RTG Colloquium *Models of Gravity*

Testing the Cosmological Principle with Distant Galaxies

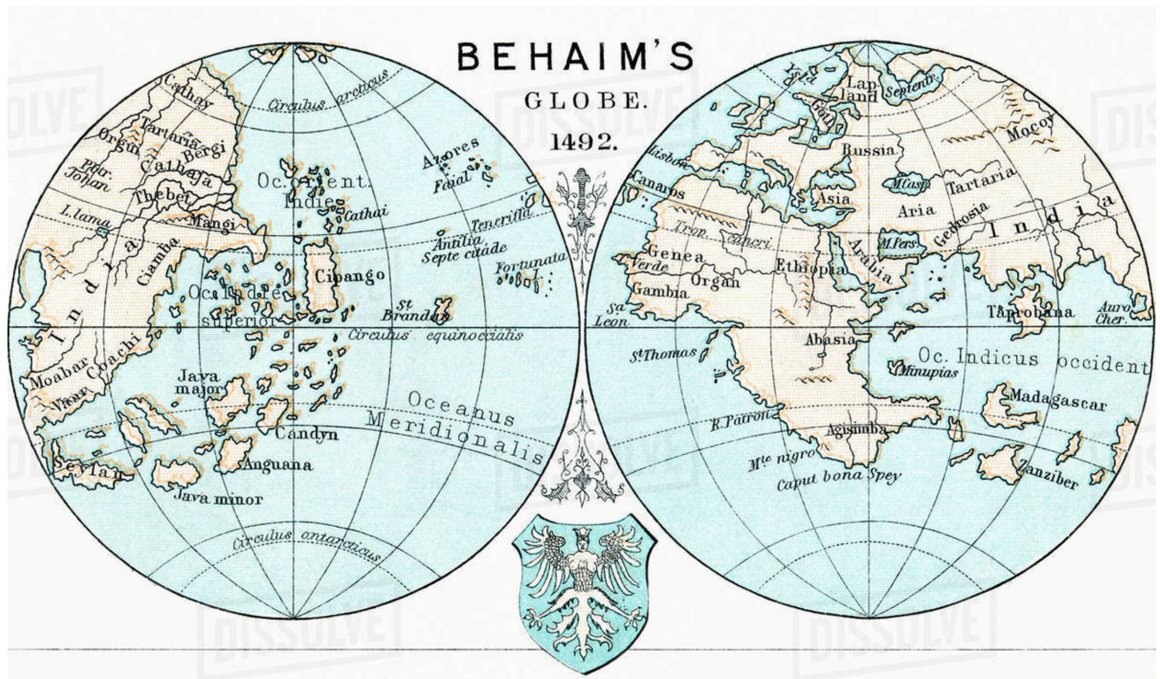
Sebastian von Hausegger

UNIVERSITY OF OXFORD

CARLSBERG FOUNDATION

Cosmography back in the days

"Erdapfel" — Martin Behaim (Nuremberg, 1492)



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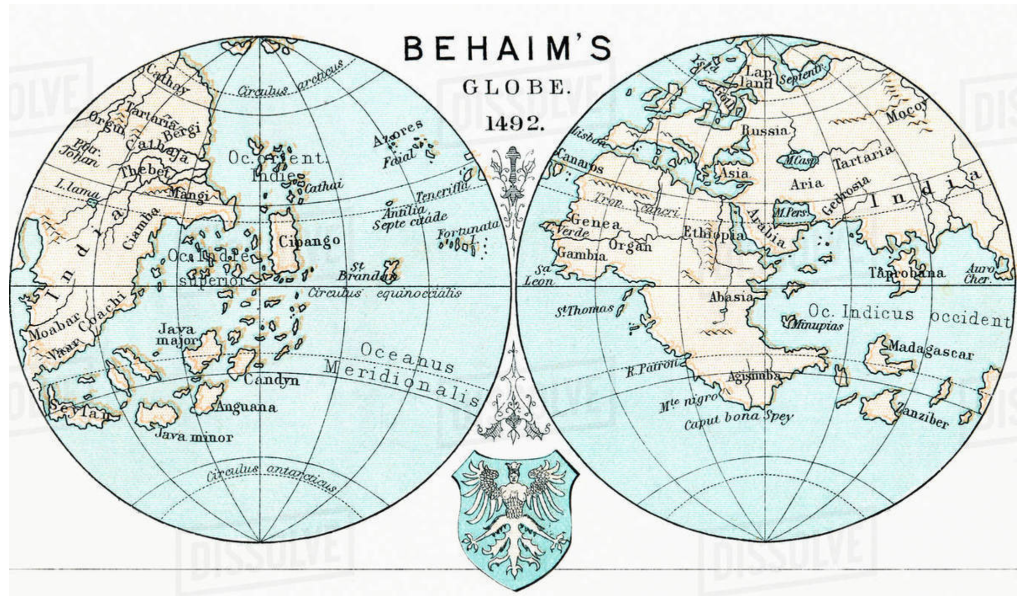
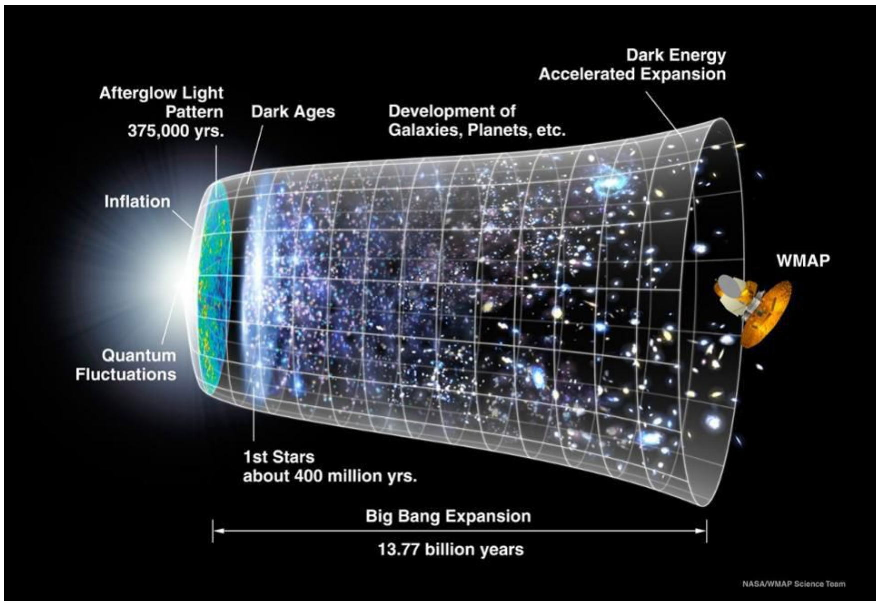


Circumference of the Earth

Ptolemy (~150AD) : ~ 30 000 km
Erastothenes (~250BC) : ~ 40 000 km

Cosmography today



Obligatory cosmology slide

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -dt^2 + a^2(t)\, d\Sigma^2$$

$g_{\mu\nu}$ is chosen to be spatially symmetric thereby fulfilling homogeneity and isotropy

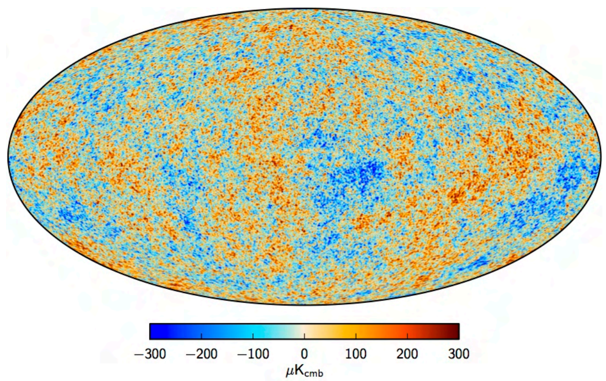
$$R_{\mu\nu} + \frac{1}{2} R g_{\mu\nu} + \lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$T_{\mu\nu}$ is an ideal fluid that in the homogeneous limit reduces to $diag(-\rho, p, p, p)$

Observations constrain the energy content in our universe using $1 = \Omega_\gamma + \Omega_m + \Omega_\Lambda + \Omega_k$, $\Omega_i = \rho_i / \rho_{cr}$.

