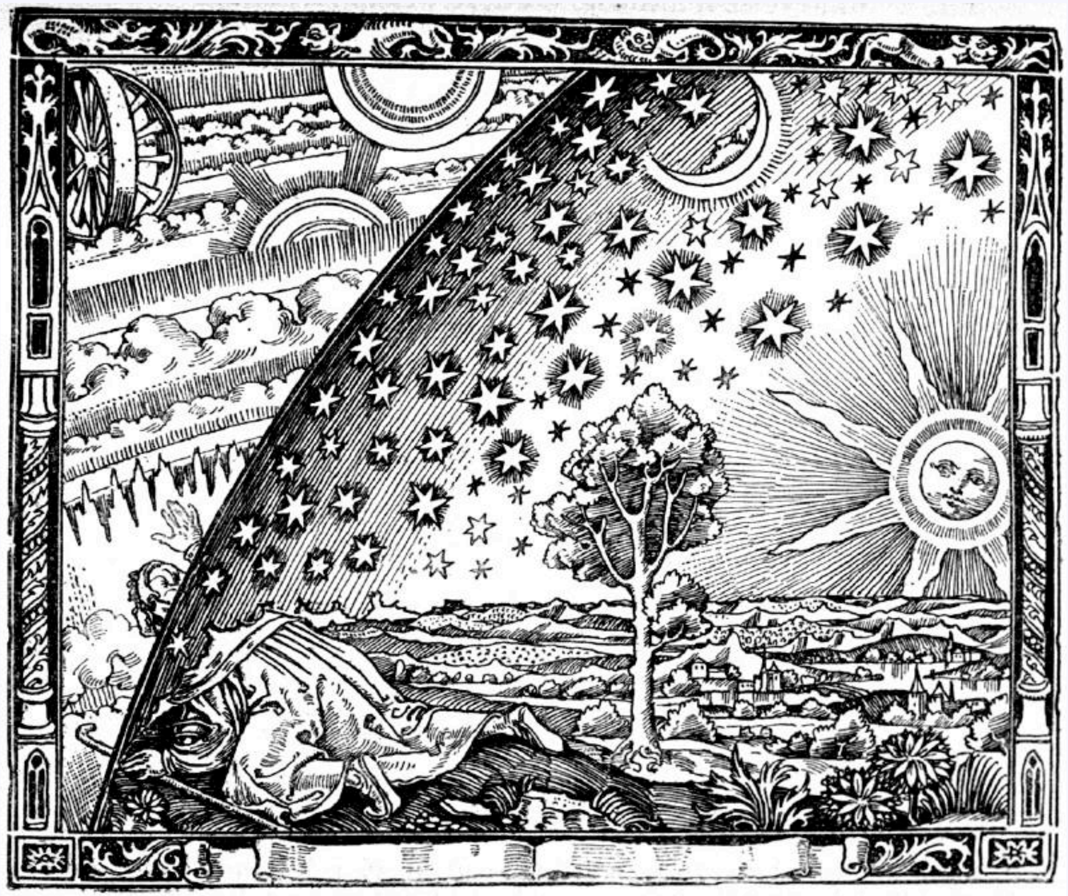
Beyond the cosmological standard model

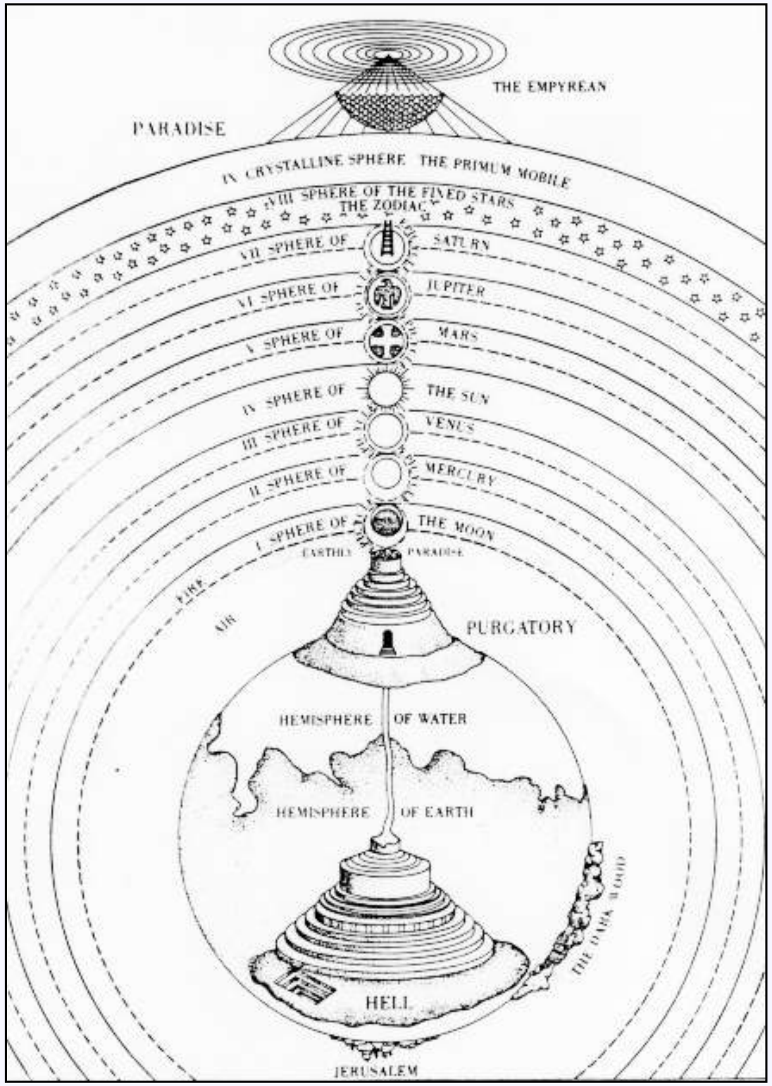


Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics, University of Oxford

DESY Particle & Astroparticle Physics Colloquium, 1 Dec 2020

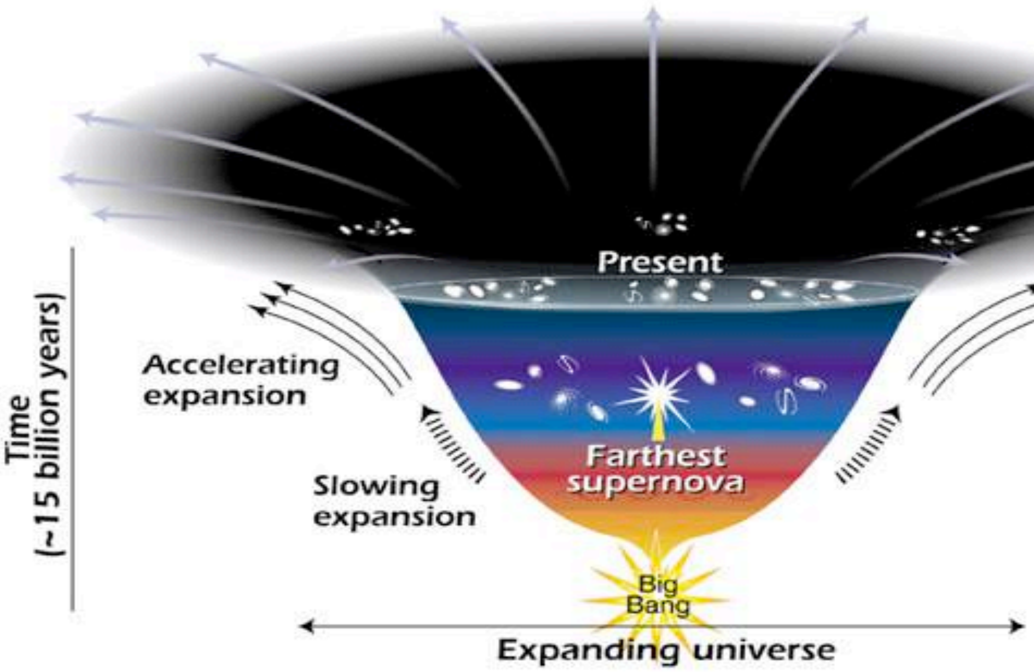
In the Ptolemic/Aristotlean standard cosmology (350 BC → 1600 AD) the universe was *static* and *finite* and centred on the Earth

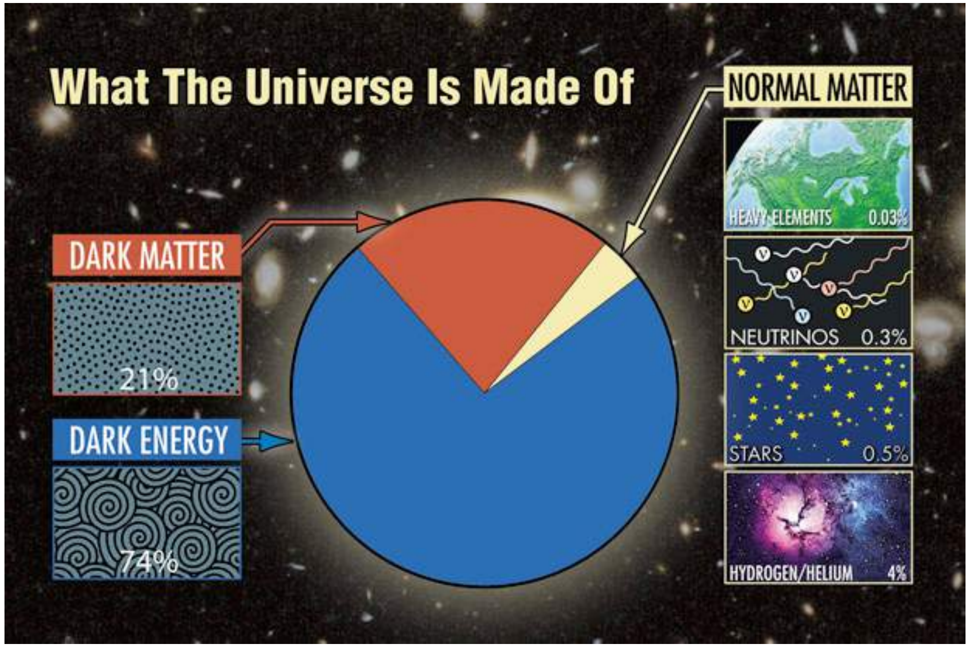


The Divine Comedy, Dante Alligheri (1321)

This was a simple model and fitted all the available data
… but the underlying principle was unphysical

Today we have a new 'standard ΛCDM model' of the universe
… dominated by dark energy and undergoing accelerated expansion





It too is 'simple' (if we count Λ as just 1 parameter) and fits all the data (with just a few anomalies) … but lacks a *physical* foundation

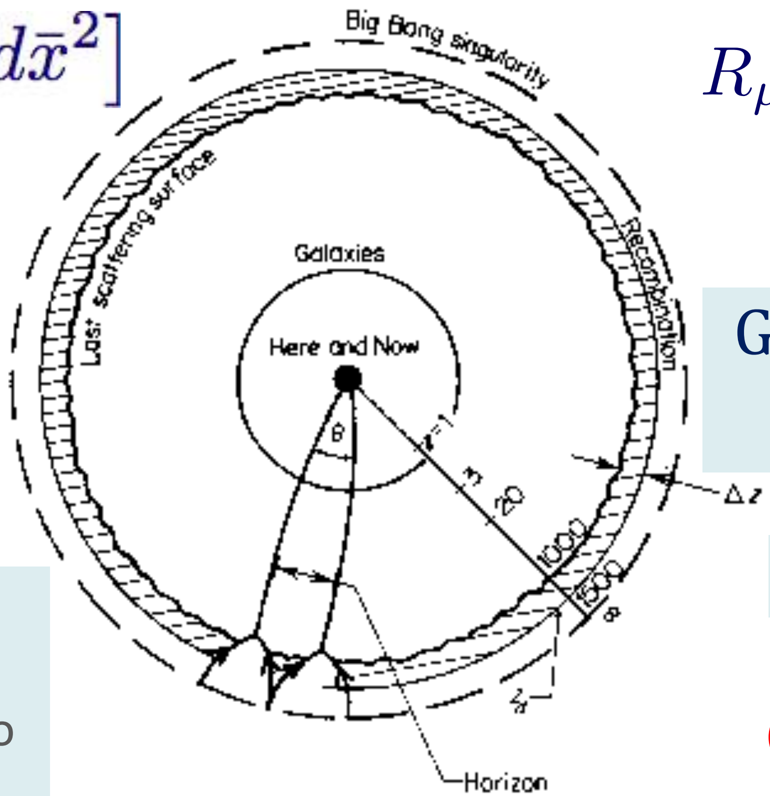
The standard cosmological model is based on several key assumptions:

maximally symmetric space-time + general relativity + ideal fluids

$$ds^2 = a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$

$$a^2(\eta)d\eta^2 \equiv dt^2$$

Space–time metric
Robertson–Walker



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Geometrodynamics
Einstein

It is the *assumed* homogeneity and isotropy that enables the Einstein eqs. to be simplified to the Friedmann-Lemaître eqs.:

'Dust' → quantum fields

$$T_{\mu\nu} = -\langle\rho\rangle_{\text{fields}}\ g_{\mu\nu}$$

$$\Lambda = \lambda + 8\pi G_N \langle\rho\rangle_{\text{fields}}$$

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho_m}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

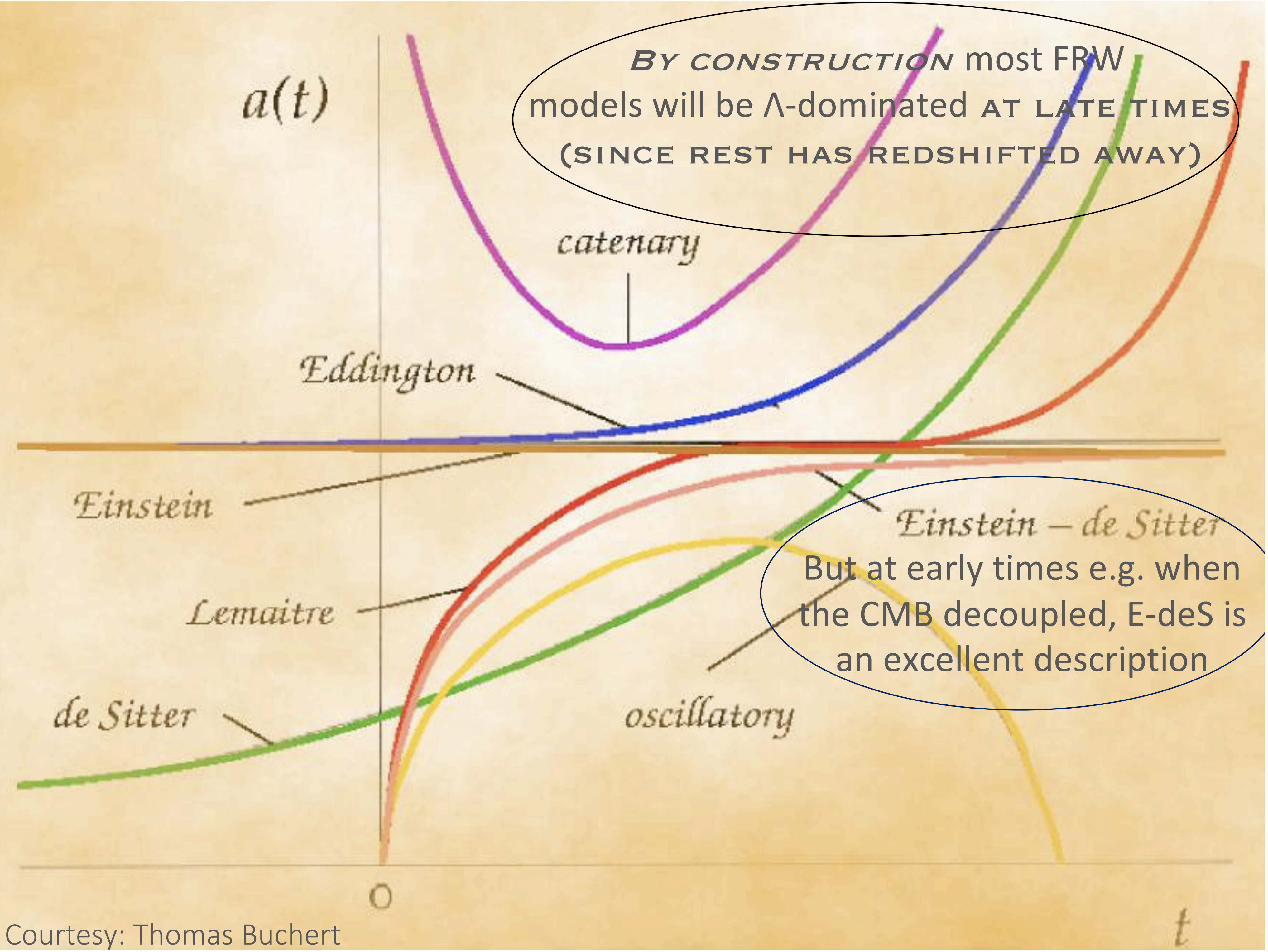
$$\equiv H_0{}^2\left[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

Negative pressure → acceleration

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

$$z \equiv \frac{a_0}{a} - 1, \Omega_m \equiv \frac{\rho_m}{3H_0^2/8\pi G_N}, \Omega_k \equiv \frac{k}{a_0^2 H_0^2}, \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2}$$

This yields the 'cosmic sum rule': $1 \equiv \Omega_m + \Omega_k + \Omega_\Lambda$

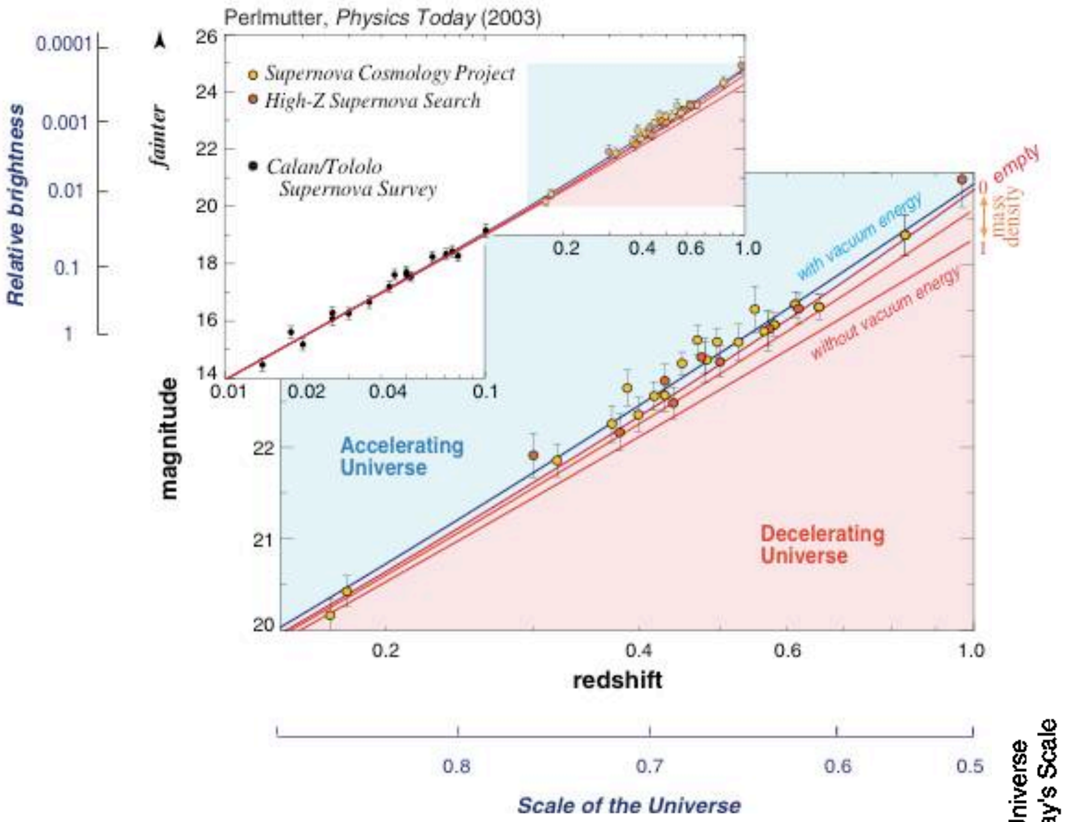


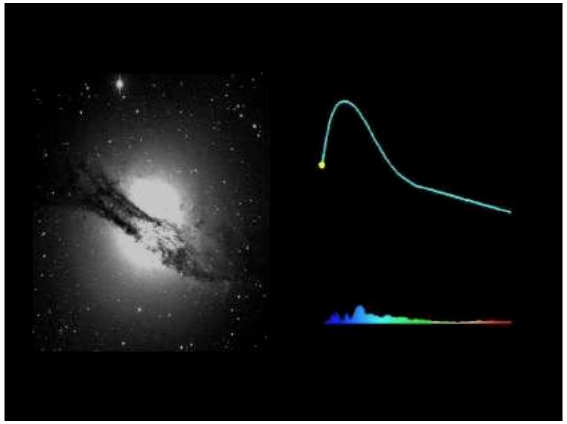
By construction most FRW models will be Λ-dominated at late times (since rest has redshifted away)

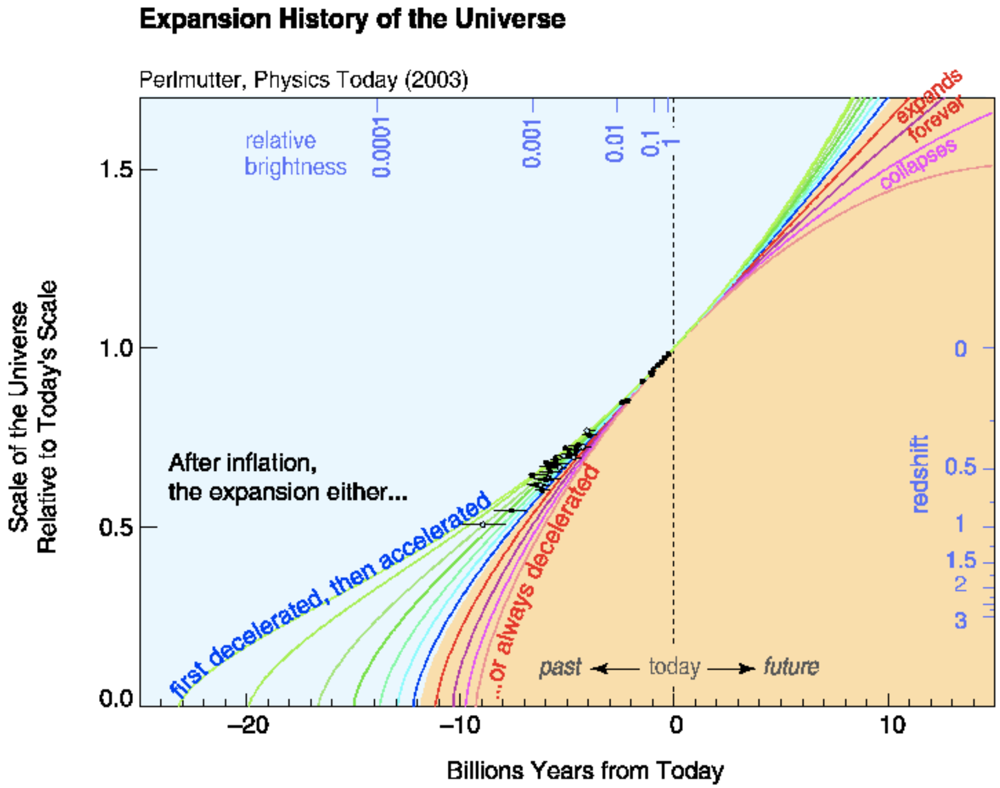
But at early times e.g. when the CMB decoupled, E-deS is an excellent description

