Journée de la Division Champs & Particules 2026

Cosmic voids: A Powerful Probe for Cosmology

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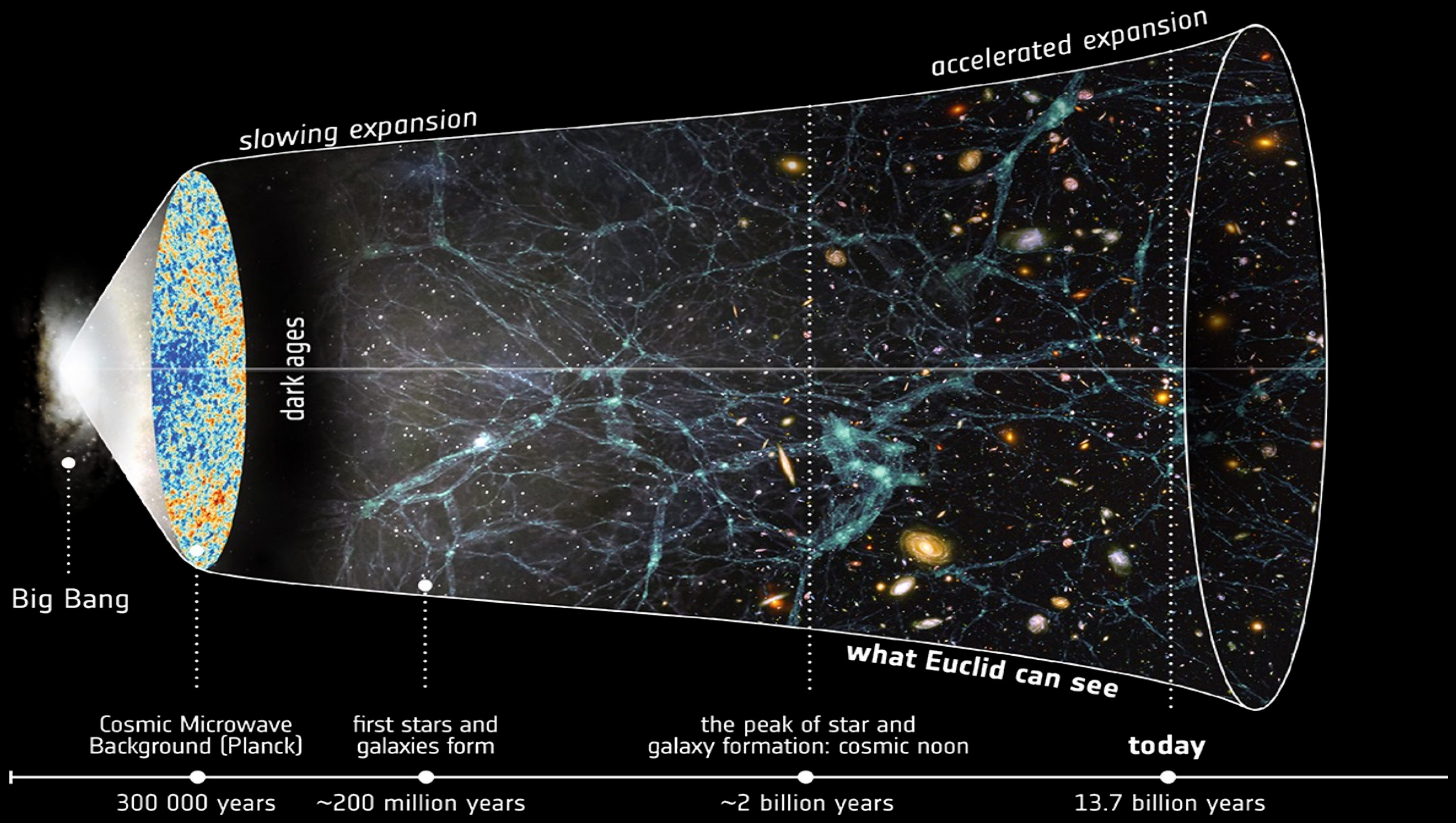
Particules de Marseille

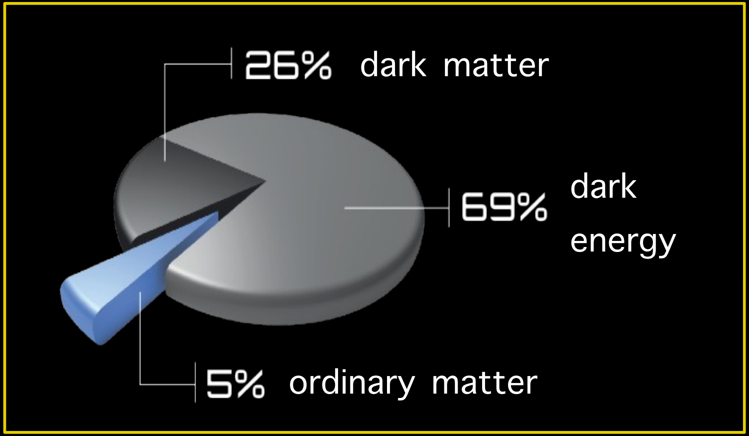
31 mars 2026

HISTORY OF THE UNIVERSE

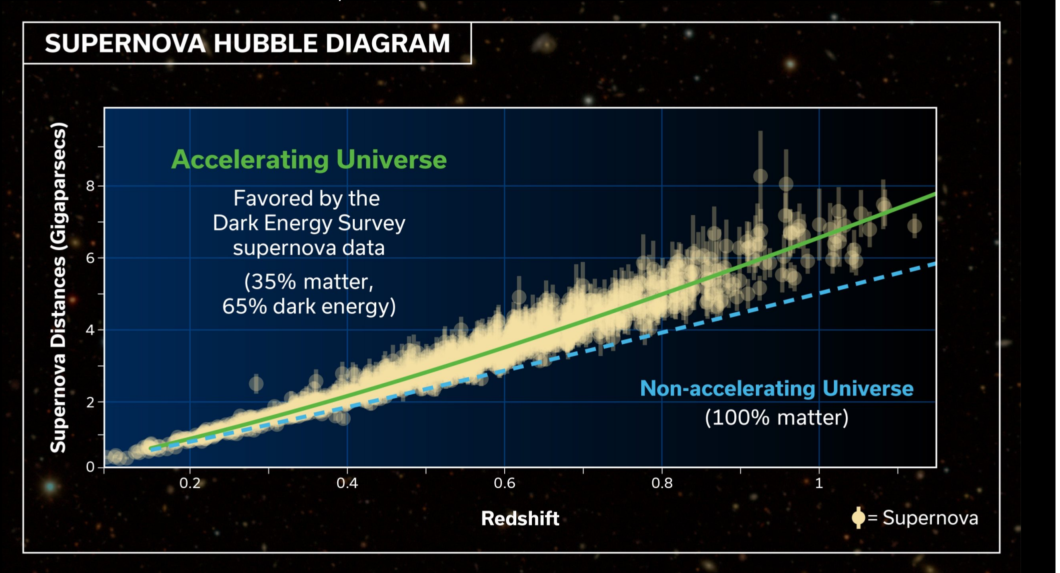


STANDARD MODEL OF COSMOLOGY

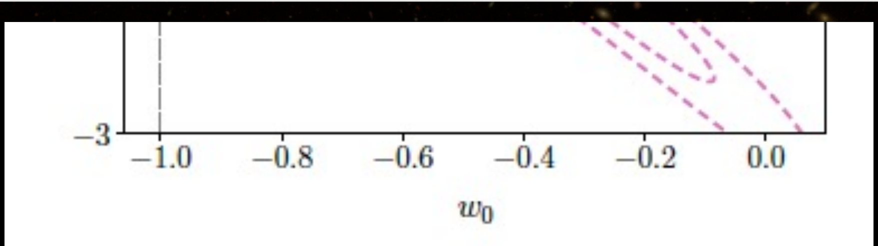
Energetic components of the Universe



Cosmological



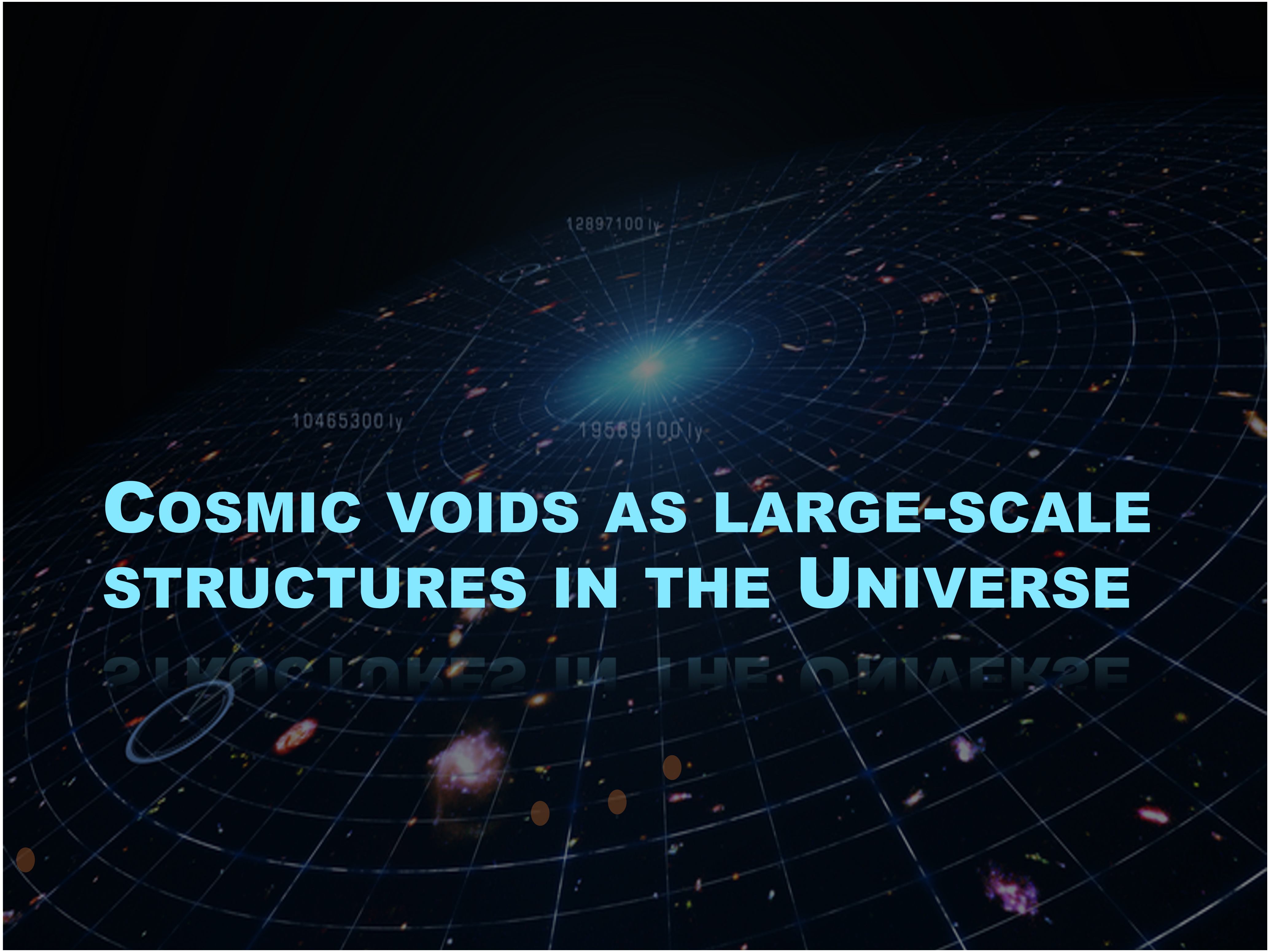
$$w(z) = w_0 + w_a \frac{z}{1+z}$$



DESI DR2 results II (2025)

What is the nature of Dark Matter and Dark Energy (Λ) ?

How do **voids** contribute to our understanding of the Universe?

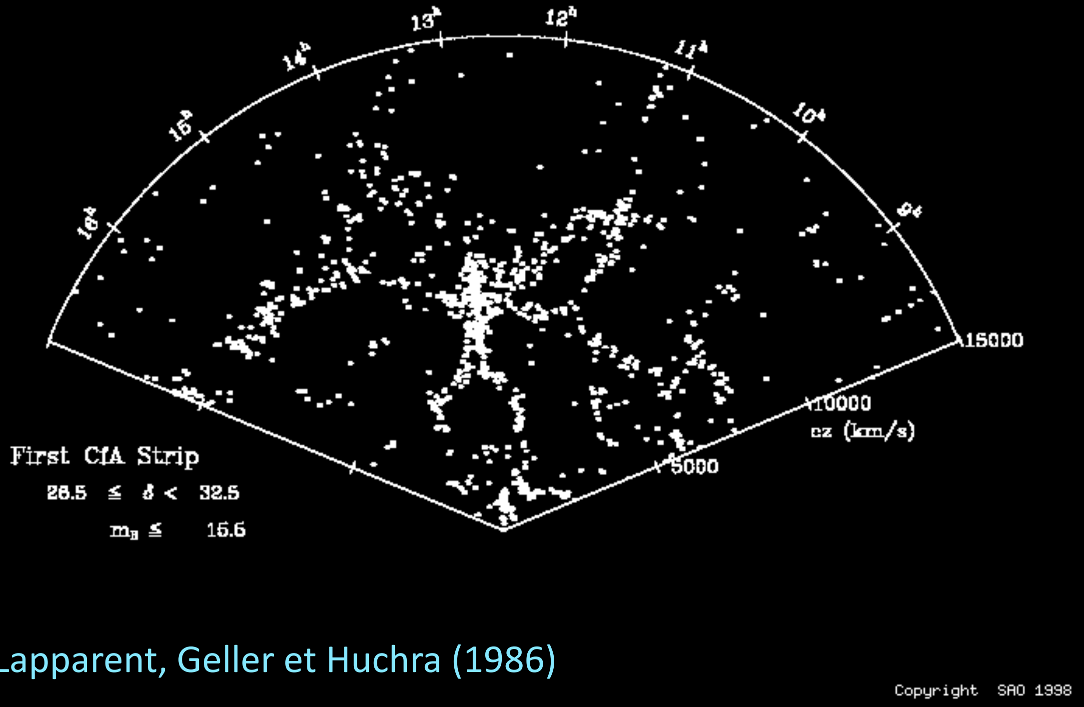


Cosmic voids as large-scale structures in the Universe

The Cosmic web

A Slice of the universe, as seen in 1980s

CfA survey of 1100 galaxies



De Lapparent, Geller et Huchra (1986)

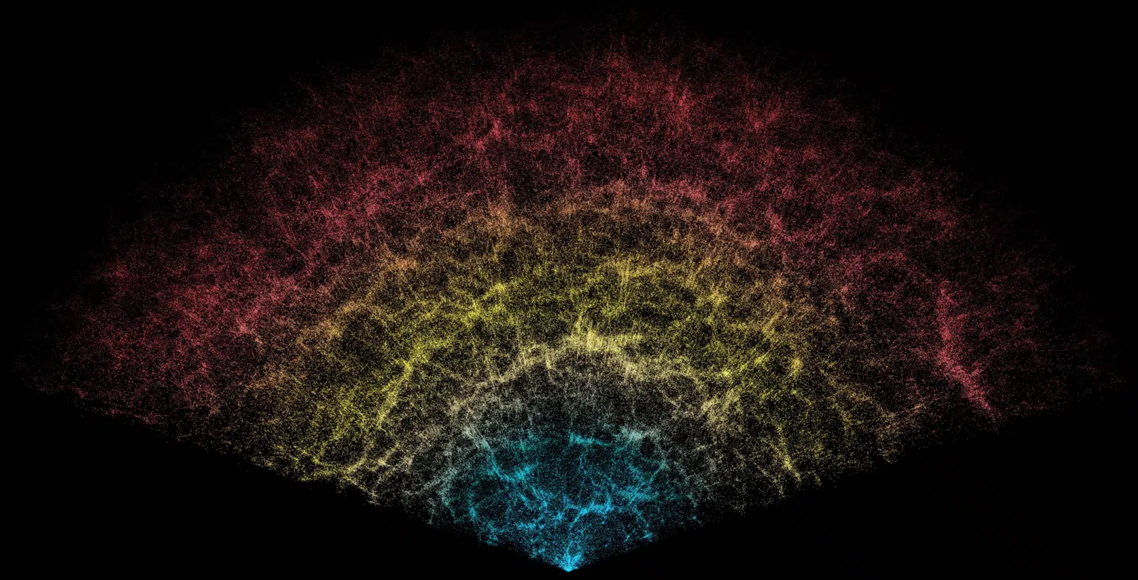
Hints of structures clearly seen..

