Weak Lensing in the Upcoming Era:
more data, better models, enough of Gauss

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Outline

0- *A motivation for this research program*

1- *Enough of Gauss* [based on LS+2022]

- Bringing non-Gaussian information to a mature level as a source of cosmological information

2- *Better models* [based on K. Hoffman, LS+ ; appearing soon]

- Modeling Intrinsic Alignments (IA) with semi-analytic models in simulations

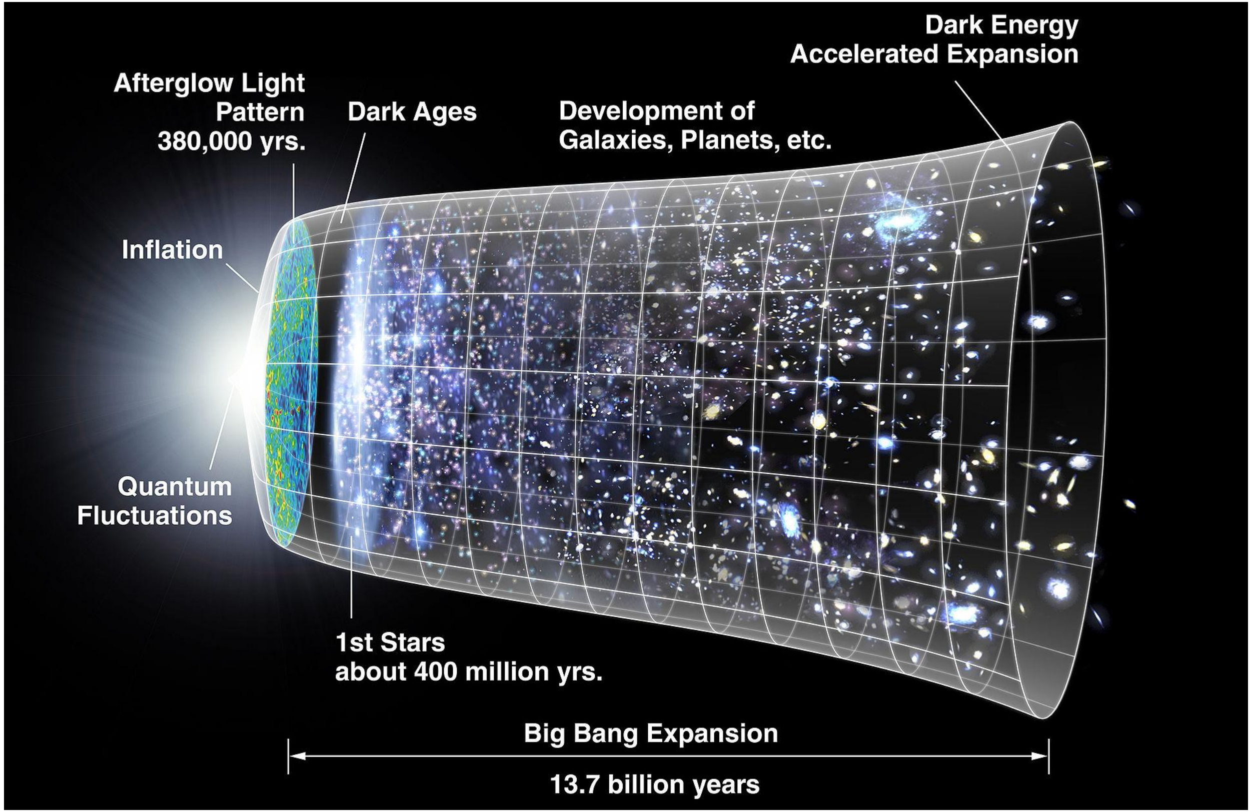
3- *More data* [ongoing]

- The near future *before Rubin*: DES Y6 and a new All-DECam data set

ΛCDM : a model with internal tensions

Flat universe +
Cosmological constant +
Cold Dark Matter +
gravity dictated by GR +
inflation.

The model predicts/explains many astrophysical phenomena but its main components (especially CDM and Λ) **are not understood.**



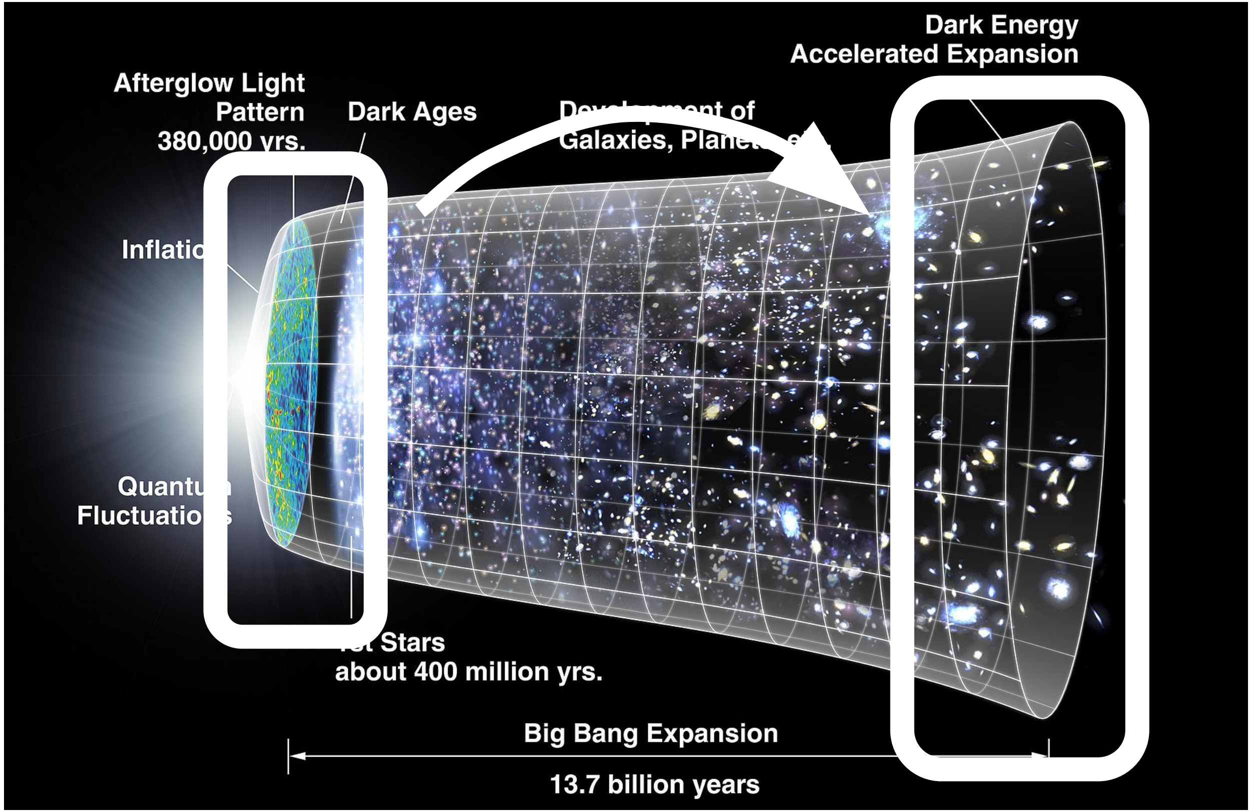
ΛCDM : a model with internal tensions

End-to-end tests of the model appear to be failing:

H0 as inferred (CMB) and as measured (supernovae, strong lensing, TRGB*) does not match

S8 as inferred (CMB) and as measured (lensing, clustering, redshift space distortions, clusters)

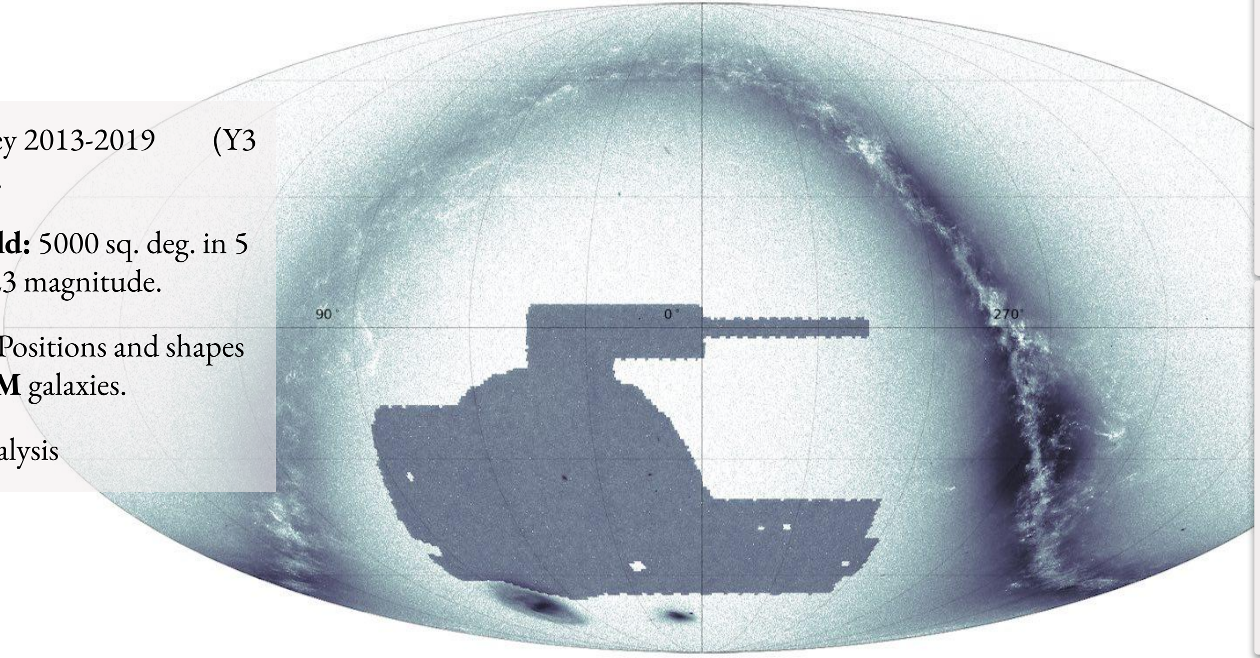
In this context, many **surveys look for answers**…

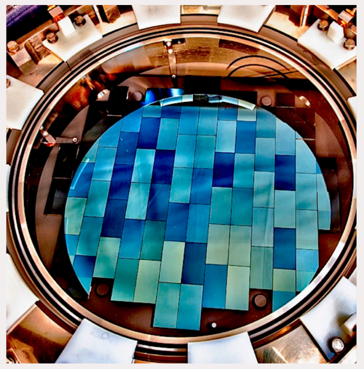


The Dark Energy Survey (DES)

(where most of the data in this talk came from!)

- 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.
- **Blind** analysis





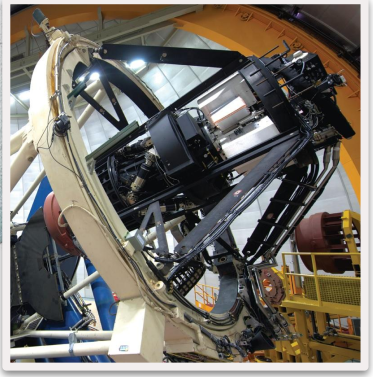


Image Credit: CosmoHub, Port d'Informació Científica (PIC)

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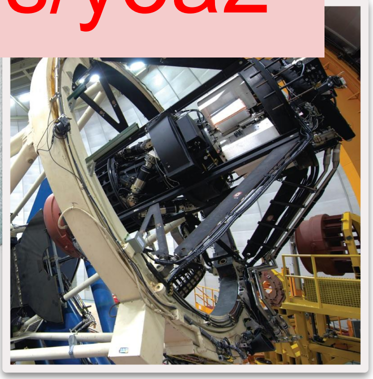


Public!

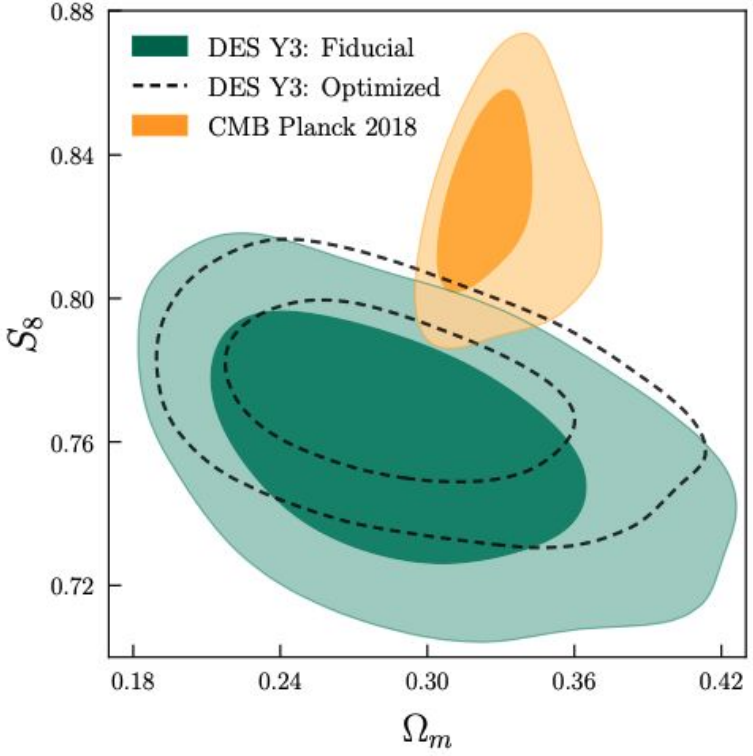
https://des.ncsa.illinois.edu/releases/y3a2

- DES Y3: Positions and shapes of > **100M** galaxies.
- **Blind** analysis

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

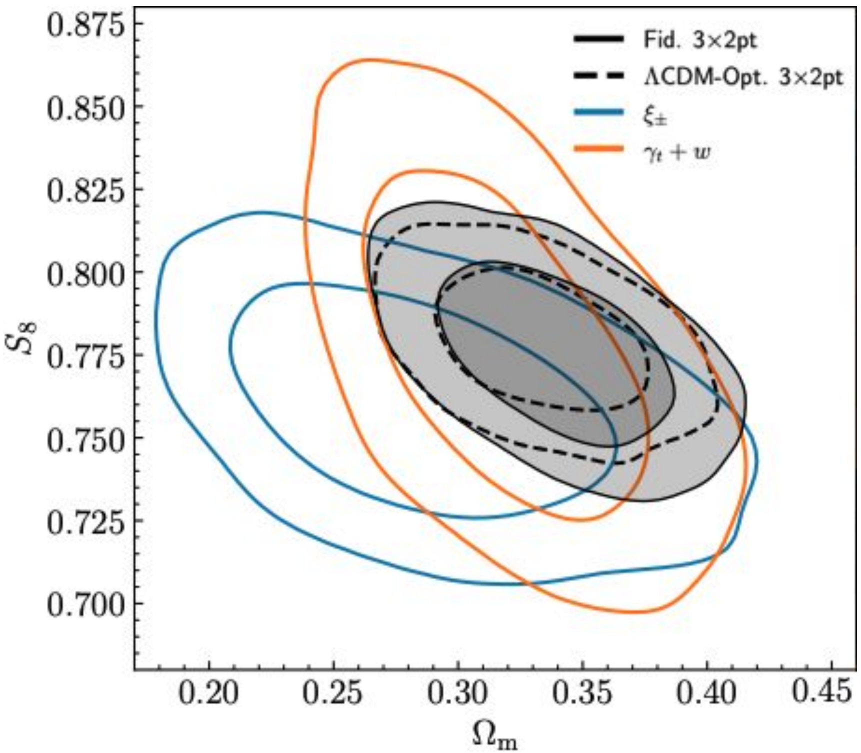
DES Y3 RESULTS: S8 marginally lower than Planck

Cosmic Shear



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

Cosmic Shear + 2x2pt (3x2pt)



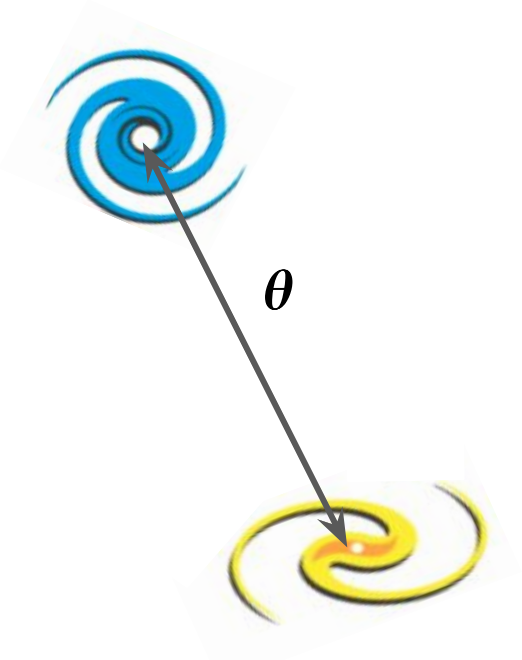
DES et al (2021); Pandey et al (2021); Porredon et al (2021)

