Testing a key foundation of the concordance model

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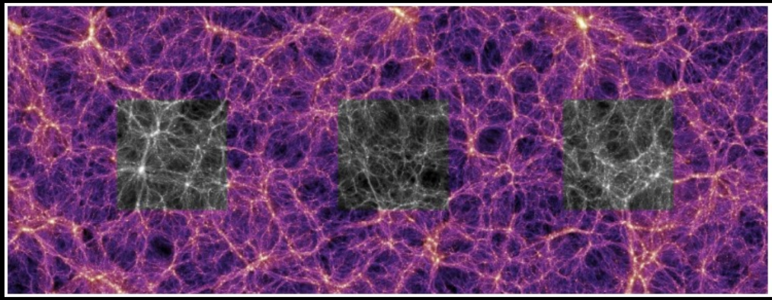
The Cosmological Principle

The Universe is statistically isotropic and homogeneous

A critical foundation stone of LCDM.

The Universe is I+H on *average*,
on large enough scales.



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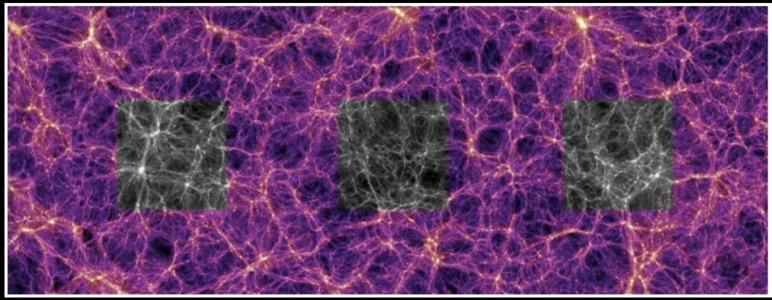


The Universe is I+H on *average*,
on large enough scales.

Key point:

The CP implies a unique frame – or 4-velocity field u^a –
in which average isotropy and homogeneity holds

- All 'fundamental' observers u^a see isotropy + homogeneity.
- Any observer with 4-velocity different from u^a does not see I+H.

Testing the consistency of matter and radiation

For practical purposes – we assume that the CP holds and apply consistency tests to a perturbed FLRW model.

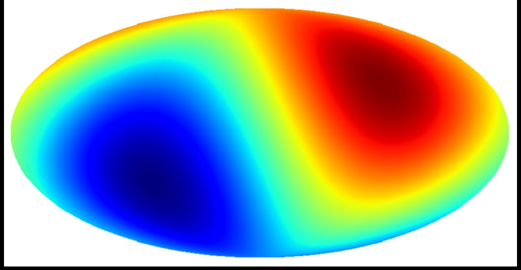
A key test:

isotropy in radiation and in matter should be consistent

Such a test was proposed by Ellis & Baldwin (1984).

Heliocentric observers are moving relative to the CMB rest-frame.

This generates a dipole in the CMB temperature –



hotter

cooler

$$\tilde{T}(\tilde{\mathbf{n}}) = T(\mathbf{n})\big(1 + \mathbf{n}\cdot\mathbf{v}_o\big) \quad v_o \approx 10^{-3}$$

$$\Rightarrow \quad \tilde{\delta}_T(\mathbf{n}) = \delta_T(\mathbf{n}) + \mathbf{n}\cdot\mathbf{v}_o$$

at first order in perturbations.

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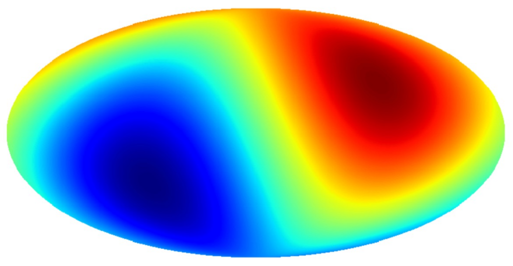

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If the Universe is isotropic about us on average, then

galaxy rest-frame = CMB rest-frame

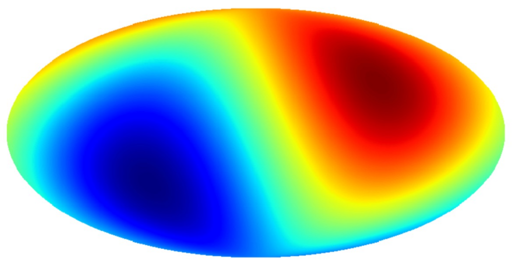
$$\mathbf{v}_o\big|_{\rm gal} = \mathbf{v}_o\big|_{\rm CMB}$$ (magnitude + direction)

– a critical test of the Cosmological Principle (Ellis & Baldwin 1984)

In other words, the same dipole should be seen in number counts:

highest counts in the direction $\mathbf{v}_o$, lowest counts in direction $-\mathbf{v}_o$

less galaxies



more galaxies

$$\tilde{\delta}_N(\mathbf{n}) = \delta_N(\mathbf{n}) + \big[2 + x(1+\alpha)\big]\mathbf{n}\cdot\mathbf{v}_o \qquad x, \alpha = \text{ constant}$$

Ellis-Baldwin

Need surveys with large sky area and high numbers.

