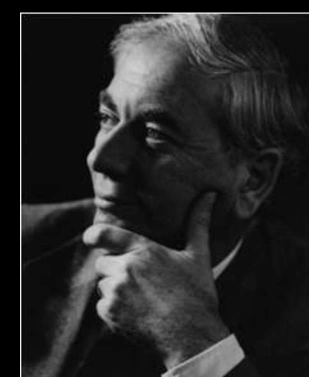
A challenge to the standard cosmological model

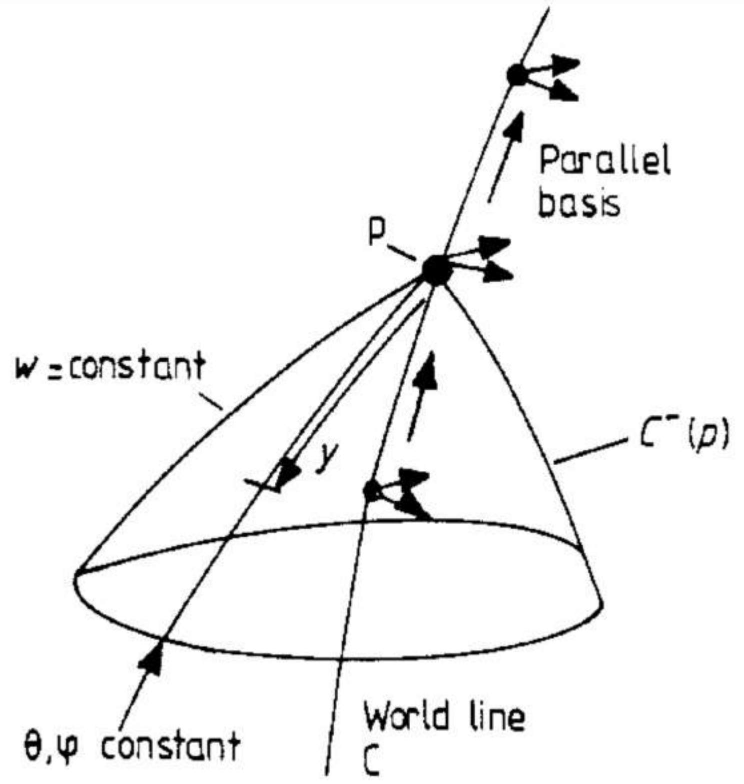
Subir Sarkar

None of us can understand why there is a Universe at all, why anything should exist; that's the ultimate question. But while we cannot answer this question, we can at least make progress with the next simpler one of what the Universe as a whole is like.

Dennis Sciama (1978)



All we can learn about the universe is contained within our past light cone



Ellis & Stoeger, CQG 4:1697,1987

We cannot move over cosmological distances and check if the universe looks the same from 'over there' … so must *assume* that our position is not special

> *"The Universe must appear to be the same to all observers wherever they are. This 'cosmological principle' …"*
>
> Edward Arthur Milne, in 'Kinematics, Dynamics & the Scale of Time' (1936)

Mathematical Proceedings of the Cambridge Philosophical Society
Volume 51, Issue 4, October 1955 , pp. 678-683

THE COSMOLOGICAL PRINCIPLE
BY D. E. LITTLEWOOD

Many models of the universe have been proposed, by de Sitter, Milne, Bondi and Gold, Hoyle and others. The observed data being insufficient, the models are usually based on some simple hypothesis. The simplest is the cosmological principle, namely, that apart from local irregularities the universe presents the same general aspect at every point. Milne (5) has used a restricted form of the principle, namely, that the aspect is independent of spatial position but is dependent on the observed time from some fixed epoch in the past. Bondi and Gold (1) have proposed the 'perfect cosmological principle' that the aspect is completely independent of space and time.

THE STEADY-STATE THEORY OF THE EXPANDING UNIVERSE

H. Bondi and T. Gold

(Received 1948 July 14)

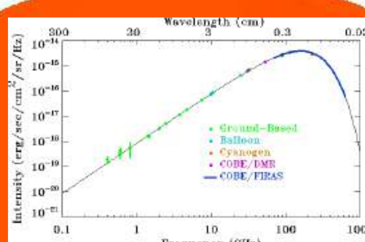
The 'Perfect' CP was abandoned following the discovery of the CMB

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

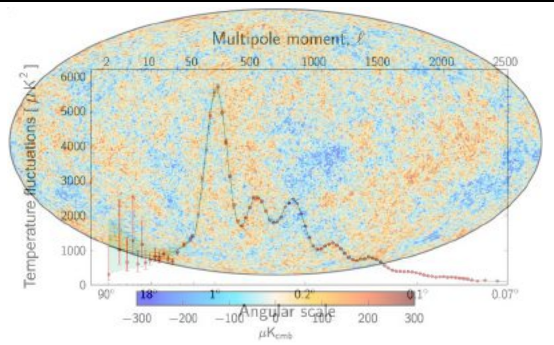
May 13, 1965

Bell Telephone Laboratories, Inc
A. A. Penzias R. W. Wilson

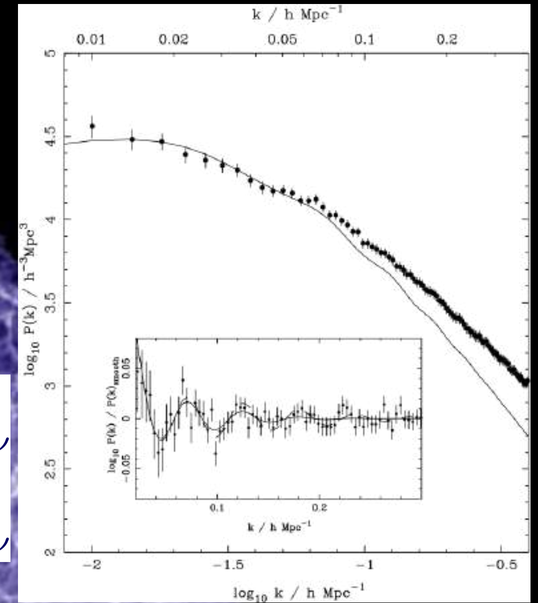


T = 2.728 K

but the (spatial) cosmological principle lived on!



The CP is the *key* assumption of the standard cosmological model:



$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu$$
$$= a^2(\eta)\left[d\eta^2 - d\bar{x}^2\right]$$
$$a^2(\eta) d\eta^2 \equiv dt^2$$

$$T_{\mu\nu} = -\langle\rho\rangle_{\text{fields}}\ g_{\mu\nu}$$
$$\Lambda = \lambda + 8\pi G_{\text{N}} \langle\rho\rangle_{\text{fields}}$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \lambda g_{\mu\nu} = 8\pi G_{\text{N}} T_{\mu\nu}$$

$$\Rightarrow H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\text{N}} \rho_{\text{m}}}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$
$$\equiv H_0{}^2 \left[\Omega_{\text{m}}(1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda\right]$$

$$\Omega_{\text{m}} \equiv \rho_{\text{m}}/(3H_0^2/8\pi G_{\text{N}}),\ \Omega_k \equiv -k/3H_0^2 a_0^2,\ \Omega_\Lambda \equiv \Lambda/3H_0^2$$

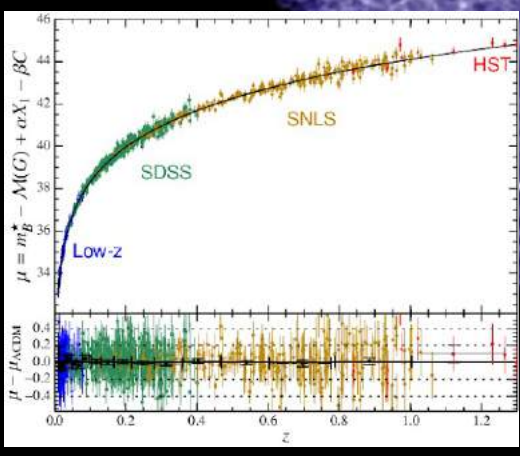
$$\ddot{a} = -\frac{4\pi G}{3}(\rho + 3P)\, a$$

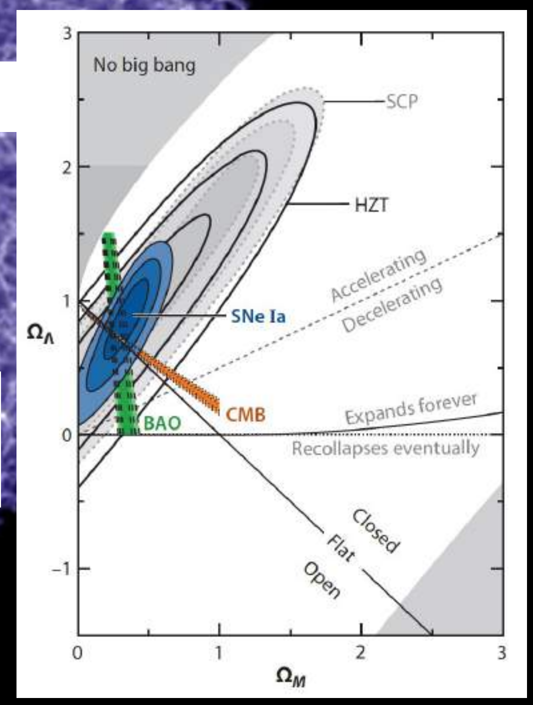
$$\Omega_{\text{m}} + \Omega_k + \Omega_\Lambda = 1$$

$0.8\Omega_{\text{m}} - 0.6\Omega_\Lambda \approx -0.2$ (SNe Ia),
$\Omega_{\text{k}} \approx 0.0$ (CMB), $\Omega_{\text{m}} \sim 0.3$ (Clusters, BAO)

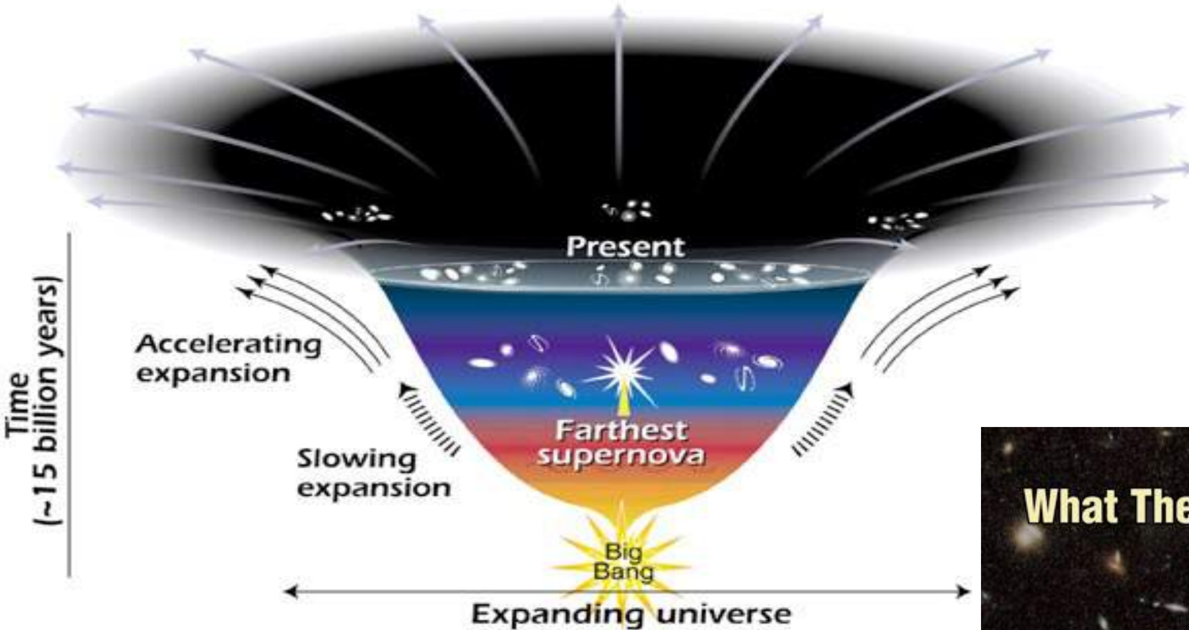
$\Omega_\Lambda = 1 - \Omega_{\text{m}} - \Omega_{\text{k}} \sim 0.7 \Rightarrow \boldsymbol{\Lambda \sim 2H_0^2}$