Part 1: non-Gaussian lensing statistics

Based on LS et al (2022)
arxiv #2201.05227

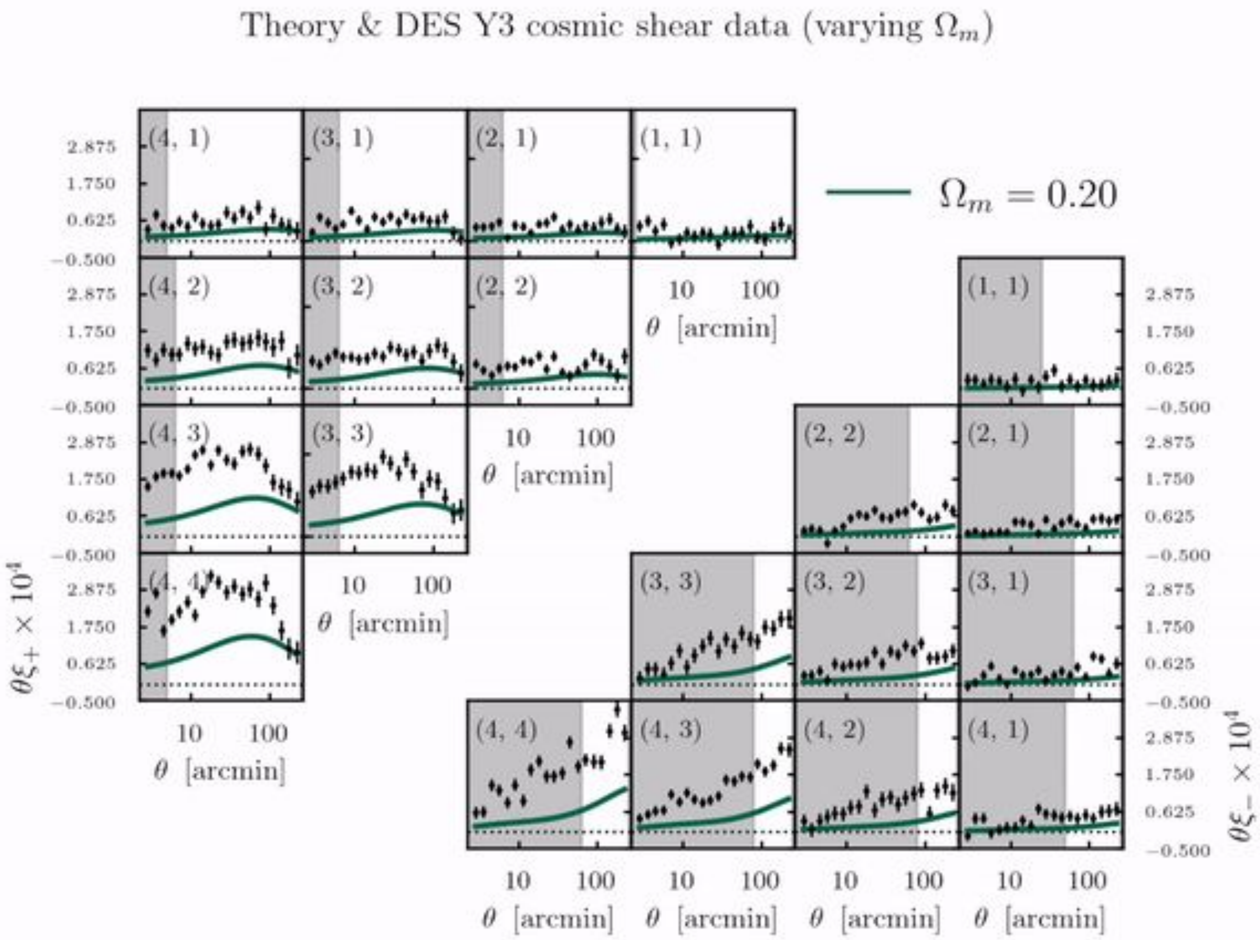
(with M. Jarvis, B. Jain, C. Chang, ++)

Constraints like these are based on decades of knowledge on how to **measure, model and mitigate systematics of** two-point (2pt) statistics



Gaussian statistics such as this **cannot contain** the entire information in our observables (galaxies, shears, …).
We would like access **non-Gaussian information**

Additionally, we would like to break **parameter degeneracies**:



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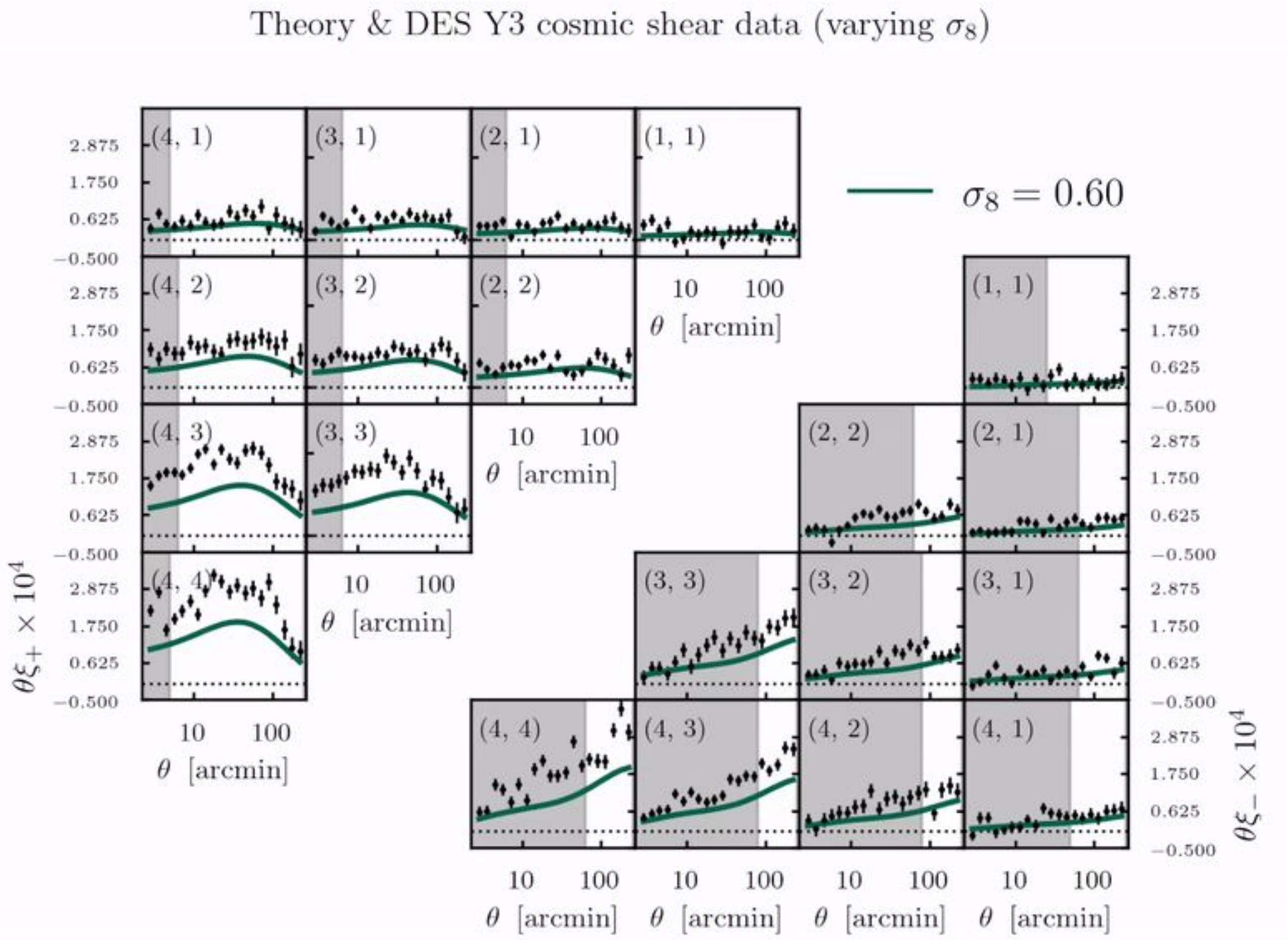
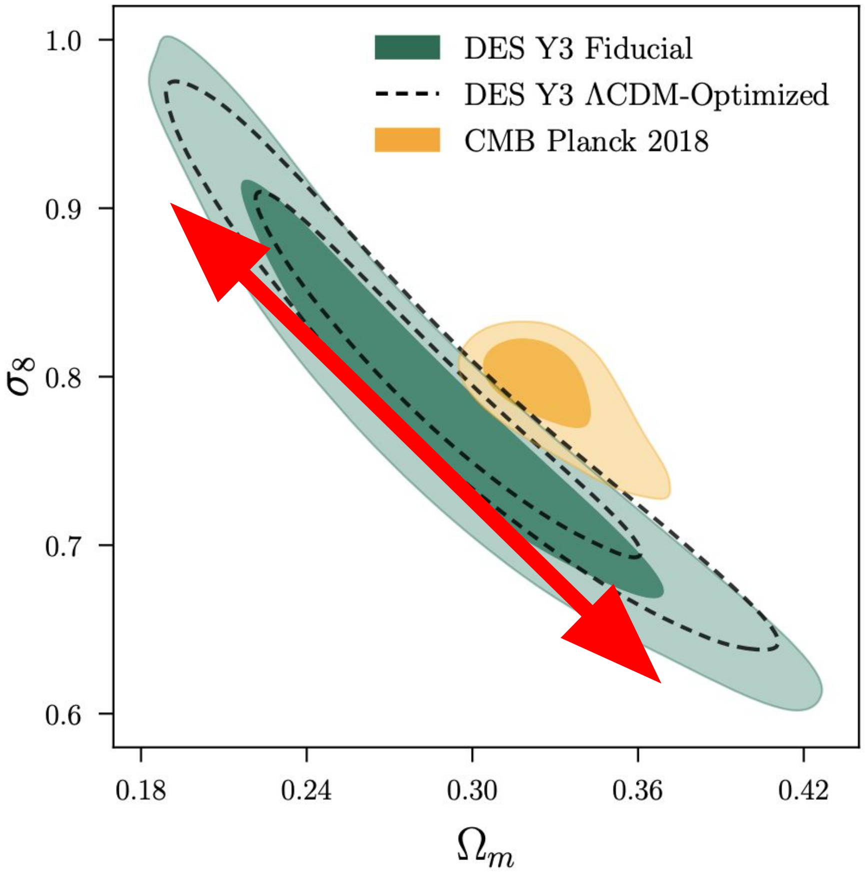
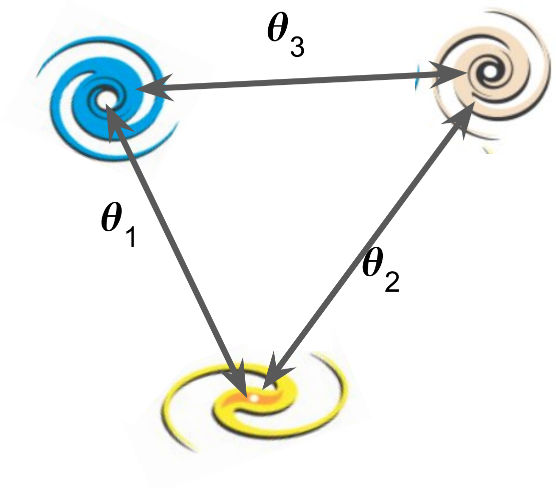


This degeneracy between sigma8 and Om is a crucial aspect in weak lensing:

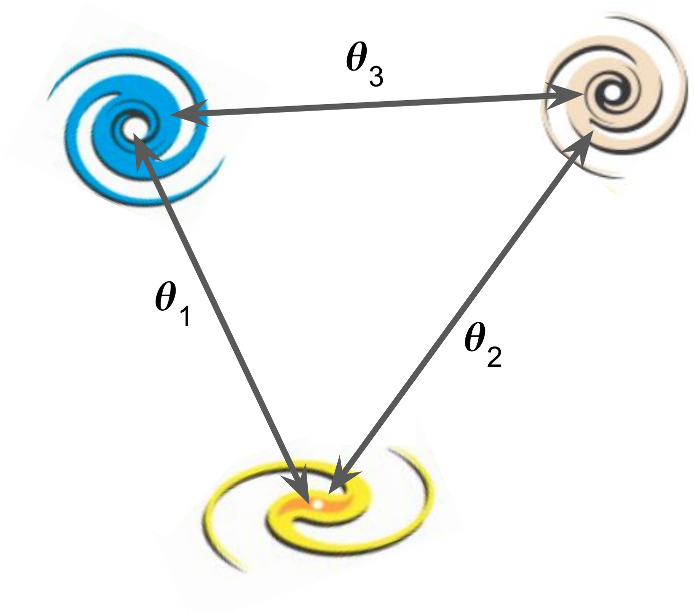


The goal is to measure a new observable that does both: accesses **extra information** (non-Gaussian) & **breaks the degeneracy in** $\Omega_\mathrm{m} \times \sigma_8$ **.**



The problem: **three-point cosmic shear** had only been detected at marginally small signal-to-noise to date.

In what follows, I present high signal-to-noise detections of **three-point cosmic shear** and **mass apertures** in DES Y3



Our question to the data: *what lensing 3-point signatures can we measure?*

Defining these statistics in their most familiar form:

Mass aperture "Map" and its cross component "M-cross"

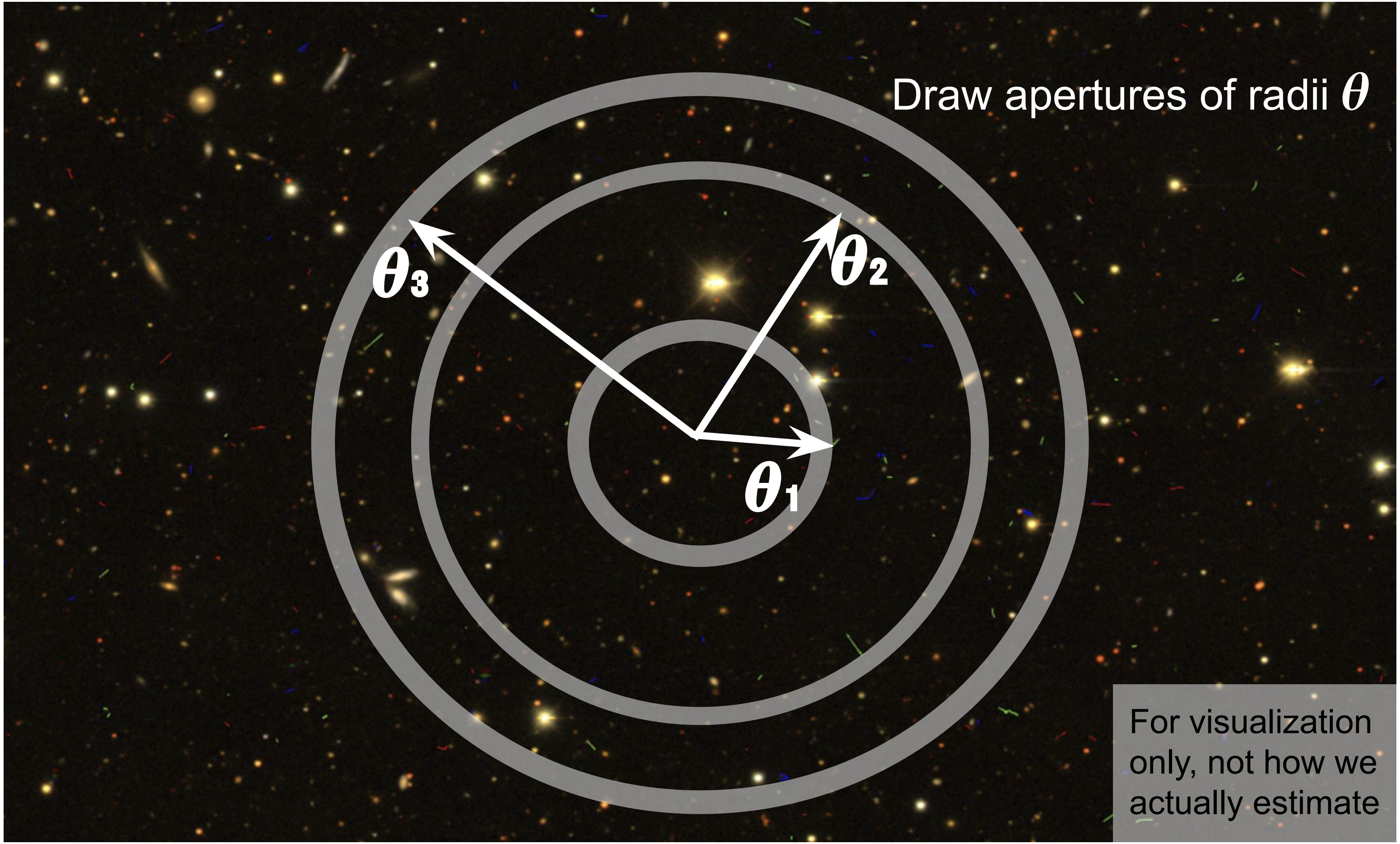
$$\boxed{\begin{aligned} M(\theta) &= M_{\mathrm{ap}}(\theta) + iM_\times(\theta) \\ &= \int d^2\boldsymbol{r} Q_\theta(r)\gamma_t(\boldsymbol{r}) + i\int d^2\boldsymbol{r} Q_\theta(r)\gamma_\times(\boldsymbol{r}), \end{aligned}}$$

