Introduction to Cosmology

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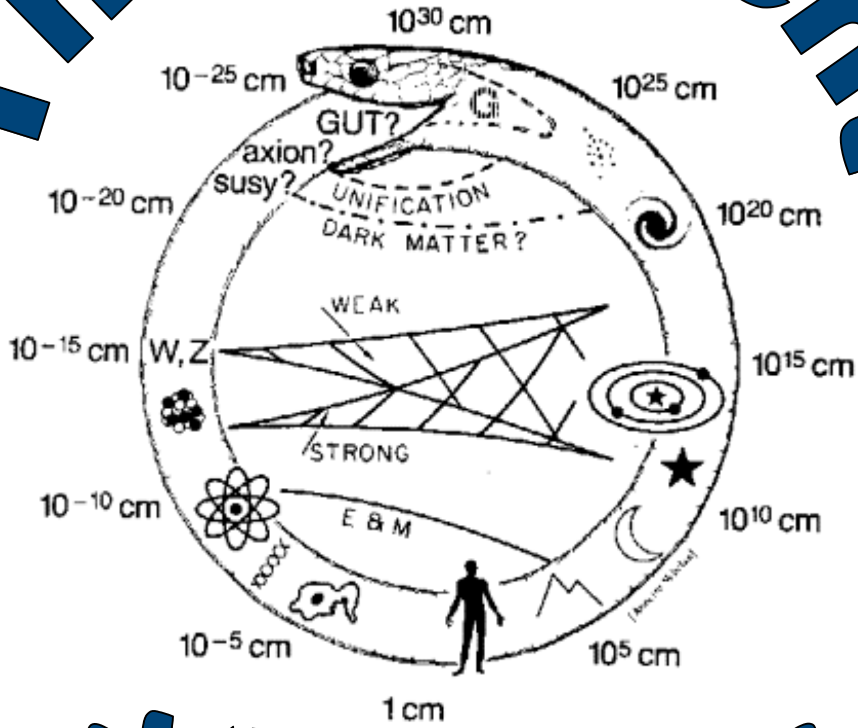
- **Seeing the edge of the Universe:** From speculation to science
- **Constructing the Universe:** Relativistic world models
- **The history of the Universe:** Decoupling of the relic radiation and nucleosynthesis of the light elements
- **The content of the Universe:** Dark matter & dark energy
- **Making sense of the Universe:** Fundamental physics & cosmology

http://www-thphys.physics.ox.ac.uk/user/SubirSarkar/cernlectures.html

Lecture 4

The content of the universe



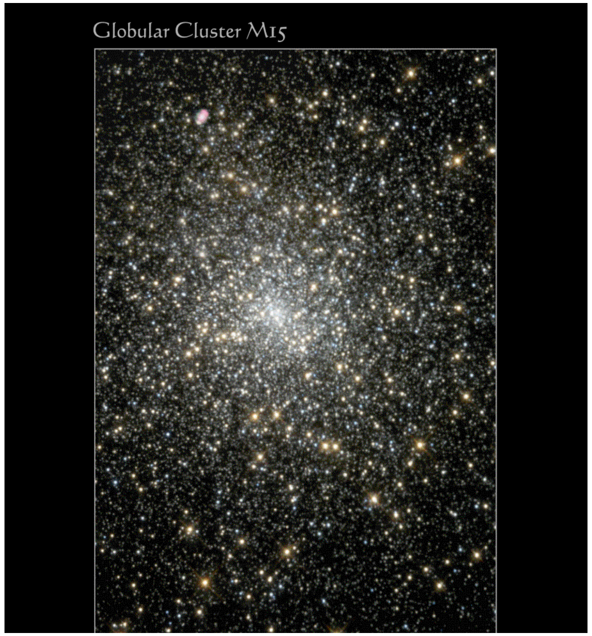
baryons, dark matter and dark energy

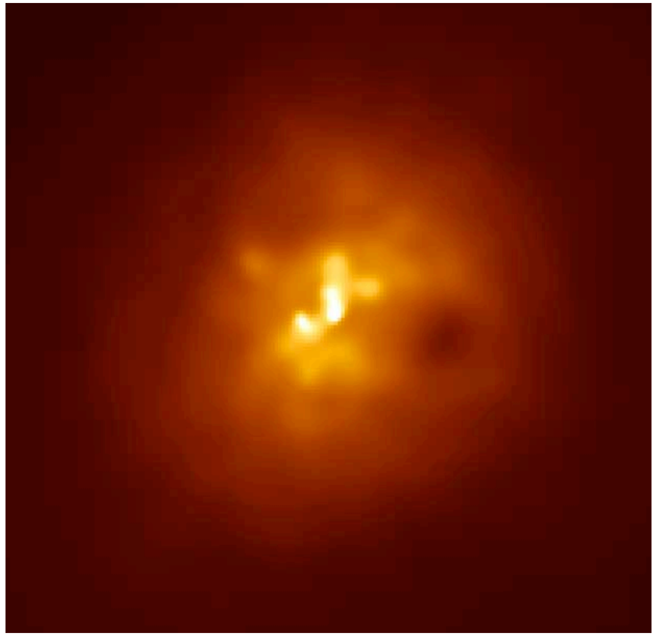
We know that *some* baryons must be dark because BBN requires $\Omega_b \sim 0.02h^{-2}$, whereas $\Omega_{luminous} \sim 0.024h^{-1}$

Stars
$\Omega \sim 0.005$

Interstellar gas
$\Omega \sim 0.005$

Hot gas in clusters
$\Omega \sim 0.03$

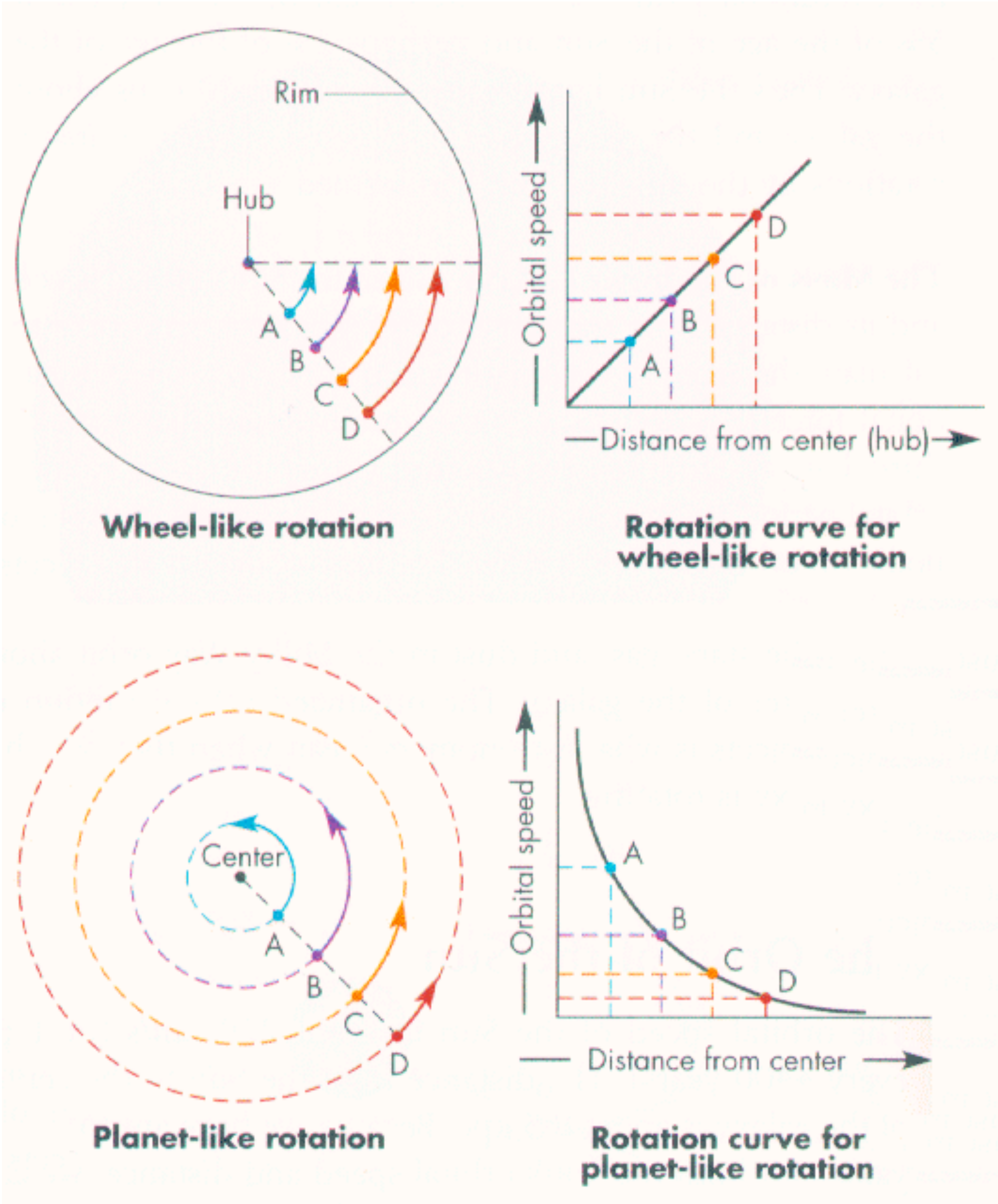




In fact observations indicate $\Omega_m \sim 0.3$ so most of the matter in the universe must be dark and *non-baryonic*

