DARK ENERGY
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Primordial non-Gaussianity with DESI.

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New Strategies for Extracting Cosmology from Galaxy Surveys
Sexten, July 10, 2025

Power spectrum with PNG

- Noticed in *Dalal et al. 2008*, **PNG** will **act** at **large scales** via the **scale-dependent bias:**

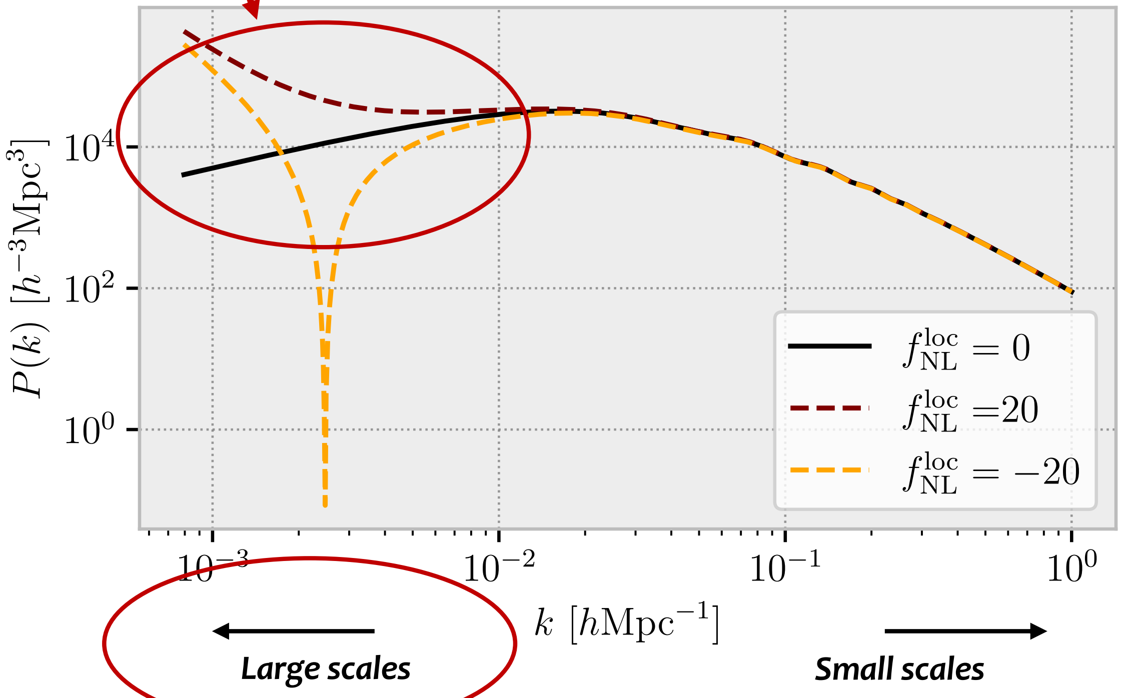
$$P(k,z) = \left(b(z) + \underbrace{\frac{b_\phi(z)}{\alpha(k,z)}} f_{NL}^{loc} \right)^2 \times P_{lin}(k,z)$$

matter power spectrum

impact of PNG $\propto \left(k^2 \times T(k)\right)^{-1}$

It tells us about the type of inflation

Strongly **contaminated** by the so-called 'imaging systematics'



Power spectrum at z=1.7 with b=2.5

- One can assume an explicit expression for b_ϕ:
  - **Universal relation:**

$$b_\phi(z) = 2\delta_c\,(b(z) - p)$$

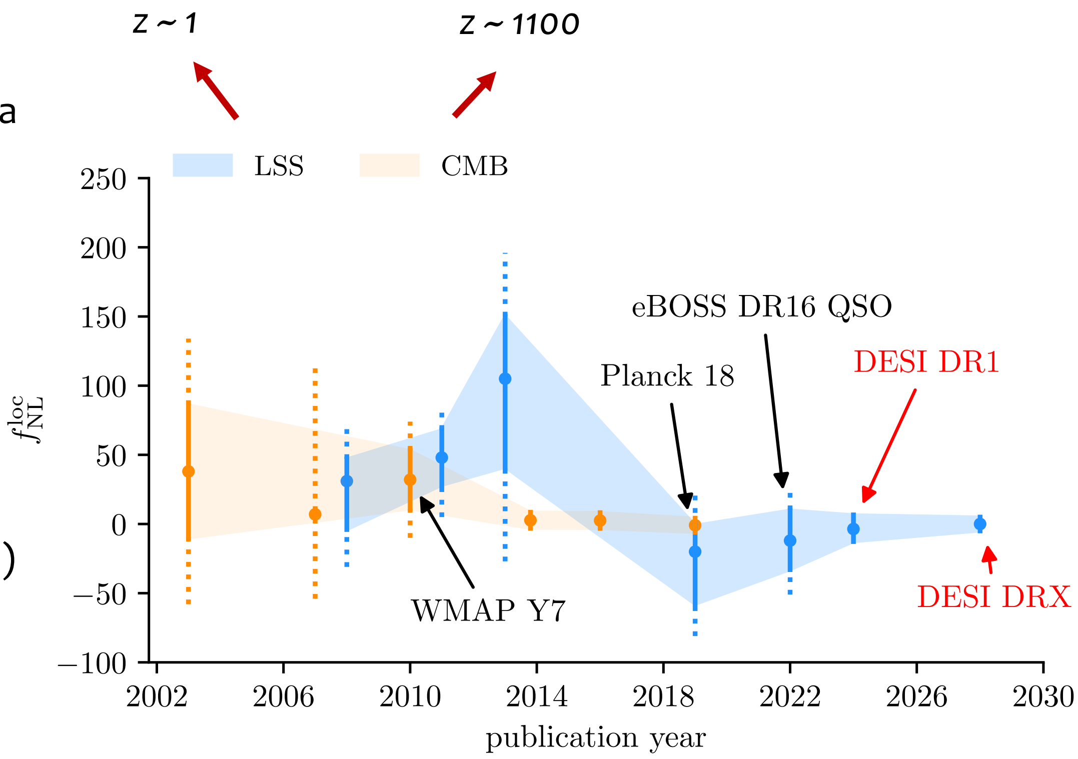
  - Not treated **here:**
    - **p = 1** for LRG.
    - **p = 1.6** for QSO.

Current constraints on PNG

- Best constraints from Planck18:
  - $f_{NL}^{loc} = -0.9 \pm 5.1$
  - but **now** limited by the **cosmic variance** (only a factor of 2 of improvement is expected with CMB-S4) !

- With scale-dependent bias:
  - eBOSS Quasar DR16 P(k) (*Mueller+2021*)
    - p=1.6: **-33 <** $\boldsymbol{f_{NL}^{loc}}$ **< 10** (at 68% CL)
  - eBOSS Quasar DR16 P(k) + B(k) (Cagliari+2025)
    - p=1.6 : **-23 <** $\boldsymbol{f_{NL}^{loc}}$ **< 14** (at 68% CL)
    - 16% gain.
  - **DESI**: *today presentation!* 😎

- Upcoming generation of surveys should be **competitive** with Planck !



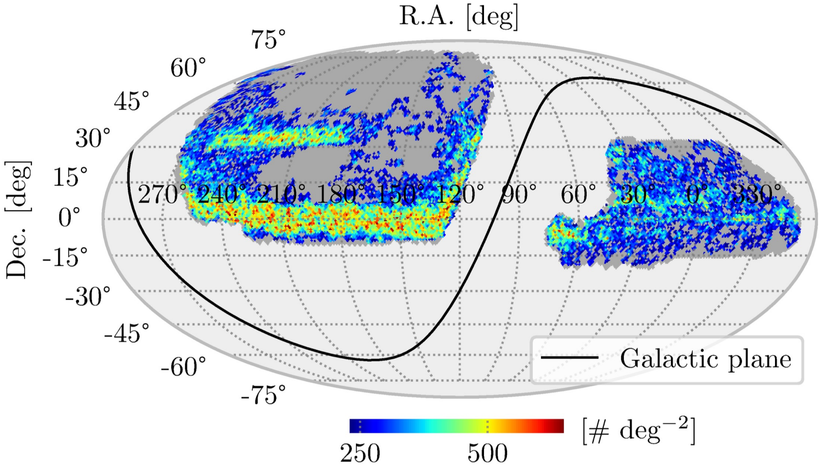
Evolution of the constrain on f_{NL}.

DESI DR1 Analysis

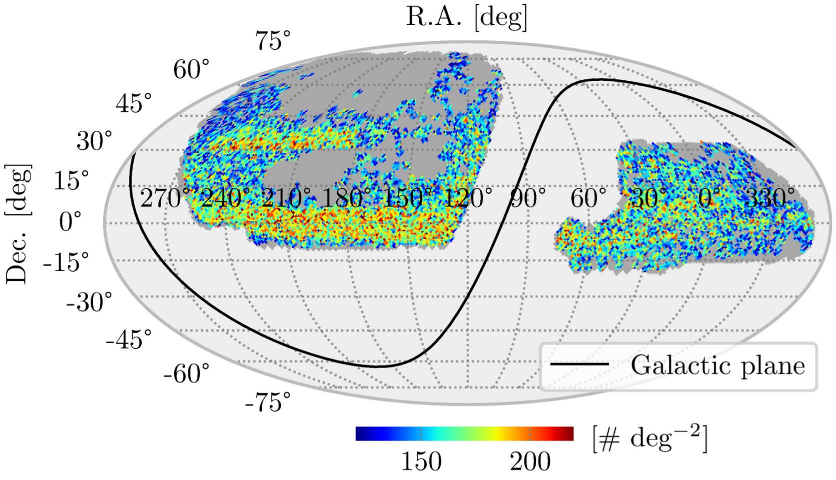
- What's new compare to eBOSS DR16 ?
  - DESI DR1 is already the **largest** galaxy clustering sample:
    - ~ **2 100 000** LRG with 0.4 < z < 1.1 (*Zhou+2023*)
    - ~ **850 000** QSOs with 0.8 < z < 3.1 (*Chaussidon+2023*)
    - **New survey:** need to study/validate all the observational systematics !
  - Analysis in conduct with a **blinding scheme** for the first time:
    - Avoid any confirmation bias !
  - Geometrical model improvement:
    - Radial Integral Constraint
    - Angular Integral Constraint

