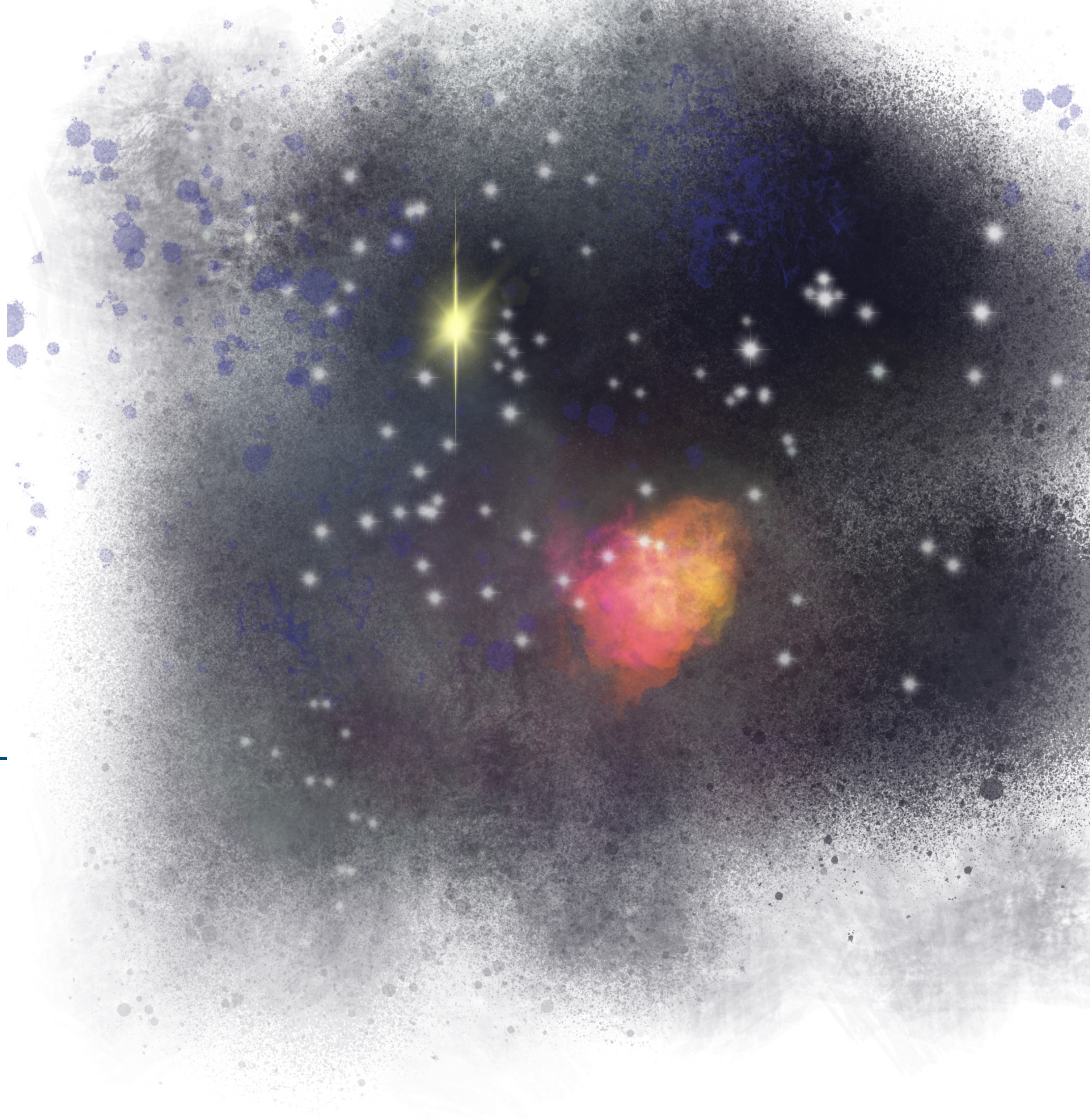
SKA Cosmology SWG meeting, Nov 4th, 2024
Observatoire de la Côte d'Azur

# Testing the Cosmological Principle with the SKA

Sebastian von Hausegger
Oxford Physics

UNIVERSITY OF OXFORD



# The Cosmological Principle and FLRW

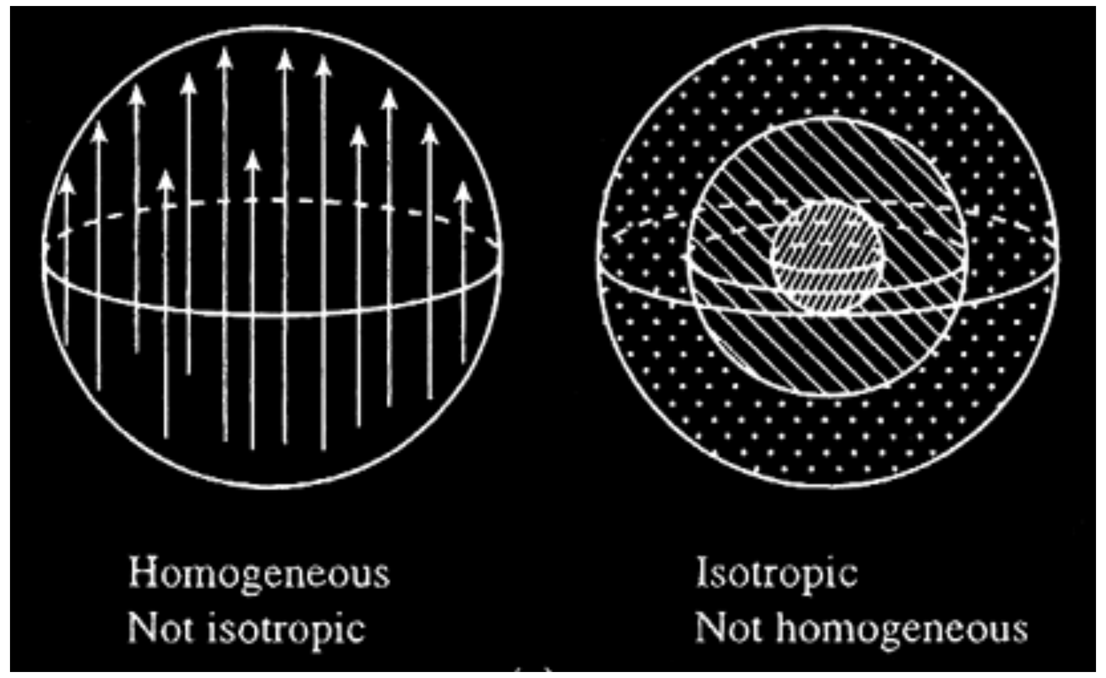
**LCDM cosmological standard model based on FLRW metric**

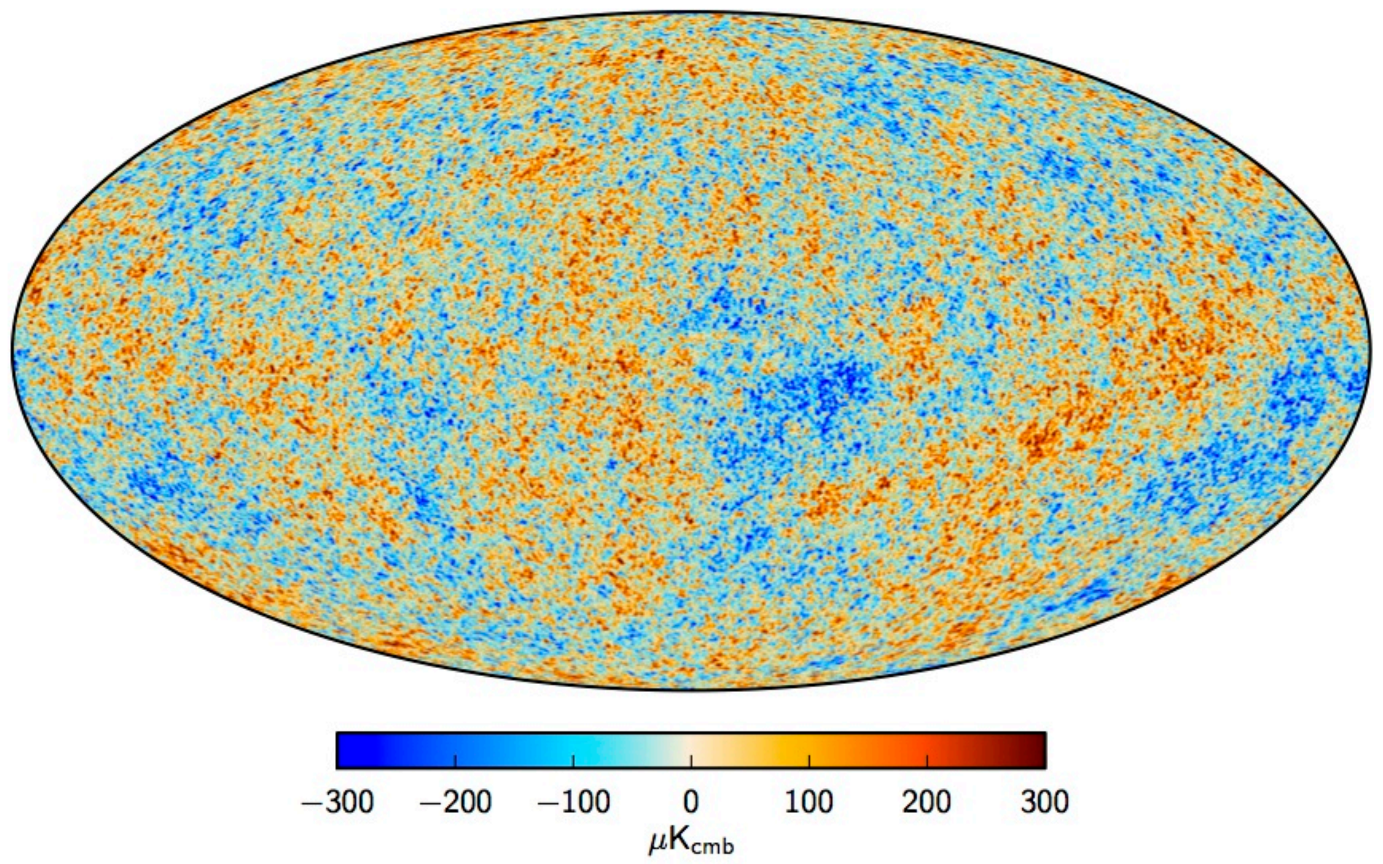
**Relies on Cosmological Principle**

**Milne (1937)**
**deSitter (1934)**

"All physical quantities measured by a comoving observer are spatially homogeneous and isotropic."

**Schwarz (2009)**




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

**Tauber&Weinberg (1961)**
**Ehlers et al. (1968)**

# The Cosmological Principle and FLRW

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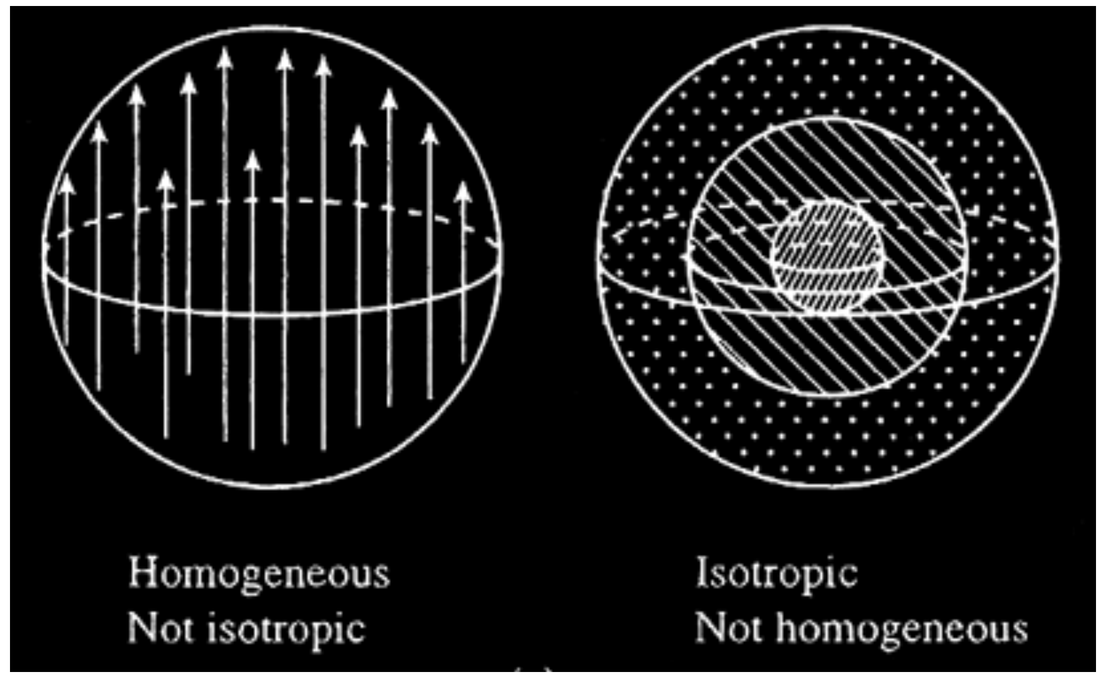
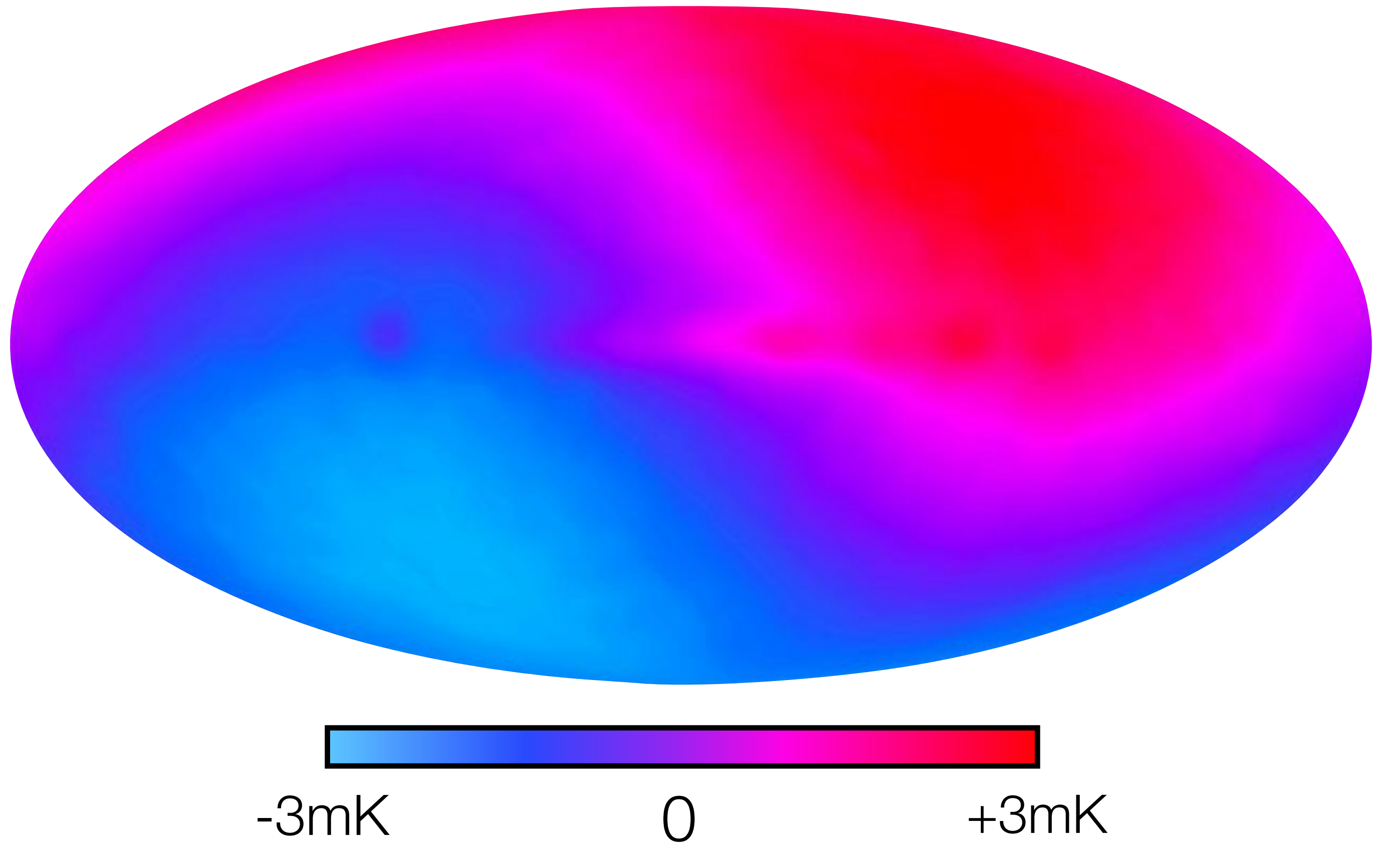



