Is it possible to measure the observer's velocity from spectroscopic redshift surveys?

Daniele Bertacca

Understanding the Galaxy/Matter Connection in the
Era of Large Surveys
Sestri Levante, 16 September 2024

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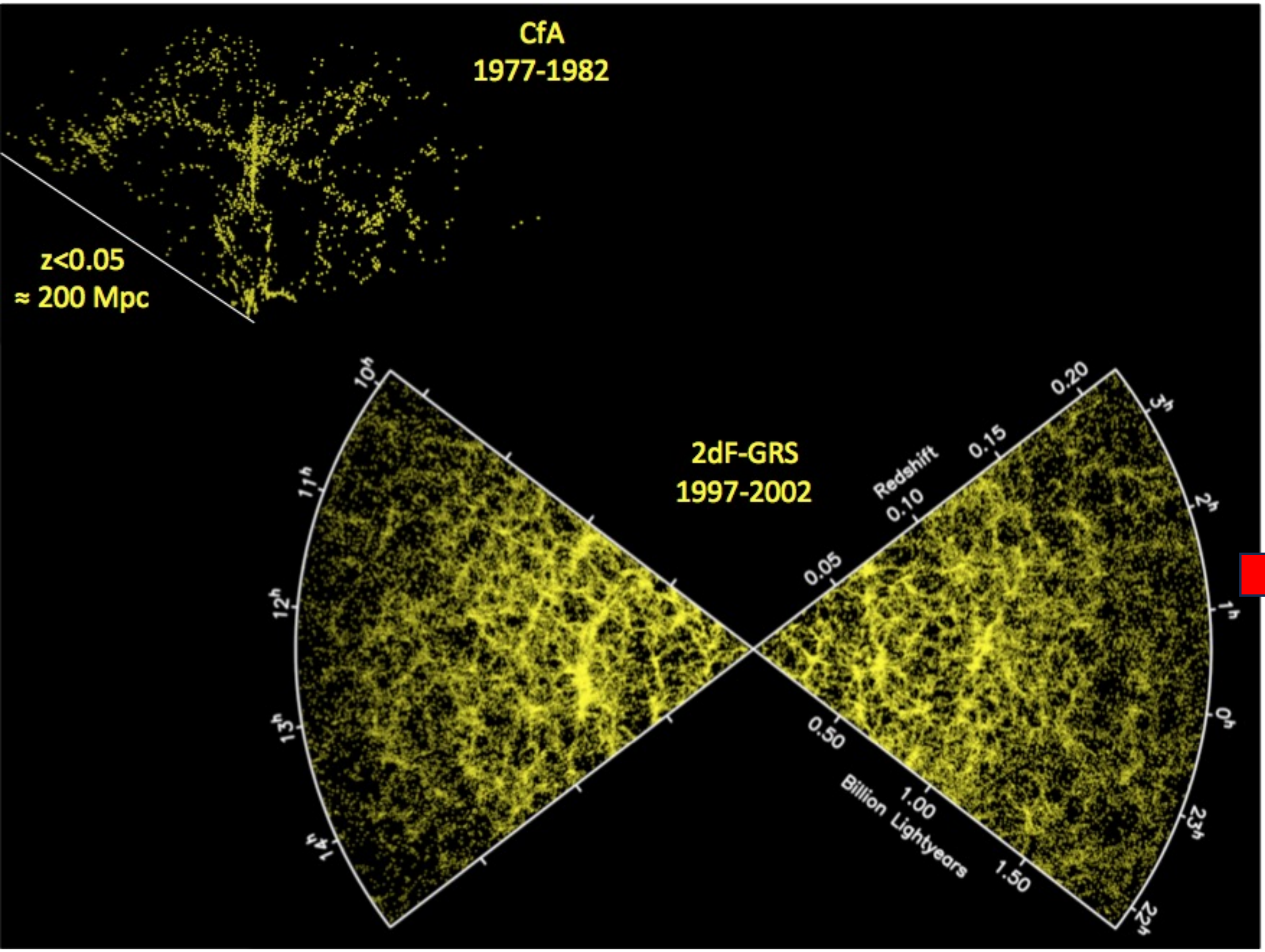
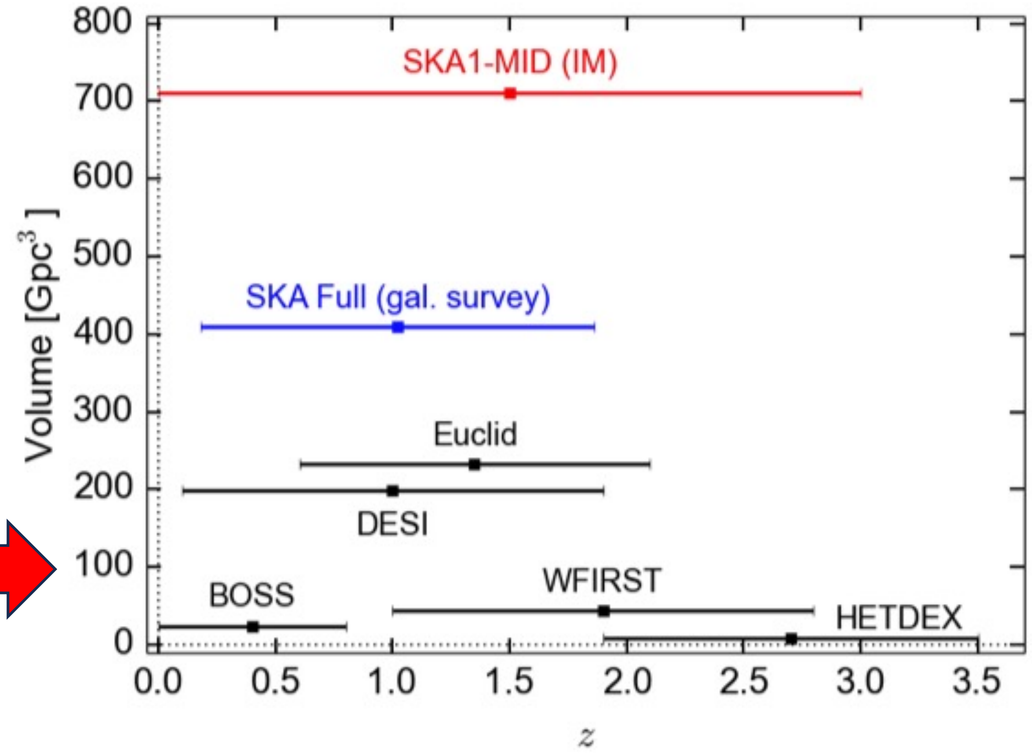


Since the 1970s, the size of galaxy catalogs has constantly increased in terms of solid-angle and redshift coverage as well as in sampling rate.

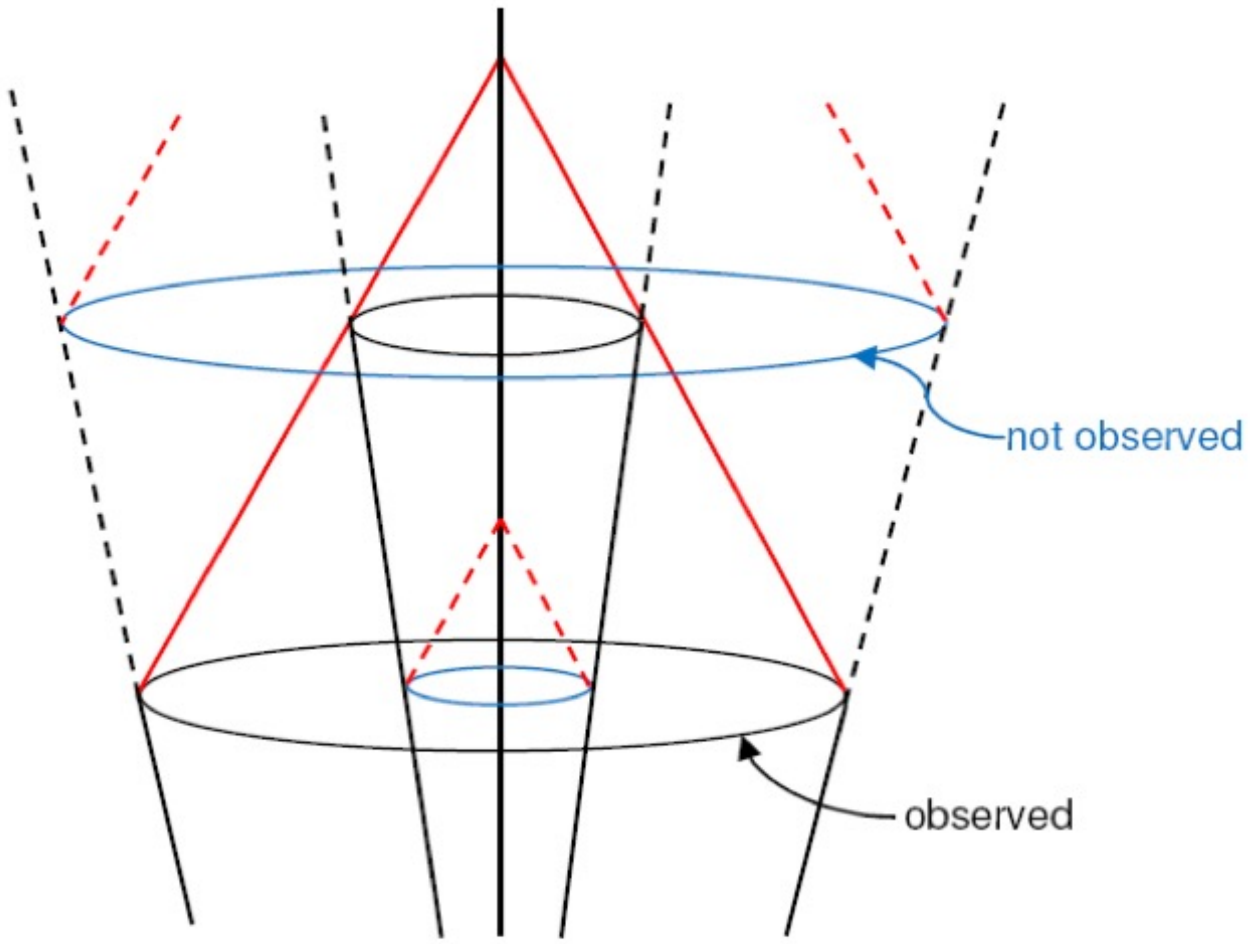


Forthcoming surveys will cover large volumes of the observable Universe and will reach to high redshifts.

General relativistic effects: Δ_g case

There are two fundamental issues:

- Correctly identify the galaxy overdensity Δ_g that we observe on the past light cone.
- Account for all the distortions arising from observing on the past light cone, e.g. **the dipole effect!**



Credit: Roy Maartens

Distortions have already been measured:

- Redshift space: the redshift is affected by galaxies velocity redshift-space distortions (Kaiser1987)
- Bias: the distribution of galaxies is a biased tracer.
- Magnification bias: gravitational lensing changes the solid angle and the threshold of observation (e.g. Broadhurst, Taylor and Peacock 1995)

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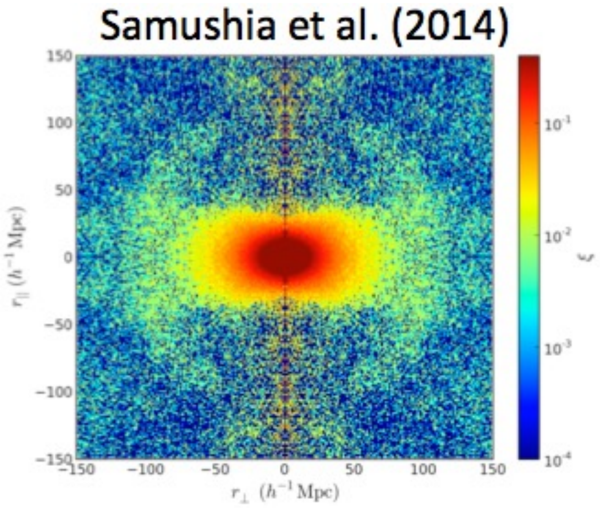
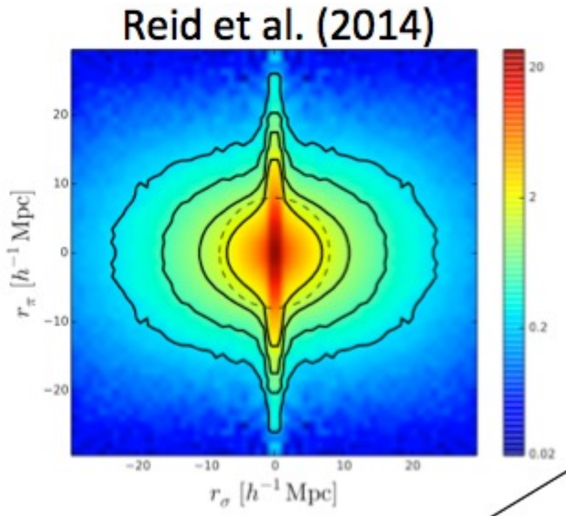
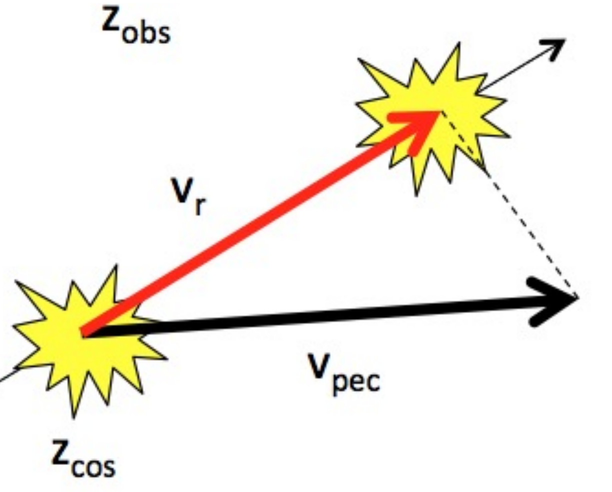
These contributions are added in ad hoc manner!

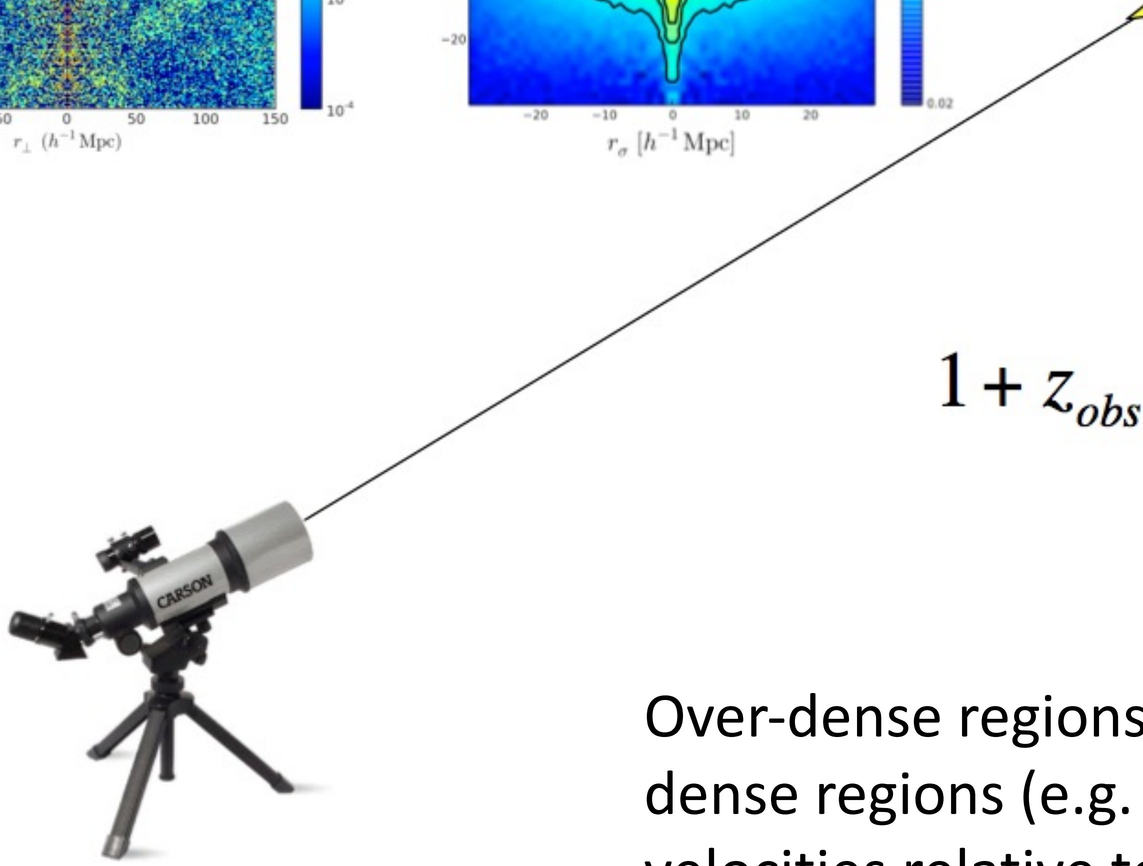
Is this everything?
Do we need to consider also the dipole effect on very large scales?

Redshift-space distortions









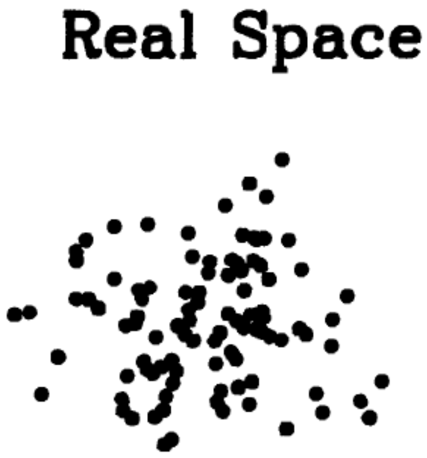
$$1 + z_{obs} = (1 + z_{cos})(1 + \frac{v_r}{c})$$

Over-dense regions (e.g. galaxy clusters) and under-dense regions (e.g. voids) induce additional peculiar velocities relative to the Hubble flow.

