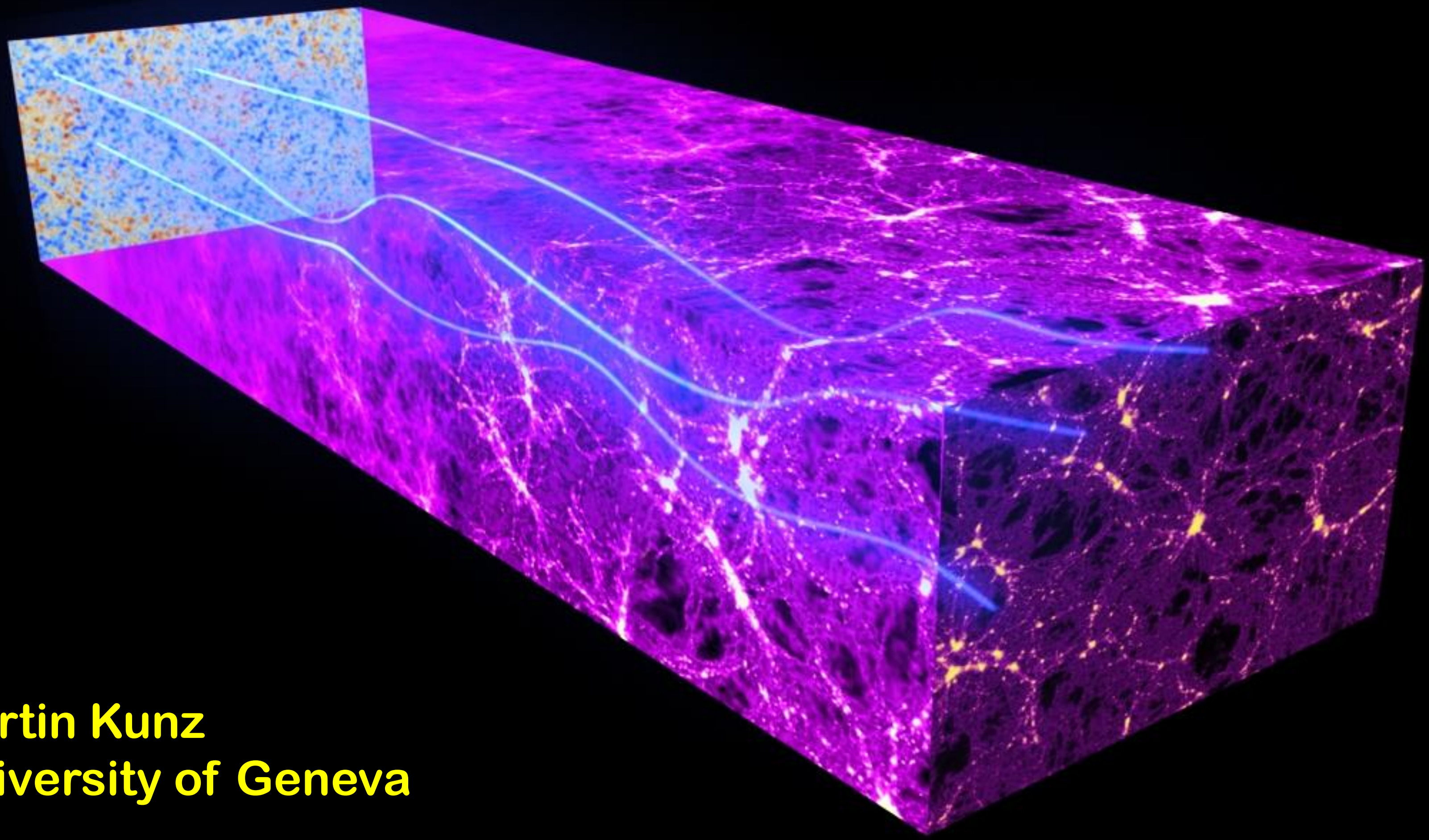
Lensing and large-scale structure observations



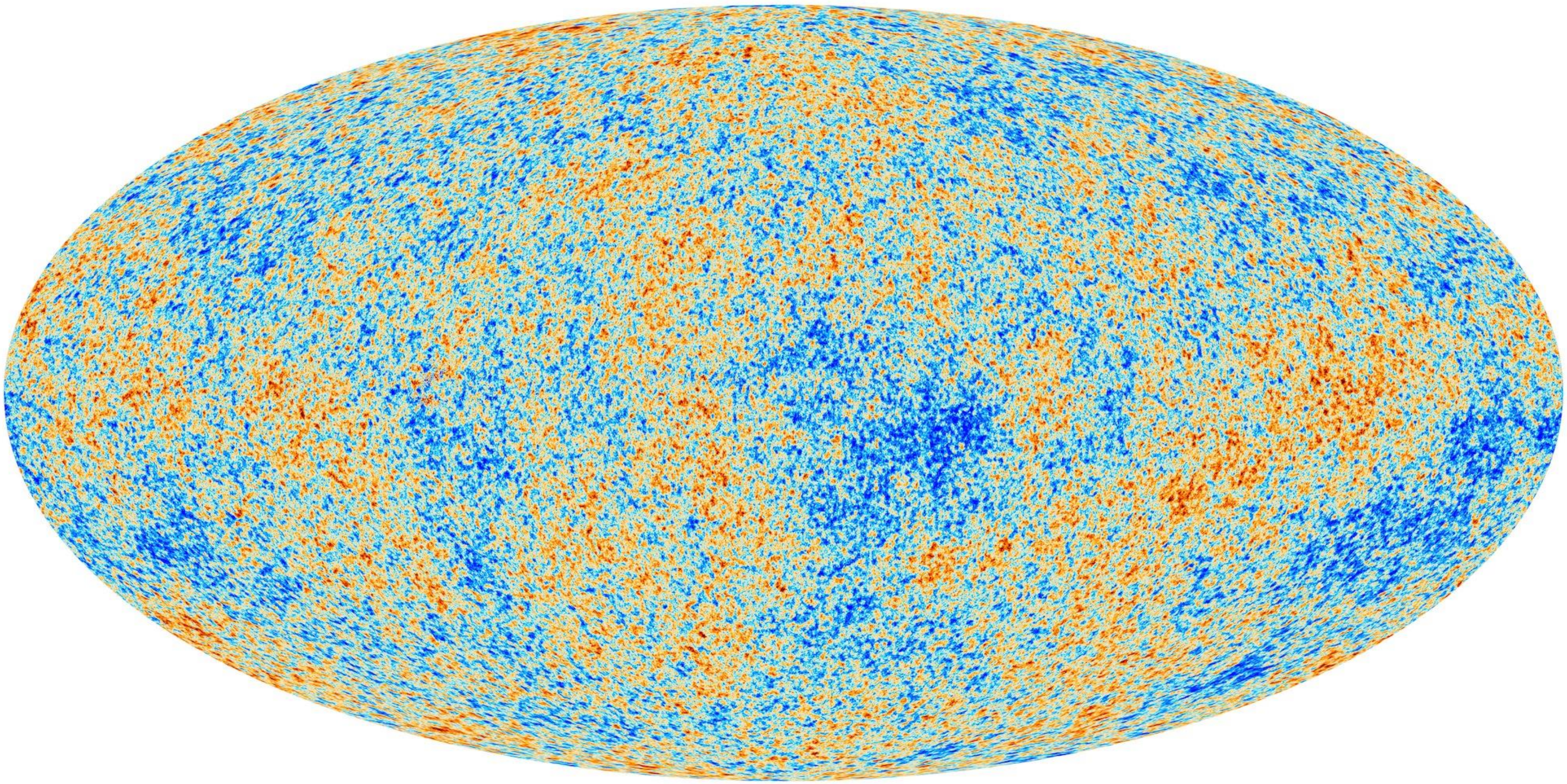
Martin Kunz
University of Geneva

with Francesca Lepori et al (Euclid, arXiv:2110.05435)
Viraj Nistane, Mona Jalilvand, Julien Carron, Ruth Durrer (arXiv:2201.04129)
Mona Jalilvand et al (arXiv:1907.00071), Planck, HIRAX, and more…

Outline

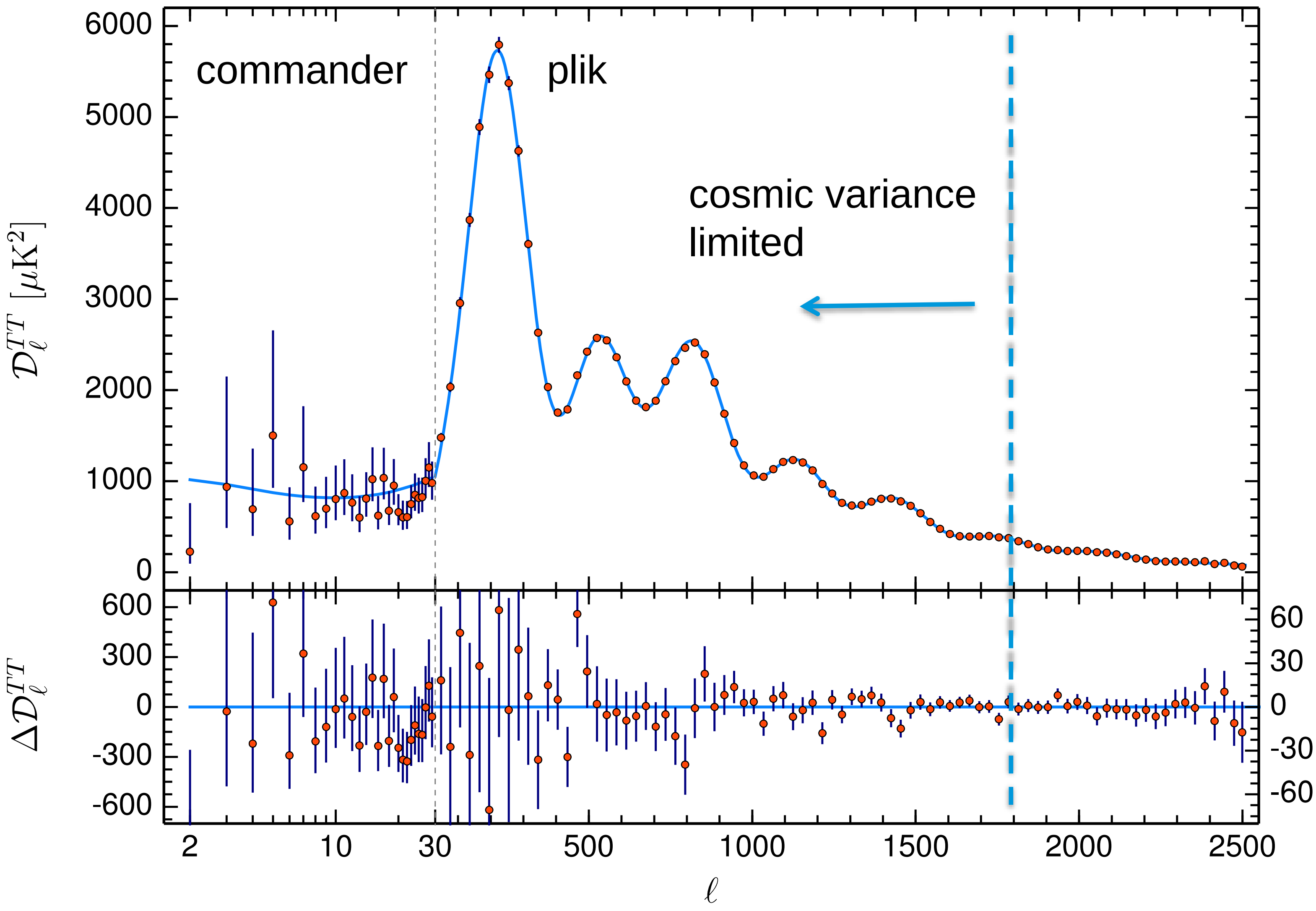
- All observations are affected by lensing.
- How does gravitational lensing work?
- What does it do to large-scale structure observations, and is it important?
- How can we reconstruct a map of the lensing effect (i.e. the lensing potential)?
- How well does it work for large-scale structure surveys?
- The end

