Cosmology with Quasars Proper Motion: Constraining the anisotropic expansion of the Universe

Rencontres du Vietnam 2025

Presented by:

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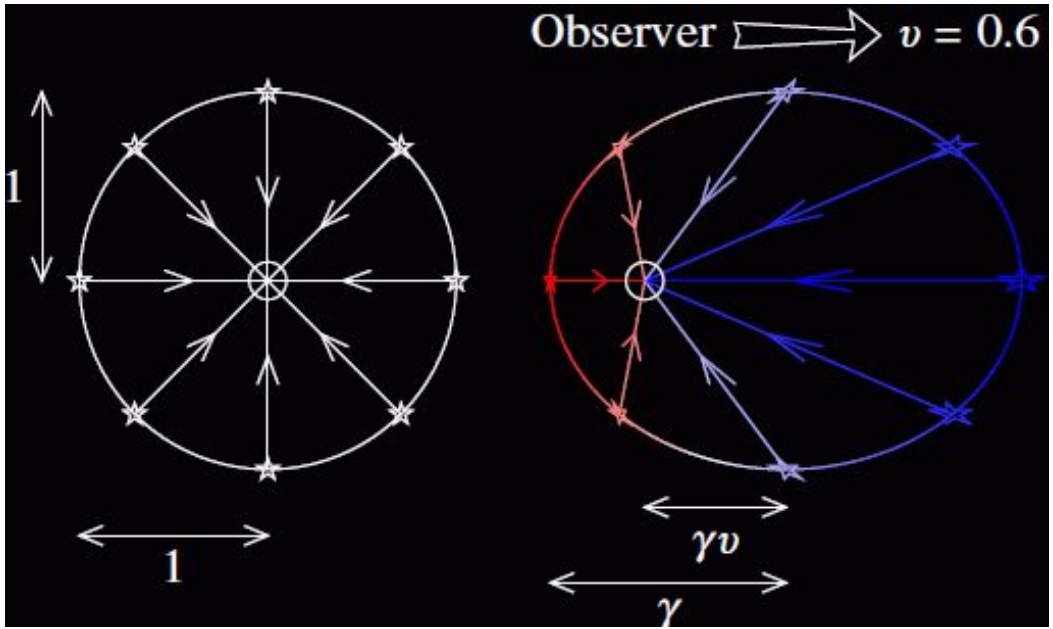
Aberration Effect

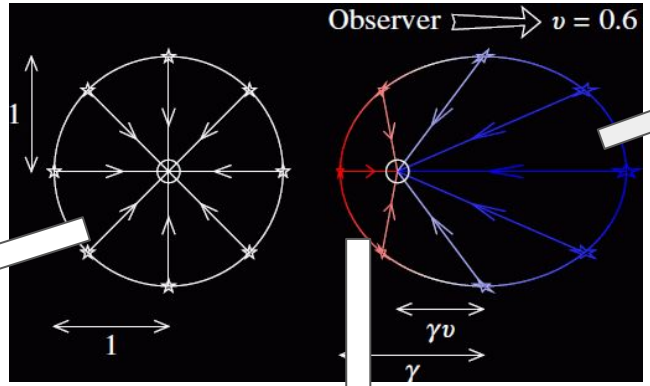
a

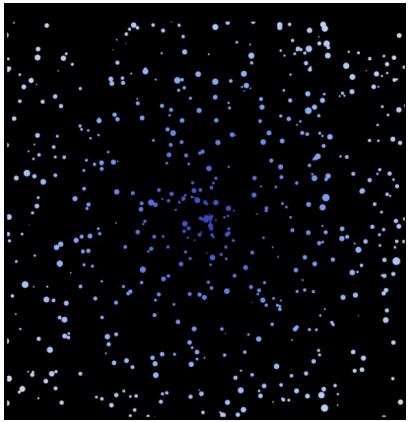
b

Aberration Effect

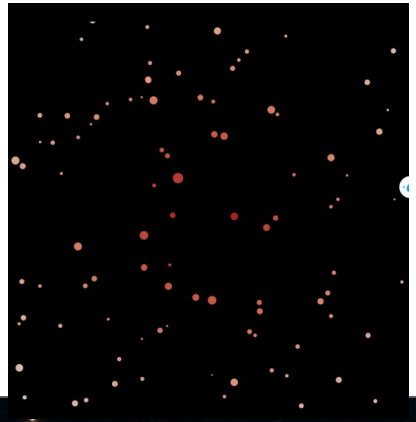


Aberration Effect





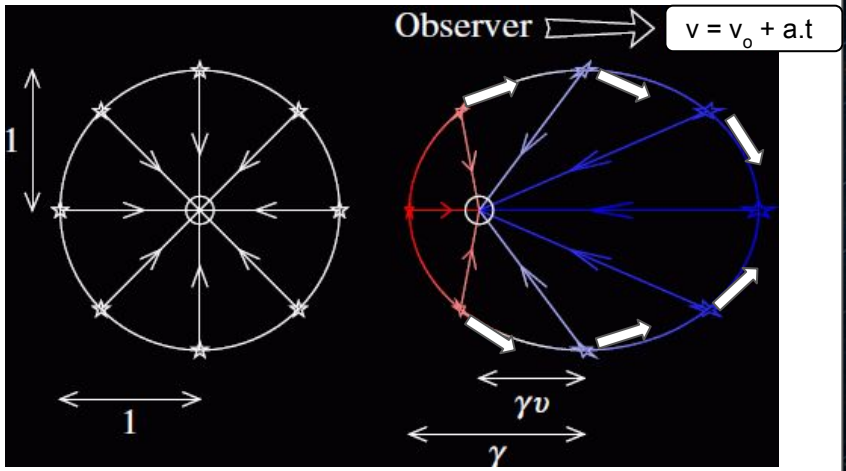
higher source density



lower source density

Proper Motion Dipole

- If the observer is accelerating
  ⇒ apparent proper motion point towards the direction of acceleration ⇒ dipole signal



Proper Motion Dipole

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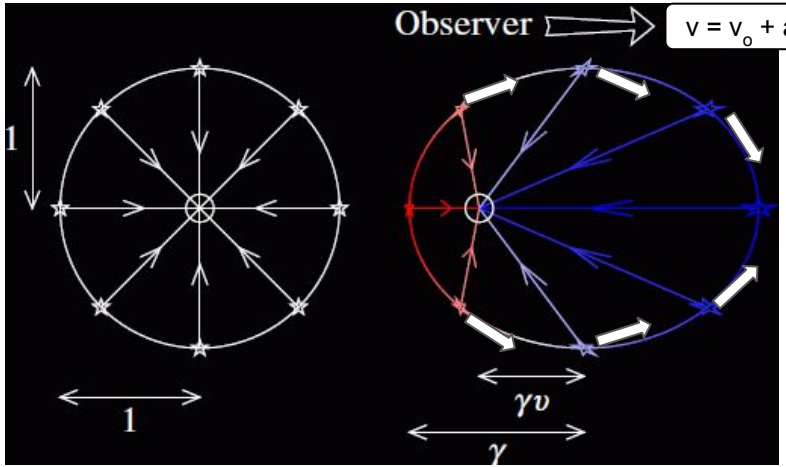
  ΛCDM ⇒ the Universe is isotropic and homogeneous on large scale
  ⇒ Dipolar pattern only for the distance objects