Courtesy: Thomas Buchert

1998: Distant SNIa appear fainter than expected for "standard candles" in a decelerating universe ... interpreted as ⇒ accelerated expansion below $z \sim 0.5$

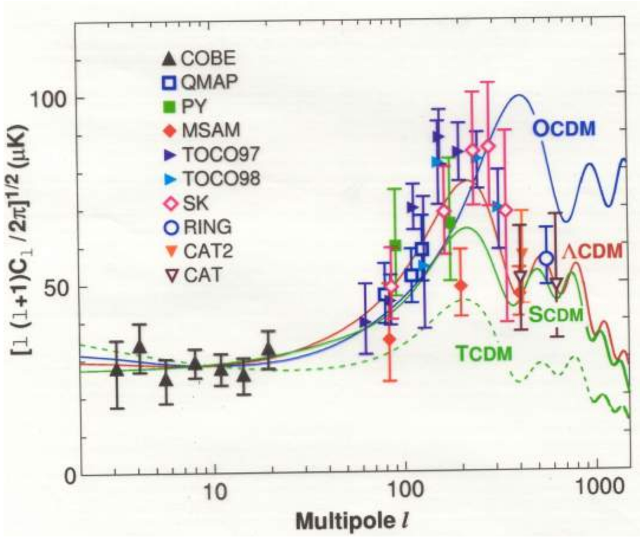




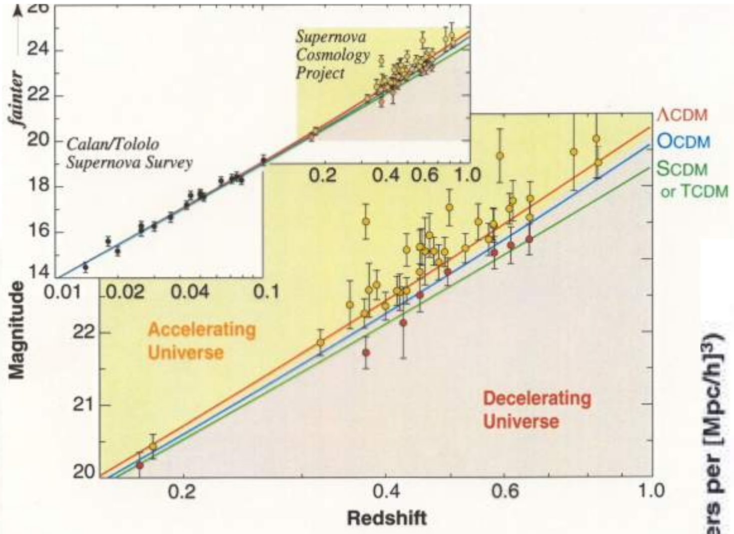


The observations are made at *one* instant (the redshift is a proxy for time) so this is not a *direct* measurement of acceleration, nevertheless it is more direct than all other 'evidence'

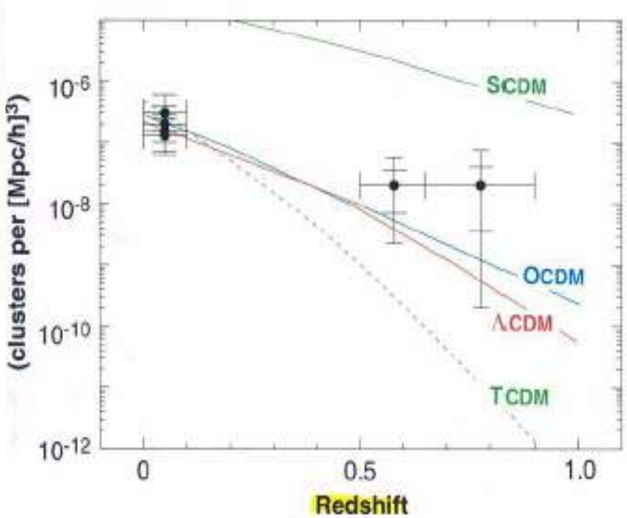
Assuming the sum rule, observations implied: $\Omega_\Lambda \sim 0.7 \Rightarrow \Lambda \sim 2H_0^2$, $H_0 \sim 10^{-42}$ GeV



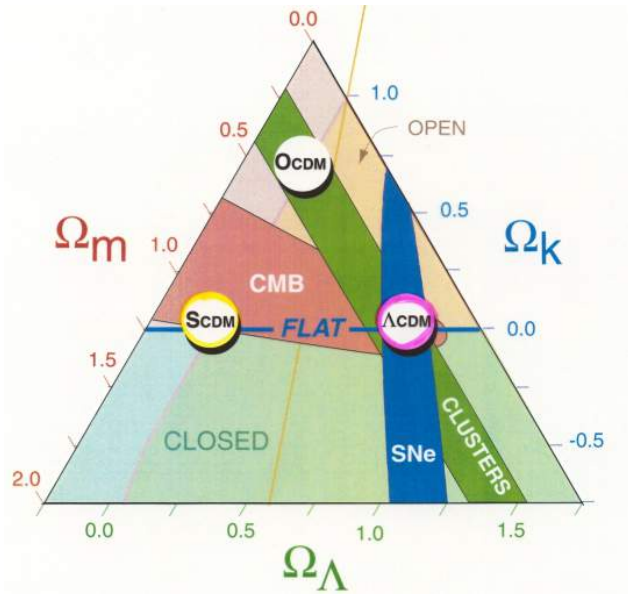
$\Omega_k \approx 0.0 \pm 0.03$



$0.8\Omega_m - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$



$\Omega_m \approx 0.3$



Bahcall *et al*, Science **284**:1481,1999

This was interpreted by astronomers as evidence for vacuum energy at a scale of meV

$\Rightarrow \rho_\Lambda = \Lambda/8\pi G \sim H_0^2 M_p^2 \sim (10^{-12}\ \text{GeV})^4$

The Standard $SU(3)_c \times SU(2)_L \times U(1)_Y$ 'Model' (viewed as an **effective field theory** up to some high energy cut-off scale M) describes *all* of microphysics

$$m_H^2 \simeq \frac{h_t^2}{16\pi^2} \int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2} M^2$$

$$+M^4 + M^2\Phi^2$$

Vacuum energy   Higgs mass correction

super-renormalisable

$$-\mu^2\phi^\dagger\phi + \frac{\lambda}{4}(\phi^\dagger\phi)^2, m_H^2 = \lambda v^2/2$$

$$\mathcal{L}_{\rm eff} = F^2 + \bar{\Psi} \not{D} \Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + V(\Phi)$$

renormalisable

However there are two 'super-renormalisable' operators …
which become increasingly important as the cut-off *M* is raised

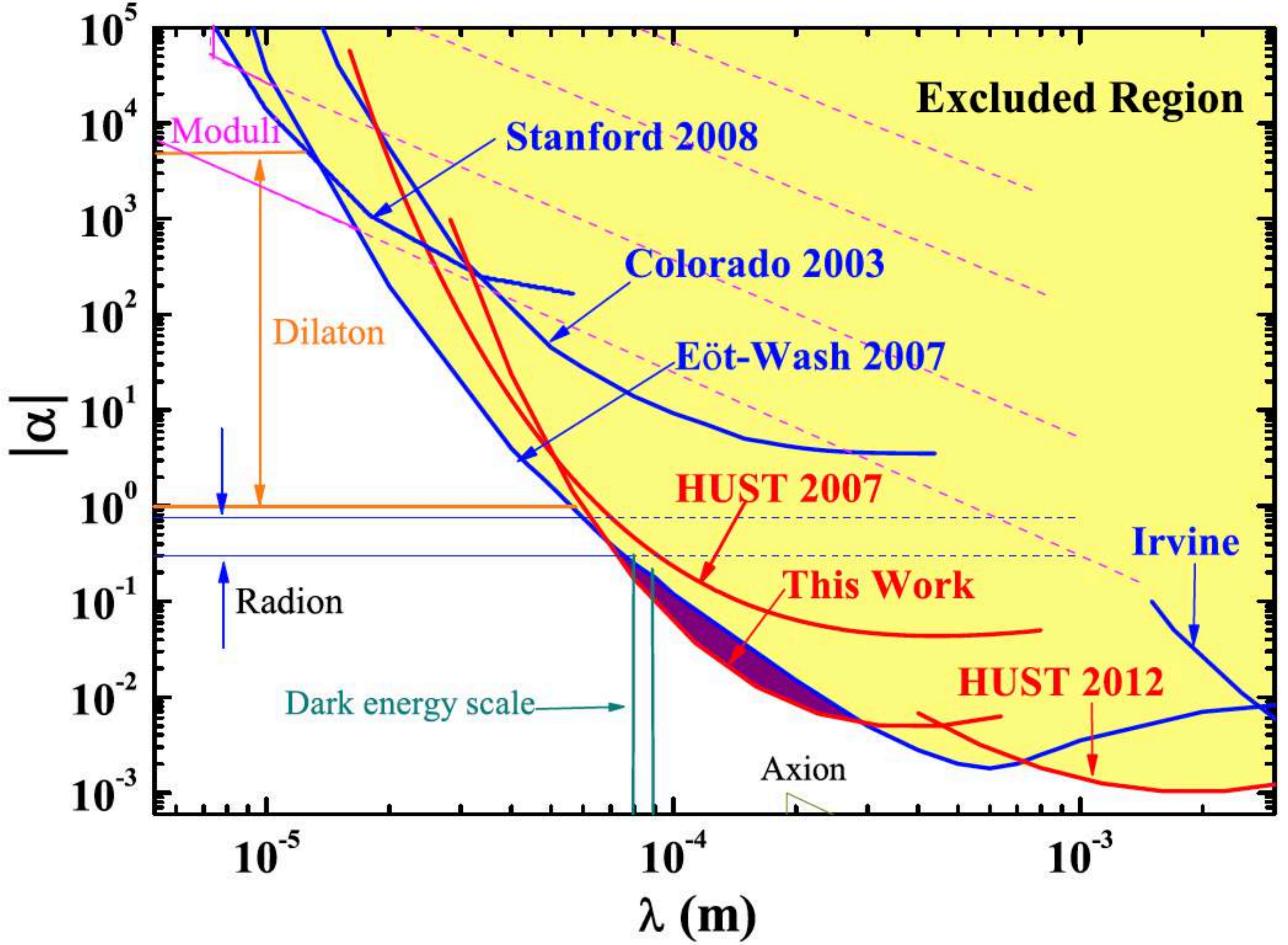
The second term gives rise to the notorious quadratic divergence of the Higgs mass
(attempted solutions: supersymmetry, compositeness …)

1st SR term couples to gravity so the *natural* expectation is
$\rho_\Lambda \sim (1\ \mathrm{TeV})^4 \Rightarrow 10^{60} \times (1\ \mathrm{meV})^4$
i.e. the universe should have been inflating since (or collapsed at): $t \sim 10^{-12}$ s after BB
There must be a *good* reason why this did *not* happen!

*"Also, as is obvious from experience, the [zero-point energy] does **not** produce any gravitational field"* - Wolfgang Pauli
Die allgemeinen Prinzipien der Wellenmechanik, Handbuch der Physik, Vol. XXIV, 1933

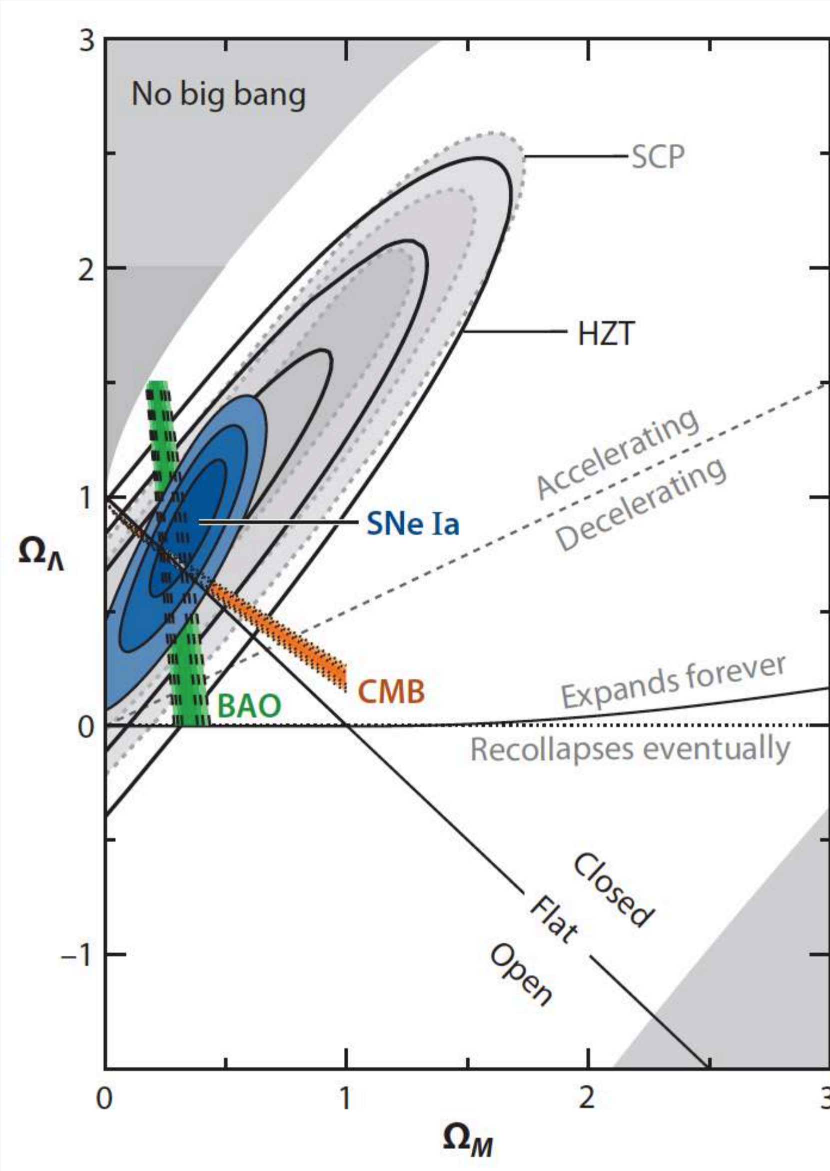
NB: There is *no* evidence for a change in the inverse-square law of gravitation at the inferred 'dark energy' scale of $\sim 10^{-3}$ eV: $\rho_\Lambda^{-1/4} \sim (H_0/\sqrt{G_N})^{-1/2} \sim 0.1$ mm

$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha \exp(-r/\lambda)]$$

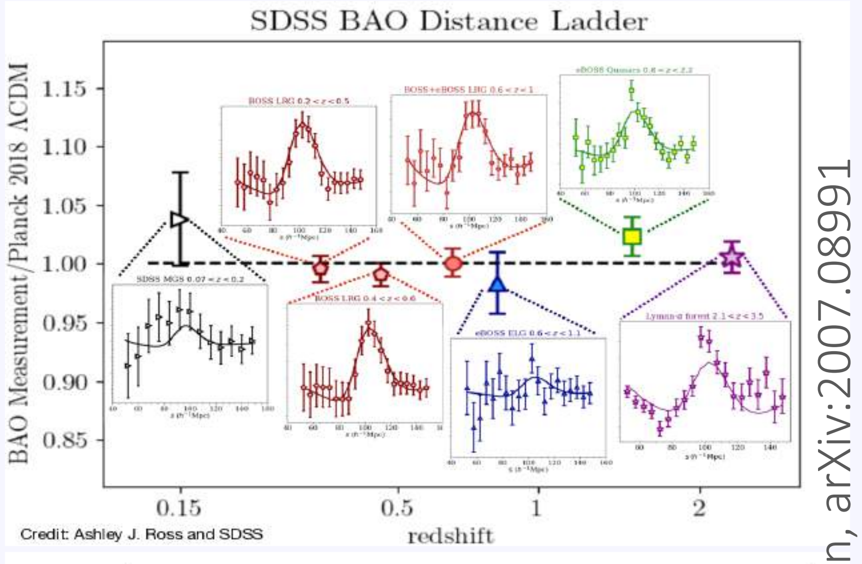


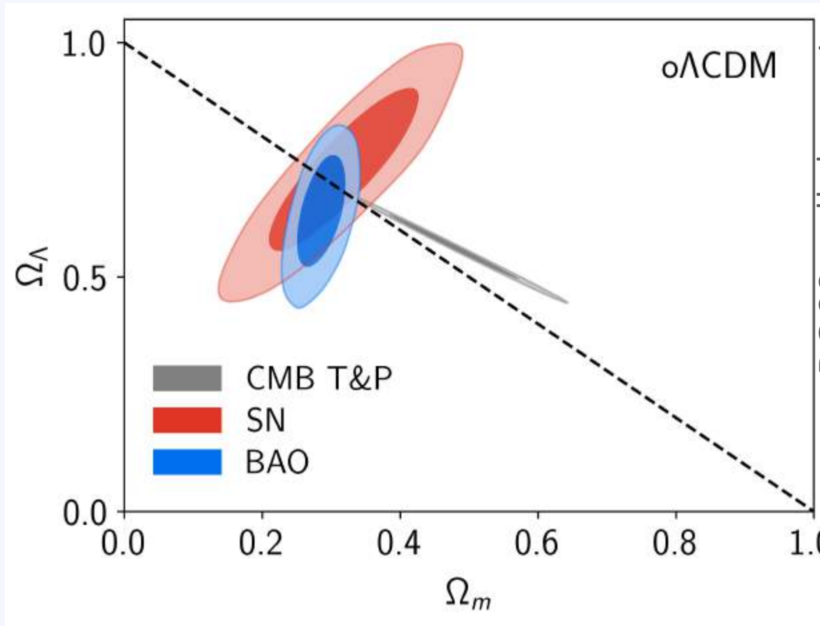
Tan et al, PRL **116**:1131101,2016

CMB data indicate $\Omega_k \approx 0$ so the FRLW model is simplified further, leaving only two free parameters (Ω_Λ and Ω_m) to be fitted to data



Goobar & Leibundgut, ARNPS 61:251,2011

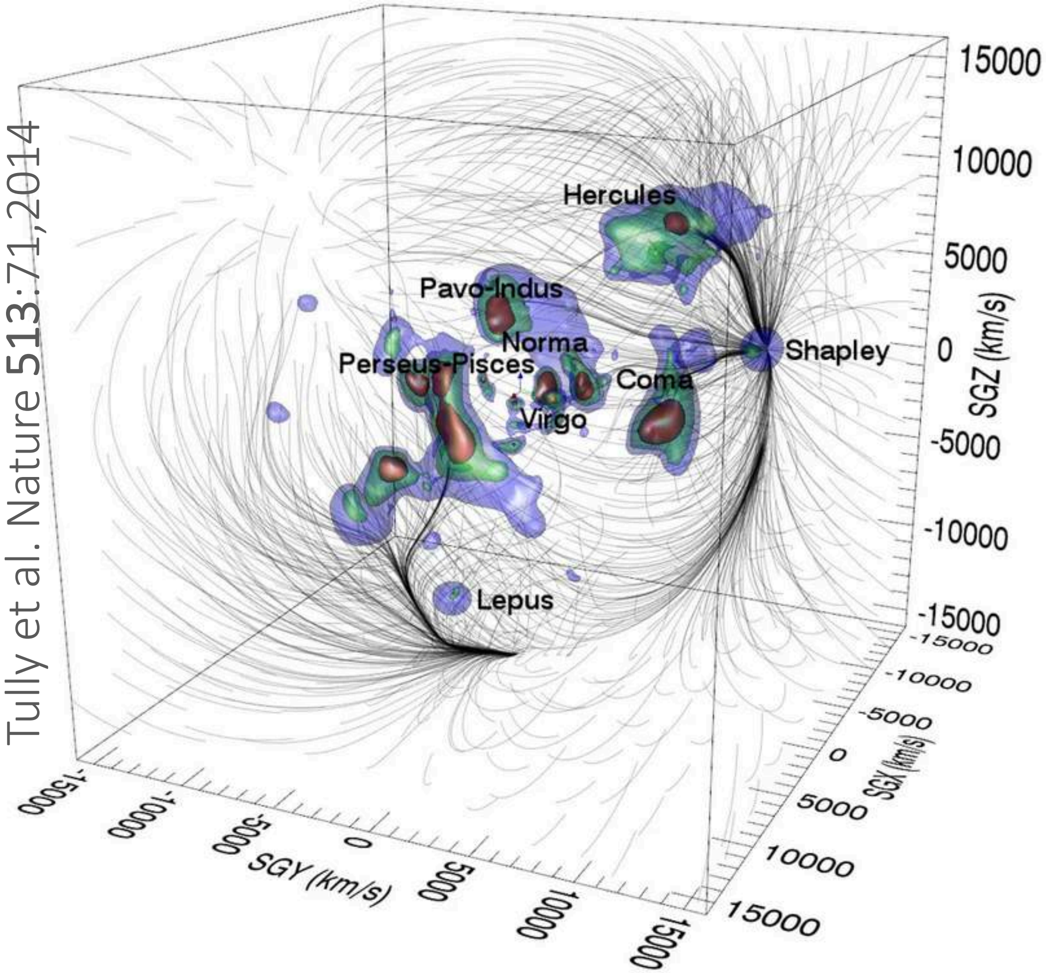




eBOSS collaboration, arXiv:2007.08991

But if we *under*estimate Ω_m … or if there is a Ω_x ($\Rightarrow$ a *new* component) which the FRLW model does *not* include, then we will *incorrectly* infer $\Omega_\Lambda \neq 0$ from the sum rule

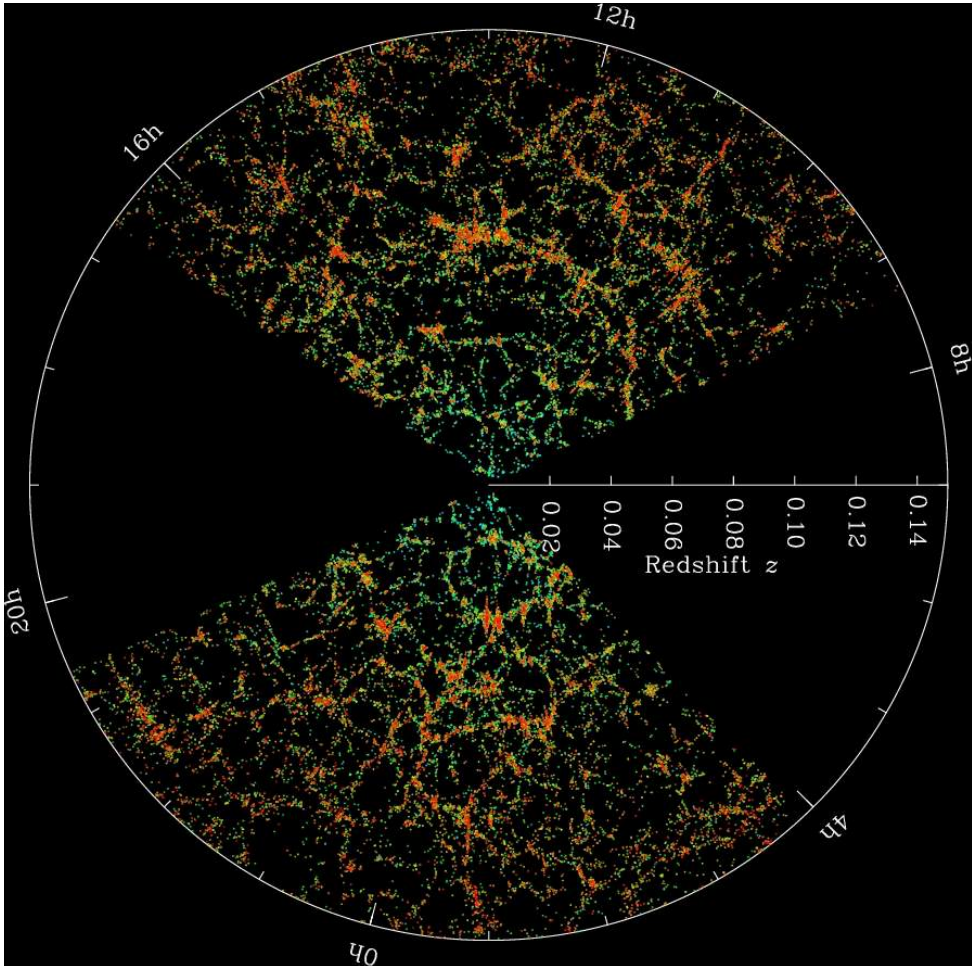
Tully et al. Nature **513**:71, 2014



Is it justified to approximate it as *exactly* homogeneous?

