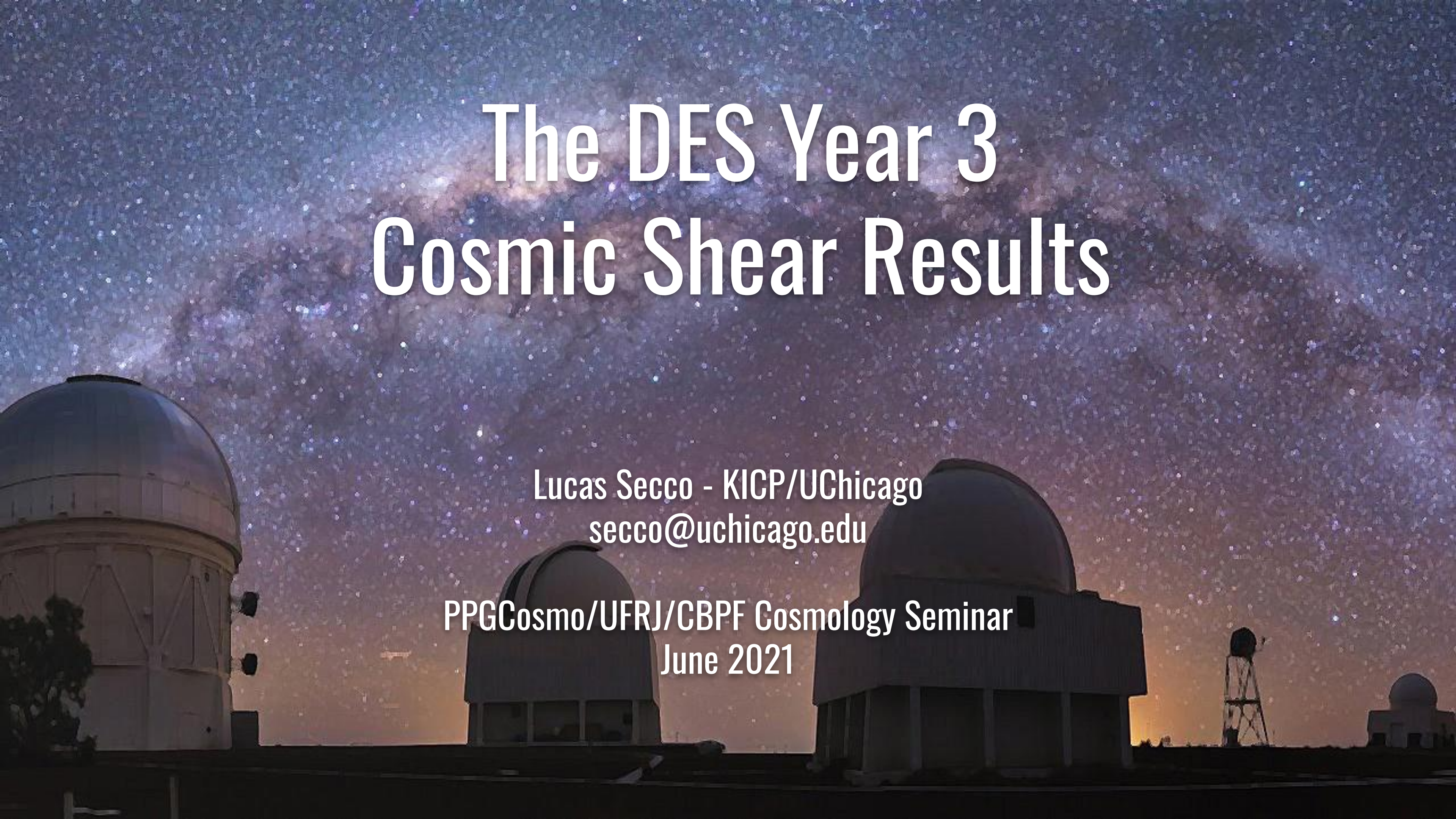
The DES Year 3 Cosmic Shear Results



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PPGCosmo/UFRJ/CBPF Cosmology Seminar
June 2021

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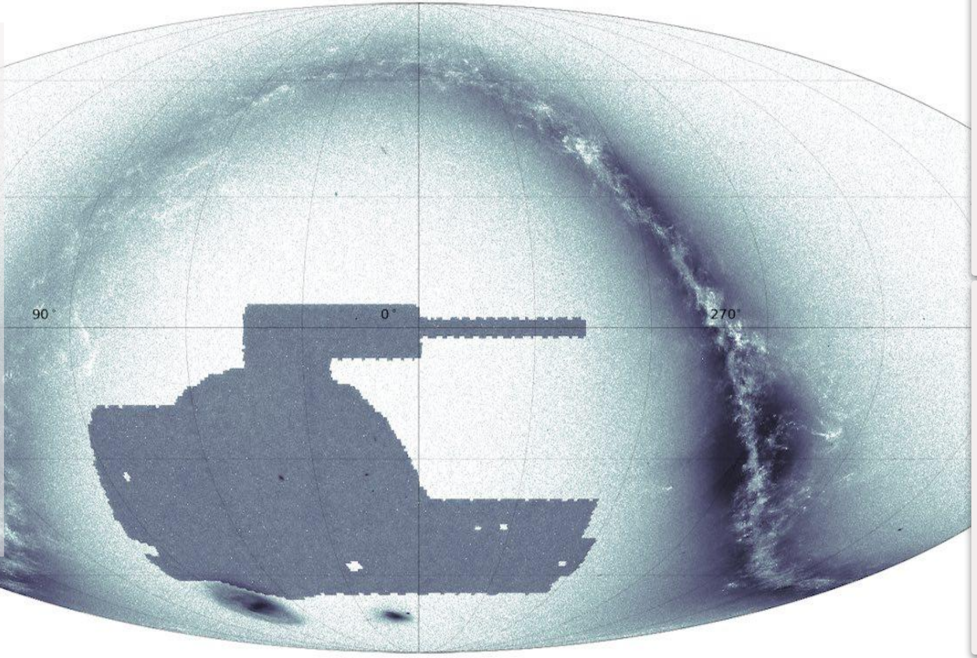
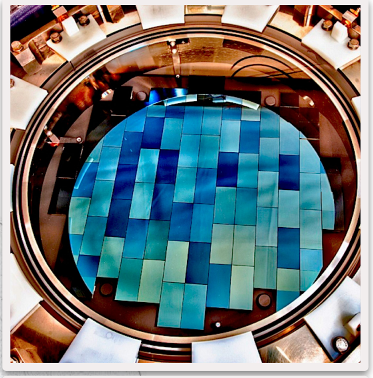
The Dark Energy Survey (DES)

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Full survey 2013-2019 (Y3 2013-16).
- **Wide field:** 5000 sq. deg. in 5 bands. ~23 magnitude.
- DES Y3: Positions and shapes of > **100M** galaxies.
- 100+ people, mainly Early Career Scientists





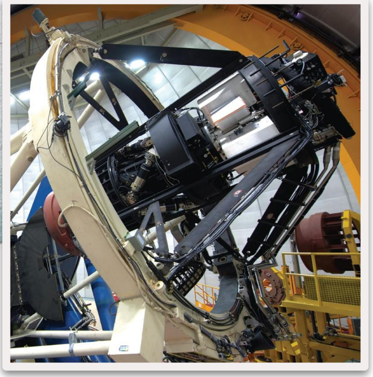


Image Credit: CosmoHub, Port d'Informació Científica (PIC)

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Dark Energy Survey Year 3 results. List of key and supporting papers

1. “Blinding Multi-probe Cosmological Experiments” J. Muir, G. M. Bernstein, D. Huterer et al., arXiv: 1911.05929, MNRAS **494** (2020) 4454
2. “Photometric Data Set for Cosmology”, I. Sevilla-Noarbe, K. Bechtol, M. Carrasco Kind et al., arXiv:2011.03407, ApJS **254** (2021) 24
3. “Weak Lensing Shape Catalogue”, M. Gatti, E. Sheldon, A. Amon et al., arXiv:2011.03408, MNRAS **504** (2021) 4312
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5. “Measuring the Survey Transfer Function with Balrog”, S. Everett, B. Yanny, N. Kuropatkin et al., arXiv:2012.12825
6. “Deep Field Optical + Near-Infrared Images and Catalogue”, W. Hartley, A. Choi, A. Amon et al., arXiv:2012.12824
7. “Blending Shear and Redshift Biases in Image Simulations”, N. MacCrann, M. R. Becker, J. McCullough et al., arXiv:2012.08567
8. “Redshift Calibration of the Weak Lensing Source Galaxies”, J. Myles, A. Alarcon, A. Amon et al., arXiv:2012.08566
9. “Redshift Calibration of the MagLim Lens Sample using Self-Organizing Maps and Clustering Redshifts”, G. Giannini et al., in prep.
10. “Clustering Redshifts – Calibration of the Weak Lensing Source Redshift Distributions with redMaGiC and BOSS/eBOSS”, M. Gatti, G. Giannini, et al., arXiv:2012.08569
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13. “Marginalising over Redshift Distribution Uncertainty in Weak Lensing Experiments”, J. Cordero, I. Harrison et al., in prep.
14. “Exploiting Small-Scale Information using Lensing Ratios”, C. Sánchez, J. Prat et al., in prep.
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16. “Unbiased fast sampling of cosmological posterior distributions”, P. Lemos, R. Rollins, N. Weaverdyck, A. Ferte, A. Liddle et al., in prep.
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18. “Dark Energy Survey Internal Consistency Tests of the Joint Cosmological Probe Analysis with Posterior Predictive Distributions”, C. Doux, E. Baxter, P. Lemos et al. arXiv:2011.03410, MNRAS **503** (2021) 2688
19. “Covariance Modelling and its Impact on Parameter Estimation and Quality of Fit”, O. Friedrich, F. Andrade-Oliveira, H. Camacho et al., arXiv:2012.08568
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22. “Galaxy Clustering and Systematics Treatment for Lens Galaxy Samples”, M.Rodríguez-Monroy, N. Weaverdyck, J. Elvin-Poole, M. Crocce et al., in prep.
23. “Optimizing the Lens Sample in Combined Galaxy Clustering and Galaxy-Galaxy Lensing Analysis”, A. Porredon, M. Crocce et al., arXiv:2011.03411 PhRvD **103** (2021) 043503
24. “High-Precision Measurement and Modeling of Galaxy-Galaxy Lensing”, J. Prat, J. Blazek, C. Sánchez et al., in prep.
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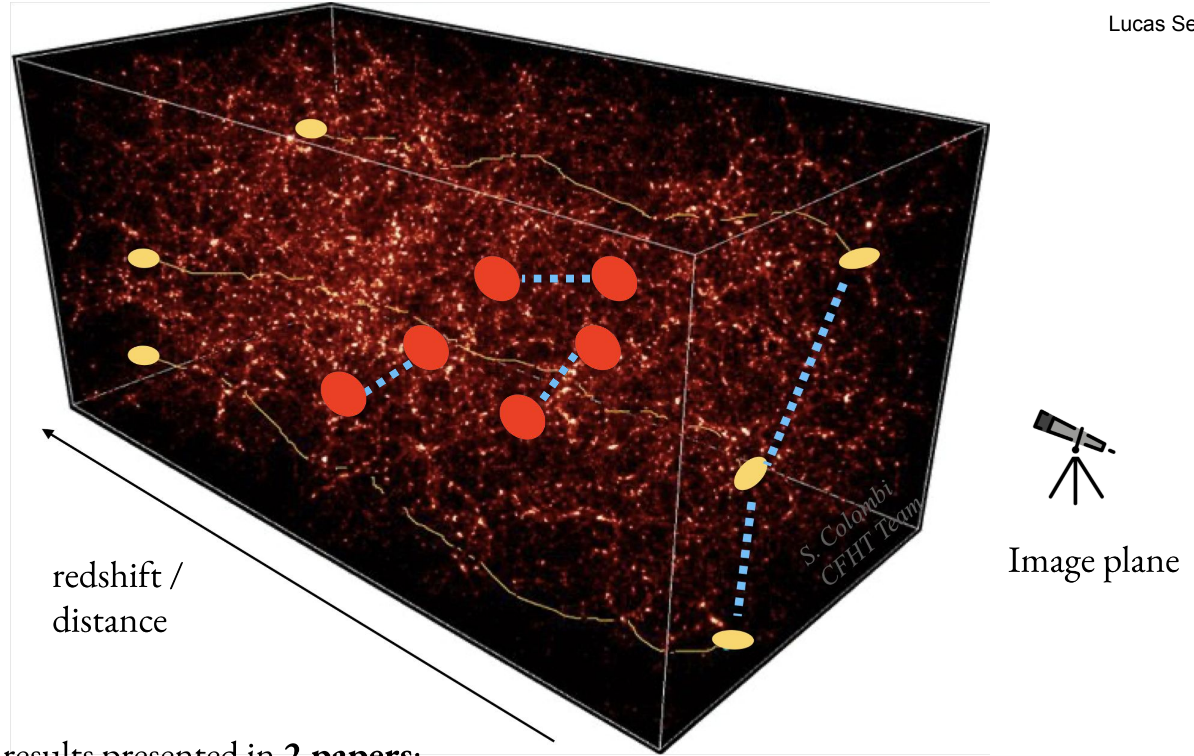
Cosmic Shear:

Correlated distortions on the shapes of galaxies as their light travels across the LSS.

