Cosmology with relativistic effects

Daniele Bertacca

Quantum Vacuum and Gravitation: Testing General Relativity in Cosmology

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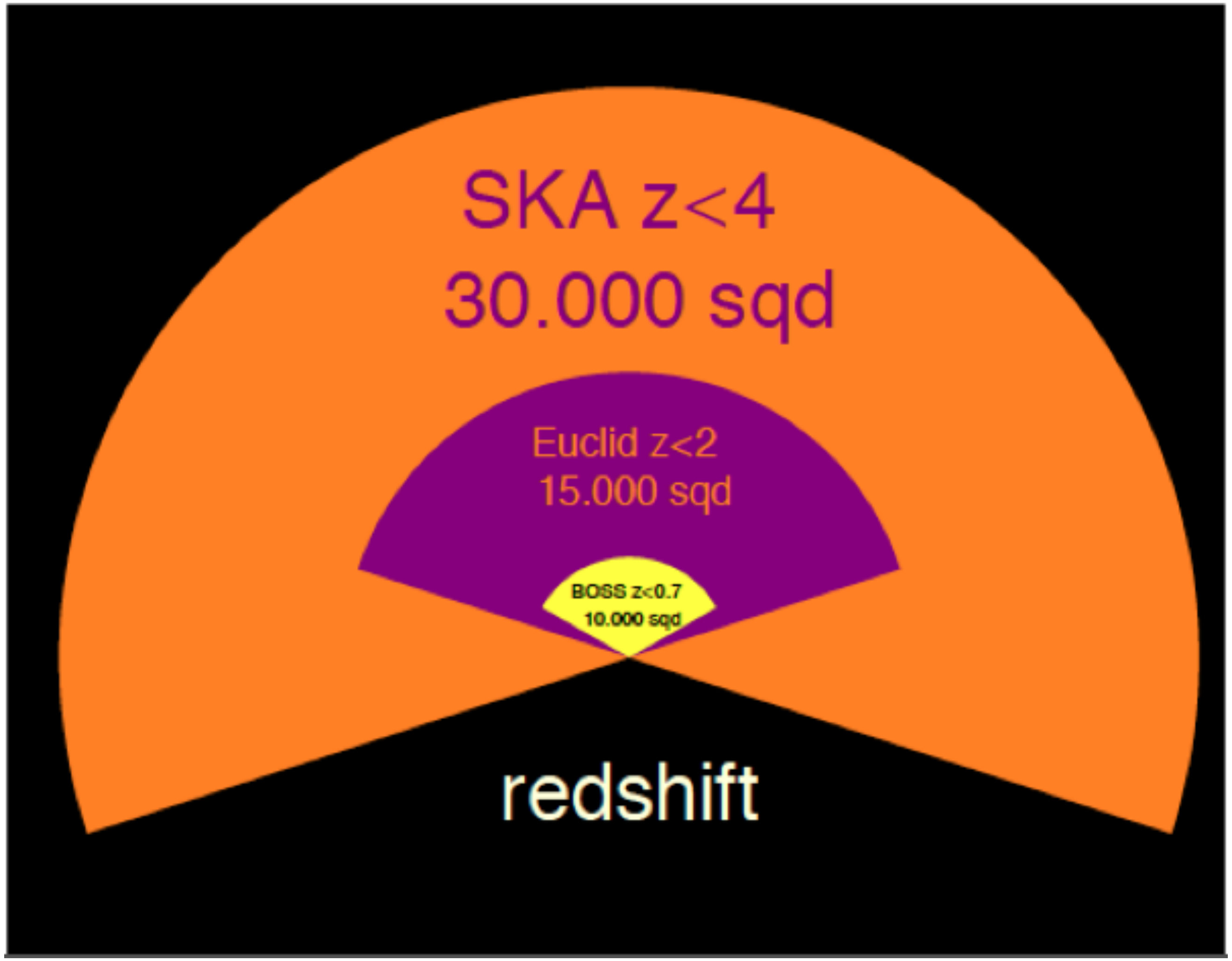
universität bonn

Argelander-Institut für Astronomie

General relativistic effects:



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

General relativistic effects: Δ_g case

- **On large scales, we need to ensure that we are using a correct general relativistic (GR) analysis.**

- **It is important to compute these effects:**

  - to avoid wrong predictions on scales ~ 1/*H(z)* *[e.g. Yoo et al 2009; Challinor et al 2011; Bonvin et al 2011; Jeong et al 2011; Bertacca et al 2012; Raccanelli (+ Bertacca) et al 1013; Di Dio et al 2013a,b; Raccanelli (+ Bertacca) et al 2015]*

  - to detect the Doppler terms *[Bonvin et al 2013; Bonvin 2014; Bonvin et al 2015, Gaztanaga et al 2015; Raccanelli (+ Bertacca) et al 2016]*

  - in order to extract the primordial non-Gaussianity *[e.g. Bruni et al 2011; Jeong et al 2011; Raccanelli (+ Bertacca) et al 2013; Camera et al 2014a,b; Raccanelli (+ Bertacca) et al 2015, 2016; Fonseca et al 2015]*

  - to compute GR corrections at 2nd order *[e.g. Bertacca et al 2014a,b ; Yoo et al 2014; Di Dio et al 2014, 2015, 2016; Bertacca 2014]*

  - in order to provide the best constraints on dark energy *[e.g. Duniya (+ Bertacca) et al 2013; Raccanelli (+ Bertacca) et al 2015]* **and modified gravity models** *[e.g. Hall et al 2012; Raccanelli (+ Bertacca) et al 2013; Bonvin et al 2013, Zumalacárregui et al 2015, Raveri, Raccanelli (+ Bertacca) et al in prep.]*

  - to estimate the neutrino masses *[e.g. Cadorna et al 2016]*

  - to measure the spatial curvature parameter *[e.g. Di Dio et al 2016]*

General relativistic effects: Δ_g case

- There are two fundamental issues:

1) Correctly identify the galaxy overdensity Δ_g that we observe on the past light cone.