$(\rho_\Lambda)^{1/4} = (2H_0{}^2/8\pi G_{\text{N}})^{1/4} \sim 10^{-12}$ GeV

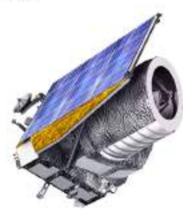


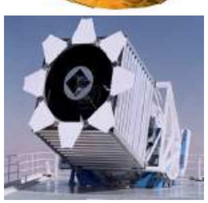


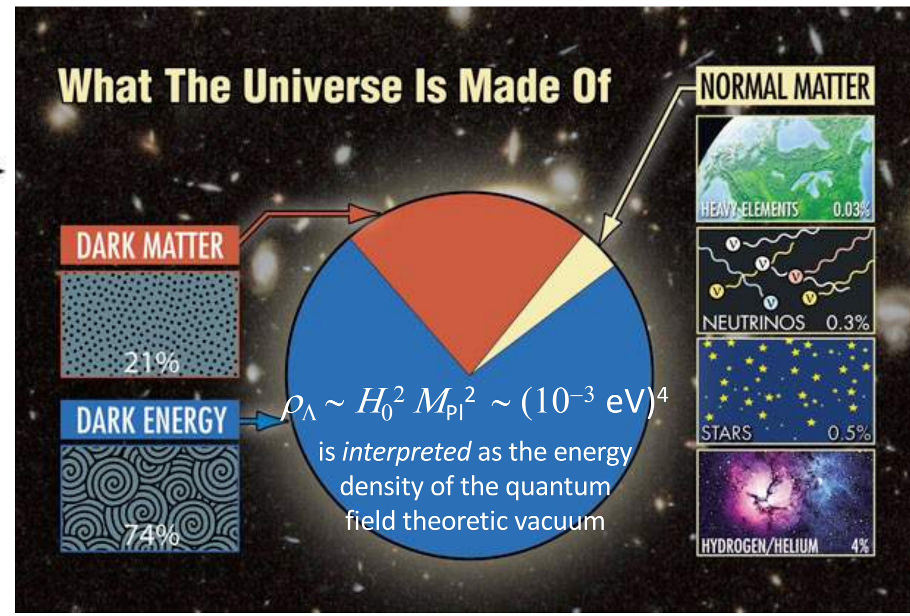
The CP is the basis of the new 'standard ΛCDM model' of the universe, dominated by Λ and undergoing accelerated expansion



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







There has been substantial investment in major satellites and telescopes to *measure the parameters* of this 'standard cosmological model' with increasing precision … but surprisingly little work on ***testing its foundational assumptions***

What do we know about Λ from the Standard $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ Model (viewed as an **effective field theory** up to some high energy cut-off scale $\boldsymbol{M}$)?

$$+M^4 + M^2\Phi^2 \qquad m_H^2 \simeq \frac{h_t^2}{16\pi^2}\int_0^{M^2} \mathrm{d}k^2 = \frac{h_t^2}{16\pi^2} M^2$$

Vacuum energy   Higgs mass correction

super-renormalisable

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

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

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 expectation (strictly speaking *not* calculable) is:

$$\rho_\Lambda \sim (1\ \text{TeV})^4 \Rightarrow 10^{60} \text{ x } (1\ \text{meV})^4$$

i.e. the universe should have been inflating since (or collapsed at): $t \sim 10^{-12}$ s after BB

There must be a very 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

Is Λ *forbidden* in S-matrix formulation of quantum gravity? (e.g. Dvali, *Symmetry* **13**:3,2021)

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

why is $\Omega_\Lambda \sim \Omega_m$ 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 H_0^{-1} so as to mimic vacuum energy … this scale is *absent* in any fundamental theory so must be put in by hand!

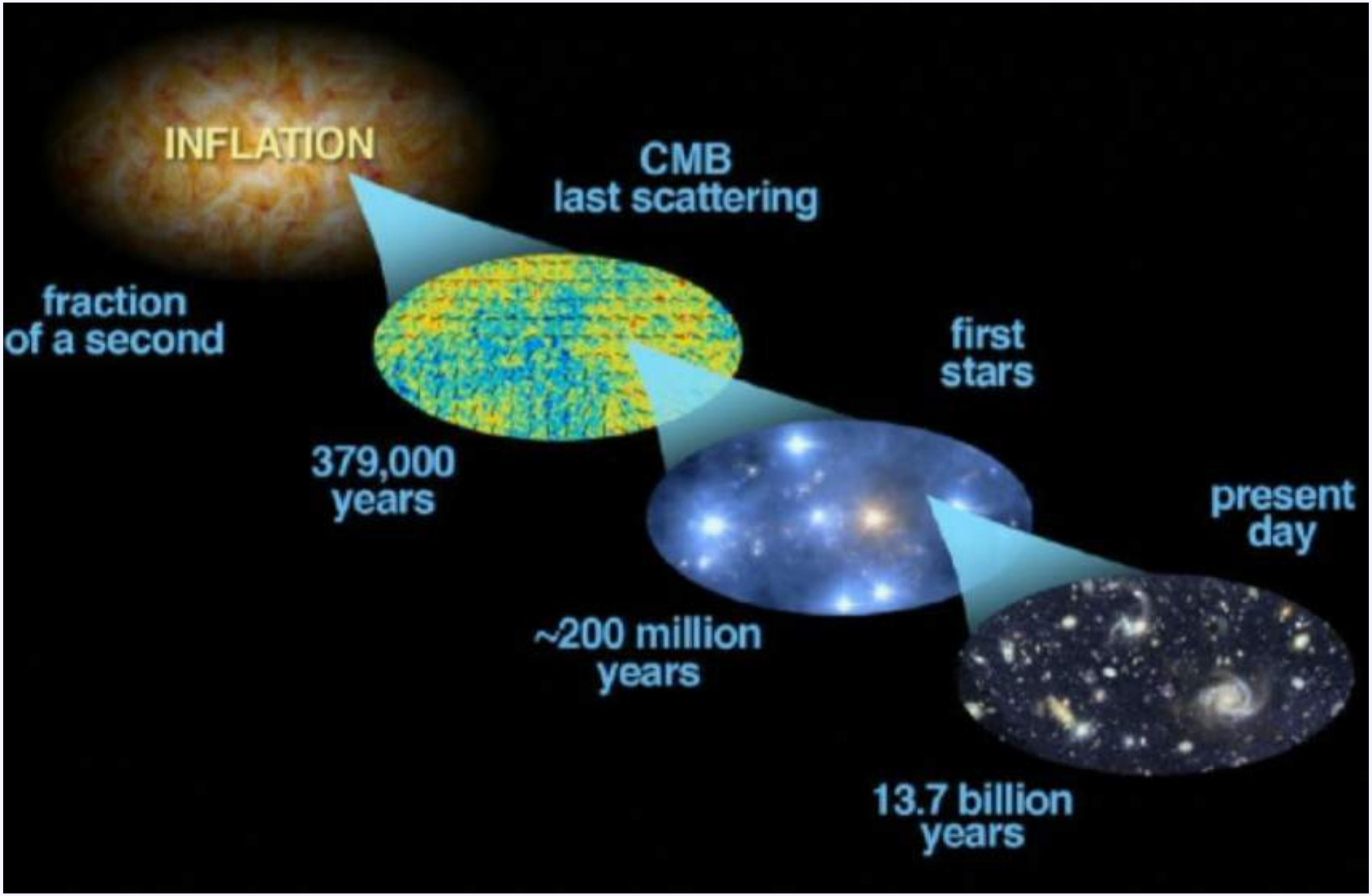
Similar fine-tuning in *every* proposal to explain DE, e.g. massive gravity, chameleon fields, …

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

There is no *physical* explanation for the 'coincidence problem'

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

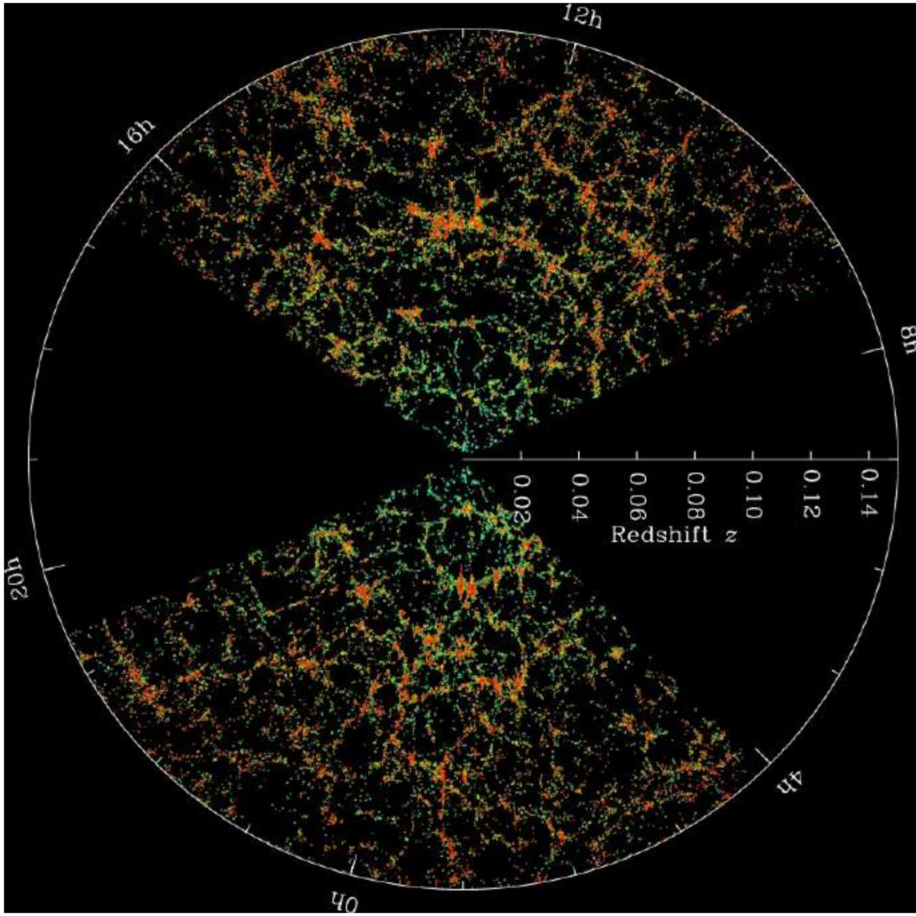
The growth of structure is indeed well-explained by ΛCDM extended with initial conditions set by an epoch of inflation



Courtesey: NASA

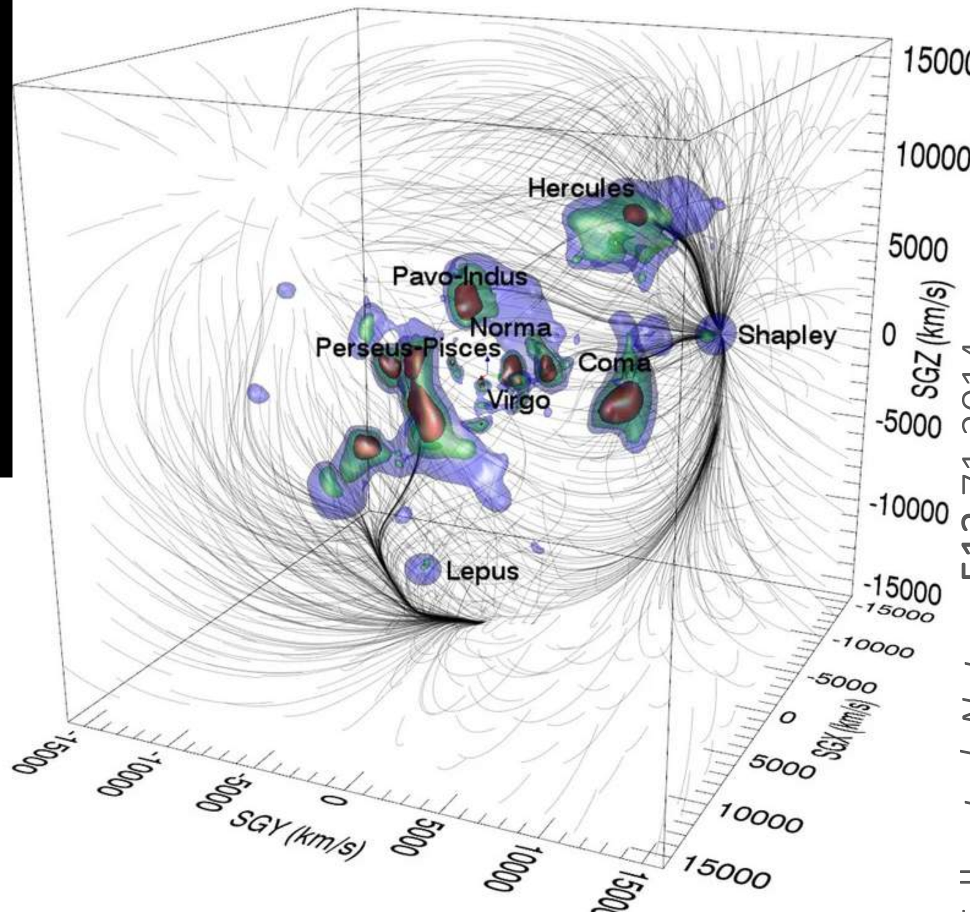
The ~10^{-5} **CMB temperature fluctuations** are understood as due to **scalar density perturbations** with an ~scale-invariant spectrum which were generated during an early de Sitter phase of **inflationary expansion** … these perturbations have subsequently grown into the **large-scale structure** of galaxies observed today through **gravitational instability** in a sea of **dark matter**

On large scales ΛCDM + inflation reproduces the observed `cosmic Web'



This is what our Universe looks like on the biggest scales (~ 600 Mpc) mapped

Locally (out to ~200 Mpc) it is very inhomogeneous



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

Is it justified to approximate it as homogeneous?

