COSMOLOGY WITH GALAXY-CMB LENSING CROSS-CORRELATIONS

Yuuki Omori in collaboration with Donnacha Kirk (UCL)
Tommaso Giannantonio (Cambridge), Pablo Fosalba (ICE-CSIC/IEEC)
and many others from DES and SPT collaborations

McGill

CROSS-CORRELATIONS

Making two independent measurements that at least in part, probe the same underlying signal and checking the overlap

(+) Noise and systematics are not correlated between the two methods and hence measurements are less susceptible to systematic errors

(-) Usually has less constraining power than auto-correlations, because the two "measurements" are not exactly the same

CROSS-CORRELATIONS > COSMOLOGY (LSS)

CMB lensing & Galaxy density

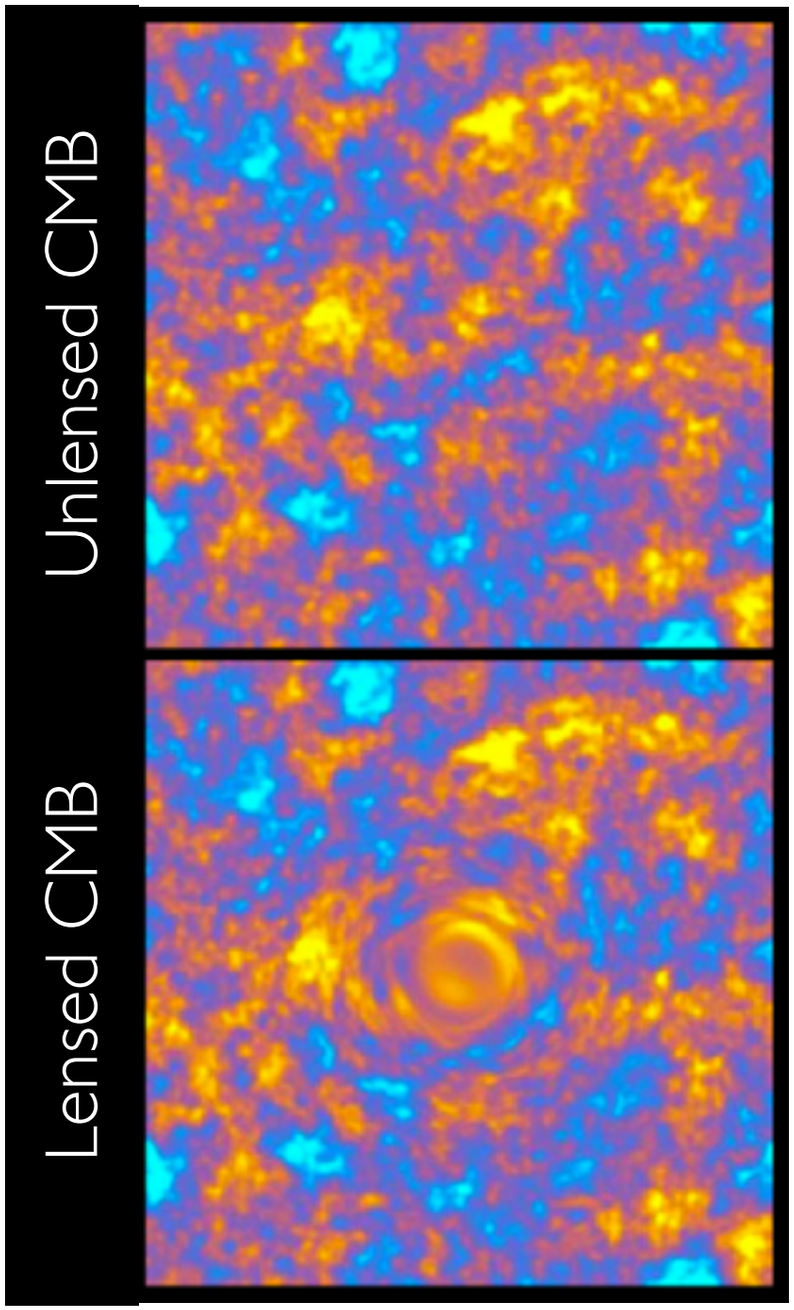
CMB lensing & Galaxy lensing

Making two independent measurements that at least in part probe the same underlying signal and checking the overlap

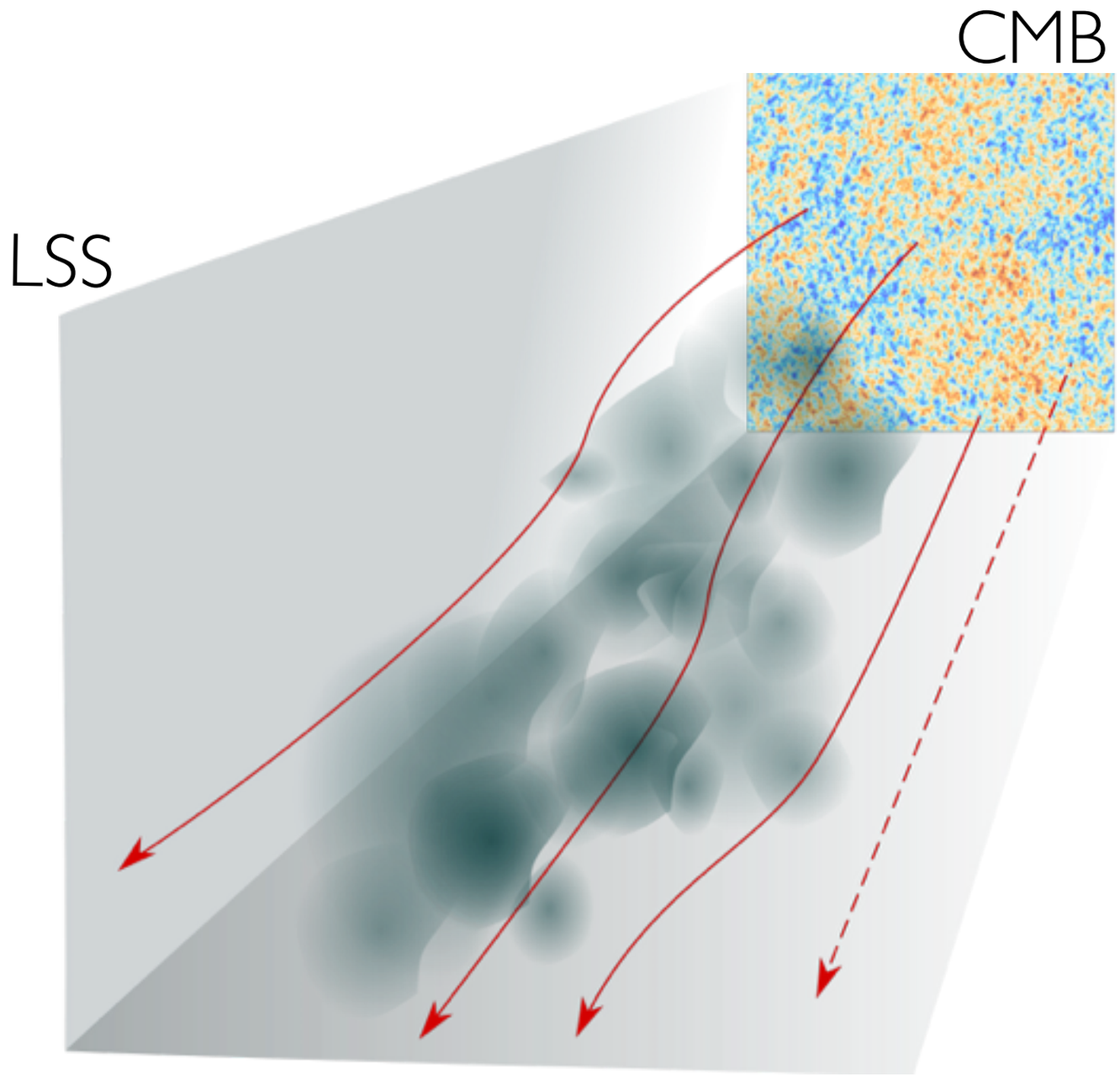
Cross-correlation

Matter distribution

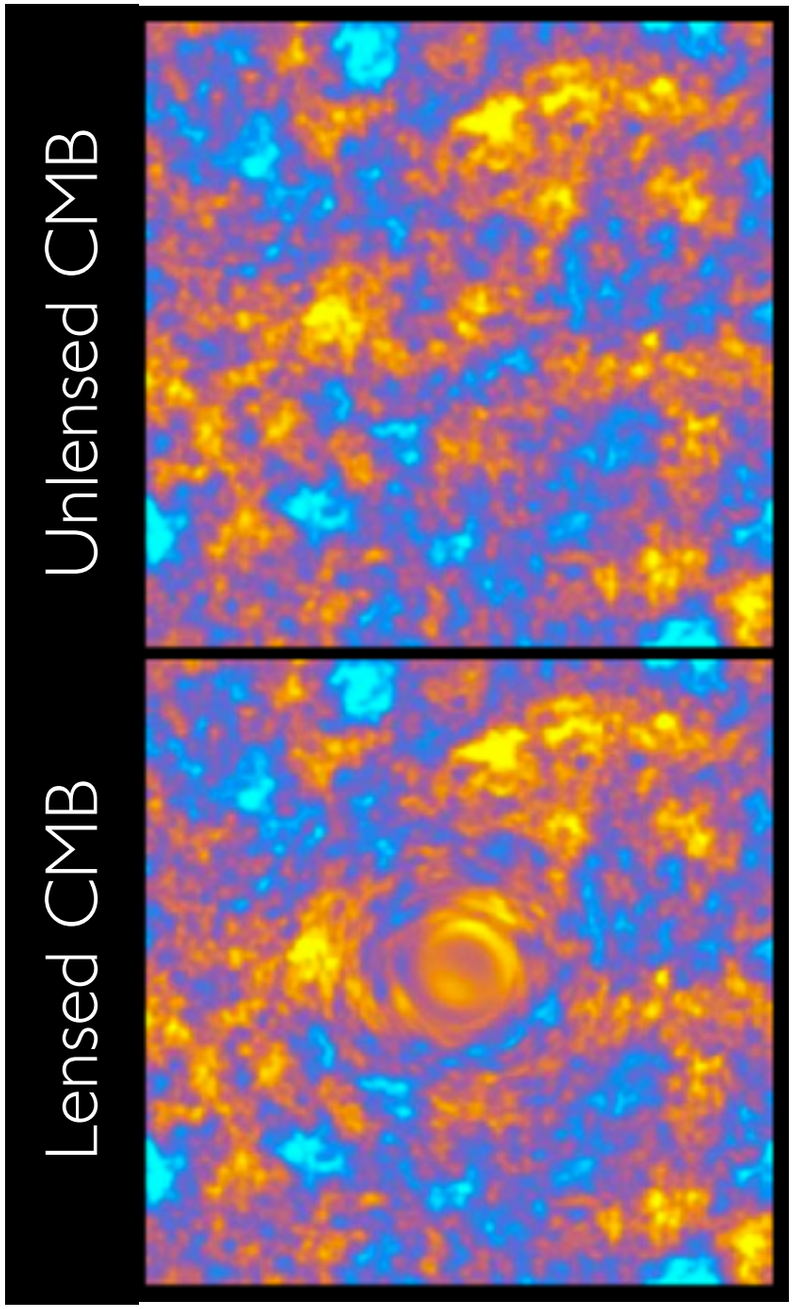
CMB LENSING



Hu & Okamoto (2001)



