CMB LENSING X LSS: SAMPLING VARIANCE CANCELLATIONS & MULTI-TRACER ANALYSIS

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TALK OUTLINE

- 1 Sampling variance cancellation
- 2 Forecast ingredients
- 3 Primordial non-Gaussianity
- 4 Neutrino mass
- 5 Measuring galaxy bias to get dark matter in 3D

All results are **preliminary**!

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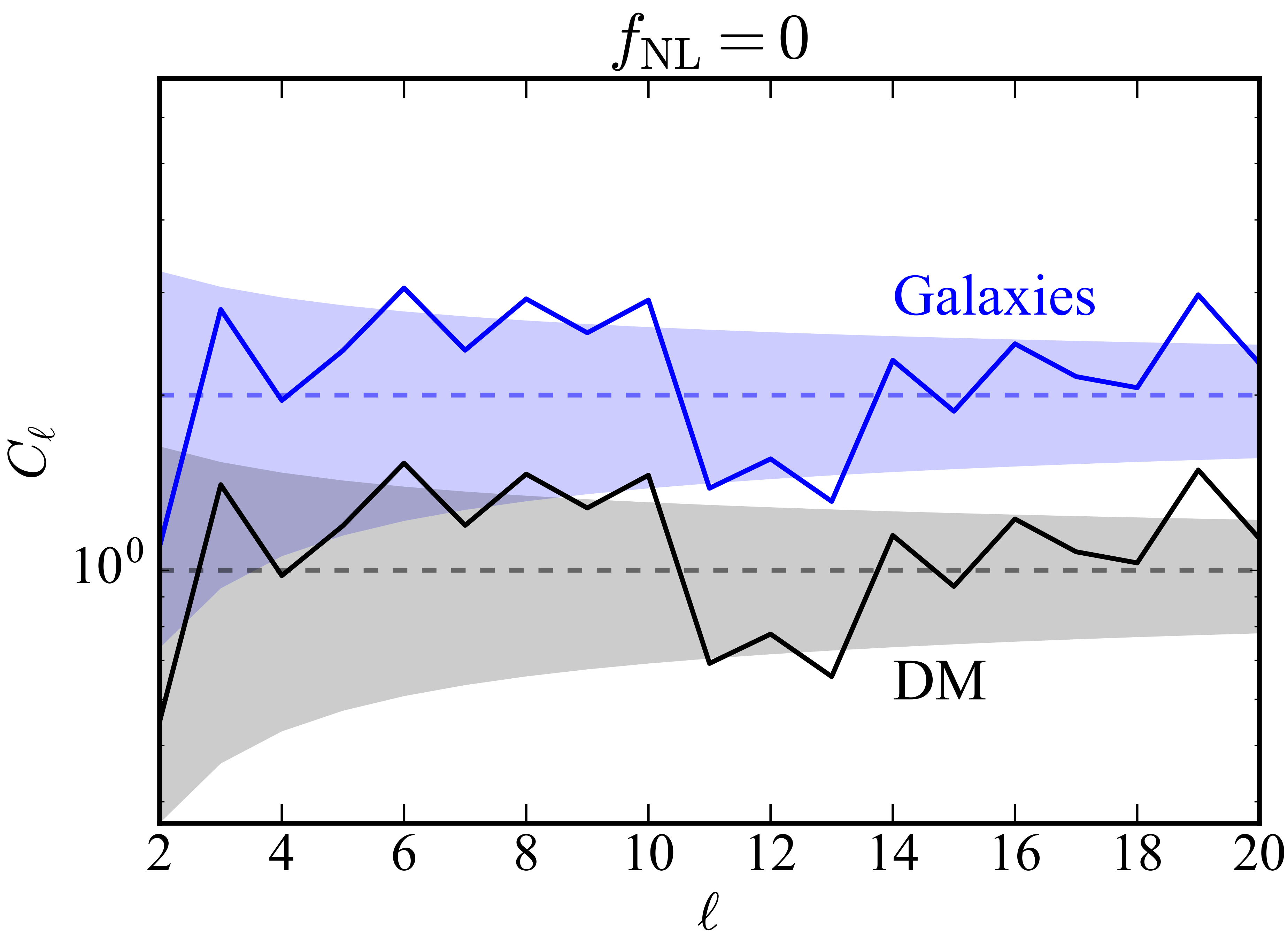
SAMPLING VARIANCE CANCELLATION

SAMPLING VARIANCE CANCELLATION

- Toy model: Gaussian fluctuations around 1
- Primordial non-Gaussianity: Rescale galaxies by $\sim \left[1 + (b-1) f_{\mathrm{NL}}/\ell^2\right]$ *Dalal et al. (2008)*



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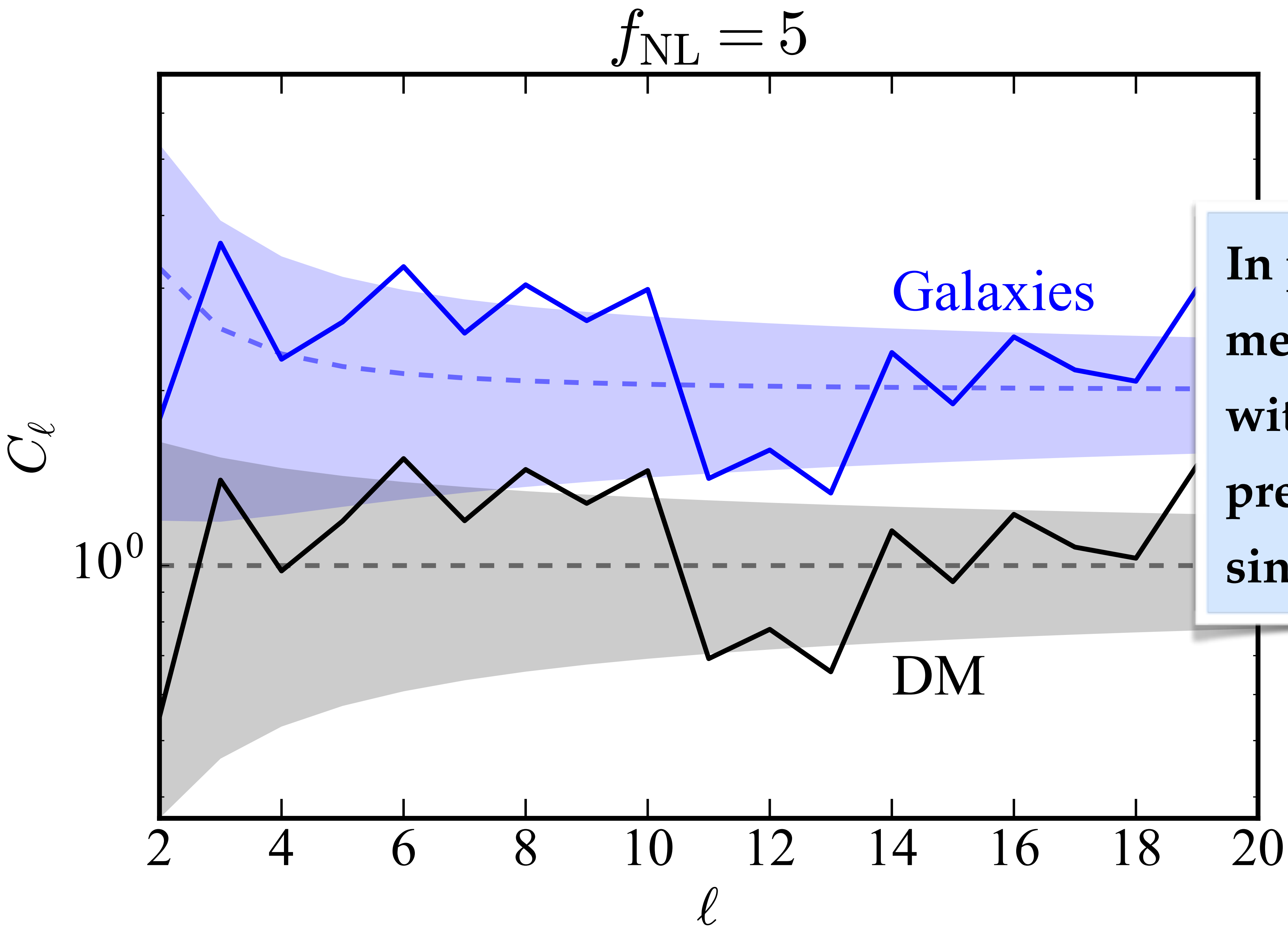
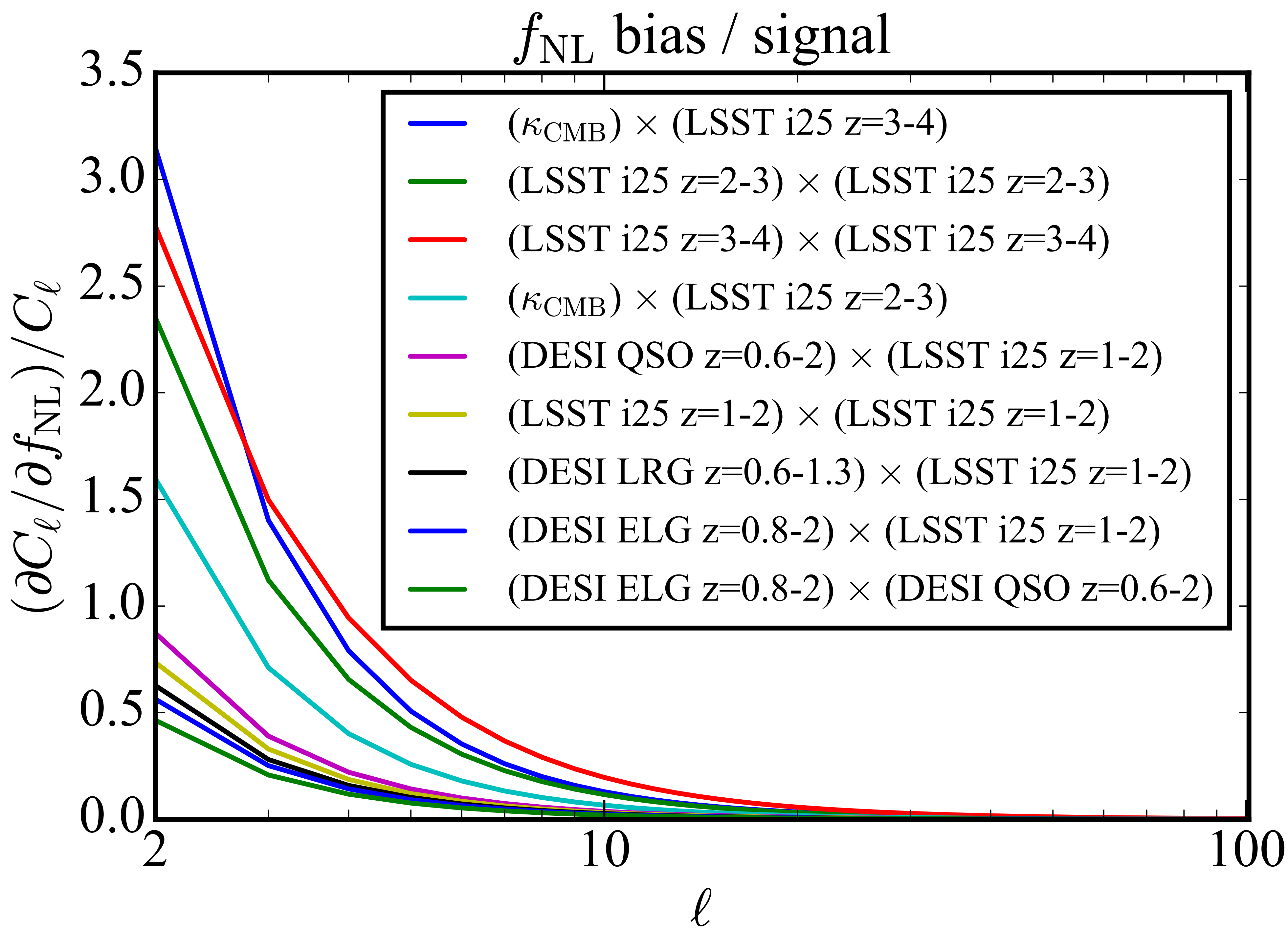