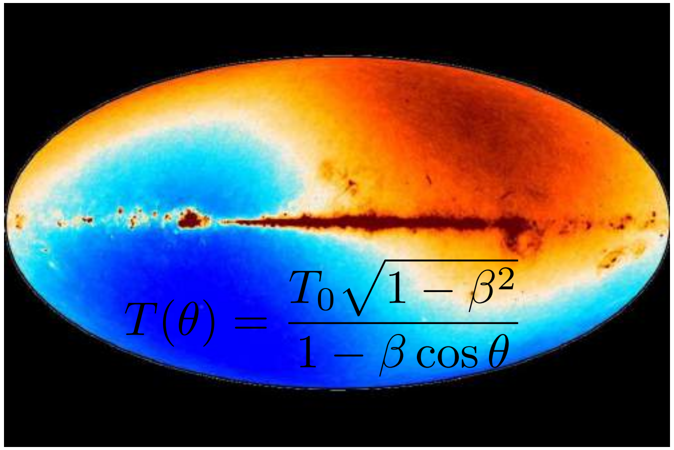
... To assume that we are a '*typical*' observer?

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

THE UNIVERSE IS *NOT* ISOTROPIC AROUND US

Stewart & Sciama *Nature* **216**:748,1967
Peebles & Wilkinson, *PRL* **174**:2168,1968

The cosmic microwave background exhibits a dipole anisotropy with $\Delta T/T \sim 10^{-3}$

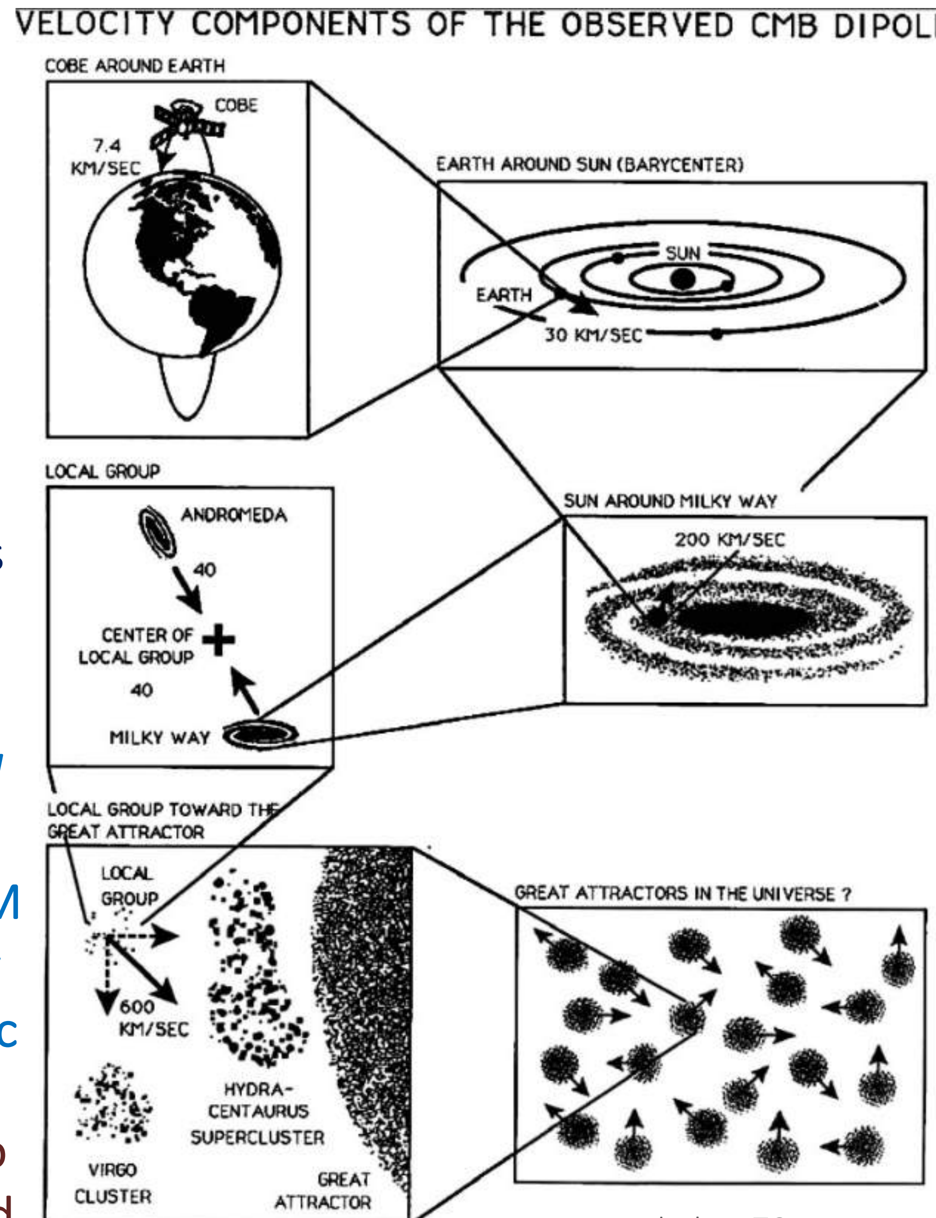


$$T(\theta) = \frac{T_0\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

We interpret this 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°

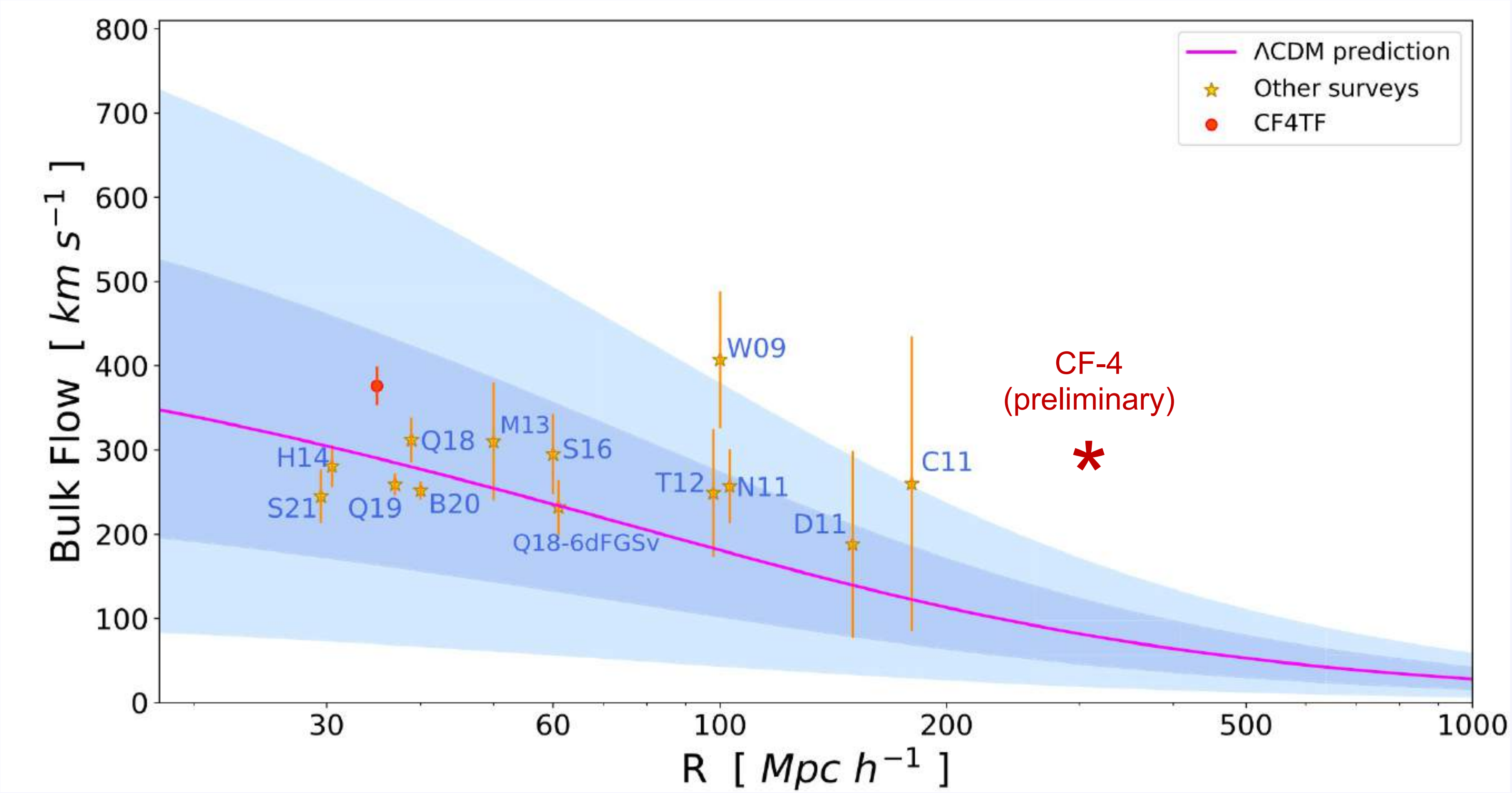
This motion is presumed to be due to *local* inhomogeneity in the matter distribution … according to structure formation in ΛCDM we should converge to the 'CMB frame' by averaging on scales larger than O(100) Mpc

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



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

CONVERGENCE TO THE 'CMB FRAME' IS NOT SEEN EVEN OUT TO ~300h^{-1} MPC



Qin *et al*, Astrophys. J.922:59,2021

Bulk flow measurements from different surveys. The pink curve is the ΛCDM prediction for a spherical top-hat window function. The shaded areas indicate the 1σ and 2σ cosmic variance.

According to ΛCDM Hubble Volume simulations (e.g. 'Dark Sky'), <1% (0.1%) of Milky Way–like observers should experience a bulk flow as large as is observed, extending out as far as is seen.

So we are *not* typical 'Copernican' observers

A TEST OF THE KINEMATIC INTERPRETATION OF THE CMB DIPOLE WAS PROPOSED AFTER RADIO SOURCES WERE OBSERVED AT COSMOLOGICAL DISTANCES

On the expected anisotropy of radio source counts

G. F. R. Ellis* and J. E. Baldwin† *Orthodox Academy of Crete, Kolymbari, Crete*

Summary. If the standard interpretation of the dipole anisotropy in the microwave background radiation as being due to our peculiar velocity in a homogeneous isotropic universe is correct, then radio-source number counts must show a similar anisotropy. Conversely, determination of a dipole anisotropy in those counts determines our velocity relative to their rest frame; this velocity must agree with that determined from the microwave background radiation anisotropy. Present limits show reasonable agreement

4. Conclusion

If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon

...

c) The standard FRW universe models

Mon. Not. R. astr. Soc. (1984) **206**, 377–381

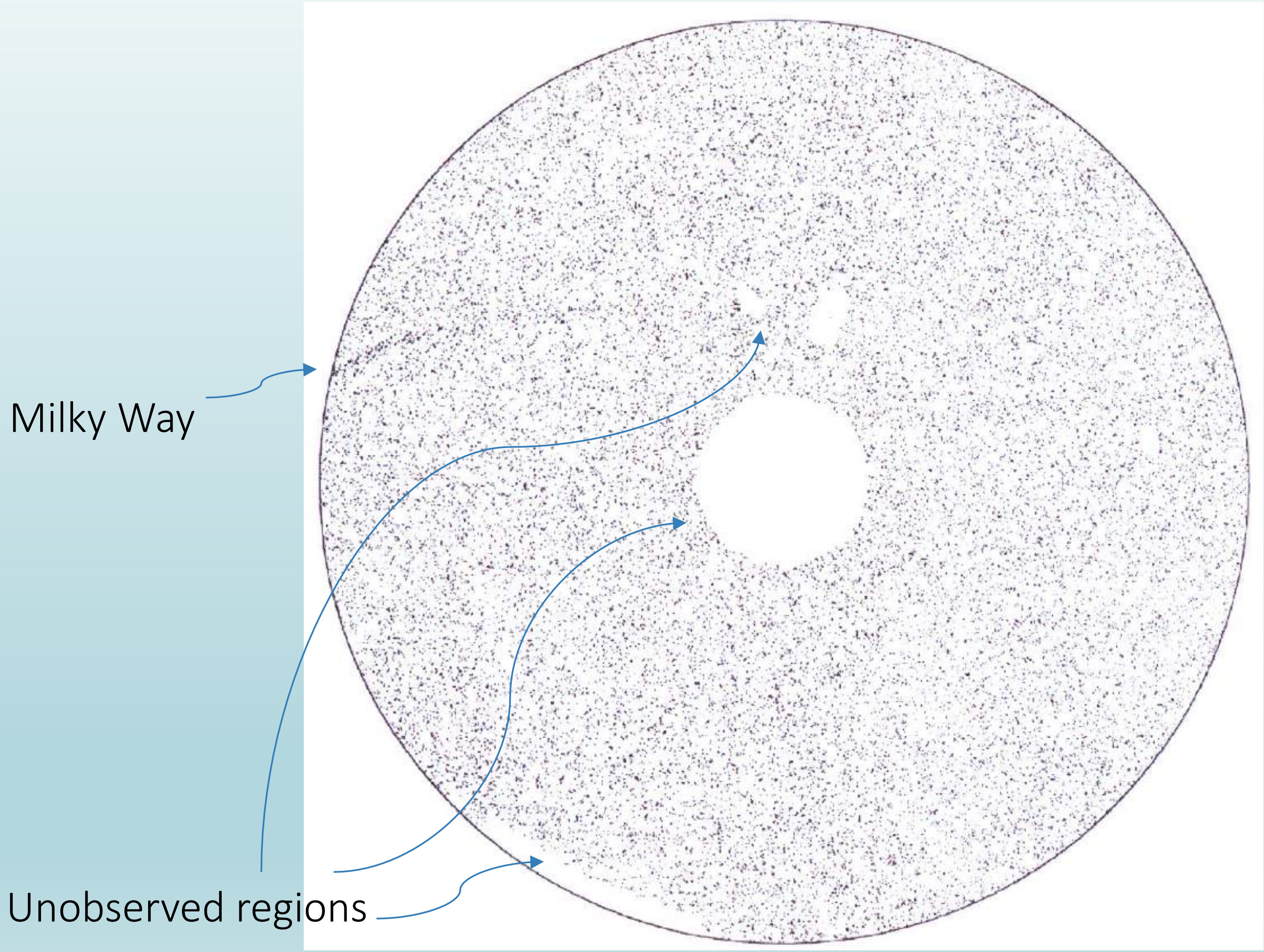
IT SEEMS TO HAVE BEEN FORGOTTEN THAT WE NEED TO THUS *TEST* THE CP ...

