

UK HEP Forum 2025 “Wandering in the Dark”
October 21st, 2025

The Cosmic Dipole Anomaly

Sebastian von Hausegger
Rudolf Peierls Centre for Theoretical Physics



The Cosmological Principle and FLRW

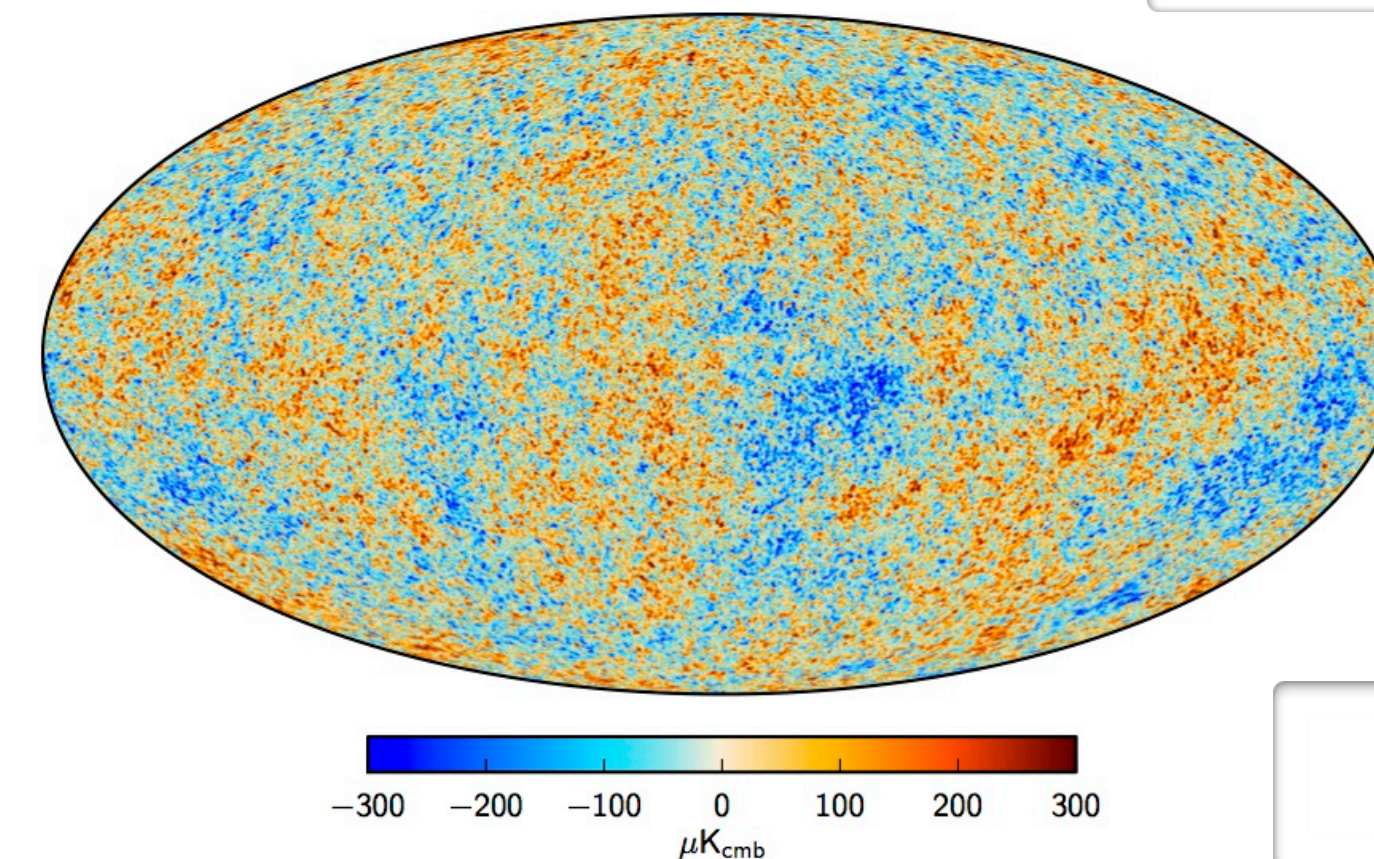
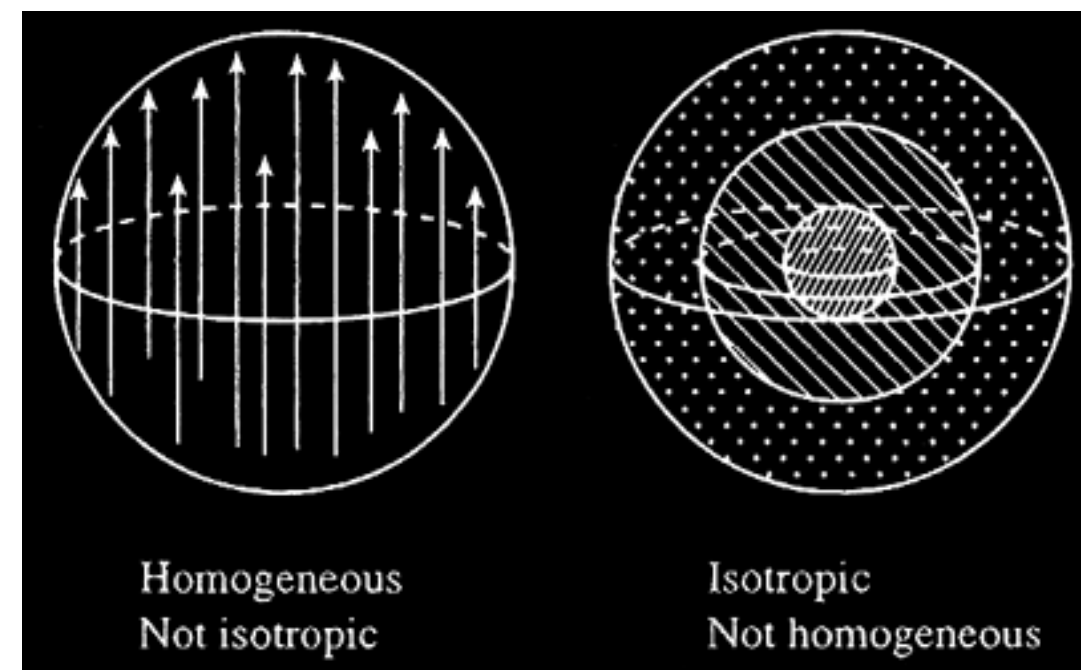
Λ CDM cosmological standard model based on **FLRW metric**

Relies on **Cosmological Principle**

“The Universe must appear the same to all observers.”

Milne (1933)

“All physical quantities measured by a **comoving** observer are spatially homogeneous and isotropic.”



Planck I (2018)

(statistically so)

If **all** comoving observers see an isotropic CMB then we must live in a FLRW Universe

Ehlers, Geren, Sachs (1968)

The Cosmological Principle and FLRW

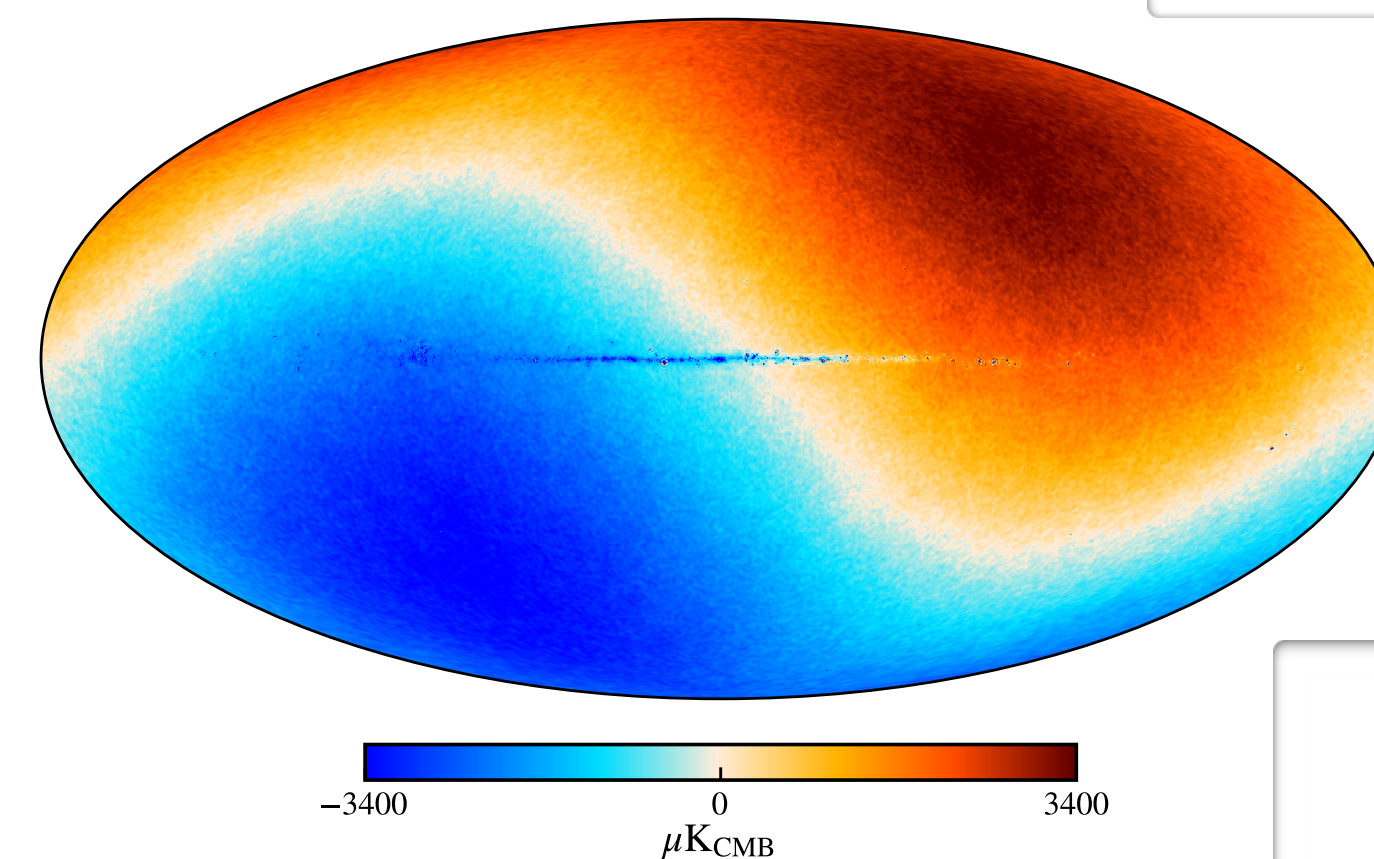
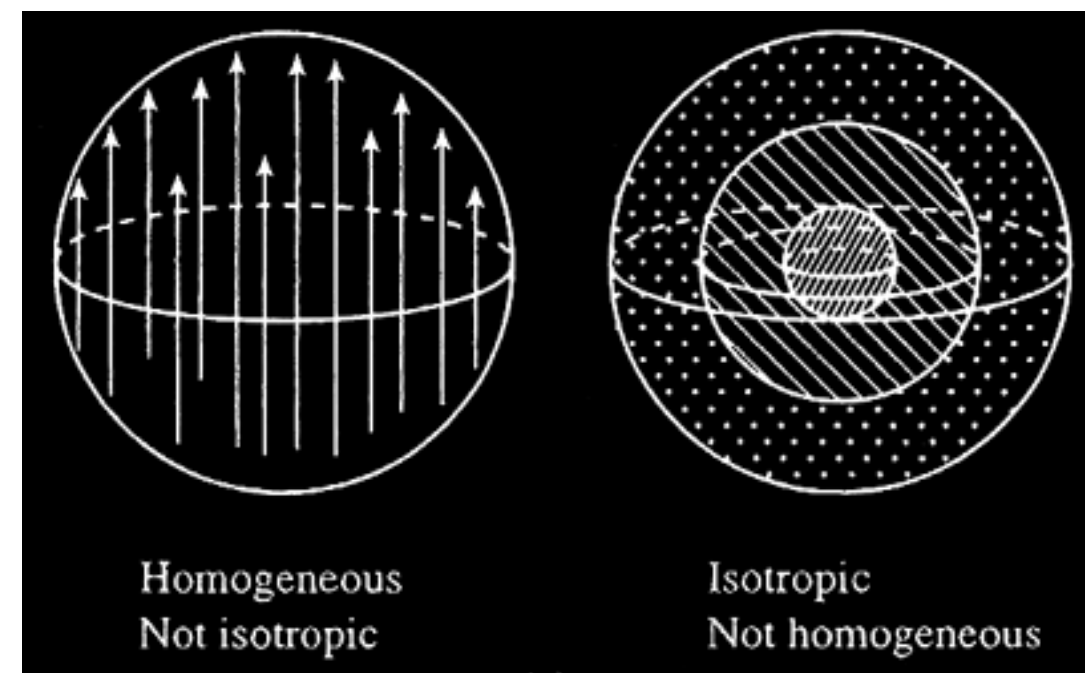
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**BeyondPlanck XI
(2023)**

(statistically so)

We are **not** even comoving observers:

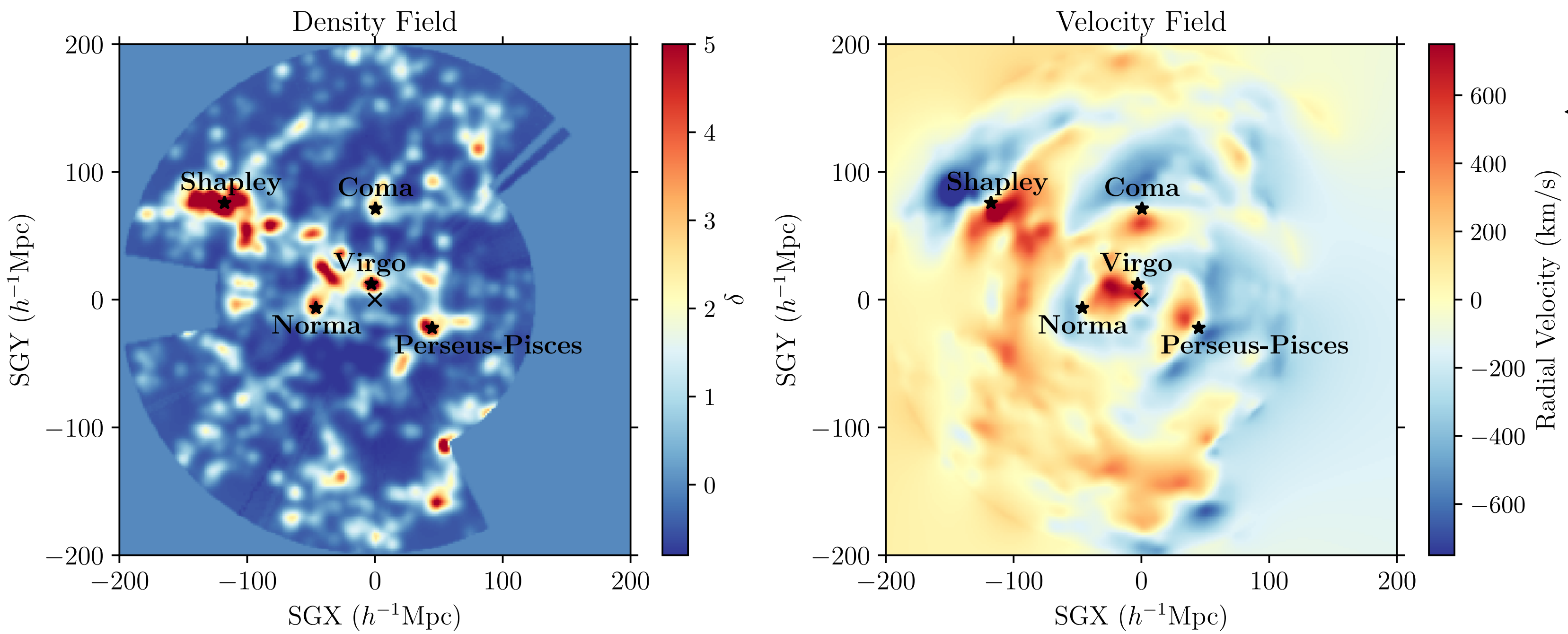
At least check for consistency between CMB rest frame and matter rest frame

Cosmography / Local dynamics

(Radial) velocity field from density field

δ & v field both give
clustering statistics

(2pt cf, bulk flows, ...)



In CMB rest frame

Boruah et al. (2020)

The kinematic CMB dipole

At least check for consistency between CMB rest frame and matter rest frame

CMB temperature is modulated by
a special relativistic boost

$$T \simeq \bar{T} [1 + \beta \cos \theta]$$

depends on velocity wrt
rest frame of sources

Peculiar Velocity of the Sun and its Relation to the Cosmic Microwave Background

by
J. M. STEWART
D. W. SCIAMA
Department of Applied Mathematics and
Theoretical Physics,
University of Cambridge

PHYSICAL REVIEW

VOLUME 174, NUMBER 5

25 OCTOBER 1968

Comment on the Anisotropy of the Primeval Fireball*

P. J. E. PEEBLES† AND DAVID T. WILKINSON†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey 08540
(Received 17 June 1968)

This note presents an exact theory for the anisotropy of the primeval fireball as a function of our motion through the radiation.

CMB dipole corresponds to

$$\beta \sim 1.23 \times 10^{-3}$$

The kinematic matter dipole

At least check for consistency CMB rest frame and matter rest frame

Number counts of sources in a **flux-limited** sample modulated by special relativistic boost

$$\frac{dN}{d\Omega}(S > S_*) = \frac{d\bar{N}}{d\Omega}(S > S_*) [1 + \mathcal{D}_{\text{kin}} \cos \theta]$$

depends on velocity wrt
rest frame of sources

$$\mathcal{D}_{\text{kin}} = [2 + x(1 + \alpha)] \cdot \beta$$

Mon. Not. R. astr. Soc. (1984) **206**, 377–381

On the expected anisotropy of radio source counts

G. F. R. Ellis[★] and J. E. Baldwin[†] *Orthodox Academy of Crete,
Kolymbari, Crete*

**Predict matter dipole
amplitude using $\beta \sim 1.23 \times 10^{-3}$**

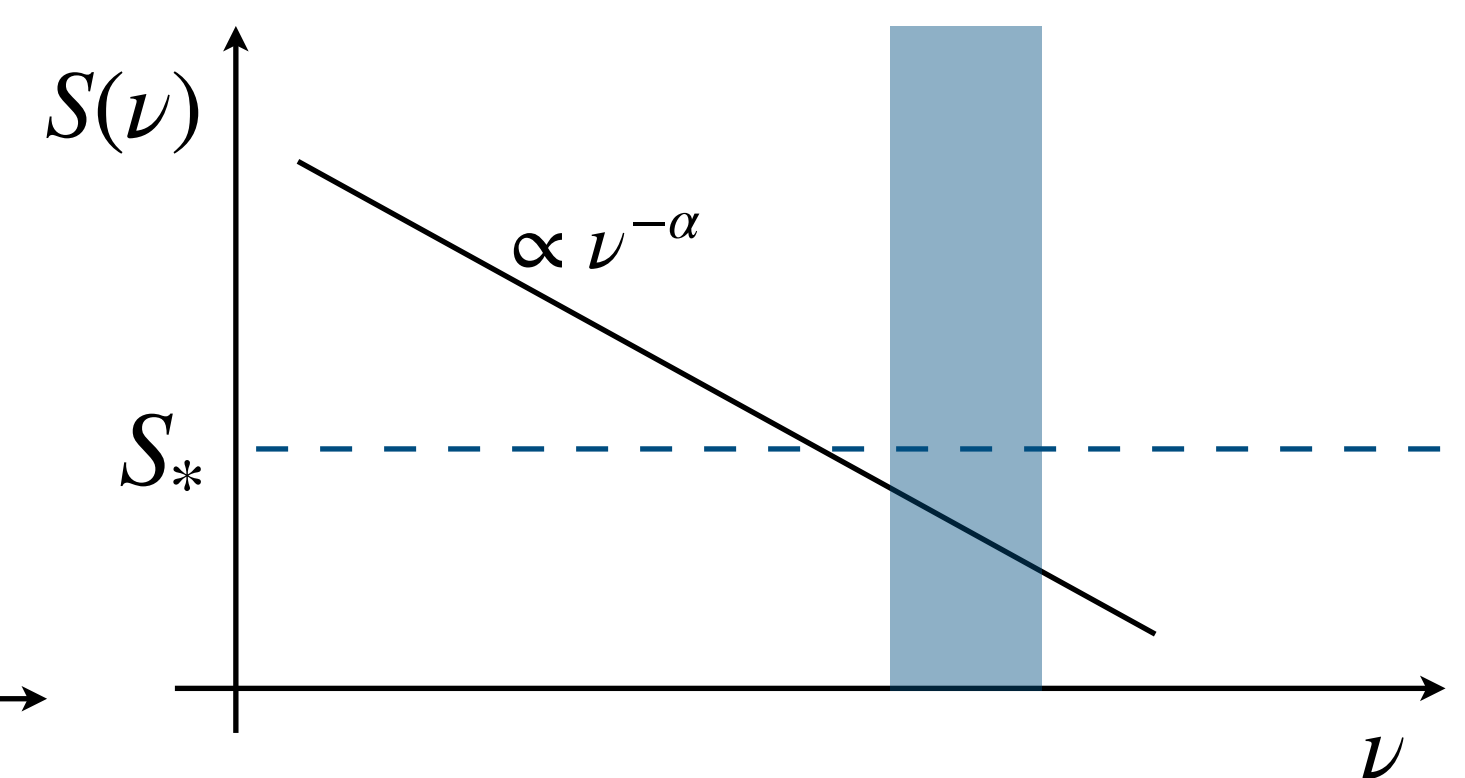
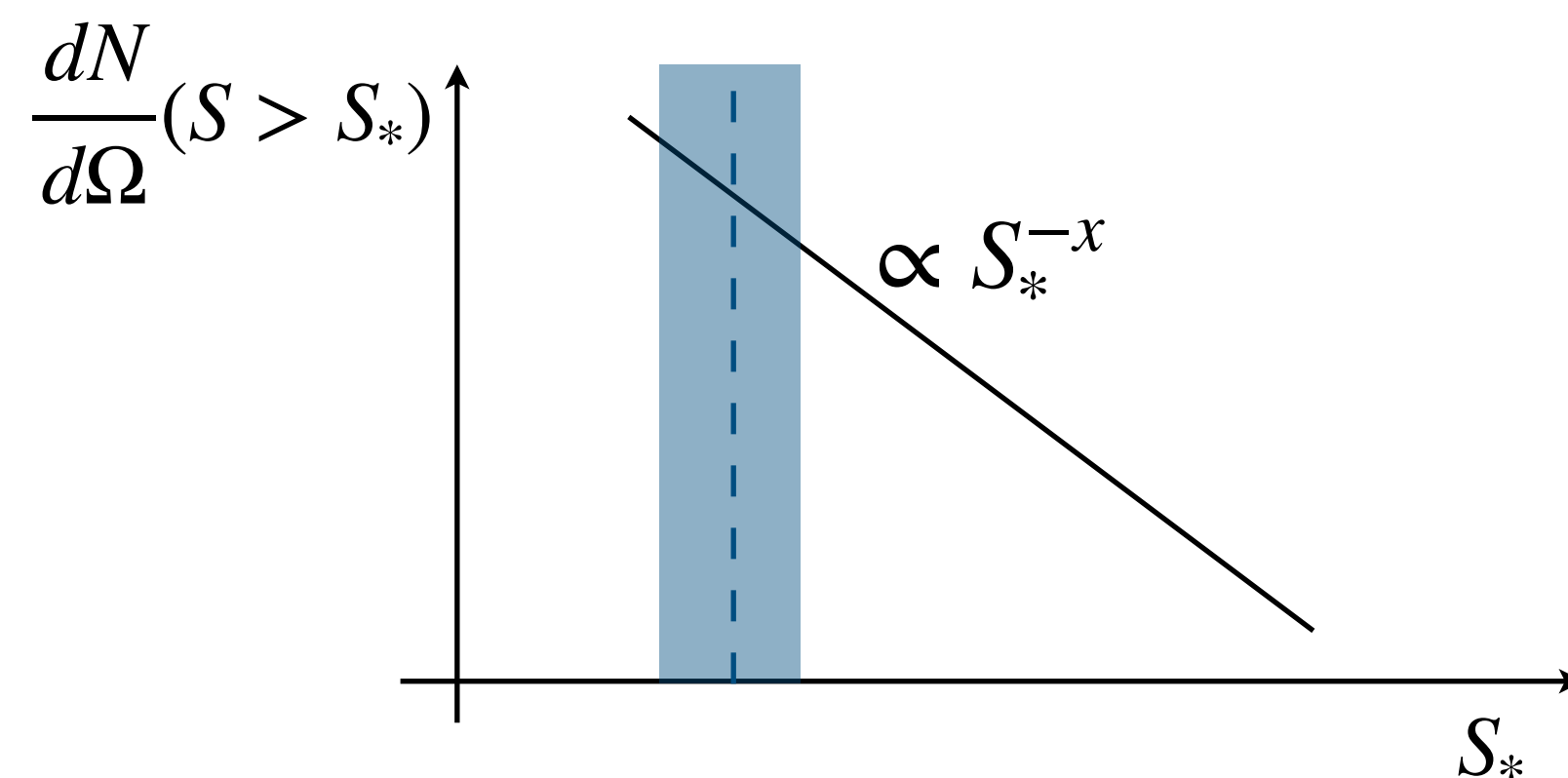
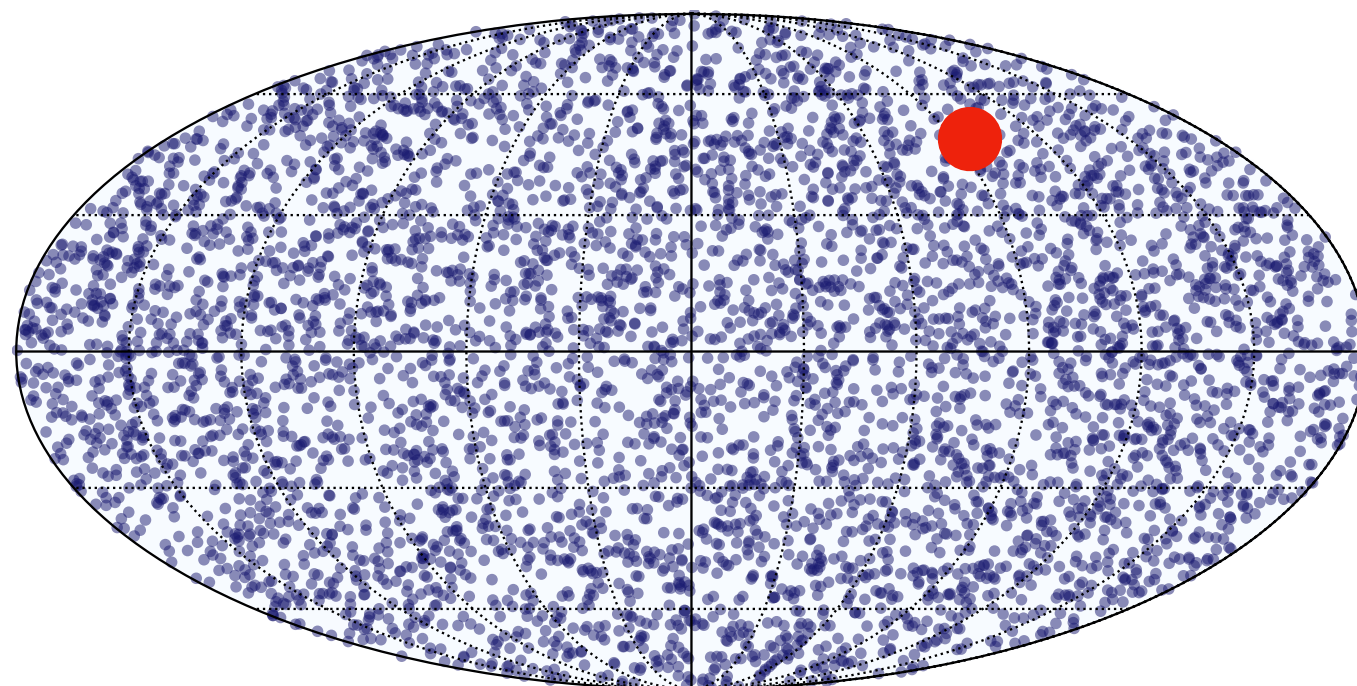
The kinematic matter dipole

Ellis & Baldwin (1984)

