Lensing reconstruction of AliCPT-1

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Beijing Normal University

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[Sci.China Phys.Mech.Astron. 65 (2022) 10, 109511]
[arXiv: 2207.07713] [Jiakang Han et al. in prep]

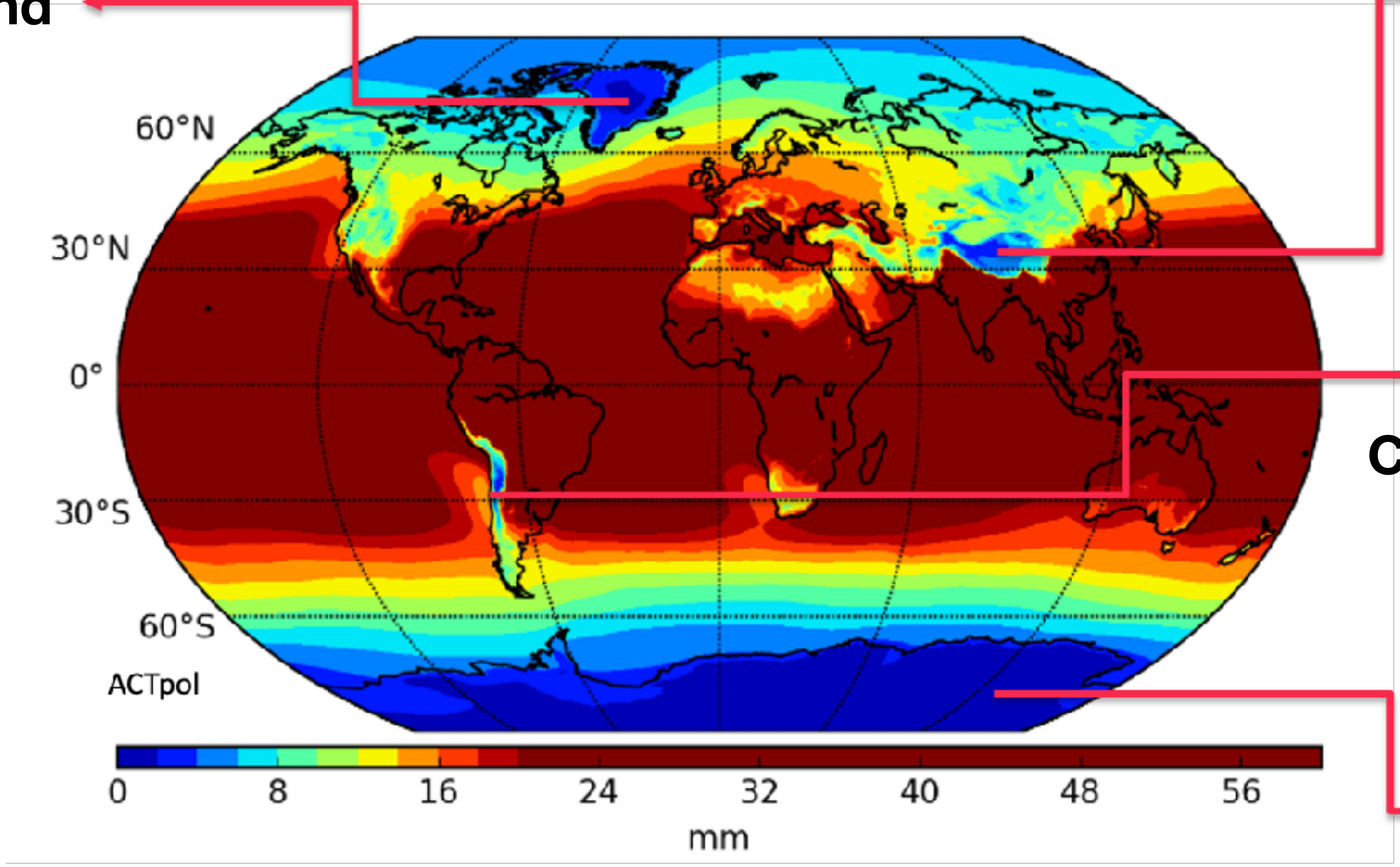
Outline

- Introduction to AliCPT-1
- Overview of CMB Lensing
- AliCPT Lensing Reconstruction
- AliCPT XC w/ DESI & CSST

1. Introduction to AliCPT

Water evaporation distribution (more bluer, more better)

Greenland



China/Tibet

AliCPT-1

Chile/Atacama

POLARBEAR

ACT, SO ...

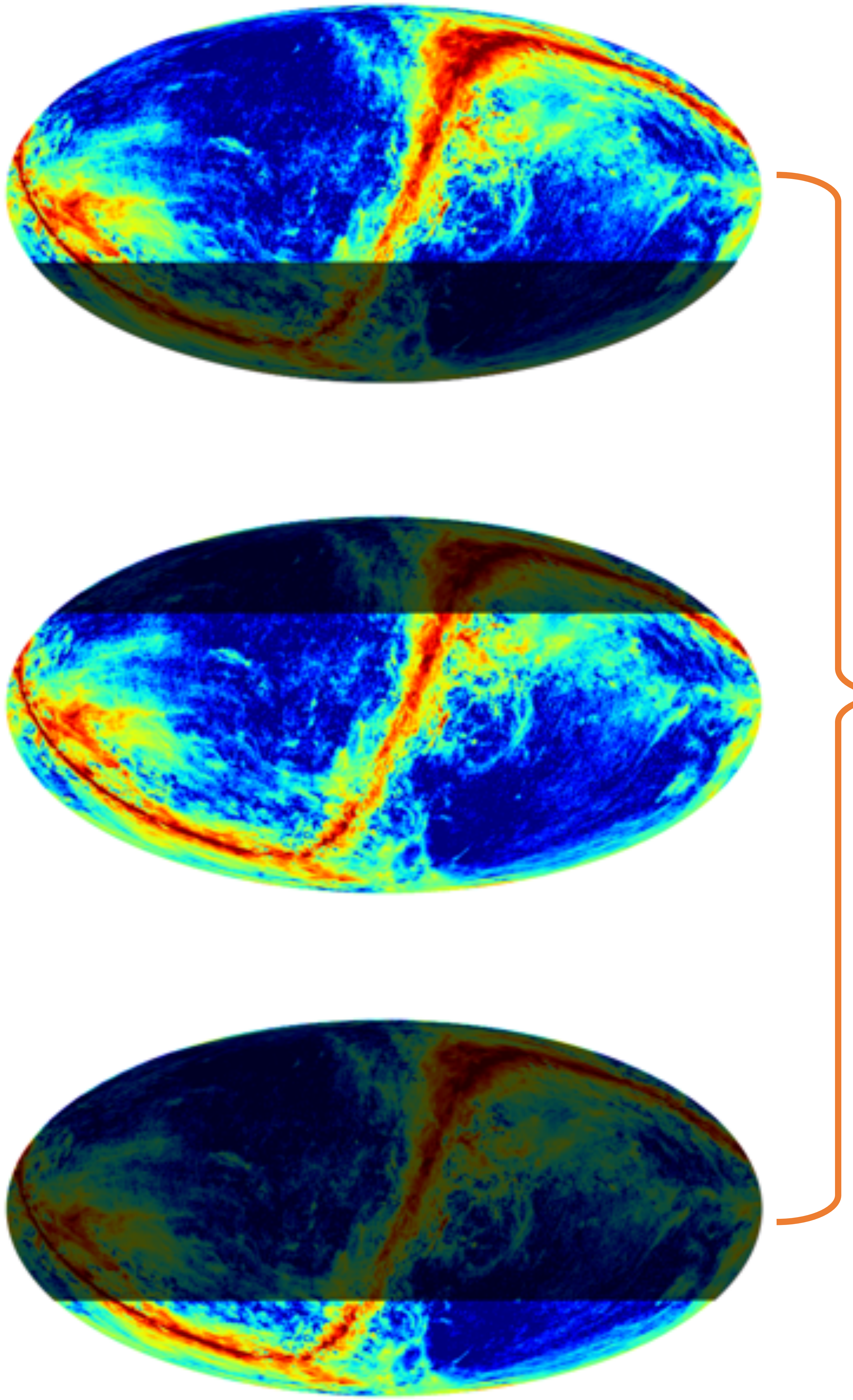
South pole

SPT and BICEP

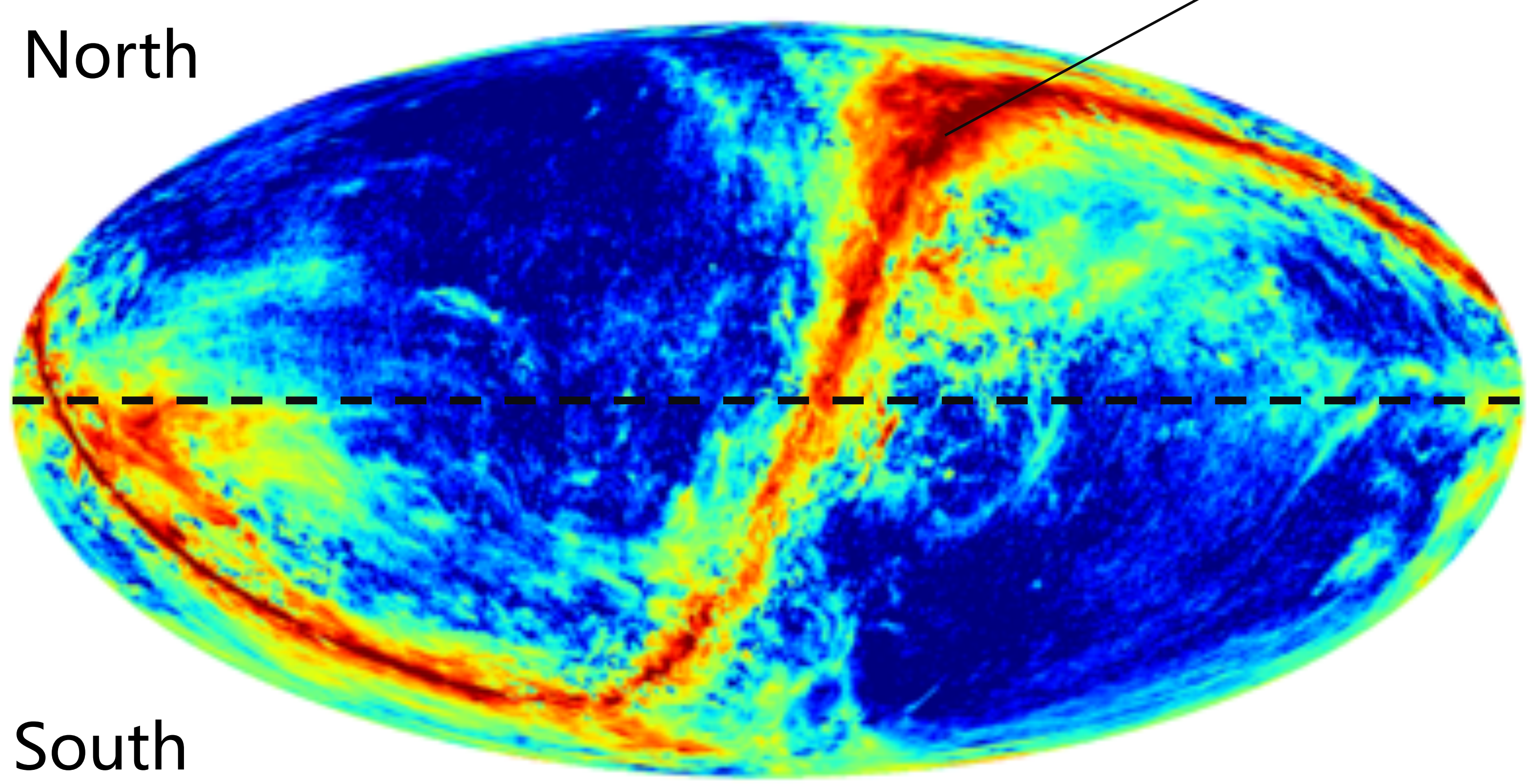
Keck Array ...

Tibet is one of the world-level ground-based milli-meter observatory

1. Introduction to AliCPT



- Ali can cover large fraction in the clean patch in the north sky



1. Introduction to AliCPT

Coordinate: Tibet/Ngari

Altitude: 5250m

Comparison of CMB observatory in the world

TABLE II: Profile for different sites. Labels [1] and [2] represent the PWV obtained with MERRA-2 and radiosondes.

water evaporation

Site	Height(m)	Time range	PWV(mm)	Sky range	Observable sky (%)
[1]AliCPT Base I / Base II	5250/6000	Oct. - Mar.	1.07/0.62	whole North + Part South	70
[2]AliCPT Base I / Base II	5250/6000	Oct. - Mar.	0.92/0.56	whole North + Part South	70
South Pole(BICEP3)	2835	Apr. - Sep.	0.27	Part South	20
Atacama(POLARBEAR)	5190	Apr. - Sep.	0.85	whole South + Part North	80
Dome A	4093	Apr. - Sep.	0.12	Part South	25

[Chao-Lin Kuo 2017 *ApJ* 848 64]
[YP. Li et al. arXiv: 1709.09053]

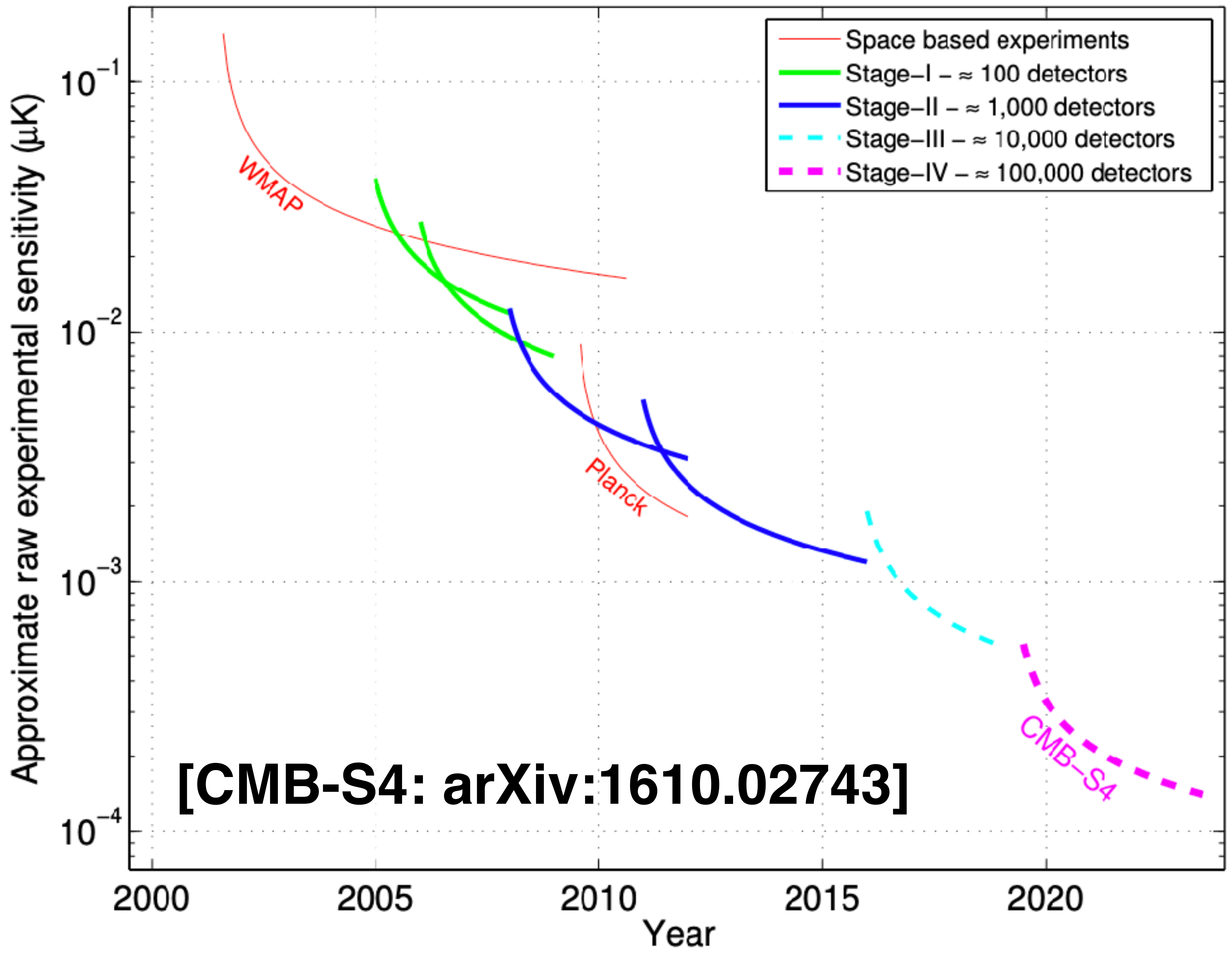
Small aperture telescope

- South pol: Bicep/Keck Array
- Chile: Simons Observatory
- China: AliCPT

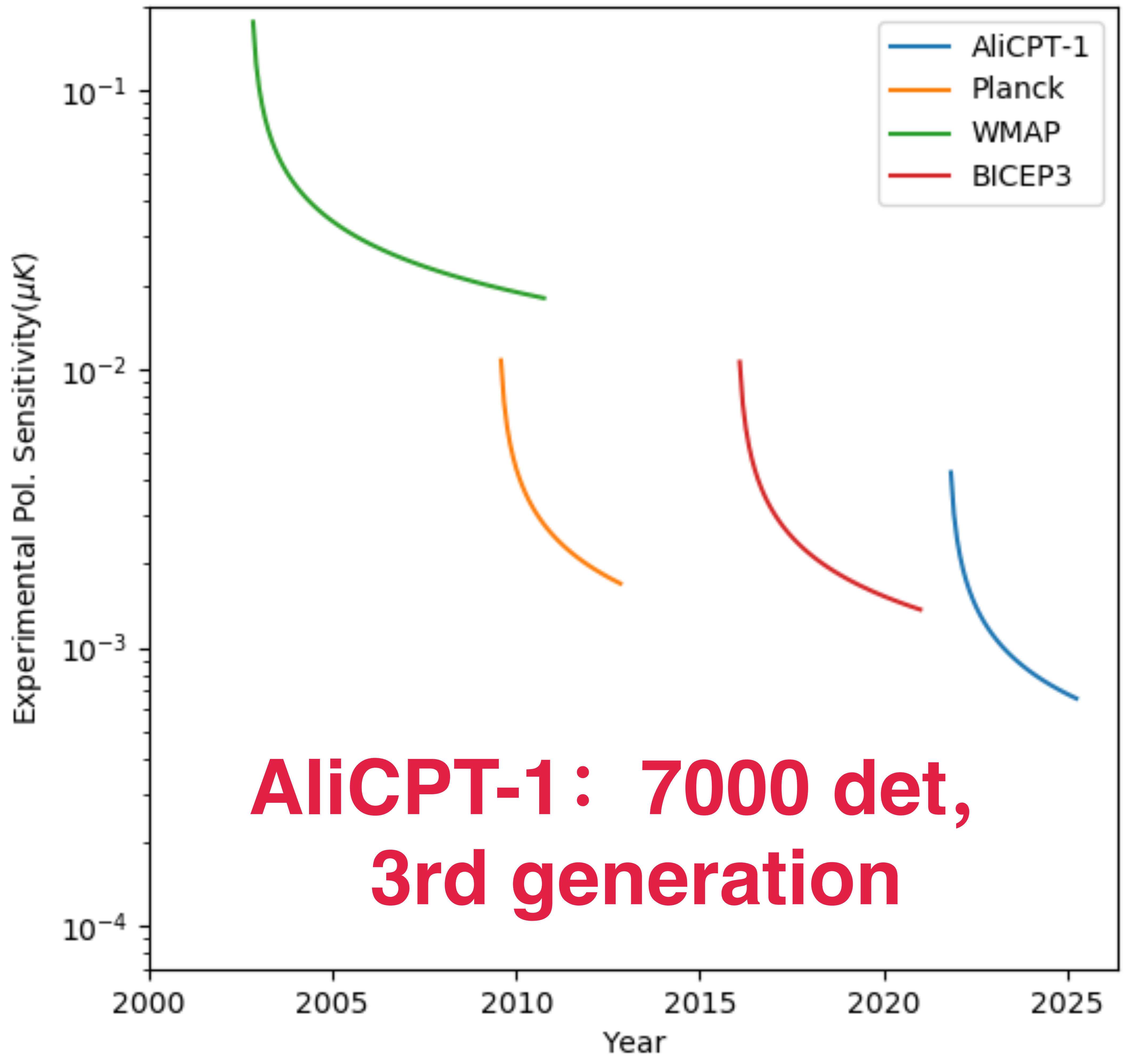
10k detectors

The AliCPT-1 Collaboration

IHEP	pipeline, data analysis, scan strategy, control system, site, mount, test/integration
Stanford	cryostat receiver, optics/AR, focal plane module
NAOC	logistics, site
NIST	det arrays and modules, feedhorns and readout components
ASU	LNAs, cryogenic harness, readout electronics
NTU	scan strategy, calibration
CNRS	science, data analysis
USTC	CMB science
SJTU	foregrounds, cross-correlations
BNU	foregrounds, lensing



