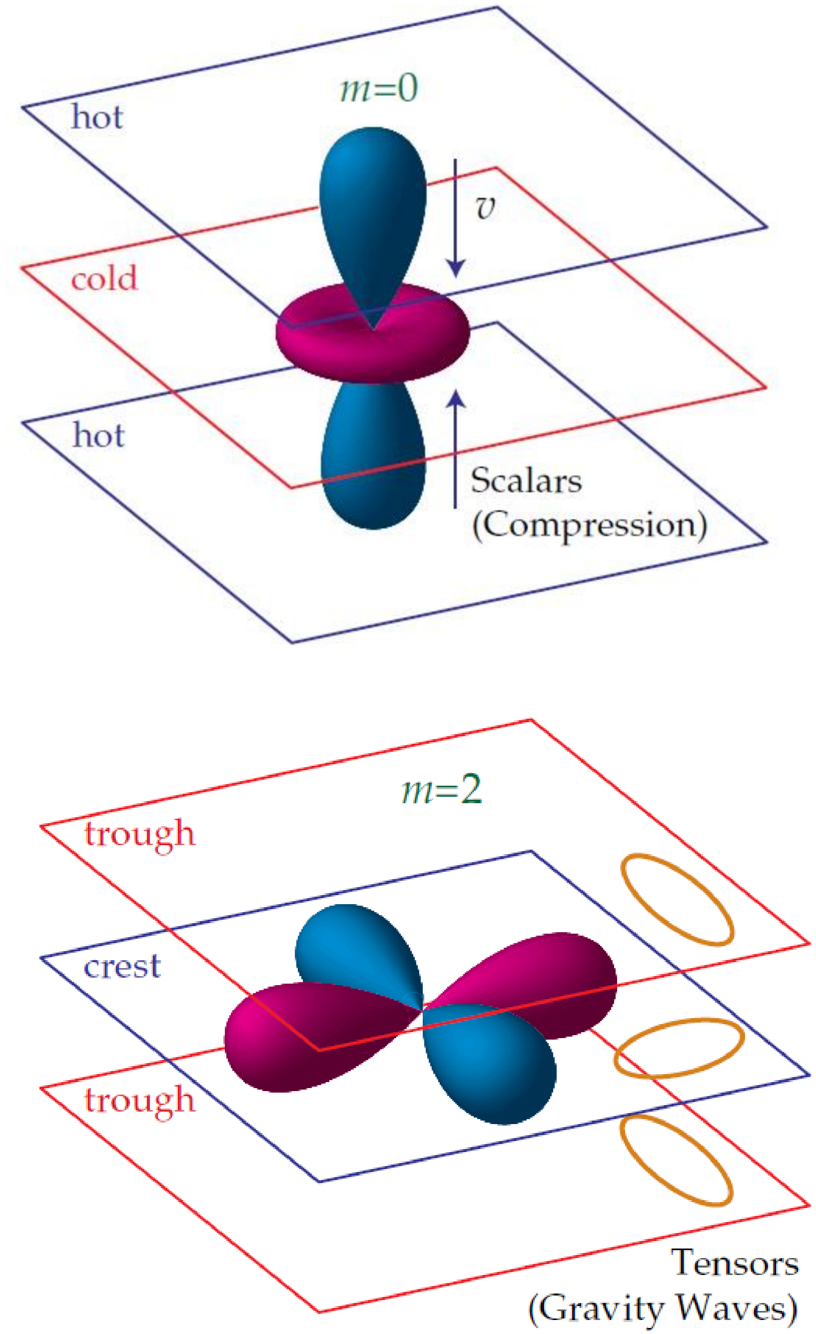
Martin White
Enrico Fermi Institute, University of Chicago, Chicago, IL 60637

ABSTRACT

We present a pedagogical and phenomenological introduction to the study of cosmic microwave background (CMB) polarization to build intuition about the prospects and challenges facing its detection. Thomson scattering of temperature anisotropies on the last scattering surface generates a linear polarization pattern on the sky that can be simply read off from their quadrupole moments. These in turn correspond directly to the fundamental scalar (compressional), vector (vortical), and tensor (gravitational wave) modes of cosmological perturbations. We explain the origin and phenomenology of the geometric distinction between these patterns in terms of the so-called electric and magnetic parity modes, as well as their correlation with the temperature pattern. By its isolation of the last scattering surface and the various perturbation modes, the polarization provides unique information for the phenomenological reconstruction of the cosmological model. Finally we comment on the comparison of theory with experimental data and prospects for the future detection of CMB polarization.

We can obtain information from the CMBR **polarisation** as well as temperature maps.



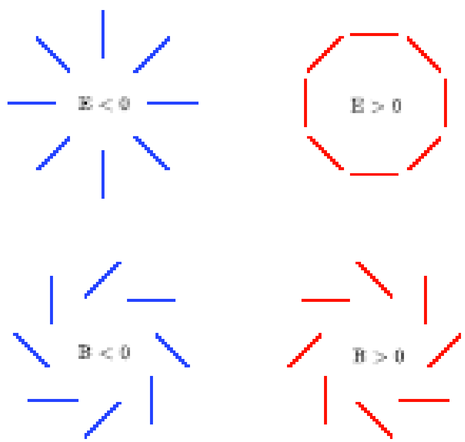


From Hu and White (1997)

Because the Thomson scattering is anisotropic, the CMBR is **polarised**.

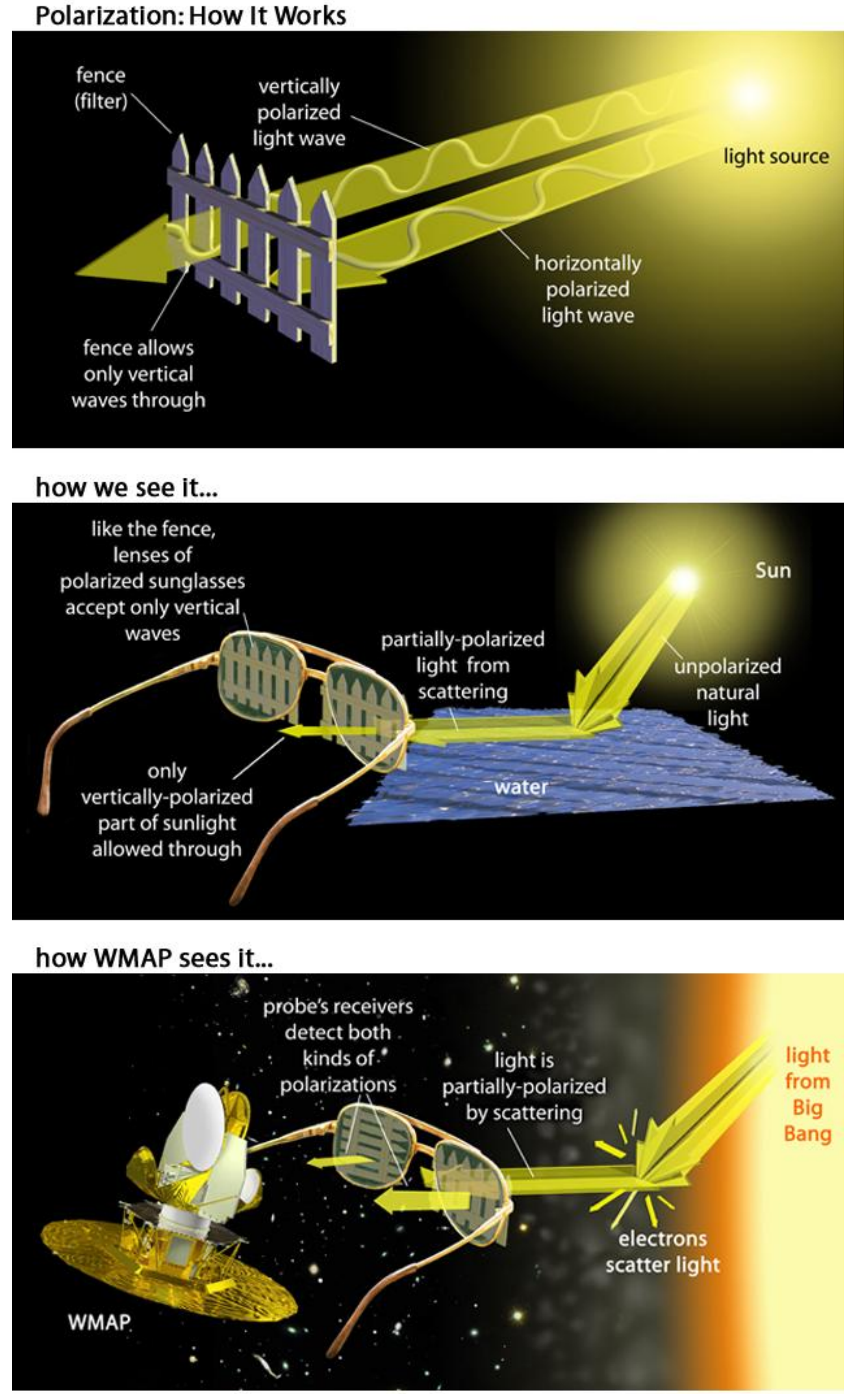
We can decompose the polarisation field into E and B modes.