Average spectral index
of source spectra
(at the flux limit)

$$\mathcal{D}_{\text{kin}} = \left[2 + x(1 + \alpha) \right] \beta$$

Average
magnification bias



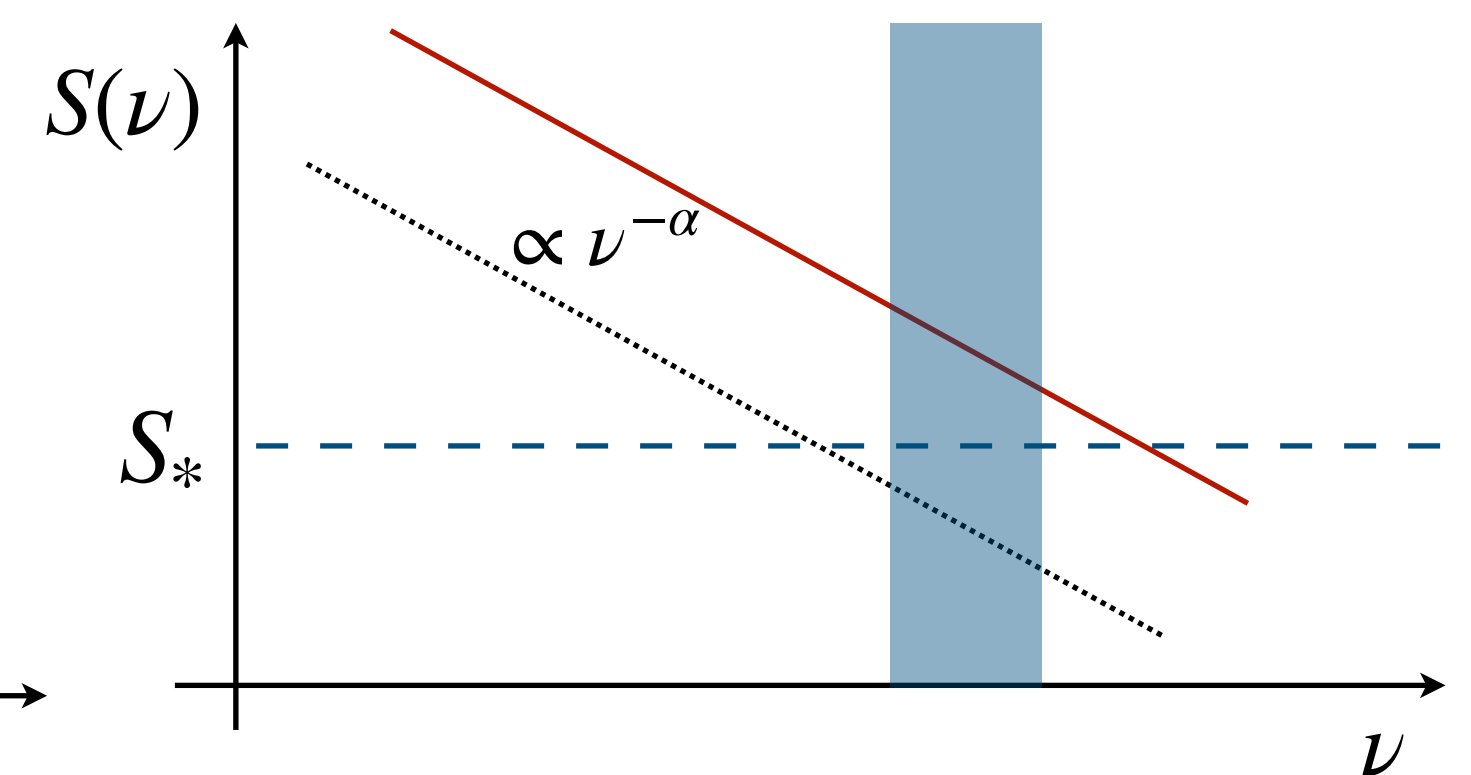
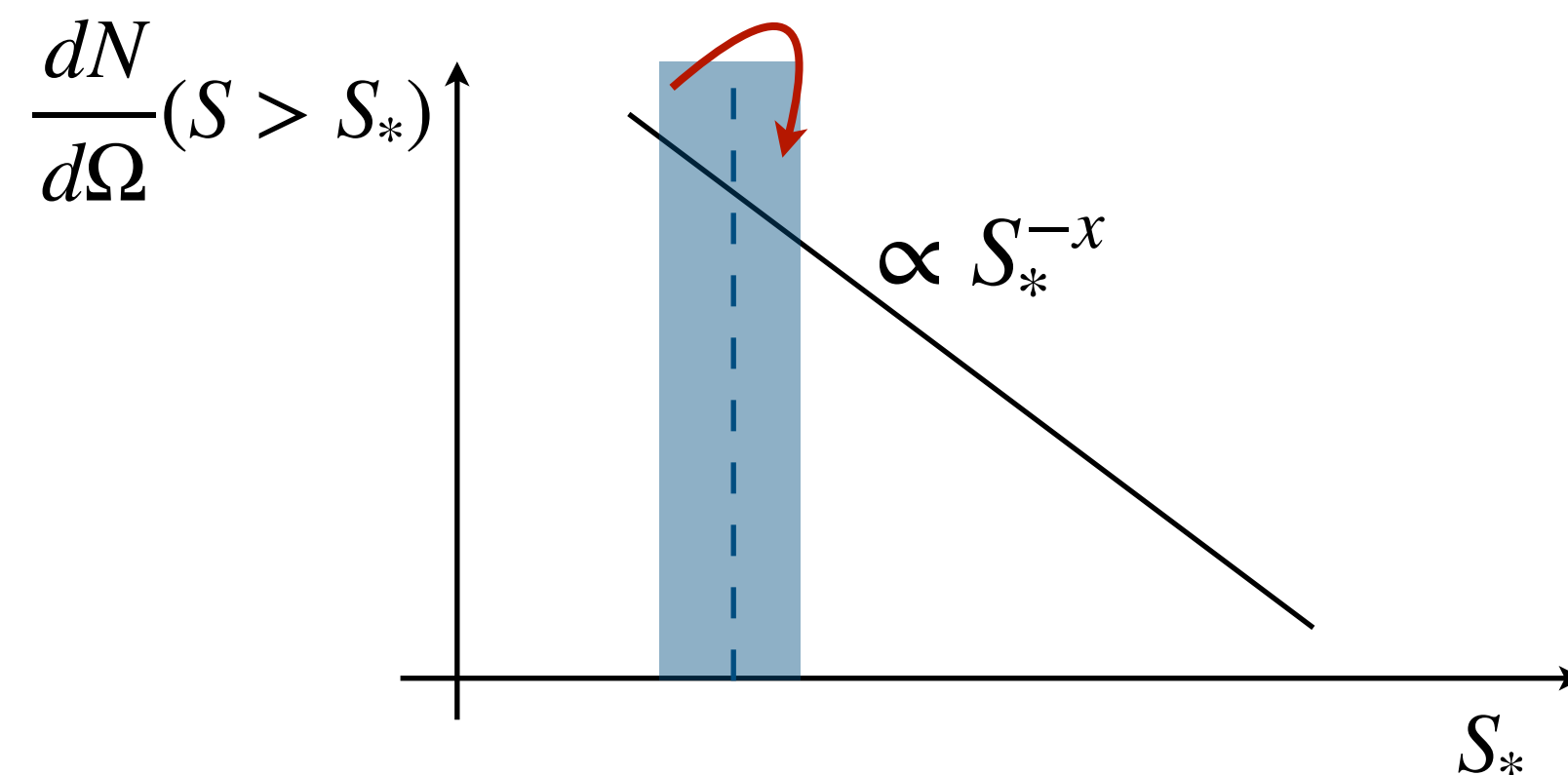
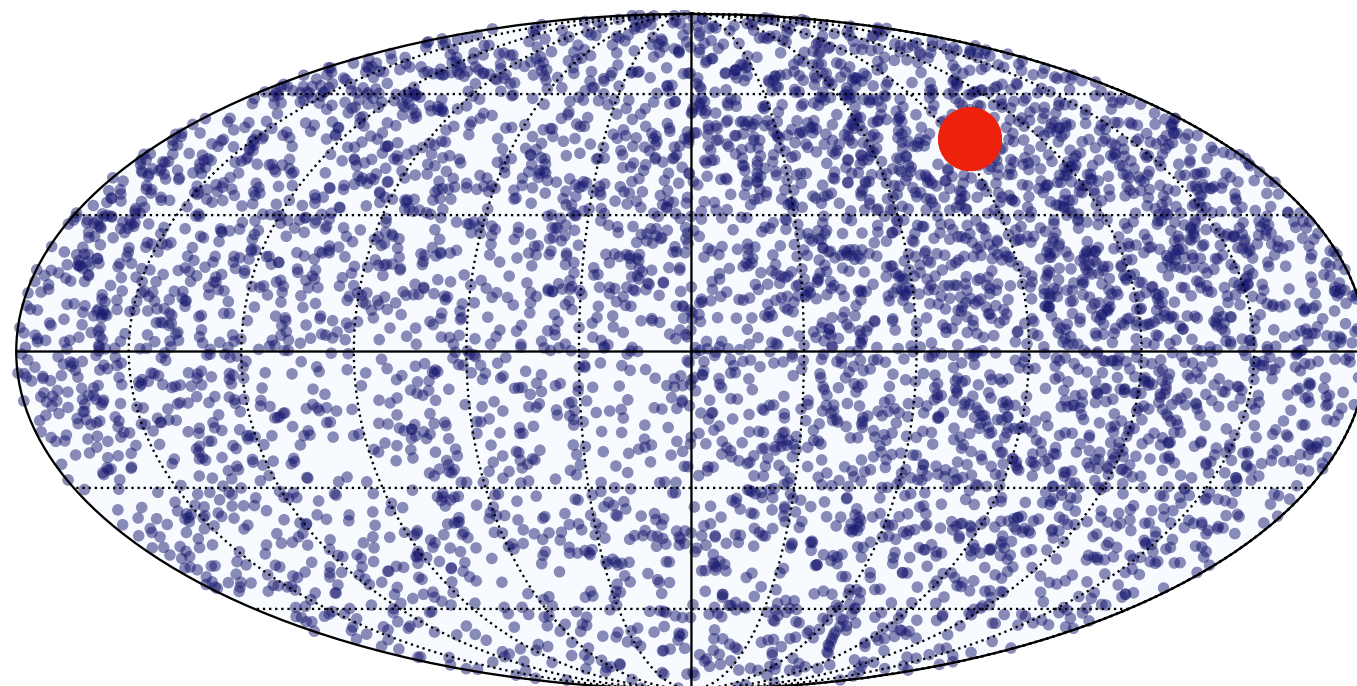
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The matter dipole — radio sources

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doi:[10.1088/2041-8205/742/2/L23](https://doi.org/10.1088/2041-8205/742/2/L23)

LARGE PECULIAR MOTION OF THE SOLAR SYSTEM FROM THE DIPOLE ANISOTROPY IN SKY BRIGHTNESS DUE TO DISTANT RADIO SOURCES

ASHOK K. SINGAL

Astronomy & Astrophysics Division, Physical Research Laboratory, Navrangpura, Ahmedabad-380 009, India; asingal@prl.res.in

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Astrono

Astronomy & Astrophysics manuscript no. NVSS'dipole
January 16, 2018 © ESO 2018

Cosmic radio dipole from NVSS and WENSS

Matthias Rubart[★], Dominik J. Schwarz^{★★}

Fakultät für Physik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany

Preprint online version: January 16, 2018

The matter dipole — radio sources

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A&A 675, A72 (2023)
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**Astronomy
&
Astrophysics**

The cosmic radio dipole: Bayesian estimators on new and old radio surveys

J. D. Wagnveld¹, H.-R. Klöckner¹, and D. J. Schwarz²

¹ Max-Planck Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
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¹ Max-Planck
e-mail: w
² Fakultät
Received 2

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MNRAS **531**, 4545–4559 (2024)
Advance Access publication 2024 June 5
<https://doi.org/10.1093/mnras/stae1399>
Royal Astronomical Society

A Bayesian approach to the cosmic dipole in radio galaxy surveys: joint analysis of NVSS & RACS

Oliver T. Oayda¹, Vasudev Mittal^{1,2}, Geraint F. Lewis¹ and Tara Murphy¹

¹Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, NSW 2006, Australia
²Department of Physical Sciences, IISER Mohali, Knowledge City, Sector 81, SAS Nagar, Manauli PO 140306, Punjab, India

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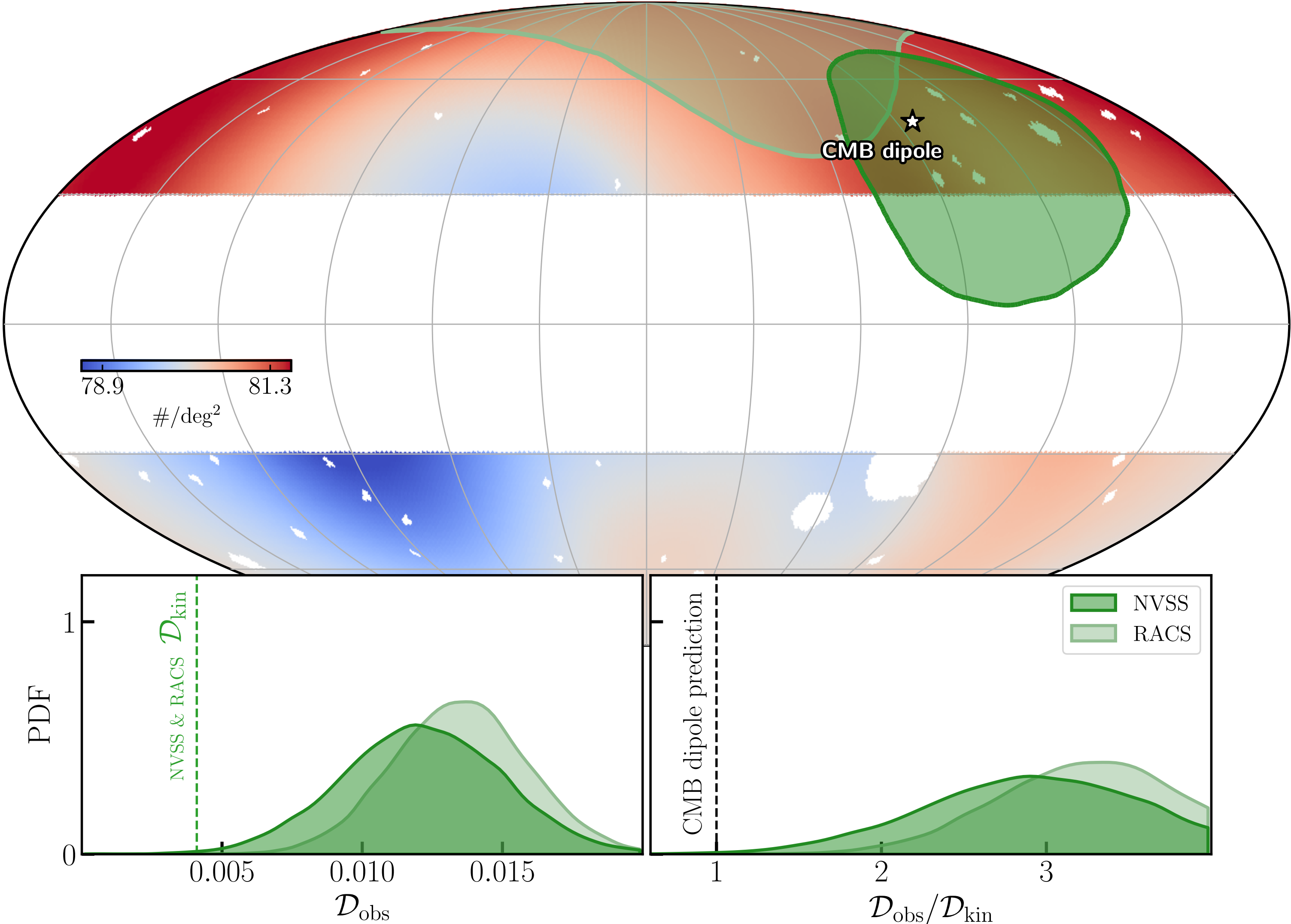
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Secrest, SvH et al. (2025)
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Rev.Mod.Phys. in press
[2505.23526]

The matter dipole — radio sources

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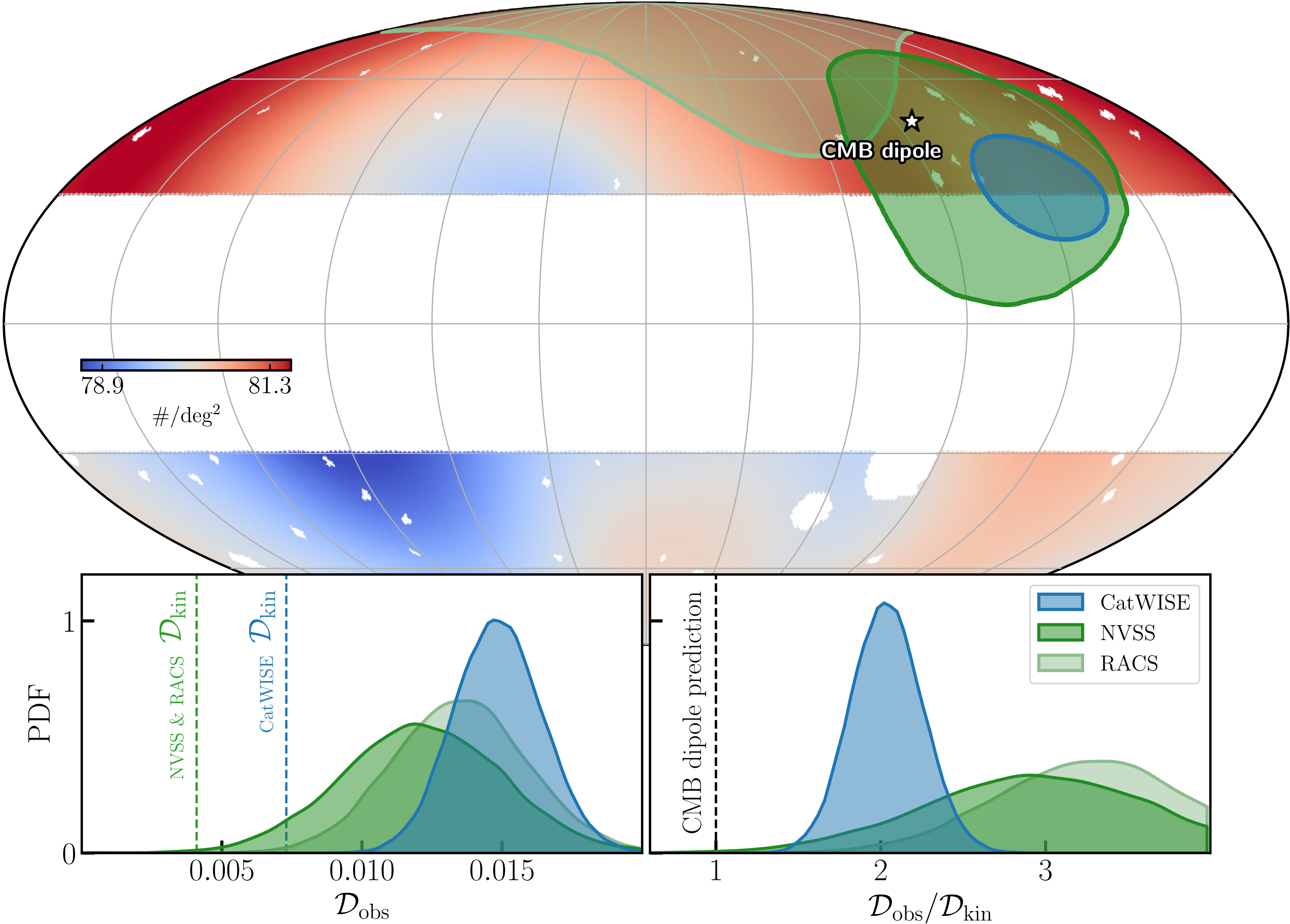
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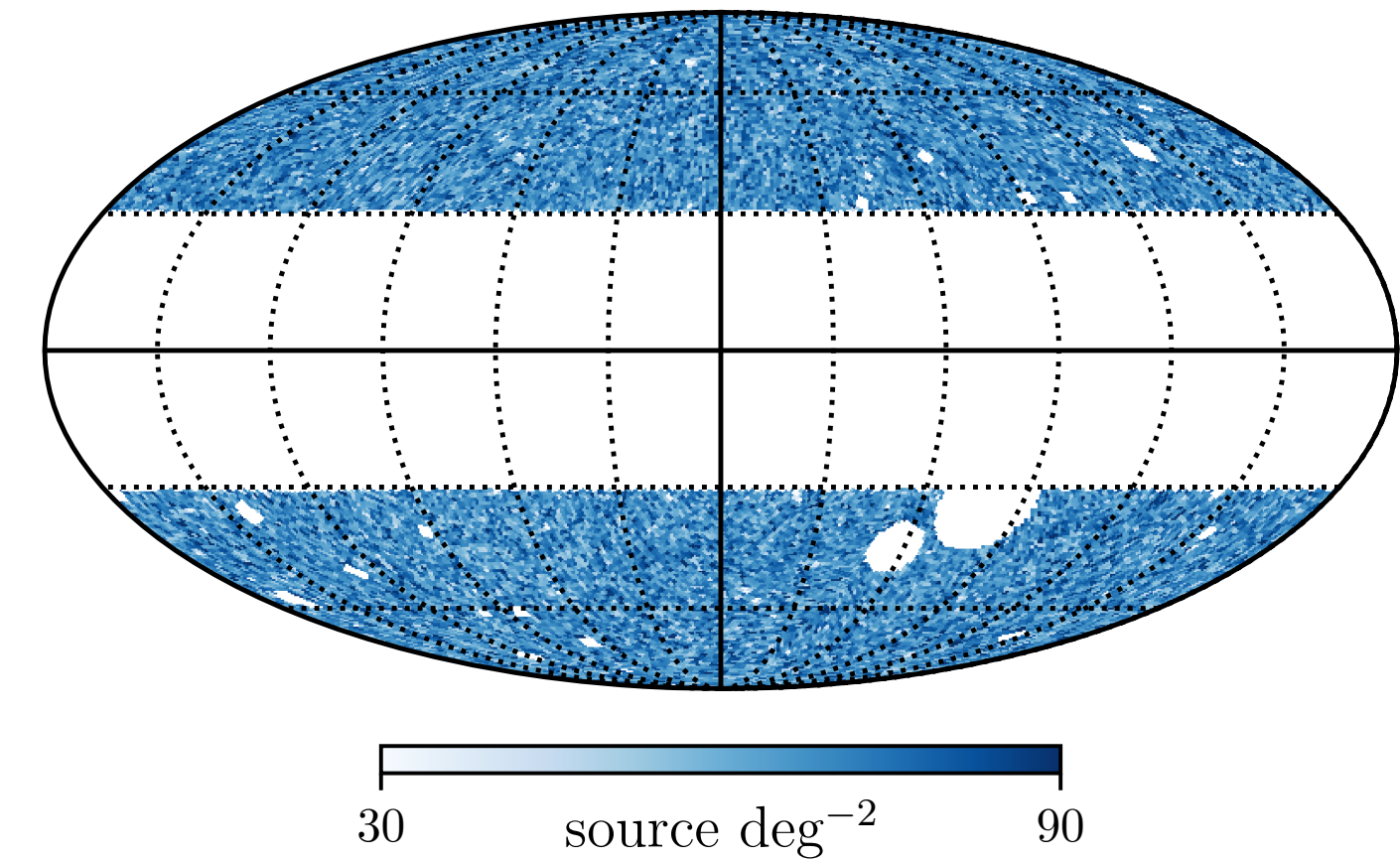
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An independent test with mid-IR quasars

$$\mathcal{D}_{\text{kin}} = [2 + x(1 + \alpha)] \cdot \beta$$

In our CatWISE AGN sample we find $x \approx 1.89$ and $\alpha \approx 1.06$

$$\Rightarrow \mathcal{D}_{\text{kin}} \approx 7.2 \times 10^{-3}$$



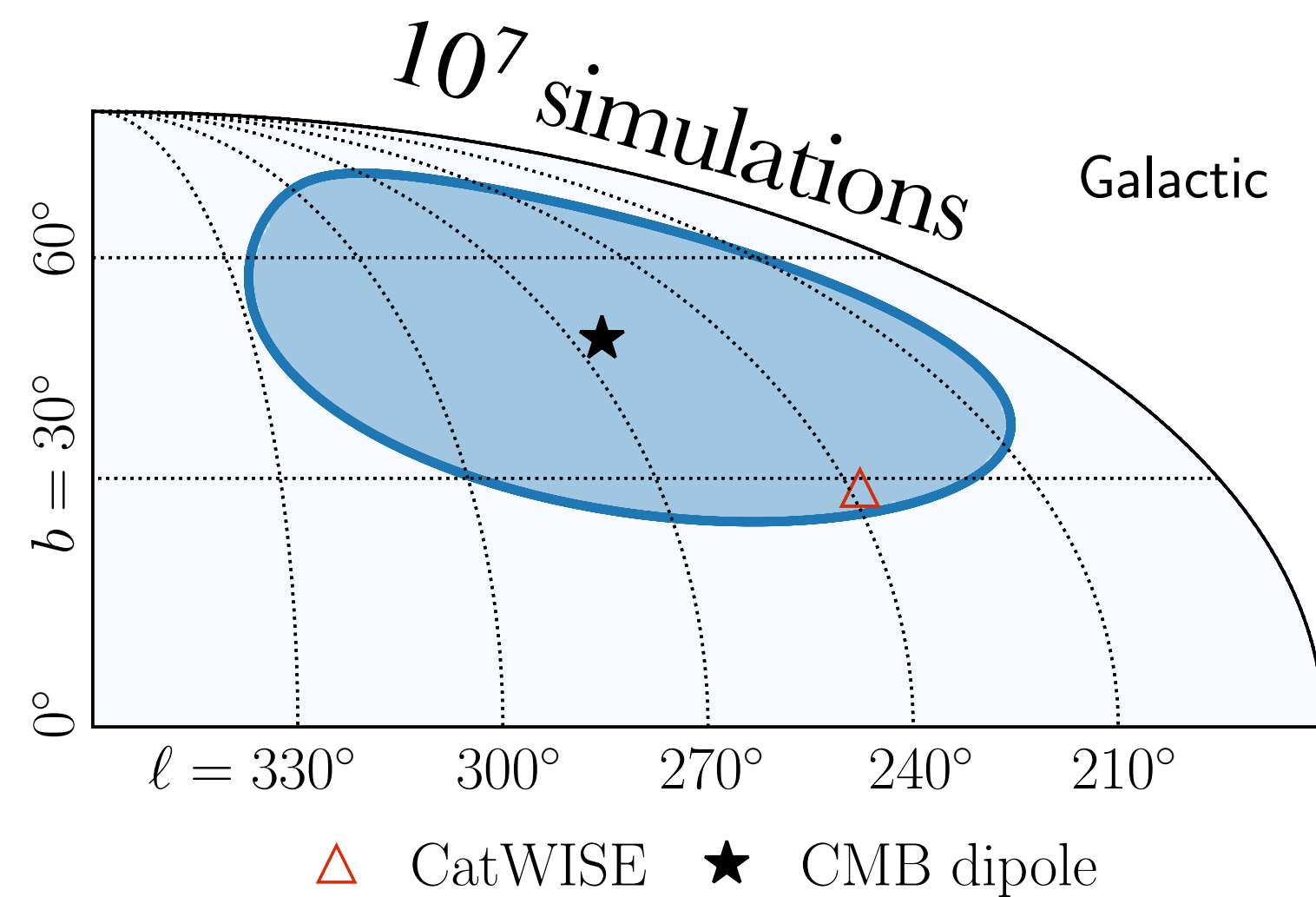
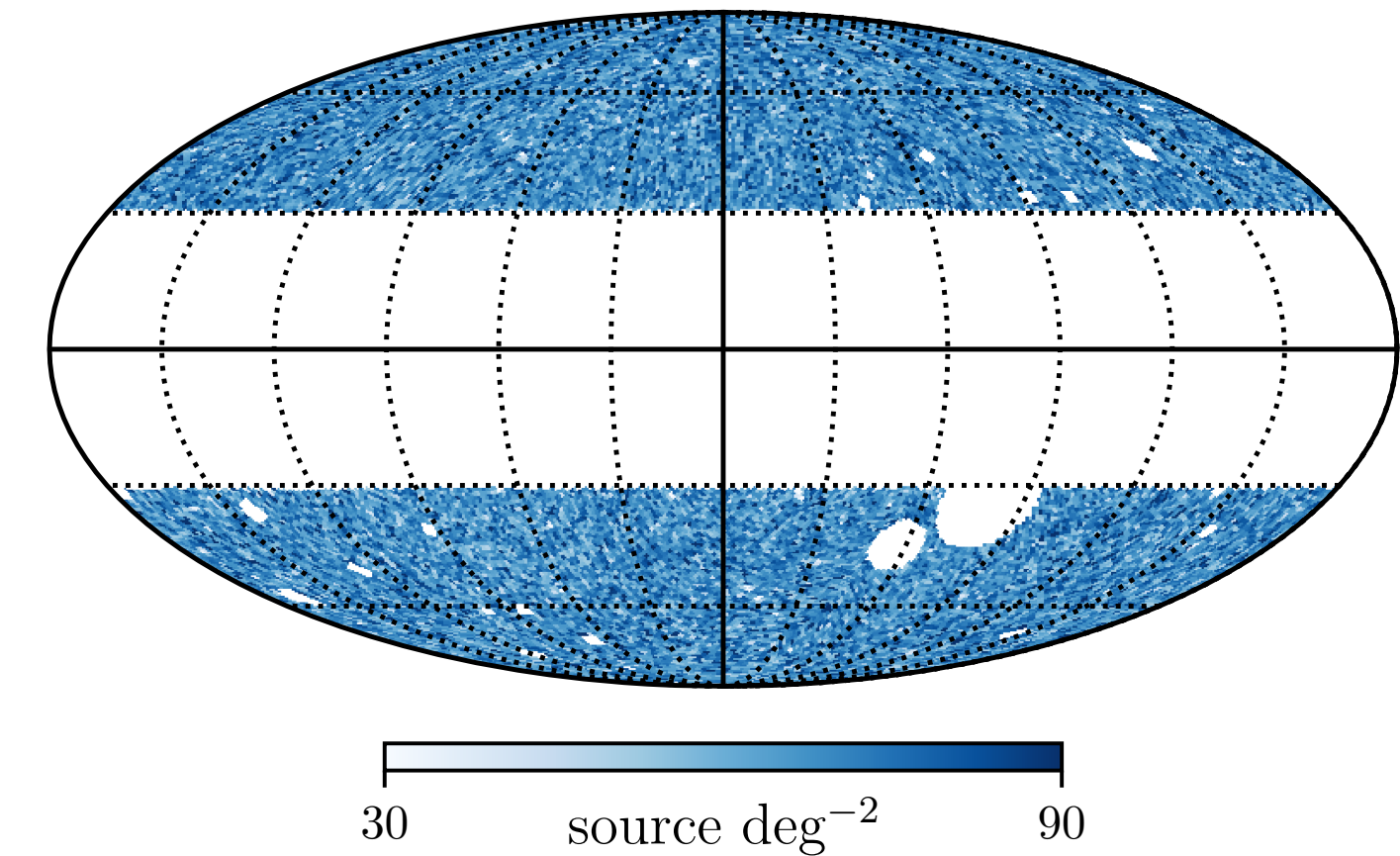
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Direction consistent with CMB dipole