A photo of the baby universe



Planck 2018 TT power spectrum

blue curve always best fit to TT,TE,EE + lowE + (CMB) lensing



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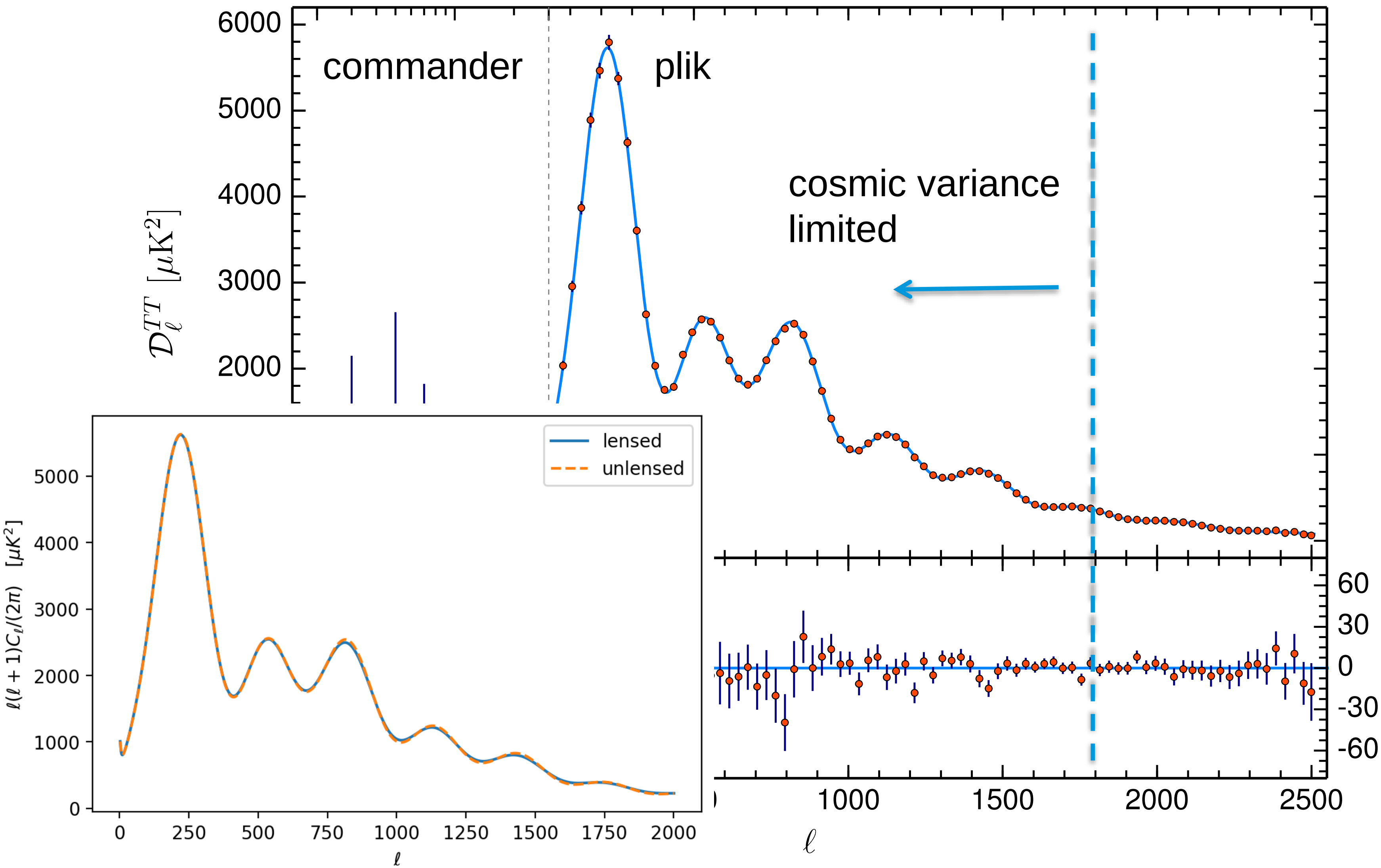

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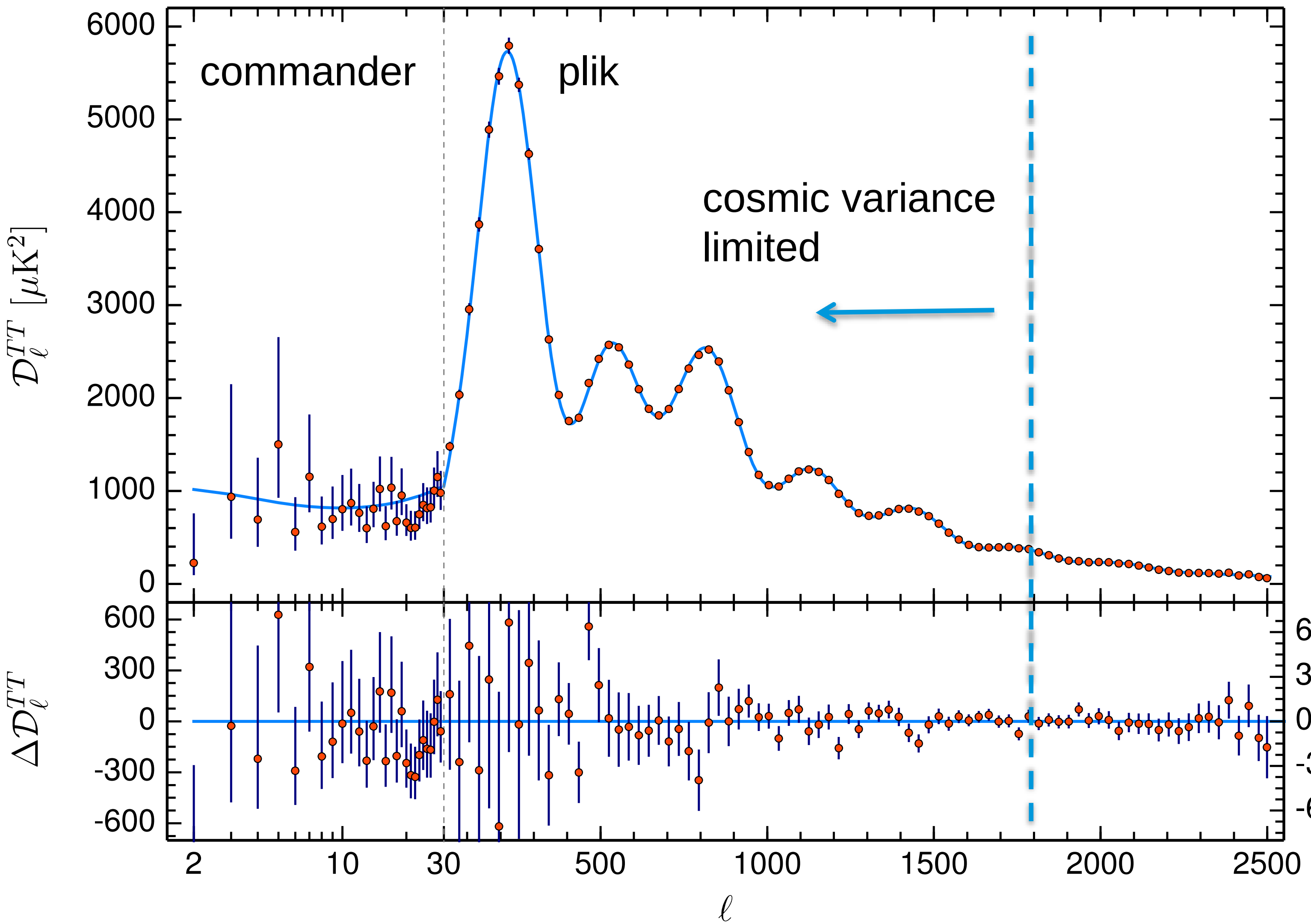

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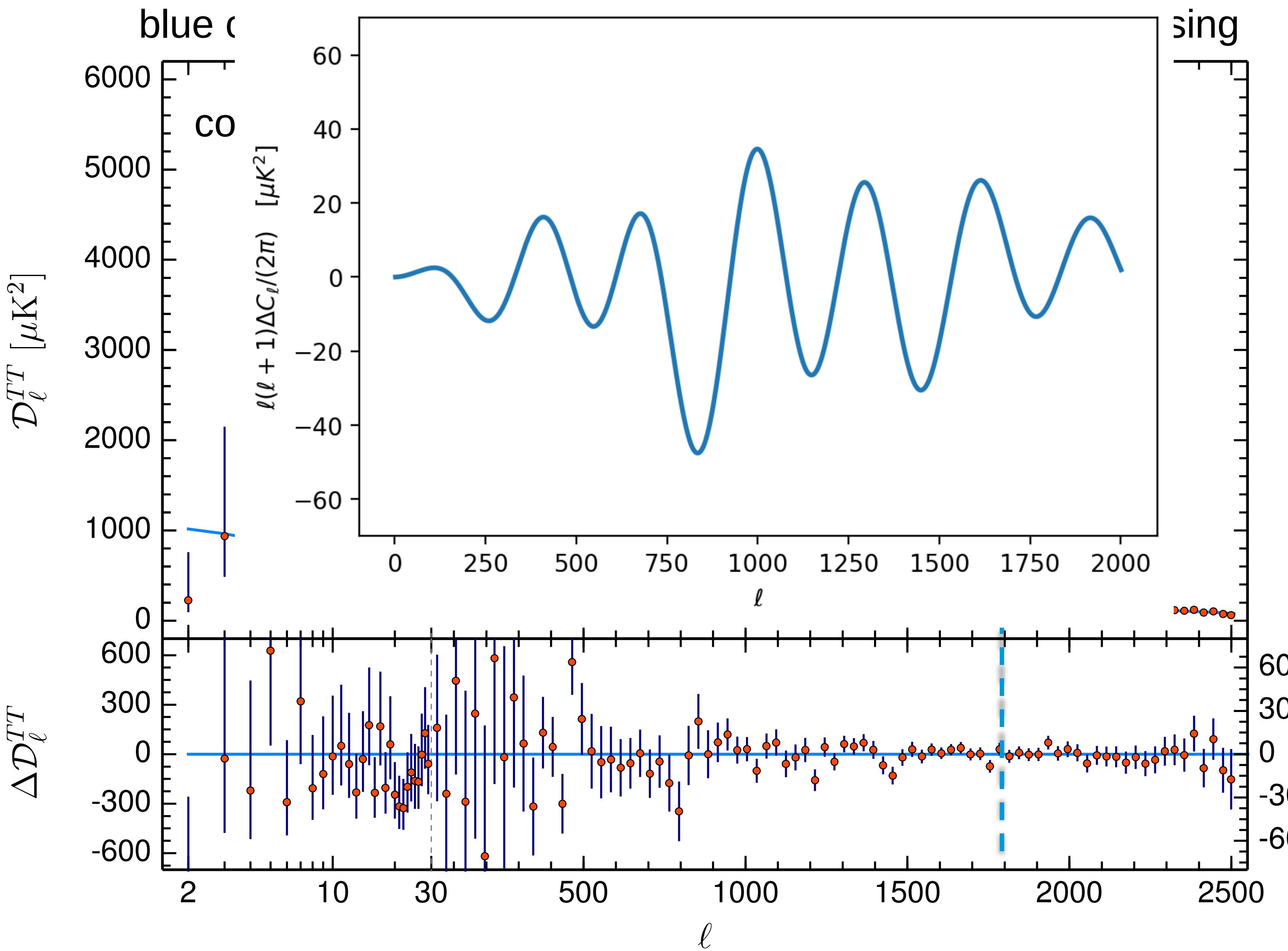
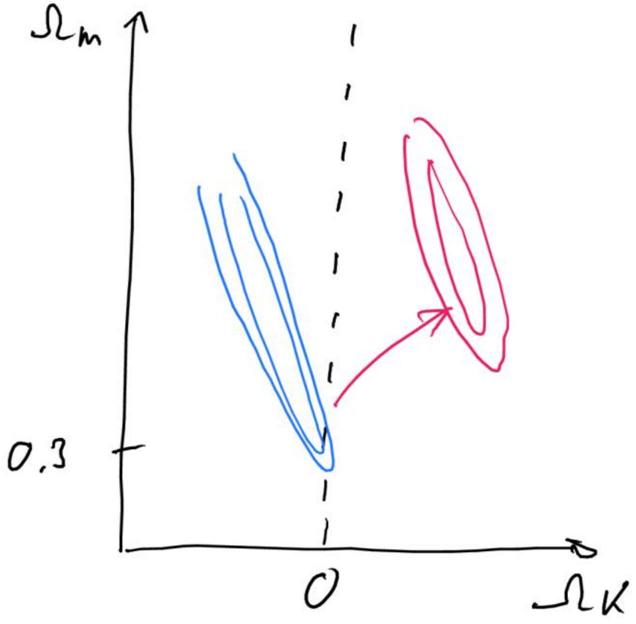
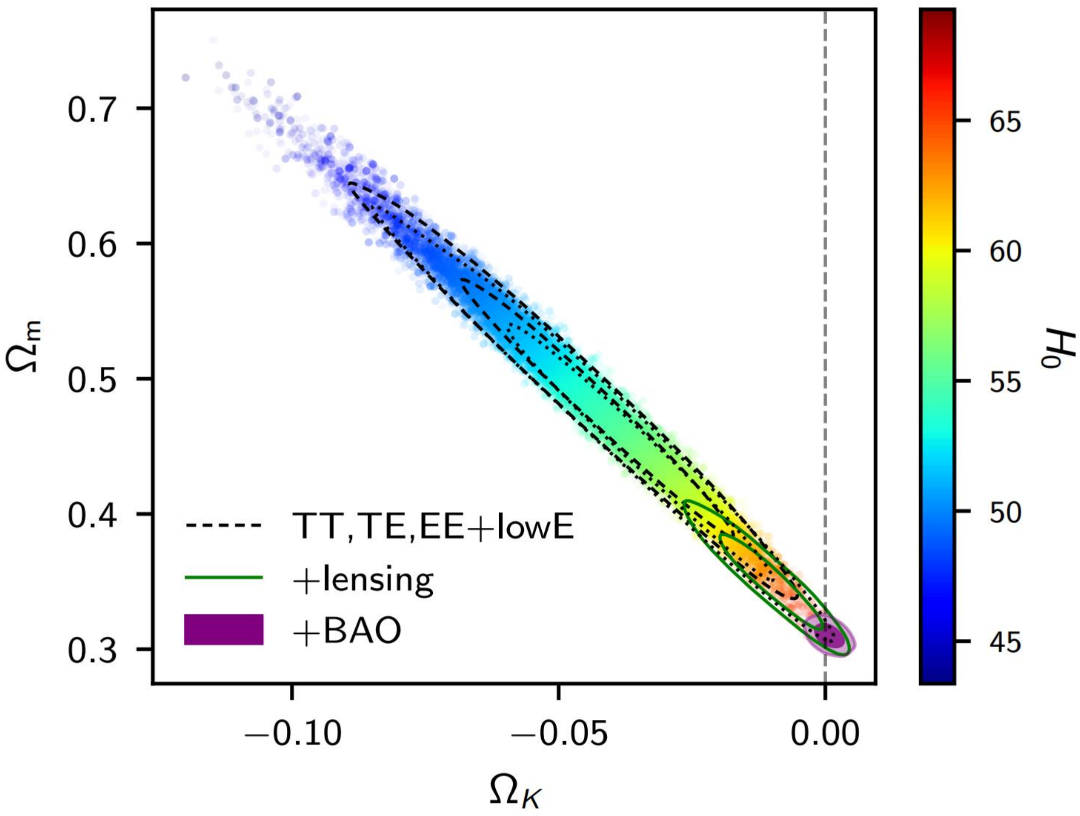