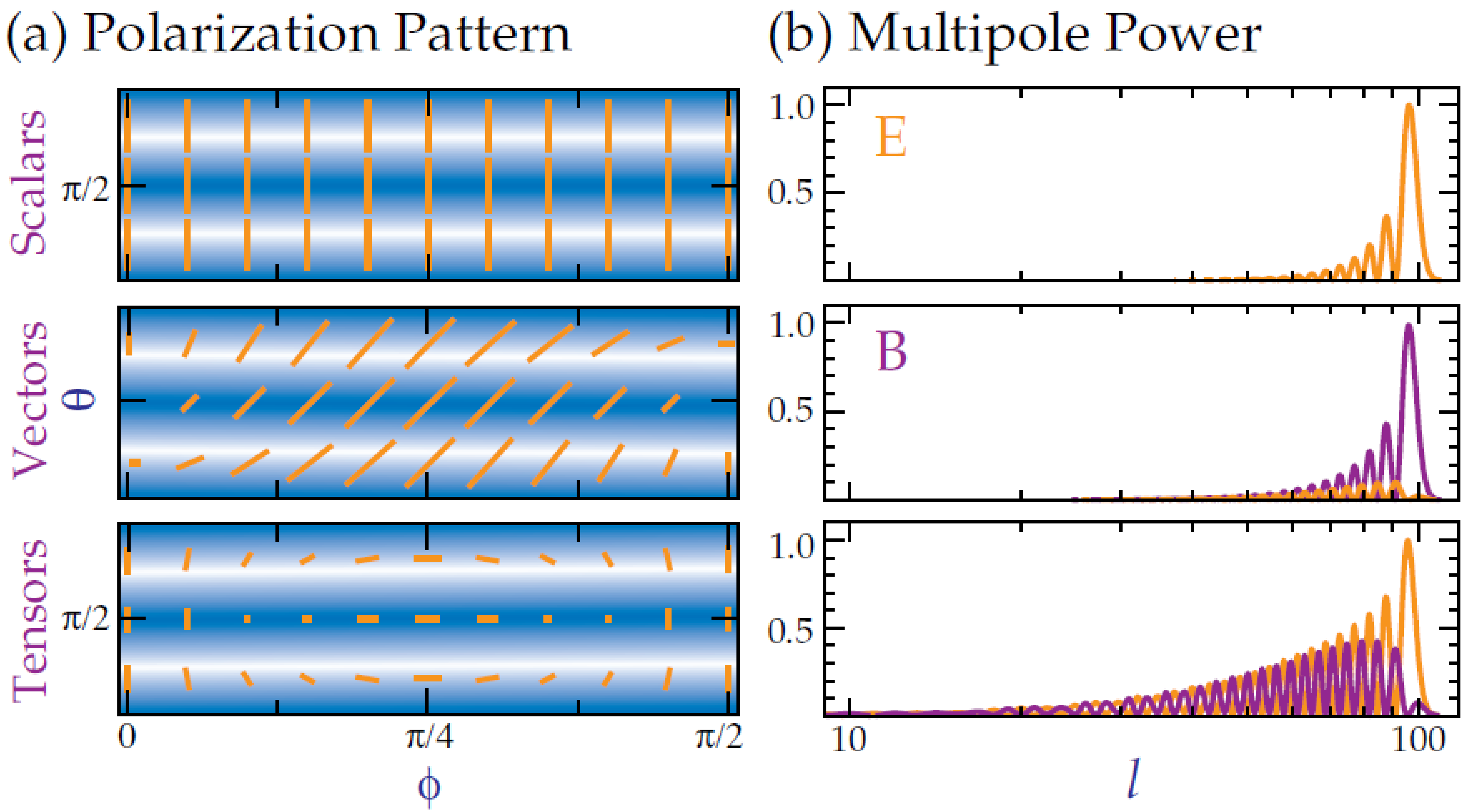
$$P(\hat{n}) = \nabla E + \nabla \times B$$



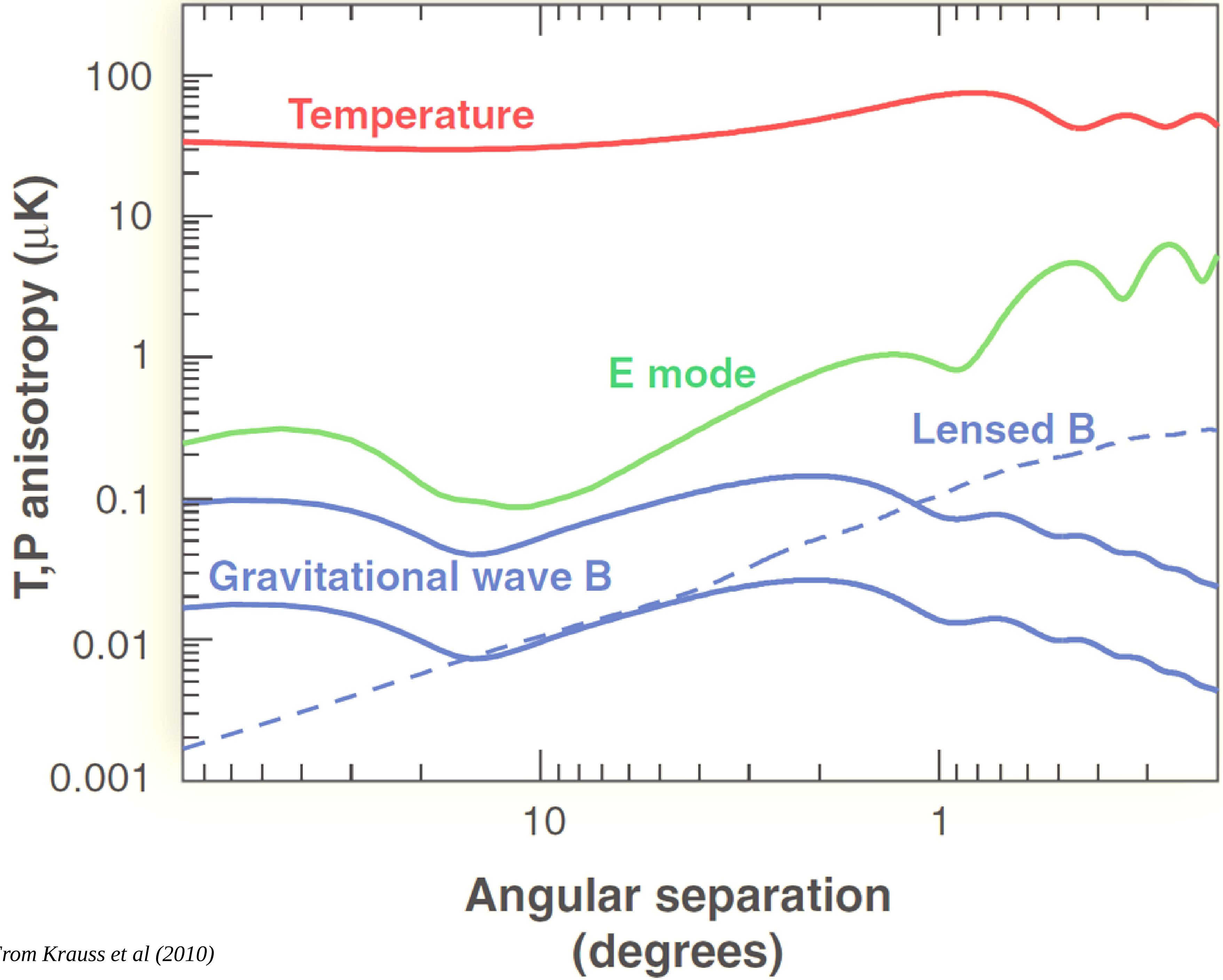
Grad

Curl





From Hu and White (1997)



From Krauss et al (2010)