[Schneider et al 1998]

And direct correlations of the shears of galaxies in real space (cosmic shear)

$$\boxed{\xi_\pm(\theta) = \langle\gamma_t\gamma_t\rangle(\theta) \pm \langle\gamma_\times\gamma_\times\rangle(\theta) \equiv \gamma_{tt} \pm \gamma_{\times\times}}$$

1) the 3rd order Mass Aperture ("Map") statistic



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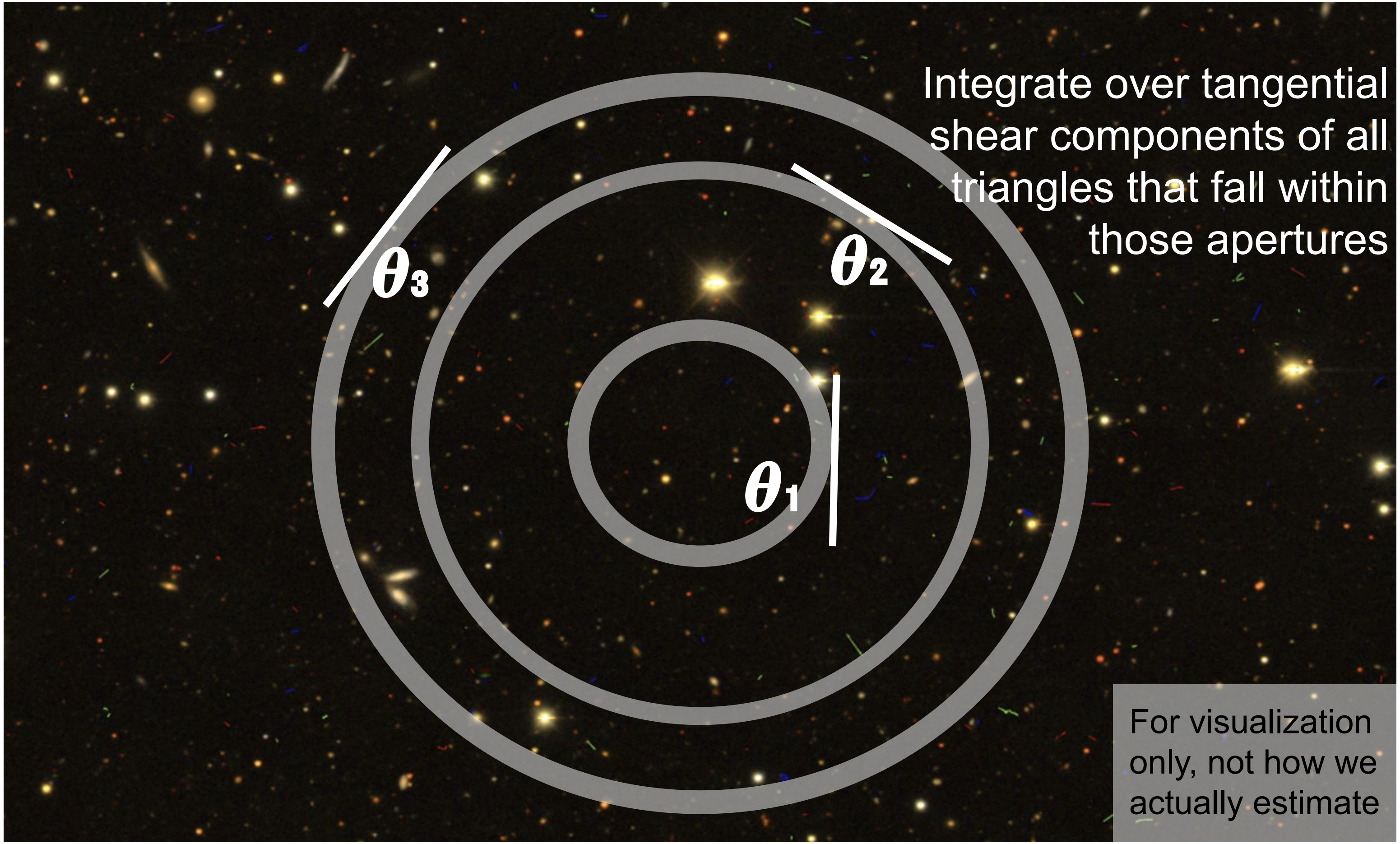

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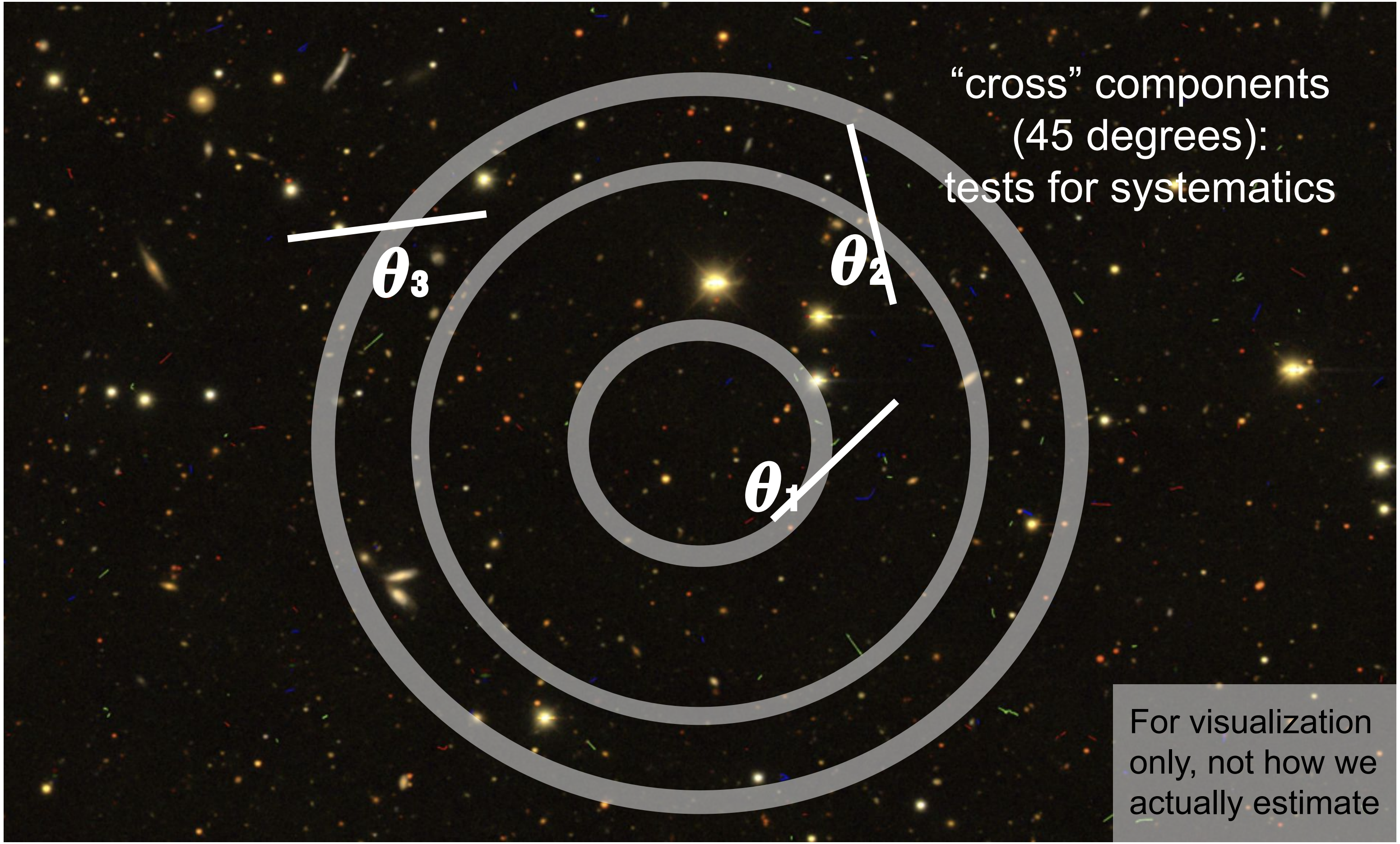
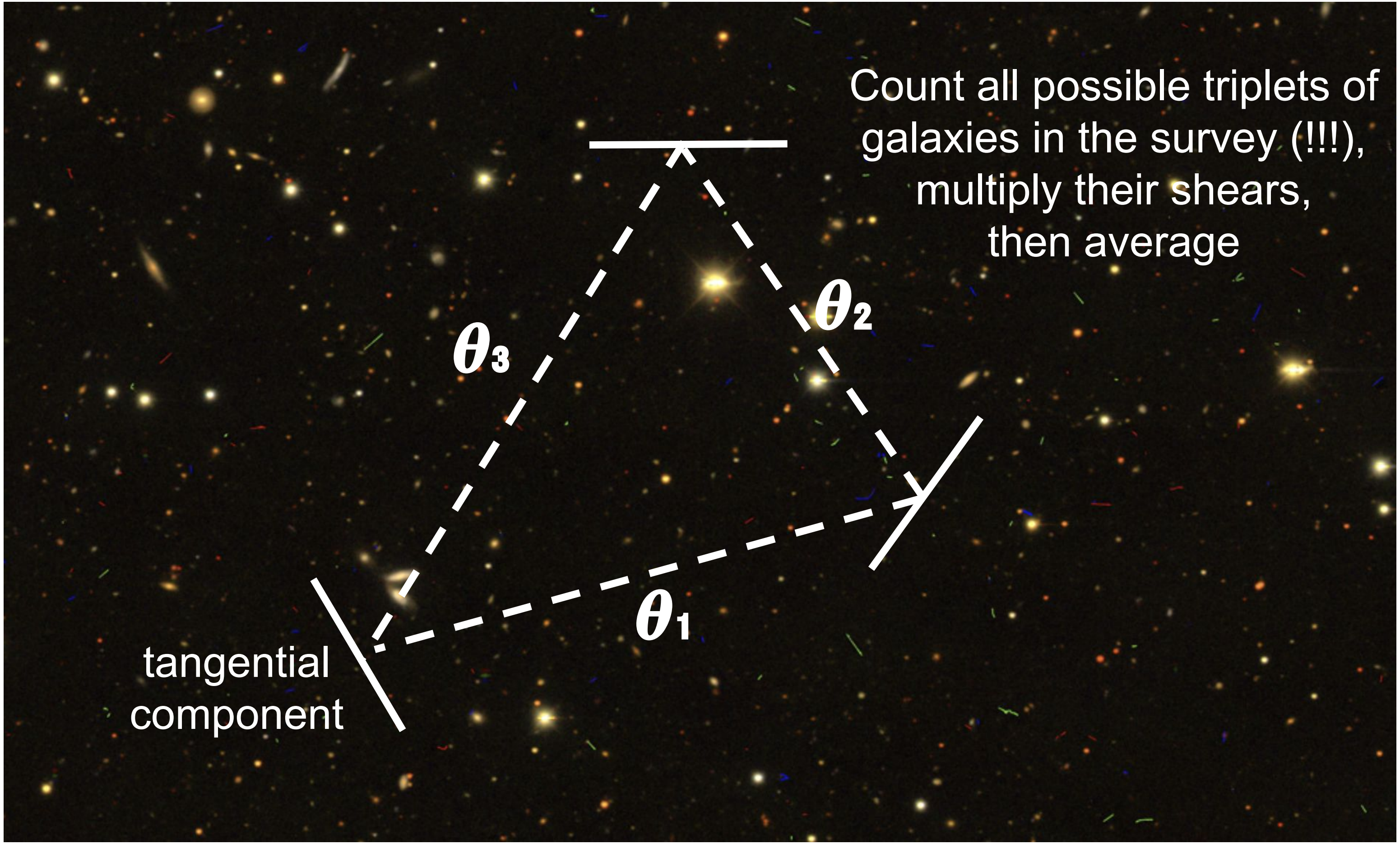


2) Three-point cosmic shear



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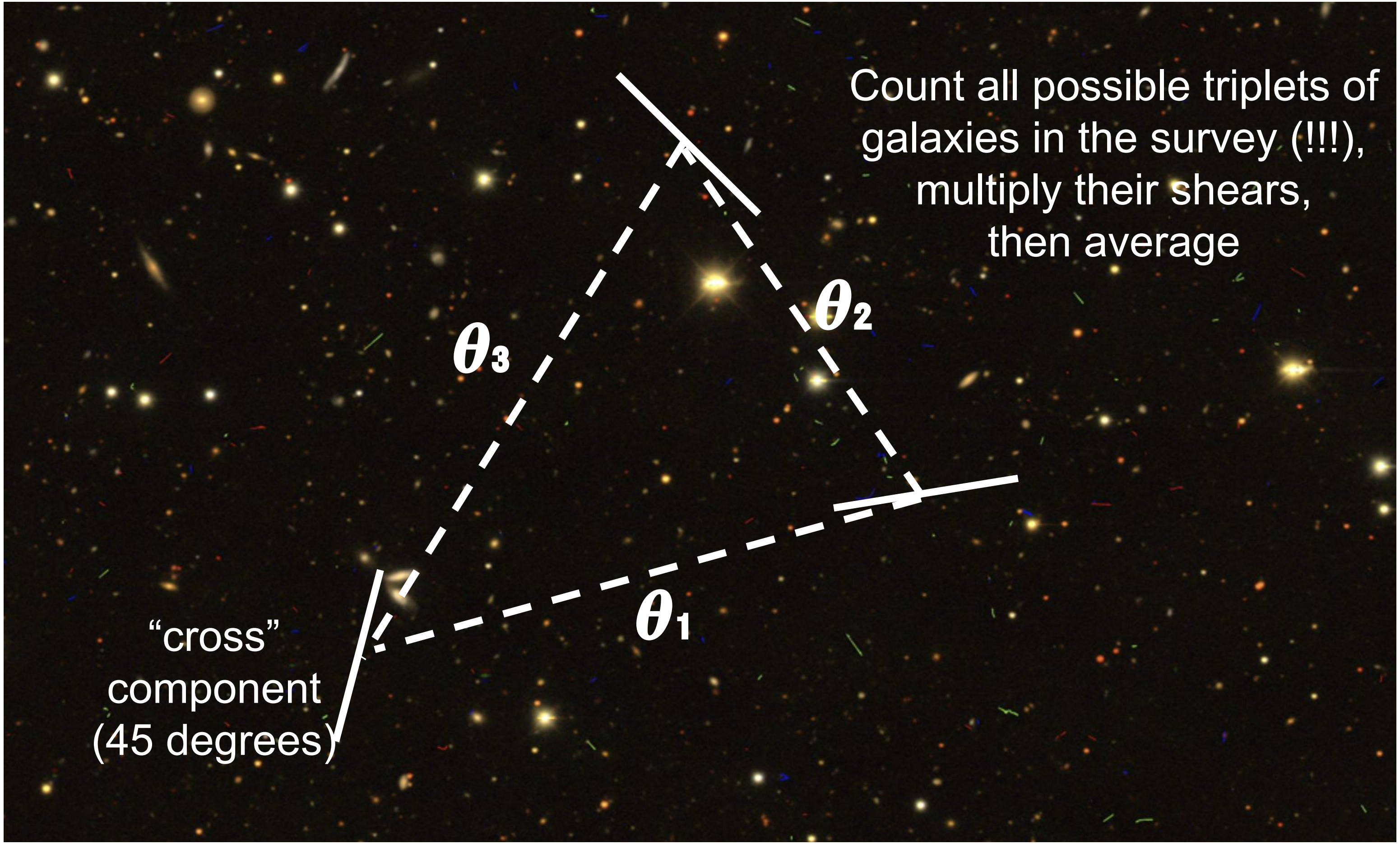