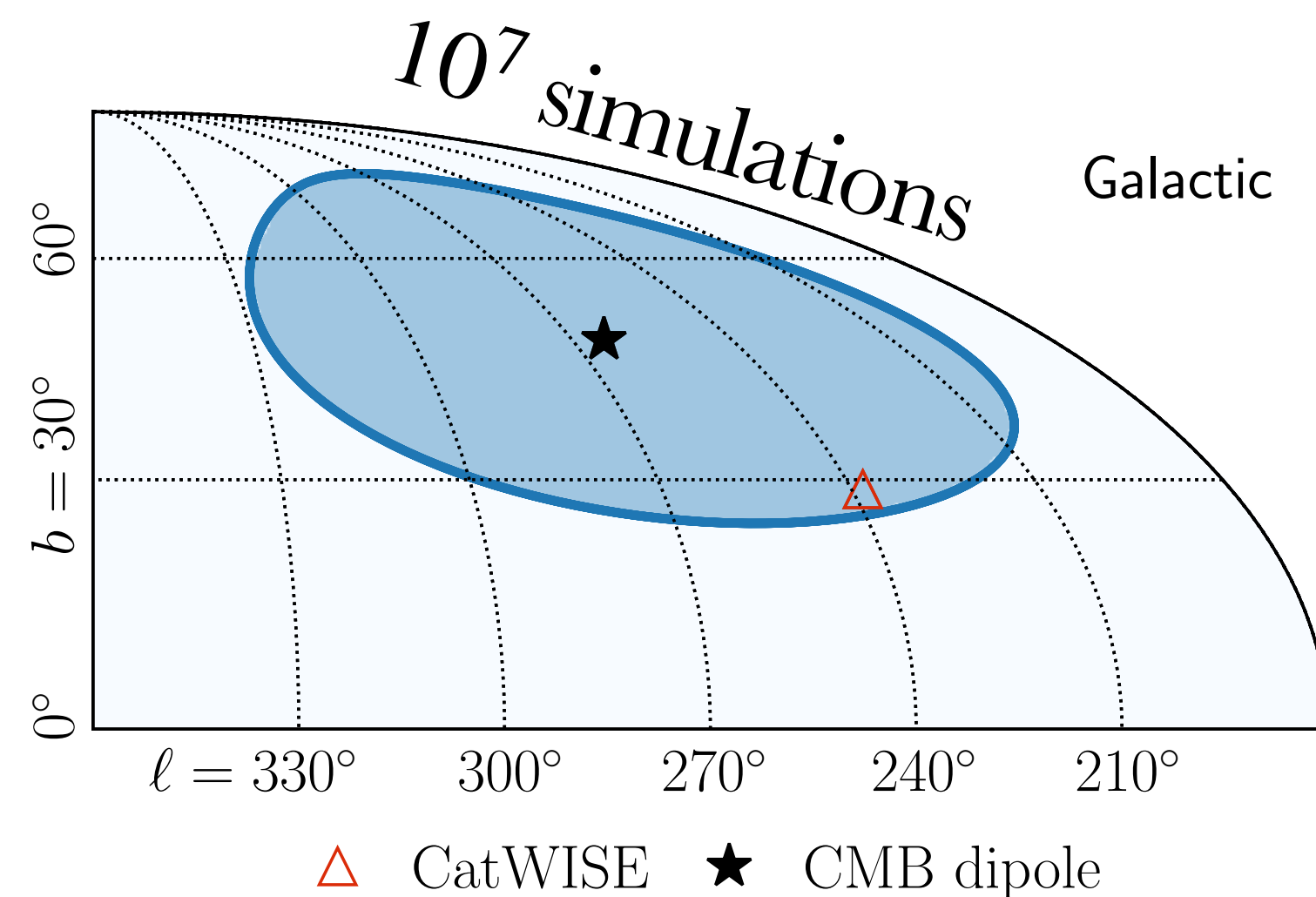
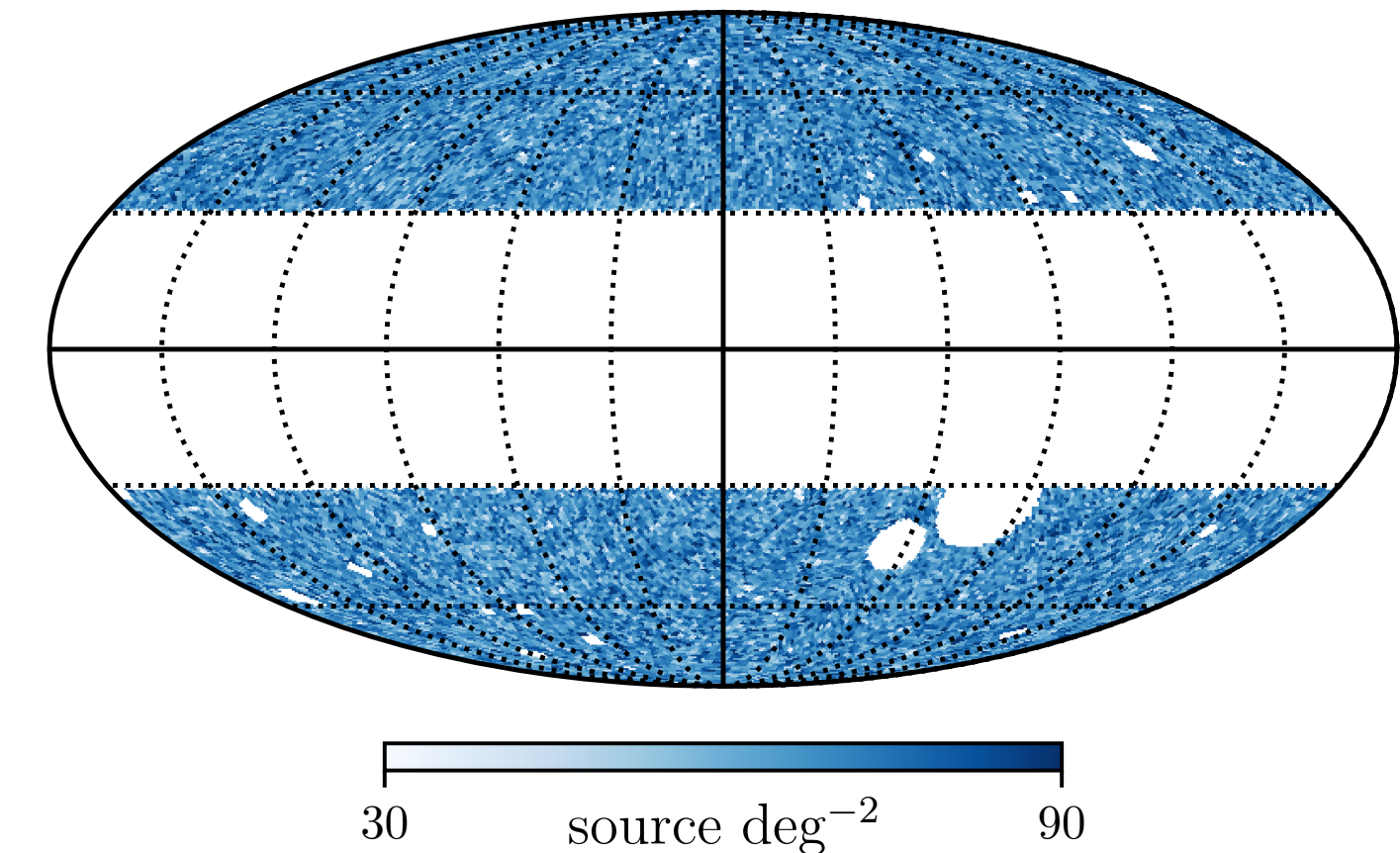
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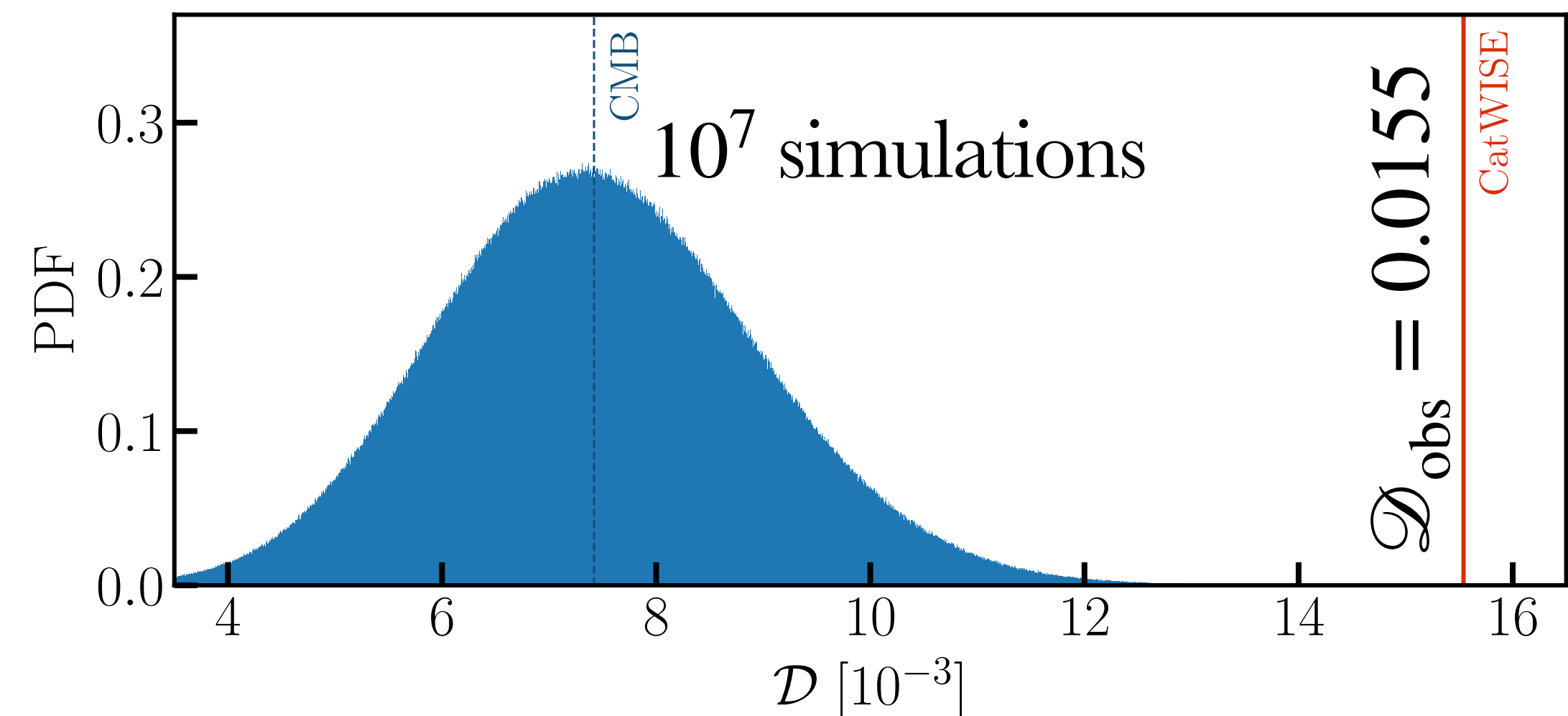
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Direction consistent with CMB dipole



Amplitude inconsistent with the kinematic hypothesis at $p = 5 \times 10^{-7}$

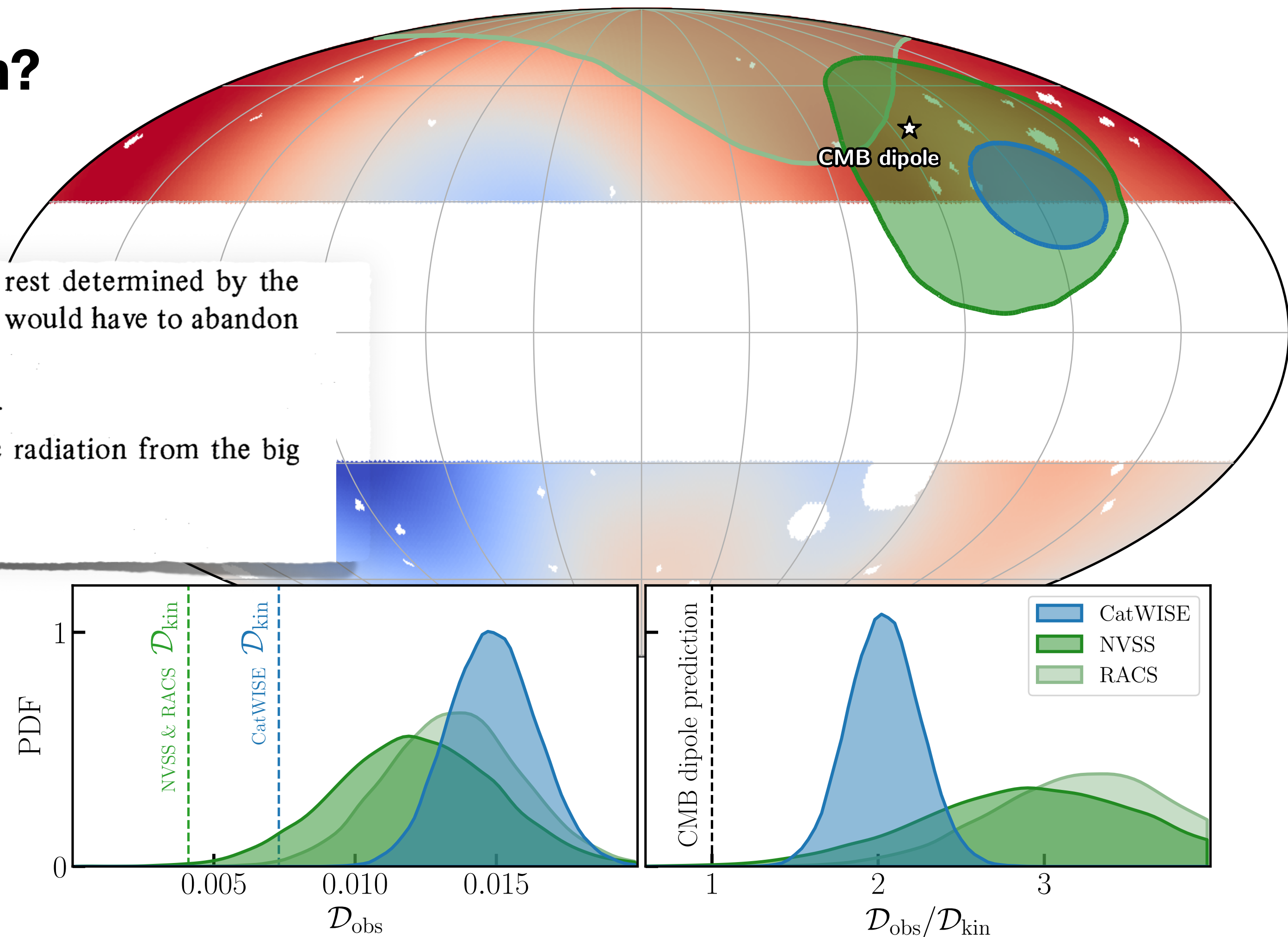
The matter dipole

What does this discrepancy mean?

variations of the microwave background radiation. If the standards of rest determined by the MBR and the number counts were to be in serious disagreement, one would have to abandon either

- (a) the idea that the radio sources are at cosmological distances, or
- (b) the interpretation of the cosmic microwave radiation as relic radiation from the big bang, or
- (c) the standard FRW Universe models.

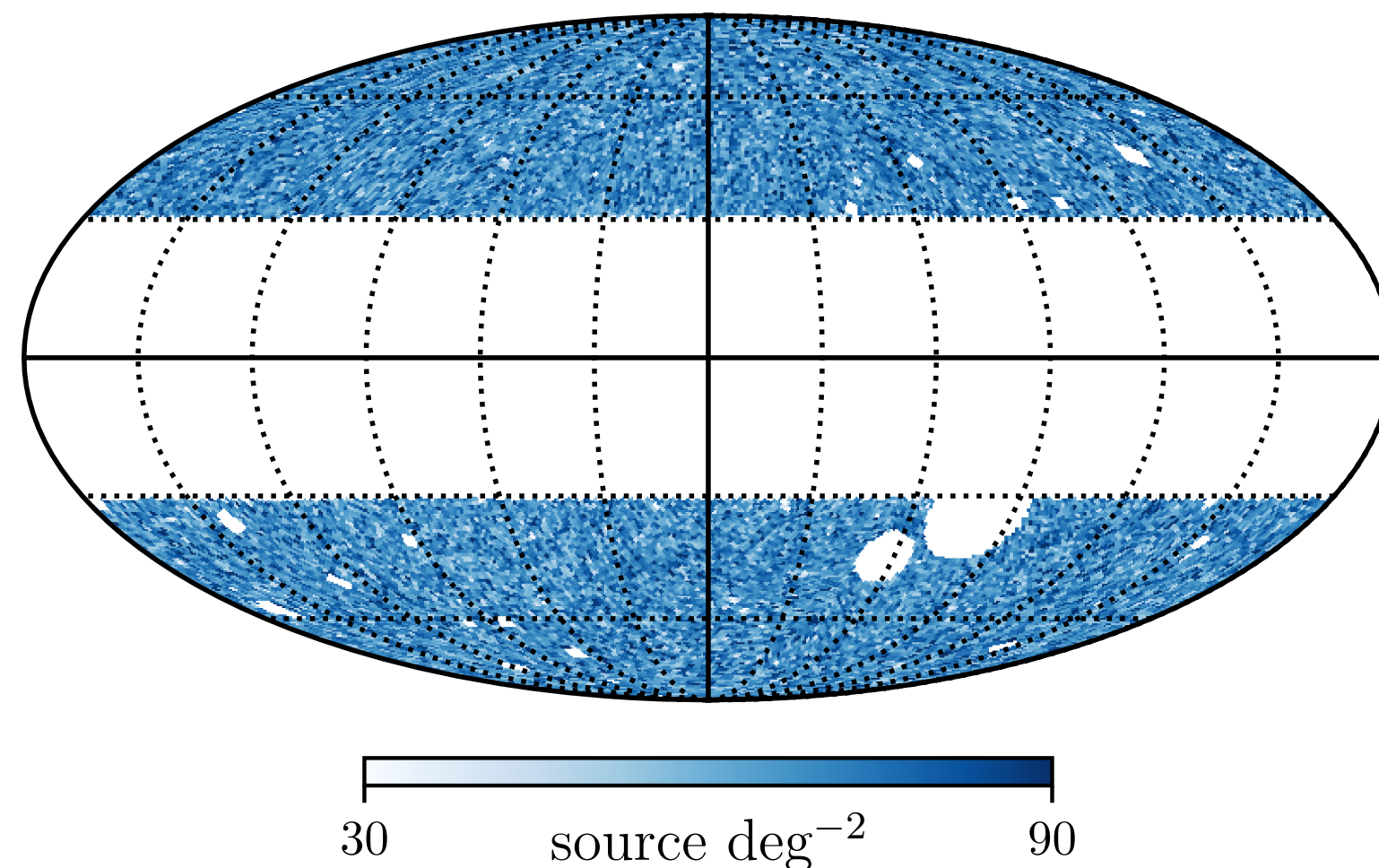
Ellis & Baldwin (1984)



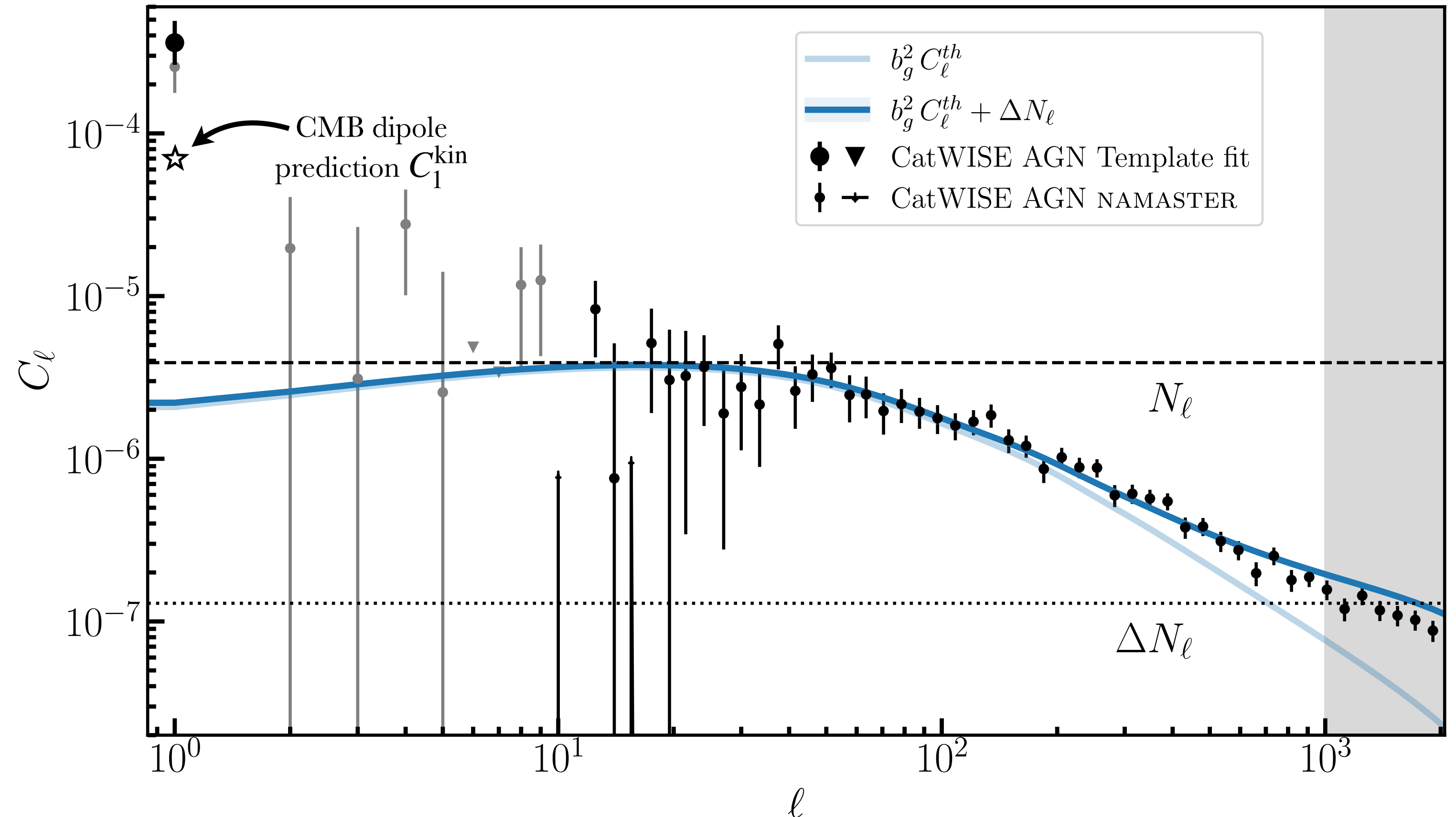
The matter dipole — mid-IR quasars

Clustering dipole prediction by extrapolation of small-scale power

(after removal of ecliptic lat. trend)



SvH et al. (2025) in prep.

