A CHALLENGE TO THE COSMOLOGICAL STANDARD MODEL

Subir Sarkar

In the standard cosmological model the universe is assumed to be statistically isotropic & homogeneous when averaged on large scales. The dipole anisotropy of the CMB is ascribed to our peculiar motion due to local inhomogeneity. There should then be a corresponding dipole in the sky map of high redshift sources. Using catalogues of radio galaxies and quasars we find that this expectation is rejected at >5σ. This undermines the standard practice of boosting to the 'CMB frame' to analyse cosmological data, in particular for inferring an isotropic acceleration of the Hubble expansion rate – which is then interpreted as due to Λ.

'Graham Day', Workshop on the Standard Model & Beyond, 1 Sep 2022

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Subir Sarkar

Dedicated to my dear mentor

Graham Ross (1944-2021)

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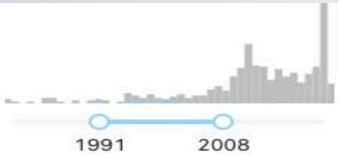

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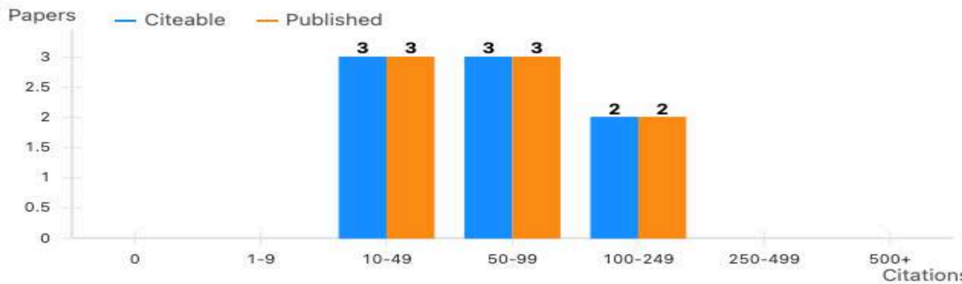

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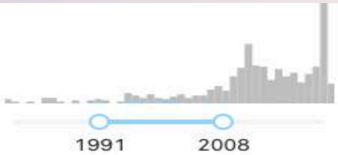

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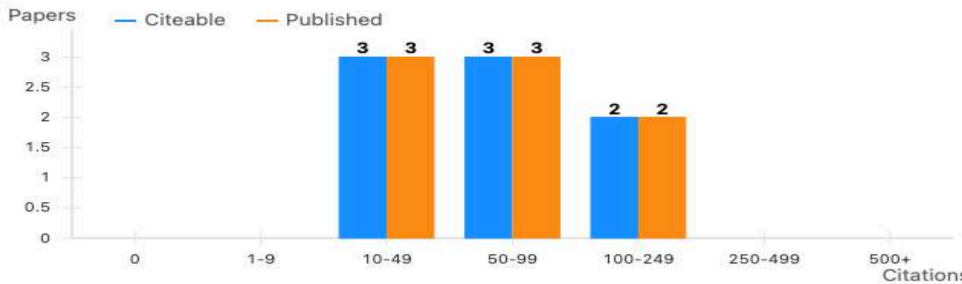

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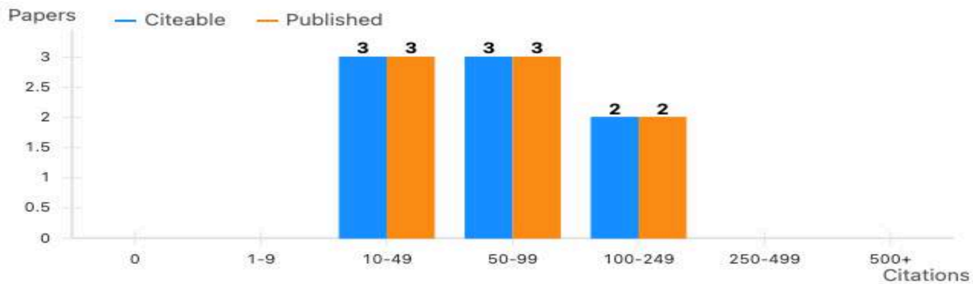

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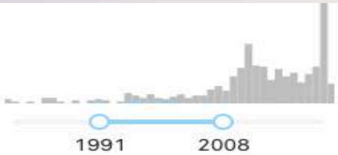

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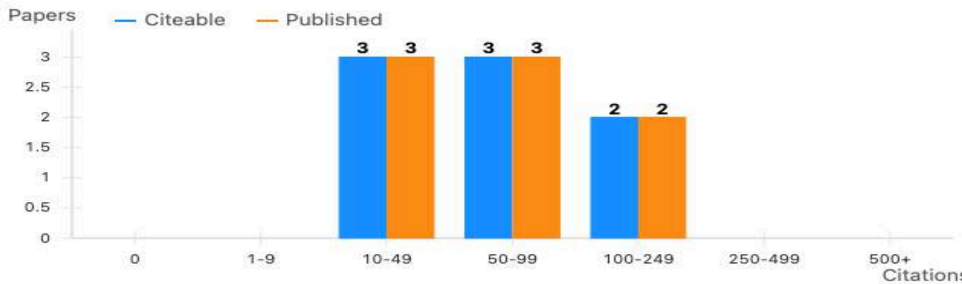

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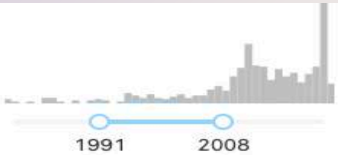

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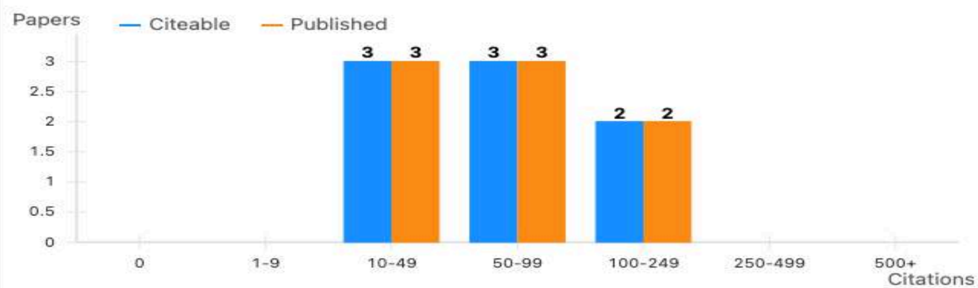

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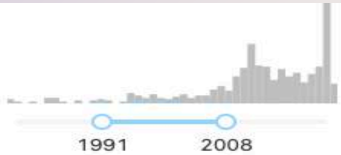

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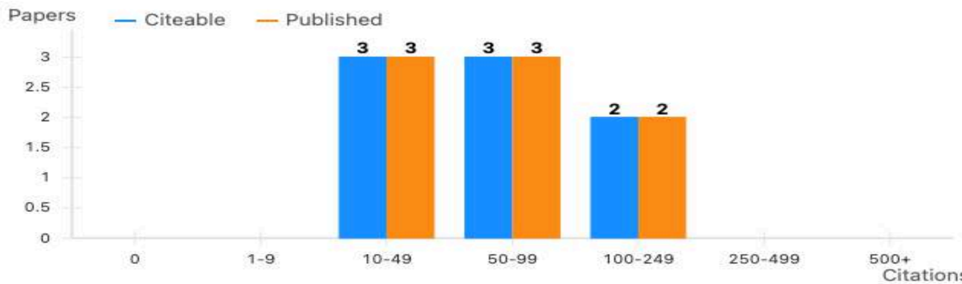

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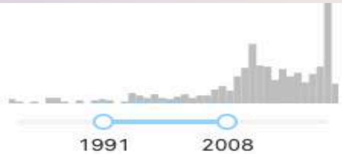

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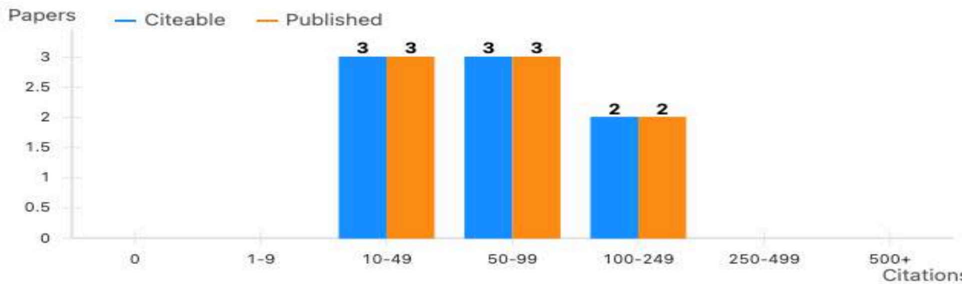

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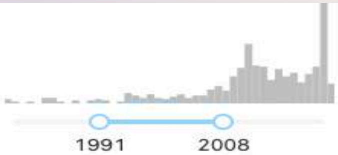

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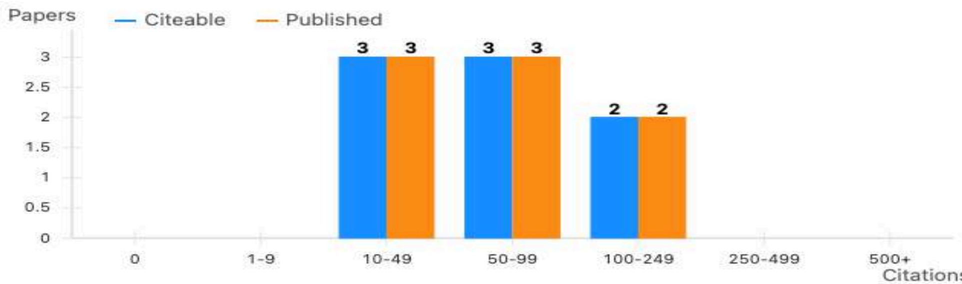

#1 Fine tuning and the ratio of tensor to scalar density fluctuations from cosmological inflation

Shaun Hotchkiss (Oxford U., Theor. Phys.), Gabriel German (Oxford U., Theor. Phys.), Graham G. Ross (Oxford U., Theor. Phys.), Subir Sarkar (Oxford U., Theor. Phys.) (Apr, 2008)

Published in: *JCAP* 10 (2008) 015 • e-Print: 0804.2634 [astro-ph]

pdf DOI cite claim 19 citations

#2 Racetrack inflation and assisted moduli stabilisation ... no overshoot

Zygmunt Lalak (CERN and Warsaw U.), Graham G. Ross (CERN and Oxford U., Theor. Phys.), Subir Sarkar (Oxford U., Theor. Phys.) (Mar, 2005)

Published in: *Nucl.Phys.B* 766 (2007) 1-20 • e-Print: hep-th/0503178 [hep-th]

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#3 Low scale inflation ... inflation is possible down to EW scale

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Published in: *Nucl.Phys.B* 608 (2001) 423-450 • e-Print: hep-ph/0103243 [hep-ph]

pdf DOI cite claim 96 citations

#4 Implementing quadratic supergravity inflation ... 'hilltop inflation'

Gabriel German (Oxford U.), Graham G. Ross (Oxford U.), Subir Sarkar (Oxford U.) (Aug, 1999)

Published in: *Phys.Lett.B* 469 (1999) 46-54 • e-Print: hep-ph/9908380 [hep-ph]

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#5 Multiple inflation ... SUGRA flat directions as 'waterfall fields'

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Published in: *Nucl.Phys.B* 461 (1996) 597-624 • e-Print: hep-ph/9506283 [hep-ph]

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#8 On the implications of a 17-keV neutrino ... unlikely to exist!

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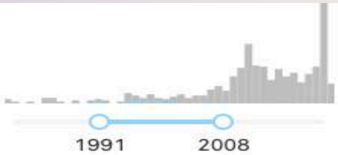
Find a Ross, G.G. and Sarkar, S.



Number of authors

- [x] 10 authors or less — 8

Exclude RPP

- [ ] Exclude Review of Particle Physics — 8

Document Type

- [ ] article — 8
- [ ] published — 8

Citation Summary

- [ ] Exclude self-citations

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h-index	8	8
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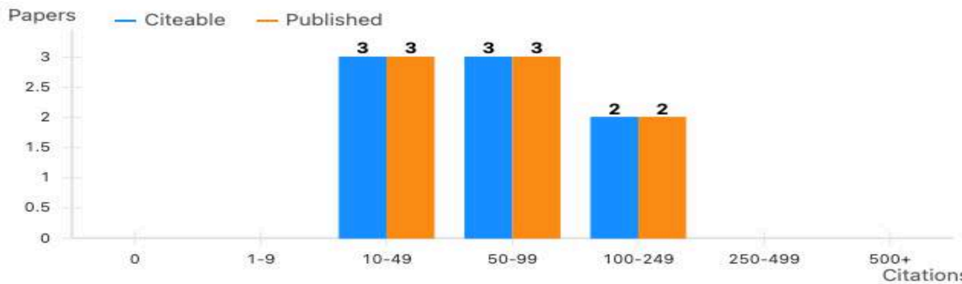

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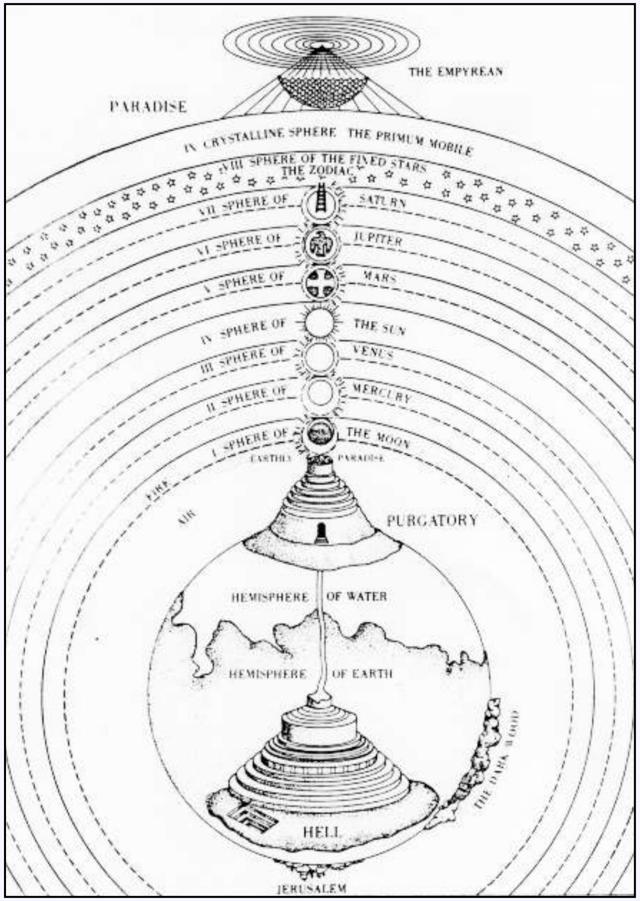
The 'standard cosmology' in Europe which lasted ~2000 yr was 'simple' and gave a good fit to all available data



Aristotle … Ptolemy → The Divine Comedy, Dante Allighieri (1321)

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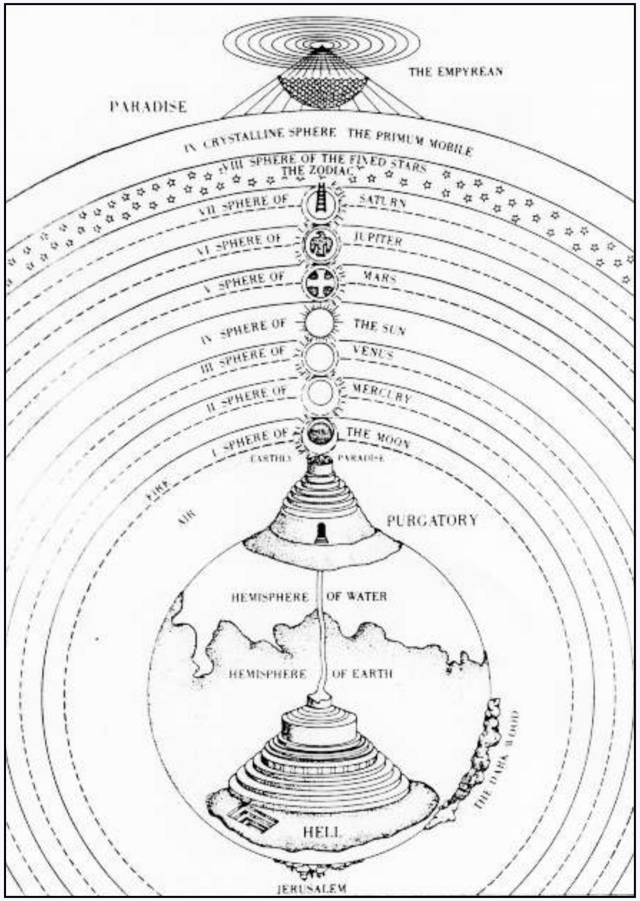

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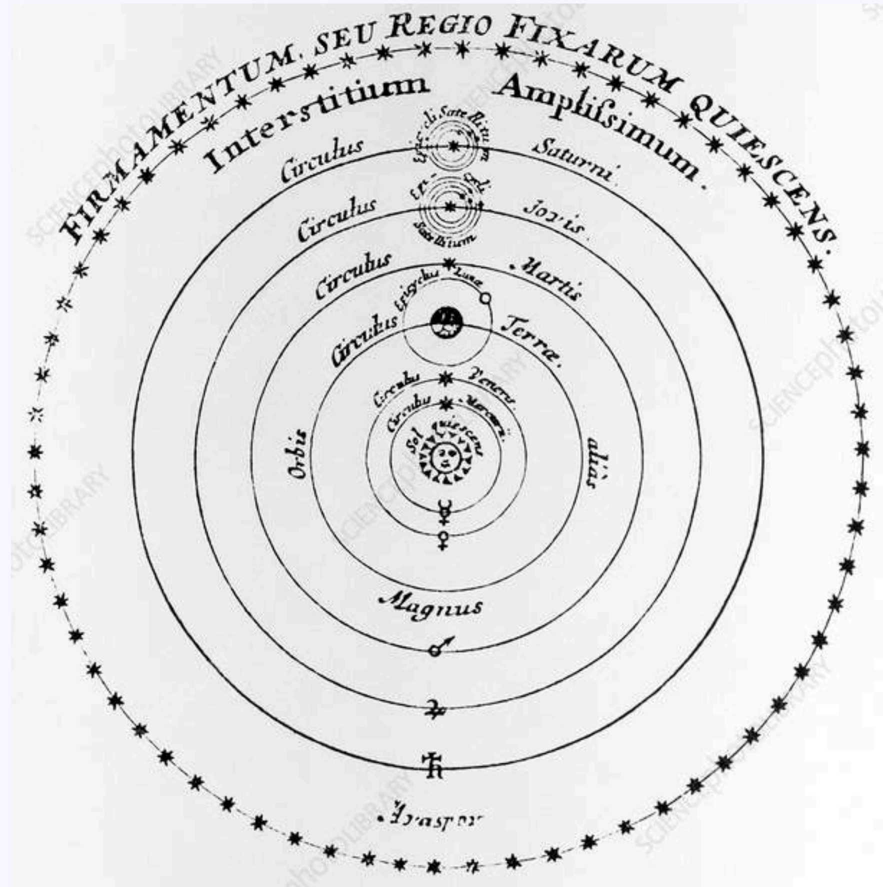

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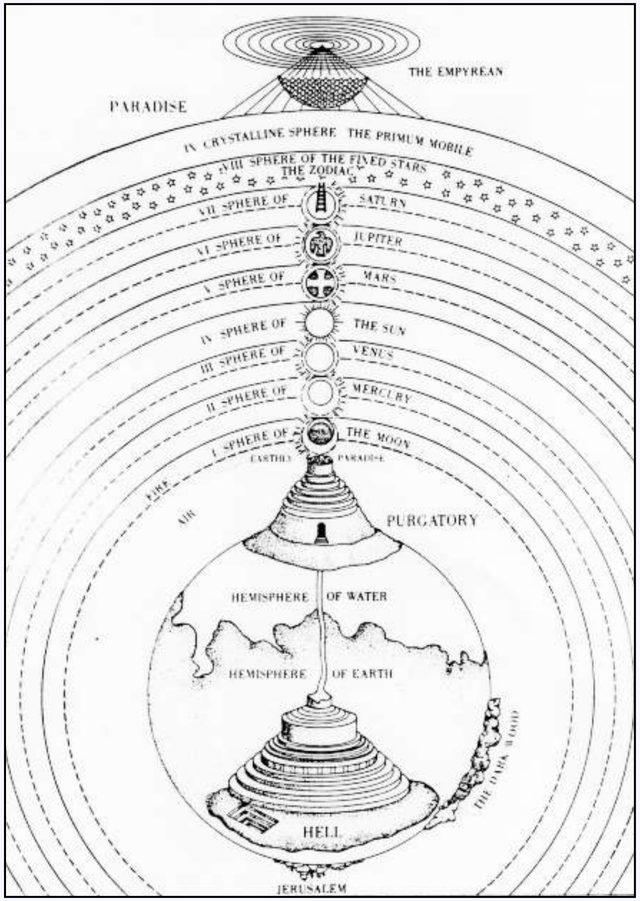

