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Detecting Relativistic Doppler in Galaxy Clustering with Tailored Galaxy Samples

Is the theory of general relativity the correct description of gravitational interaction even at the largest scales of the universe? The upcoming generation of cosmological experiments will probably be able to answer this question, proving us with the first detection of general relativistic effect on cosmological scales. Using tailored luminosity cuts, we can obtain two independent galaxy samples, whose cross-correlation power spectrum allows for a detection of the relativistic contribution well above a significance of 5 σ.

Detecting relativistic effect: why?

The concordance cosmological model is rooted on the theory of **general relativity** (GR), which has been confirmed by several stunning experimental observations. However, these tests are all conduced in strong-field regimes, whereas in cosmology we usually deal with extremely weak gravitational fields. In this context, a measurement of an effect predicted by GR on cosmological scales would be an extraordinary confirmation of the validity of the theory as the correct description of gravity, even in condition where it is still unprobed.

The **large-scale structure** of the universe offers an important test bench for gravity theories. In particular, a statistical investigation of the distribution of a certain tracer, e.g. a type of galaxy, can display signatures of various effects.

Detecting relativistic effects: how?

In cosmology, we often use the **galaxy density contrast** to trace the underlying matter distribution. However, the relation between the matter and galaxies density contrast has the same corrections, due to different phenomena that can affect the observed position of sources in the sky. Among these terms, we find a sub-dominant Doppler term which is given by GR.

Relativistic effects are mostly relevant on large scales; thus it is convenient to isolate small scales from large scales. The best way to do so is by studying clustering in Fourier space, through the **galaxy power spectrum**, that is, the Fourier-space galaxy two-point correlation function.

Galaxy power spectrum with relativistic effects…

In Fourier space, the leading contributions to the density contrast of galaxy number counts reads

$$\Delta(\vec{k}) = \left(b + f\mu^2 + i\frac{\mathcal{H} f \mu}{k}\alpha\right)\delta(\vec{k})$$

where:

- $\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$ = matter density contrast;
- $b\delta(\vec{k})$ is the real-space clustering term;
- $f\mu^2\delta(\vec{k})$ embodies the linear RSD term;
- $i\mathcal{H} f \mu k^{-1}\alpha\delta(\vec{k})$ represents the relativistic Doppler contribution,

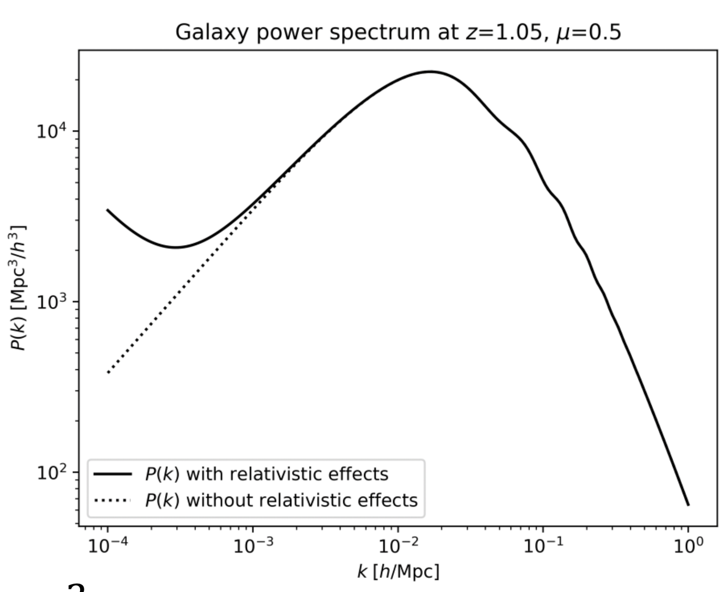
with

- $\alpha = -\mathcal{E} + 2\mathcal{Q} - 2\frac{\mathcal{Q}-1}{r\mathcal{H}} + \frac{\mathcal{H}'}{\mathcal{H}^2}$;
- $\mathcal{E} = -\frac{\partial \ln(n(z, L_c))}{\partial \ln(1+z)}$ = evolution bias;
- $\mathcal{Q} = -\frac{\partial \ln(n(z, L_c))}{\partial \ln(L_c)}$ = magnification bias.

Then, the power spectrum is given by either the variance of the density contrast of a certain type of galaxy X or the covariance between the distribution of two different tracers $X \neq Y$.