DESI DR1 LRG and QSO angular densities (corrected by completeness)

	LRG $[\mathrm{deg}^{-2}]$	QSO $[\mathrm{deg}^{-2}]$
North	531.7	186.6
South	535.3	188.7
Des	519.5	192.7

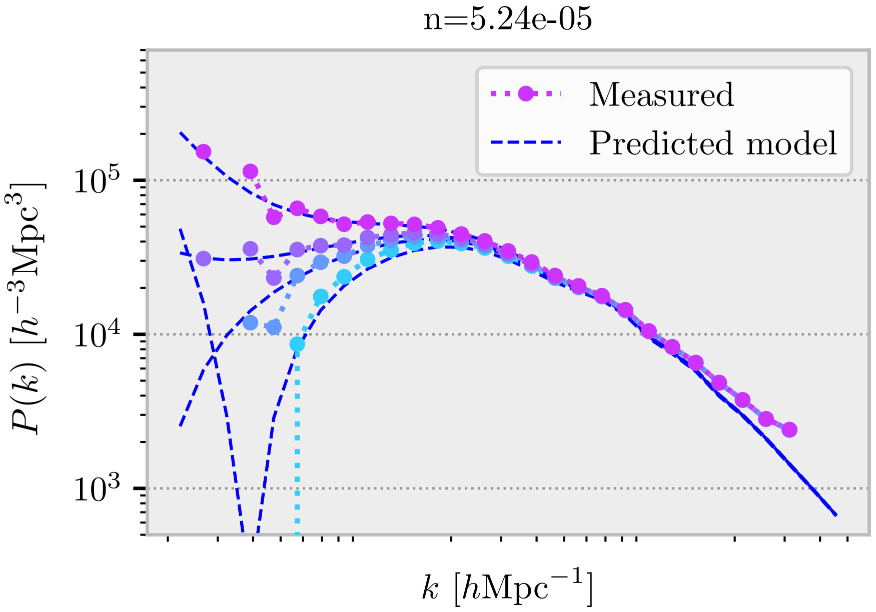


DESI DR1 LRG (top) and QSO(bottom) angular distribution without completeness correction



Blinding Scheme

- **Risk:** Force our new measurement to agree with the former one:
  - Do we find $f_{NL}^{loc} = 0$, like Planck 18 ?
- **Solution:** Blind the signal !
  - Specific weights for the data mimicking the **expected** scale-dependent bias in the power spectrum.
  - Test imaging systematic mitigation without **confirmation bias.**
- This blinding procedure is used in the default pipeline of DESI:
  - In the following, **all the data are blinded** *i.e.* the large-scales are not the true one!
  - $f_{NL}^{blind} \in [-15, 15]$
  - **Same** for all the tracer !



Power spectrums computed from simulated data with blinding weights for several blinding values.

From Chaussidon+2024a

Model

- We fit the monopole (ell=0) and quadrupole (ell=2) of the power spectrum (0.003 to 0.08 hMpc^{-1}) with a simple Kaiser term and a damping function:

$$P_{\rm theo}(k,\mu) = \frac{\left[b + \frac{b_\Phi}{\alpha(k,z_{\rm eff})} f_{\rm NL}^{\rm loc} + f\mu^2\right]^2}{\left[1+\frac{1}{2}\left(k\mu\Sigma_s\right)^2\right]^2} \times P_{lin}(k, z_{\rm eff}) + s_{n,0}$$

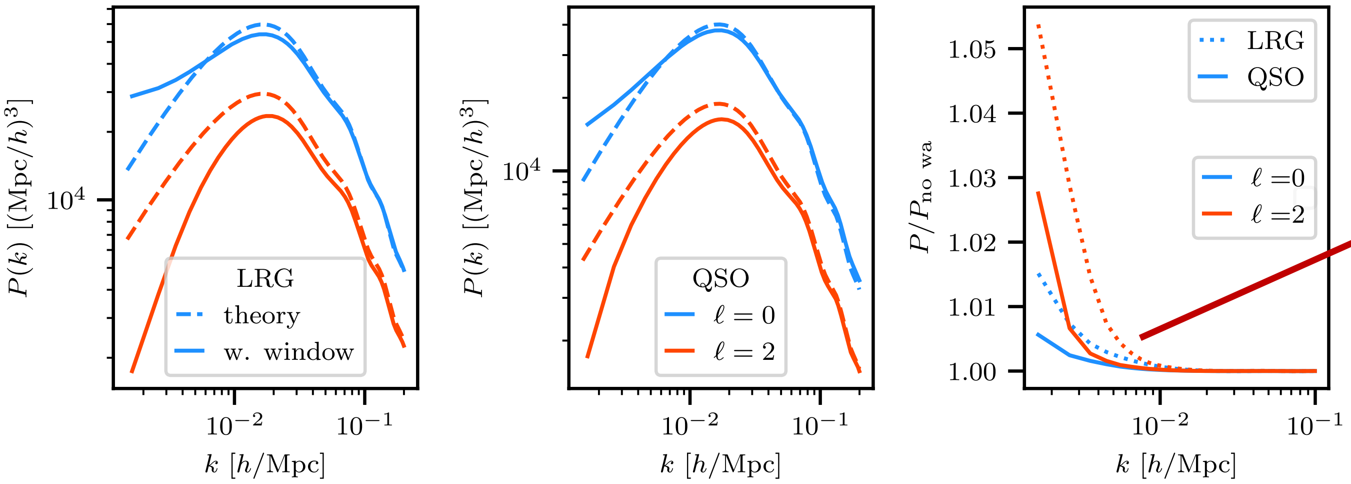
Linear RSD

Shot noise

For small scales

- Geometry impact is included via window convolution (*Beutler and McDonald 2021*):

$$\left(P_\ell^{\rm conv}\right)_i = \left(\mathcal{W}_{\ell\ell'}\right)_{ij} \cdot \left(P_{\ell'}^{\rm theo}\right)_j$$



Wide angle effect ~ 1% effect for LRG at very large scales.

Optimal weighting scheme for $f_{\mathrm{NL}}^{\mathrm{loc}}$

- Following *Castorina+2019.*

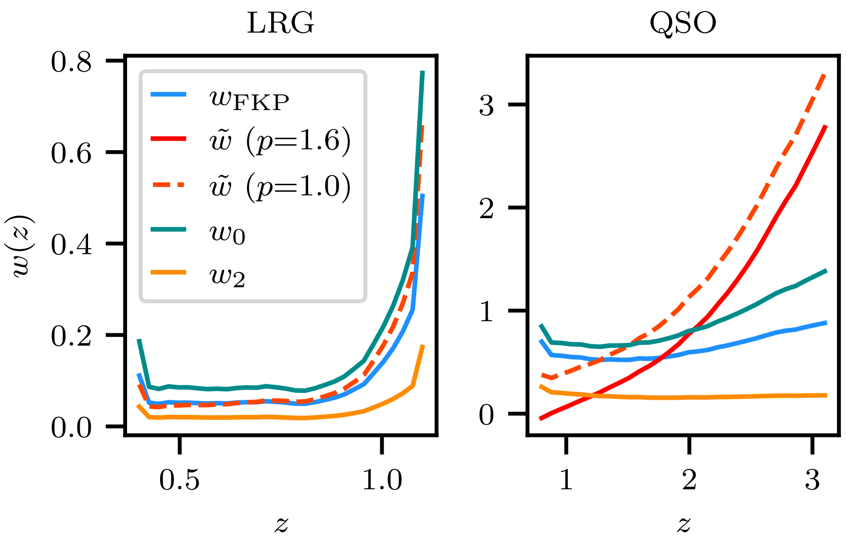
- Using FKP weights is the optimal way to measure the power spectrum.

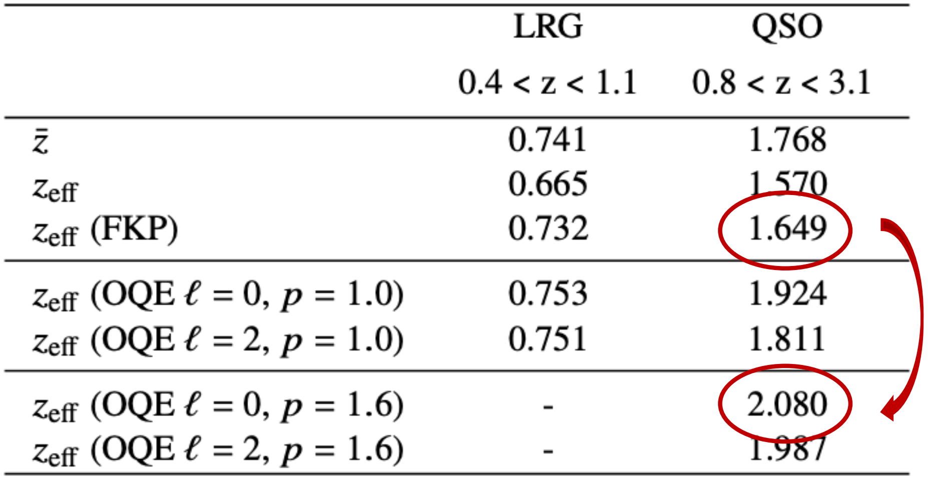
- Using OQE weights is the optimal way to measure f_{NL}^{loc} with the power spectrum:
    - **Increase the effective redshift** of the data.
    - Reducing the errors on $f_{\mathrm{NL}}^{\mathrm{loc}}$ since:

$$\propto b \times f_{\mathrm{NL}}^{\mathrm{loc}}$$

    - Weights not the same for ell=0 and ell=2

- Window function has to be computed for each weighting scheme !!



