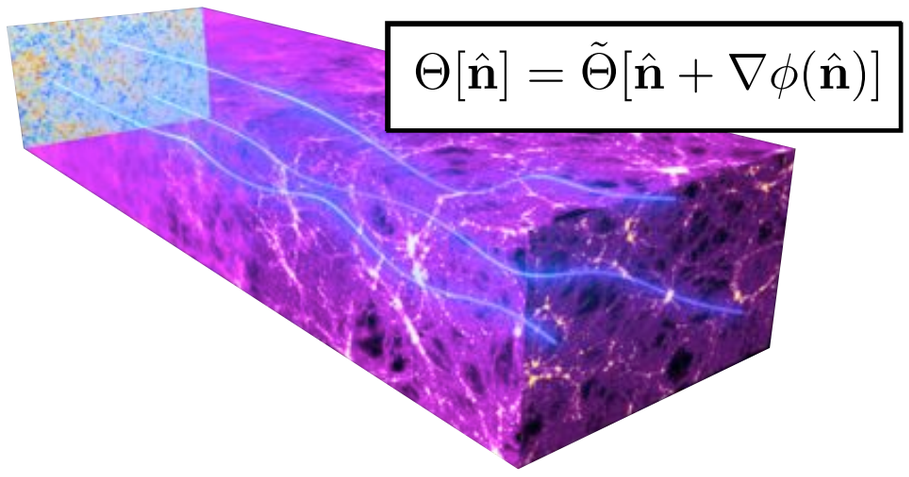


DARK ENERGY SURVEY

CMB lensing tomography with the DES Science Verification galaxies

Tommaso Giannantonio
(KICC/IoA/DAMTP Cambridge)

TG et al., arXiv:1507.05551
Crocce et al., arXiv:1507.05360

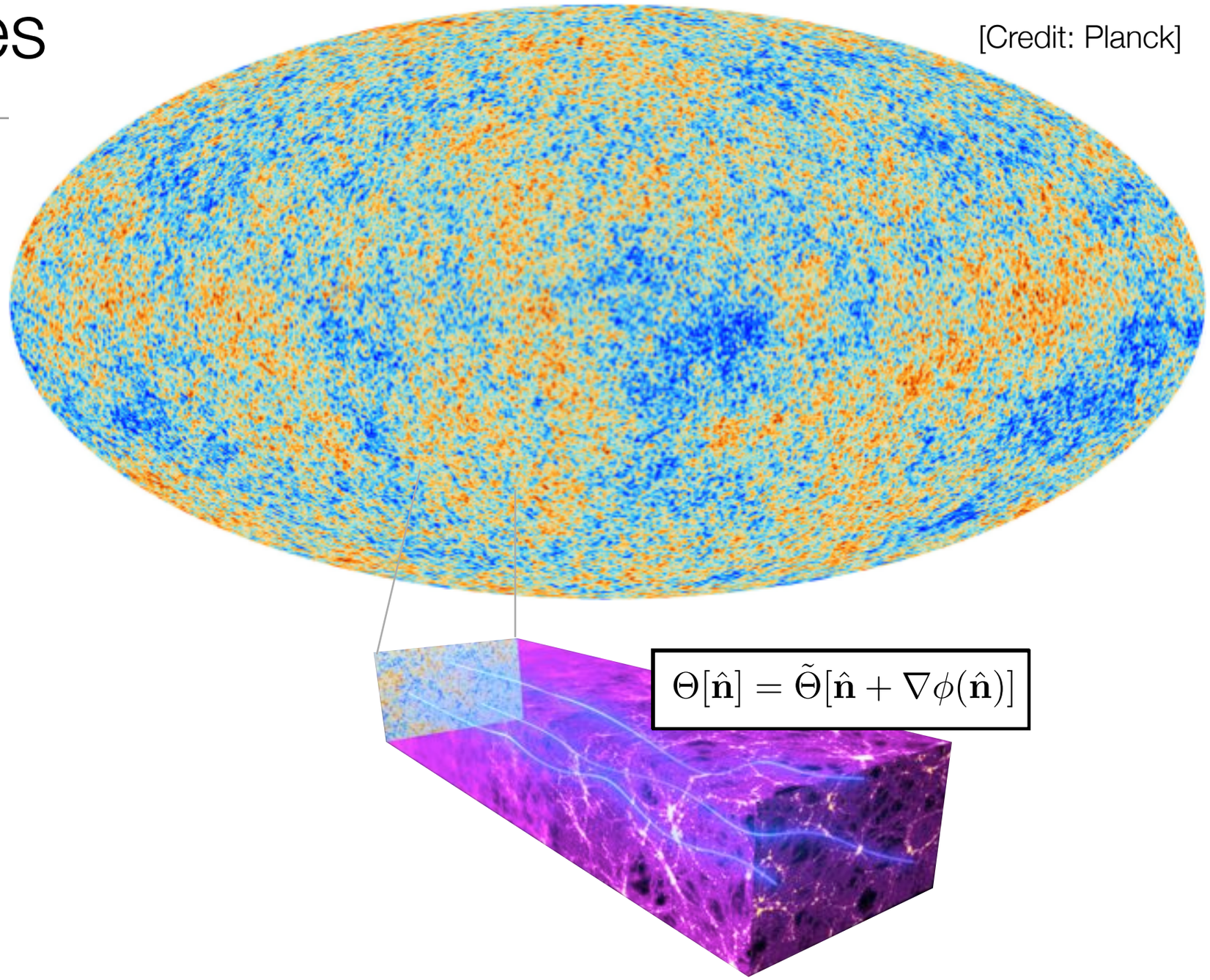
With: **P. Fosalba**, R. Cawthon, Y. Omori, M. Crocce, F. Elsner, B. Leistedt, S. Dodelson, A. Benoit-Lévy, W. Percival, H. Peiris, J. Weller, R. Crittenden, B. Soergel, *and many others* (the DES and SPT collaborations)

Garching, 24.7.2015

ioa KICC UNIVERSITY OF CAMBRIDGE

CMB anisotropies

[Credit: Planck]



$$\Theta[\hat{\mathbf{n}}] = \tilde{\Theta}[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})]$$

- **Primary**: at last scattering
- **Secondary anisotropies**:
  - **Reionisation**
  - **Gravity** (**CMB Lensing**, Integrated Sachs-Wolfe effect, kinetic SZ effect)

Tests of structure growth

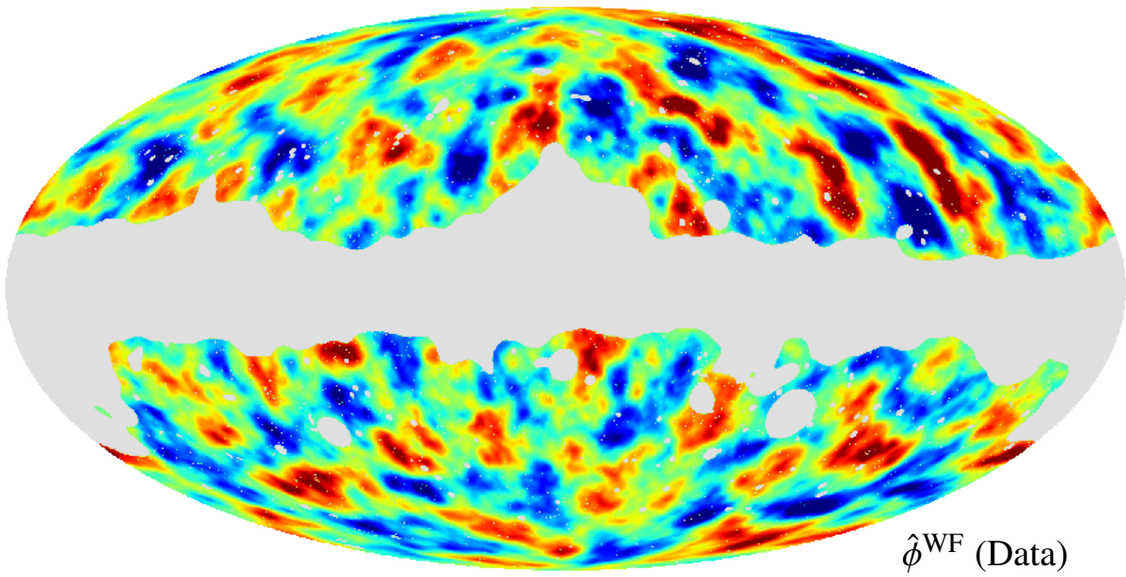
CMB lensing

- Lensing deflection: potential ϕ, convergence κ = ϕ $l^2/4$

$$\varphi(\hat{\mathbf{n}}) = -\int_0^{\chi_*} d\chi \, \frac{\chi_* - \chi}{\chi_* \chi} \, [\Phi + \Psi]\,(\chi\hat{\mathbf{n}}, \eta_0 - \chi)$$