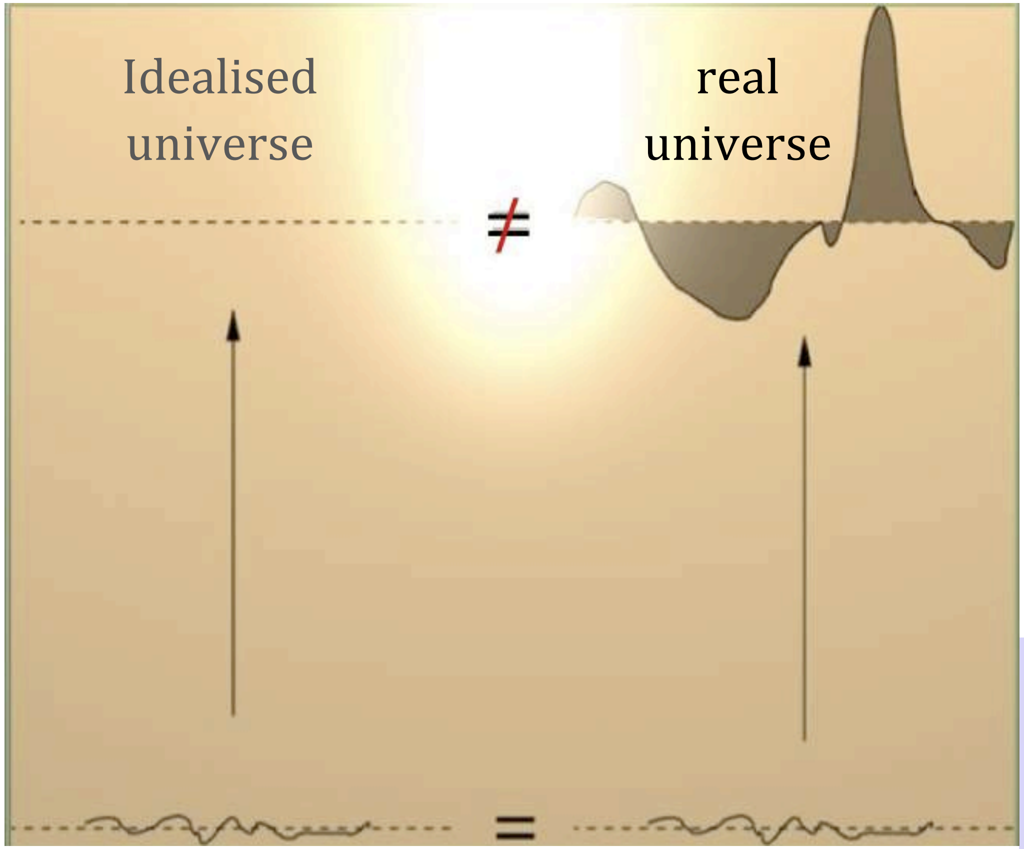
… To assume that we are a '*typical*' observer?

… To assume that all observed directions are *equivalent*?



This is what our universe *actually* looks like locally (out to ~200 Mpc)

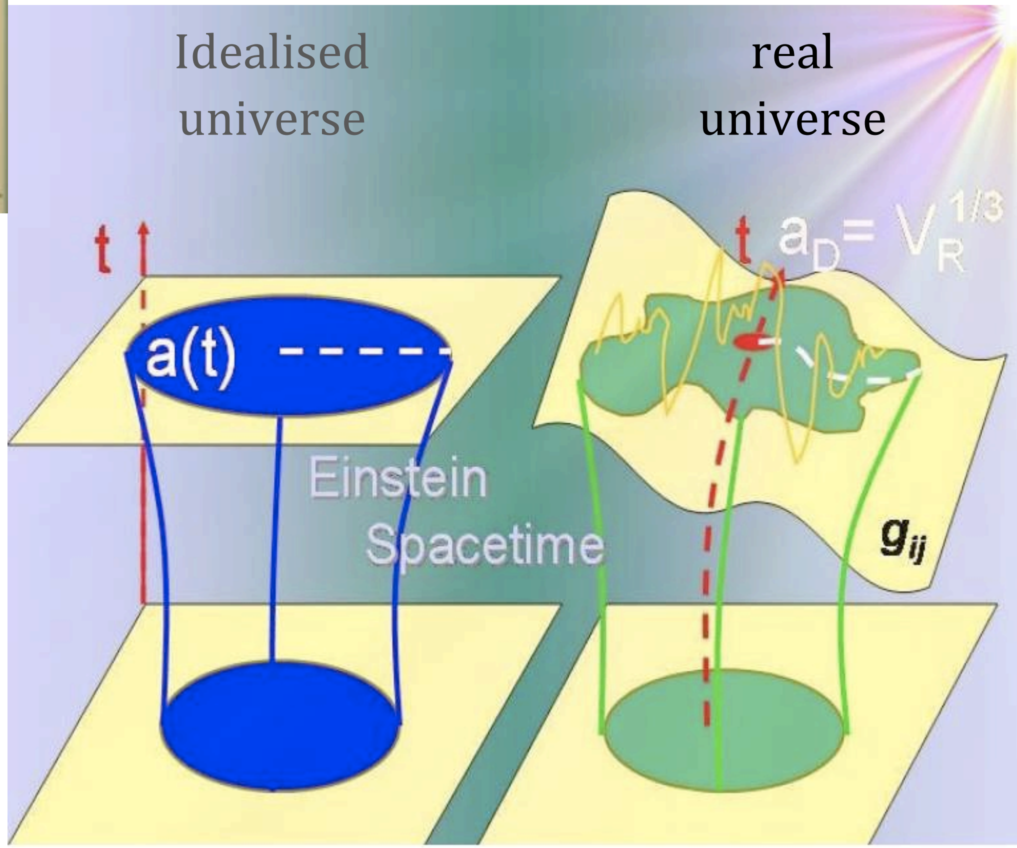
… and on the biggest scales mapped



Due to structure formation, the homogeneous solution of Einstein's equations is distorted - its average must be taken over the *actual* geometry

'Back reaction' is hard to compute because spatial averaging and time evolution (along our past light cone) do *not* commute

Relativistic numerical simulations of structure formation have just begun to be performed … and some indicate that backreaction may be significant



Courtesy: Thomas Buchert

Interpreting Λ as vacuum energy raises the 'coincidence problem':

WHY IS $\Omega_\Lambda \approx \Omega_M$ TODAY?

An evolving ultralight scalar field ('quintessence') can display 'tracking' behaviour: this requires $V(\varphi)^{1/4} \sim 10^{-12}$ GeV but $\sqrt{d^2V/d\varphi^2} \sim H_0 \sim 10^{-42}$ GeV to ensure slow-roll … i.e. just as much fine-tuning as a bare cosmological constant

A similar comment applies to models (e.g. 'DGP brane-world') wherein gravity is modified on the scale of the present Hubble radius $1/H_0$ so as to mimic vacuum energy … this scale is absent in a fundamental theory and is just put in by hand

(similar fine-tuning in every proposal – e.g. massive gravity, chameleon fields, …)

The only natural option is if $\Lambda \sim H^2$ always, but this is just a renormalisation of G_N! (recall: $H^2 = 8\pi G_N/3 + \Lambda/3$) → ruled out by Big Bang nucleosynthesis (requires G_N to be within 5% of lab value) … in any case this will not yield accelerated expansion

Thus there can be no *physical* explanation for the 'coincidence problem'

Do we infer $\Lambda \sim H_0^2$ because that is just the observational sensitivity (in the FRW cosmology framework) to the arbitrary parameter Λ, in terms of the *only* dimensionful observable H_0 in the model … which enters into *every* cosmological measurement?

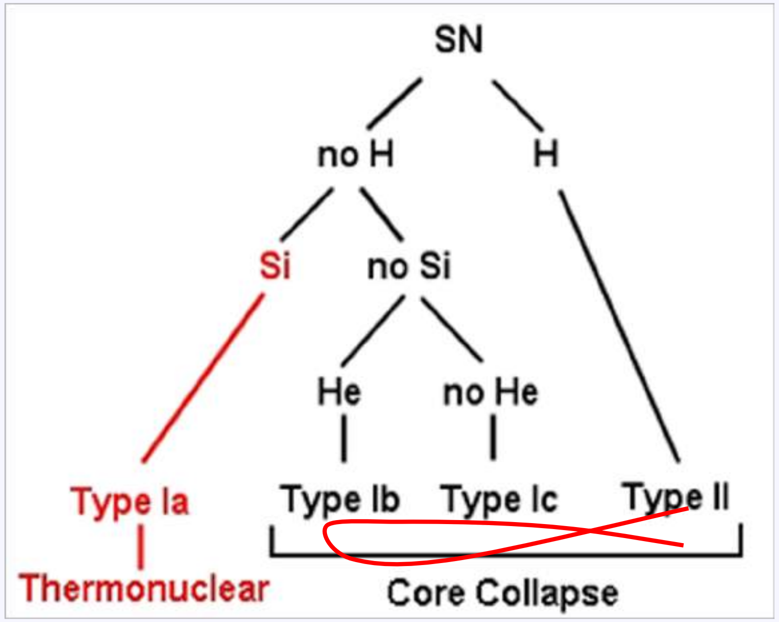
Shaw Prize 2006 *"for discovering that the expansion rate of the universe is accelerating"*

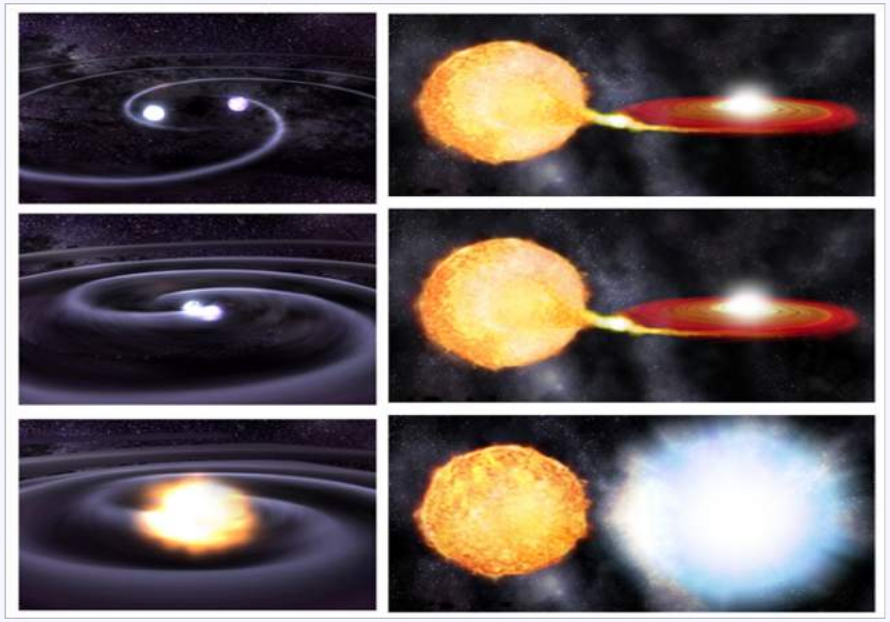
2007 Gruber Cosmology Prize *to two teams "who discovered the accelerating universe"*

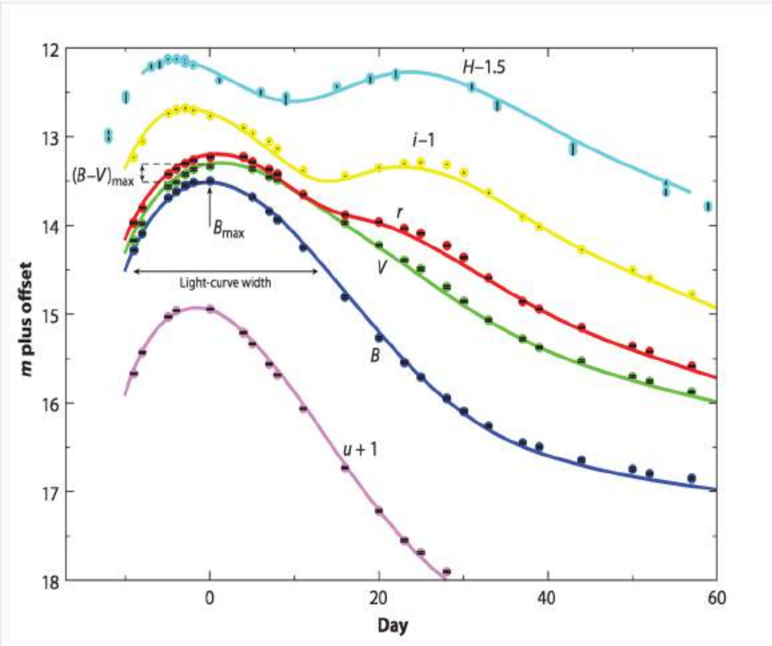
Discovery of accelerating universe wins ***2011 Nobel Prize in Physics***

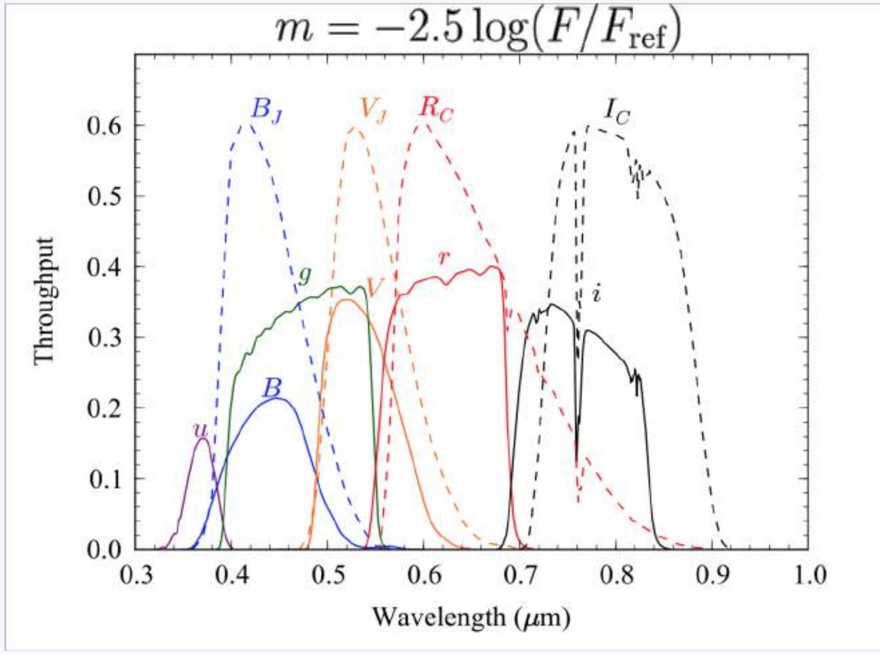
The ***2015 Breakthrough Prize in Fundamental Physics*** *"for the most unexpected discovery that the expansion of the universe is accelerating"*

What are Type Ia supernovae?









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

Identify by multiple exposure of sky (+ spectroscopy) ➙ measure peak magnitude and redshift

The magnitude-redshift data can be used to do cosmology

$$\mu \equiv 25 + 5\log_{10}(d_{\rm L}/{\rm Mpc}), \quad \text{where:}$$

$$d_{\rm L} = (1+z)\frac{d_{\rm H}}{\sqrt{\Omega_k}}\,{\rm sinn}\left(\sqrt{\Omega_k}\int_0^z \frac{H_0 {\rm d}z'}{H(z')}\right),$$

$$d_{\rm H} = c/H_0, \quad H_0 \equiv 100h\ {\rm km\,s^{-1}Mpc^{-1}},$$

$$H = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda},$$

$${\rm sinn} \to \sinh \text{ for } \Omega_k > 0 \text{ and } {\rm sinn} \to \sin \text{ for } \Omega_k < 0$$

Distance modulus

$$\mu_C = m - M = -2.5\log\frac{F/F_{\rm ref}}{L/L_{\rm ref}} = 5\log\frac{d_L}{10{\rm pc}}$$

… Or to do cosmography

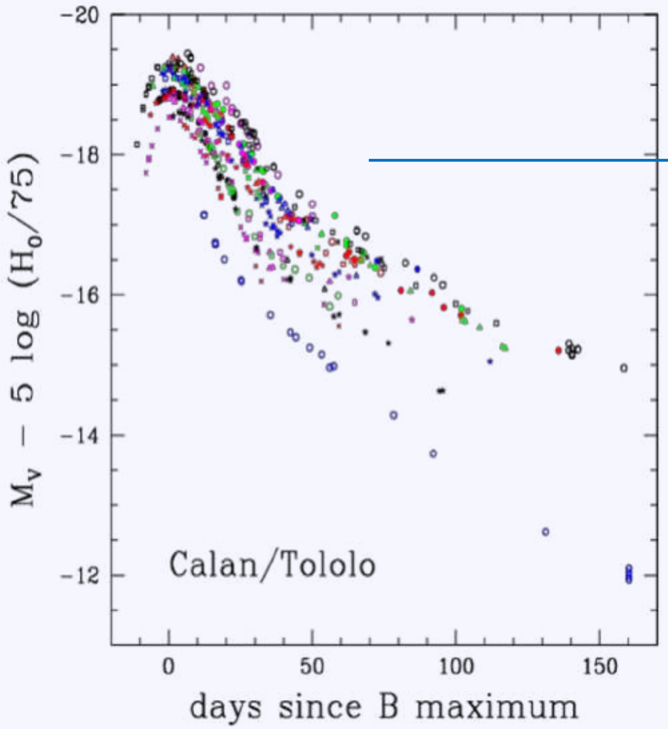
Acceleration is a kinematic quantity so the data can be analysed without assuming any dynamical model, by expanding the time variation of the scale factor in a Taylor series

(e.g. Visser, CQG **21**:2603,2004)

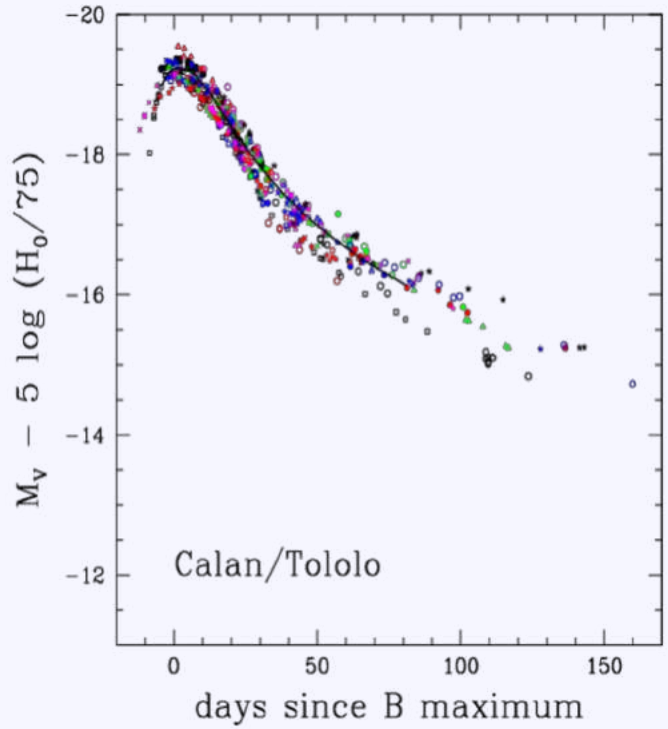
$q_0 \equiv -(\ddot{a}a)/\dot{a}^2$ $\qquad j_0 \equiv (\dddot{a}/a)(\dot{a}/a)^{-3}$

$$d_L(z) = \frac{c\,z}{H_0}\left\{1 + \frac{1}{2}[1-q_0]\,z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2\,a_0^2}\right]z^2 + O(z^3)\right\}$$