In principle, can measure ratio with infinite precision from single mode

Seljak (2009)
McDonald & Seljak (2009)

SAMPLING VARIANCE CANCELLATION

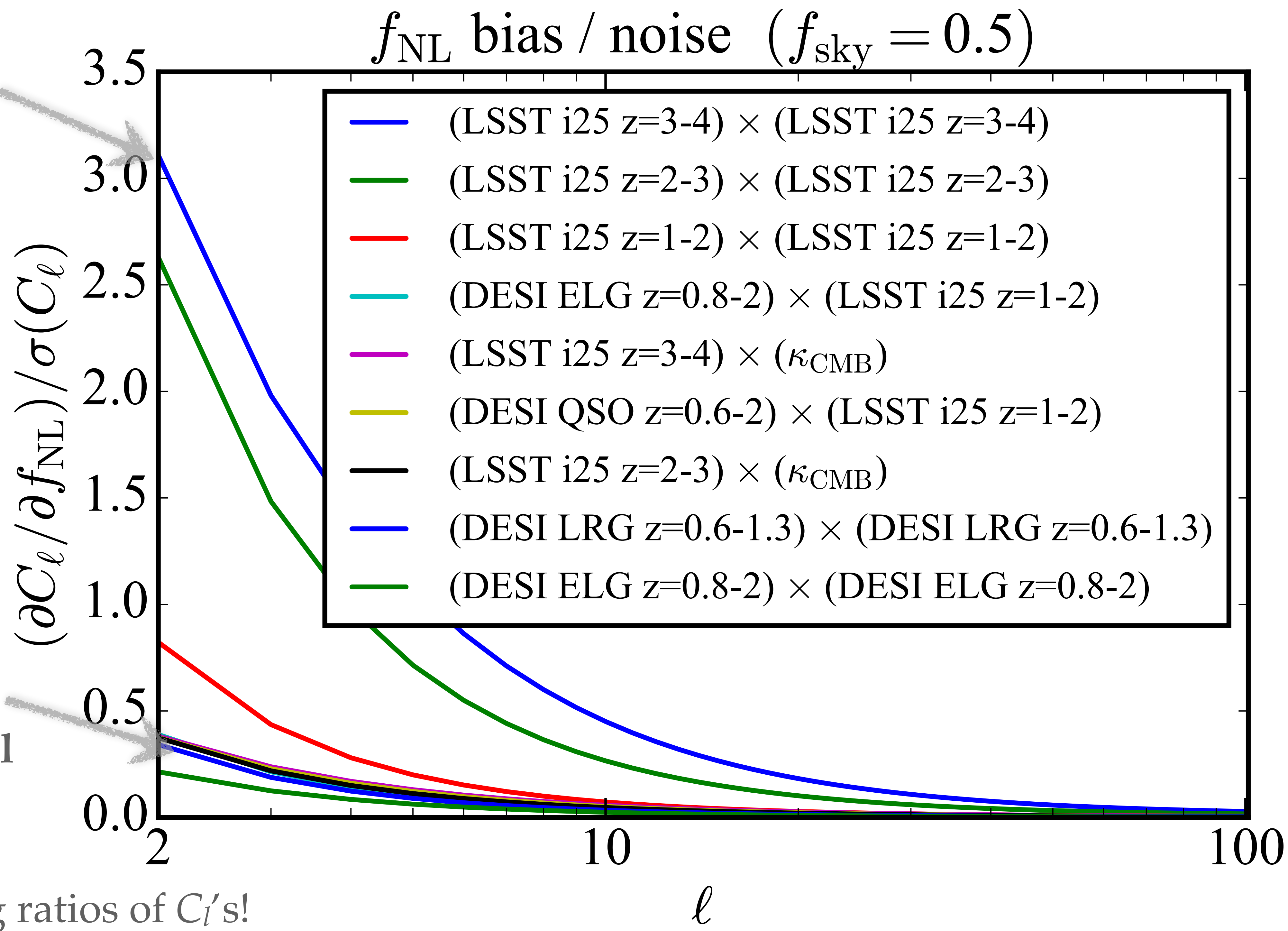
Fractional change of power spectra for f_{NL}=1: Up to 3x increase at low *l*



SAMPLING VARIANCE CANCELLATION

Compare to sampling variance noise: "By how many sigma do C_l's change if f_{NL}=1?"

3σ for f_{NL}=1



0.3σ for f_{NL}=1 but can **cancel sampling variance** by measuring ratios of C_l's!

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FORECAST INGREDIENTS

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- CMB lensing reconstruction κ from CMB-S4 (assume $\sigma_{\mathrm{FWHM}} = 1'$, $N_{\mathrm{TT}} = 1\ \mu\mathrm{K}'$)
- Various LSS samples: SDSS, DESI, LSST, [CIB]

- Limber C_l's for galaxy-galaxy, galaxy-κ and κ-κ:

$$C_\ell^{gg} = \int \mathrm{d}z\, W_g^2(z) P(\ell/\chi, z) \left\{ b^2(z) \left[1 + \alpha\, \beta(k = \ell/\chi, z)\right]^2 + \left[n_{\mathrm{com}}(z) P(\ell/\chi, z)\right]^{-1} \right\}$$

$$C_\ell^{g\kappa} = \int \mathrm{d}z\, W_g(z) W_\kappa(z) P(\ell/\chi, z) b(z) \left[1 + \alpha\, \beta(k = \ell/\chi, z)\right]$$

$$C_\ell^{\kappa\kappa} = \int \mathrm{d}z\, W_\kappa^2(z) P(\ell/\chi, z) + N_\ell^{(0)}.$$

  - α = amplitude of scale-dependent bias: f_{NL} or m_ν
  - $\beta(k, z)$ = scale-dependent bias:

$$\beta(k,z) = \frac{\Delta b}{b} = 3\frac{(b-1)}{b}\frac{\Omega_{m,0}\delta_c}{k^2 T(k) D(z)}\left(\frac{H_0}{c}\right)^2 \quad \text{or} \quad \frac{1}{m_\nu^{\mathrm{fid}}}\frac{P_{\mathrm{tot,no}\nu}(k,z) - P_{\mathrm{tot,tot}}(k,z)}{P_{\mathrm{tot,tot}}(k,z)}$$

FORECAST INGREDIENTS

- Fisher analysis for amplitude of scale-dependent bias (f_{NL} or m_ν)
- Split LSS samples into few redshift bins (typically 2-3)
- Marginalize over one bias parameter per redshift bin
- Marginalize over worst-case scenario where changes in total matter power spectrum (e.g. due to different cosmology) are perfectly degenerate with scale-dependent bias:

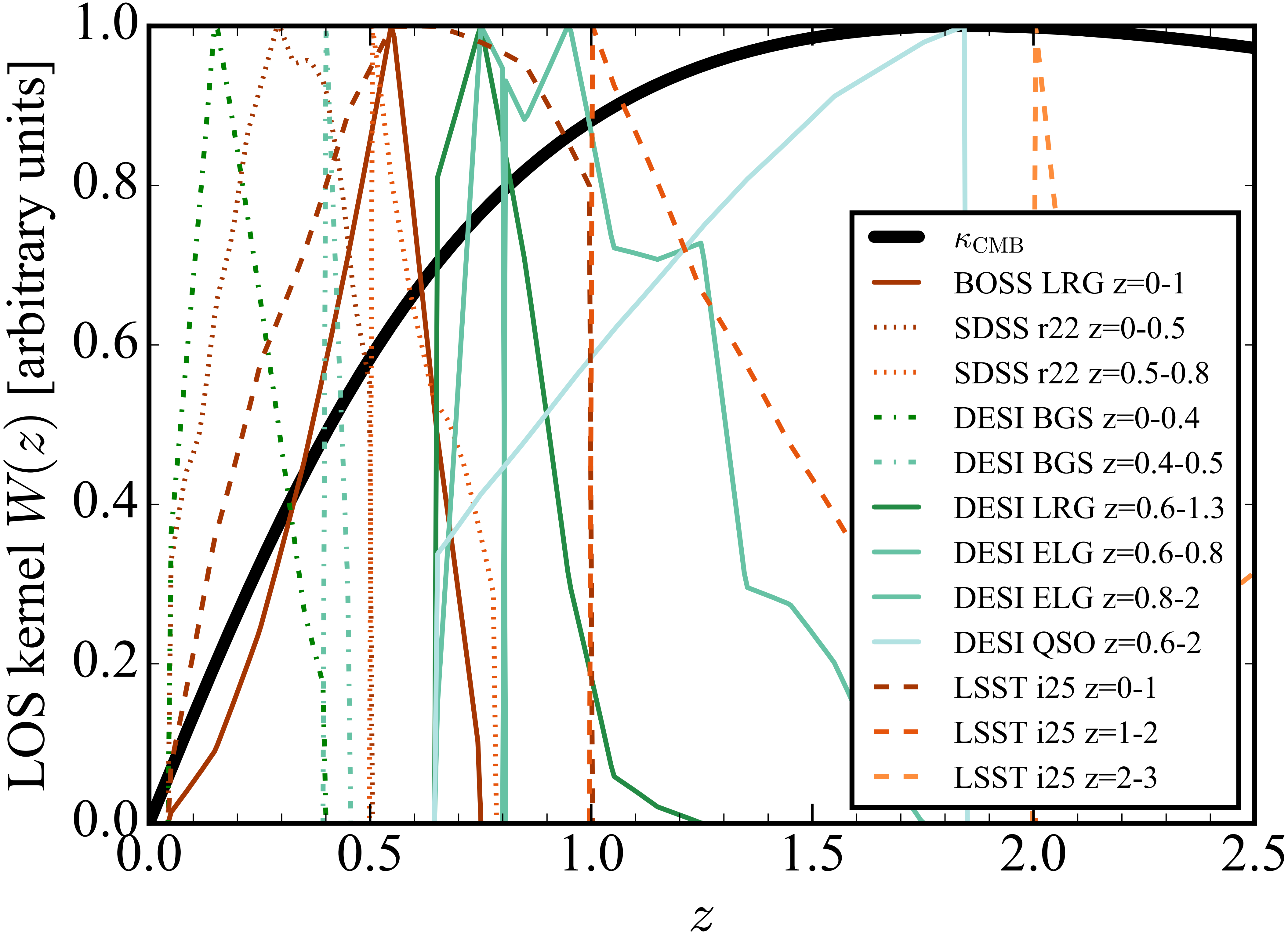
$$P(k=\ell/\chi, z) \to P(k=\ell/\chi, z)\left[1+\alpha_{\mathrm{fake}}\,\beta_{\mathrm{fake}}(k=\ell/\chi, z)\right]^2$$

- For most results, exclude LSS auto-spectra to avoid potential systematics
- Assume all surveys overlap on the sky (though probe different volume if z range does not overlap)

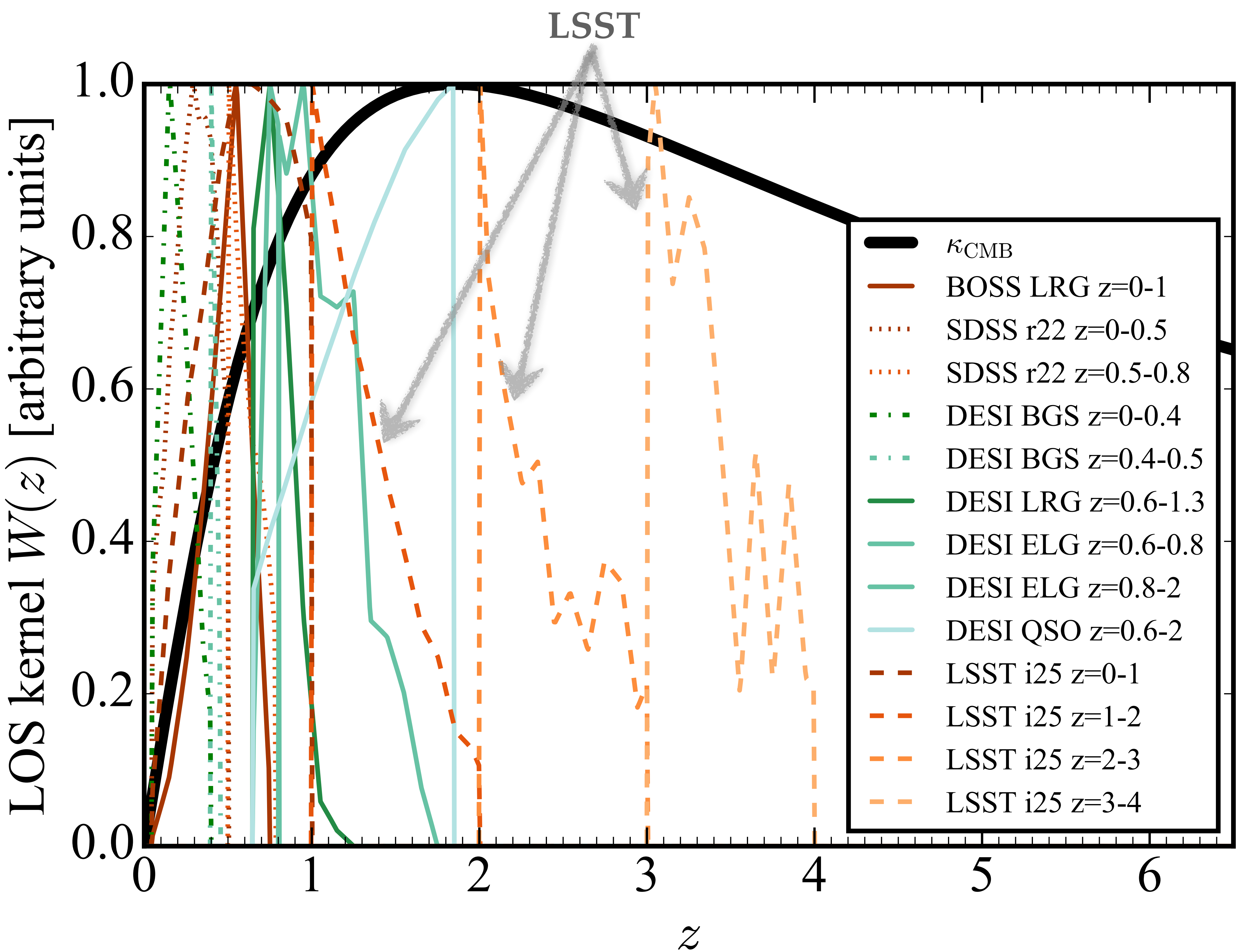
LSS SAMPLES

Sample	$N_{\rm objects}$
BOSS LRG z=0-1	1.31×10^6
SDSS $r < 22$ z=0-0.5	8.98×10^7
SDSS $r < 22$ z=0.5-0.8	1.82×10^7
DESI BGS z=0-0.4	8.71×10^6
DESI BGS z=0.4-0.5	1.95×10^5
DESI LRG z=0.6-1.3	3.34×10^6
DESI ELG z=0.6-0.8	3.34×10^6
DESI ELG z=0.8-2	1.35×10^7
DESI QSO z=0.6-2	1.28×10^6
LSST $i < 25$ z=0-1	1.4×10^9
LSST $i < 25$ z=1-2	4.75×10^8
LSST $i < 25$ z=2-3	2.95×10^7
LSST $i < 25$ z=3-4	7.31×10^6

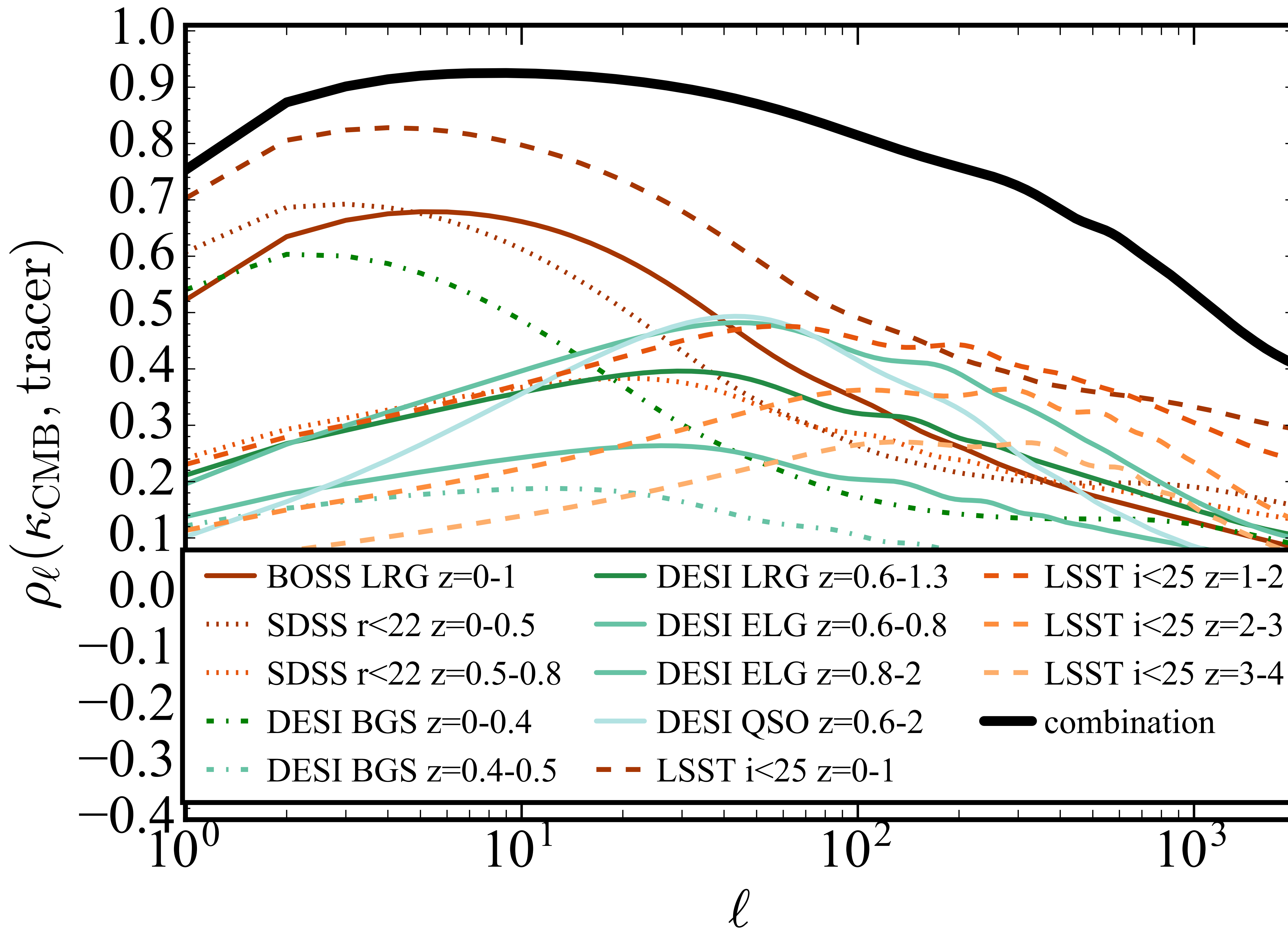
REDSHIFT KERNELS



REDSHIFT KERNELS



CORRELATION COEFFICIENT WITH CMB LENSING SIGNAL



SAMPLING VARIANCE CANCELLATION *S/N*

- Correlation ρ_ℓ of combined LSS sample and CMB lensing κ is ~93%

- Sampling variance cancellation improves signal-to-noise of e.g. $f_{\rm NL}$ as

$$\frac{S}{N} \propto \frac{1}{\sqrt{1-\rho_\ell^2}}$$

Seljak (2009)
McDonald & Seljak (2009)

