Primordial non-Gaussianity: from forecasts to data

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March 11th 2025 - Cosmic Roy and the General Roylativitis

Primordial non-Gaussianity

- Primordial non-Gaussianity of local-type: $f_{\rm NL}^{\rm loc}$
  - Insights on inflation and on the dynamics of Early Universe
  - Single-field inflation: $f_{\rm NL}^{\rm loc} \sim 0$
  - Multi-field inflation: $f_{\rm NL}^{\rm loc} \sim 1$
- Theoretical threshold to reach: $\sigma_{f_{\rm NL}} \sim 1$
- Current constraints from CMB: $\sigma_{f_{\rm NL}} \sim 5$ [*Planck* Collaboration; Akrami et al. (2018)]

[Dalal et al. (2008), Matarrese et al. (2008), Slosar et al. (2008), Castorina et al. (2019), Cabass et al. (2022), D'Amico et al. (2022), Maldacena (2003), Creminelli (2004)]

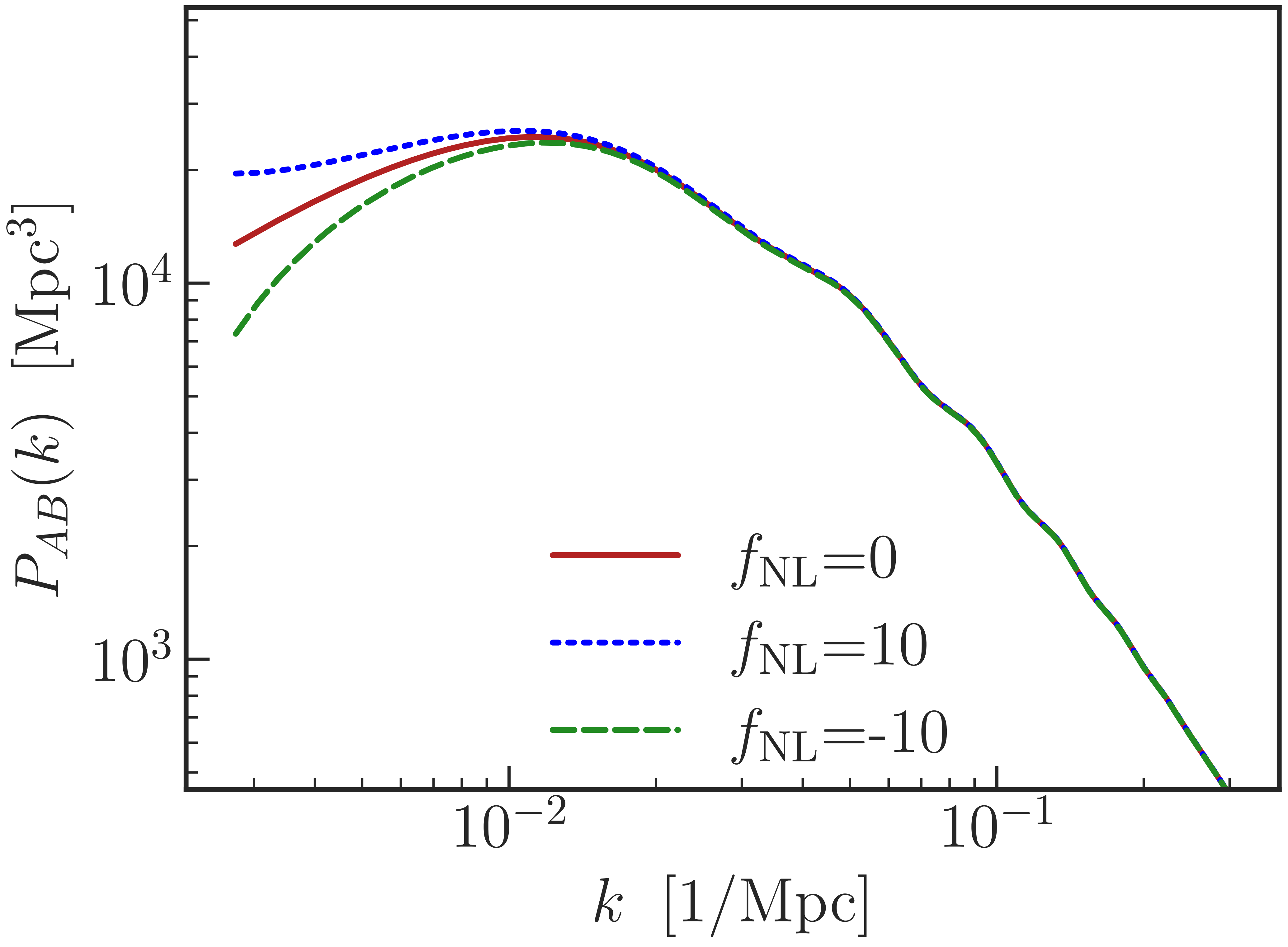
PNG imprints on the LSS

- Scale dependent biases due to the coupling of short and long scale density modes of a dark matter tracer t (t=galaxies, HI,…)
  - First order PNG bias: $b_{\phi,t}(z) = 2\delta_c \left(b_{1,t}(z) - p\right)$ with $p = 1, 1.6$ from the universality relation
    - $\delta^{(1)}_{t,\mathrm{PNG}}(k,z) \propto f^{\mathrm{loc}}_{\mathrm{NL}}\, b_{\phi,t}(z)\, k^{-2}$
  - Second order PNG bias: $b_{\phi\delta,t}(z) = b_{\phi,t}(z) + 2\left\{\delta_c\left[b_{2,t}(z) - \frac{8}{21}\left(b_{1,t}(z) - 1\right)\right] - b_{1,t}(z) + 1\right\}$
    - $\delta^{(2)}_{t,\mathrm{PNG}}(k,z) \propto f^{\mathrm{loc}}_{\mathrm{NL}}\, b_{\phi\delta,t}(z)\, k^{-2}$
- Non vanishing primordial matter bispectrum
- Current constraints from LSS
  - $\sigma_{f_{\mathrm{NL}}} \sim 15$ [Cagliari et al. (2023)]
  - $\sigma_{f_{\mathrm{NL}}} \sim 9$ [DESI Collaboration; Chaussidon et al. (2024)]

The power spectrum

$$P_{t\,t'}(k,z,\mu) = \left[b_{1,t}(z) + b_{\phi,t}(z)\mathcal{M}^{-1}(k,z) f_{\rm NL} + f(z)\mu^2\right]\left[b_{1,t'}(z) + b_{\phi,t}(z)\mathcal{M}^{-1}(k,z) f_{\rm NL} + f(z)\mu^2\right] P_{\rm m}(k)$$

$$\frac{2\,c^2\,k^2\,T(k)\,D(z)}{3\,\Omega_{\rm m}\,H_0^2}$$



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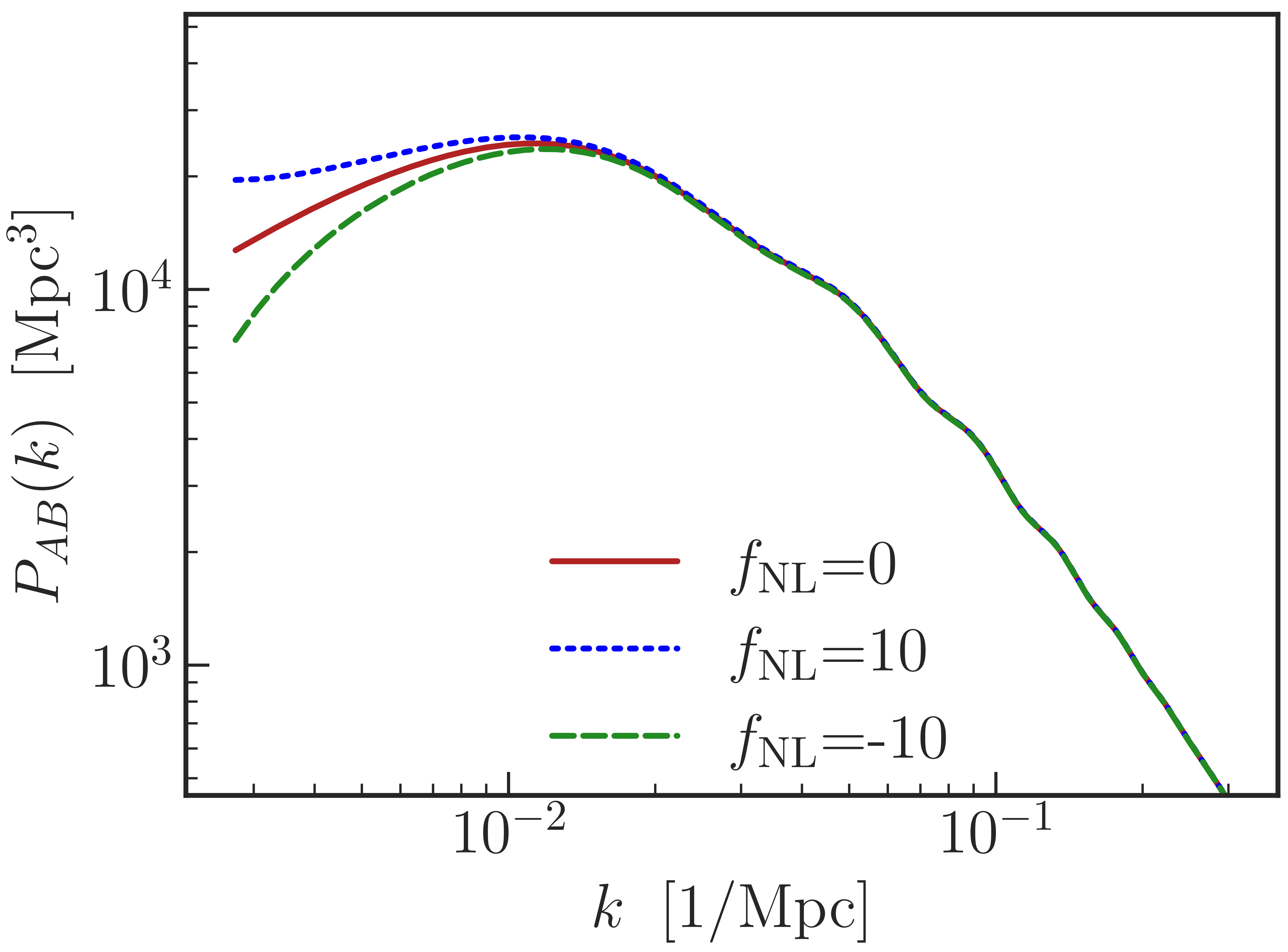


General setup

In collaboration with S. Camera, R.Maartens
[arXiv:2307.00058]

Galaxy survey

- Stage-IV spectroscopic survey
- Redshift range covered with different ELG types [Fonseca, Camera (2020)]
- Flux limit: $F_c = 2 \times 10^{-16}\,\mathrm{erg\,s^{-1}\,cm^2}$
- Sky coverage: $f_{\mathrm{sky}} = 0.36$
- Shot noise

HI intensity mapping survey

- SKAO-like survey
- Sky coverage: $f_{\mathrm{sky}} = 0.48$
- Beam damping
- Simulated signal loss at low $k_{||}$
- Thermal noise

- 12 redshift bins for $z \in \left[0.85, 4.0\right]$

- 10 k bins for $k \in \left[k_{\mathrm{min}}(z), k_{\mathrm{max}}(z)\right]$
  - $k_{\mathrm{min}}(z) = 2\,\pi\,V^{-1/3}(z)$
  - $k_{\mathrm{max}}(z) = 0.08\,(1+z)^{2/\left(2+n_s\right)}\;h\,\mathrm{Mpc}^{-1}$

Multi-tracer technique

- Large scales: cosmic variance limited
- Multi-tracer technique: combination of independent tracers of the same underlying matter distribution to overcome cosmic variance [Seljak (2008)]

- Data vector

$$\mathbf{P} = \left\{ P_{\rm gg}, P_{\rm gH}, P_{\rm HH} \right\}$$

- Analytical covariance matrix [Karagiannis et al. (2024)]

$$\text{Cov}\,(\mathbf{P}, \mathbf{P}) = \frac{2}{N_{\rm m}} \begin{bmatrix} \tilde{P}_{\rm gg}^2 & \tilde{P}_{\rm gg}\tilde{P}_{\rm gH} & \tilde{P}_{\rm gH}^2 \\ & \frac{1}{2}\left(\tilde{P}_{\rm gg}\tilde{P}_{\rm HH} + \tilde{P}_{\rm gH}^2\right) & \tilde{P}_{\rm gH}\tilde{P}_{\rm HH} \\ & & \tilde{P}_{\rm HH}^2 \end{bmatrix}$$

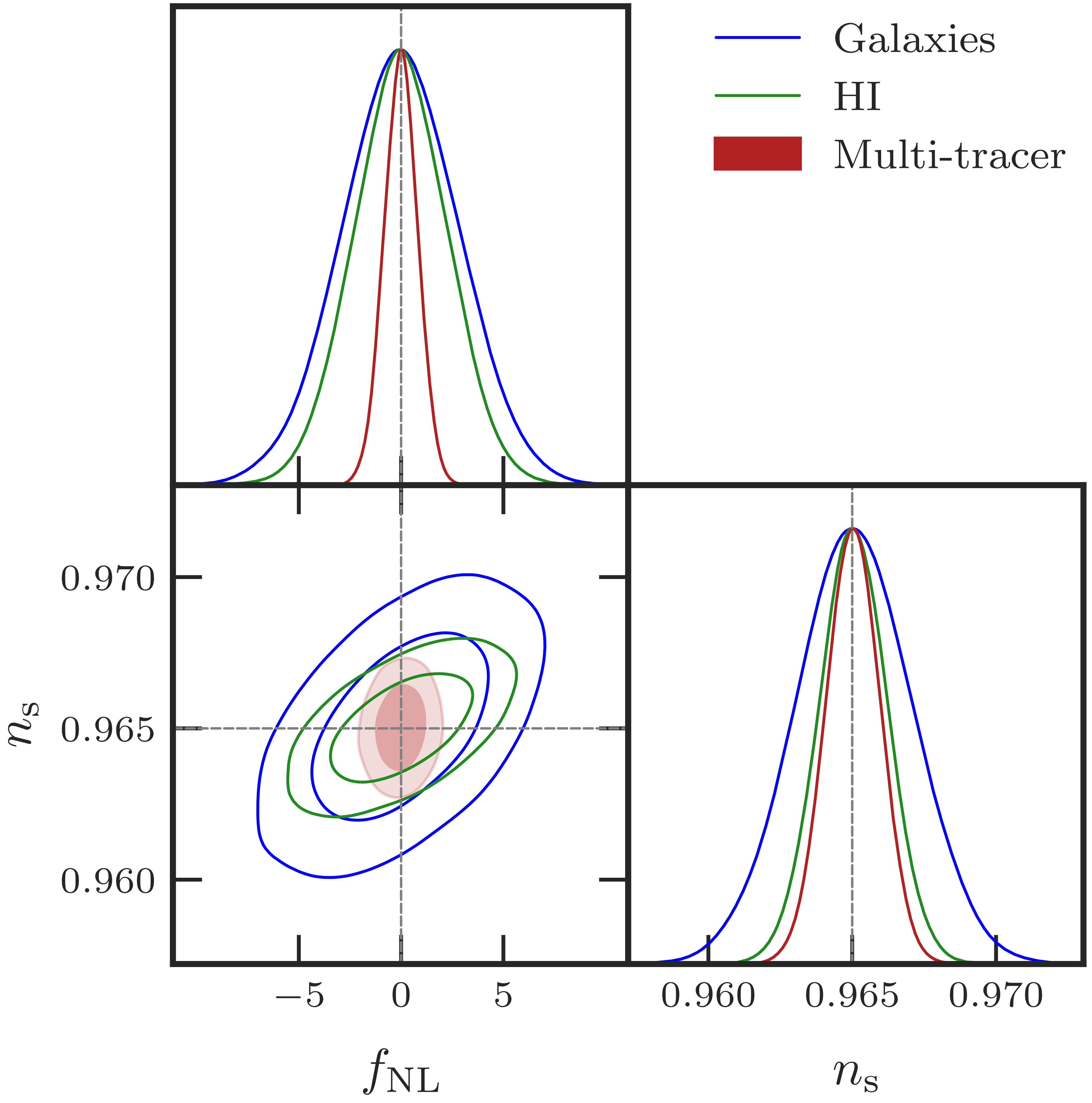
$$\tilde{P}_{t\,t'} = P_{t\,t'} + P^{\rm noise}_{t\,t'}\,\delta_{t\,t'}$$

- Multi-tracer likelihood [Viljoen et al. (2020]

$$\mathscr{L}^{\rm tot}_{\rm MT} = \mathscr{L}^{\rm overlap}_{\rm MT} + \mathscr{L}^{\rm non-overlap}_{\rm gg} + \mathscr{L}^{\rm non-overlap}_{\rm HH}$$

Analysis and results

- Free parameters: $\left\{f_{\rm NL}, n_s, b_{1,{\rm g}}(z), b_{1,{\rm H}}(z)\right\}$
- All fiducial parameters recovered and constrained
- Constraining power more than doubled with respect to the single-tracer analyses
- Marginalized uncertainty on $f_{\rm NL}$ from multi-tracer analysis: $\sigma_{f_{\rm NL}} = 0.76$
  - Constraints on the dynamics of the primordial Universe
  - Discrimination between inflationary models



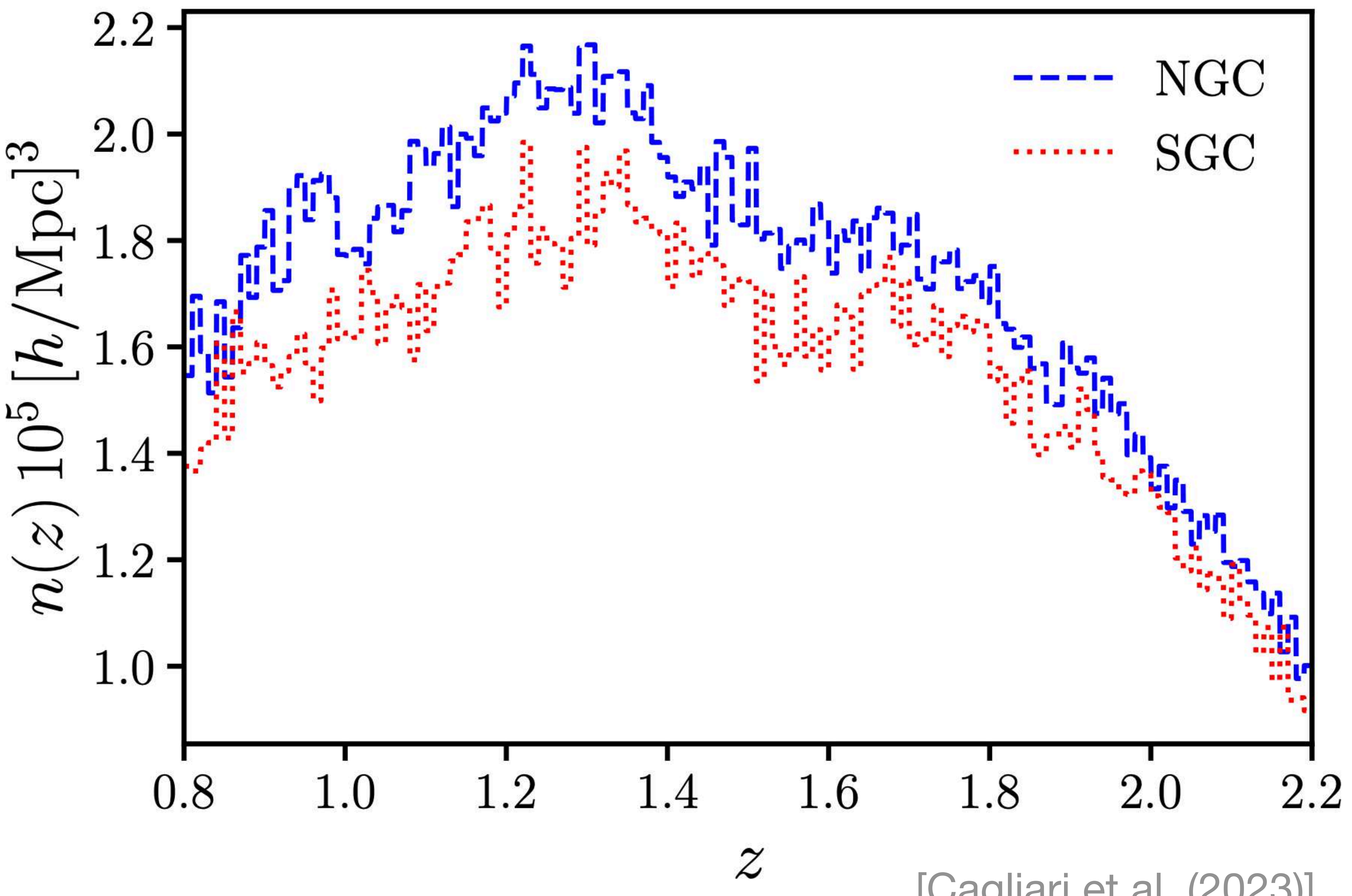
[**MBS**, Camera, Maartens (2024)]

Let's move to data!

In collaboration with M. S. Cagliari, K. Pardede, G. D'Amico, E. Castorina
[arXiv:2502.14758]

eBOSS DR16 quasar sample

- High redshift sample: $0.8 < z < 2.2$
- 343708 quasars in total
- Two disjoint patches:
  - North Galactic Cap (NGC): $2924\,\mathrm{deg}^2$
  - South Galactic Cap (NGC): $1884\,\mathrm{deg}^2$
- Linear weight for angular systematics



[Cagliari et al. (2023)]

[Ross et al. (2020), Lyke et al. (2020)]

Measurements

Power spectrum monopole

- Linear k-bins
  - $3.75 \times 10^{-3} < k\,[h/\mathrm{Mpc}] < 0.25$
  - $\Delta k = k_\mathrm{f}$
- FKP weights: $P(k) \propto \langle \delta_\mathrm{FKP}(k)\, \delta_\mathrm{FKP}(-k) \rangle$
  - $w_\mathrm{FKP}(z) = \dfrac{1}{1 + n(\bar{z})P_\mathrm{fid}}$
- Optimal weights: $P(k) \propto \langle \tilde{\delta}(k)\, \delta_0(-k) \rangle$
  - $\tilde{w}(z) = b(z) - p$
  - $w_0(z) = D(z)\left[b(z) + \dfrac{f(z)}{3}\right]$

Bispectrum monopole

- All triangle configurations
  - $0.0057 < k\,[h/\mathrm{Mpc}] < 0.075$
  - $\Delta k = 3k_\mathrm{f}$
- FKP weights: w_FKP
- Data compression through Single Value Decomposition

$$\underset{[N_\mathrm{SVD}]}{\tilde{B}} = \overset{[N_\mathrm{tri}]}{B} \cdot \underset{[N_\mathrm{tri},\, N_\mathrm{SVD}]}{R}$$

$N_\mathrm{SVD} = 9$

Analysis

- Power spectrum and bispectrum joint analysis
- $P_{0,\mathrm{qso}}(k)$ and $B_{0,\mathrm{qso}}(k)$ both modeled at tree level
- Corrections to the model (both for $P_{0,\mathrm{qso}}(k)$ and $B_{0,\mathrm{qso}}(k)$)
  - Window convolution
  - Integral constraints
- Full volume analysis: computation of the effective redshift for $P_{0,\mathrm{qso}}(k)$ and $B_{0,\mathrm{qso}}(k)$
- NGC and SGC separately and then jointly

[Wilson et al. (2015), Beutler et al. (2019), de Mattia et al. (2019)]

Analysis

- Covariance matrix estimated from the EZ realistic mocks
- Analysis performed using Hamiltonian Monte Carlo chains (HMC)
- Free parameters: $\left\{f_{\mathrm{NL}}, b_1^P, b_1^B, b_2, b_{s^2}, \mathrm{FoG}, \mathrm{SN}\right\}$

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Wide uniform prior

Analysis

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- Analysis performed using Hamiltonian Monte Carlo chains (HMC)
- Free parameters: $\{f_{\rm NL}, b_1^P, b_1^B, b_2, b_{s^2}, \mathrm{FoG}, \mathrm{SN}\}$

Linear bias for $P_{0,\mathrm{qso}}(k)$ and $B_{0,\mathrm{qso}}(k_1, k_2, k_3)$:
correlated priors

Analysis

- Covariance matrix estimated from the EZ realistic mocks
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Second order biases: uniform priors

Analysis

- Covariance matrix estimated from the EZ realistic mocks
- Analysis performed using Hamiltonian Monte Carlo chains (HMC)
- Free parameters: $\{f_{\mathrm{NL}}, b_1^P, b_1^B, b_2, b_{s^2}, \mathrm{FoG}, \mathrm{SN}\}$

Finger of God parameters: uniform priors

1 for $P_{0,\mathrm{qso}}(k)$ + 1 for $B_{0,\mathrm{qso}}(k_1, k_2, k_3)$

Analysis

- Covariance matrix estimated from the EZ realistic mocks
- Analysis performed using Hamiltonian Monte Carlo chains (HMC)
- Free parameters: $\{f_{\mathrm{NL}}, b_1^P, b_1^B, b_2, b_{s^2}, \mathrm{FoG}, \mathrm{SN}\}$

Shot Noise parameters: uniform priors

1 scale independent SN parameter for $P_{0,\mathrm{qso}}(k)$

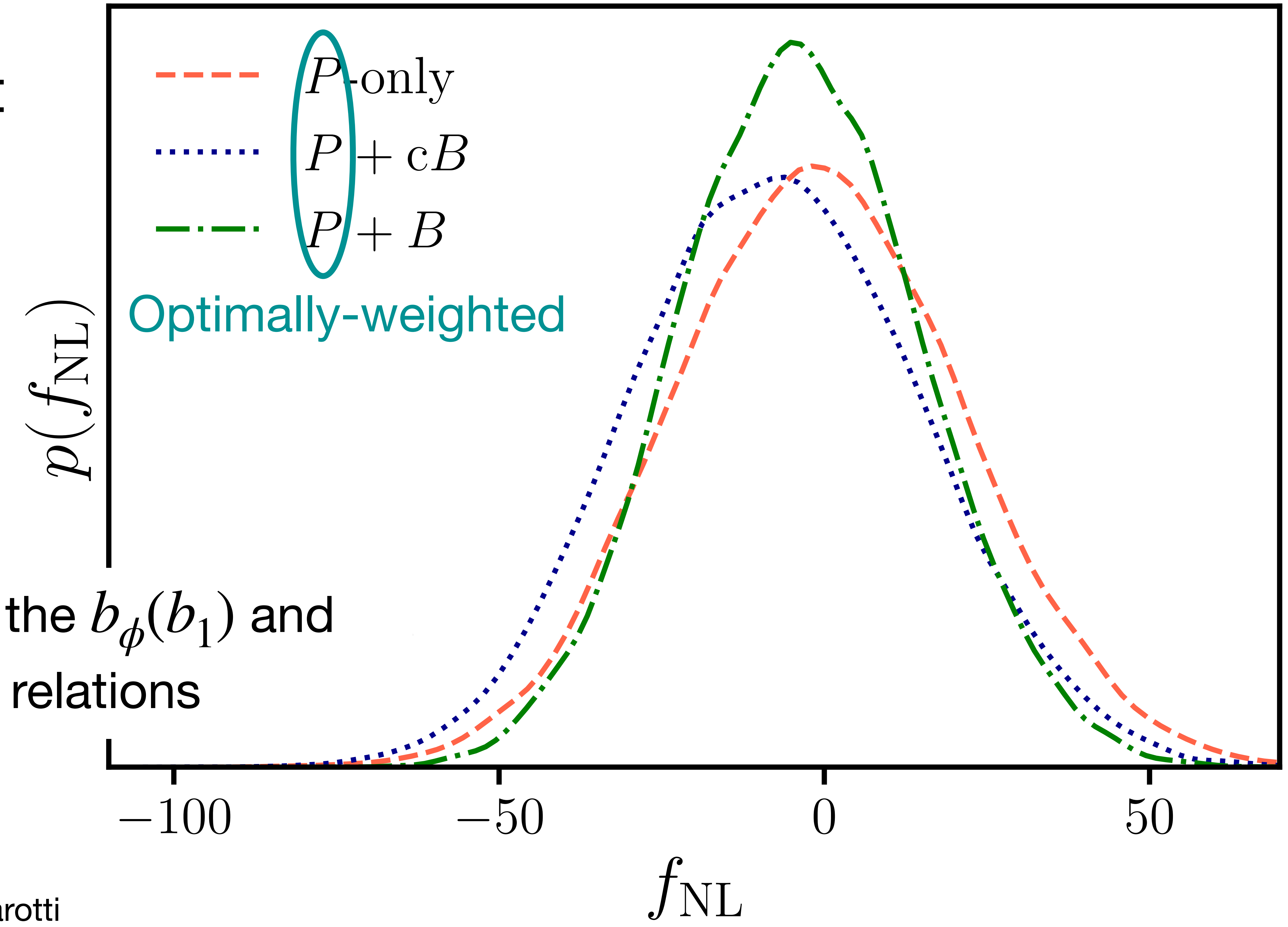
1 scale independent SN parameter for $B_{0,\mathrm{qso}}(k_1, k_2, k_3)$

1 scale dependent SN parameter for $B_{0,\mathrm{qso}}(k_1, k_2, k_3)$

Results

- We reach $\sigma_{f_{\rm NL}} \sim 13$, with an improvement up to $\sim 16\,\%$ with respect to the same analysis performed with P only
- Including the bispectrum with $\Delta k = 3k_{\rm f}$ rebinning is more constraining than the compressed bispectrum
- The sample is noise dominated: limited improvement with respect to forecasts

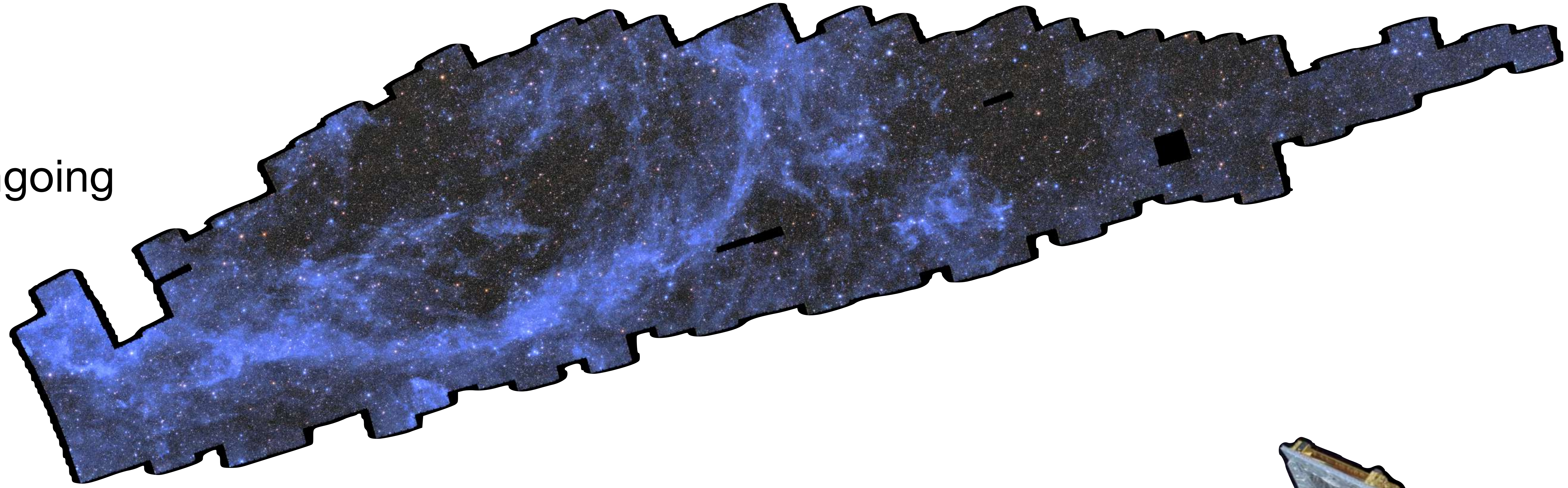
	$\sigma(f_{NL})$
P only	15.5
P+cB $\quad$ **N$_{SVD}$=9**	15.5
P+B	13



$p = 1.6$ in the $b_\phi(b_1)$ and $b_{\phi\delta}(b_1, b_2)$ relations

Towards radio-optical synergies

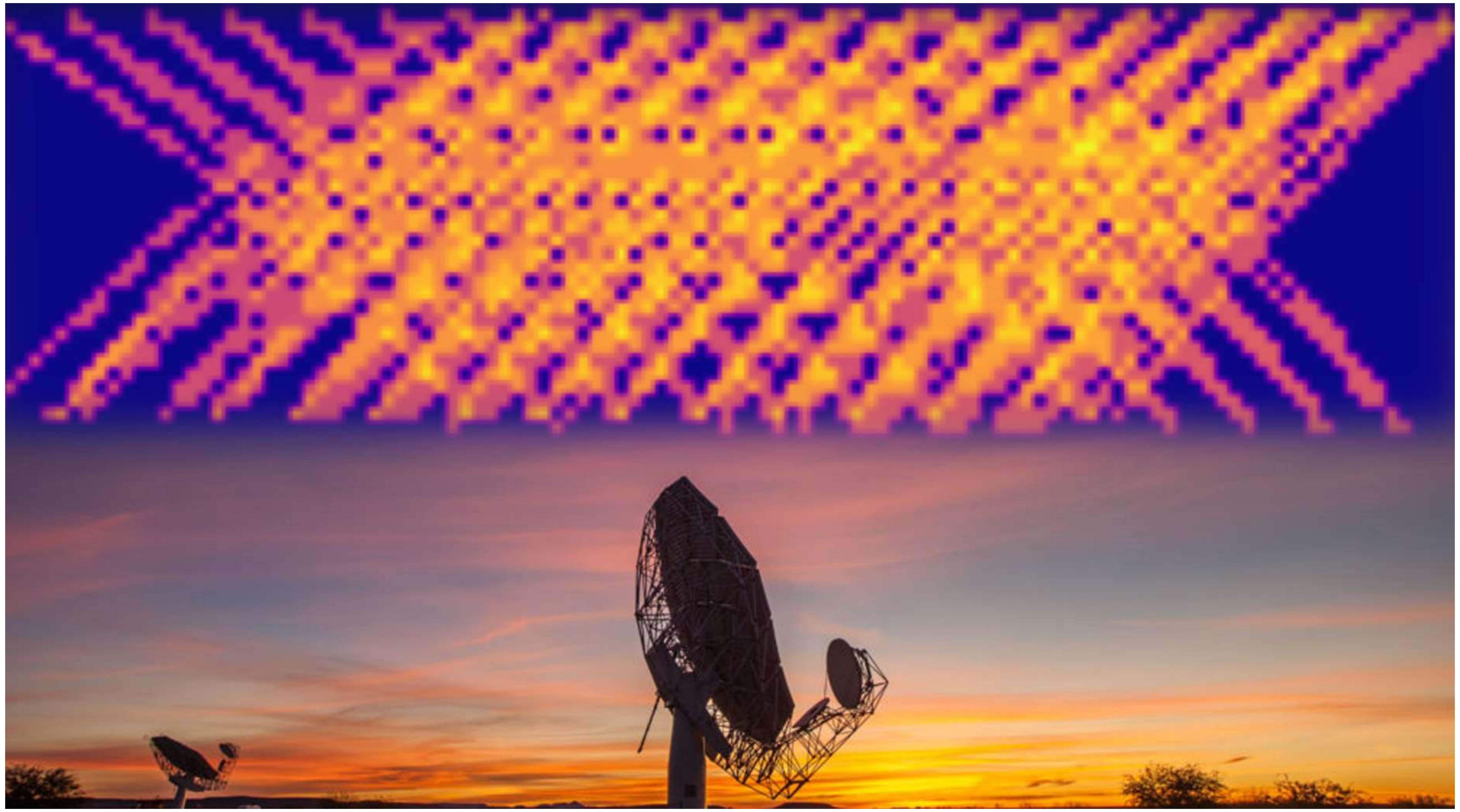
- Spectroscopic surveys
  - DESI observations and analysis ongoing
  - Euclid started surveying the sky



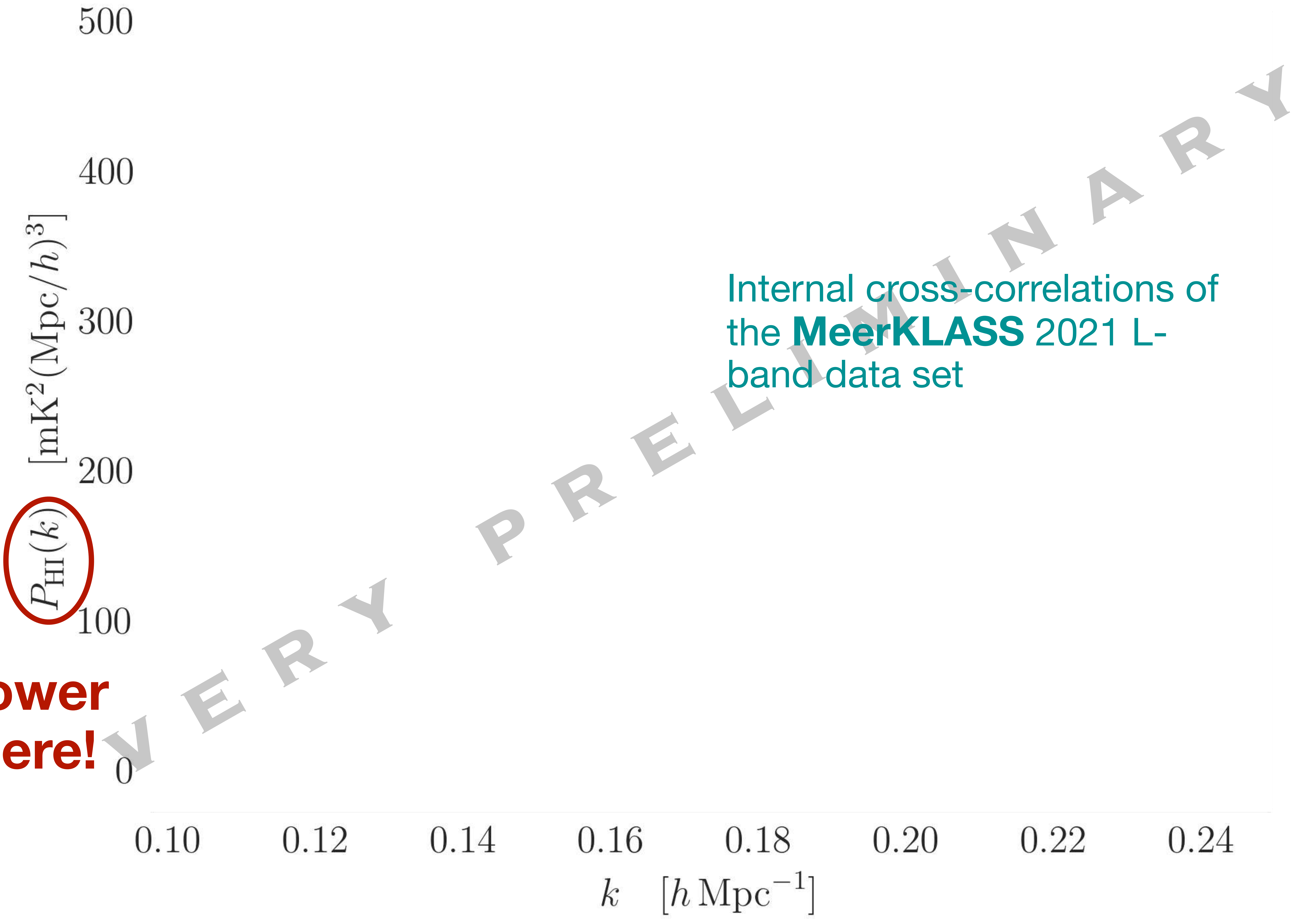
Credits: ESA, Euclid Consortium

Towards radio-optical synergies

- Spectroscopic surveys
  - DESI observations and analysis ongoing
  - Euclid started surveying the sky
- HI intensity mapping
  - SKAO precursors taking data and setting the stage for the SKAO (e.g. MeerKLASS)



Towards radio-optical synergies



Internal cross-correlations of the **MeerKLASS** 2021 L-band data set

The HI auto-power spectrum is there!