Proper Motion Dipole

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  ΛCDM ⇒ the Universe is isotropic and homogeneous on large scale
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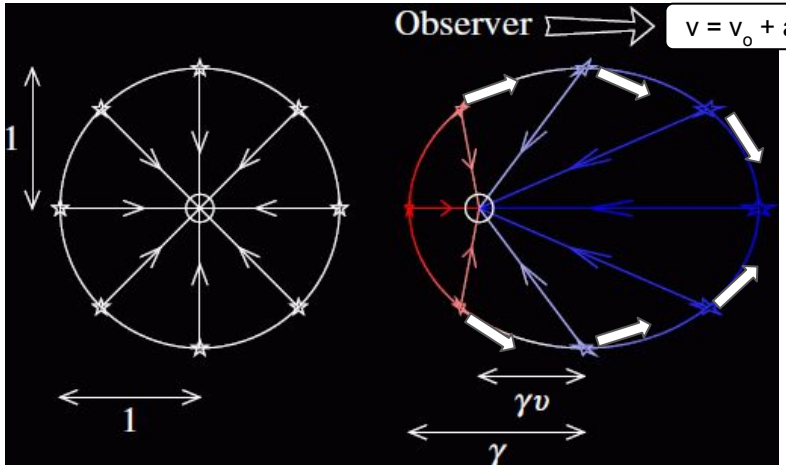
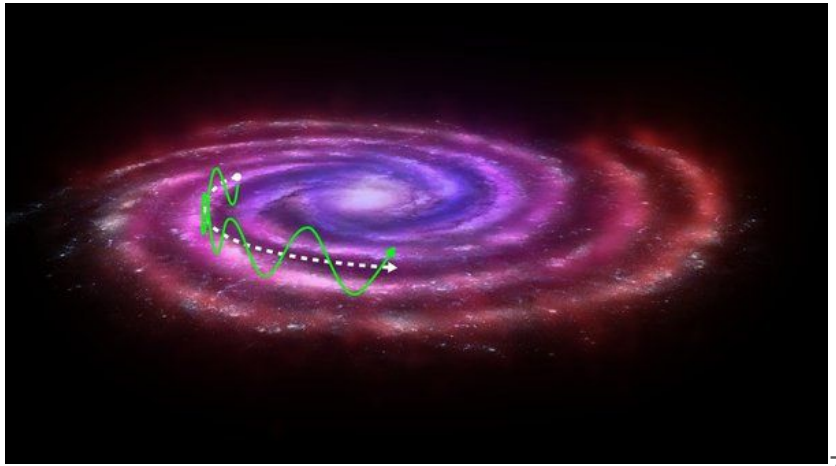
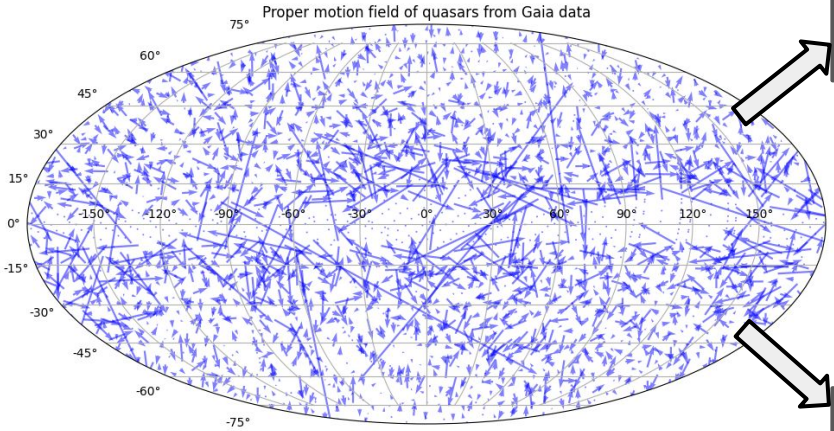
- Solar System moving around Milky Way
  ⇒ create apparent proper motion + dipole