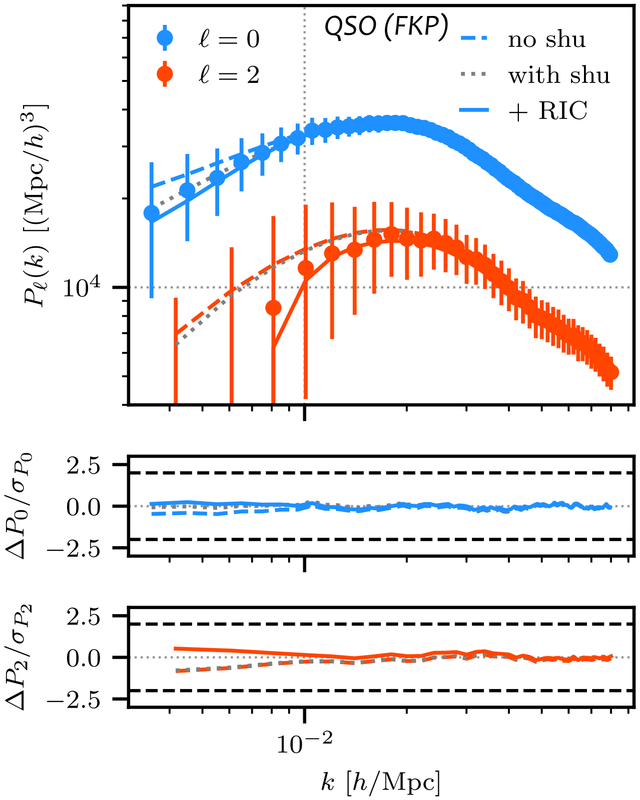


	LRG	QSO
	0.4 < z < 1.1	0.8 < z < 3.1
$\bar{z}$	0.741	1.768
z_{eff}	0.665	1.570
z_{eff} (FKP)	0.732	1.649
z_{eff} (OQE $\ell = 0$, $p = 1.0$)	0.753	1.924
z_{eff} (OQE $\ell = 2$, $p = 1.0$)	0.751	1.811
z_{eff} (OQE $\ell = 0$, $p = 1.6$)	-	2.080
z_{eff} (OQE $\ell = 2$, $p = 1.6$)	-	1.987

Radial Integral Constraint (RIC)

- Use of "*shuffling method*" leads to RIC:
  - Randoms are generated on the sky (R.A., Dec.).
  - Data redshifts are used as redshifts for the randoms (**remove radial modes …**).
- **Use mocks to infer the contribution of the** window function to correct for RIC:

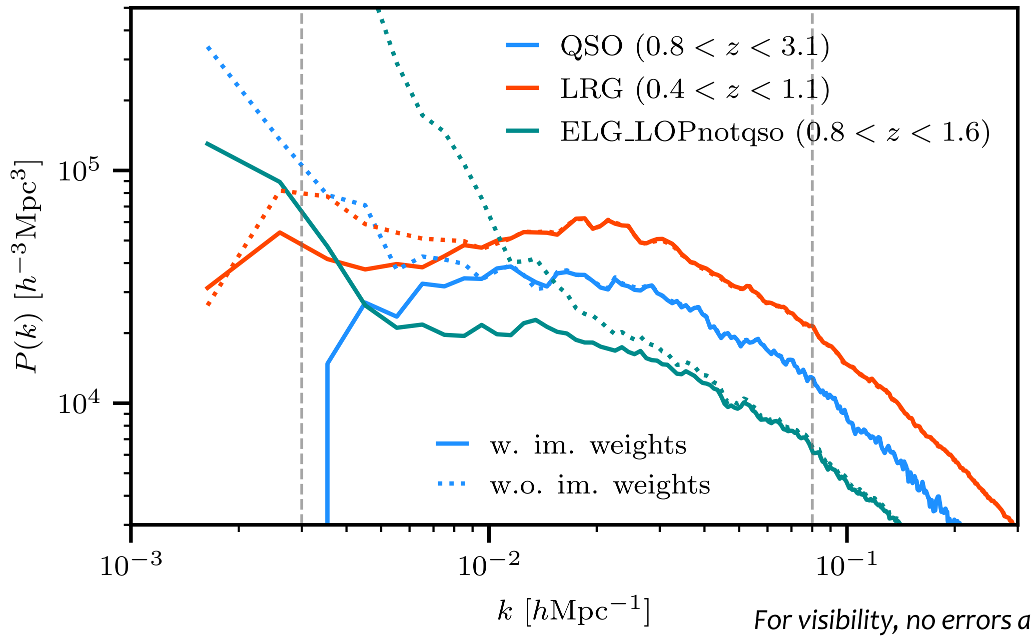
$$\left(P_\ell^{\rm obs}\right)_i = \left(\mathcal{W}_{\ell\ell'} - \mathcal{W}_{\ell\ell'}^{\rm RIC}\right)_{ij} \cdot \left(P_{\ell'}^{\rm theo}\right)_j$$



	params	no shuffle	shuffle	shuffle + RIC
LRG	$f_{\rm NL}^{\rm loc}$	7 ± 15	-4 ± 18	7 ± 16
	b_1	1.952 ± 0.033	1.948 ± 0.036	1.950 ± 0.034
	$s_{n,0}$	0.047 ± 0.060	0.059 ± 0.063	0.052 ± 0.060
	Σ_s	4.41 ± 0.47	4.69 ± 0.45	4.53 ± 0.45
QSO	$f_{\rm NL}^{\rm loc}$	4 ± 17	-7 ± 20	6 ± 17
	b_1	2.371 ± 0.048	2.376 ± 0.052	2.365 ± 0.047
	$s_{n,0}$	-0.002 ± 0.052	-0.001 ± 0.054	0.004 ± 0.054
	Σ_s	2.71 ± 0.90	3.03 ± 0.82	2.91 ± 0.84
QSO (blind 20)	$f_{\rm NL}^{\rm loc}$	29 ± 13	22 ± 15	30 ± 13
	b_1	2.368 ± 0.043	2.360 ± 0.045	2.363 ± 0.042
	$s_{n,0}$	-0.011 ± 0.049	0.006 ± 0.050	0.000 ± 0.049
	Σ_s	2.75 ± 0.88	3.02 ± 0.81	2.98 ± 0.81

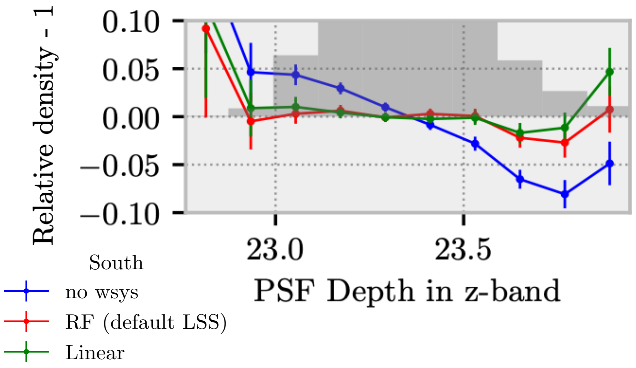
Apply this correction on mocks with the ***exact same geometry*** *but with a* ***different power spectrum***

DESI DR1 power spectra



For visibility, no errors are displayed here, but differences are significant..

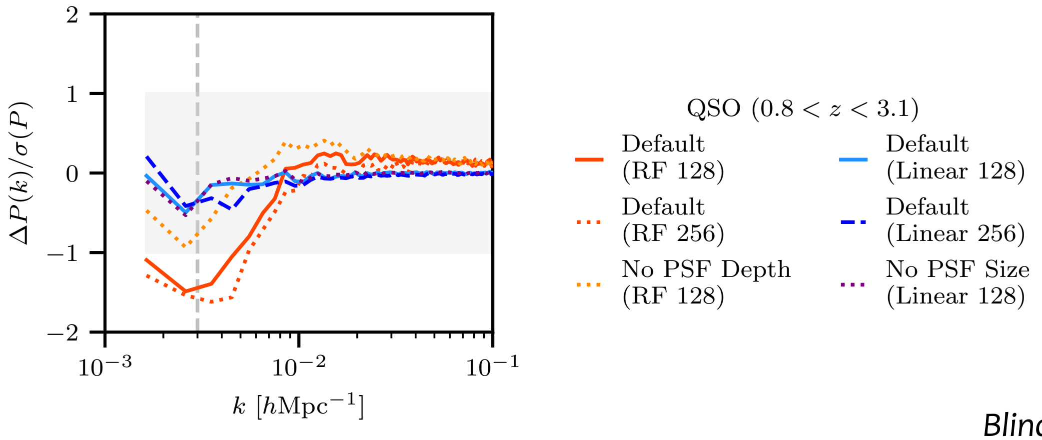
- Large scale modes are **heavily** contaminated by imaging systematics !!
  - = dependence of the target selection on imaging qualities!
  - This is **the largest systematics in this analysis !!**
- After lot of efforts:
  - QSOs look great !!! (even greater in DR2)
  - Weird excess of power with LRGs (solved in DR2 …)
  - I gave up with the ELG .. (still a major concern with DR2 data)



Angular Integral Constraint (AIC)

- Compute and apply imaging weights on mocks with **no** contamination:
  - Remove power at large scales --> Need to correct for !
  - **Expected** !! This is **pure geometry**. We are “flattening” the angular distribution i.e. we are removing the angular modes (larger than the size of the pixel!) - - > Angular Integral Constraint.
  - Infer the window correction from these mocks (similar than for RIC): $\mathcal{W} \rightarrow \mathcal{W} - \mathcal{W}^{\mathrm{RIC}} - \mathcal{W}^{\mathrm{AIC}}$

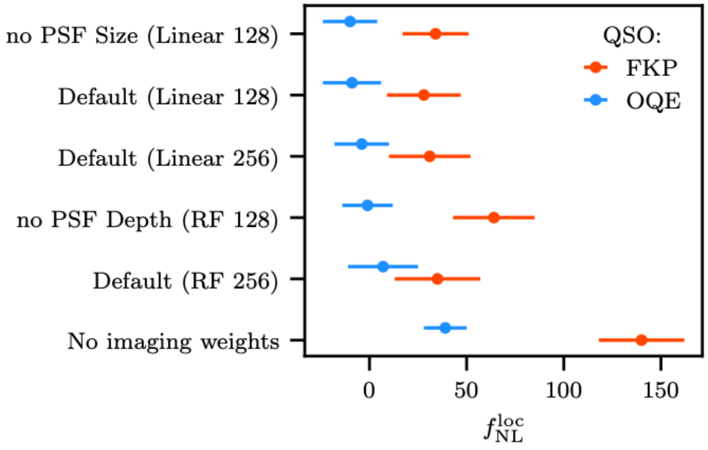
Difference between P(k) with and without w_sys applied.