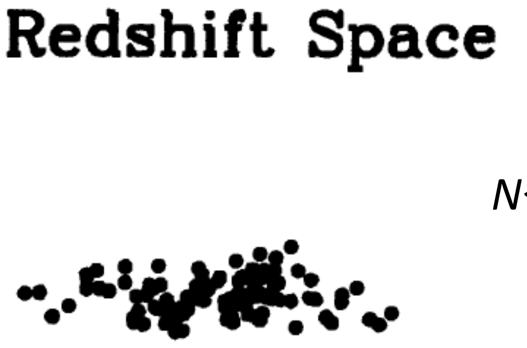
Credit: Cristiano Porciani

Redshift-space distortions

e.g. Hamilton 1997



$N^{\mathcal{R}}$



$N^{\mathcal{S}}$

$$1 + \delta^{\mathcal{S}}(\mathbf{s}) = [1 + \delta^{\mathcal{R}}(\mathbf{r})] \left(1 + \frac{\partial v_r}{\partial r}\right)^{-1} \left(1 + \frac{v_r}{r}\right)^{-2} \frac{\bar{N}(r)}{\bar{N}(r + v_r)}$$

$$\delta^{\mathcal{S}}(\mathbf{r}) = \delta^{\mathcal{R}}(\mathbf{r}) - \left(\frac{\partial v_r}{\partial r} + \frac{\alpha(\mathbf{r}) v_r}{r}\right) \qquad \alpha(\mathbf{r}) = \frac{\partial \ln r^2 \bar{N}^s(\mathbf{r})}{\partial \ln r}$$

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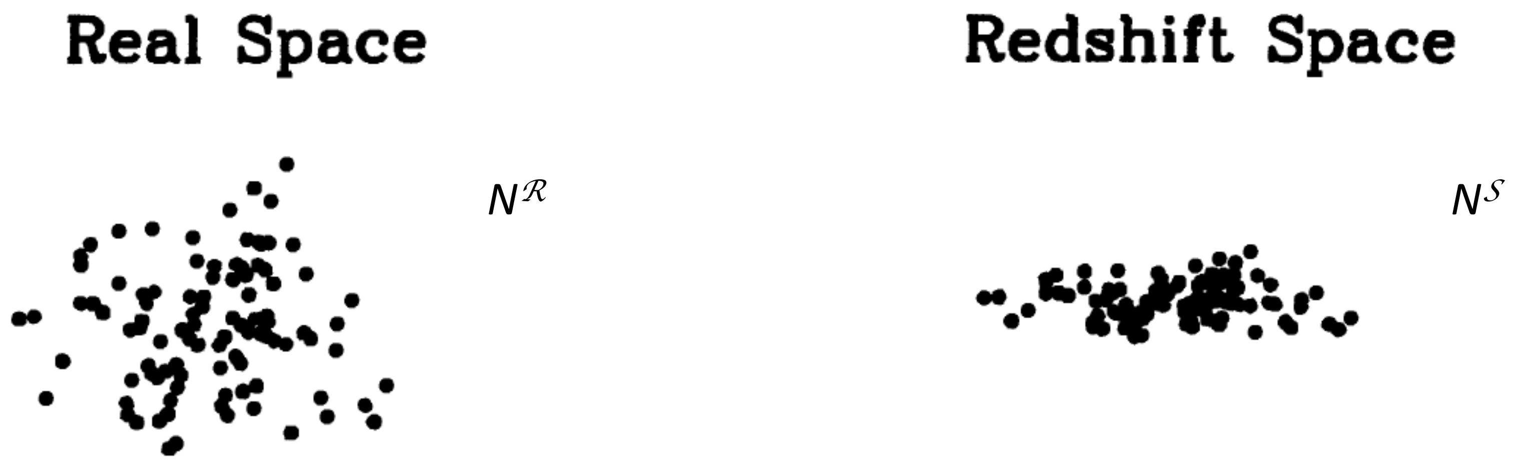
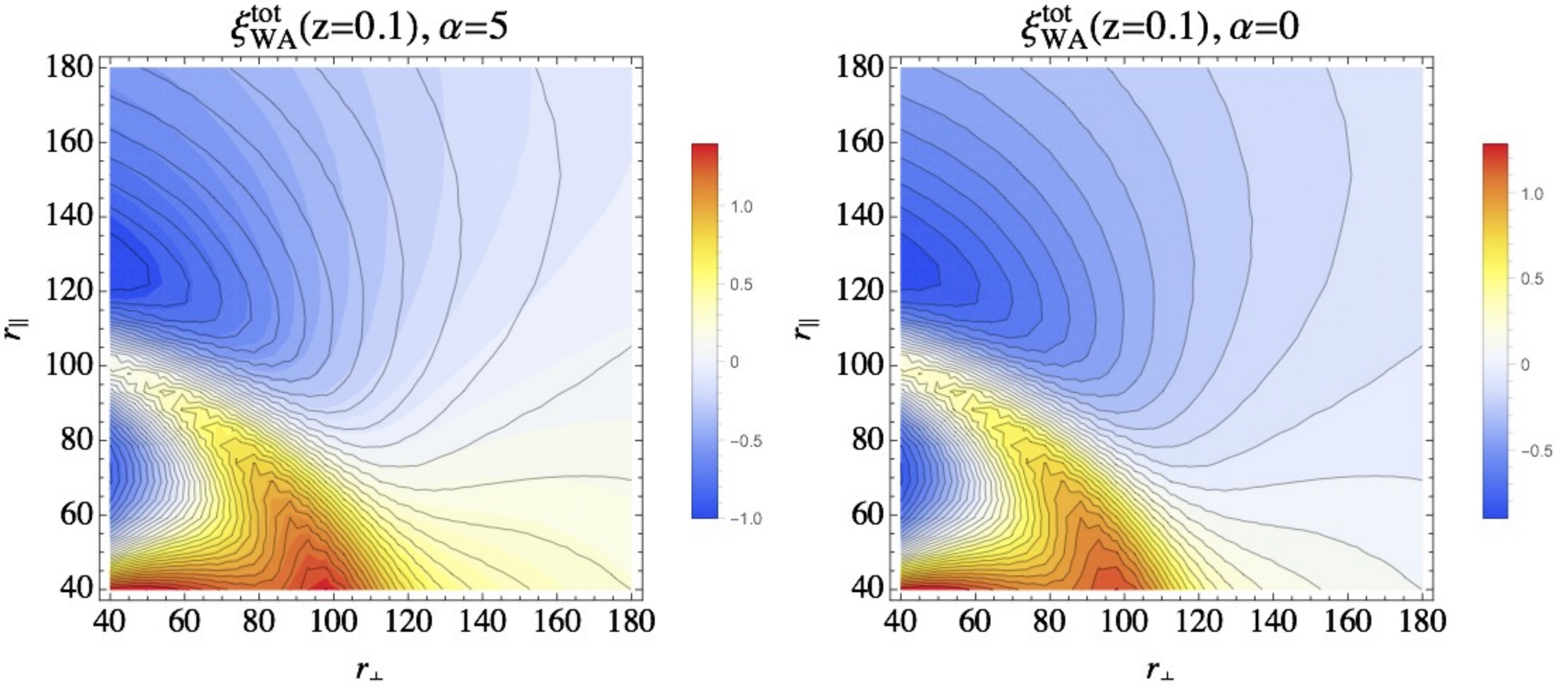


$$\delta^{\mathcal{S}}(\mathbf{r}) = \delta^{\mathcal{R}}(\mathbf{r}) - \left(\frac{\partial v_r}{\partial r} + \cancel{\frac{\alpha(\mathbf{r}) v_r}{r}} \right)$$

- **Peculiar velocities** v_r of galaxies are **small** compared to their distances r from the observer (NB: for future wide surveys probing wide angular scales, $v_r/r \approx \partial v_r/\partial r$ term, and in general cannot be neglected!)
- **Flat-sky approximation** (or plane-parallel case) $\hat{e}_r$ is the same for all galaxies considered
- **Doppler term**: $\alpha v_r/r$, does not naturally disappear, but in flat-sky approximation it is usually neglected.

Velocity and Doppler terms: α

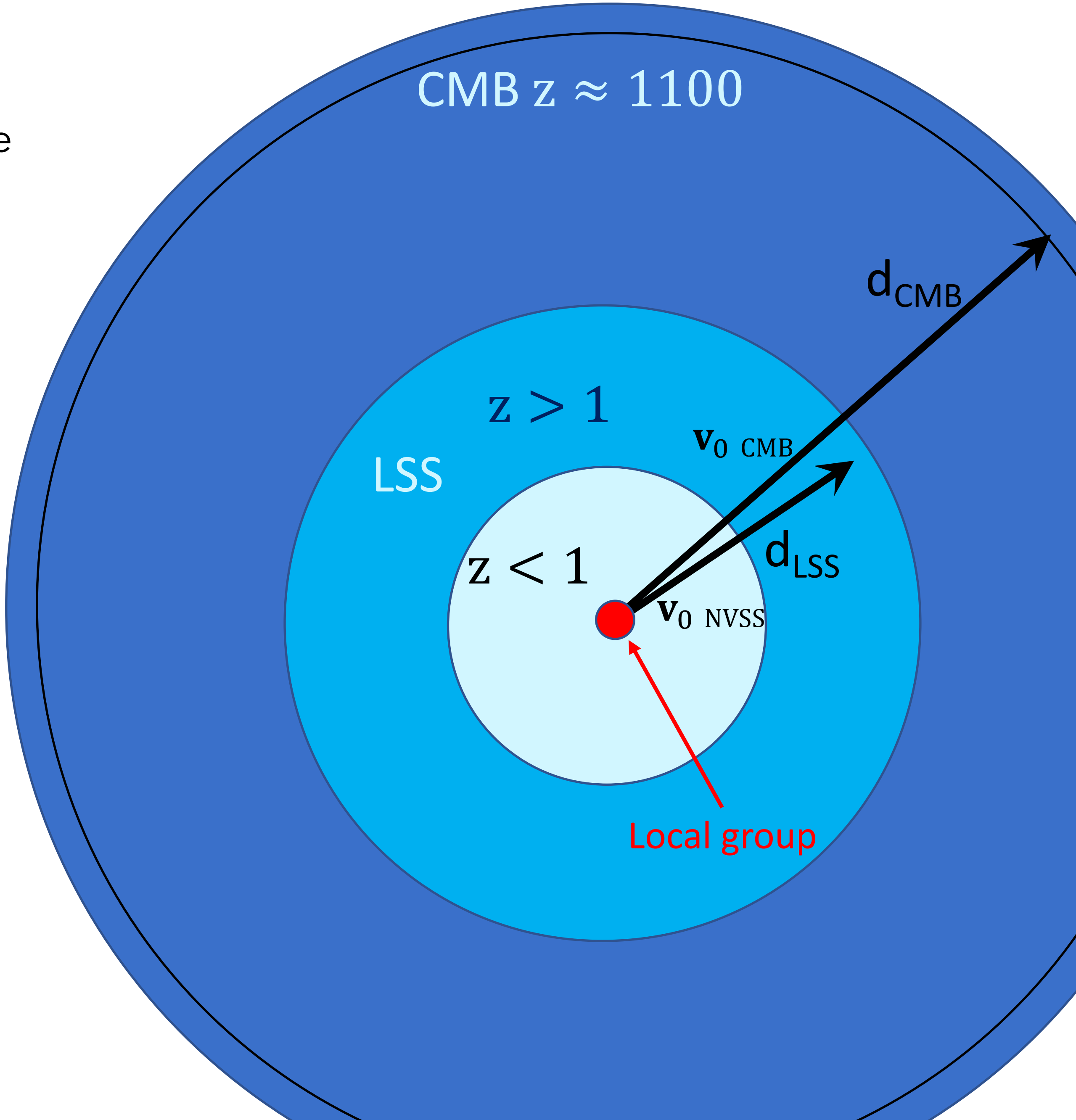
DB et al 2012, 1205.5221
Raccanelli (+ DB) et al. 2016, 1602.03186



2D redshift-space galaxy correlation function including wide-angle terms:
- The effect of $\alpha = 0$ and $\alpha = 5$ corresponds to the value obtained from a gaussian galaxy distribution centered at $z = 0.1$ and with $\sigma = 0.1$. **As expected, the deviation from the $\langle\delta\delta\rangle$ case increases with α.**
- Using **a multi-tracer approach** (e.g. see McDonald & Seljak 2009), in Borzyszkowski, DB & Porciani (2017) we show that the corresponding redshift-space distortions **can be detected at 5.5σ significance with the completed Square Kilometre Array. (See also Stefano talk)**

About the dipole on the LSS?

It is completely expected that a dipole will be present in any survey of objects that trace the Large-Scale Structure (LSS).



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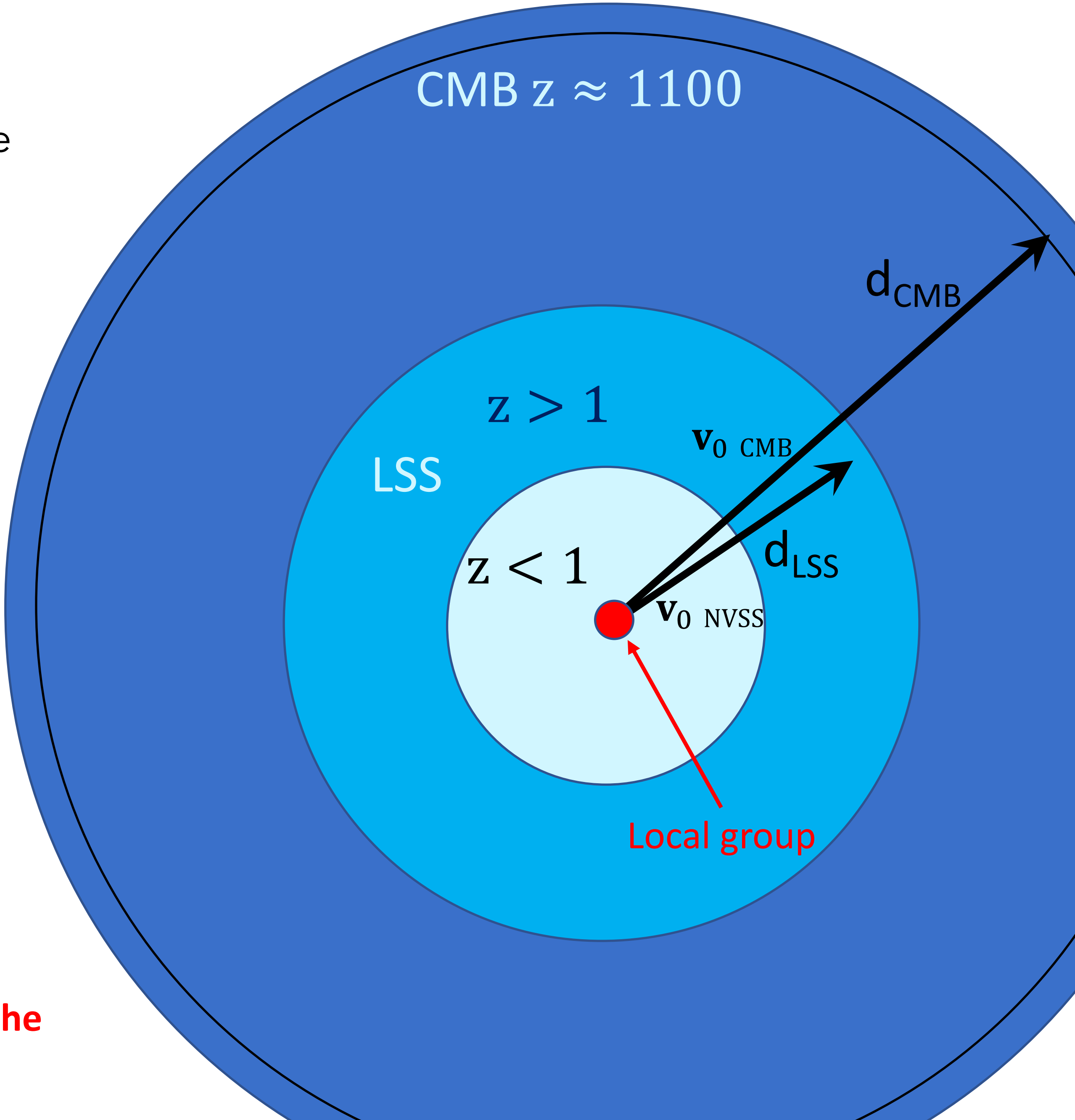
The following effects contribute to the dipole [Gibelyou and Huterer (2012)]:

(a) there are local anisotropies since the Universe is not homogeneous and isotropic except on its very largest scales, This effect is called the intrinsic dipole.

(b) the Earth has a total motion relative to the LSS rest frame that is the sum of several vector contributions:

- the Earth moves around the Sun, the Sun moves around the centre of the Milky Way, the Milky Way moves with respect to the Local Group barycentre and the Local Group barycentre moves with respect to the structure around it and, ultimately, the LSS rest frame. This is called the kinetic dipole.



