Reconstructing the sky with CMB lensing methods

Omar Darwish (Cambridge)

STFC-CDT Funding

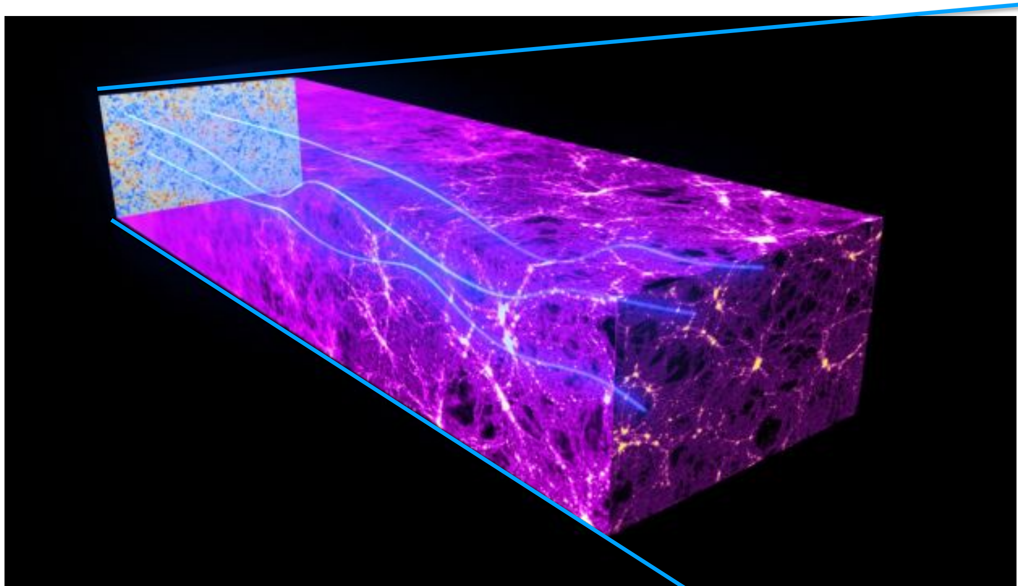
Outline

- ACT lensing maps and foreground-cleaned galaxy correlations
- Multitracer cosmological analysis from a single tracer

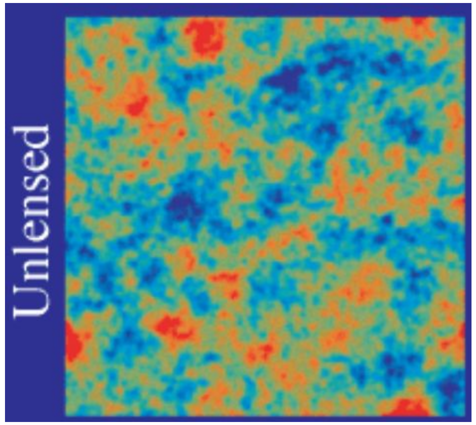
ACT lensing maps and foreground-cleaned galaxy correlations

with Blake Sherwin, Mathew Madhavacheril, Dongwon Han, Frank Qu, Toshiya Namikawa, Alexander van Engelen, Simone Ferraro, Noah Sailer, Emmanuel Schaan, Sultan Abylkairov, and the ACT Collaboration

Quick CMB lensing intro



From ESA, Planck



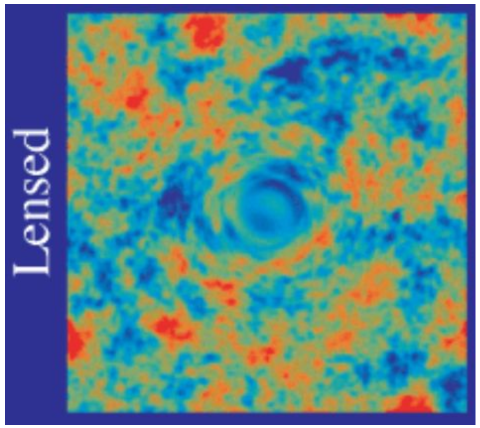
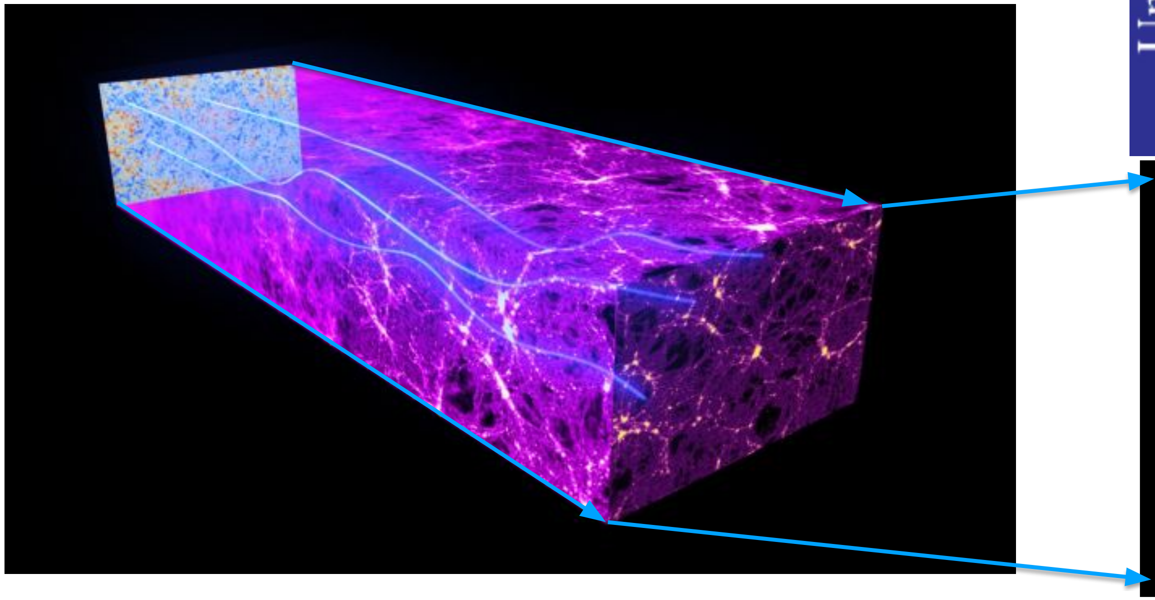


Image credit Hu, Okamoto 2001

Quick CMB lensing intro



From ESA, Planck

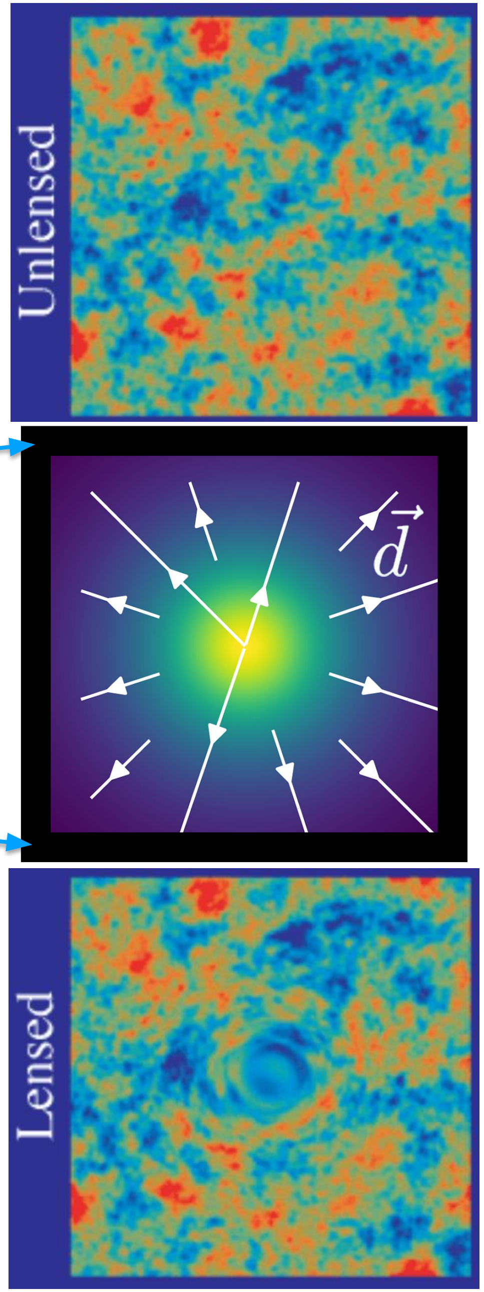
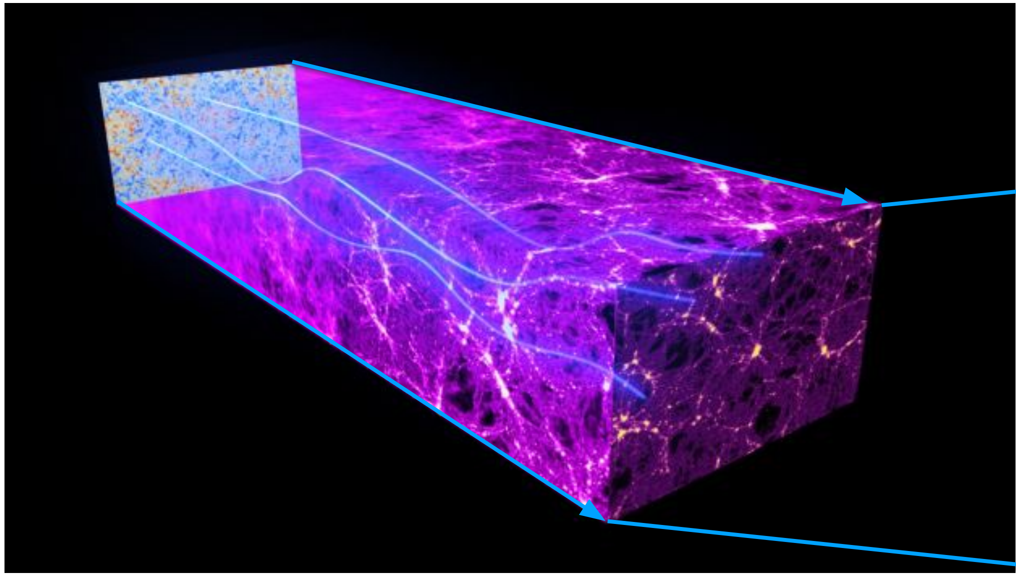


Image credit Hu, Okamoto 2001

Quick CMB lensing intro



From ESA, Planck

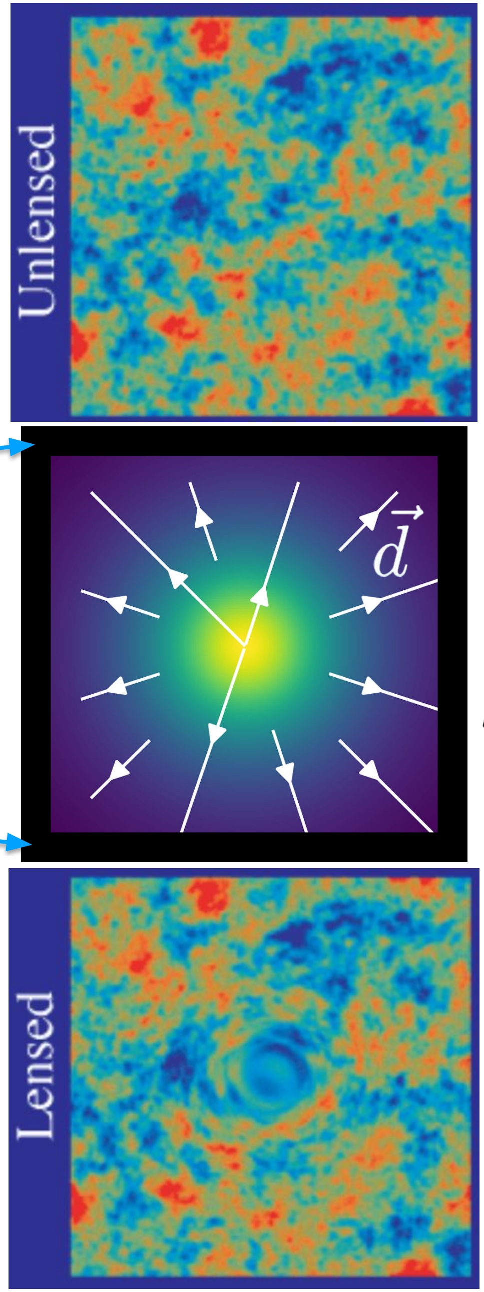


Image credit Hu, Okamoto 2001

We want

$$\kappa = \frac{1}{2}\vec{\nabla}\cdot\vec{d}$$

$$\kappa \sim \int_r dr W(r)\delta(r)$$

CMB lensing recon. basics

$$T(\vec{l}) = \tilde{T}(\vec{l}) + \int_{\vec{L}} \alpha(\vec{l}, \vec{l} - \vec{L}) \tilde{T}(\vec{l} - \vec{L}) \kappa(\vec{L})$$

$$\langle T(\vec{l}) T^*(\vec{l} - \vec{L}) \rangle_{CMB} \sim \kappa(\vec{L})$$

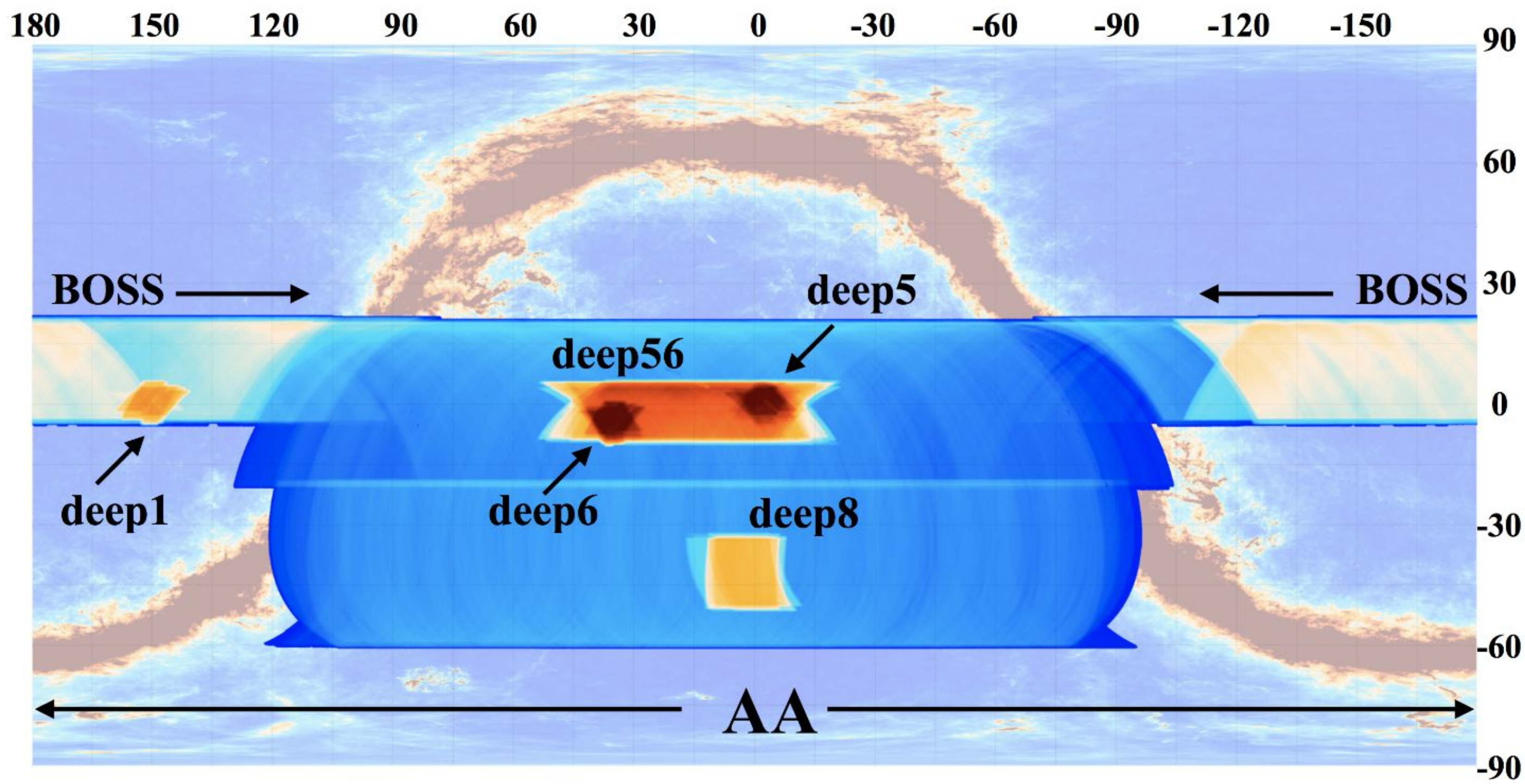
$$\hat{\kappa}(\vec{L}) \sim \sum_{\vec{l}} T_{\rm filt}(\vec{l}) T^*_{\rm filt}(\vec{l} - \vec{L})$$

Hu, Okamato (2001)

Alternative expression in real space

$$\hat{\kappa} \leftarrow \vec{\nabla} \cdot [T_{\rm filt} \vec{\nabla} T_{\rm filt}]$$

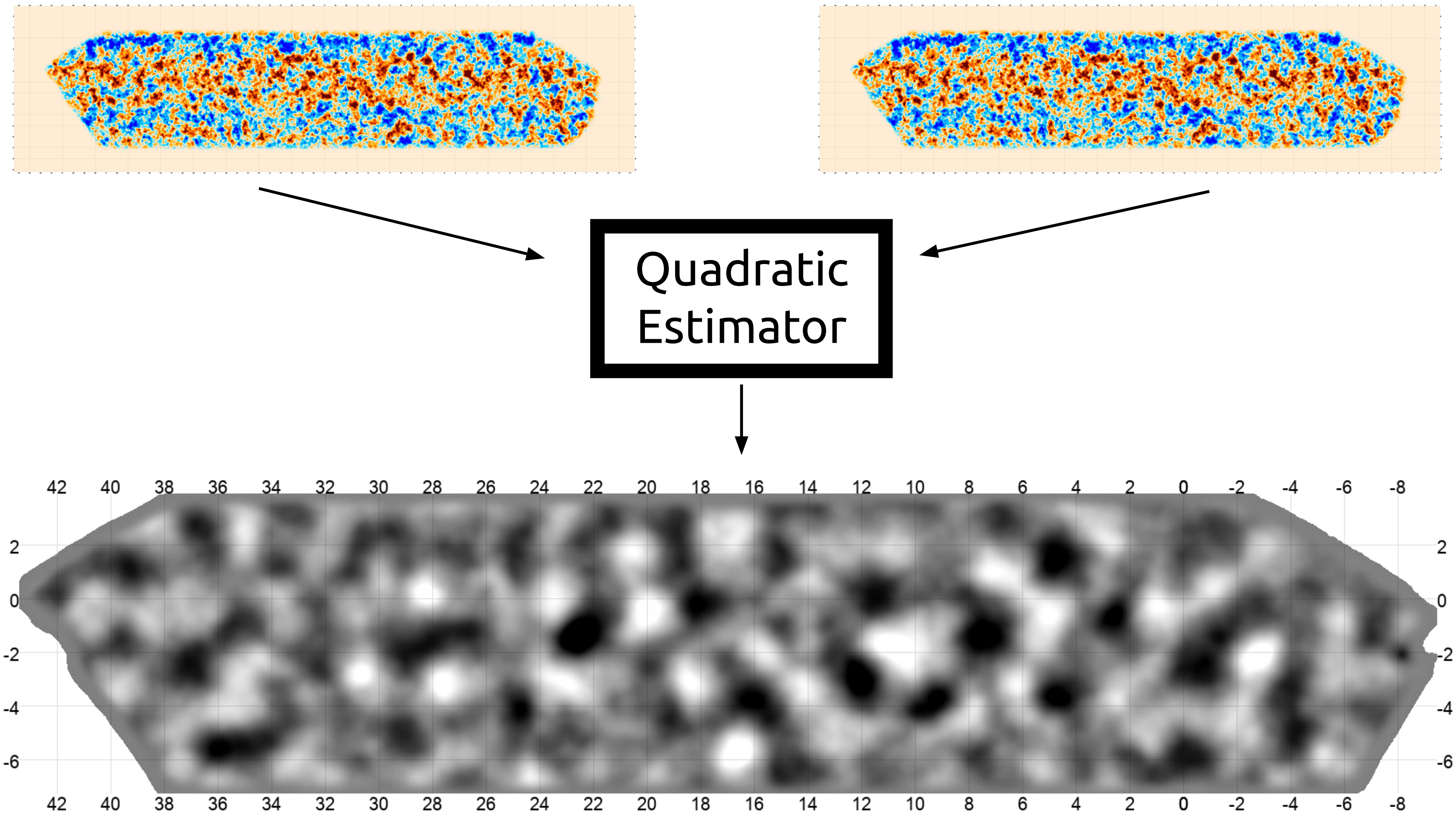
ACT survey



Credits: Simone Aiola

- ➢ Effective area BOSSN+Deep56 ~ 2100 sq deg
- ➢ Overlap with multiple surveys! (BOSS, DES,...)