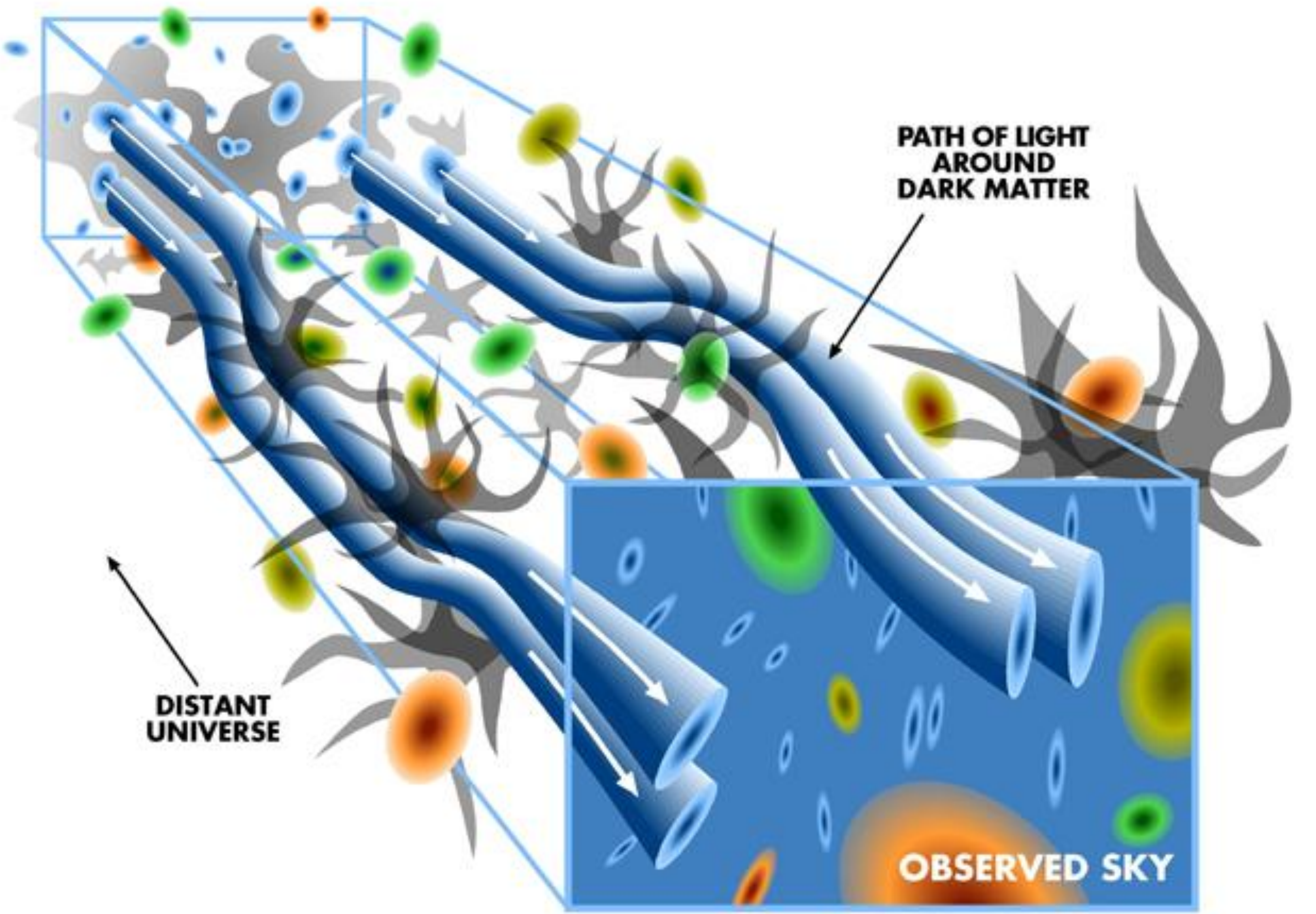
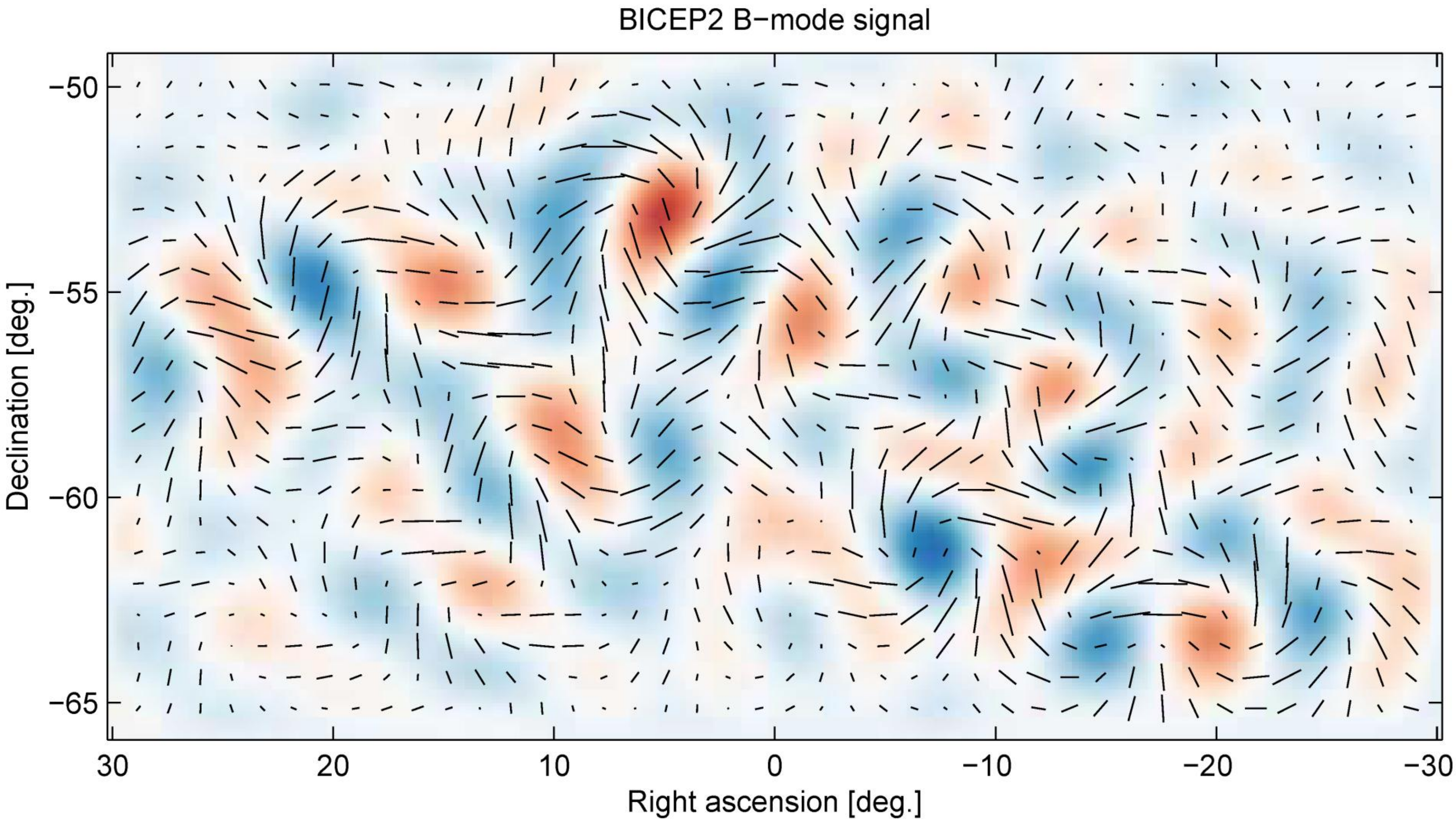
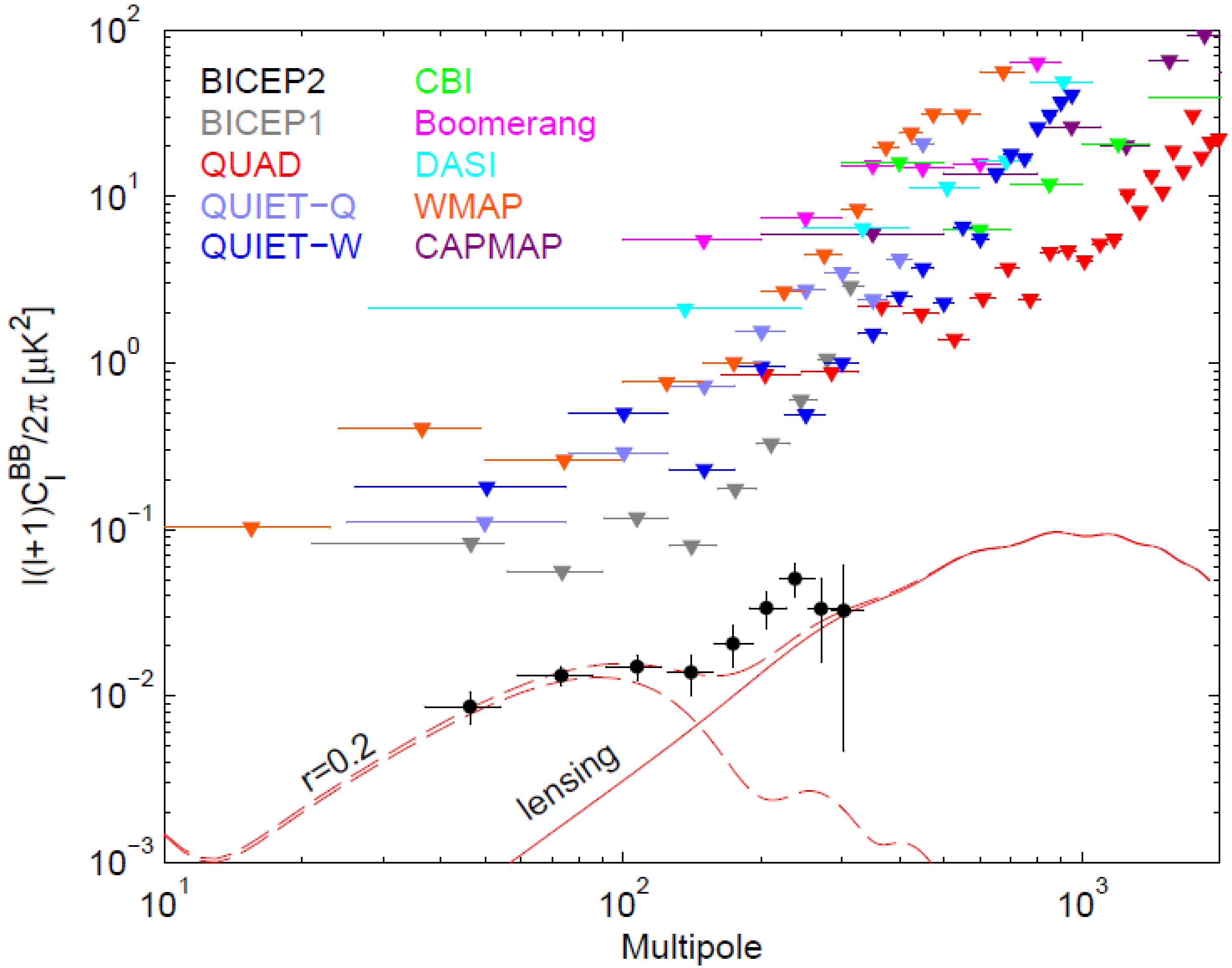


Image from www.lsst.org


BICEP2 B−mode signal
−50
−55
−60
−65
Declination [deg.]
30
20
10
0
−10
−20
−30
Right ascension [deg.]