Here we assume that the rest frame of the LSS is the same as the rest frame of the CMB

Redshift-Space Distortion at high-redshift

The previous redshift space definition

- was derived to model low-redshift surveys
- without the velocity of the observer $\mathbf{v}_0$.
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Consequences of relaxing these assumptions:

Defining $v_\parallel = \mathbf{n} \cdot \mathbf{v} = v_r$, from the Jacobian determinant of the coordinate transformation from real- to redshift-space contains some extra terms

$$\frac{\partial \Delta r}{\partial r} = \frac{(1+z)}{H} \frac{\partial v_\parallel}{\partial r} + \left[1 - \frac{\partial \ln H}{\partial \ln(1+z)}\right] (v_\parallel - v_{0\parallel})$$

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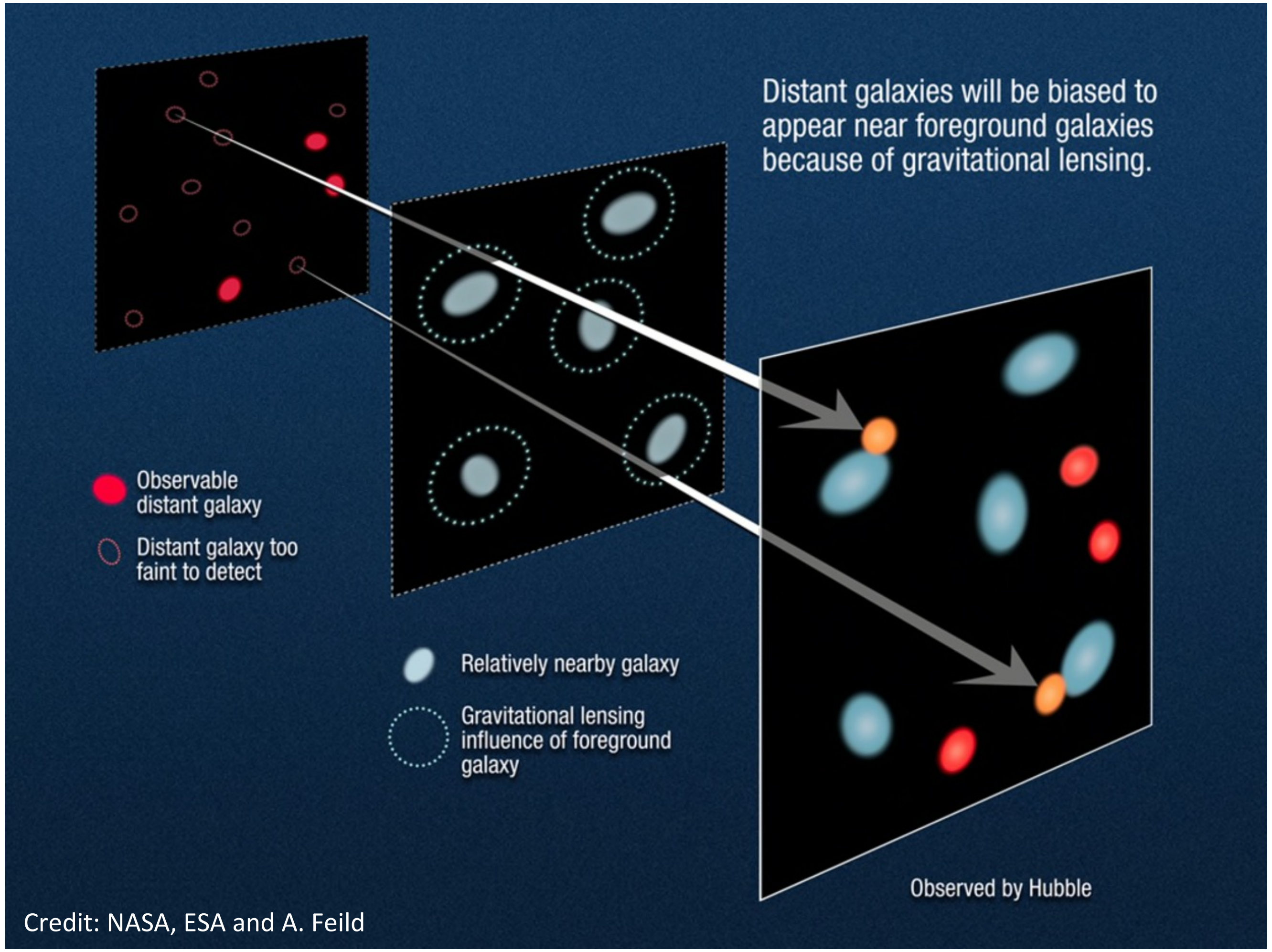
Considering the additional contribution to δ^S , the previous relation is still valid if we consider $v_{0\parallel}$ and as long as we replace α with

$$\alpha_c = \alpha + \left[1 - \frac{\partial \ln H}{\partial \ln(1+z)}\right]\frac{rH}{c(1+z)}$$

Note that the correction vanishes when $z \to 0$ but is of order unity at finite redshift.

Magnification bias

Metric perturbations also alter the solid angle under which galaxies are seen by distant observers, thereby enhancing or decreasing their apparent flux [Turner (1980), Broadhurst, Taylor & Peacock (1995)].



- **This correction needs to account for the selection of survey targets from flux limited samples.**
- Multiple imaging always magnifies the source, so lensed sources are brighter than the population from which they are drawn.
- **The magnification $\mathcal{M}$ is the Jacobian relating area on the image and source planes**

Magnification bias (extra dipole effect!)

Metric perturbations also alter the solid angle under which galaxies are seen by distant observers, thereby enhancing or decreasing their apparent flux [Turner (1980), Broadhurst, Taylor & Peacock (1995)].

In terms of the luminosity distance d_L, the magnification of a galaxy is defined as [e.g., see Challinor & Lewis 2011, Jeong, Schmidt & Hirata (2011), Bertacca (2014)]

$$\mathcal{M} = \left(\frac{d_L}{\langle d_L \rangle_z}\right)^{-2} \approx 1 - 2\left(1 - \frac{(1+z)}{H\chi}\right)\boldsymbol{n} \cdot (\mathbf{v} - \mathbf{v}_0) + 2\kappa + \cdots$$

where the brackets denote an average taken over all the sources with the same observed redshift of the galaxy, z.

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where the brackets denote an average taken over all the sources with the same observed redshift of the galaxy, z. The galaxy overdensity is then $\delta_g^S = \delta_{\text{no-mag}} + Q(\mathcal{M} - 1)$

κ contains both the **Weak Lensing convergence integral and the aberration that depends on $\mathbf{v}_0 = \mathbf{v}_{\text{obs}} = \mathbf{v}(\chi = 0)$** (which is the velocity of the observer), i.e.

$$\kappa = -v_{\parallel o} + \int_0^{\bar{\chi}} \mathrm{d}\tilde{\chi}\,(\bar{\chi} - \tilde{\chi})\,\frac{\tilde{\chi}}{\bar{\chi}}\,\tilde{\nabla}_\perp^2 \Phi$$

Then $\longrightarrow$ $2\dfrac{(1+z)}{H\chi}\boldsymbol{n}\cdot\mathbf{v}_0$ $\longrightarrow$ **Here we see an asymmetry between $\mathbf{v}_0$ and $\mathbf{v}$!!**

Relativistic corrections to α

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- Considering all relativistic corrections to linear order, one obtains [Bertacca (2019); Elkhashab, Porciani, Bertacca (2021); Elkhashab, Porciani, Bertacca in prep.]:

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

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

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

This +2 is due to the aberration.
We obtain this effect when we do the Jacobian!

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Here we have defined the evolution bias $\mathcal{E}$ and the magnification bias Q of the selected galaxy population as

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

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

In words, $\mathcal{E}$ quantifies the logarithmic change in the comoving number density of selected galaxies due to the redshift evolution of the amplitude and shape of the luminosity function at fixed L_{min}.
Instead, Q gives the response of $\ln \bar{n}$ to changes in the limiting luminosity at fixed z.
Note that $\alpha_{\mathrm{s}} \simeq \alpha_{\mathrm{o}} \simeq \alpha_{\mathrm{c}} \simeq 2\,(1-\mathcal{Q})$ when $r \ll c/H$.

GR corrections at large scales with (Newtonian) N-body simulations

- Multiple efforts have been made in the literature to investigate the detectability of subtle relativistic effects with Euclid and other forthcoming surveys.

- Generally these studies are based on the Fisher-information matrix, use idealised survey characteristics and neglect systematics.

- The ultimate test to discern what relativistic effects will be observable is to apply the very same estimators that are used for the data to mock catalogs that include all the physics.

Simulations!

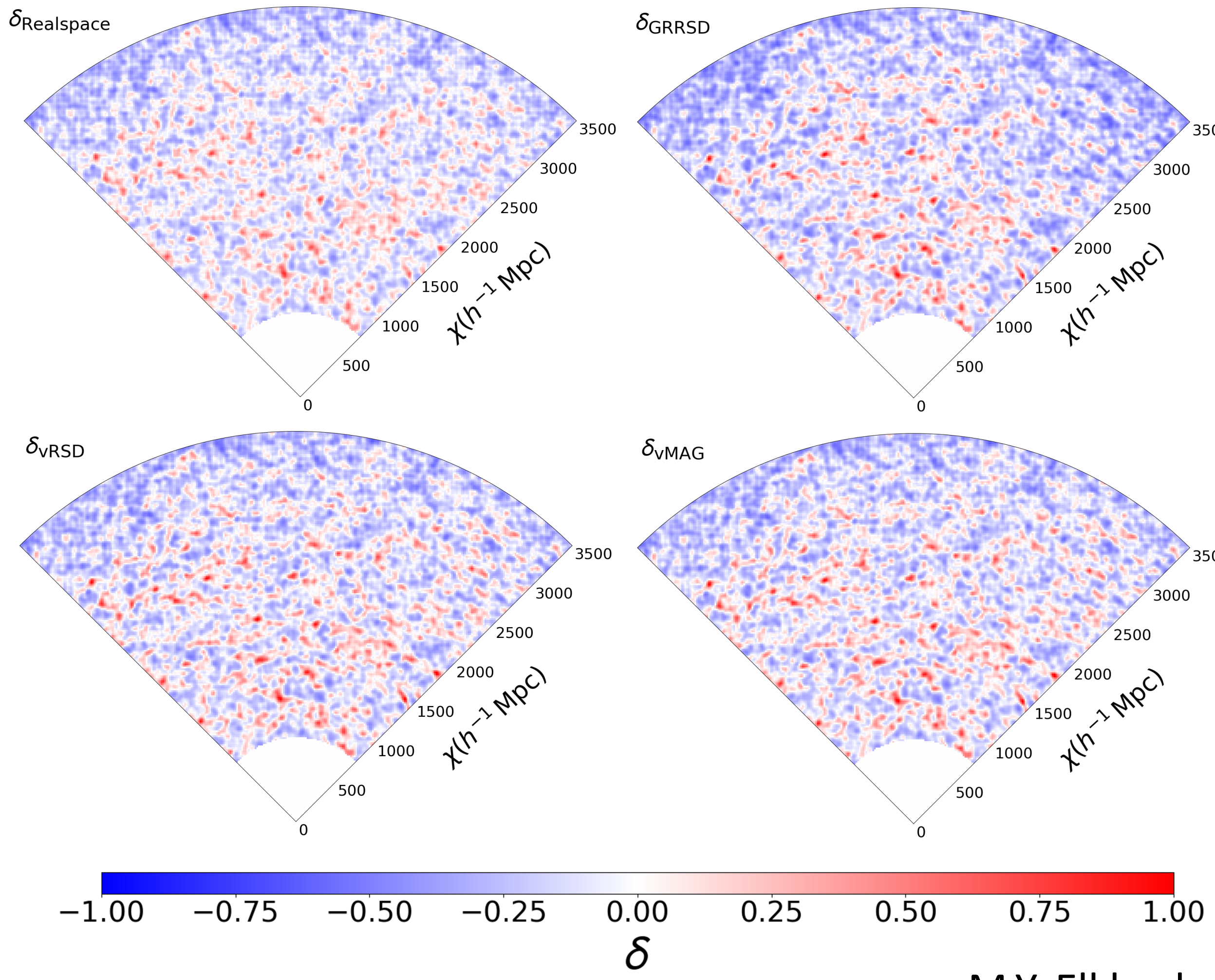
- Raul Abramo and DB 1706.01834
- Borzyszkowski, DB and Porciani, MNRAS (2017) 471, 4, astro-ph:1703.03407

Particle Shift with N-Body simulations

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

LIGER is a code that takes a Newtonian simulation (N-body or hydro) as an input and outputs the distribution of galaxies in comoving redshift space (i.e. on the light cone of a perturbed FRW background).

Newtonian simulation → **Select an observer** → **Shift & magnify galaxies** → **Extract light cone**



This is achieved by using a coordinate transformation that includes local terms and contributions that are integrated along the line of sight.

M.Y. Elkhashab
Masters thesis

Kaiser vs GR: Monopole of the power spectrum

The monopole of the power spectrum is defined as

$$P_0(k,z) = \frac{1}{2}\int_{-1}^{1} P_g(k,\mu,z)\,\mathrm{d}\mu\,,$$

where $P_g(k,\mu,z)$ is the power spectrum, ad a given (average within the bin) redshift z, i.e.

$$P_g(k,\mu,z) = \int_{V_{\mathrm{bin}}} \left\langle \delta_g\left(\boldsymbol{x}+\frac{\boldsymbol{r}}{2}\right)\delta_g\left(\boldsymbol{x}-\frac{\boldsymbol{r}}{2}\right)\right\rangle e^{-i\boldsymbol{k}\cdot\boldsymbol{r}}\mathrm{d}^3r$$

and

$$\mu = \frac{\boldsymbol{k}}{k}\cdot\boldsymbol{n},$$

and $\boldsymbol{n}$ the direction along the line of sight.

The dipole/finger observer Effect

- Galaxy redshift measurements are distorted by the peculiar velocity of the observer.
- In general, the impact of observer velocity on the galaxy clustering measurements is often neglected.
- An observer with a peculiar velocity measures an additional contribution to δ_{obs} , i.e.

$$\delta_{\text{obs}} = \delta_{\text{standard}} + \delta_{\text{dip}}$$

- δ_{dip} imprints a characteristic dipole pattern on the sky and displays a variable amplitude as a function of radial distance reflecting the properties of the selected galaxy population and the expansion history of the Universe. Here,

$$\delta_{\text{dip}} = \frac{\alpha_{\text{o}}}{r} \frac{v_{\parallel,\text{o}}}{aH} \quad \text{where} \quad \alpha_{\text{o}} = 2\,(1 - \mathcal{Q}) + \left[3 - \mathcal{E} - \frac{\mathrm{d}\ln H}{\mathrm{d}\ln(1+z)}\right] \frac{r\,H}{c\,(1+z)}$$

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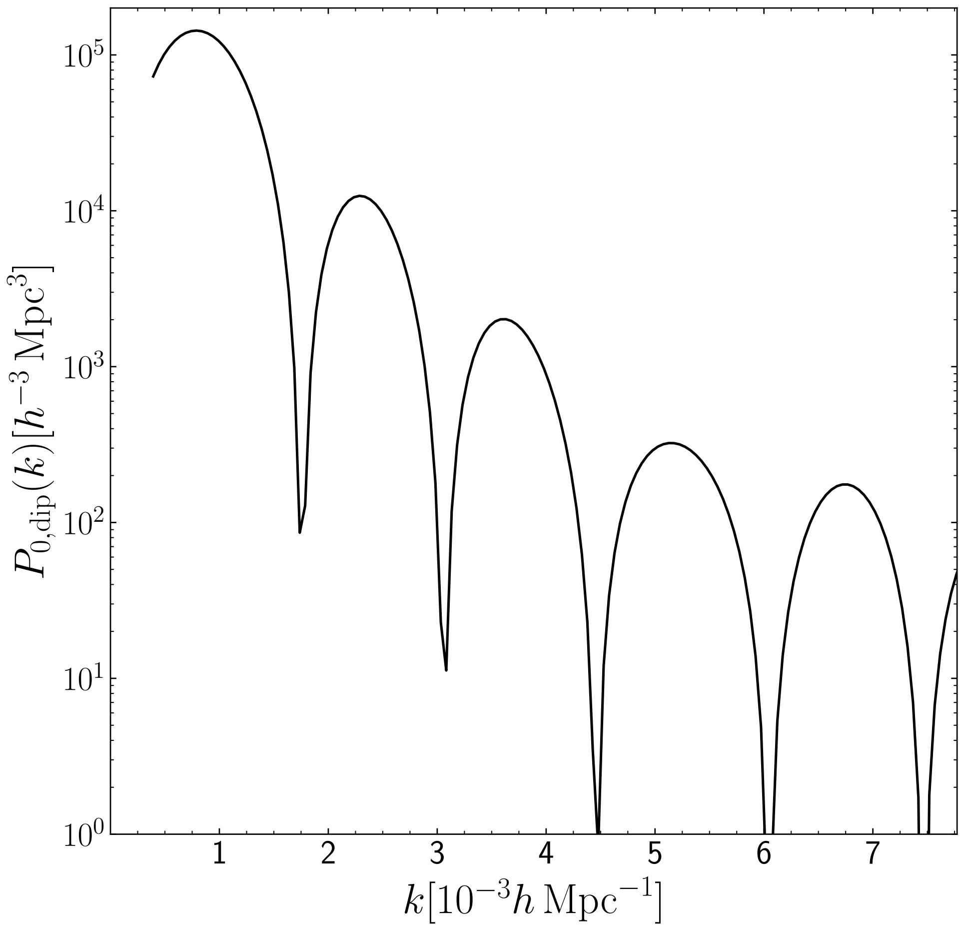
This effect on LSS is also called *the kinematic dipole* [Gibelyou and Huterer (2012)] or "Kaiser Rocket effect" [Bertacca (2019), Bahr-Kalus, DB, Verde & Heavens (2021)], or "Finger Of The Observer" (FOTO) [Elkhashab, Porciani and DB (2021)] due to our peculiar velocity.

Finger of the observer effect from LIGER method?



Now, could this effect be used to measure v_{o}=$|\mathbf{v}(0)|$?