The real reason, though, for our adherence here to the Cosmological Principle is not that it is surely correct, but rather, that it allows us to make use of the extremely limited data provided to cosmology by observational astronomy. ...

... If the data will not fit into this framework, we shall be able to conclude that either the Cosmological Principle or the Principle of Equivalence is wrong. Nothing could be more interesting.

Steven Weinberg, *Gravitation and Cosmology* (1972)

Textbooks say that the distribution of distant radio sources demonstrates the isotropy of the Universe



Peebles, *Principles of Physical Cosmology*, 1993

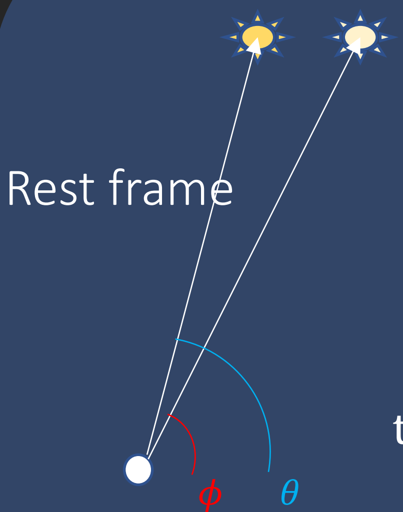
But if we are moving w.r.t. the cosmic rest frame, then distant sources *cannot* be isotropic!

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

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

Aberration

(Bradley 1727)



Moving frame

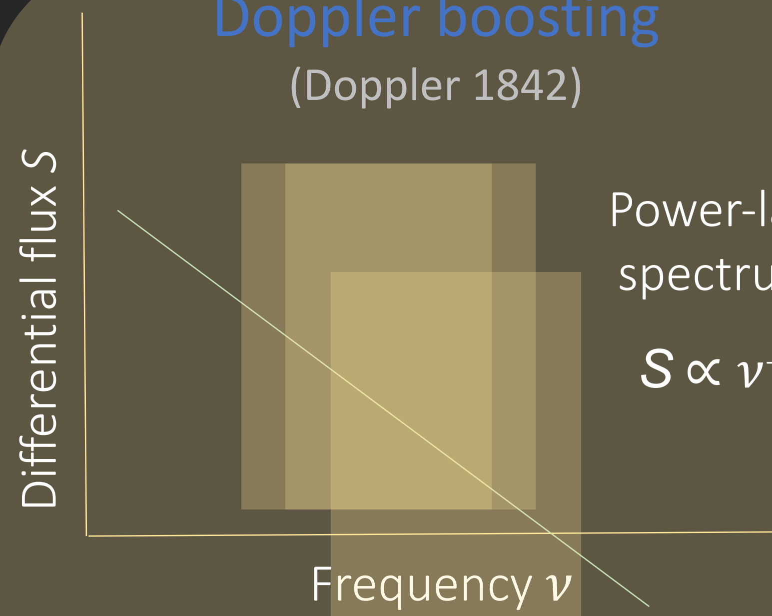
$$\tan\phi = \frac{\sin\theta}{\gamma(\cos\theta + \frac{v}{c})}$$

Observer, velocity $\boldsymbol{v}$

+

Doppler boosting

(Doppler 1842)



Power-law spectrum

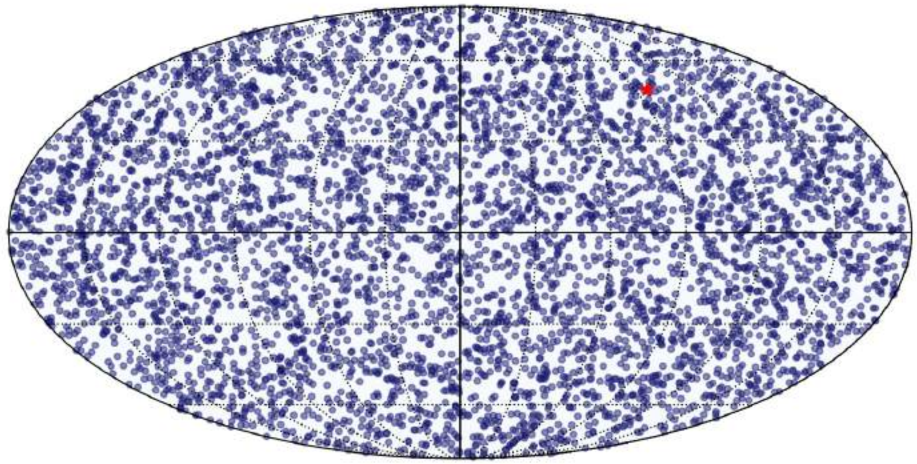
$S \propto \nu^{-\alpha}$

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

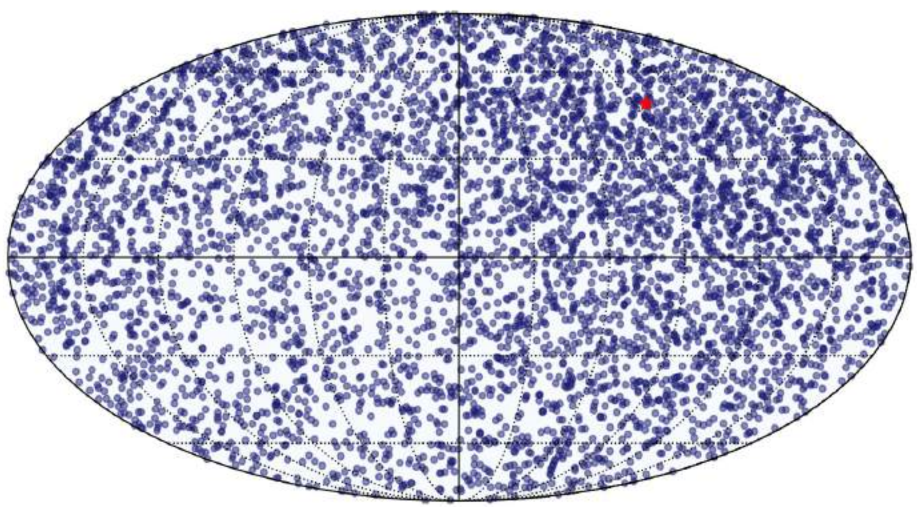
Flux-limited catalogue ➞ *more* sources in direction of motion

Ellis & Baldwin, MNRAS **206**:377,1984

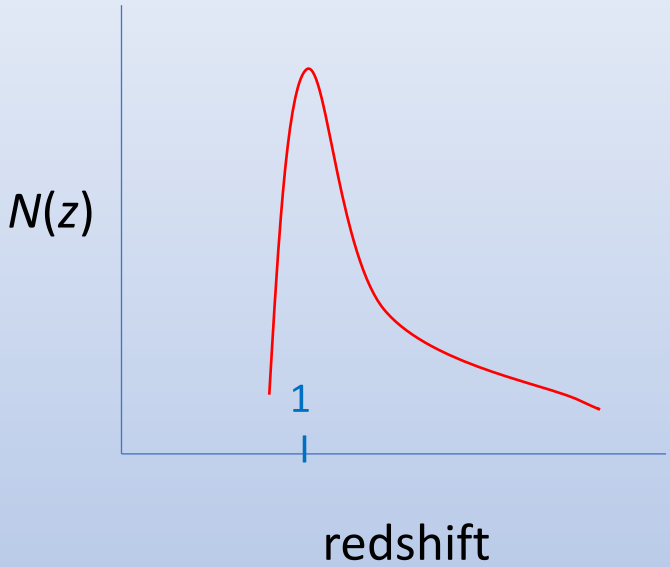
Galaxies / quasars in CMB “rest frame”



Aberration: object positions compressed in direction of motion
Doppler boosting: otherwise too-faint objects boosted into catalog flux limit



Consider an all-sky catalogue of *N* sources with redshift distribution *D*(*z*) from a directionally unbiased survey



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

$\vec{\mathcal{K}} \rightarrow$ The '**kinematic dipole**': *independent* of source distance, but depends on observer velocity, source spectrum, and source flux distribution

$\vec{\mathcal{R}} \rightarrow$ The 'random dipole' $\propto 1/\sqrt{Ntot}$ isotropically distributed

$\vec{\mathcal{S}} \rightarrow$ The 'clustering dipole' due to the anisotropy in the source distribution (significant only for shallow surveys)

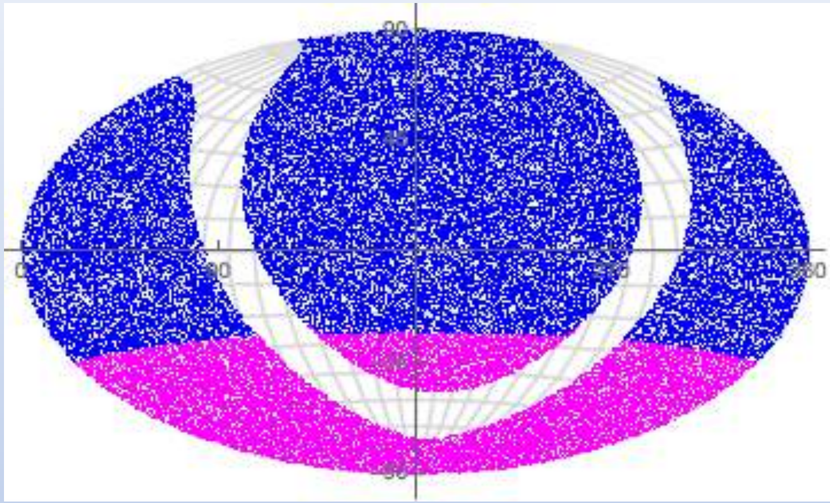
NVSS + SUMSS: 600,000 radio sources <*z*> ~ 1 (est.), $\vec{\mathcal{S}}\,(N(z)) \rightarrow 0$ (est.)
Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017

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

Wide Field Infrared Survey Explorer: 1,360,000 quasars, <*z*> ~ 1.2, $\vec{\mathcal{S}}\,(N(z))$ ~ 1%
Secrest, Rameez, von Hausegger, Mohayaee, S.S. & Colin, ApJ Lett.**908**:L51,2021

(1.4 GHz survey down to Dec = -40.4°) (843 MHz survey at Dec < -30°)

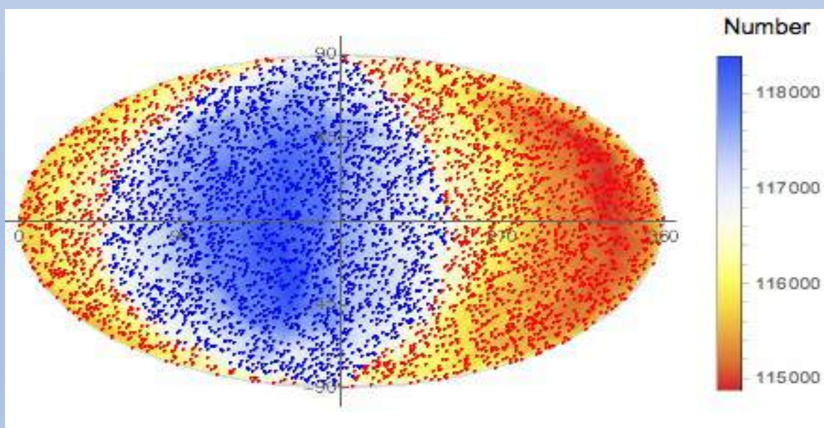
[Rescale the SUMSS fluxes by $(843\ \mathrm{MHz}/1.4\ \mathrm{GHz})^{-0.75} = 1.46$ to match with NVSS]

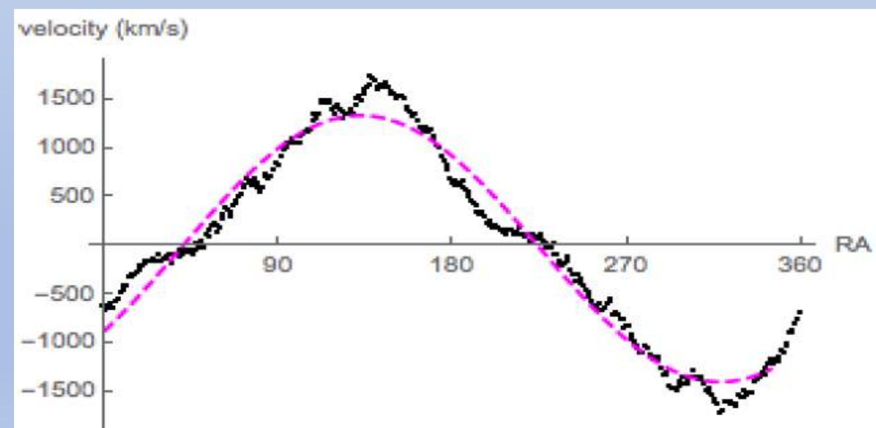


To get rid of any 'clustering dipole':