Different w_sys

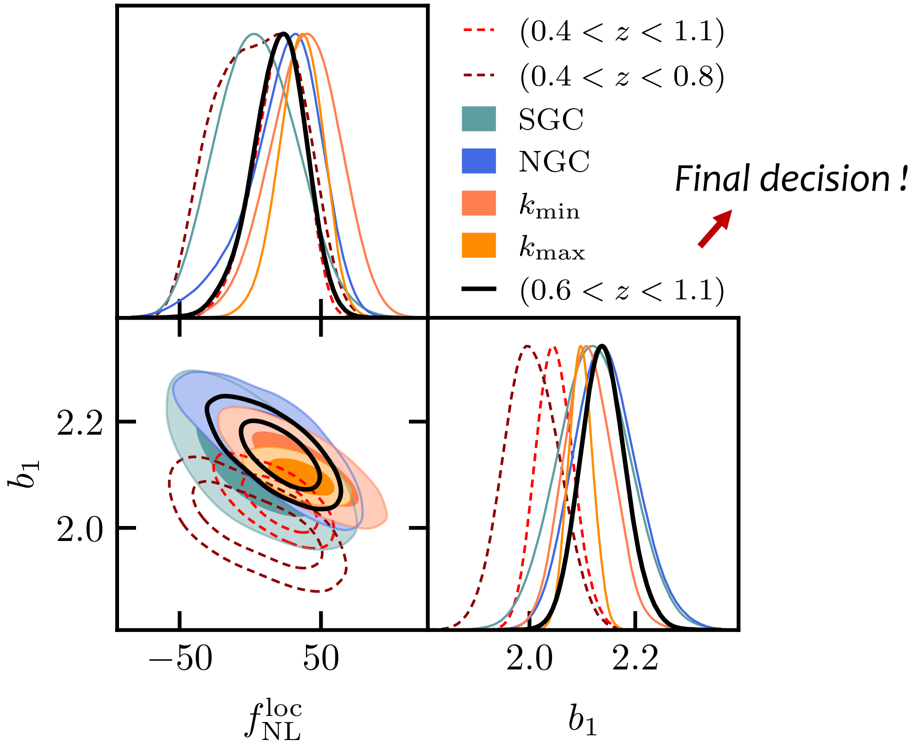
- AIC needs to be computed for each imaging weights:
  - Then, we can compare the efficiency of these different weights!

Blinded data !



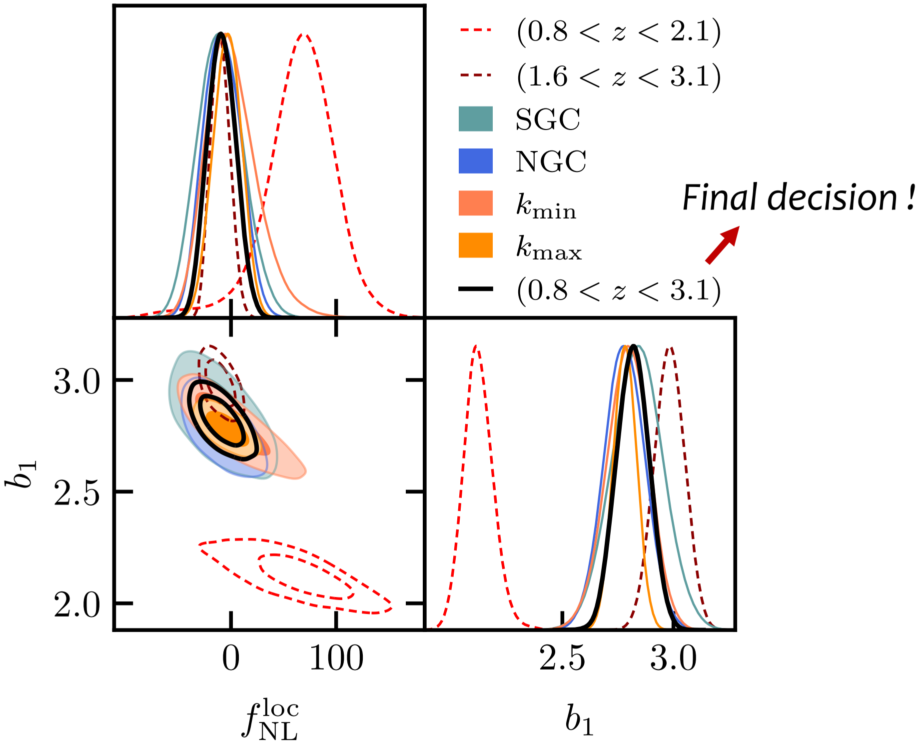
Blinded data

- Blinded LRG:
  - weird shape for the low-z part of the sample - -> use only 0.6 < z < 1.1 .
  - Largest scales exhibit inconsistent signal - -> reduce k_{min} to 0.006 h/Mpc.
- Blinded QSO:
  - Remaining systematic in the low-z sample - -> OQE **under-weighted enough this part of the sample !**



Final decision !

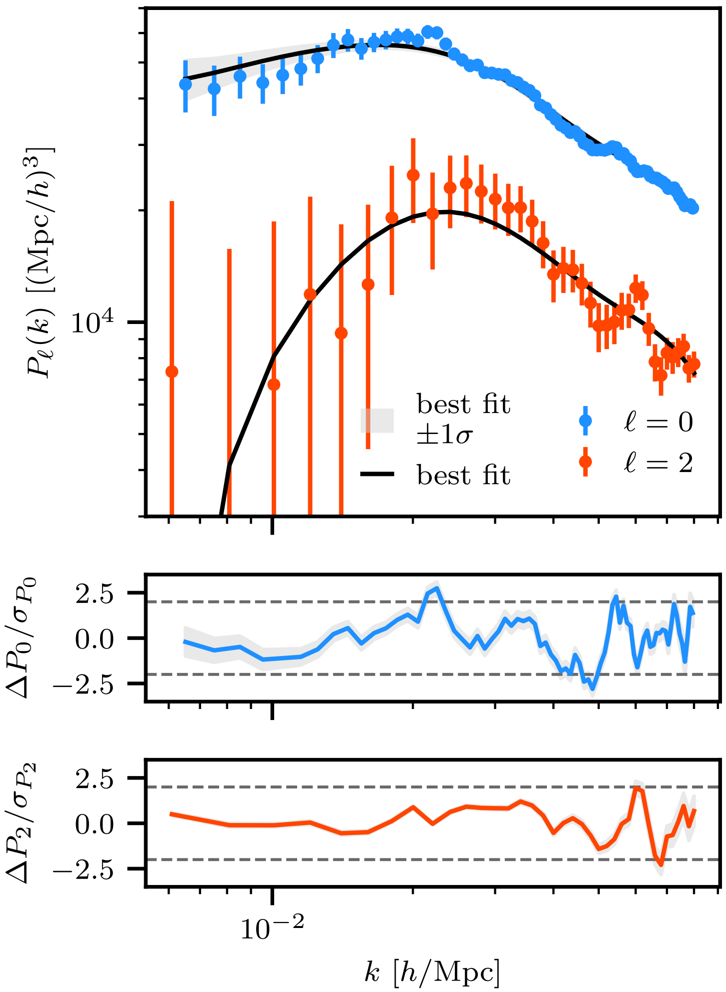
LRG blinded (FKP) high-z

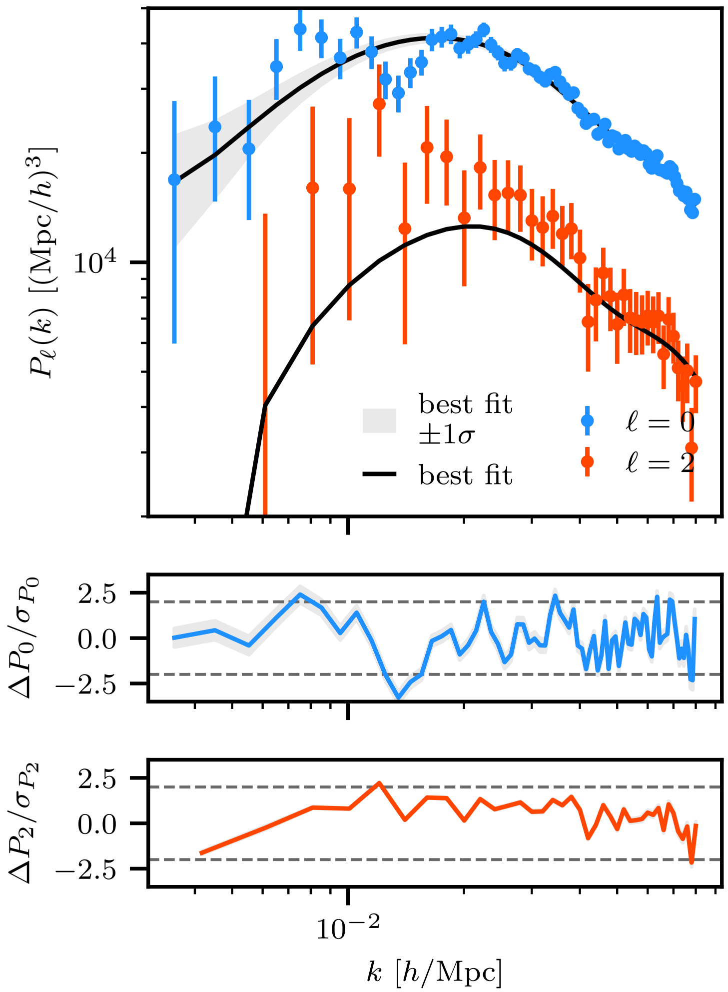


Final decision !