**We are not comoving observers:**

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

# The kinematic matter dipole anomaly

$$\mathscr{D} = [2 + x(1+\alpha)] \cdot \beta$$

For radio sources we find $x \approx 1$ and $\alpha \approx 0.75$

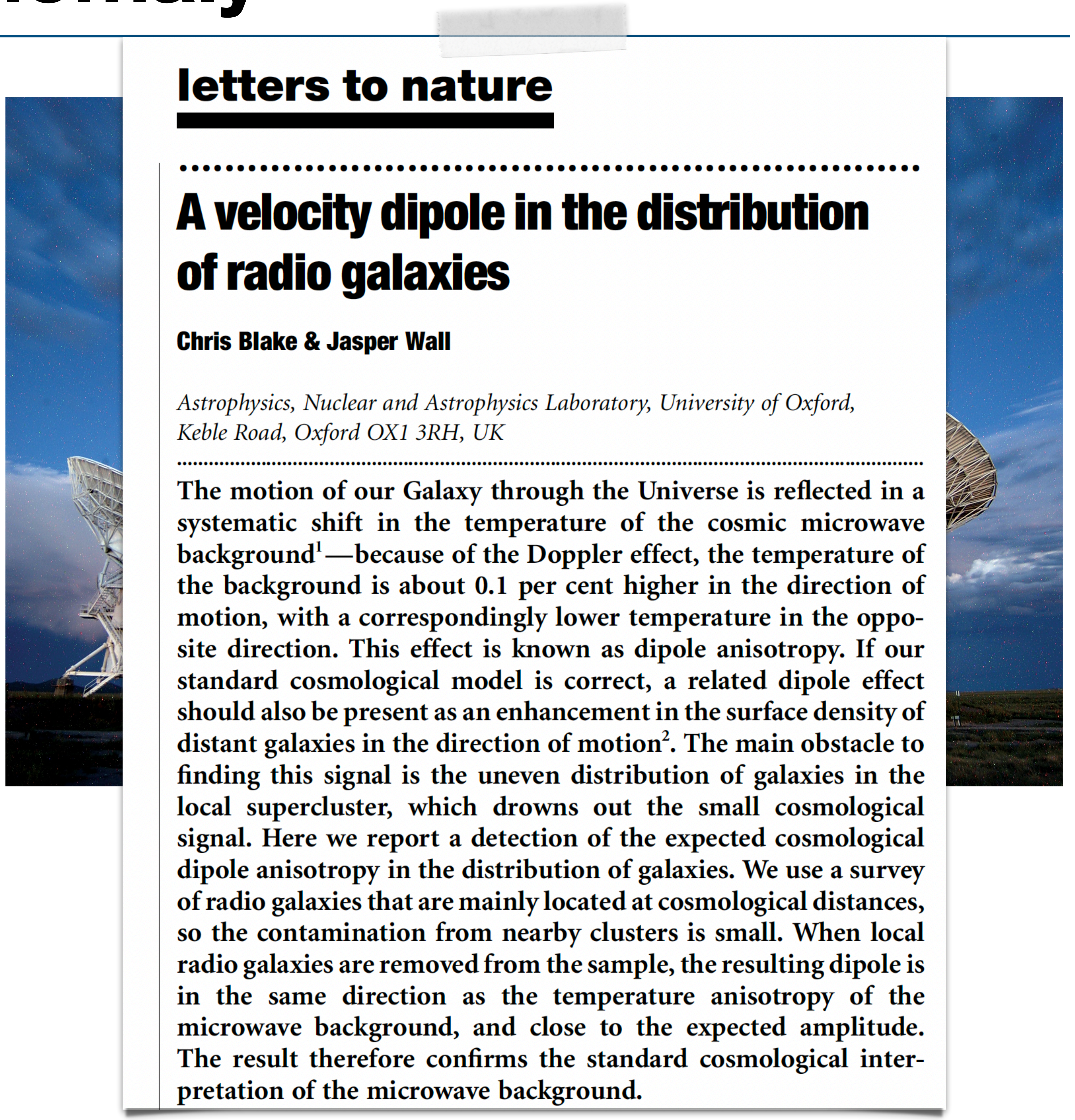
&

Our (sun's) velocity wrt the CMB is 369km/s

$$\Rightarrow \qquad \mathscr{D} \approx 4.6 \times 10^{-3}$$

**But Blake&Wall measure** $\mathscr{D}_{BW} \approx 1.1 \times 10^{-2}$

(at S>25 mJy, with ~large uncertainties, and with ~200,000 sources)



**letters to nature**

## A velocity dipole in the distribution of radio galaxies

**Chris Blake & Jasper Wall**

*Astrophysics, Nuclear and Astrophysics Laboratory, University of Oxford, Keble Road, Oxford OX1 3RH, UK*

The motion of our Galaxy through the Universe is reflected in a systematic shift in the temperature of the cosmic microwave background[1]—because of the Doppler effect, the temperature of the background is about 0.1 per cent higher in the direction of motion, with a correspondingly lower temperature in the opposite direction. This effect is known as dipole anisotropy. If our standard cosmological model is correct, a related dipole effect should also be present as an enhancement in the surface density of distant galaxies in the direction of motion[2]. The main obstacle to finding this signal is the uneven distribution of galaxies in the local supercluster, which drowns out the small cosmological signal. Here we report a detection of the expected cosmological dipole anisotropy in the distribution of galaxies. We use a survey of radio galaxies that are mainly located at cosmological distances, so the contamination from nearby clusters is small. When local radio galaxies are removed from the sample, the resulting dipole is in the same direction as the temperature anisotropy of the microwave background, and close to the expected amplitude. The result therefore confirms the standard cosmological interpretation of the microwave background.

# The kinematic matter dipole anomaly

The Astrophysical Journal Letters, 742:L23 (4pp), 2011 December 1 doi: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
Astrono

*Astronomy & Astrophysics* manuscript no. NVSS˙dipole
January 16, 2018


**Cosmic radio dipole from NVSS and WENSS**

Matthias Rubart⋆, Dominik J. Schwarz⋆⋆

The Astrophysical Journal Letters, 908:L51 (6pp), 2021 February 20 https://doi.org/10.3847/2041-8213/abdd40

OPEN ACCESS
CrossMark

A Test of the Cosmological Principle with Quasars

Nathan J. Secrest[1], Sebastian von Hausegger[2,3,4], Mohamed Rameez[5], Roya Mohayaee[3], Subir Sarkar[4], and Jacques Colin[3]

The Astrophysical Journal Letters, 937:L31 (9pp), 2022 October 1 https://doi.org/10.3847/2041-8213/ac88c0

OPEN ACCESS
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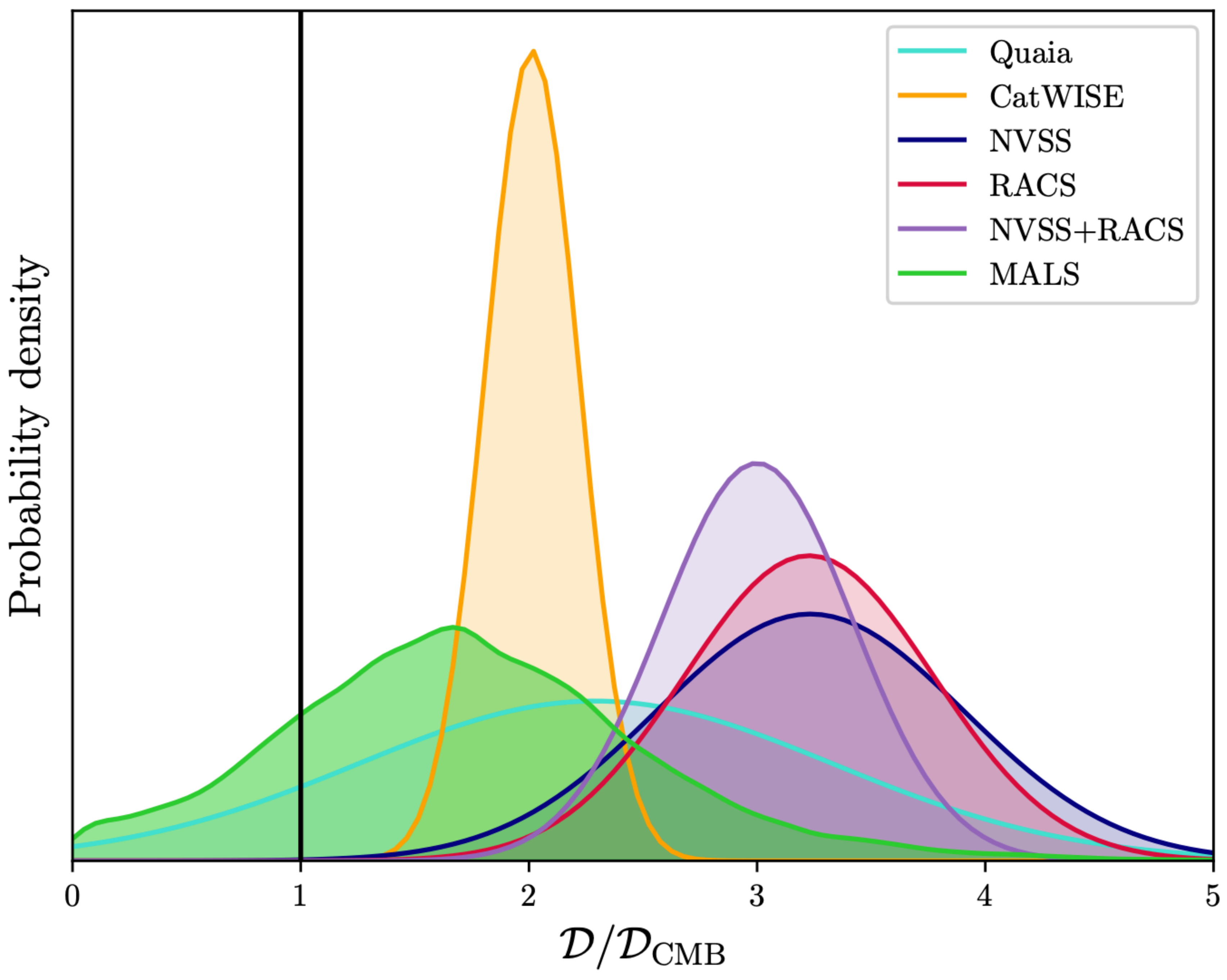
A Challenge to the Standard Cosmological Model

Nathan J. Secrest[1], Sebastian von Hausegger[2], Mohamed Rameez[3], Roya Mohayaee[2,4], and Subir Sarkar[2]
[1] U.S. Naval Observatory, 3450 Massachusetts Ave. NW, Washington, DC 20392-5420, USA; nathan.j.secrest.civ@us.navy.mil
[2] Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, UK
[3] Dept. of High Energy Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India
[4] Sorbonne Université, CNRS, Institut d'Astrophysique de Paris, 98bis Bld Arago, Paris F-75014, France
*Received 2022 June 10; revised 2022 August 9; accepted 2022 August 11; published 2022 September 28*




Wagenveld et al. (2024)

# The kinematic matter dipole

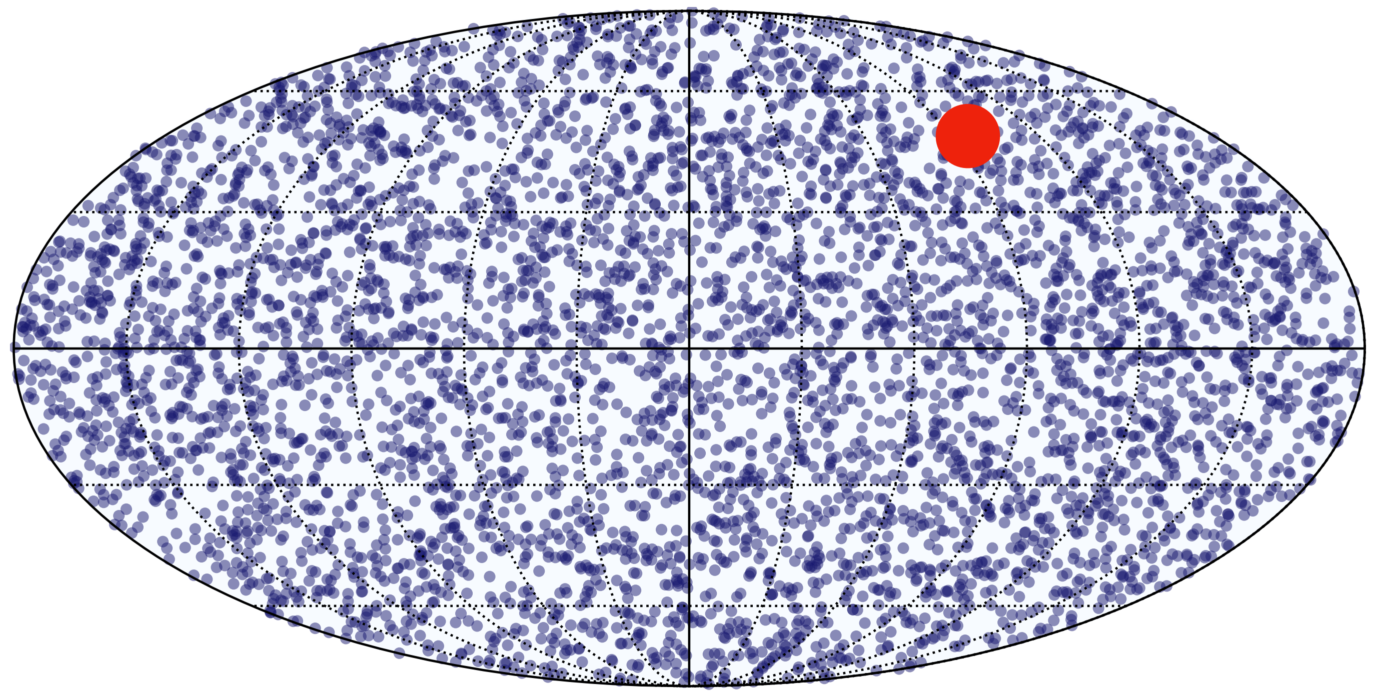
Ellis & Baldwin (1984)