- Remove Galactic plane ±10°
  (also Supergalactic plane)
- Remove nearby sources which are in common with 2MRS/LRS surveys

The direction is within 10° of CMB dipole, but velocity is ~ 1355 ± 174 km/s

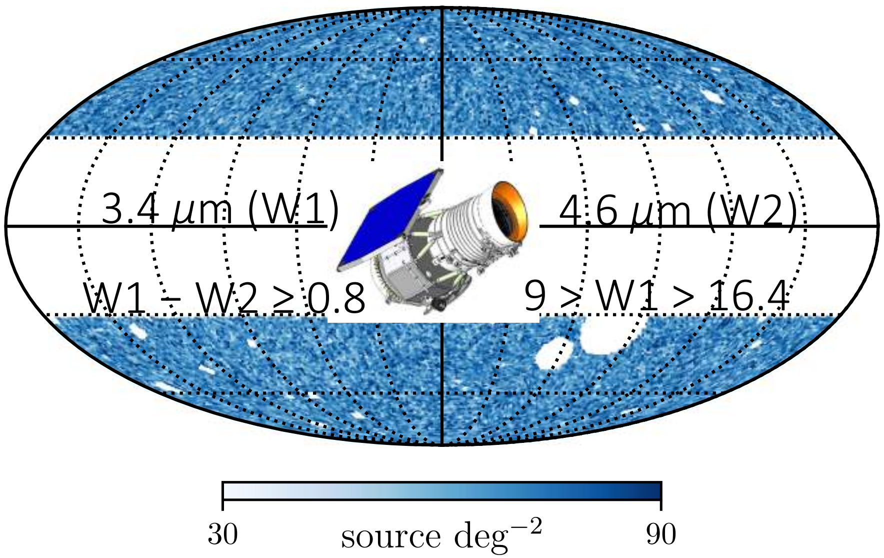


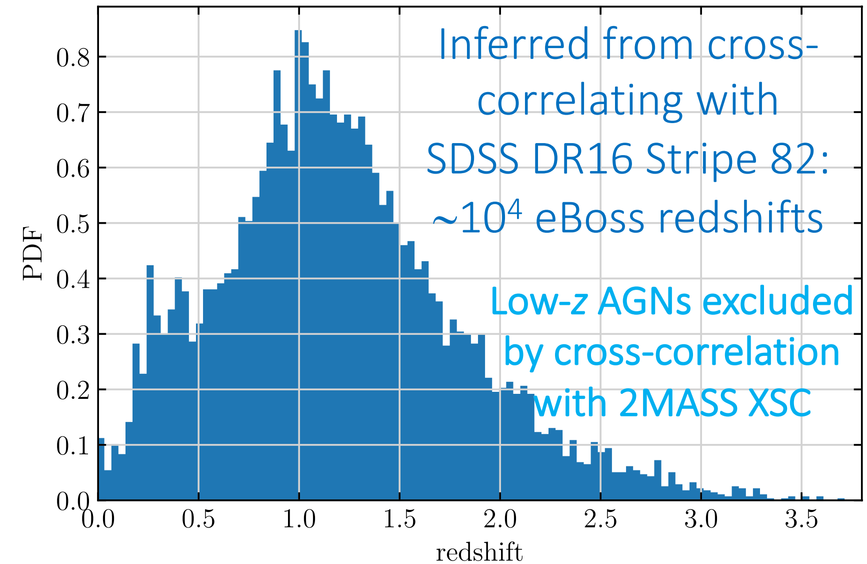


Colin, Mohayaee, Rameez & S.S., MNRAS **471**:1045,2017

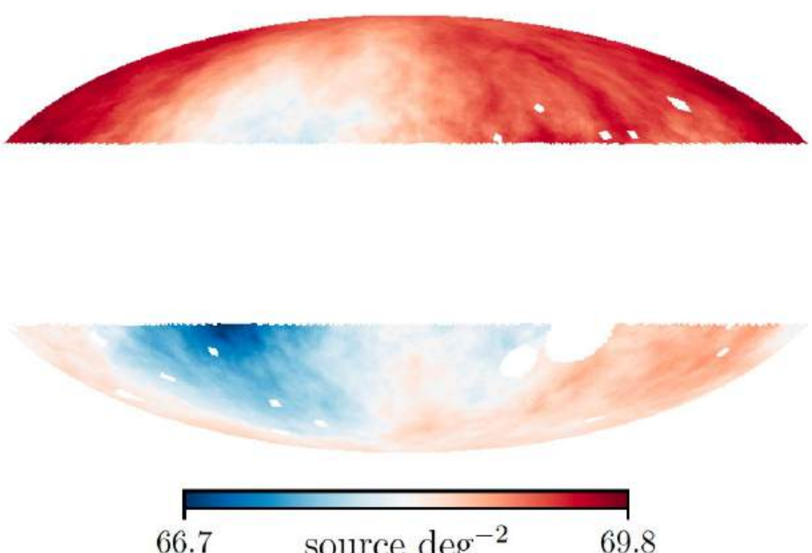
Confirms claim by Singal (ApJ **742**:L23,2011) … however source redshifts are not *directly* measured (also the statistical significance is only 2.8**σ** – by Monte Carlo)

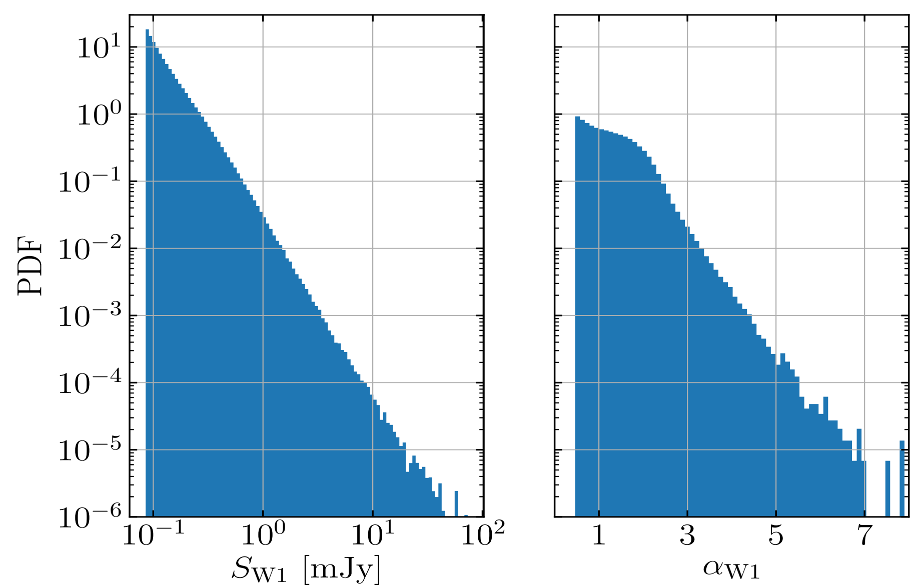
The CatWISE quasar catalogue





We now have a catalogue of ~1.5 million quasars, with 99% at redshift > 0.1

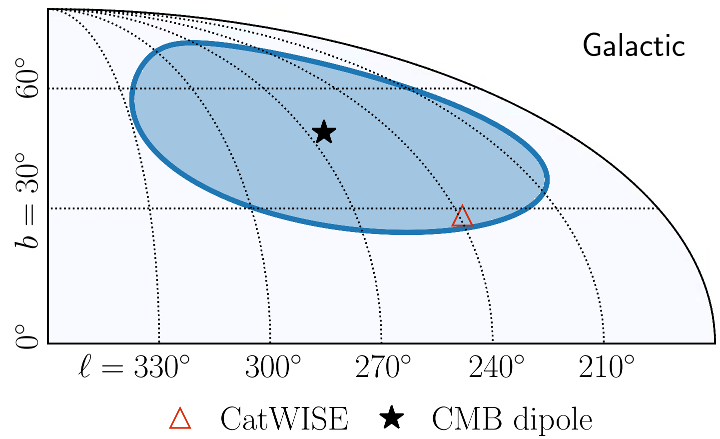




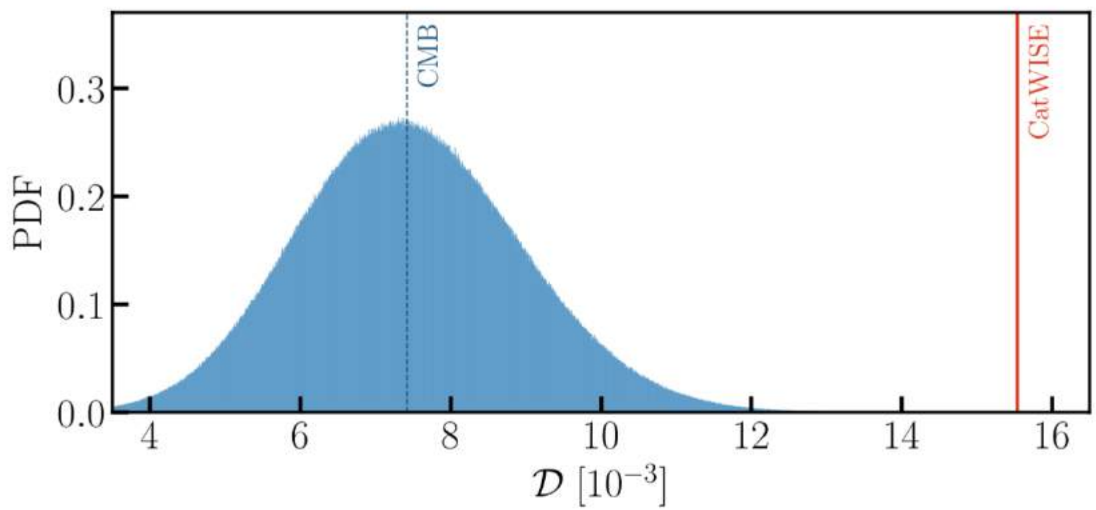
The dipole can be compared to that expected, knowing the spectrum & flux distribution

Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL **908**:L51,2021

OUR PECULIAR VELOCITY WRT QUASARS ≠ PECULIAR VELOCITY WRT THE CMB



The direction of the quasar dipole is consistent with the CMB dipole - but *not* its amplitude

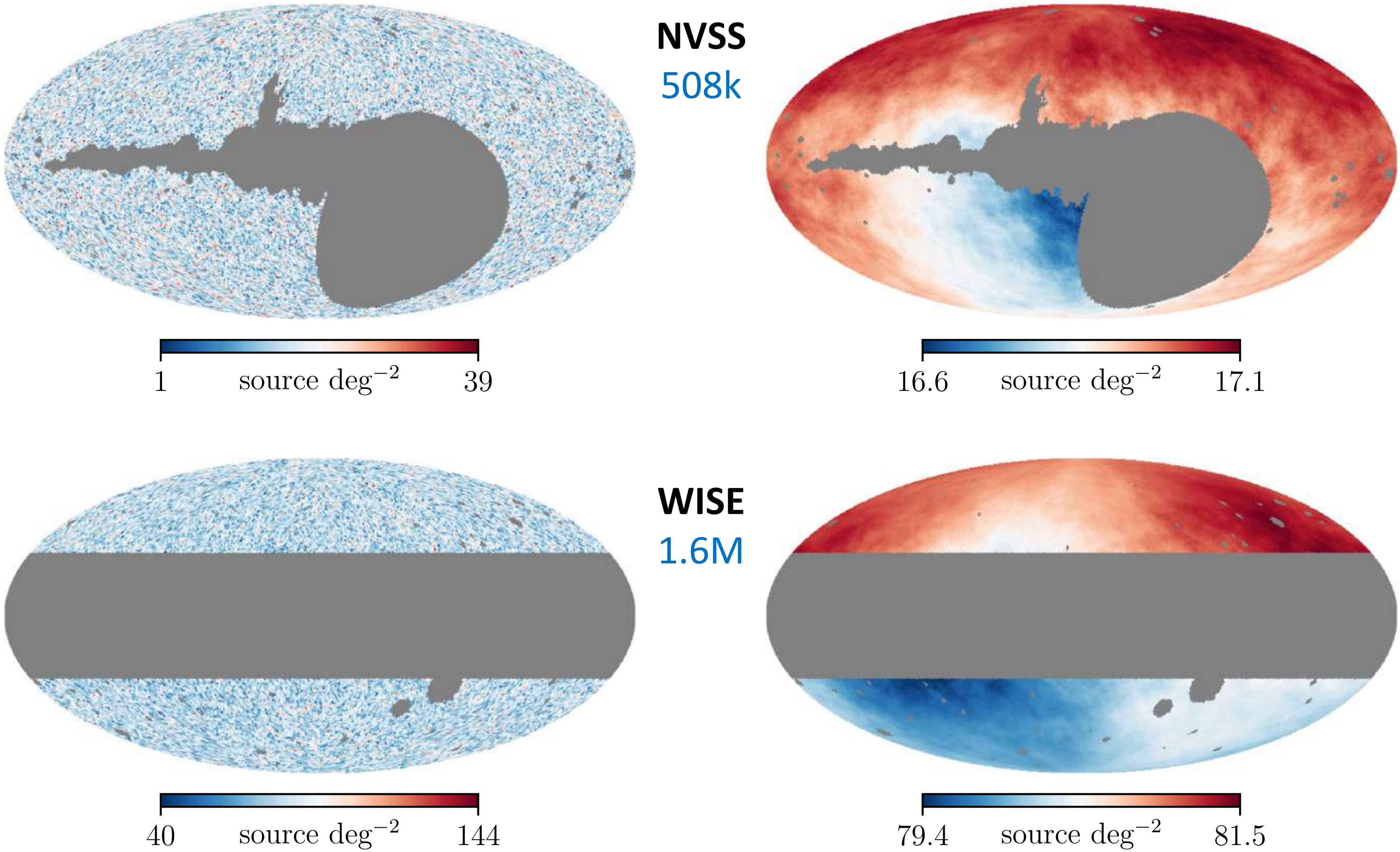


The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

(Data & code available on: https://doi.org/10.5281/zenodo.4431089)

Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL **908**:L51,2021

We have further cleaned the NVSS & WISE AGN catalogues of a variety of systematics



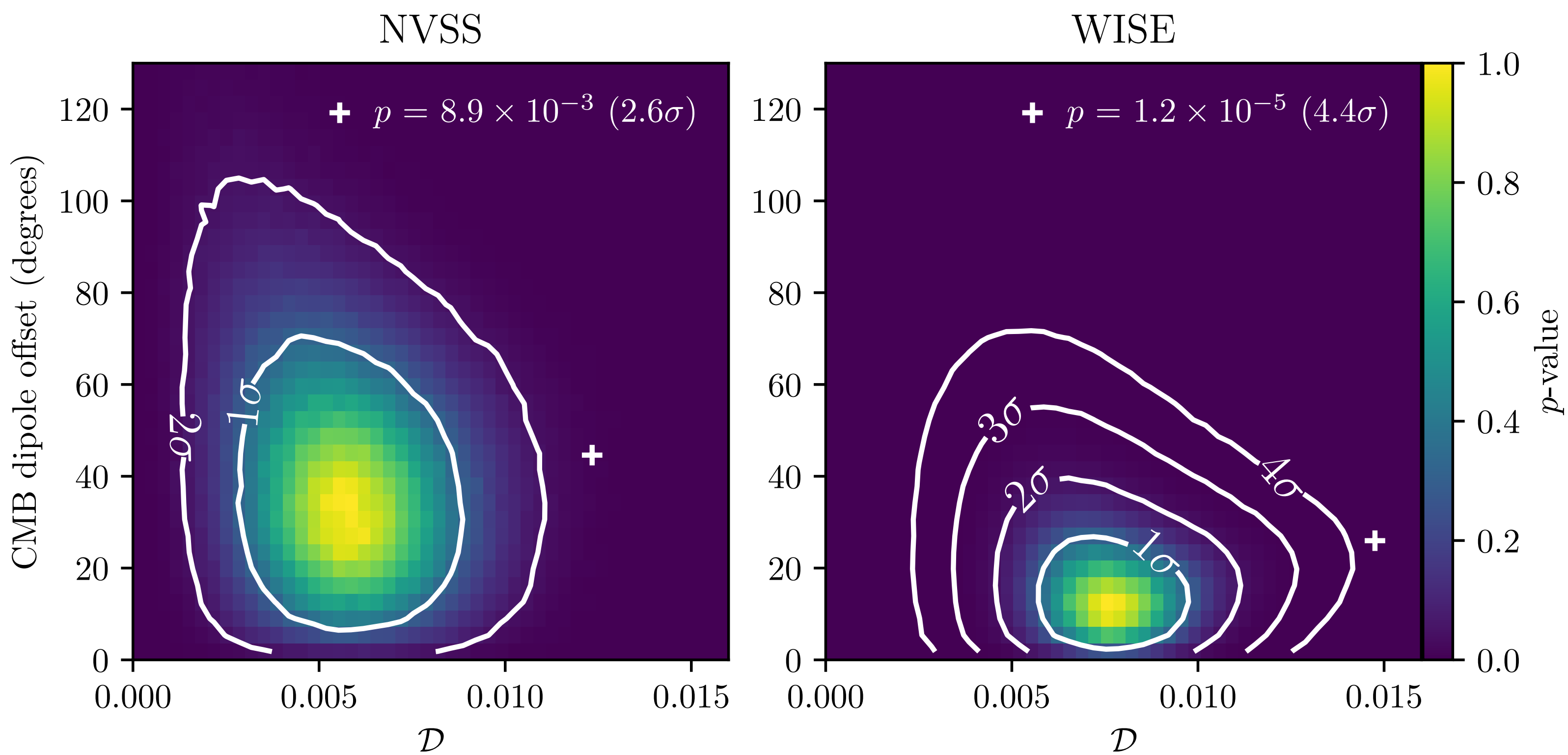
The two dipoles are *consistent* with each other; their vector mean is:

D = (1.40 ± 0.13)×10^{-2} towards (l, b) = (233.0,+34.4)

The agreement *improves* if we subtract out the CMB dipole (assumed kinematic) from both

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., Astrophys. J. Lett. 937 (2022) L31

The NVSS & WISE AGN catalogues are *independent* so we can combine the p-values by which each rejects the null hypothesis



Distribution of CMB dipole offsets & kinematic dipole amplitudes of simulated null skies for NVSS (left) and WISE (right). Contours of equal *p*-value and equivalent σ are given (where the peak of the distribution corresponds to 0σ), with the found dipoles marked with + and their *p*-values are in the legends.

Combined significance ⇒ standard cosmology expectation is rejected at 5.1**σ**

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., Astrophys. J. Lett. 937 (2022) L31

Anomalies in Physical Cosmology [arXiv:2208.05018]

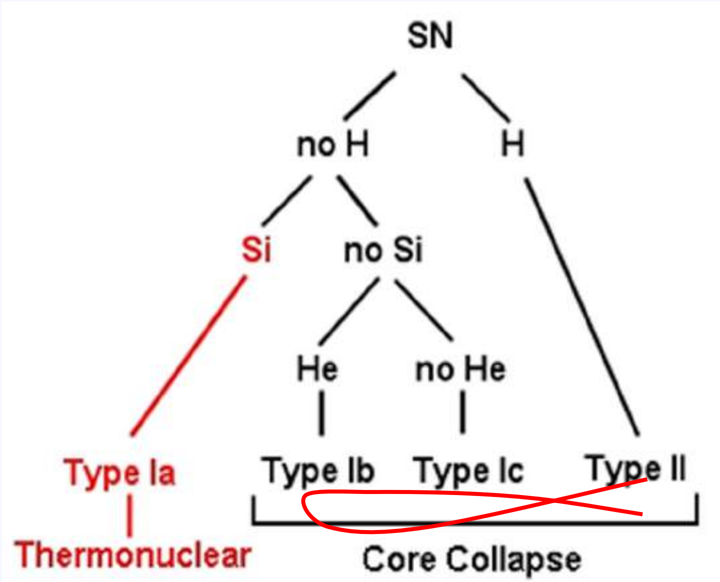
P. J. E. Peebles

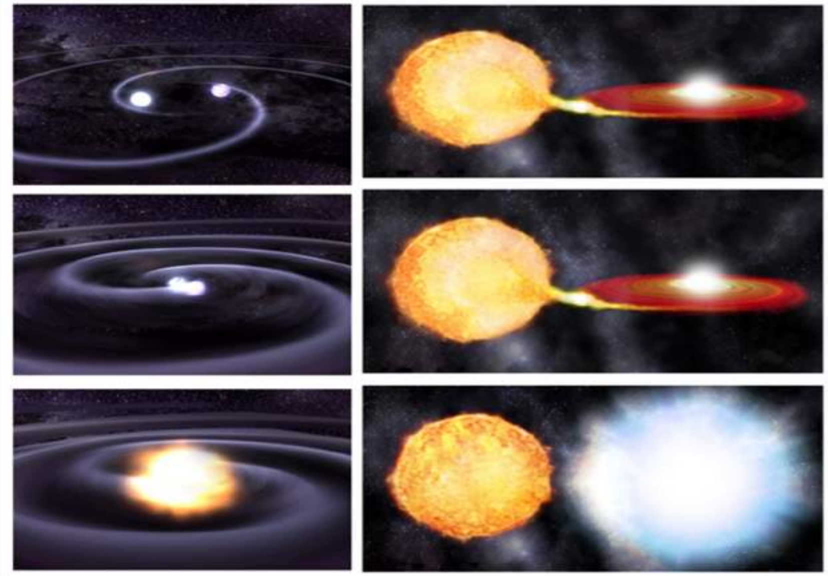
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA

11 August 2022

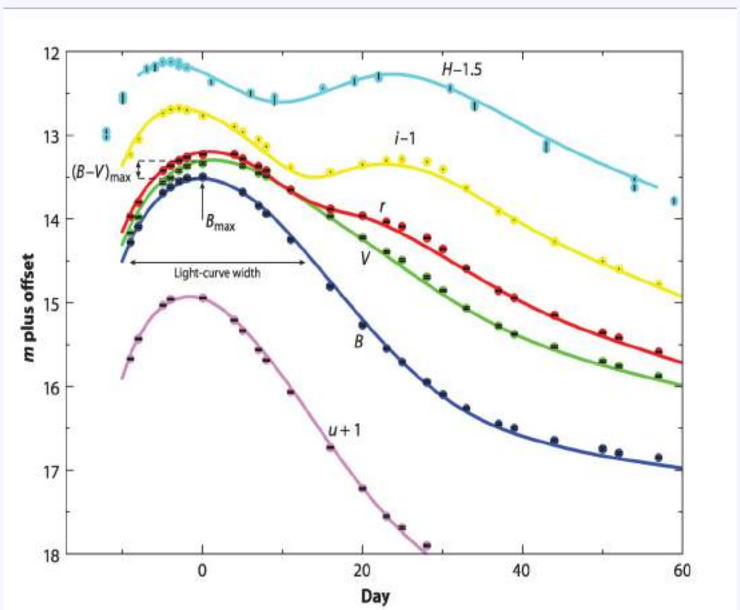
This anomaly is about as well established as the Hubble Tension, yet the literature on the kinematic effect is much smaller than the 344 papers with the phrase "Hubble Tension" in the abstract in the SAO/NASA Astrophysics Data System. (**I expect the difference is an inevitable consequence of the way we behave.**)

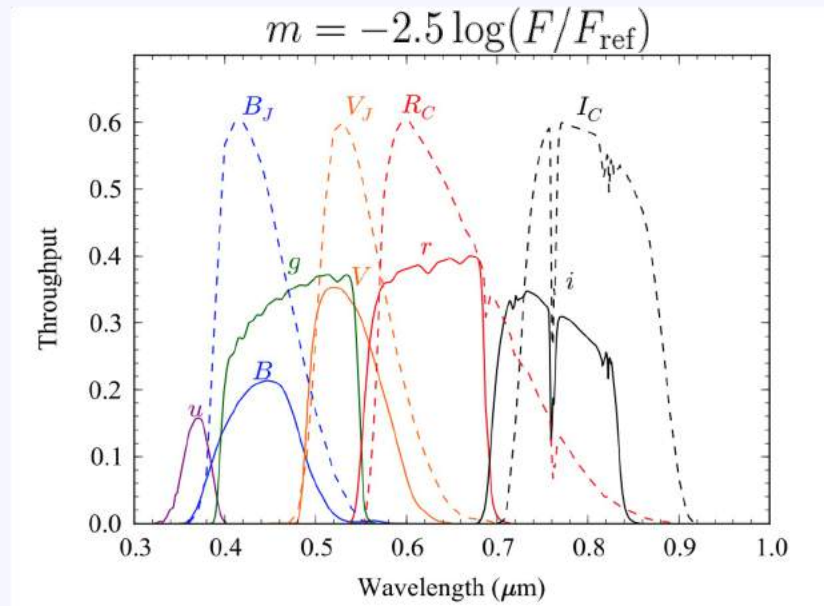
Cosmology with Type Ia supernovae





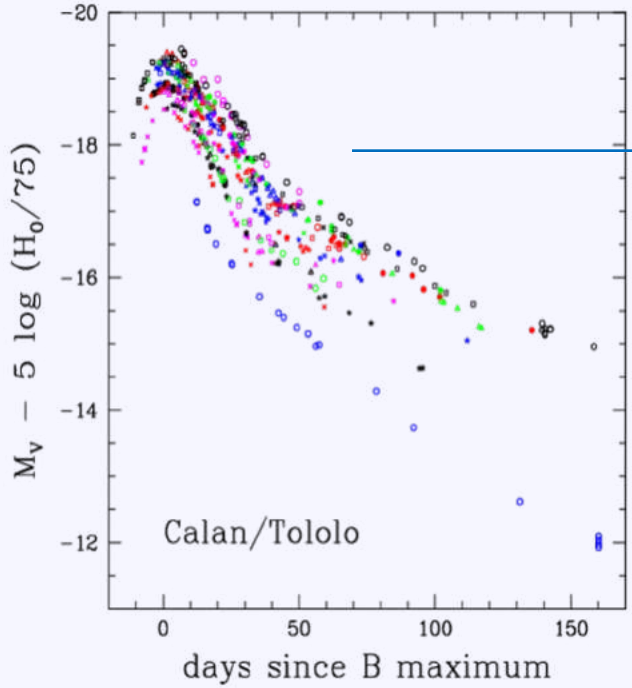
Goobar & Leibundgut, ARAA 61:251,2011



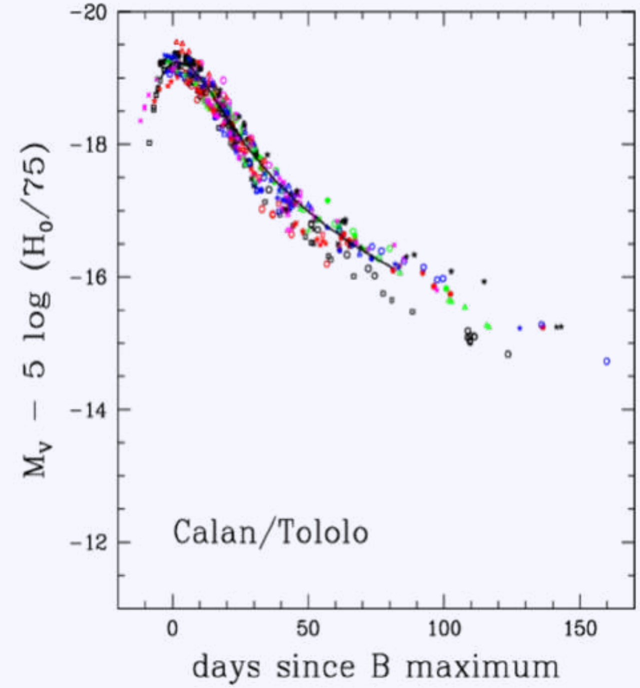


Identify by multiple exposure of sky (+ spectroscopy) ➞ measure peak **magnitude** and **redshift**