- **Auto-correlation**:

$$P_{XX}(z,k,\mu) = \\ = \left[(b_X + f\mu^2)^2 + \left(\frac{\mathcal{H} f \mu}{k}\alpha_X\right)^2\right] P_m(k)$$

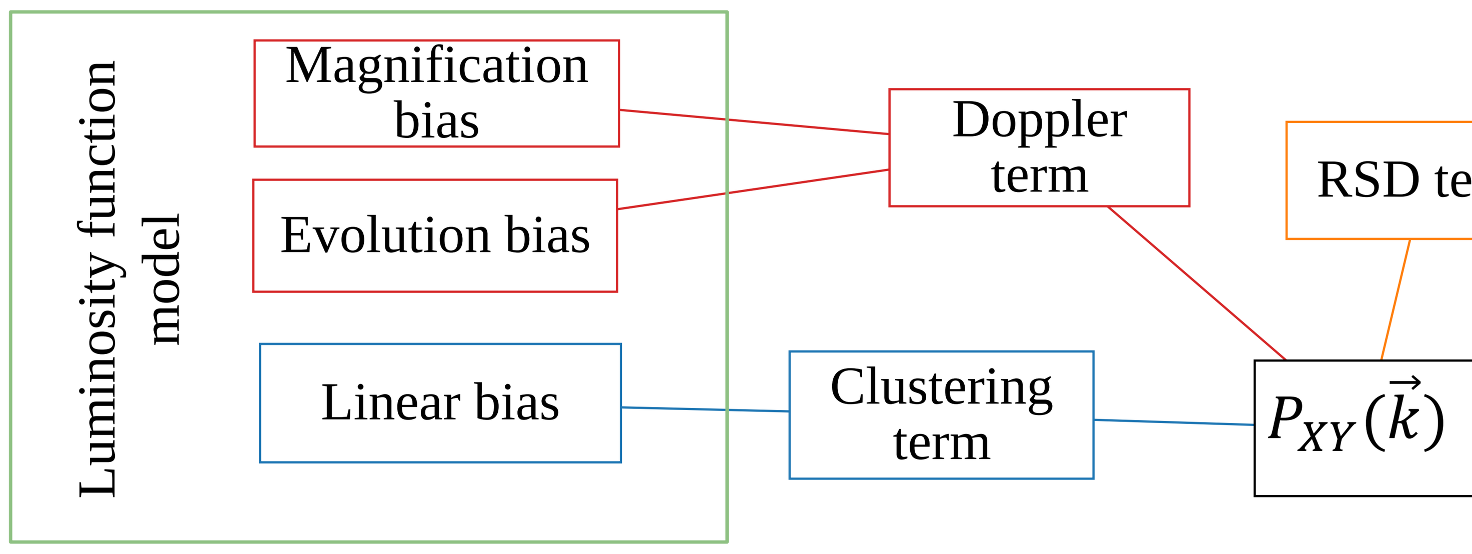


- **Cross-correlation**:

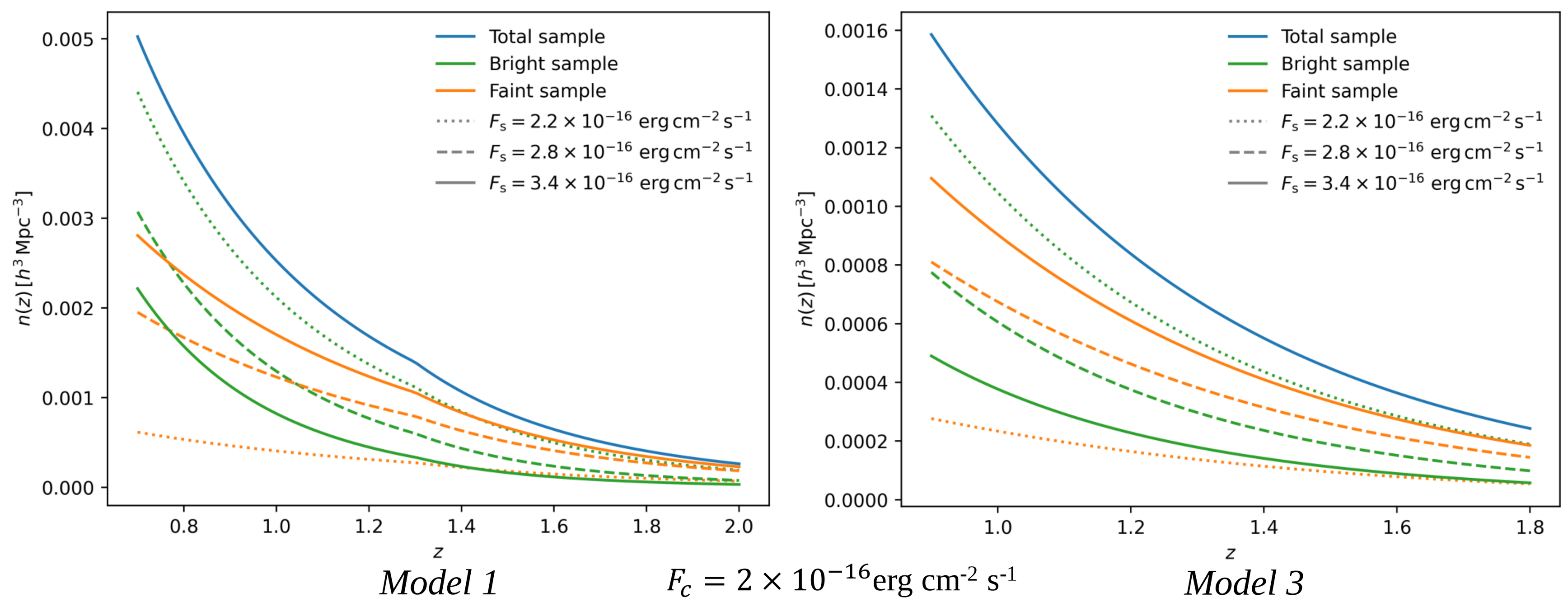
$$P_{XY}(z,k,\mu) = \\ = \left[(b_X + f\mu^2)(b_Y + f\mu^2) + \left(\frac{\mathcal{H} f \mu}{k}\right)^2 \alpha_X\alpha_Y \\ + i\frac{\mathcal{H} f \mu}{k}\left(\alpha_X(b_Y + f\mu^2) - \alpha_Y(b_X + f\mu^2)\right)\right] P_m(k)$$