[CMB-S4: arXiv:1610.02743]



AliCPT-1：7000 det, 3rd generation

1. Introduction to AliCPT

Sky Area：4000 degsq

Campaign length：6 months (Oct,Nov,Dec,Jan,Feb,Mar)

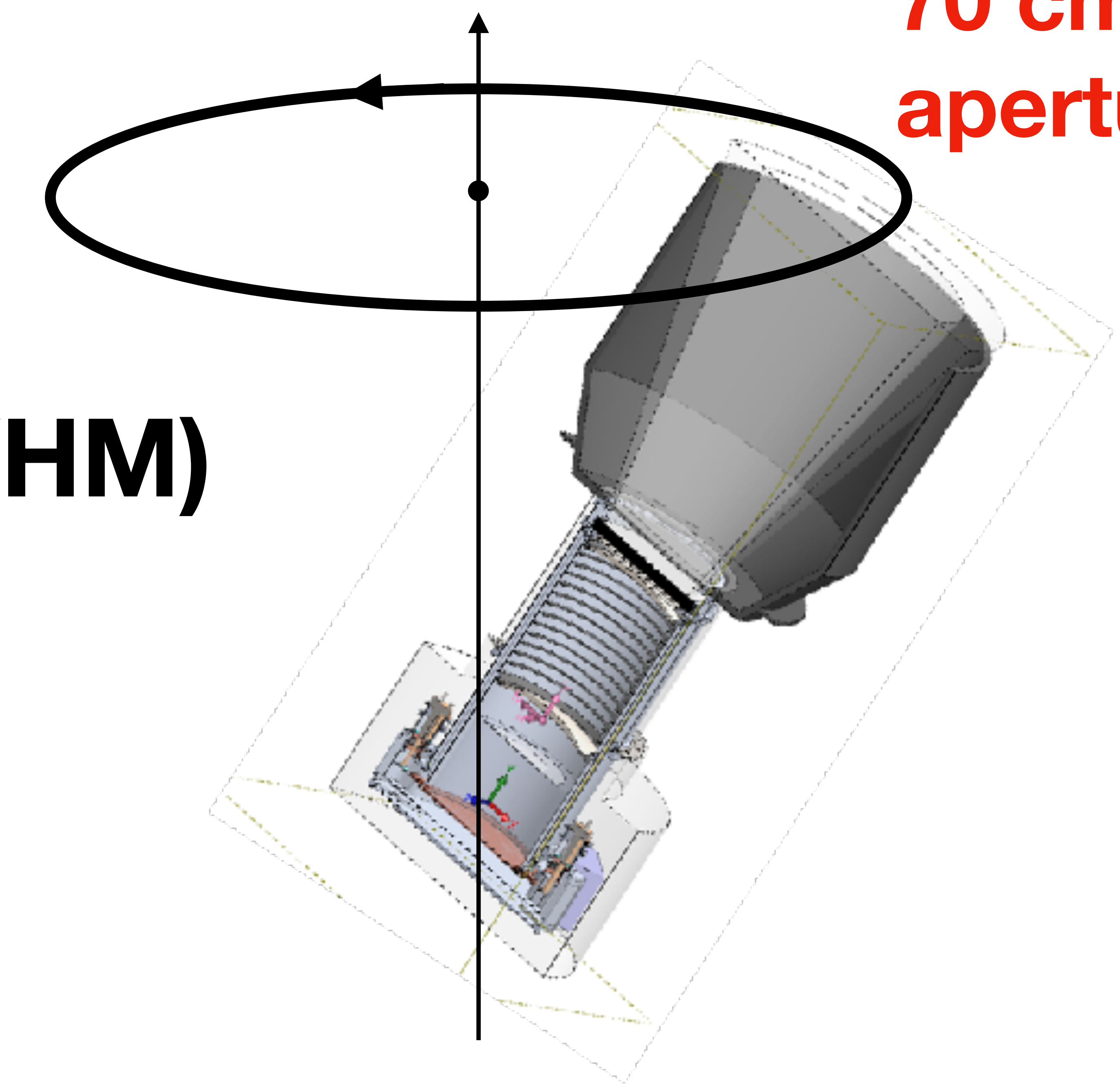
Freq：90/150 GHz

Depth：17 uK.arcmin (harmonic mean)

Scan：fix elevation and ring w/ 4 deg/s

1700 TES detectors/module

Resolution：19/11 arcmin (FWHM)

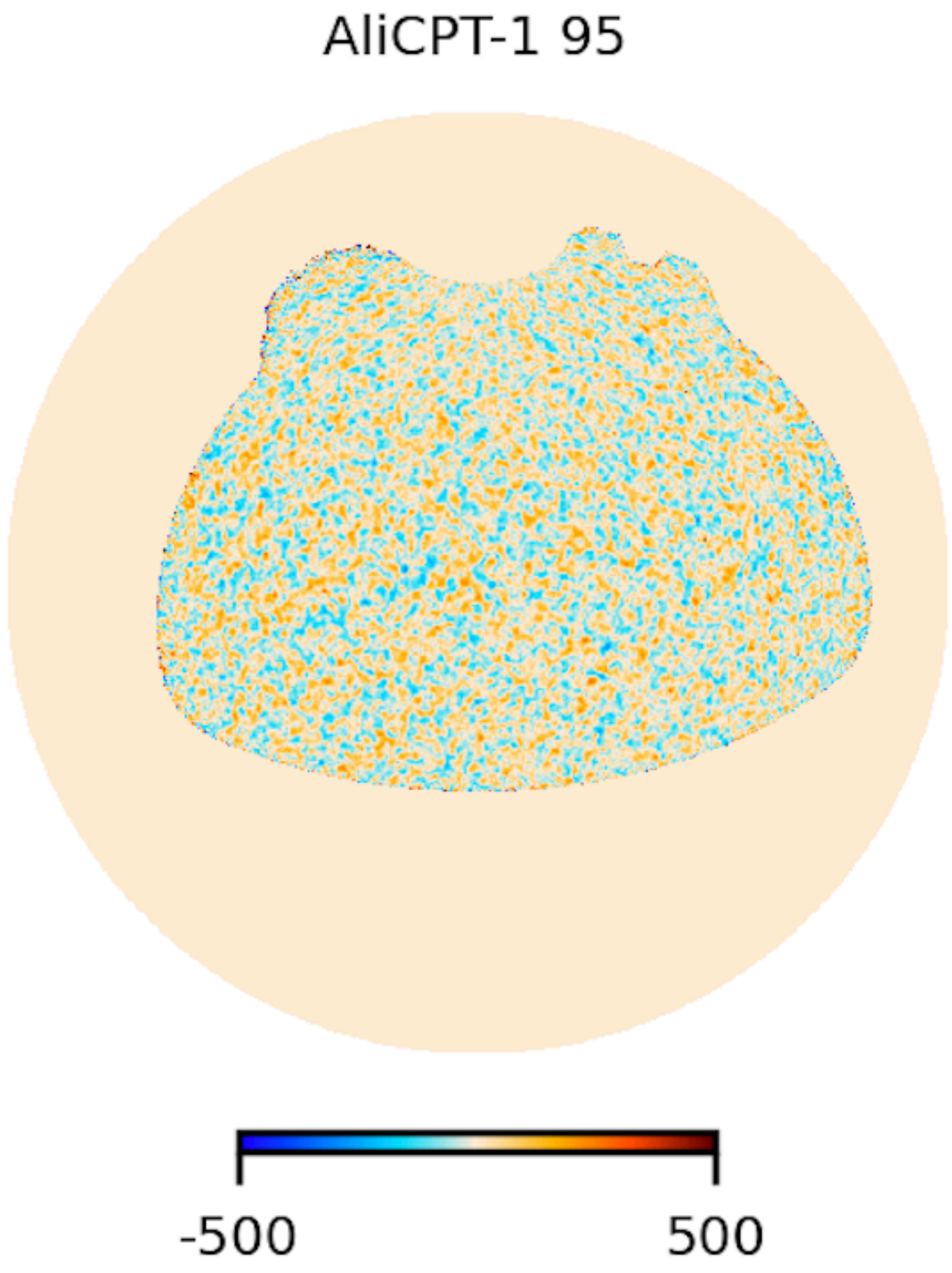


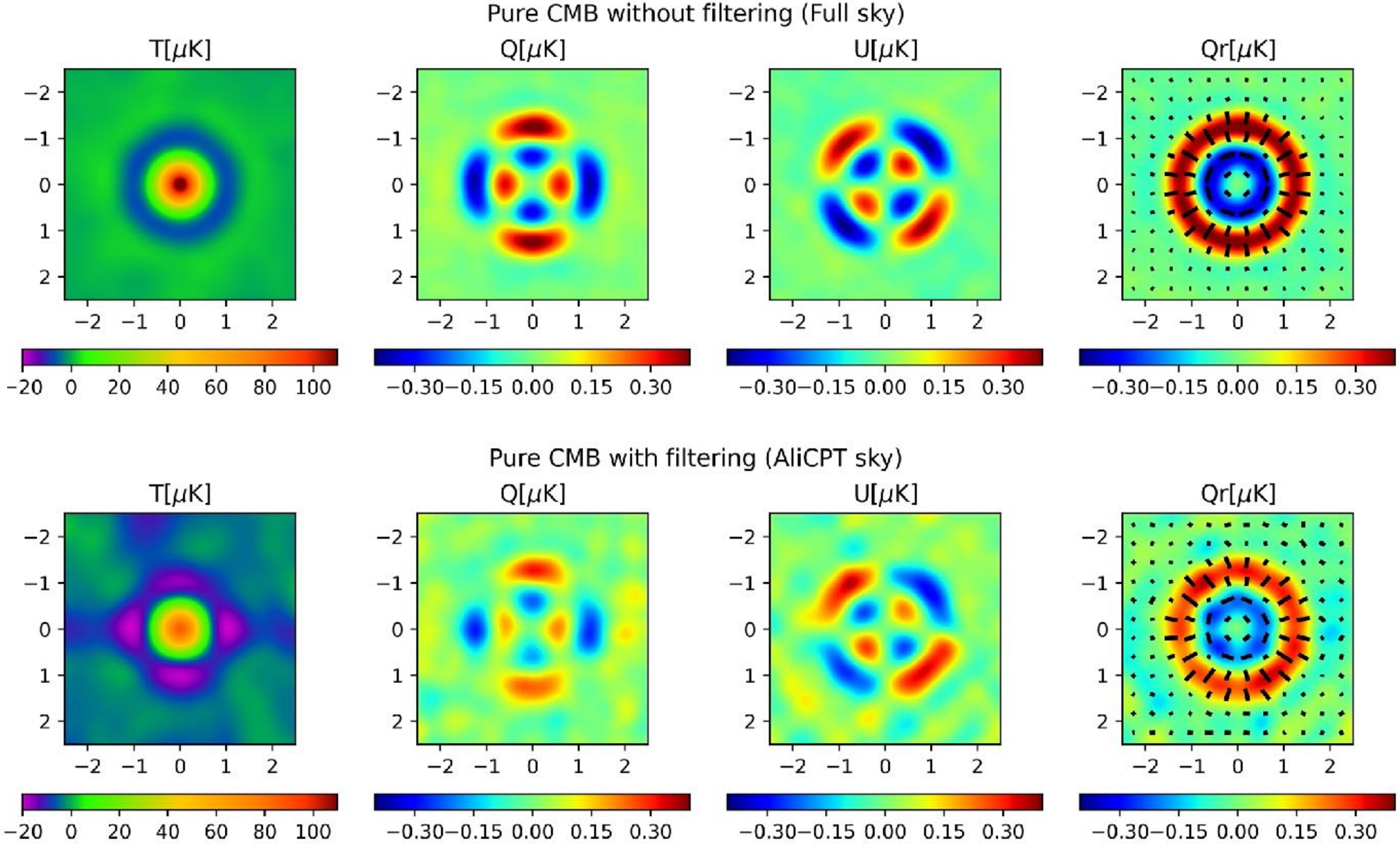
[Salatino et al. 2020, SPIE, 11453, 114532A. doi:10.1117/12.2560709]

[Salatino et al. 2021, ITAS, 31, 3065289. doi:10.1109/TASC.2021.3065289]

1. Introduction to AliCPT

[Credit: Shijie Lin (蔺是杰)]

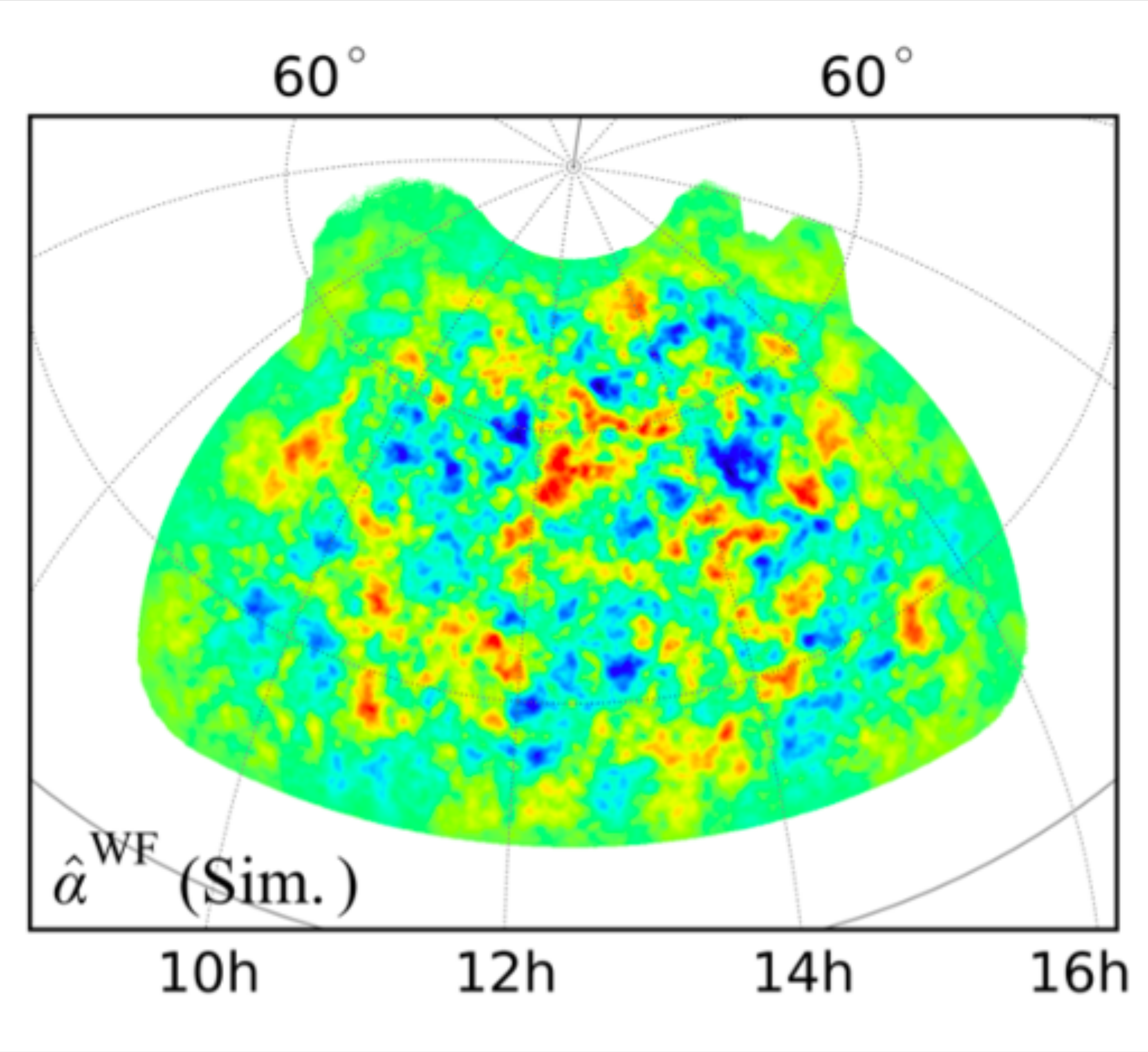




1. Introduction to AliCPT

- **Main science goal: measuring** *tensor-to-scalar ratio* **w/ error of O(0.01)**
- **By-product: a fairly good CMB lensing map**

Method	ABS	GLS	cILC	McMfL	TF (p16)
r [MAP]	0.019	0.023	0.024	0.012	0.029
ℓ range	[20,200]	[40,200]	[40,200]	[50,250]	[20,200]
$\chi^2_{\rm min}/{\rm DOF}$	4.3/8	2.4/3	2.9/3	219.6/214	248.3/236
r [MMSE]	$0.036^{+0.025}_{-0.025}$	$0.030^{+0.019}_{-0.020}$	$0.025^{+0.016}_{-0.016}$	$0.026^{+0.019}_{-0.019}$	$0.035^{+0.021}_{-0.021}$



[S. Ghosh et al. *JCAP* 10 (2022) 063, *JCAP* 10 (2022) 063]