SN IA ARE *NOT* 'STANDARD CANDLES'



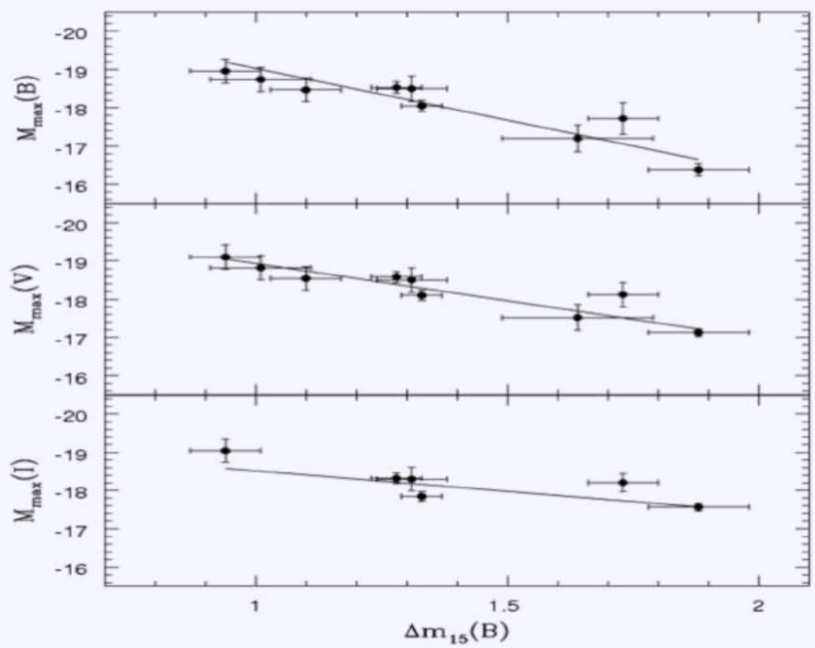
BUT THEY ARE 'STANDARDISABLE'



Hamuy, 1311.5099

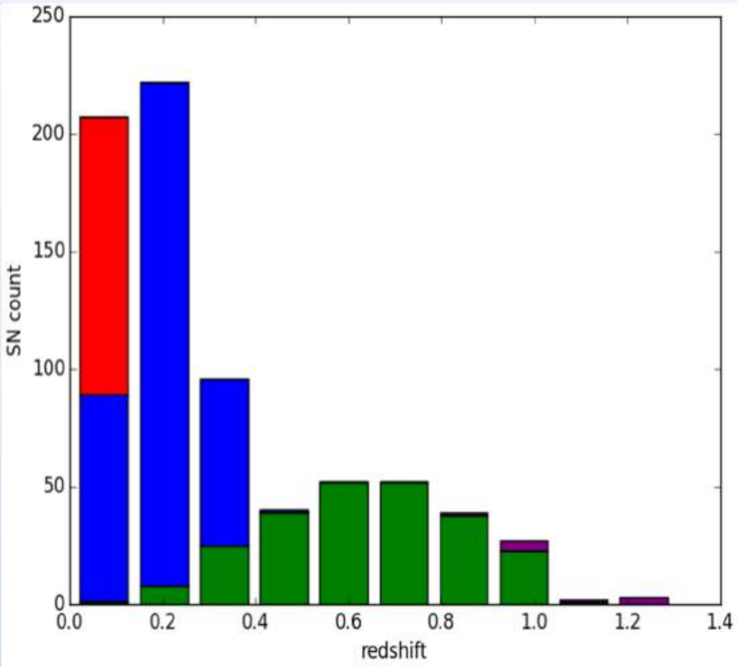
... using the observed correlation between peak magnitude and light curve width

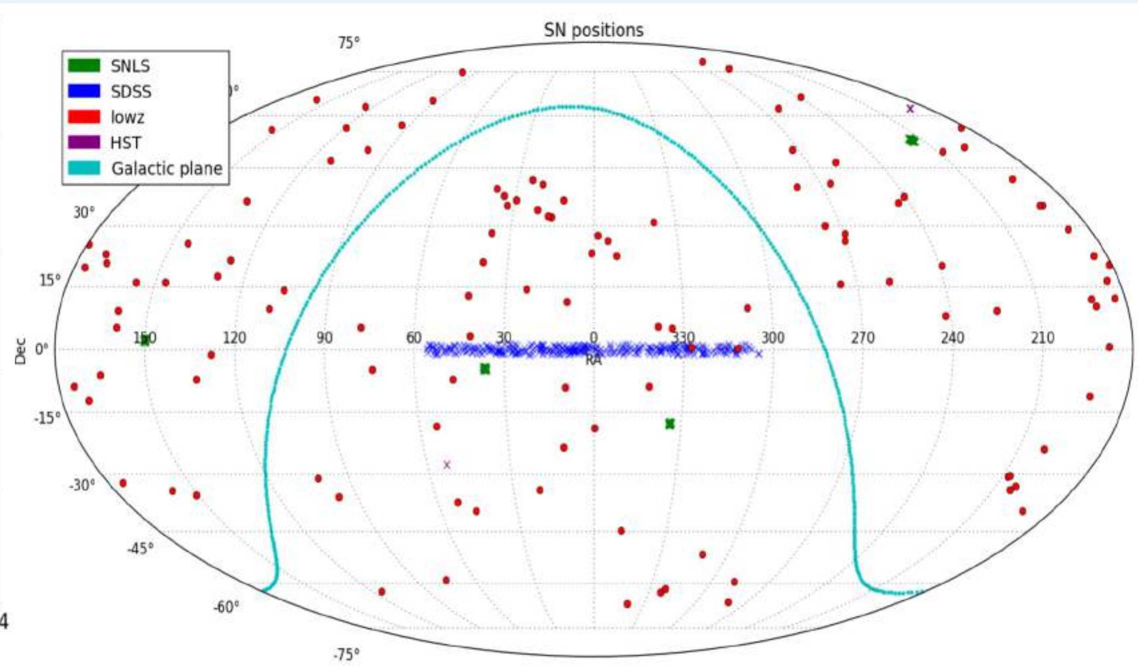
(NB: this is empirical and *not* understood theoretically)



Phillips, ApJ 413:L105,1993

Joint Lightcurve Analysis catalogue (740 SNe Ia)





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

Spectral Adaptive Lightcurve Template (SALT2) used to make 'stretch' and 'colour' corrections to the observed peak magnitude)

B-band

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

Name	$z_{\rm cmb}$	$m_B^\star$	X_1	C
03D1ar	0.002	23.941 ± 0.033	−0.945 ± 0.209	0.266 ± 0.035
03D1au	0.503	23.002 ± 0.088	1.273 ± 0.150	−0.012 ± 0.030

NB: The *measured* redshifts (in the heliocentric frame) have been 'corrected' to $z_{\rm CMB}$

Cosmology

Distance modulus

$$\mu \equiv 25 + 5\log_{10}(d_{\rm L}/{\rm Mpc}), \quad \text{where:}$$
$$d_{\rm L} = (1+z)\frac{d_{\rm H}}{\sqrt{\Omega_k}}\,{\rm sinn}\left(\sqrt{\Omega_k}\int_0^z \frac{H_0 {\rm d}z'}{H(z')}\right),$$
$$d_{\rm H} = c/H_0, \quad H_0 \equiv 100h\ {\rm km\,s^{-1}Mpc^{-1}},$$
$$H = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda},$$

Luminosity distance

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

So the μ-z data enables extraction of the parameter combination: $\sim 0.8\,\Omega_\Lambda - 0.6\,\Omega_{\rm m}$
(NB: to determine H_0 requires knowing the *absolute* magnitude M ➛ "distance ladder")

Cosmography

Acceleration is a *kinematic* quantity so data can also 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) ➝ good to <6% for JLA (extends to $z \sim 1.2$)

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

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

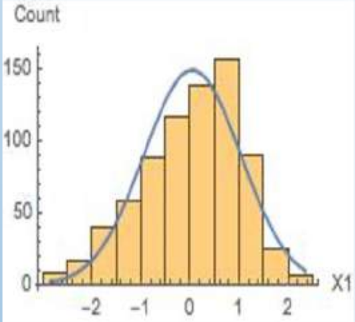
Supernova analyses use the 'adjusted chi-squared' method … wherein s_{int} is *adjusted* to get c^2 of 1/d.o.f. for the fit to the *assumed* LCDM model

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

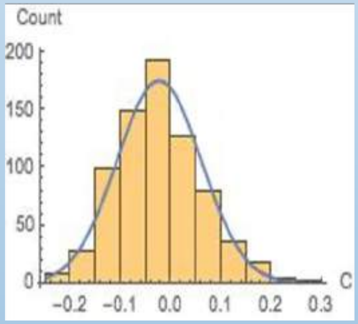
We employ a Maximum Likelihood Estimator … and get rather different results

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

… well-approximated as Gaussian



'Stretch' corrections



'Colour' corrections

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

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

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

intrinsic distributions

cosmology

SALT2

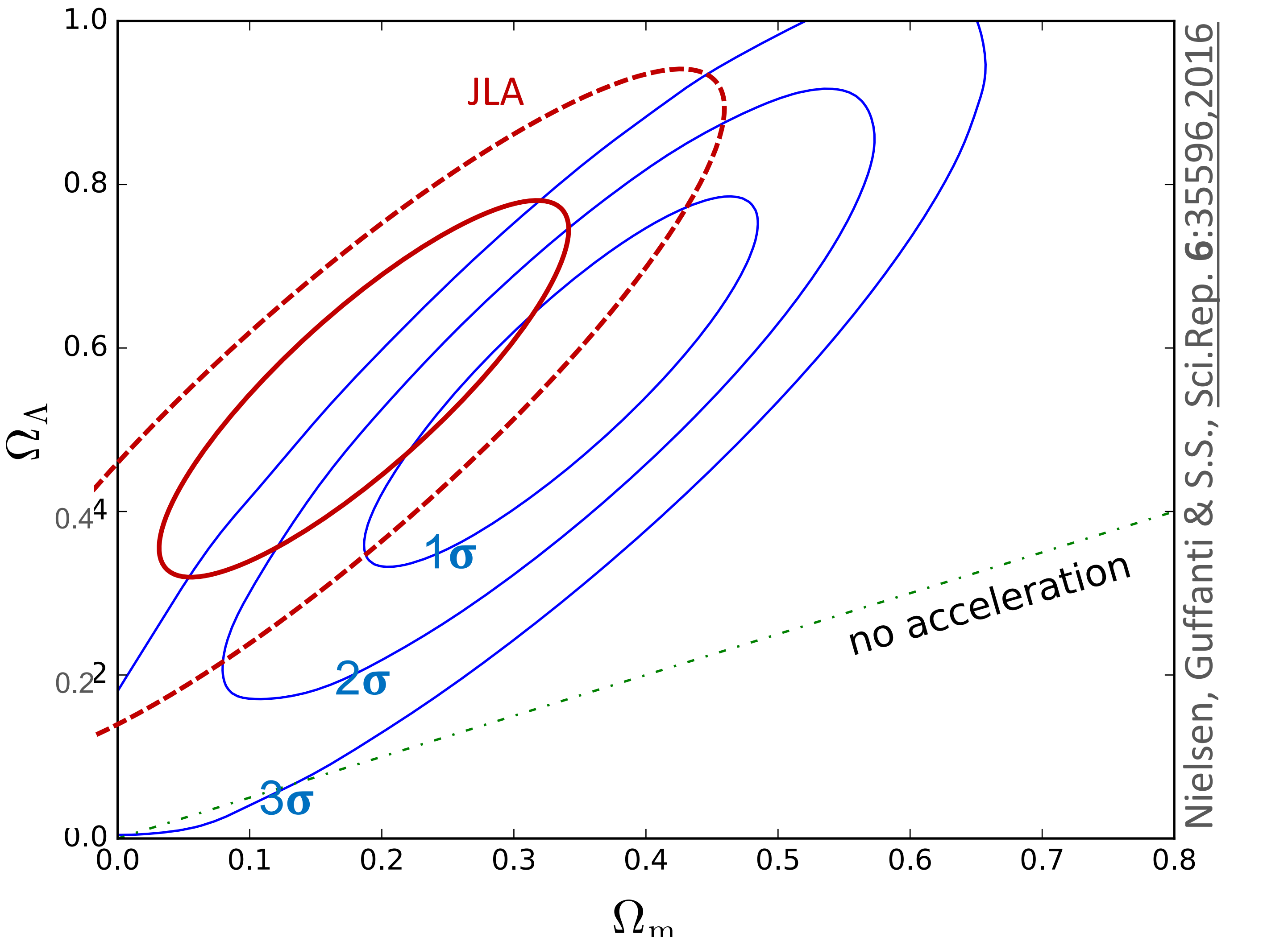
$$p[(M, x_1, c)|\theta] = p(M|\theta)p(x_1|\theta)p(c|\theta), \quad \text{where:}$$

$$p(M|\theta) = (2\pi\sigma^2_{M_0})^{-1/2} \exp\left\{-\left[(M - M_0)/\sigma_{M_0}\right]^2/2\right\},$$

$$p(x_1|\theta) = (2\pi\sigma^2_{x_{1,0}})^{-1/2} \exp\left\{-\left[(x_1 - x_{1,0})/\sigma_{x_{1,0}}\right]^2/2\right\},$$

$$p(c|\theta) = (2\pi\sigma^2_{c_0})^{-1/2} \exp\left\{-\left[(c - c_0)/\sigma_{c_0}\right]^2/2\right\}.$$

