CMB Lensing Imprints of Cosmic Voids: A test of ΛCDM

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Outline of the talk

Comprehensive Background

- Recent developments in **void science**
- Modified gravity and the need to test **the ΛCDM model**
- Previous **void x CMB cross** correlation measurements

The Dark Energy Survey

We use **redMaGiC** galaxies (LRGs) from the **DES Year 3 (DES Y3)** dataset in order to identify voids.

Void Finders

Multiple void finders such as **3D Revolver (Voxel)** and **2D algorithm** have been used, in addition to **2D superclusters (inverted voids).**

Simulations

The MICE N-body simulation is used to calibrate our **ΛCDM expectations.**

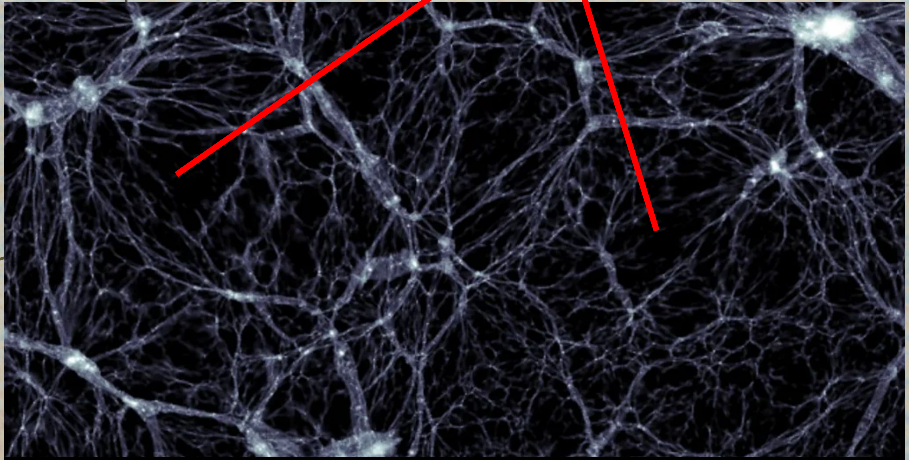
Background

Overview of ΛCDM

"Everything should be made as simple as possible, but not simpler." Albert Einstein

Why test ΛCDM?

Voids



Shown is the distribution of dark matter, with a width and height of 350 million light-years and a thickness of 300,000 light-years. Galaxies are found in the small, white, high-density dots. Markus Haider / Illustris collaboration

- 1) **Discrepancies** in the parameter estimates of the ΛCDM model from different methods (i.e early vs late).
- 2) Identifying **anomalies** that violate or challenge the assumptions.

- Recently number of **anomalies** and **tensions** within ΛCDM is observed
- S_8 Tension (Structure Growth)
- DESI DR2 BAO results (Time evolving DE)
- **Anomalies** (El Gordo cluster, "lensing is low" tension, radio dipole anisotropy, **CMB Cold Spot**, SN1A anisotropy etc)
- Excess **void-ISW** signal

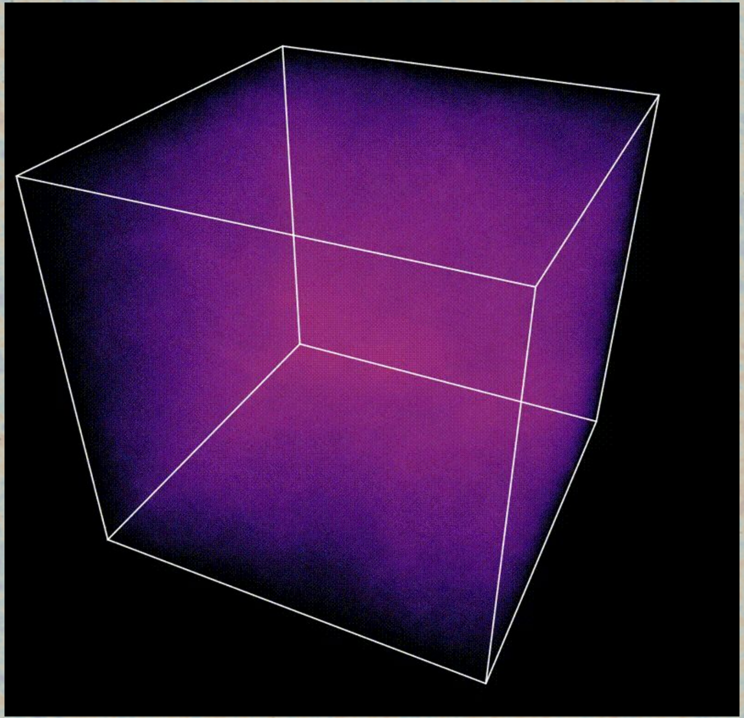
Background

Void Science

"Everything should be made as simple as possible, but not simpler." Albert Einstein

Voids & Modified Gravity

- The Fifth force is **unscreened** in **voids,** causing emptier, larger void cores in **f(R)** and **nDGP** models [1803.07533](https://arxiv.org/abs/1803.07533) (Baker, et al ,2018)
- This effect can cause **amplified weak-lensing imprints** on galaxy shapes (shear) and on **the CMB.**
- This is complicated by **neutrinos free streaming** in voids [2009.03309](https://arxiv.org/abs/2009.03309) (Contarini et al,2021)
- **Void number and size function shift** – MG adds extra large voids [1905.12450](https://arxiv.org/abs/1905.12450) (Perico et al, 2019)



Dark matter: Credited to Eagle Simulation

Voids x CMB (ISW)

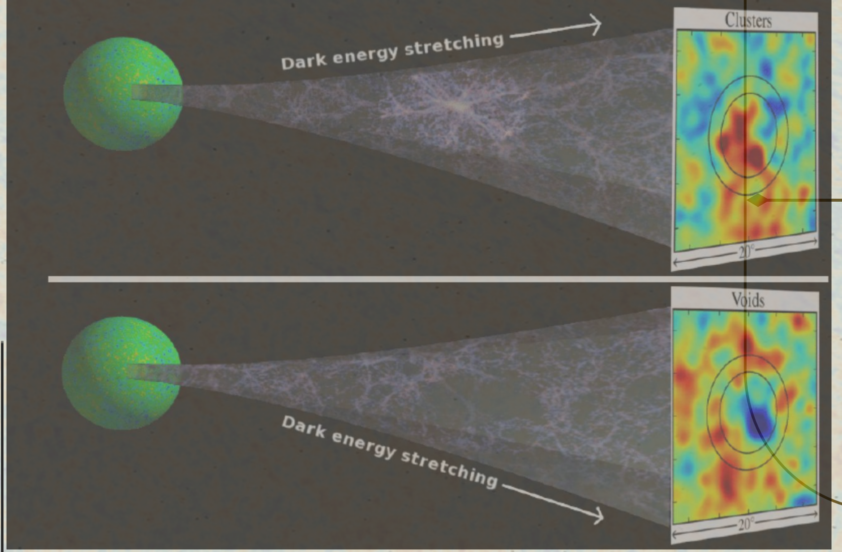
Integrated Sachs-Wolfe (ISW) Effect (Late)

- Theoretically **7.9 sigma detection of ISW** is possible in ΛCDM (Crittenden & Turok, 1996)

- **Conflicting claims** in literature (Excess signals about 2-3σ, sign change,"look elsewhere effect") (Kovacs et al, 2019 1811.07812) and (Hang et al, 2021, 2105.11936), (Nadathur & Crittenden, 2016, 1608.08638)

- **Conflicting literature** on the **CMB Cold Spot** being caused by a huge void (This can only be possible **if ISW is 5-7 times in excess of ΛCDM)**

$$\frac{\Delta T_{\rm ISW}}{\overline{T}}(\hat{\boldsymbol{n}}) = -2\int_0^{z_{\rm LS}} a\left[1-f(z)\right]\Phi\left(\hat{\boldsymbol{n}},z\right)\,\mathrm{d}z$$



Credited to Istvan Szapudi

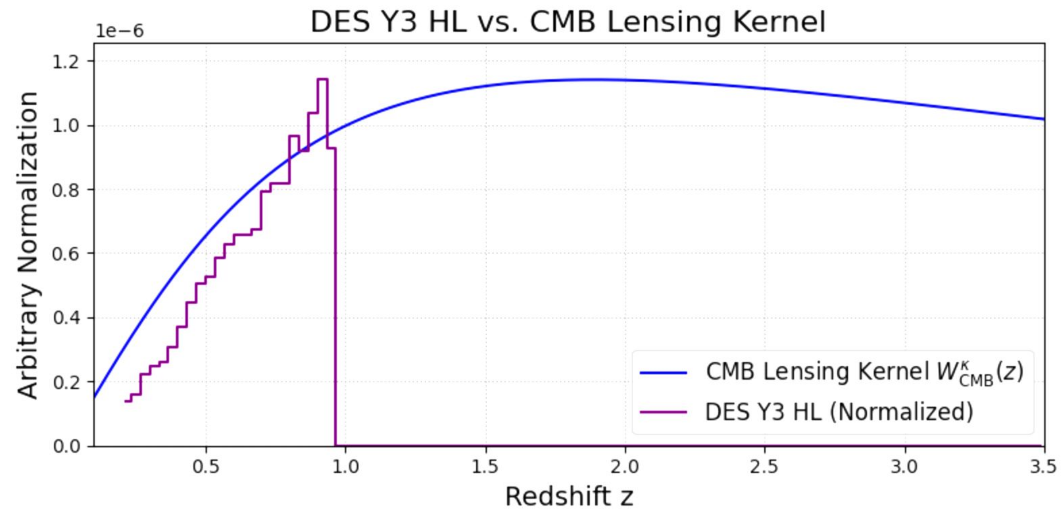
- More ISW tension from low-z **voids and filaments** claiming ISW sign- change 2506.08833 (Feldman et al, 2025) & 2506.08832 (Hansen et al, 2025)

- May receive **more attention** after DESI DR2 BAO Results

Voids x CMB (Lensing)

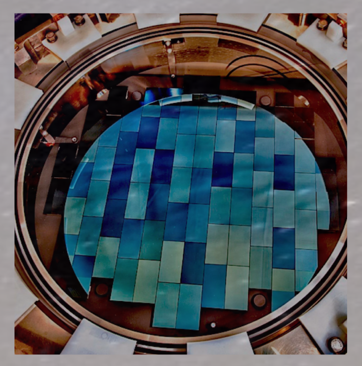
CMB Lensing

- The **Dark Energy Survey (DES)** provides high-quality **photometric data** for galaxies out to **z ≈ 1**.
- The **CMB-lensing kernel peaks near z ≈ 2**, so surveys that reach deeper redshifts overlap the region of maximum signal.
- Forthcoming projects like **Euclid (z ≳ 2)** and **Rubin-LSST (z ≳ 3)** will boost the signal-to-noise of **galaxy survey × CMB-lensing** cross-correlations due to their **high redshift** capability.
- Much higher **detection significances** compared to ISW! See Cosmoverse White paper!



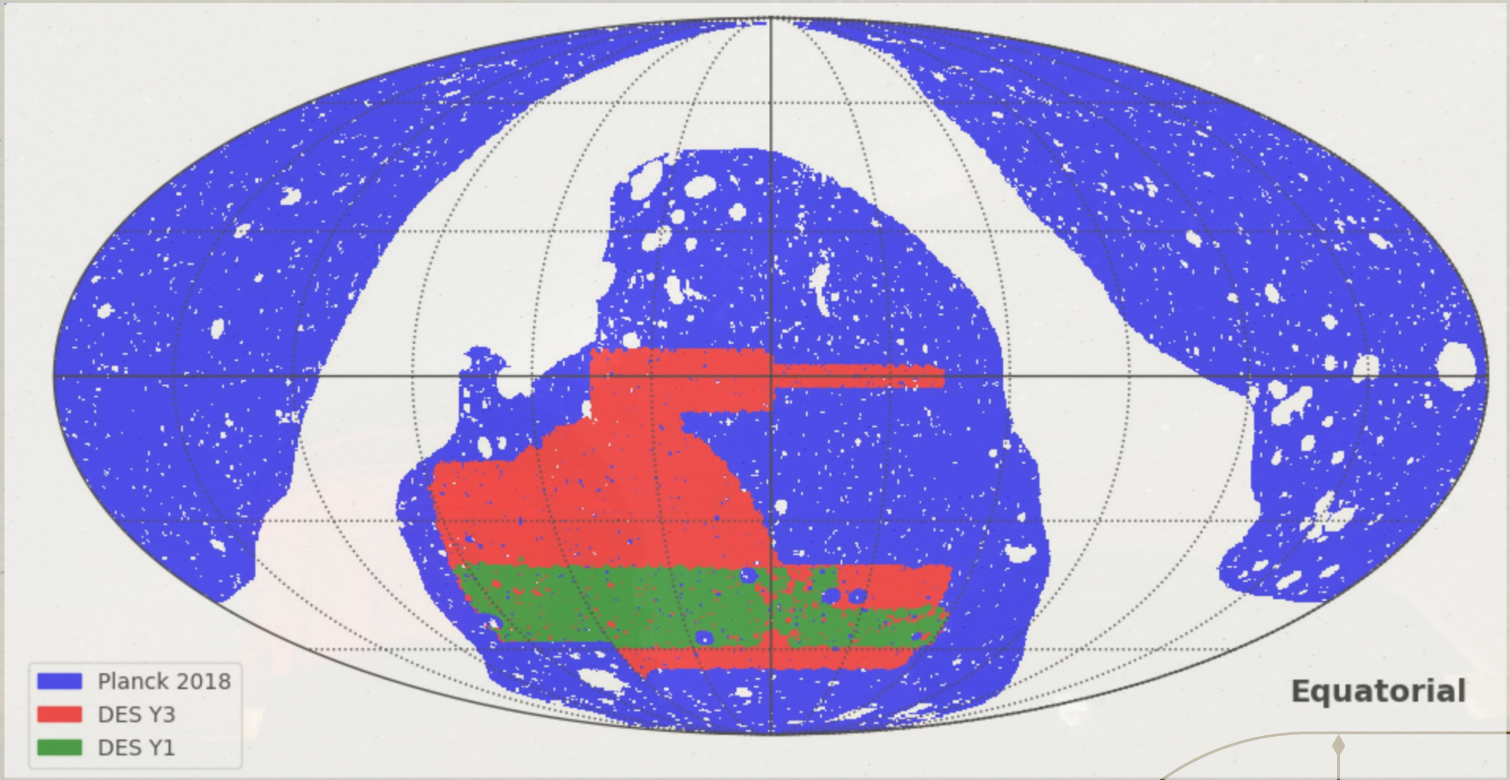
Dark Energy Survey

570 Megapixel DECam



- **Optical/photometric** grizY imaging across ~5 000 deg² of the southern sky (effectively 4200 deg²)
- **570 – MP** DECam on the Blanco 4 m telescope, **Cerro Tololo, Chile.**
- **Year 6 Gold** catalog > 400 M objects to *i* ≈ 24 mag depth.
- **Different galaxy samples (redMaGiC vs MaGliM)**
- **Full-depth Y6 cosmology results due this year (2025).**

