Weak-lensing magnification as a probe for the dark Universe

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CIEMAT

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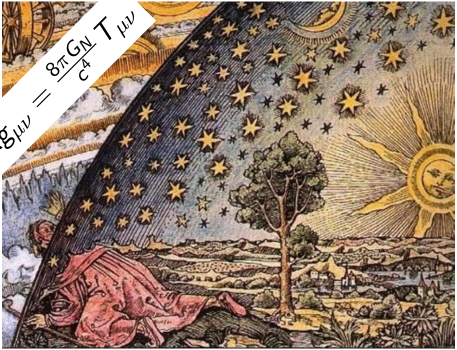
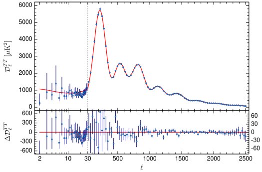
The dark Universe.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

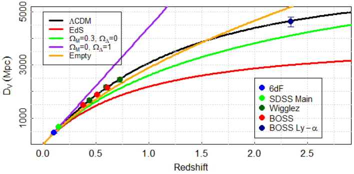


The dark Universe.

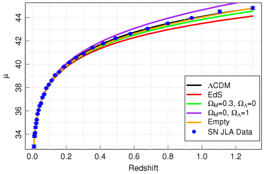
CMB



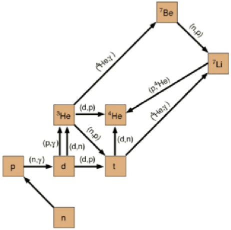
BAO



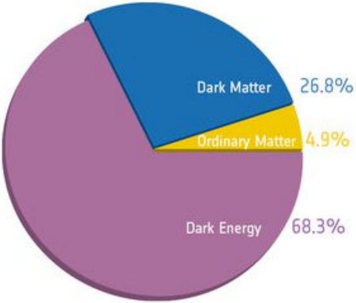
Accelerated expansion



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.

Dark Energy as the Cosmological Constant:
$\rightarrow$ Disagreement between Cosmology and HEP-Physics:

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

Alternative explanations:

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

Modeling departures from General Relativity:

- Equation of state:

$$p = wV \Rightarrow w = \mathbf{w_0} + (1-a)\mathbf{w_a}$$

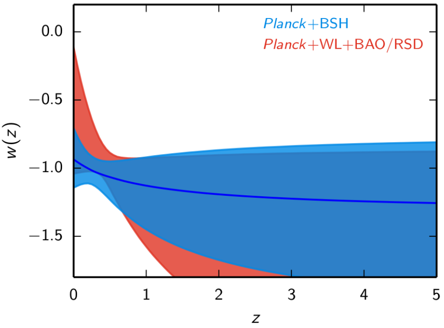
With $w_0 = -1$ and $w_a = 0$ for the Cosmological Constant.

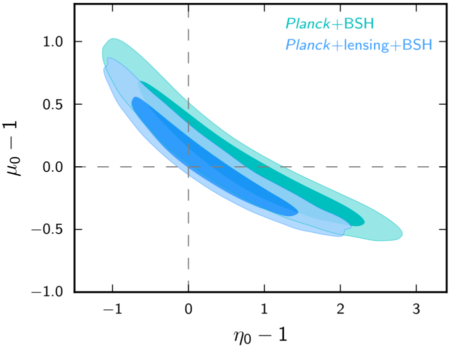
- Departures from the metric $ds^2 = a^2[-(1+2\Psi)d\tau^2 + (1-2\Phi)dx_i dx^j]$:

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

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

Status of dark energy constrains.





THE DARK ENERGY SURVEY

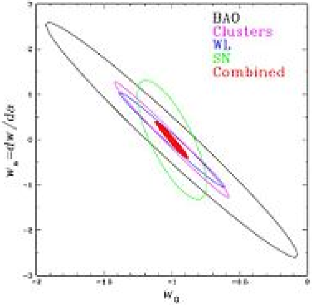
The Dark Energy Survey.

Dark Energy $\Rightarrow$ Accelerated expansion of the Universe.

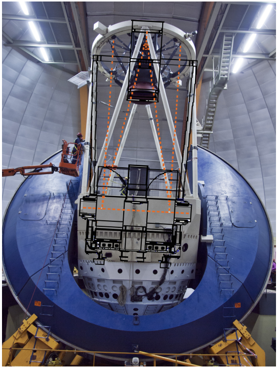
What is the nature of Dark Energy?

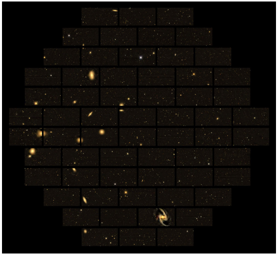
Combining 4 méthodes:

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

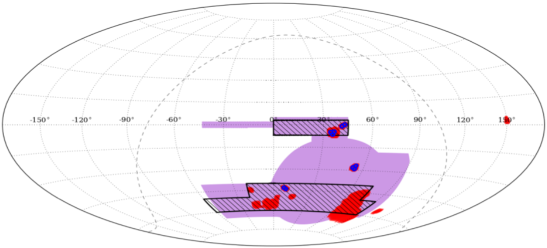


The Dark Energy Survey.