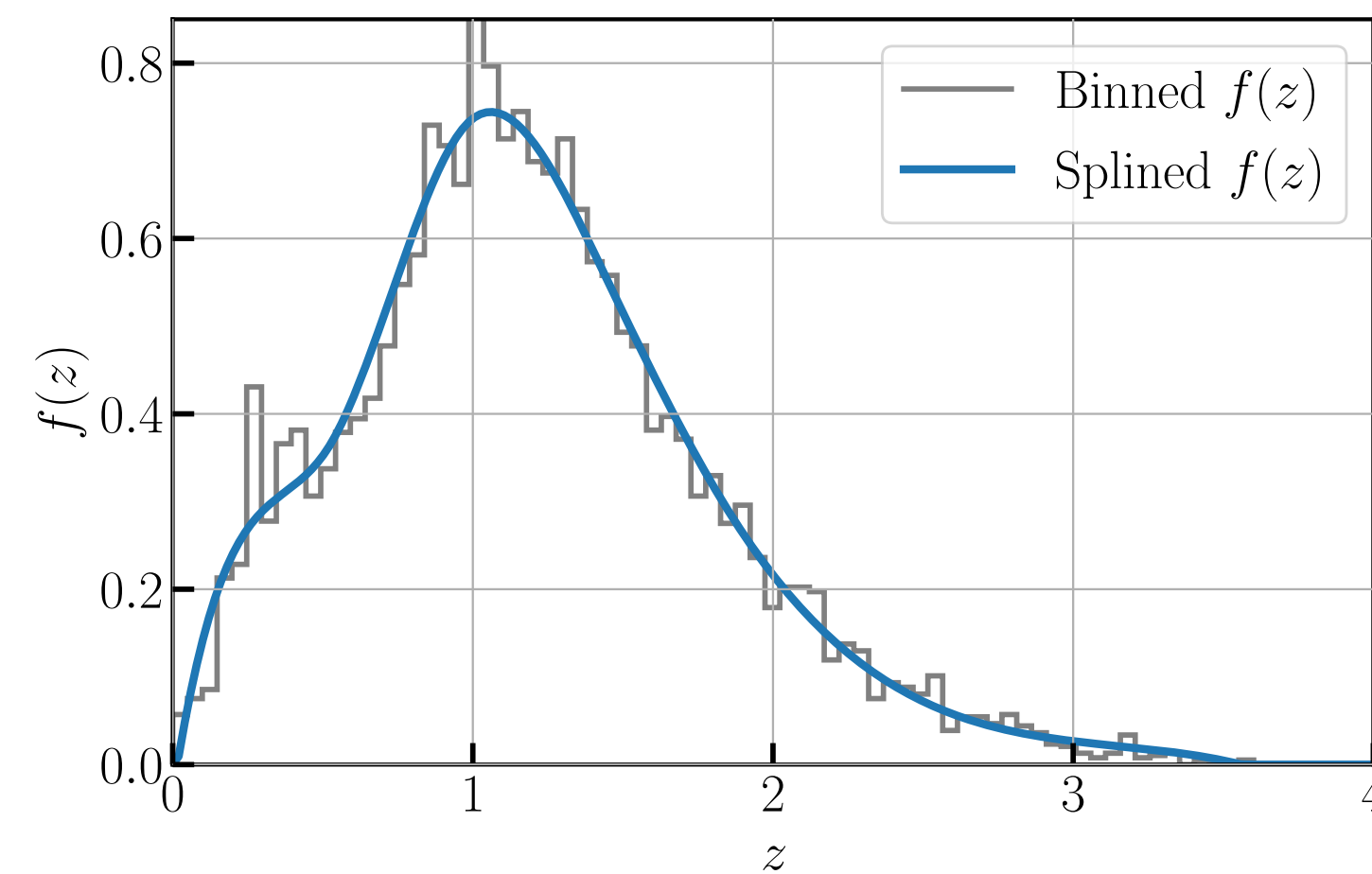


Only dipole power significantly exceeds expectation

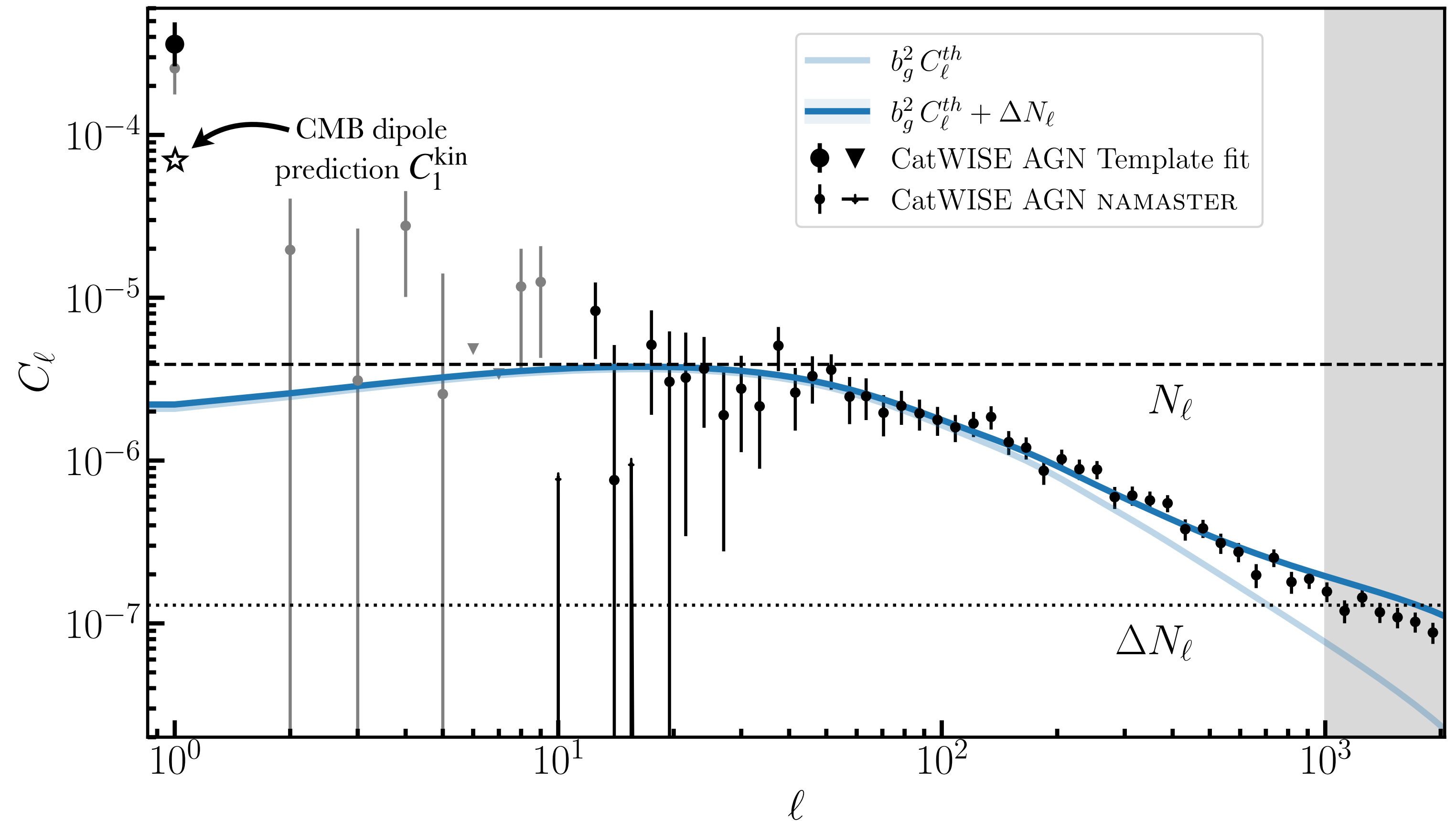
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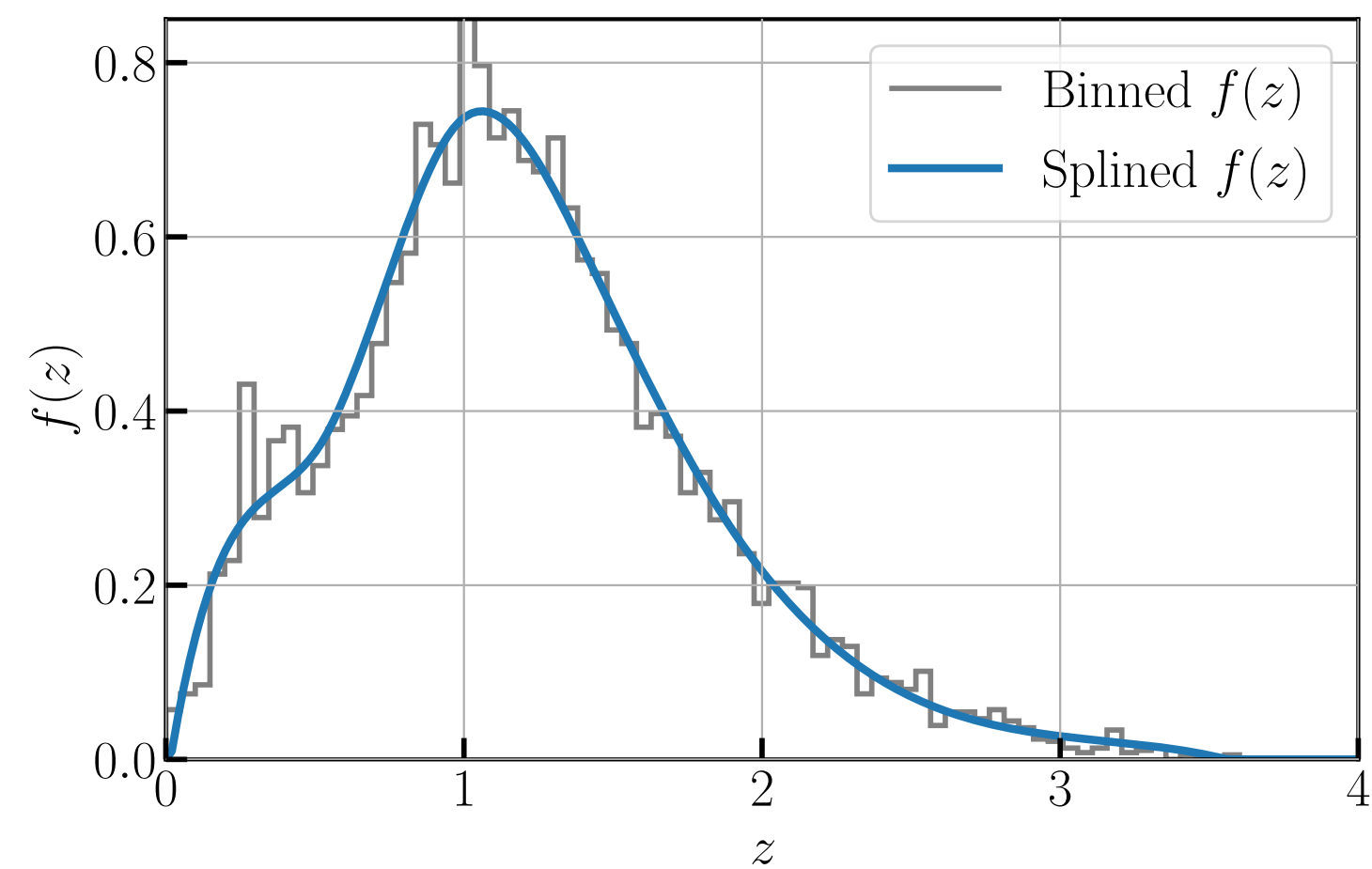


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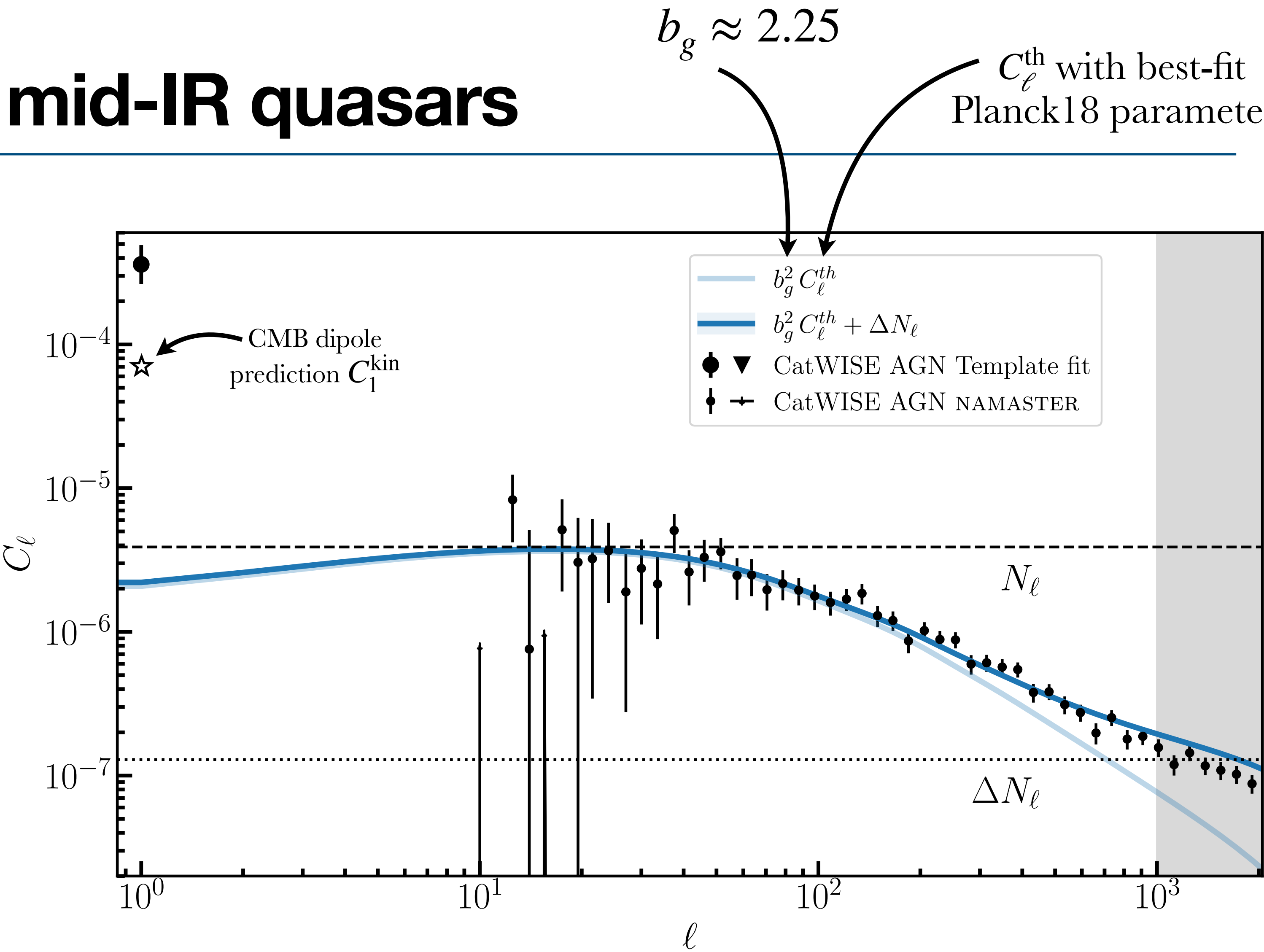
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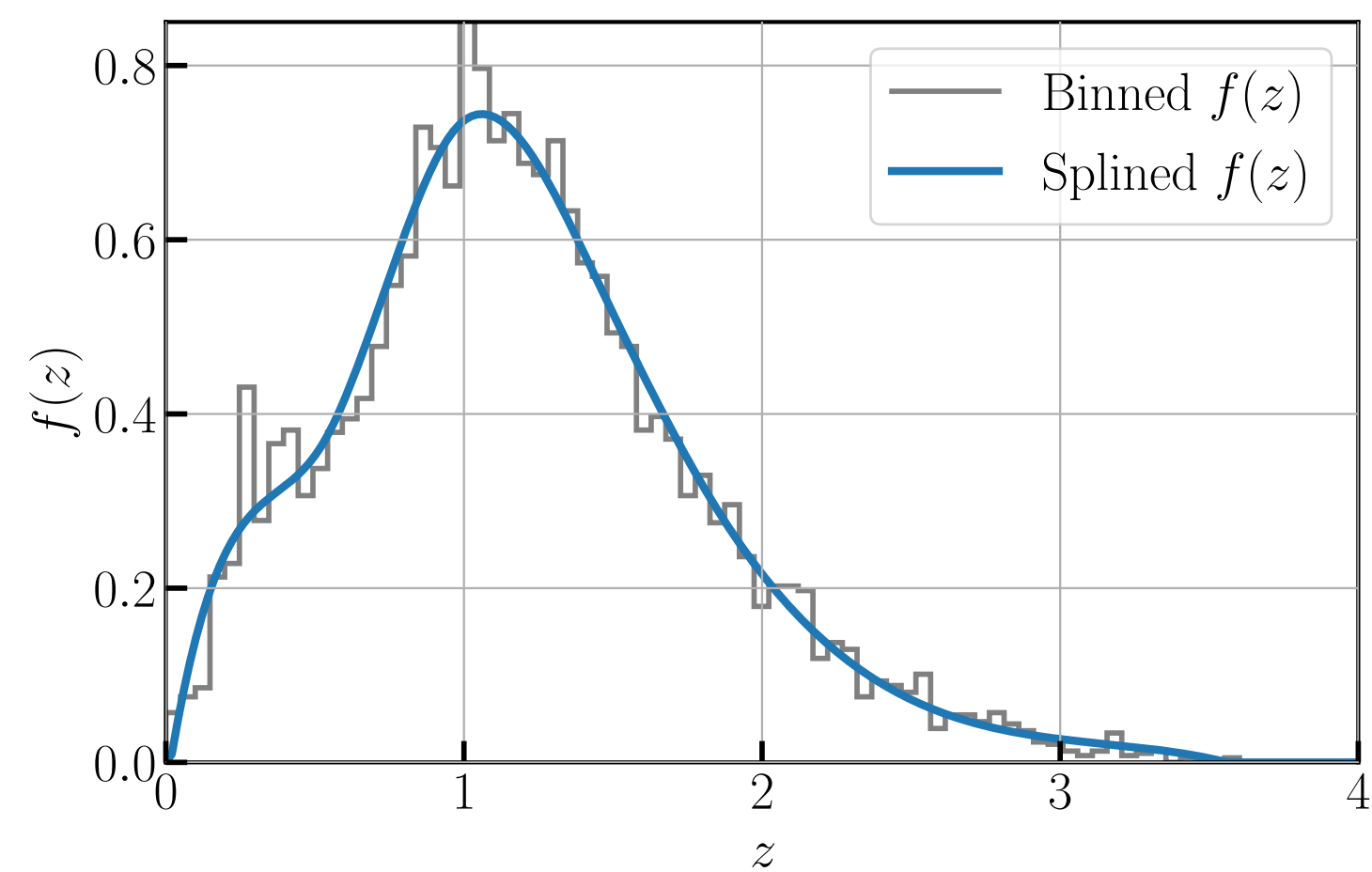


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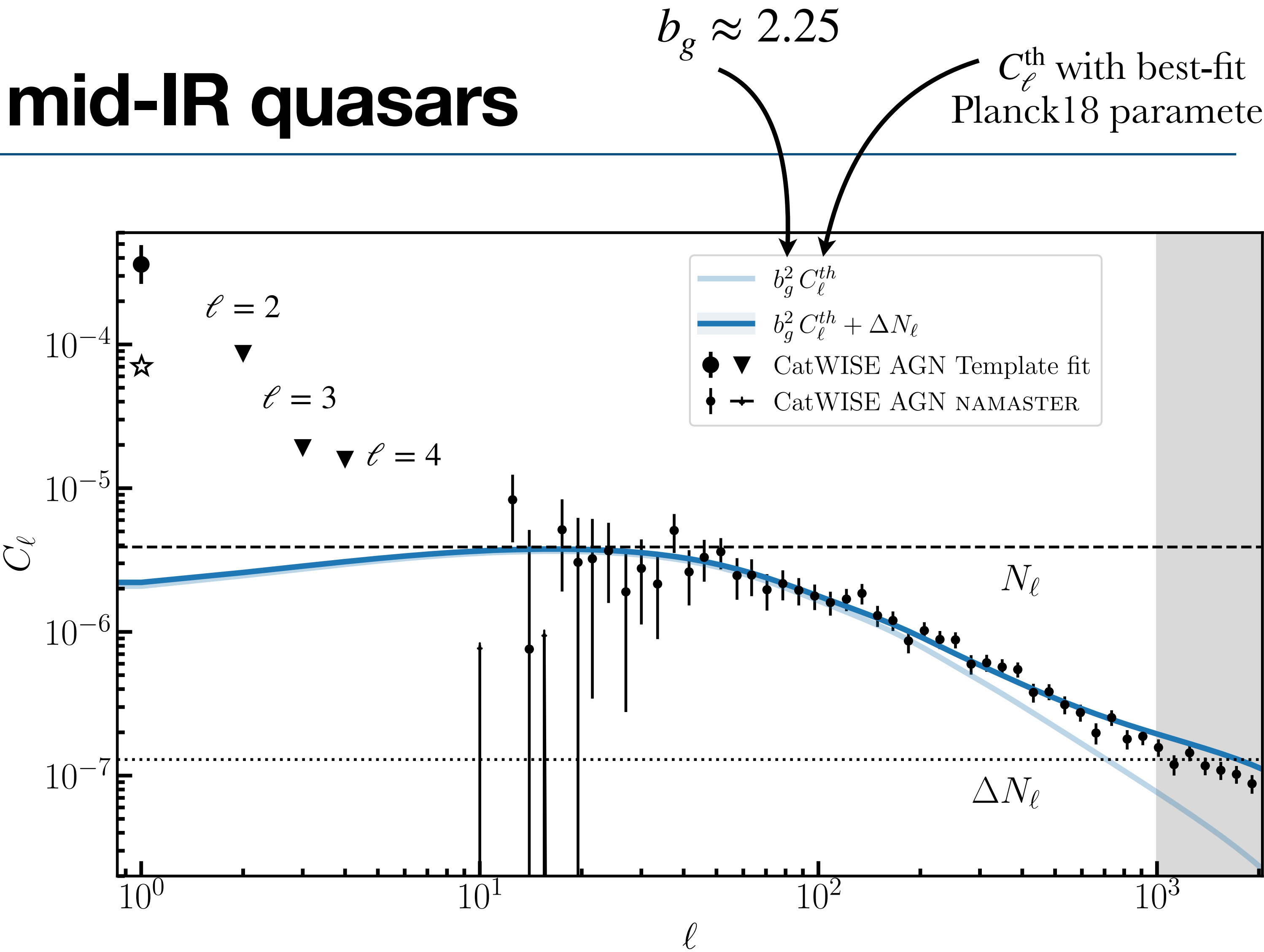
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SvH et al. (2025) *in prep.*



Only dipole power significantly exceeds expectation

Higher multipoles

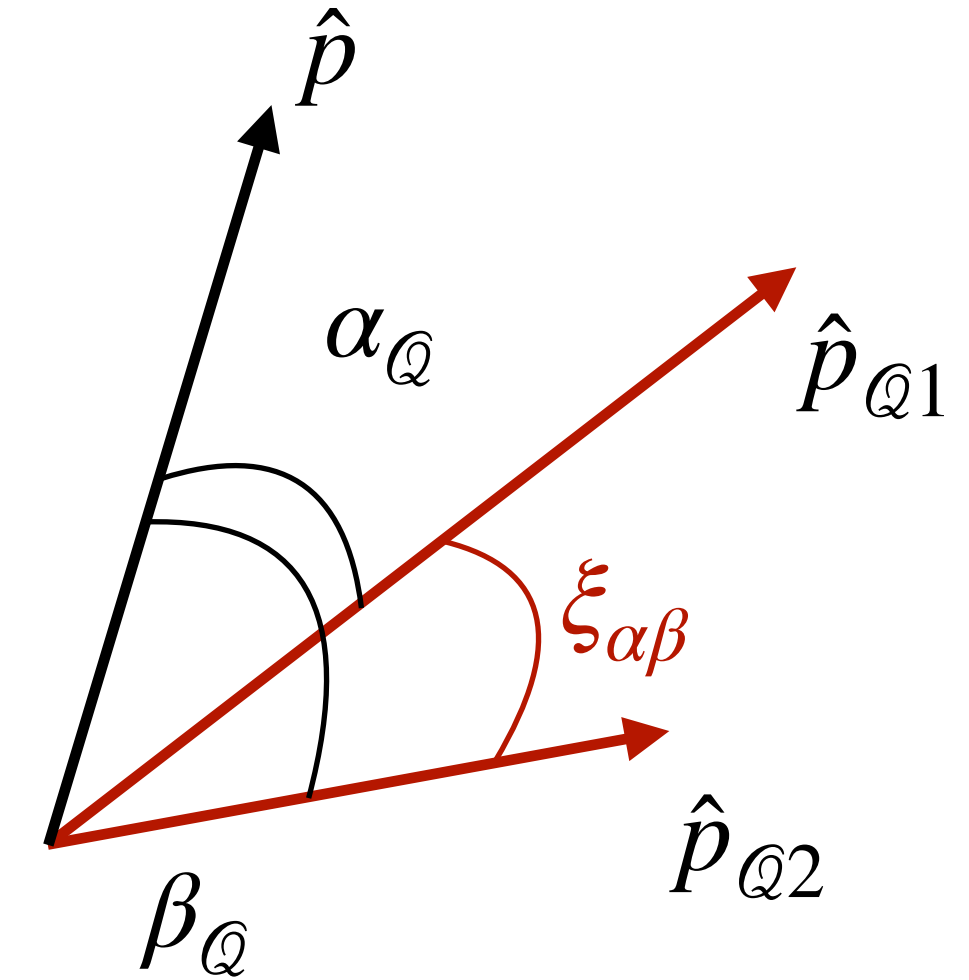
Add more multipole templates

$$\frac{dN_{\text{obs}}}{d\Omega}(S > S_*) \sim \mathcal{M} \left[1 + \mathcal{D} \cos \alpha_{\mathcal{D}} \right] \left[1 - |b_{\text{ecl}}| \mathcal{Y}_{\text{ecl}} \right]$$

$$+ \mathcal{Q} \left[\cos \alpha_{\mathcal{Q}} \cos \beta_{\mathcal{Q}} - \frac{1}{3} \cos \xi_{\alpha\beta} \right]$$

$$+ \mathcal{O} \left[\cos \alpha_{\mathcal{O}} \cos \beta_{\mathcal{O}} \cos \gamma_{\mathcal{O}} - \frac{1}{5} \left(\cos \zeta_{\alpha\beta} \cos \gamma_{\mathcal{O}} + \cos \zeta_{\beta\gamma} \cos \alpha_{\mathcal{O}} + \cos \zeta_{\gamma\alpha} \cos \beta_{\mathcal{O}} \right) \right]$$

$$+ \mathcal{H} [\dots]$$



Relation to angular power C_{ℓ}

$$C_1 = \frac{4\pi}{9} \mathcal{D}^2 \quad C_2 \in \left[\frac{4\pi}{3 \cdot 25} \mathcal{Q}^2, \frac{16\pi}{9 \cdot 25} \mathcal{Q}^2 \right] \quad C_3 \in \left[\frac{4\pi}{3 \cdot 5 \cdot 49} \mathcal{O}^2, \frac{16\pi}{25 \cdot 49} \mathcal{O}^2 \right]$$

Bayesian inference — likelihood and results

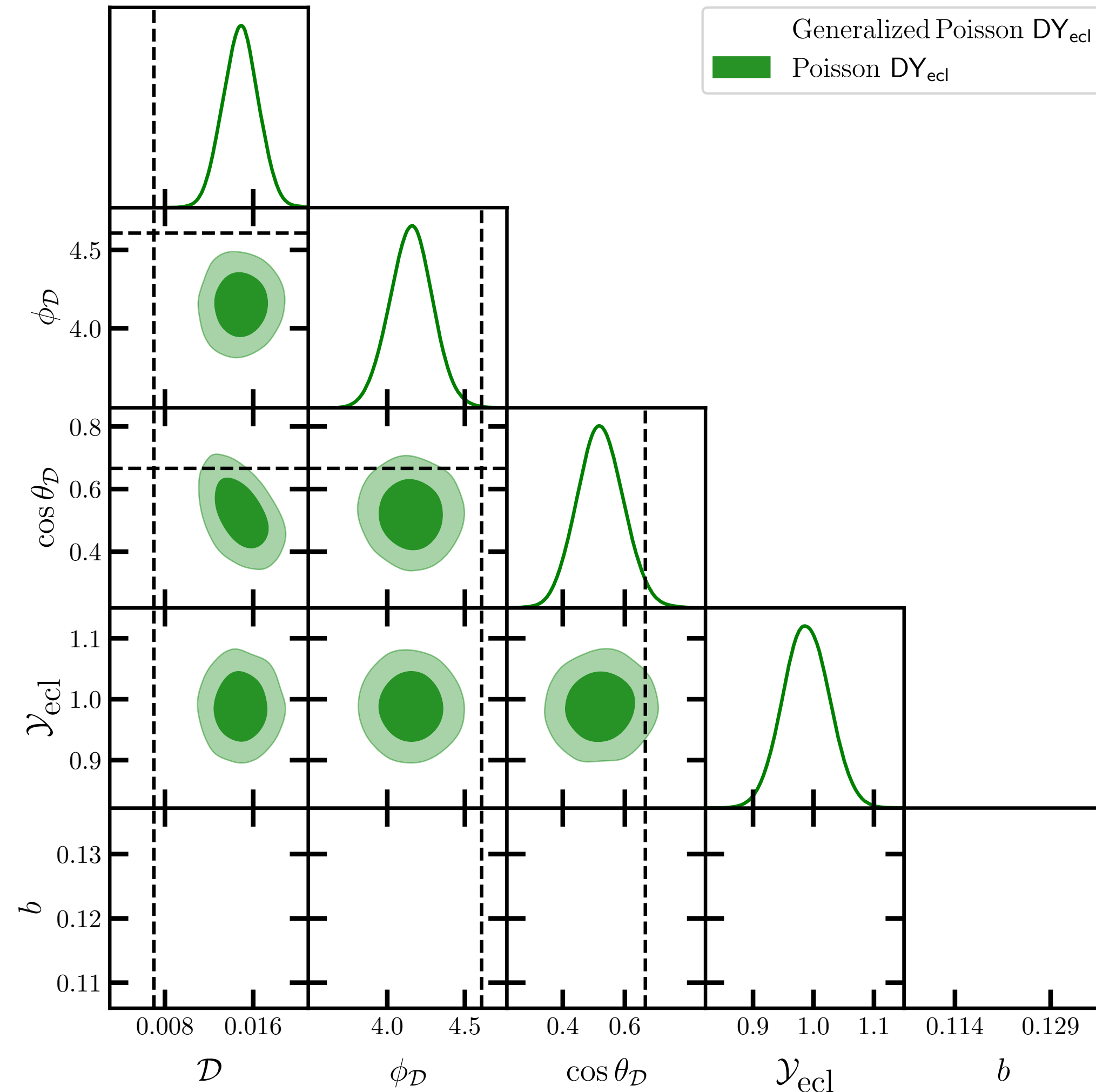
Both **frequentist and Bayesian analyses agree** on the mid-IR matter dipole excess

see, e.g.,
Dam et al. (2023),
Wagenveld, **SvH** et al. (2025),
Secrest, **SvH** et al. (2025),
SvH et al. (2025) *in prep.*

(employed Poisson Likelihoods)

Overdispersed cell counts require modeling by super-Poissonian likelihood. Still, no discernible difference.

SvH et al. (2025) *in prep.*



Bayesian inference — likelihood and results

In each pixel the likelihoods reads

Poisson

$$\ln \mathcal{L}(N_{\text{obs}} | \lambda) = N_{\text{obs}} \ln \lambda - \ln N_{\text{obs}}! - \lambda$$

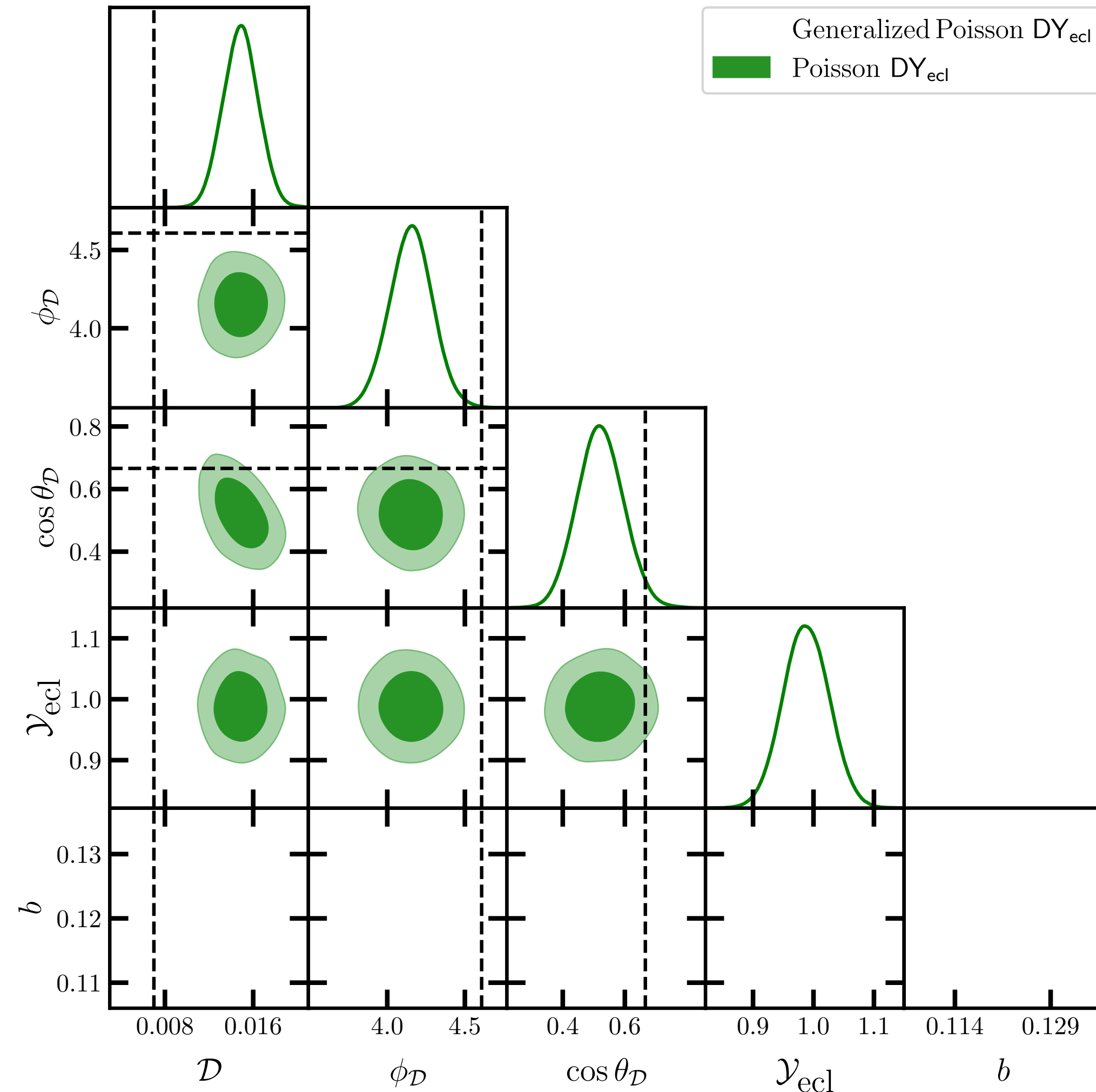
Generalized Poisson

$$\begin{aligned} \ln \mathcal{L}(N_{\text{obs}} | \lambda, b) = & \ln(\lambda(1 - b)) \\ & + (N_{\text{obs}} - 1) \ln(\lambda(1 - b) + N_{\text{obs}} b) \\ & - \ln N_{\text{obs}}! - \lambda(1 - b) - N_{\text{obs}} b \end{aligned}$$

Overdispersed cell counts require modeling by super-Poissonian likelihood. Still, no discernible difference.