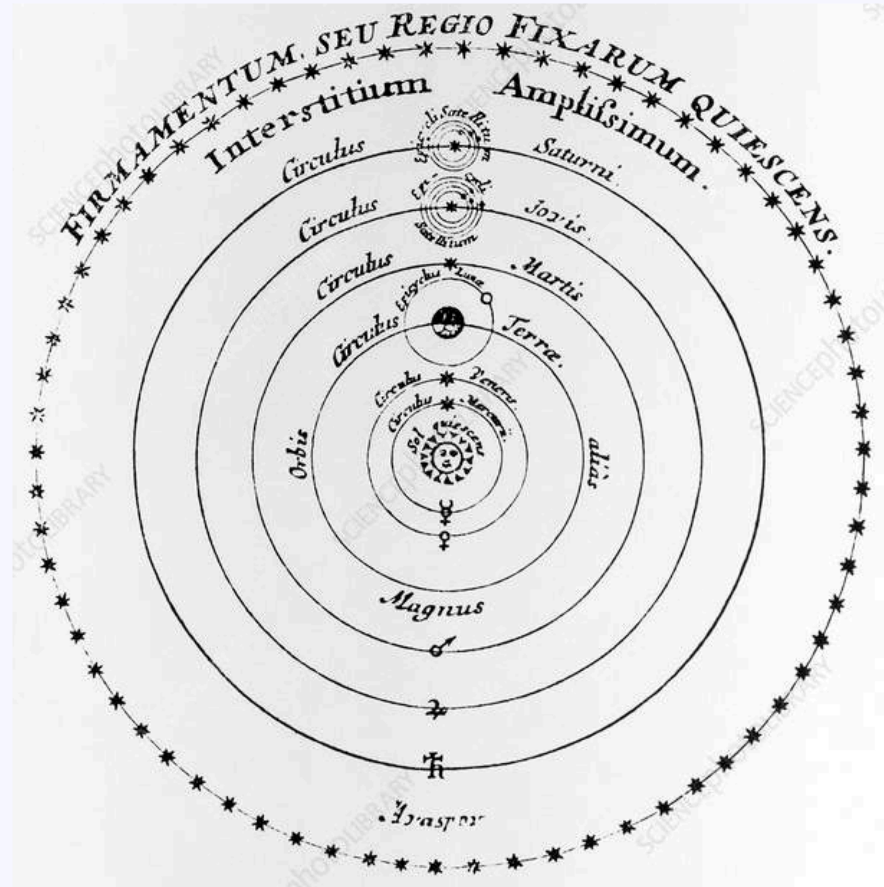

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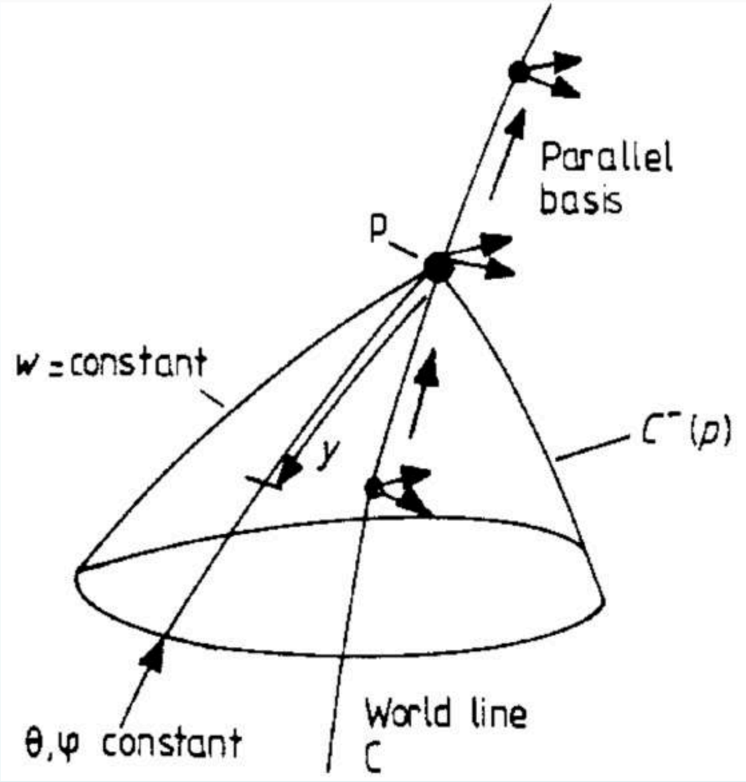
Four centuries later when the first relativistic cosmological models were constructed (Einstein 1917, Friedmann 1921, Lemaître 1927), this 'Copernican Principle' was extended further to demote the Sun too from being at the centre of the Universe …

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



Ellis & Stoeger, CQG 4:1697, 1987

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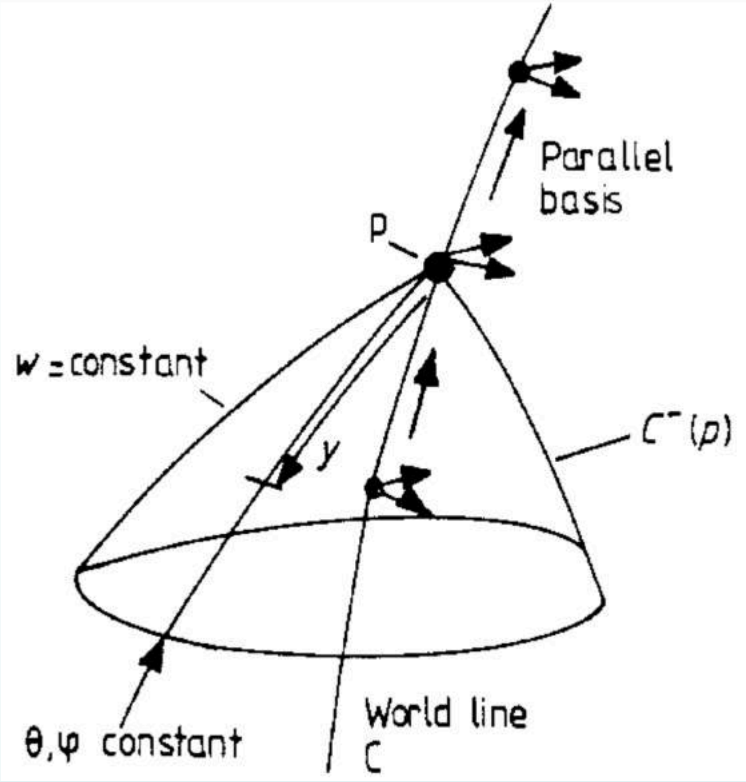

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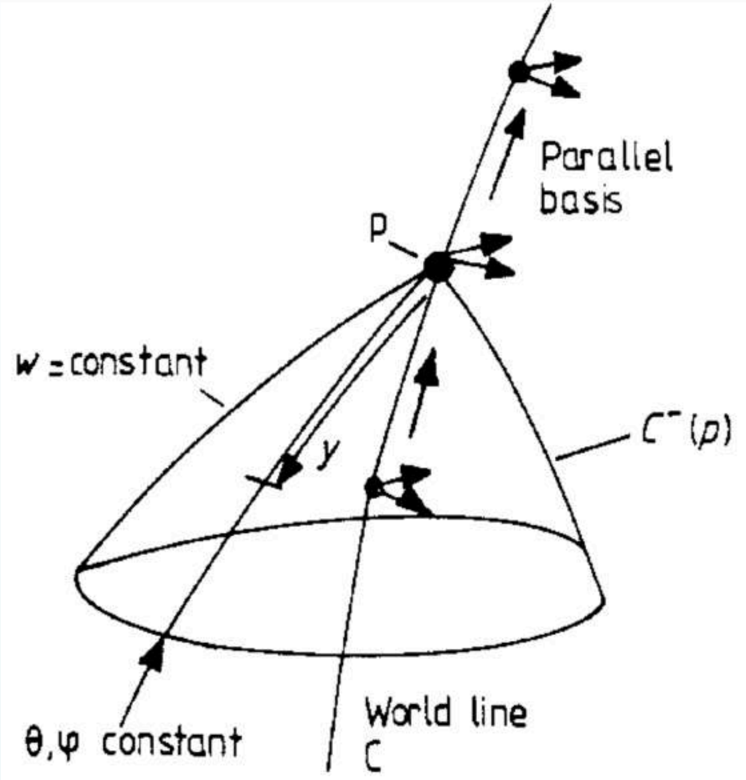

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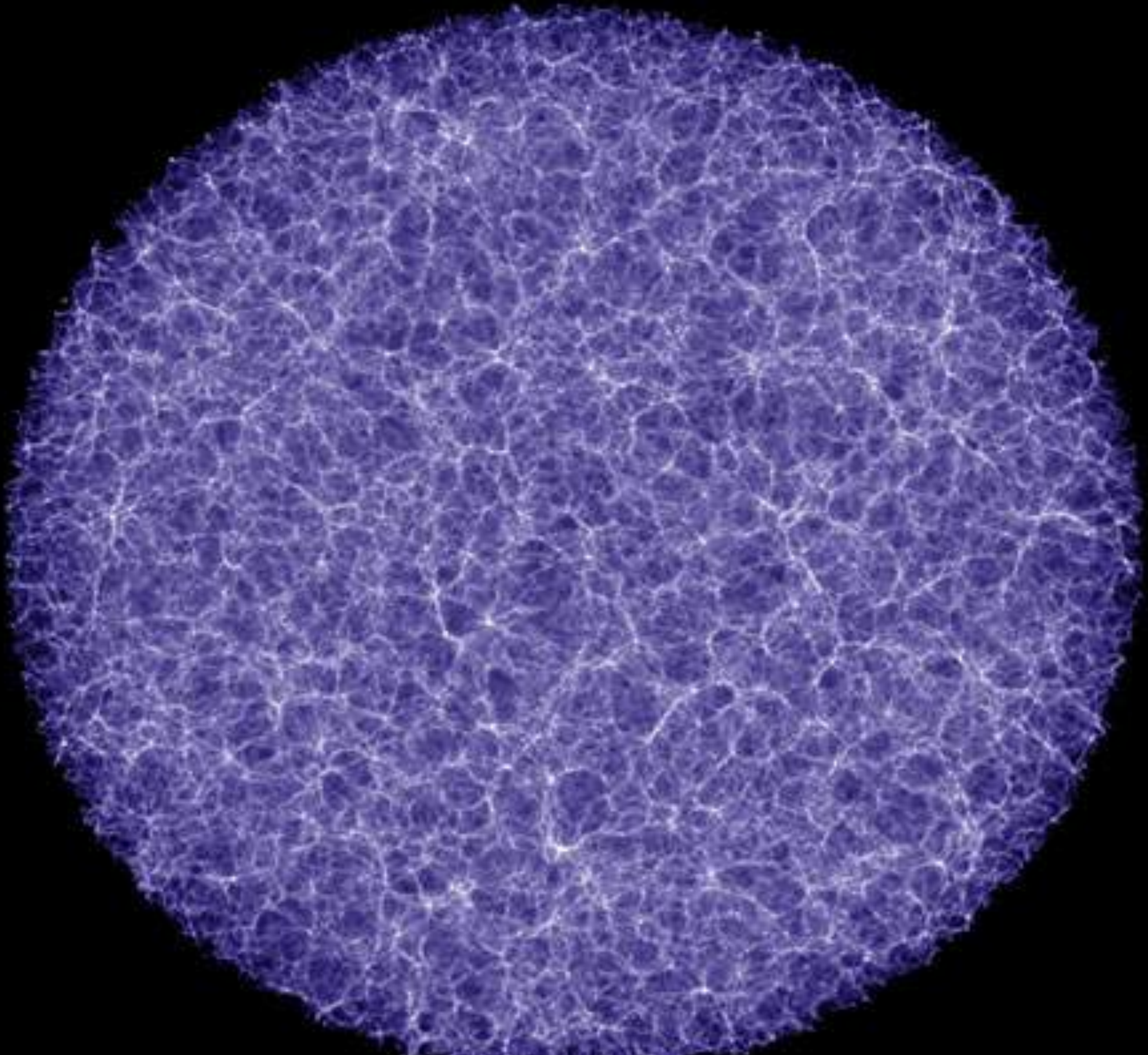
> *"The Universe must appear to be the same to all observers wherever they are. This 'cosmological principle' …"*
>
> Edward Arthur Milne, in 'Kinematics, Dynamics & the Scale of Time' (1936)



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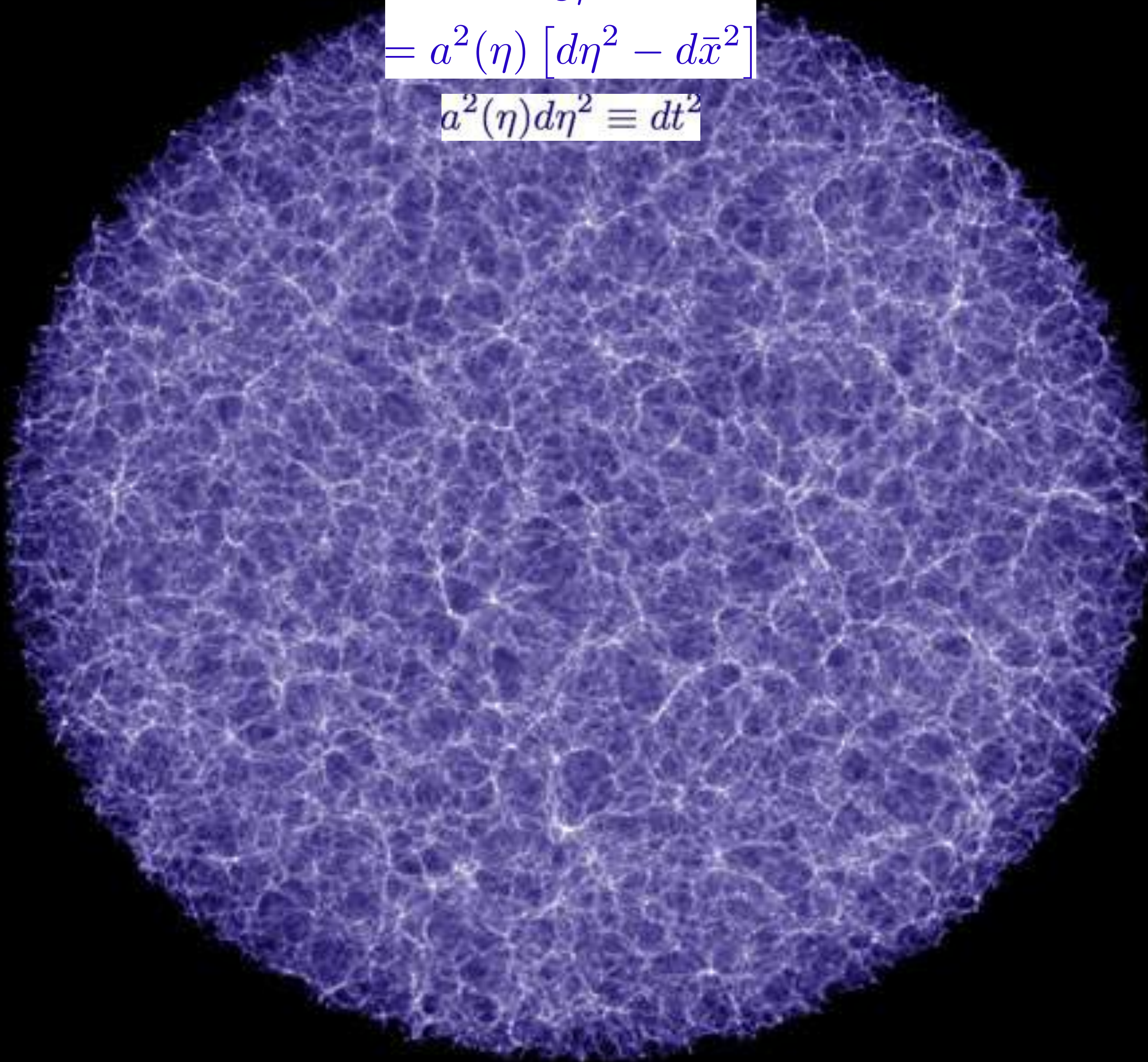

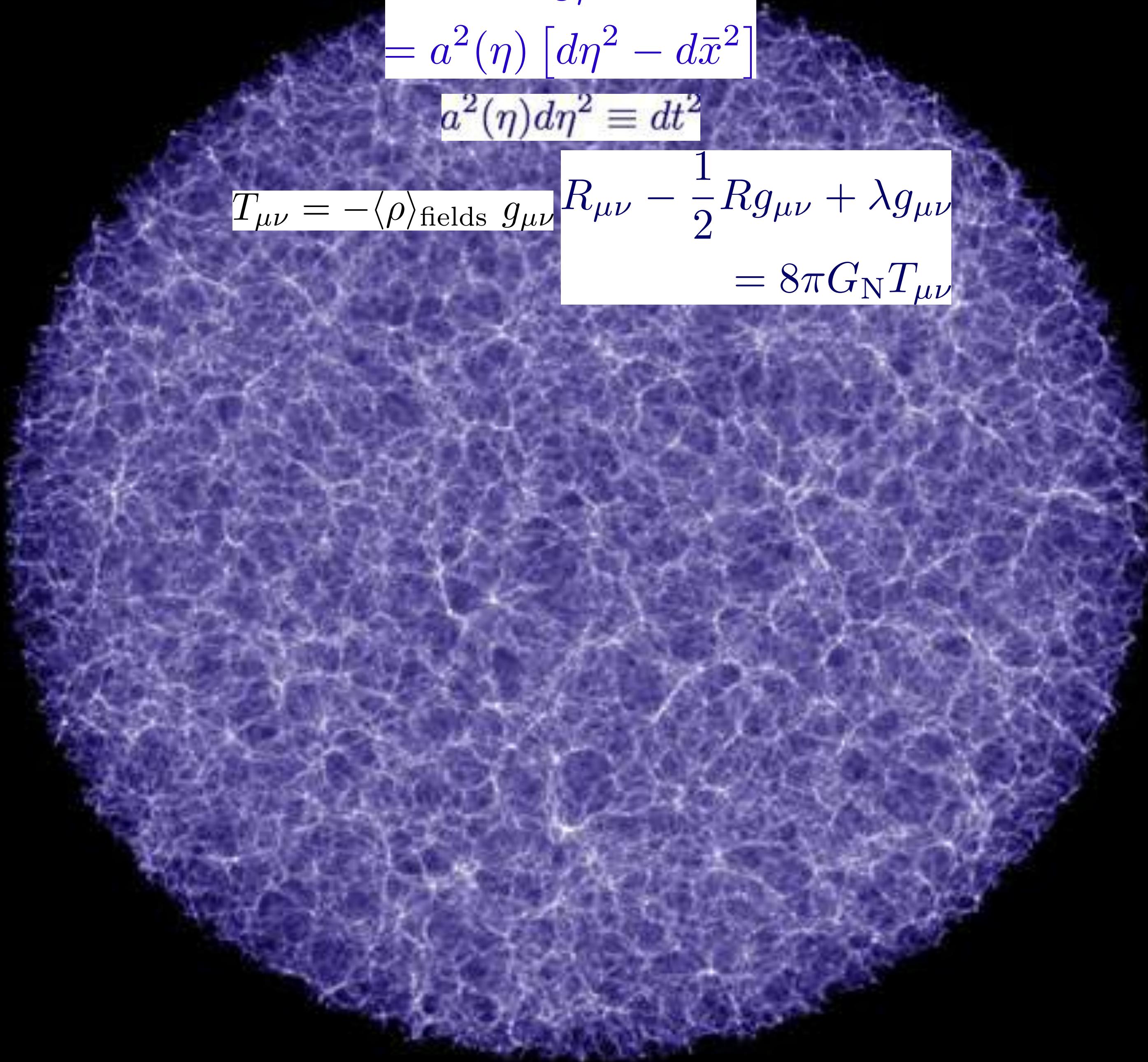

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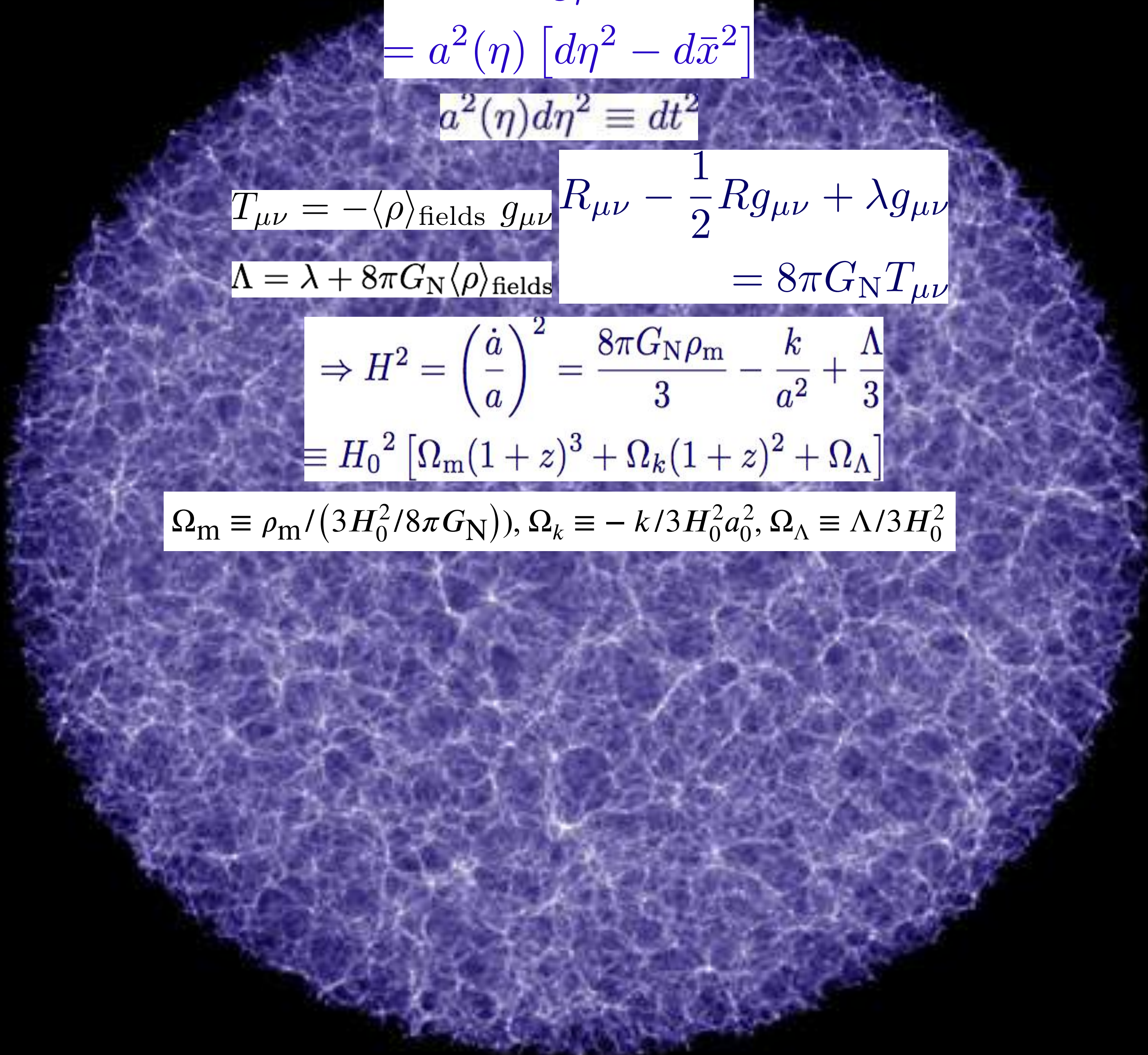
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \lambda g_{\mu\nu}$$
$$= 8\pi G_{\text{N}} T_{\mu\nu}$$



