More out of less:

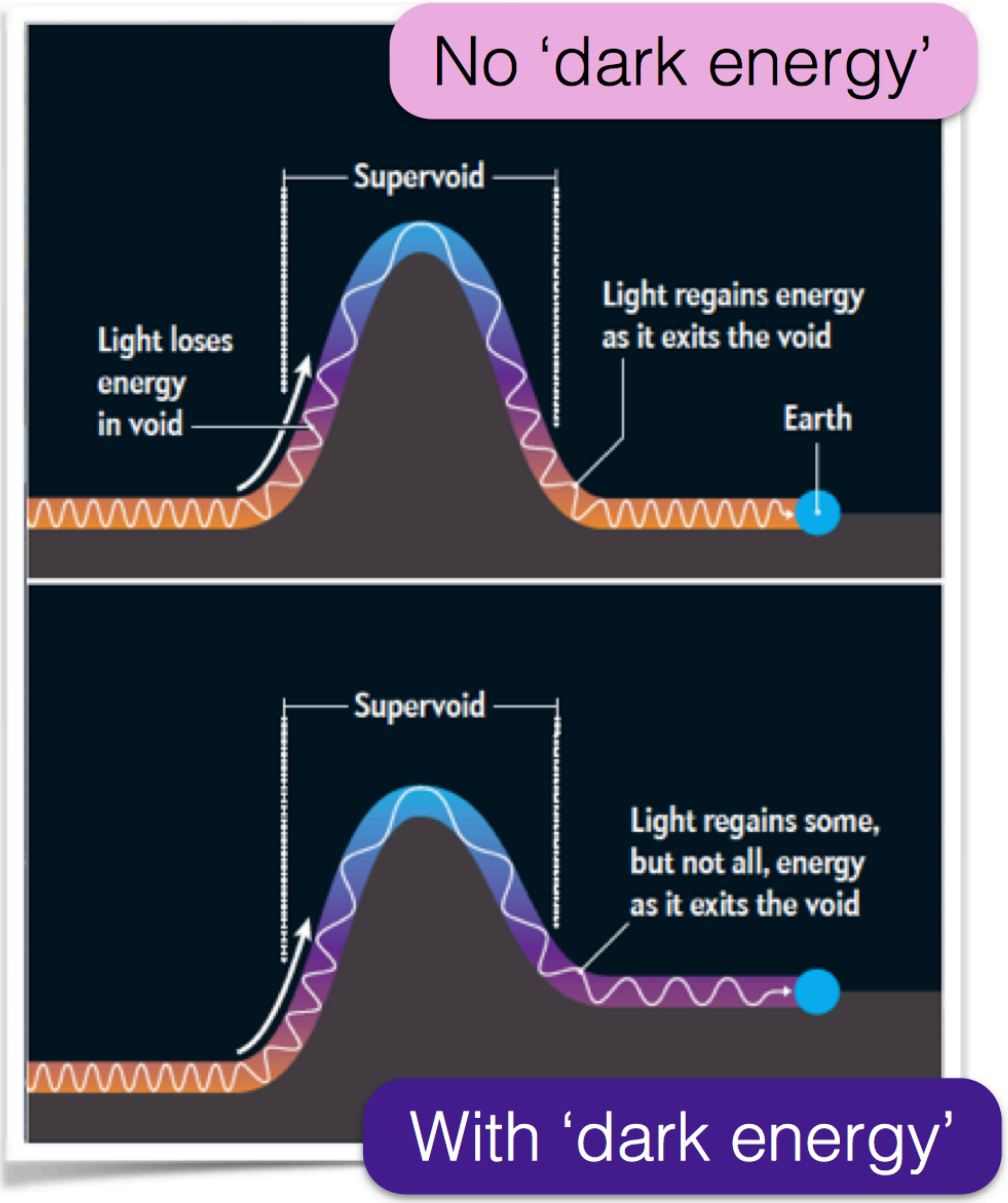
an excess integrated Sachs-Wolfe signal from supervoids mapped out by the Dark Energy Survey

András Kovács (IAC Tenerife)

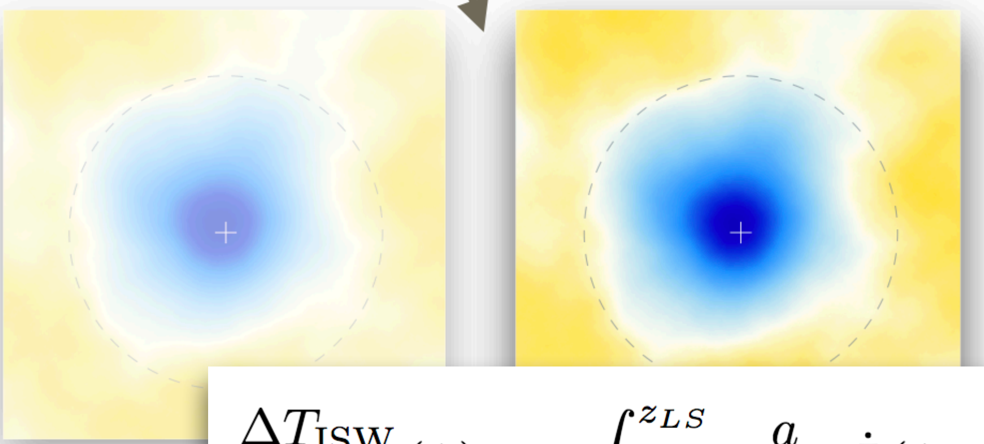
Barcelona Institute of Science and Technology

The integrated Sachs-Wolfe effect in a nutshell

Late imprint on the Early CMB



- secondary imprint on the Cosmic Microwave Background temperature
- specific time-evolution of gravitational potentials if $\Omega_m<1$
- sensitive to structure growth, dark energy properties, galaxy bias, etc.



$$\frac{\Delta T_{\rm ISW}}{T}(\hat{\mathbf{n}}) = 2\int_0^{z_{LS}} \frac{a}{H(z)}\dot{\Phi}(\hat{\mathbf{n}},z)\mathrm{d}z$$

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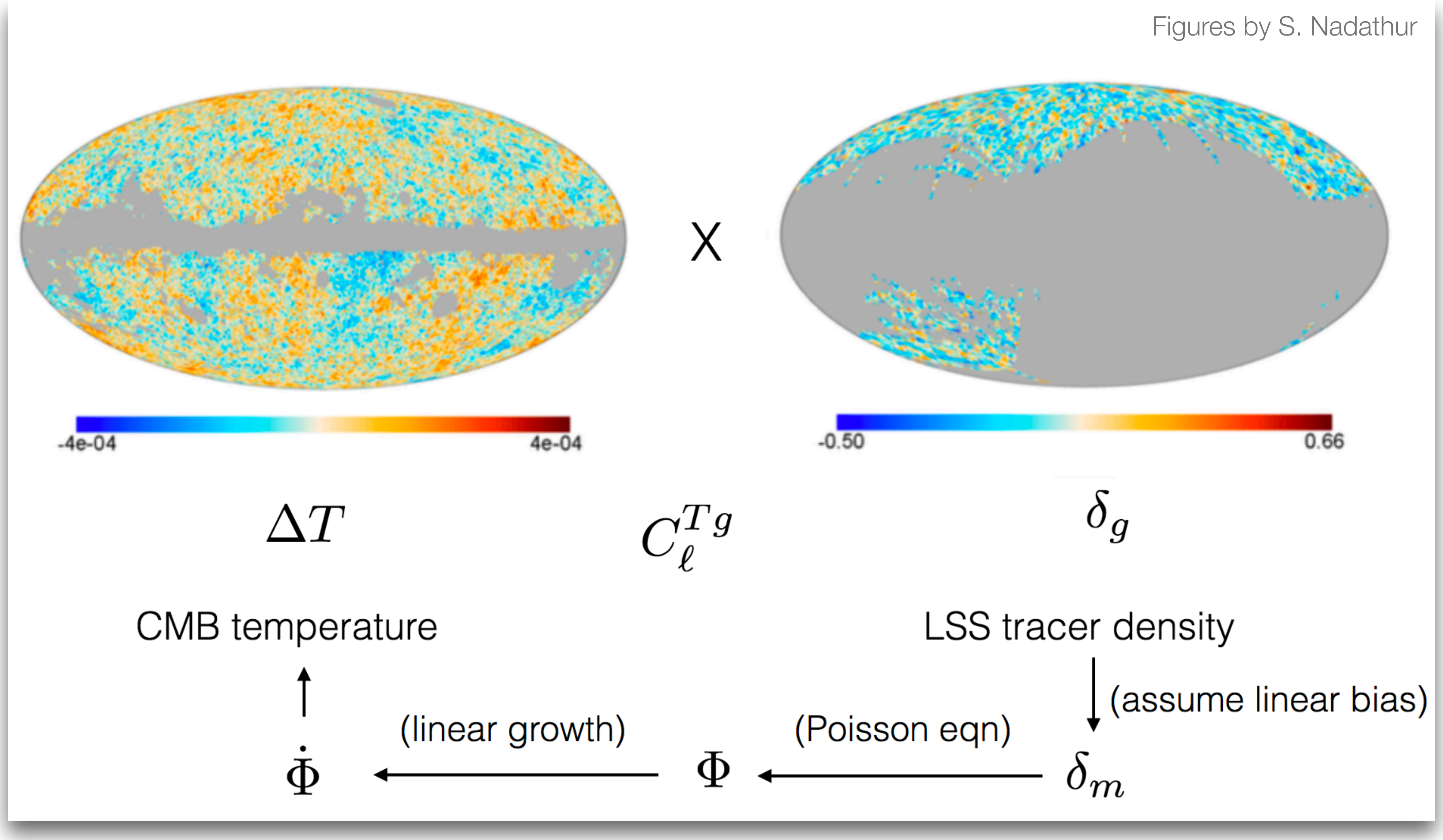
How to measure the ISW effect?

