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presentation

Fingerprinting the Universe

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The cosmological quest

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Our aim? To put in place a precision description of our Universe that can stand the test of time, and perhaps outlive us all.

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Our aim? To put in place a precision description of our Universe that can stand the test of time, and perhaps outlive us all.

This ambition is possible because

- The superb quality of new observational data, from many sources.
- The development of theoretical models containing enough ingredients to explain observed phenomena.
- The power of modern high-performance computers for data acquisition and analysis, and for determining theoretical predictions from models.

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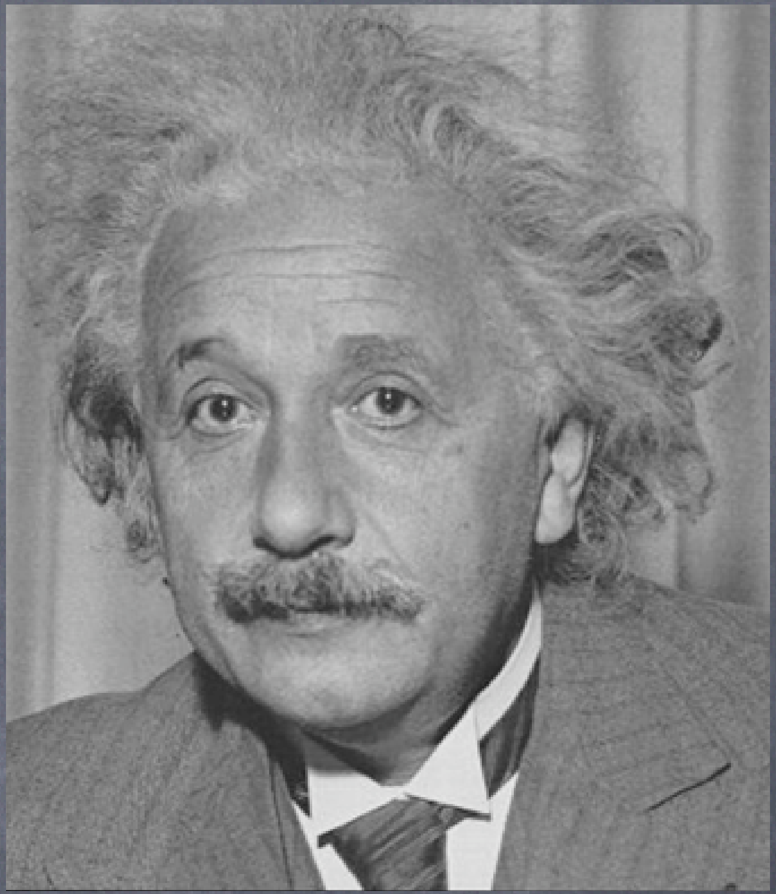
If a model is to be much good, it should be
(a) consistent with observations, and (b) predictive.

Albert Einstein

Declared `Person of the Century' by Time Magazine, 1999



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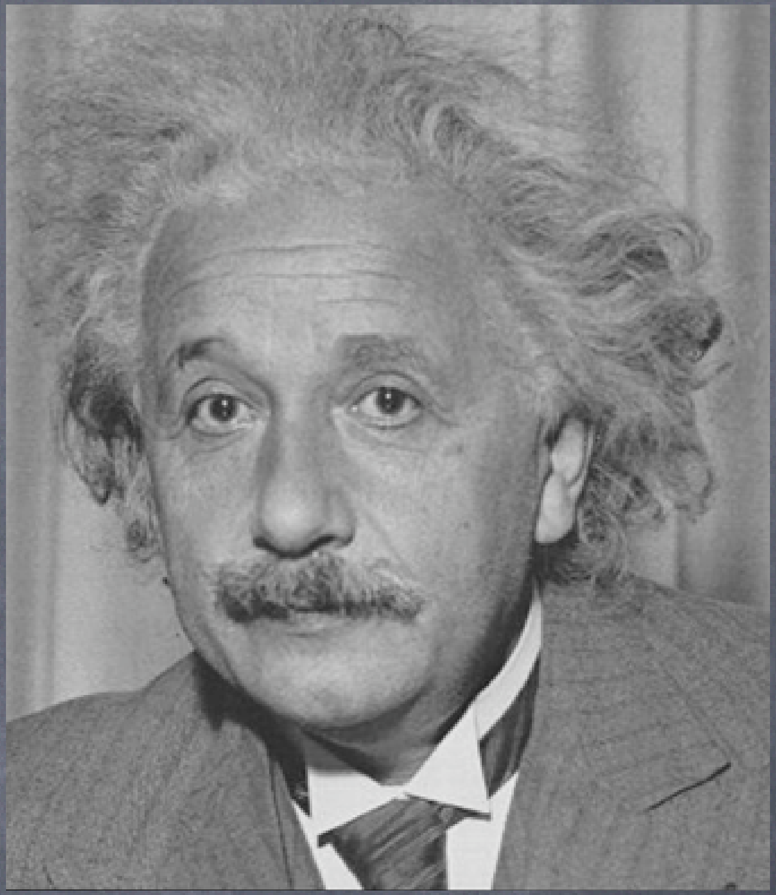

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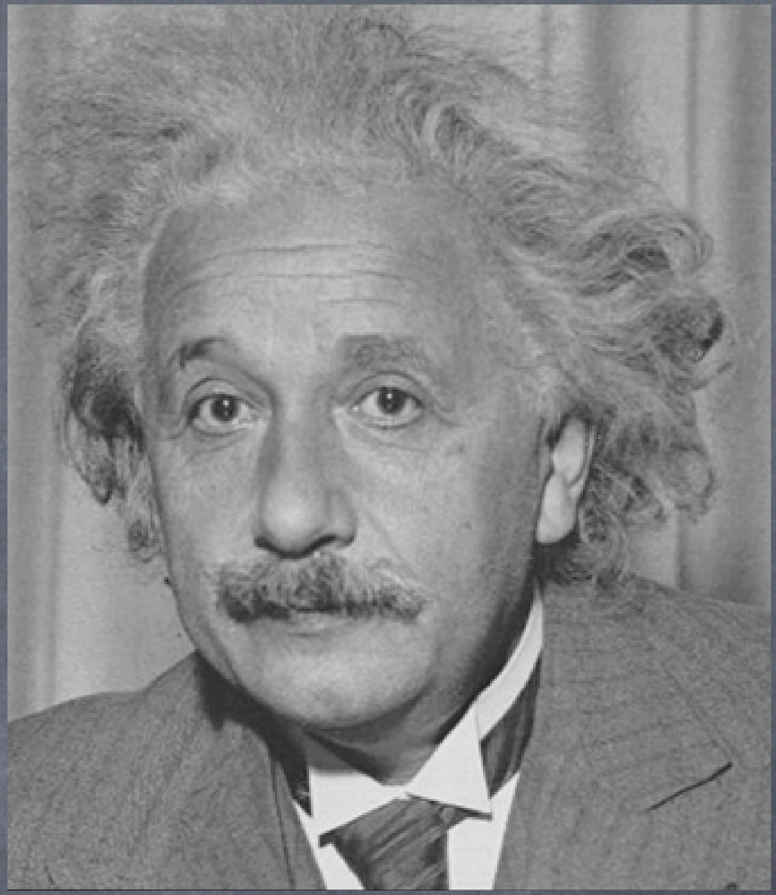

- In 1915, Einstein published his general theory of relativity. It was a theory of gravity, attributing gravitational forces to a curvature of space-time.
- Soon afterwards, working with Willem de Sitter, he made the first cosmological models, but they were static Universe models.

Alexander Friedmann

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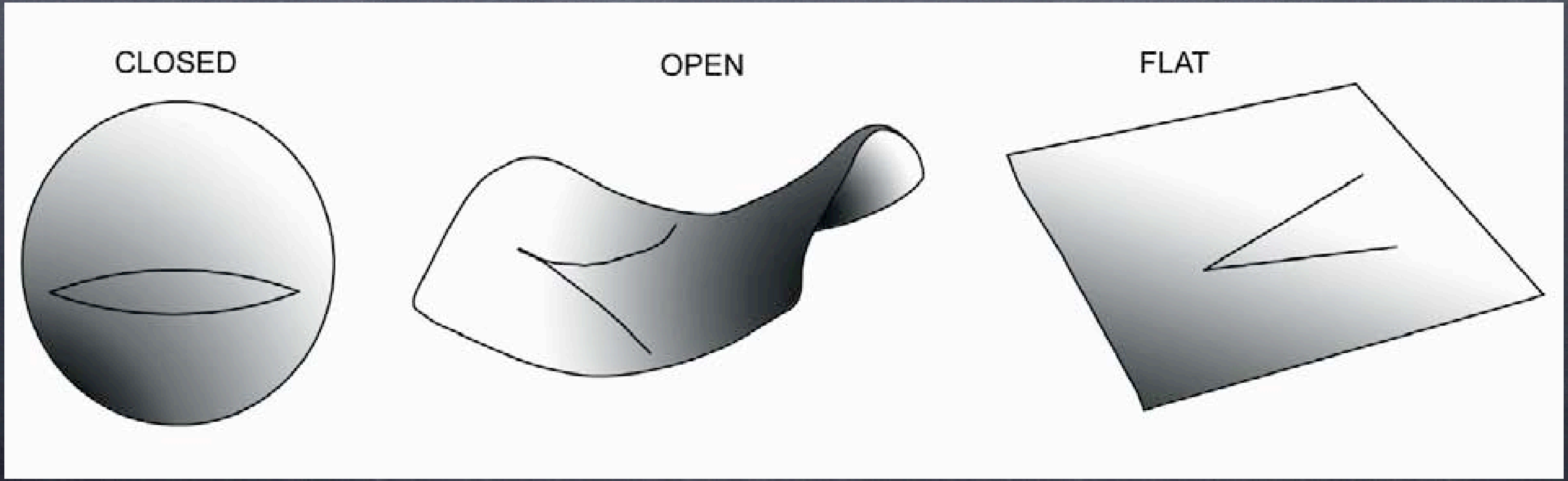

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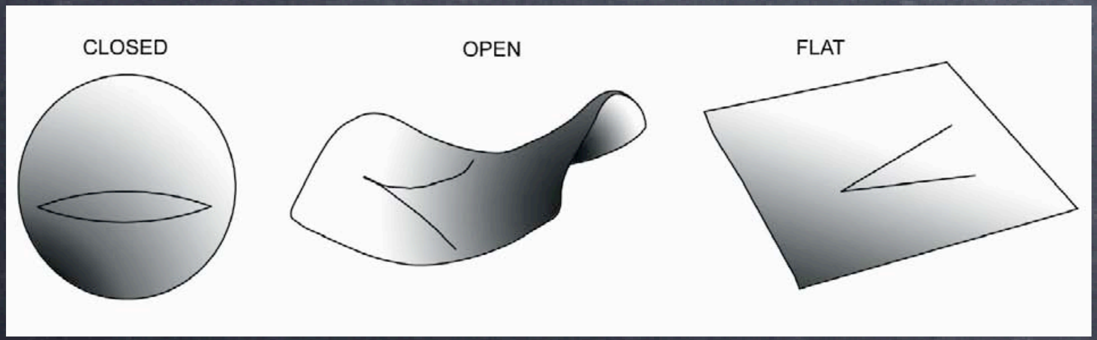

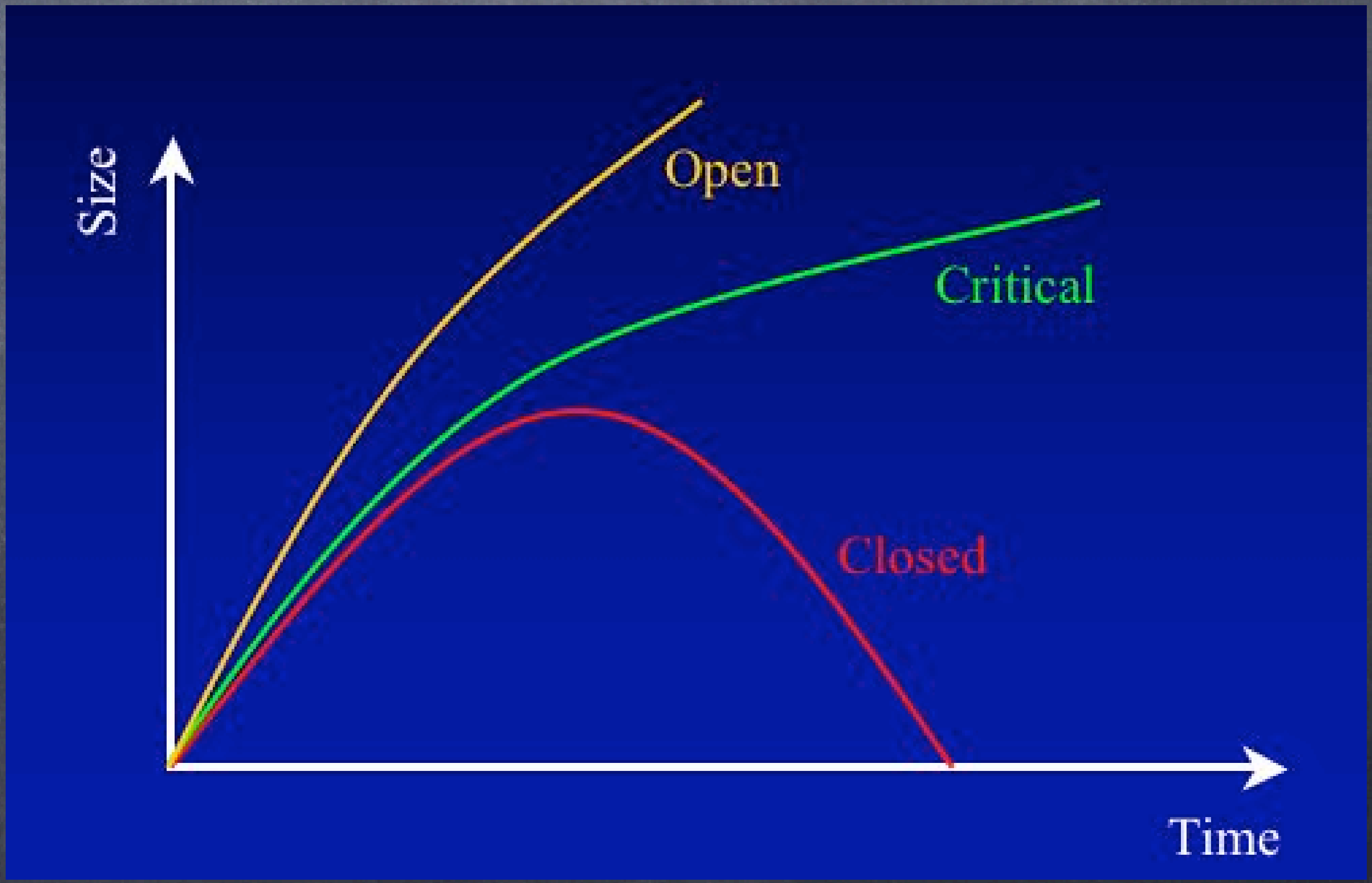

Edwin Hubble

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"... an Olympian, tall, strong, and beautiful, with the shoulders of the Hermes of Praxiteles ... there was a sense of power, channeled and directed in an adventure that had nothing to do with personal ambition and anxieties and lack of peace. There was hard concentrated effort and yet detachment. The power was controlled."