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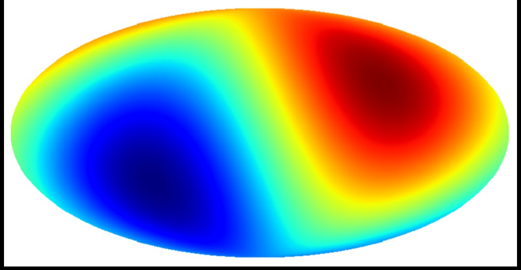

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Ellis-Baldwin

Need surveys with large sky area and high numbers.

Early tests with NVSS survey (JVLA telescope), e.g.,

Blake & Wall 2002; Singal 2011; Gibelyou & Huterer 2012;
Rubart & Schwarz 2013; Tiwari & Jain 2015; Colin et al 2017

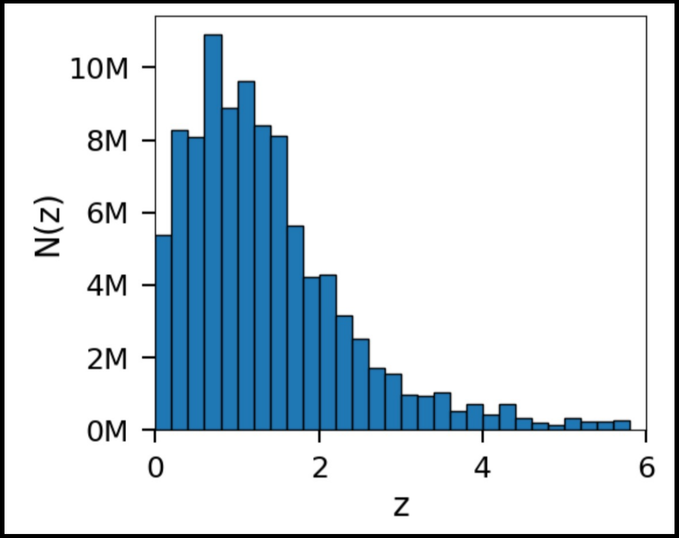
generally found consistency, with dipole magnitude > theory.

A key issue is systematics on ultra-large scales – very difficult.

Also – to measure the LSS dipole, we must remove low redshift sources to avoid nonlinear contamination of the dipole.

We need a sample with many high-z sources – like SKA:

Simulations

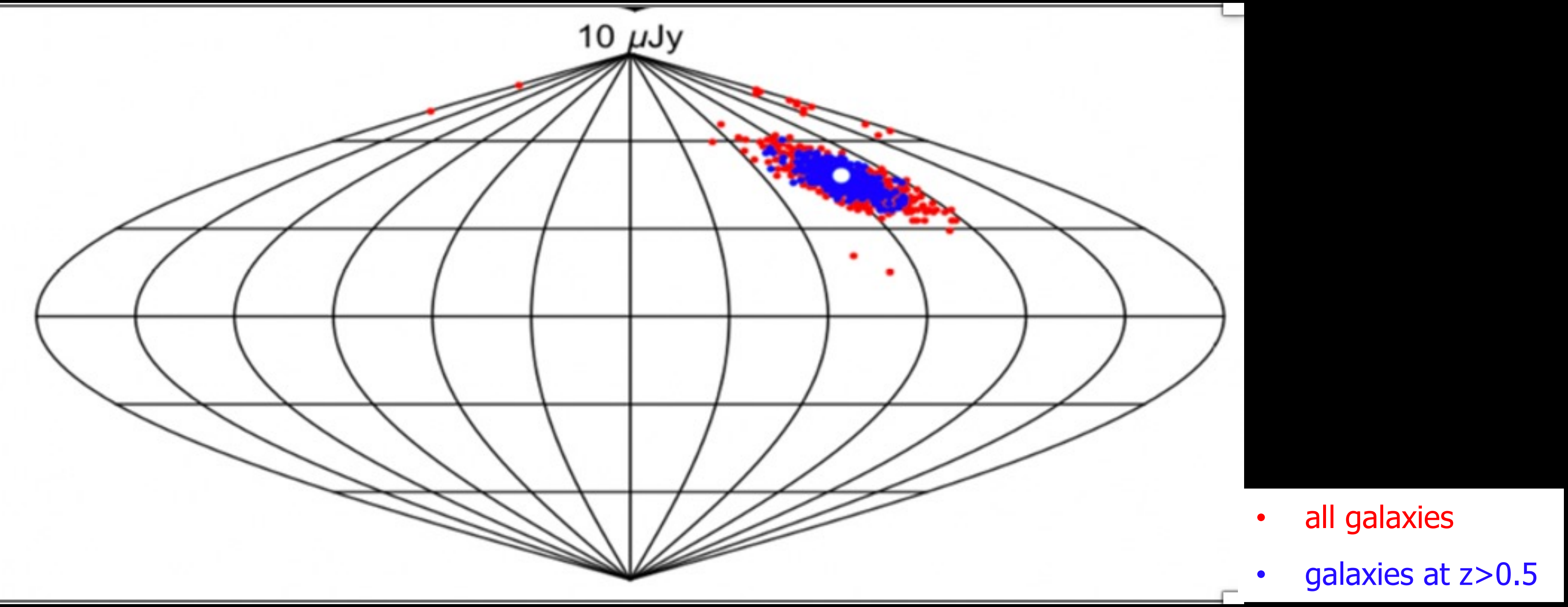


SKAO

(SKA Redbook, 2018)

To exclude low redshift radio galaxies – we can use redshift information from galaxy spectro-z and photo-z surveys.

