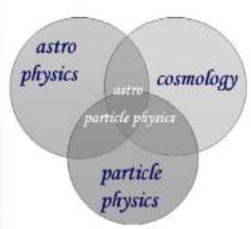
Astroparticle Physics

Hilary 2021

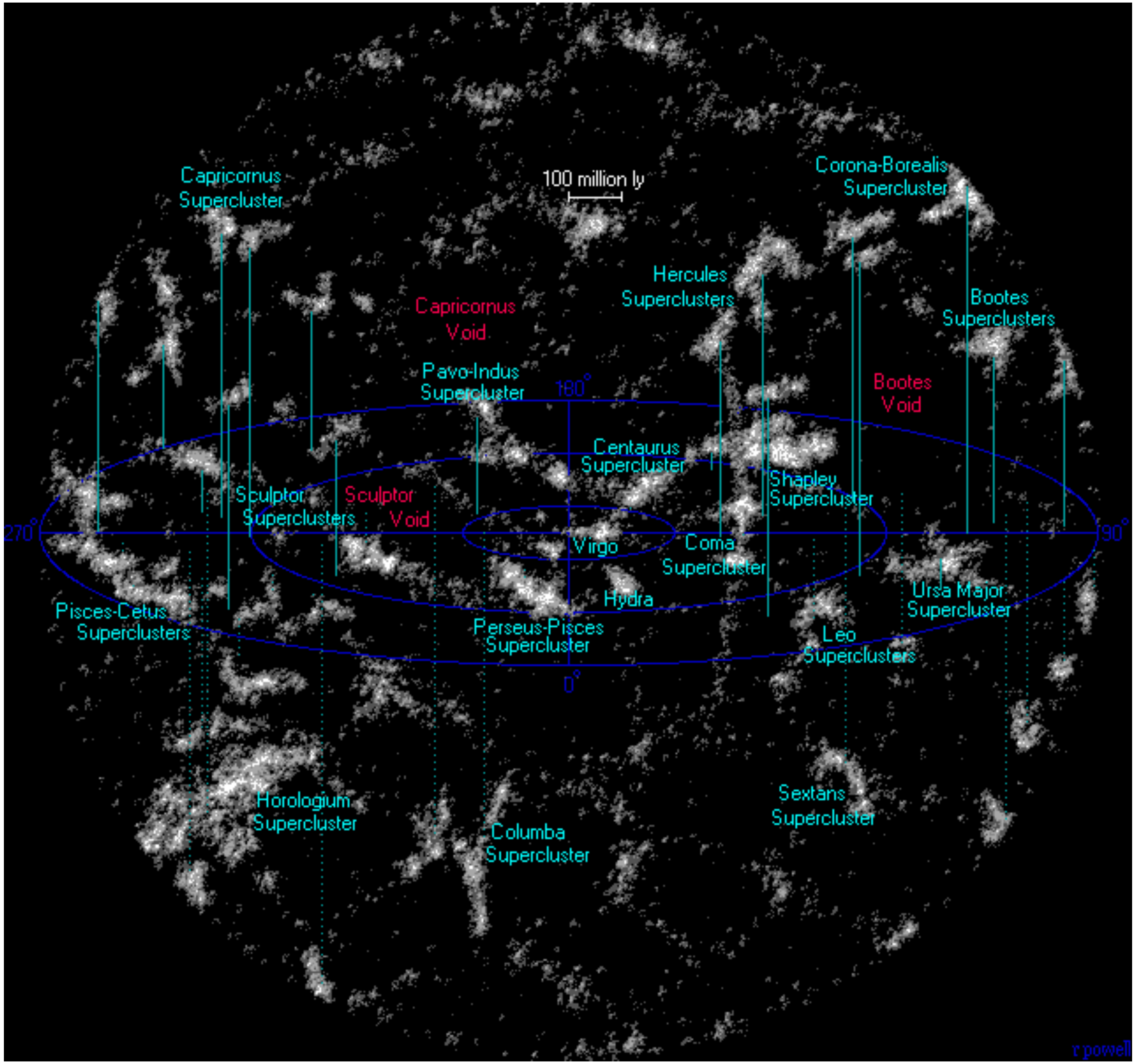


Oxford Physics

Oxford Master Course in Mathematical and Theoretical Physics

- The universe observed
- Relativistic world models
- Reconstructing the thermal history
- Big bang nucleosynthesis
- Dark matter: astrophysical observations
- Dark matter: relic particles
- Dark matter: direct detection
- Dark matter: indirect detection
- Cosmic rays in the Galaxy
- Antimatter in cosmic rays
- Ultrahigh energy cosmic rays
- High energy cosmic neutrinos
- The early universe: constraints on new physics
- The early universe: baryo/leptogenesis
- The early universe: inflation & the primordial density perturbation
- Cosmic microwave background & large-scale structure

THIS IS WHAT OUR UNIVERSE *ACTUALLY* LOOKS LIKE OUT TO ~600 MPC



Is it justified to approximate it as *perfectly* homogeneous?
To consider *all* directions as equivalent? *All* observers the same?

Special relativity

$$\mathrm{d}s^2 = \sum g_{ij}\mathrm{d}x^i\mathrm{d}x^j \ldots \text{ interval between events } x^i \text{ and } x^j (i,j = 0,1,2,3)$$

$$g_{ij}(x) \equiv g_{ji}(x) \longrightarrow 10 \text{ independent functions}$$

Minkowski metric

$$\eta_{ij} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad \frac{\delta g_{ij}}{\delta x^k} = 0 \quad \Rightarrow \mathrm{d}s^2 = \mathrm{d}t^2 - \mathrm{d}x^2 - \mathrm{d}y^2 - \mathrm{d}z^2$$

… invariant under **Lorentz velocity transformations**, *i.e. equivalent* to **local inertial coordinates** of **Newtonian mechanics**

General relativity

Now g_{ij} is related to the **distribution of matter** … but $g_{ij} = \eta_{ij}$ is a solution in the *absence* of matter – contrary to **Mach's principle***!

* inertial frames are determined relative to the matter (distant stars) in the universe

Newton's rotating bucket experiment

… the surface of the water will at first be plain, as before the vessel began to move; but the vessel by gradually communicating its motion to the water, will make it begin sensibly to revolve, and recede by little by little, and ascend to the sides of the vessel, forming itself into a concave figure (as I have experienced), and the swifter the motion becomes, the higher will the water rise, till at last, performing its revolutions in the same time with the vessel, it becomes relatively at rest in it …

Isaac Newton: *Principia* (1689)

Why does the surface of the water becomes concave? Certainly the shape of the surface is not determined by the spin of the water relative to the bucket.

Newton believed that there had to be "absolute space" to define such motion.
Leibniz disagreed - but he had *no* solution to the problem of the rotating bucket.
Berkeley claimed that the water became concave not because it was rotating w.r.t. absolute space but rather because it was rotating with respect to the fixed stars

Newton's experiment with the rotating water bucket teaches us only that the rotation of water relative to the bucket walls does not stir any noticeable centrifugal forces; these are prompted, however, by its rotation relative to the mass of the Earth and the other celestial bodies. Nobody can say how the experiment would turn out, both quantitatively and qualitatively, if the bucket walls became increasingly thicker and more massive – eventually several miles thick.

Ernest Mach (1883)

Einstein (1919) saw two possible ways out:

* add suitable boundary conditions to eliminate anti-Machian solution, *viz.* let g_{ij} take some pathlogical form (rather than becoming η_{ij}) when far away from all matter ✗
… however de Sitter pointed out obvious observational problems with this idea!

* Postulate that the matter distribution is **homogeneous** (in the average) and that matter causes space to curve so as to close in on itself (3D analogue of a 2D balloon) ✔
➔ Spatial volume finite but *no boundaries* and a non-singular metric everywhere

Einstein's world model

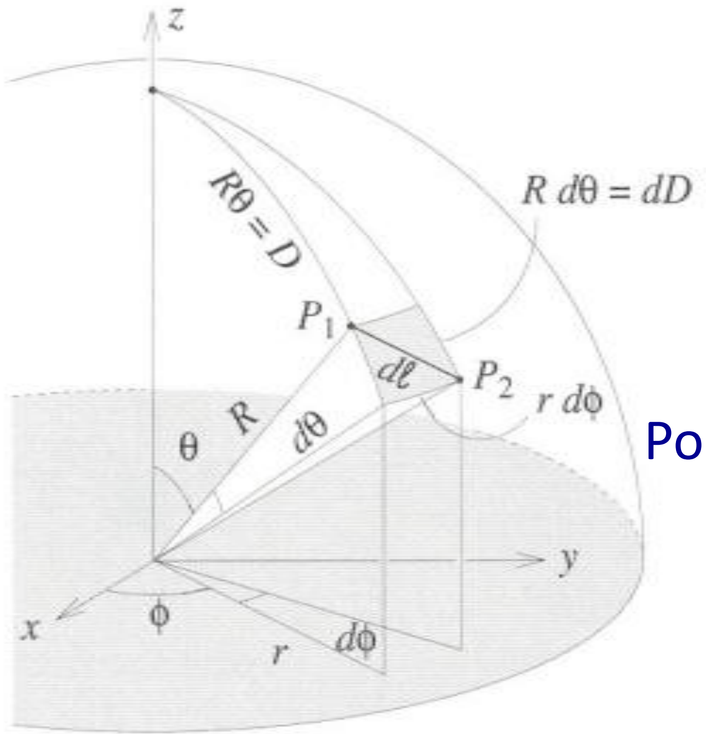
Homogeneity $\Rightarrow \frac{\mathrm{d}\mathcal{N}}{\mathrm{d}m} \propto 10^{0.6m}$ … as observed later (Hubble 1926)

… incorporating Milne's 'Cosmological Principle'

$\mathrm{d}s^2 = \mathrm{d}t^2 + g_{\alpha\beta}\mathrm{d}x^\alpha \mathrm{d}x^\beta$ … synchronous gauge (dense set of comoving observers)

This is still the 'standard model' we use *today* to interpret all observations

Picture the spatial part as $\boldsymbol{S}^3$ (3D analogue of balloon, embedded in flat 4D space)