Dark Energy Survey

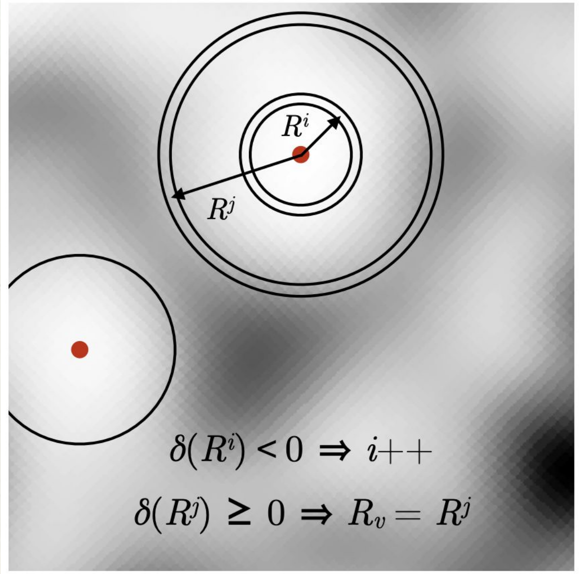


Background

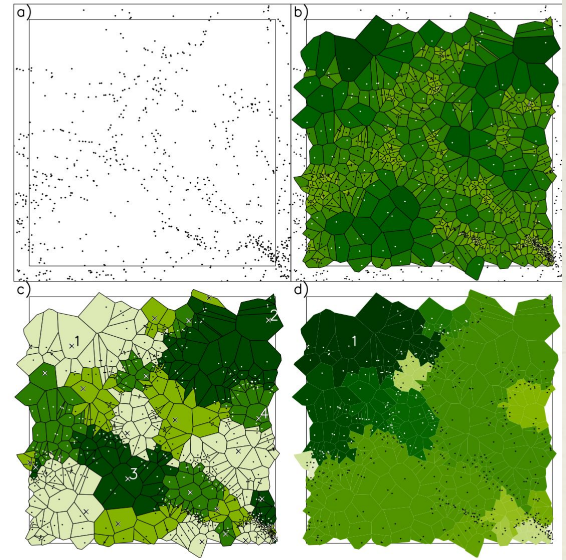
Cosmic Voids

"For small creatures such as we, the vastness of the Universe is made bearable only through love" Carl Sagan

Cosmic Voids



Credited to Sanchez et al, 2017



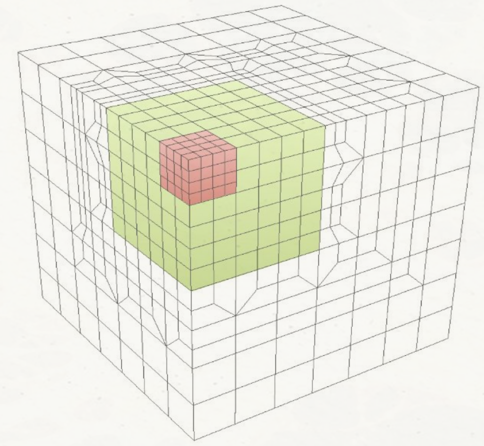
Credited to Neyrinck et al, 2008

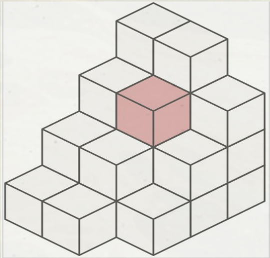
2D voids that are circular and defined on projected and smoothed **tomographic redshift bins.**

3D voids are identified using a tessellation algorithm called **ZOBOV**. VIDE voids are based on this ZOBOV algorithm. **REVOLVER** outputs two types of voids: one is based on ZOBOV, and the other is **voxel.**

Cosmic Voids – Voxel Voids

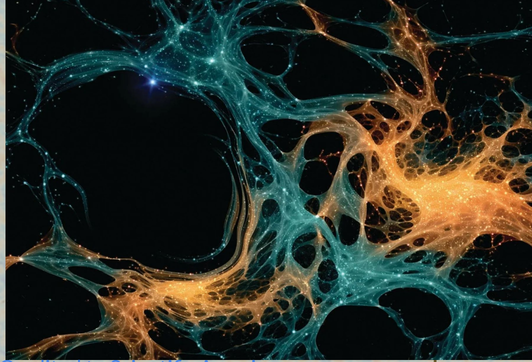
- **Voxel voids** are **watershed voids** not using **Voronoi tessellation**, but using **survey randoms**
- Density field is evaluated on a **mesh** with size N_{mesh} determined by **mean tracer number density**
- Density field is **smoothed** using a **Gaussian filter** that is a function of mean density
- **Local minima** in density field identified in the voxels (cubes), similar to ZOBOV
- **Basin growth** stops when next voxel is emptier than previous one
- Free parameters are chosen as a function of mean tracer density and **no basin** merging applied





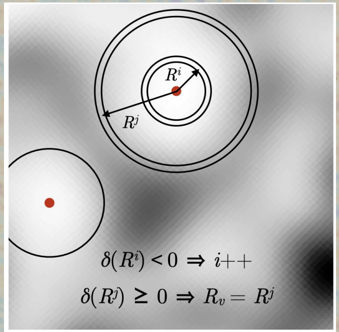
$$\lambda_v \equiv \bar{\delta}_g \left(\frac{R_v}{1\,\mathrm{Mpc}/h} \right)^{1.2}$$

Void Finders Overview


Credited to Scientific American

2D

Defined on **tomographic redshift bins** on smoothed density fields. Requires specification **smoothing scale**, **thickness of the bin** and **the maximum underdensity** level for the void center. Used in both Year-1, mass map and Year 3 studies.



REVOLVER

Outputs two void definitions with a parameter λv

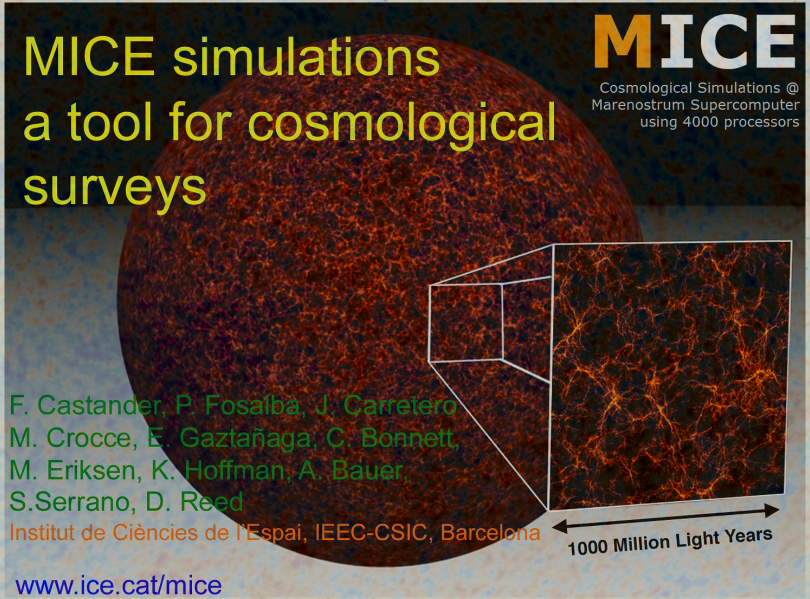
1) 3D ZOBOV-Based: No basin merging, uses maximum empty sphere center.

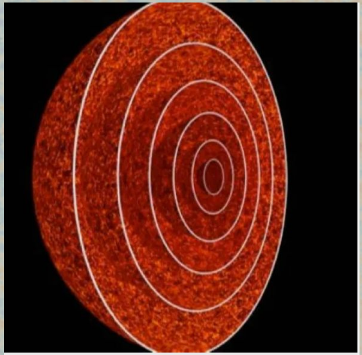
2) 3D Cubic Voxels: Galaxy density field normalized by randoms; **no basin merging** and handles **complex survey footprints better**. Uses **maximum empty sphere center** definition.

$$\lambda_v \equiv \bar{\delta}_g \left(\frac{R_v}{1\,\mathrm{Mpc}/h} \right)^{1.2}$$

Background

MICE Simulation

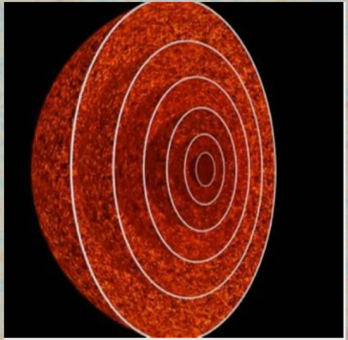




The Onion Universe

MICE Simulation

- Widely adopted for **DES mock analyses** and offers **finer mass resolution** than earlier large-volume suites.
- Generates an all-sky light-cone (one realisation) with snapshots spanning **$0 \leq z \lesssim 1.4$**; galaxies populate one octant
- Supplies a full-sky **CMB-lensing k-map** built via the **“Onion Universe” shell-stacking method**. (See 0711.1540)
- Galaxies assigned with **smooth, redshift-varying HOD parameters** to maintain continuous density across the cone.
- Used to create the **template profiles** of **CMB lensing imprints of voids in Demirbozan et al, 2024** 2404.18278

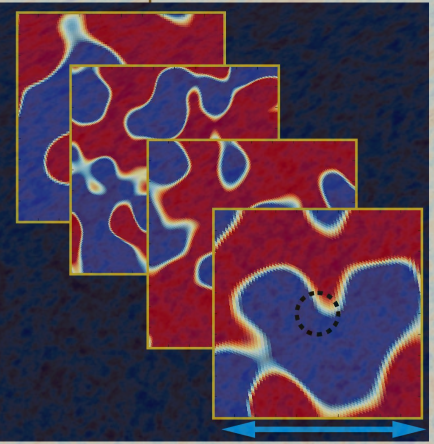


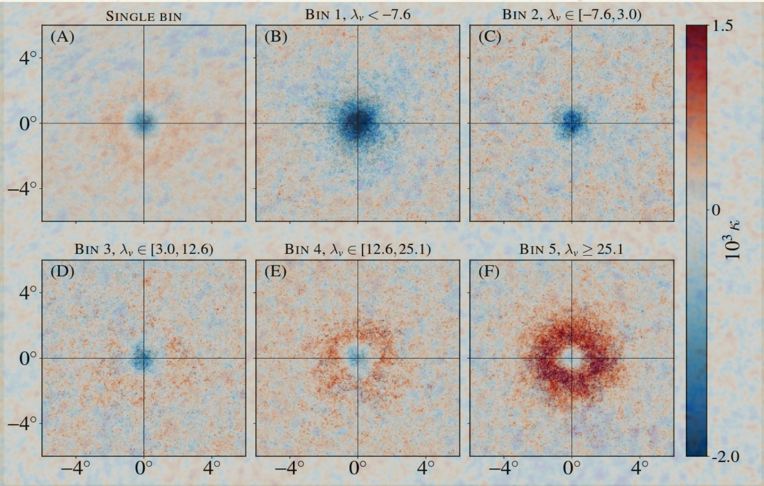
The Onion Universe

Background

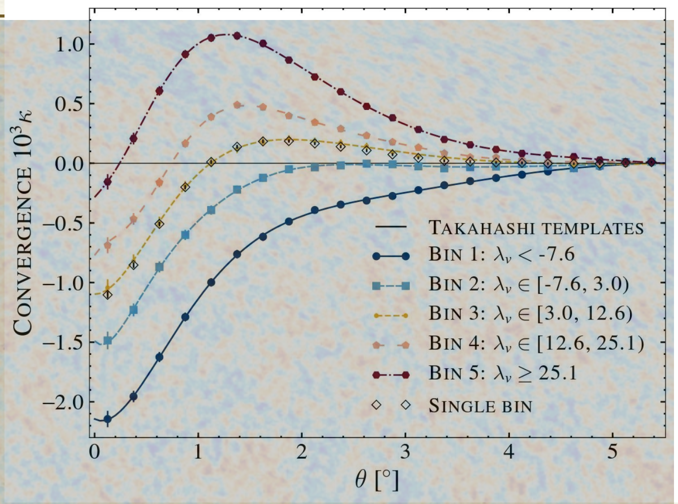
Methodology

Methodology - Stacking





Credited to Raghunathan et al 2019



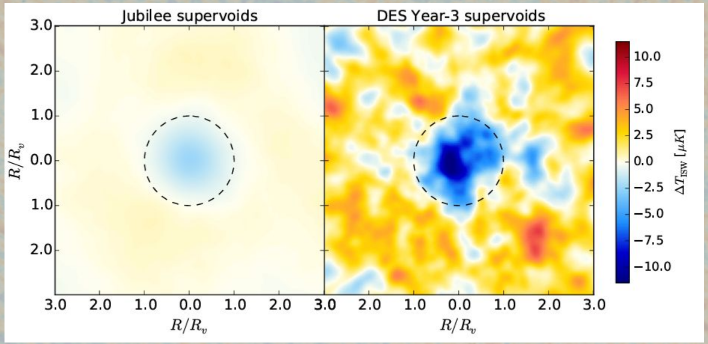
Credited to Raghunathan et al 2019

- Using *Healpy*, we **extract CMB patches centered on voids**—either **resizing them** to 5 Rv or fixing them at 10° × 10°—and stack these cutouts to improve S/N.
- We then measure **2D profiles** from the **resulting stacked images** for both the **N -body simulation** and the **observational data**.