Note that for a narrow shell of width $\Delta r \ll r$, where r is comoving distance within which all functions can be treated as constants, we have

$$P_{0,\mathrm{dip}}(k) = \frac{4\pi}{3}\alpha_o^2(z)\,(1+z)\,\frac{v_o^2}{H(z)}\,\Delta r\; j_1^2(kr)$$

where $\alpha_o(z)$ depends by the shape of $n(z), H(z), Q(z)$ etc…

In other words, δ_{dip}

- alters the monopole moment (with respect to the line of sight) of the galaxy power spectrum, $P_0(k)$, measured with traditional estimators, e.g. see Bertacca 2019, Mitsou et al. 2020, Castorina Di Dio 2020, Bahr-Kalus, DB, Verde & Heavens (2021), Elkhashab, Porciani and DB (2021), Elkhashab, Porciani and DB in perp.
- imprints a characteristic dipole pattern on the sky reflecting the properties of the selected galaxy population and the expansion history of the Universe, see Elkhashab, Porciani and DB in perp.

About higher multipoles?

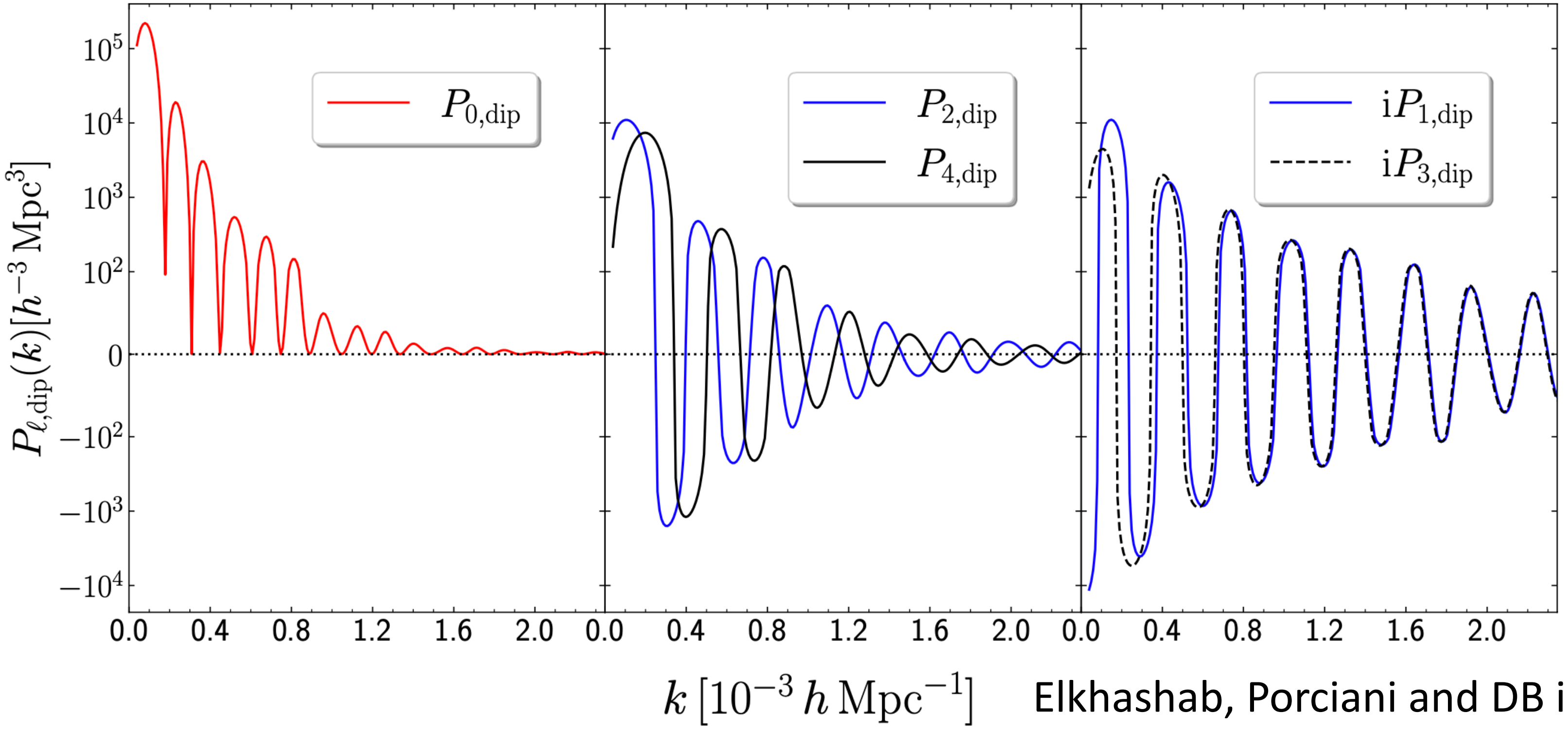
Extend the analytical treatment of Elkhashab, Porciani & DB (2021) to all the multipoles of the power spectrum.

Using the Yamamoto estimator in the local plane parallel approximation

$$\hat{P}_{\ell,\mathrm{obs}}(k) \equiv \frac{2\ell+1}{\int \bar{n}^2\, \mathrm{d}^3r} \iiint \bar{n}(r_1)\, \bar{n}(r_2)\, \delta_{\mathrm{obs}}(\boldsymbol{r}_1)\, \delta_{\mathrm{obs}}(\boldsymbol{r}_2) \mathrm{e}^{i\boldsymbol{k}\cdot(\boldsymbol{r}_2-\boldsymbol{r}_1)} \mathcal{L}_\ell(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{r}}_2)\, \mathrm{d}^3r_1\, \mathrm{d}^3r_2\, \frac{\mathrm{d}^2\Omega_k}{4\pi},$$

where $\mathcal{L}_\ell$ denotes a Legendre polynomial of order ℓ. We compute the impact of the FOTO signal by replacing δ_{obs} with the function δ_{dip}. The result reads as

$$P_{\ell,\mathrm{dip}}(k) = \frac{16\pi^2\,(2\ell+1)}{3}\, \frac{v_\mathrm{o}^2}{3\,H_0^2}\, \frac{I_1}{\int \bar{n}^2\, \mathrm{d}^3r} \left[\sum_{\ell'=0}^{\infty} \begin{pmatrix} \ell & \ell' & 1 \\ 0 & 0 & 0 \end{pmatrix}^2 (2\ell'+1)(-1)^{\ell'}(\mathrm{i})^{\ell'+1}\, I_{\ell'}\right]$$



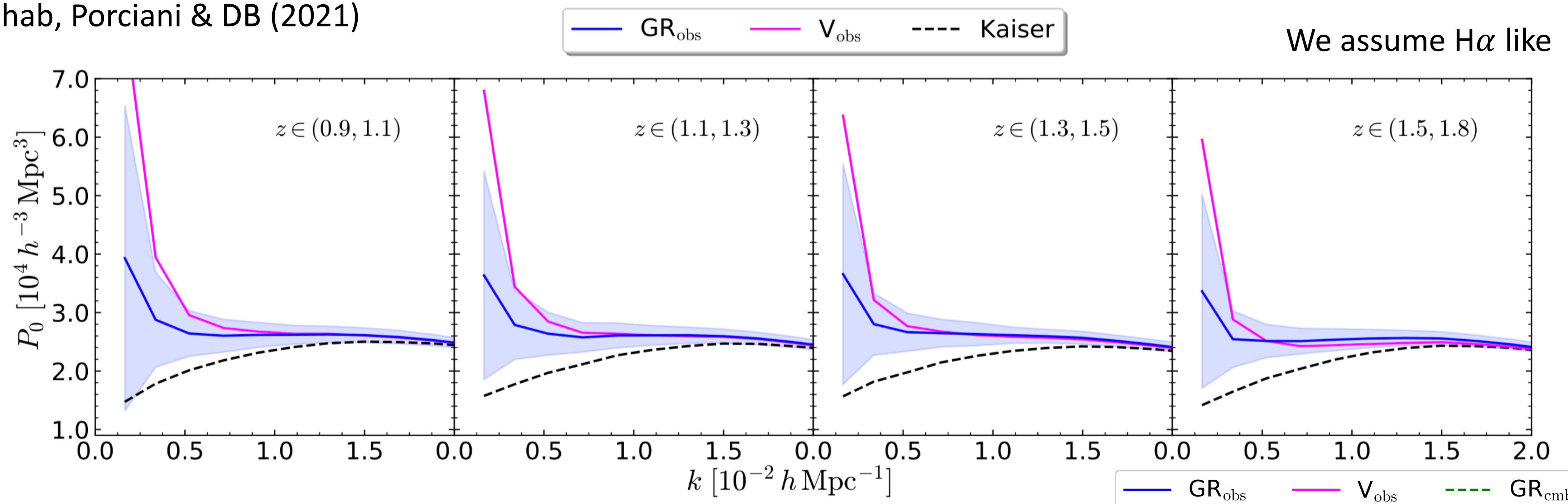
Elkhashab, Porciani and DB in perp.

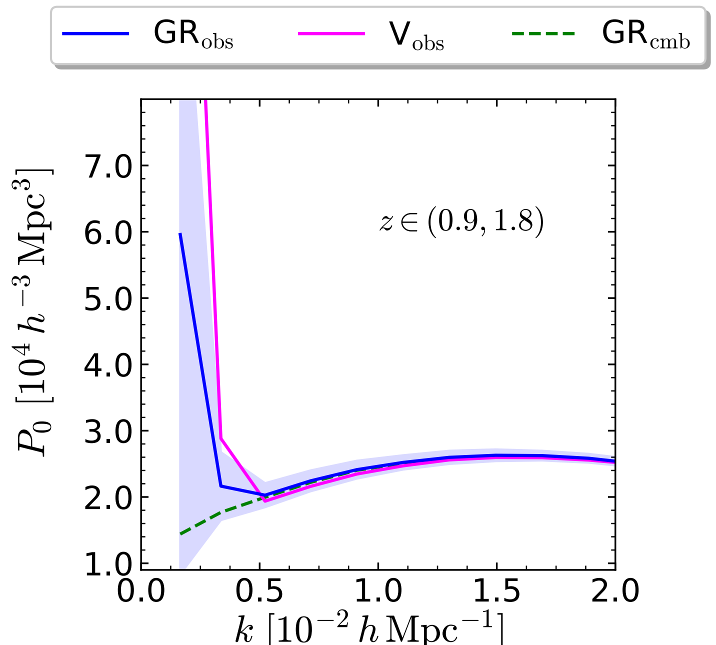
We also observe that even contributions are real, while odd contributions are purely imaginary due to the plane parallel approximation.

About the finger of the observer effect from LIGER method?

Elkhashab, Porciani & DB (2021)

We assume Hα like survey





The power-spectrum monopole (the solid curves) extracted from the GR$_{\rm obs}$ (blue) and V$_{\rm obs}$ (magenta) mocks. The shaded regions indicate the central 68% scatter for the GR$_{\rm obs}$ case. The dashed curves display the spectra obtained using the Kaiser model

- The spectra in the observer frame show a substantially higher clustering amplitude on the largest scales.
- This signal could be confused with the signature of primordial non-Gaussianity convolved with the window function.

Does Kaiser rocket mimic non-Gaussianity?

Bahr-Kalus, DB, Verde & Heavens (2021)

- The extra power induced by the Kaiser rocket effect, if unaccounted for, could mimic the signal of a small primordial non-Gaussianity of the local type.

- At the ultra-large scales that are of interest, the galaxy power spectrum monopole can be described by

$$P_g^{NG}(k) = \left(b_{\rm NL}^2(k) + \frac{2}{3} b_{\rm NL}(k) f + \frac{f^2}{5}\right) P_{\rm m}(k),$$

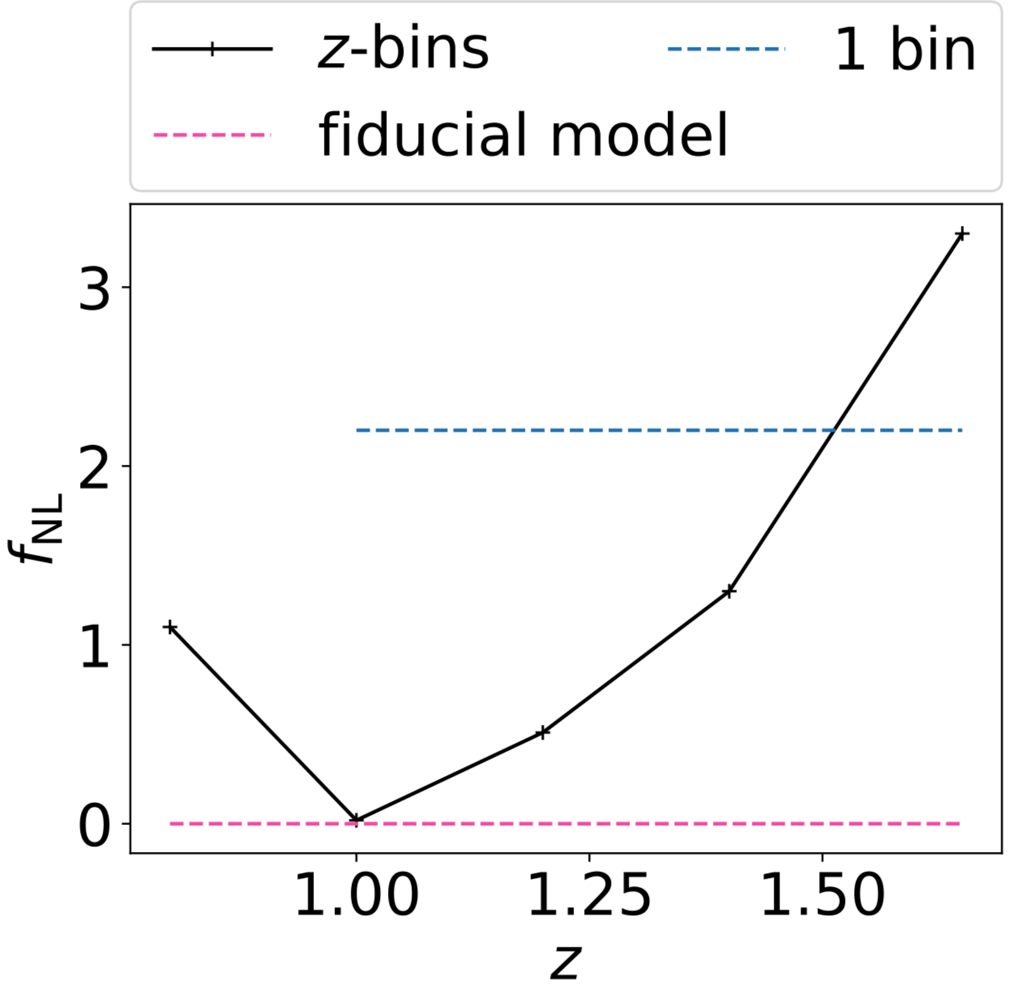
where

$$b_{NL}(k) = b_0 \left[1 + f_{NL} \frac{A}{k^2}\right]$$

- At that scales Kaiser rocket effect might mimic the same $b_{\rm NL}$ due to local PNG!!!

In Bahr-Kalus, DB, Verde & Heavens (2021):

- we estimate the bias on recovered cosmological parameters of a $f_{\rm NL}$-ΛCDM model – a ΛCDM model with an extra parameter for the amplitude of a (small) primordial local non-Gaussianity– in the presence of unsubtracted Kaiser rocket effect. (Euclid-like selection, Planck dipole)
- Kaiser rocket biases measurement of $f_{\rm NL}^{\rm (loc)}$ by 2.2 (0.23 σ)



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 : use priors on $\mathbf{v}_{obs}$ from CMB and measurements of the luminosity function to the **Finger of observer (FOTO)** effect as a cosmological probe

Credit to C. Porciani

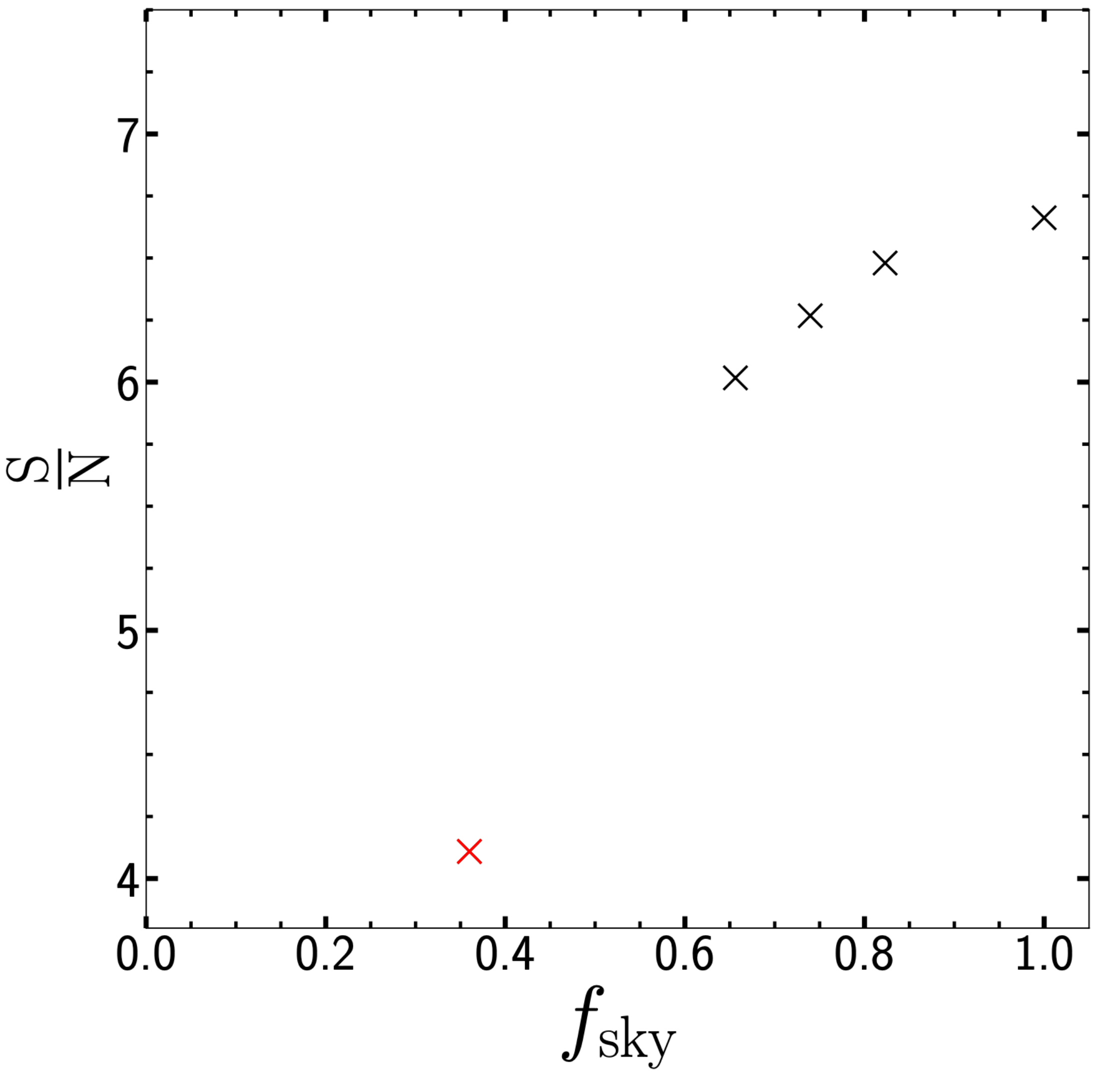
Is detectable for different survey geometries?