CMB LENSING



Hu & Okamoto (2001)

$$\Theta = \frac{\delta T}{T}$$

$$\Theta^{\rm len}(\hat{n}) = \Theta^{\rm unl}[\hat{n} + \nabla\phi(\hat{n})]$$

$$\Theta^{\rm len}(\hat{n}) = \Theta^{\rm unl}(\hat{n}) + \nabla\phi(\hat{n}) \cdot \nabla\Theta^{\rm unl}(\hat{n}) + \cdots$$

$$\langle \Theta^{\rm unl} \nabla\Theta^{\rm unl} \rangle = 0$$

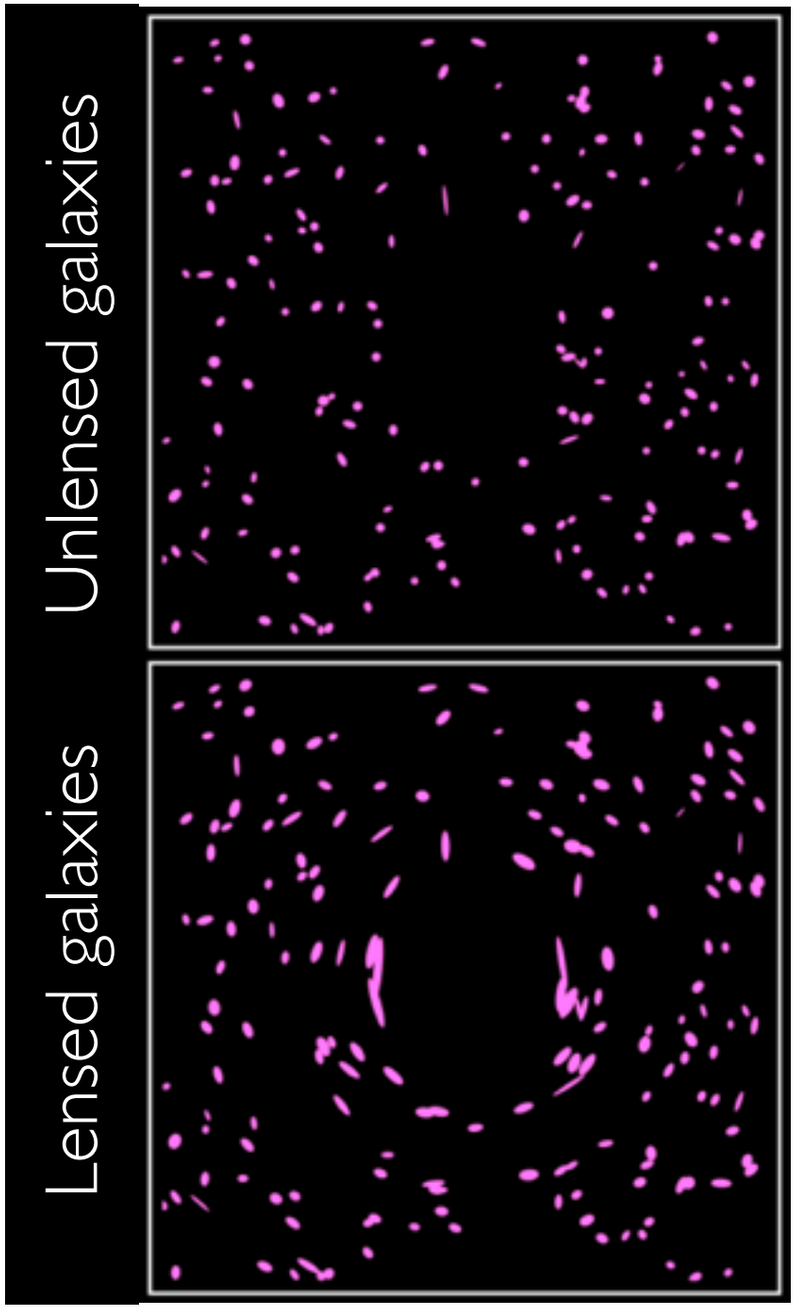
$$\nabla\phi(\hat{n}) \propto \Theta^{\rm len}\nabla\Theta^{\rm unl}$$

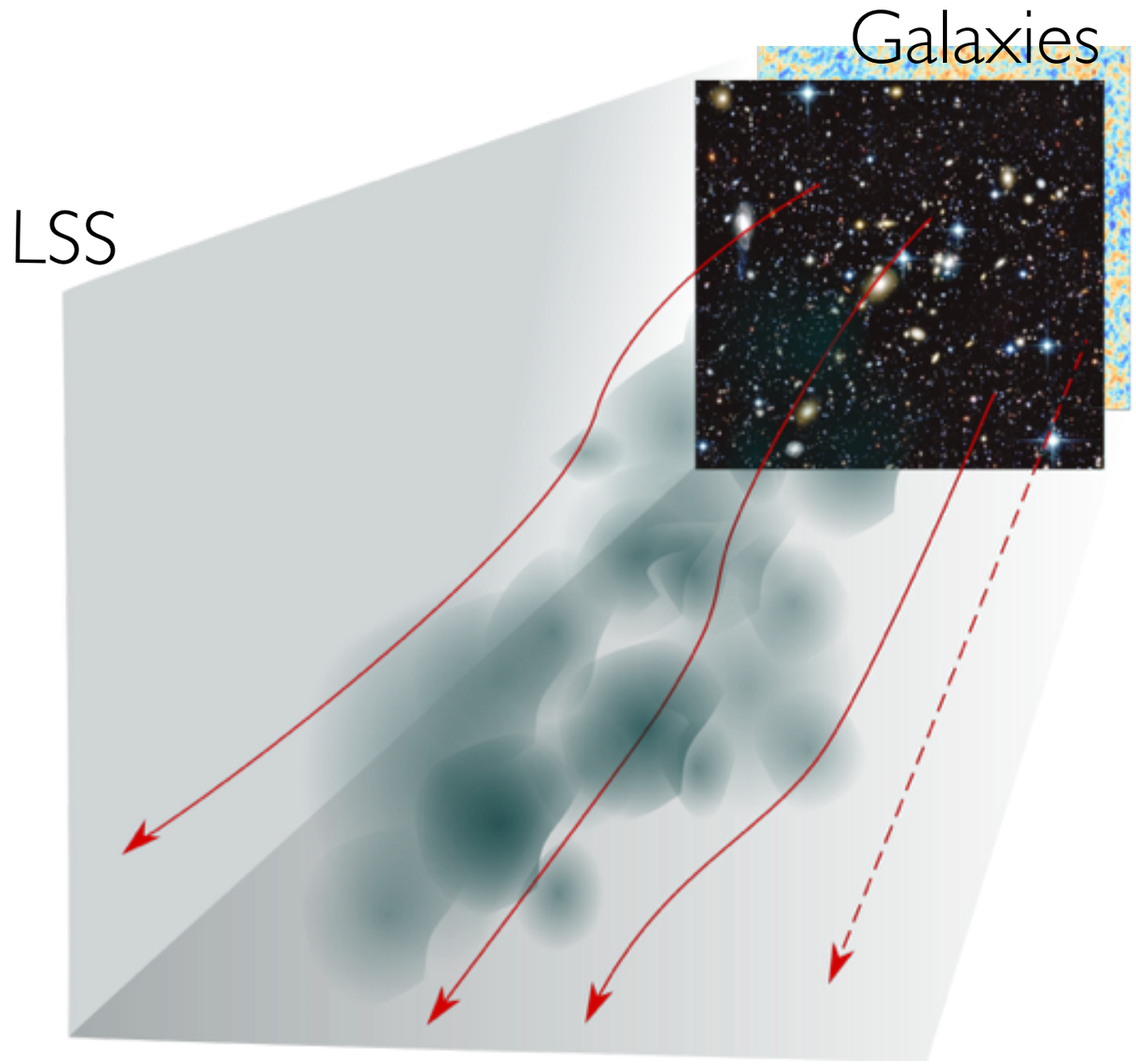
$$\hat{\phi}_{\rm LM} = A_{\rm L} \int d\Omega Y^*_{\rm LM}(\hat{n}) \nabla[V(\hat{n})\nabla U(\hat{n})]$$

$$V(\hat{n}) = \sum_{\rm LM} \frac{1}{C^{\Theta\Theta}_{\ell,{\rm fid}} + N^{\Theta\Theta}_{\ell}} \Theta_{\ell{\rm m}} Y_{\ell{\rm m}}(\hat{n})$$

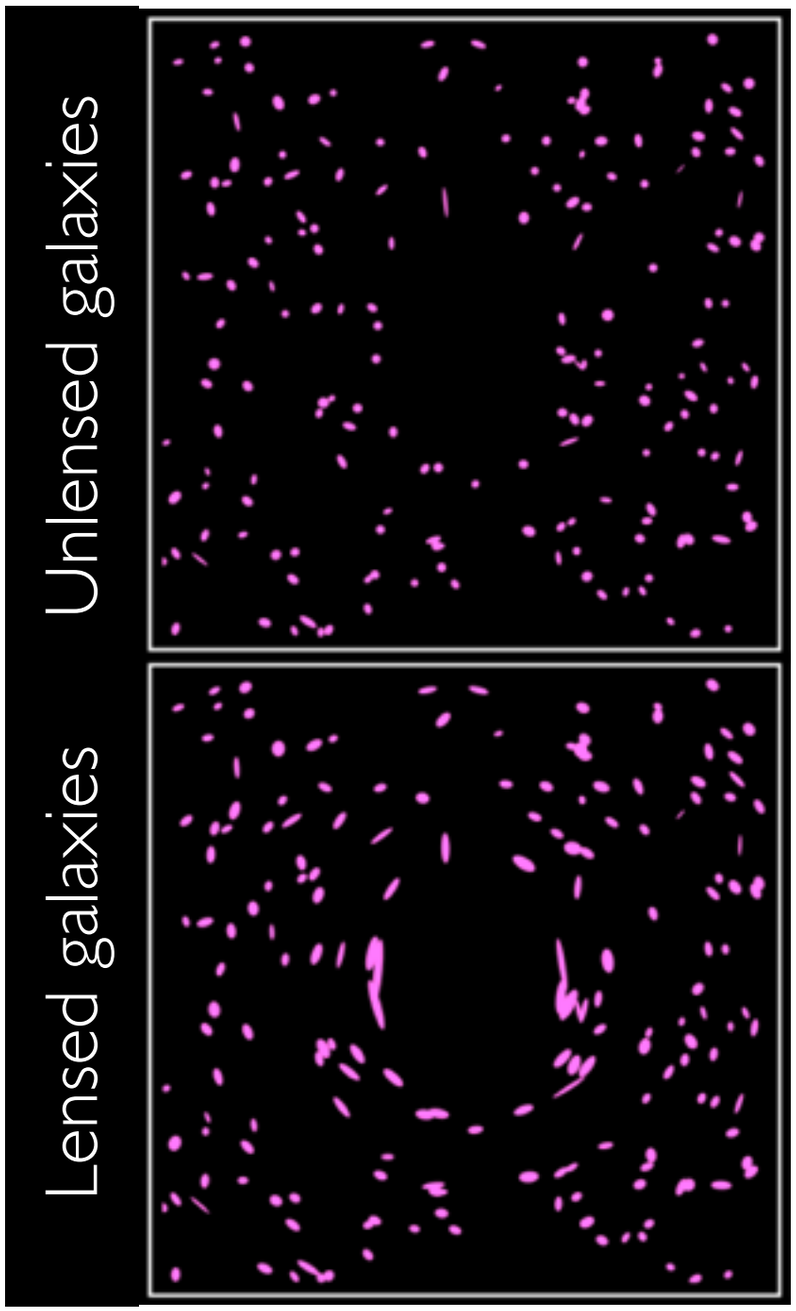
$$U(\hat{n}) = \sum_{\rm LM} \frac{C^{\Theta^{\rm unl}\Theta^{\rm unl}}_{\ell,{\rm fid}}}{C^{\Theta\Theta}_{\ell,{\rm fid}} + N^{\Theta\Theta}_{\ell}} \Theta_{\ell{\rm m}} Y_{\ell{\rm m}}(\hat{n})$$