Methodology

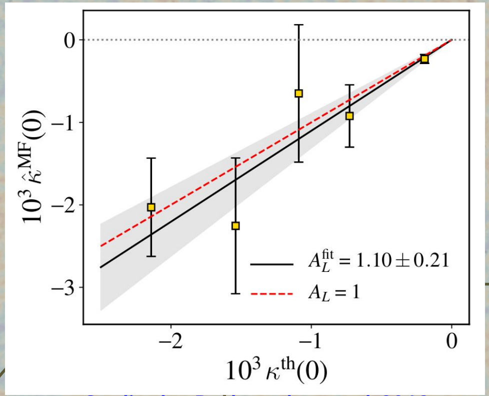
Two Methods

- Gaussian filtering
- Re-scaling CMB cutouts to void radius



Credited to Kovacs et al, 2019

- Optimal matched filtering based on simulations (templates)



Credited to Raghunathan et al, 2019

DES Y3 Voids x CMB Lensing

Matched Filtering

The Gravitational Lensing Imprints of DES Y3 Superstructures on the CMB: A Matched Filtering Approach

Umut Demirbozan, Seshadri Nadathur, Ismael Ferrero, Pablo Fosalba, Andras Kovacs, Ramon Miquel, Christopher T. Davies, Shivam Pandey, Monika Adamow, Keith Bechtol, Alex Drlica-Wagner, Robert Gruendl, Will Hartley, Adriano Pieres, Ashley Ross, Eli Rykoff, Erin Sheldon, Brian Yanny, Tim Abbott, Michel Aguena, Sahar Allam, Otavio Alves, David Bacon, Emmanuel Bertin, Sebastian Bocquet, David Brooks, Aurelio Carnero Rosell, Jorge Carretero, Ross Cawthon, Luiz da Costa, Maria Elidaiana da Silva Pereira, Juan De Vicente, Shantanu Desai, Peter Doel, Spencer Everett, Brenna Flaugher, Douglas Friedel, Josh Frieman, Marco Gatti, Enrique Gaztanaga, Giulia Giannini, Gaston Gutierrez, Samuel Hinton, Devon L. Hollowood, David James, Niall Jeffrey, Kyler Kuehn, Ofer Lahav, Sujeong Lee, Jennifer Marshall, Juan Mena-Fernández, Joe Mohr, Justin Myles, Ricardo Ogando, Andrés Plazas Malagón, Aaron Roodman, Eusebio Sanchez, Ignacio Sevilla, Mathew Smith, Marcelle Soares-Santos, Eric Suchyta, Molly Swanson, Gregory Tarle, Noah Weaverdyck, Jochen Weller, Philip Wiseman

Demirbozan, U., Nadathur, S., Ferrero, I., et al. 2024, MNRAS, 534, 2328

2404.18278

Matched Filtering

- **Maximises S/N** by projecting the Planck k-map onto the expected void profile (templates) from simulations.
- **Assuming isotropic noise** and down-weights unrelated modes automatically.
- **Tailor-made filters** depending on **void sub samples** boost detections (Nadathur & Crittenden 2016; Raghunathan et al. 2019).
- **No arbitrary smoothing scale**—all signal collapses into **one amplitude** and this make it **computationally cheaper** for covariance estimation
- Uniquely determines the **spherical harmonics coefficients** of the resulting matched filters in Fourier space
- **Encapsulates** all the signal into the $\boxed{\text{void center}}$

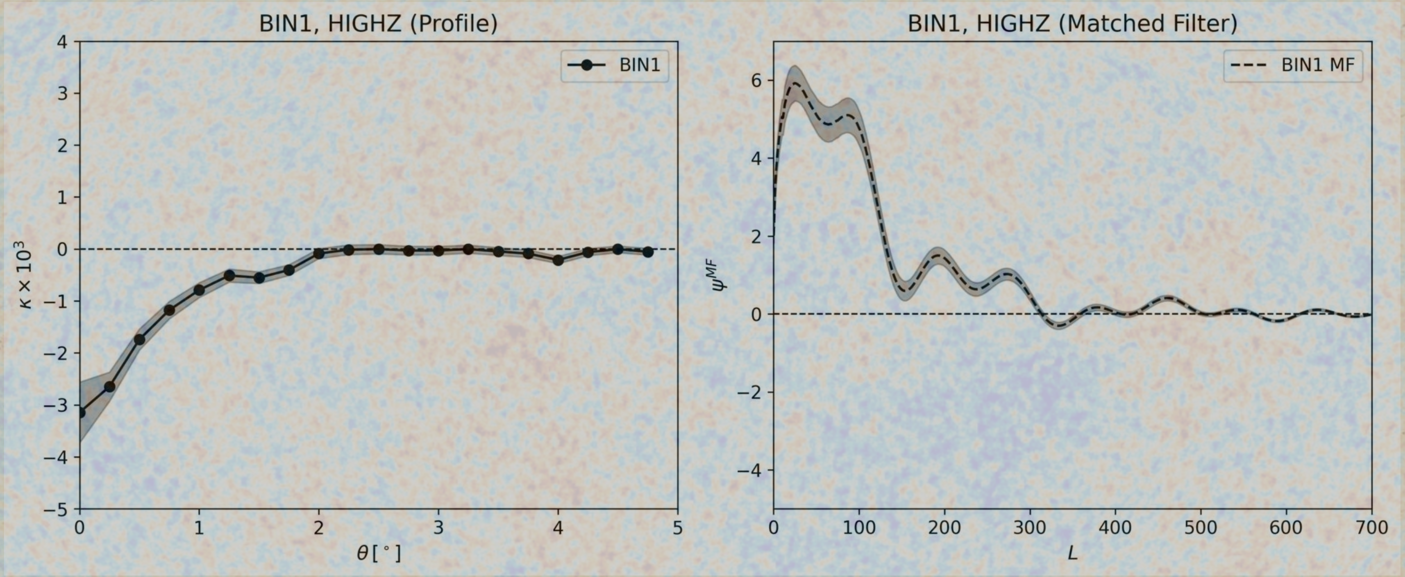
$$\kappa(\boldsymbol{\theta}) = \kappa_{\text{template}}(|\boldsymbol{\theta} - \boldsymbol{\theta}_0|; \lambda_v) + n(\boldsymbol{\theta})$$

$$\begin{aligned}\kappa_{\text{template}}(\theta;\lambda_v) &= \kappa_0(\lambda_v)k(\theta;\lambda_v) \\ &= \kappa_0(\lambda_v)\sum_{L=0}^{\infty} k_{L0}(\lambda_v)Y_L^0(\cos\theta)\end{aligned}$$

$$\Psi_{L0}^{\text{MF}}(\lambda_v) = \alpha \frac{k_{L0}(\lambda_v)}{C_L^{N,tot}}$$

$$\alpha^{-1} \equiv \sum_{L=0}^{\infty} \frac{k_{L0}^2(\lambda_v)}{C_L^{N,tot}}$$

Matched Filtering

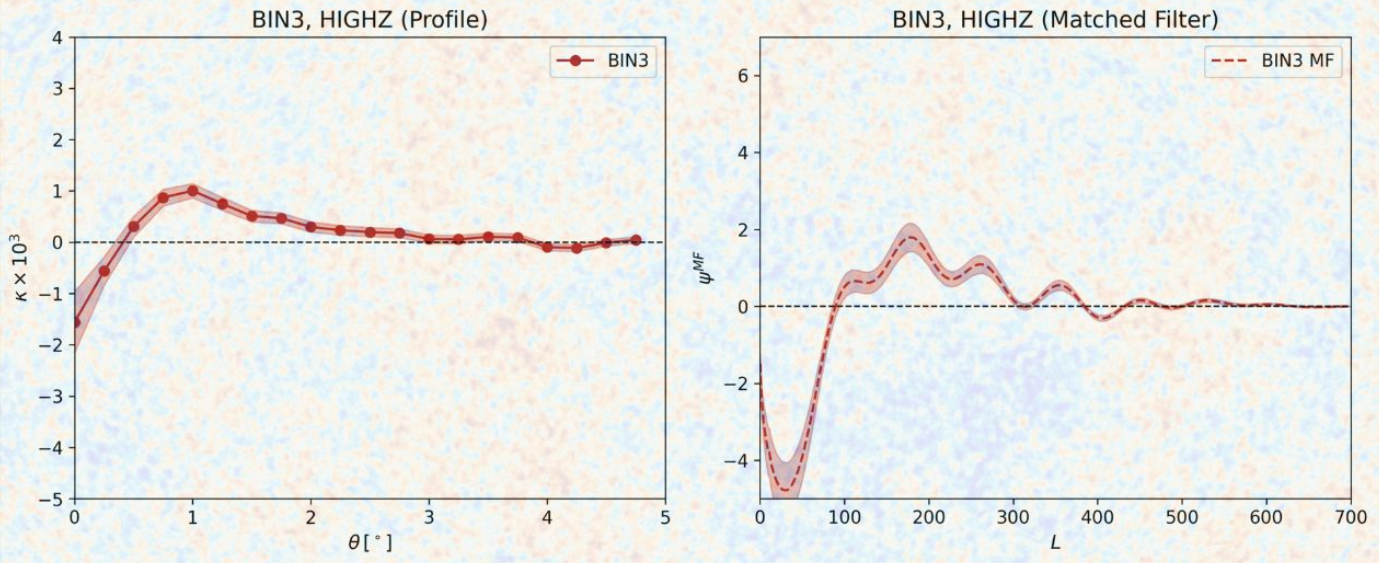


Credited to Demirbozan et al, 2024

$$\kappa_{\mathrm{template}}(\theta;\lambda_v) = \kappa_0(\lambda_v) k(\theta;\lambda_v) = \kappa_0(\lambda_v) \sum_{L=0}^{\infty} k_{L0}(\lambda_v) Y_L^0(\cos\theta)$$

$$\Psi_{L0}^{\mathrm{MF}}(\lambda_v) = \alpha \frac{k_{L0}(\lambda_v)}{C_L^{N,tot}}$$

Matched Filtering



Credited to Demirbozan et al, 2024

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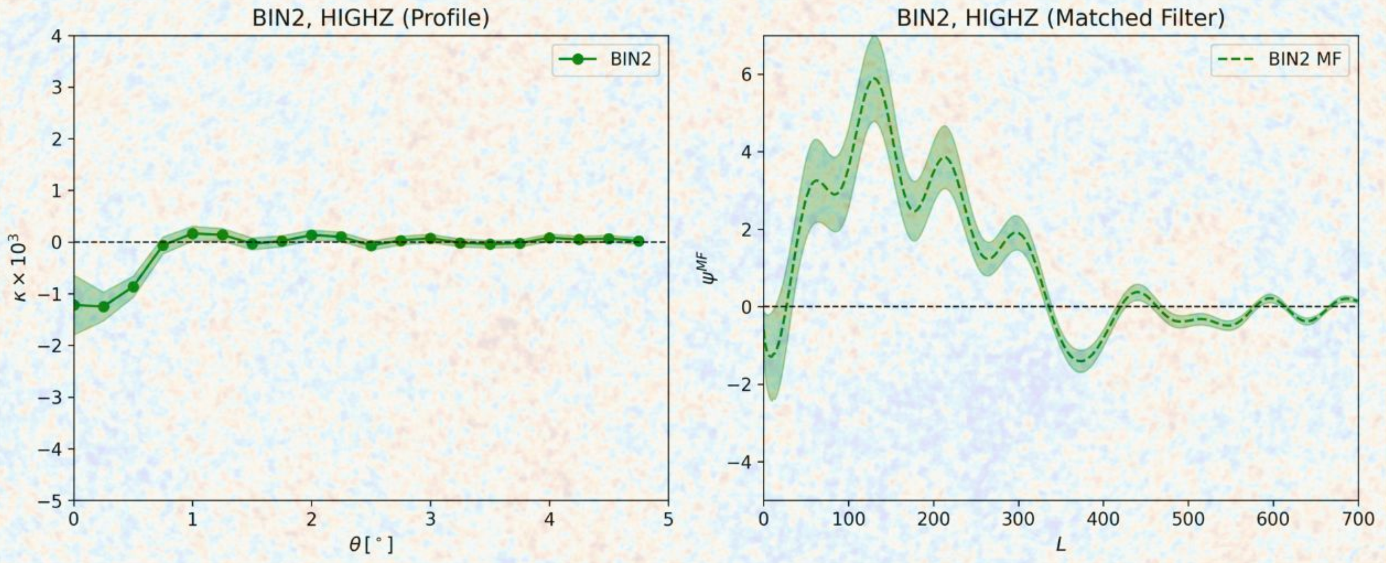
$$\Psi^{\rm MF}_{L0}(\lambda_v) = \alpha \frac{k_{L0}(\lambda_v)}{C_L^{N,tot}}$$