Several components for each statistic

$$\langle M_{\rm ap}^3 \rangle$$

$$\langle M_{\rm ap}^2 M_\times \rangle$$

$$\langle M_{\rm ap} M_\times^2 \rangle$$

$$\langle M_\times^3 \rangle$$

With Map representing **pure E-modes** and Mx representing **pure B-modes**

$$\Gamma_0 \equiv \langle \gamma(\boldsymbol{\theta}_1)\gamma(\boldsymbol{\theta}_2)\gamma(\boldsymbol{\theta}_3)\rangle = \gamma_{ttt} - \gamma_{t\times\times} - \gamma_{\times t\times} - \gamma_{\times\times t} + i\left[\gamma_{tt\times} + \gamma_{t\times t} + \gamma_{\times tt} - \gamma_{\times\times\times}\right], \quad (5)$$

$$\Gamma_1 \equiv \langle \gamma^*(\boldsymbol{\theta}_1)\gamma(\boldsymbol{\theta}_2)\gamma(\boldsymbol{\theta}_3)\rangle = \gamma_{ttt} - \gamma_{t\times\times} + \gamma_{\times t\times} + \gamma_{\times\times t} + i\left[\gamma_{tt\times} + \gamma_{t\times t} - \gamma_{\times tt} + \gamma_{\times\times\times}\right], \quad (6)$$

$$\Gamma_2 \equiv \langle \gamma(\boldsymbol{\theta}_1)\gamma^*(\boldsymbol{\theta}_2)\gamma(\boldsymbol{\theta}_3)\rangle = \gamma_{ttt} + \gamma_{t\times\times} - \gamma_{\times t\times} + \gamma_{\times\times t} + i\left[\gamma_{tt\times} - \gamma_{t\times t} + \gamma_{\times tt} + \gamma_{\times\times\times}\right], \quad (7)$$

$$\Gamma_3 \equiv \langle \gamma(\boldsymbol{\theta}_1)\gamma(\boldsymbol{\theta}_2)\gamma^*(\boldsymbol{\theta}_3)\rangle = \gamma_{ttt} + \gamma_{t\times\times} + \gamma_{\times t\times} - \gamma_{\times\times t} + i\left[-\gamma_{tt\times} + \gamma_{t\times t} + \gamma_{\times tt} + \gamma_{\times\times\times}\right] \quad (8)$$

[Schneider & Lombardi 2003]

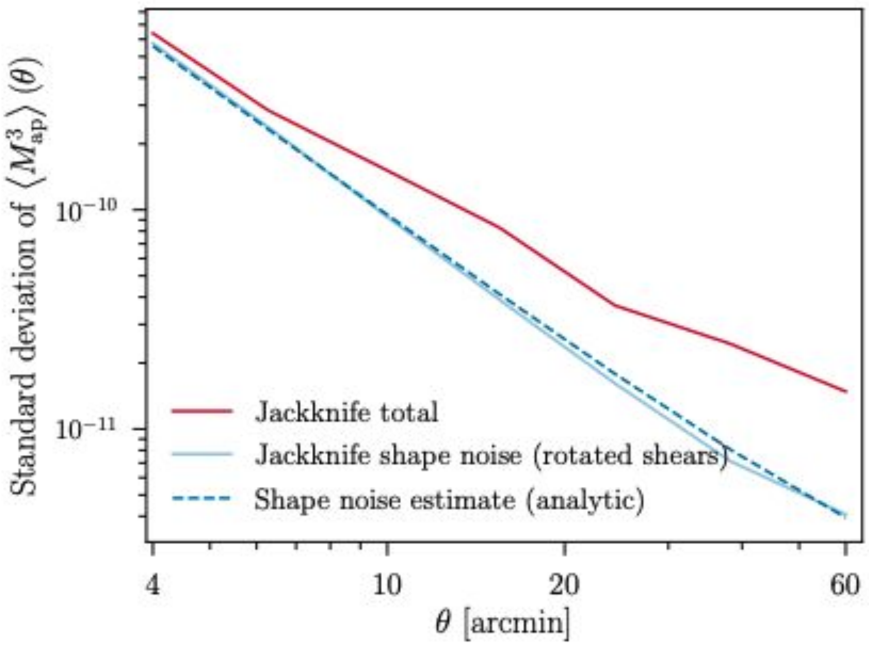
The two statistics have different properties:

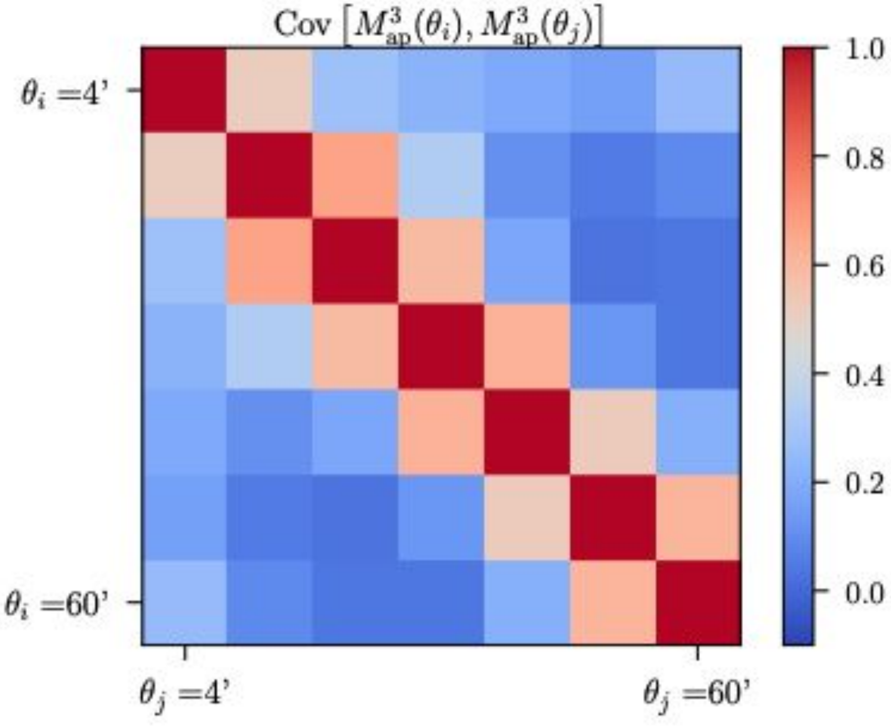
$\left\langle M_{\mathrm{ap}}^3 \right\rangle (\theta_1, \theta_2, \theta_3)$: integrated, generally **higher signal-to-noise**, easy **E/B mode split,** good for cosmology, detected in the past at up to ~2σ confidence [Jarvis et al 2004, Semboloni et al 2011, Fu et al 2014]

$\Gamma_0 (\theta_1, \theta_2, \theta_3)$: split by **shear components & triangle configuration**, E/B modes mixed in complicated ways, detections only marginal in literature

arxiv#2201.05227

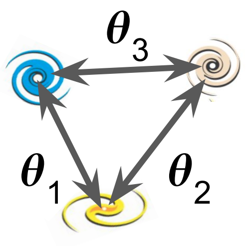
We split the DES Y3 area to allow for **jackknife estimates** of the covariances (all error bars in what follows come from that)



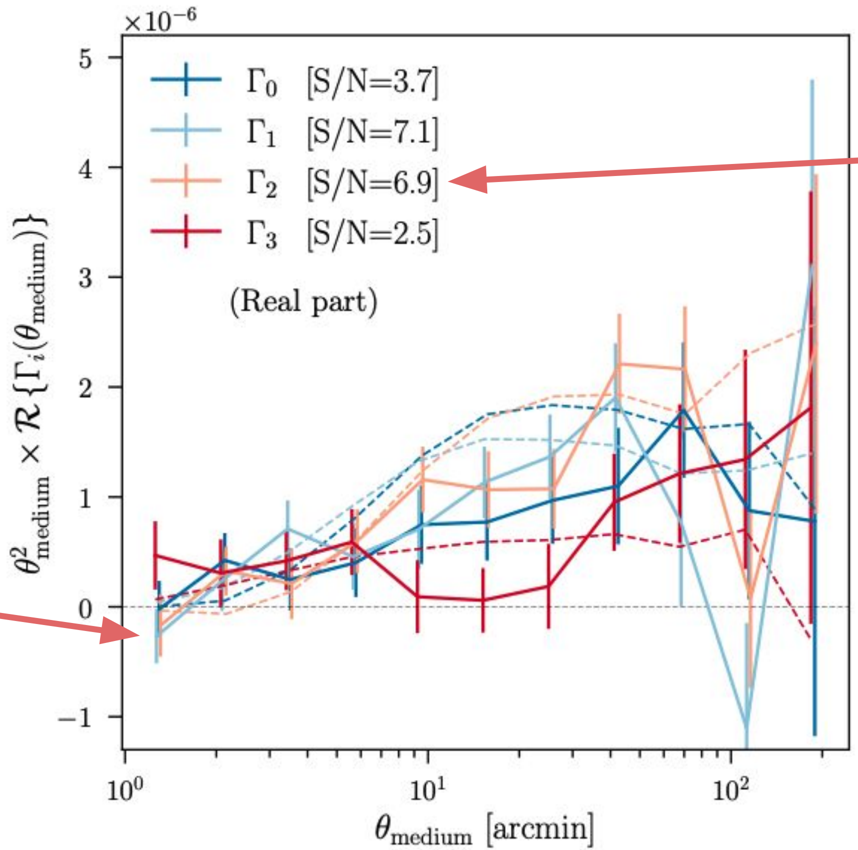


arxiv#2201.05227

The measurements: three-point cosmic shear



The three-point version of cosmic shear, binned conveniently

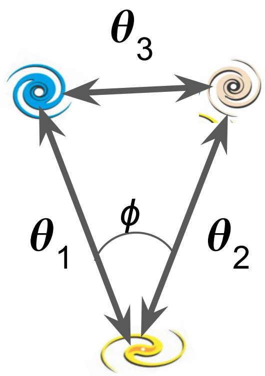


High S/N (and first detection of all these) but there are 8 such correlations!

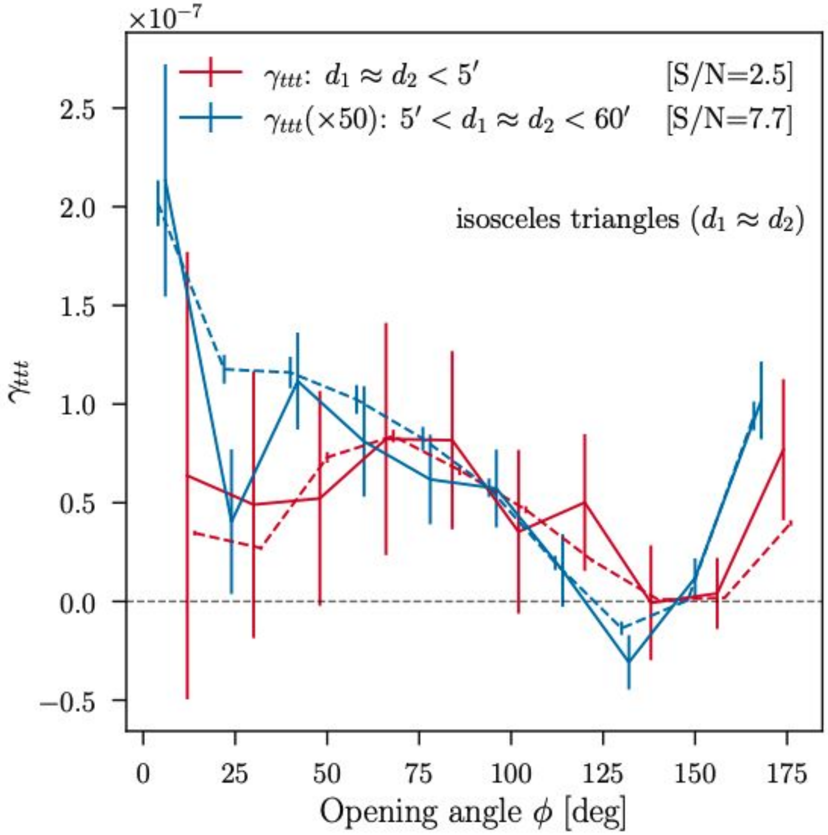
Dashed curves from [Takahashi et al 2017] N-body sims without shape-noise: qualitative agreement with theory expectation

arxiv#2201.05227

The measurements: configuration dependence of three-point shear



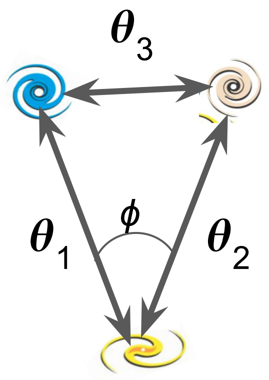
Configuration dependence of the signal (isosceles)



Different triangle configurations probe different physics: **primordial vs. gravitational** non-Gaussianities

arxiv#2201.05227

The measurements: configuration dependence of three-point shear



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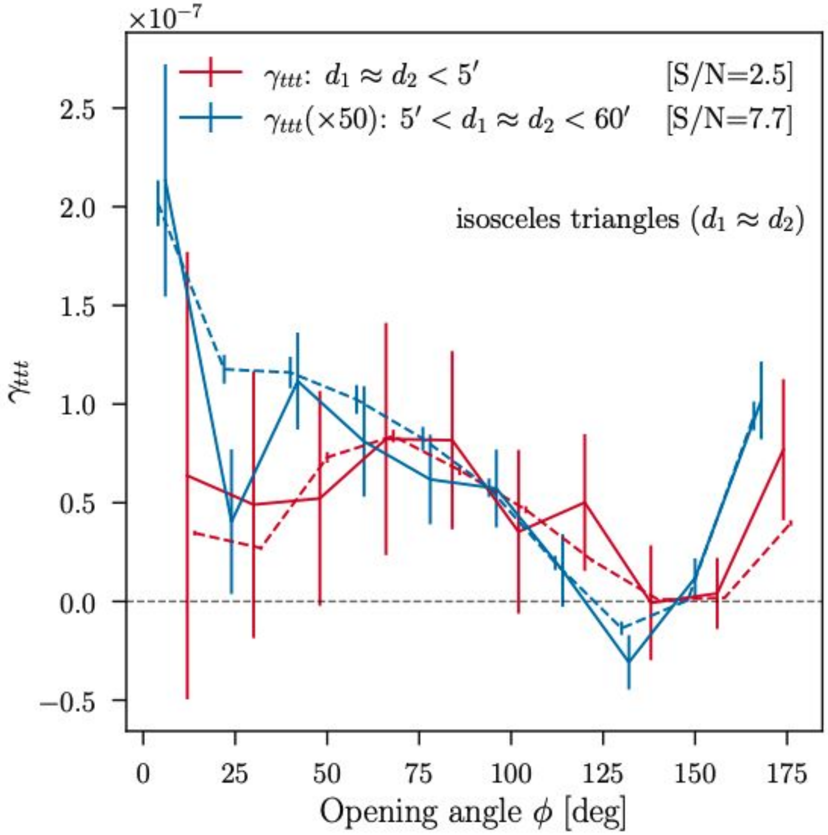


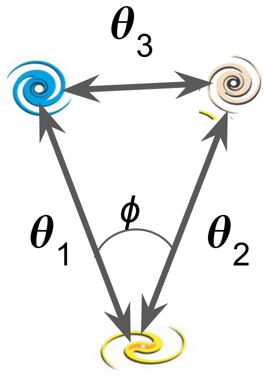
A **halo model** interpretation of these features is feasible

[Takada & Jain 2003]

Signals of the type <lens source source> may also provide information on DM **halo shapes**

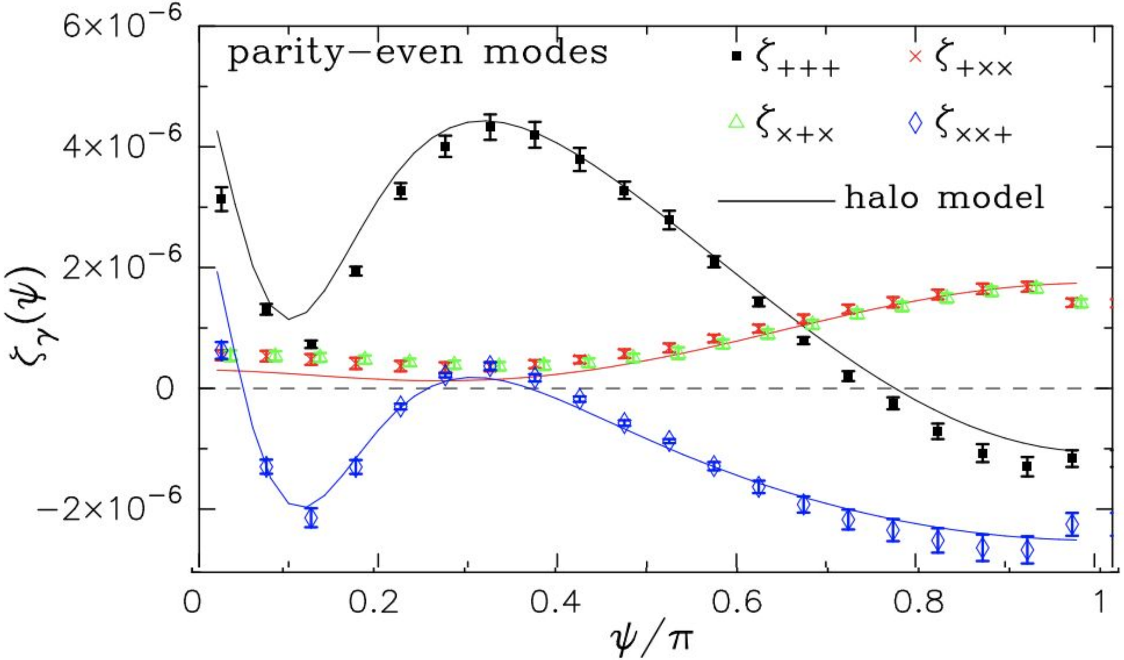
[Adhikari et al 2015]

