

Weak-lensing magnification as a probe for the dark Universe

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CIEMAT

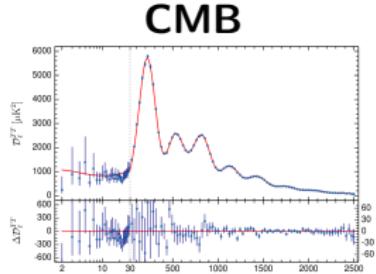
October 30th, 2017



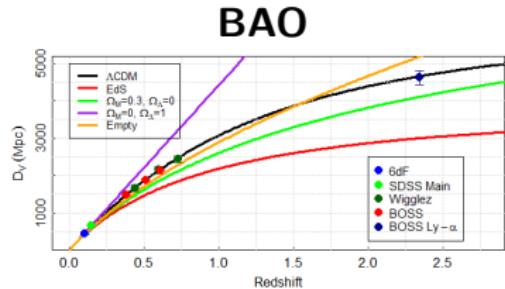
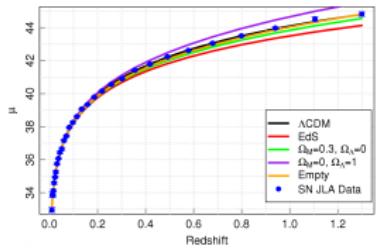
The dark Universe.



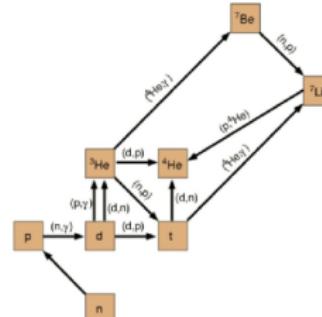
The dark Universe.



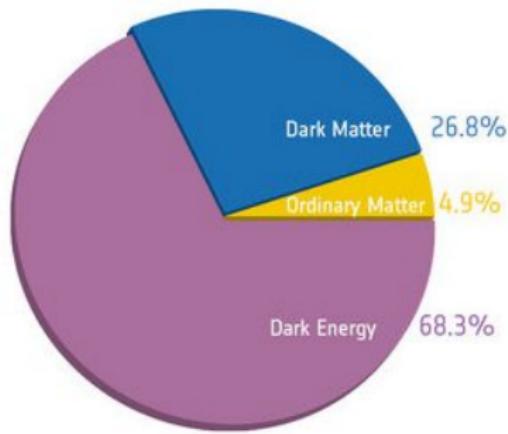
Accelerated expansion



Primordial Nucleosynthesis



The dark Universe.



Only the 5% of the Universe is known

Dark Energy: Responsible of the acceleration.

Dark matter: Only interacts through gravity.

The dark Universe.

Dark Energy as the Cosmological Constant:

→ Disagreement between Cosmology and HEP-Physics:

$$\rho_\Lambda \sim 10^{-47} \text{ GeV}^4; \quad \rho_{HEP} \sim 246 \text{ GeV}^4$$

Alternative explanations:

- **Exotic quantum fields:** quintessence, k-essence, chamaleon fields...
- **Modified gravity theories:** $f(R)$, TeVeS, Honderski...

The dark Universe.

Modeling departures from General Relativity:

- Equation of state:

$$p = w\rho \Rightarrow w = \mathbf{w}_0 + (1 - a)\mathbf{w}_a$$

With $w_0 = -1$ and $w_a = 0$ for the Cosmological Constant.

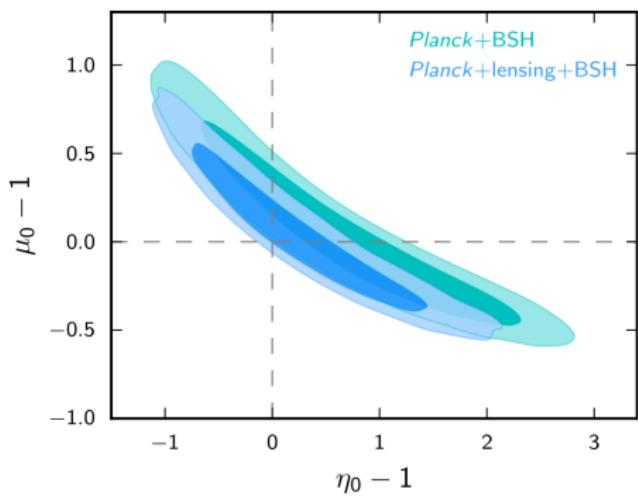
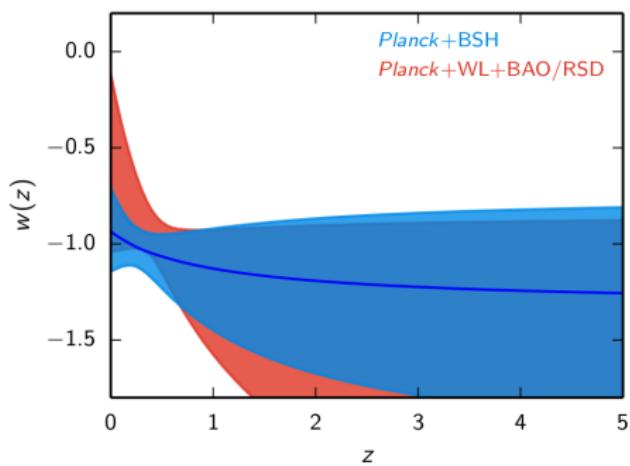
- Departures from the metric

$$ds^2 = a^2[-(1 + 2\Psi)d\tau^2 + (1 - 2\Phi)dx_i dx^j]:$$

$$2\nabla^2\Phi \frac{8\pi G_N}{c^2} a^2 \mu \bar{\rho}_M \delta_M; \quad \gamma = \frac{\Phi}{\Psi}$$

With $\mu = \gamma = 1$ for general relativity.

Status of dark energy constraints.



THE DARK ENERGY SURVEY

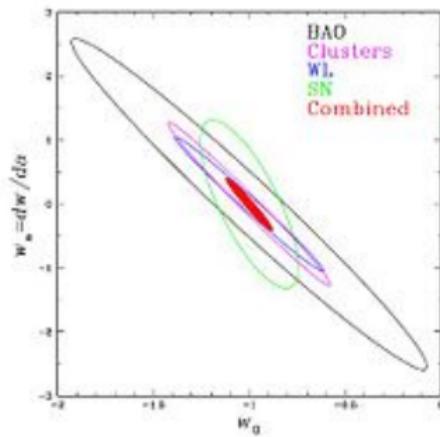
The Dark Energy Survey.

Dark Energy \Rightarrow Accelerated expansion of the Universe.

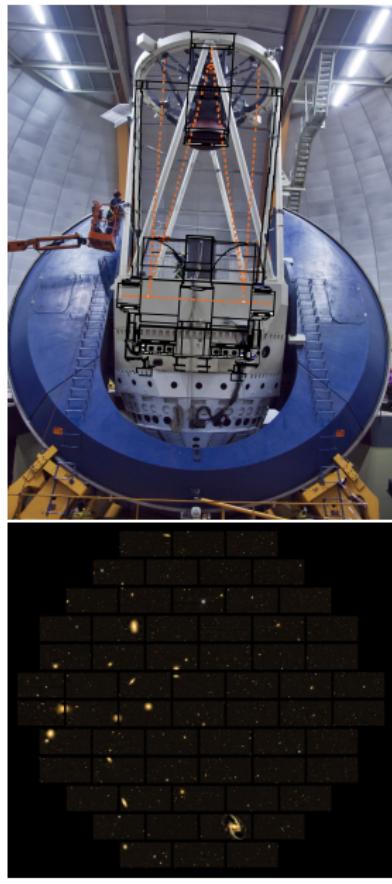
What is the nature of Dark Energy?

Combining 4 methods:

- Supernovae
- Cluster
- BAO
- **Gravitational lensing**

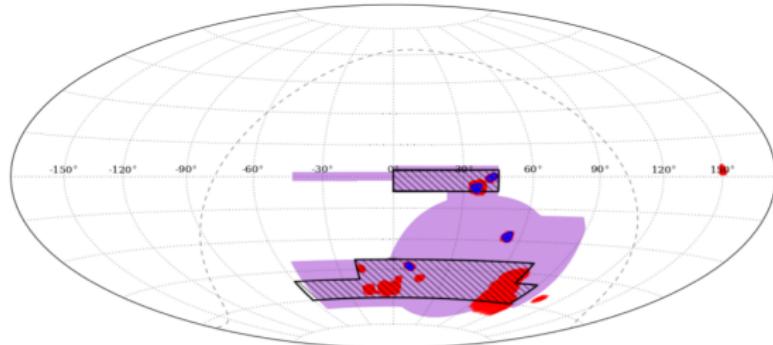


The Dark Energy Survey.