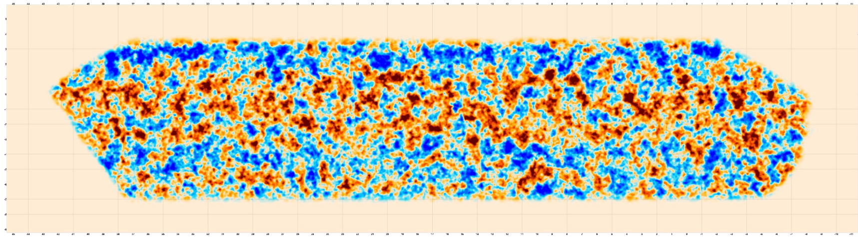
CMB lensing from ACT 2014-2015

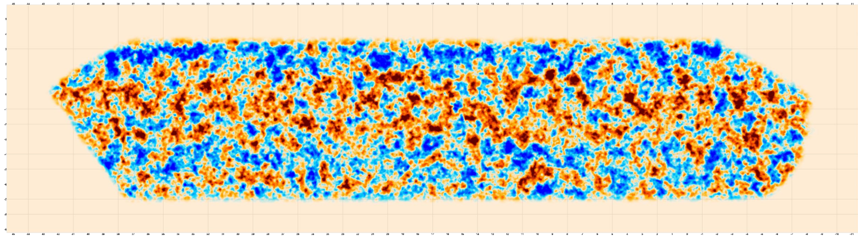


Darwish, Madhavacheril, Sherwin et al. (2020)

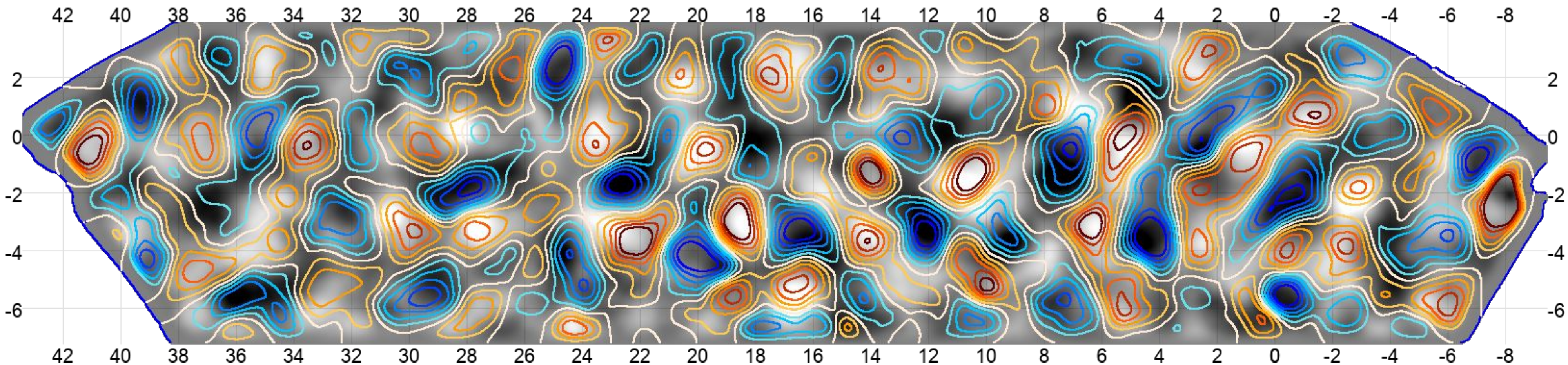
Deep56 ACTPol Lensing

CMB lensing from ACT 2014-2015





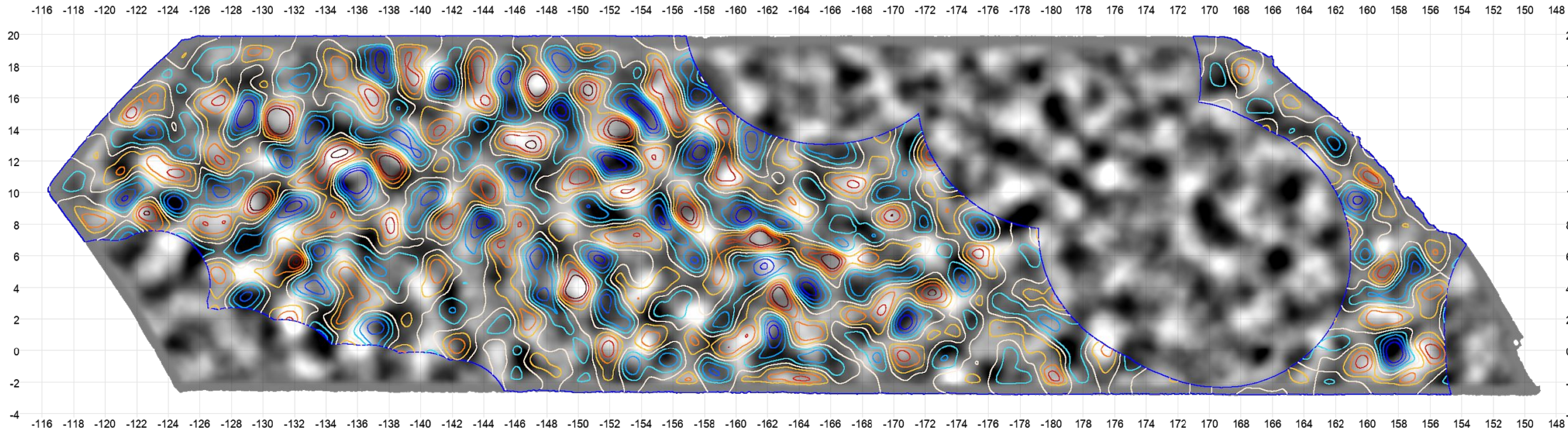
Quadratic
Estimator



See also Holder et al. (2013)

Deep56 ACTPol Lensing vs Planck CIB

CMB lensing from ACT 2014-2015



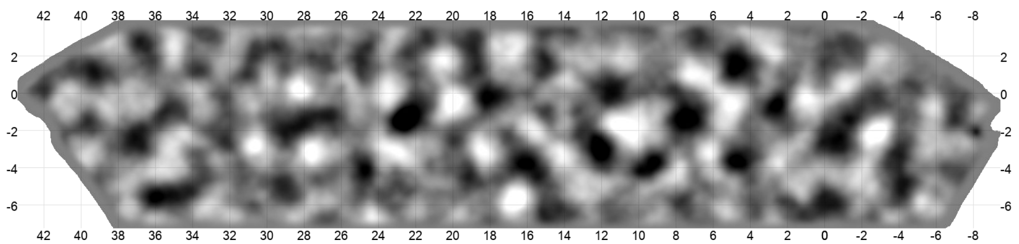
BOSSN ACTPol Lensing vs Planck CIB

Maps are available on LAMBDA!

ACT CMB lensing for cross correlations

CMB Lensing probes matter projected over a wide range of redshifts

Several applications for CMB Lensing Maps



x

Lensing

CIB

tSZ

Galaxies

…. use any tracer of matter density field

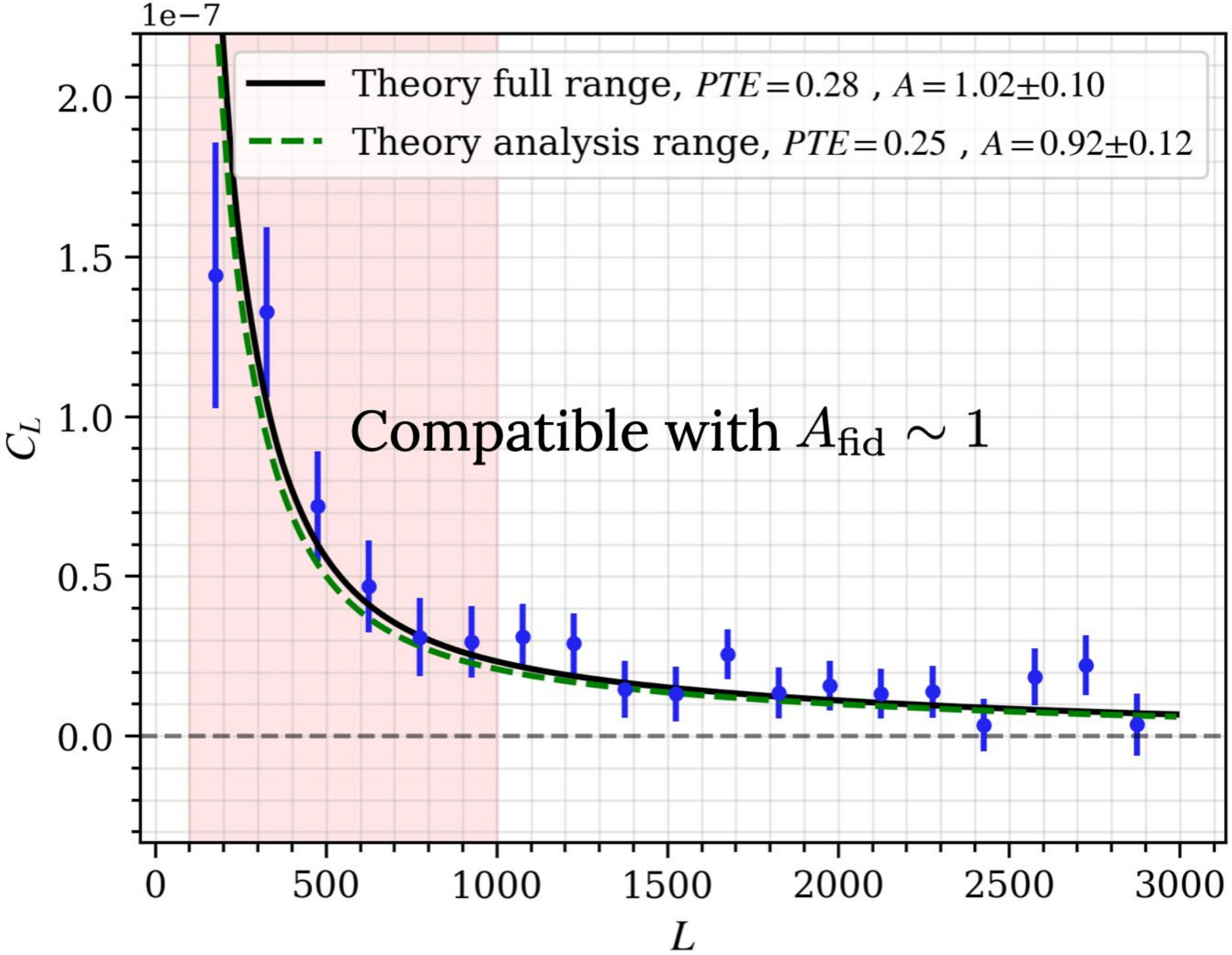
CMB lensing cross-correlation science motivation

Want to measure growth of structure, also vs redshift

Can use to constrain DE models, sum of neutrinos mass, and other cosmological parameters at low z (σ_8 **tensions?**)

How? Break degeneracy between galaxy bias and matter fluctuation amplitude with galaxy-galaxy [$b^2\sigma_8^2$] and galaxy-CMB [$b\sigma_8^2$] lensing measurements

ACTPol x BOSS CMASS



Darwish, Madhavacheril, Sherwin et al. (2020)

Next steps with ACT...

Advanced ACT CMB lensing map

PRELIMINARY

Credits: Madhavacheril, Qu+ in prep

Advanced ACT 17000 sq deg of observed sky

Great opportunity for CMB lensing analysis and cross-correlations!

ACT x unWISE

ACT up to 2018

Photometric catalog with more than 500 million galaxies

MV lensing by Madhavacheril, Qu and Namikawa, + ACT collaboration in prep.

x

unWISE

(made in Berkley)

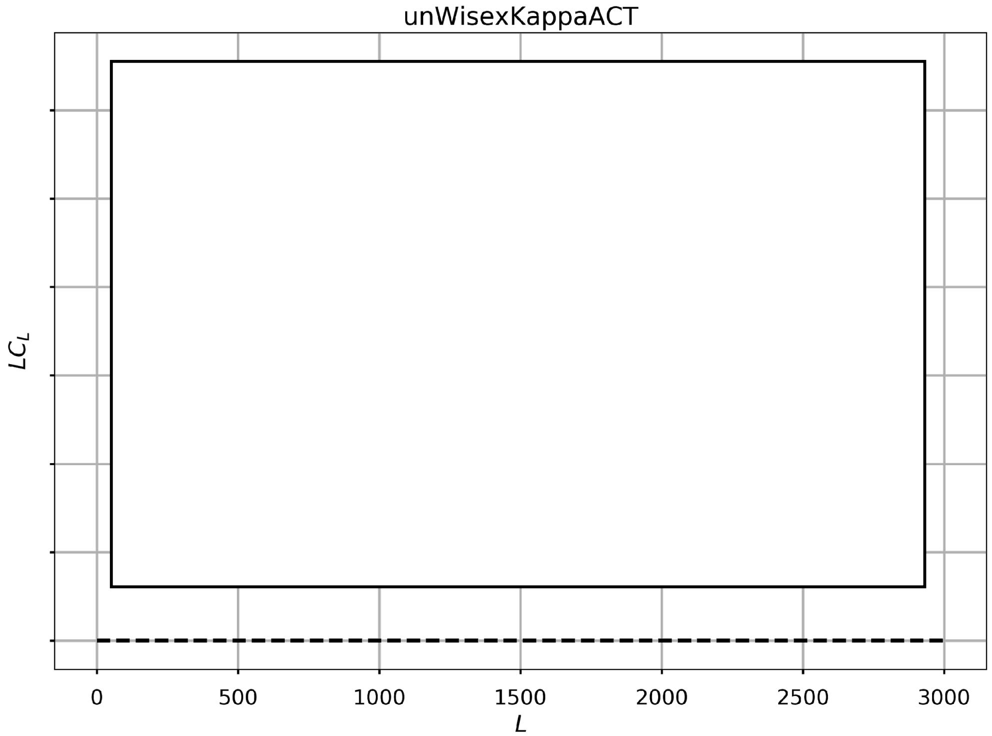
Covers redshifts [0, 2]

Galaxy over-density maps and window functions made by Krolewski, Ferraro, Schlafly, White 2019

See also Schlafly et al., 2019

ACT up to 2018 x unWISE

PRELIMINARY



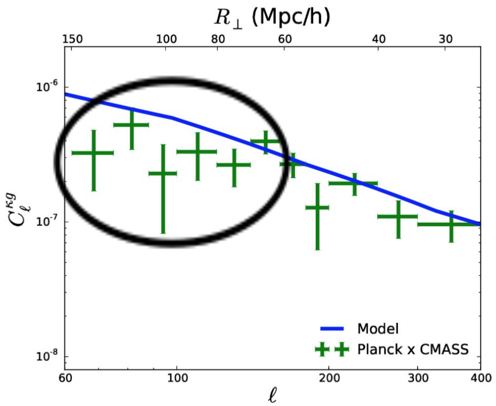
~ 79 sigma (1 redshift bin)

Things to consider:

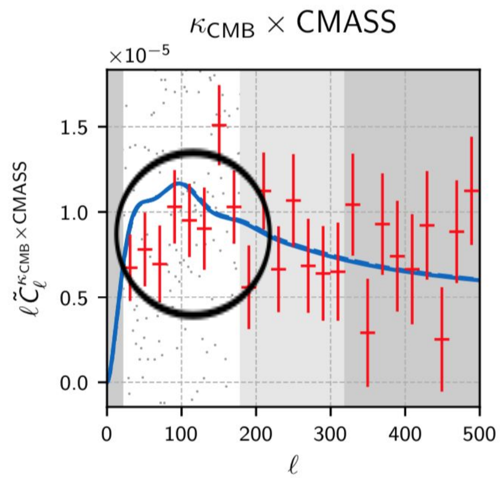
- Photo-z errors
- Non linear bias modelling and marginalisation
- **Foreground contribution limitation to high significance measurements.**

Darwish, Sherwin, Ferraro, Krolewski ++ in prep

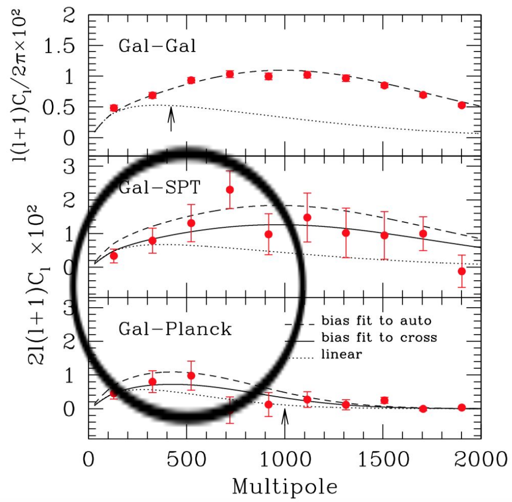
Another motivation...