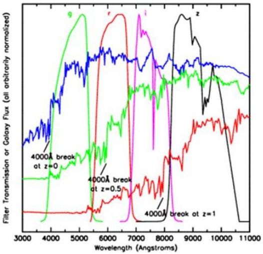




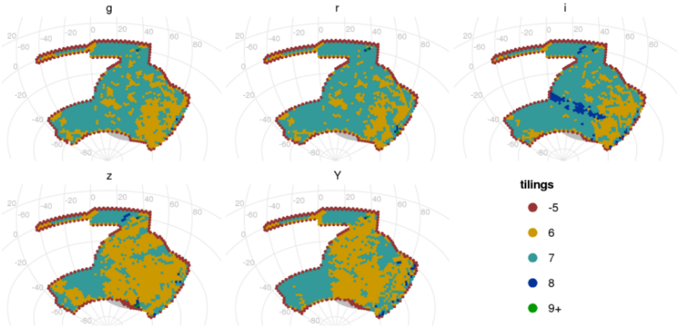
The Dark Energy Survey.



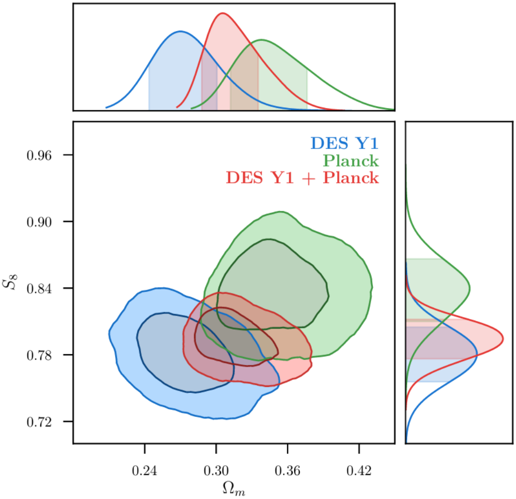
- Photometric survey.
- SV & Y1-Y4 done.
- Total de 5 campaigns.



Where are we now?

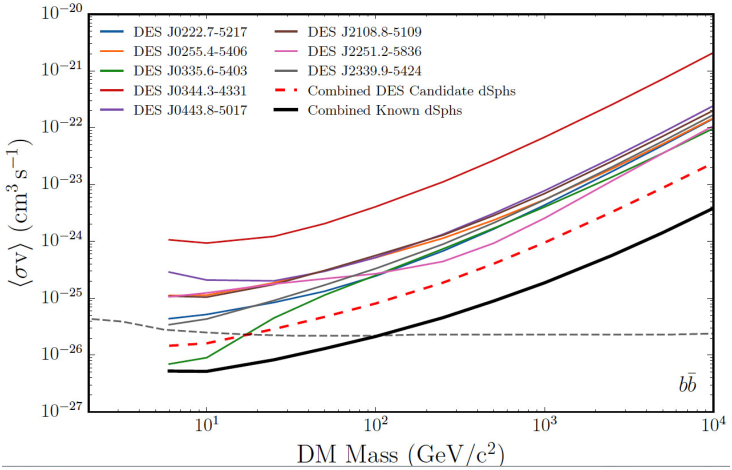


Latest cosmological results: Y1 clustering + lensing

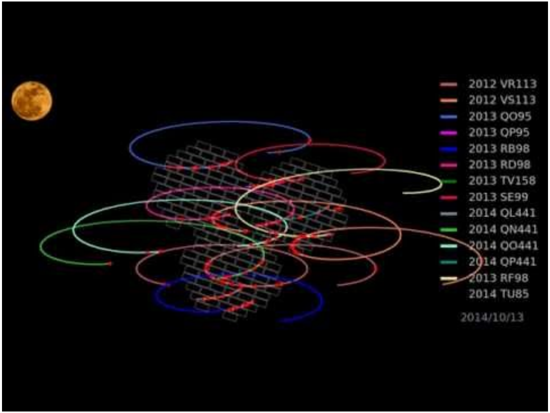


The Dark Energy Survey.

Ancillary science: Dark-matter annihilation from dSph.



Ancillary science: Solar-system astronomy.



GRAVITATIONAL LENSING

Gravitational lensing.

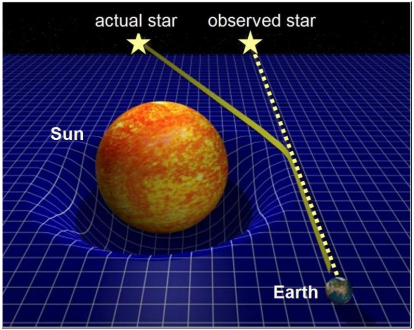
General Relativity.