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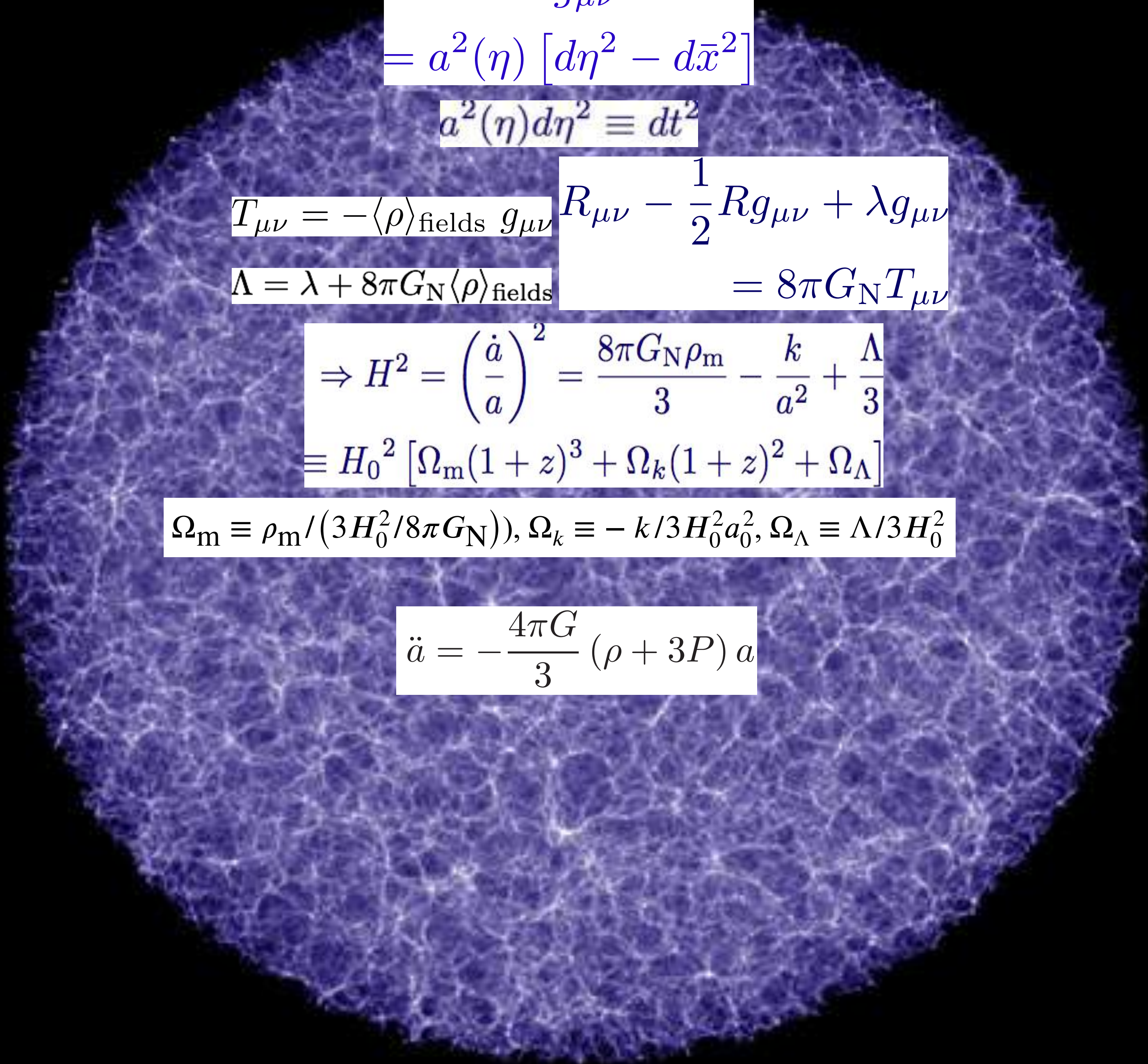

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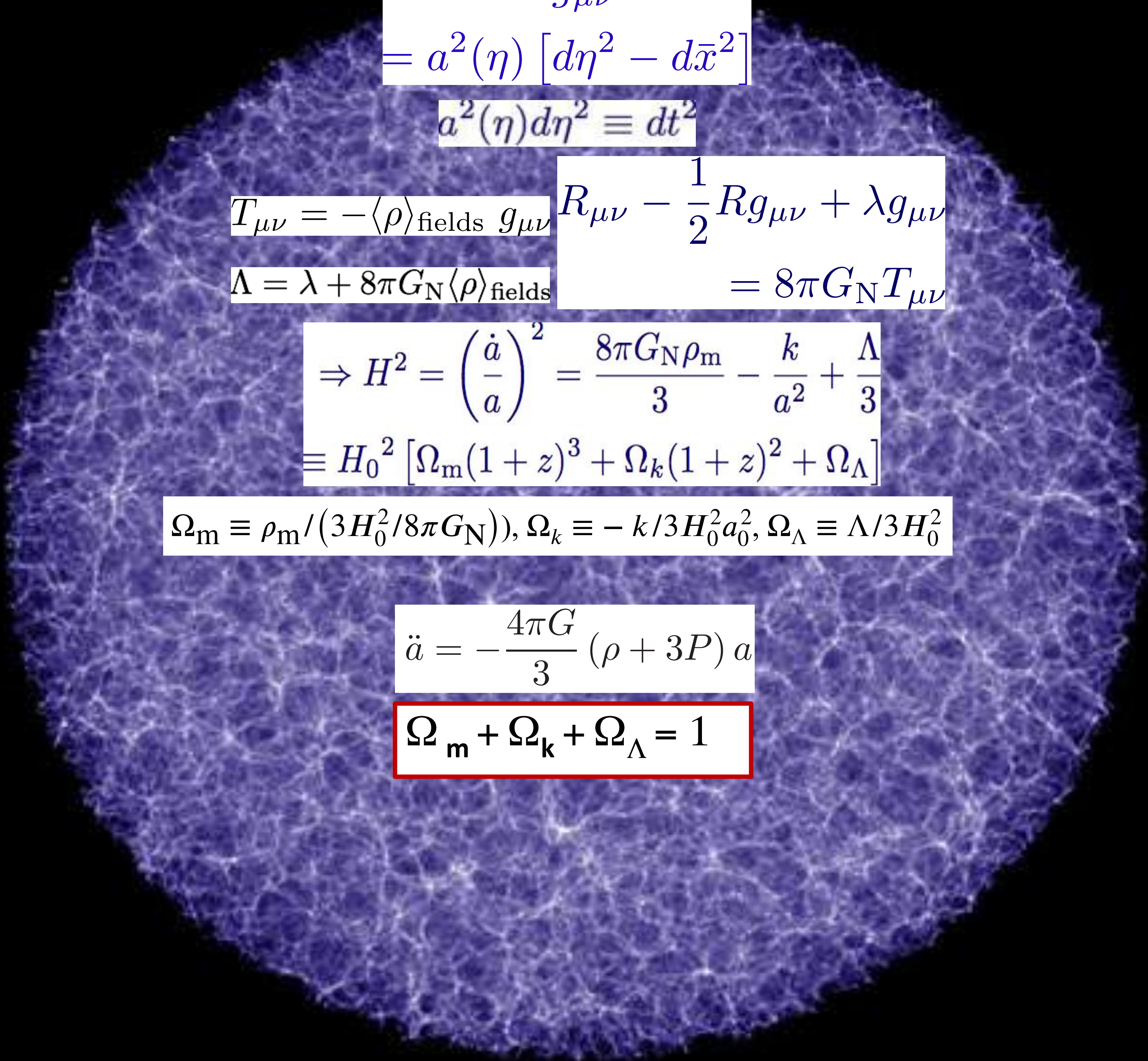

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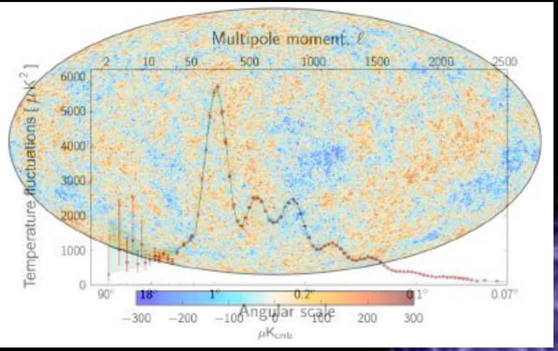

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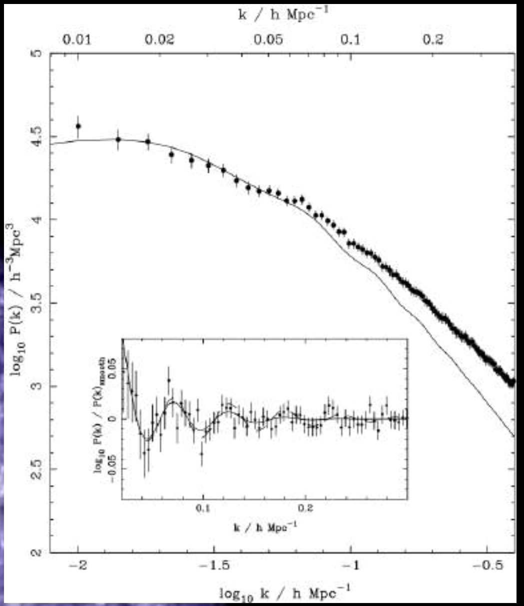

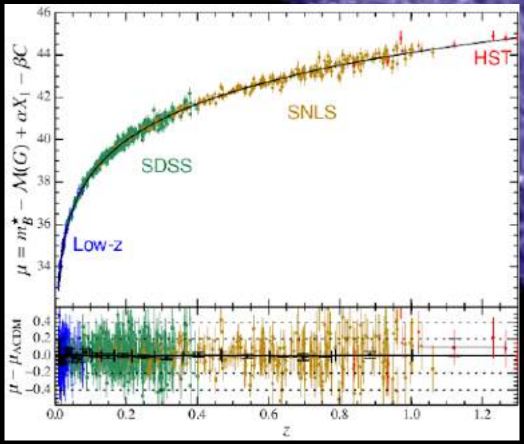

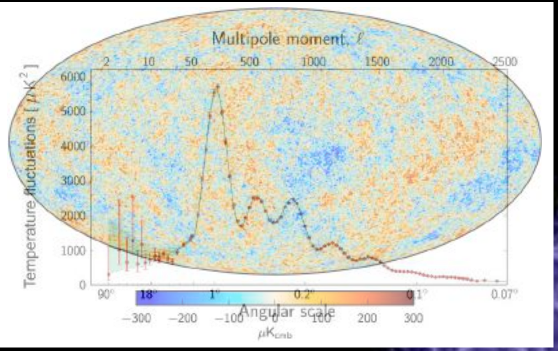

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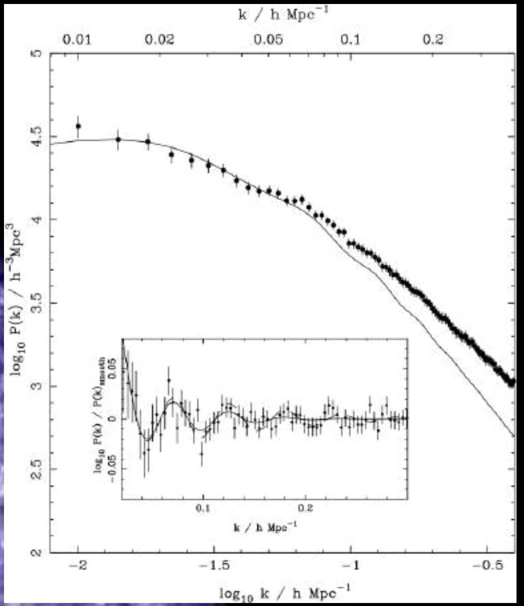

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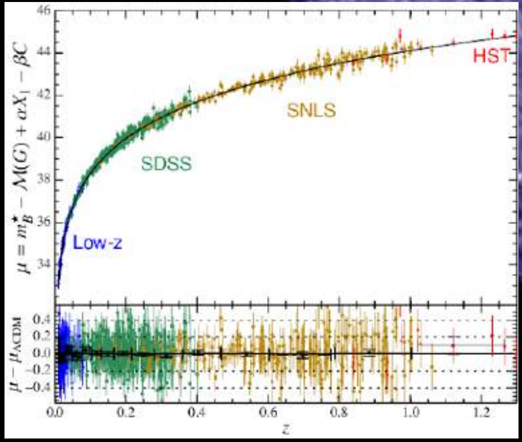

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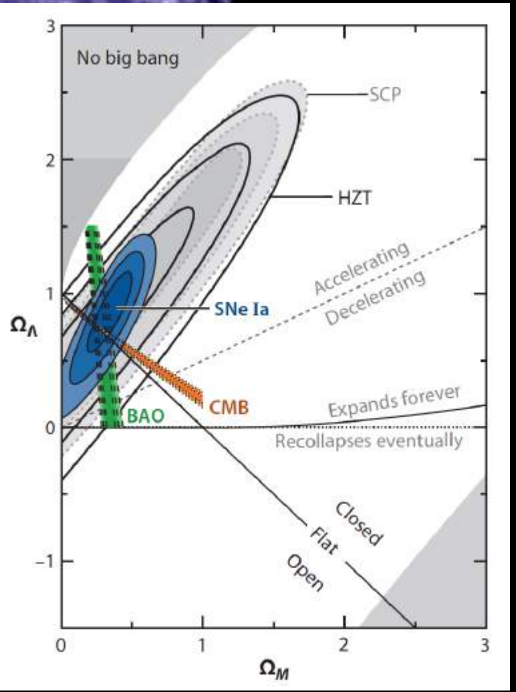

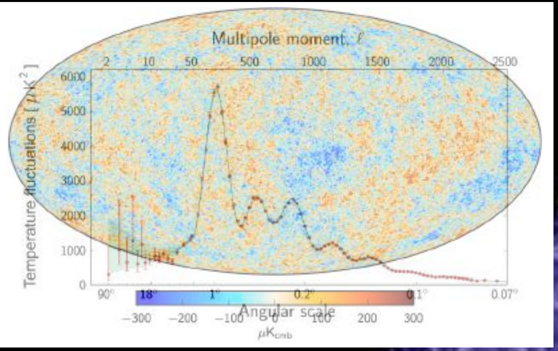

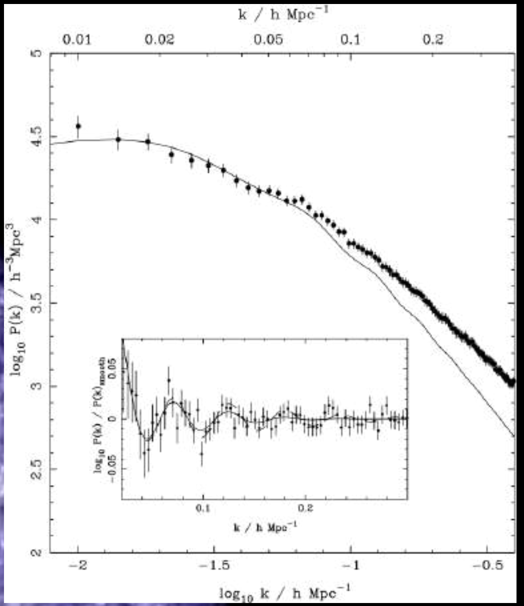

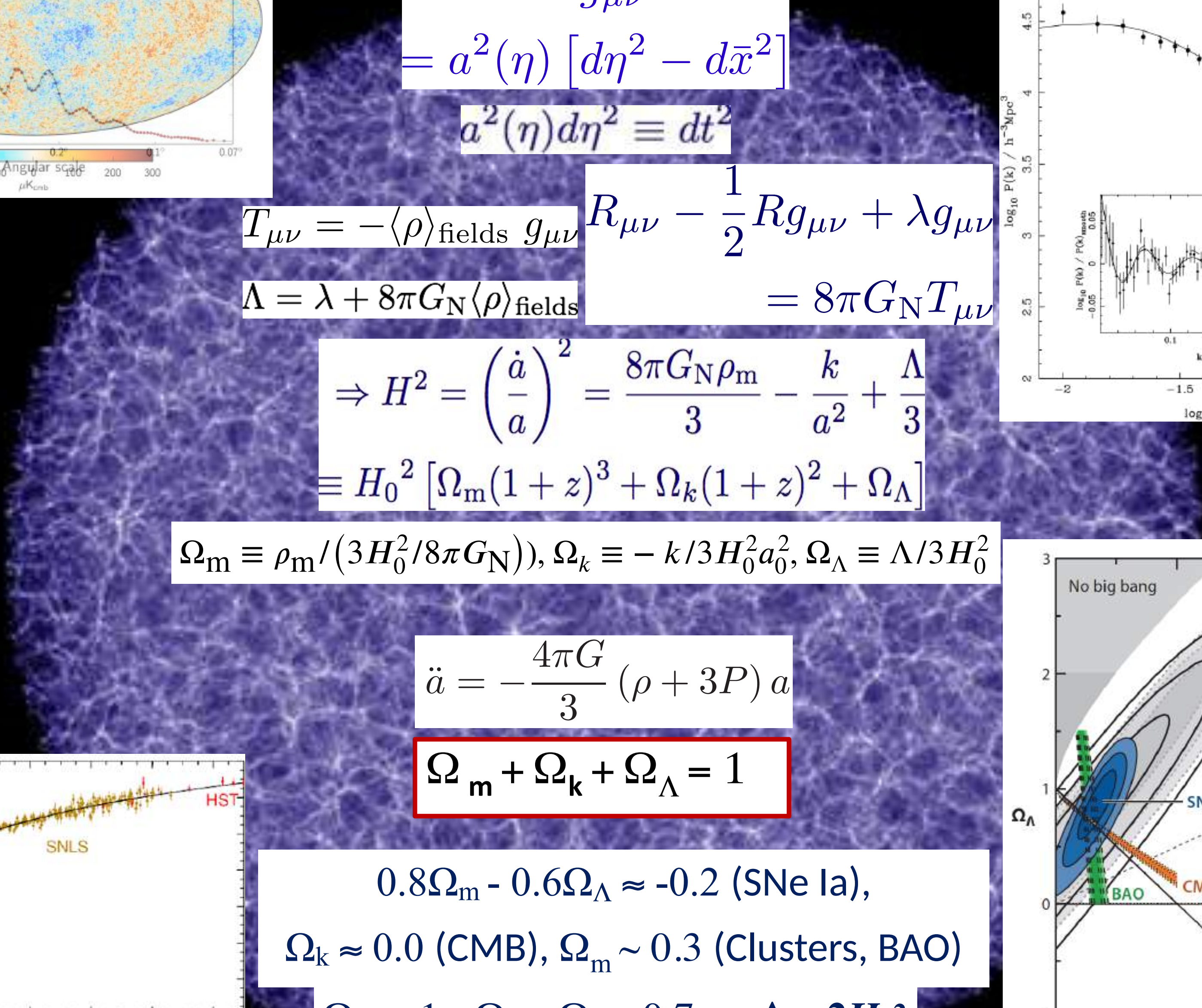

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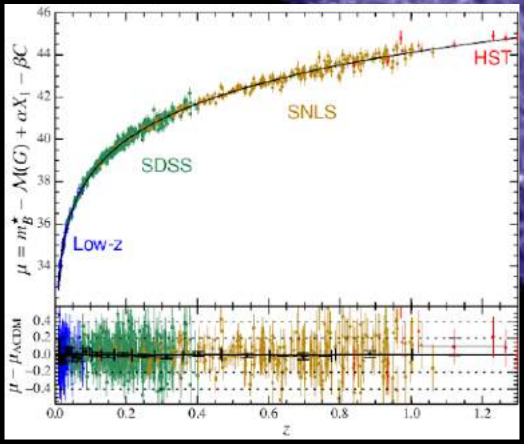
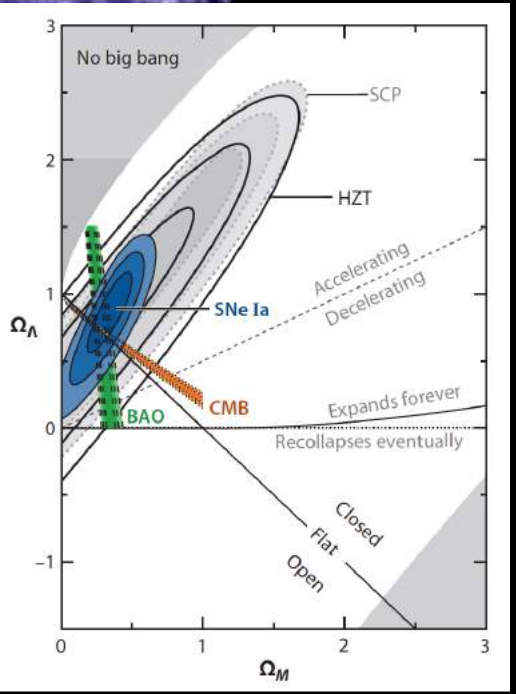
$\Omega_\Lambda = 1 - \Omega_{\text{m}} - \Omega_{\text{k}} \sim 0.7 \Rightarrow \boldsymbol{\Lambda \sim 2H_0{}^2}$

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





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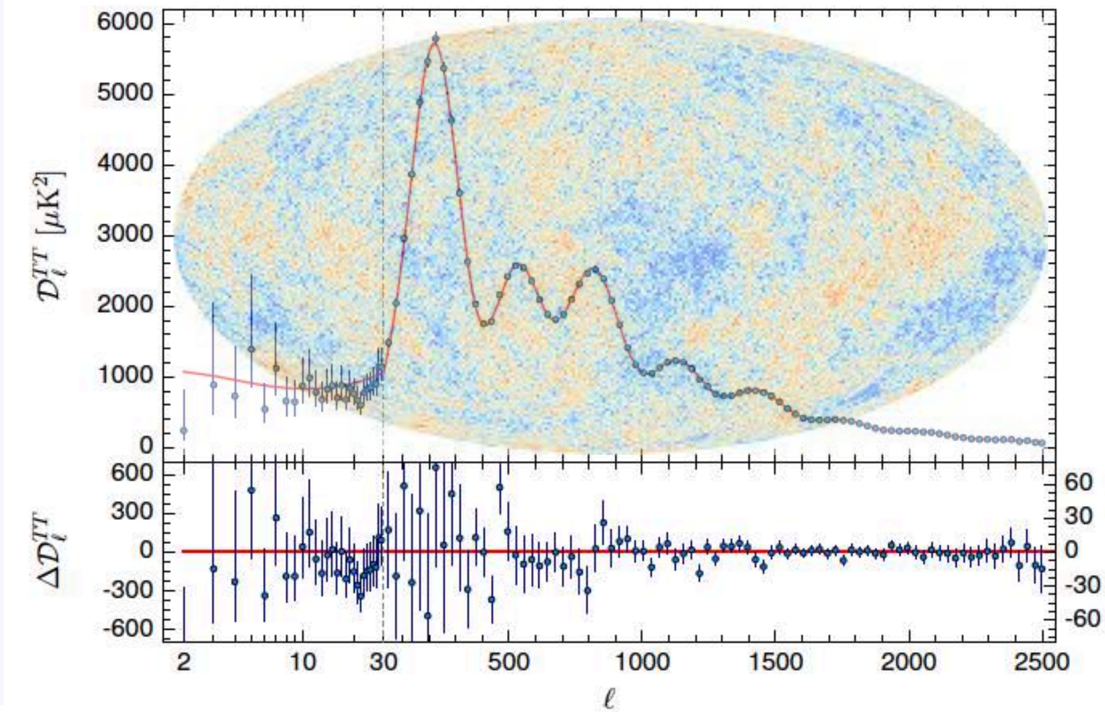

Planck collab., A&A 594:A13,2016

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$100\theta_{MC}$	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
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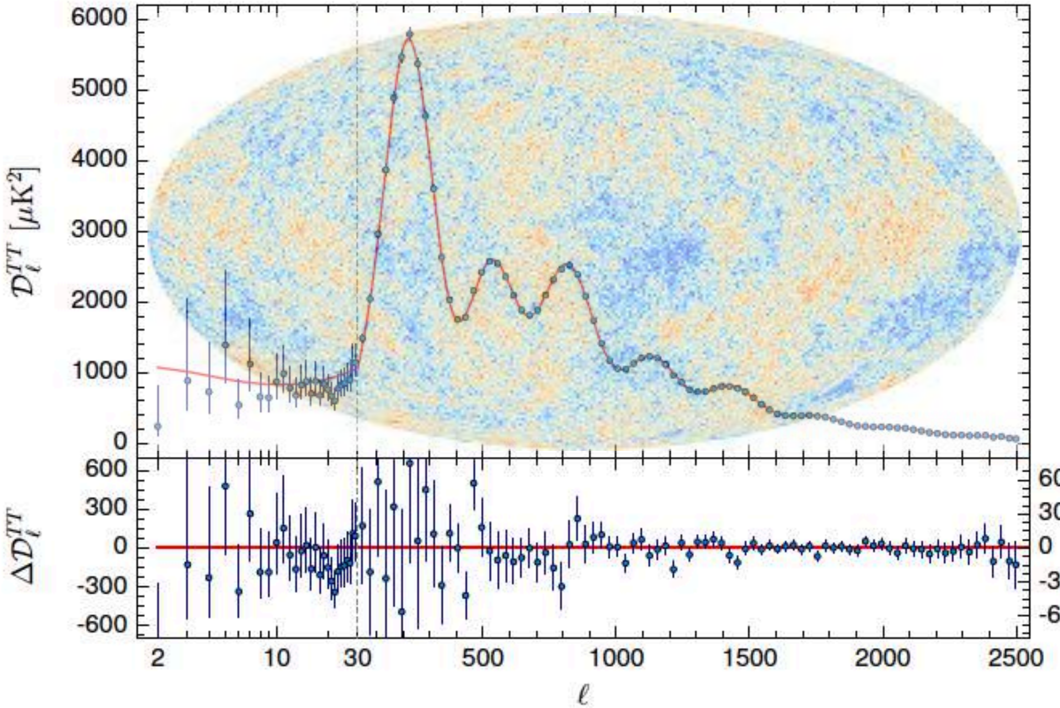