QSO blinded (OQE)

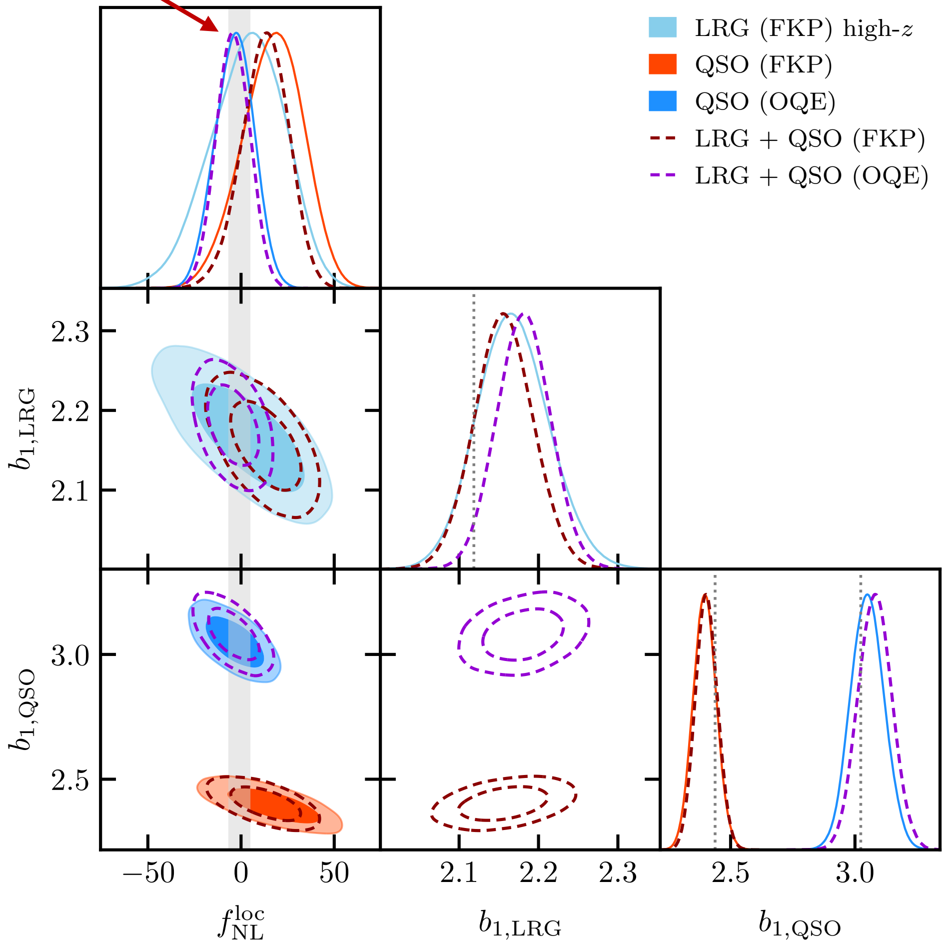
Best fit (unblinded)


LRG (FKP) high-z


QSO (OQE)

Final Measurement (unblinded)

Planck 18 (68% CL)



- DESI QSO + LRG:

$$f_{\mathrm{NL}}^{\mathrm{loc}} = \begin{cases} -\,3.6^{+9.0}_{-9.1} & (68\%) \quad \text{with } p_{\mathrm{QSO}} = 1.6 \\ 1.7^{+8.4}_{-7.7} & (68\%) \quad \text{with } p_{\mathrm{QSO}} = 1.0 \end{cases}$$

- Individual constraints:

$$f_{\mathrm{NL}}^{\mathrm{loc}} = \begin{cases} 6^{+22}_{-18} & (68\%) \quad \text{LRG only} \\ -2^{+11}_{-10} & (68\%) \quad \text{QSO only with } p_{\mathrm{QSO}} = 1.6 \\ 3.5^{+10.7}_{-7.4} & (68\%) \quad \text{QSO only with } p_{\mathrm{QSO}} = 1.0 \end{cases}$$

- Systematic error budget represents an increase of **8%** for LRGs and **12%** for QSOs.

Forecast for DESI

- With DESI DR1 (LRG+QSO):

$$f_{\rm NL}^{\rm loc} = \begin{cases} -\,3.6^{+9.0}_{-9.1} & (68\%) \quad \text{with } p_{\rm QSO} = 1.6 \\ 1.7^{+8.4}_{-7.7} & (68\%) \quad \text{with } p_{\rm QSO} = 1.0 \end{cases}$$

  - 10% gain by including LRGs
  - Improving by ~ a **factor 2** the measurement **from eBOSS DR16 !**

- What next?
  - DESI Y5 (before the extension) with k_{min} = 0.003 : LRG+QSO (p=1.6) --> $\sigma\left(f_{\rm NL}^{\rm loc}\right) = 6.5$
  - Decreasing k_{min} to 0.001 --> ~10% gain
  - p ~ 1.4 for QSO --> ~10% gain
  - Includes high-order correlation (e.g. field level inference). --> 15/20 % gain
  - Should **be close to defeat** Planck18 ($\sigma\left(f_{\rm NL}^{\rm loc}\right) = 5.1$).

Ad I: Determination of b_ϕ (Emanuele Fondi, ICC)

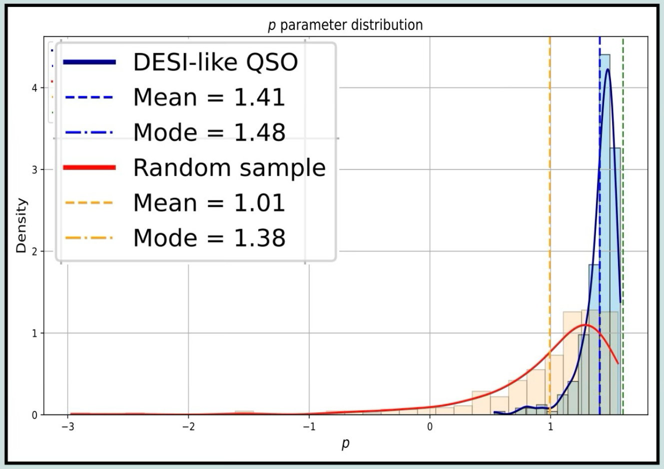
- Paper will be released soon!

$$f_{\rm NL}^{\rm loc} = -1.9 \pm 9.2, \quad p_w = 1.6$$

Strategy

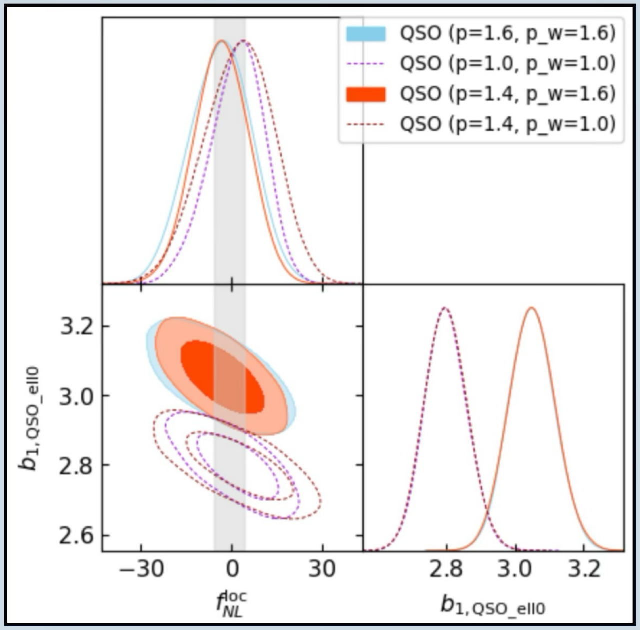
- **IllustrisTNG TNG-300**
- **Halo mass cut**
  $\log_{10} M_h > 12.2$
  (M_h of DESI QSO Yuan+ 24)
- **QSO sample: rank by Eddington ratio**
  $\lambda = \dot{M}_{BH}/\dot{M}_{Edd}$
  Sijacki+ 07
- **Measure z_f from merger trees**
- **Compute $p = p(M, z_f)$ using the ePS model**
  Reid+ 10, Fondi+ 24