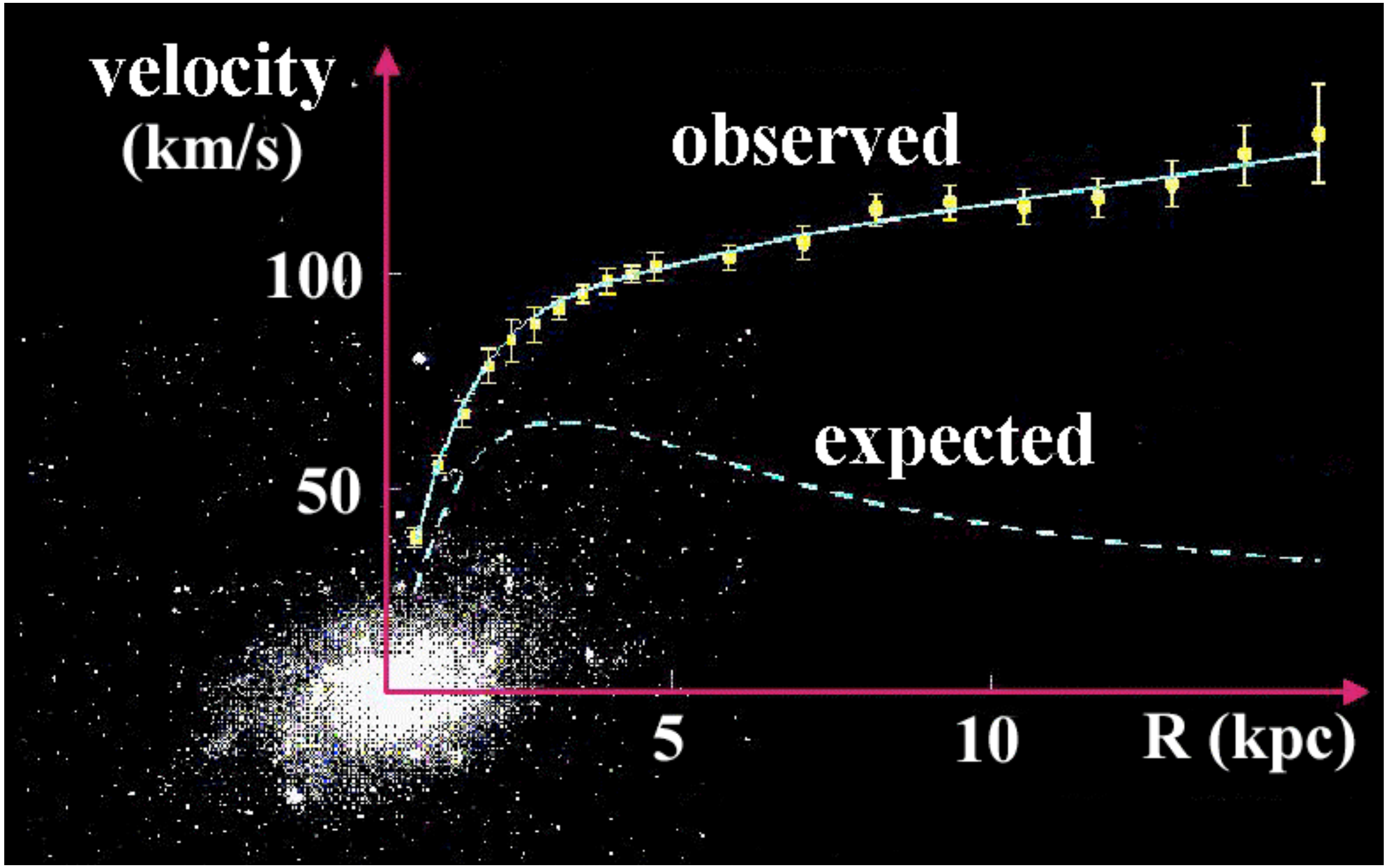
This was inferred from observations of the rotation curves of spiral galaxies …

At large distances from the centre the velocity would be expected to fall as $1/\sqrt{r}$



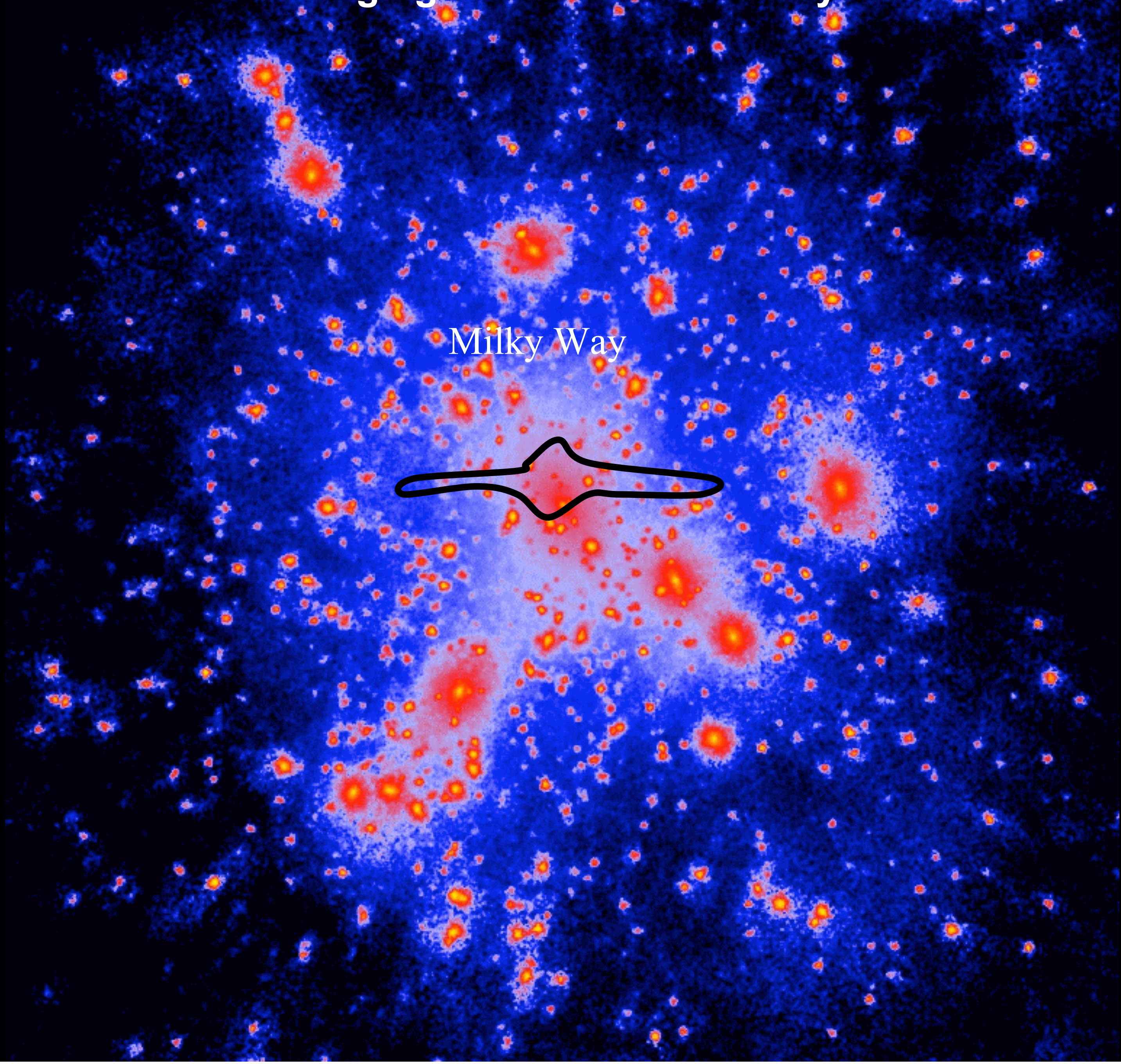
But the observed rotation curve (as traced by 21 cm emission from hydrogen) does *not* start falling outside the visible disc of stars - instead it stays ~flat !

This requires that there be a ~spherical halo of non-interacting **cold dark matter**