Lensing impact on CMB



Neglecting lensing in the CMB spectrum produces a horrible bias

Lensing also contains useful information!
(it constrains Ω_m)



Light propagation in GR

Introductory version for nearly-Newtonian fields (from my GR lectures ☺):

$$ds^2 = -(1+2\phi)dt^2 + (1-2\phi)d\mathbf{x}^2$$

Photon trajectory: $x^\mu(\lambda) = x^{(0)\mu}(\lambda) + x^{(1)\mu}(\lambda)$

background+deviation

background wave vector: $k^\mu = dx^{(0)\mu}/d\lambda$

derivative of deviation vector: $\ell^\mu = dx^{(1)\mu}/d\lambda$

geodesic eqn: $$\frac{d^2x^\mu}{d\lambda^2} + \Gamma^\mu_{\rho\sigma}\frac{dx^\rho}{d\lambda}\frac{dx^\sigma}{d\lambda} = 0 \longrightarrow \frac{d\ell^0}{d\lambda} = -2k(\mathbf{k}\cdot\nabla\phi)\,, \quad \frac{d\boldsymbol{\ell}}{d\lambda} = -2k^2\nabla_\perp\phi$$

deflection angle:
rotation of wave vector

$$\hat{\alpha} = -\frac{\Delta\boldsymbol{\ell}}{k}\,, \quad \Delta\boldsymbol{\ell} = \int\frac{d\boldsymbol{\ell}}{d\lambda}d\lambda = -2k^2\int\nabla_\perp\phi\,d\lambda \longrightarrow \hat{\alpha} = 2\int\nabla_\perp\phi\,ds$$

Shapiro time delay

$$\Delta t = \int\frac{dx^{(1)0}}{d\lambda}d\lambda = \int\ell^0 d\lambda = -2k\int\phi d\lambda \longrightarrow \Delta t = -2\int\phi ds$$

Light propagation in GR

Cosmological version (Yoo et al 2009, Bonvin & Durrer 2011, Challinor & Lewis 2011), here from arXiv:2007.04968 [Hassani, Adamek, MK]

apparent comoving 3D position:

$$\boldsymbol{s} = \chi_s \boldsymbol{n} + \underbrace{\frac{1}{H_s(\bar{z})}\delta z\, \boldsymbol{n}}_{\text{redshift perturbation}} - \underbrace{\int_0^{\chi_s} (\chi_s - \chi)\, \nabla_\perp (\Phi + \Psi) \mathrm{d}\chi}_{\text{weak gravitational lensing}} \underbrace{- \boldsymbol{n} \int_0^{\chi_s} (\Phi + \Psi) \mathrm{d}\chi}_{\text{Shapiro time delay}} ,$$

unperturbed position

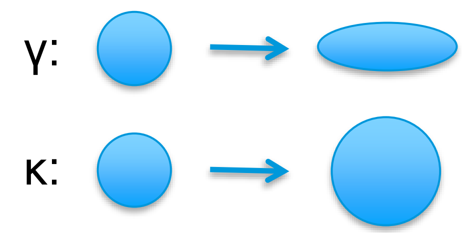
redshift perturbation:

$$\delta z = (1 + \bar{z}) \left[\underbrace{\boldsymbol{n} \cdot (\boldsymbol{v}_s - \boldsymbol{v}_o)}_{\text{Doppler}} + \underbrace{\Psi_o - \Psi_s}_{\substack{\text{gravitational} \\ \text{redshift}}} \underbrace{- \int_0^{\chi_s} \frac{\partial(\Psi + \Phi)}{\partial \tau} d\chi}_{\text{ISW-RS effect}} \right]$$

Light propagation in GR

Actually, we need to look a (small) light bundle to study magnification and shear

→ Jacobi map $\mathcal{A}_{ab} = \partial\theta_o^a / \partial\theta_s^b$



deformation: (amplification matrix)

$$\mathcal{A} = \begin{pmatrix} 1-\kappa-\gamma_1 & \omega-\gamma_2 \\ -\omega-\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

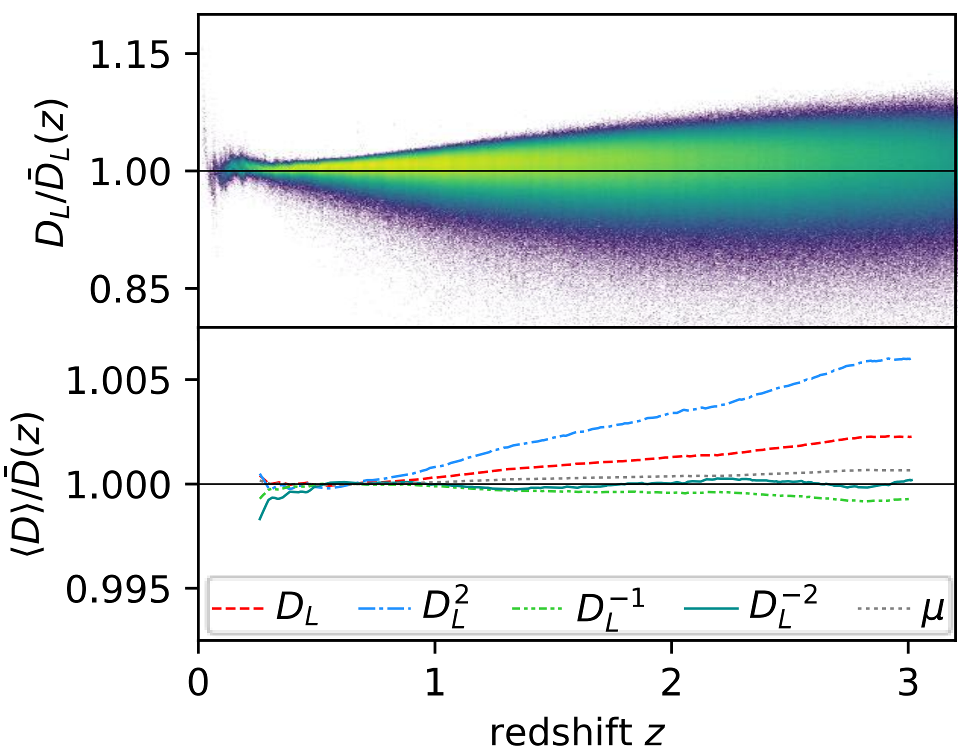
at leading order: $\mathcal{A} = \mathbb{1} + \left(\hat{\nabla}_a \hat{\nabla}_b \psi\right)$

lensing potential: $\psi(\boldsymbol{n}, z) \equiv -\int_0^{\chi_s} d\chi \frac{\chi_s - \chi}{\chi_s \chi} (\Phi + \Psi)$

magnification: $\kappa = -\frac{1}{2} \hat{\nabla}^2 \psi$

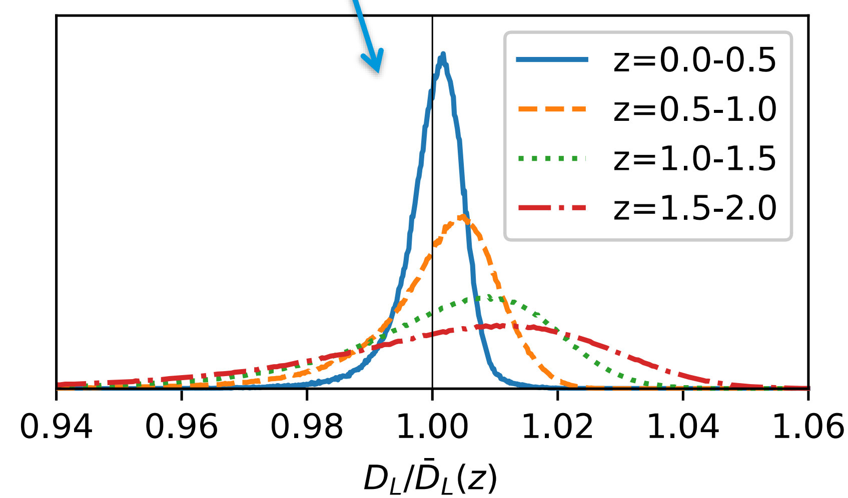
gevolution light-cone simulations (1812.04336, Adamek et al)

- relativistic N-body simulation from gevolution
- 4.5×10^{11} ‘particles’ in volume of $(2.4\ \mathrm{Gpc/h})^3$, $2.6\times10^{9}\ M_{\odot}/h$ per particle
- metric sampled on Cartesian 7680^3 grid [resolution 312.5 kpc/h]
- light-cone saved for circular 450 deg^2 beam to distance 4.5 Gpc/h
- ray-traced with exact GR Sachs equations for scalar sector (and leading order for vector sector, GW neglected)



distances for 11M halos

pdf (mostly lensing)



Impact on number counts

Lensing (shear) can be measured statistically through the correlation of galaxy shapes, but this includes also intrinsic alignments.

