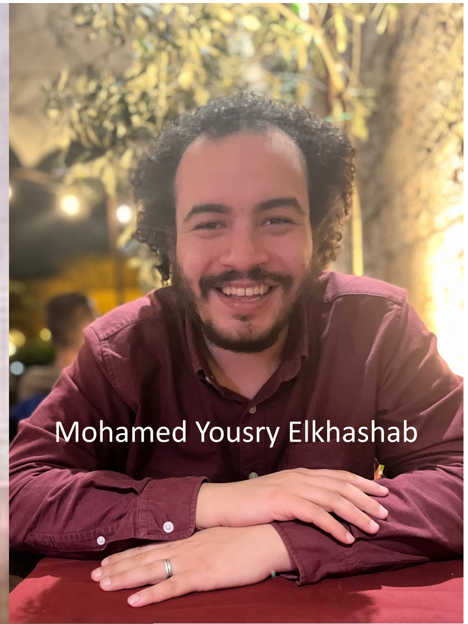
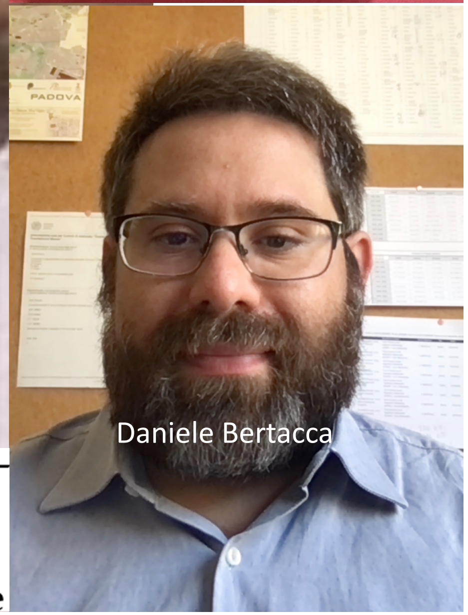
The finger of the observer effect

exploiting the impact of our peculiar velocity on galaxy redshift surveys





Cristiano Porciani

Borzyszkowski et al. 1703.03407
Elkhashab et al. 2108.13424
Elkhashab et al. 2023 in prep

UNIVERSITÄT BONN

Argelander-Institut für Astronomie

PECULIAR VELOCITY OF THE SUN AND THE COSMIC MICROWAVE BACKGROUND

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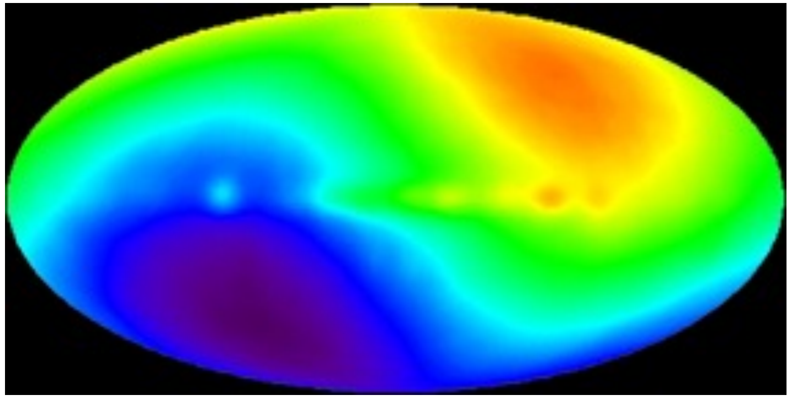
(Received 17 April 1967)

$$[3361.90 \pm 0.04\,(\text{stat.}) \pm 0.36\,(\text{syst.})]\ \mu\text{K} \Rightarrow v_{obs} \approx 370\ km/s$$

$$\ell = 263^\circ.959 \pm 0^\circ.003\,(\text{stat.}) \pm 0^\circ.017\,(\text{syst.})$$

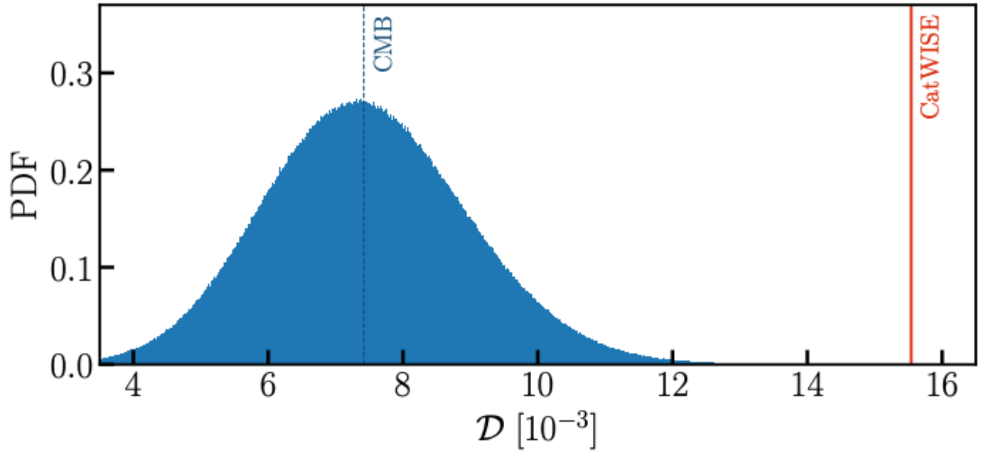
$$b = 48^\circ.260 \pm 0^\circ.001\,(\text{stat.}) \pm 0^\circ.007\,(\text{syst.})$$

Delouis et al. (2021)



Fixsen et al. (1994)

Secrest et al. (2021), Dam et al. (2022) but see also Darling (2022)



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

On the expected anisotropy of radio source counts

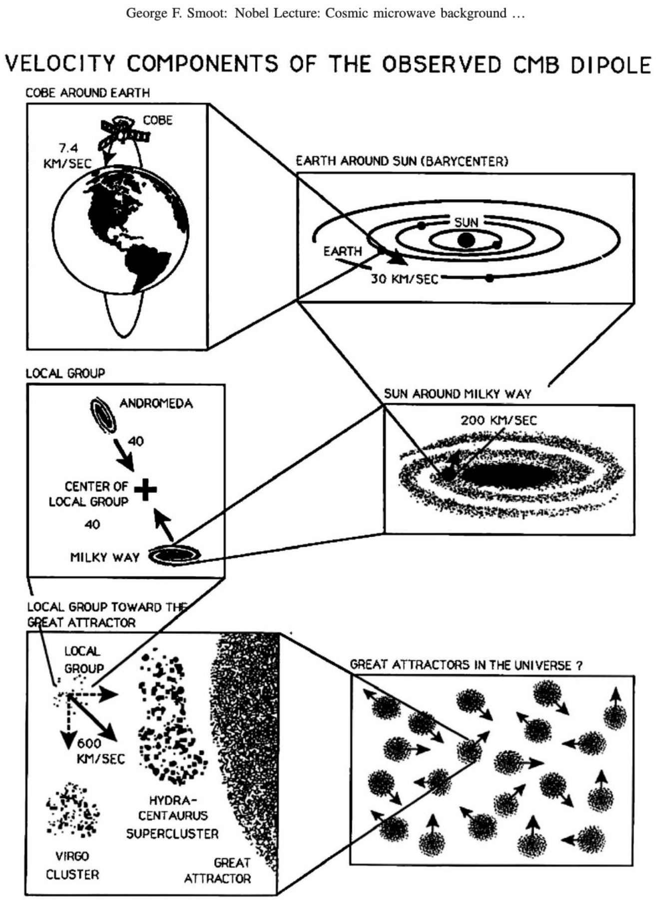
G. F. R. Ellis* and J. E. Baldwin† *Orthodox Academy of Crete, Kolymbari, Crete*