2. Overview of CMB Lensing

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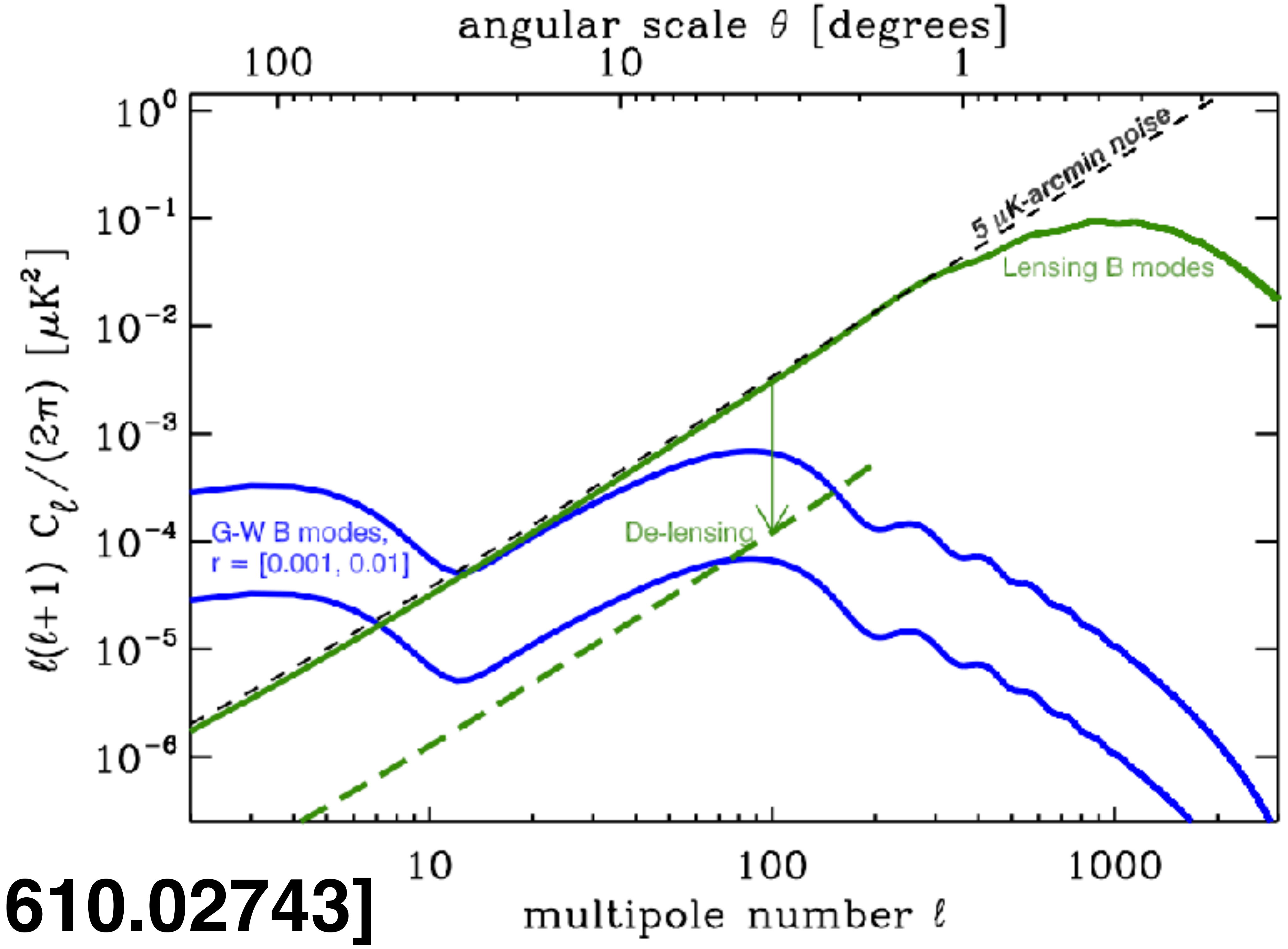
1. Deflection angle： ~2 arcmin

reference: Strong Lensing deflection angle （~1 arcsec）

2. Strength： ~5 uK*arcmin

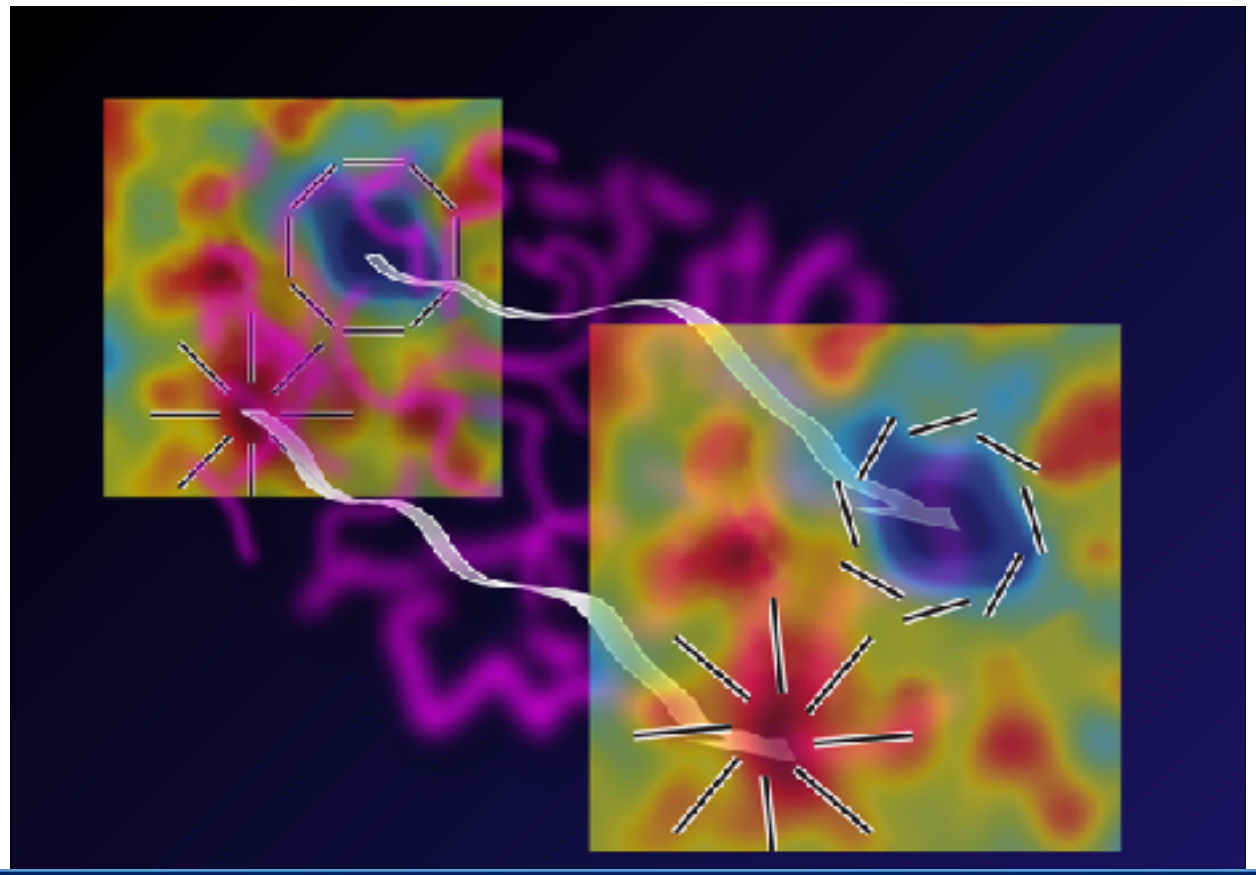
reference: 2-3 uK*arcmin (AliCPT: 48 modules*yr)



[CMB-S4: arXiv:1610.02743]

3. Re-mapping the Temperature distribution

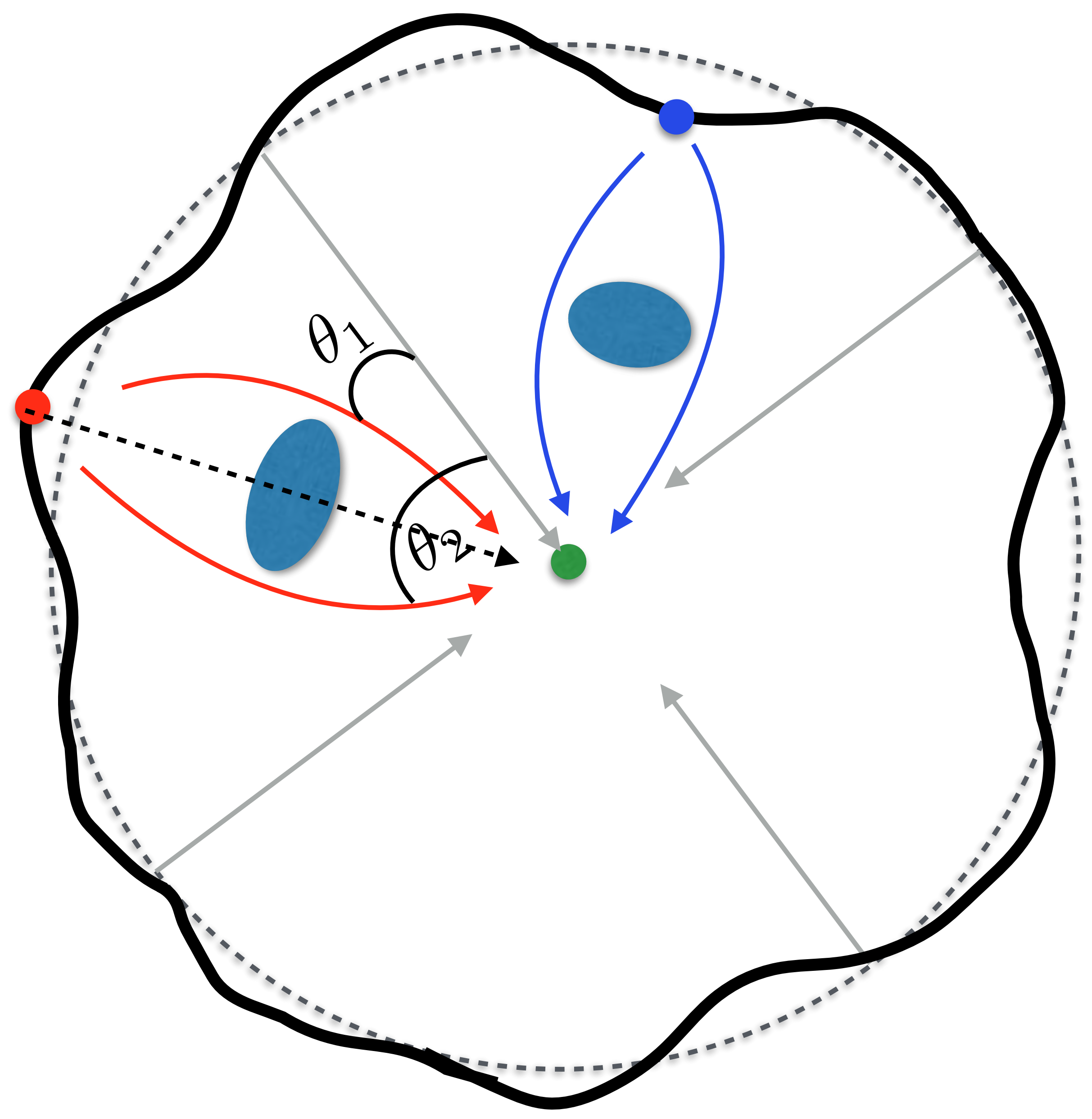
4. Converting E-mode into B-mode (Lensing B-mode)



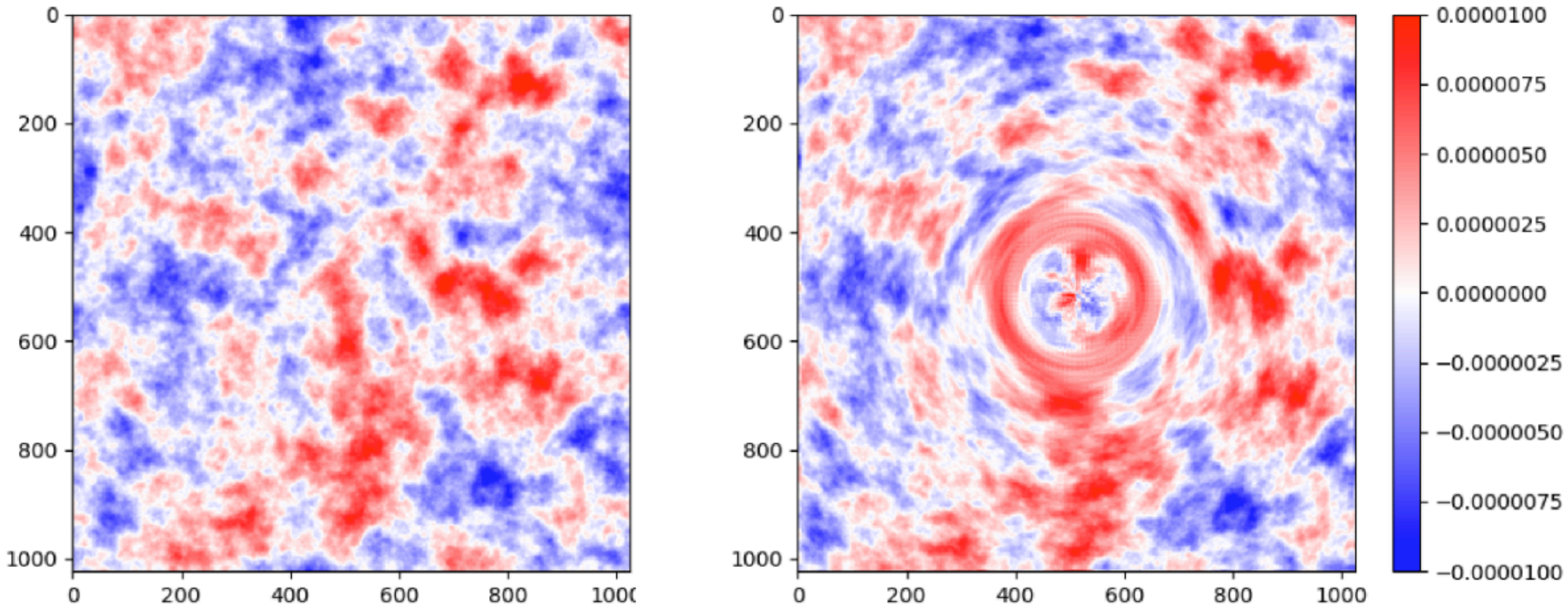
Conservation of surface brightness

$$\tilde{\Theta}(\mathbf{x}) = \Theta(\mathbf{x}') = \Theta(\mathbf{x} + \nabla\psi)$$

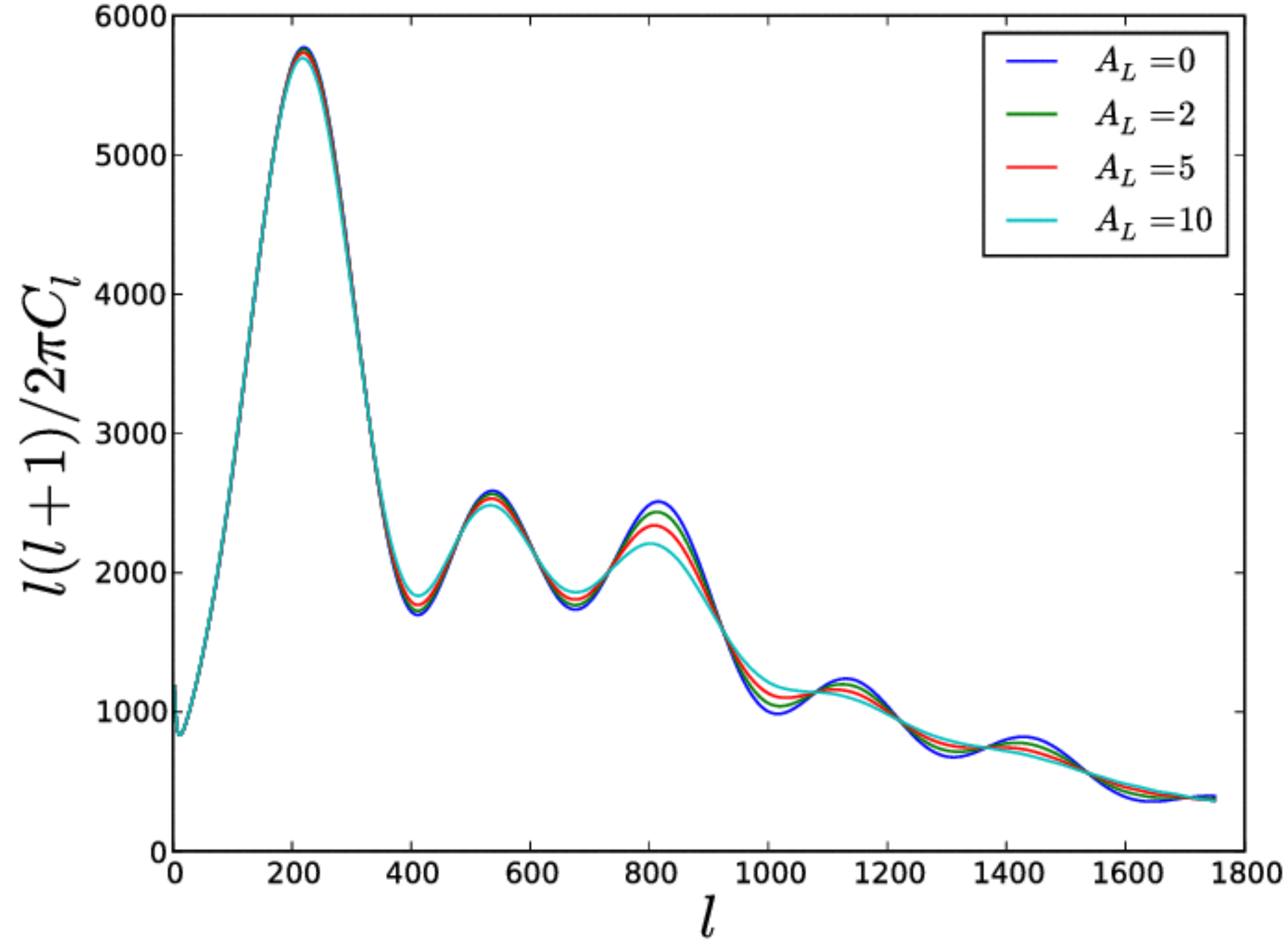
$$\tilde{\Theta}(\mathbf{l}) \approx \Theta(\mathbf{l}) - \int \frac{d^2\mathbf{l}'}{2\pi} \mathbf{l}' \cdot (\mathbf{l} - \mathbf{l}')\psi(\mathbf{l} - \mathbf{l}')\Theta(\mathbf{l}')$$



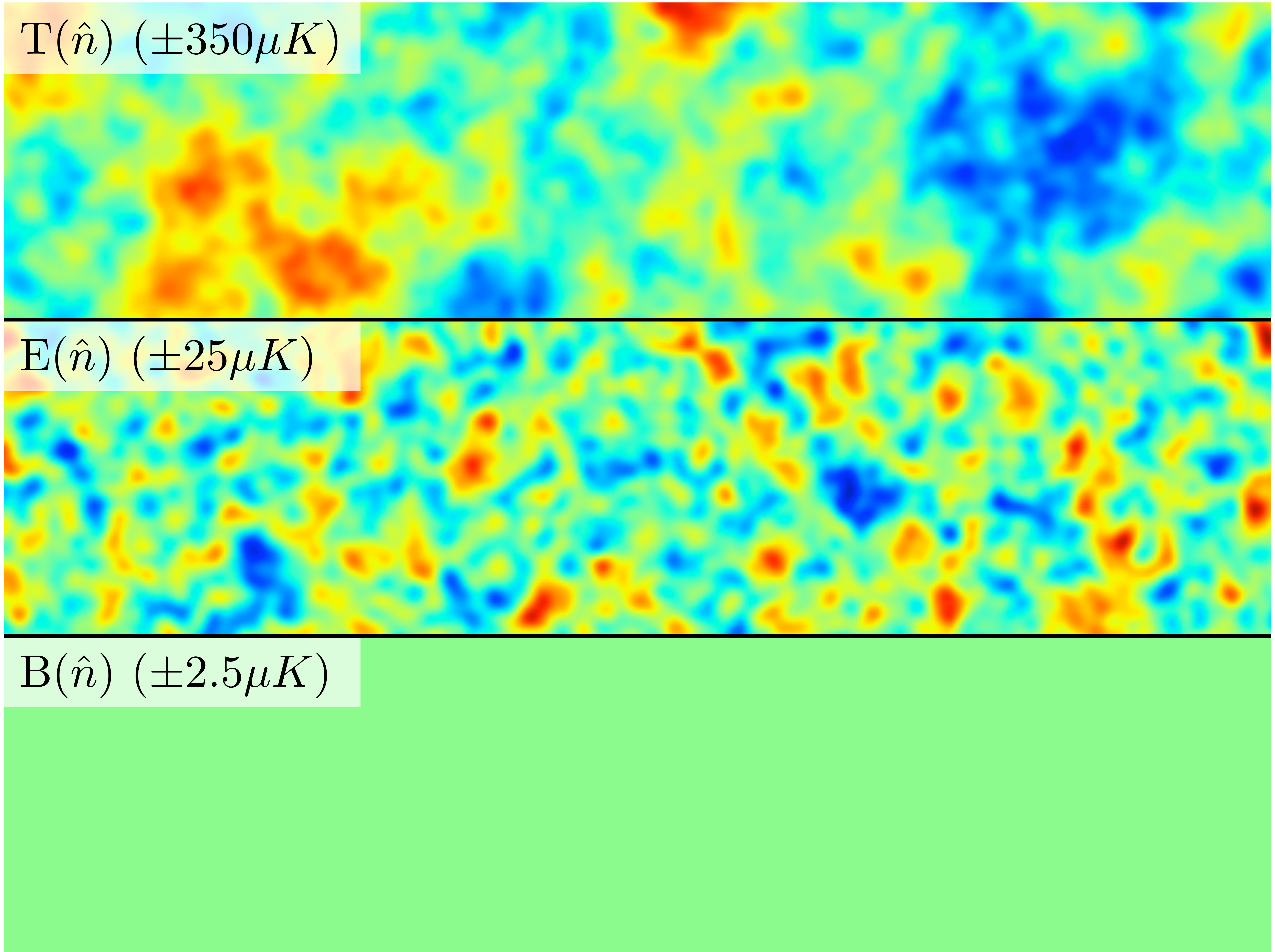
[Credit: Zhengyi Wang (王正一)]



Lensing: smearing acoustic peak



2. Overview of CMB Lensing



[credit: Antony Lewis]

