How does the large-scale structure bias the Hubble diagram?

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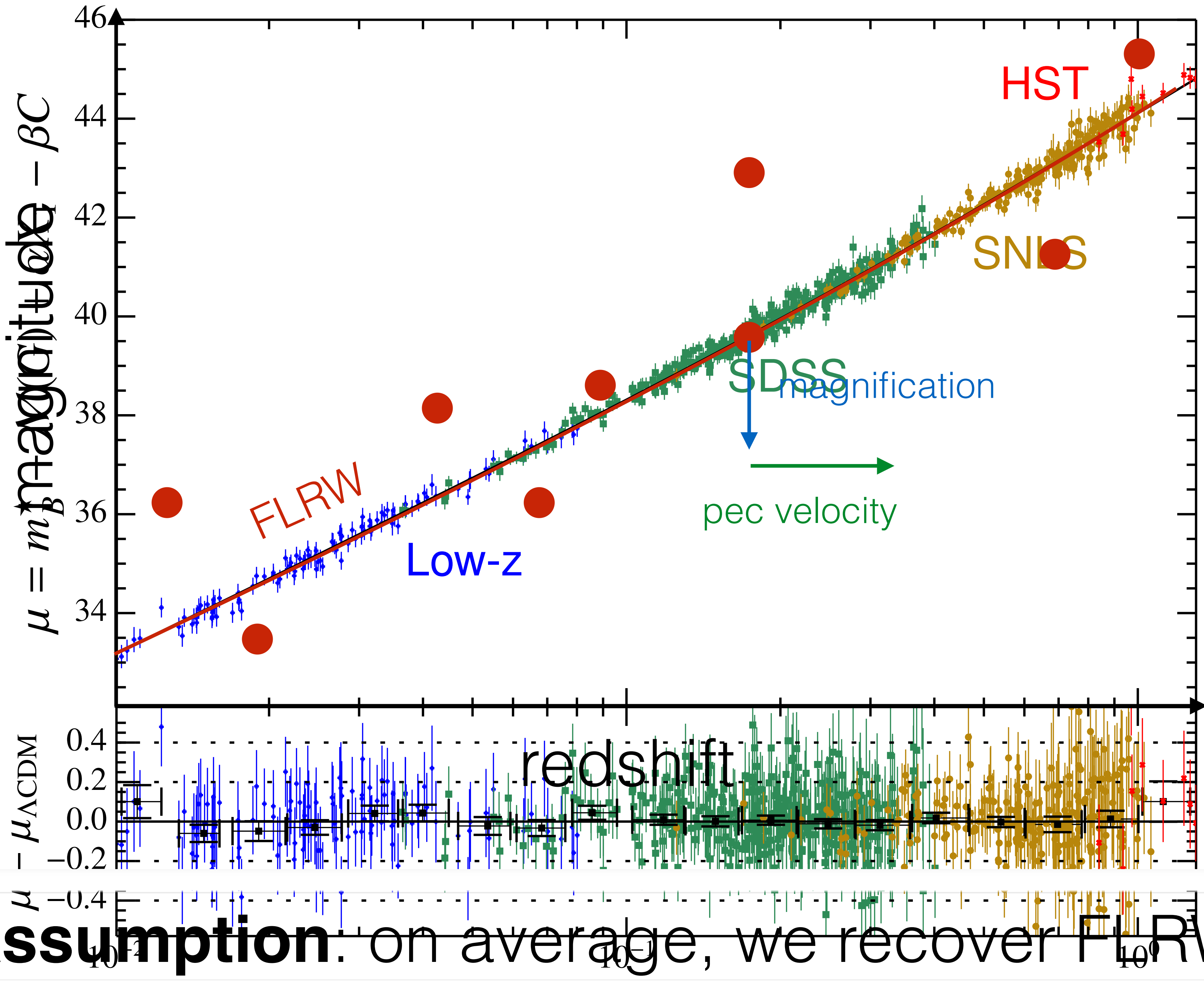
Presentation based on [1611.soon]
with C. Clarkson, R. Maartens, and O. Umeh.