The measurements: configuration dependence of three-point shear

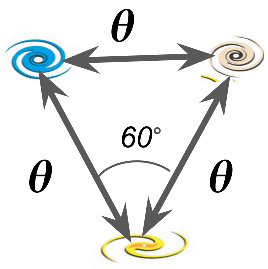


Configuration dependence of the signal (isosceles)

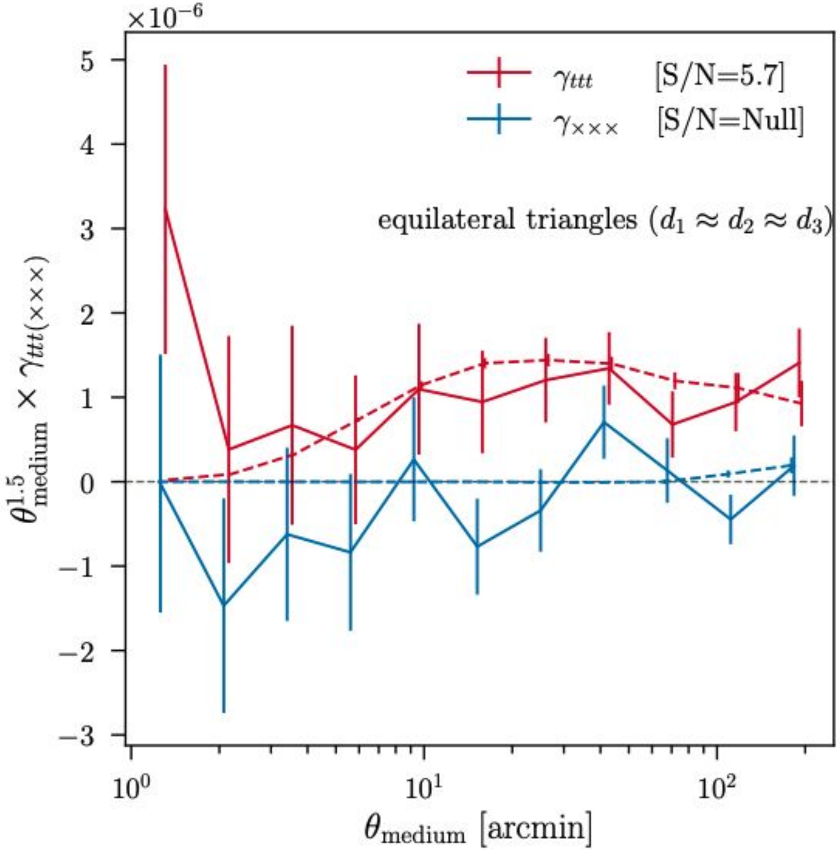
[Takada & Jain 2003]



The measurements: configuration dependence of three-point shear



Configuration dependence of the signal (equilateral)

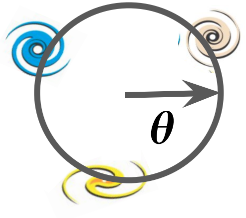


Equilateral configurations contain most of the E-mode non-Gaussian signal and provides **null tests**

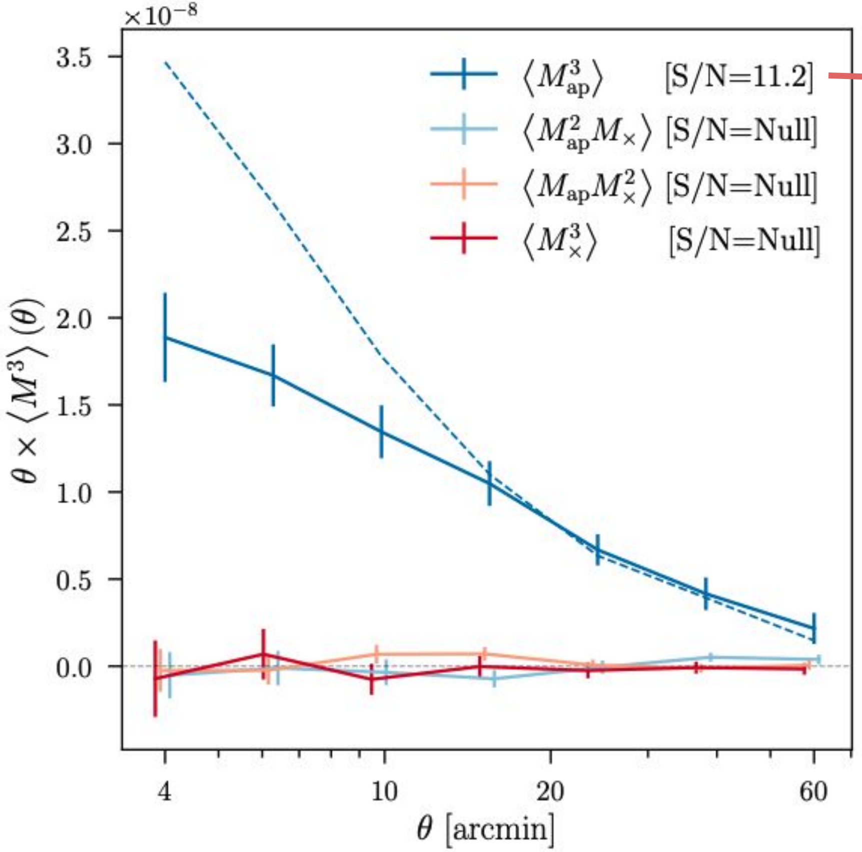
[Schneider & Lombardi 2003, Takada & Jain 2003]

arxiv#2201.05227

The measurements:
Non-tomographic mass aperture at special case $\theta_1=\theta_2=\theta_3=\theta$



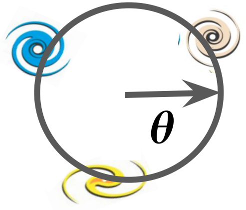
Mass (tangential shear) within an aperture theta



Compresses the E-mode signal, **highest S/N** to date

arxiv#2201.05227

The measurements: Non-tomographic mass aperture at special case $\theta_1=\theta_2=\theta_3=\theta$



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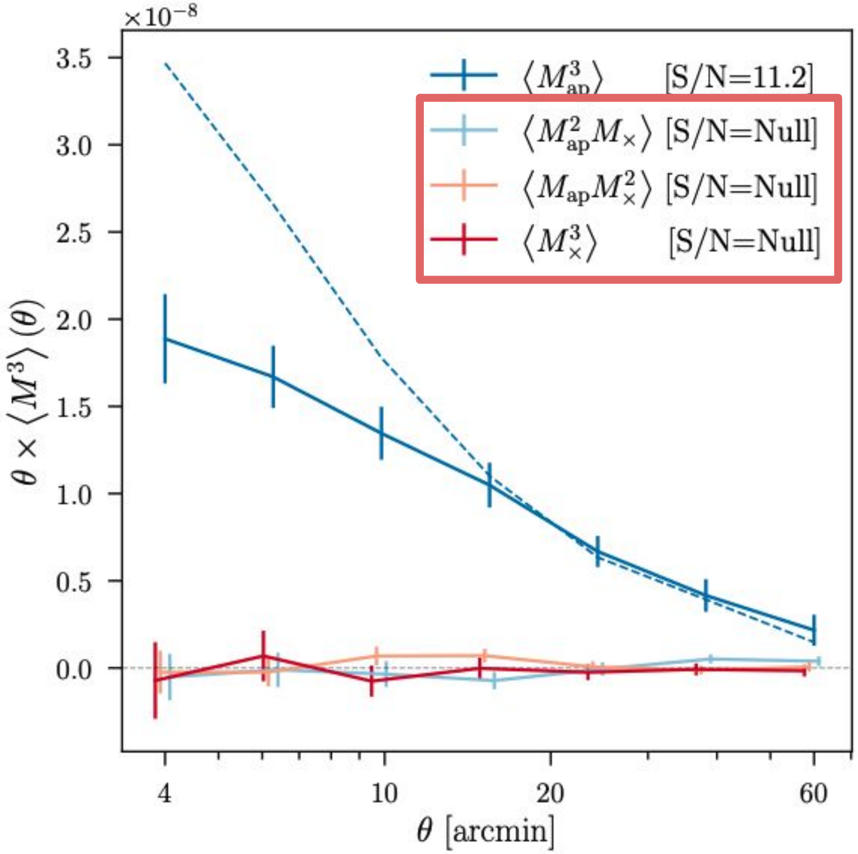
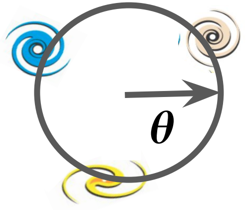


These correlations would imply a measurement of lensing B-modes and/or parity violation: **neither are found** in our measurements

(means systematics are subdominant!)

The measurements:
Non-tomographic mass aperture at special case $\theta_1=\theta_2=\theta_3=\theta$



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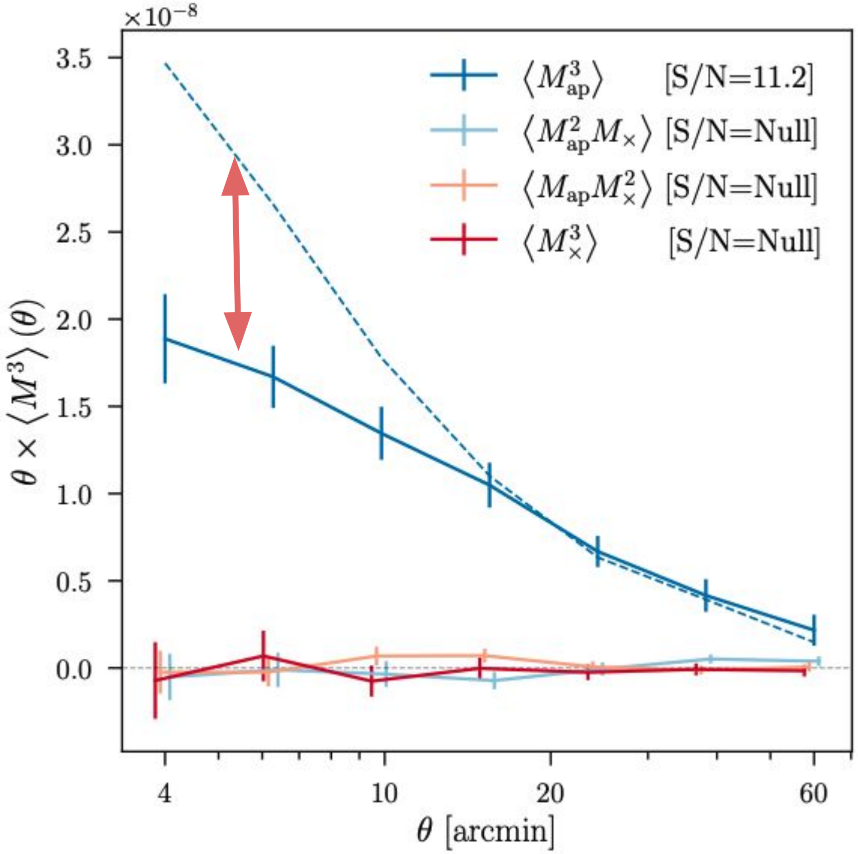
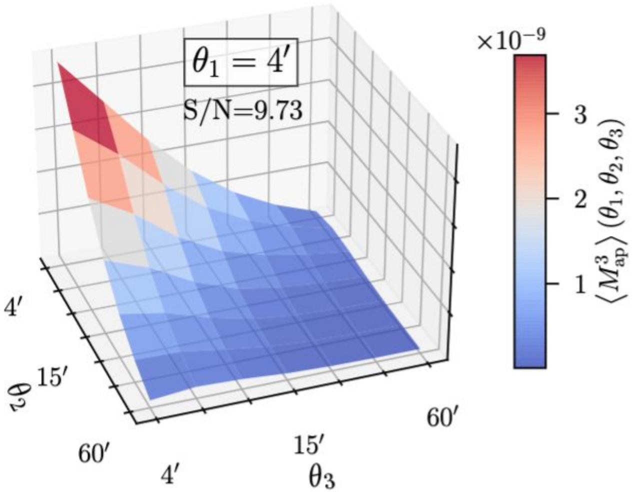
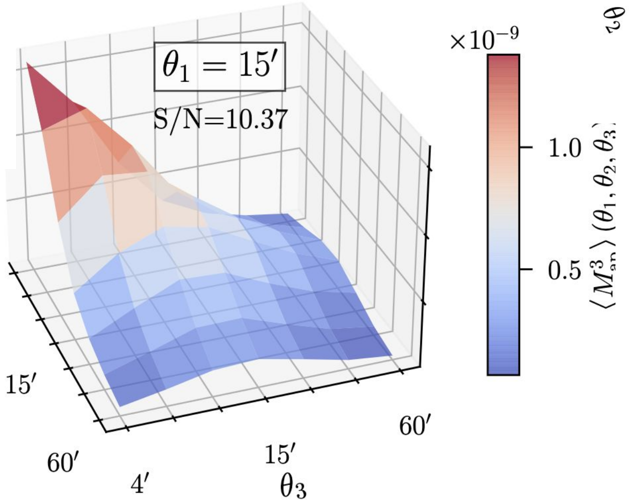


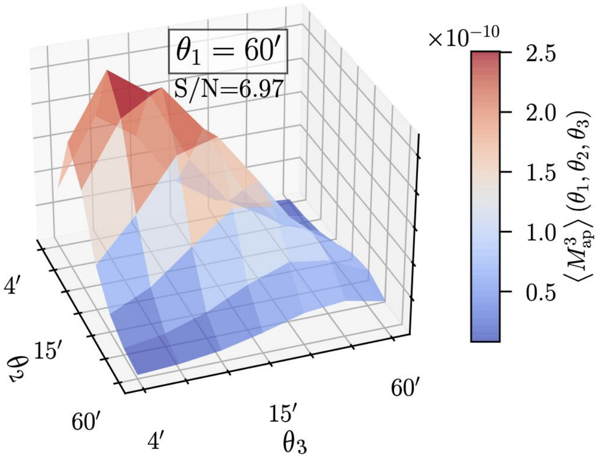
Discrepancy between data and T17 sims at small scales?
Needs more testing for a definitive answer
(no evidence for it in Gatti et al 2021)

arxiv#2201.05227

The measurements: Non-tomographic mass aperture at general case $\theta_1 \neq \theta_2 \neq \theta_3$







In each panel, one aperture length is fixed and the other two vary. The signal is stronger at small scales and still nonzero on large scales

Degeneracy breaking power: a back-of-the-envelope description

$$\kappa(\hat{\boldsymbol{n}}) = \int_0^\infty dz\, W(\chi)\delta(\hat{\boldsymbol{n}}, \chi)$$

$$\gamma \sim \kappa \sim \Omega_m \delta$$

$$\langle\gamma\rangle \sim \langle\delta\rangle = 0$$

$$\langle\gamma\gamma\rangle \sim \Omega_m^2 \langle\delta\delta\rangle \sim \Omega_m^2 P(k) \sim \Omega_m^2 \sigma_8^2$$

$$\langle\gamma\gamma\gamma\rangle \sim \Omega_m^3 B(k) \sim \Omega_m^3 P(k)^2 \sim \Omega_m^3 \sigma_8^4$$

$$\frac{\langle\gamma\gamma\gamma\rangle}{\langle\gamma\gamma\rangle^2} \sim \frac{1}{\Omega_m}$$

