DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

BERKELEY LAB

kSZ velocity reconstruction of DESI galaxies with ACT DR6 and opportunities

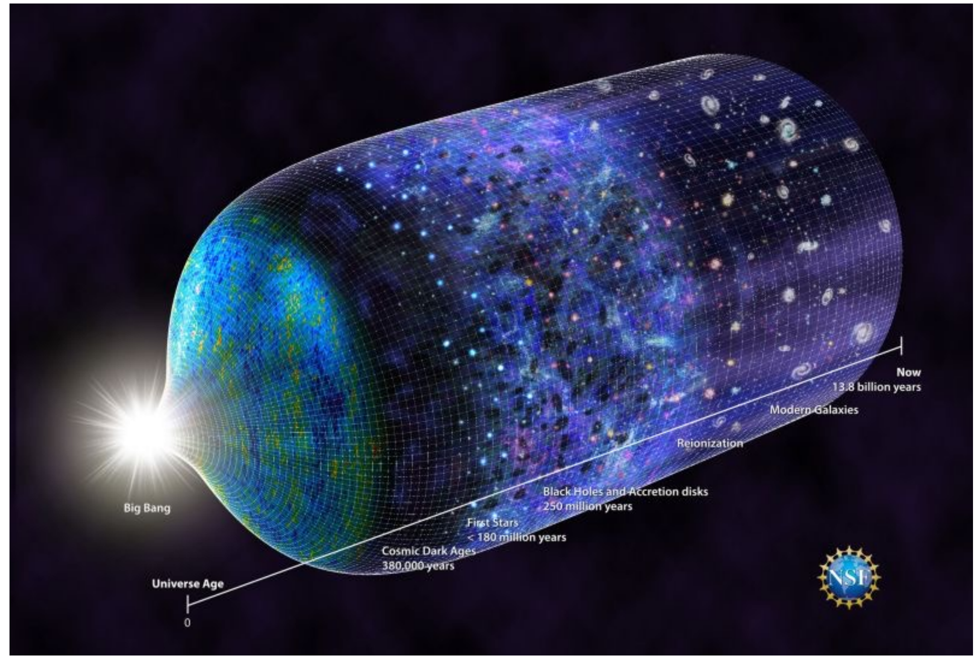
Edmond Chaussidon (LBNL)

Paris, October 29, 2025

Motivations

Primordial Non-Gaussianity (PNG)

- **No direct** observation of the very early Universe.
- **No** B-modes detection so far…
  - Not guaranteed with SO.
  - LiteBIRD is not fully funded.
  - Observation of the origin of the Universe an **open** and **compelling** quest!
- PNG is an **alternative** and **complementary** probe:
  - Slow roll single field inflation -- > tiny amount of local PNG: $\mathcal{O}\left(f_{NL}^{loc}\right) \sim 10^{-2}$
  - Local PNG are generated by multi-fields inflation: $\mathcal{O}\left(f_{NL}^{loc}\right) \sim 1$



Timeline of our Universe.

Gaussian field

$$\phi = \phi_G + f_{NL}^{loc}\left(\phi_G^2 - \langle\phi_G^2\rangle\right)$$

Primordial Gravity potential

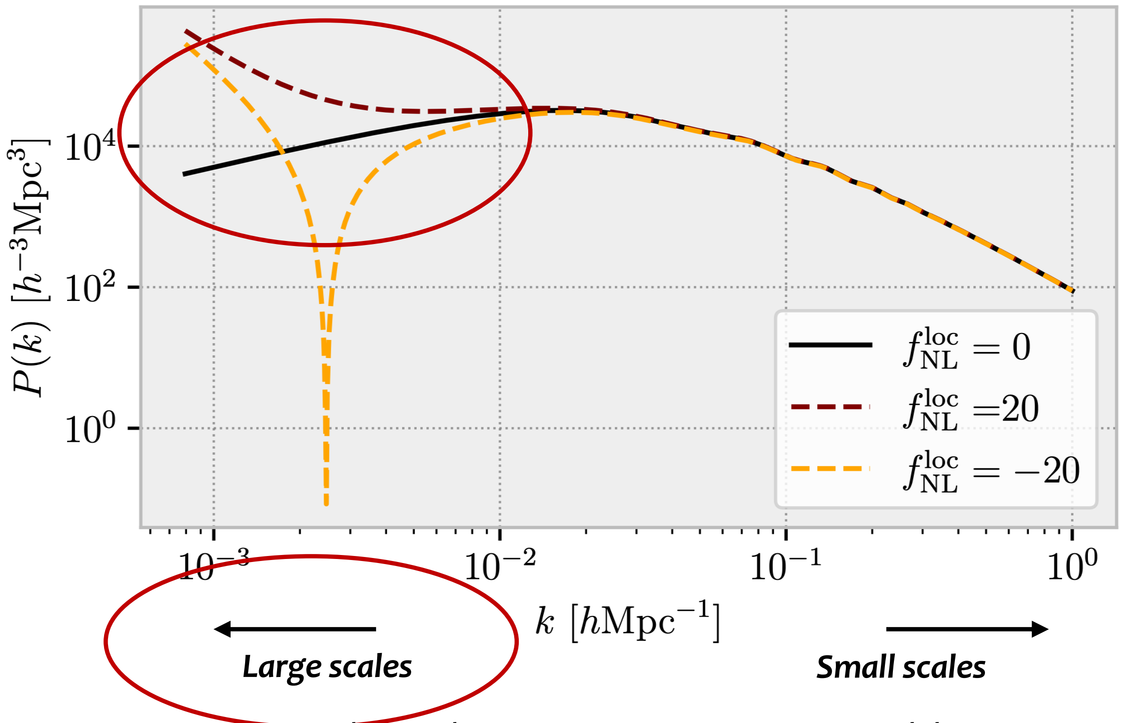
Amount of non-gaussianity

Large-scale dependent bias

- Galaxies are a biased tracer of the matter density: $\delta_g(k,\mu) = (b1 + f\mu^2)\delta_m(k)$
- Noticed in *Dalal et al. 2008*, **PNG** will **act** at **large scales** via the **scale-dependent bias:**

$$b_1(z) \to b_1(z) + \frac{b_\Phi(z)}{T_{\Phi\to\delta}(k,z)} f_{\rm NL}^{\rm loc}$$

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



Galaxy-Galaxy Power spectrum at z=1.7 with b=2.5

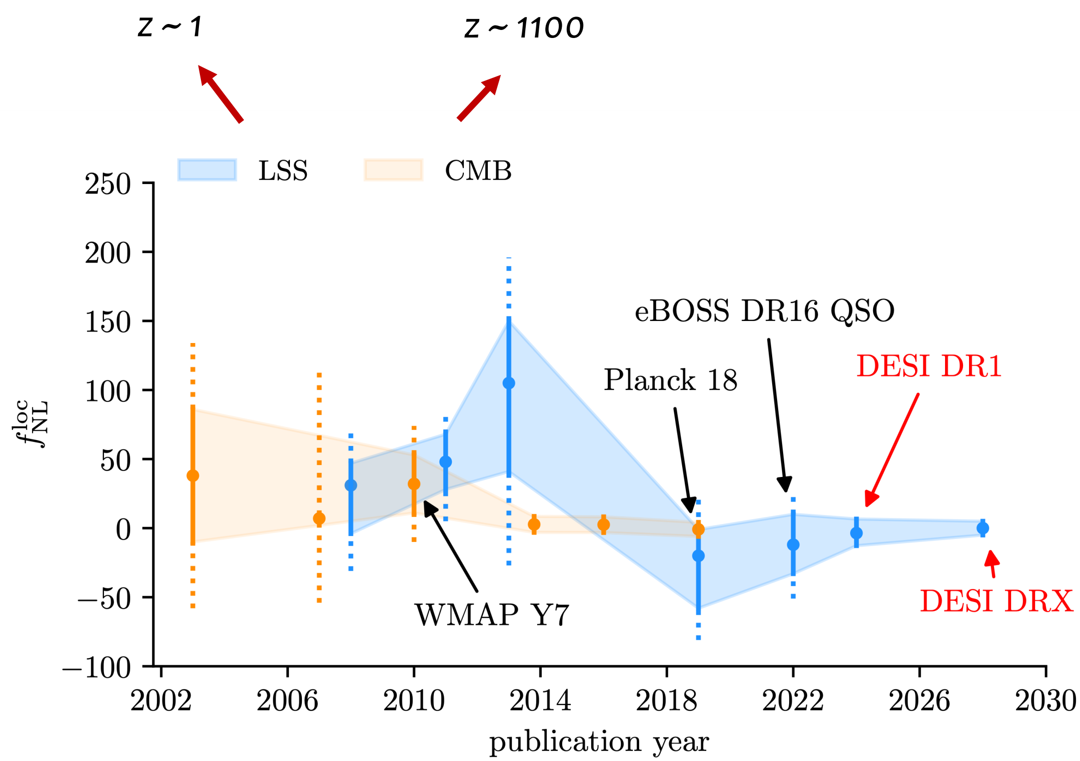
- Power Spectrum is the Fourier transform of the 2-pt correlation function:

$$P(k) = < \delta_g(k)\delta_g(k) >$$

- Value of b_ϕ can be calibrated with simulations.

Current constraints on PNG

- Best constraints from Planck18:
  - $f_{\rm NL}^{\rm loc} = -0.9 \pm 5.1$
  - but **now** limited by the **cosmic variance** (only a factor of < 2 of improvement is expected with SO) !
- With scale-dependent bias:
  - DESI DR1 (LRG+QSO): $f_{\rm NL}^{\rm loc} = -3.6^{+9.1}_{-9.0}$
- With similar methodology:
  - Forecast for final DESI survey leads to $\sigma(f_{\rm NL}^{\rm loc})\sim 4.5$
  - BUT can be strongly improved !



Evolution of the constrain on f_{NL}.

DESI DR1 Constraints

Dark Energy Spectroscopic Instrument (DESI)

- DESI is hosted by the Mayall telescope (4m) in Kitt Peak (near Tucson, Arizona)
- Study **dark energy** thanks to the expansion rate of the Universe measured from galaxy distribution.
- **First** stage 4 spectroscopic survey:
  - 5000 spectra simultaneously, covering ~ 1/3 sky area, during 5 years.
- **40 million** of secure redshifts at the end of the nominal survey (SDSS collected 4 million spectra)

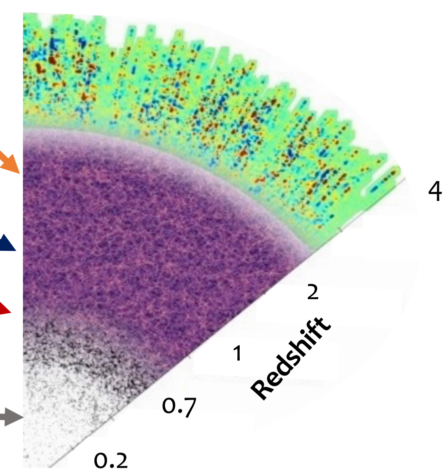
Mayall telescope (Kitt peak, Arizona).

3 million QSOs
Ly-a $z > 2.1$
Tracers $0.8 < z < 2.6$

16 million ELGs
$0.6 < z < 1.6$

8 million LRGs
$0.4 < z < 1.0$

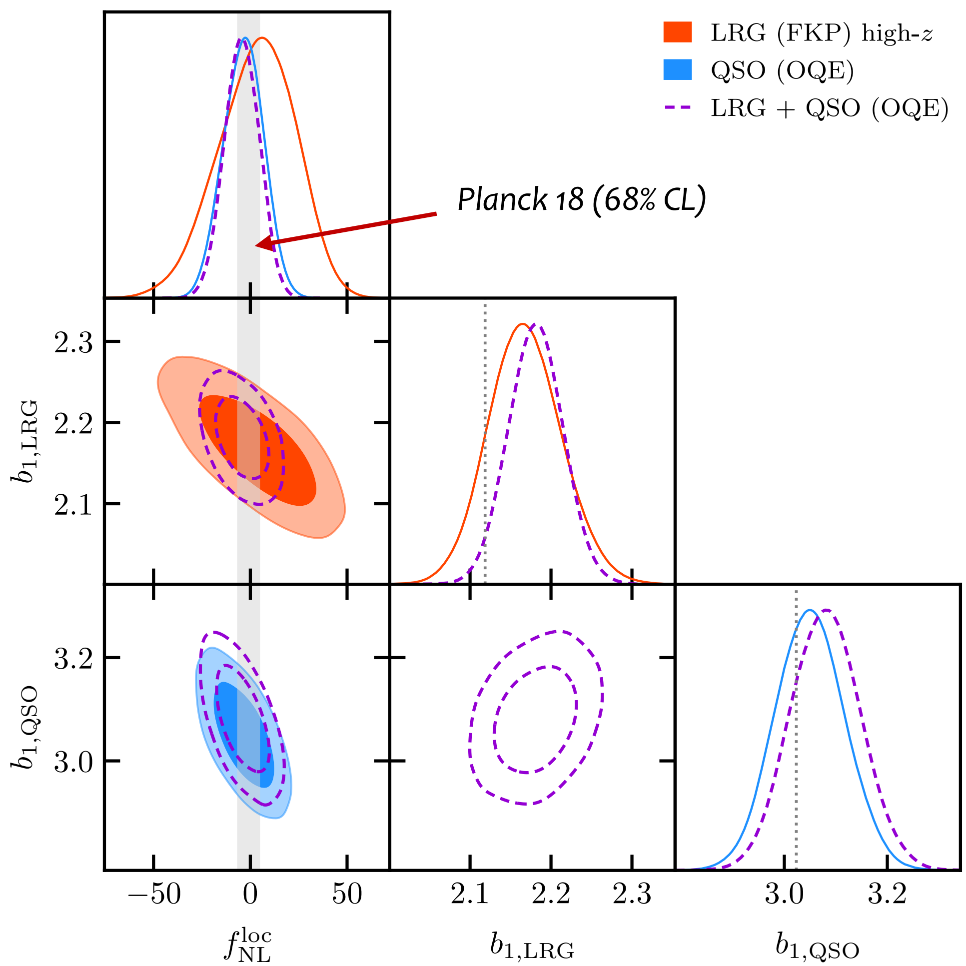
13.5 million Brightest galaxies
$0.0 < z < 0.4$

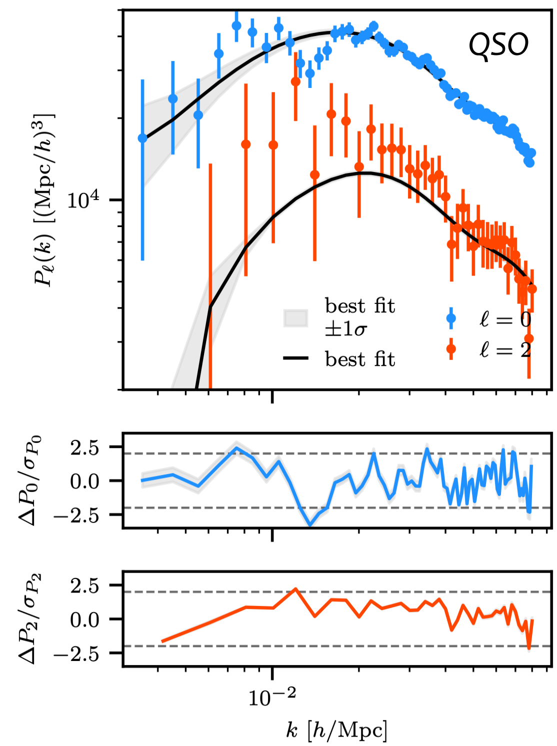


*Numbers are **outdated** due to the DESI Extension!*

PNG with DESI DR1

- From Chaussidon+24.





- DESI QSO + LRG:

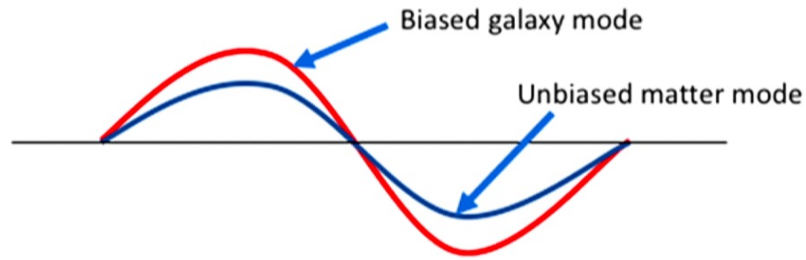
$$f_{\mathrm{NL}}^{\mathrm{loc}} = \begin{cases} -3.6^{+9.0}_{-9.1} & (68\%) \quad \text{with } p_{\mathrm{QSO}} = 1.6 \\ 1.7^{+8.4}_{-7.7} & (68\%) \quad \text{with } p_{\mathrm{QSO}} = 1.0 \end{cases}$$

- Two-fold improvement of eBOSS DR16 !

Re - Motivations

Sample variance cancellation

- Idea of sample variance cancellation (Seljak 2008):
  - Needs two measurements of the same underlying fields (signal dominated)
  - The ratio gives a perfect measurement of the relative bias!



$$\delta_1(\mathbf{k}) = b_1(\mathbf{k})\delta_m(\mathbf{k})$$
$$\delta_2(\mathbf{k}) = b_2(\mathbf{k})\delta_m(\mathbf{k})$$

- Radial velocity is an unbiased tracer of the density field !!

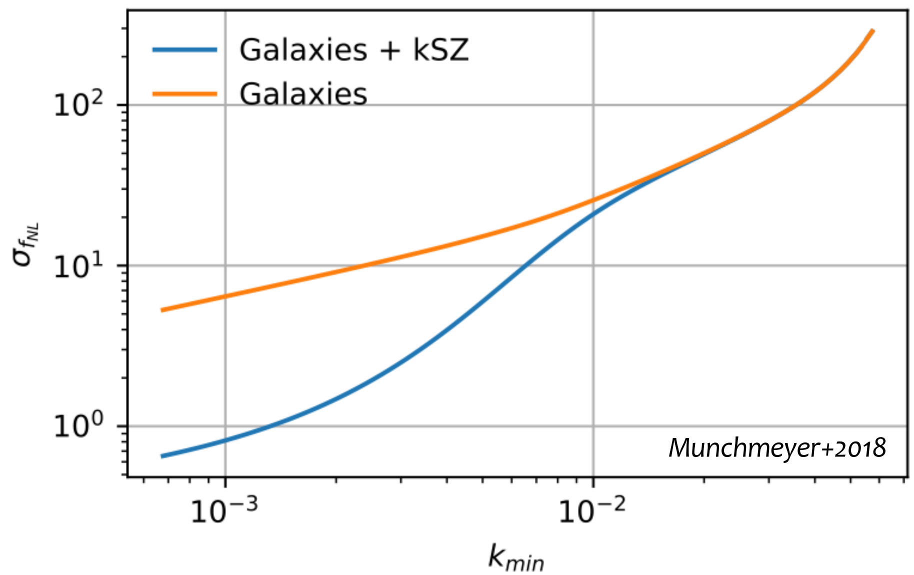
$$v_r(k) = \frac{ifaH\mu}{k}\delta_m(k) \quad \Rightarrow \quad \frac{\delta_g}{v_r} \propto \underbrace{k(b_1 + \frac{b_\Phi}{T_{\Phi\to\delta}(k)} f_{\mathrm{NL}}^{\mathrm{loc}})}_{\text{No cosmic variance!}}$$

- How can we measure the radial velocity ??
  - Use the **kinematic Sunayev-Zeldovich** (kSZ) effect!

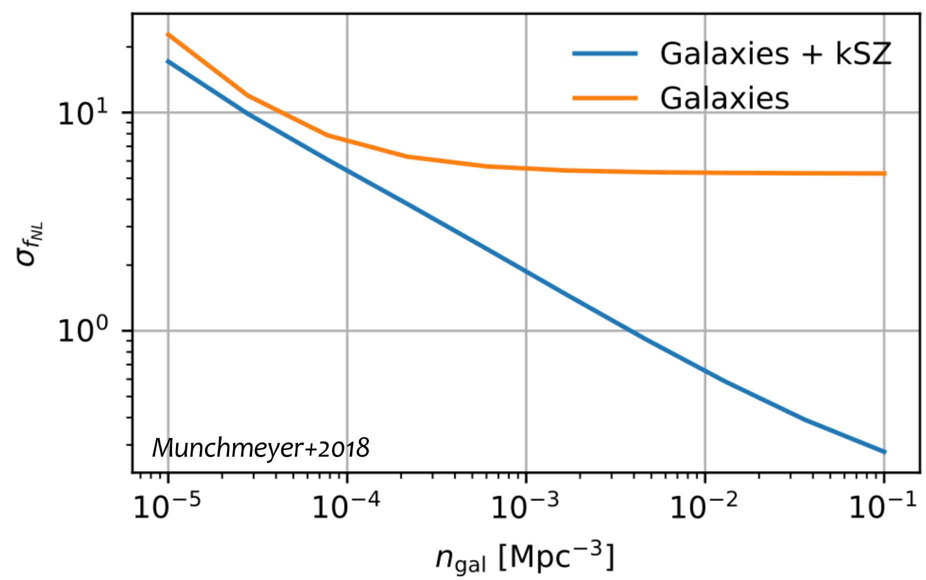
Forecast

- $v \sim 1/k$: 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 DR2.

- **IMPORTANT:** Should be systematic **free** as the LSS x Lensing



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

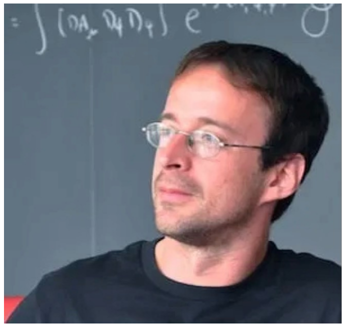


We do not saturate the constraints with number of galaxies !!

kSZ Velocity Reconstruction

Following Smith et al. 2018 & Hotinli et al. 2025

S.Hotinli (PI)



K.Smith (PI)

S.Ferraro (LBL)

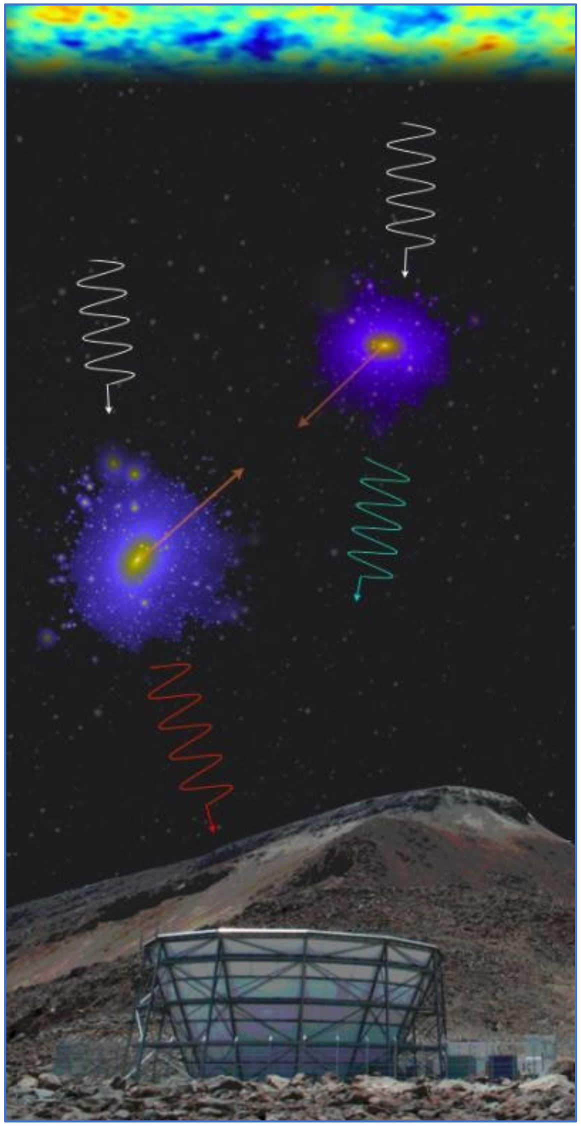
Kinematic-SZ Effect

- 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.

$$T_{\mathrm{kSZ}}(\boldsymbol{\theta}) = \int d\chi\, K(\chi)\, v_r(\chi\boldsymbol{\theta})\, \delta_e(\chi\boldsymbol{\theta})$$

with: $K(z) \equiv -T_{\mathrm{CMB}}\, \sigma_T\, n_{e0}\, x_e(z)\, e^{-\tau(z)}\, (1+z)^2$

  - A bit more complicated due to **astrophysics** describing the electron density properties, the optical depth..
- Extensively studied at small scales (stack profiles, ..)

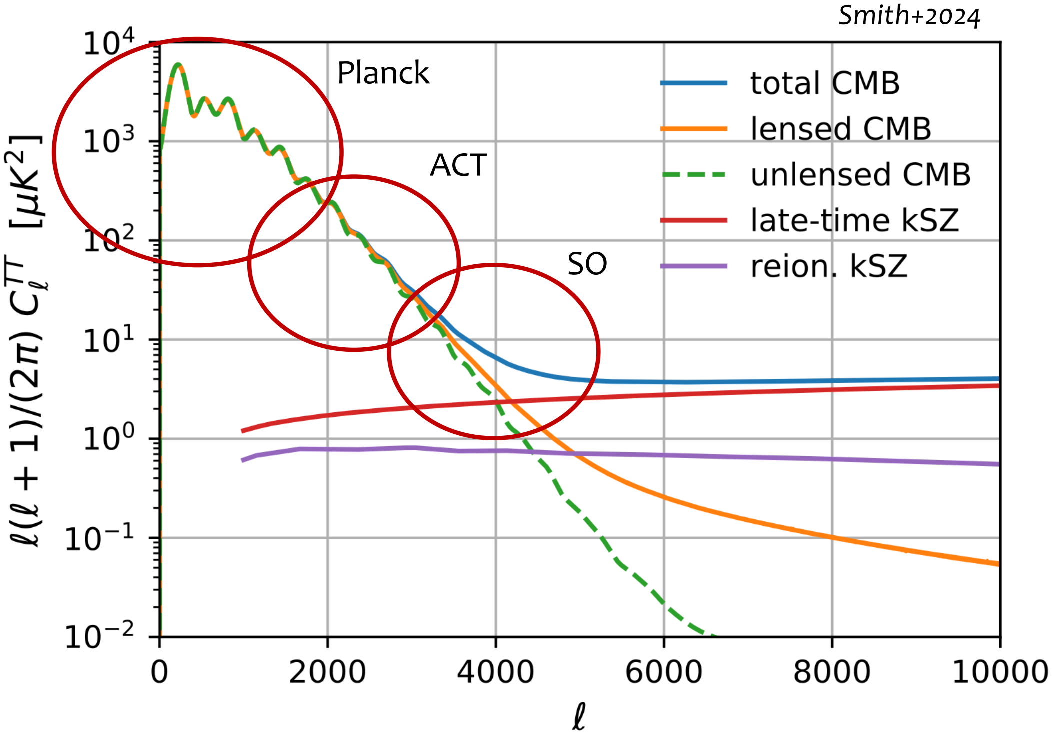


Credit: Sudeep Das

kSZ regime

- Primary CMB has been measured over the last 30 years with increasing precision, reaching different regime:
  - l < 2000: primary CMB dominates.
  - 2000 < l < 4000: large contribution from lensing.
  - l > 4000: signal is dominated by kSZ.
- New CMB experiments are targeting the small scales !

Smith+2024



kSZ Velocity Reconstruction I

- The kSZ quadratic estimator (**Smith+18**):
  - Inputs 3-d galaxy field and 2-d CMB and outputs a 3-d reconstructed velocity field:

$$\hat{v}_r(\mathbf{k}_L) \propto \int_{\mathbf{k}_S+(\mathbf{l}/\chi_*)=\mathbf{k}_L} \underbrace{\frac{P_{ge}(l/\chi_*)}{P_{gg}^{\mathrm{tot}}(l/\chi_*)}\,\frac{1}{C_l^{\mathrm{tot}}}}_{\text{Filter}} \Big(\delta_g(\mathbf{k}_S)\,T_{\mathrm{CMB}}(\mathbf{l})\Big)$$

Reconstructed 3-d velocity field

DESI galaxies

ACT map

  - Reconstruction is done for large scales ~0.01/Mpc, while RHS peaks on small scales (~1/Mpc).
  - The velocities are kSZ sensitive while correlating it with a density field -- > Bispectrum <ggT>.

- Reconstruction noise is constant in k_L -- > smaller at large scales than galaxy shot noise !

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

- Same Estimators were used earlier this year:
  - Lagüe+2024: BOSS LRG x ACT DR5 - -> 7.2 sigma
  - Hotinli+2025: DESILS LRG x ACT DR5 - -> 11.7 sigma (NGC only) with photo-z

kSZ Velocity Reconstruction II

- It is easier (and faster) to do the estimator on real space:

$$\hat{v}_r(\mathbf{x}) \propto \sum_{i \in \mathrm{gal}} \widetilde{T}(\boldsymbol{\theta}_i)\delta^3(\mathbf{x}-\mathbf{x}_i)$$

- where the CMB maps were filtered as: $\widetilde{T}(\mathbf{l}) \equiv \dfrac{P_{ge}(l/\chi_*)}{P_{gg}(l/\chi_*)} \dfrac{1}{C_l^{\mathrm{tot}}} T_{\mathrm{CMB}}(\mathbf{l})$

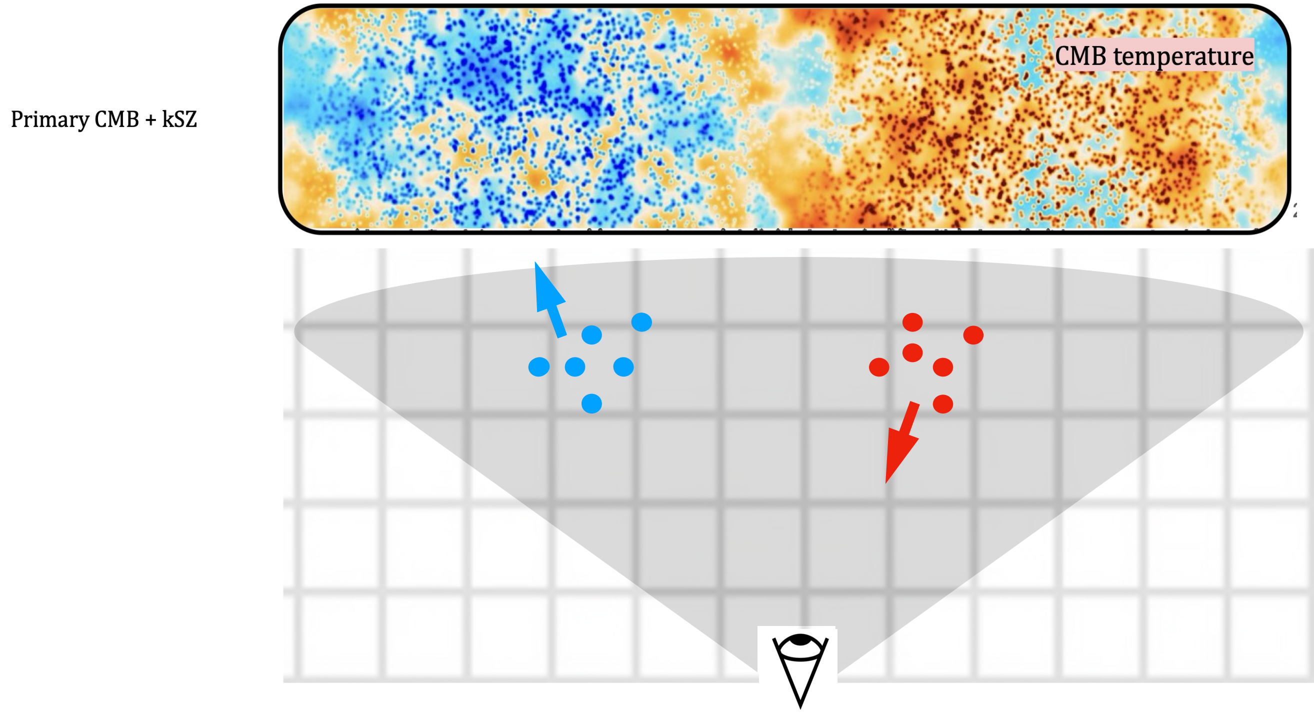
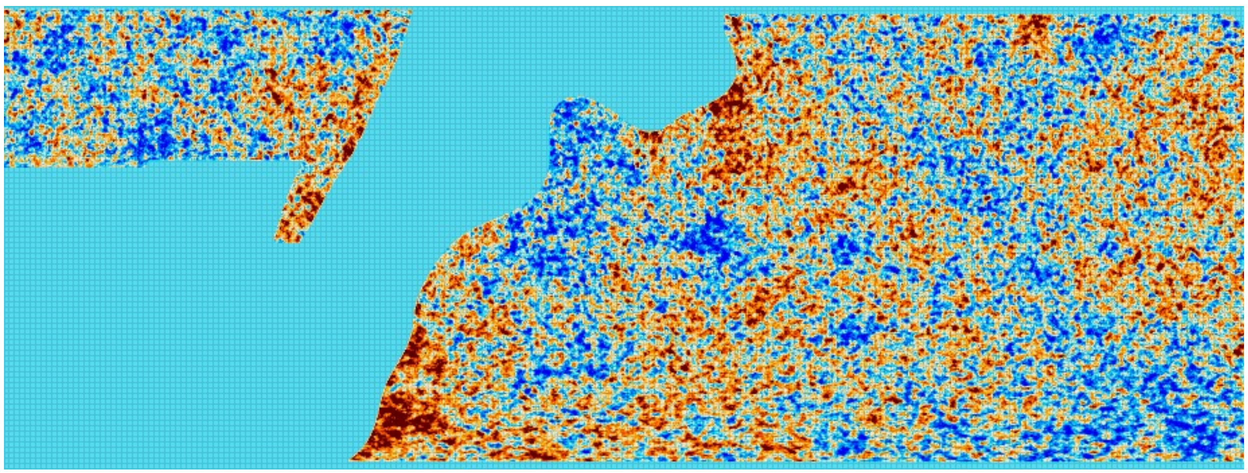
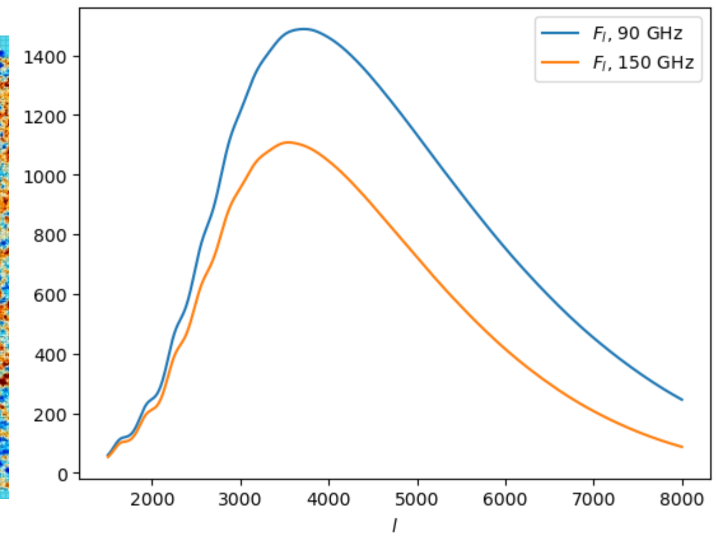


Illustration I

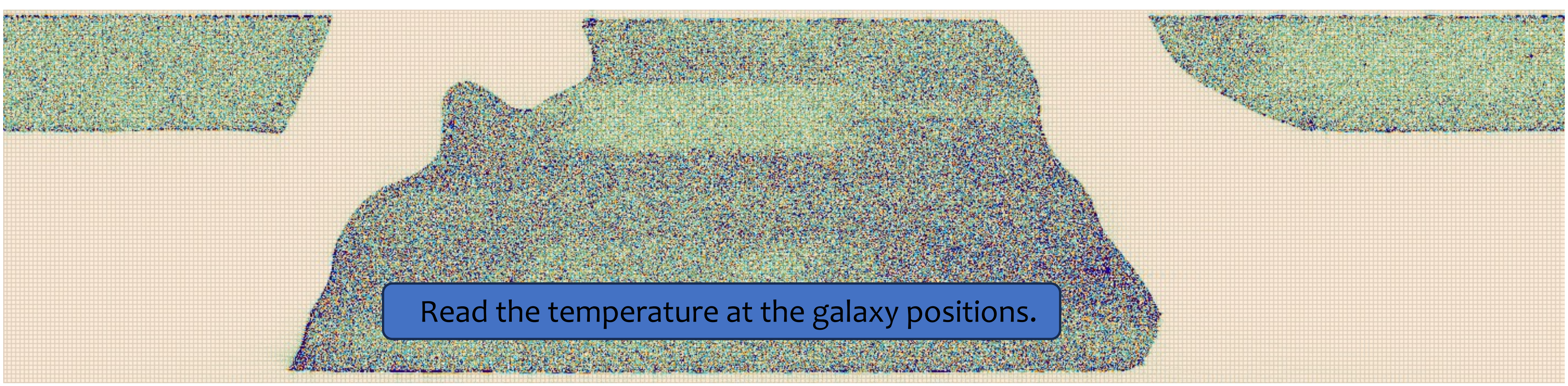




High-pass filtering
+
Noise weighting

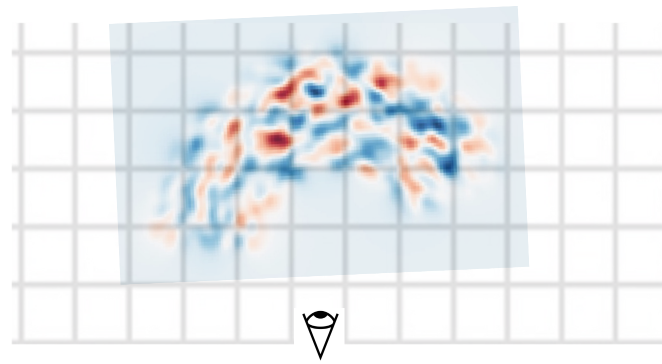
$$F_l \equiv \frac{P_{ge}(l/\chi_*)}{P_{gg}(l/\chi_*)} \frac{b_l}{C_l^{\mathrm{tot}}}$$

Include the beams



kSZ velocity bias

- The reconstructed velocity is a biased reconstruction of the true radial velocity:



$$\left\langle \hat{v}_r(\mathbf{x}) \right\rangle = b_v \, \bar{n}_v(\mathbf{x}) \, B(\mathbf{x}) \, v_r^{\rm true}(\mathbf{x})$$

3-d galaxy number density

Normalization factor from the CMB high pass filter

- b_v is the kSZ velocity bias:
  - Ratio between the true and the fiducial galaxy-electron power spectra.
  - Will be treated as a nuisance parameter, as the galaxy linear bias
  - Remark: it is a measure of the astrophysical baryonic feedback !

$$\hat{v}_r(\mathbf{k}_L) \propto \int_{\mathbf{k}_S + (\mathbf{l}/\chi_*) = \mathbf{k}_L} \frac{P_{ge}(l/\chi_*)}{P_{gg}^{\rm tot}(l/\chi_*)} \frac{1}{C_l^{\rm tot}} \left(\delta_g(\mathbf{k}_S) T_{\rm CMB}(\mathbf{l}) \right)$$

Rescale to the correct amplitude the signal!

Model

- Include Redshift Space Distortion (Kaiser + Daming term):

$$\begin{cases} \delta_g^s(k,\mu) = \left(b_1 + f\mu^2\right) D_g(k,\mu,\Sigma_s)\delta_m(k) \\ v_r^s(k,\mu) = b_v \times \dfrac{ifaH\mu}{k} D_u\left(k,\Sigma_u\right)\delta_m(k) \end{cases}$$

with

$$D_g(k,\mu,\Sigma_s) = 1/\left(1 + (k\mu\Sigma_s)^2/2\right)$$
$$D_u(k,\Sigma_u) = \mathrm{sinc}(k\Sigma_u)$$

- Include local PNG: $b_1(z) \to b_1(z) + \dfrac{b_\Phi(z)}{T_{\Phi\to\delta}(k,z)} f_{\rm NL}^{\rm loc}$

- Compute Legendre Multipoles:
  - The expected signal is in **odd** poles!
  - Foreground are projected out in **even** poles!
  - Only looking at Pgv / Pvv due to DESI policy.
    - ➢ b_1 is fixed to its value for Pgg and $\Sigma_s = 0$.

$$P^{gv}(\mathbf{k}) = < \delta_g(\mathbf{k}) v_r(\mathbf{k}) >$$

$$\Downarrow$$

$$P^{gv}_{\ell=1} = b_v \left(b1 + \frac{3}{5}f\right)\frac{ifaH}{k} D_u(k,\Sigma_u) P_{\rm lin}(k)$$

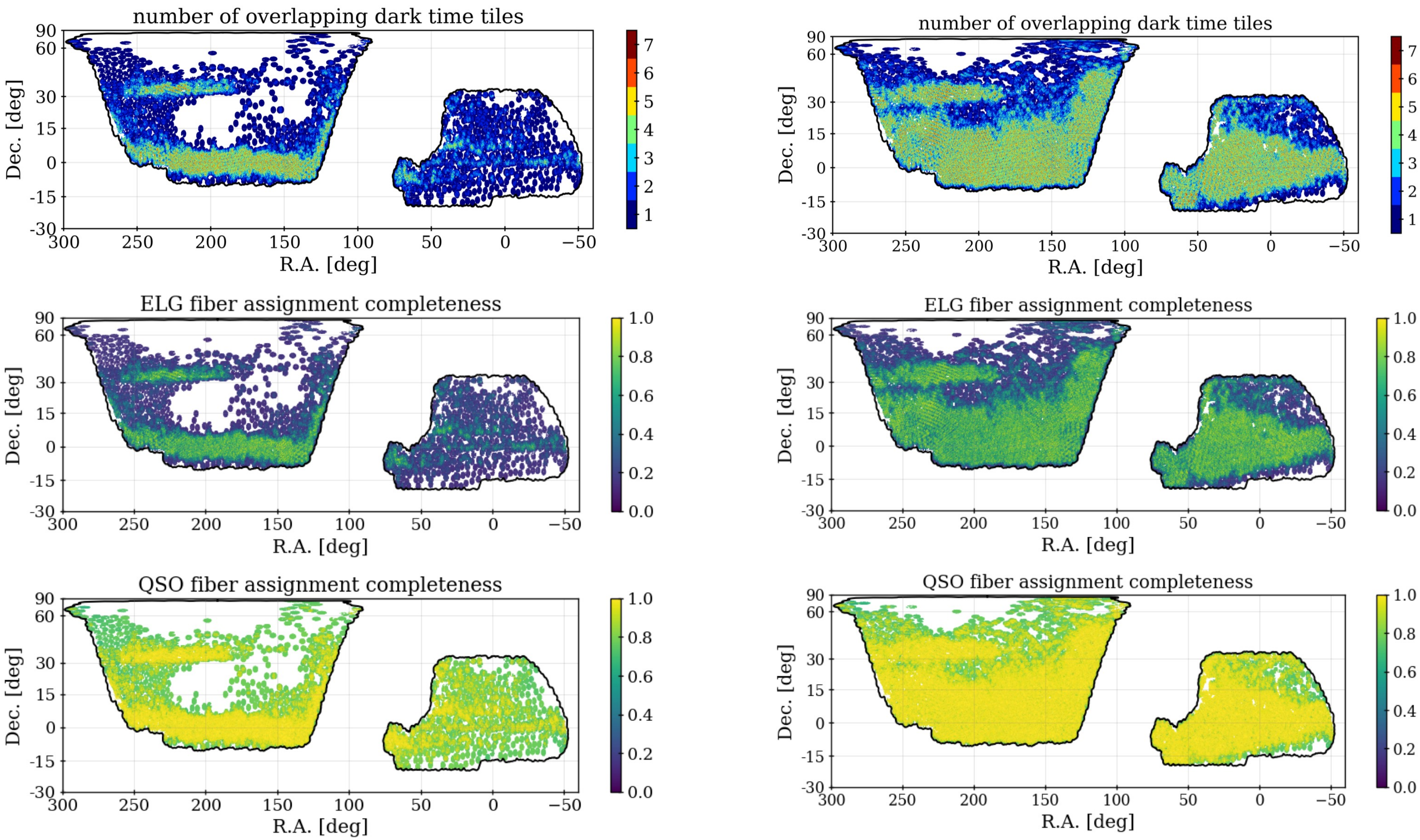
- Adopt a mocks-based approach called "Surrogates" as in Hotinli+25:

DESI DR2 x ACT DR6

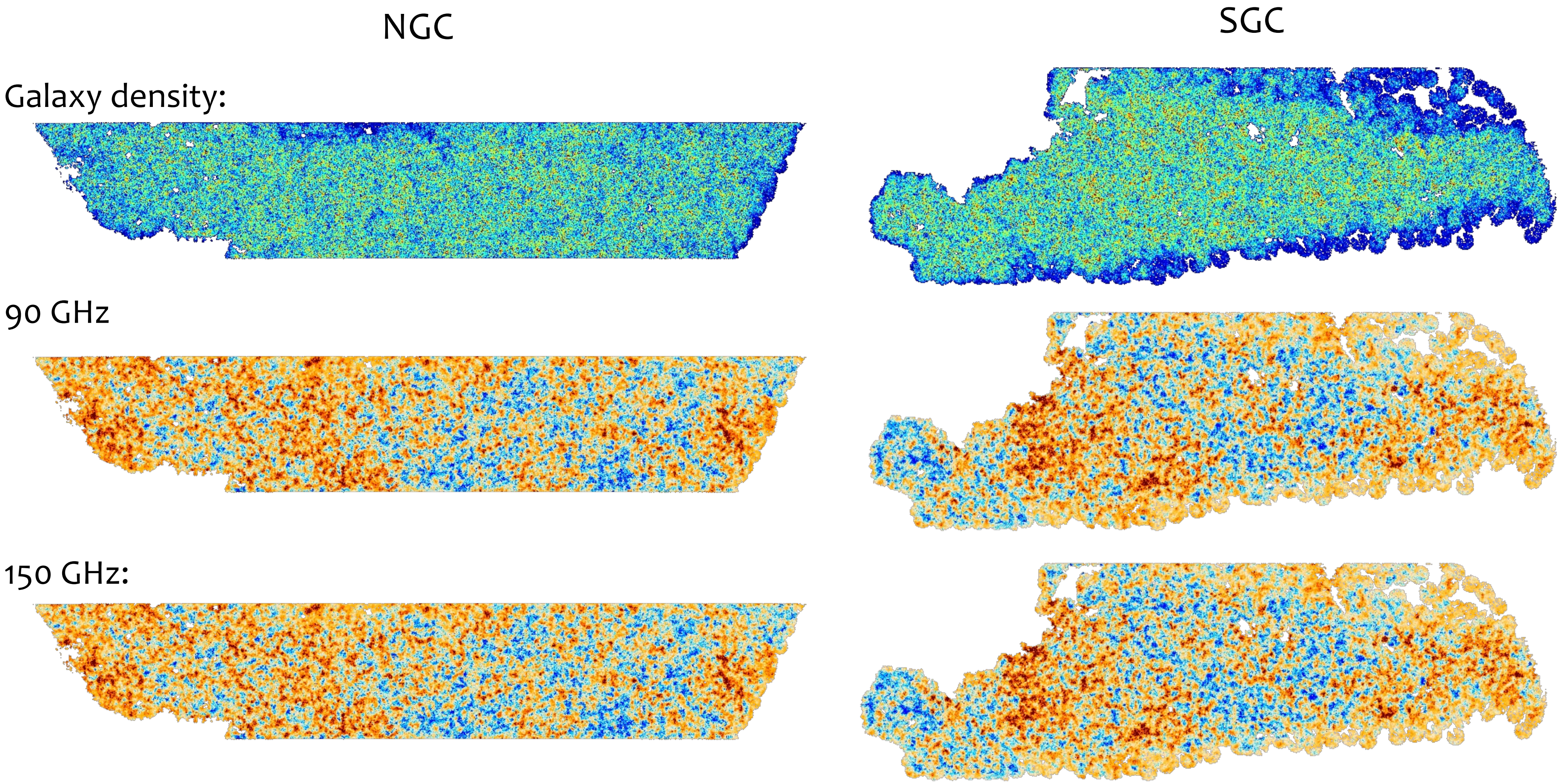
Based on Chaussidon et al (in prep) and Hotinli et al. (in prep)

DR1 to DR2

- Moving to DESI DR2 is a game changer for the cross–correlation with ACT DR6!

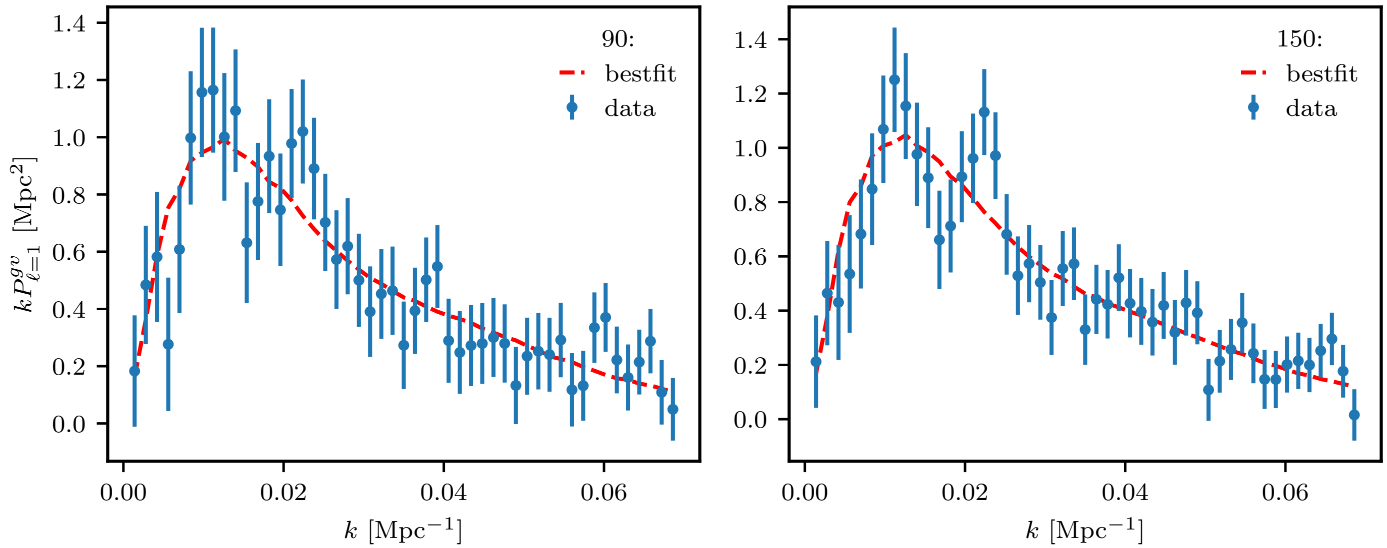


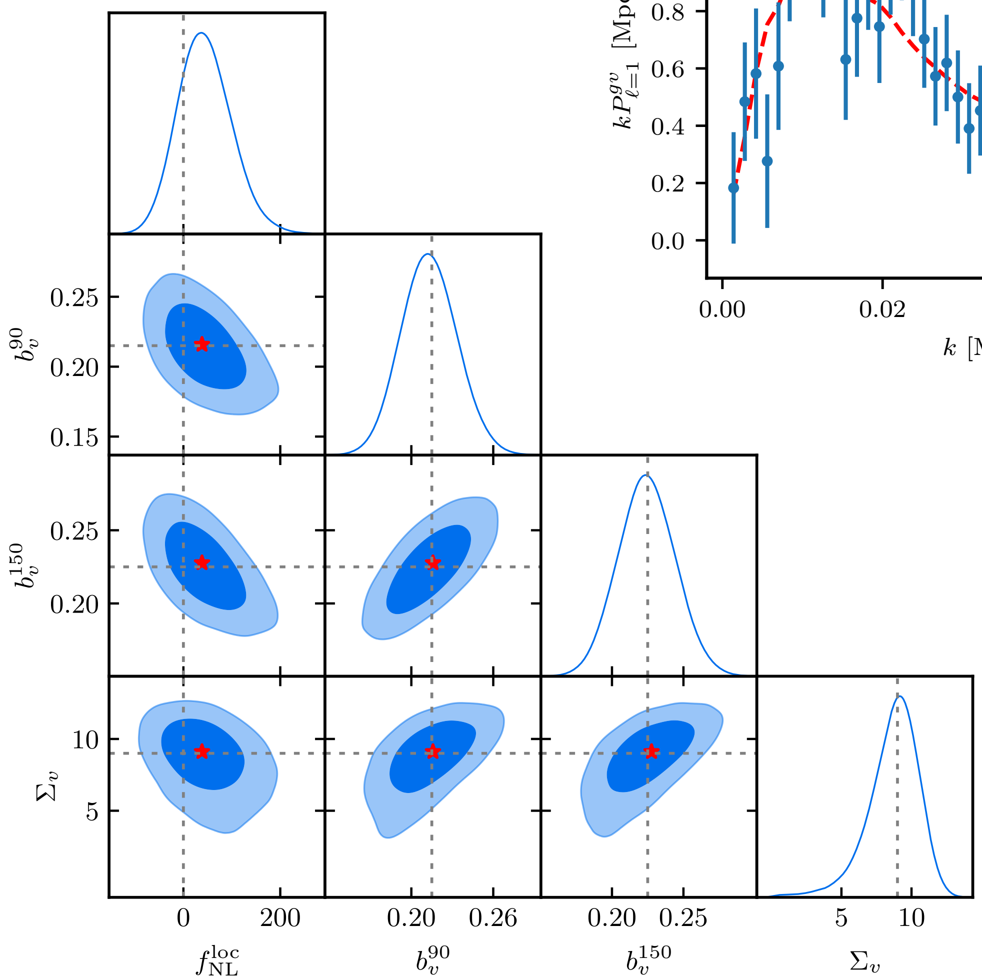
DESI DR2 LRG



- Measurements on NGC and SGC done separately, but combined for the inference.

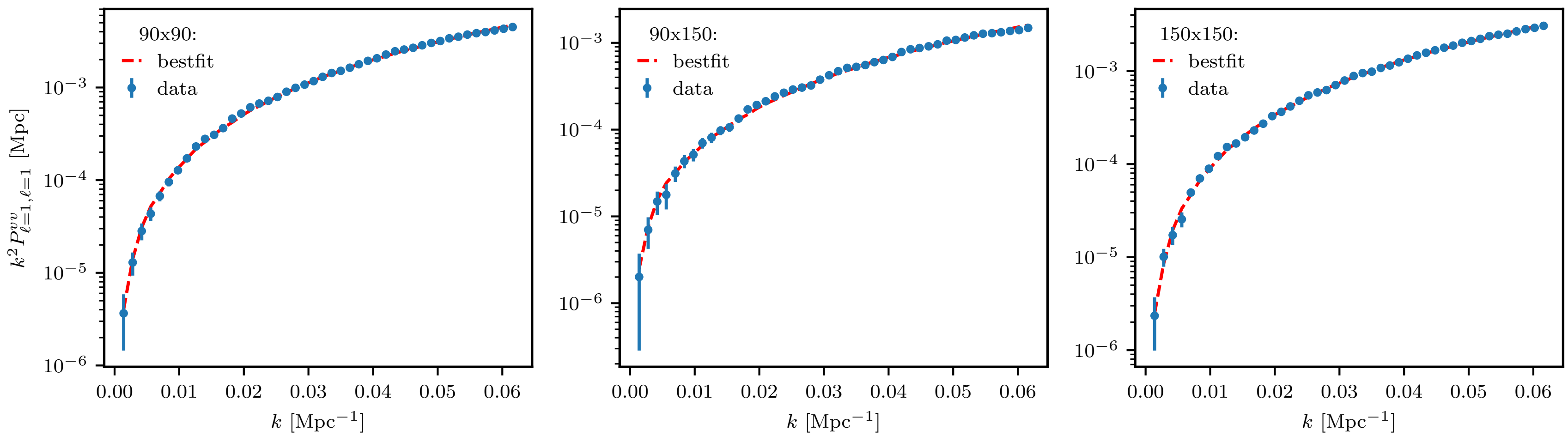
LRG: Galaxy-Velocity Power Spectrum





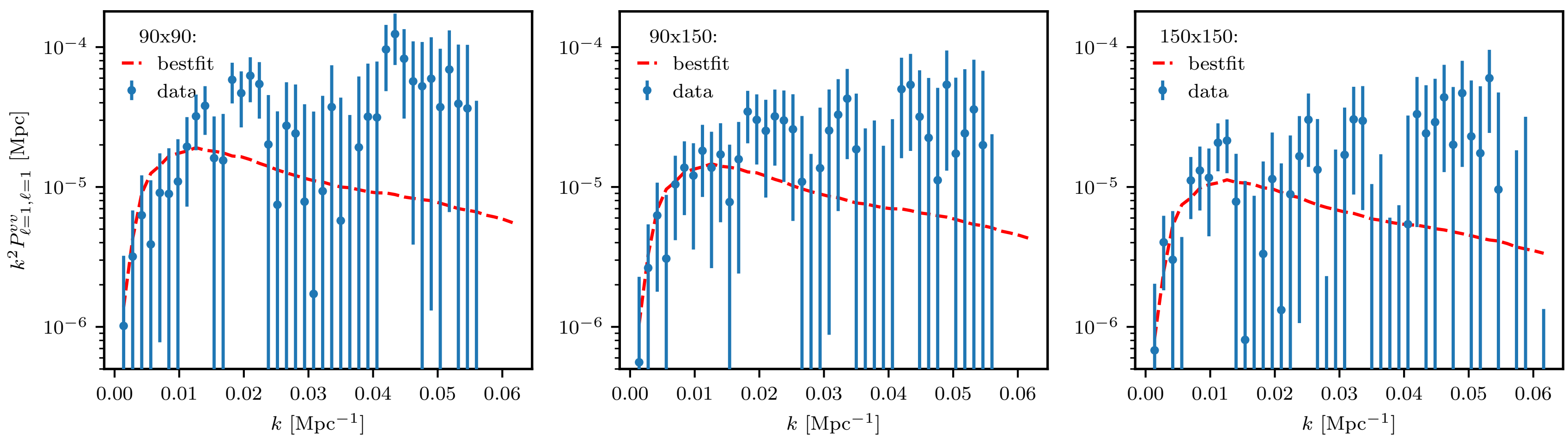
- SNR ~ 18
- Highest detection of Pgv to date!
- b_v ~ 0.23, lower than expected …
- No systematics at large scales!

LRG: Velocity-Velocity Power Spectrum

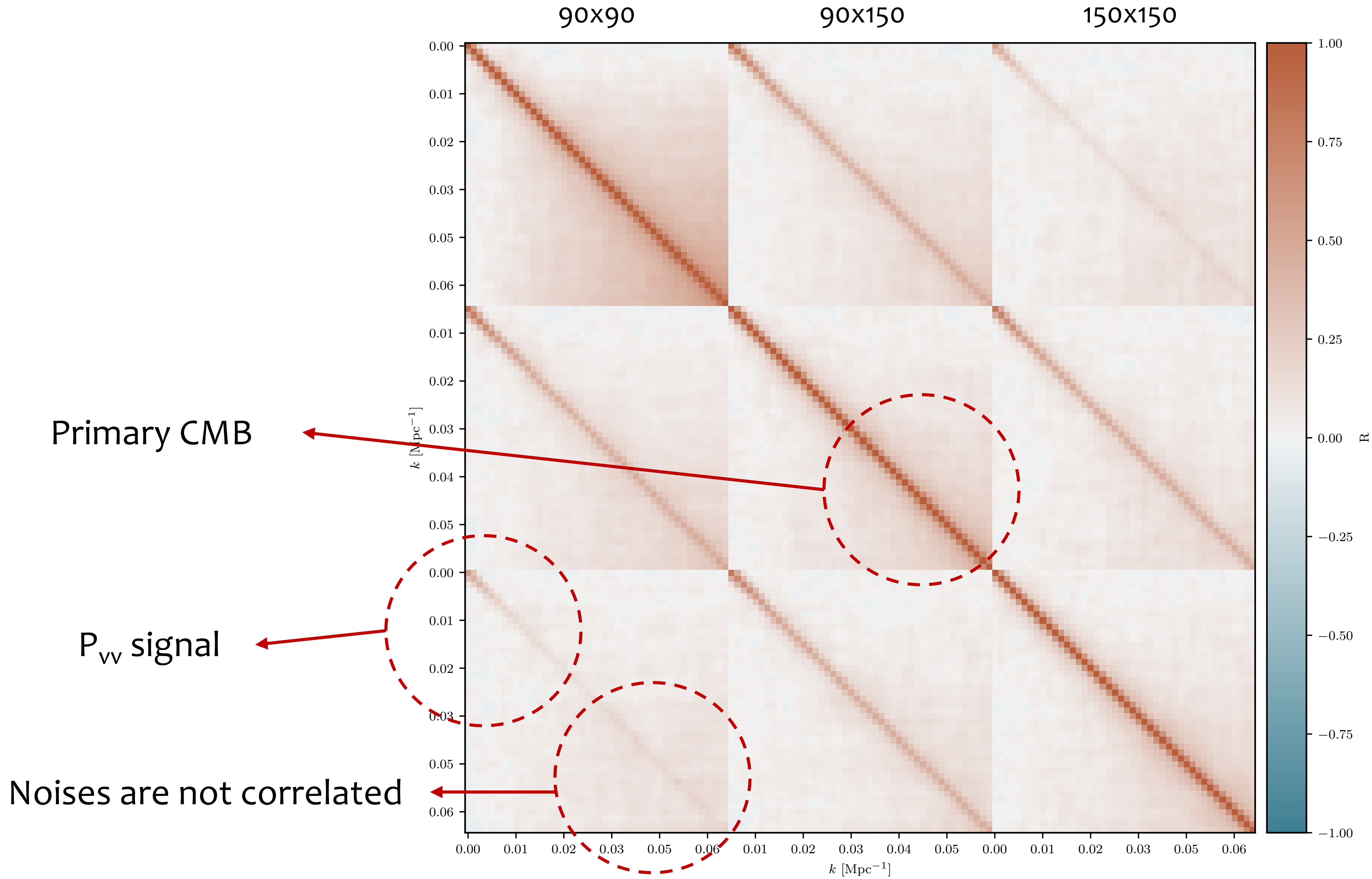


Remove the best fit noise

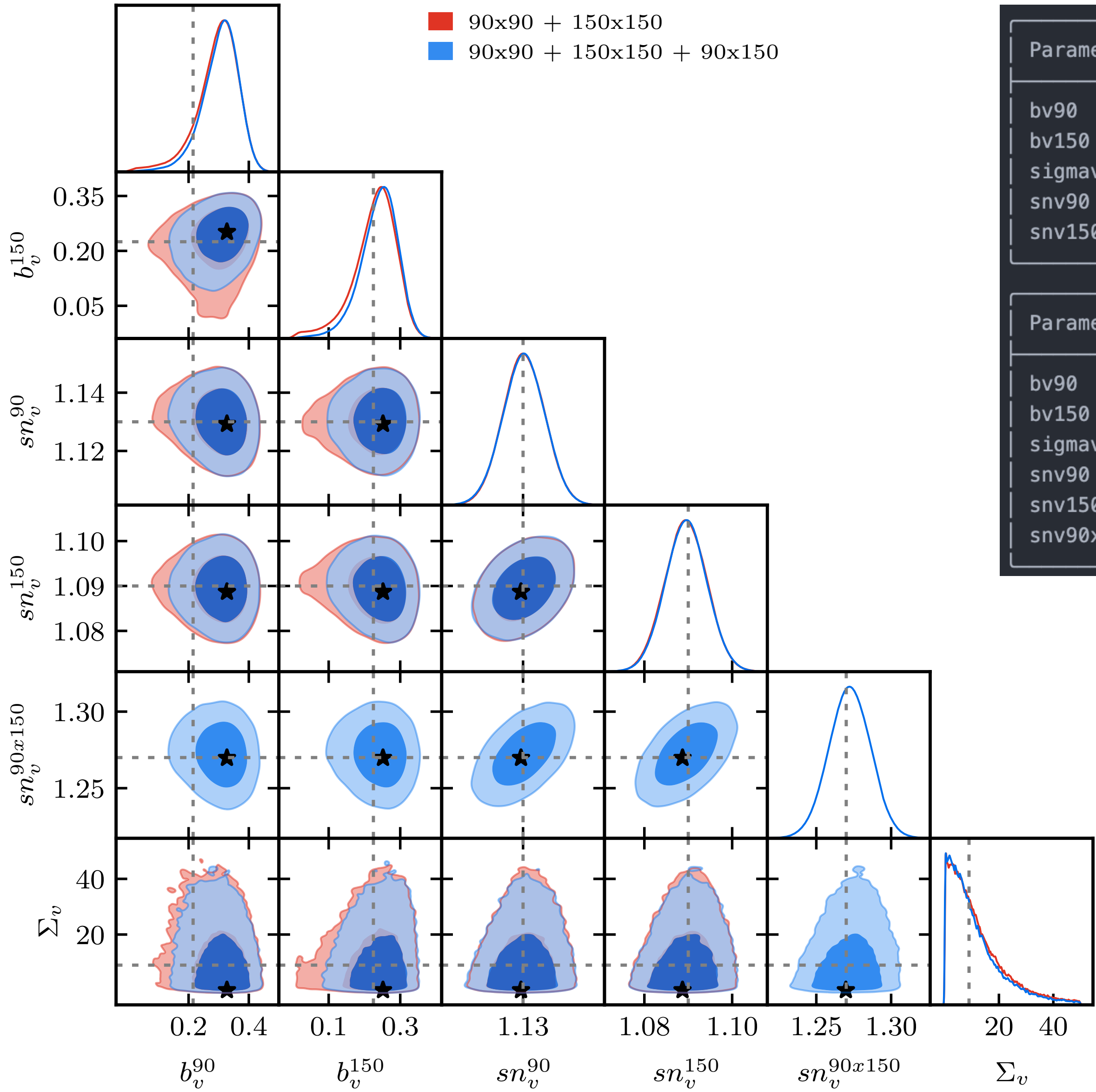
SNR ~ 3.6! (once the noise is removed..)



LRG: Velocity-Velocity Power Spectrum



LRG: Velocity-Velocity Power Spectrum

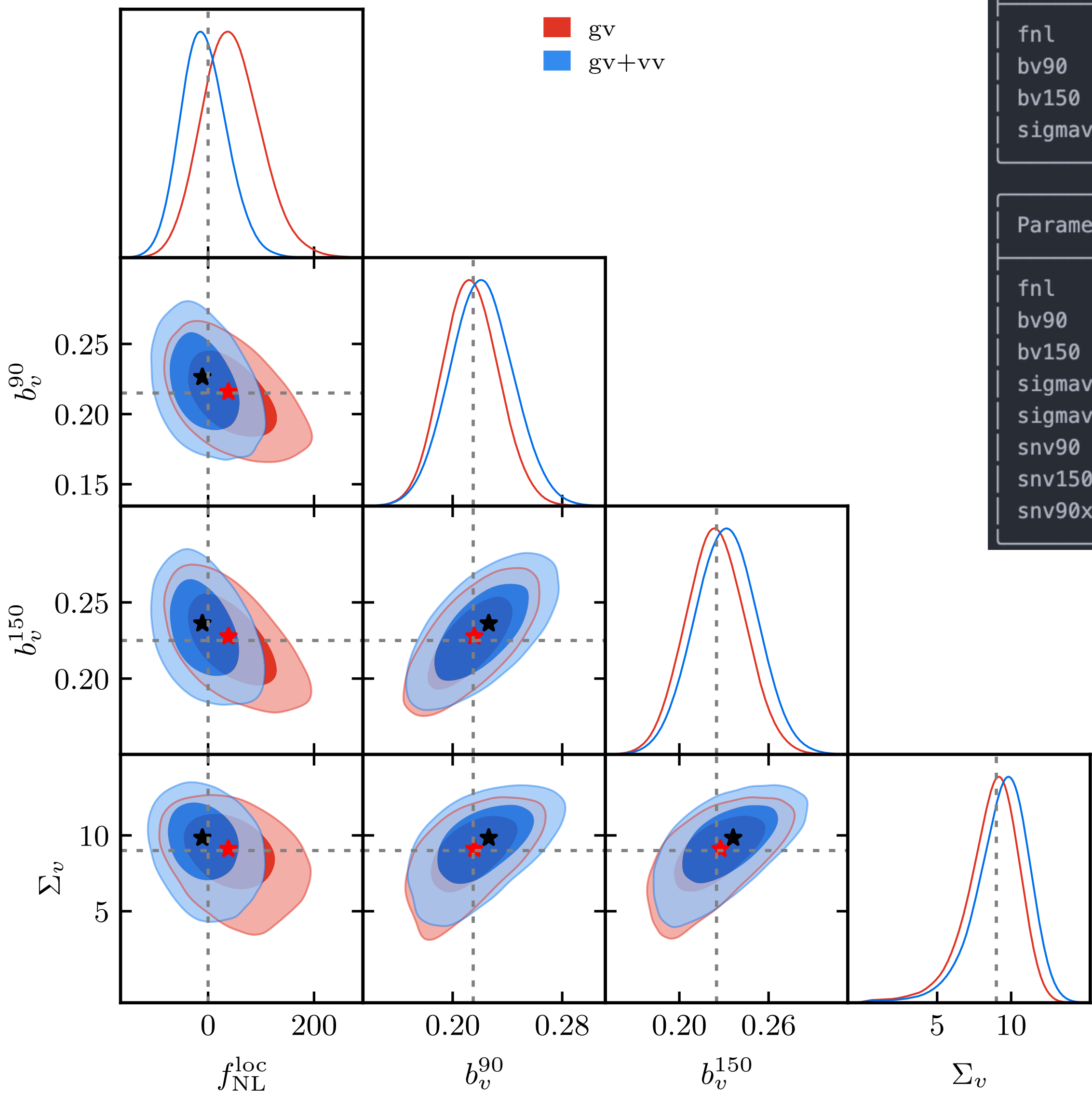


Parameter	BestFit	Mean	Std	Interval:1sigma
bv90	0.325	0.294	0.0716	-0.0639/0.0656
bv150	0.247	0.227	0.062	-0.0562/0.0579
sigmav	0.00012	12	10.3	-9.37/9.98
snv90	1.13	1.13	0.00743	-0.00737/0.00745
snv150	1.09	1.09	0.00469	-0.00468/0.00468

Parameter	BestFit	Mean	Std	Interval:1sigma
bv90	0.327	0.302	0.0642	-0.0604/0.0608
bv150	0.252	0.239	0.0529	-0.0498/0.0507
sigmav	5.63e-05	11.2	9.8	-8.75/8.96
snv90	1.13	1.13	0.00748	-0.00750/0.00743
snv150	1.09	1.09	0.00476	-0.00476/0.00480
snv90x150	1.27	1.27	0.0139	-0.0139/0.0139

- **First detection** of P_{vv} at 3.69 sigma !
- 3.52 without the cross
- Common noise between 90 and 150 (primary CMB !)

LRG: Galaxy-Velocity + Velocity-Velocity

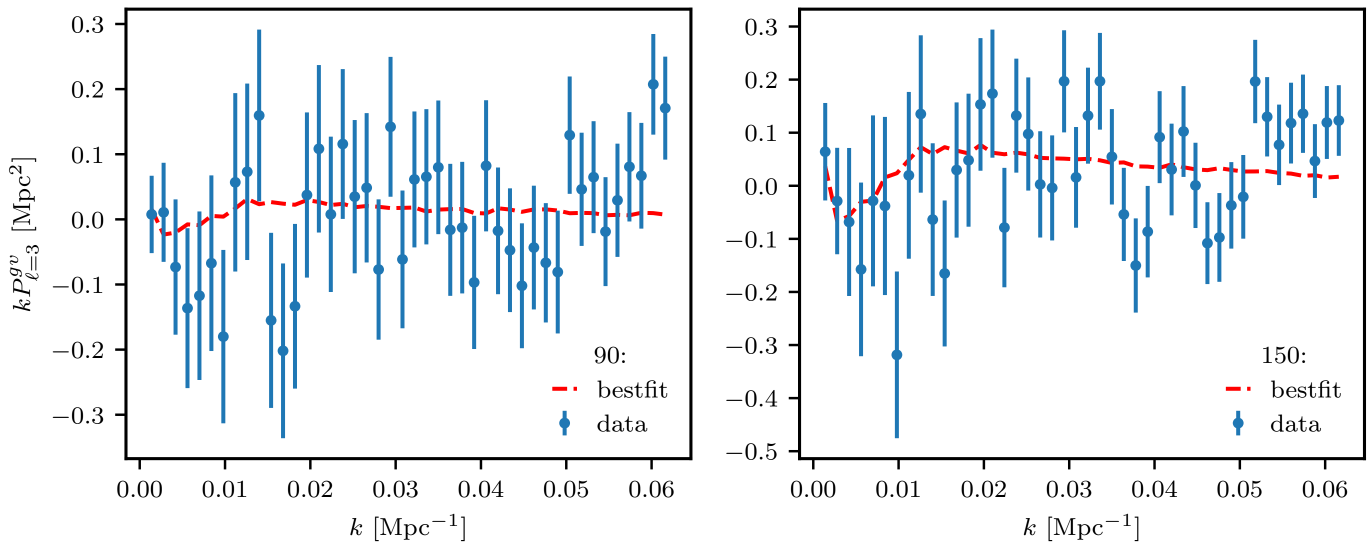


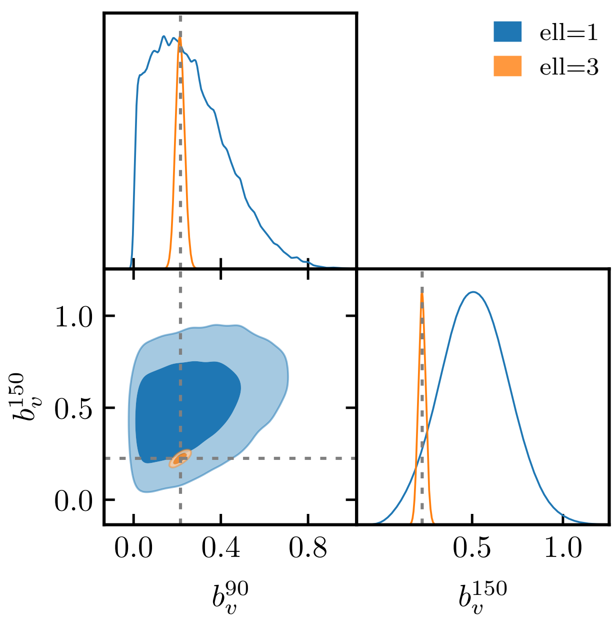
Parameter	BestFit	Mean	Std	Interval:1sigma
fnl	38.4	44.2	56	-55.4/55.4
bv90	0.216	0.213	0.0204	-0.0205/0.0205
bv150	0.228	0.224	0.0199	-0.0200/0.0200
sigmav	9.11	8.67	1.87	-1.69/1.74

Parameter	BestFit	Mean	Std	Interval:1sigma
fnl	-10.8	-7.07	44	-43.2/43.6
bv90	0.226	0.221	0.0229	-0.0229/0.0230
bv150	0.236	0.231	0.021	-0.0211/0.0210
sigmav	9.84	9.32	1.91	-1.73/1.78
sigmav_vv	1.65e-05	11.5	9.68	-8.86/9.04
snv90	1.13	1.13	0.0074	-0.00735/0.00738
snv150	1.09	1.09	0.00481	-0.00481/0.00481
snv90x150	1.27	1.27	0.0139	-0.0140/0.0138

- P_{vv} prefers larger value of bv.
- Constraint on $f_{\rm NL}^{\rm loc}$ improved by ~ 30%

LRG: Galaxy-Velocity Octupole





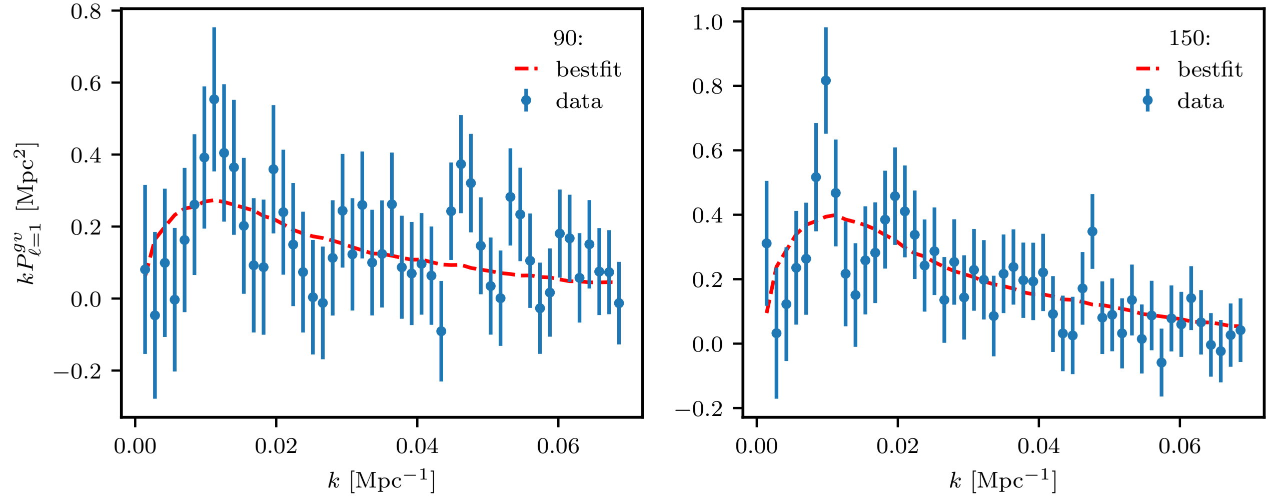
- Galaxy-Velocity as a non-zero octupole (ell=3):

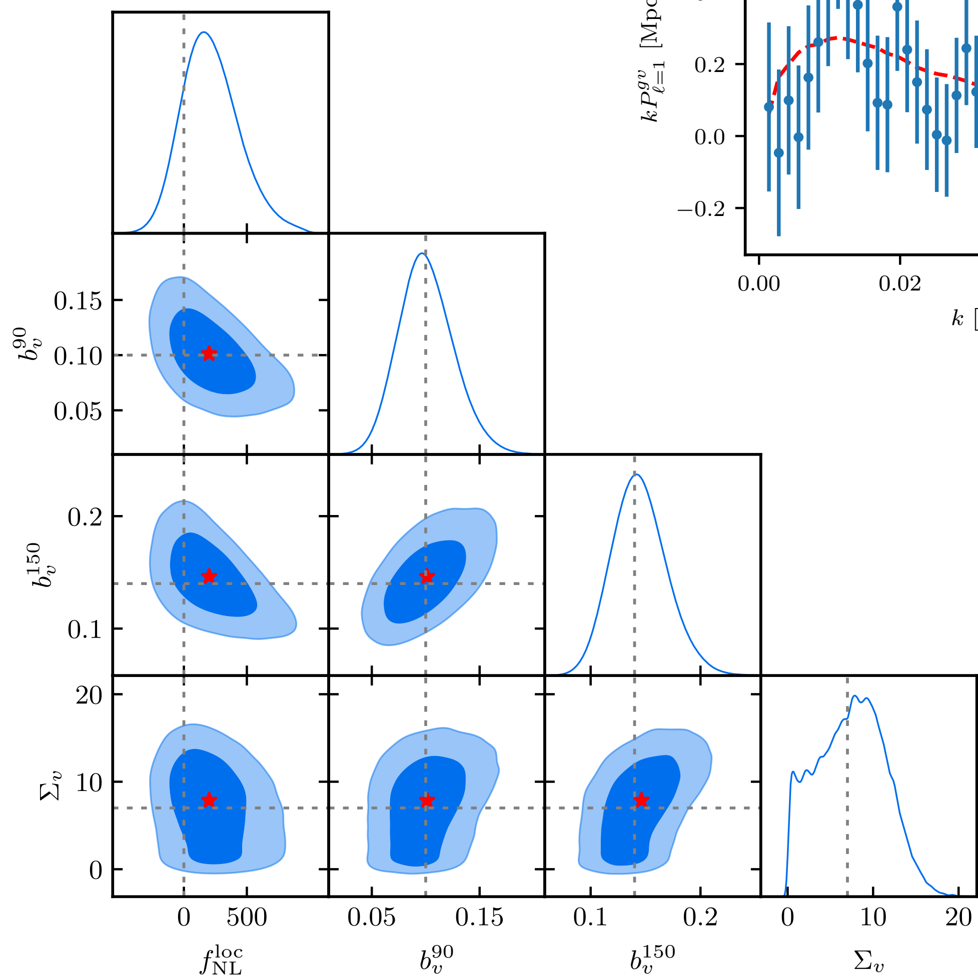
$$P^{gv}_{\ell=1} = \left(b_1 + \frac{3}{5}f\right)\frac{ifaH}{k}P_{\rm lin}(k),$$

$$P^{gv}_{\ell=3} = \frac{2}{5}\frac{if^2aH}{k}P_{\rm lin}(k).$$

- Hint of detection: SNR ~ 2.174

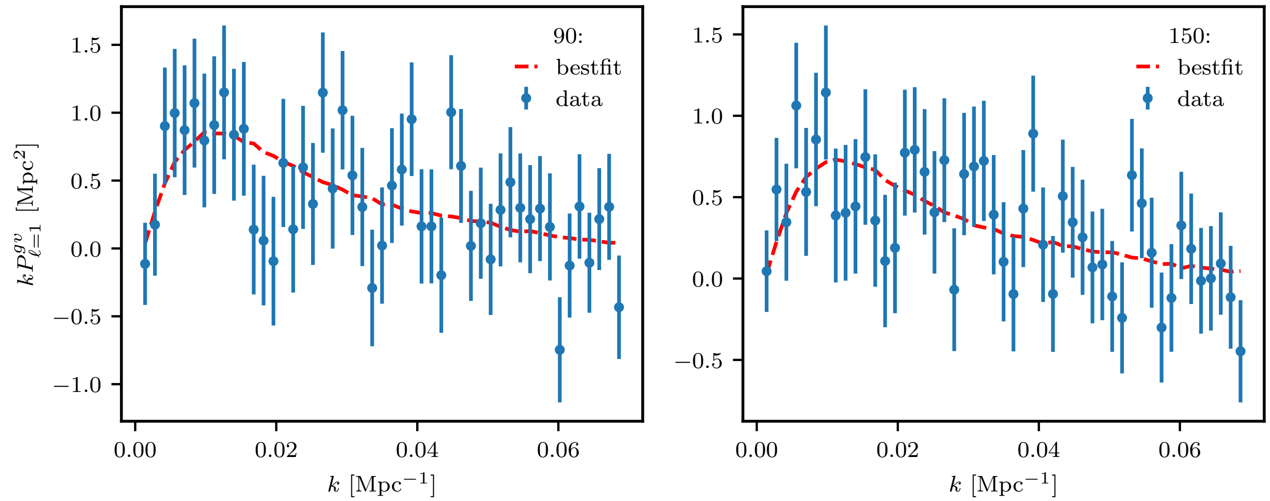
ELG: Galaxy-Velocity Power Spectrum

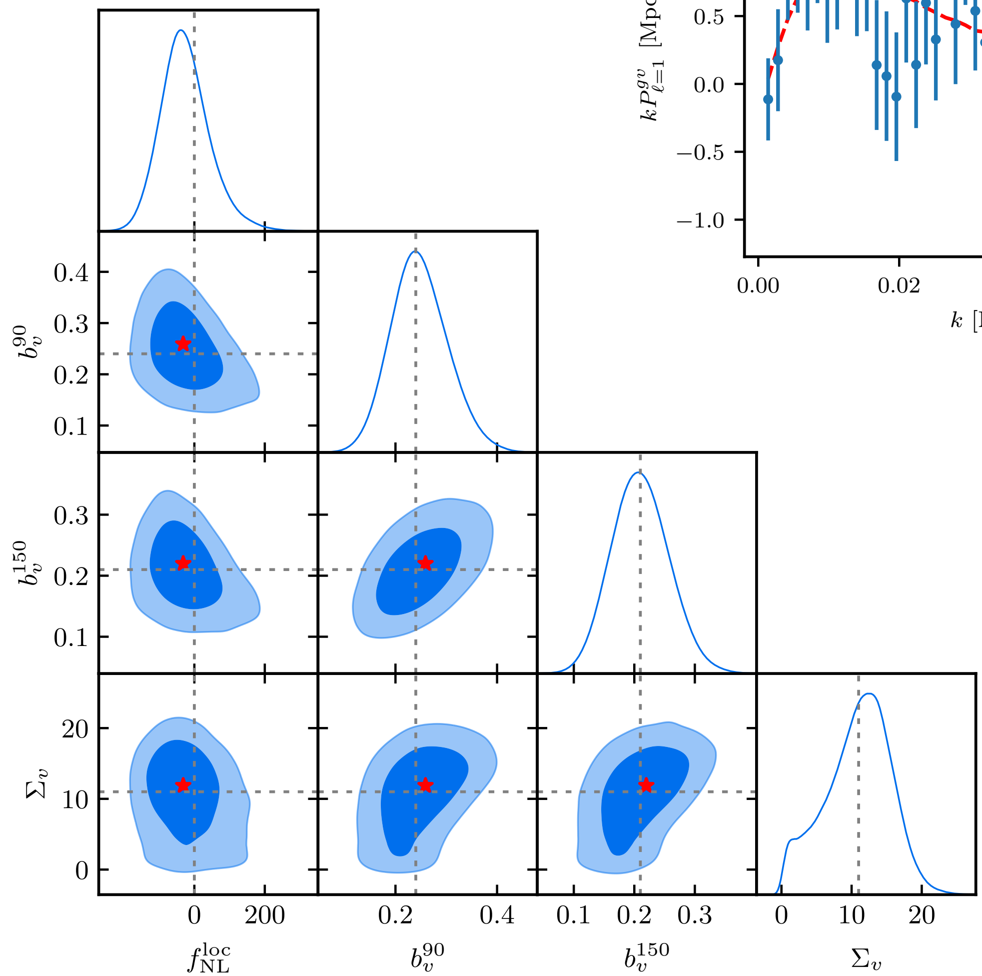




- **First detection** of kSZ signal with ELG:
  - Very exciting for Euclid !!
- Detection with SNR ~ 7.5
- Not competitive for $f_{\rm NL}^{\rm loc}$ as expected, ($b_\phi \sim 0$).
- b_v is very due to a bad HOD model.
- No detection of Pvv.

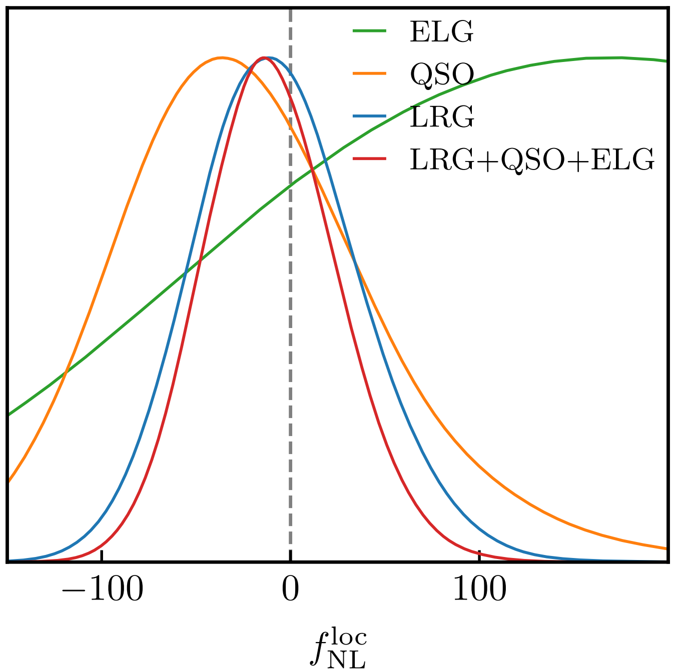
QSO: Galaxy-Velocity Power Spectrum





- **First detection** of kSZ signal with QSO!
- Detection with SNR ~ 6.5
- Competitive for $f_{\rm NL}^{\rm loc}$ with LRG (+/- 65).
- No detection of Pvv.

Final Combination



Parameter	BestFit	Mean	Std	Interval:1sigma
fnl	-12.1	-10.1	36.2	-35.9/36.0
LRG_bv90	0.224	0.222	0.0224	-0.0222/0.0224
LRG_bv150	0.235	0.233	0.0203	-0.0202/0.0203
LRG_sigmav	9.8	9.45	1.79	-1.66/1.70
LRG_sigmav_vv	18.4	11.5	9.71	-8.87/9.00
LRG_snv90	1.13	1.13	0.00751	-0.00746/0.00745
LRG_snv150	1.09	1.09	0.00476	-0.00474/0.00476
LRG_snv90x150	1.28	1.27	0.0139	-0.0138/0.0138
QSO_bv90	0.259	0.246	0.0523	-0.0523/0.0522
QSO_bv150	0.221	0.21	0.0448	-0.0448/0.0452
QSO_sigmav	12.7	10.9	4.58	-4.86/4.47
ELG_bv90	0.12	0.115	0.0254	-0.0250/0.0252
ELG_bv150	0.166	0.158	0.0242	-0.0242/0.0240
ELG_sigmav	10.6	8.2	3.99	-4.53/4.07

- Not competitive yet with respect to the galaxy-galaxy power spectrum…
- It will be the case with SO new data! (reconstruction noise will be improved by ~ 4).
- Cosmic variance cancelation not tested yet due to DESI policy.

Discussion about b_v

- We assume a fiducial **electron-galaxy power spectrum** when reconstructing the velocity:

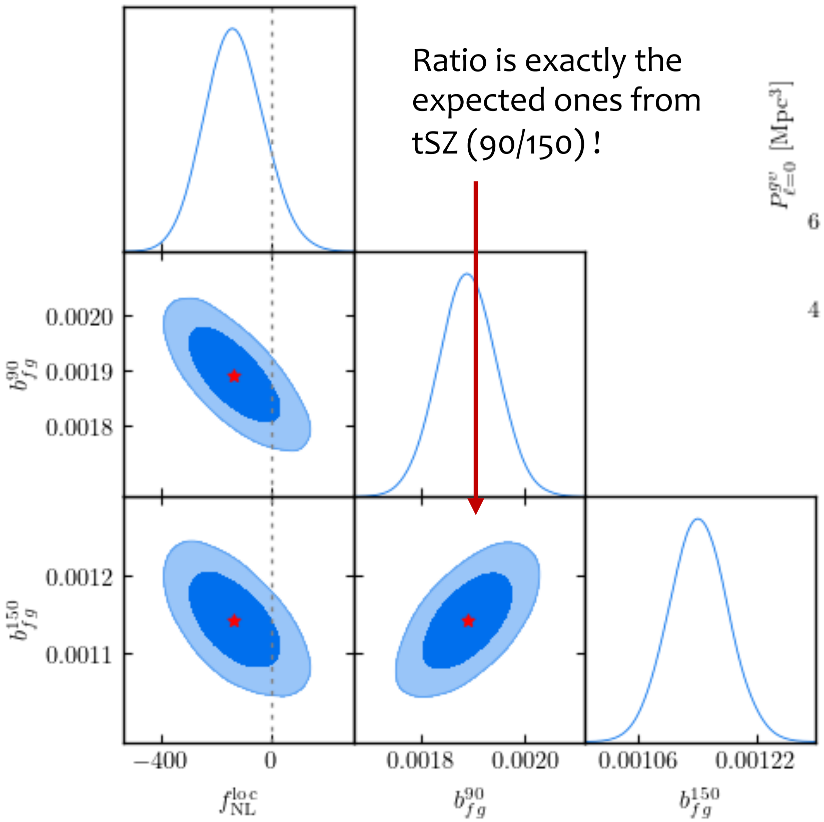
$$\hat{v}_r(\mathbf{k}_L) \propto \int_{\mathbf{k}_S+(\mathbf{l}/\chi_*)=\mathbf{k}_L} \frac{P_{ge}(l/\chi_*)}{P_{gg}^{\rm tot}(l/\chi_*)} \frac{1}{C_l^{\rm tot}} \Big(\delta_g(\mathbf{k}_S) T_{\rm CMB}(\mathbf{l})\Big)$$

- This Pge is computed using some assumption:
  - Optical depth; Battaglia profile
  - A very generic HOD model
- In this analysis we have marginalized over b_v as a nuisance parameters:
  - It contains small scale physics !
  - ELG is off because I used a very wrong HOD leading to $b_v \sim 2.3 \neq 1.3$ ...
  - $b_v \ll 1$:
    - **strong baryonic feedback** (optical depth) ?
    - Already suggested by kSZ stacking measurements (Ried Guachalla+25)

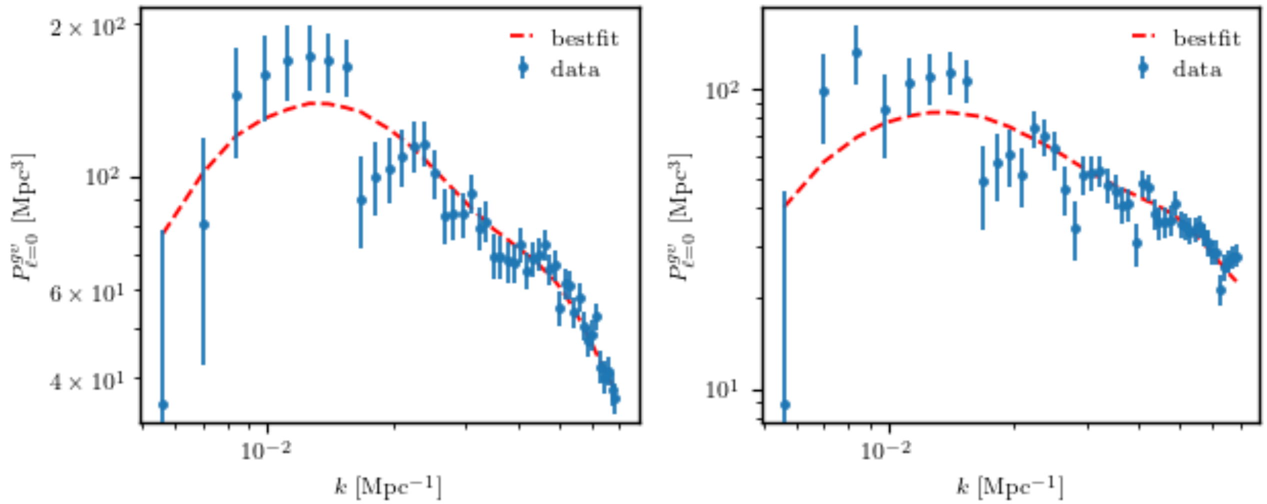
b_v	LRG	ELG	QSO
90	0.222 +/- 0.02	0.115 +/- 0.02	0.246 +/- 0.05
150	0.233 +/- 0.02	0.158 +/- 0.02	0.221 +/- 0.04

Discussion about foregrounds

- Foregrounds of the CMB (CIB, tSZ) contaminate our signal: $\hat{v_r}(k) = b_v v_{true}(k) + b_{fg}\delta_m(k)$



Ratio is exactly the expected ones from tSZ (90/150) !

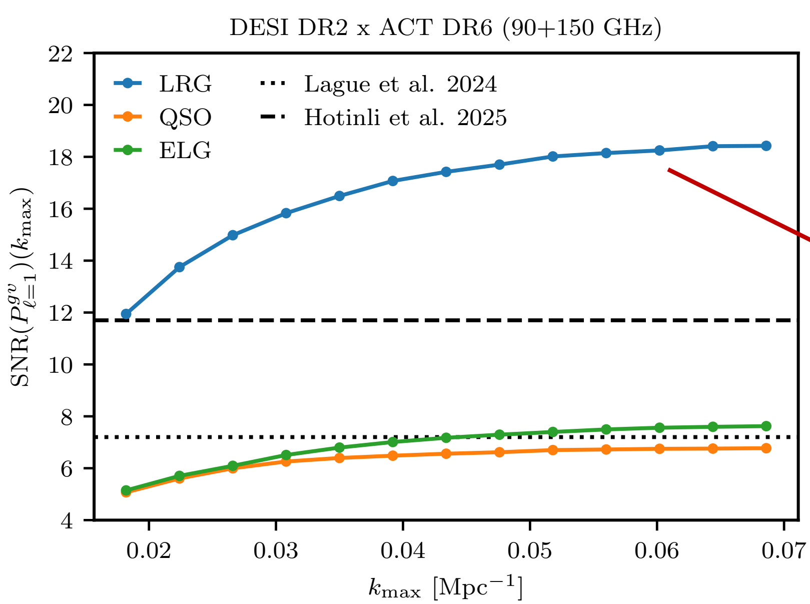


- This create a **non-zero signal** in the monopole of the galaxy-velocity!
- It leaks into the dipole via the **window** convolution -- > Tested, only **tiny impact** at small scales.
- Can use these foregrounds as a real tracer of the underlying density field …

Assuming only dependence on f_{nl} for the galaxy part (for fun here)

Summary

- **Tightest** constraints on local PNG based on Pgv to date: $\sigma(f_{\mathrm{NL}}^{\mathrm{loc}}) \sim 36$.
- DESI DR2 LRG x ACT DR6 (SNR ~ 18) improves by a factor of:
  - 2.4 the previous detection done with BOSS LRG x ACT DR5 (Lague+24).
  - 1.5 the one done with DESI LRG targets (photo-z) on NGC only (Hotinli+25).
- **First detection:**
  - with ELG (SNR ~ 7.5) and QSO (SNR ~ 6.5).
  - LRG Velocity-Velocity (SNR ~ 3.6) and hint for Octupole (SNR ~ 2.1). → We could measure the growth!



Now small scales are just noise 😞