# Improving Physical Cosmology: An Empiricists Assessment P.J.E. Peebles arXiv:2106.02672

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# Improving Physical Cosmology: An Empiricist's Assessment

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*The world is so full of a number of things,*
*I'm sure we should all be as happy as kings.*
Robert Louis Stevenson

**Abstract**

The $\Lambda$CDM cosmology passes demanding tests that establish it as a good approximation to reality, but it could be improved. I present a list of possibly interesting and less well explored things that might yield hints to a better theory.

# Peebles: ΛCDM as an approximate theory

evidence in support of this theory. Comments about the state of the cosmological tests that establish the ΛCDM cosmology as a good approximation to reality, but certainly not a perfect one, are presented here and continue

impressively good approximation to reality. Maybe more tensions will be found as the constraints improve. If so then I expect the case for ΛCDM as a useful approximation will remain compelling [2], and there will be more clues to a still better theory.

My assessments of issues assume the cosmological tests have convincingly established the ΛCDM theory as a useful approximation to reality: not exact, but not at all likely to be far off. This is for each to judge, of course.

cosmology without dark matter do as well? The idea that a seriously different theory would pass the broad range of cosmological tests seems exceedingly unlikely. That is a judgement of plausibility, of course, not

# Peebles on ffΛCDM

Would a different gravity theory and a cosmology without dark matter, built along the lines of Milgrom's MOND [43], pass the considerable array of tests of gravity physics and cosmology? It seems exceedingly unlikely.

The MOND [43] proposal to replace the dark matter of the standard model with a modified form of the gravitational central force law predicts the baryonic Tully-Fisher relation between the circular velocity in a galaxy and the mass in stars plus gas. The prediction is a remarkably good fit to the observations (Fig. 4 in [67]). This result must have something of value to teach us. What might it be?

# Peebles on the $H_0$ tension

"An error of 10% from tracing cosmic expansion back by a factor of a thousand is impressive accuracy."

So much for precision cosmology.....

# My hierarchy of models

- simple: normal GR plus
  baryons-only, HDM-only, CDM-only, or Λ-only
- more complicated but generic:
  ΛCDM, ΛHDM, TEVES (rel. MOND).......
- aΛCDM (almostΛCDM):
  warmDM; kΛCDM, $\phi$cdm, interacting-DM,
  non-scale invariance at 1Mpc

Peebles considers that in the first two categories, only ΛCDM is consistent with observation.

But if ΛCDM is an "approximate" theory, is the only possibility an even more finely-tuned aΛCDM?

Or are there other ways that the theory could be approximate?
e.g. use of ideal-gas law, RW metric....

# aΛCDM: Early Dark Energy

arXiv:2109.04451:
The Atacama Cosmology Telescope: Constraints on Pre-Recombination Early DarkEnergy

ogy Telescope (ACT) Data Release 4. We find that a combination of ACT, large-scale *Planck* TT (similar to *WMAP*), *Planck* CMB lensing, and BAO data prefers the existence of EDE at $> 99.7\%$ CL: $f_{\rm EDE} = 0.091^{+0.020}_{-0.036}$, with $H_0 = 70.9^{+1.0}_{-2.0}$ km/s/Mpc (both 68% CL). From a model-selection standpoint, we find that EDE is favored over ΛCDM by these data at roughly $3\sigma$ significance. In

# Some themes

- Importance of imprecision cosmology
- Test of cosmological principle (isotropy)
- Peculiarities of the local universe
- Formation and properties of galaxies
- Anthropics

# Importance of imprecision cosmology

Not just CMB and BAO are important:

- $\Omega_\mathrm{M}$: Virgo infall...... weak lensing
- $\Omega_\Lambda$: ages of globular clusters
- $\Omega_\mathrm{B}$ baryons in clusters, galaxies, Ly$\alpha$-forest, fast-radio bursts

The consistency of results from this broad variety of ways to observe aspects of the universe and interpret the observations by applications of different elememts of the $\Lambda$CDM theory makes an excellent case that this theory is a good approximation to what happened. If $\Lambda$CDM were wrong one might expect to encounter the occasional accidental consistency of measures of $\Omega_\mathrm{baryon}$, but it would be silly to imagine that the considerable string of consistent measures of the baryon density is accidental, or the result of a conspiracy.