Ade et al (2014) BICEP-2 results



What can we constrain with CMBR data?

It is usually a good approximation to take the power spectra as being power-laws with scale. So

Density perturbations

$$A_S^2(k) = A_S^2(k_0)\left[\frac{k}{k_0}\right]^{n_S - 1}$$

Gravitational waves

$$A_T^2(k) = A_T^2(k_0)\left[\frac{k}{k_0}\right]^{n_T}$$

Following Melchiorri (2008)

What can we constrain with CMBR data?

The 4 parameters are related to the inflaton potential and to its first two derivatives:

$$n_S - 1 \approx -\frac{m_{Pl}^2}{8\pi}\left(\frac{V_*'}{V_*}\right)^2 + \frac{m_{Pl}^2}{4\pi}\left(\frac{V_*'}{V_*}\right)'$$

$$n_T \approx -\frac{m_{Pl}^2}{8\pi}\left(\frac{V_*'}{V_*}\right)^2$$

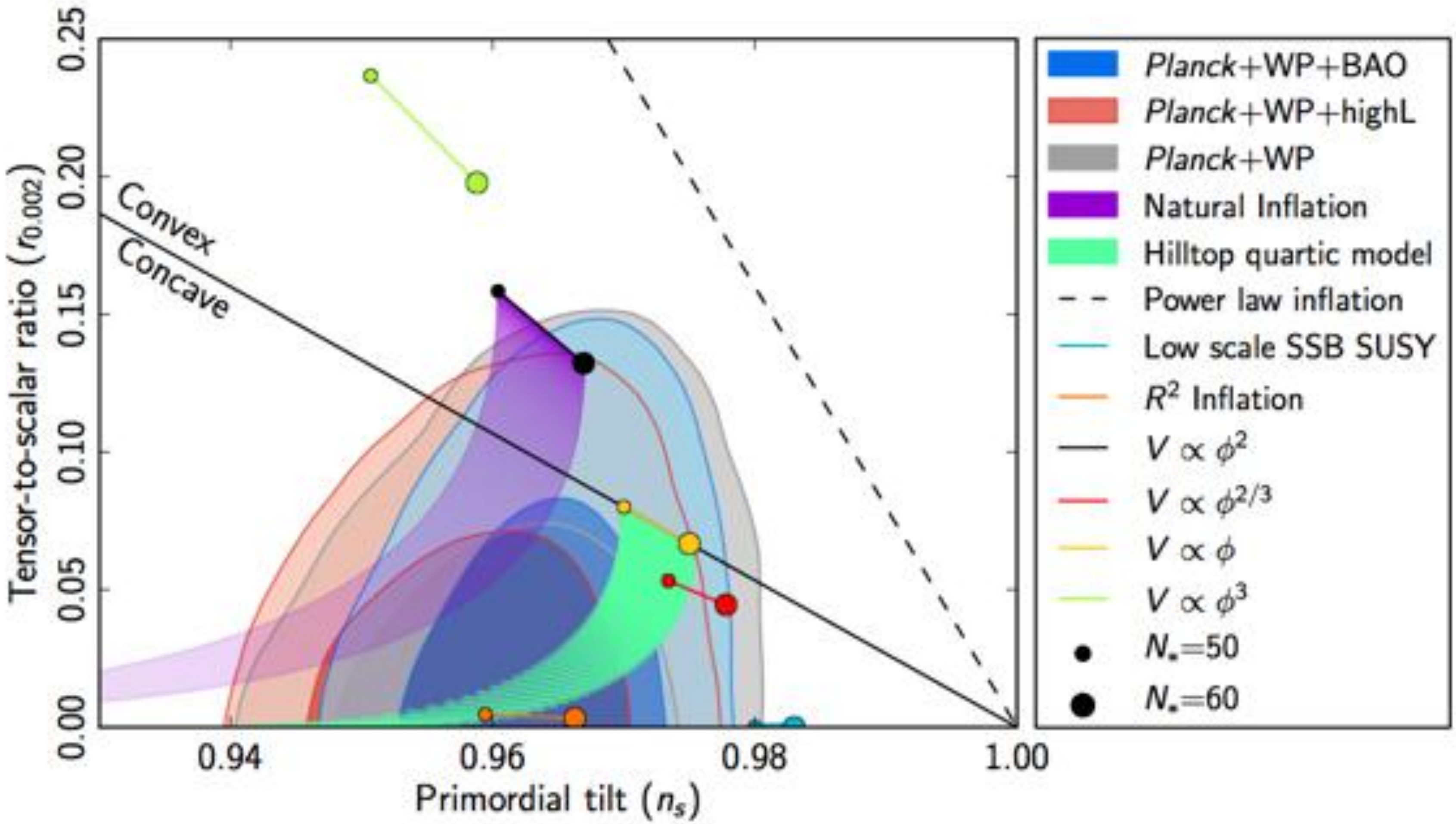
$$A_T \approx 0.61\frac{V_*}{m_{Pl}^4}$$