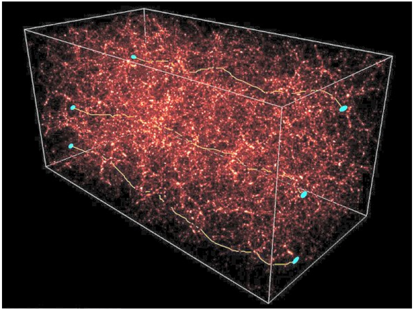
$\Downarrow$

Matter curls space-time.

$\Downarrow$

Gravity influences photons:
light 'weights'.



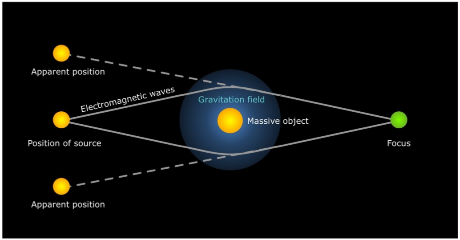


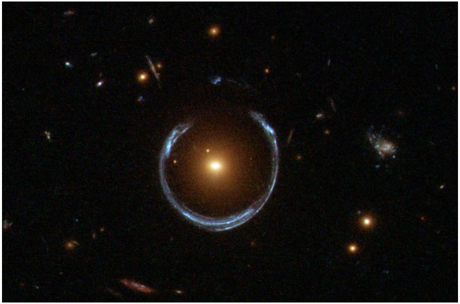
Gravitational lensing.

Specific case:
Strong field regime.

$\Downarrow$

Einstein Rings.

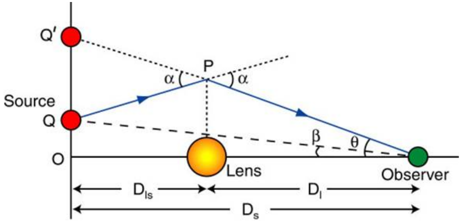




Gravitational lensing.

Point mass

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



Continuous field

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

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

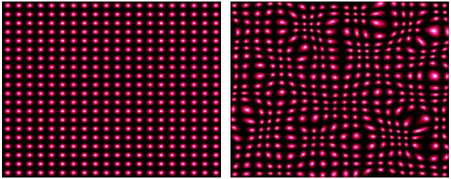
$$\Sigma_c = \frac{c^2}{4\pi G}\int_{z_l}^{\infty} dz_s \phi(z_s)\frac{r(z_s)}{r(z_l)[r(z_s) - r(z_l)]} \rightarrow \text{Cosmological distances}$$

(arXiv: 1201.2434)

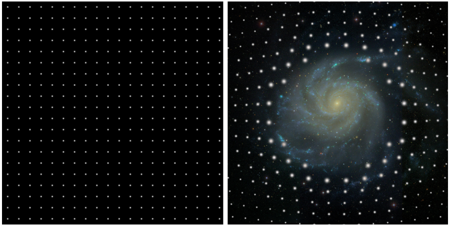
Gravitational lensing.

Weak-lensing

- Shear $\rightarrow$



- Magnification $\rightarrow$



Gravitational lensing.

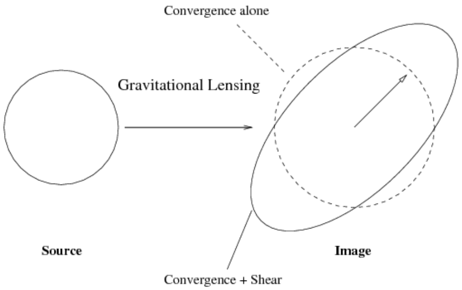
Lensing map of an extended image:

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

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

$\kappa \to$ convergence

$\gamma_1, \gamma_2 \to$ shear



Gravitational lensing.

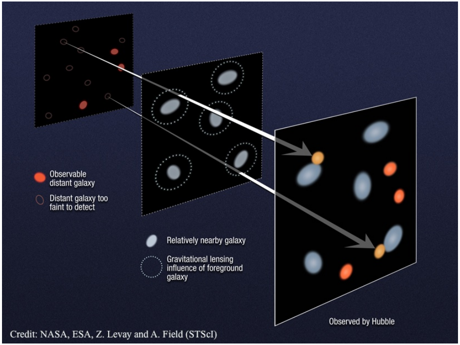
$$\text{Weak-lensing}\begin{cases}\text{Shear}\\ \textbf{Magnification}\begin{cases}\textbf{Number-count}\\ \text{Flux/magnitude}\\ \text{Size}\end{cases}\end{cases}$$

Gravitational lensing.

Magnification

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

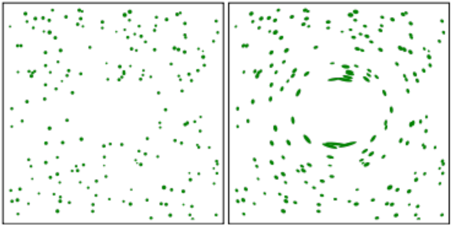
$$\kappa(\theta) = \frac{\Sigma(\theta)}{\Sigma_c}$$



gg-lensing

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

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



Gravitational lensing.