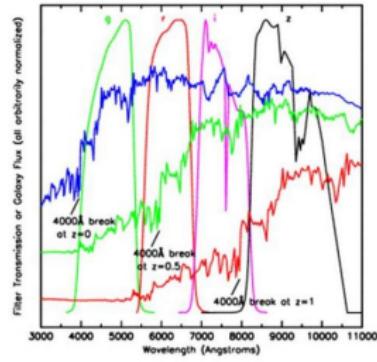


$$\text{FOV} = 3 \text{ deg}^2$$

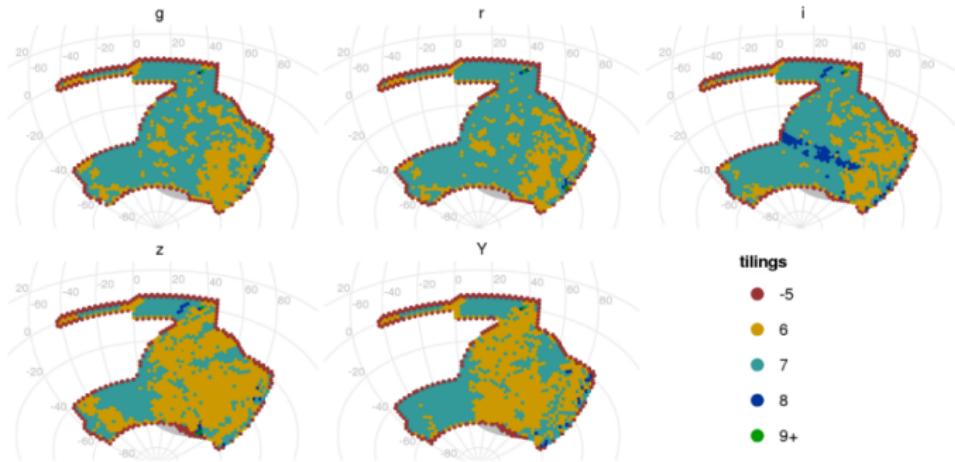
The Dark Energy Survey.



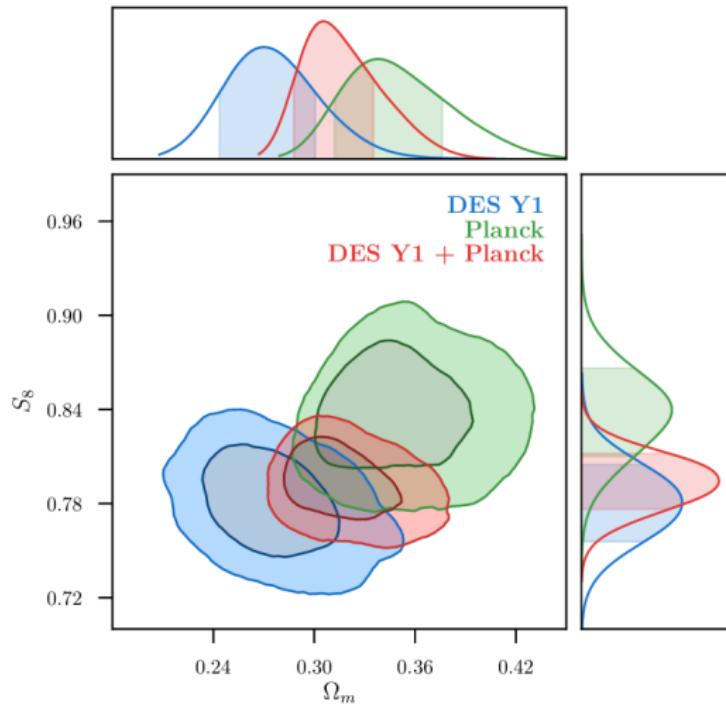
- Photometric survey.
- SV & Y1-Y4 done.
- Total of 5 campaigns.



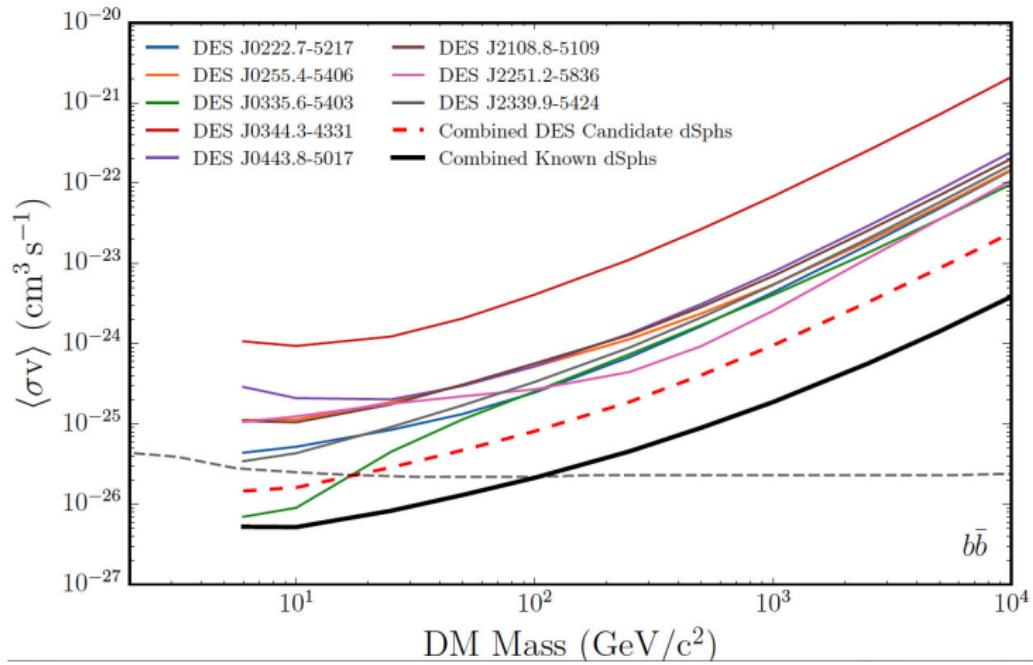
Where are we now?



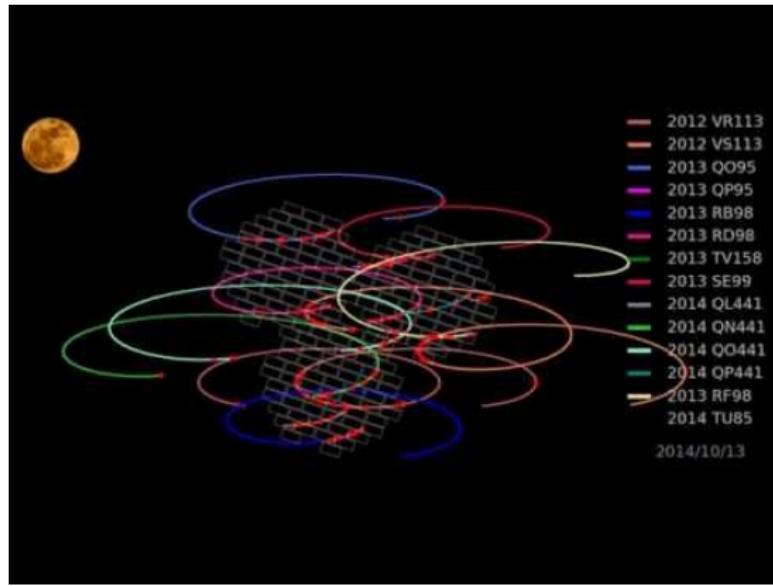
Latest cosmological results: Y1 clustering + lensing



Ancillary science: Dark-matter annihilation from dSph.



Ancillary science: Solar-system astronomy.



GRAVITATIONAL LENSING

Gravitational lensing.

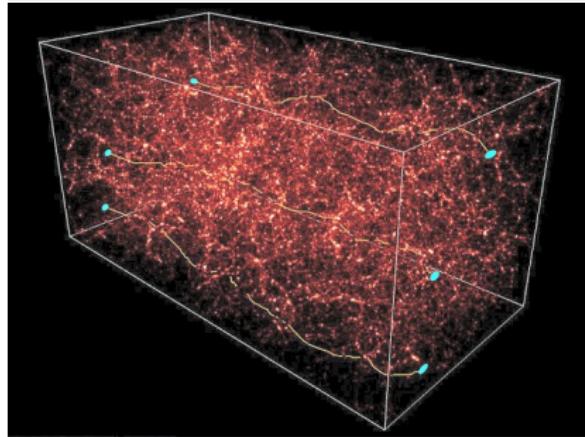
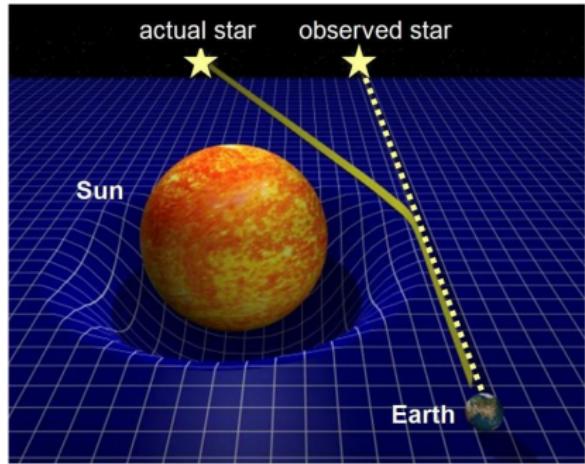
General Relativity.



Matter curls space-time.



Gravity influences photons:
light 'weights'.