Before lensing

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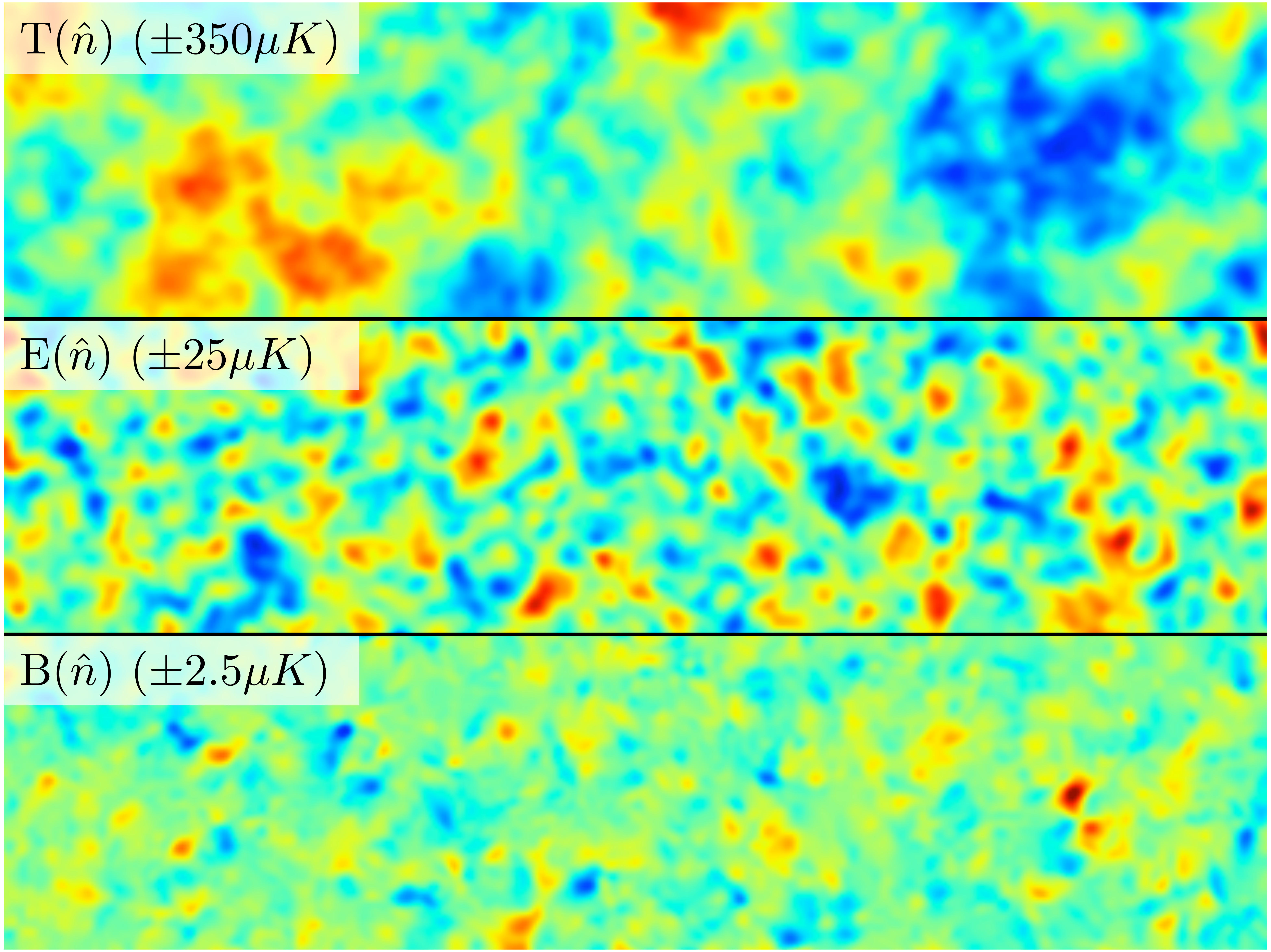
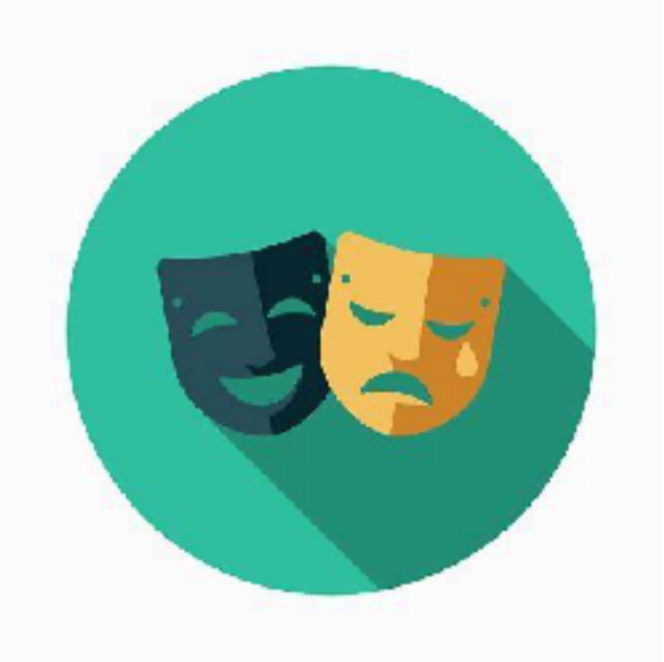


[credit: Antony Lewis]

After lensing

2. Overview of CMB Lensing

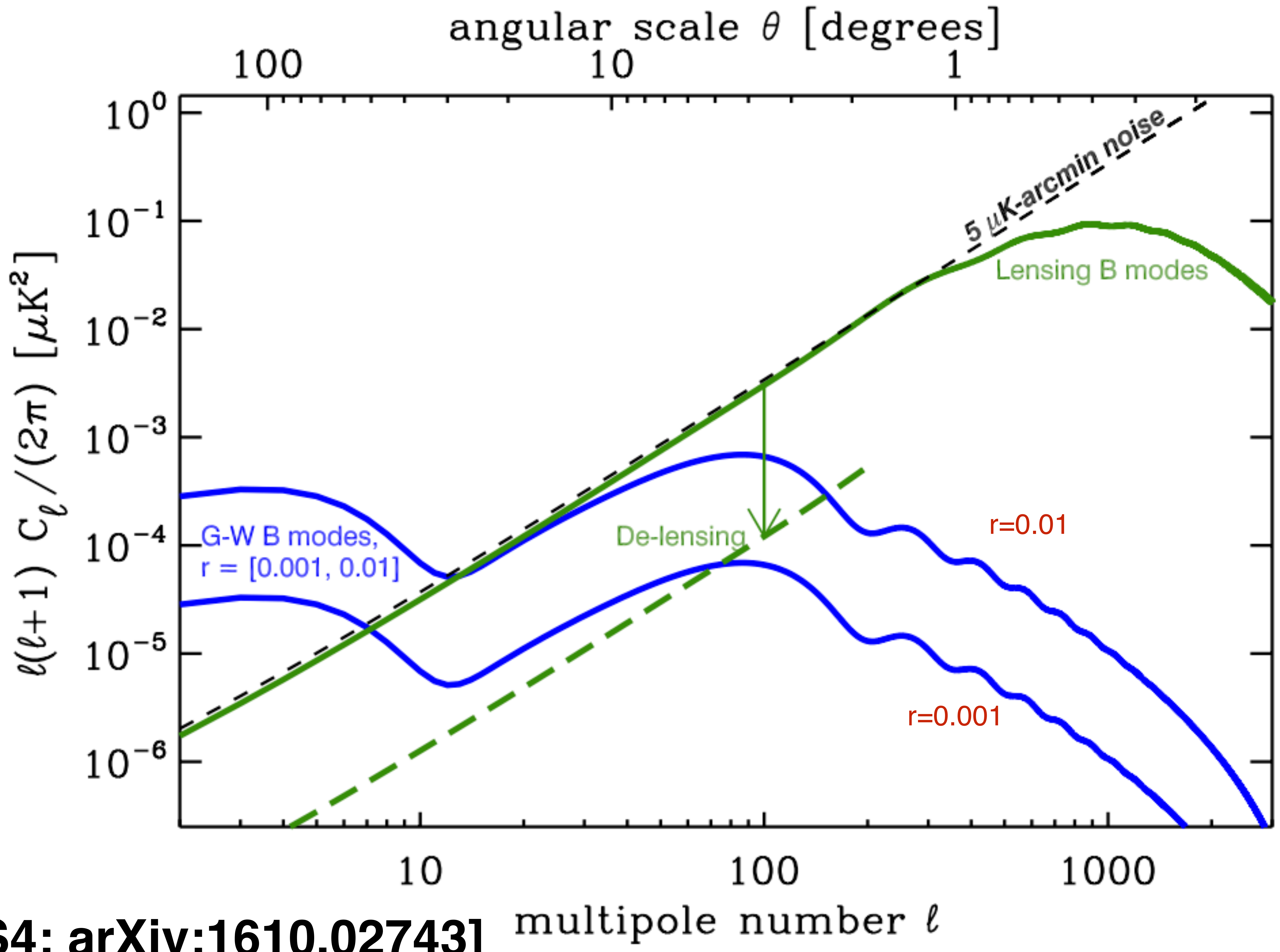
CMB Lensing carries fruit mount of information of LSS. Study on the lenses spatial distribution or XC w/ galaxies, can help us understand nature of DM, DE and Neutrinos.



CMB Lensing is also an unavoidable stochastic noise for primordial GW. It can convert E-mode into B-mode. Specially, for measuring tensor-to-scalar ratio w/ error < 0.01, we must de-lense!

2. Overview of CMB Lensing

- r>0.01, lensing B-mode is not that much serious!
- r<0.01, lensing B-mode is serious problem, need de-lensing!



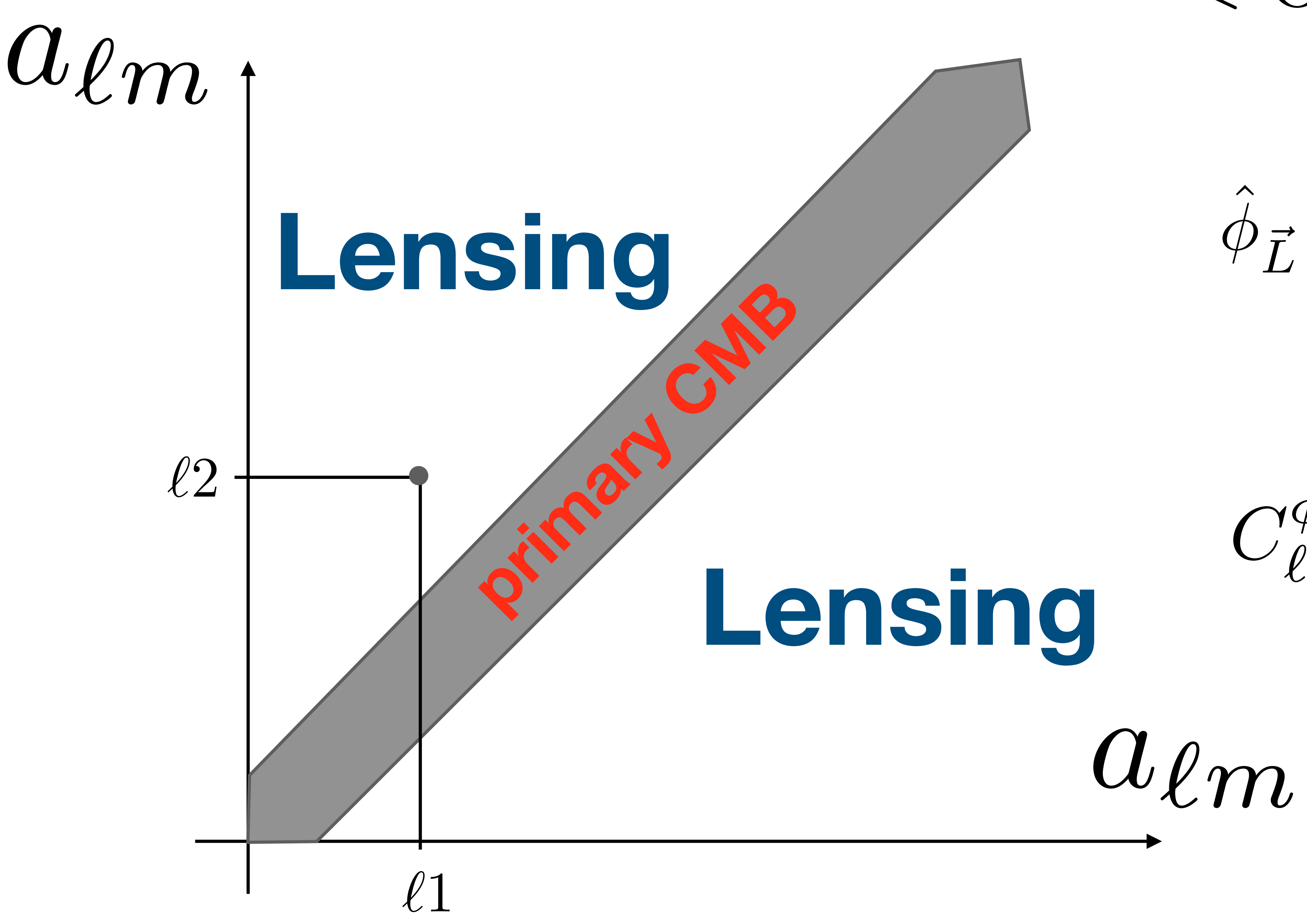
[CMB-S4: arXiv:1610.02743]

3. AliCPT Lensing Reconstruction

Quadratic Estimator

[Hu & Okamoto 2001]

Idea of reconstruction: using the mode-coupling!



$$< \tilde{\Theta}(\mathbf{l_1})\tilde{\Theta}(\mathbf{l_2}) > \neq 0 \quad \text{for} \quad \mathbf{l_1} \neq \mathbf{l_2}$$

$$\hat{\phi}_{\vec{L}} = \frac{1}{T^2} \sum_{\vec{\ell},\ \vec{\ell}'} W(\vec{\ell}, \vec{\ell}', \vec{L}) \times T_{\vec{\ell}} \times \tilde{T}_{\vec{\ell}'} \qquad \tilde{T} = T \times (1+\phi)$$

$$C_\ell^{\phi\phi} = \hat{\phi}\hat{\phi} = \sum_{\vec{\ell}1,\vec{\ell}2,\vec{\ell}3,\vec{\ell}4} T_{\vec{\ell}1}\tilde{T}_{\vec{\ell}2}T_{\vec{\ell}3}\tilde{T}_{\vec{\ell}4}$$

$$= \sum_{\vec{\ell}1,\vec{\ell}2,\vec{\ell}3,\vec{\ell}4} T_{\vec{\ell}1}T_{\vec{\ell}2}T_{\vec{\ell}3}T_{\vec{\ell}4} + T_{\vec{\ell}1}T_{\vec{\ell}2}T_{\vec{\ell}3}T_{\vec{\ell}4}\phi\phi + \cdots$$

N0 — **Unavoidable Noise from Primary CMB**

Can be normalized

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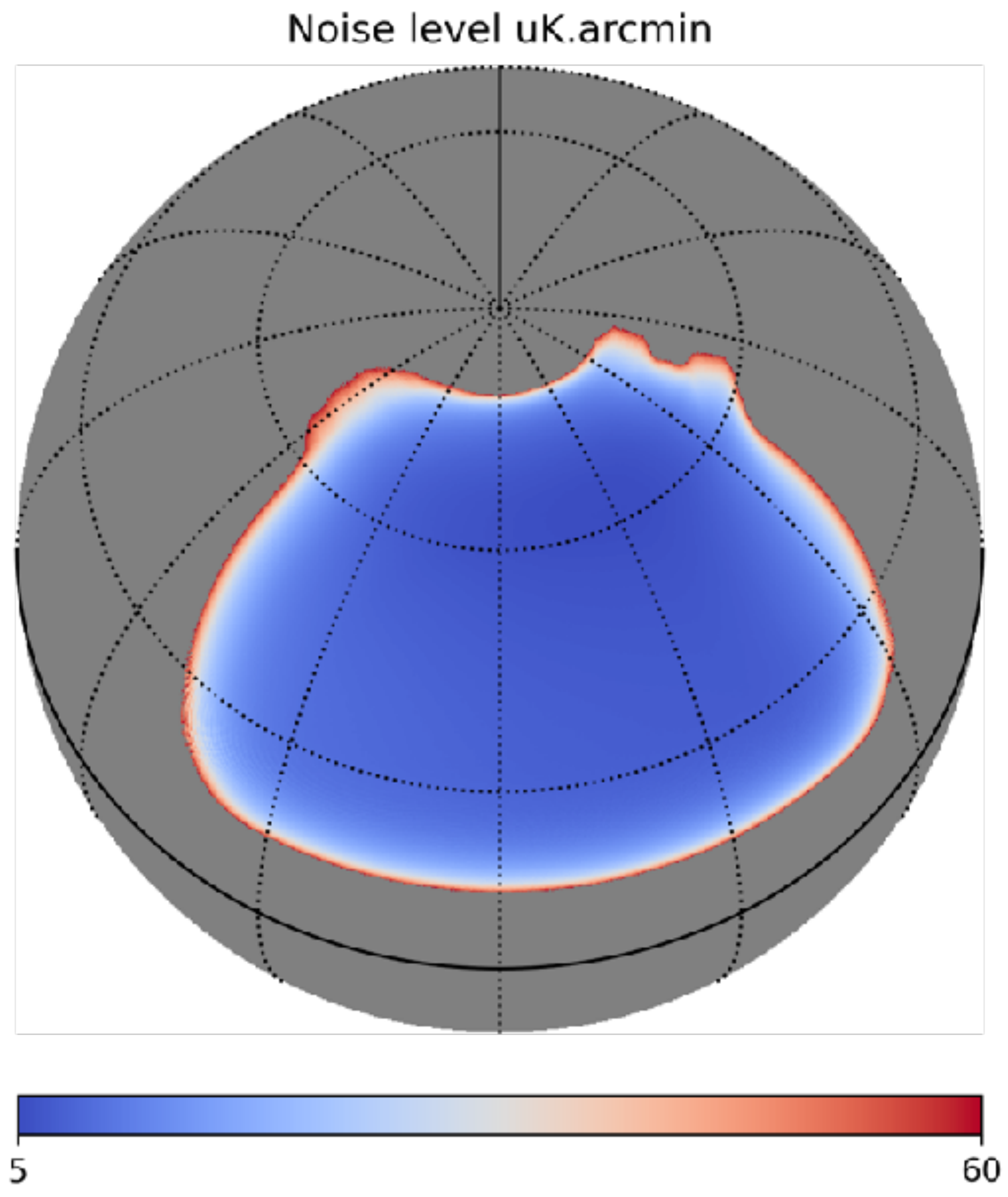
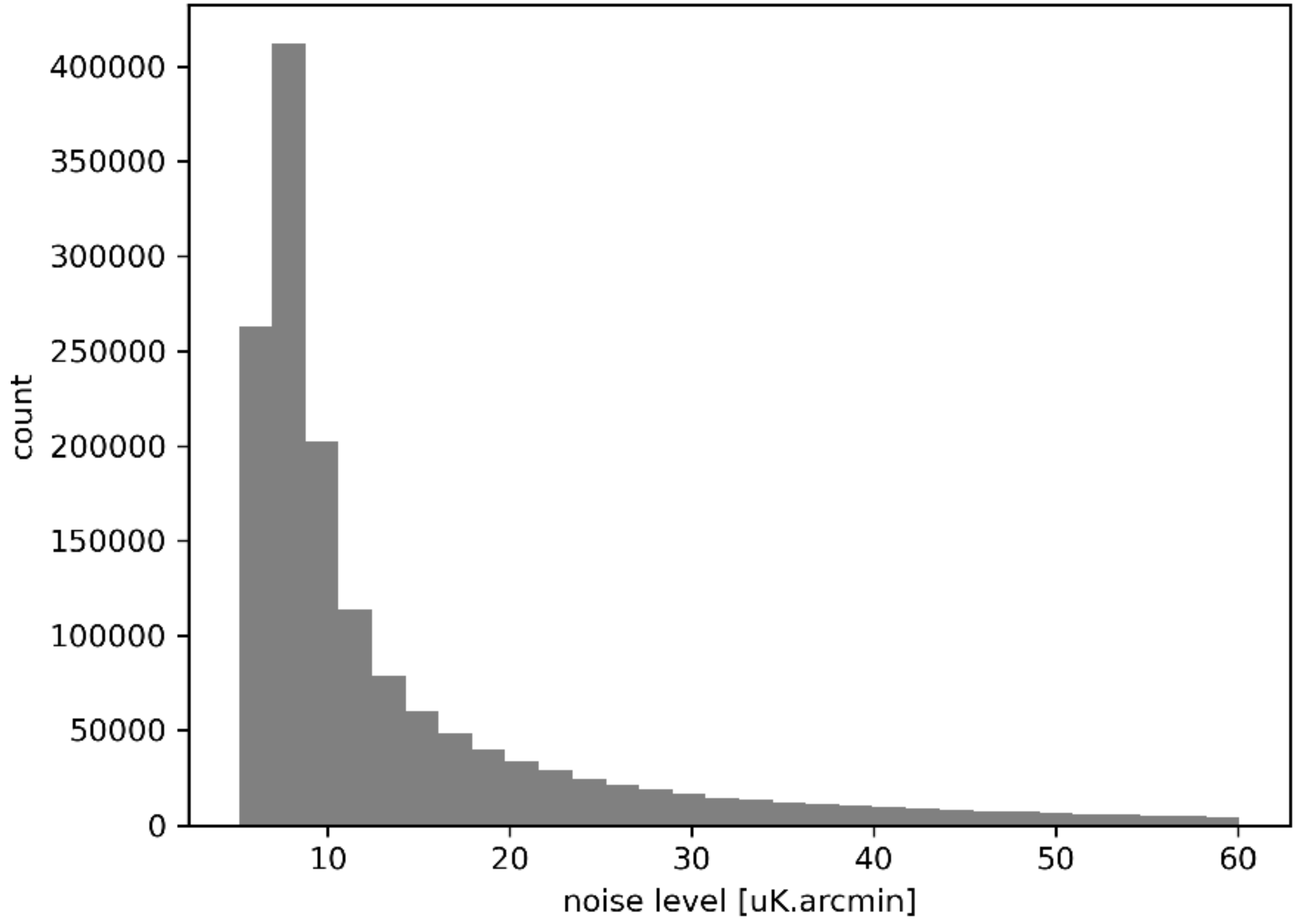
AliCPT-1 deep field

sky = 13%





3. AliCPT Lensing Reconstruction

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- **Inhomogeneous filtering**

  we deal with the filtering pixel by pixel

$$\bar{X} = \mathrm{S}^{-1}[\mathrm{S}^{-1} + \mathcal{Y}^{\mathrm{T}}\mathrm{N}^{-1}\mathcal{Y}]^{-1}\mathcal{Y}^{\mathrm{T}}\mathrm{N}^{-1}\mathbf{d}$$