Measure the FOTO signal for the Hα example survey in the $z \in (0.9, 1.8)$ redshift bin employing the following footprints:

i) a full-sky survey;

ii) removing all galaxies that are within θ, where $\theta \in \{10^\circ, 15^\circ, 20^\circ\}$ from the Galactic plane;

iii) removing all galaxies that are within 20° from the Galactic and Ecliptic planes.

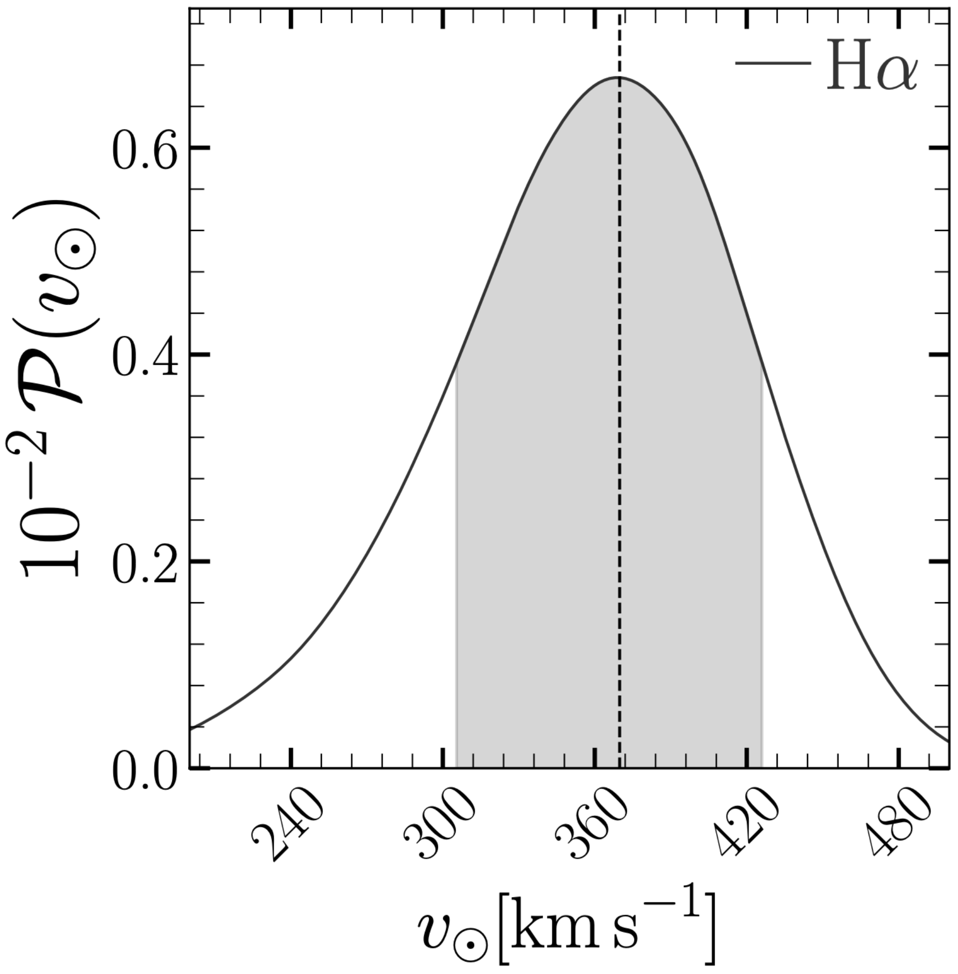


Signal-to-Noise ratio of the FOTO signal measured using the 0.9 < z < 1.8 redshift bin of the Hα survey against the fraction of the sky covered by the angular mask. The red-cross denotes the mask that removes all galaxies that are within 20° from the Galactic and Ecliptic planes.

Extracting the observer velocity.

- Using the Hα example survey, within the redshift range $z \in (0.9, 1.8)$ in the full-sky case, which led to a S/N ≈ 6.8
- We assume a Gaussian likelihood, and for the model signal and keeping the cosmological parameters and survey functions fixed. The model covariance is computed by averaging over the mock realizations.
- As for the prior distribution of the velocity magnitude, we employ a Maxwell distribution [Hamana+ 2003, Sheth & Diaferio (2001)] given by

  $\mathcal{P}(v_\odot) \sim \frac{\exp\left(-\frac{v_\odot^2}{2\sigma^2}\right)}{\sigma^3}$ with σ=289km/s.
- We are able to determine the velocity of the observer with a $\sim$ 25% precision



Can we eliminate the dipole effect in spectroscopic surveys?

- In general, it is not enough only corrected at the redshift level for spectroscopic surveys.
- Elkhashab, Porciani & **DB** (in prep.) show that **this signal cannot be cancelled**, and we are not able to recover the monopole of the power spectrum in the CMB frame.

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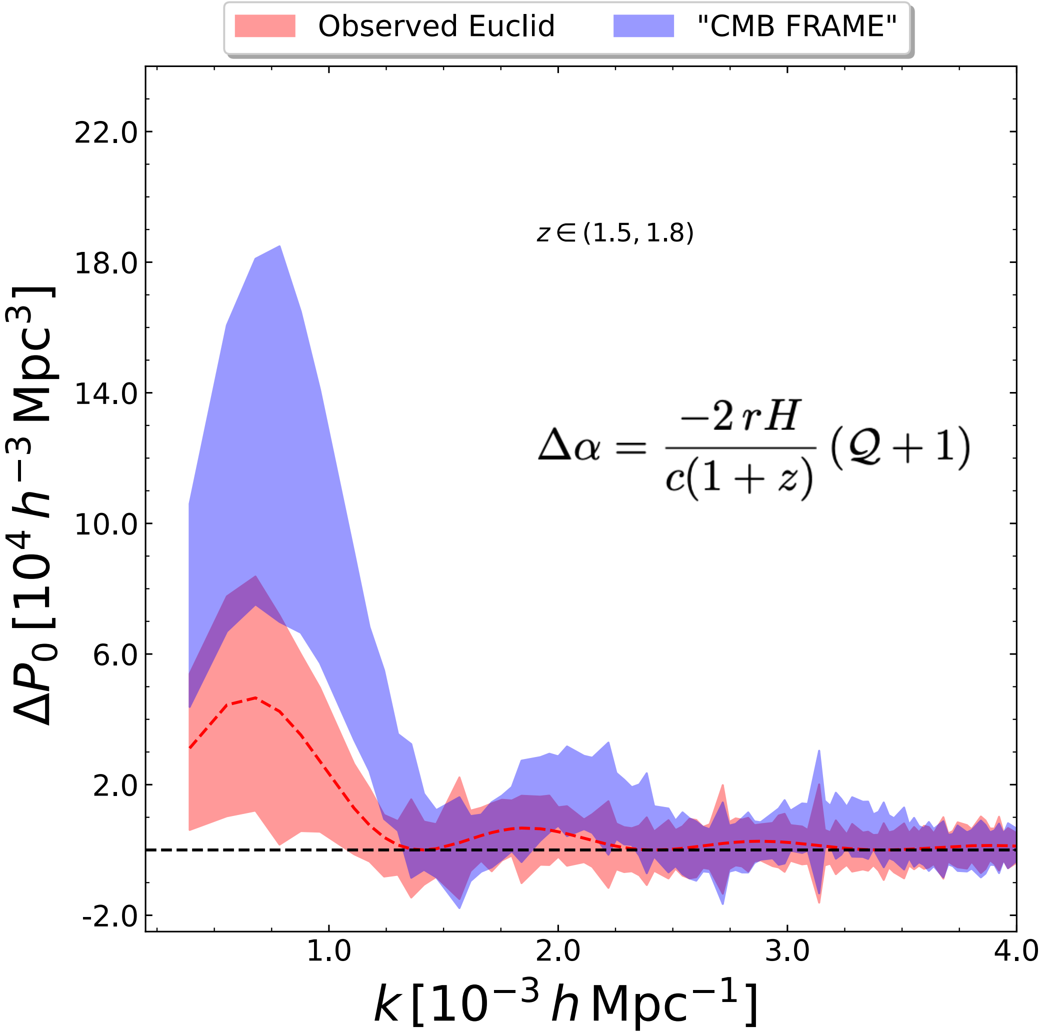
- We then test the standard redshift correction usually used to produce catalogues in the CMB by measuring the power spectrum after correcting the redshift of each individual galaxy:

Heliocentric redshift

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

"going to the CMB frame"



By comparing redshift corrected power spectra to the power spectra measured from the CMB frame mocks, we find that the correction does not cancel at all the observer velocity imprint due to purely relativistic terms that are missed. Moreover, the correction leads to a boost in the signal for surveys with redshifts $z > 0.4$.

Enhancing the signal with artificial redshift boosts, are we able to extract more cosmological information?

In the second part of the Elkhashab, Porciani & **DB** (in prep.) we have **artificially boosted** the dipole imprint on the monopole of the power spectrum by shifting the individual redshifts with 5 velocities in different directions.

This allows us to **measure the velocity of the observer** in a **new way**. In principle, through this new method, it is possible to use the dipole effect imprinted on the galaxy power spectrum to measure the expansion of the Universe.

In this way we can take advantage of it to enhance the effect.

Arbitrary boosts

The idea is as follows:

- pick an arbitrary peculiar velocity $\boldsymbol{v}_{\mathrm{art}}$;
- shift the redshift of each galaxy artificially by using the peculiar velocity $\boldsymbol{v}_{\mathrm{art}}$ and we obtain

$$1 + z_{\mathrm{art}} = \frac{1 + z_{\mathrm{obs}}}{1 + z_{\mathrm{shift}}} \ ,$$

where

$$z_{\mathrm{shift}} = \frac{\sqrt{1 - {v_{\mathrm{art}}}^2/c^2}}{1 - \boldsymbol{v}_{\mathrm{art}} \cdot \boldsymbol{n}/\boldsymbol{c}}.$$

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Then the density contrast becomes

$$\delta_{\rm art} = \delta_{\rm cmb} + \frac{\alpha_{\rm o}}{a\,H\,r}\,(\boldsymbol{v}_{\odot} \cdot \hat{r}) + \frac{\alpha_{\rm c}}{a\,H\,r}(\boldsymbol{v}_{\rm art} \cdot \hat{r}) \ ,$$

where

$$\alpha_{\rm c} = \alpha + \left[1 - \frac{{\rm d}\ln H}{{\rm d}\ln(1+z)}\right] \frac{Hr}{c(1+z)} \ .$$

- In Elkhashab, Porciani & **DB** (in prep.), we measure the monopole of the power spectrum $P_0(k)$ for the galaxies with modified redshifts and, by studying the impact of this artificial shift on the observed power spectrum signal, we are able to constrain the cosmological parameters.

Boosting the dipole signal, are we able to extract more cosmological information?

- In Elkhashab, Porciani & **DB** (in prep.) we demonstrate this method for a full-sky survey using the two example selection functions $\bar{n}_{\mathrm{H}\alpha}$ (Euclid/Roman like survey) and $\bar{n}_{\mathrm{HI}}$ (SKAO like survey)
- To showcase the constraining power of this method, we study three scenarios:

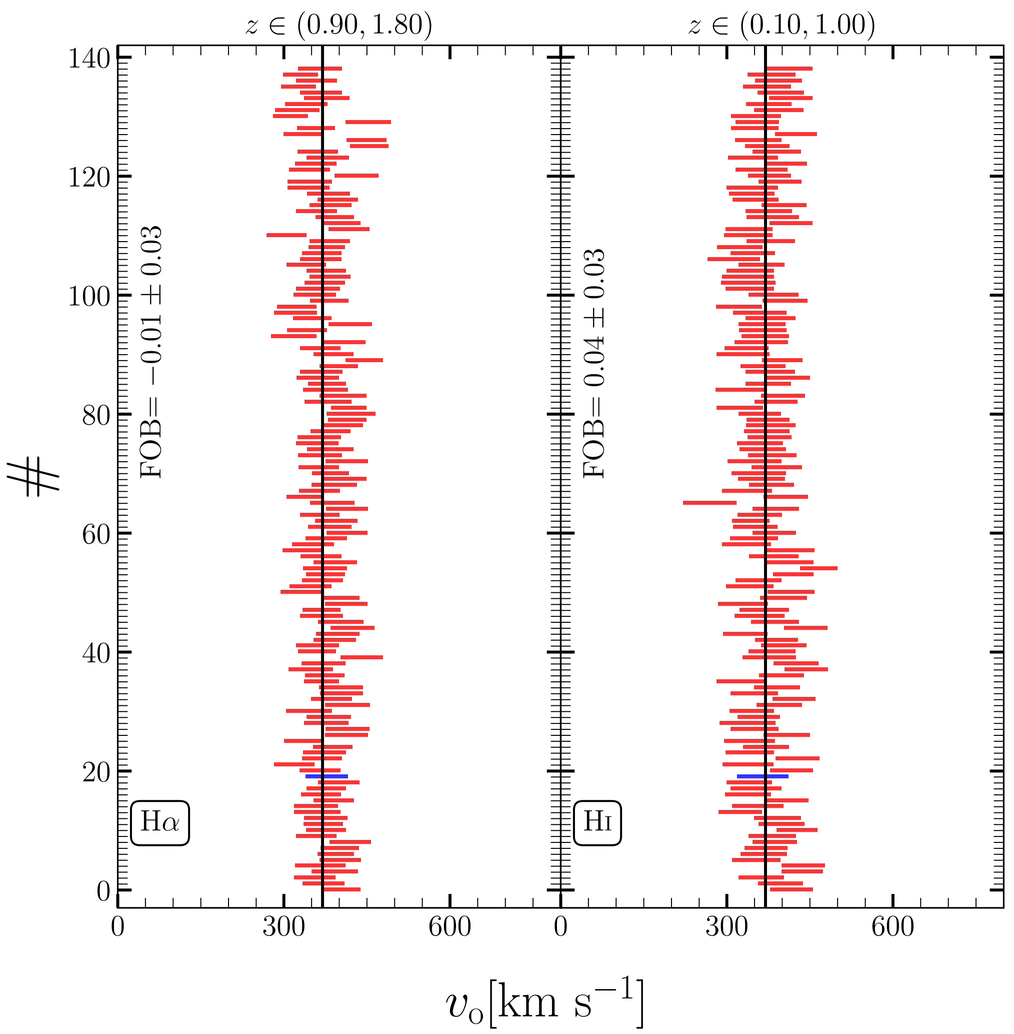
- Measuring the velocity of the observer,

- Measuring cosmological parameters,
- Measuring the survey functions: the magnification and Evolution bias.

Direct measurement of the observer's velocity vector

In order to measure the velocity vector:

- we assume that the functional form of the magnification and evolution bias is known.
- We set the cosmology to the fiducial one.
- We used 5 different directions across the sky as artificial shift to each the mock and for each galaxy in the catalogue.



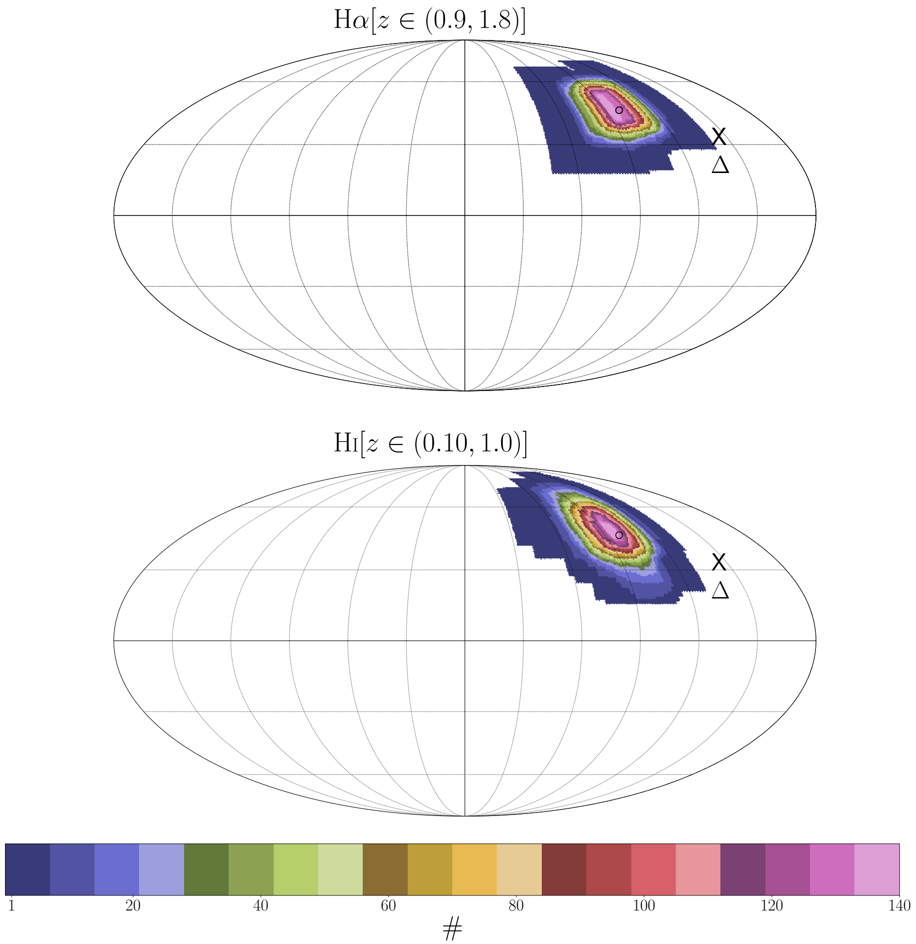
Observer velocity magnitude are shown for each realization for the $\bar{n}_{H\alpha}$ selection function on the left and the $\bar{n}_{HI}$ selection function on the right. The true value is shown by the vertical black line. Finally, the average bias value is given averaged over all realizations.