➡ Expect ~3x improvement from sampling variance cancellation if using only combined LSS sample and CMB lensing κ

- Gain even more if using all cross-spectra

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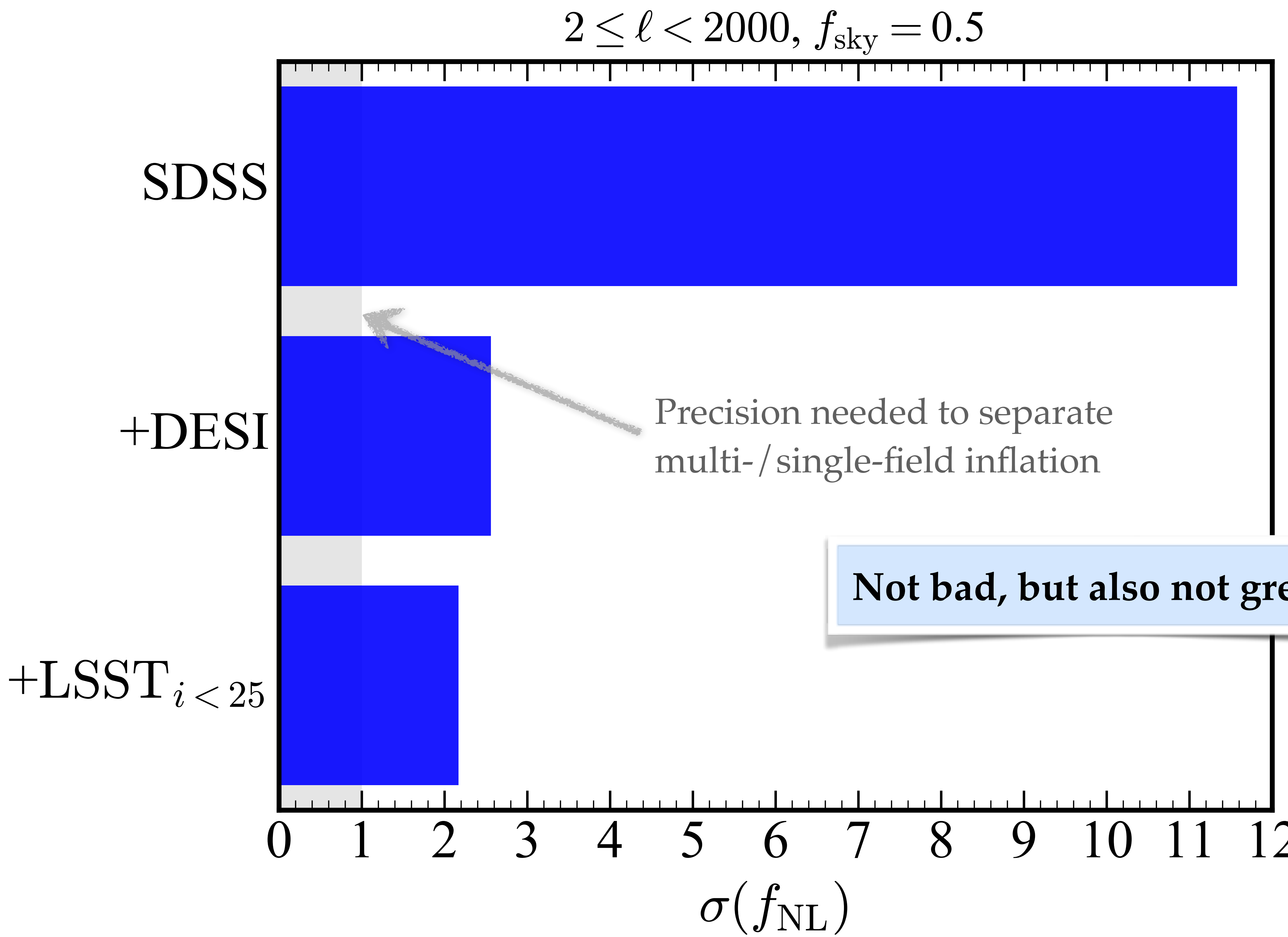
PRIMORDIAL NON-GAUSSIANITY

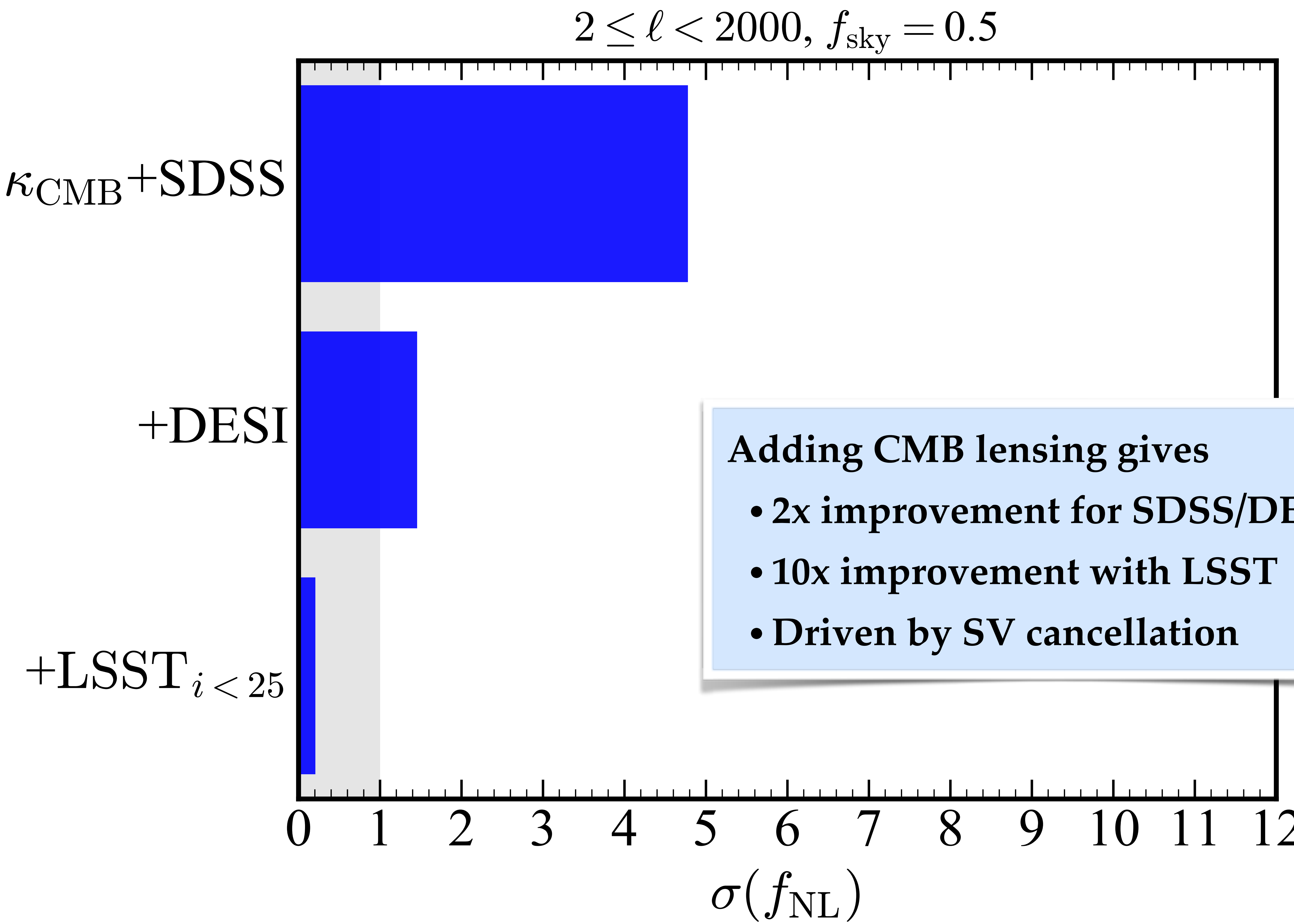
LSS ONLY



Not bad, but also not great

All LSS auto- and cross-spectra. Marginalize over bias parameters and fake $f_{\rm NL}$.

