The Dark Energy Survey Year 6: 3×2pt analysis

THE DARK ENERGY SURVEY

William d'Assignies (IFAE, PhD, redshift team)
on behalf of the Dark Energy Survey Collaboration

Institut de Física d'Altes Energies

Presentation using material from M. Crocce, G. Bernstein, C. Chang

@ C. Chang

- Intro
  - DES in few numbers
  - 3x2pt analysis
  - 3x2pt results of DES Y3

- DES Y6 :
  - Samples
  - Redshift calibration
  - Modelling

- What’s next ?
  - Y6 FOM vs Y3
  - Higher orders analysis

- Intro
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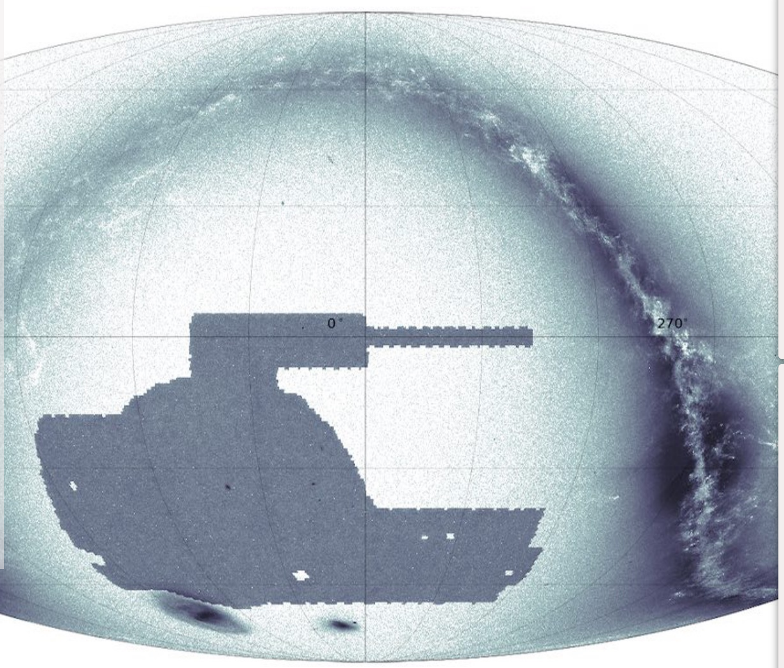
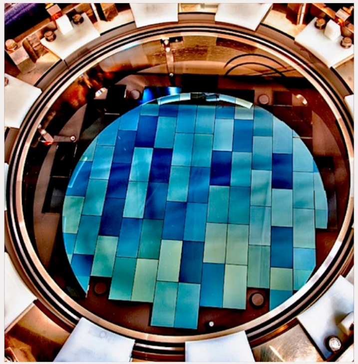
The Dark Energy Survey (DES)

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Observed in 5 imaging bands (grizY) : photometric redshifts
- Full survey 758 nights (2013-19)
- This talk DES Y6 final dataset.
- **Wide field:** 5000 sq. deg. with limiting depth i <~ 24
- **Deep field:** 30 sq. deg. with near-IR YJHK bands, 10x wide field depth





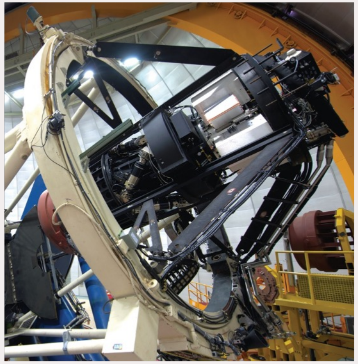


Image Credit: CosmoHub, Port d'Informació Científica (PIC)

The Dark Energy Survey (DES) as a multiprobe experiment

- **Weak lensing** (distance, structure growth) shapes of up to 200 millions galaxies
- **Baryonic acoustic oscillations** (distance) 16 millions red galaxies to $0.6 < z < 1.2$
- **Galaxy clusters** (distance, structure growth) ~ 20,000 RedMapper clusters ($z \sim 0.7$) synergies with WL, SZ, Xray
- **Type Ia supernovae** (distance) 30 sq. deg. SN fields : 1650 SNIa up to $z \sim 1.13$

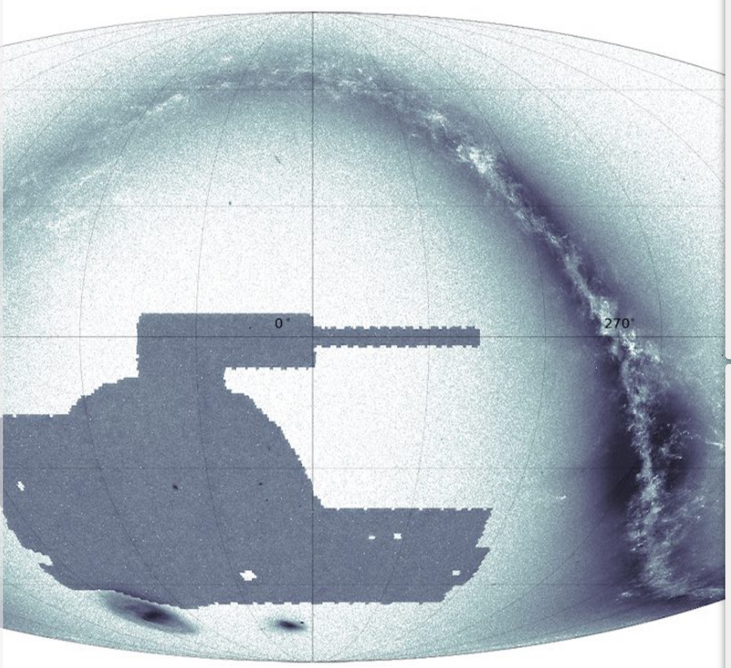
Robust combination of probes

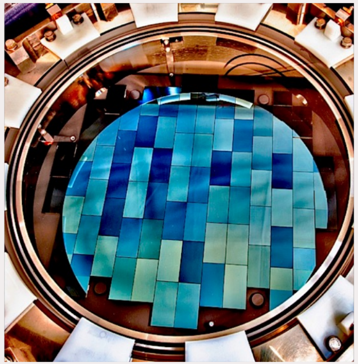
→ shared photometry / footprint

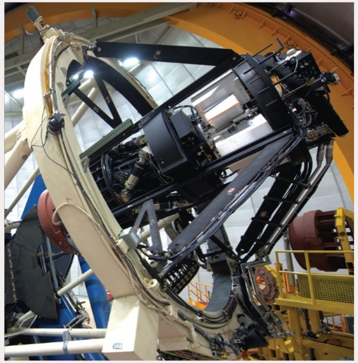
→ shared analysis of systematics

→ shared galaxy redshift estimates

→ consistent blinding strategy







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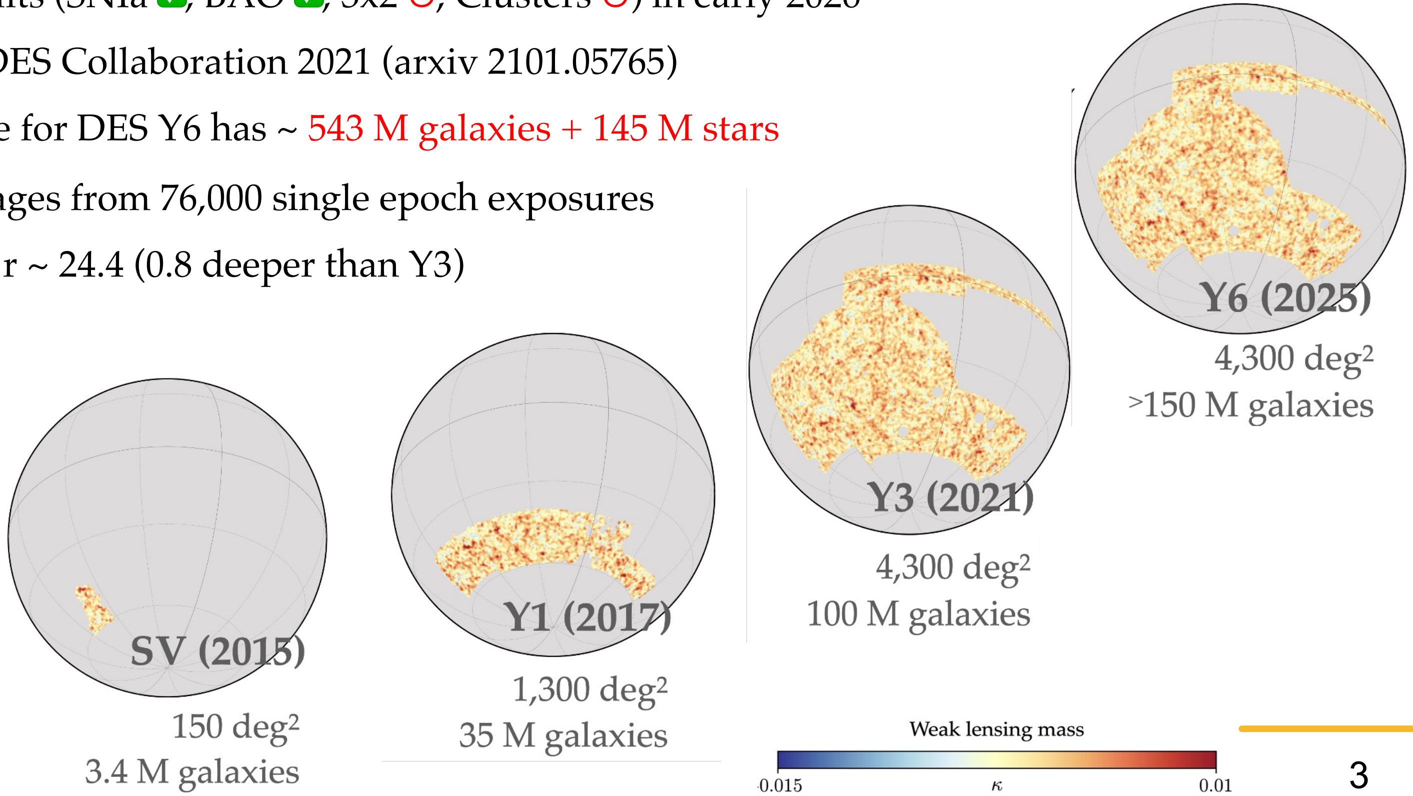
From SV to DES Year 6 and the DR2 final dataset

- DESY1 (1300 deg2/2017) to DESY3 (4300 deg2/2020) to DESY6 (4300 deg2/2025)
- **DES Y6** science results (SNIa ✅, BAO ✅, 3x2 ↻, Clusters ↻) in early 2026
- DR2 final dataset, DES Collaboration 2021 (arxiv 2101.05765)
- DR2 Gold Catalogue for DES Y6 has ~ 543 M galaxies + 145 M stars
- 10,000 co-added images from 76,000 single epoch exposures
- (co-added) lim mag r ~ 24.4 (0.8 deeper than Y3)
- 5000 deg2



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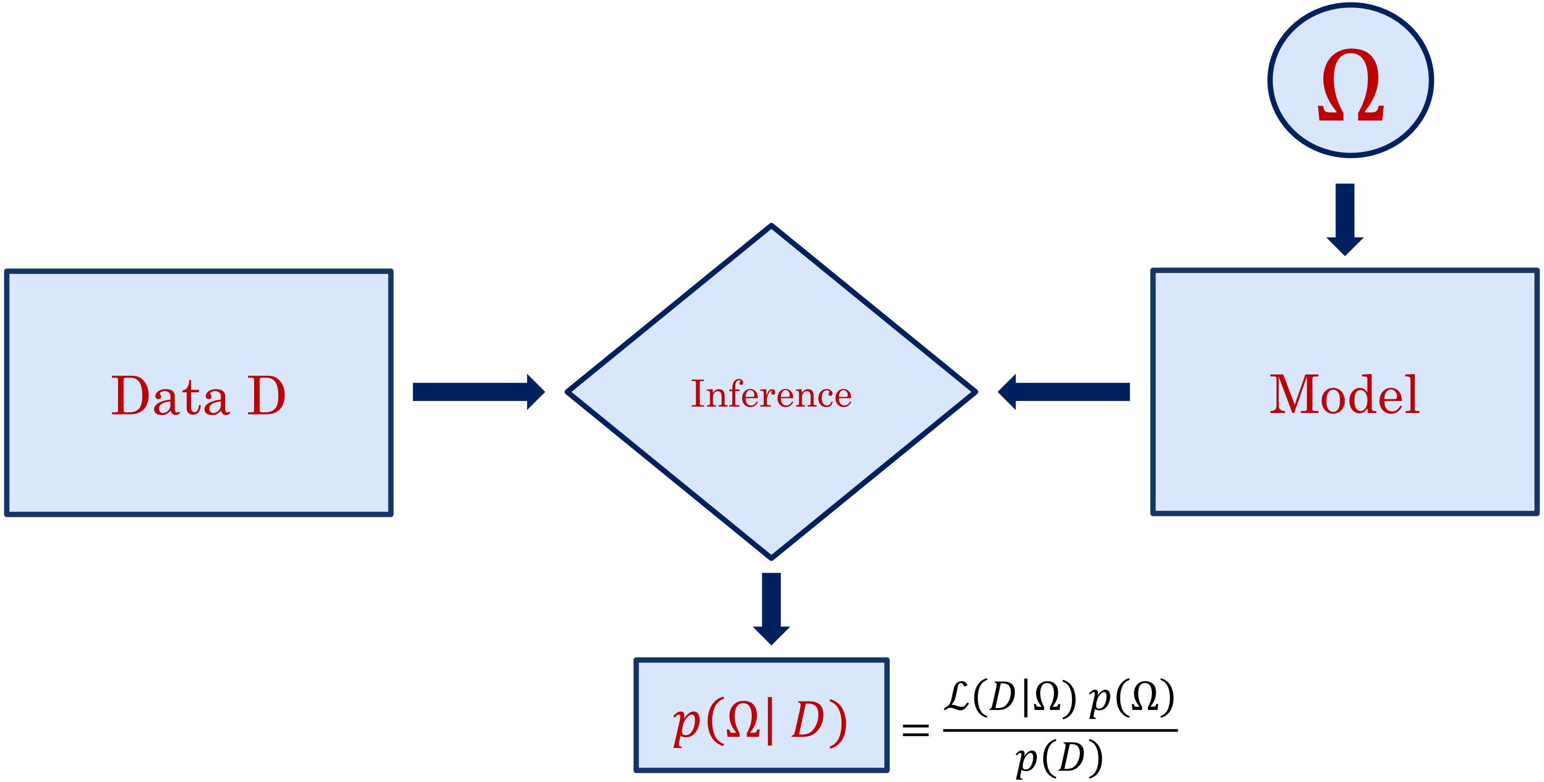
Cosmological inference

$$\Omega = \{\Omega_m, \Omega_b, \Omega_\Lambda, \sigma_8, h, n_s, \sum m_\nu, \ldots\}$$



$$p(\Omega|\, D) = \frac{\mathcal{L}(D|\Omega)\, p(\Omega)}{p(D)}$$

Cosmological inference

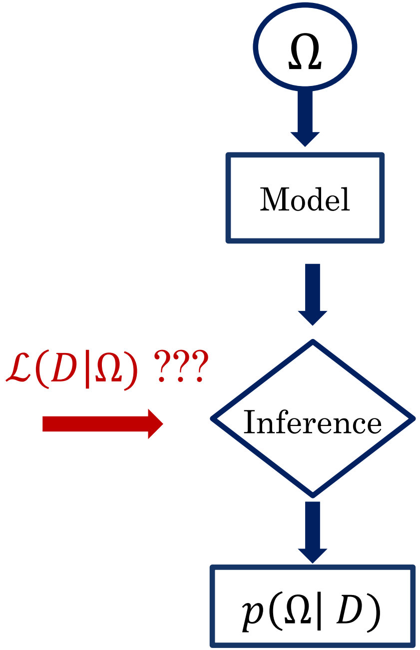
Data D:

Wide: ~80,000 exposures x 0.5 Gpix

Deep: ~10,000 exposures x 0.5 Gpix

= $5\text{x}10^{12}$ numbers

Glossing over the many steps in converting raw CCD outputs into estimates of true sky intensity in each pixel!



Cosmological inference

THE DARK ENERGY SURVEY

Glossing over more complex steps of object identification, splitting, photometry, shape/size measurement, with complex selection functions.

Data D:
= 5x10^{12}
numbers

Wide pixels

"Gold" catalog
670 M objects, with
{Ra, Dec, g, r, i, z, e_1, e_2,size,…}

6x10^9 numbers
(+image quality info)