In DES Y3: detection rejects the null hypothesis at >40sigma

(S/N~30 after scale cuts)



Main cosmic shear cosmology results presented in **2 papers**:

"Cosmology from Cosmic Shear and Robustness to Data Calibration" - Amon et al 2021 **(arXiv:2105.13543)**

"Cosmology from Cosmic Shear and Robustness to Modeling Uncertainty"
Secco, Samuroff, Krause, Jain, Blazek et al 2021 **(arXiv:2105.13544)**

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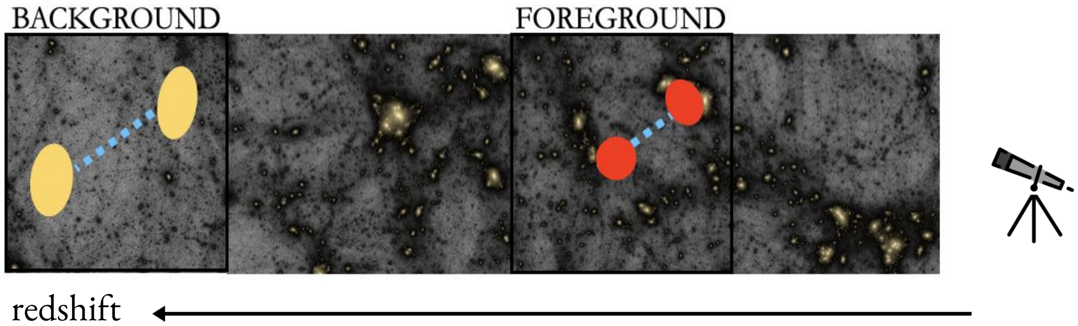
The main goal of DES Y3: *3x2pt* cosmology with self-calibration power

Cosmic Shear : shape-shape  (Sensitive to shear errors squared)

2x2pt

Galaxy Clustering : position-position  (Sensitive to galaxy bias squared)

Galaxy-Galaxy Lensing : position-shape  (Sensitive to galaxy bias times shear error)



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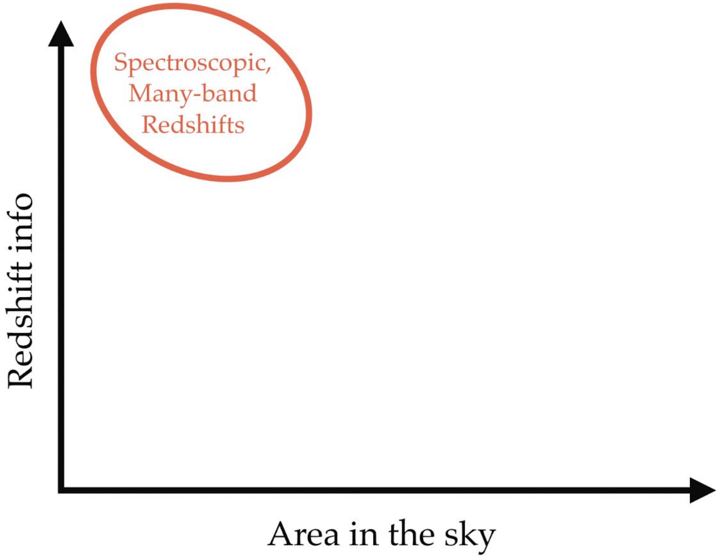
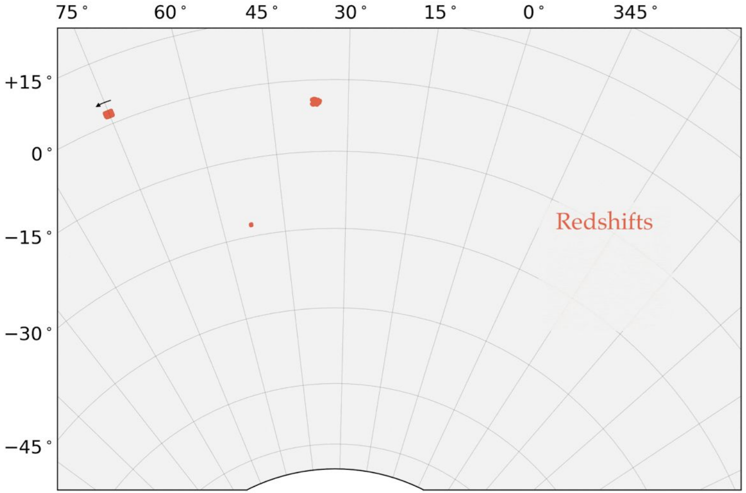
Important building blocks of the cosmic shear model in DES Y3

(in a nutshell)

Redshift distributions estimated with a novel methodology (SOMPZ), calibrated via clustering and lensing ratios [Myles, Alarcon et al 2020; Gatti et al 2021; Buchs et al 2019]

The SOMPZ essence: go from spectroscopic samples (prior) to redshift distributions (posterior) in a Bayesian way





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Important building blocks of the cosmic shear model in DES Y3

(in a nutshell)

Calibration of galaxy shape measurements resulting in shear priors
[MacCrann et al 2021]

$$\left\langle \epsilon^{\mathrm{obs}} \right\rangle = (1+m)\,\langle\gamma\rangle + c$$

lensing shear

observed ellipticity

multiplicative error

additive error

State-of-the-art approach coupling redshift distributions and blending

$$\bar{\epsilon}^{\mathrm{obs}} = \int \mathrm{d}z\, n_\gamma(z)\gamma^{\mathrm{true}}(z) + c + \mathrm{noise}$$

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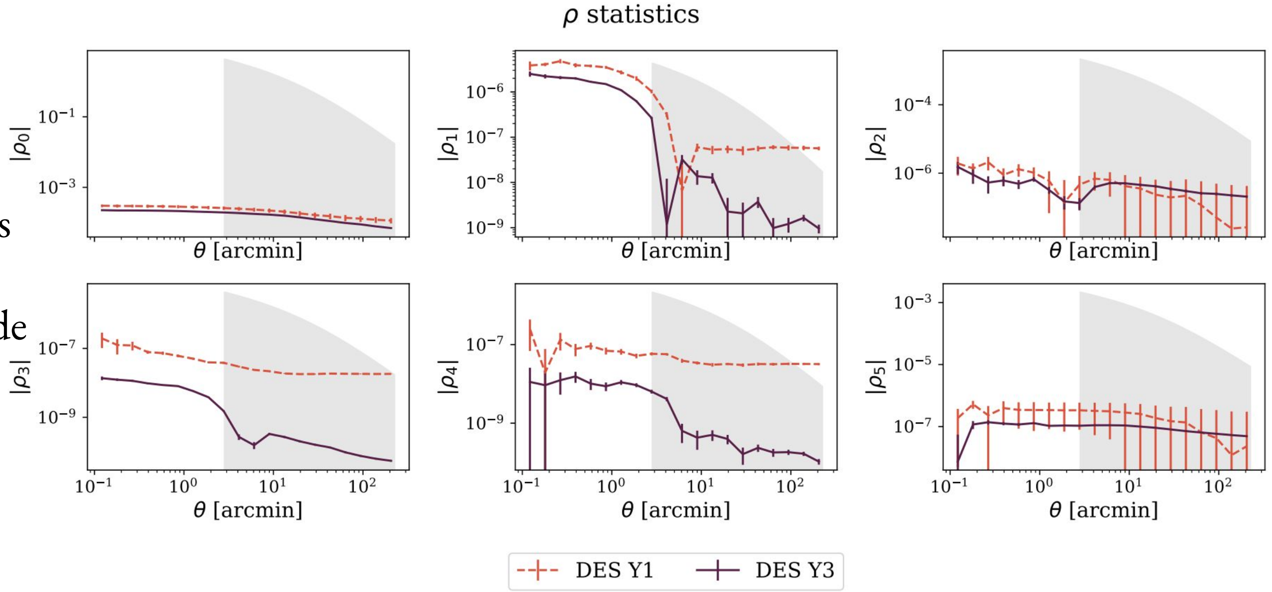
Important building blocks of the cosmic shear model in DES Y3

(in a nutshell)

Validation of a catalog of galaxy shapes with >100M galaxies: largest and widest to date!
No significant B-modes at catalog level data, negligible PSF residuals, ...
[Gatti, Sheldon et al 2021]

PSF contaminants down by orders of magnitude from Y1 to Y3



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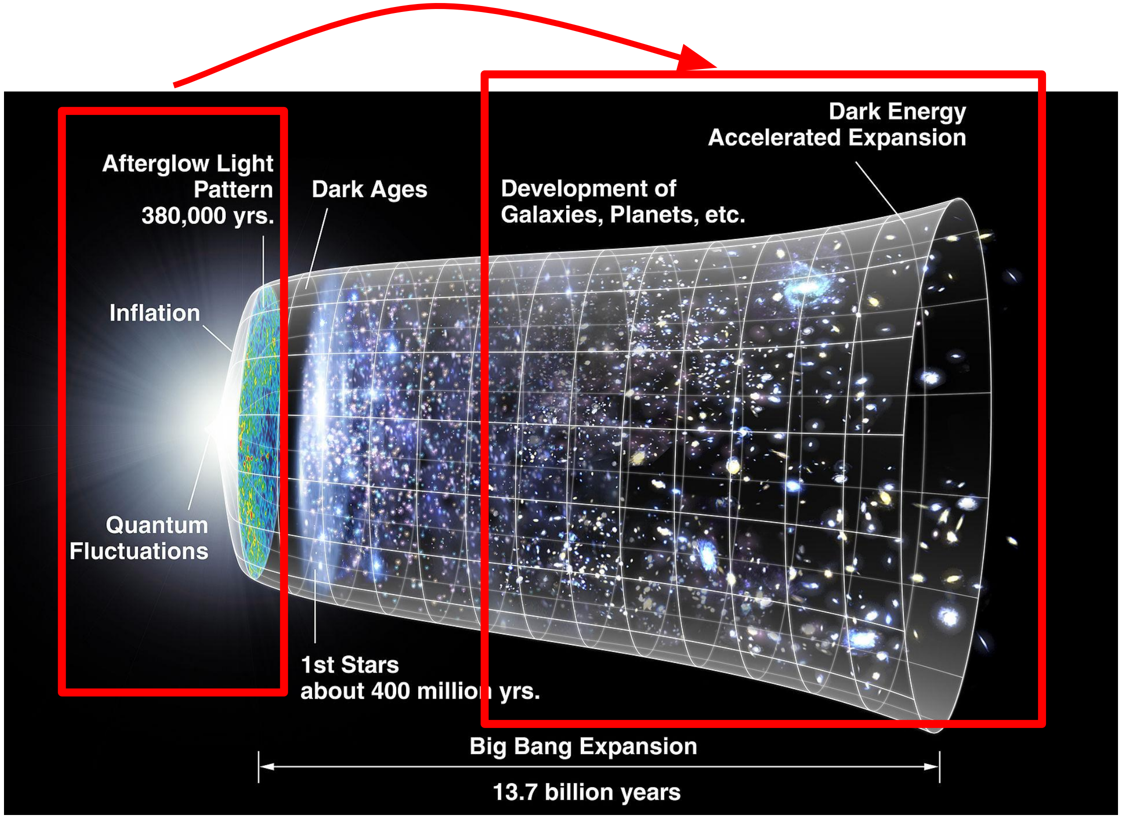
Why do we care? Questions of cosmological importance

Is **ΛCDM** the end-to-end cosmological model? That is, are cosmological parameters *the same* when measured by low-z and high-z probes?