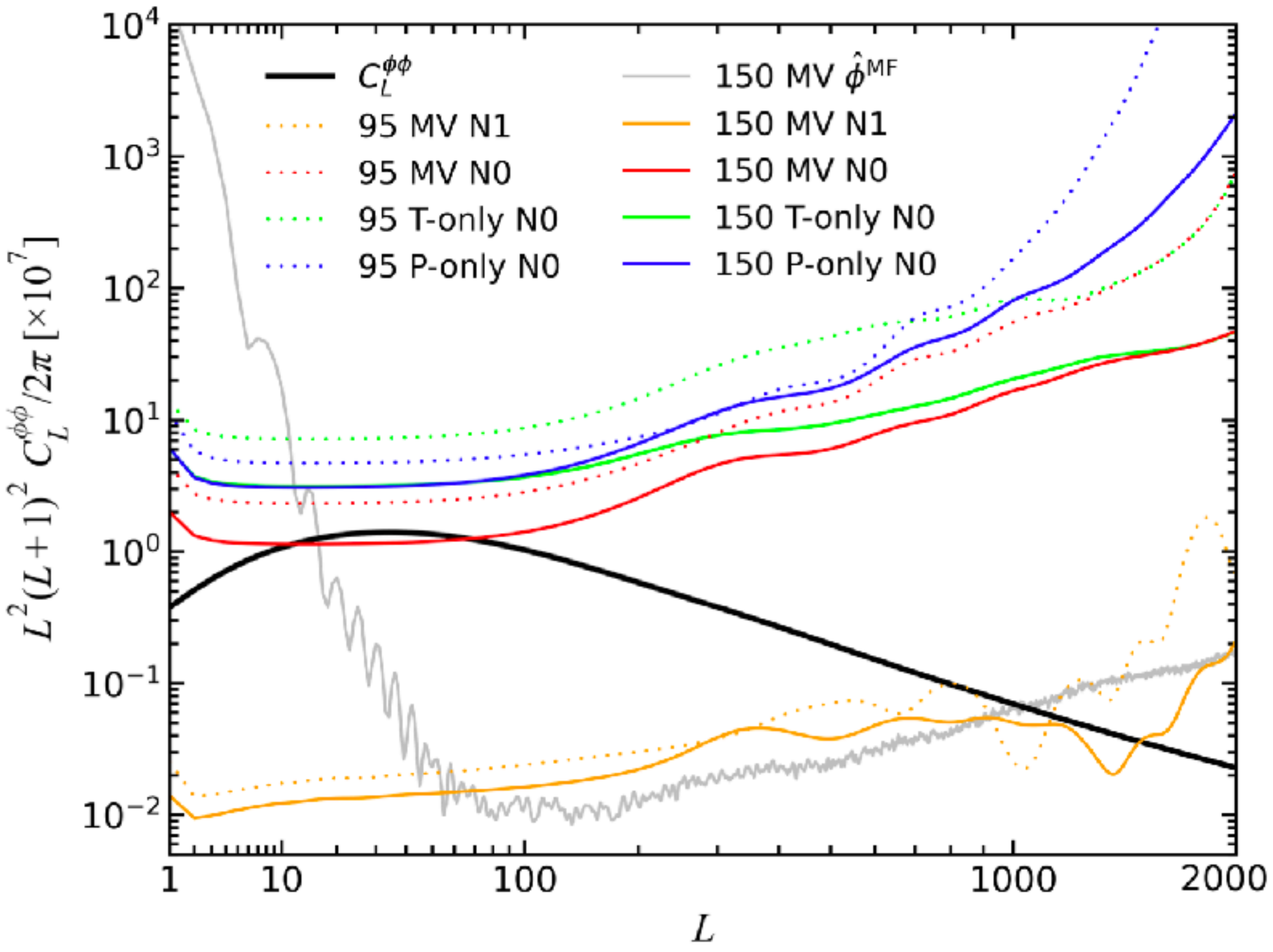
$$\hat{\phi}_{\vec{L}} = \frac{1}{T^2}\sum_{\vec{\ell},\ \vec{\ell}'} W(\vec{\ell}, \vec{\ell}', \vec{L}) \times T_{\vec{\ell}} \times \tilde{T}_{\vec{\ell}'}$$

X is {T, E, B}.
d is observed {T, Q, U} maps.
N is pixel variance.
Y is harmonic transform matrix including beam transfer function.
S is covariance matrix for {T, E, B}.

d and N are in pixel domain, S and X are in harmonic domain.

$$<\hat{\phi}>\neq 0$$ Thanks to Mask

$$\phi = \hat{\phi} - <\hat{\phi}>$$ Mean-field subtraction



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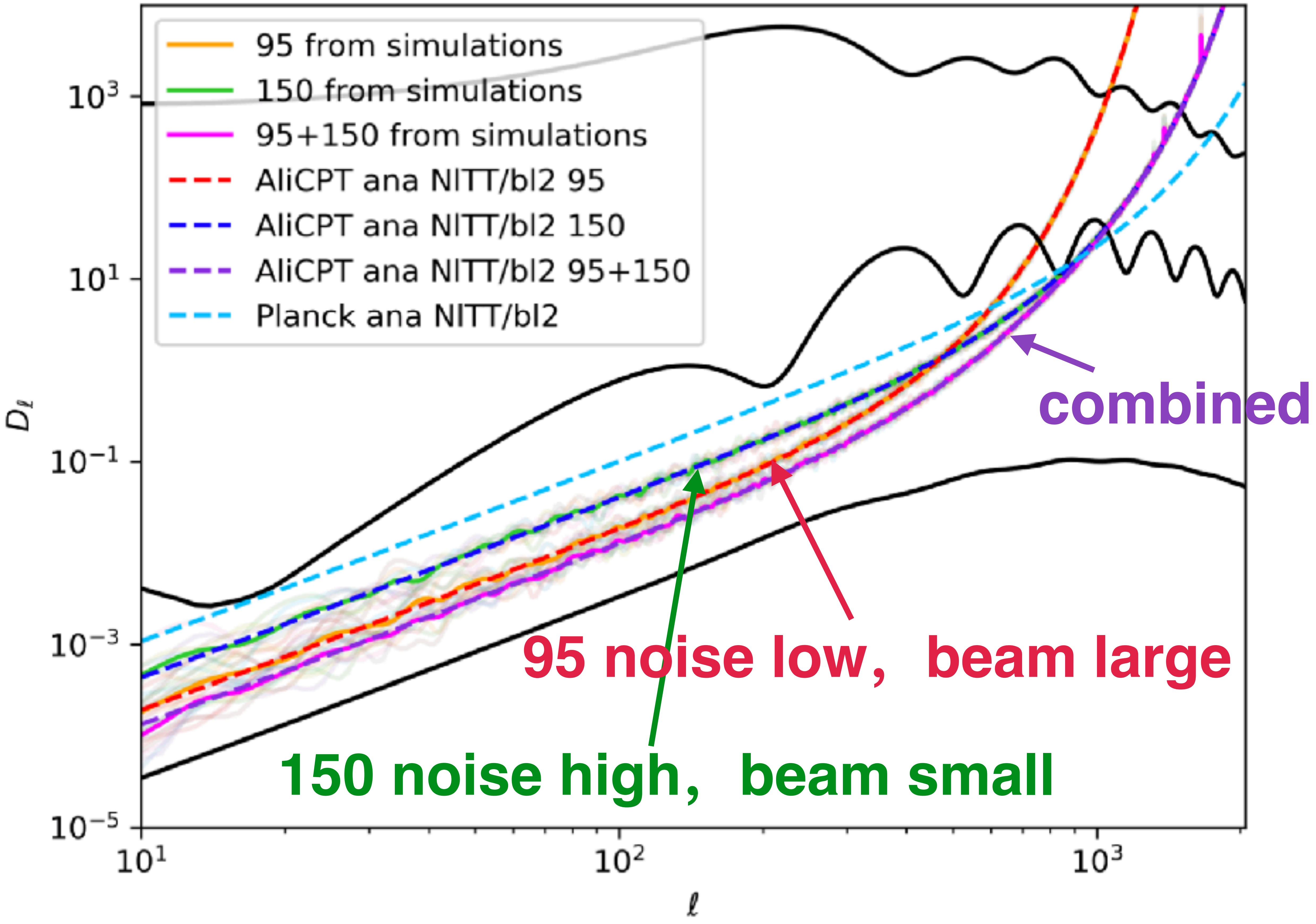
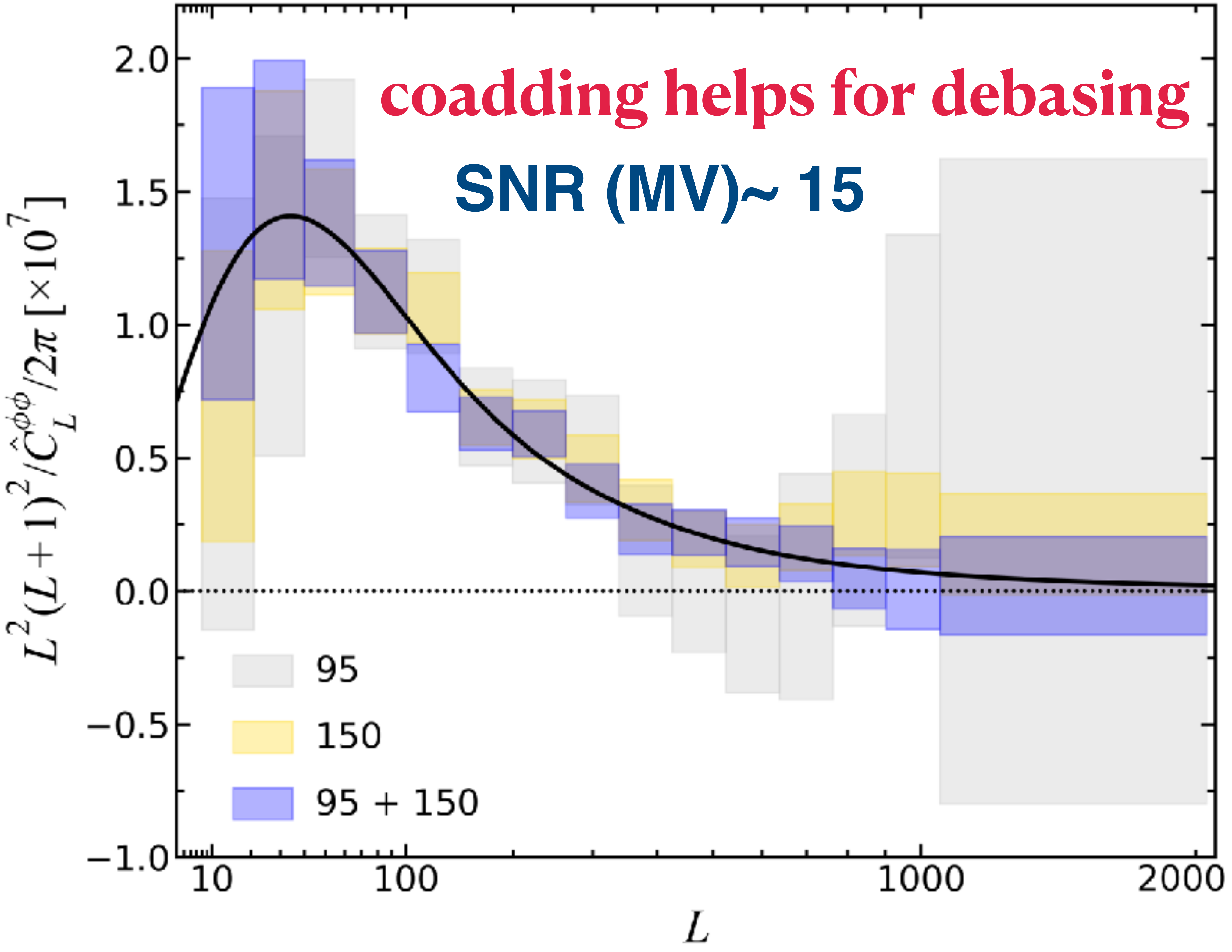
3. AliCPT Lensing Reconstruction

- Multi-freq coadding

Unfortunately, coadding helps a little

(95GHz beam is too large)





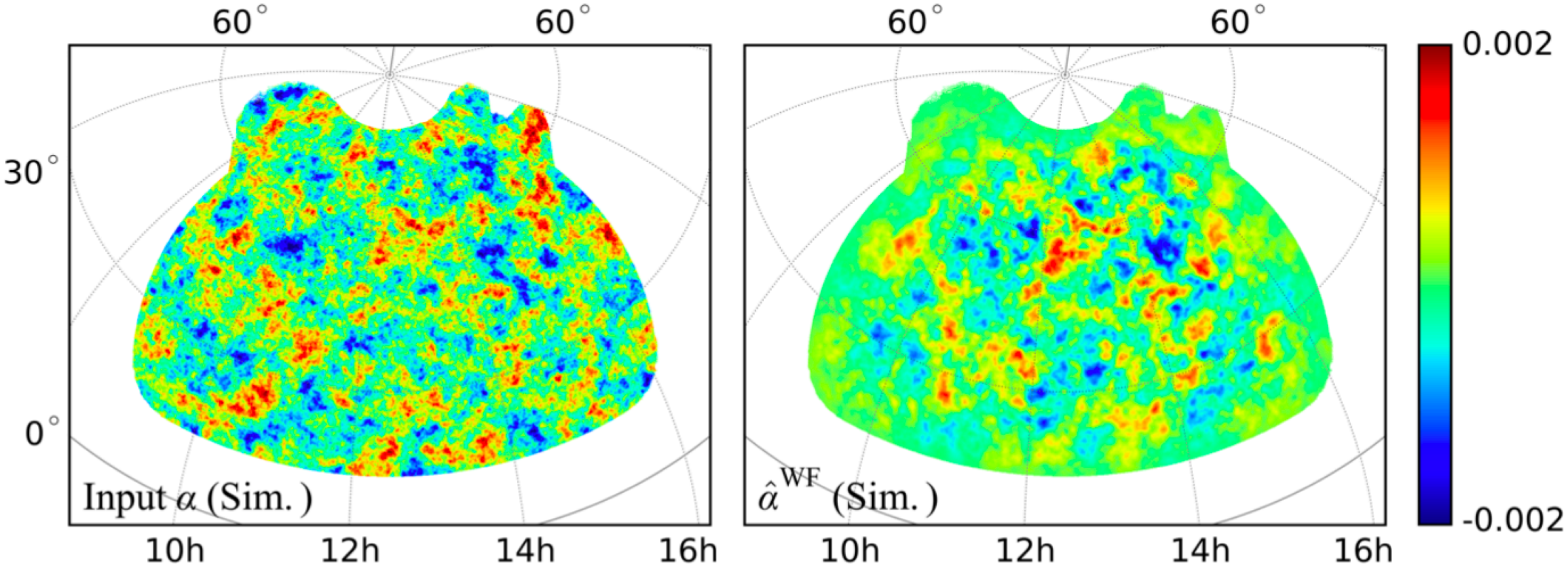
3. AliCPT Lensing Reconstruction

Table 1. Lensing reconstruction SNR

frequency	estimator	4 module*yr	48 module*yr
95 GHz	T-only	3.5	4.8
	P-only	5.1	21.7
	MV	9.2	24.3
150 GHz	T-only	8.3	8.0
	P-only	6.6	25.4
	MV	15.4	31.1

[Sci.China Phys.Mech.Astron. 65 (2022) 10, 109511]