Direct measurement of the observer’s velocity vector

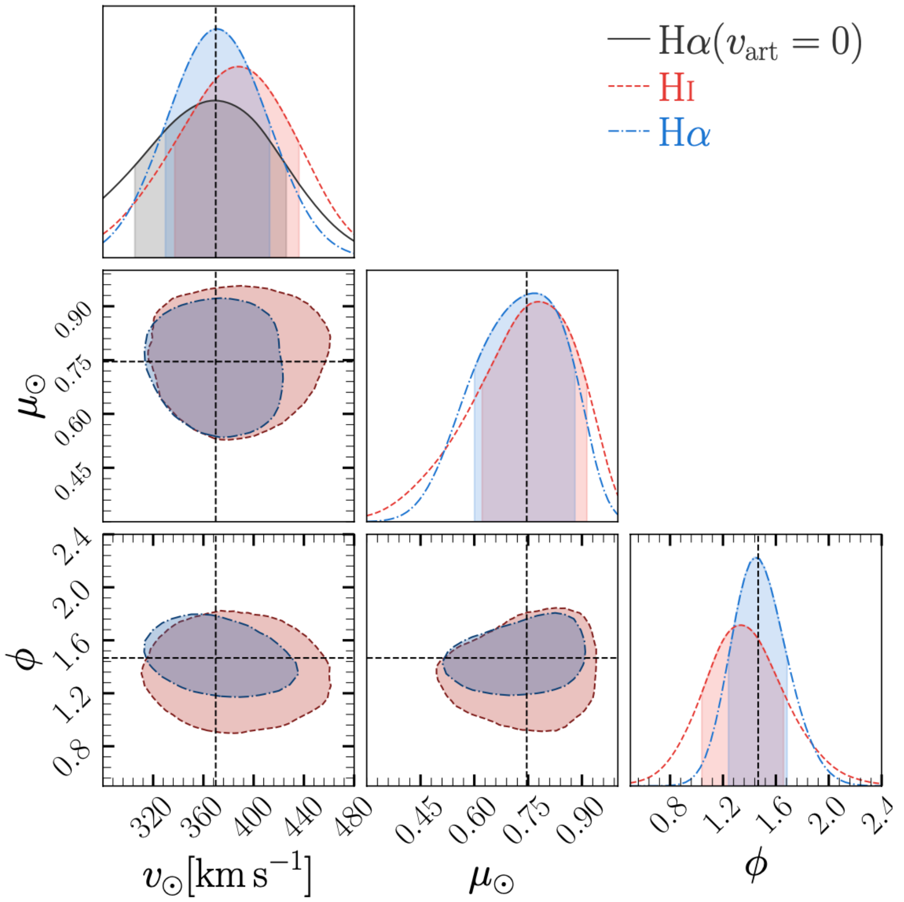
To measure the velocity vector, we assume that the functional form of the magnification and evolution bias is known. We also set the cosmology to the fiducial one

Upon averaging over all realizations, the observer velocity can be measured with an average precision of

- 21% for the Hα survey,
- 26% for HI survey



The combined posterior distributions of the directions of all realizations for Hα (top) and HI (bottom). The colour bar corresponds to the number of realizations. The true direction is marked by an ∘ while the X and ▲ are the directions inferred by the NVSS survey and TGSS surveys.



The 68% credibility contours for the observer velocity vector components are plotted for the two example surveys; $\bar{n}_{H\alpha}$ (blue) and $\bar{n}_{HI}$(red).

Constraining cosmological parameters.

- We use the large-scale oscillations in the monopole of the power spectrum measured to set constraints on the cosmological parameters! Precisely, the constraining power of the **finger of the observer effect** signal on Cosmological parameters by adopting the Kinematic interpretation of the CMB.
- We attempt to fit two distinct models:

1) **ΛCDM model:** we assume a cosmological constant, i.e.

$$w = \frac{P_{\rm DE}}{\rho_{\rm DE}} = -1.$$

Here only aim to extract the dark matter energy density $\Omega_{\rm m,0}$ today from the data.

2) **wCDM model:** we let both $\Omega_{\rm m,0}$ and w vary to test whether this method can constrain the evolution of Dark Energy. Here we adopt a flat ΛCDM model where the Hubble parameter is given by

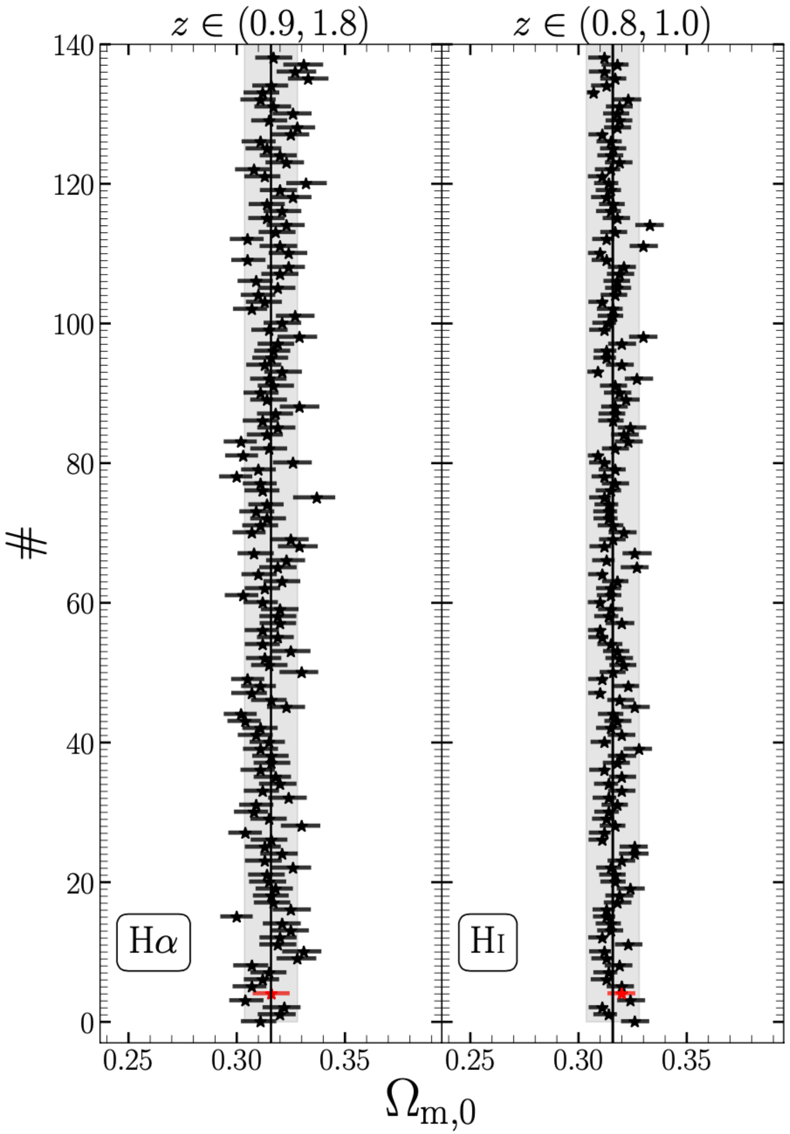
$$H^2 = H_0^2\left[\Omega_{\rm m,0}(1+z)^3 + (1-\Omega_{\rm m,0})(1+z)^{3(1+w)}\right]$$

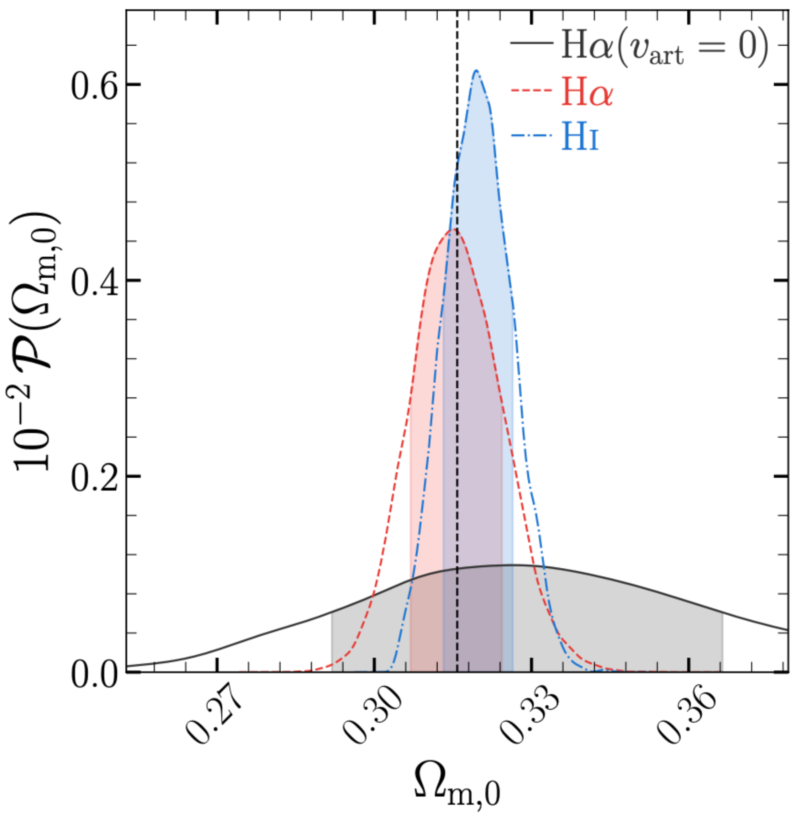
Here we assume that the functional form for the survey functions is known.

Could we constrain cosmological parameters?

ΛCDM model

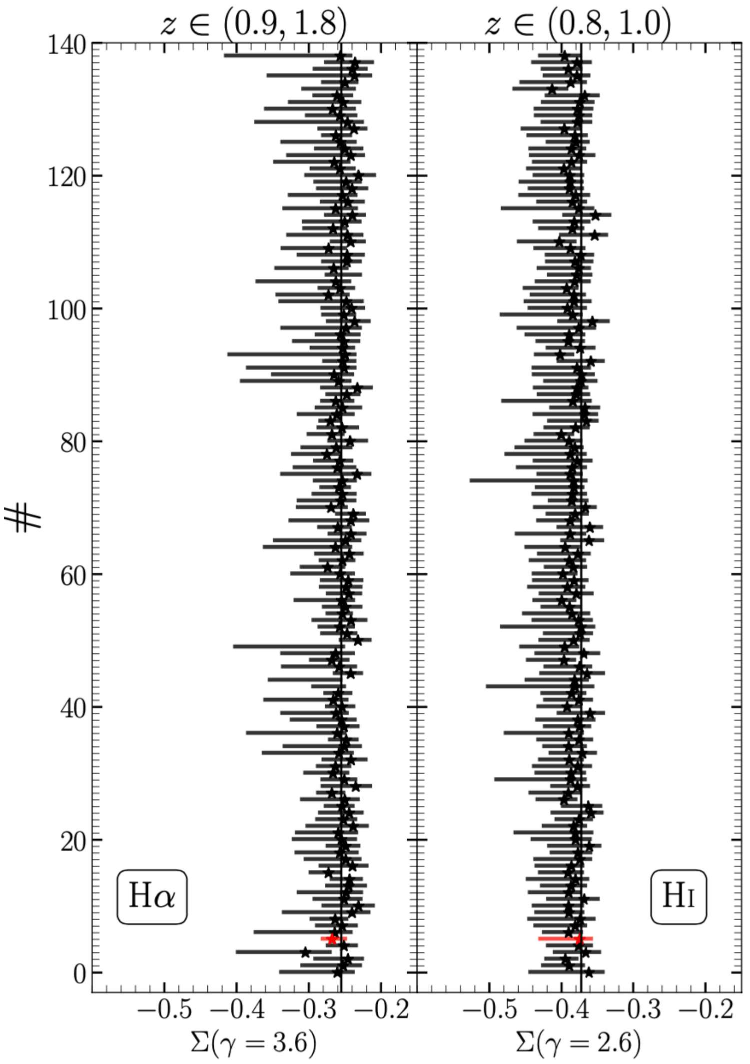
The 68% highest probability density intervals the constraints on $\Omega_{m,0}$.
We show the error of the constraint on $\Omega_{m,0}$ from the CMB [Planck 2018] as a grey band centred around the fiducial value.
The red bars represent the Hα and HI distributions shown on the right panel.





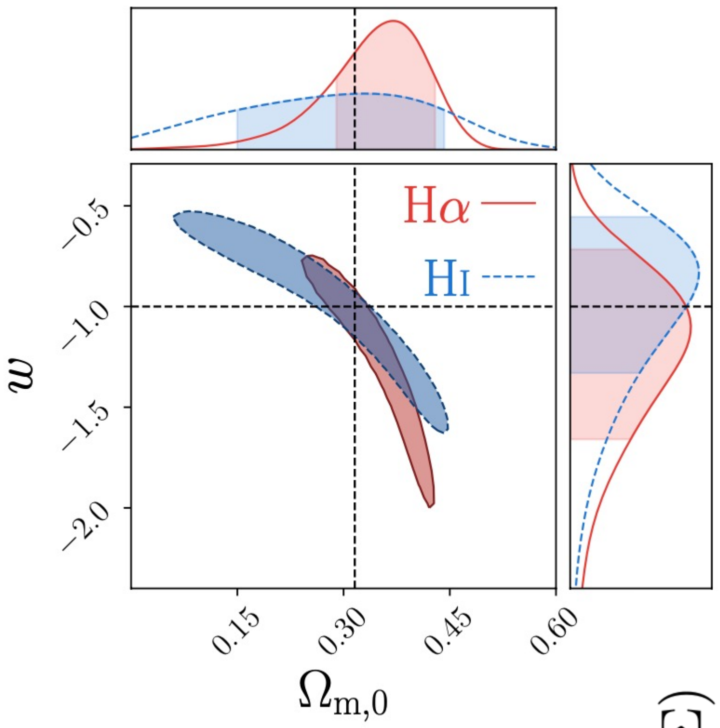
The posterior distribution of $\Omega_{m,0}$ extracted from the Boosted FOTO of the HI (blue) and Hα (red) surveys. We also show the pure FOTO signal constraint of the Hα example survey in grey.

Could we constrain cosmological parameters?



We showcase the constraints across all realizations for both surveys.

wCDM model

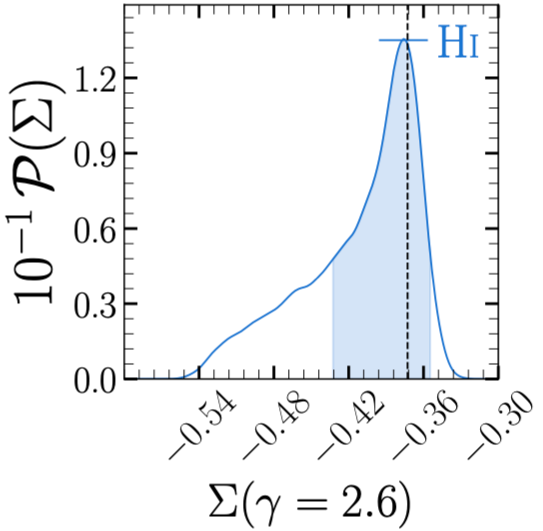


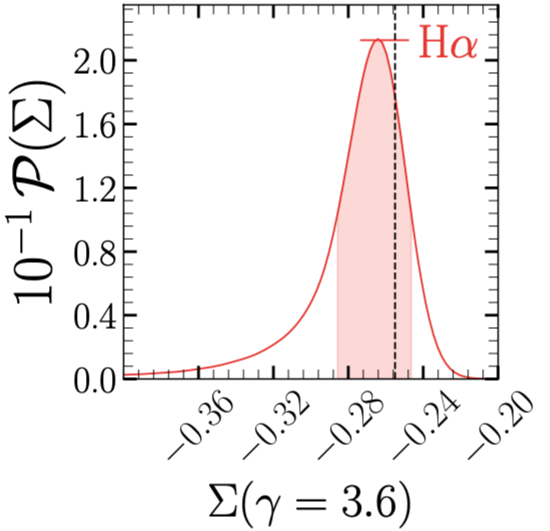
The posterior distributions of Σ. $\mathcal{P}(\Sigma)$ exhibits a long tail towards more negative values, which we attribute to the curved shape of the combined $\mathcal{P}(\Omega_{\mathrm{m},0}, w)$.

The constraining power on the derived parameter $\Sigma = (1 - \Omega_{\mathrm{m},0})^{\gamma} w$, where γ is a constant number. The derived constraints on Σ will vary depending on the value of γ.