Sn Ia are *not* 'standard candles'



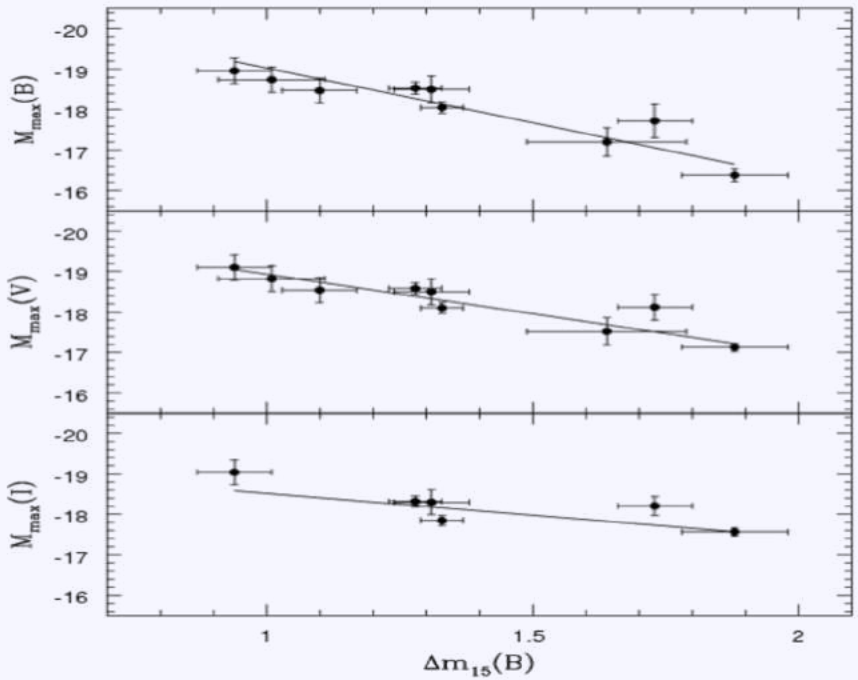
But they are 'standardisable'



Hamuy, 1311.5099

… using the observed correlation between peak magnitude and light curve width

(NB: this is empirical and *not* understood theoretically)



Phillips, ApJ 413:L105,1993

Spectral Adaptive Lightcurve Template

(For making ‘stretch’ and ’colour’ corrections to the observed lightcurves)

$$\mu_B = m_B^* - M + \alpha X_1 - \beta C$$

B-band

SALT 2 parameters

Betoule *et al.*, A&A 568:A22,2014

Name	z_{cmb}	$m_B^\star$	X_1	C	$M_{stellar}$
03D1ar	0.002	23.941 ± 0.033	−0.945 ± 0.209	0.266 ± 0.035	10.1 ± 0.5
03D1au	0.503	23.002 ± 0.088	1.273 ± 0.150	−0.012 ± 0.030	9.5 ± 0.1
03D1aw	0.581	23.574 ± 0.090	0.974 ± 0.274	−0.025 ± 0.037	9.2 ± 0.1
03D1ax	0.495	22.960 ± 0.088	−0.729 ± 0.102	−0.100 ± 0.030	11.6 ± 0.1
03D1bp	0.346	22.398 ± 0.087	−1.155 ± 0.113	−0.041 ± 0.027	10.8 ± 0.1
03D1co	0.678	24.078 ± 0.098	0.619 ± 0.404	−0.039 ± 0.067	8.6 ± 0.3
03D1dt	0.611	23.285 ± 0.093	−1.162 ± 1.641	−0.095 ± 0.050	9.7 ± 0.1
03D1ew	0.866	24.354 ± 0.106	0.376 ± 0.348	−0.063 ± 0.068	8.5 ± 0.8
03D1fc	0.331	21.861 ± 0.086	0.650 ± 0.119	−0.018 ± 0.024	10.4 ± 0.0
03D1fq	0.799	24.510 ± 0.102	−1.057 ± 0.407	−0.056 ± 0.065	10.7 ± 0.1
03D3aw	0.450	22.667 ± 0.092	0.810 ± 0.232	−0.086 ± 0.038	10.7 ± 0.0
03D3ay	0.371	22.273 ± 0.091	0.570 ± 0.198	−0.054 ± 0.033	10.2 ± 0.1
03D3ba	0.292	21.961 ± 0.093	0.761 ± 0.173	0.116 ± 0.035	10.2 ± 0.1
03D3bl	0.356	22.927 ± 0.087	0.056 ± 0.193	0.205 ± 0.030	10.8 ± 0.1

?
?
?
?
?
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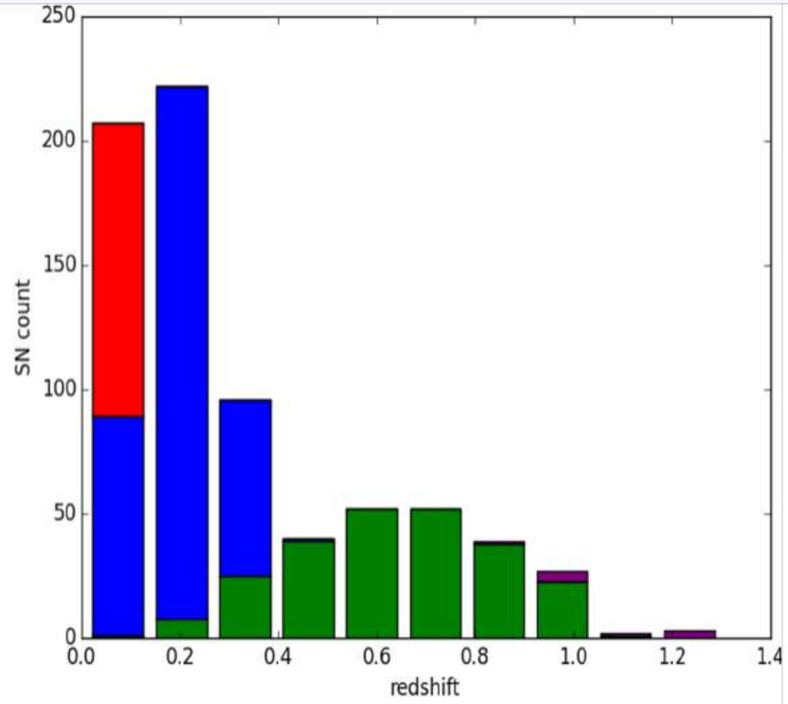
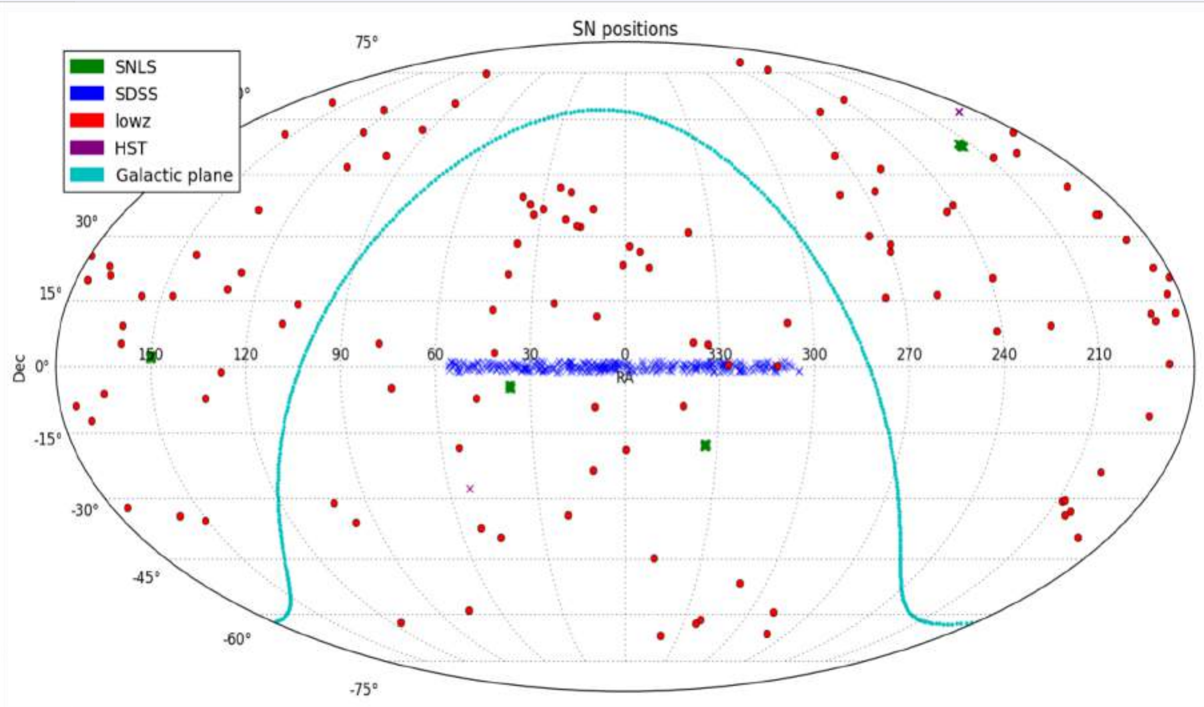
?

The host galaxy mass appears not to be relevant in the MLE fits

… but there may well be other variables that the magnitude correlates with

Joint Lightcurve Analysis data (740 SNe Ia)





Betoule, Conley, Filippenko, Frieman, Goobar, Guy, Hook, Jha, Kessler, Pain, Perlmutter, Riess, Sollerman, Sullivan … A&A 568:A22,2014) http://supernovae.in2p3.fr/sdss_snls_jla/

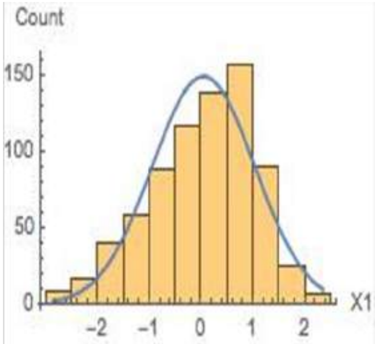
$$\chi^2 = \sum_{objects} \frac{(\mu_B - 5\log_{10}(d_L(\theta, z)/10pc))^2}{\sigma^2(\mu_B) + \sigma_{int}^2}$$

NB: Previous analyses used the 'constrained chi-squared' method … wherein $\sigma_{\rm int}$ is *adjusted* to get χ^2 of 1/d.o.f. for the fit to the assumed ΛCDM model

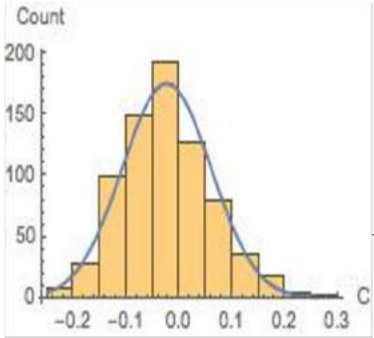
We employ a Maximal Likelihood Estimator … and obtain rather different results

Construct a Maximum Likelihood Estimator

Well-approximated as Gaussian



'Stretch' corrections



'Colour' corrections

$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

$$\mathcal{L} = p[(\hat{m}_B^*, \hat{x}_1, \hat{c})|\theta]$$
$$= \int p[(\hat{m}_B^*, \hat{x}_1, \hat{c})|(M, x_1, c), \theta_{\text{cosmo}}]$$
$$\times\, p[(M, x_1, c)|\theta_{\text{SN}}]\, dM\, dx_1\, dc$$

$$p[(M, x_1, c)|\theta] = p(M|\theta)p(x_1|\theta)p(c|\theta), \quad \text{where:}$$
$$p(M|\theta) = (2\pi\sigma_{M_0}^2)^{-1/2} \exp\left\{-\left[(M - M_0)/\sigma_{M_0}\right]^2/2\right\},$$
$$p(x_1|\theta) = (2\pi\sigma_{x_{1,0}}^2)^{-1/2} \exp\left\{-\left[(x_1 - x_{1,0})/\sigma_{x_{1,0}}\right]^2/2\right\},$$
$$p(c|\theta) = (2\pi\sigma_{c_0}^2)^{-1/2} \exp\left\{-\left[(c - c_0)/\sigma_{c_0}\right]^2/2\right\}.$$

$$p(Y|\theta) = \frac{1}{\sqrt{|2\pi\Sigma_l|}} \exp\left[-\frac{1}{2}(Y - Y_0)\Sigma_l^{-1}(Y - Y_0)^{\mathrm{T}}\right]$$

$$p(\hat{X}|X,\theta) = \frac{1}{\sqrt{|2\pi\Sigma_d|}} \exp\left[-\frac{1}{2}(\hat{X} - X)\Sigma_d^{-1}(\hat{X} - X)^{\mathrm{T}}\right]$$

$$\mathcal{L} = \frac{1}{\sqrt{|2\pi(\Sigma_d + A^{\mathrm{T}}\Sigma_l A)|}}$$
$$\times \exp\left(-\frac{1}{2}(\hat{Z} - Y_0 A)(\Sigma_d + A^{\mathrm{T}}\Sigma_l A)^{-1}(\hat{Z} - Y_0 A)^{\mathrm{T}}\right)$$

intrinsic distributions

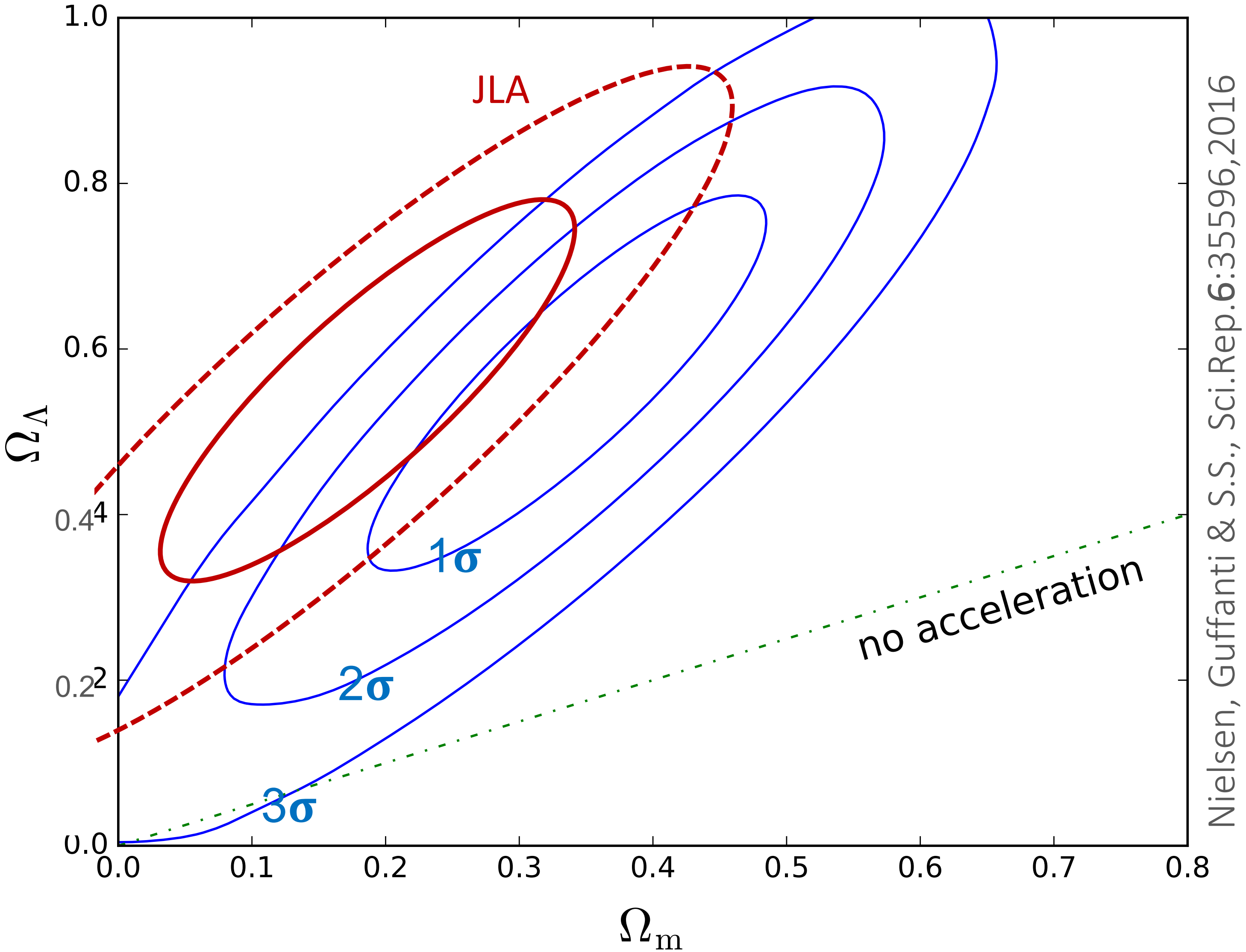
cosmology

SALT2

$$\mathcal{L}_p(\theta) = \max_{\phi} \mathcal{L}(\theta, \phi)$$

Nielsen, Guffanti & S.S., Sci.Rep. 6:35596,2016

We find the data is consistent with an *uniform* rate of expansion ($\Rightarrow \rho + 3p = 0$) at **2.8σ**



Profile Likelihood

<u>MLE, *best fit*</u>

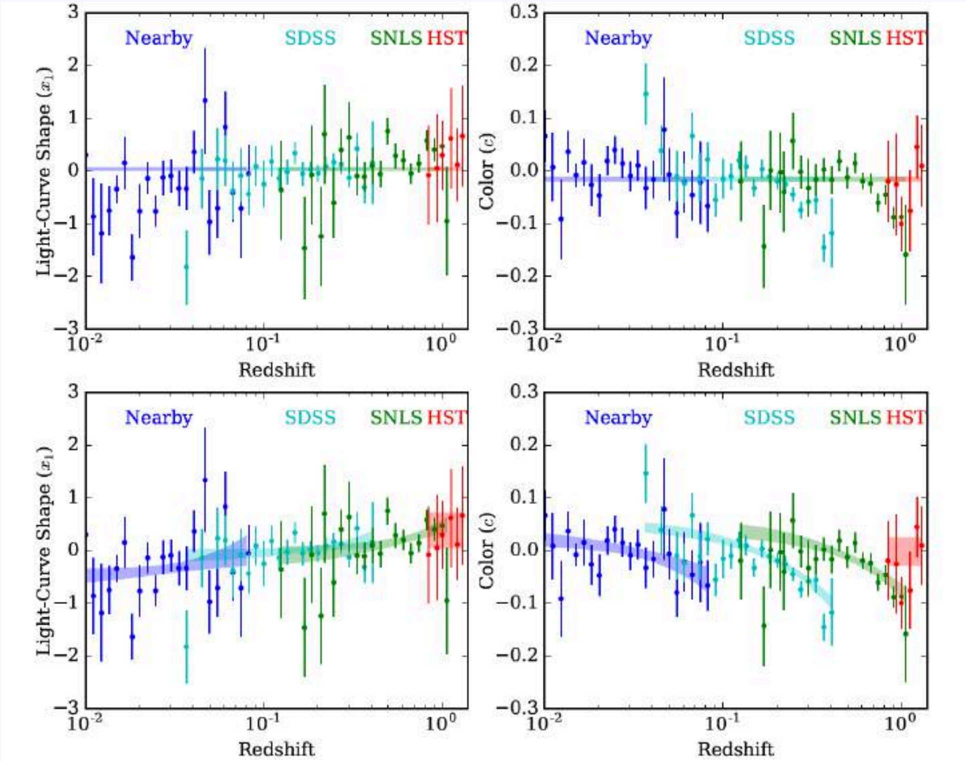
Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

NB: We show the result in the Ω_m- Ω_Λ plane for comparison with previous results (JLA)

... simply to emphasise that the statistical analysis had not been done correctly earlier

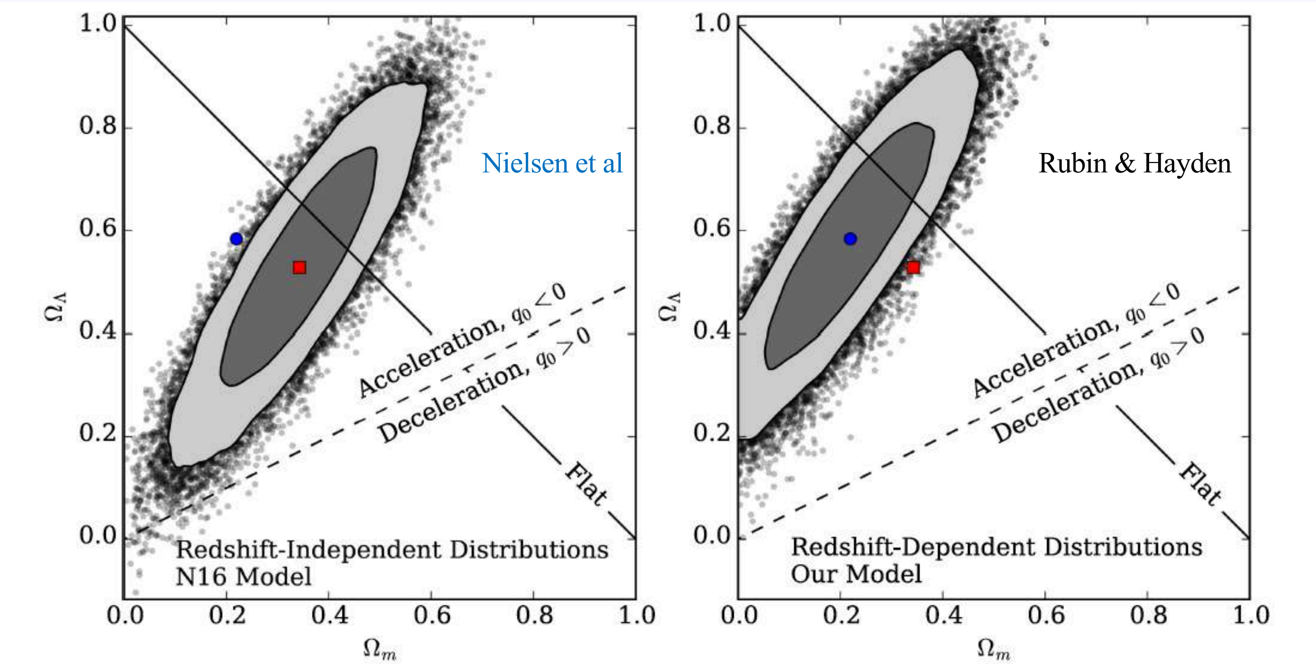
(Other constraints e.g. $\Omega_m \gtrsim 0.2$ or $\Omega_m + \Omega_\Lambda \simeq 1$ are relevant *only* to the ΛCDM model)