# Cosmological principle/isotropy controversy

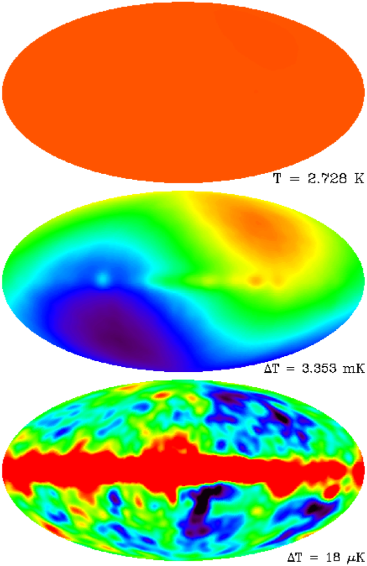
$\Lambda$CDM$\Rightarrow$ anistropy due only to our peculiar motion (600km/sec) with respect to the frame where the CMB is isotropic.

Evidence for excess anistropy, peculiar velocity from

- Quasar angular distribution on sky
- SNIa Hubble diagram
- Galaxy cluster Hubble diagram

Suggestion of movement approximately in direction of CMB anisotropy but two times too fast.

# COBE CMB dipole

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Mostly Doppler shift due to our movement

# Anisotropy from Local Group Peculiar velocity

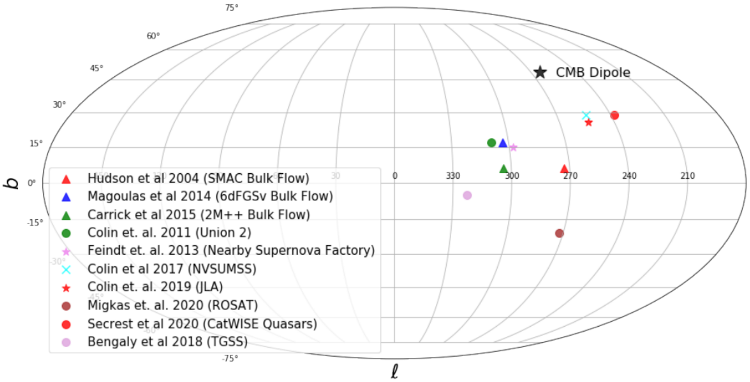



**Fig. 1.** Examples of directional anisotropy reported in studies of the local bulk flow [14, 15, 36, 38, 39], X-ray clusters [53, 54], SNe Ia [21], high redshift radio sources [49, 50] and quasars [52]. These are all close to the CMB dipole direction [43] which is also marked.

Compilation from Mohayaee, Rameez, & Sarkar arXiv:2106.03119

# Secrest et al, arXiv:2009.14826



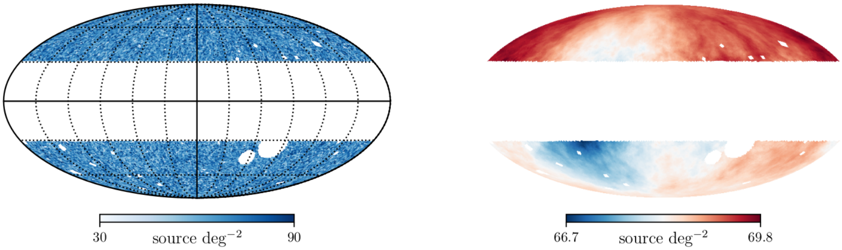



**Figure 1.** *Left:* Mollweide density map of our CatWISE quasar sample, in Galactic coordinates. *Right:* density map smoothed using a moving average on steradian scales, showing a dipole signal. Both maps have been corrected for the residual ecliptic latitude bias (Section 2).