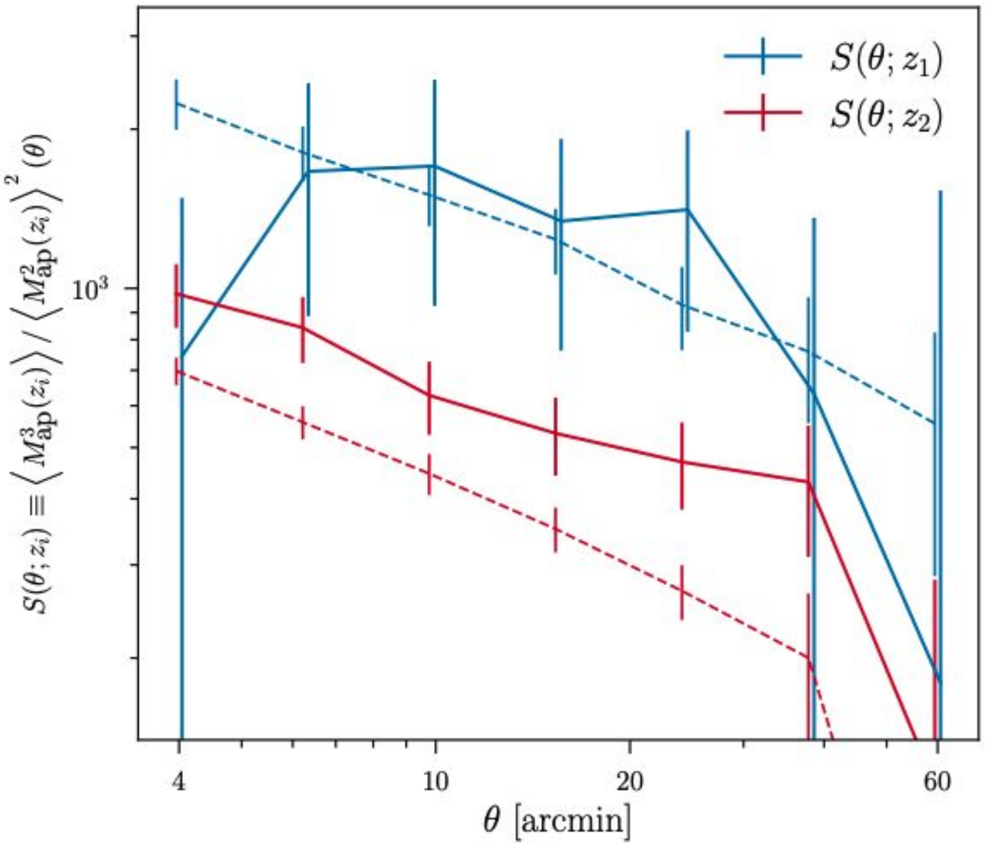
A quantity that is independent of sigma8 and thus breaks that important degeneracy.

Also largely independent of the power spectrum shape and normalization

[Takada & Jain 2004, Bernardeau et al 1997]

arxiv#2201.05227

The measurements: Reduced skewness parameter as a function of redshift



Redshift evolution: consistent with expectation [Bernardeau et al 1997]

Near-independence of the power spectrum shape and normalization means this is mostly a geometrical probe

Additionally, we want **(need!)** to be able to show that signals of interest to cosmology analyses are free of systematics.

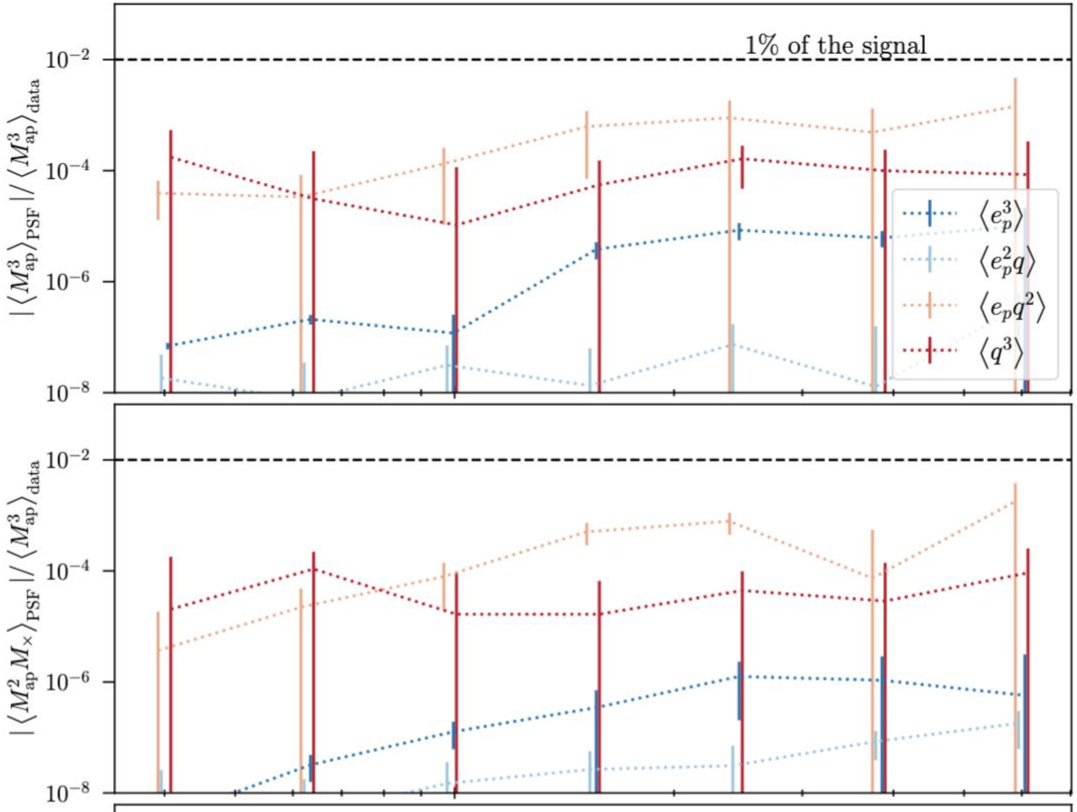
The first order of business:
observables are free of systematics of **observational origin**
[Gatti et al 2021, Li et al 2021, Giblin et al 2020, Zuntz et al 2018…]

Rely on the extensive validation of the DES Y3 shear catalog and perform **tests on the 3pt measurements** themselves

Propagating PSF residual systematics due inaccurate modeling to the 3pt level: contributions are negligible

Three-point "rho-statistics": a **typical diagnostic** for 2pt cosmic shear

[Rowe et al 2010]



Obtained from empirically measuring 3pt correlations on reserved stars

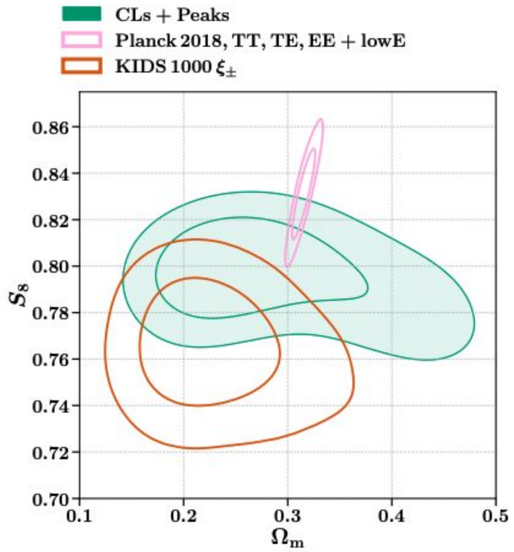
Three-point generally more robust to systematics (than 2pt)?

Easy to show that **mean shear systematics** create a contamination to $\xi_+ \equiv \gamma_{tt} + \gamma_{\times\times}$ but not to Γ_0 ,

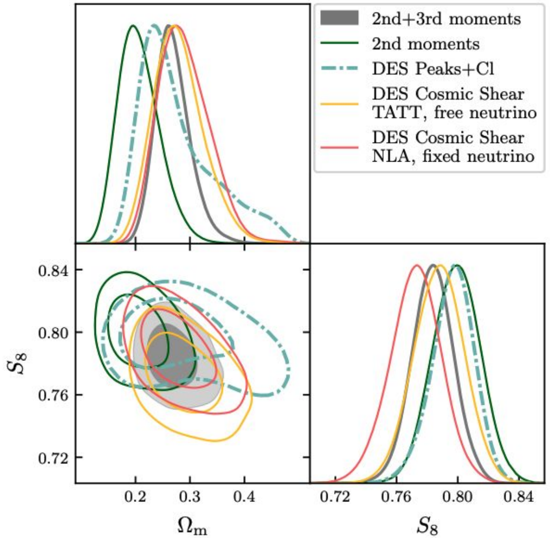
Systematics that are naturally “Gaussian-process-like” should have **suppressed 3pt signatures** (eg atmospheric PSFs),

In practice, just hard to come up with systematics that are coherent over triangles.

Different approaches to access higher (than 2nd) order information in lensing have been very successful:



DES Y3: Harmonic space correlations + density peaks with forward-modeling [Zeurcher et al 2021]



DES Y3: Second + third moments of the lensing convergence field [Gatti et al 2021]

Other methods / estimators:

Integrated statistics [Halder et al 2022]

Machine learning-inspired techniques [Cheng & Ménard 2021, Lu et al 2022]

Mass apertures [Porth et al 2021]

Minkowski Functionals [Marques et al 2019]

The variety of methods/approaches is a good thing:

- **Consistent results** from widely different methods indicates we're learning something real
  [Doux et al 2021, Asgari et al 2020, Chang et al 2019]

- **Practical aspects** about different estimators complement each other (covariance estimation, ease of modeling, …)

- **Fundamental aspects** about different estimators also complement (sensitivity to systematics, total contained information, configuration dependence…)

Part 2: modeling intrinsic alignments with N-body sims

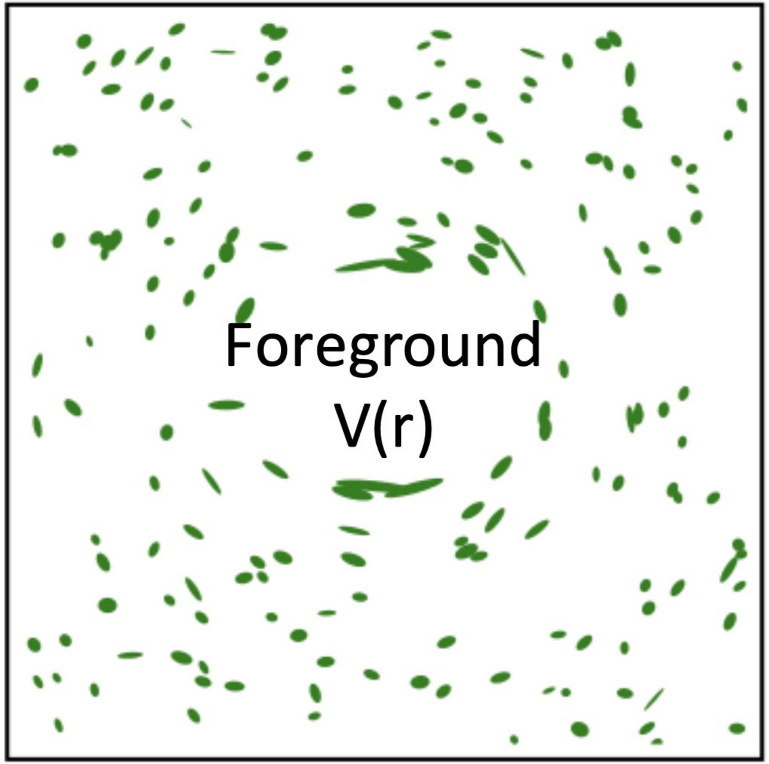
Based on K. Hoffman, LS et al (to appear soon)

(with J. Blazek, M. Crocce, P. Fosalba, S.Samuroff, ++)

Intrinsic Alignments

So far, treated galaxies as a **simple backdrop of extended objects,** distorted by an **unobservable foreground** gravitational potential.

Gravitational lensing of the background objects: **tangential pattern**



Intrinsic Alignments

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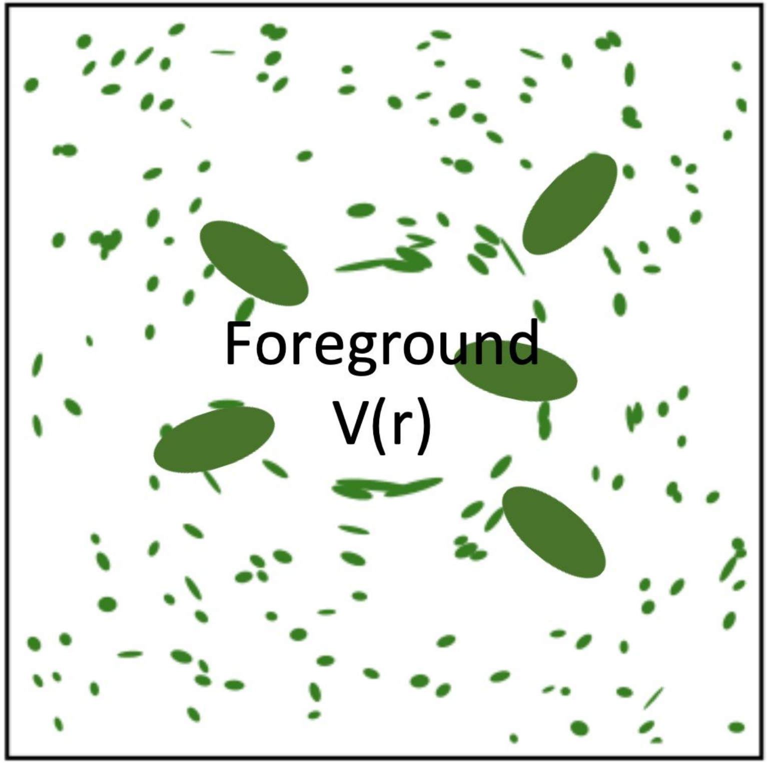
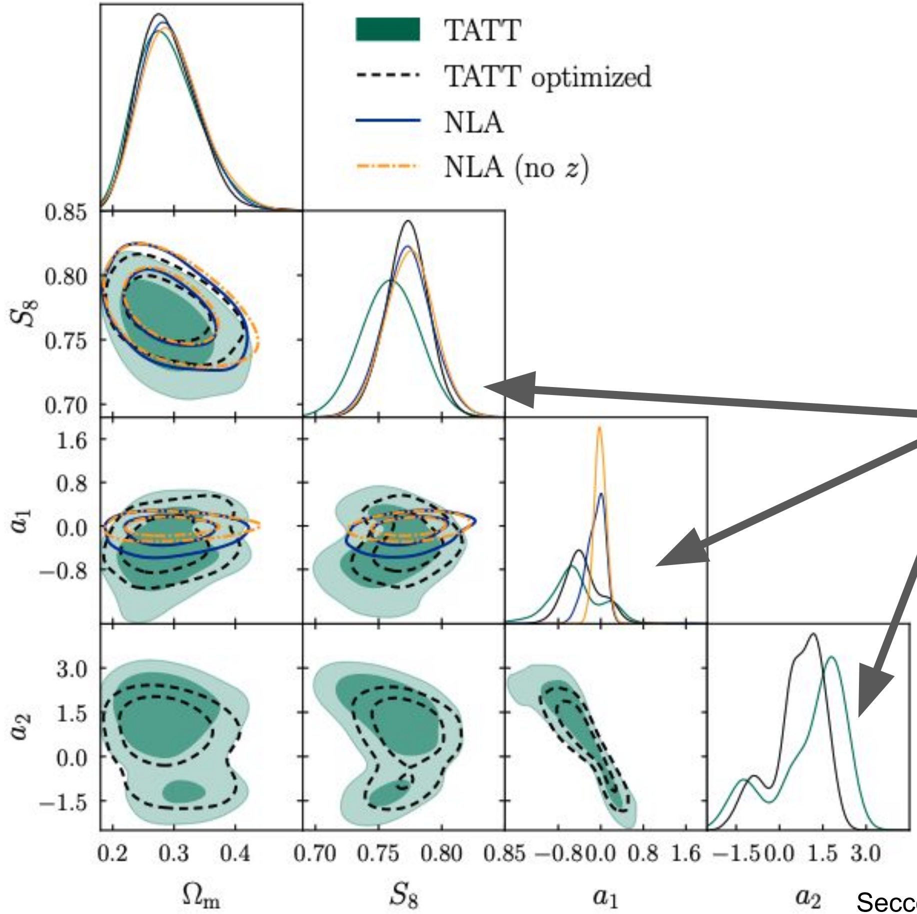


Galaxies sitting on the foreground: **tidally aligned** to first order.

Since the potential is not directly observable, this becomes a **systematic uncertainty**

How to choose a model for IA? In DES Y3, went with analysis based on **theory-generated data**, and verified **consistency of models after final results**.