ADDING CMB LENSING

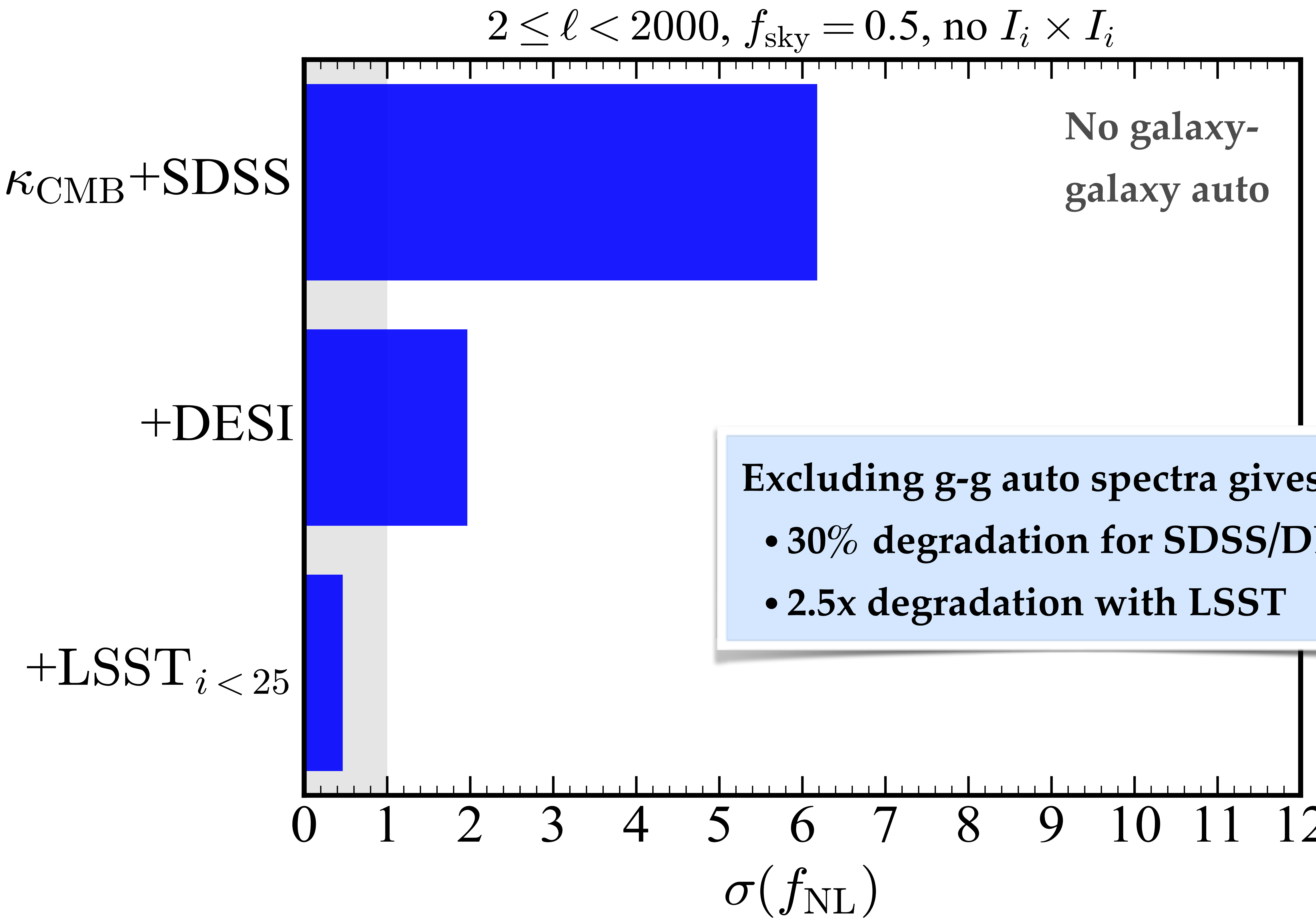


Adding CMB lensing gives

- **2x improvement for SDSS/DESI**
- **10x improvement with LSST**
- **Driven by SV cancellation**

All LSS auto- and cross-spectra. Marginalize over bias parameters and fake $f_{\rm NL}$. CMB lensing: $\sigma_{\rm FWHM} = 1'$, $N_{TT} = 1$ μK′.

EXCLUDING GALAXY-GALAXY AUTO SPECTRA



Excluding g-g auto spectra gives

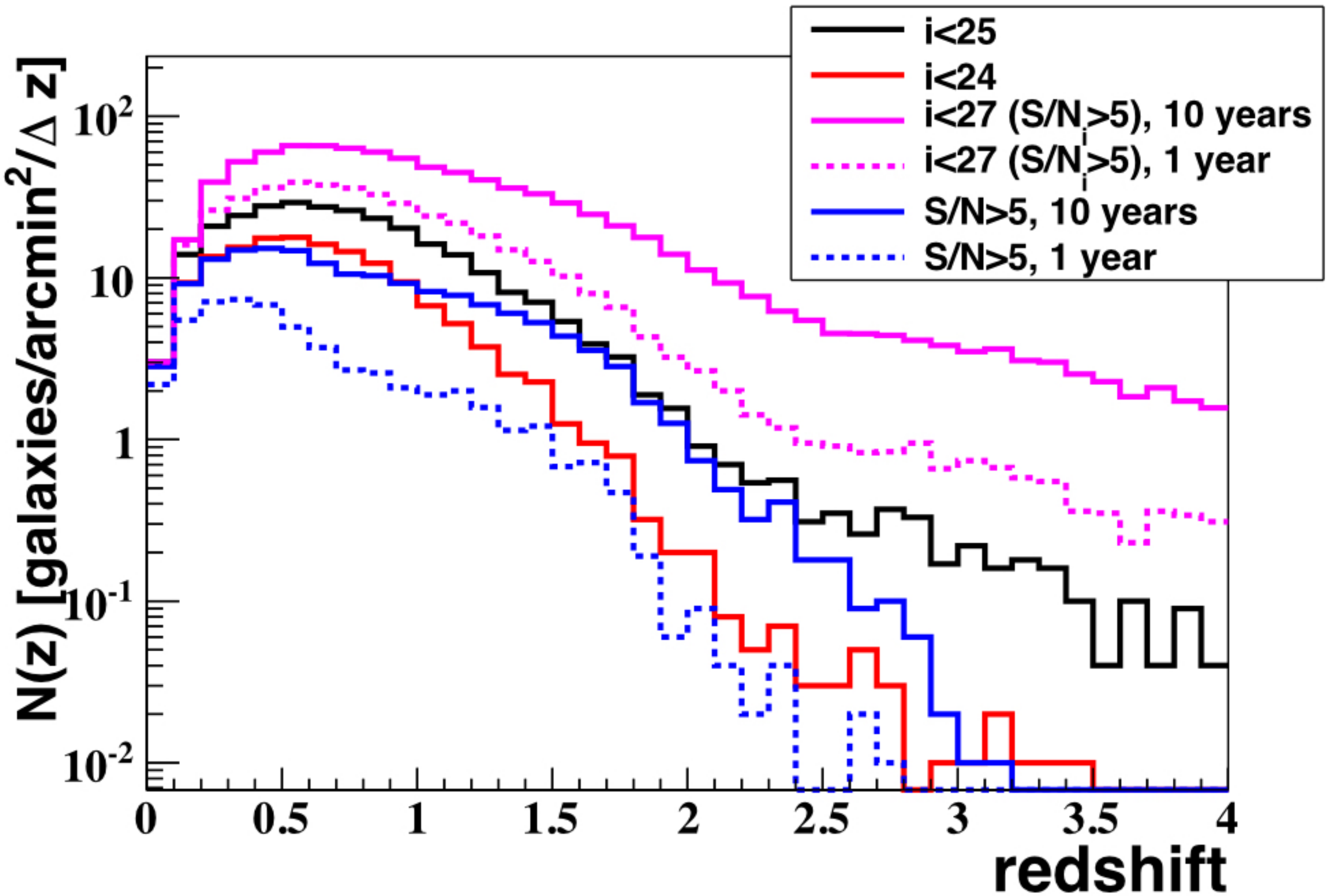
- **30% degradation for SDSS/DESI**
- **2.5x degradation with LSST**

No LSS auto spectra, all LSS cross spectra. Marginalize over bias parameters and fake f_{NL}. CMB lensing: $\sigma_{FWHM} = 1'$, $N_{TT} = 1\ \mu K'$.

BETTER LSST?

Gorecki, Abate, et al. (2014)

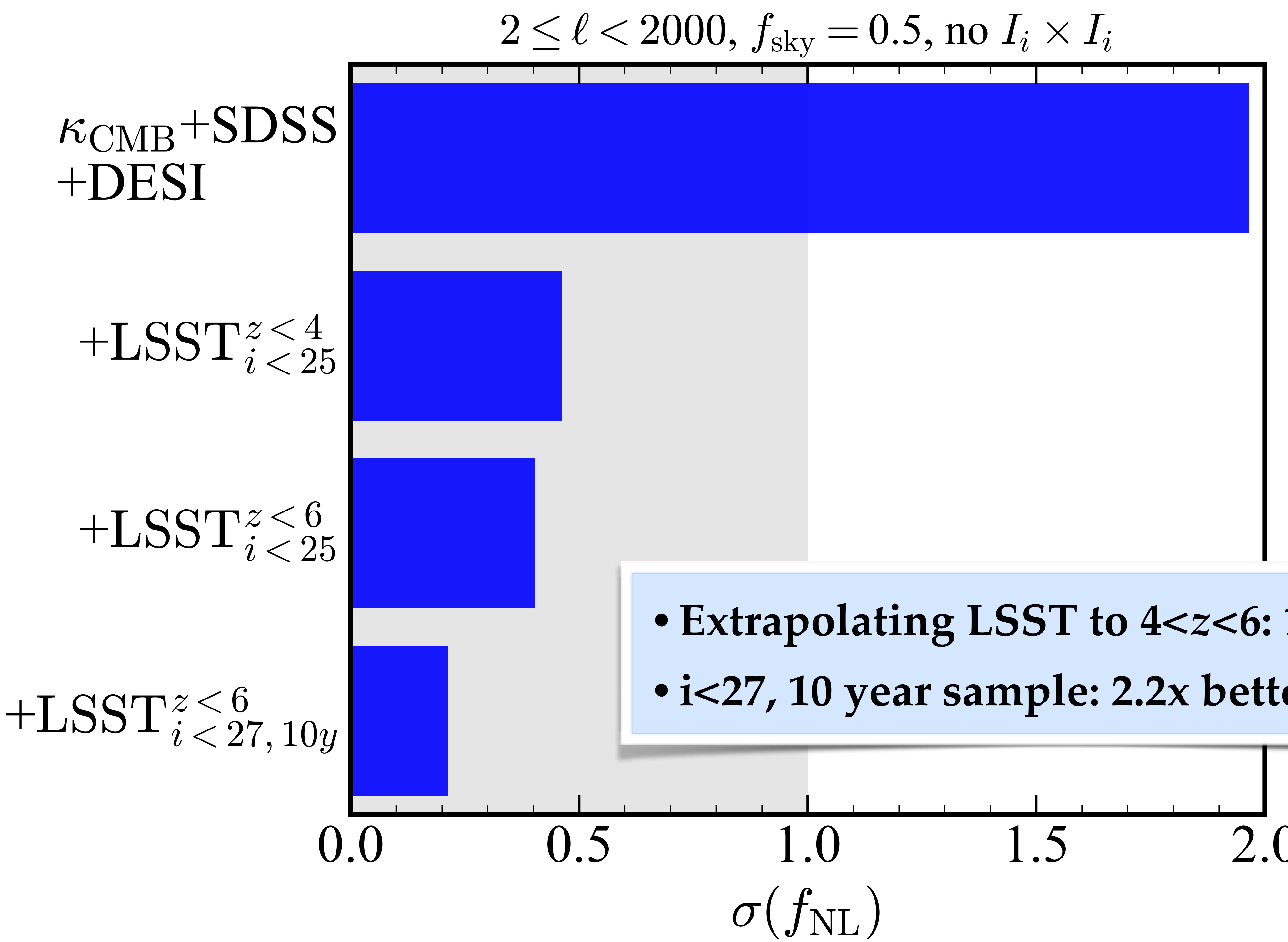
- So far, used i<25 "gold" sample at $0 < z < 4$