  - Reconstructed from higher-order temperature statistics [Okamoto & Hu 03] by Planck, SPT, ACT

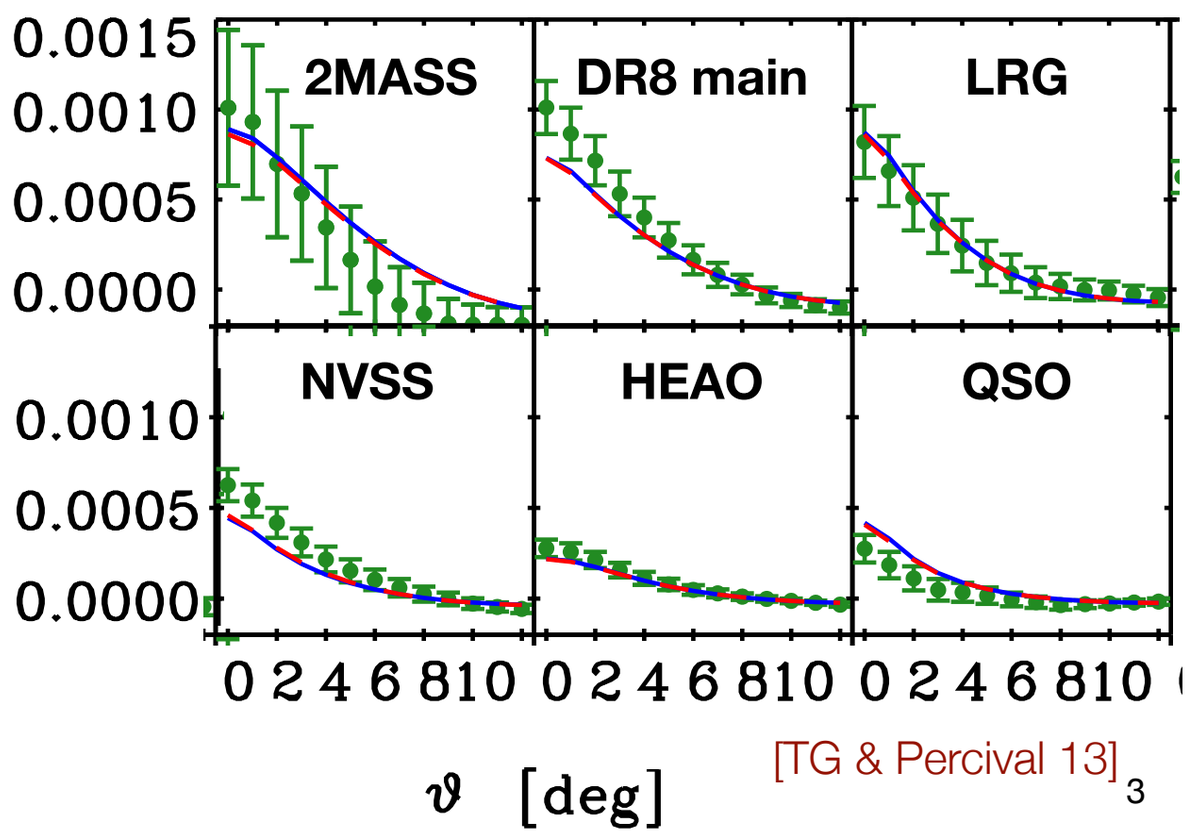
$$\Theta[\hat{\mathbf{n}}] = \tilde{\Theta}[\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})]$$



[Planck XV 15]

- Want to measure CMB lensing **tomography**
  - **Motivation**: trace evolution of structure formation, galaxy bias and the gravitational potentials (Φ+Ψ)
  - Use **cross-spectra CMB lensing-galaxies**
- Measured with WMAP **[Smith+ 07]**, Planck, SPT, ACT, [Sherwin+11, Bleem+12, Planck 13, TG&Percival 13, ...], S/N far from optimal
- CMB lensing kernel peaks at z ~ 2

DES is deeper, denser

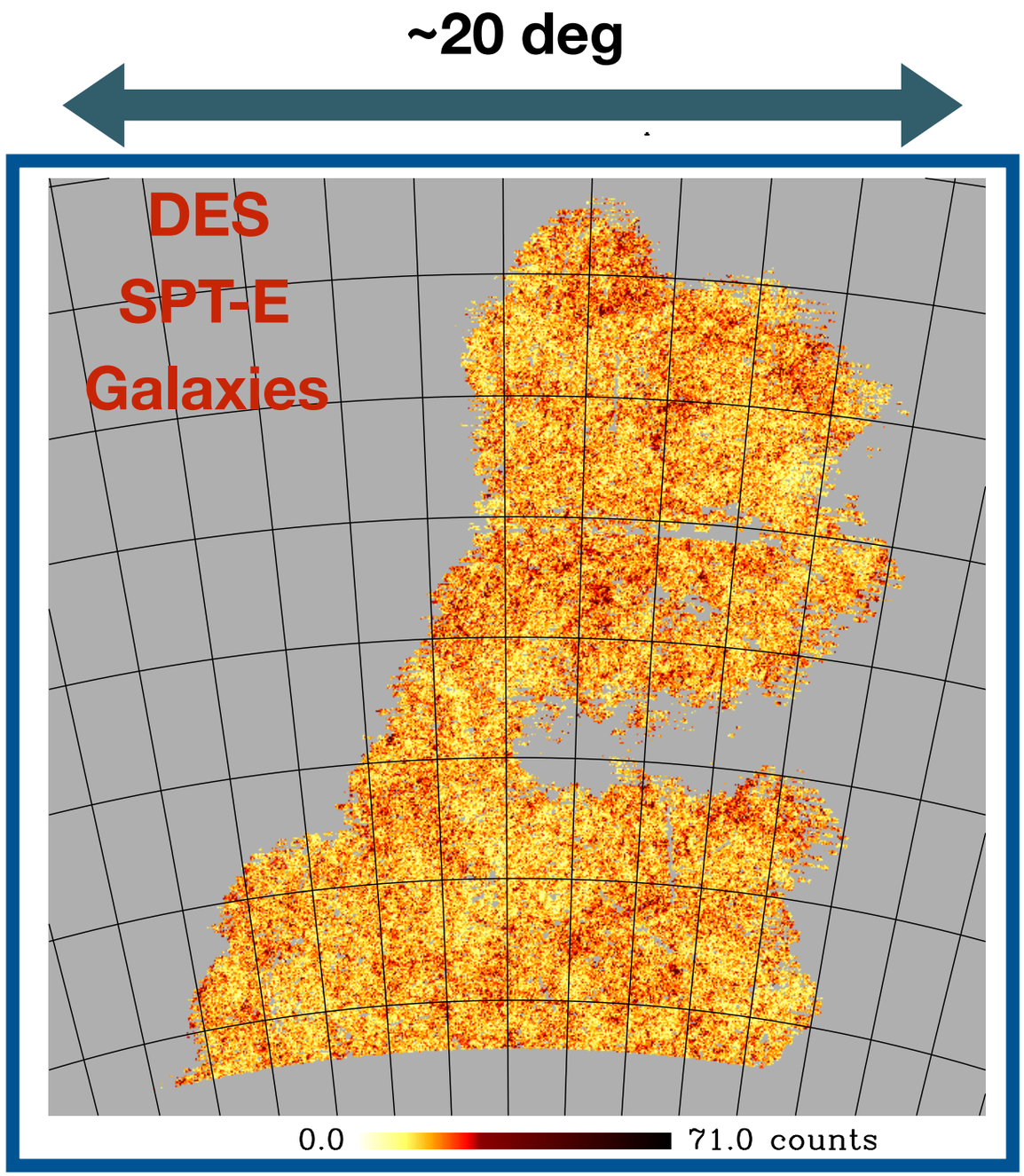


[TG & Percival 13]

DES Science Verification galaxies

[M. Crocce+, E. Rykoff+]

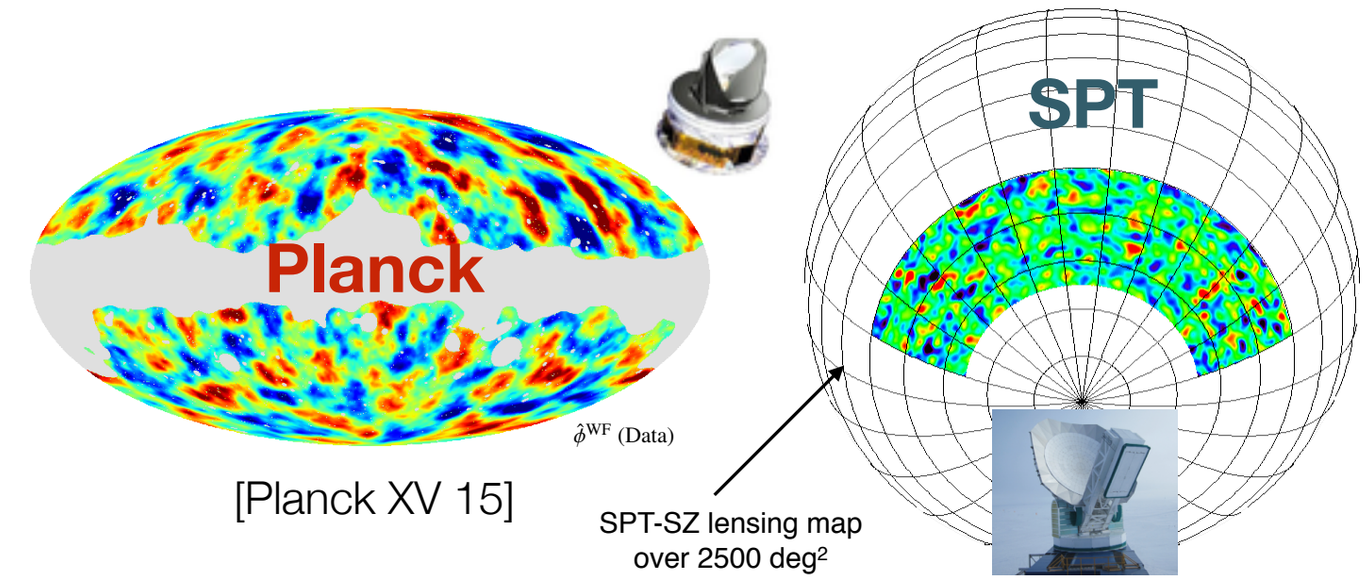
- Source extractor Gold Catalog: 25M objects
  - Star/galaxy separation
  - Artefacts cuts (crazy colours)
  - 0.2 < photo-z < 1.2
  - Completeness 18 < i < 22.5
  - **2.7M galaxies: 'Benchmark' sample**
- Mask: 131 sq. deg
  - LMC
  - Depth > 22.5
  - Good photometry



CMB lensing data

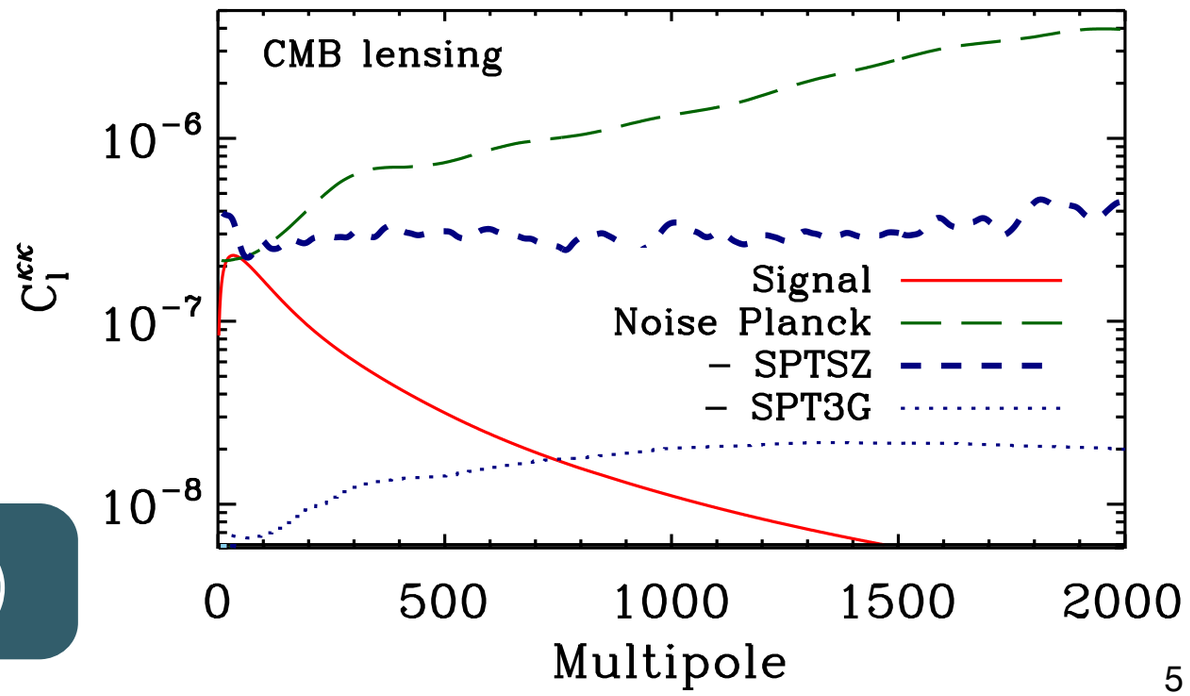
[SPT via MoU, thanks to G. Holder, L. Bleem]

- **Planck**: public lensing convergence κ map & mask [Planck15]
  - Full sky
  - Noise-dominated



[Planck XV 15]

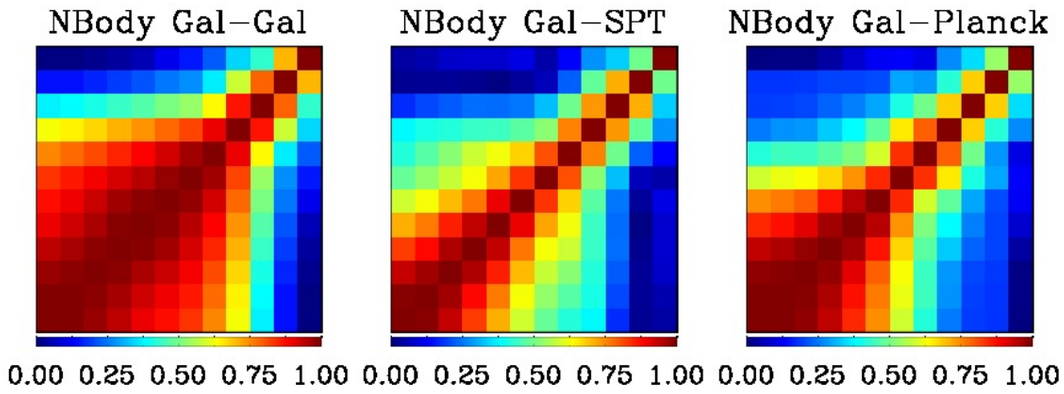
- **SPT**: lensing maps from SPT-SZ survey [van Engelen+ 12]
  - Smaller area, overlaps DES SV
  - Lower, but **anisotropic** noise
  - Higher resolution



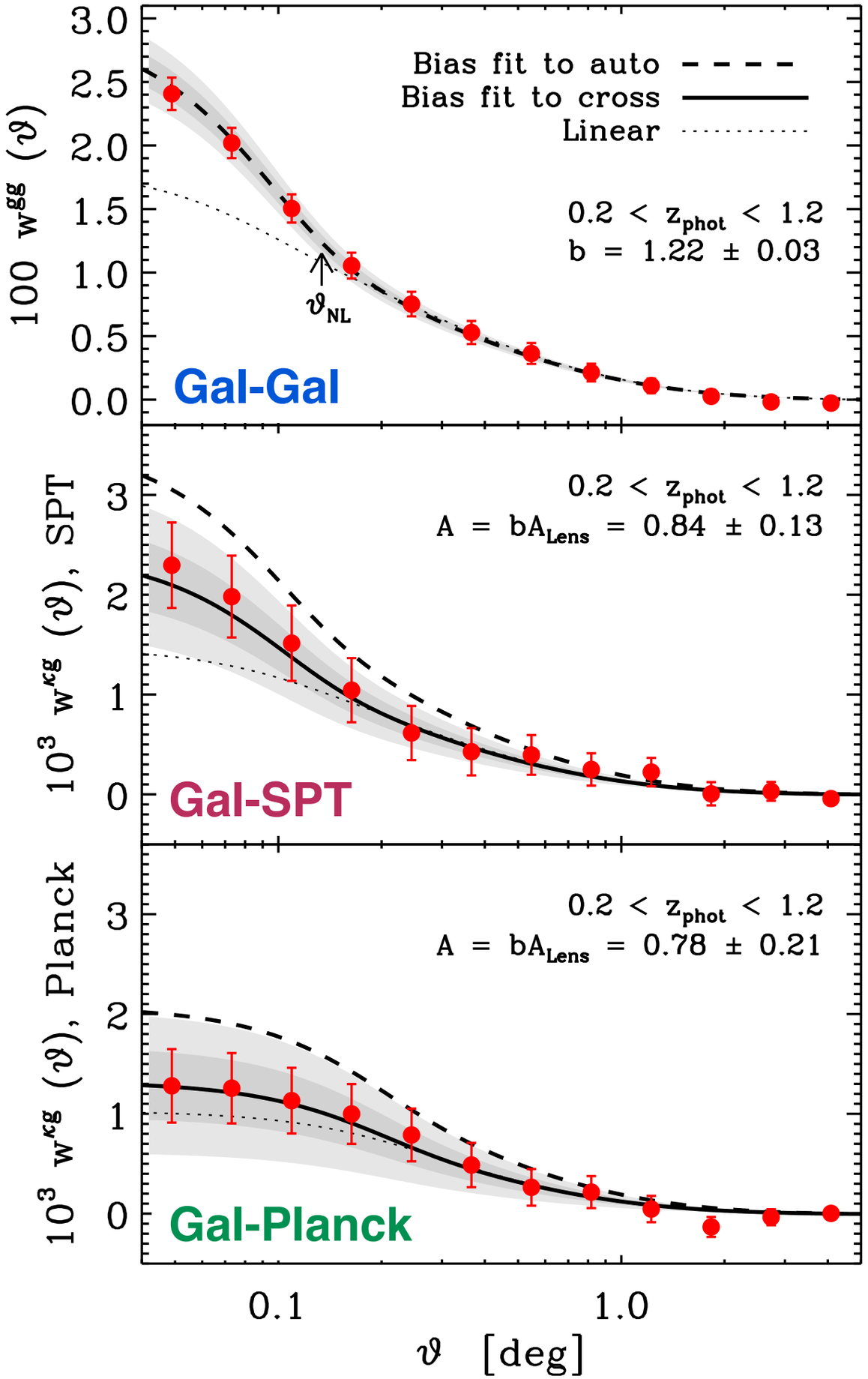
S/N ~ 8 (5) expected for SPT (Planck)

Results, real space

- **Two-point correlation function w(θ)**
- Data well-fit by Fiducial LCDM (Planck), ~2σ tension between auto and cross
- Covariances: analytical, Monte Carlos, Jack Knife, **N-body**

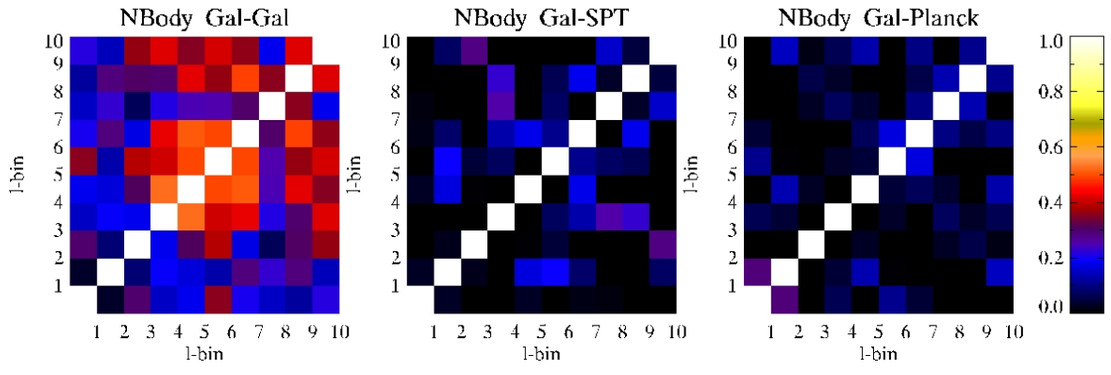


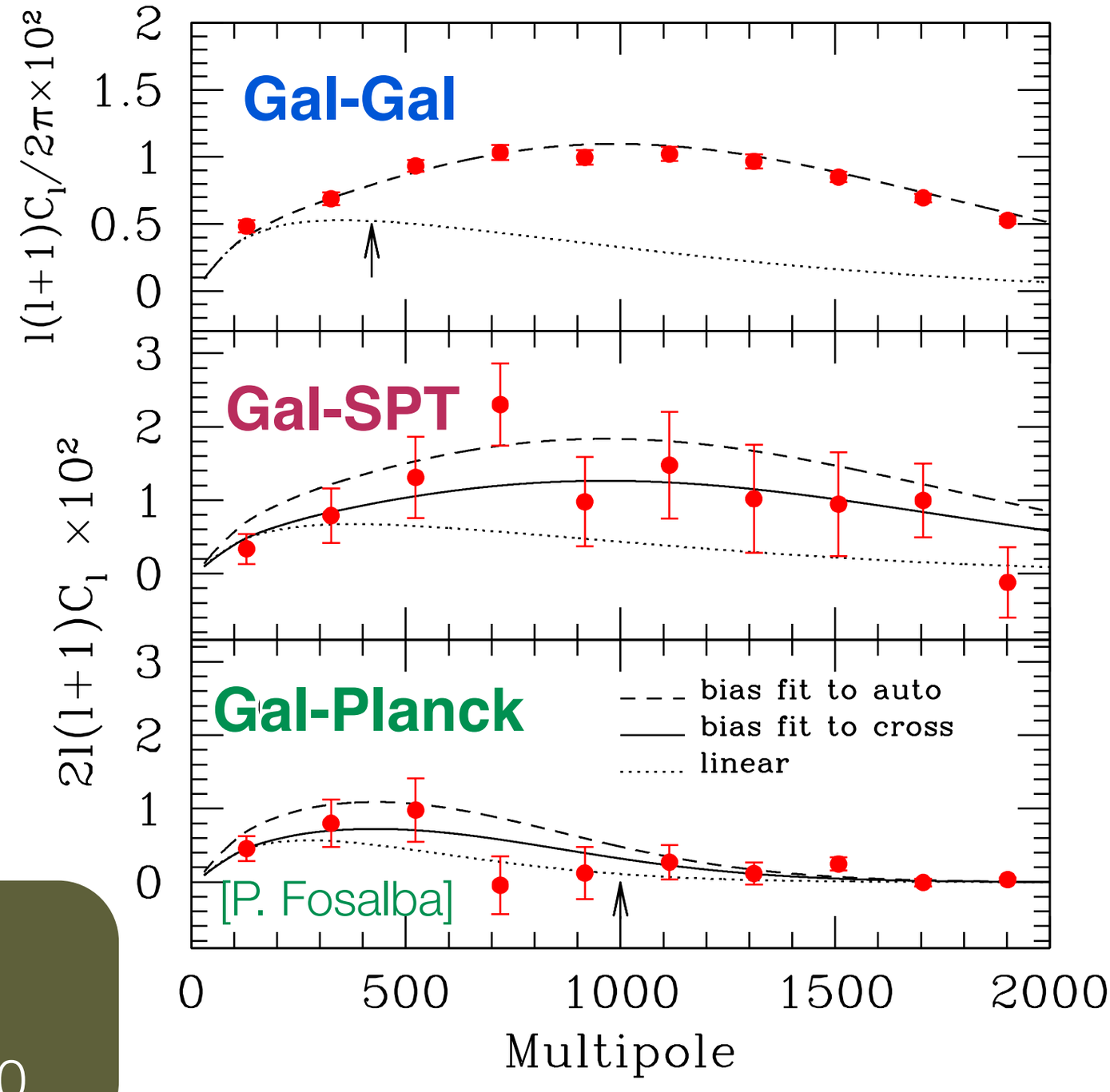
DES-DES: b = 1.22 ± 0.03
DES-SPT: 6σ: A = 0.84 ± 0.13
DES-Planck: 4σ: A = 0.78 ± 0.21



Results, harmonic space

- **Angular power spectrum C_l**
- Data well-fit by Fiducial LCDM;
  2σ tension between auto and cross
- Covariances: N-body & others



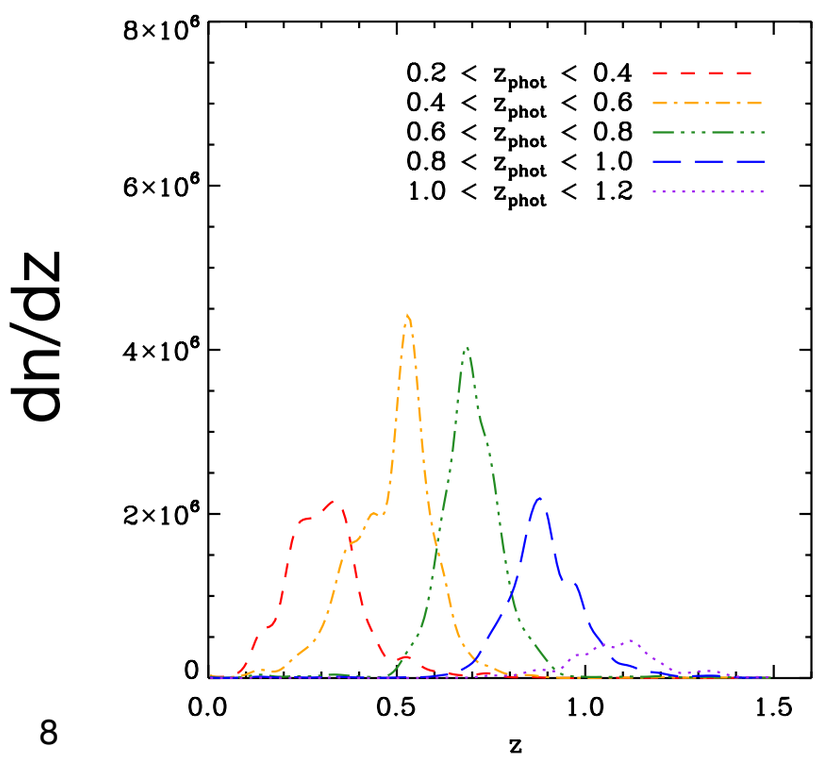


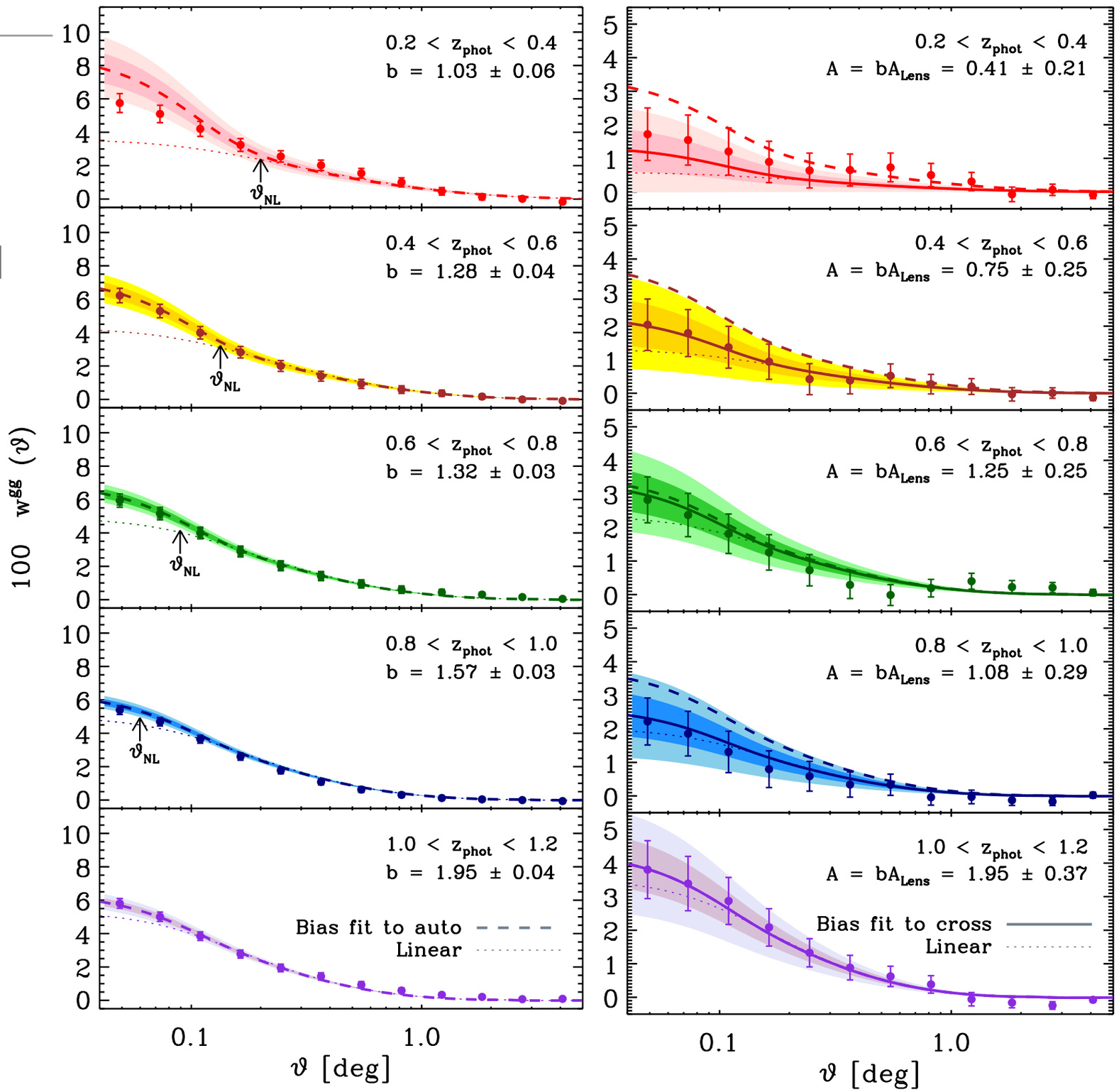
DES-DES: b = 1.22 ± 0.04
DES-SPT: 6σ: A = 0.84 ± 0.15
DES-Planck: 4σ: A = 0.81 ± 0.20

$A = b\, A_{Lens}$

Redshift tomography

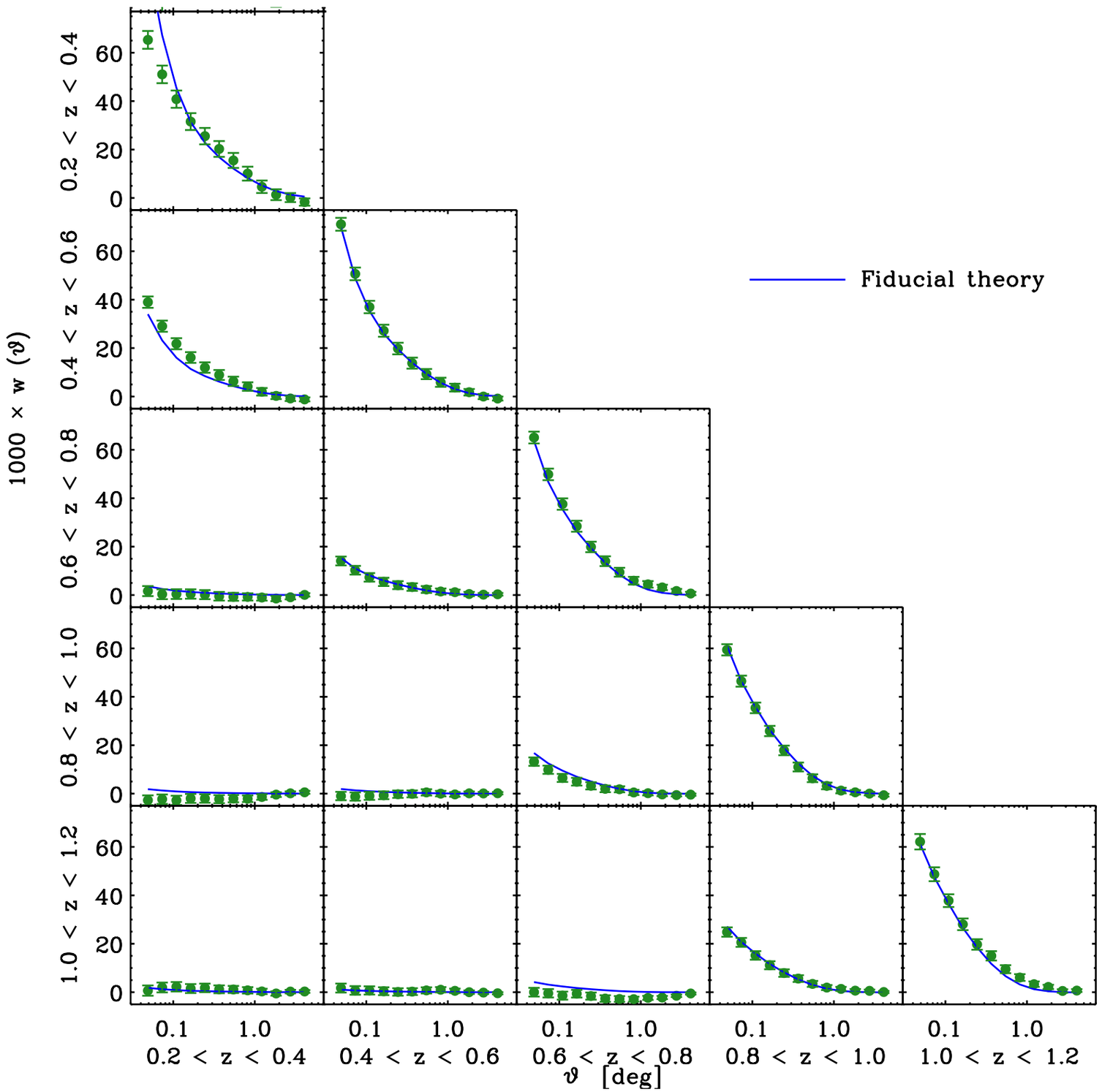
- Correlation functions in **five photo-z bins**
- Correlation always detected at >2σ
- Typically cross lower than expected from auto





Full set of galaxy-galaxy correlations

[See Crocce et al. 2015]



- Theory:
  best fit to autocorrelation
- **Most cross-correlation agree with same bias**

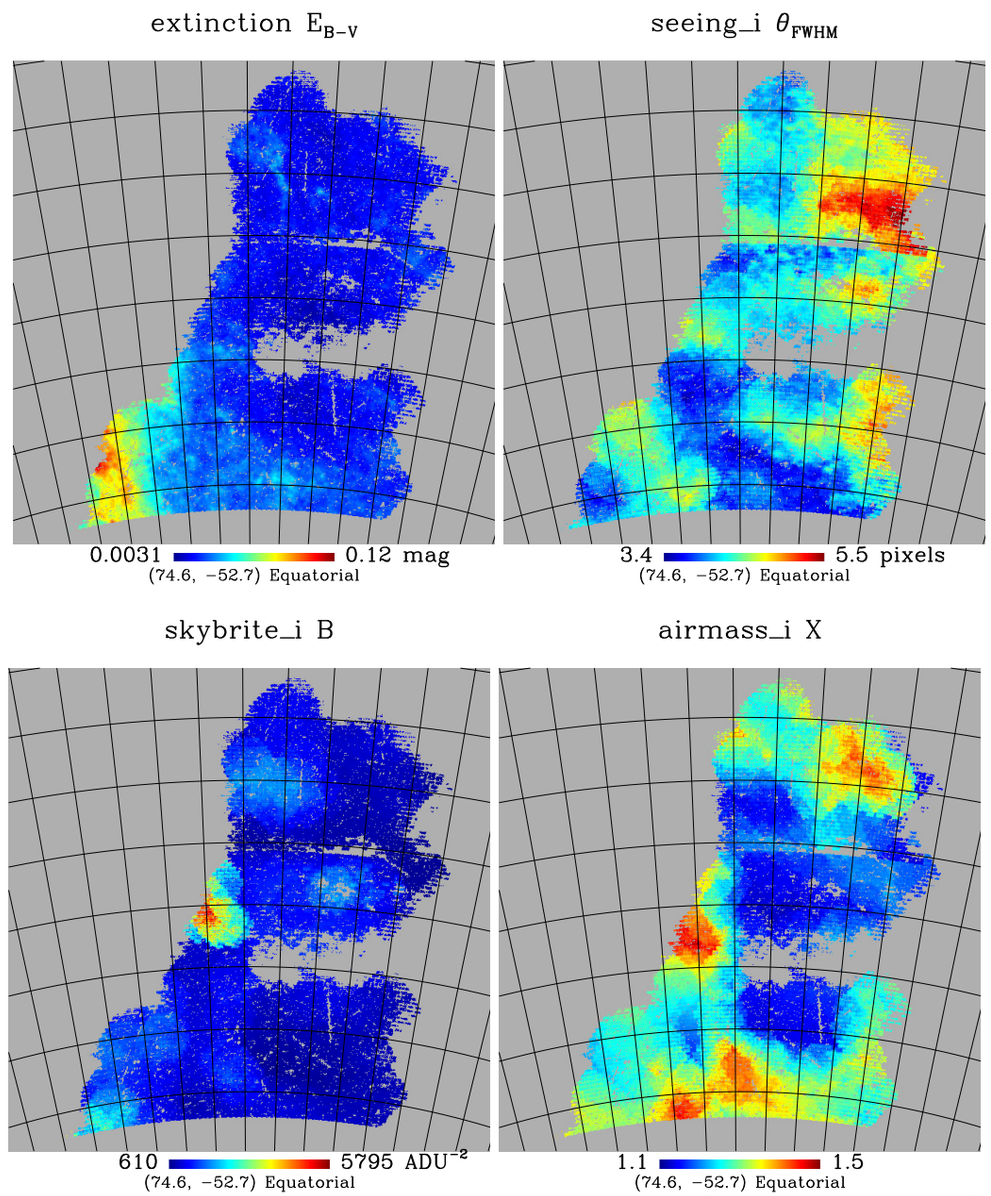
Good consistency check of the photo-z

Systematic tests

[with R. Cawthon, B. Leistedt, M. Crocce]

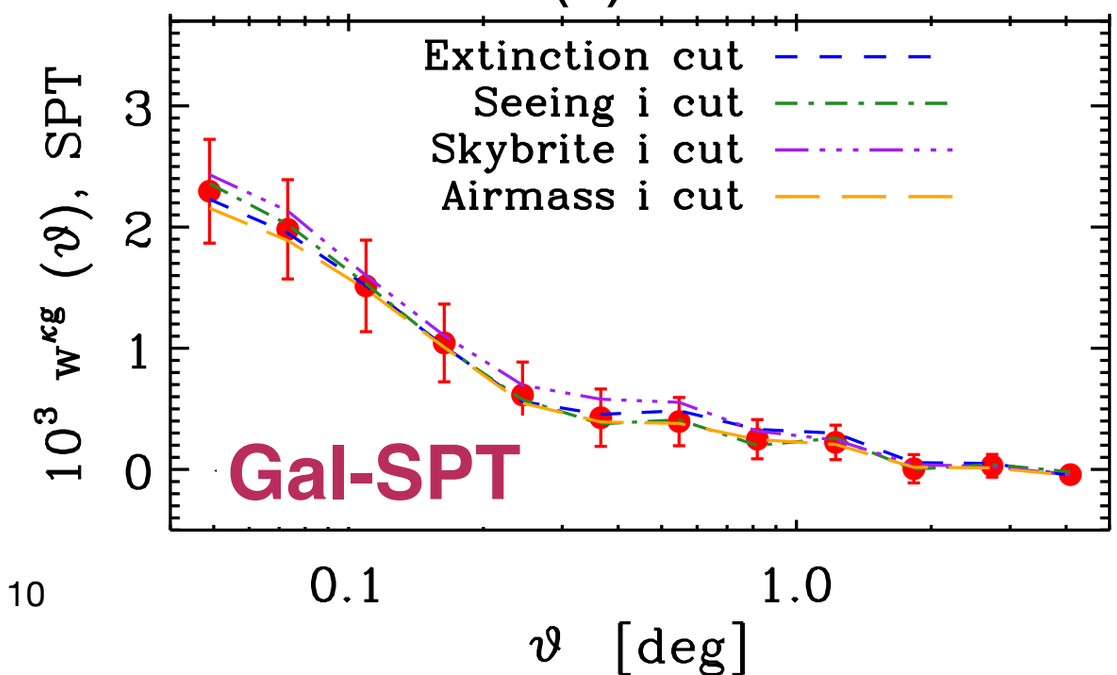
- **Dust** [Planck]**, seeing, sky brightness, air mass, …** [B. Leistedt+]**, catalog sys.** [A. Bauer]
- Cuts in **all 19 systematics:** Measured correlations are **robust**
- Correcting for systematics also robust

$$C_{\ell,\mathrm{true}}^{g\kappa} = C_{\ell,\mathrm{obs}}^{g\kappa} - \frac{C_\ell^{gs}\, C_\ell^{\kappa s}}{C_\ell^{ss}}$$



[Leistedt+ 15]

w(θ) cuts



C_l corrections

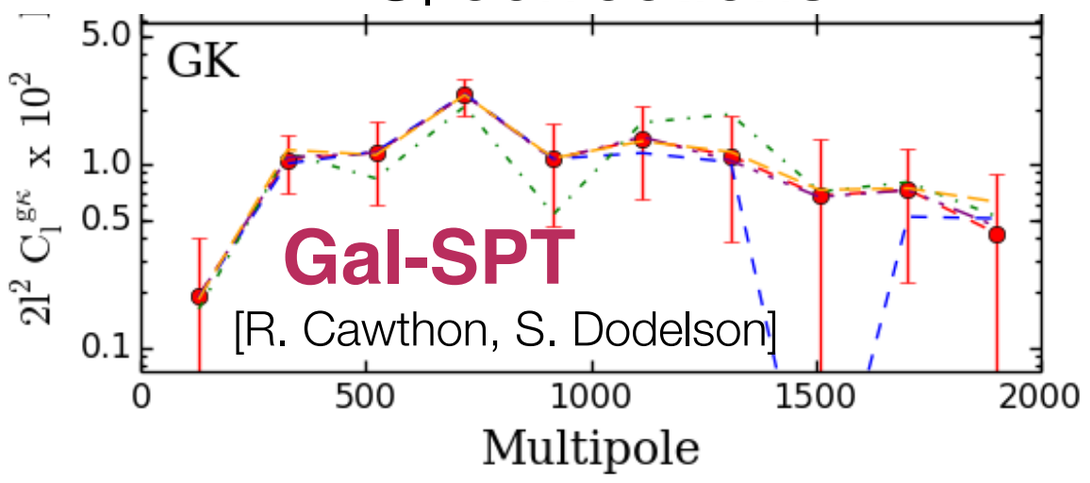
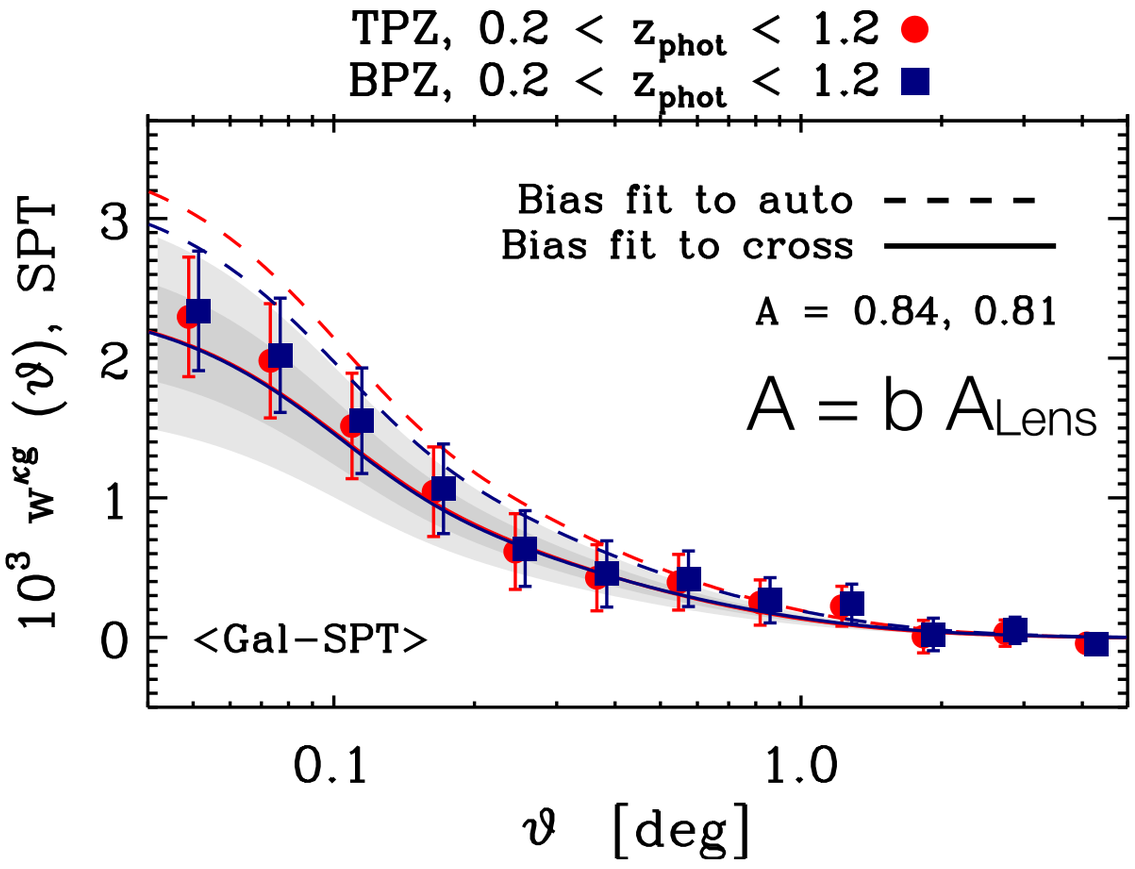
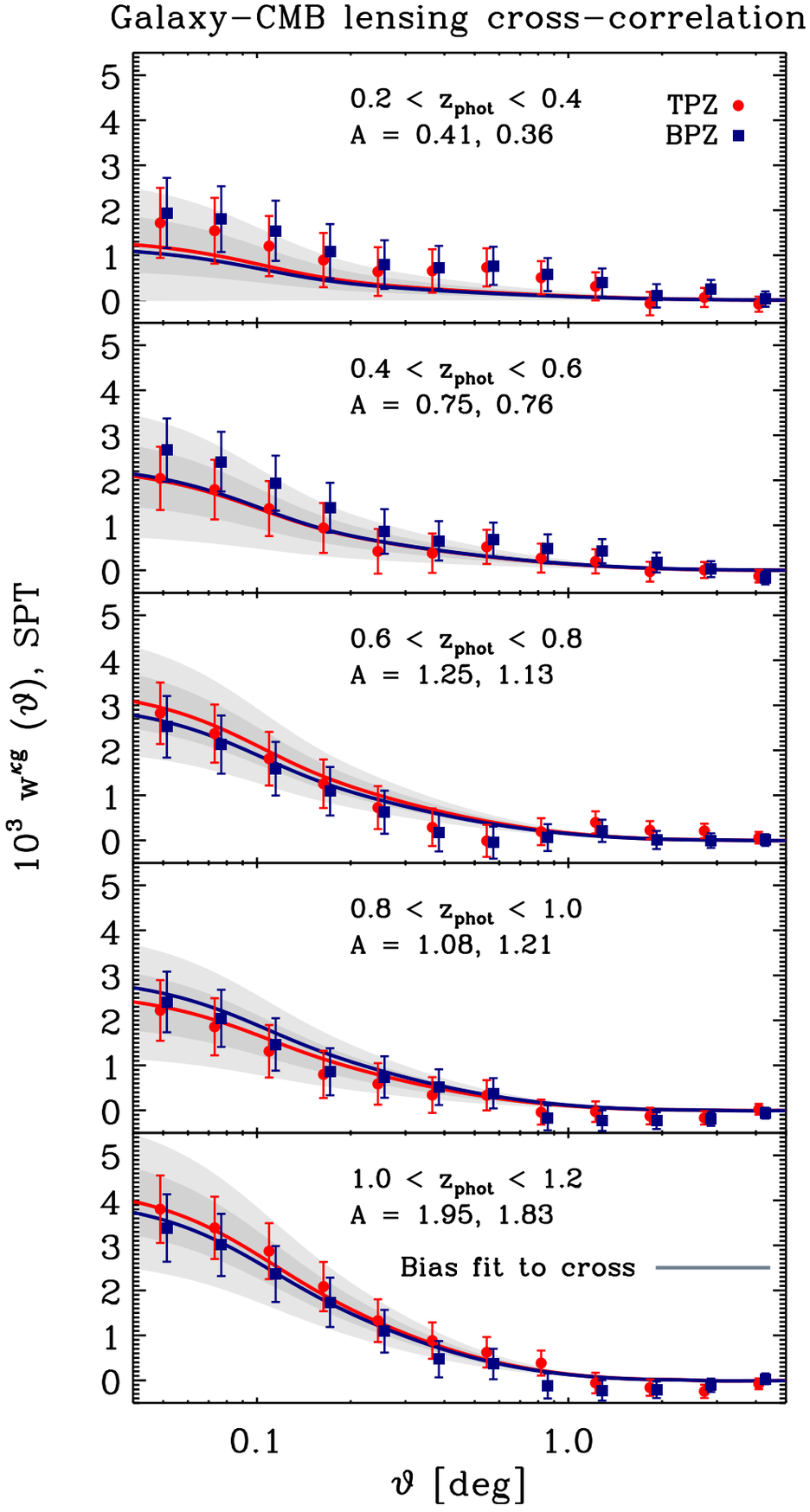