2) We need to account for all the distortions arising from observing on the past light cone:

Redshift, Magnification and Volume Distortions

for example, see Yoo et al 2009, Bonvin et al 2011, Challinor et al 1011, Jeong et al 2011

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 (Broadhurst, Taylor and Peacock 1995)

These contributions are added in ad hoc manner!

Is this everything? or are there more contributions?
We need unified treatments!

Redshift-space distortions

e.g. Hamilton 1997

Real Space

$N^{\mathcal{R}}$

Redshift Space

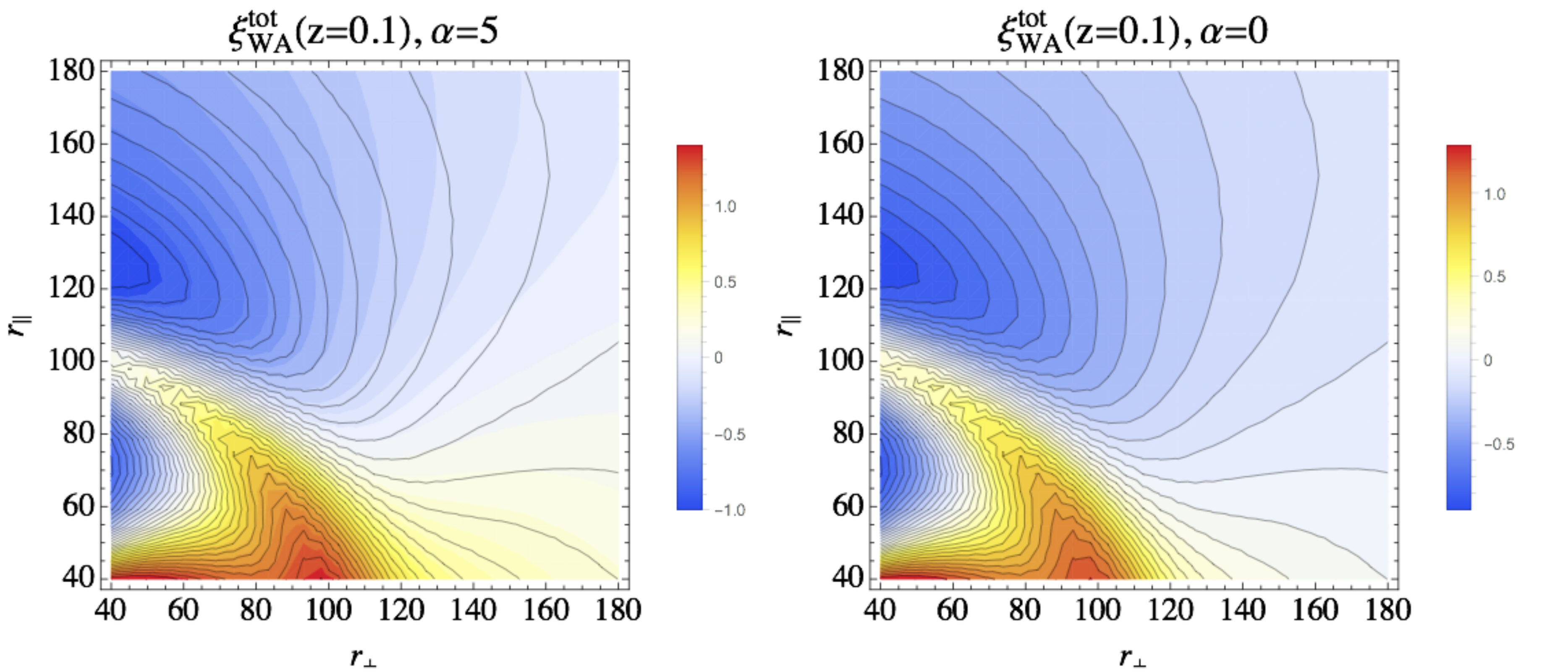
$N^{\mathcal{S}}$

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

- **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**: αv_r/r, does not naturally disappear, but in flat-sky approximation it is usually neglected.

Velocity and Doppler terms: α

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



2D redshift-space galaxy correlation function including wide-angle terms.
The effect of α = 0 and α = 5 corresponds to the value obtained from a gaussian galaxy distribution centered at z = 0.1 and with σ = 0.1.
As expected, the deviation from the ⟨δδ⟩ case increases with α.

Redshift-Space Distortion in Flat-sky: Kaiser-Hamilton formalism

Real Space

$N^{\mathcal{R}}$

Redshift Space

$N^{\mathcal{S}}$

$$\left\langle \tilde{\delta}^{\mathcal{R}}(\vec{k}_1)\tilde{\delta}^{\mathcal{R}}(\vec{k}_2)\right\rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2) P^{\mathcal{R}}(\vec{k}_1) \quad \longrightarrow \quad P^{\mathcal{S}}(k) = (1+\beta\mu_k^2)^2 P^{\mathcal{R}}(k)$$

$\mu_k = \mathbf{n}_z \bullet \mathbf{n}_k$

$$\delta^{\mathcal{S}} = \delta^{\mathcal{R}} - \frac{\partial v_r}{\partial r}$$

$$\beta = f/b \quad \longrightarrow \quad f = d\ln\delta / d\ln a$$

Expanding $P^{\mathcal{S}}$ in harmonics of μ_k → Even multipoles!

Note that adding the doppler term ($\alpha\, v_r/r$) without flat-sky limit we have both even and odd multiples! (in configuration space) **[see Szapudi 2008, Bertacca et al 2012, Raccanelli (+ Bertacca) et al 2013]**

Now we need a complete description of different effects!!