Matched Filtering



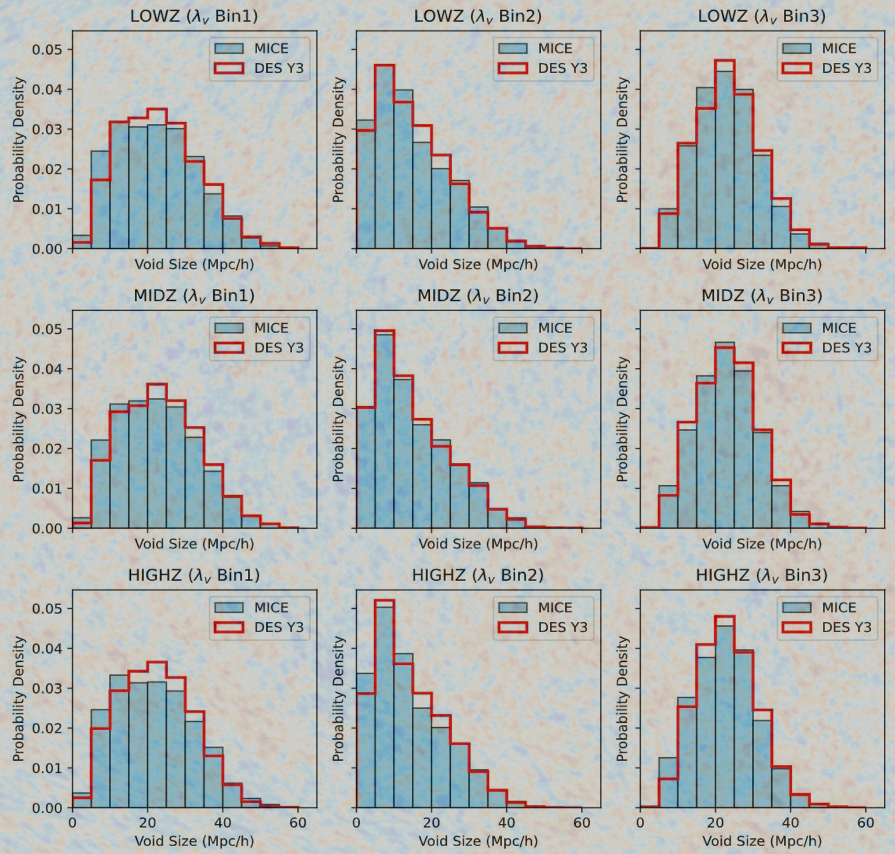
Credited to Demirbozan et al, 2024

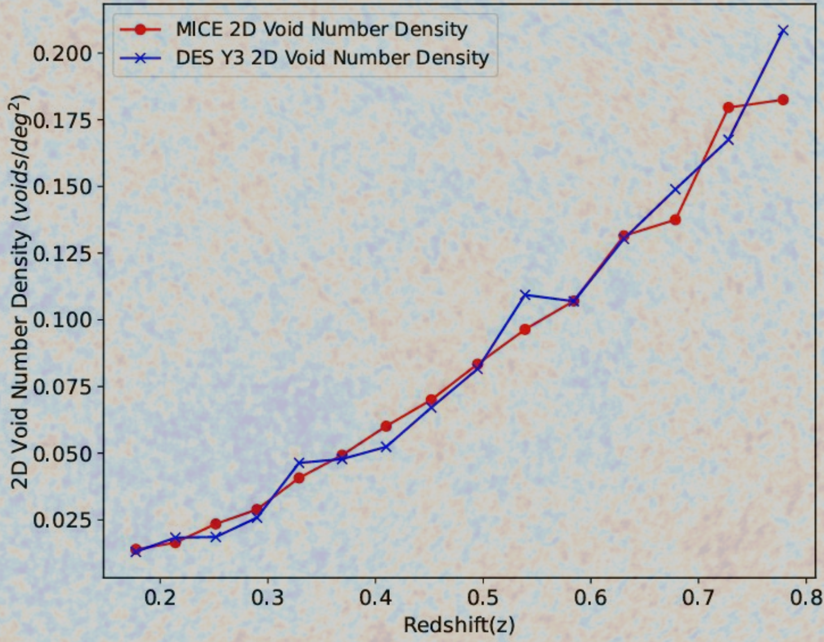
$$\kappa_{\rm template}(\theta;\lambda_v) = \kappa_0(\lambda_v)k(\theta;\lambda_v)$$
$$= \kappa_0(\lambda_v)\sum_{L=0}^{\infty} k_{L0}(\lambda_v)Y_L^0(\cos\theta)$$

$$\longrightarrow$$

$$\Psi_{L0}^{\rm MF}(\lambda_v) = \alpha\frac{k_{L0}(\lambda_v)}{C_L^{N,tot}}$$

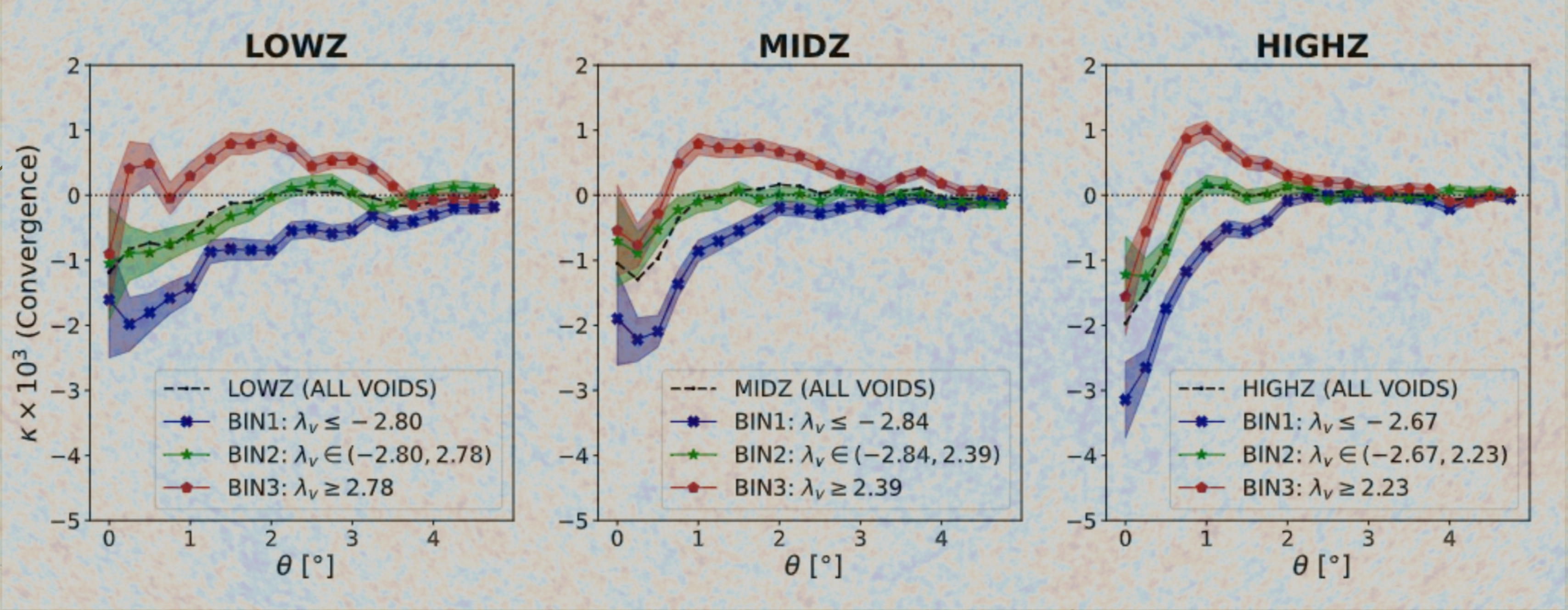
Void Size Function





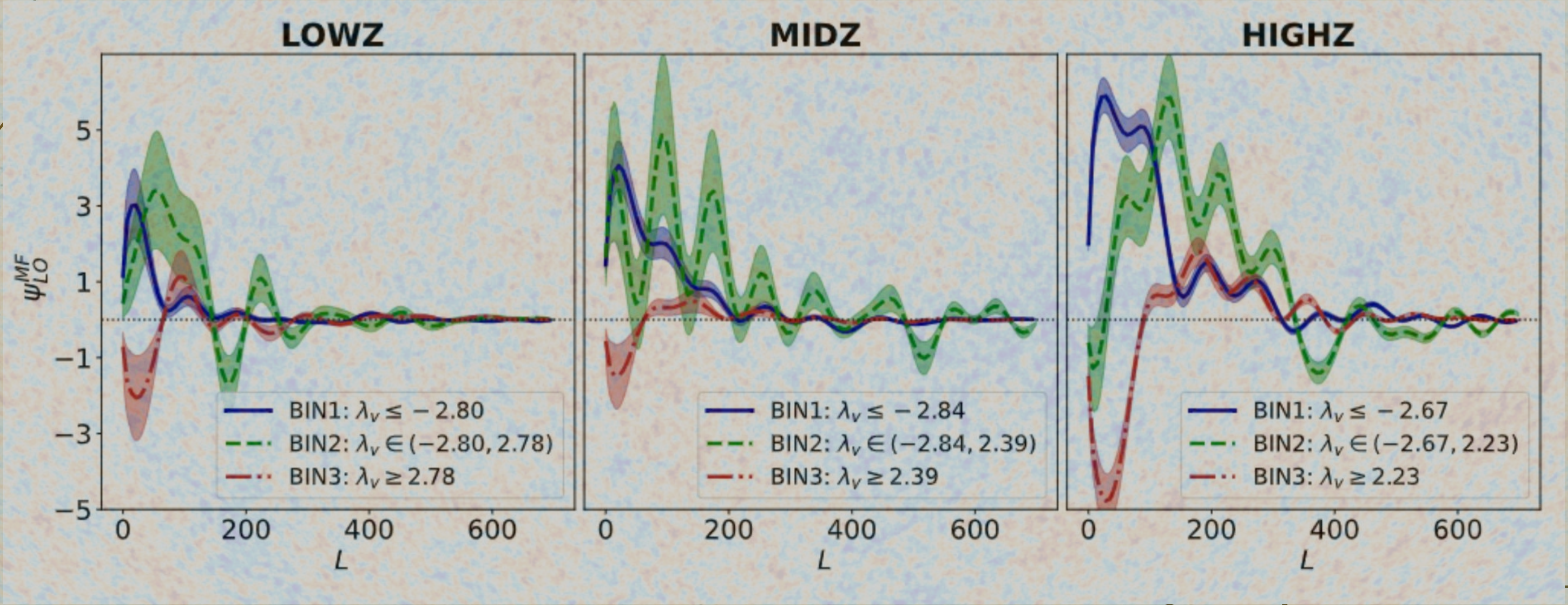
LOWZ (0.2 - 0.43)
MIDZ (0.43 - 0.59)
HIGHZ (0.59 - 0.75)