Photo-z tests

- Assume **TPZ** [Carrasco-Kind & Brunner 13,14] vs. **BPZ** [Benítez 00] in sample selection and model
- Measured correlations are **robust**: both full sample and tomography





Measuring the growth of structure

- E_G estimator [Zhang+07, Reyes+10, Pullen+15]

$$E_G \propto \frac{C_\ell^{\kappa g}}{C_\ell^{\theta g}} = \frac{C_\ell^{\kappa g}}{\beta\, C_\ell^{gg}} ,$$

Difficult with photometric survey: need RSD β = f/b, or bias prior

- Simple estimator - depends on b:

$$\hat{D}_i = \left\langle \sqrt{\frac{\left(C_\ell^{\kappa g}\right)^i_{\rm obs}}{\left(\mathcal{C}_\ell^{\kappa g}\right)^i_{\rm the}}} \right\rangle_\ell ,$$

Slash quantities: had their growth D removed

- **Better D_G estimator:** does not depend on b, nor on theory D:

$$\left(\hat{D}_G\right)_i \equiv \left\langle \frac{\left(C_\ell^{\kappa g}\right)^i_{\rm obs}}{\left(\mathcal{C}_\ell^{\kappa g}\right)^i_{\rm the}} \sqrt{\frac{\left(\mathcal{C}_\ell^{gg}\right)^i_{\rm the}}{\left(C_\ell^{gg}\right)^i_{\rm obs}}} \right\rangle_\ell$$

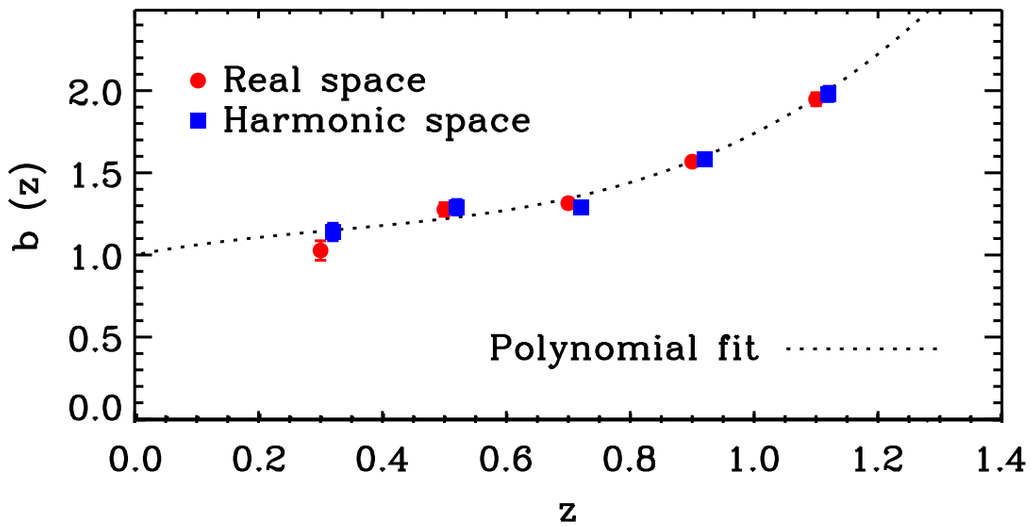
$$D_G \propto \frac{(\Omega_m H_0 \sigma_8)_{\rm true}}{(\Omega_m H_0 \sigma_8)_{\rm fiducial}} D(z)$$

Bias and Growth

- First simple application: measure bias and linear growth
- **Bias evolution**: simple polynomial fit

$$b(z) = 1 + a_1 z + a_2 z^2 + a_3 z^3$$

  - Result compatible with CFHTLS [Coupon+12] and with Nbody (MICE) [Crocce+ 15]



- Cross-correlation Amplitude A = b A_{Lens}: **lower**
- **Growth D_G**: *roughly* consistent with LCDM, 1.7σ lower

$$D_G(z) = A_D\,[D_G(z)]_{\rm fid}$$

  - Template amplitude fit: **A_D = 0.73 ± 0.16**
  - At face value, could be interpreted as shift of $\omega_m\sigma_8$ by ~25%
  - Or bias stochasticity r

- These are statistical error bars

Conclusions

- LSS-CMB correlations: many complementary probes of structure formation
- CMB Lensing — Galaxy cross-correlation
  - Detected at 6σ (SPT), 4σ (Planck), solid with respect to systematics tested
  - Redshift tomography for the first time: mainly agrees with fiducial cosmology but 1.7σ low
- DES-Year1: CMB lensing, clustering, kSZ [poster by B. Soergel], ISW: full propagation of systematics and DE/MG implications