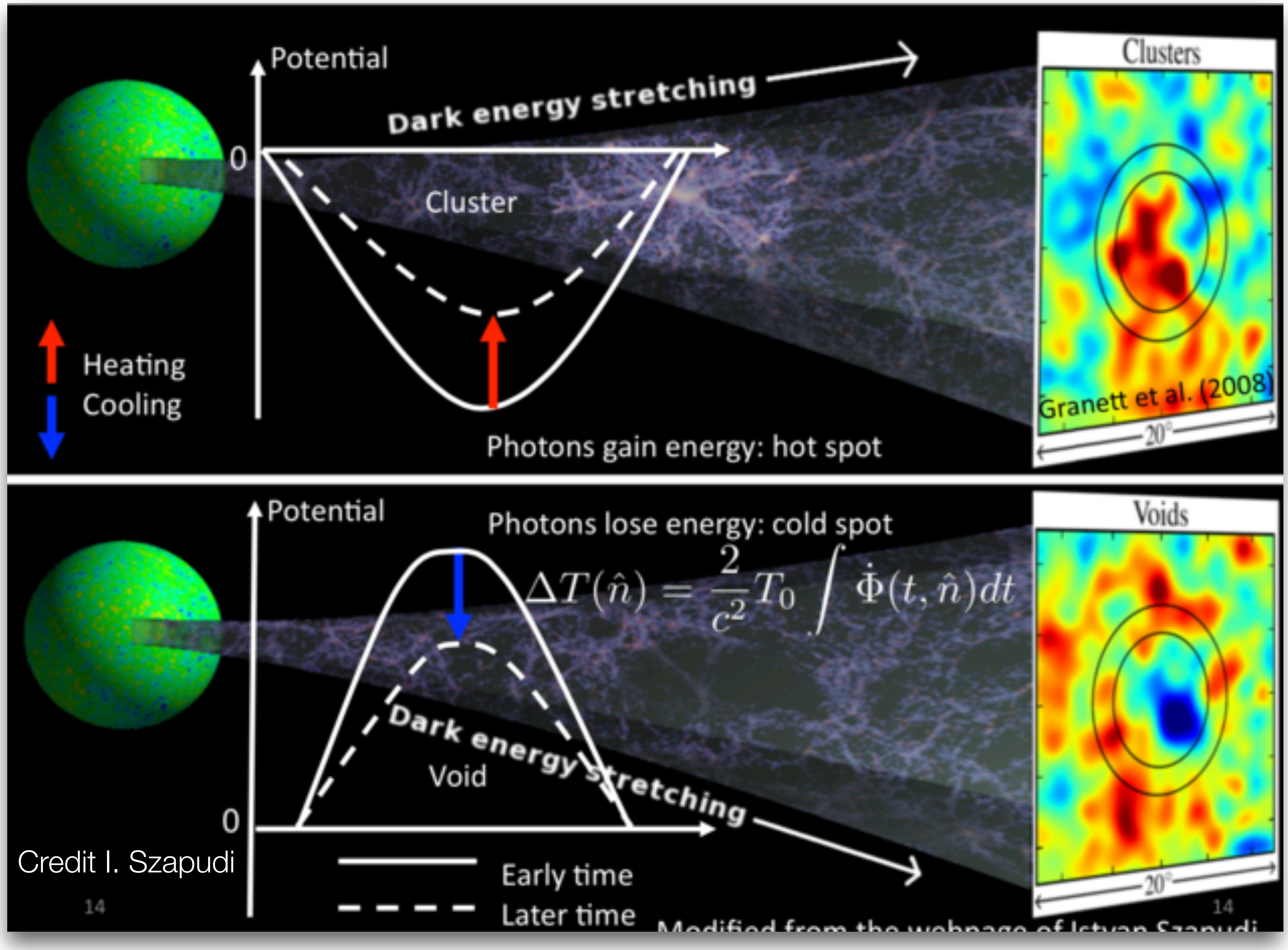


Figures by S. Nadathur

ΔT $\qquad$ C_ℓ^{Tg} $\qquad$ δ_g

$$\begin{tikzcd}
\text{CMB temperature} & & \text{LSS tracer density} \arrow[d, "\text{(assume linear bias)}"] \\
\dot{\Phi} \arrow[u] & \Phi \arrow[l, "\text{(linear growth)}"'] & \delta_m \arrow[l, "\text{(Poisson eqn)}"']
\end{tikzcd}$$

Alternative: stacking on super-structure positions

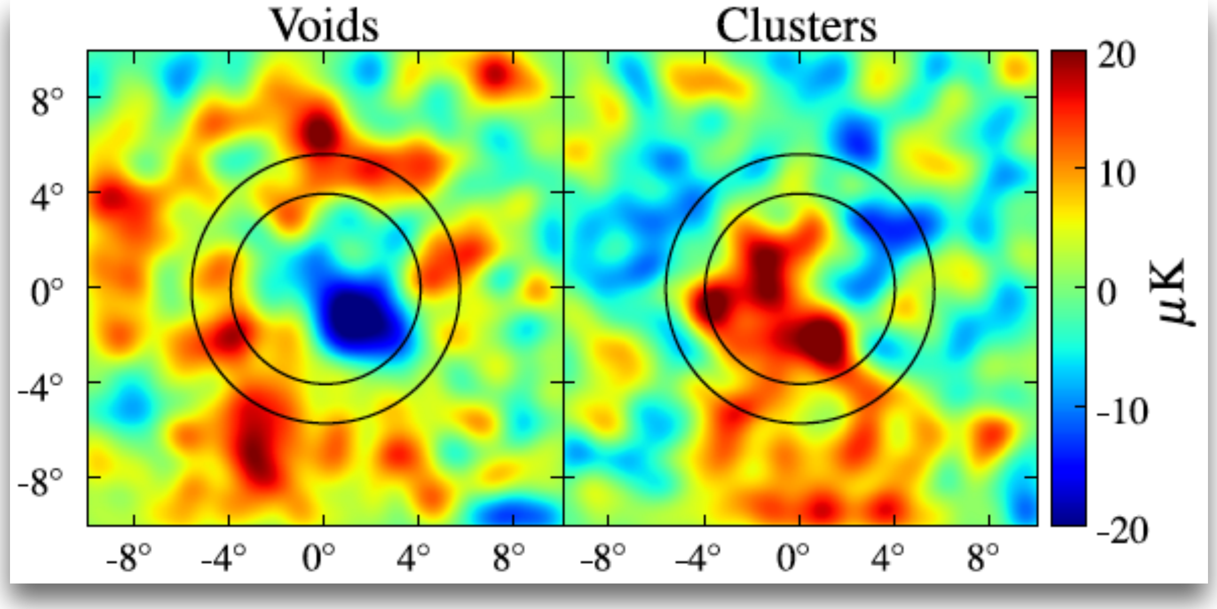


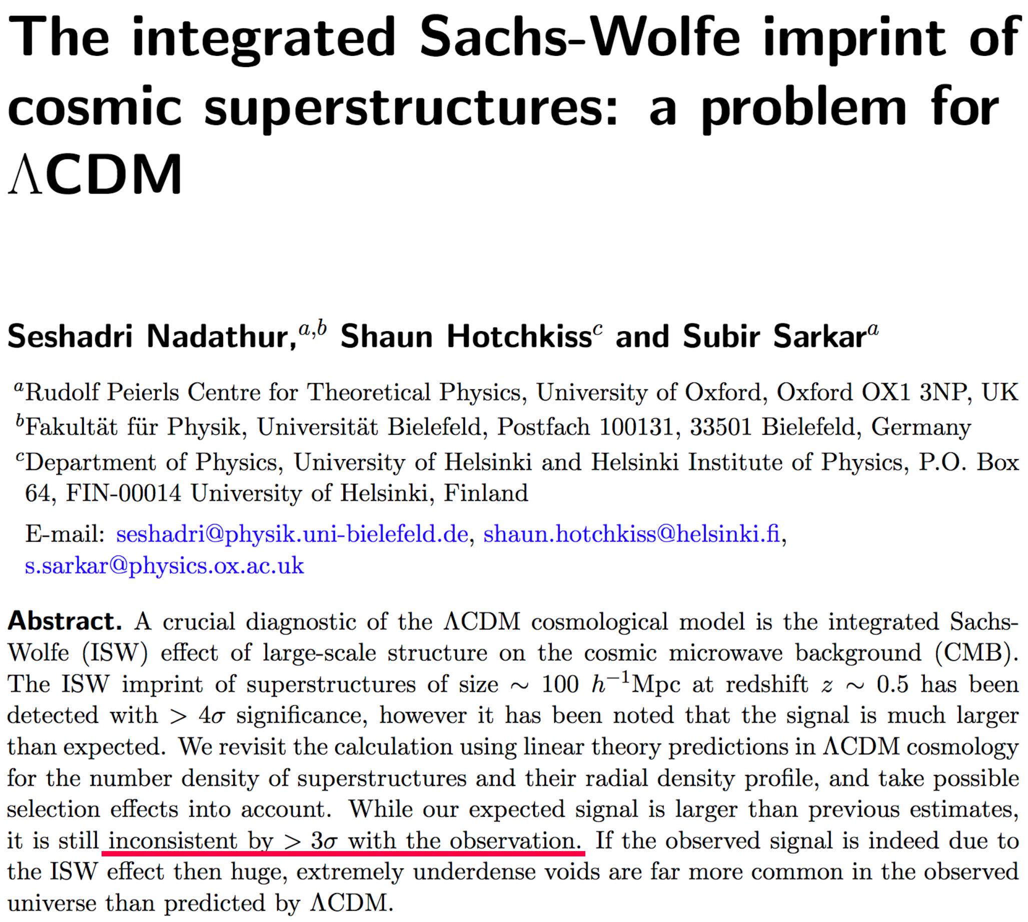
Credit I. Szapudi

A related tension (?)