GALAXY LENSING

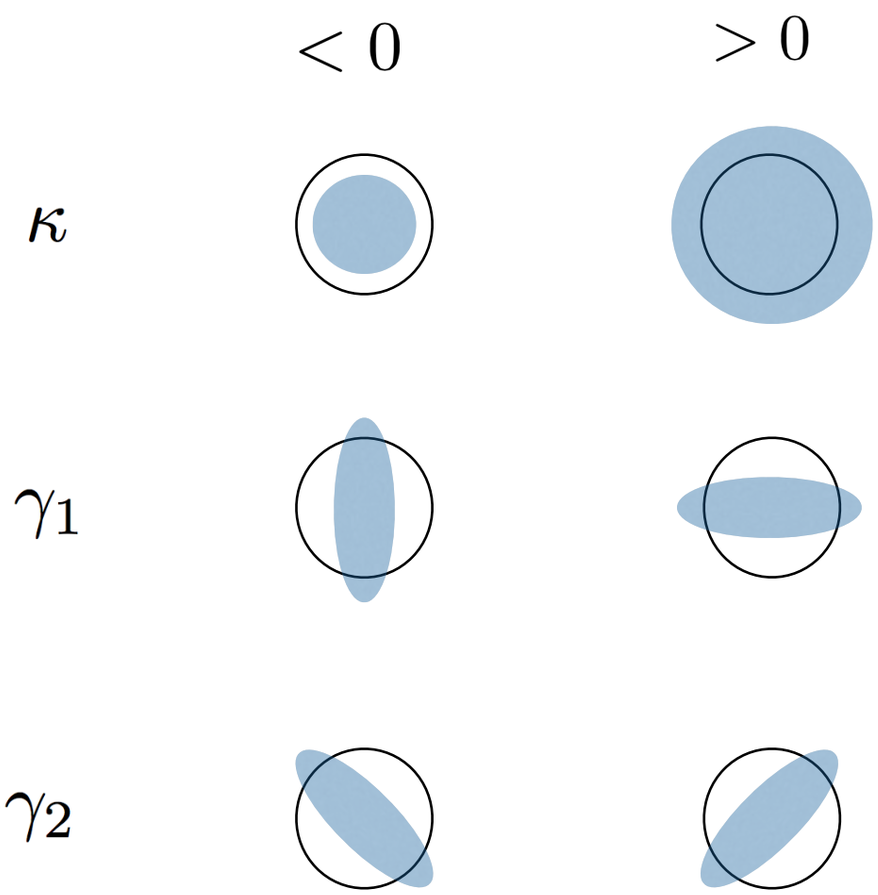




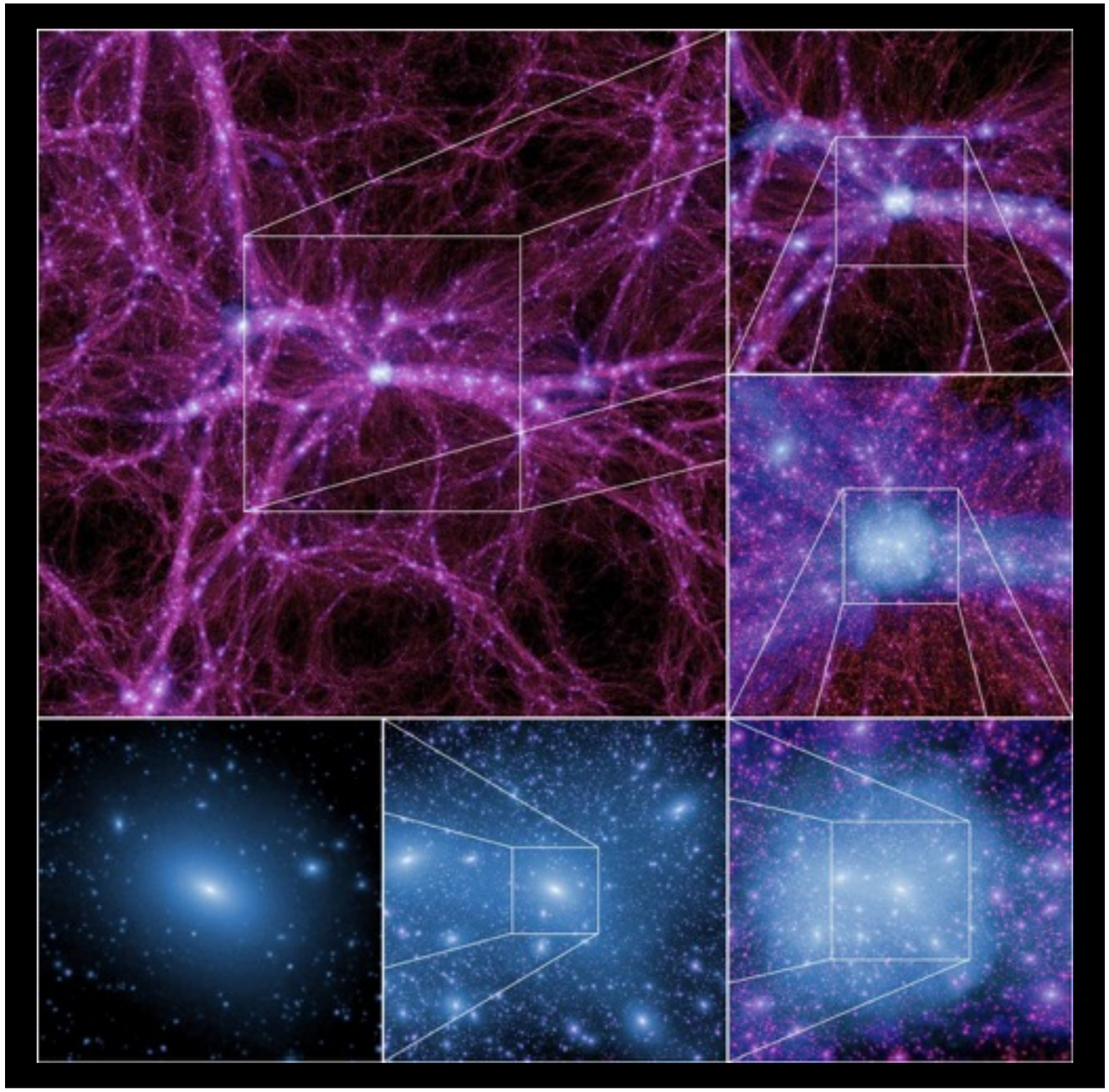
GALAXY LENSING



$$A_{ij} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

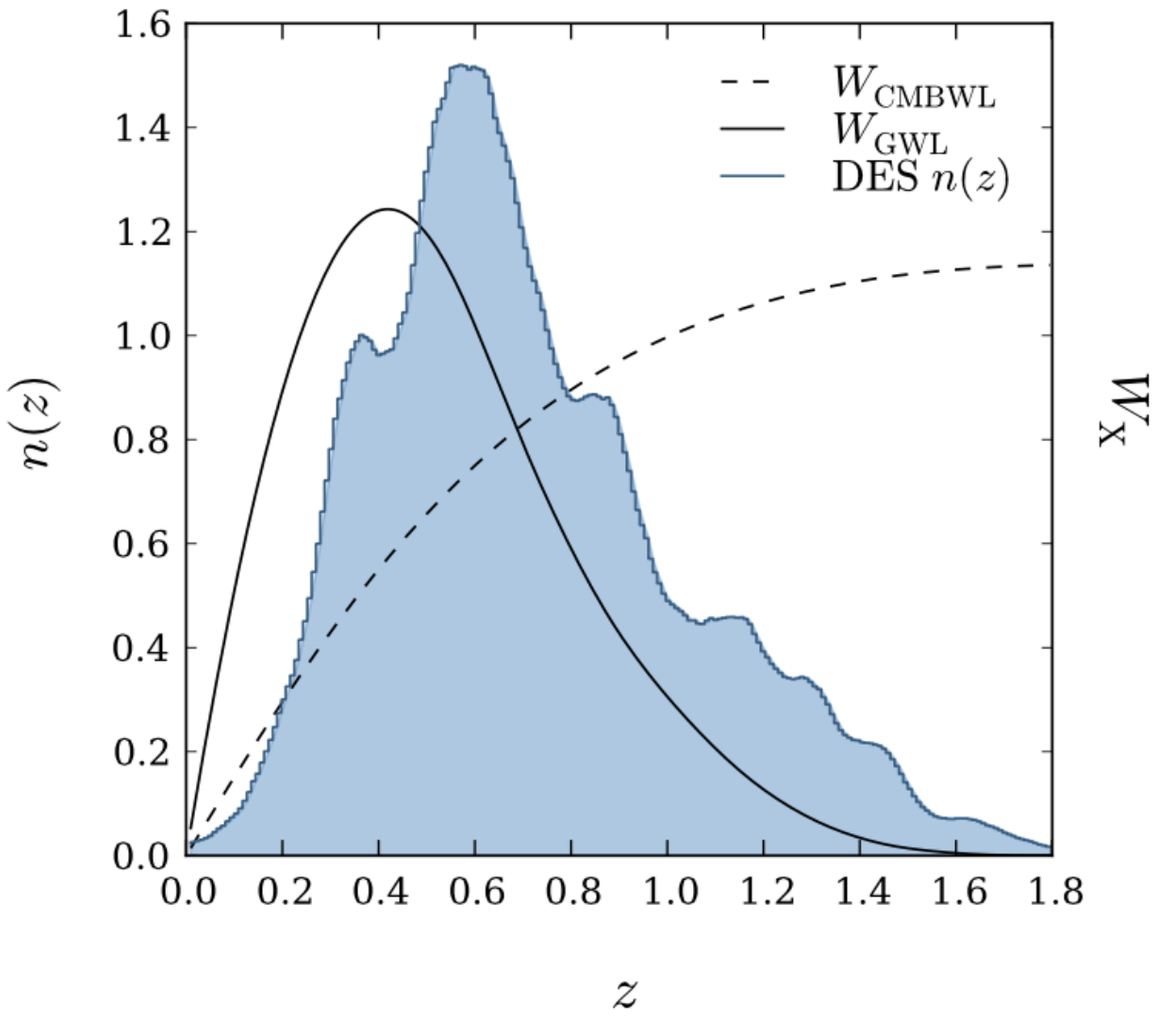


GALAXY DENSITY



Boylan Kolchin et al. (2009)

GALAXY LENSING - CMB LENSING CROSS-CORRELATION



kernels

matter power spectrum

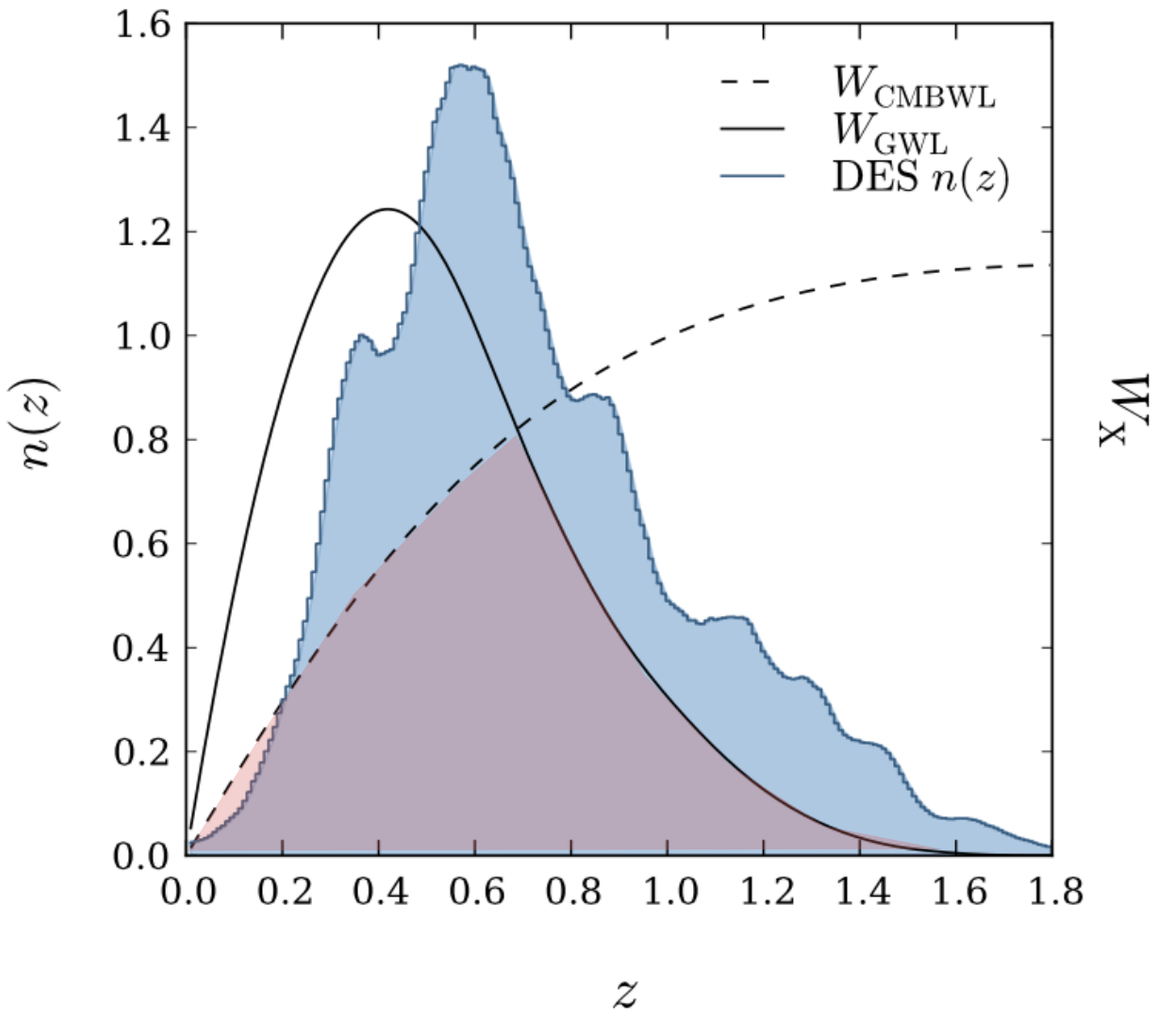
$$C_\ell^{XY} = \int dz \frac{d\chi}{dz} \frac{1}{\chi^2} W^X W^Y P\left(k = \frac{\ell}{\chi}, z\right)$$

$$W^{\rm G}\left[\chi(z)\right] = n(\chi) b(\chi)$$

$$W^{\rm GWL}\left[\chi(z)\right] = \frac{3H_0^2\Omega_{\rm m}}{2c^2} \frac{\chi}{a(\chi)} \int_{\chi'}^{\chi_*} d\chi' n^s(\chi') \frac{\chi' - \chi}{\chi'}$$

$$W^{\rm CMBWL}\left[\chi(z)\right] = \frac{3H_0^2\Omega_{\rm m}}{2c^2} \frac{\chi}{a(\chi)} \frac{\chi_* - \chi}{\chi_*}$$

GALAXY LENSING - CMB LENSING CROSS-CORRELATION



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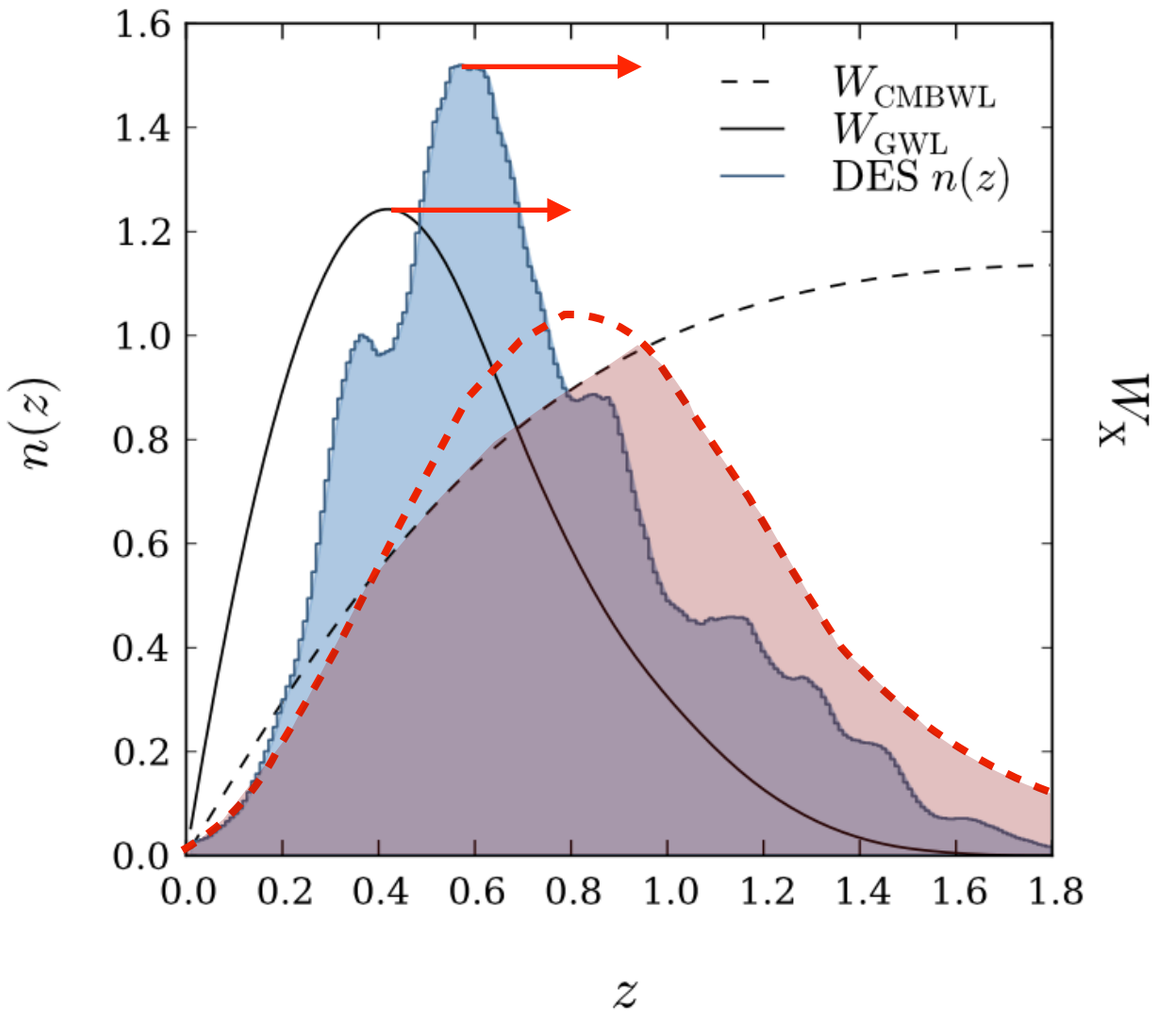
GALAXY LENSING - CMB LENSING CROSS-CORRELATION



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DATA

Galaxy number density
from DES SV

Galaxy weak lensing
from DES SV

CMB Lensing from SPT SZ
(CMB Lensing from Planck 2013/2015)

SOUTH POLE TELESCOPE (SPT)

South pole Telescope 10m
SPT SZ survey (2008-2011)
Tri-band (90,150,220 GHz)
Footprint 2500deg^2

Moving on to SPT-3G soon

DARK ENERGY SURVEY (DES)

CTIO Blanco Telescope 4m
grizY (5 filters)

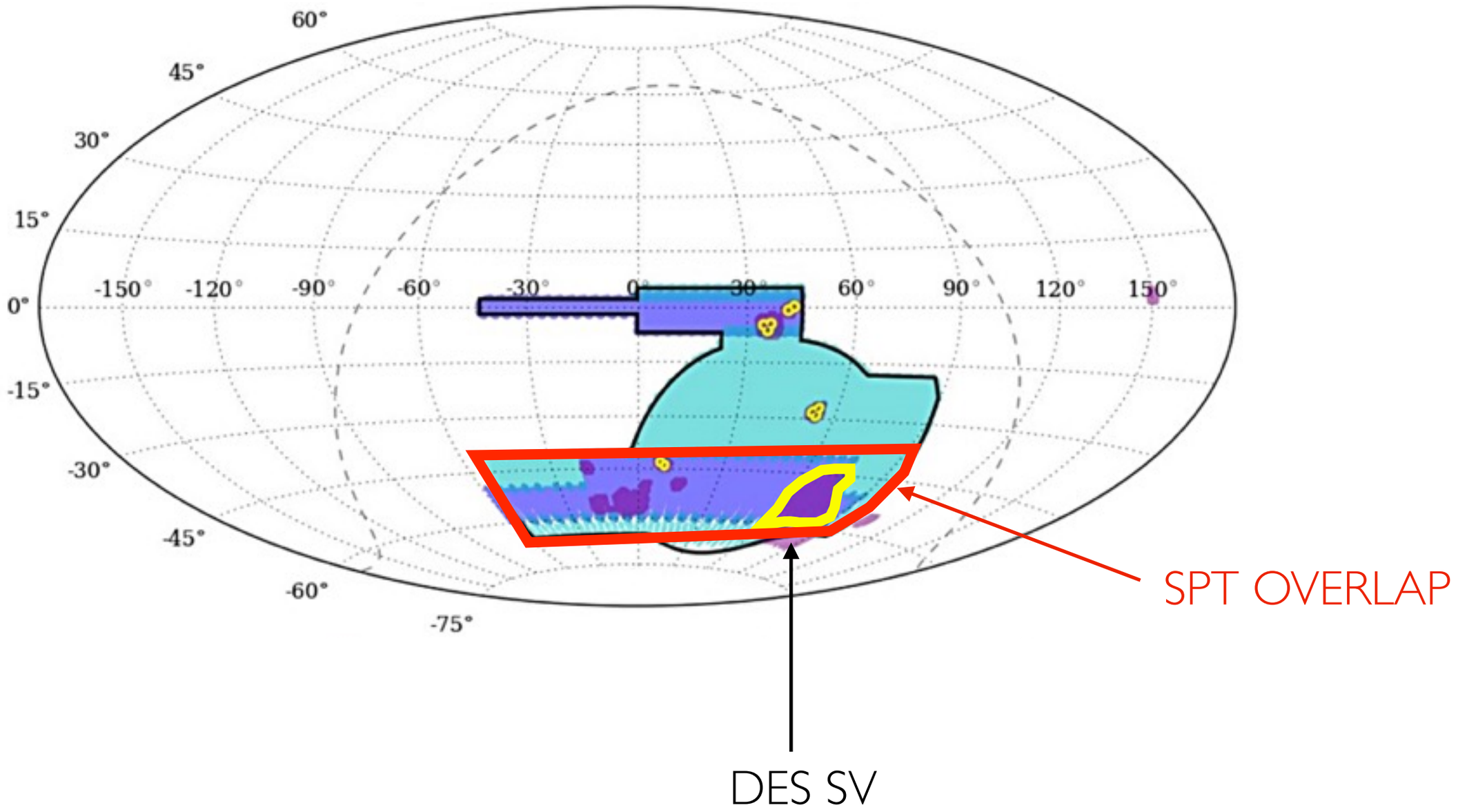
Footprint ~140 deg^2 (SV data)

~1000 deg^2 (Y1 data)

~5000 deg^2 (Y5 data)

FOTO CREDIT: Daniel Munizaga (NOAO-S/CTIO/EPO)

FOOTPRINT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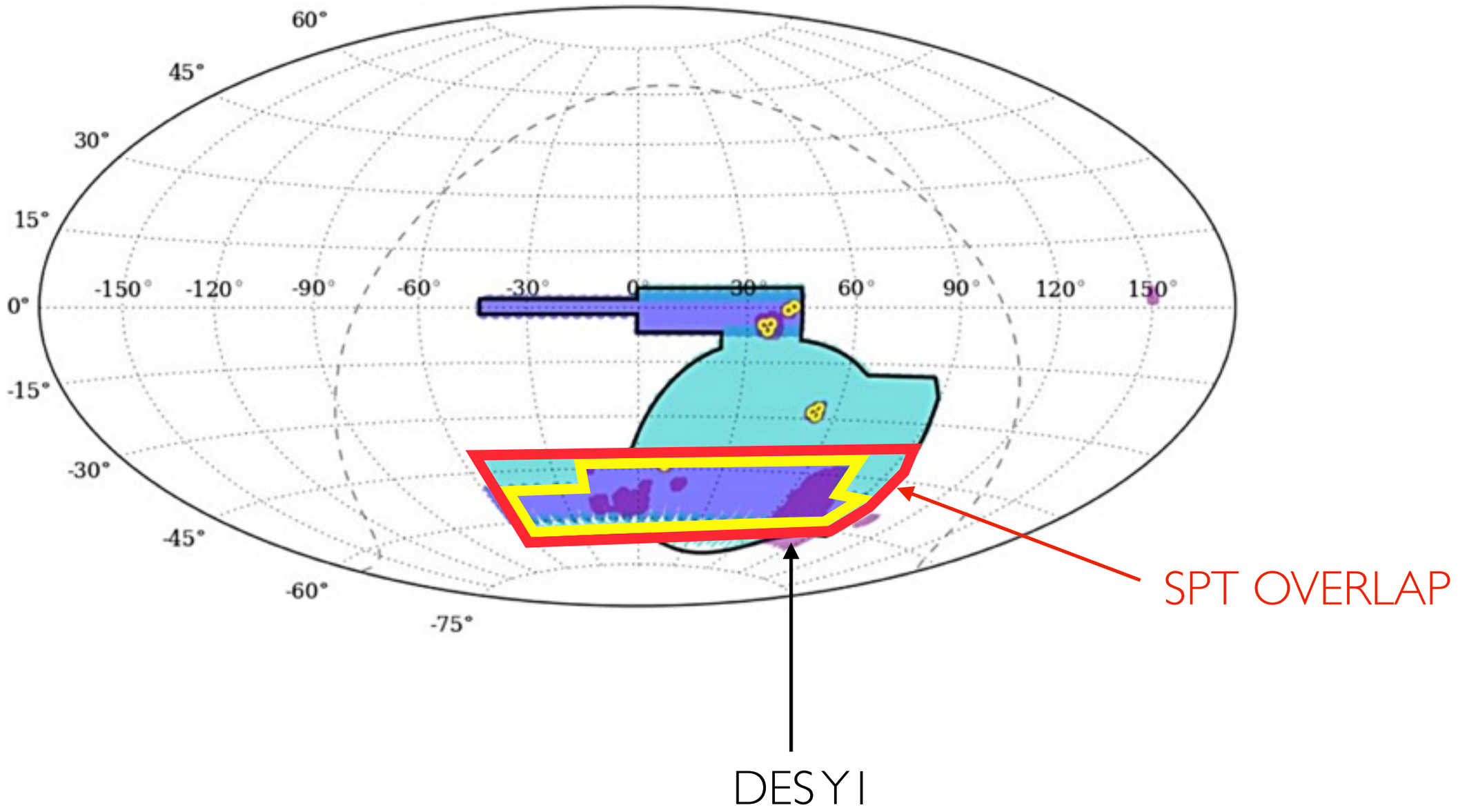
SPT OVERLAP
DES SV

FOOTPRINT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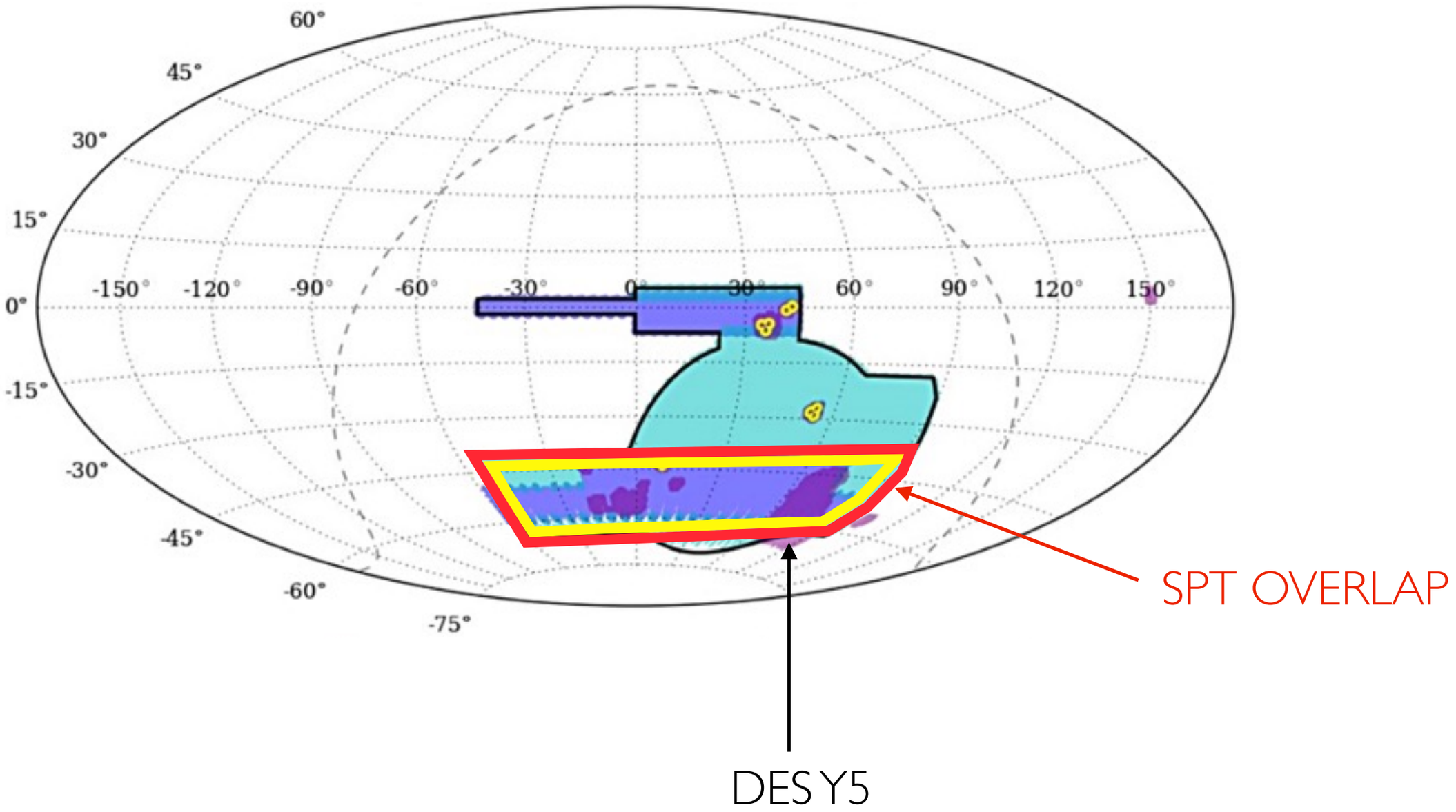
SPT OVERLAP
DES Y1

FOOTPRINT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SPT OVERLAP
DES Y5

DATA

work in progress

Galaxy number density from DES SV

Galaxy weak lensing from DES SV

Giannantonio & Fosalba et al. (arxiv:1507.055551)

Kirk & Omori et al. (arxiv:1512.04535)

CMB Lensing from SPT SZ
(CMB Lensing from Planck 2013/2015)

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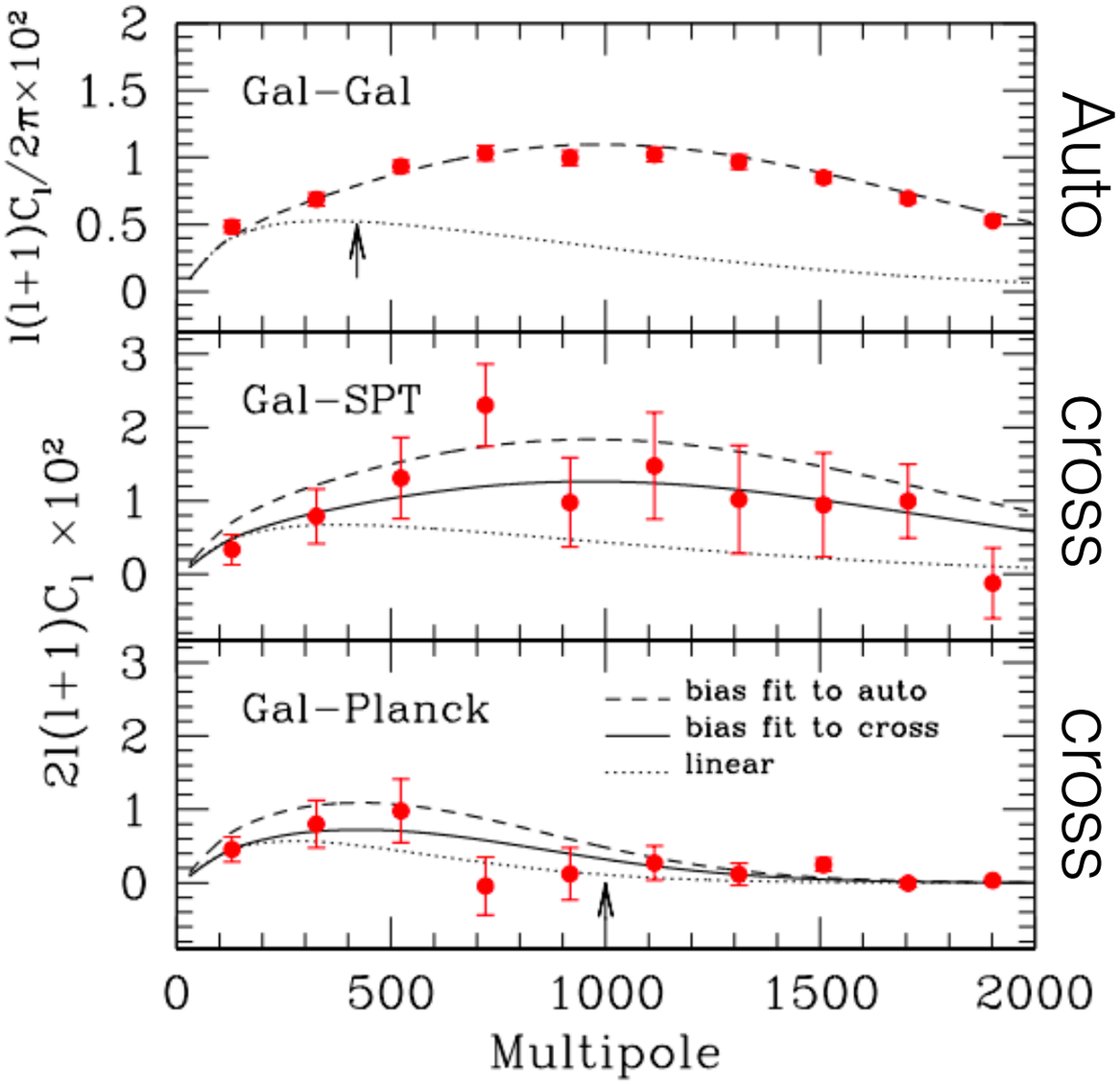
GALAXY DENSITY - CMB LENSING CROSS-CORRELATION

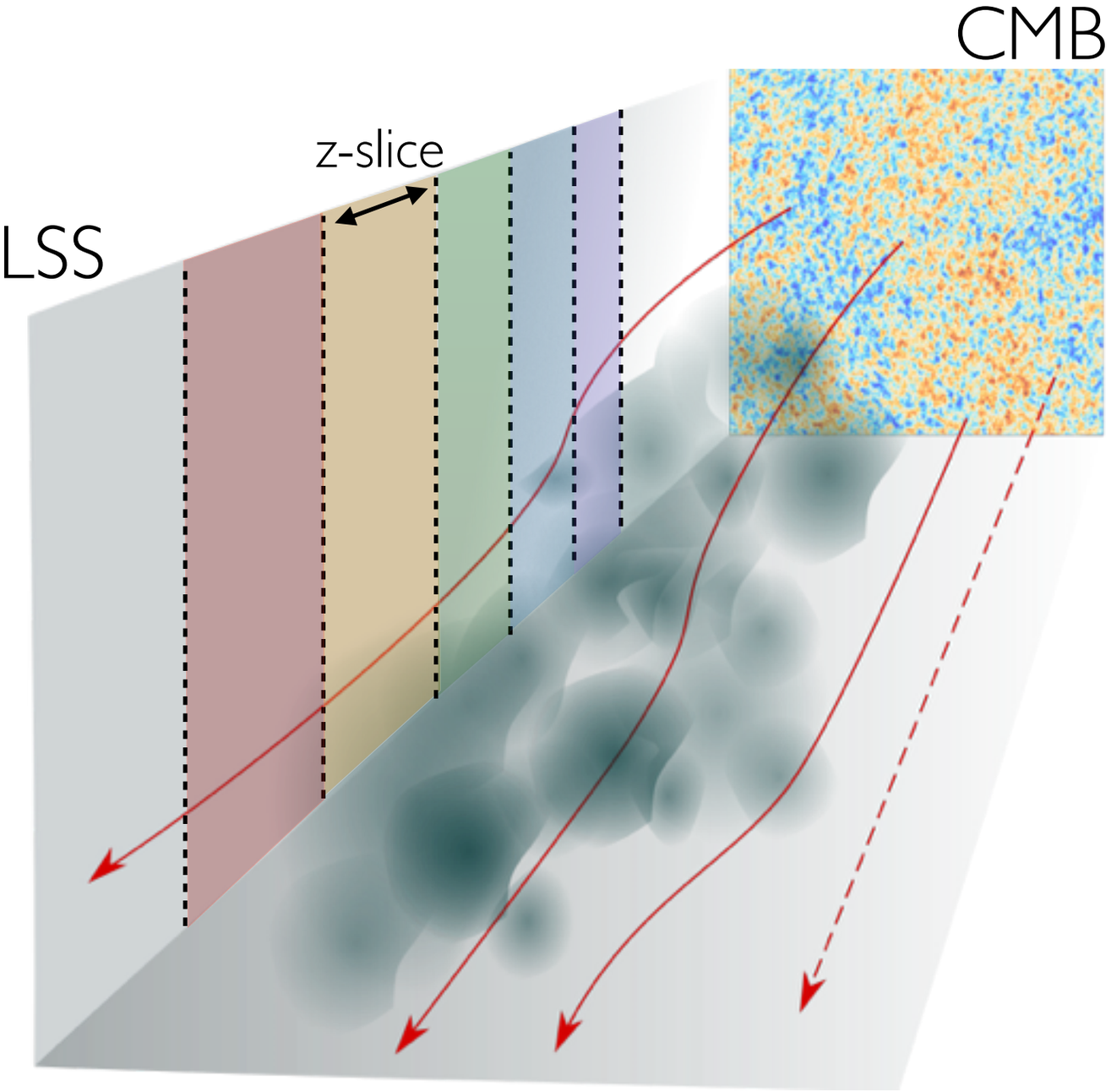
$$C_\ell^{gg} = b^2 C_{\ell,\mathrm{fid}}^{gg}$$
$$C_\ell^{\kappa g} = A C_{\ell,\mathrm{fid}}^{\kappa g}$$