Results



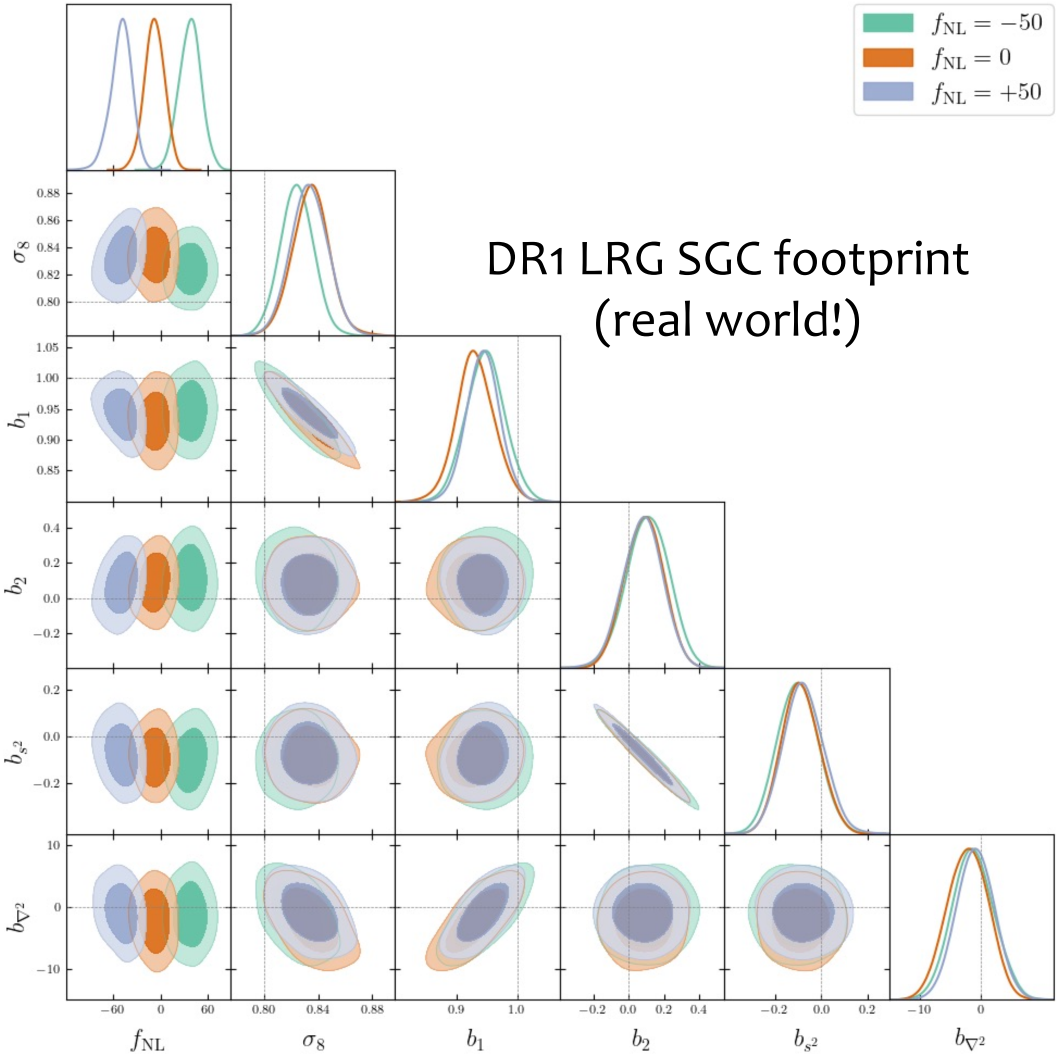
- **$p \simeq 1.4$ close to the recent merger limit $p = 1.6$**
- **Robust across redshift and selection assumptions**

Application to DR1



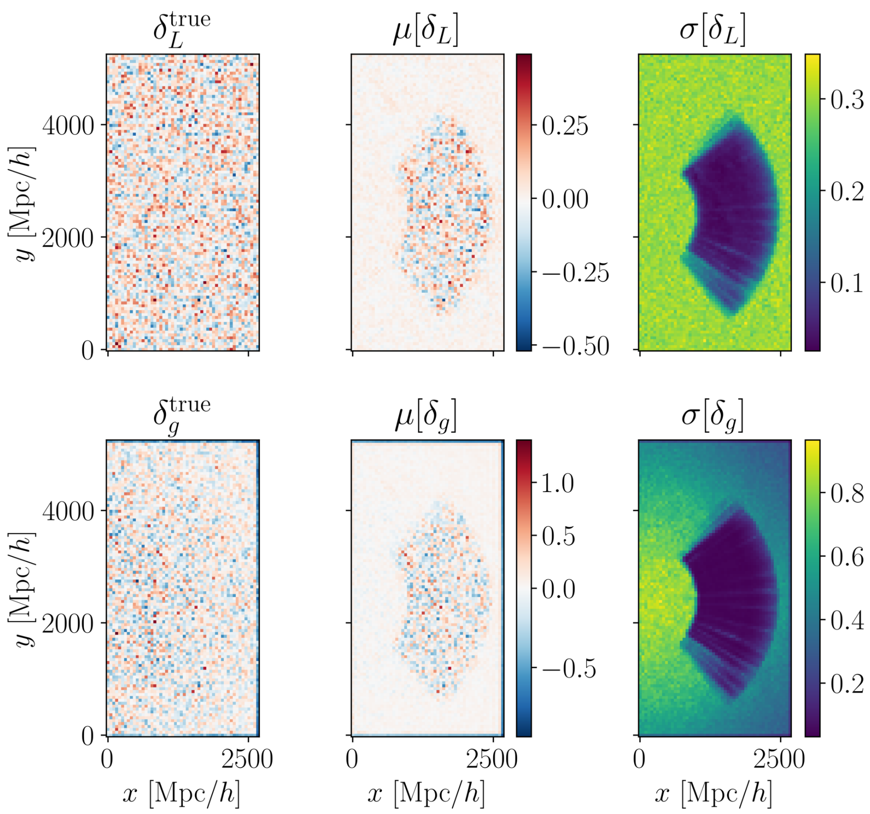
- **OQE weights $\tilde{w}(z) = b(z) - p_w$**
- **p fixed during inference**

Ad II: Field Level Inference (Hugo Simon, CEA Saclay)



DR1 LRG SGC footprint
(real world!)

$k_{\max} \sim 0.04[h/Mpc]$



- Based on JaxPM, see arXiv:2504.20130.
- Preliminary! Constraining power looks reasonable compare to power spectrum analysis

New Strategy for Extracting **PNG** from Galaxy Surveys

Kinematic-SZ Effect

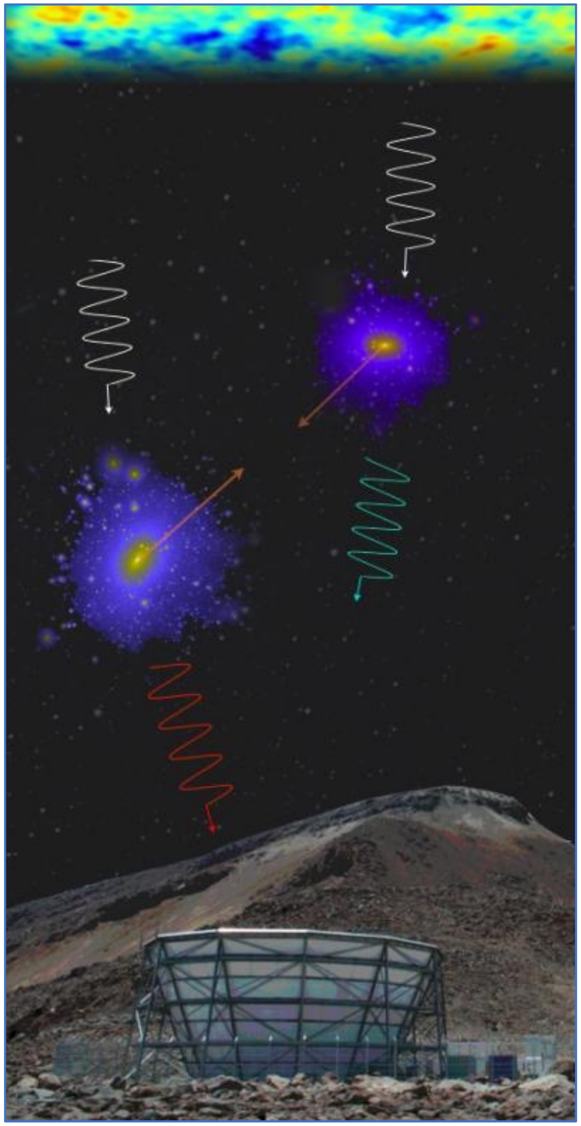
- One can use the CMB as a backlight for our DESI galaxies or quasars:
  - CMB photons can interact through *inverse Compton scattering* with high-energy electrons.
- **kSZ Effect** is the Doppler shift induced by electrons with bulk velocity:
  - Depends on the radial velocity and the electron density.

$$\frac{\Delta T_{\mathrm{kSZ}}(\mathbf{n})}{T_{\mathrm{CMB}}} \sim \int d\chi e^{-\tau(z)} v_r \delta_e(\mathbf{n}, \chi)$$

  - Radial velocities lead to **unbiased** matter perturbation modes:

$$v_r(k) = \frac{ifaH\mu}{k} \delta_m(k)$$

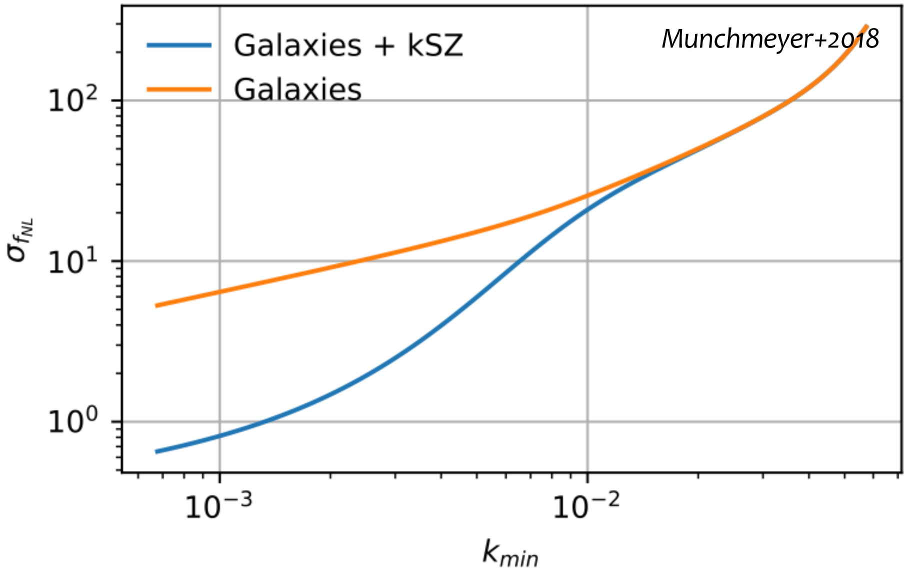
  - A bit more complicated than that due to astrophysical effects that describe the electron density.