Grace Hubble, recollecting her first meeting with her future husband.

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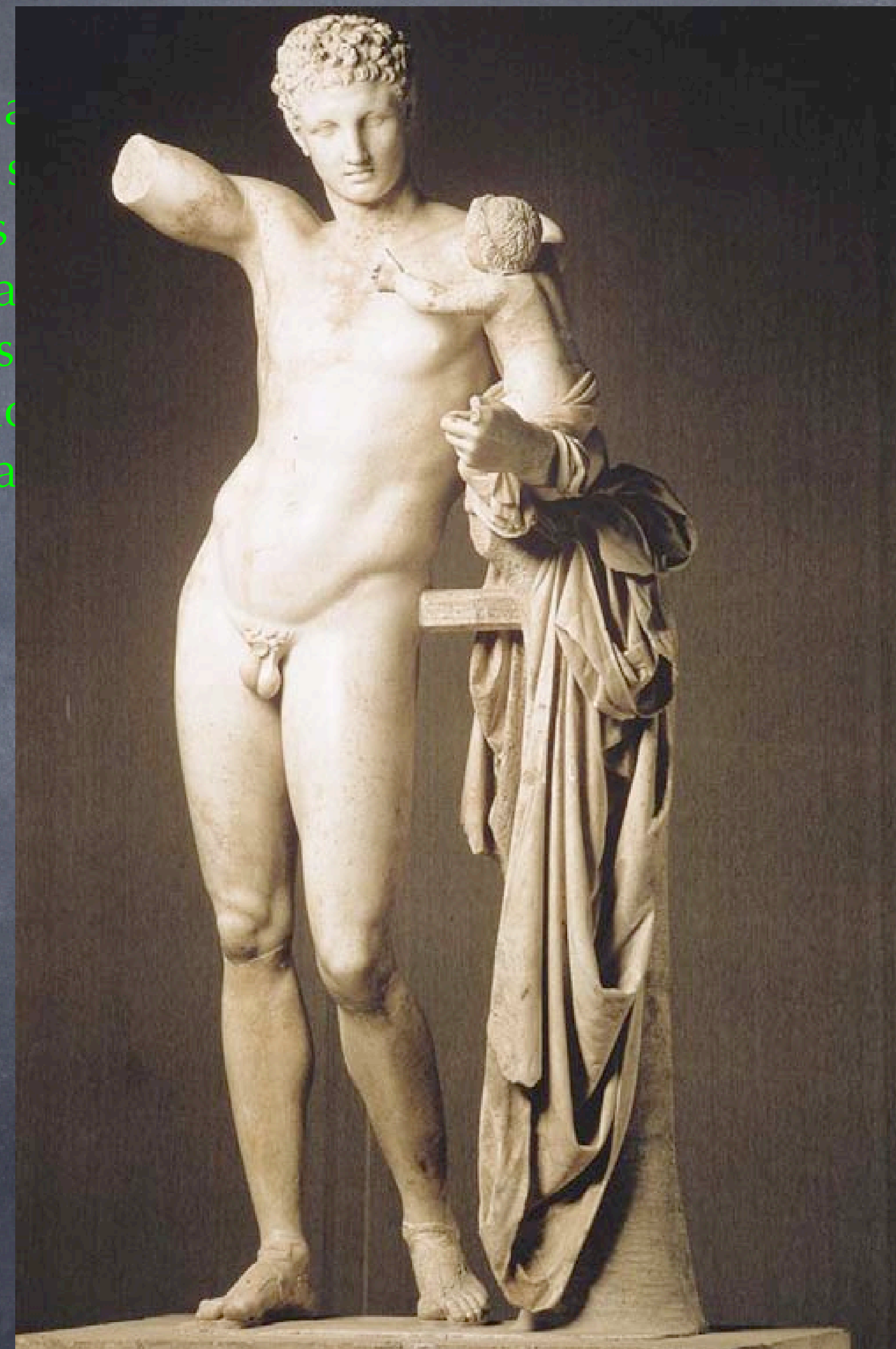

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Vesto Slipher: discoverer of the expansion of the Universe, circa 1915.

George Gamow & co

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- Gamow was especially interested in the formation of light elements by nuclear reactions, when the Universe was around one second old.
- In particular, in 1948 Alpher and Herman predicted the existence of the cosmic microwave background. Unfortunately this would soon be forgotten.

The cosmic microwave background

In 1964, Arno Penzias and Robert Wilson discovered the cosmic microwave background, a relic radiation left over from the big bang. Its existence vindicated the work of Alpher, Herman, and Gamow, and established the Hot Big Bang model as the standard description of the Universe.

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"Cosmology: a search for two numbers"

Allan Sandage

The dark stuff, part I

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Fritz Zwicky

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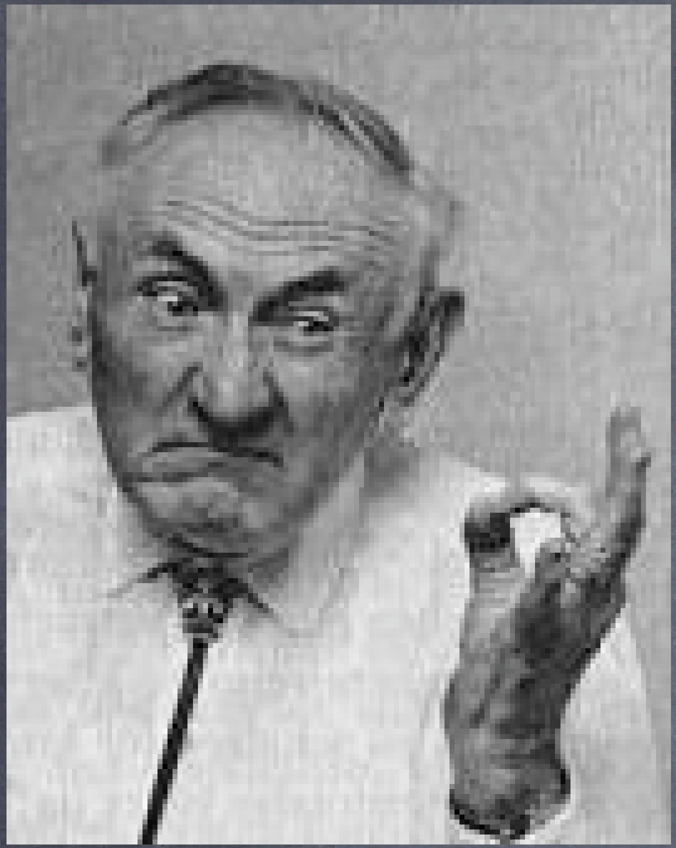

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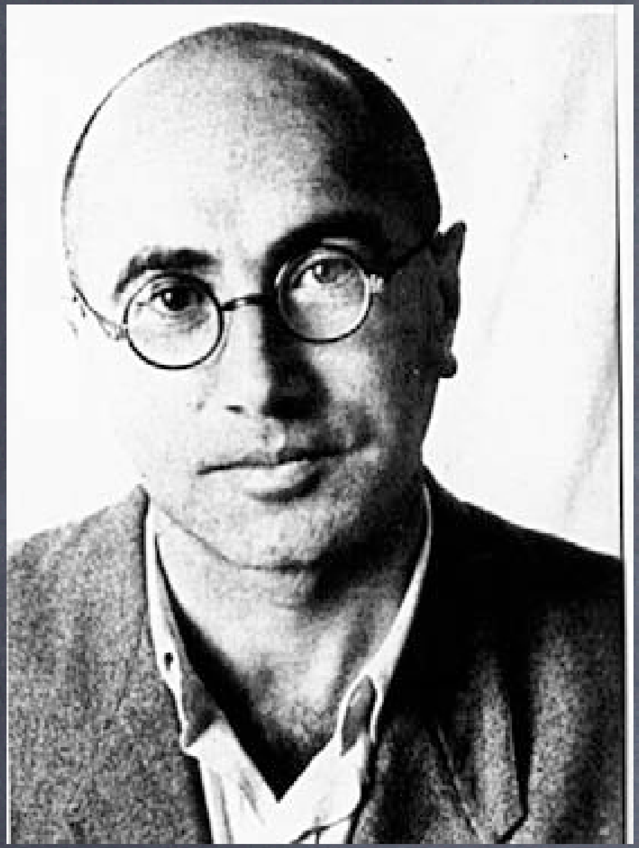
Suddenly, there were more than two cosmological parameters.

The formation of structures



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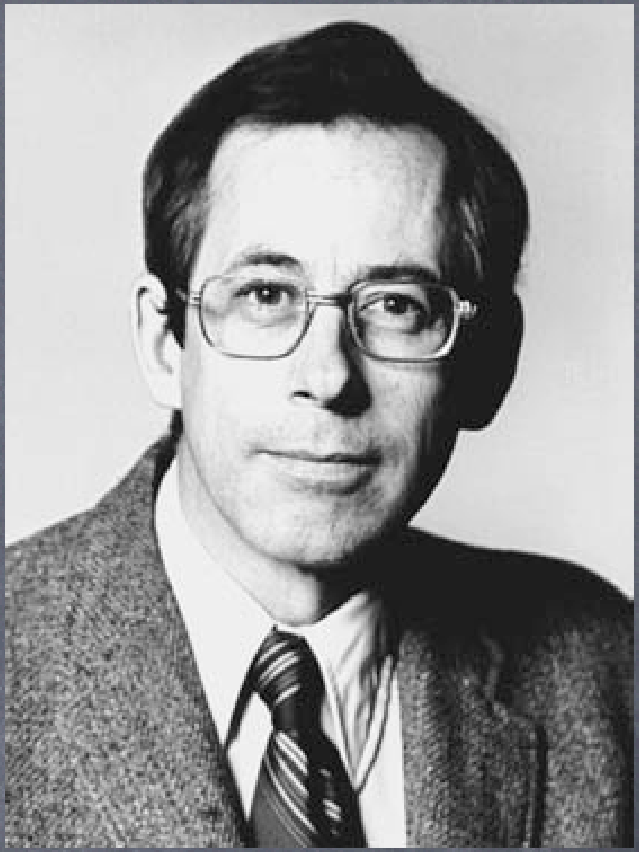

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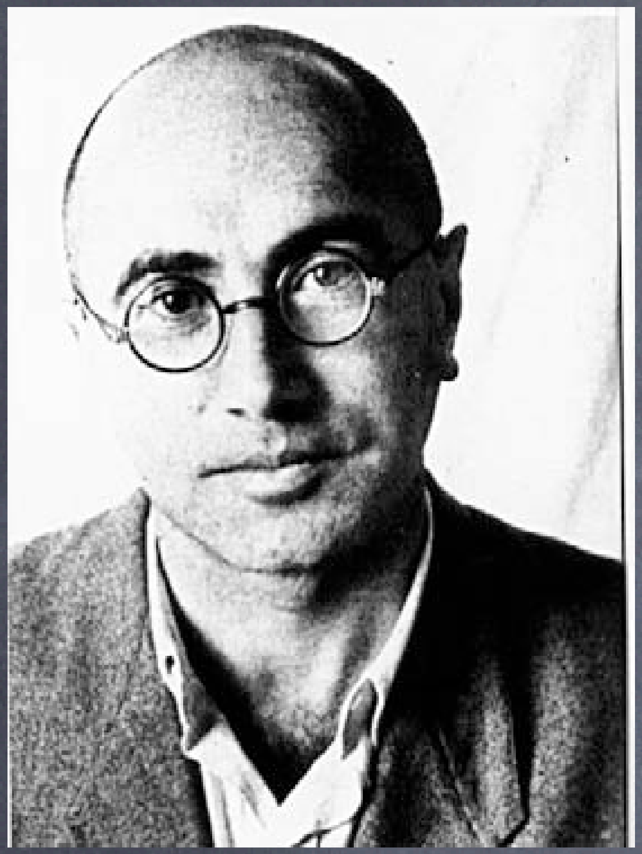

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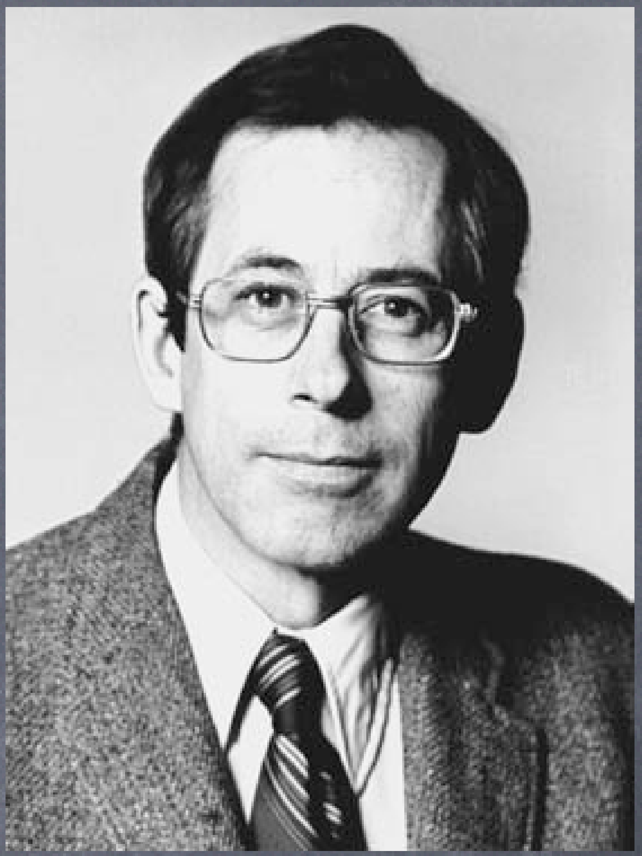