Hubble diagram and inhomogeneities



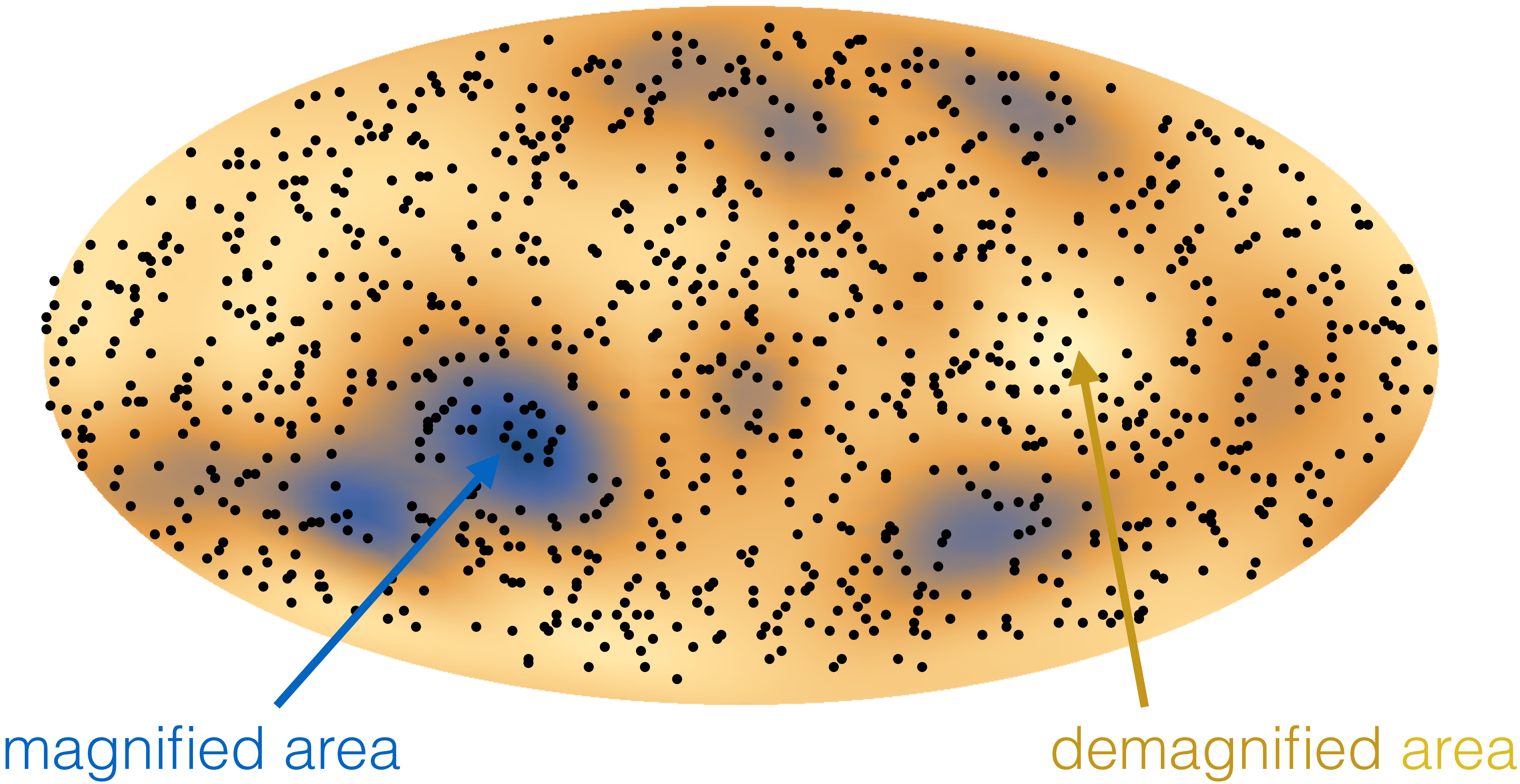
Assumption: on average, we recover FLRW

Did you say average?