- Higher-than-expected signal from SDSS super-structures
- If real, hard to interpret in ΛCDM given other precise constraints
- Not plausible to resolve with typical alternative cosmologies
- Several follow-ups, simulations, theoretical papers
- Look elsewhere effect? A posteriori bias?
- One should also see a real excess elsewhere in the sky

4.4σ detection





The integrated Sachs-Wolfe imprint of cosmic superstructures: a problem for ΛCDM

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Abstract. A crucial diagnostic of the ΛCDM cosmological model is the integrated Sachs-Wolfe (ISW) effect of large-scale structure on the cosmic microwave background (CMB). The ISW imprint of superstructures of size $\sim 100\ h^{-1}$Mpc at redshift $z \sim 0.5$ has been detected with $> 4\sigma$ significance, however it has been noted that the signal is much larger than expected. We revisit the calculation using linear theory predictions in ΛCDM cosmology for the number density of superstructures and their radial density profile, and take possible selection effects into account. While our expected signal is larger than previous estimates, it is still inconsistent by $> 3\sigma$ with the observation. If the observed signal is indeed due to the ISW effect then huge, extremely underdense voids are far more common in the observed universe than predicted by ΛCDM.

The next step: Dark Energy Survey data

- Higher-than-expected signal from SDSS super-structures
- If real, hard to interpret in ΛCDM given other precise constraints
- Not plausible to resolve with typical alternative cosmologies
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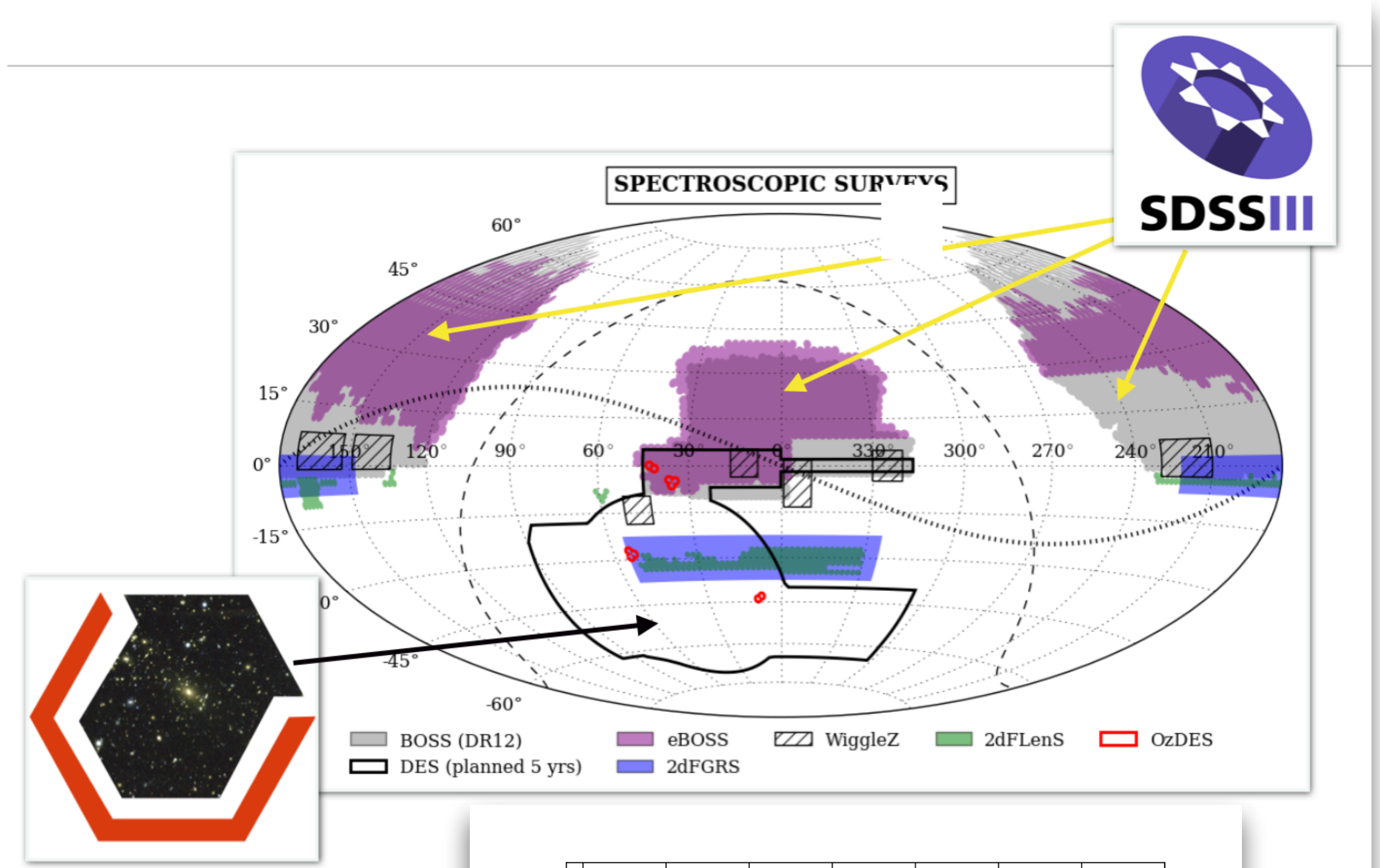
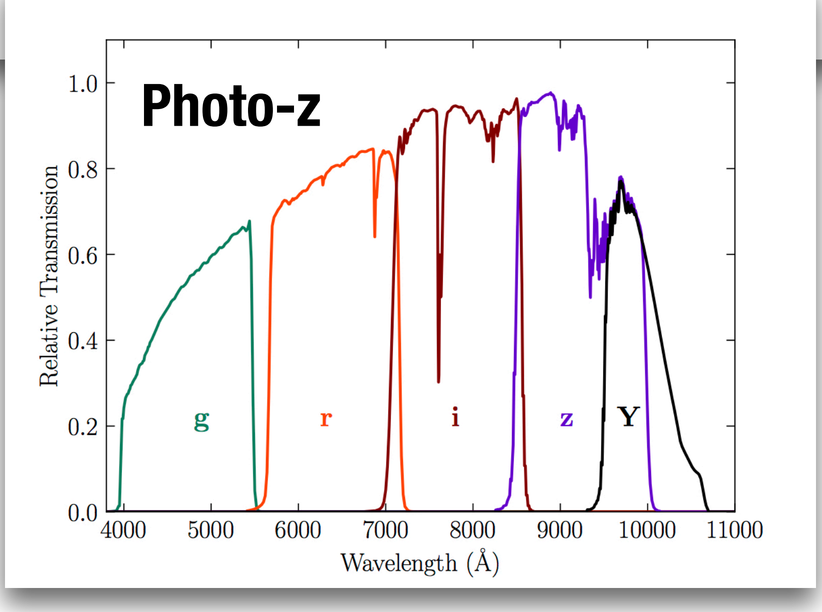
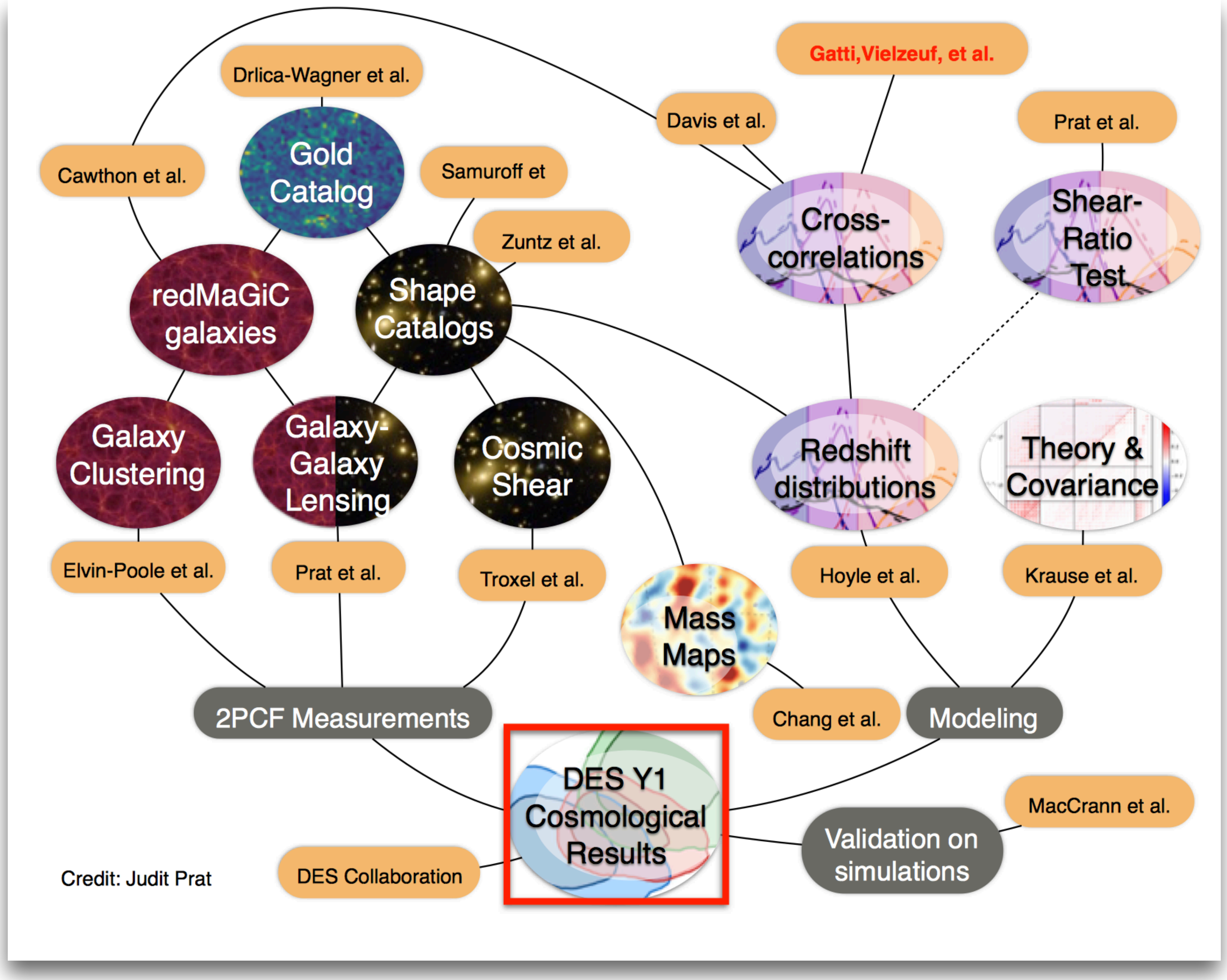