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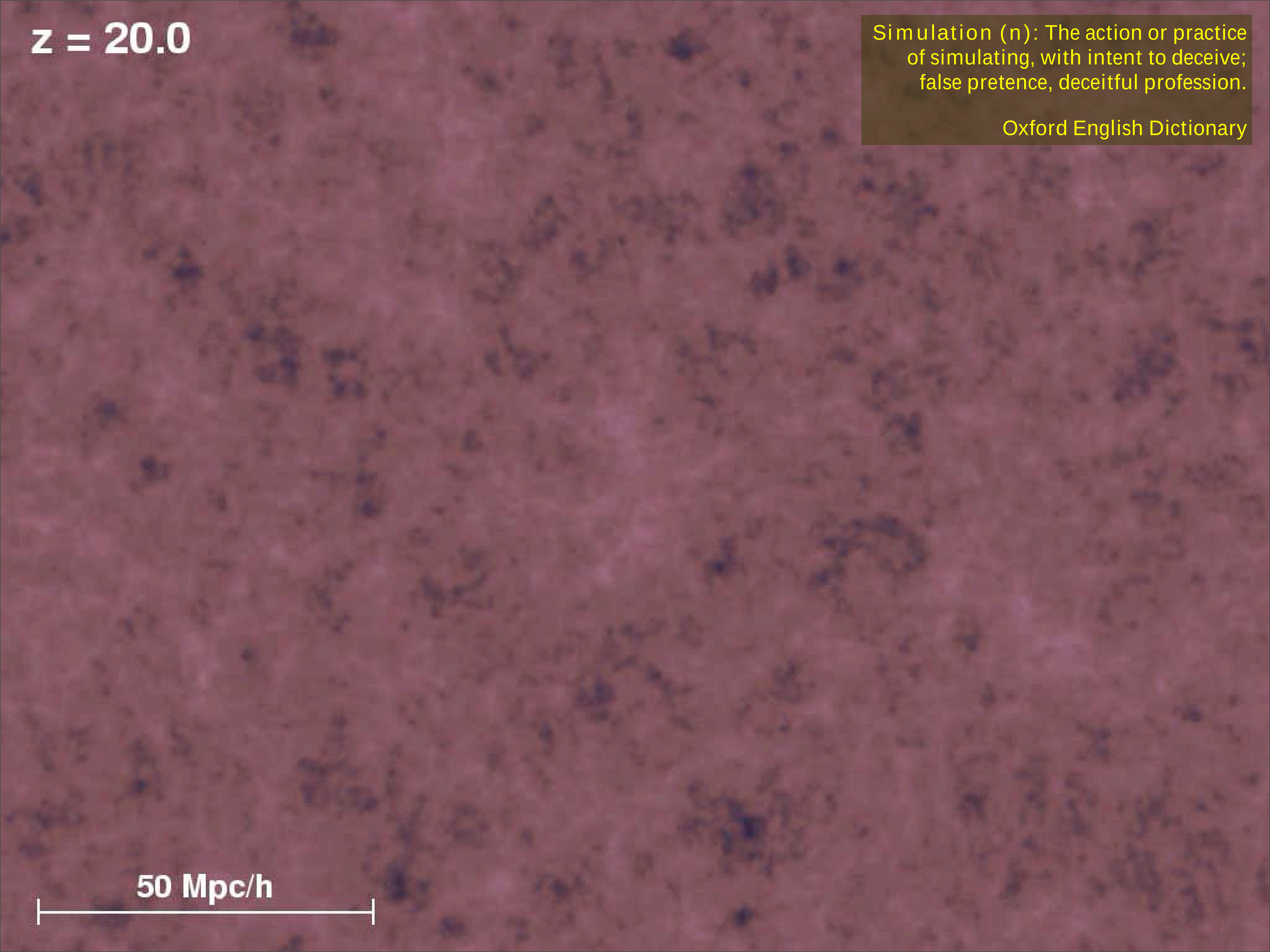
Because the way in which structures form depends on the cosmological model, accurate measurements can tell us about that model.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Simulation (n): The action or practice of simulating, with intent to deceive; false pretence, deceitful profession.
Oxford English Dictionary
50 Mpc/h

The road to precision cosmology

The COBE satellite, launched 1989.

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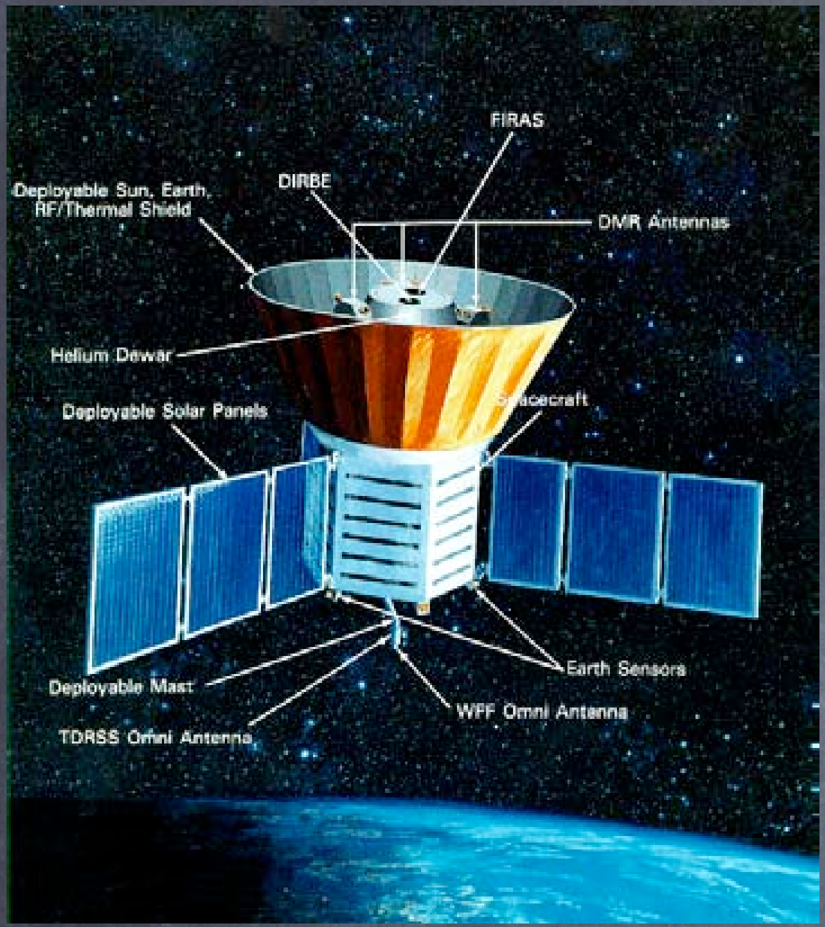

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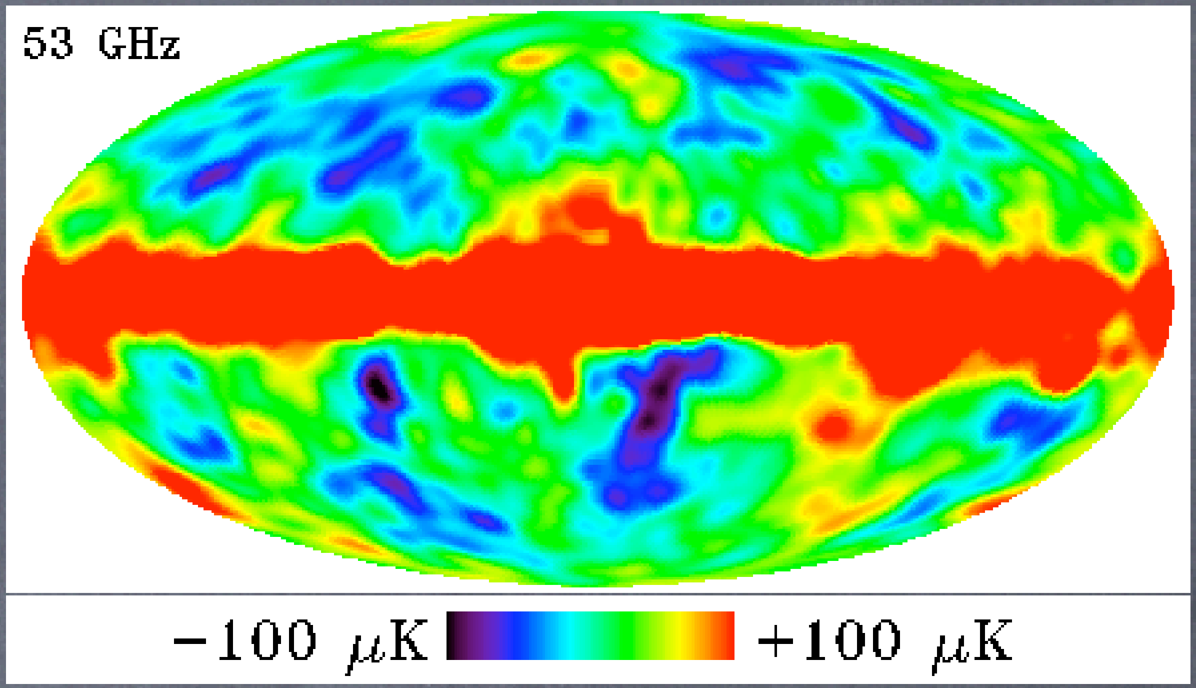
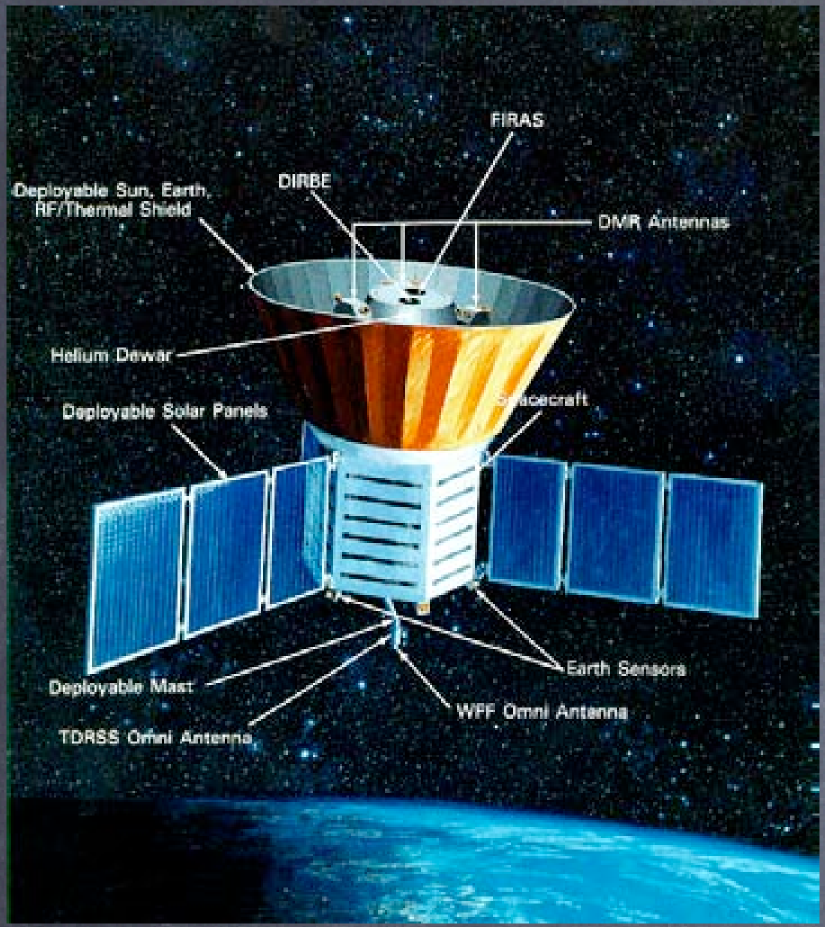


Four-year COBE map of the cosmic microwave background sky.

The road to precision cosmology



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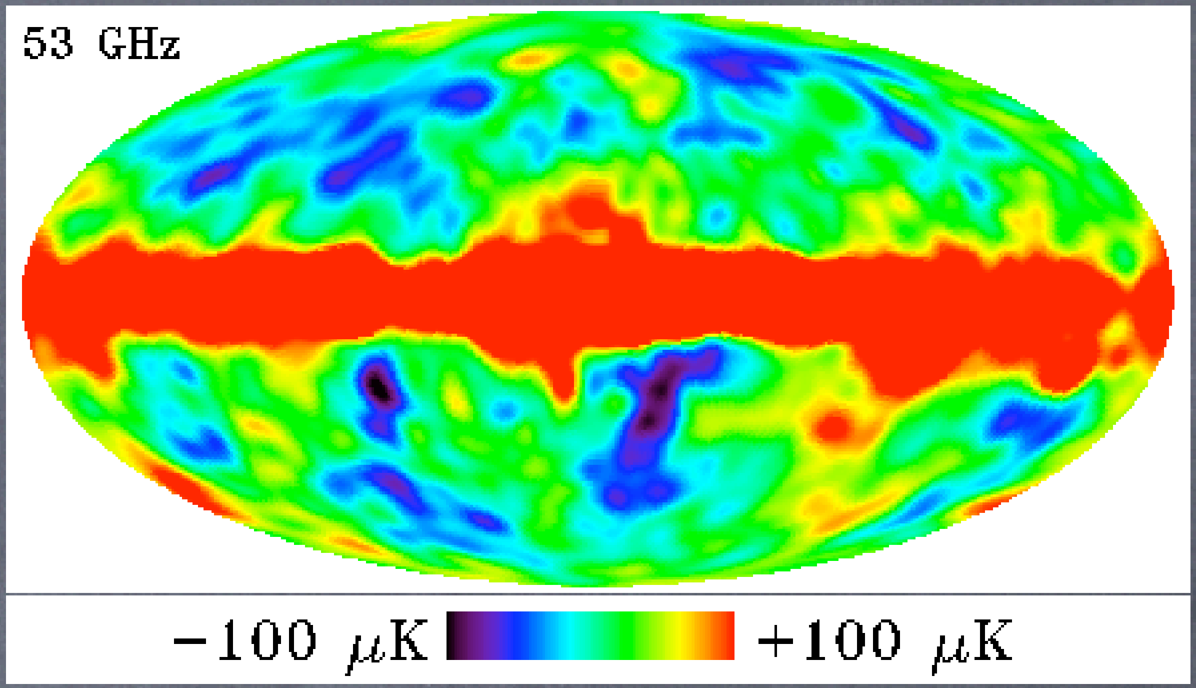

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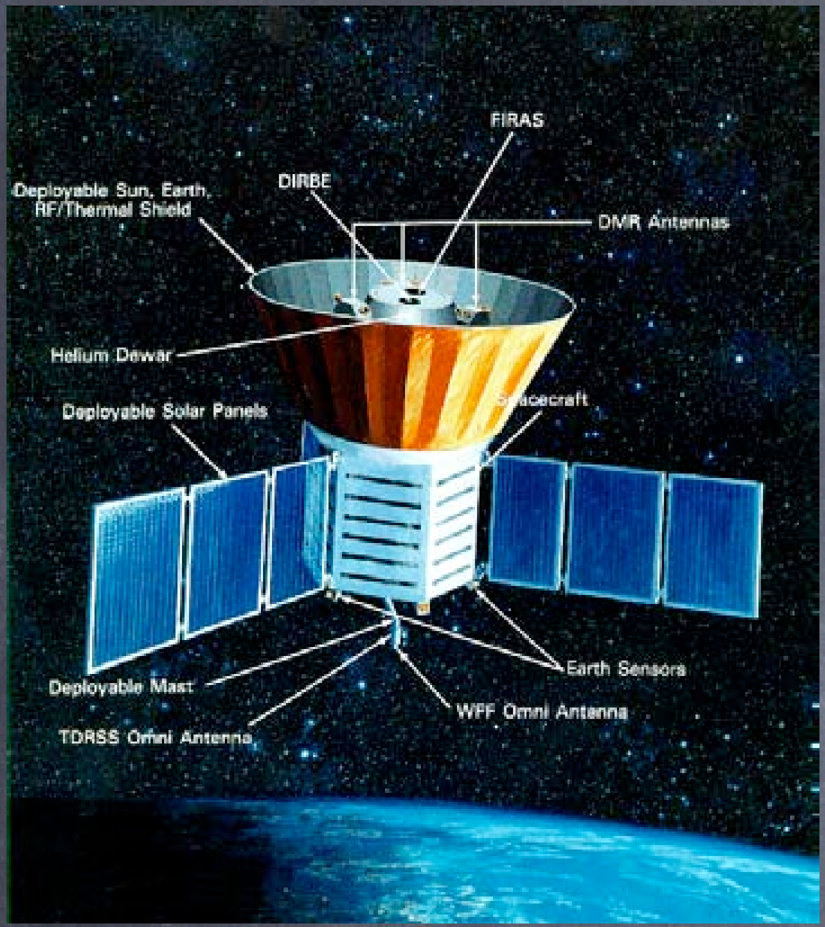