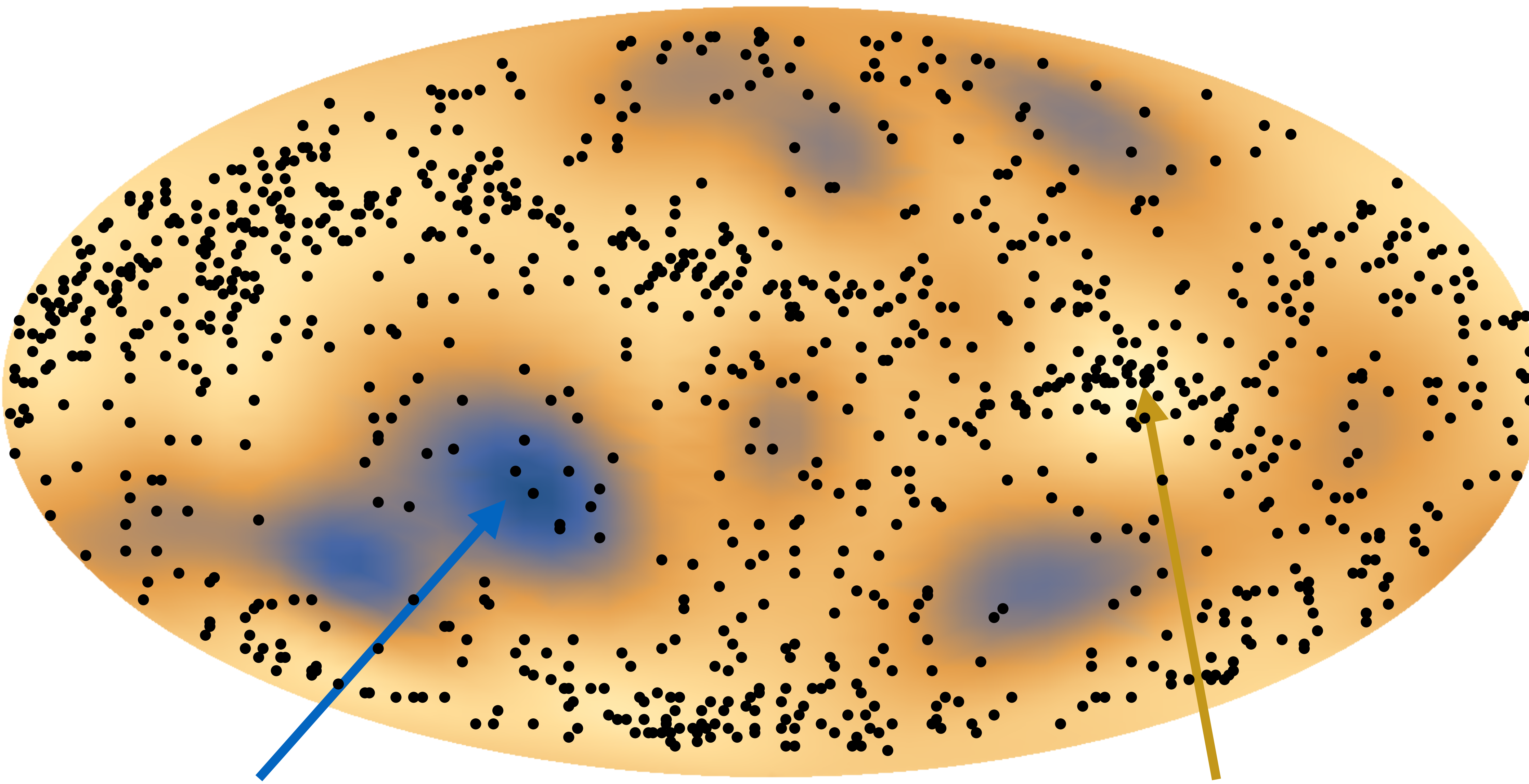
For an observable $Q(z, \boldsymbol{\theta})$, I can define:

- ensemble average $\langle Q \rangle$
- directional average $\langle Q \rangle_\Omega = \dfrac{1}{4\pi} \displaystyle\int_{\rm sky} Q \; \mathrm{d}\Omega$
- area average $\langle Q \rangle_A = \dfrac{1}{A} \displaystyle\int_{\rm sky} Q \; \mathrm{d}A$
- …