Simulations – the dipole for SKA is well above the noise:



(Bengaly, Siewert, Schwarz, RM 2018)

Removing galaxies at $z<0.5$ significantly improves the measurement.

SKA could measure the dipole with 5 – 10% error, giving a robust test of the Cosmological Principle.

Redshift-dependent dipole in galaxy redshift surveys

Radio continuum surveys detect galaxies by their radio emission – with no redshifts.

Number counts are projected on the 2D sky.

Redshift surveys in 3D lead to z-dependent dipole magnitude.

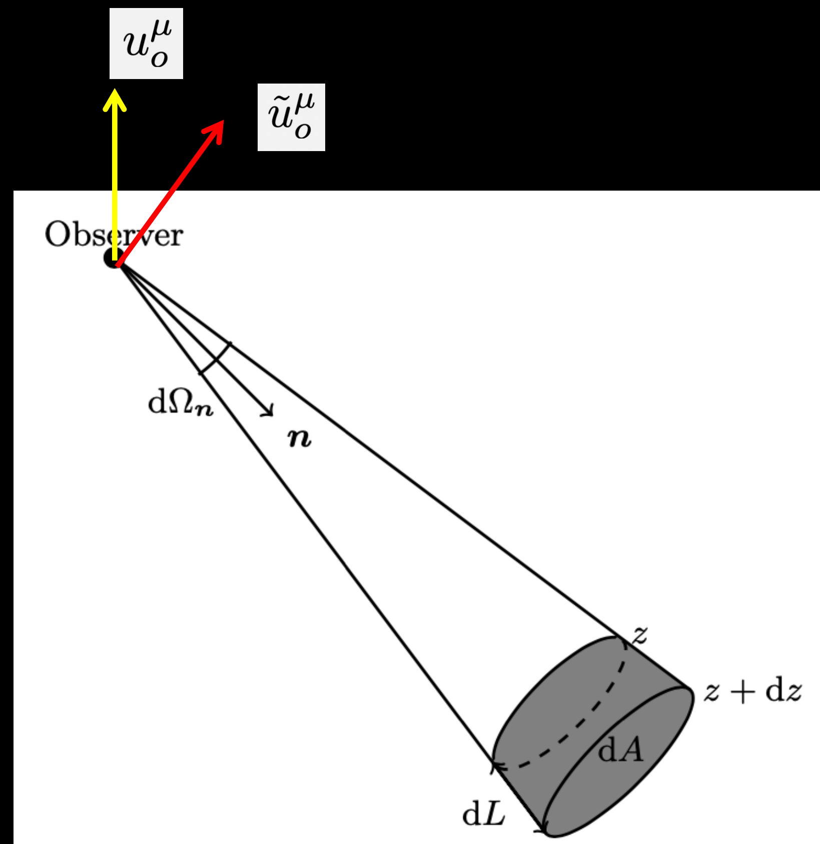
Redshift-dependent dipole in galaxy redshift surveys

Boosted observer 4-velocity:

$$\tilde{u}_o^\mu = \gamma(v_o)\left[u_o^\mu + v_o^\mu\right] = u_o^\mu + v_o^\mu + O(v_o^2) \qquad \text{where} \qquad u_o^\mu v_{o\mu} = 0$$

boosted (heliocentric)

CMB rest-frame



The boosted observer measures redshifts and directions:

$$1+\tilde{z} = (1+z)\big(1-\boldsymbol{n}\cdot\boldsymbol{v}_o\big)$$

Doppler boost

$$\tilde{\boldsymbol{n}} = \big(1-\boldsymbol{n}\cdot\boldsymbol{v}_o\big)\boldsymbol{n}+\boldsymbol{v}_o$$

aberration

Total number of particles is conserved:

$$\tilde{N}\,\mathrm{d}\tilde{z}\,\mathrm{d}\tilde{\Omega}_{\tilde{\mathbf{n}}} = N\,\mathrm{d}z\,\mathrm{d}\Omega_{\mathbf{n}}$$

Then the observed number per redshift per solid angle is

$$\tilde{N}(\tilde{z},\tilde{\boldsymbol{n}}) = N(z,\boldsymbol{n})\big[1+3\,\boldsymbol{n}\cdot\boldsymbol{v}_o\big]$$

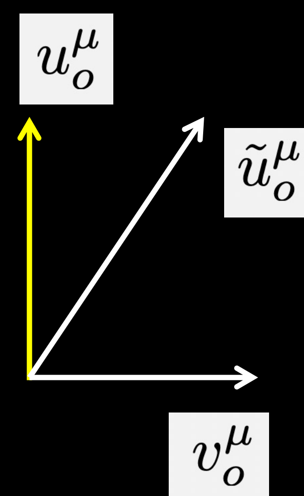
But – we must account for redshift and luminosity perturbations.