- holds in Newtonian & GR descriptions

$\downarrow$

COSMIC LABORATORY

Jeong, Hirata & Schmidt 2011
Schmidt & Jeong 2012
Bertacca, Maartens & Clarkson 2014a,b
Bertacca 2014

COSMIC LABORATORY

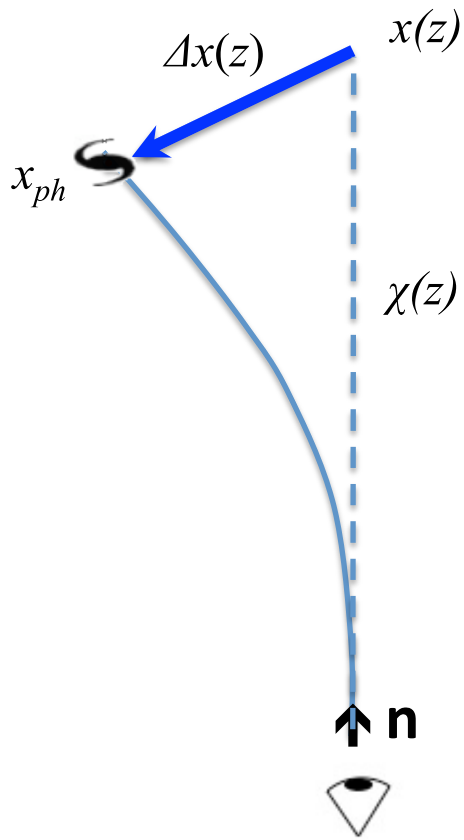
(cosmic rulers)

Jeong, Hirata & Schmidt 2011
Schmidt & Jeong 2012
Bertacca, Maartens & Clarkson 2014a,b
Bertacca 2014

$$\delta\chi = -\left(\chi_\mathrm{s} + \frac{1}{\mathcal{H}}\right)\left[\Psi_\mathrm{o} - \left(n^i_\mathrm{s} v_i\right)_\mathrm{o}\right] + \frac{1}{\mathcal{H}}\left[\Psi_\mathrm{e} - \left(n^i_\mathrm{s} v_i\right)_\mathrm{e}\right] + \int_0^{\chi_\mathrm{s}} \left[2\Psi + (\chi_\mathrm{s} - \chi)\partial_0\left(\Phi + \Psi\right)\right] \mathrm{d}\chi + \frac{1}{\mathcal{H}}\int_0^{\chi_\mathrm{s}} \partial_0\left(\Phi + \Psi\right)\mathrm{d}\chi\ ,$$

$$\delta x^0 = -\chi_\mathrm{s}\left[\Psi_\mathrm{o} - \left(n^i_\mathrm{s} v_i\right)_\mathrm{o}\right] + 2\int_0^{\chi_\mathrm{s}} \Psi\,\mathrm{d}\chi + \int_0^{\chi_\mathrm{s}} (\chi_\mathrm{s} - \chi)\,\partial_0\left(\Phi + \Psi\right)\mathrm{d}\chi\ ,$$

$$\delta x^i = -\left(v^i_\mathrm{o} + \Phi_\mathrm{o} n^i_\mathrm{s}\right)\chi_\mathrm{s} + 2n^i_\mathrm{s}\int_0^{\chi_\mathrm{s}} \Phi\,\mathrm{d}\chi - \int_0^{\chi_\mathrm{s}} (\chi_\mathrm{s} - \chi)\delta^{ij}\partial_j\left(\Phi + \Psi\right)\mathrm{d}\chi\ ,$$



- Local corrections express the Sachs-Wolfe and the Doppler effects
- Integrated along the line of sight terms derive from gravitational lensing, the Shapiro time-delay and the integrated Sachs-Wolfe effect

Observed galaxy density perturbation Δ_g

$$N_{\rm tot} = \int \sqrt{-g}\; n_{\rm phy}\; \varepsilon_{abcd}\; u^d\; \frac{\partial x^a}{\partial z_{\rm obs}} \frac{\partial x^b}{\partial \theta_{\rm obs}} \frac{\partial x^c}{\partial \phi_{\rm obs}}\; dz_{\rm obs}\; d\theta_{\rm obs}\; d\phi_{\rm obs}$$

manifestly gauge-invariant!

$$\Delta(\mathbf{n}, z) = \delta(\mathbf{n}, z) - 3\frac{\delta z}{1+\bar{z}} + \frac{\delta V(\mathbf{n}, z)}{V(z)}$$

GR effects: redshift + volume distortions

for example, see Yoo 2008, Yoo et al 2009, Bonvin et al 2011, Challinor et al 1011 and Jeong et al 2011

Bias issue:

Jeong, Hirata & Schmidt (2011)
De Putter, Dore' & Green (2015)
Bertacca et al (2015)
Bartolo, Bertacca et al (2015)
Desjacques, Jeong & Schmidt (2016)

- Galaxy bias is **scale-independent** on large scales (if the primordial fluctuations are Gaussian).
- Once GR is important, we have to specify **the physical frame** in which the scale-independent bias is defined.
- Bias can be understood in *the peak- background-split approach* [Wands & Slosar (2009), Bartolo et al. (2010)]:

The collapse of local over-density should be analyzed in the **comoving-synchronous gauge -** in the **rest physical frame of CDM -** and for scales where the density exceeding the critical value $\delta_c = 1.686$

- Then, in the simple linear model, the bias is defined via

$$\boxed{\delta_g = b(z)\, \delta^{(cs)}}$$

Primordial non-Gaussianity in the galaxy distribution

- Primordial quantum fluctuations generated during Inflation – may be non-Gaussian.
- Primordial non-Gaussianity is 'frozen' on large scales during the expansion of the Universe.
- The effect of PNG of local type is to modify the bias of galaxies relative to the underlying total matter distribution:

$$\delta_g = b\,\delta^{(cs)} \quad \text{where} \quad b \to b + \Delta b, \;\; \Delta b \propto f_{\mathrm{NL}} k^{-2}$$

- Local PNG thus boosts the clustering of galaxies on very large scales.
- The same problem of cosmic variance.
- And – degeneracy between GR effects and PNG (in flat-sky limit)

Magnification bias:

Metric perturbations also alter the solid angle under which galaxies are seen by distant observers thereby enhancing or decreasing their apparent flux.

In terms of the luminosity distance d_{L}, the magnification of a galaxy is defined as

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

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

$$\delta_{g,s} = \delta_{\text{no-mag}} + \mathcal{Q}\,(\mathcal{M}\text{-}1)$$

κ is the **Weak lensing convergence integral**

$\mathcal{Q}$ =- d ln N_g $(\mathcal{L}>\mathcal{L}_{\mathrm{lim}})$/ d ln $\mathcal{L}$ Magnification bias ($\mathcal{Q}$ =5s/2)

$-2\left(1 - \frac{(1+z)}{H\chi}\right)\mathbf{n}\cdot\mathbf{v}$ $\longrightarrow$ **Doppler Magnification!**

GR corrections at large scales with N-body simulations

- Large scale correlations
- Only analytical predictions of light cone distortions up to now.
- Need a good estimate of the errors on observables.