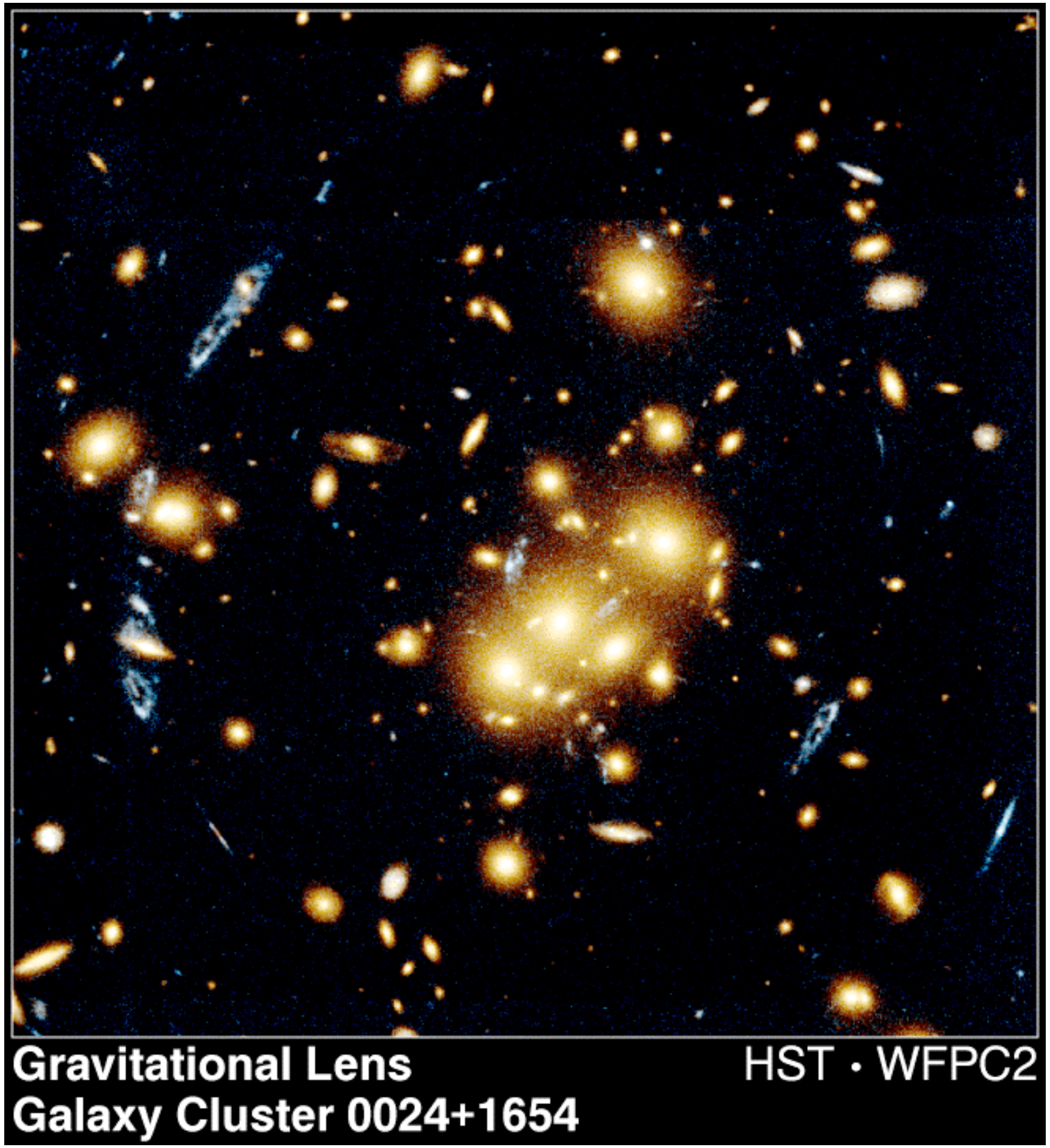


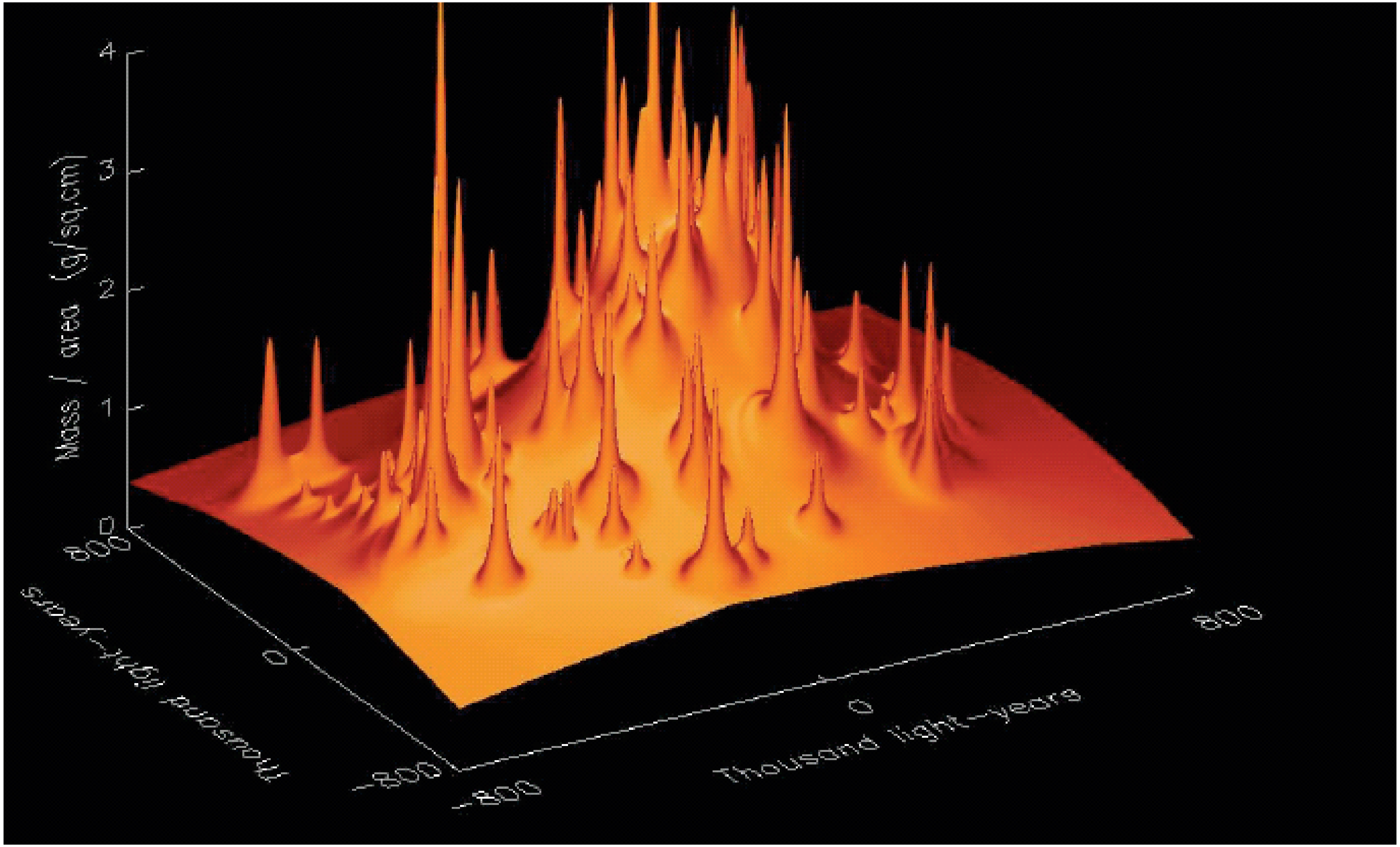
$$v_{\rm rot} = \sqrt{\frac{G_{\rm N} M(< r)}{r}} \approx \text{constant} \Rightarrow \rho \propto r^{-2}, \qquad M \sim 10\, M_{\rm luminous}$$

We can get an idea of what the Milky Way halo looks like from numerical simulations of **structure formation through gravitational instability in cold dark matter**

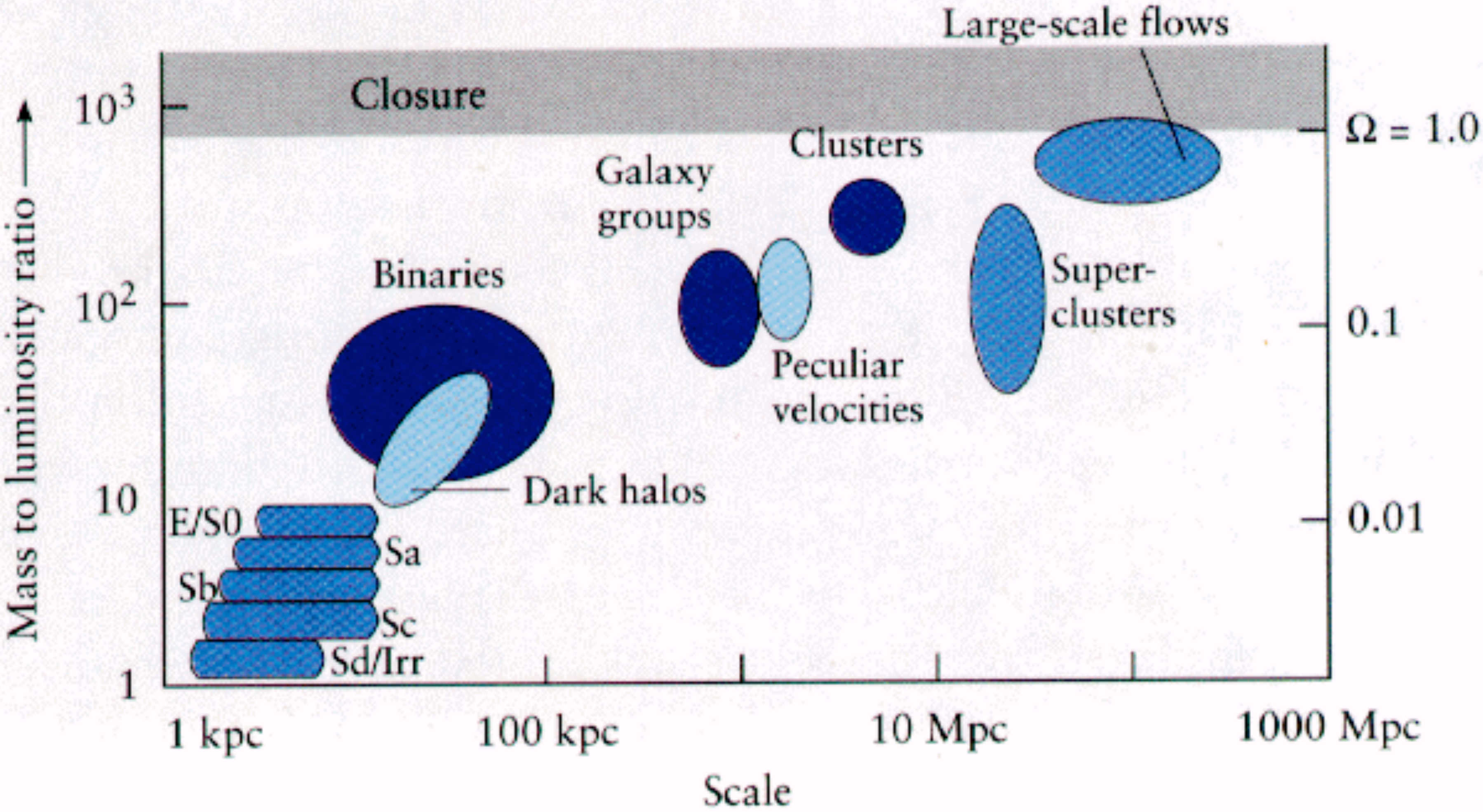


Further evidence comes from observations of **gravitational lensing** of distant sources by foreground objects … enabling the potential to be reconstructed





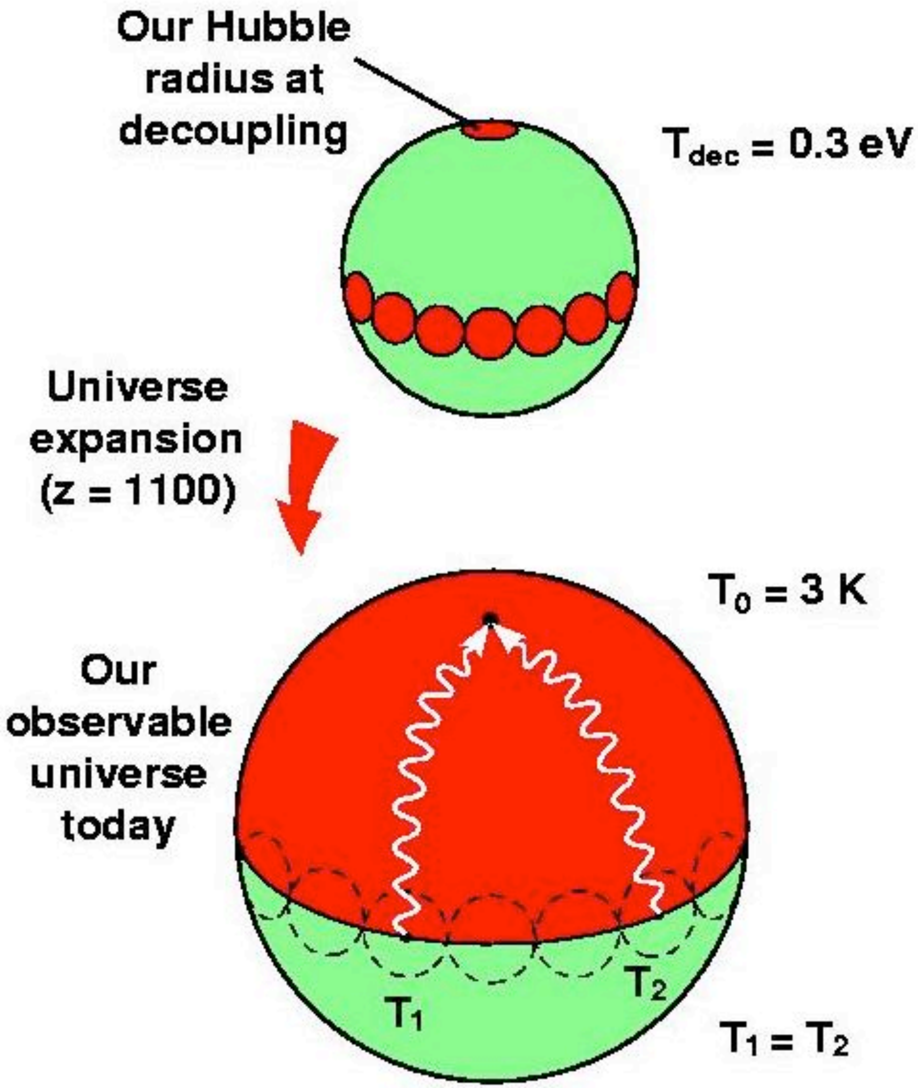
This reveals that the gravitational mass is dominated by an extended smooth distribution of *invisible* matter



A variety of such indirect observations indicate the total matter density is $\Omega_m \sim 0.3$, while baryons make up only about 1/6 of this