Deep pixels

"Deep" catalog
~Light curves
10^7 numbers

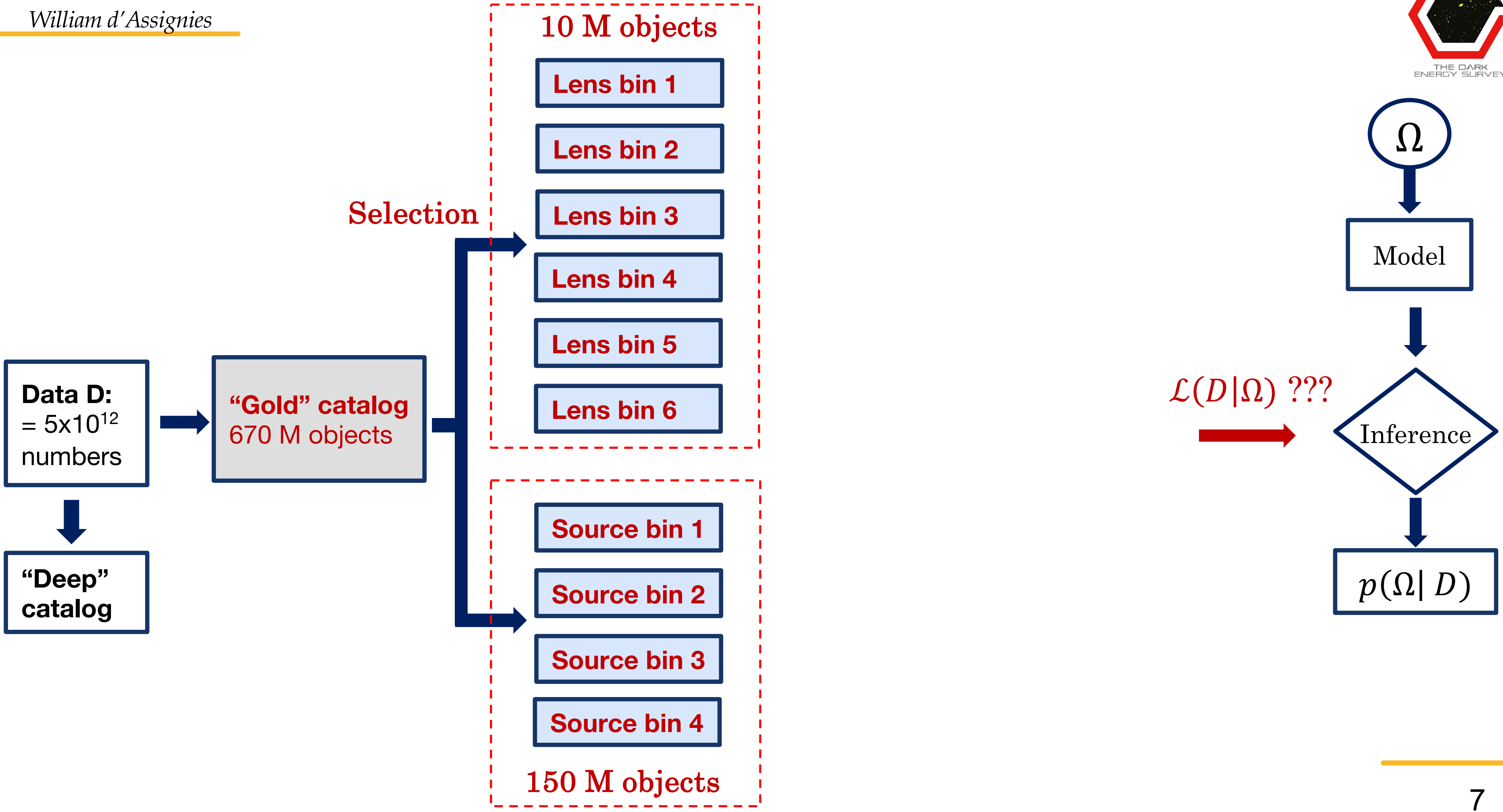
Ω

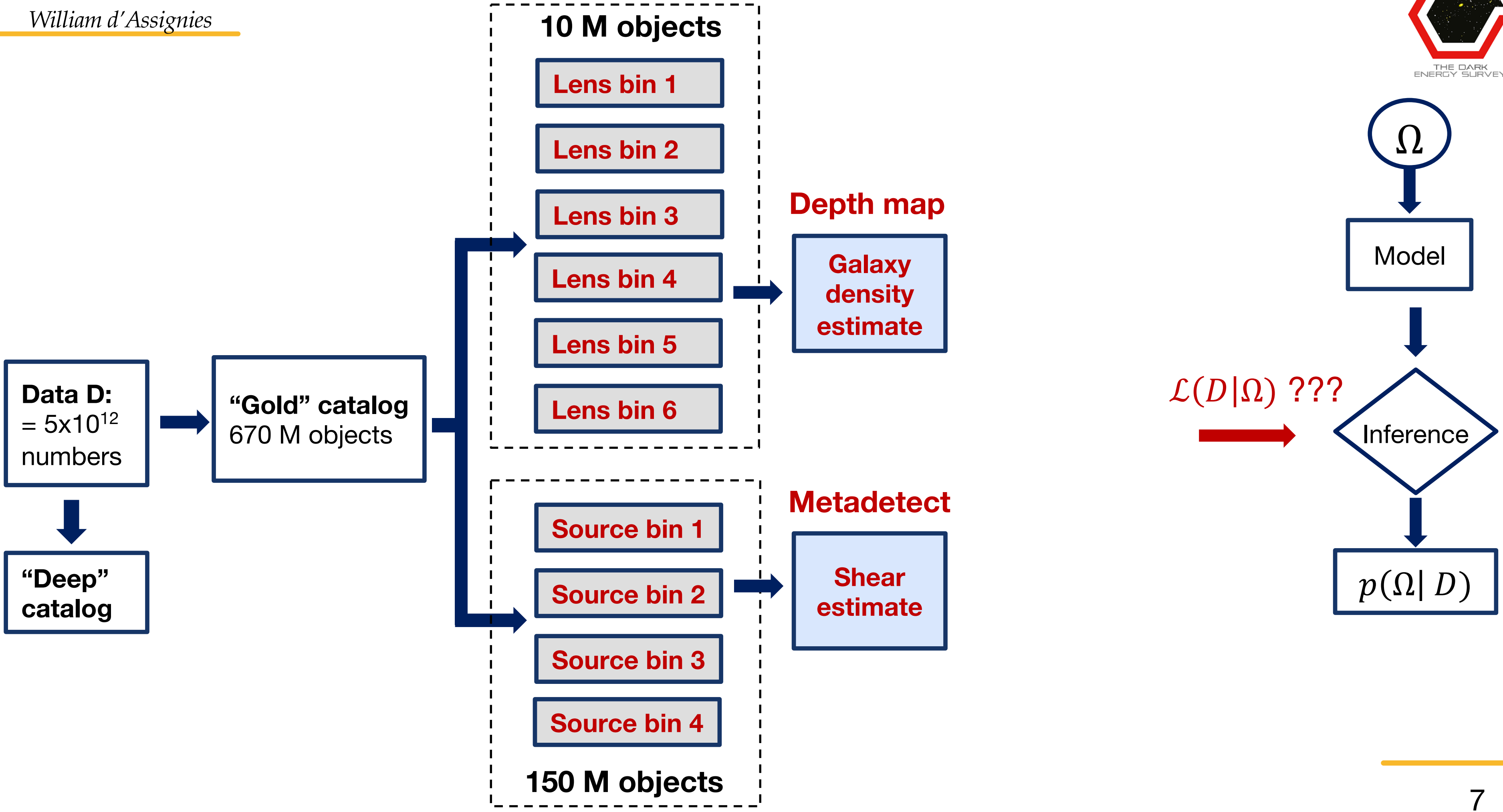
Model

$\mathcal{L}(D|\Omega)$???

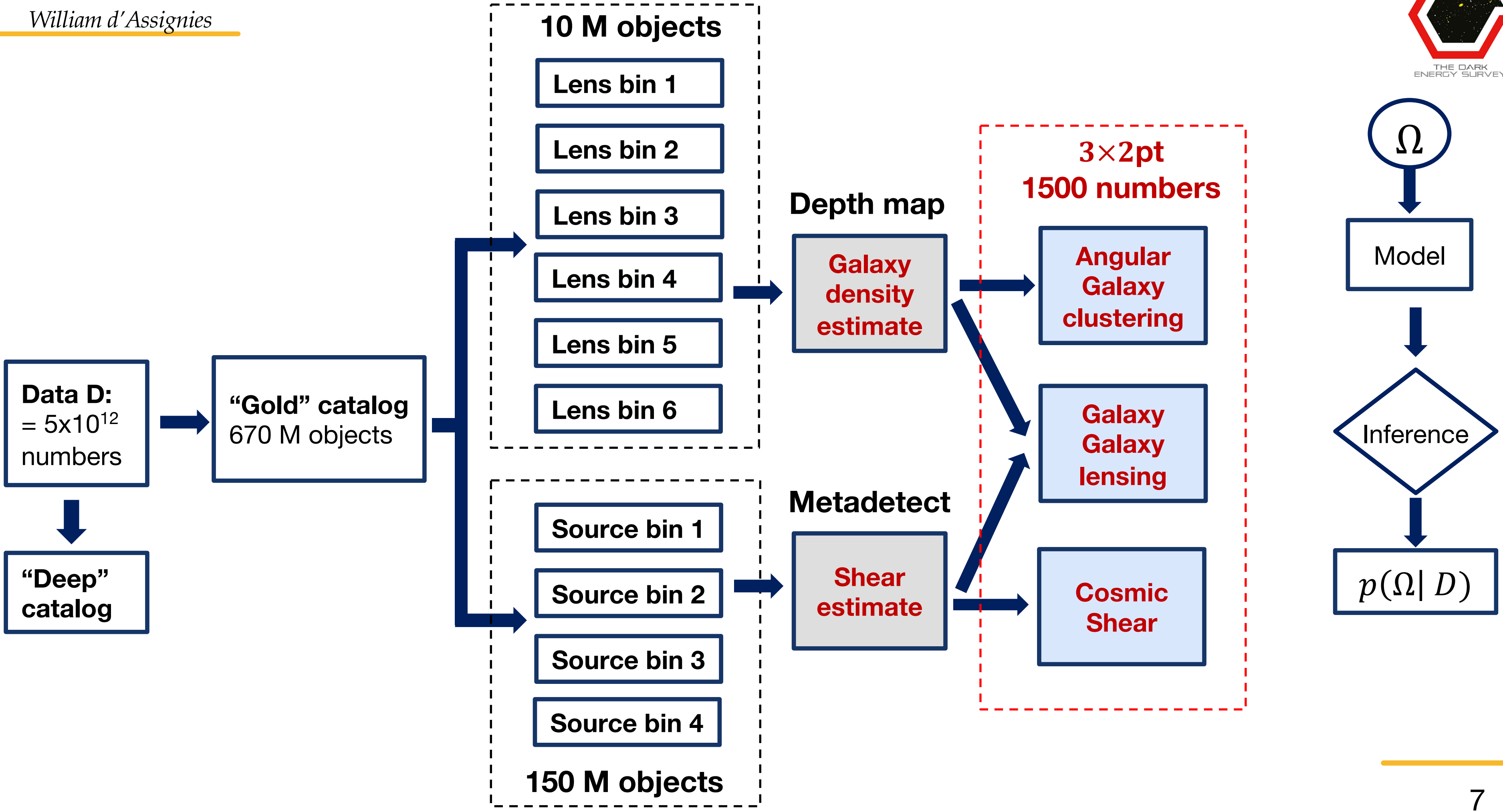
Inference

$p(\Omega|\, D)$


Data D:
= 5×10^{12}
numbers
"Deep" catalog
"Gold" catalog
670 M objects
Selection
10 M objects
Lens bin 1
Lens bin 2
Lens bin 3
Lens bin 4
Lens bin 5
Lens bin 6
Source bin 1
Source bin 2
Source bin 3
Source bin 4
150 M objects
Ω
Model
$\mathcal{L}(D|\Omega)$???
Inference
$p(\Omega|\,D)$



Data D:
= 5x10^12
numbers
"Deep" catalog
"Gold" catalog
670 M objects
10 M objects
Lens bin 1
Lens bin 2
Lens bin 3
Lens bin 4
Lens bin 5
Lens bin 6
Depth map
Galaxy density estimate
Source bin 1
Source bin 2
Source bin 3
Source bin 4
150 M objects
Metadetect
Shear estimate
Ω
Model
$\mathcal{L}(D|\Omega)$???
Inference
$p(\Omega|D)$



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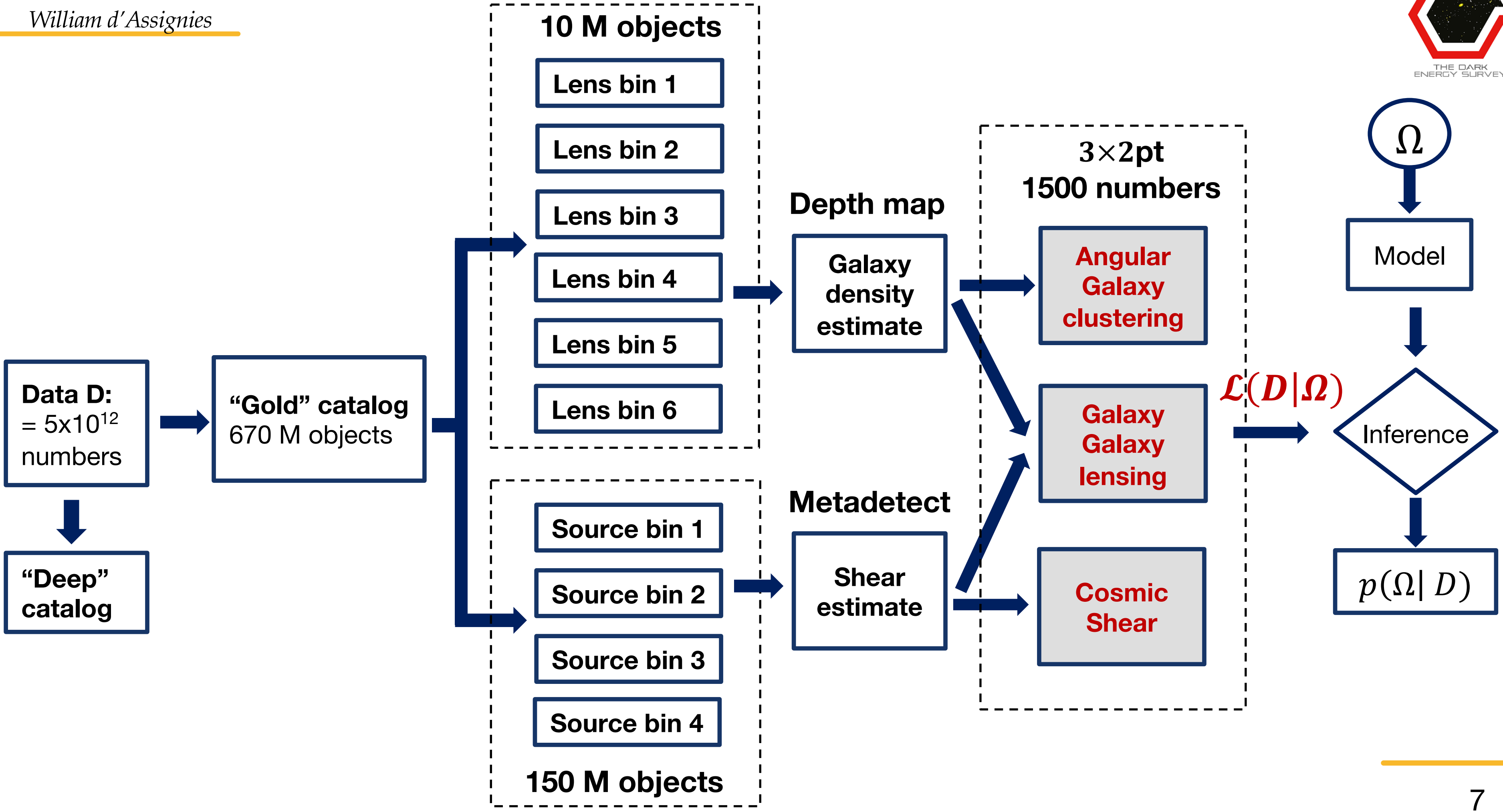
Metadetect
Shear estimate
3×2pt
1500 numbers
Angular Galaxy clustering
Galaxy Galaxy lensing
Cosmic Shear
Ω
Model
Inference
p(Ω| D)



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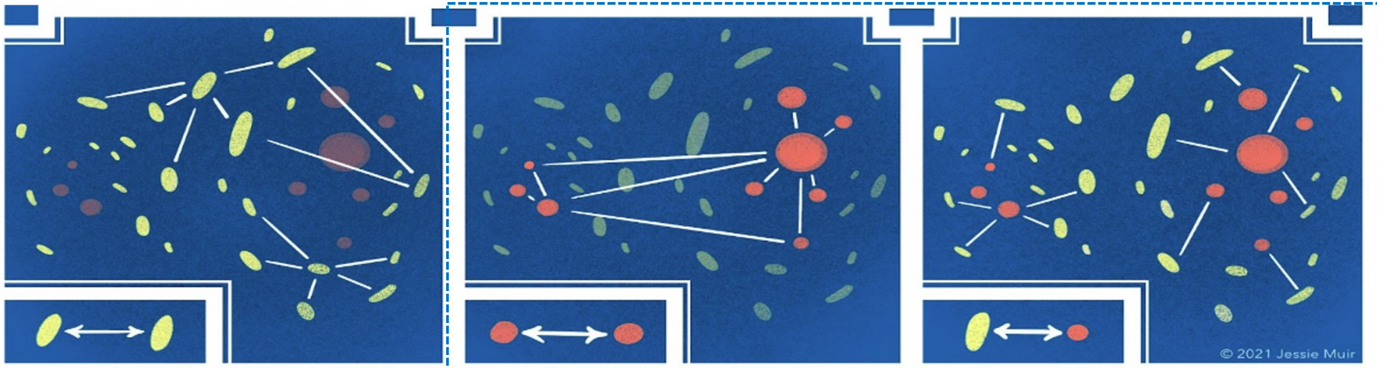
3x2 Cosmology



cosmic shear
correlation in the shapes of (source) galaxies

$$\xi_\pm = \langle e_t(\theta')e_t(\theta'+\theta)\rangle - \langle e_x(\theta')e_x(\theta'+\theta)\rangle$$

$$\propto \sigma_8^2$$

1x2pt

galaxy clustering
correlation in the positions of (lens) galaxies

$$w(\theta) = \langle \delta(\theta')\delta(\theta'+\theta)\rangle$$

$$\propto b^2\sigma_8^2$$

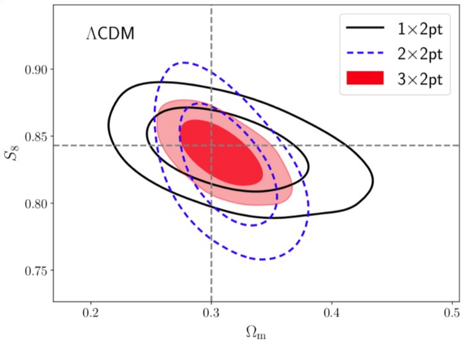
galaxy galaxy lensing
correlation between positions of the lenses and shapes of the sources