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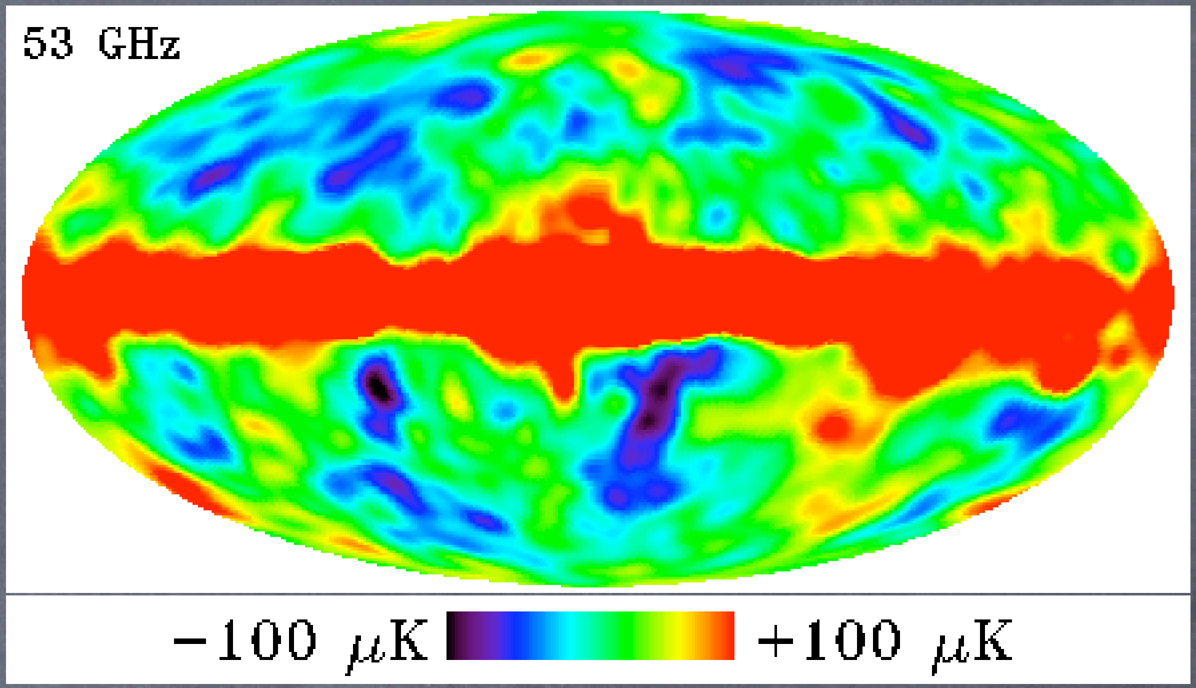
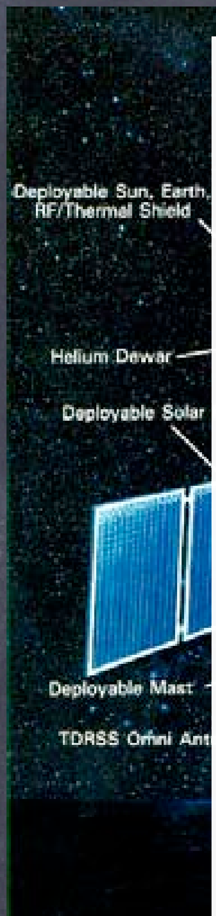
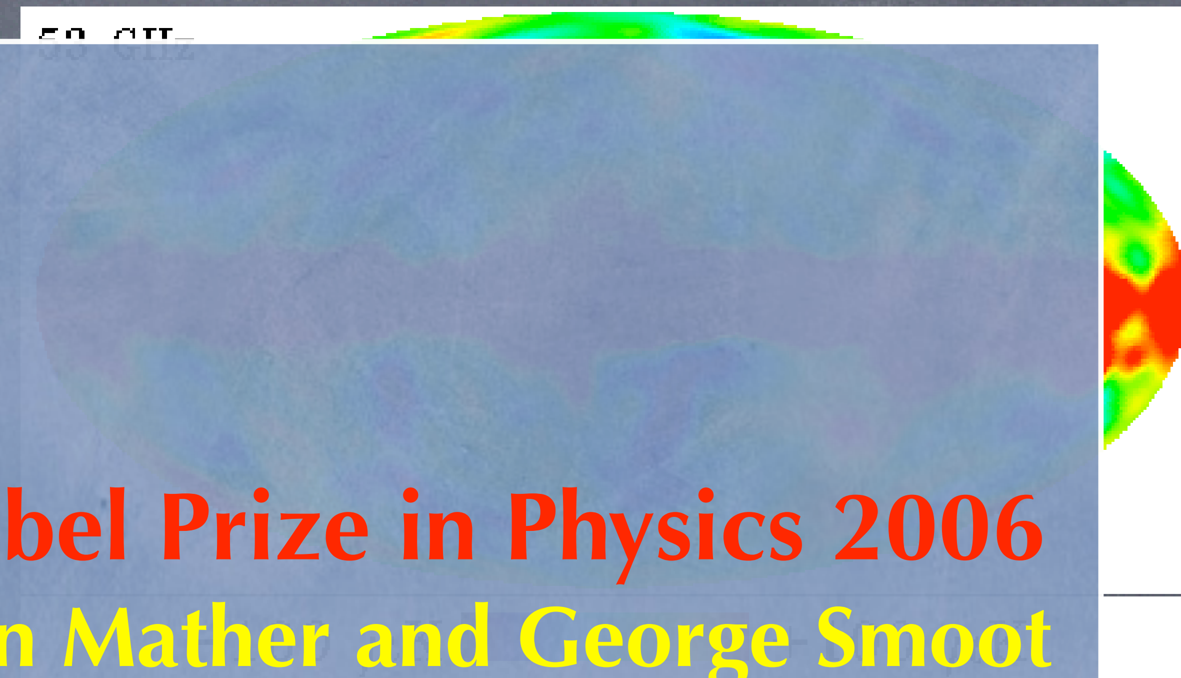


Four-year COBE map of the cosmic microwave background sky.

- The COBE satellite made the first detection of irregularities in the cosmic microwave background in 1992.
- These are the irregularities that later evolve to form galaxies. They correspond to temperature variations of only about one part in a hundred thousand.

The road to precision cosmology





Nobel Prize in Physics 2006

John Mather and George Smoot

"For the discovery of the black-body form and anisotropies of the cosmic microwave background".

The dark stuff, part II

The last ingredient of modern cosmological models fell into place in the late 1990s. Observations of distant supernovae indicated that the expansion of the Universe is accelerating. Several types of observation now support this conclusion.

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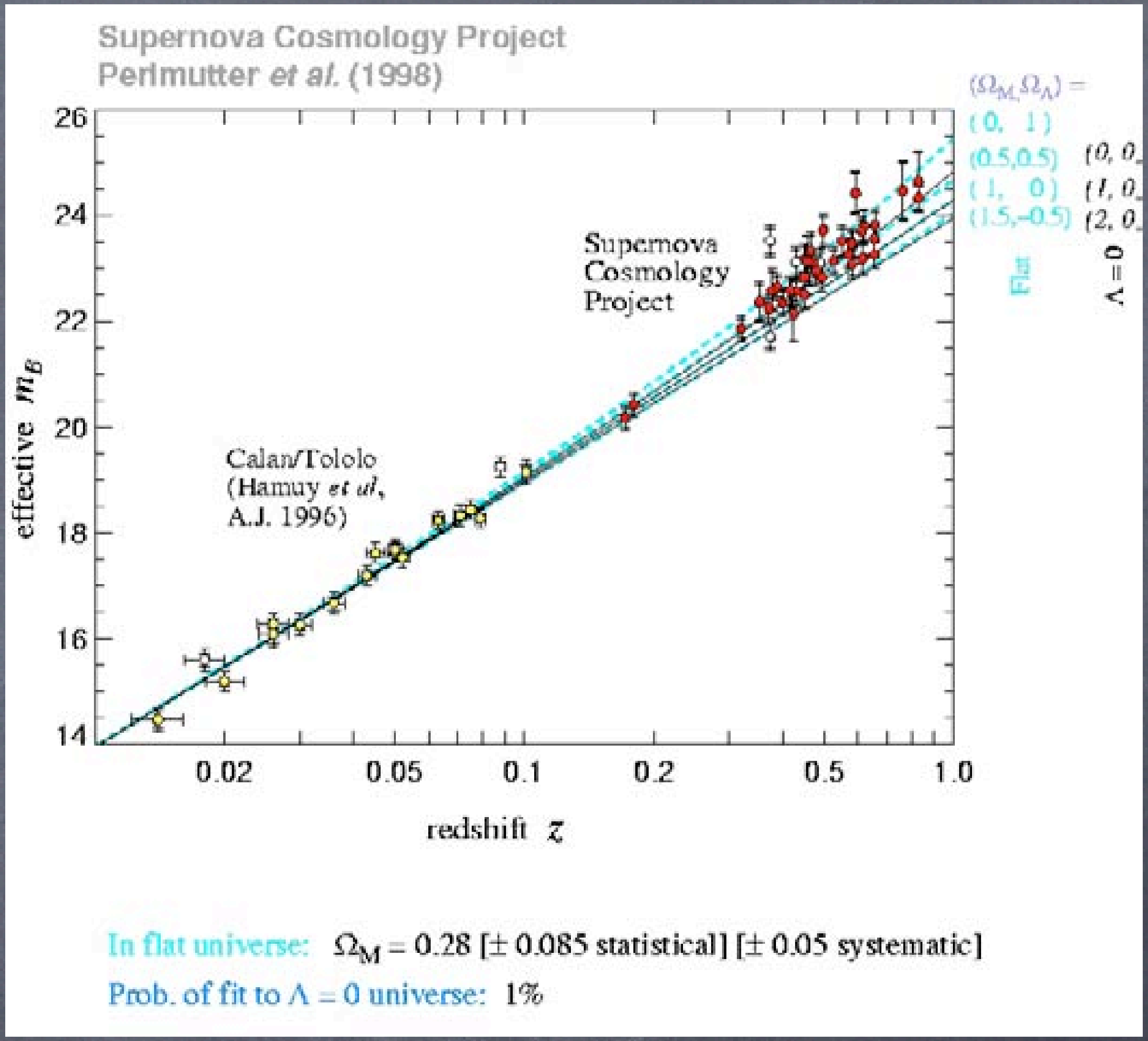

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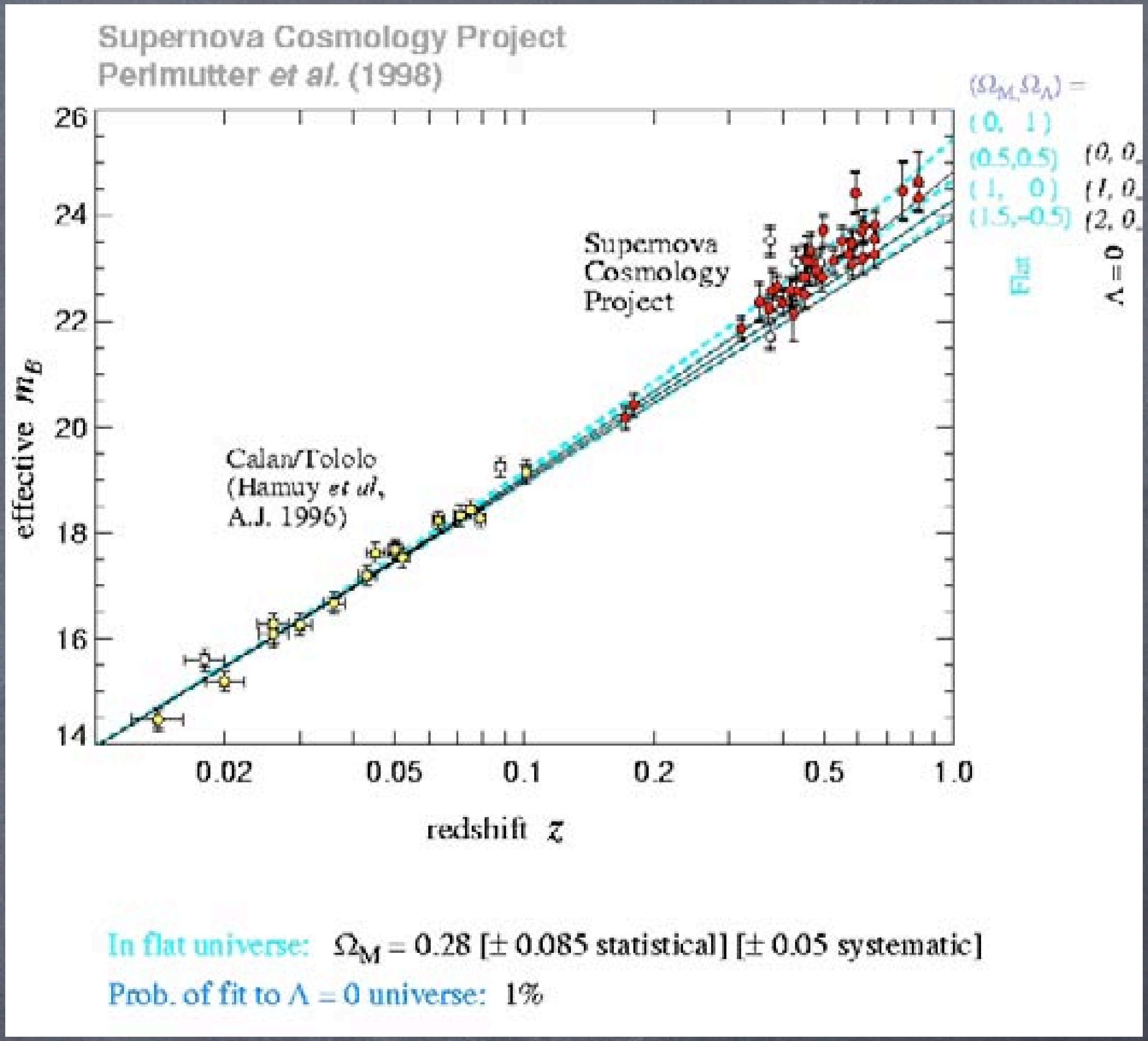