↓

Simulations!

- *Raul Abramo, Raccanelli, Bertacca et al., in prep*
- *Borzyszkowski, Bertacca and Porciani, 1703. 03407 (see also Chisari & Zaldarriaga 2011)*

LIGER (LIght cones using General Relativity) method

- Multiple efforts have been made in the literature to investigate the detectability of subtle relativistic effects from forthcoming survey data.
- 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 the LIGER mocks.

Borzyszkowski, Bertacca and Porciani, Astro-ph:1703.03407

LIGER (LIght cones using General Relativity) method

1. Newtonian simulation
2. Select an observer
3. Shift & magnify galaxies
4. Extract light cone

Borzyszkowski, Bertacca and Porciani, Astro-ph:1703.03407

LIGER (LIght cones using General Relativity) method

-To evaluate $\Delta x^i(z)$ and $\mathscr{M}$, we need to compute the gravitational potentials.

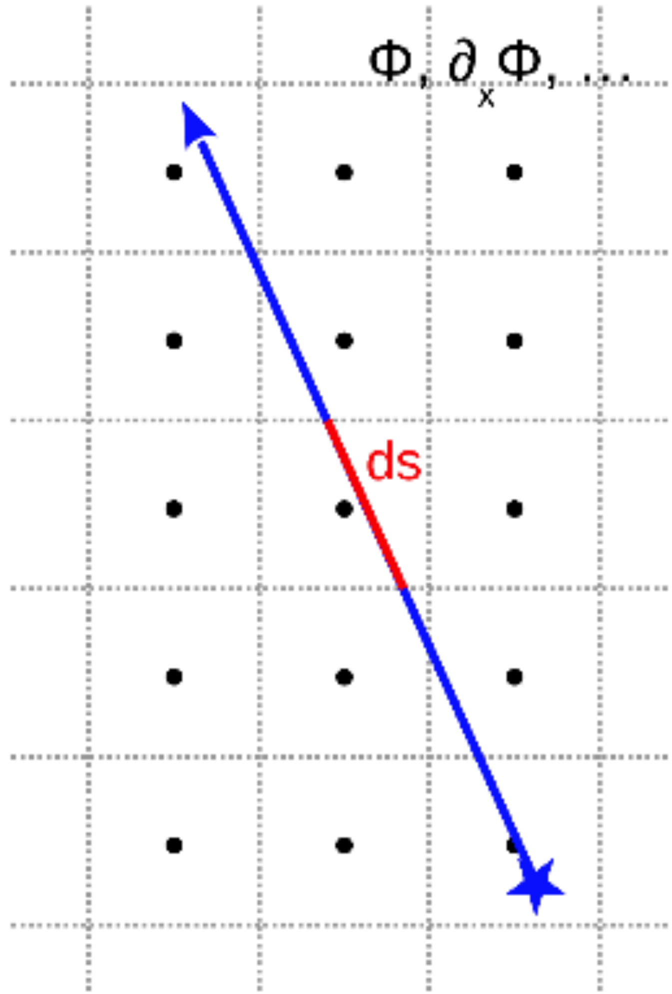
- In simulations, we need to derive the potentials starting from the particle distribution:
This corresponds to using the matter density contrast in the synchronous comoving gauge, i.e. $\delta_{\rm sim} \equiv \delta_{\rm SC}$ (syncronous comoving gauge).

- At linear order in the perturbations and for a pressureless fluid in a universe with ΛCDM background, the source equation for Ψ in the Poisson gauge can be re-written in terms of $\delta_{\rm SC}$ as the standard Poisson equation (e.g. Chisari & Zaldarriaga 2011; Green & Wald 2012):

$$\Phi = \Psi = \phi\,, \quad \nabla^2\phi = 4\pi G a^2 \bar{\rho}_{\rm m}\delta_{\rm sim}\,, \text{ and } v^i = v^i_{\rm sim}$$

Particle Shift

- All fields are sampled on a grid.
- Integration is performed as sum of the light path intersections with the grid.
- Field values are redshifted in time by interpolating the snapshots.
- Use Born approximation



Borzyszkowski, Bertacca and Porciani, Astro-ph:1703.03407

LIGER's functionality

- We reanalyse results which have already been widely discussed in the literature:

1) The impact of magnification bias in the observed cross-correlation of galaxy samples at substantially different redshifts.
2) We discuss the more challenging detection of Doppler terms in the galaxy angular power spectrum at low redshift.

Borzyszkowski, Bertacca and Porciani, Astro-ph:1703.03407

1) The impact of magnification bias

- Assume Euclid like survey.

In order to evaluate the relative importance of the velocity-induced shift, we build two other new Euclid mock catalogues

1) GR mock includes relativistic effects

2) KD model (Kaiser and Doppler):
where $\delta\chi = -\mathbf{n}\,\mathbf{v}/\mathcal{H}$, $\delta\mathbf{x} = 0$ and $\mathcal{M} = 1$, respectively
(this is the standard way to implement redshift-space distortions in simulations and omits the terms proportional to Q in α).

3) κKD model (WL + KD):
the redshift-space distortions + weak lensing assuming that the convergence is the only source of magnification, i.e. $\mathcal{M}_\kappa = 1 + 2\kappa$
(i.e. we do not consider doppler magnification!)