How else can we observe lensing? Nearly everywhere, as we saw, e.g. lensing (magnification) affects galaxy number counts in two ways

- It increases the size of the solid angle
- It increases the luminosity of galaxies

Together these two effects lead to:

slope of luminosity function

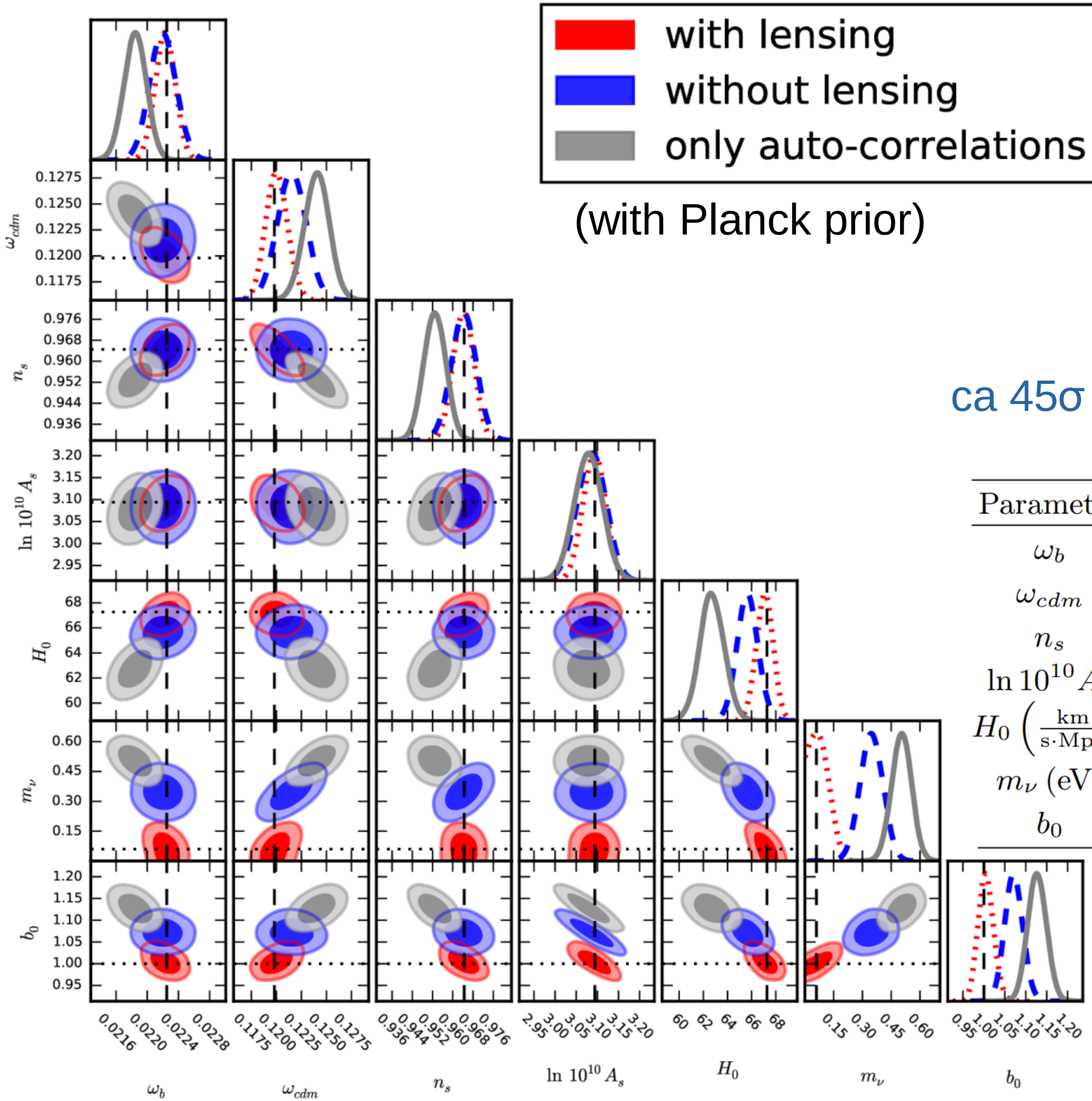
$$\Delta_g(\mathbf{n}, z) = b_g(z)\delta(\mathbf{n}, z) + (5s(z) - 2)\kappa(\mathbf{n}, z)$$

where s(z) encodes how magnified galaxies enter the sample, and is given by

$$5s(z, F_*) = 2 \left. \frac{\partial \log \bar{n}(z, L)}{\partial \log L} \right|_{L=L_*(z)}$$

For intensity measurements (like the CMB) the two effects cancel to first order (photon conservation), effectively s = 2/5

Is it important?



(with Planck prior)

arXiv:1603.06481 (Cardona, Durrer, MK, Montanari):

For Euclid-like photometric catalogue it appears to be indeed important!

ca 45σ lensing detection!

ii) Neglecting lensing: $\Delta\chi^2 = 2082$

Parameter	Mean	Best fit	σ	shift: Mean	Best fit
ω_b	0.02220	0.02219	0.00017	0.3σ	0.4σ
ω_{cdm}	0.1215	0.1214	0.0014	1.2σ	1.1σ
n_s	0.9643	0.9640	0.0049	$< 0.1\sigma$	0.1σ
$\ln 10^{10} A_s$	3.085	3.090	0.034	0.3σ	0.1σ
$H_0\left(\frac{\text{km}}{\text{s}\cdot\text{Mpc}}\right)$	65.66	65.64	0.87	1.8σ	1.9σ
m_ν (eV)	0.35	0.34	0.06	4.8σ	4.7σ
b_0	1.072	1.070	0.022	3.3σ	3.3σ

Updated Euclid forecast

(arXiv:2110.05435, Lepori et al [Euclid collaboration])

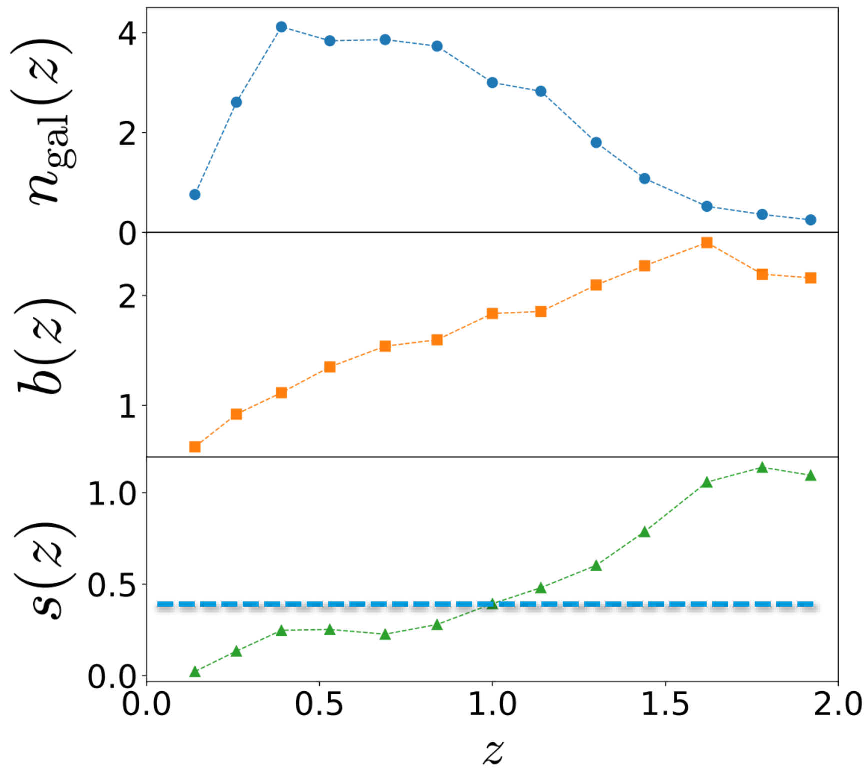
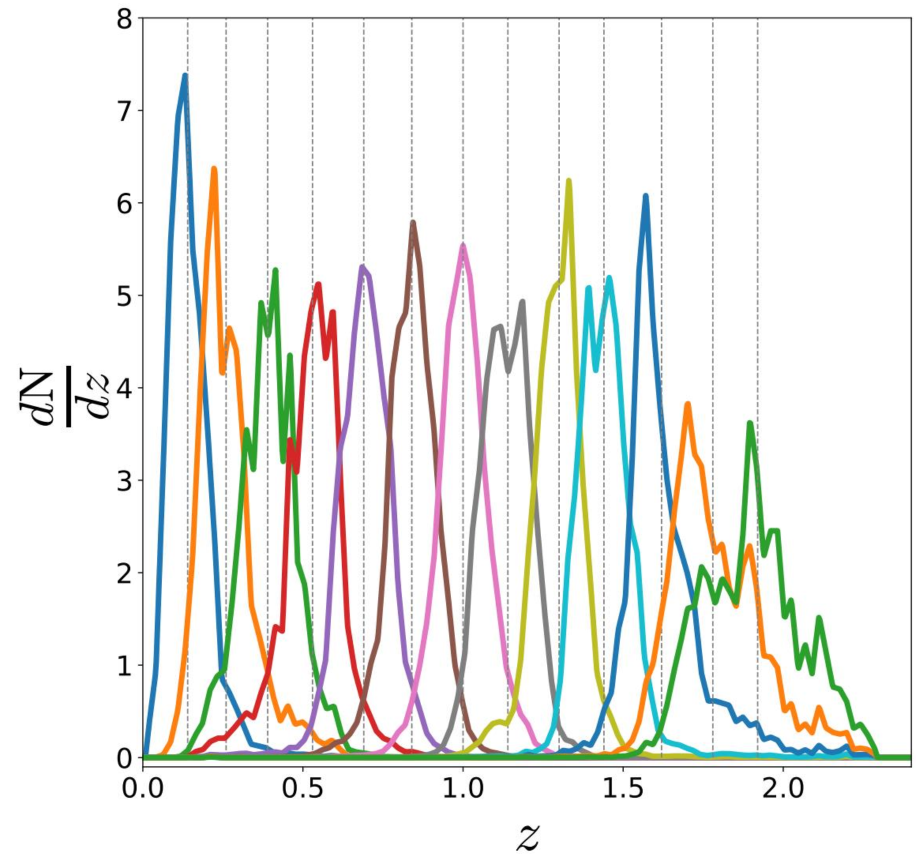
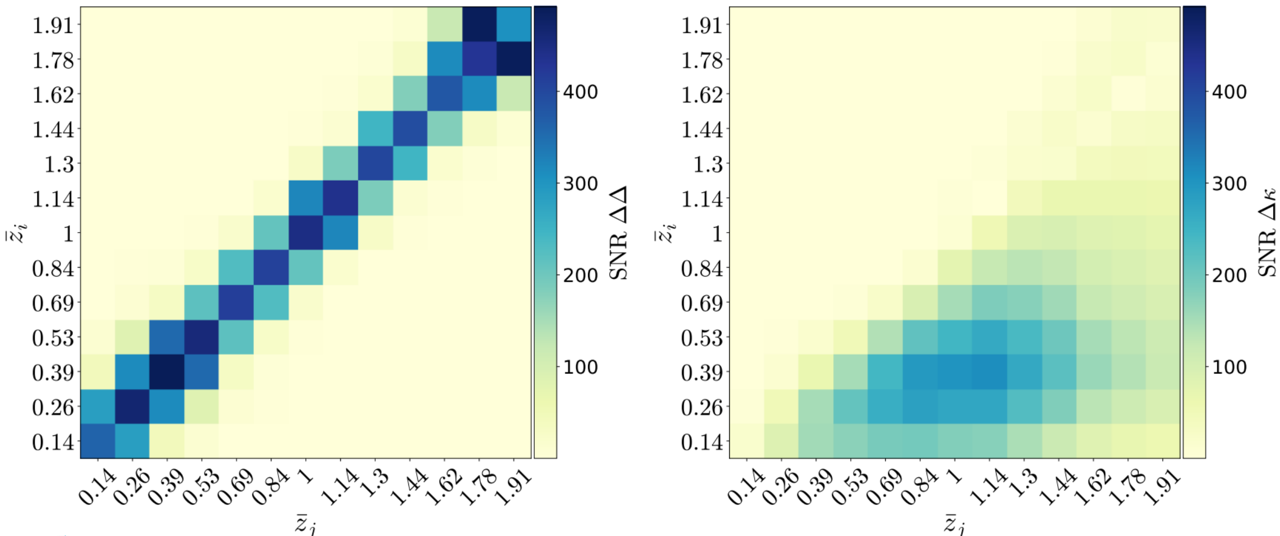


Fig. 4: The galaxy number density in units of gal/bin/arcmin^2 (top panel), galaxy bias (middle panel), and local count slope (bottom panel) as a function of redshift are shown. These results are obtained from the Flagship simulation. Note that at $z = 1$ we have $s \simeq 0.4$ so that $2 - 5s(z = 1) \simeq 0$. Hence the lensing term exactly cancels at this redshift. A simple fit for $b(z)$ and $s(z)$ is found in Appendix C.