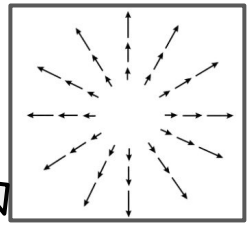




Vector Spherical Harmonics

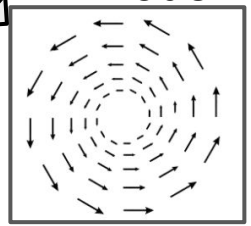


E-mode



Curl - free

B-mode

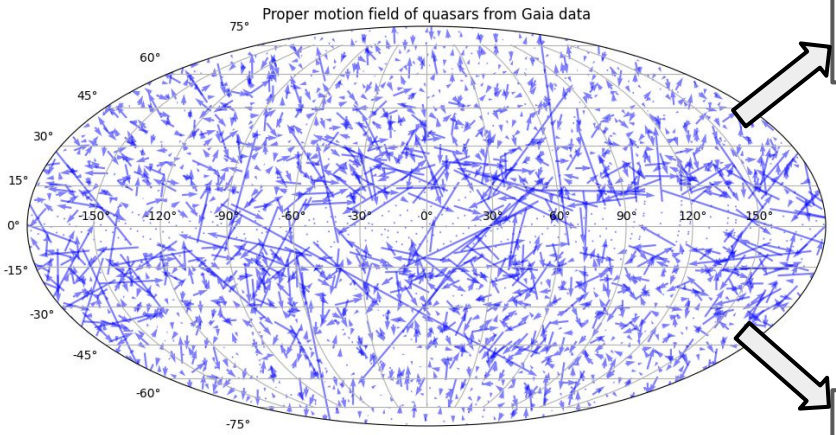


Div - free

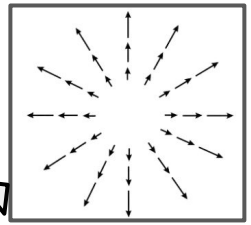
Vector Spherical Harmonics

degree: ℓ
order: m

$s_{\ell m}$ → magnitude → E-mode



E-mode

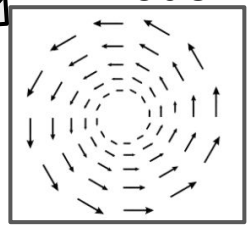


Curl - free

$s_{\ell m}$, $t_{\ell m}$ ⇒ $a_{\ell m}$

$t_{\ell m}$ → magnitude → B-mode

B-mode



Div - free

Vector Spherical Harmonics

degree: ℓ
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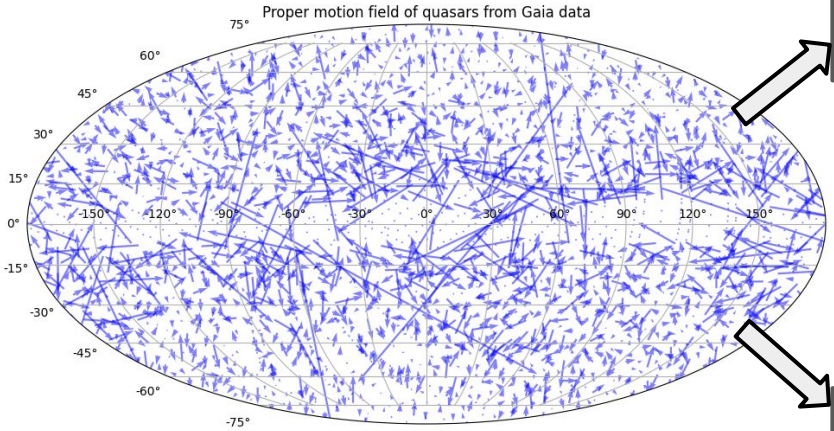
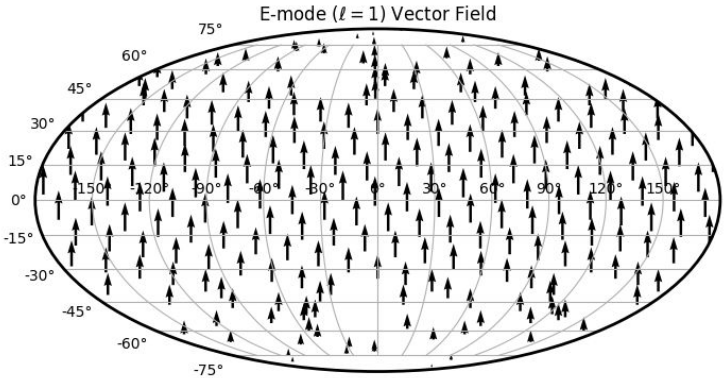
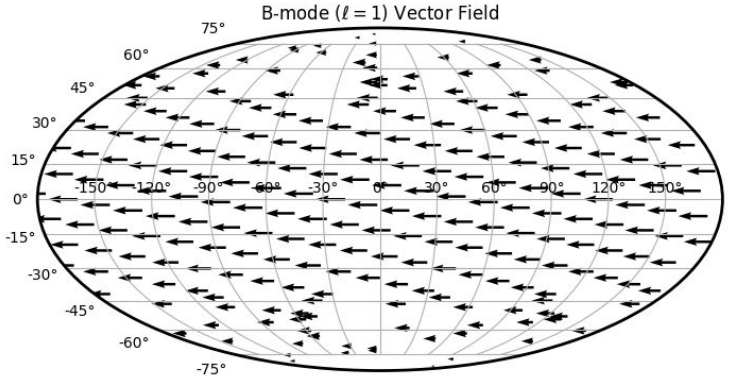
$s_{\ell m}$ → magnitude → E-mode → Curl - free





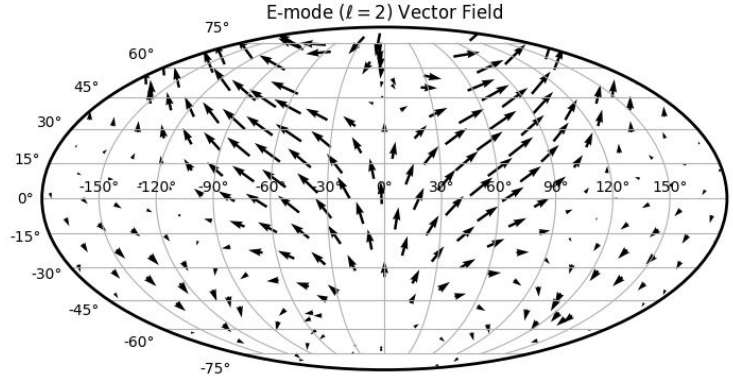
$s_{\ell m}$, $t_{\ell m}$ ⇒ $a_{\ell m}$

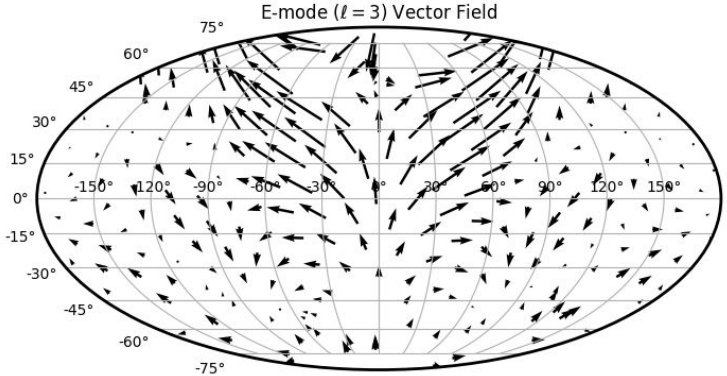
$t_{\ell m}$ → magnitude → B-mode → Div - free

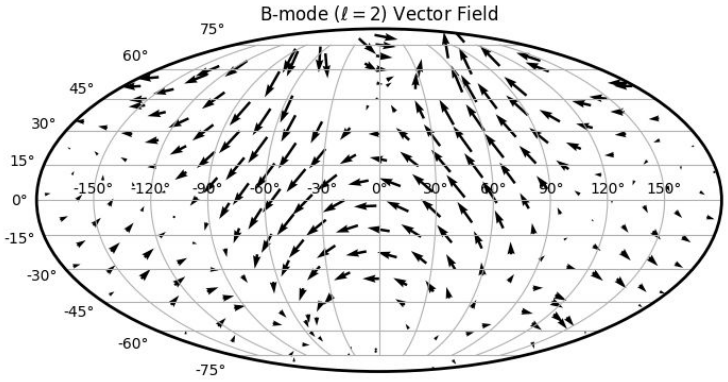


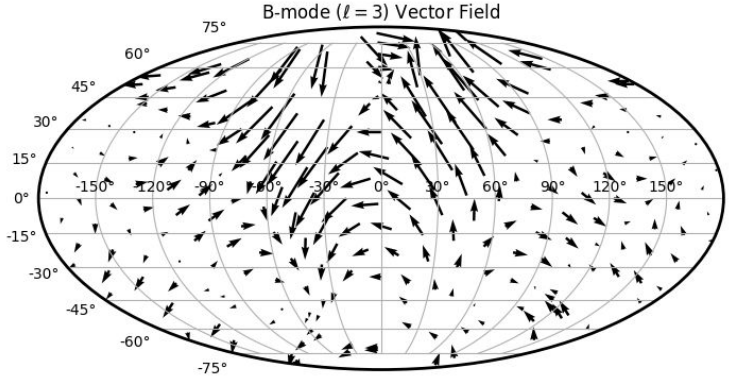
Vector Spherical Harmonics

Higher degree of ℓ (correspond to smaller scales) leads to more sophisticated patterns