Utilizing the computed MCMC chains, we determine that

- $\gamma \simeq 3.6$ yields the highest constraining power on Σ for the Hα survey, while
- $\gamma \simeq 2.6$ results in the strongest constraints for the HI survey.





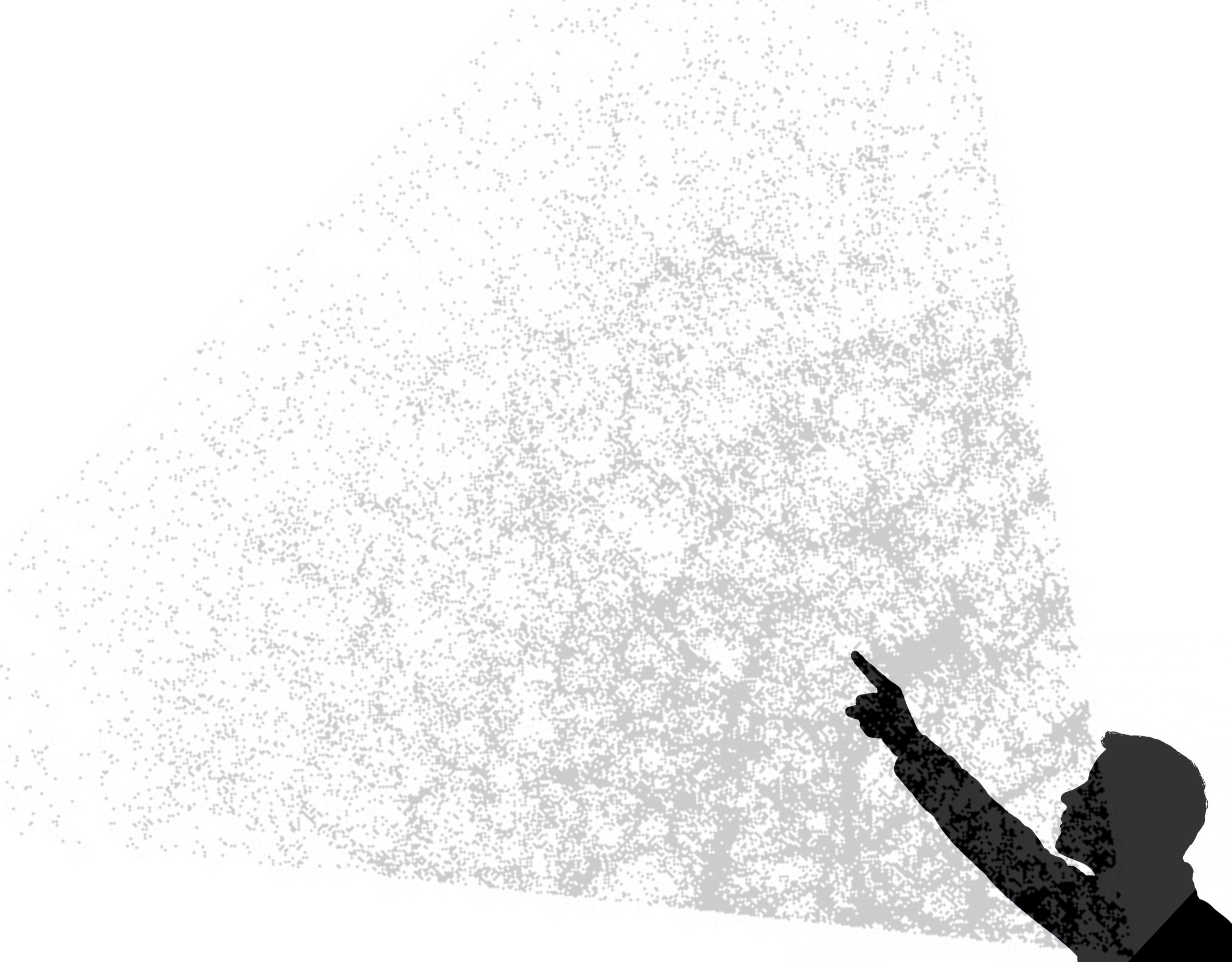
Possible caveats

- 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 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 $\mathbf{v}_{obs}$, i.e. the ***Finger of the observer effect****:*
  - This effect 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
  - If clustering statistics can be robustly measured on such large scales, the ***Finger of the observer effect*** gives a handle to measure $\mathbf{v}_{obs}$ and constrain the expansion history of the Universe

Thanks!



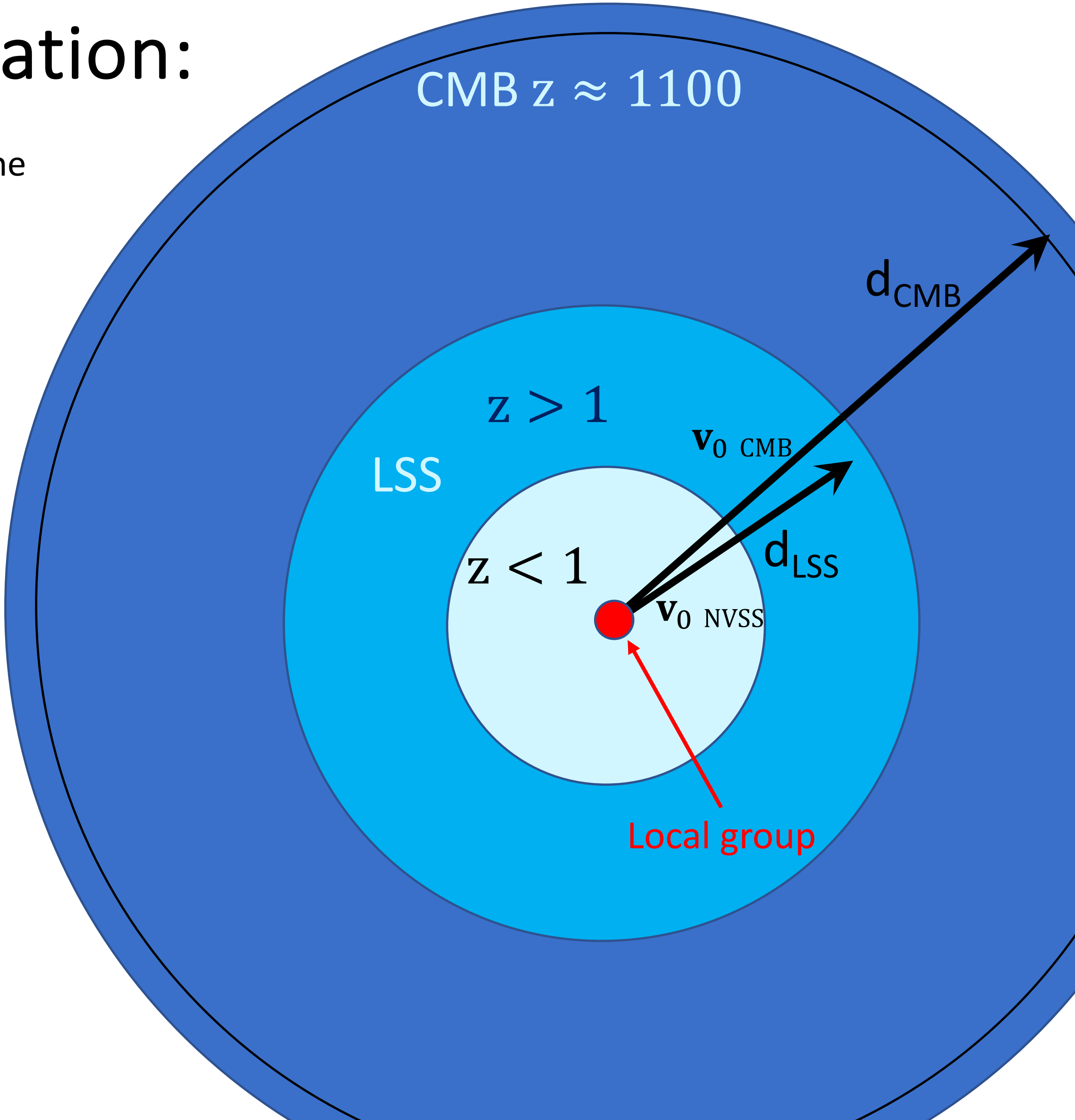
Extra slides

Dipole terms in the wide-angle galaxy two-point correlation:

- Therefore, we are not observing the galaxy catalogs at rest frame to the CMB. For example, the motion of our galaxy is related to the peculiar velocity of the Local Group (LG), $v_r(\mathbf{0})$ [Juszkwwicz, Vittorio, Wise (1989), Lahav Kaiser Hoffman (1989)]
- Using the continuity equation and assuming the linear theory we can write the velocity field in the following way:

$$v_r(\mathbf{0}) = \frac{1}{H_0}\hat{\mathbf{r}}\cdot\mathbf{v}(\mathbf{0}) = \frac{f_0}{4\pi}\int_{V^{\mathcal{R}}} \mathrm{d}^3\mathbf{r}'\,\frac{\hat{\mathbf{r}}\cdot\hat{\mathbf{r}'}}{r'^2}\delta_{\mathrm{m}}^{\mathcal{R}}(\mathbf{r}')$$

(It guarantees that the peculiar velocities of the galaxies in the LG frame are small with respect to the distances r)
Here the bulk flow of a spherical region is determined by the gravitational pull of the dipole of the external mass distribution.



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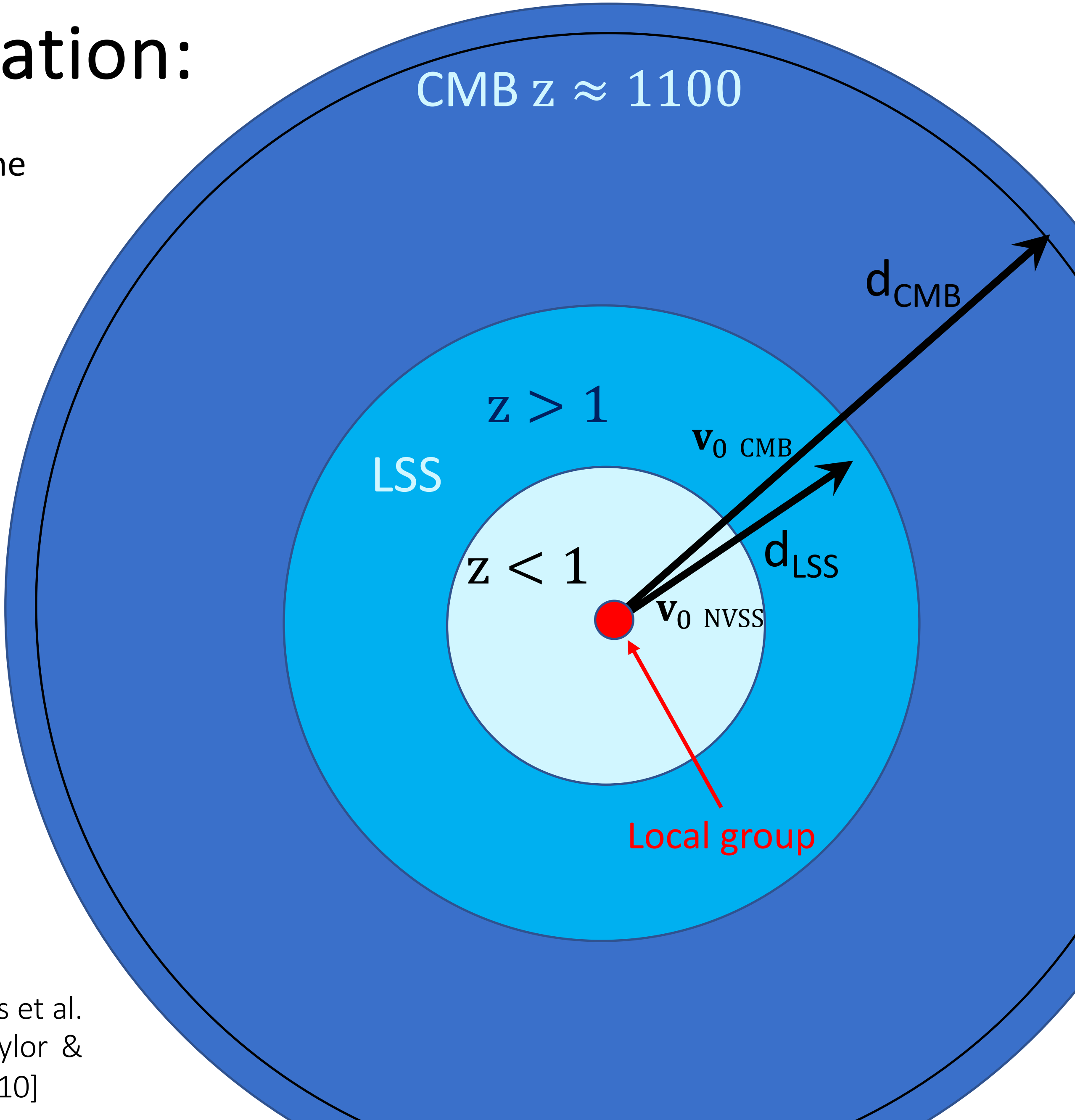
$\Longrightarrow$ **The local group's motion is the result of the cumulative gravitational pull of the surrounding distribution of matter in the Universe** [e.g., Peebles (1980)]

[See also Yahil et al. 1980; Davis & Huchra 1982; Meiksin & Davis 1986; Strauss et al. 1992; Hamilton & Culhane 1996; Hamilton 1998; Schmoldt et al. 1999; Taylor & Valentine 1999; Kocevski & Ebeling 2006, Erdoğdu et al. 2006, Lavaux et al. 2010]



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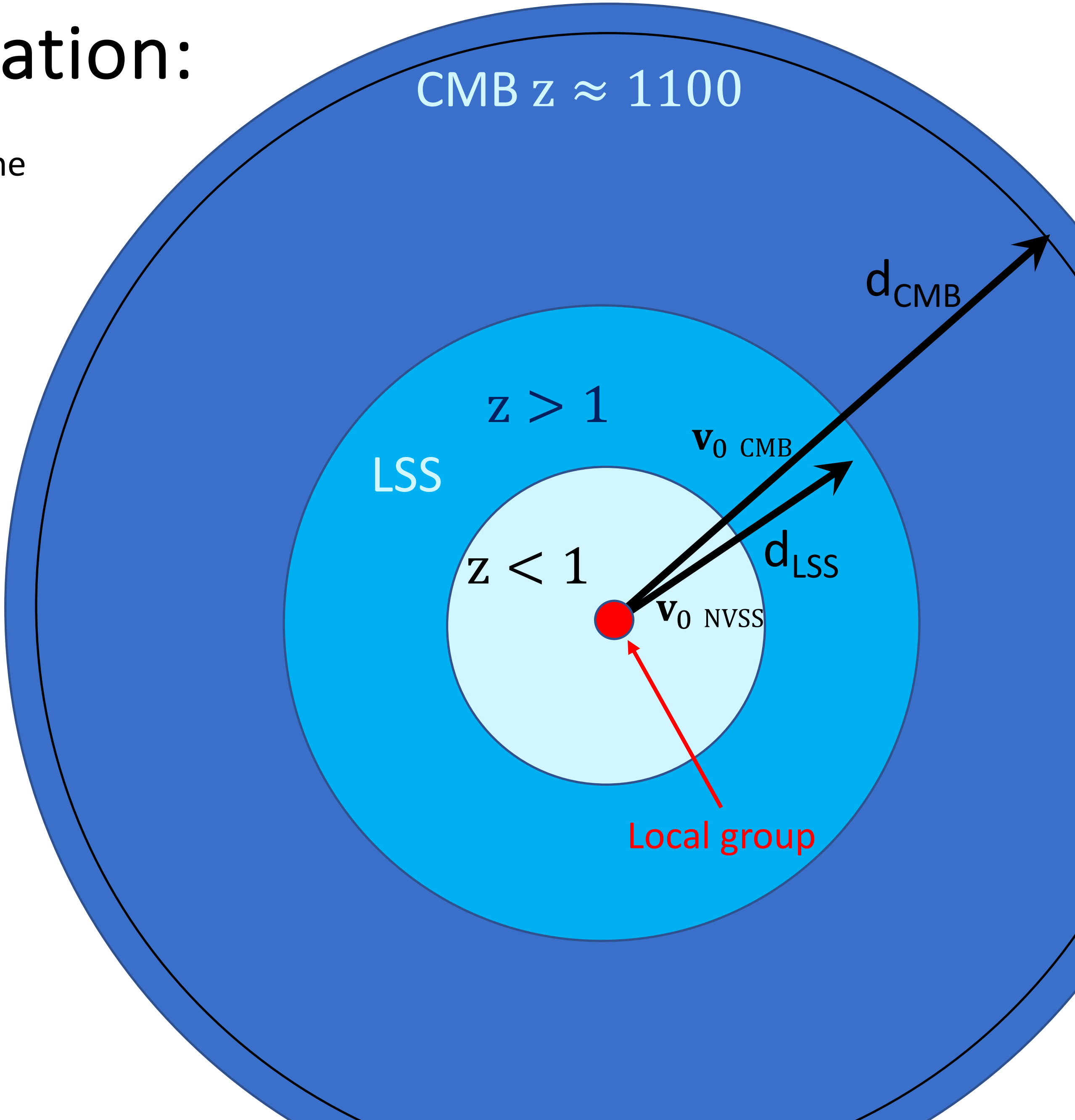
- The dipole due to our motion with respect to a rest frame where the galaxy distribution is statistically isotropic is expected to converge to the CMB kinematic dipole if the galaxy survey is deep enough:

A. Nusser, M. Davis and E. Branchini (2014) concluded that the CMB frame can be gradually reached but the LG motion cannot be recovered to better than 150-200 km/s in
amplitude and within an error of 10’ in direction.
Perhaps, is it due to the intrinsic dipole? [e.g., see Gibelyou and D. Huterer (2012).]