MICE Template Profiles



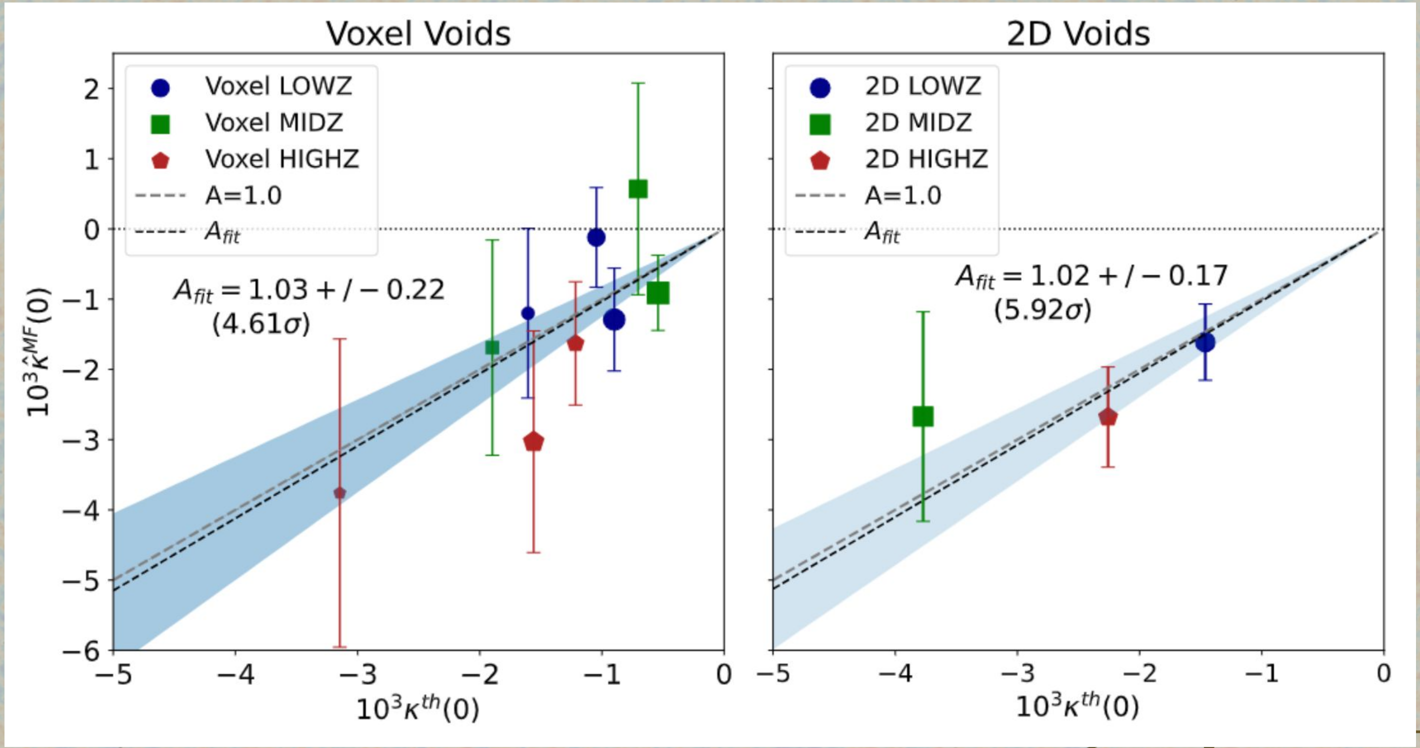
Credited to Demirbozan et al, 2024

Corresponding Matched Filters



Credited to Demirbozan et al, 2024

Results – Matched Filter

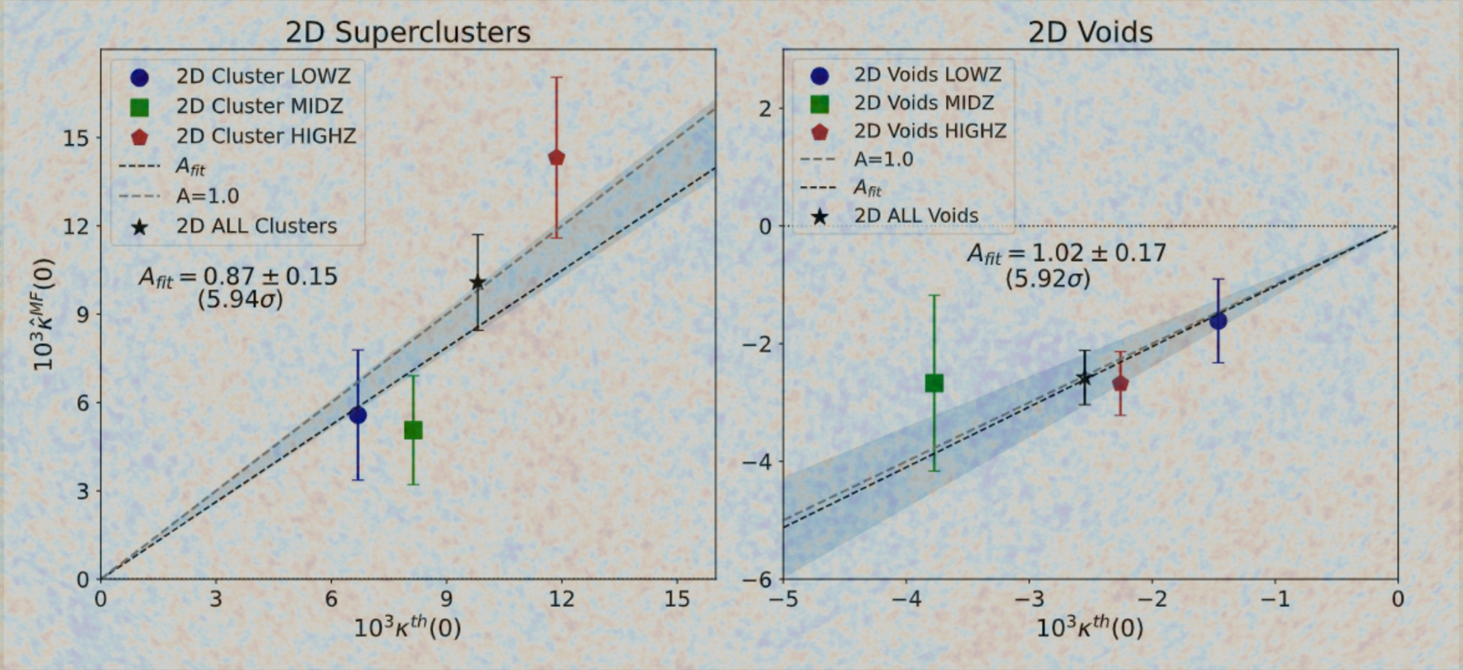


DES Y3

MICE

Results – 2D Superclusters

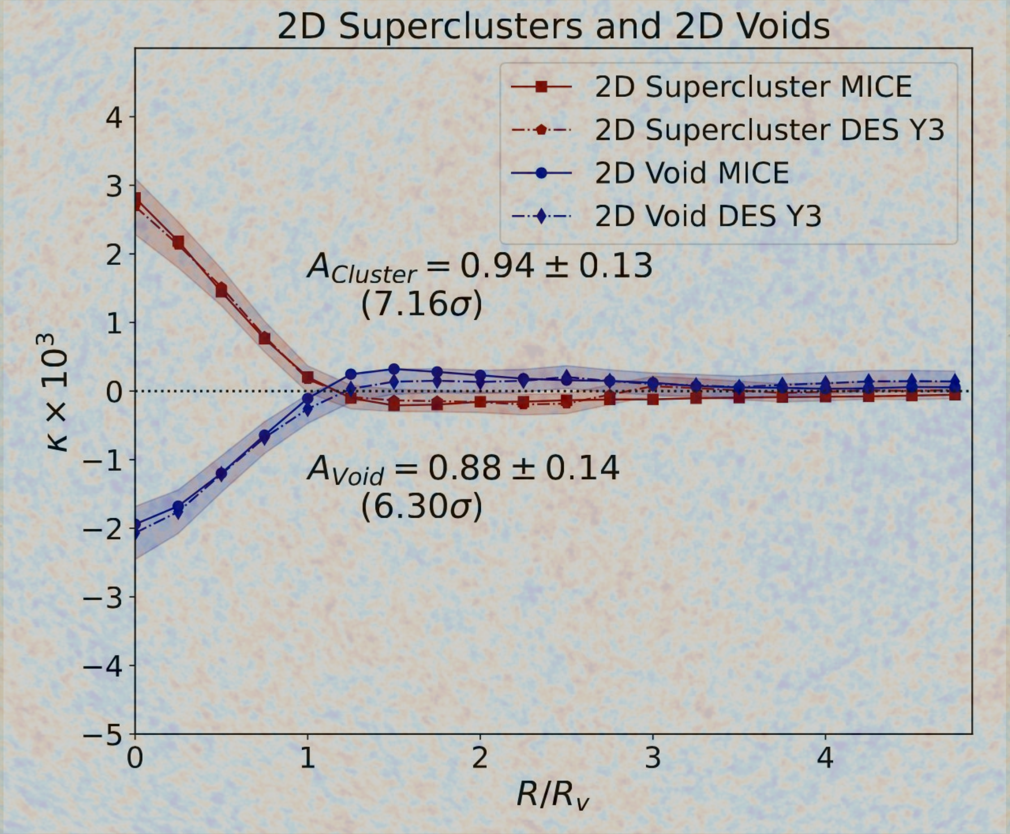
DES Y3



Credited to Demirbozan et al, 2024

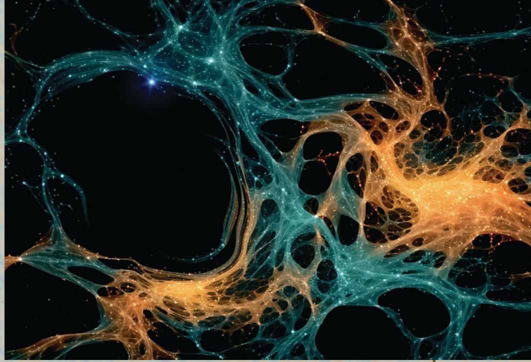
MICE

Results– 2D Voids



Credited to Demirbozan et al, 2024

Conclusions


Credited to Scientific American

Key takeaway

- We have investigated **CMB lensing imprints on voxel voids for the first time,** and showed that the signal is **comparable to that from 2D voids,** albeit with lower detection significance.

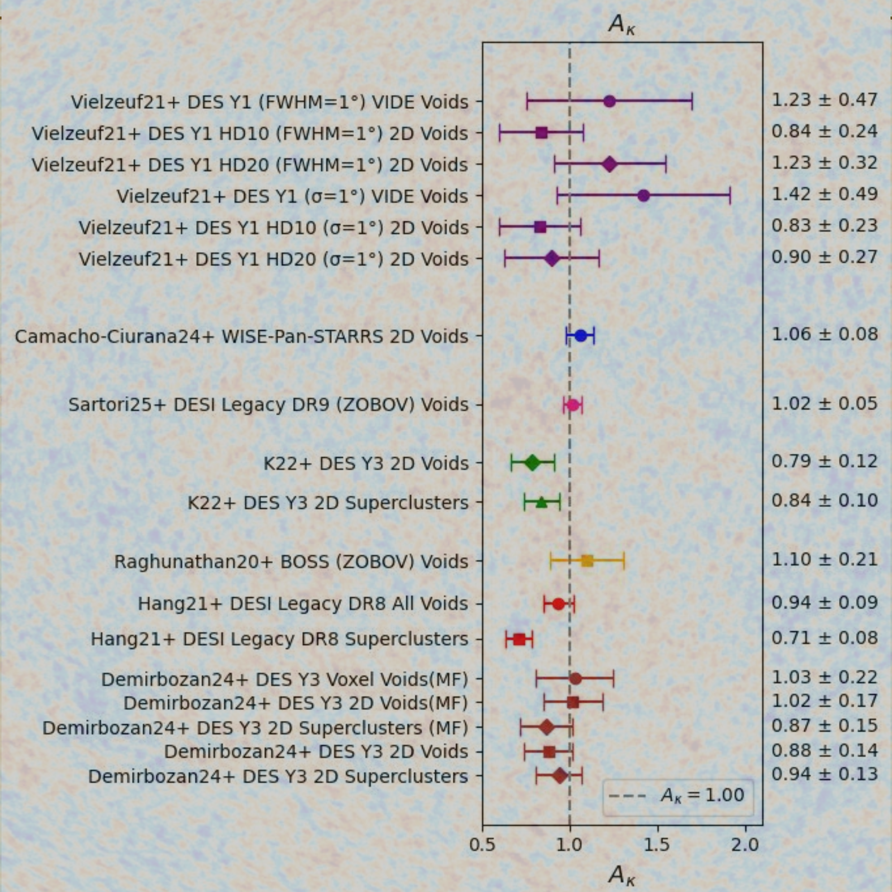
- We have used a **dual methodology** involving both optimal **matched filters** and the **Gaussian filtering** technique (**unique in the literature**).

Key takeaway

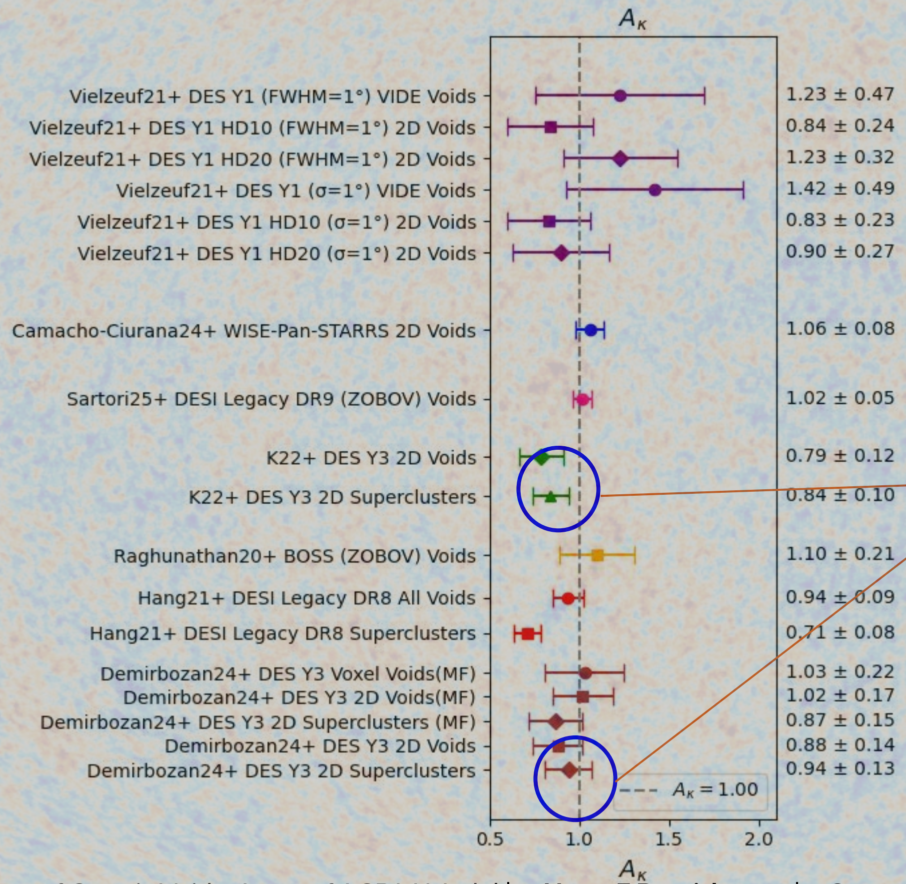
- We have also used **2D superclusters,** defined by inverting the 2D void finder.

