Looking at the cosmic voids, a promising cosmological probe

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seminar @CPPM February 22nd 2021

Timeline

- Introduction to cosmology : a brief history to what brings us where we are
- How can we understand it better : Observational tools
- Cosmic voids : a promising probe
- Application to DES data : VOIDSXCMB

A brief history of cosmology

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu},$$

A. Einstein

1916

The universe is expanding

E. Hubble

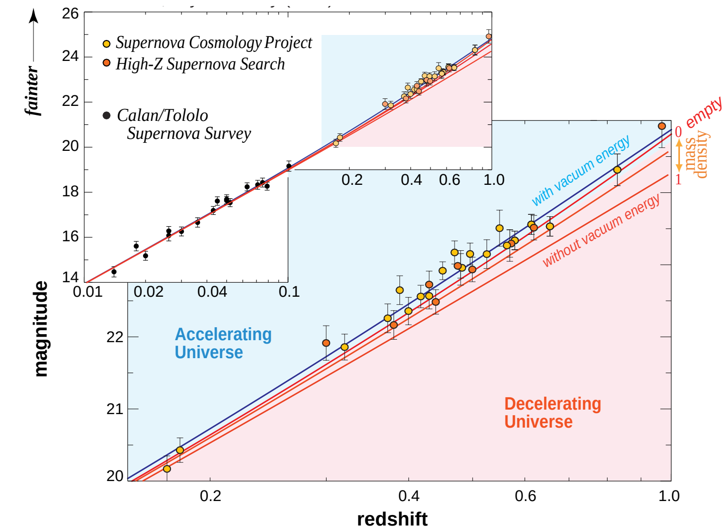
1929

CMB Detection

A. Penzias **G. Wilson**

1965

Accelerated Expansion



1998

1922

A. Friedmann

1927

The universe might not be static

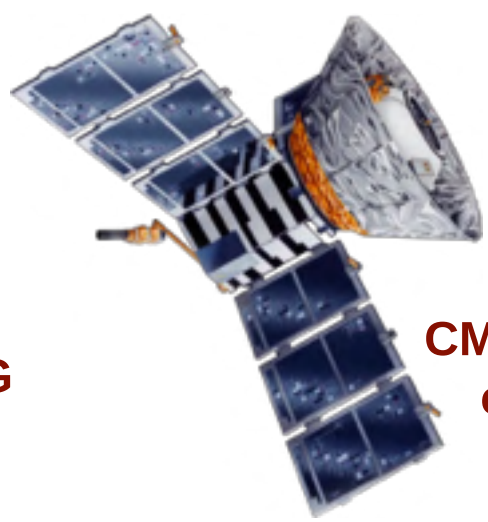
G. Lemaître

1946

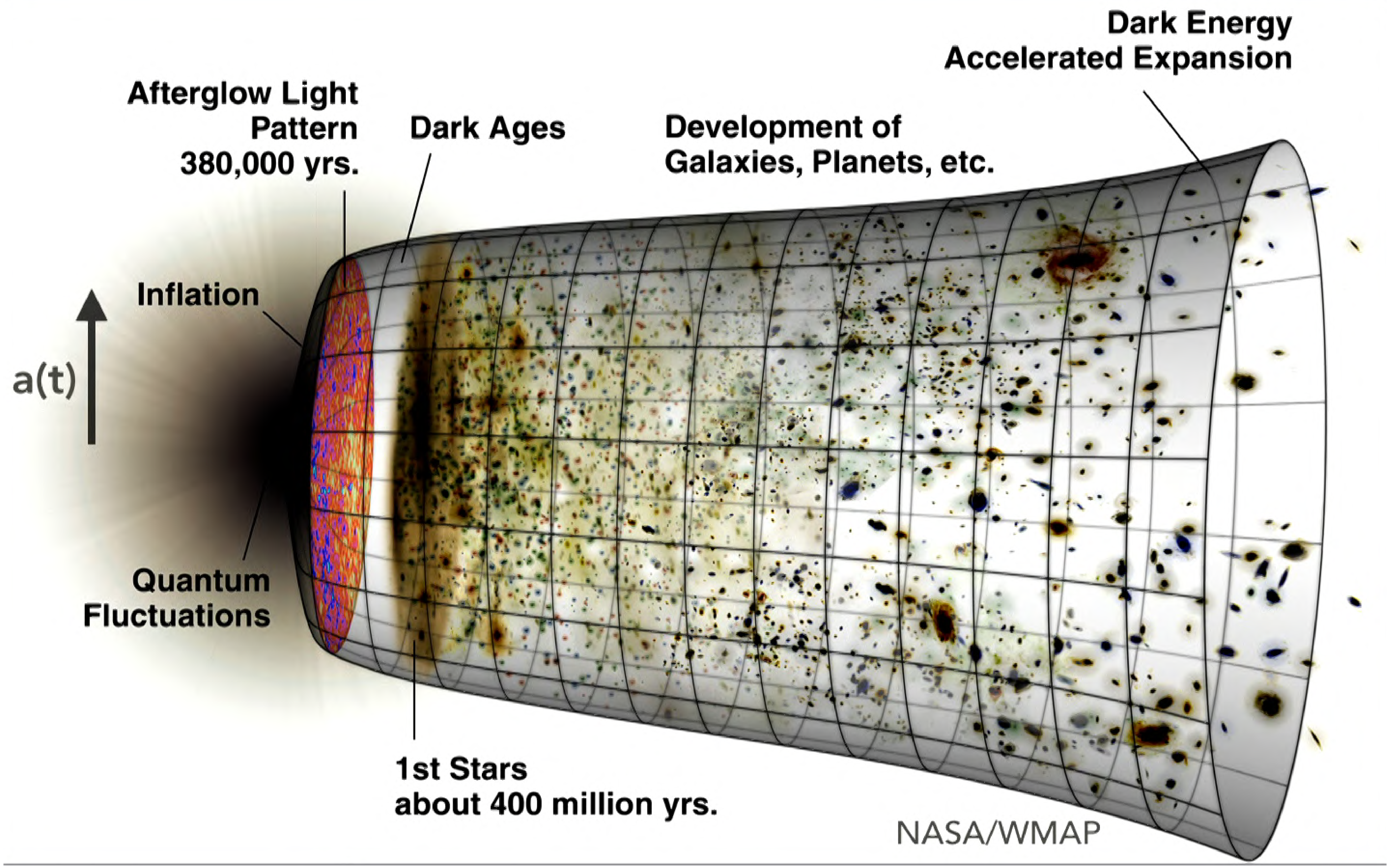
G. Gamov

BIG BANG THEORY

1989



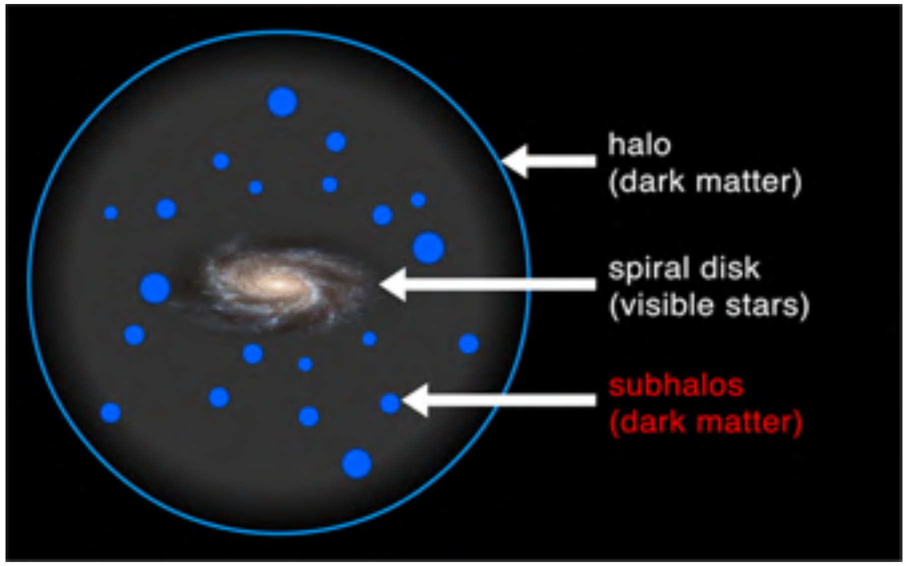
COBE CMB Detection confirmed


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
a(t)
Quantum
Fluctuations
1st Stars
about 400 million yrs.
NASA/WMAP

A brief history of cosmology
+ Cold Dark Matter

Dark matter is a hypothetical type of matter which does not emit or interact with electromagnetic radiation, but its presence can be inferred through its gravitational effect.

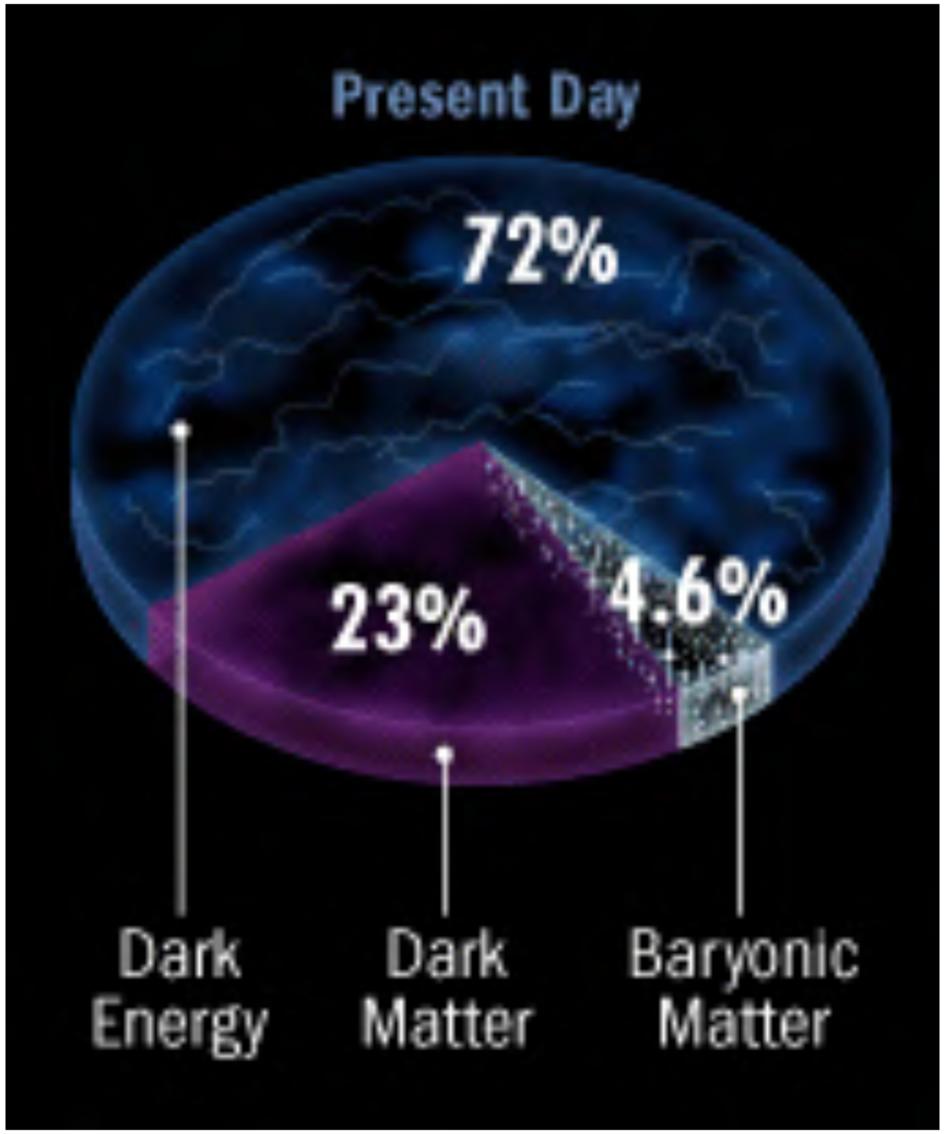
Introduced by Fritz Zwicky in the 30's (!) to explain the total mass of the Coma cluster and have been indirectly detected after in different cosmological probes.



$$\Omega_m = \Omega_{dm} + \Omega_b,$$

STATE OF THE ART OF COSMOLOGY

$$\frac{H(a)^2}{H_0^2} = \Omega_{0,r}a^{-4} + \Omega_{0,m}a^{-3} + \Omega_{0,k}a^{-2} + \Omega_{0,\Lambda}$$

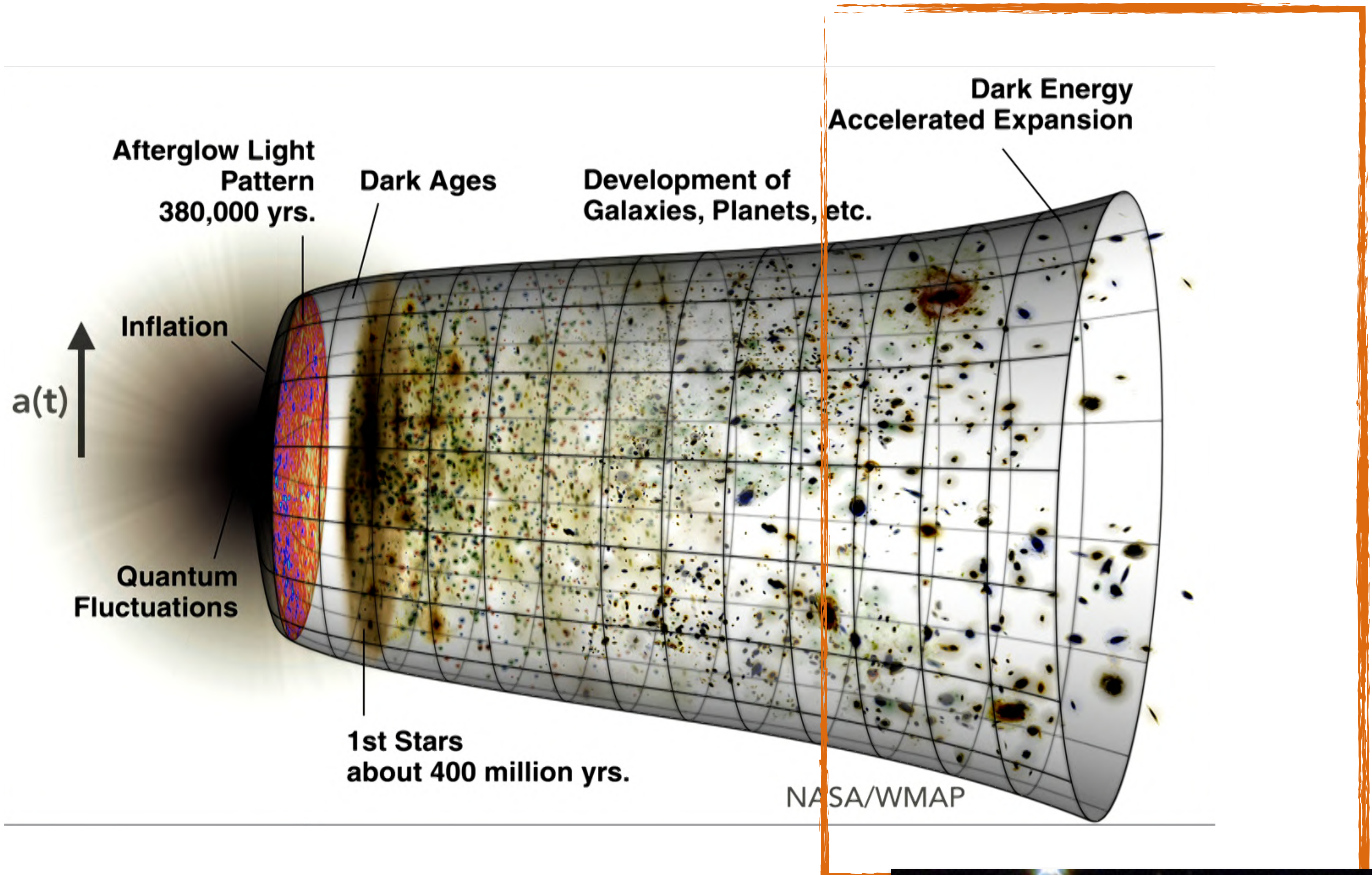


What causes the late cosmic acceleration? Dark Energy? our theory of gravity is wrong?

What is the Nature of Dark Matter?

How can we probe our theory?

Galaxy Surveys :
looking at the late universe



Large Scale Structure

Observing the Universe at low-z : Galaxy Surveys

Spectroscopic surveys

Provide precise 3D information for each object, getting galaxy spectras

$$\sigma(z)/(1+z) \quad < \quad 0.001$$

- No shapes,
- Time consuming,
- not complete

- RSD
- BAO
- clustering

Photometric surveys

Observed through pass-band filters, get color and shape information for a lot of object at the same time

$$\sigma(z)/(1+z) \quad \sim \quad 0.05$$

- Difficult to infer radial position of objects

- Cosmic shear
- Galaxy clustering
- Galaxy-Galaxy lensing

Survey	Number of galaxies[a]	redshift	area (deg^2)	Observation period
Sloan Digital Sky Survey (SDSS Legacy) York et al. (2000)	$\sim 1M$ galaxies ~ 120000 Quasars	$z \lesssim 0.25$	7500	observation finished 2000-2008
Wiggle-Z Drinkwater et al. (2010)	239000 ELGs	$0.2 < z < 1.0$	1000	observation finished 2006-2011
The Baryon Oscillation Spectroscopic Survey (BOSS) Dawson et al. (2013)	1.5M LRGs 160000 Quasars	$z < 0.7$ $2.2 < z < 3$	10000	observation finished 2008-2014
The Extended Baryon Oscillation Spectroscopic Survey (eBOSS) Dawson et al. (2016)	300000 LRGs 189000 ELGs 573000 Quasars	$0.6 < z < 0.8$ $0.6 < z < 1.0$ $0.9 < z < 3.5$	7500 1000 7500	2014-2020
Dark Energy Spectroscopic Instrument (DESI) DESI Collaboration et al. (2016)	$4M$ LRGs $18M$ ELGs $2.4M$ Quasars	$z < 1$ $z < 1.7$ $2.1 < z < 3.5$	14000	First light in 2019
Euclid Laureijs et al. (2011)	50M galaxies	$0.5 < z < 2.0$	15000	Launching in 2021

Launch is now foreseen for 2022

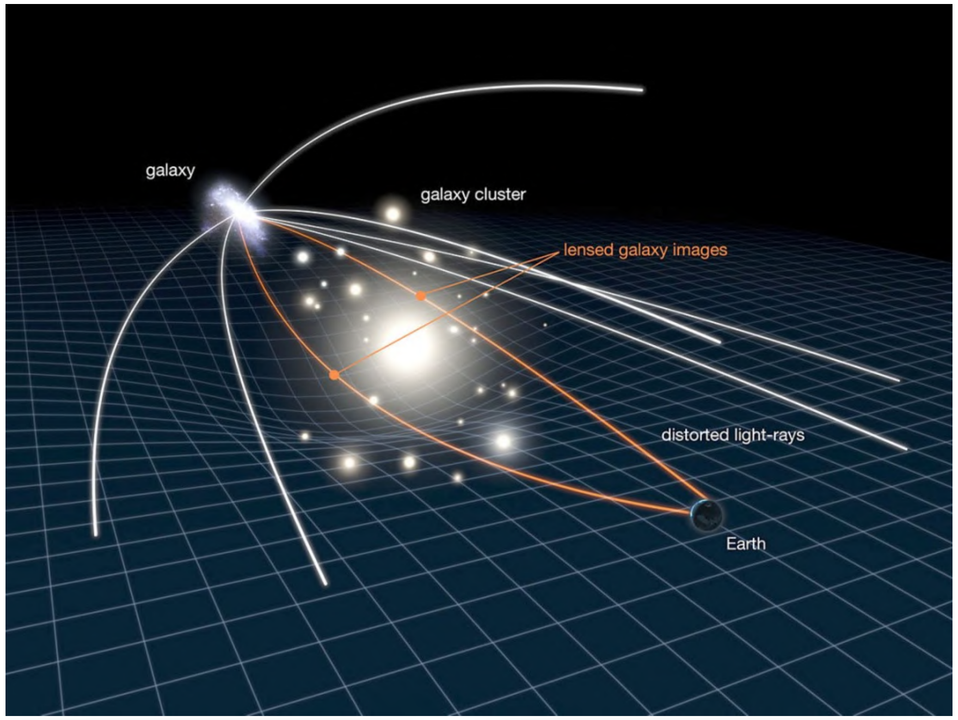
TABLE 2.1.1 – Summary of recent and future spectroscopic surveys.

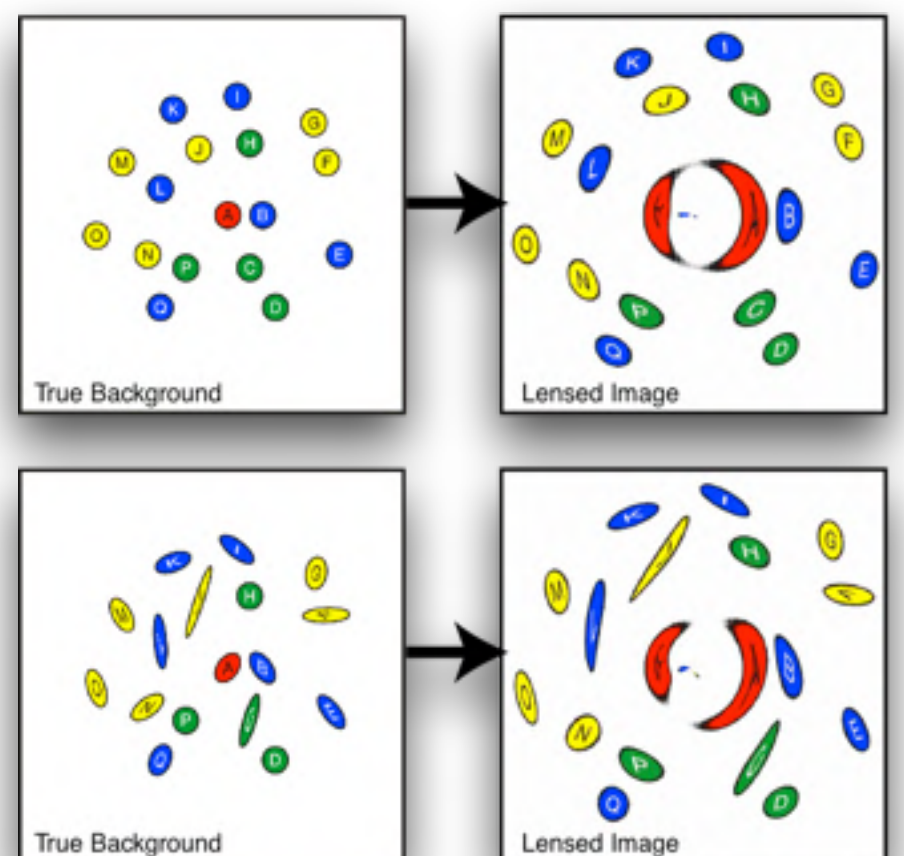
photometric Survey	photometric bands	Number of galaxies	area deg^2	observation period
Canada-France-Hawaii Telescope Legacy Survey (CFHTLS)	ugriz	$38M$	4 fields over $171deg^2$	observation finished 2004-2009
Kilo Degree Survey (KiDS) de Jong et al. (2015)	ugri	90M	1500	First light in 2011
Dark Energy Survey (DES) The Dark Energy Survey Collaboration (2005)	grizy	300M	5000	started in 2013 for 577 nights of observation
Hyper Suprime-Cam (HSC) Aihara et al. (2018)	grizy	100M	1400	started in 2014 for 300 nights of observation
Physics of the Accelerating Universe Survey (PAU) Martí et al. (2014)	40 narrow bands	2M	100	started in 2015 123 nights of observation
Large Synoptic Survey Telescope (LSST) LSST Science Collaboration et al. (2009)	ugrizy	4B	20000	First light 2021
Euclid Laureijs et al. (2011)	R,I,Z YJH	1.5B	15000	Launching in 2021
COSMOS-30 band) Laigle et al. (2016)	30 UV/Visible/IR bands	> 500000	2	Combined sample of various surveys in the COSMOS field

Launch is now foreseen for 2022

TABLE 2.1.2 – Summary of recent and future photometric surveys.

Lensing



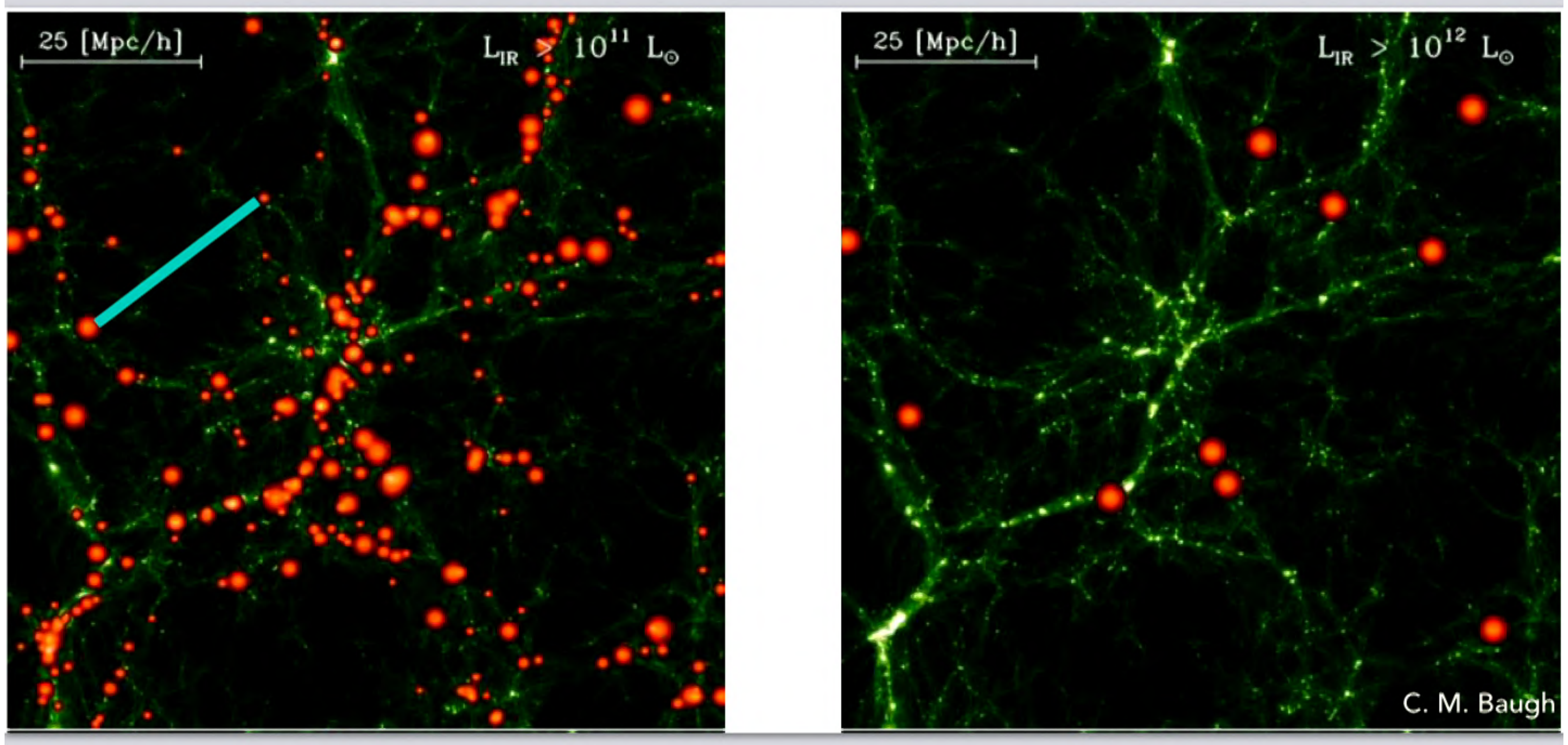


General relativity predicts the deviation of light trajectories due to gravity

Background galaxy will be observed with a distorted shape due to the matter density field between them and us

Measuring this effect will give us information on the foreground matter distribution, including Dark Matter

Galaxy clustering

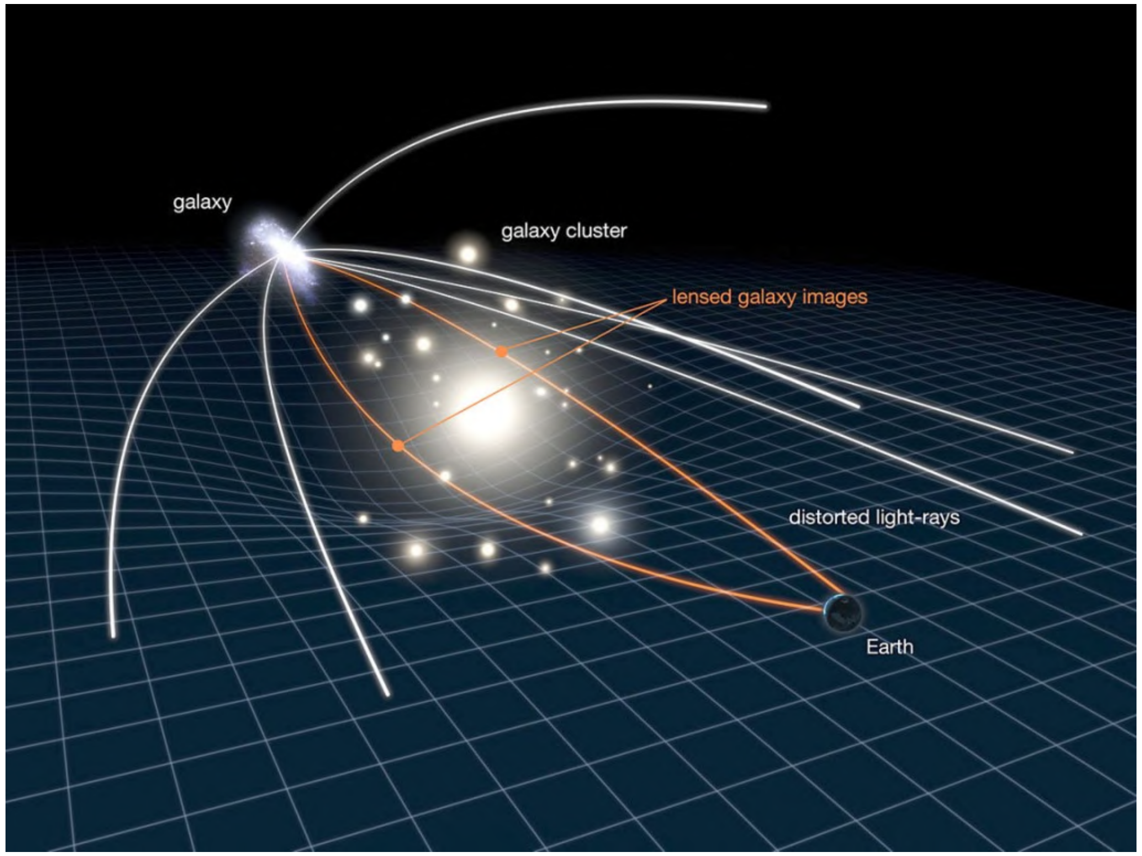


Galaxies tend to trace Dark matter

$$\delta_i(\vec{k}, z) = b_i(z, \vec{k})\delta(\vec{k}, z)$$

Galaxy galaxy lensing

Source : Shape of background galaxies



Lenses: position of foreground galaxies

Surface mass excess :

$$\Delta\Sigma(\leq \theta) := \langle \gamma_{\rm t} \rangle (\theta)\, \Sigma_{\rm cr} = \bar{\Sigma}(\theta) - \langle \Sigma \rangle (\theta).$$

Main probe of photometric galaxy surveys
3X2pts

Galaxy Clustering

$$< \delta_g \delta_g >$$

Cosmic Shear

$$< \delta_\epsilon \delta_\epsilon >$$

Galaxy Galaxy lensing

$$< \delta_g \delta_\epsilon >$$

Galaxy-Galaxy correlation

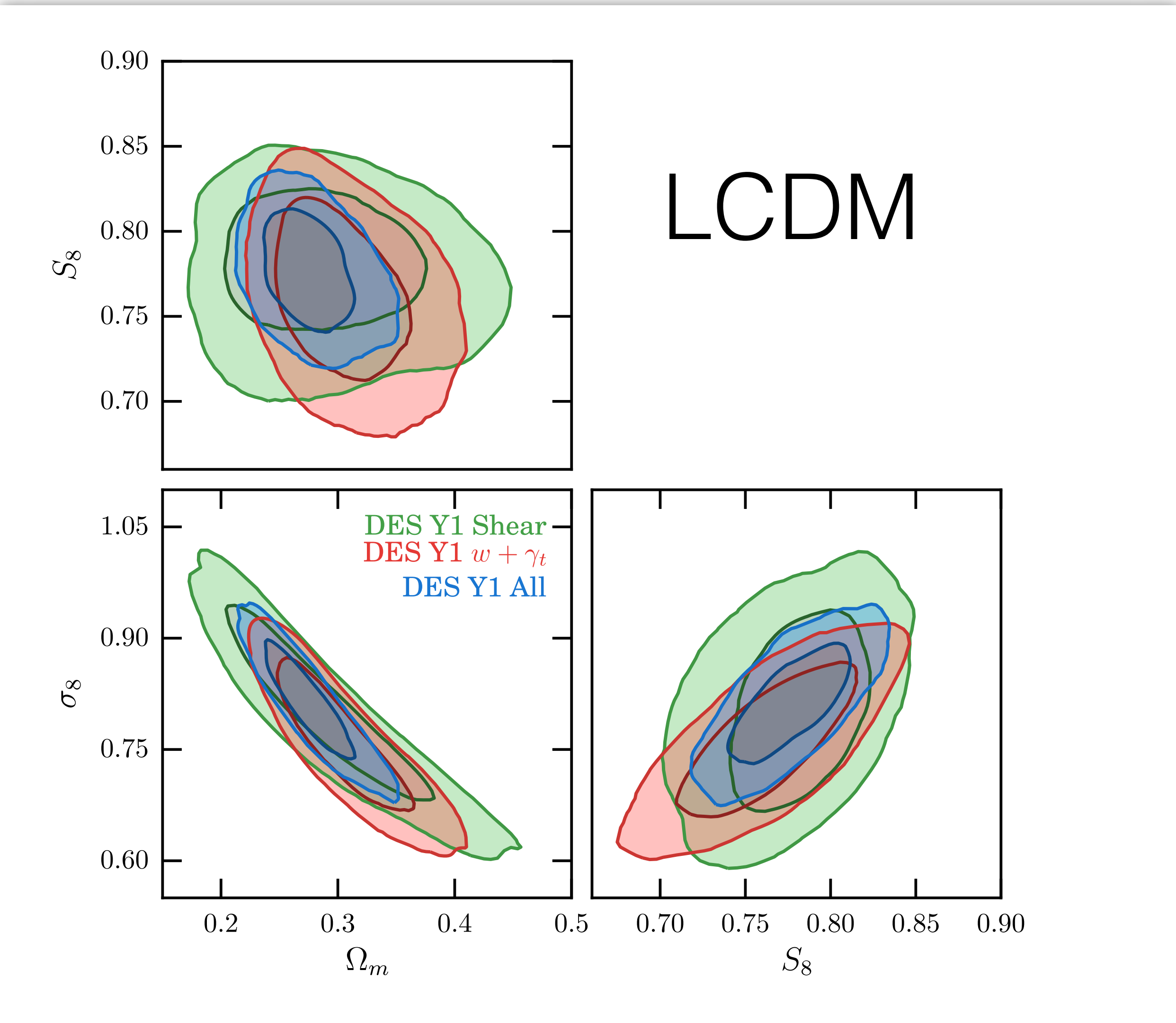
correlations between galaxy **position** as a function of their separation

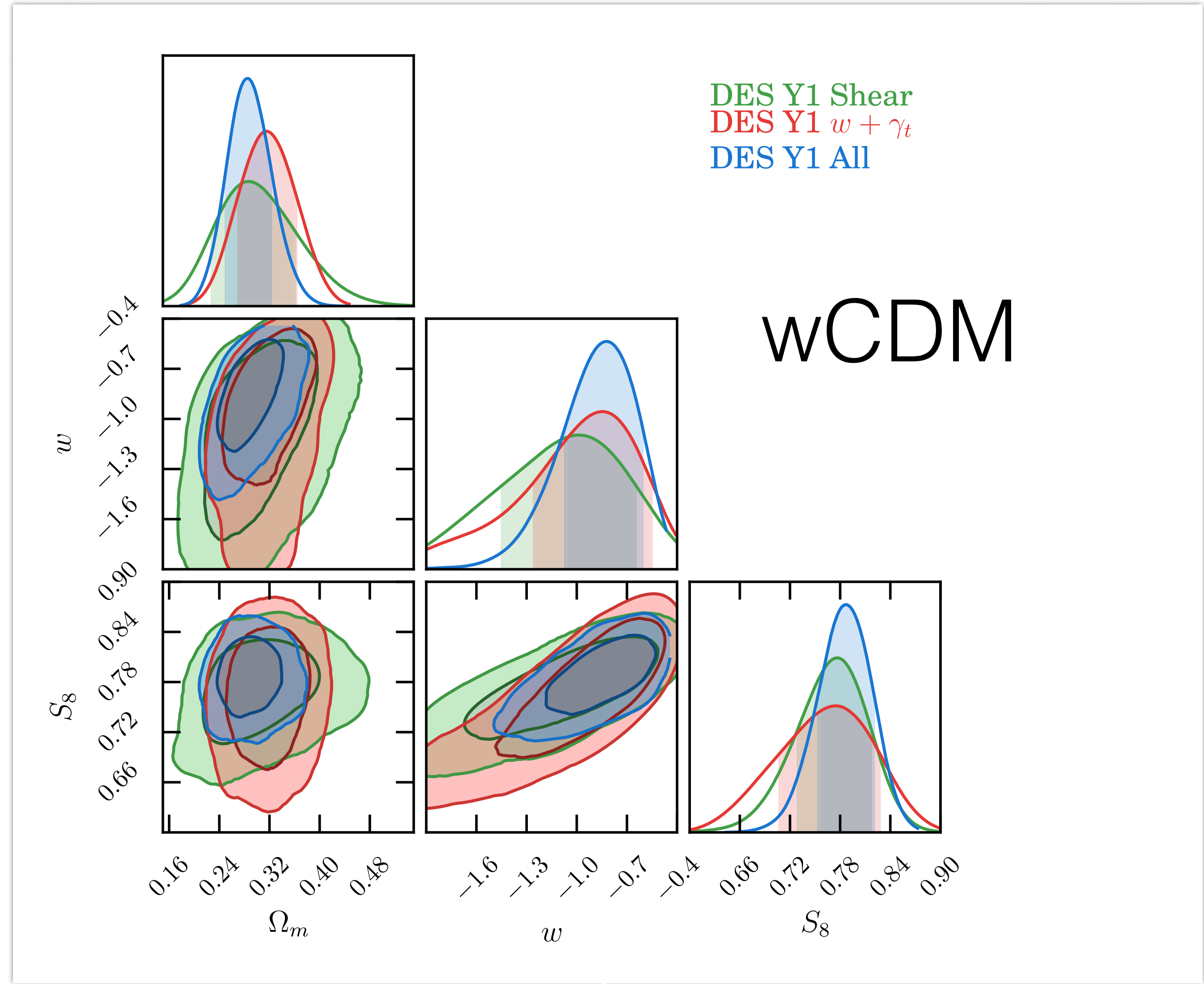
Shear-Shear correlation

correlations between galaxy **ellipticity** as a function of their separation

Galaxy-Shear correlation

correlations between the **ellipticity** of background galaxy with the **position** of foreground ones as a function of their separation





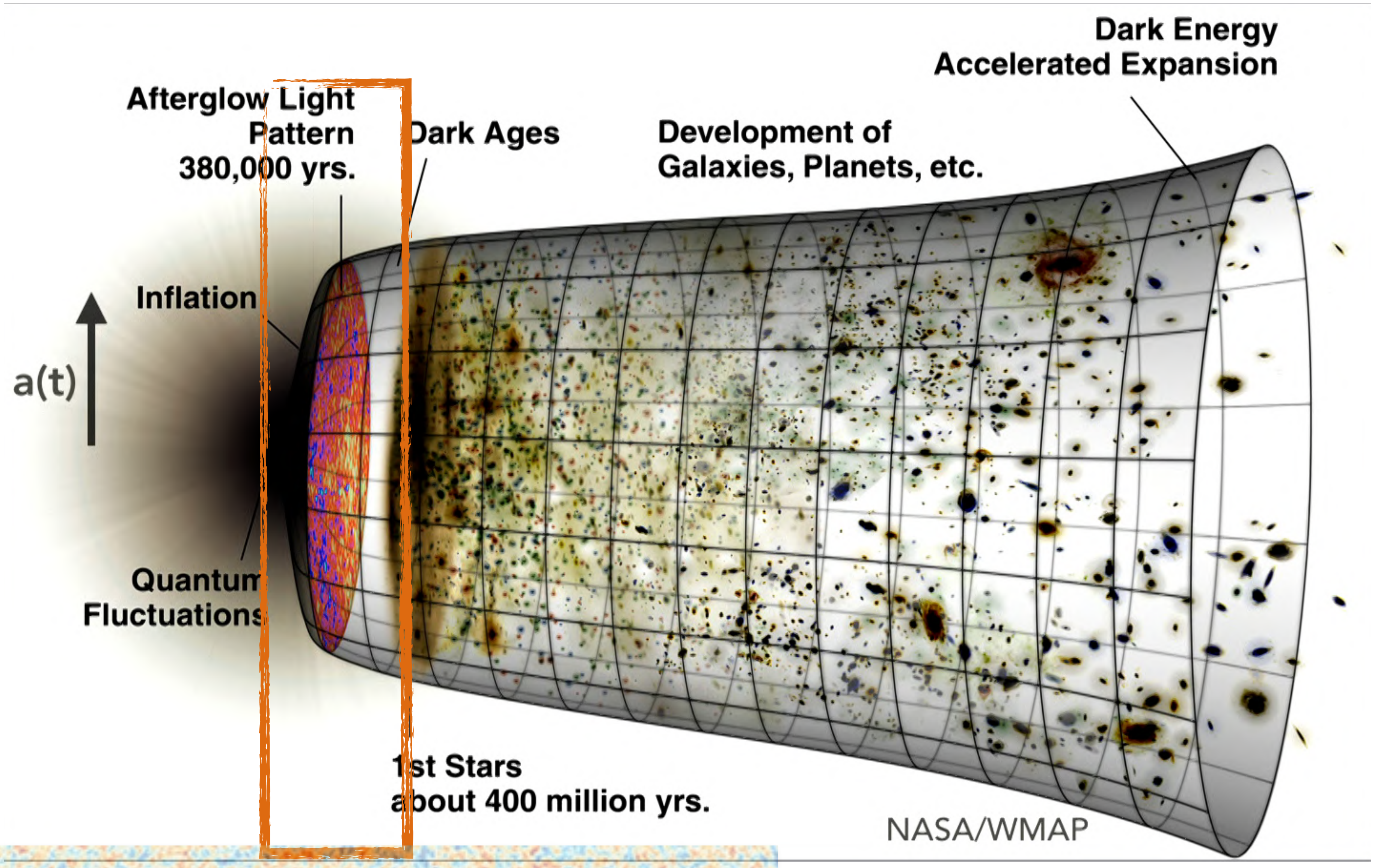
Agreement between lensing and clustering

Model	Data Sets	Ω_m	S_8
ΛCDM	DES Y1 $\xi_{\pm}(\theta)$	$0.323^{+0.048}_{-0.069}$	$0.791^{+0.019}_{-0.029}$
ΛCDM	DES Y1 $w(\theta)+\gamma_t$	$0.293^{+0.043}_{-0.033}$	$0.770^{+0.035}_{-0.030}$
ΛCDM	DES Y1 3x2	$0.264^{+0.032}_{-0.019}$	$0.783^{+0.021}_{-0.025}$

No evidence of wCDM model

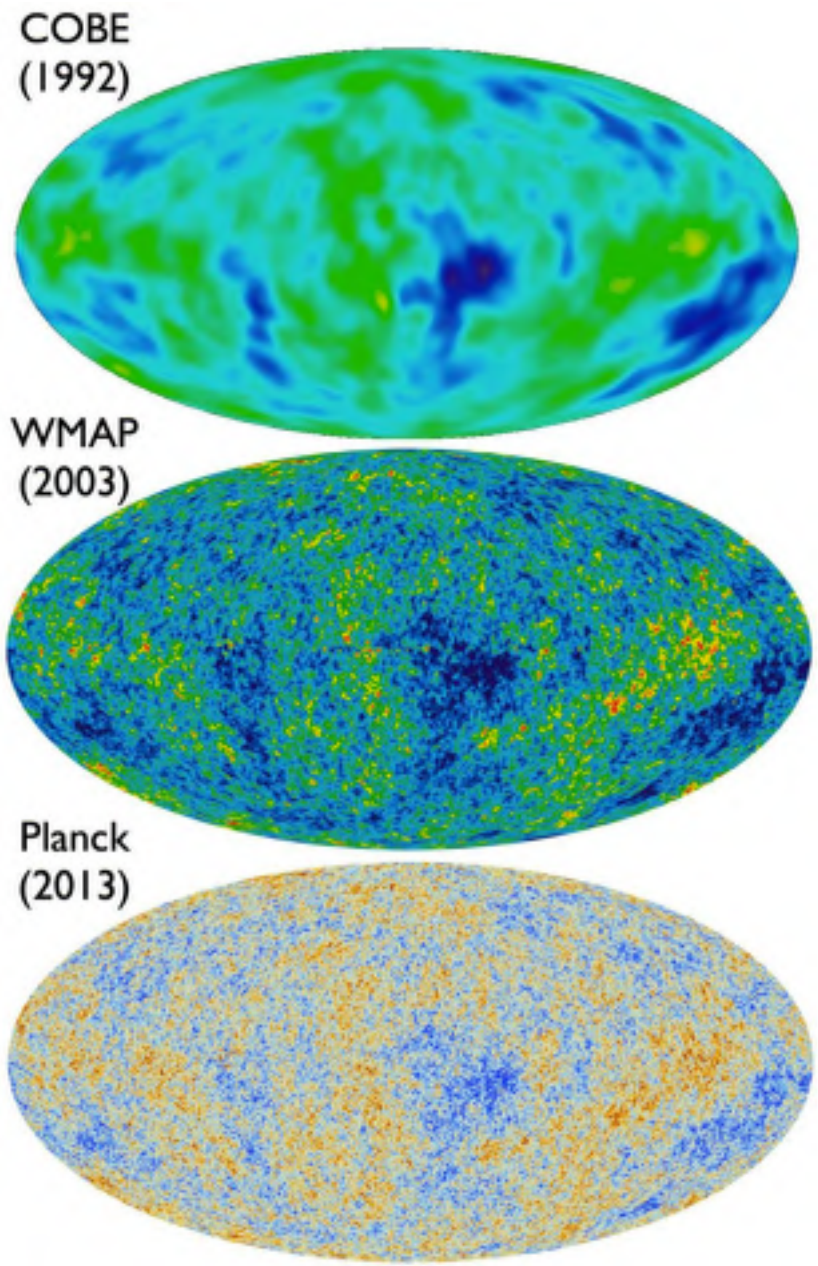
Model	Data Sets	Ω_m	S_8	w
wCDM	DES Y1 $\xi_{\pm}(\theta)$	$0.317^{+0.074}_{-0.054}$	$0.789^{+0.036}_{-0.038}$	$-0.82^{+0.26}_{-0.47}$
wCDM	DES Y1 $w(\theta)+\gamma_t$	$0.317^{+0.045}_{-0.041}$	$0.788^{+0.039}_{-0.067}$	$-0.76^{+0.19}_{-0.45}$
wCDM	DES Y1 3x2	$0.279^{+0.043}_{-0.022}$	$0.794^{+0.029}_{-0.027}$	$-0.80^{+0.20}_{-0.22}$

CMB experiments:
Looking at the early universe



Cosmic Microwave Background

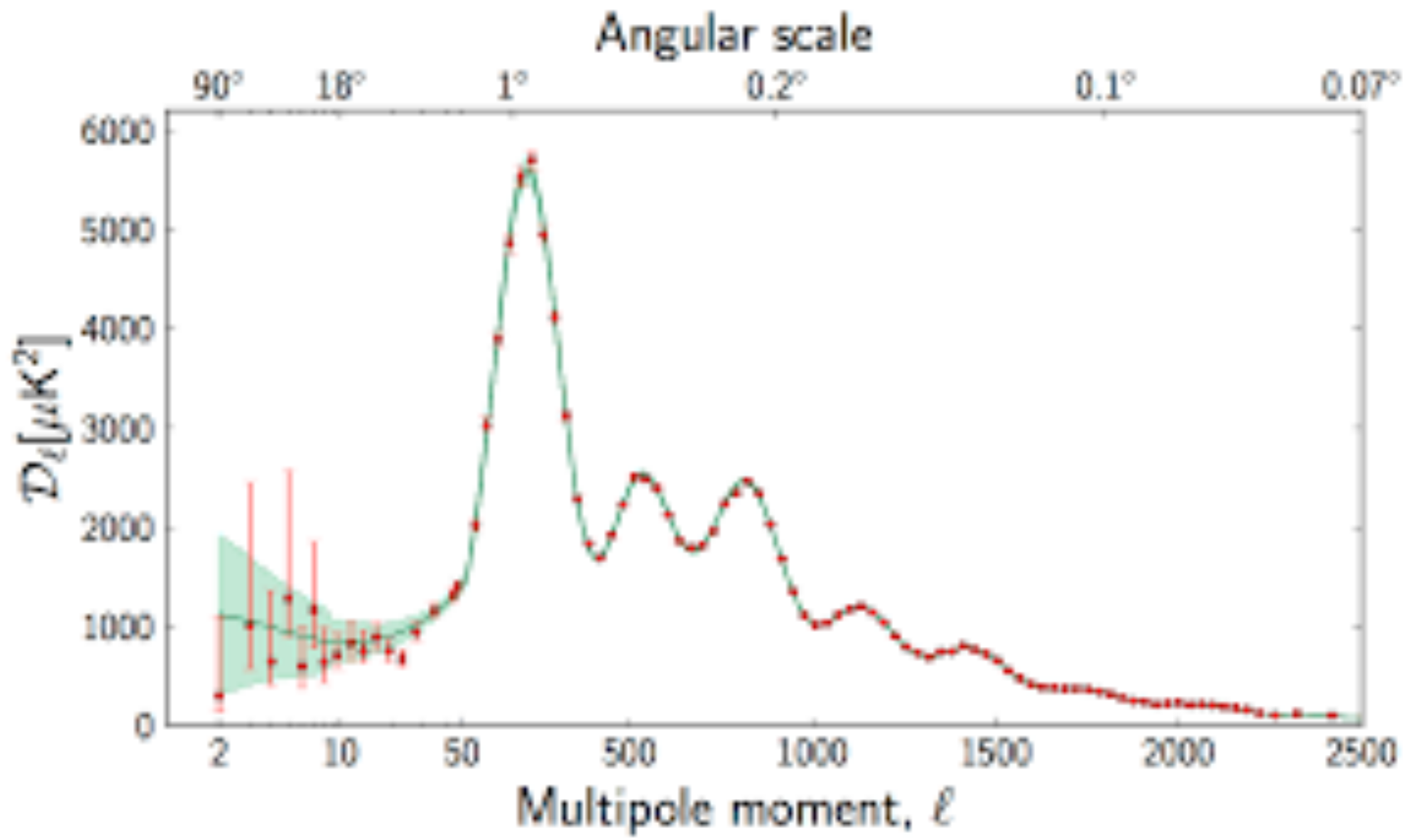
Cosmic Microwave Background



Small anisotropies

↓

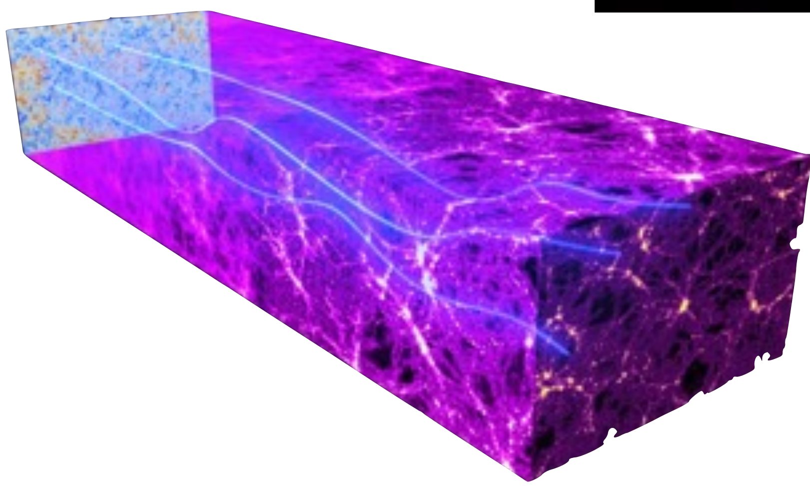
Seeds of the Large structures we are observing

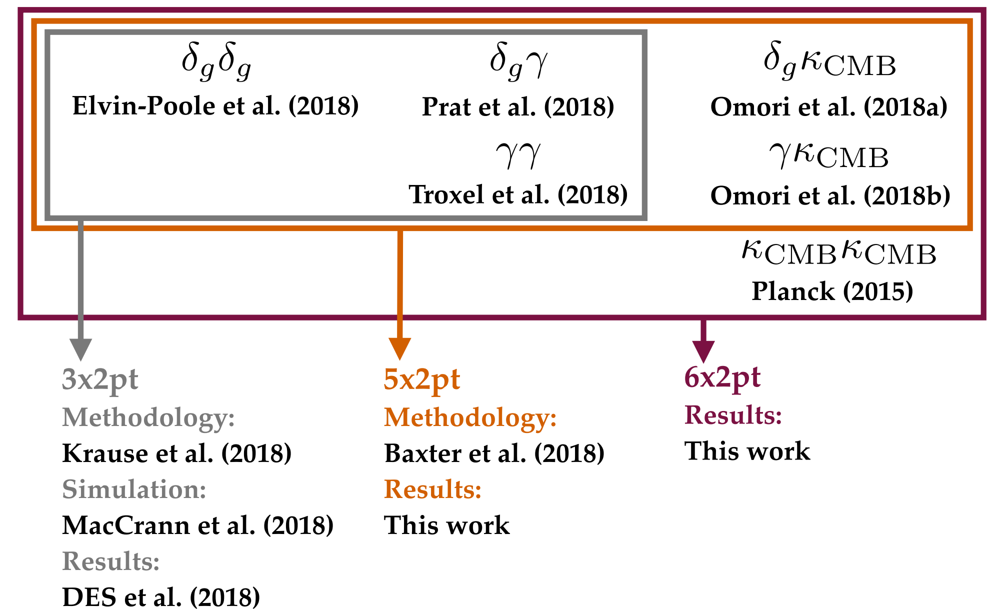


$\delta T/T \sim 10^{-5}$

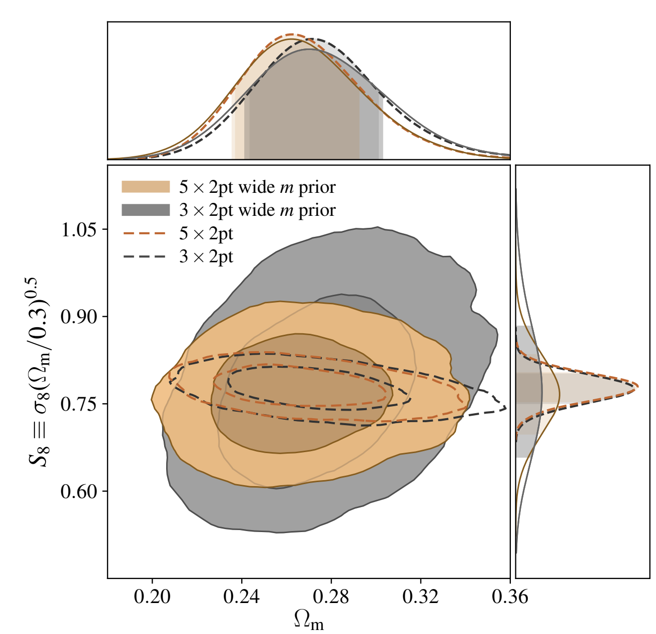
Cosmic Microwave Background : lensing

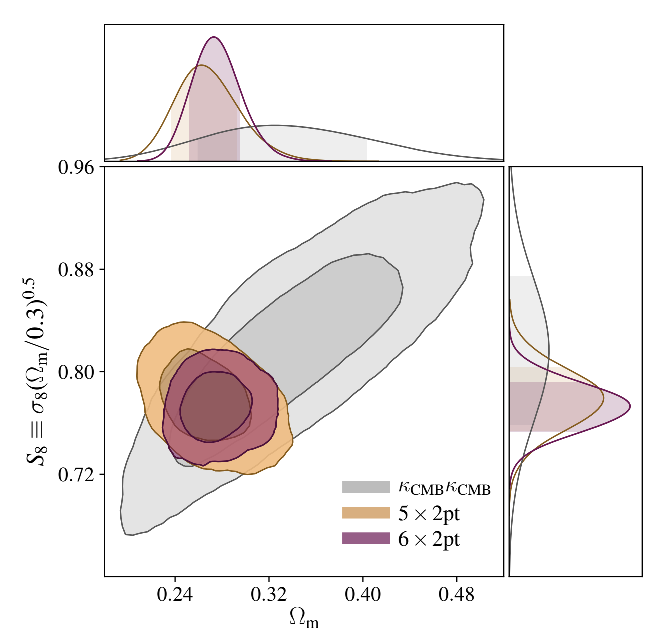
Dark Energy Survey Year 1 Results: Joint Analysis of Galaxy Clustering, Galaxy Lensing, and CMB Lensing Two-point Functions



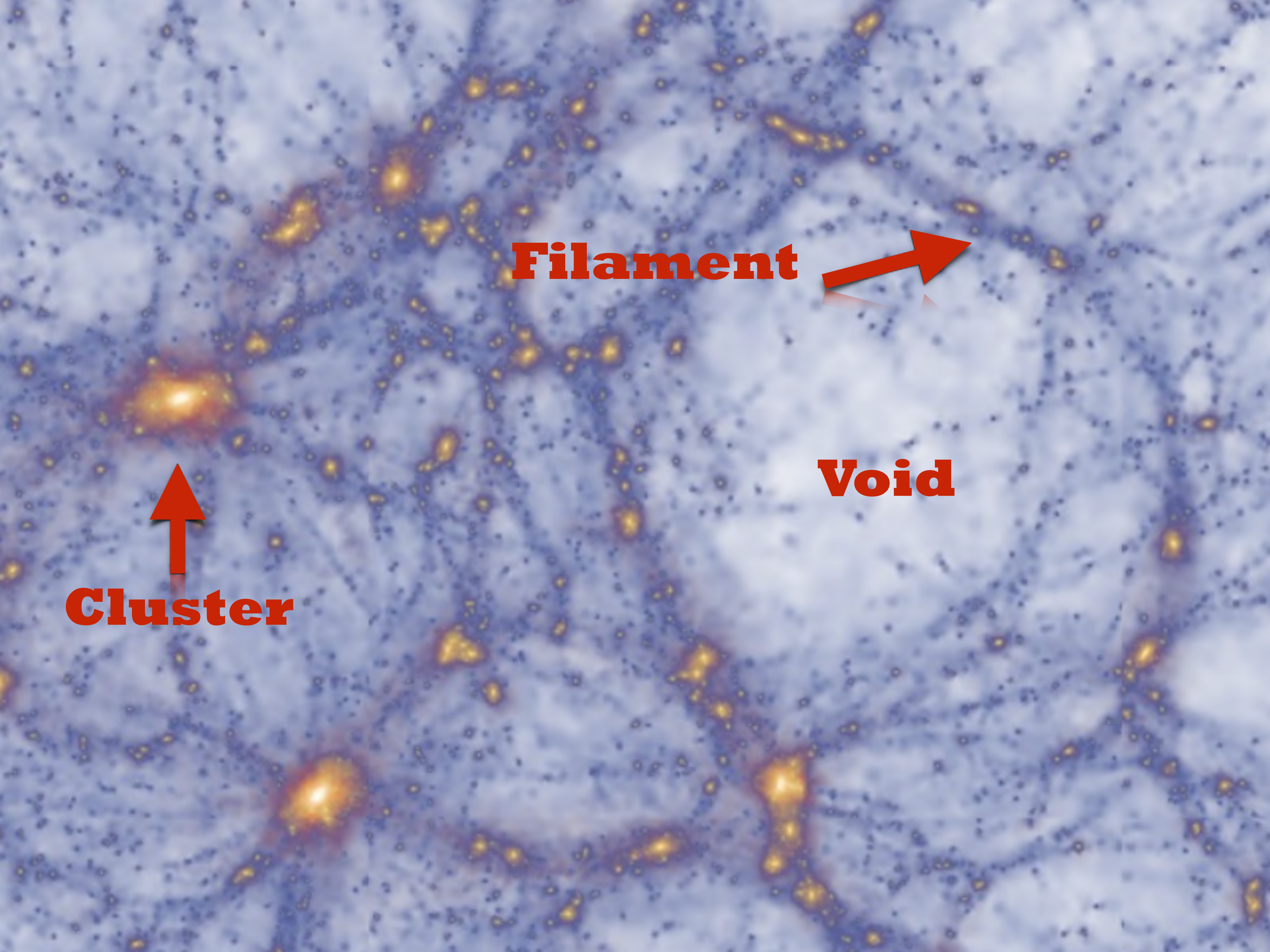


similarly to the deflection effects induced by the large structures that we observe on the sky on the photons coming from background galaxies, we should have lensing effects by the foreground matter field on the photons that come from the CMB

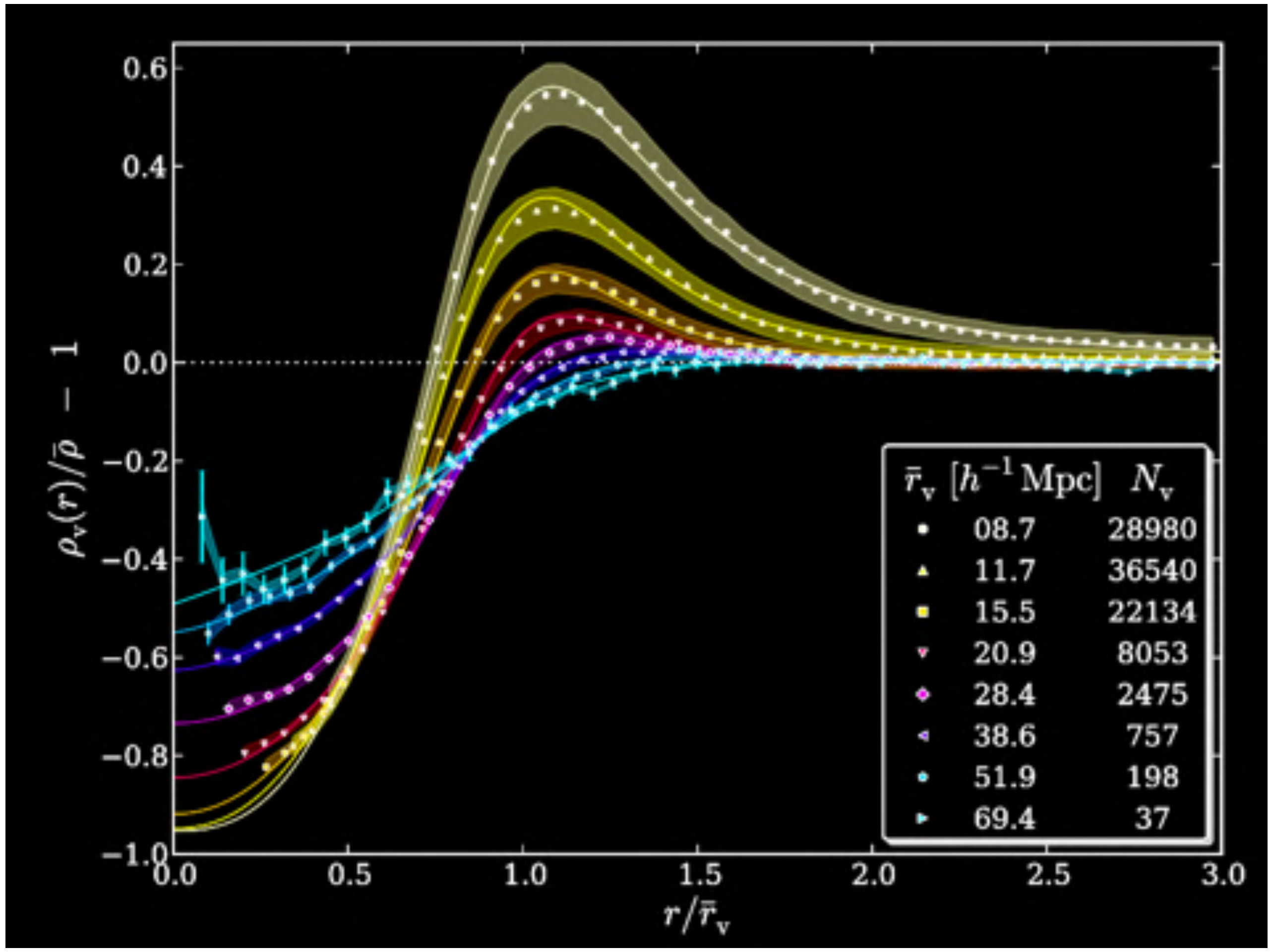




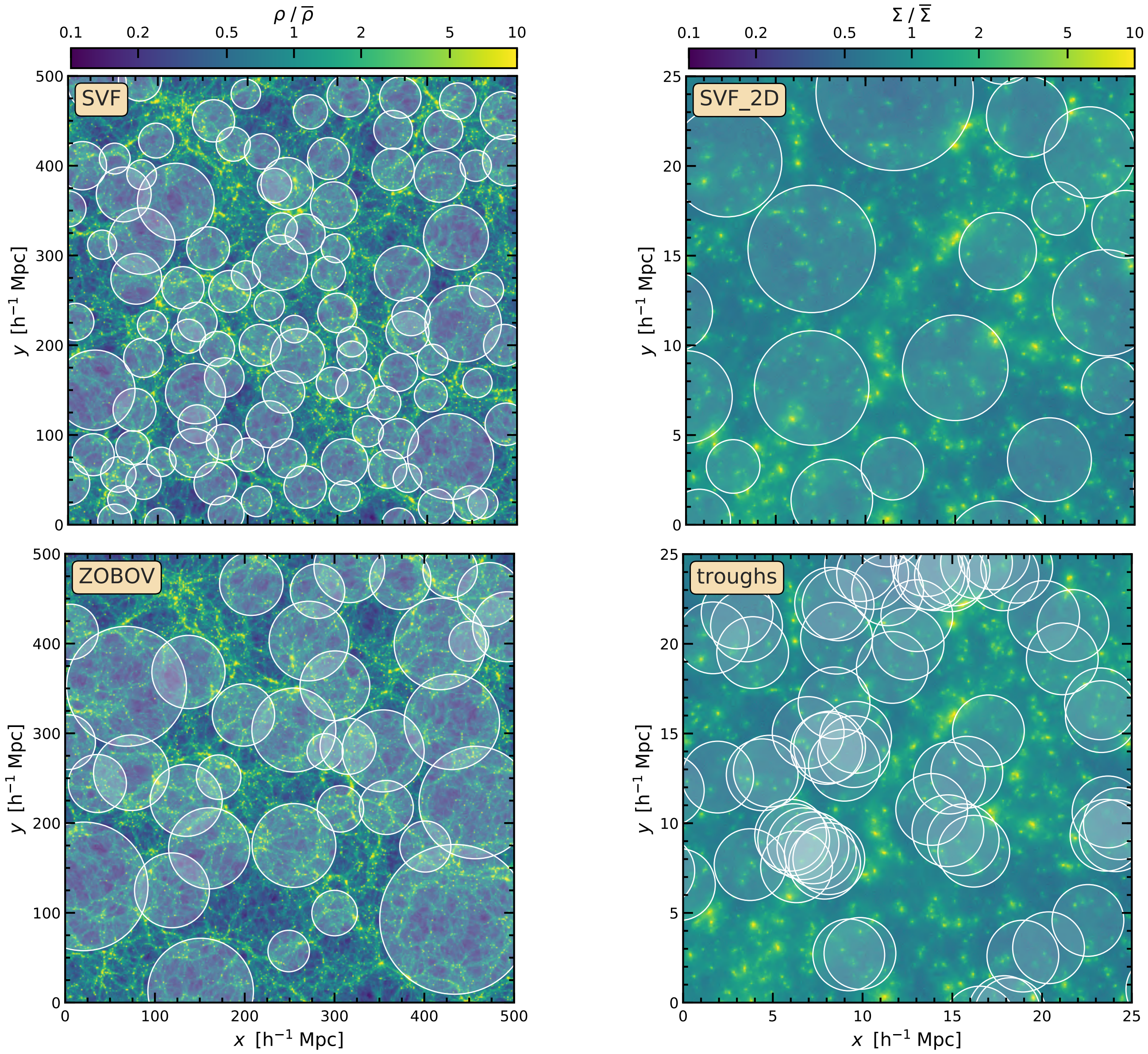
The cosmic voids and their potential role for future observations


Filament
Void
Cluster

Voids definition



Hamaus et al. 2014

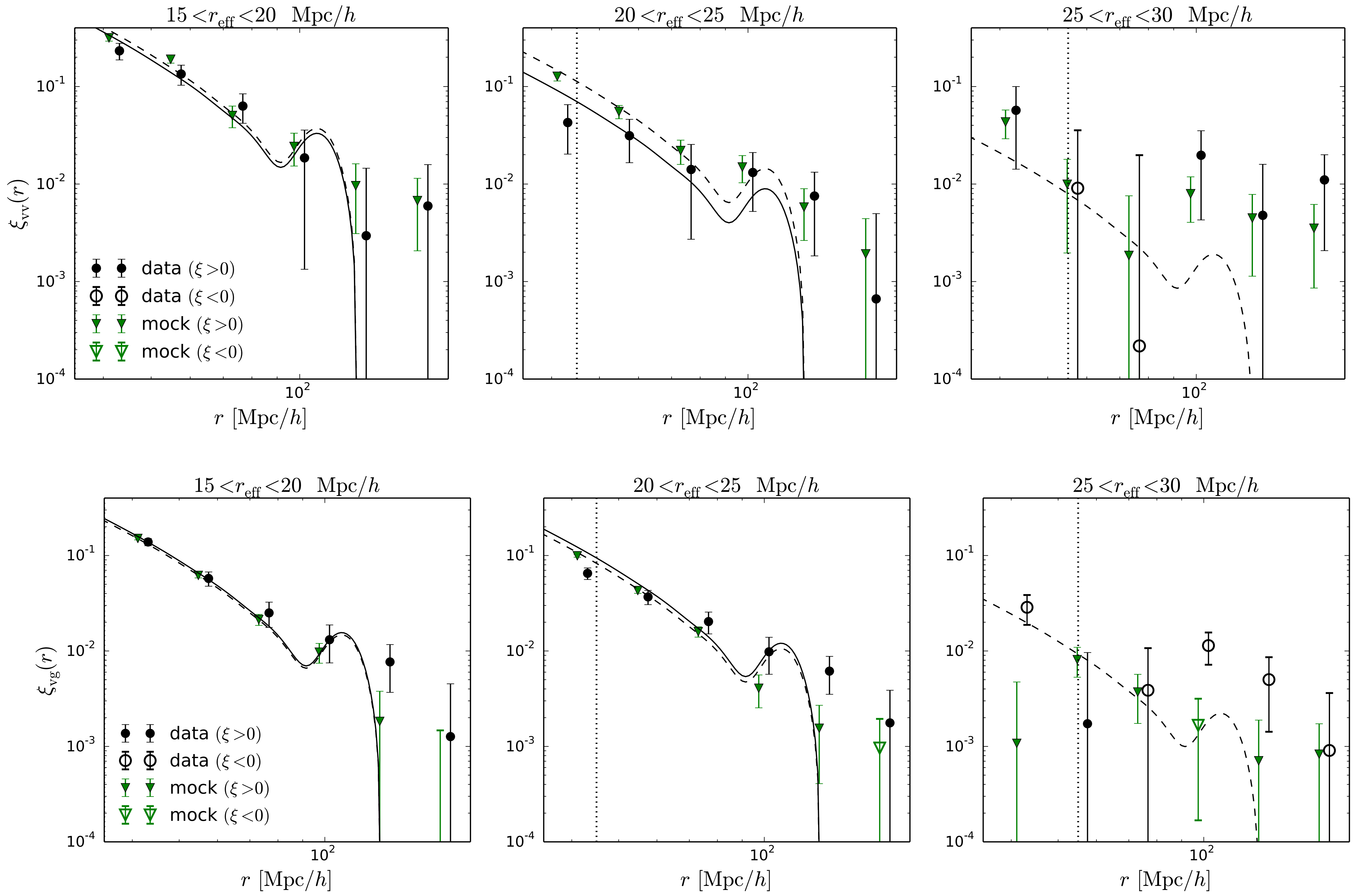


Cautun et al. (2018)

Voids has tracer of the matter field

Clampitt 2016

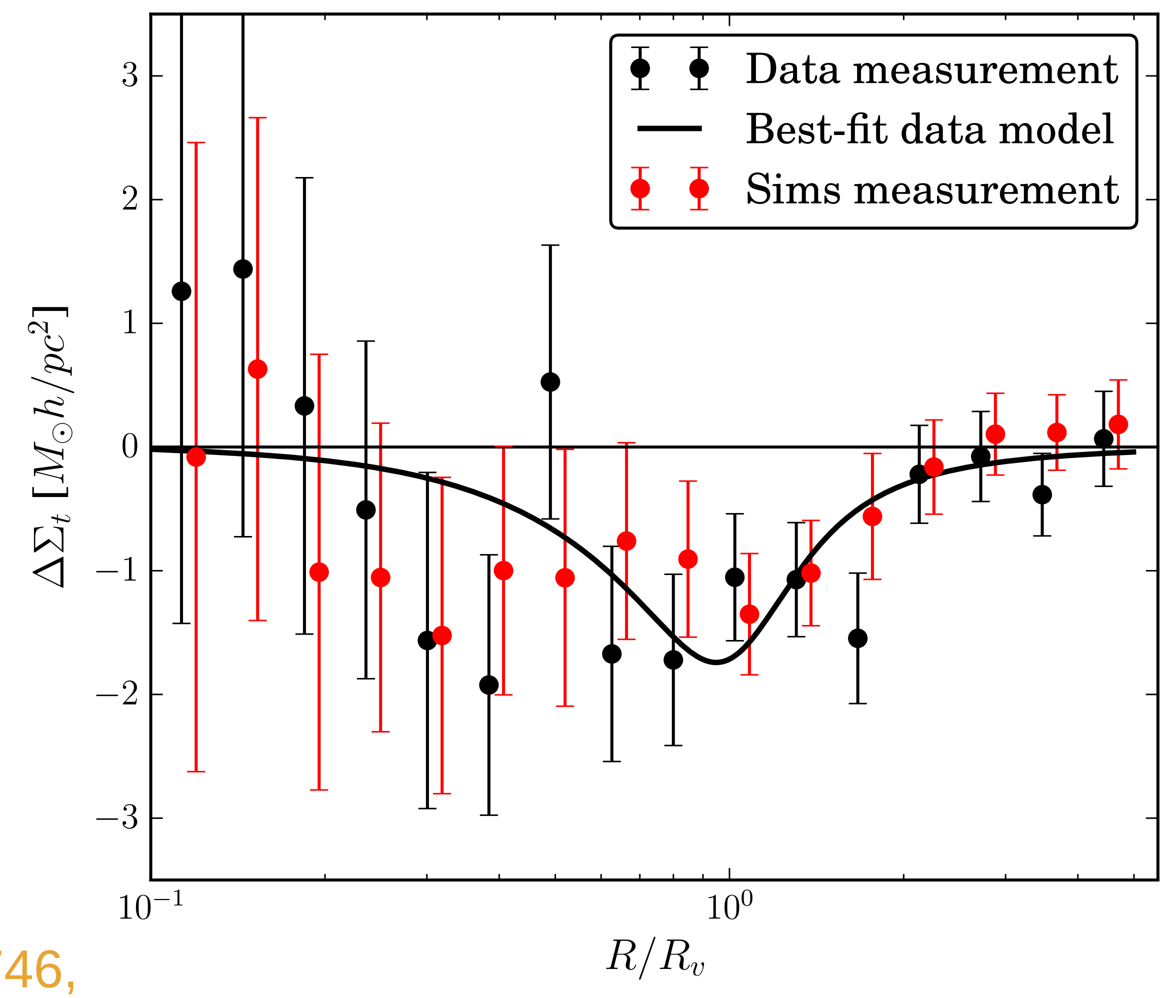
$$\xi(r) = \frac{DD(r) - DR(r) - RD(r) + RR(r)}{RR(r)},$$



Gravitational lensing of cosmic voids

The *tangential shear* γ_+ of background galaxies (sources) induced by voids (lenses) is a direct probe of the excess surface mass density $\Delta\Sigma$ around voids, defined as

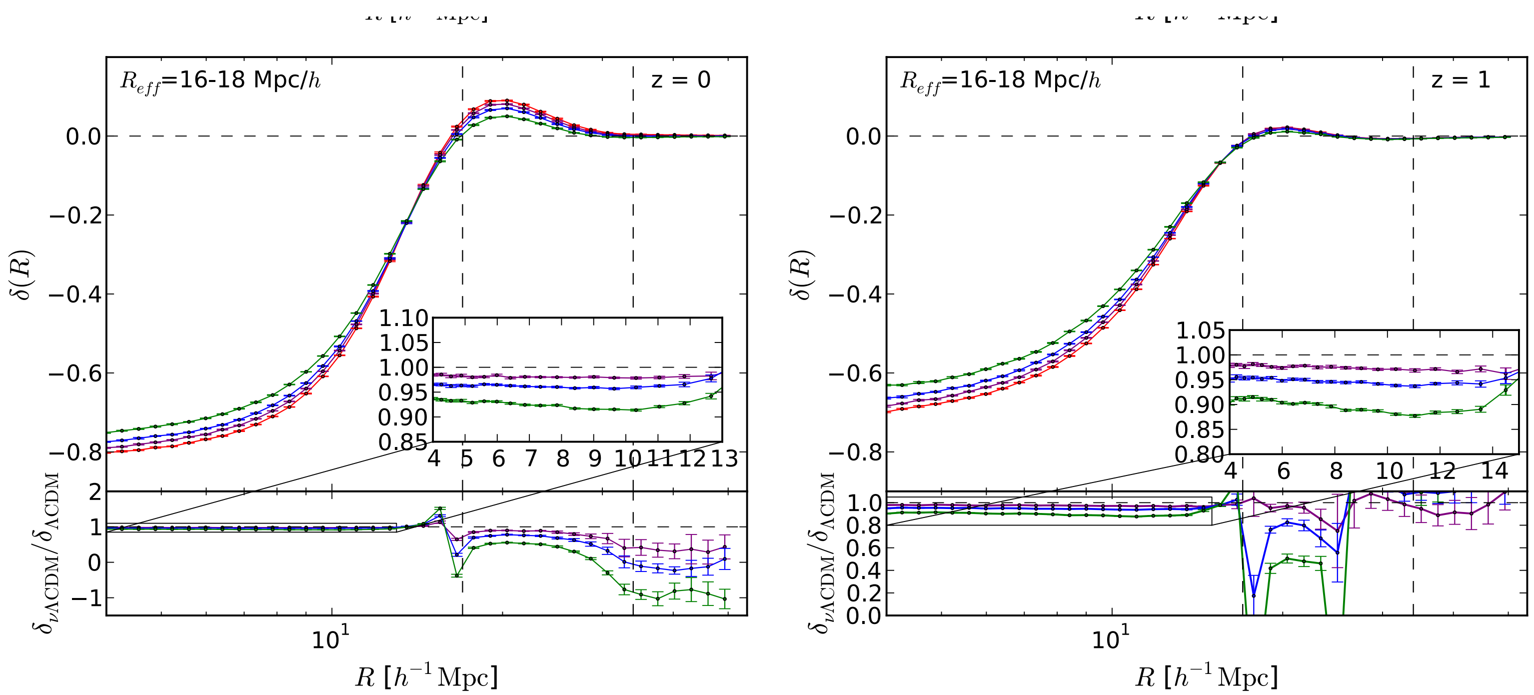
$$\Delta\Sigma(r_p/R_v) \equiv \overline{\Sigma}(< r_p/R_v) - \Sigma(r_p/R_v) = \Sigma_{\rm crit}\,\gamma_+(r_p/R_v)\,, \qquad (1)$$



Sánchez et al. (DES Collaboration), MNRAS 465, 746, 2017.

So adding lensing + clustering information from cosmic void can also be considered

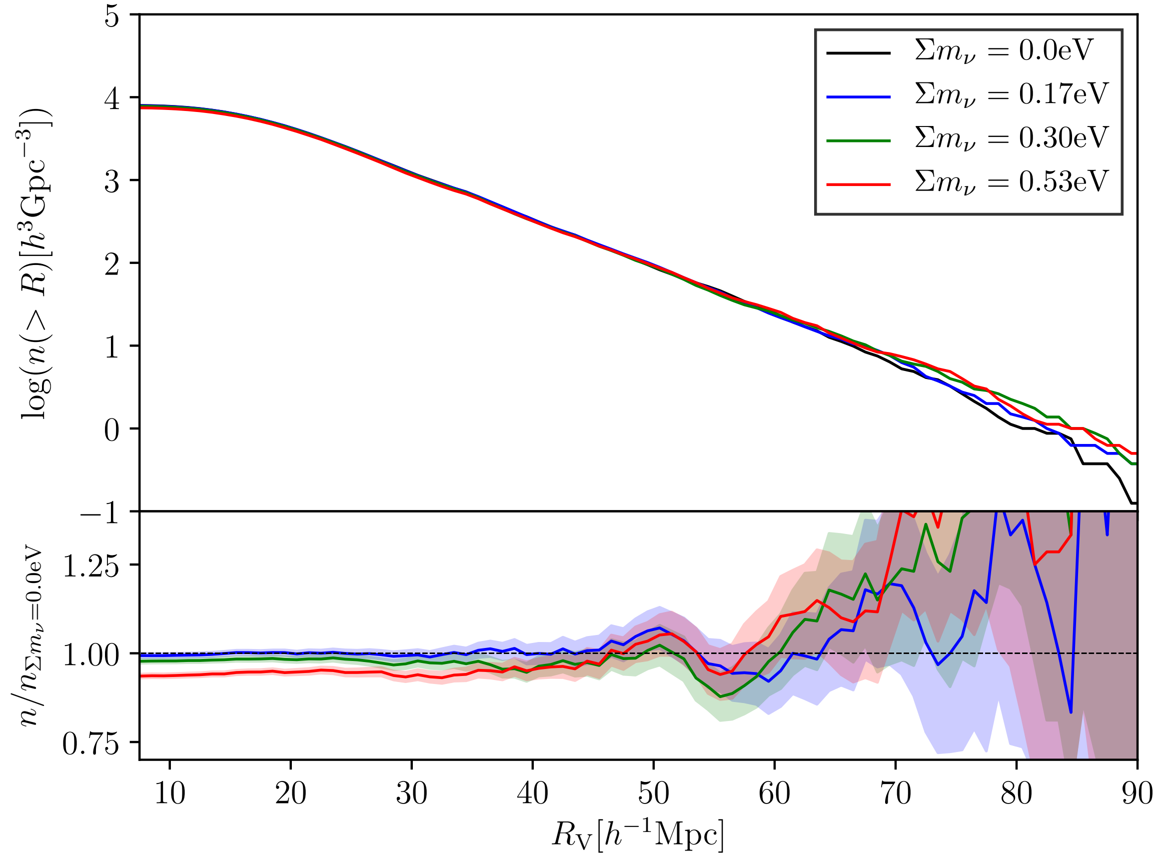
Voids and massive neutrinos



Massara et al. 2015

Intuitively, the neutrino field being less clustered with respect to the matter field (CDM and baryons) we expect the ratio between matter and neutrino to be higher at the maximum of the potential field, that is to say in cosmic voids.

Kreisch, 2019

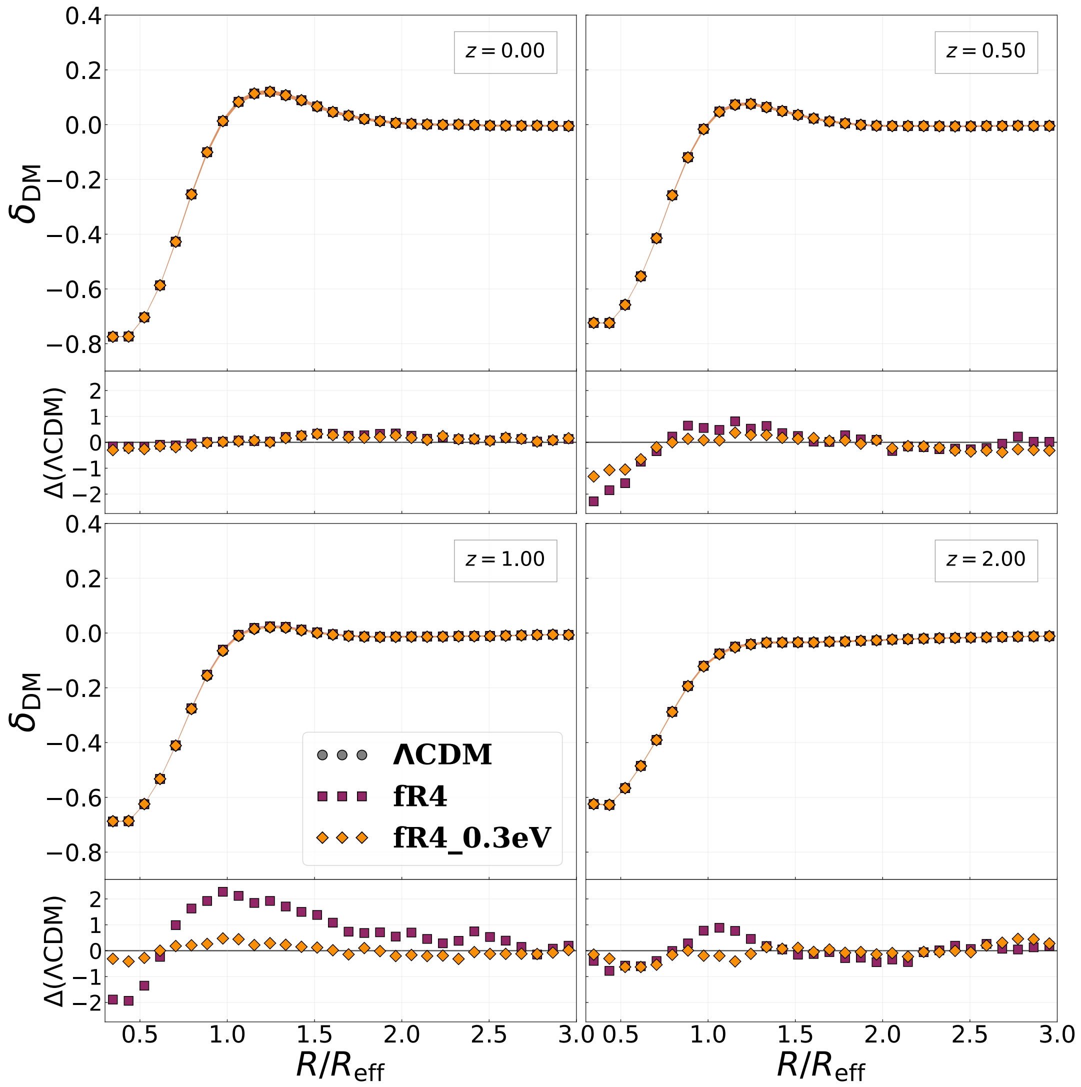


Voids and alternative cosmologies

voids are by definition 'matter less' , corresponding then to really large zone where matter domination is down

-> good target to study Dark Energy

Contarini et al (2020)

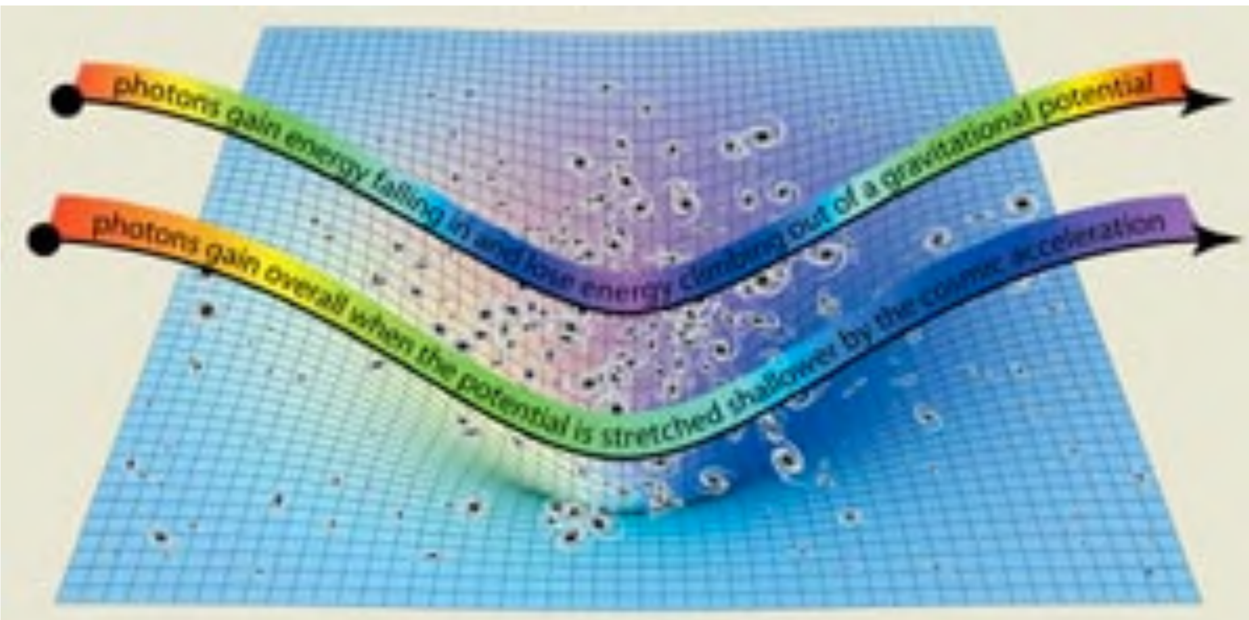


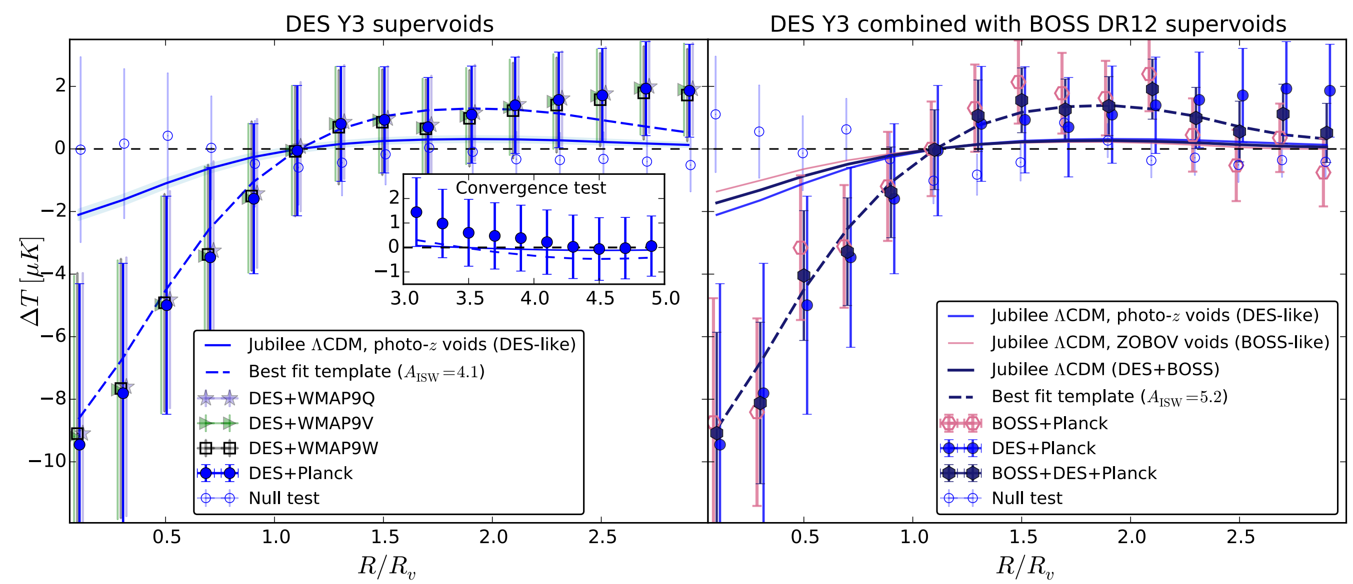
Example modified gravity models

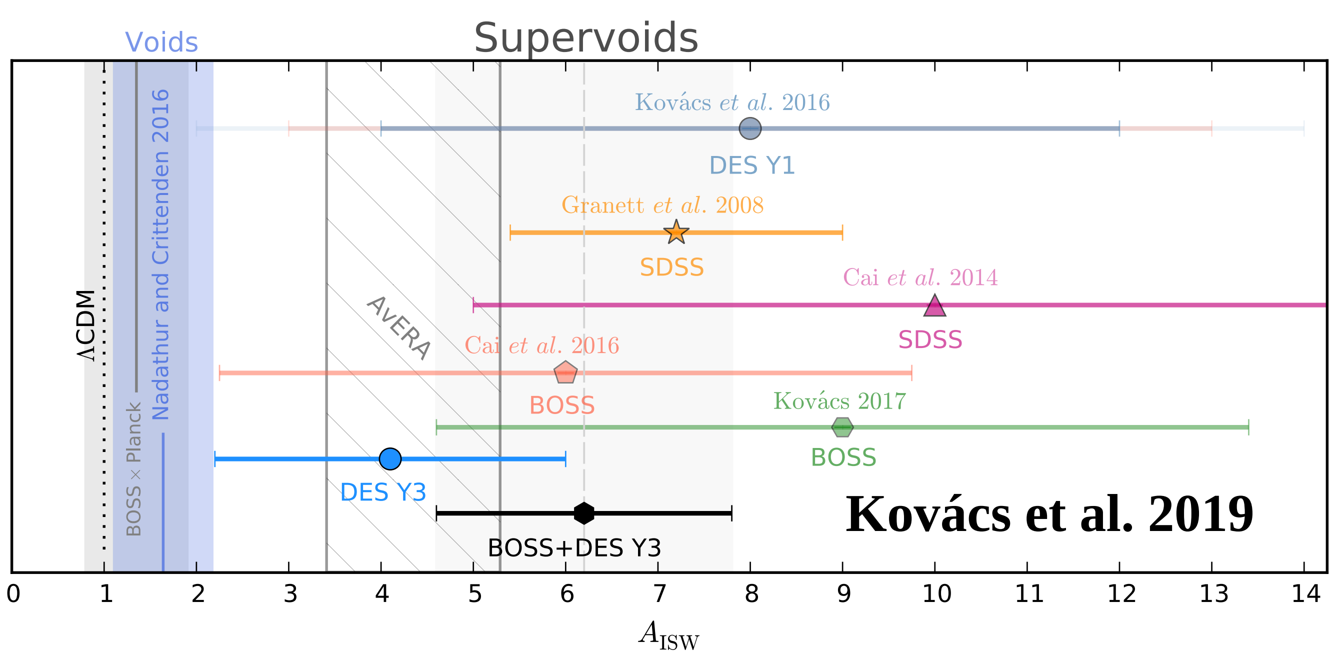
screening mechanisms operate weakly within cosmic voids, making them potentially more affected by the possible deviations from GR

Voids still unexplained: ISW

$$\Theta = \frac{\Delta T}{T_{\rm CMB}} = -\frac{2}{c^3}\int_0^{\chi_{\rm CMB}} {\rm d}\chi \frac{\partial \Phi}{\partial \chi}.$$







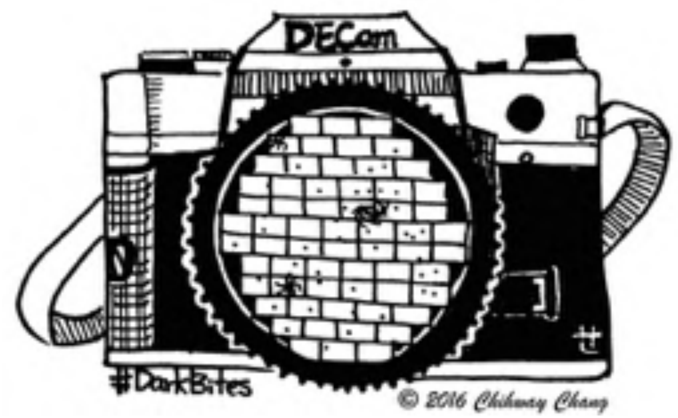
The Dark Energy Survey Camera

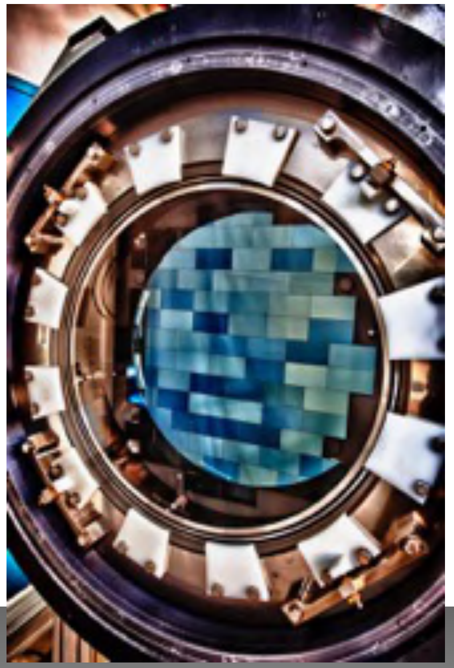
Imaging galaxy survey.

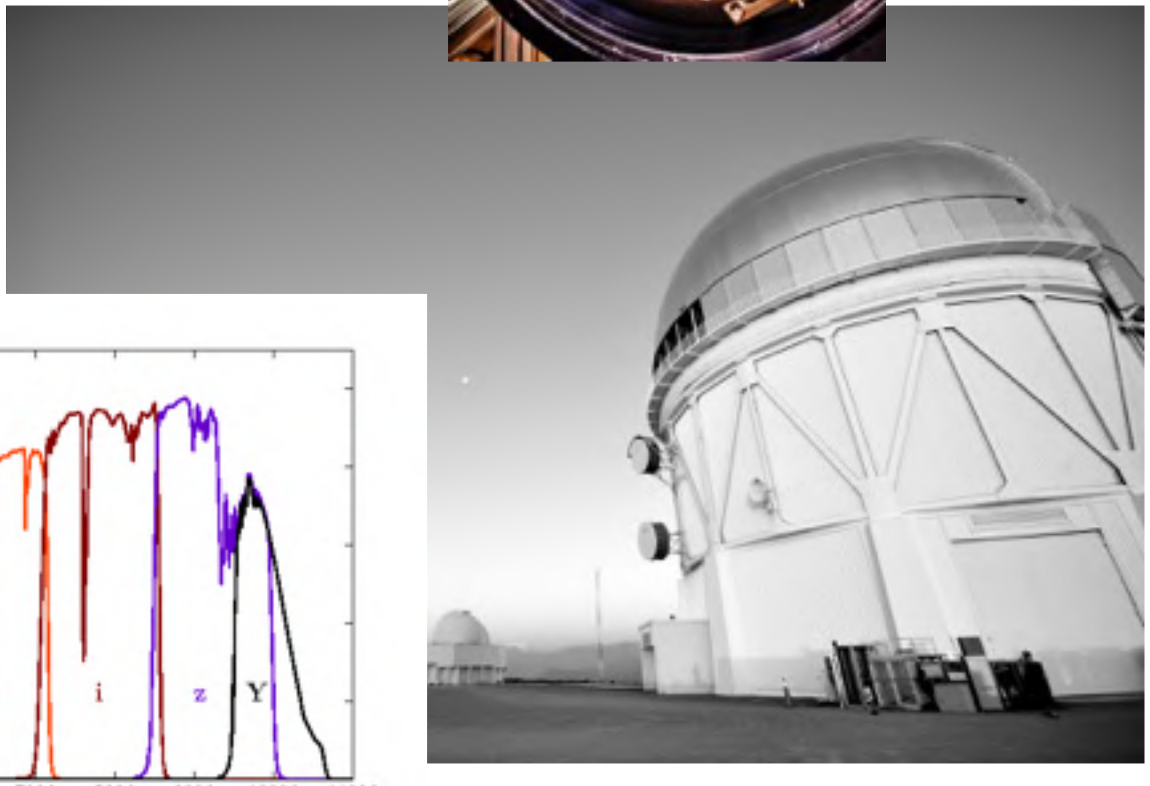
5000 sq. deg. after 6 years (2013-2019)

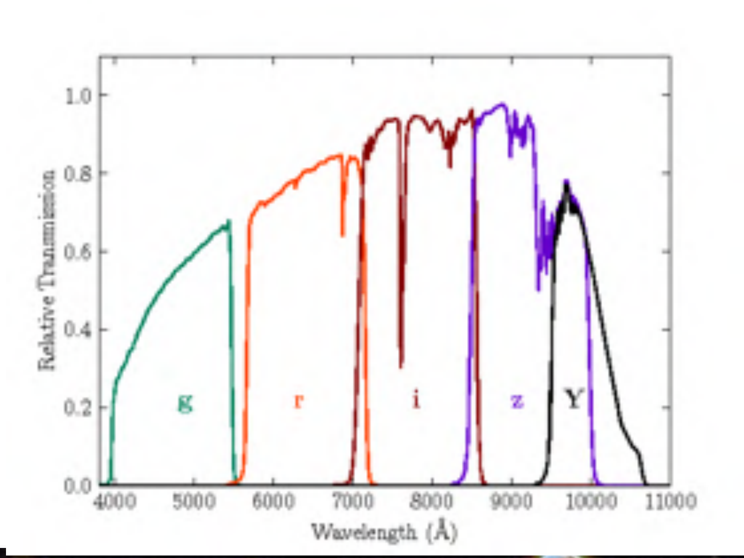
570-Megapixel digital camera, DECam, mounted on the Blanco 4-meter telescope at Cerro Tololo Inter-American Observatory (Chile).

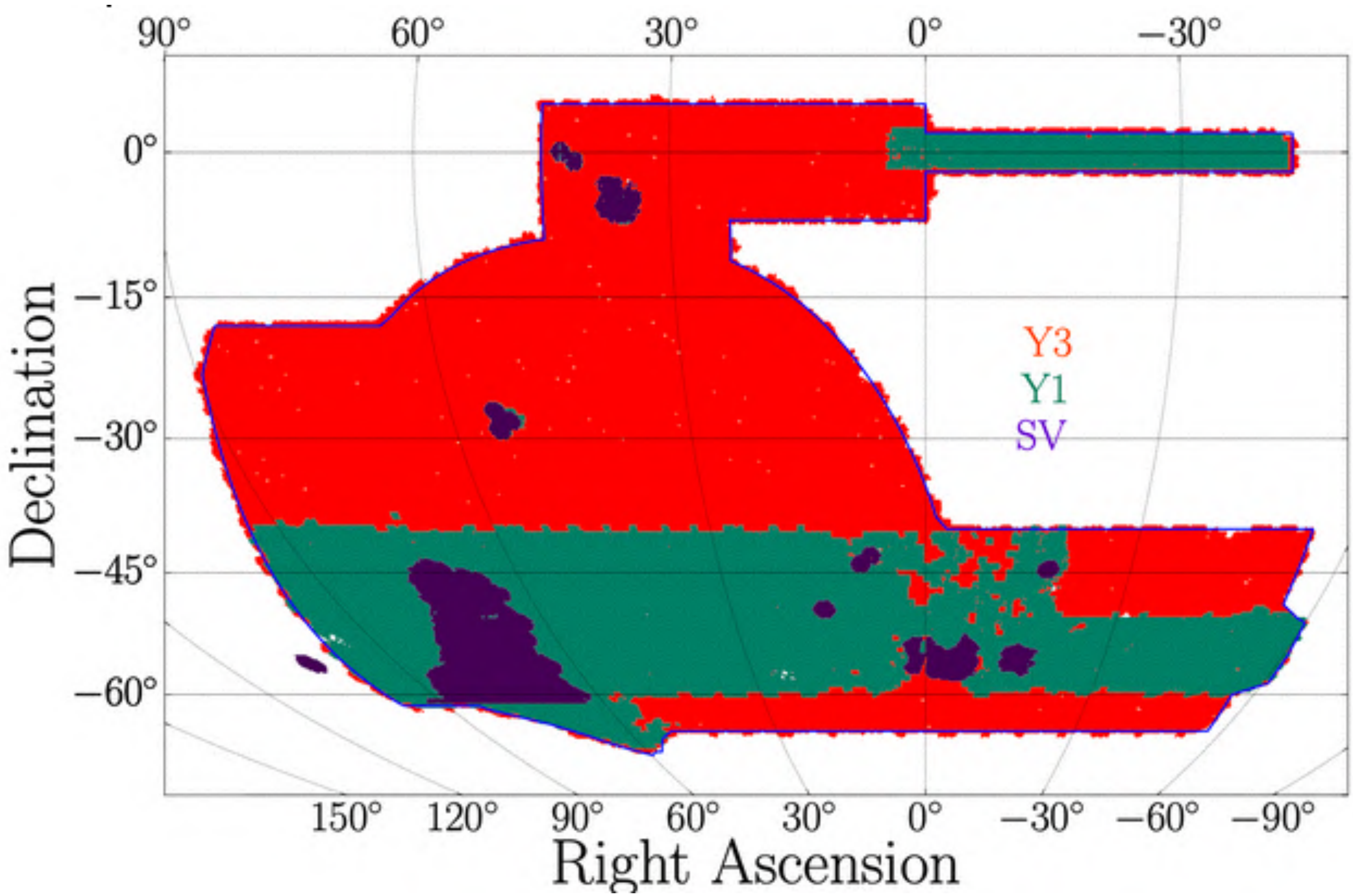
Five filters are used (grizY) with a nominal limiting magnitude $i_{AB} \simeq 24$ and with a typical exposure time of 90 sec for griz and 45 sec for Y

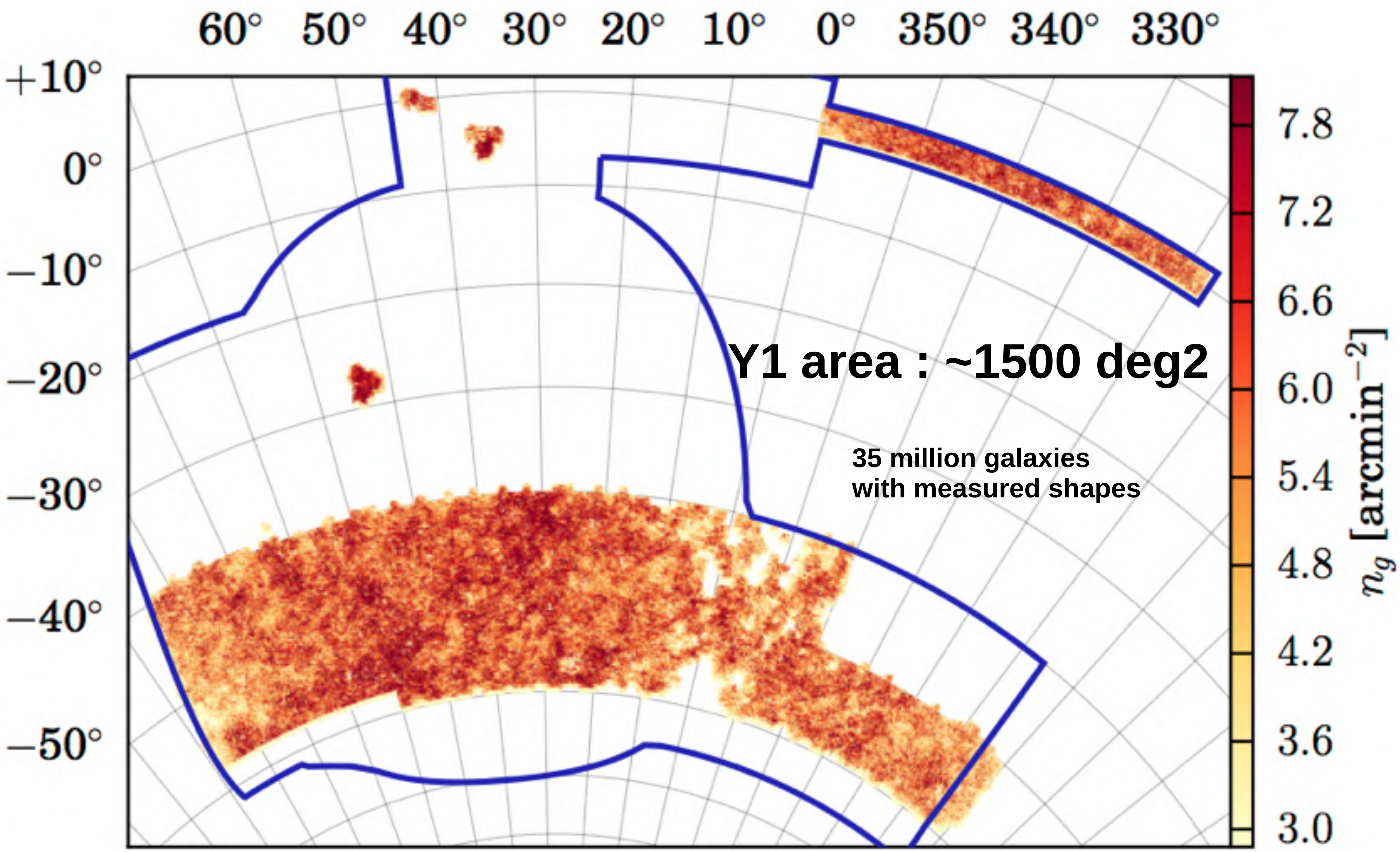









90°
60°
30°
0°
−30°
0°
−15°
−30°
−45°
−60°
Declination
Y3
Y1
SV
150°
120°
90°
60°
30°
0°
−30°
−60°
−90°
Right Ascension

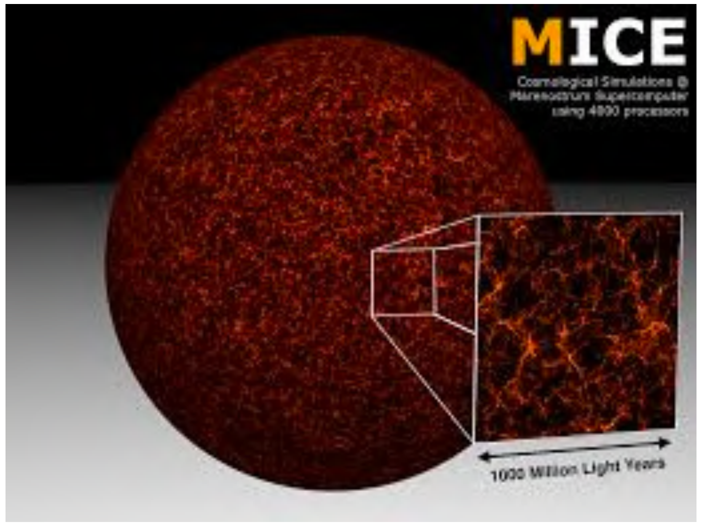

60° 50° 40° 30° 20° 10° 0° 350° 340° 330°
+10°
0°
−10°
−20°
−30°
−40°
−50°
7.8
7.2
6.6
6.0
5.4
4.8
4.2
3.6
3.0
n_g [arcmin^{-2}]
Y1 area : ~1500 deg2
35 million galaxies
with measured shapes

Dark Energy Survey Year 1 Results: the lensing imprint of cosmic voids on the Cosmic Microwave Background

P. Vielzeuf[1,2,3*] A. Kovács[1,4,5†], U. Demirbozan[1], P. Fosalba[6,7], E. Baxter[8], N. Hamaus[9], D. Huterer[10], R. Miquel[11,1], S. Nadathur[12], G. Pollina[9], C. Sánchez[8], L. Whiteway[13], T. M. C. Abbott[14], S. Allam[15], J. Annis[15], S. Avila[16], D. Brooks[13], D. L. Burke[17,18], A. Carnero Rosell[19,20], M. Carrasco Kind[21,22], J. Carretero[1], R. Cawthon[23], M. Costanzi[24,25], L. N. da Costa[20,26], J. De Vicente[19], S. Desai[27], H. T. Diehl[15], P. Doel[13], T. F. Eifler[28,29], S. Everett[30], B. Flaugher[15], J. Frieman[15,31], J. García-Bellido[16], E. Gaztanaga[6,7], D. W. Gerdes[32,10], D. Gruen[33,17,18], R. A. Gruendl[21,22], J. Gschwend[20,26], G. Gutierrez[15], W. G. Hartley[13,34], D. L. Hollowood[30], K. Honscheid[35,36], D. J. James[37], K. Kuehn[38,39], N. Kuropatkin[15], O. Lahav[13], M. Lima[40,20], M. A. G. Maia[20,26], M. March[8], J. L. Marshall[41], P. Melchior[42], F. Menanteau[21,22], A. Palmese[15,31], F. Paz-Chinchón[21,22], A. A. Plazas[42], E. Sanchez[19], V. Scarpine[15], S. Serrano[6,7], I. Sevilla-Noarbe[19], M. Smith[43], E. Suchyta[44], G. Tarle[10], D. Thomas[12], J. Weller[45,46,9], J. Zuntz[47]

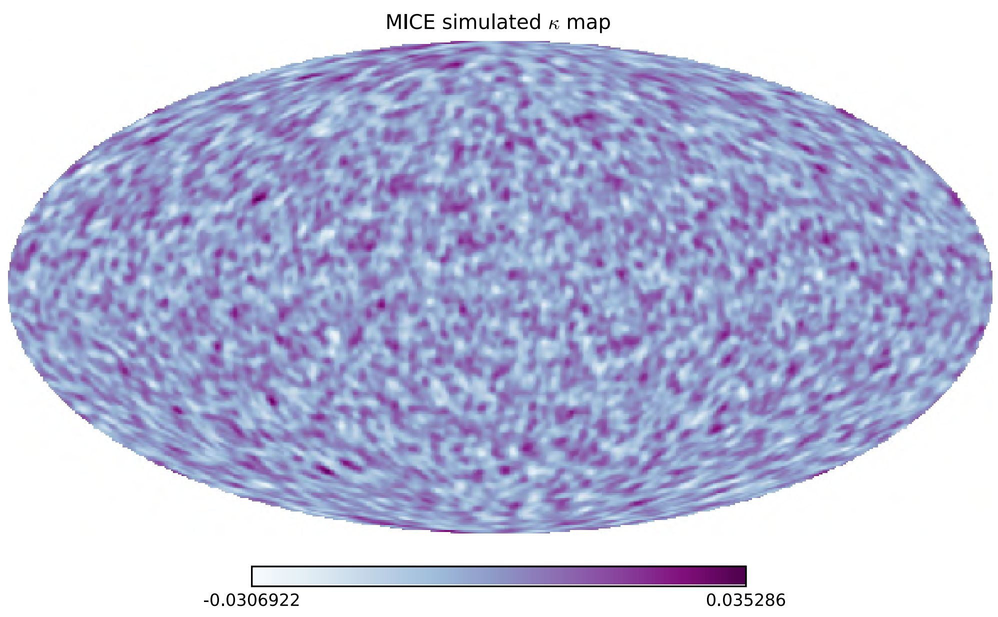
(THE DES COLLABORATION)

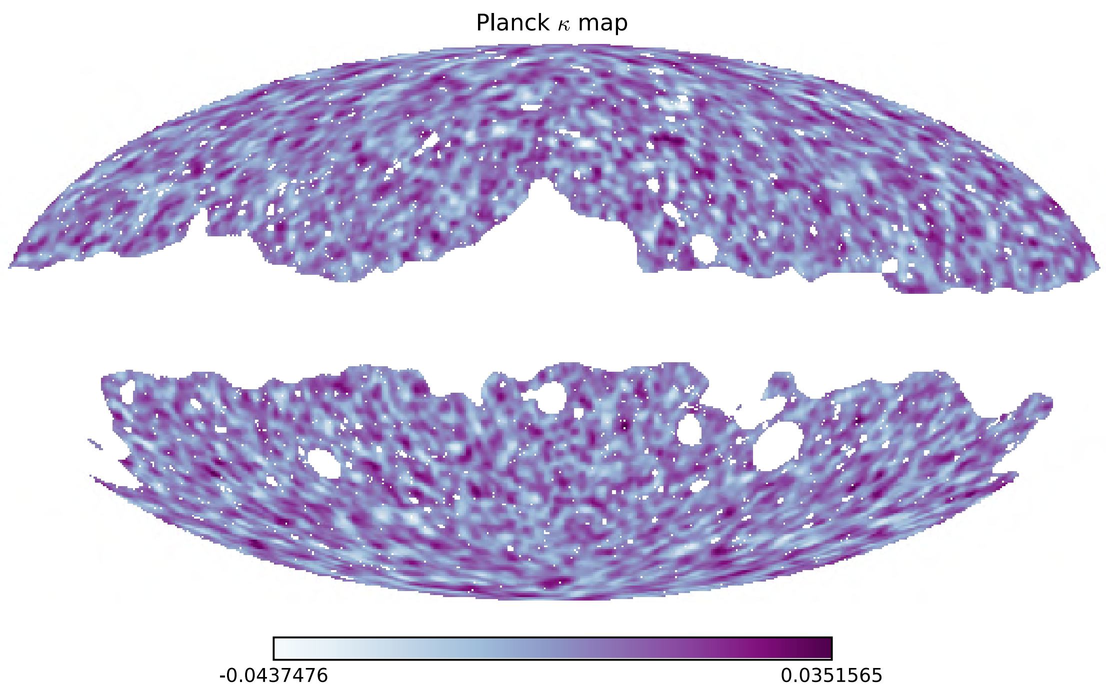
Author affiliations are listed at the end of this paper



Comparison with MICE simulation

Goal : compare the correlation signal of cosmic voids with CMB lensing in simulation with DES observations





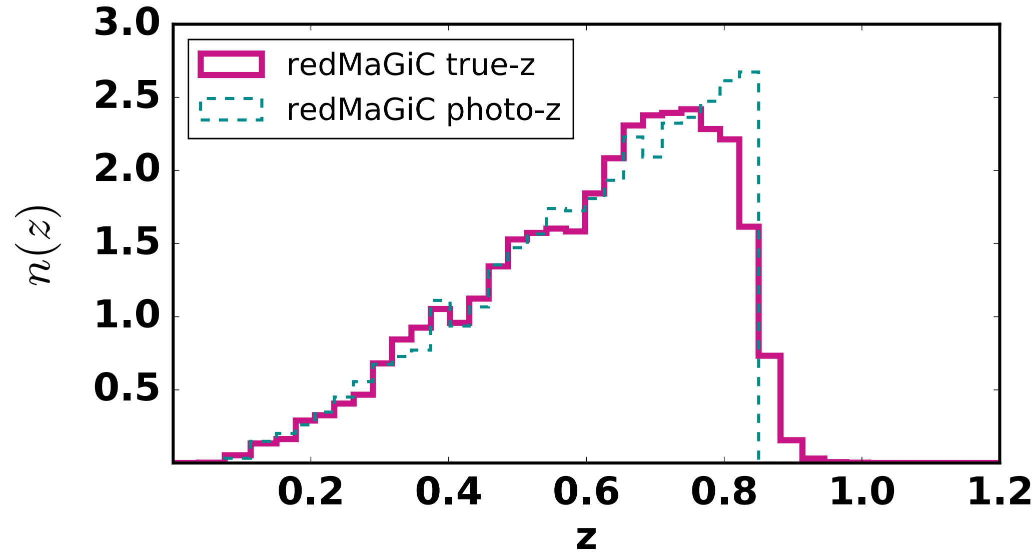
flat standard ΛCDM

$$\Omega_m = 0.25, \Omega_\Lambda = 0.75, \Omega_b = 0.044,$$

$$\sigma_8 = 0.8 \text{ and } h = 0.7$$

Planck 2015 results. XV. (2016)

Tracer of the matter field : RedMagic Galaxies

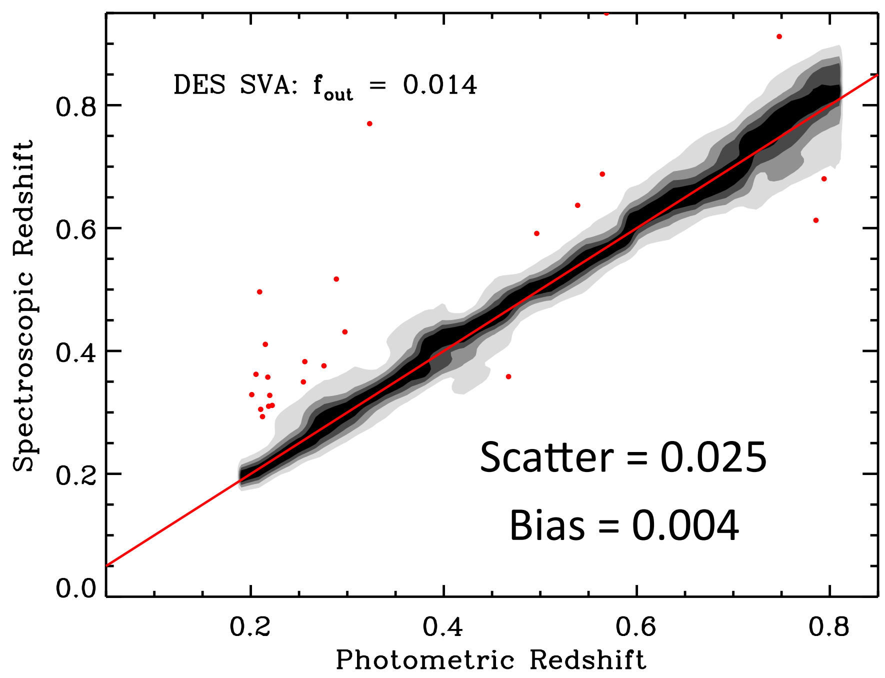


redMaGiC algorithm is designed to select luminous red galaxies with high quality photometric redshift estimates (Rozo + 2016)

0.15<z<0.85

DES redMaGiC galaxies

$\sigma_z \sim 0.02$



z range	$L_{\rm min}/L_*$	$n_{\rm gal}$ (deg^{-2})	$N_{\rm gal}$
$0.15 < z < 0.3$	0.5	0.0134	63719
$0.3 < z < 0.45$	0.5	0.0344	163446
$0.45 < z < 0.6$	0.5	0.0511	240727
$0.6 < z < 0.75$	1.0	0.0303	143524
$0.75 < z < 0.9$	1.5	0.0089	42275

Finding the voids

- **Divide the sample in redshift slices. 100*Mpc/h* slices are shown to be a good compromise considering *photometric* redshift accuracy.**

- **Compute the density field for each slice by counting the galaxy number in each pixel and smoothing the field with a Gaussian with a predefined smoothing scale.**

- **Select the most underdense pixel and grow around it the void until it reaches the mean density.**

- **Save the void, erase it from the density map and iterate the process with the following underdense pixel.**

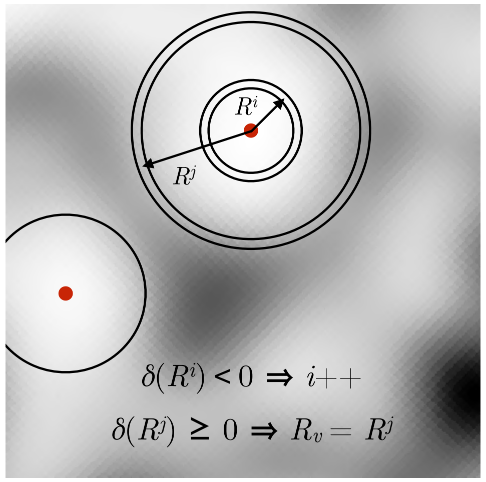
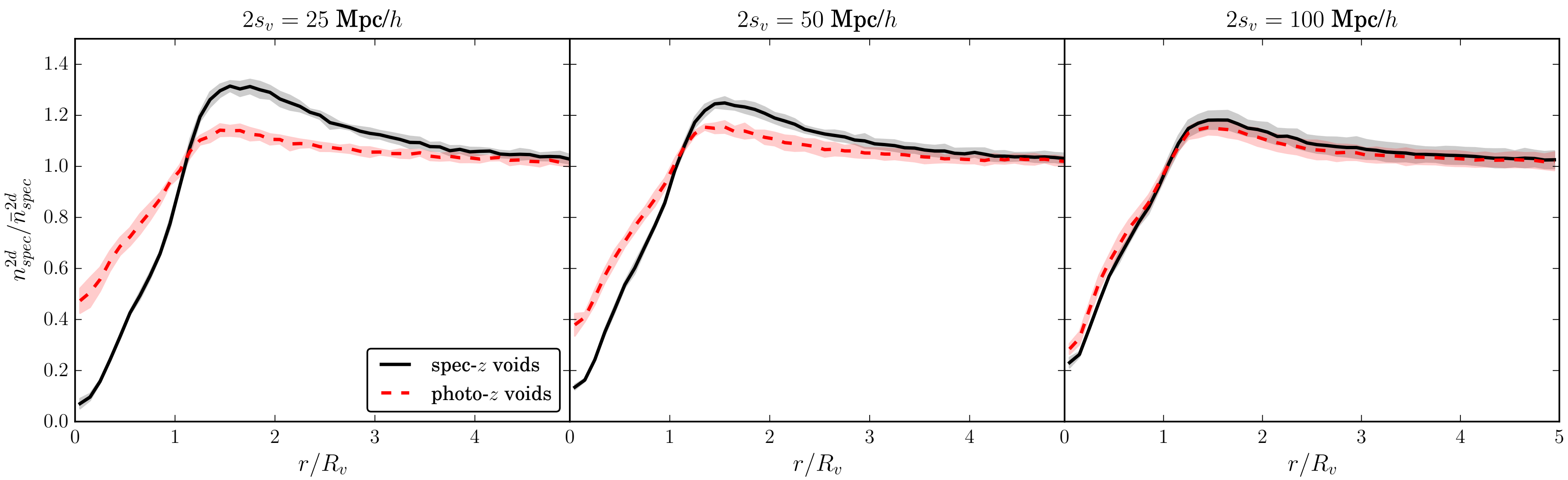
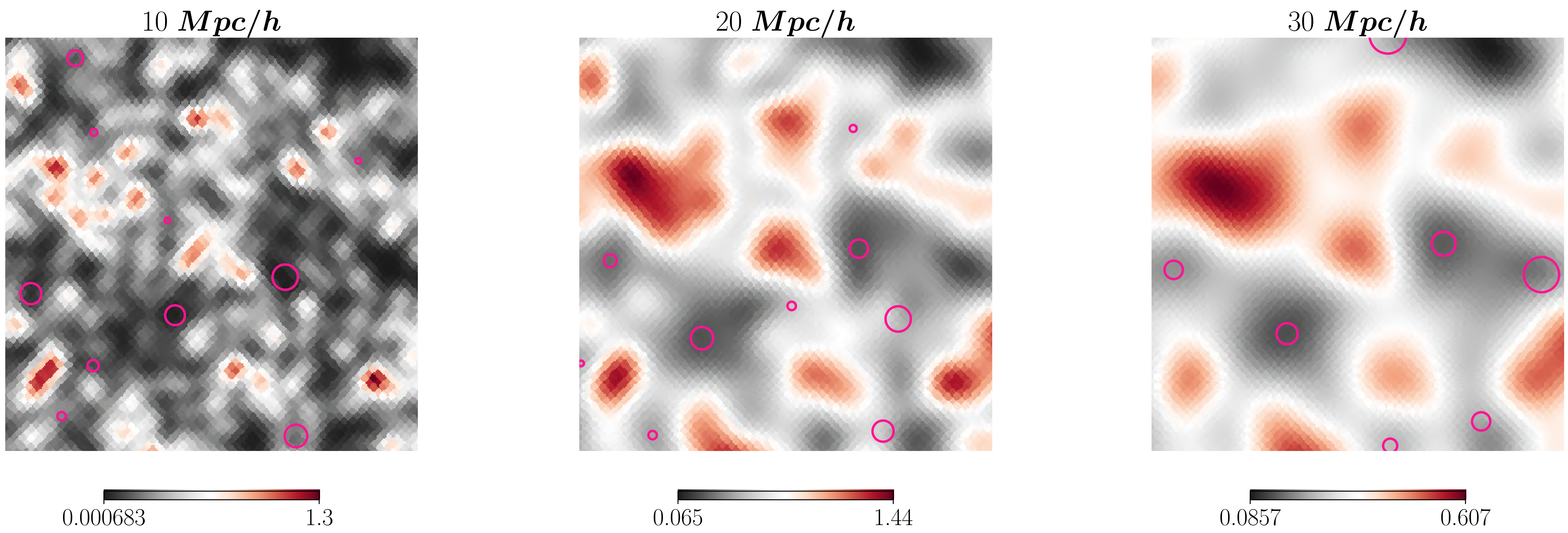


Figure 1. Graphical description of the void-finding algorithm presented in this paper. The background gray-scaled field is the smoothed galaxy field ($\sigma = 10$ Mpc$/h$) in a redshift slice used by the void-finder. The two solid (red) dots show two void centers. For the upper void, we show a circular shell or radius R^i. Since the density contrast $\delta(R^i) < 0$, the algorithm checks larger shells, up to radius R^j such that $\delta(R^j) \geqslant 0$. The void radius is then defined as $R_v = R^j$.

Sánchez et al. (DES Collaboration), MNRAS 465, 746, 2017.

Impact on the finder parameters





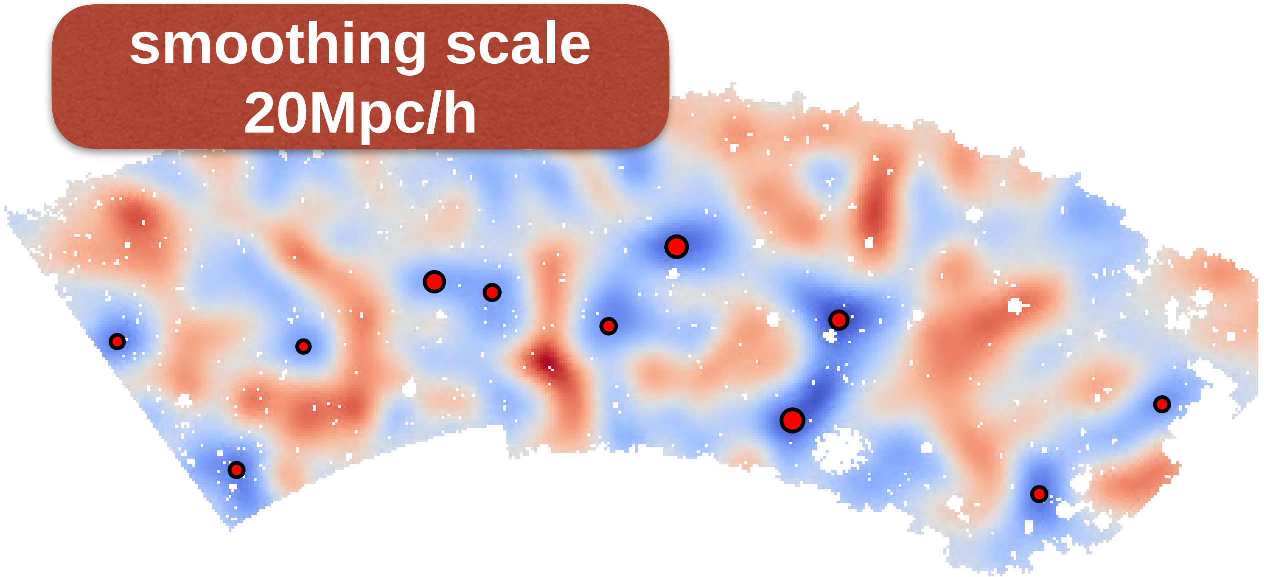
Finding the voids

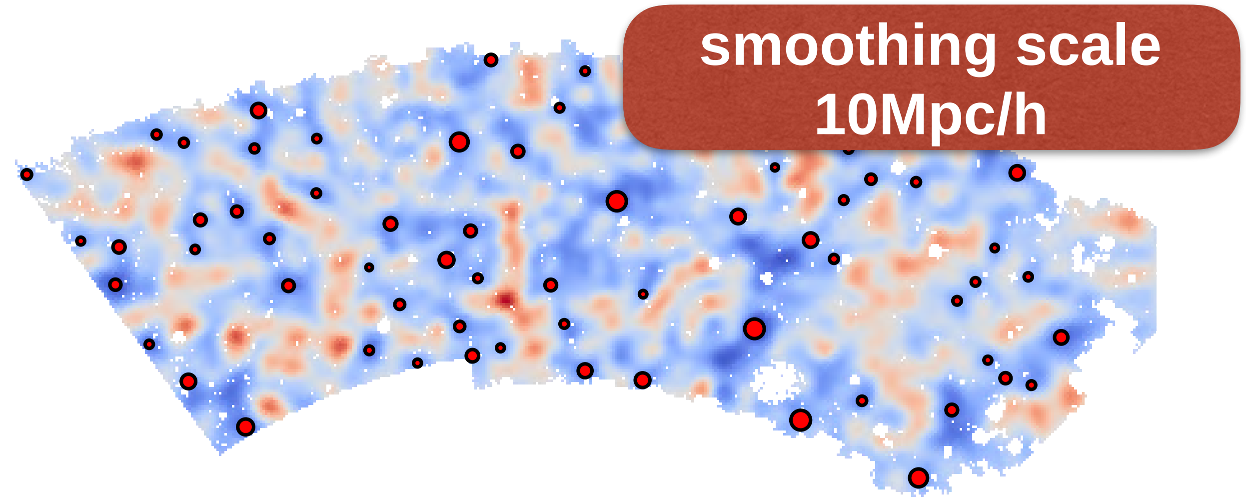
Two tracers :

- RedMagiC High-luminosity sample
- RedMagiC High-density sample

Two smoothing scales:
10 Mpc/h
20 Mpc/h

4 void catalogs





Catalog comparison

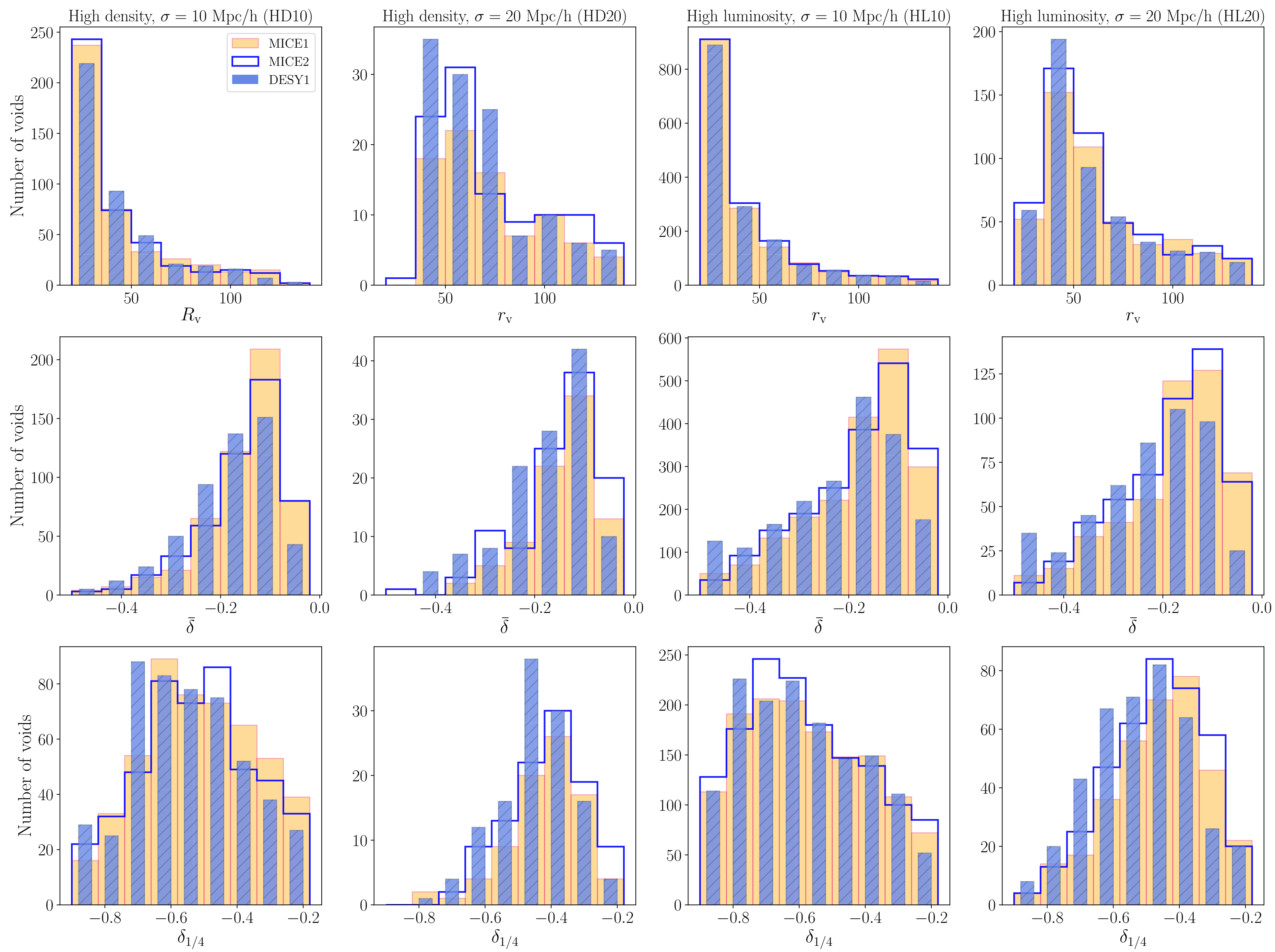
High luminosity (HL)

Smoothing	DES Y1	MICE 1	MICE 2
10 Mpc/h	1218	1158	1219
20 Mpc/h	411	364	400

High density (HD)

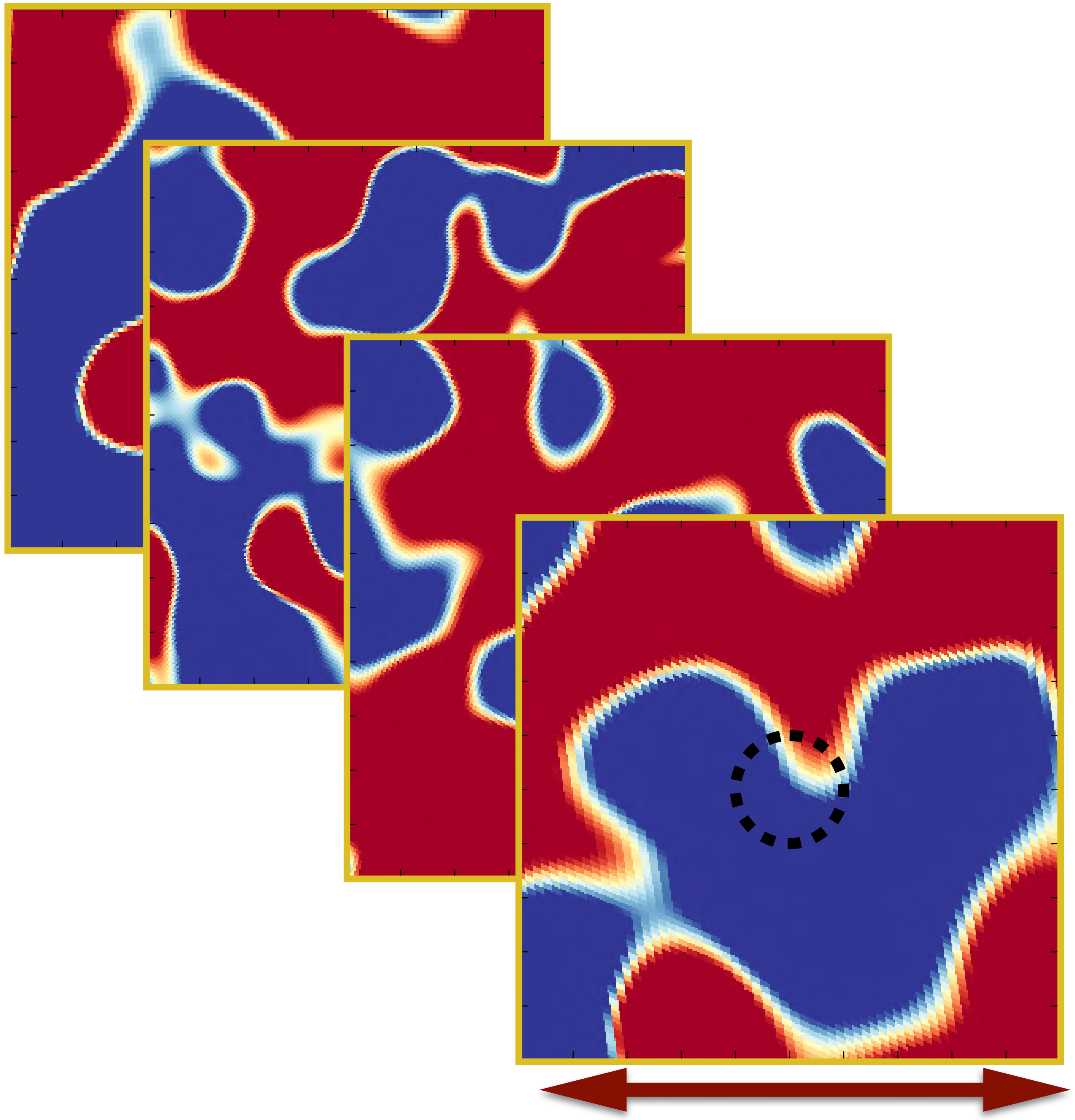
Smoothing	DES Y1	MICE 1	MICE 2
10 Mpc/h	518	521	495
20 Mpc/h	122	85	106

`VIDE`	DES Y1	MICE
All	7383	36115
Pruned	239	1687



Correlation methodology

Grannett et al., 2008

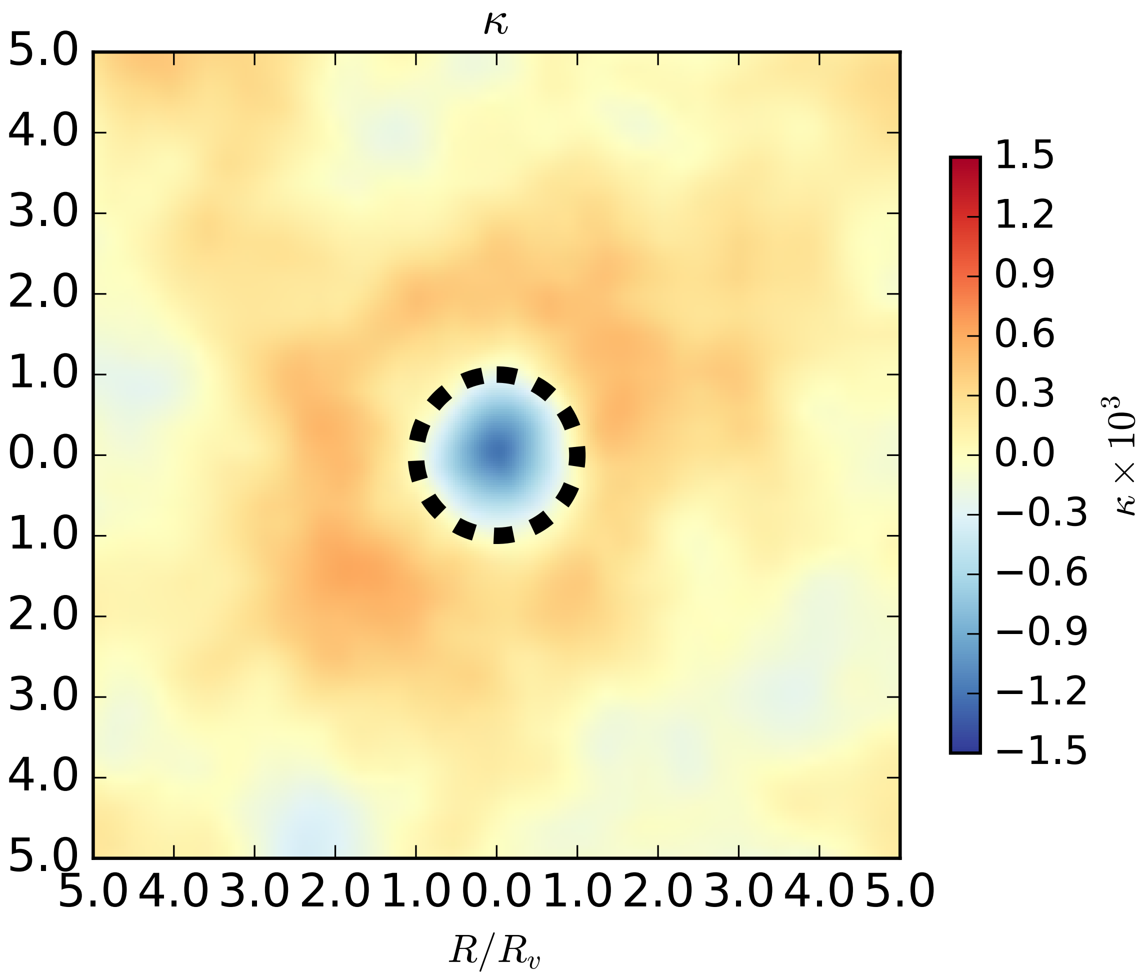


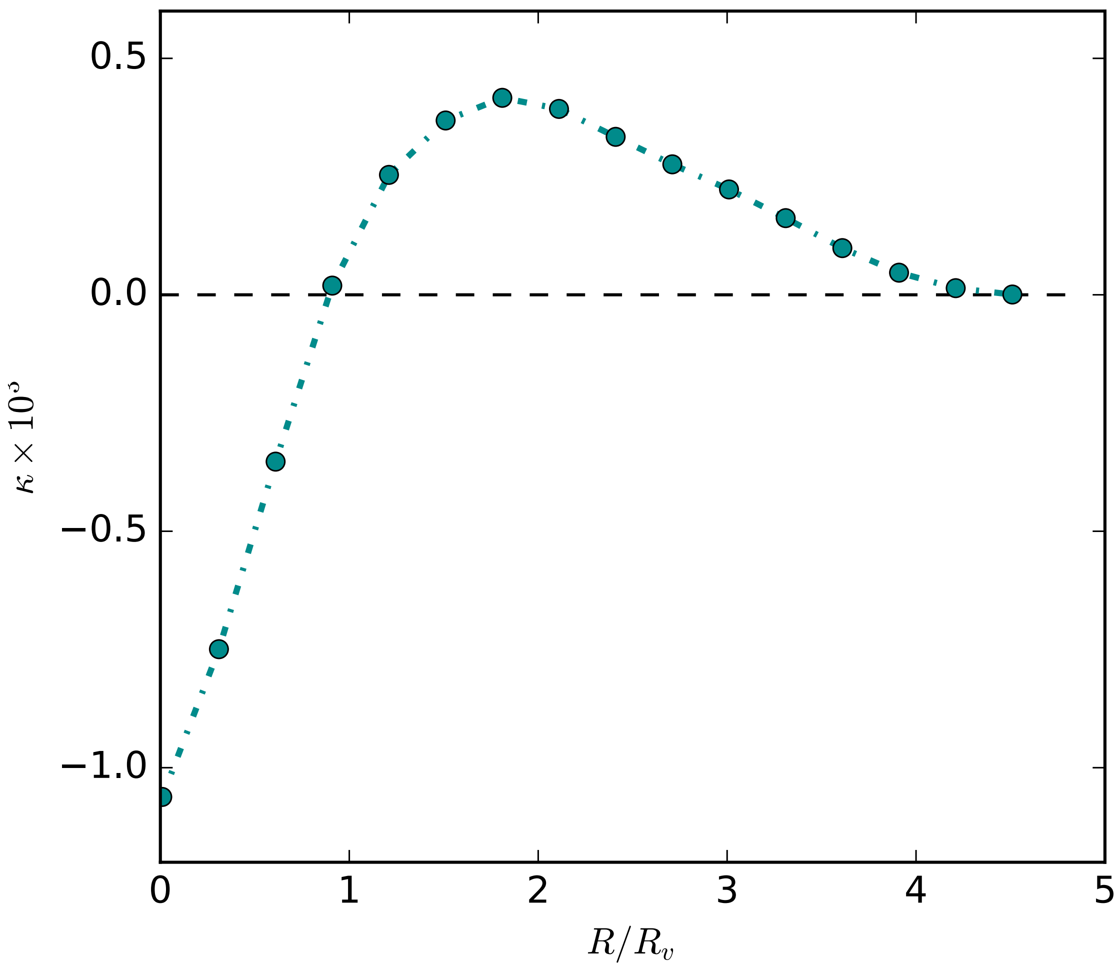
5 times the structure radius

- Cutting out patches of the CMB map centered at superstructure position using healpix (Górski et al., 2005).
- Re-scaling the patches given the angular size of the structure.
- Stacking all patches and measuring the average signal in different concentric radius bins around the center.

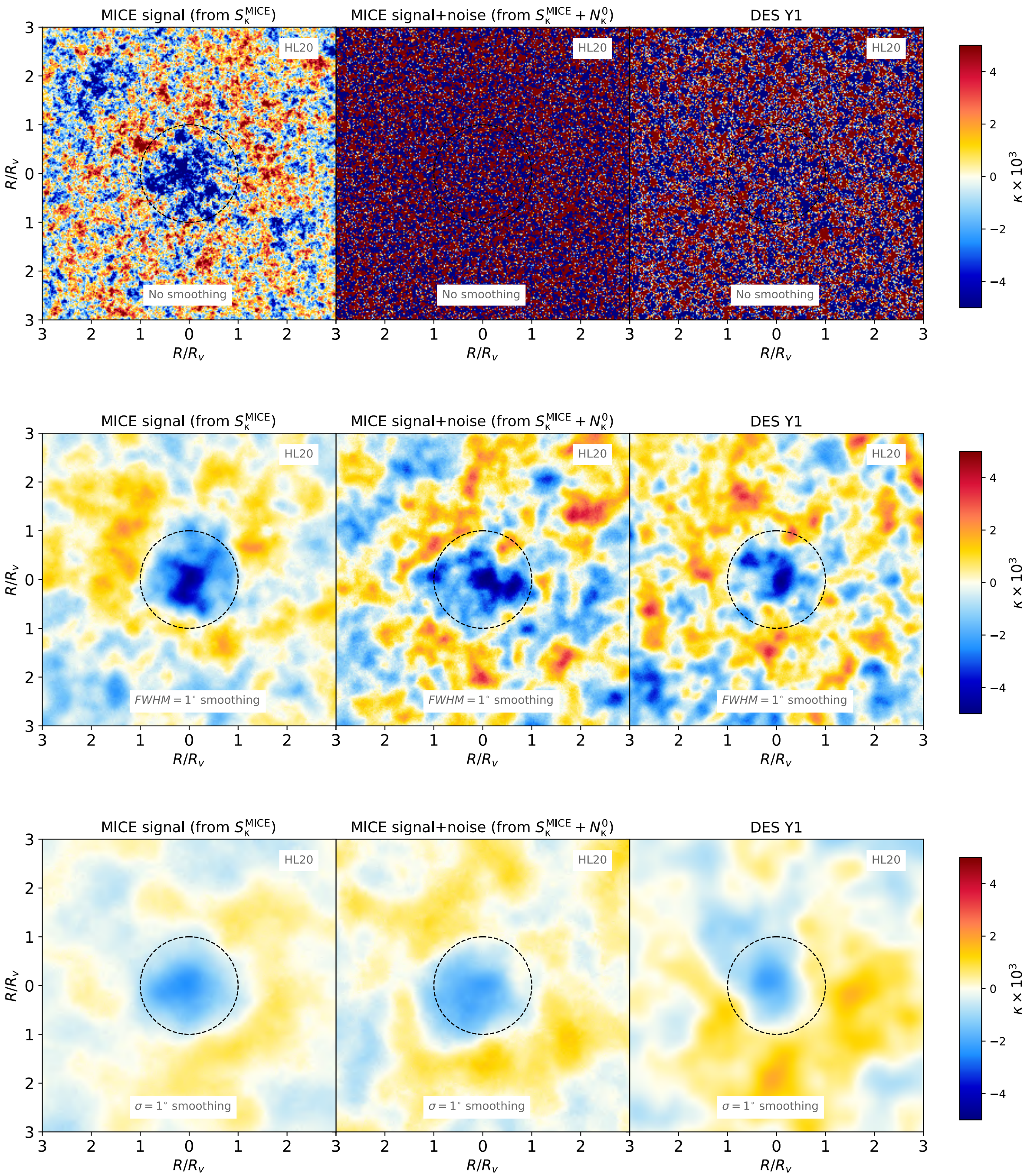
Correlation signal

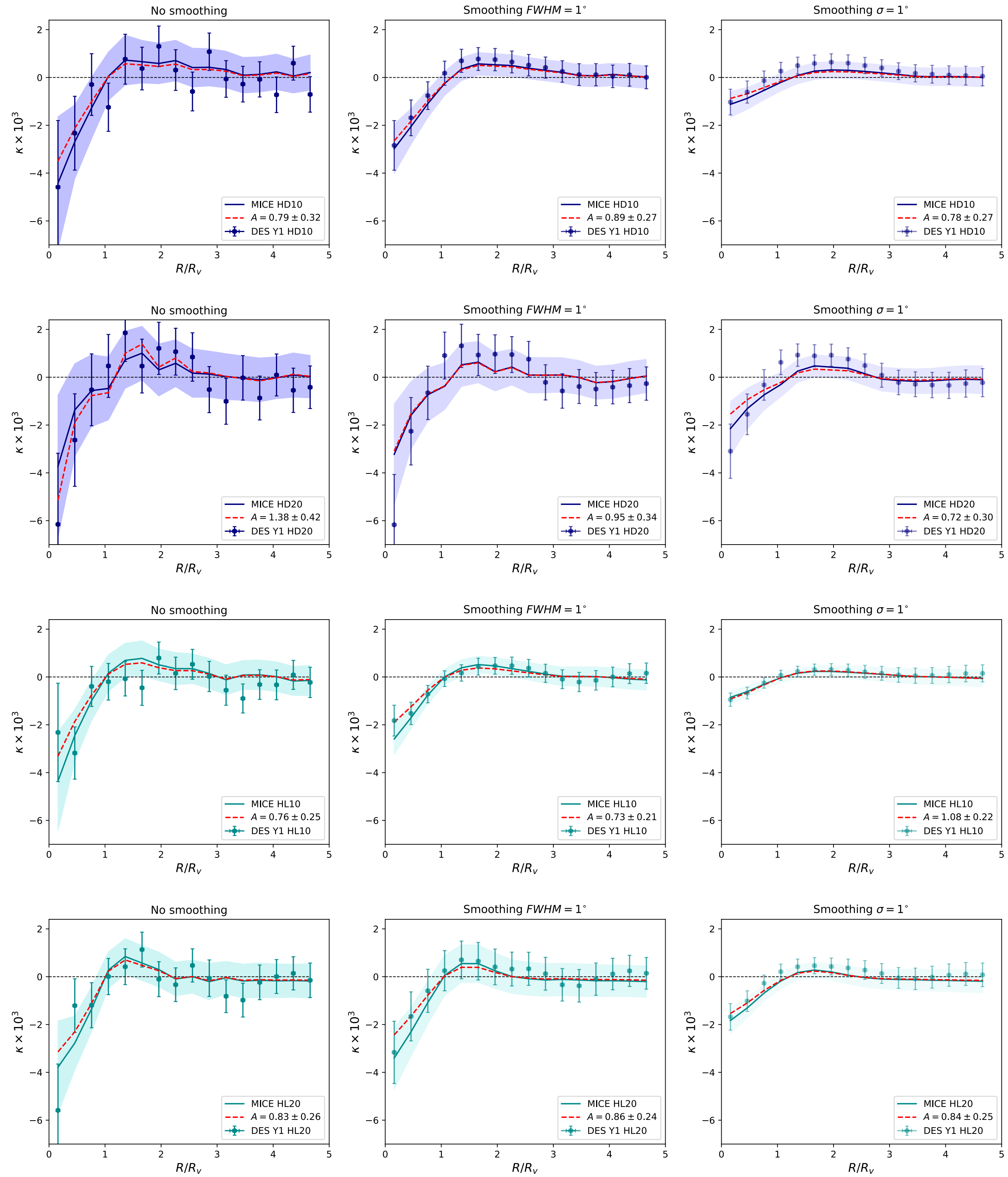
Stacked Healpix image → **CMB convergence profile**



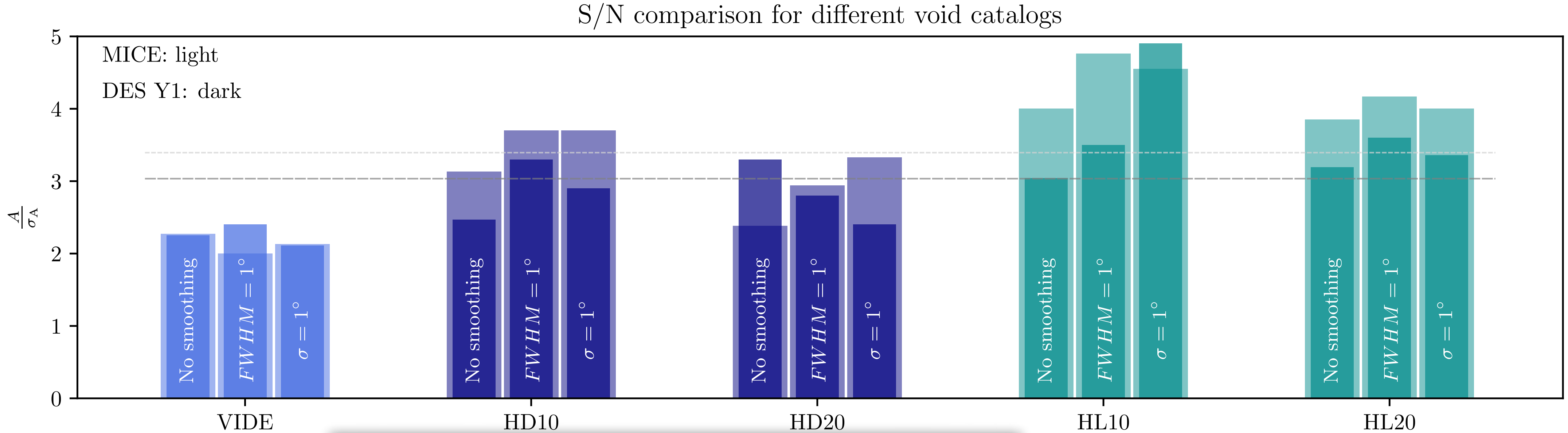


Correlation signal





Results



No smoothing

Catalogue	VIDE	HD10	HD20	HL10	HL20
MICE	2.27	3.13	2.38	4.00	3.85
DES Y1	2.25	2.47	3.29	3.04	3.36

***FWHM*= 1° smoothing**

Catalogue	VIDE	HD10	HD20	HL10	HL20
MICE	2.00	3.70	2.94	4.76	4.17
DES Y1	2.42	3.30	2.79	3.48	3.58

σ = 1° smoothing

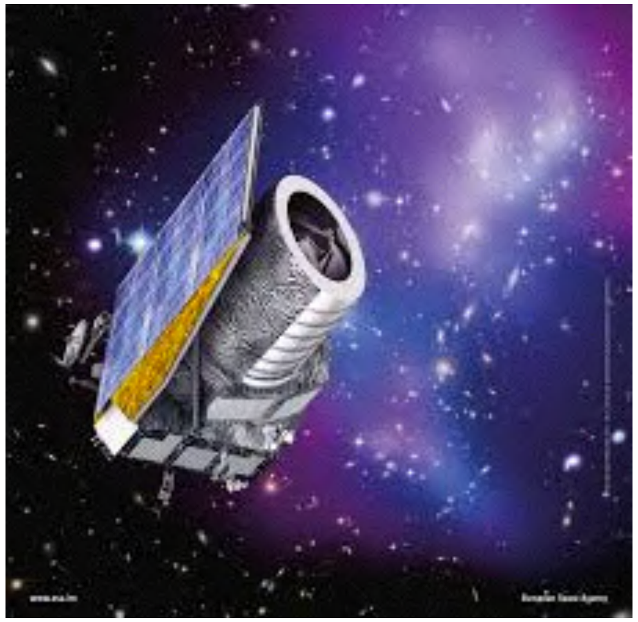
Catalogue	VIDE	HD10	HD20	HL10	HL20
MICE	2.13	3.70	3.33	4.55	4.00
DES Y1	2.11	2.89	2.40	4.91	3.19

- **3σ significance level**

- We then comprehensively searched for the best combination of parameters that guarantees the best chance to detect a signal with observed DES data. We concluded that the lower tracer density of the higher luminosity *redMaGiC* galaxy catalogue is preferable to achieve a higher signal-to-noise for both 10 Mpc/h and 20 Mpc/h initial Gaussian smoothing.

And now, waiting for

DESY3 : coming soon!



Coming not soonish but hopefully after COVID: LSST

DESI and Euclid coming soonish!

Conclusions

- Data are coming, be prepared!
- Promising tool for future cosmology : LSSxCMB
- We are reaching the time where Cosmic voids could be part of the cosmological analysis
- Cosmic voids are promising in various field : general cosmological inference, Modified Gravity constraints, Massive Neutrino constraints,…
- Using DES observations we manage to detect the imprint of cosmic void in the CMB lensing map with an unprecedented accuracy and future survey will manage to perform better

merci pour votre attention !