The role of lensing



The role of lensing



Source-averaging

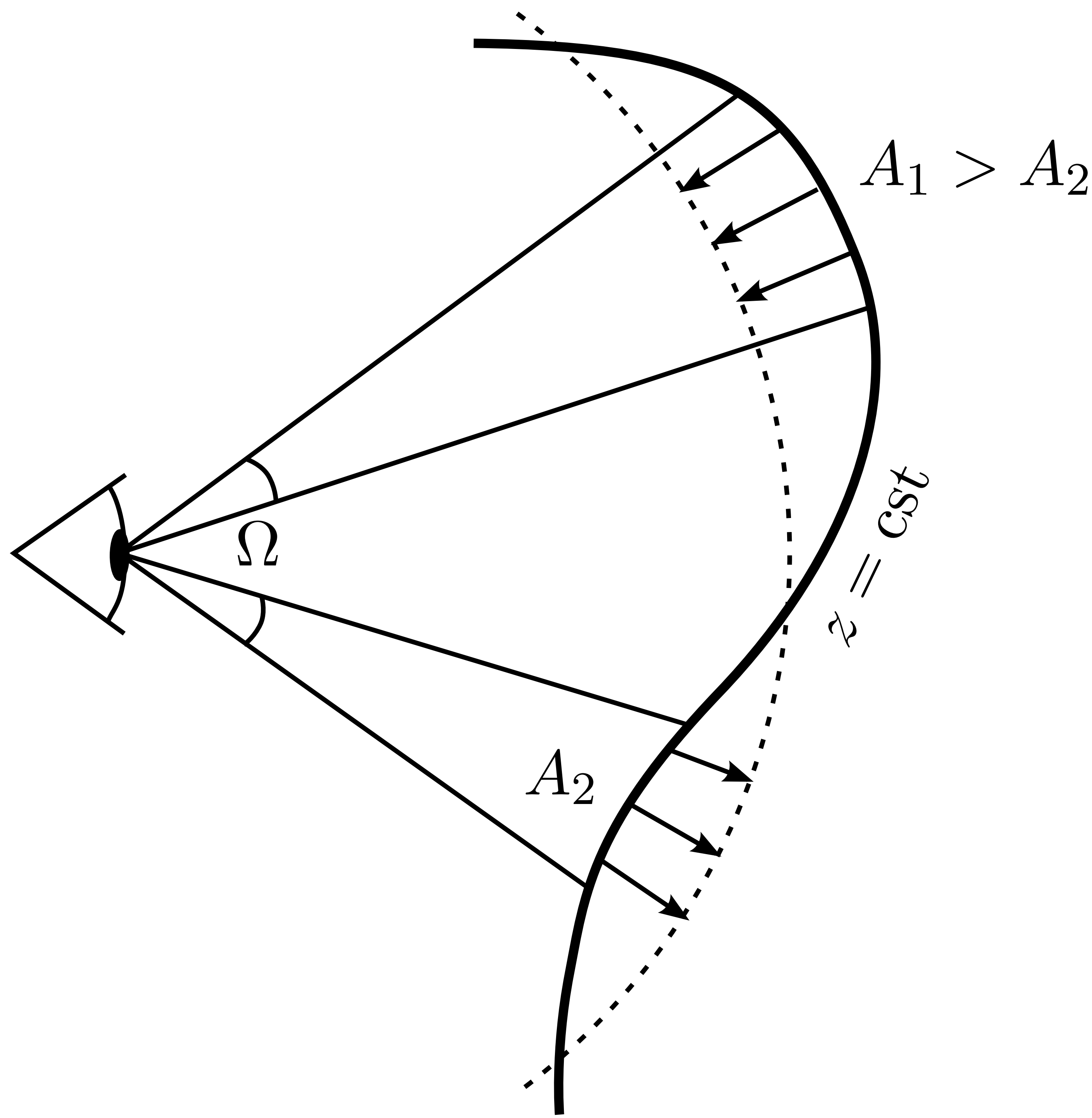
$$\langle Q \rangle_N = \frac{1}{\mathcal{N}} \int_{\text{sky}} Q \, \rho_{\text{s}} d_{\text{A}}^2 H_{||}^{-1} \, \mathrm{d}\Omega$$