This generates a dipole in the observed number density contrast:

$$\delta_{\tilde{N}} = \delta_N + \delta_N^{\mathbf{v_o}} \qquad \text{where} \qquad \delta_N^{\mathbf{v}_o} = \mathcal{D}(z, m_*)\, \mathbf{n} \cdot \hat{\mathbf{v}}_o$$

For galaxies (RM, Clarkson, Chen 2017)

$$\mathcal{D}_{\rm gal} = \left[3 + \frac{\dot{H}}{H^2} + (2 - 5s)\frac{(1+z)}{rH} - b_e\right] v_o.$$



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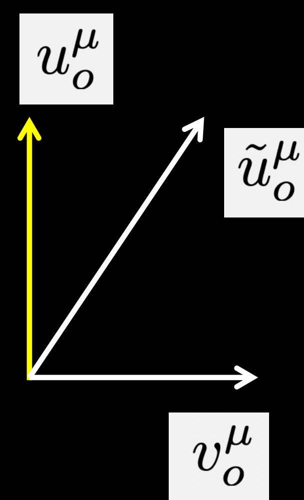
evolution bias

$$b_e(\bar{z}, m_*) = -\frac{\partial \ln\left[(1+\bar{z})^{-3}\bar{\mathcal{N}}_s(\bar{z}, m < m_*)\right]}{\partial \ln(1+\bar{z})}$$

magnification bias

$$s(\bar{z}, m_*) = \frac{\partial \log \bar{\mathcal{N}}_s(\bar{z}, m < m_*)}{\partial m_*}$$



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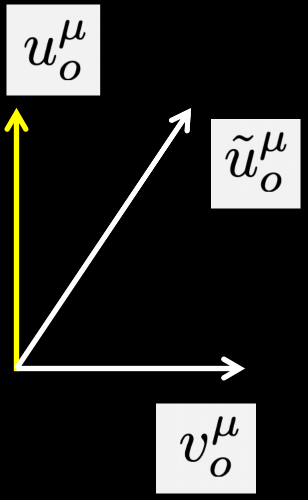

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$$s(\bar{z}, m_*) = \frac{\partial \log \bar{\mathcal{N}}_s(\bar{z}, m < m_*)}{\partial m_*}$$

luminosity function

$$\bar{\mathcal{N}}_s(\bar{z}, m < m_*) = \frac{2}{5}\ln 10 \int_{-\infty}^{m_*} dm\, \bar{n}_s(\bar{z}, m).$$

proper no. density (at source)

where

$$\bar{N} = \left(\frac{r^2}{H}\right)(1+z)^{-3}\bar{\mathcal{N}}_s$$

observed density related proper density

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NB This is first-order – does not include nonlinearities that arise at low redshift

The projected 2D dipole

The 3D galaxy redshift dipole :

$$\mathcal{D}_{\mathrm{gal}} = \left[3 + \frac{\dot{H}}{H^2} + (2-5s)\frac{(1+z)}{rH} - b_e\right] v_o.$$

Do we recover the Ellis-Baldwin result for a 2D dipole

$$\langle\mathcal{D}_{\mathrm{gal}}\rangle_{\mathrm{EB}} = \left[2 + x(1+\alpha)\right] v_o \quad \text{where} \quad x, \alpha \text{ constant}$$

from our 3D expression?

Projection onto the 2D sky (Nadolny et al 2021)

$$\frac{\langle \mathcal{D}_{\rm gal}\rangle(< m_*)}{v_o} = \frac{1}{\bar{N}_\Omega(< m_*)} \int_0^\infty {\rm d}z\, \mathcal{D}_{\rm gal}(z, < m_*)\bar{N}(z, < m_*)$$

$$\bar{N}_\Omega(< m_*) = \int_0^\infty {\rm d}z\, \bar{N}(z, < m_*)$$

This leads to

$$\frac{\langle \mathcal{D}_{\rm gal}\rangle}{v_o} = 2 + \frac{1}{\bar{N}_\Omega} \int_0^\infty {\rm d}z\, x(1+\alpha)\bar{N}$$

where

$$x = 2.5s$$

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- The original Ellis-Baldwin formula is only recovered if we assume x and α are *constant*
- Using $x(z)$ and α(z) in the EB formula is incorrect
- x and α should be determined from the luminosity function

The simplified Ellis-Baldwin model

$$\langle \mathcal{D}_{\rm gal} \rangle_{\rm EB} = \Big[2 + x(1+\alpha)\Big] v_o$$

means that in principle, the apparent excess dipole magnitude

$$v_{o,\rm gal} > v_{o,\rm cmb}$$

could be due to the implicit approximation of constant magnification bias and spectral index (Dalang & Bonvin 2021).