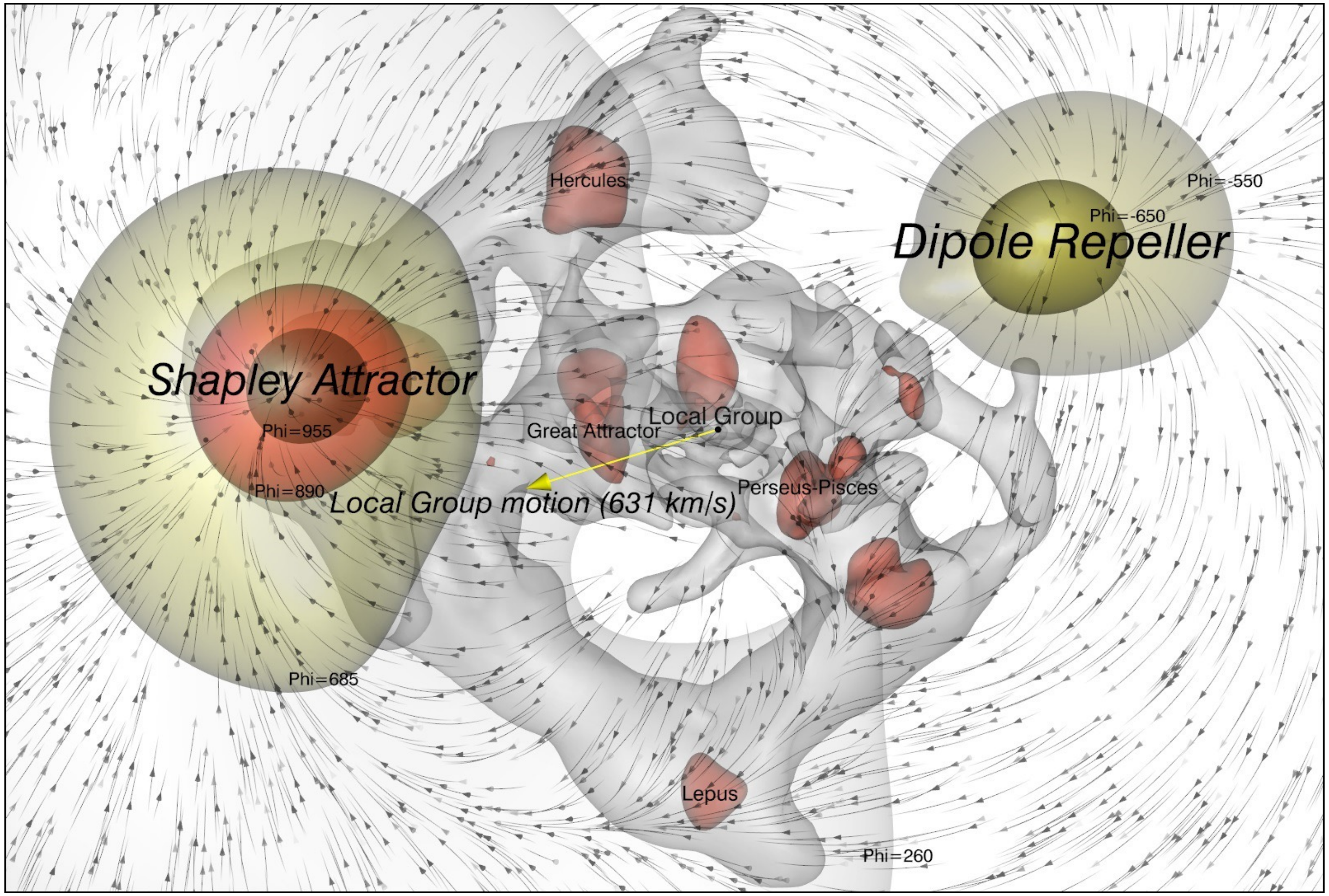
Systematic errors? Low-redshift contamination? …

… Bulk flows? Tilted universe? Superhorizon isocurvature perturbations?

Mass inhomogenities are pulling and pushing us

Hoffman et al. (2017)





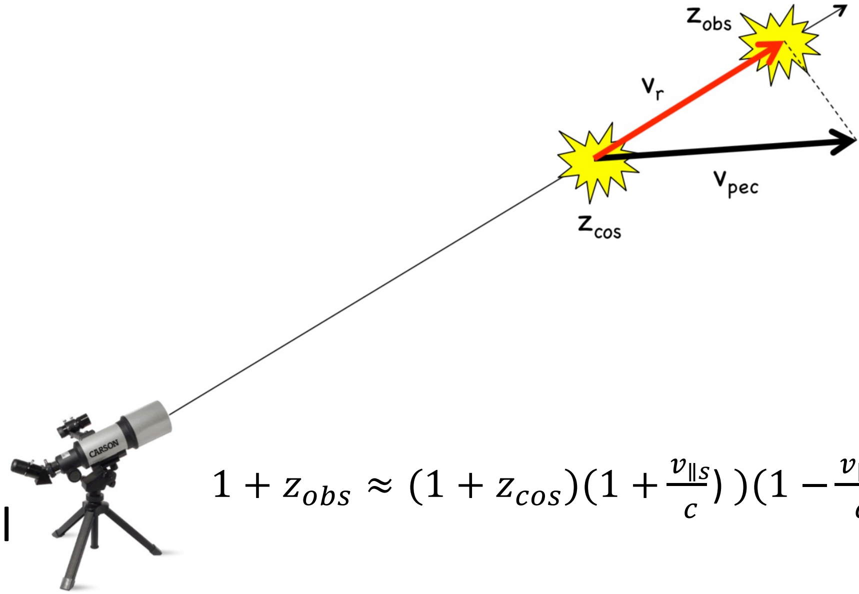
The peculiar velocity generated within 200 Mpc/h points 10^{o} away from the CMB dipole and an external contribution of 160 km/s should arise from sources lying beyond the this volume (Carrick et al. 2015)

Motivation

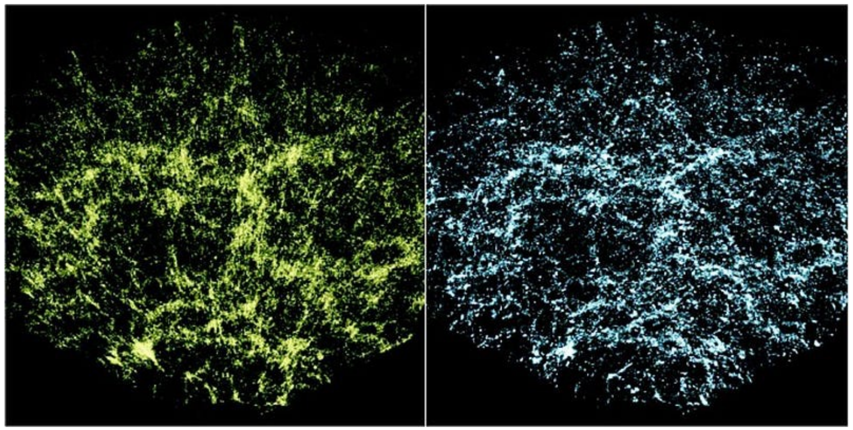
- The current photometric quasar and radio-galaxy samples have limitations
- The quest for dark-energy is driving unprecedentedly large galaxy surveys with accurate redshift measurements ($\frac{\Delta z}{1+z} \ll 10^{-3}$)
- Can we measure $\mathbf{v}_{\rm obs}$ from summary statistics of galaxy clustering?
- And, in general, what is the effect of $\mathbf{v}_{\rm obs}$ on our observables?