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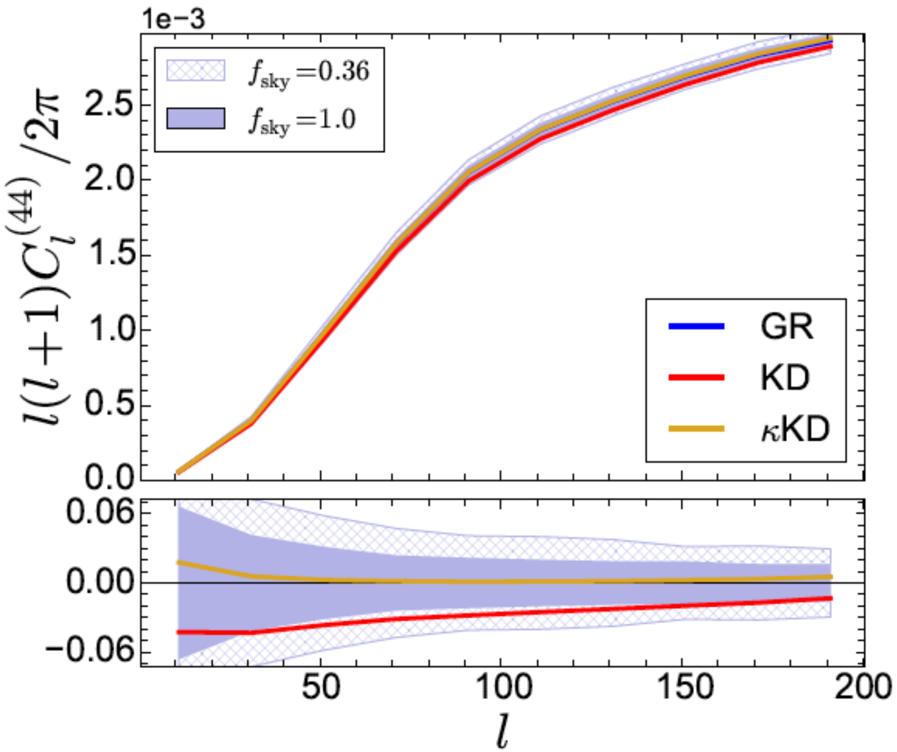
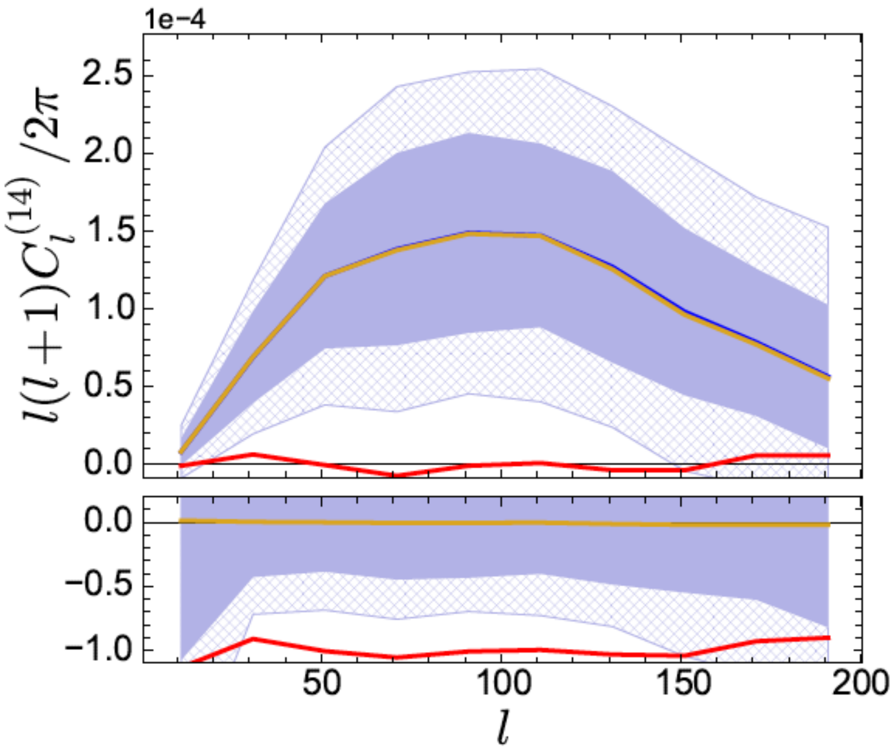
1) The impact of magnification bias

- Assume Euclid like survey.





Auto-correlation

Cross-correlation

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1) The impact of magnification bias

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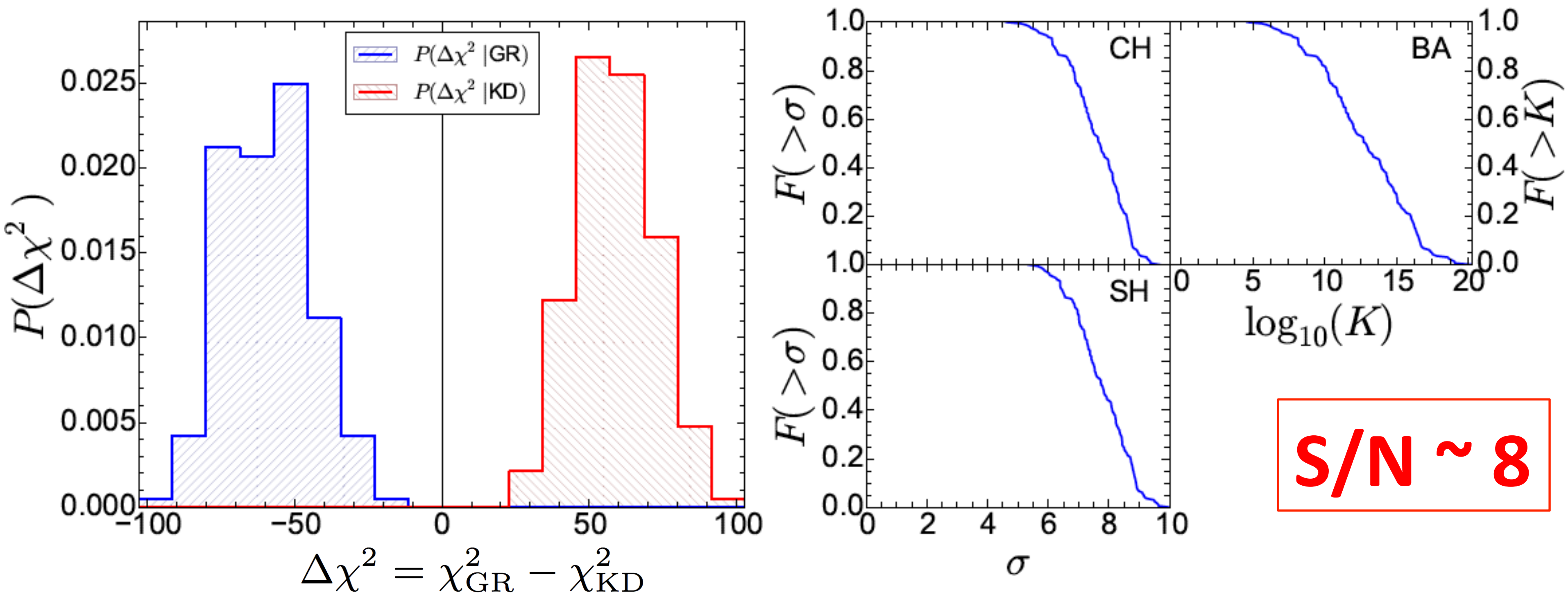

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1) The impact of magnification bias

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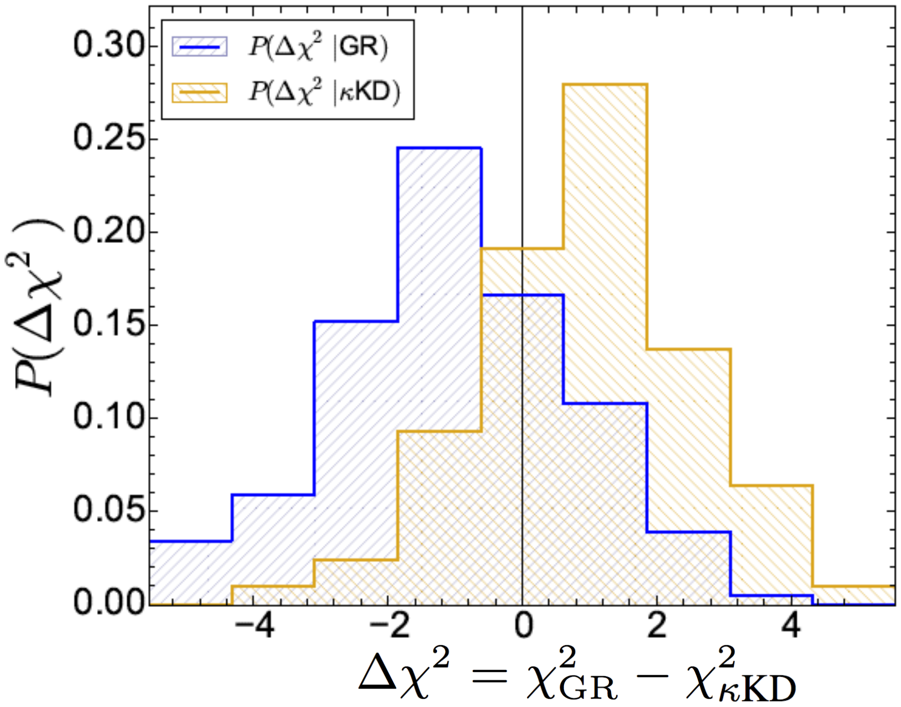

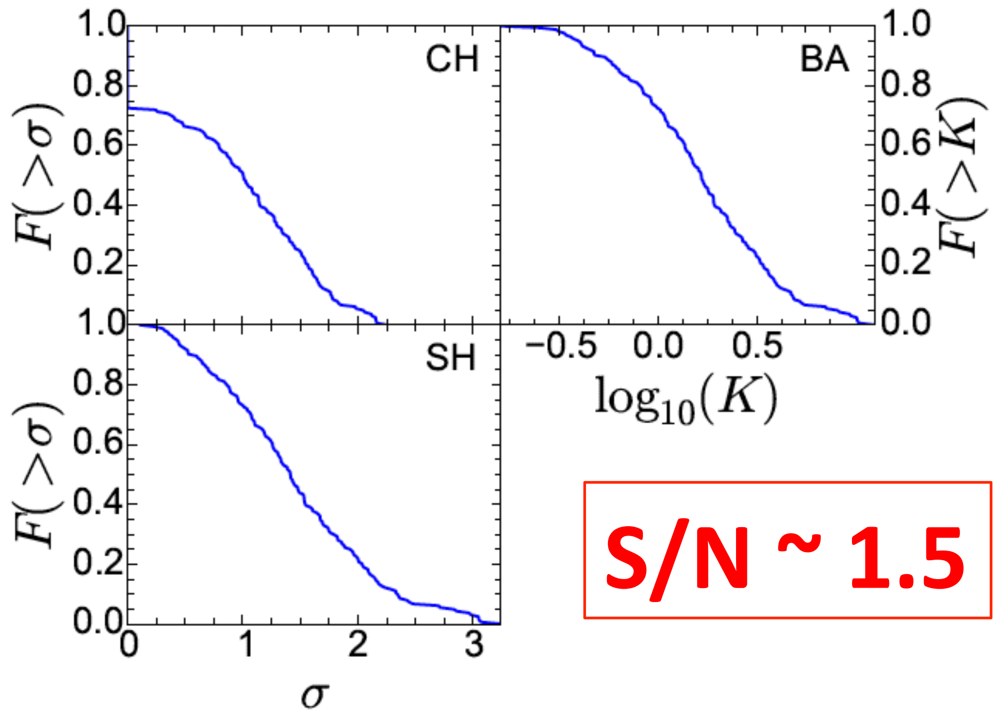

S/N ~ 1.5

due to the doppler magnification!