➡ **Extrapolate to $4 < z < 6$**

➡ **Use i<27 10 years**

EXTRAPOLATING LSST TO 4<z<6



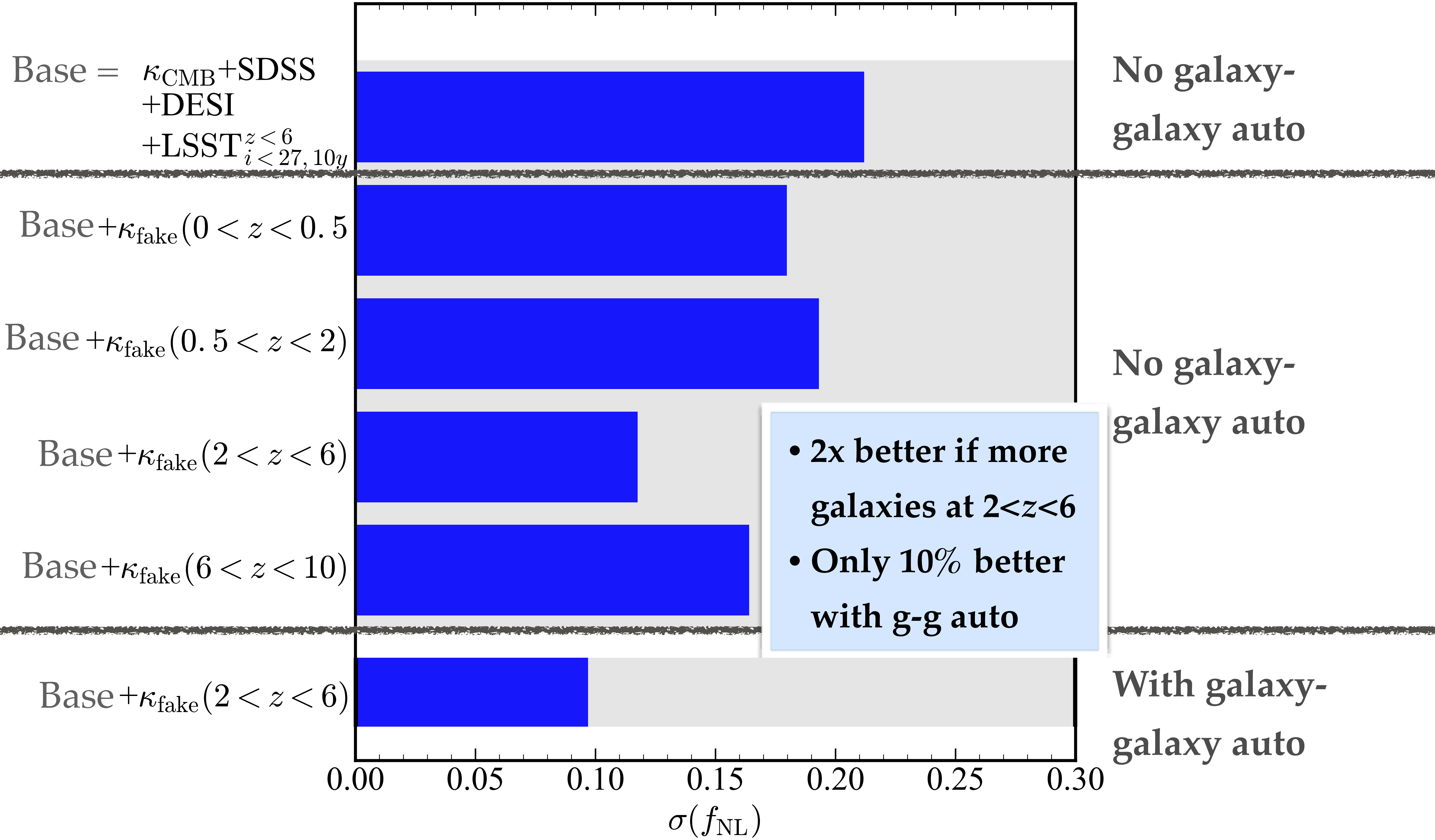
No galaxy-galaxy auto

- **Extrapolating LSST to 4<z<6: 15% better**
- **i<27, 10 year sample: 2.2x better**

No LSS auto spectra, all LSS cross spectra. Marginalize over bias parameters and fake $f_{\rm NL}$. CMB lensing: $\sigma_{\rm FWHM} = 1'$, $N_{TT} = 1$ μK′.

ADDING PERFECT "FAKE" CMB LENSING TRACER

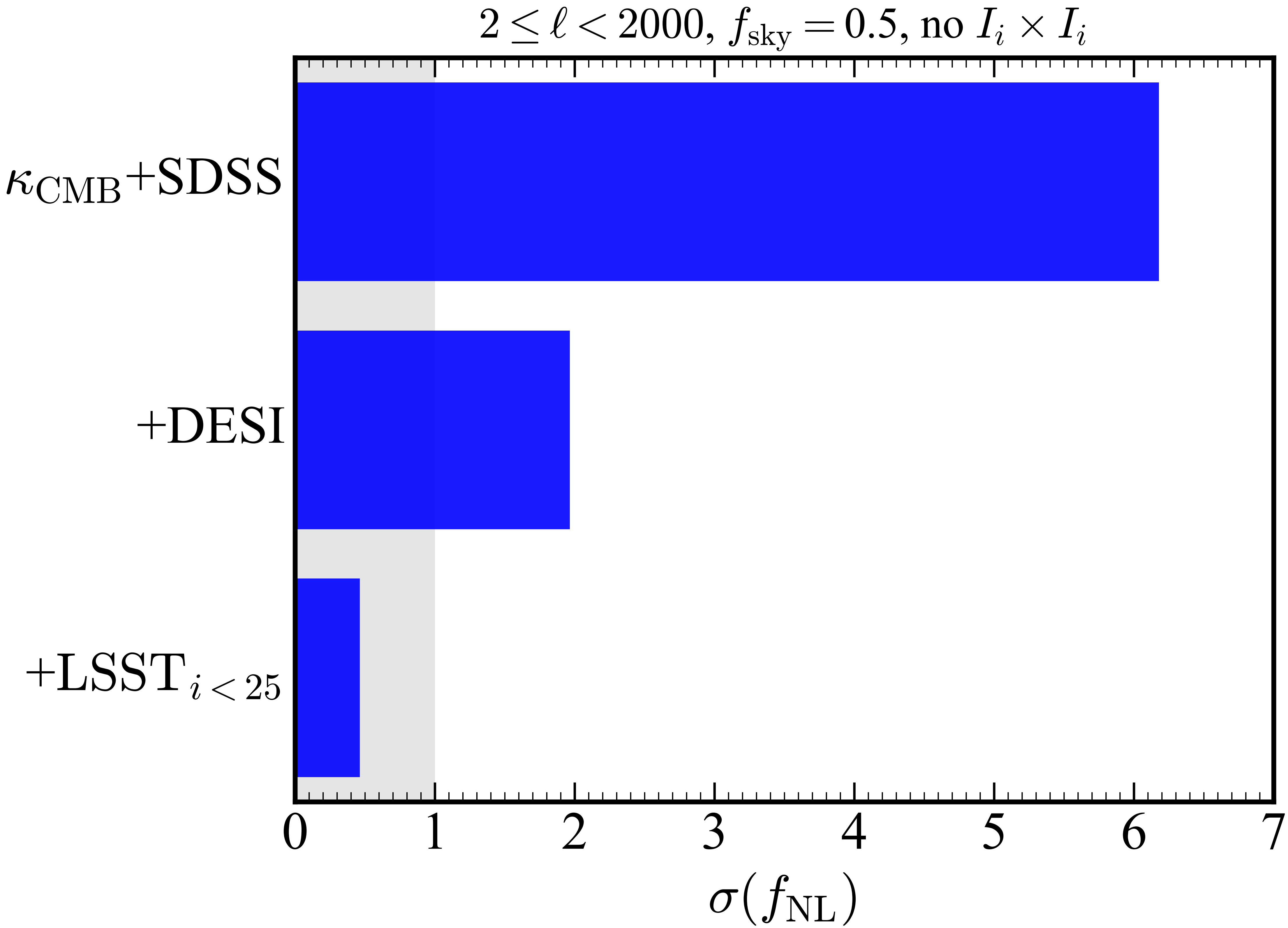
(dn/dz matched to CMB lensing kernel, no shot noise, bias b=1+z)