$$A_S \approx -\frac{1}{7}\frac{A_T}{n_T}$$

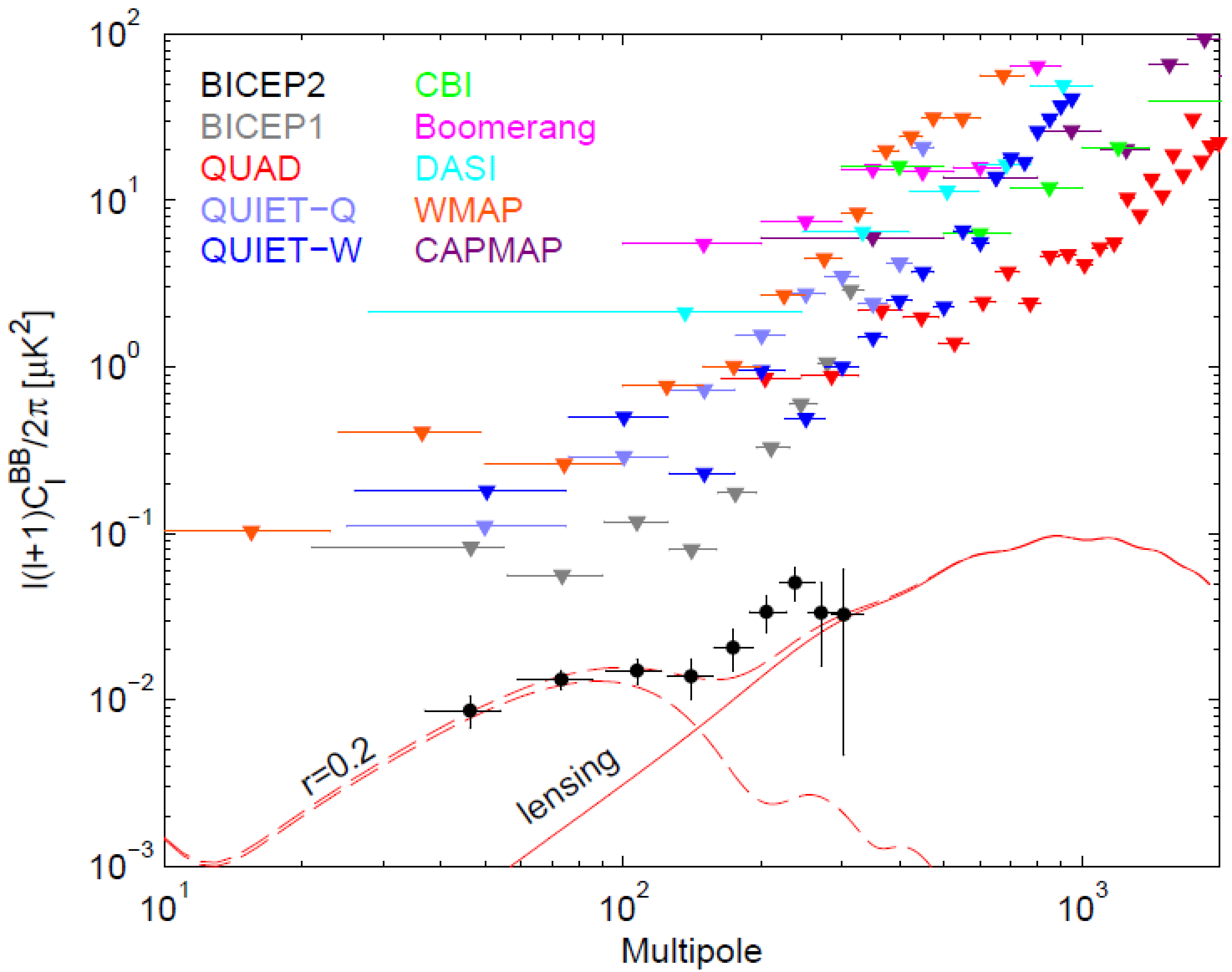
$$\boxed{r = \frac{A_T}{A_S}}$$

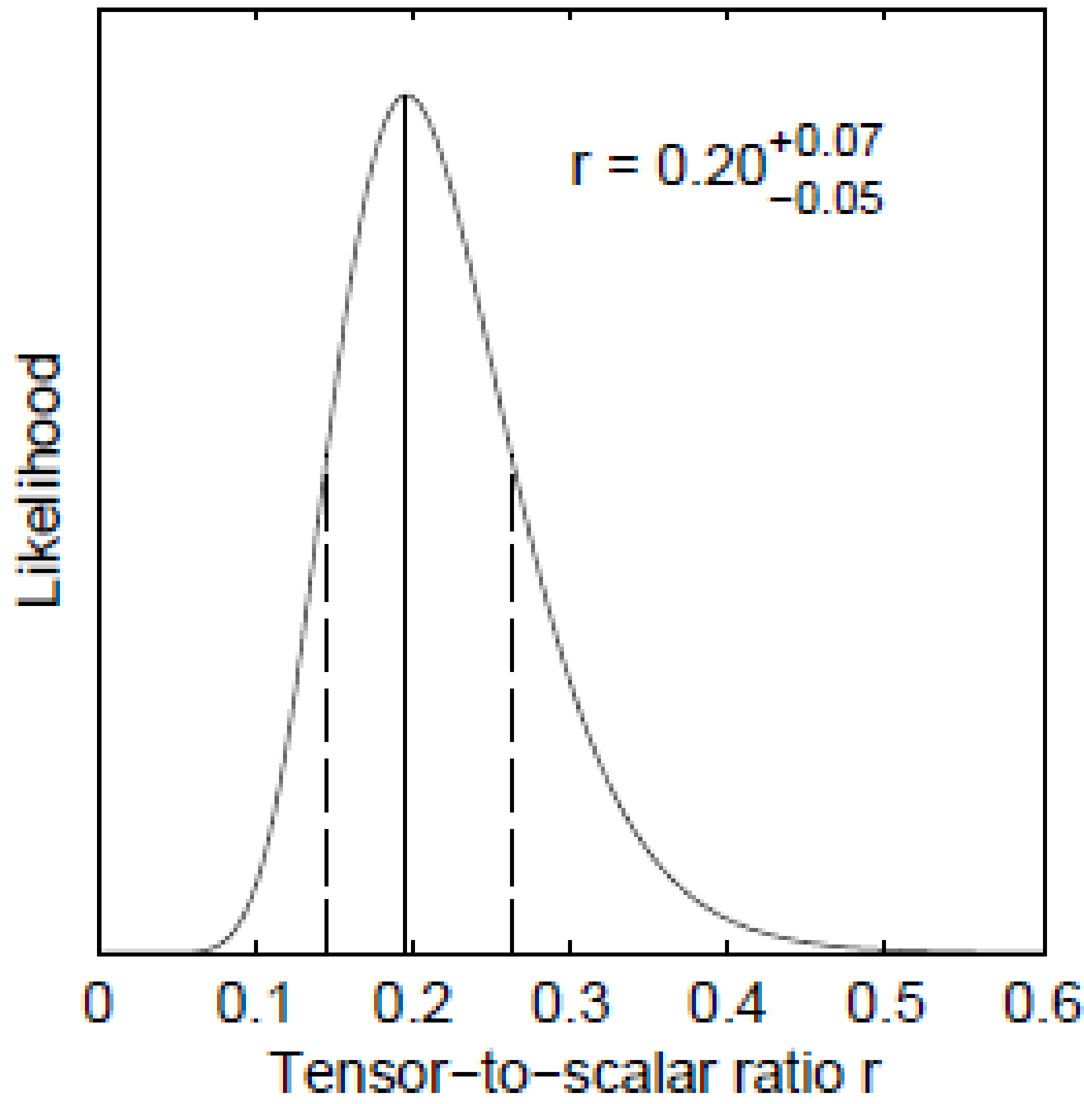
Following Melchiorri (2008)