$$\gamma_t(\theta) = \langle \delta(\theta')e_t(\theta'+\theta)\rangle$$

$$\propto b\sigma_8^2$$

2x2pt

3x2pt

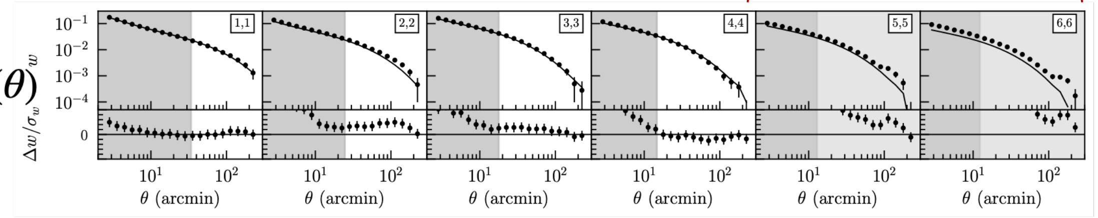


Scale cuts, removing data

Removing all the data for 2 bins

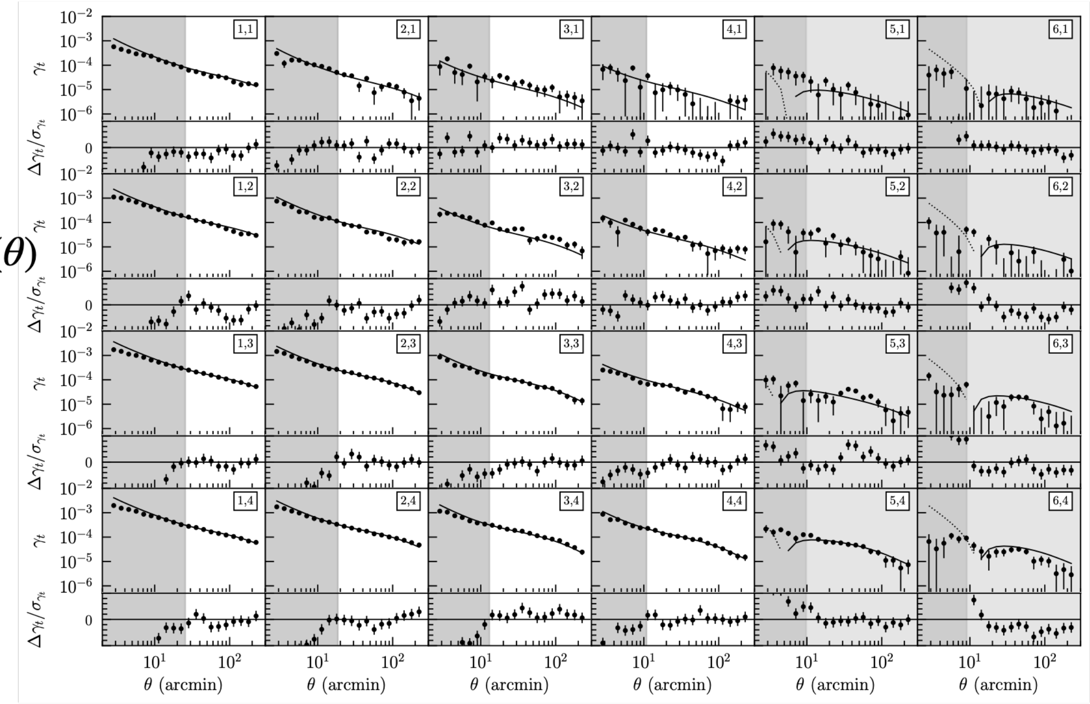
Galaxy clustering

Y3 $w(\theta)$



Galaxy-galaxy lensing

Y3 $\gamma_t(\theta)$

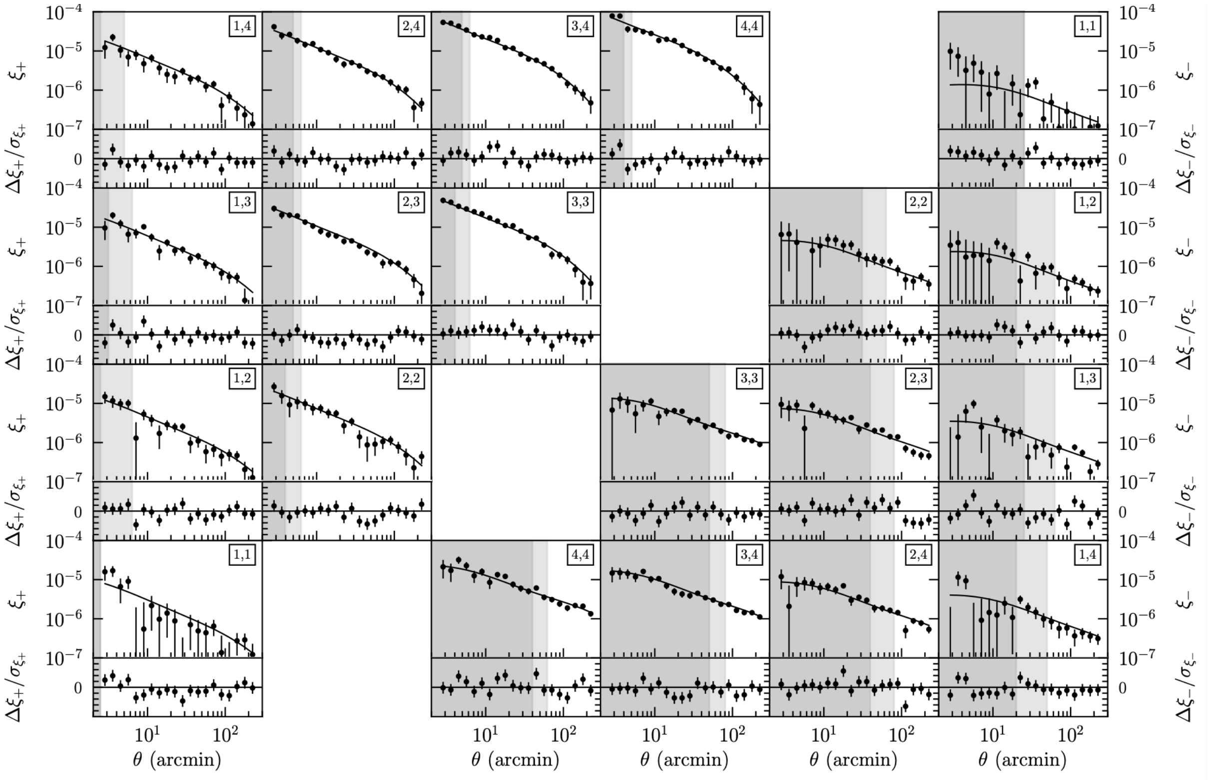


Y3 ξ_θ)

Scale cuts, removing data

Y3 $\xi_+(\theta)$

Cosmic Shear



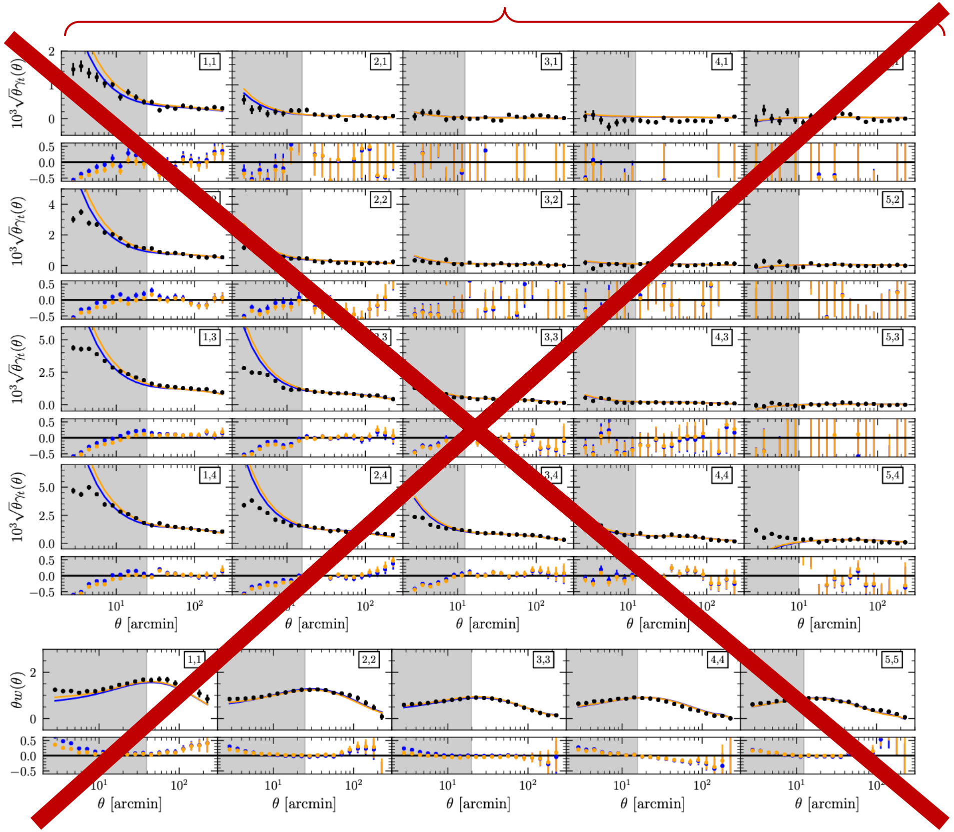
Scale cuts, removing data

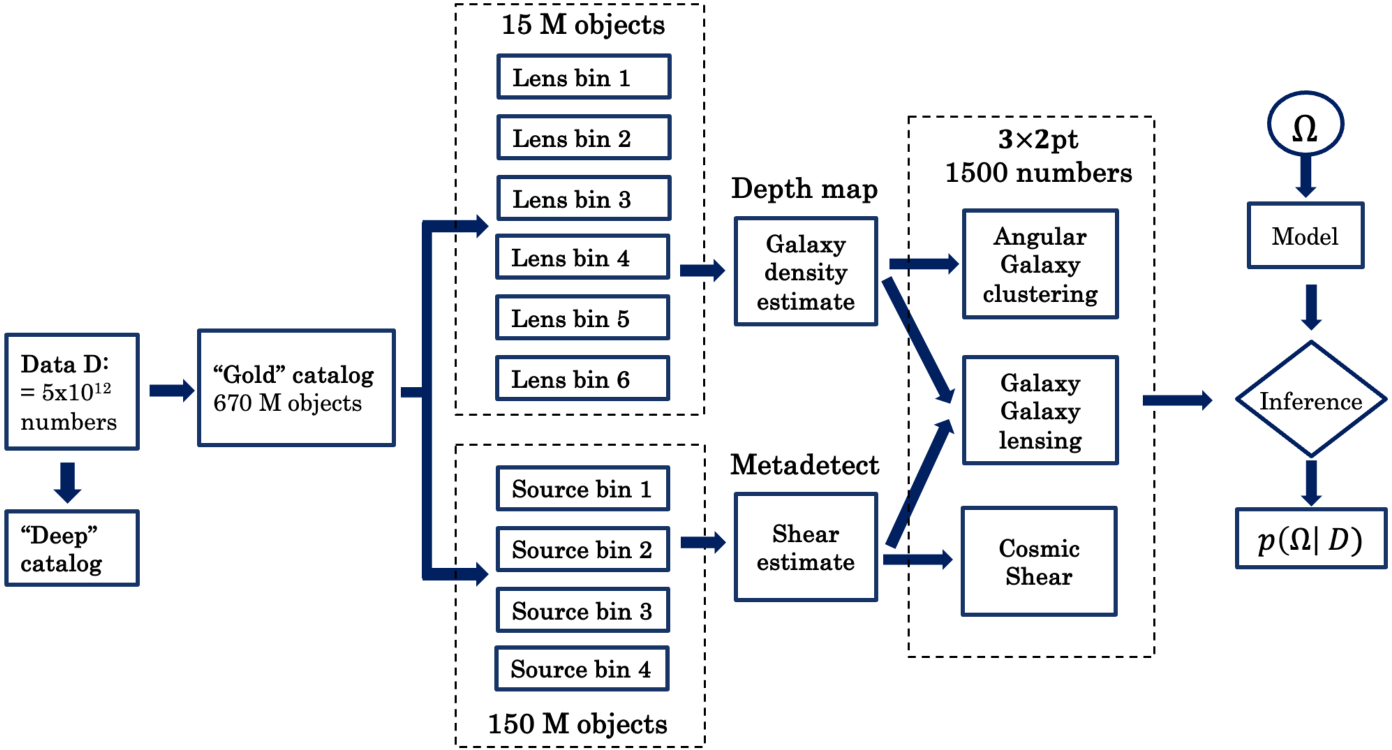
Y3 Redmagic curse

Removing all the data for 5 bins

Galaxy clustering

Galaxy-galaxy lensing




15 M objects
Lens bin 1
Lens bin 2
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Lens bin 4
Lens bin 5
Lens bin 6
Data D:
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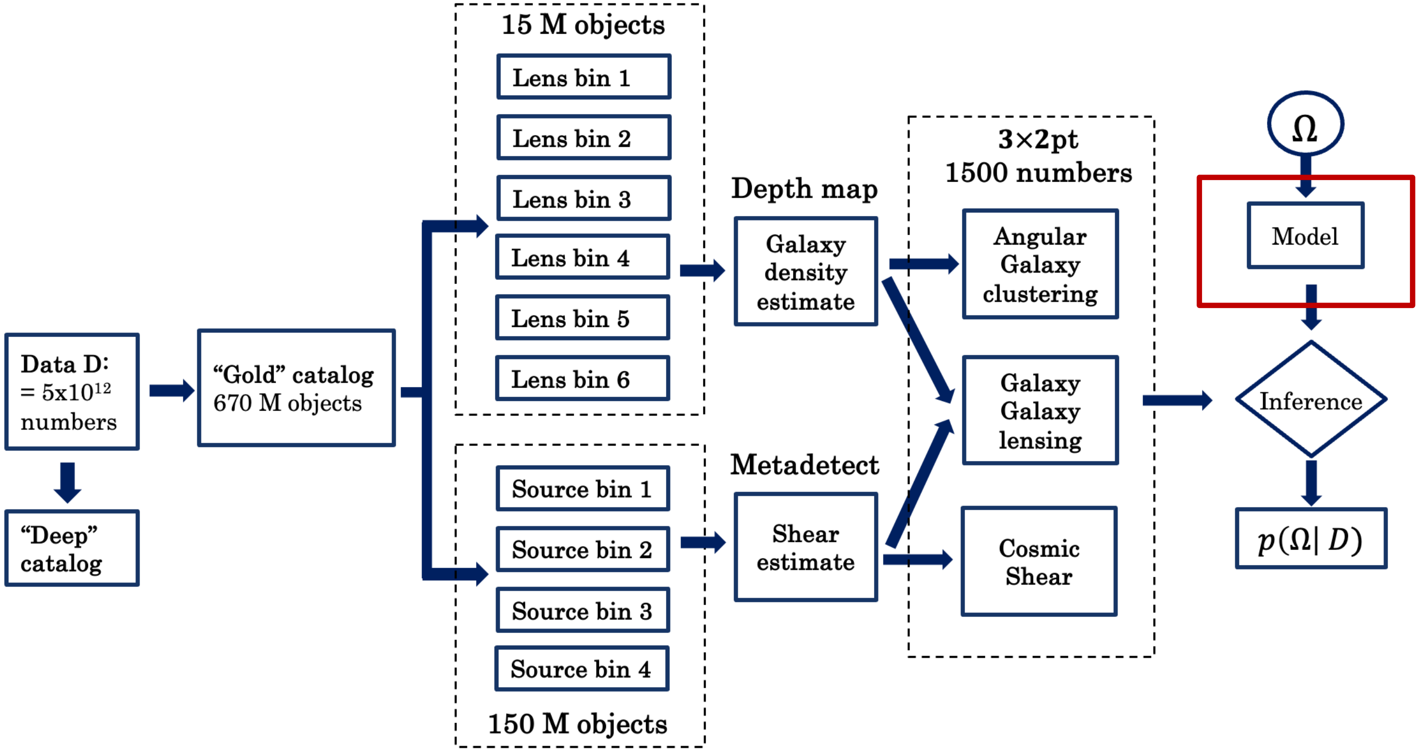
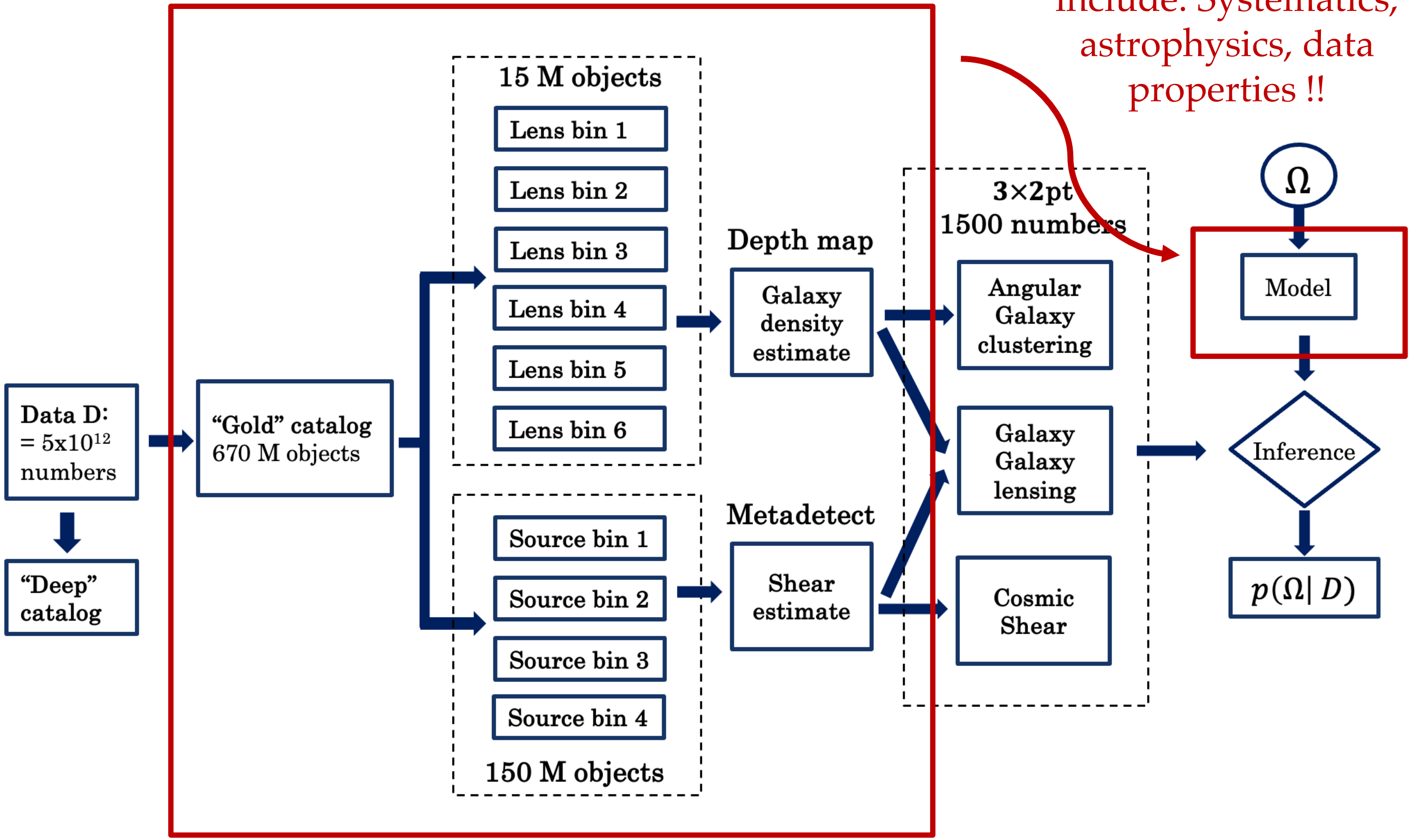


We need a model for the data $\overline{D}$ and $\mathrm{cov}(\overline{D})$

Selection steps have to be include. Systematics, astrophysics, data properties !!