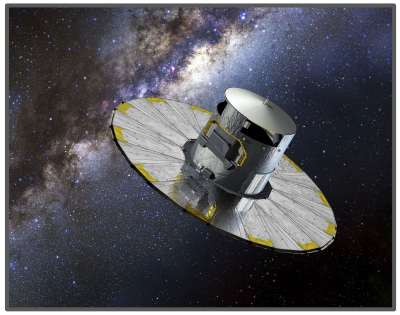


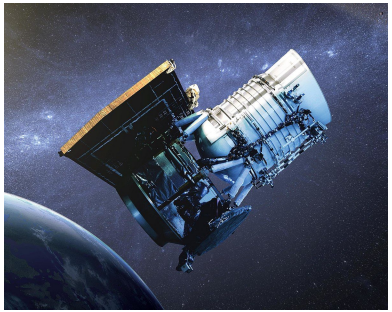


Quasar Samples

Conditions

- Full-sky
- High-precision astrometry
- High purity and completeness





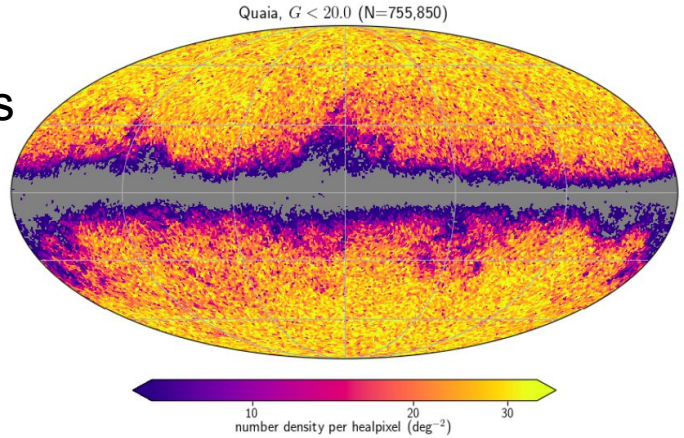
Gaia
Early Data Release 3

→ 1,215,942 quasars

∧ higher purity

Gaia x WISE
Quaia catalog

→ 755,850 quasars



Auto-Correlation of Proper Motion

The auto-correlation power spectrum shows how similar the proper motions of quasars are across different angular scales on the sky.

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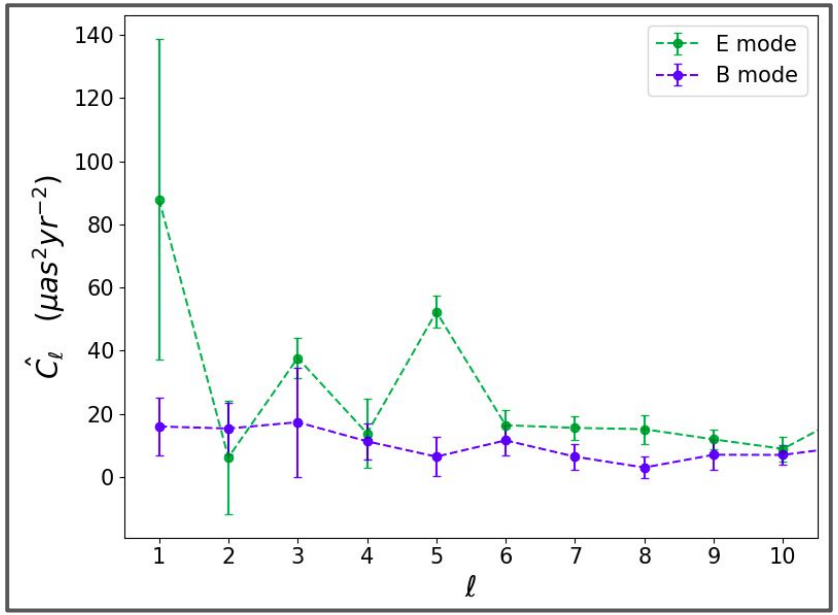

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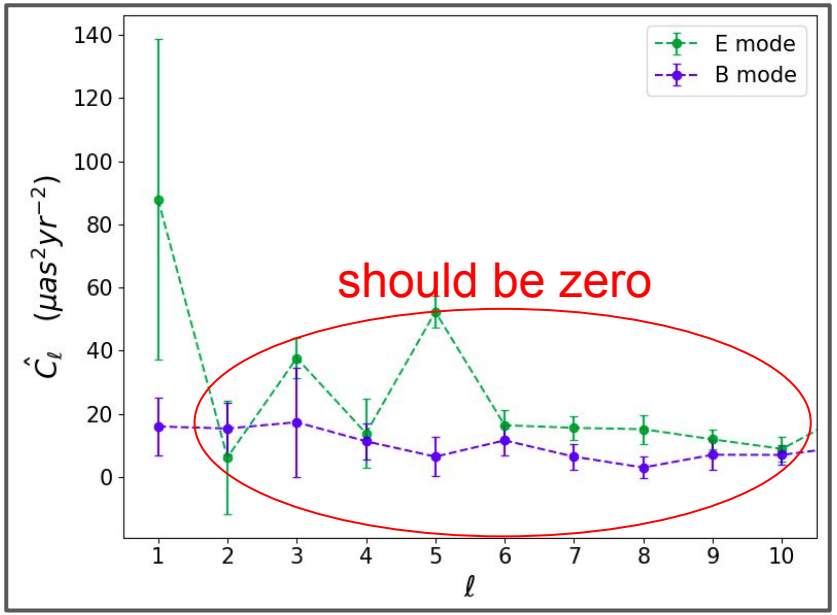

- Expect **zero** value of C_ℓ for higher multipoles ($\ell \geq 2$)
- Existence of multipoles probably due to:
  - the systematics such as: scanning strategy, stellar density, etc.
  - Noise
  - Inhomogeneity and anisotropy (less likely)

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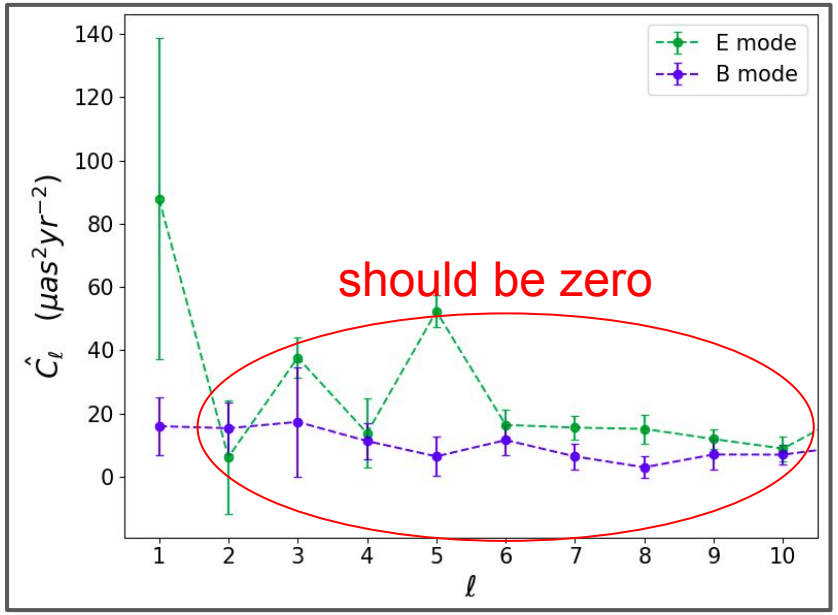