SvH et al. (2025) *in prep.*

see also *Böhme* et al. (2025)



Bayesian inference — likelihood and results

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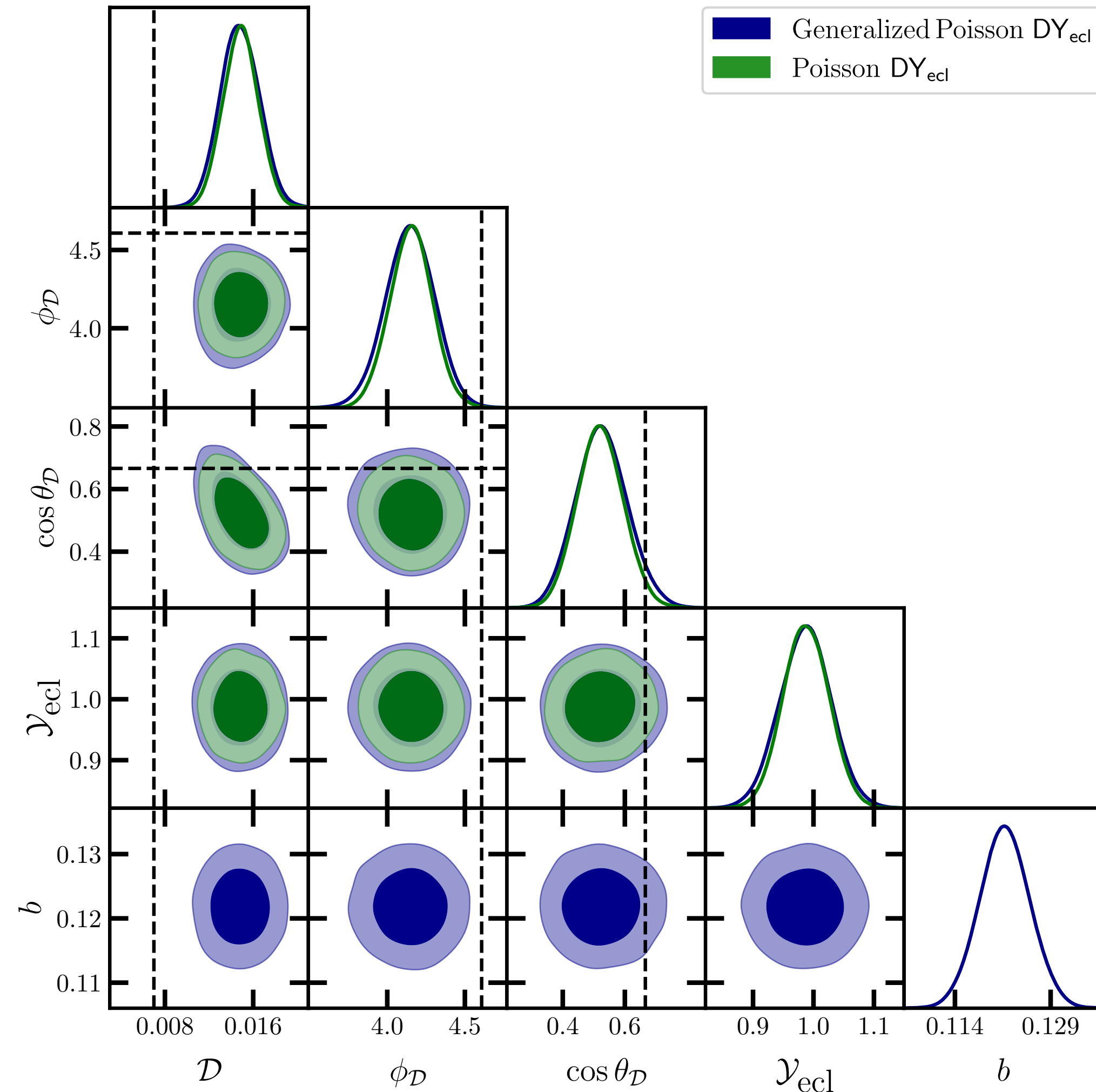
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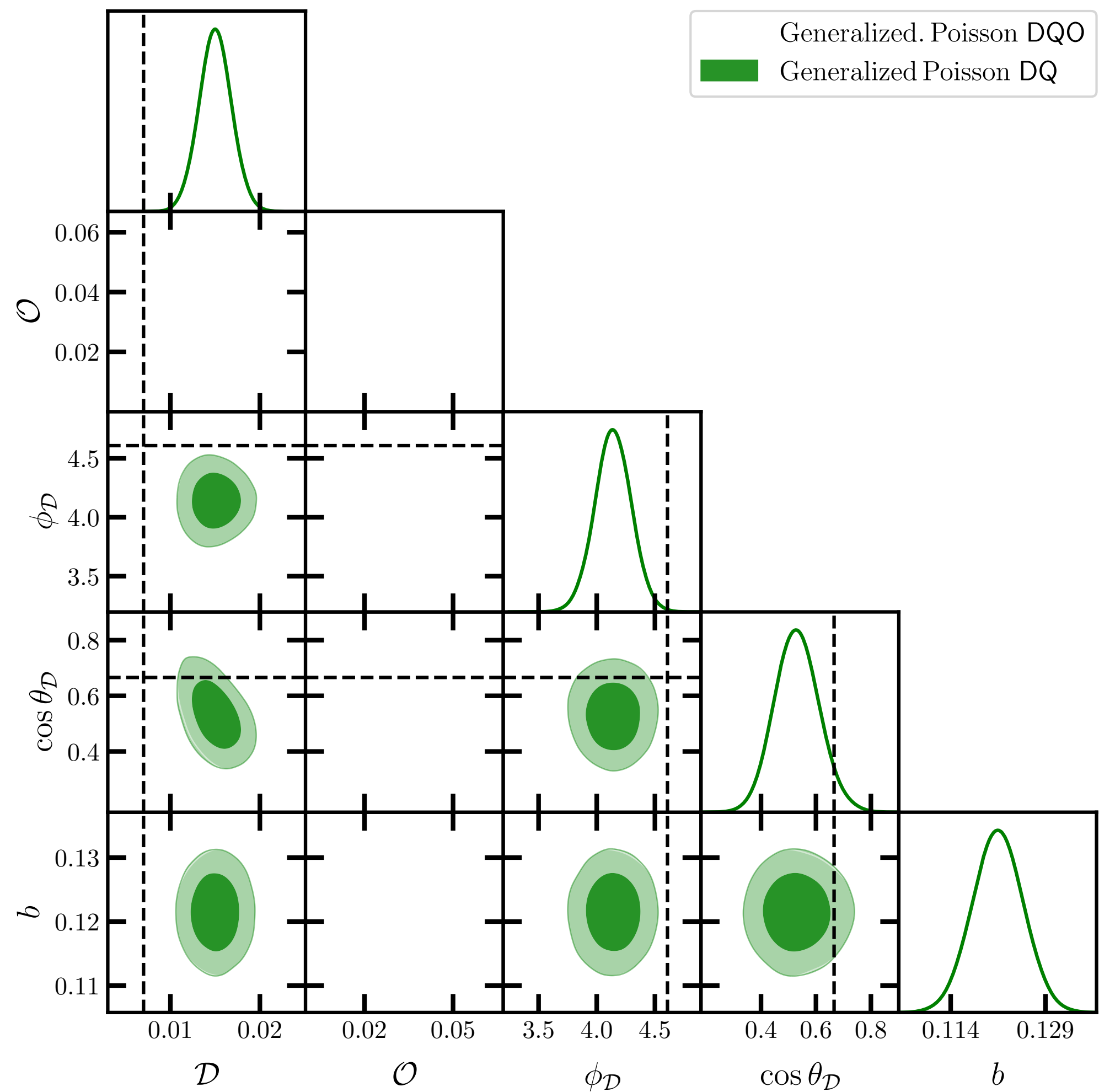
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No (evidence for) octupole in CatWISE 2020 AGN

SvH et al. (2025) in prep.

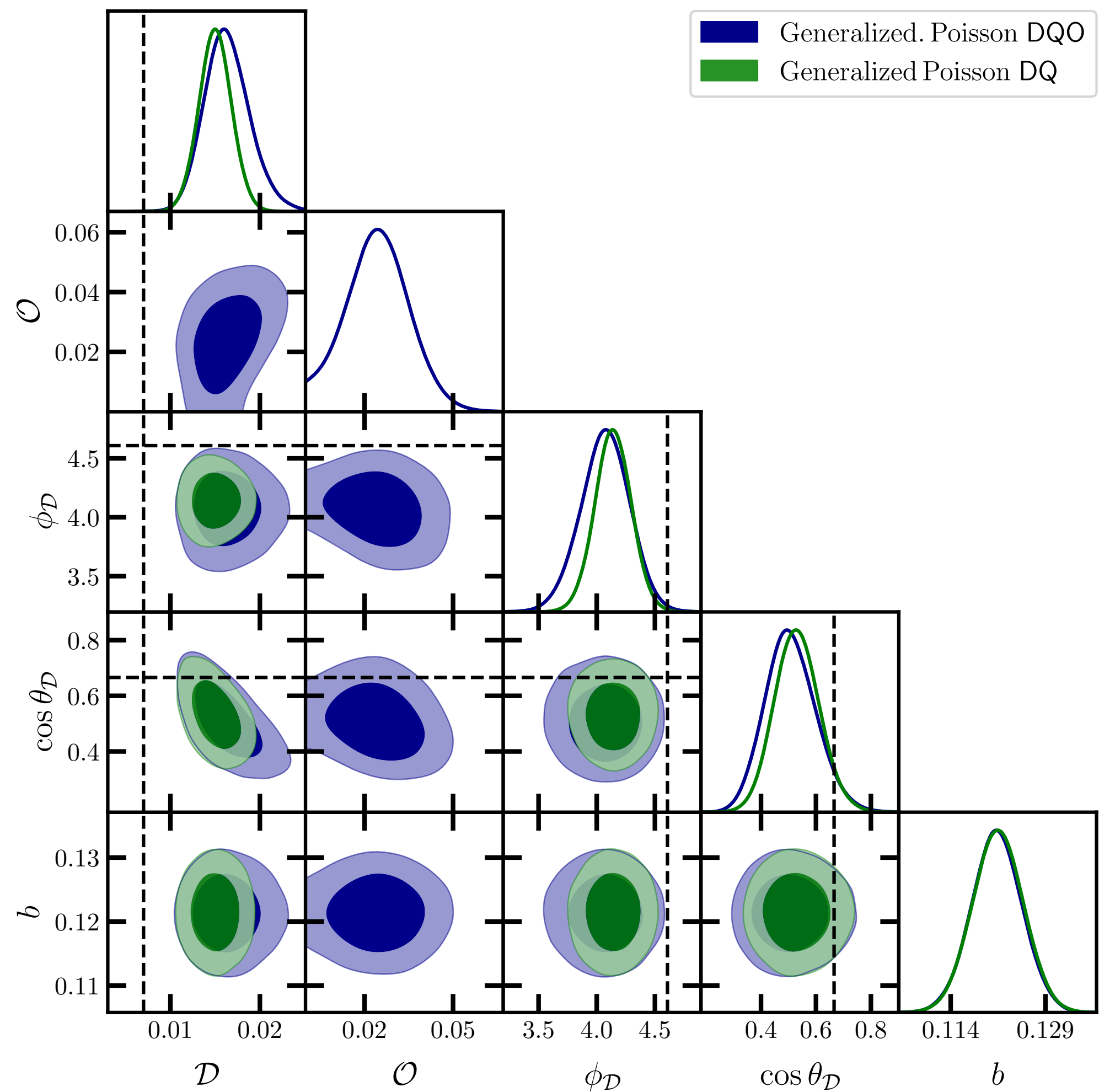
Combined fit with dipole and octupole does not remove dipole excess



No (evidence for) octupole in CatWISE 2020 AGN

SvH et al. (2025) in prep.

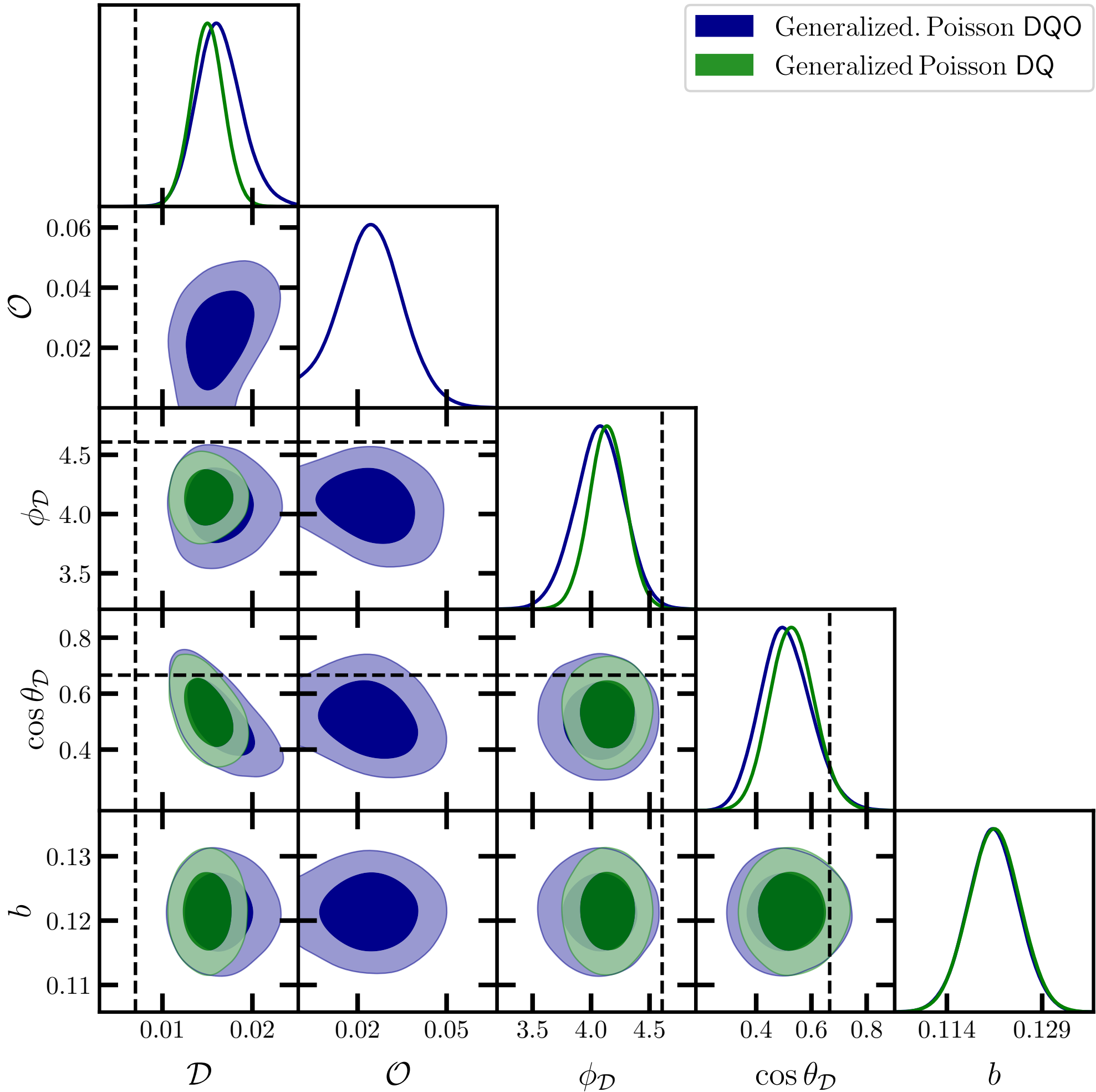
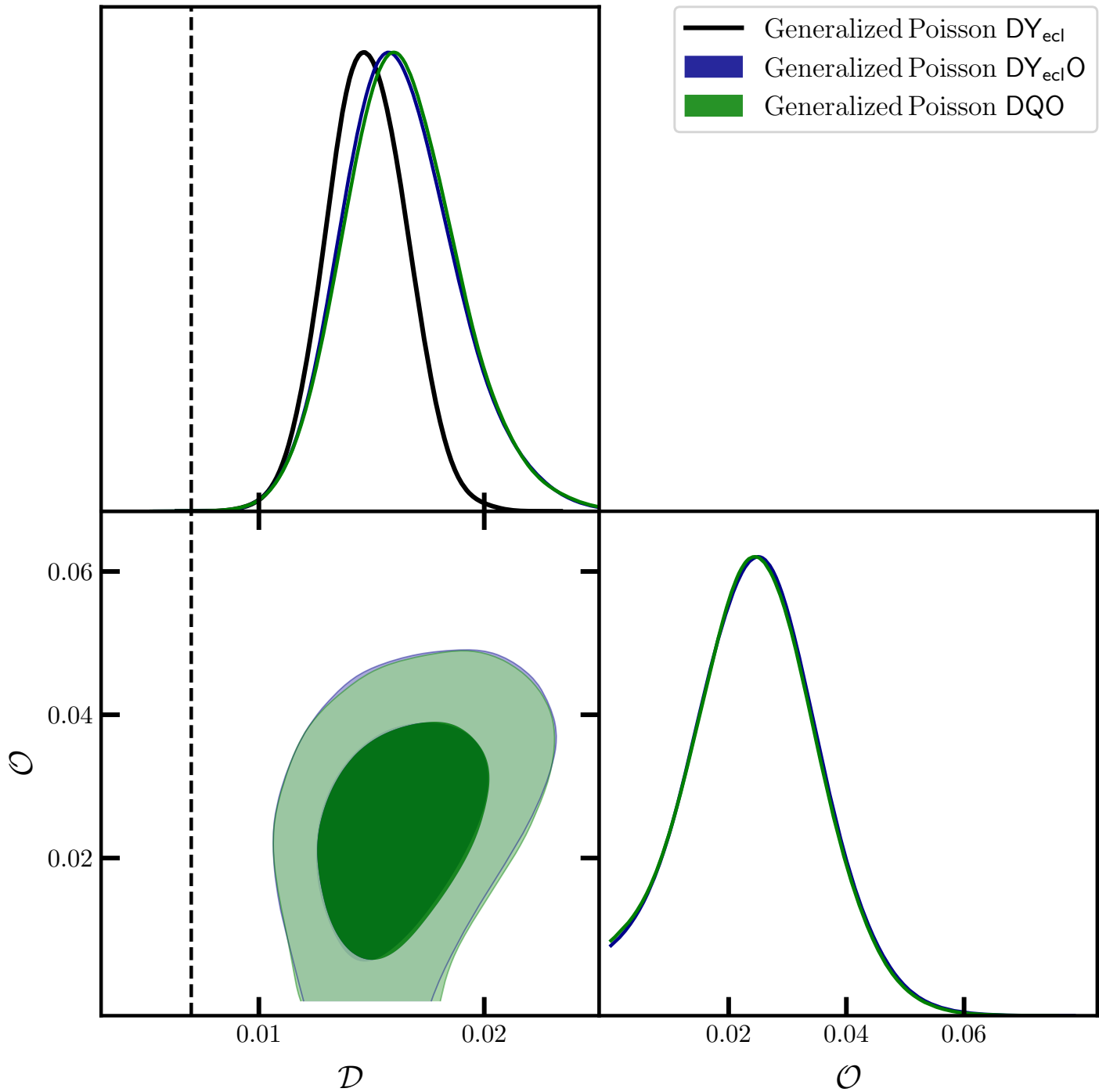
Combined fit with dipole and octupole does not remove dipole excess



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The matter dipole anomaly

- Radio samples give dipoles
~3 times larger than kinematic expectation from CMB dipole
- Mid-IR quasar sample gives dipole
~2 times larger
- Both at significance of $\gtrsim 5\sigma$

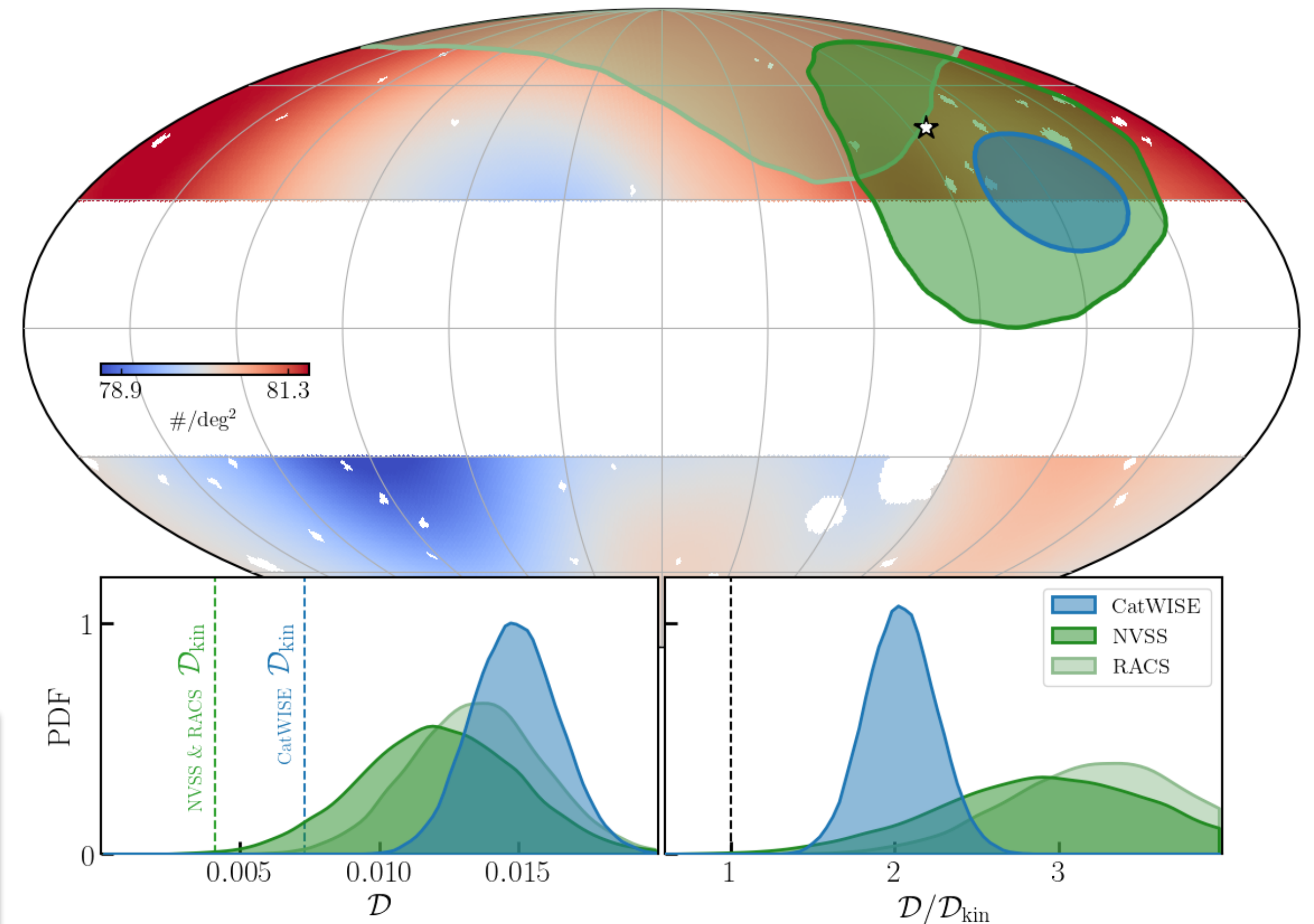
For radio-only see
Böhme et al. (2025)

Comment | Published: 06 January 2025

Forty years of the Ellis–Baldwin test

[Nathan Secrest](#) , [Sebastian von Hausegger](#), [Mohamed Rameez](#), [Roya Mohayaee](#) & [Subir Sarkar](#)

[Nature Reviews Physics](#) 7, 68–70 (2025) | [Cite this article](#)



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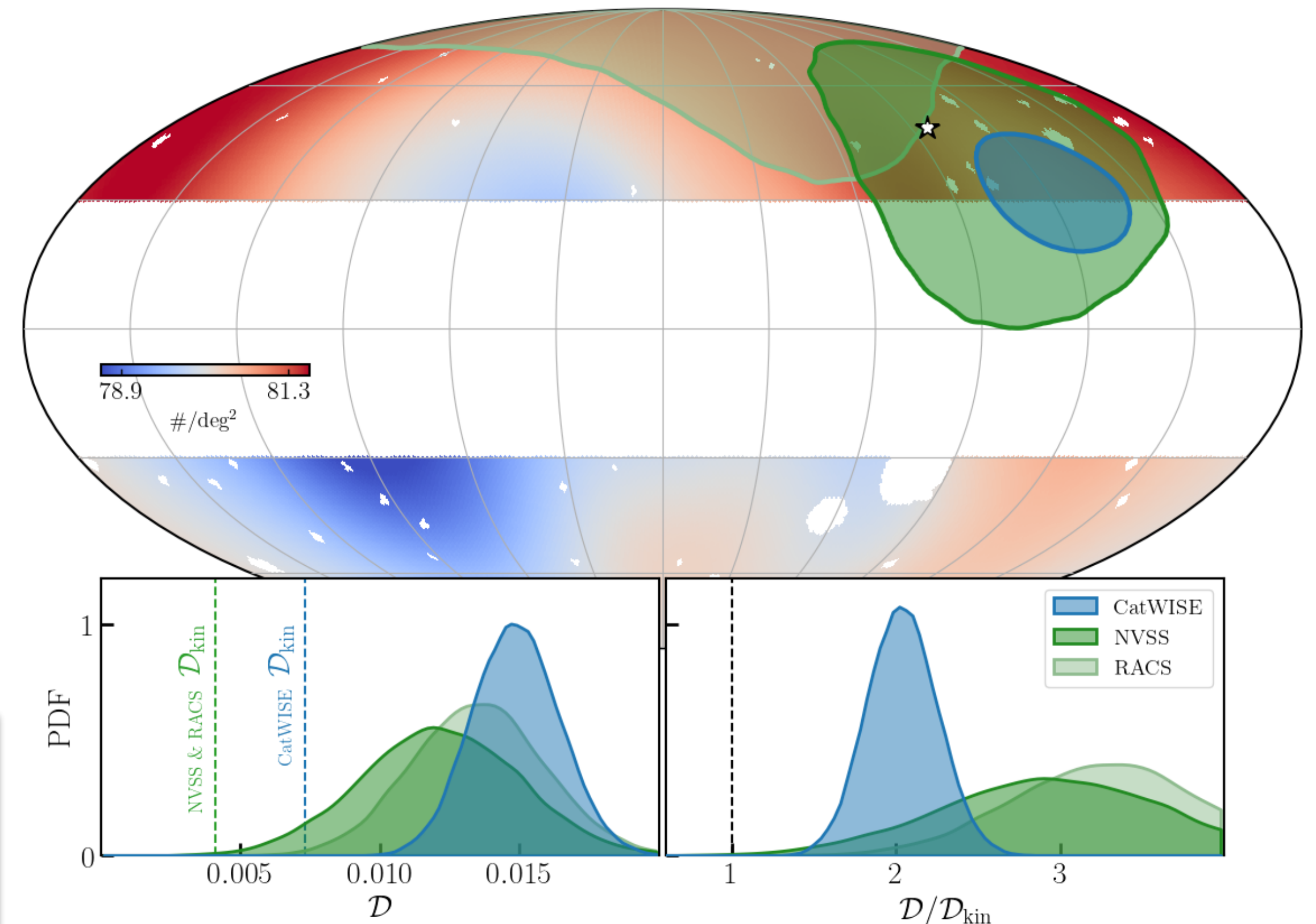
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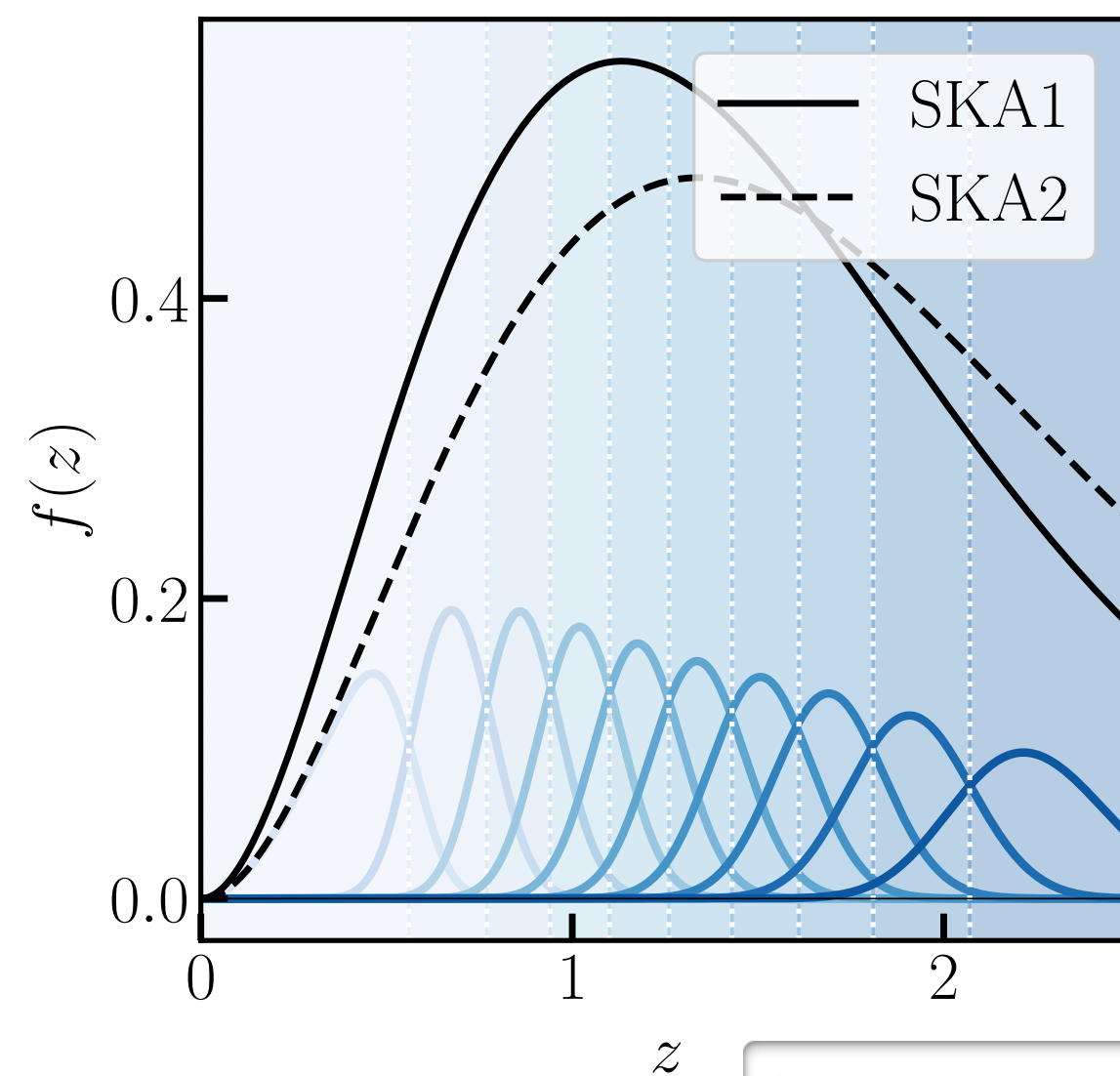


What is causing the too-large matter dipole? Is the matter dipole kinematic?