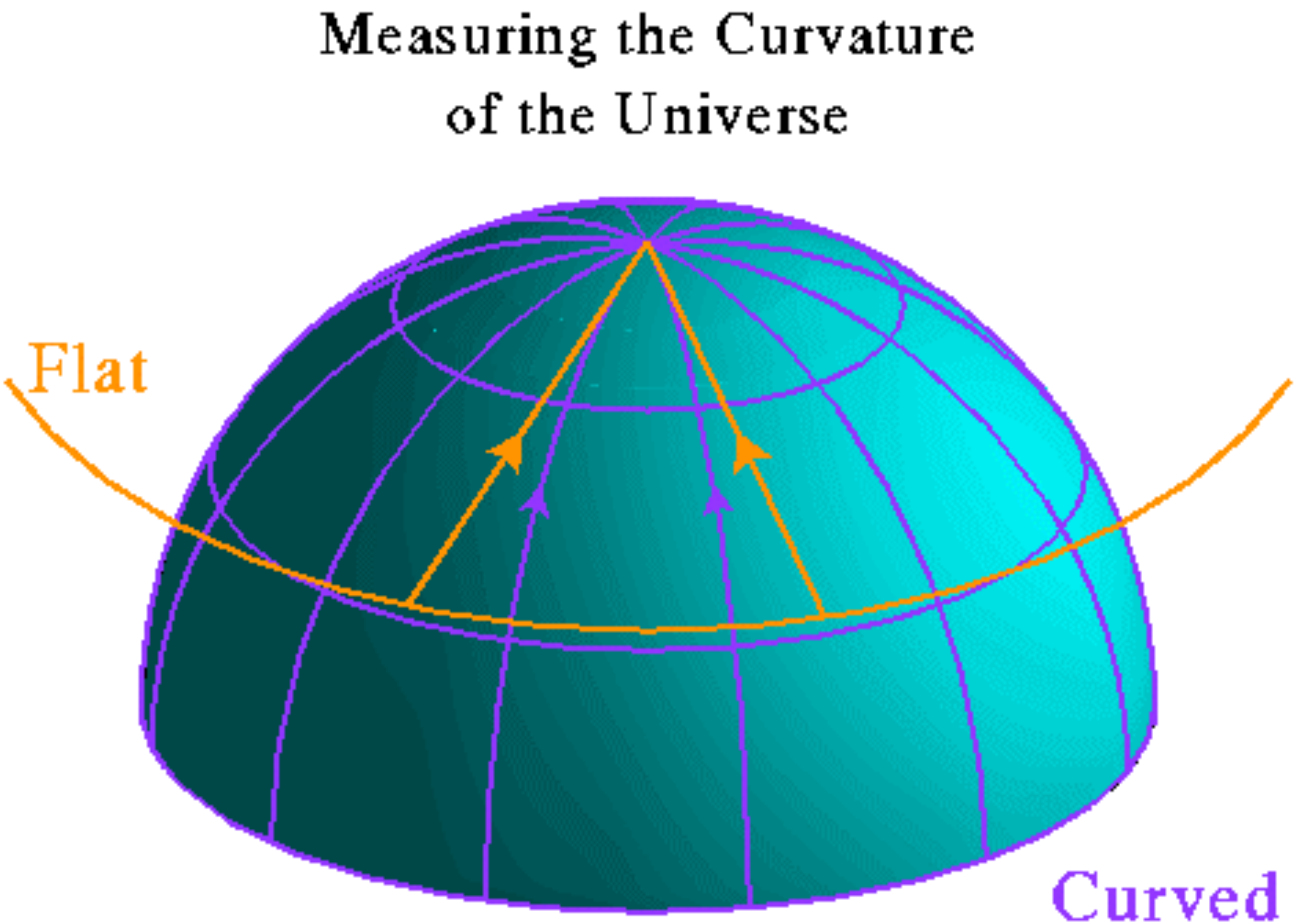
Is the geometry of the universe open?

The characteristic scale of the observed hot/cold spots on the Last Scattering Surface is determined by how far sound waves have propagated in the plasma since the Big Bang



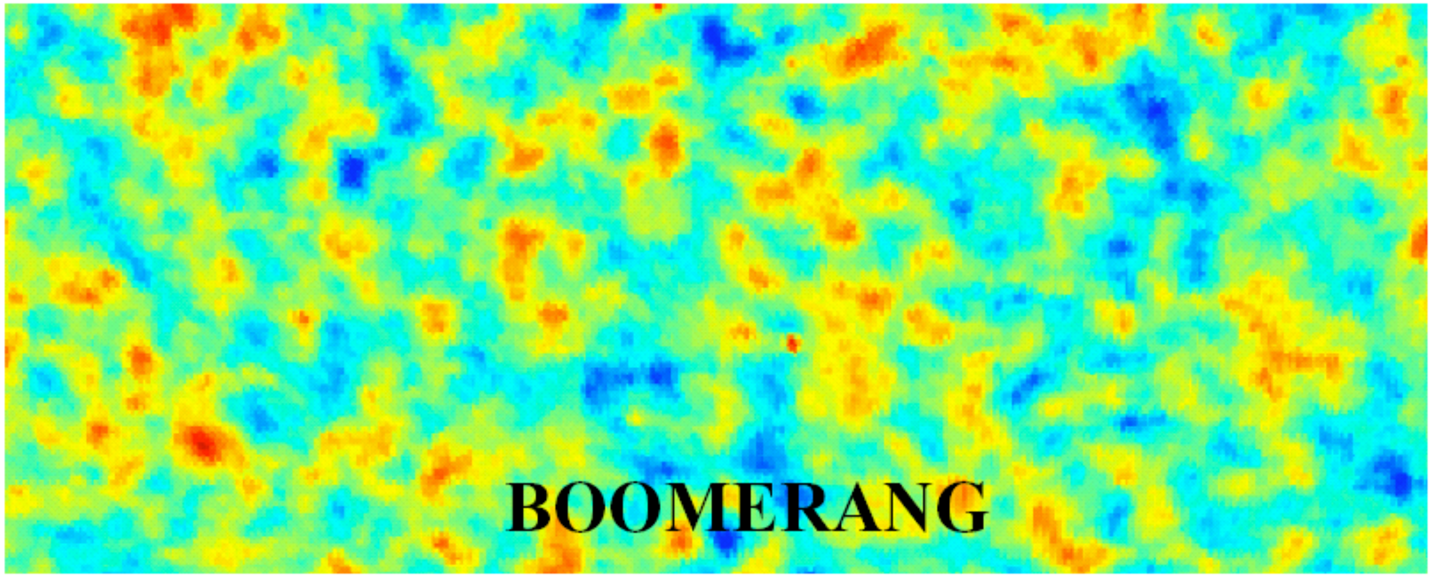
(Courtesey: Wayne Hu)

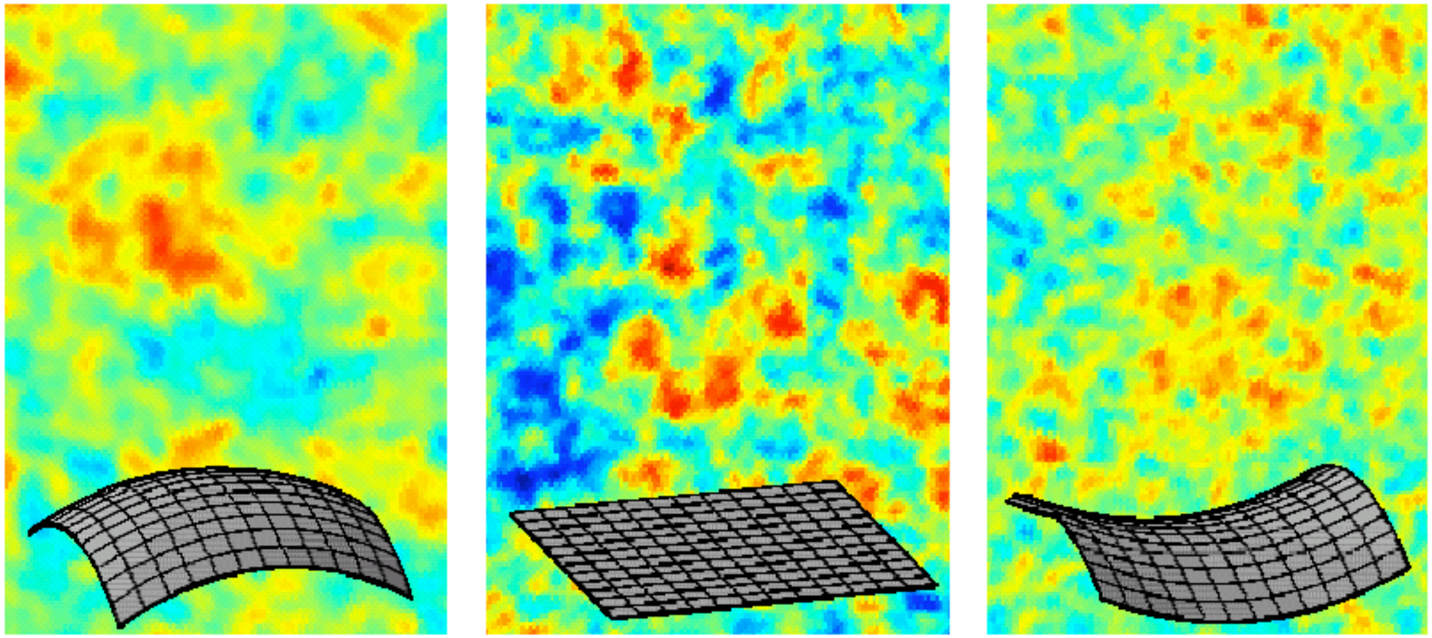
… with this ‘standard ruler’ we can determine the geometry of the intervening space

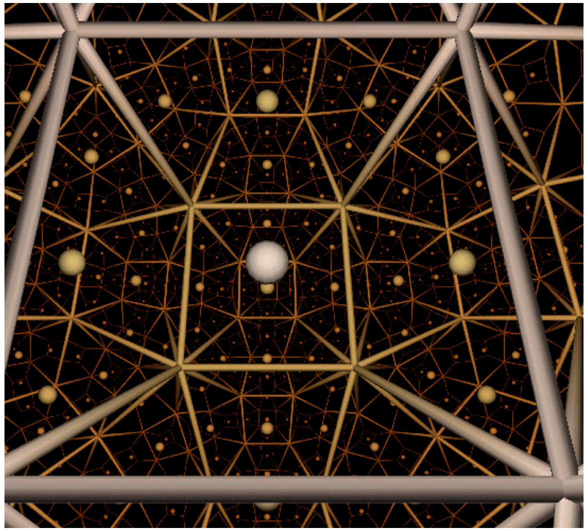


(Courtesey: Wayne Hu)

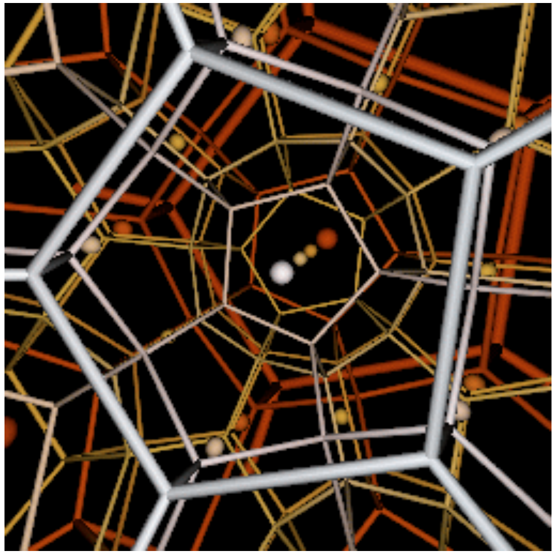
The observed size of hot/cold patches on the microwave sky indicates that
the geometry of space is Euclidean – the universe is flat!