Rubin & Hayden (ApJ **833**:L30,2016) say that our model for the distribution of the JLA light curve parameters should have included a dependence on redshift - which *no* previous analysis had allowed for



... they added 12 more parameters to our (10 parameter) model to describe this individually for each data sample

Such *a posteriori* modification is not justified by the Bayesian information criterion

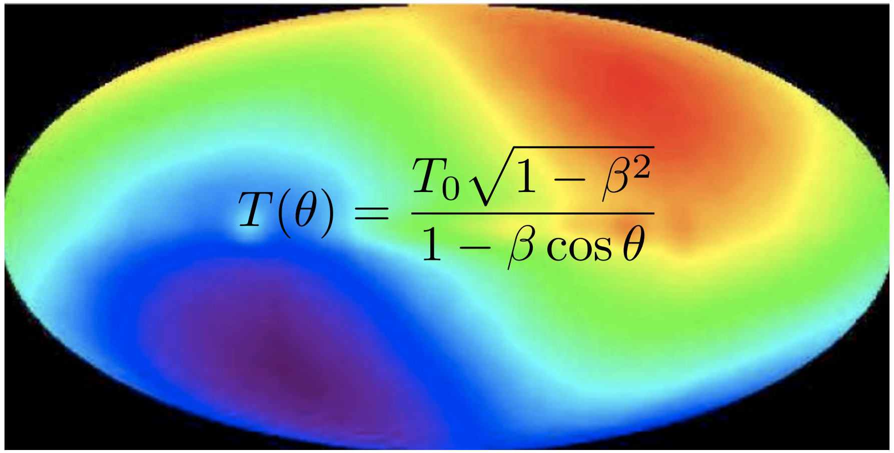


In any case this raises the significance with which a non-accelerating universe is rejected to only 3.7σ … still inadequate to claim a 'discovery' (even though the dataset has increased from ~100 to 740 SNe Ia in 20 yrs)

Morever the universe is *not* isotropic around us

We see a dipole anisotropy in the CMB with $\Delta T/T \sim 10^{-3}$

Stewart & Sciama 1967
Peebles & Wilkinson 1968

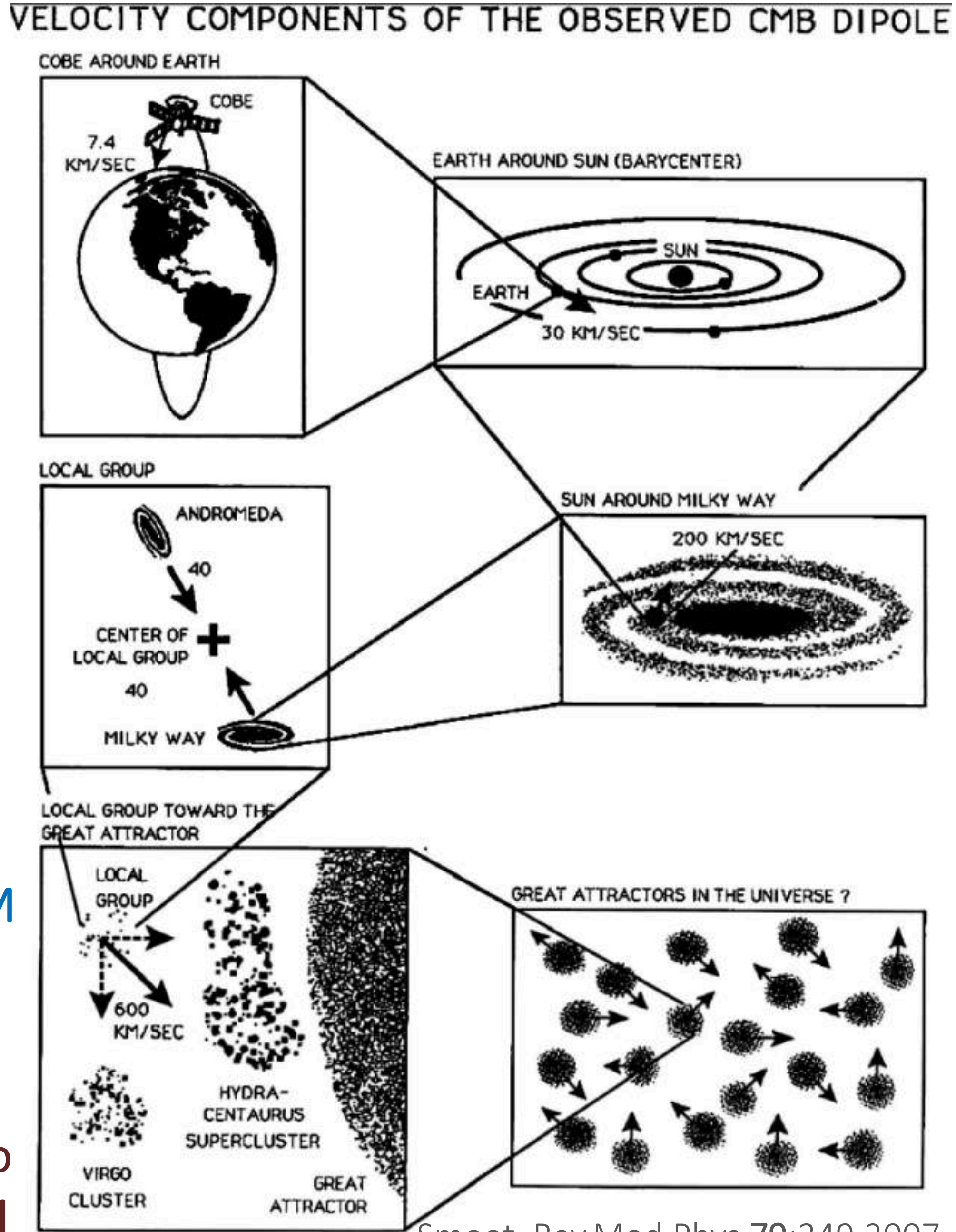


$$T(\theta) = \frac{T_0\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

This is interpreted as due to our motion at 370 km/s wrt the frame in which the CMB is truly isotropic ⇒ motion of the Local Group at 620 km/s towards l=271.9°, b=29.6°

This motion is presumed to be due to *local* inhomogeneity in the matter distribution … according to structure formation in ΛCDM we should converge to the 'CMB frame' by averaging on scales larger than ~100 Mpc

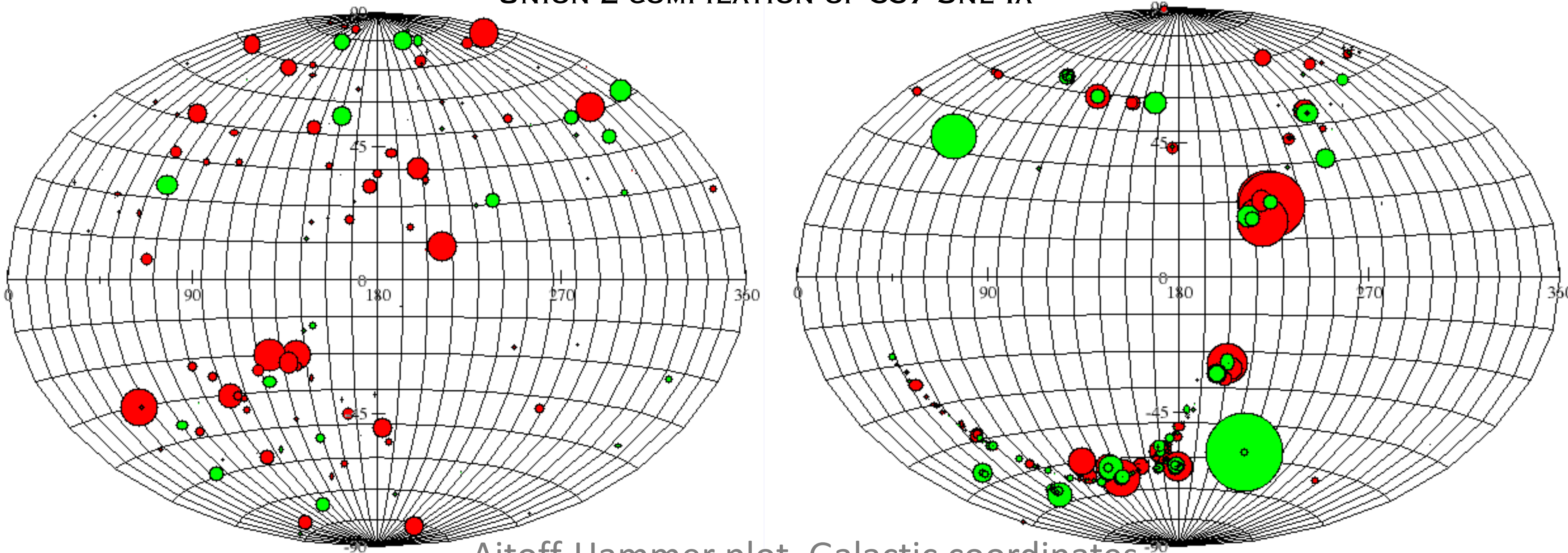
So the data is 'corrected' by transforming to the CMB frame - in which FLRW *should* hold



Smoot, Rev.Mod.Phys.**79**:349,2007

THE BULK FLOW SHOULD RESULT IN A DIPOLE ANISOTROPY OF THE SNE IA

UNION 2 COMPILATION OF 557 SNE IA



Aitoff-Hammer plot, Galactic coordinates

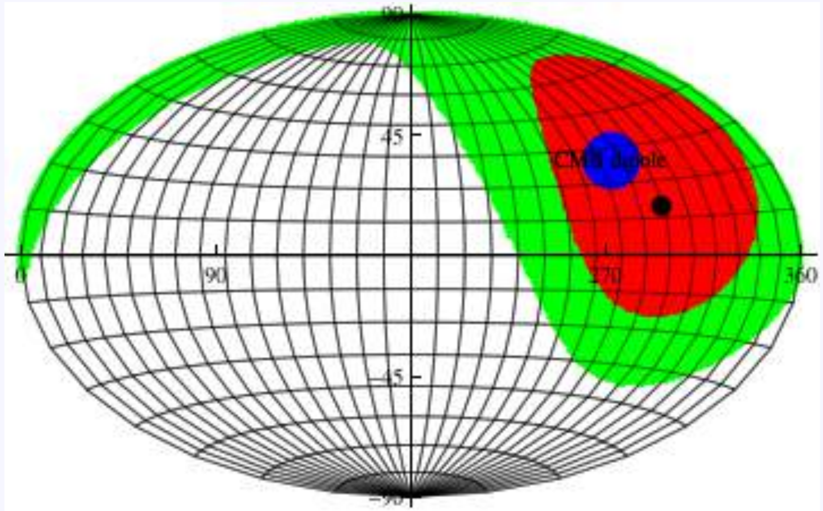
Left panel: The red spots represent the data points for $z < 0.06$ with distance moduli μ_{data} bigger than the values μ_{CDM} predicted by ΛCDM, and the green spots are those with μ_{data} less than μ_{CDM}; the spot size is a relative measure of the discrepancy. A dipole anisotropy is visible around the direction $b = -30^{\circ}$, $l = 96^{\circ}$ (red points) and its opposite direction $b = 30^{\circ}$, $l = 276^{\circ}$ (small green points), which is the direction of the CMB dipole. **Right panel**: Same plot for $z > 0.06$

We perform *tomography* of the Hubble flow by testing if the supernovae are at the expected Hubble distances: **Residuals ⇒ 'peculiar velocity' flow in local universe**

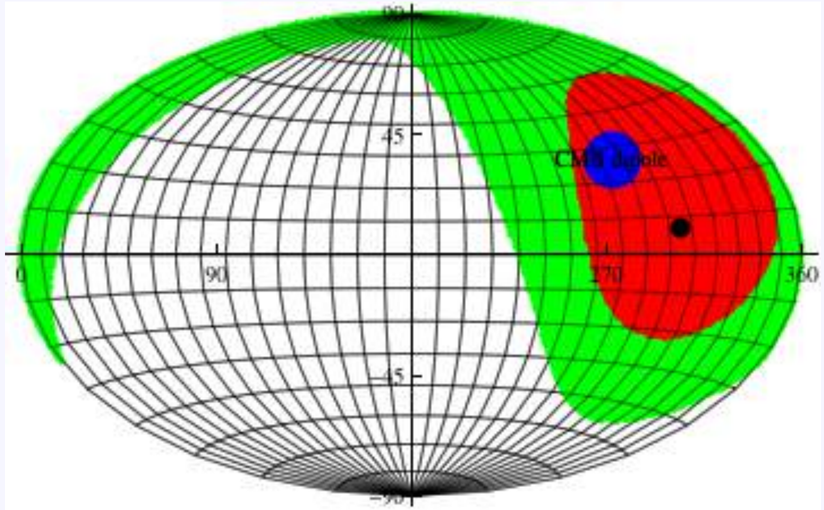
Colin, Mohayaee, S.S. & Shafieloo, MNRAS **414**:264,2011

DIPOLE IN THE SN IA VELOCITY FIELD *ALIGNED* WITH THE CMB DIPOLE

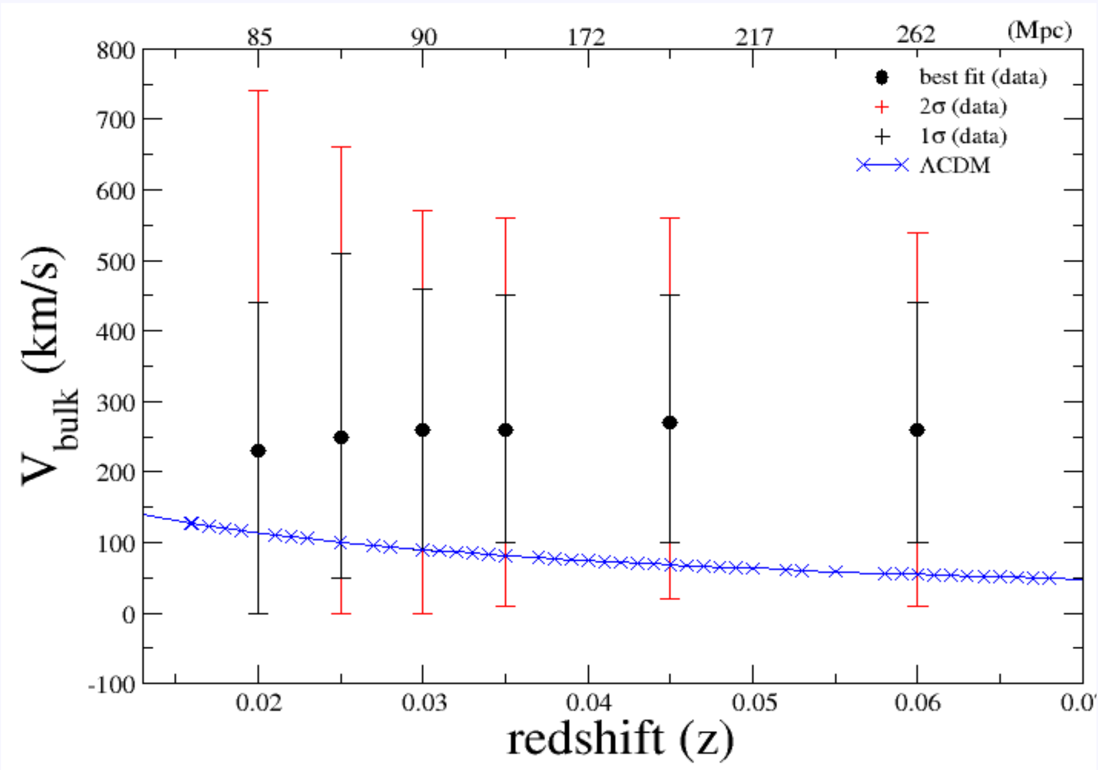
$0.015 < z < 0.045$, $v = 270$ km/s, $l = 291$, $b = 15$



$0.015 < z < 0.06$, $v = 260$ km/s, $l = 298$, $b = 8$



Colin et al, MNRAS **414**:264,2011



This is ≳1σ faster than expected for the standard ΛCDM model … and extends *beyond* Shapley (at 260 Mpc)

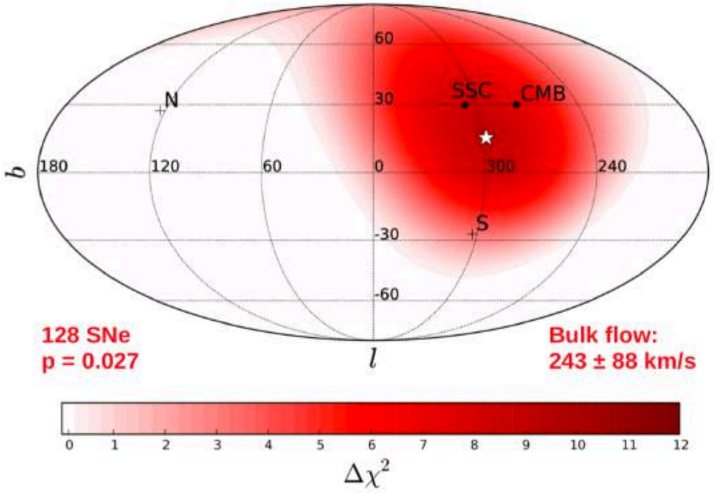
… consistent with Watkins *et al* (2009) who found a bulk flow of 416±78 km/s towards $b = 60 \pm 6^0$, $l = 282 \pm 11^0$ extending up to ~100 h^{-1} Mpc

No convergence to CMB frame,even well beyond 'scale of homogeneity'

Bulk Flow Analysis

Dipole fit: 0.015 < z < 0.035

Full dataset: 279 SNe (z < 0.1) from SNfactory & Union2 compilation



Bulk flow modeled as velocity dipole:

$$\tilde{d}_{\mathrm{L}}(z) = d_{\mathrm{L}}(z) + \frac{(1+z)^2}{H(z)} \vec{n} \cdot \vec{v}_{\mathrm{d}}$$

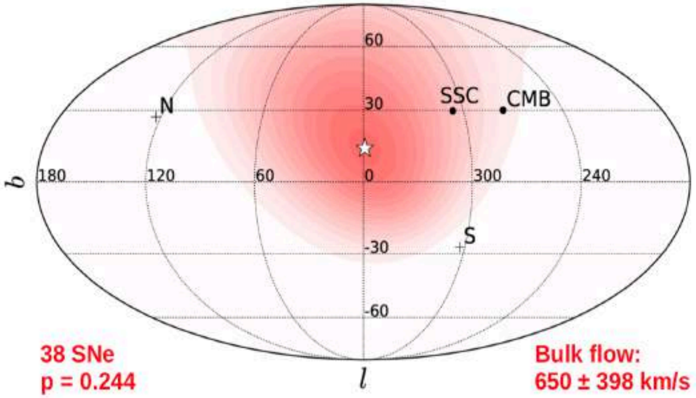
Best fit direction consistent with direction to Shapley

➔ Amplitude matches previous studies

Feindt *et al*, A&A **560**:A90,2013

Nearby Supernova Factory survey

Dipole fit: 0.045 < z < 0.06



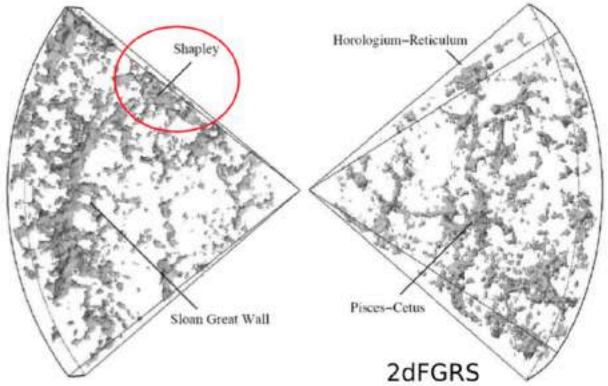
No backside infall behind Shapley

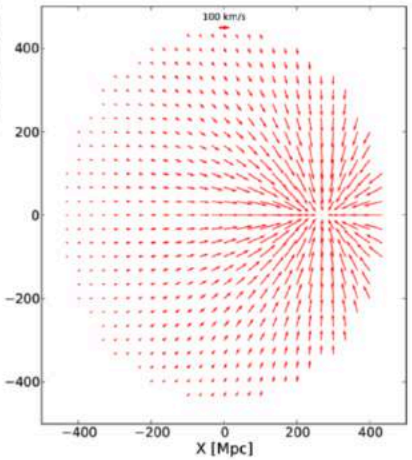
- Contradicts Shapley as the main source of the bulk flow
- Results in this shell are driven by SNfactory data