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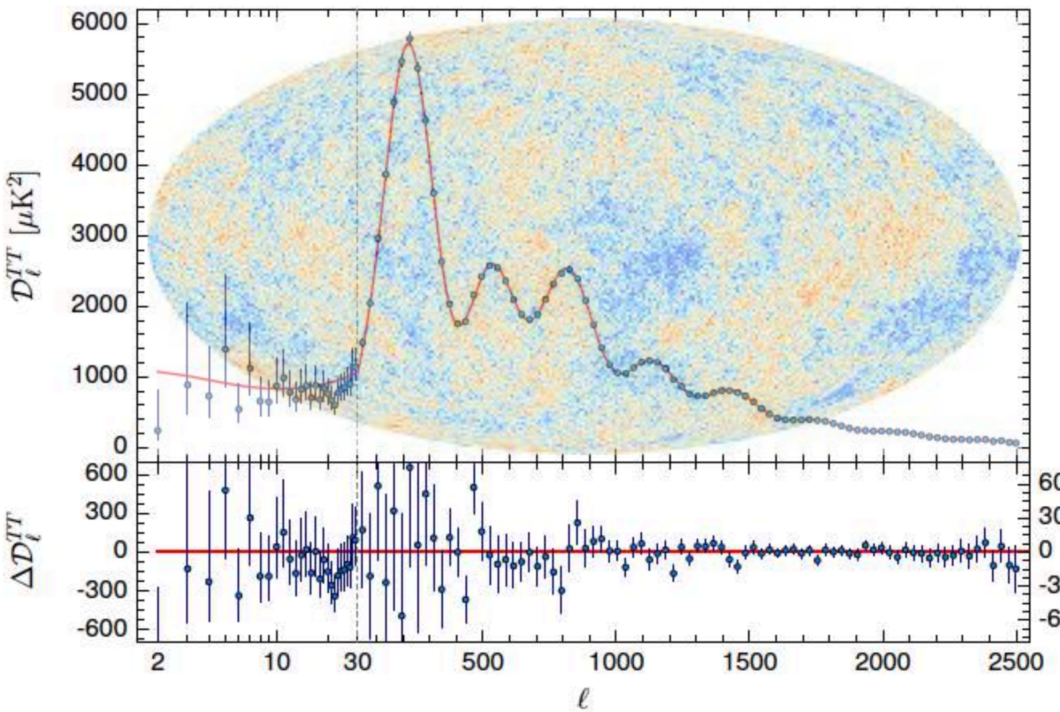

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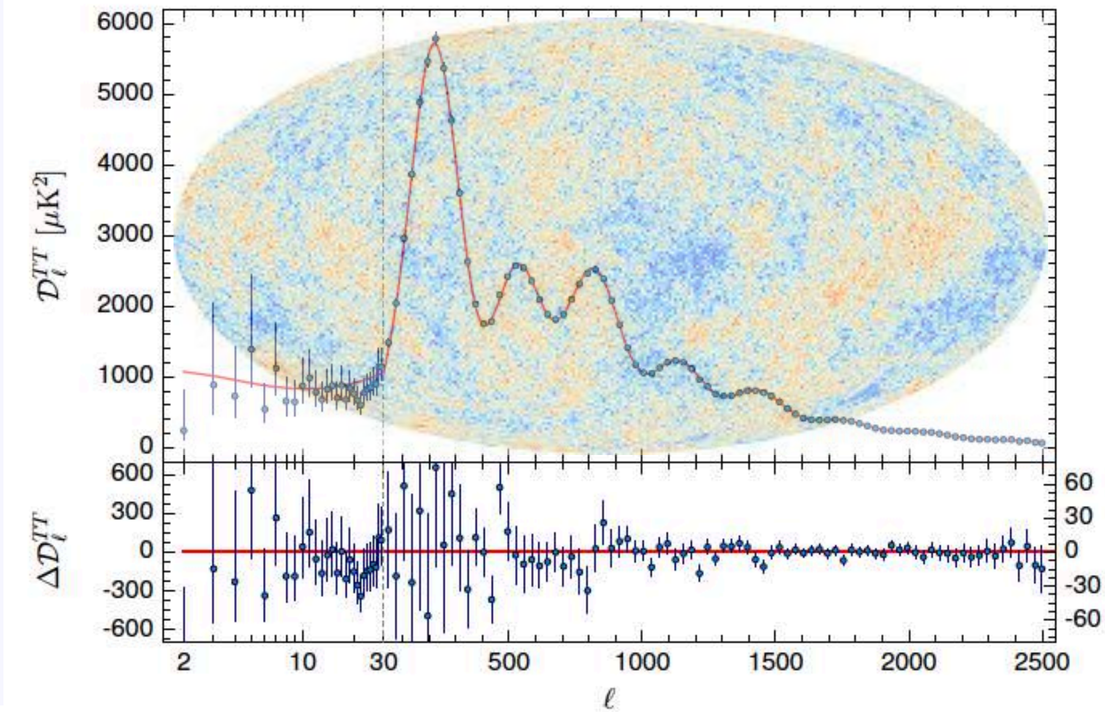

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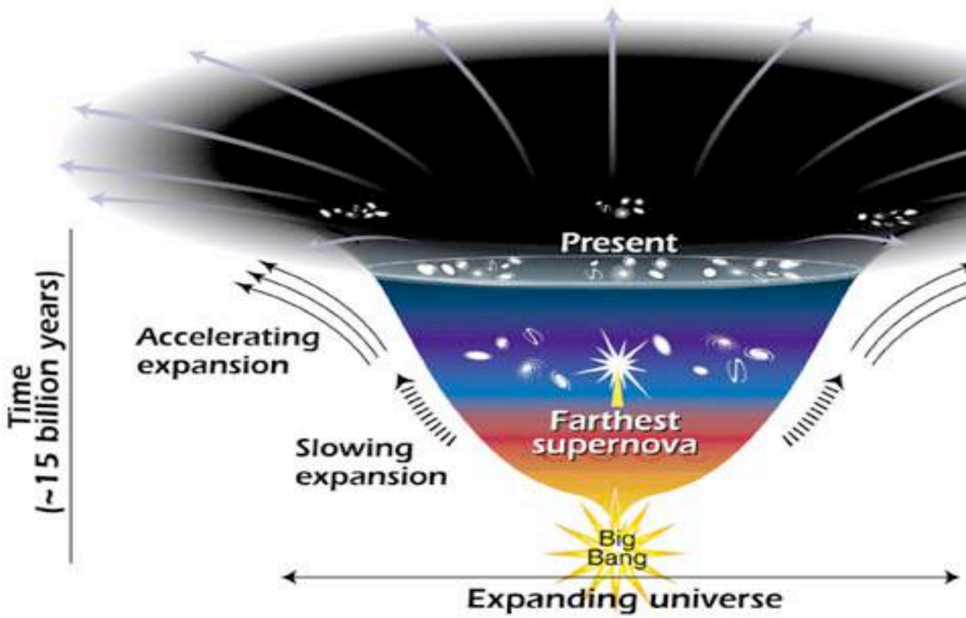
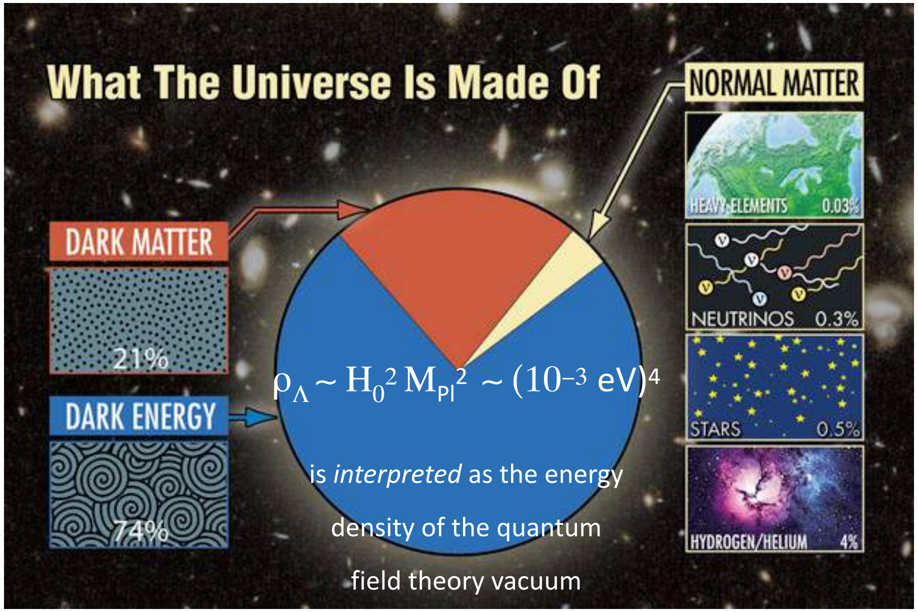
(To detect the late-ISW correlations between CMB & structure induced by Λ will require 10 million redshifts)

It is the Cosmic Sum sum rule that is used to infer a non-zero Λ of $O(H_0^2)$ from observations of SNe Ia, CMB, BAO, lensing etc ...

There is as yet no compelling *dynamical* evidence for Λ (e.g. the late-ISW effect)





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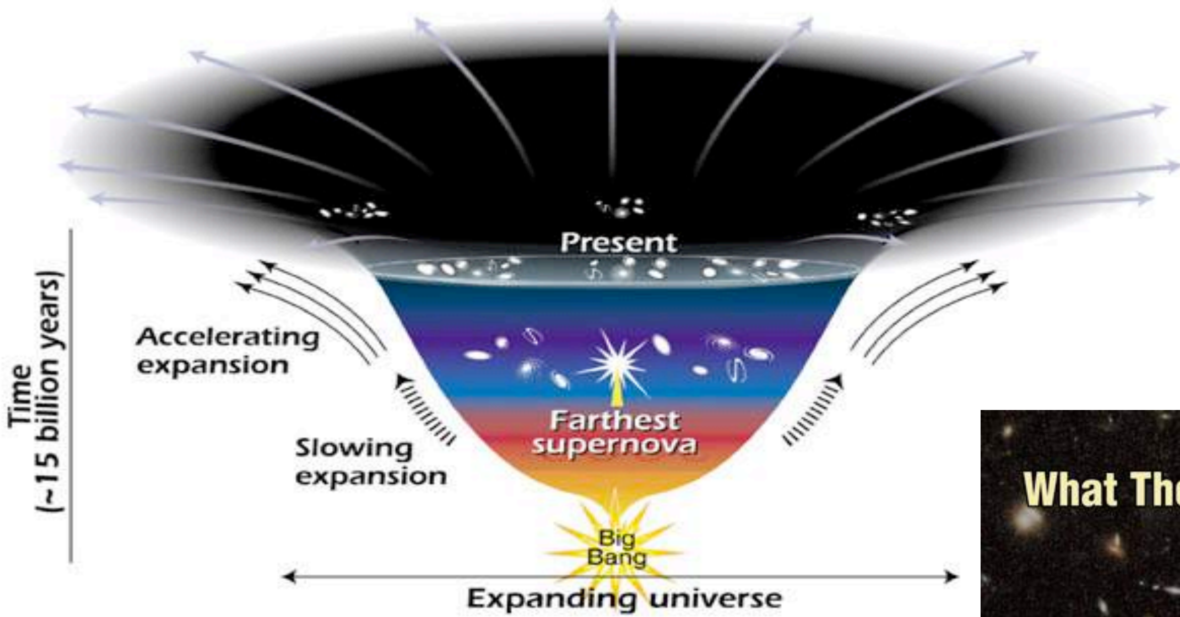
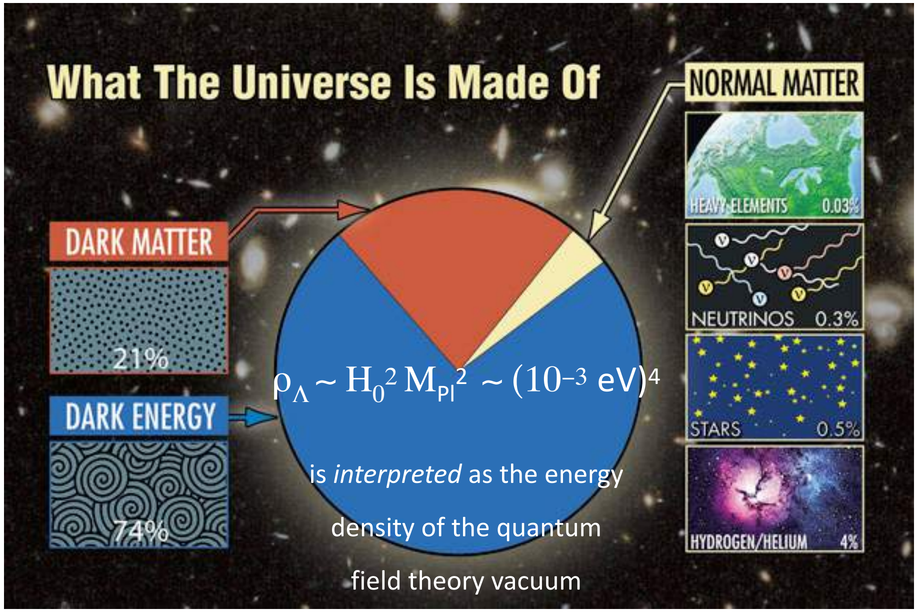


The ΛCDM model is 'simple' (if we take Λ to be just another parameter!) and fits the data (with just a few anomalies) … but lacks a *physical* foundation`



$\rho_\Lambda \sim H_0^2 M_{Pl}^2 \sim (10^{-3}\ \mathrm{eV})^4$

is *interpreted* as the energy density of the quantum field theory vacuum

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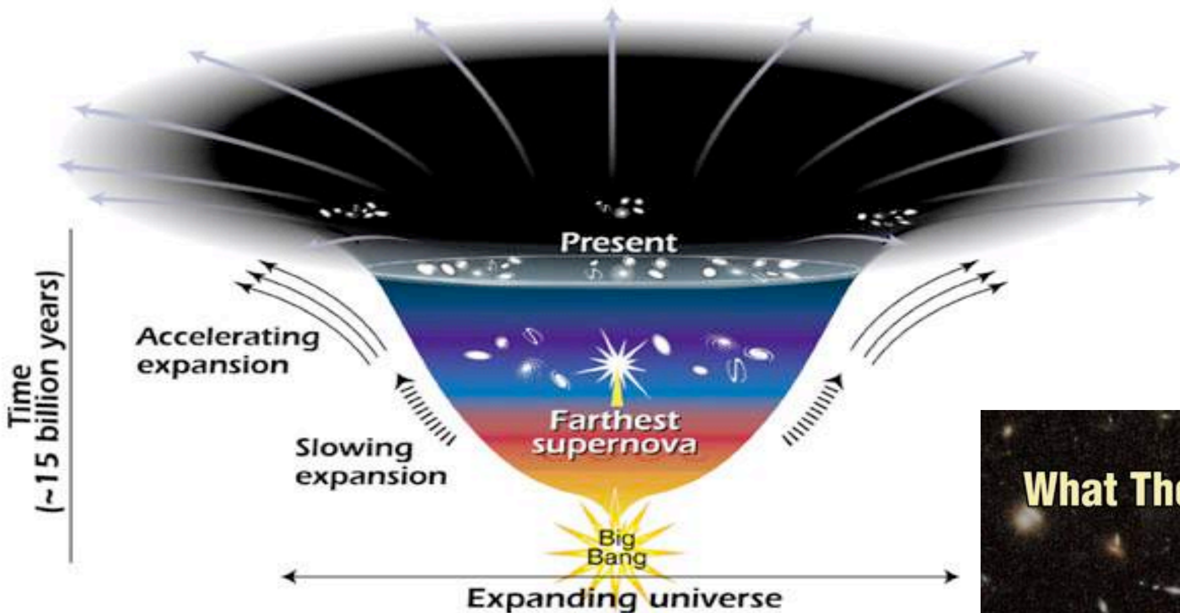

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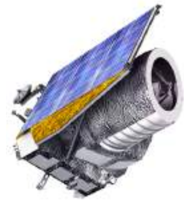
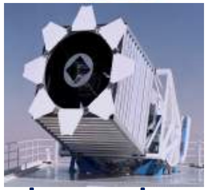

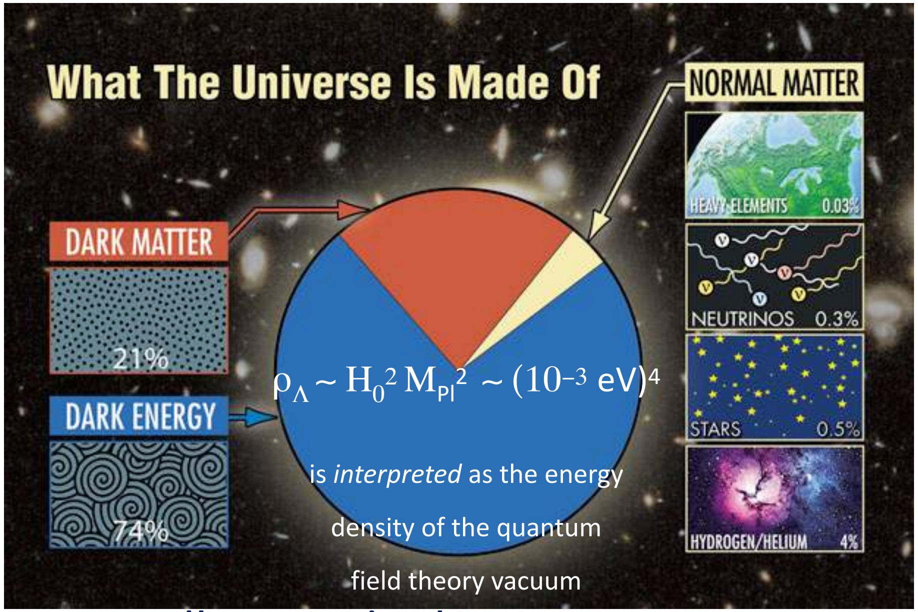

There has been substantial investment in major satellites and telescopes to *measure the parameters* of this standard cosmological model with increasing precision

… but surprisingly little work on ***testing its foundational assumptions***

How well does the real universe conform to the standard FLRW model description?

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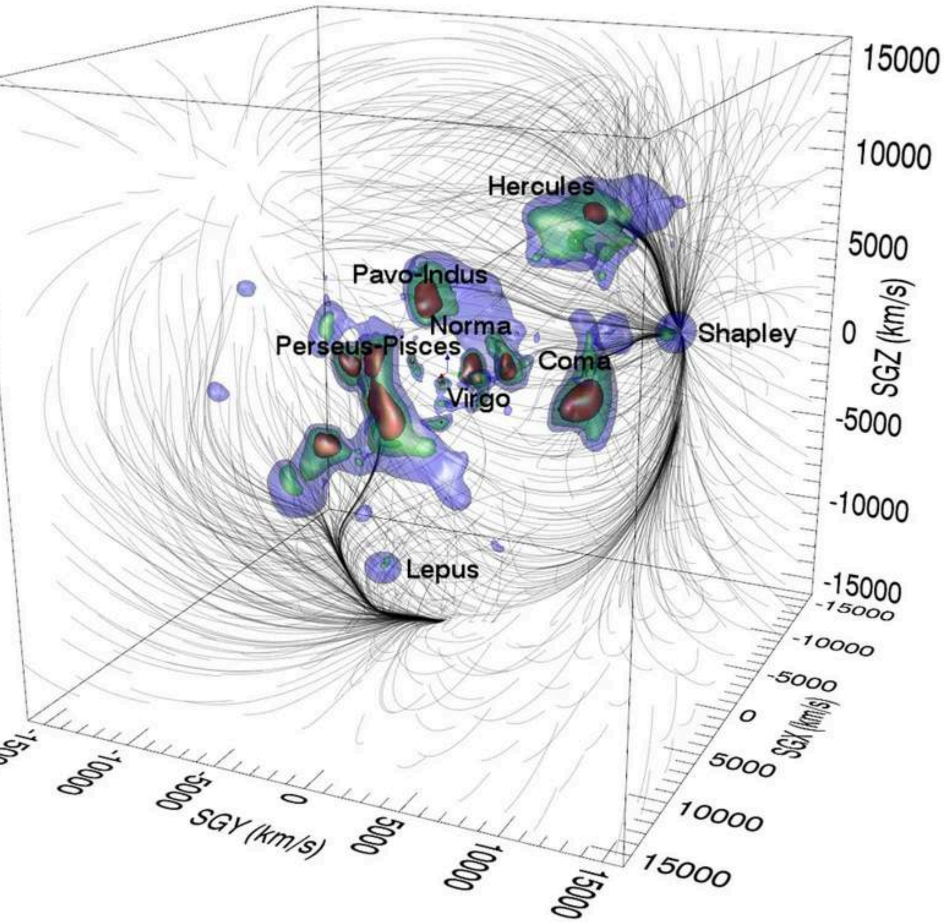
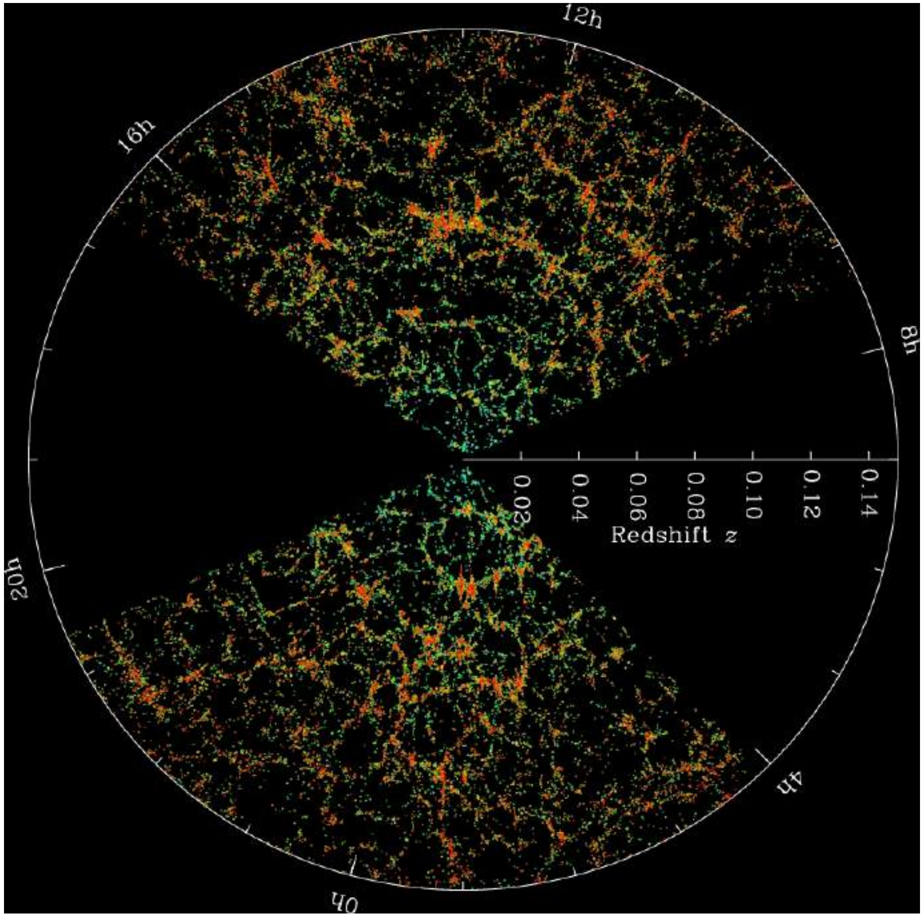
Tully *et al.* *Nature* 513:71,2014