- **2x better if more galaxies at 2<z<6**
- **Only 10% better with g-g auto**

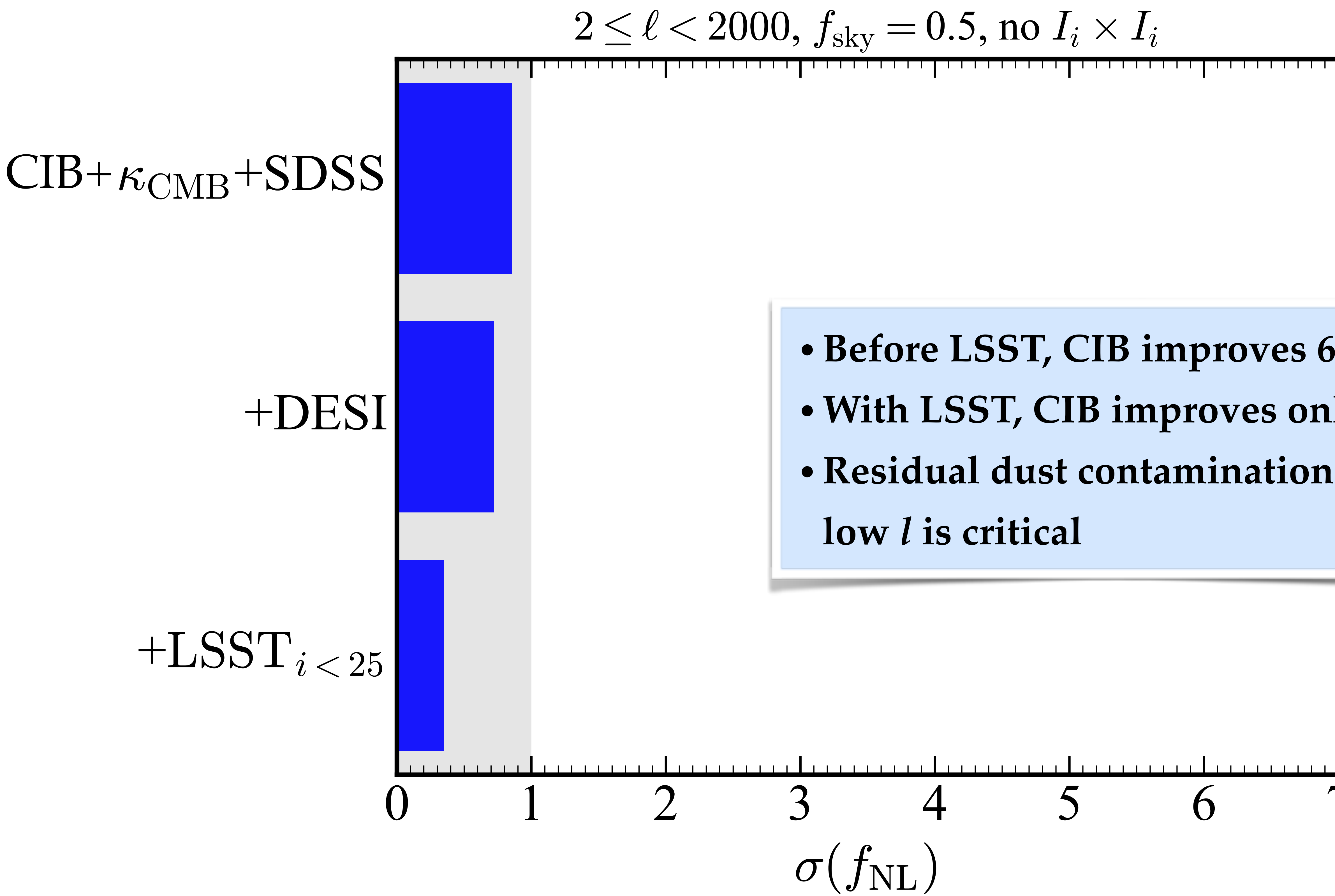
No LSS auto spectra, all LSS cross spectra. Marginalize over bias parameters and fake $f_{\rm NL}$. CMB lensing: $\sigma_{\rm FWHM}=1'$, $N_{TT}=1$ μK′.

NO CIB



No LSS auto spectra, all LSS cross spectra. Marginalize over bias parameters and fake $f_{\rm NL}$. CMB lensing: $\sigma_{\rm FWHM} = 1'$, $N_{TT} = 1\ \mu K'$.

WITH CIB



- **Before LSST, CIB improves 6x-2x**
- **With LSST, CIB improves only 20%**
- **Residual dust contamination at low *l* is critical**

No LSS auto spectra, all LSS cross spectra. Marginalize over bias parameters and fake $f_{\rm NL}$. CMB lensing: $\sigma_{\rm FWHM} = 1'$, $N_{TT} = 1$ μK′.
CIB: 4 Planck frequencies, assume their best-fit model and 1% residual dust.

PRIMORDIAL NON-GAUSSIANITY

- LSS probes $f_{\rm NL}$~1. Multi-field inflation would be ruled out if $f_{\rm NL}$>1!
- **Adding CMB lensing to LSS helps (10x improvement with LSST)**
- Can exclude galaxy-galaxy auto spectra. Then, unknown auto systematics
  - do not bias expectation values $\langle C_\ell^{AB} \rangle$
  - only affect error bars as $\mathrm{var}(C_\ell^{AB}) = \left[(C_\ell^{AB})^2 + C_\ell^{AA} C_\ell^{BB}\right] / (2\ell + 1)$
- Alternatively, go to space and use galaxy-galaxy auto: SPHEREx
- Adding more galaxies at $2 < z < 6$ helps
- Very sensitive to $l_{\rm min}$, i.e. need large area

  Also sensitive to shot noise
- CIB could also help, but worry about residual dust contamination at low l

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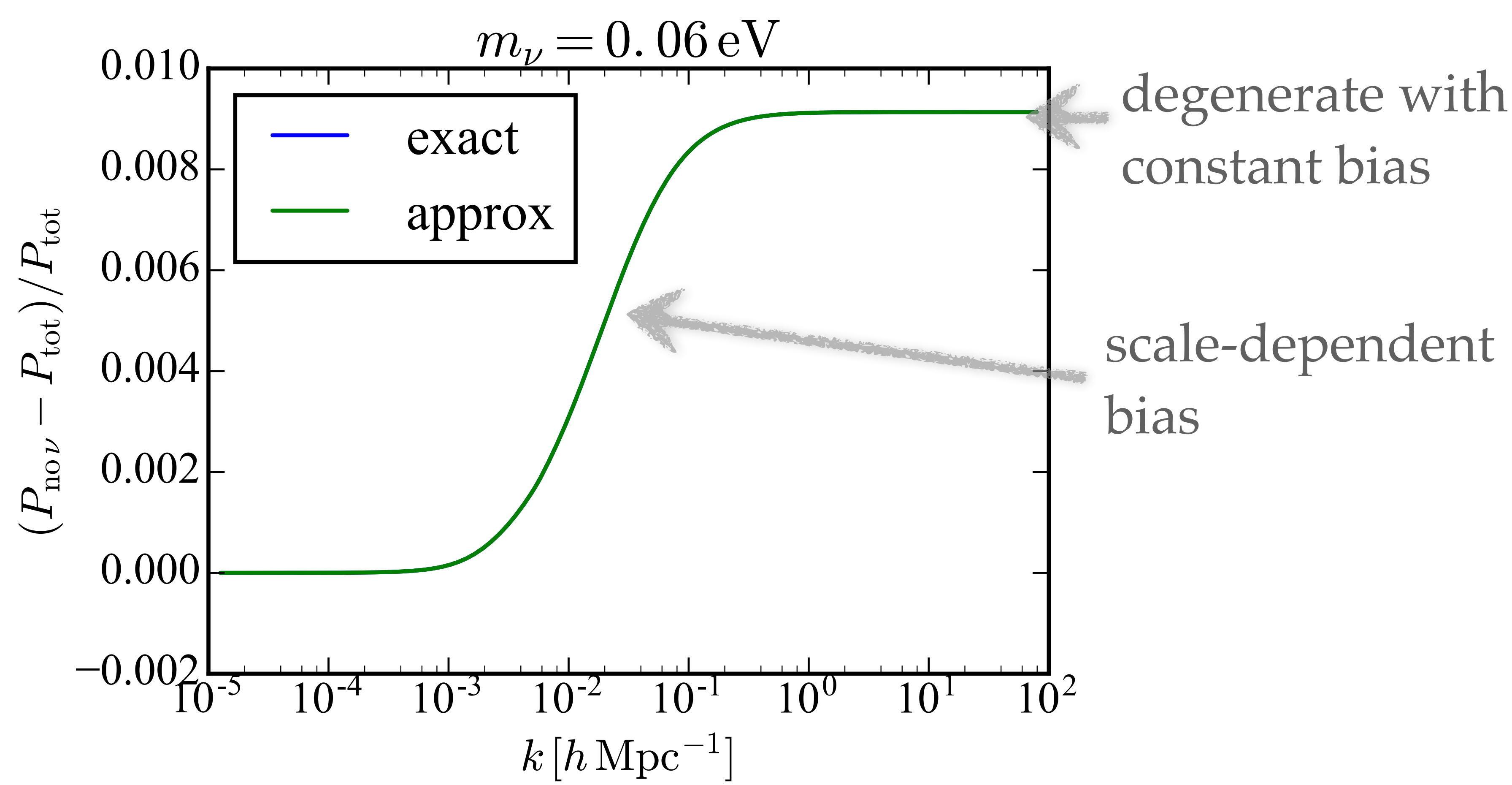
NEUTRINO MASS