Pullen et al., 2016 (PlanckxBOSS)



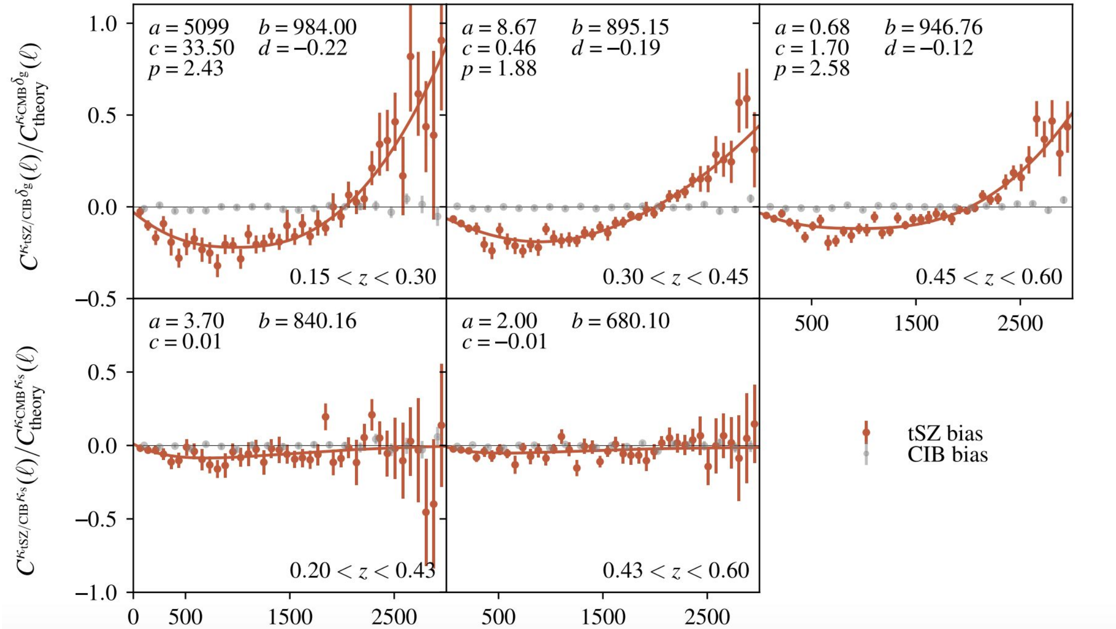
Doux et al., 2018 (PlanckxBOSS)



Giannantonio et al., 2016 (SPTxDES, PlanckxDES)

All discussed foreground effect.

Problem: lensing x low z galaxy tSZ contamination



On large scales, negative biases around ~ 10% (Baxter et al. 2019). See also van Engelen et al. 2014

E.g. (hand wavy estimate):

$$\frac{\Delta \sigma_8}{\sigma_8} \sim \frac{\Delta C^{\kappa g}}{C^{\kappa g}}$$

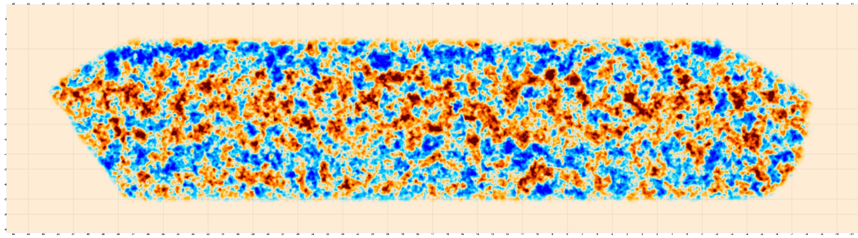
Bad with such tSZ systematic!

We want precision cosmology

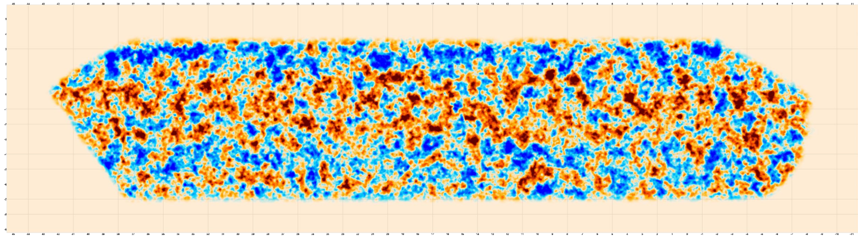
Improving cross-correlation measurement systematics

Systematics: tSZ contamination

CMB+tSZ+...



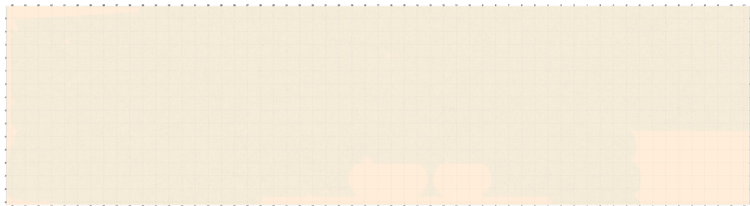
CMB+tSZ+...



Quadratic Estimator

Important for TT dominated lensing maps

x

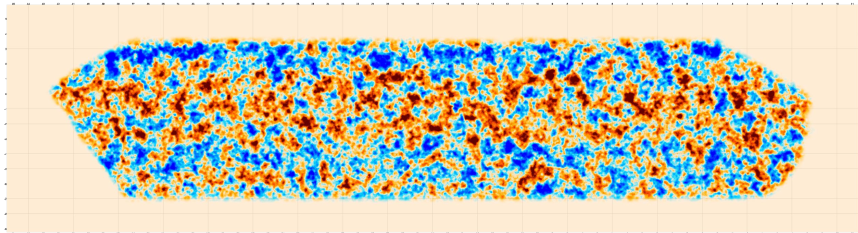


Negative Bias ~ 10-20%

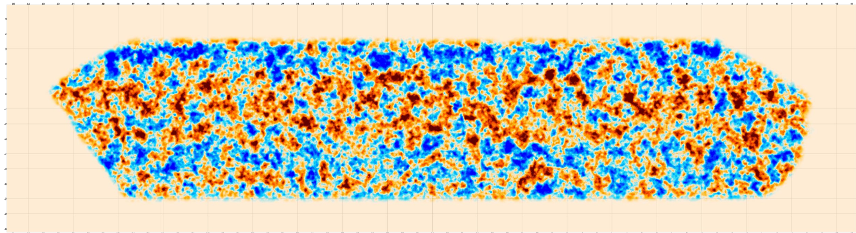
$$\langle g\hat{\kappa}\rangle \sim \langle gTT\rangle \sim \langle gT_{CMB}T_{CMB}\rangle + \boxed{\langle gT_{tSZ}T_{tSZ}\rangle} \text{ !!! } \longrightarrow \frac{\Delta\sigma_8}{\sigma_8} \sim \frac{\Delta C^{\kappa g}}{C^{\kappa g}}$$

What if I try multi-frequency cleaning on both legs...

no tSZ



no tSZ

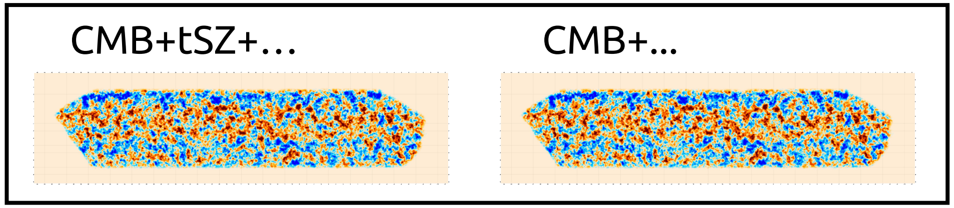


Quadratic Estimator

Cleaned lensing map!

Strong degradation in signal over noise of lensing map from temperature estimator

Removing tSZ contamination in CMB lensing x galaxy



Madhavacheril, Hill, (2018)

Hu, DeDeo, Vale (2007)

Non Gradient Leg

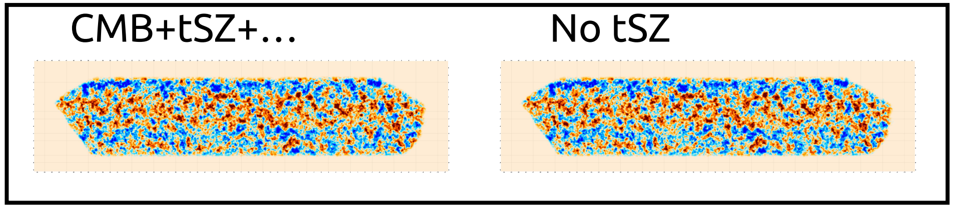
Gradient Leg

$$\hat{\kappa} \sim \vec{\nabla} \cdot (T \vec{\nabla} T_{\mathrm{notSZ}})$$

Removing tSZ contamination in CMB lensing x galaxy

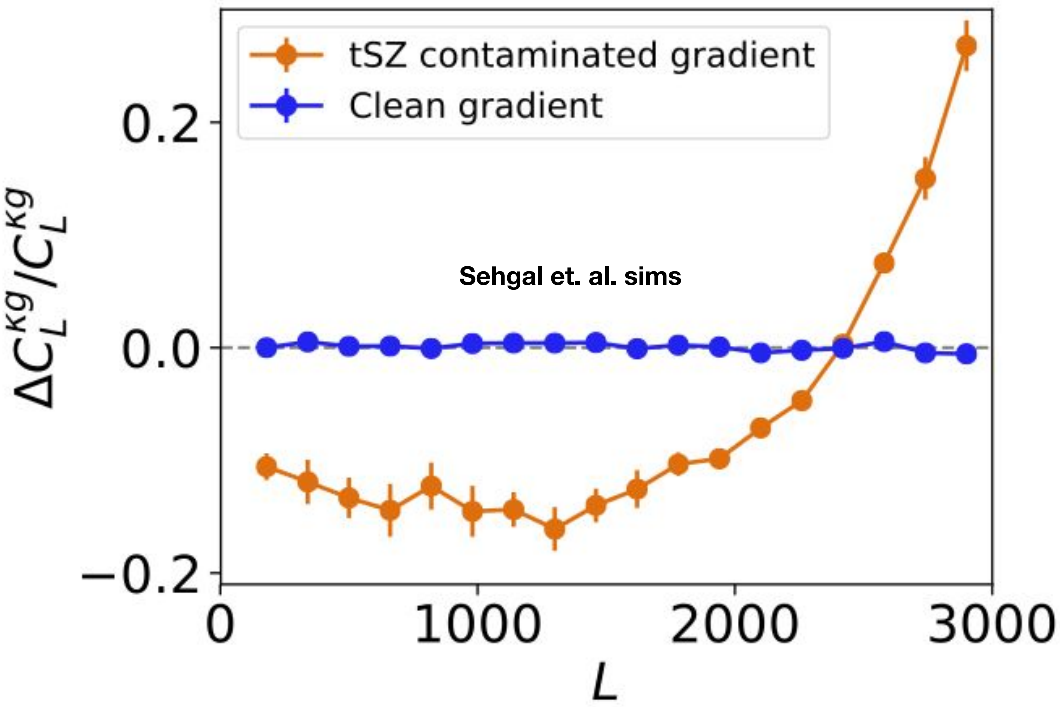
Non Gradient Leg

Gradient Leg



Madhavacheril, Hill, 2018 PRD

Hu, DeDeo, Vale (2007)



Bias << 1%!

Madhavacheril, Hill, 2018 PRD

tSZ cleaned CMB lensing maps from ILC ACT+Planck

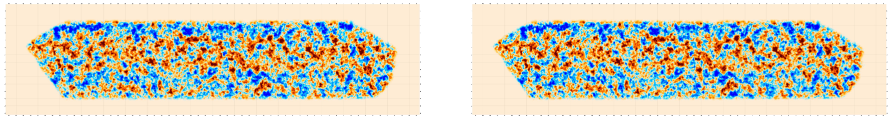
Madhavacheril, Hill, Naess (2019)

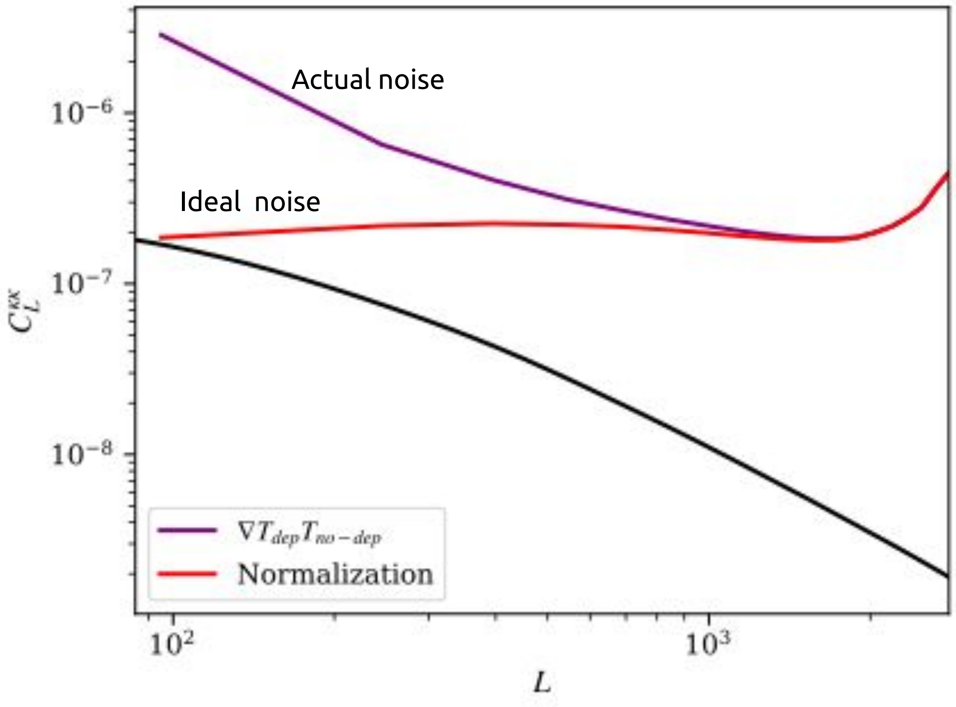
Non Gradient Leg

Gradient Leg

CMB+tSZ+…

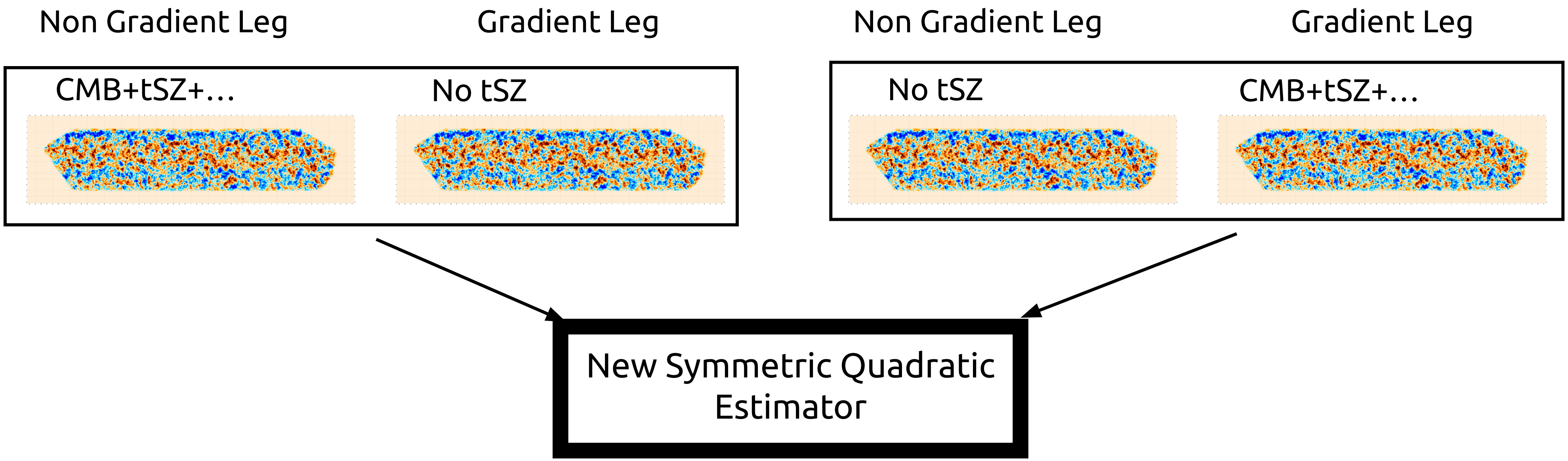
No tSZ

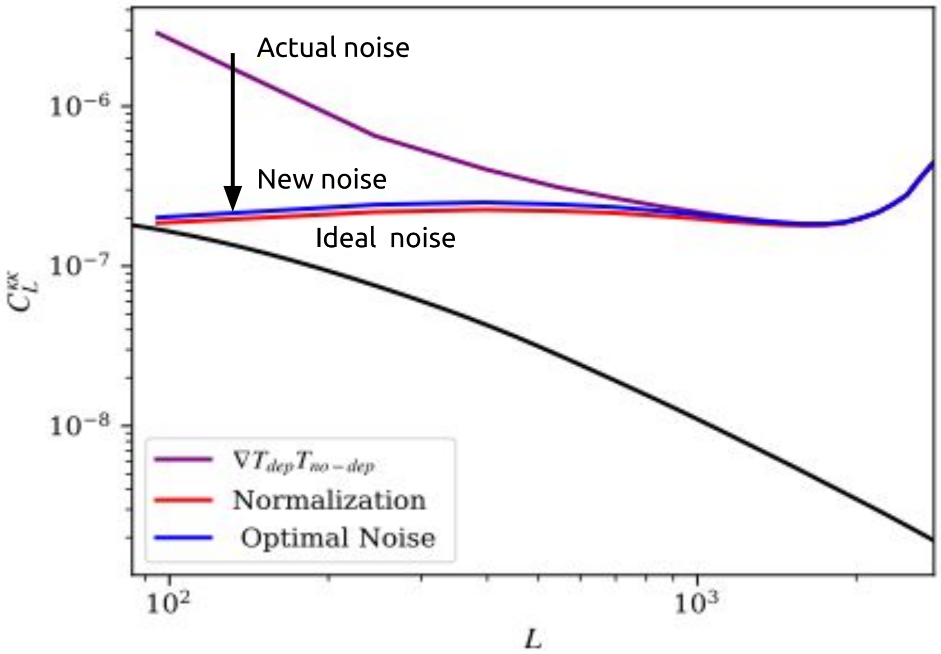




Still losing too much signal over noise!