Set of points defining $\boldsymbol{S}^3$: $R^2 = x^2 + y^2 + z^2 + w^2$

where: $r^2 = x^2 + y^2 + z^2$

Line element: $\mathrm{d}l^2 = \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 + \mathrm{d}w^2$

i.e. $\mathrm{d}l^2 = \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 + r^2\mathrm{d}r^2/(R^2\text{-}r^2)$

Polar coordinates ($z{=}r\cos\theta$, $x{=}r\sin\theta\cos\varphi$, $y{=}r\sin\theta\sin\varphi$):

$$\mathrm{d}l^2 = \mathrm{d}r^2 + r^2\,(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2) + r^2\mathrm{d}r^2/(R^2\text{-}r^2)$$
$$= \mathrm{d}r^2/(1 - r^2/R^2) + r^2\,(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2)$$

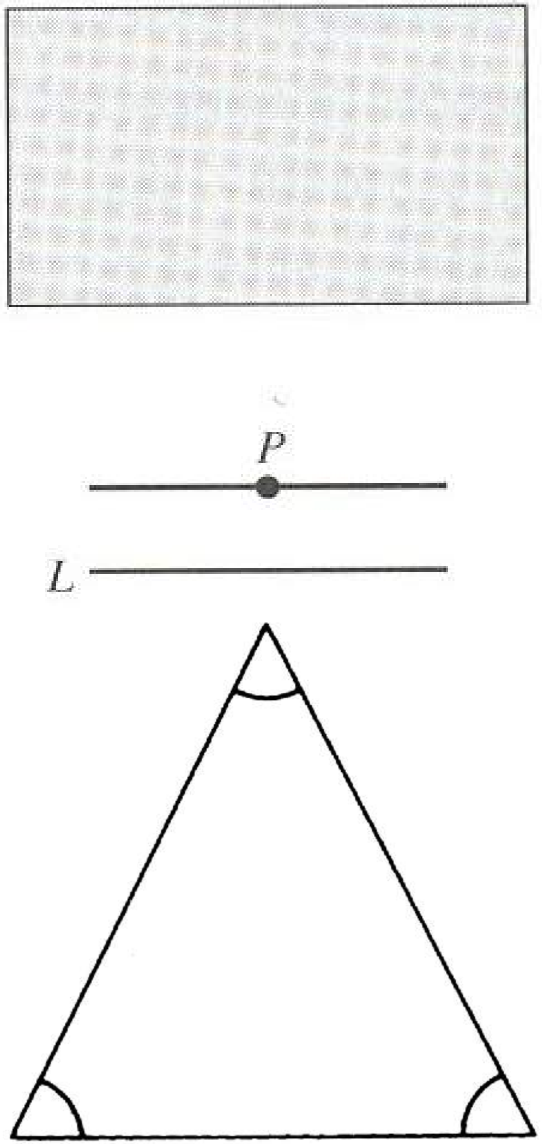
or, $\mathrm{d}s^2 = \mathrm{d}t^2 - R^2\,[\mathrm{d}\chi^2 + \sin^2\chi\,(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2)]$,
where, $r = R\sin\chi$, $\chi \Rightarrow$ polar angle of hypersphere

Note interesting visual effects in curved space (when $r \sim R$), e.g. the angular size $\delta = D/R\sin\chi$ reaches minimum at $\chi = \pi/2$ and diverges to fill the entire sky when $\chi = \pi$ (this point is the just the 'Big Bang' – the antipodal point of the hypersphere)

Also the parallax, $\varepsilon = A\cot\varphi/R$, *vanishes* at $\chi = \pi/2$

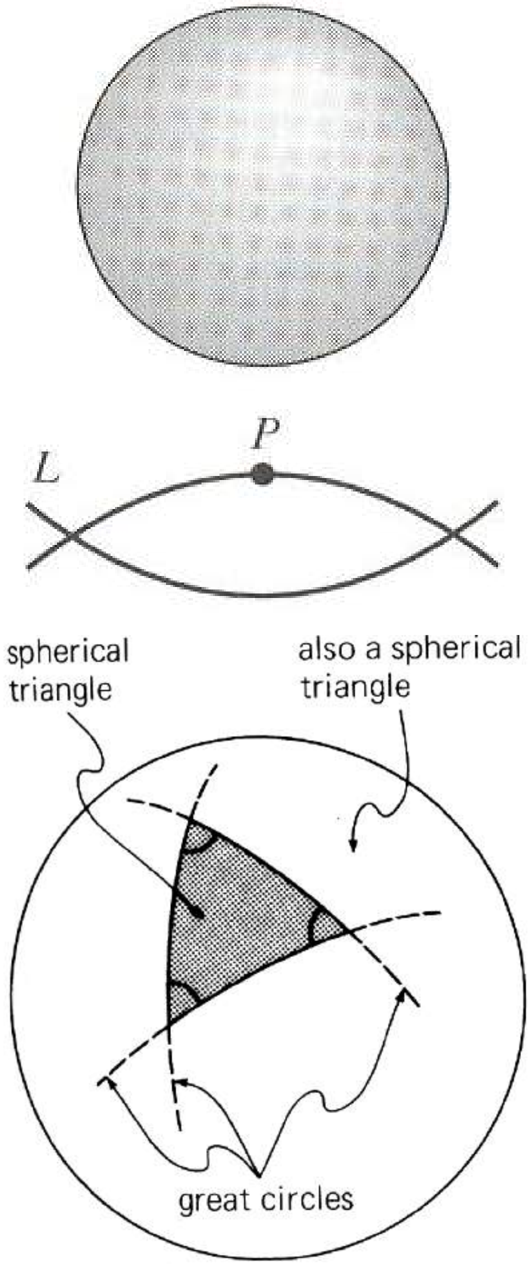
THE 3 GEOMETRIES OF MAXIMALLY-SYMMETRIC SPACE

(However there is no correspondence in general with whether the space is *finite*)

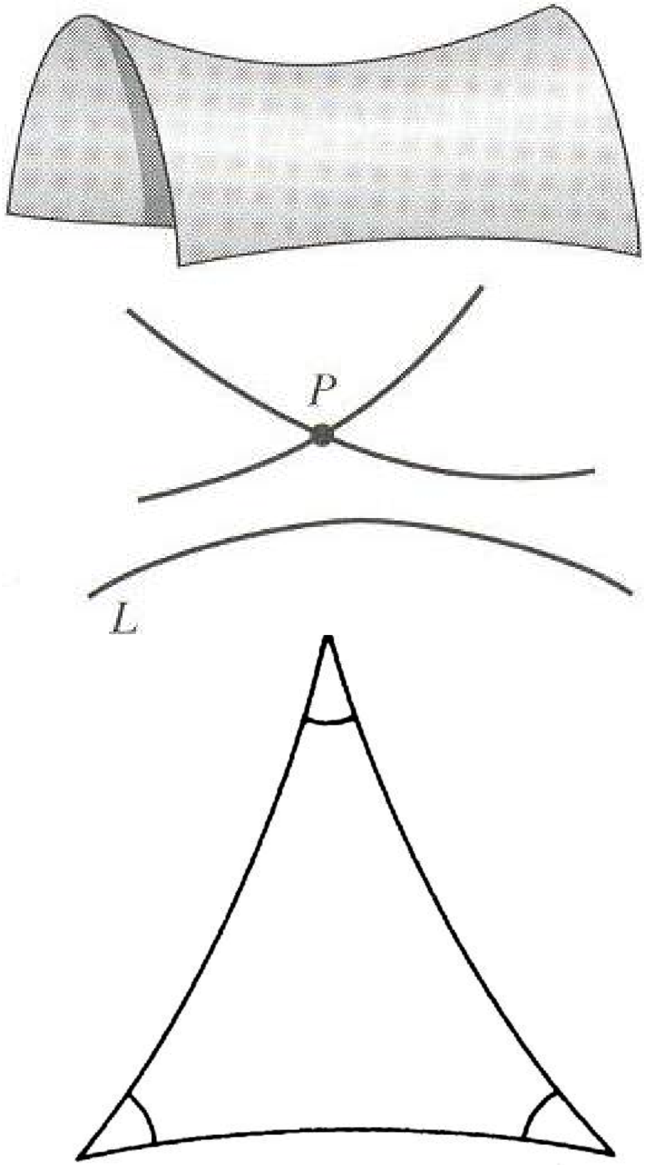


flat space

= 180°



> 180°



hyperbolic space

< 180°

Could the universe have non-trivial topology?

(... as has been suggested e.g. to explain observed anomalies in the CMB)