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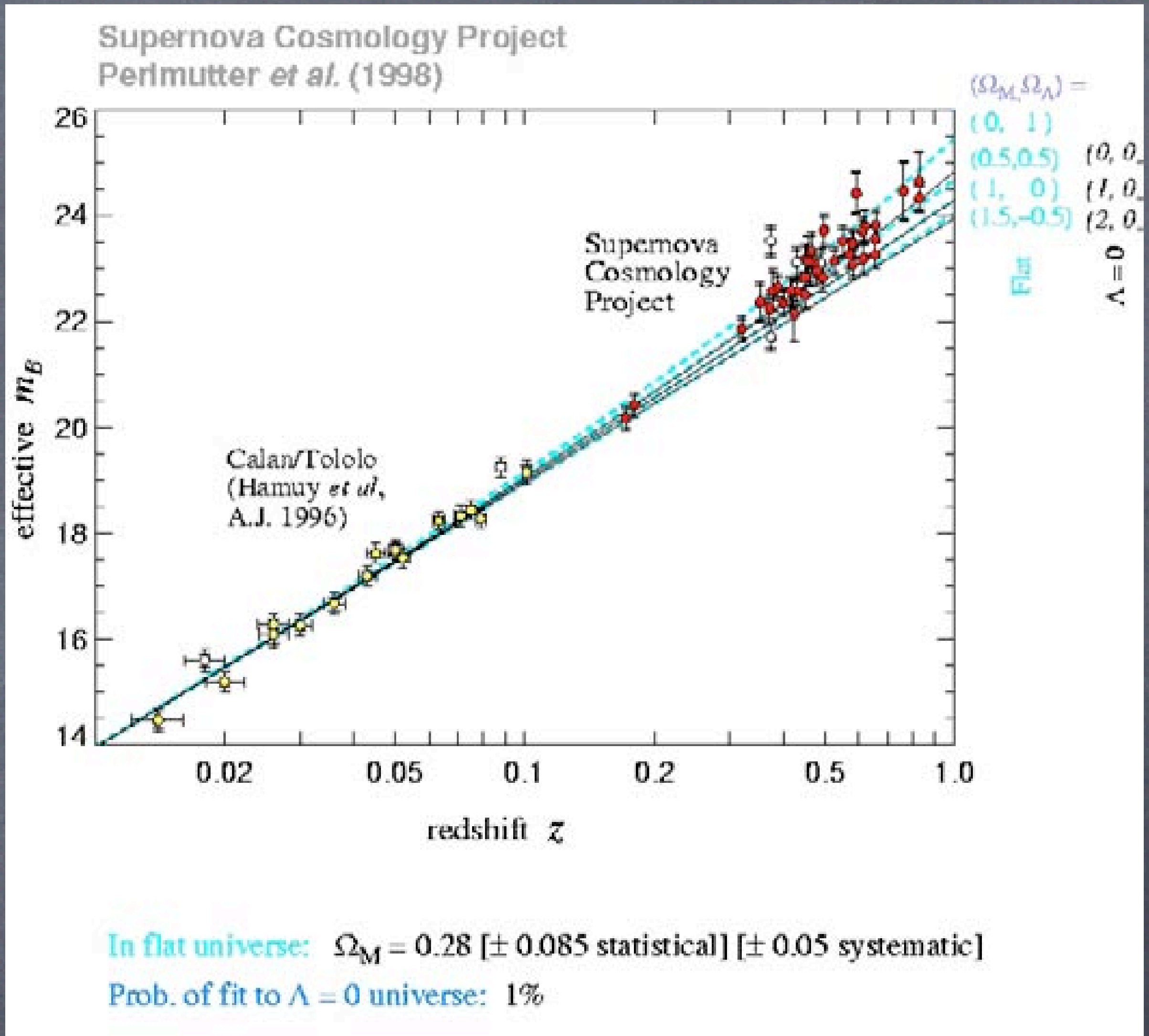

- No-one knows what is responsible for this acceleration, but whatever it is has come to be known as **dark energy**.
- The simplest type of dark energy, known as a cosmological constant, was actually first considered by Albert Einstein!

Interlude

What does a theoretical cosmologist actually do?

A day in the life ...

A day in the life ...

What cosmology actually looks like ...

"Karma police, arrest this man
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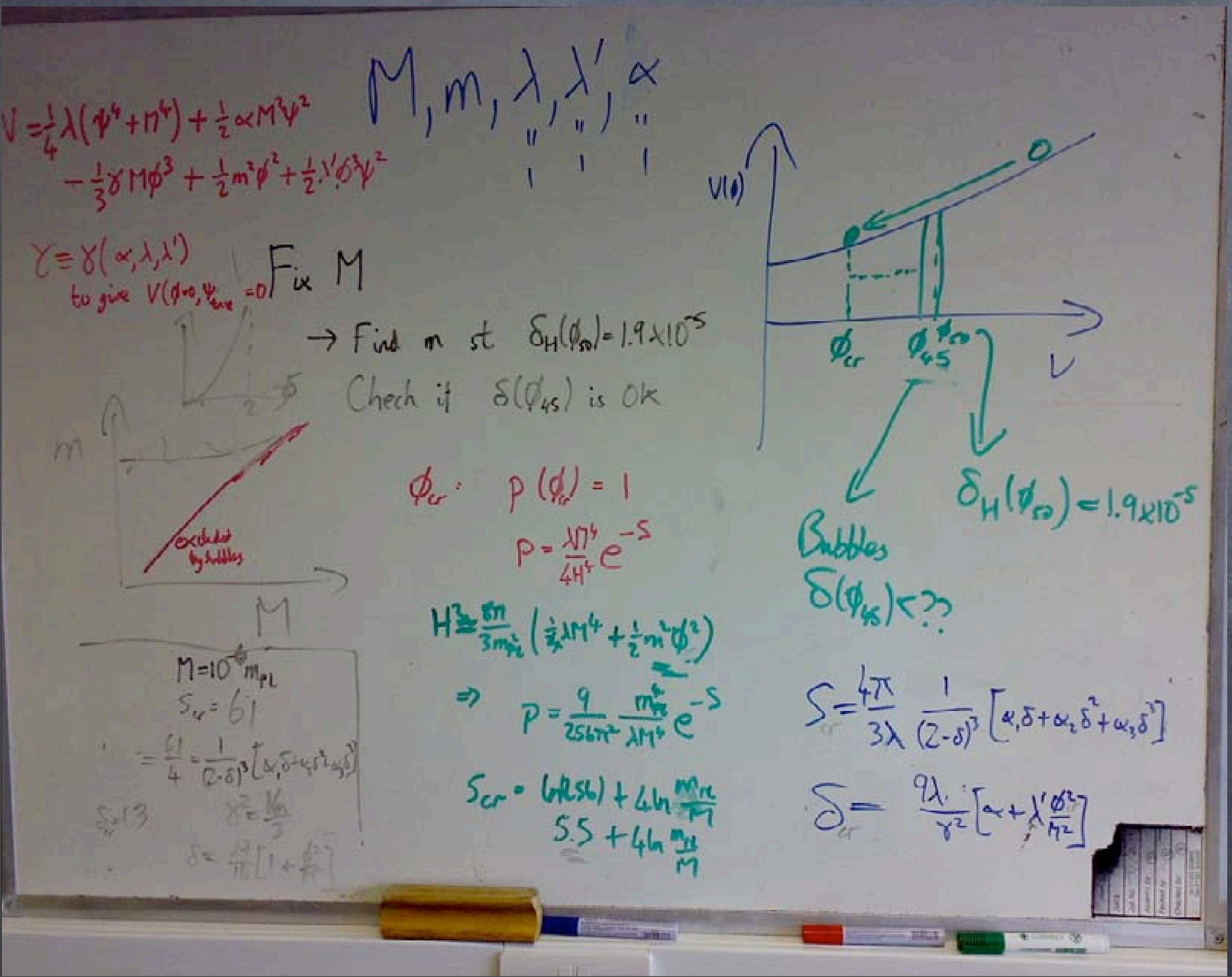

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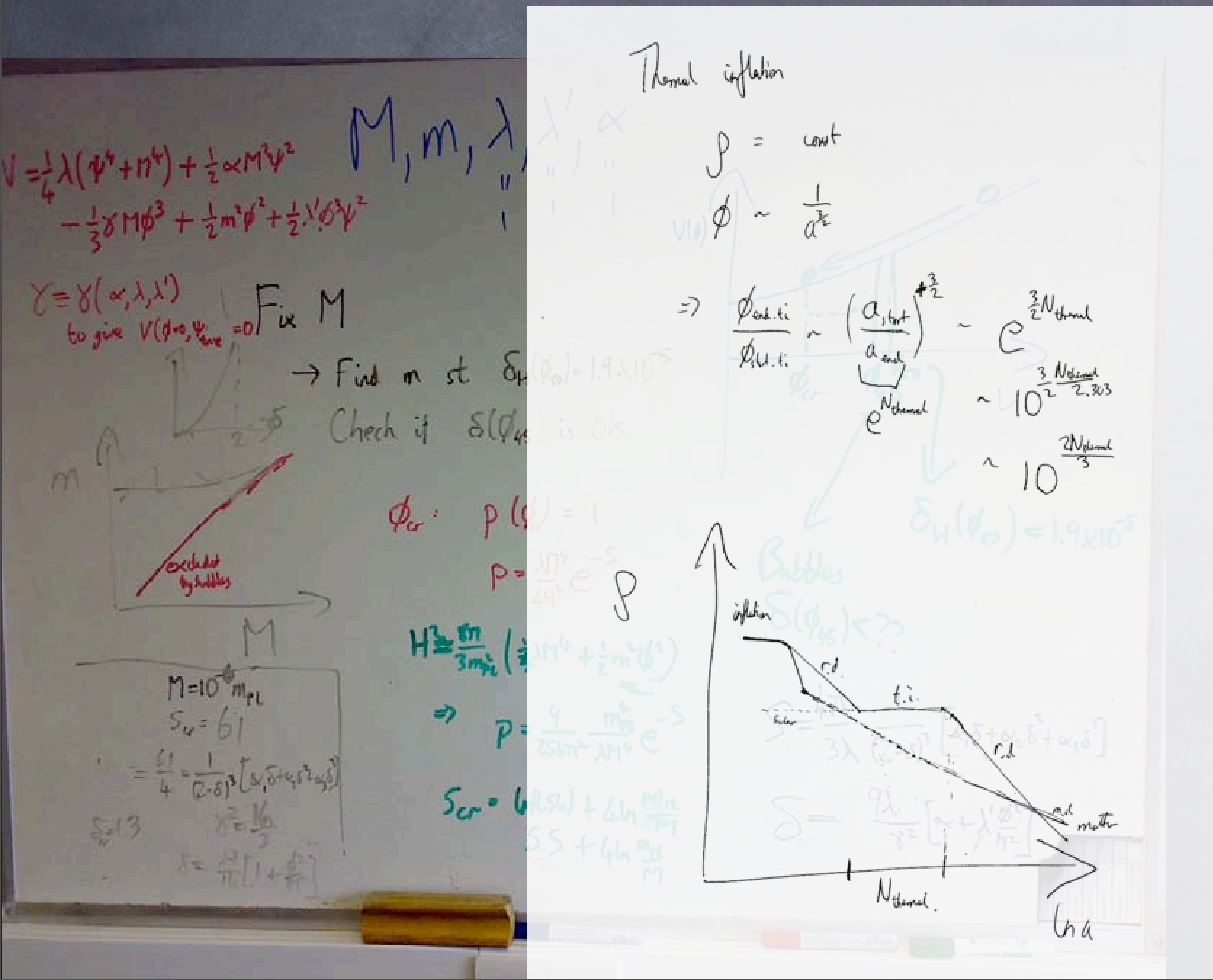

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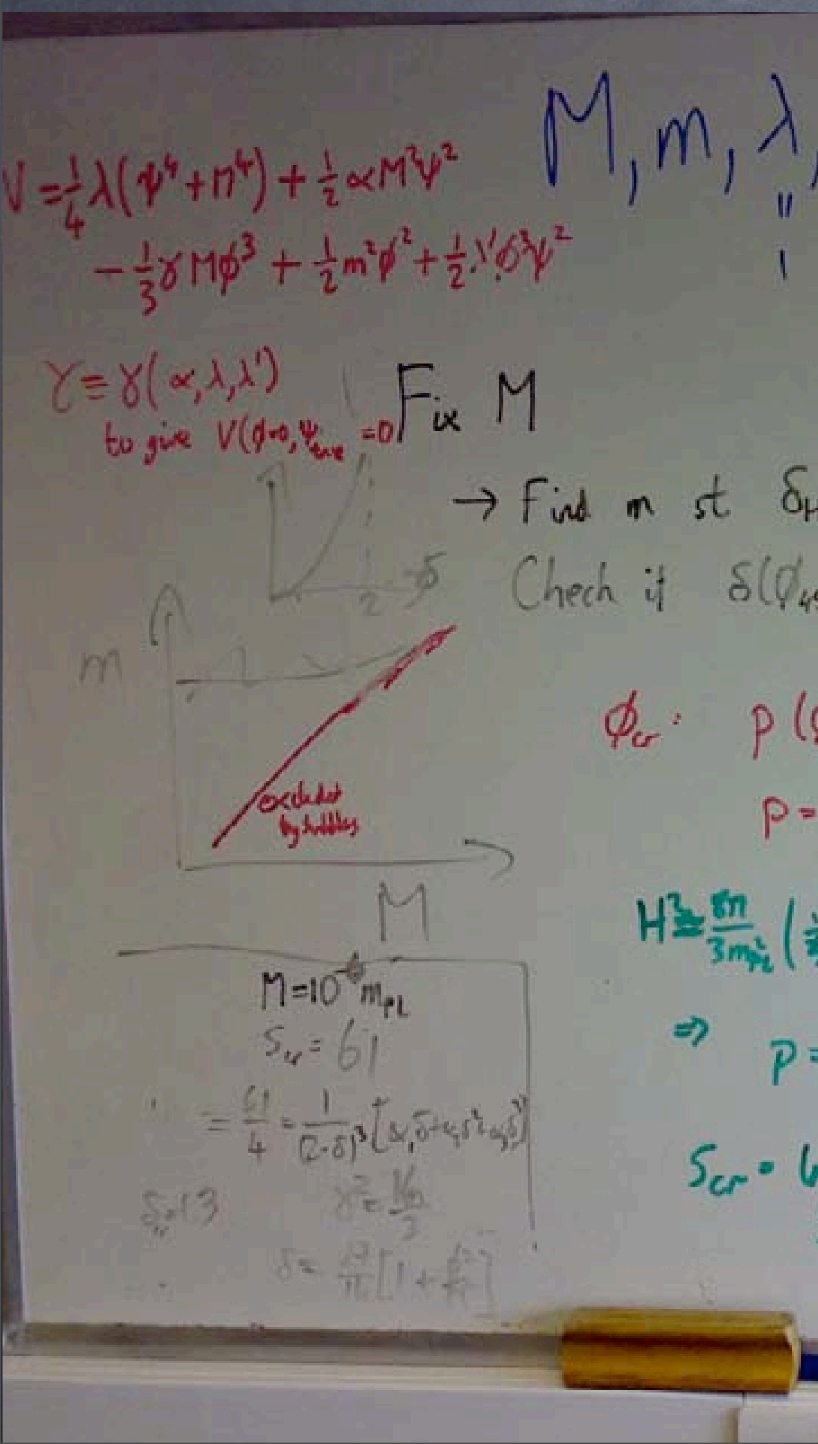

C. Tracker potentials

Cosmological tracker potentials/solutions have been studied in detail by numerous authors [2, 17, 18, 19, 20]. These potentials are such that the late-time evolution of the field can be essentially independent of initial conditions, thus providing a possible solution to the coincidence problem. This behaviour is achieved through a type of dynamical attractor solution, and the conditions for it to be possible given a particular potential have been given and studied in detail by Steinhardt *et al.* [18]. Defining $\Gamma \equiv V''V/V'^2$, where prime denotes a derivative with respect to the field, the two sufficient conditions for a potential to possess a tracker solution are

$$\Gamma > 1 - \frac{1-w_b}{6+2w_b}\,, \qquad (16)$$

$$\left|\Gamma^{-1}\frac{d\Gamma}{d\ln a}\right| = \left|\frac{d\phi}{d\ln a}\left(\frac{V'}{V}+\frac{V'''}{V''}-2\frac{V''}{V'}\right)\right| \ll 1\,. \qquad (17)$$

The first of these conditions ensures convergence to the tracker solution (i.e. perturbations away from it are suppressed), and the second ensures an adiabatic evolution of the field that is necessary for the first condition to be applicable (and is what one would expect of a function that is to maintain a dynamical attractor independent of initial conditions).