# Secrest et al, arXiv:2009.14826

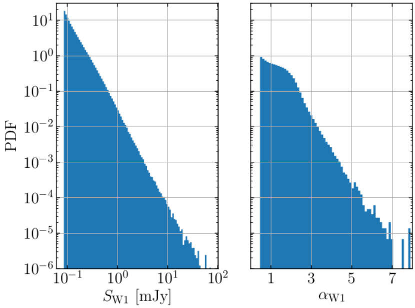



**Figure 2.** Distribution of flux densities $S_\nu$ ($\propto \nu^{-\alpha}$) and spectral indices $\alpha$ (W1 band) in our CatWISE quasar sample, normalized as a probability density function (PDF).

nificant contaminant. Consider a population of sources with power-law spectra $S_\nu \propto \nu^{-\alpha}$, and integral source counts per unit solid angle $\mathrm{d}N/\mathrm{d}\Omega\,(>S_\nu) \propto S_\nu^{-x}$, above some limiting flux density $S_\nu$. If we are moving with velocity $v \ll c$ with respect to the frame in which these sources are isotropically distributed, then being "tilted observers" we should see a dipole anisotropy of amplitude (Ellis & Baldwin 1984):

$$\mathcal{D} = [2 + x(1+\alpha)]v/c. \qquad (1)$$

Note: to see 3% variation in $N_{qso}$ need variations in threshold $< 1\%$.

# Criticisms of standard SNIa analysis

Mohayaee, Rameez, & Sarkar arXiv:2106.03119

## 5 Conclusions

We have shown [18] that the acceleration of the Hubble expansion rate inferred from SNe Ia magnitudes and redshifts as measured (in the heliocentric frame) is described by a dipole anisotropy. To infer an isotropic component of the acceleration i.e. a monopole (such as can be attributed to $\Lambda$), it is necessary to boost to the (possibly mythical) CMB frame, and 'correct' the redshifts of the low-$z$ supernovae further for their motion w.r.t. the CMB frame [20]. This is done using bulk flow models [36, 38] which already *assume* that the universe is well-described by the standard $\Lambda$CDM model. Moreover to boost the significance of the (monopole) acceleration above $\sim 3\sigma$ the supernova lightcurve parameters need to be empirically modelled *a posteriori* as being both sample- and redshift-dependent [13] — violating both basic principles of unbiased hypothesis testing and the Bayesian Information Criterion [81]. Only by doing so can the significance of acceleration be raised to $4.2\sigma$ [13, 20].

# Soltis et al, arXiv:1902.07189

No anisotropy seen in Hubble diagram residuals:

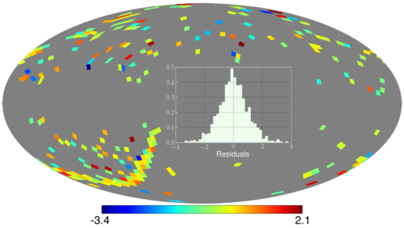



FIG. 1. Mollweide-projection map of SNIa magnitude residuals, defined in Eq. (1), in Galactic coordinates and at **HEALPix** resolution NSIDE = 16. Each pixel contains the average of the residuals of SNIa that fall in it. The inset shows the histogram of the SNIa residuals.

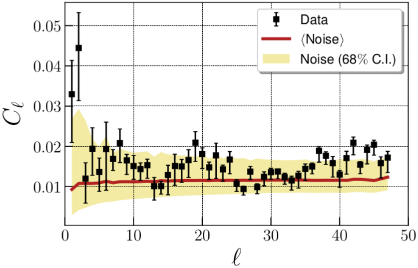



FIG. 3. Angular power spectrum of SNIa magnitude residuals in the Pantheon sample (black data points; errors show the effect of uncertain cosmological parameters). The near-horizontal thin red line shows the mean values of $C_\ell$ expected due to statistical fluctuations (noise) in an isotropic-universe, while the yellow region shows the 68% confidence interval uncertainty in it. See text for details.

# Rahman et al, arXiv:2108.12497

We adopt the Bayesian hierarchical model BAHAMAS to constrain a dipole in the distance modulus in the context of the $\Lambda$CDM model and the deceleration parameter in a phenomenological Cosmographic expansion. We do not find any evidence for anisotropic expansion, and place a tight upper bound on the amplitude of a dipole, $|D_\mu| < 5.93 \times 10^{-4}$ (95% credible interval) in a $\Lambda$CDM setting, and $|D_{q_0}| < 6.29 \times 10^{-2}$ in the Cosmographic expansion approach. Using Bayesian model comparison, we obtain posterior odds in excess of 900:1 (640:1) against a constant-in-redshift dipole for $\Lambda$CDM (the Cosmographic expansion). In the isotropic case, an accelerating universe is favoured with odds of $\sim 1100:1$ with respect to a decelerating one.