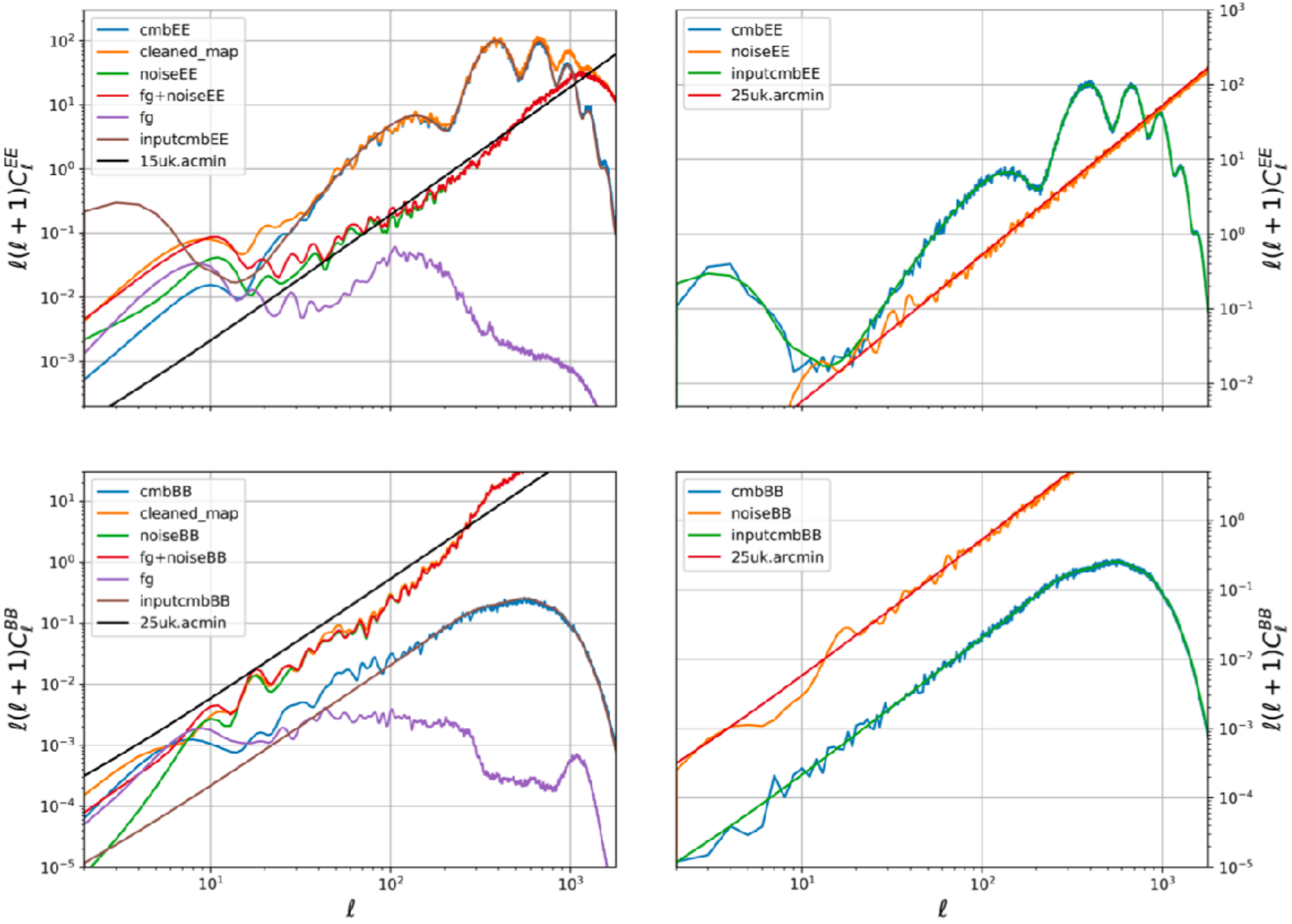
3. AliCPT Lensing Reconstruction



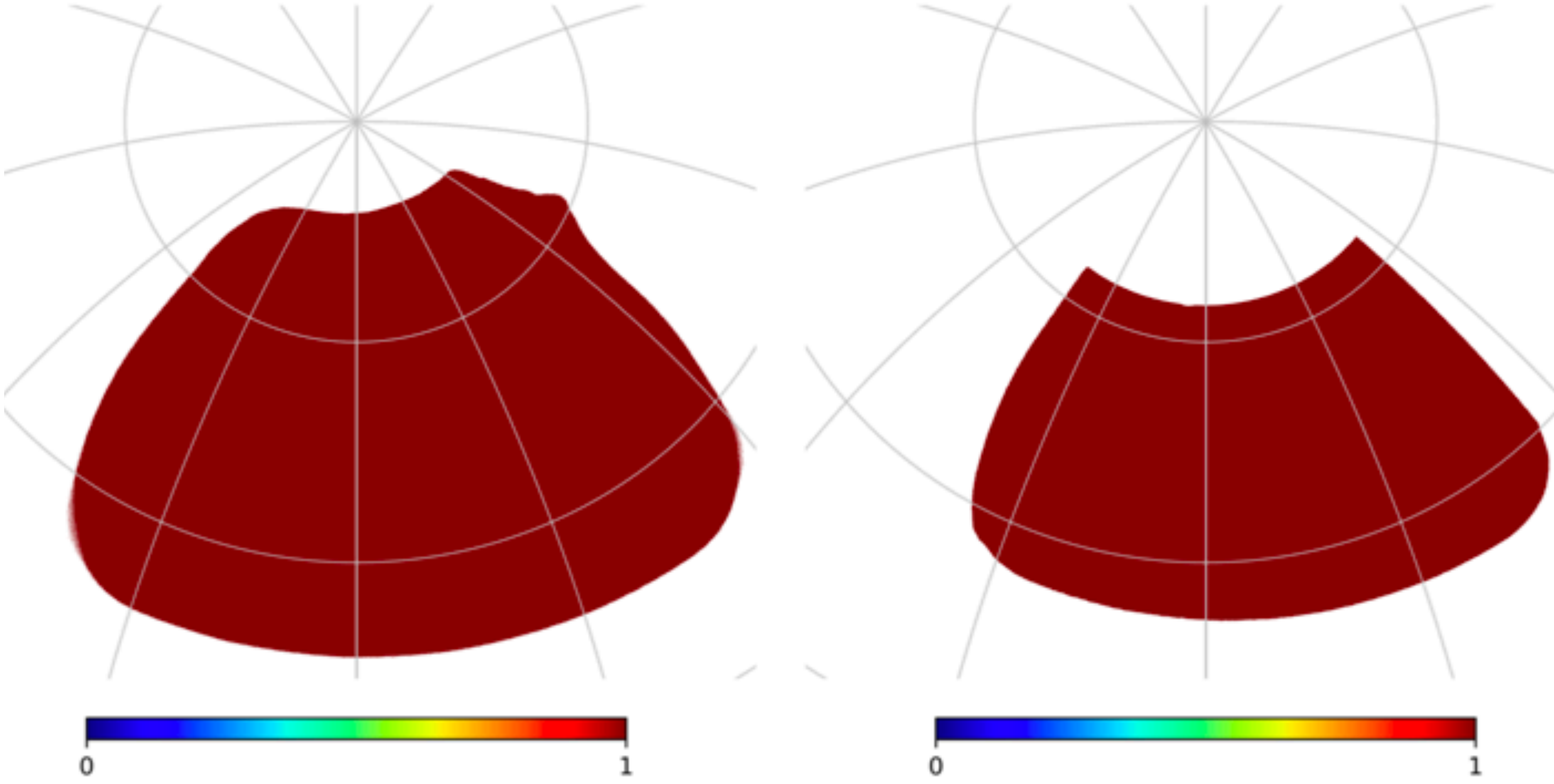
[Sci.China Phys.Mech.Astron. 65 (2022) 10, 109511]

3. AliCPT Lensing Reconstruction **Adding fg**

[Jiakang Han et al. in prep]



NILC for T/E, cILC for B

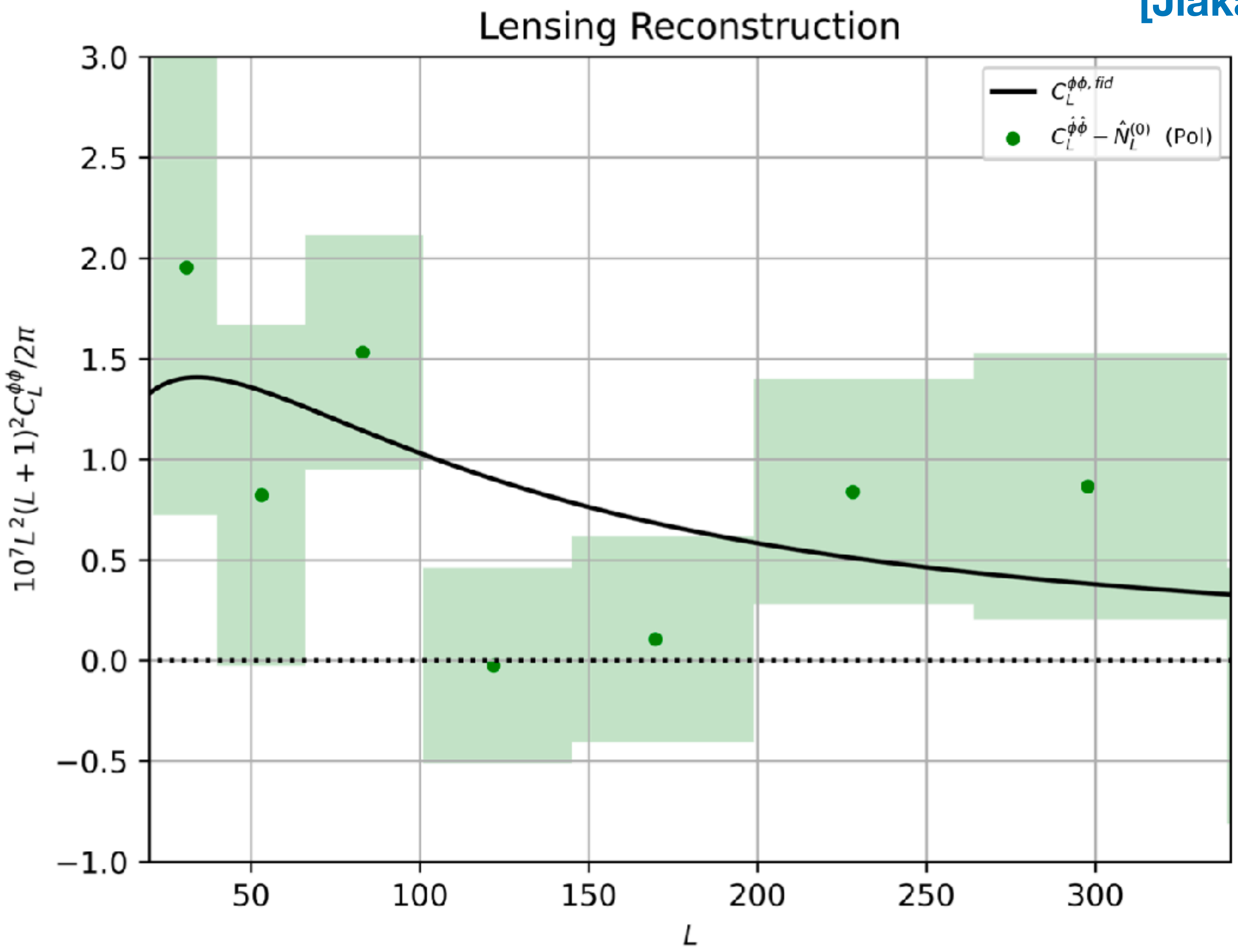


B-map has larger noise

additional constraints on average frequency scaling of the dust and synchrotron to remove these at the expense of noisy maps

3. AliCPT Lensing Reconstruction **Adding fg**

[Jiakang Han et al. in prep]



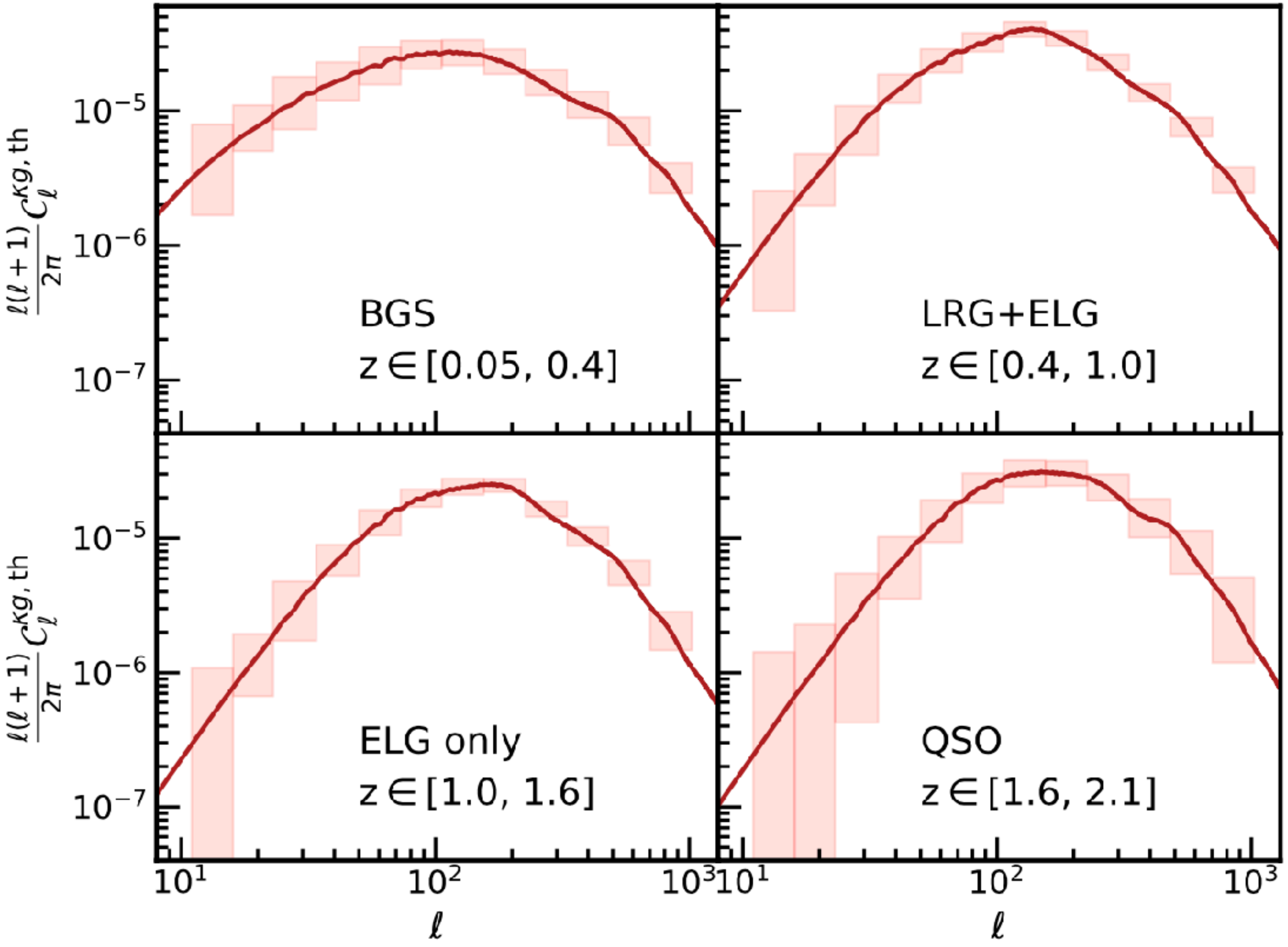
SNR=4.5 (w/ fg)

SNR=6.6 (w/o fg)

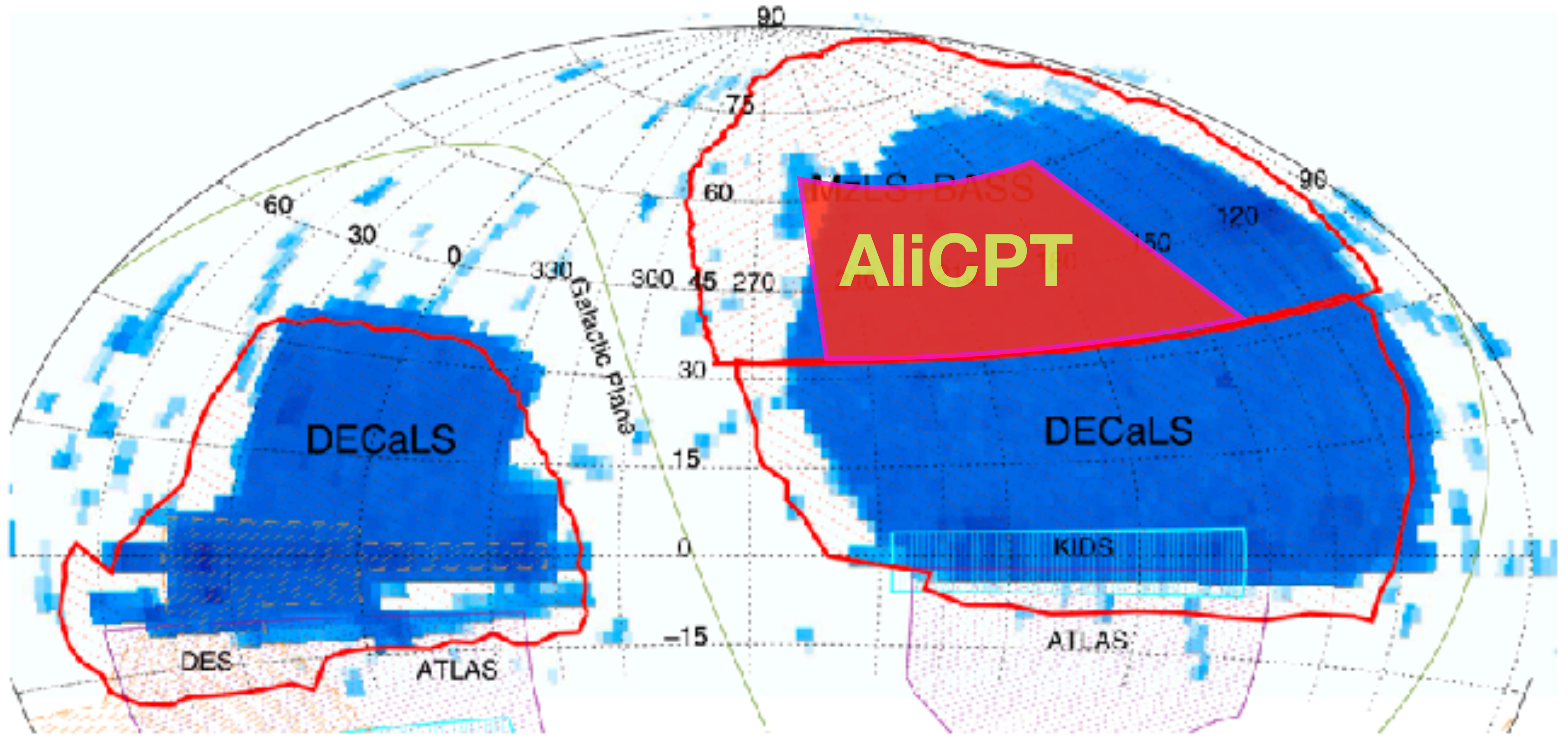
4. AliCPT XC w/ DESI/CIB/CSST

Dark Energy Spectroscopic Instrument (DESI)

[Credit: Zeyang Sun (孙则阳)]



DESI footprint completely cover AliCPT



z	targets	S/N
0.05-0.4	BGS	13.4
0.4-1.0	LRG + ELG	18.7
1.0-1.6	ELG only	19.4
1.6-2.1	QSO	10.6

Total XC SNR ~ 32

4. AliCPT XC w/ DESI/CIB/CSST

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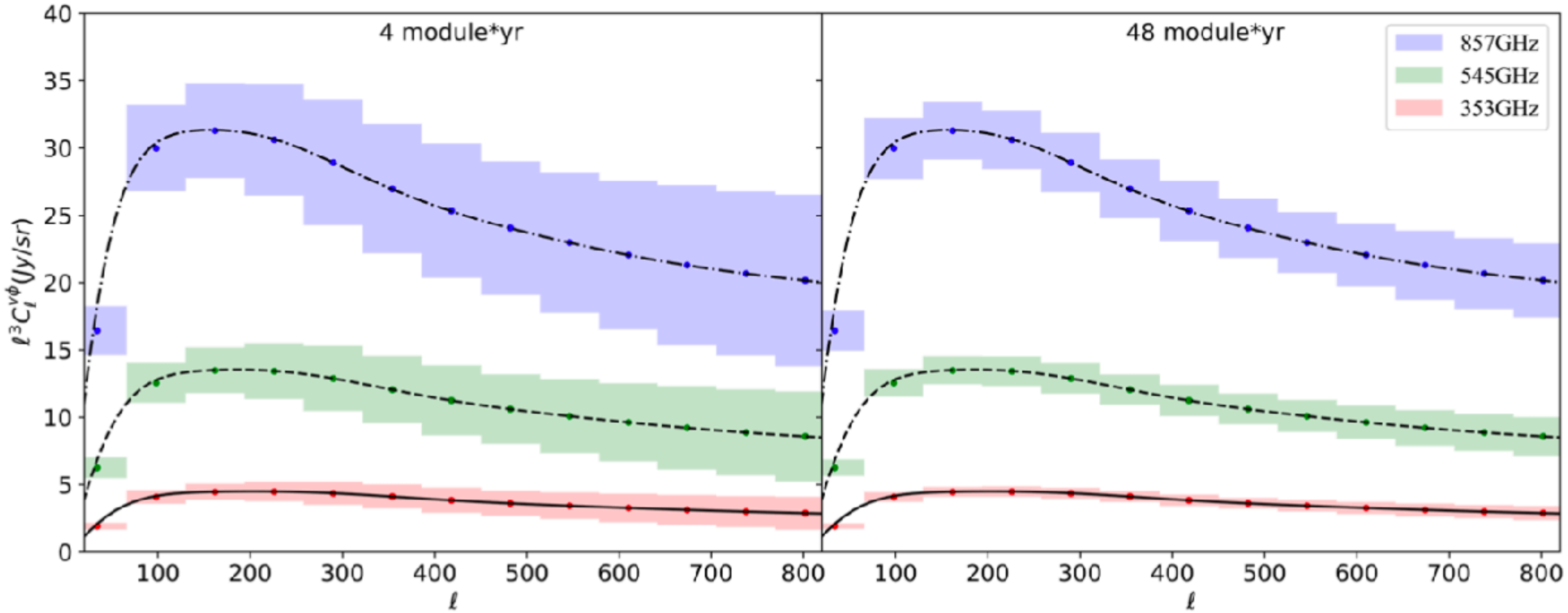
Cosmic
Infrared
Background
from
unresolved
dusty
star forming
galaxy
is highly
correlated
(80%)
with CMB
lensing

Table 4. Lensing-CIB cross-correlation SNRs

frequency(GHz)	4 module*yr	48 module*yr
353	18.2	25.1
545	19.3	33.2
857	23.1	42.2
total	23.2	43.0



4. AliCPT XC w/ DESI/CIB/CSST

Optical Module for Astronomy

Chinese Space Survey Telescope

A 2m space telescope in the same orbit as the China Manned Space Station, serviceable while docking with the station.