Redshift-space distortions

- Redshift catalogs list angular positions and redshifts for a selected sample of galaxies (often flux limited)
- We use the observed redshift as a distance indicator for galaxies
- The conversion from redshift to comoving radial distance is done using an unperturbed FLRW model
- However, z_{obs} differs from z_{cos} due to perturbations
- The reconstructed position of a galaxy is shifted with respect to the actual one

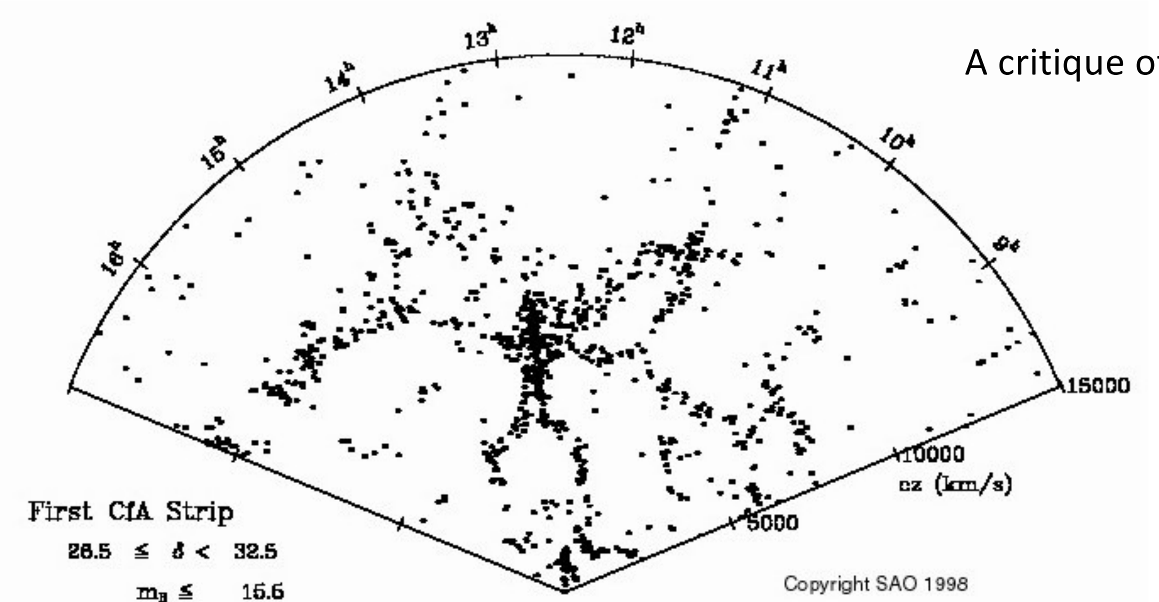


$$1 + z_{obs} \approx (1 + z_{cos})(1 + \frac{v_{\parallel s}}{c})\,)(1 - \frac{v_{\parallel o}}{c})\,...$$



Subbarao et al. (2008)

Finger-of-God effect



de Lapparent et al. (1986)

Fingers of God
A critique of Rees's theory of primordial gravitational radiation
J.C. Jackson (1971)
arXiv: 0810.3908

"The galaxies appear to fall into long chains or cigar-shaped configurations, all pointing at the Earth. Unless one is prepared to assign to the Earth a very special place in the Universe, one must conclude that D is not a good distance indicator, and that in reality the galaxies exist in roughly spherical configurations whose internal velocity dispersions are several times that which would be observed if these systems were expanding with the Universe"

Nick Kaiser’s 1987 seminal paper

in real space

usually neglected

$$\delta_{\rm obs} = \delta - \frac{1}{aH}\frac{\partial v_{\parallel}}{\partial r} - \frac{\alpha}{r}\frac{v_{\parallel} - v_{\parallel,{\rm o}}}{aH}$$

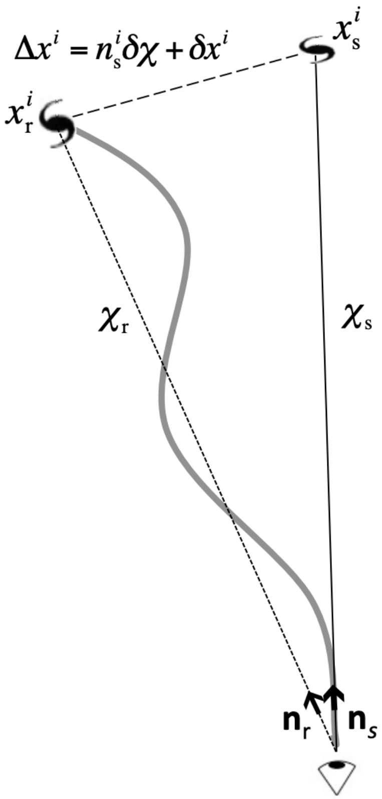
in redshift space

classical redshift-space distortions

$$\alpha = \frac{{\rm d}\ln(r^2\,\bar{n})}{{\rm d}\ln r} = 2 + \frac{{\rm d}\ln\bar{n}}{{\rm d}\ln r}$$

Nick Kaiser (1954-2023)

General relativistic (or light-cone projection) effects



Borzyszkowski et al. (2017)

- Bending of light rays due to intervening density fluctuations (gravitational-lensing deflection and magnification)
- Gravitational redshift, integrated and not-integrated Sachs-Wolfe efffects
- Difference between the rest frames of sources and observer (relativistic aberration)
- Shapiro time delay

General relativistic effects (linear order)

$$\delta_{\rm obs} = \delta - \frac{1}{aH}\frac{\partial v_{||}}{\partial r} - \frac{\alpha_{\rm s}}{r}\frac{v_{||}}{aH} + \frac{\alpha_{\rm o}}{r}\frac{v_{||,\rm o}}{aH} + \dots$$

Yoo et al. (2009)
Challinor & Lewis (2011)
Bonvin & Durrer (2011)
Jeong et al. (2012)
Bertacca (2015, 2019)
Bertacca et al. (2021)
Castorina & di Dio (2022)

In a flux limited survey, assuming a flat background for simplicity:

$$\alpha_{\rm s} = 2\,(1-\mathcal{Q}) + \left[1 + 2\mathcal{Q} - \mathcal{E} - \frac{{\rm d}\ln H}{{\rm d}\ln(1+z)}\right]\frac{r\,H}{c\,(1+z)}\,,$$

$$\alpha_{\rm o} = 2\,(1-\mathcal{Q}) + \left[3 - \mathcal{E} - \frac{{\rm d}\ln H}{{\rm d}\ln(1+z)}\right]\frac{r\,H}{c\,(1+z)}\,,$$

galaxy population

cosmic expansion history

Evolution bias

$$\mathcal{E}(z) = -\left.\frac{\partial \ln n(L_{\rm min}, z)}{\partial \ln(1+z)}\right|_{L_{\rm min}=L_{\rm lim}(z)}$$

$$\mathcal{Q}(z) = -\left.\frac{\partial \ln n(L_{\rm min}, z)}{\partial \ln L_{\rm min}}\right|_{L_{\rm min}=L_{\rm lim}(z)}$$