Ade et al (2013) Planck results



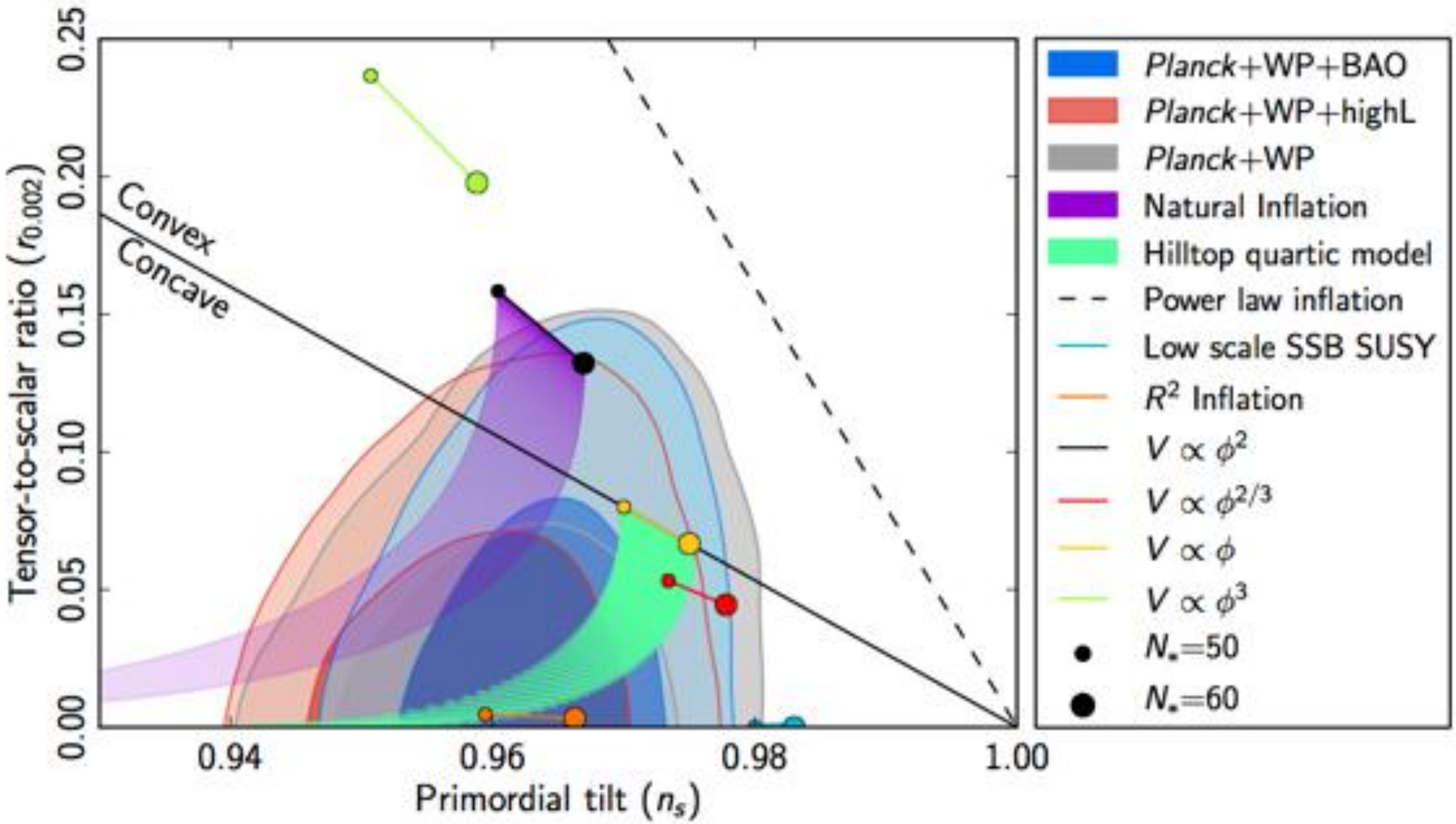
Ade et al (2014) BICEP-2 results



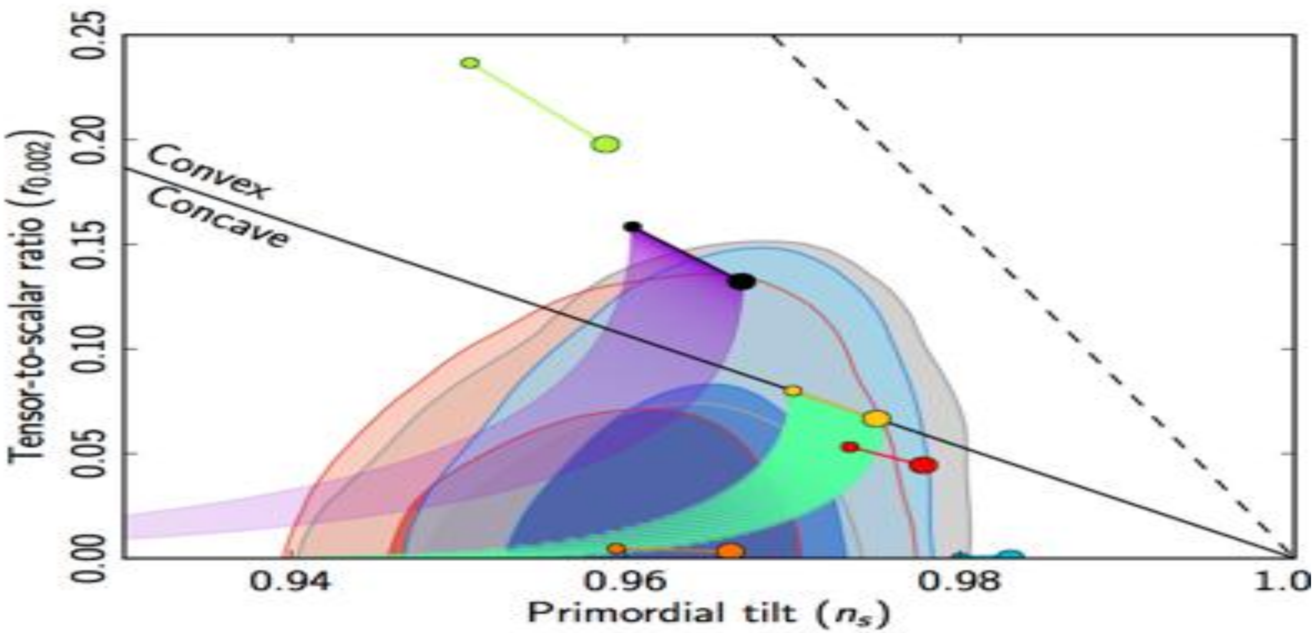


$r = 0.20^{+0.07}_{-0.05}$
Likelihood
0
0.1
0.2
0.3
0.4
0.5
0.6
Tensor−to−scalar ratio r