Symmetrising gradient cleaning for foreground removal



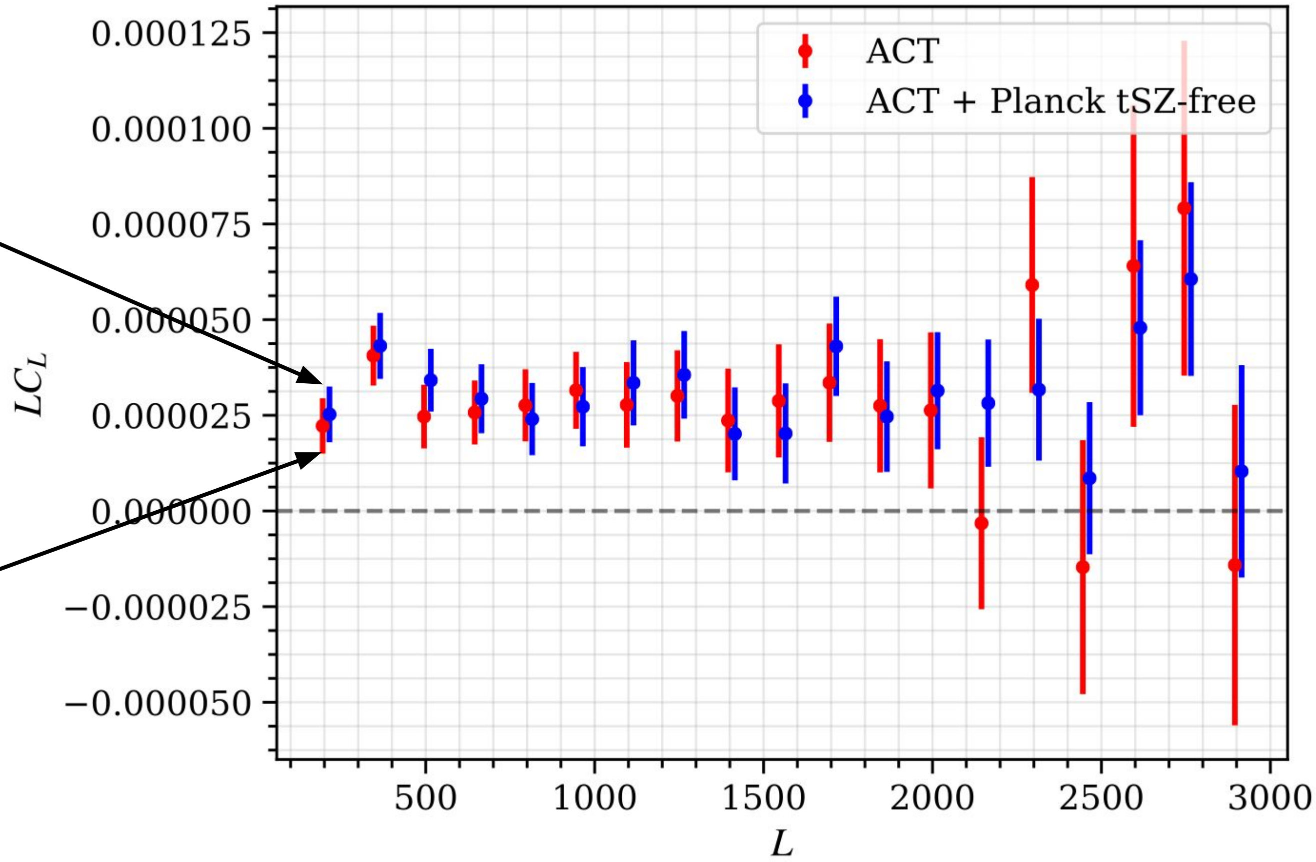


Ideal noise recovered!

Contaminated vs non contaminated measurement

tSZ Cleaned Measurement

Contaminated Measurement

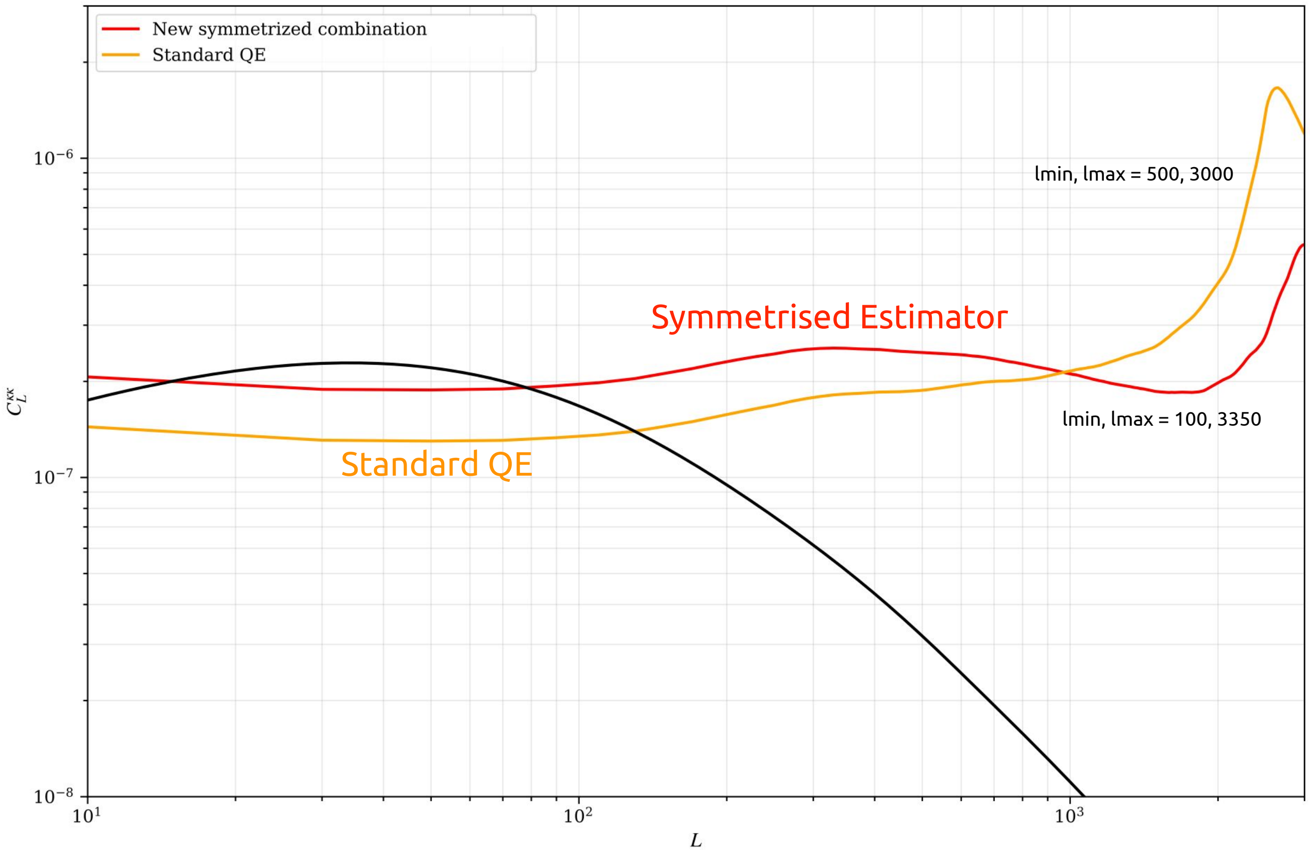


Standard and cleaned maps are available on LAMBDA!

Use CMASS BOSS

Noise curves

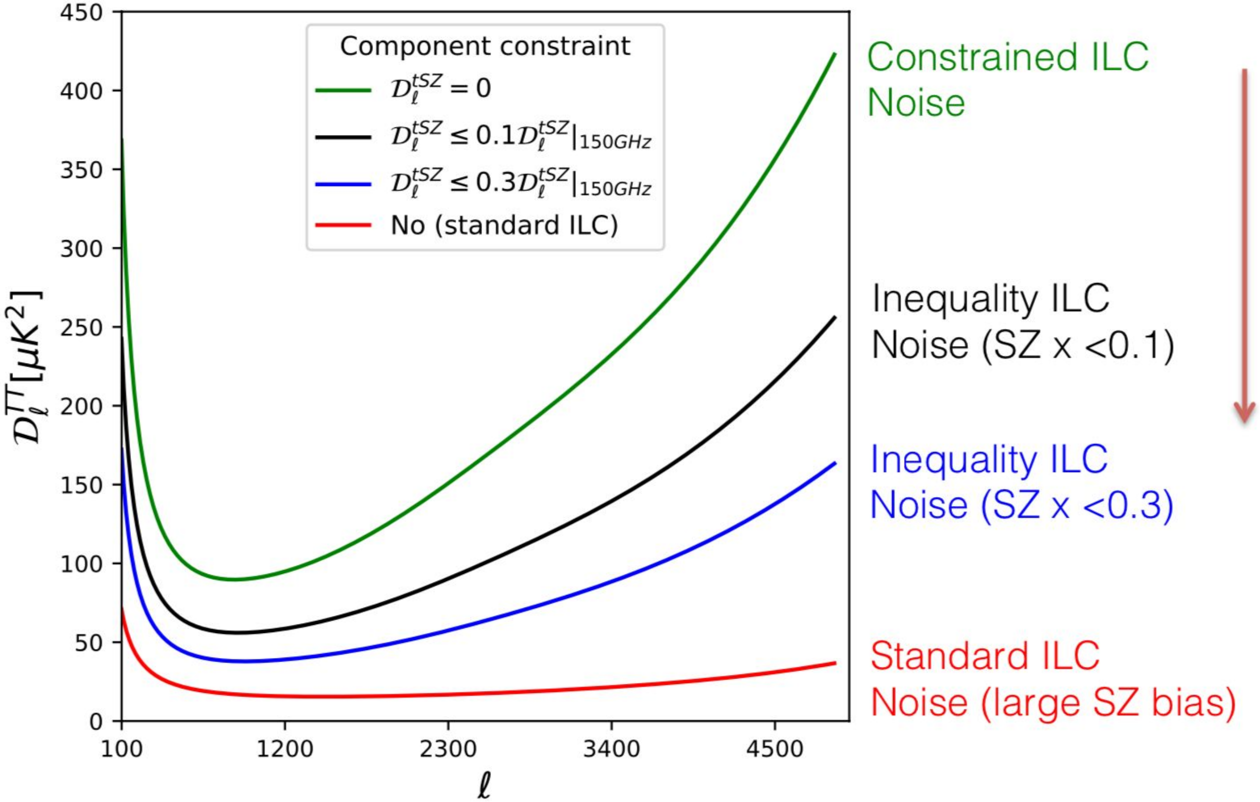
increase ~40% on large scales



Can we do better?

Ongoing work A
Improving frequency cleaning: Bias-Variance tradeoff

Sultan Abylkairov

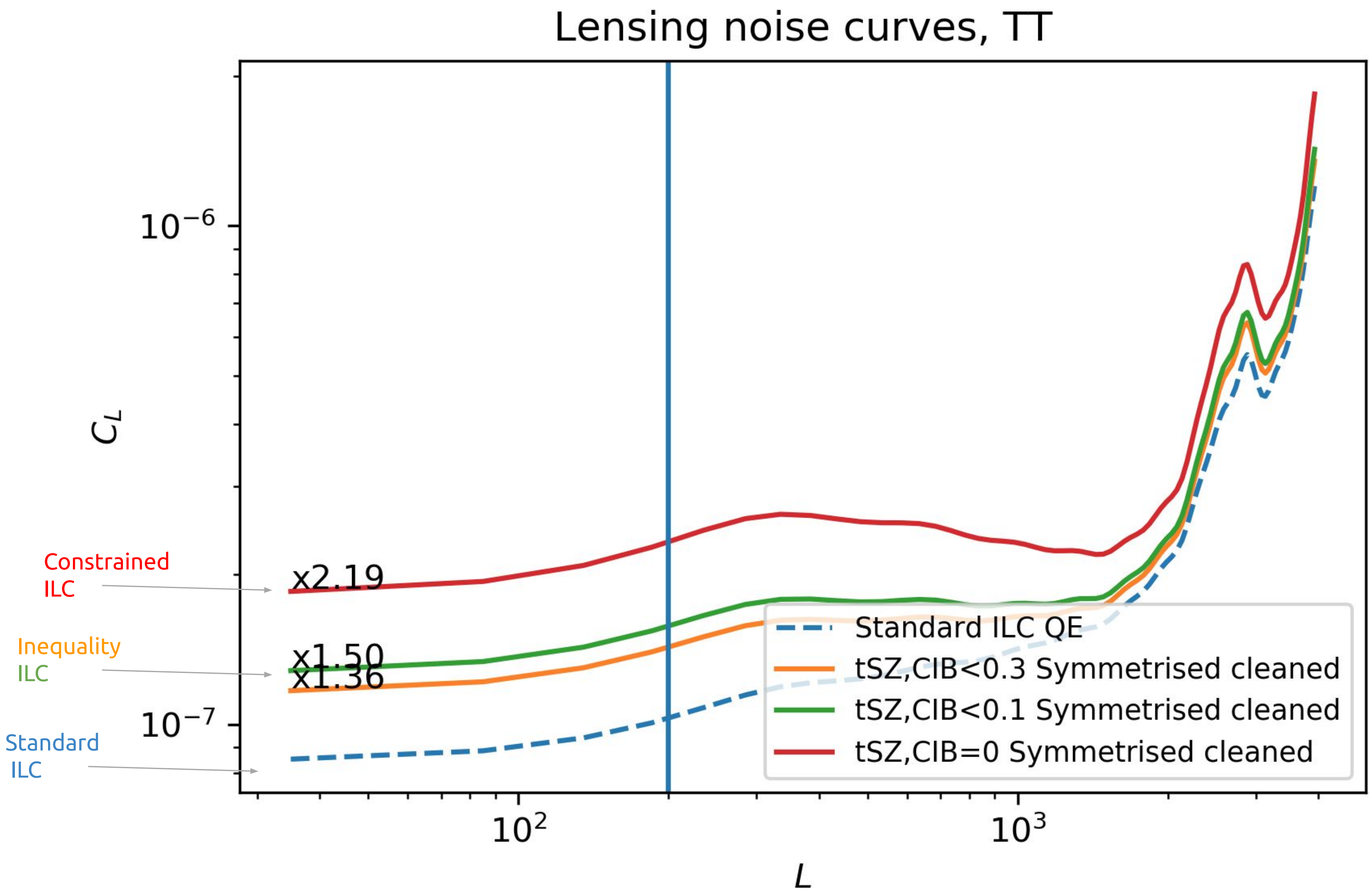


Preliminary result: can reduce noise level by factor ~2 while keeping foregrounds low (<~0.2x original)

Text credits: Blake Sherwin

Abylkairov, Darwishi, Sherwin, Hill in prep.

Ongoing work A
Improving frequency cleaning:
Bias-Variance tradeoff



Ongoing work B
Combining lensing estimators

Several different methods for reducing foreground biases: Shear,

Frequency clean, Bias Hardening,...

$$Q = a * \underbrace{\boxed{QE(l_{\mathrm{max,QE}}, T_{QE})}}_{\text{QE}} + b * \underbrace{\boxed{SH(l_{\mathrm{max,SH}}, T_{Sh})}}_{\text{Shear}} + c * \underbrace{\boxed{BH(l_{\mathrm{max,BH}}, T_{Bh})}}_{\text{Bias Hardening}} + d * \underbrace{\boxed{A(l_{\mathrm{max,A}}, T_{A})}}_{\text{Frequency clean}} + ...$$

What is the best combination of these methods

that gives you smallest bias impact and noise

penalty, for an auto and cross spectra analyses?

With Noah Sailer,
Simone Ferraro,
Emmanuel Schaan,
Blake Sherwin)

Ongoing work B
Combining lensing estimators, basic idea

Preliminary

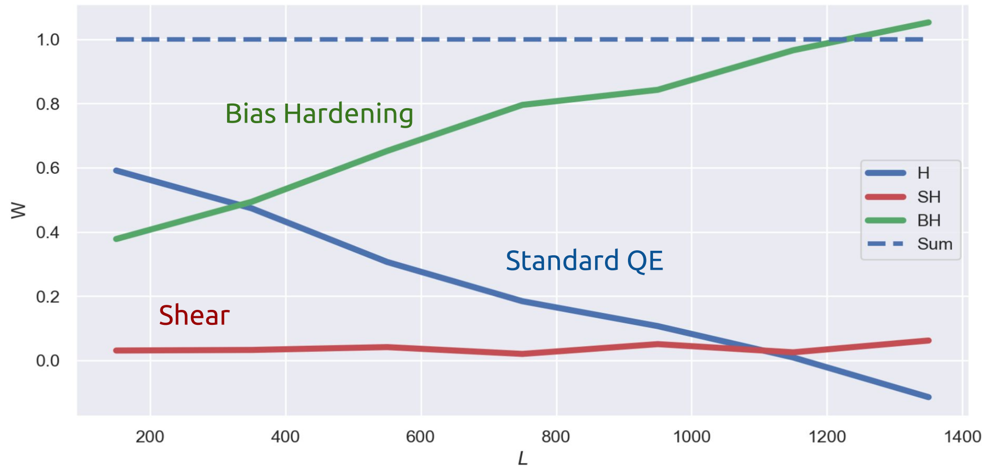
Look at bias in the combined amplitude on the spectrum

$$\hat{A} \sim \int_{\vec{L}} \sum_i \hat{A}_i(\vec{L})$$

$$min_W \{\sigma^2(\hat{A}) + M(B(\hat{A}))\}$$

Variance Measure of the bias impact

Weights



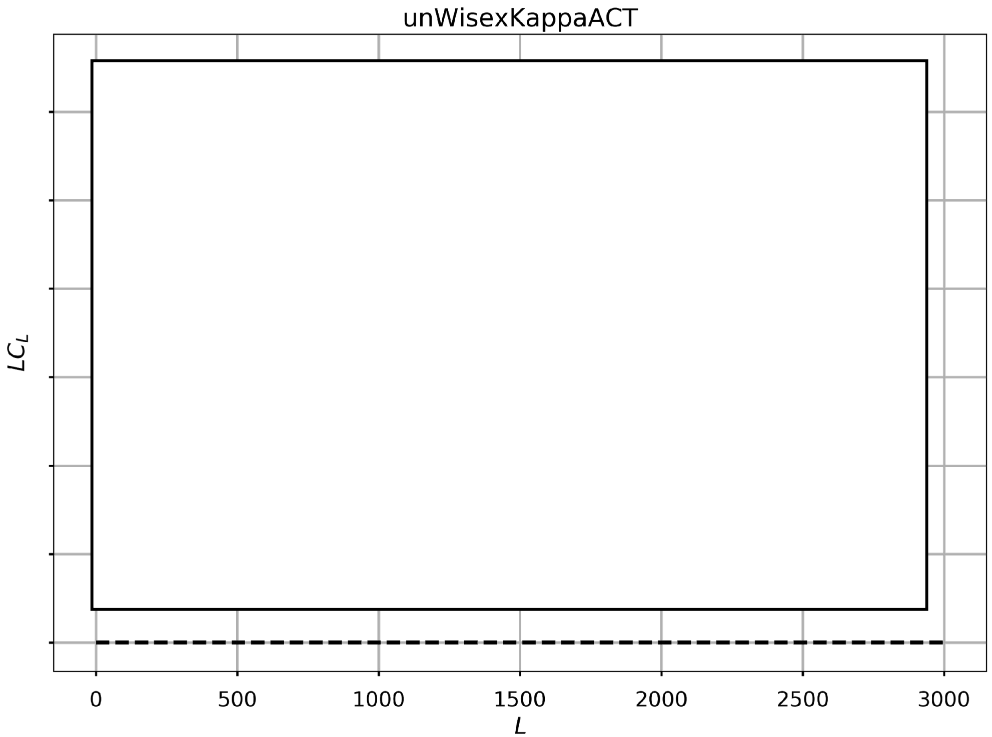
$$Q(\vec{L}) = \sum_i W_i(\vec{L}) \int_{\vec{l}} g_i(\vec{l}, \vec{L}) T_{i1}(\vec{l}) T_{i2}(\vec{L} - \vec{l})$$

Conclusions

- CMB Lensing cross-correlation science **quickly advancing** with new lensing maps: measurements of ACTPol x CMASS(SNR~10), AdvACT x unWISE(SNR > 80),....

- Importance of accounting for systematics and theoretical modelling will be crucial. In particular **extragalactic foreground biases** (SZ, CIB,….).