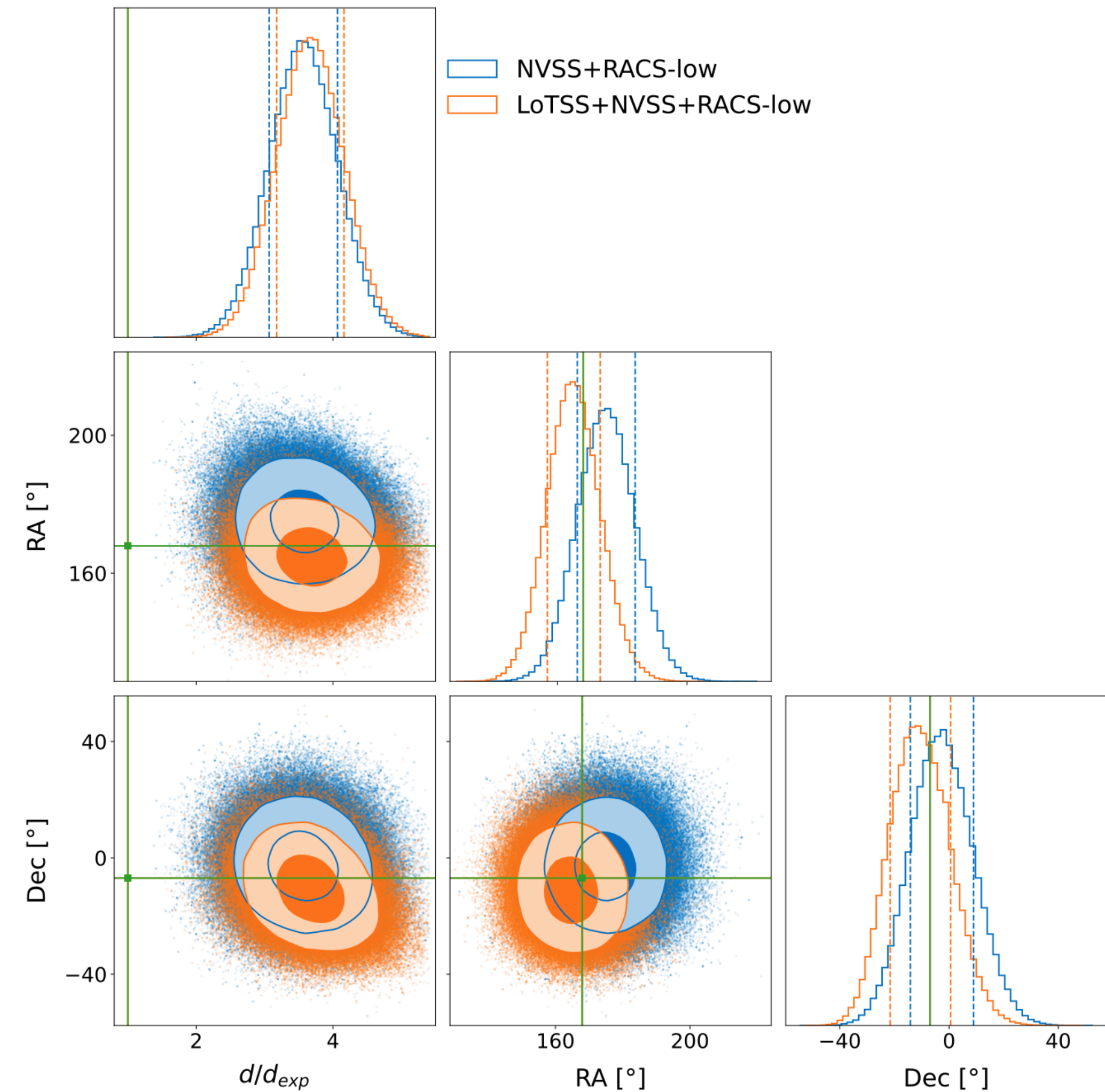
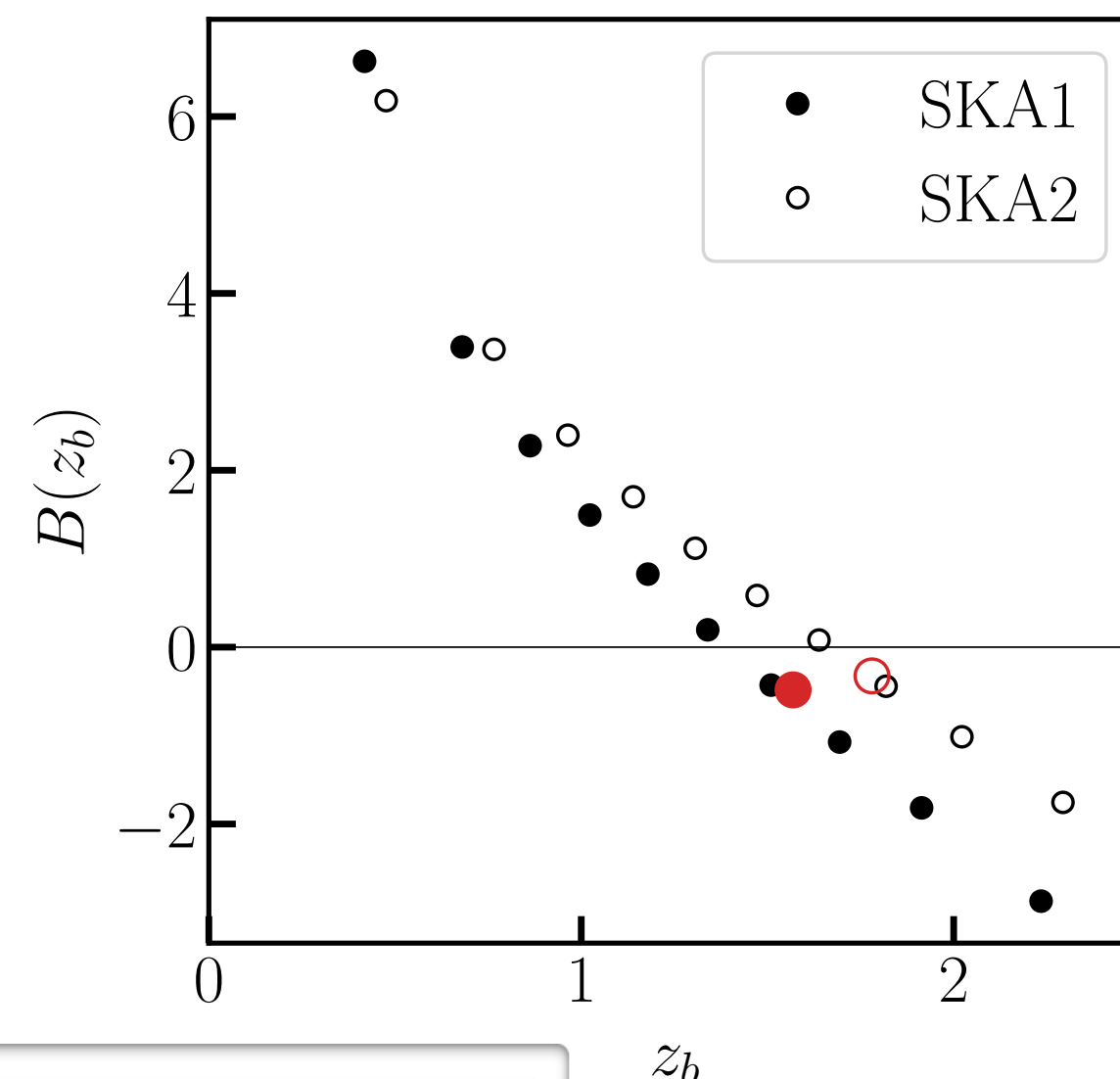
Kinematic vs intrinsic matter dipole

Böhme et al. (2025)

- old NVSS supplemented with newer radio data from RACS and LoTSS (LOFAR) (as well as TGSS and VLASS...)
- joint analysis gives large significance of radio data along
- “radio dipole anomaly” confirmed but more to be found with SKA...



SvH & Dalang (2025)



Kinematic vs intrinsic matter dipole

Wagenveld, SvH et al. (2025)

The kinematic contribution to the cosmic number count dipole

J.D. Wagenveld¹, S. von Hausegger², H-R. Klöckner¹, and D.J. Schwarz³

¹ Max-Planck Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

² Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK

³ Fakultät für Physik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany

Combined fit & model
comparison

$$\mathcal{D}_{\text{kin}} = [2 + x(1 + \alpha)] \cdot \beta$$

observed
dipole

Ansatz: $\vec{\mathcal{D}}_i = \vec{\mathcal{D}}_{\text{kin},i}(\beta, x_i, \alpha_i) + \vec{\mathcal{D}}_{\text{resid}}$

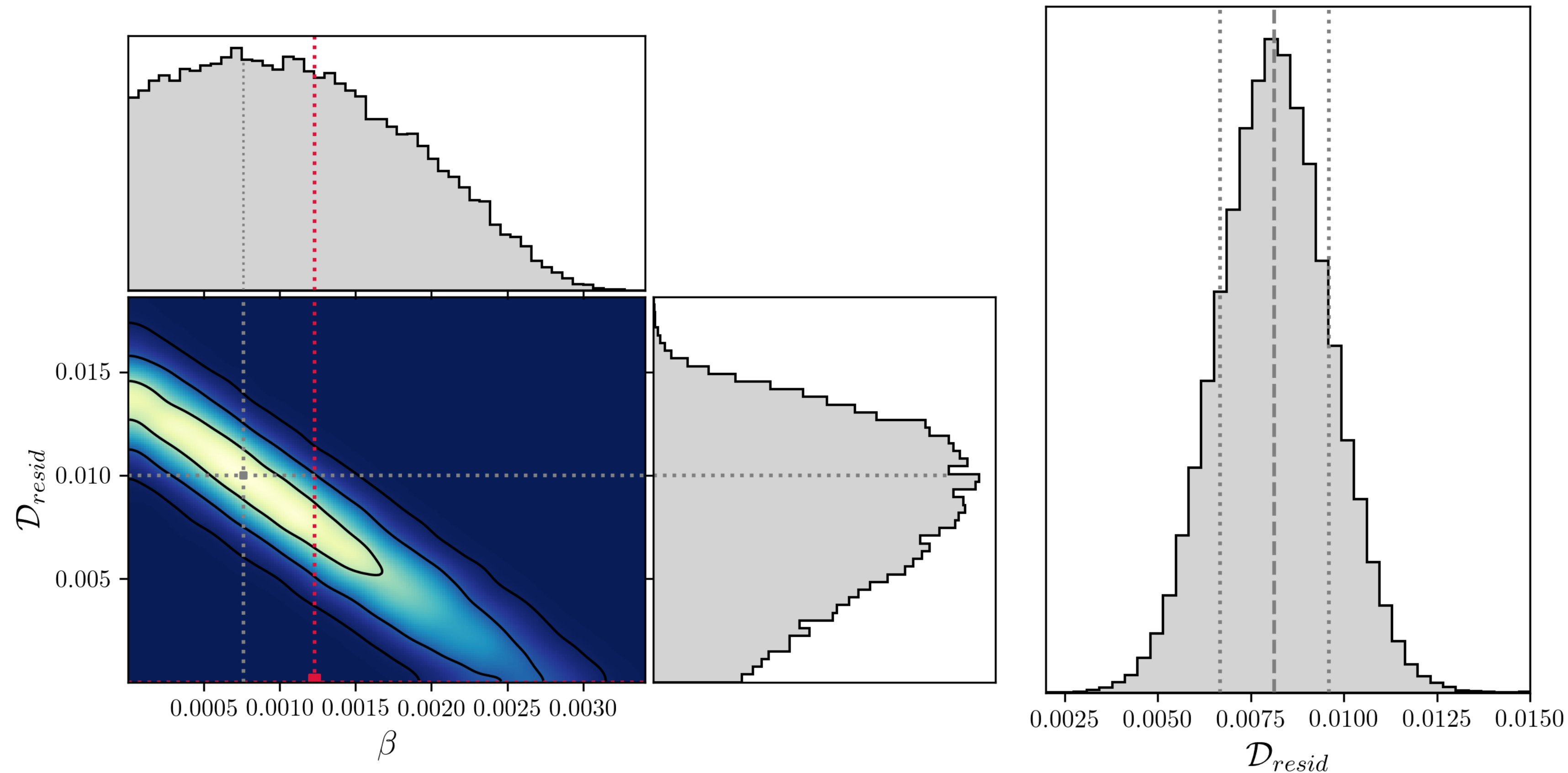
assumed constant across
catalogs

Depends on catalog / source properties
(e.g. radio vs. IR)

Kinematic vs intrinsic matter dipole

Wagenveld, SvH et al. (2025)

$$\vec{\mathcal{D}}_i \approx \vec{\mathcal{D}}_{\text{kin},i}(\beta) + \vec{\mathcal{D}}_{\text{resid}}$$



Bayesian evidence prefers
Model 2 over Model 1

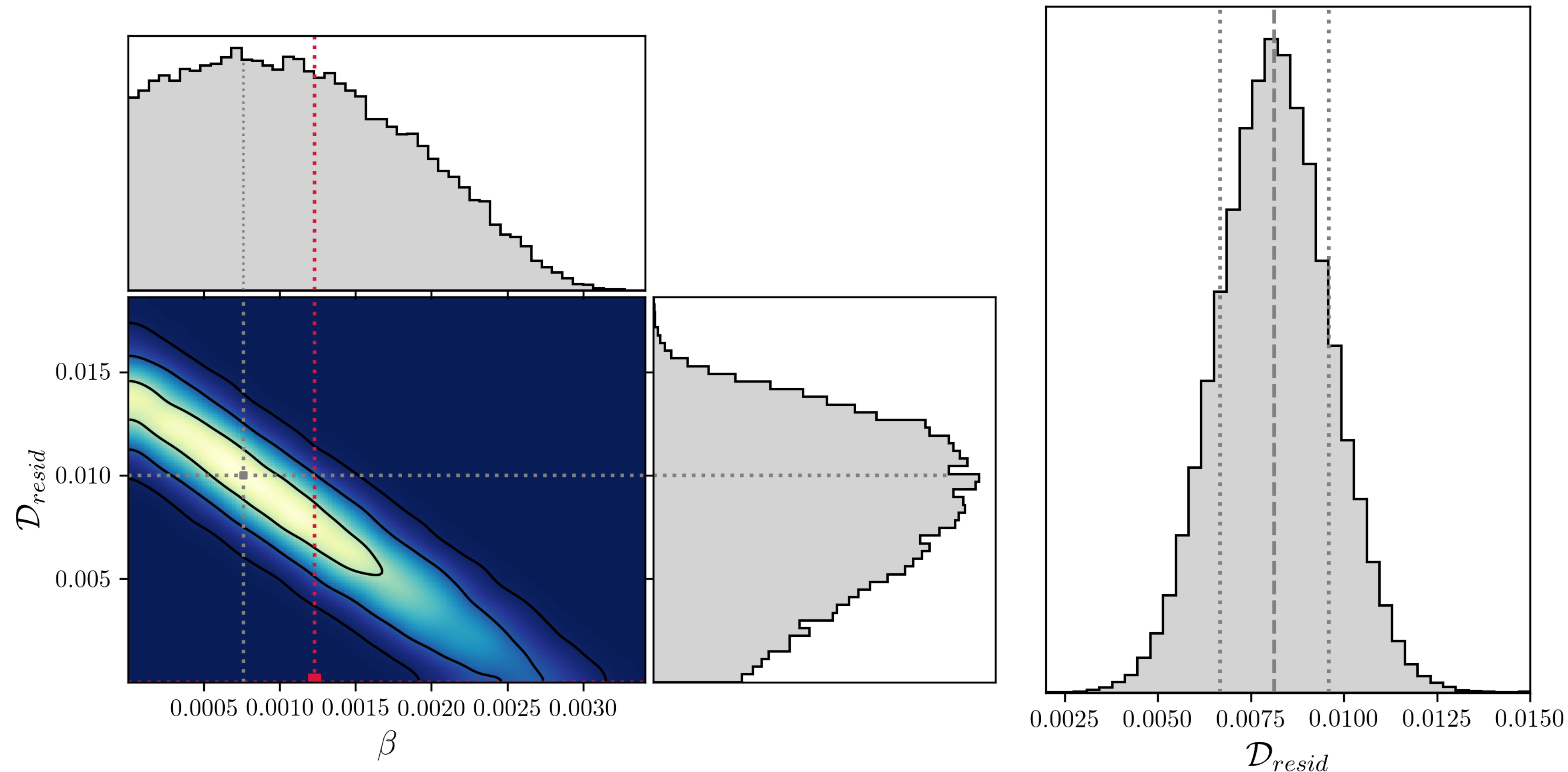
$$\Delta \log_{10} \mathcal{Z} = 2.79$$

(and each over the $\mathcal{D}_{\text{kin}}$ -only
model with
 $\Delta \log_{10} \mathcal{Z} \approx 1.3 - 1.5$)

Kinematic vs intrinsic matter dipole

Wagenveld, SvH et al. (2025)

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 $\Delta \log_{10} \mathcal{Z} \approx 1.3 - 1.5$)

**Evidence for a non-
kinematic component?**

see e.g. Turner (1991),
Domenech et al. (2022)

Specific take aways — make better



SKAO

LSST
Large Synoptic Survey Telescope

...and more?



Radio and mid-IR measurements of the matter dipole **show significant excess!**

variations of the microwave background radiation. If the standards of rest determined by the MBR and the number counts were to be in **serious disagreement, one would have to abandon** either

- (a) the idea that the radio sources are at cosmological distances, or
- (b) the interpretation of the cosmic microwave radiation as relic radiation from the big bang, or
- (c) the standard FRW Universe models.**

The kinematic matter dipole integrated over redshift is exactly as given by Ellis&Baldwin — **no change by redshift evolution**

Measurements of matter dipole **in redshift bins** possible with upcoming data — boundary terms important

SKA, Euclid, SPHEREx, and LSST will offer ample opportunity for resolve the source of this outstanding anomaly

Additional slides...

The kinematic matter dipole

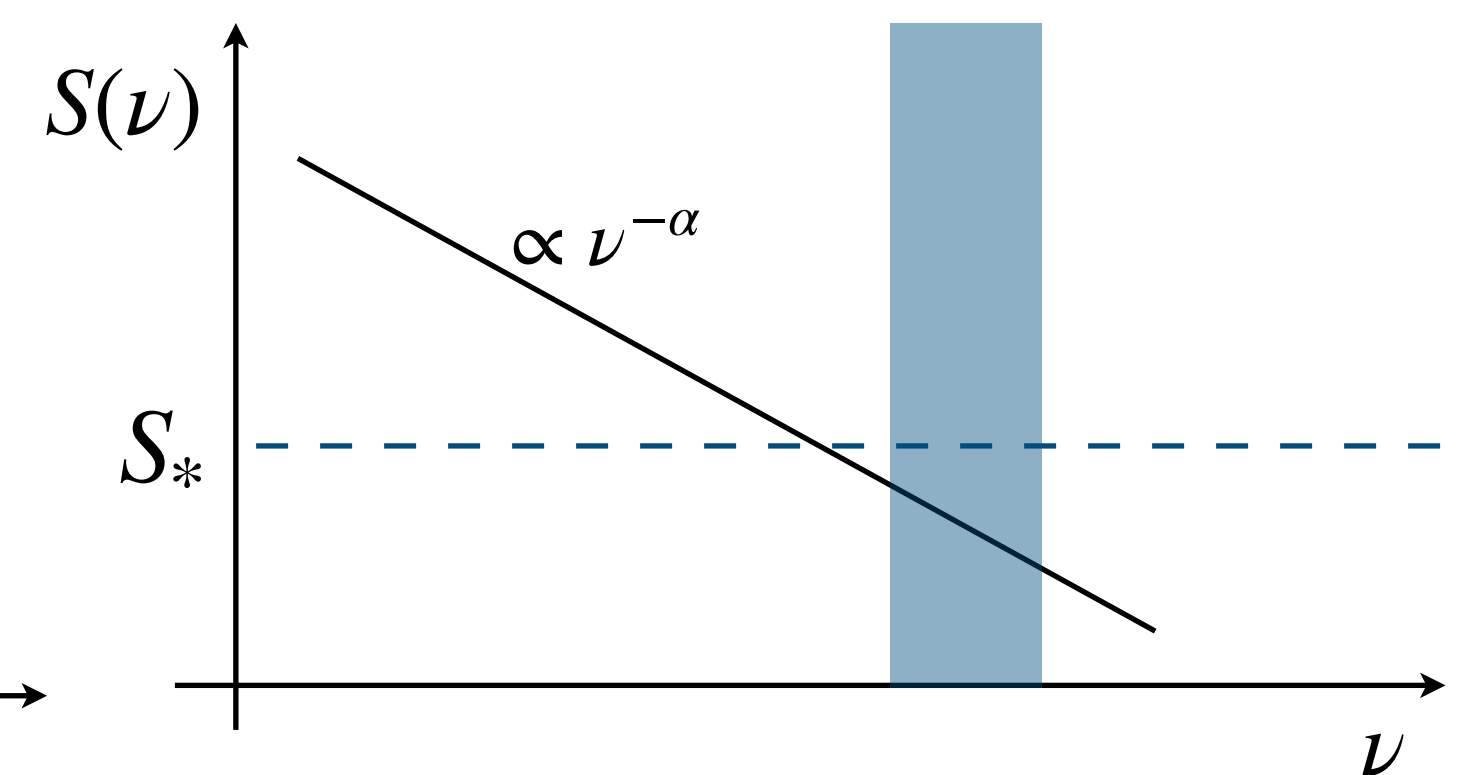
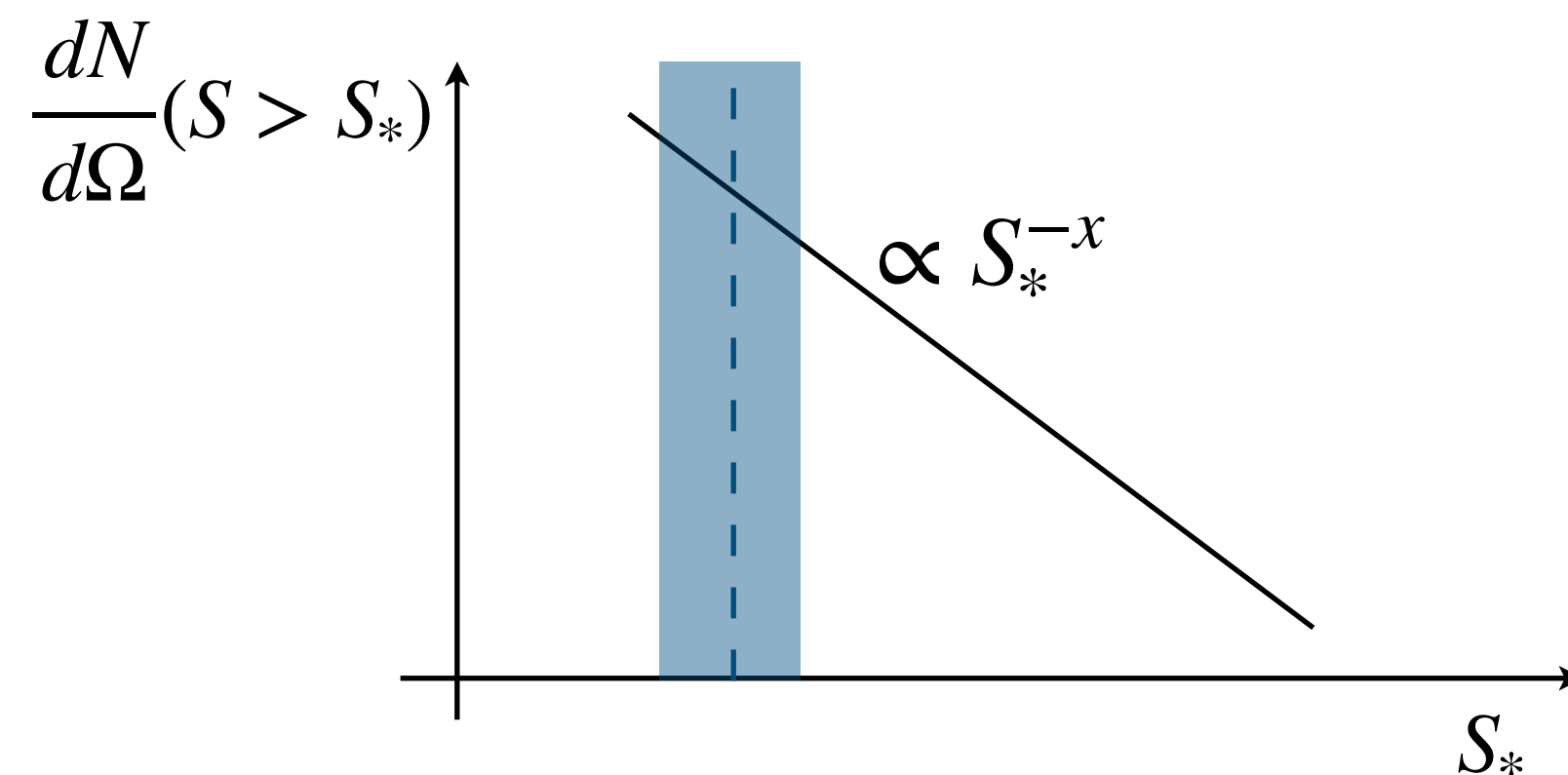
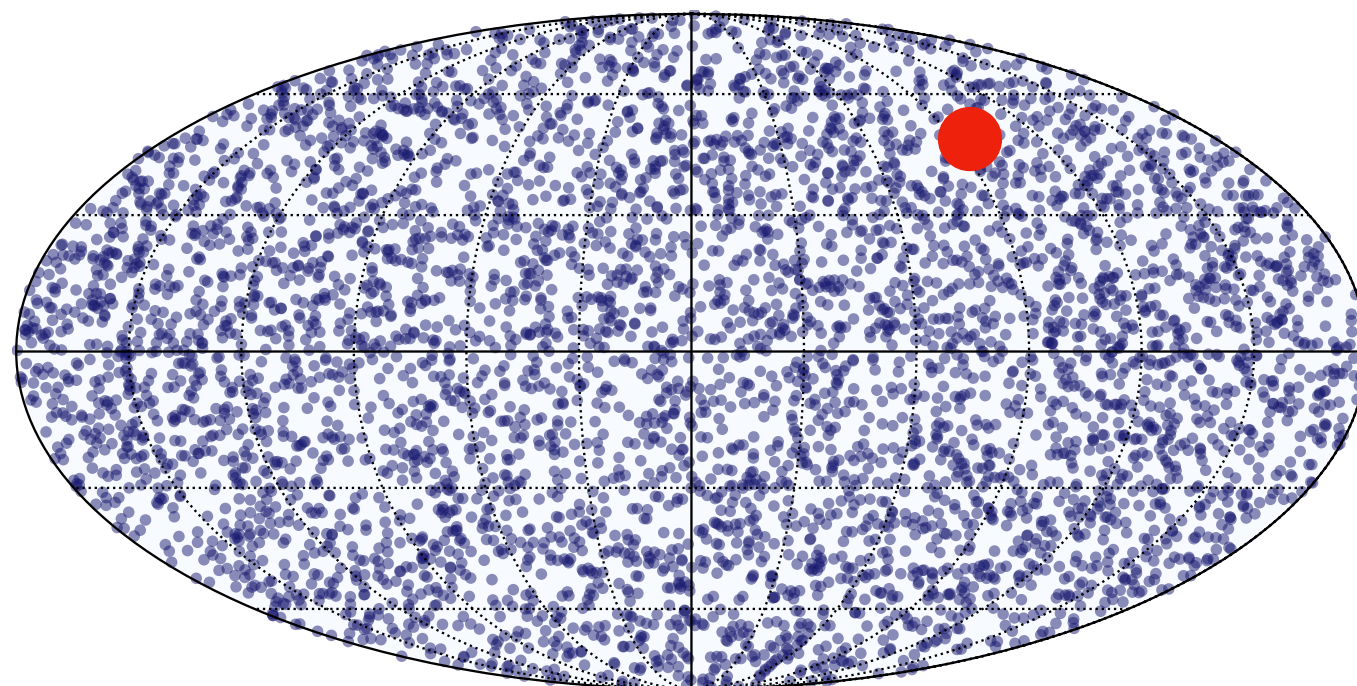
Ellis & Baldwin (1984)

Average spectral index
of source spectra

$$\tilde{\mathcal{D}}_{\text{kin}} = \left[2 + \tilde{x}(1 + \tilde{\alpha}) \right] \beta$$

Average
magnification bias

“Tilde” quantities refer
to what we measure
(without redshifts!)