14 *Rahman* et al.

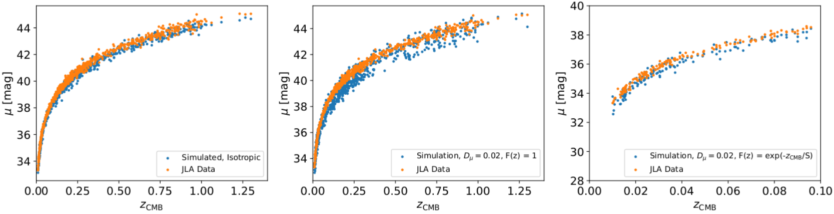



**Figure 6.** Simulated SNIa data generated using the JLA dataset as a reference point. The simulations assume a $\Lambda$CDM model and no anisotropy in the distance modulus for the left most model. A dipole of value $D_\mu = 0.02$ is present for the second plot. The third plot also has this value of the dipole, but restricted to a local scale ($z \sim 0.1$) by multiplying the dipole term by the function $F(z) = \exp(-z/0.026)$. For this third plot the redshift has been truncated to only show the redshift range where the dipole is noticeable.

# Migkas et al, arXiv:2103.13904

Anisotropic Hubble diagram of galaxy clusters:

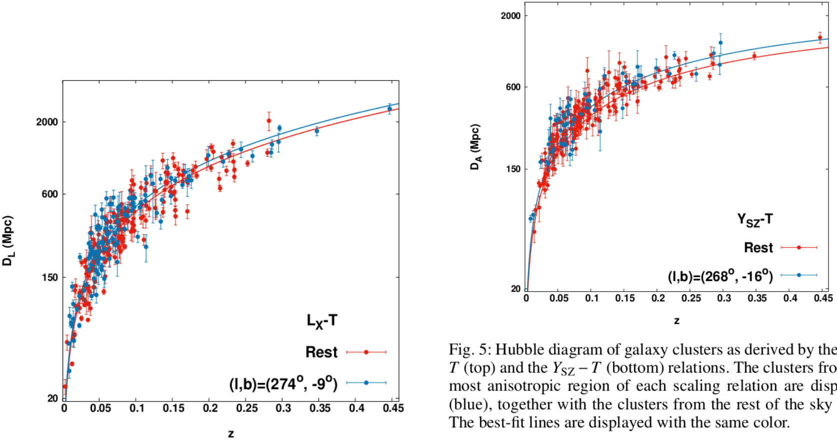



Fig. 5: Hubble diagram of galaxy clusters as derived by the $L_X - T$ (top) and the $Y_{SZ} - T$ (bottom) relations. The clusters from the most anisotropic region of each scaling relation are displayed (blue), together with the clusters from the rest of the sky (red). The best-fit lines are displayed with the same color.

# But is isotropy really really fundamental?

Sarkar et al:

As Ellis & Baldwin (1984) emphasized, a serious disagreement between the standards of rest defined by distant quasars and the CMB may require abandoning the standard FLRW cosmology itself. The importance of the test we have carried out can thus not be overstated.

Peebles (unflappable!):

If the peculiar velocity anomaly is well determined to be much larger than the predicted effect, including suprahorizon fluctuations and the effect of bias in the tracers of the mass distribution, what might be the conclusion? Since the cosmological tests make a case that persuades me that the ΛCDM

theory is a good approximation to reality, I expect that the anomaly, if real, adds to clues to a still better theory. It would be an advance rather than a revolution.