Found posterior distributions on both IA and cosmological parameters to be consistent regardless of IA model, but **constraining power changes**

Secco, Samuroff et al (2021)

We would like to:

1- Have simulation-based information **while choosing an IA model for a wide cosmological analysis** (in order to avoid biases & loss of constraining power)

2- Learn about IA in general, since it is an **interesting astrophysical probe**
(eg. Chisari & Dvorkin 2013, Okumura+ 2020, Taruya+2020, …)

But challenges include…

1- While much can be learned from **hydro simulations,** they tend to come in small volumes (small compared to wide lensing surveys)
(eg. Shi et al 2021, Samuroff et al 2020)

2- Direct detections of IA in data are **limited to low redshifts** (z~<0.8)

(eg. Singh & Mandelbaum 2016)

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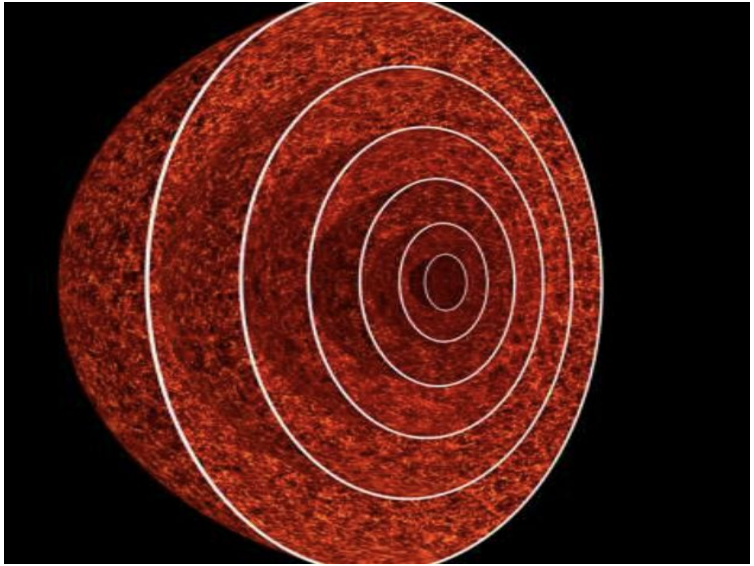
This is where MICE comes in! [https://cosmohub.pic.es/, Carretero et al. 2015, Crocce et al. 2015, Fosalba et al. 2015]

- Gravity-only, 4096^3 collisionless particles with ~3 Msun/h
- ~3Gpc box with a flat ΛCDM cosmology
- DM halos are identified as friends-of-friends groups, populated with synthetic galaxies (HOD+SHAM)
- One of the main DM simulations supporting DES science.

Recipe for IAs in the MICE N-body simulation:

- Assign intrinsic shapes and orientations to point-like galaxies in MICE DM-only simulation
- Include dependence of shapes and alignment on magnitude, color, type, redshift, … **(2D axis ratios match COSMOS data)**
- Calibrate IA model by randomizing galaxy-halo misalignments to match constraints from observations **(BOSS LOWZ)**
- Construct large mock galaxy catalogs in DES-like volumes with lensing & IA



Galaxies in MICE populate halos via Halo Occupation Distributions (HOD) and Subhalo Abundance Matching (SHAM) [Fosalba et al 2008, Carretero et al 2014]

Caveat: statistics will miss baryonic contributions tied to galaxy formation (J. Shi et al 2021, S. Samuroff et al 2020)

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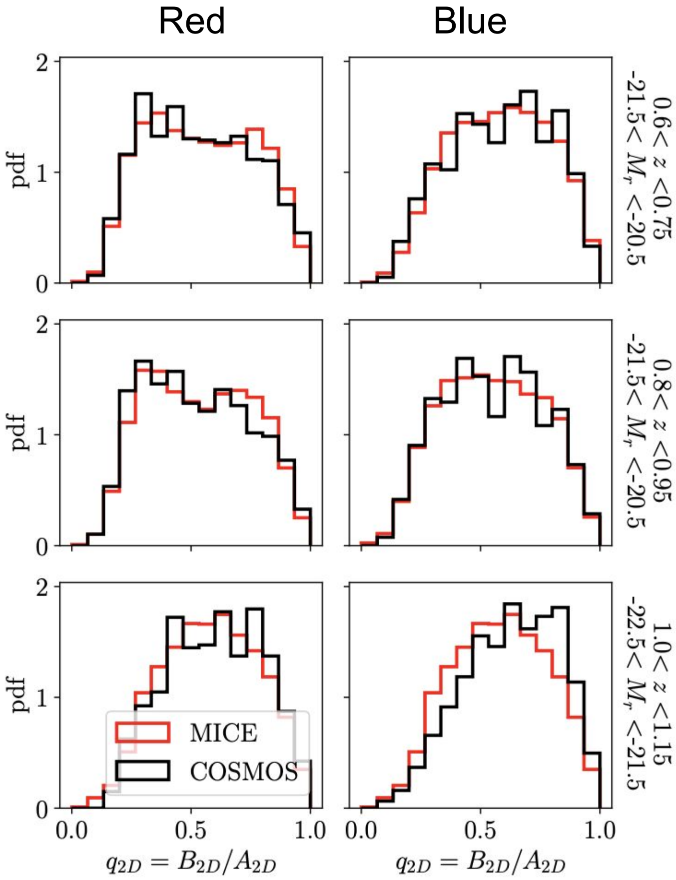

Hoffman, LS et al (to appear)

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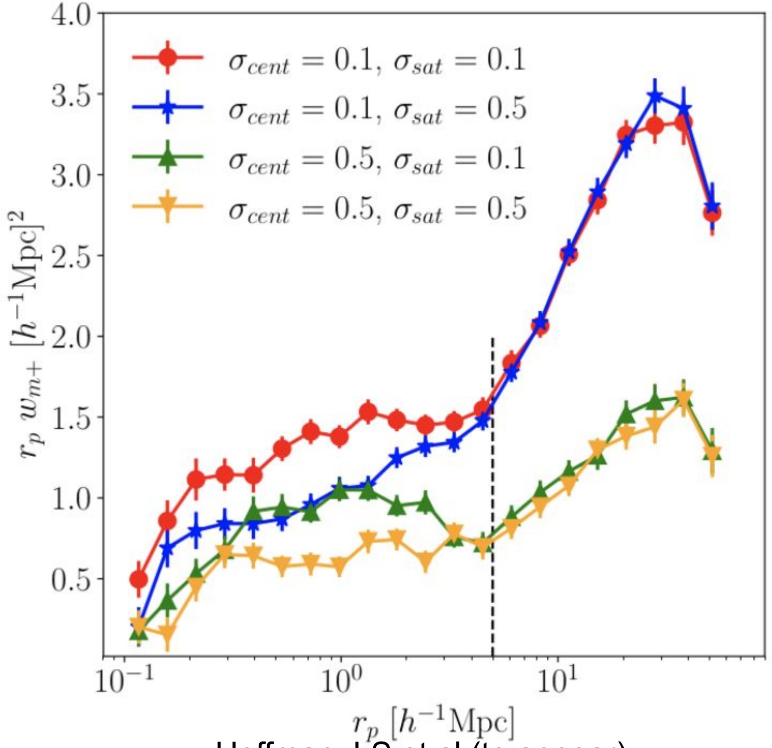
Projected matter-intrinsic correlations (wm+) as a function of model misalignment parameters for centrals and satellites (sigma)



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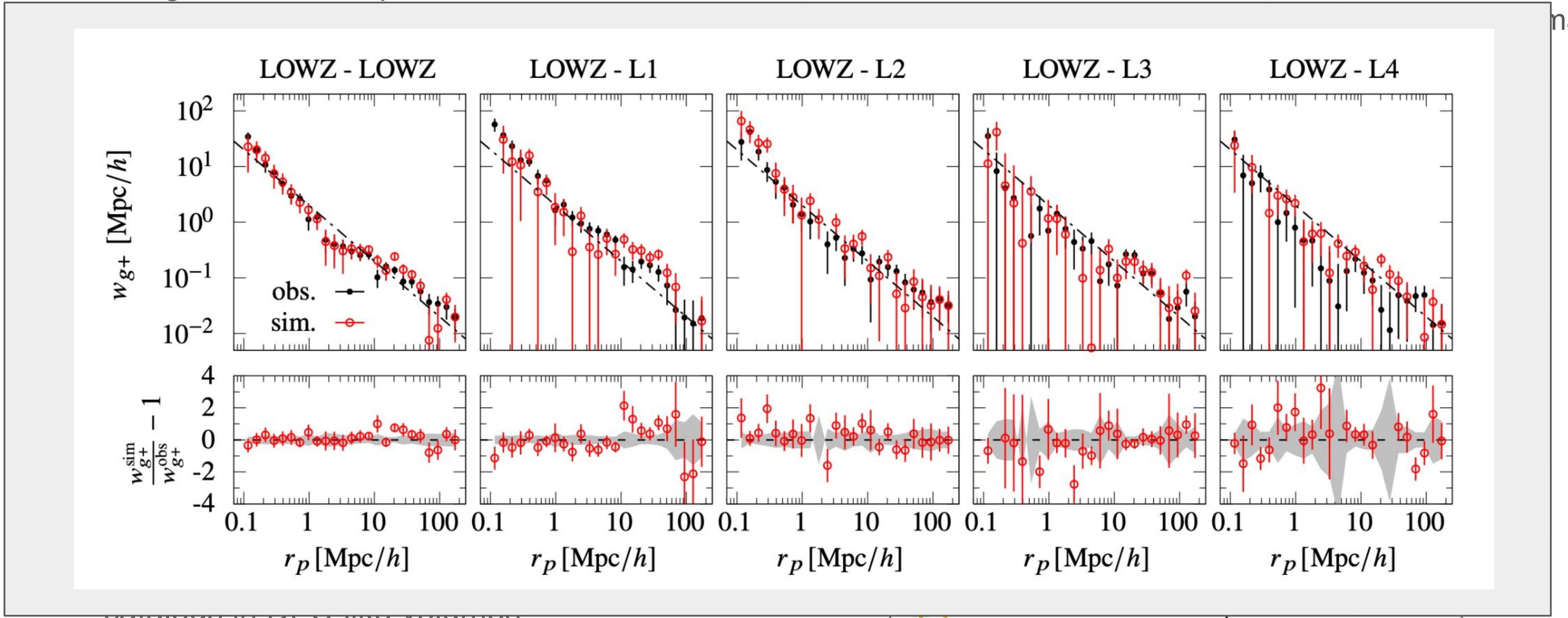
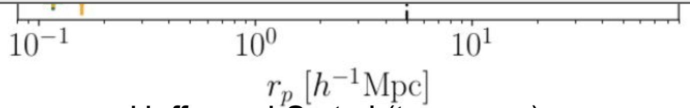


with lensing & IA



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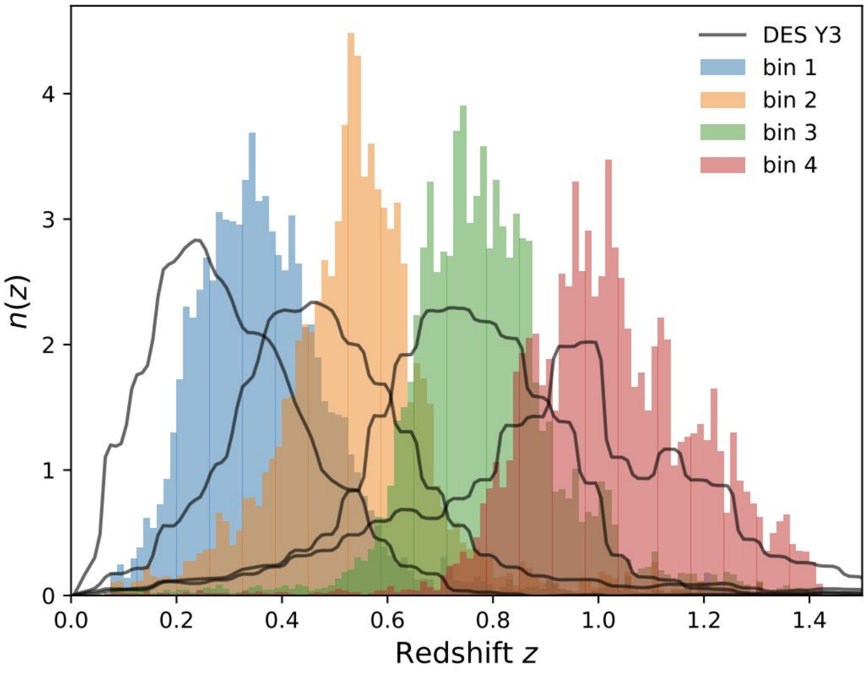
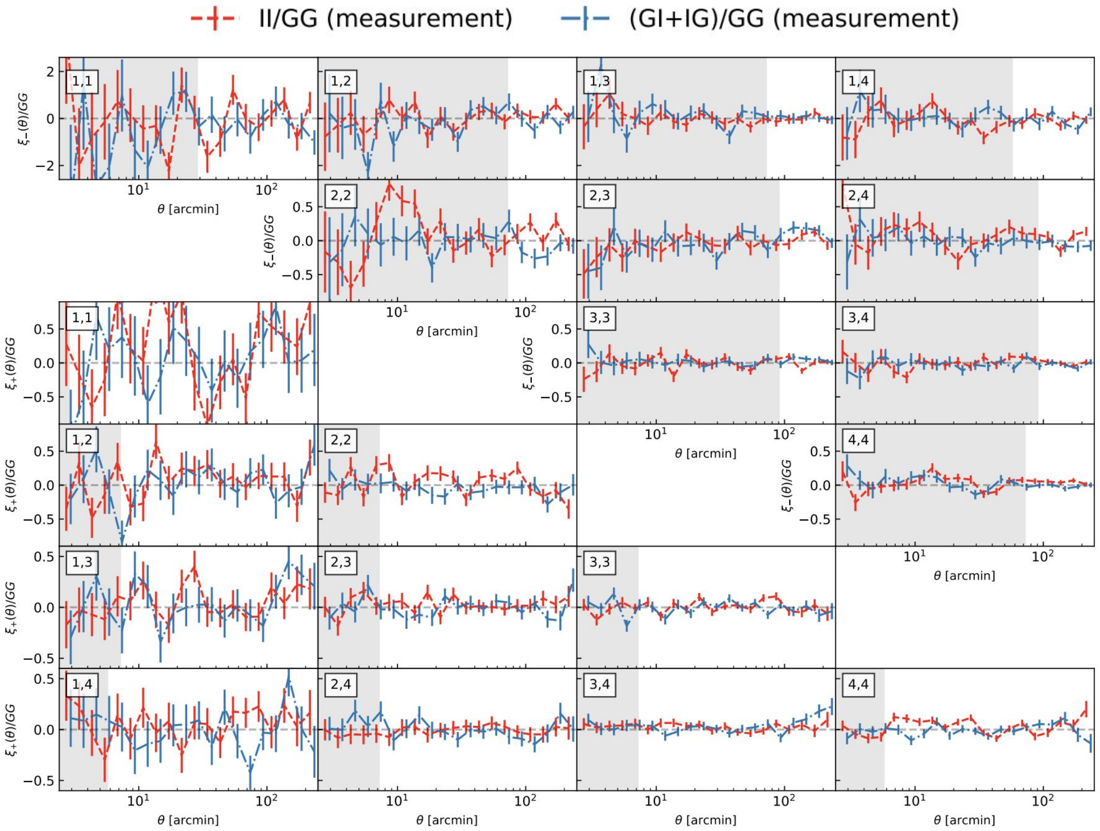
Photometric redshift distributions estimated on MICE and realistic when compared to eg. DES Y3



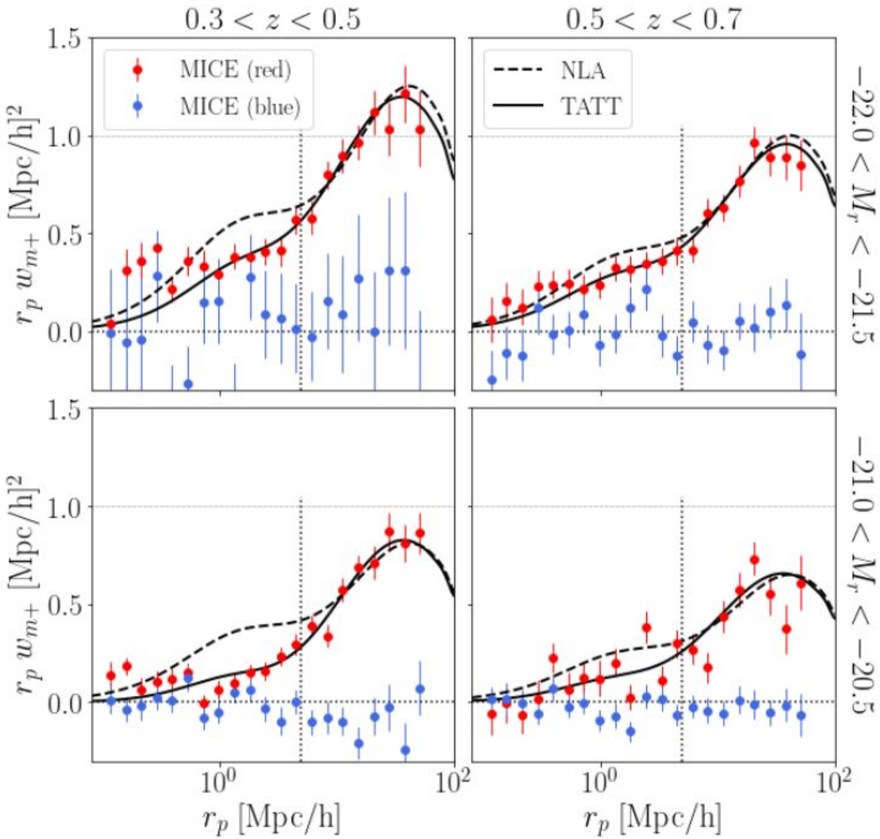
Predictions made by the semi-analytic model:

Very weak alignments in a DES-like sample due to dominance of a blue galaxy population (which itself is negligibly aligned with halos). This is verified in Y3 data.