Need attractor mass of $>10^{17}$ M_{Sun} at ~300 Mpc to account for the flow

Finding the Attractors

Modeling the velocity field



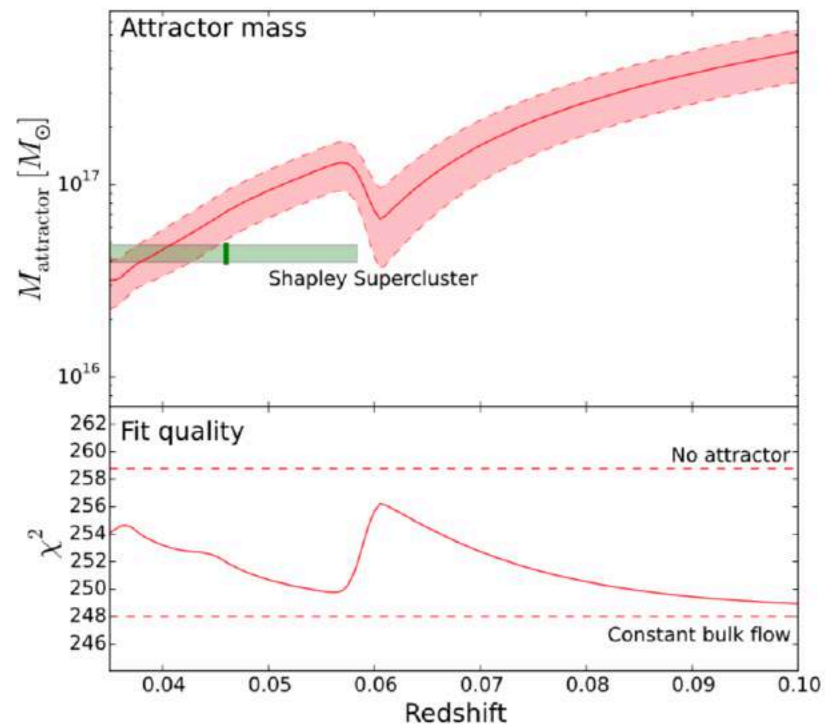


Simplest model:
Infall into spherical mass concentration

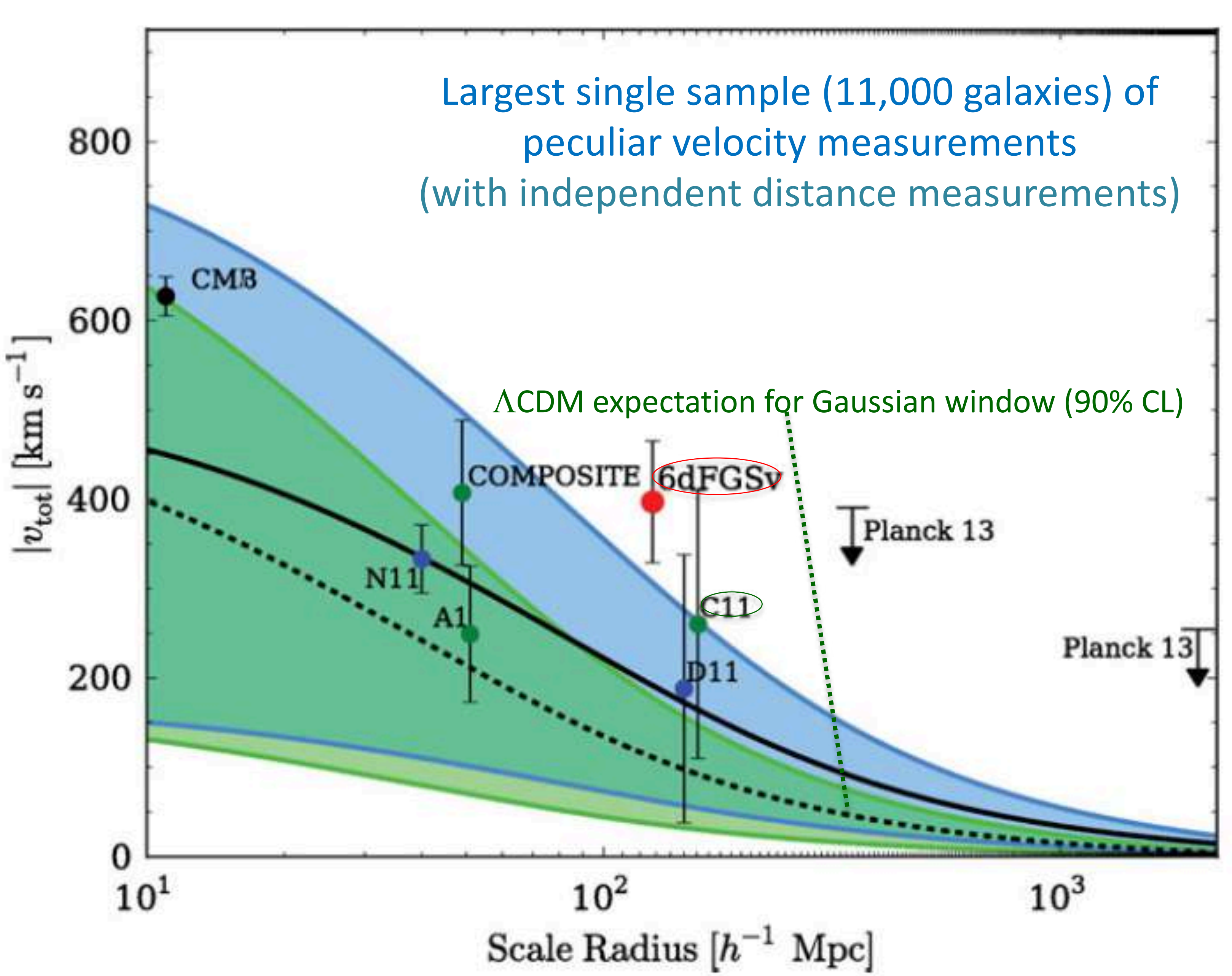
$$M_{\mathrm{tot}} = \frac{4\pi}{3} R^3 \Omega_{\mathrm{M}} \rho_{\mathrm{crit}} (1+\delta)$$

$$v_p(\vec{y}) = \frac{a\Omega_{\mathrm{M}}^{0.55} H}{4\pi} \int \frac{\vec{y}-\vec{x}}{|\vec{y}-\vec{x}|^3} \delta(\vec{y}) \mathrm{d}^3 y$$

Courtesey: Ulrich Feindt



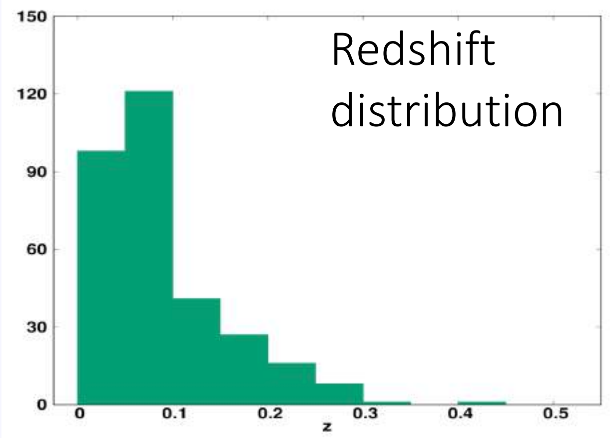
ANOMALOUS BULK FLOW IS **CONFIRMED** BY THE 6-DEGREE FIELD GALAXY SURVEY

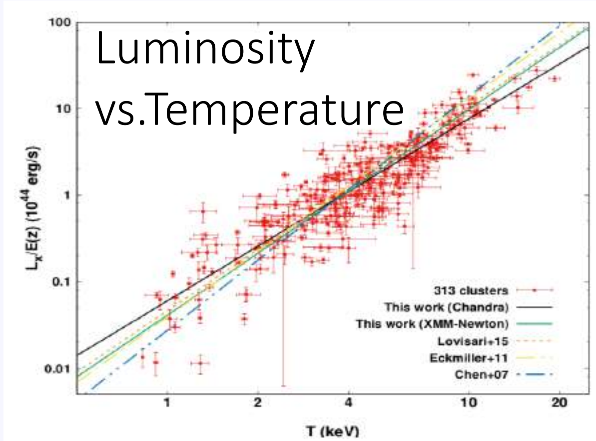


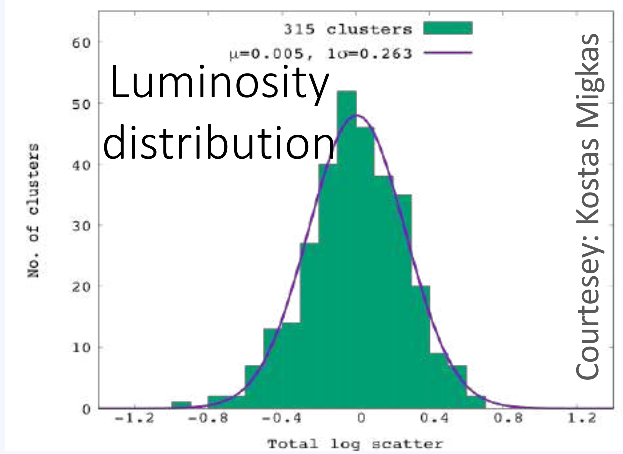
Magoulas, Springbob, Colless, Mould, *et al* (2016)

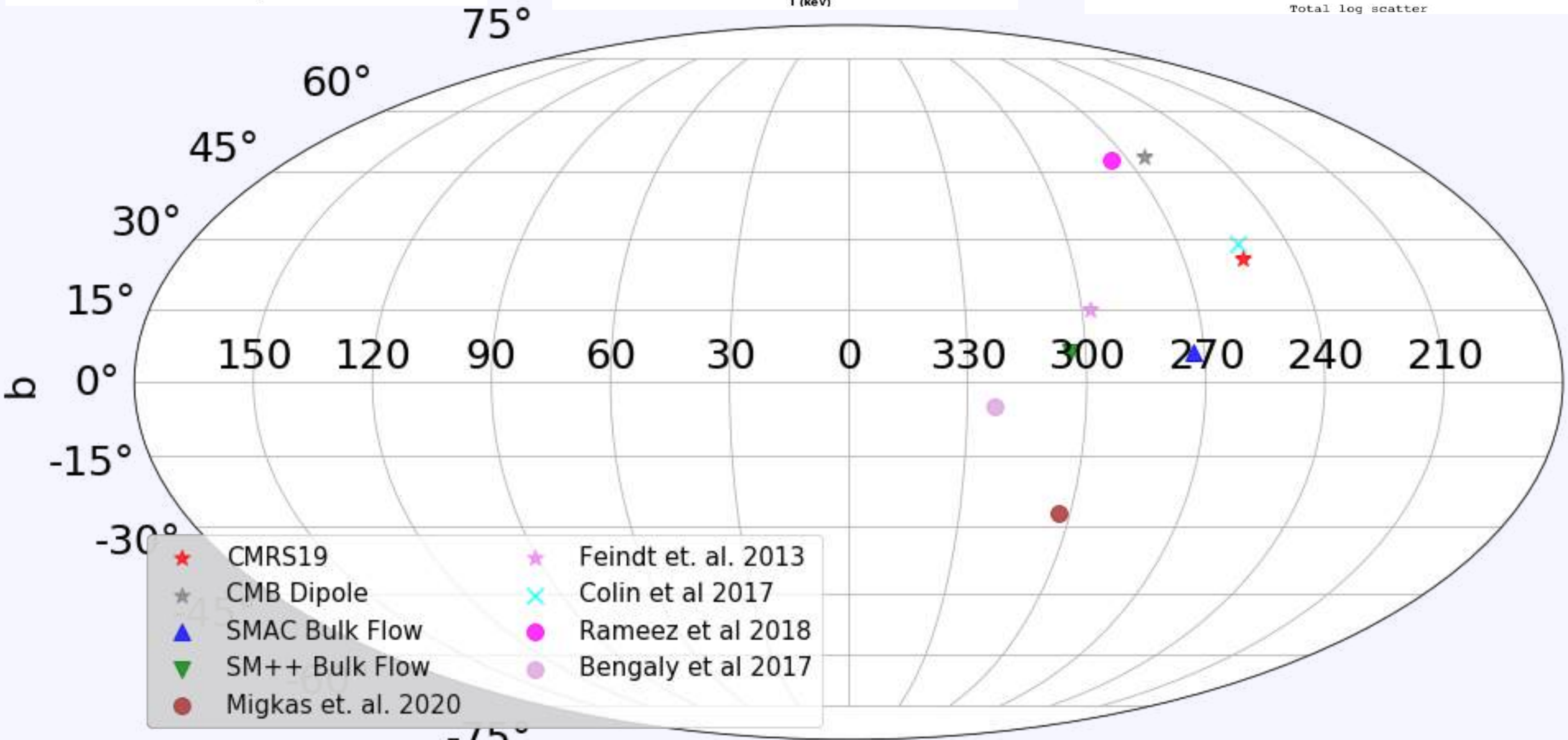
According to the 'Dark Sky' ΛCDM Hubble Volume simulations, *less than 1%* of Milky Way–like observers should experience a bulk flow as large as is observed, extending out as far as is seen

ANISOTROPY (DUE TO BULK FLOW?) IN A SAMPLE OF 313 X-RAY CLUSTERS







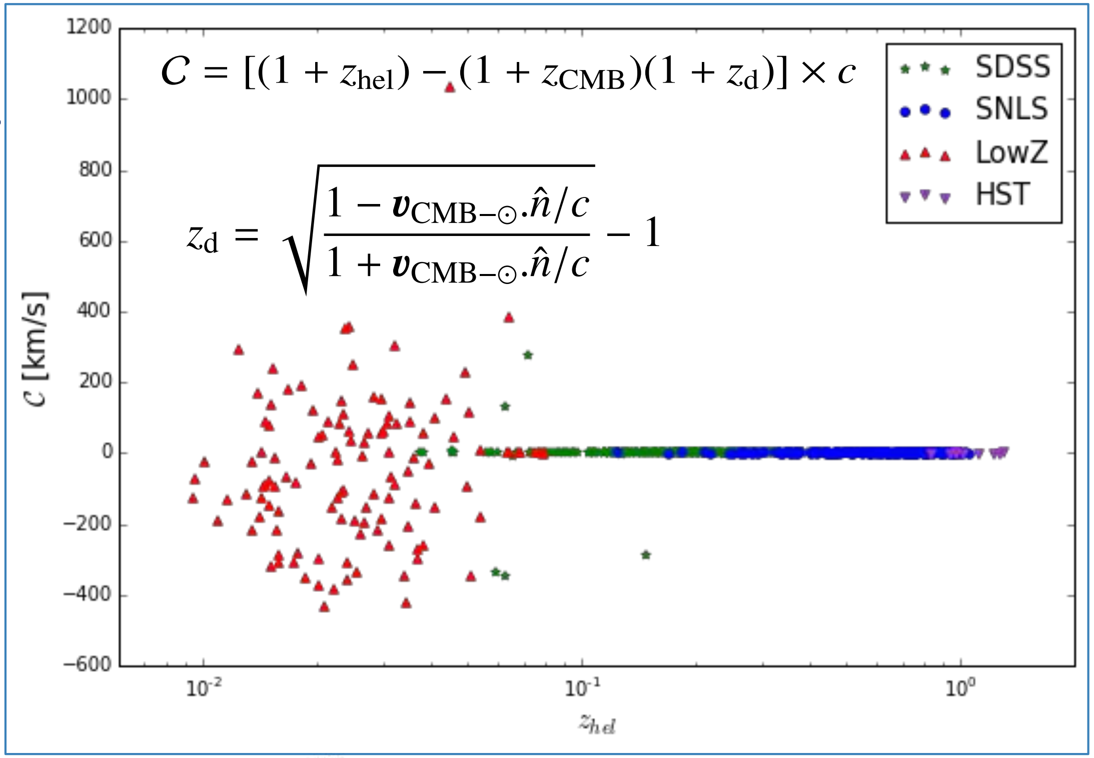


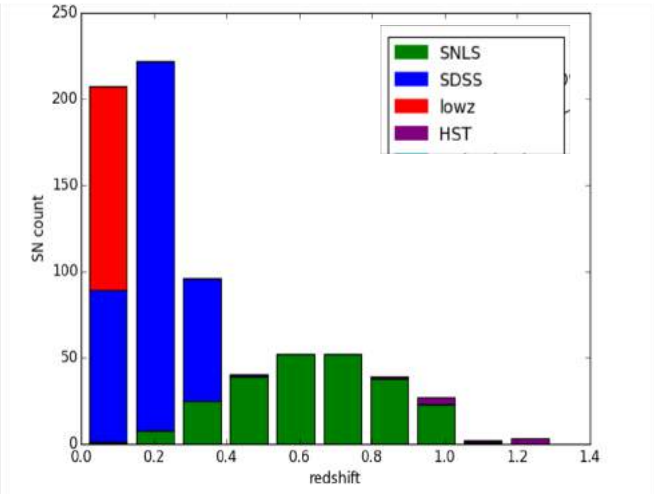
Migkas *et al*, A&A **636**:A15,2020

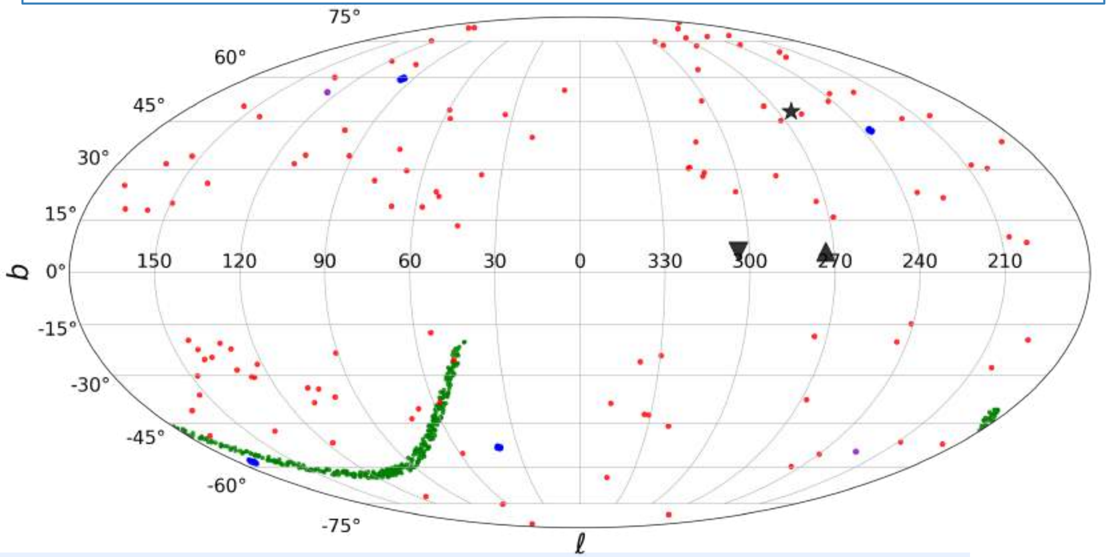
We find the peculiar velocity 'corrections' applied to the JLA catalogue are suspect … the bulk flow had been assumed to drop to *zero* at ~150 Mpc - even though it is **observed** to continue beyond 300 Mpc!

So we *undid* the corrections to recover the original data in the heliocentric frame … to check if the inferred acceleration of the expansion rate is indeed isotropic

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



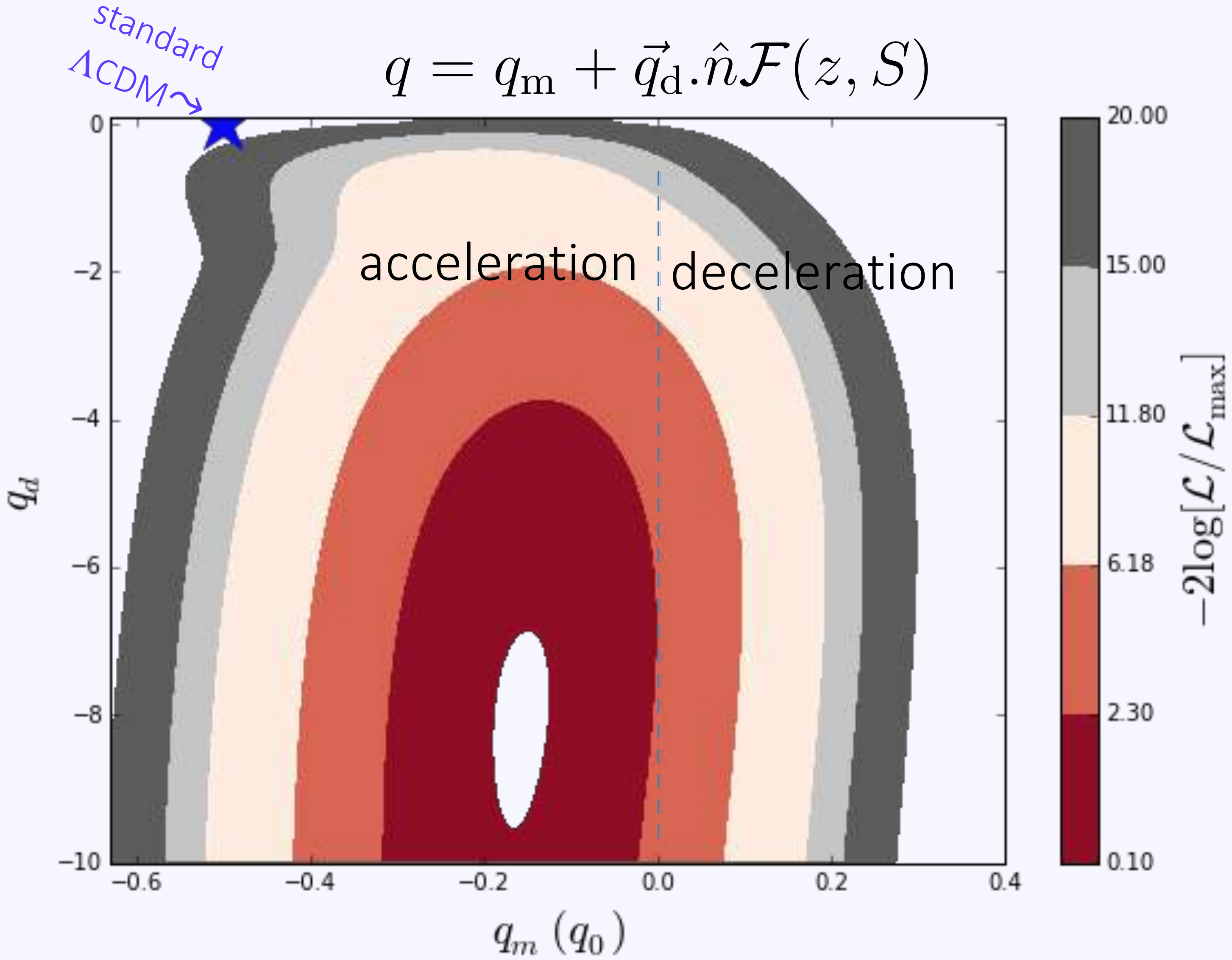




Sky distribution of the 4 sub-samples of the JLA catalogue in Galactic coordinates: SDSS (red dots), SNLS (blue dots), low redshift (green dots) and HST (black dots). CMB dipole (star), SMAC bulk flow (triangle), 2M++ bulk flow (inverted triangle)

When the acceleration is analysed allowing for a dipole, the MLE indeed *prefers* one (~50 times bigger than the monopole) … in the same direction as the CMB dipole

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



Colin, Mohayaee, Rameez & S.S., A&A **631**:L13,2019

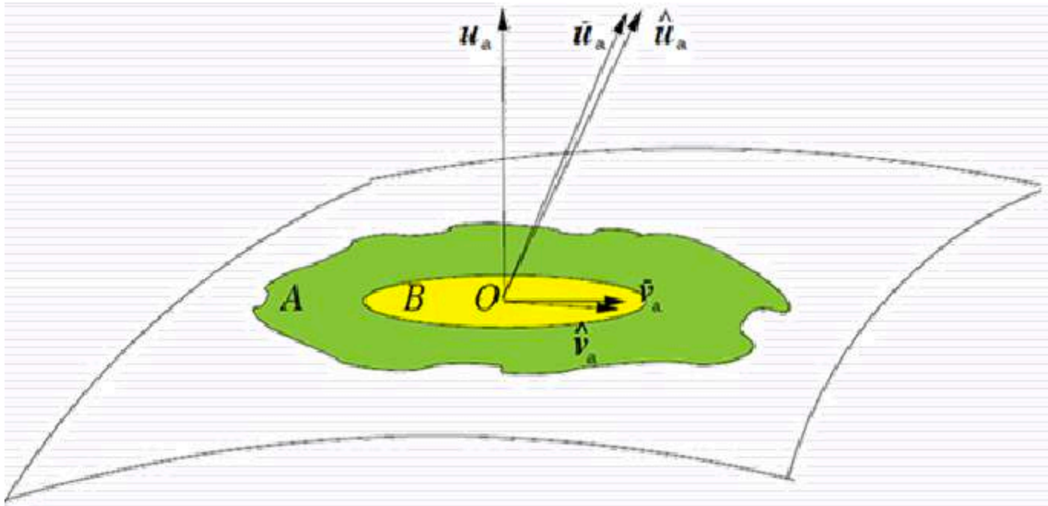
The significance of q_o being negative has now *decreased* to only 1.4σ

This suggests that cosmic acceleration is an *artefact* of our being located within a bulk flow (which includes 3/4 of the observed SNe Ia) - and *not* due to Λ

Do we infer acceleration even though the expansion is actually decelerating ... because we are *inside* a local 'bulk flow'?