Magnification bias

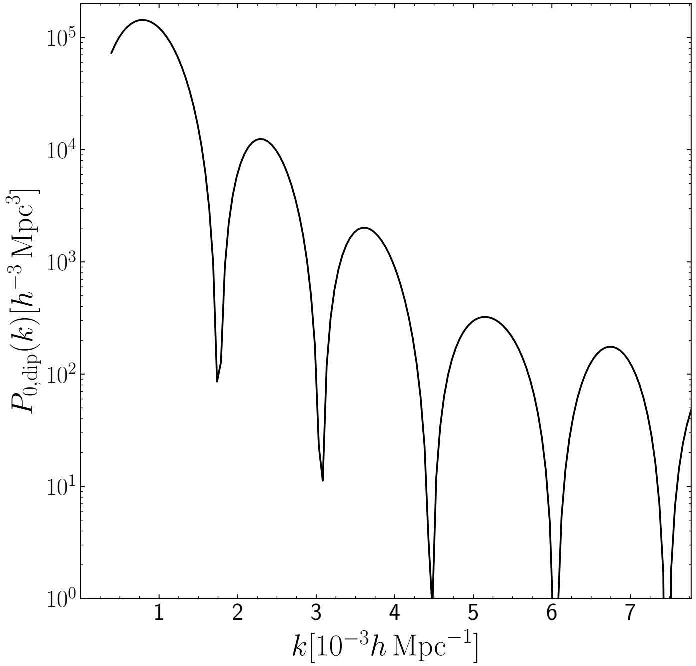
The Finger of the Observer (FOTO) Effect

Overdensity
in the rest frame
of a comoving observer
(CMB frame)

$$\delta_{\rm obs} = \delta_{\rm com} + \alpha_{\rm o} \frac{\boldsymbol{v}_{\rm o} \cdot \hat{\mathbf{r}}}{aHr}$$

Overdensity
in the rest frame
of the observer

Deterministic
dipole term



The FOTO effect superimposes oscillations to the monopole of the power spectrum on large scales (also adds other signatures to higher multipoles). The correction can be computed analytically, in general.
For a full-sky thin radial shell:

Elkhashab et al. 2021

$$P_{0,\rm dip}(k) \simeq \frac{4\pi}{3}\,\alpha_{\rm o}^2 \left[\left(\frac{v_{\rm o}}{aH}\right)^2 \Delta r\right] j_1^2(kr)$$

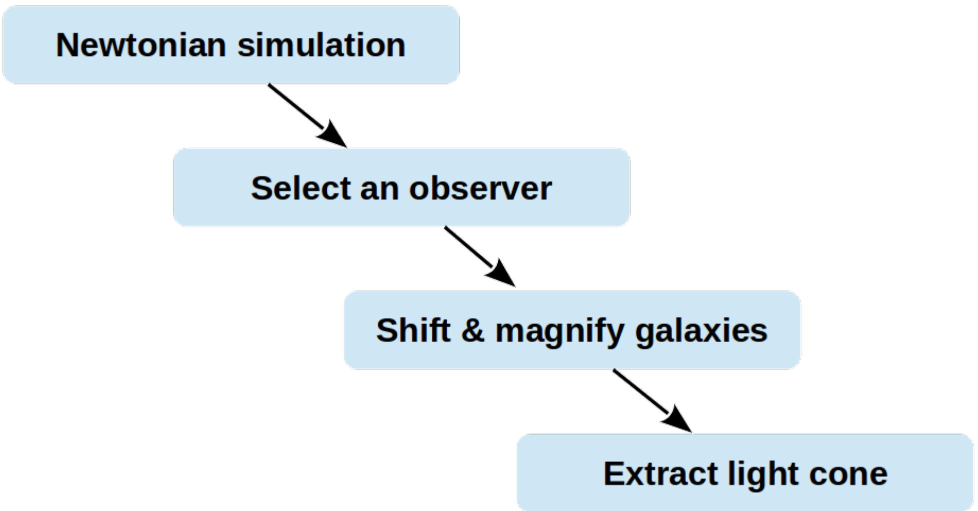
L I G E R v2.0

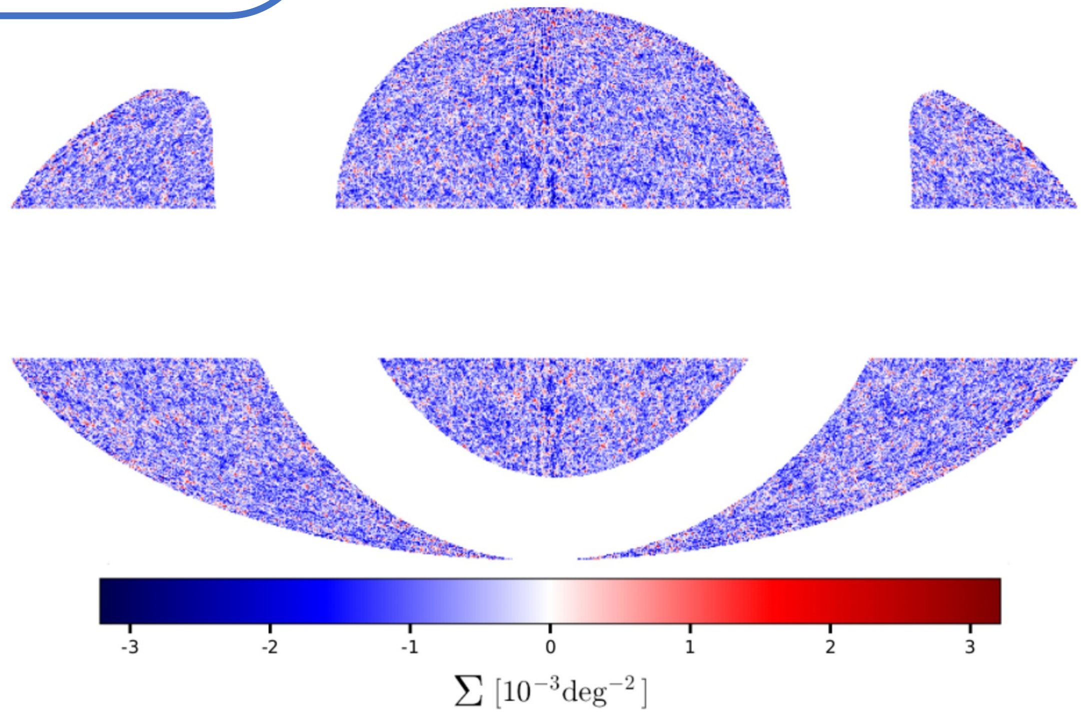
LIght cones using GEneral Relativity

Borzyszkowski, Bertacca & Porciani (2017)
Elkhashab, Porciani & Bertacca (2021)