Pessimistic scenario of arXiv:1910.09273 Blanchard et al, [Euclid collaboration], photometric data, using Flagship simulation

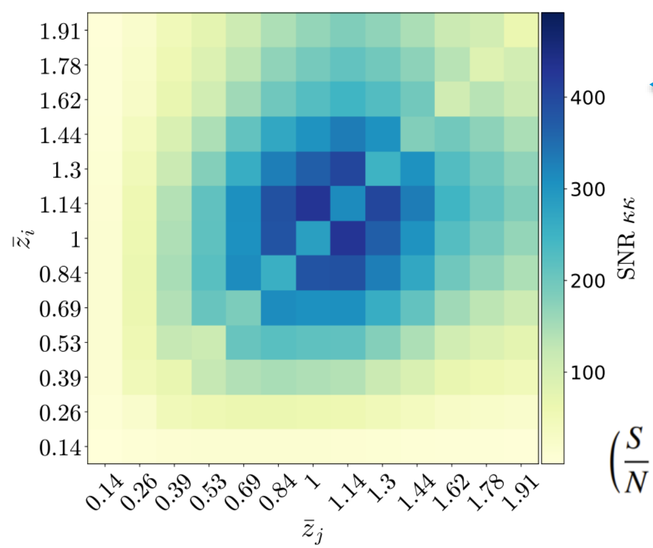


Signal in the observables



XC signal dominated by cosmic shear at intermediate redshifts and GCph at low redshifts

GCph signal is mostly on diagonal (i.e. $z_i = z_j$)



Cosmic shear signal is highest in cross-correlation of nearby bins at intermediate redshifts

$$\left(\frac{S}{N}\right)_{ij}^{AB} = \sqrt{\sum_{\ell=\ell_{\min}}^{\ell_{\max}} C_\ell^{AB}(i,j)\, \mathsf{C}^{-1}\left[C_\ell^{AB}(i,j), C_\ell^{AB}(i,j)\right] C_\ell^{AB}(i,j)}\,,$$

Fig. 5: SNR per bin neglecting lensing magnification for the observables: GCph (top left), GGL (top right), and WL (bottom). The index i refers to the ith redshift bin defined in Table 1. The SNR is computed from Eq. (43).

Signal in lensing magnification

Lensing magnification contributes to galaxy number counts:

→ in ΔΔ the magnification in a high-z (background) bin is correlated with density in a low-z foreground bin [also s=0.4 at z=1]; in Δκ the signal is from correlation of shear (mid-z) and magnification (high-z).

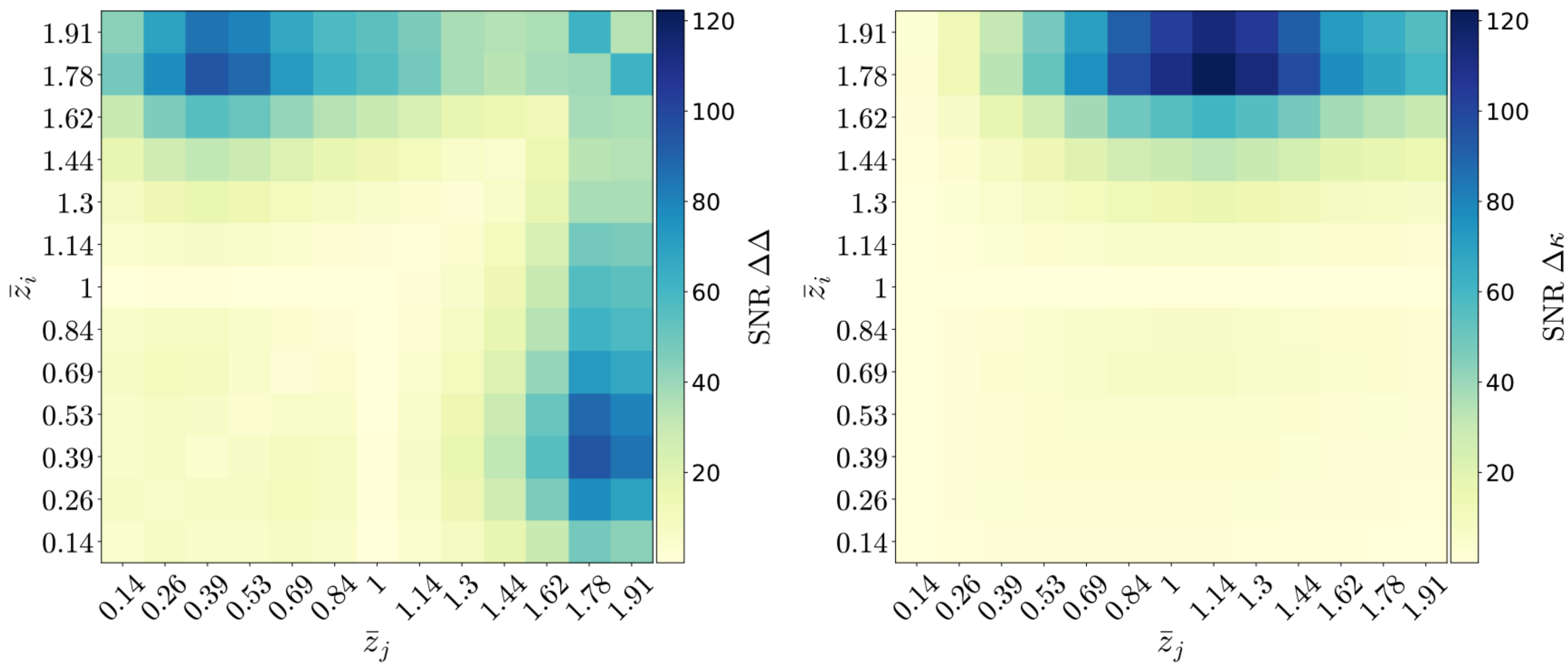
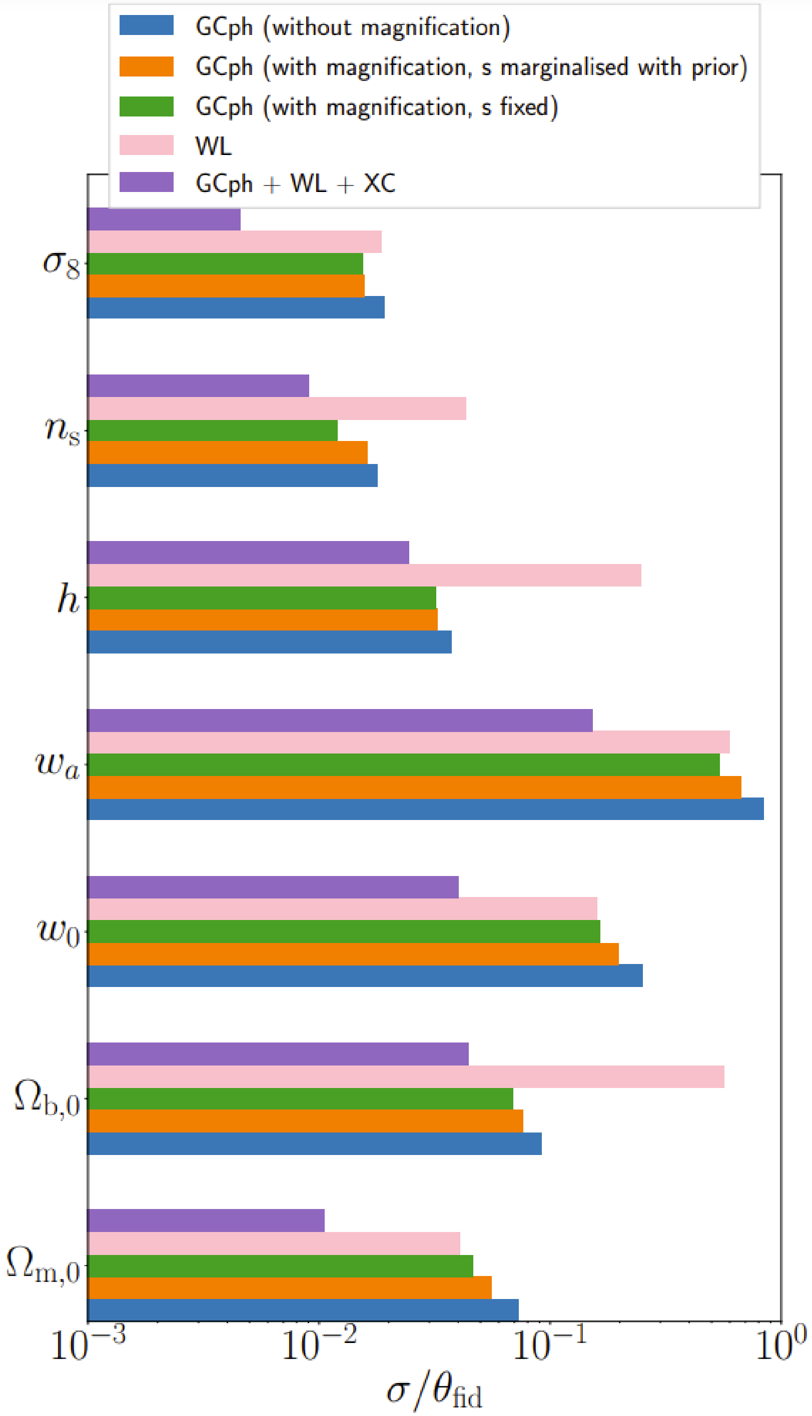


Fig. 6: SNR per bin from lensing magnification in the GCph (left panel) and GGL analysis (right panel).The index i refers to the ith redshift bin defined in Table 1. The SNR is computed from Eq. (44).

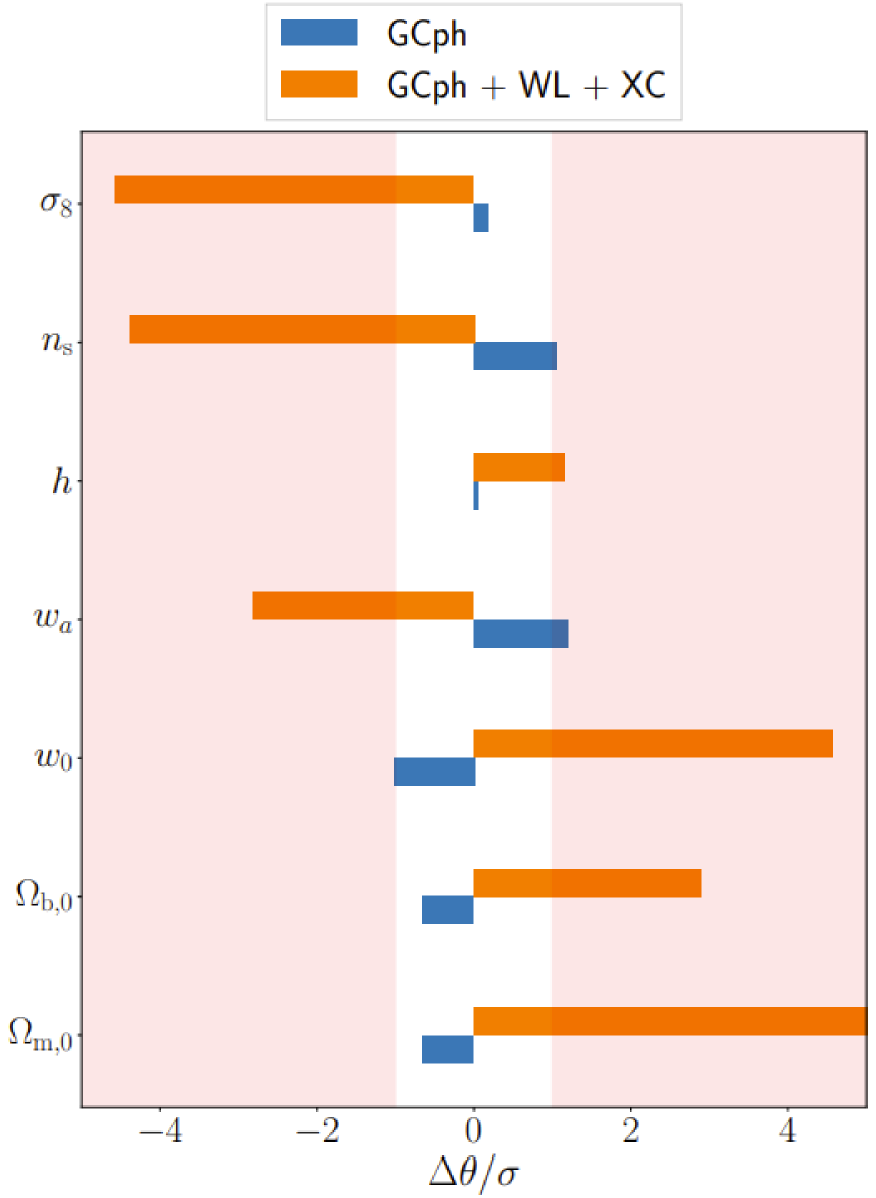
How much does magnification help?