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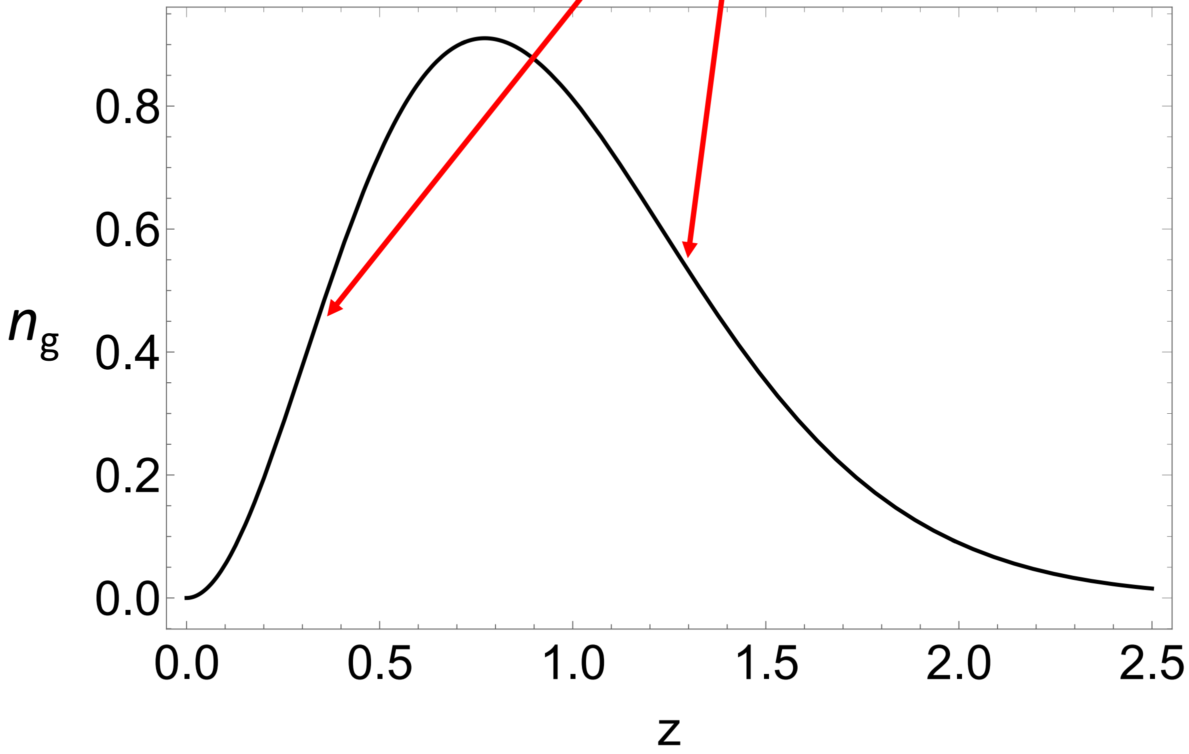
- **The peculiar motion of the observer, if not accurately accounted for, is bound to induce a well-defined clustering signal in the distribution of galaxies.** This signal is related to the *Kaiser rocket effect* [Kaiser (1987), Strauss et al. (1992)]

$$W_r(r)\left(2 + \frac{\partial \ln \bar{n}_{\mathrm{g}}(r)}{\partial \ln r}\right)$$

The ***rocket effect*** **might become huge!**



The local group motion induce a spurious apparent overdensity in the direction of motion!

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Bertacca (2019); Bahr-Kalus, DB, Verde & Heavens (2021);
Elkhashab, Porciani & **DB** (2021), Elkhashab, Porciani & **DB** in prep.

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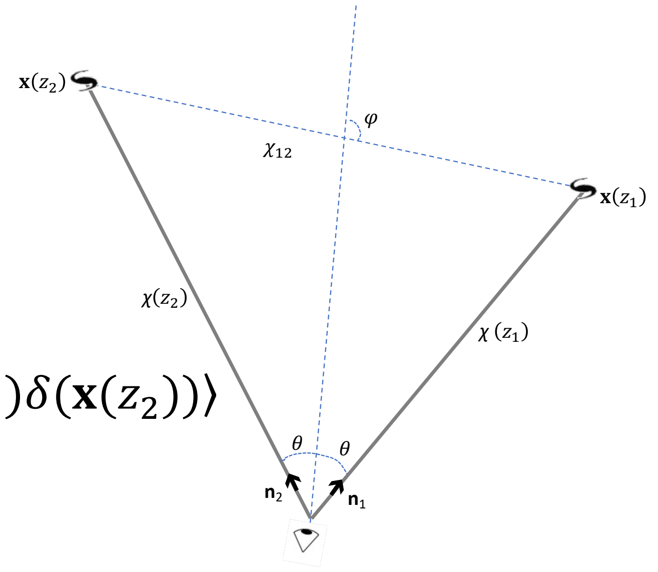
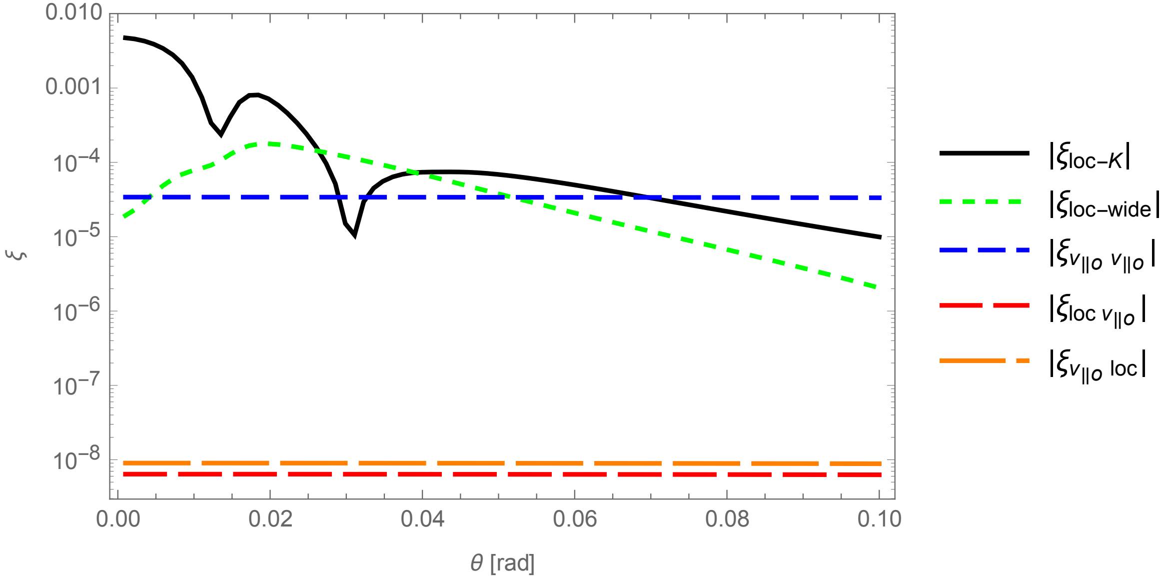
- **Signature of the *rocket effect* becomes very important if we consider the reconstructed LG motion at radii larger than 100h^{-1} Mpc**, for example see [Nusser, Davis, and Branchini (2014)].
- This effect on LSS is also called ***the kinematic dipole*** due to our peculiar velocity [e.g., see Nadolny, Durrer, et al. (2021)] or **"finger of the observer"** [Elkhashab, Porciani and DB (2021)]



$$\xi = \langle \delta(\mathbf{x}(z_1))\delta(\mathbf{x}(z_2))\rangle$$

z_1=1, z_2=1.05



Bertacca (2019), suggested that the Kaiser Rocket effect could dominate the local signal of the 2-point correlation function of galaxies at very large scales.

Impact on Measurements (1)

Bahr-Kalus, DB, Verde & Heavens (2021),

- Cartesian 3D power spectrum

$$P\ (k) = P_{\rm cosmo}(k) + P_{\rm dip}(k)$$

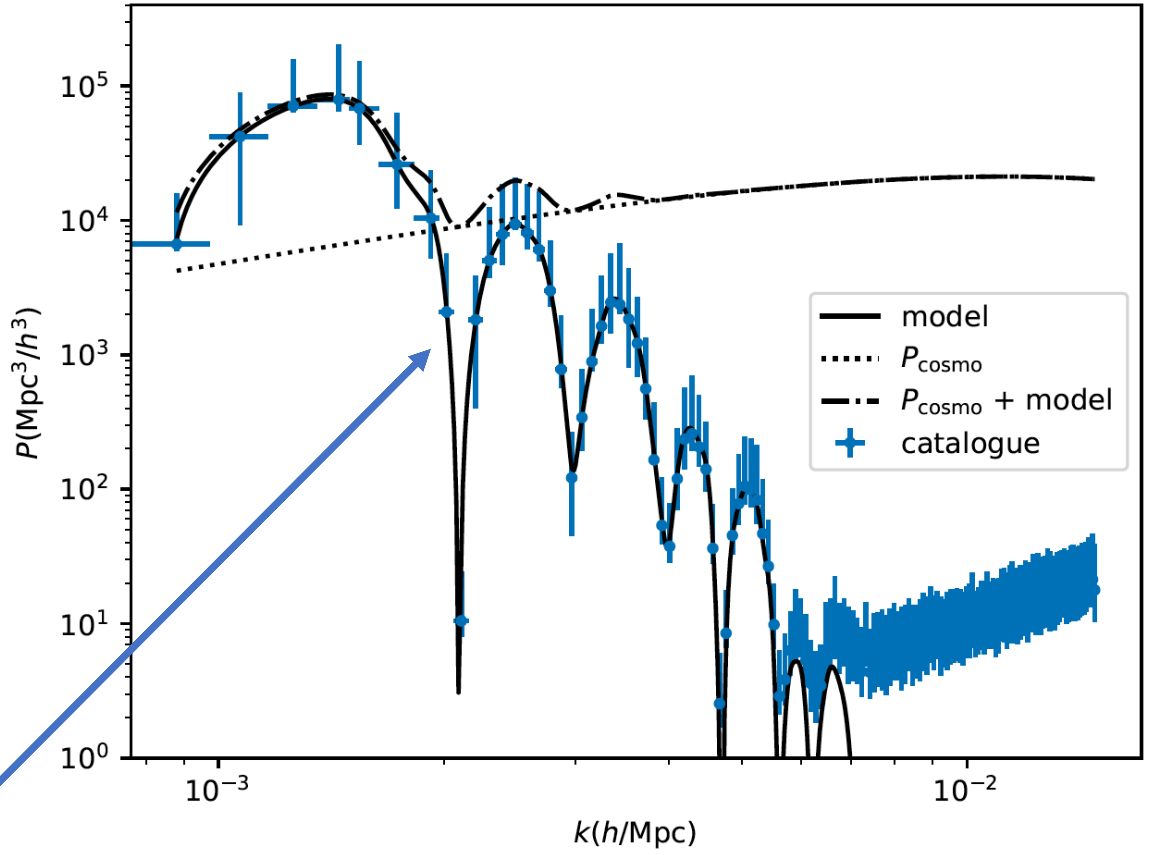
where

$$P_{\rm rocket}(k) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}\,\mu \left\langle \left| \delta_{\rm rocket}\left(k\sqrt{1-\mu^2}, k\mu\right)\right|^2 \right\rangle$$

- We make predictions using random catalogues (i.e. w/o clustering) where we shift redshifts to the values observed by observer in motion.

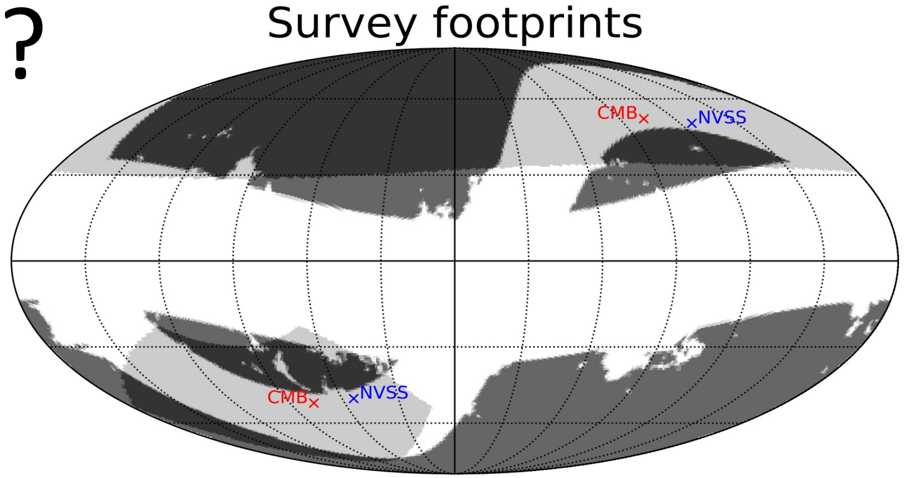
A non-vanishing $v_{\rm obs}$ alters the redshifts of the galaxies and generates a dipolar pattern in the reconstructed galaxy distribution in redshift space that we name the Kaiser Rocket or the finger of the observer effect.

The monopole moment of the power spectrum measured in the observer's rest frame has an additive component showing a characteristic damped oscillatory pattern on large scales.

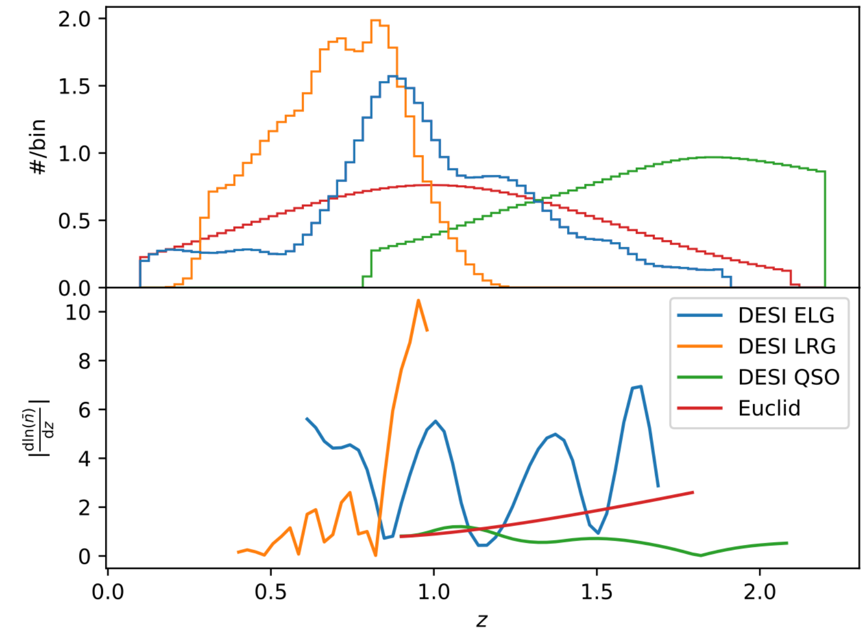


Rocket power computed from a mock realisation of a full-sky survey

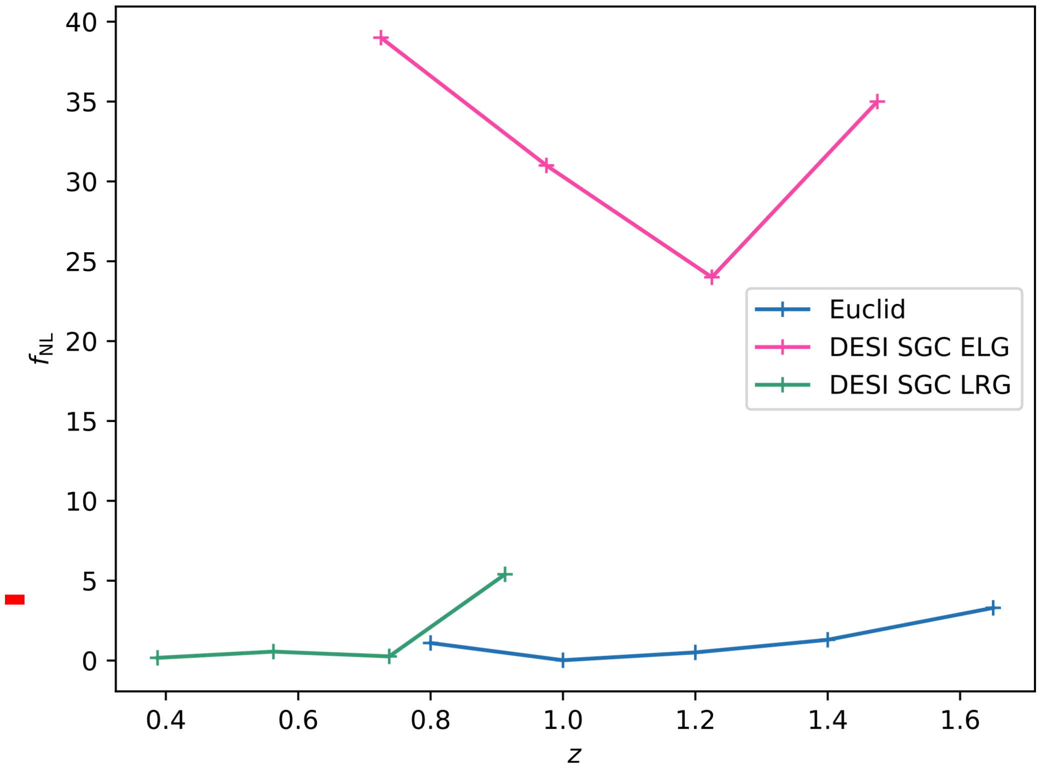
What about DESI?



Light grey: DESI,
Darker grey: Euclid,
Dark grey: overlap



Forecasts for DESI:



	Δf_{NL}	σ
NGC QSO	3,8	0,19
SGC QSO	14	0,65
NGC ELG	5,5	0,25
SGC ELG	71	2,1
NGC LRG	4,9	0,13
SGC LRG	13	0,21

Does Kaiser rocket mimic non-Gaussianity?