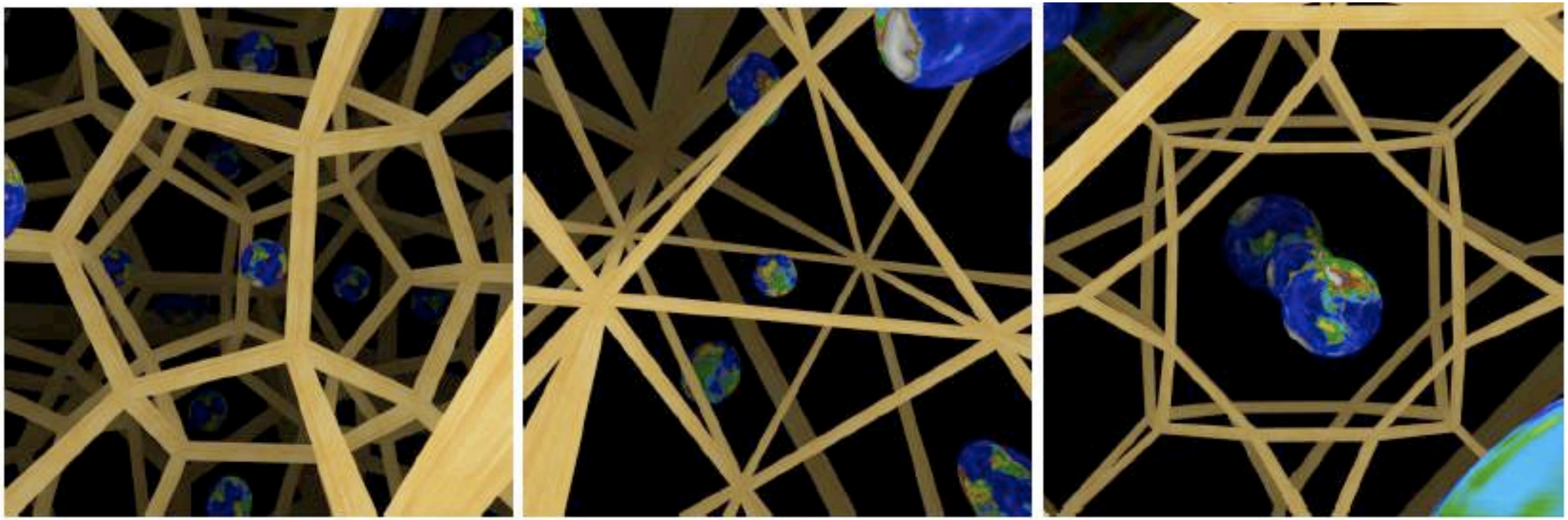
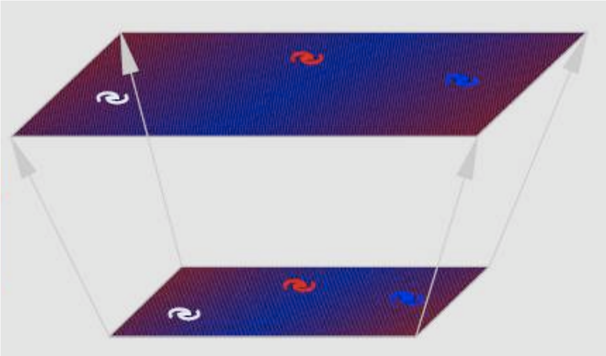


Figure 3: The many shapes of the universe

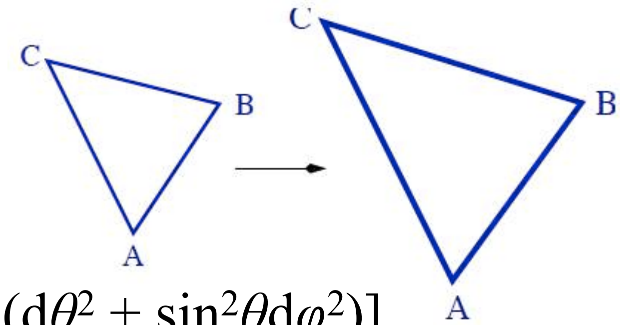
The Poincaré dodecahedral space (left) can be described as the interior of a "sphere" made from 12 slightly curved pentagons. However, this shape has a big difference compared with a football because when one goes out from a pentagonal face, one comes back immediately inside the ball from the opposite face after a 36° rotation. Such a multiply connected space can therefore generate multiple images of the same object, such as a planet or a photon. Other such spaces that fit the WMAP data are the tetrahedron (middle) and octahedron (right). [Credit: Jeff Weeks] see: Luminet, arXiv:0802.2236, Phys. Rep. **254**:135,1995, arXiv:1601.03884

The expanding universe (Friedmann 1922, Lemaitre 1931)



Generalise line element:

$R(t) = R_0\, a(t)$



$$ds^2 = dt^2 - a^2(t)\, R_0^2\, [d\chi^2 + \sin^2\chi\, (d\theta^2 + \sin^2\theta d\varphi^2)]$$

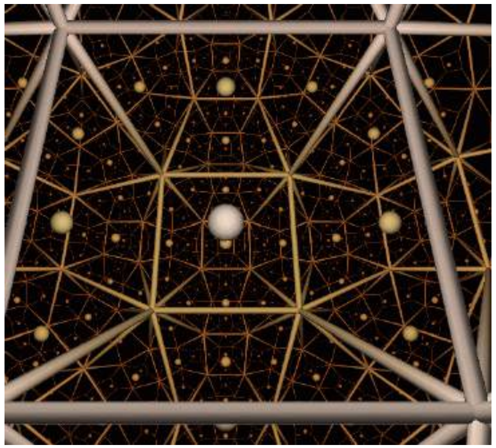
… a spatially **closed** expanding universe

To describe a spatially **open** expanding universe, change: $\chi \rightarrow i\chi$, $R_0 \rightarrow iR_0$, so

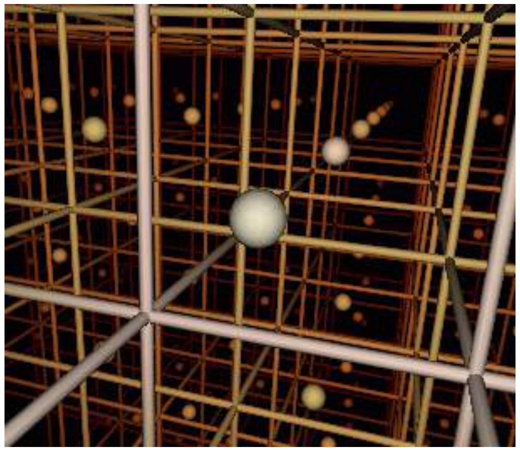
$$ds^2 = dt^2 - a^2(t)\, R_0^2\, [d\chi^2 + \sinh^2\chi\, (d\theta^2 + \sin^2\theta d\varphi^2)]$$

This is the Robertson-Walker line element (*maximally*-symmetric space-time):

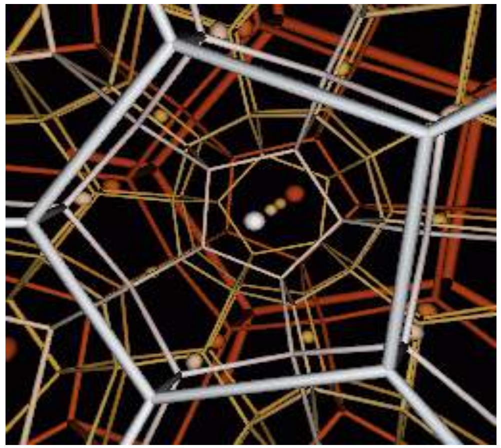
$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$



$k = -1$

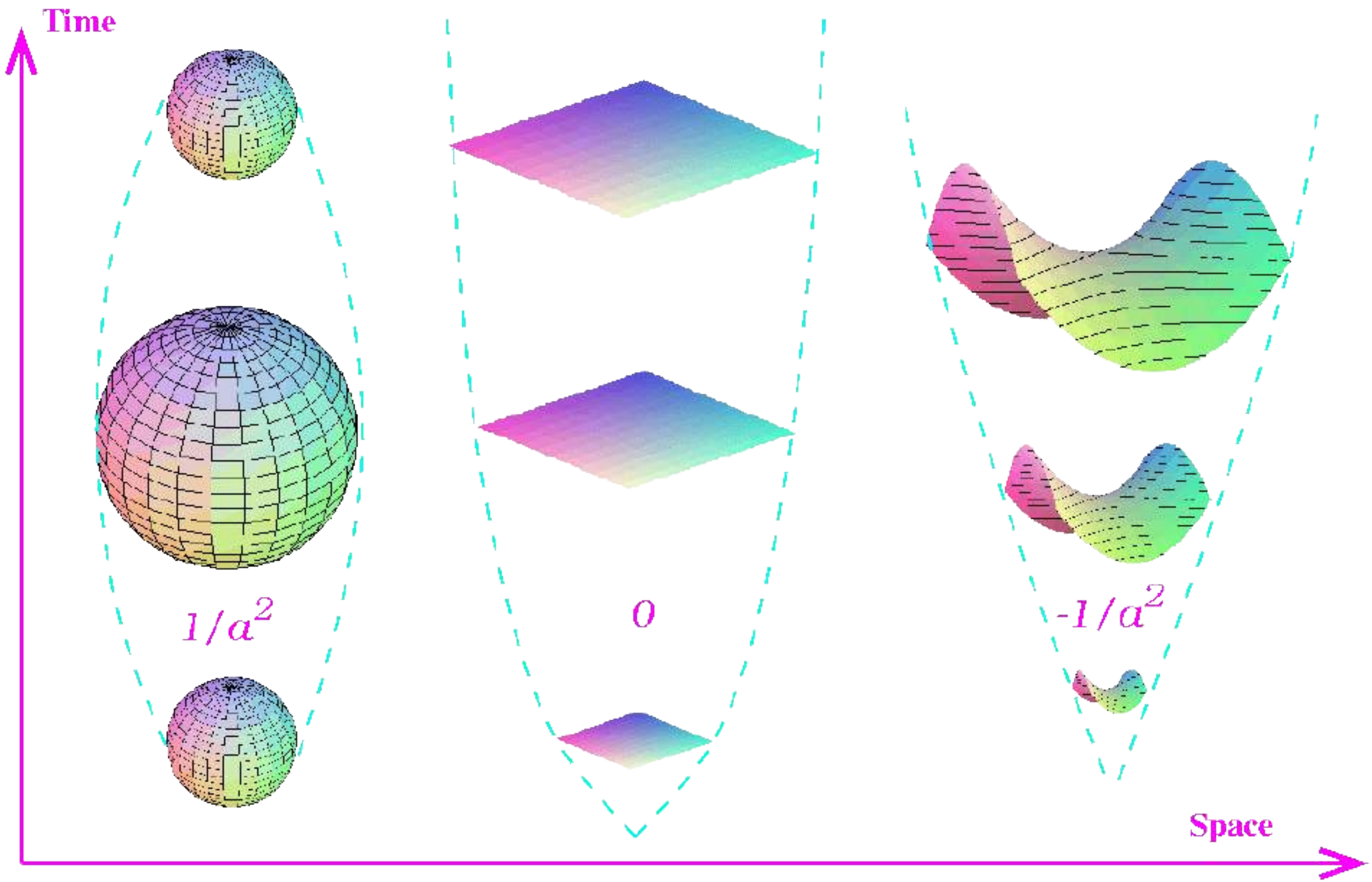


$k = 0$



$k = +1$

Homogeneous and isotropic world models



For other interesting possibilities, see Thurston & Weeks: "The Mathematics of Three-dimensional Manifolds", Sci. Am. **251**:108,1984 (https://www.jstor.org/stable/10.2307/24969417)