# Some themes

- Importance of imprecision cosmology
- Test of cosmological principle (isotropy)
- Peculiarities of the local universe
- Formation and properties of galaxies
- Anthropics

# The local supercluster

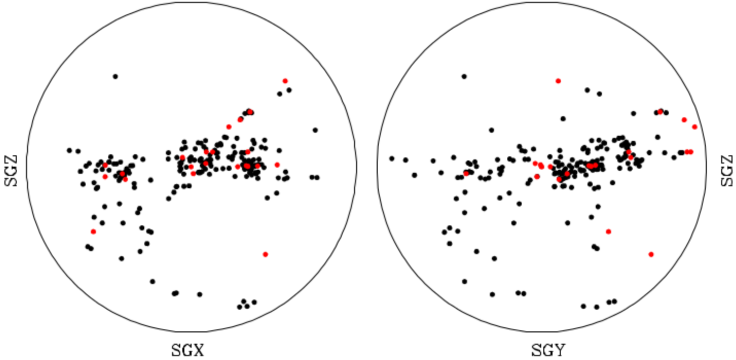
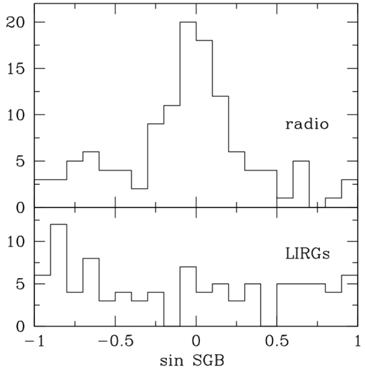



Figure 2: The distribution of galaxies within 8 megaparsecs, in orthogonal projections in supergalactic coordinates.

At distances $D < 85$Mpc galaxies that are exceptionally luminous at radio wavelengths tend to be close to the plane of the Local Supercluster .....defined by the galaxies at $D < 10$Mpc, along with the Virgo cluster at $D = 20$ kpc. But LIRGs, which are exceptionally luminous at $\lambda \approx 60\mu$m, show no preference for the plane.




Little has been made of the striking contrast between the distributions of galaxies that are exceptionally luminous in the infrared and those exceptionally luminous at radio wavelengths. This is not surprising because it is difficult to know what to make of it.

# Fundamental physics to the rescue?

Maybe early generations of cosmic strings or domain walls ran across parts of space when they were causally connected. Recall the curious alignment of radio galaxies, and clusters of galaxies, with the extended plane of the Local Supercluster shown in Figure 1, and the curious contrast to the absence of alignment of the LIRGs, galaxies exceptionally luminous in the infrared. Might something have imprinted seeds that encouraged formation of AGNs and clusters of galaxies but not LIRGs? Might an inhomogeneous baryon mass fraction account for the curiously empty Local Void? These are vague thoughts, but the empiricist philosophy calls for obsessive attention to the search for and possible interpretation of phenomena that seem strange, not likely to be accidental, and maybe have something of interest to teach us.

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# SDSS nearby-galaxy color-magnitude diagram

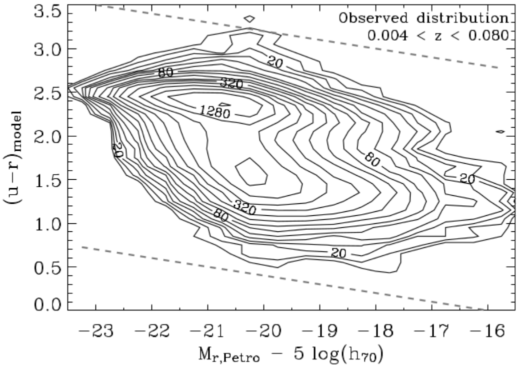


FIG. 1.— Observed bivariate distribution of the sample in rest-frame color versus absolute magnitude. The *contours* are determined for galaxy number counts in 0.1 color × 0.5 magnitude bins (with a total of 66846 galaxies). The contour levels are on a logarithmic scale, starting at 10 and doubling every two contours. The *dashed lines* represent the limits used in the double-Gaussian fitting described in Section 4.

arXiv:0309710

Bright,red,elliptical

Faint,blue,spiral

# Peebles: do we understand bimodality?

clear; large galaxies exhibit a distinct bimodality. How did this come about?

It is said that elliptical galaxies formed by dry mergers, spirals by wet. Perhaps evidence of this is seen in the Centaurus group with its two large galaxies. The satellites around the elliptical Centaurus A are largely early types, and the satellites around M 83, a spiral with an inconspicuous bulge, are almost all late types [71]. Thus we can put the question two ways. Why is there a prominent bimodality of galaxy morphologies? Or why did some galaxies form by mergers of dry subhalos, others wet, in what looks like a bistable process?

# Peebles: Merging insensitive to environment?

In the scatter plot of galaxy color and absolute magnitude the ratio of counts of red to blue galaxies increases with increasing galaxy luminosity, but again the position of the red sequence in the color-magnitude plot is quite insensitive to environment [78]. This is not what one might have expected if red galaxies grew by mergers of less luminous early type galaxies that would have had less red colors if they had evolved in isolation. Here again the degree of assembly by mergers had to have been almost indifferent to environment.

# Isolated galaxies

a. The dwarf galaxy KK 246 seems to have evolved in splendid isolation in its lonely position in the Local Void (Topic 11). So why is the distribution of stars in KK 246 tilted from the H I cloud that surrounds it [90]? A

# Bulge-to-total ratio

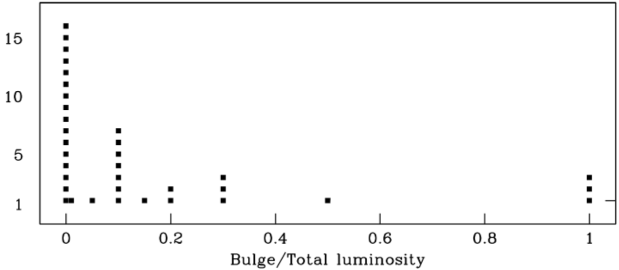


Figure 3: Frequency distributions of ratios of bulge to total luminosities of nearby $L \sim L_*$ galaxies.

"Simulations of the formation of large galaxies with masses comparable to the Milky Way usually produce spirals with prominent classical bulges of stars that rise out of the disk in the center of the galaxy……But the classical bulge issue has been in the literature for a decade [68], and simulated galaxy images continue to have prominent bulges."

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# Is the Anthropic solution excessive?

(21) *The anthropic principle*

Anthropic explanations have the flavor of just so stories, such as how the leopard got its spots. But how else can we account for the allowed contribution of zero-point energies to the cosmic vacuum energy density represented by the cosmological constant? We had to have flourished in a galaxy capable of containing the debris that was recycled through a few generations of stars to produce the heavy elements we require. But our universe of vast numbers of galaxies containing immense numbers of planets seems to be an excessive response to the anthropic condition. Inflation need not have produced the enormous numbers of galaxies seen in our universe to make the single one we need; smaller primeval curvature fluctuations would produce quite a few

Do we really need all these galaxies and stars to get one civilization?

Question also asked by Penrose

# Some biologists think so

"The origin of the eukaryotic cell was a singular event. Here on earth it happened just once in 4 billion years of evolution. .......
Complex life might arise elsewhere, but it is unlikely to be common, for the same reasons it did not arise repeatedly here."

Nick Lane
The Vital Question:
Energy, Evolution, and the Origins of Complex Life

# End of the story?

(23) *The Theory of Everything*

Martin Rees [132] rightly celebrates the concept of the multiverse as the next layer in the sequence of revolutions in understanding of the world around us. We can list many layers: the Ptolemy universe with the earth centered in the crystal spheres that hold the astronomical objects; the Copernican universe with the sun at the center; the Kapteyn universe centered on the Milky Way galaxy; Hubble's realm of the nebulae with no center; and the multiverse of which our universe is a speck. The layers of discovery go down in scale too. Henri Poincaré [133] remarked that the Mariotte/Boyle law is simple and wonderfully accurate for many gases, but these gas examined in sufficiently fine detail break up into the complex motions of enormous numbers of particles. Poincaré asked whether gravity examined in sufficiently fine detail also departs from the simplicity of Newton's law into complex behavior. Poincaré suggested we consider that "then again [there may be] the simple under the complex, and so on, without our being able to foresee what will be the last term." Underlying the particle physicists' "theory of everything" could be more layers of Poincaré's successive approximations. And why should the layers of structure on large scales end with multiverses? This grand hierarchical vision must end with nonempirical assessments of conjectures about the extremes of large and small scales that the world economy cannot afford to test. But there is immense room in between for continued empirical exploration.

# My summary: my questions

- Do we need galactic astronomy (and biology) to understand cosmology?
- Can we learn to love a$\Lambda$CDM?
(like R.L.S would have)