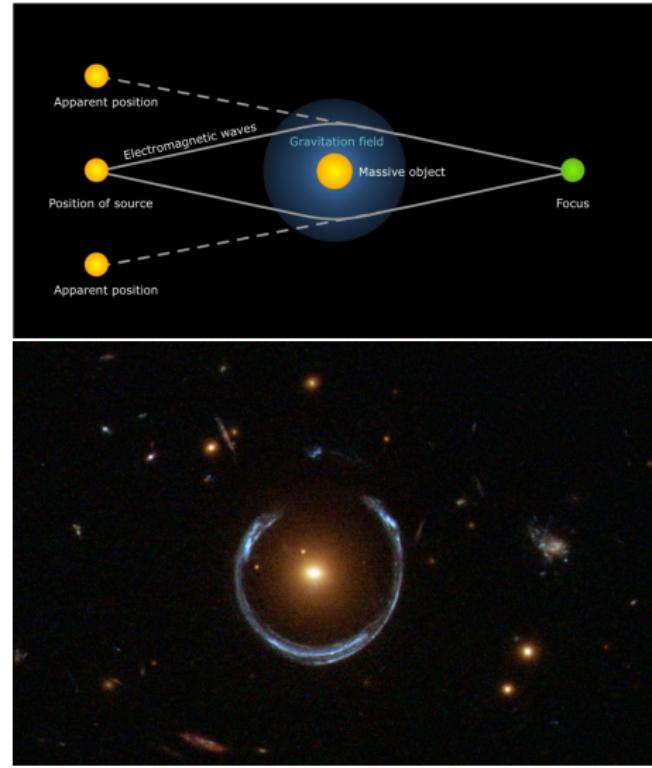


Gravitational lensing.

Specific case:
Strong field regime.



Einstein Rings.



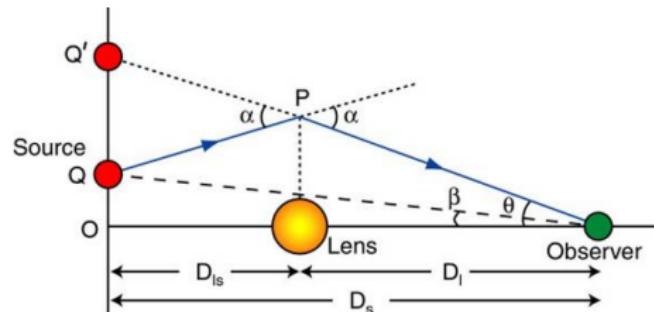
Gravitational lensing.

Point mass

$$\text{Deflection angle: } \alpha = \frac{4GM}{c^2 r} \hat{r}$$

Extended mass

$$\vec{\alpha}(\hat{n}) = \frac{1}{\pi} \int d^2 \vec{r}'_{\perp} \frac{\Sigma(\vec{r}'_{\perp})}{\Sigma_c} \frac{\vec{r}_{\perp} - \vec{r}'_{\perp}}{|\vec{r}_{\perp} - \vec{r}'_{\perp}|^2}$$



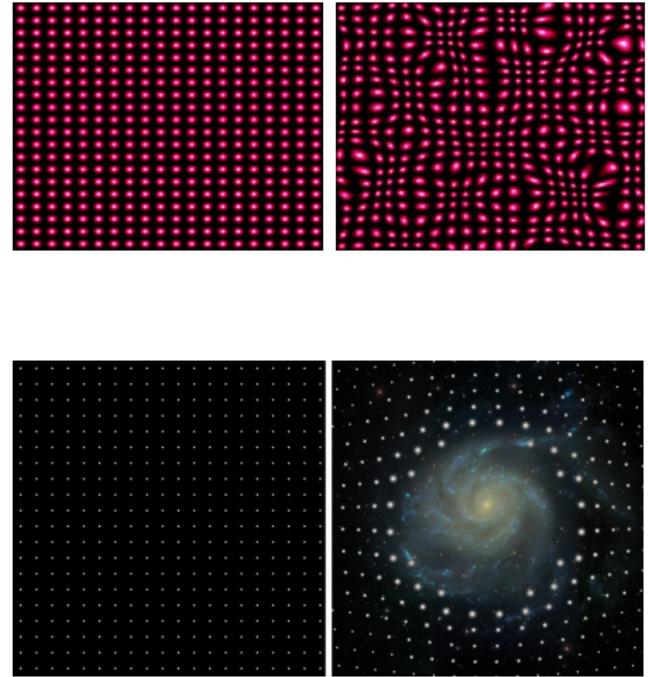
$$\Sigma(\vec{r}_{\perp}) = \int dr_3 \bar{\rho} \delta_M(\vec{r}_{\perp}, r_3) \rightarrow \text{Matter content along LoS}$$

$$\Sigma_c = \frac{c^2}{4\pi G} \int_{z_l}^{\infty} dz_s \phi(z_s) \frac{r(z_s)}{r(z_l)[r(z_s) - r(z_l)]} \rightarrow \text{Cosmological distances}$$

(arXiv: 1201.2434)

Gravitational lensing.

Weak-lensing {
Shear →
Magnification →



Weak-gravitational lensing.

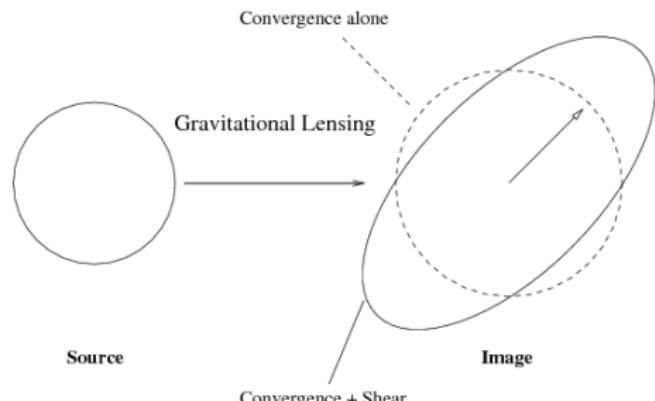
Lensing map of an extended image:

$$\mathcal{I}(\vec{\beta}) = \mathcal{I}[\vec{\beta}(\vec{\theta})] = \mathcal{I}[\vec{\beta}(\vec{\theta}_0) + \mathcal{J} \cdot (\vec{\theta} - \vec{\theta}_0)]$$

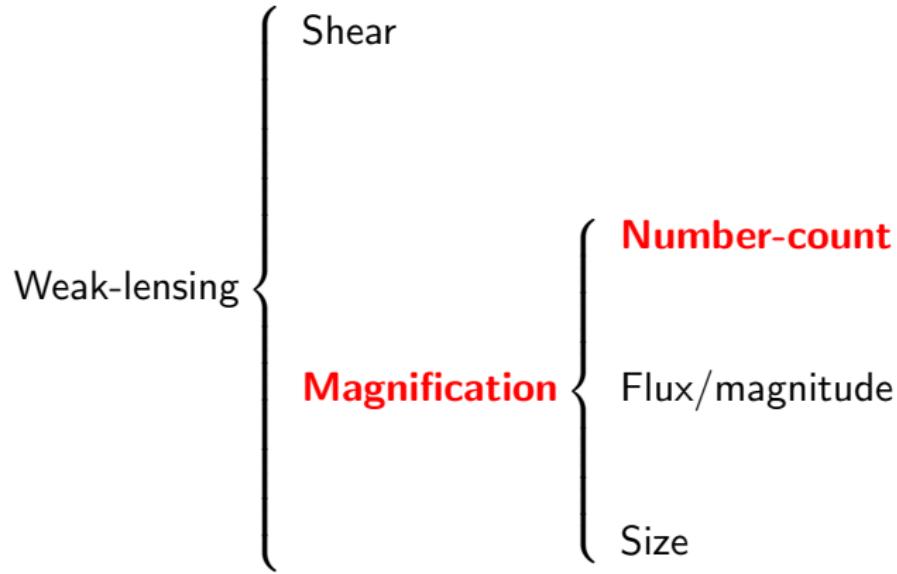
$$\mathcal{J} = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ \gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix}$$

$\kappa \rightarrow$ convergence

$\gamma_1, \gamma_2 \rightarrow$ shear



Weak-gravitational lensing.

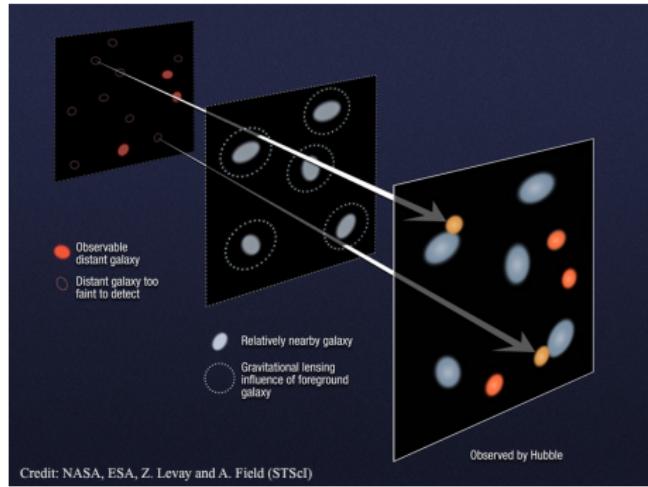


Weak-gravitational lensing.

Magnification

$$\delta_\mu(\theta) = [\alpha(m) - 1]2\kappa(\theta)$$

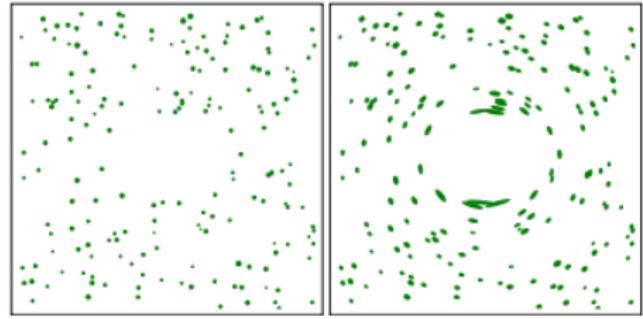
$$\kappa(\theta) = \frac{\Sigma(\theta)}{\Sigma_c}$$



gg-lensing

$$\langle \gamma_t \rangle(\theta) = \frac{\Delta\Sigma(\theta)}{\Sigma_c}$$

$$\Delta\Sigma(\theta) = \bar{\Sigma}(\theta' < \theta) - \Sigma(\theta)$$



Weak-gravitational lensing.

Probes of the underlying **(dark-)matter field**.

Magnification & shear **complementary effects** of same phenomena.

Different systematic effects:

- gg-lensing: shape-related systematic.
- magnification: redshift- & completeness- related systematics.

Magnification has **low S/N** .

Weak-gravitational lensing.

Why should we care about gravitational lensing?

- Direct matter probe:
 - No galaxy-bias assumption.
 - No HOD modeling.
- Different complementary probes of the same phenomena:
 - **Better control of systematic error.**

The intrinsic-alignment conundrum.

KiDS: $A_{IA} = +1.10, -1.17$, DES: $A_{IA} = +0.5$, CFHTLens: $A_{IA} = -3.6$

Magnification does not depend of the IA!

OBJECTIVES OF THIS THESIS

OBJECTIVES:

Two different analyses with two different goals:

- DES-SV: Develop and test a new methodology to measure magnification.
- DES-Y1: Use magnification with a new set of probes to constrain dark energy on an optimal environment.

MAGNIFICATION DES-SV

Magnification DES-SV.

Traditional approach to overcome low S/N (arXiv:1204.2830).

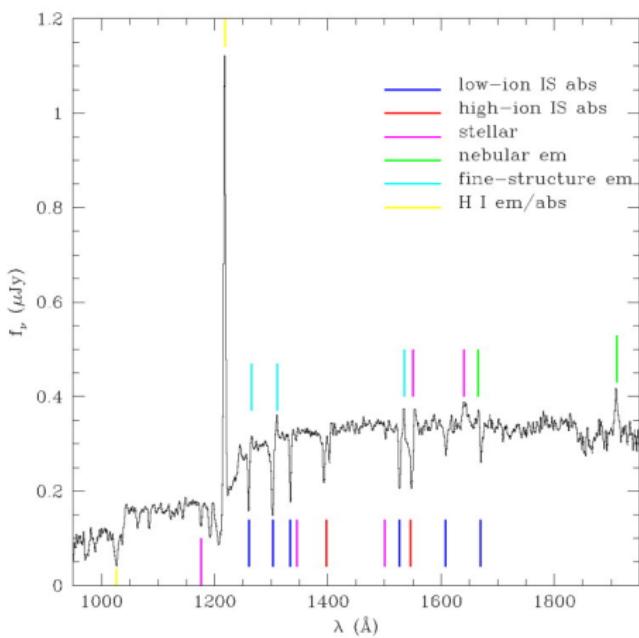
Use Lyman Break Galaxies (LBGs):

- Steep $N(m) \rightarrow$ High $\alpha(m)$.
- $2 \lesssim z \lesssim 4$
- Clean photo-z determination.
- Downside: **low density**.

Only 10^4 at DES-SV



Lack of sensitivity!



(arXiv:astro-ph/0301230)

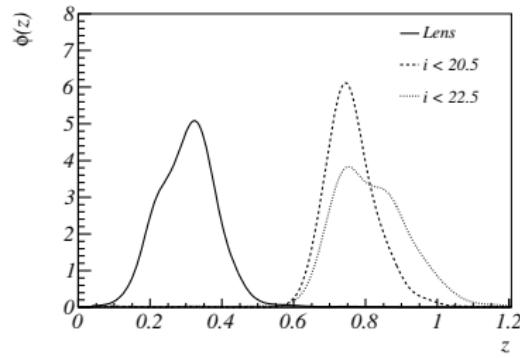
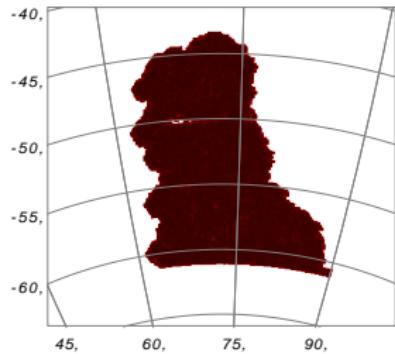
Magnification DES-SV.

New approach! Use all galaxies w/ hard photo-z cuts.

- Large density of galaxies.
- Downside: need well controlled photo-z mixing.

Developed methodology with Dark Energy Survey SV-data.

$$A = 121 \text{ deg}^2; \quad N_l \sim 500000; \quad N_s \sim 700000$$



(des.ncsa.illinois.edu/releases/SVA1)

Magnification DES-SV.

The data sample: DES-SV-Gold.

- S/G-separation: `modest_class`.
- Depth: $r_{lim} > 23.0 \ \& \ i_{lim} > 22.5 \ \& \ z_{lim} > 22.0$.
- Mask: worst 4% & bright-star halos removed.
- Edges: $r_{fracdet} = 1 \ \& \ i_{fracdet} = 1 \ \& \ z_{fracdet} = 1$.
- Uniformity: $r < 23.0 \ \& \ i < 22.5 \ \& \ z < 22.0$.
 - Also improves the S/G separation.
 - Compatibility with Crocce et al. 2015 benchmark sample.
- ‘Crazy colors’ removed.

Magnification DES-SV.

The measurement of number-count magnification:

- 1 Divide lens & source sample.
- 2 Divide magnitude sub-samples: trace the number-count slope.

$$\alpha(m) = \frac{d}{dm}[N(m)]$$

- 3 Cross-correlate samples Landy-Szalay estimator:

$$\omega_{LS}(\theta) = \frac{D_L D_S - D_L R_S - D_S R_L + R_L R_S}{R_L R_S}$$

Magnification DES-SV.

Lens:

$\rightarrow 0.2 < z_{TPZ} < 0.4 \text{ & } i < 22.5.$

Sources:

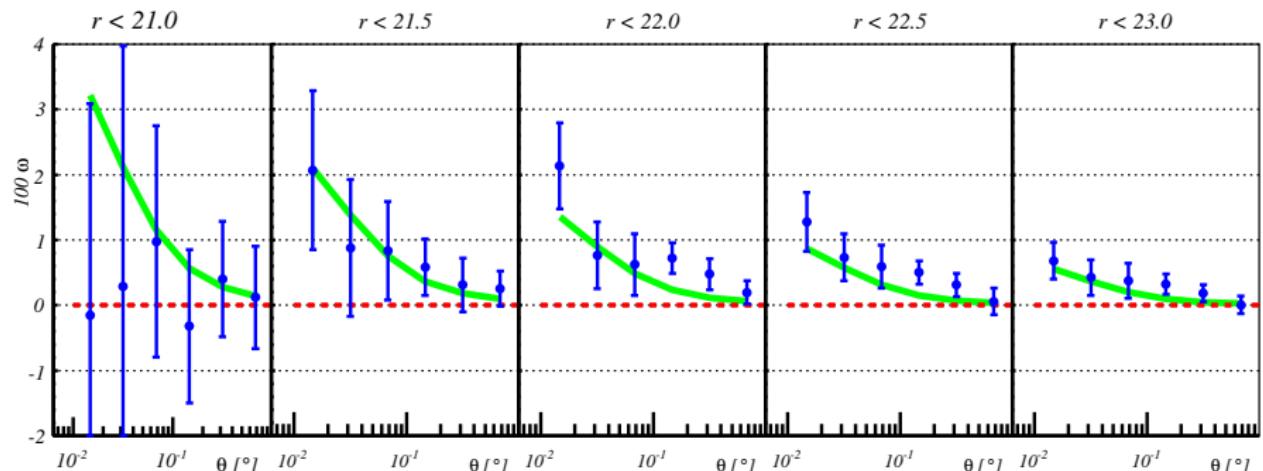
$\rightarrow 0.7 < z_{TPZ} < 1.0.$

Five subsamples **nested** within each band:

- R: $r < 21.0; r < 21.5; r < 22.0; r < 22.5; r < 23.0.$
- I: $i < 20.5; i < 21.0; i < 21.5; i < 22.0; i < 22.5.$
- Z: $z < 20.0; z < 20.5; z < 21.0; z < 21.5; z < 22.0.$

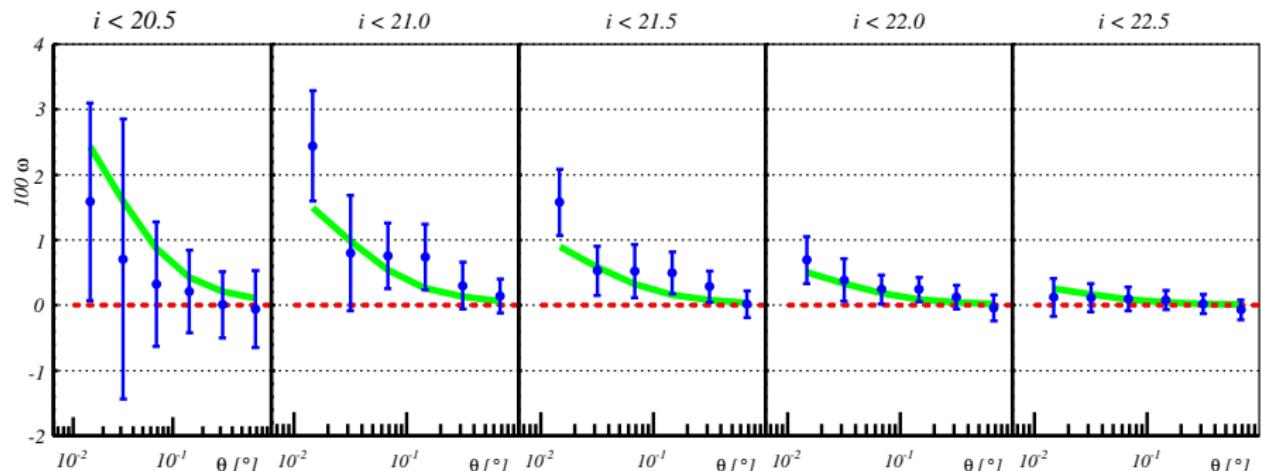
To trace the evolution of the number-count slope parameter.

Magnification DES-SV.



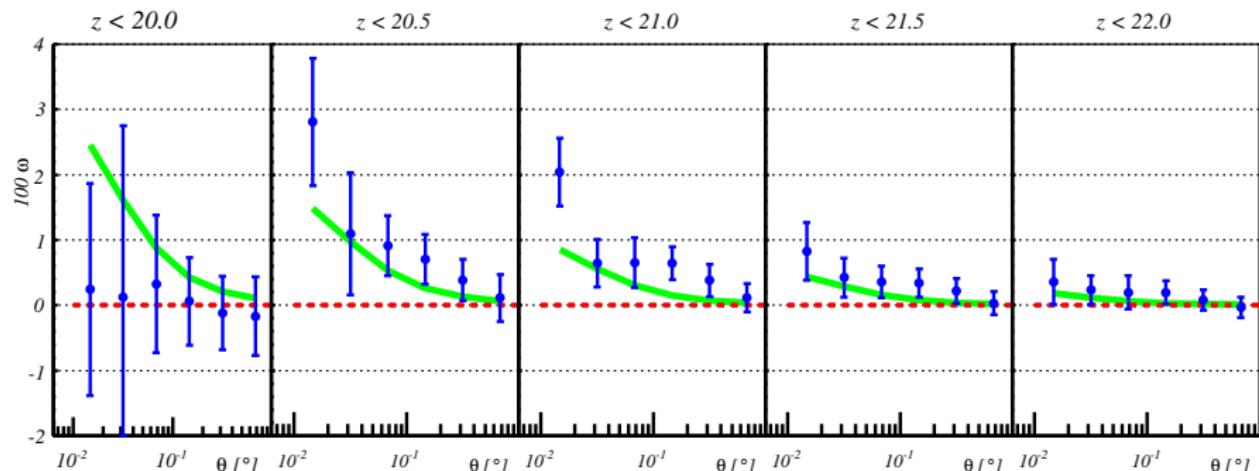
(arXiv:1611.10326)

Magnification DES-SV.



(arXiv:1611.10326)

Magnification DES-SV.



(arXiv:1611.10326)

Theoretical calculations:

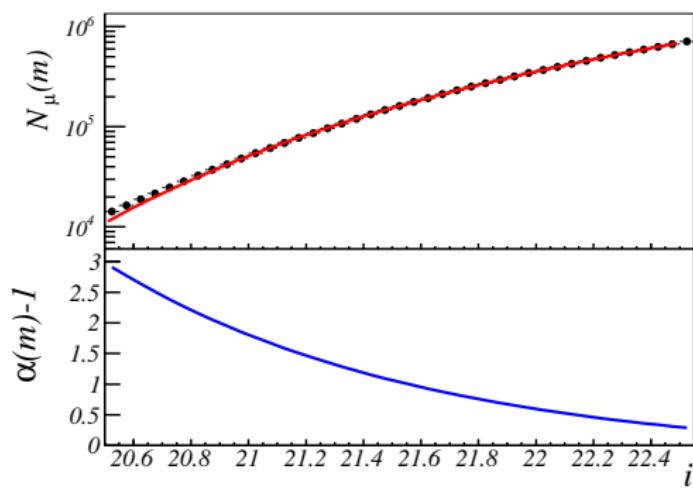
$$\omega(\theta) = b_L[\alpha(m) - 1]2\kappa(\theta)$$

- κ from weak-lensing theory.
- Assume a Λ CDM Universe with Planck 2015 parameters.
- Linear, constant, redshift independent bias from Crocce et al. 2015.

Magnification DES-SV.

- α Fit $N(m)$ to Schechter function and do derivative (analytical).

$$N_\mu(m) = A \left[10^{0.4(m-m_*)} \right]^\beta \times \exp \left[-10^{0.4(m-m_*)} \right]$$



Magnification DES-SV.

Compatibility with theory:

$$\chi_{\text{Planck}}^2 = \sum_{\eta\nu ij} [\tilde{\omega}_{\text{LS}_i}(\theta_\eta) - \omega_{\text{LS}_i}(\theta_\eta)] \\ C^{-1}(\omega_{\text{LS}_i}(\theta_\eta); \omega_{\text{LS}_j}(\theta_\nu)) [\tilde{\omega}_{\text{LS}_j}(\theta_\nu) - \omega_{\text{LS}_j}(\theta_\nu)]$$

$$\chi_{\text{zero}}^2 = \sum_{\eta\nu ij} \tilde{\omega}_{\text{LS}_i}(\theta_\eta) C^{-1}(\omega_{\text{LS}_i}(\theta_\eta); \omega_{\text{LS}_j}(\theta_\nu)) \tilde{\omega}_{\text{LS}_j}(\theta_\nu)$$

Significance of the detection:

$$\mathcal{B} = \frac{P(M|\Theta)}{P(Z|\Theta)} \frac{P(M)}{P(Z)}$$

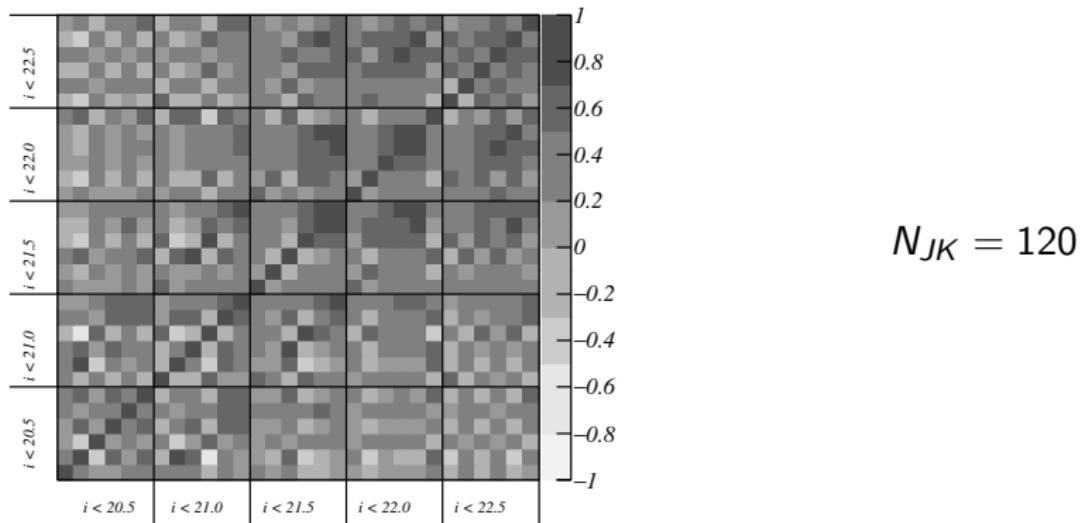
$$P(M|\Theta) = e^{-\chi_{\text{Planck}}^2/2}; P(Z|\Theta) = e^{-\chi_{\text{zero}}^2/2}$$

$$P(M) = P(Z)$$

Magnification DES-SV.

Covariance matrix:

$$\begin{aligned} C_S(\omega_{LS_i}(\theta_\eta); \omega_{LS_j}(\theta_\nu)) &= \frac{N_{JK}}{N_{JK}-1} \\ &\times \sum_k^{N_{JK}} [\omega_{LS_i}^k(\theta_\eta) - \omega_{LS_i}(\theta_\eta)][\omega_{LS_j}^k(\theta_\nu) - \omega_{LS_j}(\theta_\nu)] \end{aligned}$$



Magnification DES-SV.

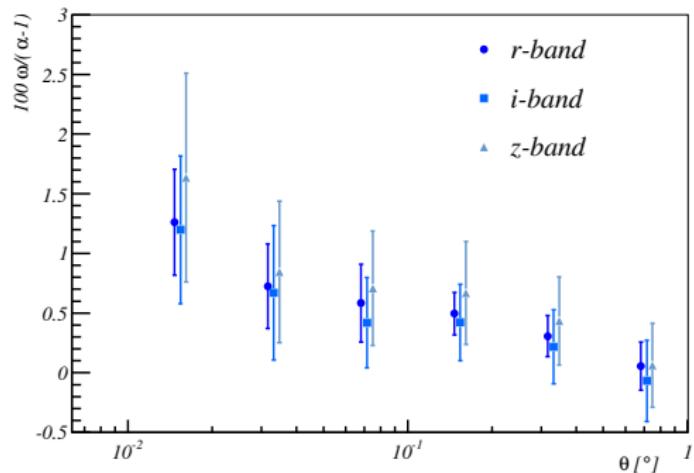
Sample	$\log_{10} \mathcal{B}$	$\chi^2/ndof$	$\log_{10} \mathcal{B}$	$\chi^2/ndof$
$r < 21.0$	-0.3	1.9/6		
$r < 21.5$	0.8	0.8/6		
$r < 22.0$	2.0	6.6/6	3.9	21.6/30
$r < 22.5$	2.3	7.0/6		
$r < 23.0$	1.1	4.2/6		
<hr/>				
$i < 20.5$	0.2	0.9/6		
$i < 21.0$	2.1	2.0/6		
$i < 21.5$	2.5	4.5/6	3.5	24.2/30
$i < 22.0$	1.0	1.7/6		
$i < 22.5$	0.0	1.5/6		
<hr/>				
$z < 20.0$	-0.4	2.6/6		
$z < 20.5$	2.3	2.6/6		
$z < 21.0$	2.6	8.8/6	3.9	37.9/30
$z < 21.5$	0.9	3.5/6		
$z < 22.0$	0.5	2.1/6		

Magnification has been detected!

Magnification DES-SV.

Systematic analysis:

- Stellar contamination.
- Number-count slope determination.
- Dust extinction.



None of them had a relevant impact.

Magnification DES-SV.

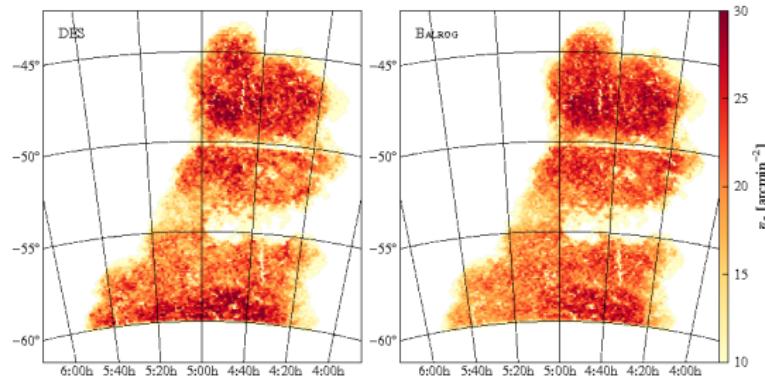
Survey observing conditions.

- Uniform depth allows uniform randoms.
- Used the BALROG simulations:
(<https://github.com/emhuff/Balrog>)
 - 1 Synthetic images of galaxies are generated.
 - 2 Images are convolved with measured PSF.
 - 3 Individual images injected into real DES images.
 - 4 Real + simulated go through the whole pipeline.

Magnification DES-SV.

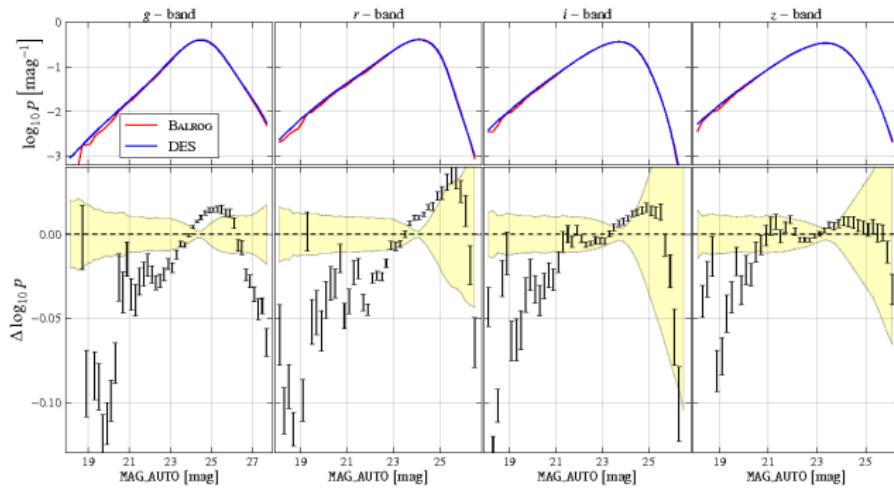
Balrog:

- Map *real* \rightarrow *observed* quantities.
- **Determines the window function of the survey.**
- Measures the completeness, depth, uniformity...
- Takes into account deblending.



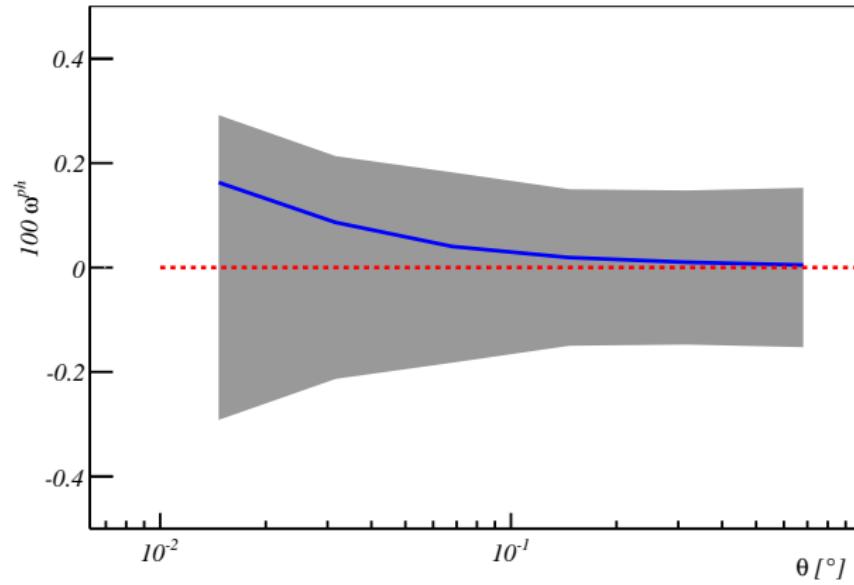
Magnification DES-SV.

- First time BALROG is used for a science measurement.
- Provides reliable and un-biased way to deal with systematic.
- **Downside:** as good as your input catalog. → COSMOS is enough for DES image-quality.



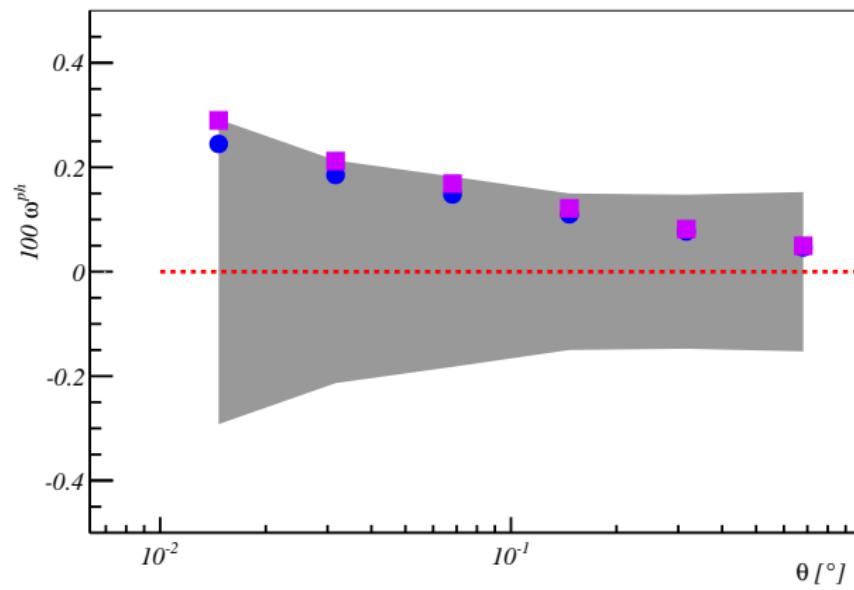
Magnification DES-SV.

Photo-z contamination: Theoretical expected contamination.



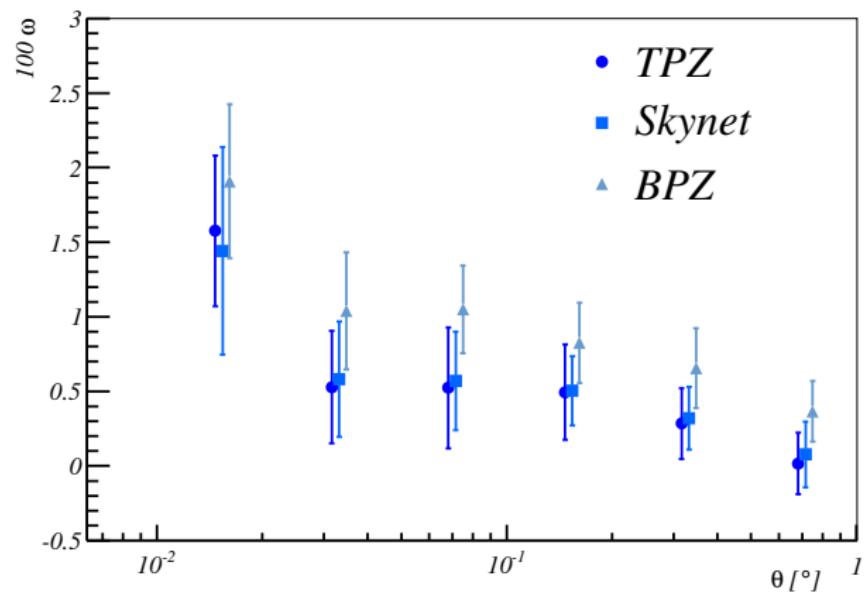
Magnification DES-SV.

Photo-z contamination: Simulated contamination.



Magnification DES-SV.

Photo-z contamination: Code comparison.