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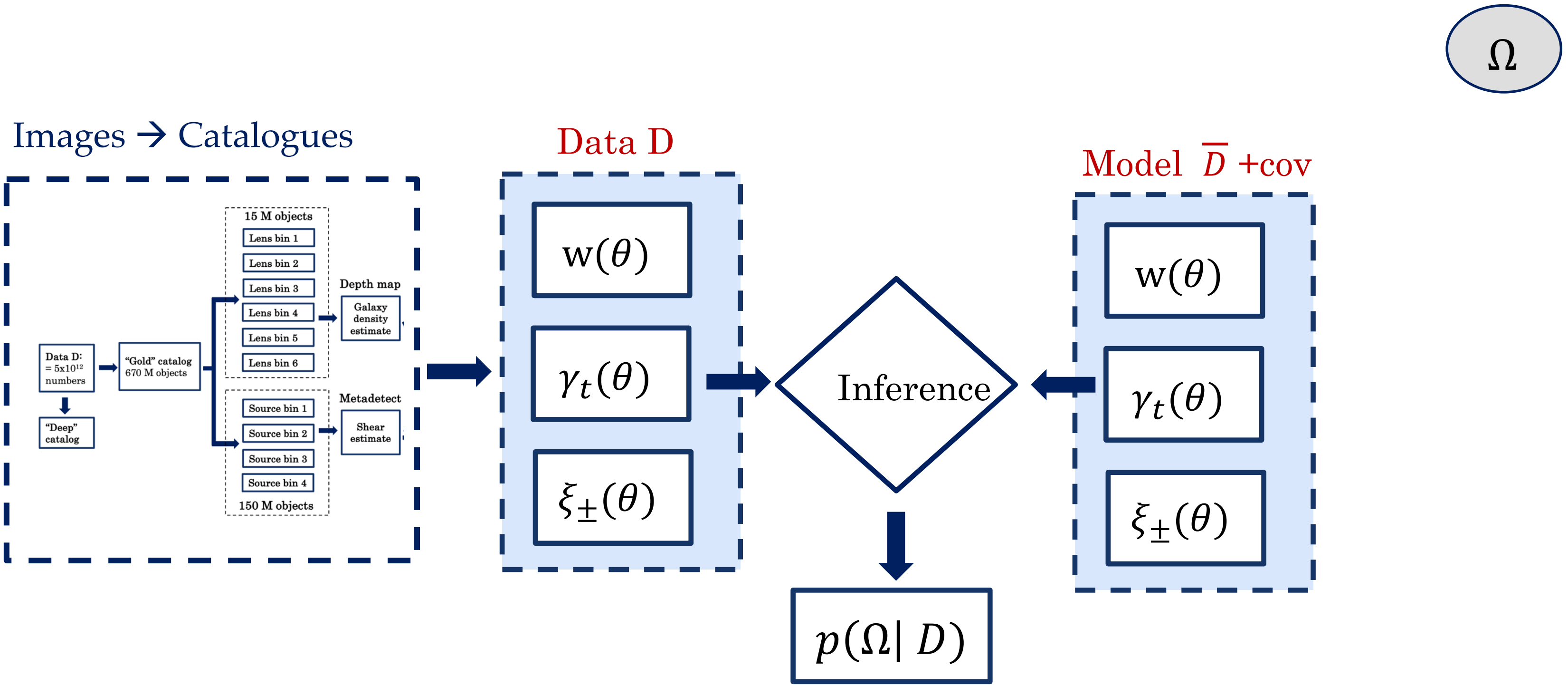
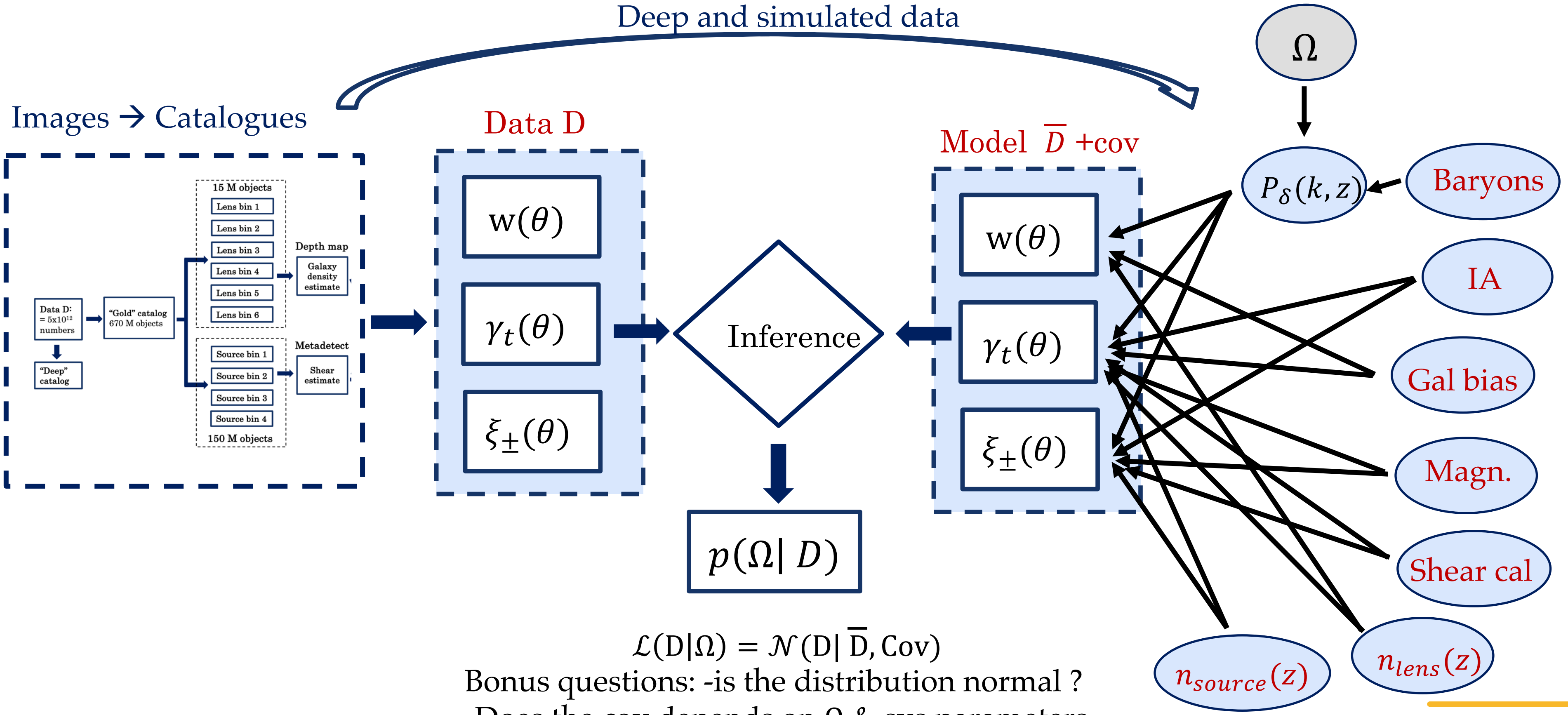


3x2pt inference

$\Omega = \{\Omega_m, \Omega_b, \Omega_\Lambda, \sigma_8, h, n_s, \sum m_\nu, \dots\}$



$\mathcal{L}(\mathrm{D}|\Omega) = \mathcal{N}(\mathrm{D}|\,\overline{\mathrm{D}}, \mathrm{Cov})$

Bonus questions: -is the distribution normal ?

-Does the cov depends on Ω & sys parameters

3x2pt 'pre-unblinding' papers

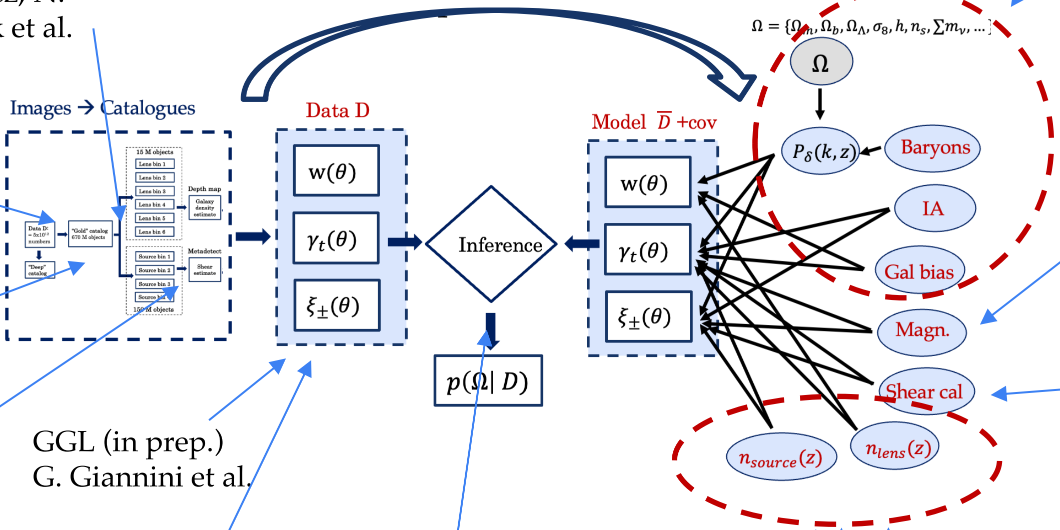
Modelling (in prep.),
D. Sanchez, A. Ferté et al.

Balrog (2501.05683)
D. Anbajagane et al.

Cardinal (2303.12104)
C. To et al.

Mask (2509.07943).
M. Rodríguez, N. Weaverdyck et al.

Simulated data



Gold paper (2501.05739)
K. Bechtol et al.

PSF(2501.05781)
T. Schutt et al.

Metadetect (2501.05665)
M. Yamamoto, M. Becker et al.

GGL (in prep.)
G. Giannini et al.

GC and obs sys (in prep.)
N. Weaverdyck, Rodríguez, N. et al.

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Magnification (in prep.),
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S. Mau. M. Becker, et al.

SOM (2509.07964 & 2510.23566):
B. Yin et al, G. Giannini et al
WZ (2510.23565): W. d'Assignies et al.
z-priors (2506.00758): G. Bernstein et al.

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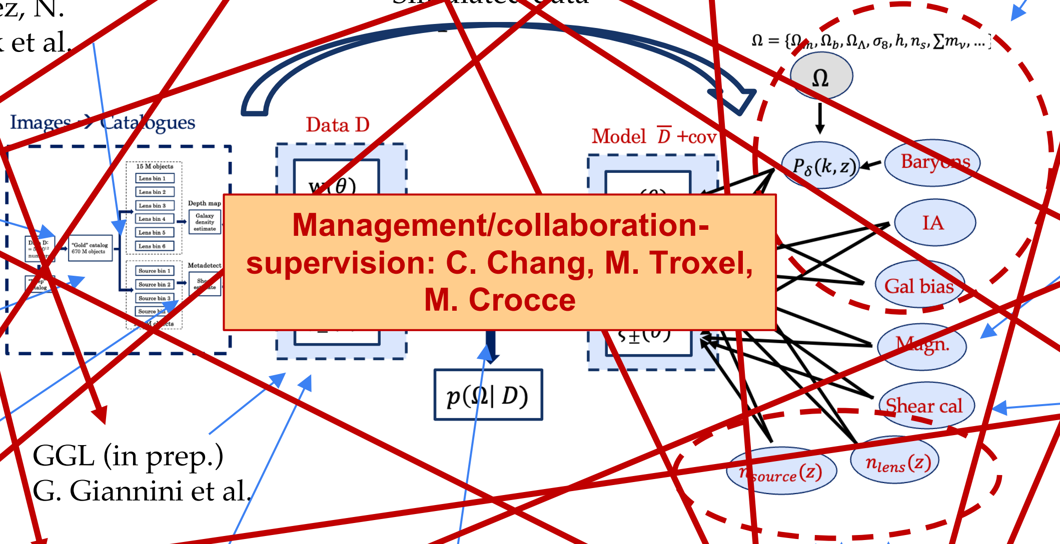

Management/collaboration-supervision: C. Chang, M. Troxel, M. Crocce

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DES Y3 3x2pt results

DES Collab(2021)arxiv 2105.13549

In ΛCDM:

$$S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776)$$

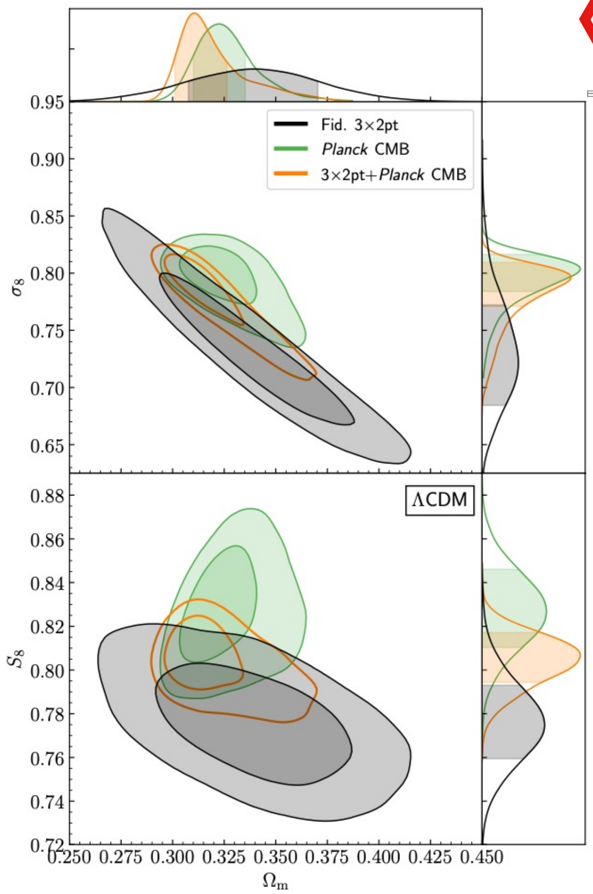
$$\Omega_\mathrm{m} = 0.339^{+0.032}_{-0.031} \quad (0.372)$$

$$\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)$$

In wCDM:

$$\Omega_\mathrm{m} = 0.352^{+0.035}_{-0.041} \quad (0.339)$$

$$w = -0.98^{+0.32}_{-0.20} \quad (-1.03)$$



DESY3 3x2 in agreement with Planck $< 2\sigma$

Still competitive (e.g. same S_8 constraint as KiDS Legacy arxiv 2503.19441 shear-only)

DES Y3 3x2pt results

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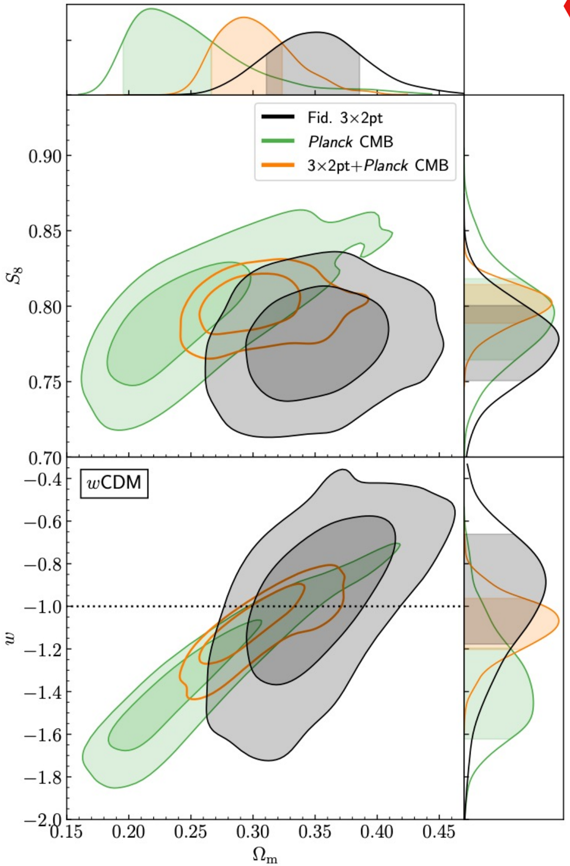

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    - Samples
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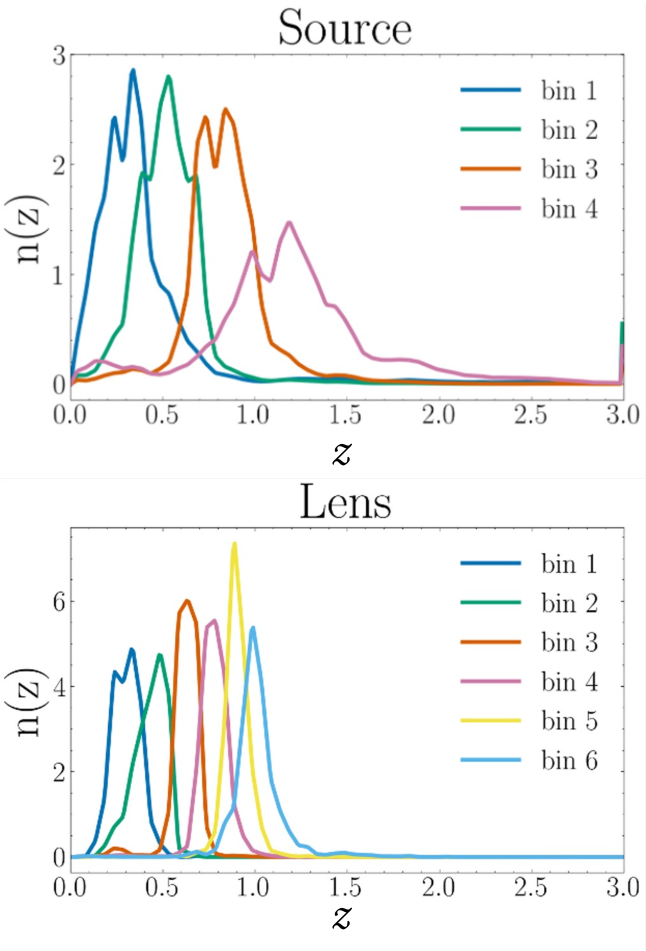
- What's next ?
    - Y6 FOM vs Y3
    - Higher orders analysis

- DES Y6 :
  - Samples and their properties
  - Redshift calibration
  - Modelling

Samples



THE DARK ENERGY SURVEY

source sample = Metadetection (*Yamamoto, Becker et al.*)

- ~ 150 million galaxies
- neff = 8 gals / arcmin2 and σ_e= 0.272
- Reduced shear bias (e.g. in blended objects).
- 50% more sources than Y3.

lens sample = MagLim ++ (*Weaverdyck, Rodriguez et al.*)

- 10 million galaxies with mag cut : i < 4 z_{photo} + 18
- Selected by optimizing the wCDM constraints by balancing density and photo-z.