- Developed/Developing several new avenues for **cleaning of foreground contamination**: at CMB frequency level and at geometric level.



Multitracer cosmological analysis from a single tracer

with Simon Foreman, Muntazir Abidi, Tobias Baldauf, Blake Sherwin and Daan Meerburg

CMB lensing reconstruction again

$$T(\vec{l}) = \tilde{T}(\vec{l}) + \int_{\vec{L}} \alpha(\vec{l}, \vec{l} - \vec{L}) \tilde{T}(\vec{l} - \vec{L}) \kappa(\vec{L})$$

$$\langle T(\vec{l}) T(\vec{L} - \vec{l}) \rangle_{\mathrm{CMB}} = K(\vec{l}, \vec{L}) \kappa(\vec{L})$$

$$\vec{L} \neq \vec{0}$$

$$\hat{\kappa}(\vec{L}) = \int_{\vec{l}} g(\vec{l}, \vec{L}) T(\vec{l}) T(\vec{L} - \vec{l})$$

CMB lensing reconstruction again

$$T(\vec{l}) = \tilde{T}(\vec{l}) + \int_{\vec{L}} \alpha(\vec{l}, \vec{l} - \vec{L})\tilde{T}(\vec{l} - \vec{L})\kappa(\vec{L})$$

$$\delta_g(\vec{k}) \approx b_1\delta_1(\vec{k}) + \int_{\vec{q}} F(\vec{q}, \vec{k} - \vec{q})\delta_1(\vec{q})\delta_1(\vec{k} - \vec{q})$$

$$\langle T(\vec{l})T(\vec{L} - \vec{l})\rangle_{\mathrm{CMB}} = K(\vec{l}, \vec{L})\kappa(\vec{L})$$

$$\vec{L} \neq \vec{0}$$

...

$$\hat{\kappa}(\vec{L}) = \int_{\vec{l}} g(\vec{l}, \vec{L})T(\vec{l})T(\vec{L} - \vec{l})$$

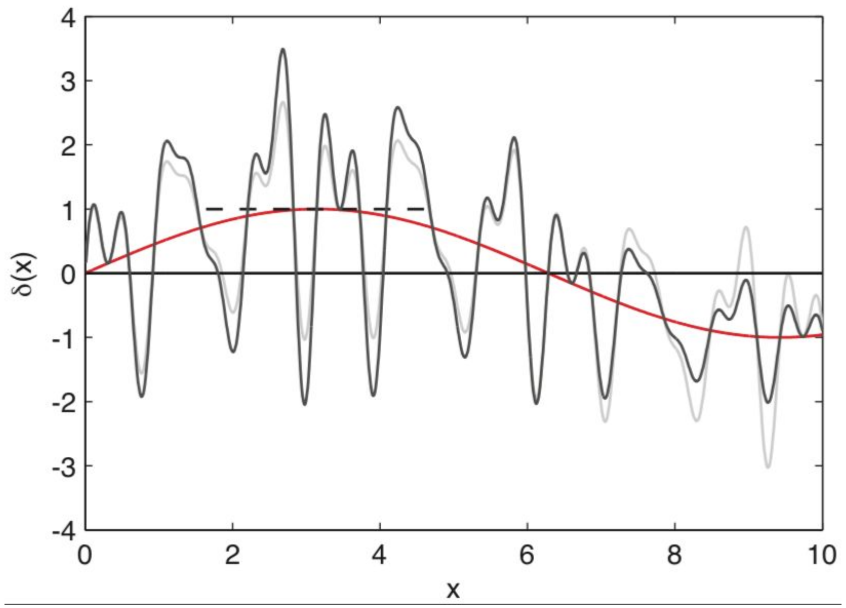
A simple model for the clustered field

$$\delta_g(\vec{k}) \approx b_1\delta_1(\vec{k}) + \int_{\vec{q}} F(\vec{q}, \vec{k} - \vec{q})\delta_1(\vec{q})\delta_1(\vec{k} - \vec{q})$$

E.g. $F \sim 1$ Growth term

Reconstructing the long wavelength mode

$$\langle \delta_{\rm g}(\vec{k})\delta_{\rm g}(\vec{K}-\vec{k})\rangle_{\delta_1(\vec{K})\text{fixed}} \sim f(\vec{k},\vec{K}-\vec{k})\delta_1(\vec{K}), \quad \vec{K}\neq\vec{0}$$



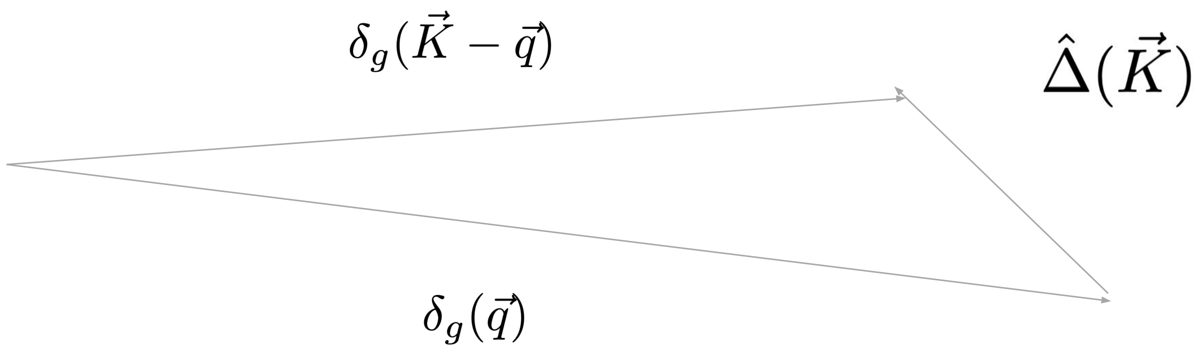
Fixed large scale

Reconstructing the long wavelength mode

Reconstruct long wavelength mode from the mode-coupling it induces into pairs of small scale modes. A second field:

$$\hat{\Delta}(\vec{K}) \sim \hat{\delta}_1 \sim \int_{\vec{q}, k_{\min} < |\vec{q}| < k_{\max}} g(\vec{q}, \vec{K} - \vec{q}) \delta_{\rm g}(\vec{q}) \delta_{\rm g}(\vec{K} - \vec{q})$$

e.g. , Foreman & Meerburg ++ 2018



Now we have two fields!

Reconstructing the long wavelength mode

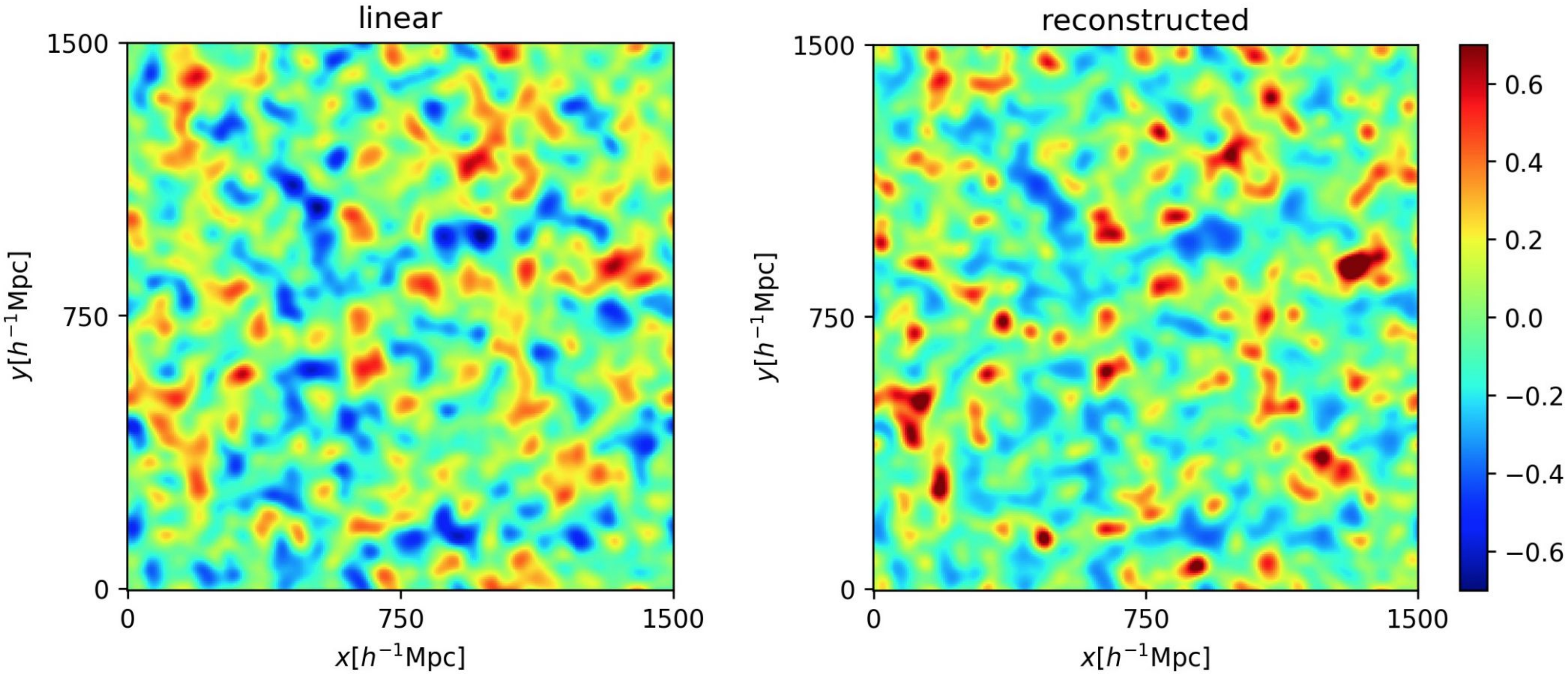
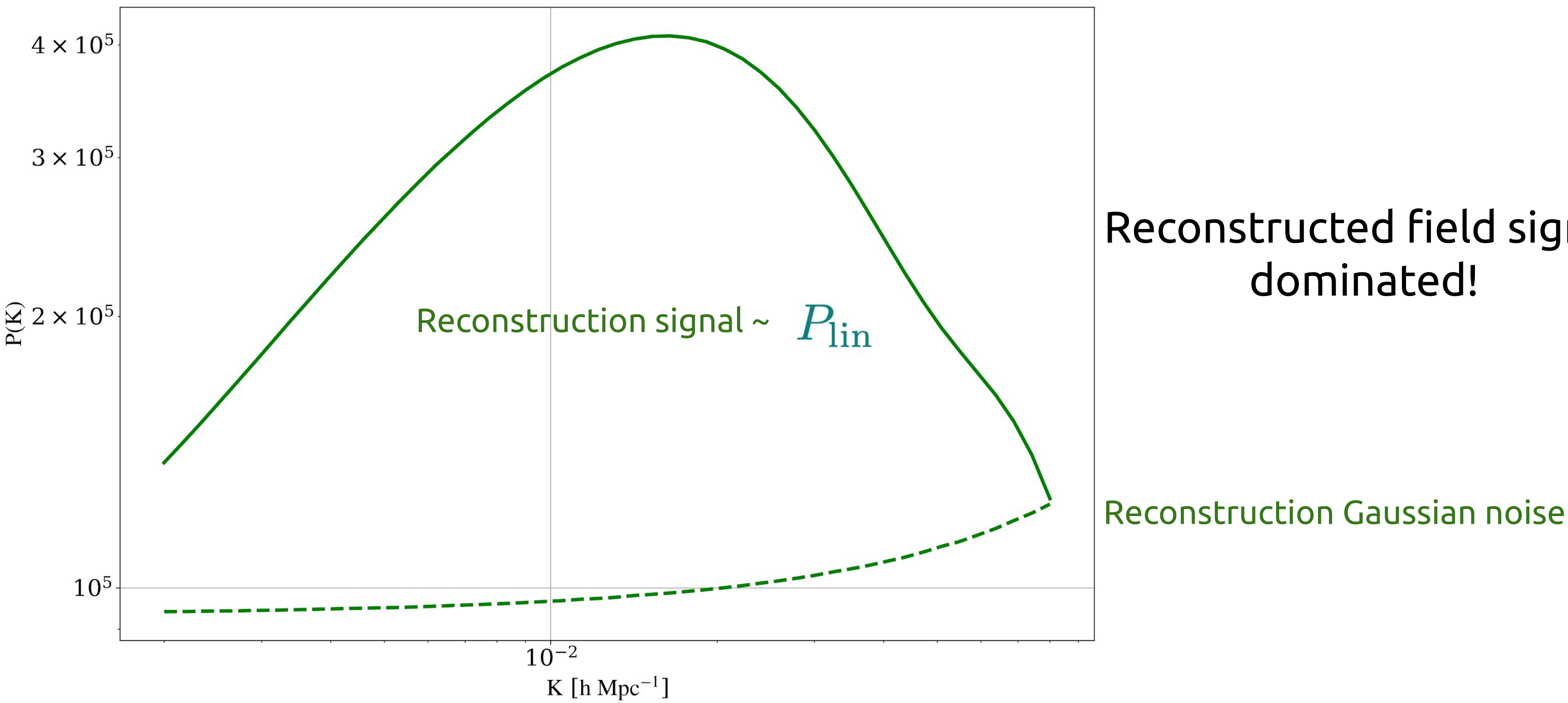


Image from application to simulations, credits Muntazir Abidi

See Darwish, Foreman, Abidi, et al. (2020) for details.

Properties of reconstructed field: power spectra

MegaMapper like 2<z<2.5 bin example



Reconstructed field signal dominated!

You can use this new field **alone**, as you would do in a CMB lensing autospectrum analysis, or you can **combine it** with the original field or other matter tracer fields.

Applications

Introduction

Local primordial non Gaussianity

$$\phi = \phi_{\mathrm{G}} + (\phi_{\mathrm{G}}^2 - \langle \phi_{\mathrm{G}}^2 \rangle) f_{\mathrm{NL}} + \ldots$$

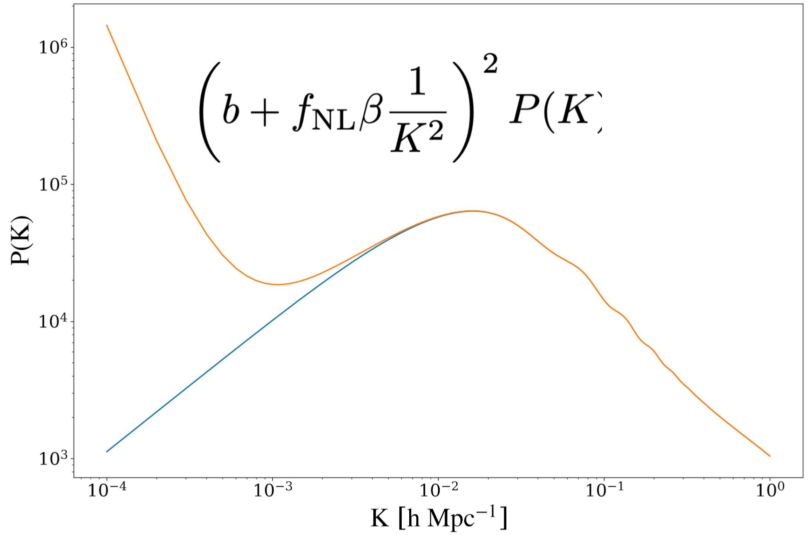
Detection of O(1) would rule out standard slow roll single field inflation

Current best constraints from Planck bispectrum (2019)

$$\sigma(f_{\mathrm{NL}}) \in \mathcal{O}(5)$$

Scale dependent bias on non-Gaussianity

Key observable for next generation fNL constraint:
scale-dependent bias measured in power spectrum



Problem: signal peaks on large scales, which are limited by cosmic variance

Cosmic variance cancellation for scale dependent bias constraints on non-Gaussianity

Solution: use multiple tracers to cancel sample variance:

$$\frac{\delta_{\rm gA}}{\delta_{\rm gB}} \sim \frac{b_{\rm A}(f_{\rm NL})\delta}{b_{\rm B}(f_{\rm NL})\delta} \sim \frac{b_{\rm A}(f_{\rm NL})}{b_{\rm B}(f_{\rm NL})}$$

First appeared in Seljak 2008

See also

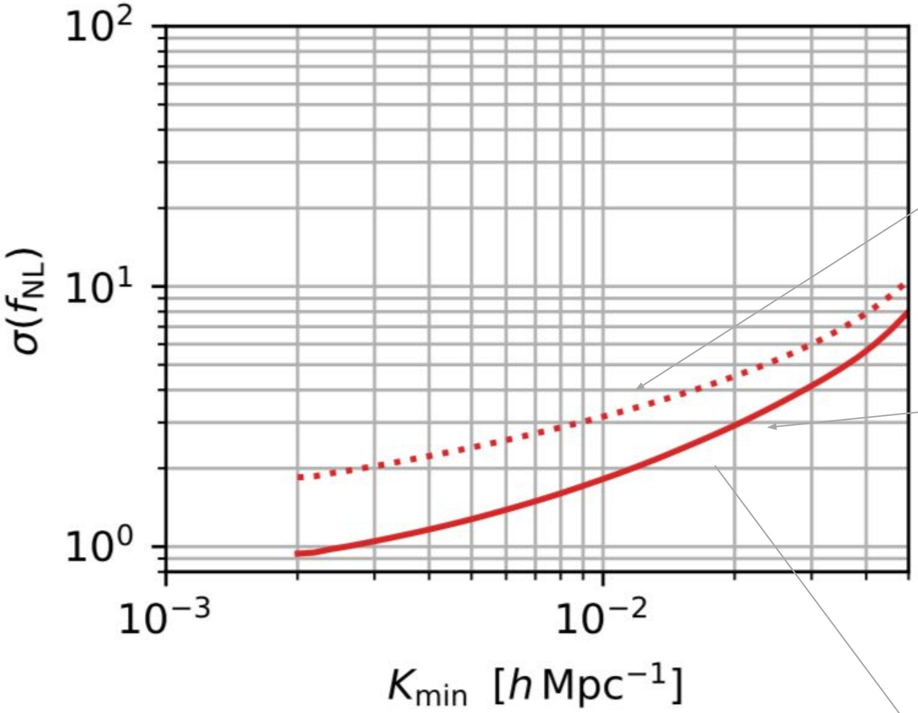
Schmitfull & Seljak 2017,
Münchmeyer++ 2018

Now can also do sample variance cancellation with just a single tracer.