DES *3x2pt* constrains mainly the lensing amplitude S8, defined as

$$S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$$

Discrepancies in S8 could mean a breakdown in **ΛCDM**



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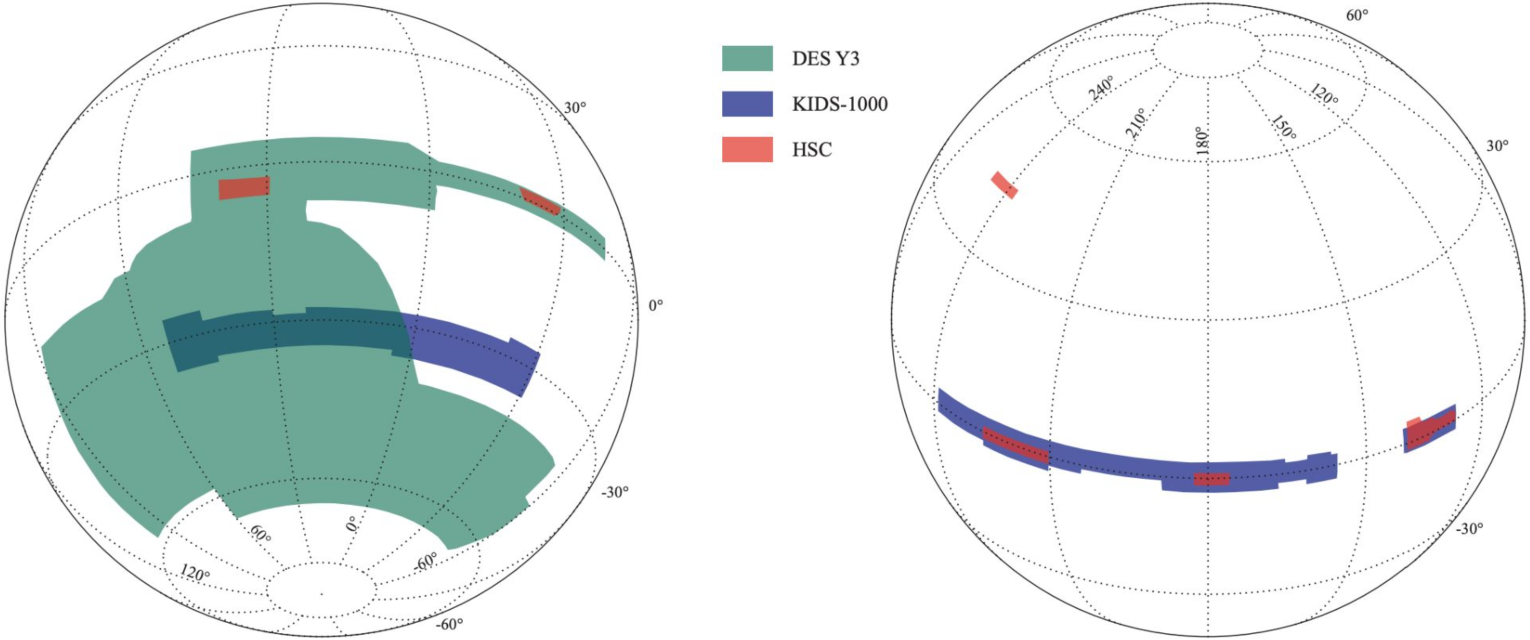
Why do we care? Stage-III Dark Energy experiments are at full-speed ahead and will inform Rubin/LSST, and hints of differences in S8 with respect to the CMB do exist (as well as a full-blown H0 tension!)



[Secco, Samuroff et al 2021, arXiv:2105.13544]

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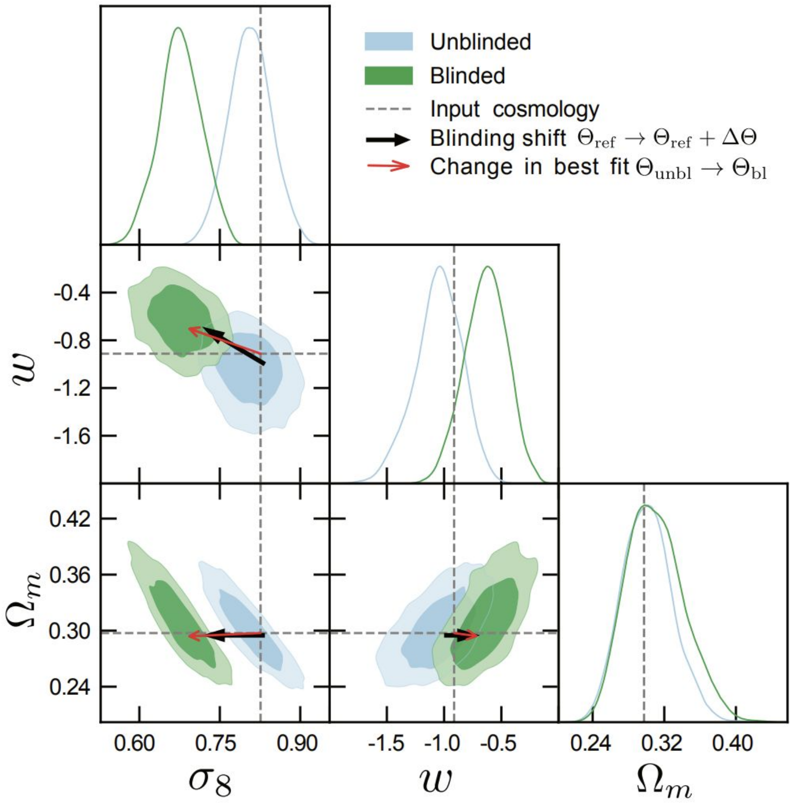
A tool to avoid confirmation bias: *blinding*

1- Shear quantities in the catalog multiplied by an unknown factor

2- Data vector (2pt measurements) shifted by an unknown data template in wCDM space

3- Contour plots with parameters shifted in wCDM



[Muir et al 2020]

[arXiv:2105.13544]

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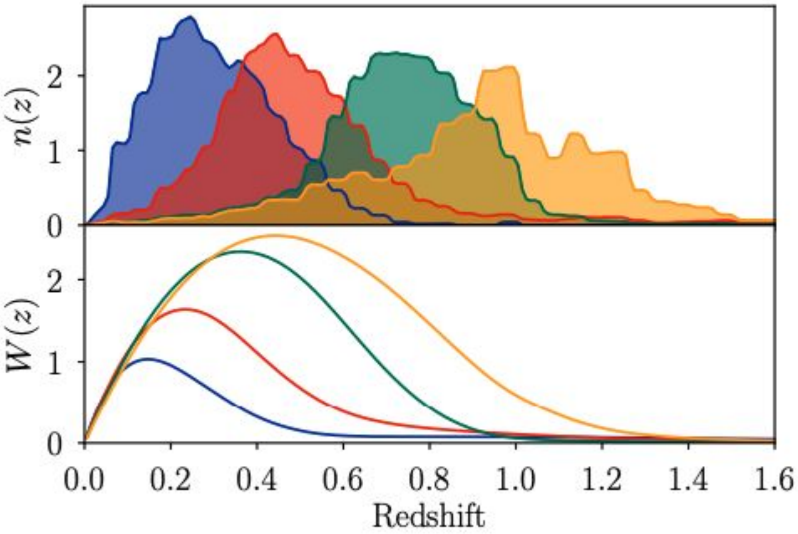
The cosmic shear model in DES Y3



Kernels *W(z)* peaking on redshifts between *z*=0.1 and *z*=0.5

We map the matter power spectrum *P(k)* into harmonic-space *C(l)* with Limber, and use a full-sky projection to obtain the cosmic shear correlations over tomographic redshift bins: [Krause et al 2021]

$$\xi_{\pm}^{ij}(\theta) = \sum_{\ell} \frac{2\ell+1}{2\pi\ell^2(\ell+1)^2}\left[G_{\ell,2}^{+}(\cos\theta) \pm G_{\ell,2}^{-}(\cos\theta)\right] \times \left[C_{EE}^{ij}(\ell) \pm C_{BB}^{ij}(\ell)\right]$$

Will *not* set to zero, as some (systematics-free) astrophysical contributions can impart B-modes on the cosmic shear signal. In our model: II term in IA.

[arXiv:2105.13544]

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The cosmic shear model in DES Y3

With a mapping from the matter power spectrum to cosmic shear correlations, need to look at *P(k)* modeling uncertainties, especially in the nonlinear regime

DES Y3: make the *choice* of a gravity-only HALOFIT *P(k)* [Takahashi+2012], with 2 main consequences:

- Modeling of baryons and their associated uncertainties/parameters is not necessary (DM-only regime)
- Power spectrum modes contributing to the signal come from relatively larger scales & more linear physics

Counterpoint: the model is *certainly insufficient*, so evolution beyond DM needs to be mitigated with scale cuts

A joint 3x2pt analysis (lensing + clustering):
The modeling methods need to *optimize both lensing and clustering* and guarantee all are ~unbiased
[Krause et al 2021]

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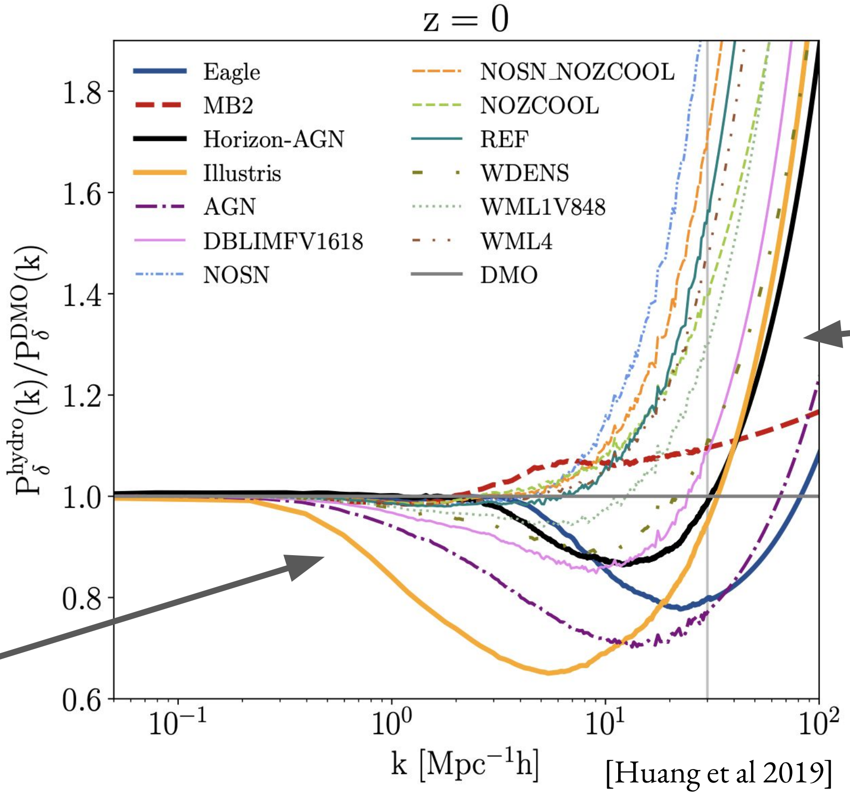
The cosmic shear model in DES Y3
P(k) uncertainties



[Huang et al 2019]

Increased metallicity allows for faster cooling (enhances small scale power)

Suppression of clustering on relatively large scales

[arXiv:2105.13544]