Lensing magnification improves GCph measurements significantly.

For full probe combination (GCph + WL + XC), the additional information from lensing magnification is however small.

bias from lensing magnification



Parameter shift in Fisher-matrix formalism:

$$\Delta\theta_\alpha = \sum_\beta \left(\mathsf{F}^{-1}\right)_{\alpha\beta} B_\beta$$

$$B_\beta = \sum_{\ell=\ell_{\min}}^{\ell_{\max}} \sum_{\substack{ABCD\\ ij,mn}} \frac{\partial C_\ell^{AB}(i,j)}{\partial\theta_\beta} \mathsf{C}^{-1}\left[C_\ell^{AB}(i,j), C_\ell^{CD}(m,n)\right] \frac{\partial C_\ell^{CD}(m,n)}{\partial\epsilon_{\mathrm{L}}}$$

For large shifts (>1σ) this tends to be inaccurate, but indicates at least that the shift is large (could use MCMC)

Fig. 9: Shift in the best-fit estimation of cosmological parameters induced by neglecting magnification in our theoretical model. The values of the shift are expressed in units of the marginalised 1σ constraints. The blue histogram refers to the parameters estimated from the GCph alone analysis, while the orange histogram represent the shifts for the 3×2pt analysis GCph + WL + GGL. The red regions highlight shifts above 1σ in absolute value. The values of the shifts computed with the Fisher formalism cannot be trusted quantitatively in this region.

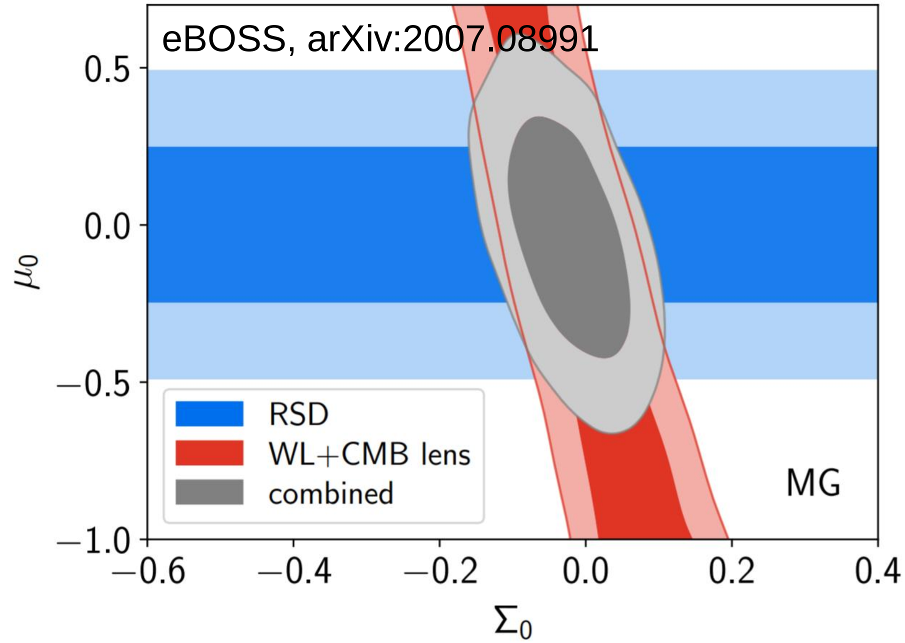
Why do we want to know the lensing potential?

Modifications of gravity or additional (dark energy) fluids change the link between matter and the gravitational potentials.

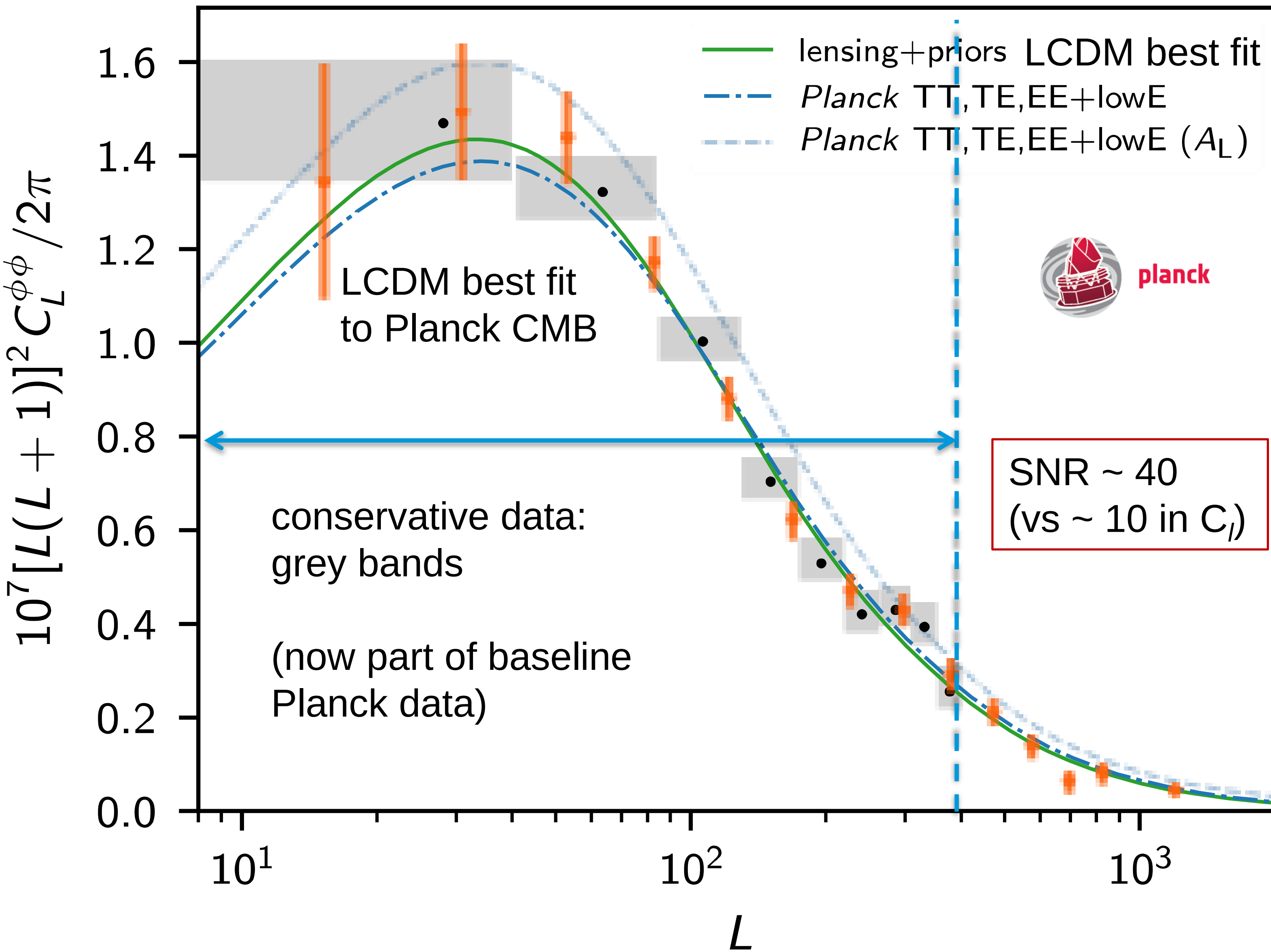
$$-k^2\Psi \equiv 4\pi G a^2 \mu(a,k)\rho(a)\delta(a,k) \qquad \text{RSD}$$

$$-k^2(\Phi+\Psi) \equiv 8\pi G a^2 \Sigma(a,k)\rho(a)\delta(a,k) \qquad \text{lensing/magnification}$$

- Clear complementarity between RSD and lensing measurements
- Current data:
  - ca 0.25 in μ
  - ca 0.05 in Σ (for cosmic shear + CMB lensing)



CMB lensing



lensing+priors LCDM best fit
Planck TT,TE,EE+lowE
Planck TT,TE,EE+lowE (A_L)
LCDM best fit
to Planck CMB
conservative data:
grey bands
(now part of baseline
Planck data)
SNR ~ 40
(vs ~ 10 in C_l)
planck
$10^7[L(L+1)]^2 C_L^{\phi\phi}/2\pi$
L

arXiv:2201.04129

Lensing 'CMB-style'

The presence of the foreground metric perturbation breaks statistical isotropy of the observations and creates inter-ell correlations.

This can be extracted with a quadratic estimator:

- Assume lensing potential is fixed (to a specific realization)
- Average only over background source (CMB or IM or … galaxies)

$$X(\boldsymbol{\ell}, z) = \tilde{X}(\boldsymbol{\ell}, z) + g(\ell, z)\phi(\boldsymbol{\ell}) + \underbrace{\int \frac{d^2\ell'}{2\pi} K_X(\boldsymbol{\ell}', \boldsymbol{\ell}, z)\tilde{X}(\boldsymbol{\ell}', z)\phi(\boldsymbol{\ell} - \boldsymbol{\ell}')}_{\text{modulation and re-mapping}} + \mathcal{O}(\phi^2)$$

g = $-\ell^2(1-5s/2)$, CMB / radio IM: *g* = 0

$$\langle X(\boldsymbol{\ell}) X(\mathbf{L} - \boldsymbol{\ell})\rangle_\phi = \frac{1}{2\pi} f_X(\boldsymbol{\ell}, \mathbf{L} - \boldsymbol{\ell})\phi(\mathbf{L})$$

(L≠0) normally this would vanish

estimator: $$\phi_X(\mathbf{L}, z) = A(L, z) N_X(L, z) \int \frac{d^2\ell}{2\pi} X(\boldsymbol{\ell}, z) X(\mathbf{L} - \boldsymbol{\ell}, z) F_X(\boldsymbol{\ell}, \mathbf{L} - \boldsymbol{\ell}, z) + $$
$$+ (1 - A(L, z))\frac{X(\mathbf{L}, z)}{g(L, z)}$$

$$\longrightarrow \quad \langle \phi_X(\mathbf{L})\rangle_\phi = \phi(\mathbf{L})$$

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$$\boxed{\Delta_g = \tilde{\Delta}_g - (2-5s)\kappa - (2-5s)\kappa\tilde{\Delta}_g + \nabla^a\phi\nabla_a\tilde{\Delta}_g}$$

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modulation and re-mapping

$$\langle X(\boldsymbol{\ell})X(\mathbf{L}-\boldsymbol{\ell})\rangle_\phi = \frac{1}{2\pi} f_X(\boldsymbol{\ell}, \mathbf{L}-\boldsymbol{\ell})\phi(\mathbf{L})$$

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$g = -\ell^2(1-5s/2)$, CMB / radio IM: $g = 0$

$$\boxed{K_\Delta(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2, z) = -\left(1 - \frac{5}{2}s(z)\right)(\boldsymbol{\ell}_2 - \boldsymbol{\ell}_1)^2 - \boldsymbol{\ell}_1\cdot(\boldsymbol{\ell}_2 - \boldsymbol{\ell}_1)}$$ anish

estimator: $$\phi_X(\mathbf{L}, z) = A(L, z)N_X(L, z)\int \frac{d^2\ell}{2\pi} X(\boldsymbol{\ell}, z)X(\mathbf{L}-\boldsymbol{\ell}, z)F_X(\boldsymbol{\ell}, \mathbf{L}-\boldsymbol{\ell}, z) + (1 - A(L, z))\frac{X(\mathbf{L}, z)}{g(L, z)}$$

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g = -ℓ^2(1-5s/2), CMB / radio IM: g = 0