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

… and on the biggest scales (~ 600 Mpc) mapped



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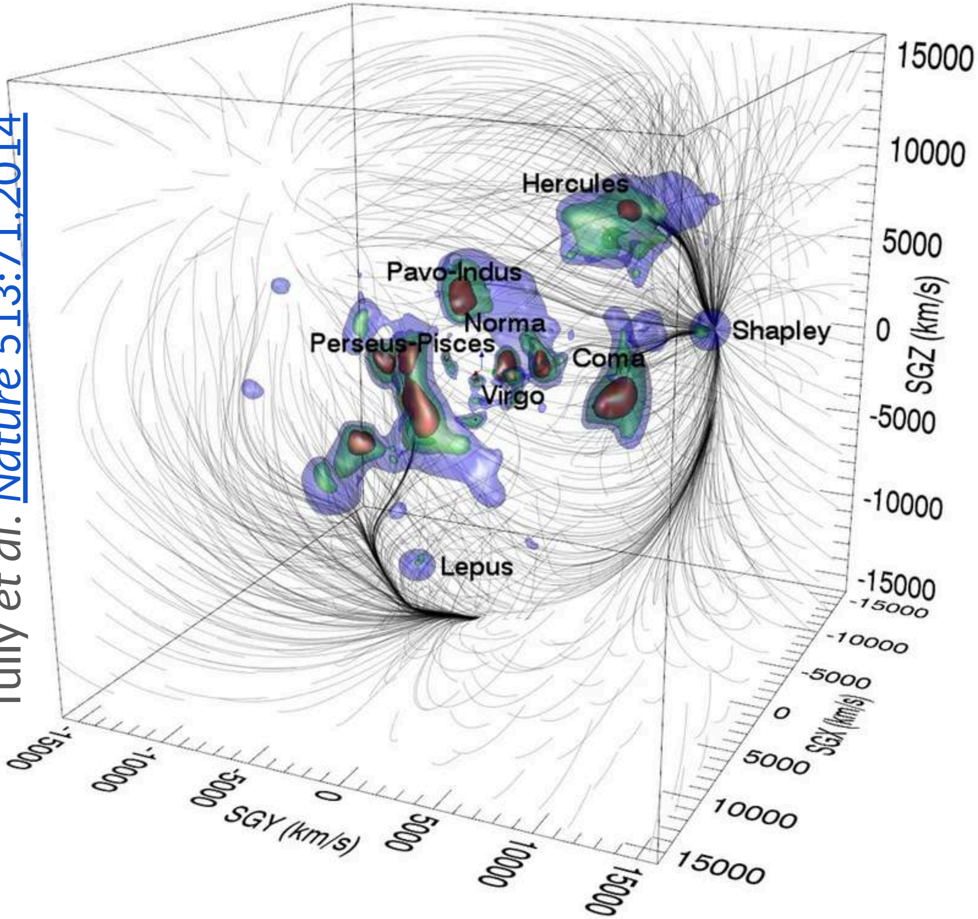

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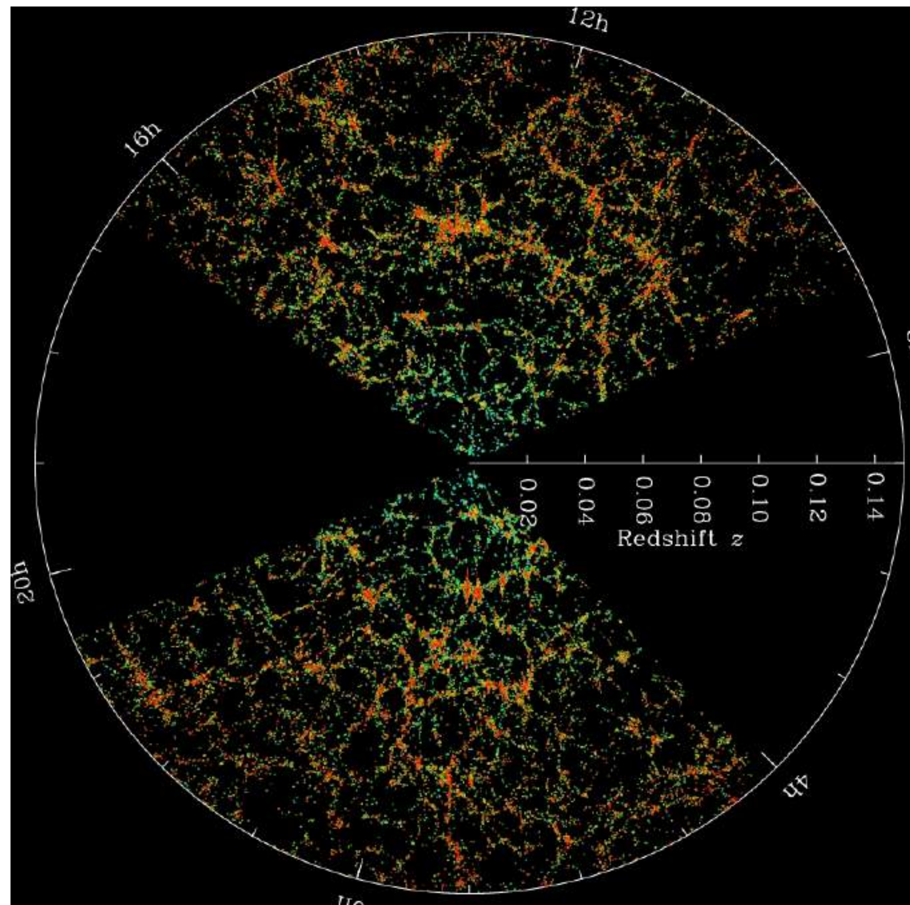

Is it justified to approximate it as *exactly* homogeneous?

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

… To assume that all observed directions are

THE UNIVERSE IS NOT ISOTROPIC AROUND US

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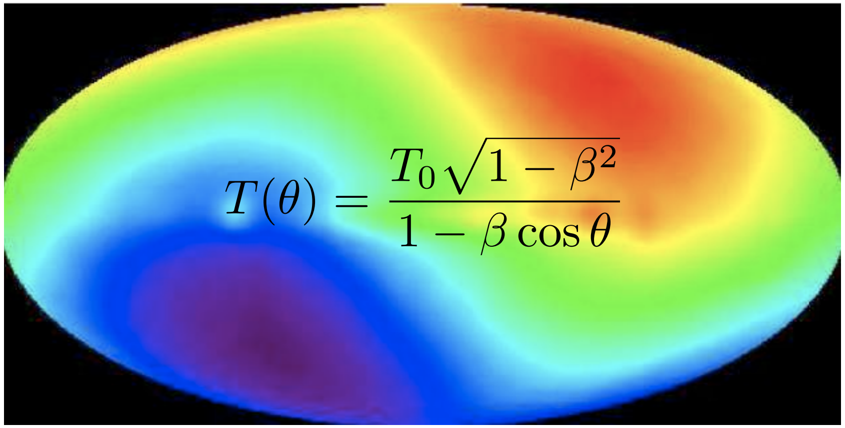
The cosmic microwave background exhibits a dipole anisotropy with $\Delta T/T \sim 10^{-3}$



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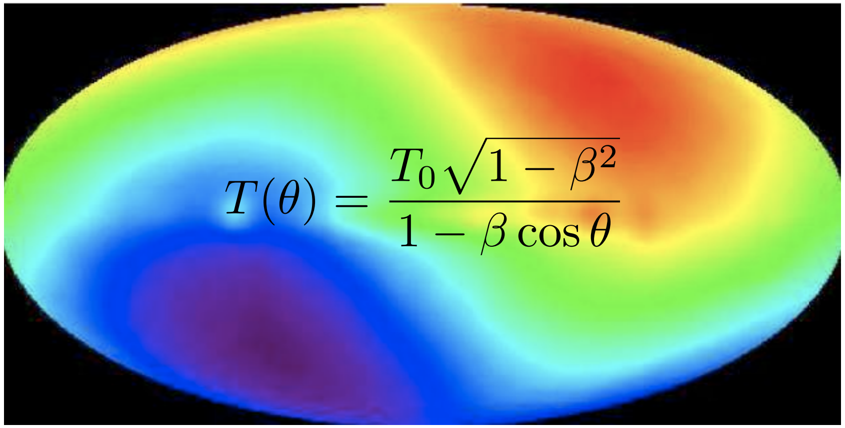

We interpret this as due to our motion at 370 km/s wrt the frame in which the CMB is truly isotropic ⇒ motion of the Local Group

at 620 km/s towards l = 271.9^{o}, b = 29.6^{o}

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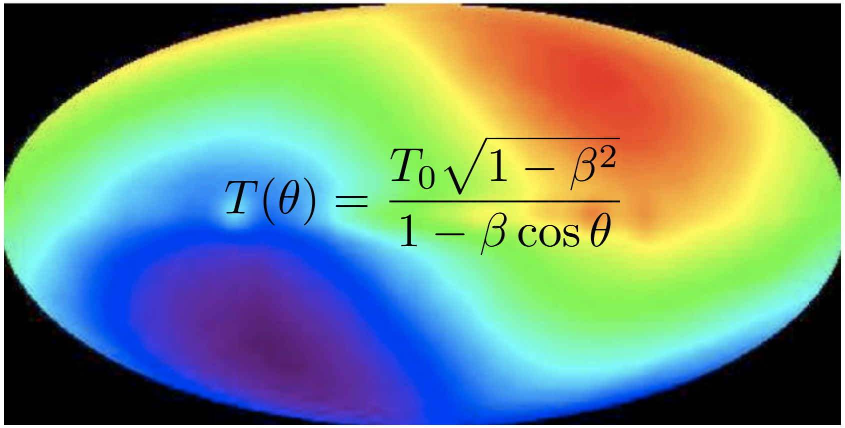

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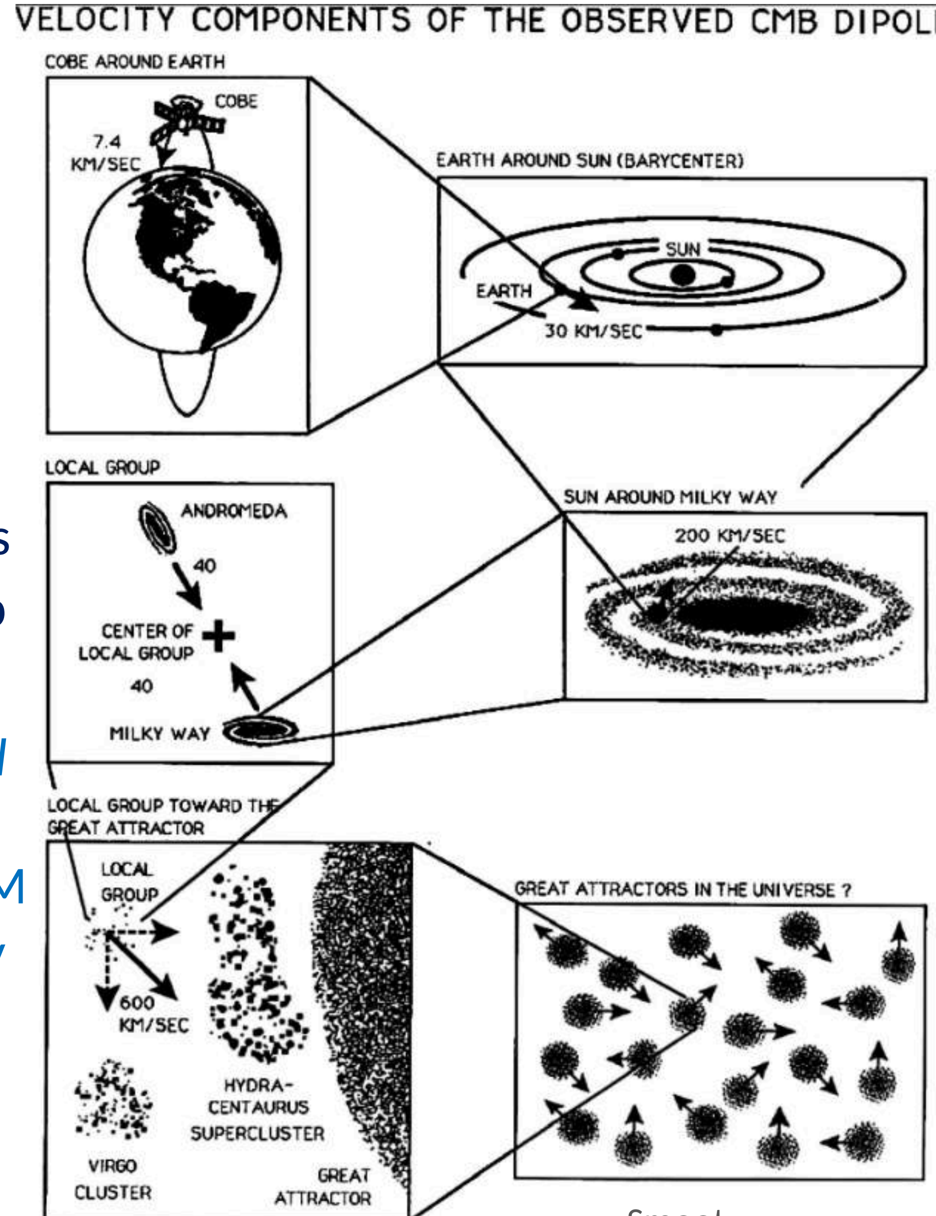

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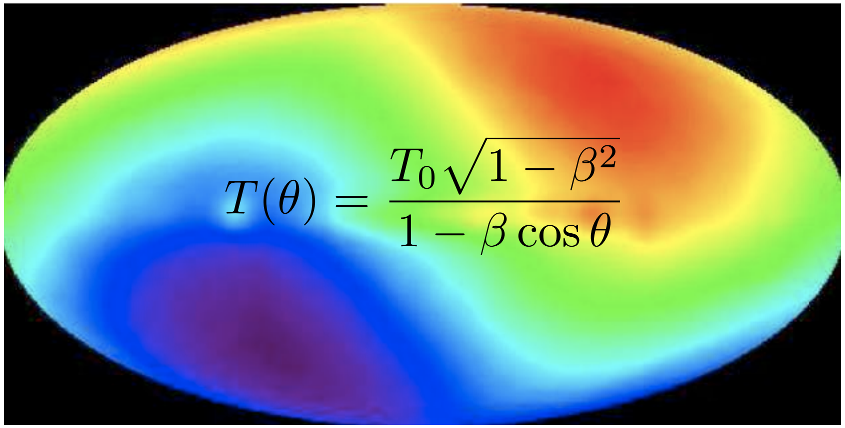

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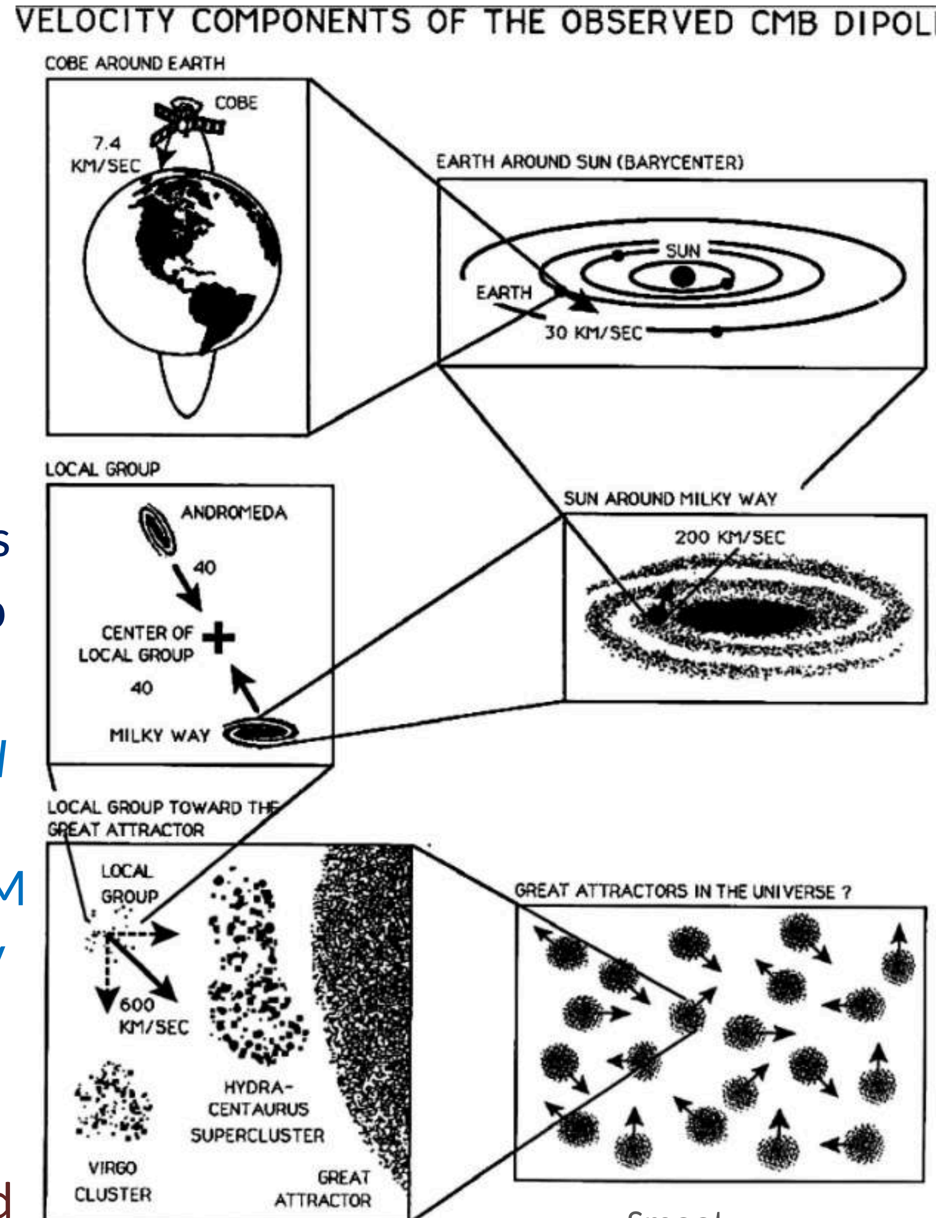
So all data is 'corrected' by transforming to the CMB frame - in which FLRW *should* hold



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A test was proposed after cosmologically distant radio sources were observed

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 between these velocities.

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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

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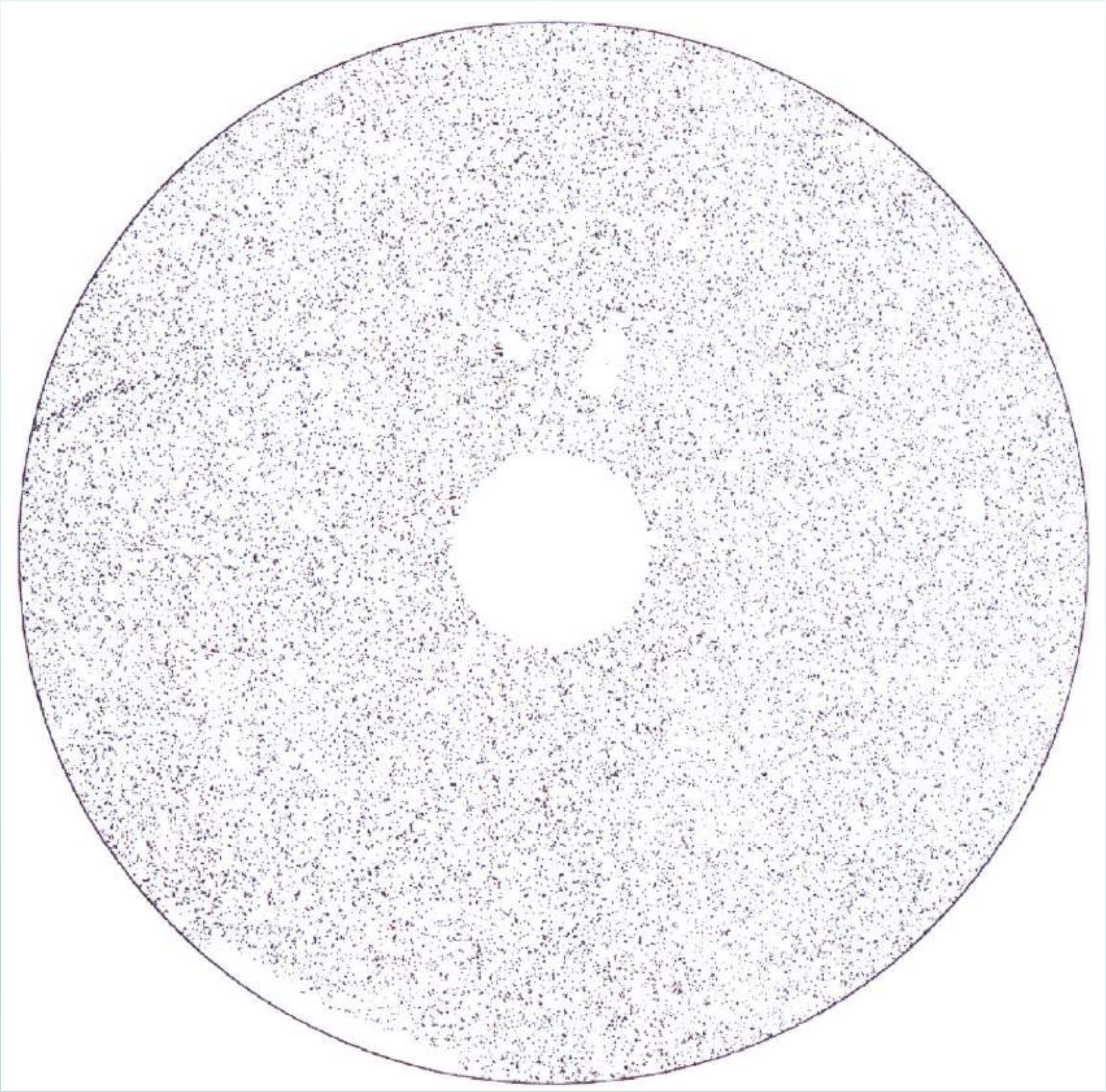
on very large scales (z ~ 1) the distribution of radio sources supposedly demonstrates the isotropy of the Universe



Peebles, *Principles of Physical Cosmology*, 1993

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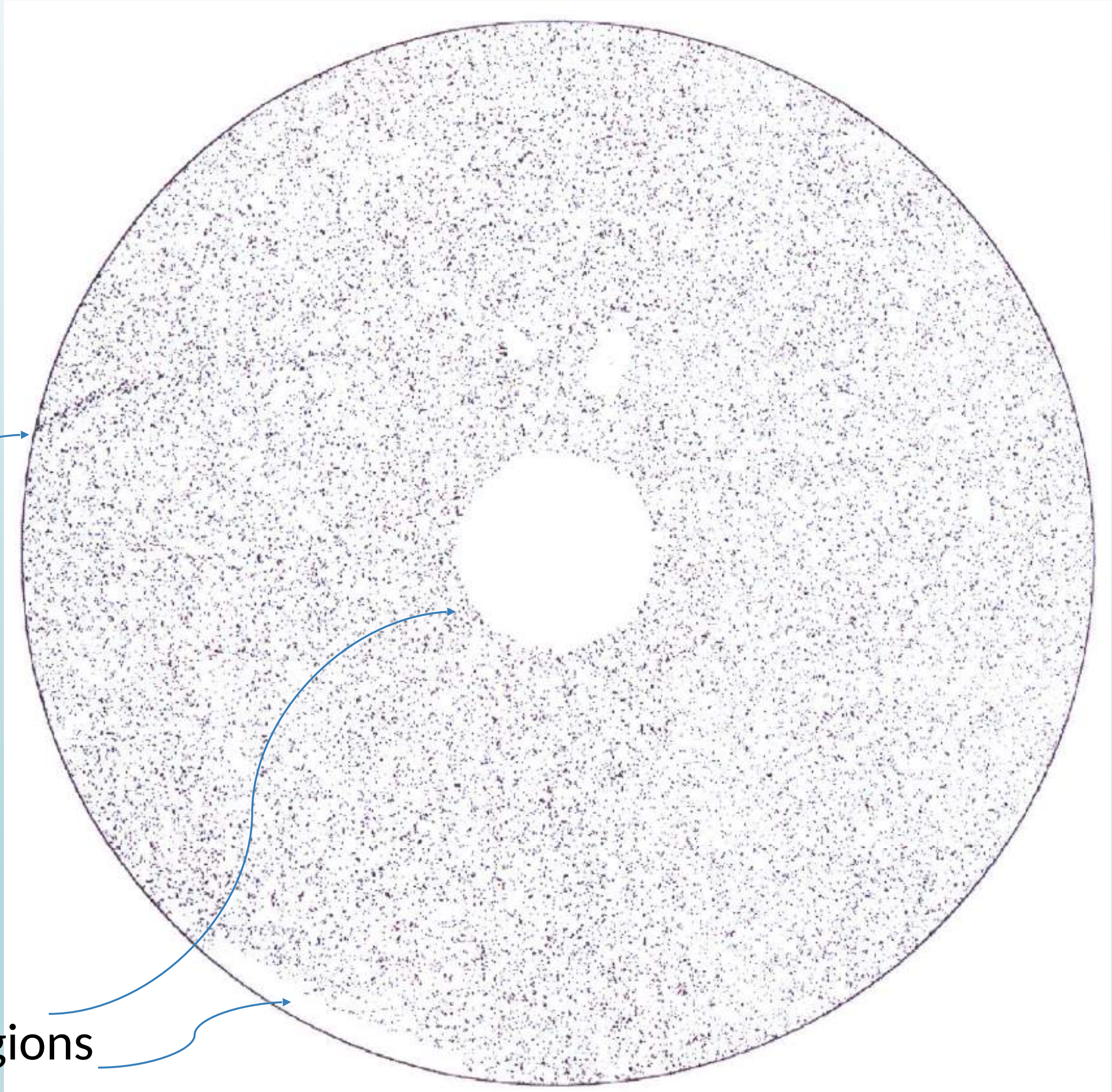

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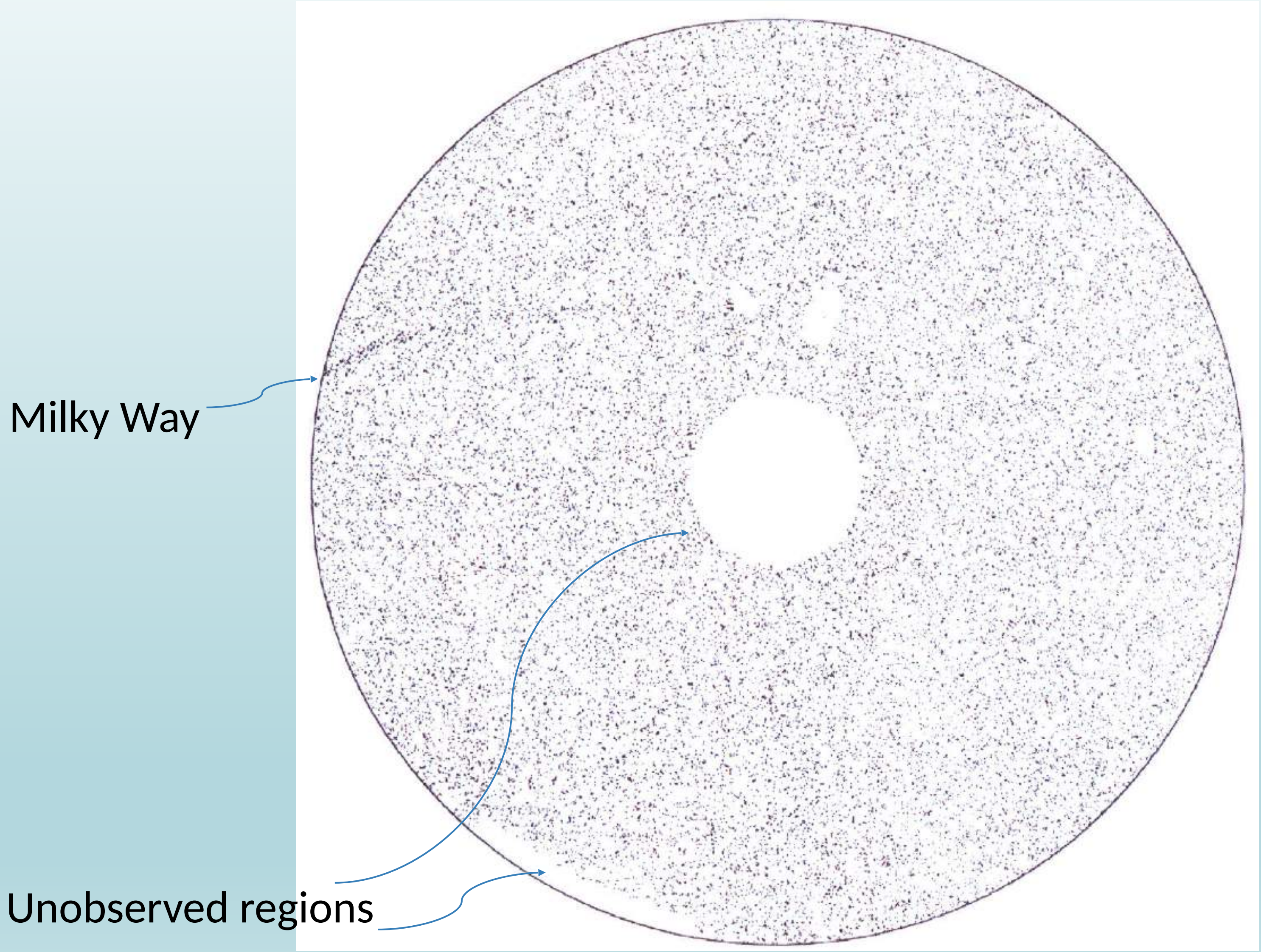

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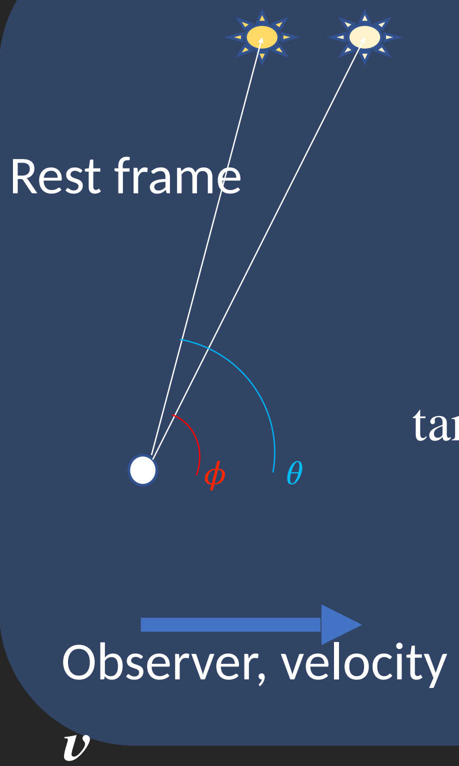
But if we are moving w.r.t. the cosmic rest frame, then distant sources *cannot* be isotropic!

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

Aberration

(Bradley 1727)



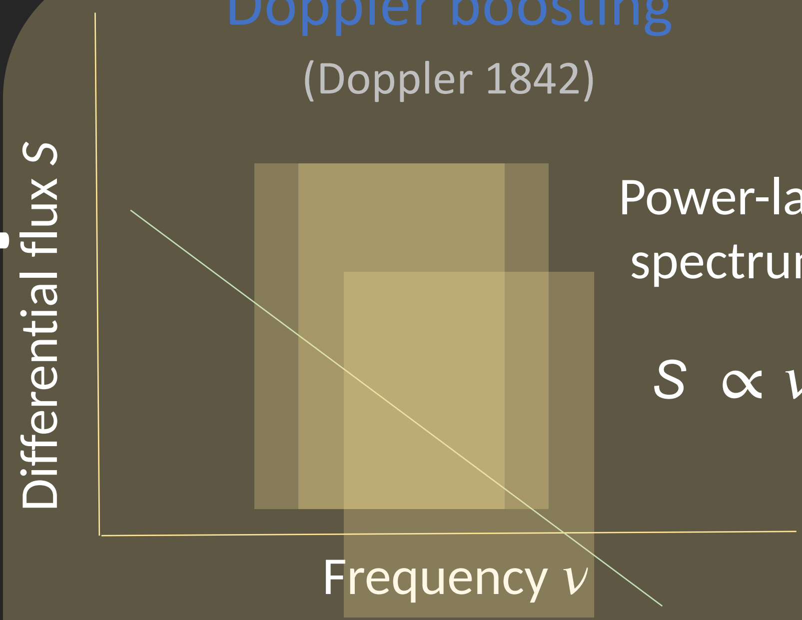
Moving frame

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

+

Doppler boosting

(Doppler 1842)



Power-law spectrum

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

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

Ellis & Baldwin, MNRAS 206:377,1984

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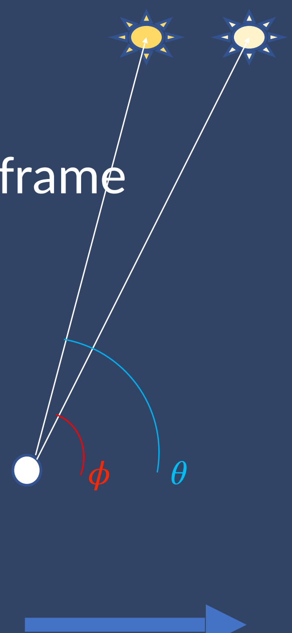
$$\sigma(\theta)_{obs} = \sigma_{rest}[1 + [2 + x(1+\alpha)]\frac{v}{c}\cos(\theta)]$$

Aberration

(Bradley 1727)

Rest frame



Moving frame

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Observer, velocity $\boldsymbol{v}$

+

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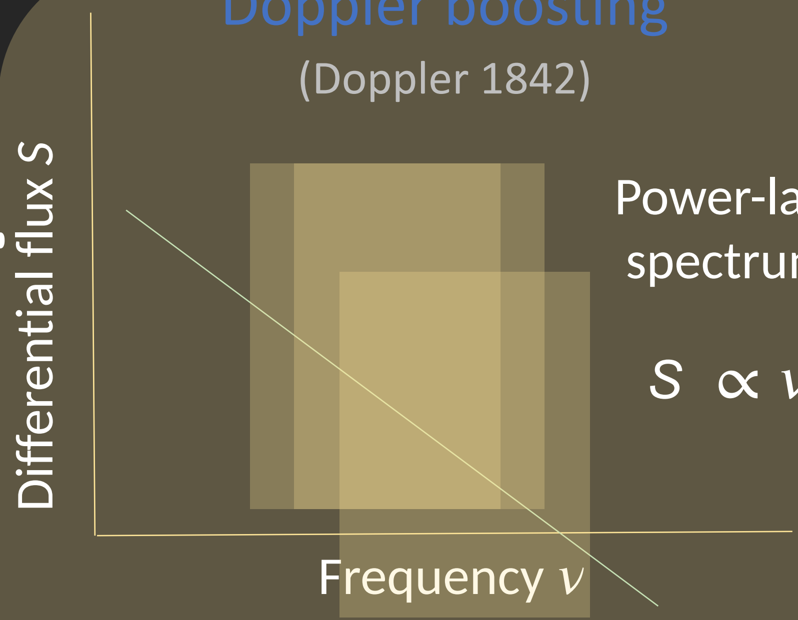

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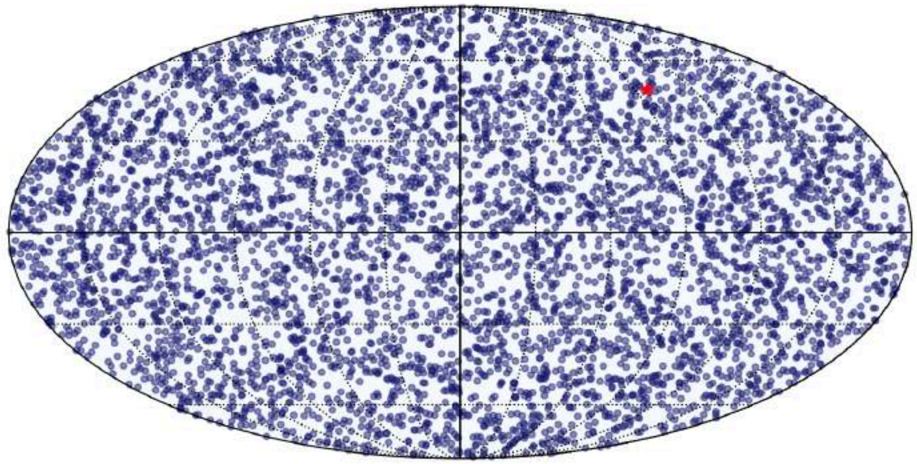
Integral flux distribution: $N(>S) \propto S^{-x}$

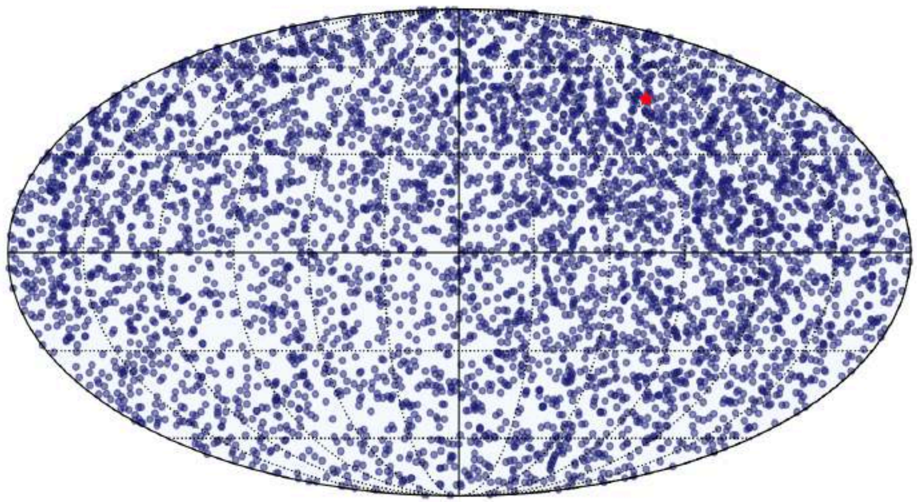
Flux-limited catalogue → *more* sources in direction of motion

Ellis & Baldwin, MNRAS 206:377,1984

Galaxies / quasars in CMB "rest frame"

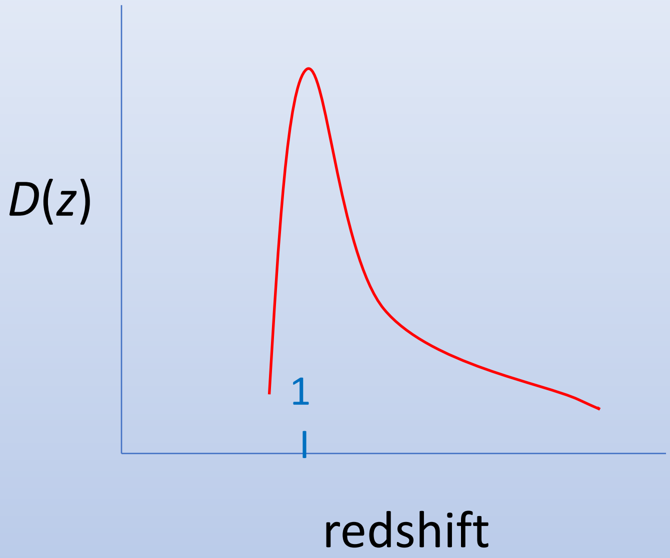


Aberration: object positions compressed in direction of motion
Doppler boosting: otherwise too-faint objects boosted into catalog flux limit



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

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



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

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

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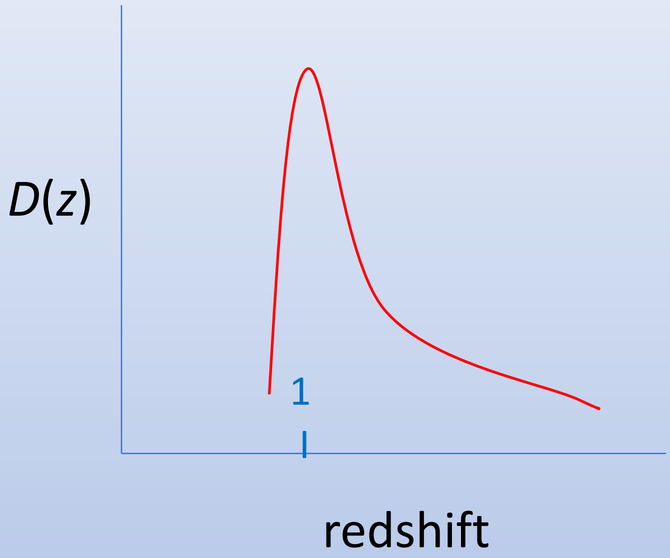

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NVSS + SUMSS: 600,000 radio sources <*z*> ~ 1 (est.), $\vec{\mathscr{S}}$ (D(z)) $\rightarrow$ 0 (est.)

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

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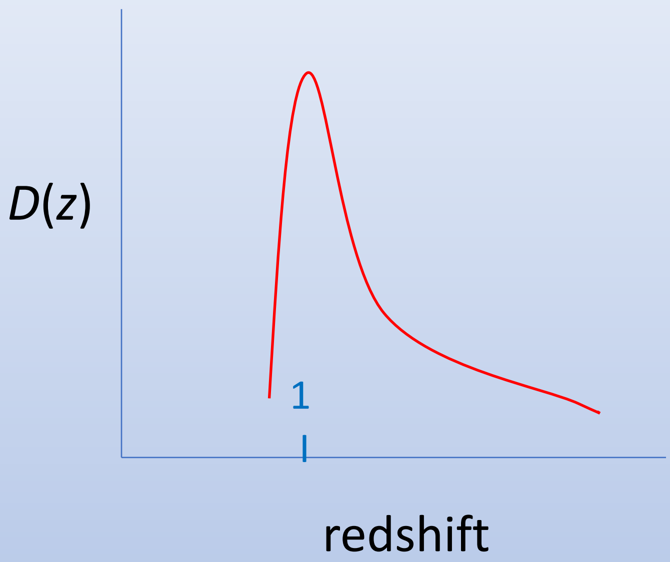

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Rameez, Mohayaee, S.S. & Colin, MNRAS 477:1722,2018

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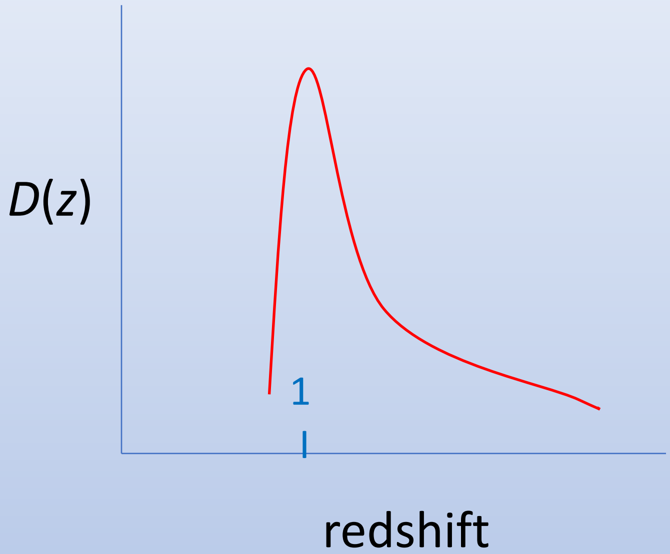

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Rameez, Mohayaee, S.S. & Colin, MNRAS 477:1722,2018

Wide Field Infrared Survey Explorer: 1,360,000 quasars, <*z*> ~ 1.2, $\vec{\mathscr{S}}$ (D(z)) ~ 1%

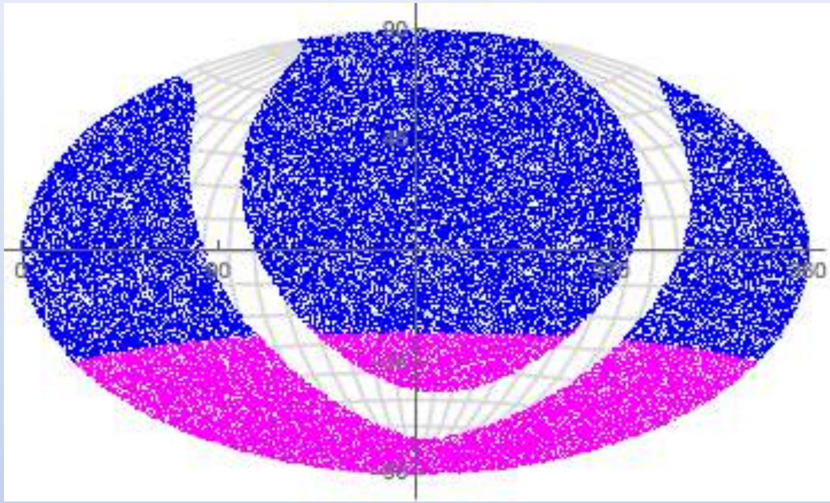
Secrest, Rameez, von Hausegger, Mohayaee, S.S. & Colin, ApJ Lett.908:L51,2021