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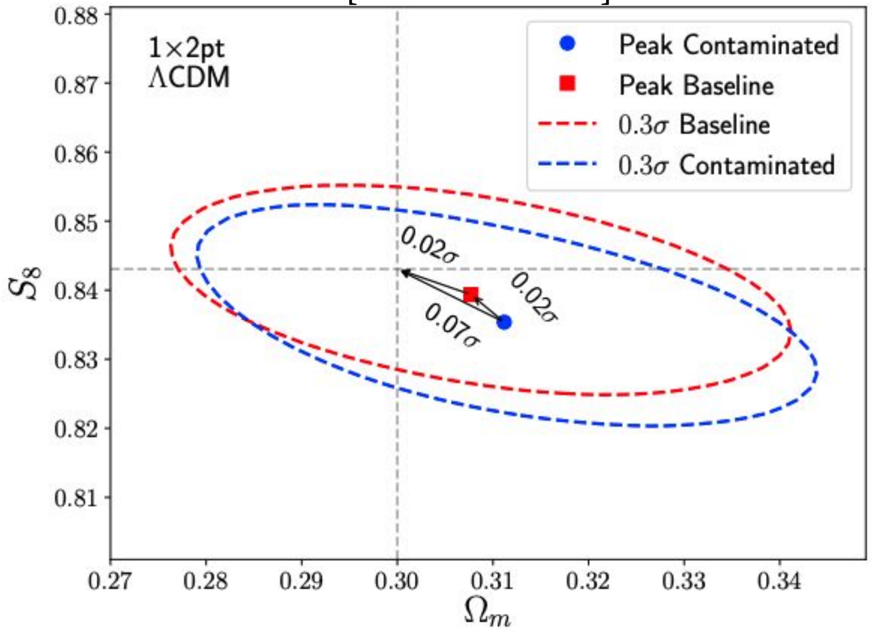
The cosmic shear model in DES Y3

1. Set a threshold for tolerance between the cosmology inference at (synthetic) baseline and contaminated data : 0.3sigma in S8 x Om for cosmic shear, 2x2pt, 3x2pt in both **Λ/*w*CDM** (main contaminant in cosmic shear: small scale baryonic feedback)
2. Iterate on many possible scale cuts until constraining power is maximized within the threshold

This procedure leads to overly strict and large "Fiducial" scales in a cosmic shear-only analysis (figure on the right)

Explored also an optimization for **ΛCDM** cosmic shear and 3x2pt only, enabling the use of more small scales *that still fulfill the 0.3 sigma requirement*

[Krause et al 2021]



[arXiv:2105.13544]

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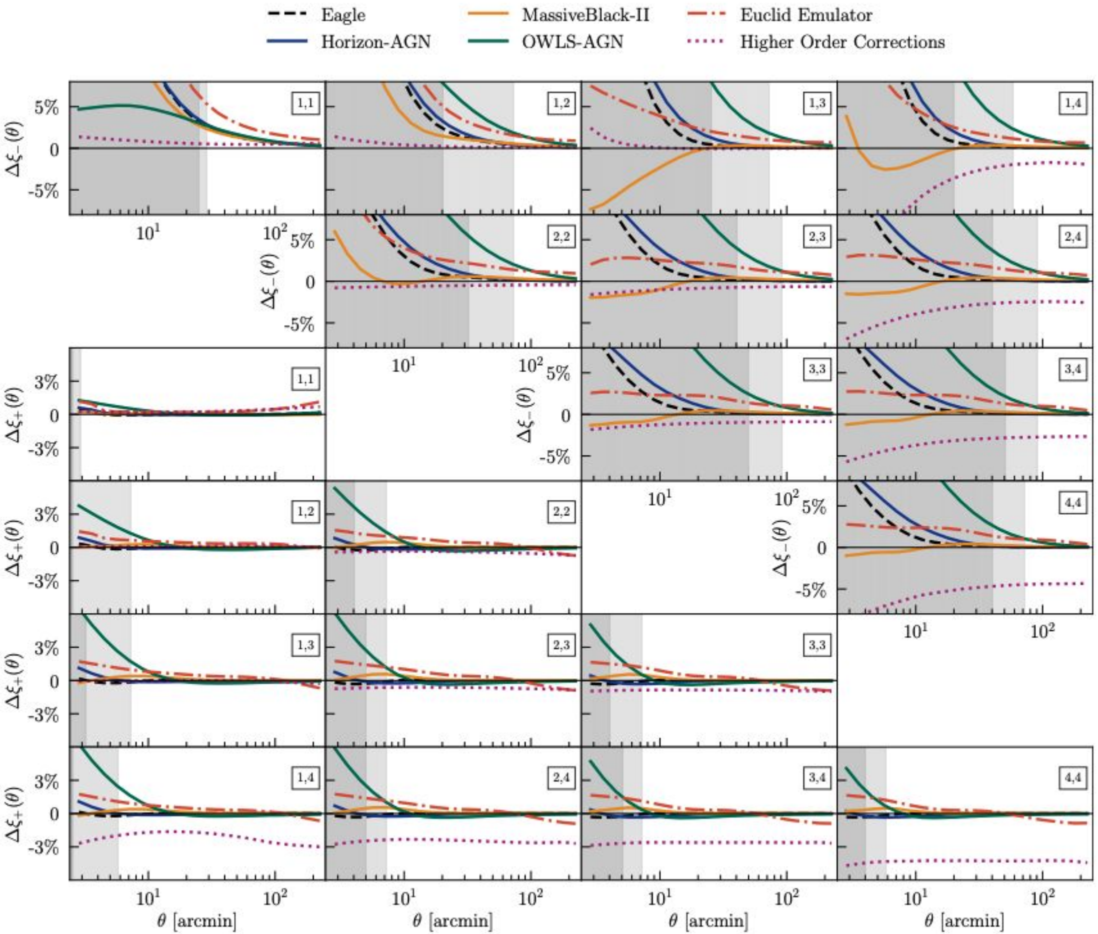
The cosmic shear model: scale cuts result



Dominating contaminant: feedback with the strength of OWLS-AGN

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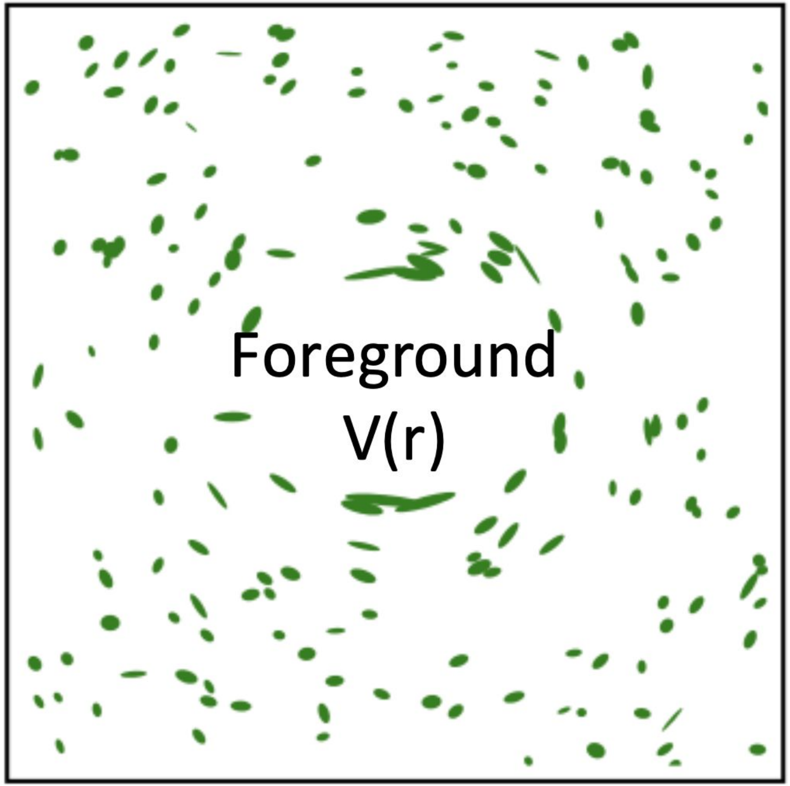
In tandem with scale cuts, need to select also the model for one of the main astrophysical systematics in weak lensing: Intrinsic Alignments (IA). Note that *we're still blind at this stage*.

IA: Galaxies are not simply a backdrop of shapes behind (unobservable) gravitational potentials



[arXiv:2105.13544]

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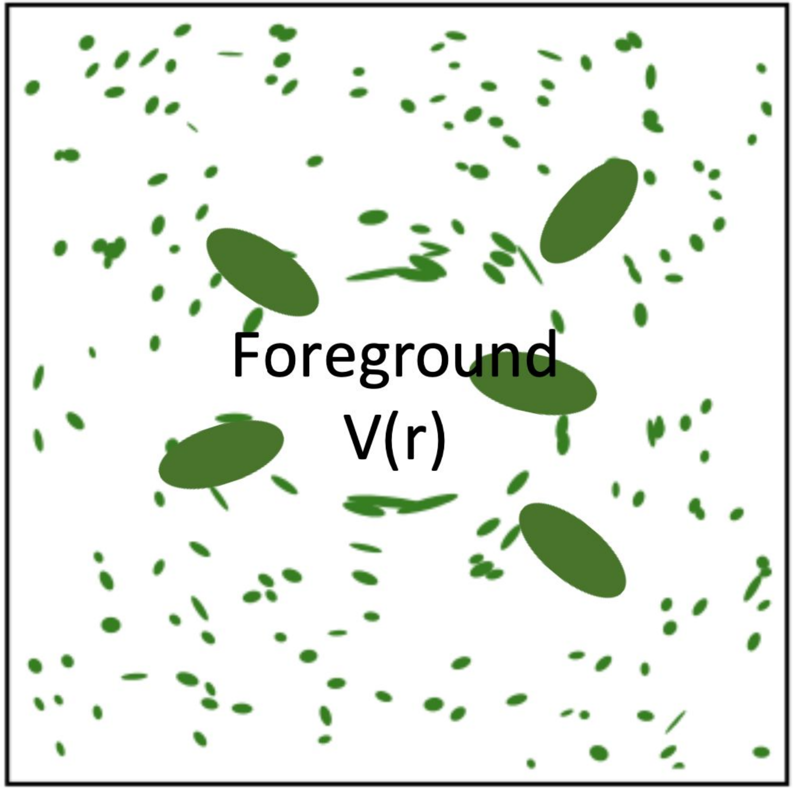
IA: Galaxies are not simply a backdrop of shapes behind (unobservable) gravitational potentials

"Intrinsically aligned" with the local environment



How much model complexity to be added? In the simplest case, galaxies align with the *tidal* forces of the potential

[arXiv:2105.13544]

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Use existing DES Y1 constraints on IA (Samuroff et al 2019; S19) to estimate how large that systematic can be.