If these conditions are fulfilled, the field will eventually approach the tracker solution (unless the initial quintessence energy density is too low), and the equation of state will then evolve according to

$$w_\phi \approx w_{\rm tracker} = \frac{w_b - 2(\Gamma-1)}{1+2(\Gamma-1)}\,, \qquad (18)$$

possibly breaking away from the tracker solution if either of the conditions later become violated. In assessing whether tracking is taking place, one also has to check whether the actual evolution on the tracker potential corresponds closely to the tracker solution. An illustration of tracker behaviour can be seen in Fig. 1.

We additionally impose the condition $w_\phi < w_b$, where w_b is the background energy density. This is to ensure a possible solution of the coincidence problem by having the dark energy density grow with respect to the matter. This third condition is usually avoided by specifying the tracker condition as $\Gamma > 1$ rather than Eq. (16). The reason for not choosing $\Gamma > 1$ as our condition is related to our numerical treatment, and is discussed further in Section IV C 1.

As we need a non-zero second derivative of the potential with respect to the field for Γ to fulfil the tracker conditions, we restrict ourselves to the quadratic potential and the Padé series for the tracker viability analysis.

III. OBSERVABLES

The observables used are essentially geometric and are hence related to the comoving distance for a cosmology

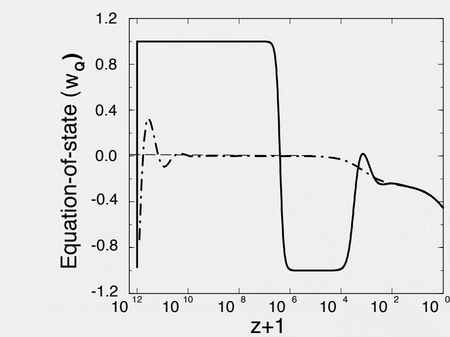

FIG. 1: Examples of the behaviour of the equation of state (here called w_Q) for a tracker potential. The thin-dashed line originating at $w_Q = 0$ corresponds to the tracker solution. Reproduced from Ref. [18].

described by the parameter vector Θ, given by

$$r(z;\Theta) = H_0^{-1}\int_0^z \frac{dz'}{E(z';\Theta)} \qquad (19)$$

where

$$E(z;\Theta) = \left[\Omega_m(1+z)^3 + (1-\Omega_m)e^{F(z;\Theta)}\right]^{1/2} \qquad (20)$$

and

$$F(z;\Theta) = 3\int_0^z (1+w_\phi(z';\Theta))\,d\ln(1+z')\,. \qquad (21)$$

We have not included growth-of-structure observations, which are not yet competitive with the measures we do use (see e.g. Ref. [21] for a directly-comparable example).

A. SNIa luminosity–redshift relation

The luminosity distance is given by

$$d_L(z;\Theta) = \frac{\mathcal{D}_L(z;\Theta)}{H_0} = (1+z)r(z;\Theta)\,. \qquad (22)$$

The apparent magnitude $m(z;\Theta)$ of a type Ia supernova can be expressed as

$$m(z;\Theta) = M + 5\log_{10}\frac{d_L(z;\Theta)}{\rm Mpc} + 25\,, \qquad (23)$$

where M is the absolute magnitude of SNIa (supposing they are standard candles). This can be rewritten as

$$m(z;\Theta) = \mathcal{M} + 5\log_{10}\mathcal{D}_L(z;\Theta)\,, \qquad (24)$$

where $\mathcal{M} = M - 5\log_{10}(H_0\,{\rm Mpc}) + 25 = M - 5\log_{10}(h_{70}) + 43.16$ [where $h_{70} = H_0/(70\,{\rm km/s/Mpc})$].

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- Large cosmological surveys

  We are involved in large ground- and space-based observational programmes.

The era of precision cosmology

Precision observations

Precision theory

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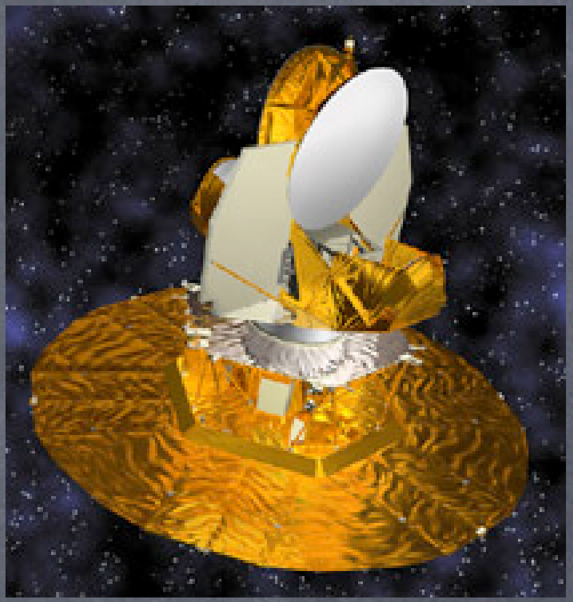

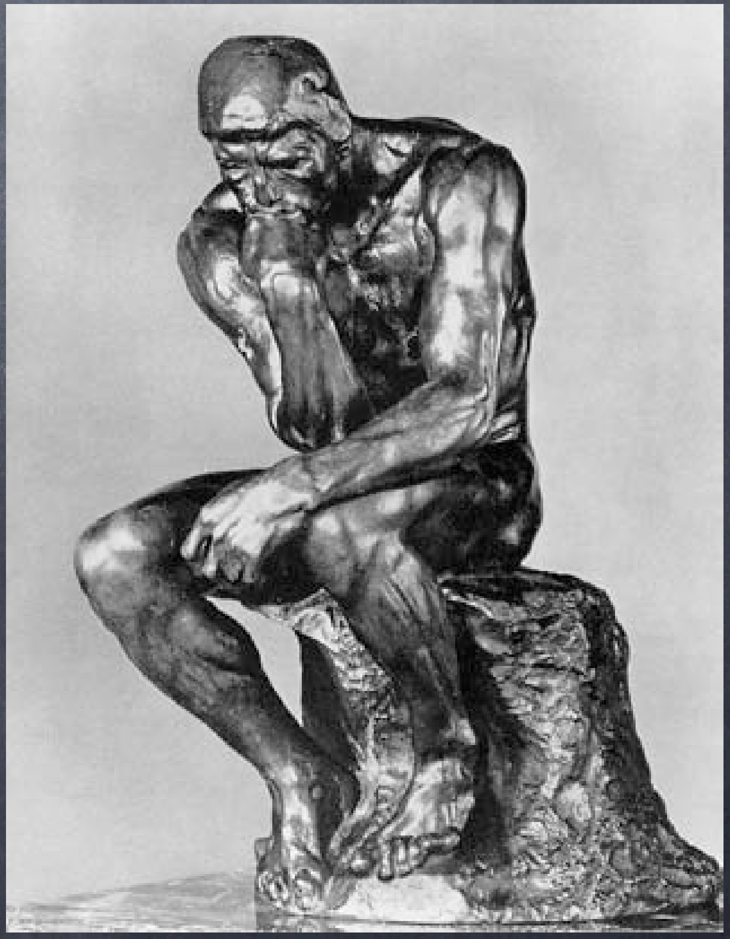

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- Structure formation by gravitational instability

  Describes the growth of structure from initially-small irregularities. Gravity for the initial collapse, lots of other physics in the details.

- Inflationary cosmology

  The leading candidate theory for explaining where those initial irregularities came from: quantum fluctuations during rapid expansion of the young Universe.

The cosmic fingerprint

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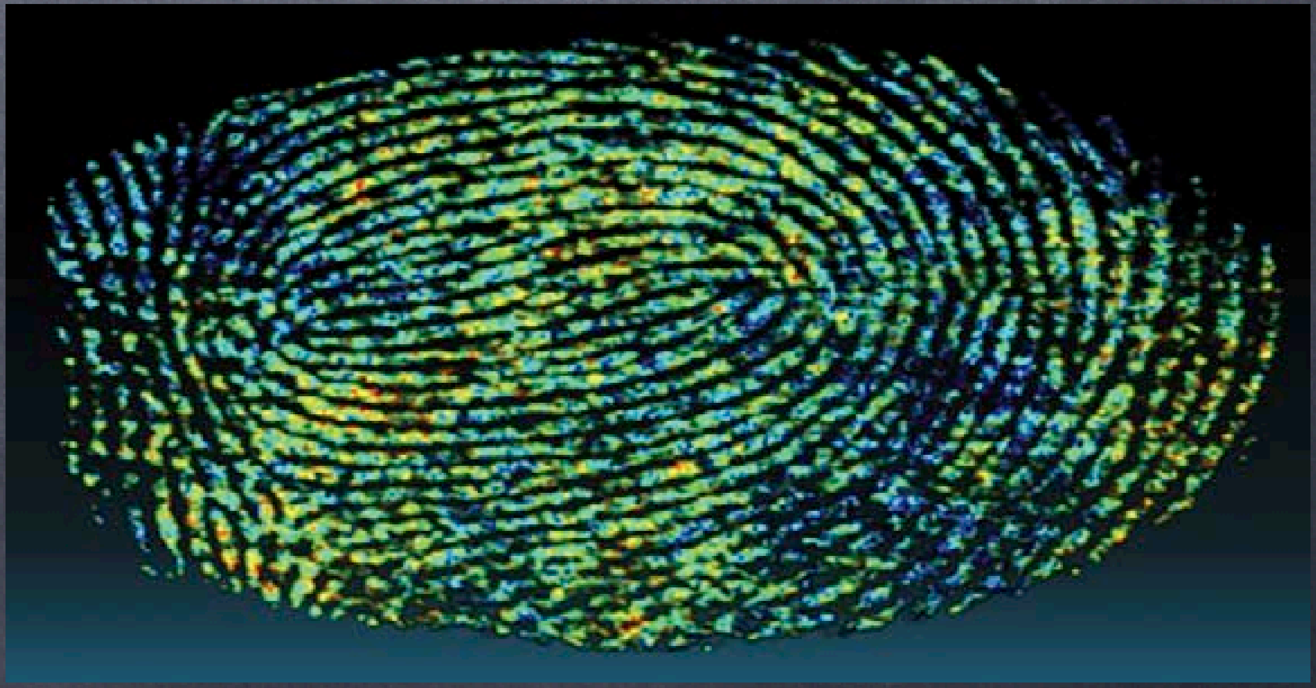
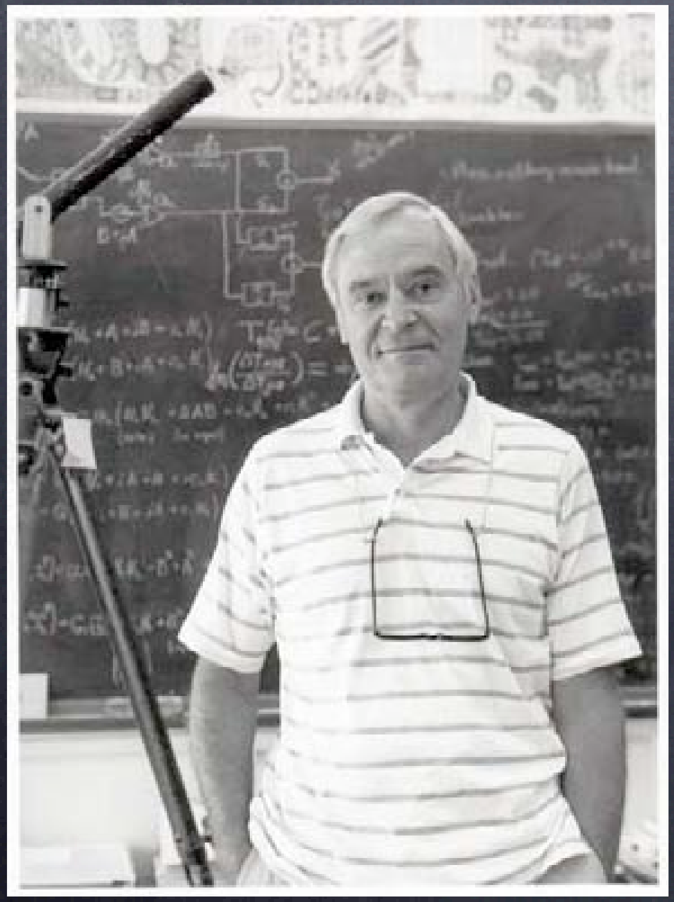
Each of these different possible Universes predicts a distinctive pattern in the structures seen in the cosmic microwave background. Measure them, and we find out which Universe is ours!



The Wilkinson Microwave Anisotropy Probe

The WMAP satellite was the successor to COBE, aiming to make precision maps of the CMB, with higher sensitivity and angular resolution...