Predictions made by the semi-analytic model:

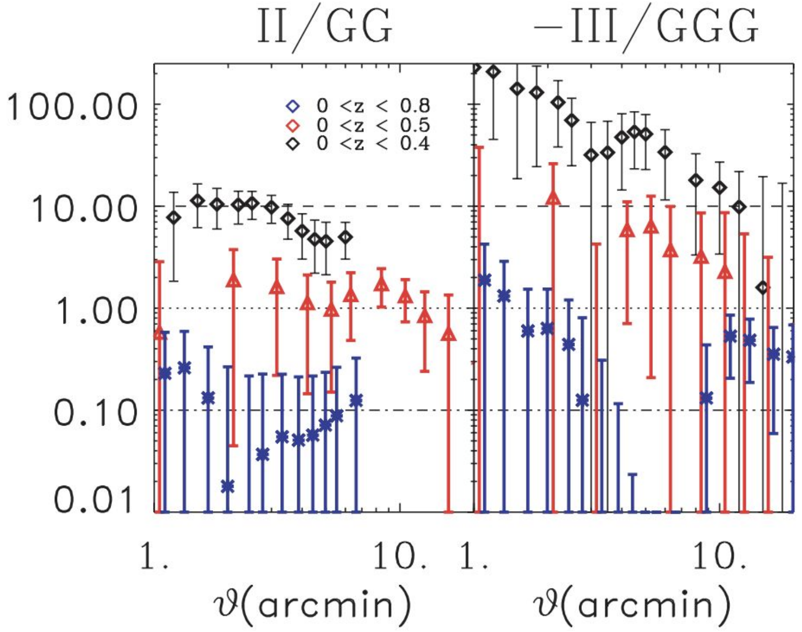
A model containing Tidal Torquing terms as well as Tidal Alignment (TATT; Blazek et al 2019) performs better at fitting the simulated data (down to ~1Mpc), as opposed to NLA which breaks down at ~5Mpc.



BONUS: measuring **three-point IA** in MICE

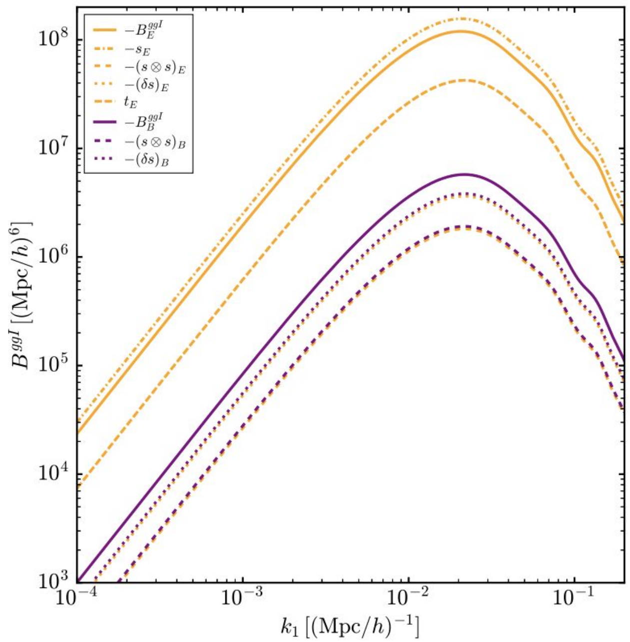
(as part of the echoIA project in DESC - with K. Hoffman, J. Blazek, L. Linke, S. Pyne, B. Joachimi)

IA boosted at the 3pt level compared to GG (esp. at low redshift)



Semboloni et al 2008

Higher-order functions probing IA time evolution



Schmitz et al 2018

Part 3: more data and the future

More to learn from DECam-based surveys - DES Y6 and DELVE

From DES Y3 to DES Y6: what to expect (preliminary!)

1- **Increased depth** but same area of Y3 with roughly double exposure number: the statistical gain will come from galaxy number density (pushing shot noise down)

2- **New shear catalog(s)**: Meta*detect* (Sheldon et al 2020) and BFD (Bernstein & Armstrong 2014)

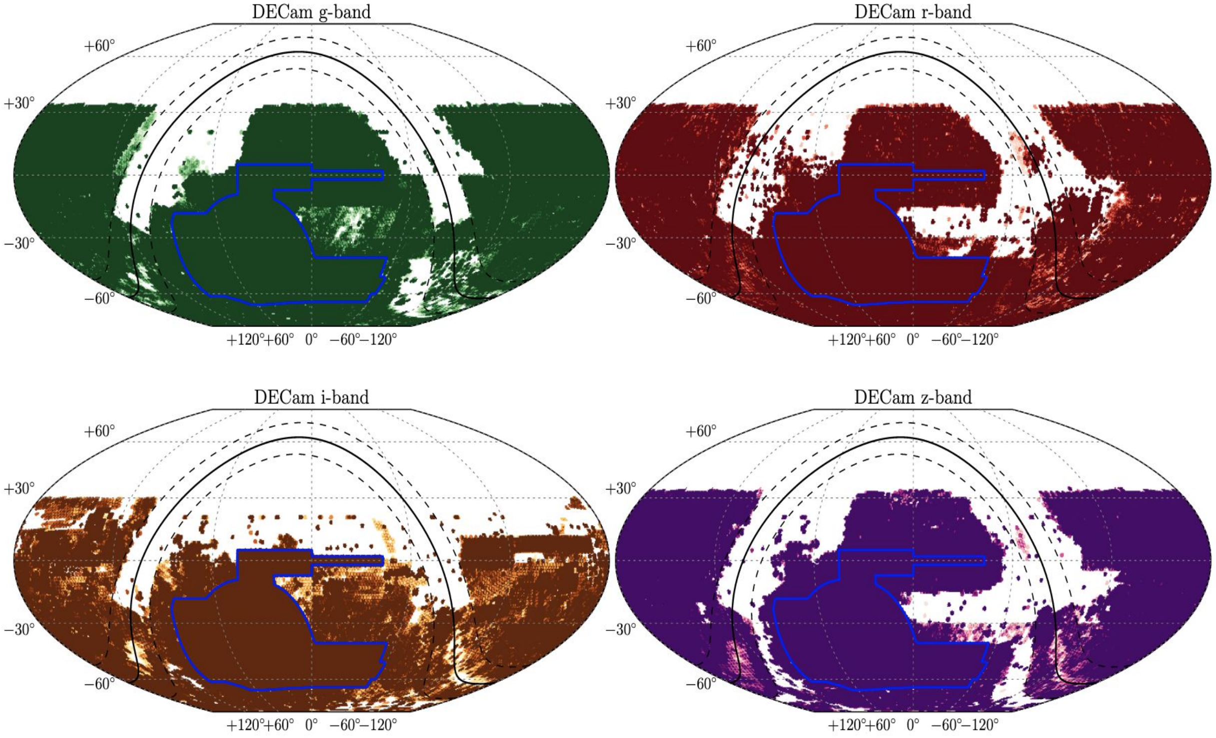
3- Studying introducing **baryon parameters** in a Halofit approach (will allow going to smaller scales, but still need to show whether constraining power increase is warranted)

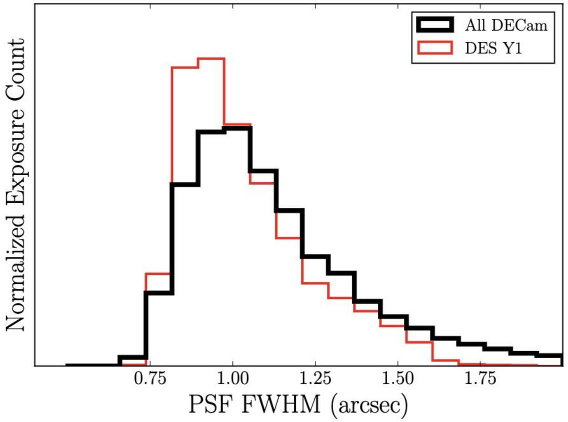
Already have preliminary (and obscured/“blinded”) **cosmic shear measurements**

How about using even more DECam data for cosmic shear?

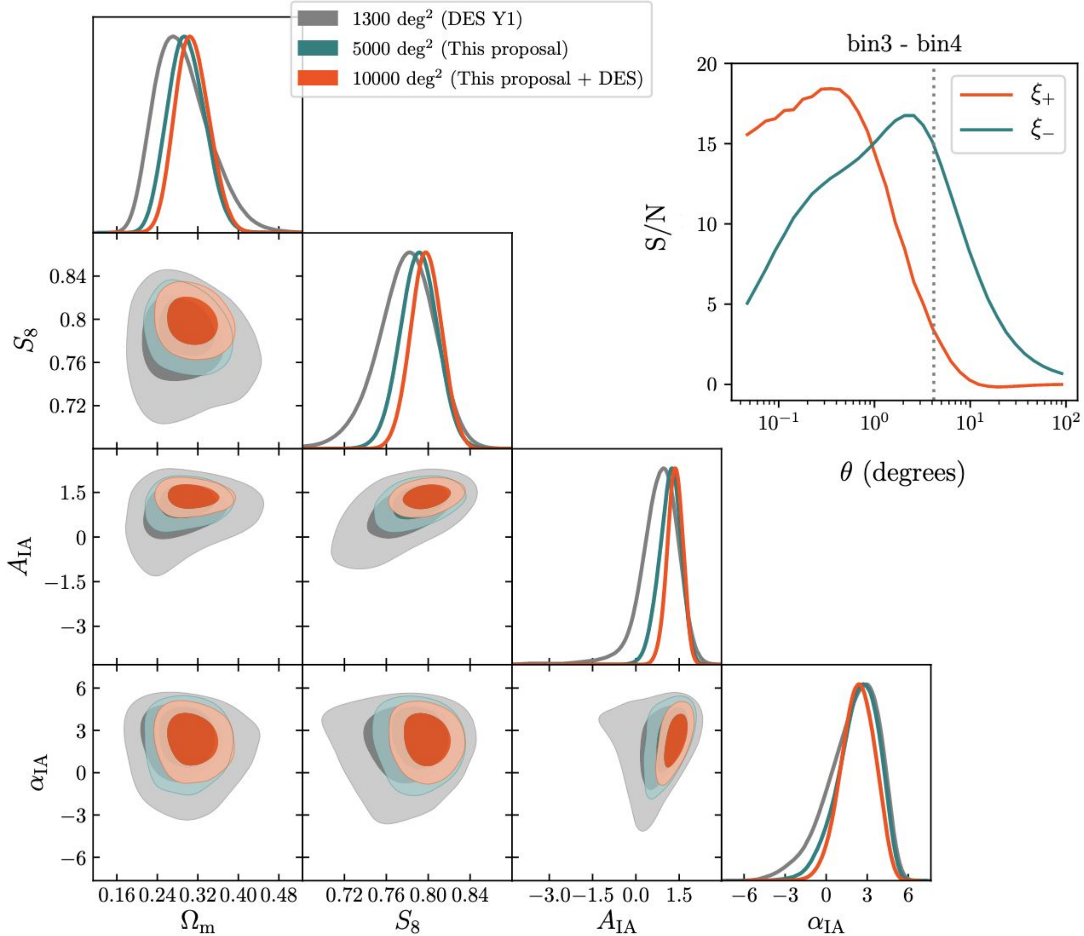
(with C. Chang, A. Drlica-Wagner, M. Becker, R. Gruendl, D. Anbajagane, C. Tan, A. Alarcon, +)

DES is the blue outline. The DECam Local Volume Exploration Survey (DELVE) includes a much wider area. We expect **~5000 deg^2 outside of the DES footprint**, with roughly 80M galaxies, and only marginally inferior seeing.





Forecasting gains (and comparing with DES Y1)



How about using even more DECam data for cosmic shear?

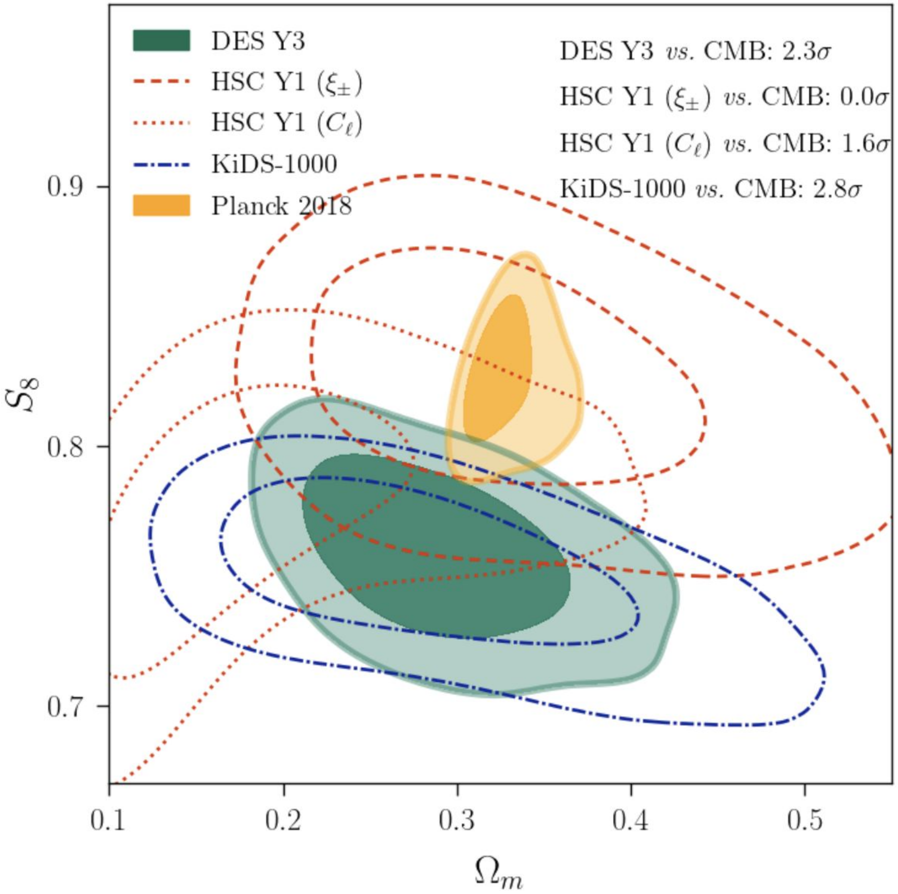
Interesting aspects of this analysis:

1- New **5,000 deg^2 to constrain S8 with**: are results from different surveys **consistent**?

2- Combined with DES at the likelihood level yields a **10,000 deg^2 survey***** (widest until LSST Y1 comes along!)

3- Re-purposing public tools, processing pipelines and expertise from DES & DELVE collaborators, using Metacalibration for shears and BPZ for redshifts: a relatively small team with a shorter timescale in mind.

4- Extended catalog will have more overlap with eg. SPT, allowing for **more statistics in lensing x CMB studies**.



In the long run: Rubin-LSST

Over >12,000 deg^2 in LSST-Y1, with over >10 galaxies per arcmin^2, will completely change the game as far as any cosmic shear analysis goes (from 2pt to 3pt to IA and more!)

In the meantime: come meet us in Chicago for the DESC collaboration meeting in August!

Conclusions:

Analysis with 2pt+3pt are happening and will become standard, and we’re reaching **high enough signal-to-noise** to make interesting new explorations

Model control is more important than ever: need to avoid losing constraining power. **Intrinsic alignments can be helped** by the use of large-volume simulations.

Ever increasing amount of data (**including DES Y6 and DELVE** in the near term) will pin down self-consistency between surveys and pave the way for LSST.

Thank you!

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