The Cosmological principle

Definitions from *Thoughts on the Cosmological Principle* - Schwarz [0905.0384]

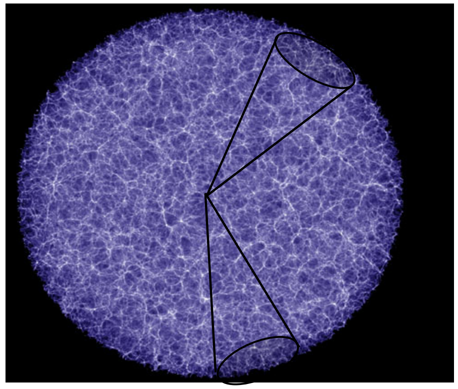


Fluctuations with $\ell > 1$:

Statistically isotropic and Gaussian to high degree

$\mathcal{O}(10^{-5})$ fluctuations, mostly primordial

"The distribution of light and matter in the Universe is statistically isotropic around any point, apart from anisotropies of local origin."



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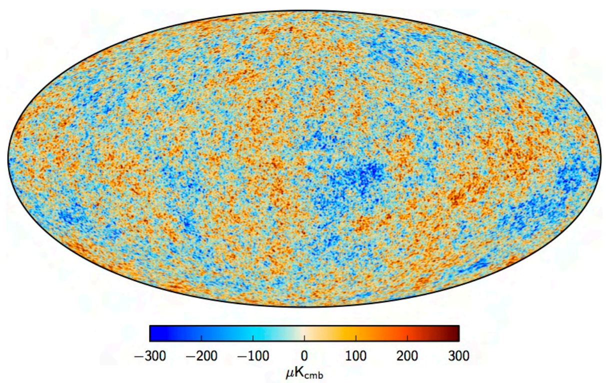

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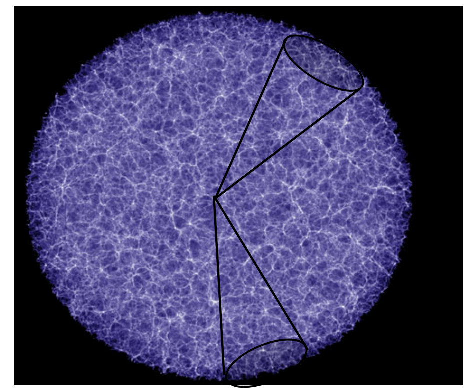

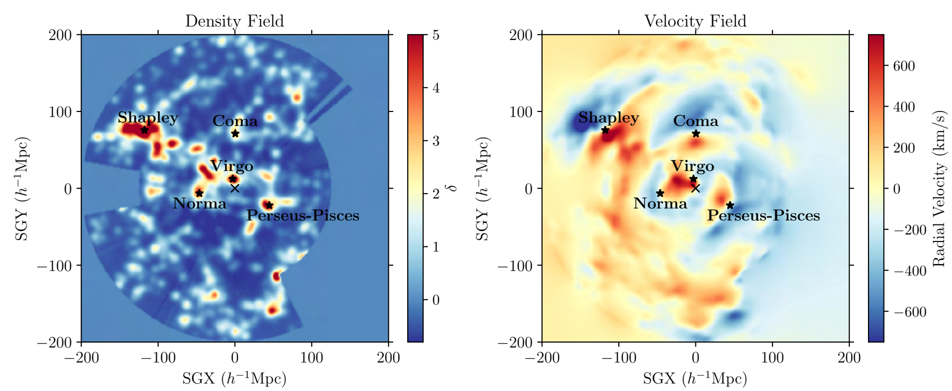

Boruah, Hudson, Lavaux [1912.09383]

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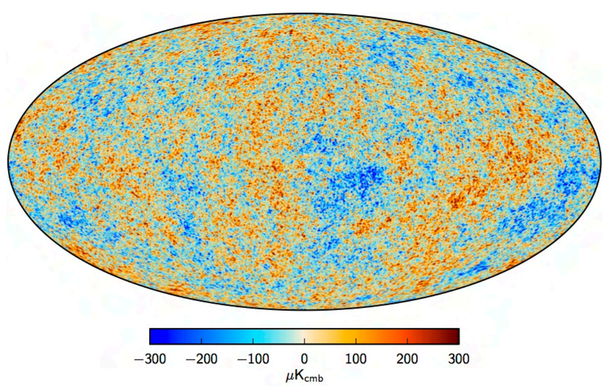

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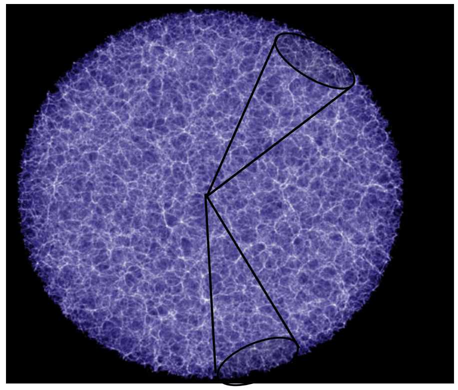
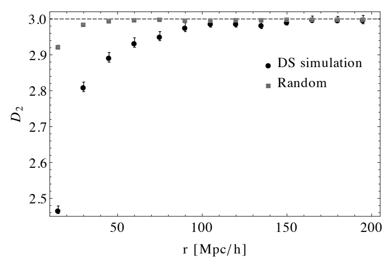
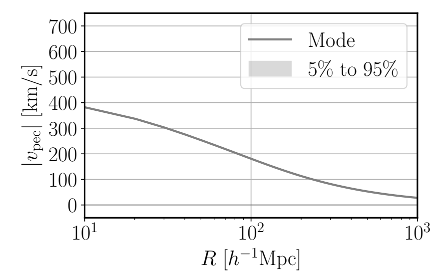




Kraljic [1410.4107]



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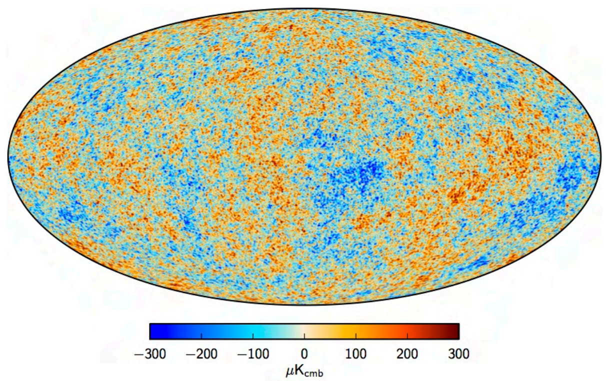

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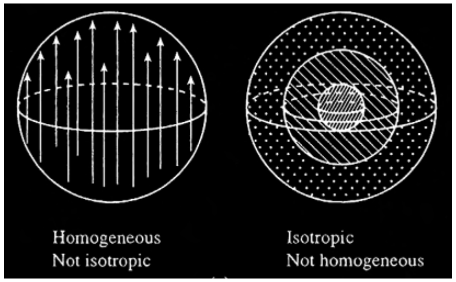

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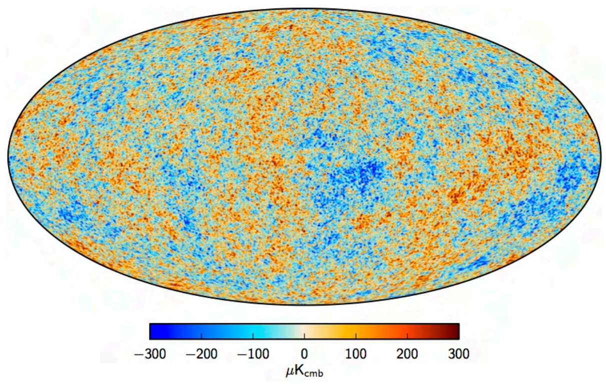