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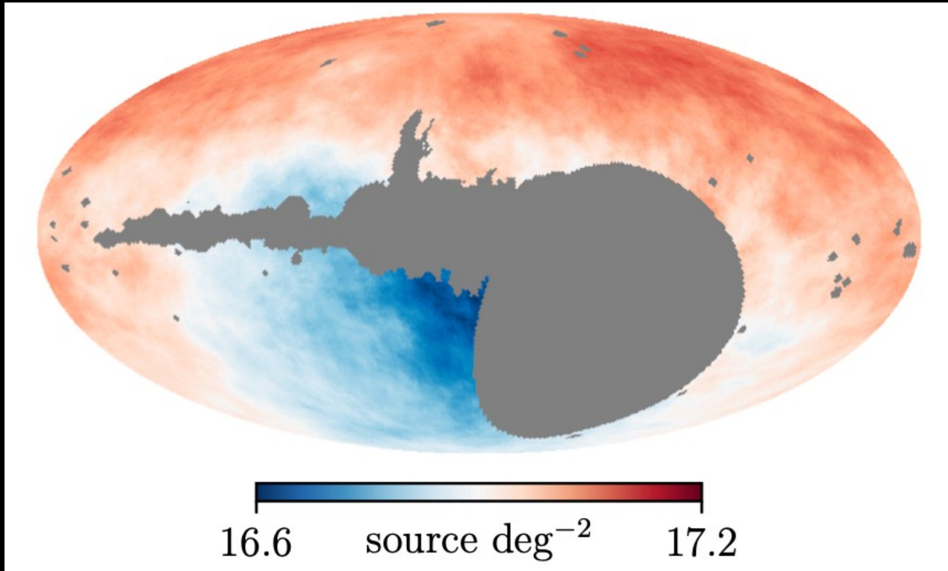
could be due to the implicit approximation of constant magnification bias and spectral index (Dalang & Bonvin 2021).

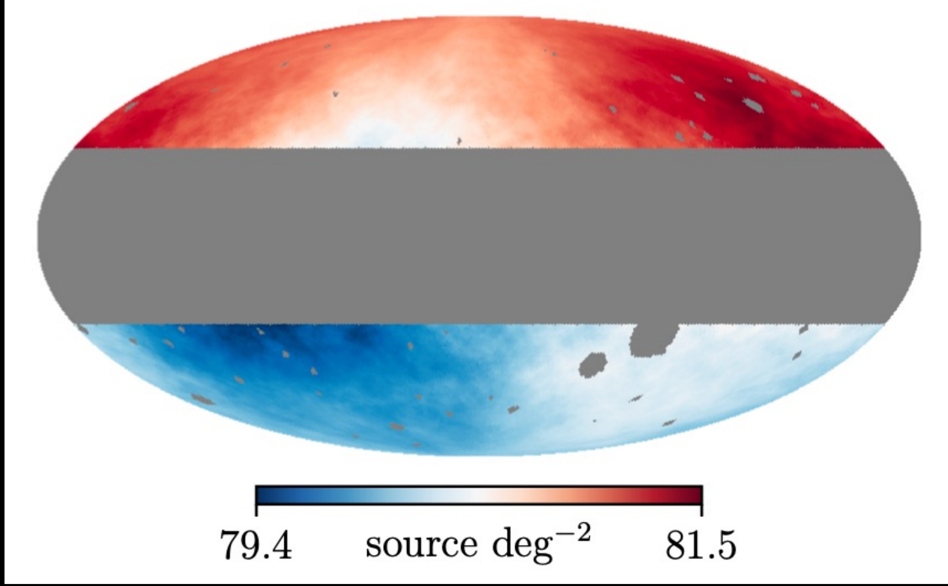
In other words, it is possible that

$$v_{o,\rm gal} \approx v_{o,\rm cmb} \quad \text{since} \quad \langle \mathcal{D}_{\rm gal} \rangle_{\rm EB} < \langle \mathcal{D}_{\rm gal} \rangle_{\rm true}$$

Measuring the dipole in a better 2D sample



NVSS



CatWISE2020
(1.36M quasars, mid-IR)

(Secrest et al 2022)

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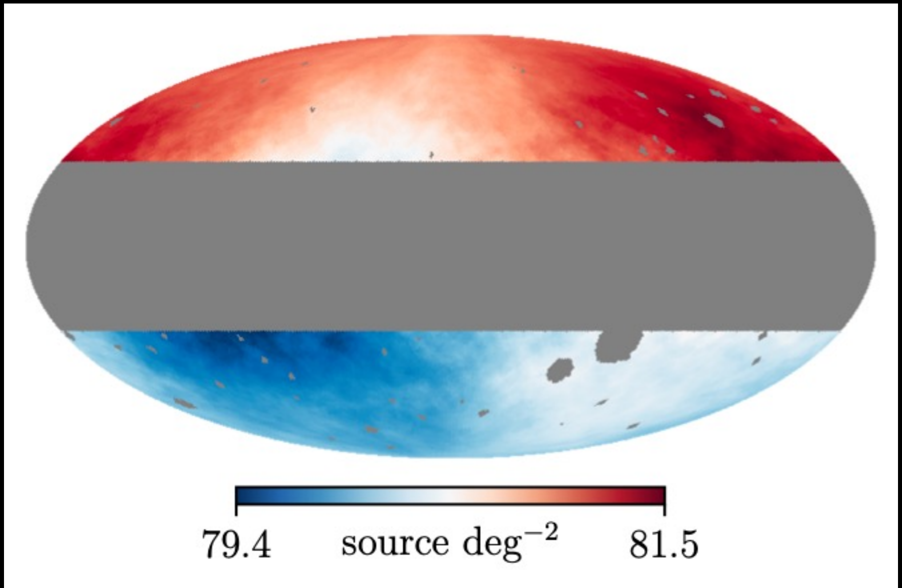

CatWISE2020

Secrest et al 2021, 2022 use the Ellis-Baldwin formula to find that

the dipole magnitude is in tension with the CMB at >4σ

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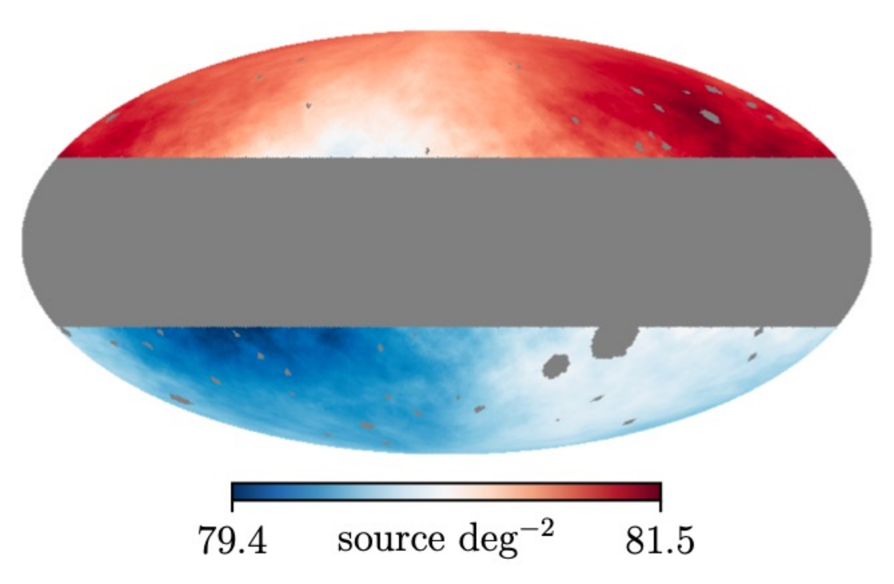

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Is this robust?

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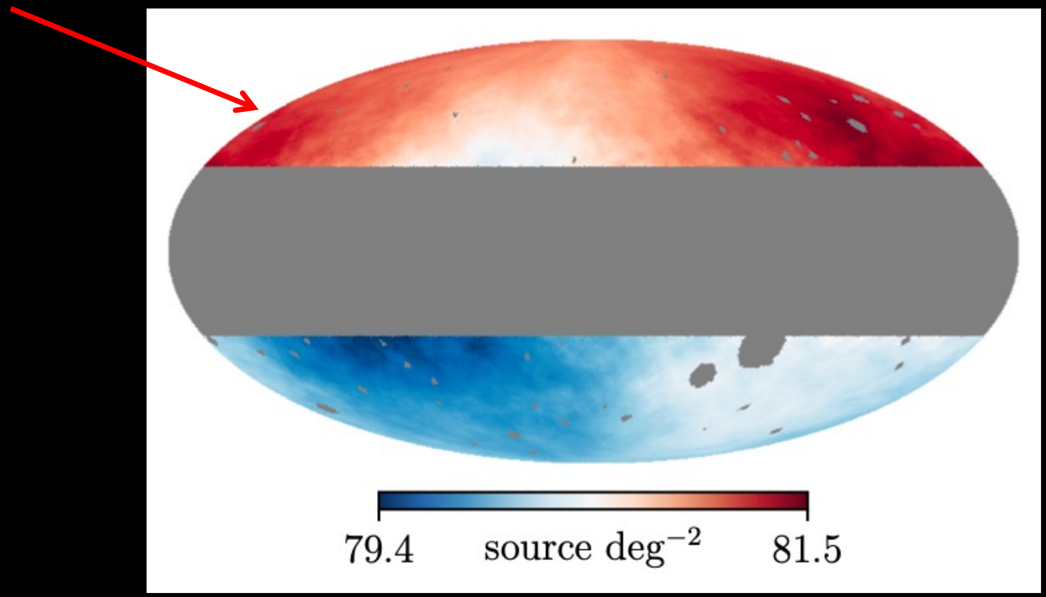

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- There could be unaccounted for systematics on very large scales

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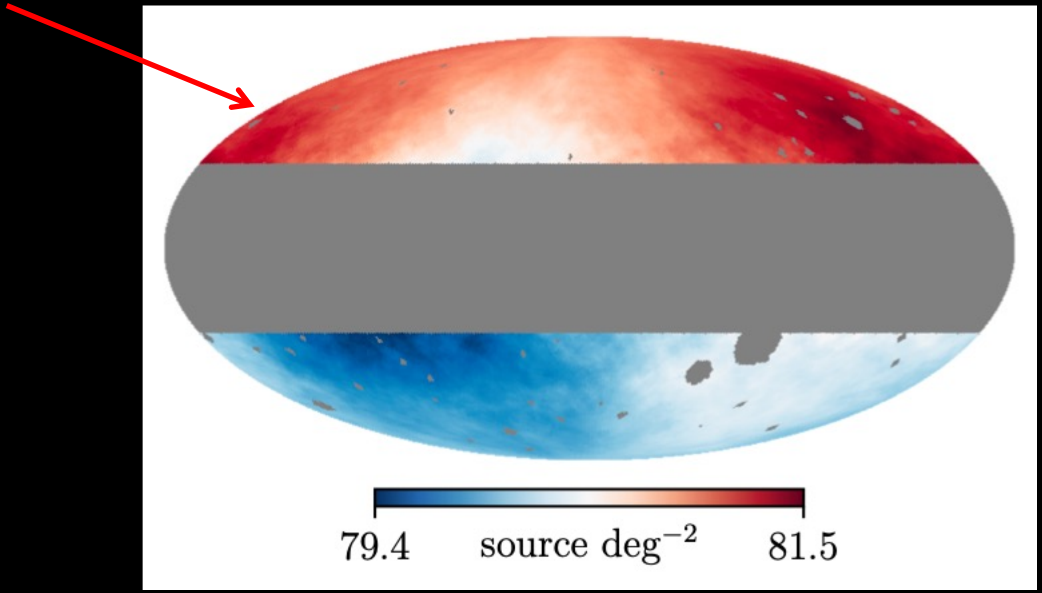

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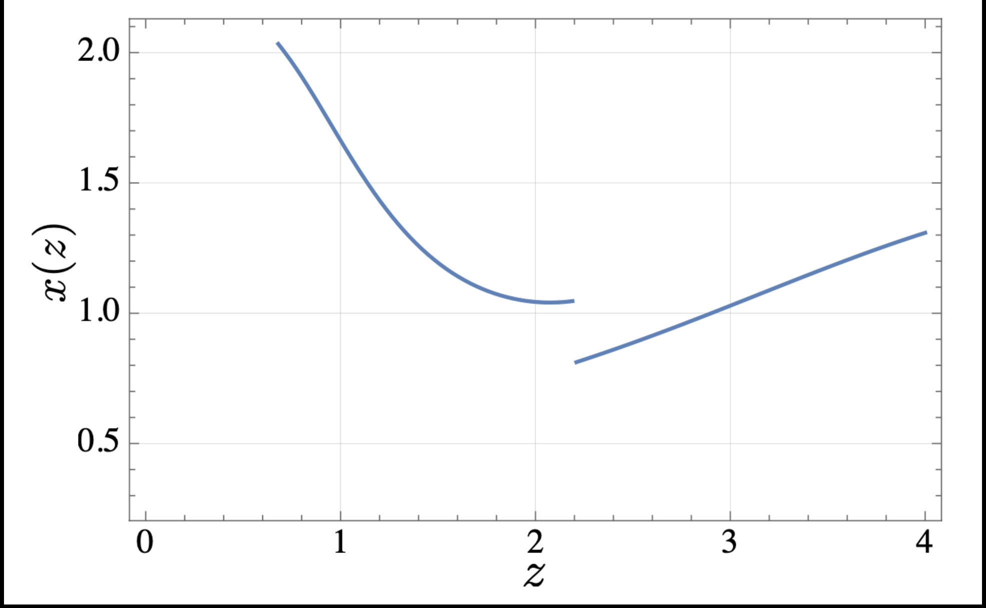
Is this robust?

- There could be unaccounted for systematics on very large scales
- The Ellis-Baldwin formula could be a bad approximation

x and α should be determined by the luminosity function.

For example – the eBOSS quasar LF (Wang et al 2020) gives for $x(z)$:



(Dalang & Bonvin 2021)

Clearly x is not constant – and neither is α.

Extrapolating from eBOSS to CatWISE2020 –

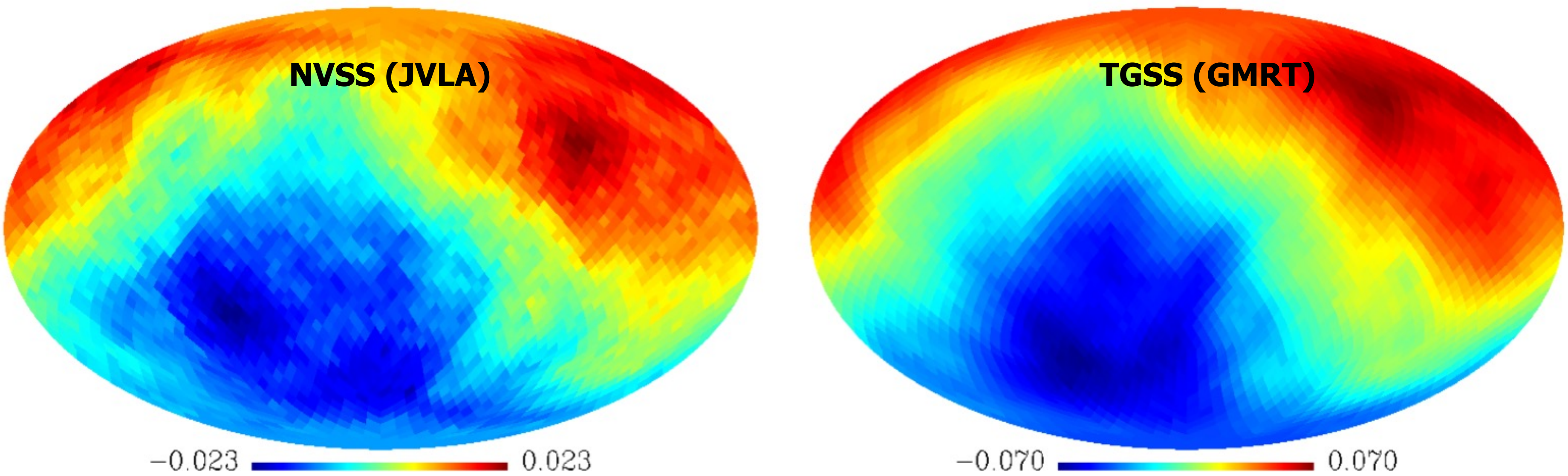
the tension with CMB can in principle be removed (Dalang & Bonvin 2021)