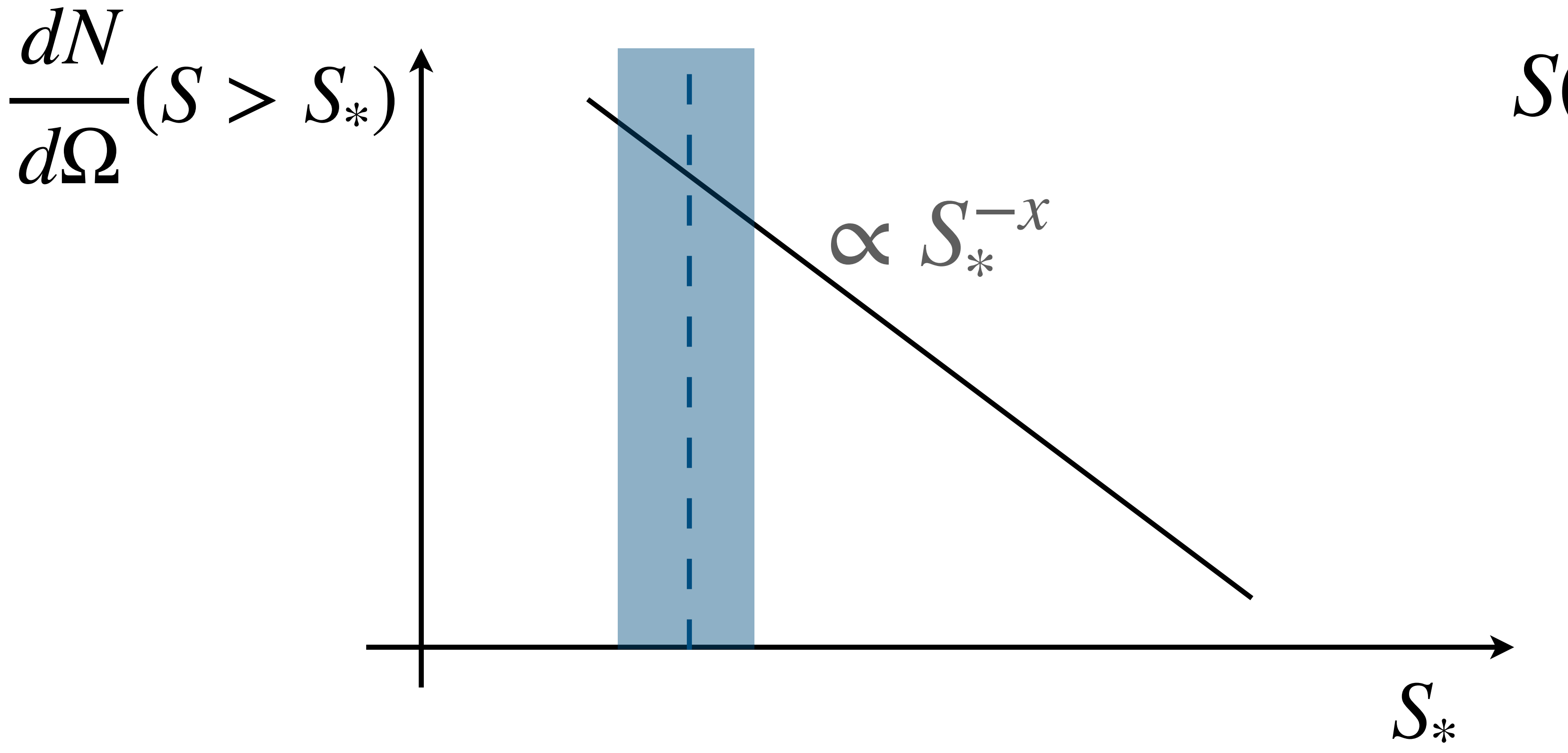
**Average spectral index of source spectra**

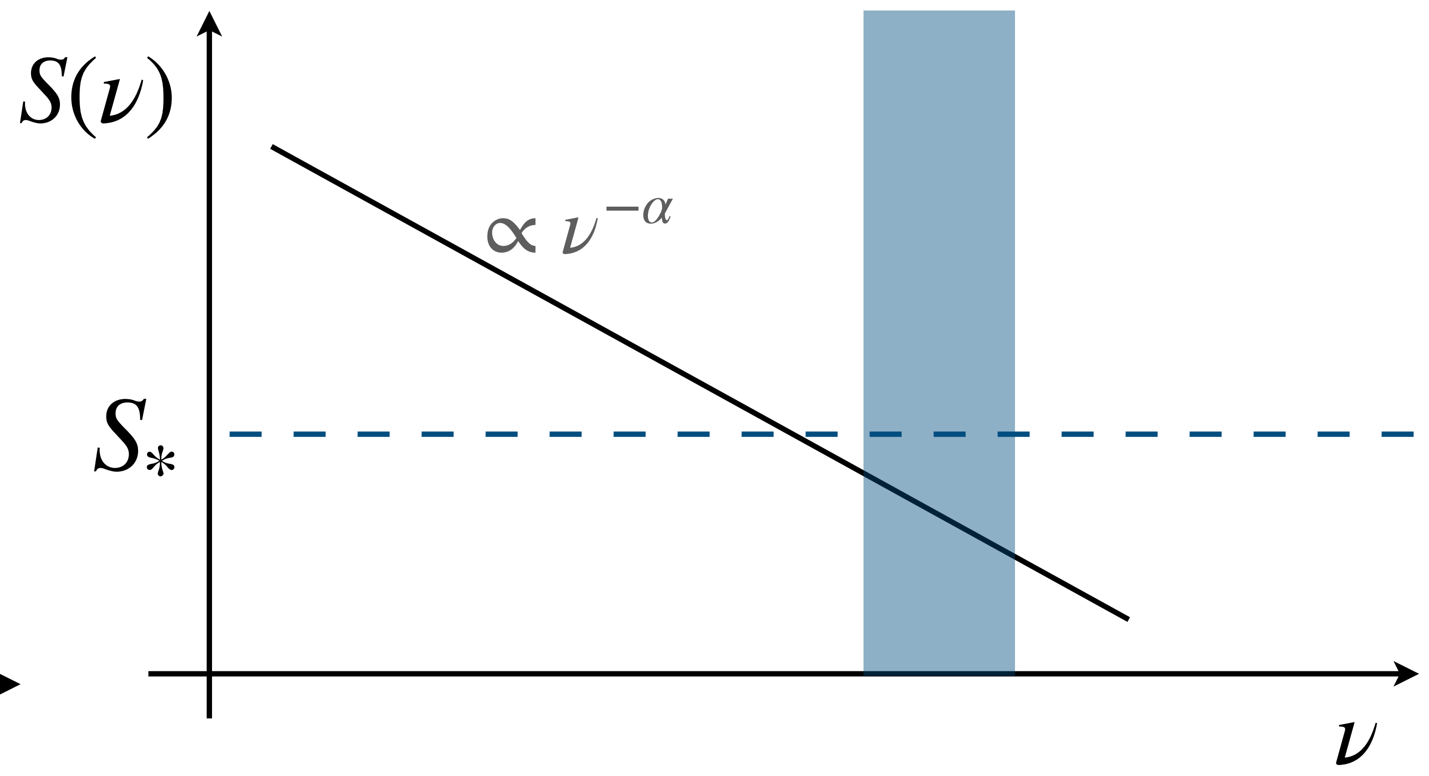
$$\tilde{\mathscr{D}} = \left[2 + \tilde{x}(1 + \tilde{\alpha})\right] \beta$$

**Related to magnification bias**

**"Tilde" quantities refer to what we measure (without redshifts!)**





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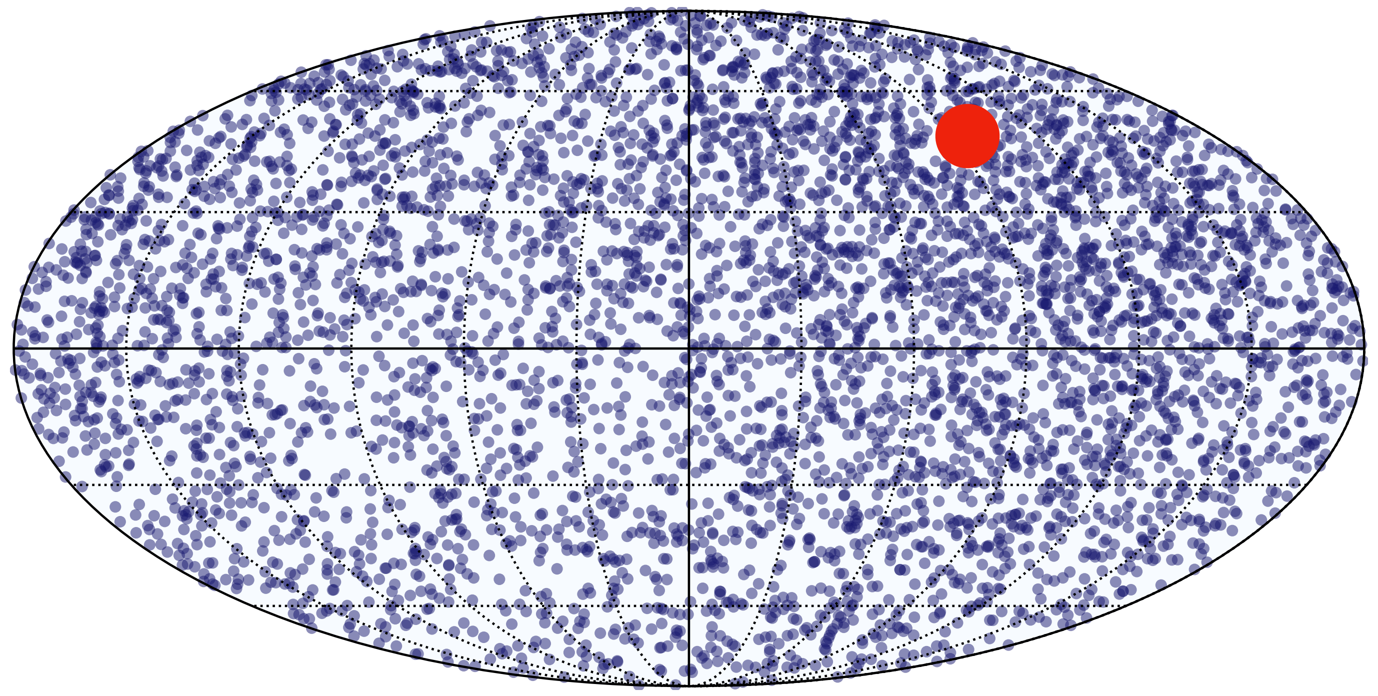