inhomogeneity of sources in space

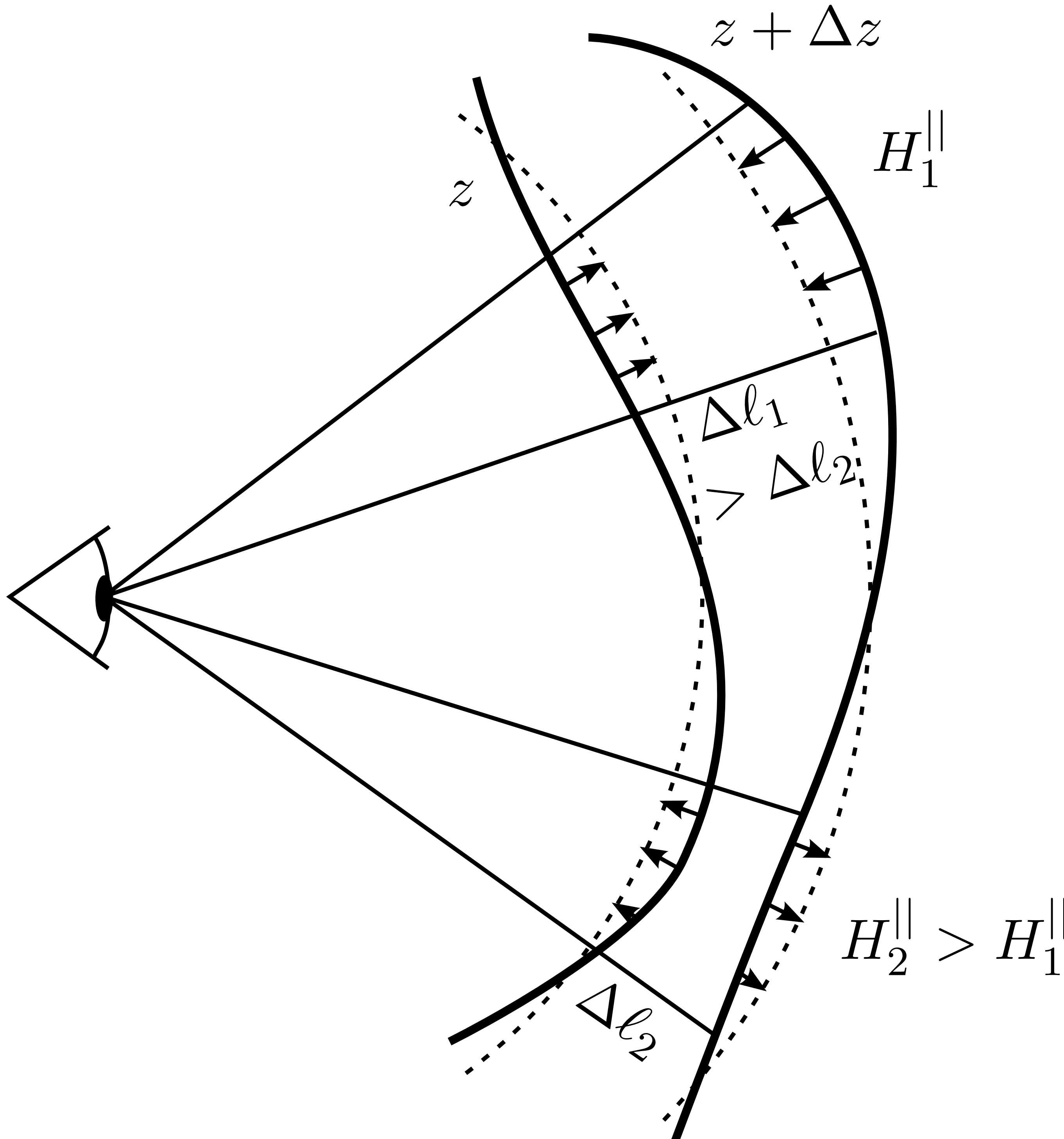
lensing, peculiar velocities

RSD

Peculiar velocities



Redshift-space distortions