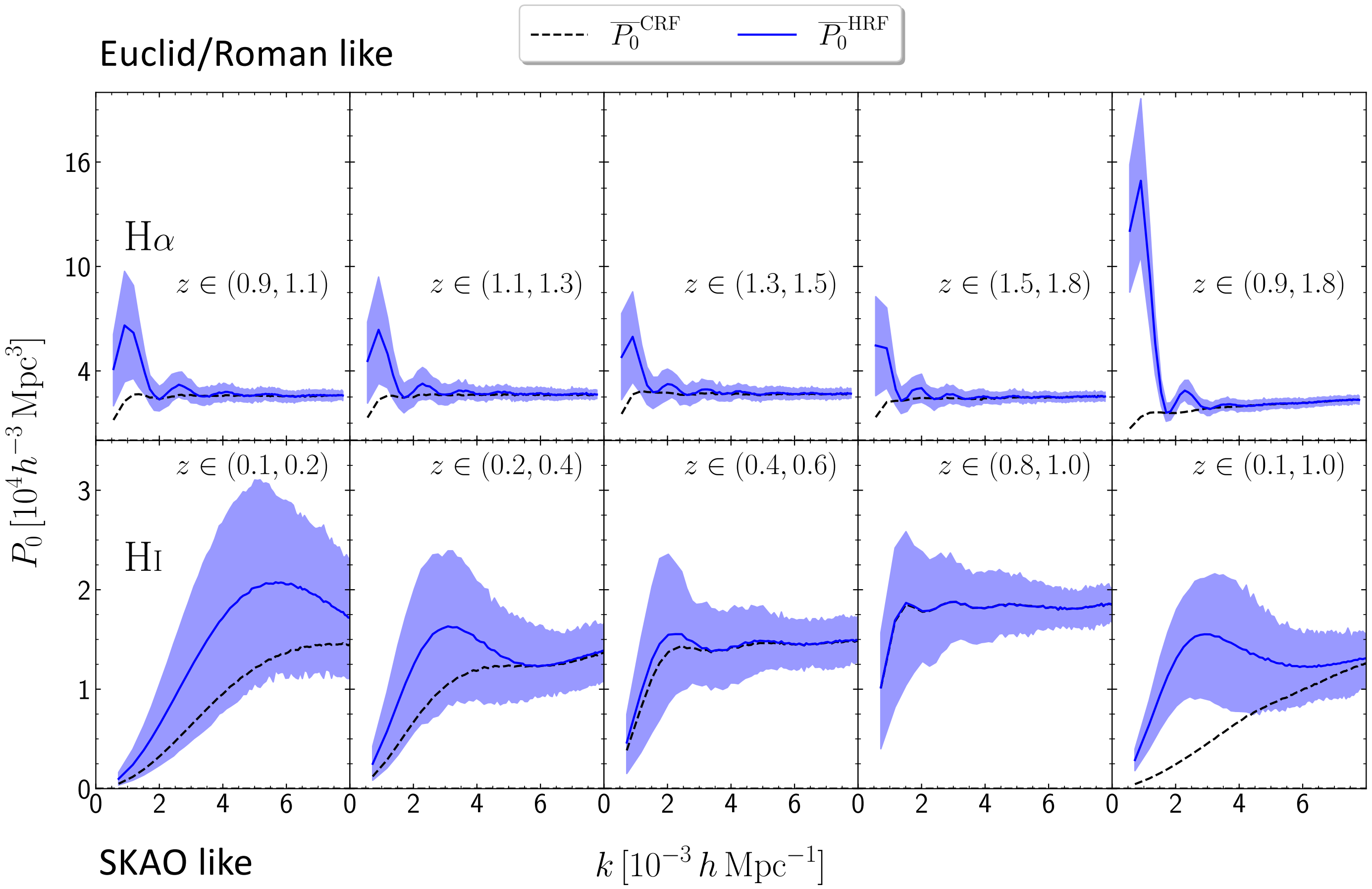
https://astro.uni-bonn.de/~porciani/LIGER/