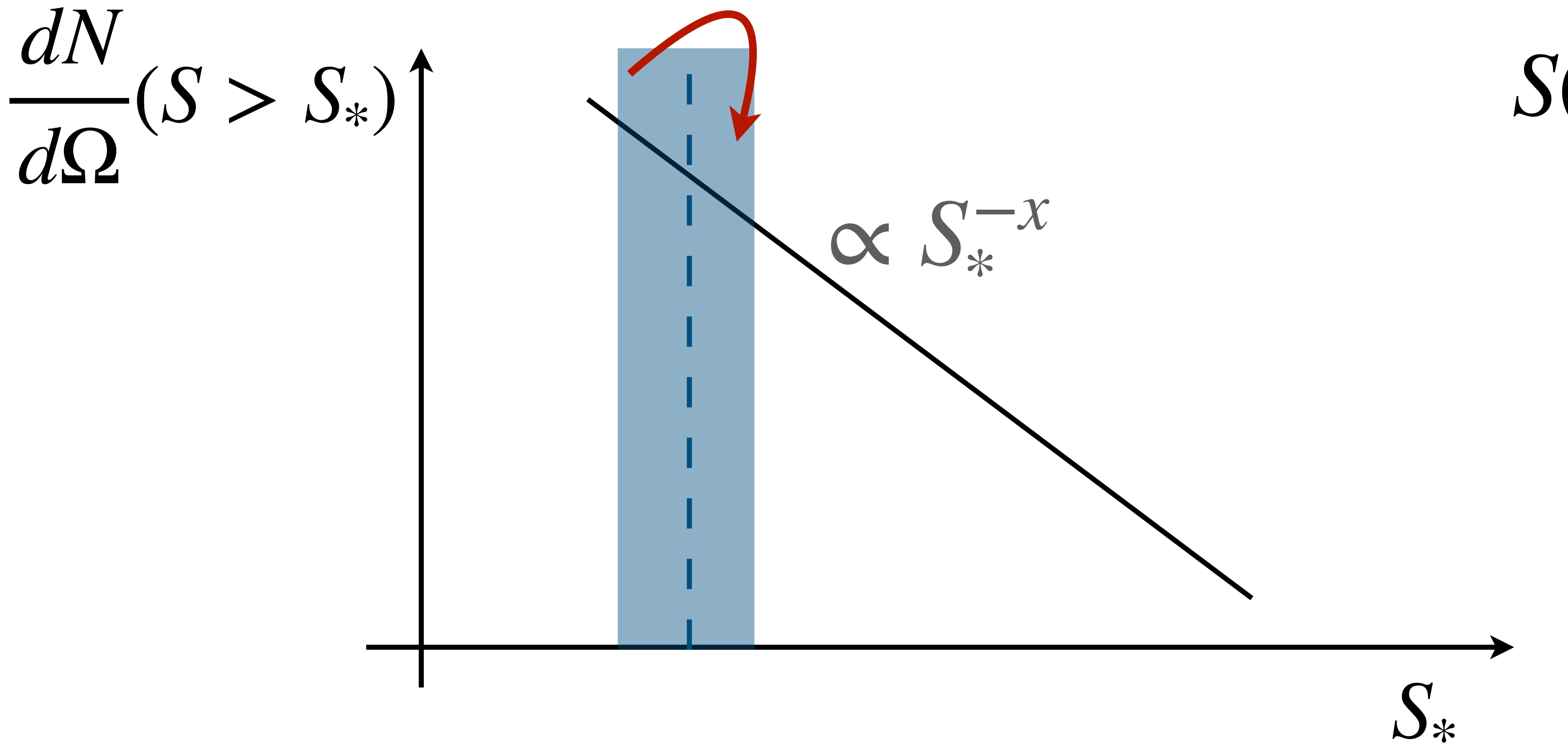


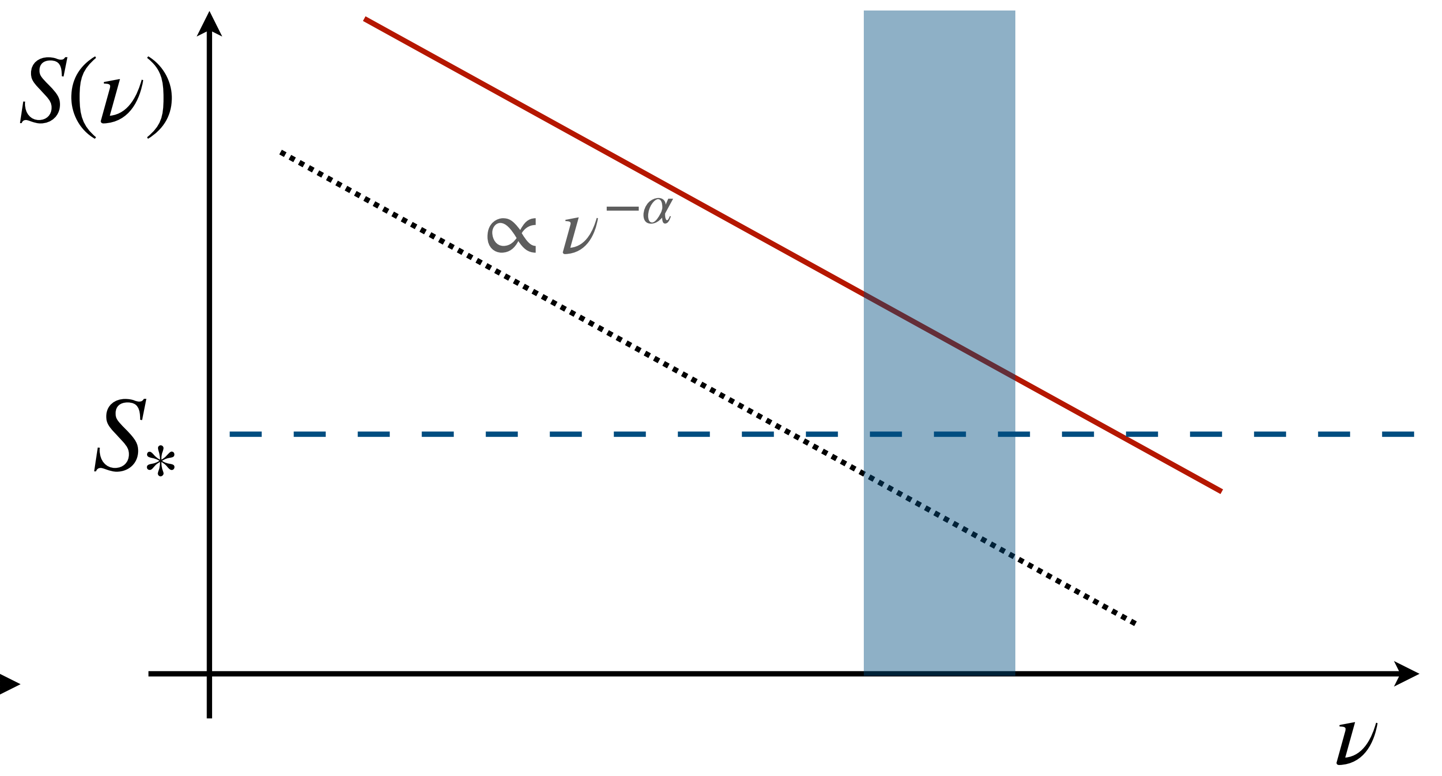

# Redshift dependence

Ellis & Baldwin (1984)

**Average** spectral index of source spectra

$$\tilde{\mathscr{D}} = \left[2 + \tilde{x}(1 + \tilde{\alpha})\right] \beta$$

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

$$\mathscr{D} = \int_0^\infty \mathrm{d}z \, f(z) \mathscr{D}(z)$$

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

**(normalised) redshift distribution**

$$\mathscr{D} = \int_0^\infty \mathrm{d}z\, f(z) \mathscr{D}(z)$$

**kinematic dipole per redshift**

# Redshift dependence

Ellis & Baldwin (1984)

$$\tilde{\mathscr{D}} = \left[2 + \tilde{x}(1 + \tilde{\alpha})\right] \beta$$

**Are the observed quantities enough to predict the dipole correctly?**

Maartens et al. (2017)

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

**See also, Dalang & Bonvin (2022)**

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$$\mathscr{D} = \int_0^\infty \mathrm{d}z\, f(z) \mathscr{D}(z)$$

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Nadolny et al. (2021)

$$\mathscr{D}(z) = \left[3 + x(z)\big(1 + \alpha(z)\big) + \frac{\mathrm{d}\log n(z)}{\mathrm{d}\log(1+z)}\right] \beta$$

**See also, Dalang & Bonvin (2022)**

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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **535,** L49–L53 (2024) https://doi.org/10.1093/mnrasl/slae092
Advance Access publication 2024 September 26

**The expected kinematic matter dipole is robust against source evolution**

Sebastian von Hausegger ★
*Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK*

Accepted 2024 September 23. Received 2024 September 2; in original form 2024 July 29

**Yes!**

arXiv:2404.07929

**(normalised) redshift distribution**

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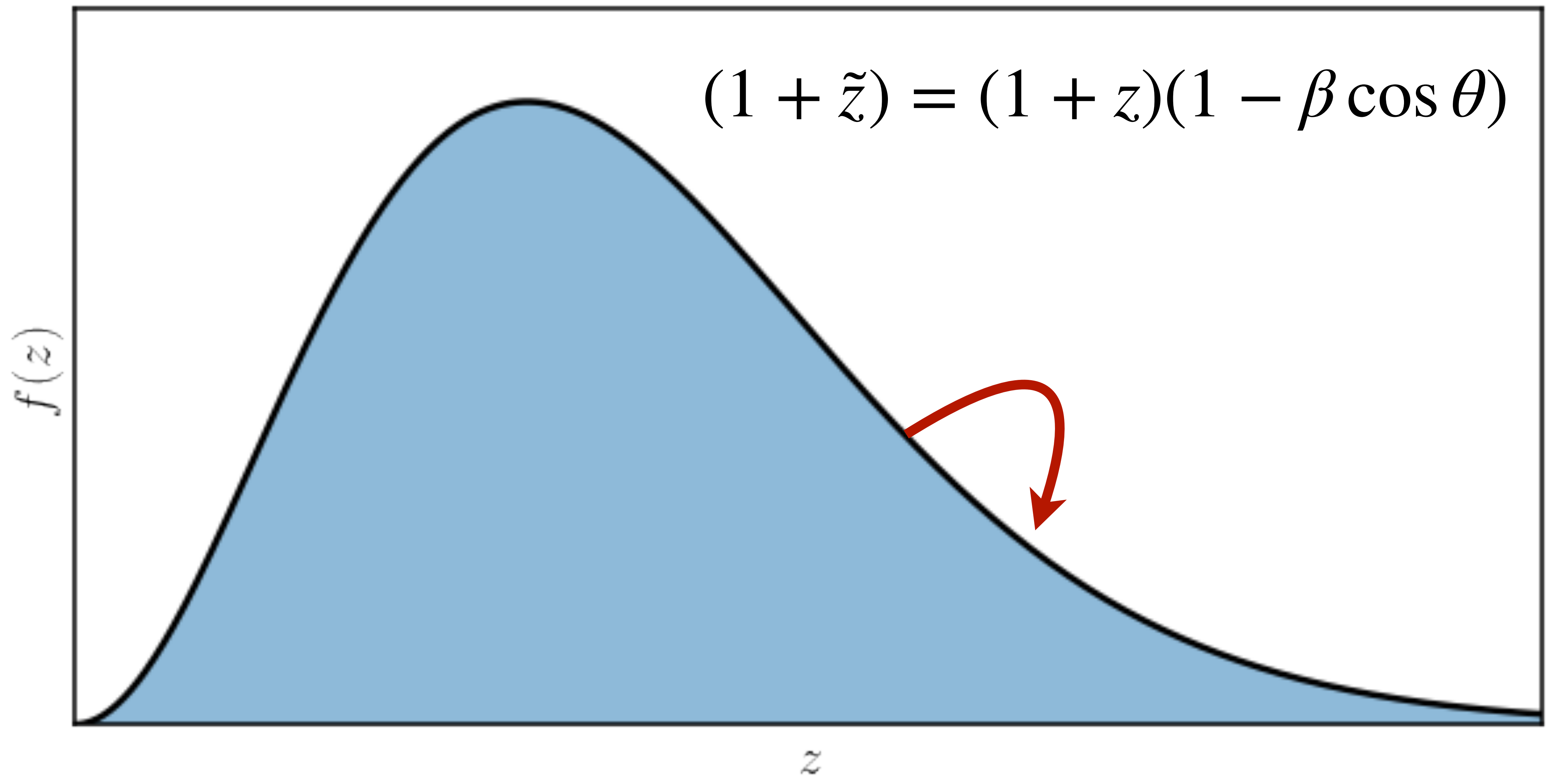
# Redshift dependence