THE COSMIC WEB

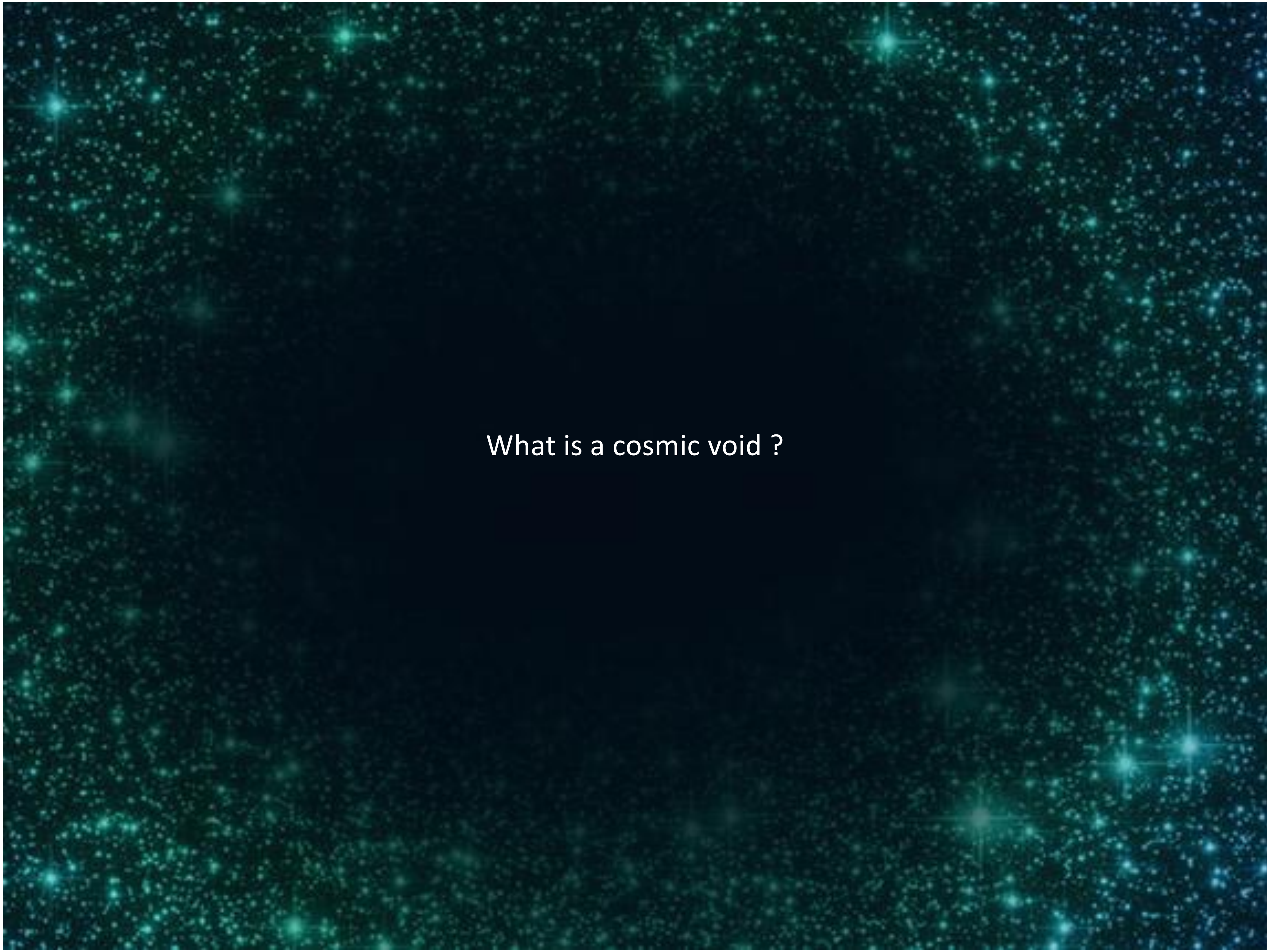
A Slice of the universe, as seen in 1980s

2dFGRS survey of 250 000 galaxies
SDSS survey with 1 M galaxies
DESI and Euclid survey with 40 M galaxies

A map revealing clusters, filaments, and void regions….



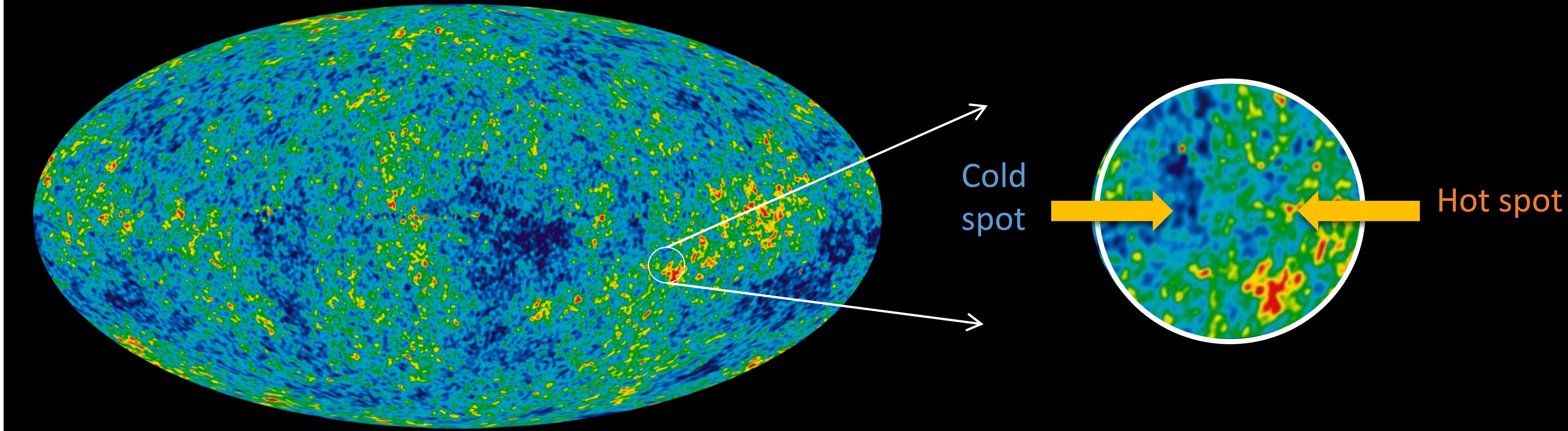
Hints of structures clearly seen..



What is a cosmic void ?

FORMATION OF COSMIC VOIDS

The **Cosmic Microwave Background (CMB)** is the imprint of the matter distribution at the time of recombination, approximately 380,000 years after the Big Bang.

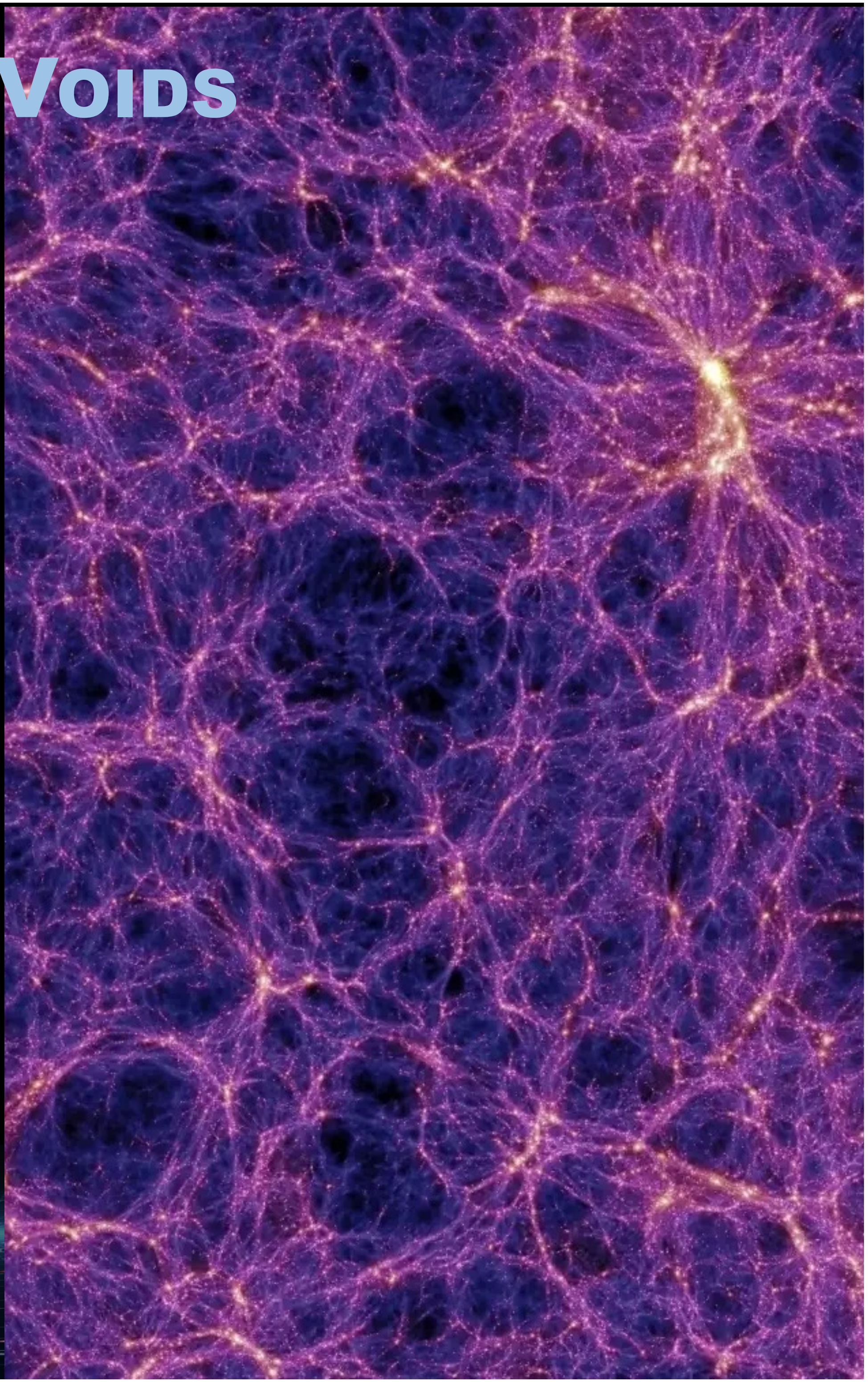


Formation of cosmic structures

- Hot spots: Gas gravitationally collapses in regions slightly denser than average. These overdensities later gave rise to the Universe's large-scale structures (galaxy clusters).
- Cold spots: Regions of underdense matter, which evolved into cosmic voids.

Cosmic Voids

- Large underdense regions in the Universe
- Accounts for over 60% of the total volume of the late-time Universe
- Typically have a density of order 10% of the mean density of the Universe
- Multi-scale, ranging from 10 to 100 Mpc/h
- Regions where cosmic expansion and acceleration dominate—making them critical laboratories for cosmological study



COSMIC VOIDS

Identification

COSMIC VOIDS: IDENTIFICATION

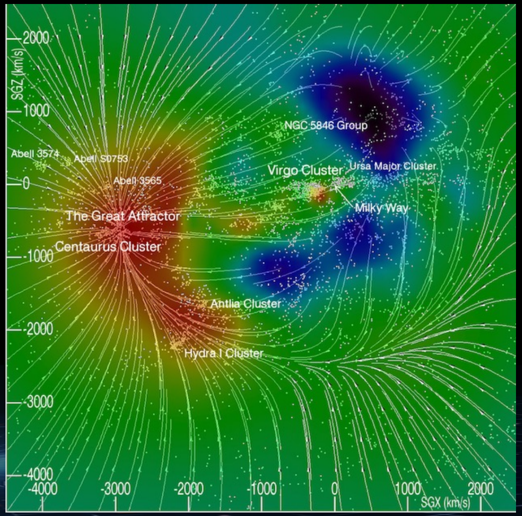
Void finders can be divided into two main categories:

Cosmic voids defined from the density field. *as geometrical underdense structures*

- Watershed based algorithms (ZOBOV-like)
- Spherical void finding algorithms

Cosmic voids defined from the displacement field. *as regions from which matter is escaping*

- Dynamical void finding algorithms



Courtois al. 2013

VOID FINDERS

ZOBOV (Neyrinck 2008),
VIDE (Sutter et al 2015),
REVOLVER (Nadathur et al. 2019)

Cosmic voids defined from the density field.

ZOBOV (ZOnes Bordering On Voidness) algorithms (*VIDE, REVOLVER*)

Three main steps in the void identification:

i. **Voronoi Tessellation**: The plane is partitioned into cells based on a discrete set of points.

Here, the points are **galaxies**.

galaxie

A cell consists of all the points closest to that galaxy.

Each cell (galaxy) is associated with a volume $\mathbf{V_i}$ and a related density:

$$\rho = \frac{1}{V_i}$$

VOID FINDERS

Cosmic voids defined from the density field.

ZOBOV (Neyrinck 2008),
VIDE (Sutter et al 2015),
REVOLVER (Nadathur et al. 2019)

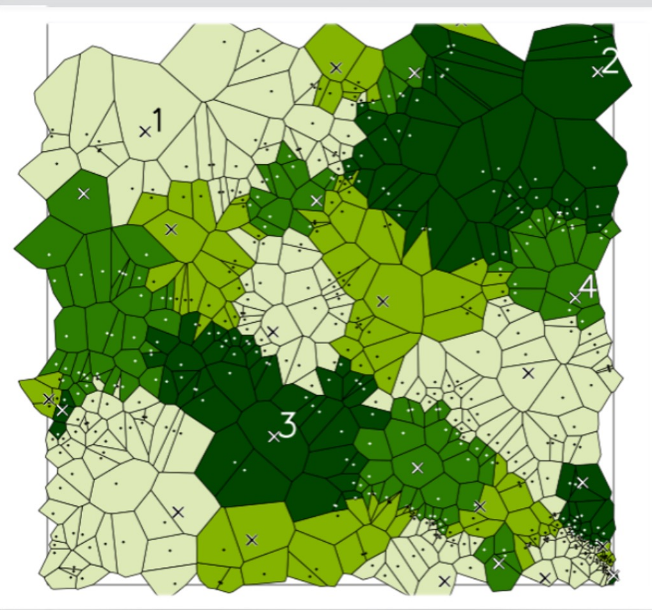
ZOBOV (ZOnes Bordering On Voidness) algorithms (*VIDE, REVOLVER*)

Main steps in the void identification:

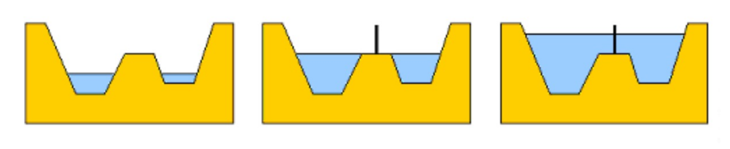
i. **Voronoi Tessellation**: The plane is partitioned into cells based on a discrete set of points.

ii. Localisation of **density minima**: cores

iii. Neighboring cells with a **watershed transform**



The basins are combined into a single cosmic void when the boundary between them corresponds to the lowest-density region.



VOID FINDERS

Cosmic voids defined from the density field.

Spherical void finders (*Sparkling, PopCorn, DIVE, VAST*)

Main steps in the void identification:

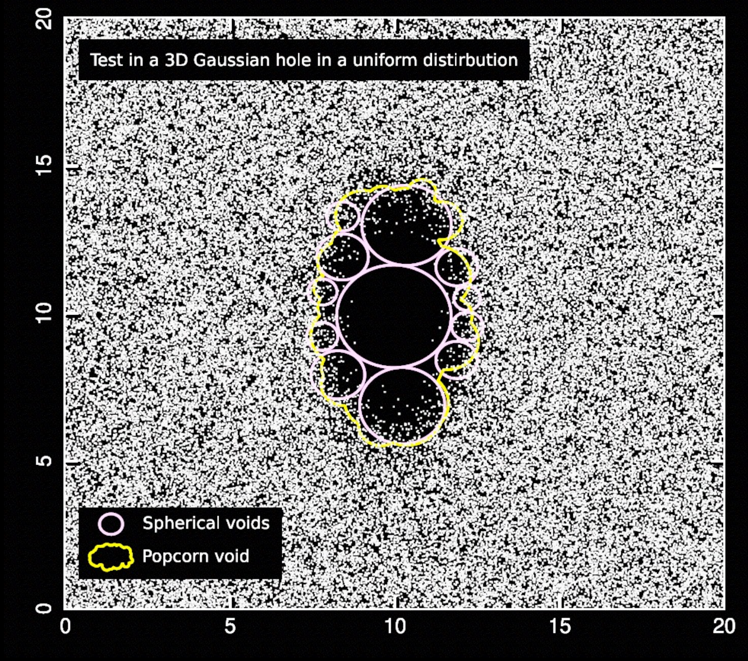
i. **Voronoi Tessellation**: The plane is partitioned into cells based on a discrete set of points.

ii. Localisation of **density minima**: cores

iii. Iteratively computation of the integrated density contrast inside **spheres of increasing radius,** keeping an integrated density contrast below a given threshold

iv. Optional: Adding more spheres to closely cover the void region (Popcorn algorithm)

Sparkling (Ruiz et al. 2015)
PopCorn (Paz et al. 2023)



VOID FINDERS

Cosmic voids defined from the displacement field.