The NRAO VLA Sky Survey (NVSS) + Sydney University Molonglo Sky Survey (SUMSS)

(1.4 GHz survey down to Dec = -40.4^o)

(843 MHz survey at Dec < -30^o)

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



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

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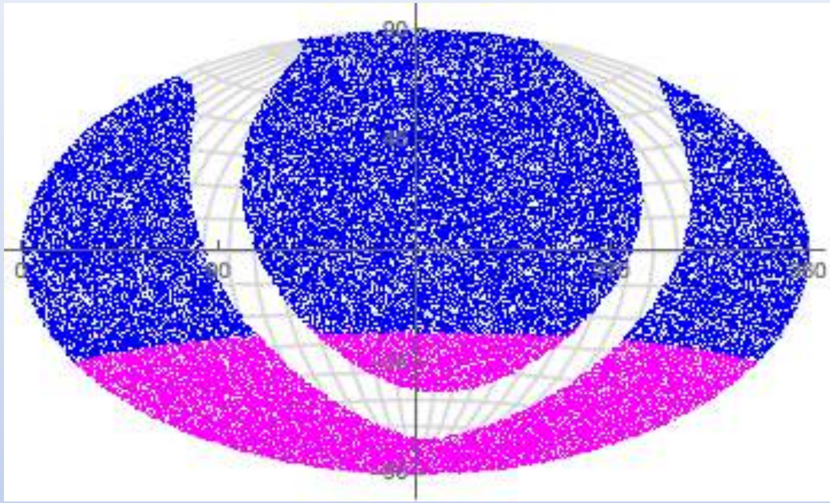

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Colin, Mohayaee, Rameez & S.S., MNRAS 471:1045,2017

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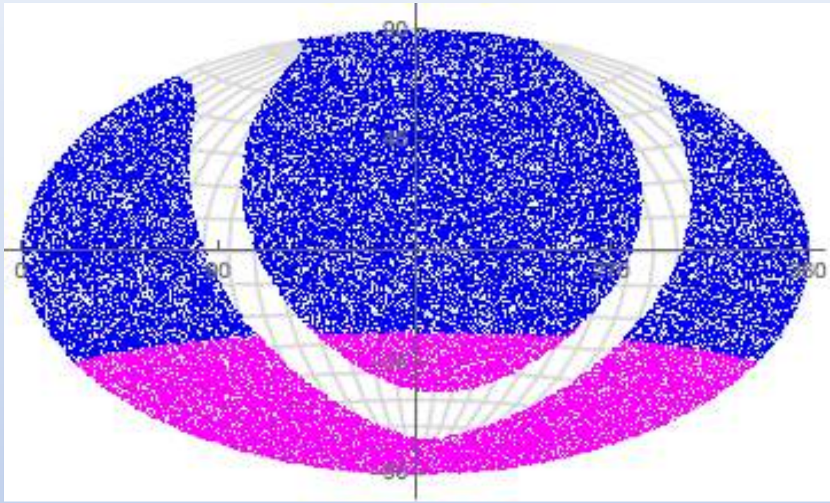

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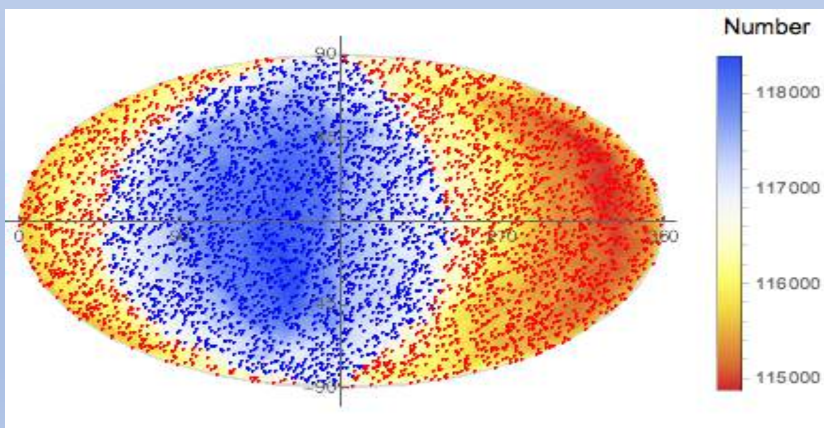

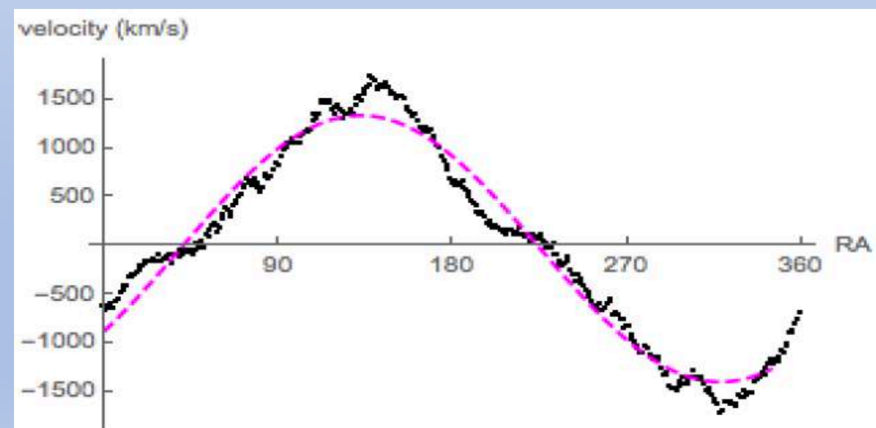

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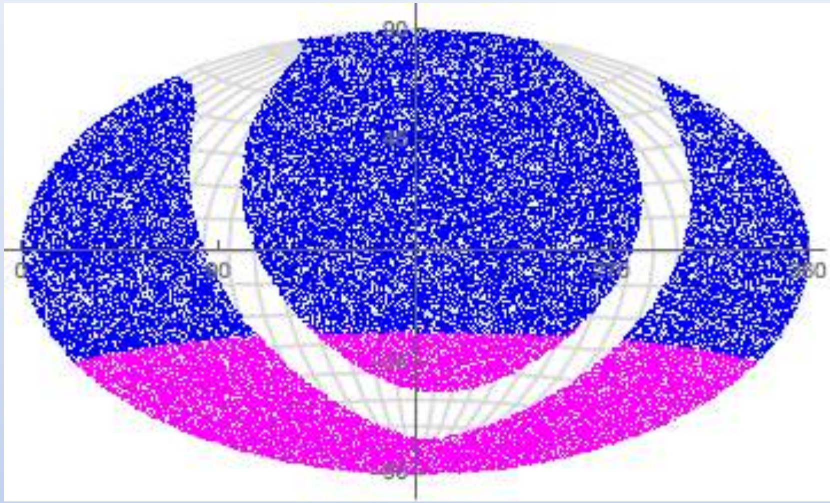

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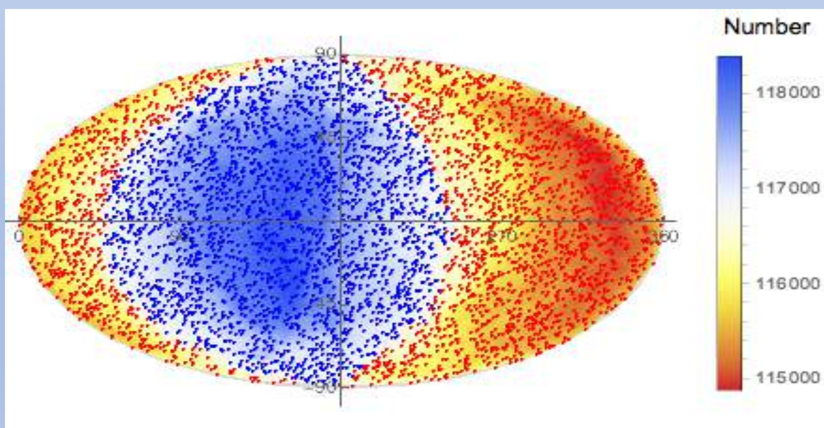

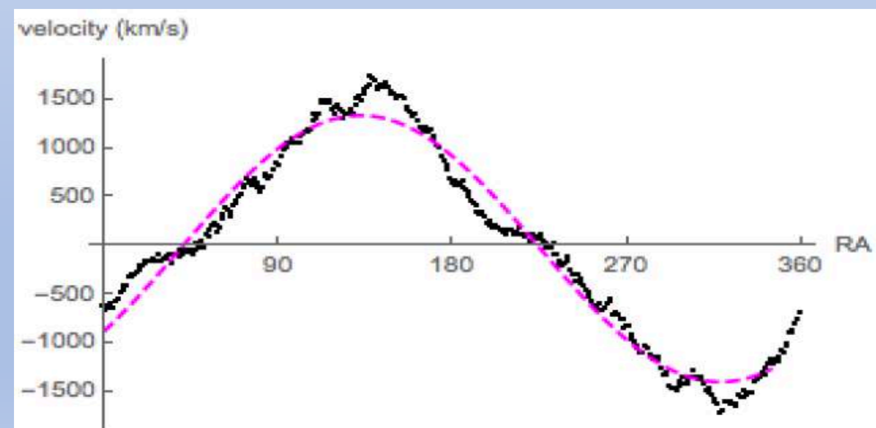

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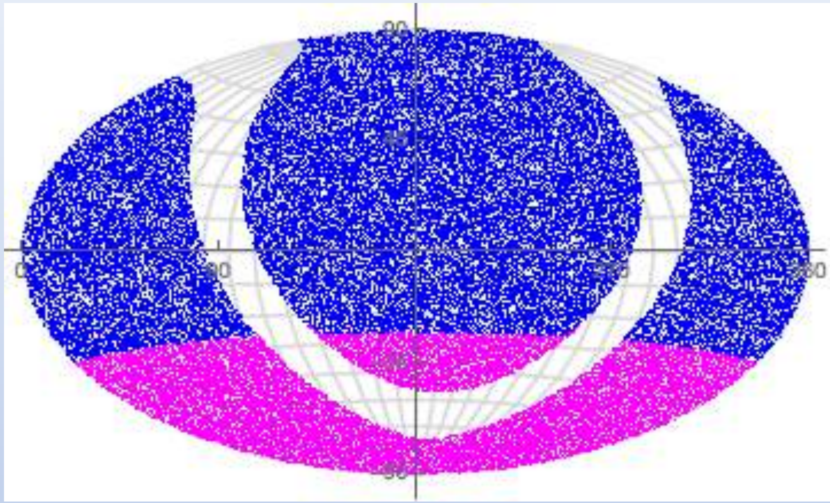

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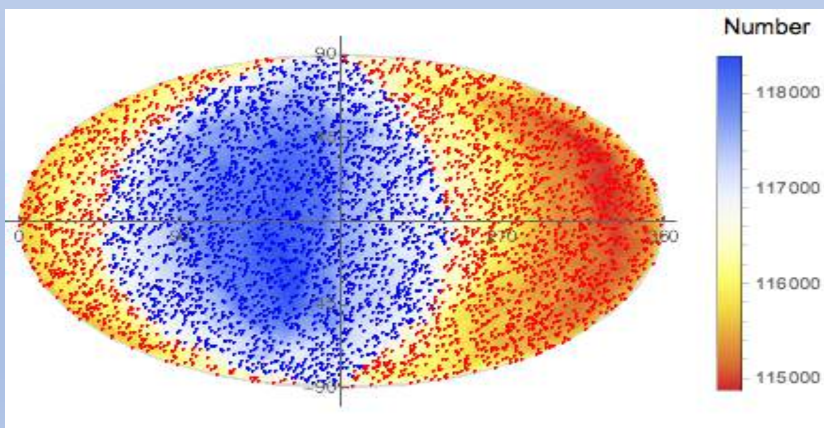
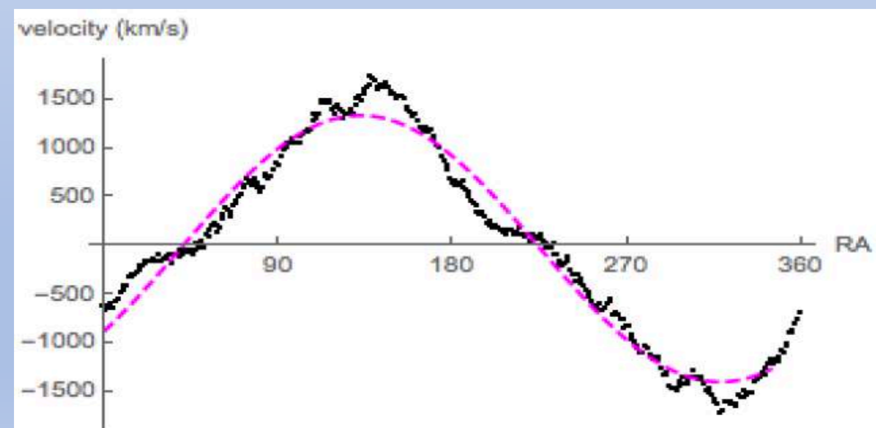
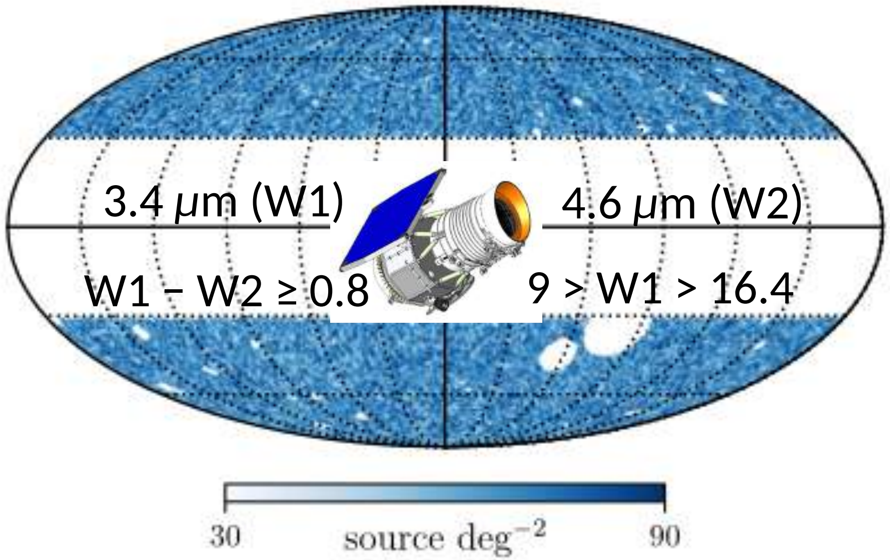




Confirms claim by Singal (ApJ **742**:L23,2011) … however source redshifts are not *directly* measured (also the statistical significance is only 2.8**σ** – by Monte Carlo)

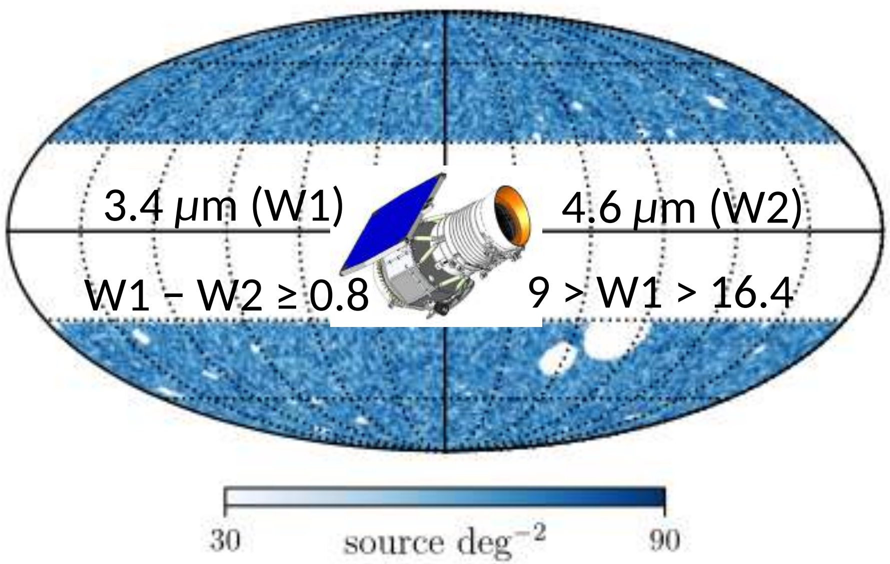
Colin, Mohayaee, Rameez & S.S., MNRAS 471:1045,2017

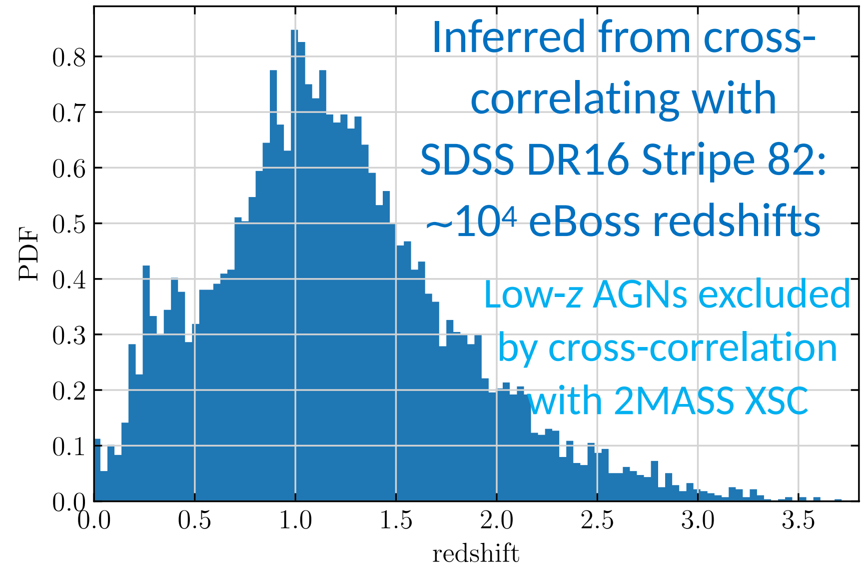
Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL 908:L51,2021



We now have a catalogue of 1.36 million quasars, with 99% at redshift > 0.1

The CatWISE quasar catalogue





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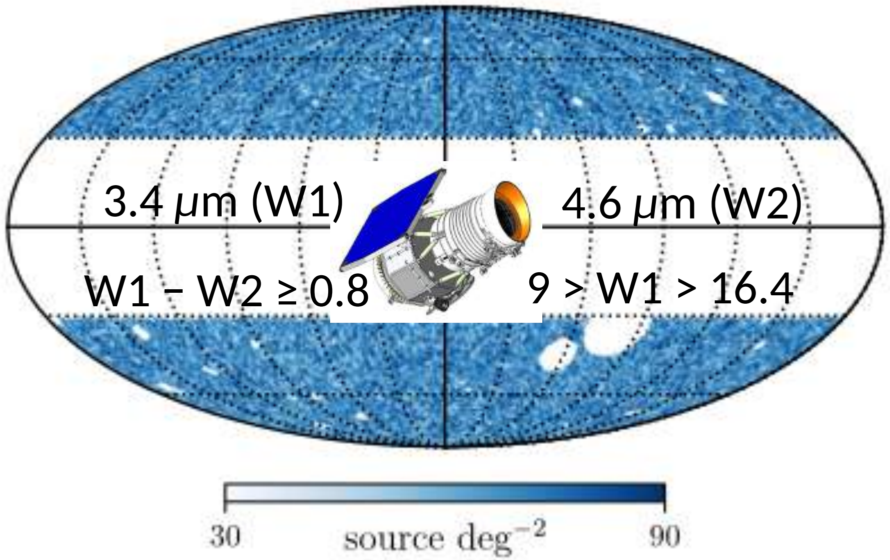

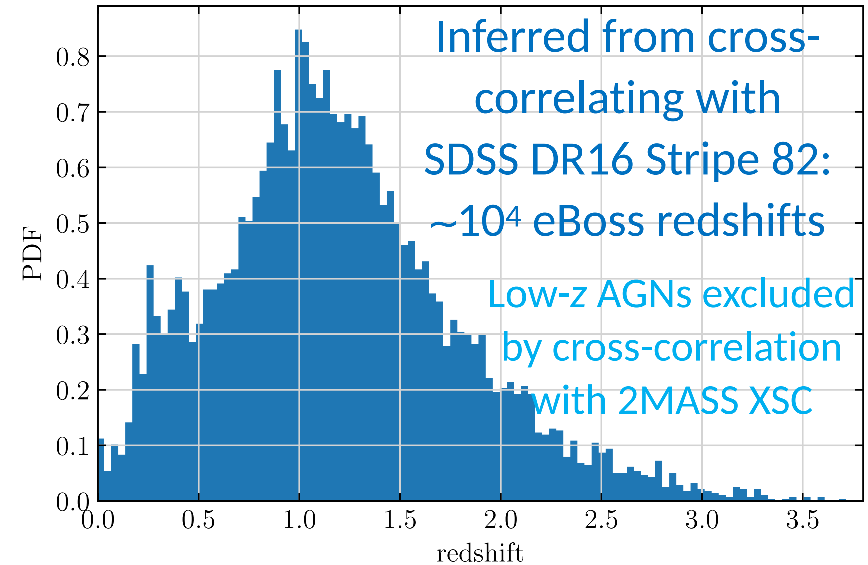

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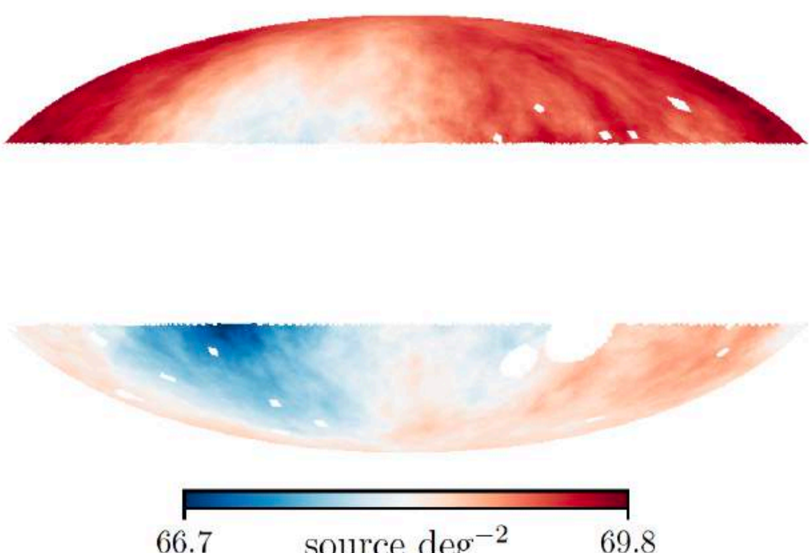