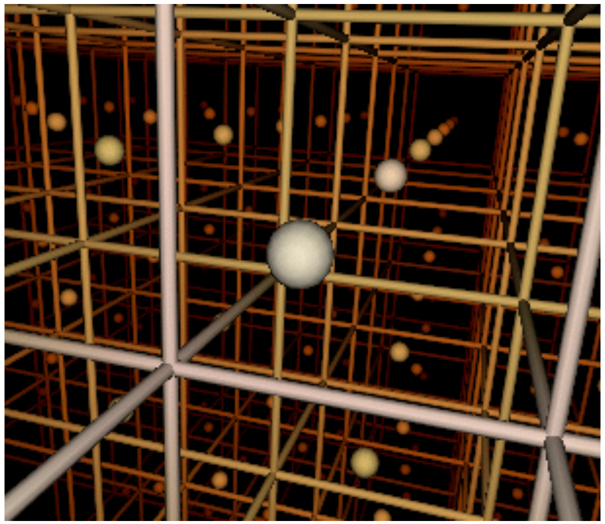




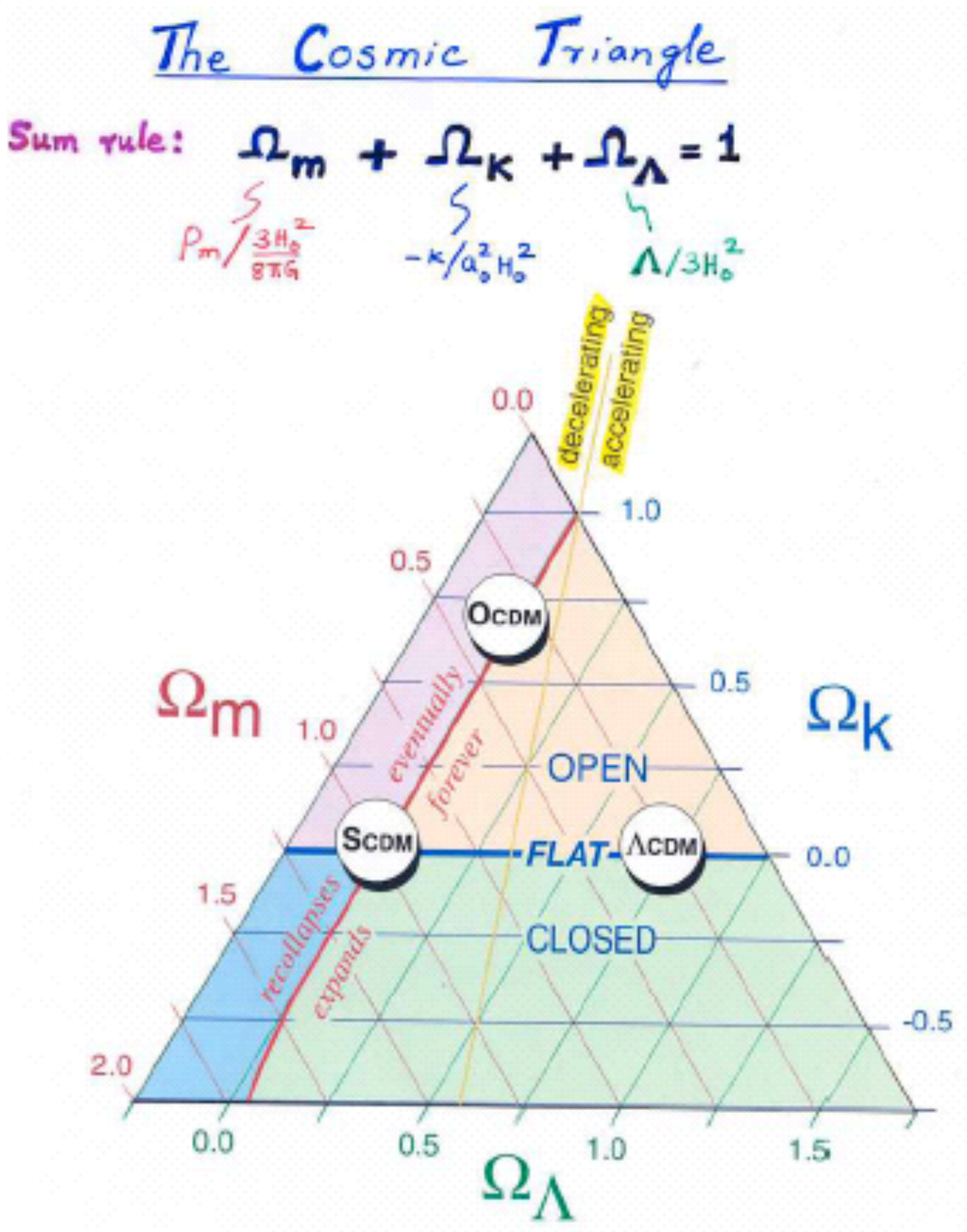
Hyperbolic Universe



Elliptical Universe



Flat Universe



Bahcal *et al* (1999)

The characteristic scale of CMB fluctuations $\Rightarrow \Omega_k \sim 0$, and observations of clustered matter $\Rightarrow \Omega_m \sim 0.3$ … so by this sum rule: $\Omega_\Lambda \sim 0.7$

In an expanding universe described by the R-W metric, the apparent luminosity ℓ of a source of intrinsic luminosity L is :

$$\ell = \frac{L}{4\pi a_0^2 r^2 (1+z)^2}$$

Since $a(t)$ is dynamically determined by the F-L equations, this yields (Mattig 1958):

$$a_0 r = \frac{c}{H_0 q_0^2 (1+z)} \left\{ q_0 z + (q_0 - 1)\left[(1+2q_0 z)^{1/2} - 1\right]\right\}$$

for $q_0 > 0$, where $H_0 \equiv \dot{a}_0 / a_0$ and $q_0 \equiv -\ddot{a}_0 / a_0 H_0^2$

This gives the intrinsic luminosity as

$$L = 4\pi \ell c^2 H_0^{-2} q_0^{-2} \left\{ q_0 z + (q_0 - 1)\left[(1+2q_0 z)^{1/2} - 1\right]\right\}$$

implying the magnitude-redshift relationship

$$m = 5 \log q_0^{-2} \left[z q_0 + (q_0 - 1)\left\{-1 + (2 z q_0 + 1)^{1/2}\right\}\right] + C$$

$$\simeq 5 \log z + 1.086 (1 - q_0 z) + O(z^2) \ldots$$

for $z \lesssim 0.3$

$= 2.5 \log 4\pi + 5 \log (c/H_0)$

Rewriting Friedmann's equation as

$$\left(\frac{da}{d\tau}\right)^2 = 1 + \Omega_m (a^{-1} - 1) + \Omega_\Lambda (a^2 - 1) \; ; \quad a \equiv \frac{1}{1+z} \; , \; \tau \equiv H_0 t$$

$\Omega_m \equiv \frac{8\pi G}{3 H_0^2} \rho_{m_0}$, $\Omega_\Lambda \equiv \frac{\Lambda}{3 H_0^2}$

we see that: $q_0 = \frac{\Omega_m}{2} - \Omega_\Lambda$

... so measurement of the present expansion rate and its rate of change yields, in principle, the dynamical parameters

Sandage's programme was *unsuccessful* because a complete understanding of **evolutionary effects** is essential to determine cosmological parameters

⇒ galaxy counts:

$$\frac{dN_{gal}}{dz\,d\Omega} = \frac{n_c(z)}{H_0^3 a_0^3 (1+z)^3 q_0^4} \frac{\left\{ z q_0 + (q_0 - 1)\left(\sqrt{2 q_0 z + 1} - 1\right) \right\}^2}{\left[1 - 2q_0 + 2q_0(1+z)\right]^{1/2}}$$

⇒ angular diameter:

$$H_0 d_A = \frac{1}{q_0^2 (1+z)^2} \left[z q_0 + (q_0 - 1)\left(\sqrt{2 q_0 z + 1} - 1\right) \right]$$

$$= \frac{D}{\delta} = a(t_e) r_e \qquad \simeq z - \frac{1}{2}(3 + q_0) z^2 + \cdots$$

... many other tests (surface brightness ...) >

but all subject to bias by evolutionary effects

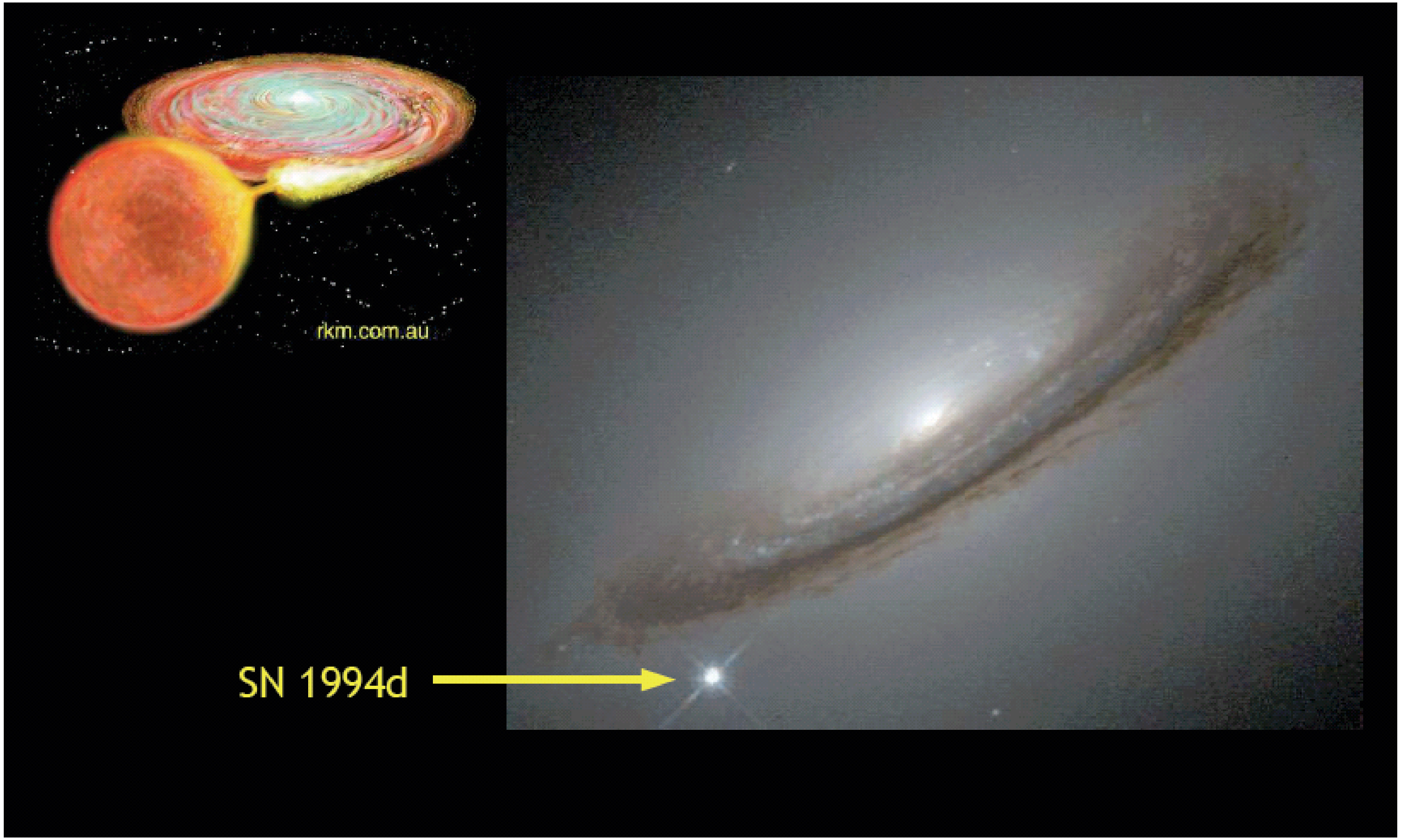
e.g. if $L(t) = L_0 \left[1 + \alpha (t - t_0) \right]$

then $\ell = \frac{L}{4\pi} \left(\frac{H_0}{z} \right)^2 \left[1 + (q_0 - 1) z - \alpha H_0^{-1} z + \cdots \right]$