Aim:

- Constraining the dipole
- Explaining for the existence of multipoles

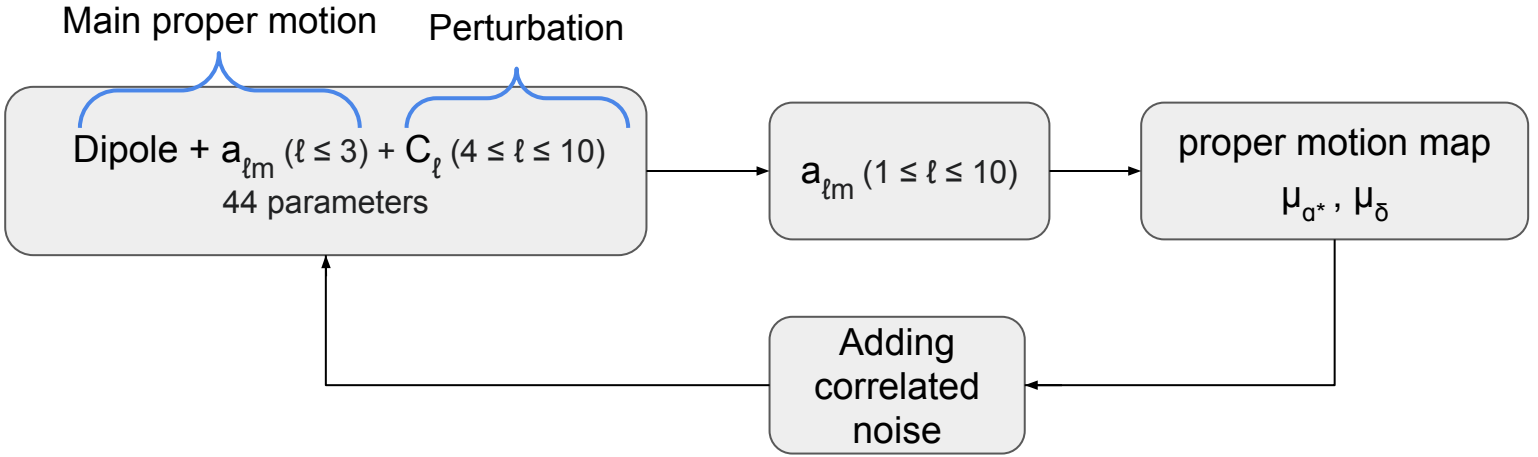
Inference Model

- Applied Bayes theorem:

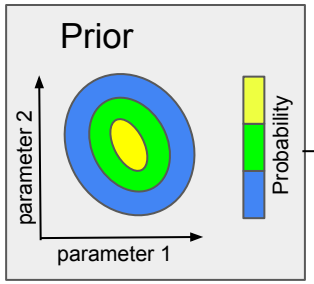
$$P(H|E) = \frac{P(E|H) \cdot P(H)}{P(E)}$$

where H is the hypothesis (model) and E is the evidence (observational data)

- Model:

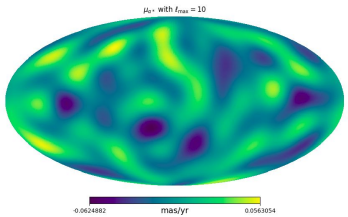


Simulation-Based Inference (SBI)

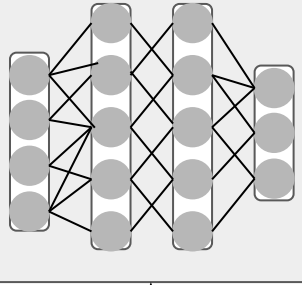


Model

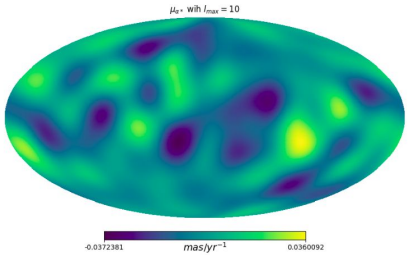
Simulated Data

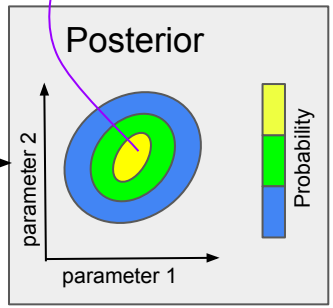


Neural Density Estimator



Observation





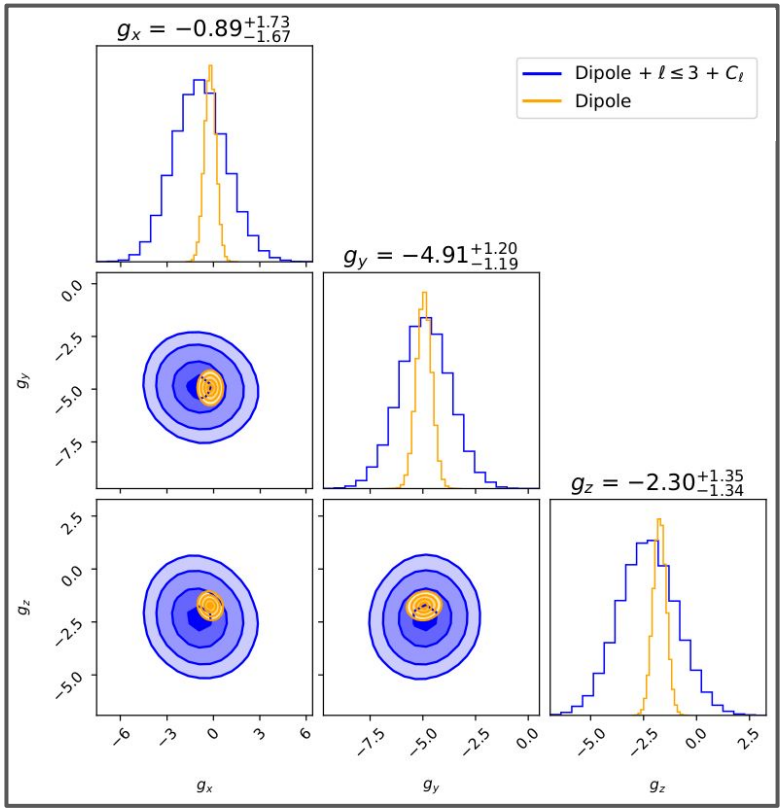
Dipole

$a_{\ell m}$ ($\ell \leq 3$)