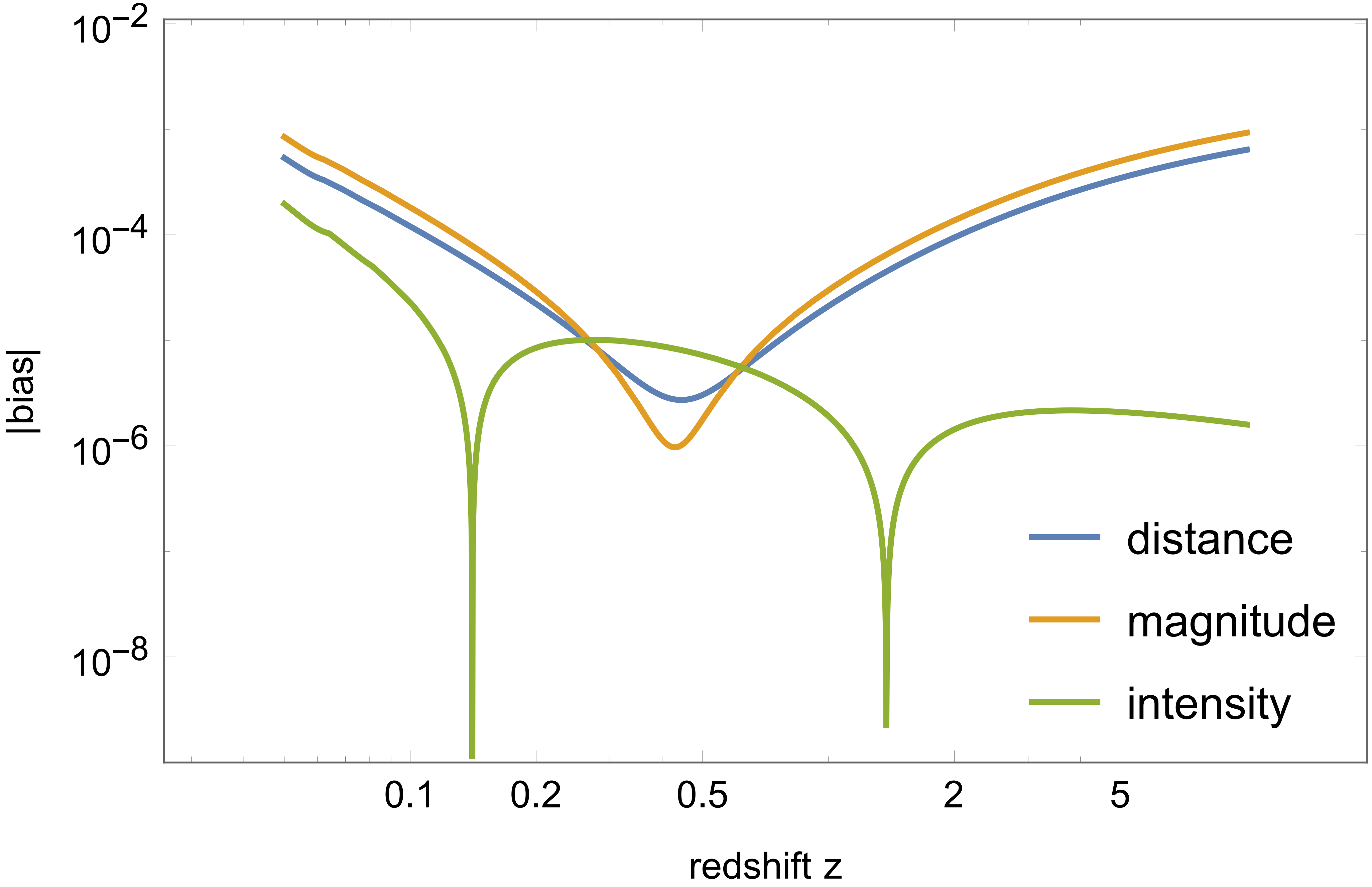
Bias of distance observables

$$\Delta_D \equiv \frac{\langle D \rangle_N - \bar{D}}{\bar{D}}$$

distance observable
(distance, magnitude, intensity, …)