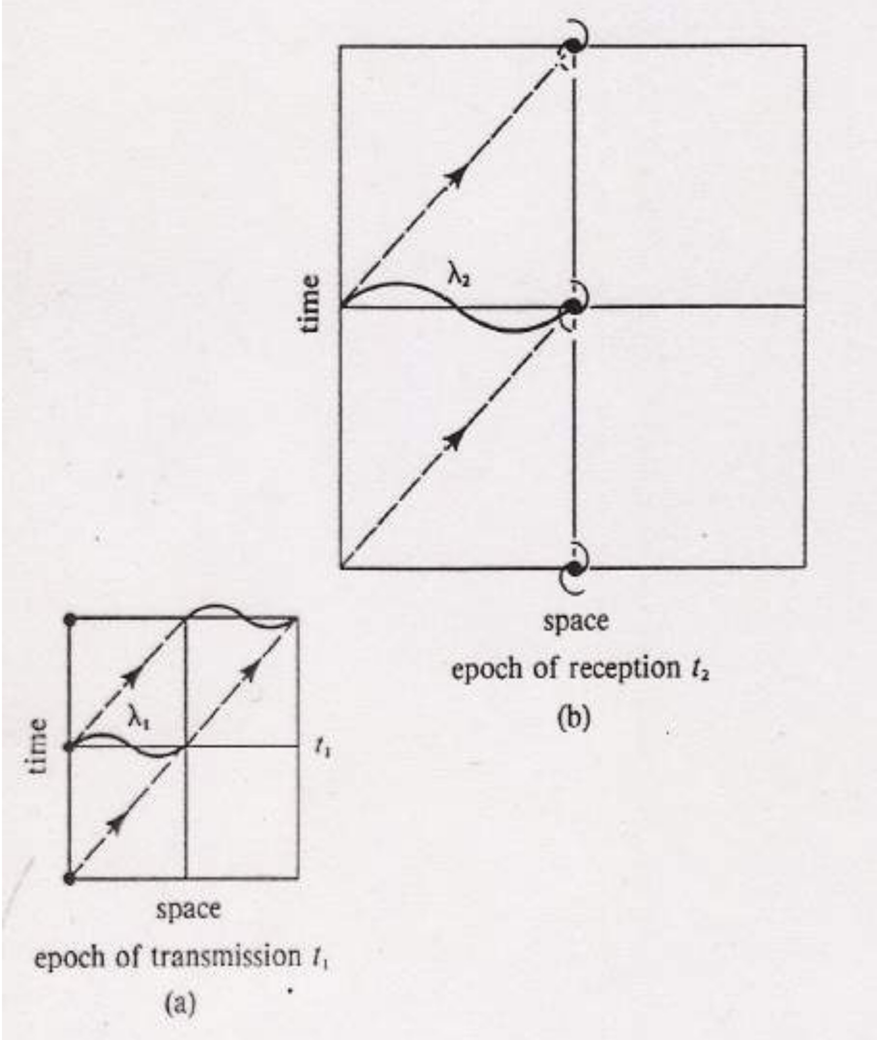
The redshift happens because, for null geodesics:

$$\int_t^{t_0} \frac{\mathrm{d}t}{a(t)} = \int_0^r \frac{\mathrm{d}r}{\sqrt{1-kr^2}} = \mathrm{const}$$

... for a galaxy (in co-moving coordinates), so crests of adjacent waves, separated by Δt at emission, will be received with separation, Δt_0:

$$\frac{\Delta t_0}{\Delta t} = 1 + \frac{\Delta\lambda}{\lambda_0} \equiv 1 + z = \frac{a(t_0)}{a(t)}$$

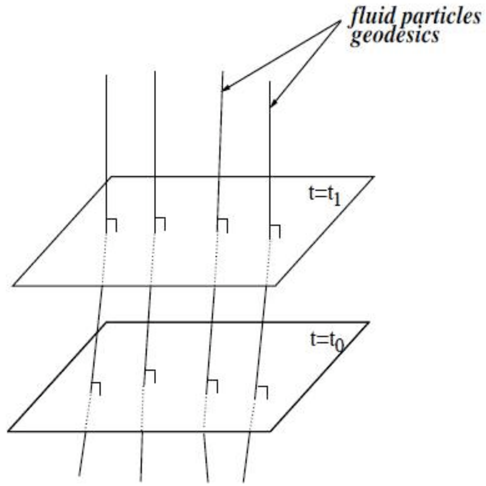
This is the cosmological time dilation or redshift - $z = \infty$ is the 'Big Bang' at *t* = 0 (the antipodal point of the hypersphere) ... the furthest we can look back in principle



Everything is not expanding (how would we know?) ... certainly not bound structures like atoms or planets or galaxies – it is only the large-scale *smoothed* space-time metric which is stretching with cosmic time (and there is no restriction on the rate!)

The 'expansion' is in a sense *illusory* ... because we can always transform to a "comoving" coordinate system where galaxies are *at rest* wrt each other

Ideal fluid: $T_{ij} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$



Poisson's equation: $\nabla . g = -4\pi G_{\mathrm{N}}(\rho + 3p)$

Birkhoff's theorem: If $T_{ij} = 0$ in some region within a spherically symmetric distribution of matter, then the solution in the hole ⇒ flat space-time

Einstein's field equations

$$R_{ij} + \tfrac{1}{2} g_{ij} R_{\mathrm{c}} = 8\pi G_{\mathrm{N}} T_{ij}, \;\text{ where } R_{ij} \equiv g^{\lambda k} R_{\mu\nu\lambda k} \text{ and } R_{\mathrm{c}} \equiv g^{\mu\nu} R_{\mu\nu}$$

For the RW metric, the 00 and 11 components simplify to the Friedmann equations:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\mathrm{N}}}{3}\rho - \frac{k}{a^2}$$

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{4\pi G_{\mathrm{N}}}{3}(\rho + 3p)$$

'Newtonian' Cosmology

Consider sphere of radius l embedded in homogeneous background (McCrea & Milne 1934):

$$\ddot{\ell} = -G_{\rm N}M/r^2 = -\tfrac{4\pi}{3}G_{\rm N}(\rho+3p)\ell; \text{ also } {\rm d}U \equiv \rho{\rm d}V + V{\rm d}\rho = -p{\rm d}V$$

$$\Rightarrow \dot{\rho} = -(\rho+p)\frac{\dot{V}}{V} = -3(\rho+p)\frac{\dot{\ell}}{\ell} \text{ ... energy eq. for ideal fluid}$$

$$\text{So, } \ddot{\ell} = \tfrac{8\pi}{3}G_{\rm N}\rho\ell + \tfrac{4\pi}{3}G_{\rm N}\dot{\rho}\frac{\ell^2}{\dot{\ell}} \Rightarrow \dot{\ell}^2 = \tfrac{8\pi}{3}G_{\rm N}\rho\ell^2 + K$$

To obtain a *static* solution (Einstein's "greatest blunder") we have to set:

$$\rho + 3p = 0 \text{ i.e. } p = -\tfrac{\rho}{3} \text{ (!)} \Rightarrow \text{ universe of radius: } \mathcal{R}^2 = -\tfrac{\ell^2}{k} = [\tfrac{8\pi}{3}G_{\rm N}\rho]^{-1}$$

The static solution is in fact *unstable* (metric perturbations grow exponentially fast) but we do *not* have the freedom, as Einstein said, to "do away with the cosmological constant" … it is a *necessary* consequence of **general coordinate invariance** which allows any *arbitrary* constant multiplying the metric tensor to be added to the l.h.s.

So must modify the field equations to: $R_{ij} + \frac{1}{2}g_{ij}R_{\rm c} - \Lambda g_{ij} = 8\pi G_{\rm N}T_{ij}$

… which can be *interpreted* (when moved to r.h.s.) as a fluid with: $\rho_\Lambda = -p_\Lambda = \Lambda/8\pi G_{\rm N}$

FLRW Dynamics

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_{\mathrm{N}}}{3}(\rho + 3p) \pm \frac{1}{a^2\mathcal{R}^2} \to -\frac{4\pi G_{\mathrm{N}}}{3}(\rho_{\mathrm{b}} + 3p_{\mathrm{b}}) \pm \frac{1}{a^2\mathcal{R}^2} + \frac{\Lambda}{3}$$

b ⇒ 'background' (i.e. "ordinary" matter/radiation)

Conservation of energy-momentum: $\dot{\rho_{\mathrm{b}}} = -3(\rho_{\mathrm{b}} + p_{\mathrm{b}})\frac{\dot{a}}{a}$

$$\Rightarrow \left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi G_{\mathrm{N}}}{3}\rho_{\mathrm{b}} \pm \frac{1}{a^2\mathcal{R}^2} + \frac{\Lambda}{3},\quad \text{where + is open/- is closed universe}$$

Two interesting solutions describing an expanding universe:

Einstein-De Sitter:

$$p_{\mathrm{b}} \ll \rho_{\mathrm{b}}, \Lambda = \frac{1}{a^2\mathcal{R}^2} = 0 \Rightarrow a(t) \propto t^{2/3}, t = \frac{2}{3H} = \frac{1}{\sqrt{6\pi G_{\mathrm{N}}\rho}}$$

De Sitter:

$$\rho_{\mathrm{b}} = p_{\mathrm{b}} = 0 \Rightarrow a(t) = \exp\left(H_\Lambda t\right), \text{ where } H_\Lambda = \sqrt{\frac{\Lambda}{3}}$$

The de Sitter universe was "motion without matter" (violating Mach's Principle!) *cf.* Einstein's static universe which was "matter without motion"