Ade et al (2013) Planck results

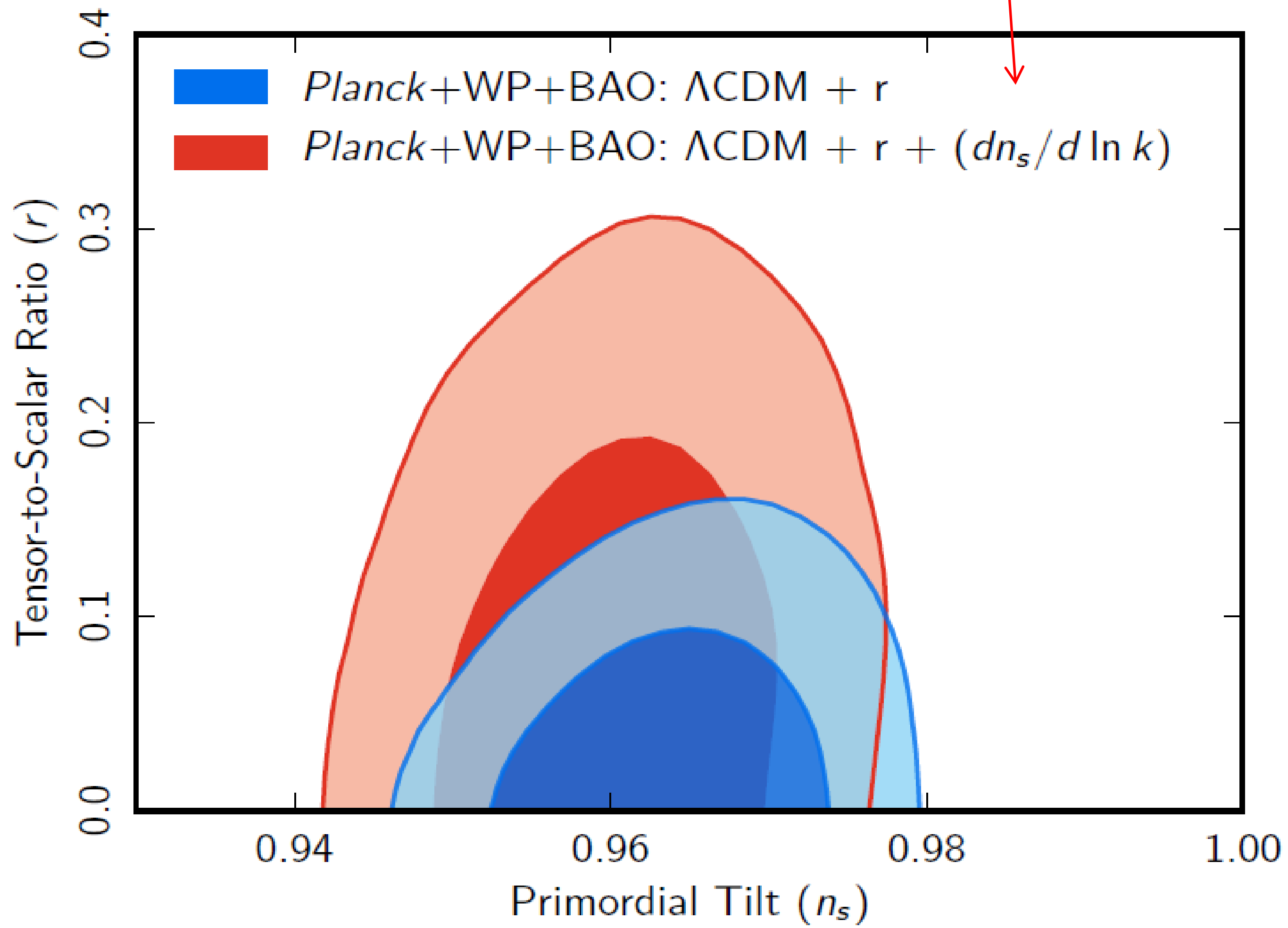


Ade et al (2013) Planck results

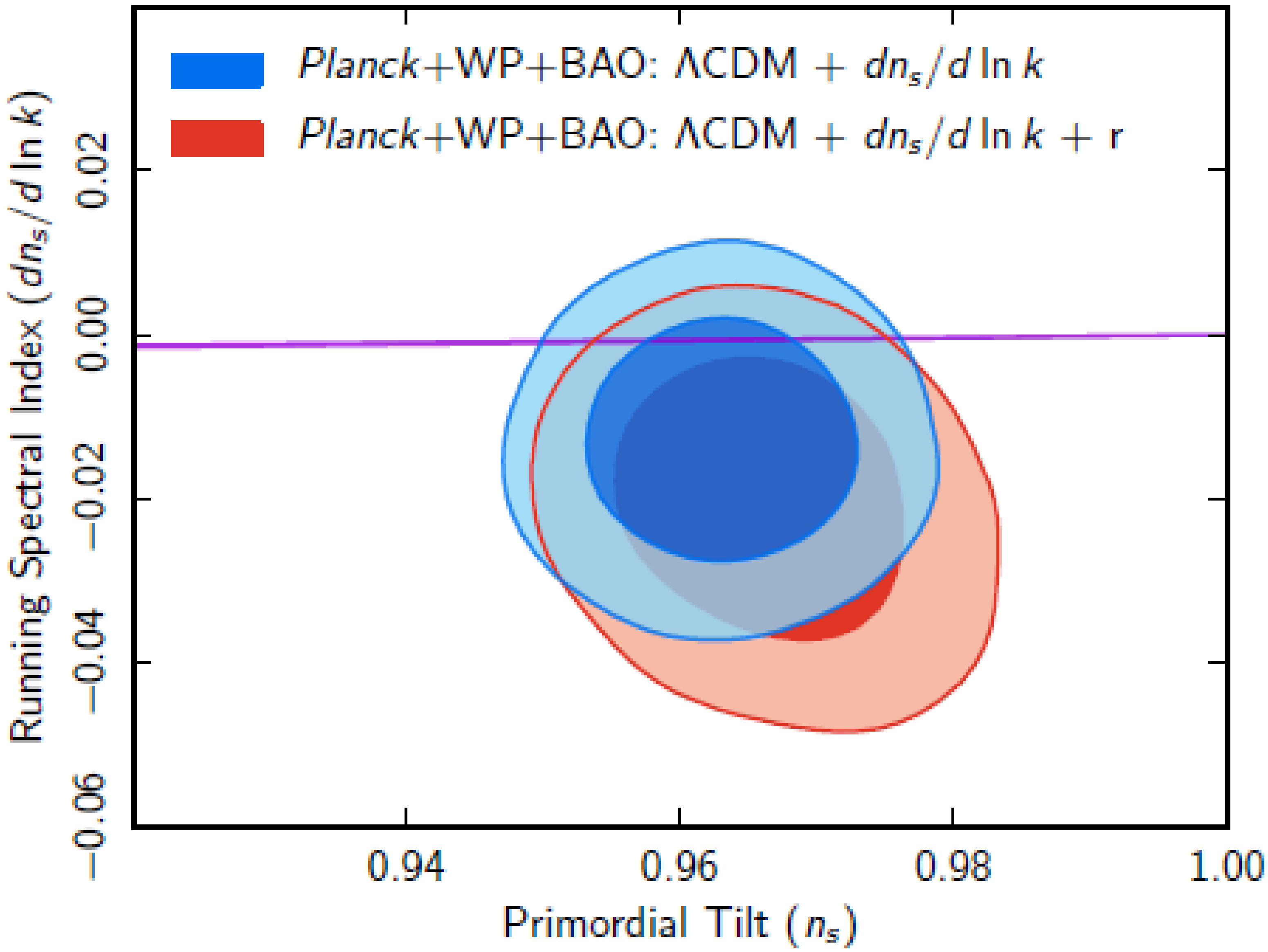


Ade et al (2013) Planck results

Allows for a running spectral index

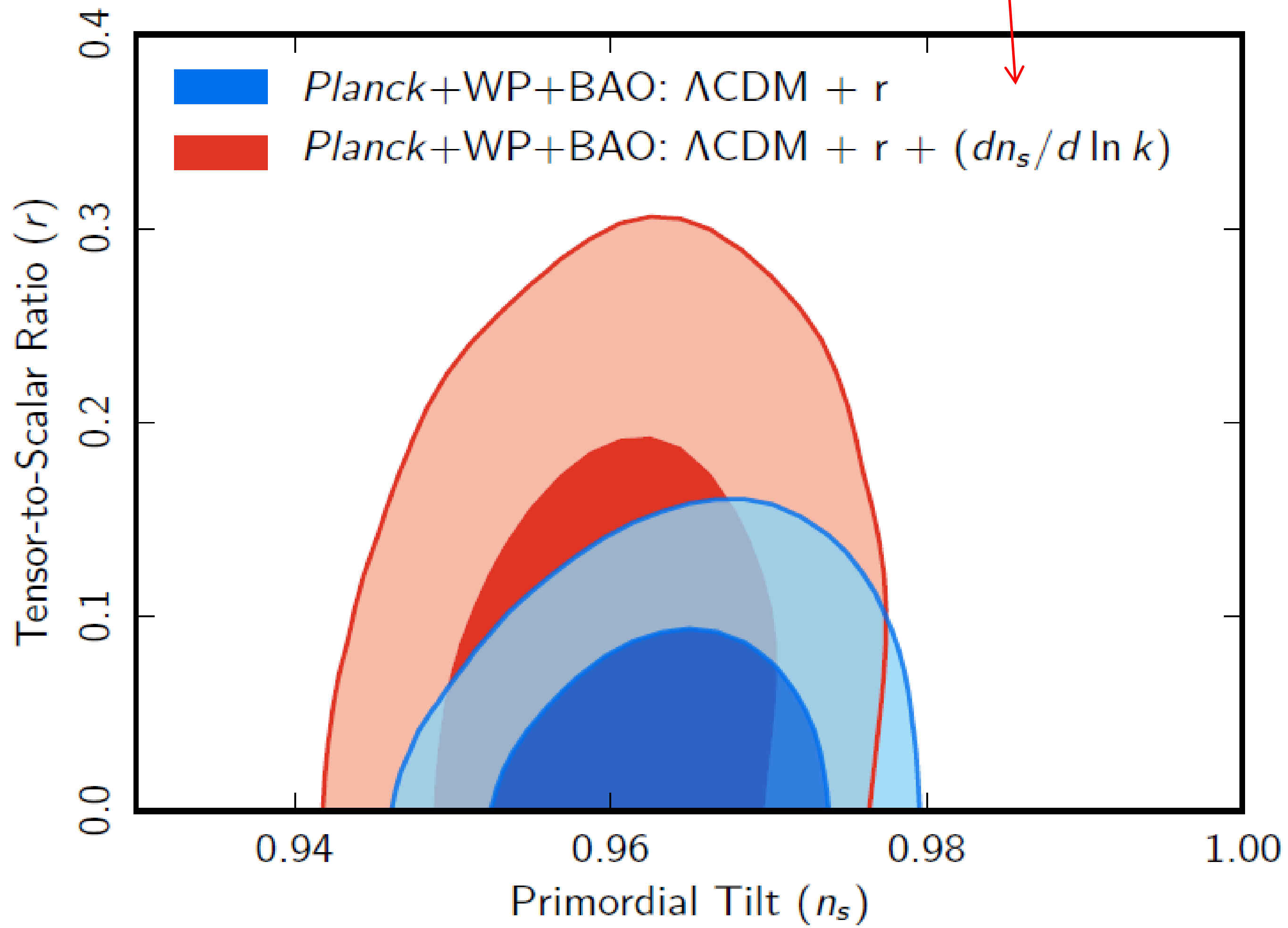


Ade et al (2013) Planck results

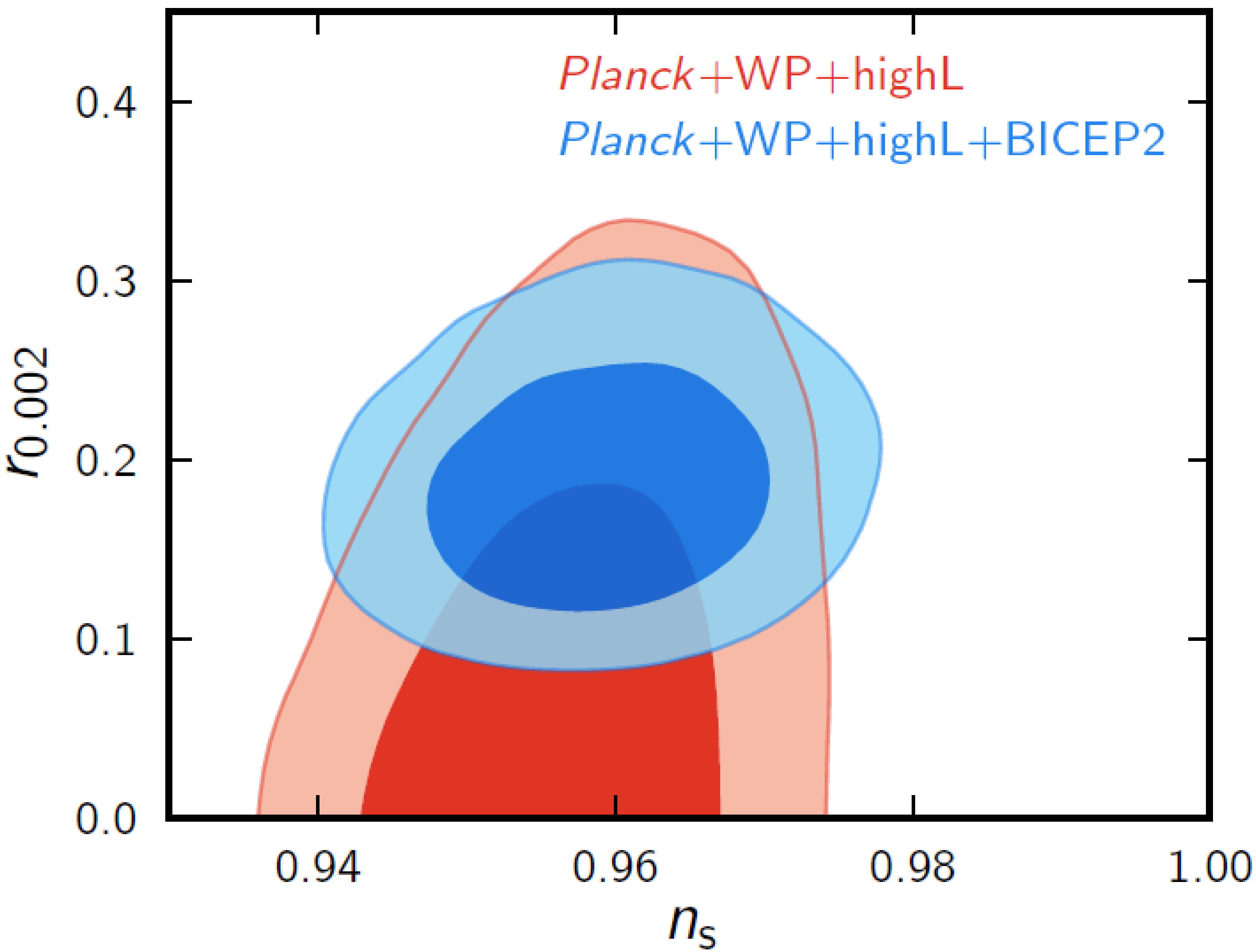


Ade et al (2013) Planck results

Allows for a running spectral index

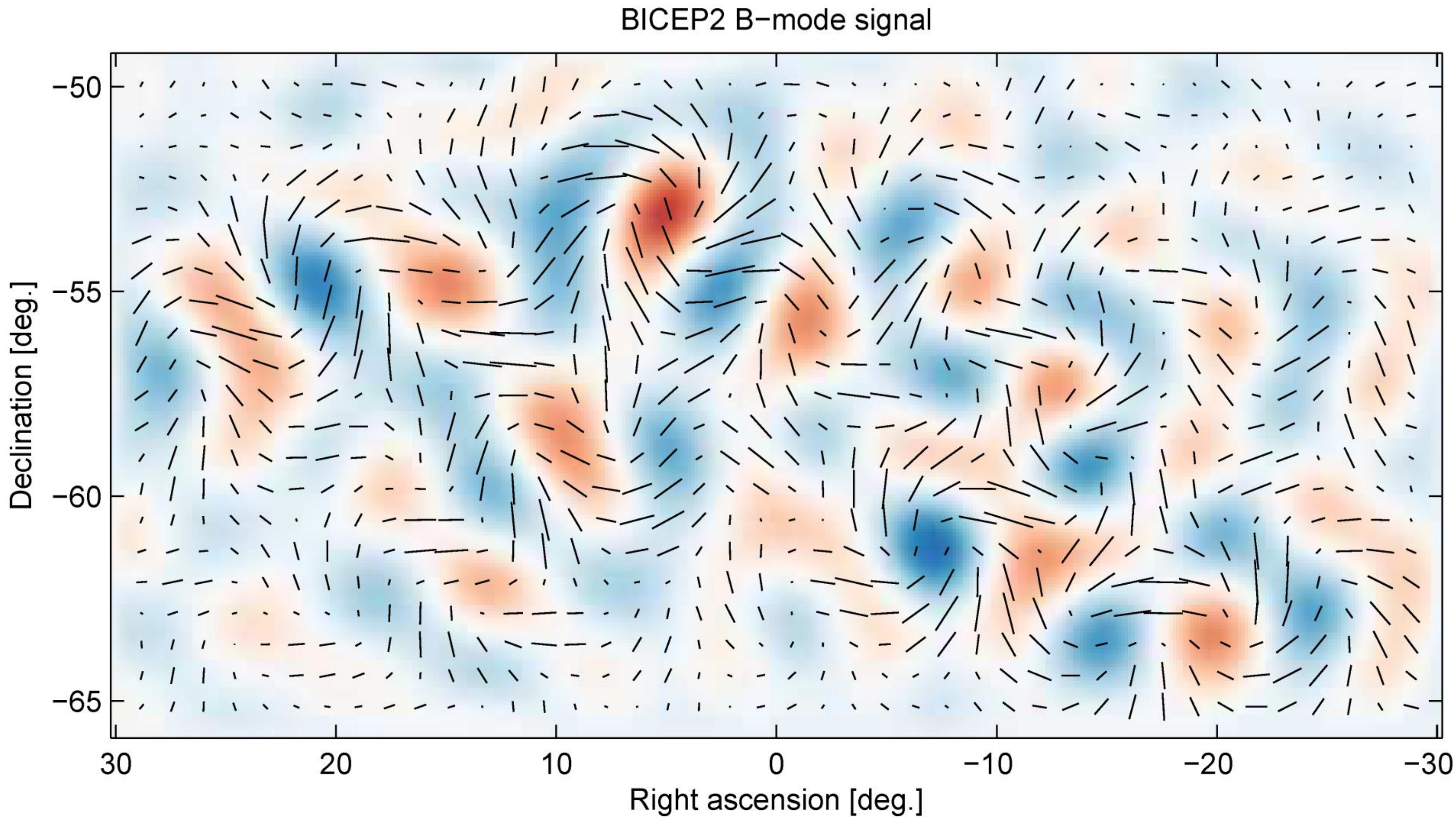


Ade et al (2014) BICEP-2 results



So...

- *Detection of B-mode polarisation looks secure.   Is it primordial?....*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So...

- *Detection of B-mode polarisation looks secure. Is it primordial?....*

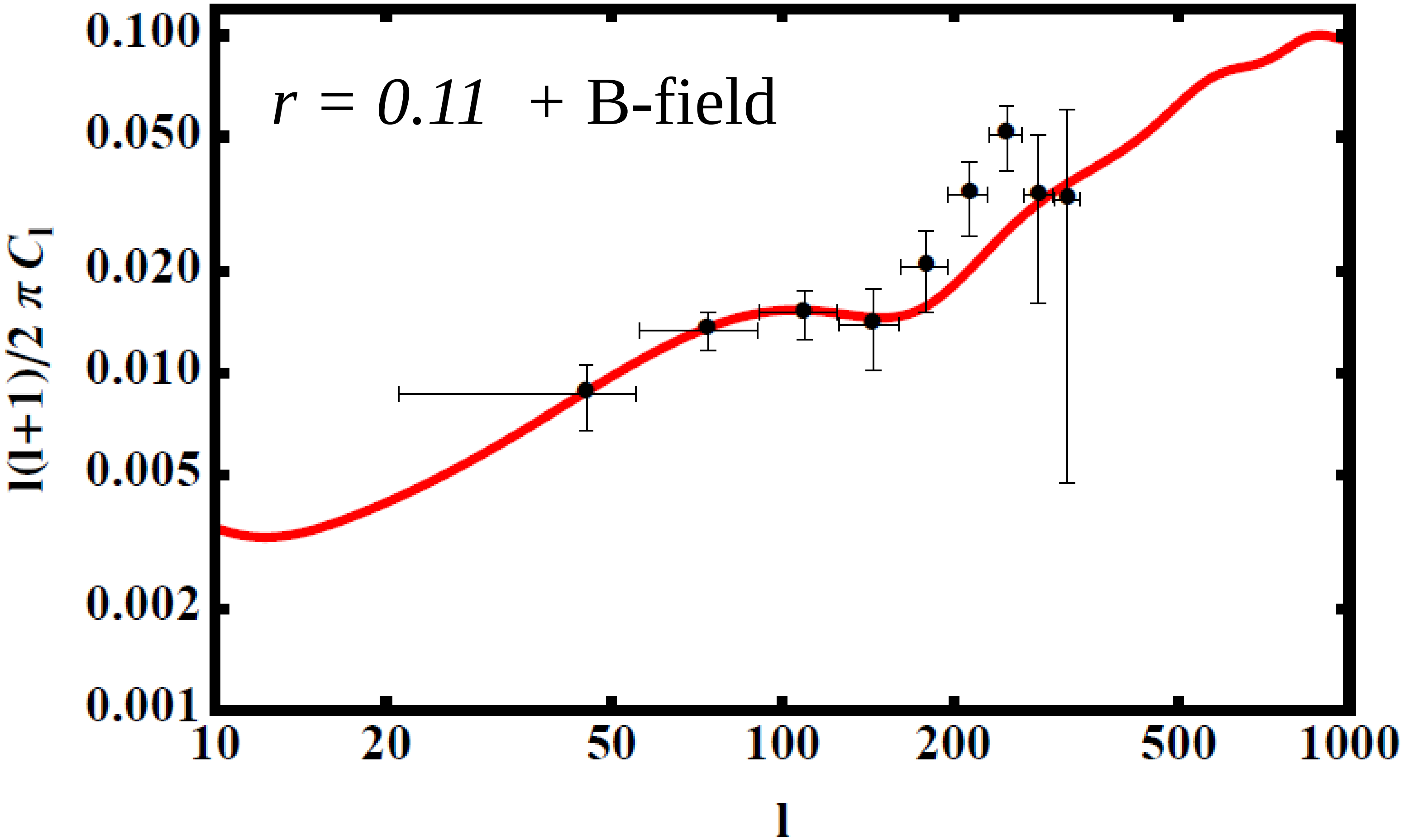