Credit: Sudeep Das

Forecast

- Forecast few years ago (Munchmeyer+2018) as **THE** observable for local PNG.
- $v \sim 1/k$: kSZ is a great probe of matter density with good SNR on large scales !
  - Should lead to sample variance cancellation (*Seljak 2009*).
  - Expect already ~10/20% gain with DESI DR1 and more with DESI DR2.
- **IMPORTANT:** Should be systematic **free** as the LSS x Lensing



Forecast for LSST x CMB S4
(less optimistic for DESI x SO)

kSZ tomography

- The radial velocity will be reconstructed following *Smith+2018*:

$$\hat{v}_r\left(\mathbf{k}_L\right)=N^{(0)}_{v_r}\left(k_L\right)\frac{K_*}{\chi_*^2}\int\frac{d^3\mathbf{k}_S}{(2\pi)^3}\frac{d^2\mathbf{l}}{(2\pi)^2}\frac{P_{ge}\left(k_S\right)}{P^{\mathrm{tot}}_{gg}\left(k_S\right)C_l^{TT,\ \mathrm{tot}}}\left(\delta_g^*\left(\mathbf{k}_S\right)T^*(\mathbf{l})\right)(2\pi)^3\delta^3\left(\mathbf{k}_L+\mathbf{k}_S+\frac{\mathbf{l}}{\chi_*}\right)$$

radial velocity

Theory power spectrum (just a filter)

DESI galaxies

ACT map

  - With the following power spectrum noise:

$$N^{(0)}_{v_r}=\frac{\chi_*^2}{K_*^2}\left[\int\frac{k_S dk_S}{2\pi}\left(\frac{P_{ge}\left(k_S\right)^2}{P^{\mathrm{tot}}_{gg}\ \left(k_S\right)C_l^{TT,\ \mathrm{tot}}}\right)_{l=k_s\chi_*}\right]^{-1}$$

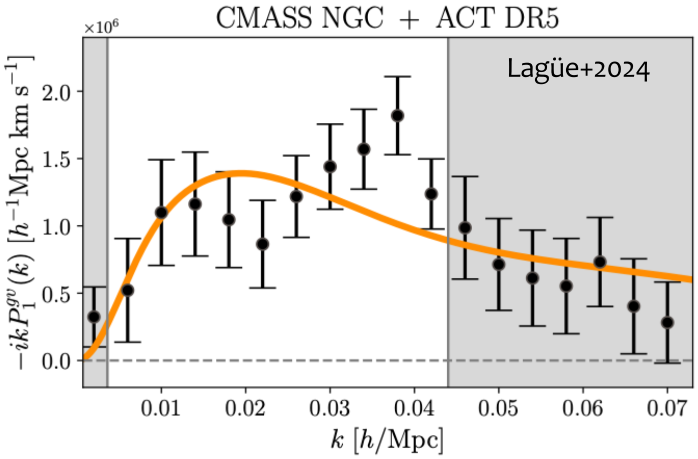
  - *After filtering the modes that contain only CMB information, we just "read" the temperature value of the position of the galaxy …*

Current status

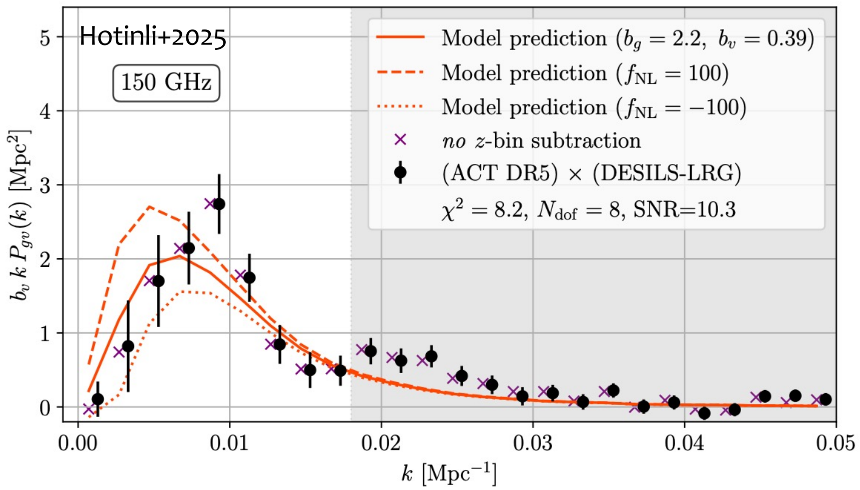
- Thanks to ACT DR5, the signal is detectable:
  - Lagüe+2024: BOSS LRG x ACT DR5 --> $P_{gv}(k)$ measured at 7.2 sigma
  - Hotinli+2025: DESILS x ACT DR5 --> measured at 11.7 sigma

- These are nice proof of concepts ! DESI DR2 will do much much better.

Spectroscopic sample:

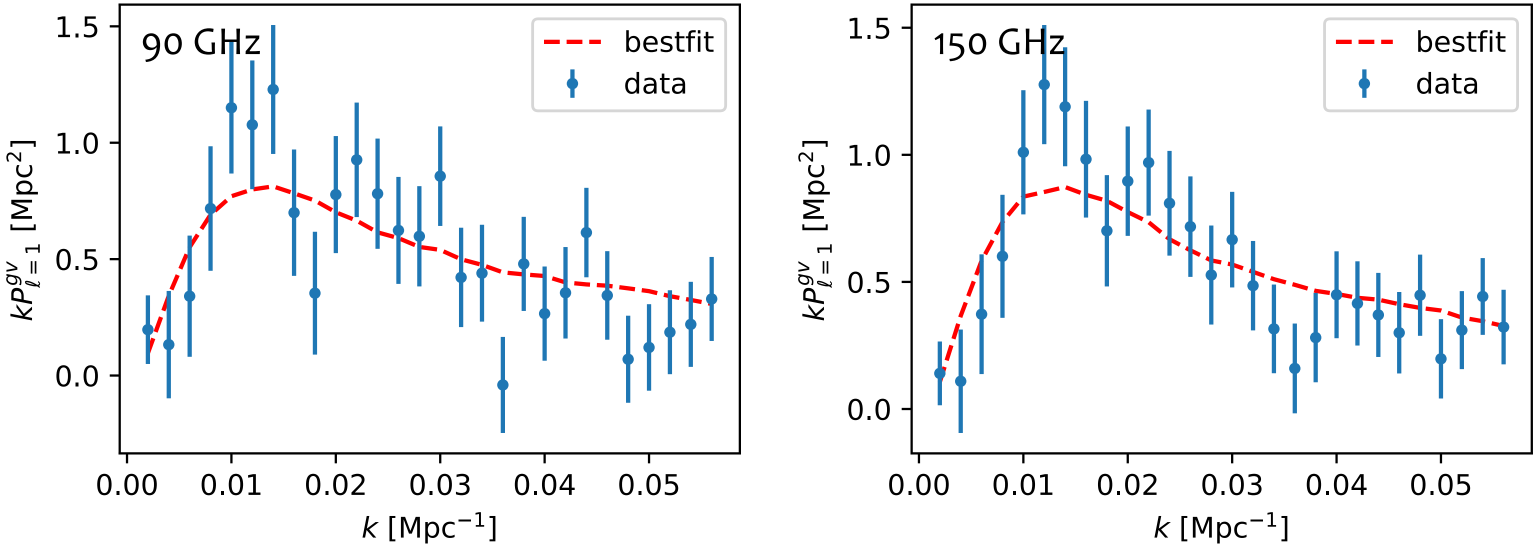


Photometric sample:



Preliminary result: DESI DR1 LRG

- Reconstructed velocity is biased: $\hat{v_r}(k) = b_v v_{true}(k)$
  - b_v represents the ratio between the true and fiducial galaxy-electron power spectra.
  - It measures *astrophysical baryonic feedback ! (Hotinli+2025: $b_v \sim 0.4$)*
  - Need to fit for a free amplitude in the galaxy-velocity power spectrum.