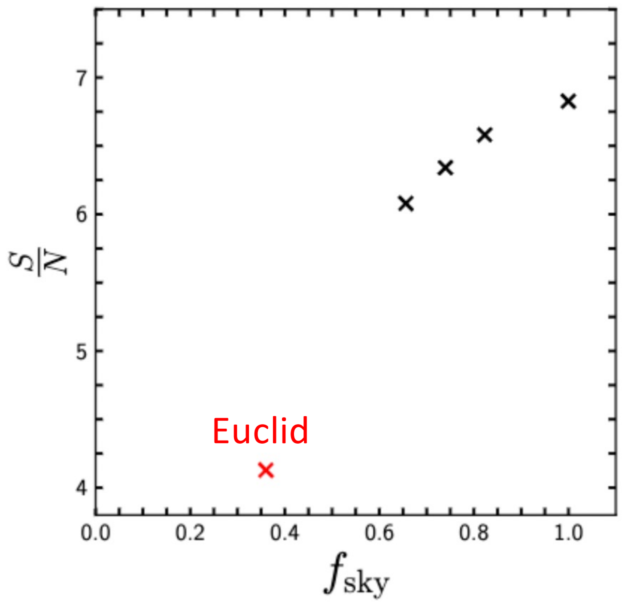
Points to the GitLab link



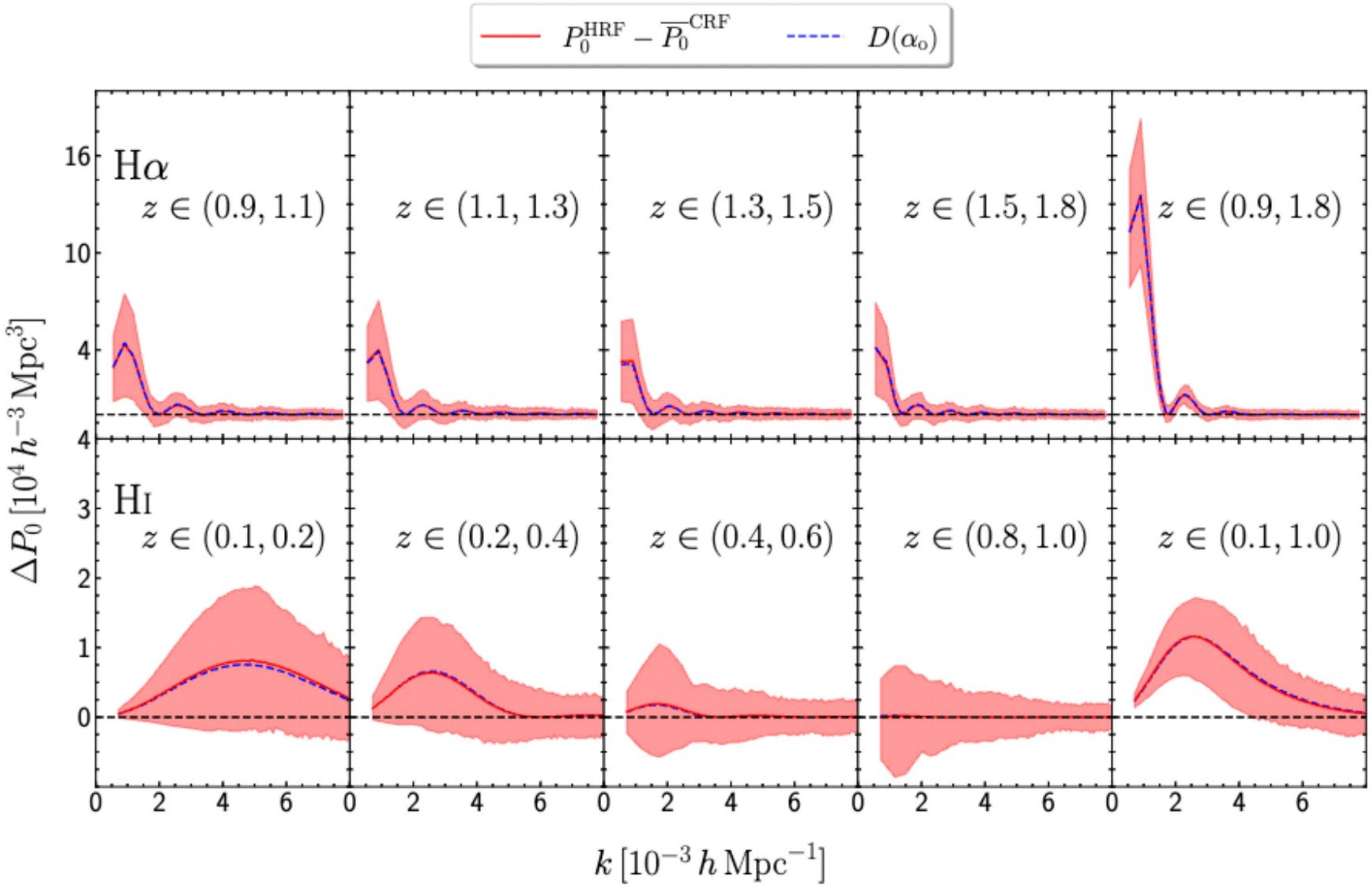


Measurements from 140 mock catalogs





Is the model accurate?

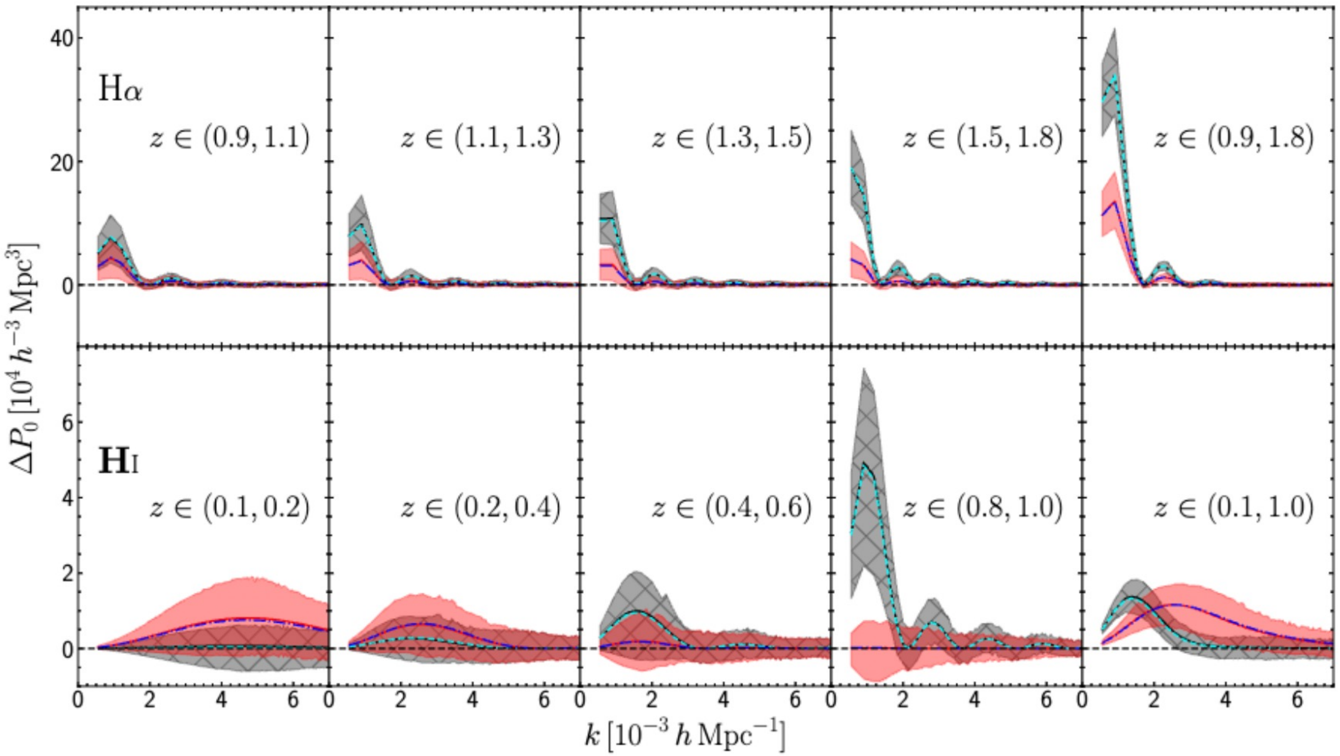


Does a redshift boost cancel the FOTO effect?

Heliocentric redshift

$$1 + z_{com} = \frac{1 + z_{obs}}{1 + z_{\odot}(\hat{r})}$$

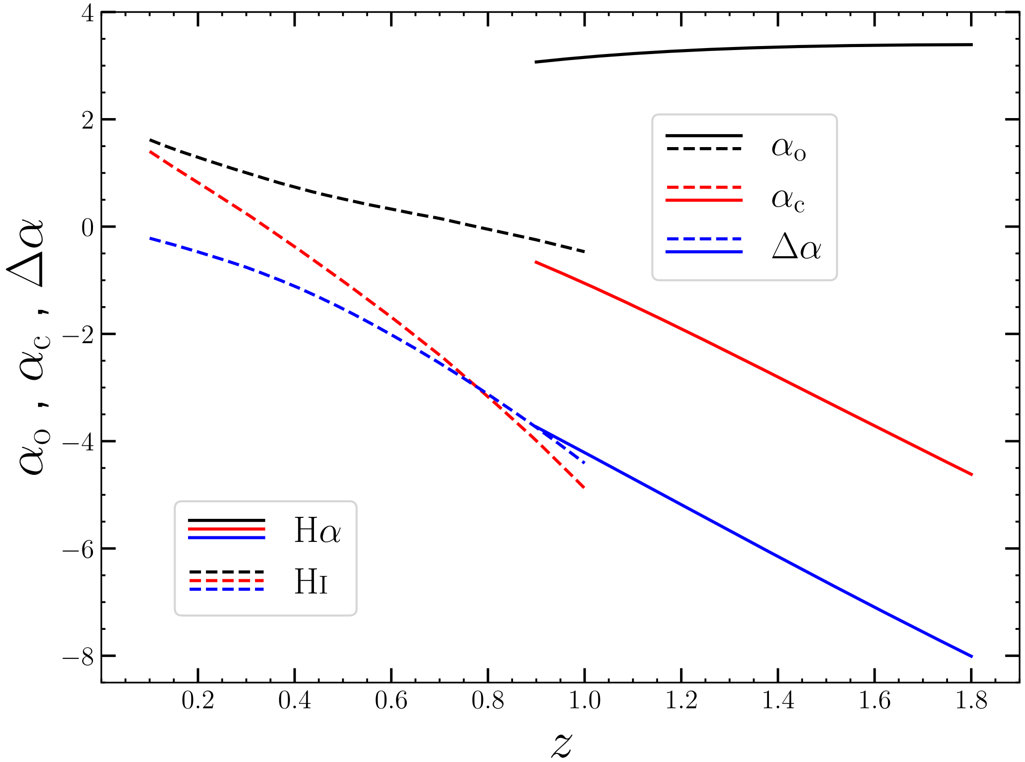
"going to the CMB frame"



- The FOTO effect is not erased because the correction only changes the redshifts of the sources and not their angular positions, sizes and luminosities. In many cases the effect is actually enhanced!
- The net effect of the redshift correction is to modify the α_o parameter in a calculable way.