Dynamical void finders (DIVA, LZVF, *BitVF*)

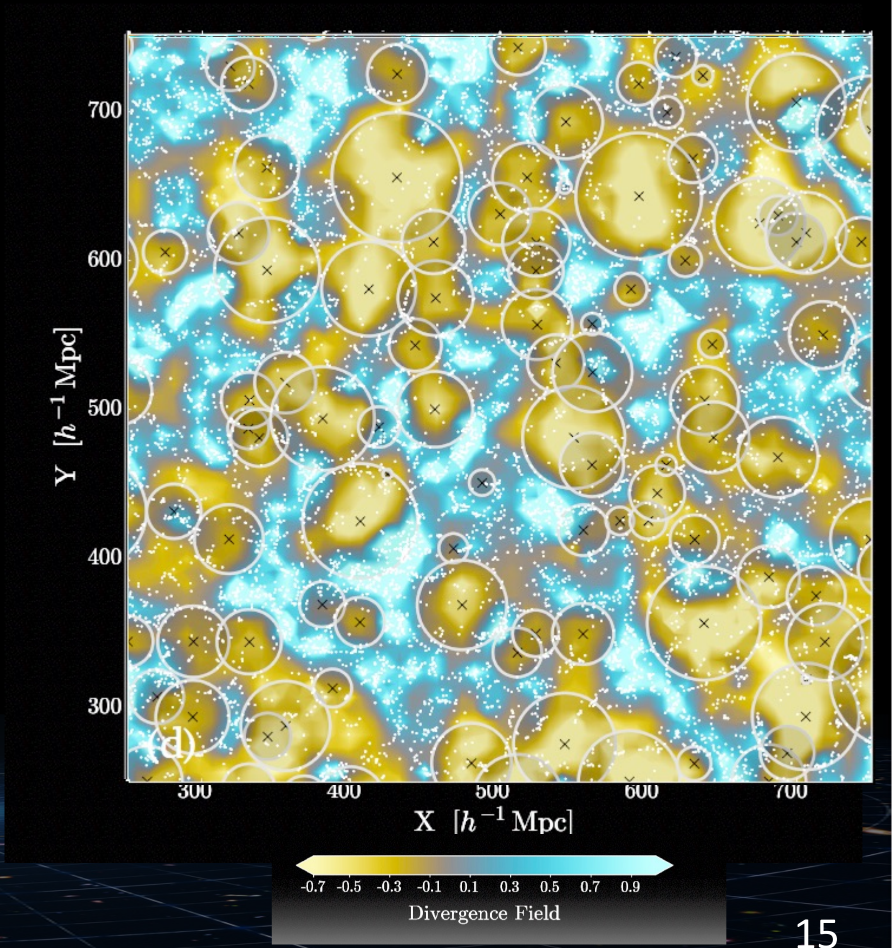
DIVA (Lavaux & Wandelt 2010),
LZVF (Elyiv et al. 2015),
BitVF (Sartori et al. 2026)

Main steps in the void identification:

i. **Displacement field** is reconstructed from the observed galaxy distribution using an optimal transport approach based on Zel’dovich Approximation (PIZA)

ii. **Divergence of the displacement field** is computed on a regular grid.

iii. **Watershed void identification**, based on local minima of the divergence field, yielding dynamically void regions.



COSMIC VOIDS

- Detecting cosmic voids relies on a variety of algorithms, each offering a specific definition of these structures.

- There is no universal or "best" definition: the choice primarily depends on the intended scientific application and the ability to maximize the desired signal.

PRECISION COSMOLOGY WITH VOIDS

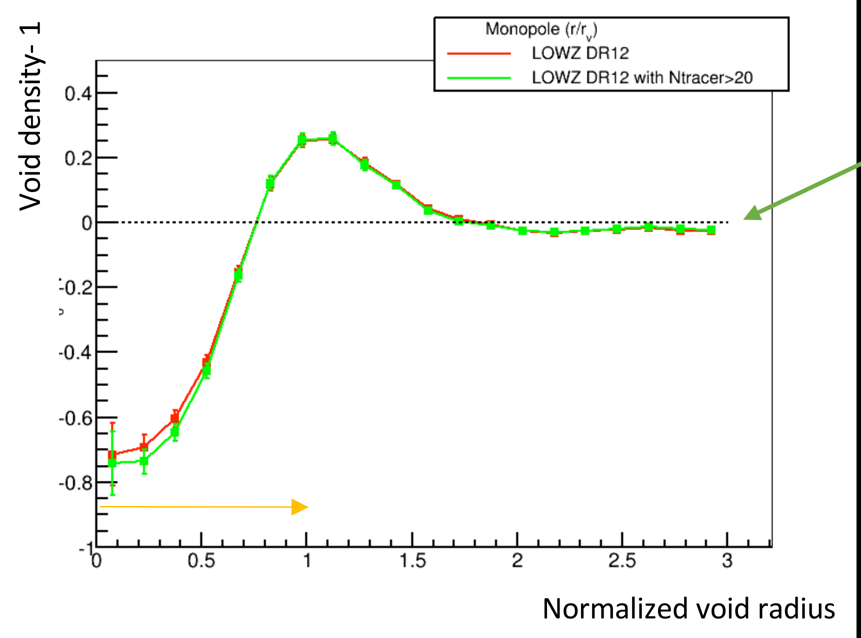
- Void statistics:
  1. Void clustering
  2. Void abundance
  3. Void lensing
  4. Combination

VOID STATISTICS

1. Void clustering

VOID DENSITY PROFILES

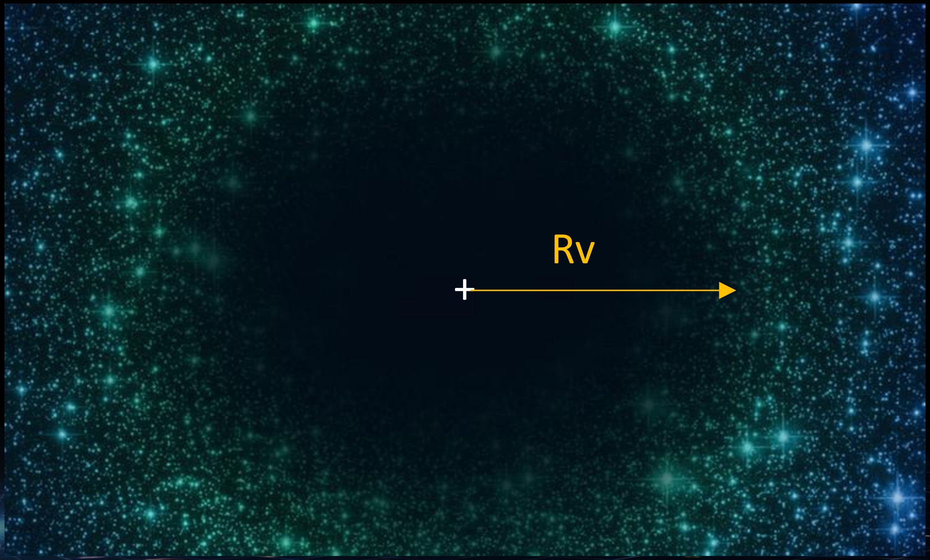
Density profile of a 3D void : void-galaxy cross-correlation function



Mean density of the Universe

$\bar{\rho} - 1$

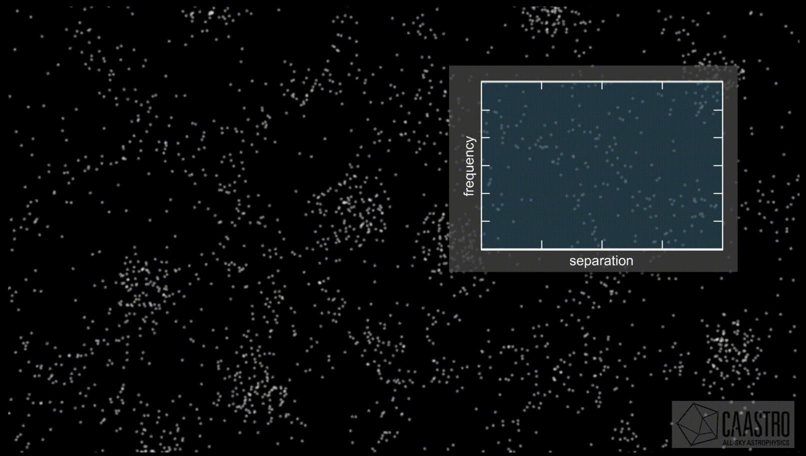
$$R_v = \left(\frac{3V}{4\pi}\right)^{1/3}$$

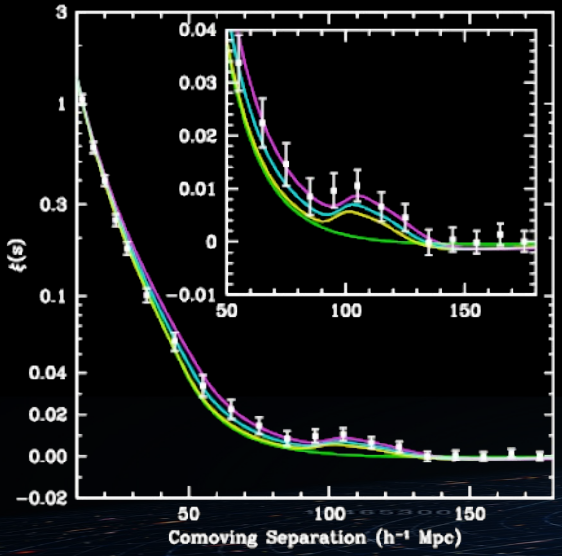


Lavaux & Wandelt (2012) : Stacking of voids

CORRELATION FUNCTION

Galaxy-galaxy correlation function (GGCF)

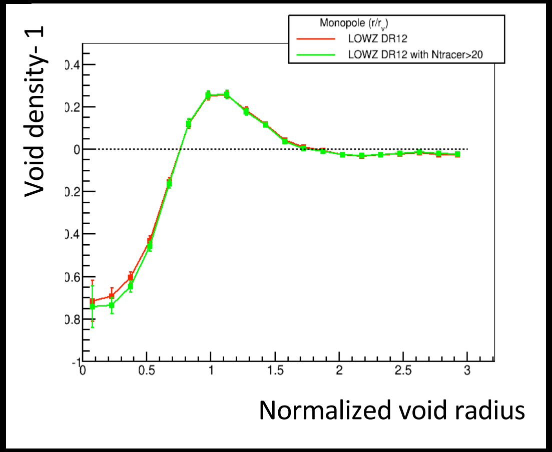




GGCF

Eisenstein et al. 2005

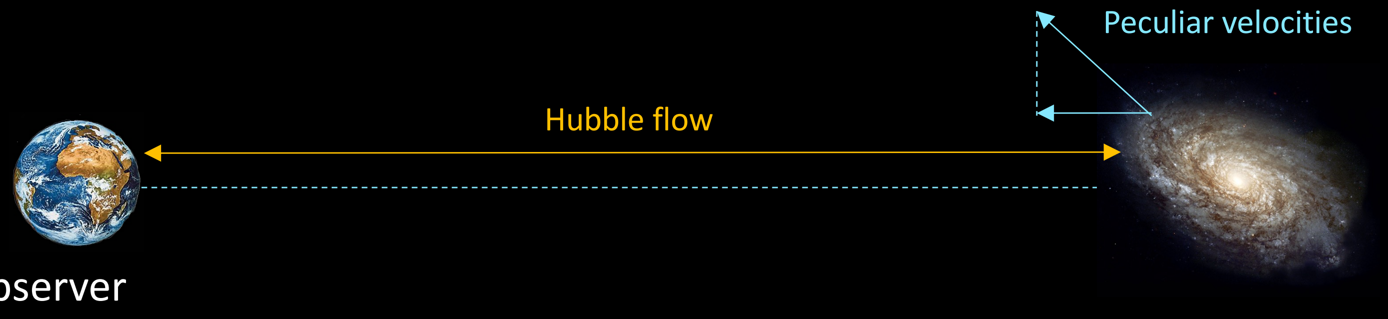
Void-galaxy correlation function (VGCF)



VGCF

Deviations from the homogeneity are conveniently and readily characterised by their spatial two-point correlation function that measures the departure from a purely Poisson distribution.

PECULIAR VELOCITIES



Measured redshift has two main contributions:

$$z = \frac{H_0 d}{c} + \frac{v}{c}\cos\theta$$

cosmological redshift
Hubble flow

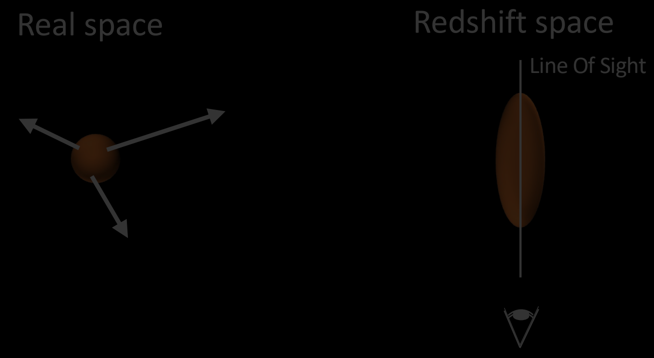
Doppler redshift
Peculiar velocities along the LOS

Peculiar velocities introduce **Redshift Space Distortions (RSD)**, which generate significant anisotropy in the observed distribution of galaxies.

DYNAMICAL DISTORTIONS

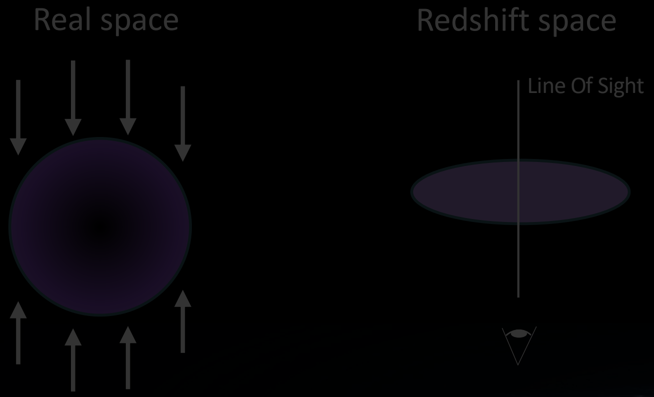
Two regimes of distortions: Redshift Space Distortions (RSD)

I. Random motion (Fingers-of-God effect)

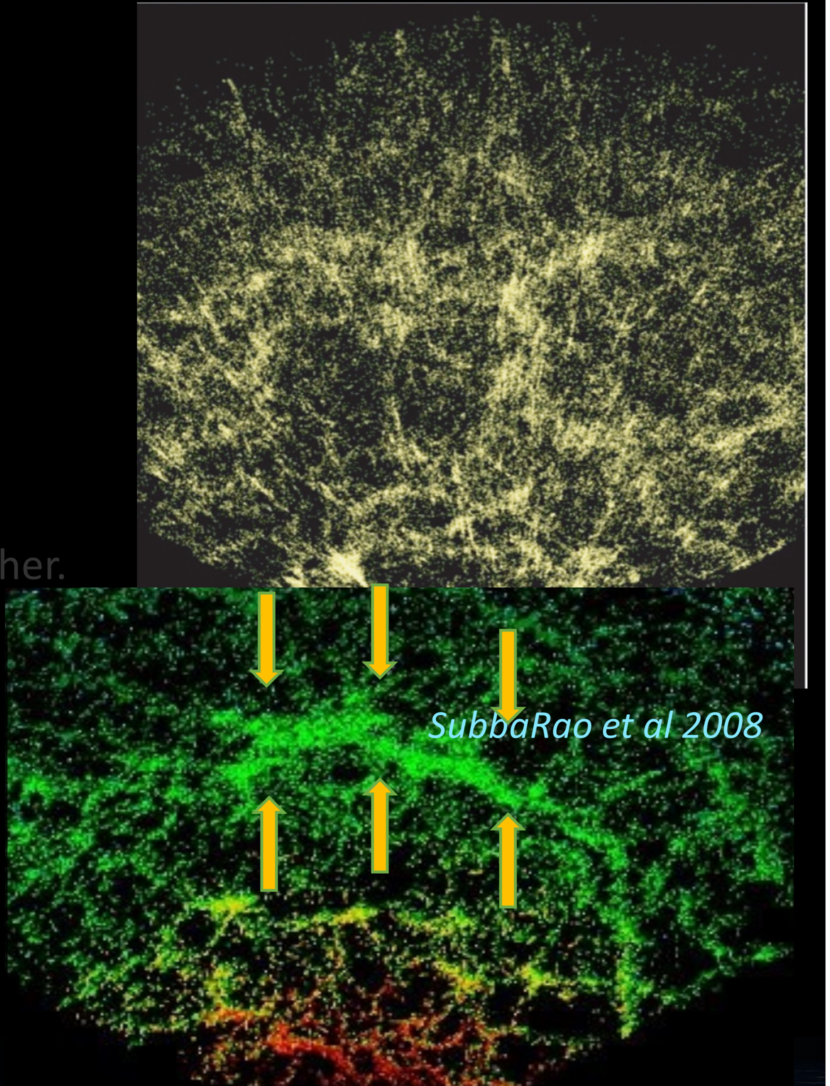


Dominant contribution at small scales (< 1 Mpc):
Arises from the random velocities of galaxies relative to each other.