DE SITTER (1917) PRESENTED A THIRD (APPARENTLY) *STATIC* SOLUTION:

$$\mathrm{d}s^2 = \left(1 - \frac{r^2}{\mathcal{R}^2}\right)\mathrm{d}t^2 - \mathrm{d}r^2/\left(1 - \frac{r^2}{\mathcal{R}^2}\right) - r^2(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2)$$

For a clock at rest at a particular point ($\mathrm{d}r = \mathrm{d}\theta = \mathrm{d}\varphi = 0$), the time-like interval, $\mathrm{d}s^2 = \mathrm{d}t^2\,(1 - r^2/R^2)$ now depends on the radial distance, and becomes smaller as r increases ⇒ redshift of light from distant sources, but with:

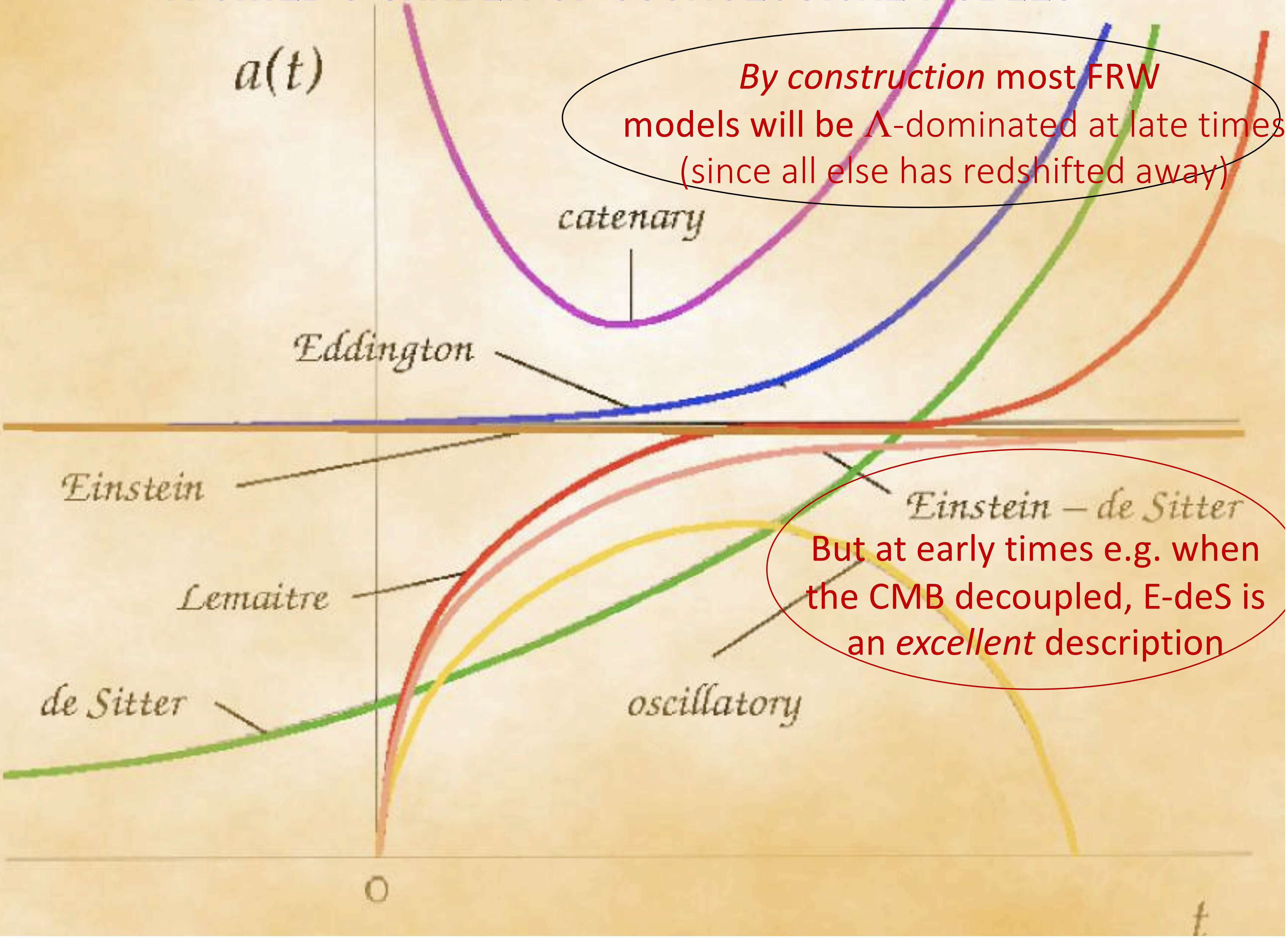
$$\frac{\mathrm{d}t}{\mathrm{d}t_0} = \sqrt{1 - \frac{r^2}{\mathcal{R}^2}} = \frac{\lambda}{\lambda_0} = 1 + \frac{\Delta\lambda}{\lambda_0} \Rightarrow z \simeq \frac{1}{2}\frac{r^2}{\mathcal{R}^2}, \quad \text{for } r \ll \mathcal{R}$$

But De Sitter showed later (1933) that the redshift-distance relationship is in fact linear (as it *should* be for inertial observers in any homogeneous space-time) since observers in this (De Sitter) space are in fact *accelerating* … meanwhile observers (Stromberg, Lundmark, Wirtz, Silberstein *et al*) were misled into looking for the "De Sitter effect".

Hubble (1929) tried to fit the redshift-distance data to a *quadratic* relationship (in fact he never mentioned the 'expanding universe' which is widely attributed to him!

Later Hubble (1931) wrote to De Sitter: "*The interpretation, we feel, should be left to you and the very few others who are competent to discuss the matter with authority* "

A child's garden of cosmological models



By construction most FRW models will be Λ-dominated at late times (since all else has redshifted away)

But at early times e.g. when the CMB decoupled, E-deS is an *excellent* description

The R-W metric does *not* reduce to the Minkowski form when $r \to \propto$ (*cf.* the Schwarzchild metric), however when written in terms of the **conformal time** $\mathrm{d}\eta = \mathrm{d}t/a(t)$, it is **globally conformal to the Minkowski metric** (for $k = 0$):

$$\mathrm{d}s^2 = a^2(\eta)\left[\mathrm{d}\eta^2 - \mathrm{d}r^2/(1-kr^2) - r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2\right]$$

This is (relatively) easy to work with, however should we not consider less symmetric metrics which describe our (inhomogeneous) universe better?

The problem is that *very few* exact cosmological solutions are known … so we tend to use 'toy models' rather than attempt a more realistic description

For example, a less symmetric possibility is the Lemaitre-Tolman-Bondi metric describing an universe that is *inhomogeneous* but isotropic around our position

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2\left[\left(1 + \frac{r}{a}\frac{\partial a}{\partial r}\right)^2 \mathrm{d}r^2/(1-k(r)r^2) + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2\right]$$

This requires us to be in a special position i.e. exactly at the centre of a radial inhomogeneity as specified by $k(r)$ (e.g. a void), but can completely **change the interpretation of the data** (in particular there is no need then to invoke $\Lambda \neq 0$ to explain the SN Ia Hubble diagram in terms of cosmic acceleration!

Using the RW metric we can define *observational quantities* to be measured

Expand in Taylor series: $$\frac{a(t)}{a(t_0)} = 1 + H_0(t - t_0) - \frac{1}{2} q_0 H_0^2 (t - t_0)^2 + \ldots,$$

$$H_0 \equiv \dot{a}(t_0)/a(t_0), \quad q_0 \equiv -\ddot{a}(t_0)a(t_0)/\dot{a}^2(t_0)$$

Invert to obtain: $$z = H_0(t_0 - t) + (1 + q_0/2)H_0^2(t_0 - t)^2 + \ldots,$$

$$\Rightarrow (t_0 - t) = H_0^{-1}\left[z - (1 + q_0/2)z^2 + \ldots\right]$$

Coordinate distance: $$r_{\mathrm{e}} = a^{-1}(t_0)H_0^{-1}\left[z - (1 + q_0/2)z^2 + \ldots\right]$$

$$\text{using:} \int_{t_{\mathrm{e}}}^{t_{\mathrm{o}}} \frac{\mathrm{d}t}{a(t)} = \int_0^{r_{\mathrm{e}}} \frac{\mathrm{d}r}{\sqrt{1 - kr^2}} = r_{\mathrm{e}}, \quad \text{for } k = 0$$

$$= \sin^{-1} r_{\mathrm{e}}, \quad \text{for } k = 1$$

$$= \sinh^{-1} r_{\mathrm{e}}, \quad \text{for } k = -1$$

`Hubble law': $$H_0 d_{\mathrm{L}} = z + \tfrac{1}{2}(1 - q_0)z^2 + \ldots$$

$$\text{where}: d_{\mathrm{L}} \equiv a^2(t_0)r_{\mathrm{e}}^2(1 + z)^2 \Rightarrow \text{“luminosity distance”}$$

The apparent luminosity of a source of absolute luminosity L is:

$$\ell = \frac{L}{4\pi a(t_0)^2 r_e^2 (1+z)^2}$$

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

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

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

Hence the intrinsic luminosity is related to the apparent luminosity as:

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

… which gives the magnitude-redshift relation:

$$m = 5\log q_0^{-2}\left[zq_0 + (q_0-1)\left(-1+\sqrt{2zq_0+1}\right)\right] + C$$
$$\simeq 5\log z + 1.086(1-q_0 z) + \mathcal{O}(z^2) + \ldots,\ \text{for } z \lesssim 0.3$$

Rewriting Friedmann's equation as:

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

$$\text{where } \Omega_\mathrm{m} \equiv \frac{8\pi G_\mathrm{N}}{3H_0^2}\rho_{\mathrm{m}_0}, \quad \text{and } \Omega_\Lambda \equiv \Lambda/3H_0^2,$$

We see that: $q_0 = \Omega_\mathrm{m}/2 - \Omega_\Lambda$

i.e. measurement of the present expansion rate H_0 and its rate of change q_0 yields the dynamical parameters of the FRLW cosmology