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2) Detection of Doppler terms

We build two sets of mock catalogues:

1) GR mock includes relativistic effects

2) DS (Doppler suppressed):
we drop the Doppler terms that are proportional to b_e and $\mathcal{Q}$.
$\alpha_{\rm DS} = 2 + [1 - (3/2)\Omega_m(z)]\mathcal{H}\chi$ (in ΛCDM model)

- We consider the interval $0.15 < z < 0.25$ which we further divide into bins I: $0.15 < z < 0.2$ and II: $0.2 < z < 0.25$.
- For SKA II (Yahya et al. 2015):
  Bright sample: with fluxes above 60μJy.
  Total sample with flux above 23 μJy

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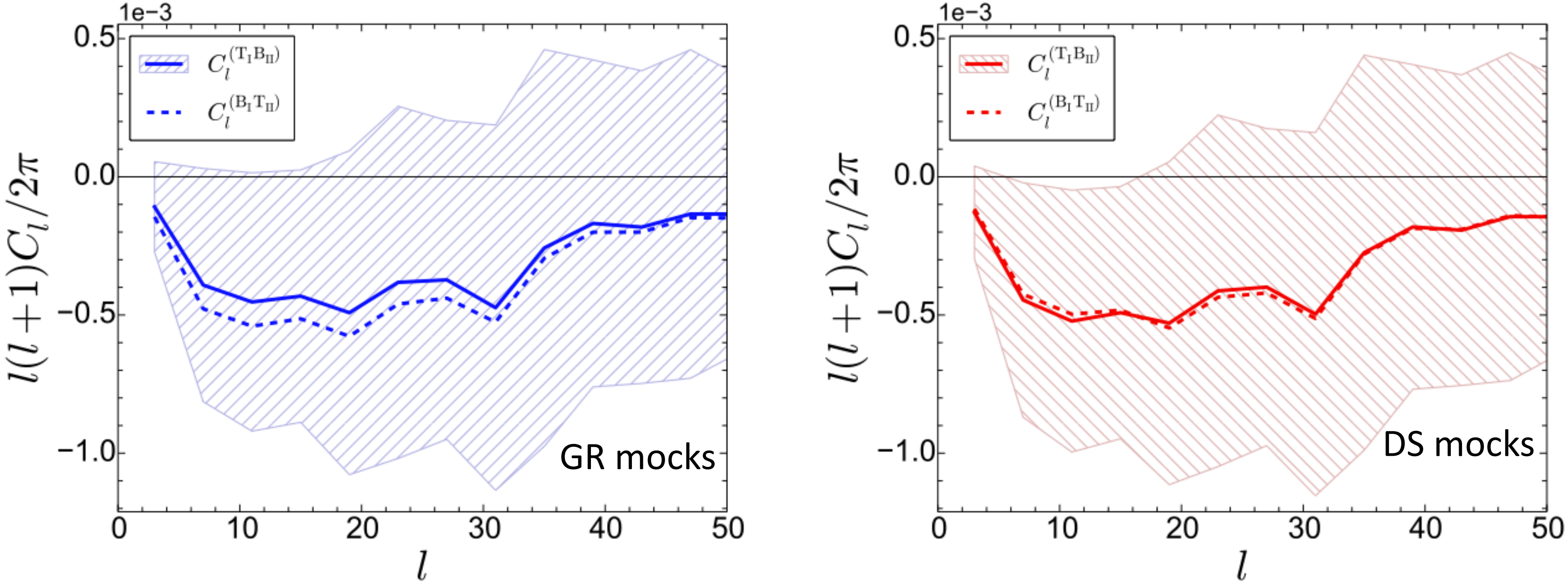
2) Detection of Doppler terms



The shaded areas indicate the standard deviation for $C_l^{(\mathrm{T_I\,B_{II}})}$ (the scatter for $C_l^{(\mathrm{B_I\,T_{II}})}$ is of comparable size).

It is evident that the cross spectra extracted from the galaxy survey will be very noisy.

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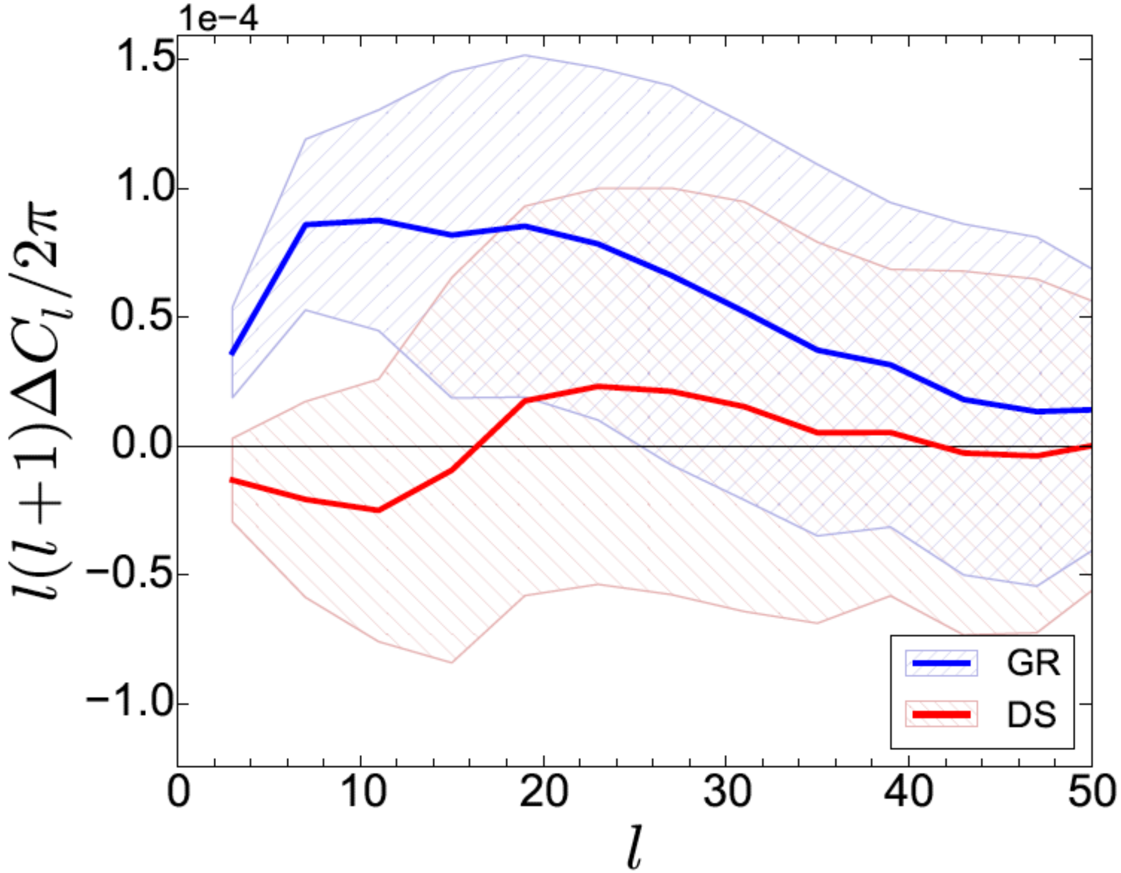
2) Detection of Doppler terms

$$\boxed{\Delta\hat{C}_l = \hat{C}_l^{(\mathrm{T_I\,B_{II}})} - \hat{C}_l^{(\mathrm{B_I\,T_{II}})}}$$

While the relative error on the single cross-spectra is very large, **ΔC_l can be measured!!** (especially for l < 25).



-Both galaxy populations trace the same large-scale structure → most of the noise in the cross-spectra is correlated and thus does not appear in the difference.

- This exemplifies the advantage of using **a multi-tracer approach** (McDonald & Seljak 2009)

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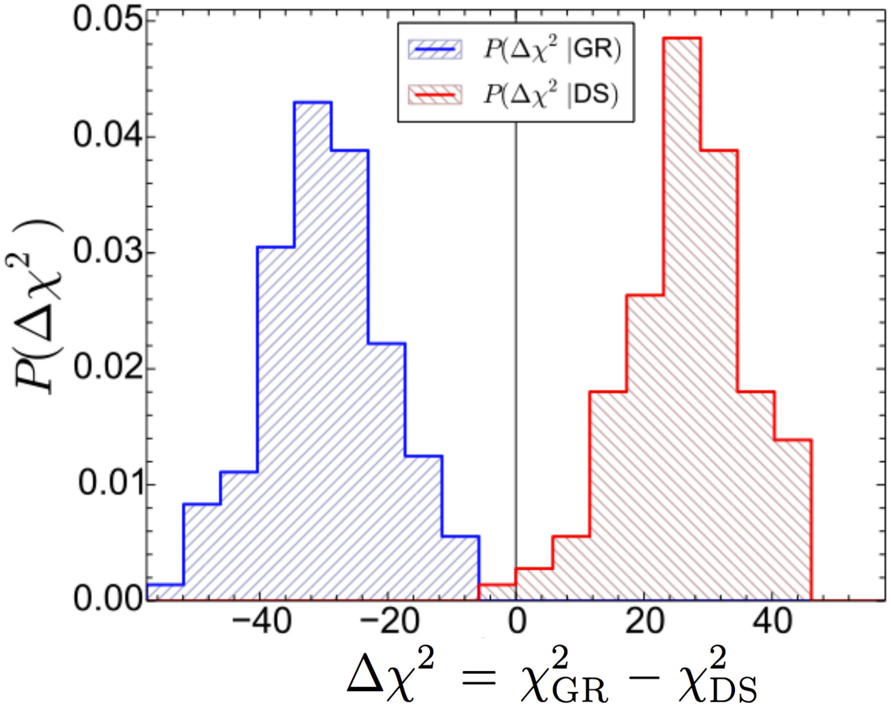
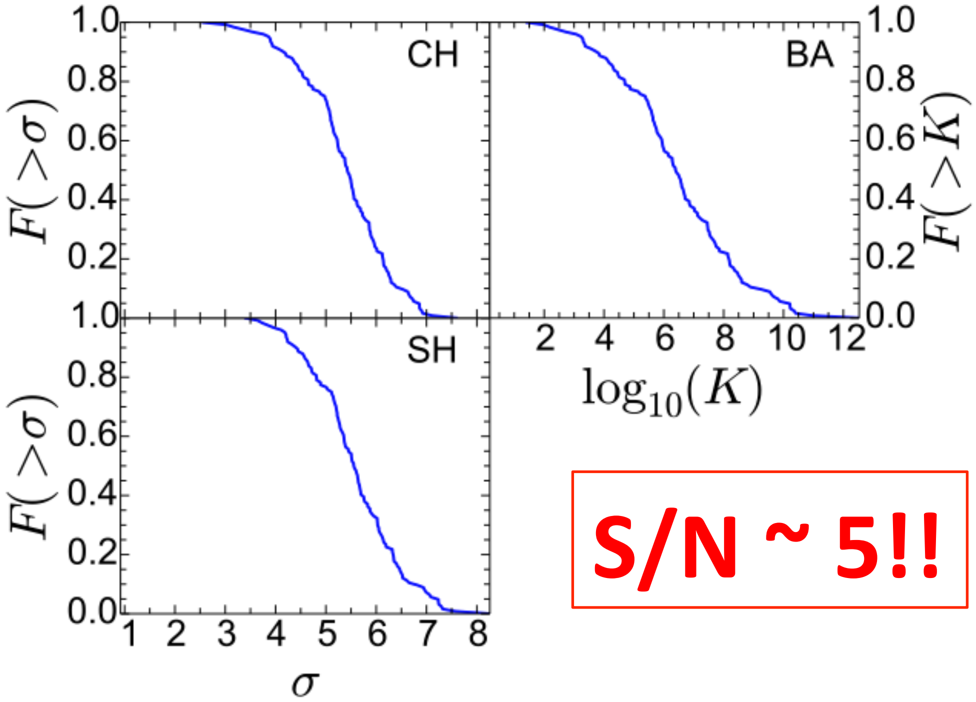
2) Detection of Doppler terms





S/N ~ 5!!

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Conclusions

There are multiple reasons for which galaxy clustering requires a proper general relativistic description:

(i) We observe events lying on our past light cone.

(ii) The propagation of light is affected by the presence of inhomogeneities in the matter distribution.

(iii) In consequence, galaxy observables (i.e. redshift, flux in some waveband and angular position on the sky) are influenced by the large-scale structure intervening between the source and the observer.

(iv) Large scale effects:

-non-Gaussianity, compute GR corrections at 2^{nd}, best constraints on dark energy and modified gravity models, neutrino masses etc..

(v) For future surveys [such as SKA, PFS, WFIRST and Euclid (+ SPHEREx)], which aim to measure the clustering with a comparable precision, we have to taken in account all corrections!

Thank You