…and tailored galaxy samples

Populations of galaxies described by different luminosity functions display different contributions in their power spectra. [R. Maartens *et al.*, 2021]



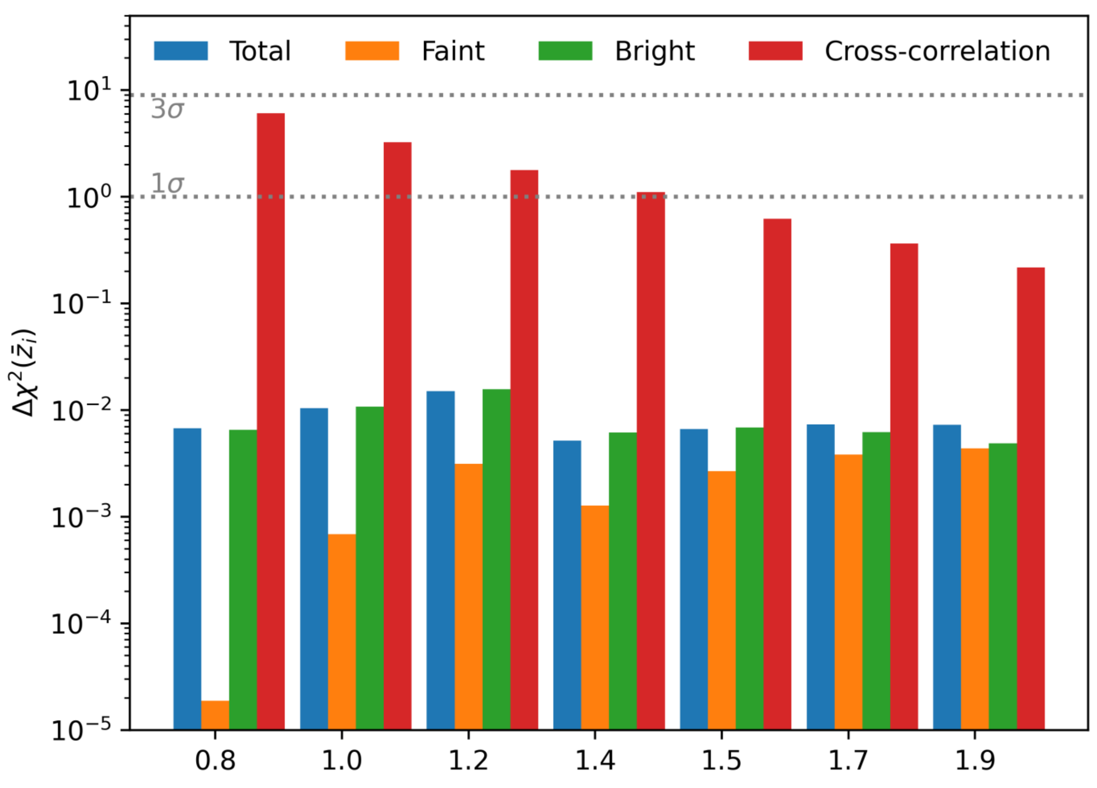
We consider **two sub-samples** of a galaxy population in order to perform a cross-correlation power spectrum analysis. [C. Bonvin *et al.*, 2014]