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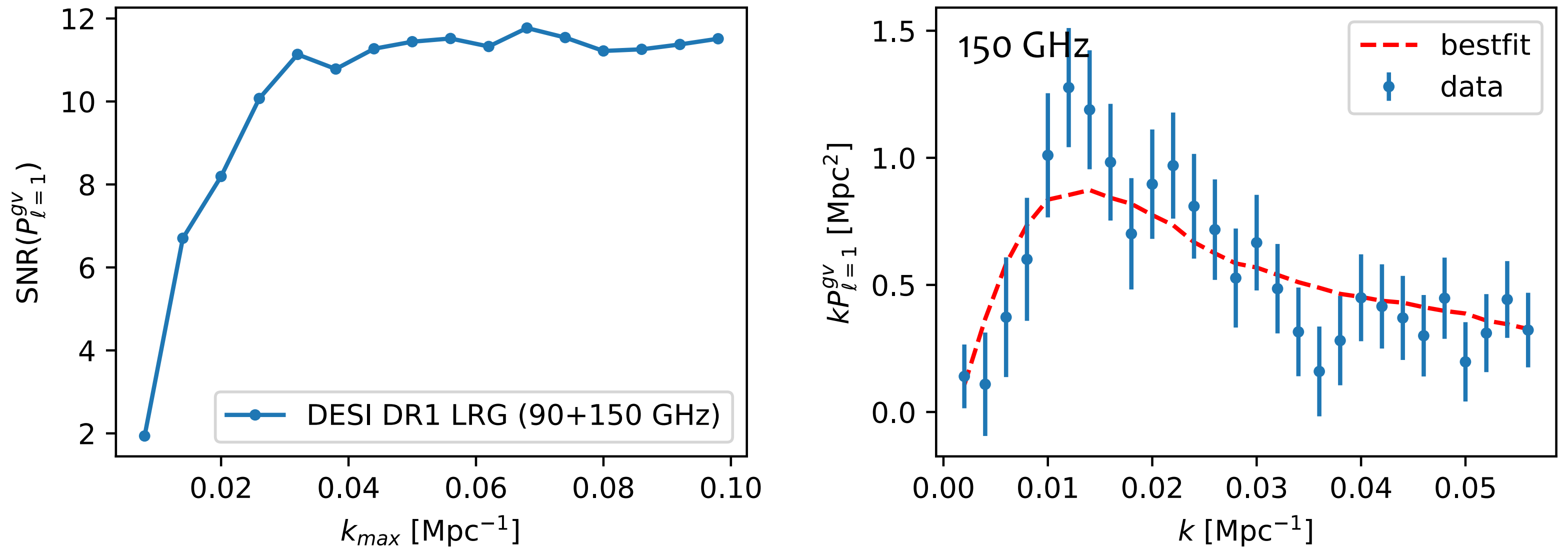
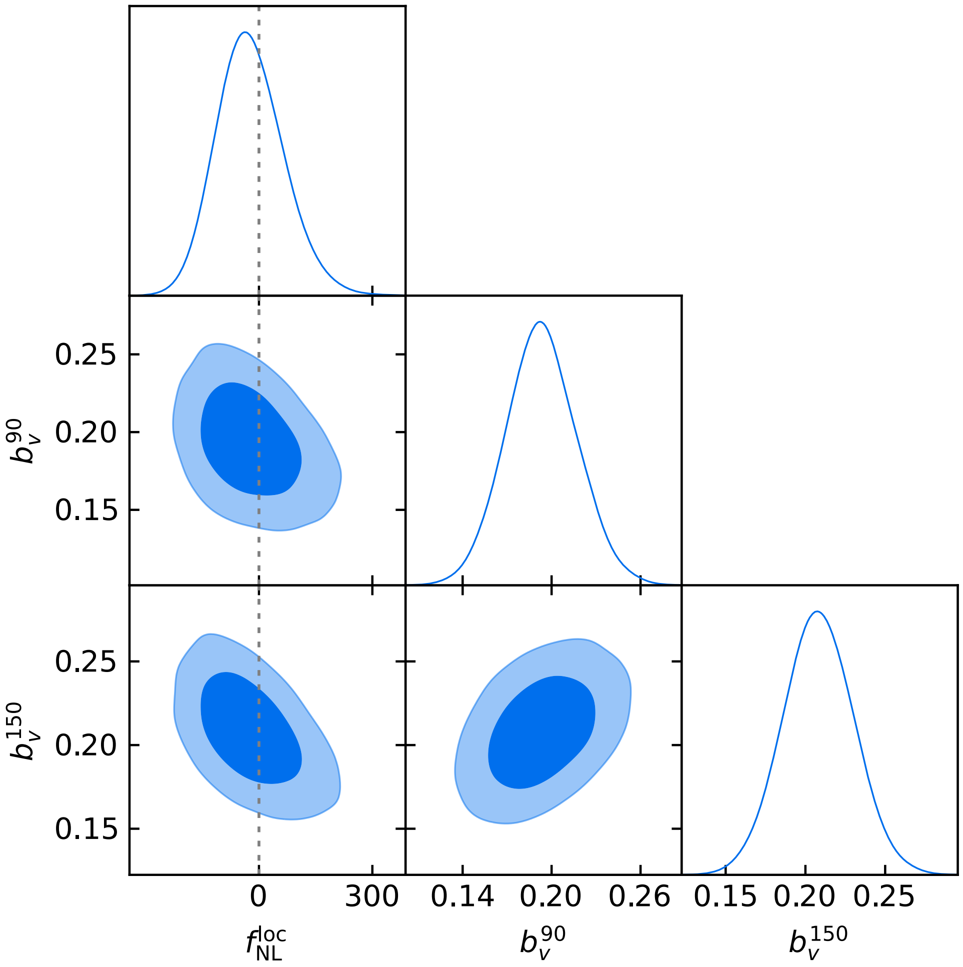


- SNR is a bit low because I find b_v ~ 0.2 … (here, I did not model the RSD in Pgv)

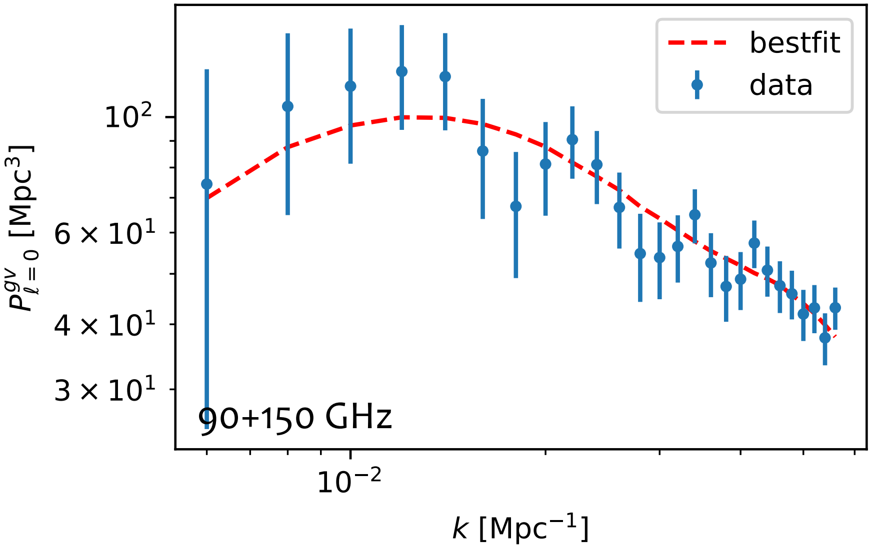
Preliminary result: DESI DR1 LRG

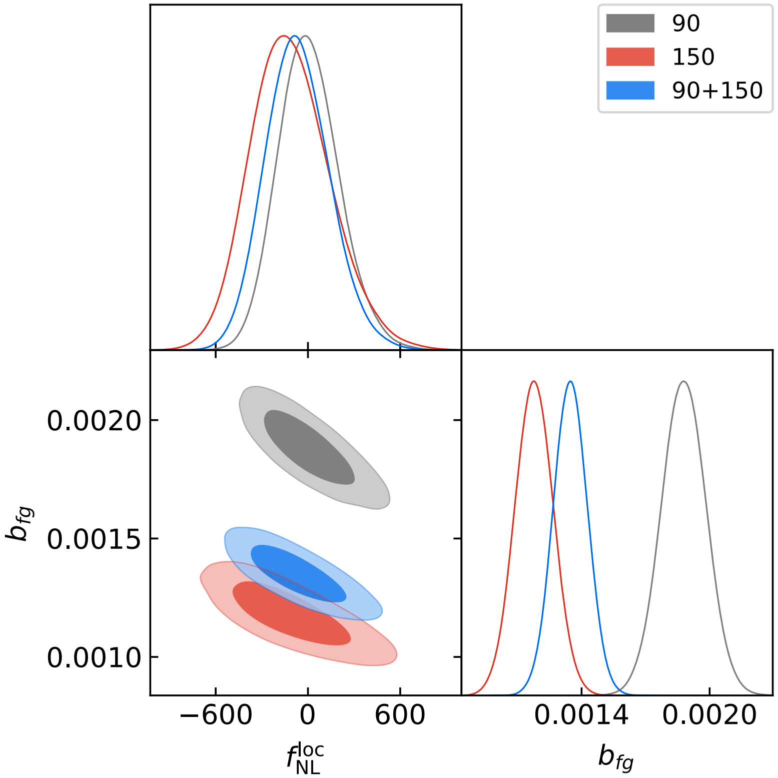


- Constraints are not as good as expected:
  - sigma ~ 100 from P_{gv} (vs. 30 from P_{gg})
  - due to small value of bv.
- No cosmic Variance Cancelation observed for now…
  - P_{gg} and P_{gv} are less correlated than expected
  - due to small value of bv.
- It is **under** investigation !!

Foregrounds

- CMB does have foregrounds that contaminate the signal:
  - Emissive light of galaxies (like star forming galaxies)
  - Can be introduce in the model: $\hat{v_r}(k) = b_v v_{true}(k) + b_{fg}\delta_g(k)$
  - They contribute on the monopole and very few (via window function) to the dipole and only on small scales.





Strategy

- DR2 x ACT DR6 will be the most accurate measurement of this kind until new CMB experiment !
  - DR2 increases **by a factor ~4** the overlap between ACT and DESI.
  - Upcoming DESI extension will increase as well the overlap.
- As a ~ blinding procedure, we will first fully validate the pipeline with DR1 data:
  - Main advantage: it is a power spectrum.
  - Almost there ! The paper should be ready soon.

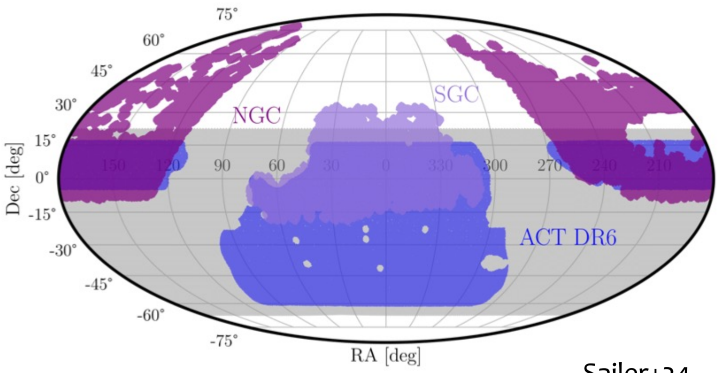


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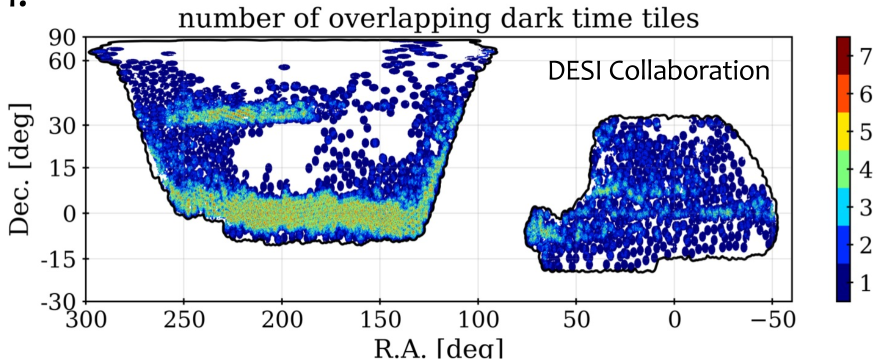
FIG. 1: ACT DR6 and DESI LRG Y1 footprints in equatorial coordinates. In gray, we show the full ACT footprint, while in blue, we show a section of the ACT DR6 survey, where the galactic plane has been masked

DR1:



DESI Collaboration

DR2: