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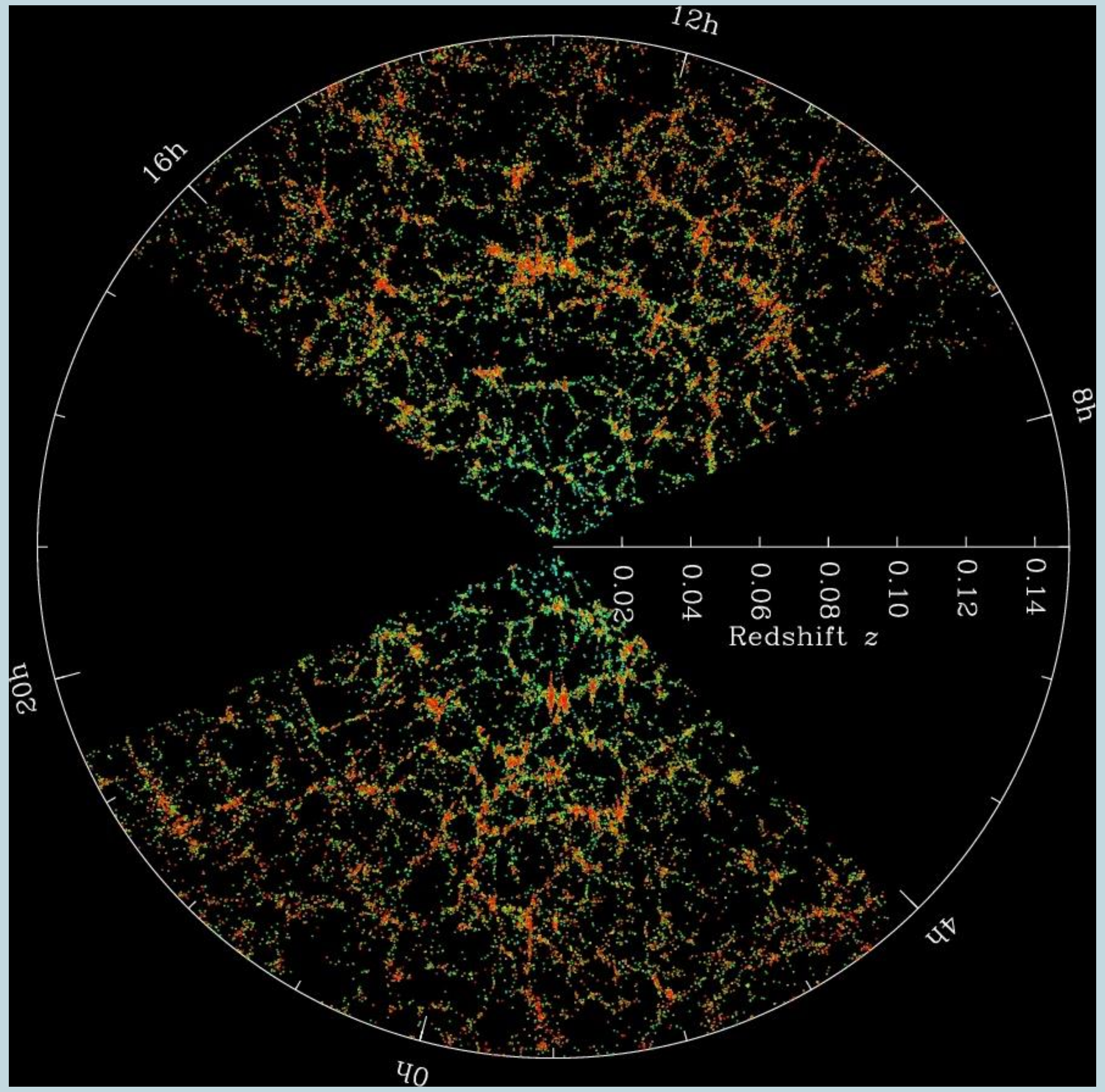
UWC ASTROPHYSICS

Multitracer forecast:Euclid-like Halpha or Photoz, and SKAO/MeerKAT HI IM

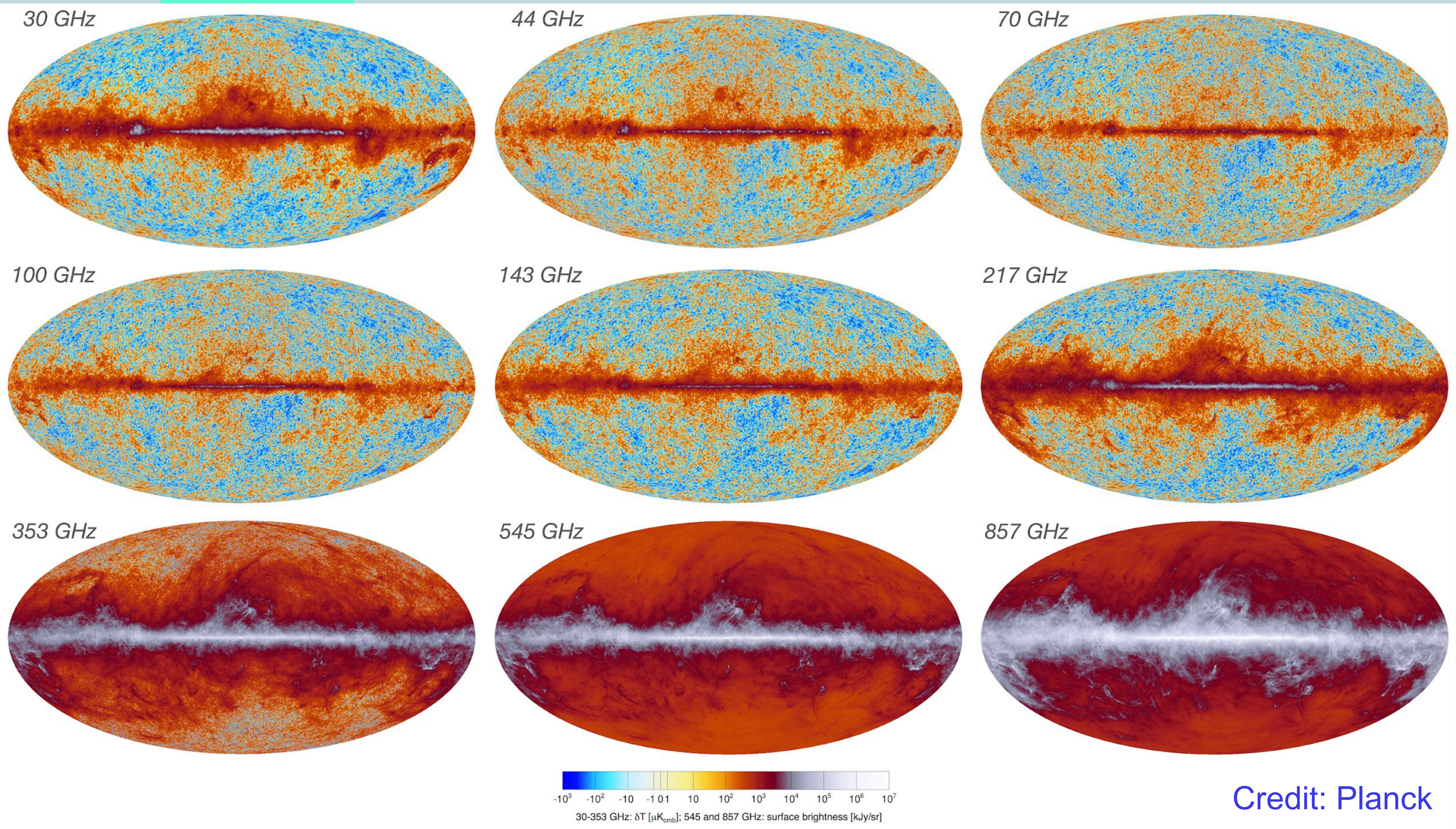
Cosmology

CMB $\frac{\Delta T}{T} \sim 10^{-4}$

LSS



Credit: SDSS



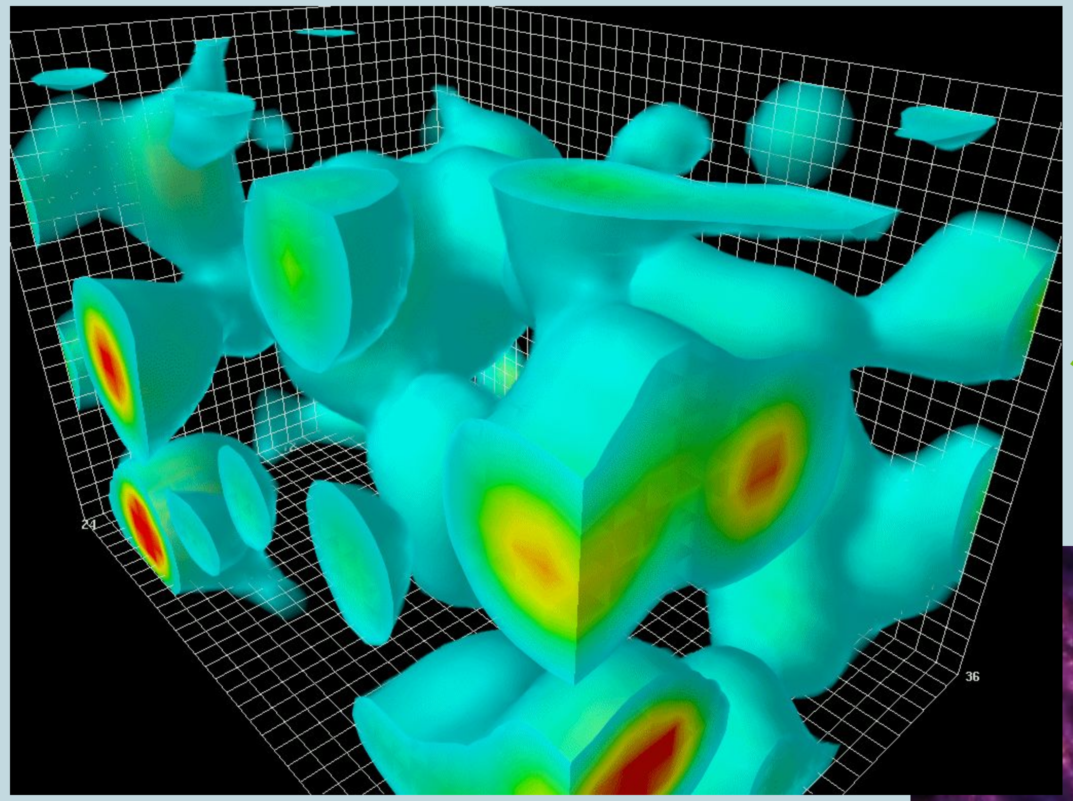
Credit: Planck

Statistical Isotropy and Homogeneity

What seeds such fluctuations?

Inflation

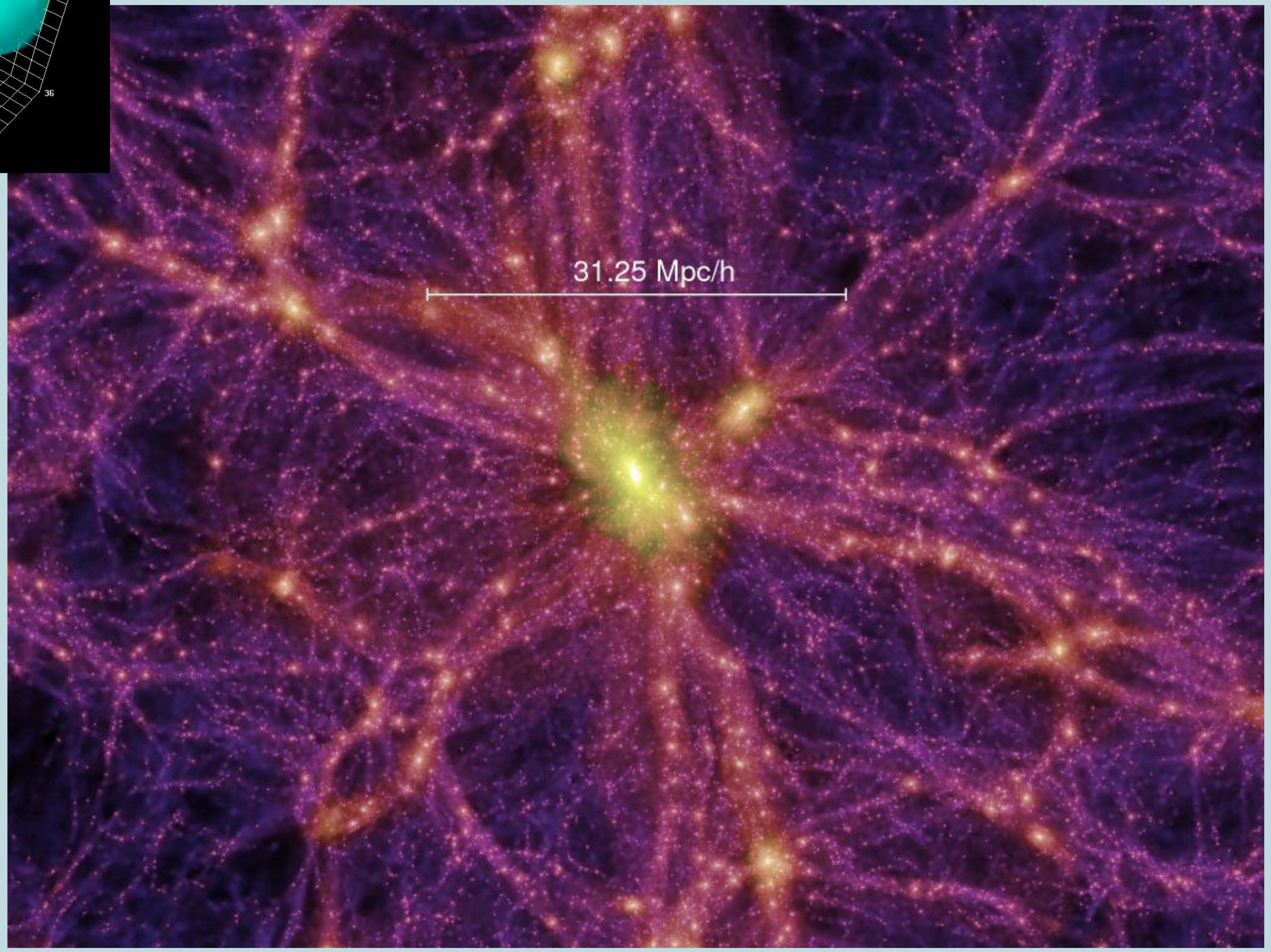
- Period of exponential expansion of the universe;
- As it stretches the universe all the universe is causally connected in the past light cone.
- During Inflation the seeds of density fluctuations are created - quantum fluctuations are stretched until they become (classic) density fluctuations;



Credit: Wikipedia

Inflation

Credit: Millenium Simulation



Variance of the fluctuations

$$\mathcal{P}(k) = \mathcal{A}_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

State of the art: Planck 2018 results X

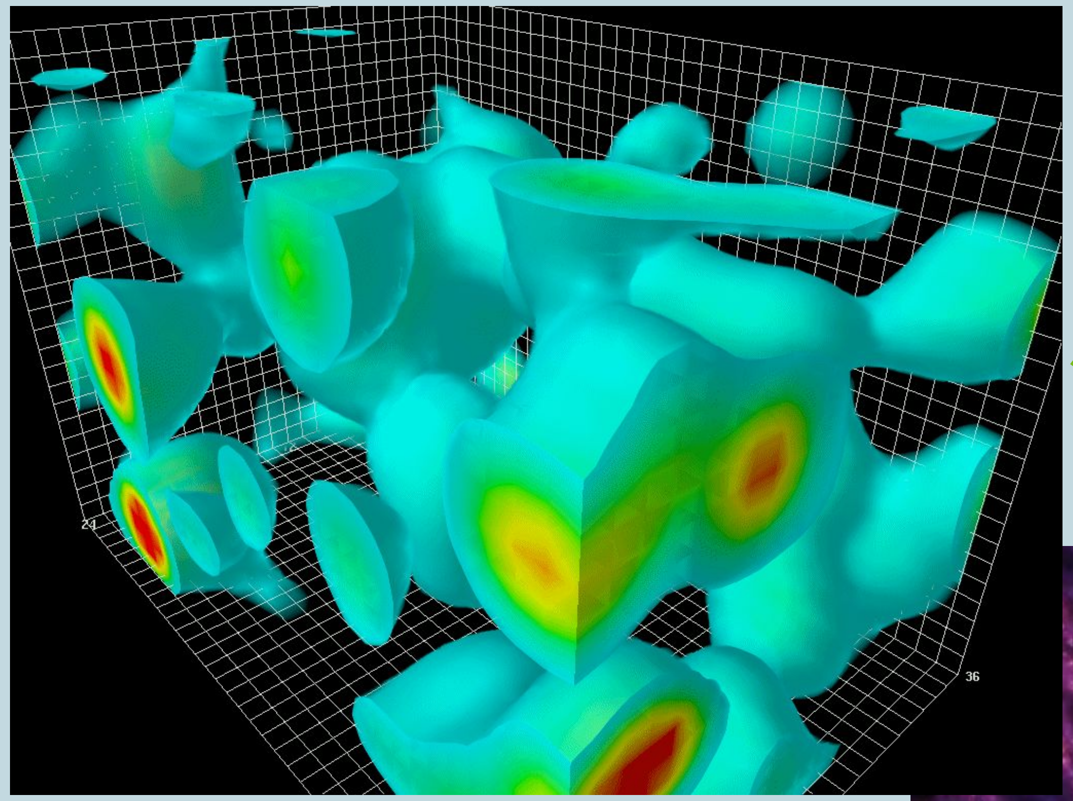
What seeds such fluctuations?

Inflation

- Any non-linearities will make the gravitational potential that seeds galaxies to be different from the one induced by energy fluctuations;

$$\Phi = \Phi_G + f_{\rm NL}(\Phi_G^2 - \langle \Phi_G \rangle^2)$$

- Primordial non-Gaussianities (PNG) are a further test to the physics of Inflation! E.g., a fNL<1 constraint reduces substantially the Inflationary model range.



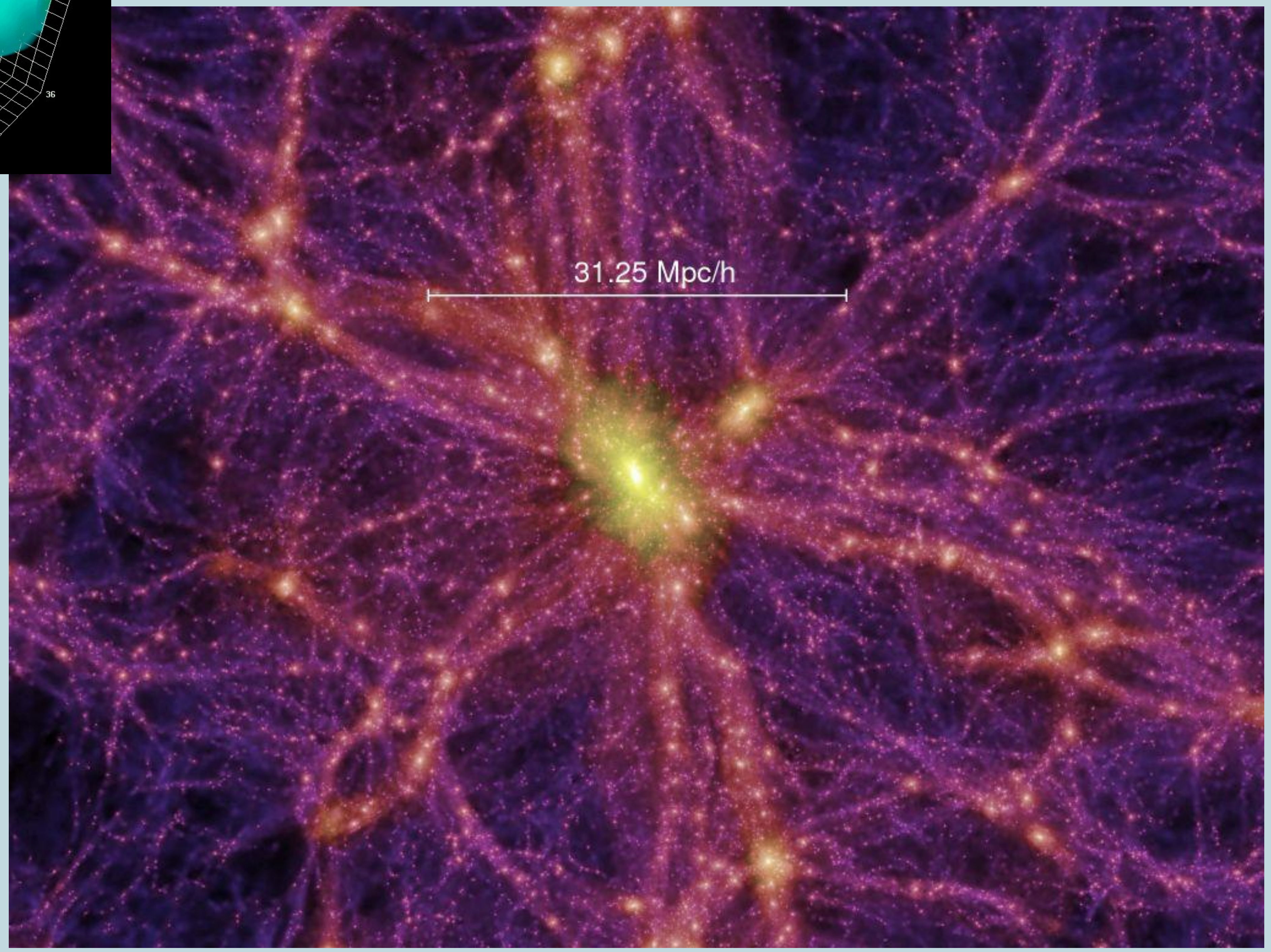
Credit: Wikipedia

$$\sigma(f_{\rm NL}) = 5.1$$

Planck 2018 results IX

Inflation

Credit: Millenium Simulation



What seeds such fluctuations?

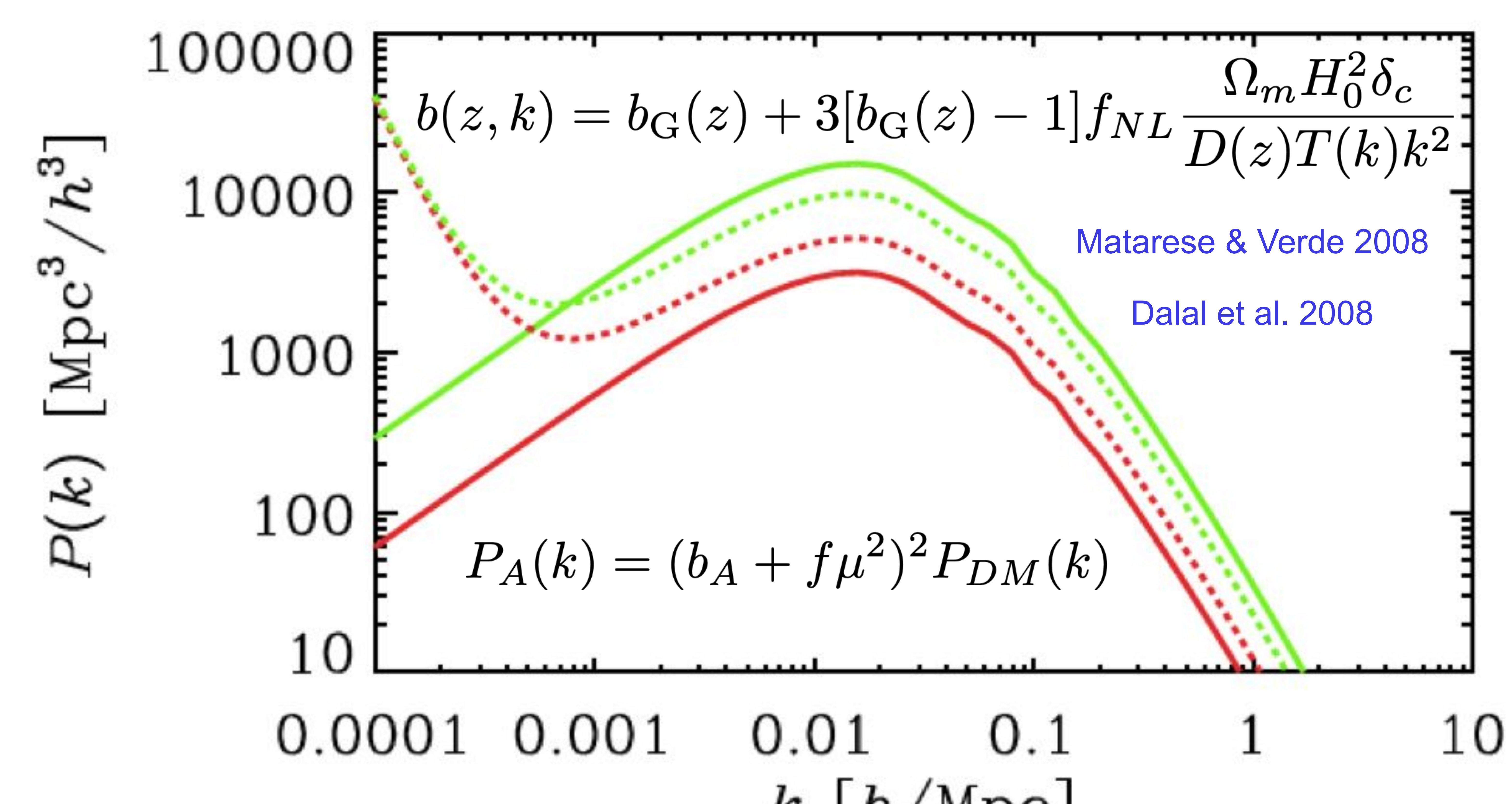
LSS and PNG

- PNG seed a scale dependent bias
- Forecasts:

$$\sigma_{SKA1,IM}(f_{\rm NL}) \simeq 3, \quad \sigma_{SKA2,Gal}(f_{\rm NL}) \simeq 1.6$$
$$\sigma_{Spectr,Euclid}(f_{\rm NL}) \simeq 6.6, \quad \sigma_{Photo,LSST}(f_{\rm NL}) \simeq 4.3$$

Camera et al 2013, Alonso et al 2015 (See also Giannantonio et al 2012)

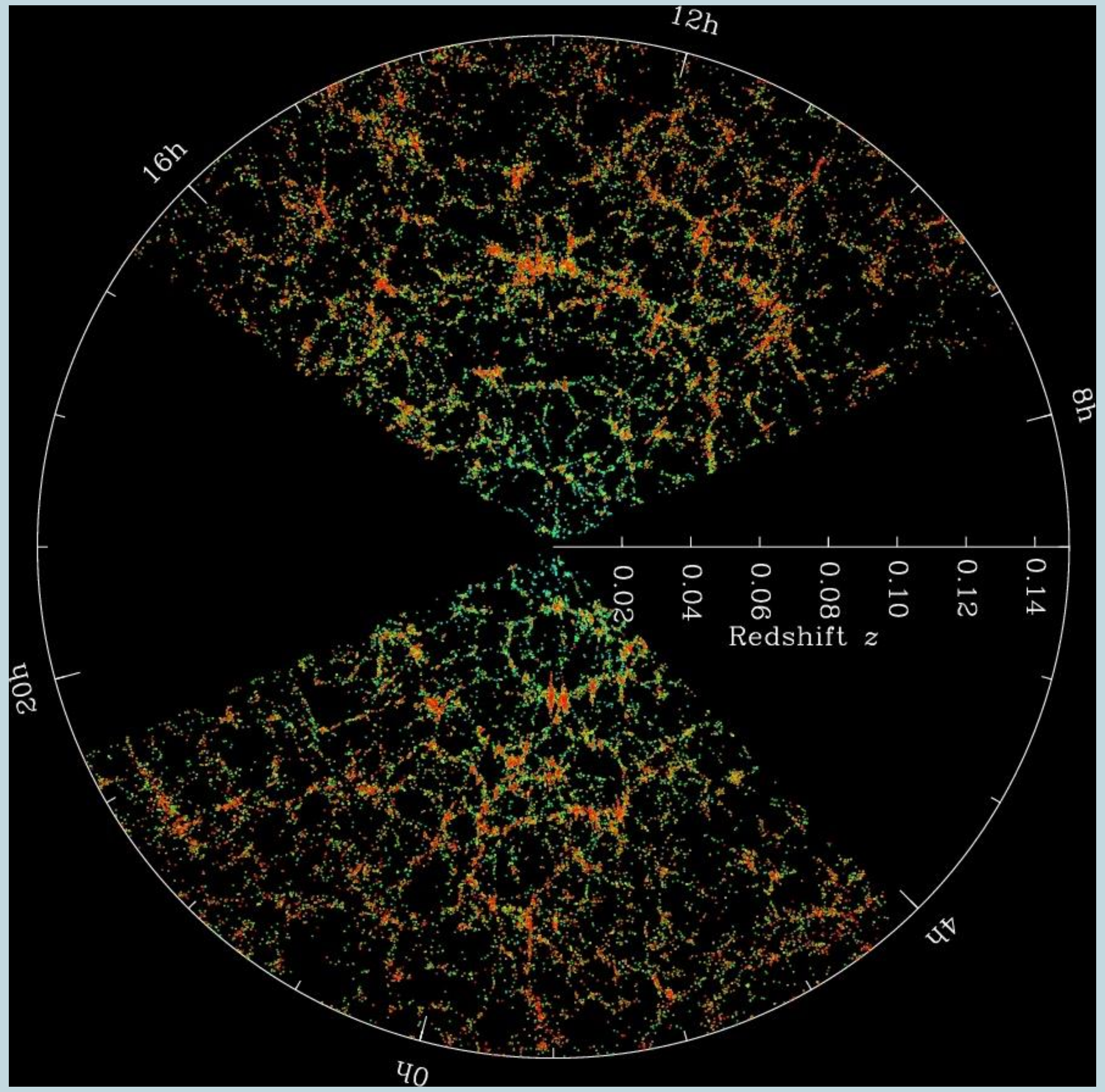
- Fundamentally they are Cosmic Variance limited!



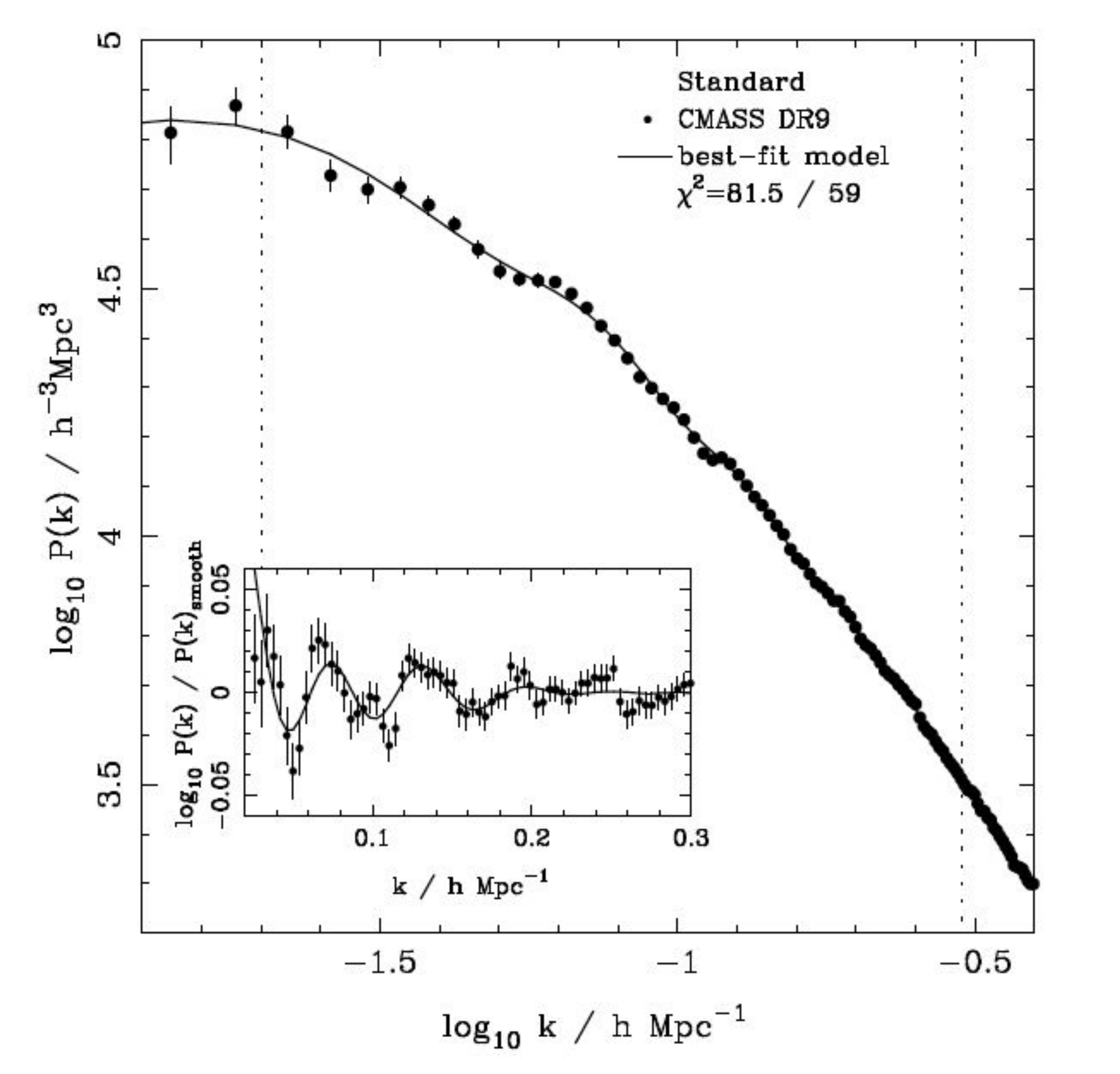
Credit: Camera et al. 2013

The observed density fluctuations?

$$\Delta(z_i, \boldsymbol{n}) = \frac{\mathbb{N}(z_i, \boldsymbol{n}) - \bar{\mathbb{N}}(z_i)}{\bar{\mathbb{N}}(z_i)}$$



Credit: SDSS

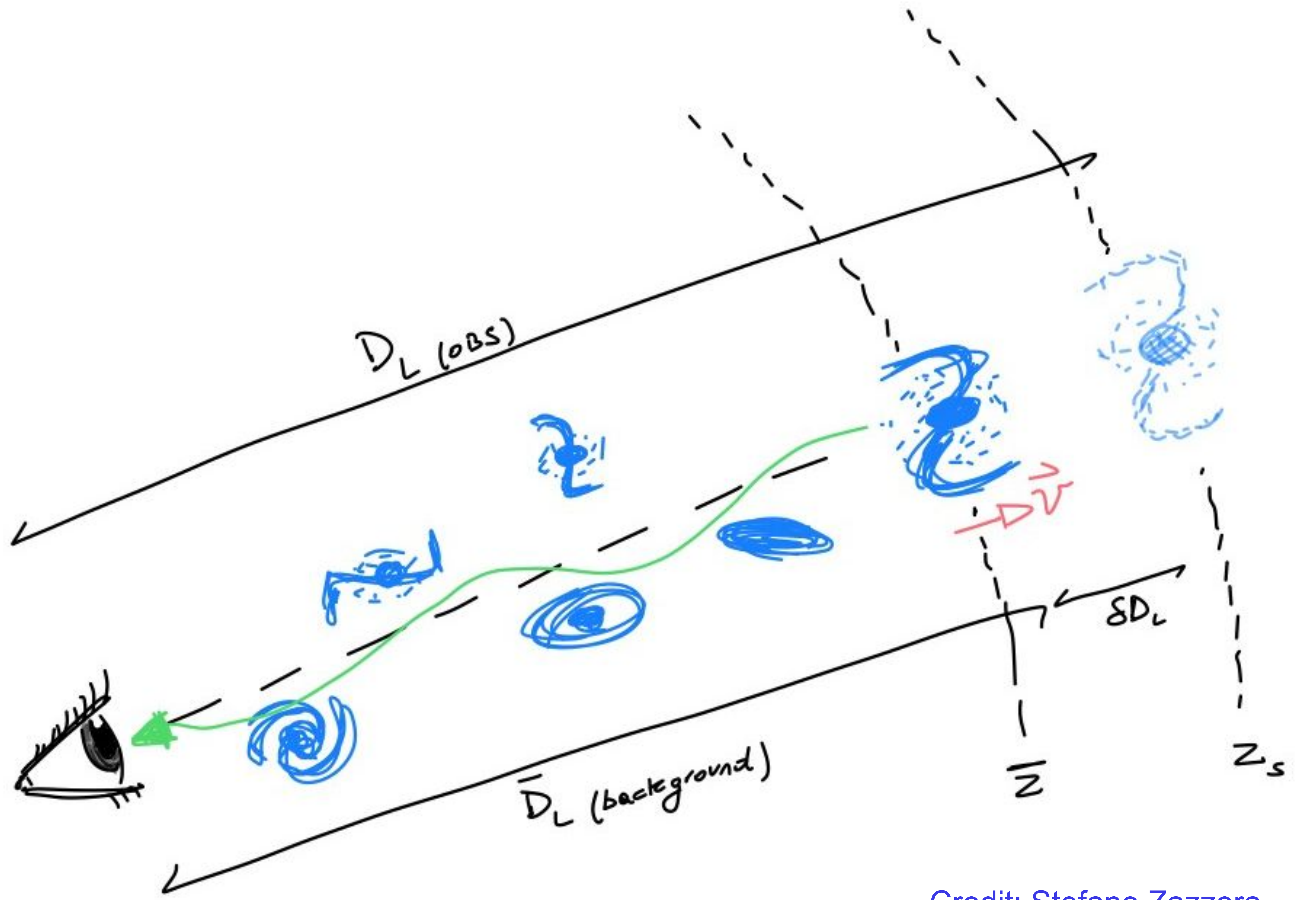


BOSS: Anderson et al. 2012

Which density contrast do we observe?

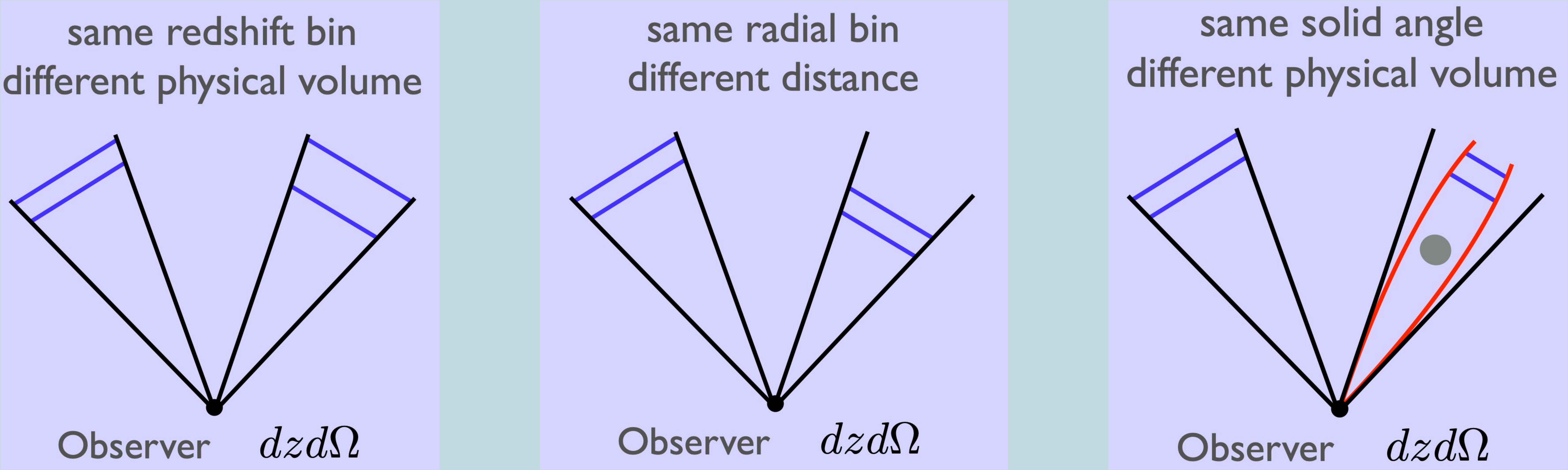
Density contrast

$$\Delta(z_i, \boldsymbol{n}) = \frac{\mathrm{N}(z_i, \boldsymbol{n}) - \bar{\mathrm{N}}(z_i)}{\bar{\mathrm{N}}(z_i)}$$



Credit: Stefano Zazzera

The observed density fluctuations?



Credit: Camille Bonvin

See Challinor & Lewis 2011, Bonvin & Durrer 2011 for full derivation

$$\Delta = \text{density} + \text{RSD} + \text{Doppler effect} + \text{Magnification Lensing} + \text{Potential terms}\,.$$

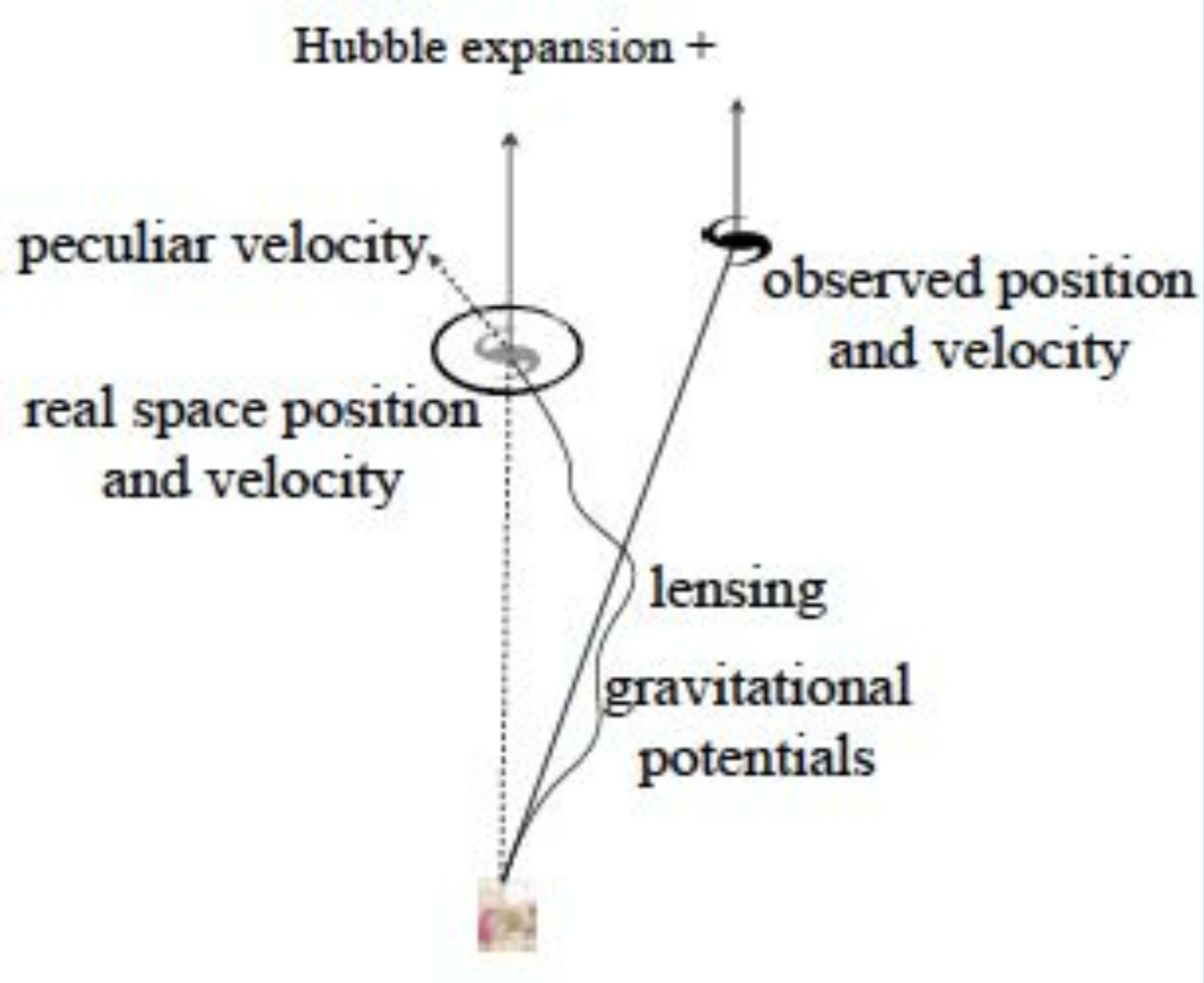
The observed density fluctuations?

GR effects

- Mimic local PNG (Bruni et al 2012, Jeong et al 2012, Camera et al 2013)

- "Detectability"

$$\frac{\sigma\left(f_{\rm GR}\right)}{f_{\rm GR}} \simeq \begin{cases} 2.8 & \text{SKA, IM ,} \\ 2.6 & \text{Spect, Euclid,} \\ 2.3 & \text{Photo, LSST.} \end{cases}$$

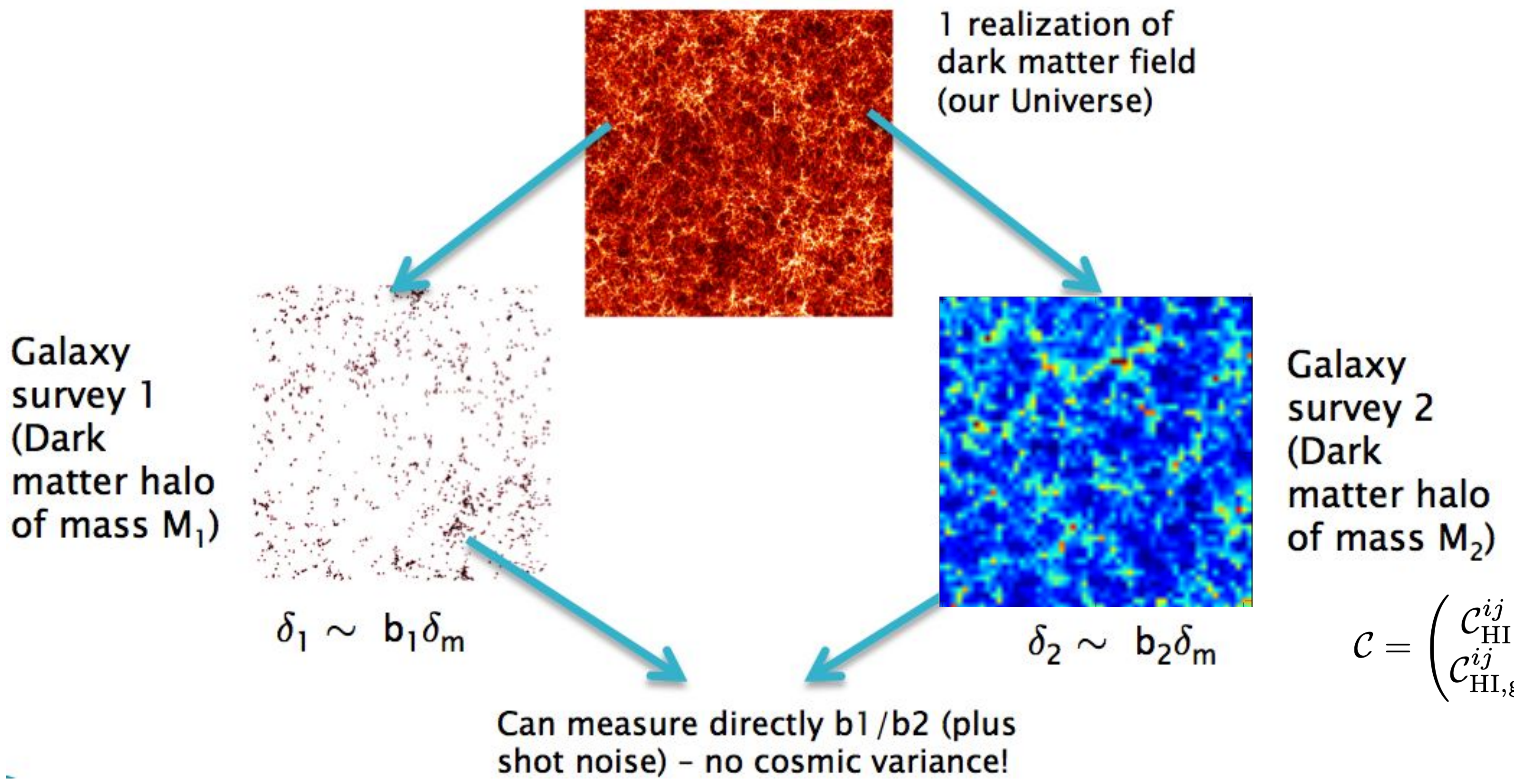


Why bother?

- fNL opens a new window to probe the primordial universe. Error below 1 starts probing the different types of inflationary models (de Putter el al 2017).
- “GR effects” are further probes of general relativity, namely the potential and the metric theory;
- Probes of effects on large scales beyond standard physics;
- Can we do better?

Yes with Multiple Tracers

The Multi-tracer technique



Seljak PRL 2009

$$\sigma_\vartheta(\delta_1/\delta_2) < \sigma_\vartheta(\delta_1,\delta_2)$$

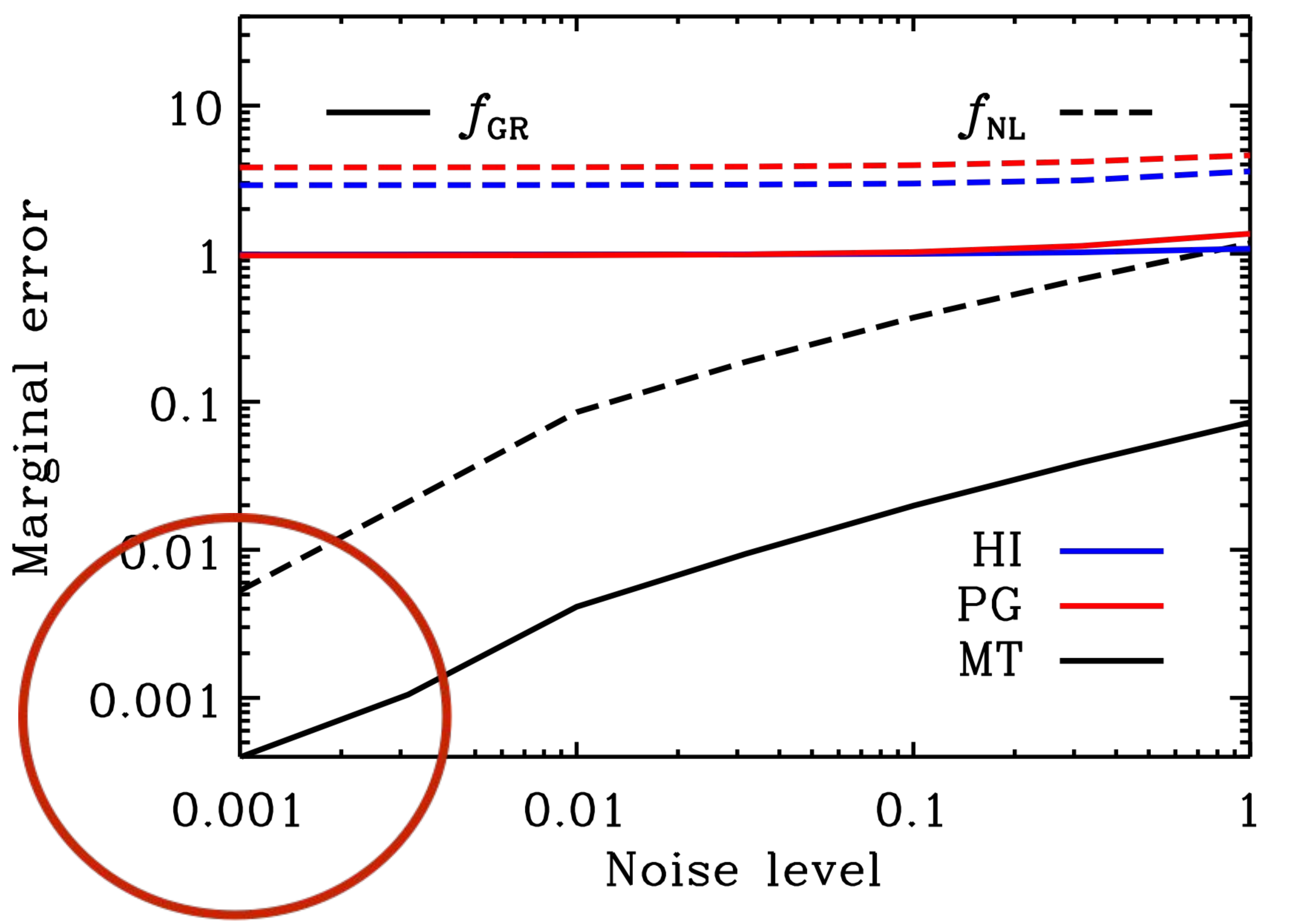
To properly use the MT technique one needs to compare the same tomographic map

$$\mathcal{C} = \begin{pmatrix} \mathcal{C}^{ij}_{\rm HI} & \mathcal{C}^{ij}_{\rm HI,g} \\ \mathcal{C}^{ij}_{\rm HI,g} & \mathcal{C}^{ij}_{g} \end{pmatrix} + \begin{pmatrix} \mathcal{N}^{ij}_{\rm HI} & \mathcal{N}^{ij}_{\rm HI,g} \\ \mathcal{N}^{ij}_{\rm HI,g} & \mathcal{N}^{ij}_{g} \end{pmatrix} + \begin{pmatrix} \mathcal{I}^{ij}_{\rm HI} & 0 \\ 0 & \mathcal{I}^{ij}_{g} \end{pmatrix} + \begin{pmatrix} \mathcal{F}^{ij}_{\rm HI} & 0 \\ 0 & \mathcal{F}^{ij}_{g} \end{pmatrix}$$

$$F_{\vartheta_i\vartheta_j} = \sum_{\ell_{\rm min}}^{\ell_{\rm max}} \frac{(2\ell+1)}{2} f_{\rm sky}\, {\rm Tr}\left[\left(\partial_{\vartheta_i} C_\ell\right)\Gamma_\ell^{-1}\left(\partial_{\vartheta_j} C_\ell\right)\Gamma_\ell^{-1}\right] .$$

The Multi-tracer technique

The estimator does not have Cosmic Variance



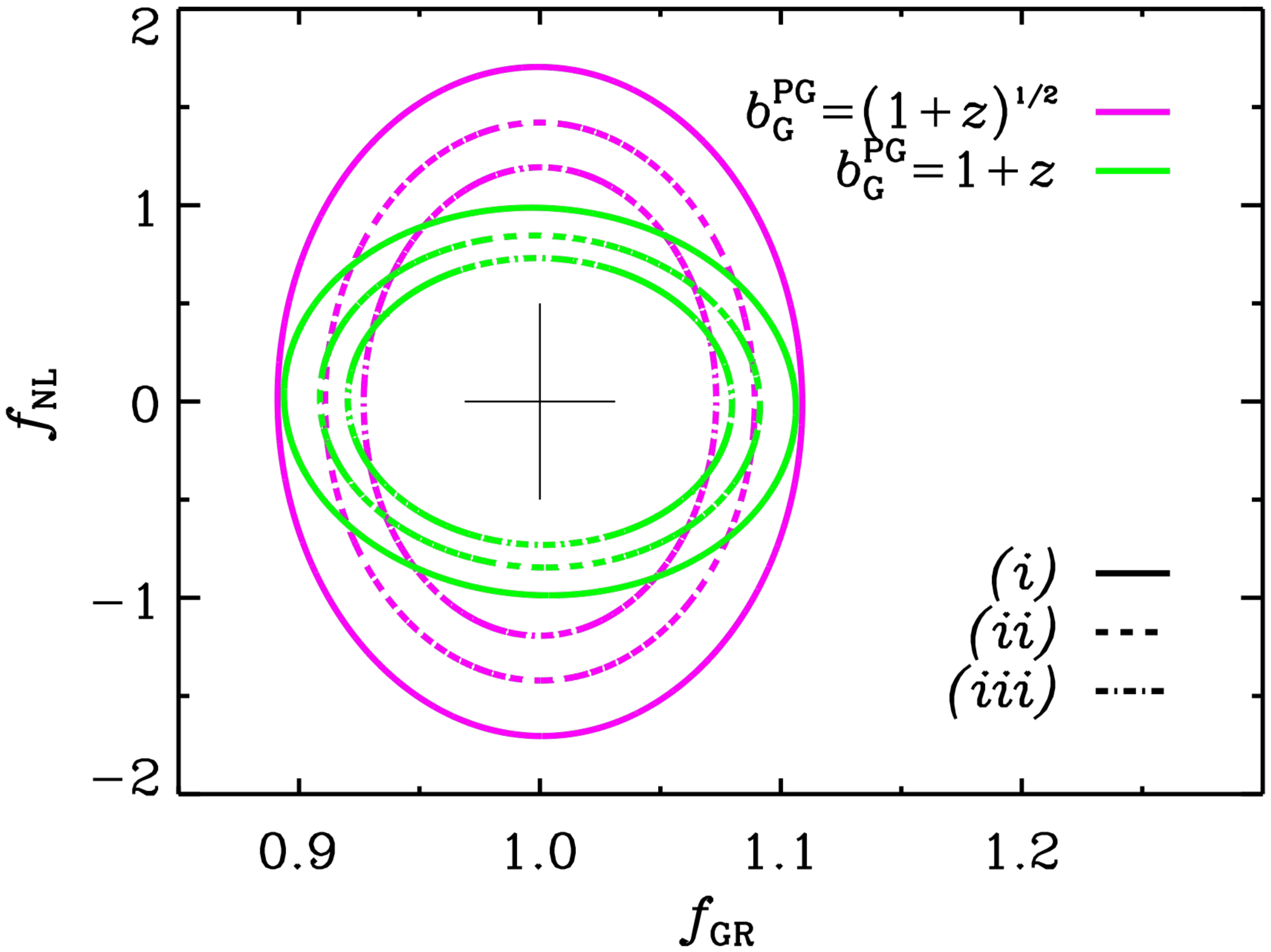
$$\frac{\delta_1}{\delta_2} = \frac{b_1 + \dots}{b_2 + \dots}$$

$$b(z,k) = b_{\rm G}(z) + 3[b_{\rm G}(z) - 1] f_{NL} \frac{\Omega_m H_0^2 \delta_c}{D(z)T(k)k^2}$$

JF, Stefano Camera, Mário G. Santos & Roy Maartens ApJL 2015

Constraints on Ultra Large Scale Effects

Photometric Galaxies x HI IM



Euclid-like
LSST-like

Marginal errors from the MT analysis for the three photo-z scenarios with Gaussian bias $\sqrt{1+z}$ (or $1+z$) and $\ell_{max} = 300$.

	$\sigma(f_{GR})$		$\sigma(f_{NL})$	
(i)	0.071	(0.070)	1.12	(0.65)
(ii)	0.059	(0.060)	0.94	(0.56)
(iii)	0.048	(0.053)	0.79	(0.48)

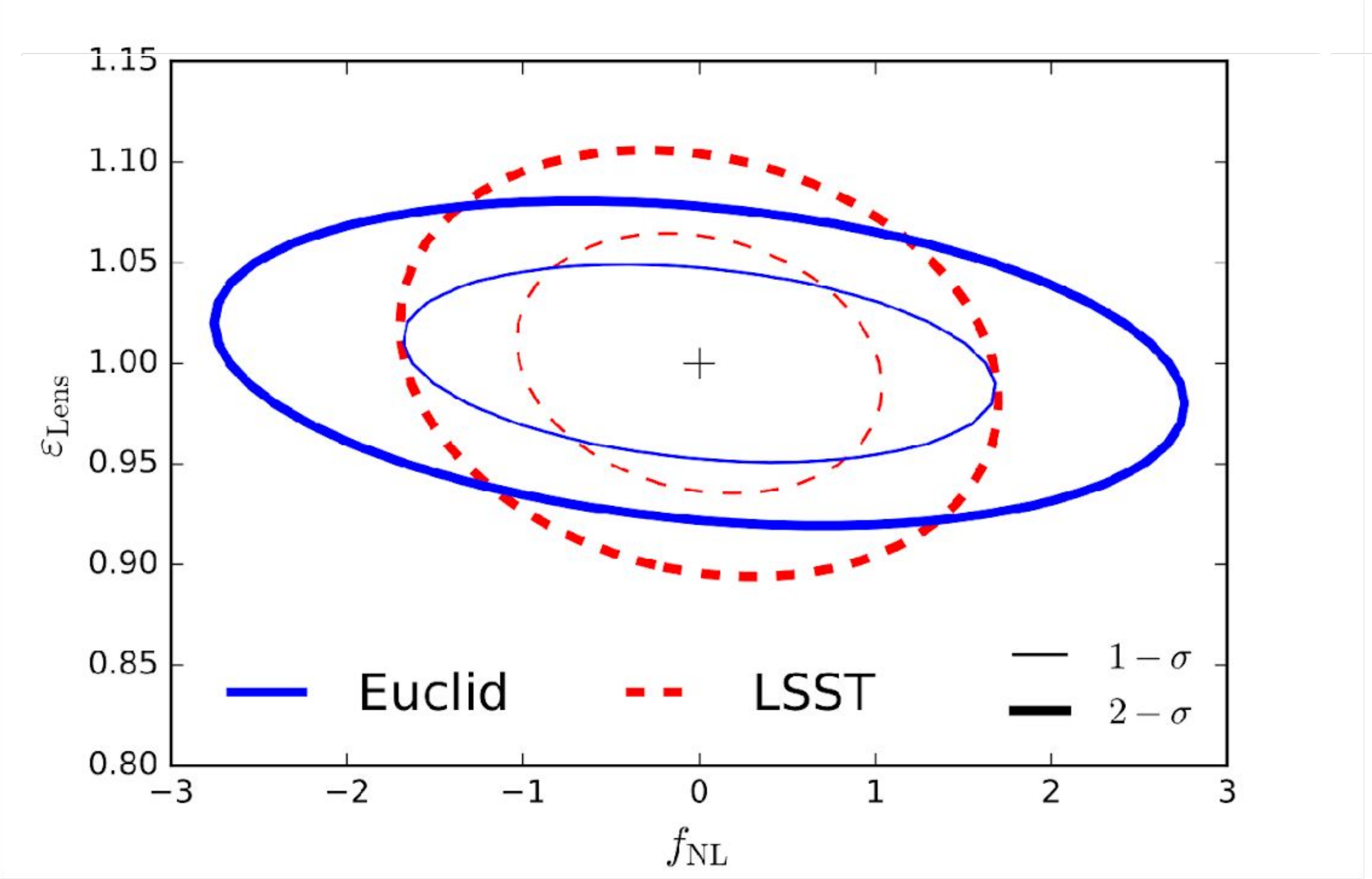
JF, Stefano Camera, Mário G. Santos & Roy Maartens ApJL 2015

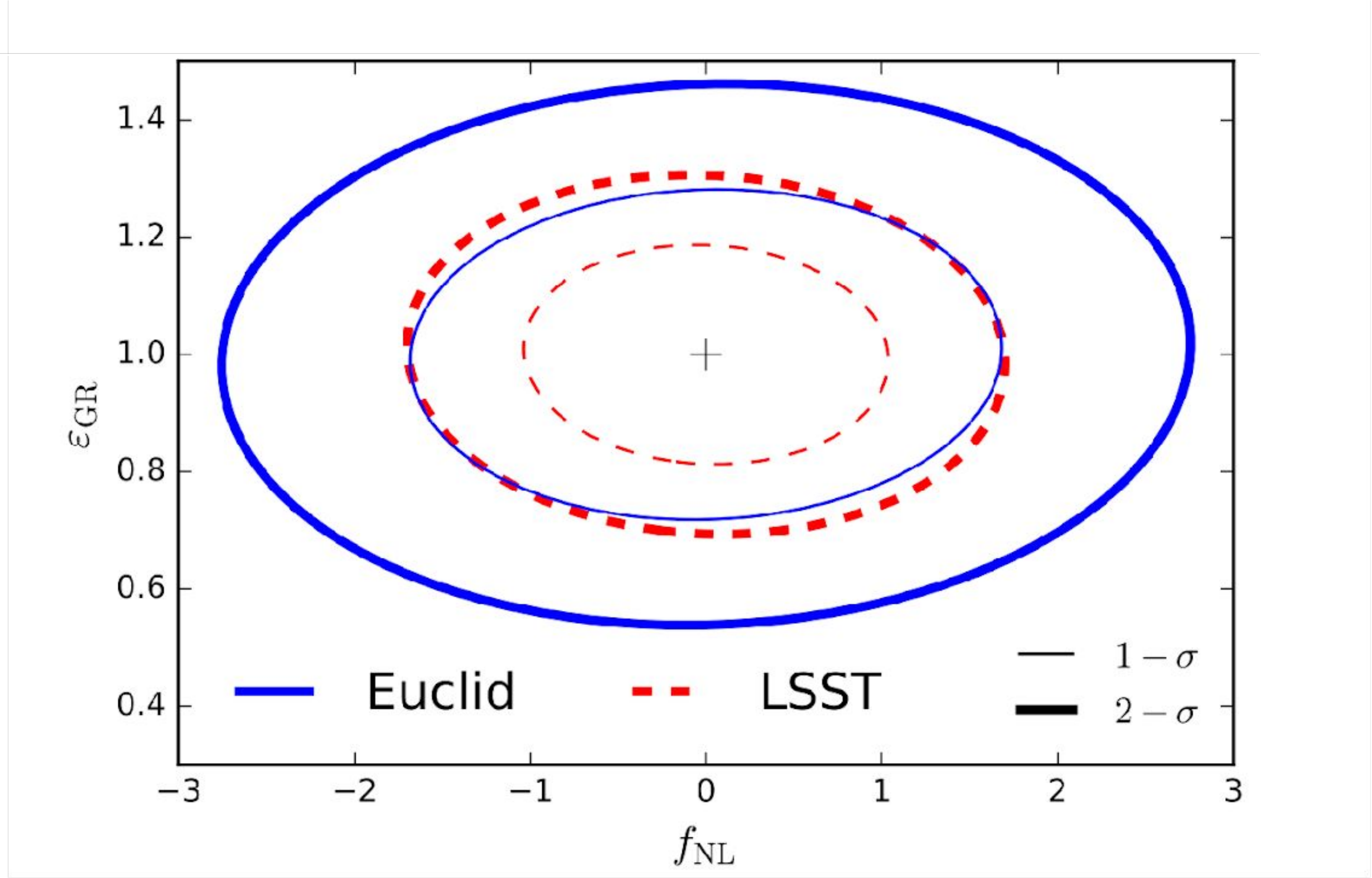
Constraints on Ultra Large Scale Effects

Photometric Galaxies x HI IM

Updates for the SKA red book
Bacon et al 2020

Synergy	$\sigma(f_{\rm NL})$	$\sigma(\varepsilon_{\rm Lens})$	$\sigma(\varepsilon_{\rm GR})$	$\sigma(\varepsilon_{\rm Doppler})$	$\sigma(\varepsilon_{\rm TD})$	$\sigma(\varepsilon_{\rm SW})$	$\sigma(\varepsilon_{\rm ISW})$
SKA1 HI IM × Euclid	1.1	-	-	-	-	-	-
	1.1	0.033	0.19	-	-	-	-
	1.3	0.033	-	0.19	5.3	5.5	16
SKA1 HI IM × LSST	0.67	-	-	-	-	-	-
	0.68	0.043	0.12	-	-	-	-
	0.96	0.043	-	0.13	5.7	4.0	7.5

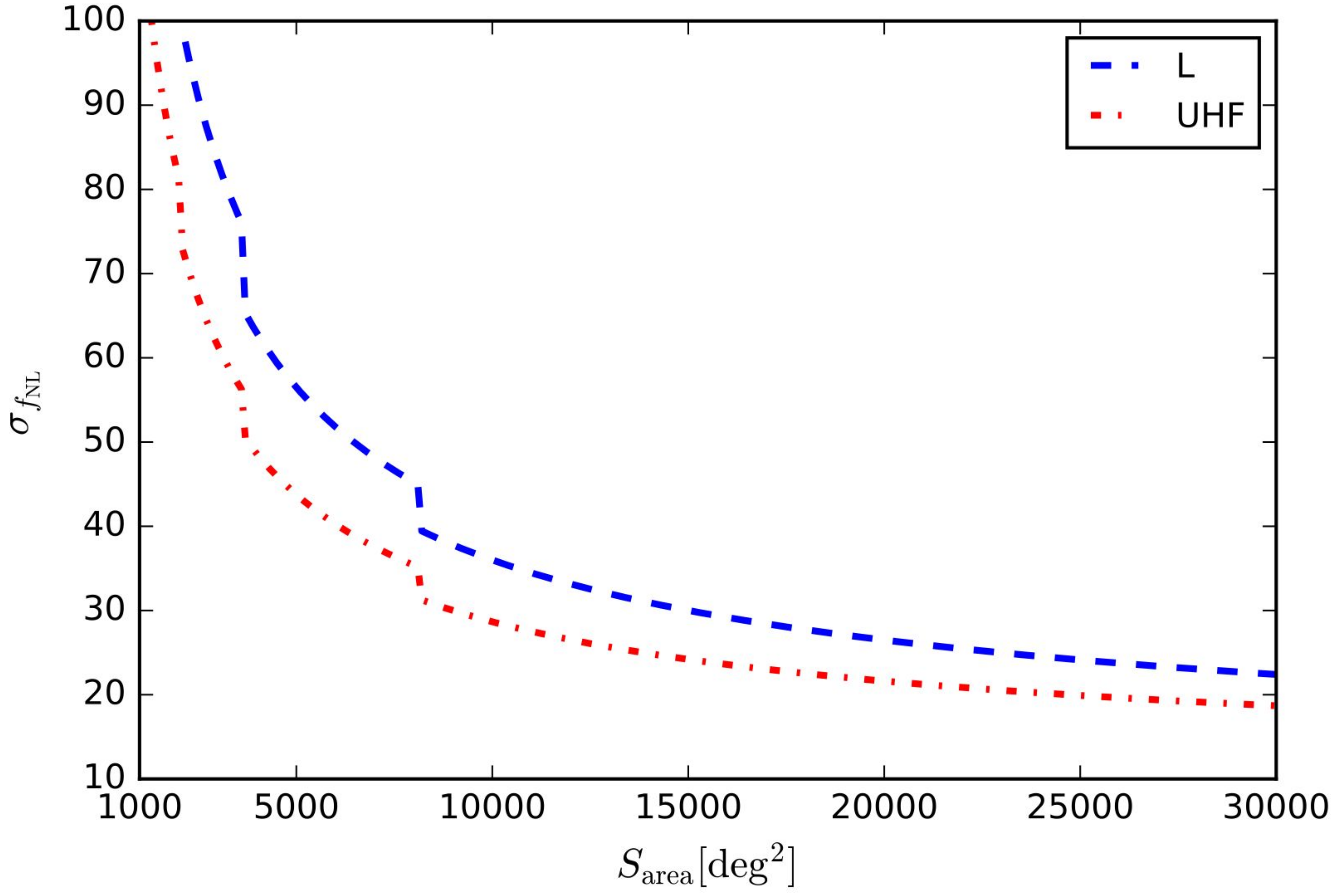


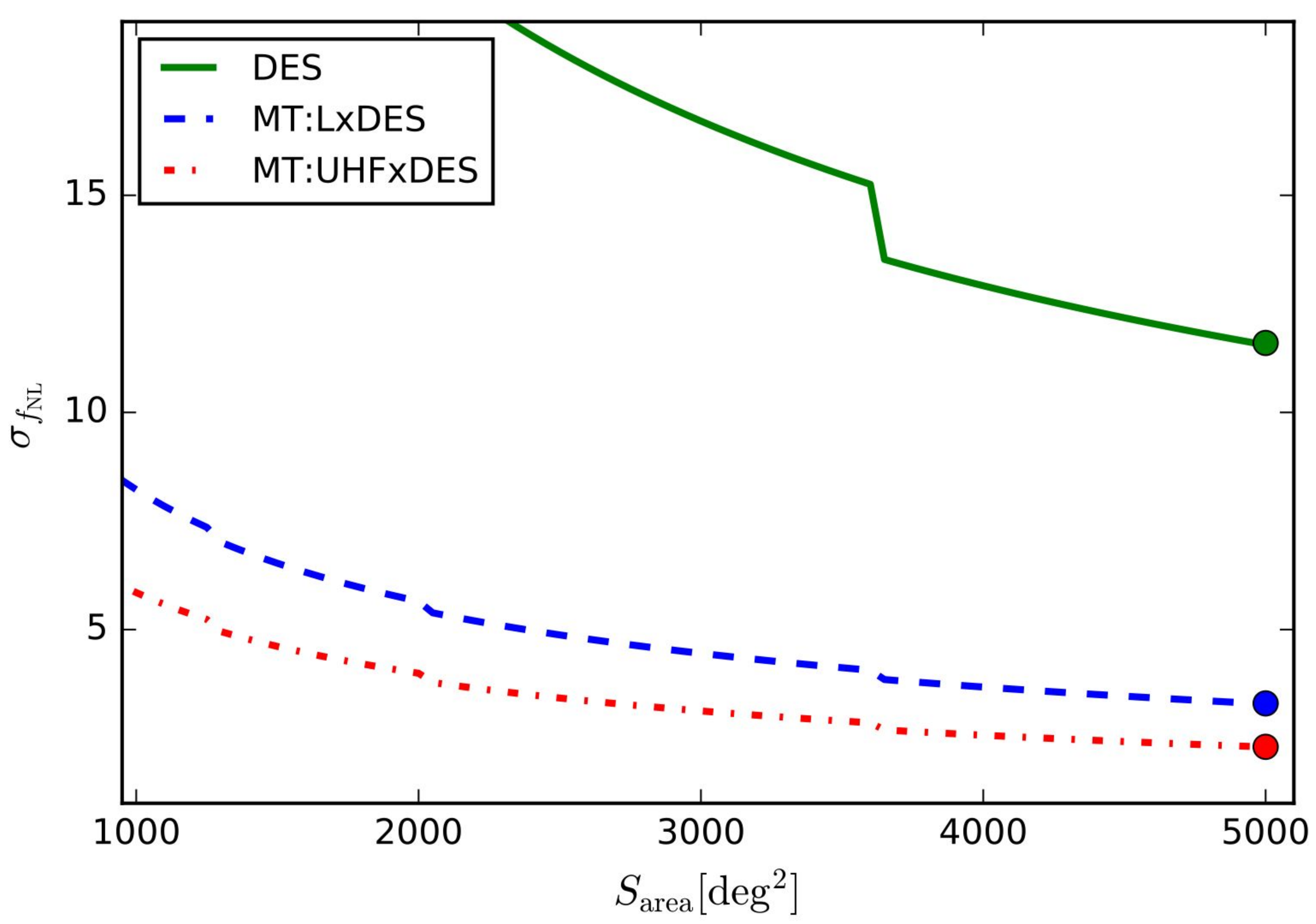


Constraints on Ultra Large Scale Effects

But those will only happen in a decade, what about the data we will have soon?

combining MeerKLASS with the overlapping publicly available DES data (5,000 deg2), Euclid Photoz (1+5K deg2) or the up-coming LSST/VRO (10,000 deg2) will achieve σ(fNL) ≈ 5.9, 5.4 and 2.8, for l>20 only.





JF, Mário G. Santos & Roy Maartens, MNRAS 2017

Constraints on Ultra Large Scale Effects

Spectroscopic (Euclid or DESI) x HI IM (SKAO)

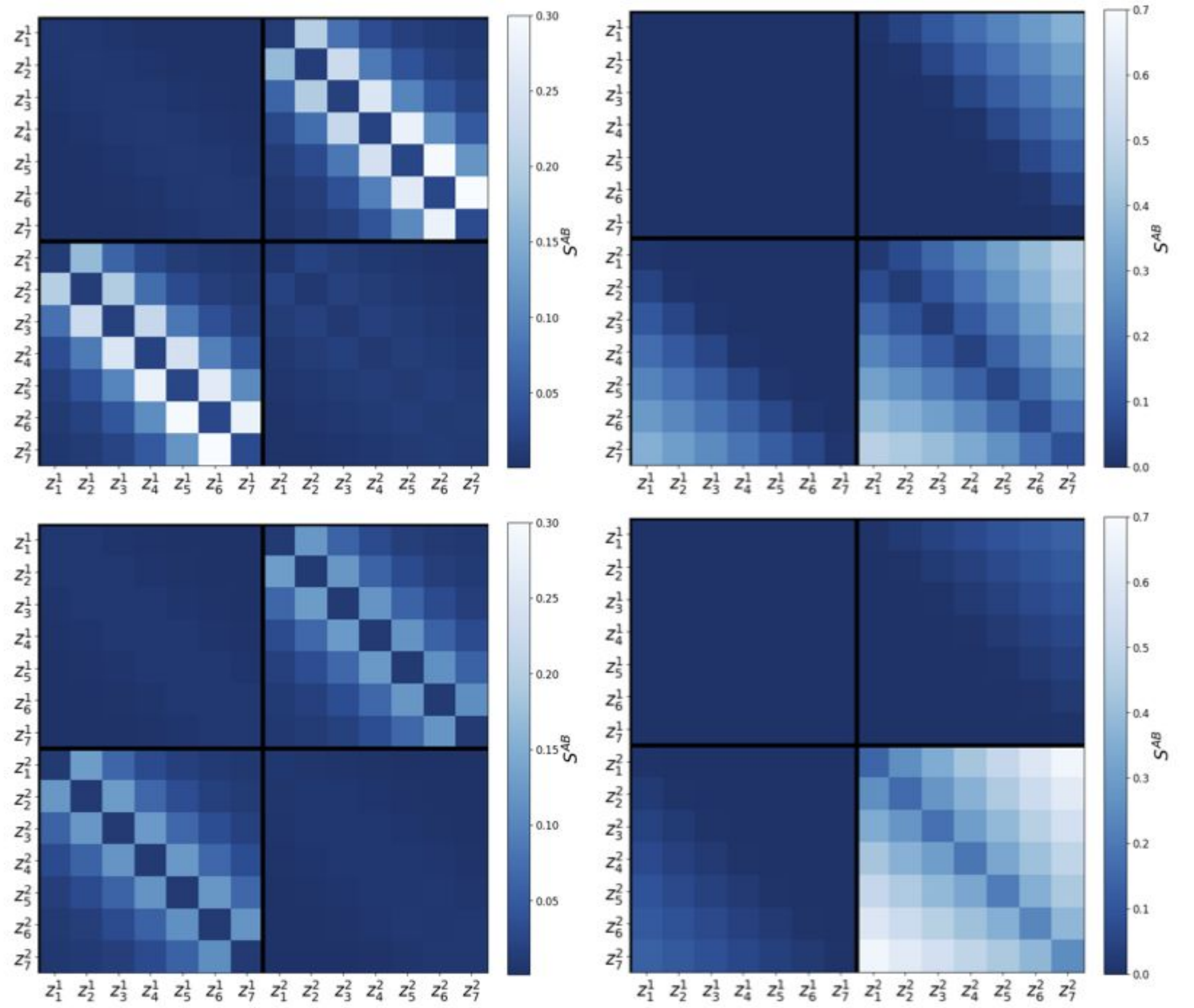
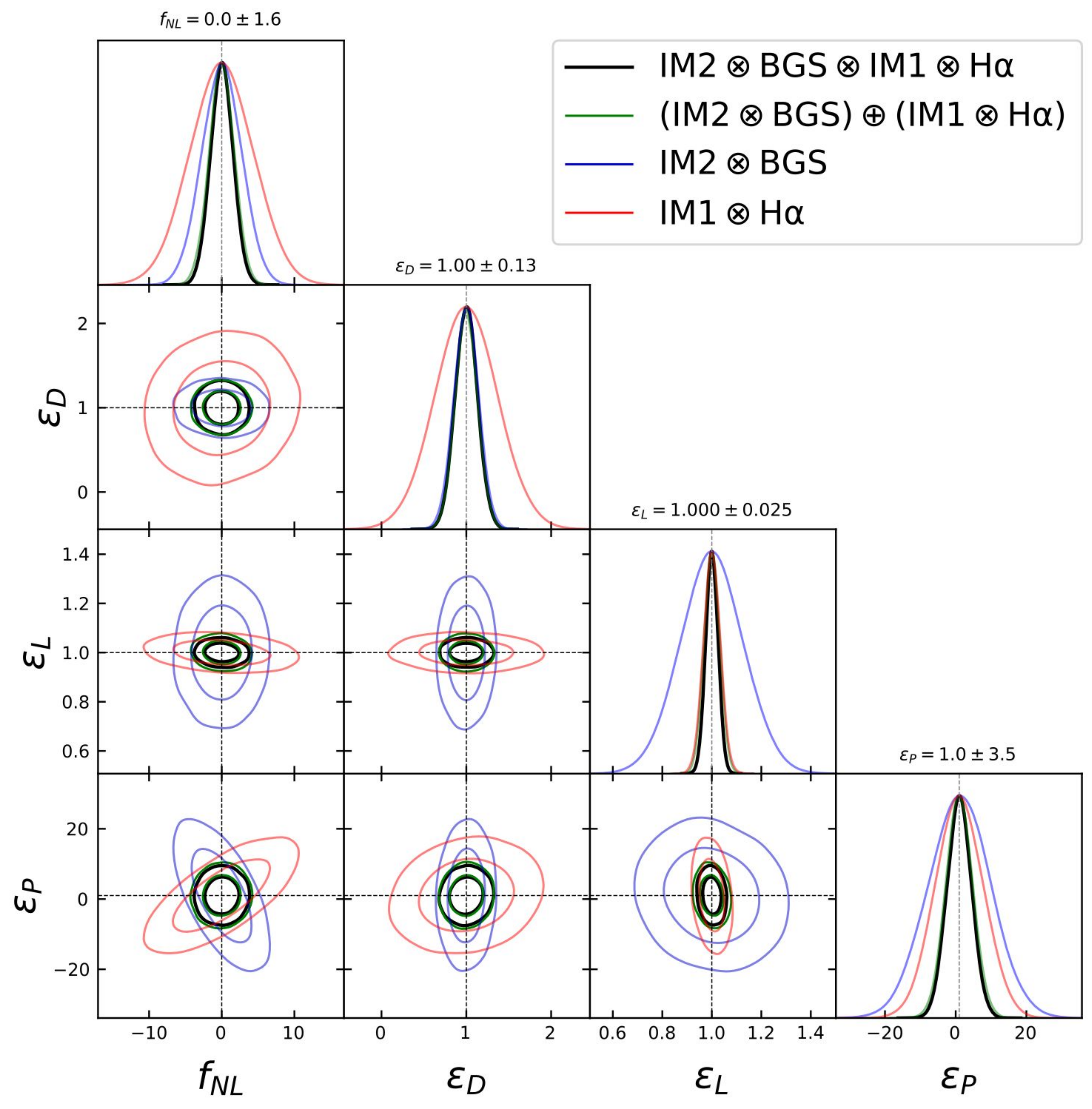


Figure 5. Signal-to-noise $S^{AB}(\theta, z_i^A, z_j^B)$ for the Doppler contribution ($\theta = \varepsilon_D$) (*left*) and the lensing magnification contribution ($\theta = \varepsilon_L$) (*right*). *Top panels:* $1 \otimes 2 = \mathrm{IM2} \otimes \mathrm{BGS}$ for $0.35 < z < 0.56$. *Bottom panels:* $1 \otimes 2 = \mathrm{IM1} \otimes \mathrm{H\alpha}$ for $0.90 < z < 1.15$. Colour bar shows the signal-to-noise.



Jan-Albert Viljoen, JF, Roy Maartens, JCAP 2021

Doing HI IM in practice

- Mask, remove RFI,…
- Unpolarised Point Source to calibrate the noise diodes;
- Use the model to calibrate the HH and VV at each time stamp and frequency;
- Use a model for the galaxy and any other component;
- Me:
  - forecasts;
  - Brandon Engelbert looking at ways to model GNSS satellites;

Wang et al, Hi intensity mapping with MeerKAT: Calibration pipeline for multi-dish autocorrelation observations, MNRAS 2021

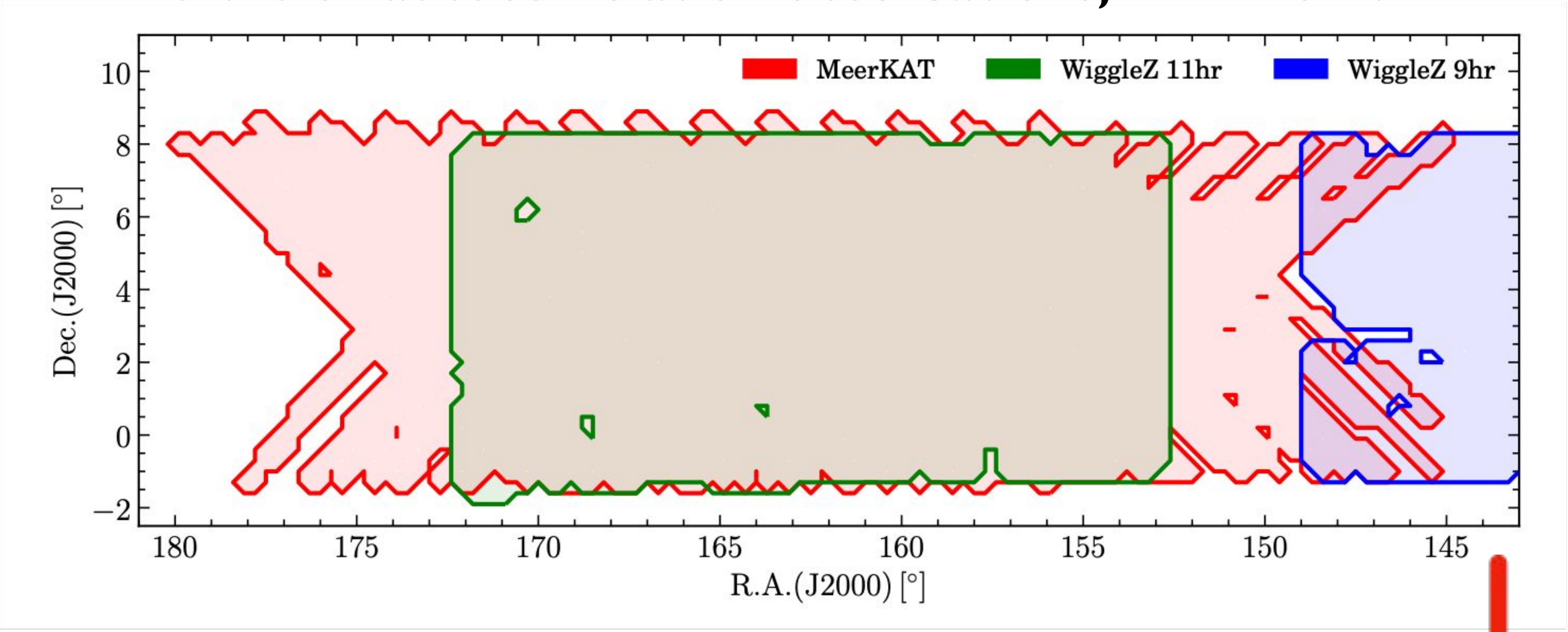


Figure 1. The footprint of the MeerKAT survey field and the WiggleZ survey fields.

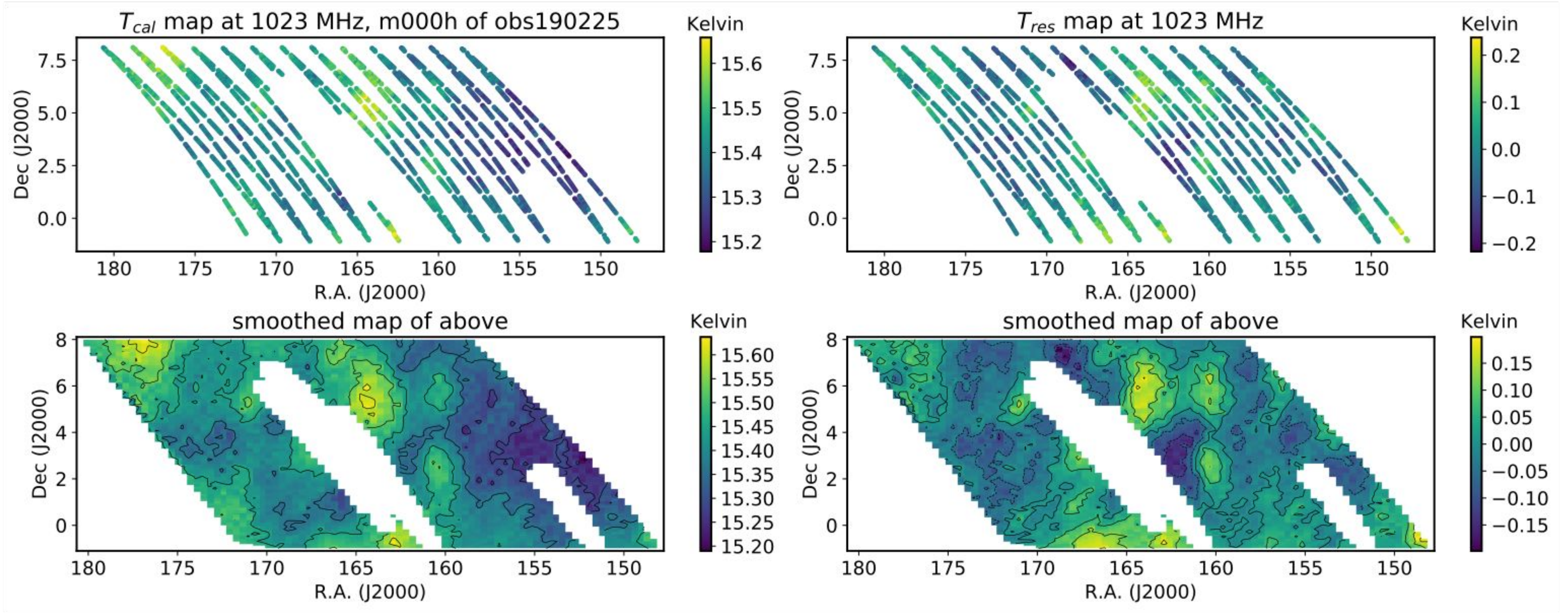


Figure 12. The calibrated data (upper panel) and interpolation maps (lower panel) for the total temperature (left) and residual (right), for a single frequency channel at 1023 MHz, receiver m000h, and observation obs190225.

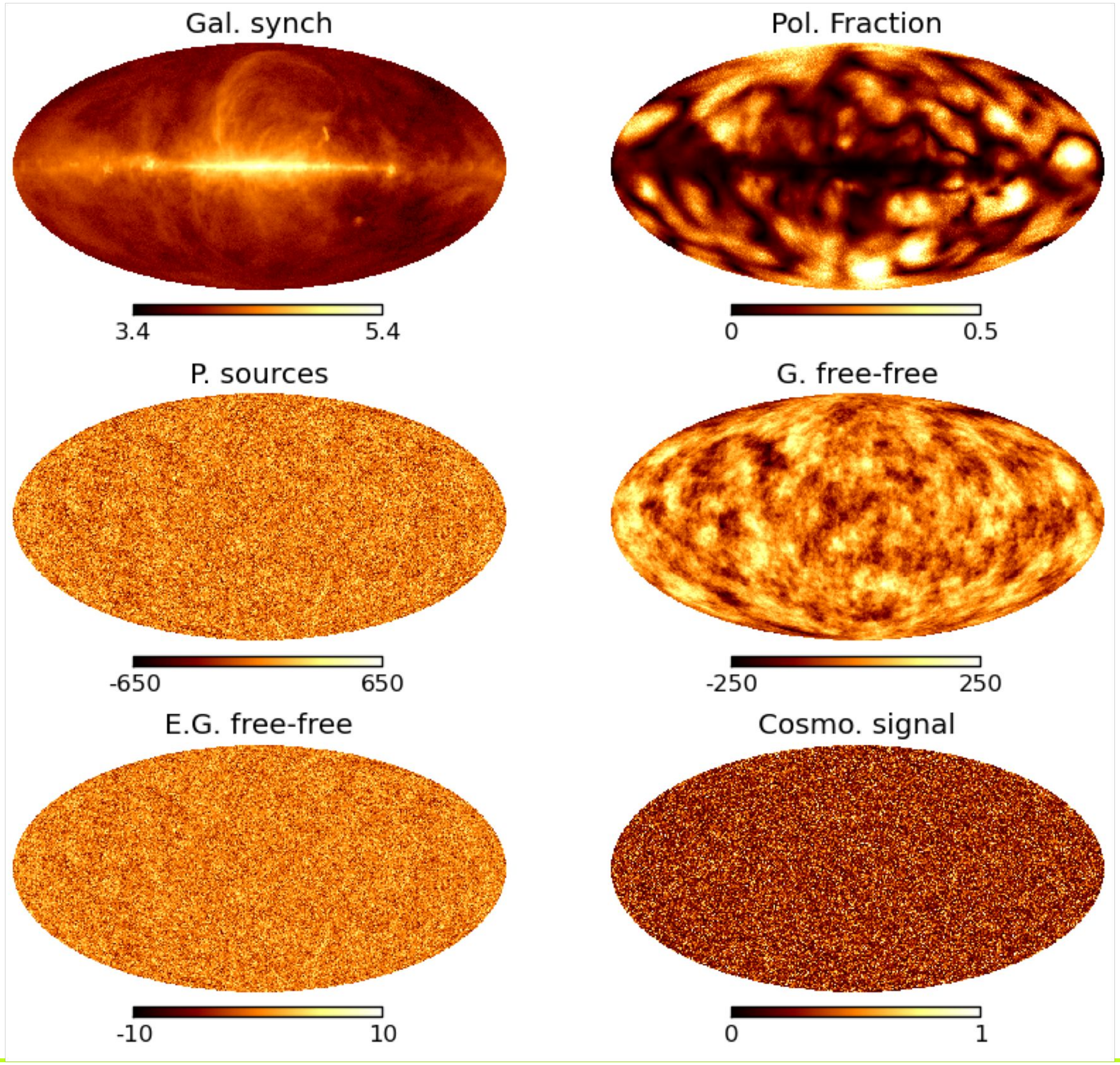
Doing HI IM in practice

We have foregrounds!

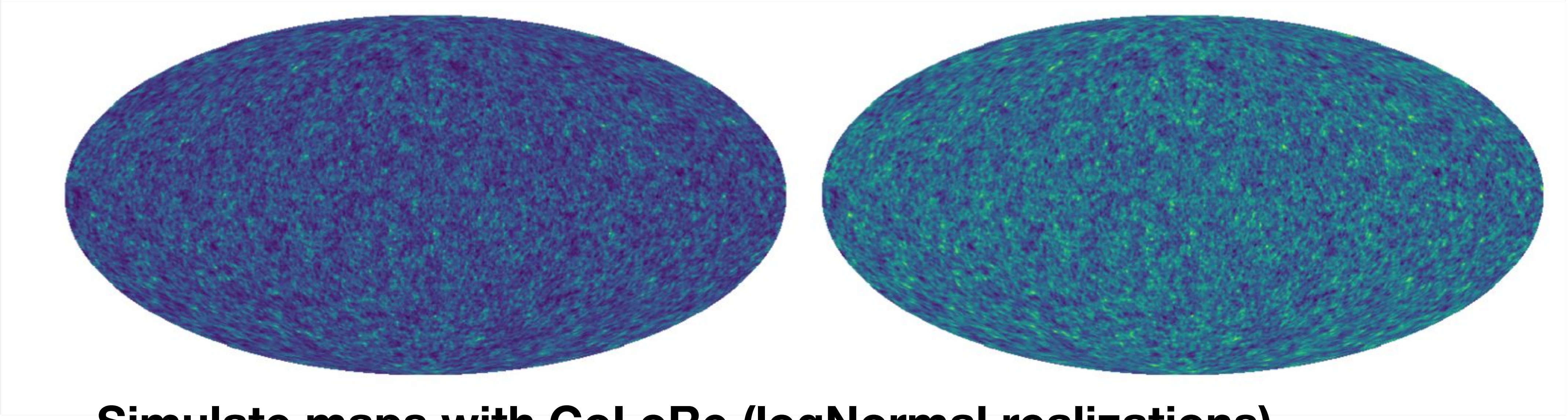
- Several orders of magnitude higher than the HI signal;
- … they are smooth in frequency;
- How to deal with them:

  - *Foreground Avoidance*: find some k range where foregrounds do not affect the power spectrum (see e.g. Shaw et al 2015). For k||<0.01/Mpc we can't use this approach.

  - *Foreground Cleaning*: ICA, PCA, GMCA, … Blind method that works well but dumps power on large scales - a simulations calibrated transfer function is required to reconstruct the large scales (see e.g. Witzemann et al 2019, Cunnington et al. arxiv:2007.12126) clean all bias the estimate of fNL;



Doing HI IM in practice



Simulate maps with CoLoRe (logNormal realizations)

- Define estimators

$$\epsilon_{\mathrm{A},\ell} \equiv \sqrt{\frac{\hat{C}_\ell^{\mathrm{HH}} - N_\ell^{\mathrm{HH}}}{(T_\ell B_\ell)^2 \left(\hat{C}_\ell^{gg} - N_\ell^{gg}\right)}},$$

- Include beam

$$\epsilon_{\mathrm{X},\ell} \equiv \frac{\hat{C}_\ell^{\mathrm{H}g}}{T_\ell B_\ell \left[\hat{C}_\ell^{gg} - N_\ell^{gg}\right]}, \qquad \epsilon_{\mathrm{opt}} = \frac{\sum_{i,j} \mathsf{C}_{ij}^{-1} \epsilon_j}{\sum_{ij} \mathsf{C}_{ij}^{-1}},$$

- do foreground removal using PCA (7 components)
- Correct for transfer function of the fg_rm

$$T_\ell = \frac{\langle C_\ell^{\tilde{\mathrm{H}}\mathrm{H}} \rangle - N_\ell^{\tilde{\mathrm{H}}\mathrm{H}}}{\langle C_\ell^{\mathrm{HH}} \rangle - N_\ell^{\mathrm{HH}}}$$

Mask

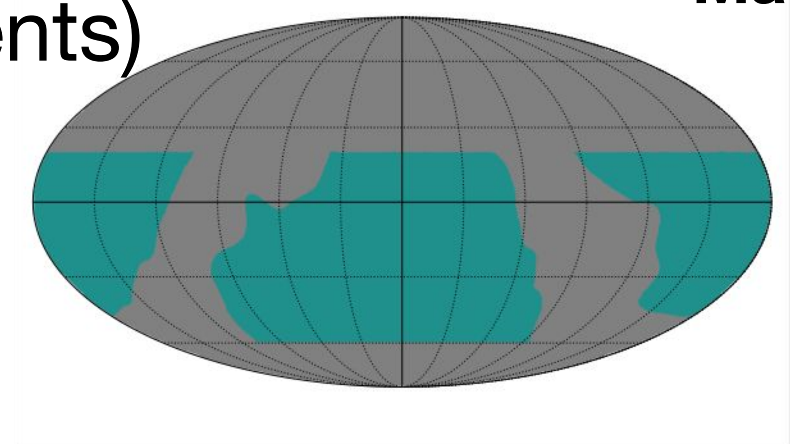
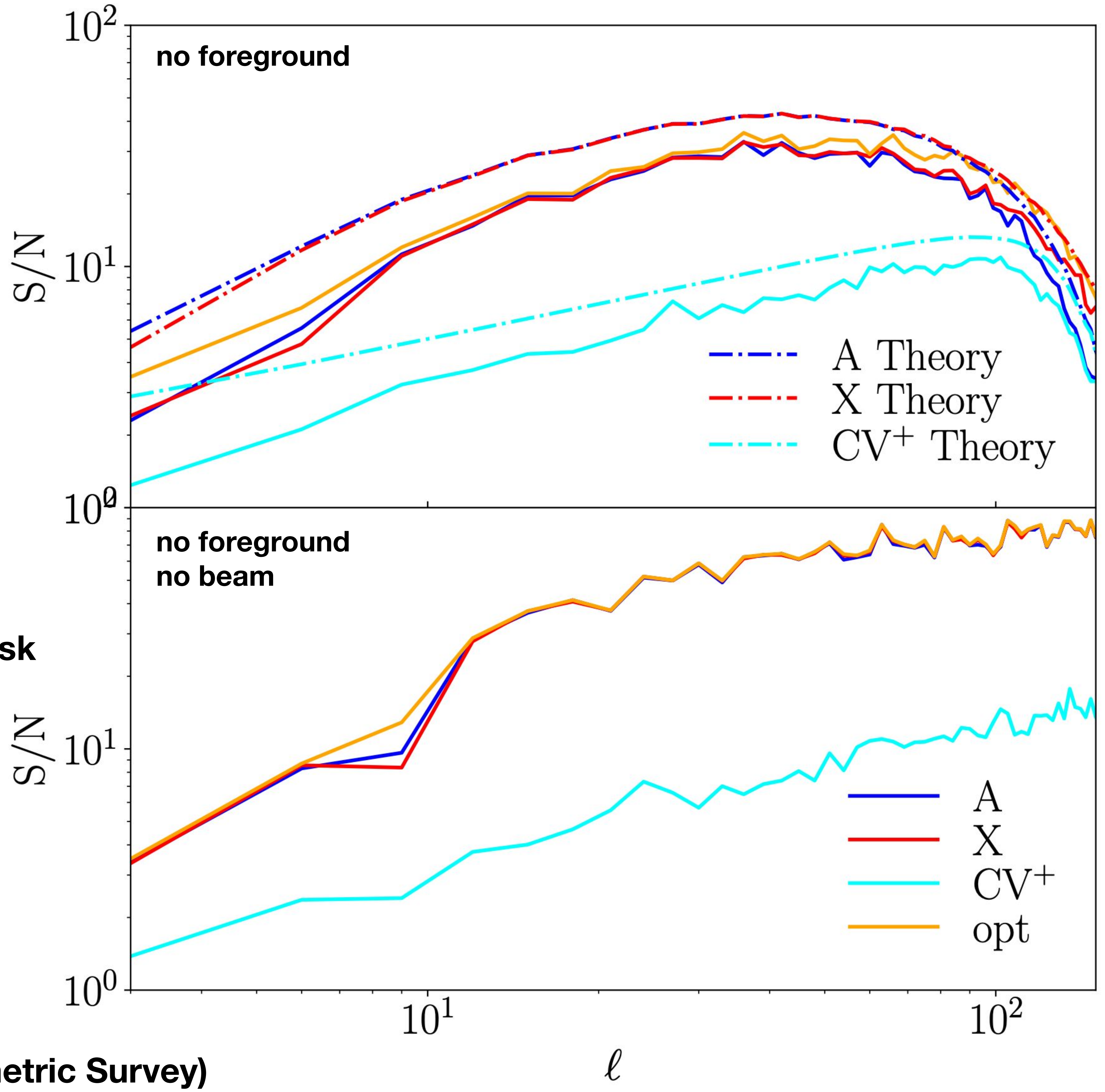
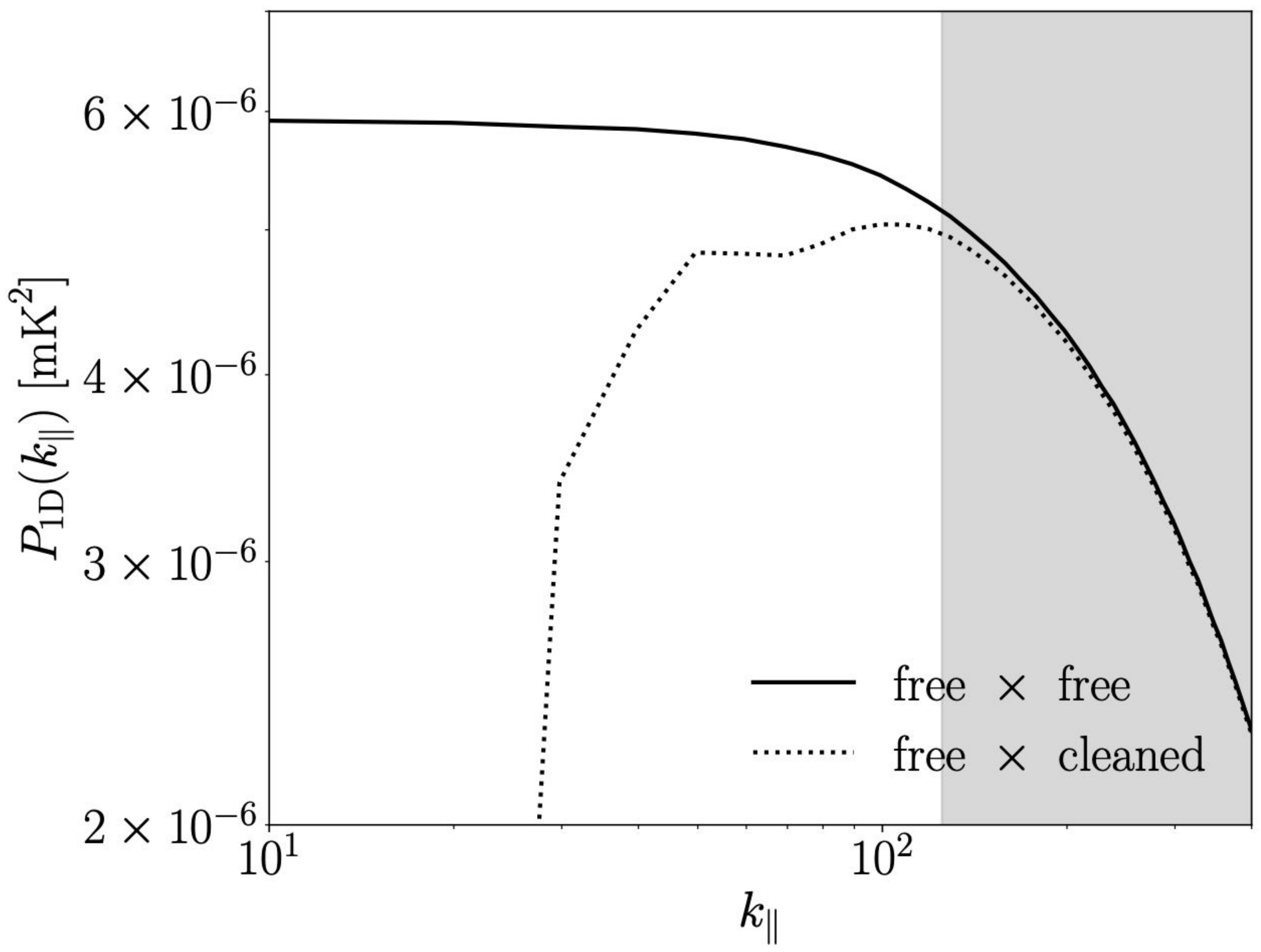
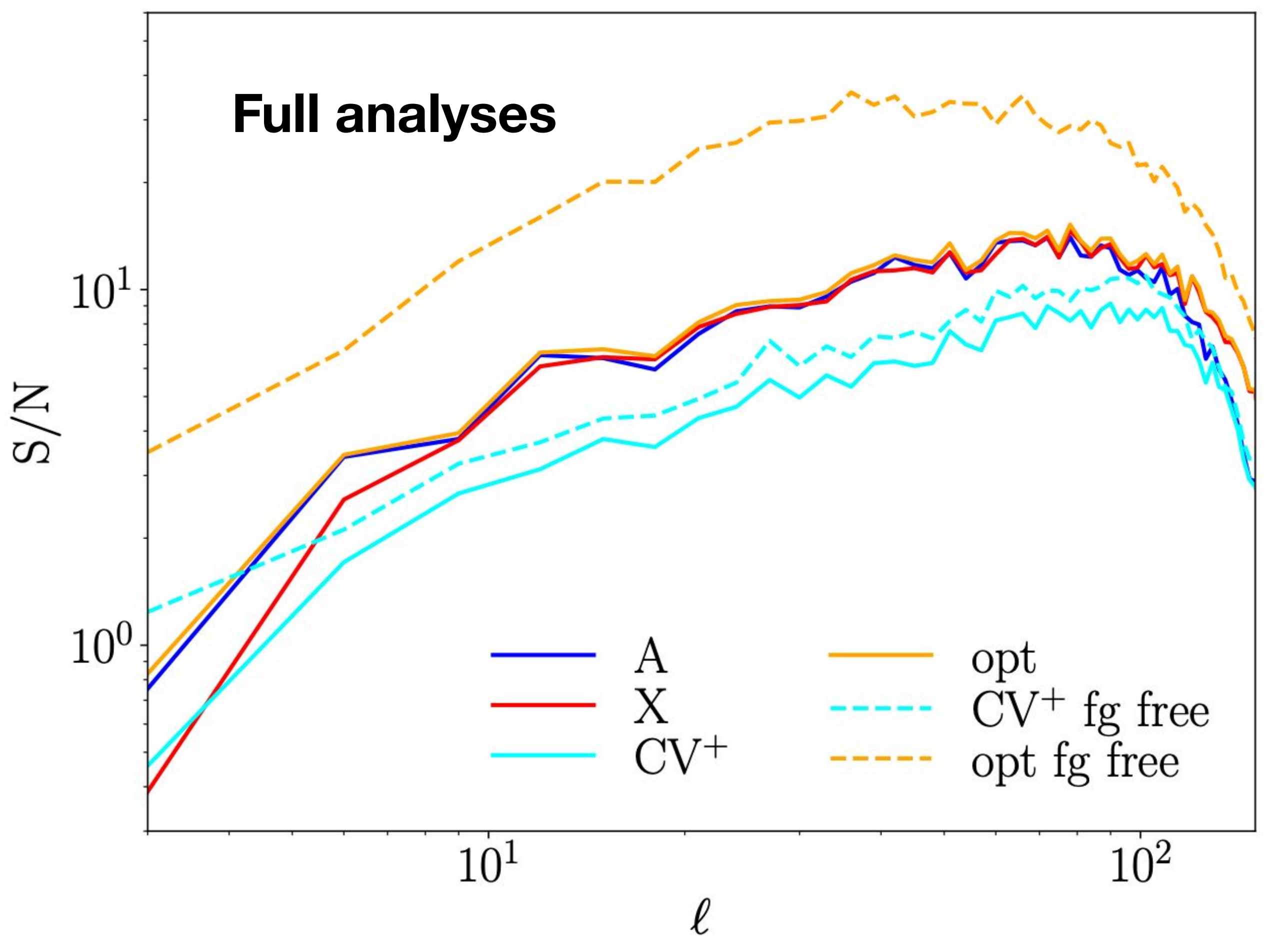


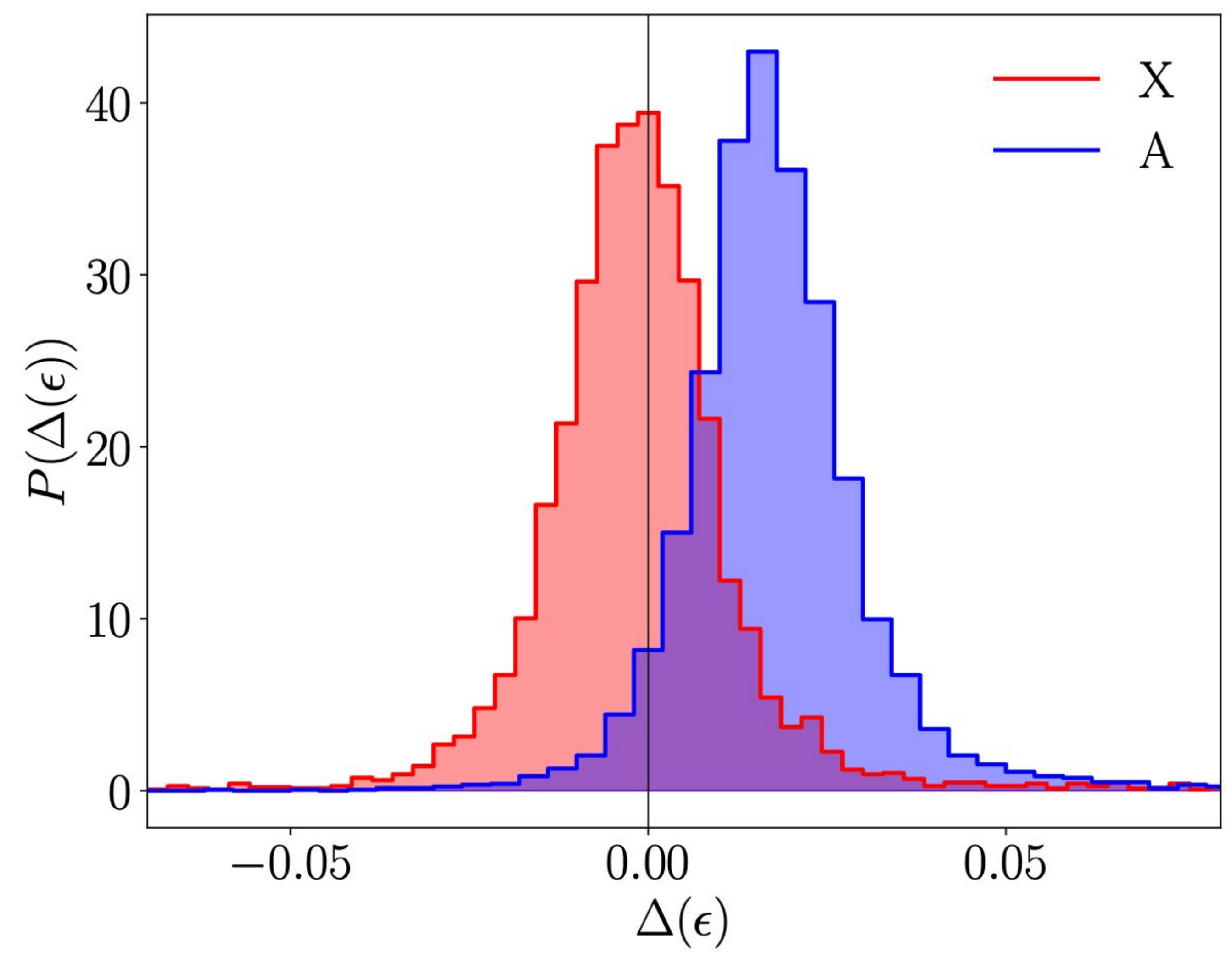
Figure 1. Sky mask used in our analysis, shown in Mollweide's projection and equatorial coordinates. The masked area is shown in grey. The footprint corresponds to the sky observable from the LSST and SKA with the regions of highest galactic emission (both in synchrotron and dust) removed. The total unmasked area is 16900 deg^2 ($f_{\mathrm{sky}} = 0.41$.)



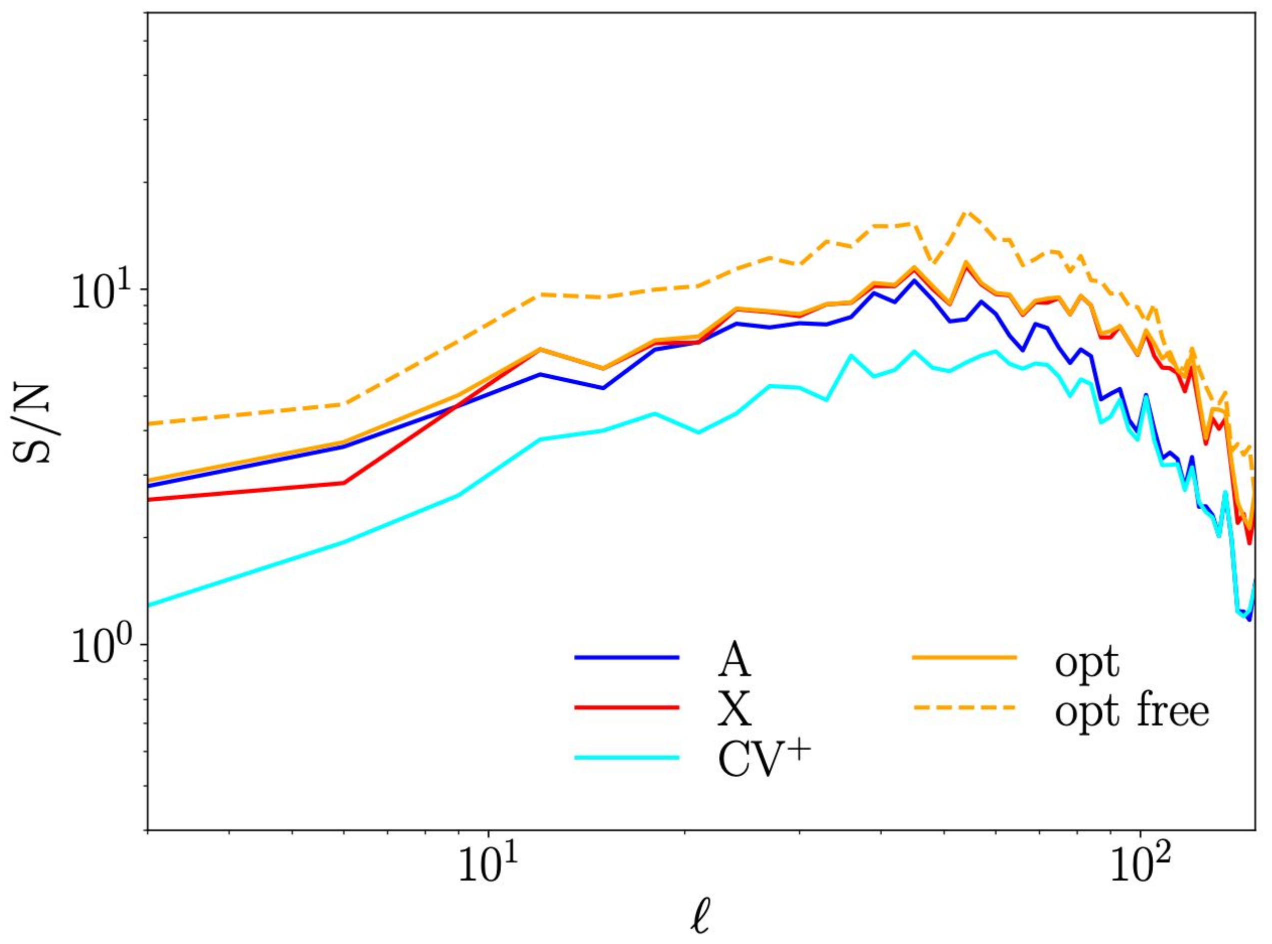
Amadeus Witzemann, David Alonso, JF, Mário G. Santos, MNRAS 2019 (HI IM with Photometric Survey)

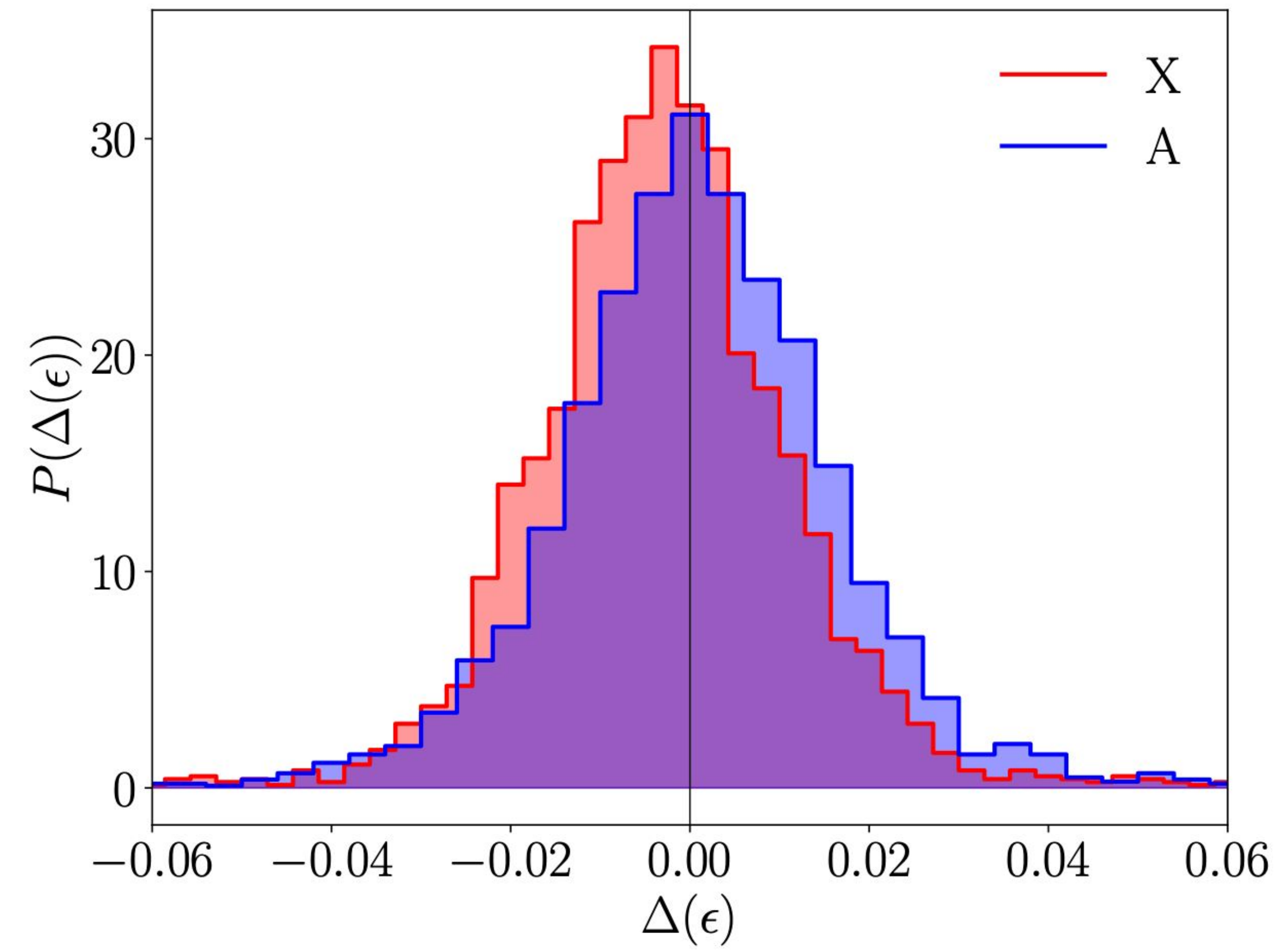






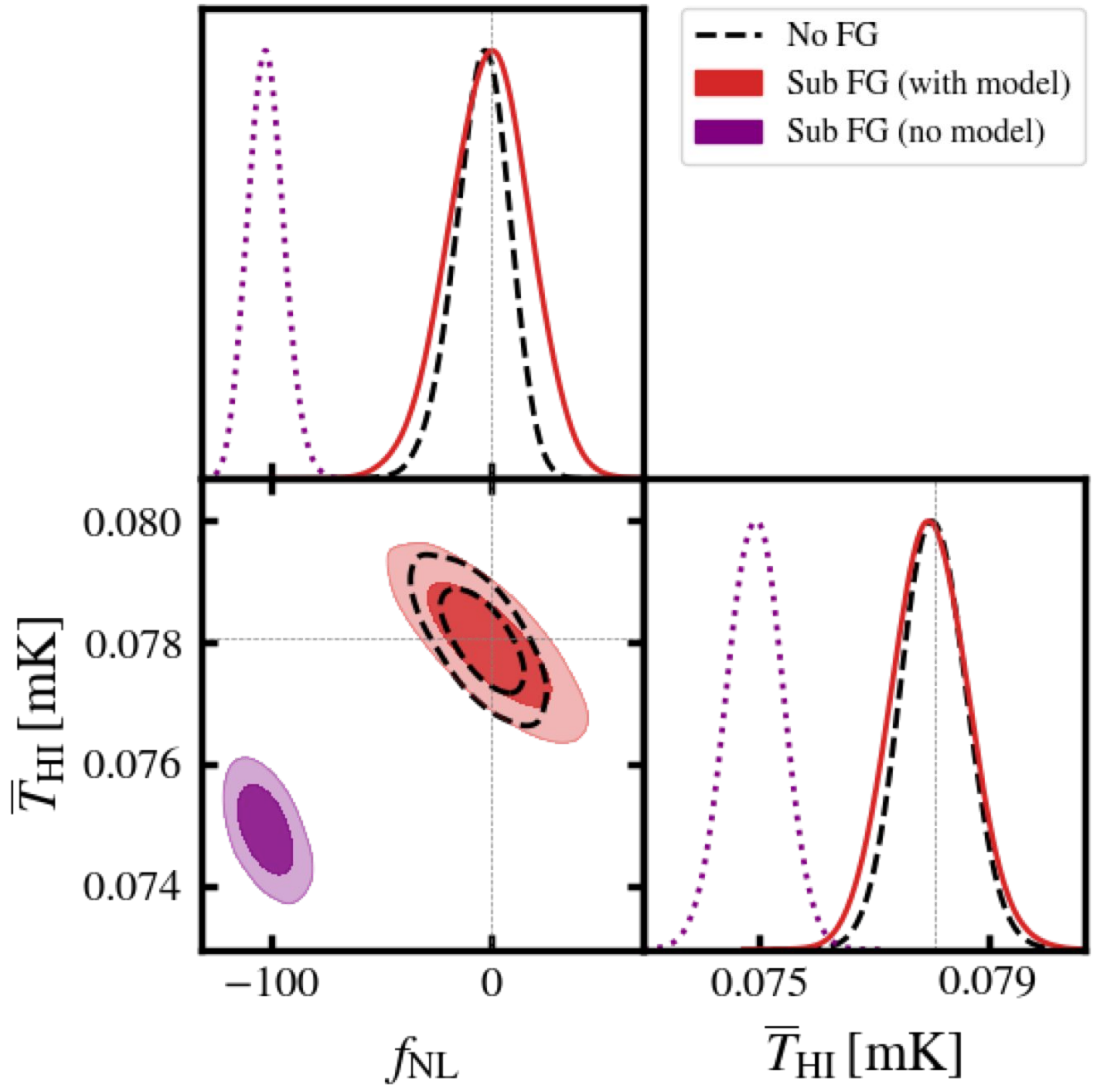
Thinner bins (a la spectroscopic survey)





Amadeus Witzemann, David Alonso, JF, Mário G. Santos
MNRAS 2019 (HI IM with Photometric Survey)

A way to solve the loss of large scales in HI IM



Cunnington et al. 2020

- Foreground clean all bias the estimate of fNL;
- A model of the transfer function is needed to unbiased the result;

$$\widetilde{B}_{\rm FG}(k,\mu) = \alpha_{\rm FG}\,\Theta_{\rm FG}(k_\parallel)\left(1-\exp\left[-\left(\frac{k_\parallel}{k_\parallel^{\rm FG}}\right)\right]\right)$$

Marginalise over the foregrounds?

Model of observed power spectra

$$C_\ell^{\mathcal{M}}(\nu_i,\nu_j) = C_\ell^{\mathcal{S}}(\nu_i,\nu_j) + C_\ell^{\mathcal{F}}(\nu_i,\nu_j) + C_\ell^{\mathcal{N}}(\nu_i,\nu_j)$$

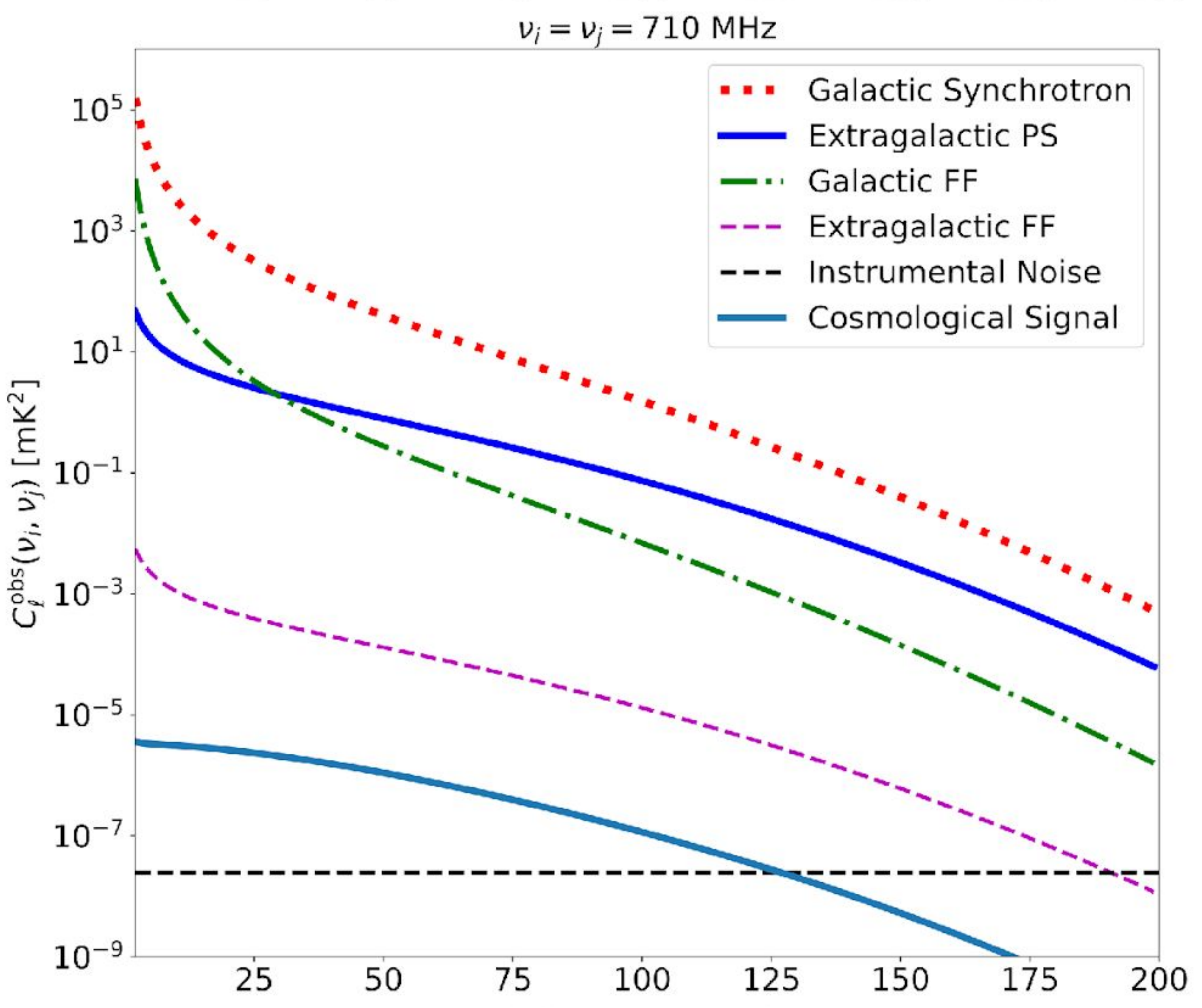
Santos et al. 2005 Foregrounds model

$$C_\ell^{\rm MS05}(\nu_i,\nu_j) = \mathcal{A}\left(\frac{\nu_{\rm ref}^2}{\nu_i\nu_j}\right)^{\alpha}\left(\frac{\ell_{\rm ref}}{\ell}\right)^{\beta} e^{-\frac{\left(\log \nu_i/\nu_j\right)^2}{2\xi^2}}$$

Foreground	$\mathcal{A}$ [mK^2]	β	α	ξ
Extragalactic Point Sources	57.0	1.1	2.07	1.0
Extragalactic Free-Free	0.014	1.0	2.10	35
Galactic Synchrotron	700	2.4	2.80	4.0
Galactic Free-Free	0.088	3.0	2.15	35

Include the beam

$$B_\ell(z_i) = e^{-\ell(\ell+1)\theta_{FWHM}^2(z_i)/16\ln 2}$$



JF & Michele Liguori MNRAS 2021

Marginalise over the foregrounds?

Fisher Forecast

$$\vartheta_{Cosmology} = \{A_s, n_s, \Omega_{\rm CDM}, \Omega_{\rm b}, w, H_0, f_{\rm NL}, \epsilon_{\rm GR}\}$$

$$\vartheta_{Foregrounds} = \{ \mathcal{A}_{EPS}, \beta_{EPS}, \alpha_{EPS}, \xi_{EPS}, \mathcal{A}_{EFF}, \beta_{EFF}, \alpha_{EFF}, \xi_{EFF}, \mathcal{A}_{GS}, \beta_{GS}, \alpha_{GS}, \xi_{GS}, \mathcal{A}_{GFF}, \beta_{GFF}, \alpha_{GFF}, \xi_{GFF} \}$$

$$\mathbf{F}_{\vartheta_\alpha \vartheta_\beta} = \sum_\ell \frac{\partial C^{\mathcal{M}}_{\ell,ij}}{\partial \vartheta_\alpha} \Gamma^{-1}_{\ell,ij,mn} \frac{\partial C^{\mathcal{M}}_{\ell,mn}}{\partial \vartheta_\beta}$$

$$\sigma_\vartheta = \sqrt{(\mathbf{F}^{-1})_{\vartheta\vartheta}}$$

$(\sigma_\vartheta/\vartheta)$	$\mathcal{A}_{GS}$	β_{GS}	α_{GS}	ξ_{GS}
w/o cosmology	7.3E-11	5.5E-12	5.4E-12	9.5E-12
w/ cosmology	2.1E-09	1.7E-10	1.5E-10	3.3E-10
	$\mathcal{A}_{GFF}$	β_{GFF}	α_{GFF}	ξ_{GFF}
w/o cosmology	6.6 E-09	2.0E-10	2.5E-10	2.4E-10
w/ cosmology	2.2E-07	6.4E-09	9.0E-09	8.8E-09

	$\mathcal{A}_{EPS}$	β_{EPS}	α_{EPS}	ξ_{EPS}
w/o cosmology	8.2E-07	3.4E-08	9.3E-09	1.8E-07
w/ cosmology	4.0E-05	1.7 E-06	3.8E-07	8.7E-06
	$\mathcal{A}_{EFF}$	β_{EFF}	α_{EFF}	ξ_{EFF}
w/o cosmology	3.3E-03	2.0E-04	5.7E-5	9.7E-04
w/ cosmology	1.6E-01	9.4E-03	2.7E-3	4.8E-02

$(\sigma_\vartheta/\vartheta)$	A_s	n_s	H_0	Ω_{CDM}	Ω_b	w
w/o foregrounds	3.57	1.42	2.31	2.32	4.05	2.41
w/ foregrounds	3.60	1.43	2.32	2.38	4.11	2.52

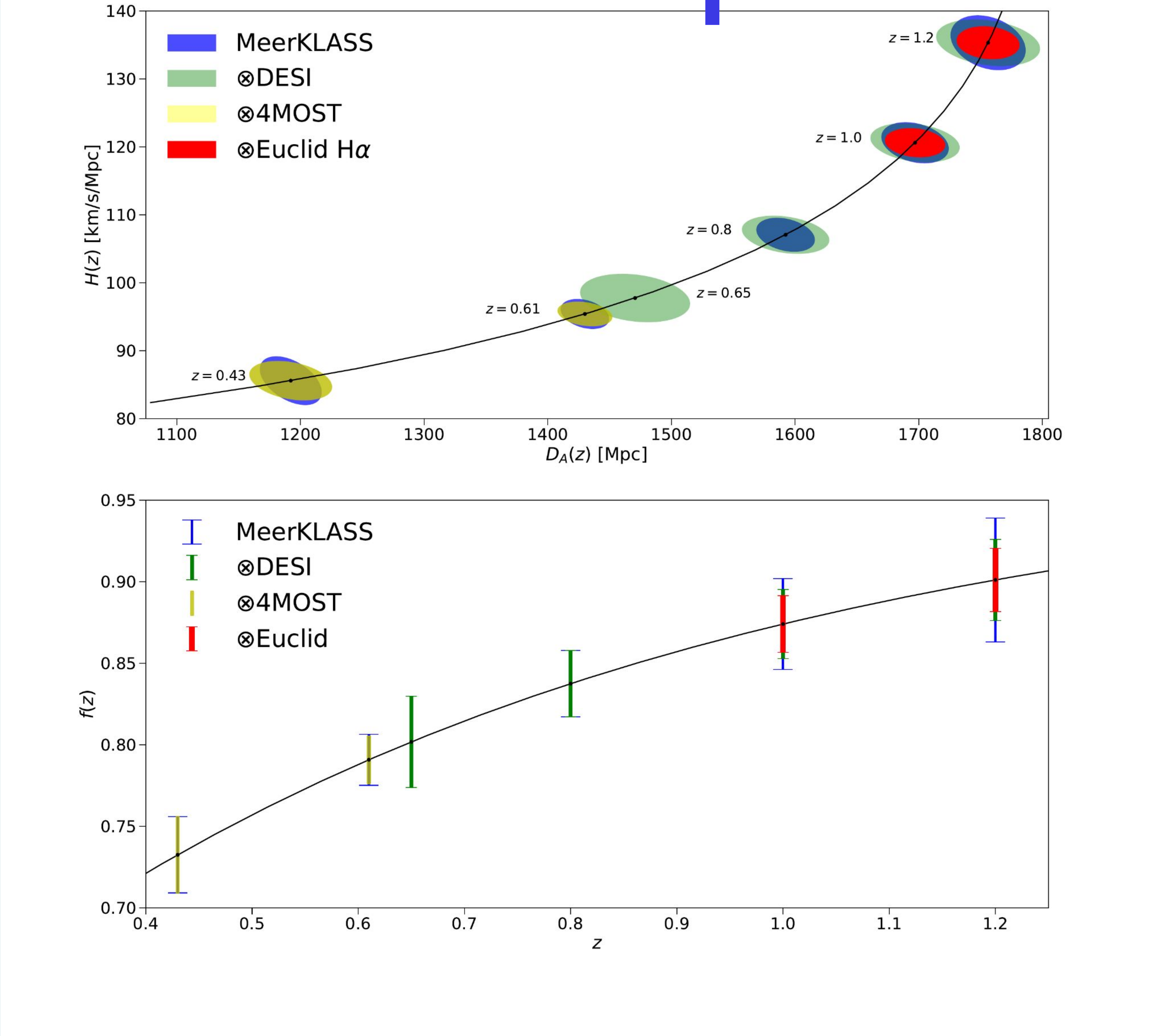
σ_ϑ	f_{NL}	ϵ_{GR}
conditional	4.1	4.8
w/o foregrounds	4.81	5.17
+ bias fixed	4.62	5.15
w/ foregrounds	8.50	6.70
+ bias fixed	7.94	6.64
+ cosmology fixed	6.6	6.3

JF & Michele Liguori MNRAS 2021

What else is there to be done?

- Can the MT help in adding information on the foregrounds?
- Will the MT approach help in controlling Photo-z systematics?
- Can HI be used to characterise the compamination fraction of Halpha by OIII?

Standard Optical-Radio synergies



For cross-correlations only, we can achieve a BAO detectability of SNR= [4.8, 7.2] for z = [0.43, 0.61] with 4MOST and SNR=[3.7, 4.1] for z = [0.65, 0.8] with DESI. Combining DESI with Euclid, it will be even possible to make a detection at z = 1.0 and 1.2.

What else is there to be done?

- Can the MT help in adding information on the foregrounds?
- Will the MT approach help in controlling Photo-z systematics?
- Can HI be used to characterise the compamination fraction of Halpha by OIII?