- Our results show that the CMB lensing imprints of **DES Y3 voids agree well with ΛCDM**, a finding further confirmed by studies from other surveys.

Conclusions

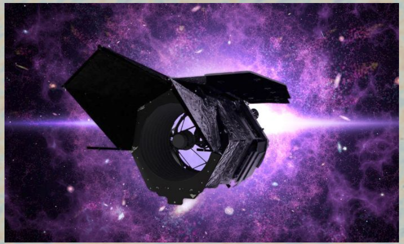


Conclusions

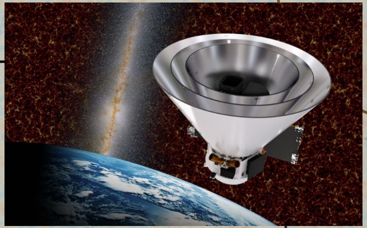


- **Strong evidence for ΛCDM model.**
- **Multiple surveys with different methods are consistent**
- **Update over K22 results which show a moderate tension**

Conclusions & Future



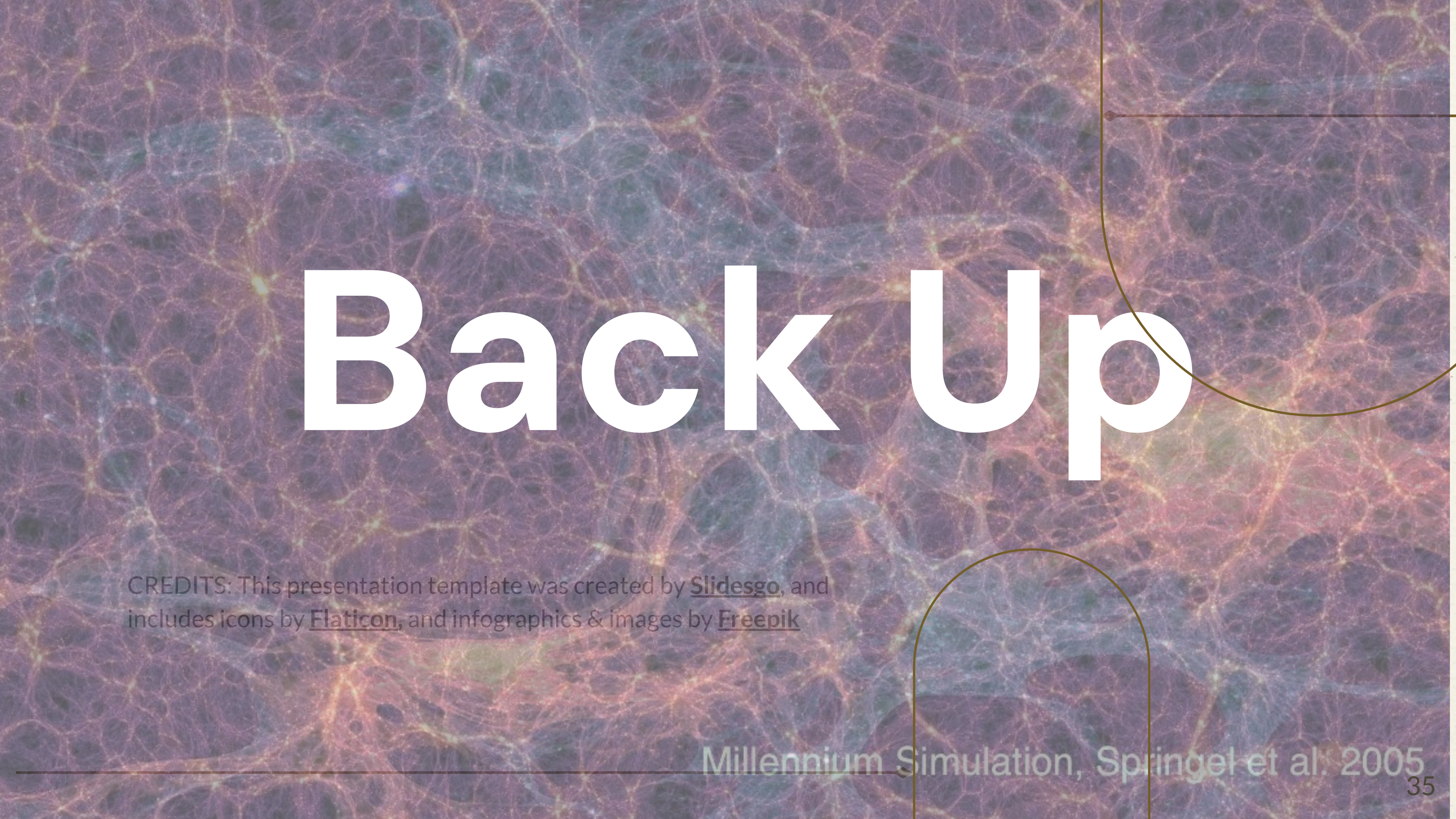
Future of void science



- **Current and upcoming surveys** such as SphereX, DESI, Euclid, Roman, Rubin-LSST and CSST will provide on the orders of 100k voids or more.
- Simon's observatory (SO), ACT, SPT-3G, CMB-S4(?) will enable **higher S/N studies** with (ML/DeepL) techniques helping to provide **low noise CMB lensing a**nd temperature **maps**
- Cross correlating independent datasets will be more important
- **Simulation Based Inference (SBI)** for void x galaxy lensing to constrain cosmology (Su et al,2025, [2504.15149](2504.15149))
- Joint **ISW** and **CMB lensing** studies
- **Currently available for postdocs & visiting postdoc positions!**

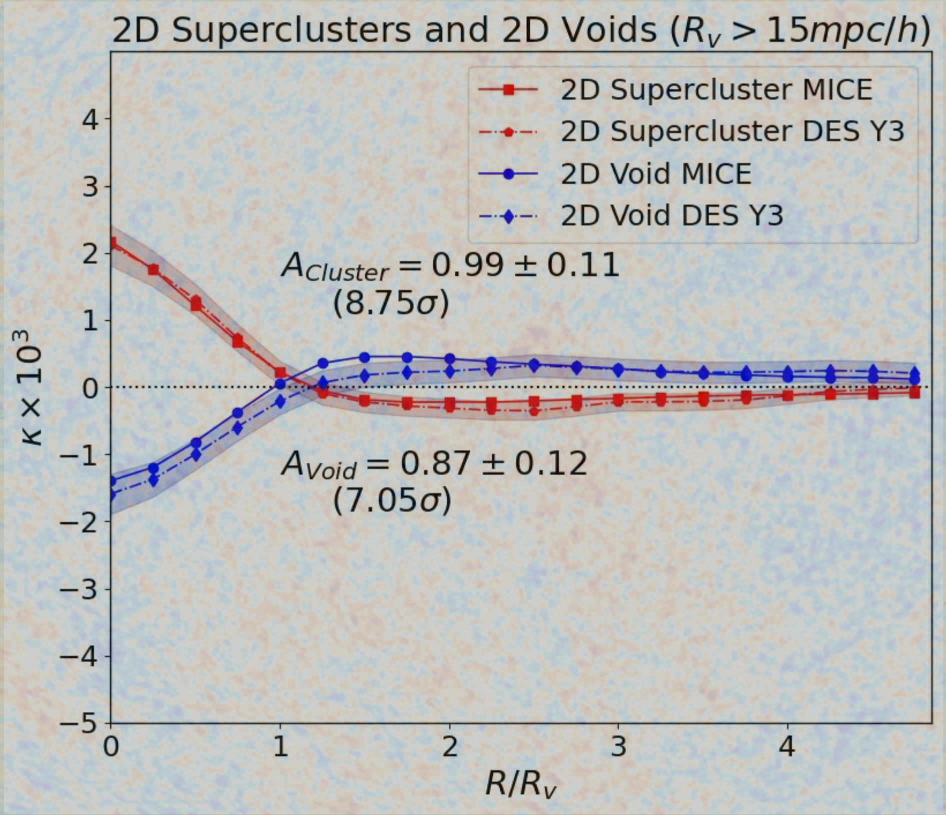
Back Up

CREDITS: This presentation template was created by Slidesgo, and includes icons by Flaticon, and infographics & images by Freepik



Millennium Simulation, Springel et al. 2005

Results- Radius Cut



Credited to Demirbozan et al, 2024

- Instead of using R_v>20 (Mpc/h), we tested using a more liberal cut R_v>15 (Mpc/h) to increase our sample of 2D voids.
- This reduces the noise and increases S/N!
- A future work may investigate this cut more.

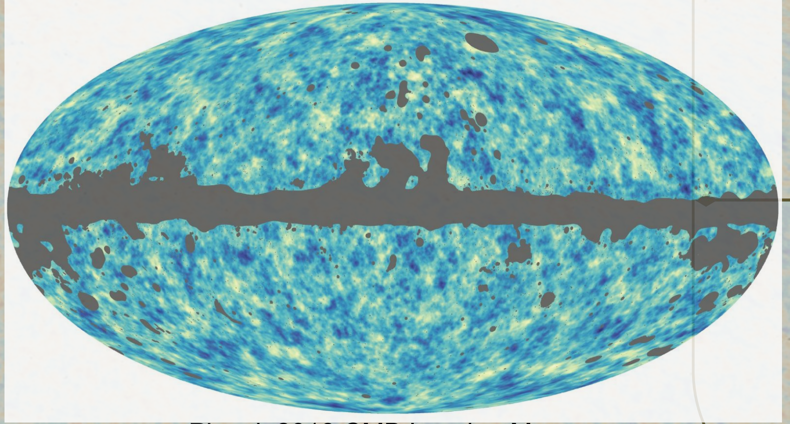
Void Numbers	$R_v > 20$ Mpc/h	$R_v > 15$ Mpc/h
MICE	6,295	10,148
DES Y3	5,148	8,851

Voids x CMB (Lensing)

CMB Lensing Overview

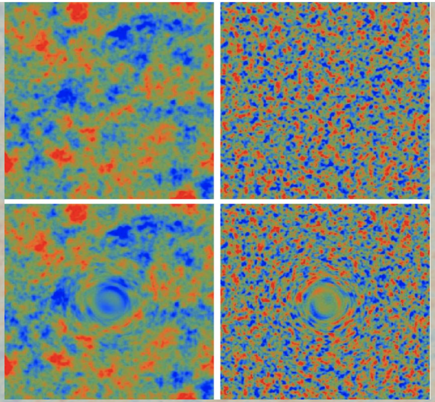
- CMB photons are **deflected by large-scale gravitational potentials** along the line of sight.
- The **lensing potential ϕ** is a kernel-weighted LOS integral of the Newtonian potential.
- **Convergence (k) = ∇²ϕ** traces the **projected mass density**; its power spectrum peaks at **l ≈ 60**.
- Lensing **distorts CMB temperature/polarization**, coupling different multipoles.
- These mode couplings enable to derive convergence and therefore **cross-correlations with galaxy/void surveys**.

$$\kappa(\theta) = \frac{3H_0^2\Omega_m}{2c^2}\int_0^{r_{\max}} \frac{(r_{\max}-r)r}{r_{\max}}\delta(r,\theta)\,dr$$



Planck 2018 CMB Lensing Map

$$\Phi(\hat{n}) = -2\int_0^{x_{\rm cmb}} \frac{d\chi\,(x_{\rm cmb}-\chi)}{x_{\rm cmb}\chi}\Psi(\chi\hat{n};t)$$