… so astronomers like Sandage embarked on a quest to measure these

His programme was however *unsuccessful* because a complete understanding of **evolutionary effects** is essential to determine cosmological parameters

$$\text{e.g.} \quad \text{galaxy counts:} \ \frac{\mathrm{d}N_{\text{gal}}}{\mathrm{d}z\mathrm{d}\Omega} = \frac{n_{\text{c}}(z)}{H_0^3 a_0^3 (1+z)^3 q_0^4} \frac{\left[zq_0 + (q_0 - 1)\left(\sqrt{2q_0 z + 1} - 1\right)\right]^2}{\sqrt{1 - 2q_0 + 2q_0(1+z)}}$$

$$\text{e.g.} \quad \text{angular diameter:} \ H_0 d_{\text{A}} = \frac{1}{q_0^2 (1+z)^2} \left[zq_0 + (q_0 - 1)\left(\sqrt{2q_0 z + 1} - 1\right)\right]$$

$$\simeq z - \frac{1}{2}(3 + q_0)z^2 + \ldots, \ \text{where} \ d_{\text{A}} \equiv \frac{D}{\delta} = a(t_{\text{e}})r_{\text{e}}$$

… and other such tests (e.g. surface brightness) but all these are biased by *evolutionary effects*

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

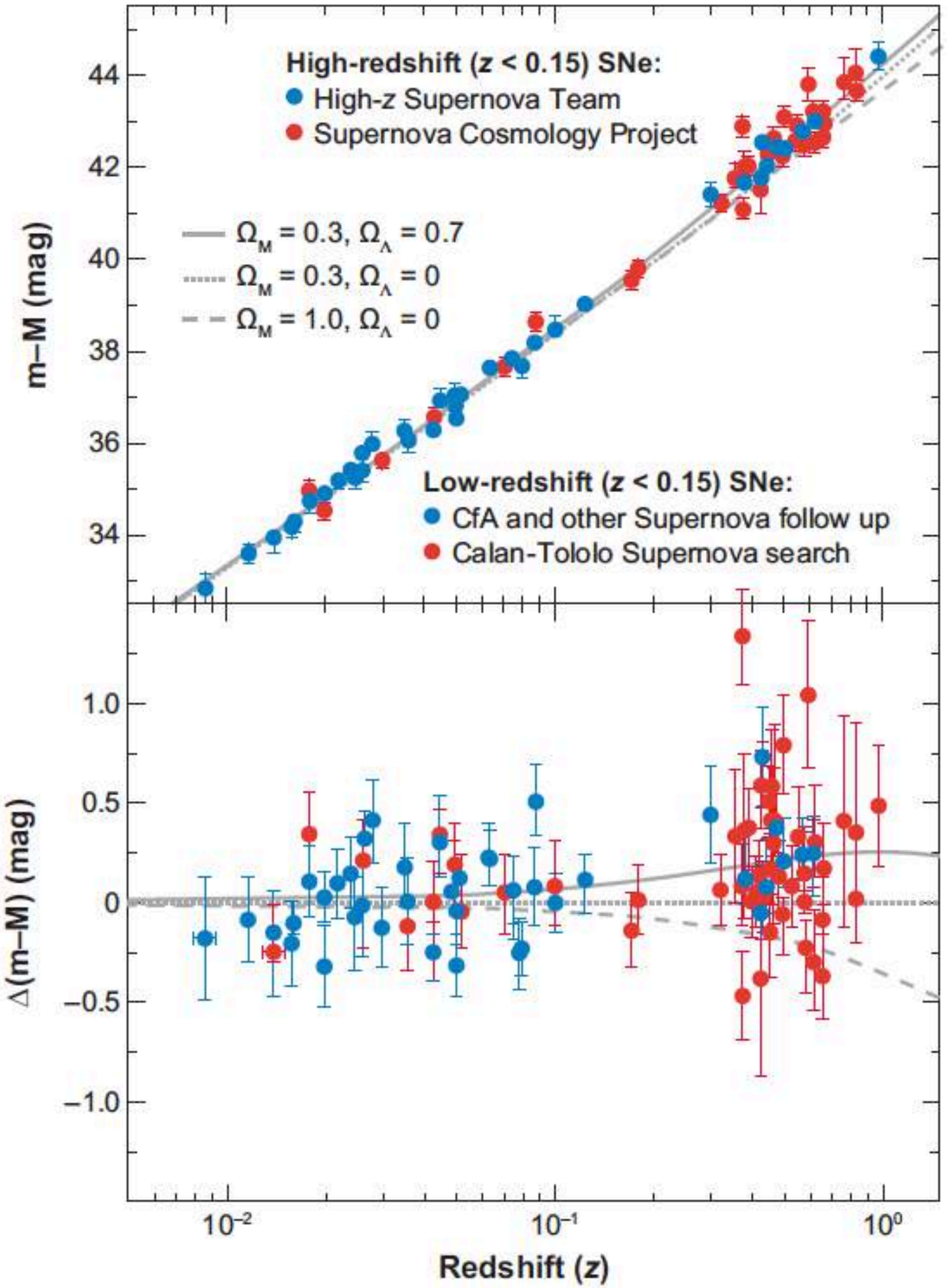
$$\text{then,} \ \ell = \frac{L}{4\pi}\left(\frac{H_0}{z}\right)^2 \left[1 + (q_0 - 1)z - \alpha H_0^{-1} z + \ldots\right]$$

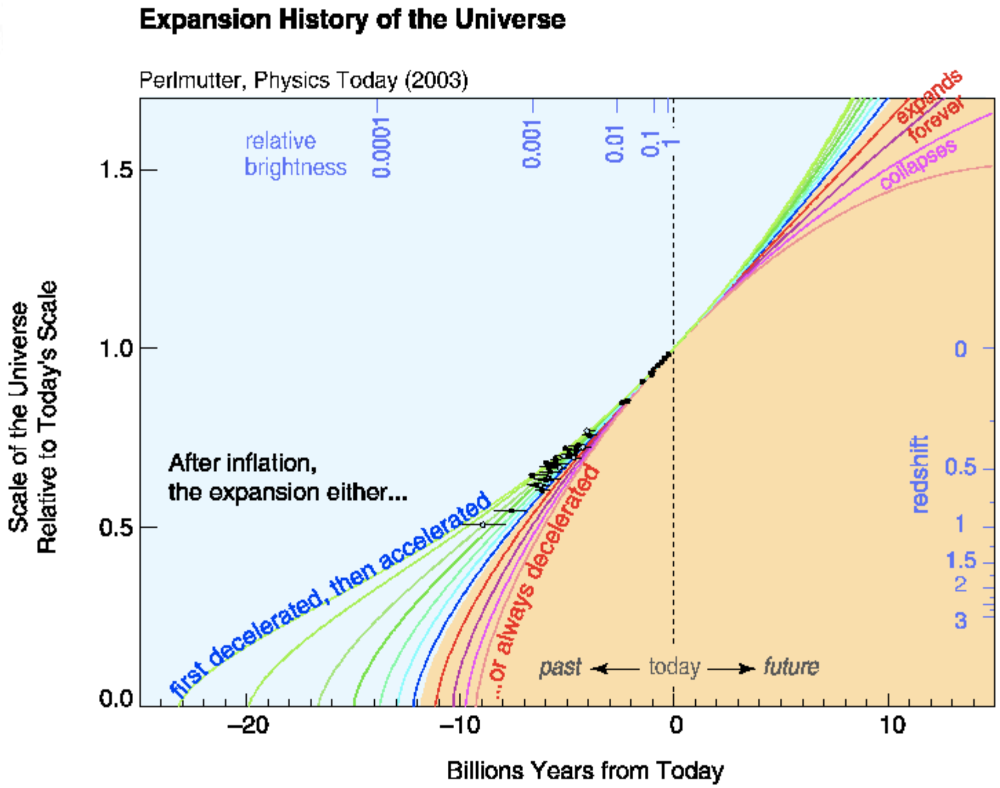
so will obtain *wrong* answer for q_0 if unaware of possible luminosity evolution

There have been several claims for *negative* q_0 ($\Rightarrow \Lambda > 0$) from such 'classic' cosmological tests – which were however discounted subsequently

(see e.g. Peebles & Ratra, RMP **75** (2013) 559, Sahni & Starobinsky IJMPD **9** (2000) 73)