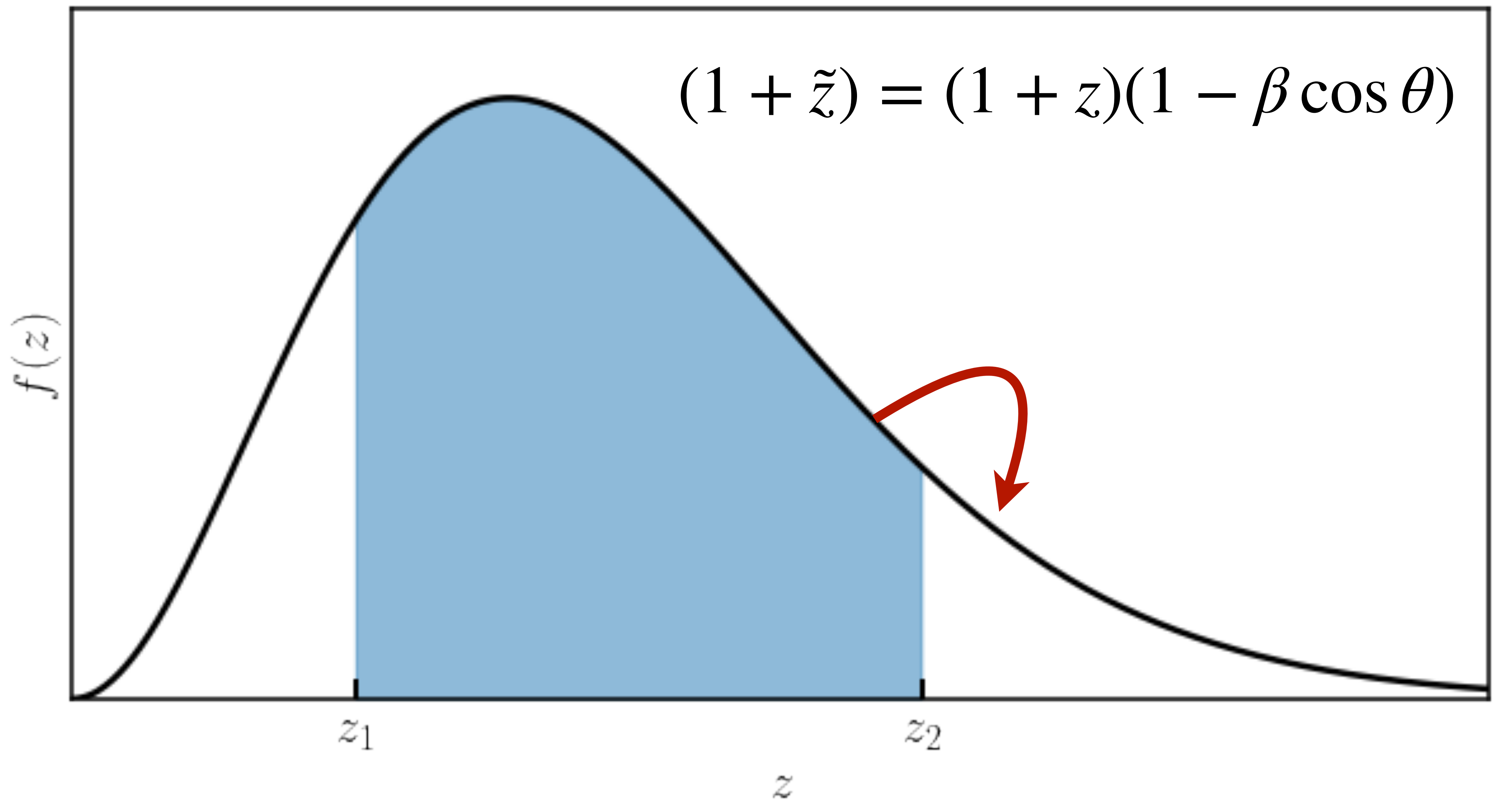



(normalised) redshift distribution

$$\mathscr{D} = \int_0^\infty \mathrm{d}z\, f(z)\mathscr{D}(z)$$

**kinematic dipole per redshift**

# Redshift dependence

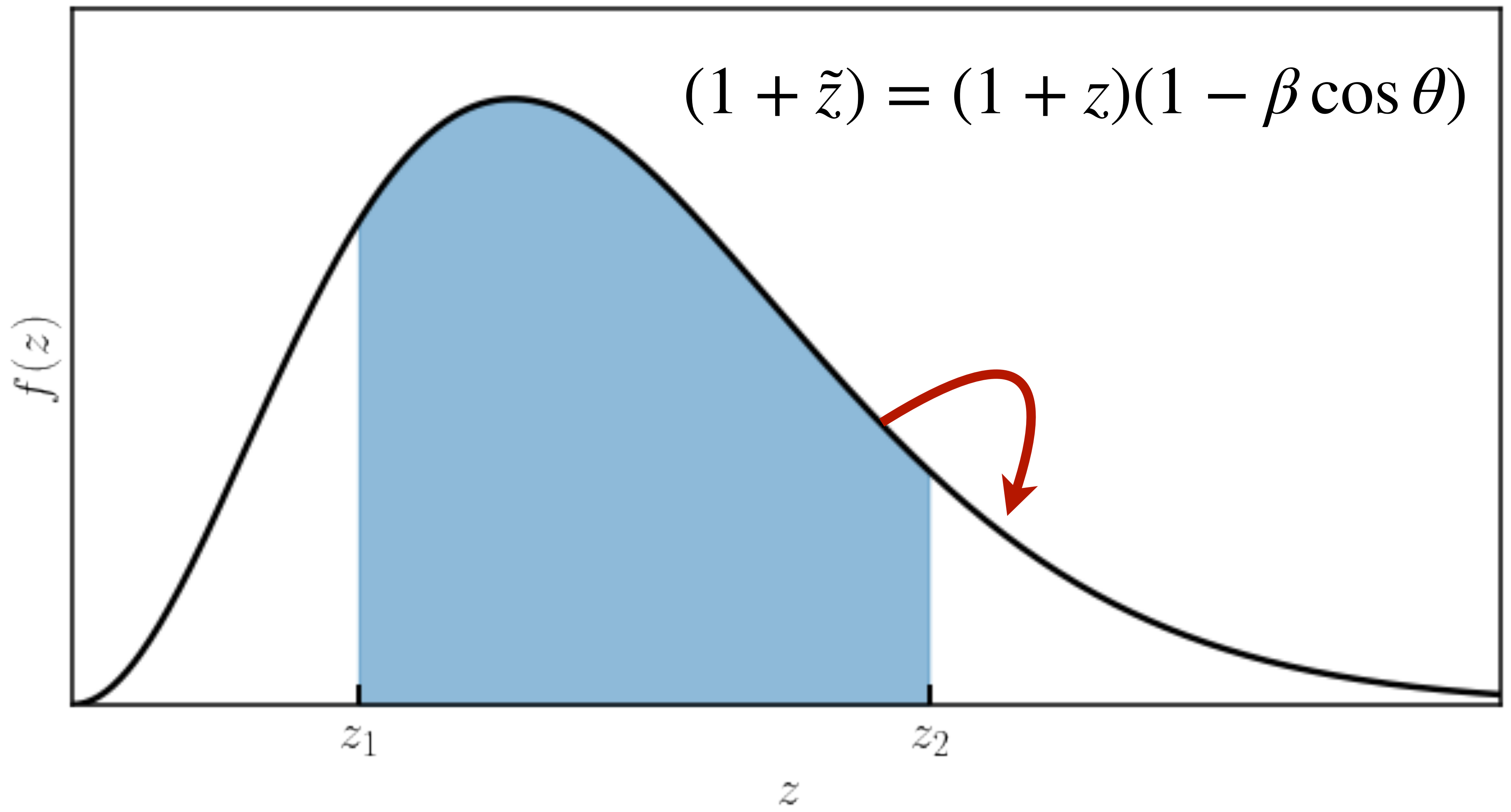



**(normalised) redshift distribution**

$$\mathscr{D} = \int_{z_1}^{z_2} \mathrm{d}z\, f_b(z) \mathscr{D}(z)$$

**kinematic dipole per redshift**

# Redshift dependence

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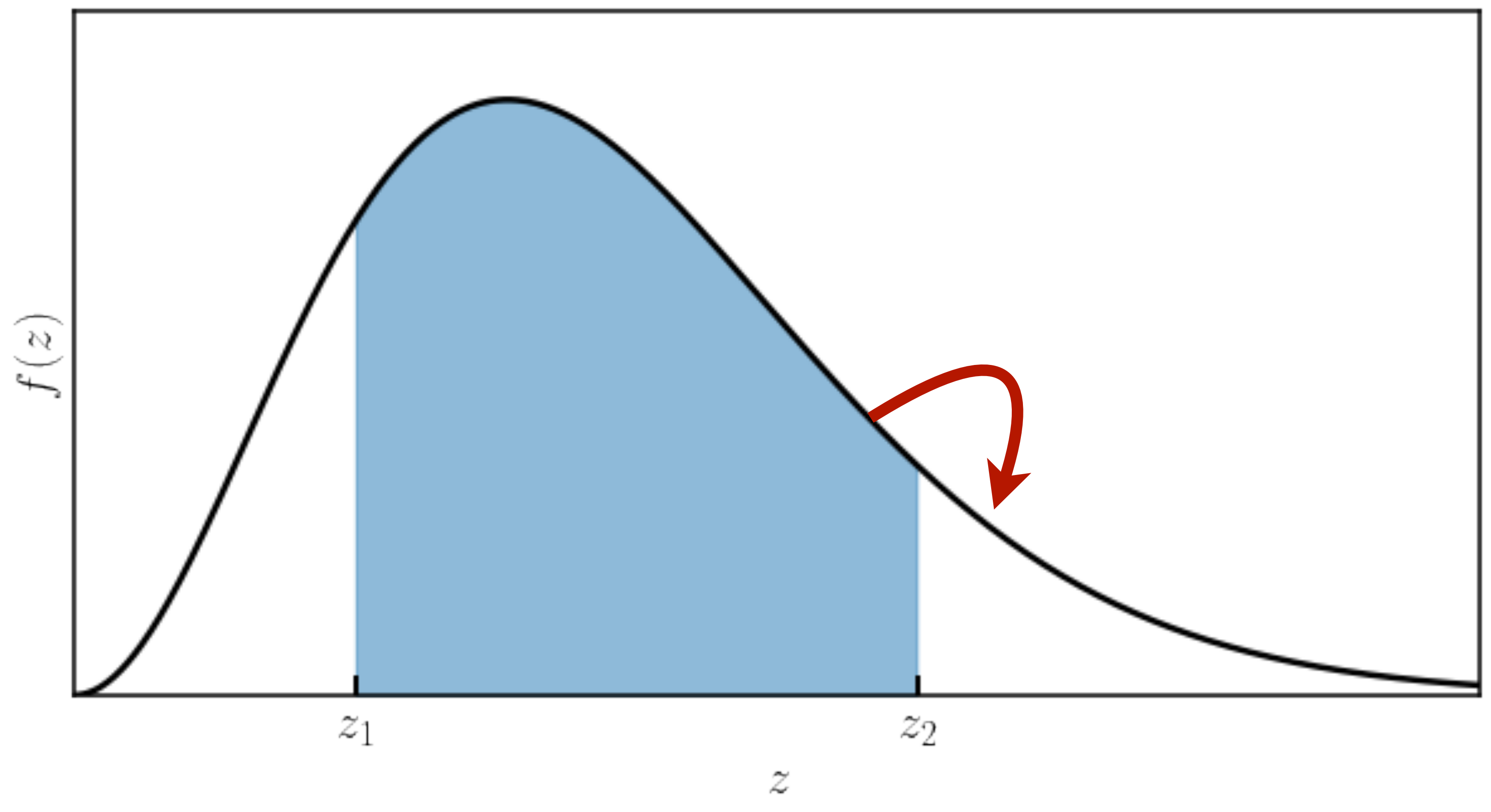
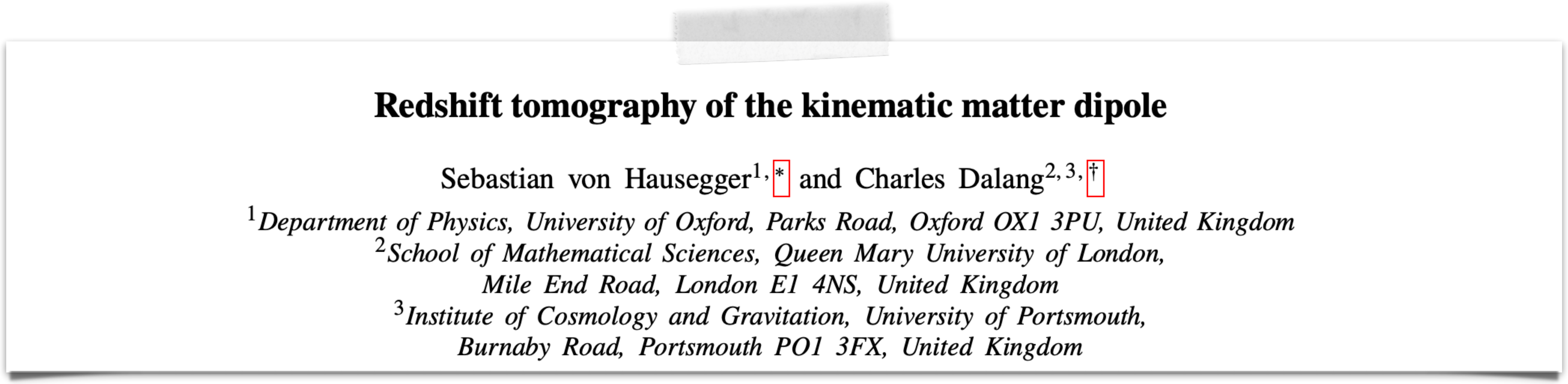
**(normalised) redshift distribution**

**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*



arXiv:2411.xxxx


(normalised) redshift distribution

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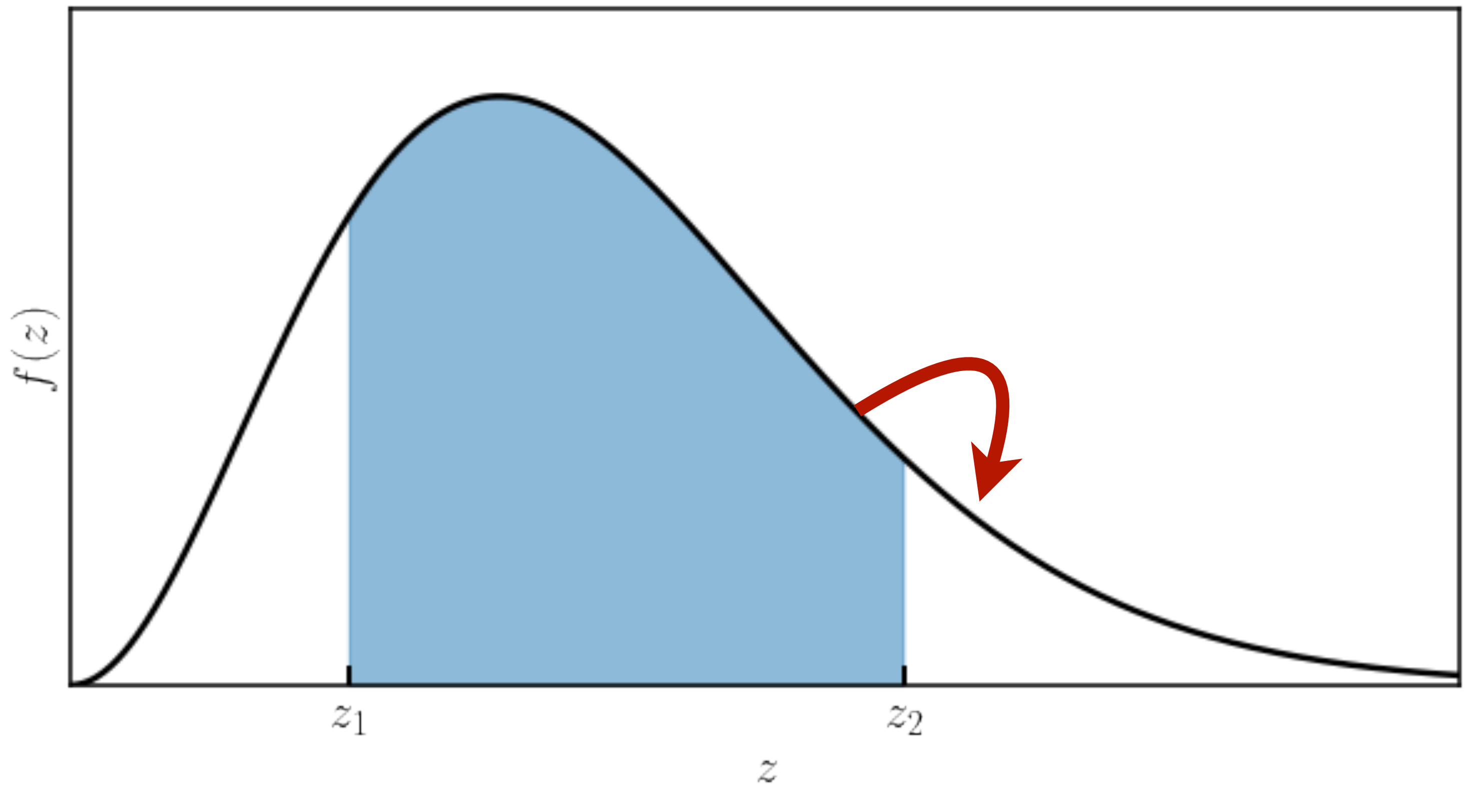
**kinematic dipole per redshift**

# Redshift tomography




Additional "boundary term"