→ Both selections are being used in Stage IV

lens sample 2 *= broad redmagic* χ^2
Twice more galaxies, a bit worse photo-z than Y3
source sample 2 *= BFD [bayesian fourier domain*
200 million shapes a bit worse shape noise than metadetect
[BFD → Bernstein and Armstrong 2014]

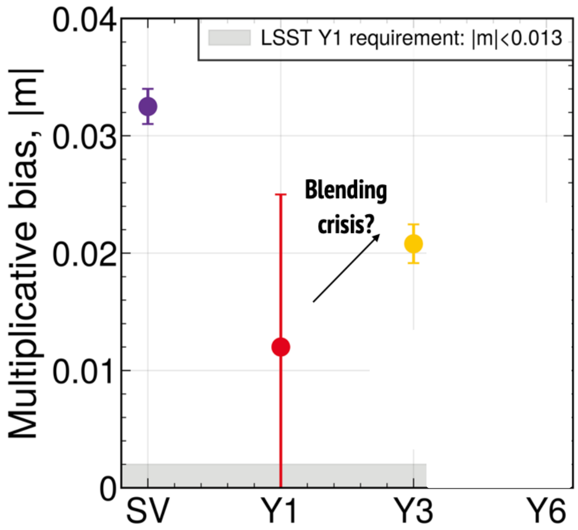
Metadetect *(Yamamoto, Becker et al.)*

- We have access to apparent ellipticities, but we are interested in the shear.

$$\mathbf{e} = \mathbf{e}\big|_{\gamma=0} + \frac{\partial \mathbf{e}}{\partial \gamma}\bigg|_{\gamma=0} \gamma + \ldots$$

Shear response

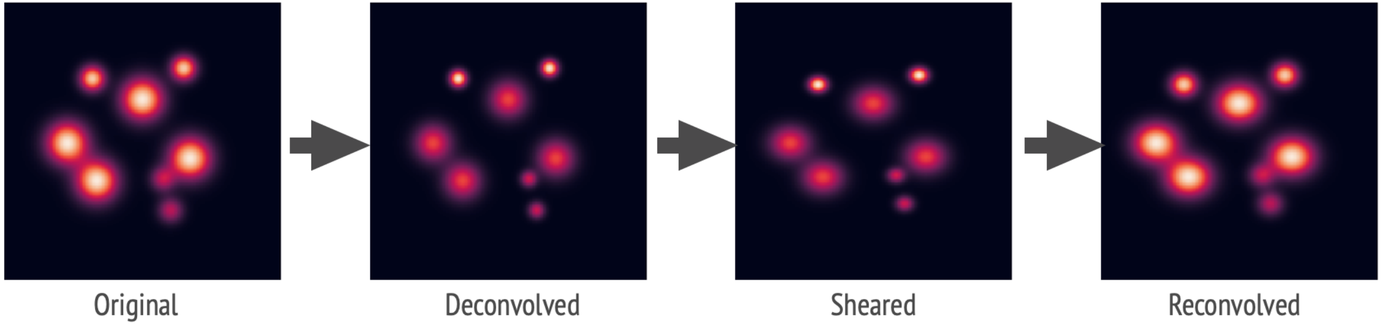
$$\mathbf{R} \equiv \frac{\partial \mathbf{e}}{\partial \gamma}\bigg|_{\gamma=0} = \begin{pmatrix} \partial e_1/\partial\gamma_1 & \partial e_2/\partial\gamma_1 \\ \partial e_1/\partial\gamma_2 & \partial e_2/\partial\gamma_2 \end{pmatrix}$$



- We want an unbias shear estimate.
- Shear biases c and m should be close to 0 : $\gamma_{obs} = (1+m)\gamma_{true} + c$

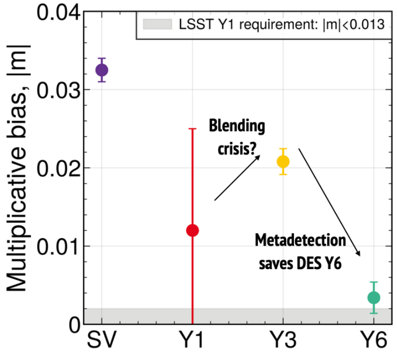
Metadetect *(Yamamoto, Becker et al.)*

Metadetect: A technic to self-calibrate raw galaxy shape measurements that contain noise bias, model bias, and selection bias by artificially process the image and calculating the shear response R



Improvements :

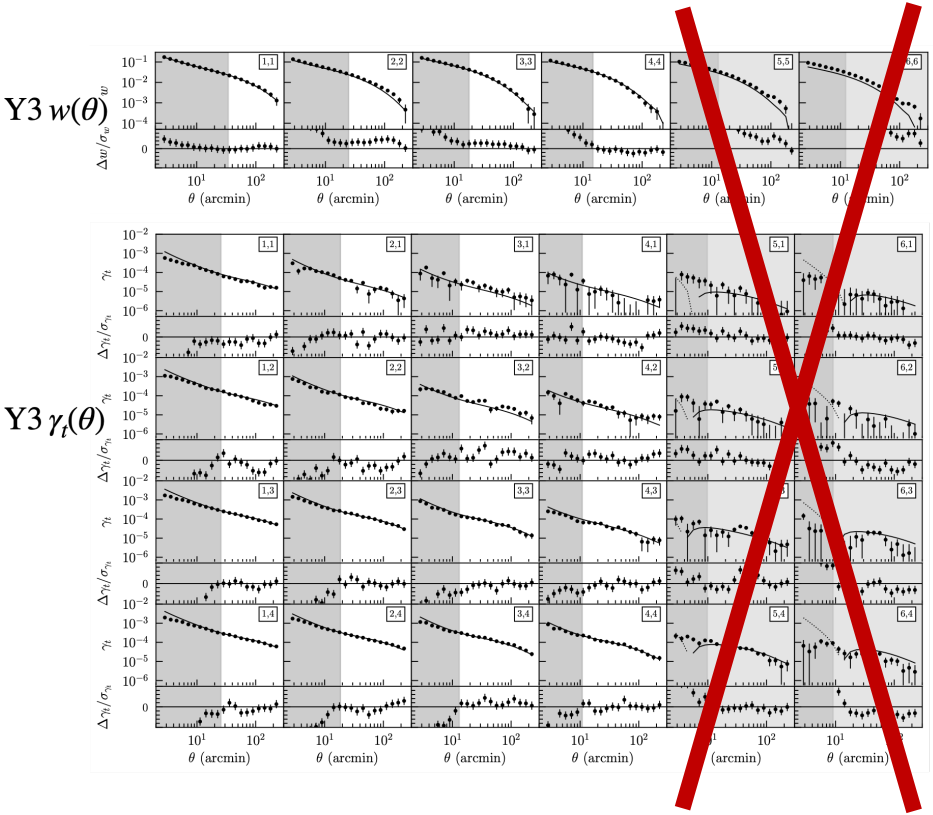
- Addition of chromatic PSF allows us to use g-band flux for photo-z, and reduce shear bias. *(T. Schutt et al.)*
- Improvement to Metadetect improves multiplicative shear bias
- Multiplicative bias from im-sim + accounting for the impact on $n(z)$s *(S. Mau et al., in prep.)*



Maglim++ *(Weaverdyck, Rodriguez et al.)*

Maglim++

- In Y3, we had to remove 2 bins from the analysis because of systematics contamination, internal inconsistencies



Maglim++ *(Weaverdyck, Rodriguez et al.)*

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Maglim++

- (i) mag-lim sample, 10 M galaxies into 6 (photo-z) bins: $i < 4 \times z_{\mathrm{DNF}} + 18, \quad i > 17.5$
- Improve purity and reduce systematics wrt Y3 Maglim

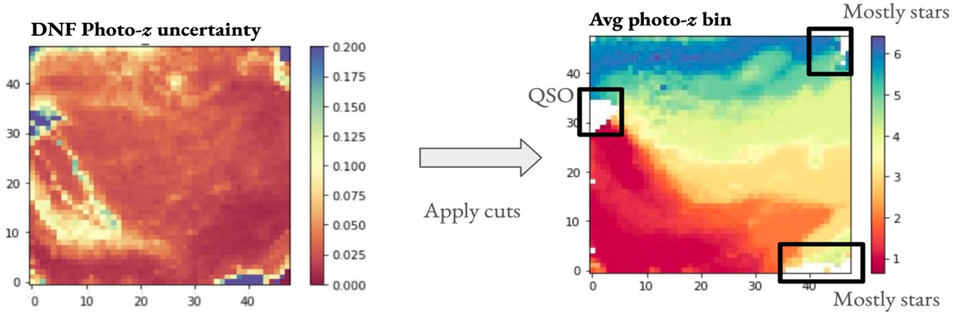
Maglim++ *(Weaverdyck, Rodriguez et al.)*

Maglim++

- (*i*) mag-lim sample, 10 M galaxies into 6 (photo-*z*) bins: $i < 4 \times z_{\mathrm{DNF}} + 18, \quad i > 17.5$
- Improve purity and reduce systematics wrt Y3 Maglim

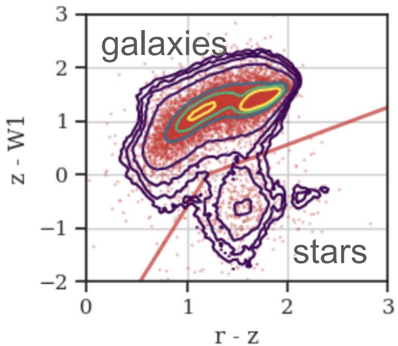
Photo-z quality cuts

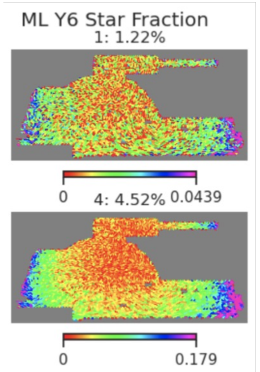
- Use SOM to group galaxies, identify and remove colors with *bad photo-zs*



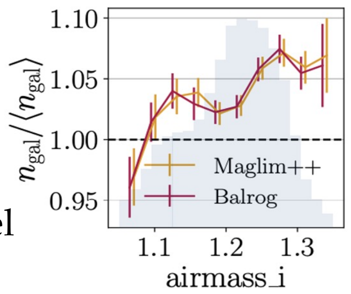
Improved star-galaxy separation

- (Bin) optimized cuts in the $(r - z, z - W_1)$ color space to isolate and remove stars
- Uses W_1, a NIR magnitude (unWISE catalog)





Simulation datasets



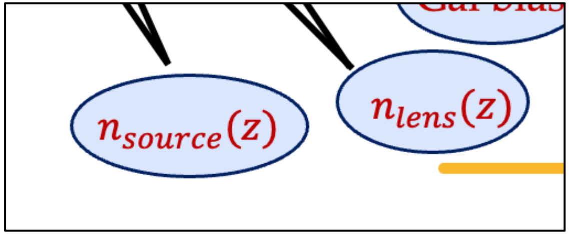
- **BALROG** *(D. Anbajagane et al. 2501.05683)*
  - Synthetic source injection of sources (from deep fields) into pixel-level wide field images
  - 146 million injections spanning the entire 5000 deg2 DES footprint !
  - Generate co-added images, detection catalogues, metadetect catalogues, maglim, etc
  - Critical to map deep-to-wide survey, lens magnification, star/gal separation, systematics

- **IMAGE SIMS** *(S. Mau et al.)*
  - Injecting galaxy stamps in DES configuration images with known shear, 1/10th of survey
  - Apply the same shear measurements and image co-addition (+mask) as real data
  - Calibrate multiplicative shear bias and effective redshifts distributions (e.g. in the presence of blending)

- **CARDINAL** *(Chun-Hao To et al, arxiv 2303.12104)*
  - N-body simulation + Update SHAM catalogue to i < 27. Characterize bias and clustering

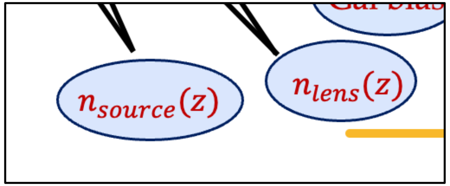
- DES Y6 :
  - Samples
  - Redshift calibration
  - Modelling

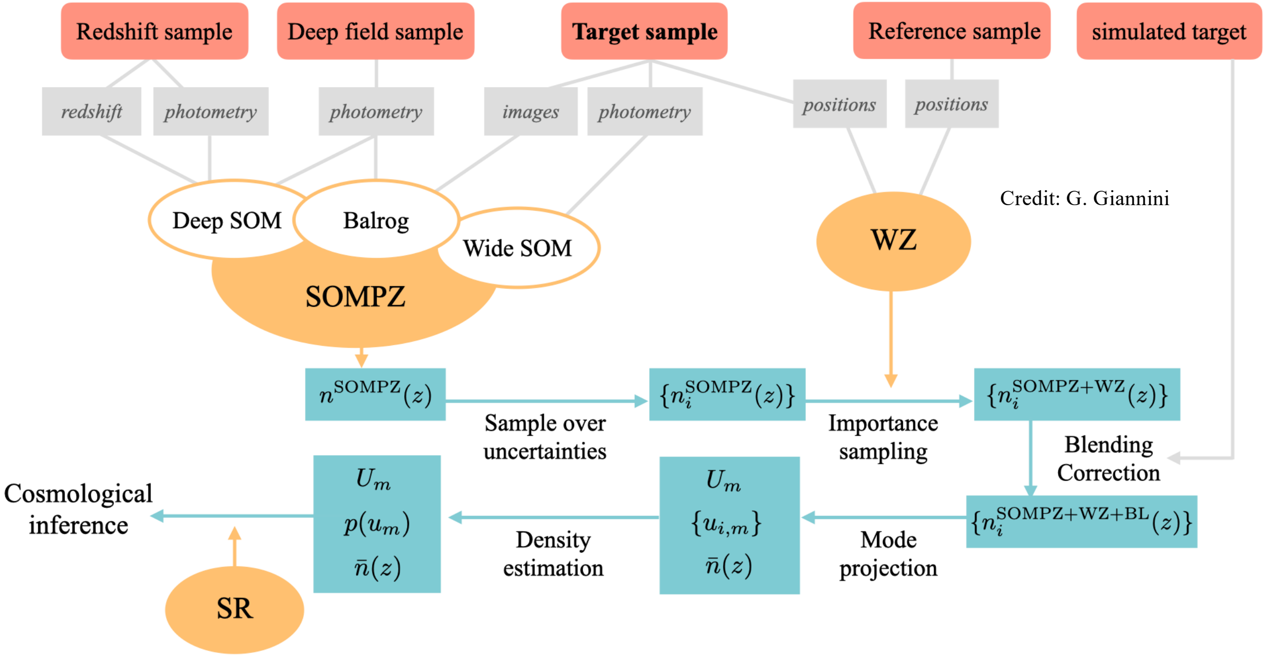
Do you remember these guys ?



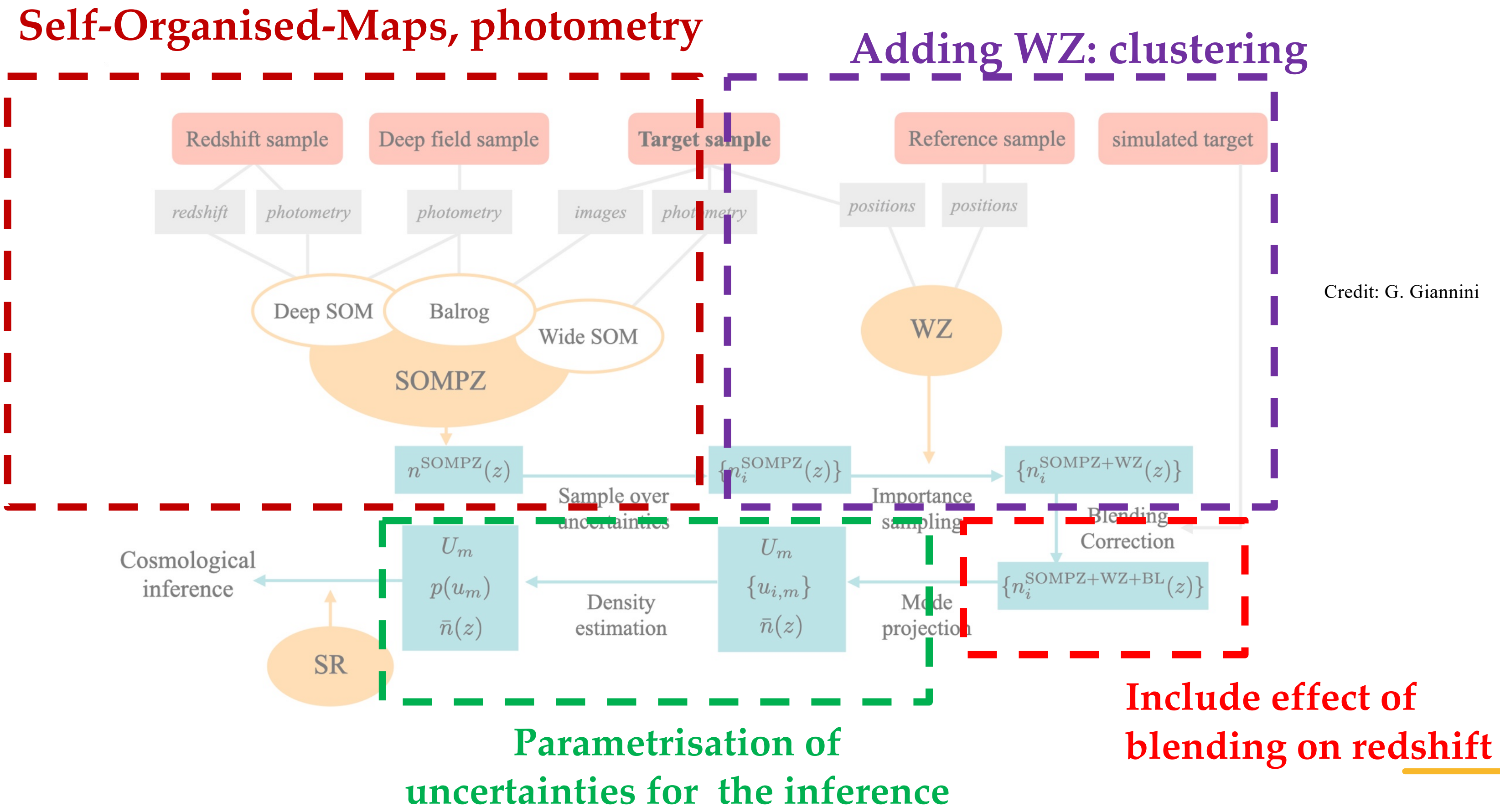
DES redshift calibration pipeline:

Do you remember these guys ?





DES redshift calibration pipeline:

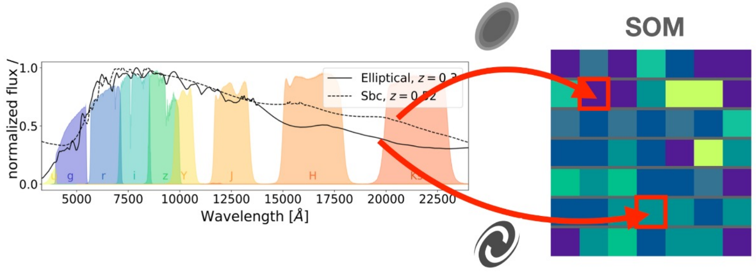


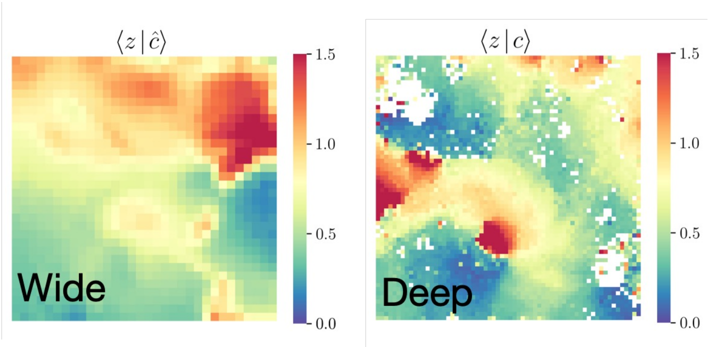
Credit: G. Giannini

Self-Organised-Maps

(Yin et al. Giannini, Alarcon et al.)

- Wide-survey galaxies live in the *griz* space (we call it $\hat{c}$).
- A tomographic bin b is a region of $\hat{c}$ space.
- We want to know their distribution $p(z \mid b)$
- Key concept: introduce latent *ugrizJHK* space c, the deep som, then:





@B. Yin

Redshift distribution of a bin

Redshift info on the deep

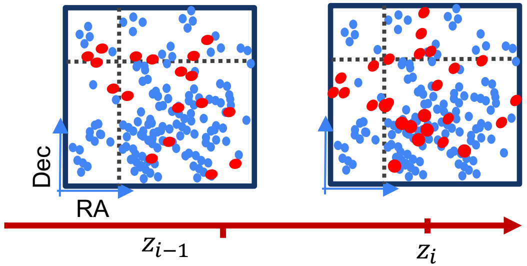
How deep would look like in the wide

$$p(z|b) = \sum_{c,\hat{c}} \underbrace{p(z|c,\hat{c})}_{\text{Redshift}} \; \underbrace{p(c|\hat{c})}_{\text{Deep-Balrog}} \; \underbrace{p(\hat{c}|b)}_{\text{Wide}} .$$

Clustering redshifts (Wz or Cz)

(d'Assignies, Bernstein et al.)