Enhancing the signal with artificial redshift boosts

$$\delta_{\rm cor} = \delta_{\rm com} + \frac{\alpha_{\rm o}}{a\,H\,r}[(\boldsymbol{v}_{\rm cor} + \boldsymbol{v}_{\odot}) \cdot \hat{\mathbf{r}}] + \frac{\Delta\alpha}{a\,H\,r}(\boldsymbol{v}_{\rm cor} \cdot \hat{\mathbf{r}})$$

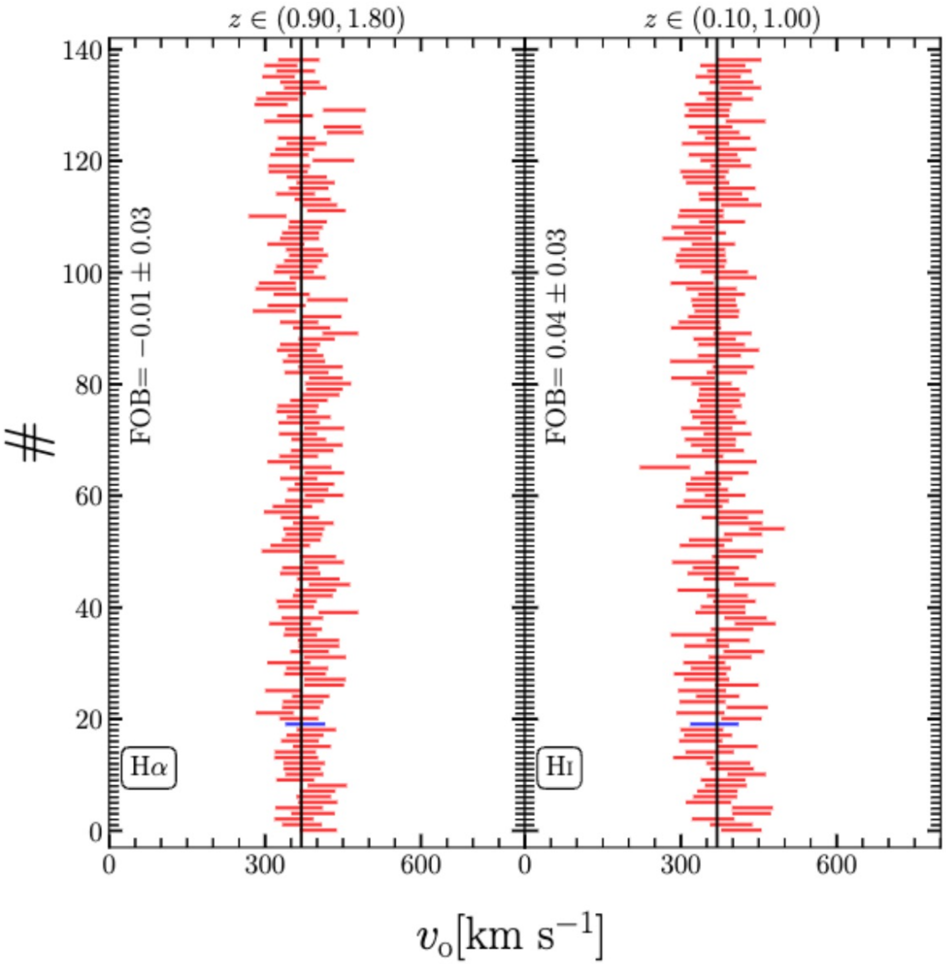


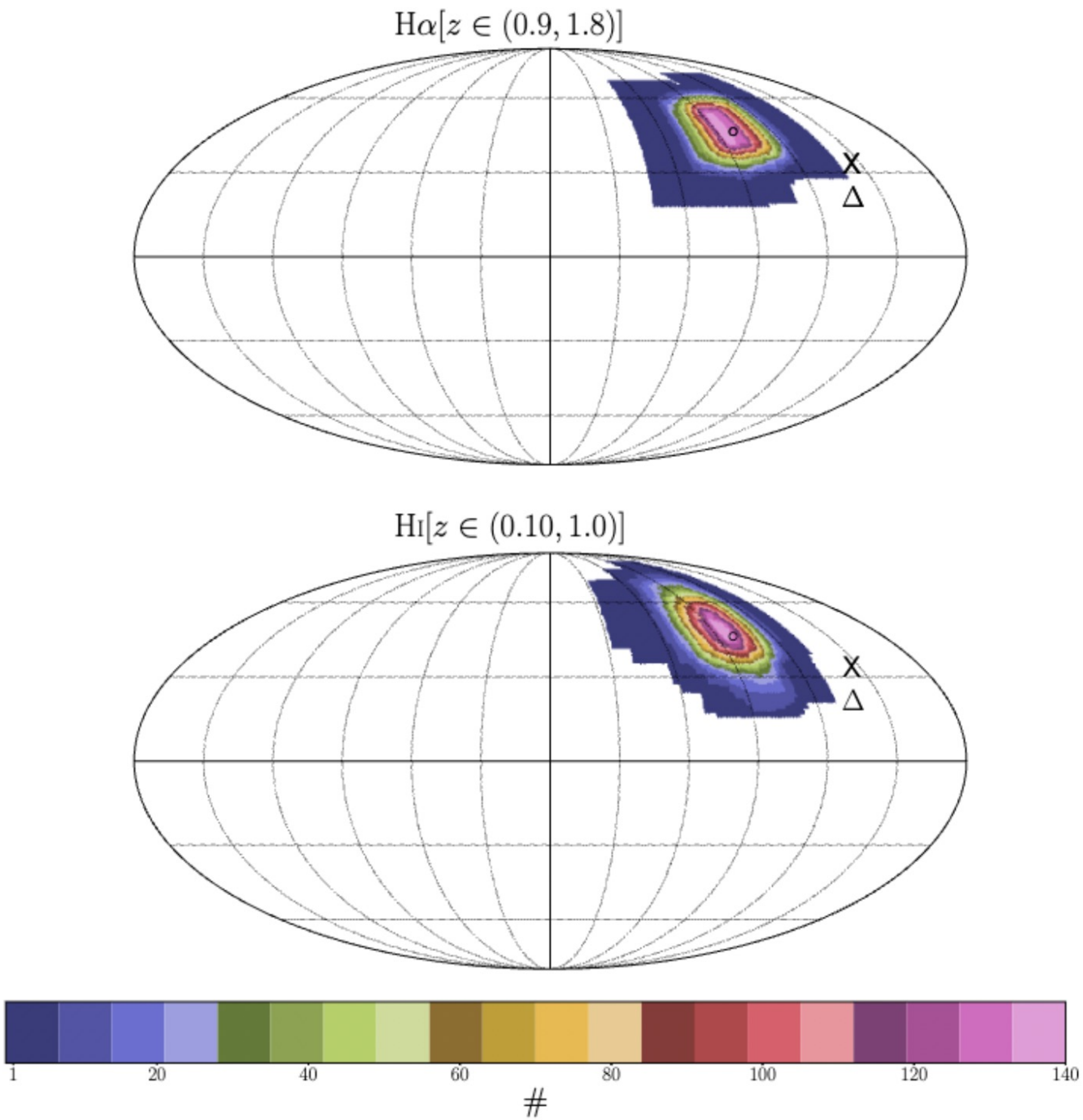
- We simultaneously analyse spectra taken by using up to 5 redshift boosts with different $\mathbf{v}_{cor}$ and accounting for their covariances
- This gives us a handle on the direction of the peculiar velocity of the Sun