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

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

Different systematic effects:
$\rightarrow$ gg-lensing: shape-related systematic.
$\rightarrow$ magnification: redshift- & completeness- related systematics.

Magnification has **low S/N** .

Why should we care about gravitational lensing?

- Direct matter probe:
  $\rightarrow$ No galaxy-bias assumption.
  $\rightarrow$ No HOD modeling.

- Different complementary probes of the same phenomena:
  $\rightarrow$ **Better control of systematic error.**

The KiDS-CFHTLens-DES conundrum.

The intrinsic alignment:

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

Magnification does not depend of the IA!

MAGNIFICATION DES-SV

Magnification DES-SV.

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

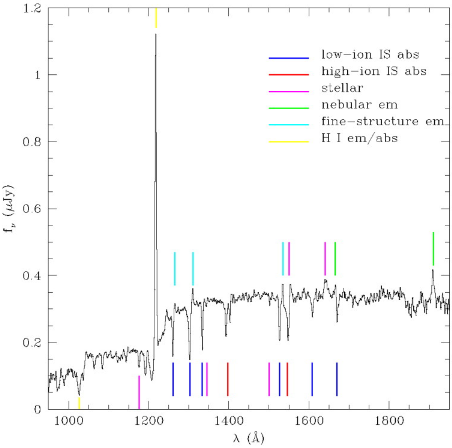
Use Lyman Break Galaxies (LBGs):

- 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

$\Downarrow$

Impossible the detection!



(arXiv:astro-ph/0301230)

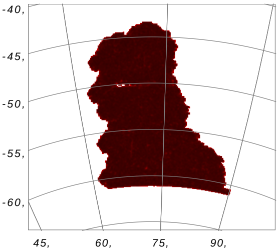
Magnification DES-SV.

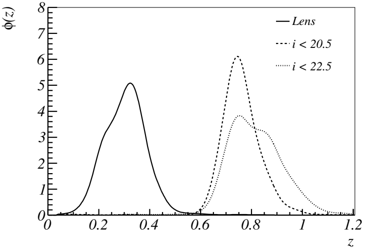
New approach! Use all galaxies w/ hard photo-z cuts.

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

Developed methodology with Dark Energy Survey SV-data.

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





(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:

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

Sources:

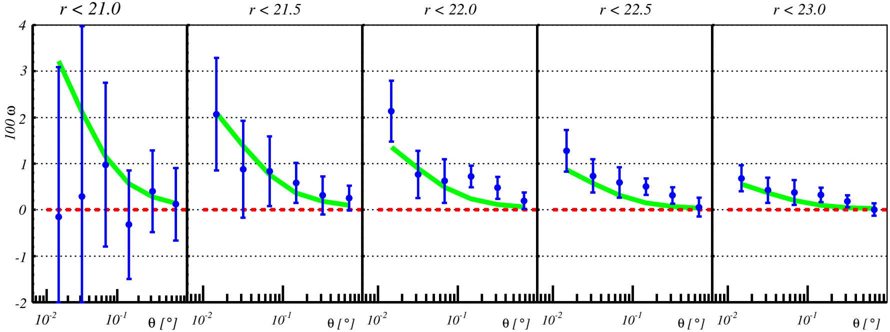
$\rightarrow 0.7 < z_{TPZ} < 1.0$.

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: $z < 20.0$; $z < 20.5$; $z < 21.0$; $z < 21.5$; $z < 22.0$.

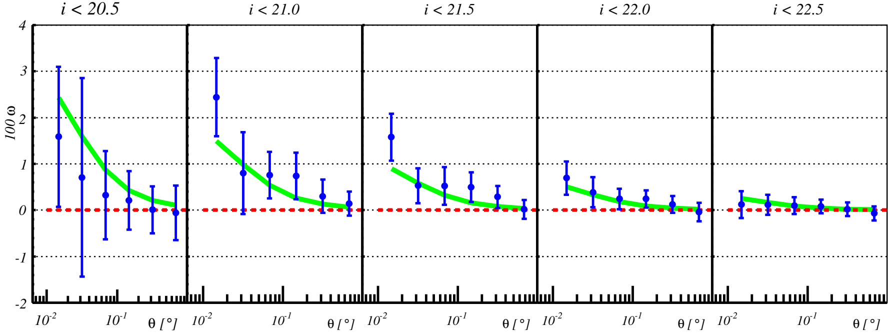
To trace the evolution of the number-count slope parameter.

Magnification DES-SV.



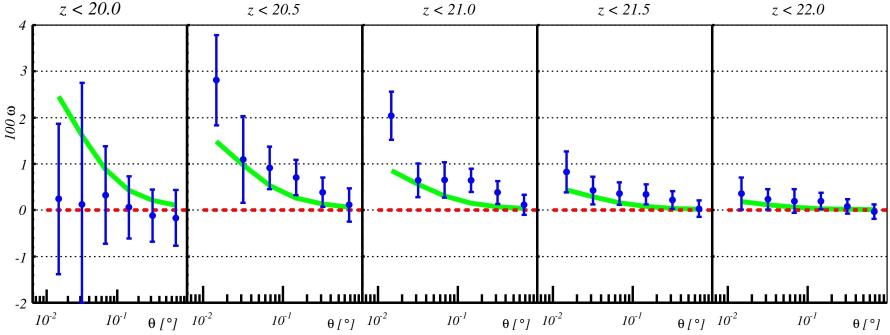
(arXiv:1611.10326)

Magnification DES-SV.