- **A photometric galaxy sample** is spread over a large redshift range
- Idea : Correlate it with **many spectroscopic samples** at different –z, compare random expectation



What we want

Photo galaxy bias

Cross-correlation spec-photo

$$w_{\rm sp}(\theta) = \int {\rm d}z\, n_{\rm s}(z)\, n_{\rm p}(z)\, b_{\rm p}(z)\, b_{\rm s}(z)\, w_{\rm m}(z,\, \theta) + w^{\mu}_{\rm sp}(\theta)$$

What we know

Magnification

Clustering redshifts (Wz or Cz)

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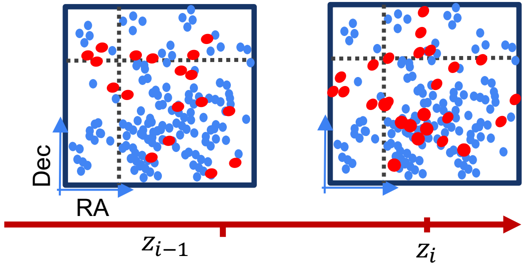

Cross-correlation spec-photo

What we want

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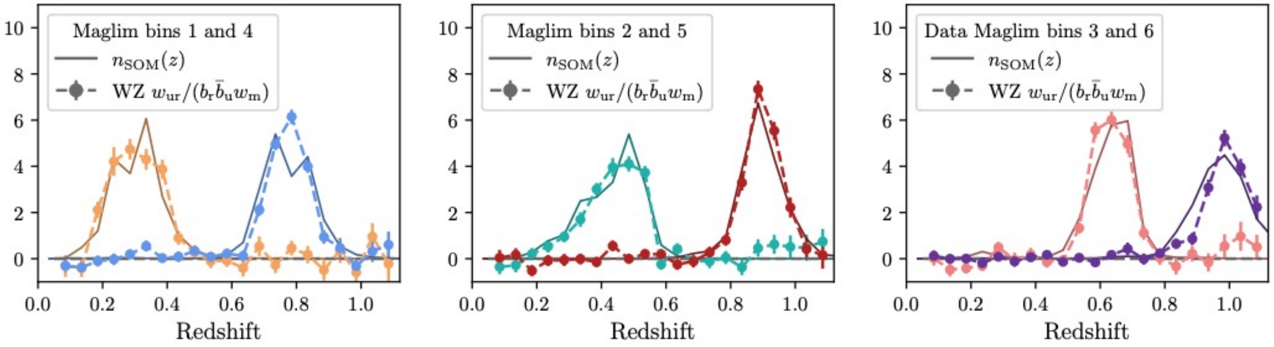
What we know

Magnification



Combining WZ with SOM

(d'Assignies, Bernstein et al.)

Proba of a proposed n(z)s given our photometry and clustering z

Proba clustering-z given n(z)s (previous slide)

Proba of n(z)s given our photometry(3sDir)

$$p(\mathbf{n}|\mathrm{PZ}, \mathrm{WZ}) \propto p(\mathrm{WZ}|\mathbf{n})\, p(\mathbf{n}|\mathrm{PZ})$$

- Both probability on the right, analytical models, with explicit systematics marginalisation

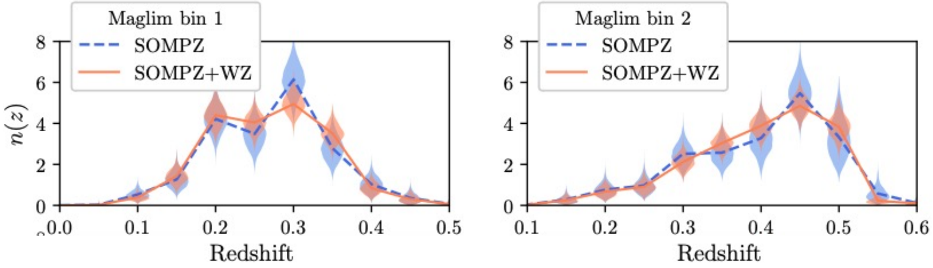
- We start from 100M n(z)s candidates from 3sDir, all equi-prob.
- We select 1000 of them, with proba p(WZ | n)

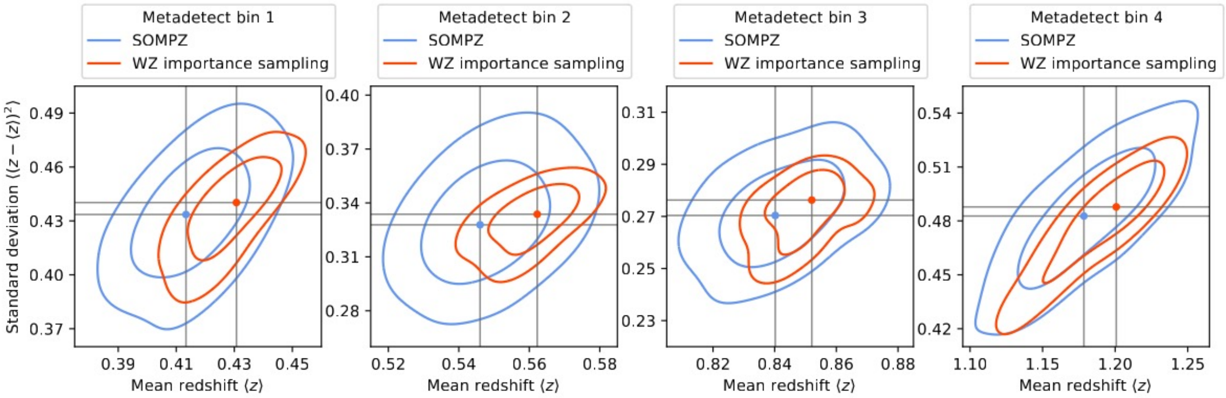
- The resulting sample ~ $p(n|\mathrm{PZ}, \mathrm{WZ})$

Combining WZ with SOM

(d'Assignies, Bernstein et al.)

- The procedure 'produces' a smoothing of the n(z) (Right for lenses)
- It reduces uncertainties on the mean-z and std-z (bottom)

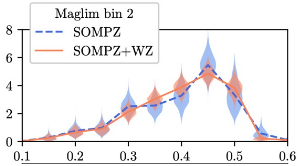




- DES Y6 :
  - Samples
  - Redshift calibration
  - Modelling

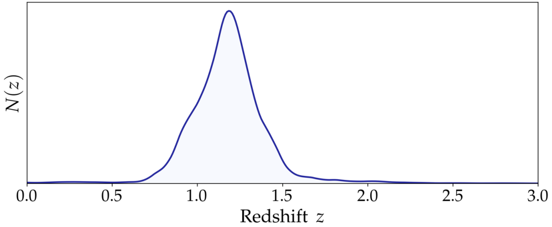
Redshift uncertainty : modes vs shift and stretch

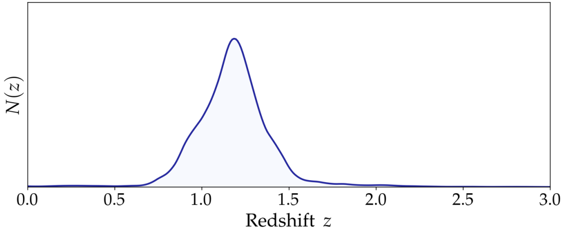
(Bernstein, d'Assignies, Troxel et al.)



- Y3: **shift and stretch** → Y6: **redshift modes** (PCA)
- MCMC: sample mode coefficients u_i:

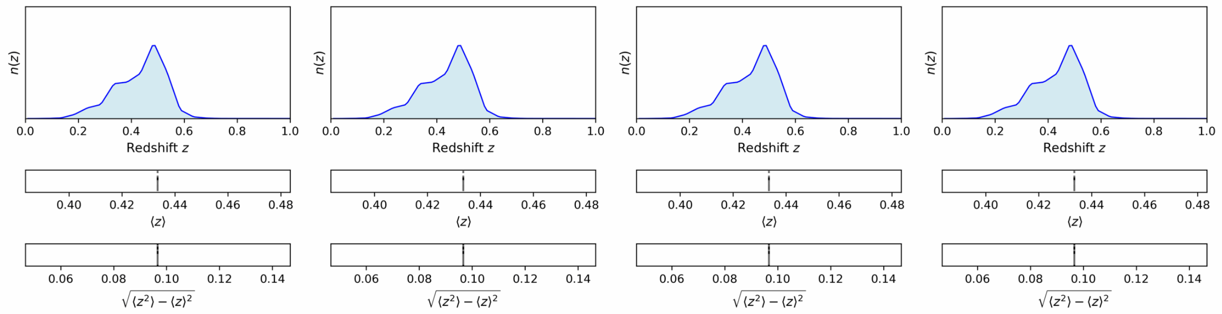
$$\hat{n}(z, \delta z, s) = \frac{1}{s} n_0 \left(\frac{z - \delta z}{s} \right)$$





$$\hat{n}(z) = n_0(z) + \sum_i u_i \,.\, U_i(z)$$

First 4 modes of one lens bin



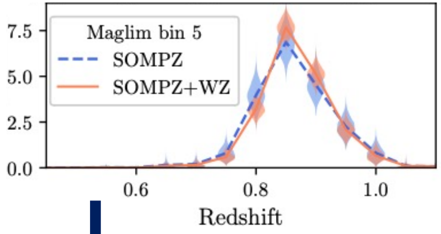
Redshift uncertainty : modes

(Bernstein, d'Assignies, Troxel et al.)

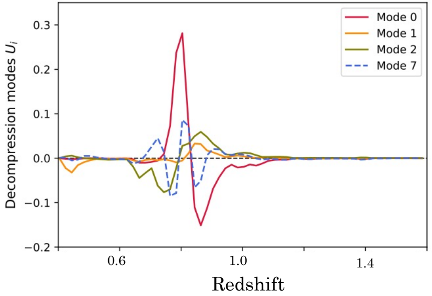
- Idea: Use Principal Component Analysis to extract a set of redshift modes $U_i(z)$
- MCMC: sample mode coefficients u_i:

$$\hat{n}(z) = n_0(z) + \sum_i u_i \,.\, U_i(z)$$

- We don't capture all the variations of the $n(z)$, only the variations which have an impact on *cosmology observables* $\hat{c}$ (1x2 or 3x2 or whatever).



'PCA'



$$\langle \chi^2 \rangle = \frac{1}{N_\alpha} \sum_\alpha \left[\hat{\mathbf{c}}(\mathbf{q}, \mathbf{n}_\alpha) - \hat{\mathbf{c}}(\mathbf{q}, \hat{\mathbf{n}}_\alpha)\right]^T C_c^{-1} \left[\hat{\mathbf{c}}(\mathbf{q}, \mathbf{n}_\alpha) - \hat{\mathbf{c}}(\mathbf{q}, \hat{\mathbf{n}}_\alpha)\right].$$

Quantity to minimize

Sum over realisations

Calibration realisation

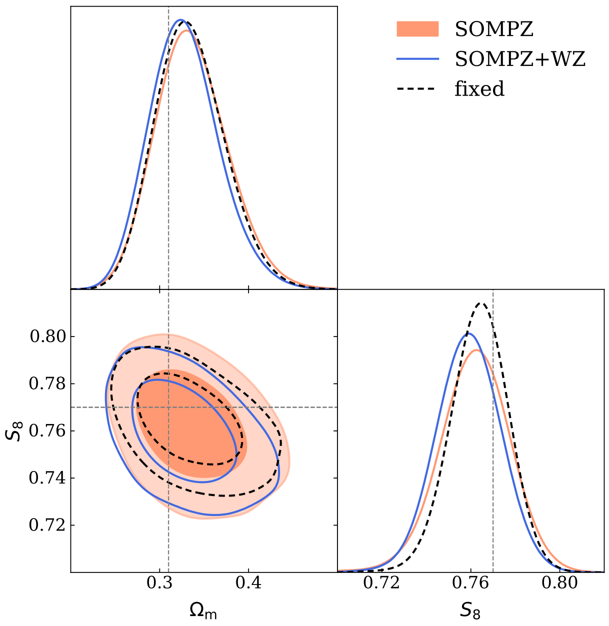
Observables (1x2, 3x2pt)

Mode model of the realisation

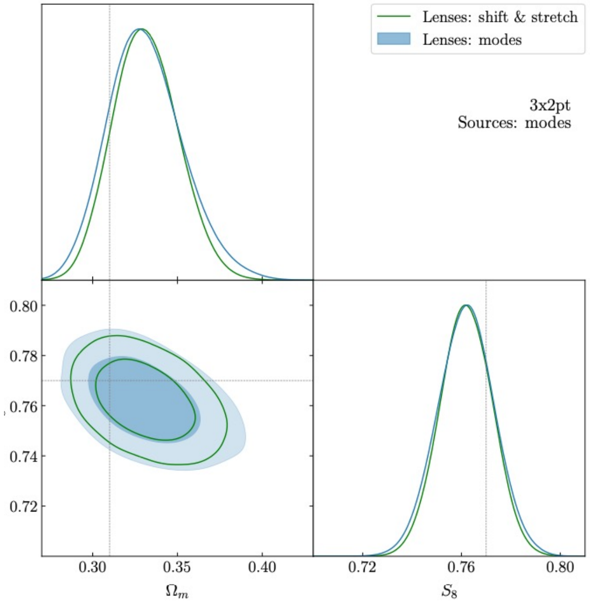
Observables covariance

Redshift uncertainty : cosmology inference

Cosmic Shear (1x2), **simulated DV**



GGL, GC (3x2), **simulated DV**



4 takeaways:

Left:

- Improvement 10% level adding WZ (1x2 and 3x2)
- Very good consistency between SOM and WZ
- Still loosing some constraining power (10-15% for 1x2 and 3x2)

Right:

- Shifts&stretch on 3x2 underestimates uncertainty (1x2 it overestimates)

@G. Gianinni, W. d'Assignies, B. Yin

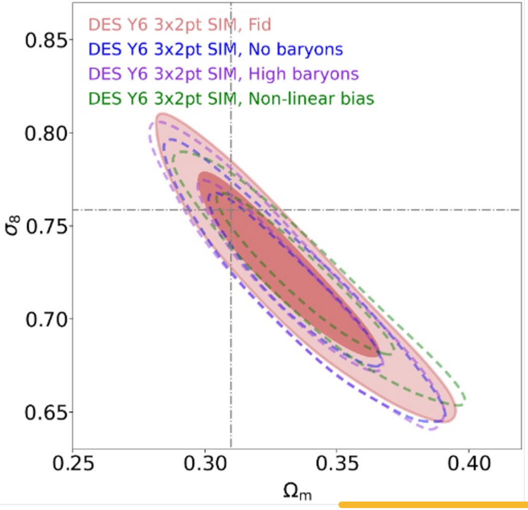
Analysis choices for DESY6

(D. Sanchez, A. Fertè, J. Blazek, S. Samuroff et al)

Analysis choices changes wrt Y3 :

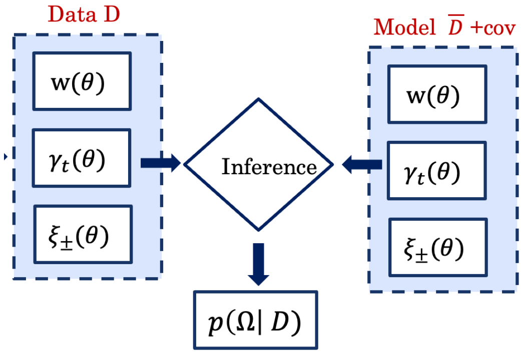
- HMCode 2020 for **nonlinear DM P(k)** *(+baryons)*
- **Linear and Nonlinear bias** are baseline now → helps pushing to smaller scales
- Inclusion of fixed **baryon feedback** signal with log(Tagn) = 7.7
- **Intrinsic alignment** - TATT 4 parameters for 3x2 and 2x2 (bta=1)
  - NLA and TATT for 1x2

- We use more complex models or simulations to set scale cuts
  - Scale-cuts defined such that biases in front of nonlinear bias and baryons are < 0.5 σ in 2D posterior $S_8 - \Omega_m$
  - Min scales: 8.7′ for $\gamma_t(\theta)$, 13′′ for $w(\theta)$, and 3′ for ξ_+



Inference and unblinding

- CosmoSIS and nautilus algorithm sampling over **50+ parameters**
- Params = Cosmology (6/7) + Galaxy bias (6) + Intrinsic alignments (4) + Lens Magnification (6) + shear calibration (4) + Redshift Modes (18 lenses + 7 sources)
- **Computing cost:** 5k-40k CPU-hours per chain *OR ~ 1 day in 256 cores* → 100's of chains (few M CPU hrs) !!!



William d'Assignies

Inference and unblinding

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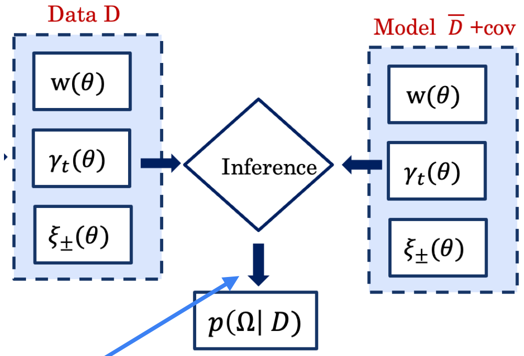
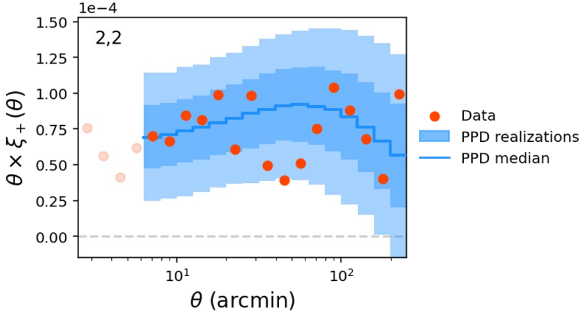




J. Muir, C. Doux et al

We use Posterior Predictive Distributions (PPDs) to assess goodness of fit and internal consistency

Generate a trial Cov, run first MCMC chain, blindly update Covariance

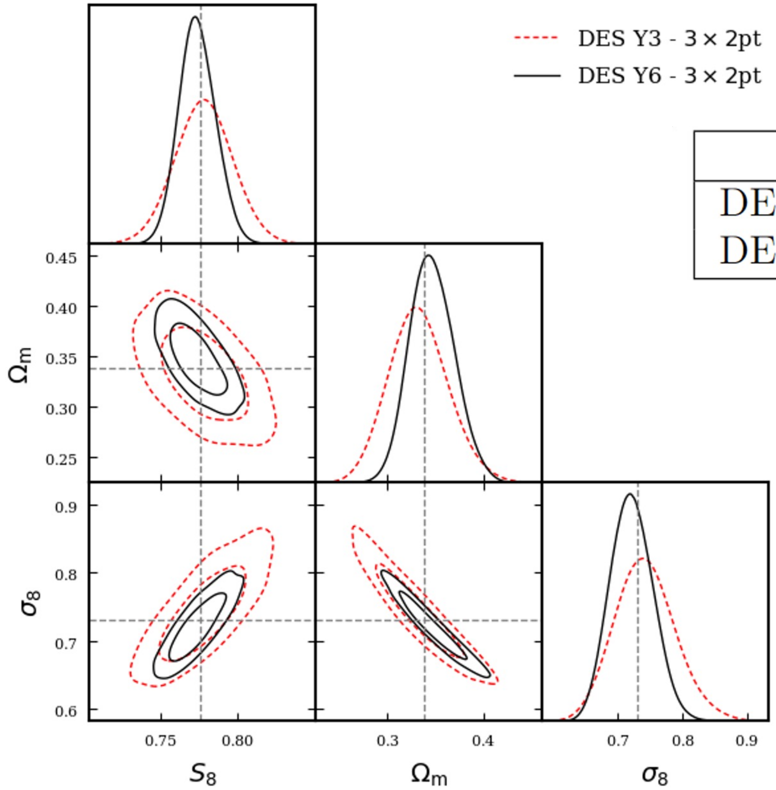
2. Run a set of MCMC chains and check
   - Compute p-value of 3x2, 2x2,1x2 and check posterior of calibrate nuisance
   - Compute PPD(1x2|2x2), PPD(wt|cs+gt), PPD (gt|cs+wt)
3. Unblind if all consistent

- Intro
  - DES in few numbers
  - 3x2pt analysis
  - 3x2pt results of DES Y3

- DES Y6 :
  - Samples
  - Redshift calibration
  - Modelling
  - FOM (blinded)

- What's next ?
  - Y6 FOM vs Y3
  - Higher orders analysis

From DES Y3 to DES Y6



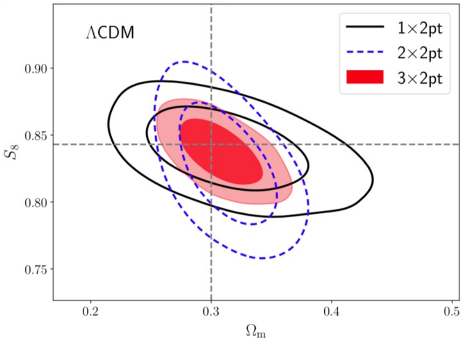
Case	$\mathrm{FoM}_{\Omega_m,\sigma_8}$	Relative Difference (%)
DES Y3 - 3×2pt	2011.20	-
DES Y6 - 3×2pt	4942.84	145.77%

The Y3 results here correspond to the published DES Y3 results (4 lens bins, linear galaxy bias, non-optimised LCDM scale-cuts, no shear ratios). More than a factor of 2 from Y3 to Y6

Fiducial cosmology papers (early 2026):

- 3x2pt and combined probes (BAO, SN, clusters, cmb, ...)
- 3x2pt ext-models (w0wa CDM, gravity, ...)