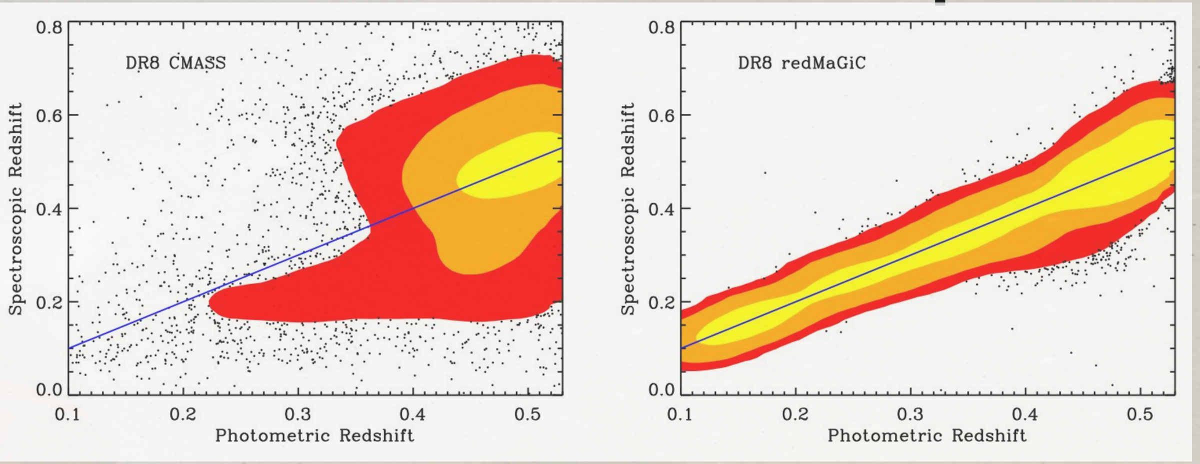


Credited to Hu & Okamato, 2003

Dark Energy Survey

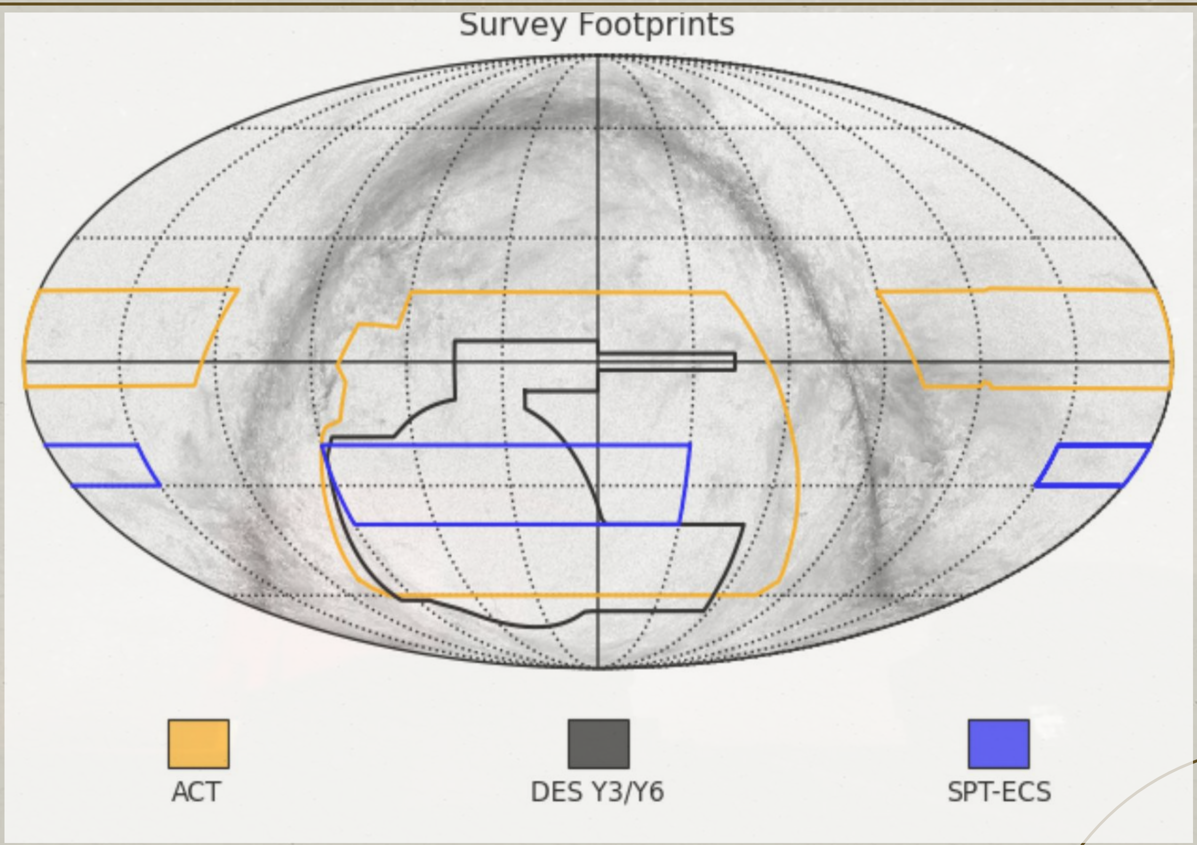
- **redMaGiC** galaxies are **luminous red galaxies (LRGs)** selected for their **exceptionally low photo-z errors.**
- The sample has **high clustering bias** and **high completeness.**
- **Three number-density subsets** are provided (HD, HL, and Higher-L).
- They typically reside in dark-matter haloes with log10 (M_{halo}/M_☉) ≈ 13.7.
- The **redMaGiC** photo-z's are **substantially more precise** than those of the SDSS CMASS DR8 LRG sample (Rozo et al. 2016).
-

redMaGiC Tracer Sample



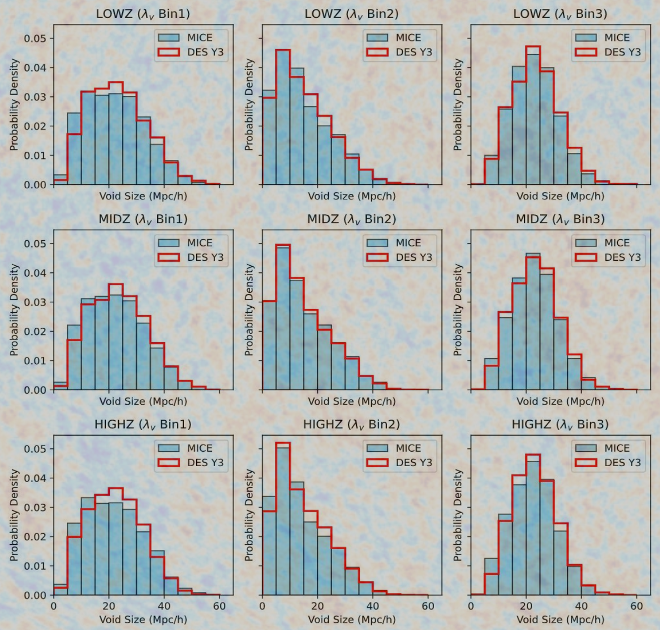
Credit: Rozo et al, 2016

Dark Energy Survey



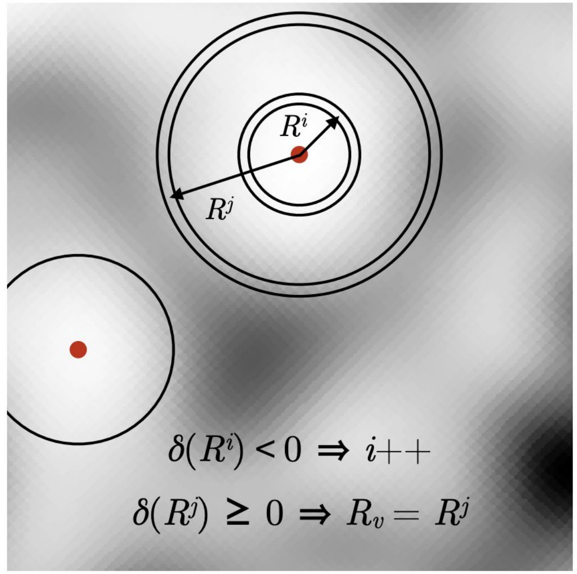
Voxel Void Sizes

	MICE Void Count	DES Y3 Void Count	MICE Mean Void Size	DES Y3 Mean Void Size
LOWZ (0.2 - 0.43)	9298	6821	20.01 (Mpc/h)	20.57 (Mpc/h)
MIDZ (0.43 - 0.59)	14679	10861	20.22 (Mpc/h)	20.54 (Mpc/h)
HIGHZ (0.59 - 0.75)	20449	15027	19.58 (Mpc/h)	20.02 (Mpc/h)

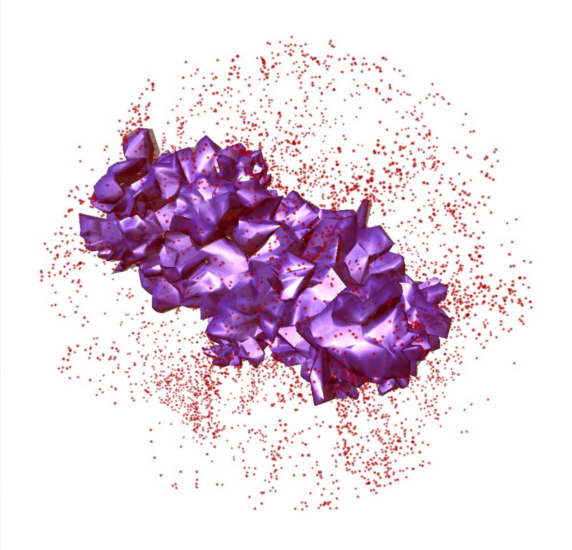


- **We divide the total Voxel void sample into 3 redshift bins to improve S/N.**
- **Each redshift bin is then divided into 3 $\boldsymbol{\lambda}$ bins**

Cosmic Voids



Credited to Sanchez et al, 2017

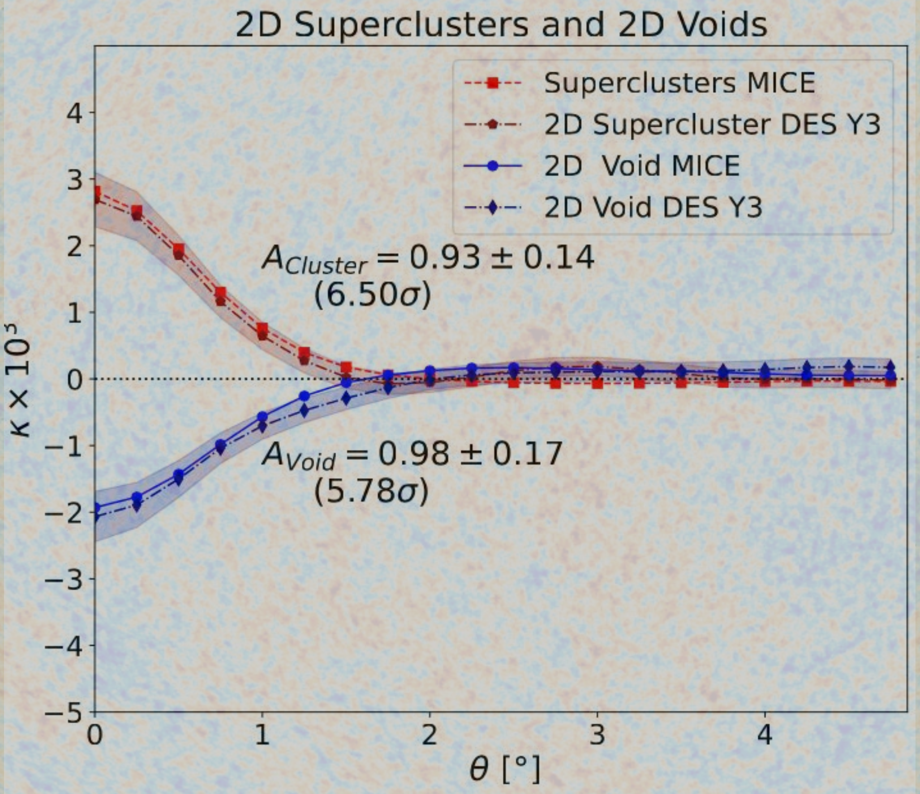


Credited to Sutter et al, 2014

2D voids that are circular and defined on projected and smoothed **tomographic redshift bins.**

3D voids are identified using a tessellation algorithm called **ZOBOV**. VIDE voids are based on this ZOBOV algorithm. **REVOLVER** outputs two types of voids: one is based on ZOBOV, and the other is **voxel.**

Results –FWHM Smoothing



Credited to Demirbozan et al, 2024

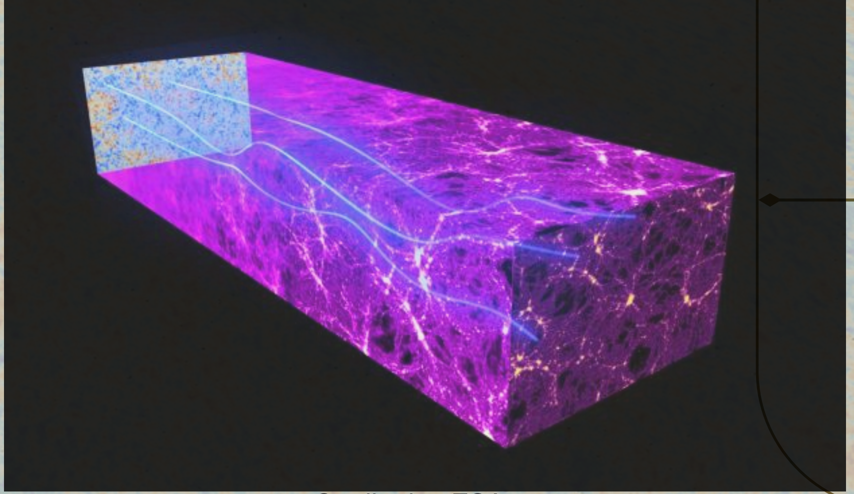
A fixed patch of 10 x 10 degrees was used, with FWHM = 1 degree CMB smoothing, as opposed to re-scaling to void radius.

Different smoothing scales possibly change S/N levels and this is a free parameter!