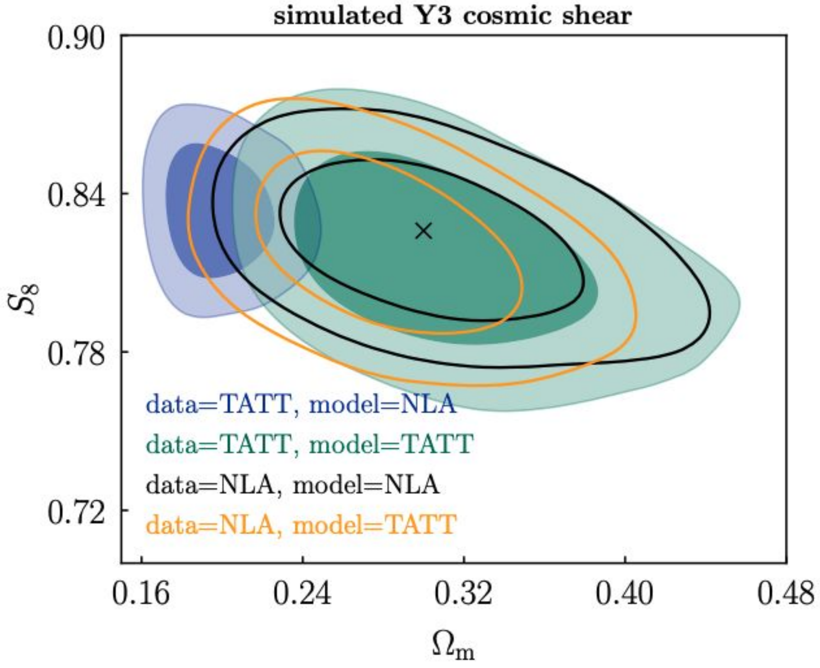
S19 found constraints for a 5-parameter model including tidal alignments (TA) as well as tidal torquing (TT), based on perturbation theory [Blazek et al 2019].
Simpler 2-parameter treatment: NLA, adopted widely

5 parameters, with NLA being a 2-parameter subset

- 2 amplitudes,
- 2 power-law redshift evo.
- Effective source galaxy bias

NLA fails to meet bias criteria with synthetic data generated at the S19 best-fit:

Our way forward is the full **TATT model**



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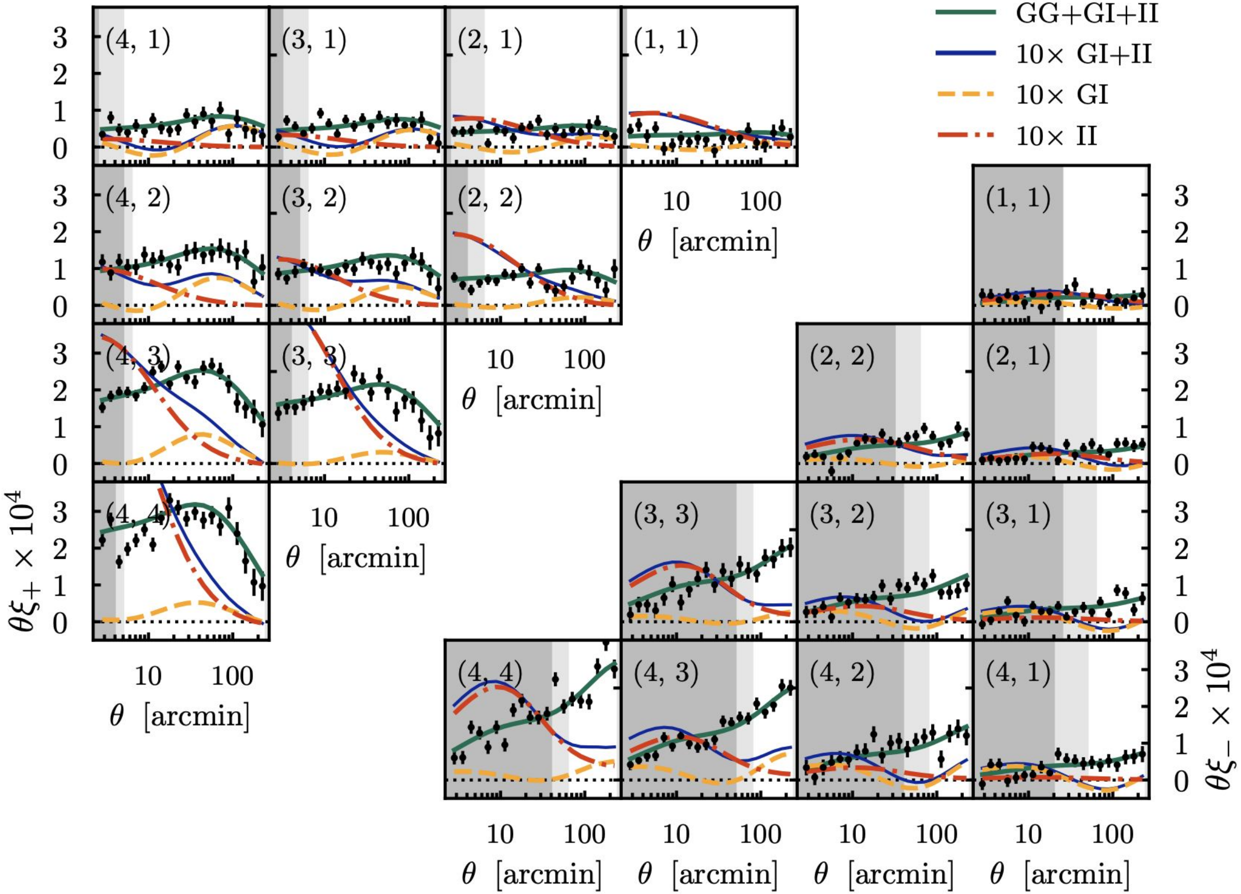
The full model: 6+1 cosmological parameters & 19 nuisance parameters

Parameter	Prior
Cosmological Parameters	
$\Omega_{\rm m}$	U$[0.1, 0.9]$
$A_{\rm s}$	U$[0.5, 5.0] \times 10^{-9}$
$\Omega_{\rm b}$	U$[0.03, 0.07]$
$n_{\rm s}$	U$[0.87, 1.07]$
h	U$[0.55, 0.91]$
$\Omega_\nu h^2$	U$[0.6, 6.44] \times 10^{-3}$
w	U$[-2, -0.333]$
Calibration Parameters	
m_1	$\mathcal{N}(-0.0063, 0.0091)$
m_2	$\mathcal{N}(-0.0198, 0.0078)$
m_3	$\mathcal{N}(-0.0241, 0.0076)$
m_4	$\mathcal{N}(-0.0369, 0.0076)$
Δz_1	$\mathcal{N}(0.0, 0.018)$
Δz_2	$\mathcal{N}(0.0, 0.015)$
Δz_3	$\mathcal{N}(0.0, 0.011)$
Δz_4	$\mathcal{N}(0.0, 0.017)$
Intrinsic Alignment Parameters	
a_1	U$[-5, 5]$
a_2	U$[-5, 5]$
η_1	U$[-5, 5]$
η_2	U$[-5, 5]$
$b_{\rm TA}$	U$[0, 2]$
Shear Ratio Parameters	
$\Delta z_1^{\rm lens}$	$\mathcal{N}(-0.009, 0.007)$
$\Delta z_2^{\rm lens}$	$\mathcal{N}(-0.035, 0.011)$
$\Delta z_3^{\rm lens}$	$\mathcal{N}(-0.005, 0.006)$
$\delta_{z,1}^{\rm lens}$	$\mathcal{N}(0.975, 0.062)$
$\delta_{z,2}^{\rm lens}$	$\mathcal{N}(1.306, 0.093)$
$\delta_{z,3}^{\rm lens}$	$\mathcal{N}(0.870, 0.054)$
b_g^{1-3}	U$[0.8, 3]$

[arXiv:2105.13544]

Post-unblinding, our model provides a very good fit to the data:
chi2/dof = 237.7/222 (a *p*-value of 0.22) with 6+1 (cosmological) plus 19 (nuisance) parameters



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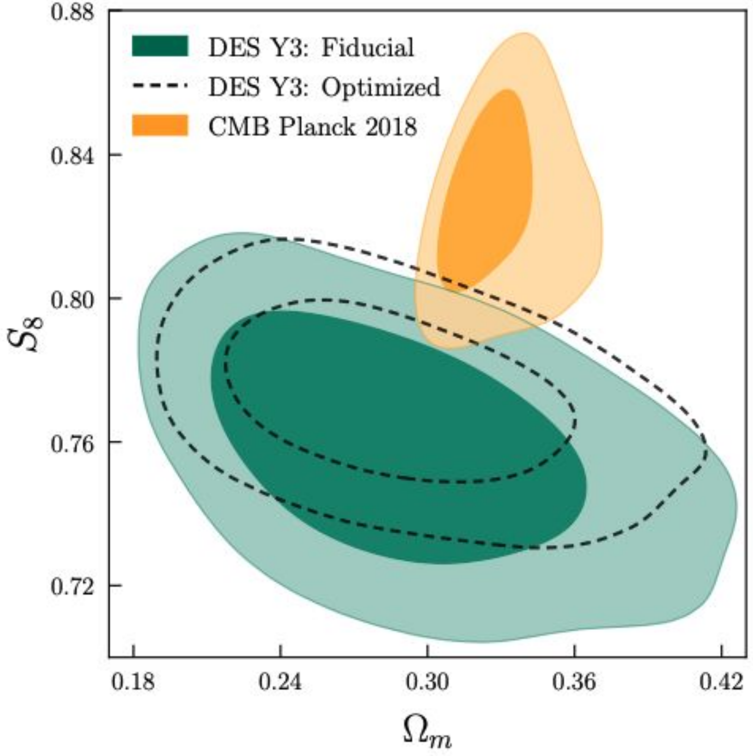
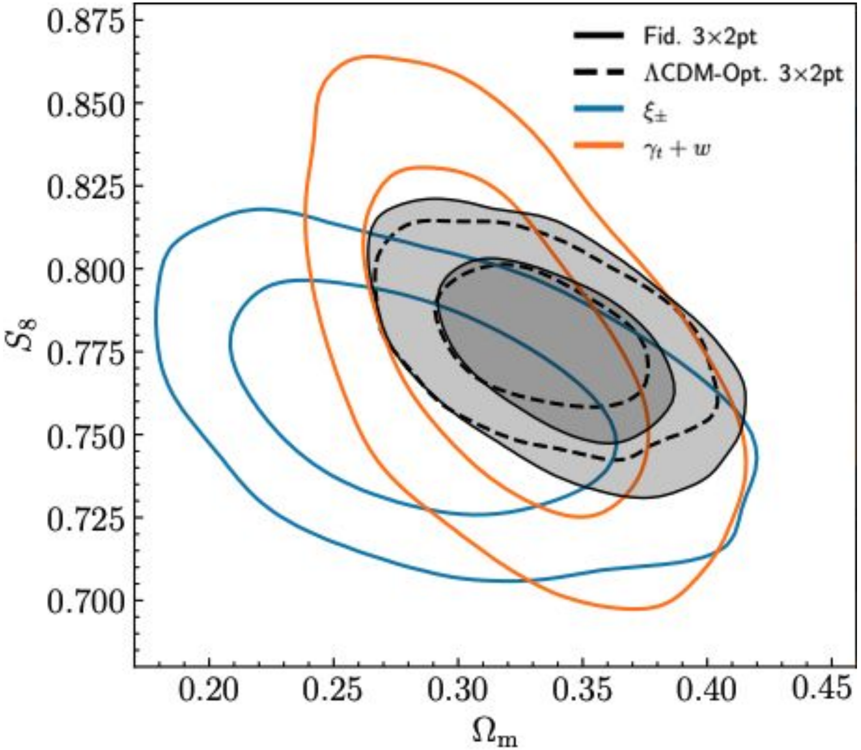
DES Y3 RESULTS

Cosmic Shear



Amon et al (2021); Secco, Samuroff et al (2021)

Cosmic Shear + 2x2pt (3x2pt)



DES et al (2021); Pandey et al (2021); Porredon et al (2021)

[arXiv:2105.13544]

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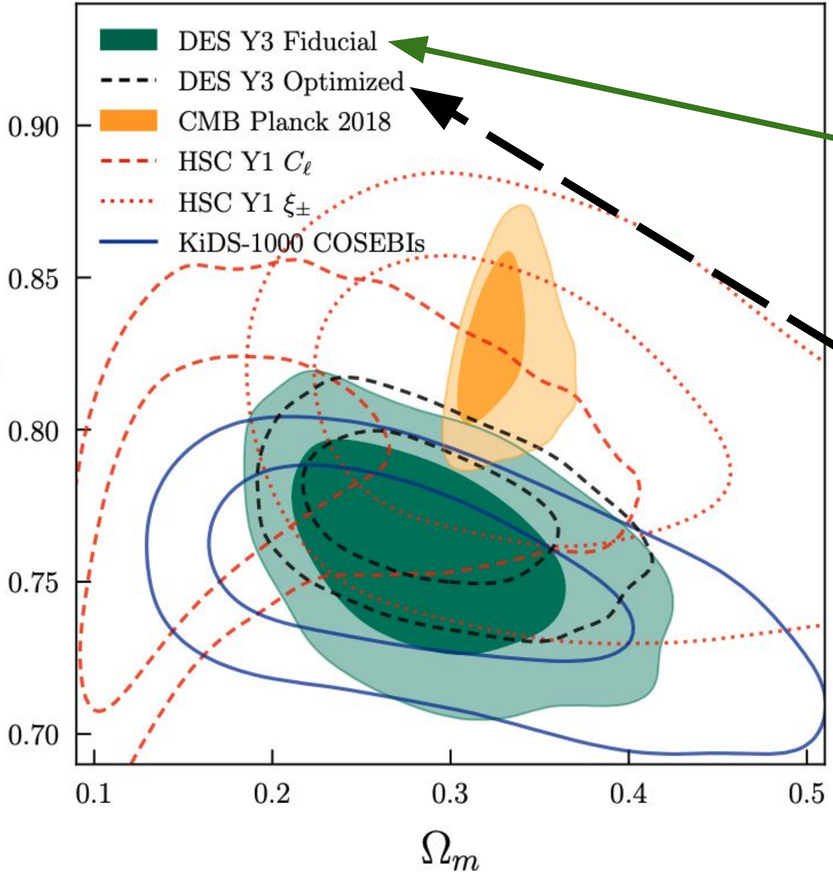
Quantifying agreement:



Agreement with respect to Planck 2018:

Suspiciousness:	$2.3\sigma \pm 0.3\sigma$	(DES *vs* Planck ΛCDM)
Parameter shift:	2.3σ	(DES *vs* Planck ΛCDM),

Suspiciousness:	$2.0\sigma \pm 0.4\sigma$	(DES optim. *vs* Planck ΛCDM)
Parameter shift:	2.1σ	(DES optim. *vs* Planck ΛCDM),

with respect to WL surveys:

Hard to draw quantitative conclusions (see Chang+2018), though qualitative agreement across blinded Stage-III analyses

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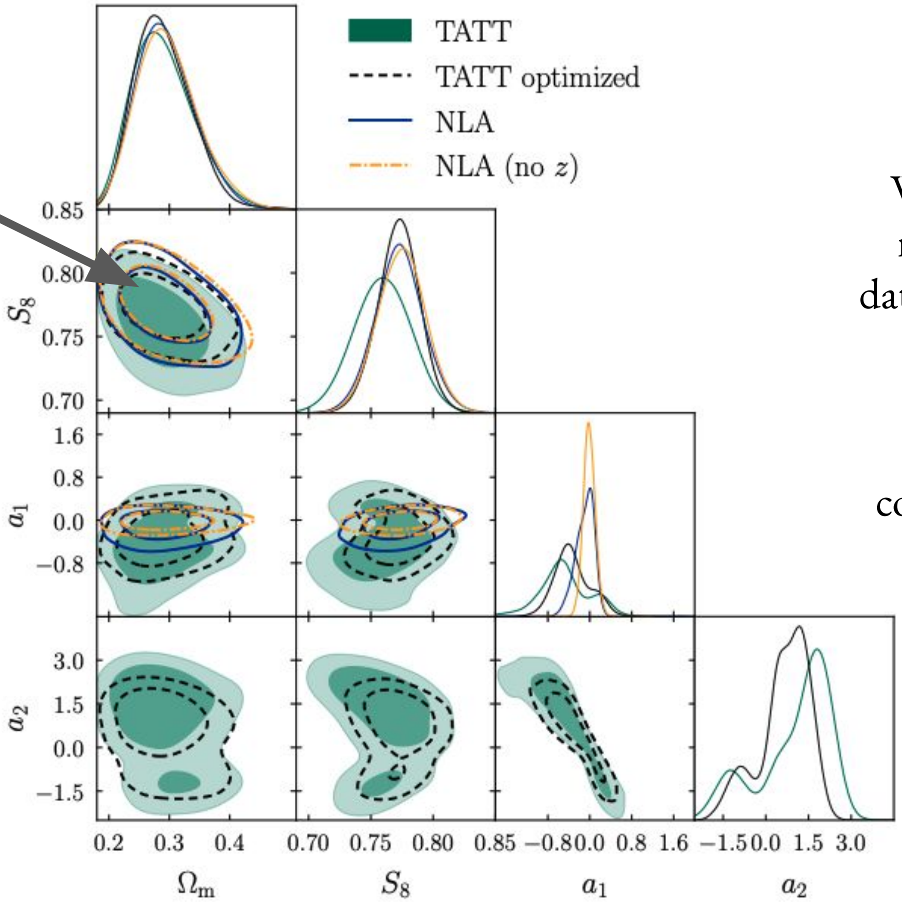
IA results and variations (simplifications) of the fiducial model are consistent:

Are simplified IA models giving consistent results in cosmological parameters? Yes!



We also utilize lensing (shear) ratios on small scales as extra data, informing photo-z’s and IA [Sanchez, Prat et al 2021];

Amon et al shows IA and cosmology results are robust to assumptions to go in there

[arXiv:2105.13544]

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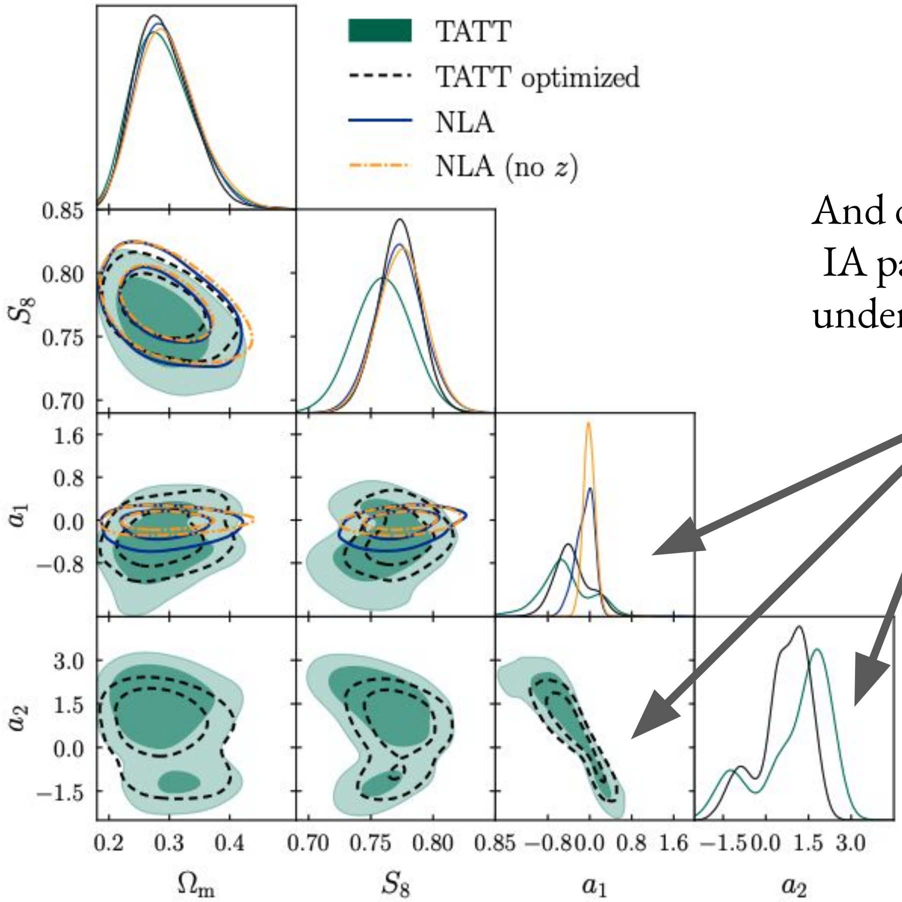

And do we get consistent IA parameter posteriors under different modeling choices? Yes!

[arXiv:2105.13544]

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What is ***the data*** saying about the IA signal?
Mixed approaches in the cosmic shear literature:

$$\text{No IAs} \longrightarrow A_1 \longrightarrow A_1(z) \longrightarrow A_1(z), A_2 \longrightarrow A_1(z), A_2(z) \longrightarrow A_1(z), A_2(z), A_{1\delta}$$

(!) (KiDS) (HSC, DES Y1) (DES Y3)

At each step, compare Bayesian evidence ratios and chi2 improvement:

IA Model (free parameters)	χ^2/d.o.f	log Evidence	R (w.r.t. TATT)	R (w.r.t. above)	a_1	η_1	a_2	η_2	b_{TA}
No IAs	240.6 / 225	3215.79 ± 0.11	9.48 ± 1.66	N/A	-	-	-	-	-
NLA no z-evo. (a_1)	238.6 / 224	3213.89 ± 0.12	1.42 ± 0.30	0.18 ± 0.03	$0.34^{+0.25}_{-0.23}$	-	-	-	-
NLA (a_1, η_1)	238.3 / 224	3214.07 ± 0.13	1.70 ± 0.36	1.19 ± 0.24	$0.36^{+0.43}_{-0.36}$	$1.66^{+3.26}_{-1.05}$	-	-	-
TA (a_1, η_1, b_{TA})	238.8 / 224	3213.87 ± 0.13	1.38 ± 0.25	0.81 ± 0.14	$0.27^{+0.35}_{-0.31}$	$2.10^{+2.89}_{-0.71}$	-	-	$0.83^{+0.31}_{-0.82}$
No z-evo. (a_1, a_2, b_{TA})	238.6 / 223	3211.81 ± 0.14	0.17 ± 0.03	0.12 ± 0.02	$0.18^{+0.21}_{-0.30}$	-	$0.10^{+0.55}_{-0.57}$	-	$0.80^{+0.29}_{-0.78}$
No a_2 z-evo. (a_1, η_1, a_2, b_{TA})	238.2 / 223	3212.09 ± 0.14	0.23 ± 0.04	1.32 ± 0.26	$-0.02^{+0.71}_{-0.31}$	$2.17^{+2.82}_{-0.70}$	$-0.27^{+0.59}_{-0.50}$	-	$0.87^{+0.38}_{-0.83}$
TATT ($a_1, \eta_1, a_2, \eta_2, b_{TA}$)	233.1 / 222	3213.54 ± 0.13	1	4.28 ± 0.83	$-0.24^{+0.98}_{-0.41}$	$2.38^{+2.62}_{-0.61}$	$0.63^{+1.93}_{-1.89}$	$3.11^{+1.77}_{-0.31}$	$0.87^{+0.38}_{-0.84}$

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Most TATT parameters don't significantly improve the chi2

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Evidence ratios seem to prefer simpler or zero IA

[arXiv:2105.13544]

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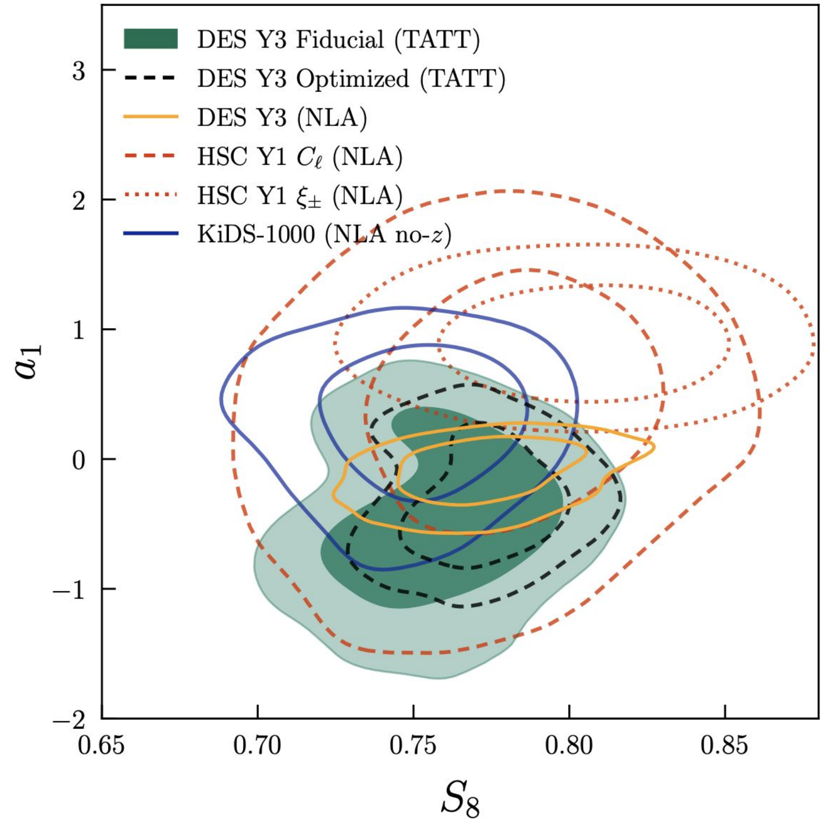
While (again) quantitative comparisons are difficult, weak lensing surveys seem to agree on the amplitude of the IA signal