Instruments: Survey Camera (SC), Terahertz Receiver (THz), Multichannel Imager (MCI), Integral Field Spectrograph (IFS), Cool-Planet Imaging Coronagraph (CPIC).

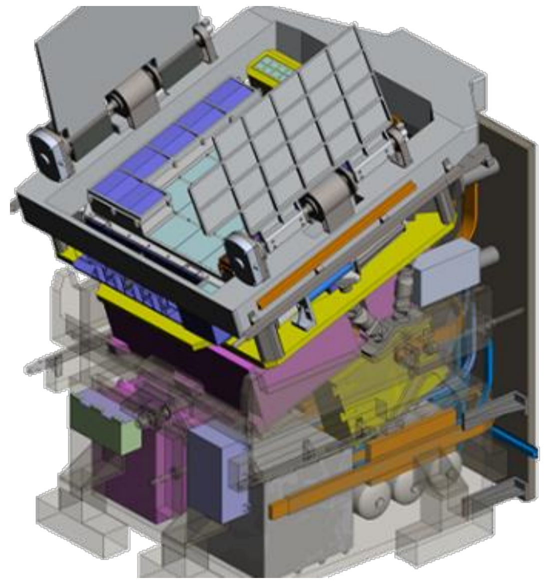
Mission: wide-area multiband imaging & slitless spectroscopic survey (7yr); other key programs & GO programs (2+yr).

Stage-IV galaxy survey

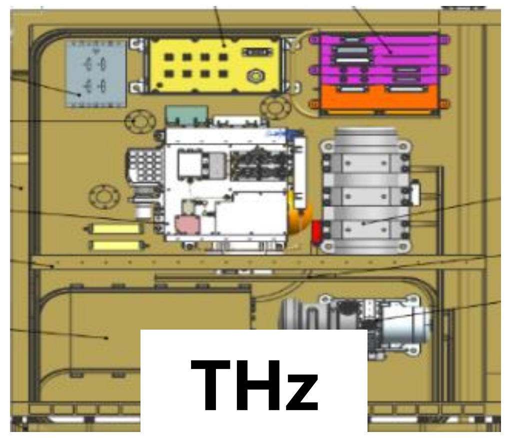
Sky area: 17k Degsq

 # density: 20 gal/arcmin2

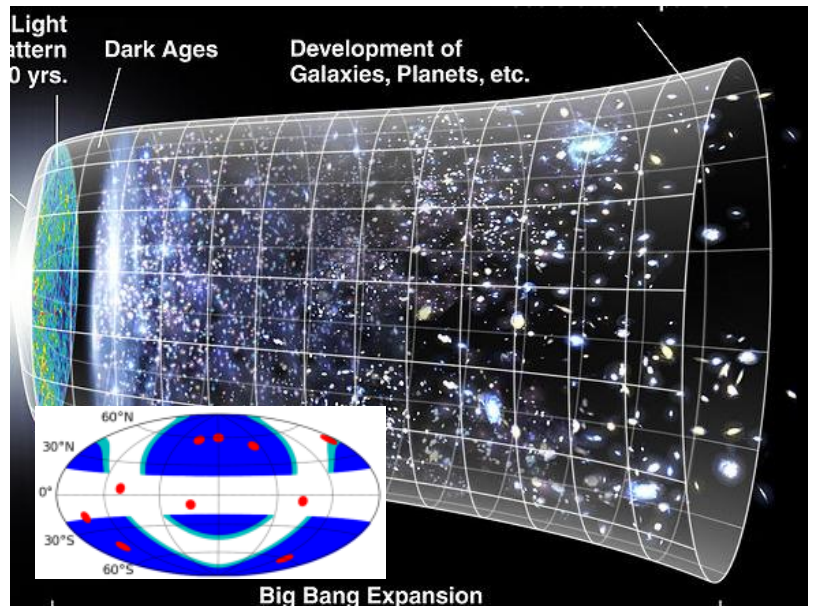
Optical Module (~2024)

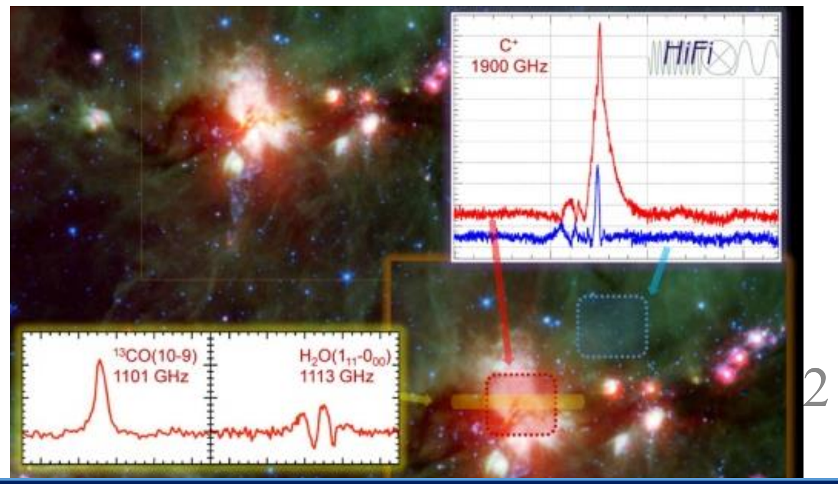


Survey Cam



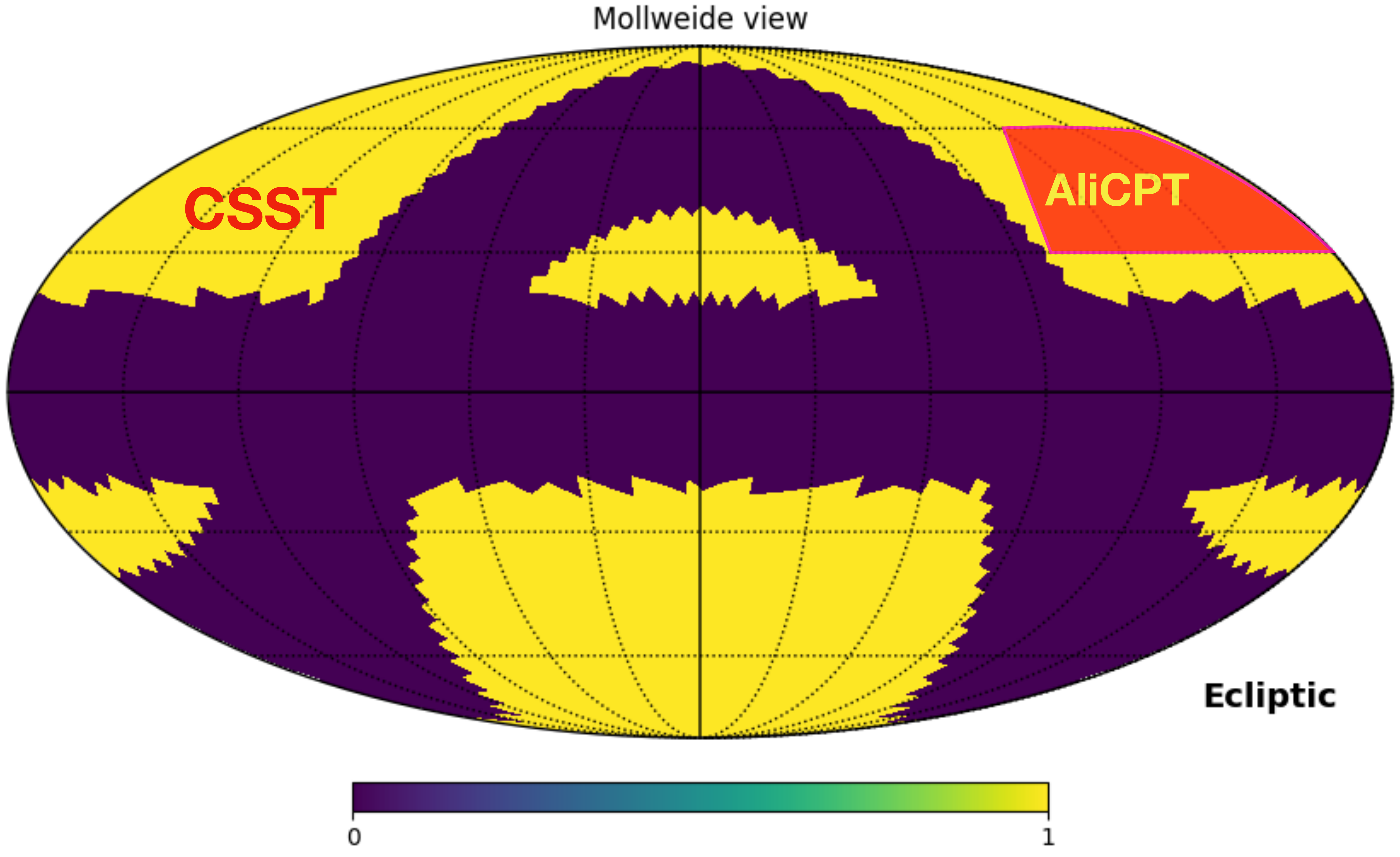
THz

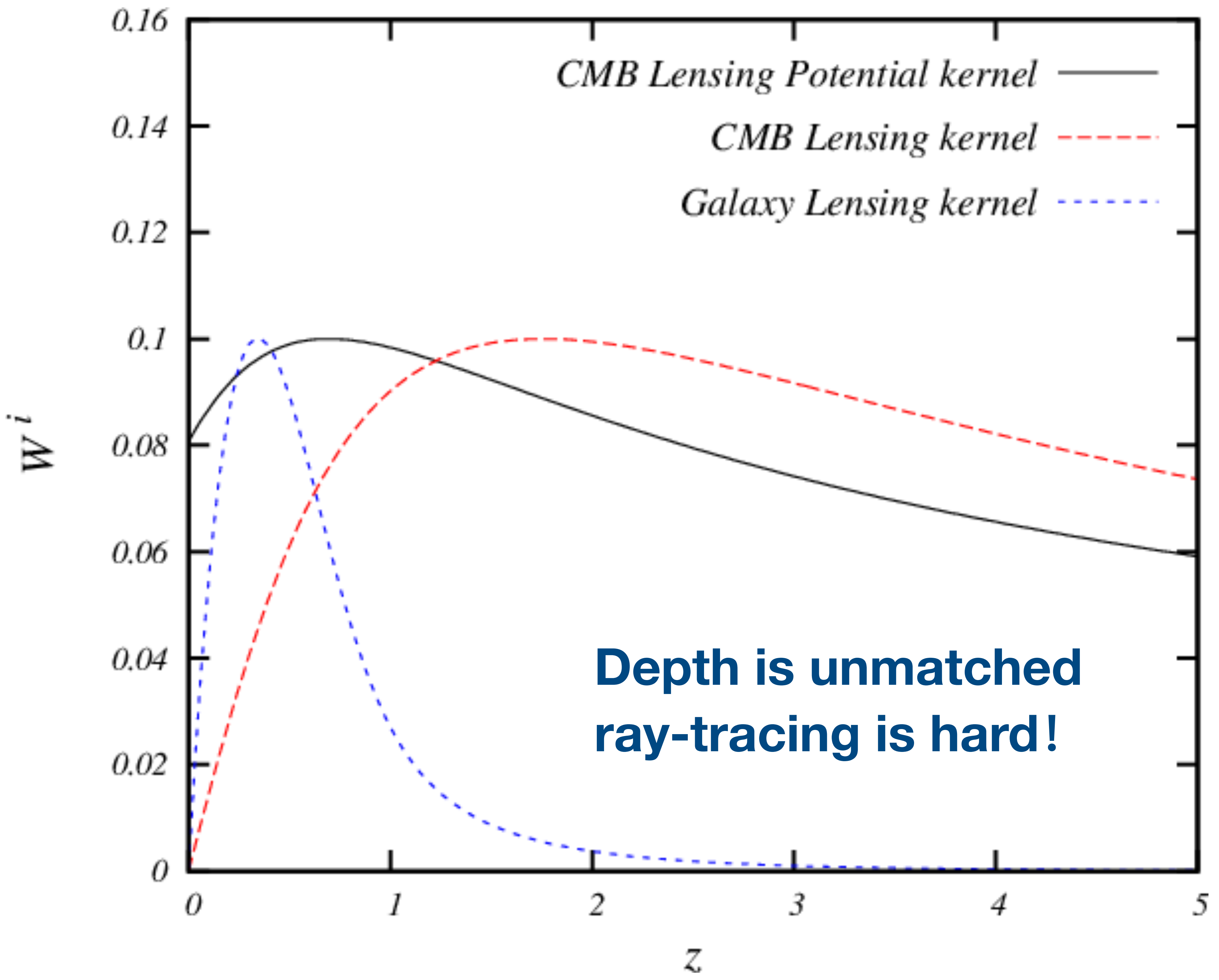




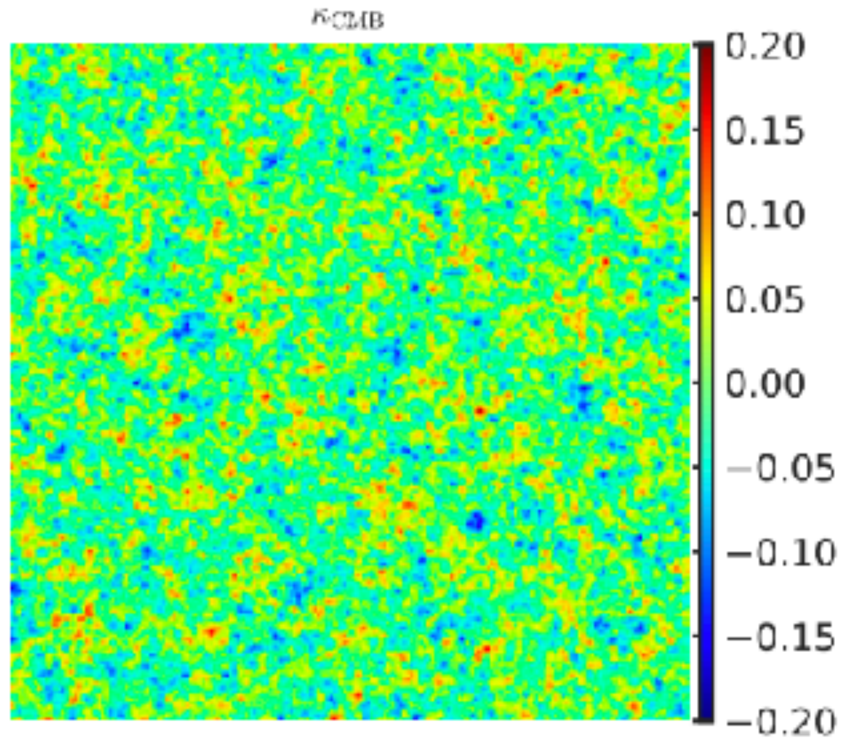
[credit: Hu Zhan (詹虎)]