The next step: Dark Energy Survey data



Gatti,Vielzeuf, et al.

Drlica-Wagner et al.

Davis et al.

Prat et al.

Cawthon et al.

Gold Catalog

Samuroff et

Zuntz et al.

Cross-correlations

Shear-Ratio Test

redMaGiC galaxies

Shape Catalogs

Galaxy Clustering

Galaxy-Galaxy Lensing

Cosmic Shear

Redshift distributions

Theory & Covariance

Elvin-Poole et al.

Prat et al.

Troxel et al.

Mass Maps

Hoyle et al.

Krause et al.

2PCF Measurements

Chang et al.

Modeling

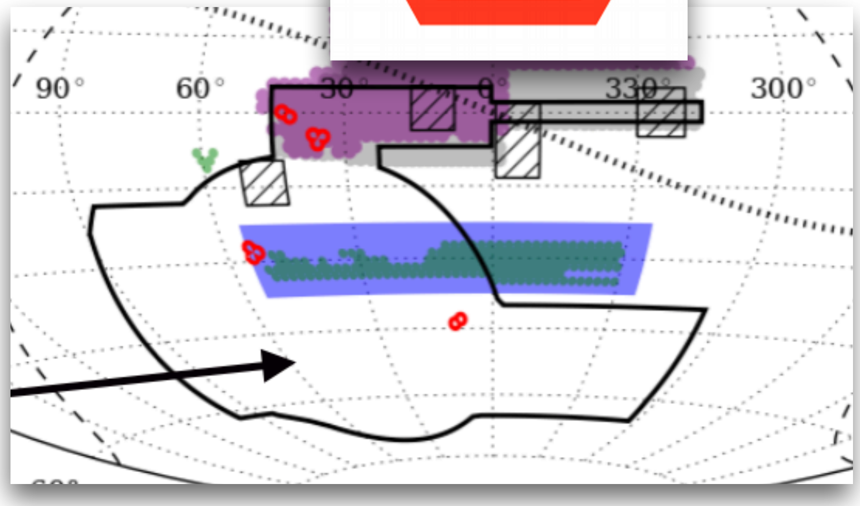
DES Y1 Cosmological Results

MacCrann et al.

Validation on simulations

DES Collaboration

Credit: Judit Prat



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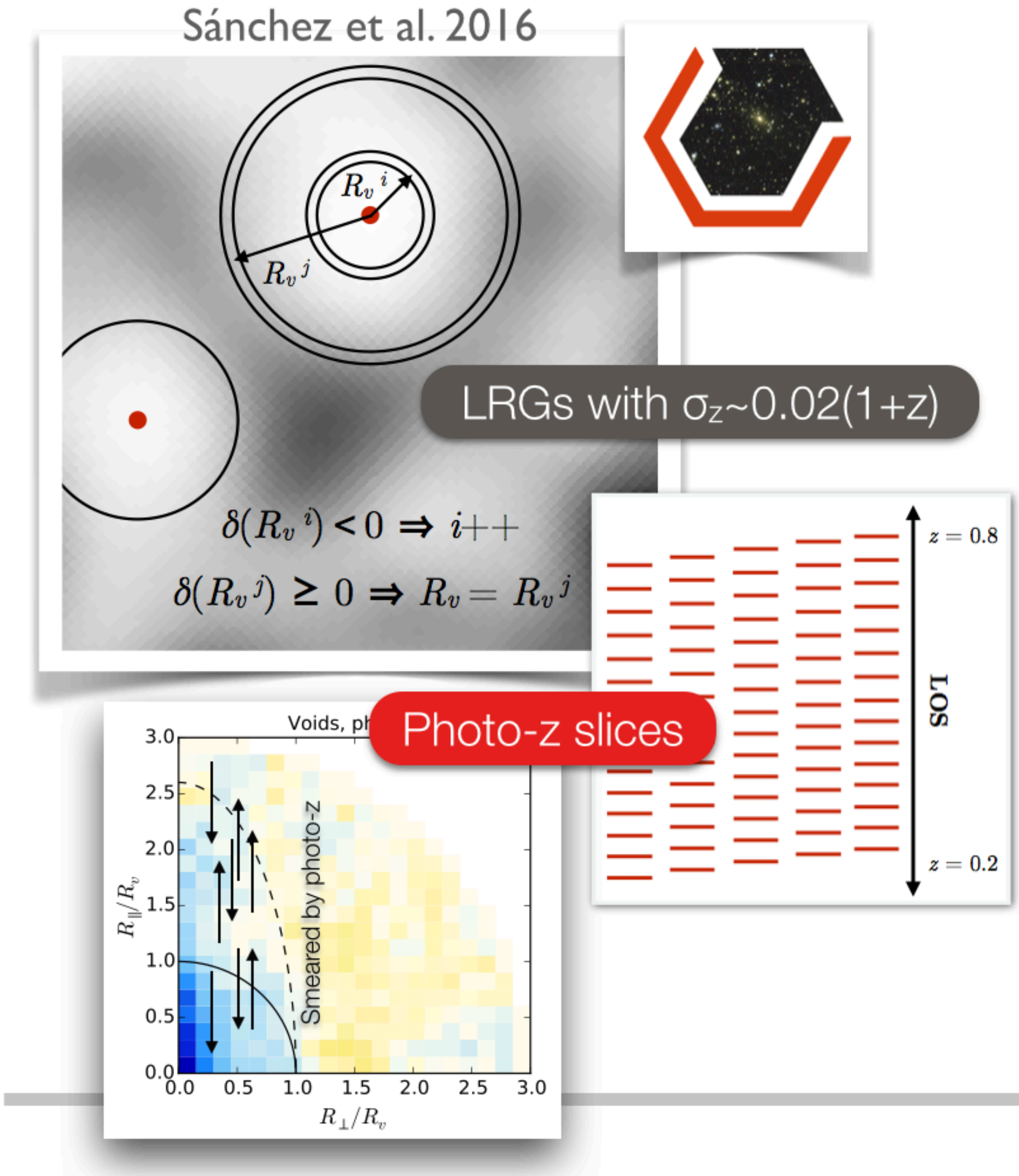
How do we find voids? How can we test them?