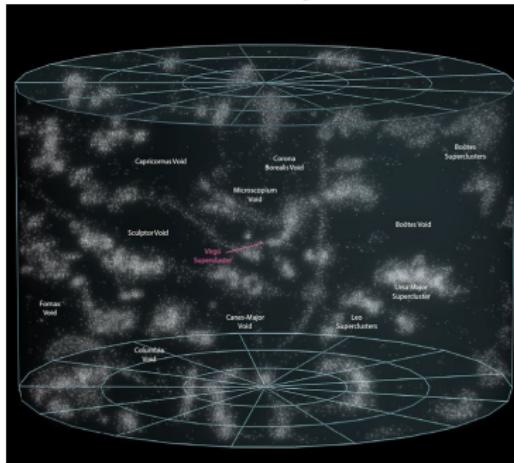


MAGNIFICATION DES-Y1

Magnification DES-Y1.

The possible science with magnification:

- Combination with other probes.
 - Caution with systematic.
 - Covariances reduce the impact on the measurement.
- Search for new alternative and independent probes.
 - **The clever solution:**
Search for environments dominated by DE.

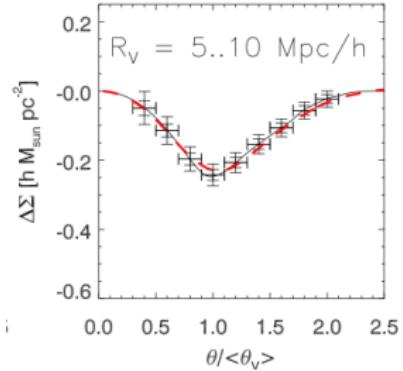
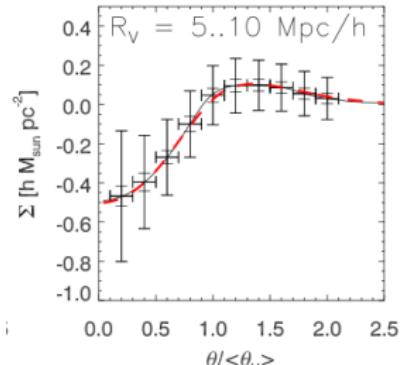


Magnification DES-Y1.

Dense sources allows low dense lenses:

- **Voids.**
- Troughs.
- Clusters.

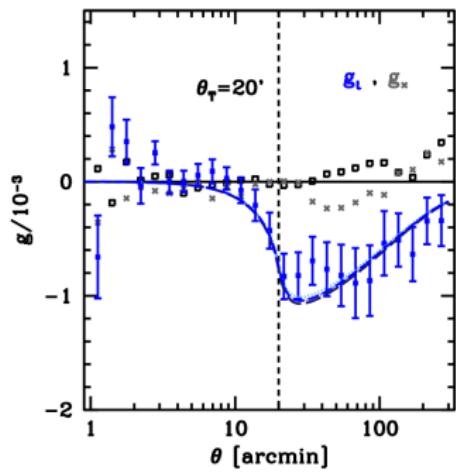
Direct probe of the matter profile.



(arXiv:1210.2446)

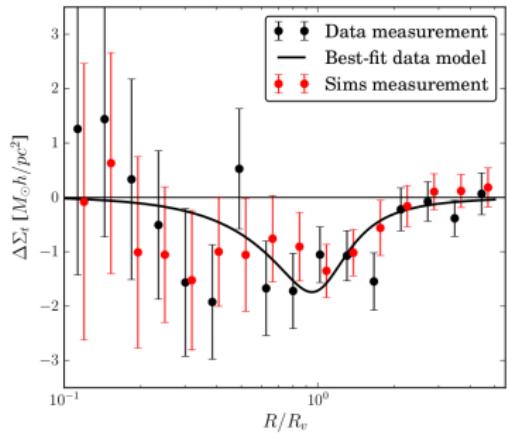
Magnification DES-Y1.

Trough gg-lensing.



(arXiv:1507.05090)

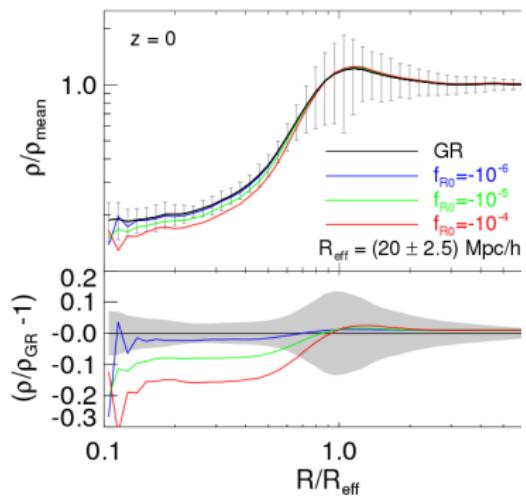
Void gg-lensing.



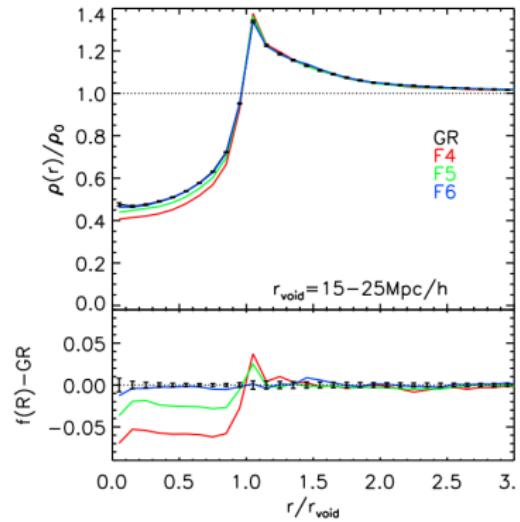
(arXiv:1605.03982)

Magnification DES-Y1.

Void profile with Modified Gravity $f(R)$ models.



(arXiv:1511.01494)

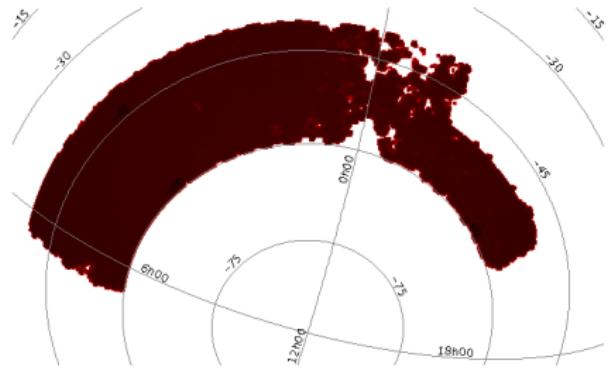


(arXiv:1410.8355)

Magnification DES-Y1.

The source data sample:
DES-Y1-Gold.

- S/G-separation: modest_class & spread_model_i + $3 \times \text{spreaderr_model_i} > 0.007$.
- Depth: $i_{lim} > 22.0$ & $i < 20.5$.
- Mask: worst 4% & bright-star halos removed.
- $0.8 < z_{BPZ} < 1.5$.

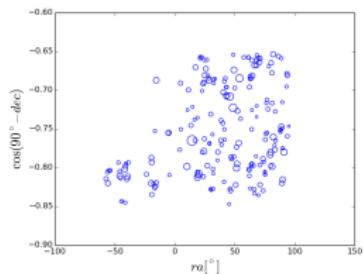


Magnification DES-Y1.

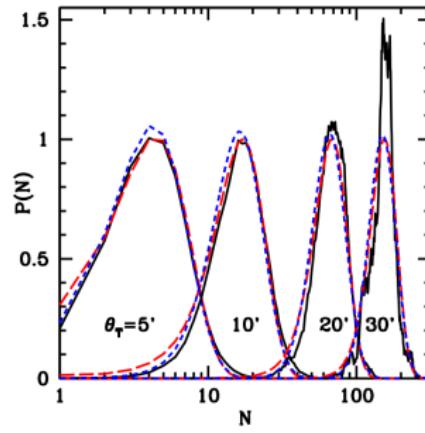
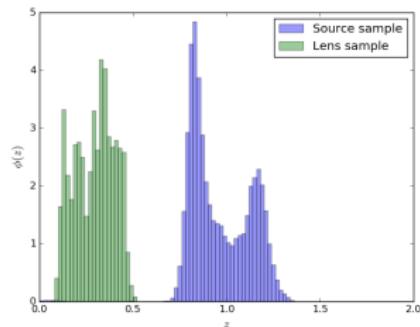
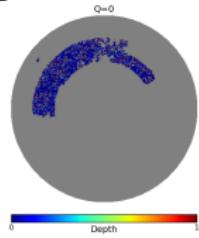
Two lenses: DES-Y1-redmagic.

$$0.2 < z_{red} < 0.45$$

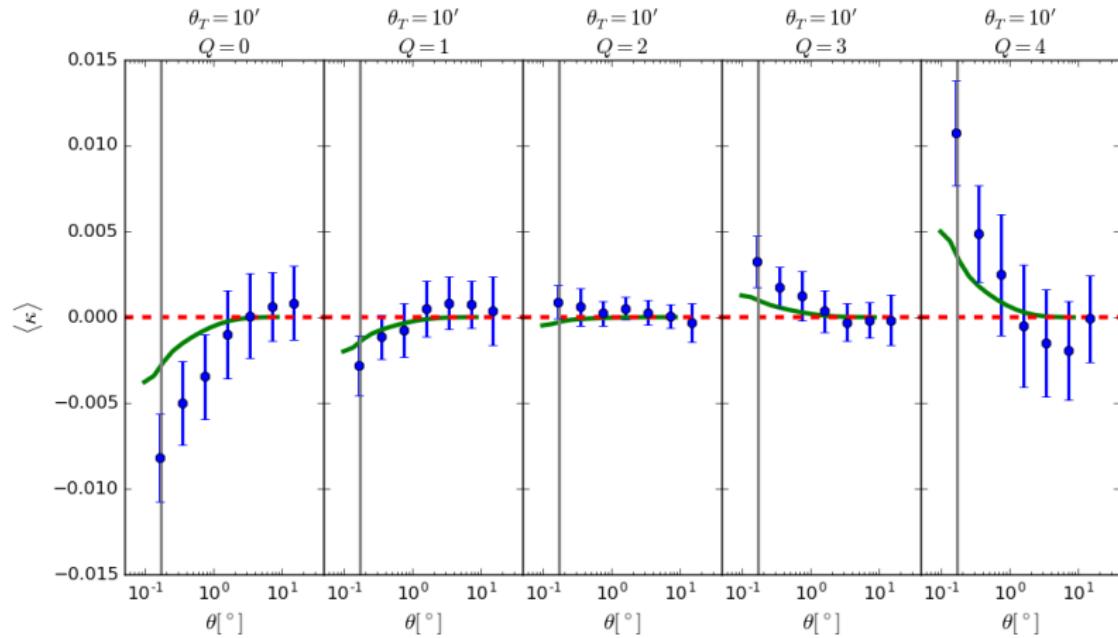
- Voids.