(arXiv:1611.10326)

Magnification DES-SV.



(arXiv:1611.10326)

Magnification DES-SV.

Theoretical calculations:

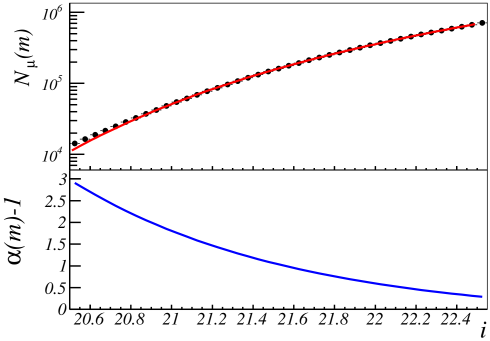
$$\omega(\theta) = b_L[\alpha(m) - 1]2\kappa(\theta)$$

- κ from weak-lensing theory.
- Assume a ΛCDM 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:

$$\chi^2_{\mathrm{Planck}} = \sum_{\eta\nu ij} [\tilde{\omega}_{\mathrm{LS_i}}(\theta_\eta) - \omega_{\mathrm{LS_i}}(\theta_\eta)]$$
$$C^{-1}(\omega_{\mathrm{LS_i}}(\theta_\eta); \omega_{\mathrm{LS_j}}(\theta_\nu))[\tilde{\omega}_{\mathrm{LS_j}}(\theta_\nu) - \omega_{\mathrm{LS_j}}(\theta_\nu)]$$

$$\chi^2_{\mathrm{zero}} = \sum_{\eta\nu ij} \tilde{\omega}_{\mathrm{LS_i}}(\theta_\eta) C^{-1}(\omega_{\mathrm{LS_i}}(\theta_\eta); \omega_{\mathrm{LS_j}}(\theta_\nu))\tilde{\omega}_{\mathrm{LS_j}}(\theta_\nu)$$

Significance of the detection:

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

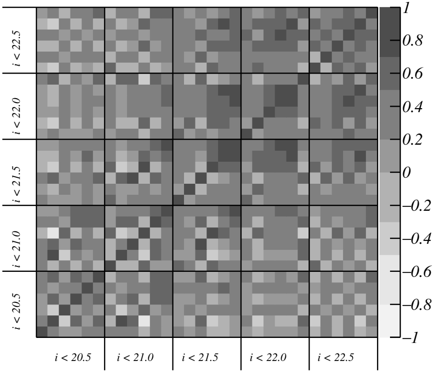
$$P(M|\Theta) = e^{-\chi^2_{Planck}/2}; P(Z|\Theta) = e^{-\chi^2_{zero}/2}$$

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

Magnification DES-SV.

Covariance matrix:

$$C_{\mathrm{S}}(\omega_{\mathrm{LS_i}}(\theta_\eta);\omega_{\mathrm{LS_j}}(\theta_\nu)) = \frac{N_{\mathrm{JK}}}{N_{\mathrm{JK}}-1}$$
$$\times \sum_{k}^{N_{\mathrm{JK}}} [\omega^{k}_{\mathrm{LS_i}}(\theta_\eta) - \omega_{\mathrm{LS_i}}(\theta_\eta)][\omega^{k}_{\mathrm{LS_j}}(\theta_\nu) - \omega_{\mathrm{LS_j}}(\theta_\nu)]$$



$N_{JK} = 120$

Magnification DES-SV.

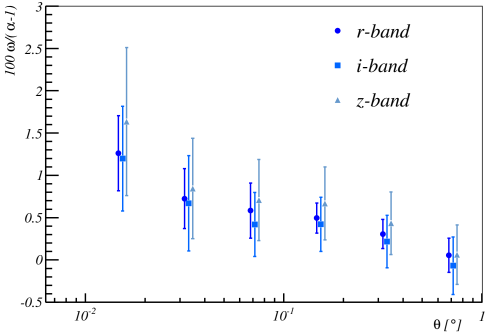
Sample	$\log_{10}\mathcal{B}$	$\chi^2/ndof$	$\log_{10}\mathcal{B}$	$\chi^2/ndof$
$r < 21.0$	-0.3	1.9/6		
$r < 21.5$	0.8	0.8/6		
$r < 22.0$	2.0	6.6/6	**3.9**	**21.6/30**
$r < 22.5$	2.3	7.0/6		
$r < 23.0$	1.1	4.2/6		
$i < 20.5$	0.2	0.9/6		
$i < 21.0$	2.1	2.0/6		
$i < 21.5$	2.5	4.5/6	**3.5**	**24.2/30**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

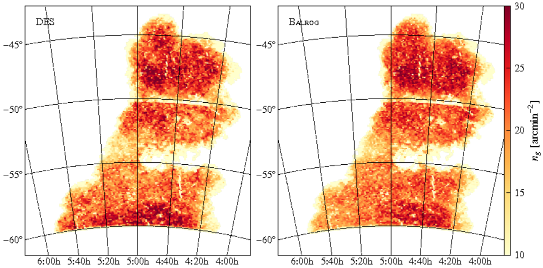
Survey observing conditions.

- 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 though the whole pipeline.

Magnification DES-SV.

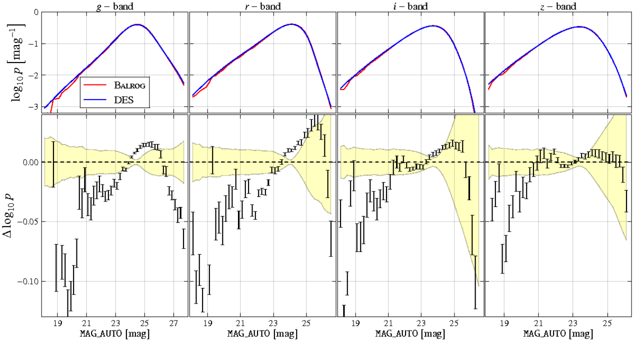
Balrog:

- Map *real* → *observed* quantities.
- **Determines the window function of the survey.**
- Measures the completeness, depth, uniformity...
- Takes into account un-blending.



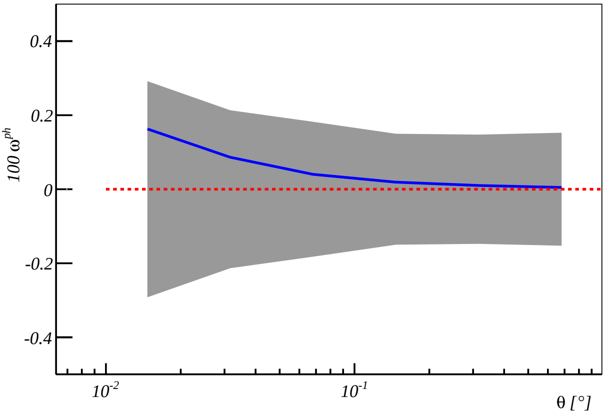
Magnification DES-SV.

- 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.

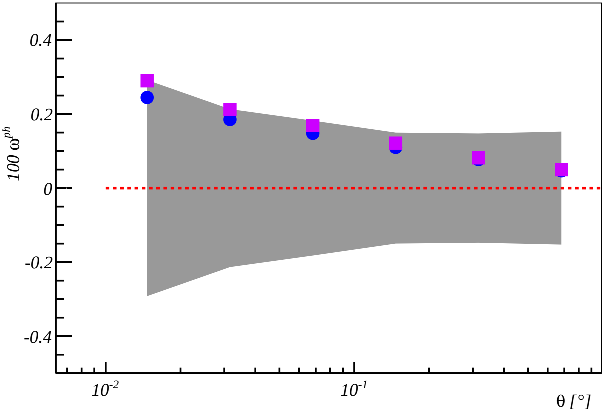
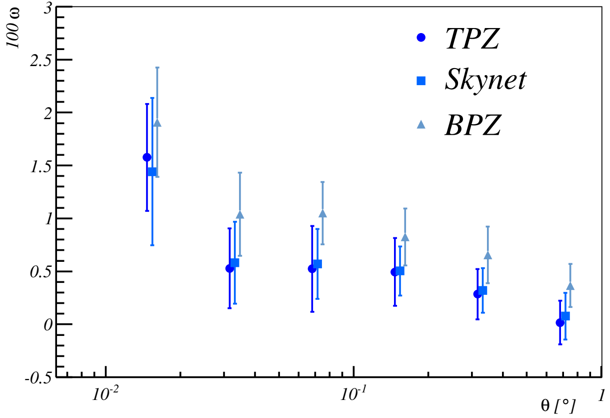


Photo-z contamination: Code comparison.



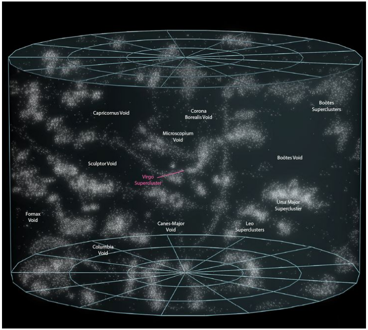
MAGNIFICATION DES-Y1

Magnification DES-Y1.

The possible science with magnification:

- Combination with other probes.
  $\rightarrow$ Caution with systematic.
  $\rightarrow$ Covariances reduce the impact on the measurement.

- Search for new alternative and independent probes.
  $\rightarrow$ **The clever solution:**
  Search for environments dominated by DE.

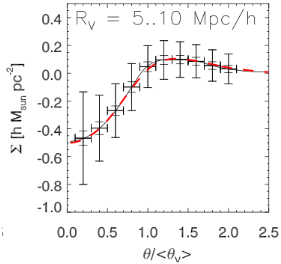


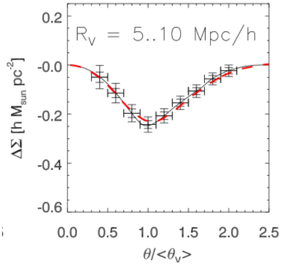
Magnification DES-Y1.

Dense sources allows low dense lenses:

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

Direct probe of the matter profile.

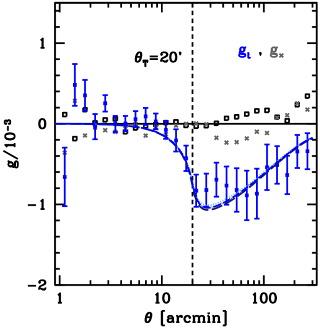




(arXiv:1210.2446)

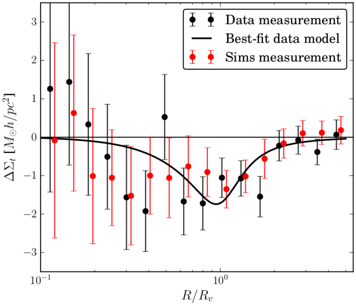
Magnification DES-Y1.

Trough gg-lensing.



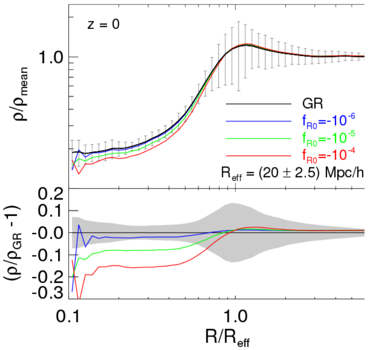
(arXiv:1507.05090)

Void gg-lensing.

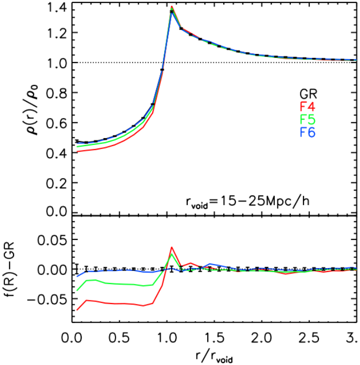


(arXiv:1605.03982)

Void profile with Modified Gravity f(R) models.



(arXiv:1511.01494)

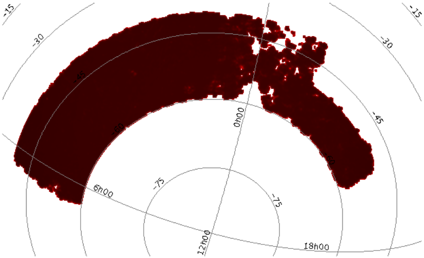


(arXiv:1410.8355)

Magnification DES-Y1.

The source data sample:
DES-Y1-Gold.

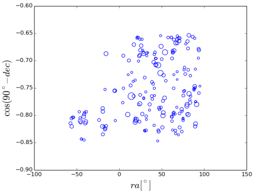
- S/G-separation: `modest_class` & spread_model_i + 3×spreaderr_model_i > 0.007.
- Depth: $i_{lim} > 22.0$ & $i < 20.5$.
- Mask: worst 4% & bright-star halos removed.
- $0.8 < z_{BPZ} < 1.5$.



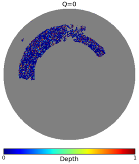
Magnification DES-Y1.

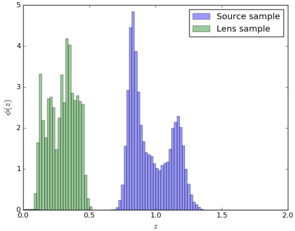
Two lenses: DES-Y1-redmagic.
$0.2 < z_{red} < 0.45$

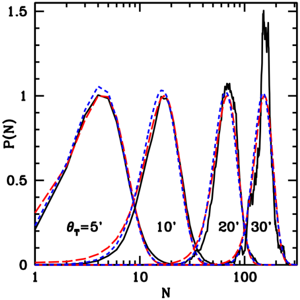
- Voids.



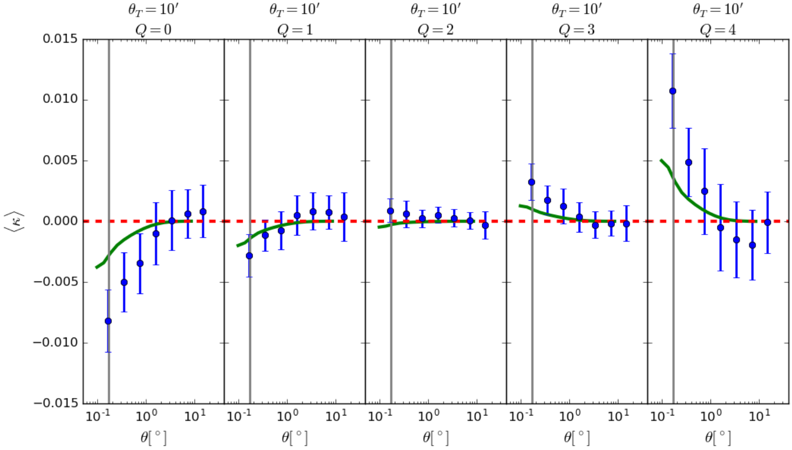
- Troughs.



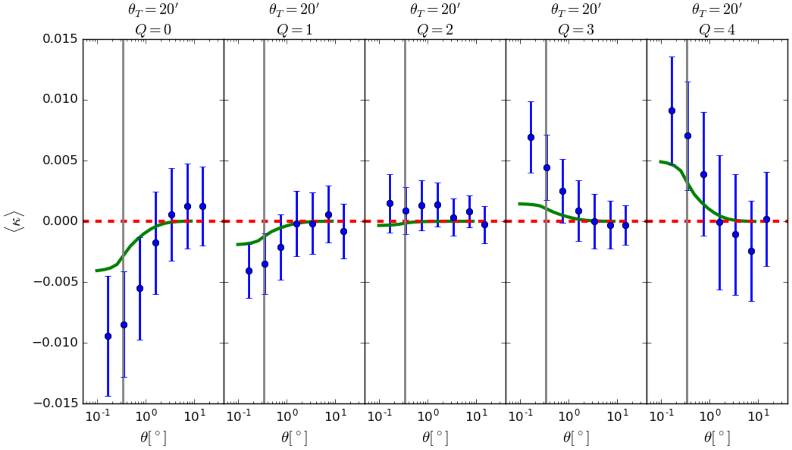




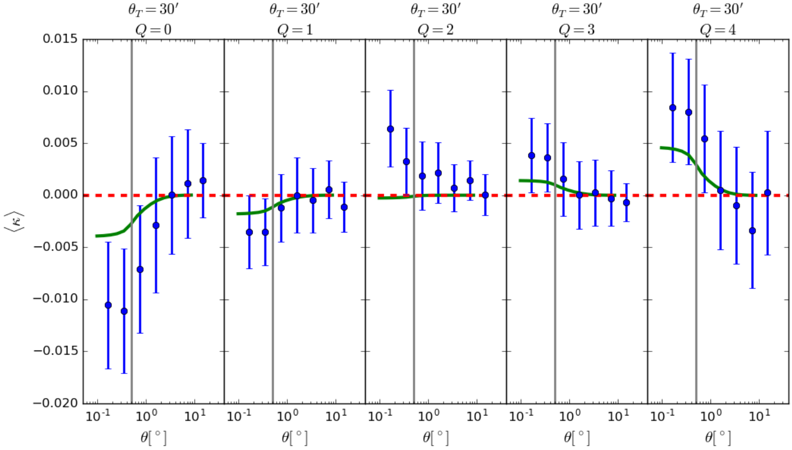
Magnification DES-Y1.



Magnification DES-Y1.



Magnification DES-Y1.



Magnification DES-Y1.

Theory:

$\rightarrow$ Used Fiedrich et al. (in prep) and Gruen et al. (2016) theory.

$\rightarrow$ Planck 2015 parameters blinded.

Covariances:

$\rightarrow$ Bootstrap resampling **only** the lenses.

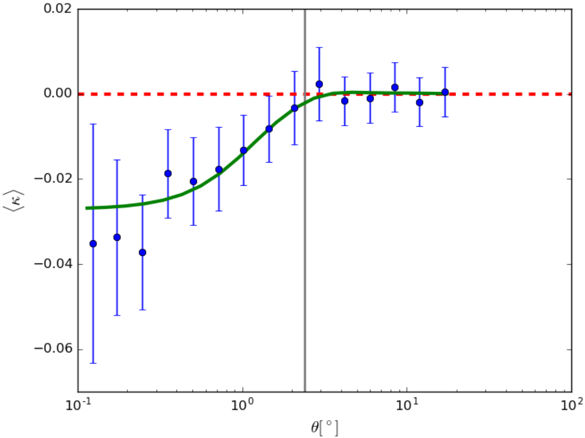
Magnification DES-Y1.

Significance of detection:

$\rightarrow$ Defined by the χ^2 against zero.

θ_T	10′				
Q	0	1	2	3	4
$\chi^2_z/ndof$	43.5/7	10.5/7	1.3/7	10.3/7	45.3/7
θ_T	20′				
Q	0	1	2	3	4
$\chi^2_z/ndof$	19.0/7	7.5/7	4.0/7	18.3/7	17.0/7
θ_T	30′				
Q	0	1	2	3	4
$\chi^2_z/ndof$	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.

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

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.
  $\rightarrow$Including a novel way to deal with systematic errors.
- Magnification allows access to lowest voids scales
- Lowest void scales provide constrains on Modified Gravity scenarios.
- First direct measurement of a void convergence profile.
  $\rightarrow$Opens a new window to probe the dark Universe!