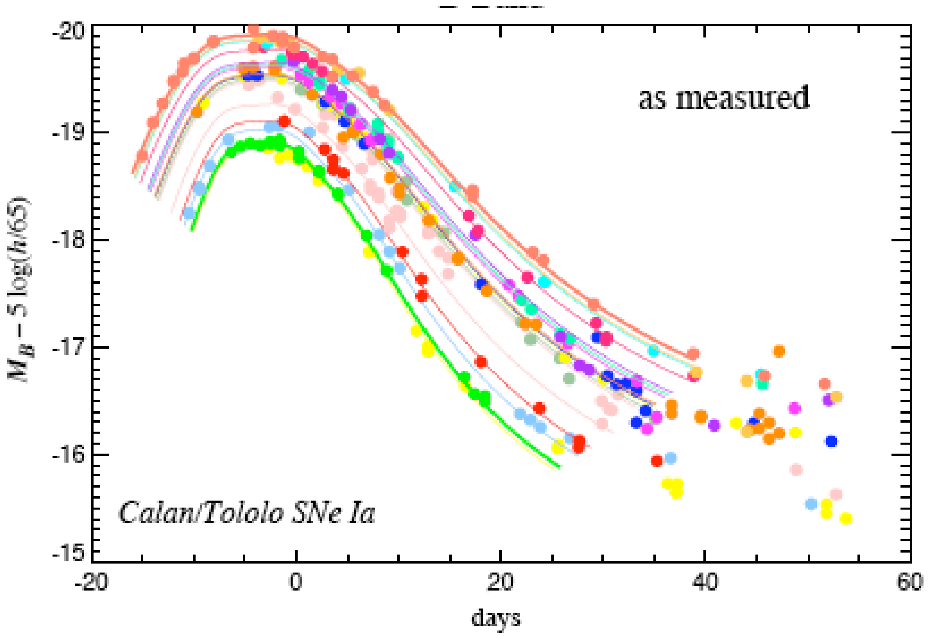
so will obtain *wrong* answer for q_0 if unaware of such luminosity evolution

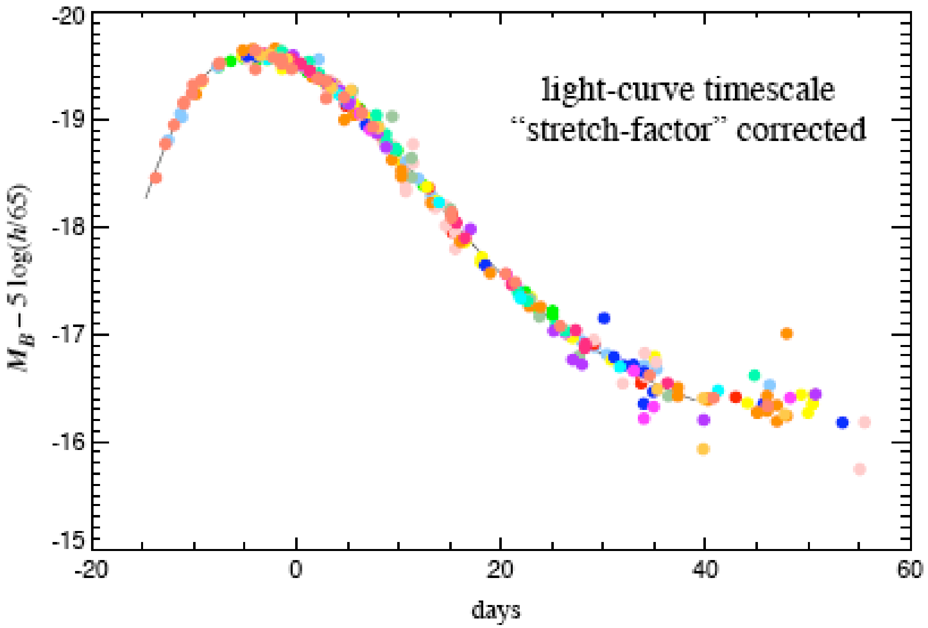
However this has now become possible through the automated detection of **Type Ia supernovae** (likely to be thermonuclear disruption of a white dwarf accreting matter from a giant companion) which have a *distinctive spectrum*

Although their intrinsic peak luminosities vary by x10, the brighter ones are observed to fade faster so they *can* be used as ‘standard(isable) candles’

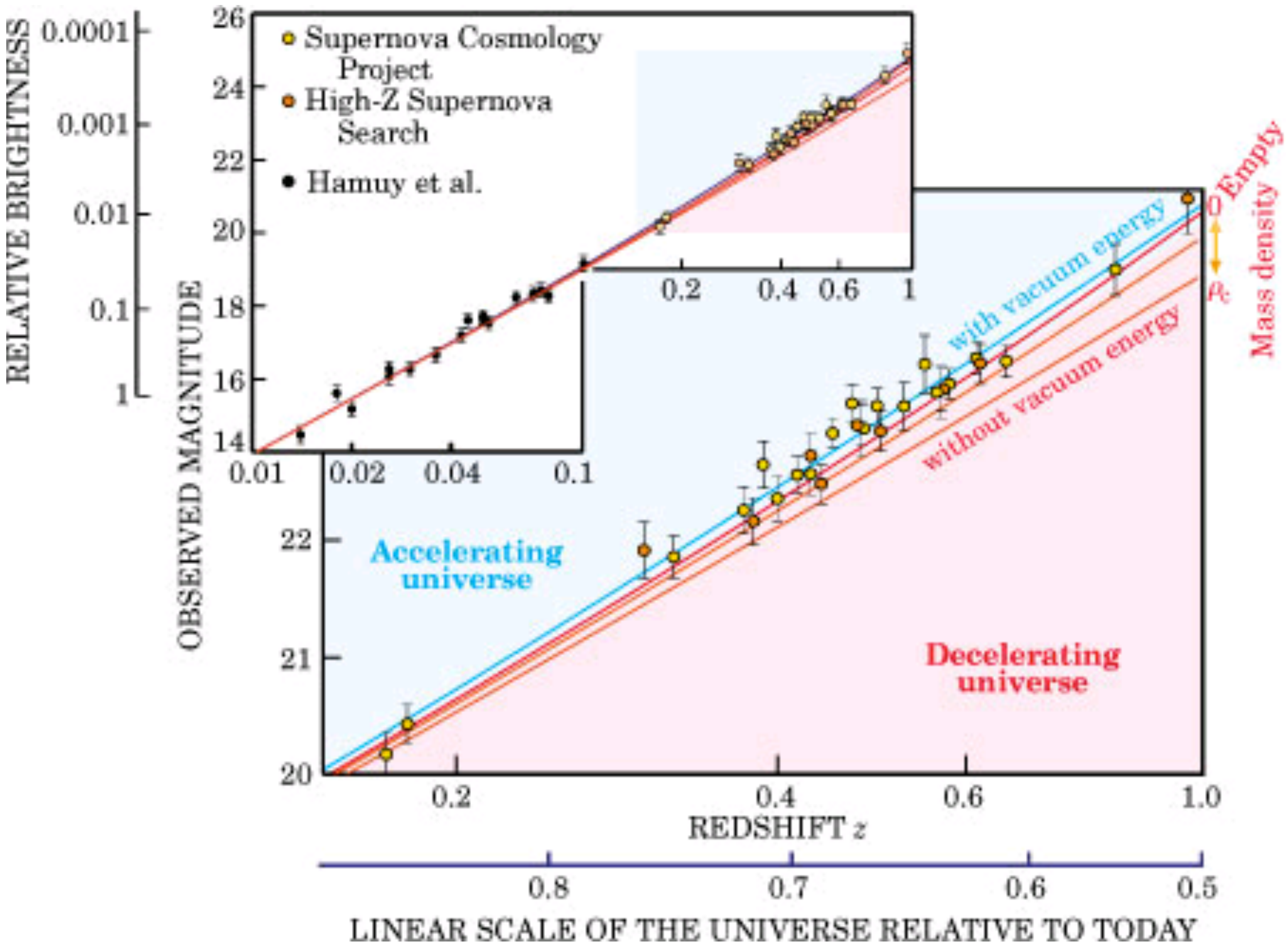


The (supernova) physics behind why this works so well is not yet understood …
so there are still some concerns about extrapolation to objects at high z