The kinematic matter dipole

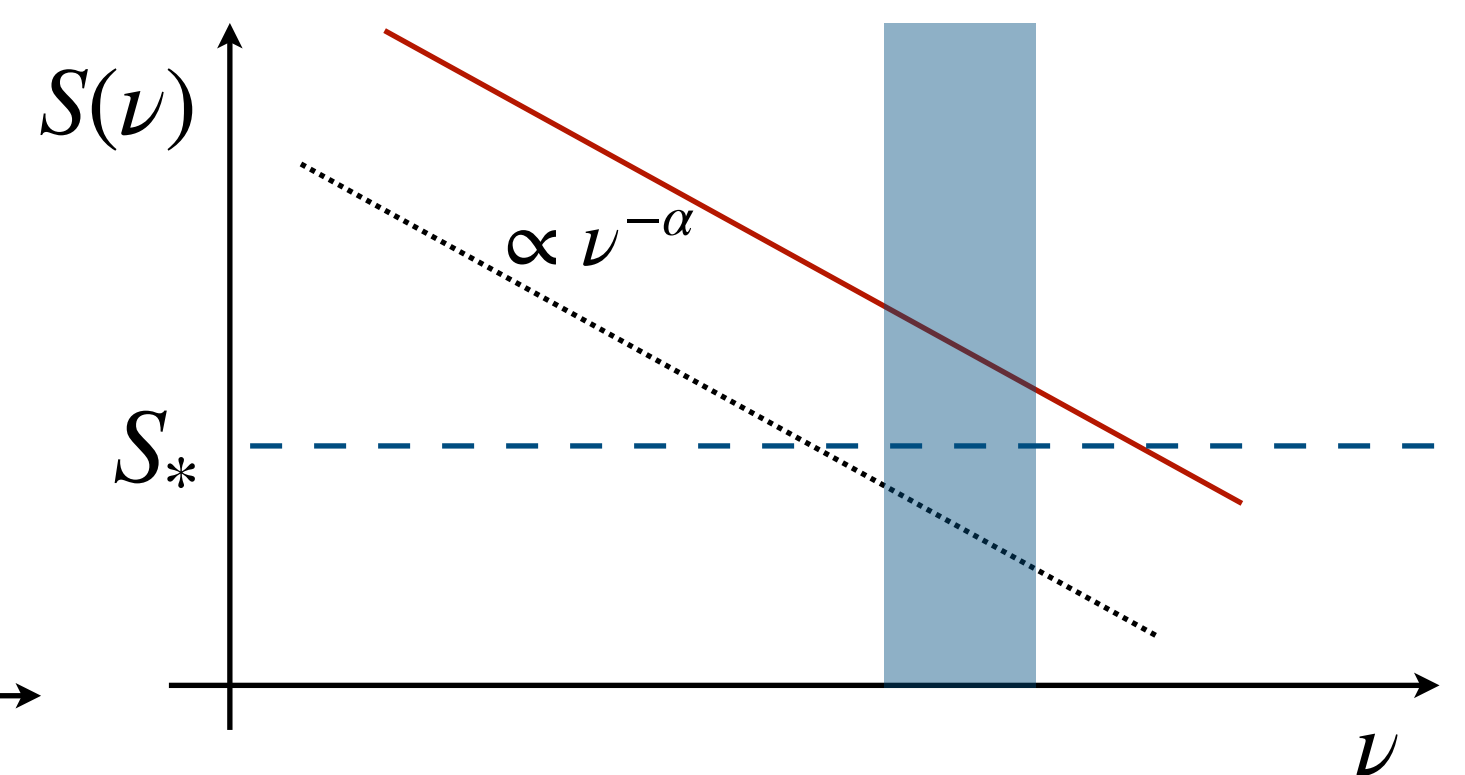
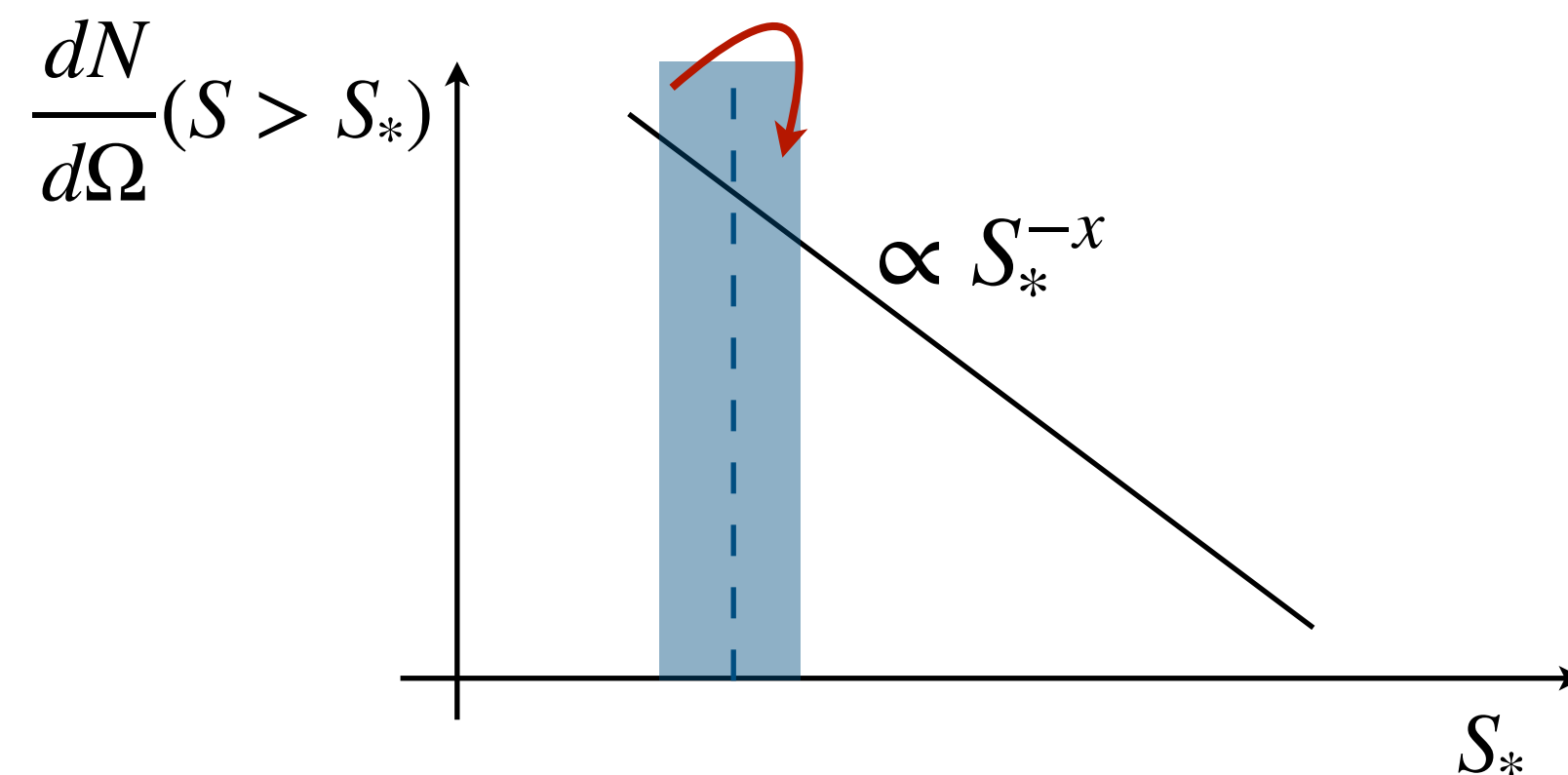
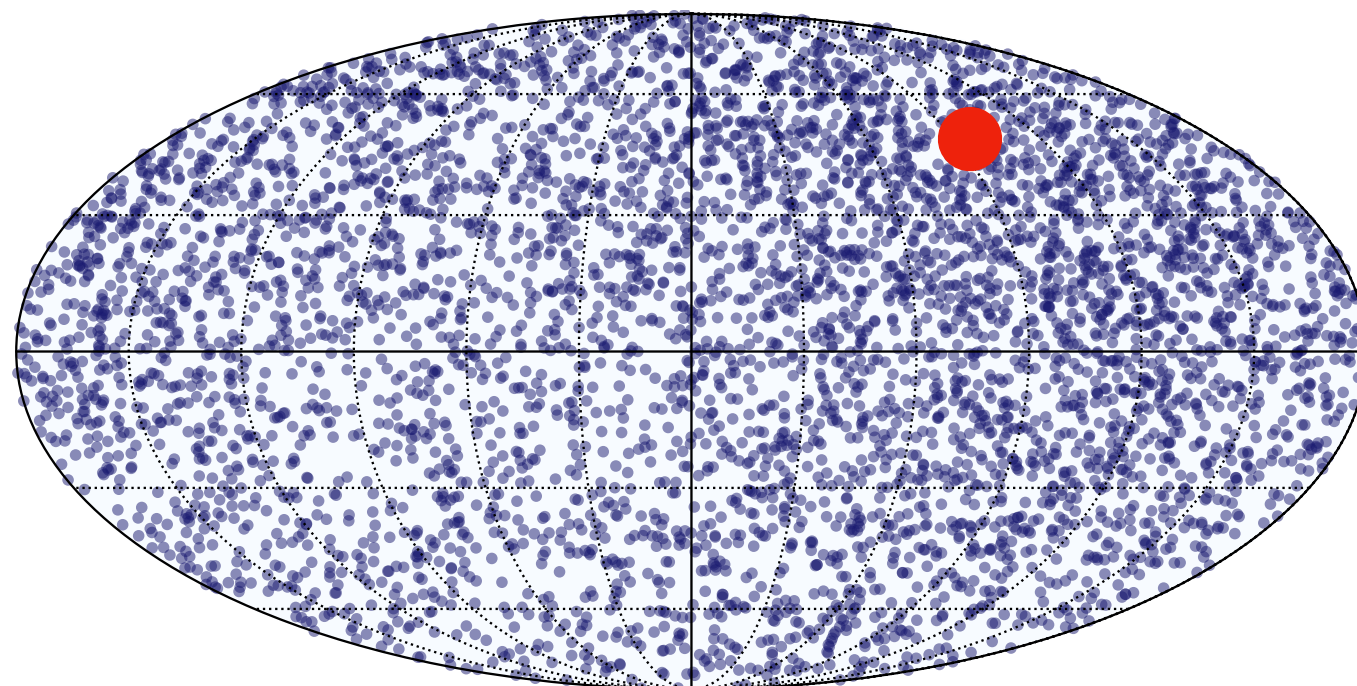
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Redshift dependence

Ellis & Baldwin (1984)

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Average
magnification bias

“Tilde” quantities refer
to what we measure
(without redshifts!)

$$\mathcal{D}_{\text{kin}} = \int_0^\infty dz f(z) \mathcal{D}_{\text{kin}}(z)$$

Redshift dependence

Ellis & Baldwin (1984)

Average spectral index
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$$\tilde{\mathcal{D}}_{\text{kin}} = \left[2 + \tilde{x}(1 + \tilde{\alpha}) \right] \beta$$

Average
magnification bias

“Tilde” quantities refer
to what we measure
(without redshifts!)

(normalised)
redshift
distribution

$$\mathcal{D}_{\text{kin}} = \int_0^\infty dz f(z) \mathcal{D}_{\text{kin}}(z)$$

kinematic dipole
per redshift

Redshift dependence

Ellis & Baldwin (1984)

$$\tilde{\mathcal{D}}_{\text{kin}} = [2 + \tilde{x}(1 + \tilde{\alpha})] \beta$$

Redshift-independent

Maartens, Clarkson, Chen (2017)

$$\mathcal{D}_{\text{kin}}(z) = \left[2 + \frac{\dot{\mathcal{H}}(z)}{\mathcal{H}^2(z)} + \frac{2(1 - x(z))}{r(z)\mathcal{H}(z)} - b_e(z) \right] \beta$$

Redshift-dependent

(normalised)
redshift
distribution

$$\mathcal{D}_{\text{kin}} = \int_0^\infty dz f(z) \mathcal{D}_{\text{kin}}(z)$$

kinematic dipole
per redshift

Redshift dependence

Ellis & Baldwin (1984)

$$\tilde{\mathcal{D}}_{\text{kin}} = [2 + \tilde{x}(1 + \tilde{\alpha})] \beta$$

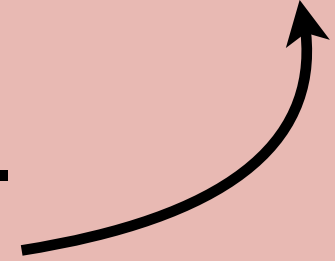
Are the observed quantities
enough to predict the dipole
correctly?

Dalang & Bonvin (2022)

Nadolny et al. (2021)

$$\mathcal{D}_{\text{kin}}(z) = \left[3 + x(z)(1 + \alpha(z)) + \frac{d \log n(z)}{d \log(1 + z)} \right] \beta$$

= -1 when inte-
grated over all z



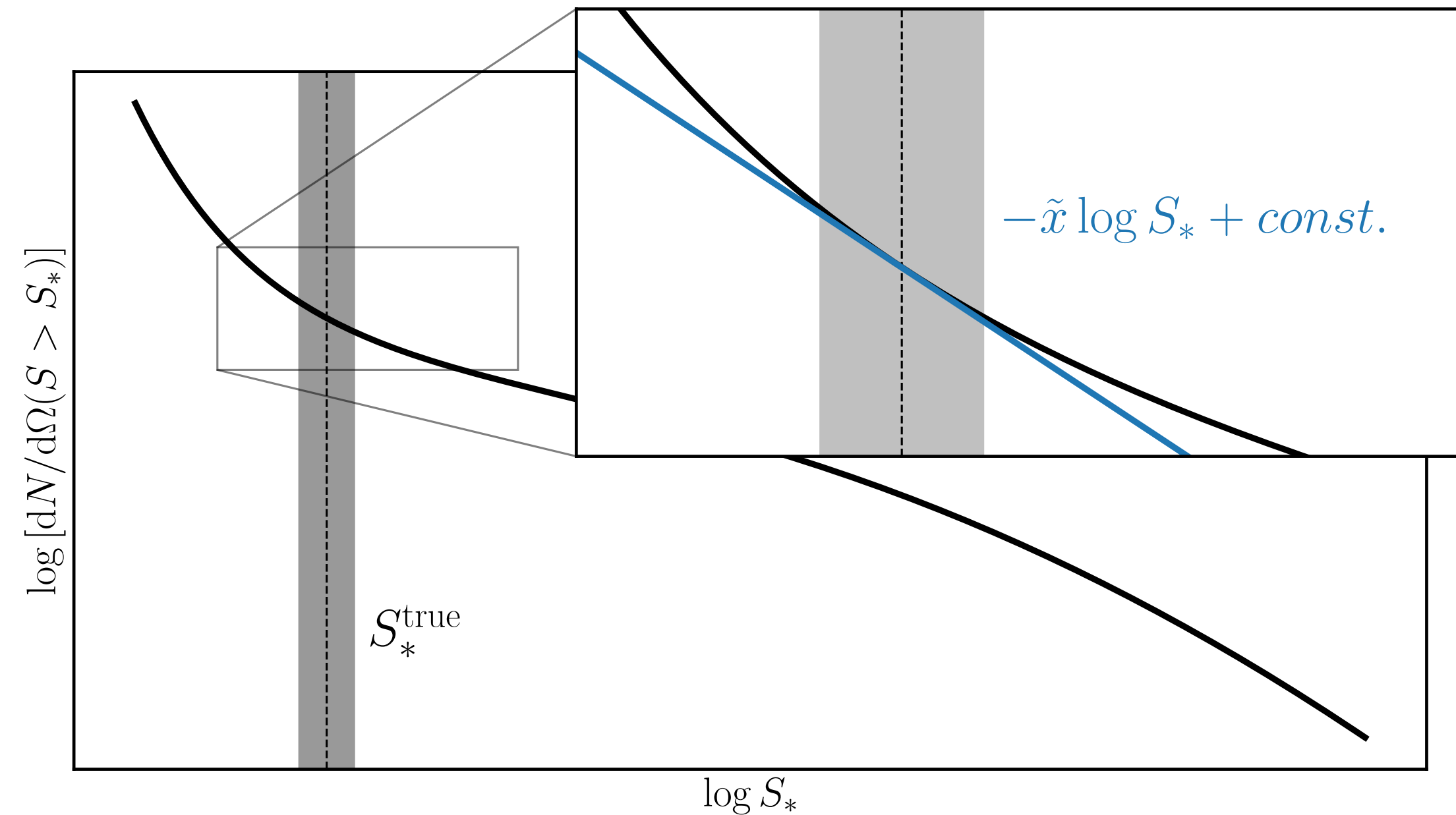
(normalised)
redshift
distribution


$$\mathcal{D}_{\text{kin}} = \int_0^\infty dz f(z) \mathcal{D}_{\text{kin}}(z)$$

kinematic dipole
per redshift



Source evolution accounted



$$\tilde{\mathcal{D}}_{\text{kin}} = [2 + \tilde{x}(1 + \tilde{\alpha})] \beta$$

$$\tilde{x} = \int_0^\infty dz x(z) f(z)$$

Relate $\tilde{x}$ to $x(z)$

integral source counts

SvH (2024)

$$\tilde{x} = -\frac{d \log}{d \log S_*} \frac{dN}{d\Omega}(S > S_*) \quad \frac{dN}{d\Omega}(S > S_*) = \int_0^\infty dz \frac{dN}{d\Omega dz}(z, S > S_*) \quad \tilde{x} = N^{-1} \int_0^\infty dz x(z) \frac{dN}{d\Omega dz}(z, S > S_*)$$

Source evolution accounted

$$\mathcal{D}_{\text{kin}} = \int_0^\infty dz f(z) \mathcal{D}_{\text{kin}}(z)$$

$$\mathcal{D}_{\text{kin}}(z) = \left[3 + x(z)(1 + \alpha(z)) + \frac{d \log n(z)}{d \log(1 + z)} \right] \beta$$

Nadolny et al. (2021), Dalang & Bonvin (2022)

$$\tilde{\mathcal{D}}_{\text{kin}} = [2 + \tilde{x}(1 + \tilde{\alpha})] \beta$$

$$\tilde{\alpha} = \int_0^\infty dz x(z) \tilde{f}(z)$$

Relate $\tilde{\alpha}$ to $\alpha(z)$

differential source counts at S_*

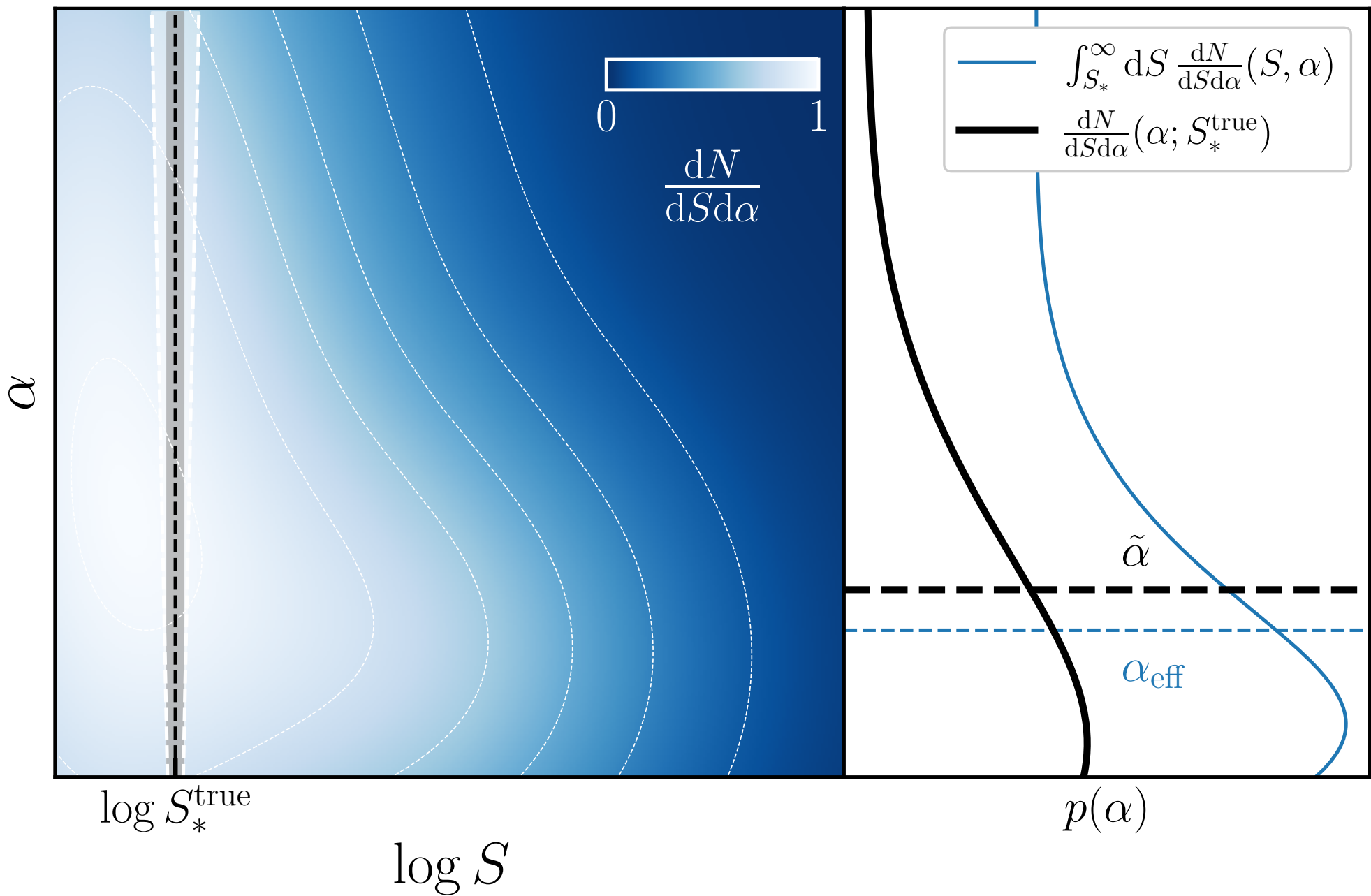
$$\tilde{\alpha} = \tilde{N}^{-1} \int_0^\infty dz \alpha(z) \frac{dN}{d\Omega dz dS}(z, S_*)$$

SvH (2024)

Source evolution accounted

$$\tilde{\mathcal{D}}_{\text{kin}} = \left[2 + \tilde{x}(1 + \tilde{\alpha}) \right] \beta$$

$$\tilde{\alpha} = \int_0^\infty \text{d}z \, x(z) \tilde{f}(z)$$

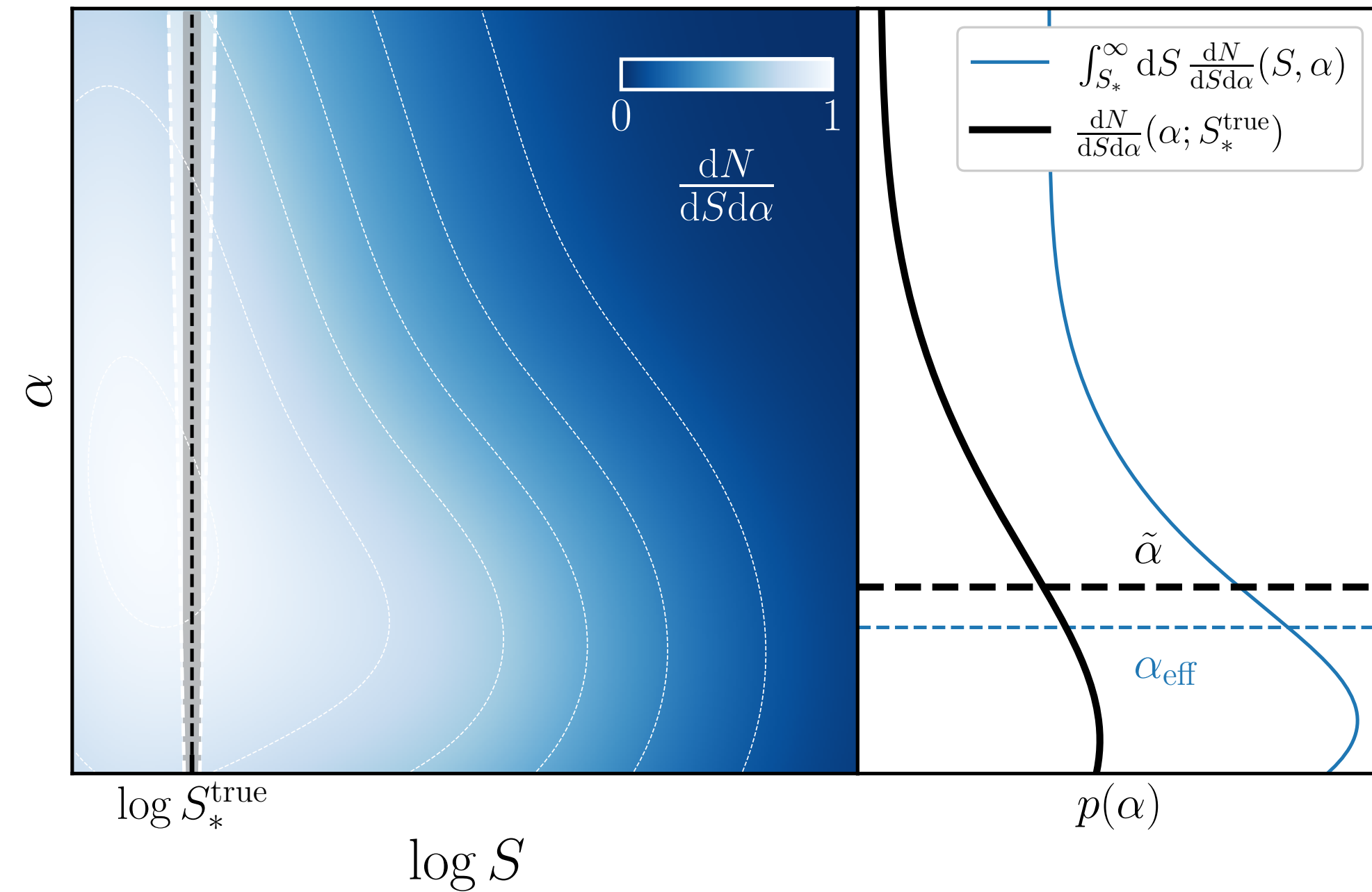


Relate $\tilde{\alpha}$ to $\alpha(z)$

SvH (2024)

$$\tilde{\alpha} = \frac{\int_0^\infty \text{d}z \, \alpha(z) x(z) \frac{\text{d}N}{\text{d}\Omega \text{d}z}(z, S > S_*)}{\int_0^\infty \text{d}z \, x(z) \frac{\text{d}N}{\text{d}\Omega \text{d}z}(z, S > S_*)}$$

Source evolution accounted



$$\tilde{\mathcal{D}}_{\text{kin}} = \left[2 + \tilde{x}(1 + \tilde{\alpha}) \right] \beta$$

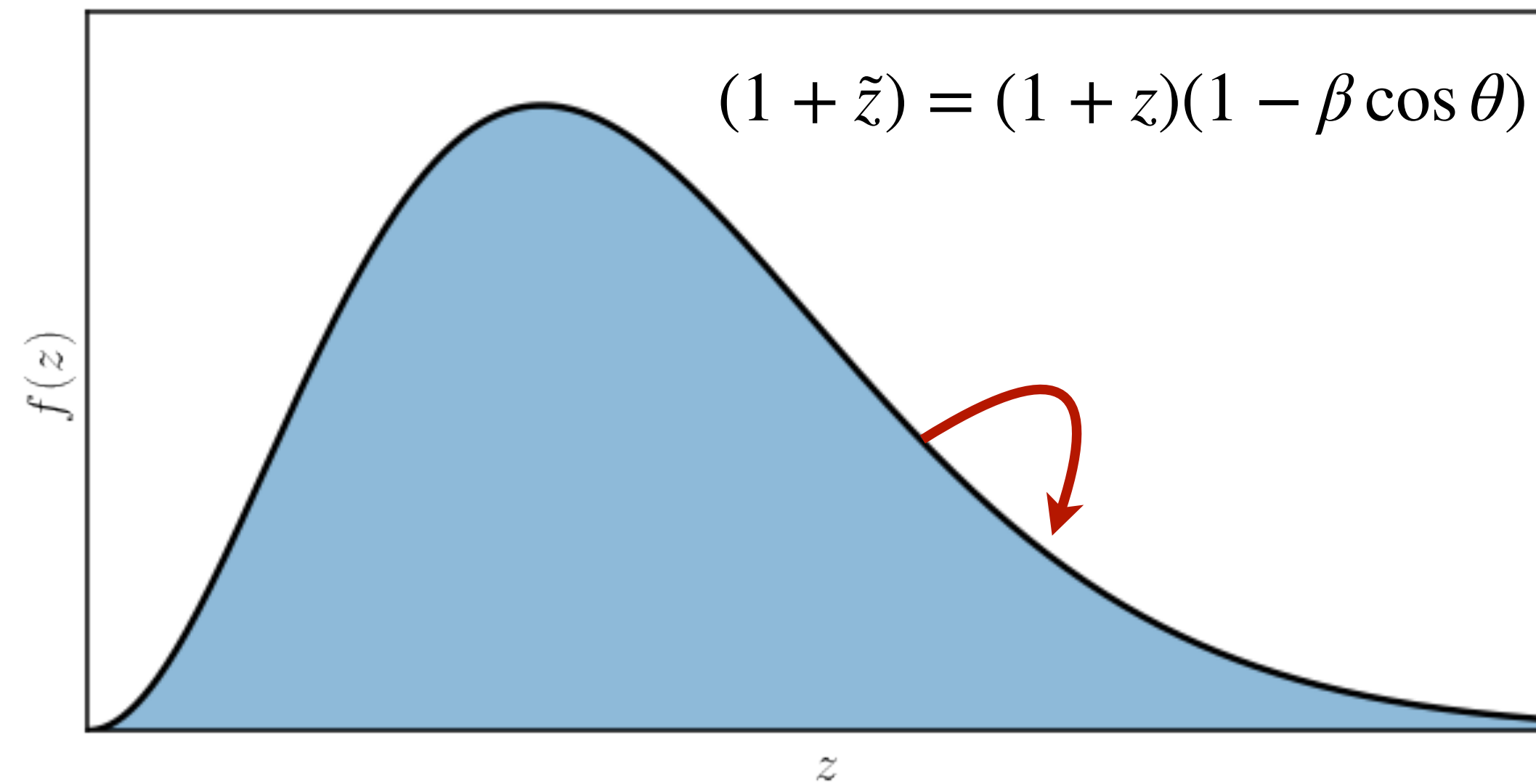
Only observed quantities dictate the kinematic dipole amplitude