4. AliCPT XC w/ DESI/CIB/CSST



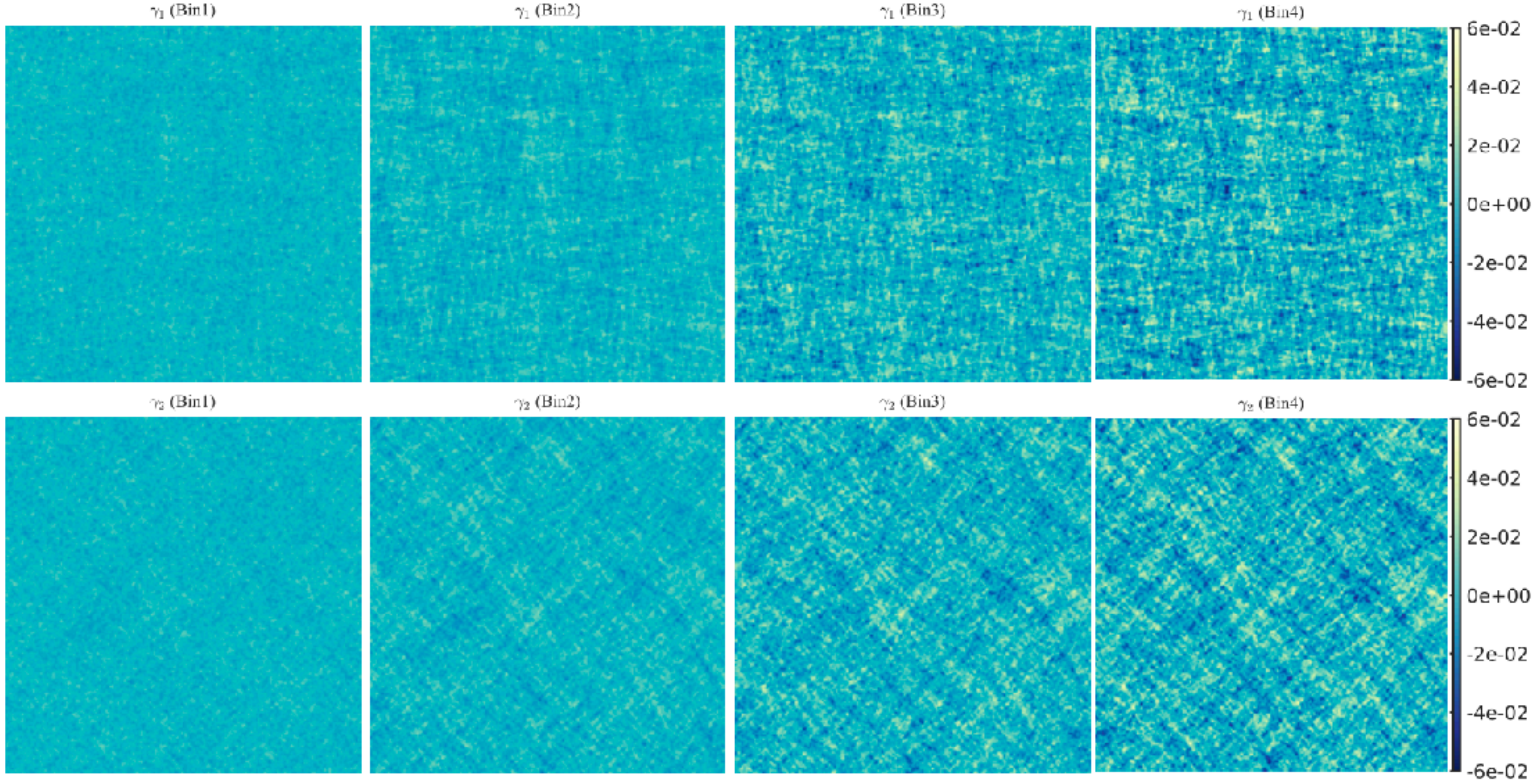


4. AliCPT XC w/ DESI/CIB/CSST



Simulated Signals

30 deg X 30 deg



4. AliCPT XC w/ DESI/CIB/CSST

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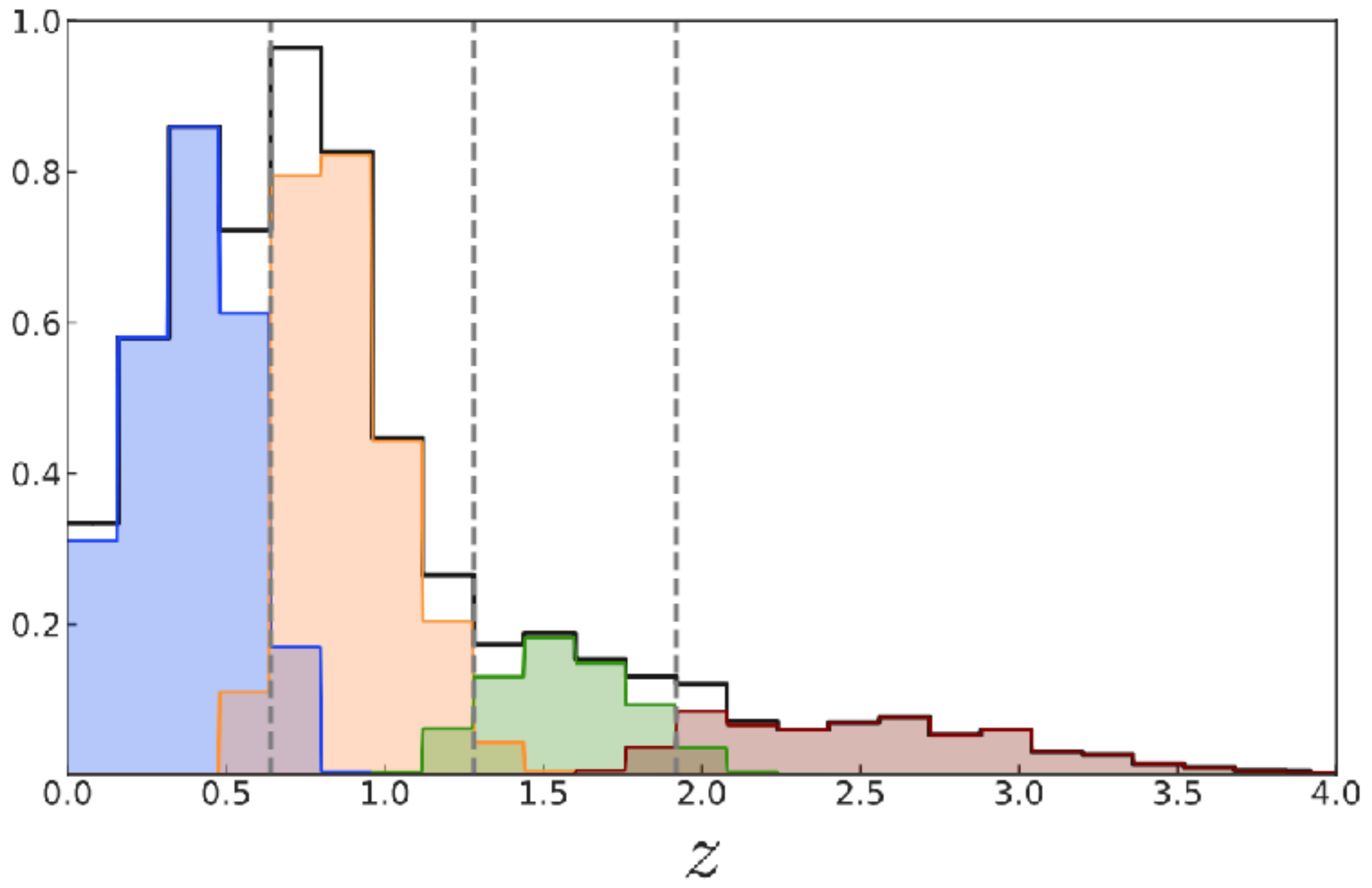
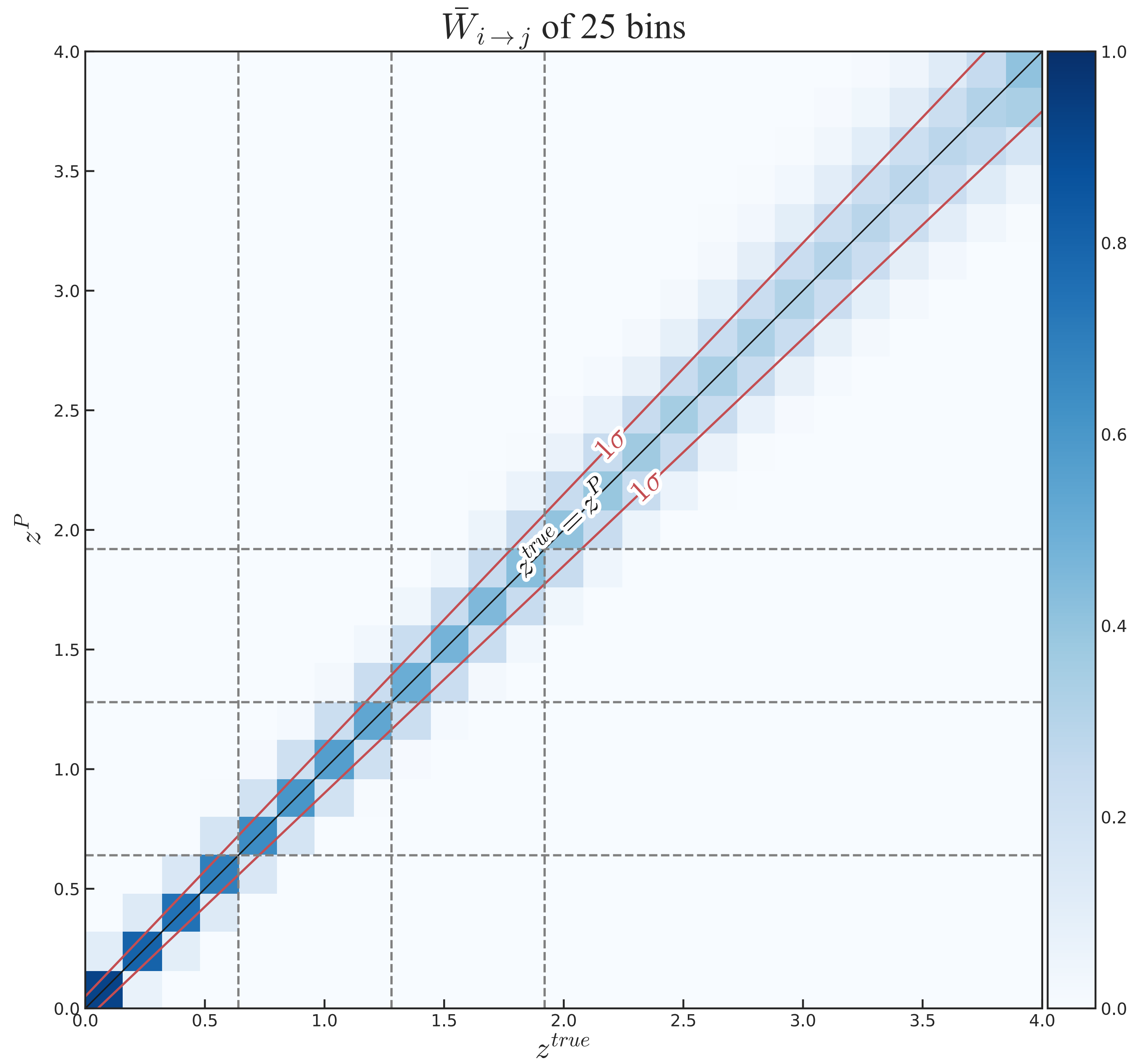
Error budget：
photo-z,
shape noise,
Intrinsic Alignment

$$n(z) \propto z^{\alpha} \exp\left[-\left(\frac{z}{z_0}\right)^{\beta}\right], \quad (20)$$

$$p(z^P|z) = \frac{1}{\sqrt{2\pi}\sigma_z(1+z)} \exp\left[-\frac{(z - z^P - \Delta_z^i)^2}{2(\sigma_z(1+z))^2}\right]. \quad (21)$$





$\sigma_z = 0.05$ **photo-z error**

$(1+z)\Delta_z = 0.005$ **photo-z bias**

z~(2,4) has the highest SNR

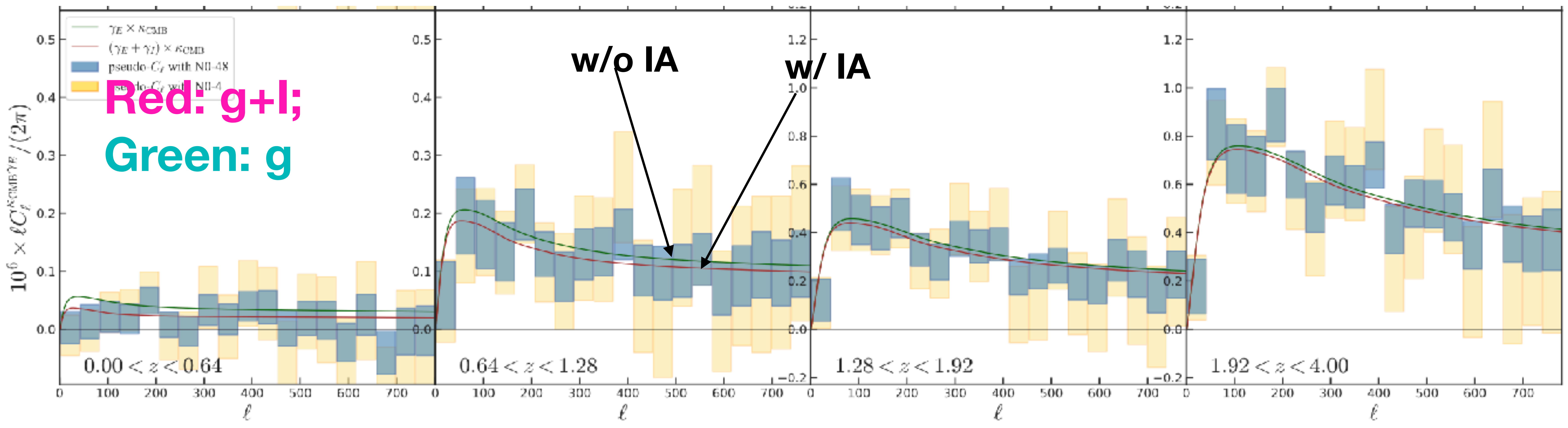
4. AliCPT XC w/ DESI/CSST

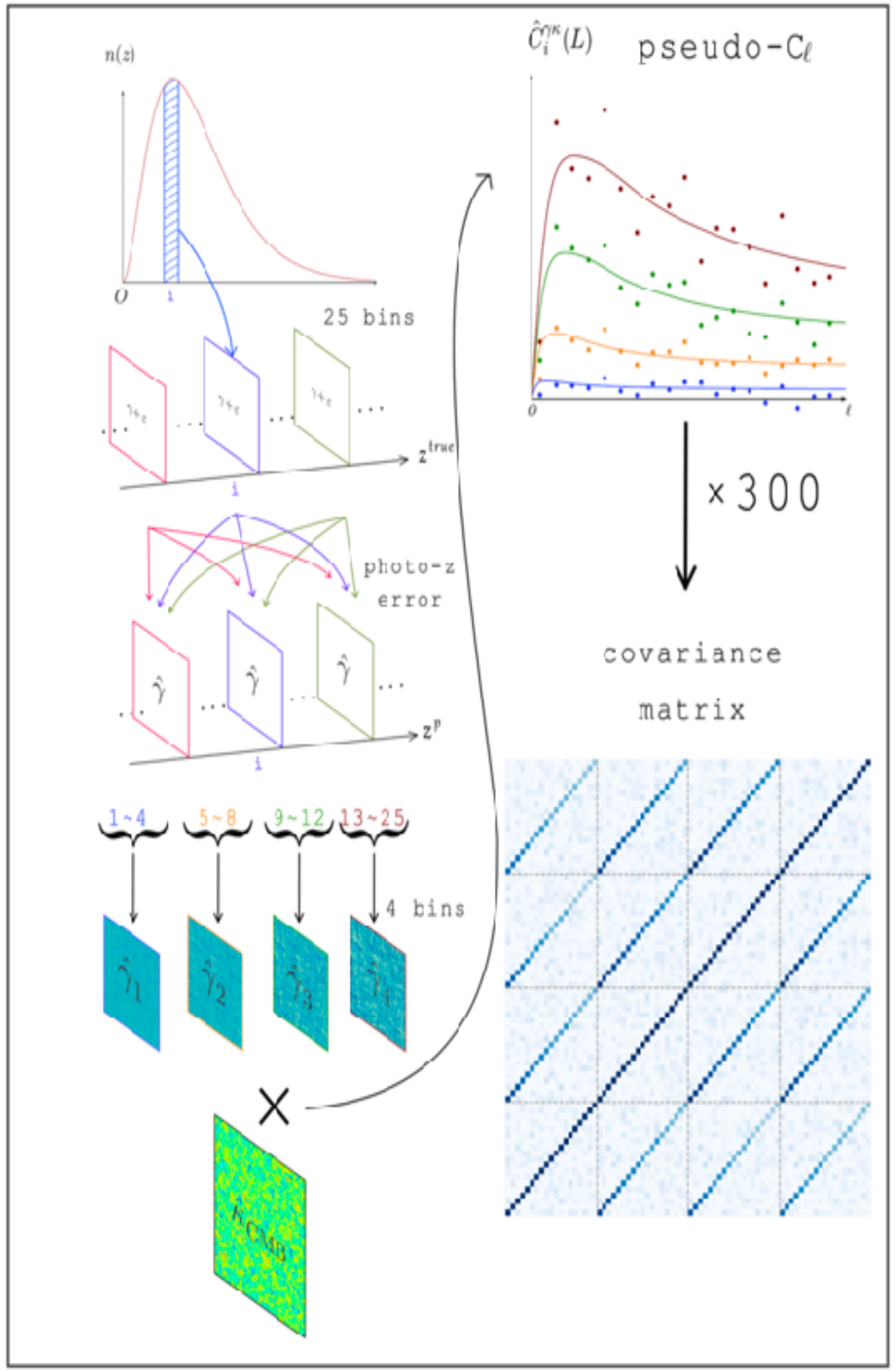
Shape Noise

$$p(\varepsilon_s) = \frac{\exp(-|\varepsilon_s|^2/\sigma_\varepsilon^2)}{\pi\sigma_\varepsilon^2[1-\exp(-1/\sigma_\varepsilon^2)]}$$

Where ellipticiy dispersion $\sigma_\varepsilon \approx 0.2$

Intrinsic Alignment





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Similar level of DES-Y3

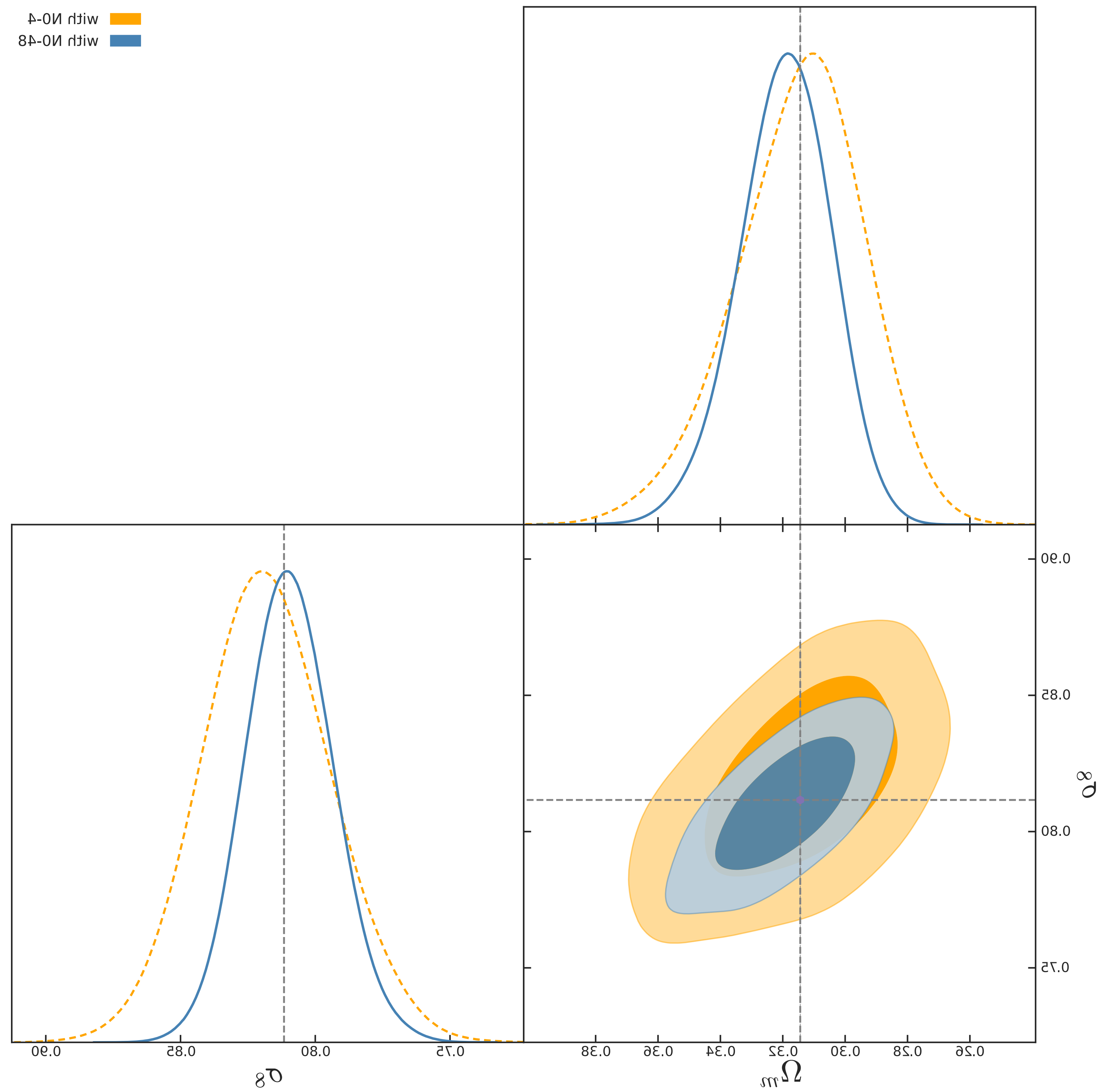
	I	II	III	IV
Data	N04+photo-z	N04+photo-z+IA	N048+photo-z	N048+photo-z+IA
Model	shear	shear+IA		

$$S_8 = \sigma_8 \times \left(\frac{\Omega_m}{0.3}\right)^{\alpha}$$

DES-Y3: 3x2pt

S8 = 0.776+-0.017

[*Phys.Rev.D* 105 (2022) 2, 023520]



Parameter	Data(I)+Model(I)	Data(II)+Model(I)	Data(II)+Model(II)	Data(III)+Model(I)	Data(IV)+Model(I)	Data(IV)+Model(II)
Ω_m	$0.321^{+0.025}_{-0.031}$	$0.301^{+0.021}_{-0.026}$	$0.327^{+0.029}_{-0.036}$	$0.310^{+0.017}_{-0.019}$	$0.286^{+0.013}_{-0.016}$	$0.312^{+0.019}_{-0.023}$
σ_8	0.780 ± 0.029	0.791 ± 0.027	0.770 ± 0.034	0.805 ± 0.020	$0.822^{+0.020}_{-0.018}$	0.801 ± 0.023
S_8	$0.801^{+0.029}_{-0.025}$	0.792 ± 0.028	0.797 ± 0.028	0.816 ± 0.015	0.804 ± 0.016	0.813 ± 0.016
A_{IA}	/	/	1.20 ± 0.57	/	/	1.19 ± 0.40
α	0.42	0.44	0.44	0.43	0.44	0.43

Conclusion

- AliCPT-1 telescope is a collaboration from China/USA, is the one of the 3G ground-based CMB experiment in the northern hemisphere

- A fairly good CMB lensing maps, especially via the polarisation data

- It overlap w/ several 3rd/4th generation galaxy surveys, can provide complimentary information for cosmology studies

The AliCPT-1 Collaboration

IHEP	pipeline, data analysis, scan strategy, control system, site, mount, test/integration
Stanford	cryostat receiver, optics/AR, focal plane module
NAOC	logistics, site
NIST	det arrays and modules, feedhorns and readout components
ASU	LNAs, cryogenic harness, readout electronics
NTU	scan strategy, calibration
CNRS	science, data analysis
USTC	CMB science
SJTU	foregrounds, cross-correlations
BNU	foregrounds, lensing

谢谢