Possible objectives

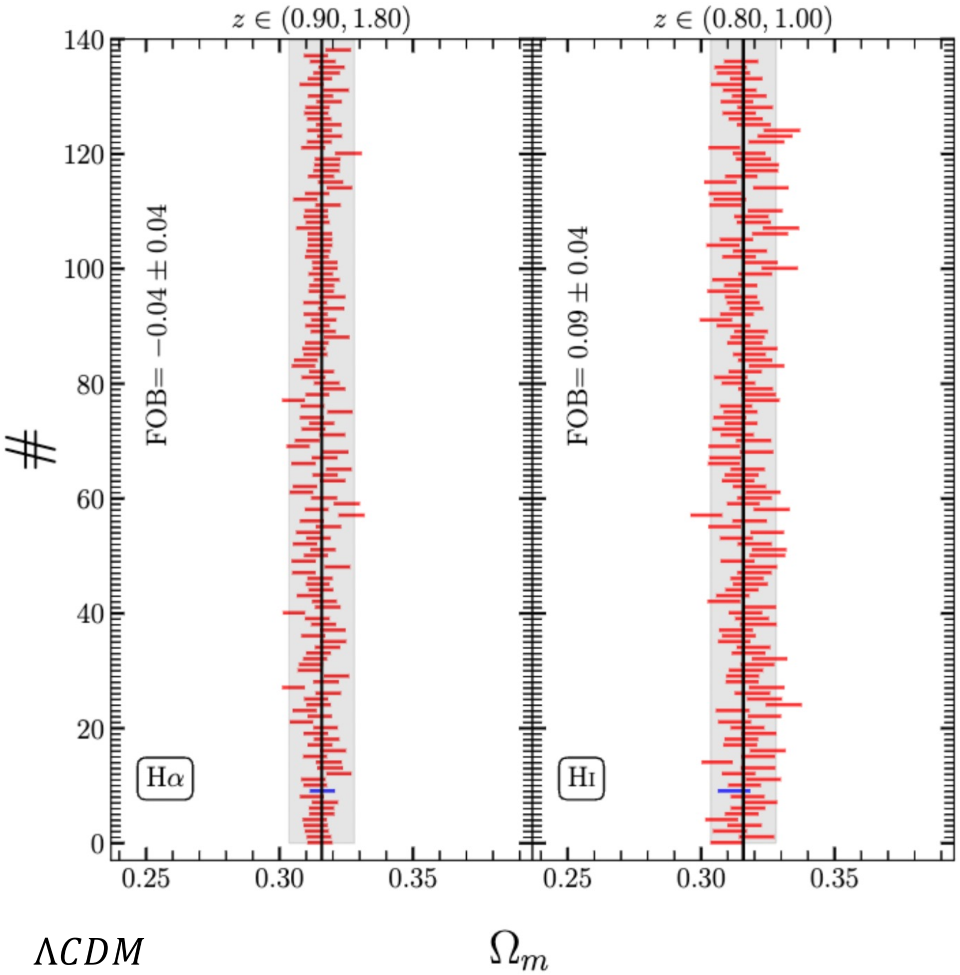
- Low ambition: use priors on cosmology and $\mathbf{v}_{obs}$ from CMB studies and measure the evolution and magnification bias of the sources
- Medium ambition: use priors on cosmology and the measurements of the luminosity function to set constraints on $\mathbf{v}_{obs}$
- High ambition (madness?): use priors on $\mathbf{v}_{obs}$ from CMB and measurements of the luminosity function to the FOTO effect as a cosmological probe

Could we measure v_{obs}?

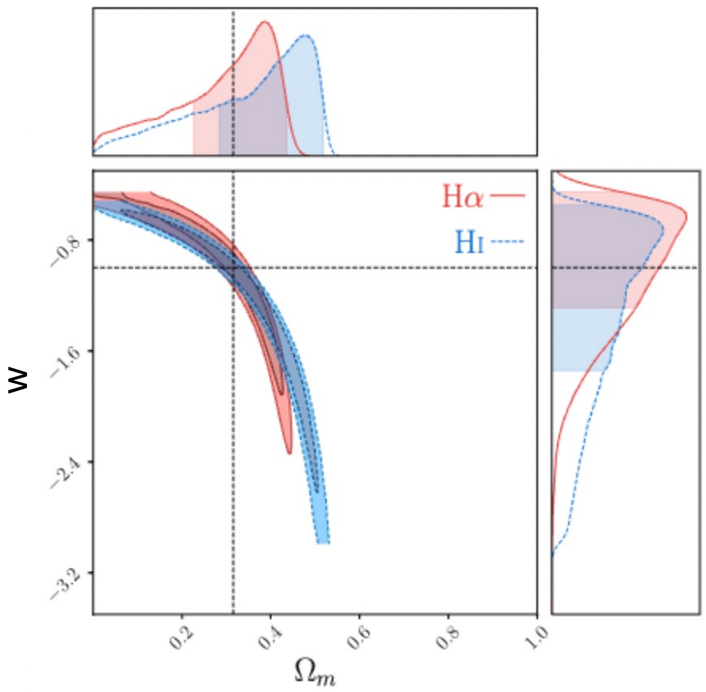




Could we constrain cosmological parameters?

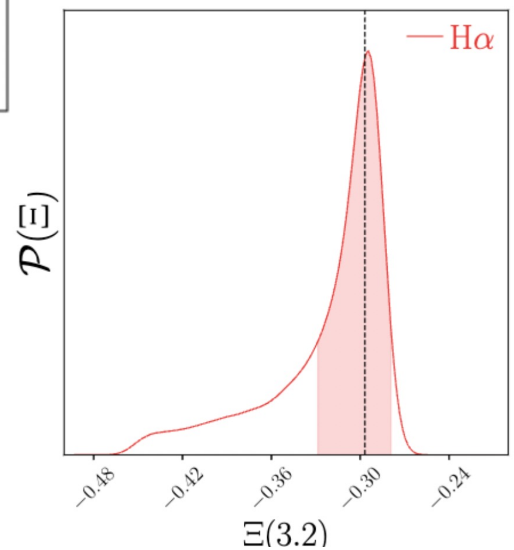


ΛCDM



$wCDM$

$\Xi = (1 - \Omega_m)^{3.2} w$



Caveat

- Measuring the power spectrum on very large scales is challenging
- Variations of the flux limit between areas observed at different times and other systematic effects (e.g. dust corrections) could create spurious clustering
- On the other hand, the signal we are after has a very characteristic signature

Conclusions

- Our peculiar velocity modifies the redshift, size, and luminosity of cosmological sources
- The observed galaxy overdensity contains a dipolar deterministic term proportional to $v_{\|obs}$ (the FOTO effect)
- This generates characteristic oscillatory patterns in the monopole moment of the power spectrum on large scales
- This signal cannot be erased with a simple redshift transformation. Actually, we can take advantage of it to enhance the effect.
- If clustering statistics can be robustly measured on such large scales, the FOTO effect gives a handle to measure $\mathbf{v}_{obs}$ and constrain the expansion history of the Universe