$$\delta_{\rm gA} = \delta_{\rm g}\ ,\ \ \delta_{\rm gB} = \delta_{\rm rec}$$

Forecasts for future surveys

MegaMapper like 4.5 < z < 5 bin example



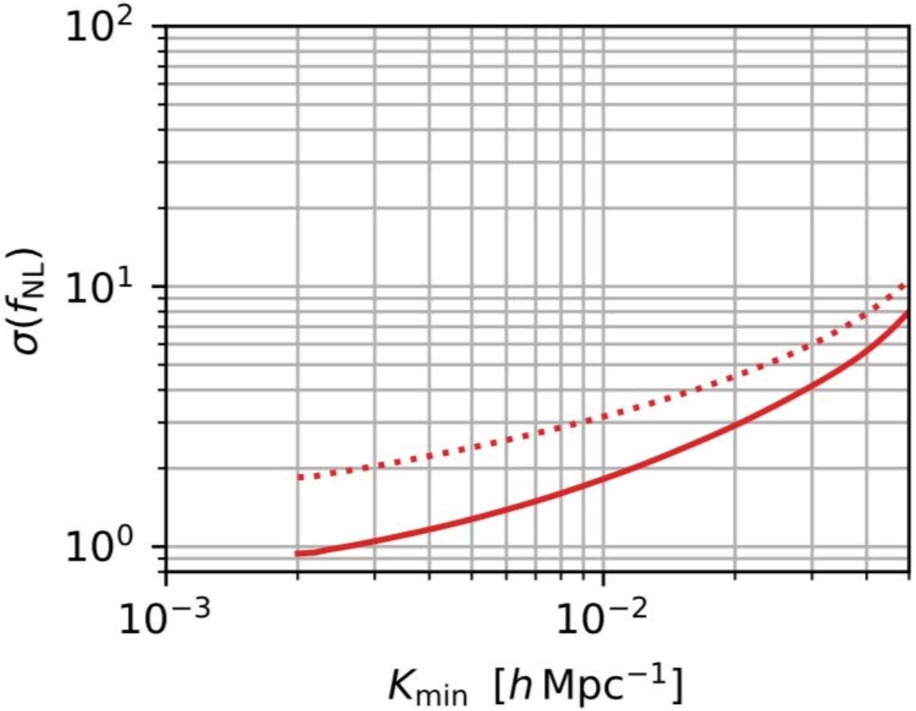
Standard constraint from galaxy power

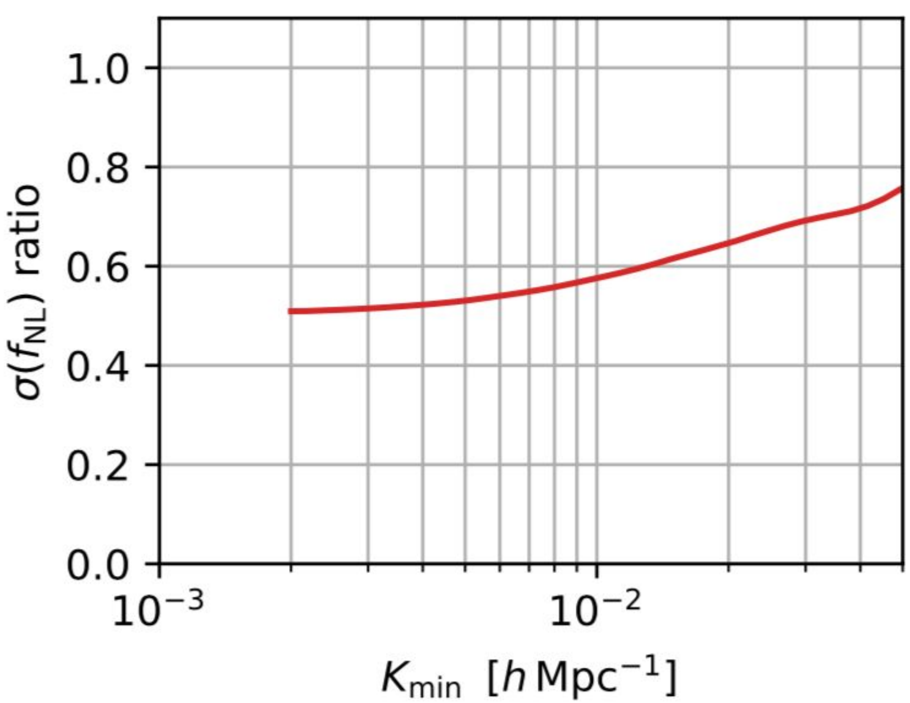
Constraint including new reconstruction method

Cosmic variance cancellation can give significant improvements!

Forecasts for future surveys

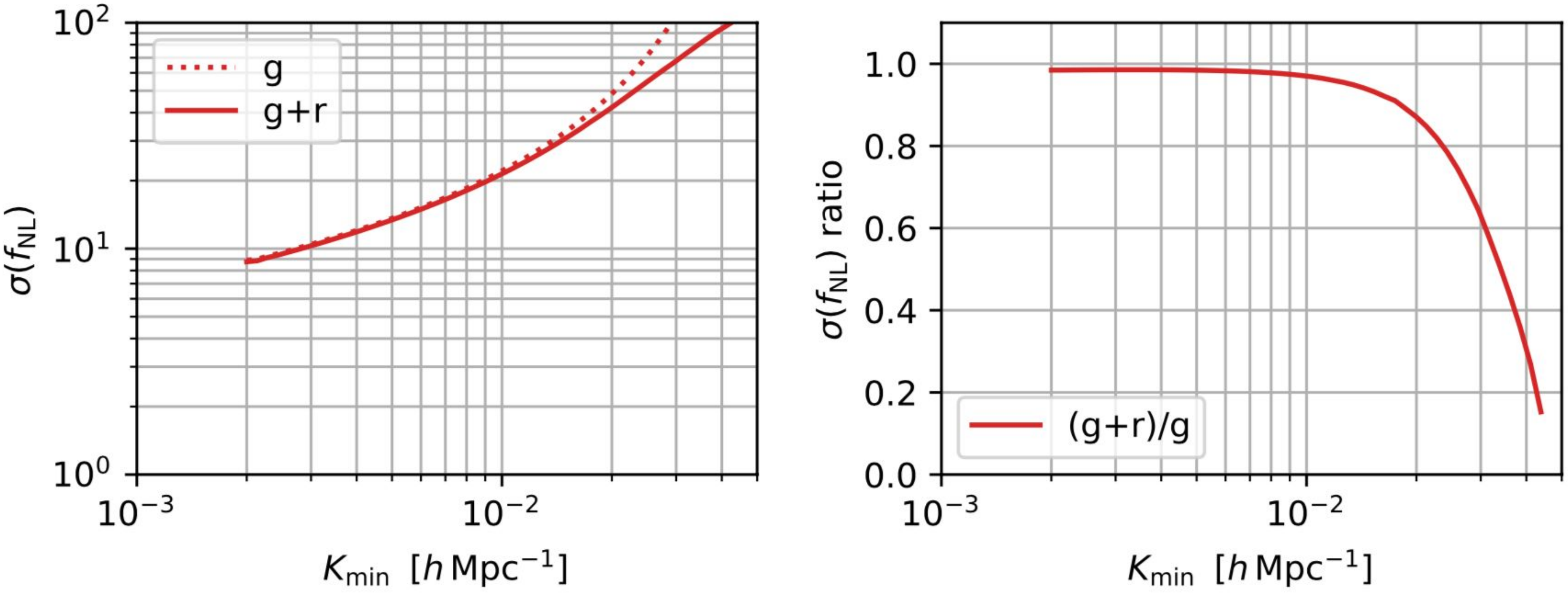
MegaMapper like 4.5 < z < 5 bin example



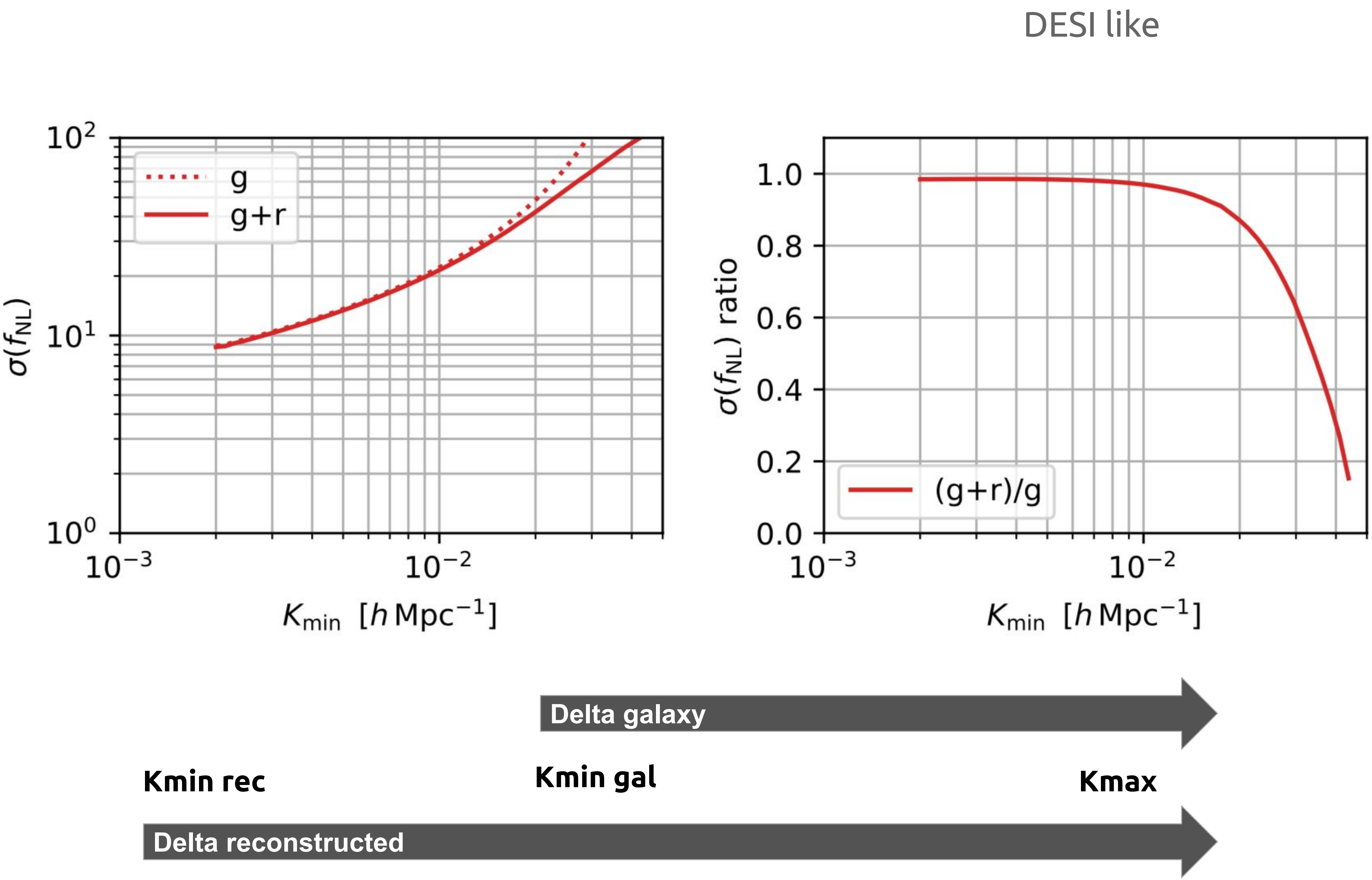


But: only small gains for current surveys

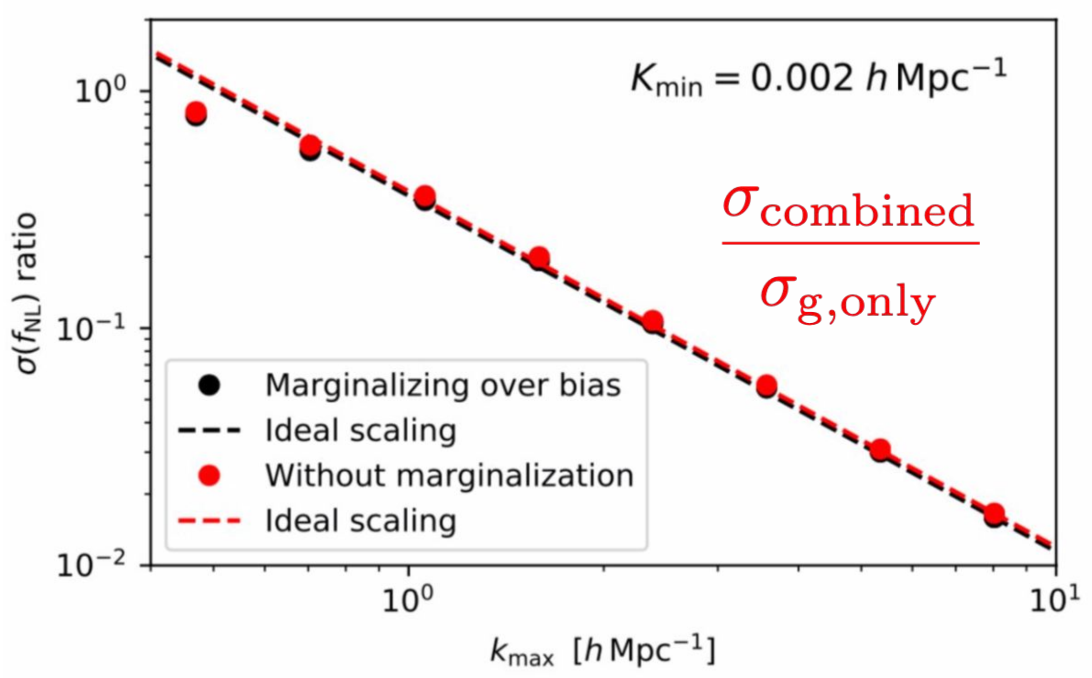
DESI like



But: only small gains for current surveys



Super futuristic case



$$\propto k_{\rm max}^{-3/2}$$

Lower reconstruction noise

Properties

- Extra shot noise from input tracer trispectrum and bispectrum in reconstructed autospectrum and cross correlation with tracer field. We account for this in the forecasts.

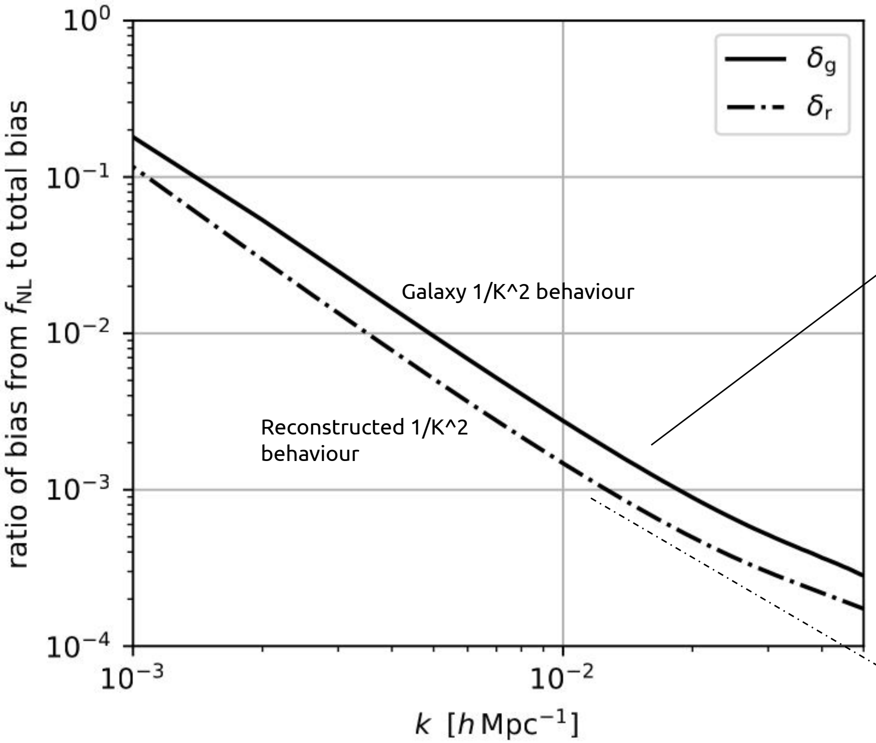
Properties

- fNL Contamination coming from primordial local non Gaussianity at the higher order level. We account for this in the forecasts.

$$\delta_g(\vec{k}) \approx b_1\delta_1(\vec{k}) + \underbrace{\boxed{\int_{\vec{q}} F(\vec{q},\vec{k}-\vec{q})\delta_1(\vec{q})\delta_1(\vec{k}-\vec{q})}}_{\text{Part we want}} + \underbrace{\boxed{f_{\rm NL}\int_{\vec{q}} F_{f_{\rm NL}}(\vec{q},\vec{k}-\vec{q})\delta_1(\vec{q})\delta_1(\vec{k}-\vec{q})}}_{\text{Part from fnl}}$$

Properties

- fNL Contamination coming from primordial local non Gaussianity at the higher order level. We account for this in the forecasts.



$$(b + f_{\mathrm{NL}}\beta\frac{1}{K^2})\delta_1(k)$$

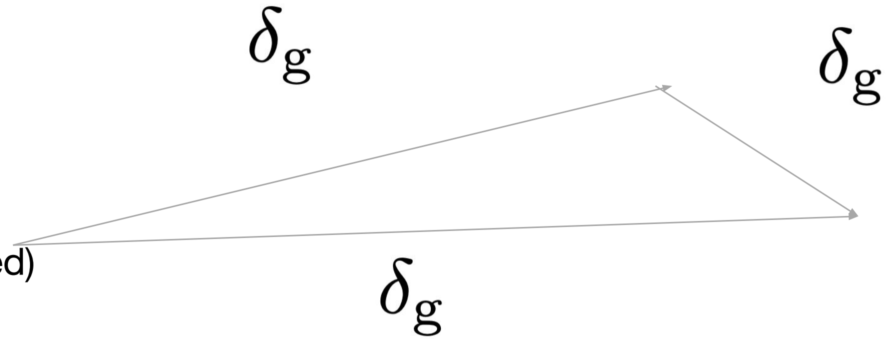
$$(b_{\mathrm{r}} + f_{\mathrm{NL}}\beta_{\mathrm{r}}\frac{1}{K^2})\delta_1(k)$$

Includes primordial fNL mode coupling

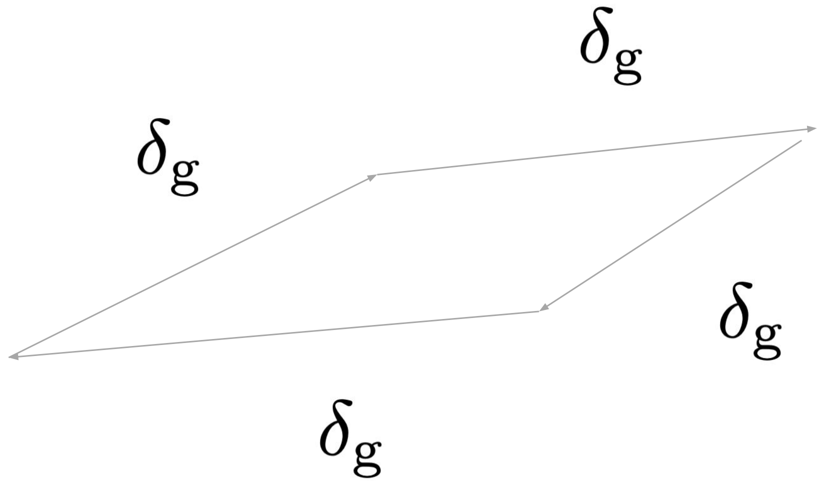
See Darwish, Foreman, Abidi, et al. (2020) for details.