(Tsagas, Phys.Rev.D**84**:063503,2011; Tsagas & Kadiltzoglou, Phys.Rev.D**92**:043515,2015)

... if so expect a dipole asymmetry in the inferred deceleration parameter in the *same* direction – i.e. aligned with the CMB dipole

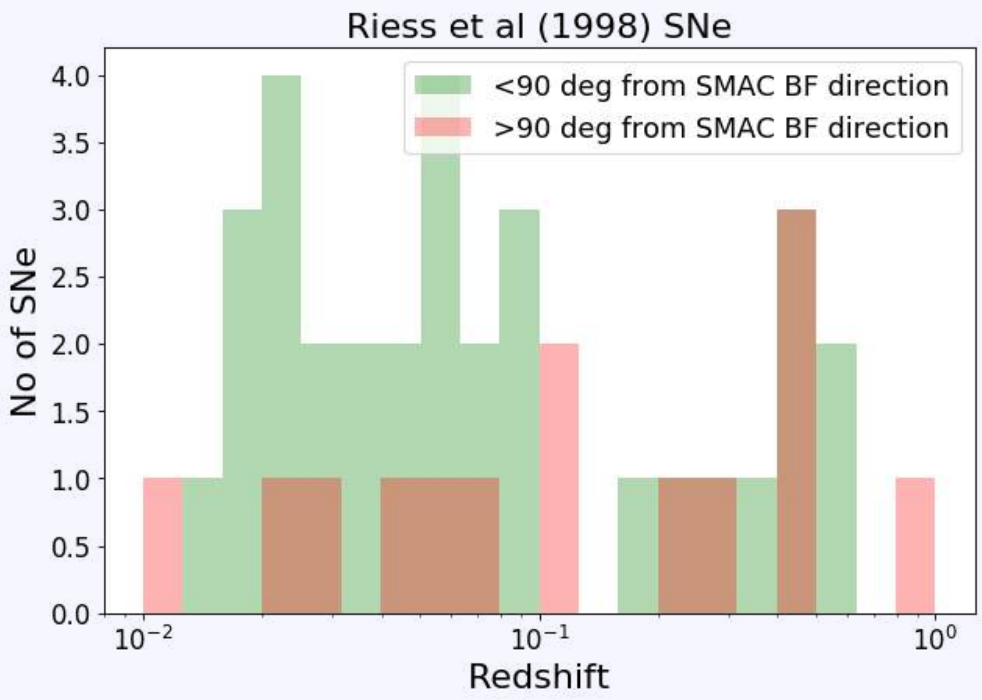


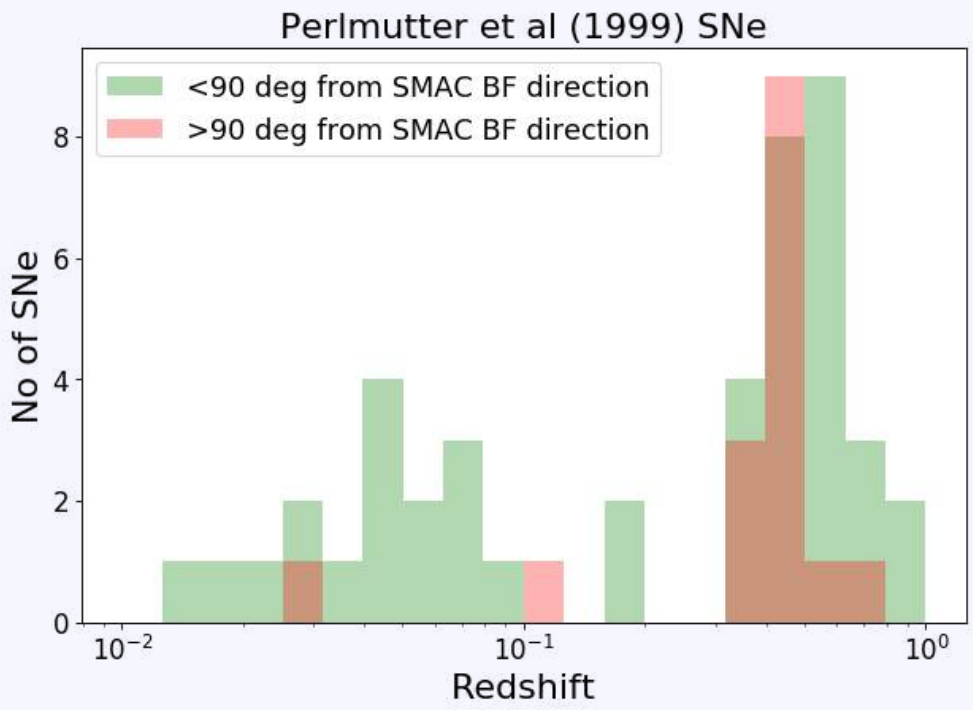
The patch A has mean peculiar velocity $\tilde{v}_a$ with $\vartheta = \tilde{\mathrm{D}}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$
(the sign depending on whether the bulk flow is faster or slower than the surroundings)

Inside region B, the r.h.s. of the expression

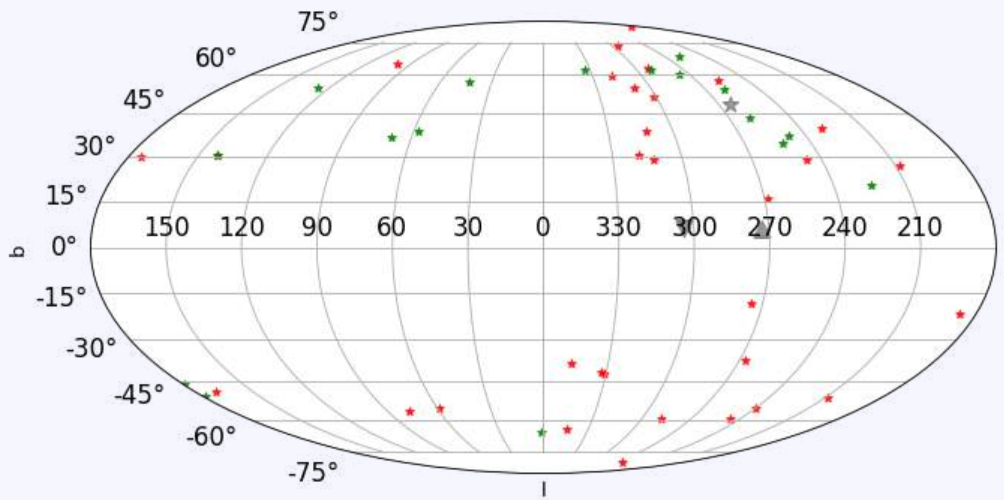
$$1 + \tilde{q} = (1+q)\left(1 + \frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1 + \frac{\vartheta}{\Theta}\right)^{-2}, \qquad \tilde{\Theta} = \Theta + \vartheta,$$

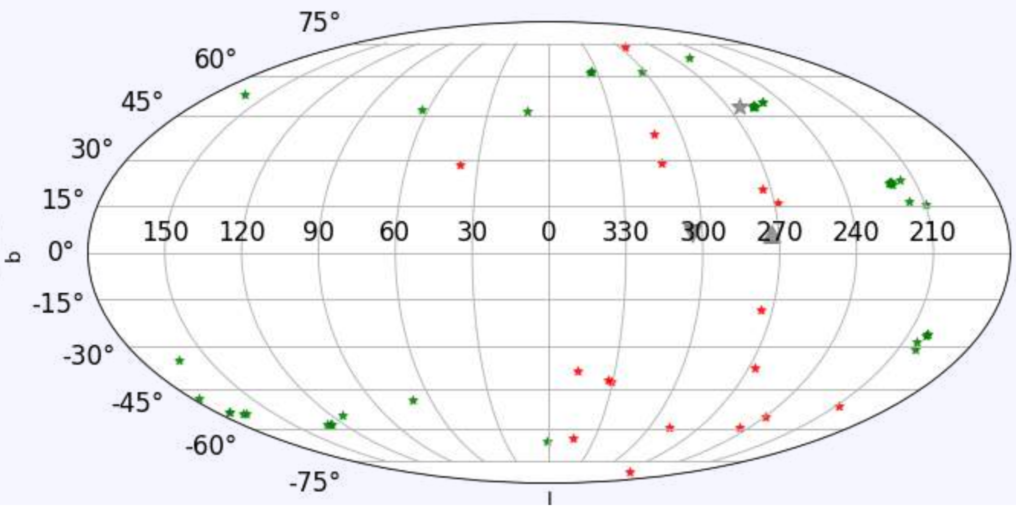
drops below 1 and the comoving observer 'measures' *negative* deceleration parameter





Interestingly, most of the 60 SNe Ia studied by the High-*z* Team and the 45 SNe Ia studied by the Supernova Cosmology Project were *in the direction* of the bulk flow

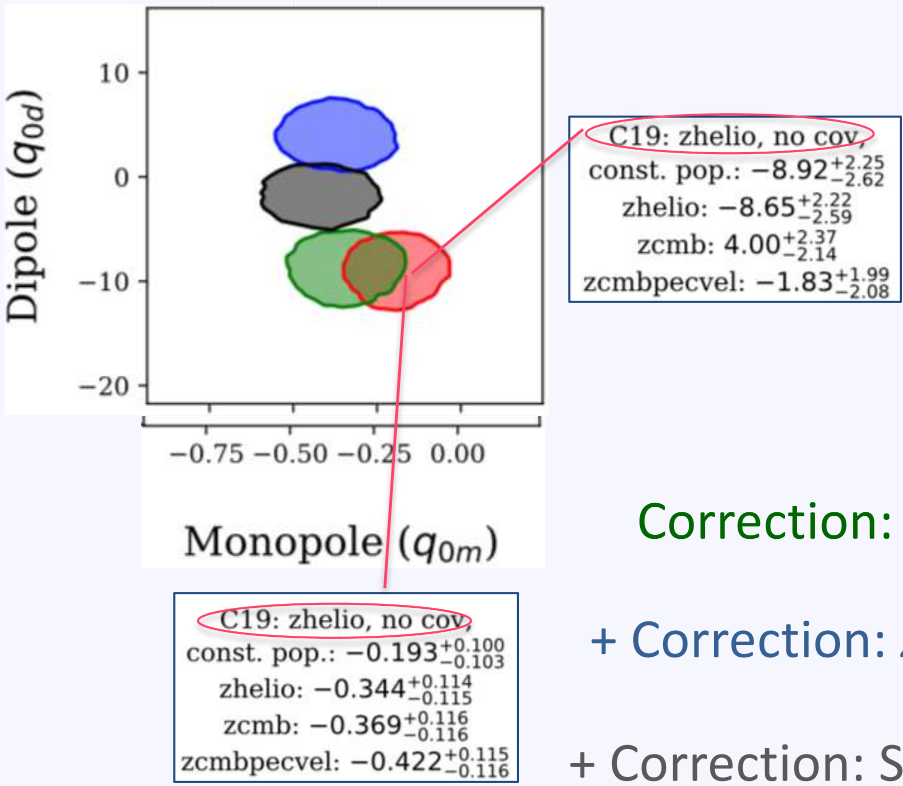




Rubin & Heitlauf (ApJ **894**:68,2020) *confirm* our findings (C19), but criticise us for:

- "Incorrectly" not allowing redshift-dependence of light-curve parameters (BIC?)
- "Shockingly" using heliocentric redshifts

Without JLA peculiar velocity covariance



Correction: x_1 & c z-dep.

\+ Correction: $z_{\rm hel} \rightarrow z_{\rm CMB}$

\+ Correction: SNe peculiar velocities

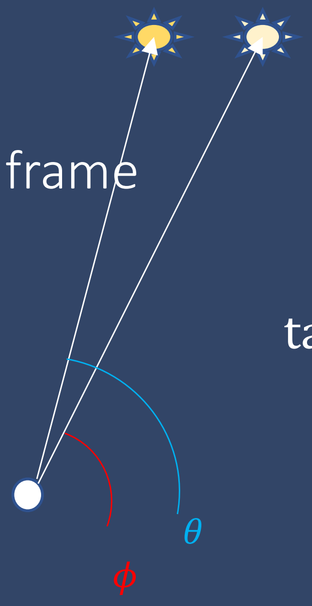
This illustrates just how many "corrections" need to be made to extract evidence for isotropic acceleration q_{0m}, when the data in fact indicate *anisotropic* acceleration q_{0d}!

Most importantly, is the CMB frame the 'correct' frame? (Colin *et al*, arXiv:1912:04257)

If the dipole in the CMB is due to our motion *wrt* the 'CMB frame' then we should see *similar* dipole in the distribution of distant sources

$$\sigma(\theta)_{obs} = \sigma_{rest}[1 + [2 + x(1+\alpha)]\frac{v}{c}\cos(\theta)]$$

Aberration



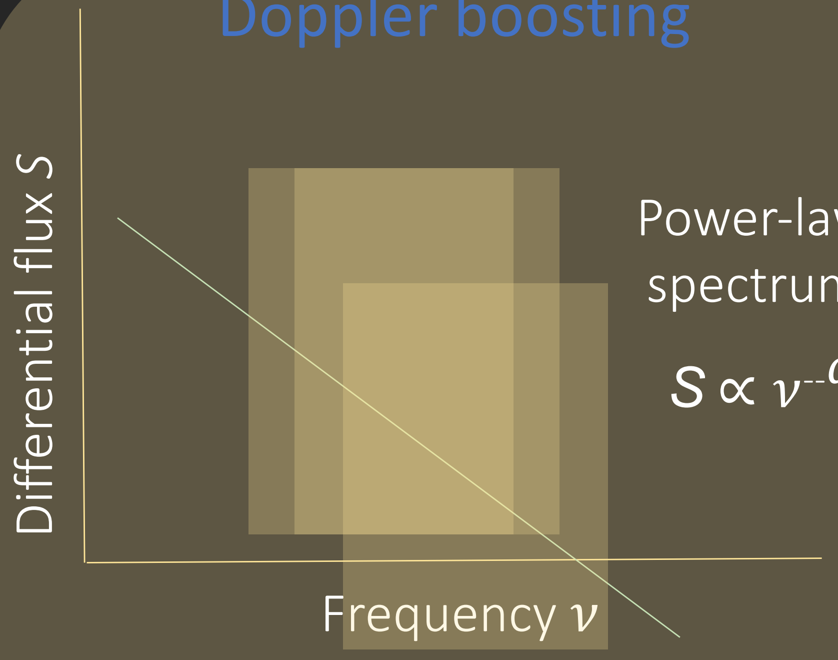
Moving frame

$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta \; - \frac{v}{c}}$$

Observer, velocity $\boldsymbol{v}$

+

Doppler boosting



Power-law spectrum

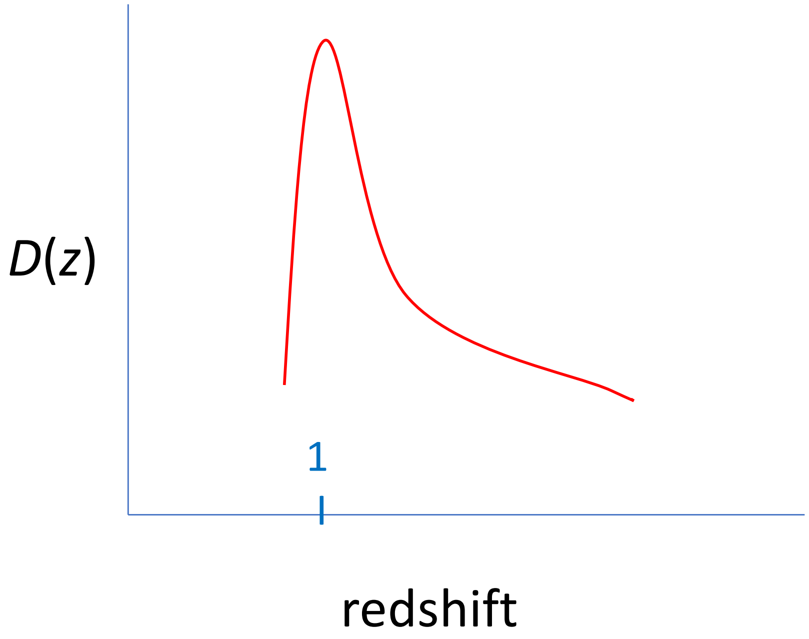
$S \propto \nu^{--\alpha}$

Integral flux distribution: $N\,(>S) \propto S^{-x}$

Flux-limited catalog → *more* sources in direction of motion

Ellis & Baldwin, MNRAS 206:377,1984

All-sky catalogue with N sources with redshift distribution $D(z)$ from a directionally unbiased survey



$$\vec{\delta} = \vec{\mathcal{K}}\,(\vec{v}_{obs}, x, \alpha) + \vec{\mathcal{R}}\,(N) + \vec{\mathcal{S}}\,(D(z))$$

$\vec{\mathcal{K}}$ → The kinematic dipole: independent of source distance, but depends on source spectrum, source flux function, observer velocity

$\vec{\mathcal{R}}$ → The random dipole: $\propto 1/\sqrt{N}$
- isotropically distributed

$\vec{\mathcal{S}}$ → The dipole component of any actual anisotropy in the distribution of sources in the cosmic rest frame (significant for shallow surveys)

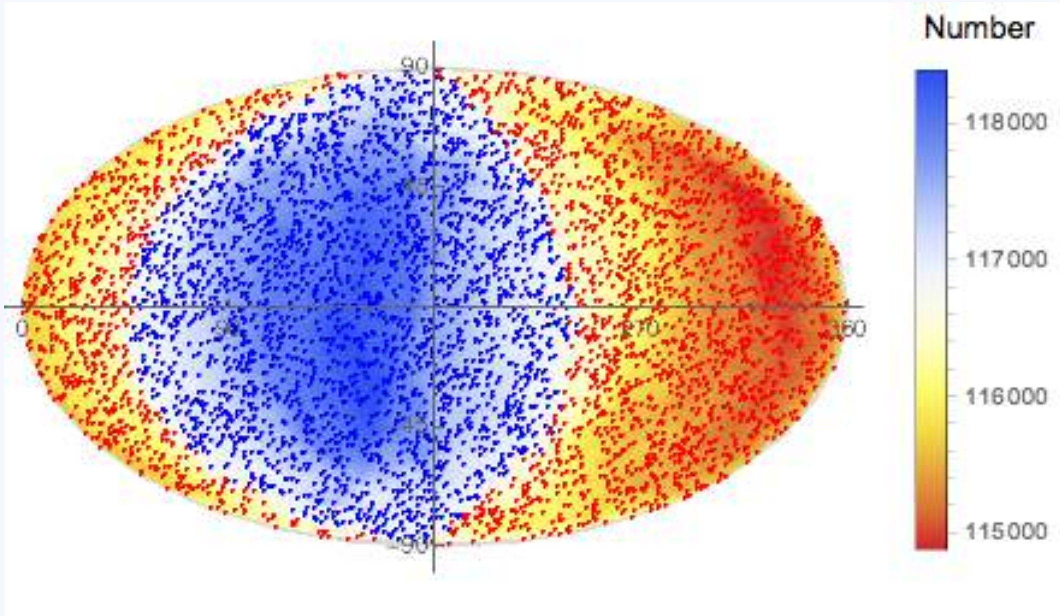
Radio sources: NVSS + SUMSS, 600,000 sources $z \sim 1$, $\vec{\mathcal{S}}\,(D(z)) \rightarrow 0$
Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017

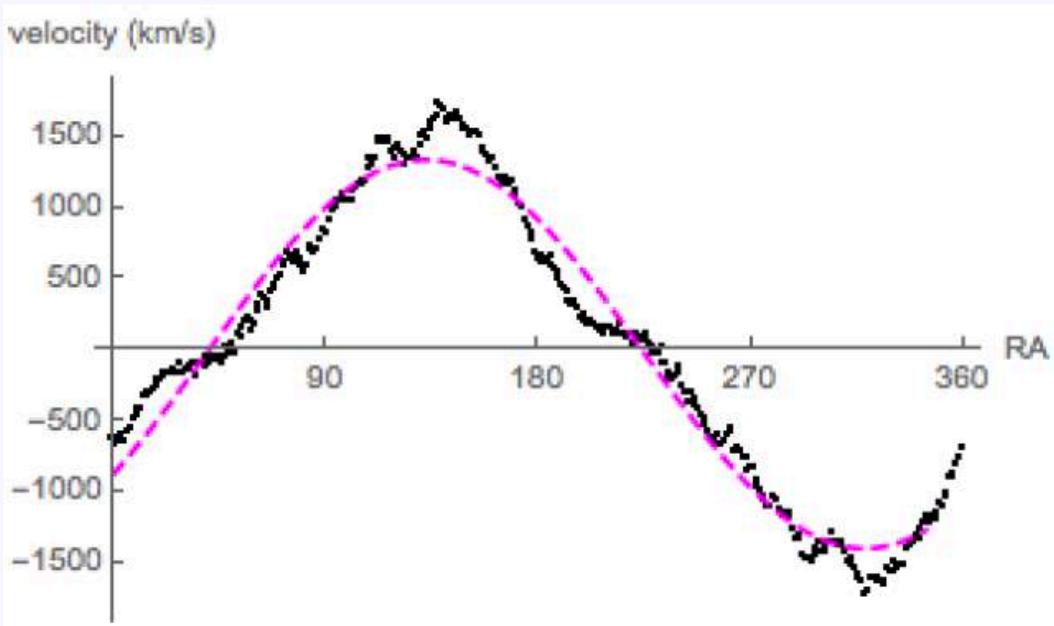
Wide Field Infrared Survey Explorer, 1,200,000 galaxies, $z \sim 0.14$, $\vec{\mathcal{S}}\,(D(z))$ significant
Rameez, Mohayaee, S.S. & Colin, MNRAS **477**:1722,2018

Wide Field Infrared Survey Explorer, 1,300,000 quasars, $z \sim 1$, $\vec{\mathcal{S}}\,(D(z)) \sim 1\%$
Secrest, Rameez, von Hausegger, Mohayaee, S.S. & Colin, arXiv:2009.14826

Our Peculiar velocity wrt radio galaxies ≠ peculiar velocity wrt the CMB

Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017





Velocity ~ 1355 ± 174 km/s
(with the 3D linear estimator)

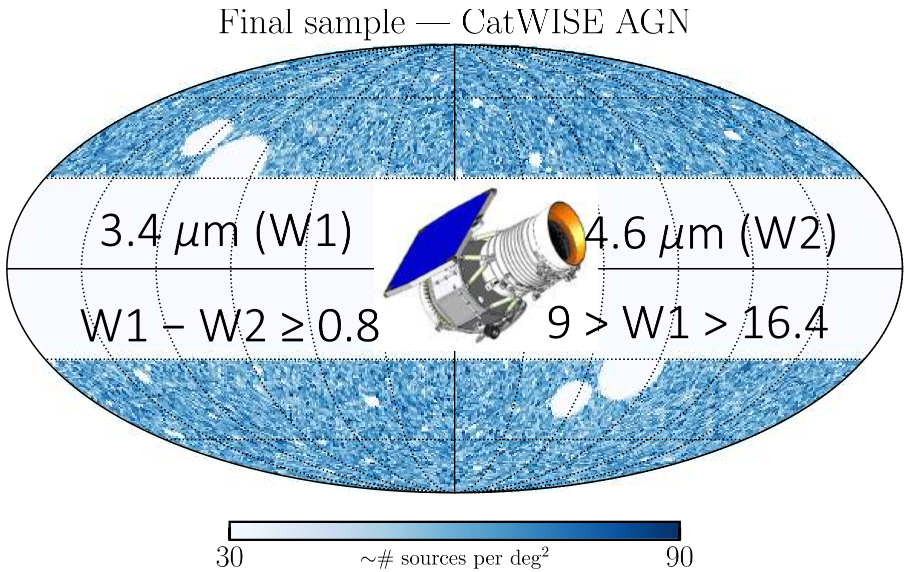
Direction within 10° of CMB dipole (but **much *faster***)!