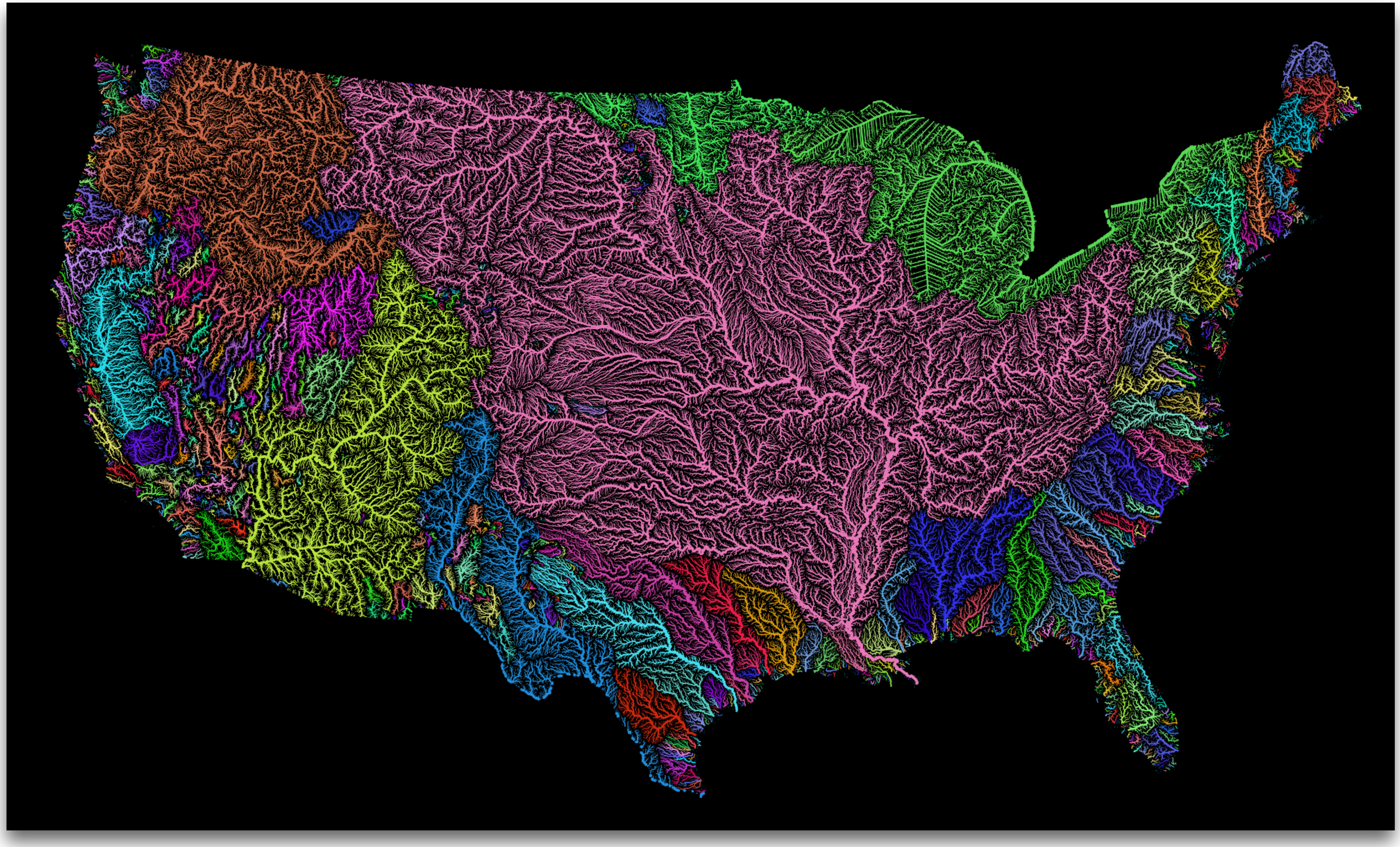
Sánchez et al. 2016

LRGs with σ_z~0.02(1+z)

Photo-z slices

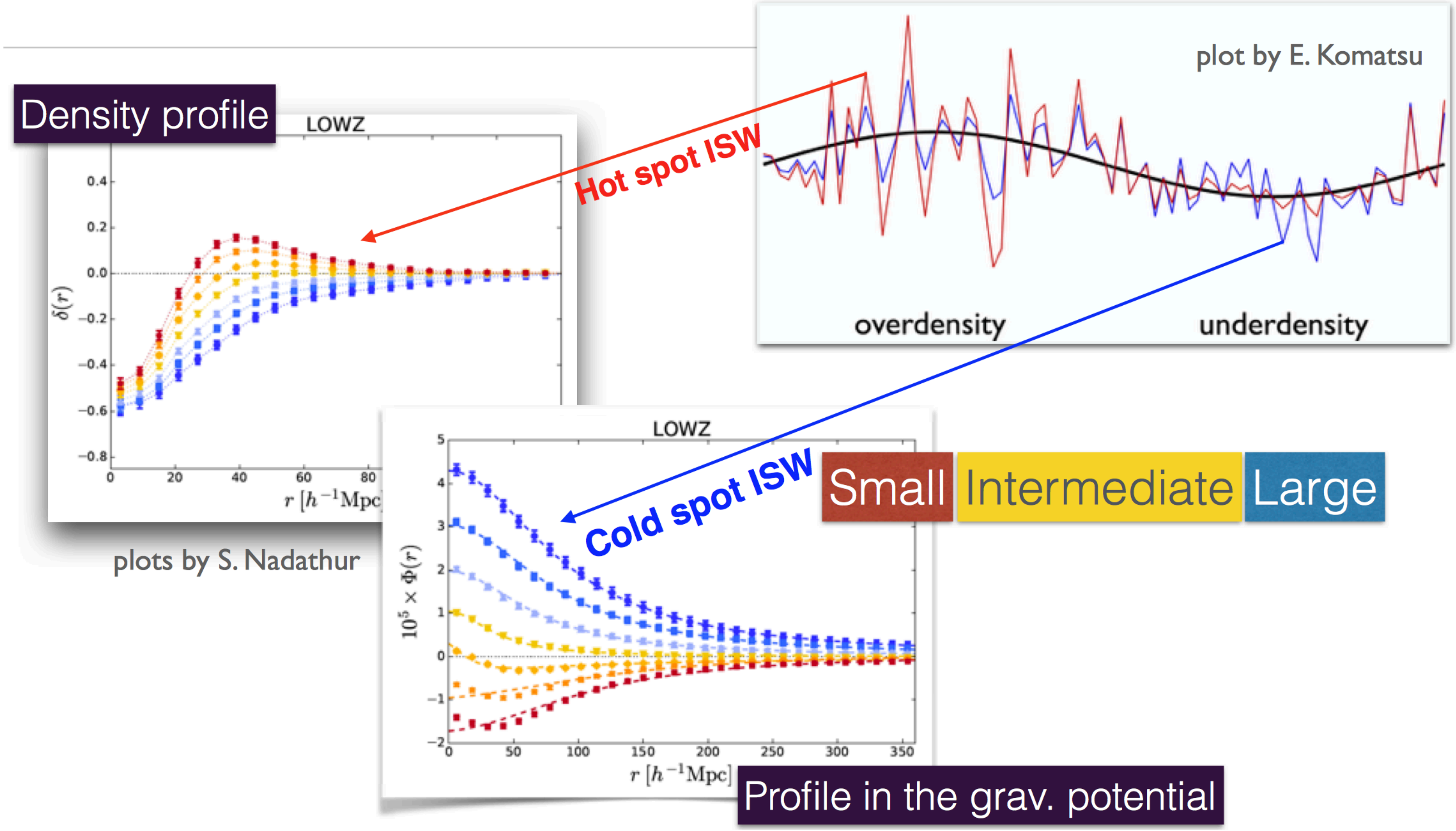
- first step: finding voids in photo-z data set (non-trivial but possible)
- the method includes a 'slicing' of the density field and then circle-growing around minima
- DES redMaGiC higher luminosity data was used at 0.2<z<0.9 to maximize the volume
- void finding in slices of 100 Mpc/h
- only huge "supervoids" with R > 100 Mpc/h
- *stacking* CMB on these void locations with re-scaling to void size

How do we define supervoids?



How do we define supervoids?

Subclasses in void catalogues are important!



Density profile

Hot spot ISW

plot by E. Komatsu

Cold spot ISW

Small Intermediate Large

plots by S. Nadathur

Profile in the grav. potential

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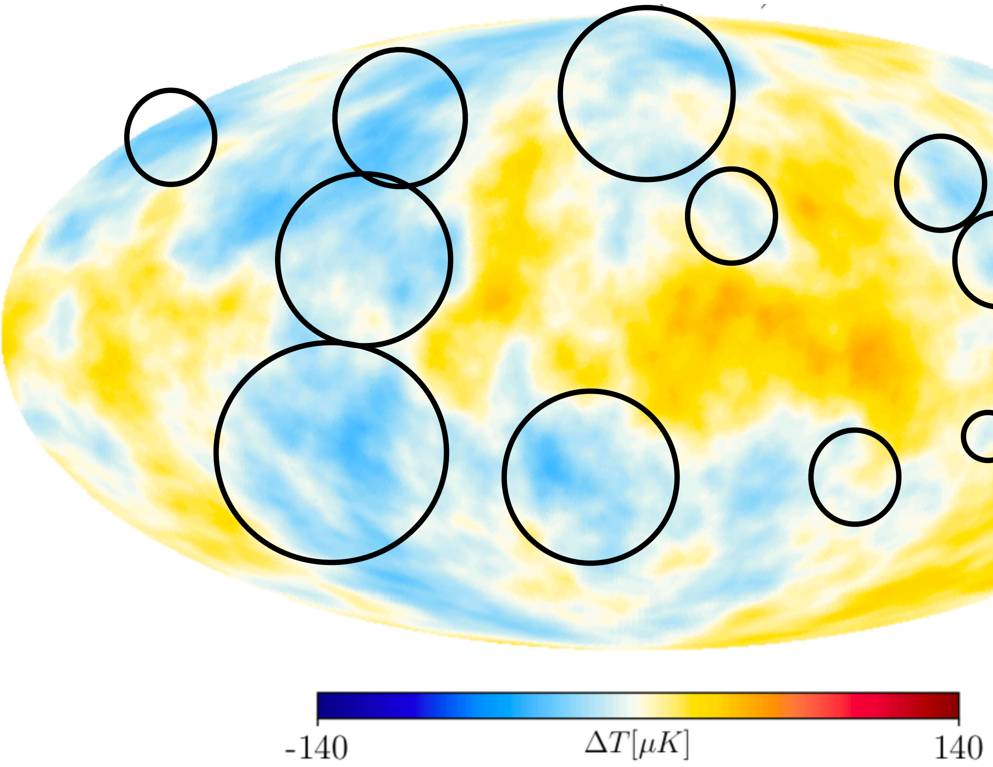
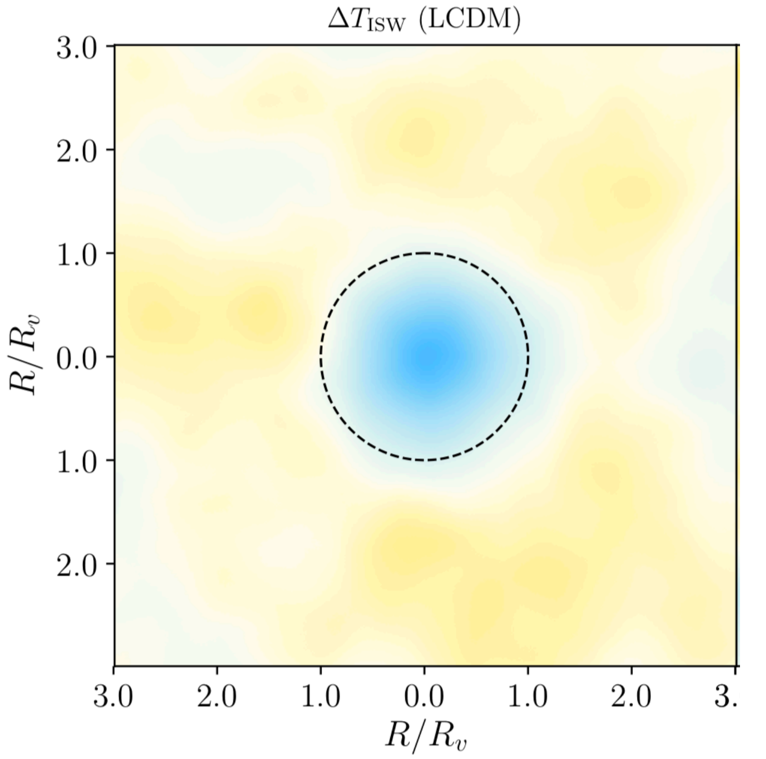
Measurement technique