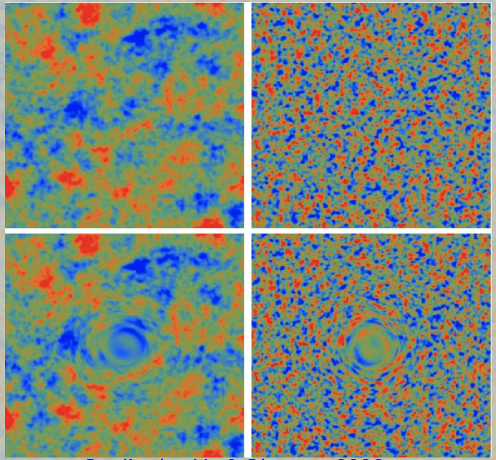
Voids x CMB (Lensing)

CMB Lensing

- Attracted less attention then ISW and first detection in voids started with (Cai et al, 2016) 1609.00301 in SDSS
- Results are generally in **agreement** with each other
- Can give insights about **matter distribution within voids** and testing linear bias assumption within voids
- Much higher **CMB lensing detection significances** achieved compared to ISW up to 14-15σ
- Be used to test **ΛCDM predictions** as calibrated by N-body simulations



Credited to ESA

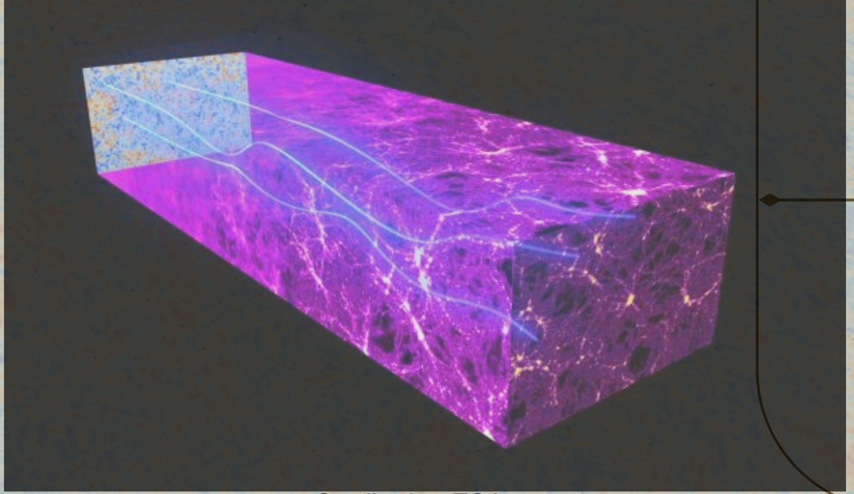


Credited to Hu & Okamato 2003

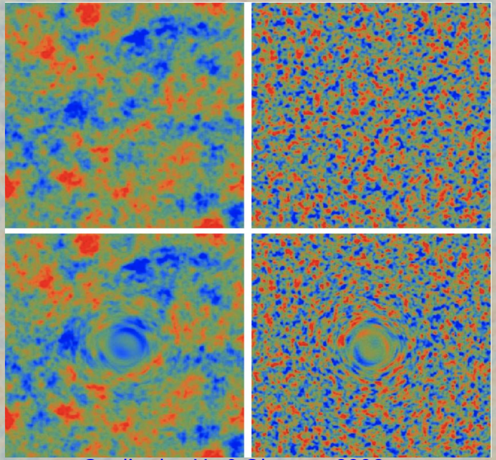
Voids x CMB (Lensing)

CMB Lensing Overview

- CMB photons are deflected by **intervening gravitational potentials.**
- This lensing slightly **distorts CMB temperature** producing characteristic signatures.
- The effect induces non-zero correlations between **different multipoles** (angular scales).
- These correlations make CMB lensing a powerful **cross-correlation tool with galaxy surveys.**



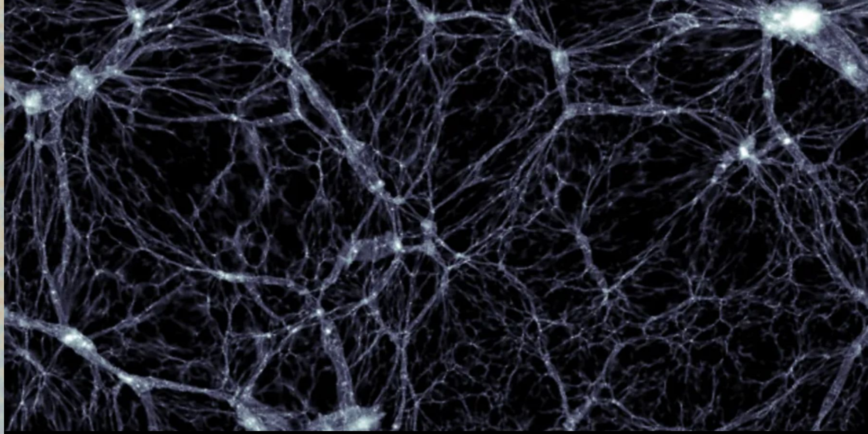
Credited to ESA



Credited to Hu & Okamato 2003

Void Science

Why voids are so useful?



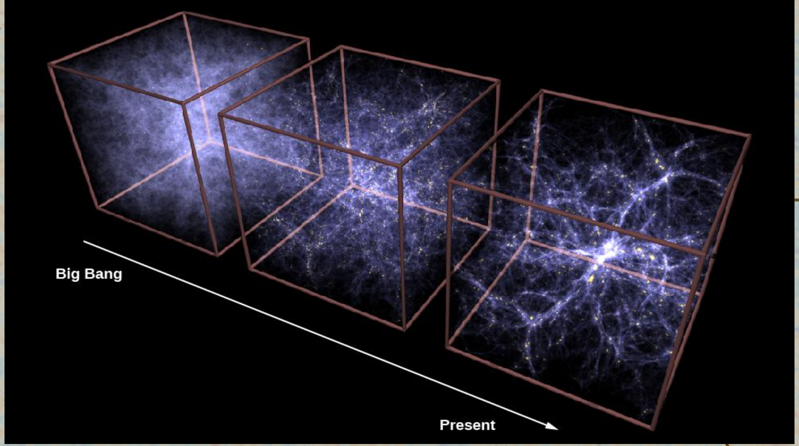
Shown is the distribution of dark matter, with a width and height of 350 million light-years and a thickness of 300,000 light-years. Galaxies are found in the small, white, high-density dots. Markus Haider / Illustris collaboration

- Occupy about **60% of the late-time** Universe
- Void properties directly probe **the initial conditions** of the Universe
- Information beyond traditional **2-point clustering** from galaxy surveys and dominated by **dark energy**
- **Mostly linear** and free of non-linear gravitational effects , baryonic physics(RSD improvement, advantage over galaxy auto power spectrum)
- Explored in **alternative/exotic cosmological** models (**Timescape model** 2403.15134 (Williamson et al,2025) and **AveRa model** 1607.08797 (Racz et al, 2017)
- Also see 2503.22532 (Cai,& Neyrinck,2025) and 2407.03882 (Bromley & Geller, 2025) for recent overview.

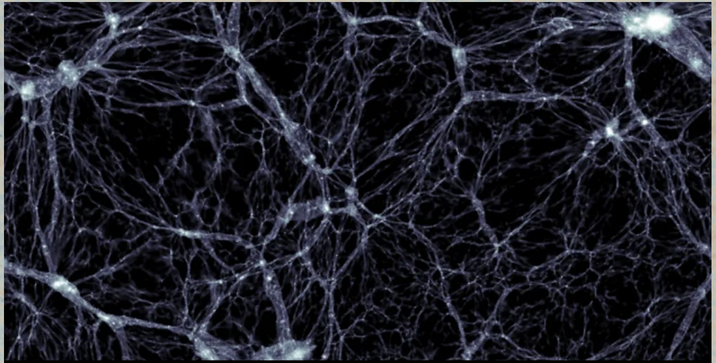
Void Science

Why voids are so useful?

- **Multi-scale** sensitivity: effective across ≈ 10–150 h^{-1} Mpc
- Ideal low-density environments: well-suited to tests of **modified-gravity** models and high **neutrino-mass fraction**
- Used as **Standard Spheres** to obtain **Alcock-Paczynski** parameter (fAP)
- Complements existing information from galaxy surveys (BAO and RSD) to **constrain cosmological parameters**
- **Void- galaxy** cross correlation (free, a factor of two improvement)
- **Tightens H0** constraints obtained from BBN + BAO
- **Void size function** and **void ellipticity** is highly sensitive to dark energy equation of state (w)

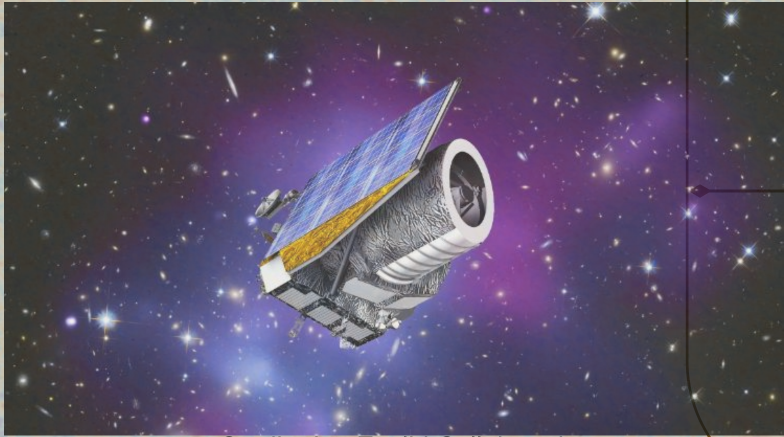


Credited to MPE/Springel



Shown is the distribution of dark matter, with a width and height of 350 million light-years and a thickness of 300,000 light-years. Galaxies are found in the small, white, high-density dots. Markus Haider / Illustris collaboration

Void Science

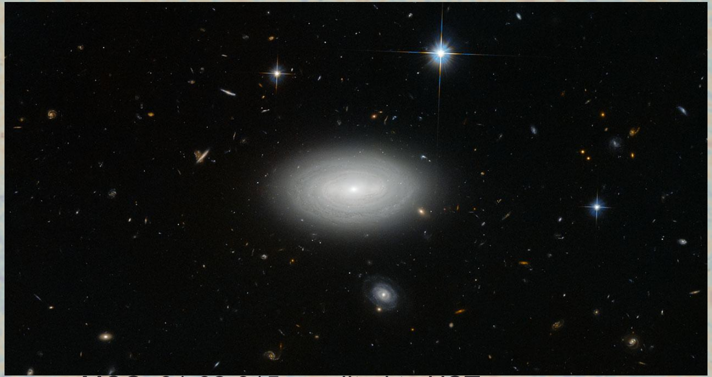

Credited to Euclid Collaboration

Euclid voids will

- Measure **Alcock –Paczynski (AP) parameter** to about **0.3%** precision
- Growth rate **fσ8** to **5–8%** precision per redshift bin
- Matter density uncertainty **$\Delta\Omega_m=\pm0.0028$**, outperforming clustering or lensing alone
- Dark energy equation-of-state to **6%** precision
- See 2302.05302 (Radinovic et al, 2023) and 2205.11525 (Contarini et al, 2022) for more details

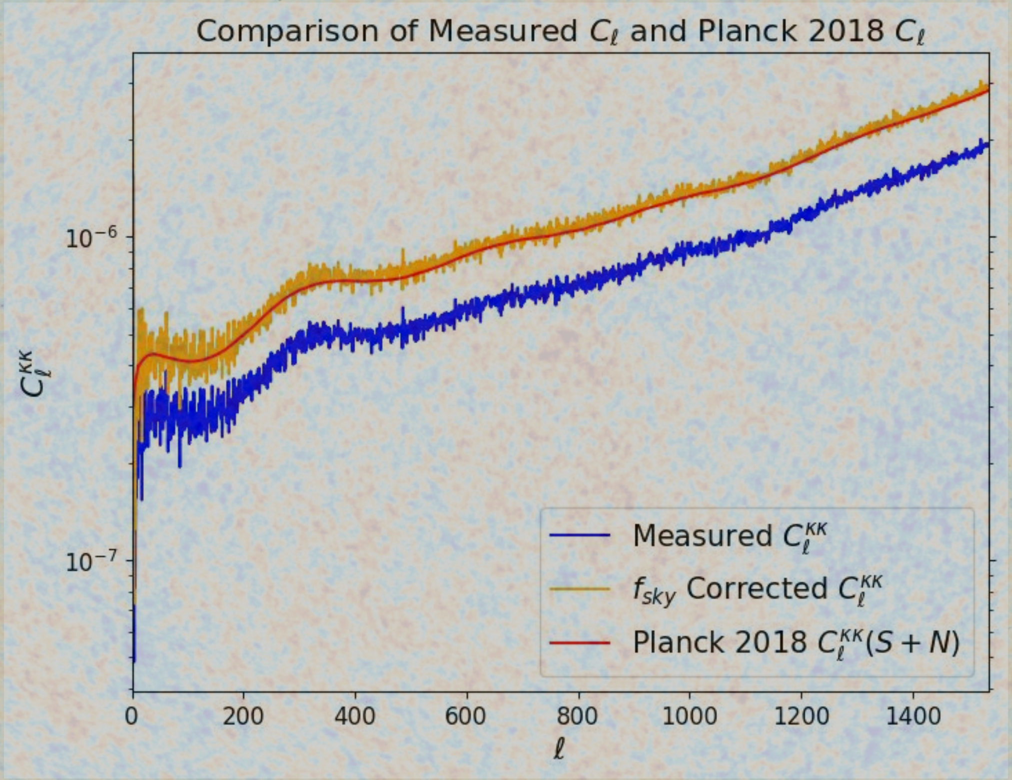
Void Galaxies


NGC 6503, credited to HST


MCG+01-02-015, credited to HST

- Galaxies that live in very **underdense regions**
- **Void galaxies** host ≈ 20–30 % more combined H I + H_2 gas than higher density counterparts
- **Less merger rates,** lower mass, bluer, higher star formation rate but slower galaxy evolution 2306.16818 (Dominguez-Gomez, 2023)
- More likely to be **spirals** (80 % show late-type disk morphologies)
- Can **tighten** the **cosmological constraints** obtained from galaxies 2405.04447 (Wong et al, 2024)
- Can be used to test **modified gravity** 2207.12917 (Cataldi, et al, 2022**)**

Covariance Estimation



- We use provided power spectrum from Planck 2018.

- We create 1000 random CMB maps from (S+N) power spectrum