WMAP launch, June 2001



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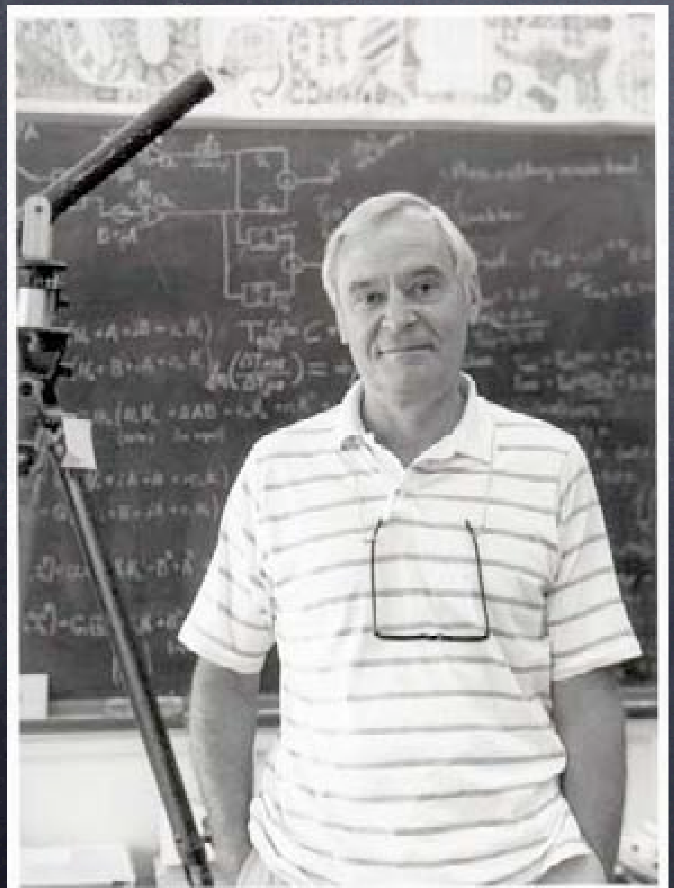

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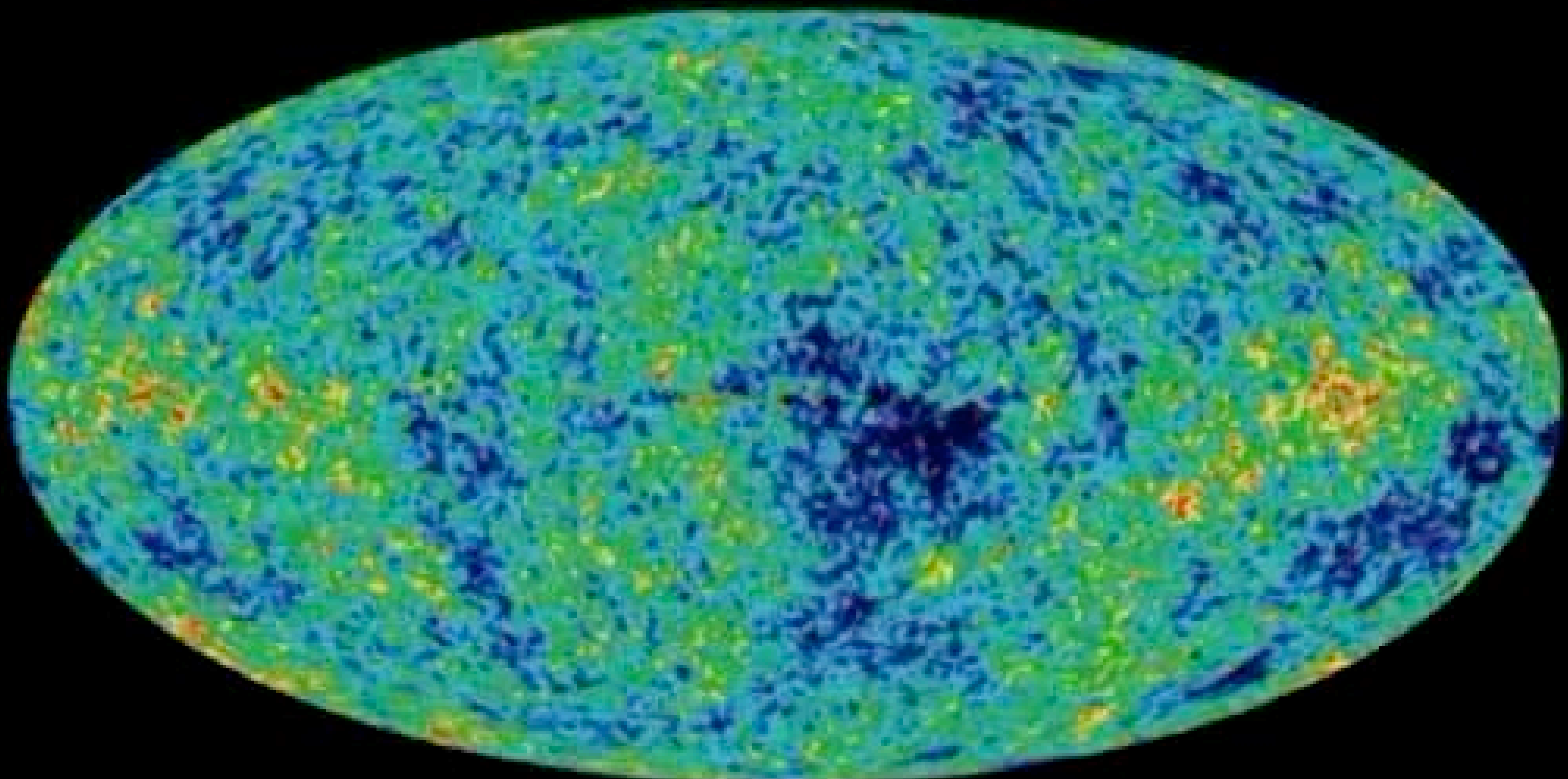
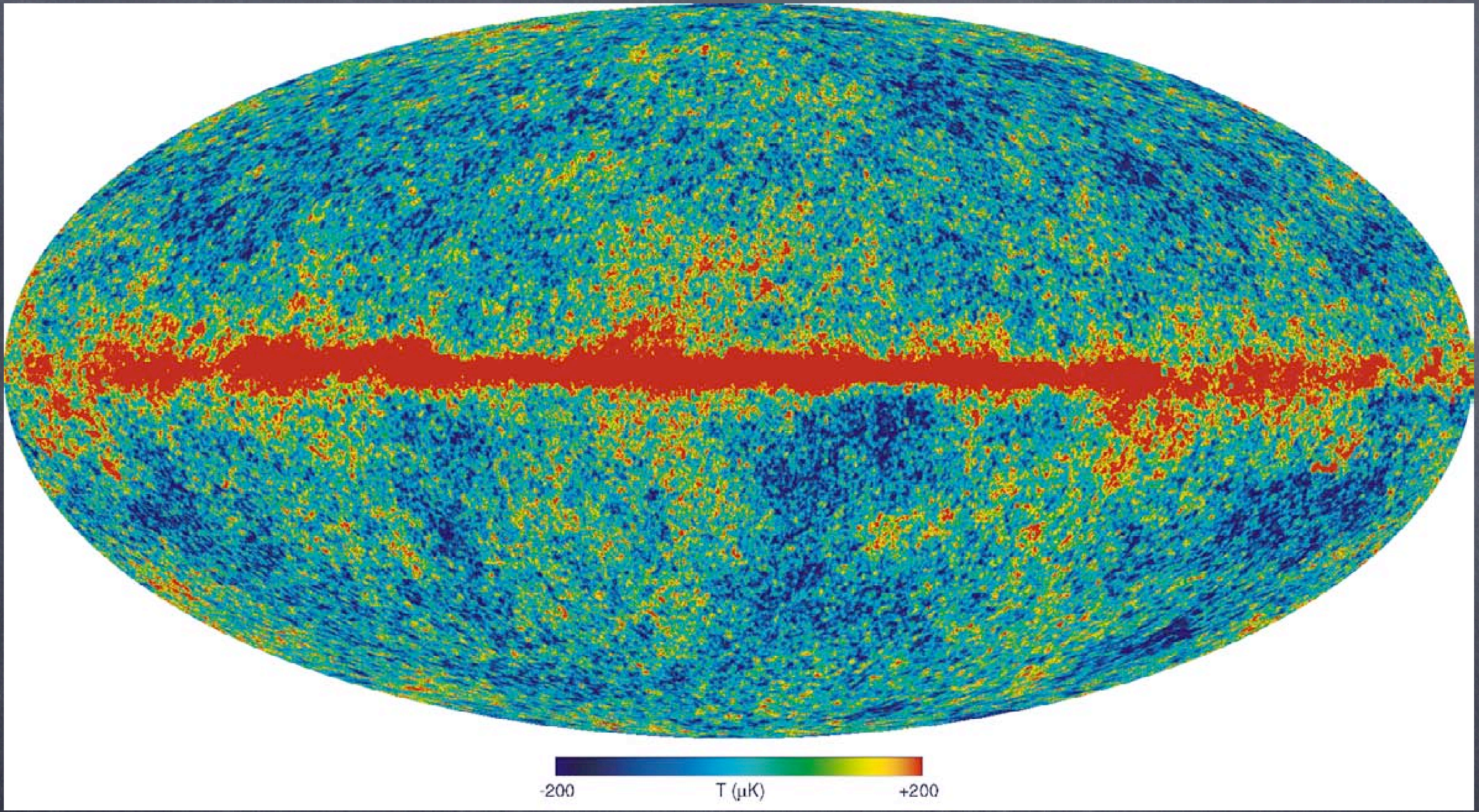
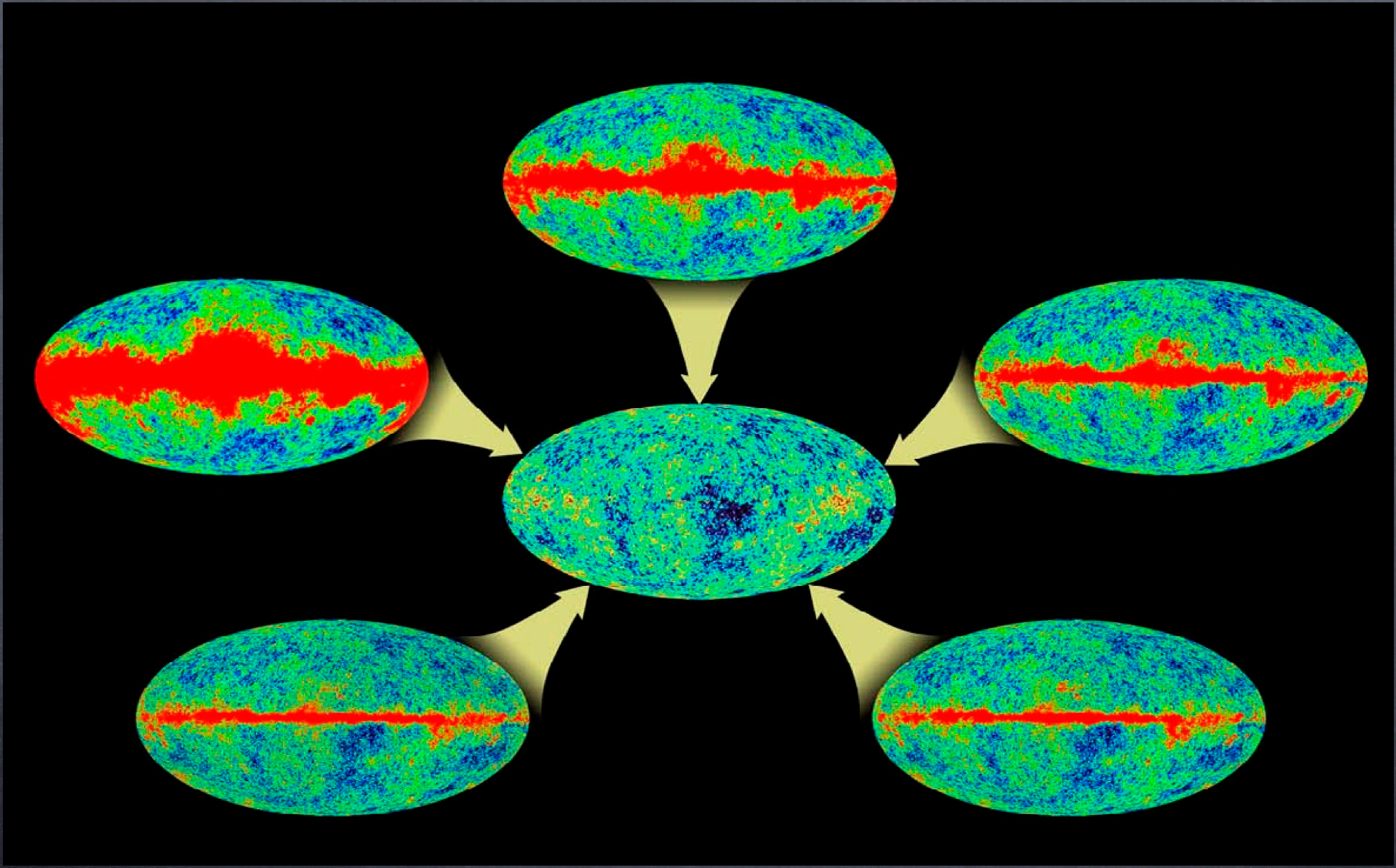


Movie credit: NASA/WMAP Team



The cosmic microwave background as imaged by WMAP (three years of data, released March 2006).

To make the best map of the sky, combine several frequencies.