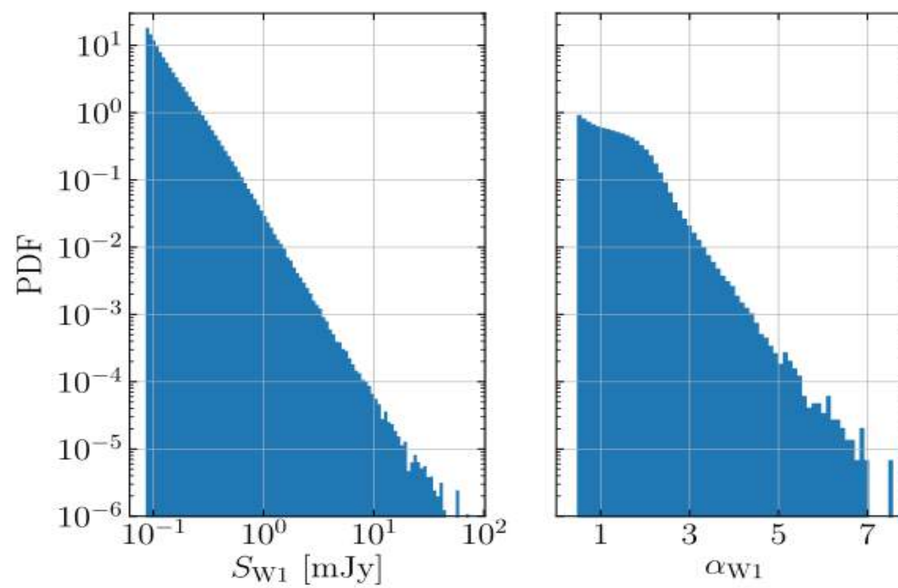

The dipole can be compared to that expected, knowing the spectrum & flux distribution

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

Our peculiar velocity wrt quasars ≠ peculiar velocity wrt the CMB

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

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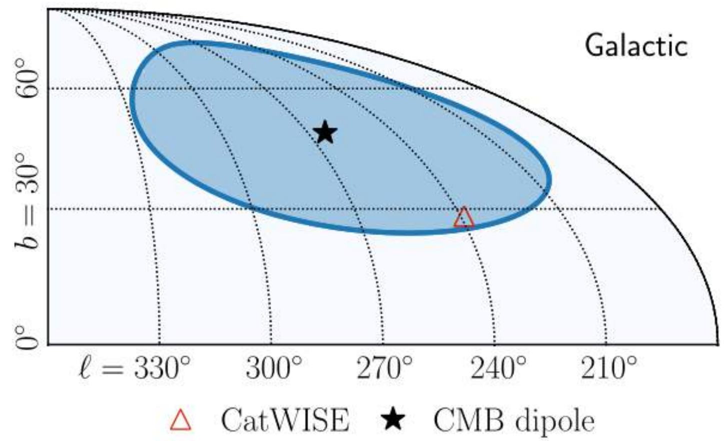

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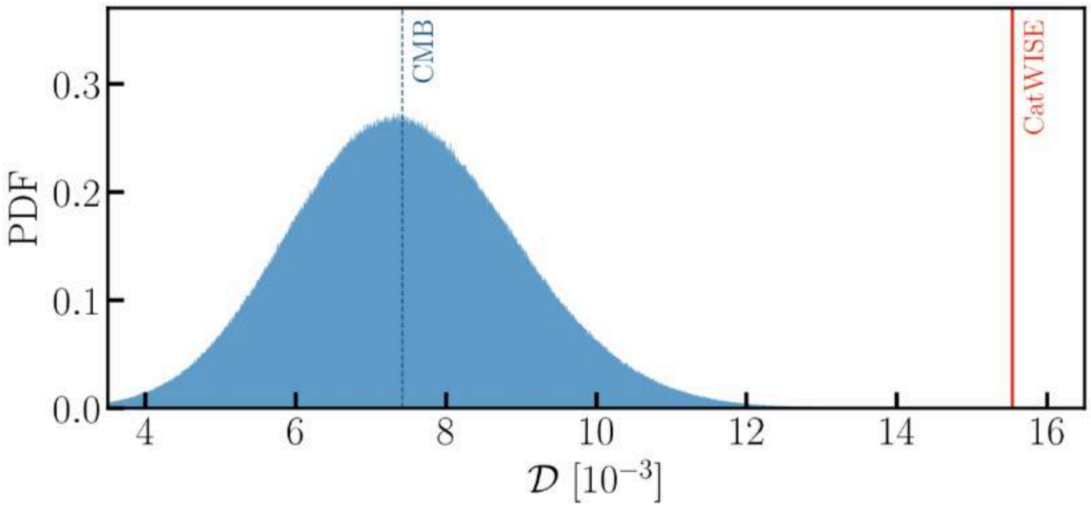

Secrest, Rameez, Von Hausegger, Mohayaee, S.S. & Colin, ApJL 908:L51,2021

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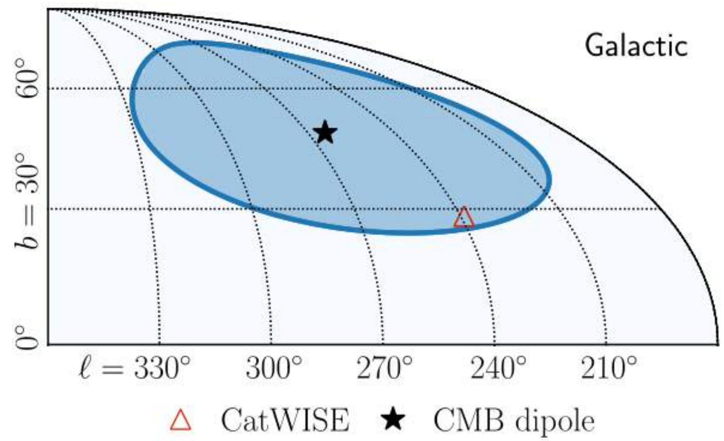

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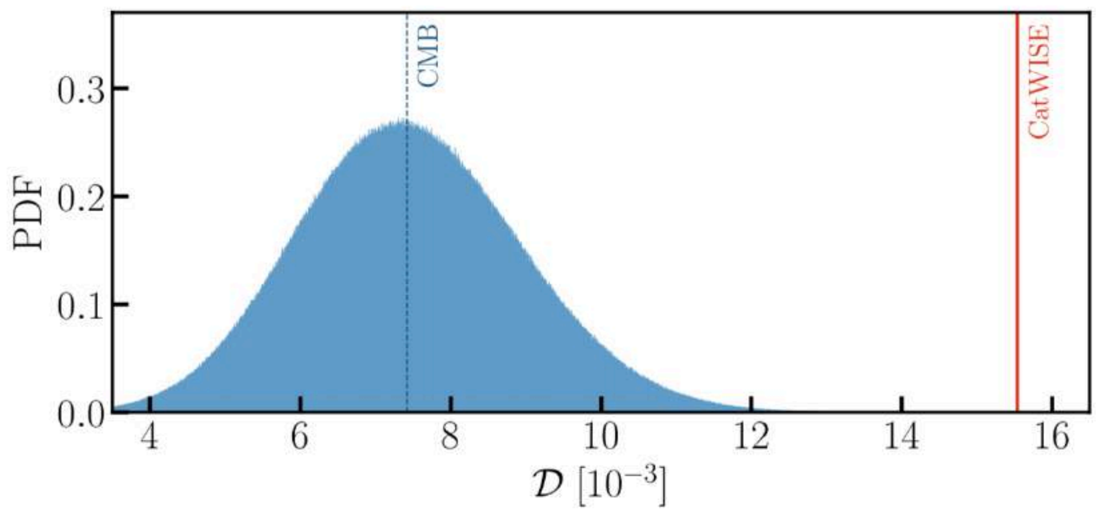
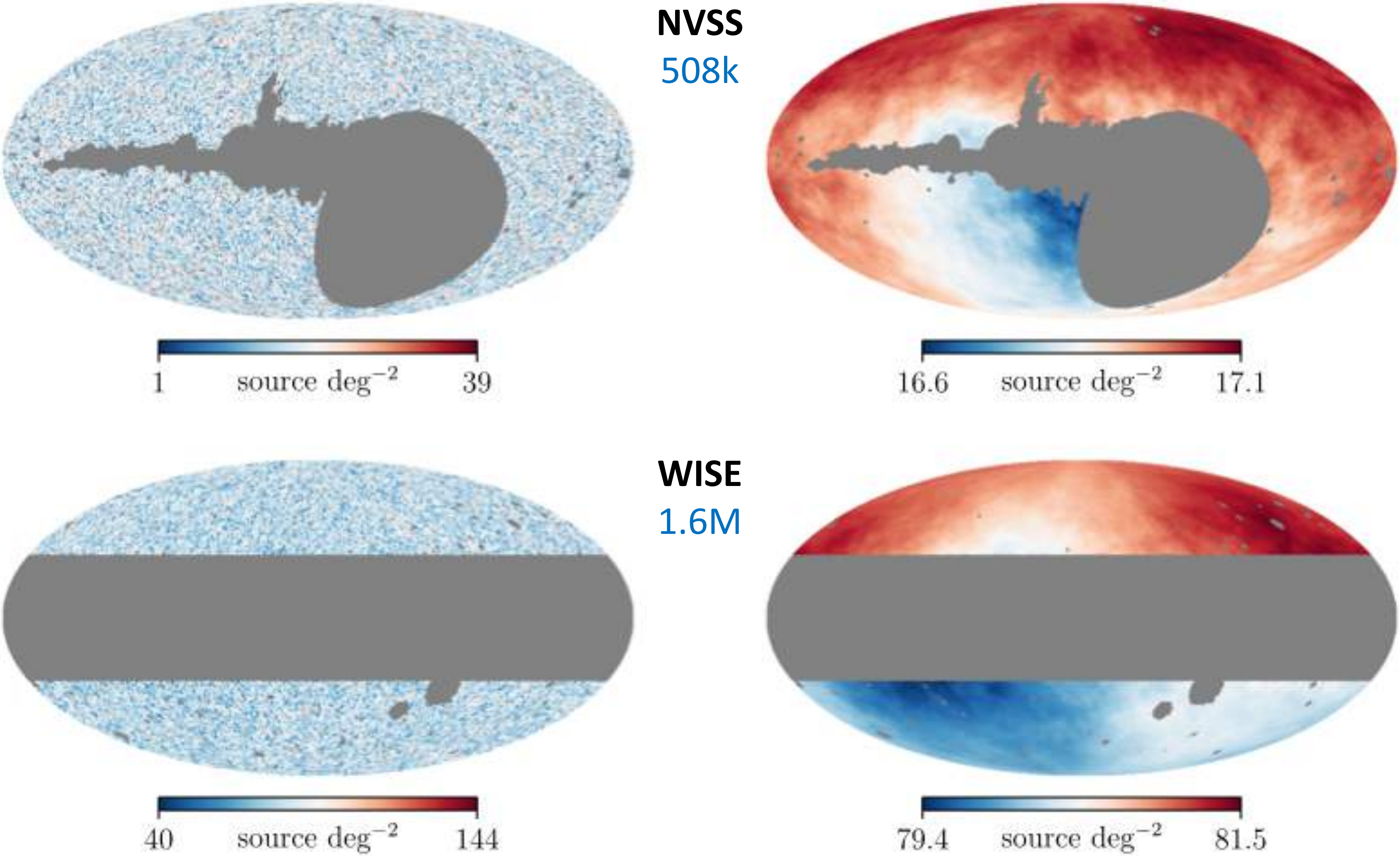


The kinematic interpretation of the CMB dipole is *rejected* with $p = 5 \times 10^{-7} \Rightarrow 4.9\sigma$

(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



Secrest, Rameez, Von Hausegger, Mohayaee, S.S., arXiv:2206.05624

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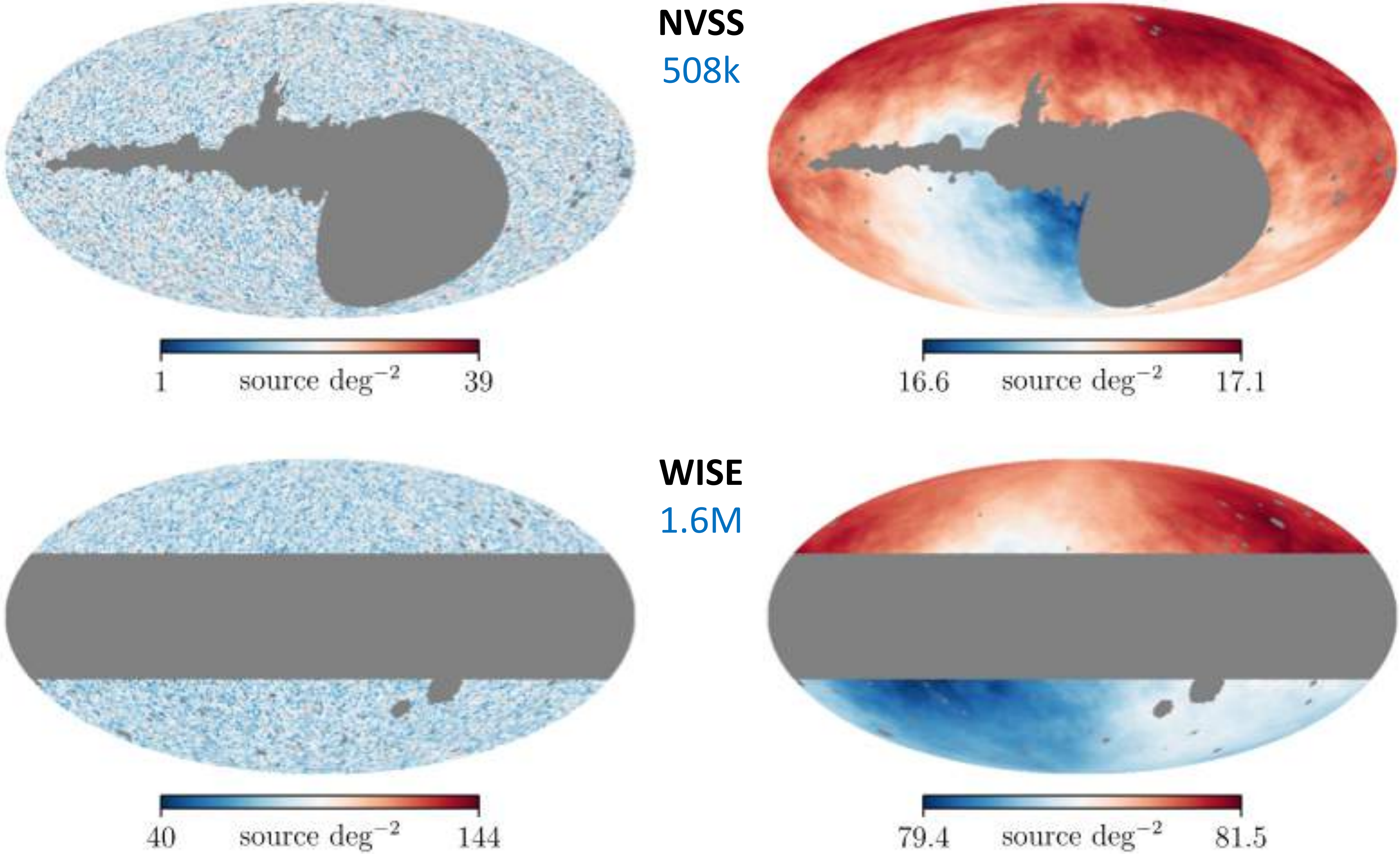
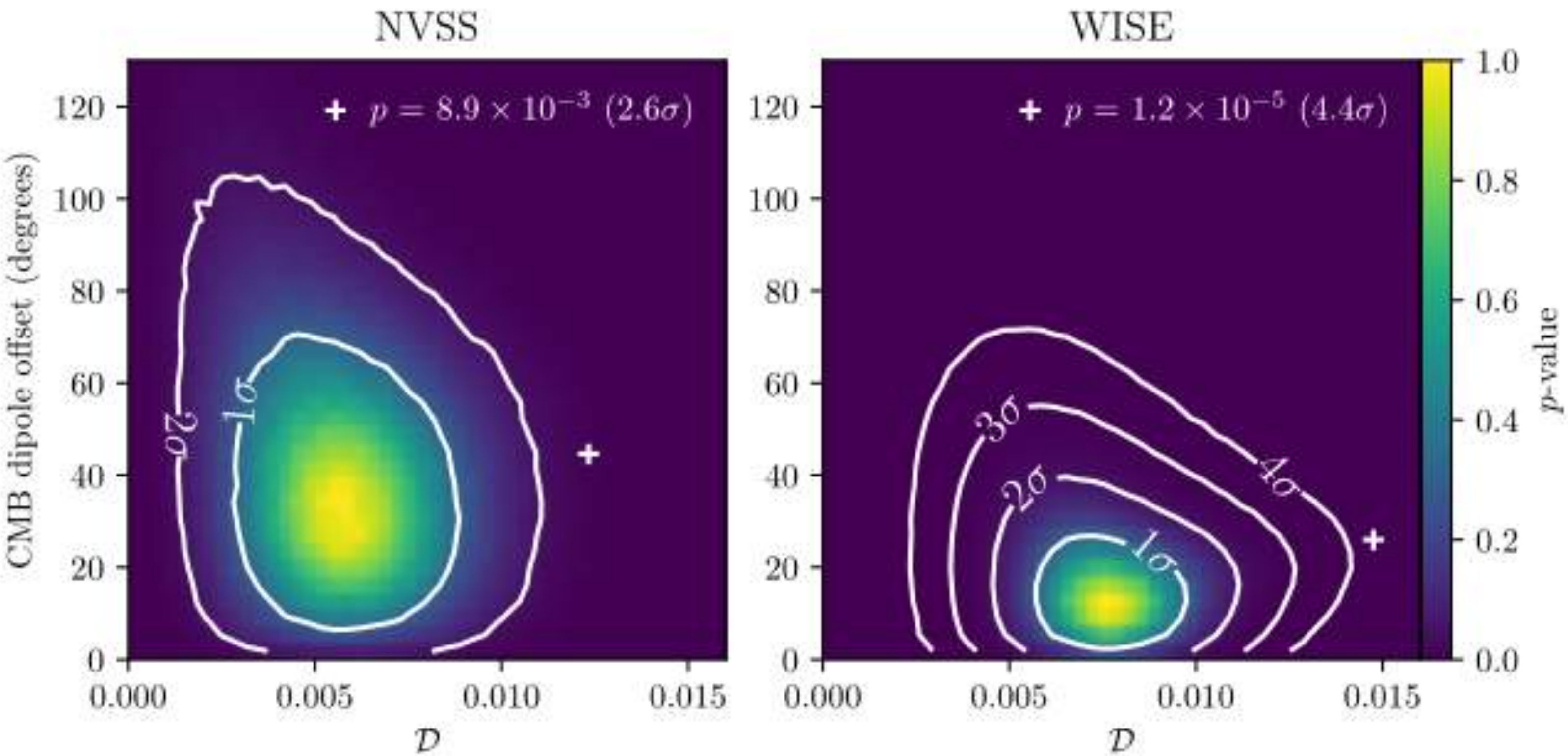


The two dipoles are *consistent* with each other; their vector mean is:

$D = (1.40 \pm 0.13)\times10^{-3}$ towards $(l, b) = (233.0, +34.4)$

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., [arXiv:2206.05624]

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.

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., Astrophys. J. Lett. *in press* [arXiv:2206.05624]

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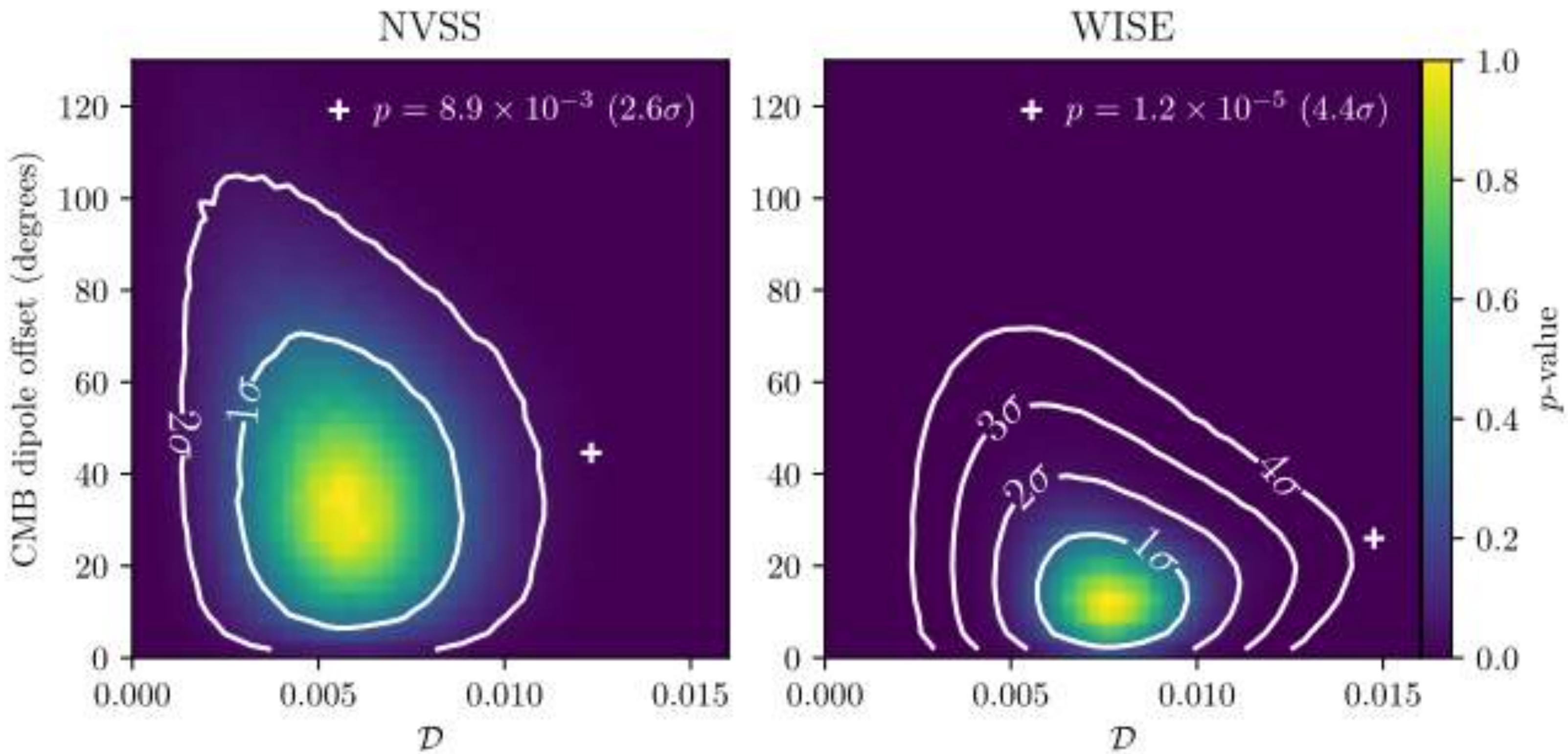

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Combined significance ⇒ standard cosmology expectation is rejected at 5.1**σ**

Secrest, Rameez, Von Hausegger, Mohayaee, S.S., Astrophys. J. Lett. *in press* [arXiv:2206.05624]

Anomalies in Physical Cosmology

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.)

https://arxiv.org/abs/2208.05018

Summary

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

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$\Rightarrow$ cosmic acceleration may be just an artefact of our local bulk flow

We must begin again, to construct a new standard model of cosmology

(following the manifesto of Ellis & Stoeger, CQG 4:1697,1987 'The fitting problem')