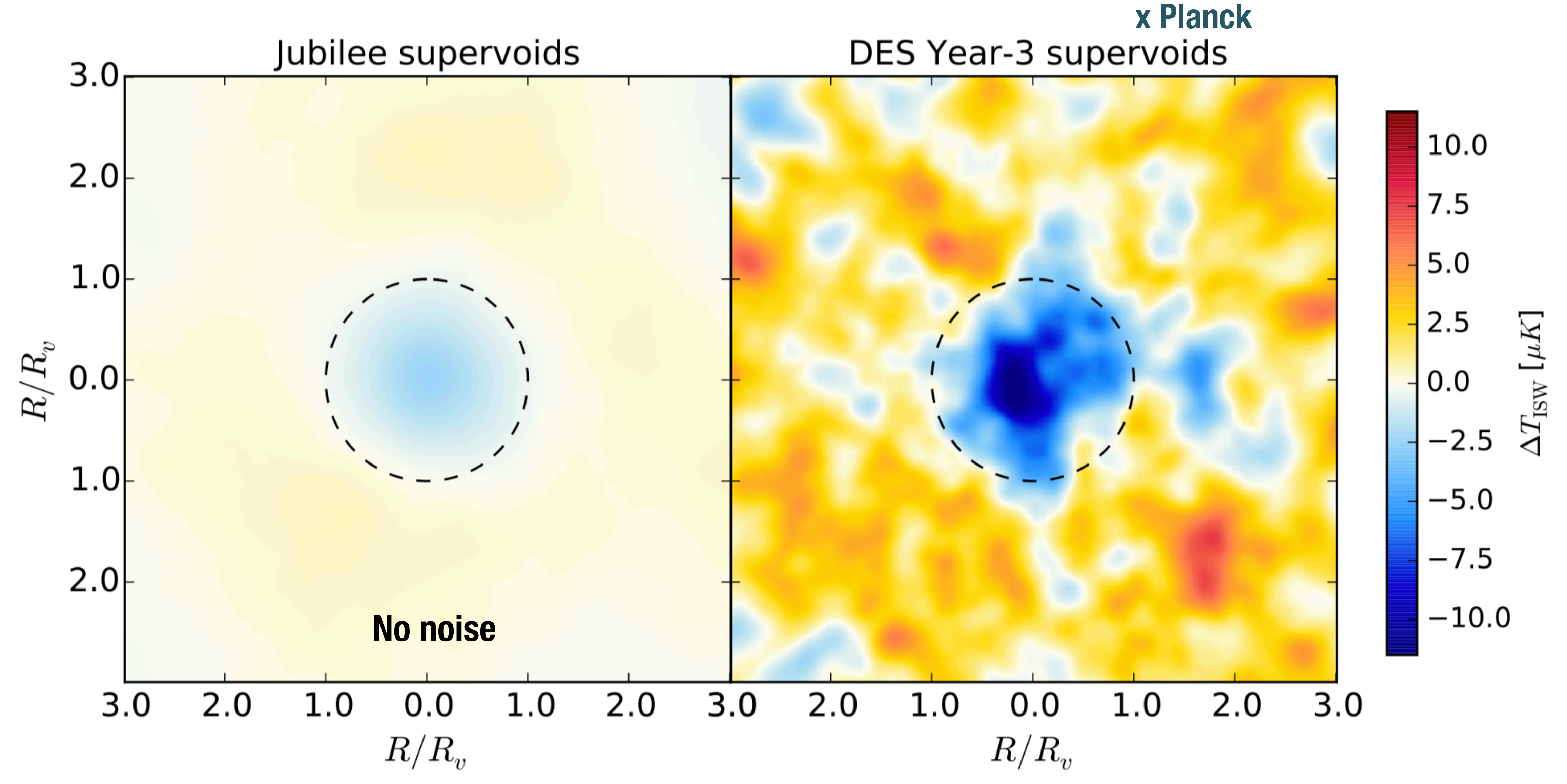
- **Blind analysis using simulations**
- **Optimization of the void catalog**
- **CMB cutouts at void locations**
- **Re-scaling to void radius**
- **Stacking in simulations and in data**
- **Comparison of ΛCDM predictions with data**




ΔT_{ISW} (LCDM)

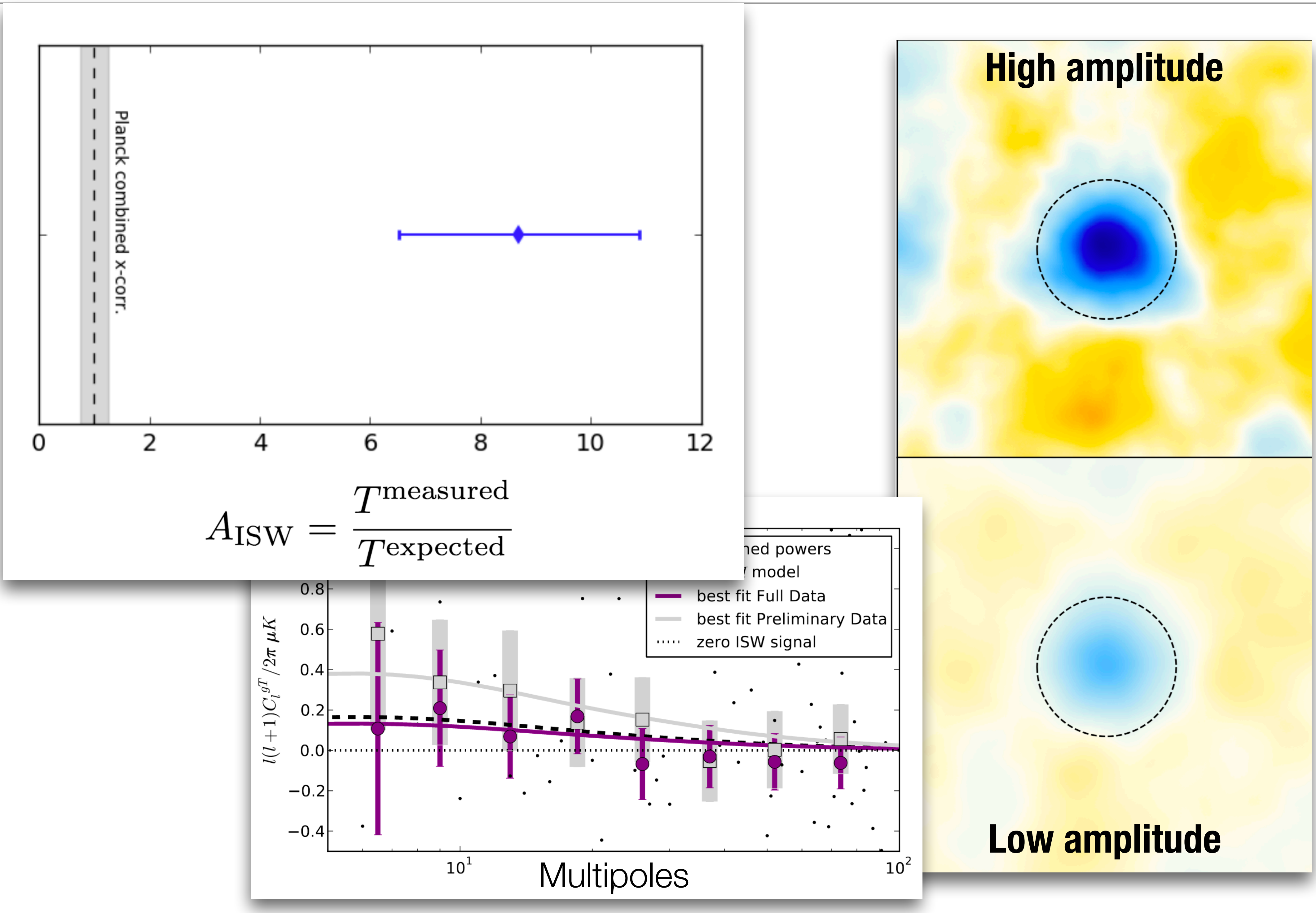
The stacked signals in simulation and DES Y3 data

Kovács et al. 2019



MNRAS Vol 484, Issue 4, p. 5267-5277 or arXiv:1811.07812

Constraints on the ISW “amplitude"