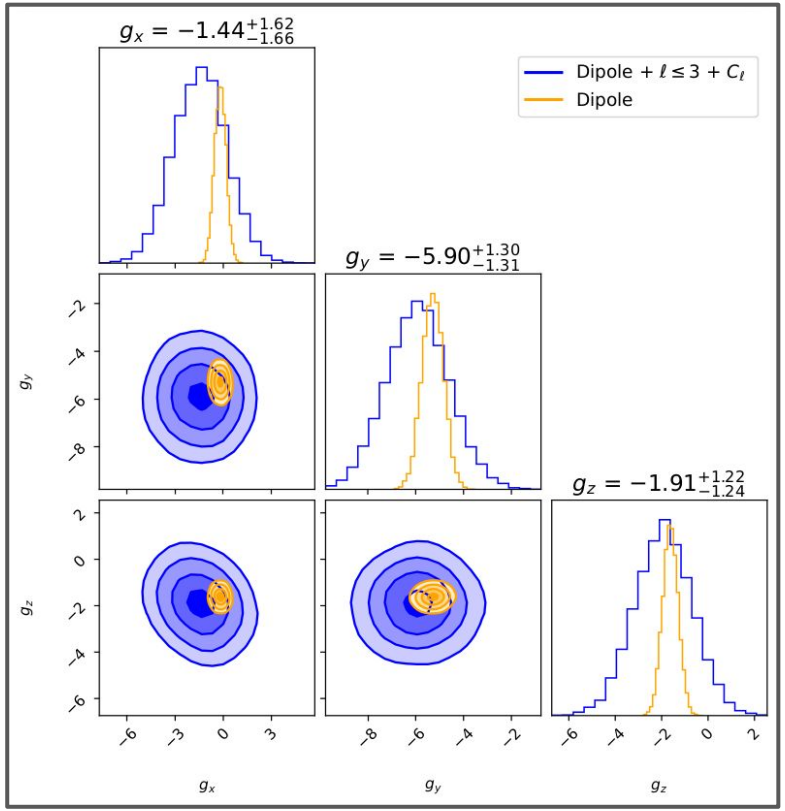
C_ℓ ($4 \leq \ell \leq 10$)