II. Coherent infall (Kaiser effect) Kaiser 1987



Contribution at large scales : Corresponds to the gravitational infall of galaxies toward massive structures


SubbaRao et al 2008

$$\beta = \frac{f}{b} \approx \frac{\Omega_m^\gamma}{b}$$

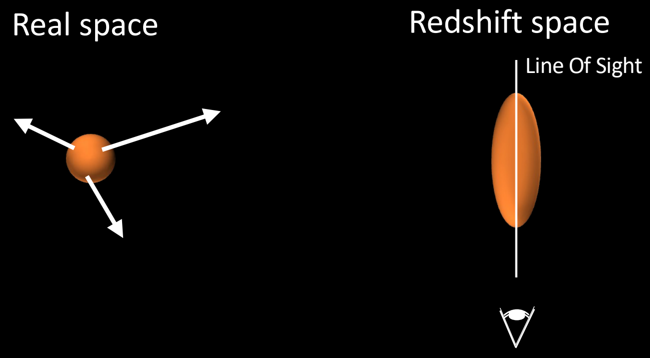
GR : $\gamma = 0.55$

f: linear growth rate
b: galaxy biais

DYNAMICAL DISTORTIONS

Two regimes of distortions: Redshift Space Distortions (RSD)

I. Random motion (Fingers-of-God effect)

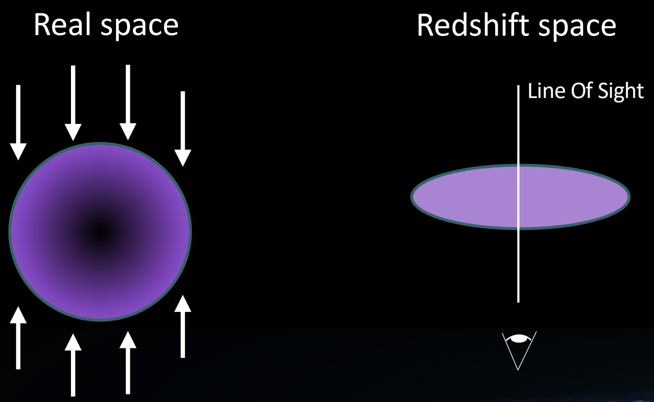

Real space

Redshift space

Line Of Sight

Dominant contribution at small scales (< 1 Mpc):

II. Coherent infall (Kaiser effect)

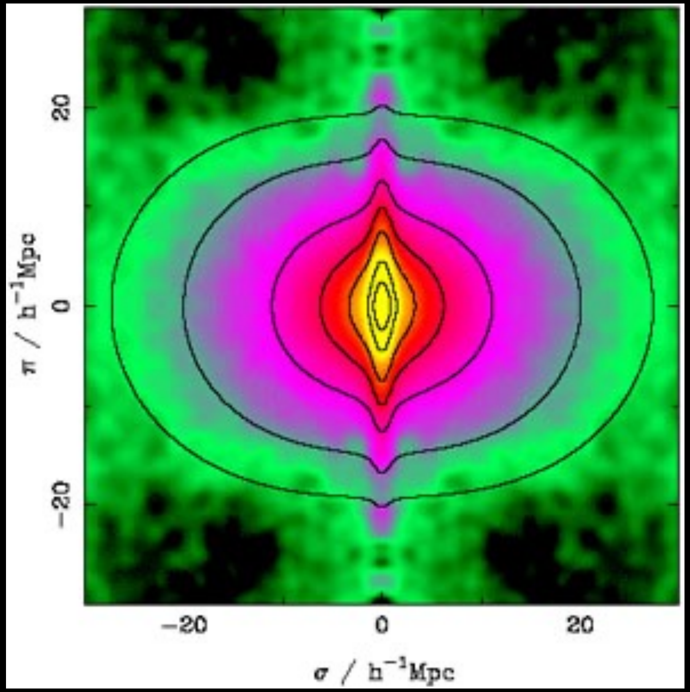

Real space

Redshift space

Line Of Sight

Contribution at large scales

2D galaxy-galaxy CF



Peacock 2001, Hawkins 2003

$$\beta = \frac{f}{b} \approx \frac{\Omega_m^{\gamma}}{b}$$

f: linear growth rate
b: galaxy biais

GR predicts a growth rate γ = 0.55

VOID-GALAXY CROSS-CORRELATION FUNCTION

$$\xi_{vg}(s_\perp, s_\parallel) = \xi^r(r) + \frac{1}{3}\beta\xi^r(r) + \beta\mu^2\left[\xi^r(r) - \overline{\xi^r(r)}\right]$$

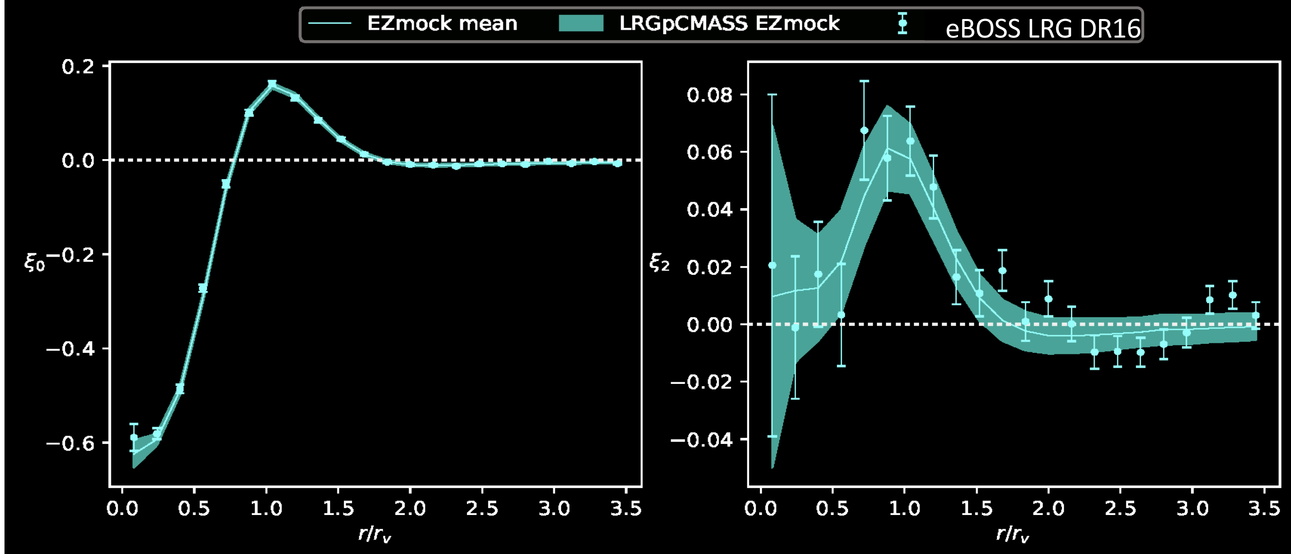
$$\beta = \frac{f}{b}$$

f: linear growth rate
b: galaxy biais

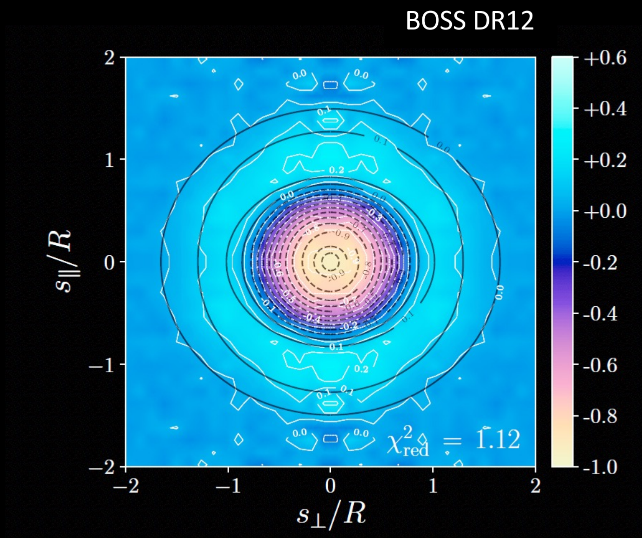
decomposition into
Legendre polynomials

monopole

quadrupole



Aubert et al. (2022)



Hamaus, Pisani et al. (2022)

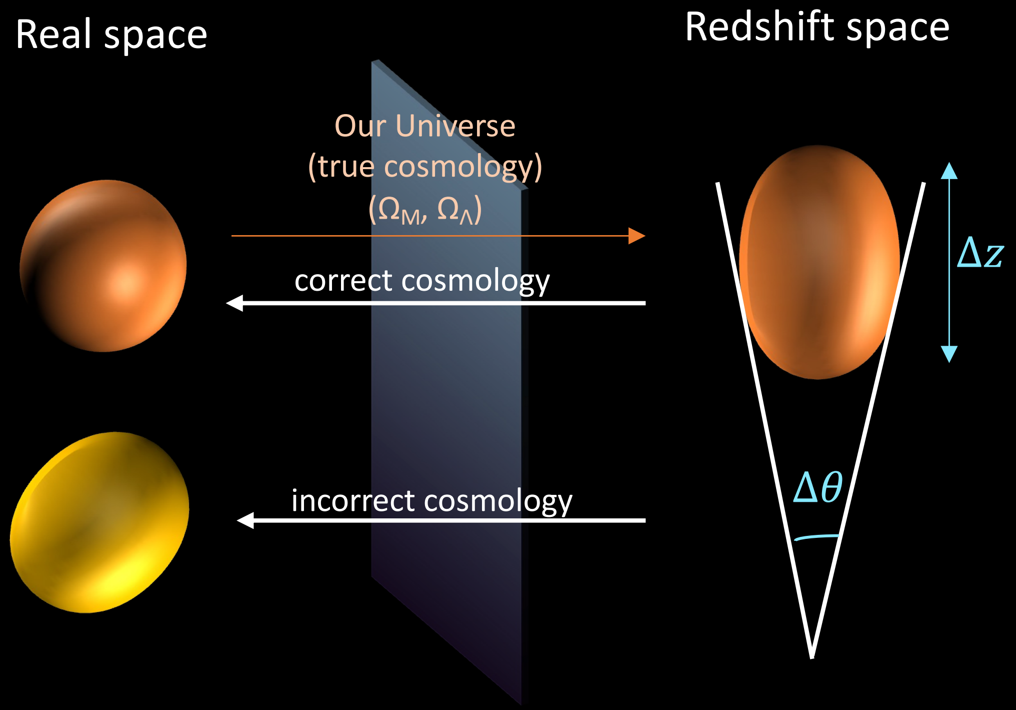
Redshift space distortions (RSD)
Alcock-Paczynski effect (AP)

GEOMETRICAL DISTORTIONS

Alcock-Paczynski effect

Alcock & Paczynski 1979

The Alcock-Paczynski (AP) effect refers to the geometric distortion when incorrect cosmological models are adopted for transforming redshift to comoving distance.



$$\Delta r_\perp = D_M(z)\Delta\theta$$

$$\Delta r_\parallel = \frac{c}{H(z)}\Delta z$$

where
$D_M(z)$ is the angular diameter distance
$H(z)$ is the Hubble parameter

➔ requires the assumption of a fiducial cosmological model: AP test

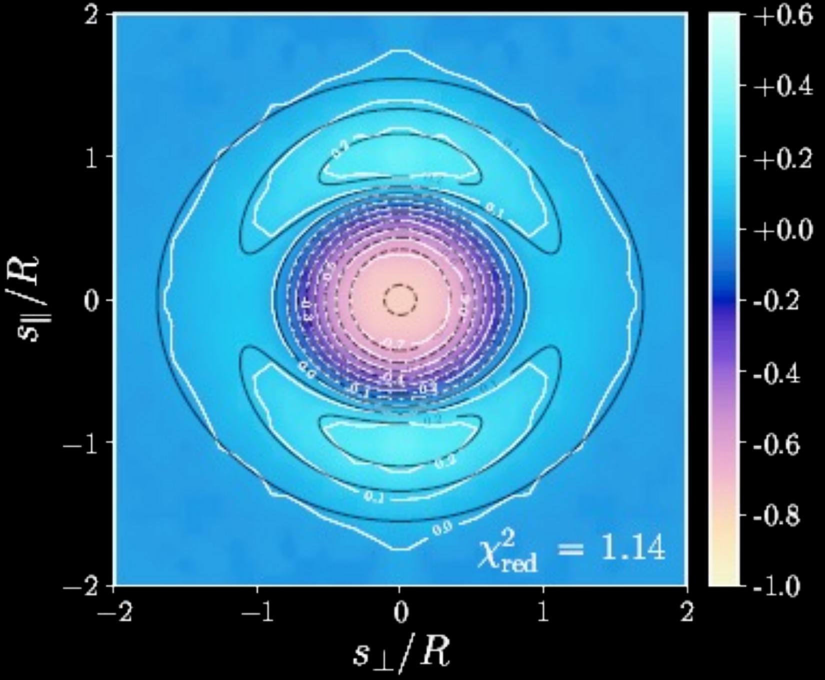
$$\varepsilon = \frac{D_M^*(z)H^*(z)}{D_M(z)H(z)}$$

AP distortion more evolves with redshift than RSD, so both effects can be disentangle.

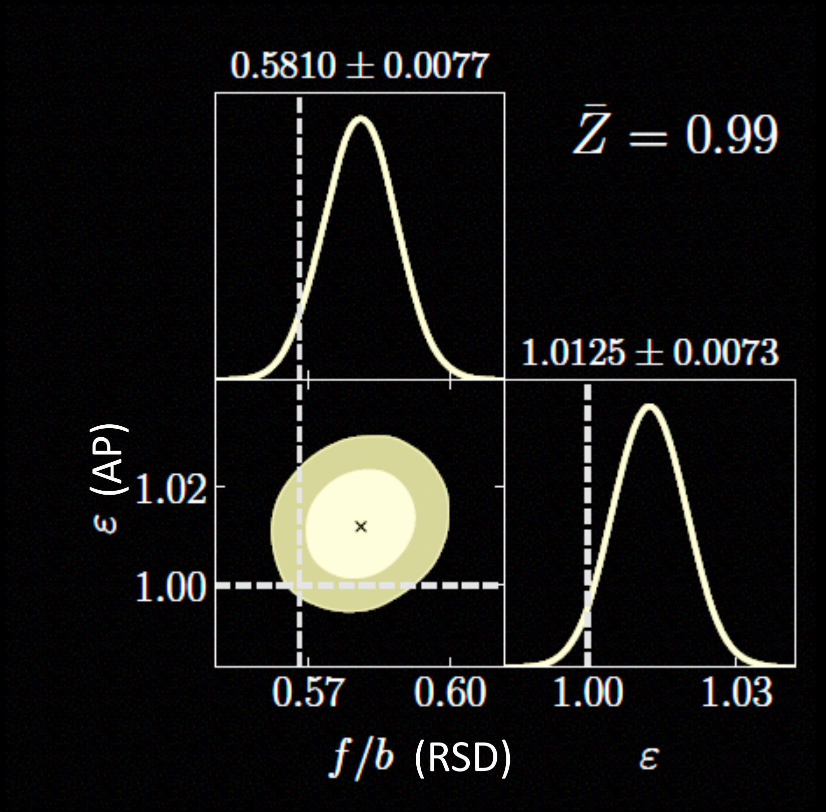
PARAMETER CONSTRAINTS

Void-galaxy cross-correlation function

Euclid forecasts



Stacked VGCF in 2D (white contours)
and its best-fit model (black contours)

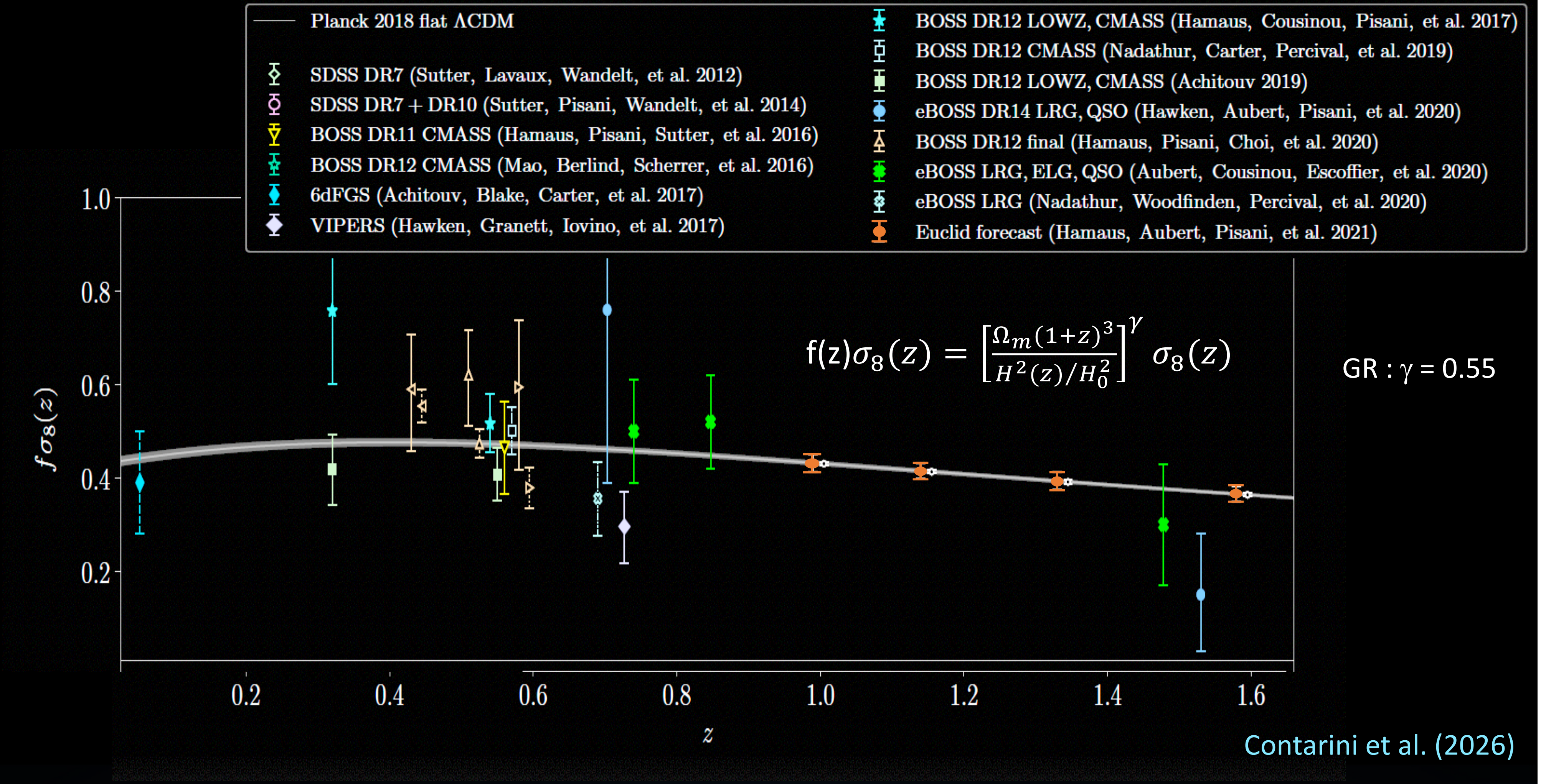


Posterior probability distribution

Hamaus, Aubert et al. (2022)

PARAMETER CONSTRAINTS

Constraints on the growth rate



$$f(z)\sigma_8(z) = \left[\frac{\Omega_m(1+z)^3}{H^2(z)/H_0^2}\right]^{\gamma} \sigma_8(z)$$

GR : γ = 0.55

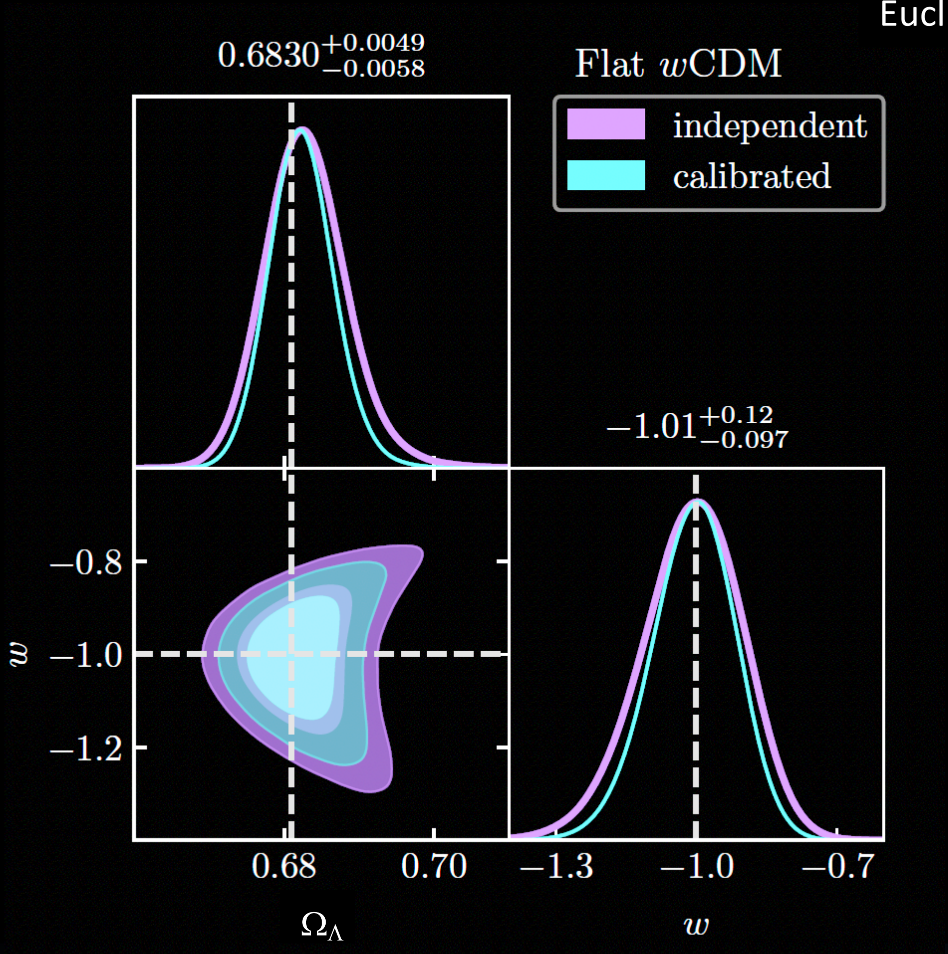
Contarini et al. (2026)

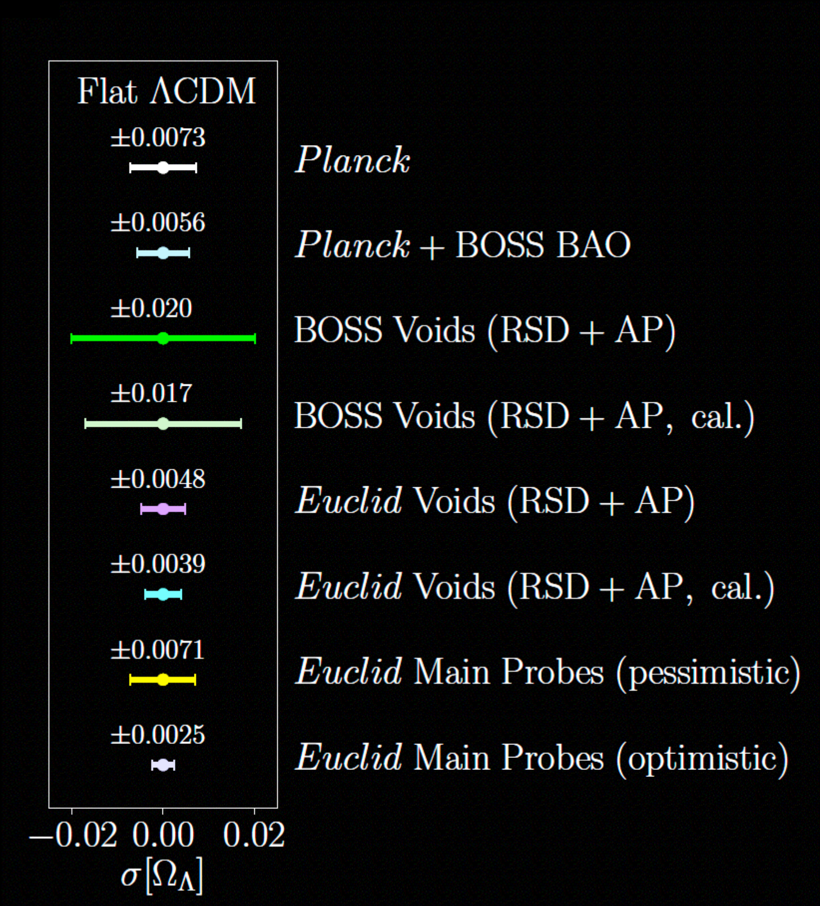
Any measured deviation from γ=0.55 would signal a potential departure from GR

PARAMETER CONSTRAINTS

Forecast on dark energy parameters with Euclid

Euclid forecasts





Hamaus, Aubert et al. (2022)

VOID STATISTICS

2. Void Abundance

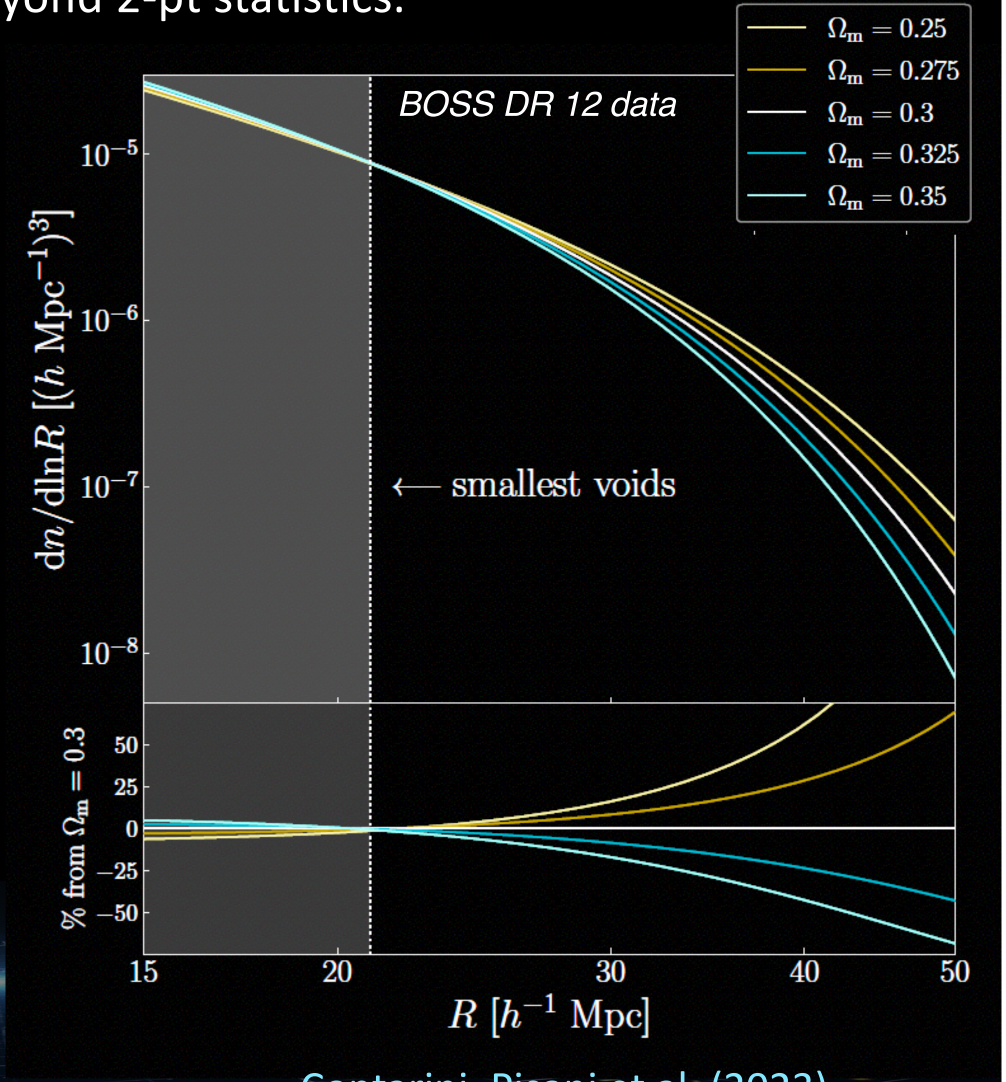
DISTRIBUTION OF VOIDS

Void Size Function (VSF), void probability function, or the void abundance function

VSF is influenced by correlations of all orders beyond 2-pt statistics.

Measure cosmological parameters, including the sum of neutrino masses, and test theories of gravity.

But fundamentally connected to the initial conditions and evolution of the individual voids => model dependent



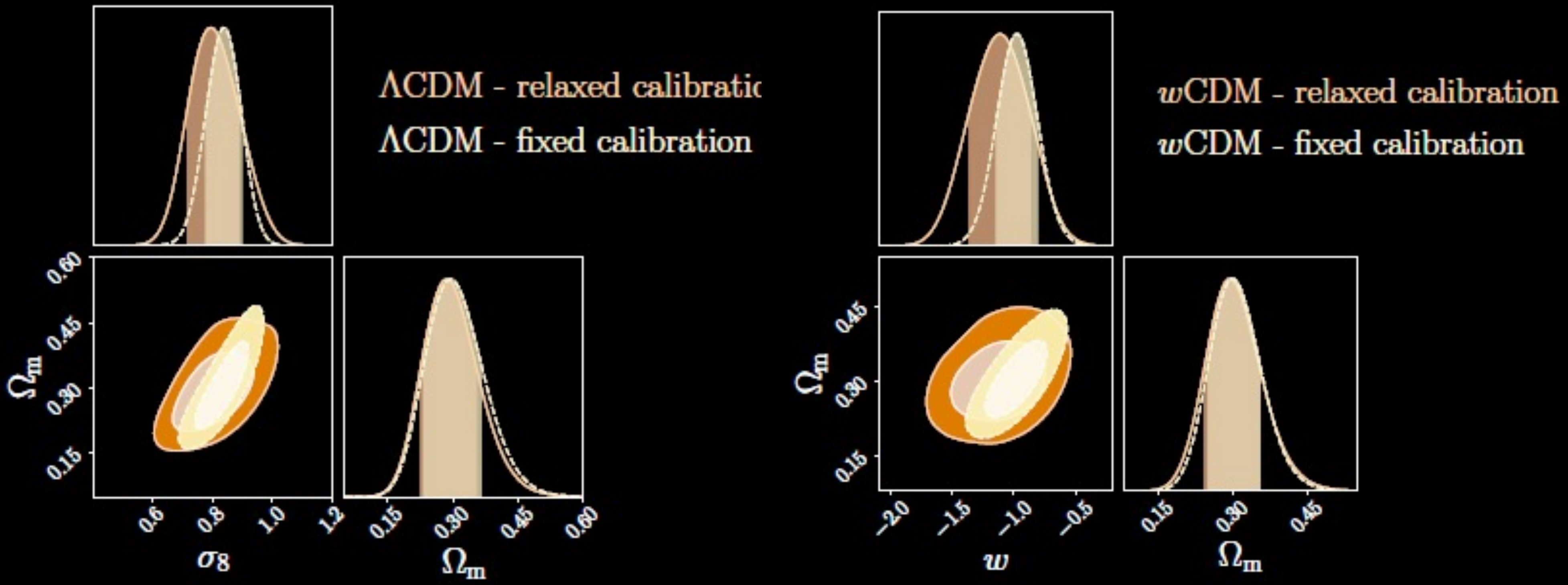
Contarini, Pisani et al. (2023)

DISTRIBUTION OF VOIDS

Parameter constraints

VSF is influenced by correlations of all orders beyond 2-pt statistics.

BOSS DR12 data



Contarini, Pisani et al. (2023)

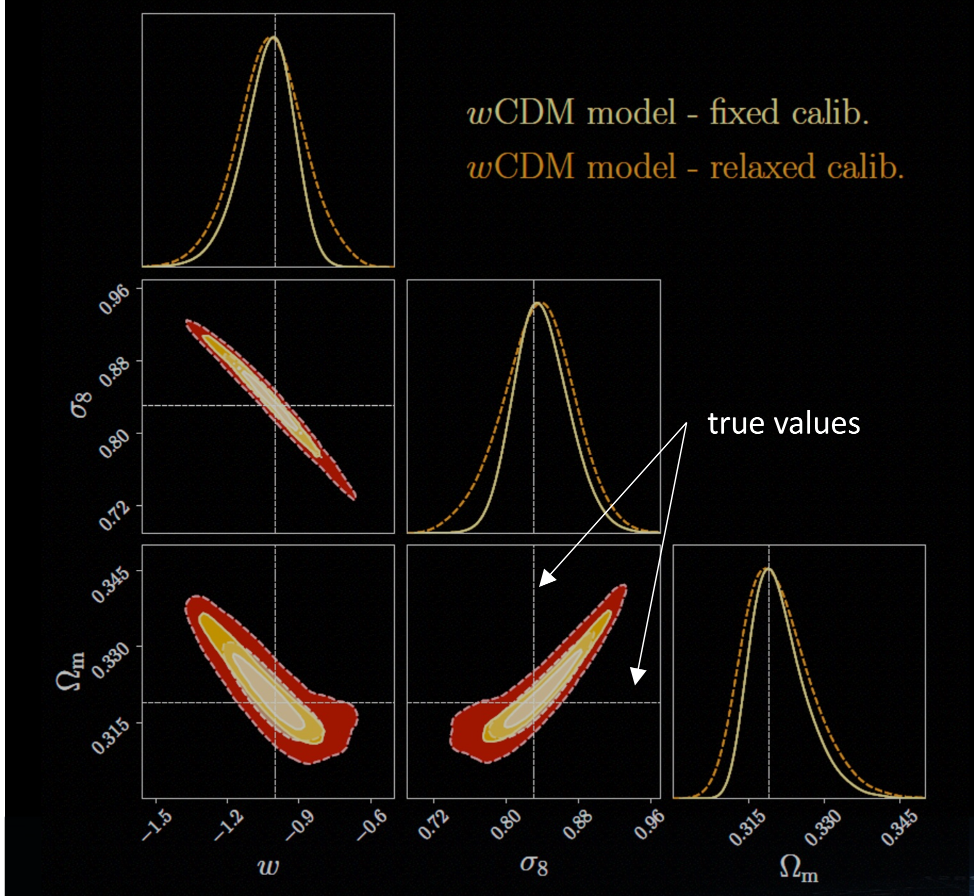
σ_8: amplitude of matter density fluctuations

DISTRIBUTION OF VOIDS

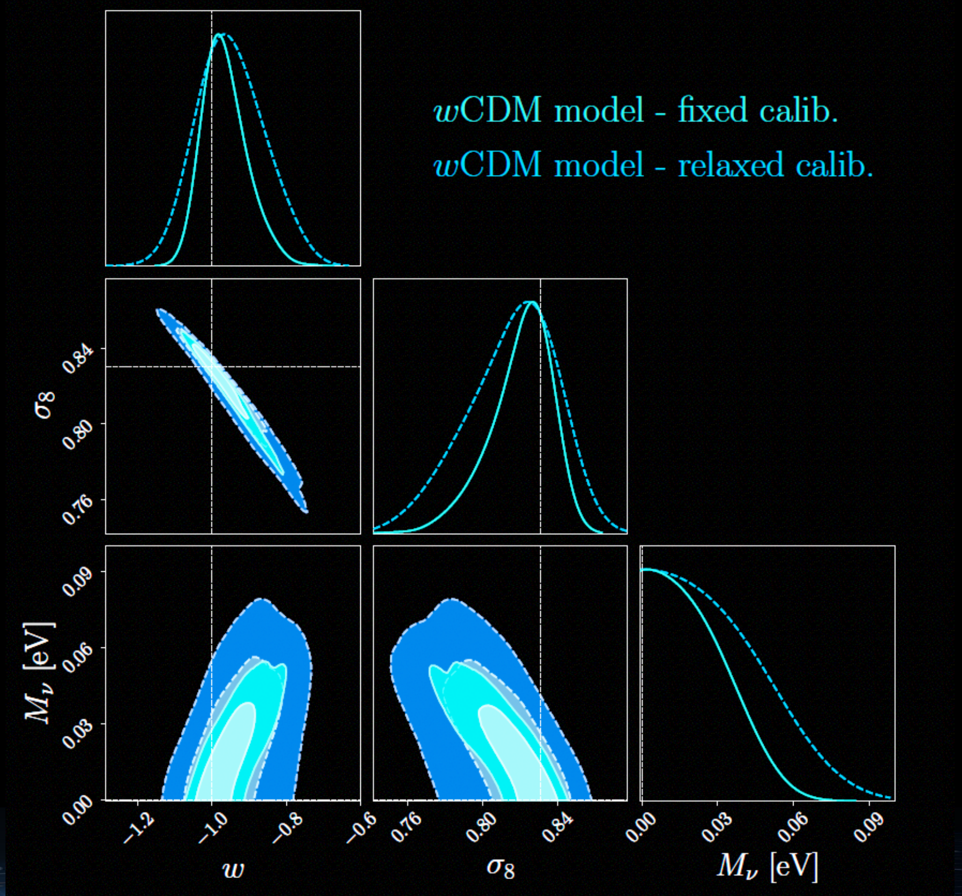
Parameter constraints

Euclid forecasts

Contarini et al. (2022)



true values



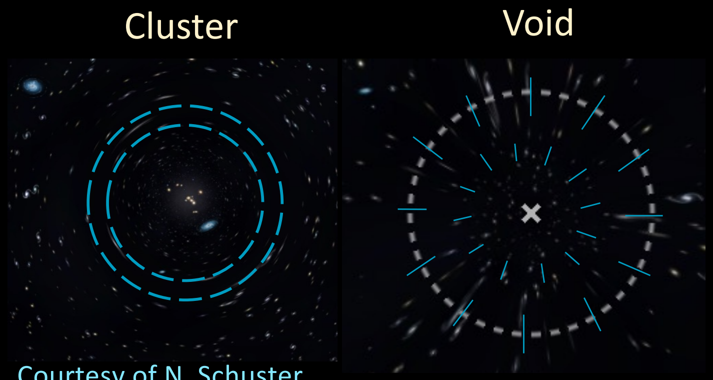
Inference of cosmological parameters, including the sum of neutrino masses

VOID STATISTICS

3. Void lensing

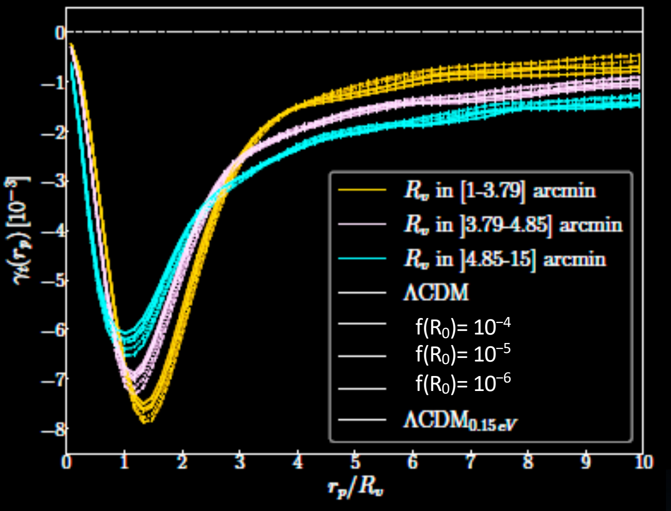
VOID LENSING

Constraints on modified gravity models



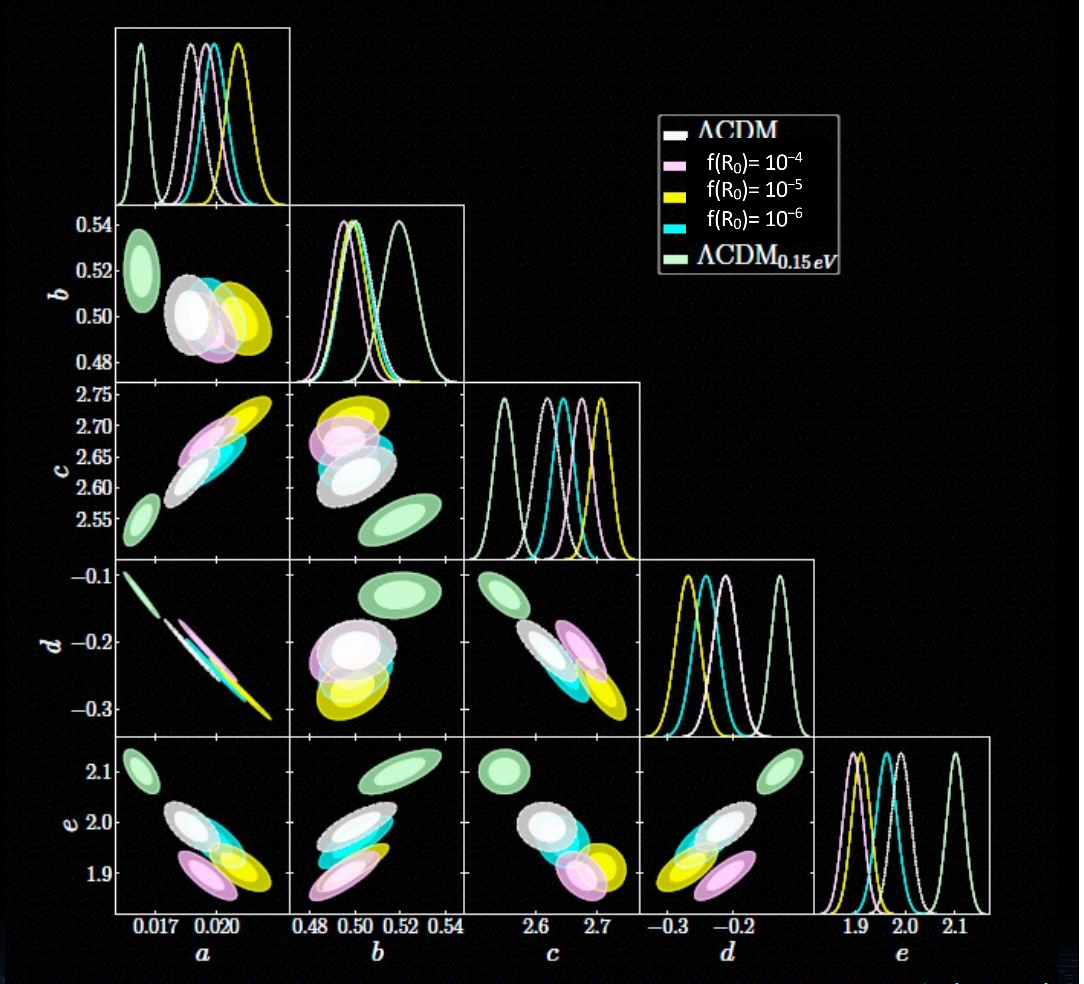
Courtesy of N. Schuster

Stacked tangential shear profiles



$$\gamma_t(r_p) = a.r_p\left(\frac{1-r_p^b}{1+r_p^c} - \frac{\exp(d.r_p)}{1+\exp(e.r_p-(d+e))}\right)$$

Hu-Sawicki f(R) modified gravity models



Maggiore et al. (2025)

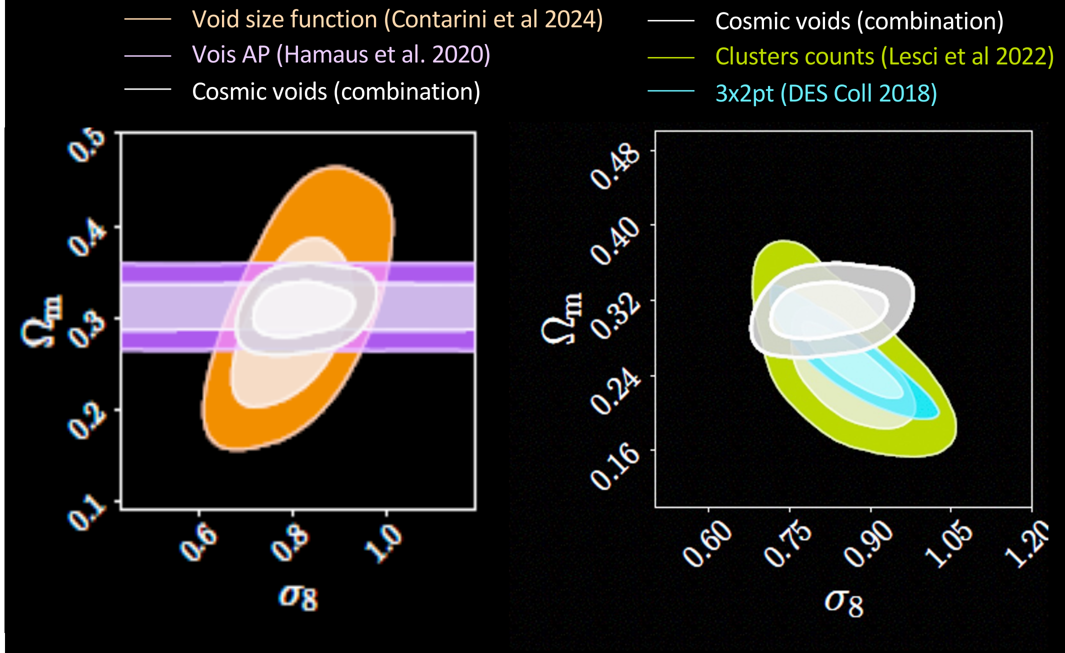
VOID STATISTICS

4. Combination

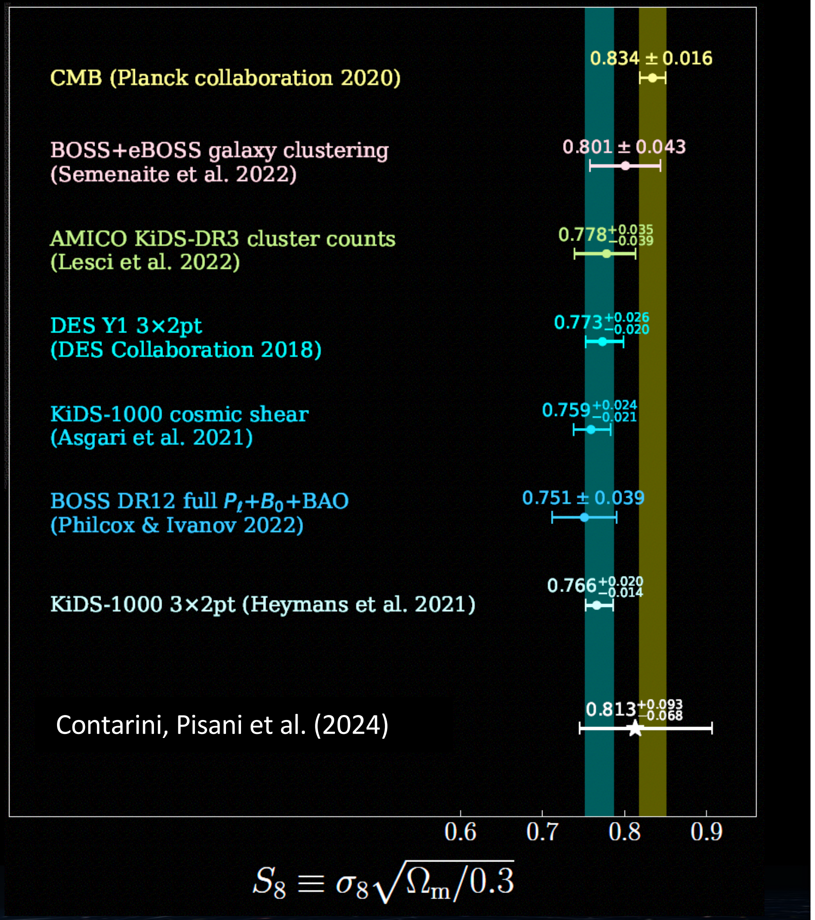
COMBINATION OF VOID STATISTICS

Parameter constraints on S_8, using combination between VSF and VGCF

DR12 DOSS data



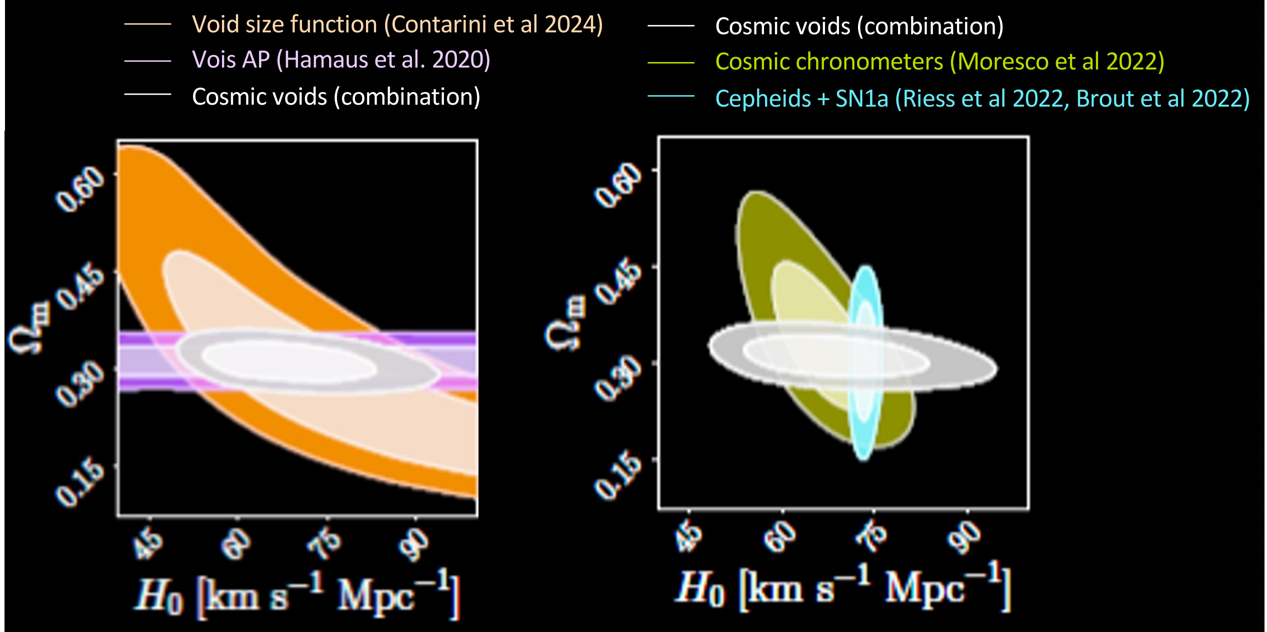
Contarini, Pisani et al. (2024)



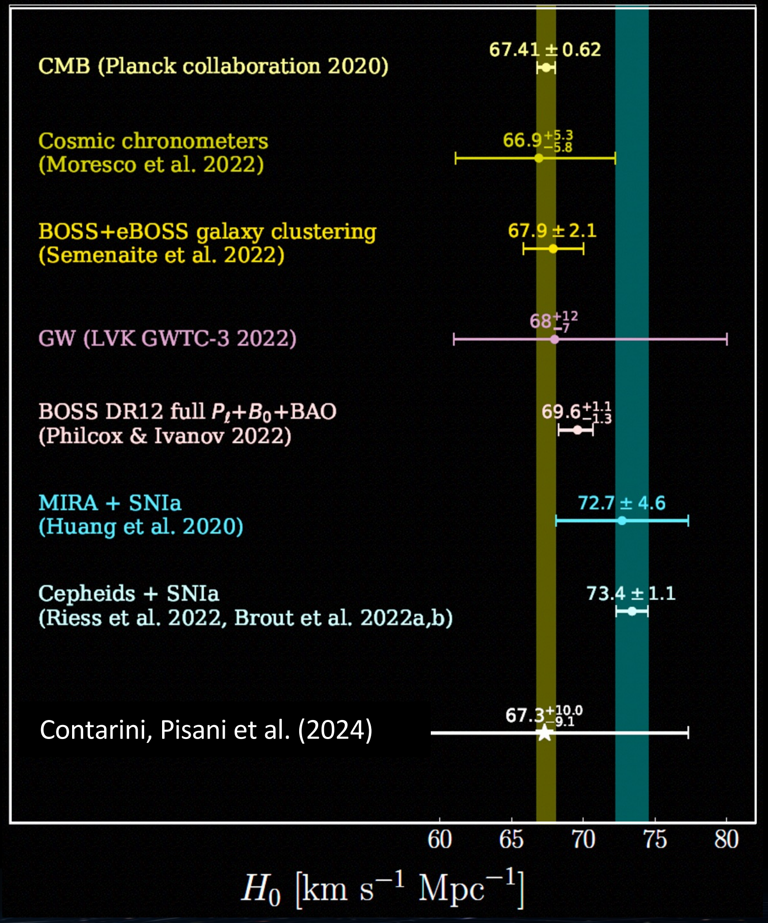
COMBINATION OF VOID STATISTICS

Parameter constraints on H_0, using combination between VSF and VGCF

DR12 DOSS data



Contarini, Pisani et al. (2024)

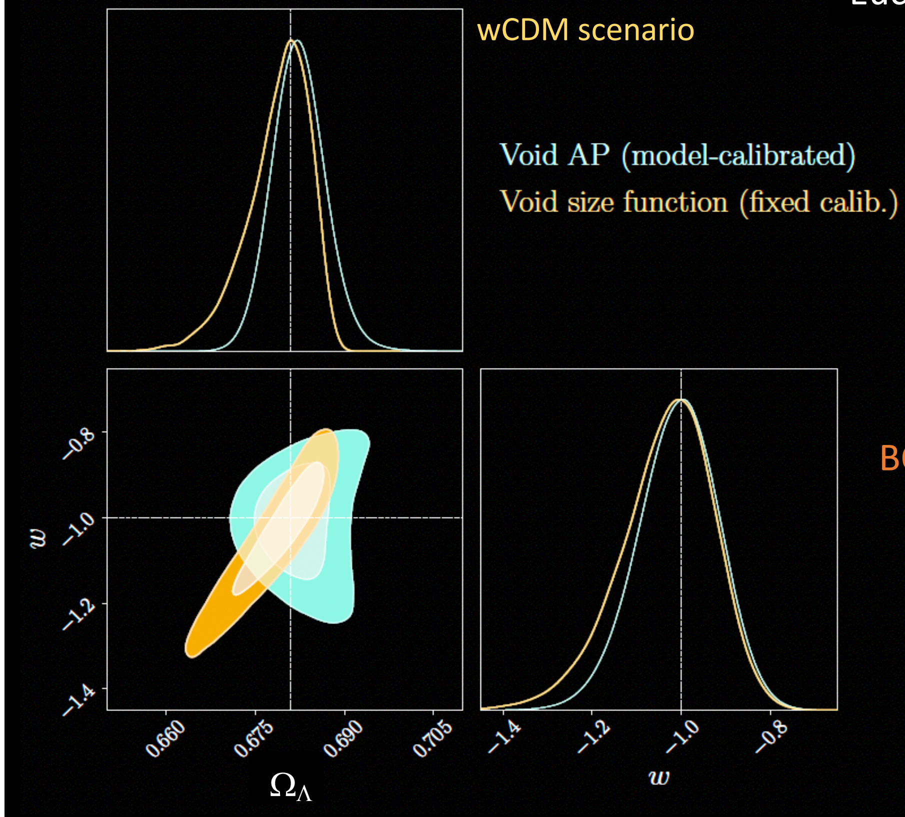


COMBINATION OF VOID STATISTICS

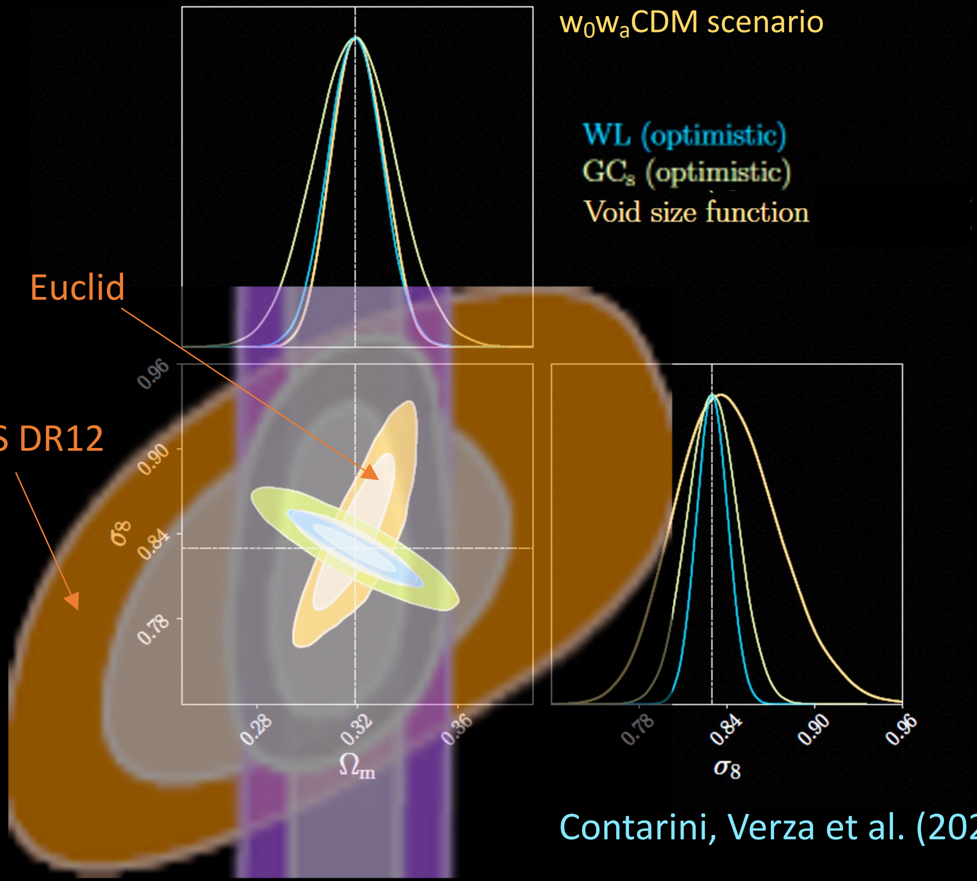
Parameter constraints on DE and DM

Euclid forecasts

wCDM scenario



w_0w_aCDM scenario



Euclid

BOSS DR12

Contarini, Verza et al. (2022)

Comparison between the void size function and different Euclid forecasts confidence level.

PRECISION COSMOLOGY WITH VOIDS

- Voids x CMB:
  1. Integrated Sachs-Wolfe effect
  2. CMB lensing

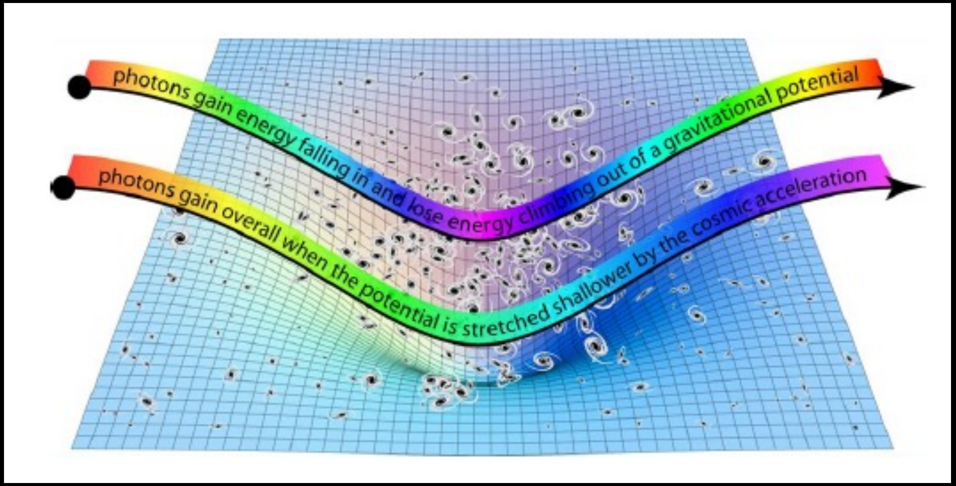
Void x CMB

1. Integrated Sachs-Wolfe (iSW) effect

THE IMPRINTS OF VOIDS ON THE CMB

The (late-time) Integrated Sachs-Wolfe (ISW) effect

Sachs and Wolfe (1967)



During the travel time of the photon:

- If the potential does not change

➔ the net effect is null

- If the potential changes, in the presence of dark energy or curvature

➔ the photon will emerge either red- or blue-shifted

The ISW effects probe the time-dependence of the potential.

$$\frac{\Delta T}{T_{CMB}} = -\frac{1}{c^2}\int (\Phi + \Psi)\, dt$$

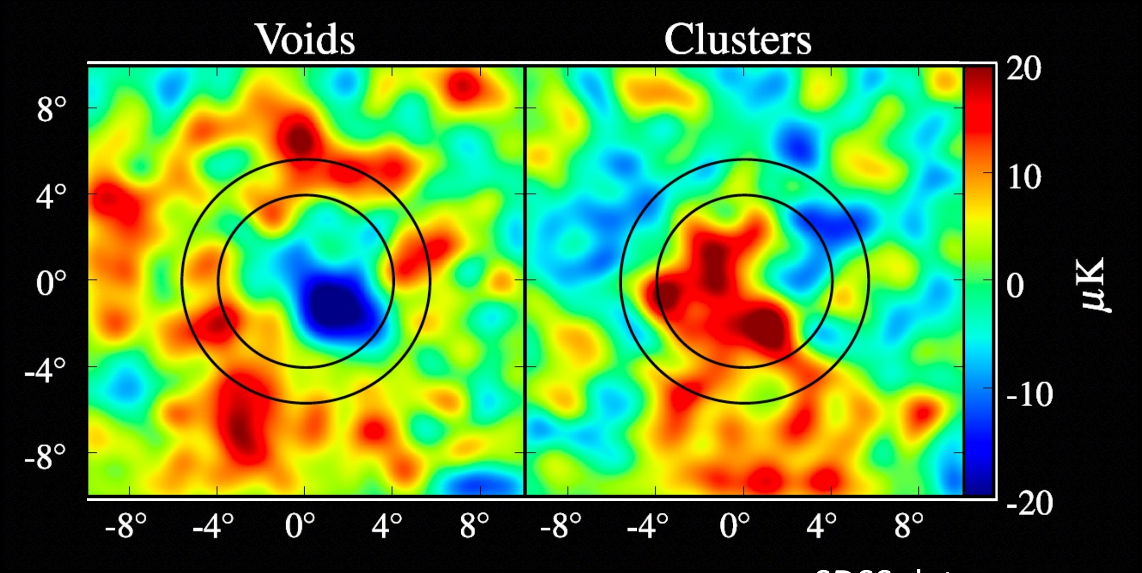
where the Φ and Ψ are the time derivative of the metric potentials

secondary CMB anisotropies << primordial CMB fluctuations

THE IMPRINTS OF VOIDS ON THE CMB

The (late-time) Integrated Sachs-Wolfe (ISW) effect

Stacking of CMB temperature map beyond each void/cluster



Granett et al. (2008)

SDSS data

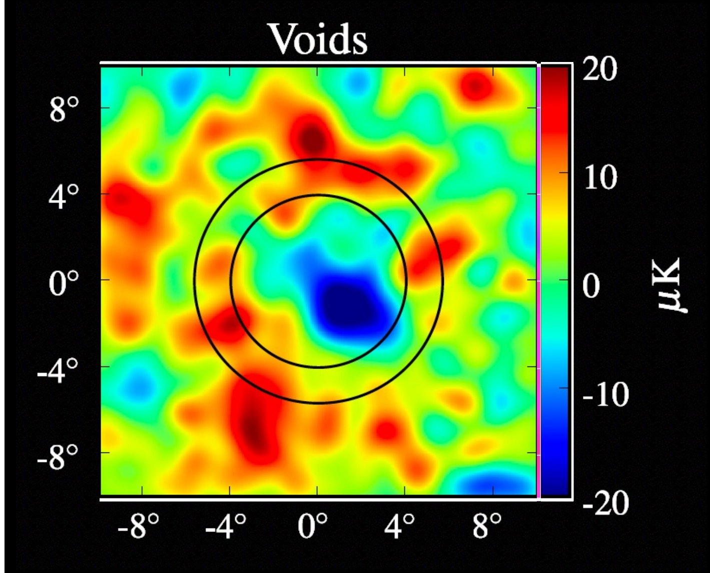
$$A_{ISW} = \frac{\Delta T^{ISW}_{data}}{\Delta T^{ISW}_{\Lambda CDM}}$$

$A_{ISW} = 1$ corresponds to the concordance ΛCDM prediction

THE IMPRINTS OF VOIDS ON THE CMB

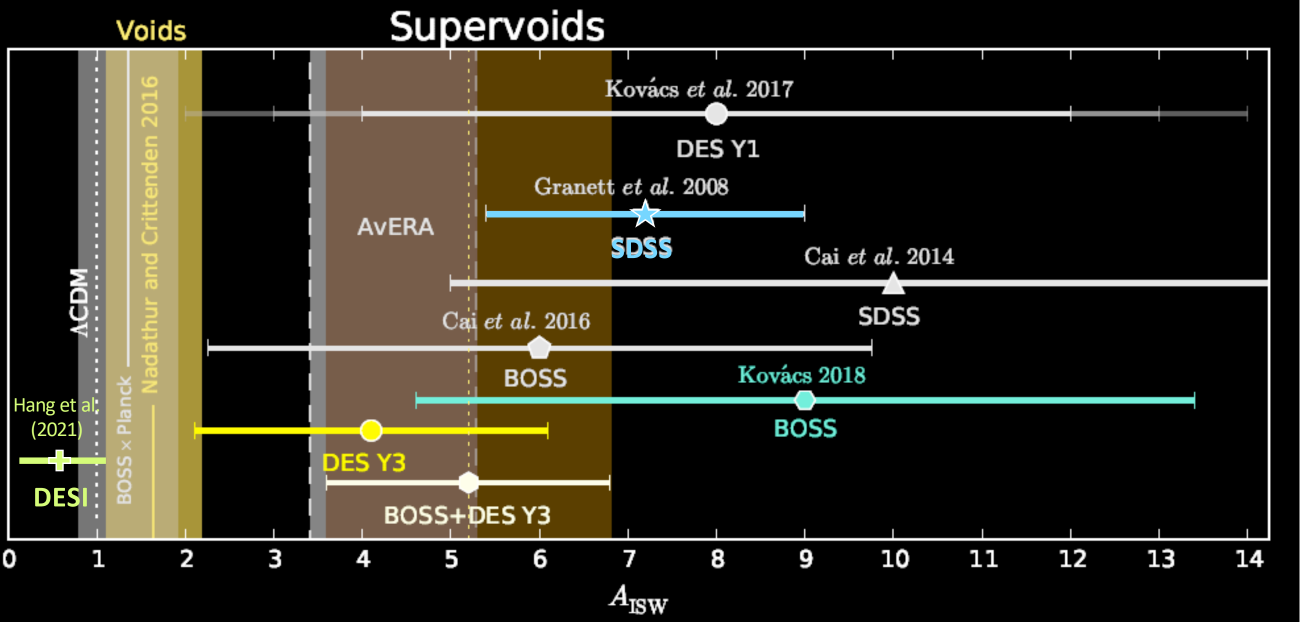
The (late-time) Integrated Sachs-Wolfe (ISW) effect

DES **supervoids** with radius R_v > 100 Mpc/h



Granett et al. (2008)

Kovacs et al. (2019)



$A_{ISW} = 5.2 \pm 1.6$

2.6σ tension with ΛCDM

➔ ISW anomalies from supervoids ?

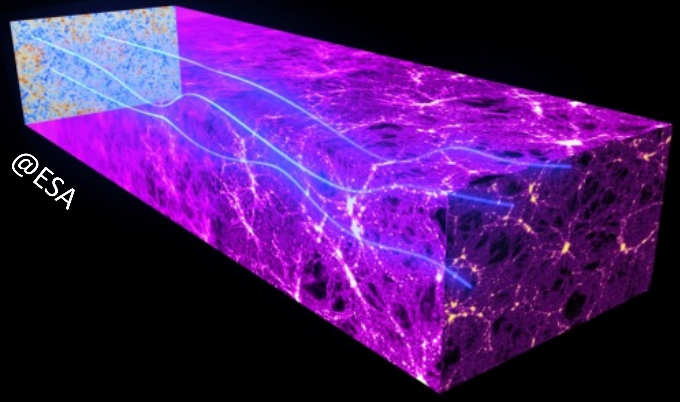
ISW in voids: a promising probe for cosmology—but still in its early stages

VOID X CMB

2. CMB lensing

THE IMPRINTS OF VOIDS ON THE CMB

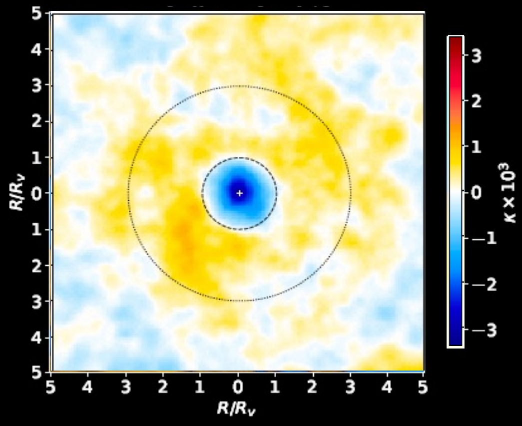
The CMB lensing

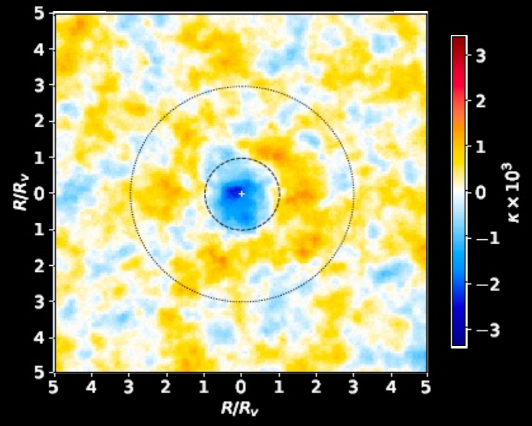


CMB is deflected by the gravitational lensing effect of massive cosmic structures

The lensing effects probe spatial variations of the potential.

Voids cause de-magnification effect and therefore correspond to local minima in the lensing convergence (κ) maps.


simulations MICE


Planck x DES data

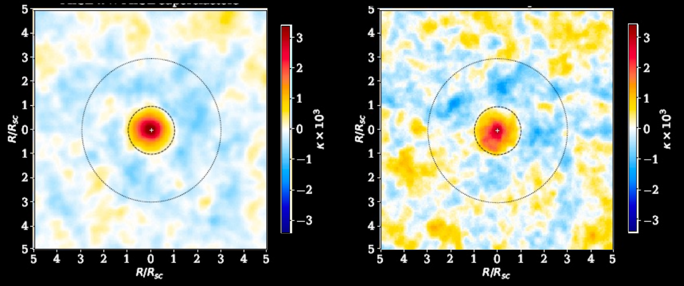
Vielzeuf, Kovacs et al. (2021)
Kovacs, Vielzeuf et al. (2022)

THE IMPRINTS OF VOIDS ON THE CMB

The CMB lensing

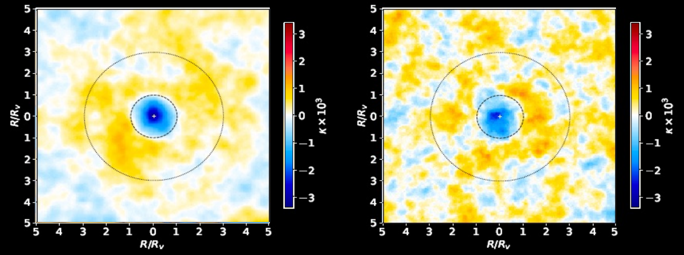
Superclusters

simulations MICE   Planck x DES data

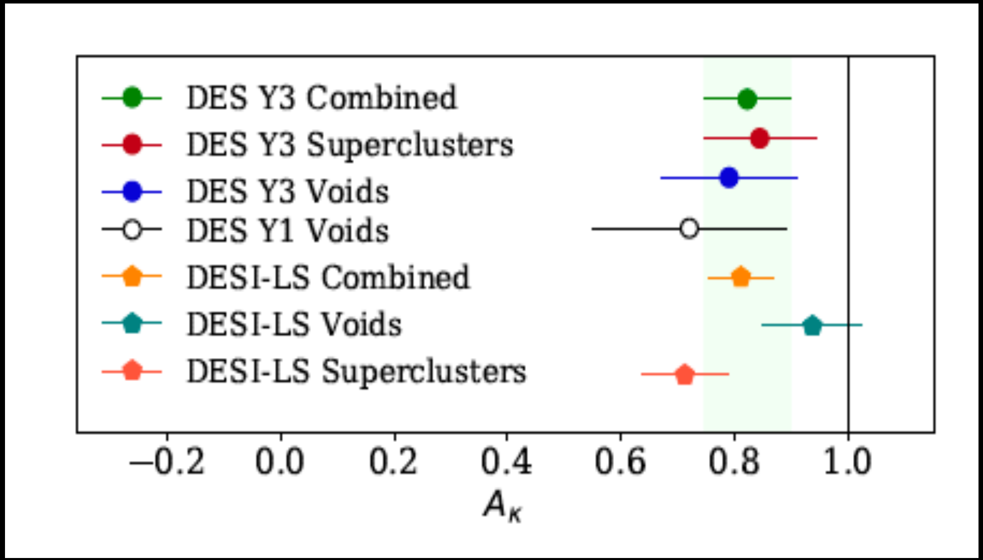


Voids

simulations MICE   Planck x DES data



DES data



Moderate tensions with ΛCDM

$$A_\kappa = \frac{\kappa_{data}}{\kappa_{\Lambda CDM}}$$

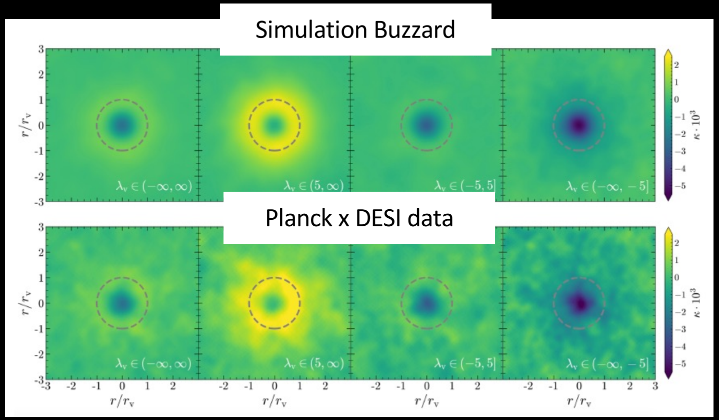
Vielzeuf, Kovacs et al. (2021)

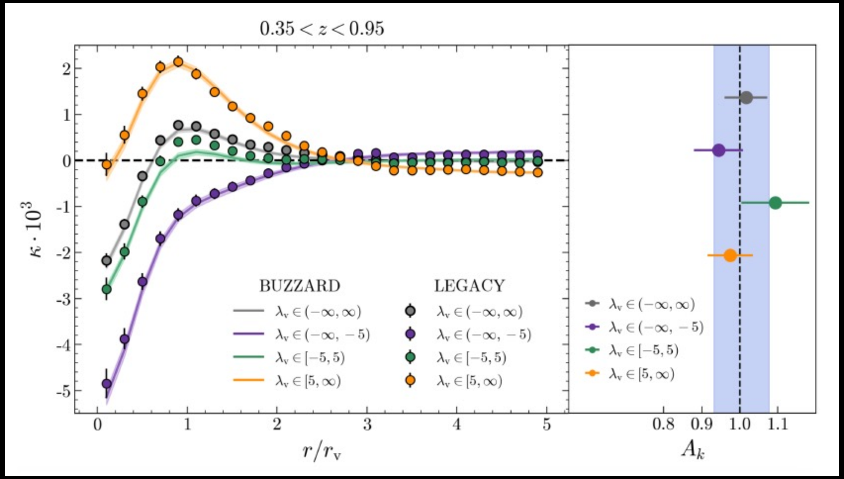
Kovacs, Vielzeuf et al. (2022)

THE IMPRINTS OF VOIDS ON THE CMB

The CMB lensing

DESI data

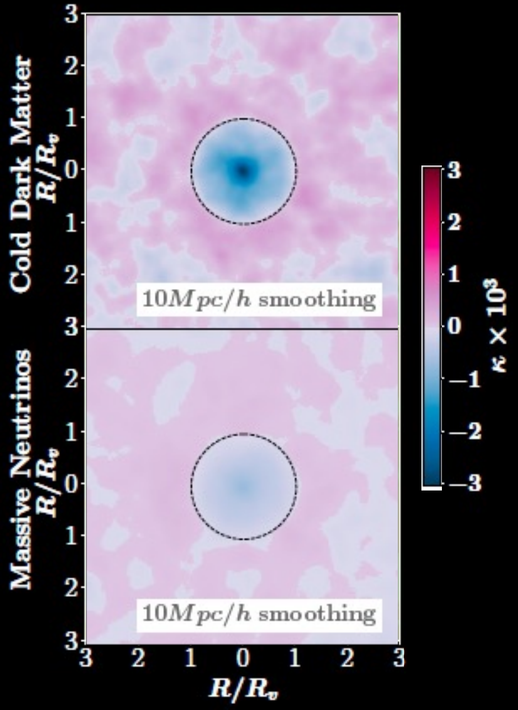




Sartori, Vielzeuf et al. (2026)

No tensions with latest measurements from DESI (with 17σ detection)

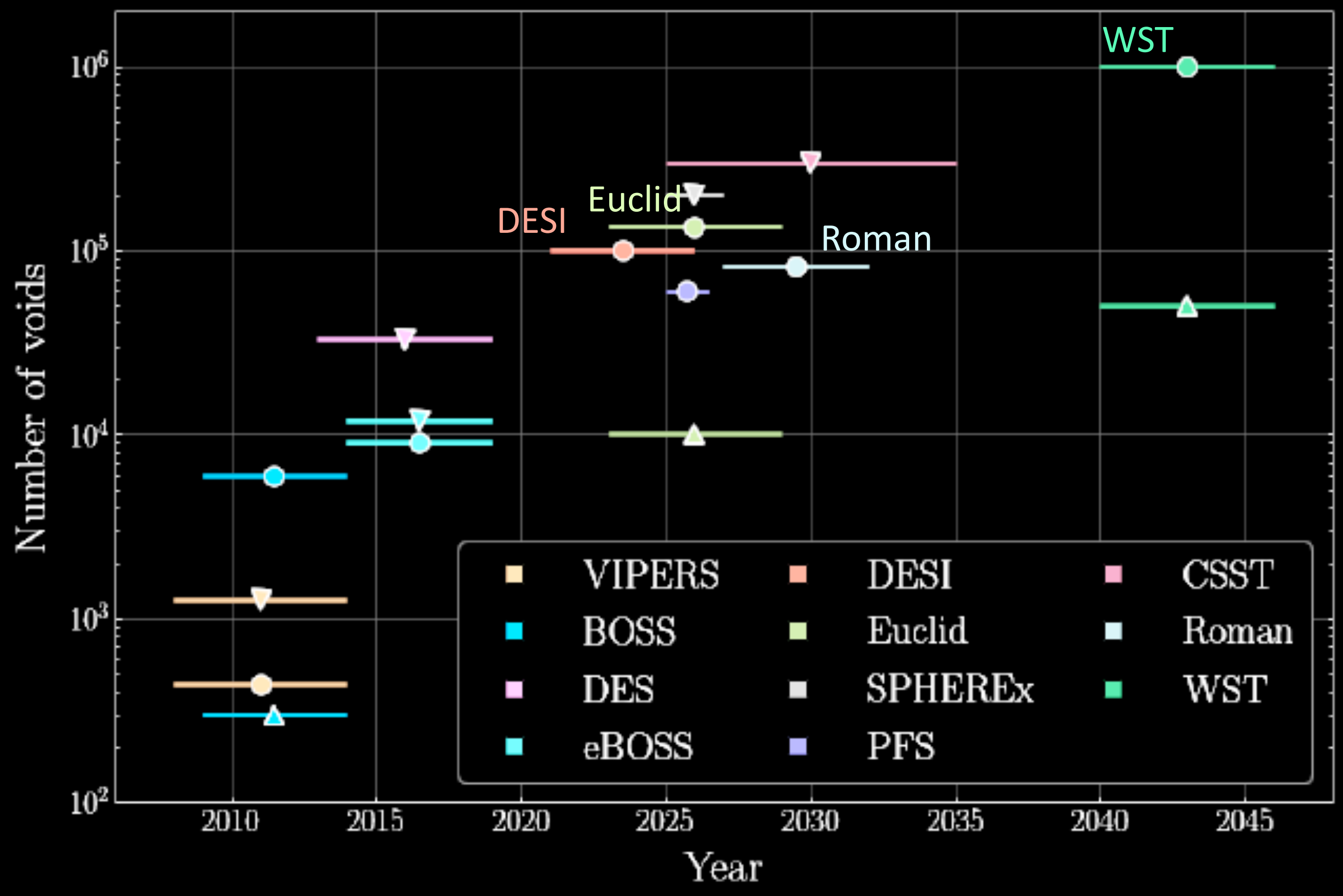
Euclid data



Vielzeuf et al. (2023)

Imprint of voids on CMB lensing, with/o massive neutrino with m_ν = 0.53 eV

COSMIC VOIDS IN LSS



With the advent of Stage IV galaxy surveys, we anticipate a wealth of void statistics—promising for compelling cosmological constraints.

SUMMARY

- Cosmic voids are large underdense regions of the Universe.

- Several statistics and observational applications of voids: density profiles, *redshift-space distortions, void size function, gravitational lensing and their imprints on the cosmic-microwave background + …*

- Cosmic voids are emerging as a major cosmological probe, with constraints on cosmology, including the sum of neutrino masses and the law of gravity.

Voids are entering a new era of precision