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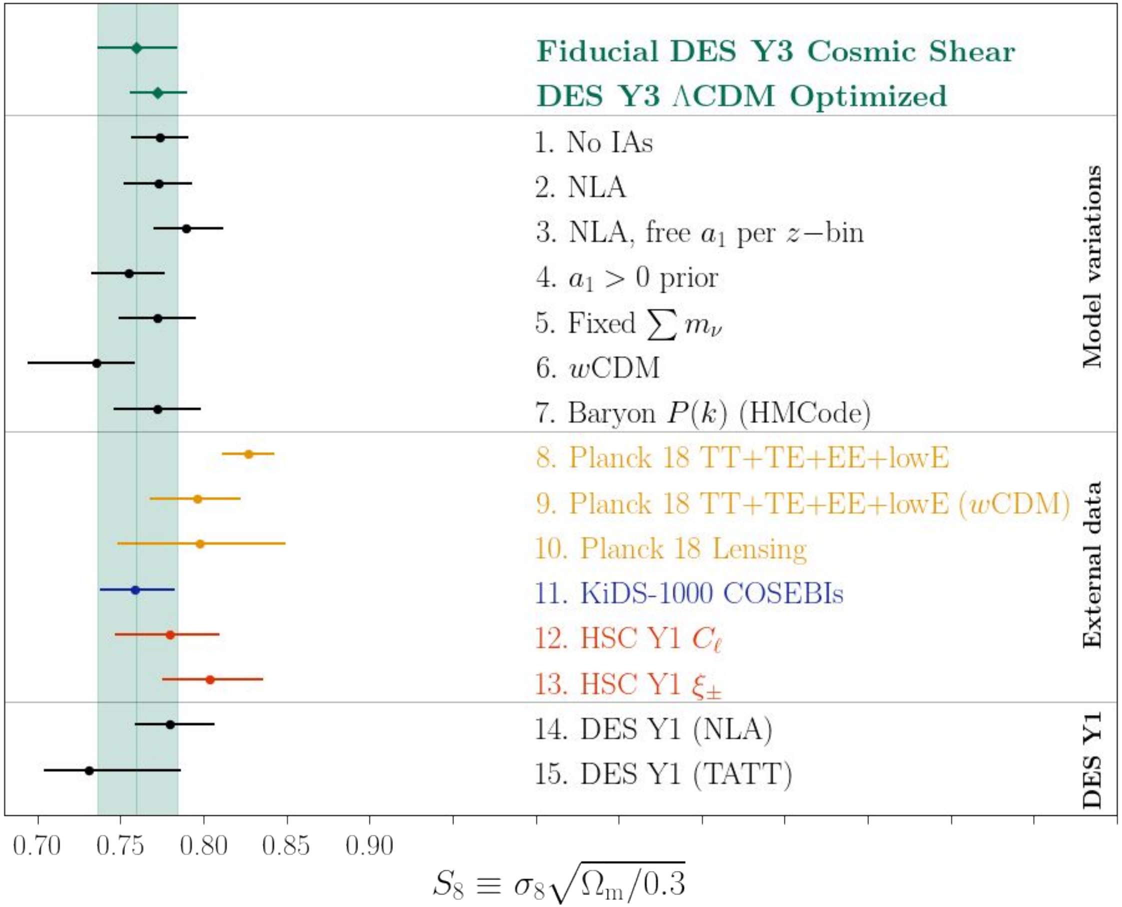
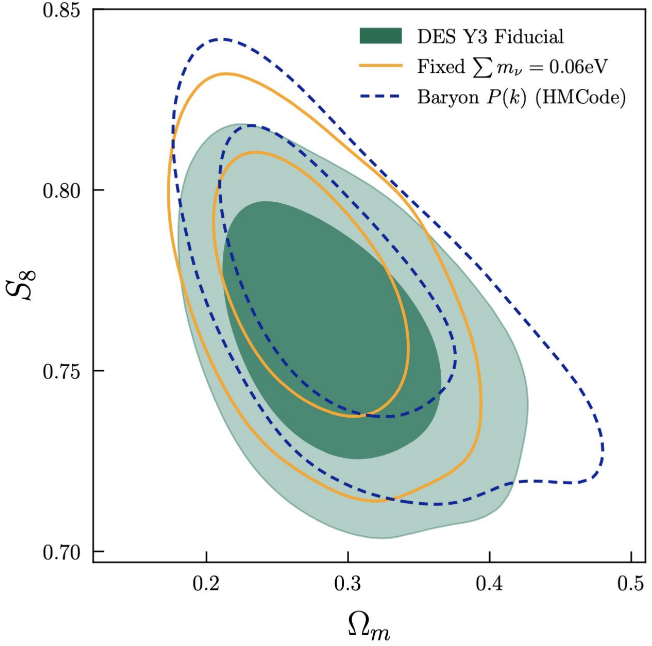
[arXiv:2105.13544]

More general model variations also lead to consistent cosmology:





[arXiv:2105.13544]

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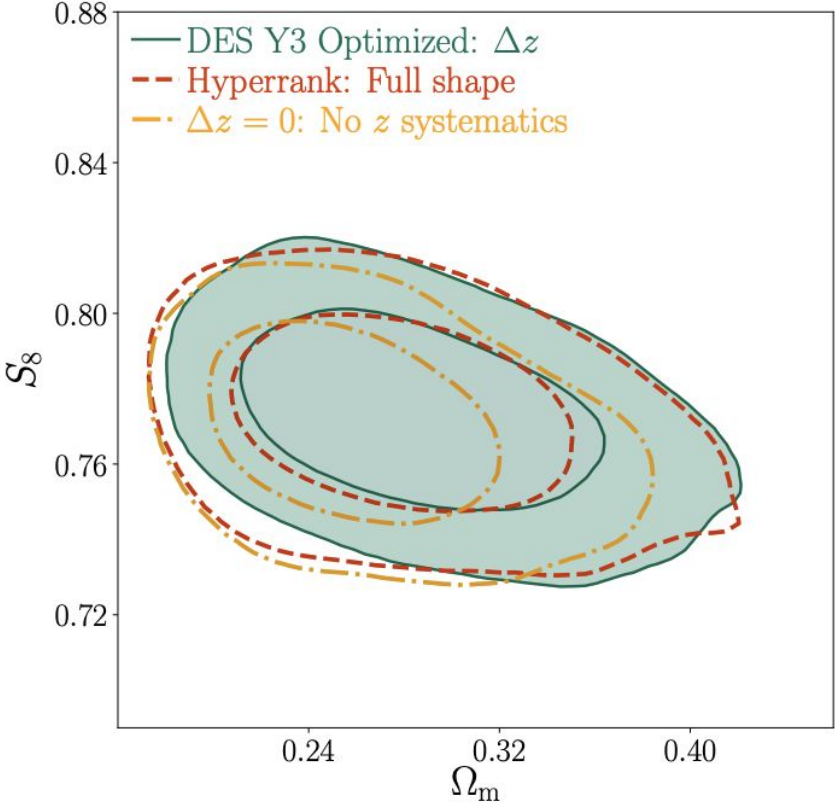
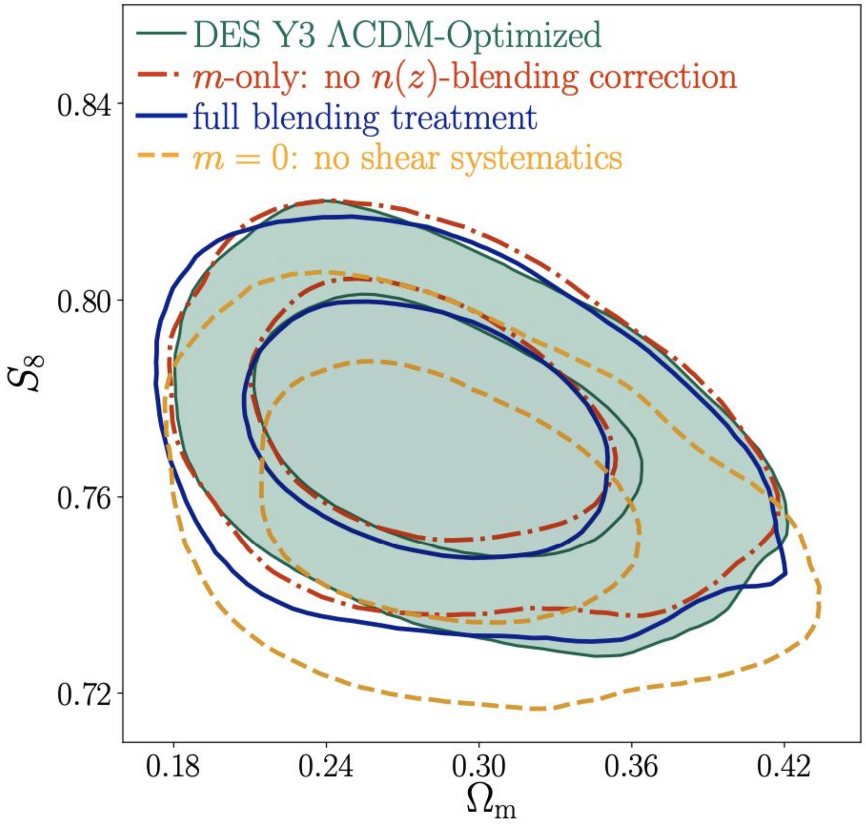
Data calibration variations also lead to consistent cosmology: [Amon et al 2021]





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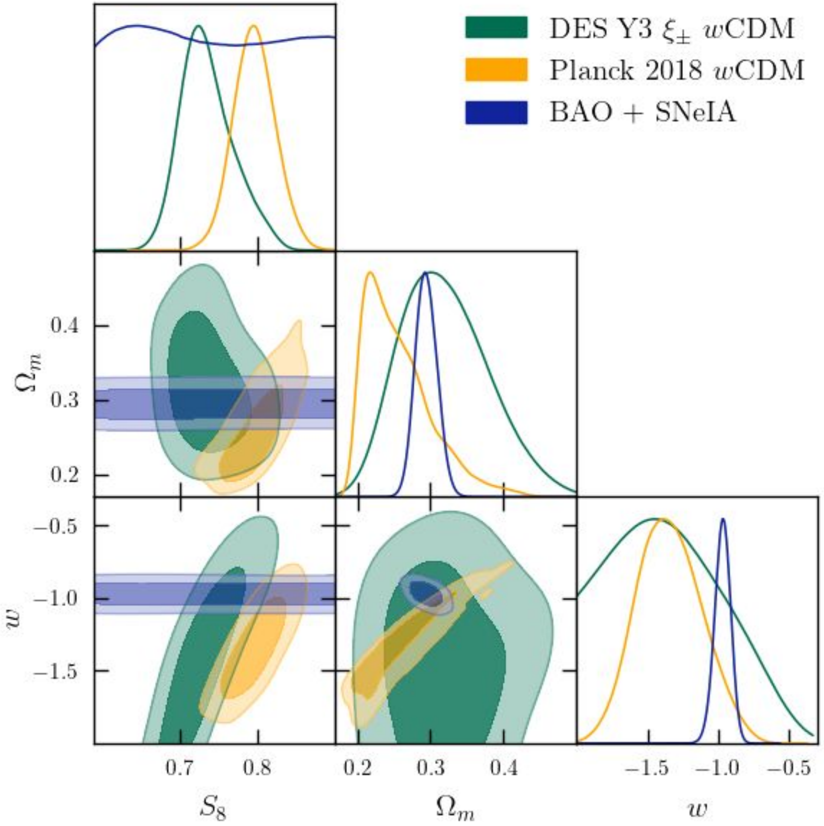
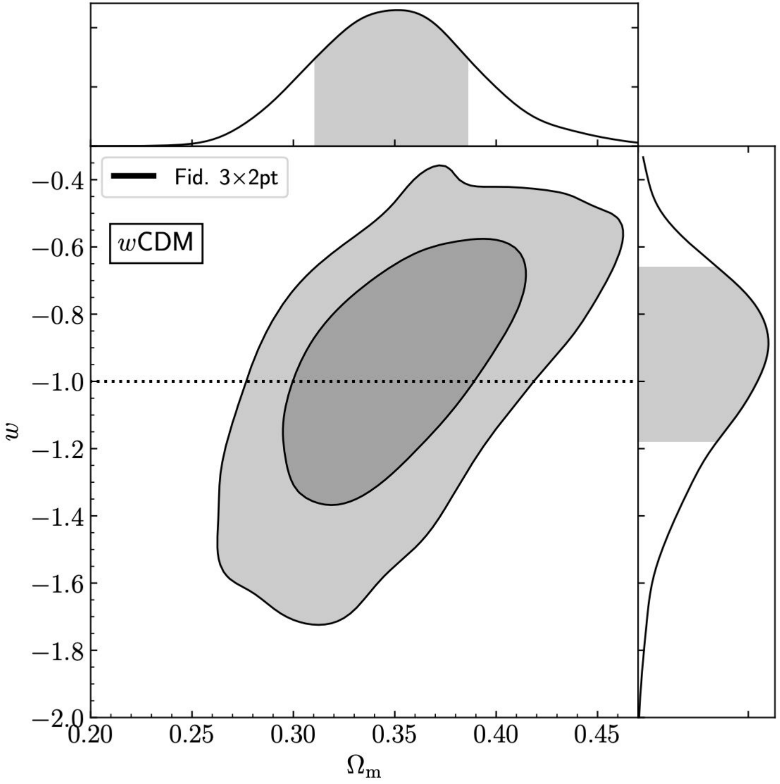
w not constrained by DES Y3 cosmic shear data alone (consistent with *w*=-1 in 3x2pt, constrained to ~25% errors)