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(L≠0) normally this would vanish

$$\boxed{f_X(\boldsymbol{\ell}_1, \boldsymbol{\ell}_2, z) = K_X(-\boldsymbol{\ell}_1, \boldsymbol{\ell}_2, z)\tilde{C}_{\ell_1}(z) + K_X(-\boldsymbol{\ell}_2, \boldsymbol{\ell}_1, z)\tilde{C}_{\ell_2}(z)}$$

$$+(1 - A(L, z))\frac{X(\mathbf{L}, z)}{g(L, z)}$$

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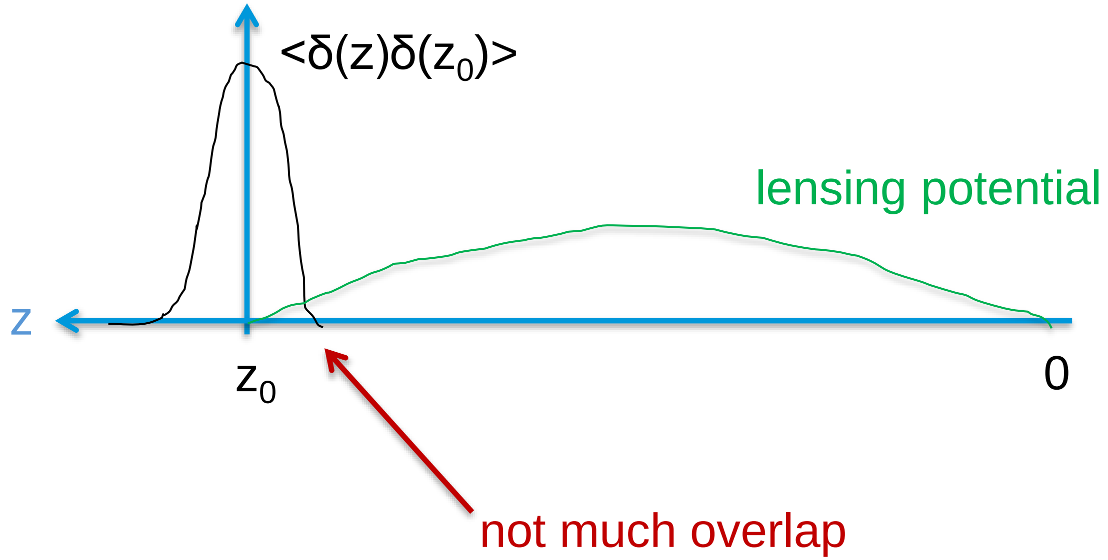
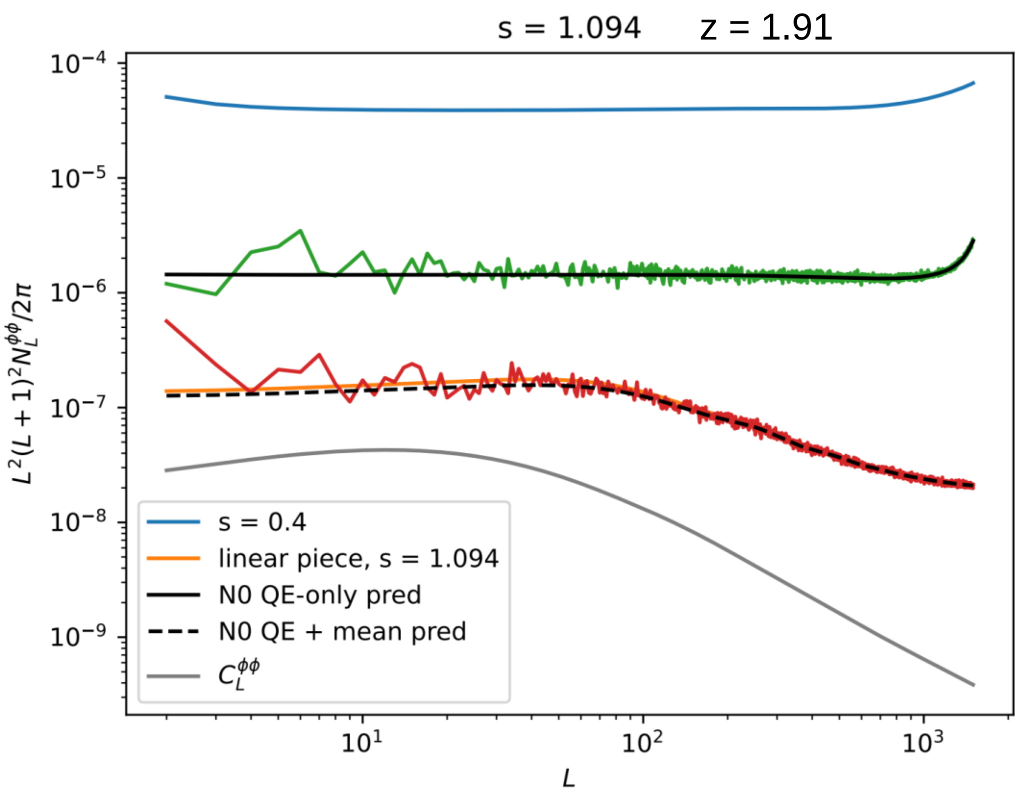
Correlations?

Is it justified to vary the density separately from the lensing potential?
Actually, even for large-scale structure it is!



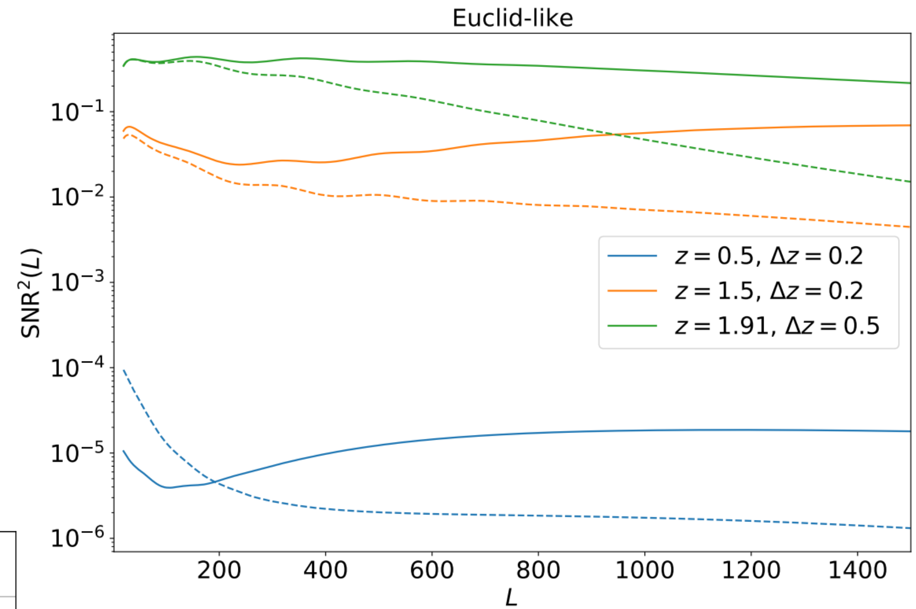
Detectability of lensing

Power spectrum of lensing potential vs variance of estimator:



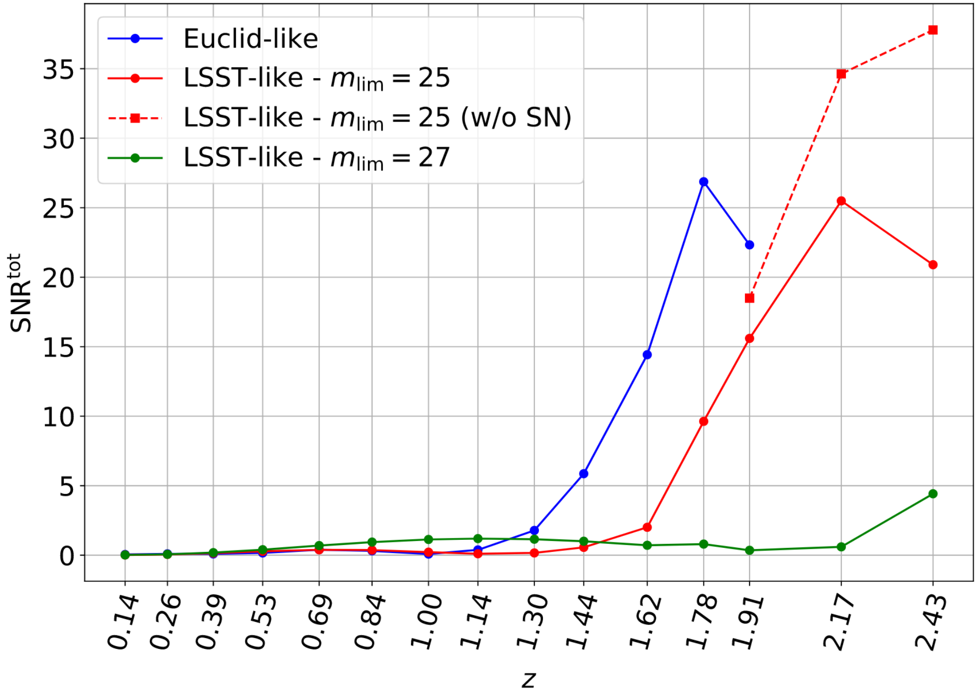
- s=0.4 (blue) is w/o linear term [~IM/CMB], signal is small-ish
- First-order term in number counts enhances QE signal by over an order of magnitude (black/green) [SNR ~ 2 in this bin]
- Linear term (red/yellow/dashed) increases signal further [SNR ~ 20]

Where is the signal?



Scale dependence:

- Fairly constant as a function of L
- So going to higher L increases SNR
- Non-linearities enter already at very low L!



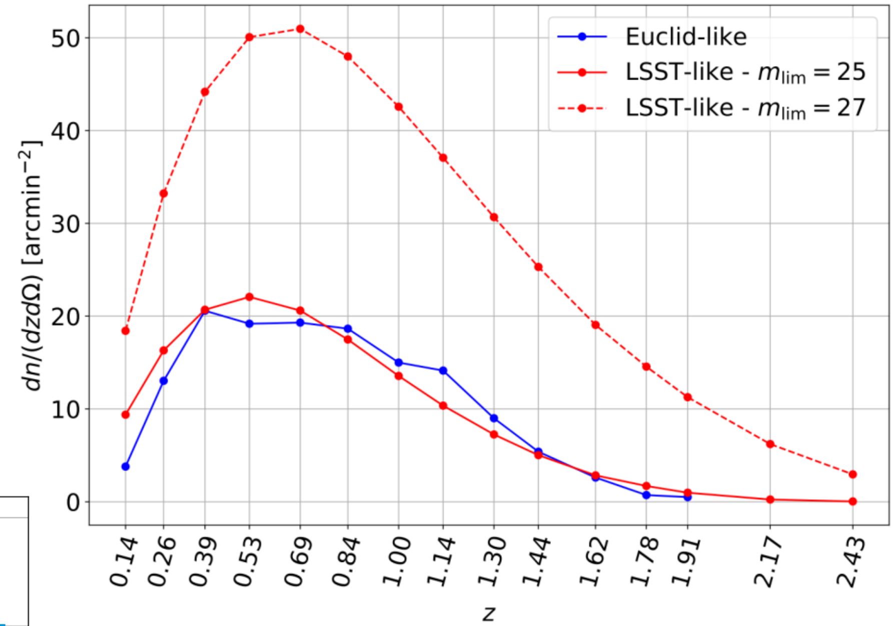
Redshift dependence:

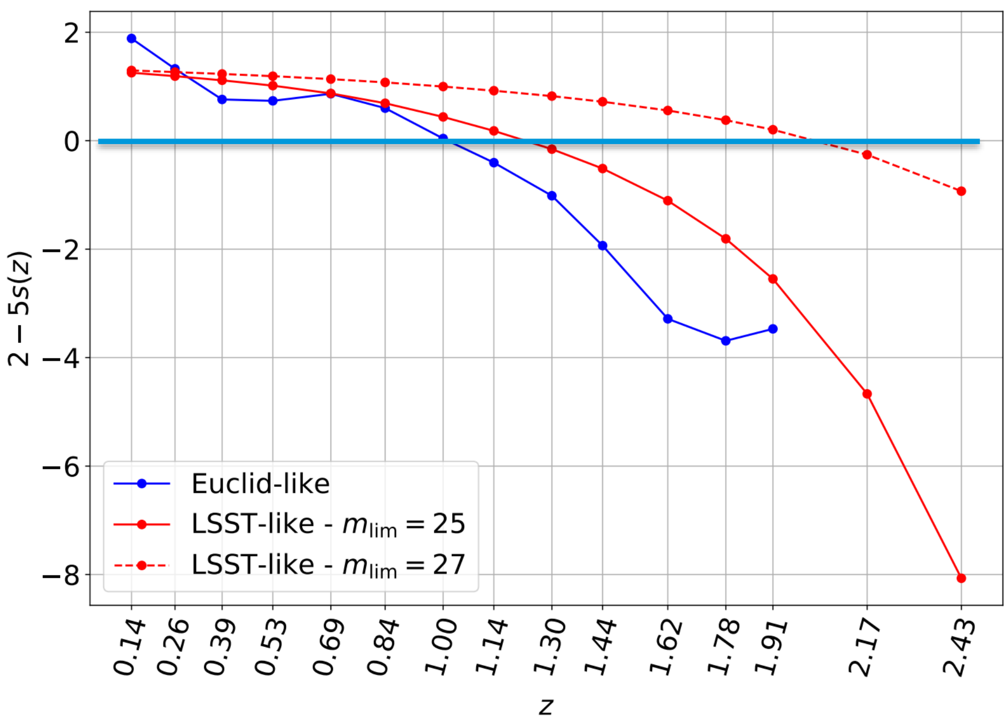
- Signal peaks strongly at high z, before being cut-off by shot noise
- Total SNR ~ 37
- We expect the lensing signal to increase with redshift – but so much?
- And what happed to LSST m_{lim} 27?