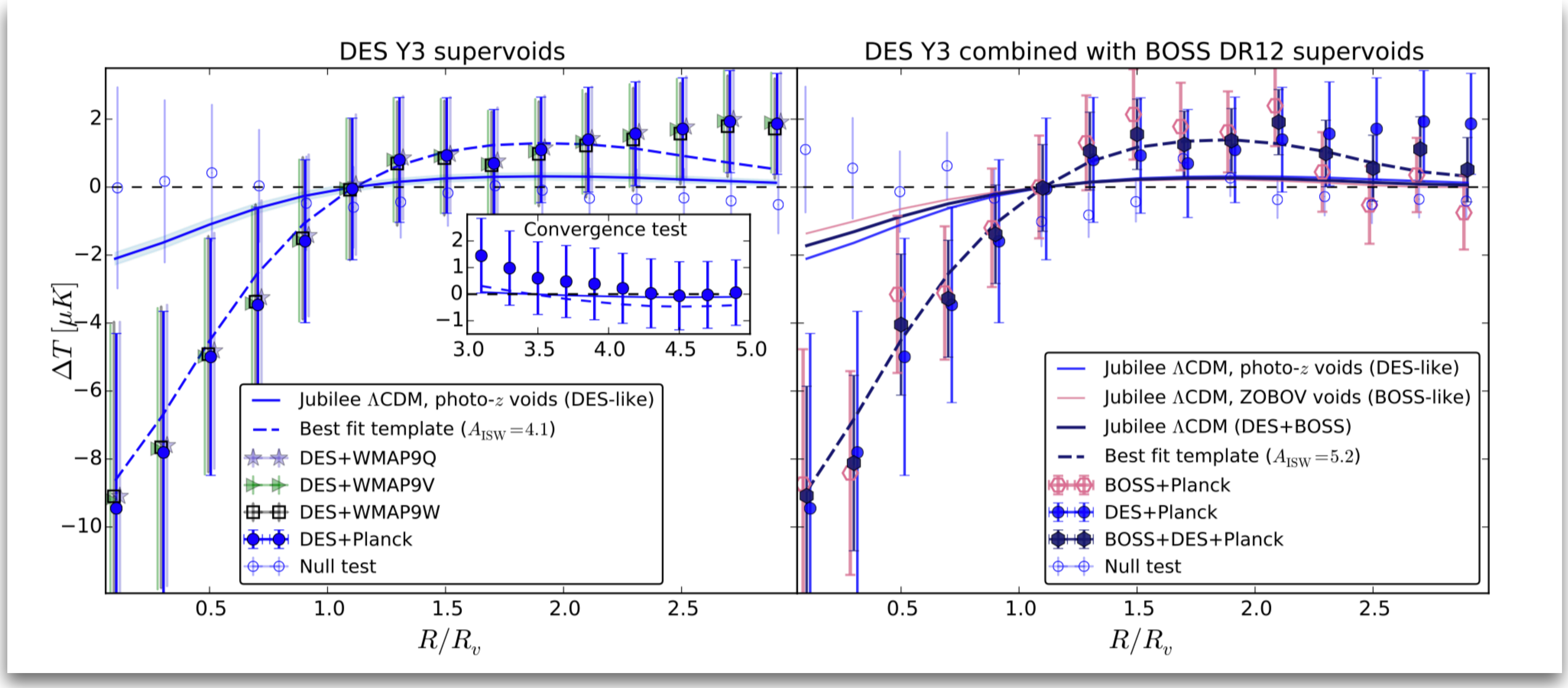


$$A_{\rm ISW} = \frac{T^{\rm measured}}{T^{\rm expected}}$$

+extra tests

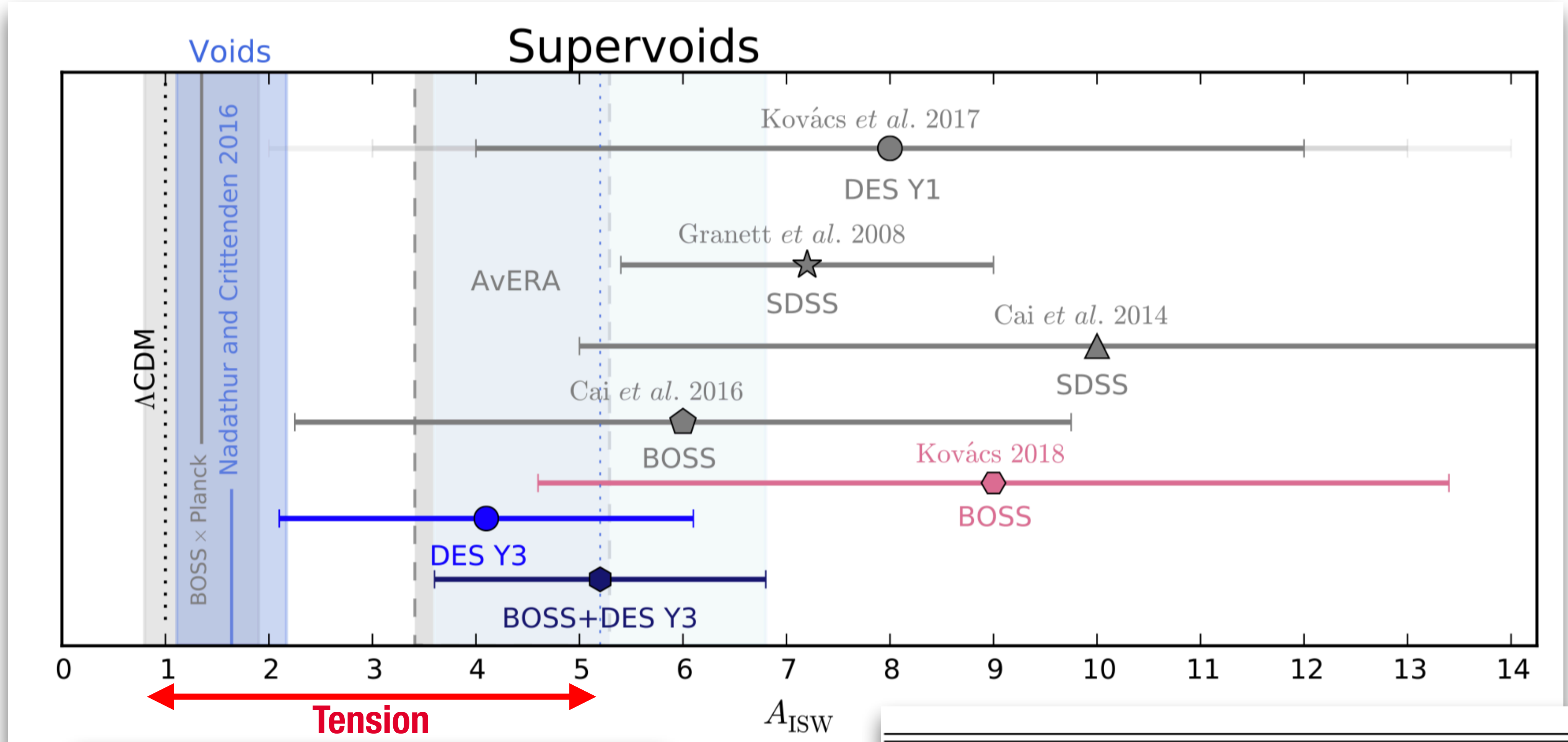
Radial profiles from the stacked images

Null tests passed **+WMAP Q,V,W: same results** **+BOSS DR12: similar results**

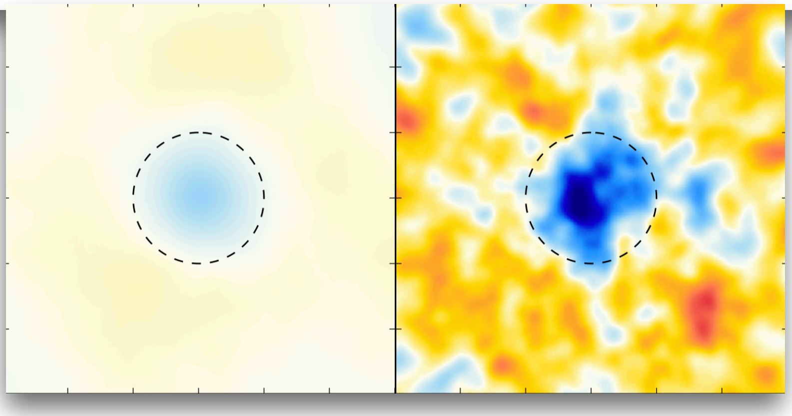


Kovács et al. 2019

Main result: joint fit using DES Y3 and BOSS DR12

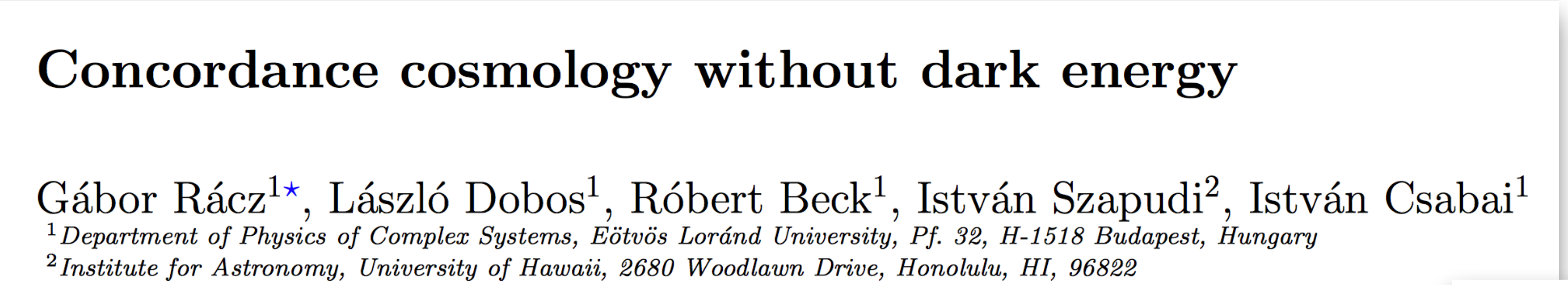


Kovács et al. 2019



Cross-correlated data sets	A_{ISW}	S/N	Tension
DES Y3 × Planck	4.1 ± 2.0	2.1	1.6σ
DES Y3+BOSS DR12 × Planck	5.2 ± 1.6	3.3	2.6σ

AvERA: a possible solution (?)