[arXiv:2105.13544]

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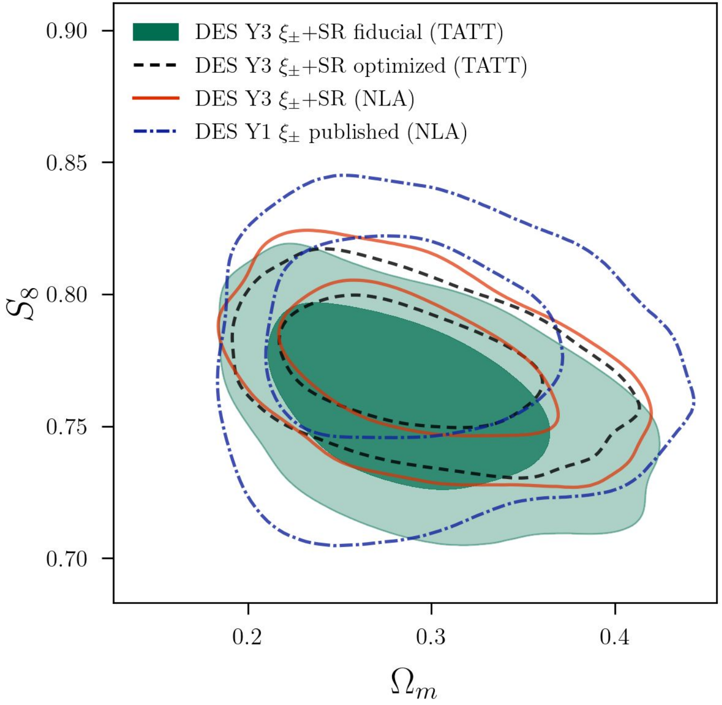
Conclusions & the future

DES Y3 cosmic shear is the state-of-the-art, blind weak lensing measurement of S8 (methodology *and* constraining power)



We find an S8 which is ~2sigma below Planck 2018 and in (qualitative) agreement with other lensing surveys.
No statistically significant tension: **ΛCDM** wins again

From published DES Y1 to DES Y3 (plot on the left):
increasing constraining power in-place,
S8 discrepancy in DES Y1 vs Planck 2015: ~1sigma
(see Amon et al 2021 for re-analyzed version)

In 3x2pt (specially in addition to external data):
more consistency with the CMB with tension metrics <1 sigma.

[arXiv:2105.13544]

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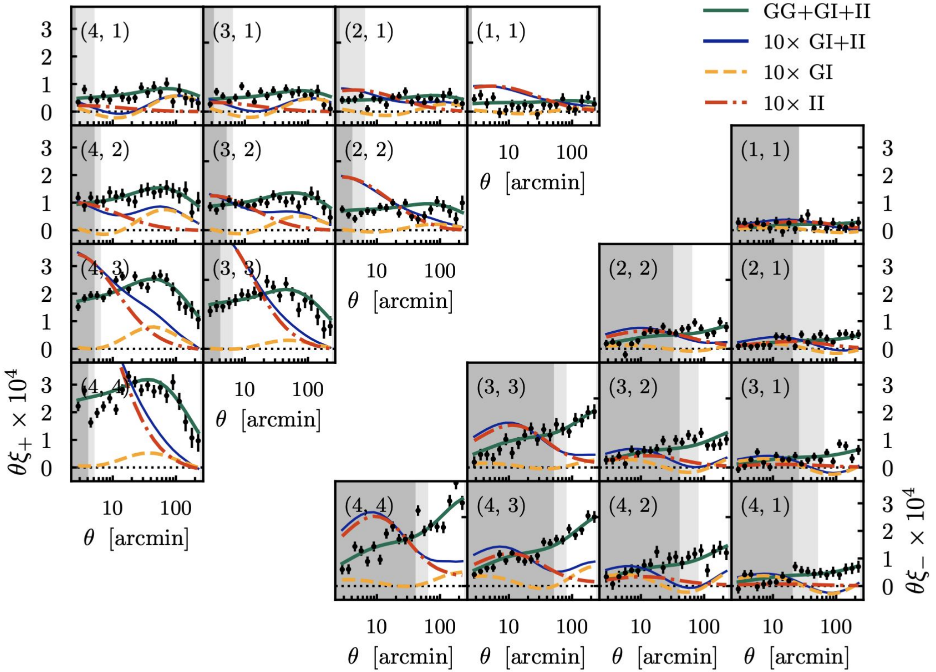
Conclusions & the future



Intrinsic Alignments: started conservative to prevent biases, found signal be smaller than most of our estimates, let the data pick simplicity. Qualitative agreement with other cosmic shear studies.

Simpler models (eg NLA) might be sufficient for future analyses (depending on samples and constraining power), but I'd personally like to see more model-selection ideas: Can we make data-driven model selection while blinded? Can we improve priors? IA in simulations? (upcoming work on MICE)

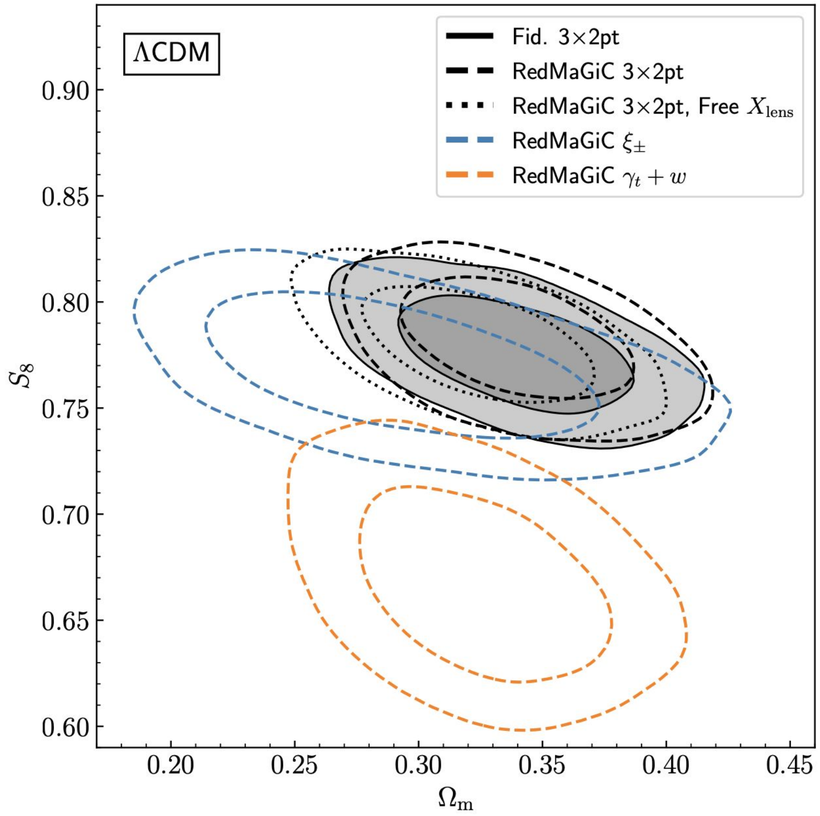
Thanks!

After unblinding of the full 3x2pt constraints data, we find galaxy-galaxy lensing and galaxy clustering appear to be de-correlated from the matter field, with a parameter *X_lens* accounting for their discrepancy. In LCDM, this new parameter must be consistent with 1:

$$w^{ii}(\theta) = b_i^2 \xi_{\mathrm{mm}}^{ii}(\theta)$$
$$\gamma_t^{ij}(\theta) = X_{\mathrm{lens}} b_i \xi_{\mathrm{mm}}^{ij}(\theta)$$

In LCDM, fitting for *X_lens* shifts the 2x2pt combination significantly, but does not affect the 3x2pt constraints appreciably.

This systematic seems to be scale- and redshift-independent, and further studies within the collaboration are finding potential culprits in the lens galaxy sample.



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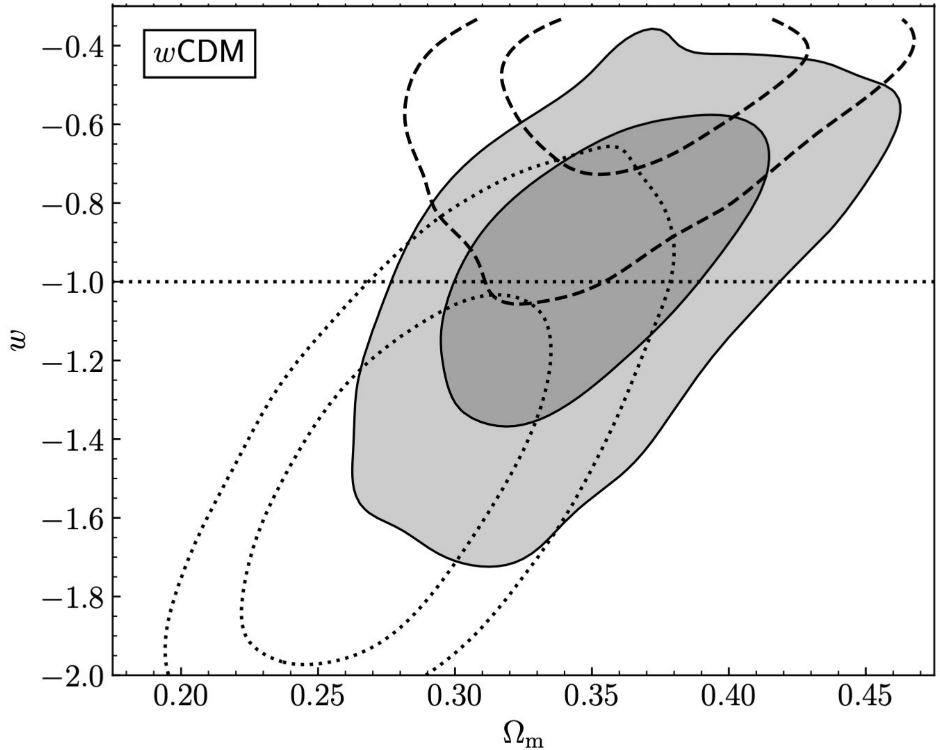
$$\gamma_t^{ij}(\theta) = X_{\rm lens} b_i \xi^{ij}_{\rm mm}(\theta)$$

In *w*CDM, unfortunately *X_lens* couples to the equation-of-state parameter of DE, changing significantly our results. We change lens samples post-unblinding due to this systematic

What *X_lens* is not:

- A manifestation of "lensing is low"
  - Large-scales stochastic bias
- Evidence to fundamental changes in LCDM



More information and testing in Pandey et al 2021