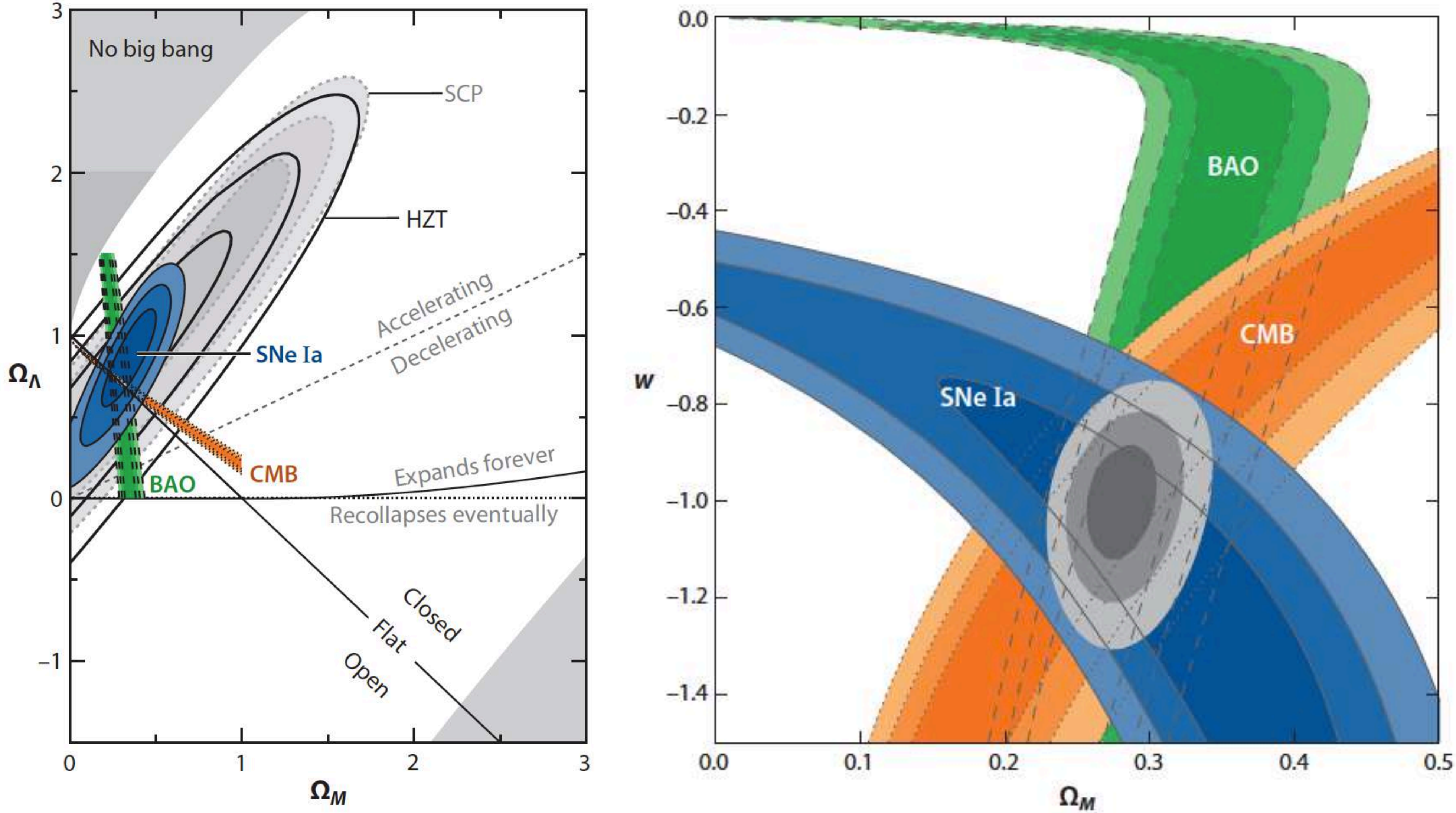
Recently it has proved possible to routinely detect SN Ia in distant galaxies and use them as 'standard candles' to trace the Hubble expansion out to $z \sim 1$





These observations have been interpreted to mean that the expansion rate is *accelerating* as if driven by a dominant Cosmological Constant term

Along with other *geometric* measurements this implies a Cosmological Constant today with $\Lambda \simeq 2H_0^2 \Rightarrow \Omega_\Lambda \simeq 0.7$ (e.g. Weinberg *et al*, Phys.Rep.**530**:87,2013) … but this is yet to be confirmed by *dynamical* measurements (*i.e.* making no assumptions about the metric)



Goobar & Leibundgut, ARNPS **61**:251,2011

The data have been *interpreted* more generally as implying 'dark energy' with *negative* pressure ($w = p/\rho \simeq$ -1) but there is no direct evidence yet (*e.g.* late ISW effect) for this unique property

The SN Ia data can in fact be fitted equally well *without* Λ

… by simply adopting a different metric (Celerier, A&A **353**:63,2000)

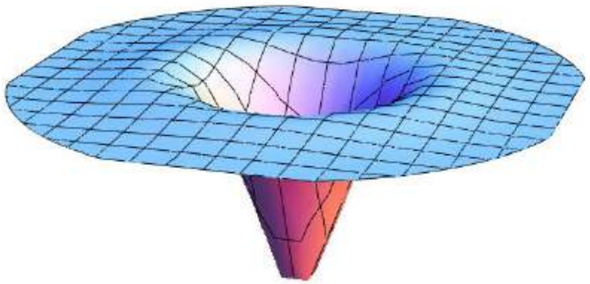
LTB metric: $ds^2 = -c^2dt^2 + \frac{A'^2(r,t)}{1+K(r)}dr^2 + A^2(r,t)d\Omega^2$

Two Hubble rates: $H_T(r,t) \equiv \frac{\dot{A}}{A}$ and $H_L(r,t) \equiv \frac{\dot{A}'}{A'}$

Obtain modified version of Friedmann equation -

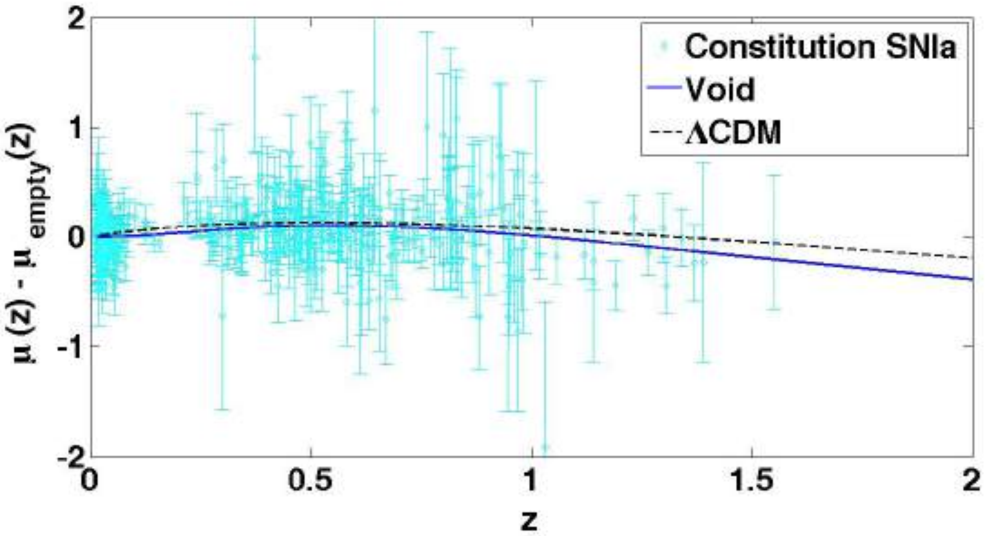
$$H_T^2(r,t) = H_0^2(r)\left[\Omega_m(r)\left(\frac{A_0(r)}{A(r,t)}\right)^3 + \Omega_K(r)\left(\frac{A_0(r)}{A(r,t)}\right)^2\right]$$

Choose a density profile



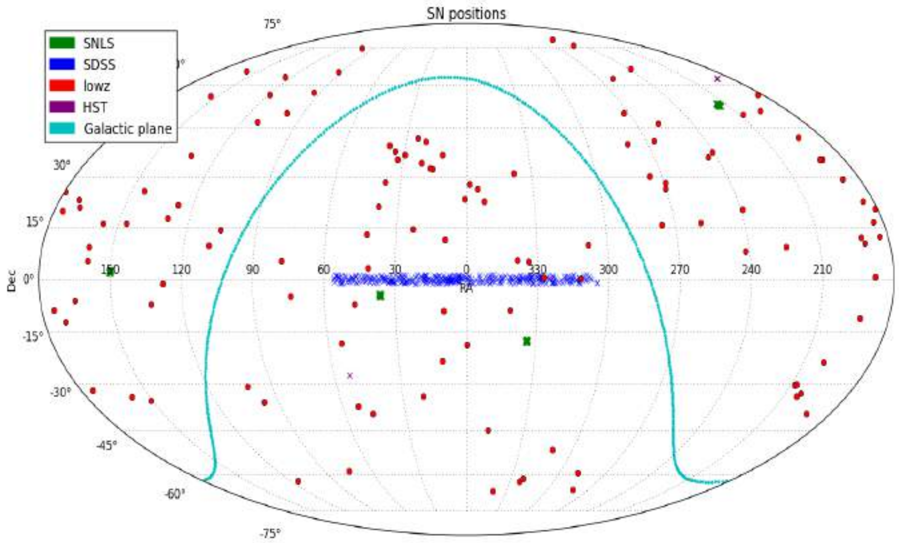
- Solve modified Friedmann equation numerically for $A(r,t)$
- Luminosity distance $D_L(z) = (1+z)^2 A(r,t)$

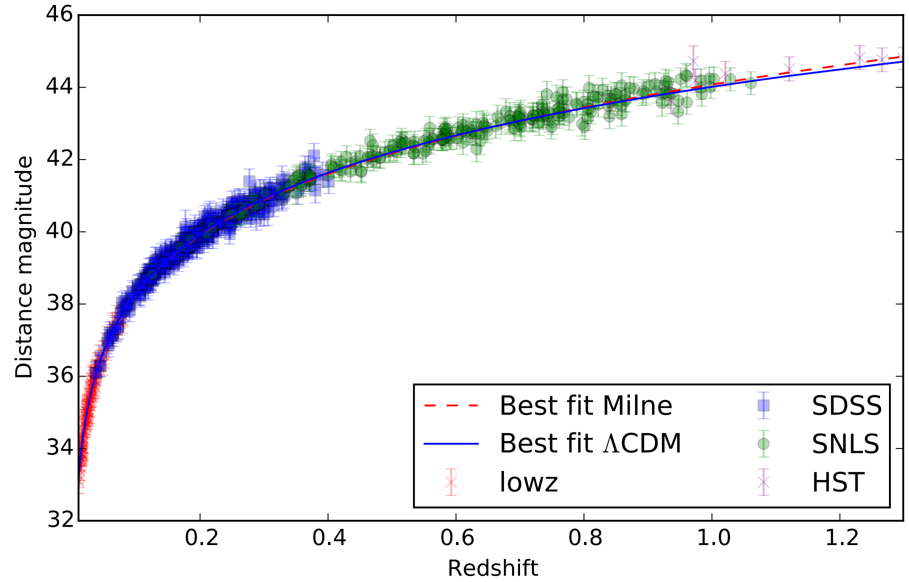
Can get a very good fit to supernovae data:

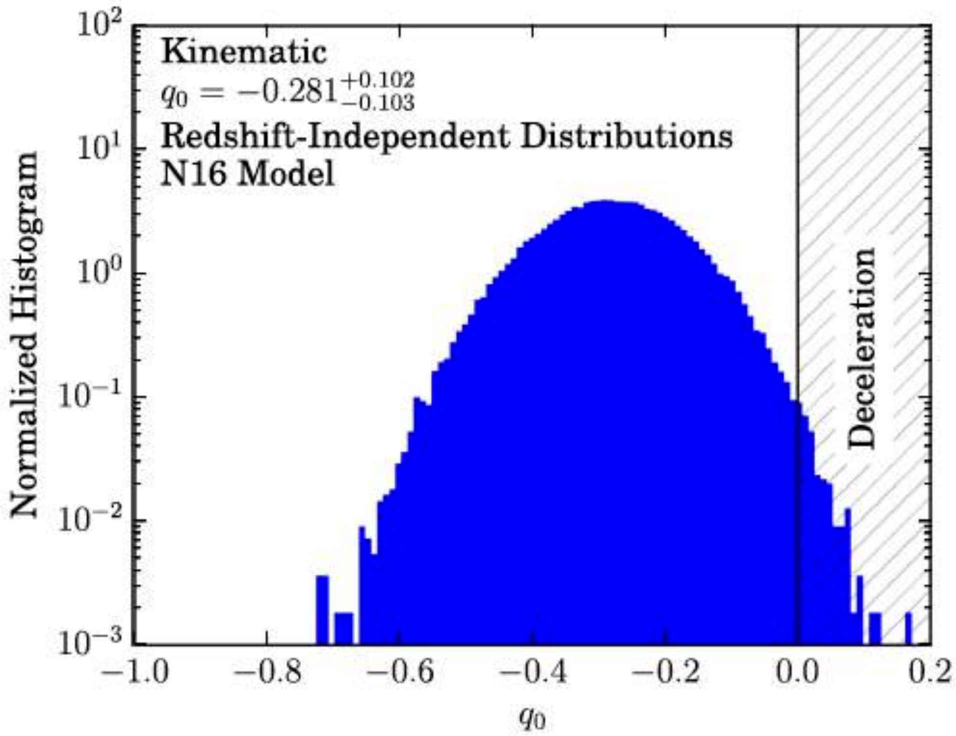


… in fact the evidence for cosmic acceleration is <3σ

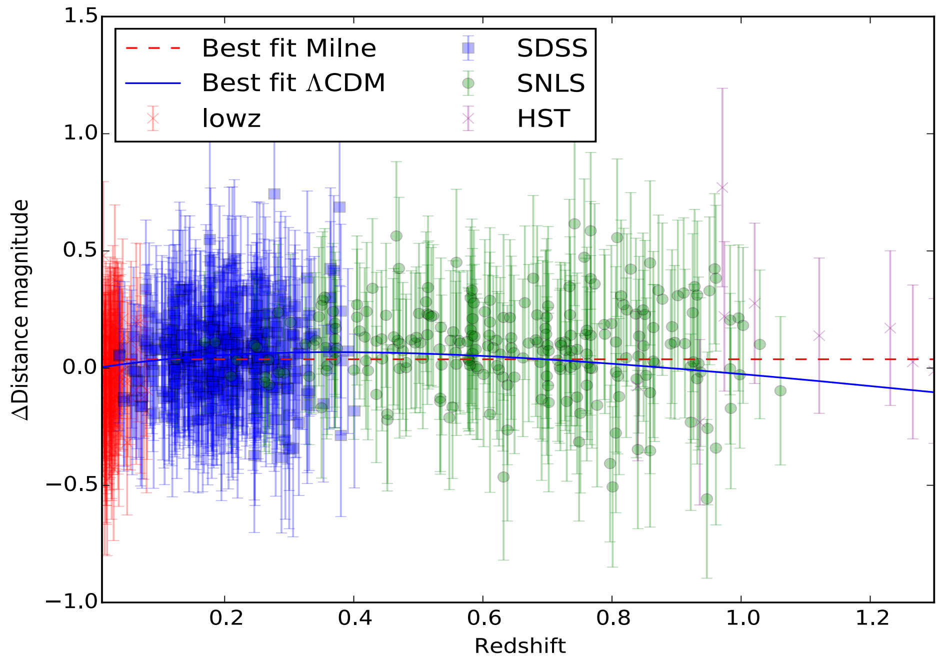
Joint Lightcurve Analysis (JLA) dataset: 740 SN Ia (Betoule *et al*, A&A **568**:222014)







Rubin & Hayden, ApJ **833**:L30,2016

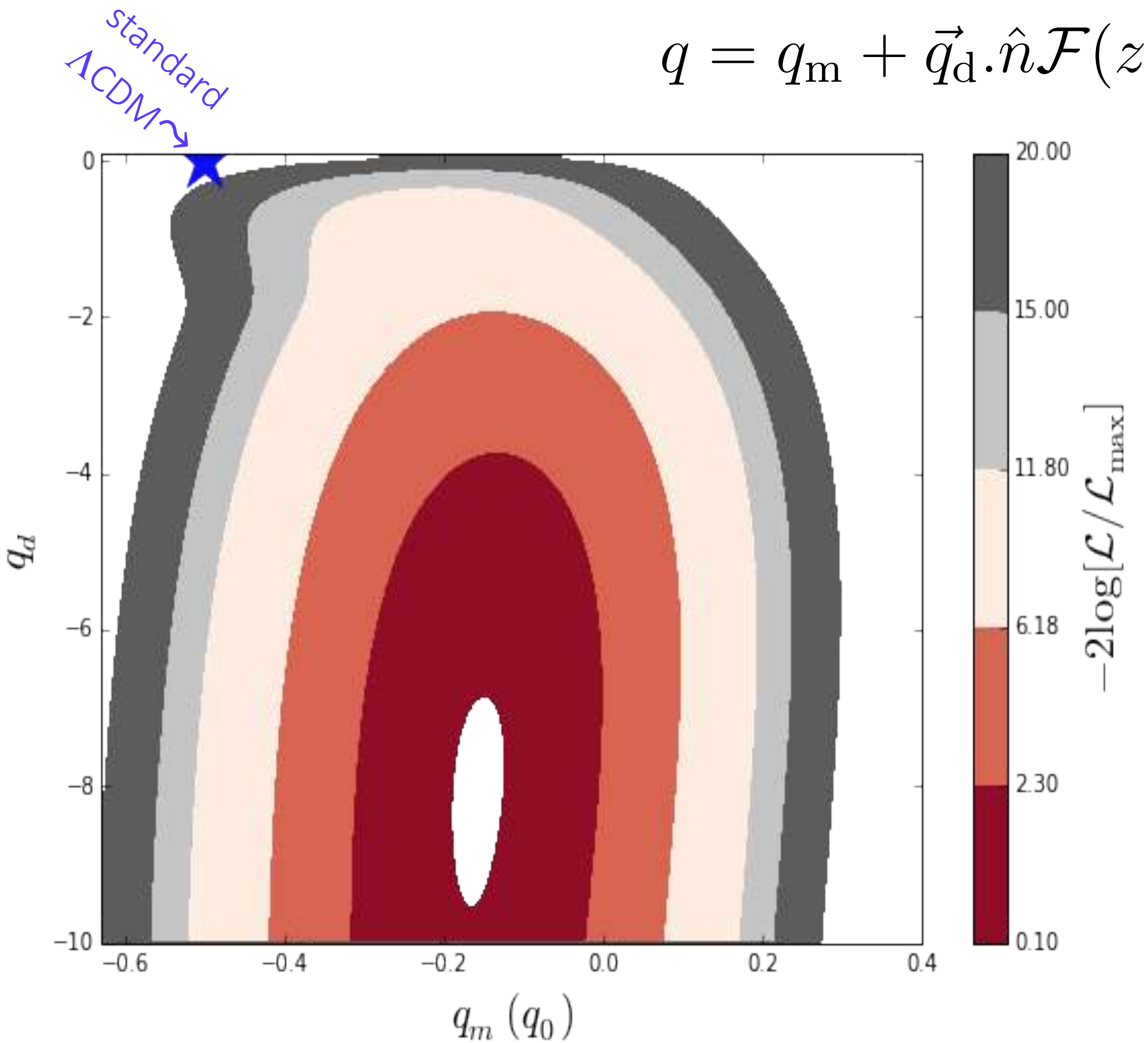


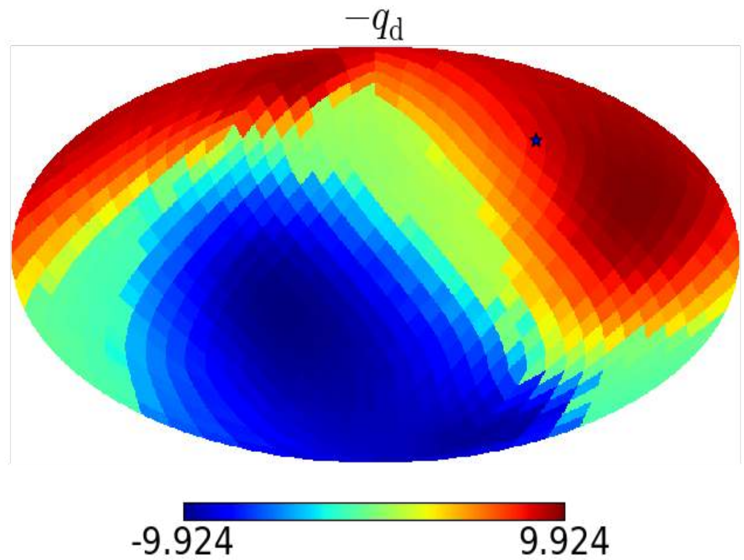
Nielsen *et al*, Sci. Rep. **6:**35596,2016

Even more worryingly the acceleration is in just one direction ...

Joint Lightcurve Analysis (JLA) dataset: 740 SN Ia (Betoule *et al*, A&A **568**:222014)

$$q = q_{\rm m} + \vec{q}_{\rm d}.\hat{n}\mathcal{F}(z, S)$$





The significance of q_o being negative has now *decreased* to only 1.4σ

Colin *et al*, A&A **631**:L13,2019

The inferred acceleration may therefore be an artefact of our being non-Copernican observers embedded in a 'bulk flow', rather than evidence for a Cosmological Constant

Whether the expansion rate is accelerating will be tested by the Extremely Large Telescope by measuring the ‘redshift drift’