But this does not take account of differences in selection criteria and redshift range.

This seems to be an open question for further investigation – which is critical for testing the Cosmological Principle.

Extra slides

Including a newer radio continuum survey TGSS:



(Bengaly, RM, Santos 2017)

- Dipole direction is roughly consistent with CMB.
- Dipole magnitude in TGSS even larger – due to flux calibration systematics (Tiwari et al 2019; Secrest et al 2022).

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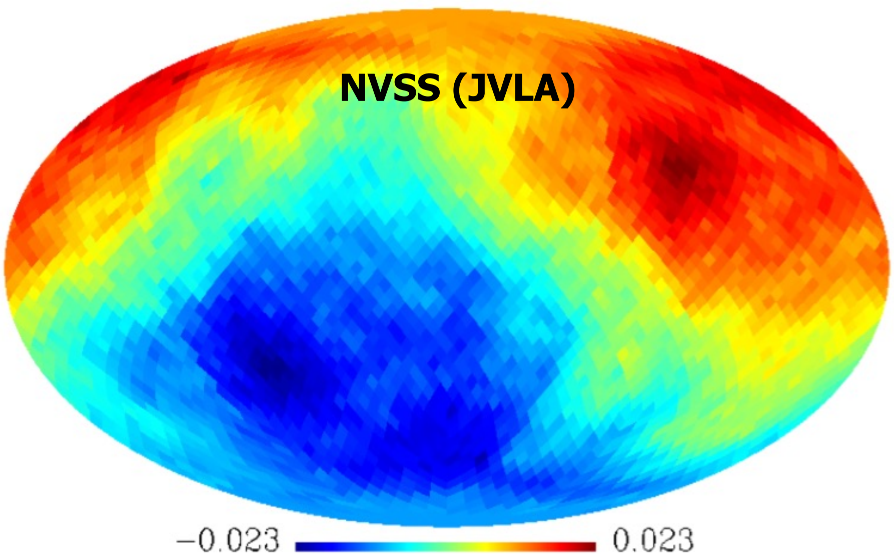

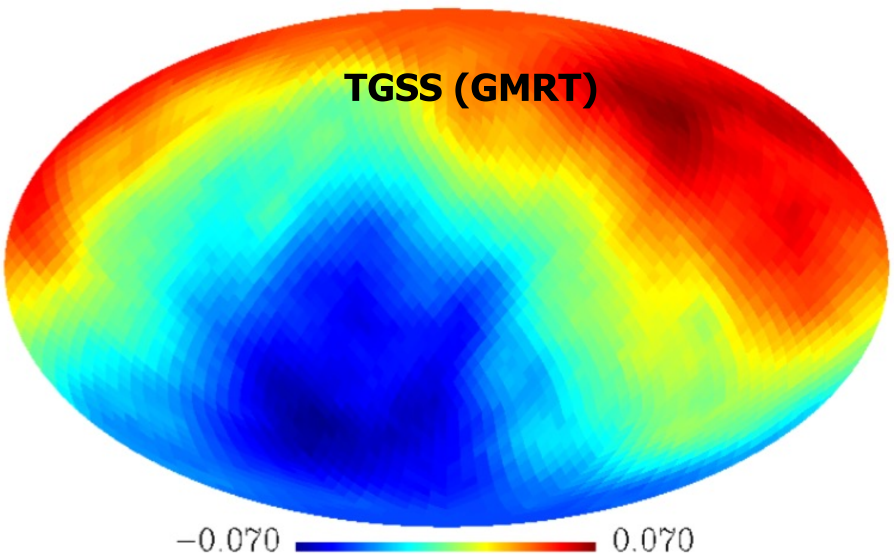

(Bengaly, RM, Santos 2017)

Conclusions:

- Dipole noise is too large (not enough galaxies).
- The test is not robust with current radio continuum surveys.

Angular power spectrum dipole:

$$\tilde{C}_1 = C_1 + C_1^{v_o}$$

intrinsic << kinematic

$$C_1^{v_o}(z, z', m_*) = \frac{4\pi}{9}\mathcal{D}(z, m_*)\mathcal{D}(z', m_*)$$

SKA dipole relative to CMB dipole for $z'=z$