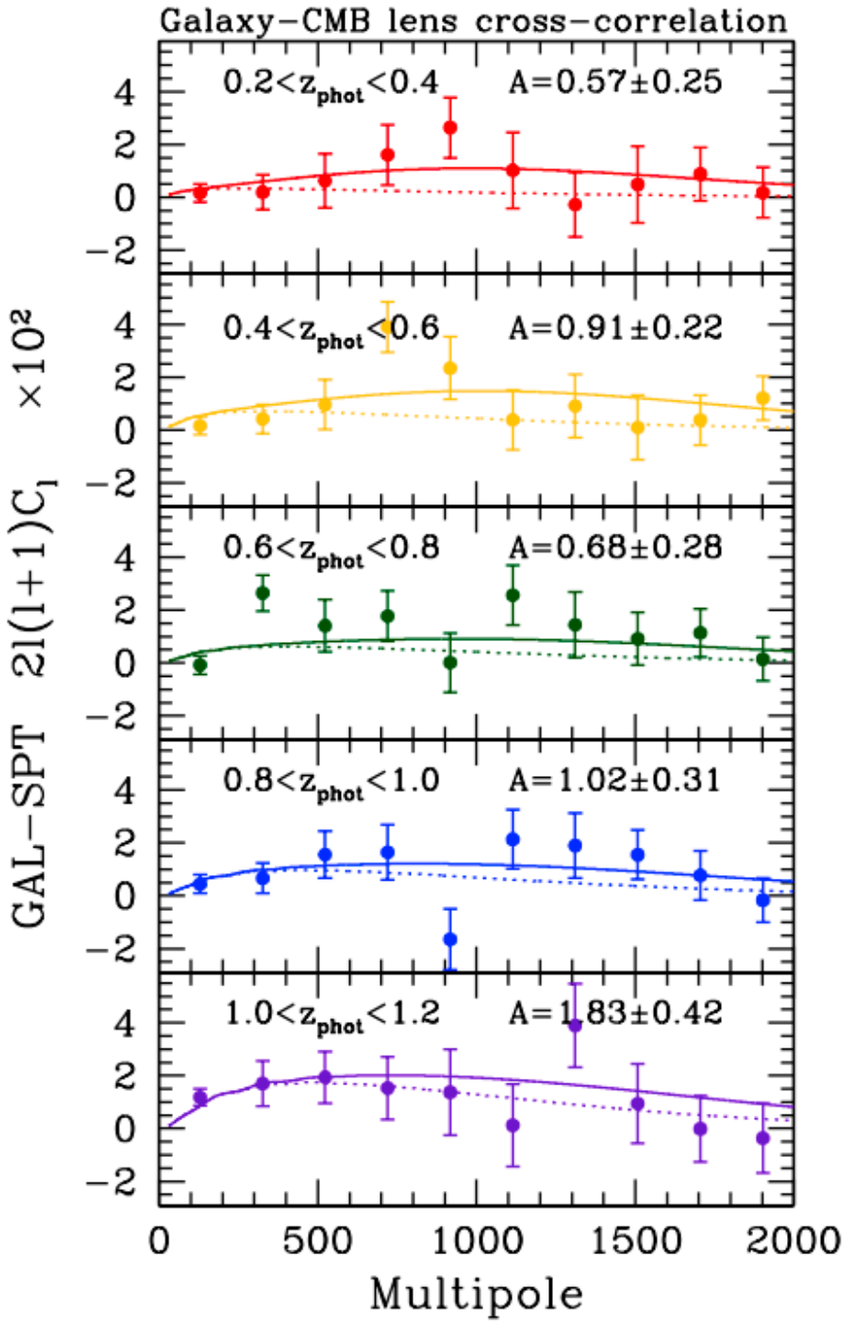
$$A = b A_{\mathrm{lens}}$$

Full sample, $0.2 < z_{\mathrm{phot}} < 1.2$		Harmonic space		
Correlation	Covariance	$b \pm \sigma_b$	S/N	χ^2/ d.o.f.
Gal-Gal	*N*-body	1.22 ± 0.04	34	2.7 / 3
Correlation	Covariance	$A \pm \sigma_A$	S/N	χ^2/ d.o.f.
Gal-SPT	*N*-body	0.84 ± 0.15	5.6	8.7 / 19
Gal-*Planck*		0.81 ± 0.20	3.8	7.7 / 9



GALAXY DENSITY - CMB LENSING CROSS-CORRELATION





GALAXY DENSITY - CMB LENSING CROSS-CORRELATION

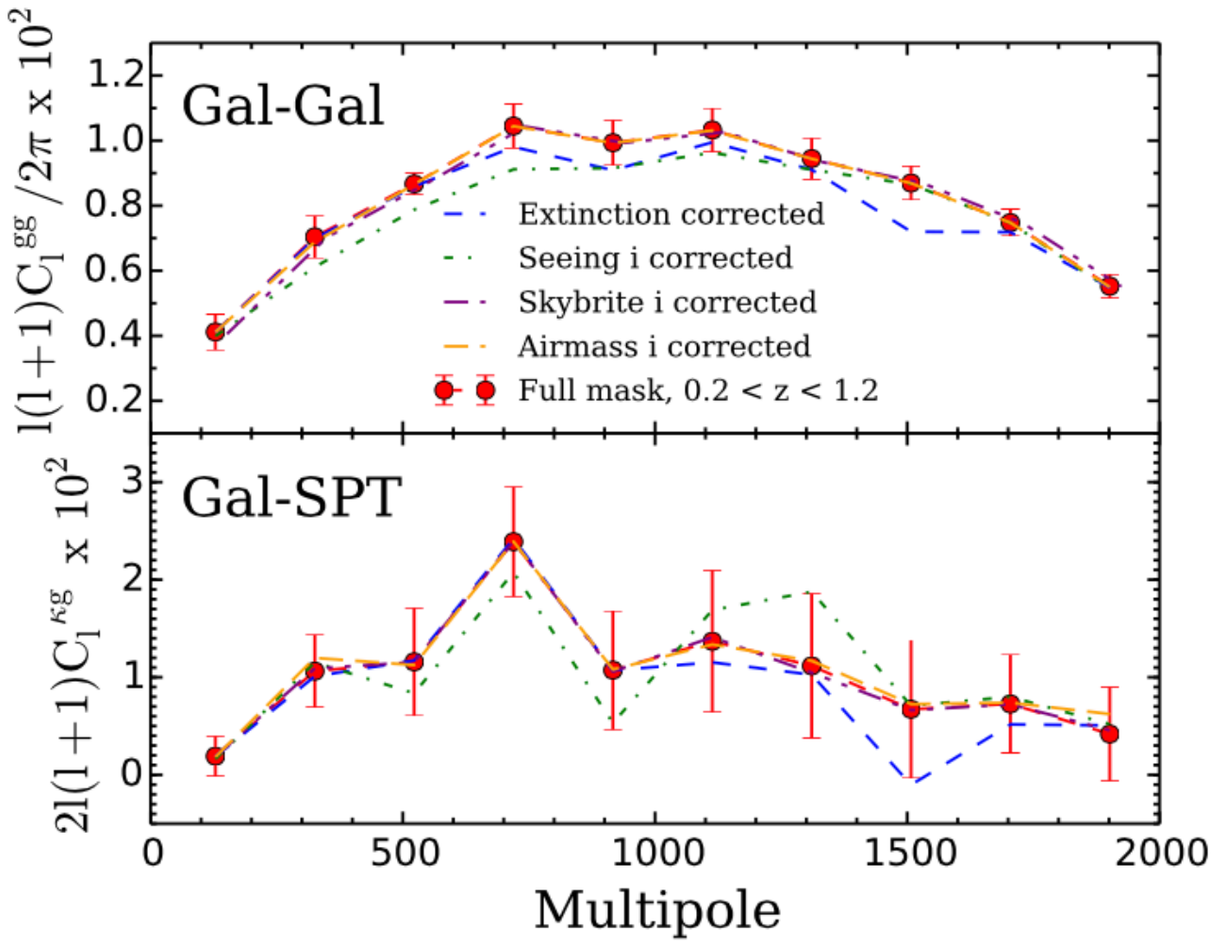
Tests

Cross-correlation with external datasets

Covariance estimation

Real/harmonic space analyses

CMB lensing systematics



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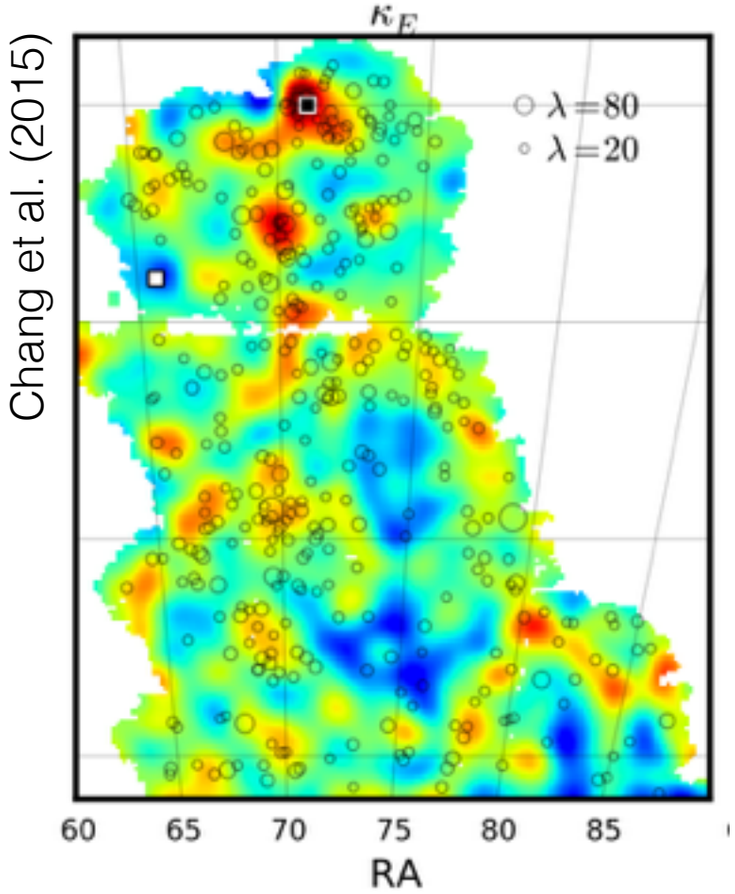
CMB Lensing from SPT SZ
(CMB Lensing from Planck 2013/2015)

GALAXY LENSING - CMB LENSING CROSS-CORRELATION

flat-sky

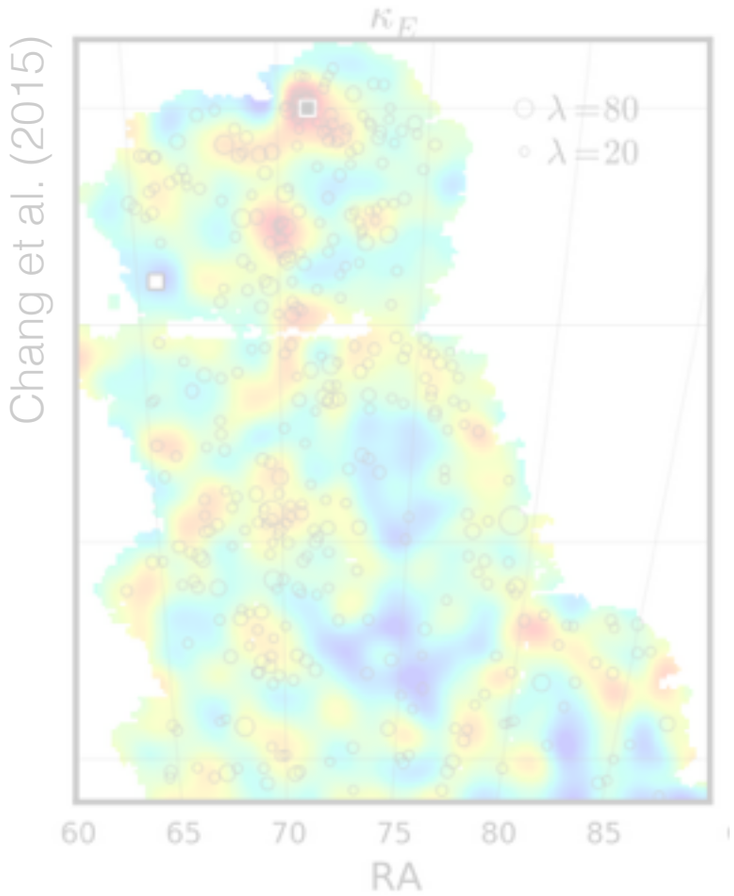
$$\gamma_{\rm E}(\boldsymbol{\ell_x}, \boldsymbol{\ell_y}) = \gamma_1(\boldsymbol{\ell_x}, \boldsymbol{\ell_y}) \frac{\ell_x^2 - \ell_y^2}{\ell_x^2 + \ell_y^2} + \gamma_2(\boldsymbol{\ell_x}, \boldsymbol{\ell_y}) \frac{2\ell_x \ell_y}{\ell_x^2 + \ell_y^2}$$



Chang et al. (2015)

GALAXY LENSING - CMB LENSING CROSS-CORRELATION

$$\gamma_{\rm E}(\boldsymbol{\ell_x}, \boldsymbol{\ell_y}) = \gamma_1(\boldsymbol{\ell_x}, \boldsymbol{\ell_y}) \frac{\ell_x^2 - \ell_y^2}{\ell_x^2 + \ell_y^2} + \gamma_2(\boldsymbol{\ell_x}, \boldsymbol{\ell_y}) \frac{2\ell_x \ell_y}{\ell_x^2 + \ell_y^2}$$



spherical

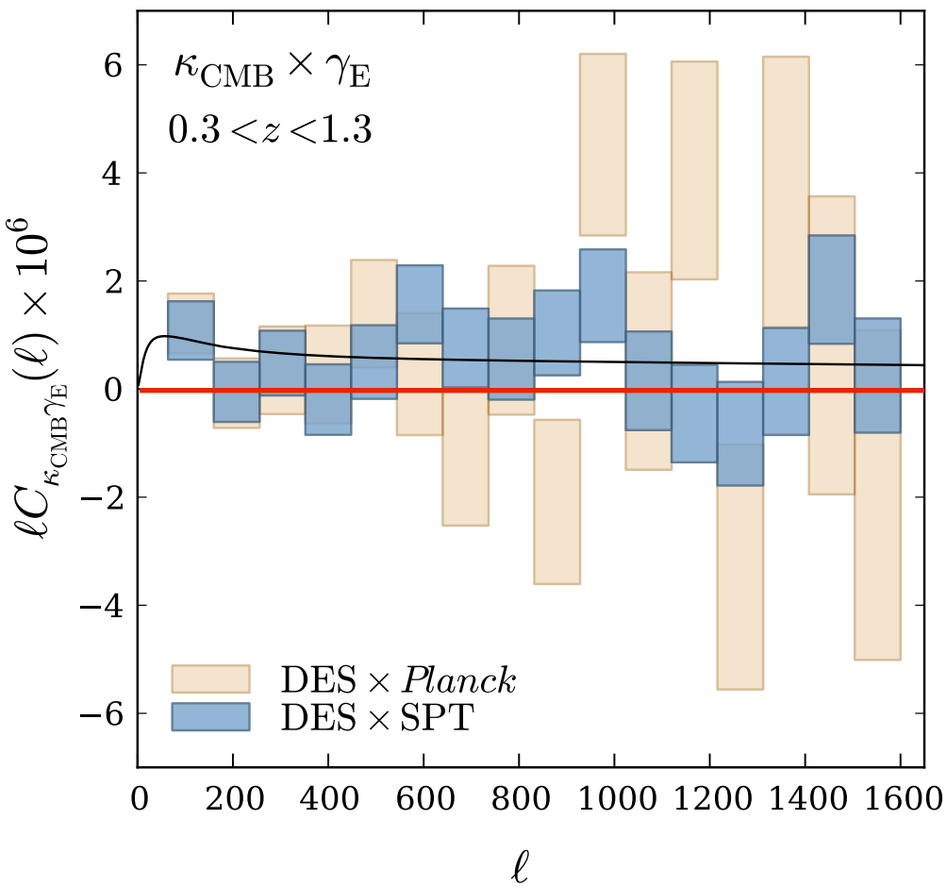
$$\frac{1}{2}(\gamma_1(\hat{n}) + i\gamma_2(\hat{n})) = \sum_{\ell m} p_{\pm 2,\ell m}\ {}_{\pm 2}Y_{\ell m}$$

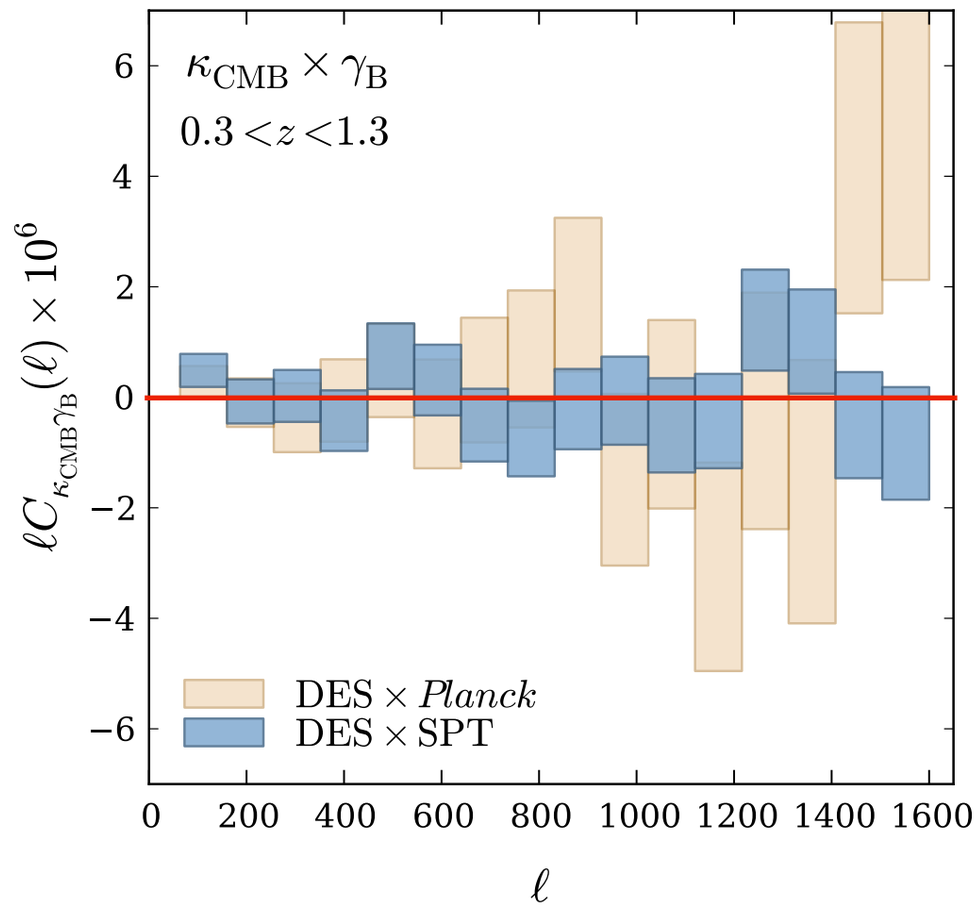
$$\gamma_{{\rm E},\ell m} = -(p_{+2,\ell m} + p_{-2,\ell m})$$

$$\gamma_{{\rm B},\ell m} = -i(p_{+2,\ell m} - p_{-2,\ell m})$$

$$\kappa_{\ell m} = \sum_{\ell m} \kappa(\hat{n}) Y^*_{\ell m} = \frac{1}{2}\ell(\ell+1)\phi_{\ell m}$$

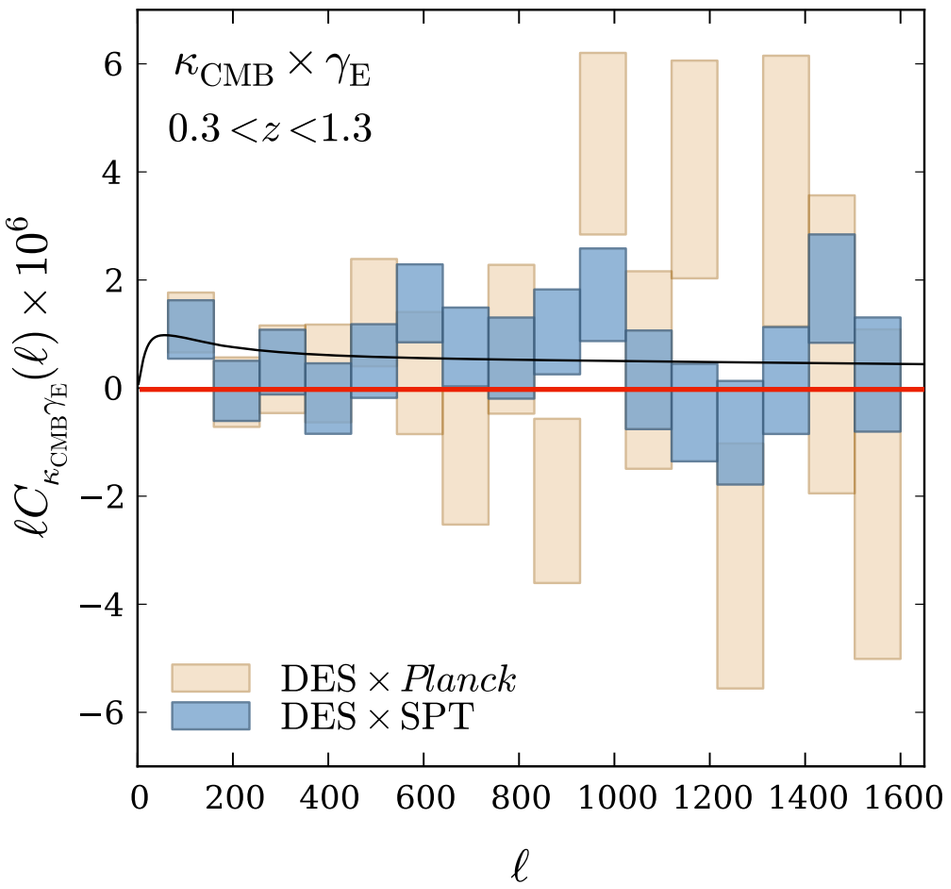
GALAXY LENSING - CMB LENSING CROSS-CORRELATION

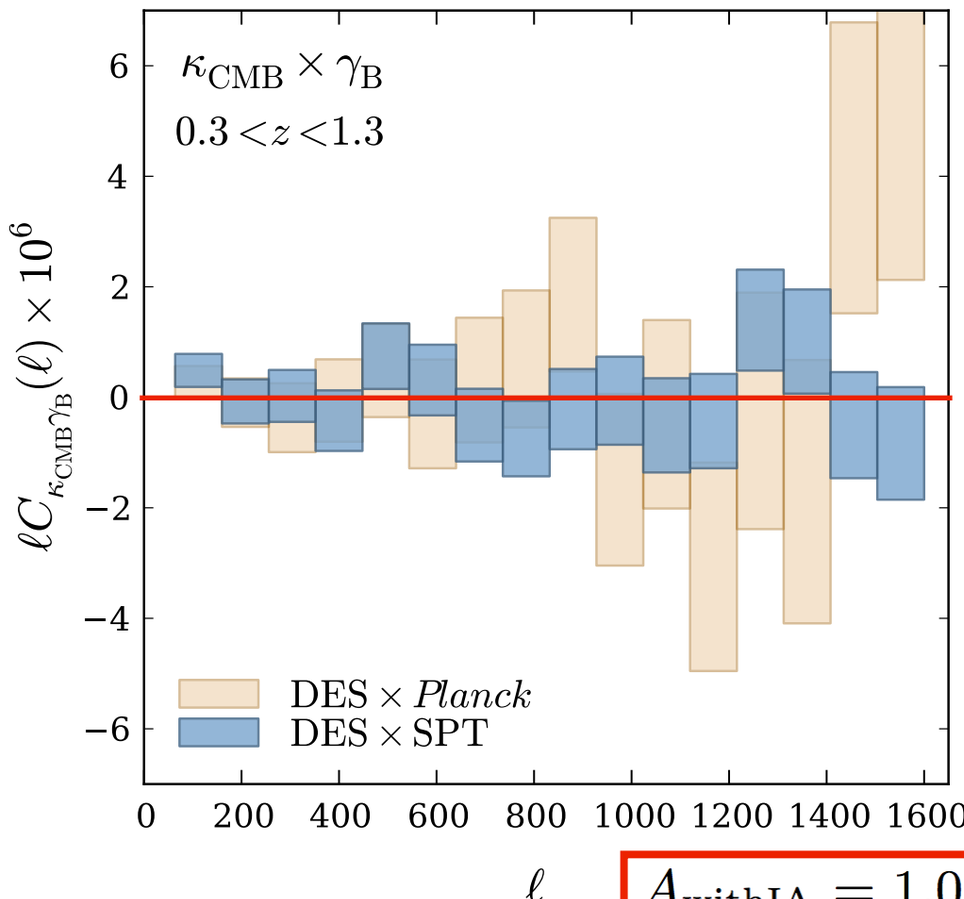




	Surveys	Overlap [deg^2]	n [arcmin^{-2}]	A	σ
Kirk & Omori et al. (2015)	DES(SV) × SPT(SZ)	139	5.7	0.88 ± 0.30	3
Hand et al. (2015)	CFHT stripe-82 × ACT	121	12.3	0.92 ± 0.22	4
Liu & Hill (2015)	CFHTLenS × Planck	140	12.5	0.44 ± 0.22	2

GALAXY LENSING - CMB LENSING CROSS-CORRELATION





$A_{\rm withIA} = 1.08 \pm 0.36$

	Surveys	Overlap [deg^2]	n [arcmin^{-2}]	A	σ
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GALAXY LENSING - CMB LENSING CROSS-CORRELATION