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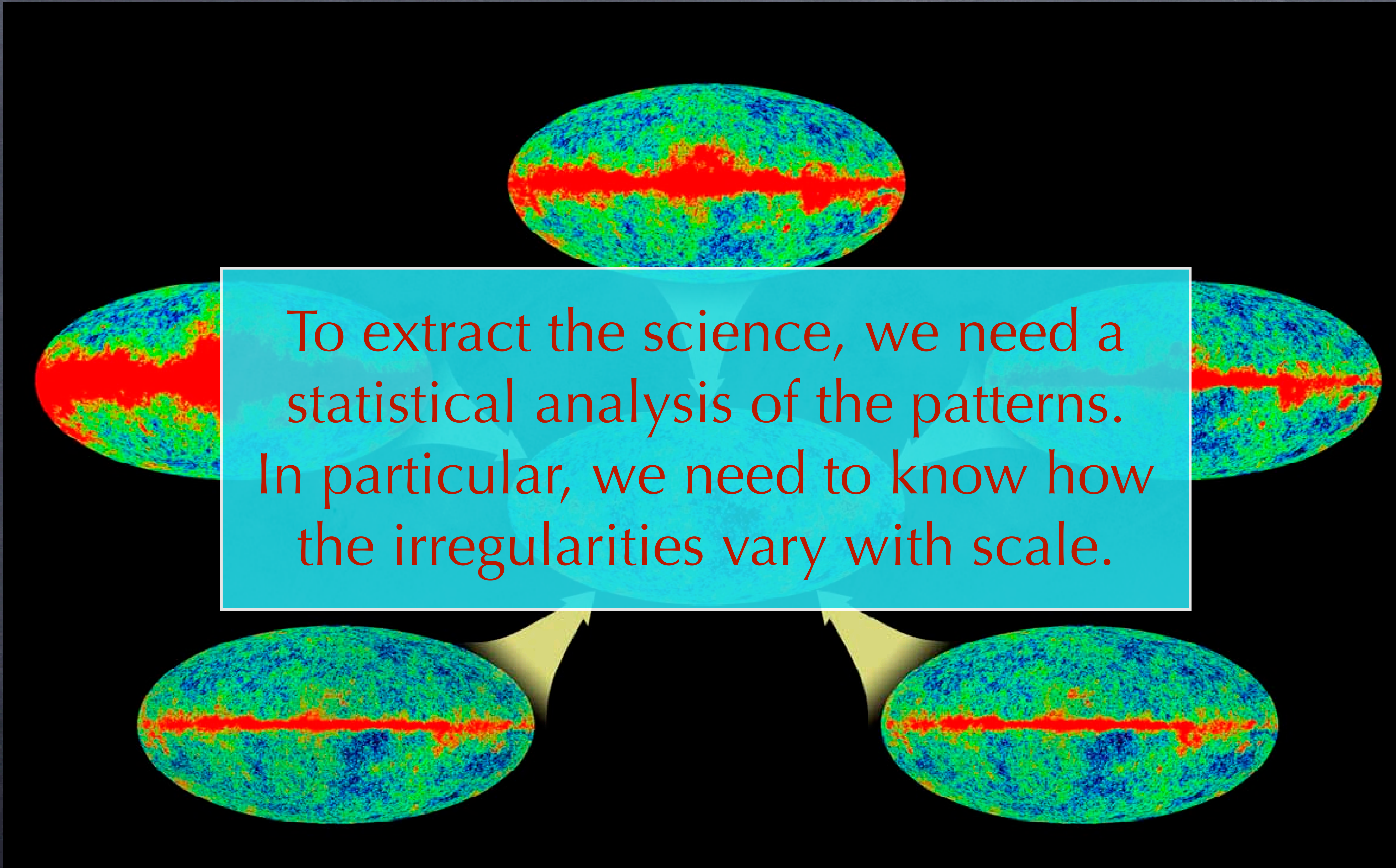
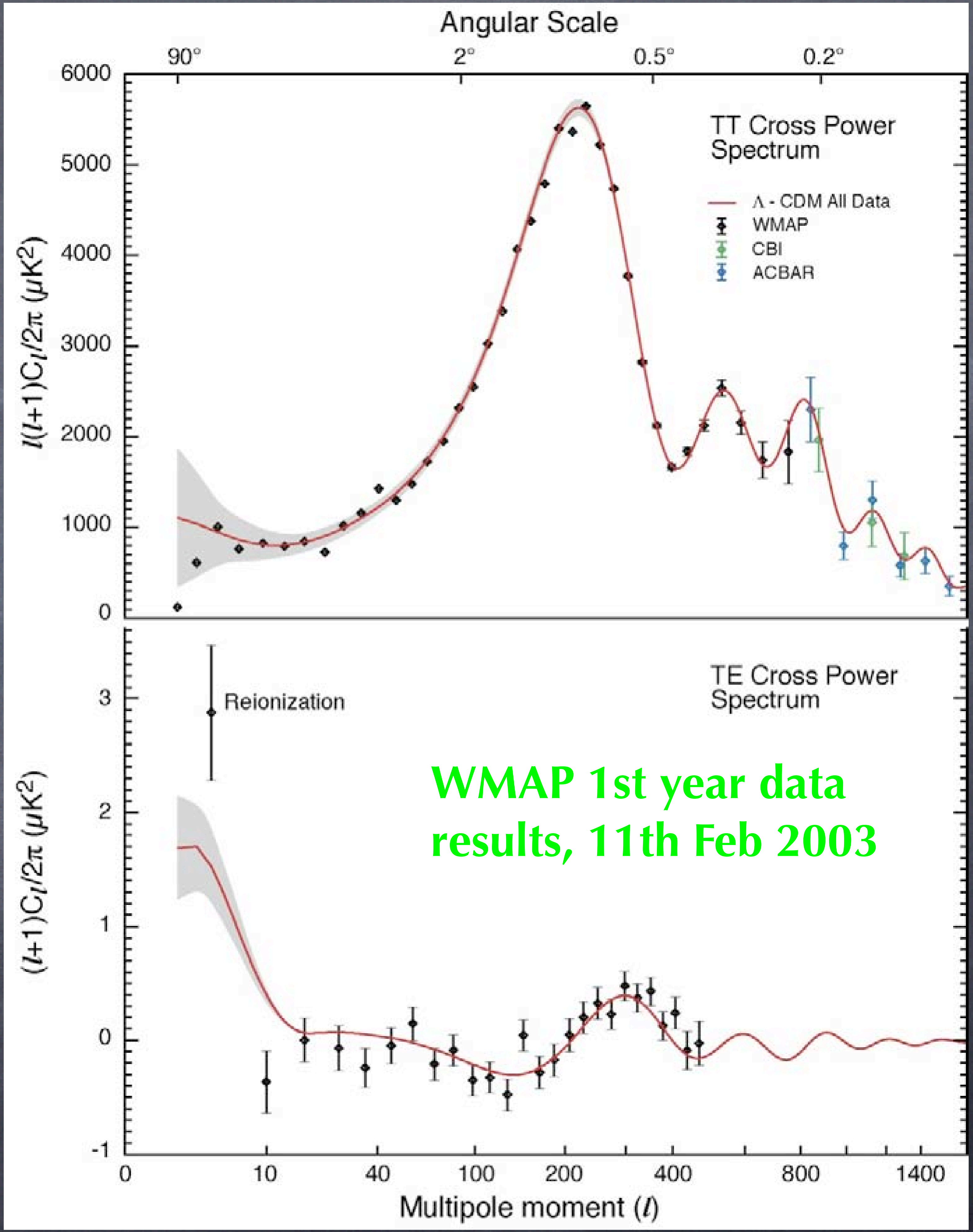


To extract the science, we need a statistical analysis of the patterns. In particular, we need to know how the irregularities vary with scale.

The Cosmic Microwave Background

WMAP has given an exquisite measurement of the CMB irregularities.



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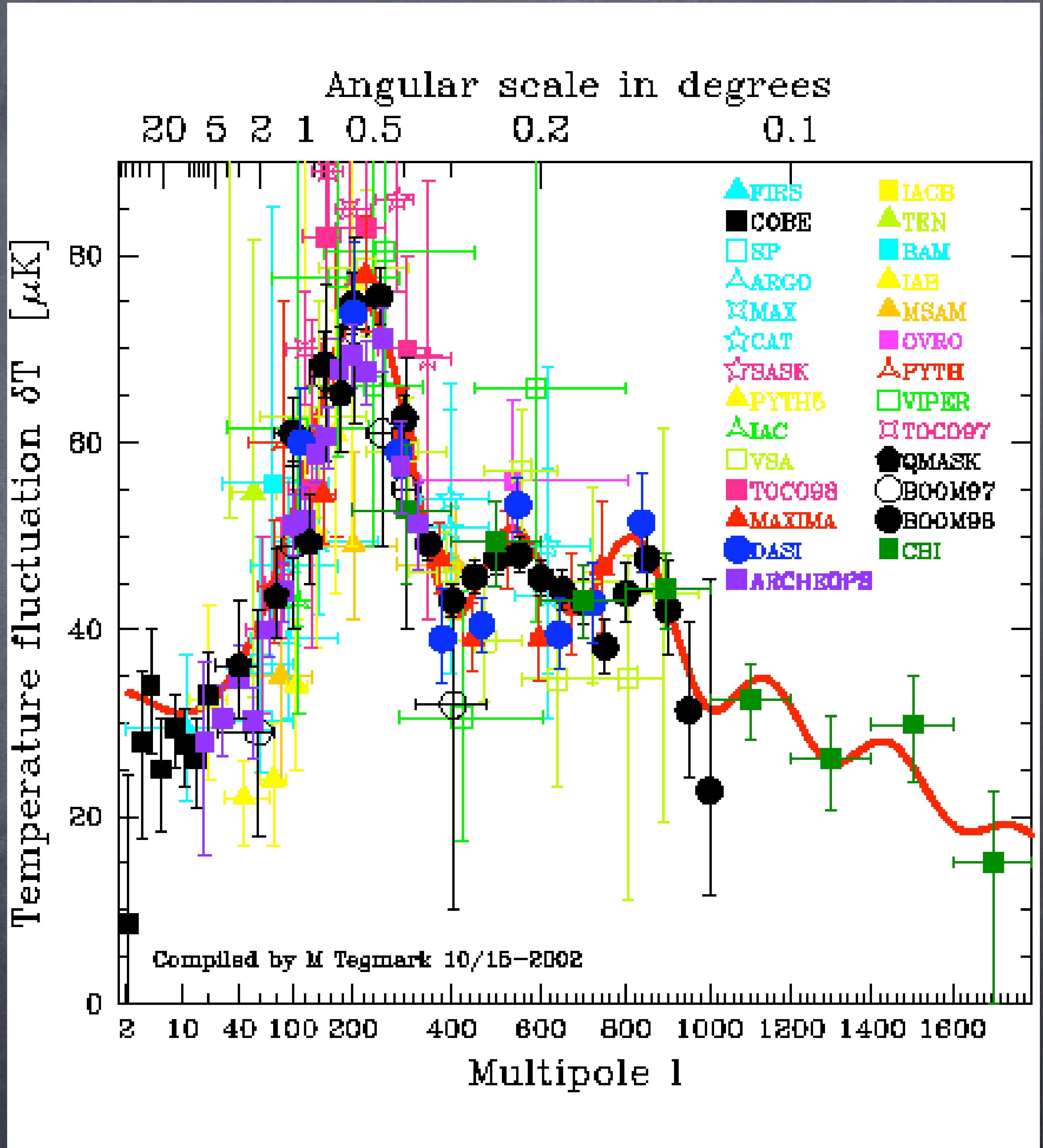

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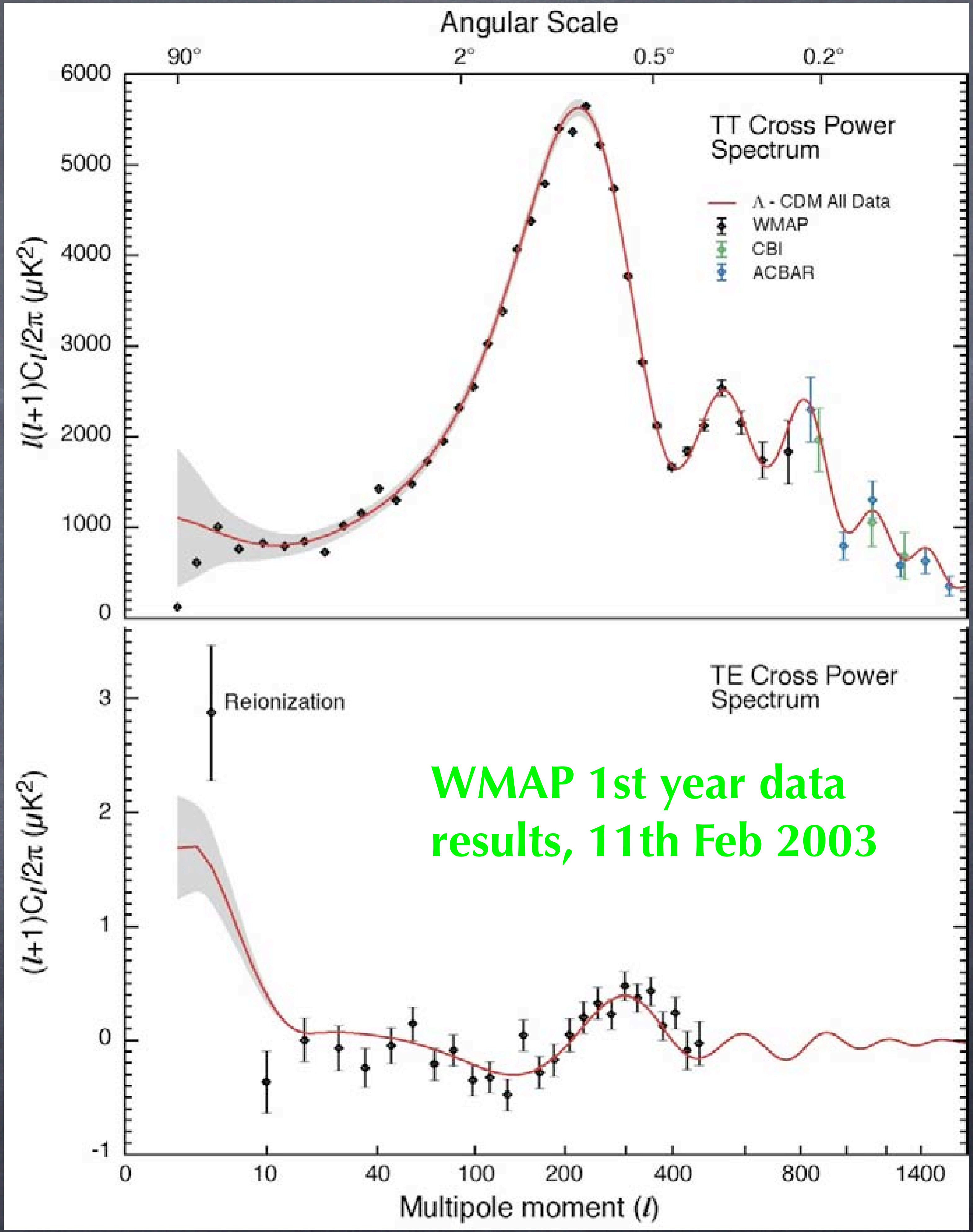

Old Universe – ***New*** Numbers

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$

$w < -0.78$ (95% CL)

$\Omega_{\Lambda} = 0.73^{+0.04}_{-0.04}$

$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$

$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27^{+0.04}_{-0.04}$

$\Omega_{\nu} h^2 < 0.0076$ (95%CL)

$m_{\nu} < 0.23$ eV (95% CL)

$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K

$n_{\gamma} = 410.4^{+0.9}_{-0.9}$ cm^{-3}

$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$

$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$

$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$A = 0.833^{+0.086}_{-0.083}$

$n_s = 0.93^{+0.03}_{-0.03}$

$dn_s/d \ln k = -0.031^{+0.016}_{-0.018}$

$r < 0.71$ (95% CL)

$z_{dec} = 1089^{+1}_{-1}$

$\Delta z_{dec} = 195^{+2}_{-2}$

$h = 0.71^{+0.04}_{-0.03}$

$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr

$t_{dec} = 379^{+8}_{-7}$ kyr

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17^{+0.04}_{-0.04}$

$z_r = 20^{+10}_{-9}$ (95% CL)

$\theta_A = 0^{\circ}.598^{+0.002}_{-0.002}$

$d_A = 14.0^{+0.2}_{-0.3}$ Gpc

$l_A = 301^{+1}_{-1}$

$r_s = 147^{+2}_{-2}$ Mpc

WMAP Science Team

Nice models, shame about the physics

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... the reason we were making all those measurements is because we were hoping to understand something about why the Universe is as it is. And there the picture is not so rosy.

To the future ...

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