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

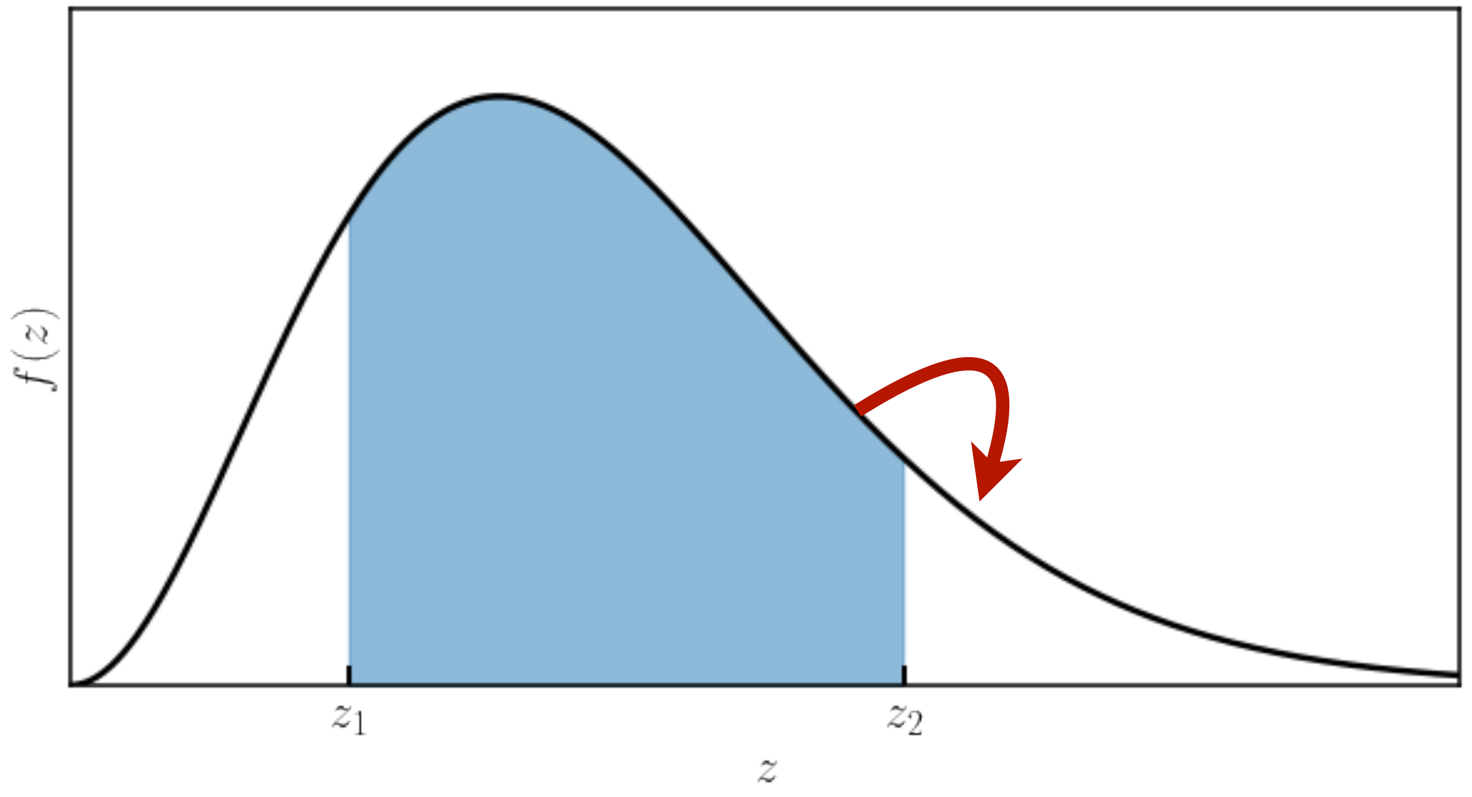
$$\equiv B(z_1, z_2)$$

(normalised) redshift distribution

$$\mathscr{D} = \int_{z_1}^{z_2} \mathrm{d}z\, f_b(z)\mathscr{D}(z)$$

kinematic dipole **per redshift**

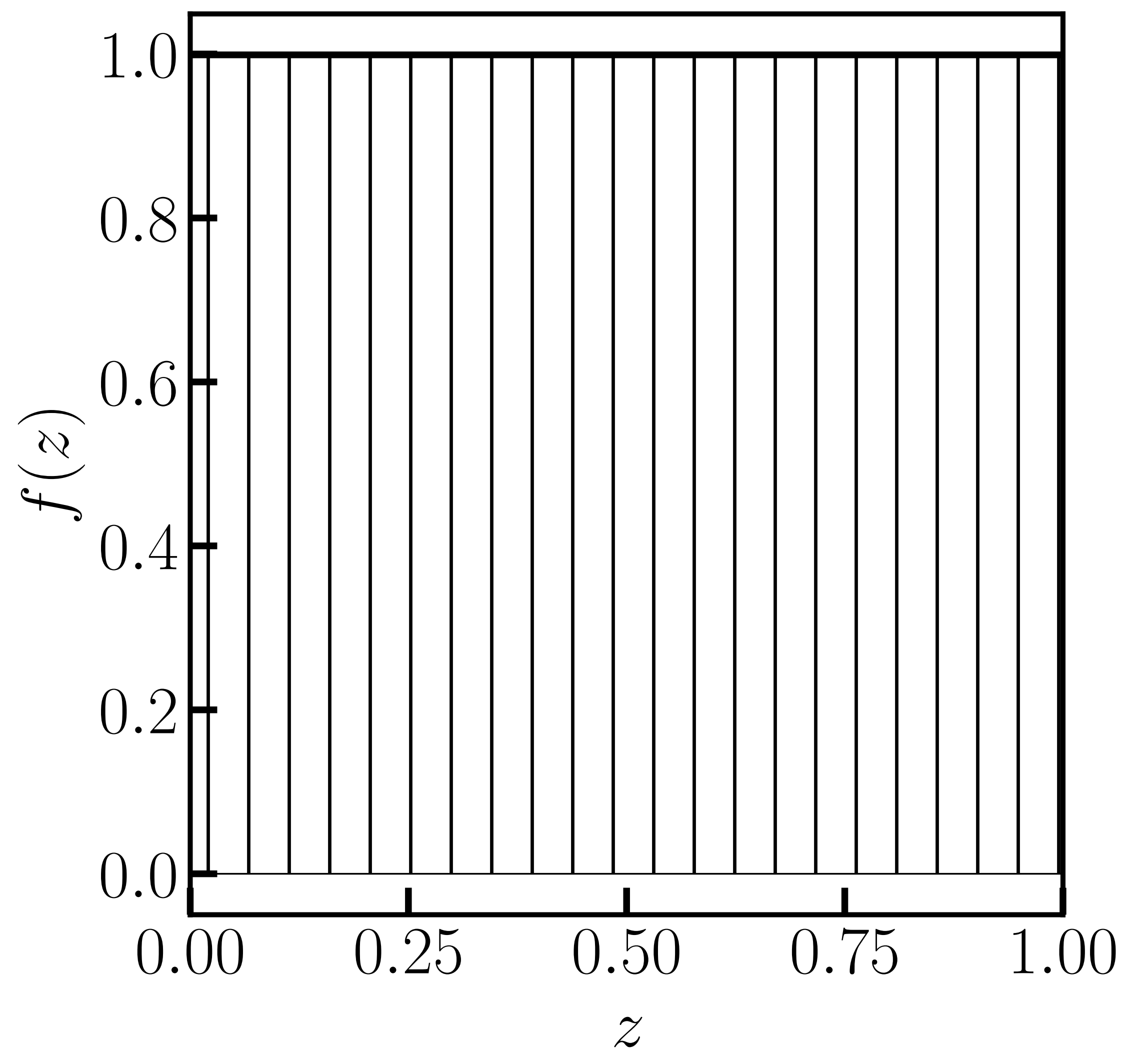
# Redshift tomography

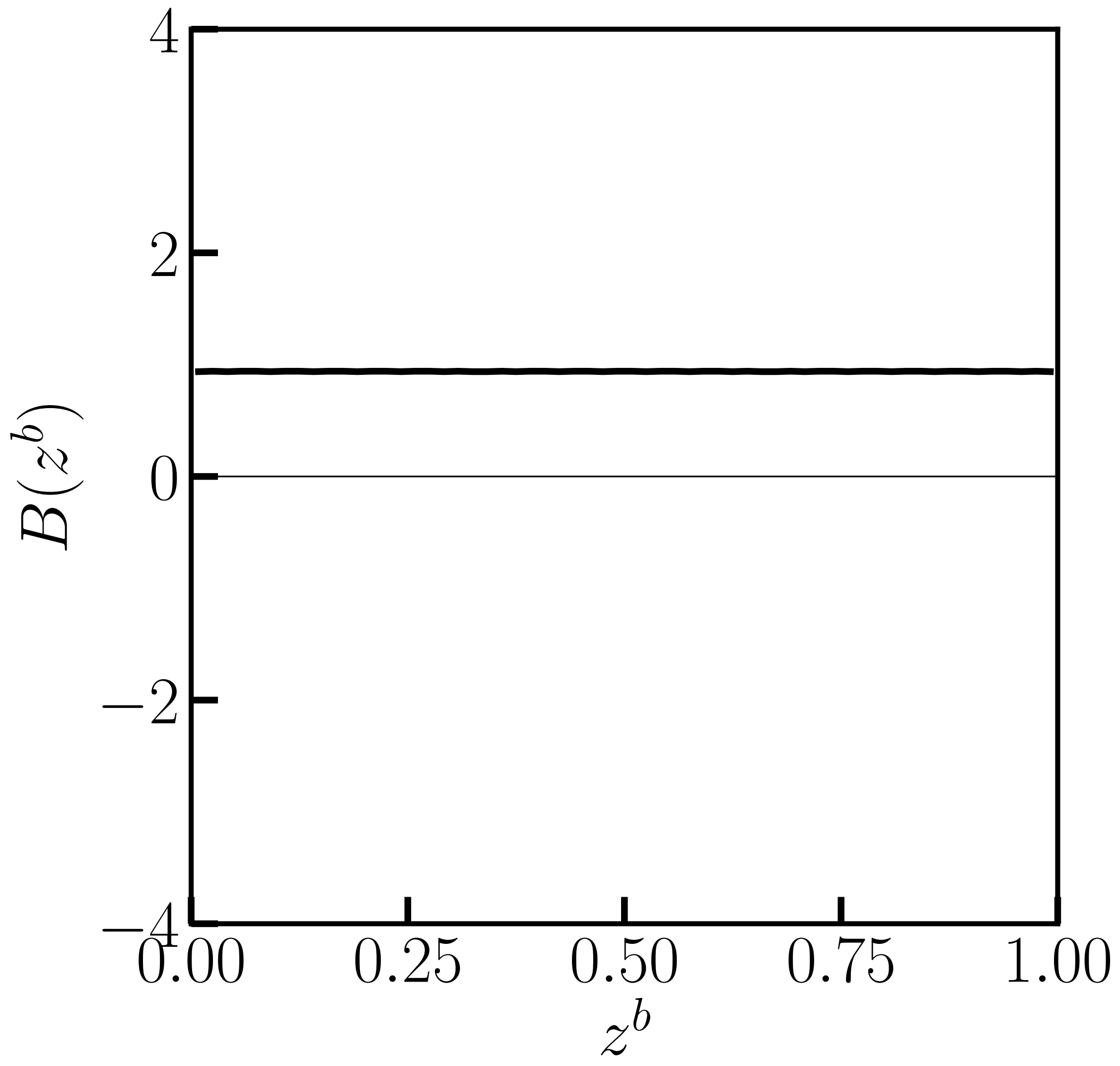



**Constant redshift distribution**

**Additional "boundary term"**

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



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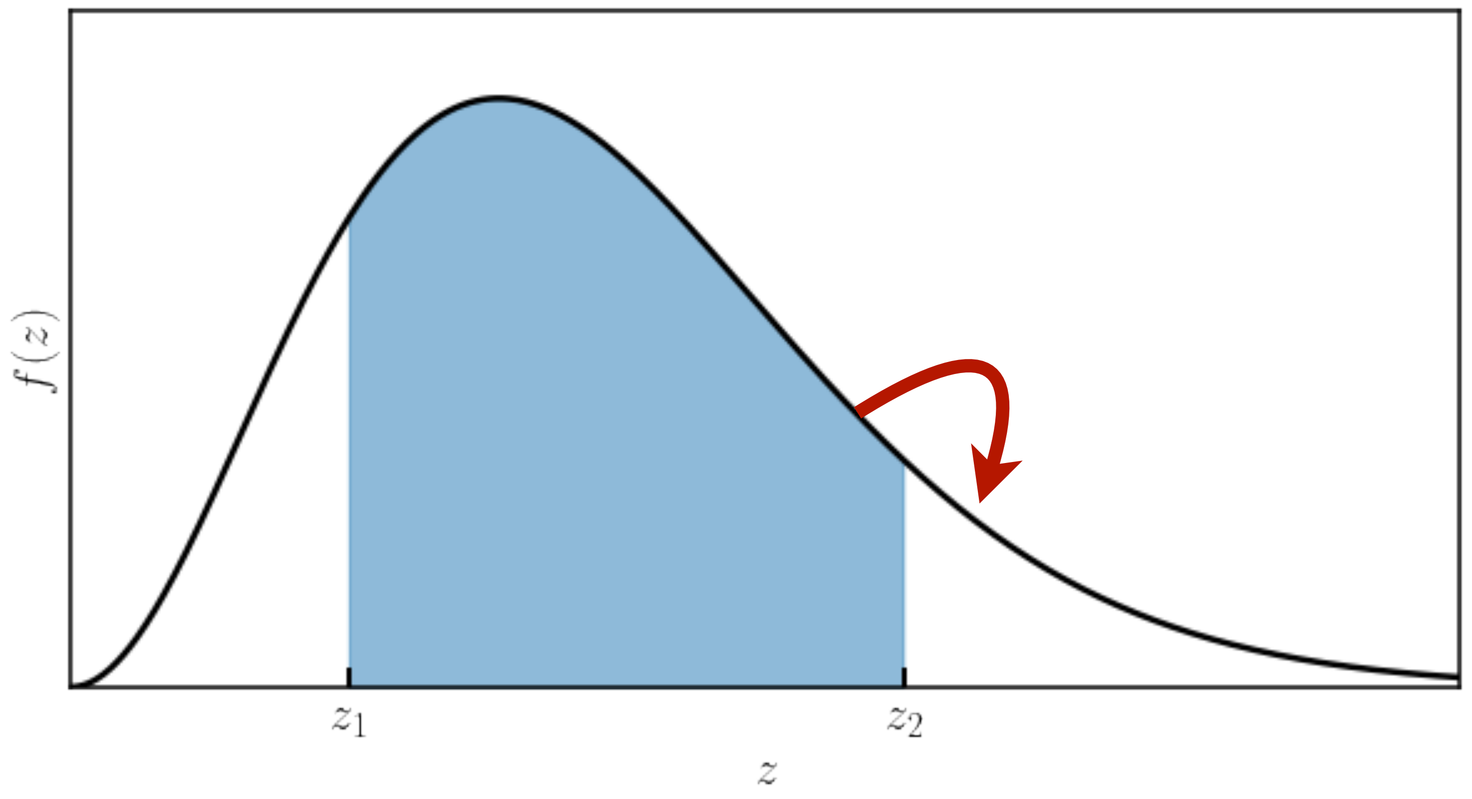
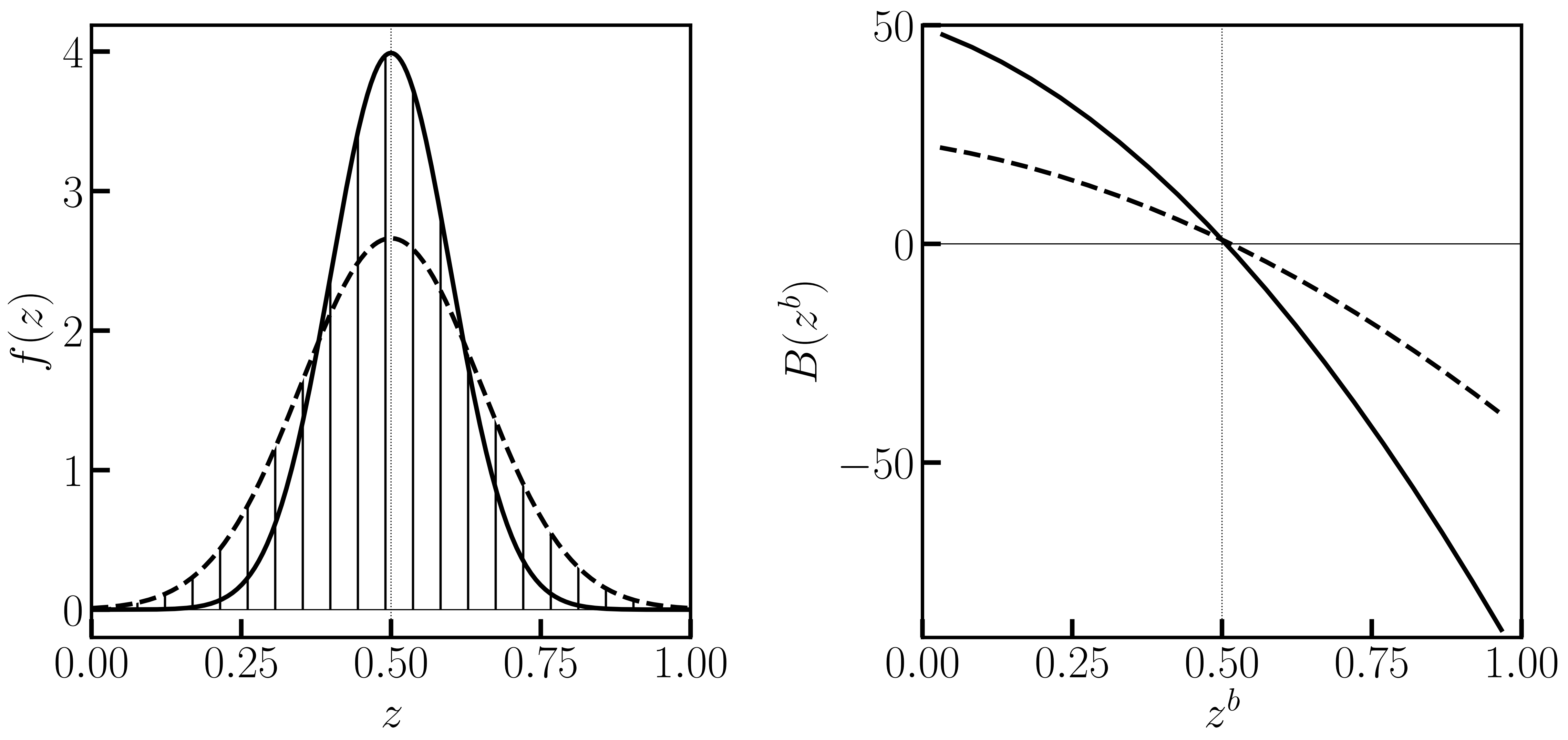
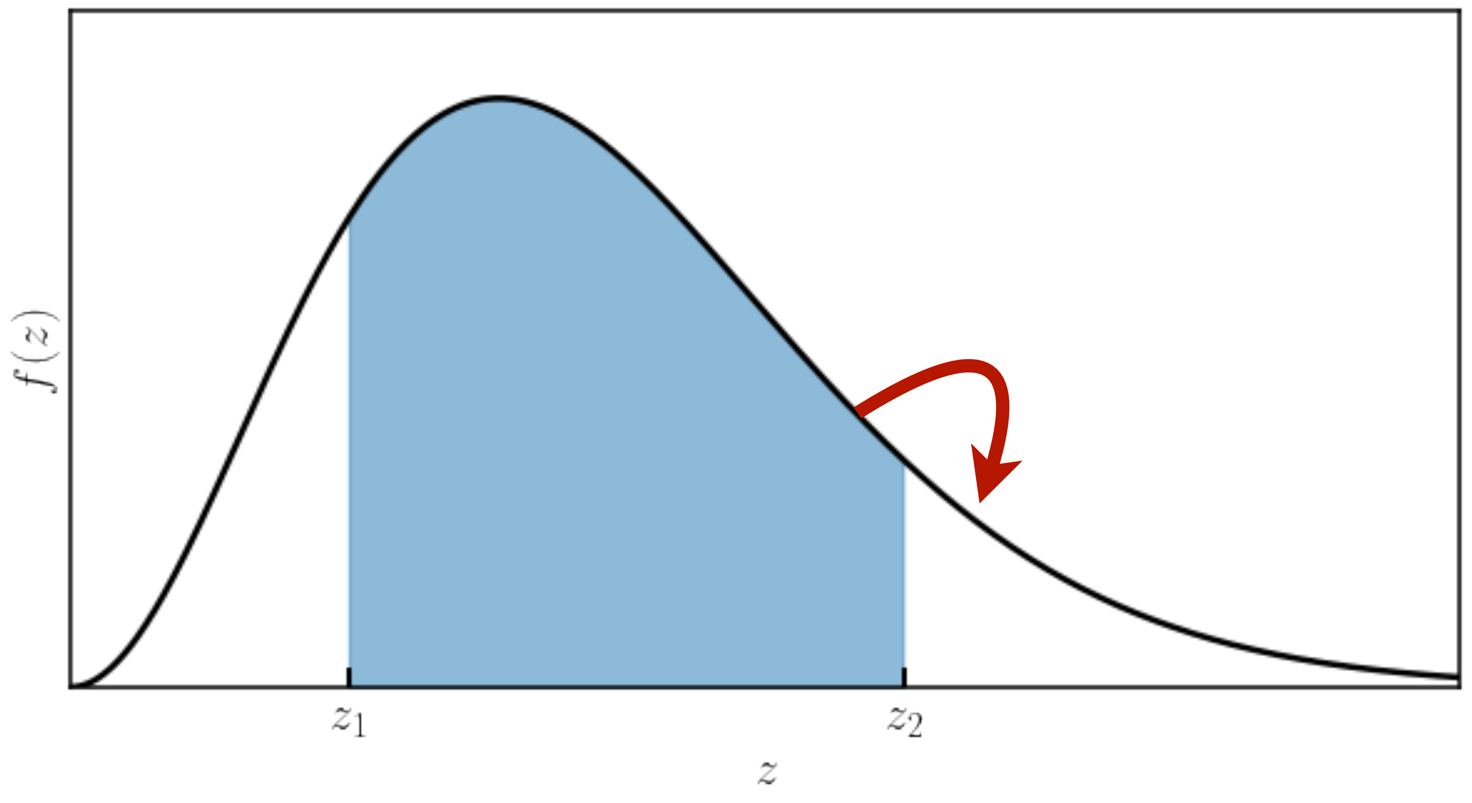



**Gaussian redshift distributions**



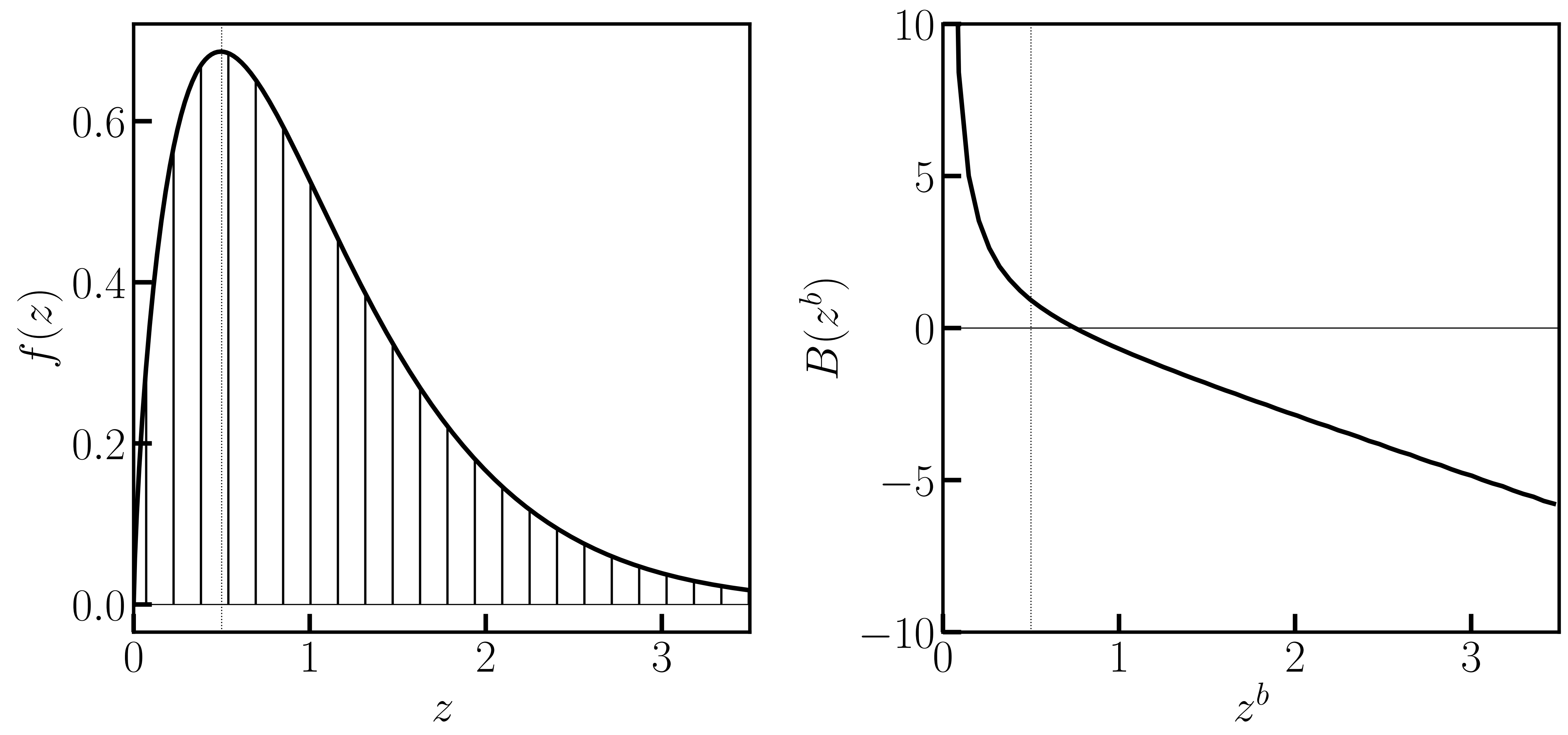
# Redshift tomography



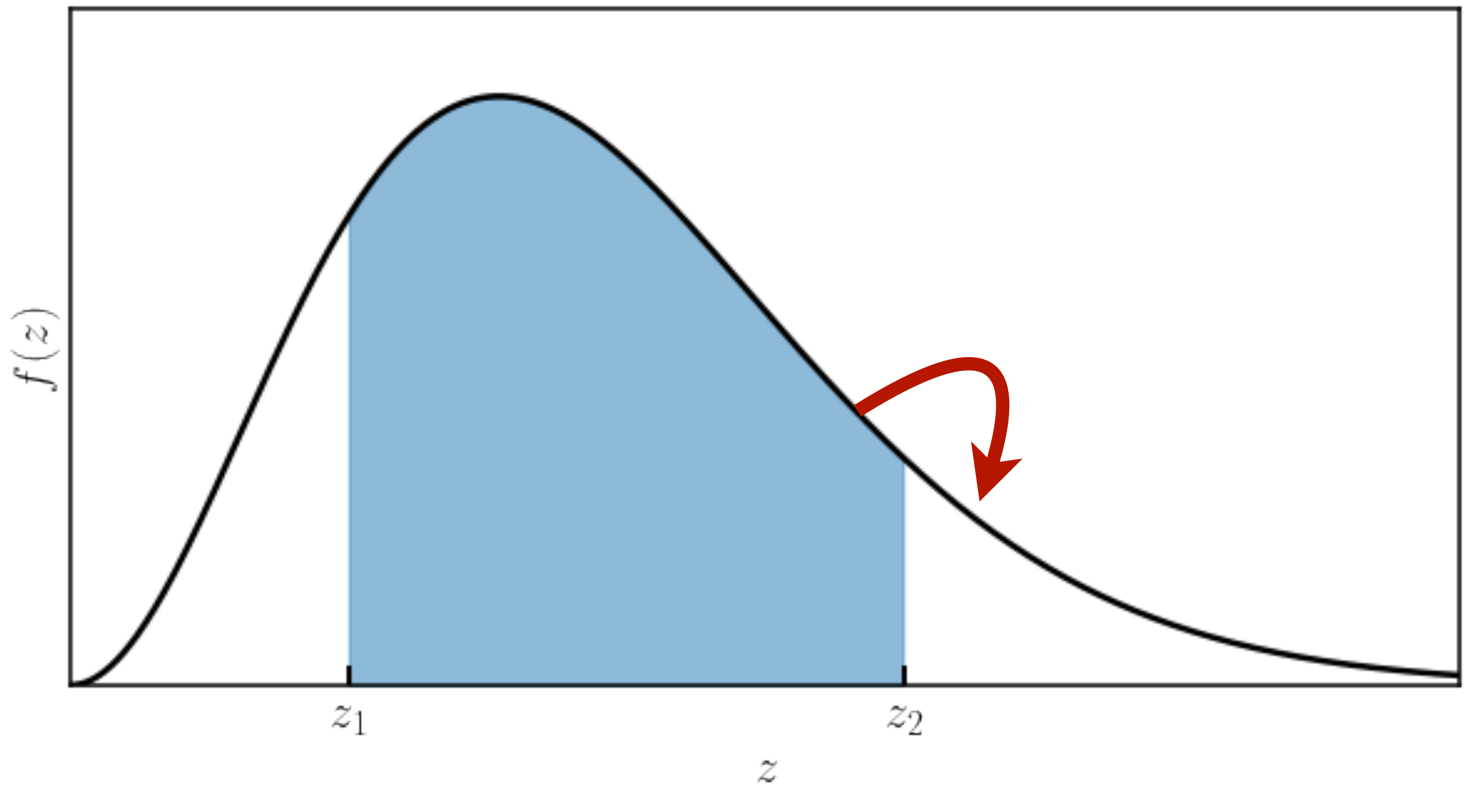

**Additional “boundary term”**

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

**NVSS redshift distribution**



# Redshift tomography — Selection functions




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

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

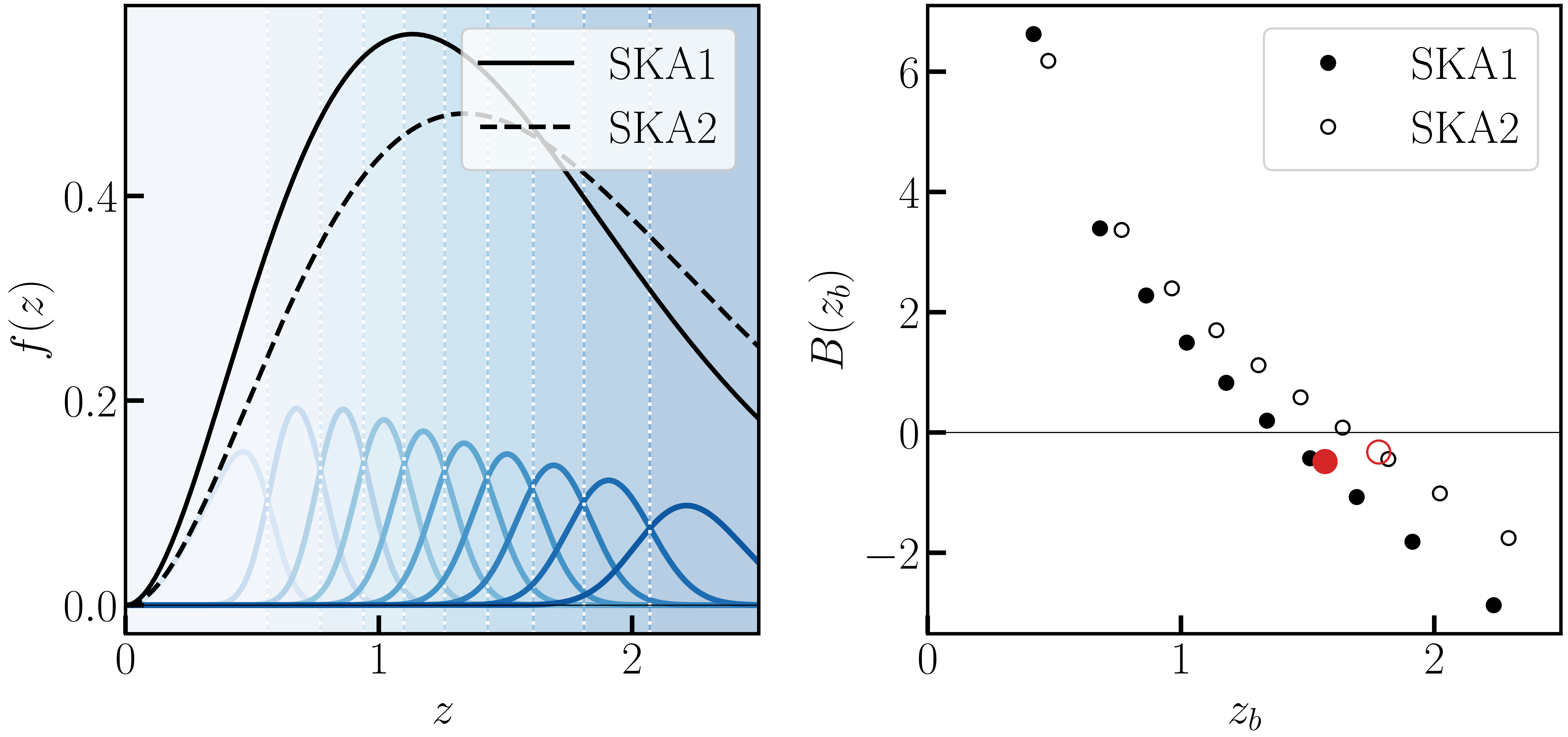
**Redshift distribution**

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

$$\mathscr{D} = \left[ 2 + \tilde{x}(1 + \tilde{\alpha}) - \int_0^\infty \mathrm{d}z \, f_b(z) \frac{\mathrm{d} \log W(z)}{\mathrm{d} \log(1+z)} \right] \beta$$