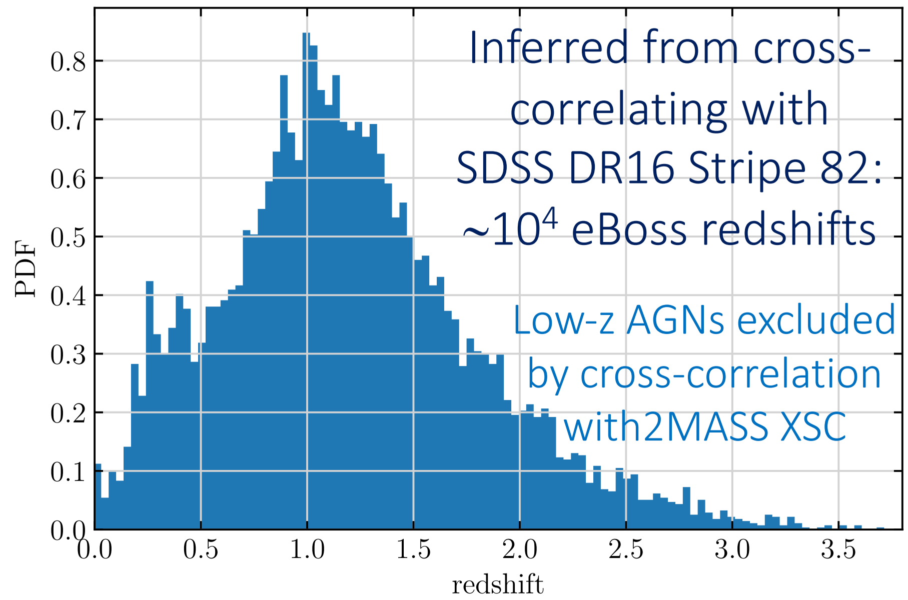
Statistical significance: 99.75%
⇒ 2.8σ (by Monte Carlo)

Confirms claim by Singal (2011) which was criticised subsequently
(Gibelyou & Huterer 2012, Rubart & Schwarz 2013, Nusser & Tiwari 2015)

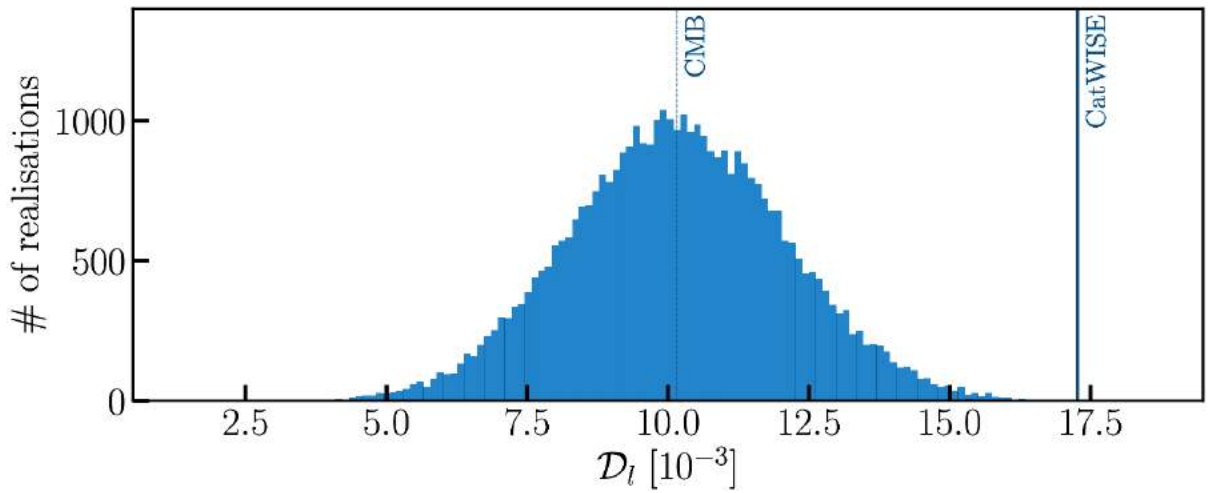
We have addressed *most* concerns but this strange anomaly remains … and casts doubt on the kinematic interpretation of the CMB dipole

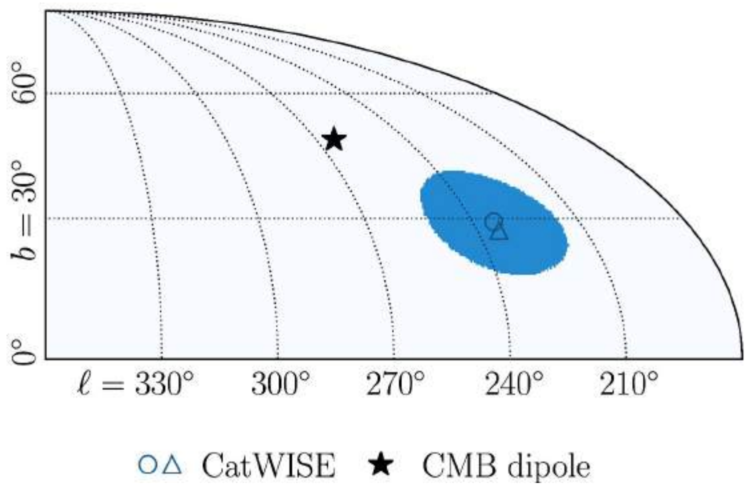
Our Peculiar velocity wrt quasars ≠ peculiar velocity wrt the CMB





We now have a catalogue of ~1.3 million quasars, with 99% at redshift > 0.1

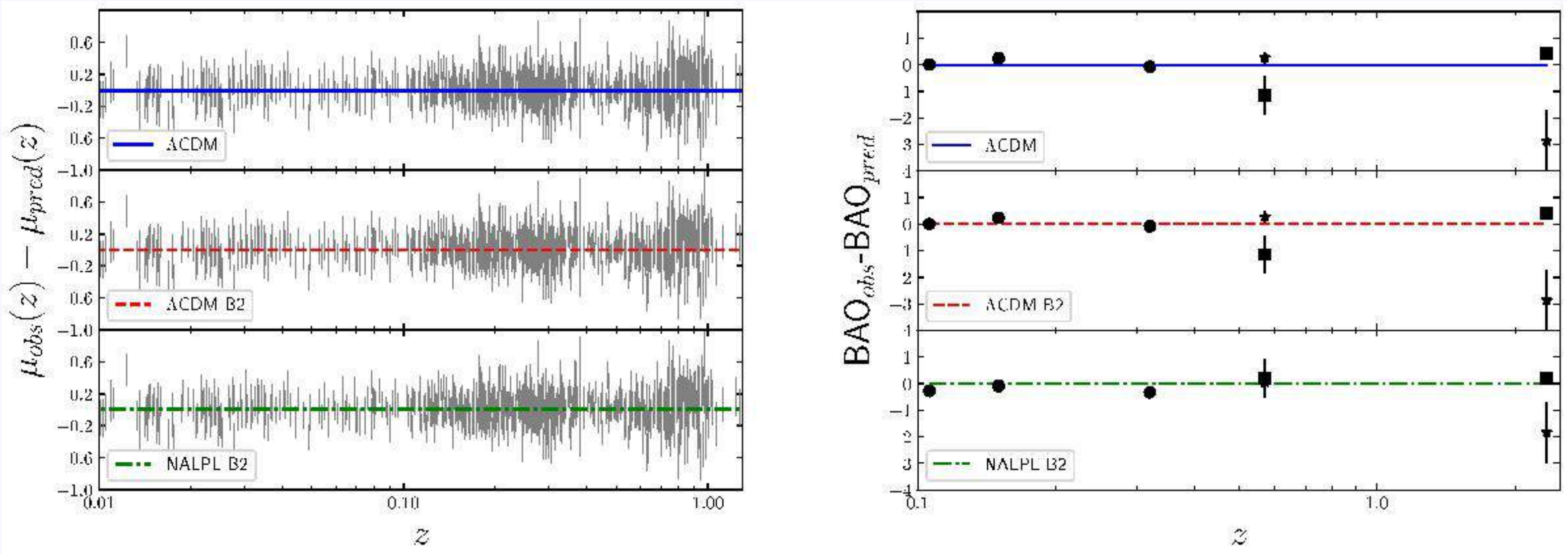




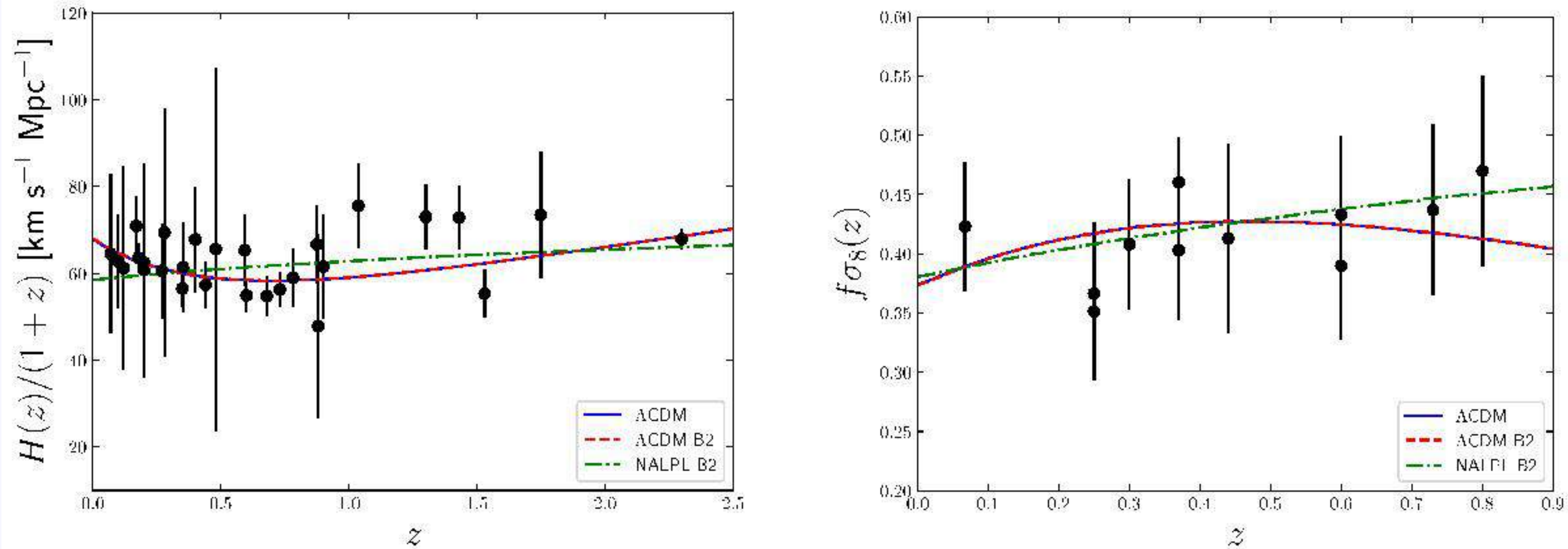
The kinematic interpretation of the CMB dipole is *rejected* with $p=10^{-4}$ ⇒ 3.9σ

Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, arXiv:2009.14826

What about the evidence from BAO, $H(z)$, growth of structure etc?



The 'independent' lines of evidence are obtained *assuming* ΛCDM!

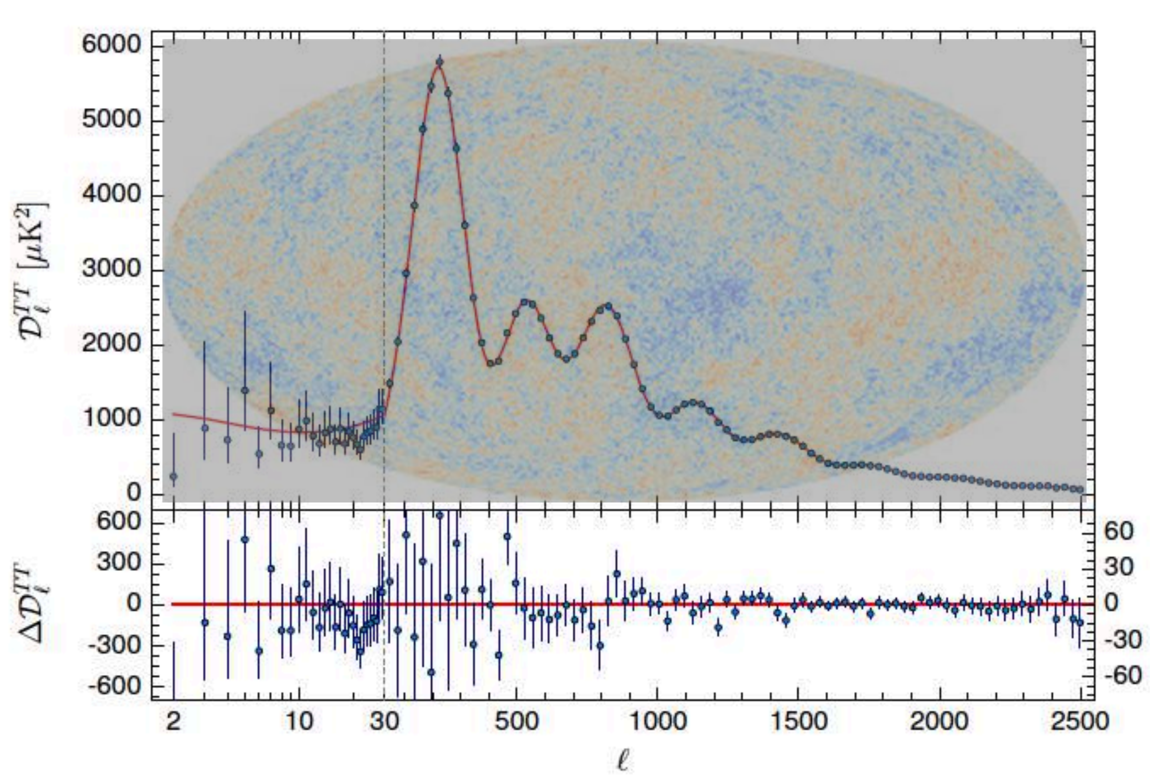


Tutusaus, Lamine, Dupays & Blanchard, A&A **602**:A73,2017

In fact all data are equally consistent with no acceleration (best fit: $a \sim t^{0.9}$)

… will need ~5x10^6 galaxy redshifts to see BAO peak *without* ΛCDM template

What about the precision data on CMB anisotropies?



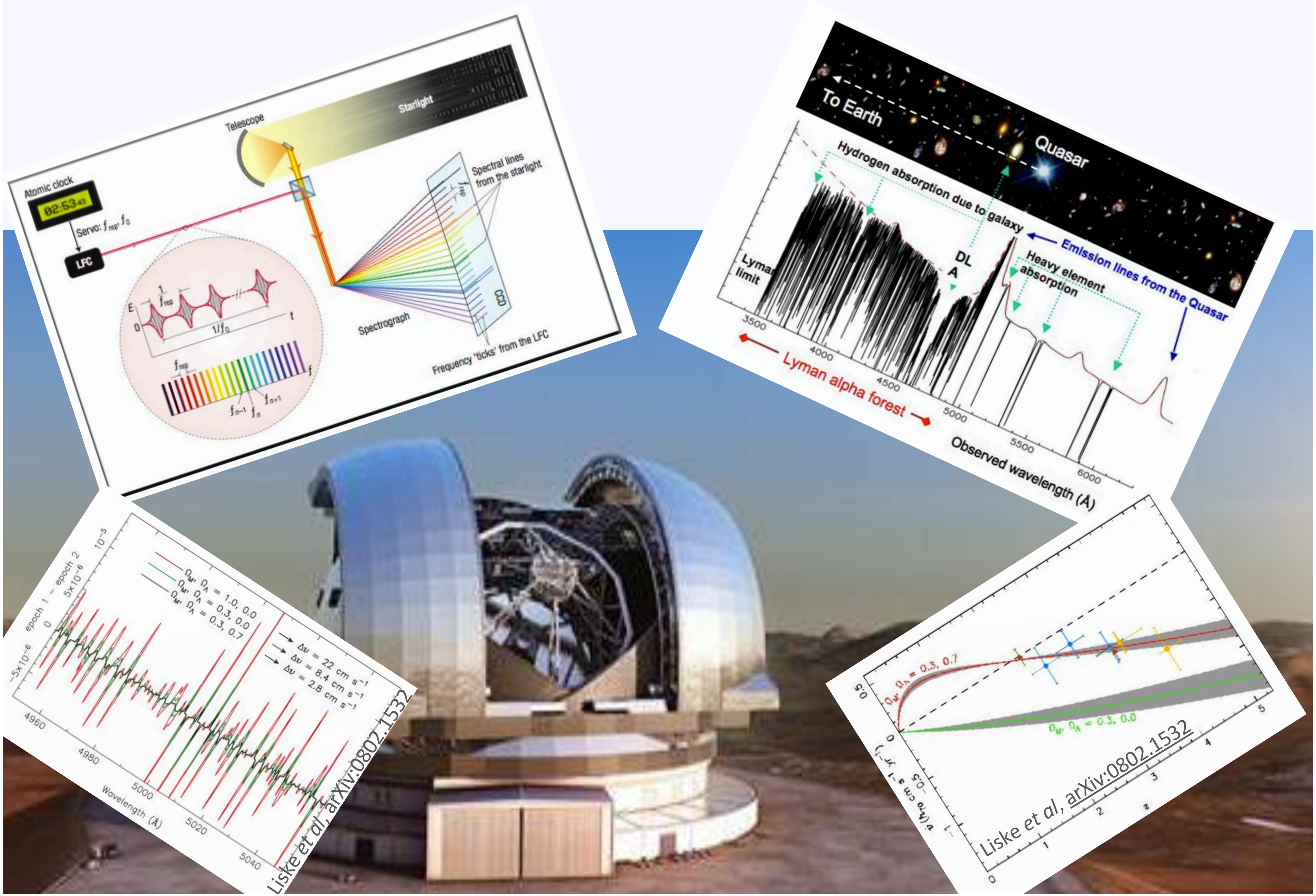
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012

Where is the entry for Λ?!

There is no *direct* sensitivity of CMB anisotropy to dark energy … it is all inferred (in the framework of ΛCDM)

(To detect the late-ISW correlations between CMB & structure induced by Λ will require 10 million redshifts)

Whether the expansion rate is accelerating will be *directly* tested using a Laser Comb on the **European Extremely Large Telescope** to measure redshift drift of the Lyman-α forest over ~10 yr



Summary

- The ‘standard model’ of cosmology was established long before there was any observational data … and its empirical foundations (homogeneity, isotropy) have never been rigorously tested.
Now that we have data, it should be a priority to *test the model assumptions* – not simply measure the model parameters

- There is a dipole in the recession velocities of host galaxies of supernovae ⇒ we are in a ‘bulk flow’ stretching out *beyond* the scale at which the universe supposedly becomes statistically homogeneous
The inference that the Hubble expansion rate is *accelerating* may be just an artefact of this bulk flow (and *not* due to a Cosmological Constant)

- The rest frame of distant quasars ≠ the rest frame of the CMB

Do we need to start again to construct a standard model of cosmology?
(following the manifesto outlined by G. Ellis, *Gen. Rel. Grav.*, p.215, 1984)

ORAL HISTORIES
Interview date: Monday, 3 April 1989

Lightman:

Taking into account a large body of work besides the Geller, de Lapparent, Huchra work - your own work on the large-scale motions and the work of the Seven Samurai & all of that **work which has shown that the universe is more inhomogeneous than might have been present in simple models - has that altered your view** of the big bang model at all, or **of the validity of model**, the assumptions of the model, that kind of thing?

Rubin et al, *Motion of the Galaxy and the local group determined from the velocity anisotropy of distant SC I galaxies*, Astron.J.**81**:719,1976
Dressler et al, *A Large-Scale Streaming Motion in the Local Universe* Astrophys.J.**313**:L37,1987

Rubin:

It certainly has convinced me that we're not living in a homogeneous, isotropic [universe]. I mean these things that I really suspected in the back of my mind, I can now say publicly. **I'm not sure the Robertson-Walker universe exists.** I can think of more questions to ask because of what they've done, which go more in the direction of making things more inhomogeneous, and I've at least asked some of my theorist friends some of them. No, it hasn't concerned me about the big bang - maybe because I just don't put my mind to it. **If someone came out with a different model that could incorporate such large-scale inhomogeneities, I would be delighted to see it**, but until then I will just live with the big bang model.