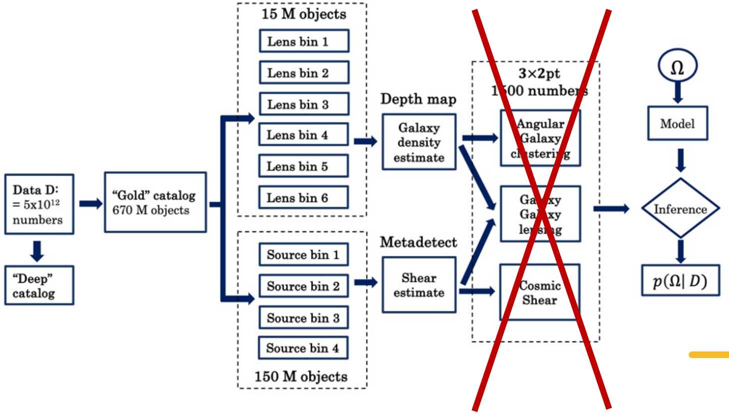
- 1x2pt (CS)
- 2x2pt (GC+GGL)



Higher orders statistics

- Use non-gaussian info
- SBI, peaks, etc..

- Later !!



Summary

THE DARK ENERGY SURVEY

DES as a collaboration – over 420 publications (cosmology and legacy science). Massive imaging dataset (optimal and near IR). Trained a very large group of scientists, developed methodology usable for Stage IV surveys

- DES BAO - arxiv 2402.10696, DES SNIa - arxiv 2401.02929, cosmology from 1500 SNIa (soon re-ananlysis)

- 3x2pt is hard!
- DES Y6 3x2 cosmology - to appear in early 2026 (IR next week!)

- Higher orders and additional work

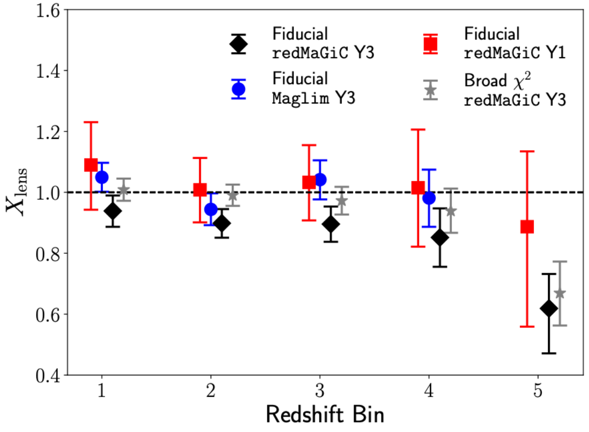
- Data, catalogues, calibrations will be public soon, as well as chains. Best data sets for a couple more years, **use them** !!!

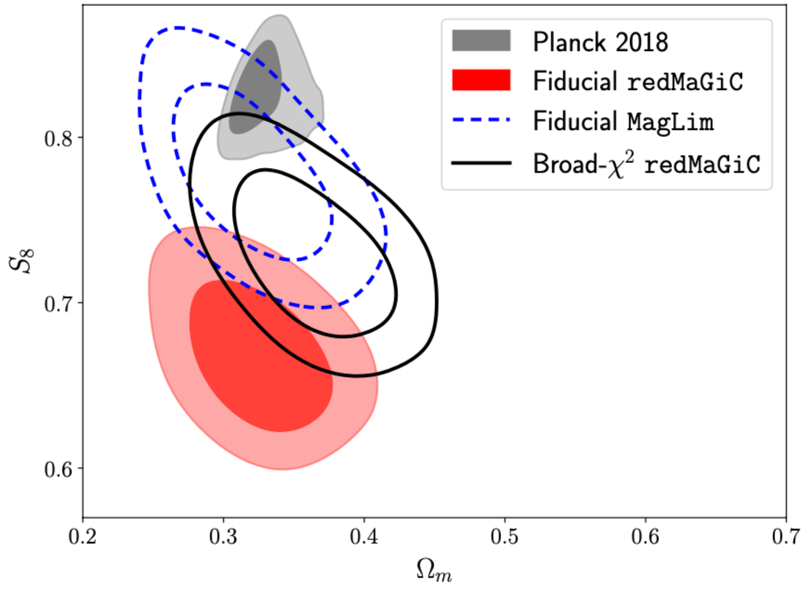
@J. Muir

(On my side, first overview talk, happy to take any feedback, also looking for postdocs!)

Y3 Redmagic curse

- Inconsistent with Maglim: same physics, same volume…
- Inconsistent 3x2pt and 2x2pt, visible on galaxy bias:
- $X_{lens} = b_{3\times2}/b_{2\times2}$, not consistent with 1…
- Had to change sample after unblinding, still ?, reason why PPDs in Y6





3x2pt 'pre-unblinding' papers

Modelling (in prep.),
D. Sanchez, A. Ferté et al.

Balrog (2501.05683)
D. Anbajagane et al.

Cardinal (2303.12104)
C. To et al.

Mask (2509.07943).
M. Rodríguez, N. Weaverdyck et al.

Gold paper (2501.05739)
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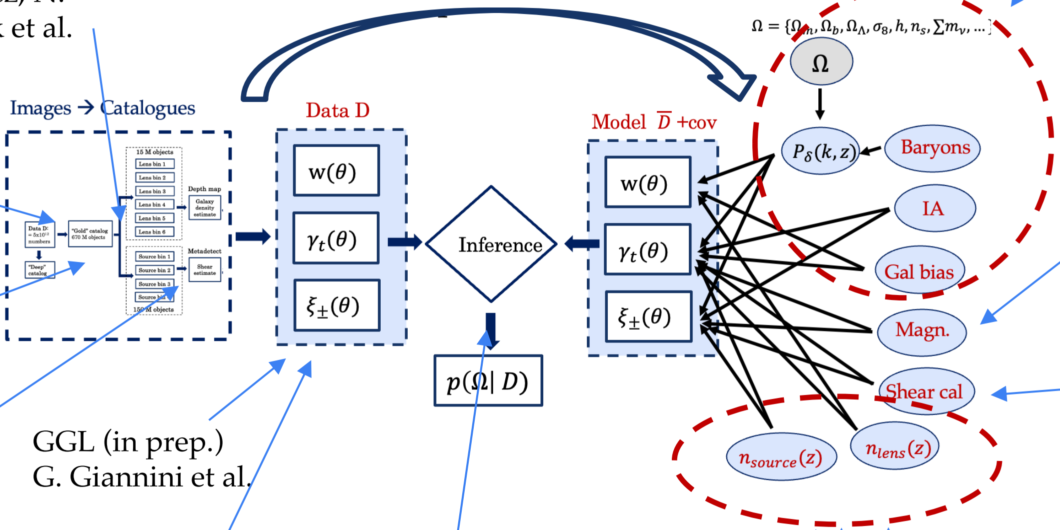

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Image Sim (in prep.)
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Metadetect (2501.05665)
M. Yamamoto, M. Becker et al.

GGL (in prep.)
G. Giannini et al.

GC and obs sys (in prep.)
N. Weaverdyck, Rodríguez, N. et al.

PPDs (in prep.)
C. Doux, J. Muir, et al.

SOM (2509.07964 & 2510.23566):
B. Yin et al, G. Giannini et al
WZ (2510.23565): W. d'Assignies et al.
z-priors (2506.00758): G. Bernstein et al.

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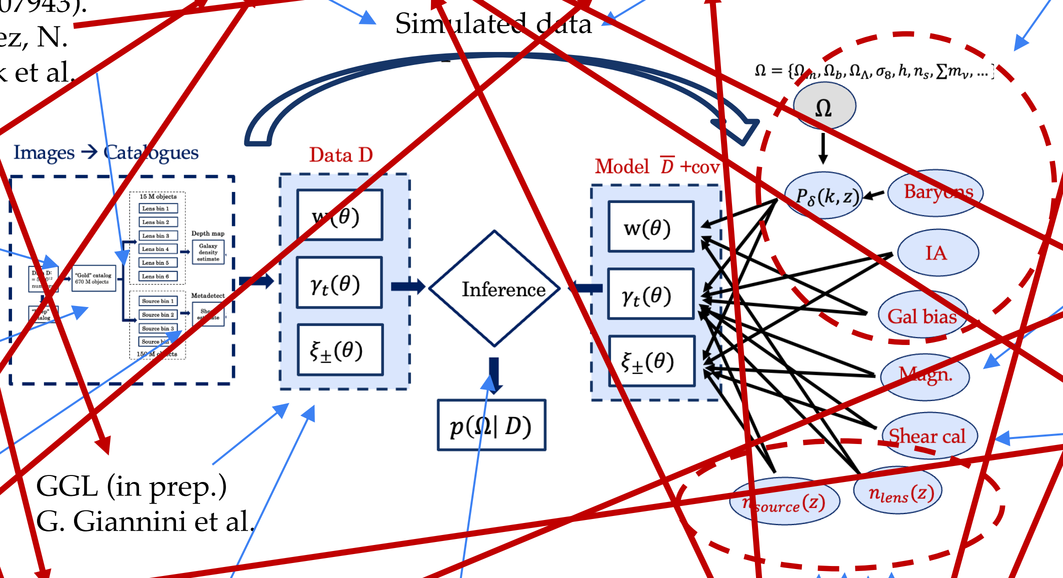

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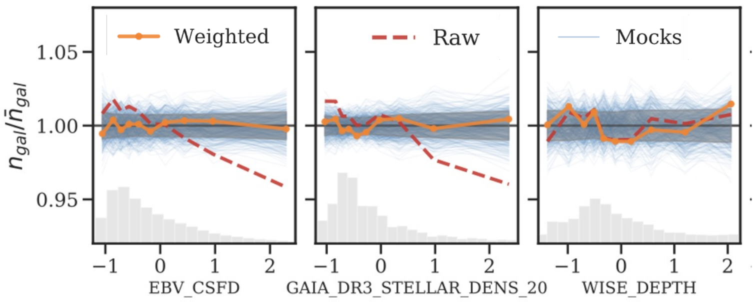
Mitigation of large-scale observational systematics

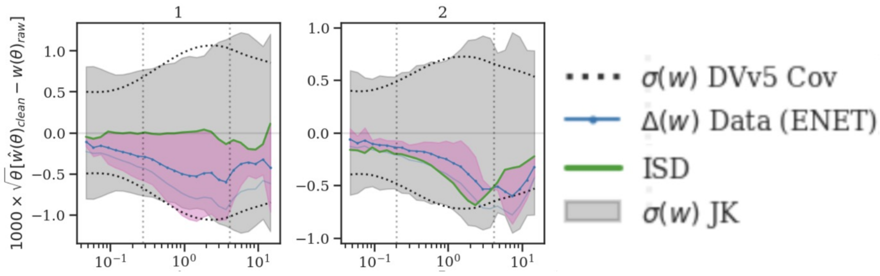
(Weaverdyck, Rodriguez Monroy et al)

Correlation of survey properties and astrophysical maps are unphysical

We check for correlation with ~ 20 maps:
seeing, airmass, depth, stellar density, dust, sky brightness



Iterative Decontamination (IDS) Significance of 1D correlations estimated with mock catalogues, we iterative apply weights the galaxies to remove the trends, starting from the most significant



Neural Net (ENet) Multilinear combination of all SP maps, very fast, allows non-linear relations

Complementary Methods - Cross-validation - We analytically marginalize over the difference.

Combining WZ with SOM.

THE DARK ENERGY SURVEY

Likelihood of clust-z data given a proposed n(z)s

Clust-z data and Cov

Model for Clust-z data, including n, magn, sys

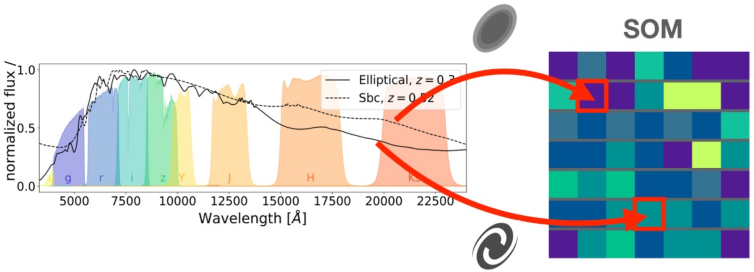
$$p(\mathbf{w}|\mathbf{n}) \propto \int \mathrm{d}\mathbf{q} \, \exp\left[-(\mathbf{w}-\hat{\mathbf{w}})^T C_w^{-1} (\mathbf{w}-\hat{\mathbf{w}})/2\right]$$

$\hat{w}$ is linear in q, this is Gaussian in q

$$\times \underbrace{\exp\left[-\left(\alpha_{\mathrm{r}}-\alpha_{\mathrm{r}}^{(0)}\right)^2/2\sigma^2(\alpha_{\mathrm{r}})\right]}_{\text{Magnification spec-sample Gaussian priors}} \underbrace{\prod_{\mathrm{u}} \exp\left[-\left(\alpha_{\mathrm{u}}-\alpha_{\mathrm{u}}^{(0)}\right)^2/2\sigma^2(\alpha_{\mathrm{u}})\right]}_{\text{Magnification photo-sample Gaussian priors}} \underbrace{\prod_{\mathrm{u},k} \exp\left[-s_{\mathrm{u}k}^2/2\sigma^2(s_{\mathrm{u}k})\right]}_{\text{WZ systematic coefficients Gaussian priors}}$$

- Everything is Gaussian !
- Integral reduces to the product of one exponential and one determinant !

Self-Organised-Maps

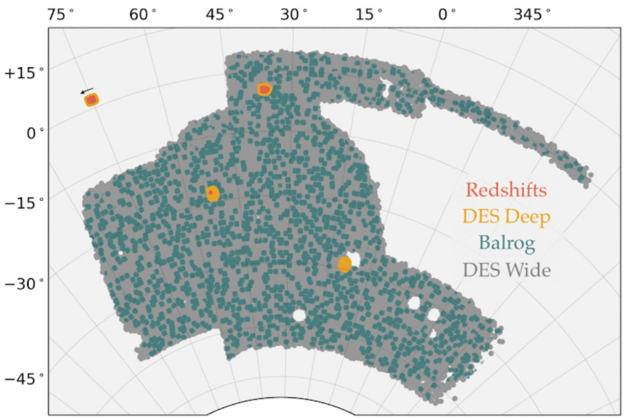


- **Self Organising Map (SOMs)** are used to classify galaxies multi-band fluxes in phenotypes 'cells'—> c

- 4 small but **Deep Fields** with 8 bands coverage ($ugrizJHKs$) at 25.4

  - Galaxies from wide and deep fields are grouped into two SOMs
  - The two SOMs are mapped through a transfer function using **BALROG**

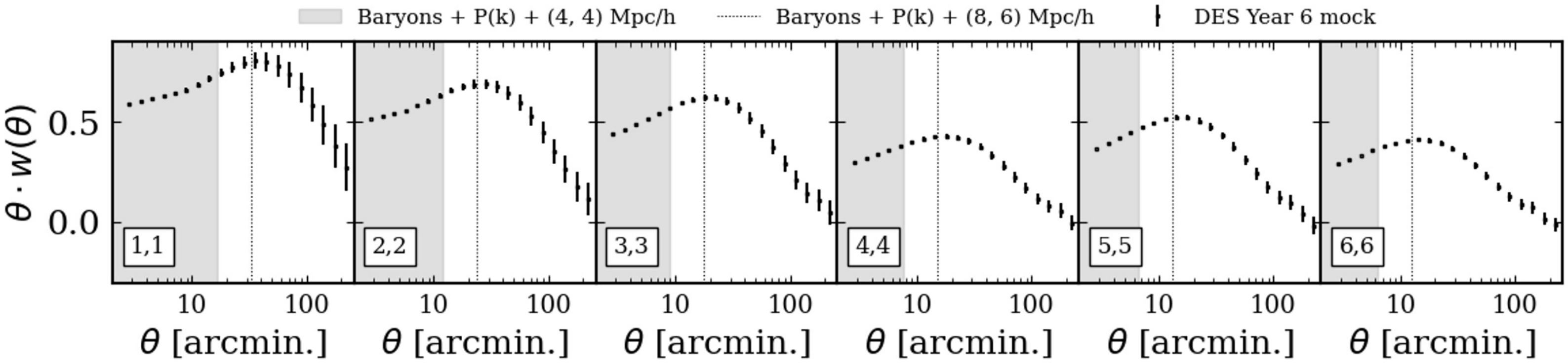
  - Photo-z's in the deep fields are validated through a high precision redshift sample