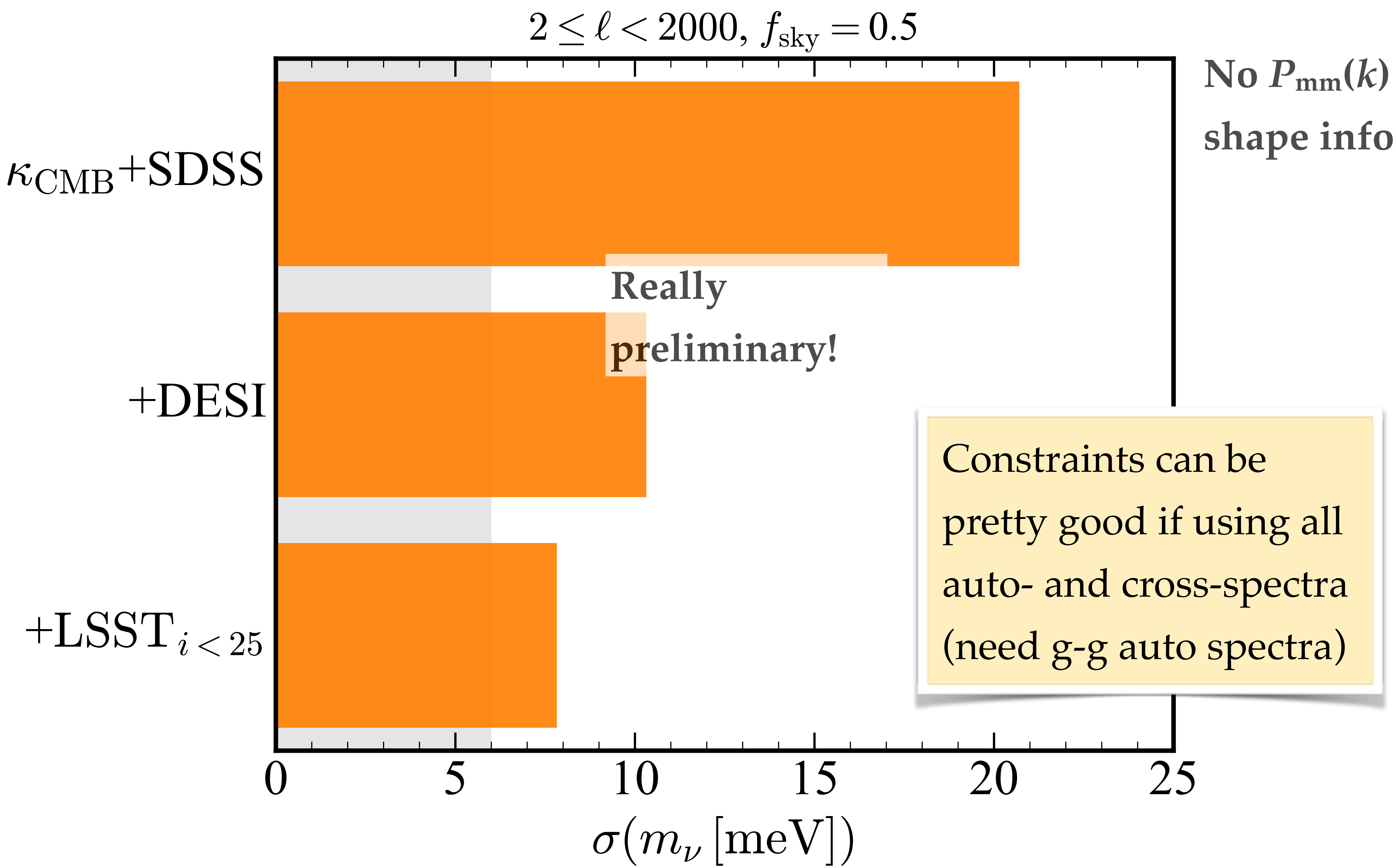
NEUTRINO MASS

Villaescusa-Navarro et al (2014)
LoVerde (2016)

- **Ignore main signal** from shape of total matter power spectrum
- Only use signal from scale-dependent bias $\frac{\Delta b}{b} = \frac{1}{m_\nu^{\rm fid}} \frac{P_{\rm tot,no\nu}(k,z) - P_{\rm tot,tot}(k,z)}{P_{\rm tot,tot}(k,z)}$
- This adds to main signal from shape of total matter power spectrum (independent information)



NEUTRINO MASS FROM SCALE-DEPENDENT BIAS



Constraints can be pretty good if using all auto- and cross-spectra (need g-g auto spectra)

All LSS auto- and cross-spectra. Marginalize over bias parameters but not fake m_ν. CMB lensing: $\sigma_{\rm FWHM} = 1'$, $N_{TT} = 1\ \mu K'$.

NEUTRINO MASS FROM SCALE-DEPENDENT BIAS

No $P_{mm}(k)$ shape info

- **Promising constraints from CMB lensing x LSS**
- **Need galaxy-galaxy auto**
- Sensitive to CMB-S4 specifications: 2x worse CMB beam and noise degrades $\sigma(m_\nu)$ from scale-dependent bias by ~30%
- Depends on l_{max} (e.g. 1.5-2x worse for l_{max}=1000 instead of 2000)
- Degeneracies with changes of total matter power spectrum can degrade constraints somewhat (1.5x-2x)

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MEASURING BIAS / 3D DARK MATTER

BIAS CONSTRAINTS / 3D DARK MATTER

Ue-Li Pen (2004)

- With signal-dominated CMB lensing maps, can constrain bias
- Error should go like $1/N_{\text{modes}}$, so sub-% level achievable
- Error even smaller with sampling variance cancellation (by $1/(1-r^2)$)
- Once bias parameters all measured:
  - Divide each sample by its bias to get dark matter density at each redshift
  - Get 3D dark matter modes of the universe, including their amplitude!

CONCLUSIONS

- CMB lensing x LSS is useful for primordial non-Gaussianity, neutrino mass, and measuring 3D dark matter modes
- Relies on sampling variance cancellation to measure scale-dependent bias
- Especially CMB lensing x LSST very promising for f_{NL}
- f_{NL} forecasts promising even if galaxy-galaxy auto-spectra are excluded (avoiding unknown systematics)
- Neutrino mass constraints from scale-dependent bias need galaxy-galaxy auto-spectra
- All preliminary! Comments welcome :)

BONUS SLIDES

FORECAST INGREDIENTS: FISHER ANALYSIS

- Fisher analysis at the field level

$$F_{ij} = \sum_{\ell} \frac{2\ell+1}{2} \sum_{abcd=0}^{1} \frac{\partial C_\ell^{ab}}{\partial \theta_i} (C^{-1})_\ell^{bc} \frac{\partial C_\ell^{cd}}{\partial \theta_j} (C^{-1})_\ell^{da}$$

- Fisher analysis at the power spectrum level

$$F_{ij} = \sum_{\ell} \frac{\partial \mathbf{d}_\ell}{\partial \theta_i} [\mathrm{cov}(\mathbf{d}_\ell, \mathbf{d}_\ell)]^{-1} \frac{\partial \mathbf{d}_\ell}{\partial \theta_j}.$$

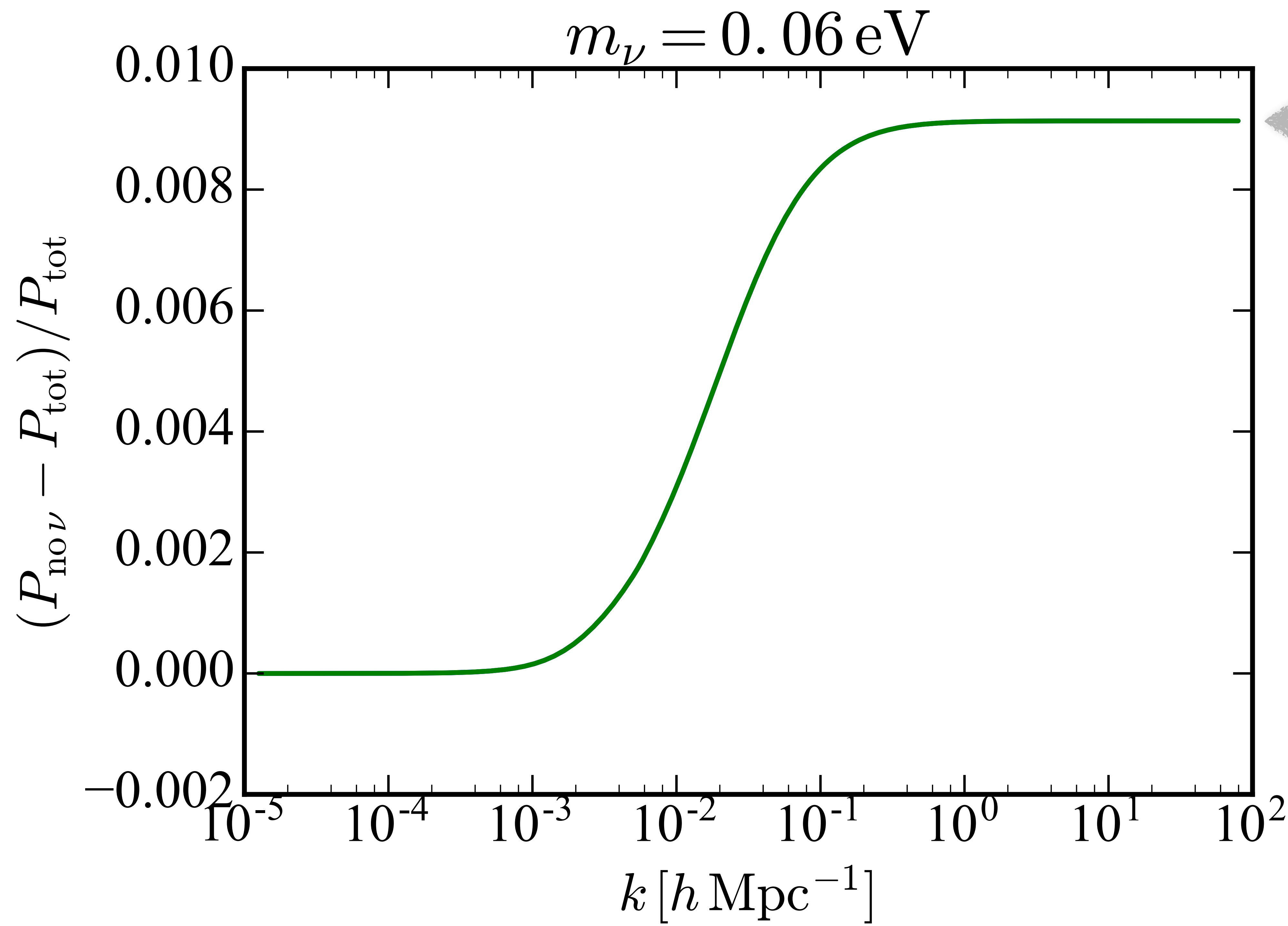
where $\mathbf{d} = (C_{\ell_{\min}}^{00}, C_{\ell_{\min}}^{01}, \ldots, C_{\ell_{\min}}^{0,N-1}, C_{\ell_{\min}}^{11}, C_{\ell_{\min}}^{12}, \ldots, C_{\ell_{\min}}^{1,N-1}, \ldots, C_{\ell_{\min}}^{N-1,N-1}, C_{\ell_{\min}+1}^{00}, \ldots, C_{\ell_{\max}}^{N-1,N-1}),$

$$\mathrm{cov}(\hat{C}_{\ell_1}^{UV}, \hat{C}_{\ell_2}^{U'V'}) = \delta_{\ell_1 \ell_2} \frac{1}{2\ell_1+1} \left(\hat{C}_{\ell_1}^{UU'} \hat{C}_{\ell_1}^{VV'} + \hat{C}_{\ell_1}^{UV'} \hat{C}_{\ell_1}^{VU'} \right)$$

- Agree if all power spectra and fields are included

SCALE-DEPENDENT BIAS FROM NEUTRINOS

Fractional change of power spectra for m_ν=1eV



degenerate with bias