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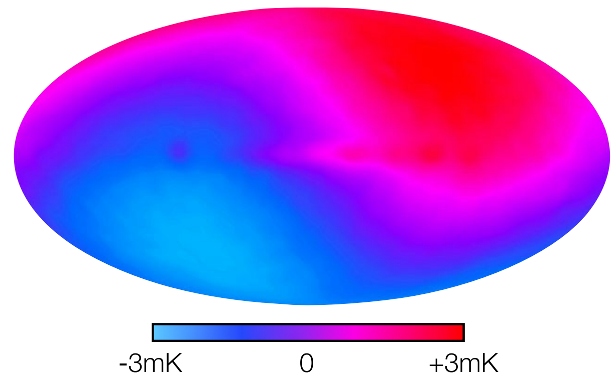

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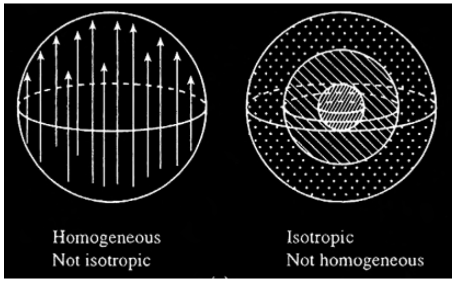
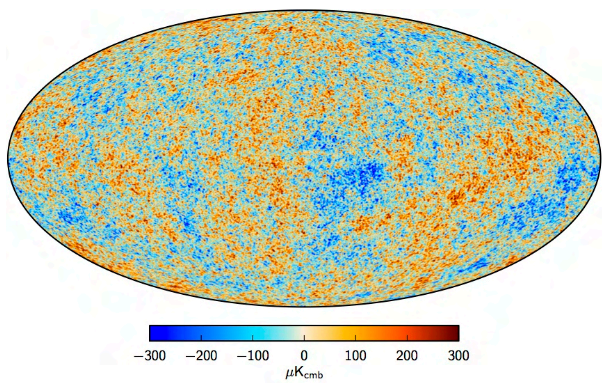


The CMB rest frame

Defined as the frame in which the CMB dipole is zero



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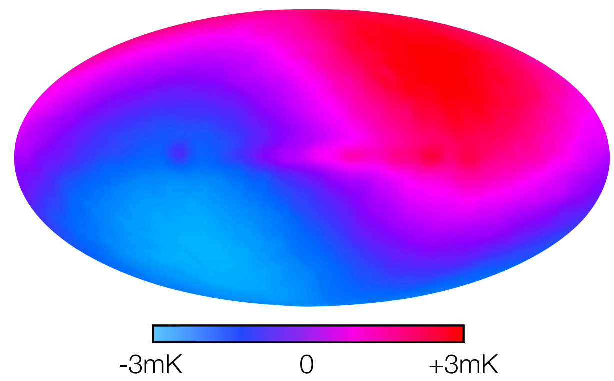

Dipole anisotropy $\ell = 1$:

$\mathcal{O}(10^{-3})$ fluctuation, mostly not primordial

Instead attributed to Doppler boosted monopole with $\beta \sim 10^{-3}$

$v_\odot = 369.82 \pm 0.11\,\text{km/s}$

$(l, b) = (264.021 \pm 0.011, 48.253 \pm 0.005)^\circ$

Planck Collab. 2018, I [1807.06205]

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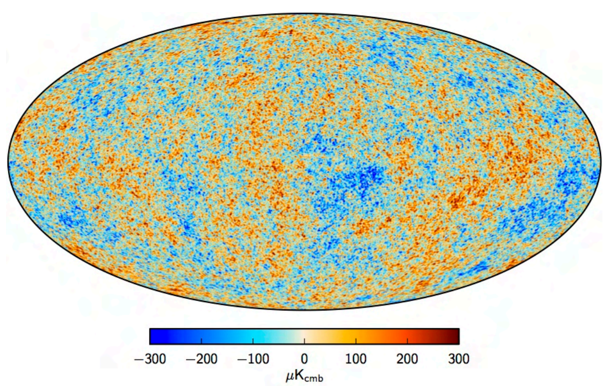

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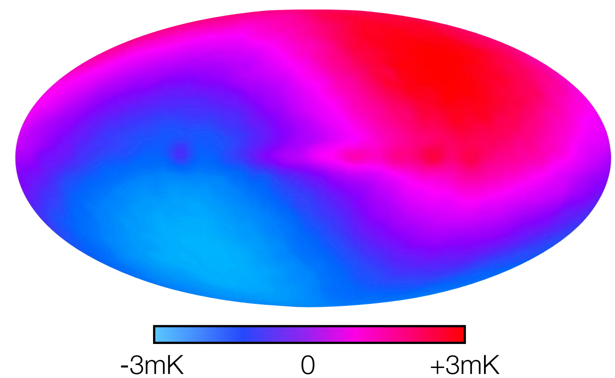

Table 3. Relative velocities involving the CMB frame, the Galactic centre, and the Local Group.

Relative velocity	Speed [km s^{-1}]	l [deg]	b [deg]
Sun–CMB [a]	369.82 ± 0.11	264.021 ± 0.011	48.253 ± 0.005
Sun–LSR [b]	17.9 ± 2.0	48 ± 7	23 ± 4
LSR–GC [c]	239 ± 5	90	0
GC–CMB [d]	565 ± 5	265.76 ± 0.20	28.38 ± 0.28
Sun–LG [e]	299 ± 15	98.4 ± 3.6	−5.9 ± 3.0
LG–CMB [d]	620 ± 15	271.9 ± 2.0	29.6 ± 1.4

Planck Collab. 2018, I [1807.06205]

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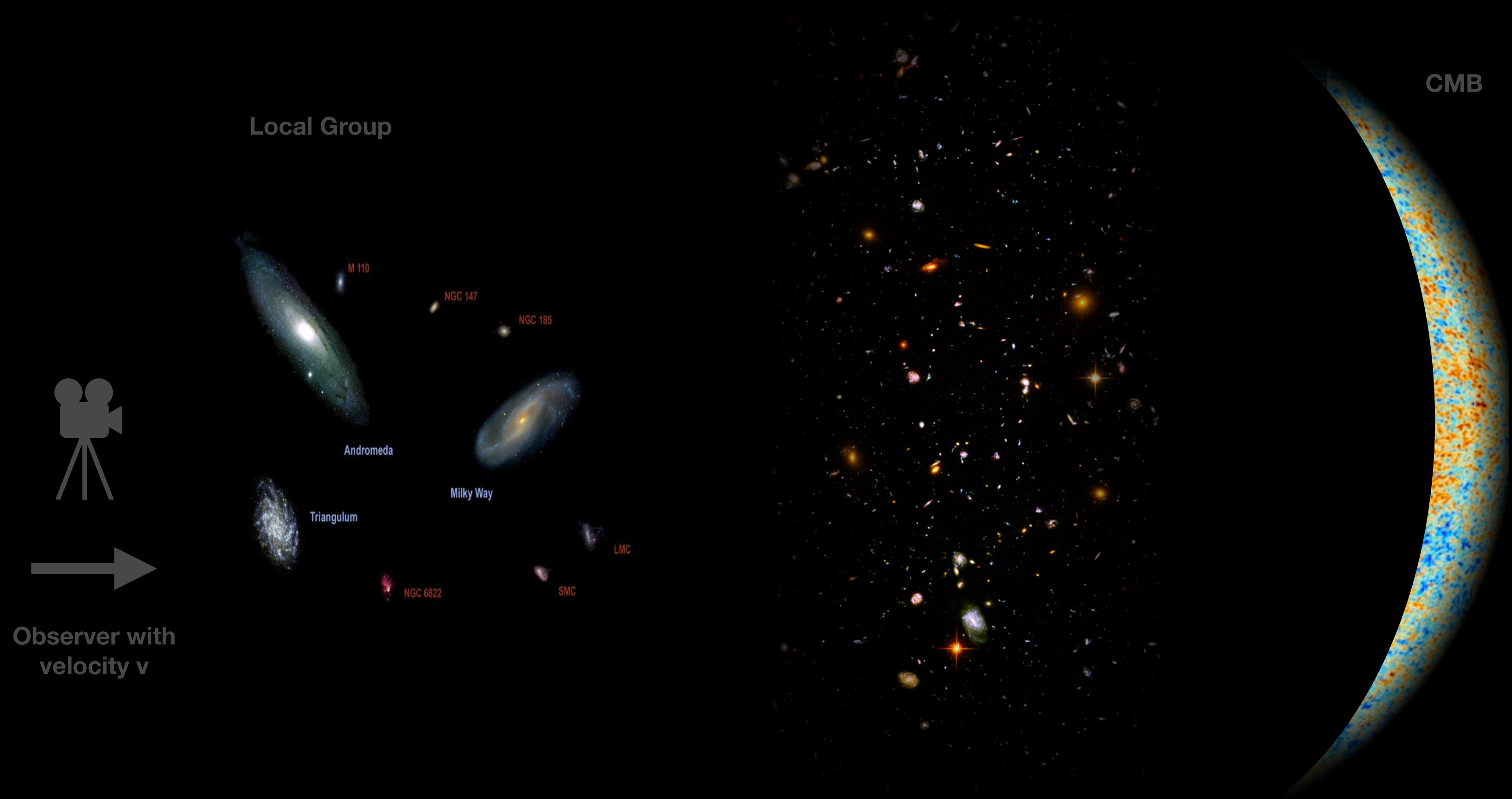
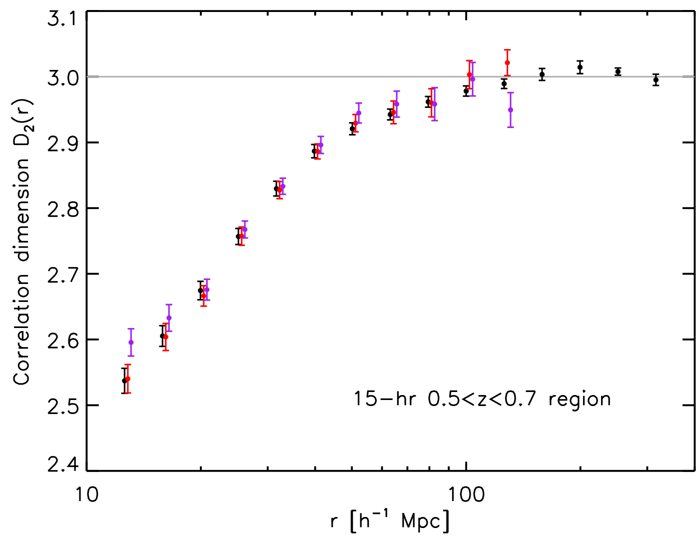
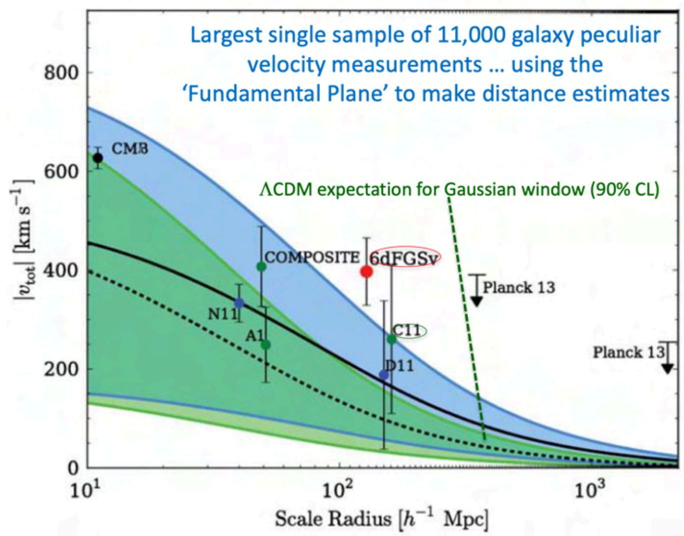


Other tests of the Cosmological Principle



Scringeour et al. (2012) MNRAS 425



Magoulas et al. (2014) Proc.IAU 11 S308

$$D_2(r) = \frac{\ln N(< r)}{\ln r}$$

$$\langle v(r)^2 \rangle \propto \int dk\, P(k) \widetilde{W}(kr)$$

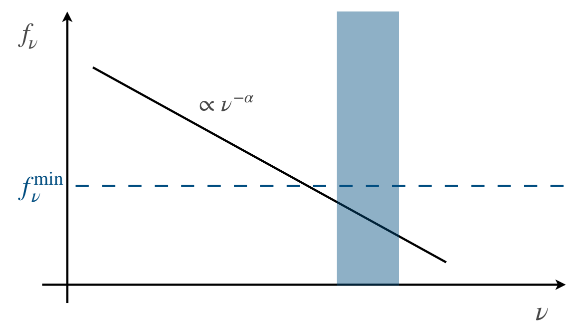
Ellis and Baldwin (1984)

- Isotropic sample of objects on the sky
- Spectra are power laws in flux density $f_\nu \propto \nu^{-\alpha}$
- Differential number counts of flux-limited catalog follows $dN/d\Omega\ (f_\nu > f_\nu^{\min}) \propto (f_\nu^{\min})^{-x}$

➡ Dipole in the number density with amplitude $[2 + x(1+\alpha)] \cdot \beta$

Doppler boosting spectra

$$f_{\rm obs}(\nu_{\rm obs}) = f_{\rm rest}\left(\frac{1+\beta\cos\theta}{\sqrt{1-\beta^2}}\right)^{1+\alpha}$$



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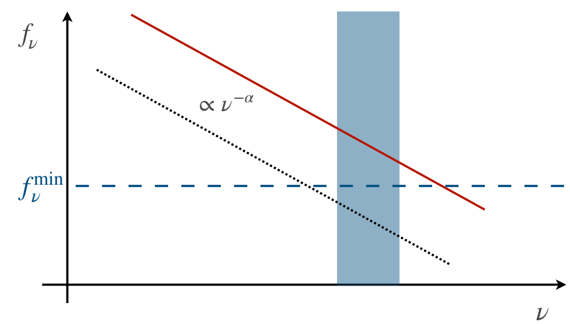

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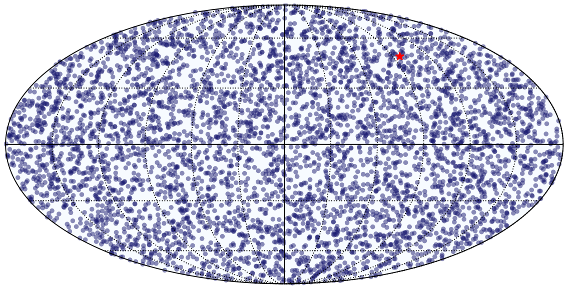
Aberrating sources

$$\tan\theta' = \frac{\sin\theta\sqrt{1-\beta^2}}{\beta + \cos\theta}$$



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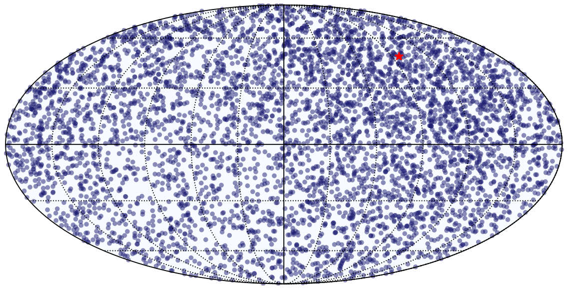

Radio dipole(s)

- For radio sources we expect $d = [2 + x(1+\alpha)] \cdot \beta = 0.0046$

- Radio catalogs of $\mathcal{O}(10^5)$ sources from ground-based surveys (NVSS, SUMSS, TGSS, WENSS, …) lead to dipoles around $d = 0.01 - 0.03$

  e.g. Blake and Wall [astro-ph/0203385], Singal [1110.6260], Gibelyou and Huterer [1205.6476], Rubart and Schwarz [1301.5559], Tiwari et al. [1307.1947], …
  or see summary by Siewert, Schmidt-Rubart and Schwarz [2010.08366]

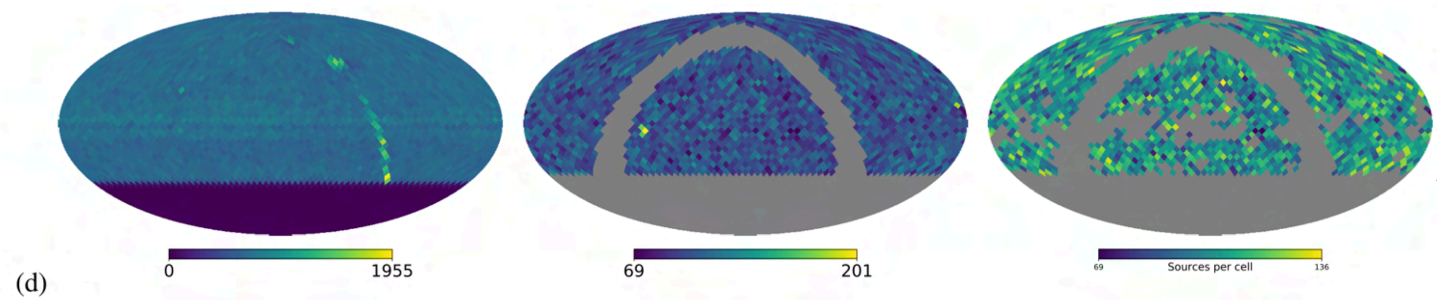

Fig 4, Siewert, Schmidt-Rubart and Schwarz [2010.08366]

- Most (so far) have in common: ~low statistics, atmospheric systematics, biased estimators, local contamination, …

Dipole contributions

- $\vec{d}_{total} = \vec{d}_{kin} + \vec{d}_{local} + \vec{d}_{bias} + \vec{d}_{noise}$
- Kinematic dipole is expected to dominate over local clustering dipole at higher redshifts

  e.g. Bengaly et al. [1810.04960]
- Local clustering dipole ($z<0.1$) studied using similar techniques

  e.g. Gibelyou and Huterer [1205.6476], Yoon et al. [1406.1187], Alonso et al. [1412.5151], Bengaly et al. [1606.06751], Rameez et al. [1712.03444], …
- Bias contribution depends on dipole estimator, and on dipole already in the sample

  e.g. amplitude bias of the linear estimator Rubart and Schwarz [1301.5559], *directional bias of the linear estimator* Siewert, Schmidt-Rubart and Schwarz [2010.08366]
- Dipole from shot noise decreases with size of ($\gtrsim \mathcal{O}(10^6)$) galaxy sample

- If these are modelled correctly, one can produce a set of galaxy number density simulations!

Dipole estimators

- "Linear estimator" $\vec{D}_l = \frac{3}{N}\sum_i^N \hat{r}_i$

  e.g. Crawford [0810.4520], Singal [1110.6260], Rubart and Schwarz [1301.5559], Siewert, Schmidt-Rubart and Schwarz [2010.08366], …

  Very fast

  Biased, even worse when sky is masked

- "Quadratic estimator" $$\chi^2 = \sum_p \frac{\left[n_p - \bar{n}\left(1 + \vec{D}_q \cdot \hat{r}_p\right)\right]^2}{\bar{n}\left(1 + \vec{D}_q \cdot \hat{r}_p\right)} \to Min\,.$$

  e.g. Bengaly et al. [1810.04960]

  Unbiased on full sky and under certain conditions

  Comparably slow (num. minimisation)

- Spherical harmonics

  e.g. Blake and Wall [astro-ph/0203385]

  Somewhat natural choice

  Coupling between multipoles on incomplete sky

- Template fitting $$\sum_p \left[n_p - \sum_i^m a_i t_i(\hat{r}_p)\right]^2 \to Min\,.$$

  e.g. Blake and Wall [astro-ph/0203385] (*in slightly different form*), Hirata [0907.0703], Secrest et al. [2009.14826], …

  Very fast, unbiased on full sky and under certain cond.

  (Possible coupling between templates)

Computed with catalog (linear estimator)

Computed on density maps (quadratic estimator, spherical harmonics, template fitting)

Mid-IR Quasar sample

Based on
ApJ Lett. (2021) 908:L51 | [2009.14826]
with N. Secrest, M. Rameez,
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  (i.e. 4+3-band- and post-cryo, NEOWISE, NEOWISE-R)
  and employs an updated source detection algorithm

  Eisenhardt et al. [1908.08902] / Marocco et al. [2012.13084]

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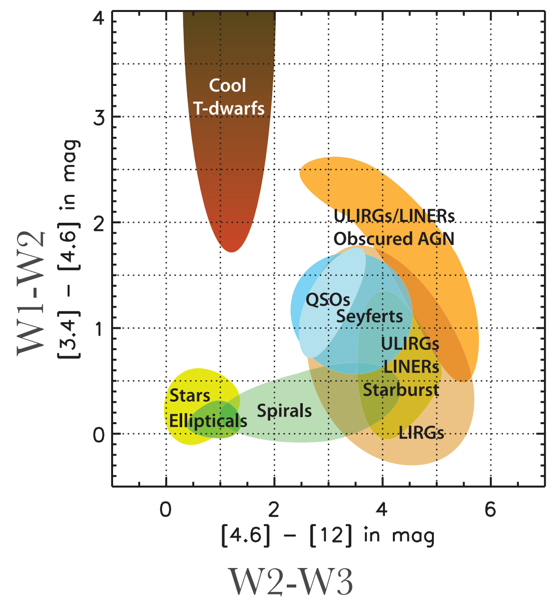

Wright et al. [1008.0031]

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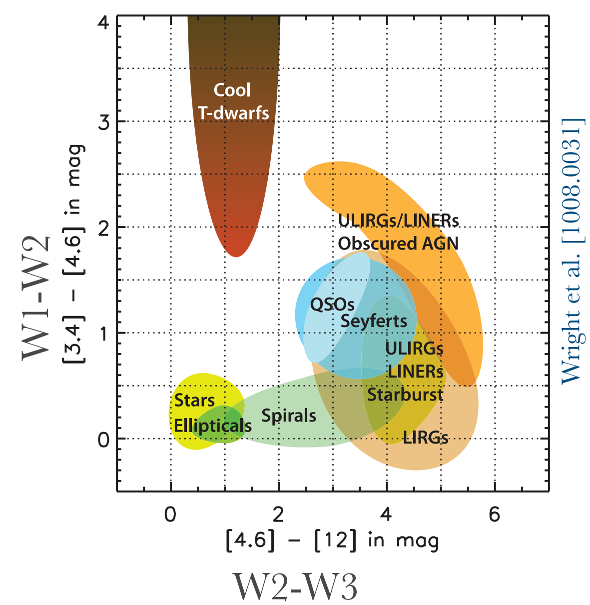
- Sample selection:
  - Correct for Galactic dust extinction
  - Color cut (W1-W2>0.8)
  - Flux cut (corresponding to 9<W1<16.4)
  - Remove 2MASS LGA, and other bright objects
  - Galactic plane mask (|b|>30 deg)



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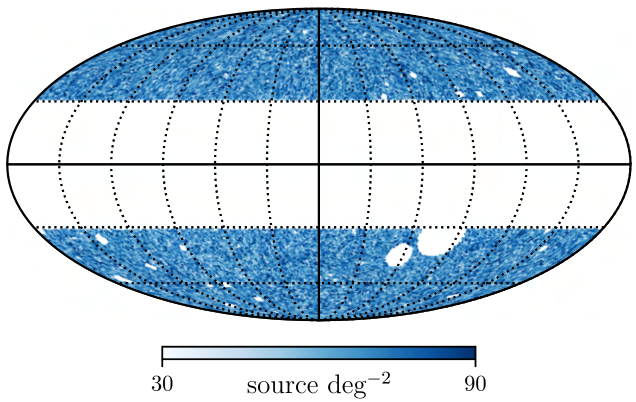
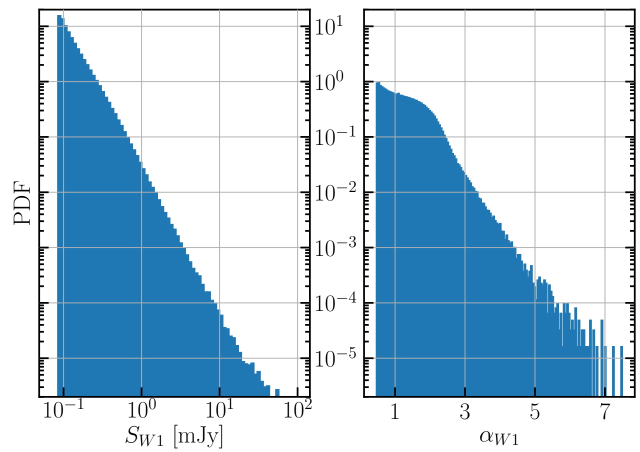
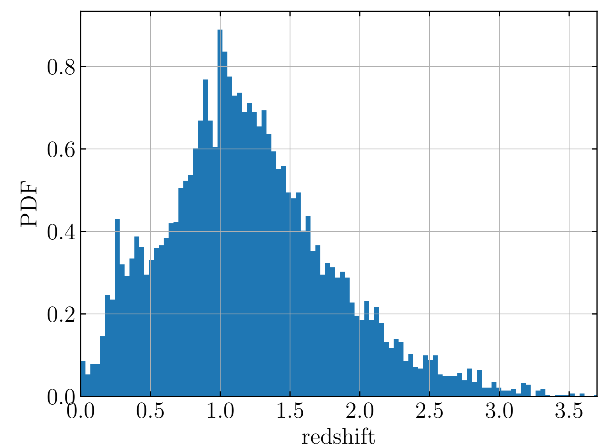






- Flux density $f_\nu \propto \nu^{-\alpha}$, with median($\alpha$) = 1.16
- Differential number counts $dN/d\Omega\ (f_\nu > f_\nu^{\rm min}) \propto (f_\nu^{\rm min})^{-x}$, with $x = 1.7$
- Cross-matched sources with SDSS (e-BOSS) give redshifts
  with mean(z) = 1.2

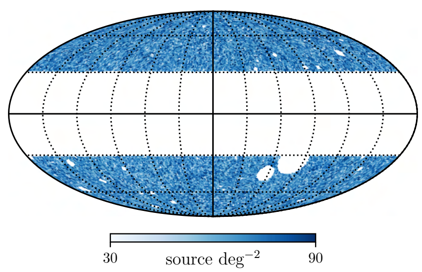
- Estimate clustering (local) dipole from linear theory

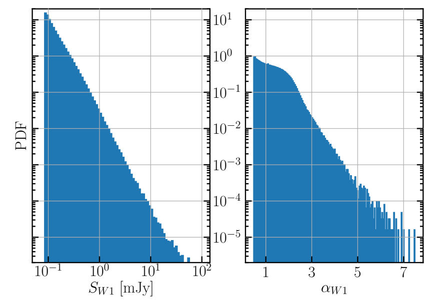
$$C_1 = b^2 \frac{2}{\pi} \int_0^\infty f_1^2(k) P(k) k^2\, dk$$

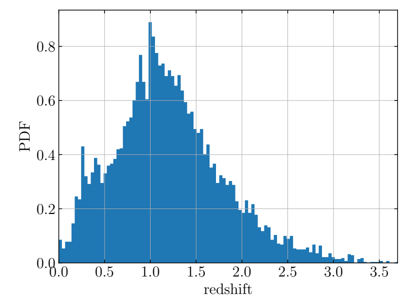
- We find $d_{local} = 0.00024\, b^2$ compared with the measured dipole $d = 0.01554$

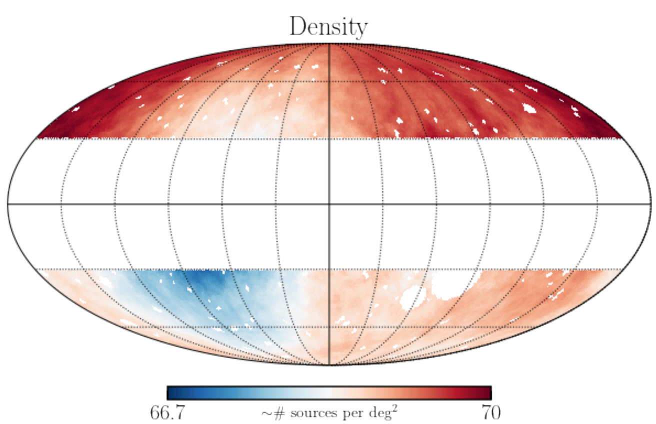
$$\vec{d}_{total} = \vec{d}_{kin} + \vec{d}_{local} + \vec{d}_{bias} + \vec{d}_{noise}$$

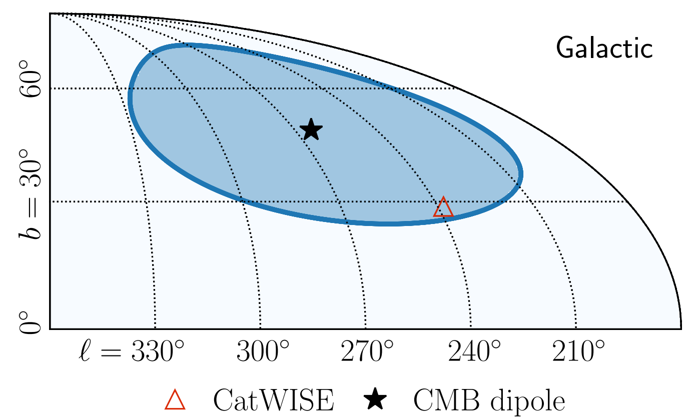
Mid-IR Quasar sample



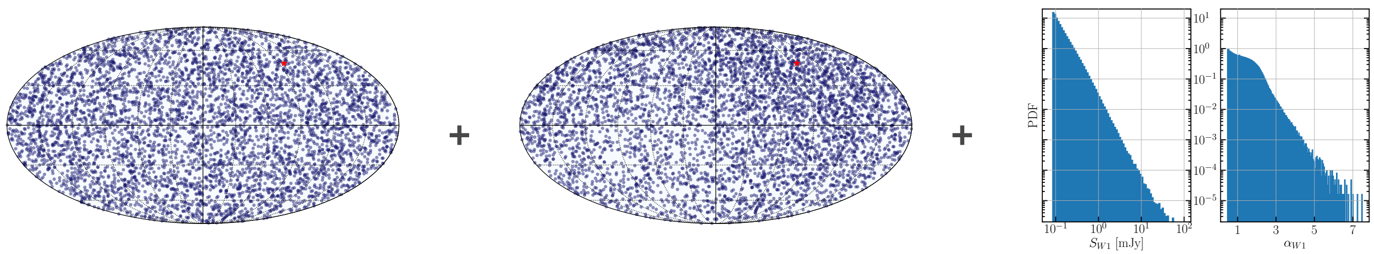


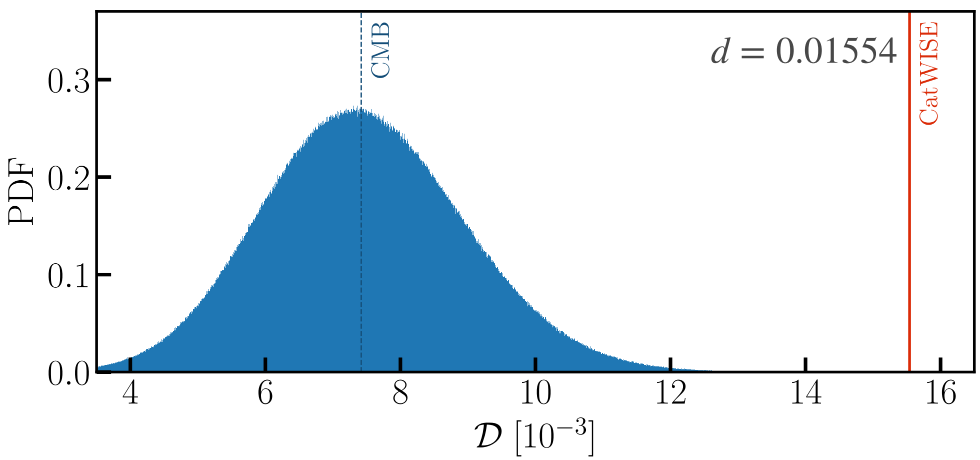






Mid-IR Quasar sample dipole — simulations





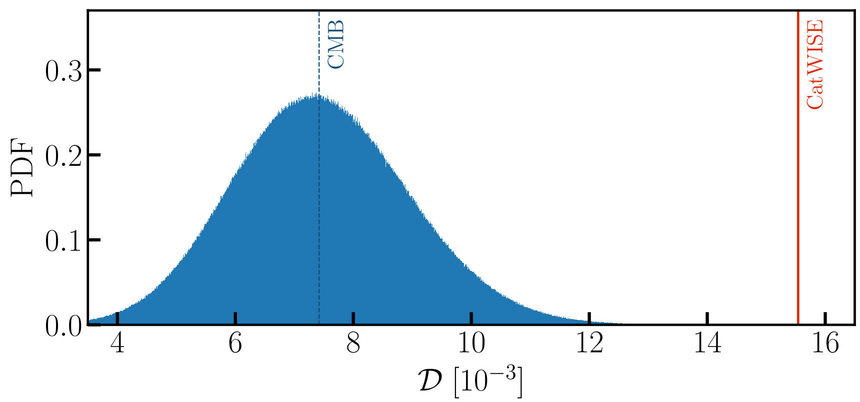
- 10 million simulations run with input velocity of $v_{\odot} = 369.82\,\mathrm{km/s}$ in direction $(l, b) = (264.021, 48.253)^{\circ}$
- Sources resample α and f_{ν} from sample's distributions
- Number of sources cut to that in sample
- The dipole we find in the CatWISE2020 AGN sample is inconsistent with this at $p = 5 \times 10^{-7}$

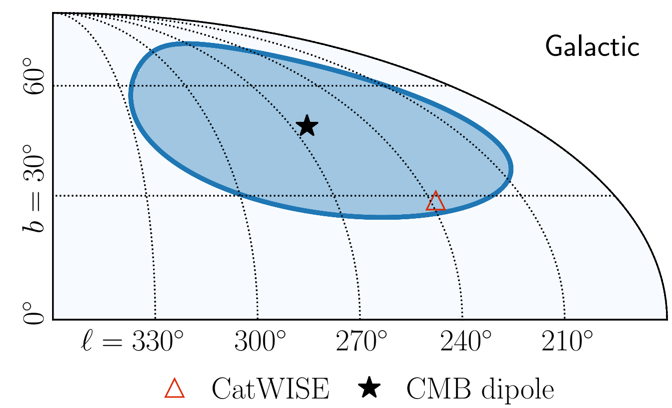
What could have gone wrong?

- Small-scale clustering enhanced through double counting (radio lobes)
- Point sources
- Not kinematic, but large-scale clustering at redshifts $z\sim1$
- Scanning strategy / Striping
- Temperature shifts of the instrument? Time-dependent sensitivity?
- Leakage of higher multipoles due to cut sky
- Populations of unremoved local (Galactic) sources

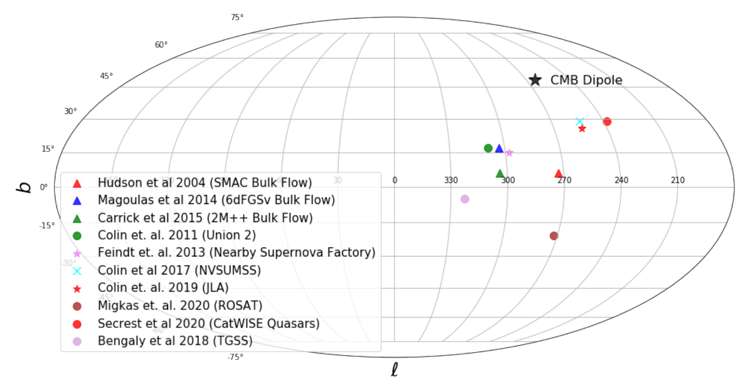
- All ideas welcome!

Mid-IR Quasar sample dipole — dipole direction





- Radio dipoles *e.g,* Siewert, Schmidt-Rubart and Schwarz [2010.08366]
- SNIa bulk velocity *e.g,* Colin et al. [1011.6292]
- X-ray cluster $L_X - T$ relation Migkas et al. [2004.03305]
- SNIa "cosmic" acceleration Colin et al. [1808.04597]
- kinetic Sunyaev-Zeldovich effect ("dark flow") Kashlinsky et al. [0910.4958], *see also* [1303.5090] *and* [1411.4180]
- CMB anomalies Schwarz et al. [1510.07929]

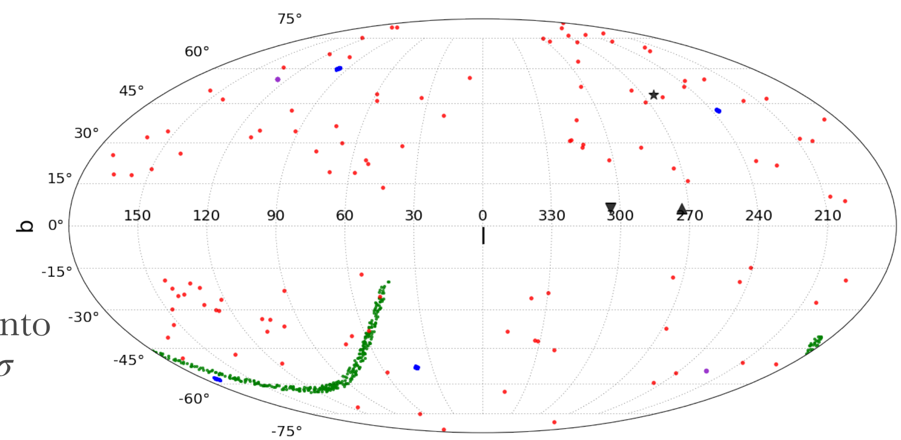


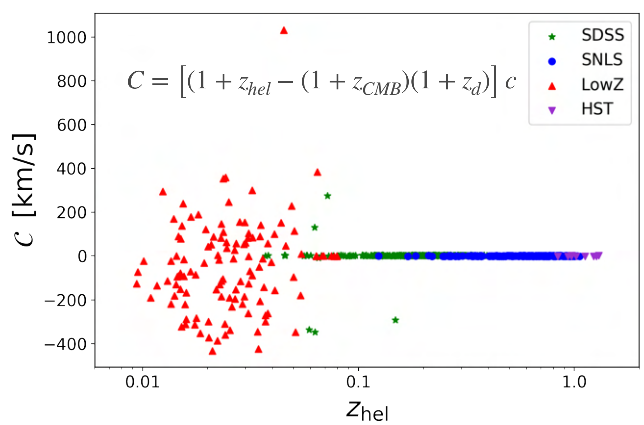
Mohayaee et al. [2106.03119]