Survey properties

Galaxy density:

- At high redshift, we run out of galaxies and shot noise grows …
- … LSST can go deeper than Euclid, and so has more galaxies … but …



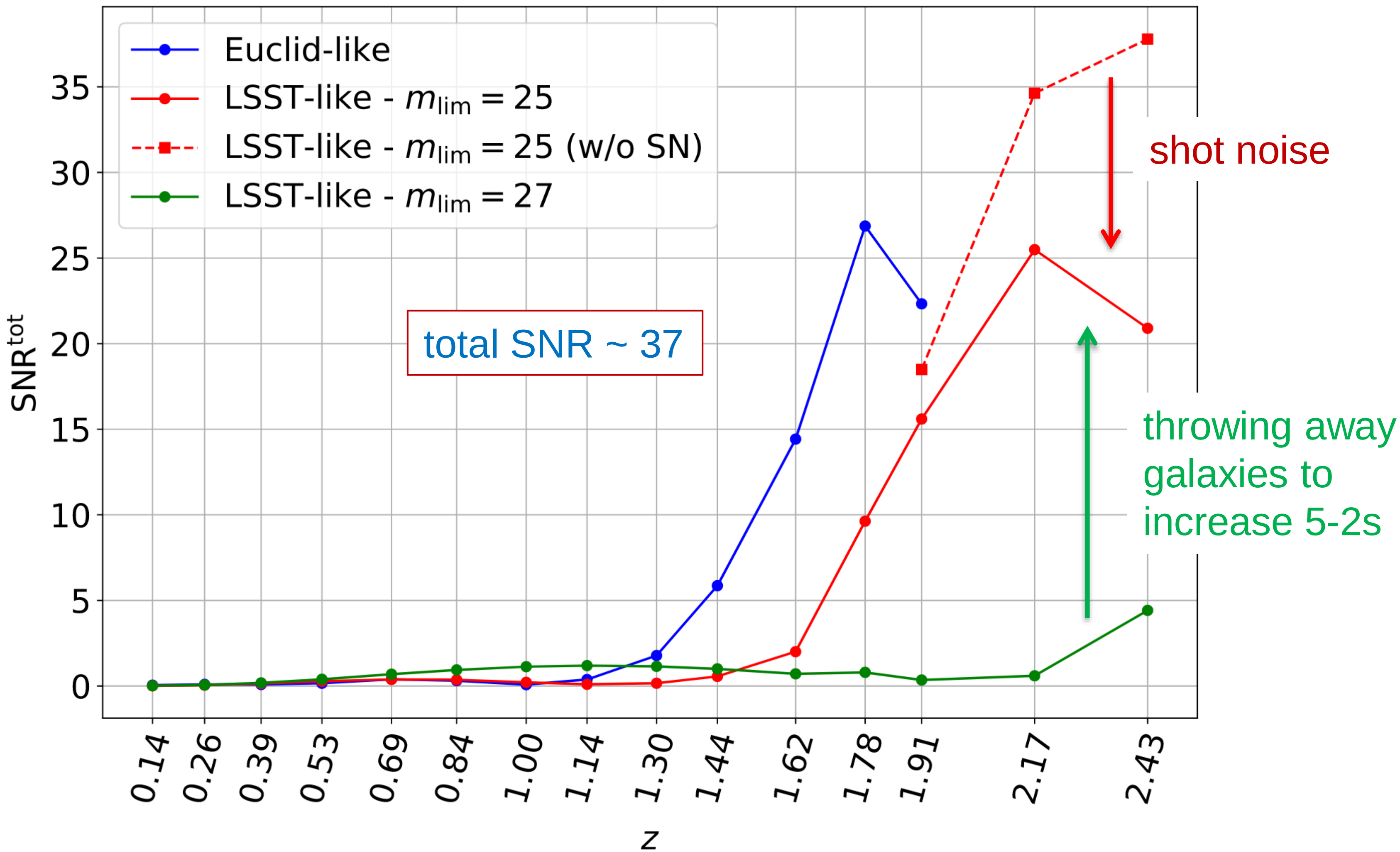


Magnification bias:

- … if s ~ 2/5 then the linear term is suppressed, and SNR is small.
- It can even be better to reduce galaxy density and accept bigger shot noise to avoid 2 – 5s ~ 0

High-z SNR enhancement driven by higher z and s

Where is the signal?



What about IM? GIMCO!

Intensity mapping has no first order magnification
→ IM x GC – GC x IM can isolate the magnification

$$E_\ell^\times \equiv \langle \hat{E}_\ell^\times \rangle = \boxed{\frac{1}{2} b_{\rm HI}(z_f)(2 - 5s(z_b)) C_\ell^{\delta\phi}(z_f, z_b)}$$
$$\cancel{- \frac{1}{2} b_{\rm HI}(z_b)(2 - 5s(z_f)) C_\ell^{\phi\delta}(z_f, z_b)}$$
$$+ \left[b_{\rm HI}(z_f) b_g(z_b) - b_g(z_f) b_{\rm HI}(z_b) \right] C_\ell^{\delta\delta}(z_f, z_b)$$

- Density-density contribution suppressed by bias difference in addition to decay with redshift separation
  - This allows to use closer redshift pairs
  - The covariance is dominated by equal-z density-density, which is also reduced by the bias difference (squared)
  - ~ 5x higher SNR at z < 1.6
- Only cross-correlations, robust to survey systematics
- GIMCO does not have a ϕϕ term, only measures ϕδ
  - 'pure' ☺ but less sensitive at high redshift

arXiv:1907.00071

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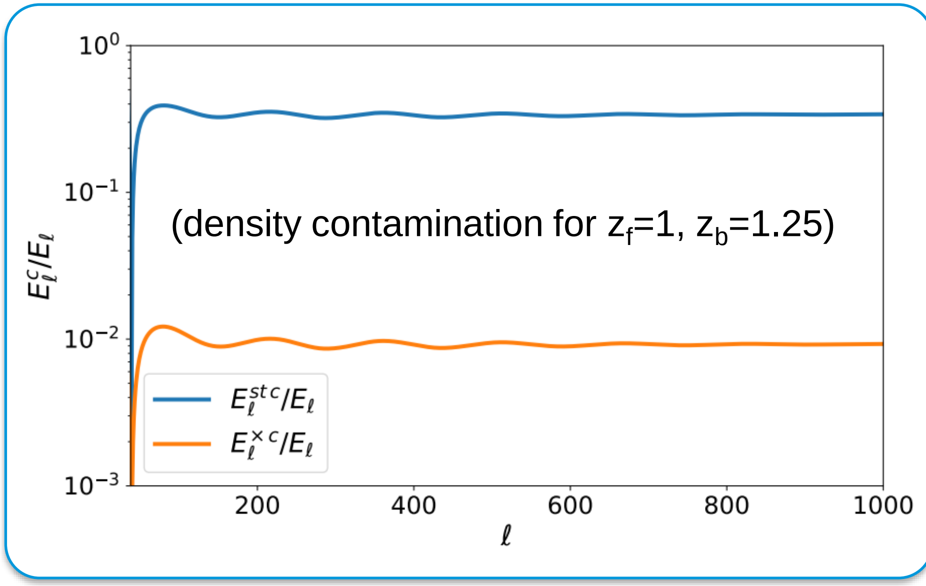

t order magnification
plate the magnification

$$- 5s(z_b))C_\ell^{\delta\phi}(z_f, z_b)$$

$$)\cancel{C_\ell^{\phi\delta}(z_f, z_b)}$$

$$z_f)b_{\mathrm{HI}}(z_b)]C_\ell^{\delta\delta}(z_f, z_b)$$

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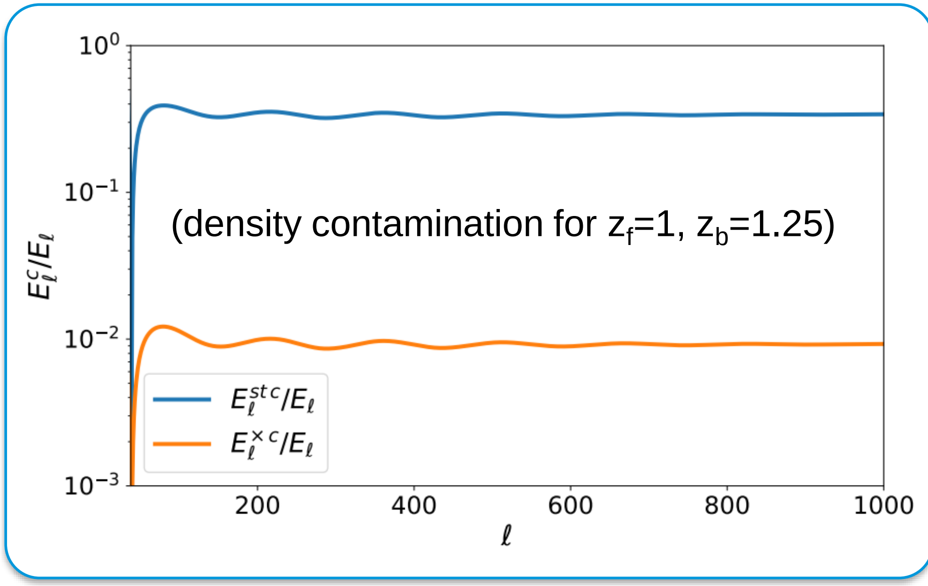

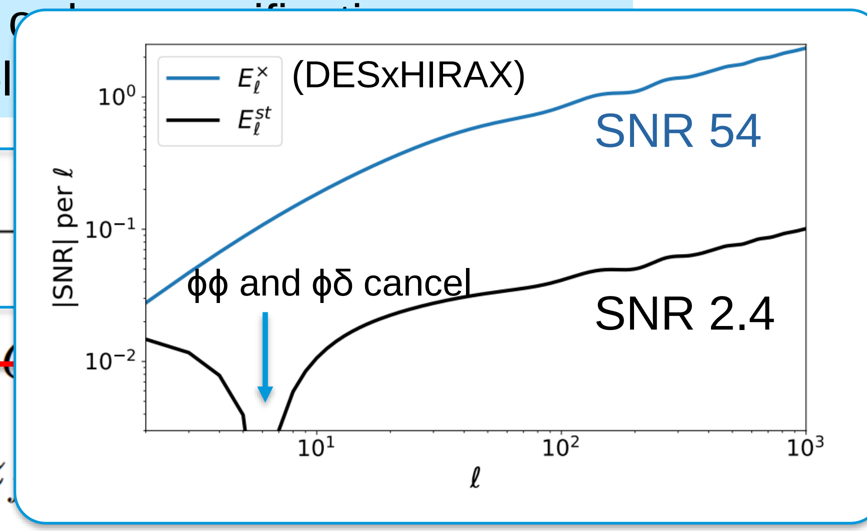

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Summary & conclusions

- All light that we observe has to traverse a clumpy universe (also GW)
- This necessarily affects ***all*** our observations
- If we neglect it then we can bias our results
  - CMB surveys take it into account
  - Future photometric galaxy surveys definitely cannot neglect it
  - (Intensity mapping surveys probably can neglect it until SKA2, arXiv:1807.01351)
- Including it adds new information on the lensing potential
- We can use this to test gravity on large scales and check for biases in other lensing observations! (What's not to like? ☺)
- Different ways to isolate lensing/magnification in LSS surveys, e.g.
  - "Quadratic" estimators for galaxy surveys to obtain ϕ map
  - Galaxy – IM cross-correlation (GIMCO) for $\phi\delta$ spectrum