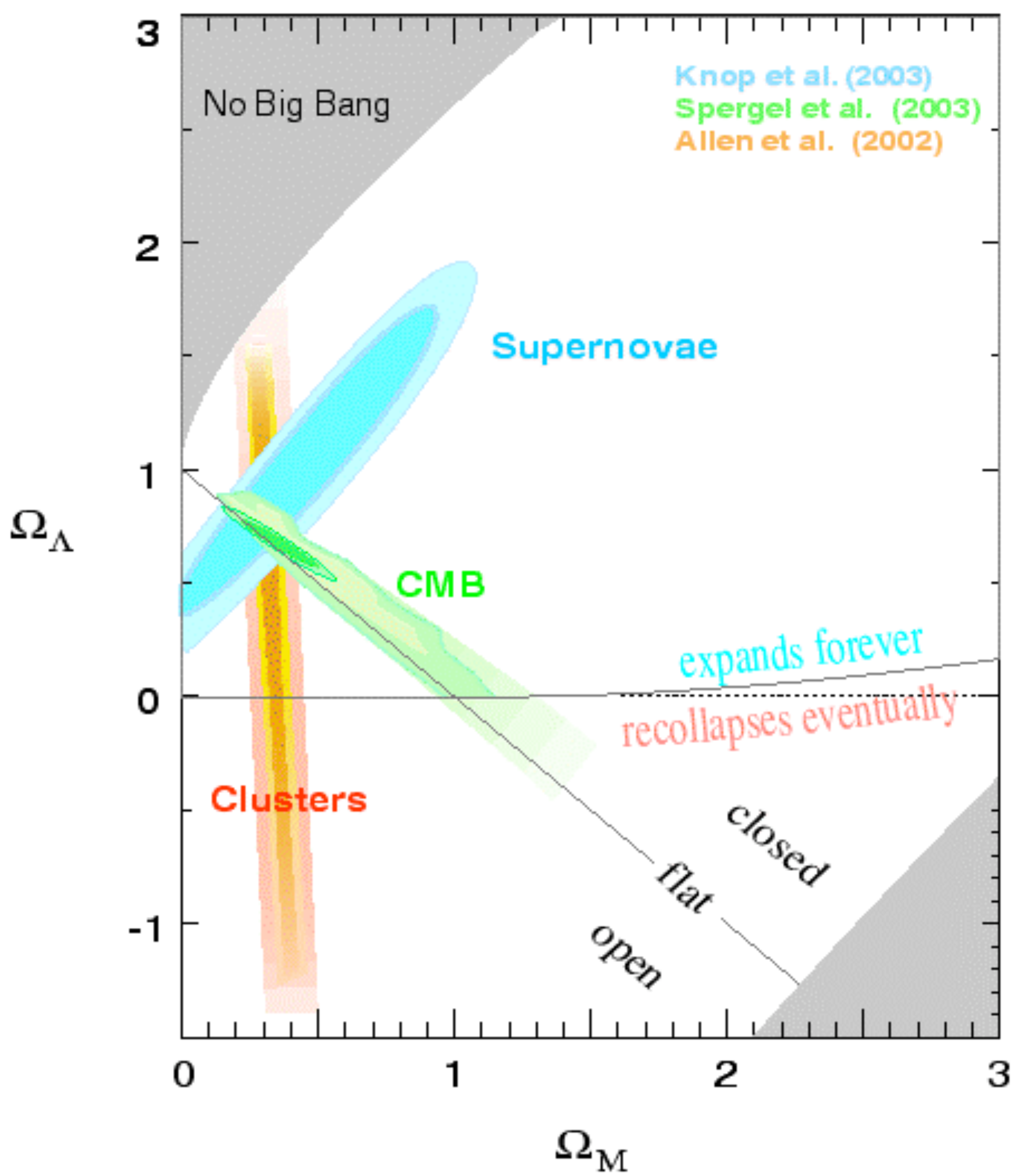


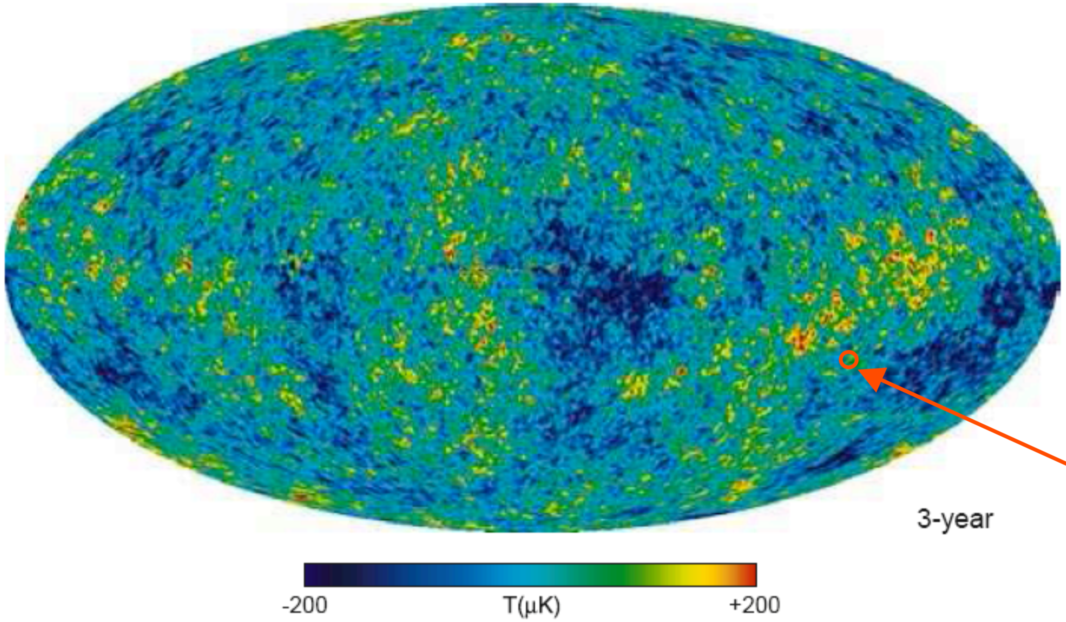


These observations show that q_0 is negative i.e. the expansion rate is *accelerating* as if driven by a dominant **cosmological constant**



This is also indicated by other measurements - *“Cosmic complementarity”*





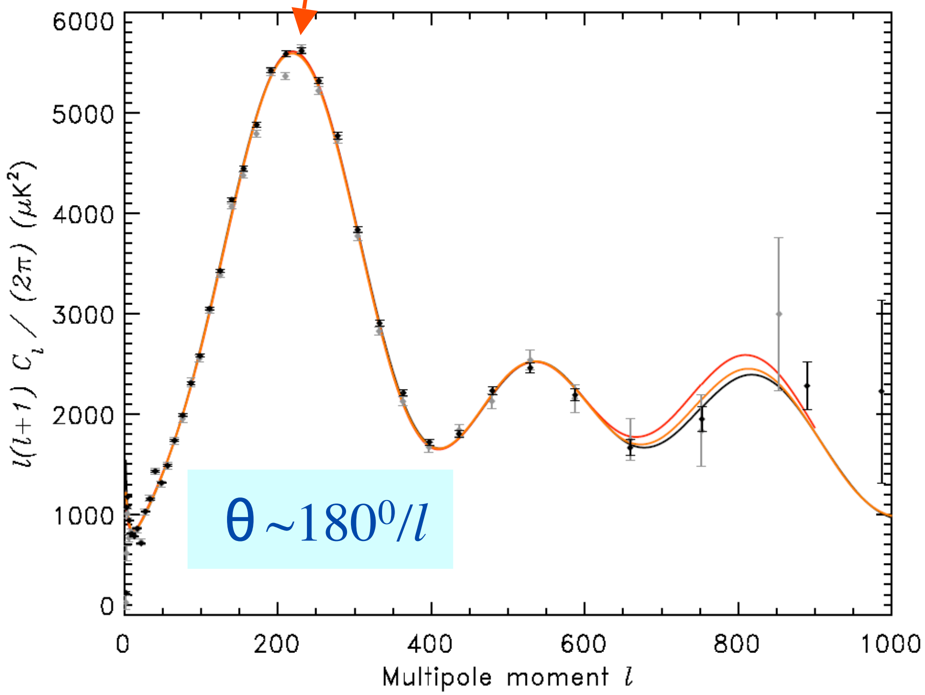
The temperature variations are the imprint of coherent oscillations in the coupled photon-baryon plasma, excited by **primordial density perturbations** on *super*-horizon scales …

(Hubble radius at t_{rec})

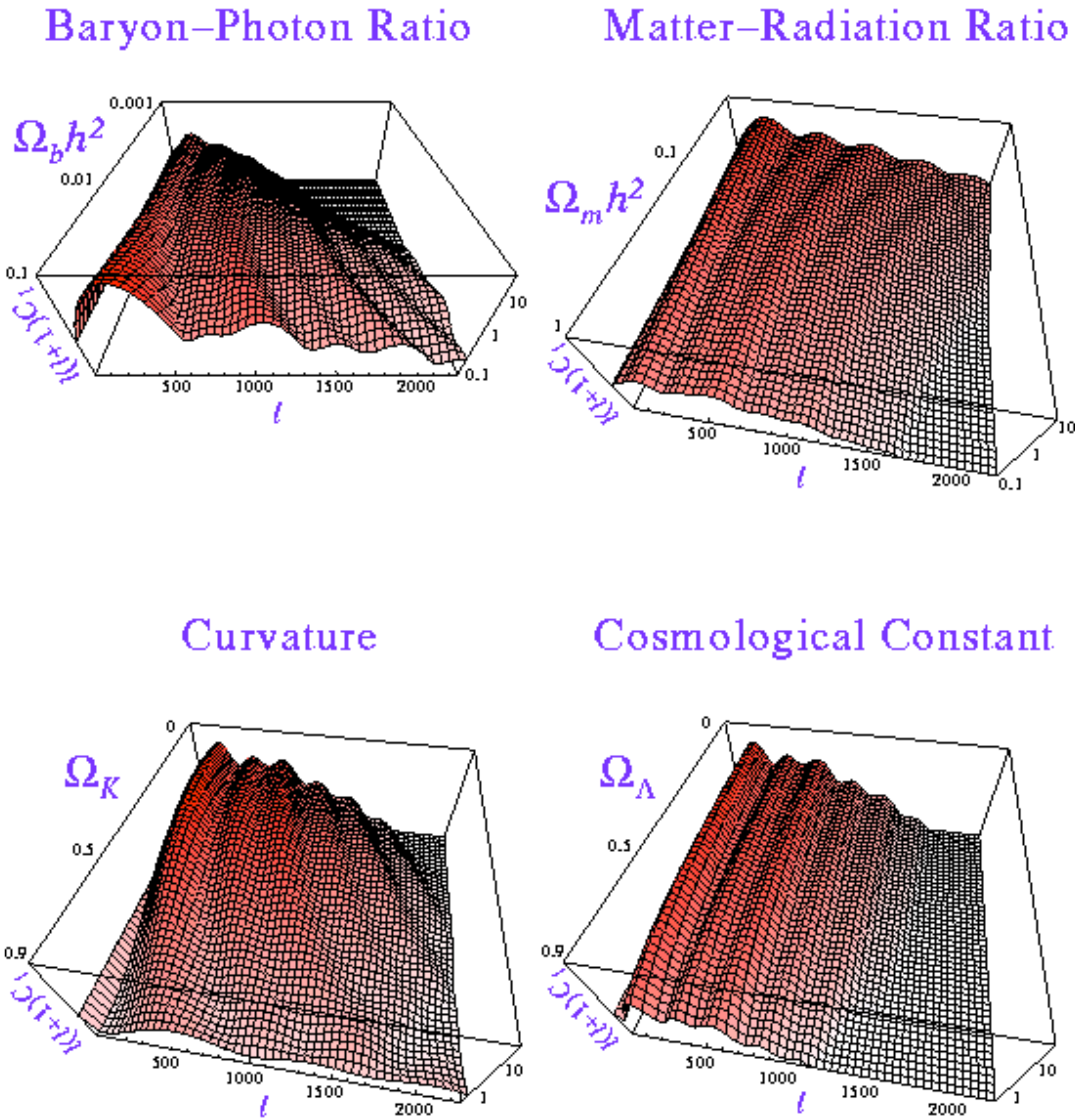
For a statistically isotropic gaussian random field, the **angular power spectrum** can be constructed by decomposing in spherical harmonics:

$$\Delta T(\mathbf{n}) = \sum a_{lm} Y_{lm}(\mathbf{n})$$

$$C_l \equiv \frac{1}{2l+1} \sum |a_{lm}|^2$$

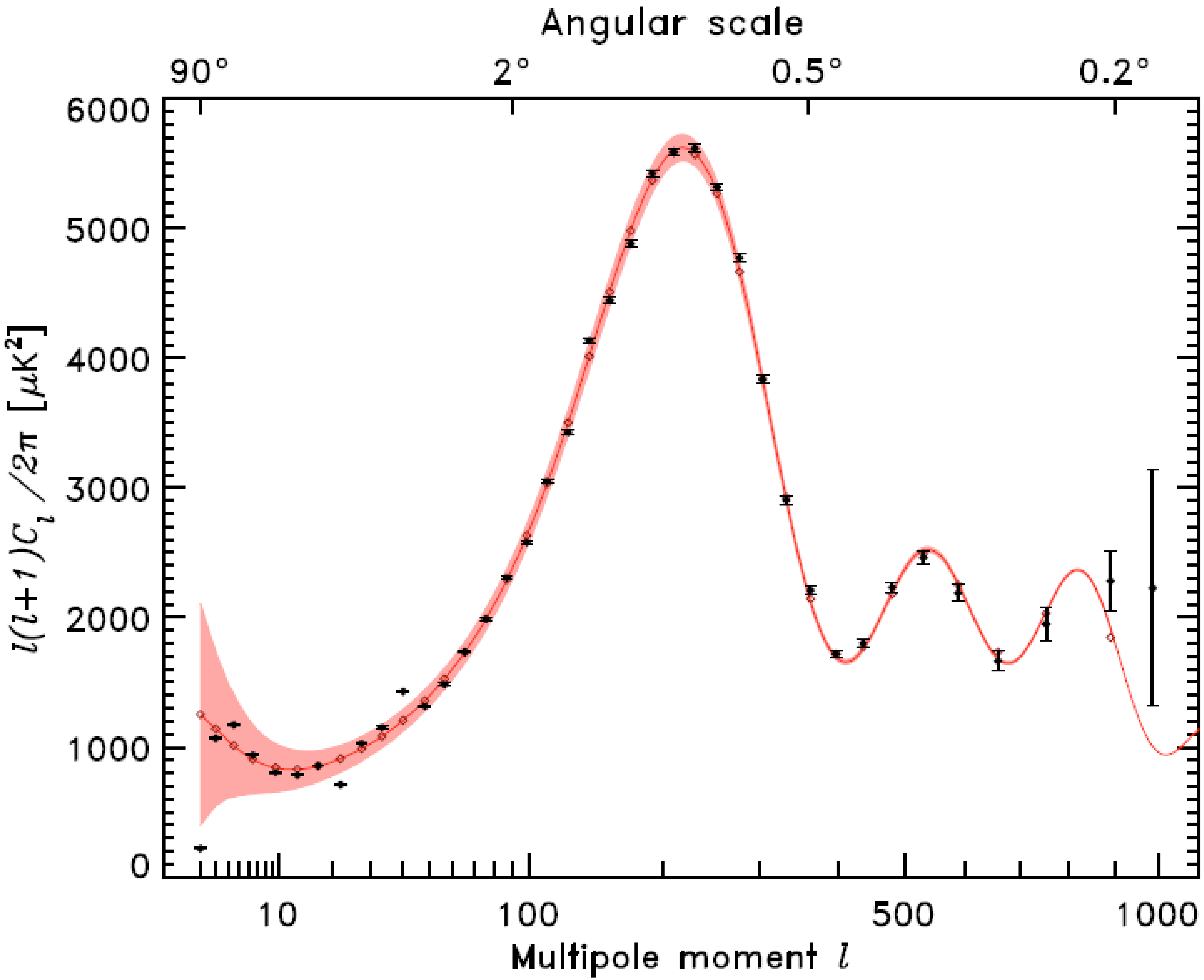


Cosmological parameters in the CMB



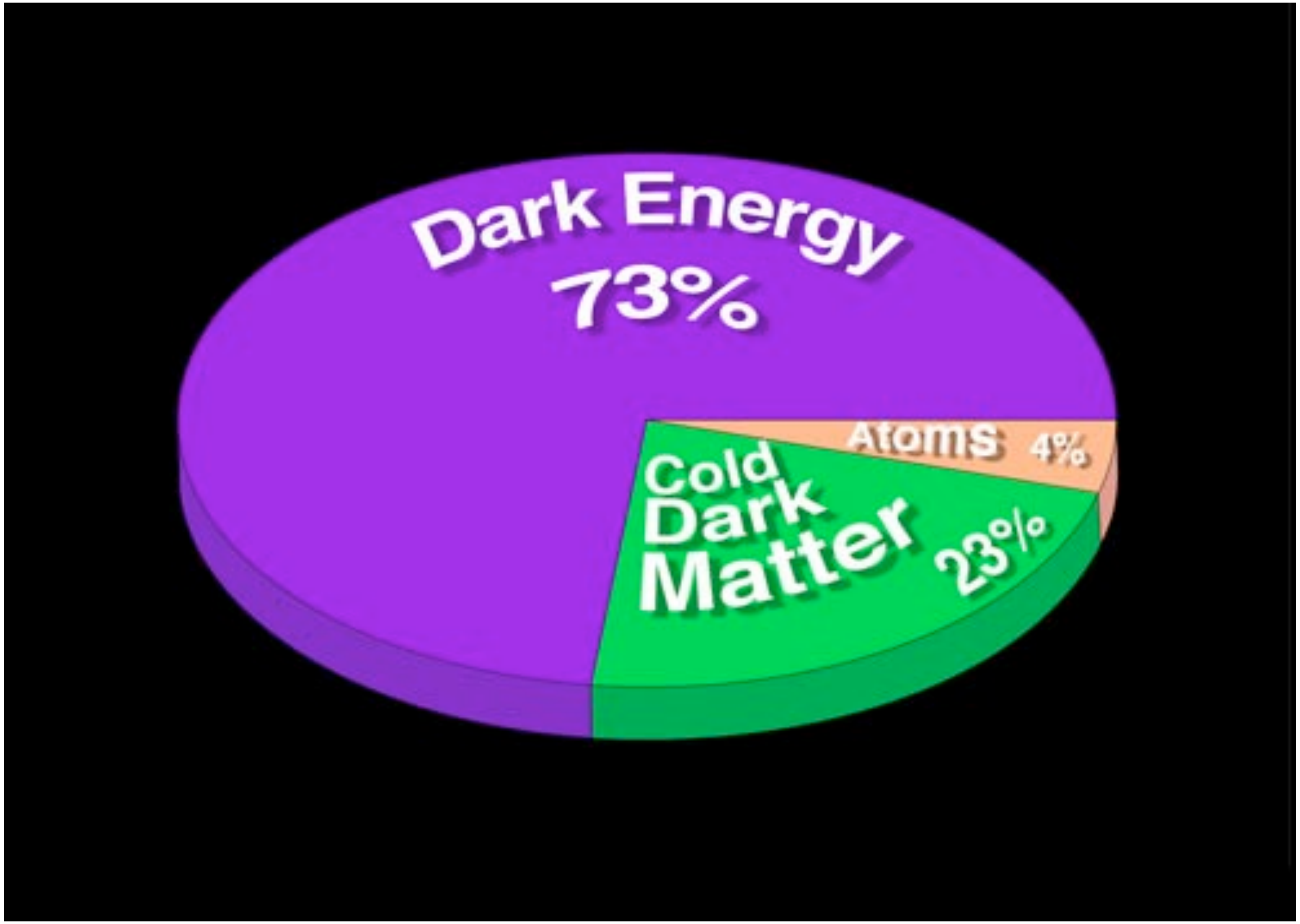
(Courtesey: Wayne Hu)

The precision *WMAP* data are consistent with the ΛCDM cosmology



Best-fit: $\Omega_m h^2 = 0.13 \pm 0.01$, $\Omega_b h^2 = 0.022 \pm 0.001$, $h = 0.73 \pm 0.05$

The content of the Universe



All these observations (and others) indicate that the bulk of the matter in the universe is in a *dark* form

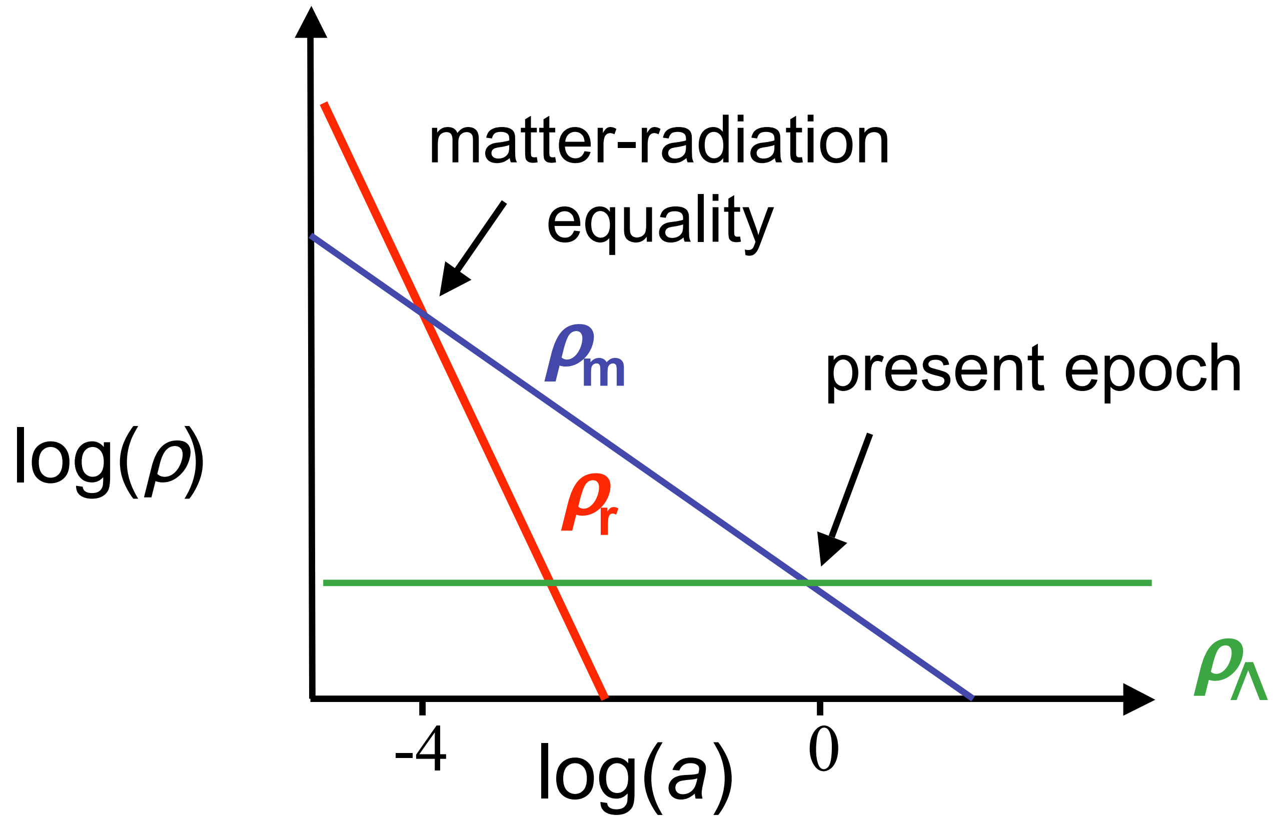
Determining the nature of the **'dark matter'** is among the outstanding challenges in astroparticle physics …

There is a generic expectation that it consists of a new stable particle from *physics beyond the Standard Model*

An even bigger challenge is posed by the observation that the Hubble expansion rate is *accelerating,* implying that the dominant content of the universe is not only dark but also has *negative* pressure – **'dark energy'**

… there is *no* explanation for this in fundamental physics

Einstein's "greatest blunder" has come back to haunt us



Coincidence problem: Why has Λ begun to dominate the universe *right now* … ~10^{10} yr after the Big Bang!

Why is $\Lambda \sim H_0^2$ rather than $\Lambda \sim M_P^2$ (or even M_W^2)?

Is it possible that **dark matter** and/or **dark energy** are illusory?

Modified Newtonian Dynamics (MOND) gives an even *better* account of galactic rotation curves than does dark matter - moreover it *predicts* the observed correlation between the luminosity and rotation velocity: $L \propto v_{rot}^4$ ("Tully-Fisher relation") … however MOND *fails* on the scale of galaxy clusters

The inferred acceleration of the expansion rate may be due to using an over-idealised (homogeneous) model to interpret the luminosity distance of SNe Ia - the growth of inhomogeneity is associated with the recent growth of large-scale structure so this solves the 'coincidence problem' … whether such 'back reaction' can account for the data remains an open question