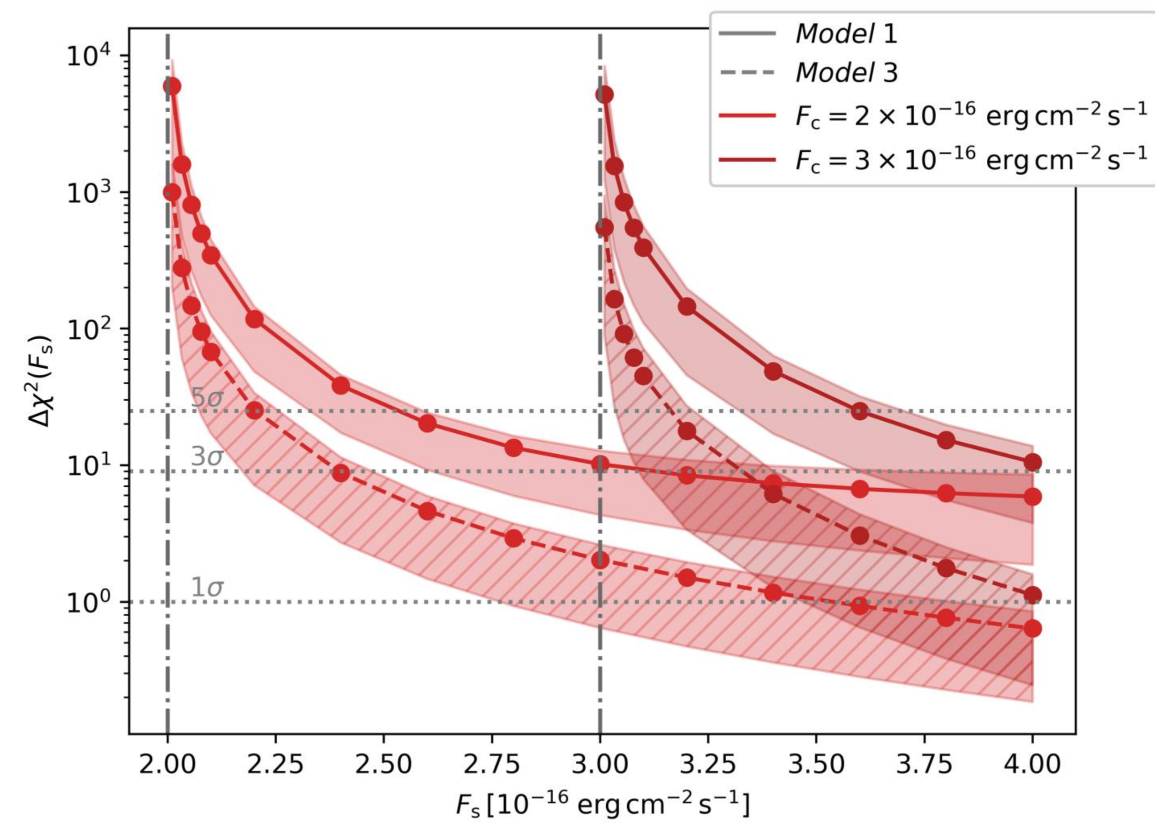
The forecast corner

$$\chi^2(z_i) = \sum_{m,j} \frac{\left|P_{XY}^{(w/\,Doppler)}(z_i, k_m, \mu_j) - P_{XY}^{(w/o\,Doppler)}(z_i, k_m, \mu_j)\right|^2}{\Delta P_{XY}^2(z, k_m, \mu_j)}$$

Due to the Doppler scaling $\propto k^{-1}$ [P. McDonald, 2009] in the imaginary part of the power spectrum, **cross-correlation measurements are much more promising** than auto-correlation ones. Regarding the faint-bright cross-power spectrum, the luminosity cut technique is able to **boost the relativistic contribution** as long as the faint sample is less populated than the bright selection. [C. Bonvin *et al*, 2023]



Differential detection significance associated with a detection of the relativistic Doppler term for *Model 1* and flux cut $F_c = 2 \times 10^{-16}$ erg cm^{-2} s^{-1}



Cumulative statistical significance for the Doppler contribution in a faint-bright cross-power spectrum measurement, as a function of the flux split F_s, for two different flux cuts.

The cumulative results appear to depend mostly on the difference $F_s - F_c$, rather than the flux cut. Therefore, this strategy seems also able to somehow **overcome even the natural worsening** of constraining power due to reduced sensitivity.

A sample optimisation work is useful in the quest for a relativistic signature in cosmic structures.

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