- *Are we seeing gravitational waves from inflation?*

See Dent, Krauss & Mathur arxiv: 1403.5166

Isocurvature perturbations – not quite ruled out!

See Bonvin, Durrer & Maartens arxiv: 1403.6768

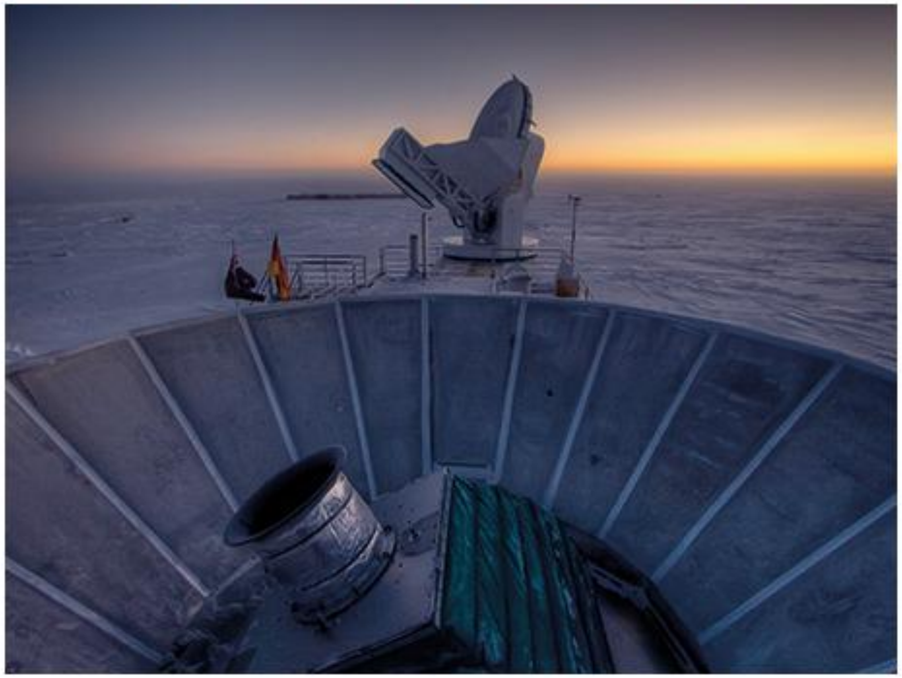
Some of B-mode signal from magnetic fields



Bonvin, Durrer & Maartens arxiv: 1403.6768

TOP STORY

› Multiverse gets real with glimpse of big bang ripples



The first direct signs of a cosmic growth spurt that set space-time rippling means that we may live in just one of an infinite number of universes

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Max Tegmark
MIT physicist, author of "Our Mathematical Universe"

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