value in FLRW

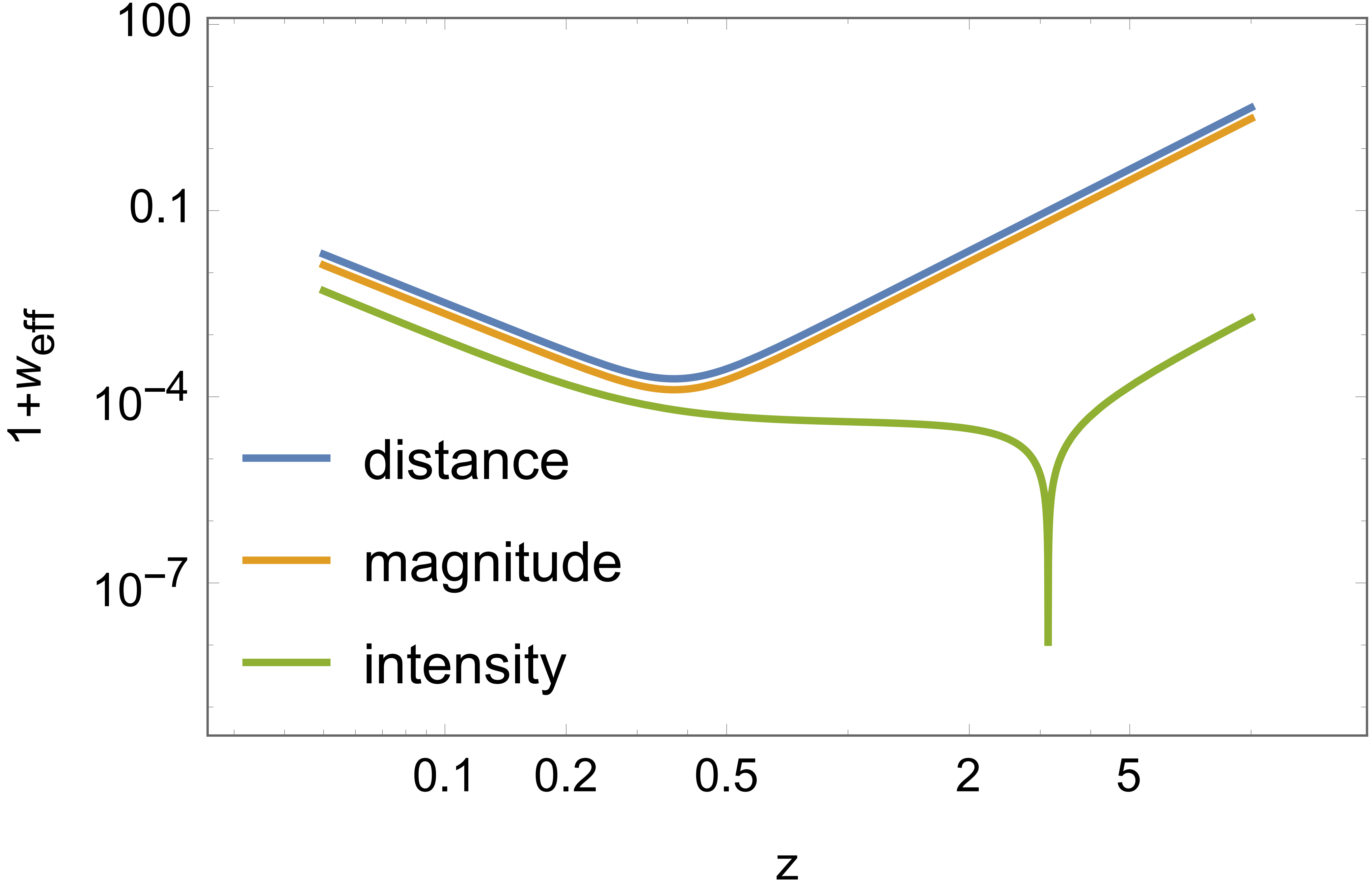
Bias of distance observables



Effective DE EoS

- In FLRW, the dark-energy equation of state $w(z)$ **influences** the relation $D(z)$
- If you interpret a **biased** Hubble diagram with FLRW, the bias can translate into a **spurious** $w_{\rm eff}(z)$