Dipole

Gaia

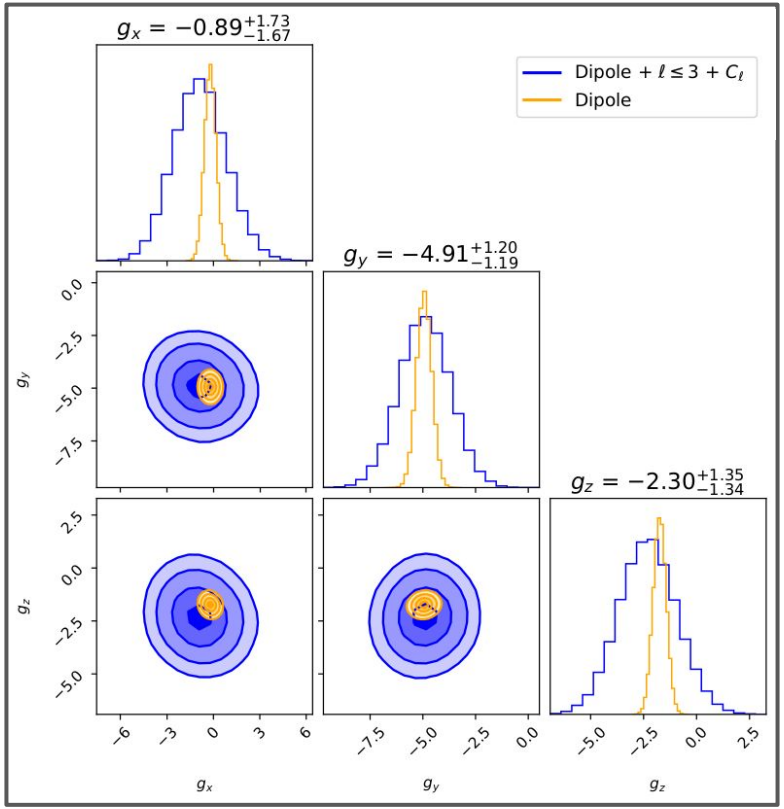


Quaia



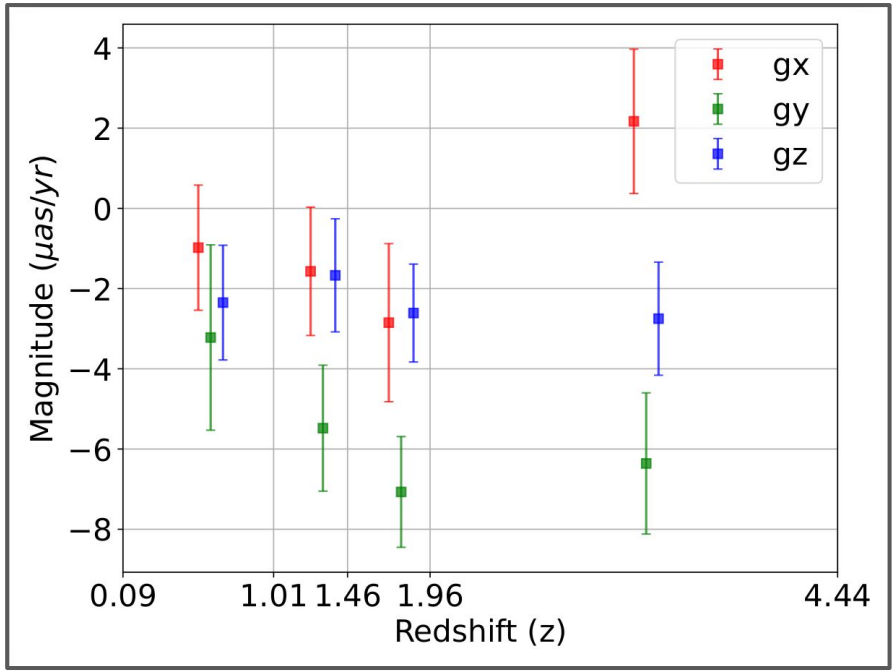
Dipole

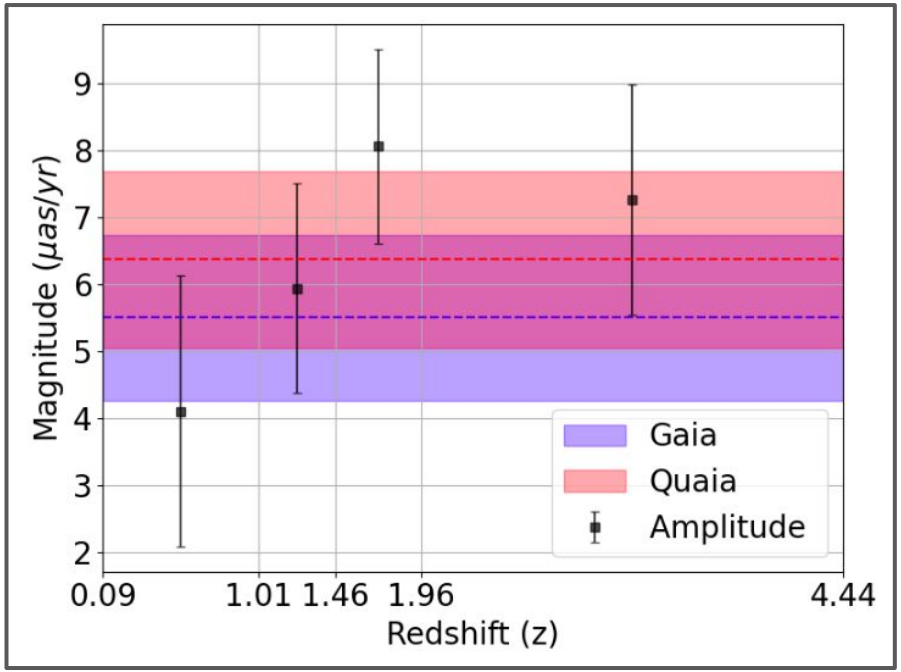
Gaia



- This is our acceleration with respect to the distant universe
- Align with previous work:
  (a_x, a_y, a_z) = (-0.07 ± 0.41, -4.30 ± 0.35, -2.64 ± 0.36) μas/yr (Klioner et al. 2020)
- Larger uncertainties

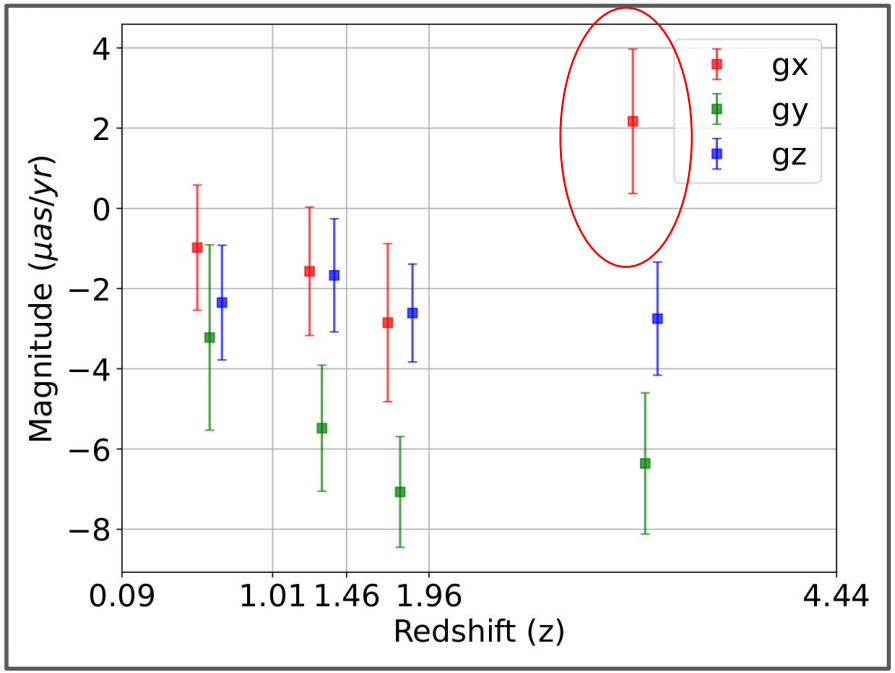
Dipole at different redshift



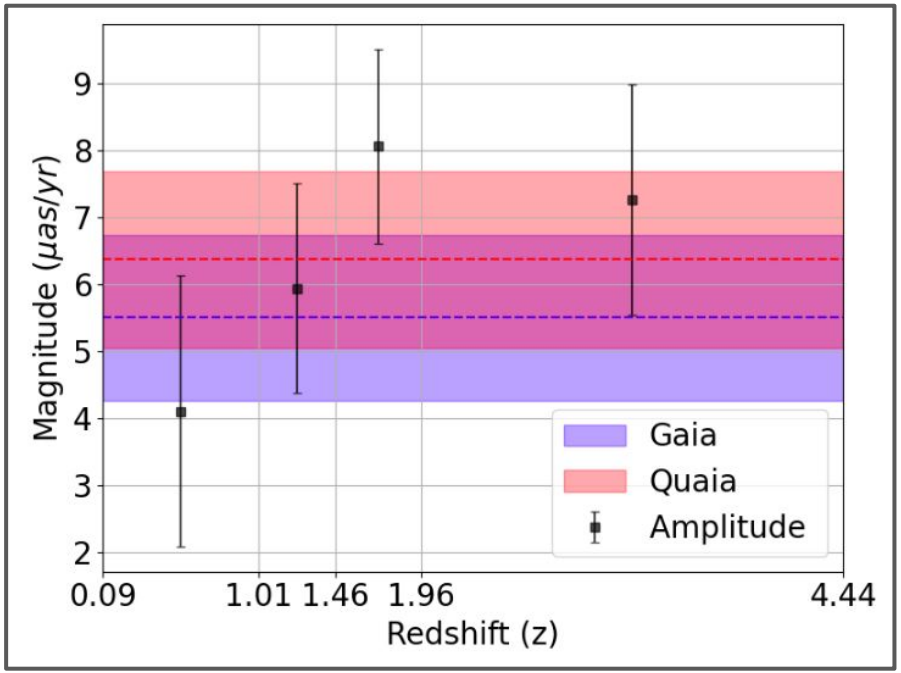


Dipole at different redshift

what!!!



OK!!