The data is consistent with an *uniform* rate of expansion (Averaged over the sky)



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

Profile Likelihood
MLE, best fit

NB: We show the result in the Ω_m- Ω_Λ plane for comparison with previous results (JLA) to emphasise that their statistical analysis was *not* principled

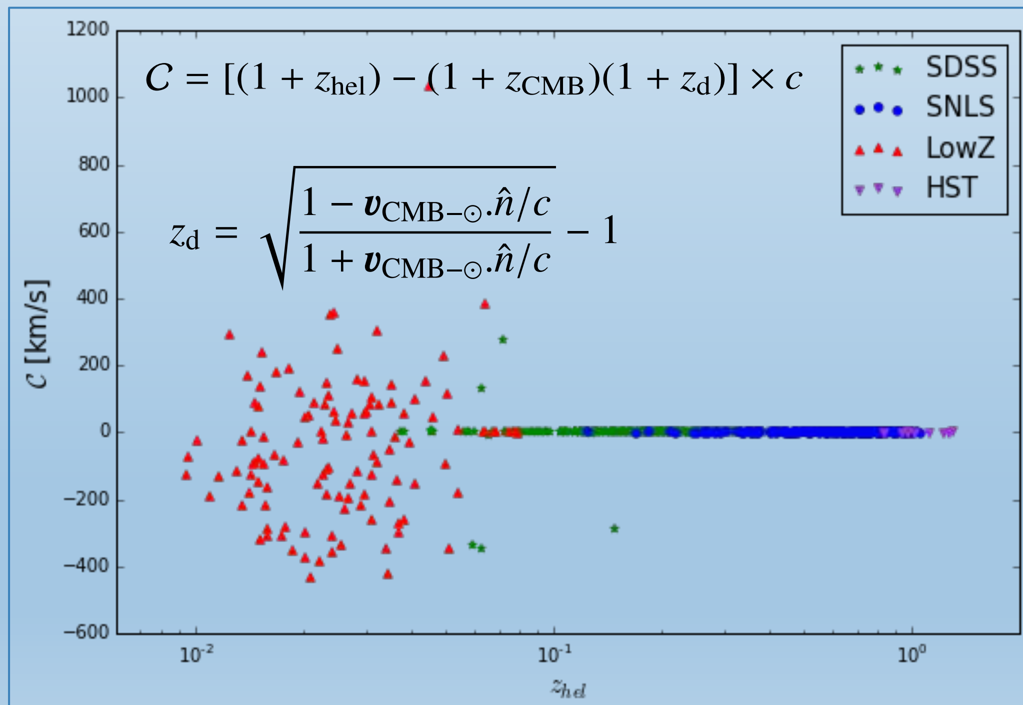
(Other constraints e.g. $\Omega_m \gtrsim 0.2$ or $\Omega_m + \Omega_\Lambda \simeq 1$ are relevant *only* to the ΛCDM model)

The measured redshift z_{hel} is converted to z_{CMB} ($\equiv z$) *assuming* the CMB dipole is due to our motion w.r.t. the **cosmic rest frame** in which the universe is supposedly isotropic:

$$1 + z_{\mathrm{hel}} = (1 + z_{\odot}) \times (1 + z_{\mathrm{SN}}) \times (1 + z)$$

where $z_{\odot}$ is the redshift induced by our motion w.r.t. the CMB and z_{SN} is the redshift due to the peculiar motion of supernova host galaxy in the CMB frame

Moreover the peculiar velocity ‘corrections’ applied to the JLA catalogue have assumed that we have converged to the CMB frame at 180/h Mpc (contrary to observations)



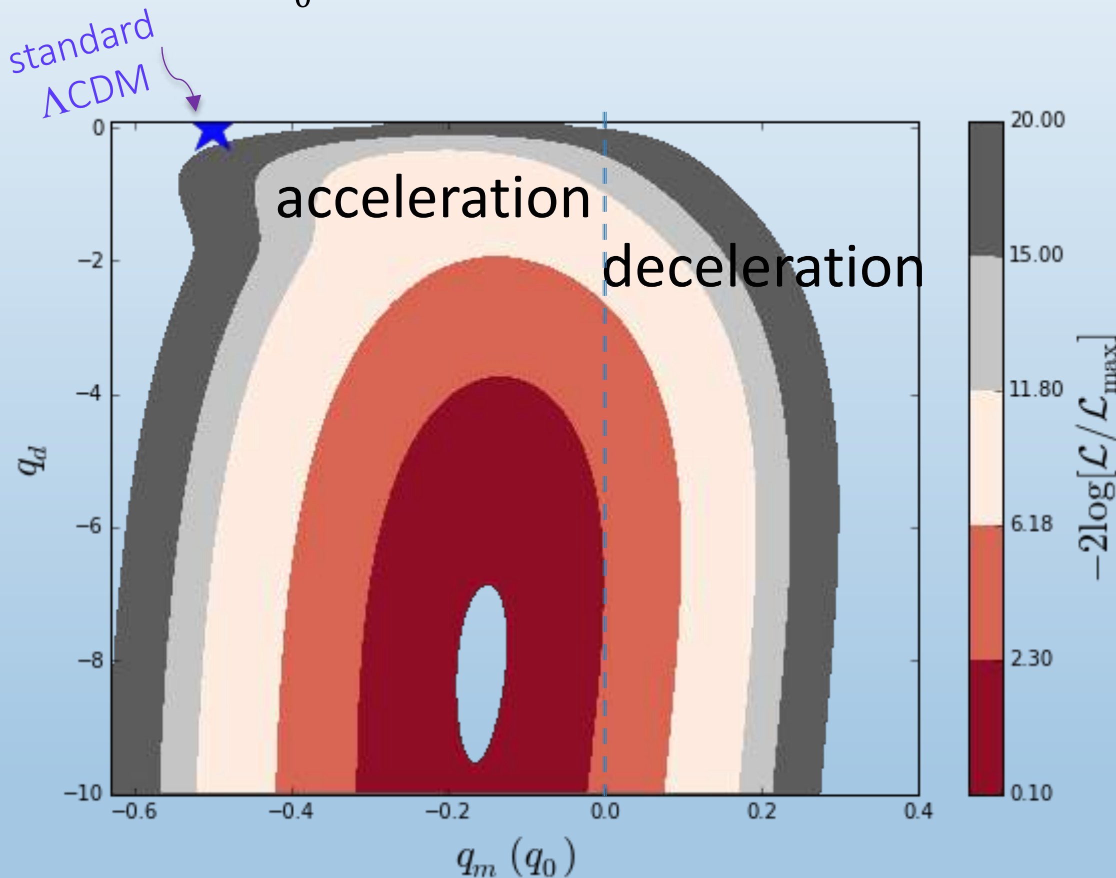
Colin *et al*, A&A **631**:L13,2019

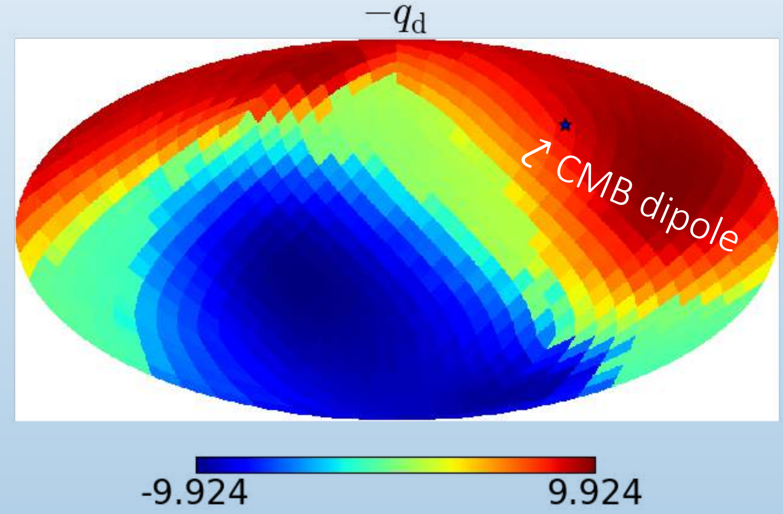
So we *undid* the corrections to recover the original data in the **heliocentric frame**

… to check if the inferred acceleration of the expansion rate is indeed isotropic

A cosmographic analysis of SNe Ia luminosity distances shows that the inferred acceleration is indeed aligned with the local bulk flow

$$d_L(z) = \frac{cz}{H_0}\left[1 + \frac{1}{2}(1 - q_0)z + \ldots\right],\ q_0 \equiv -(\ddot{a}a)/\dot{a}^2 \implies q_{\rm m} + \vec{q}_{\rm d}.\hat{n}\mathcal{F}(z, S)$$





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

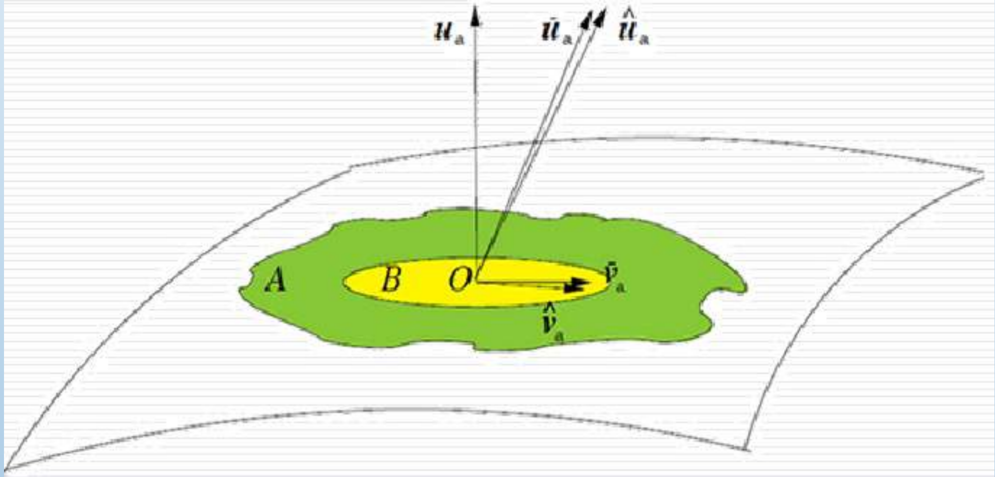
The significance of $\boldsymbol{q_0}$ being negative has now *decreased* to only 1.4σ

This strongly suggests that cosmic acceleration is an artefact of our being located in a deep bulk flow (which includes most of the observed SNe Ia) … and *not* due to Λ

Do we infer acceleration although the expansion is actually decelerating … because we are '*tilted* observers' in a bulk flow?

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

… if so, there should be 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

Summary

- The 'standard model' of cosmology was established before there was any data … and its assumptions (homogeneity, isotropy) have not been tested.

Now that we have data, it should be a priority to *test the cosmological model assumptions* – not simply measure the model parameters with `precision'

- The rest frame of distant quasars & radio sources ≠ CMB rest frame

… **This is a challenge to the assumption of a FLRW metric**

- The standard procedure of boosting measured redshifts and magnitudes of SNe Ia to the 'cosmic rest frame', and making corrections for the peculiar velocities of their host galaxies in order to infer cosmic acceleration (which is then interpreted as due to Λ), is *unjustified*

The measurements made in the heliocentric rest frame reveal a dipole asymmetry in the recession velocities and in the inferred acceleration

⇒ cosmic acceleration may be just an artefact of our local bulk flow

We must construct a new standard model of cosmology from *observations*

(Ellis & Stoeger: 'The fitting problem', CQG 4:1697,1987)