Equivalence to (squeezed) bispectrum and trispectrum

$$\langle \delta_g \hat{\Delta} \rangle \sim_{\text{(squeezed)}}$$



$$\langle \hat{\Delta} \hat{\Delta} \rangle \sim_{\text{(squeezed)}}$$



Quick and easy

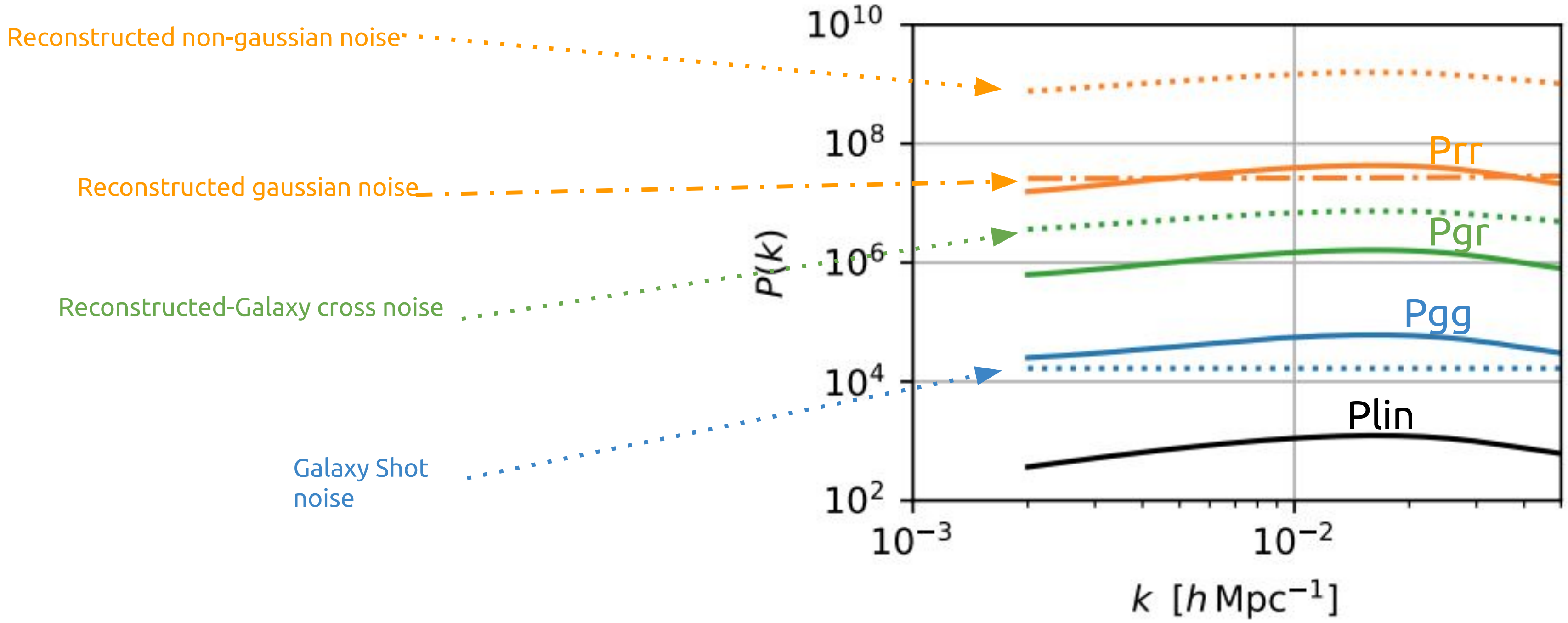
Conclusions

- **Reconstruct linear density field** from a biased tracer field with a quadratic estimator, retaining information about higher n-point statistics.
- Theoretical predictions agree with **Simulation** results for high kmax
- **One application**: constraining primordial local non-Gaussianity, and improvement cosmic variance cancellation**.**
- Still to explore well systematics and other terms (stellar contamination, redshift space, photo-z), for practical application.
- Measuring better larger scale to constrain turnover of power spectrum? Neutrino mass?

Backup slides

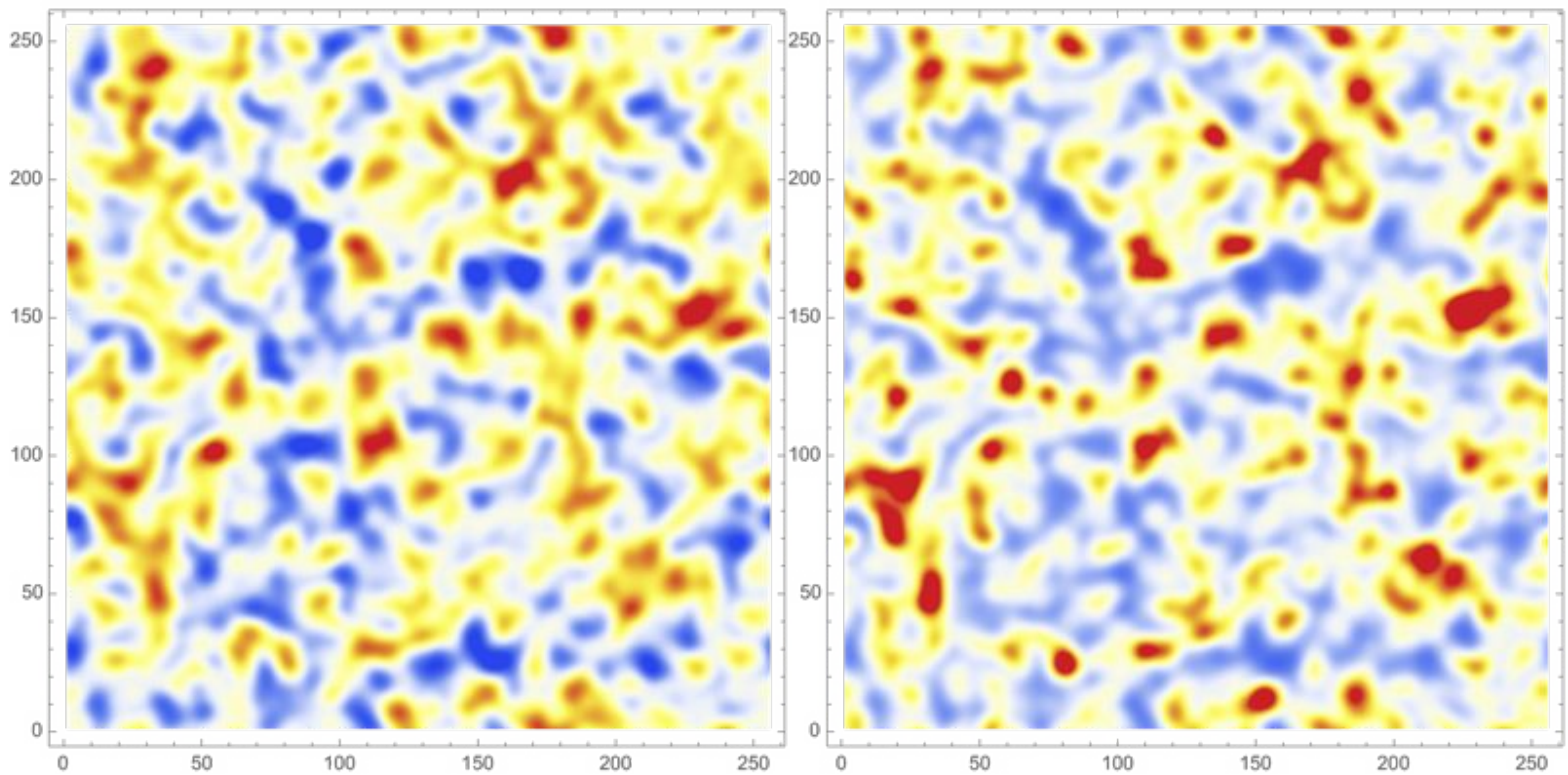
Properties

- Extra shot noise from input tracer trispectrum and bispectrum in reconstructed autospectrum and cross correlation with tracer field.



Simulation Results

$\delta_{\text{lin}}(x)$ $\hat{\Delta}_{\text{G}}(x)$



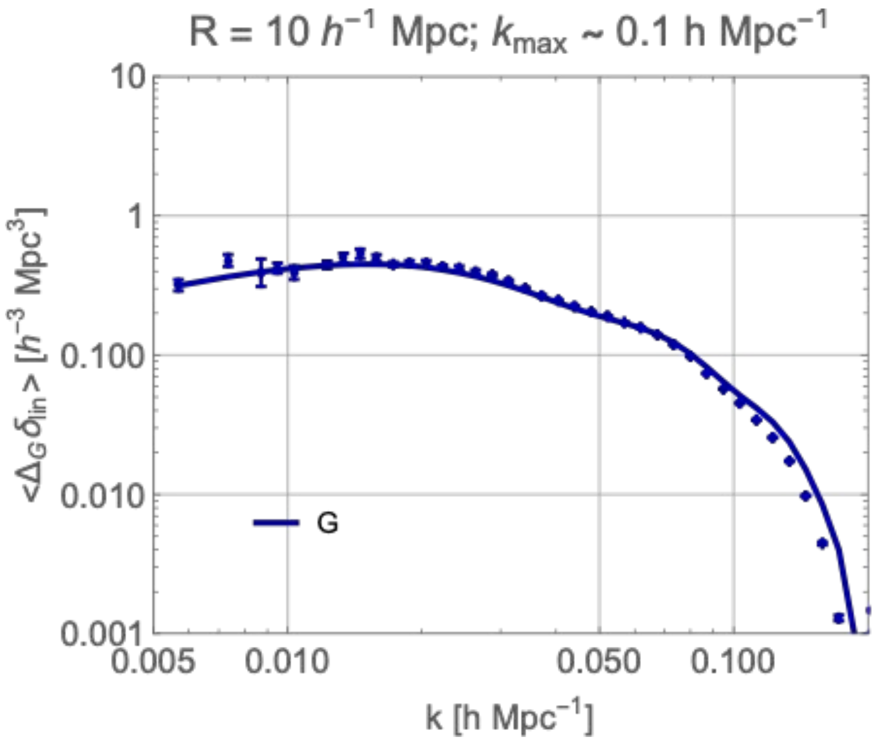
Reconstruction: $k_{\text{max}} = 0.25h$ Mpc^{-1}

External Smoothing: $R = 20h^{-1}$ Mpc

- **YES this method is practical!**
- Application to halos in Cosmological **N-body** simulations
- Auto- and cross-correlations of **quadratic estimators**
- Effective and fast - only requires **FFT**
- Reconstruct the **linear field**, model **biases** and understand the **noise** properties

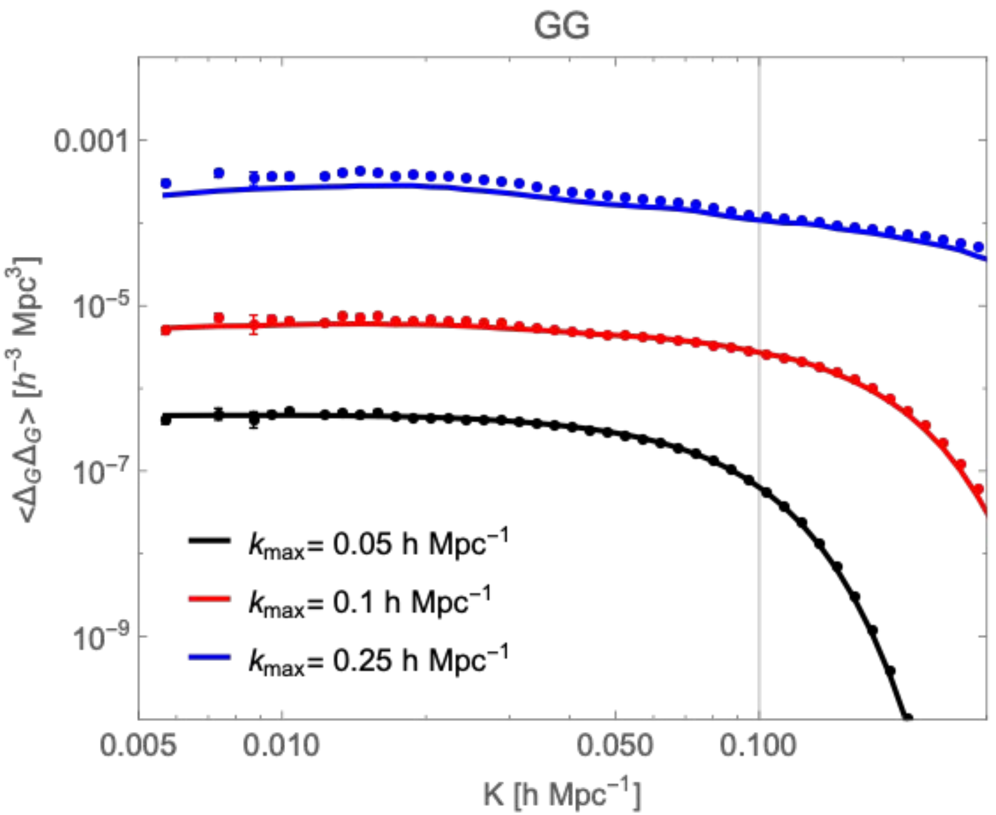
Correlation with the Initial density field

$$\left\langle \hat{\Delta}_{\mathrm{G}}(\mathbf{k})\delta_{\mathrm{lin}}(-\mathbf{k})\right\rangle = \text{Signal } (\propto P_{\mathrm{lin}}) + \text{Shot Noise}$$

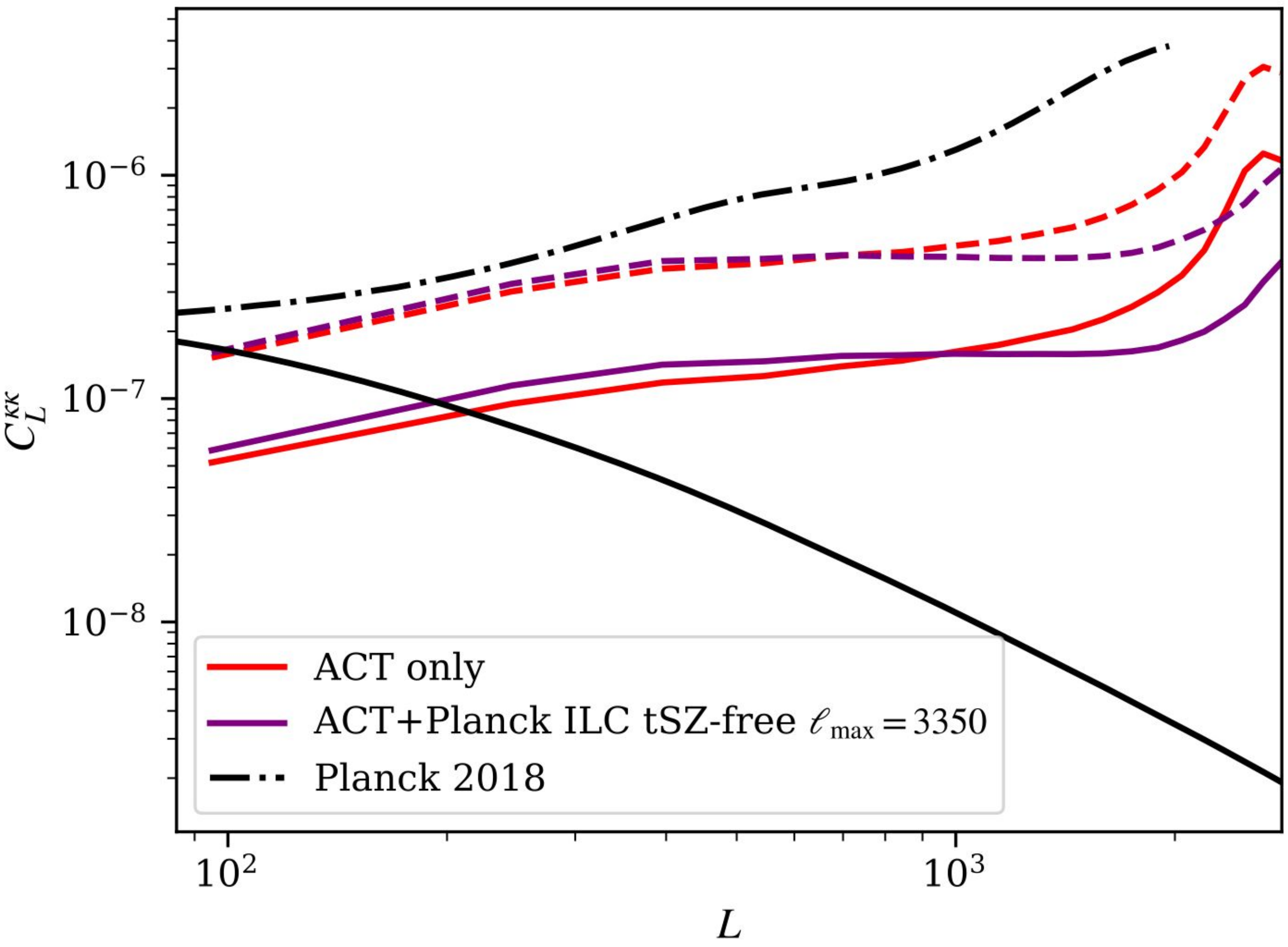


Auto-correlation

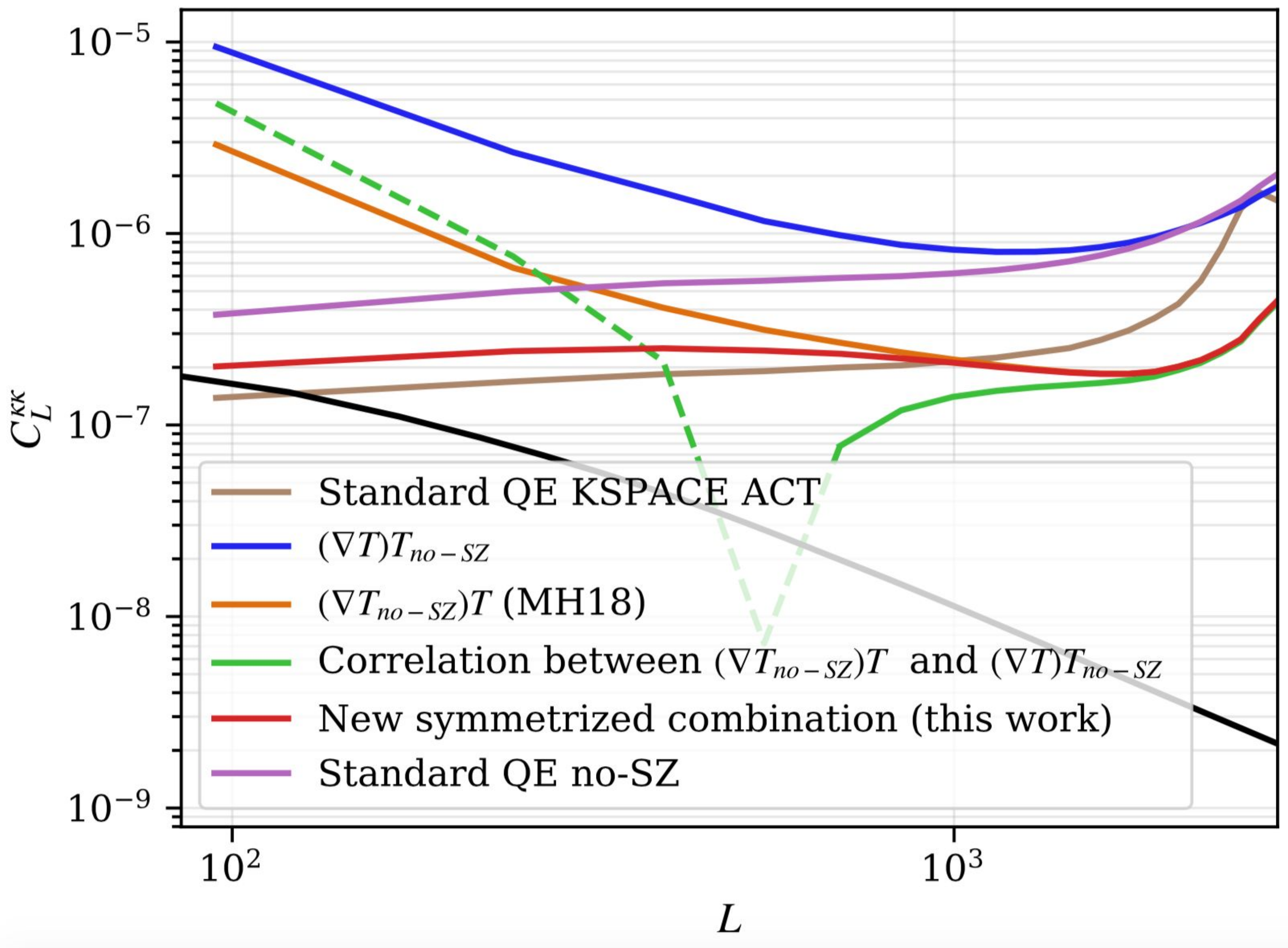
$$\left\langle \hat{\Delta}_G(\mathbf{k})\hat{\Delta}_G(-\mathbf{k})\right\rangle = \text{Signal} \; (\propto P_{\text{lin}}) + \text{Reconstructed Noise} + \text{Shot Noise}$$