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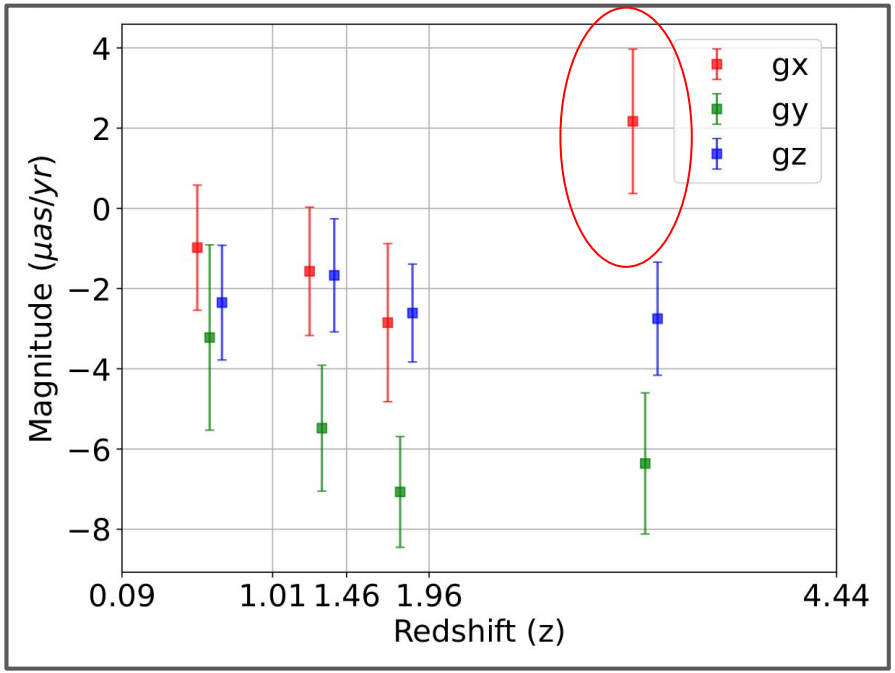
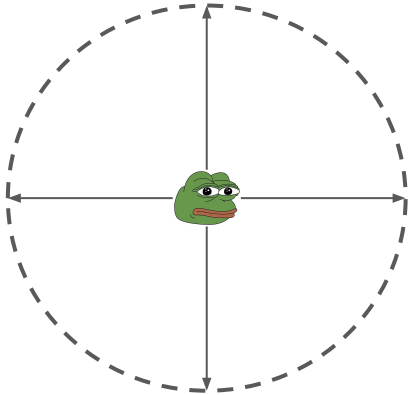
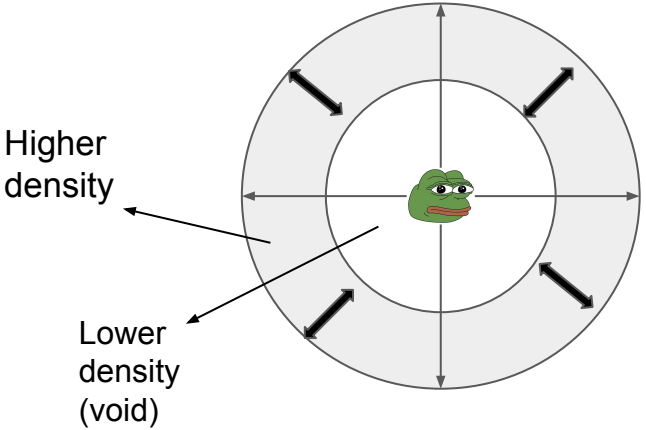


- Amplitudes don't present significant dependence on z
- Offset of gx at 4th redshift bin may due to systematics since quasars there are much fainter
  (need to investigate more)
- Next task:
  Explaining the multipoles

Lemaitre-Tolman-Bondi (LTB) Void Model

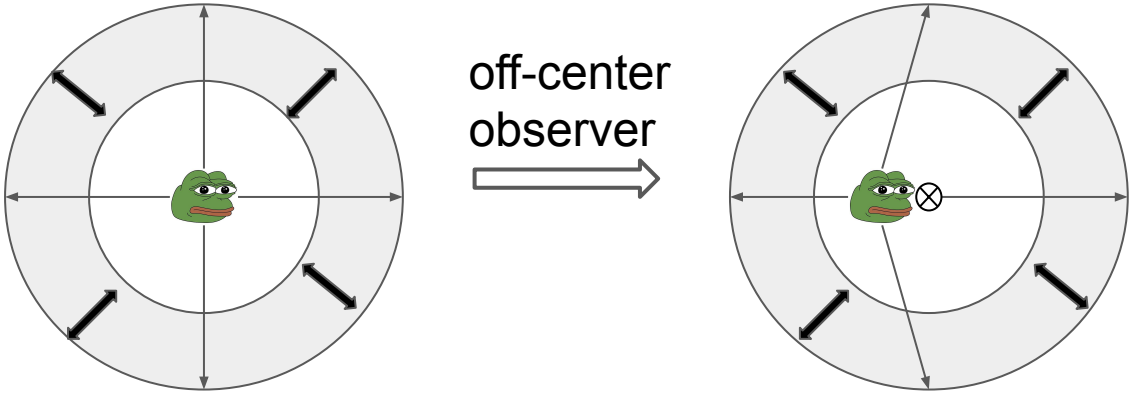


ΛCDM model:
Universe is isotropic and homogeneous on large scale



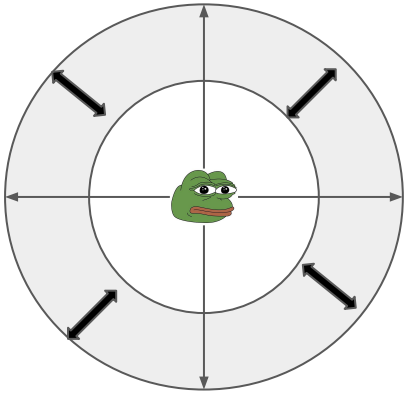
LTB void model:
Universe is radially homogeneous but isotropic if the observer is at the center of the Universe

Lemaitre-Tolman-Bondi (LTB) Void Model

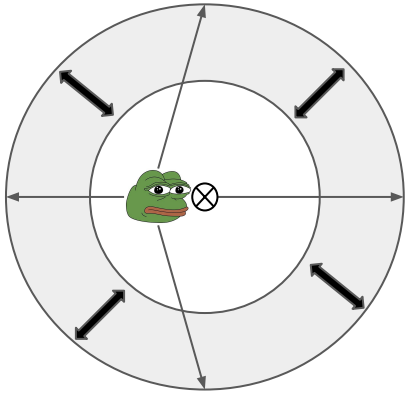


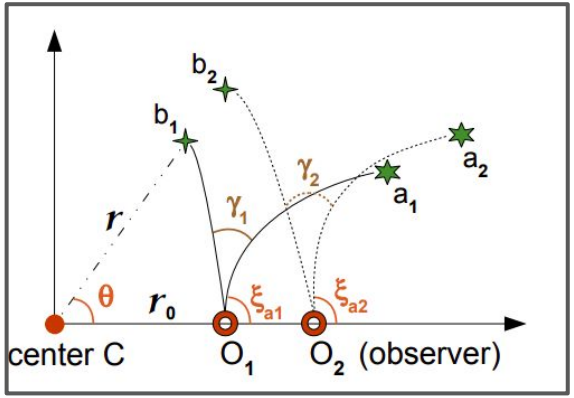
- Off-center observer ⇒ anisotropic expansion ⇒ CP

Lemaitre-Tolman-Bondi (LTB) Void Model



off-center observer





Cosmic Parallax (CP)

(Quartin et al. 2009)

- Off-center observer ⇒ anisotropic expansion ⇒ CP
- In FRW metric, $\Delta\gamma = \gamma_2 - \gamma_1 = 0$
  In anisotropic metric, $\Delta\gamma \neq 0$
- CP ⇒ proper motion

IN PROGRESS!

Conclusion

Summarize:

- Revealed the existence of multipoles in proper motion field
- Robustly measured the Solar System acceleration from proper motion field, but need to check for quasars at very high redshift

Future:

- Constraining the LTB void model
- Checking if proper motion caused by CP contribute significantly to the multipoles

THANK YOU FOR LISTENING!