Relate $\tilde{\alpha}$ to $\alpha(z)$

SvH (2024)

$$\tilde{\alpha} = \int_0^\infty dz \alpha(z) x(z) \frac{dN}{d\Omega dz}(z, S > S_*) \bigg/ \int_0^\infty dz x(z) \frac{dN}{d\Omega dz}(z, S > S_*)$$

Redshift dependence

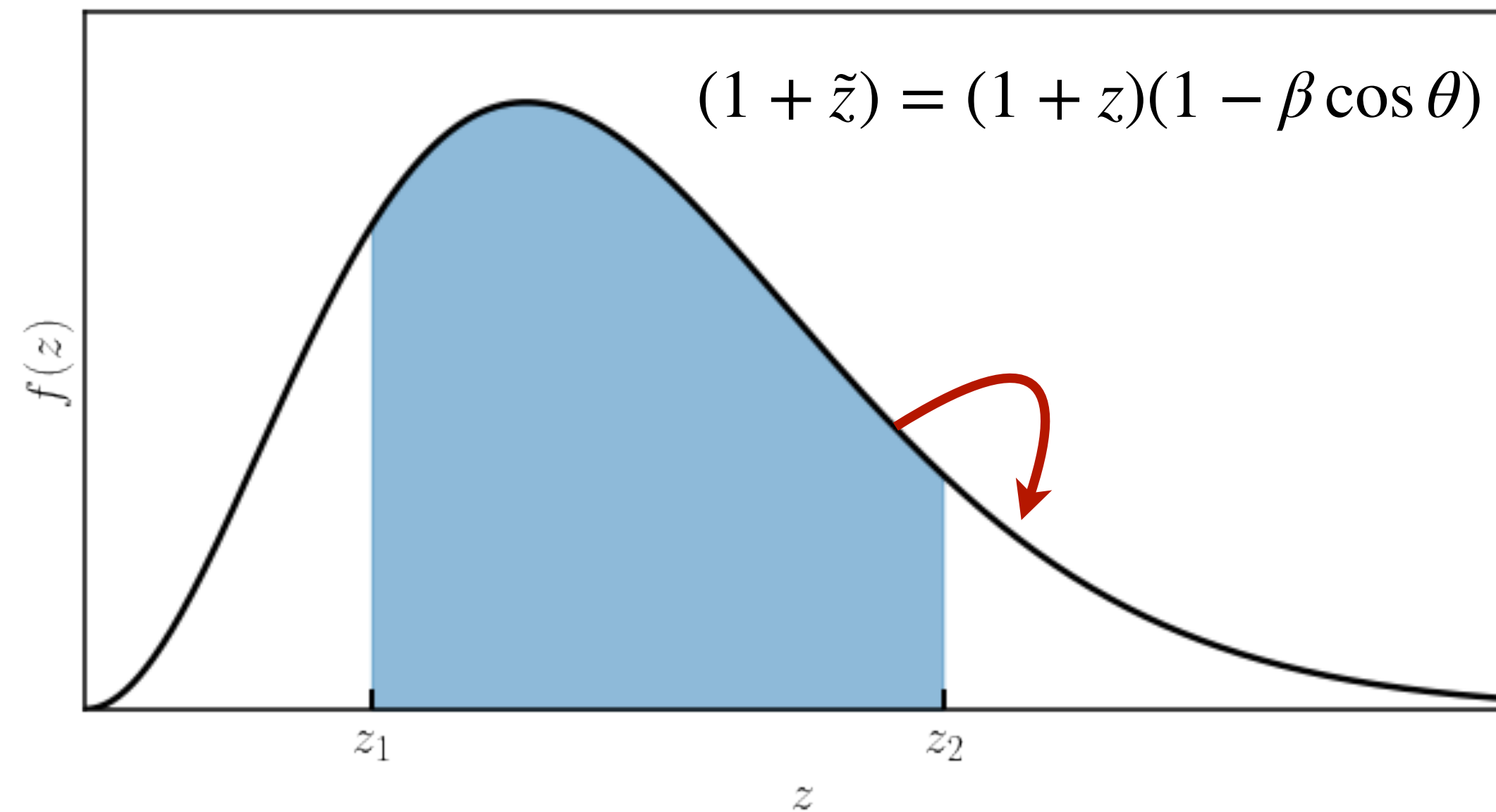


(normalised)
redshift
distribution

$$\mathcal{D}_{\text{kin}} = \int_0^{\infty} dz f(z) \mathcal{D}_{\text{kin}}(z)$$

kinematic dipole
per redshift

Redshift dependence

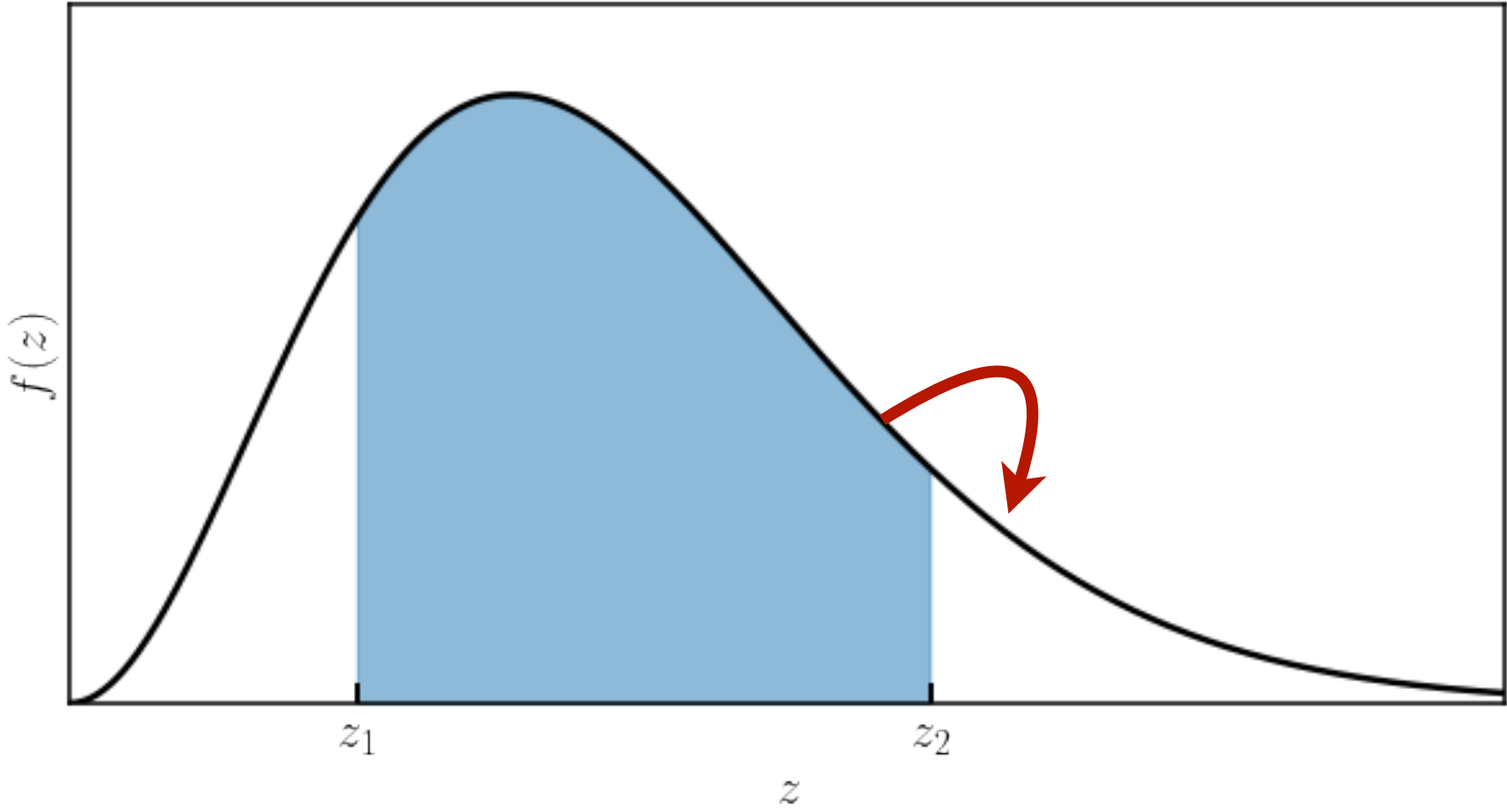


(normalised)
redshift
distribution

$$\mathcal{D}_{\text{kin}} = \int_{z_1}^{z_2} dz f_b(z) \mathcal{D}_{\text{kin}}(z)$$

kinematic dipole
per redshift

Redshift tomography



Redshift tomography of the kinematic matter dipole

Sebastian von Hausegger^{1,*} and Charles Dalang^{2,3,†}

¹*Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*

²*School of Mathematical Sciences, Queen Mary University of London,
Mile End Road, London E1 4NS, United Kingdom*

³*Institute of Cosmology and Gravitation, University of Portsmouth,
Burnaby Road, Portsmouth PO1 3FX, United Kingdom*

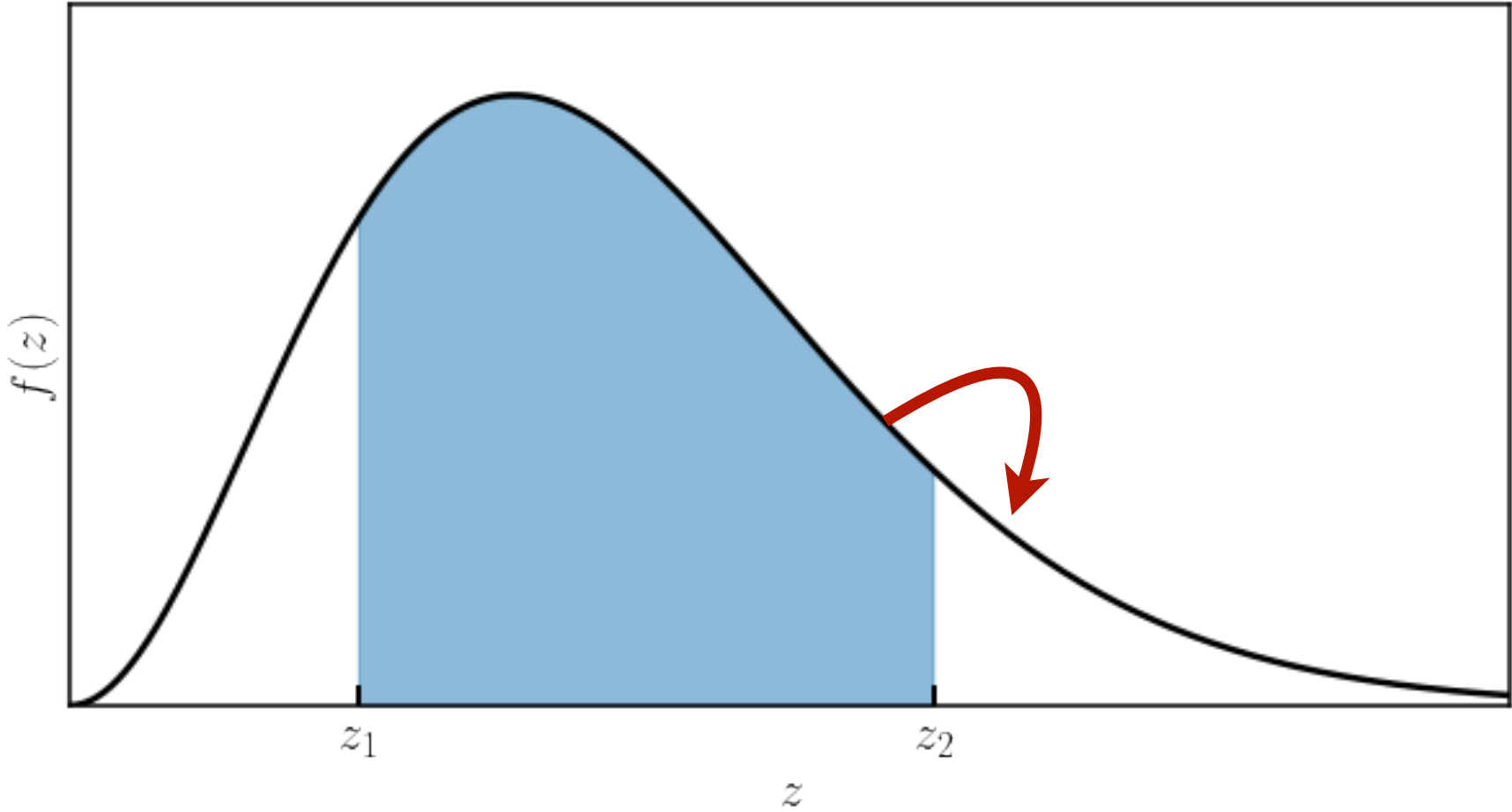
SvH & Dalang (2025)

(normalised)
redshift
distribution

$$\mathcal{D}_{\text{kin}} = \int_{z_1}^{z_2} dz f_b(z) \mathcal{D}_{\text{kin}}(z)$$

kinematic dipole
per redshift

Redshift tomography



Additional
“boundary term”

$$\mathcal{D}_{\text{kin}} = \left[2 + \tilde{x}(1 + \tilde{\alpha}) + (1 + z)f_b(z) \right] \Big|_{z_1}^{z_2} \beta$$

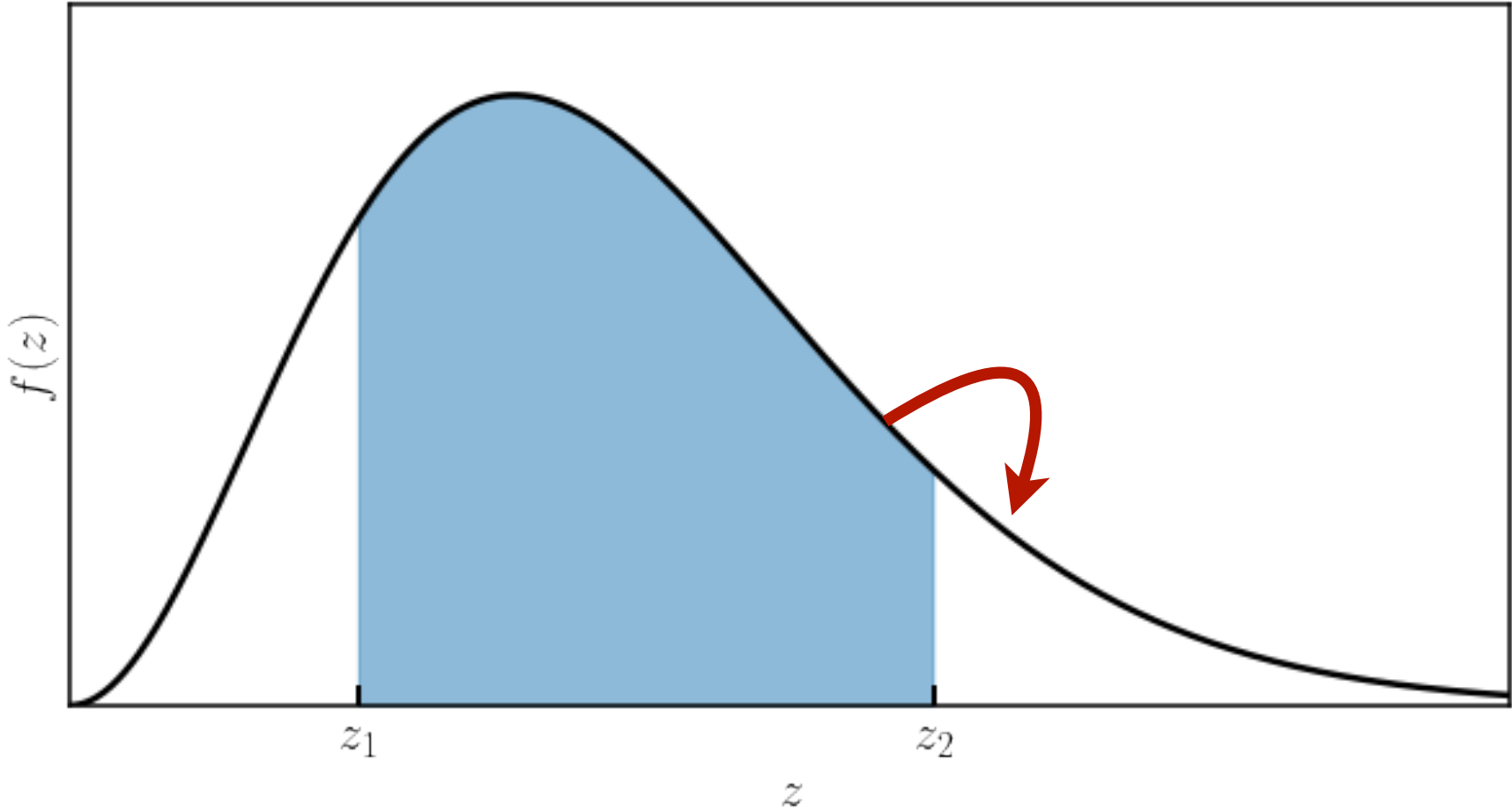
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kinematic dipole
per redshift

Redshift tomography

SvH & Dalang (2025)



Additional
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$$\mathcal{D}_{\text{kin}} = \left[2 + \tilde{x}(1 + \tilde{\alpha}) + (1 + z)f_b(z) \right] \Big|_{z_1}^{z_2} \beta$$

$$\equiv B(z_1, z_2)$$

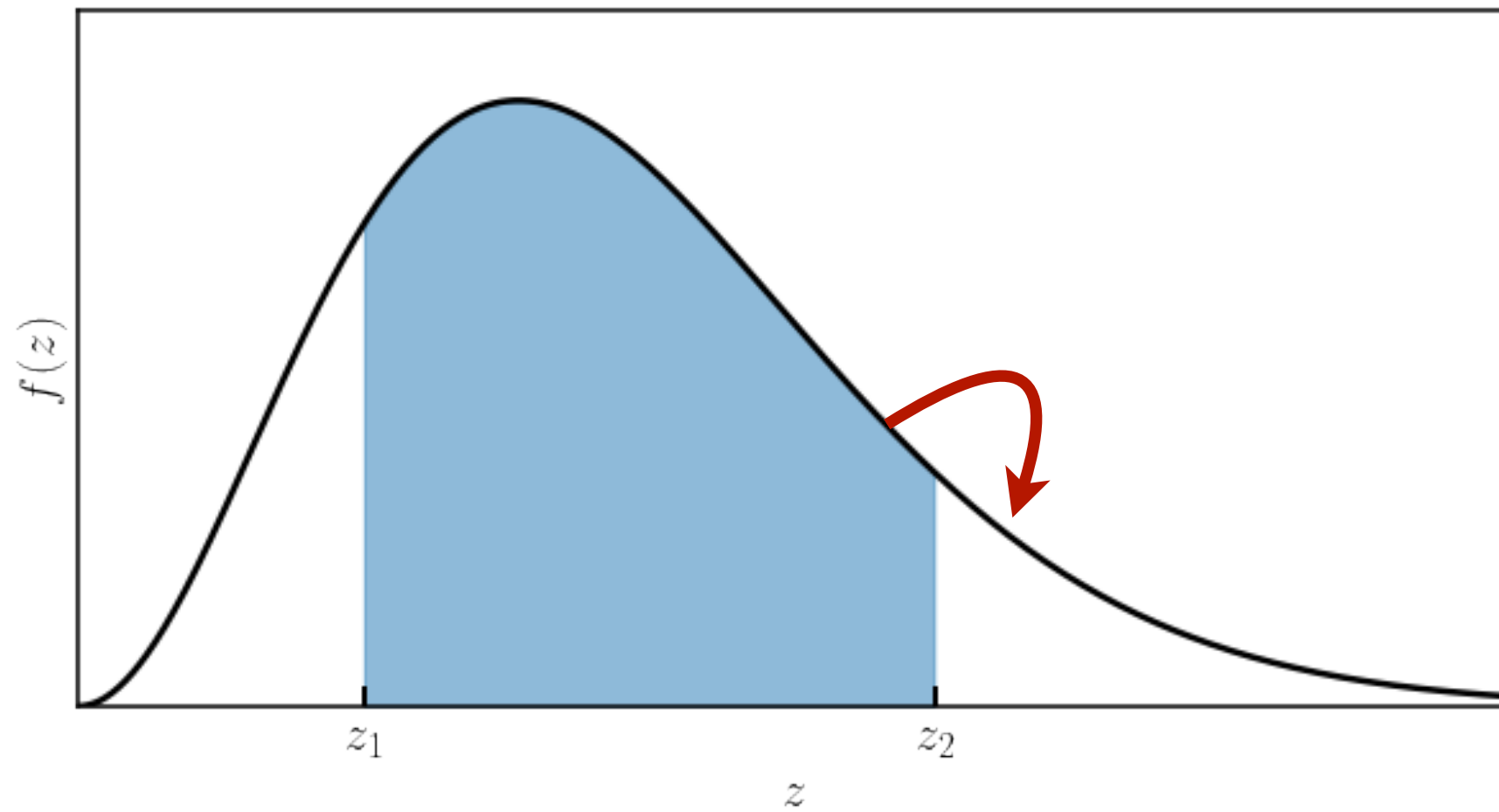
(normalised)
redshift
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$$\mathcal{D}_{\text{kin}} = \int_{z_1}^{z_2} dz f_b(z) \mathcal{D}_{\text{kin}}(z)$$

kinematic dipole
per redshift

Redshift tomography — Selection functions

SvH & Dalang (2025)



$$W_b(z) = \int_{z_1}^{z_2} dz' P(z', z)$$

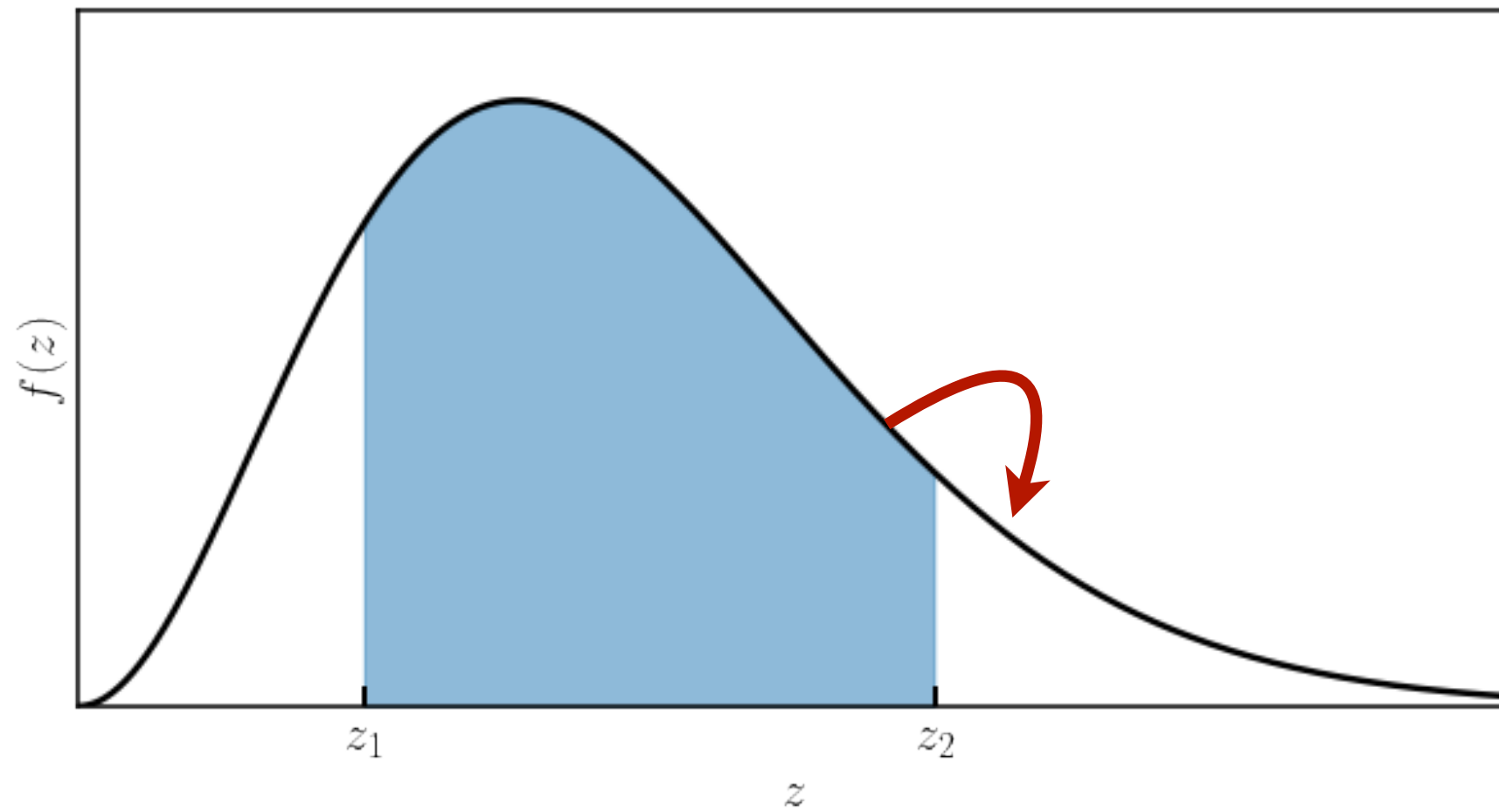
**Top-hat in phot- z
gives selection
 W_b in spec- z**

**Redshift
distribution**

$$n_b(z) = n(z) W_b(z)$$

Redshift tomography — Selection functions

SvH & Dalang (2025)



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 W_b in spec- z**

**Redshift
distribution**

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$$\mathcal{D}_{\text{kin}} = \left[2 + \tilde{x}(1 + \tilde{\alpha}) - \int_0^\infty dz f_b(z) \frac{d \log W(z)}{d \log(1 + z)} \right] \beta$$

Influence by higher multipoles

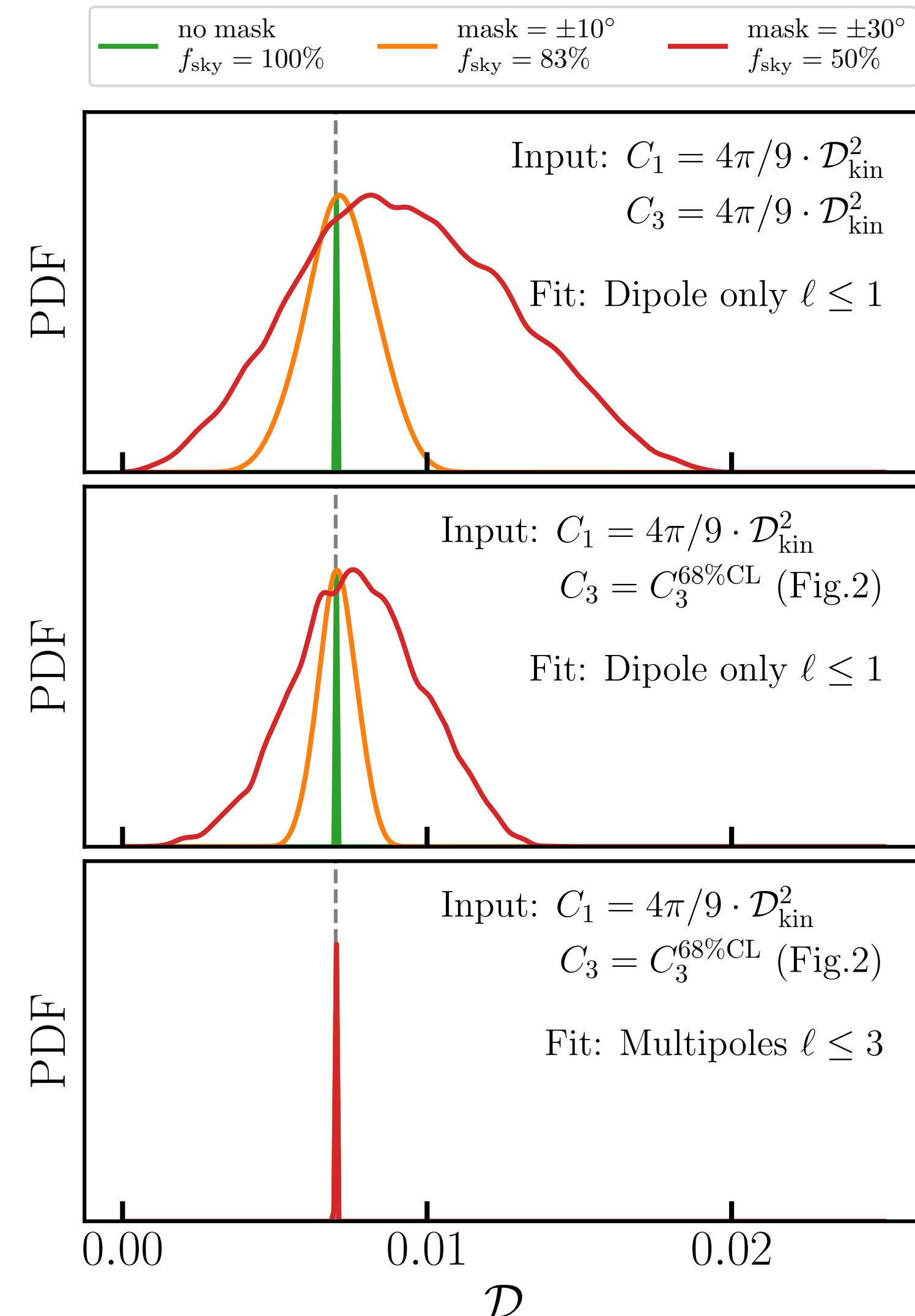
Concern by Abghari et al. (2025)

- Quadrupoles and octupoles might bias dipole measurement (due to mask)
- Least-squares estimator like analyses in Secrest et al. (2021,2022)
- Simulate via Poisson mocks including dipole expectation + quadrupole and octupole
- Claim: no influence by quadrupole, large influence by octupole.

Our response

SvH et al. (2025)

- Template fits show no evidence for octupole power in data (see power spectrum)
- Abghari assume $C_3 = C_{1,\text{kin}}$ but in fact $C_3 \lesssim \frac{1}{3}C_{1,\text{kin}}$
- Solution: just fit for higher multipoles too...



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