Effective DE EoS



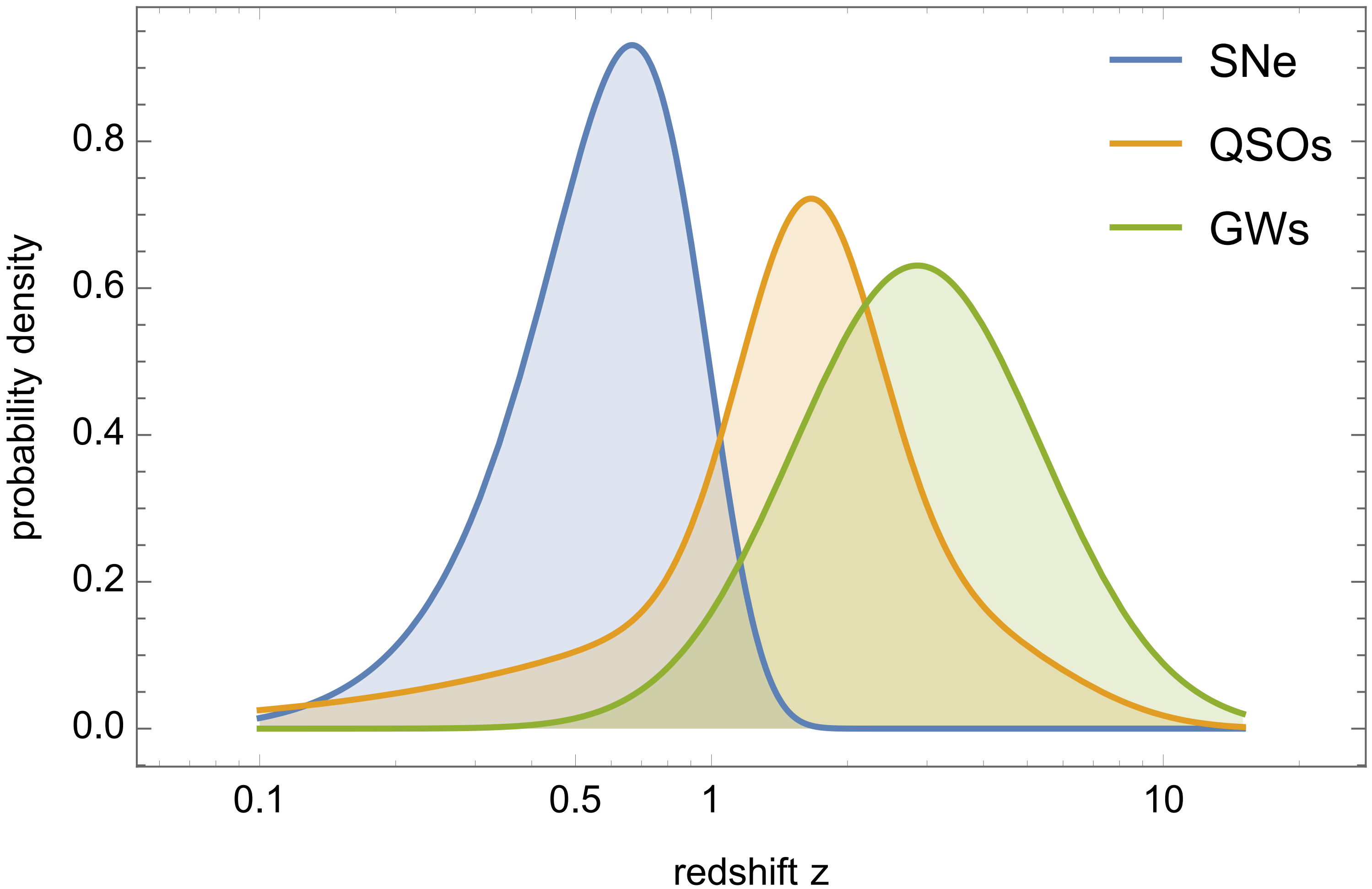
Question

How is the measurement of cosmological parameters influenced?

Bias of cosmological parameters

We consider three different kinds of surveys:

- type Ia supernovae (SNe) like LSST
- quasars (QSOs)
- gravitational waves (GWs) like eLISA



Bias of cosmological parameters

		$w_0 w_a$CDM			ΛKCDM	
survey	D	$\Omega^*_{\mathrm{m}0} - \bar{\Omega}_{\mathrm{m}0}$	$w^*_0 + 1$	w^*_a	$\Omega^*_{\mathrm{m}0} - \bar{\Omega}_{\mathrm{m}0}$	Ω^*_{K0}
SNIa	d_{L}	-4.5×10^{-4}	4.3×10^{-4}	4.6×10^{-3}	-2.7×10^{-4}	4.7×10^{-4}
	m	-6.1×10^{-4}	5.4×10^{-4}	7.0×10^{-3}	4.9×10^{-5}	-1.2×10^{-4}
	I	-2.0×10^{-3}	2.6×10^{-3}	1.7×10^{-2}	1.0×10^{-3}	-1.7×10^{-3}
QSOs	d_{L}	-9.0×10^{-4}	-9.7×10^{-4}	2.0×10^{-2}	-1.1×10^{-3}	2.4×10^{-3}
	m	-5.2×10^{-4}	4.0×10^{-5}	8.4×10^{-3}	-5.3×10^{-4}	1.0×10^{-3}
	I	-6.0×10^{-3}	8.0×10^{-3}	5.1×10^{-2}	5.9×10^{-3}	-9.3×10^{-3}
GWs	d_{L}	-1.0×10^{-3}	-2.7×10^{-3}	3.0×10^{-2}	-1.4×10^{-3}	3.1×10^{-3}
	m	-6.0×10^{-4}	-4.6×10^{-4}	1.2×10^{-2}	-7.2×10^{-4}	1.5×10^{-3}
	I	-3.3×10^{-6}	3.7×10^{-5}	-1.2×10^{-4}	-2.2×10^{-5}	4.8×10^{-5}

- starred parameters are the best fit of mock data
- barred parameters are the background

Conclusions

- When interpreting data, be careful with the notion of average that you use
- The bias of the Hubble diagram due to inhomogeneities is smaller than 10^{-3}
- The impact on parameter inference is small…
- …but it must absolutely be taken into account for direct measurements of $w(z)$

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COLLABORATION IN ASTRONOMY

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