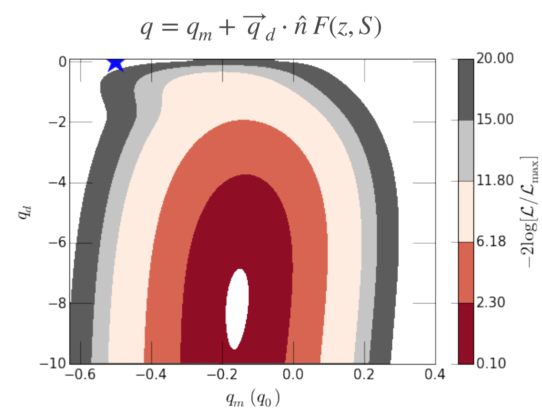
SNIa acceleration — including a dipole

Colin et al. [1808.04597]

- Due to peculiar velocities of SNIa, redshifts are conventionally corrected to be in CMB rest frame
- Corrections can only be made with a model, that is ignorant beyond ~150 Mpc
- Undoing corrections and instead including a dipole into the fit of the deceleration parameter results in $\sim 1.4\sigma$ "detection" of cosmic acceleration.





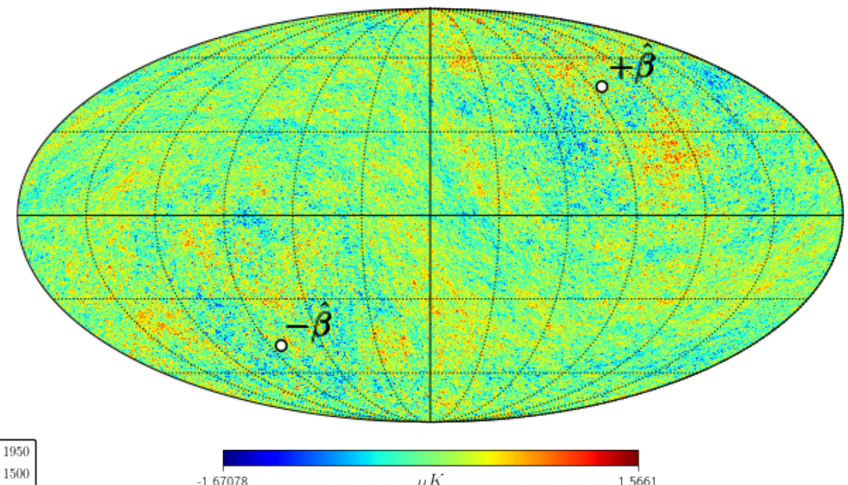


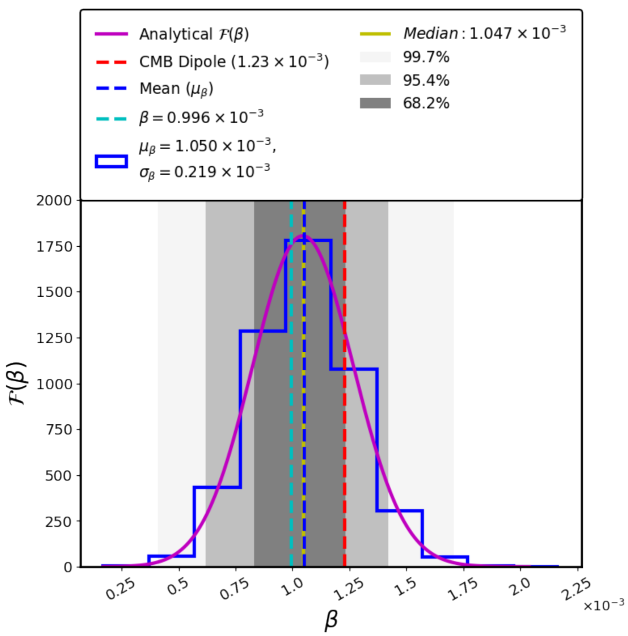
CMB aberration and modulation

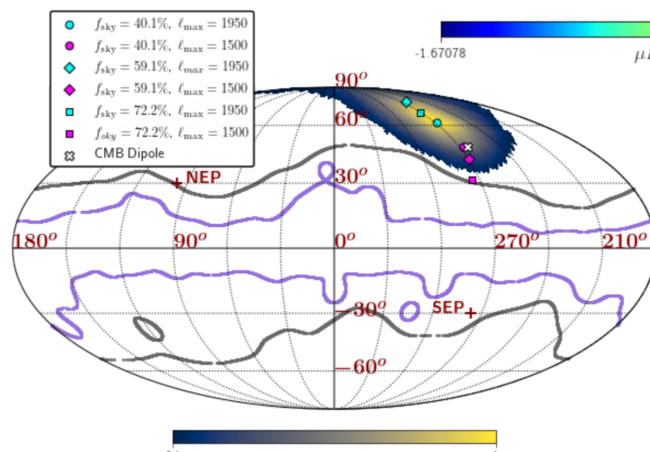
Saha et al. [2106.07666], Planck Collab. XXVII [1303.5087]

- A boosted observer also sees the CMB fluctuations aberrated and modulation by a degree proportional to the velocity

- Saha et al. (2021) find the inferred velocity to be consistent with that inferred from the CMB dipole







What now?

- Dipole could originate from kinematic effects, but could also arise from larger-scale clustering than expected

- Disentangle kinematic from non-kinematic effects, and CMB dipole from matter dipole

  - Spectrum of CMB dipole/quadrupole, aberration in the CMB, other estimators, …
    e.g., Kamionkowski&Knox [0210165] *e.g.,* Planck Collab. XXVII [1303.5087]

  - Test other effects, e.g. kinematic Sunyaev-Zeldovich-effect ("dark flow"), X-ray dipole, …
    Planck Collab. Int. Res. XIII [1303.5090], Atrio-Barandela et al. [1411.4180] Migkas et al. [2004.03305]

  - Investigate theoretical aspects, e.g. Grishchuk-Zeldovich effect ("tilted universe")
    see also Gunn (1988), and Turner (1991)

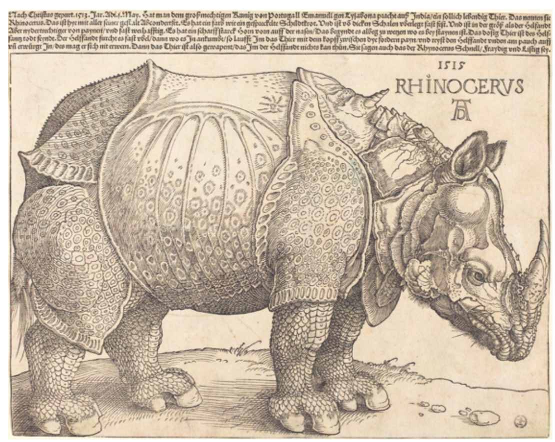
  - Larger samples expected from various upcoming surveys (Square Kilometre Array, Vera Rubin Obs., Nancy Grace Roman Space Tel., …)

Summary

- Most cosmological probes rely on the validity of the Cosmological Principle, and more

This work:

- High-z quasar sample of 1.36×10^6 sources (largest so far, for such studies)
- Dipole amplitude is inconsistent with having kinematic origin and $v_\odot = 369\,\mathrm{km/s}$ with a significance of $p \approx 5 \times 10^{-7}$



"Rhinocerus" — Albrecht Dürer (Nuremberg, 1515)