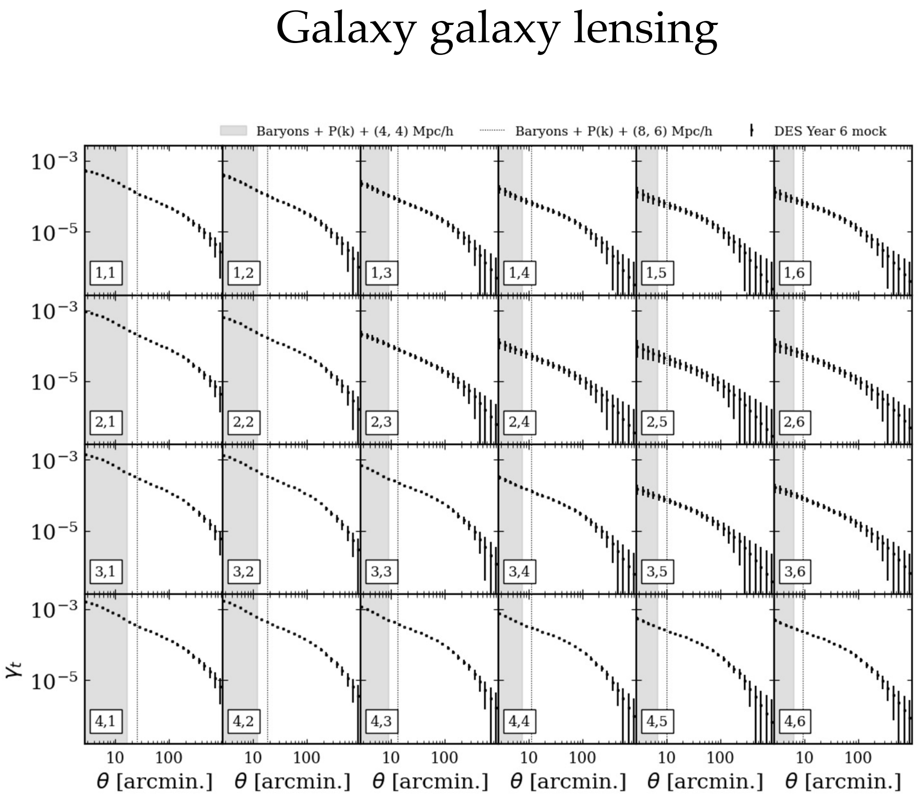
Credit C. Sánchez

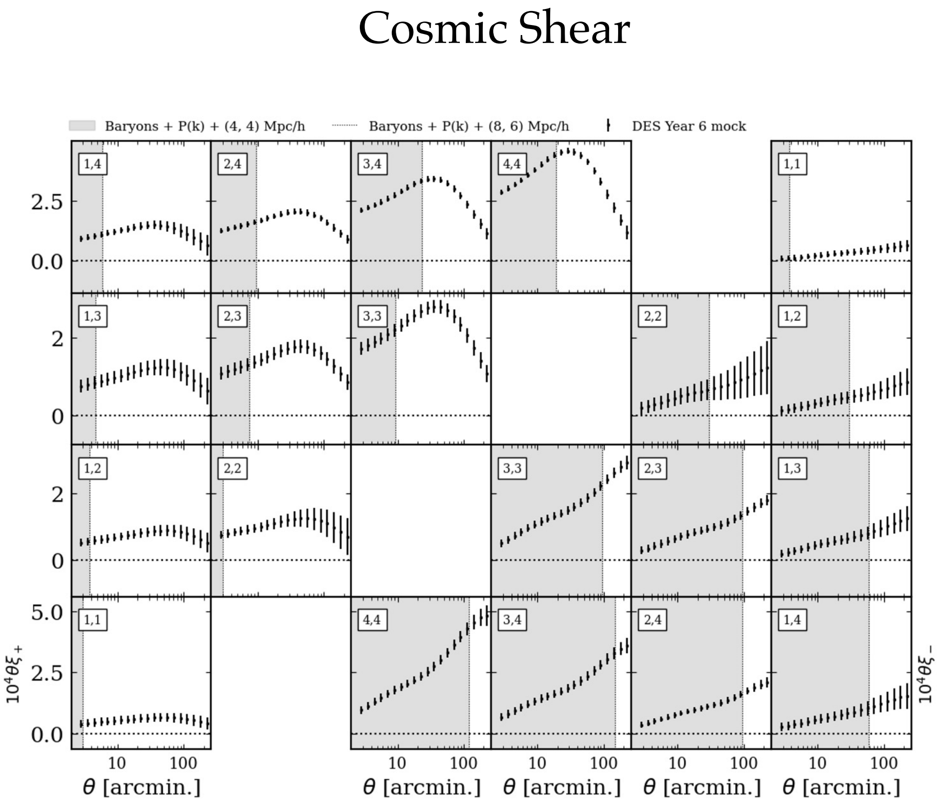
What to expect from DES Y6 ?

nonlinear gal bias   linear gal bias

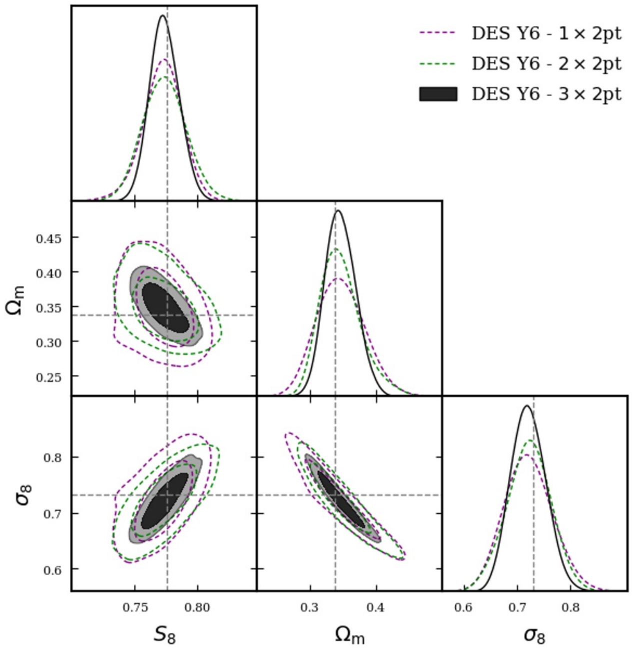


Analysis	Scale cuts	ξ_+	ξ_-	γ_t	$w(\theta)$	Total	SNR
Cosmic shear NLA	$\Delta\chi^2 = 3.5$	178	89	-	-	267	37.52
Cosmic shear TATT-4	$\Delta\chi^2 = 5$	183	99	-	-	282	39.76
2×2pt ΛCDM Linear scales	(9, 6) Mpc/h	-	-	312	66	378	114.71
3×2pt w/ΛCDM Linear scales	(9, 6) Mpc/h + $\Delta\chi^2 = 5$	183	99	312	66	660	115.85
2×2pt ΛCDM Non-linear scales	(4, 4) Mpc/h	0	0	348	87	435	171.58
3×2pt ΛCDM Non-linear scales	(4, 4) Mpc/h + $\Delta\chi^2 = 5$	183	99	348	87	717	172.2


Galaxy galaxy lensing
Baryons + P(k) + (4, 4) Mpc/h
Baryons + P(k) + (8, 6) Mpc/h
DES Year 6 mock
γ_t
θ [arcmin.]


Cosmic Shear
Baryons + P(k) + (4, 4) Mpc/h
Baryons + P(k) + (8, 6) Mpc/h
DES Year 6 mock
$10^4\theta\xi_+$
$10^4\theta\xi_-$
θ [arcmin.]

The sustained gain of 1x2 + 2x2 :



Case	$\mathrm{FoM}_{\Omega_m,\sigma_8}$	Relative Difference (%)
DES Y6 - 1 × 2pt	1812.45	-
DES Y6 - 2 × 2pt	2019.41	11.42%
DES Y6 - 3 × 2pt	4942.84	172.72%

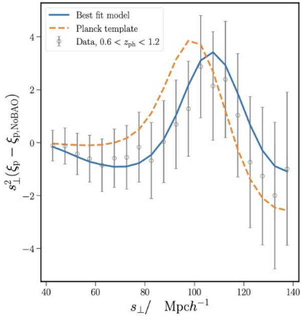
- More than a **factor of 2 increase** in FoM in LCDM from combining three 2pt combination (as in Y3)
- **3x2 is very robust to systematics** in general

ΛCDM	S_8	Ω_m	σ_8	$\mathrm{FoM}_{\sigma_8,\Omega_m}$
DES Data Y3				
3×2pt	$0.776^{+0.017}_{-0.017}$ (0.776)	$0.339^{+0.032}_{-0.031}$ (0.372)	$0.733^{+0.039}_{-0.049}$ (0.696)	2068
$\gamma_t+w(\theta)$	$0.778^{+0.031}_{-0.037}$ (0.809)	$0.320^{+0.034}_{-0.041}$ (0.306)	$0.758^{+0.063}_{-0.074}$ (0.801)	927
$\xi_\pm$	$0.759^{+0.025}_{-0.023}$ (0.755)	$0.290^{+0.039}_{-0.063}$ (0.293)	$0.783^{+0.073}_{-0.092}$ (0.763)	740

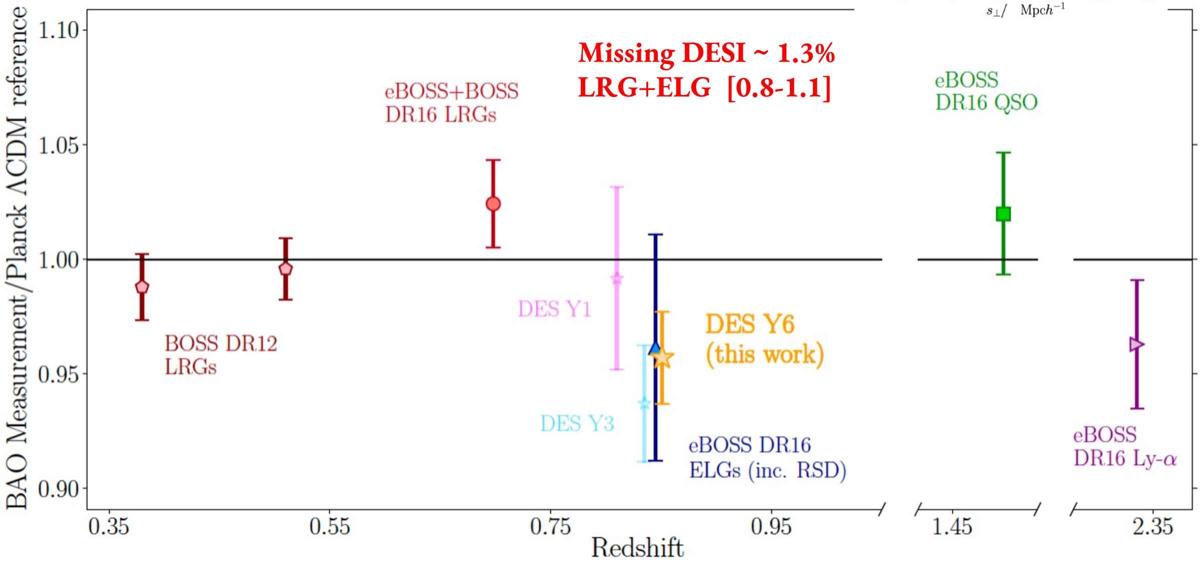
Credit = DES Modeling team (led by D. Sanchez, A. Fertè, J. Blazek)

DES beyond 3x2 : BAO at z ~ 0.85

A 2.1% measurement of the angular Baryonic Acoustic Oscillation scale at z_{eff}=0.85 from the DES final dataset (submitted in **Feb 2024**, arxiv 2402.10696)

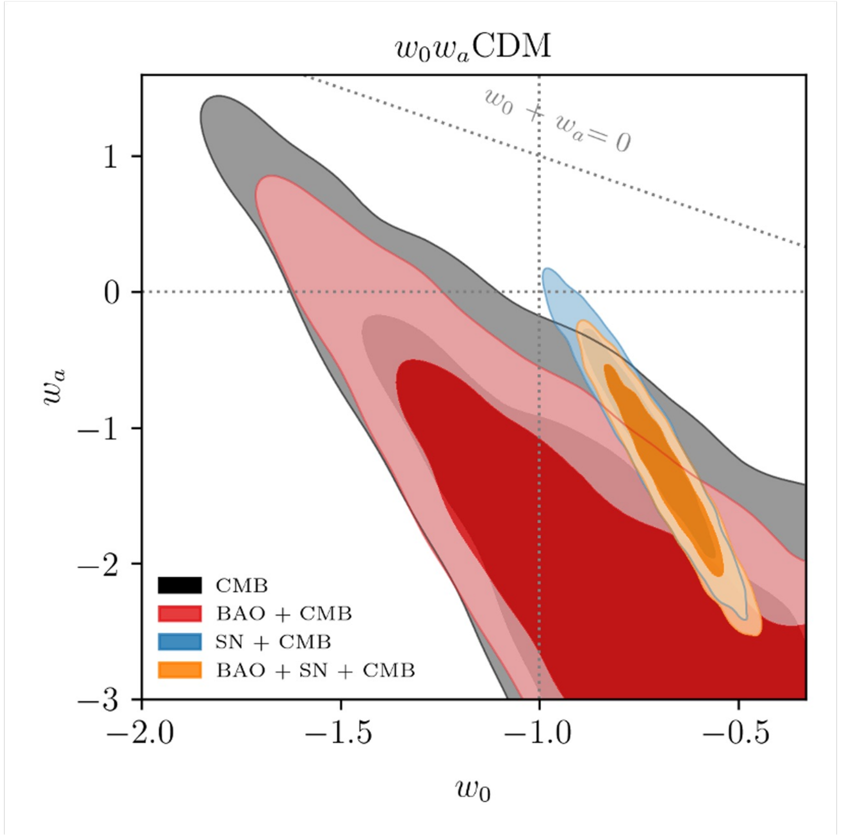


- 16 M galaxies in 0.6 < z < 1.2
- 2.1σ below Planck (4.3%)
- 3.5σ significance of the BAO peak
- Most precise BAO measurement from a photometric survey
- Competitive with spectroscopic surveys
- Angular BAO at the closure of Stage-III surveys



$$(D_M/r_d)/(D_M/r_d)_{\rm Planck} = 0.957 \pm 0.02$$

Y5 DES SNIa + DESY6 BAO + CMB



Cosmology from DES Y6 BAO and DES Y5 SN represent the culmination of what the final DES can tell us about the expansion of the Universe via geometric probes.

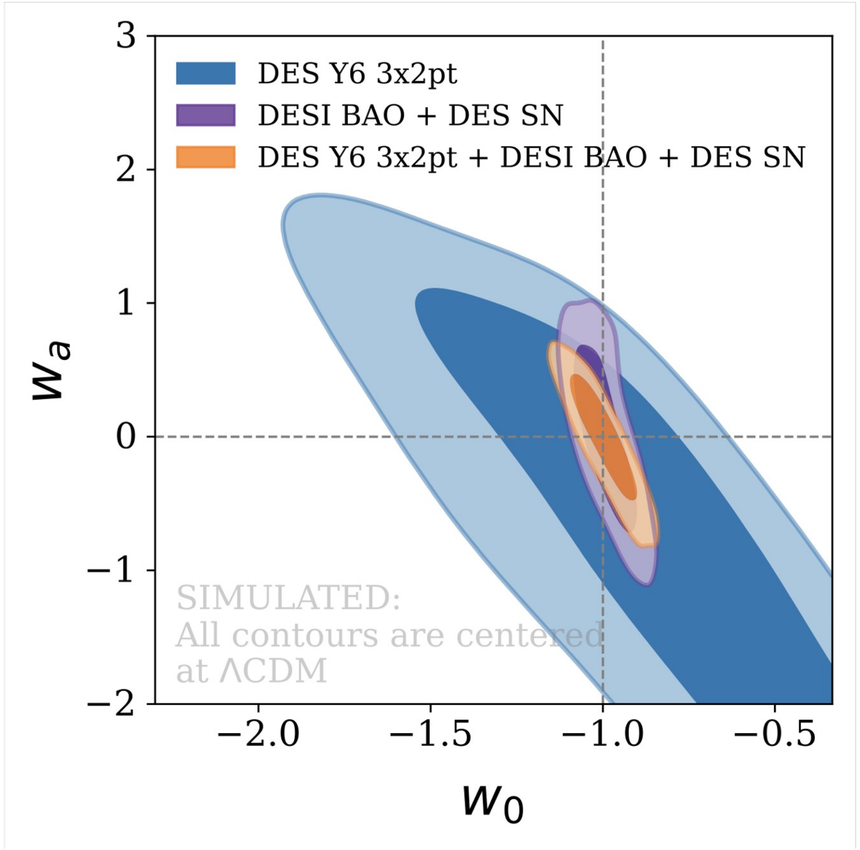
DES Collaboration 2025, **March**, arXiv:2503.06712

In ΛCDM BAO tends to pull towards lower Ωm, SNIa towards higher Ωm, with some ~2-3σ tensions between data combinations (assuming minimal neutrino mass).

Dynamic dark energy w0waCDM shows **~3.2 σ discrepancy** with ΛCDM (similar, but a bit lower, than using DESI Y1 BAO).

See also *Notari et al arXiv:2411.11685*

Evolving dark energy from low-z probes



- DES 3x2pt

$w_0 > -1.64$ (95% bound)

$w_a = -0.5^{+1.3}_{-1.1}$

- DESI DR2 BAO + DES Y5 SN

$w_0 = -0.994^{+0.053}_{-0.062}$

$w_a = 0.01 \pm 0.46$

- DES 3x2pt + DESI DR2 BAO + DES Y5 SN

$w_0 = -0.996 \pm 0.064$

$w_a = -0.02^{+0.35}_{-0.28}$

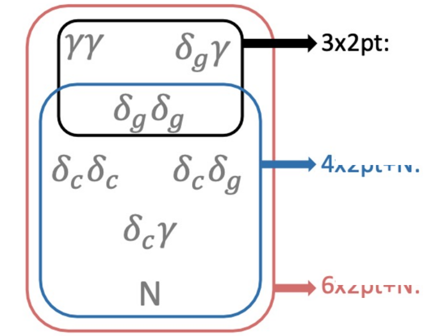
3x2 helps in constraining mainly w_a

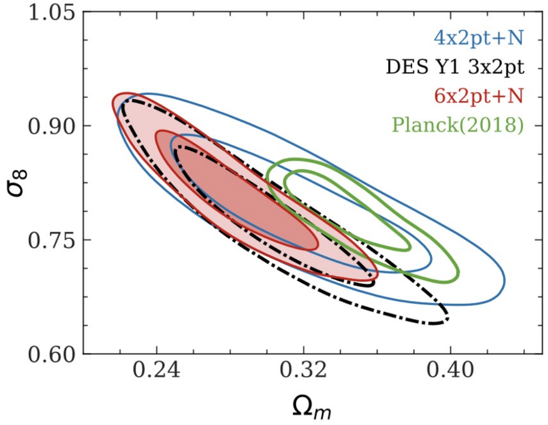
DES beyond 3x2 : Combination with Clusters

[1] To, Krause et al arxiv 2002.11124
[2] Costanzi 2020 arxiv 2010.13800

Largest virialized objects in the Universe, sensitive probe of structure growth - requires "mass-observable" relation between observed mass proxy (richness) and halo mass. One can use stacked WL profiles (selection biases at low richness, see [1]), or SPT + WL (limited to high richness and overlap area, see [2])

4x2pt+N: same sample, **mass calibration from large-scale clustering** – marginalized over wide range of selection bias (C. To et al 2020, 2010.01138)





1. From **DESY1** consistent cosmology with 3x2.
2. Possible to combine because of "large-scale covariance"
3. Limited gain (1500 clusters) and conservative scale cuts

18,000 Y3 RedMaPPer clusters (λ>20 and z < 0.65) combined with Y6 3x2 – 25% gain in FoM(OmS8)

The Dark Energy Survey
Year 6: 3×2pt analysis

THE DARK ENERGY SURVEY

William d'Assignies (IFAE, PhD in the redshift team)
on behalf of the Dark Energy Survey Collaboration

Institut de Física d'Altes Energies

Presentation using material from M. Crocce, G. Bernstein, C. Chang

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