**General "boundary term"**

# Redshift tomography with SKA




**Redshift distributions from Harrison et al. (2016)**

**Boundary terms' size comparable to Ellis&Baldwin signal**

**Redshift cuts to remove contamination adds boundary terms**

# Some requirements for Science Book Chapter

*Number counts* — **Which number densities can AA4 provide?**

**(Shot noise, sky coverage, contaminants/systematics…)**

*Redshift tomography* — **Which accuracy for redshift distributions?**

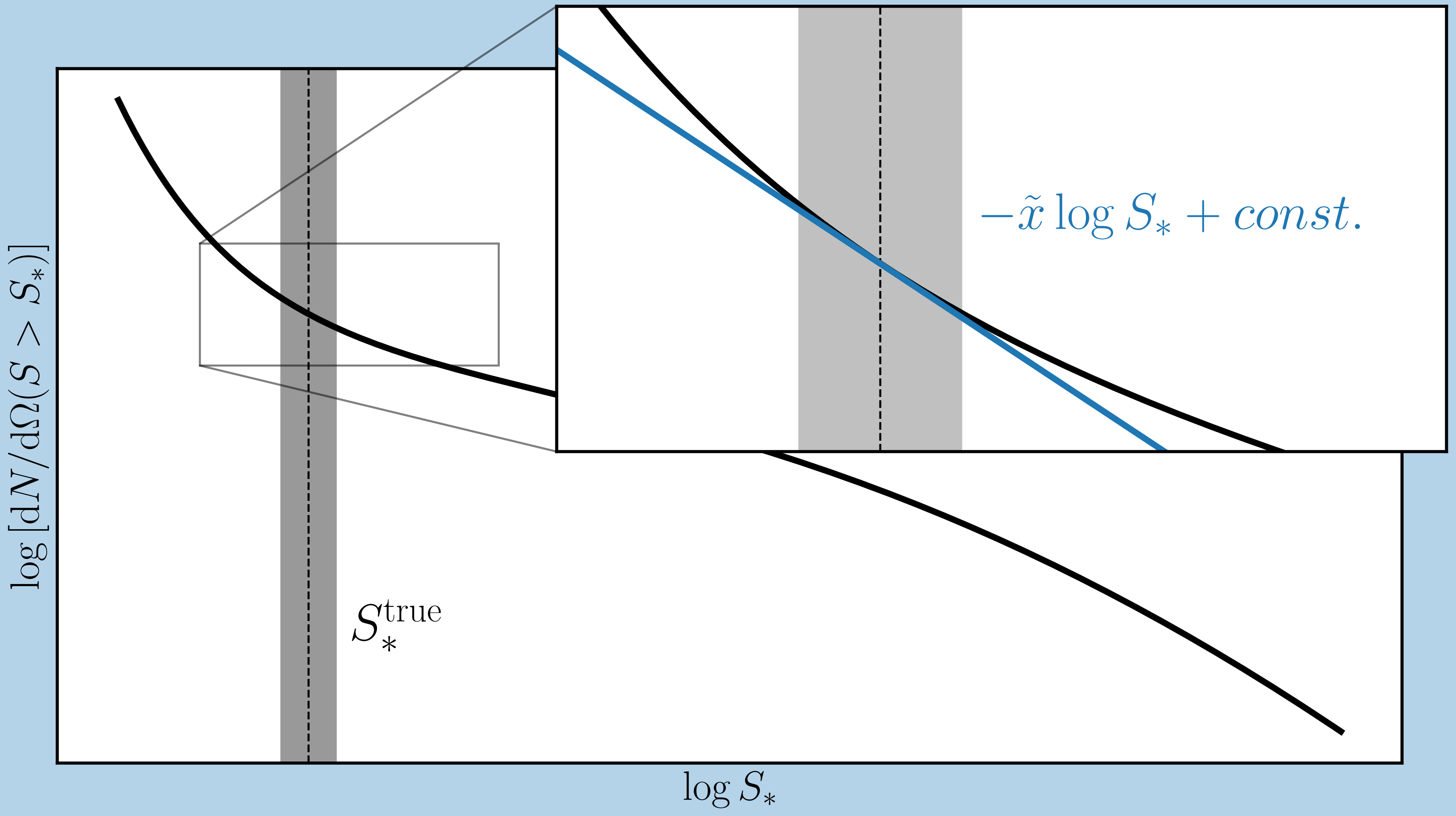
**(cross-matched spec-z sample, estimate biases…)**

# Future directions (also for Science Book Chapter)

**Flux cut dependence of the kinematic matter dipole**

$$\mathscr{D}(S_*) = \left[2 + \tilde{x}(S_*)(1 + \tilde{\alpha}(S_*))\right]\beta$$

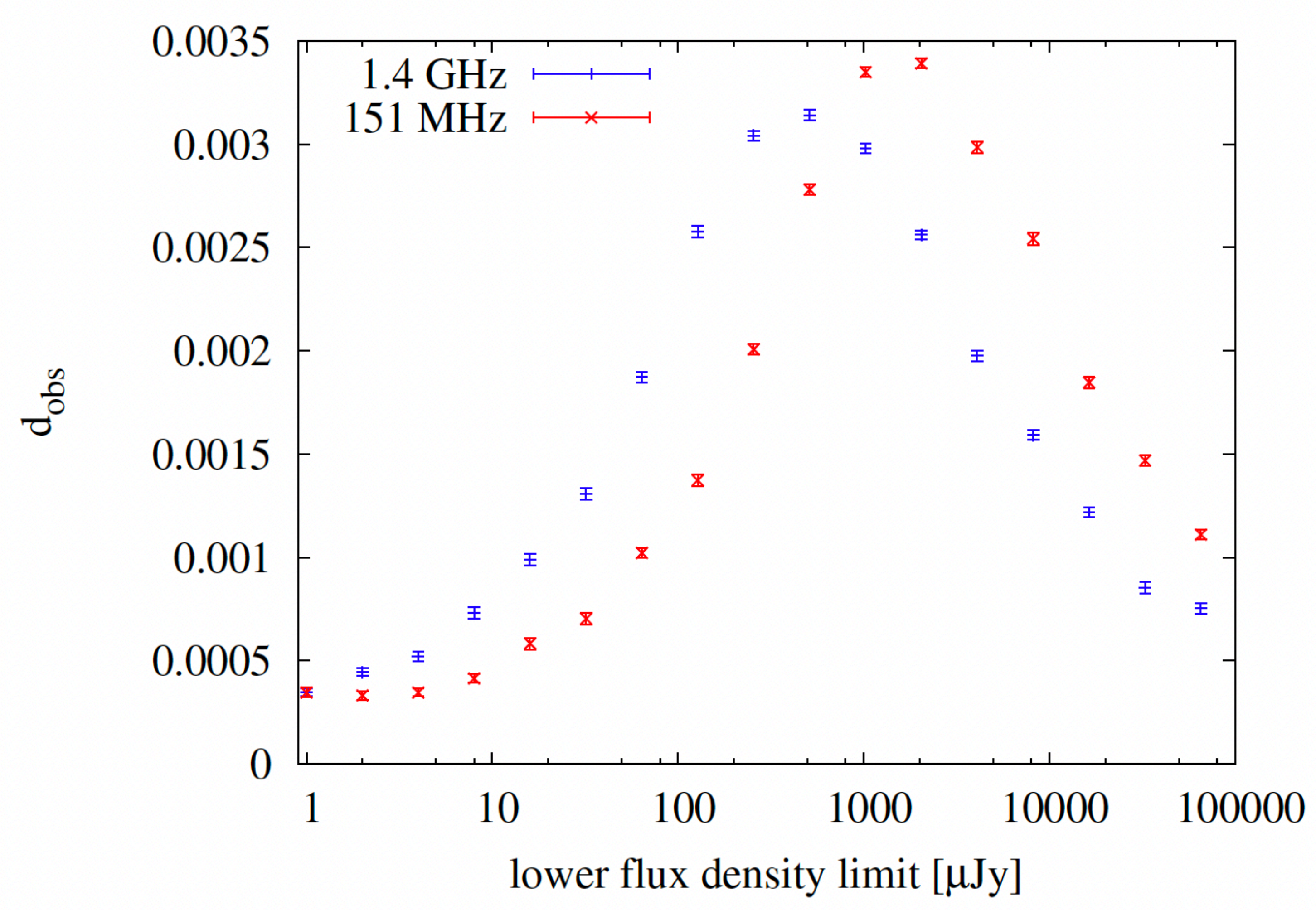
**Also dependent on luminosity function — but projected counts sufficient**



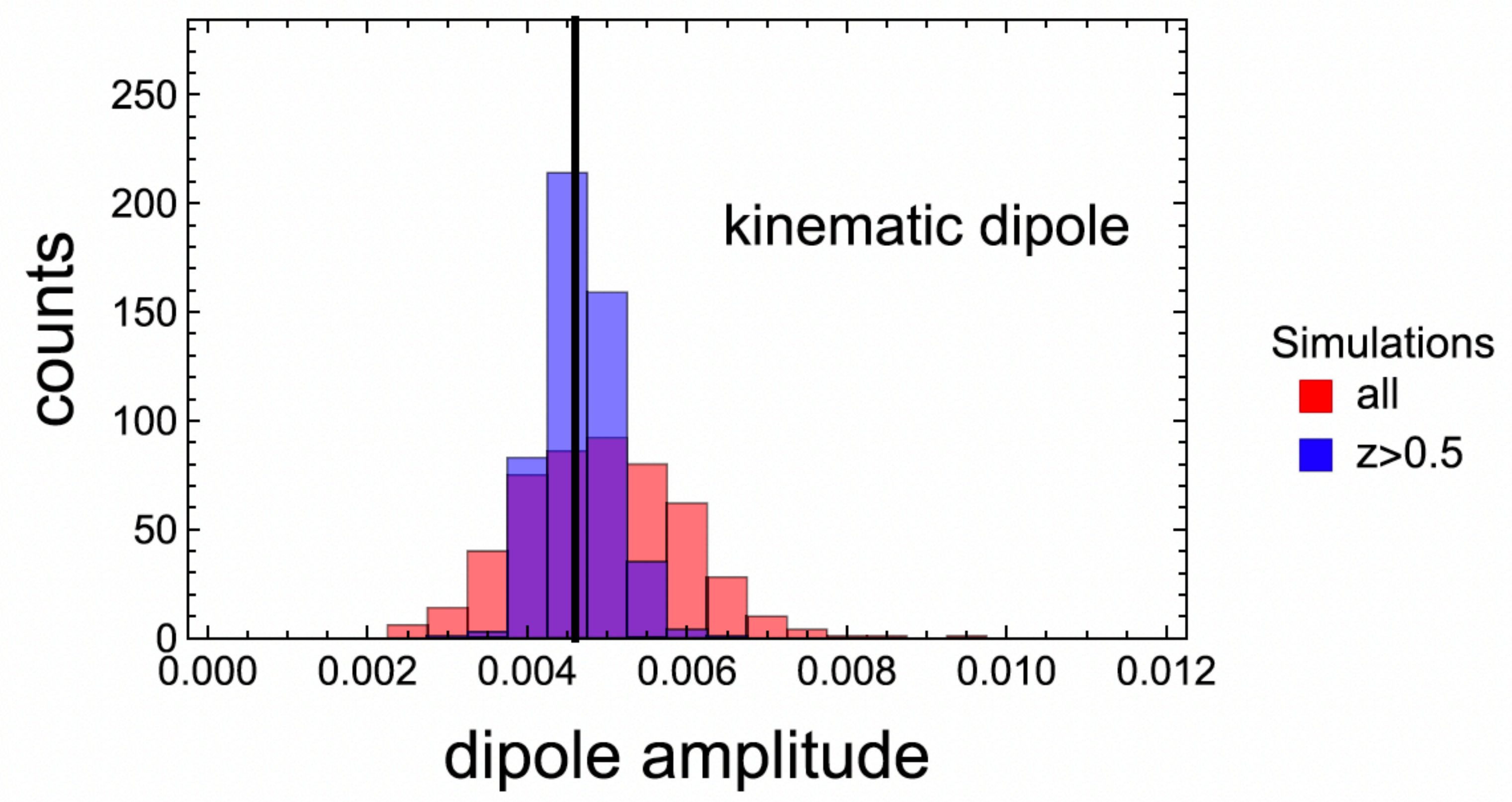

**SvH (2024)** [arXiv:2404.07929]

# Future directions (also for Science Book Chapter)

## Flux cut dependence of the kinematic matter dipole




## Redshift cut dependence of the kinematic matter dipole




**from Science Book and Red Book**

# Future directions (also for Science Book Chapter)

**Kinematic matter dipole in HI**

**Dependent on luminosity function**

$$\mathscr{D}_{IM} = \left[3 + \frac{\dot{H}}{H} - b_e\right]\beta$$

**Maartens et al. (2017)**

# Specific take aways

**SvH & Dalang (2024)** [arXiv:2411.xxxx]

**The matter dipole in redshift bins is not the same as expected from Ellis&Baldwin alone**

**Strong dependency on redshift distribution (at edges of bins)**

**Photometric measurements require modelling of** $W(z)$

**SKA but also Euclid, SPHEREx, and LSST will leverage this**