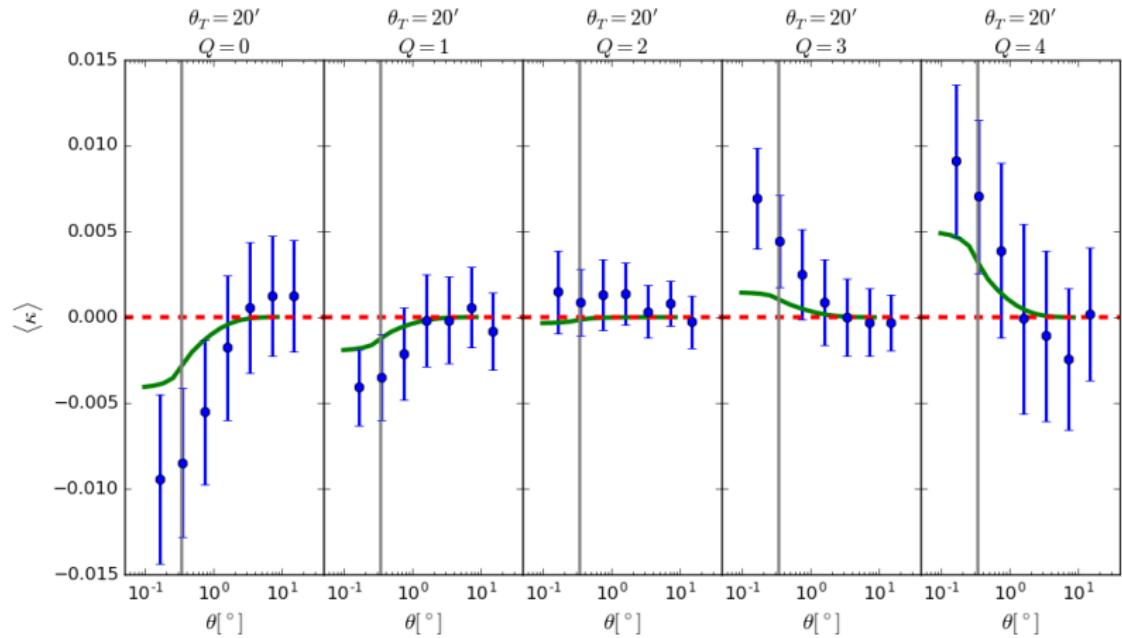
- Troughs.



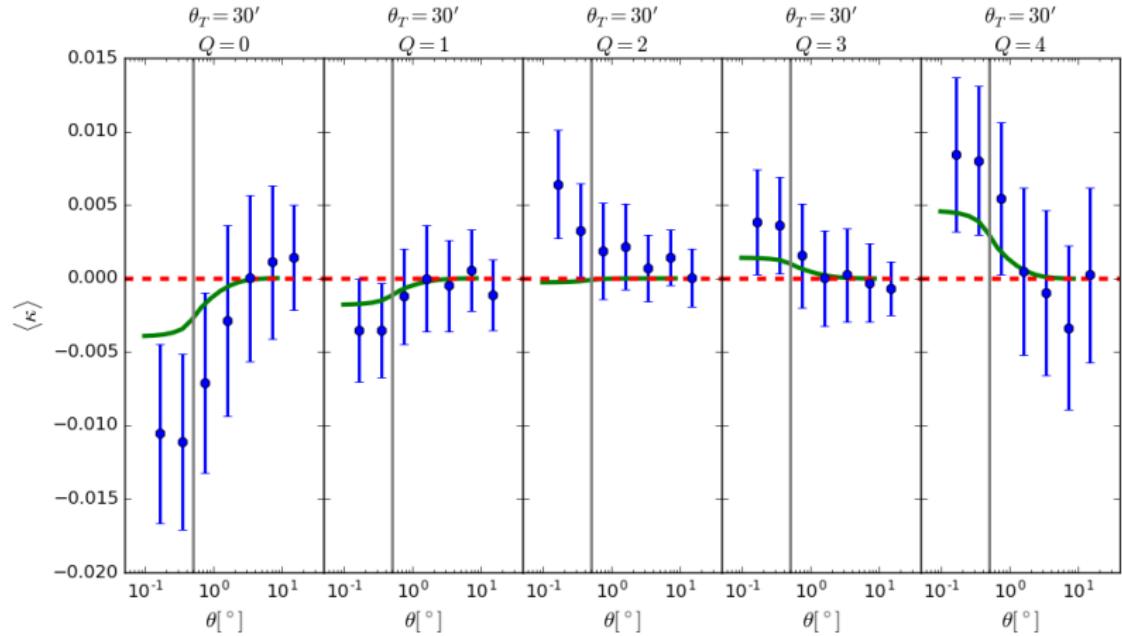
Magnification DES-Y1.



Magnification DES-Y1.



Magnification DES-Y1.



Magnification DES-Y1.

Theory:

- Used Fiedrich et al. (in prep) and Gruen et al. (2016) theory.
- Planck 2015 parameters blinded.

Covariances:

- Bootstrap resampling **only** the lenses.

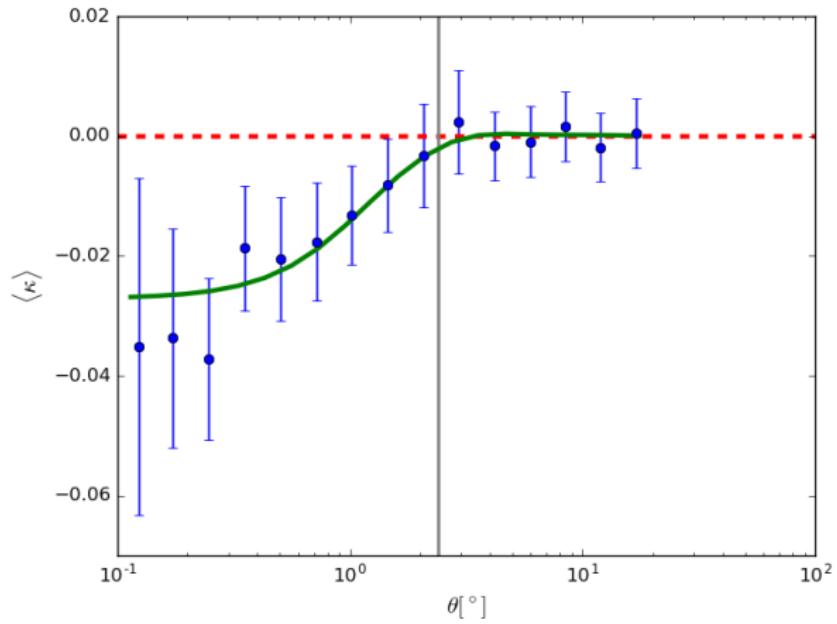
Magnification DES-Y1.

Significance of detection:

→ Defined by the χ^2 against zero.

θ_T	10'				
Q	0	1	2	3	4
$\chi_z^2/ndof$	43.5/7	10.5/7	1.3/7	10.3/7	45.3/7
<hr/>					
θ_T	20'				
Q	0	1	2	3	4
$\chi_z^2/ndof$	19.0/7	7.5/7	4.0/7	18.3/7	17.0/7
<hr/>					
θ_T	30'				
Q	0	1	2	3	4
$\chi_z^2/ndof$	28.3/7	3.8/7	16.4/7	5.1/7	17.3/7

Magnification DES-Y1.



Magnification DES-Y1.

Theory:

- Used KGB (Kovacs & Garcia-Bellido) profile.
- Planck 2015 parameters blinded.

Covariances:

- Bootstrap resampling **only** the voids.

Significance:

- Defined by the χ^2 against zero.

$$\chi^2_{\text{zero}} / \text{ndof} = 33.6 / 15$$

First detection ever of void (de-)magnification.

CONCLUSIONS

Conclusions.

- Magnification is a powerful probe for the matter profile.
- Combined with gg-lensing provide good systematic control.
- A new technique to measure magnification has been developed.
→ Including a novel way to deal with systematic errors.
- Magnification allows access to lowest voids scales
- Lowest void scales provide constraints on Modified Gravity scenarios.
- **First direct measurement** of a void convergence profile.
→ Opens a new window to probe the dark Universe!