Tests

B-mode test

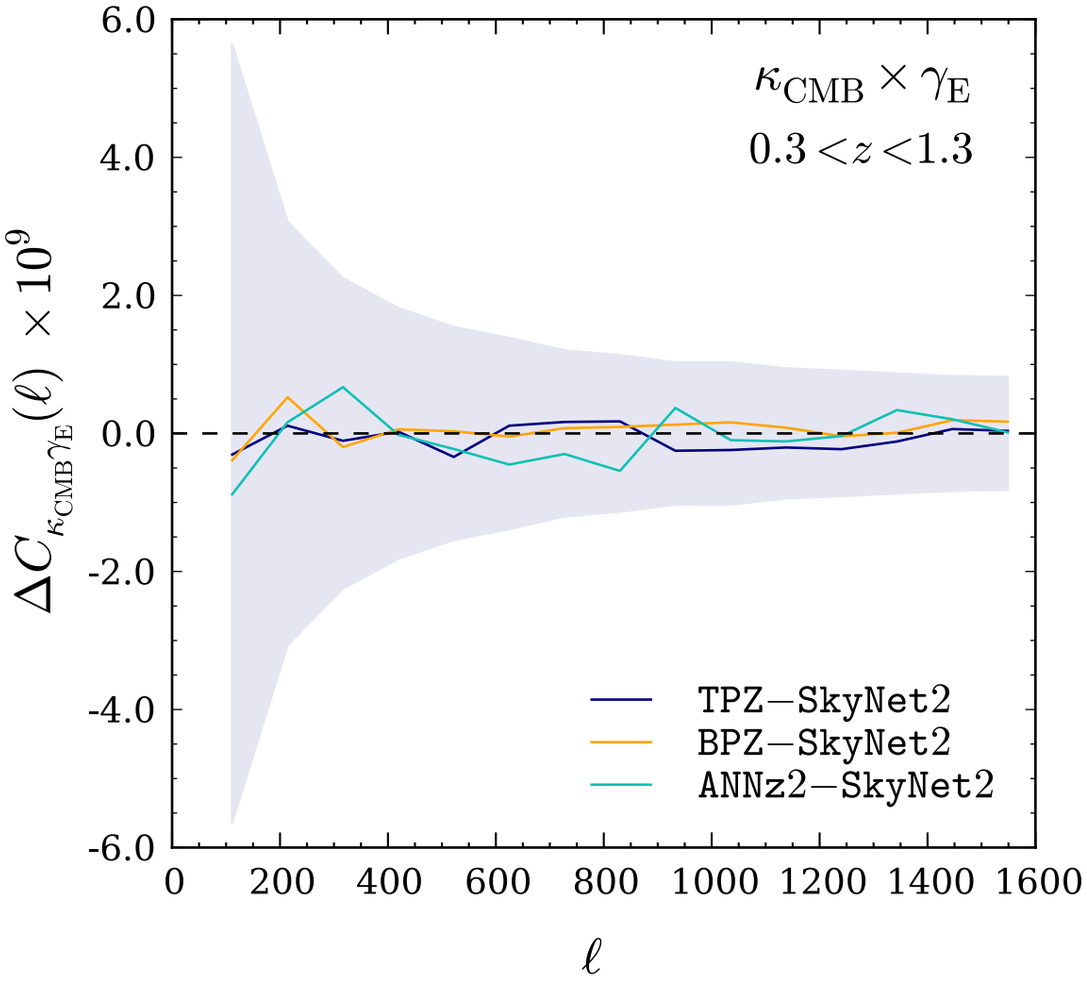
Covariance estimation

Shape codes: ngmix/im3shape

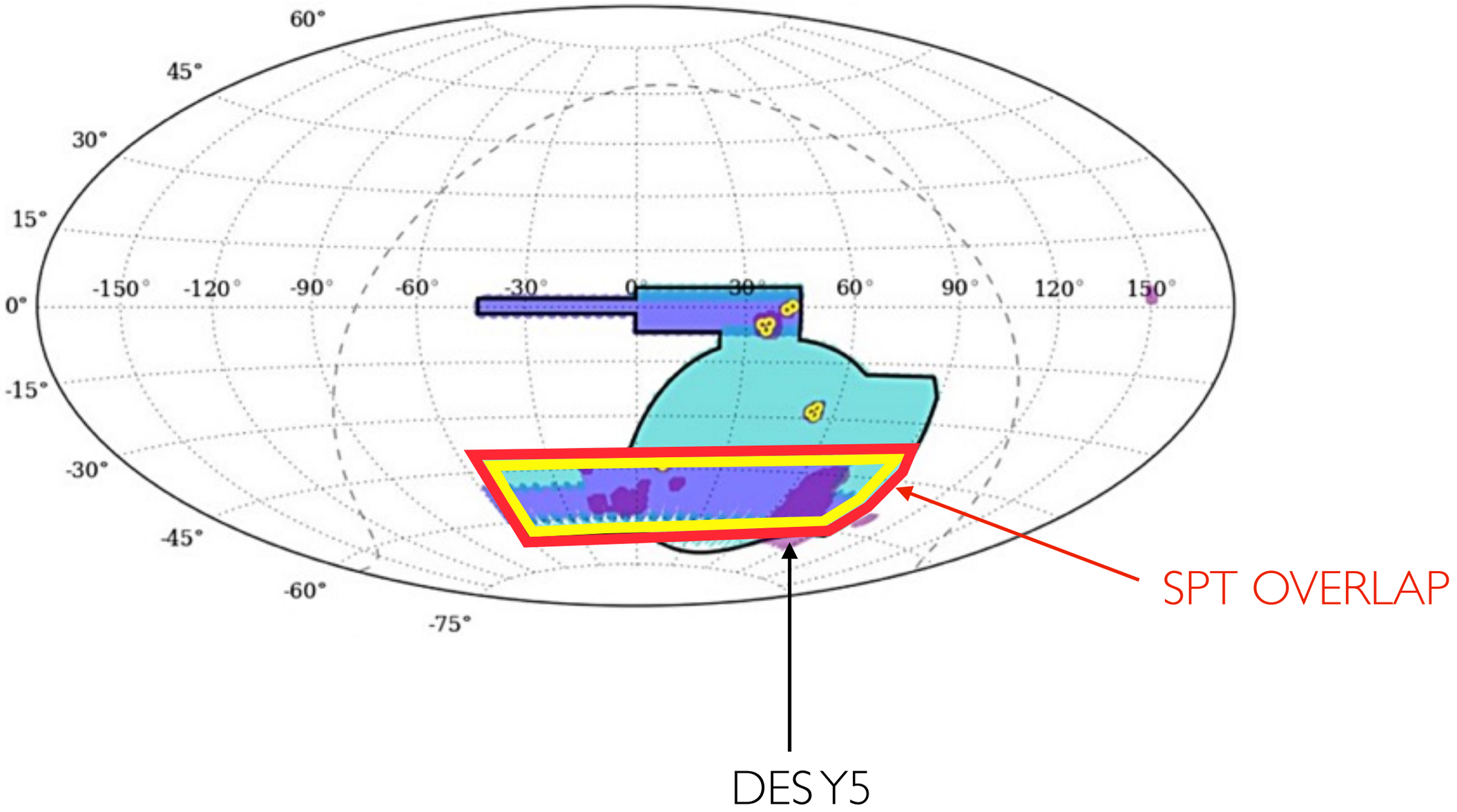
Pipeline: spherical vs flatsky

Photo-z codes: TPZ, BPZ, ANNz2, skynet2

CMB lensing systematics



FUTURE WORK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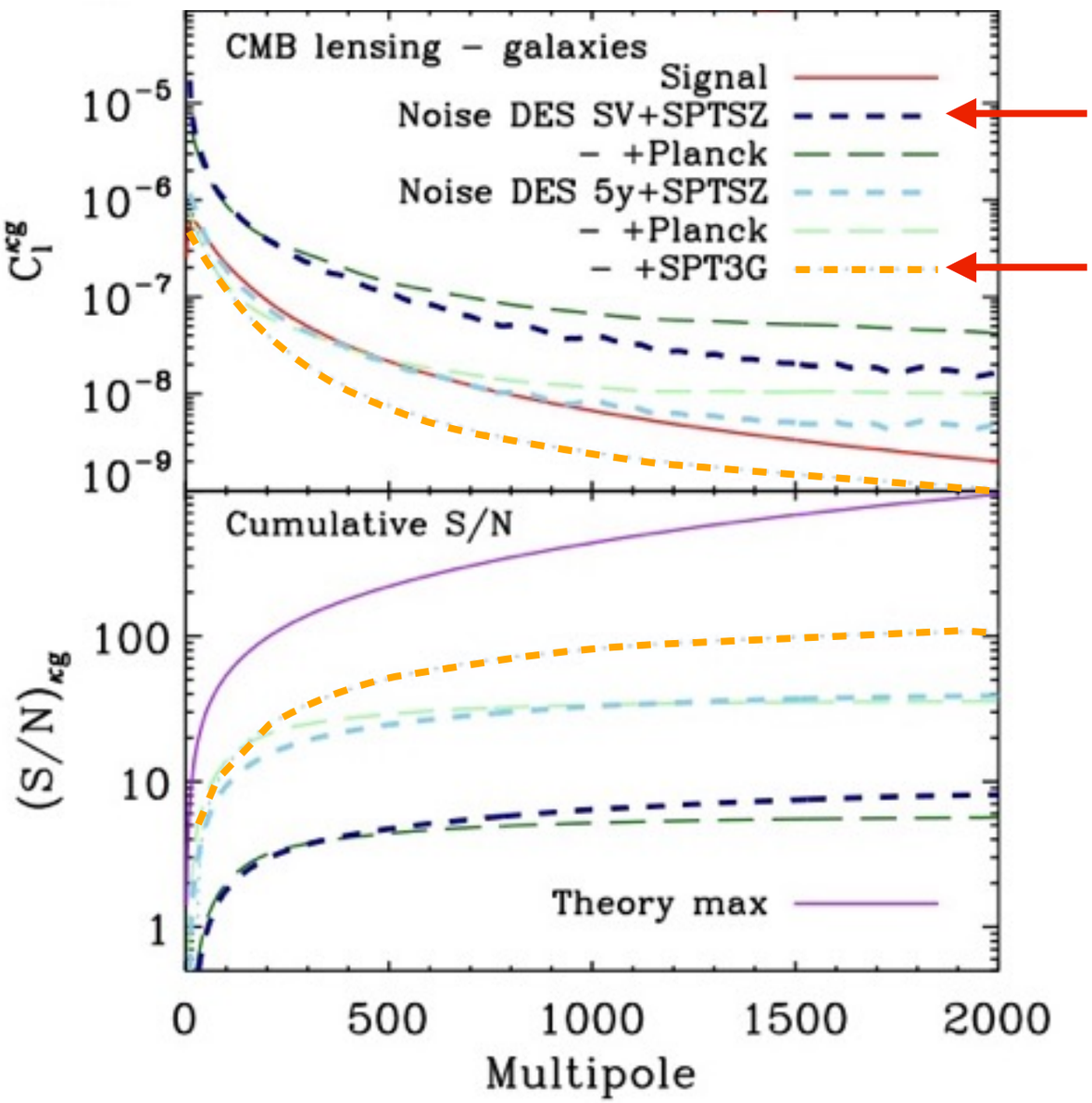
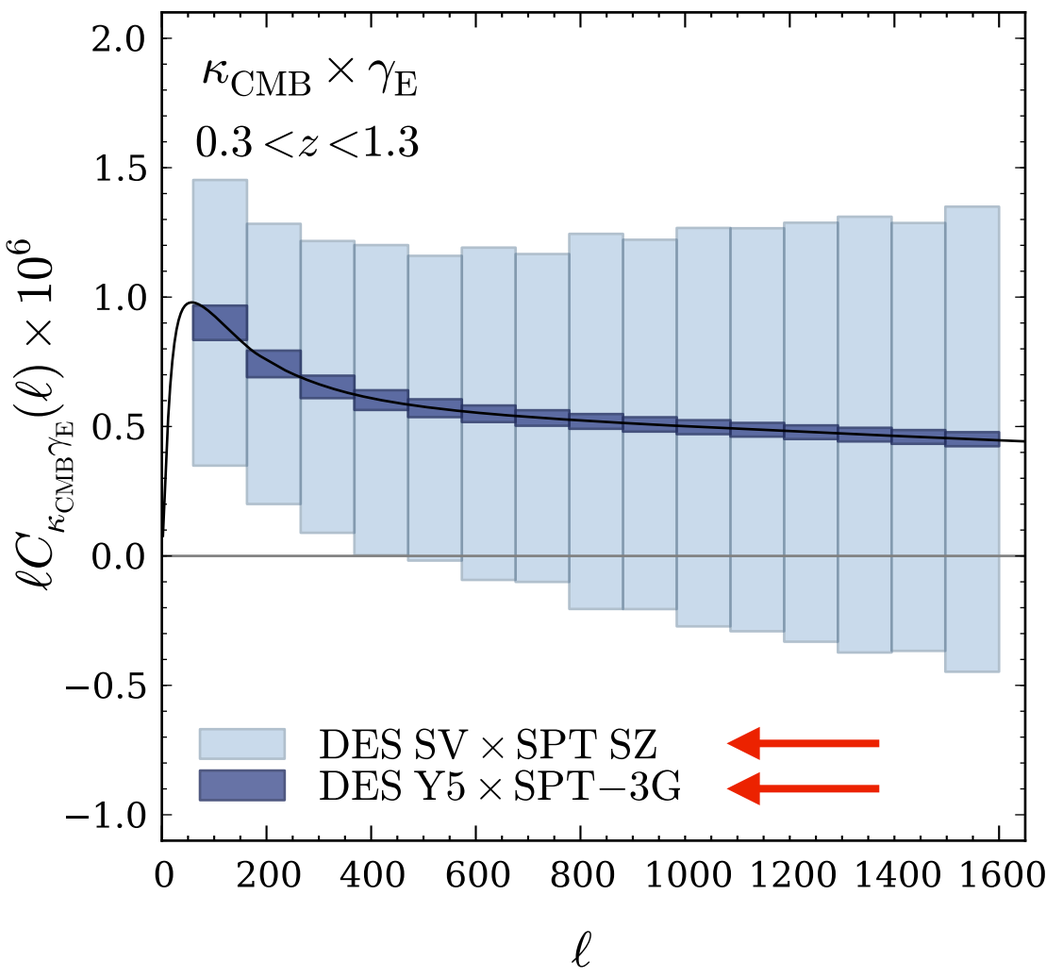
SPT OVERLAP
DES Y5

FUTURE WORK

Galaxy density x CMB lensing forecast



Galaxy lensing x CMB lensing forecast



SUMMARY

We have made **initial** measurements of scientifically interesting quantities.

In the upcoming data releases, we will have much better signal
Higher signal> better constraints + better tomography + higher order statistics

Will be able to constrain neutrino mass, growth of structure, intrinsic alignment

Many other cross-correlation projects are in progress in and out of DES x SPT constraining other cosmological and astrophysical parameters.

DES 2015-0048
Fermilab PUB-15-308-AE

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CMB lensing tomography with the DES Science Verification galaxies

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Cross-correlation of gravitational lensing from DES Science Verification data with SPT and *Planck* lensing

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