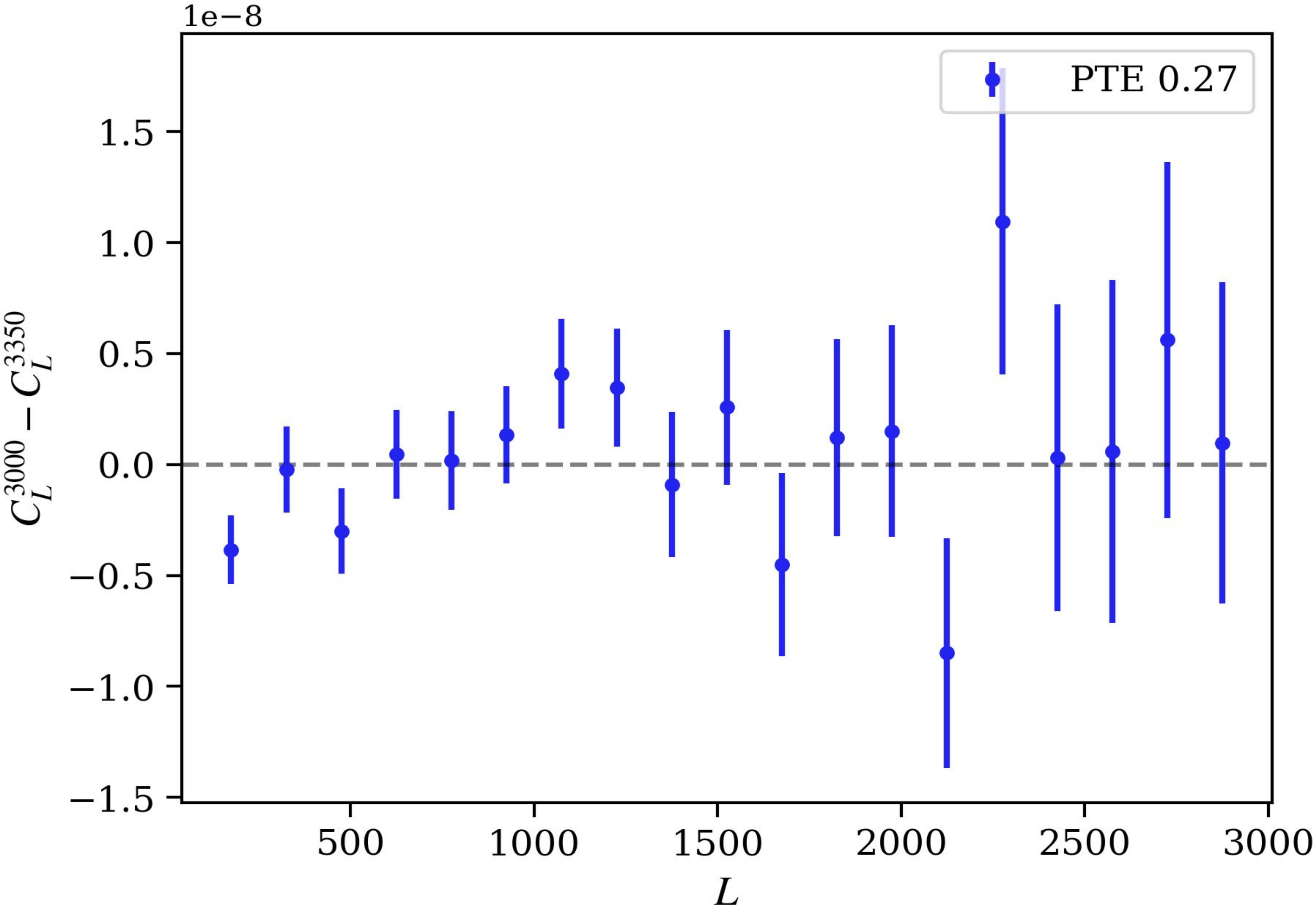
Noise curves



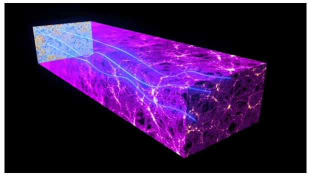
Noise curves



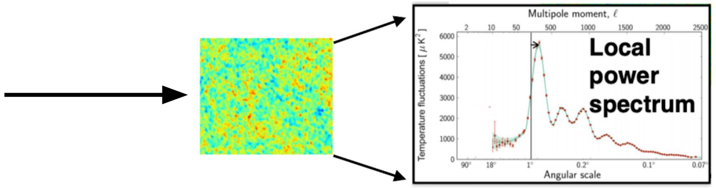
Foreground test



Systematics: tSZ contamination in kxg

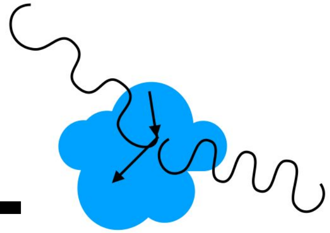


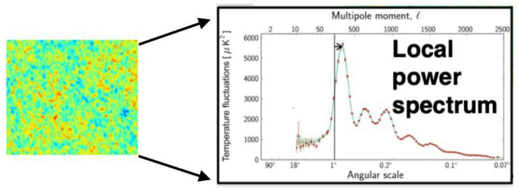
From ESA,
Planck

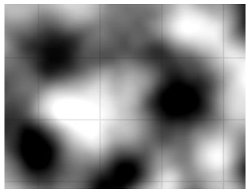


From
Schmitfull

+







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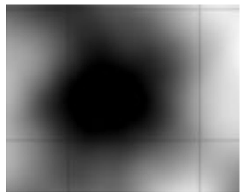
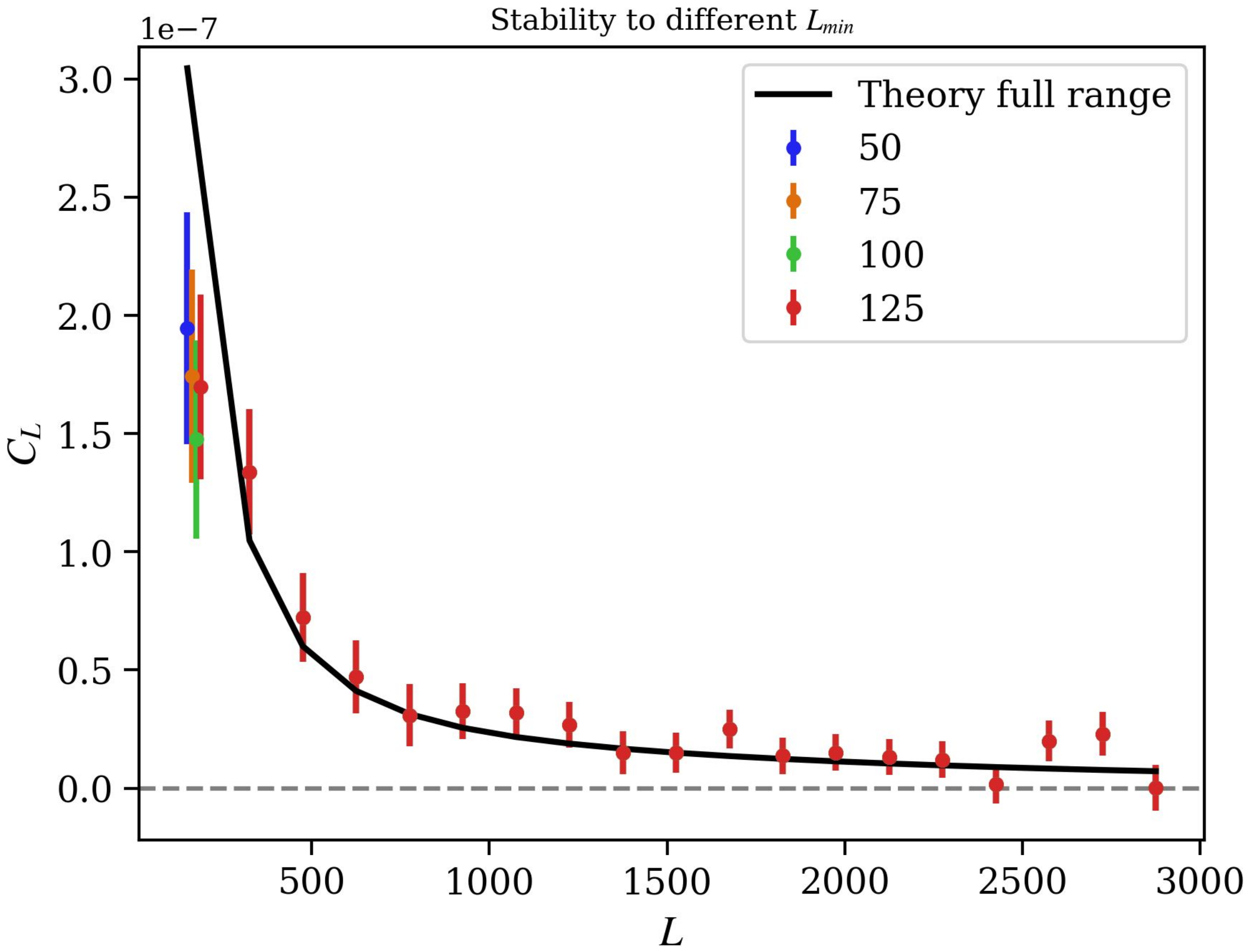
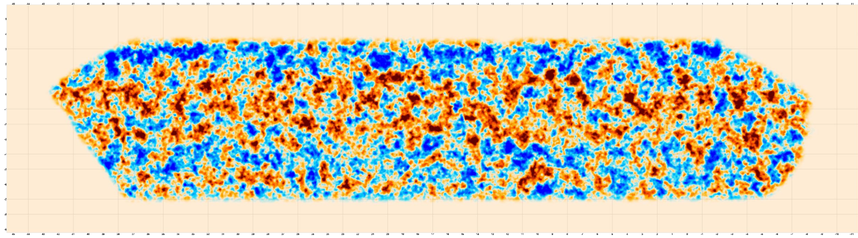


L min stability

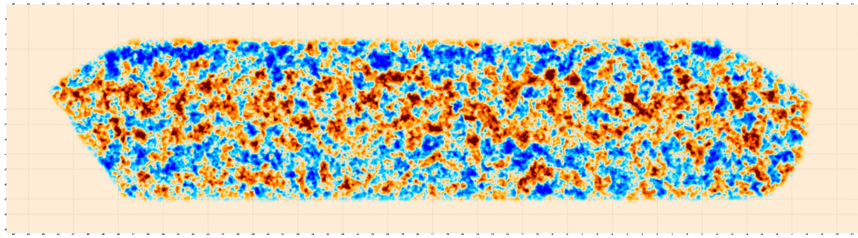


What if I try symmetric

no tSZ



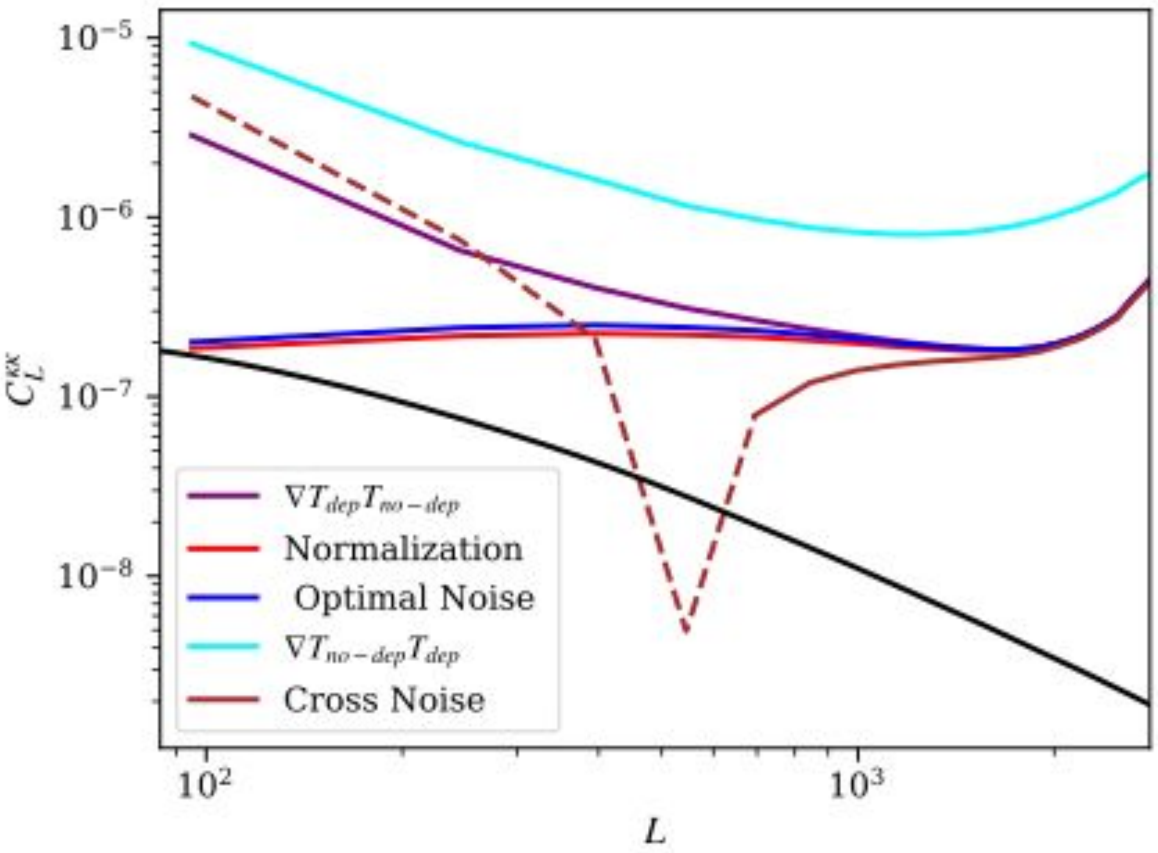
no tSZ



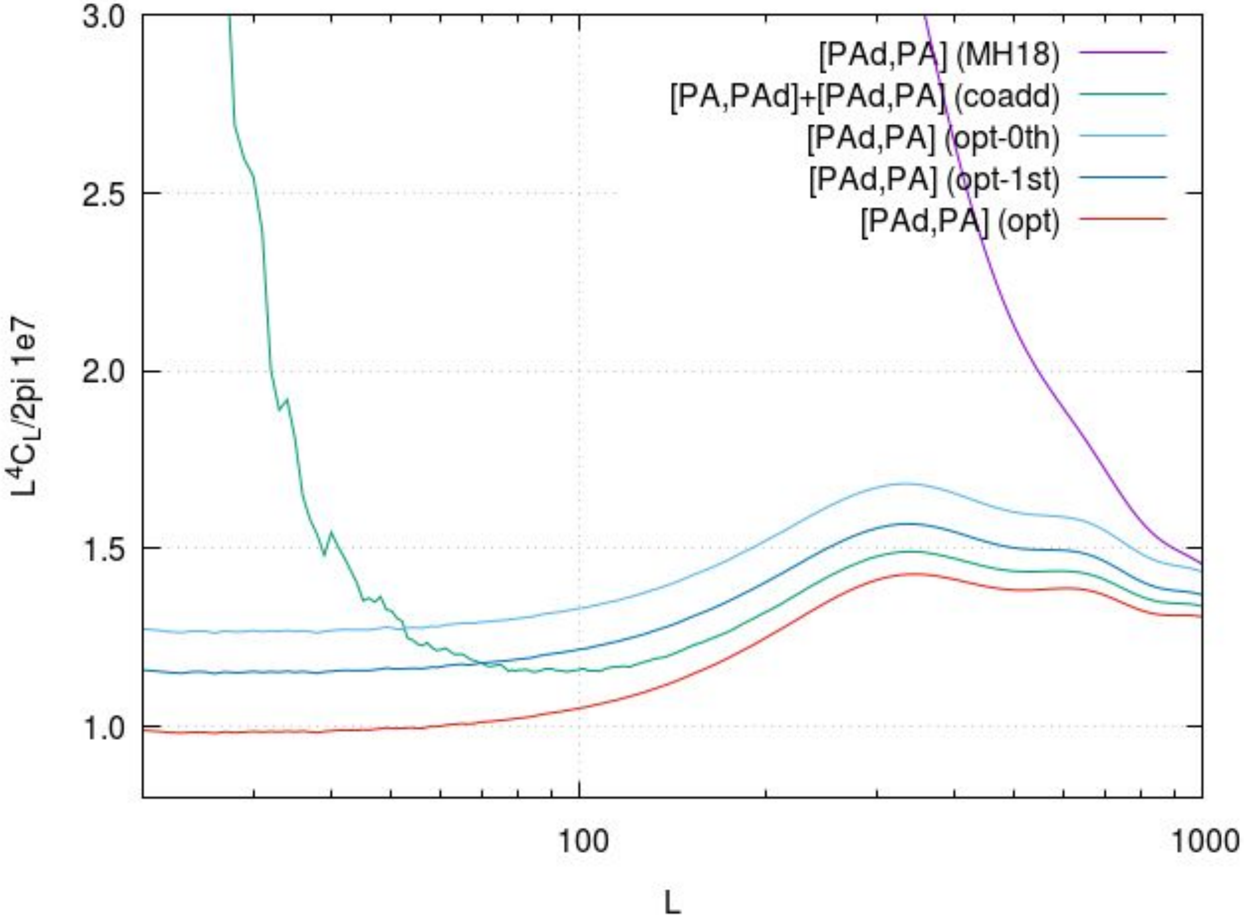
Quadratic
Estimator

Cleaned lensing map!

Mixed estimator



Optimal Estimator



Credits Toshiya Namikawa