Concordance cosmology without dark energy

Gábor Rácz[1]*, László Dobos[1], Róbert Beck[1], István Szapudi[2], István Csabai[1]
[1] *Department of Physics of Complex Systems, Eötvös Loránd University, Pf. 32, H-1518 Budapest, Hungary*
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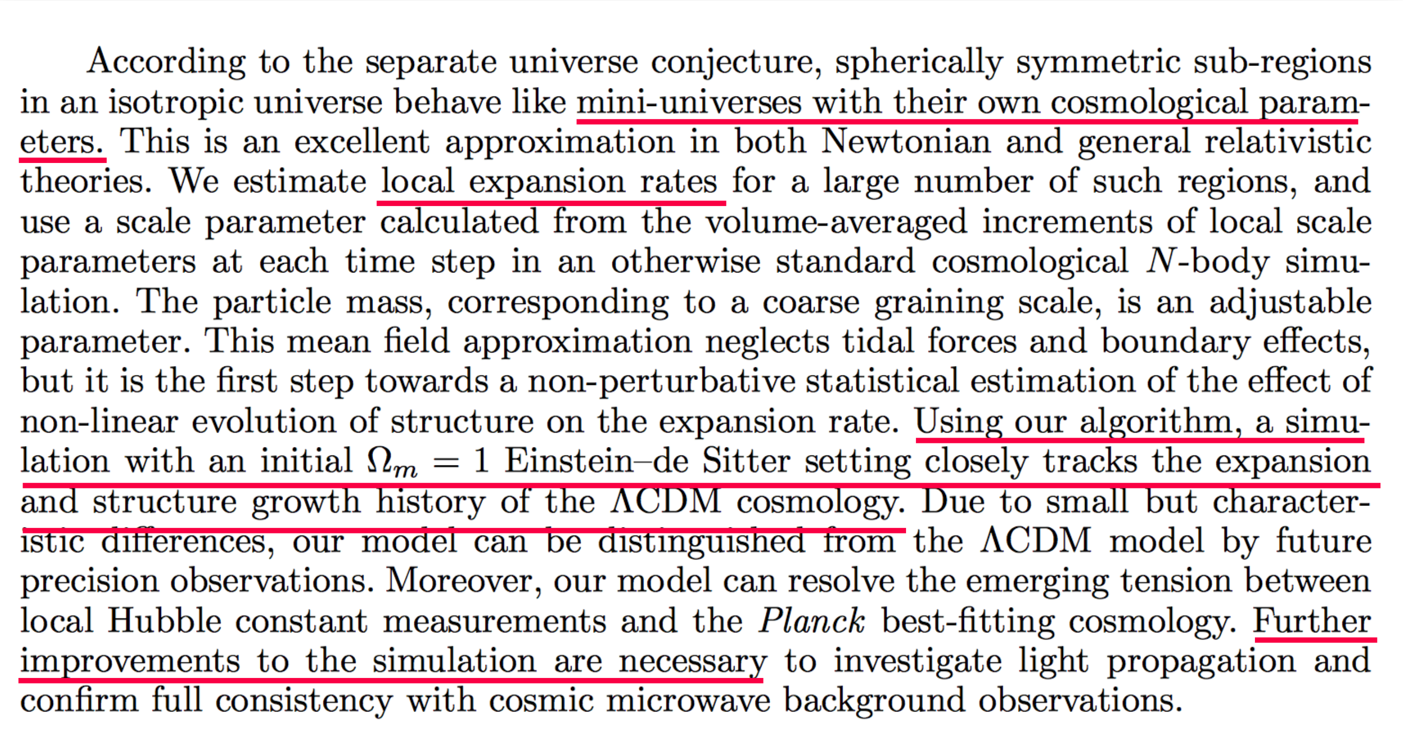
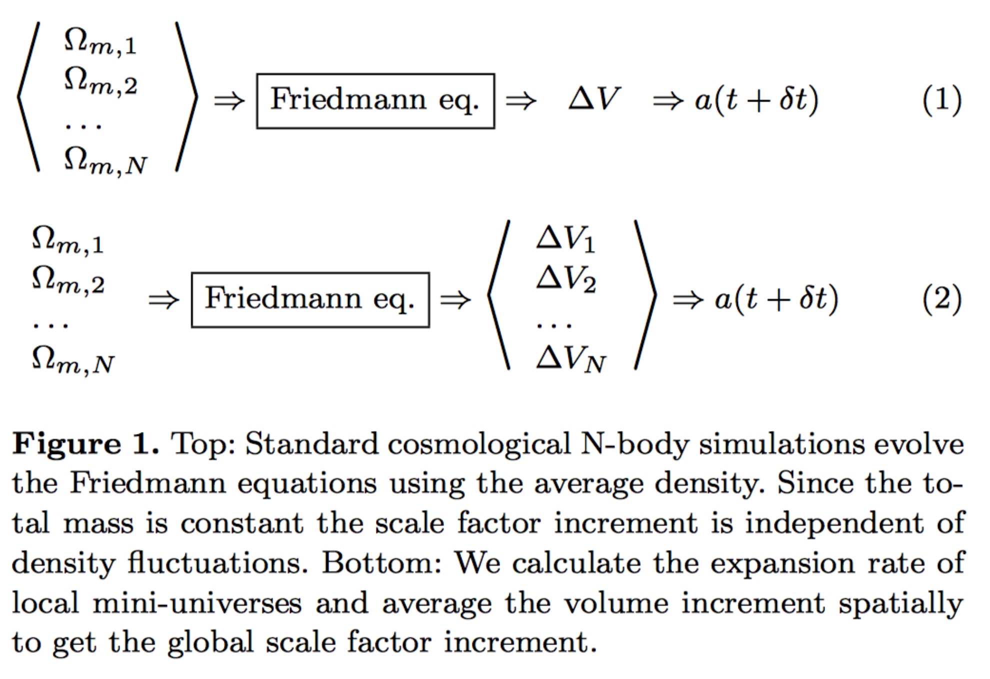
Rácz et al. 2018:
the Hubble tension can be explained



According to the separate universe conjecture, spherically symmetric sub-regions in an isotropic universe behave like mini-universes with their own cosmological parameters. This is an excellent approximation in both Newtonian and general relativistic theories. We estimate local expansion rates for a large number of such regions, and use a scale parameter calculated from the volume-averaged increments of local scale parameters at each time step in an otherwise standard cosmological N-body simulation. The particle mass, corresponding to a coarse graining scale, is an adjustable parameter. This mean field approximation neglects tidal forces and boundary effects, but it is the first step towards a non-perturbative statistical estimation of the effect of non-linear evolution of structure on the expansion rate. Using our algorithm, a simulation with an initial $\Omega_m = 1$ Einstein–de Sitter setting closely tracks the expansion and structure growth history of the ΛCDM cosmology. Due to small but characteristic differences, our model can be distinguished from the ΛCDM model by future precision observations. Moreover, our model can resolve the emerging tension between local Hubble constant measurements and the *Planck* best-fitting cosmology. Further improvements to the simulation are necessary to investigate light propagation and confirm full consistency with cosmic microwave background observations.



$$\left\langle \begin{matrix}\Omega_{m,1}\\ \Omega_{m,2}\\ \dots\\ \Omega_{m,N}\end{matrix}\right\rangle \Rightarrow \boxed{\text{Friedmann eq.}} \Rightarrow \Delta V \Rightarrow a(t+\delta t) \tag{1}$$

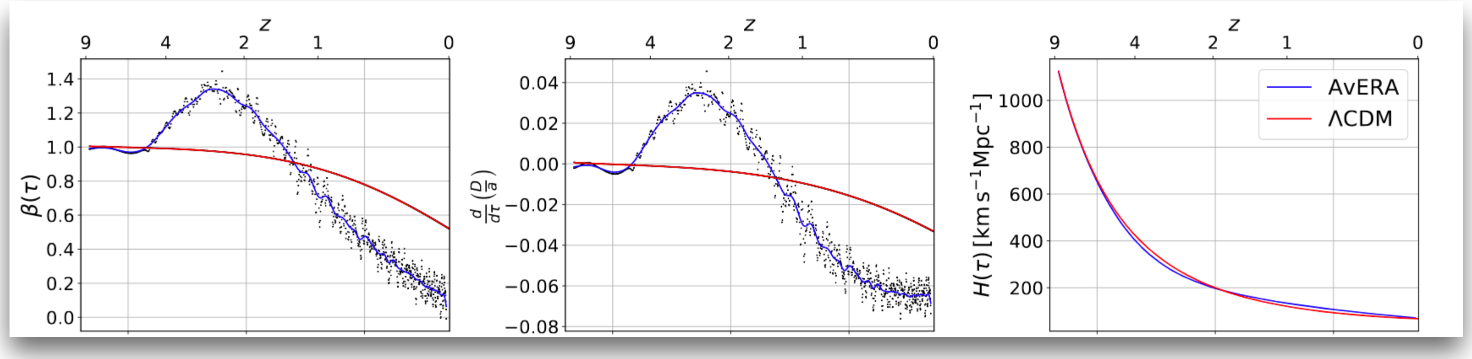
$$\begin{matrix}\Omega_{m,1}\\ \Omega_{m,2}\\ \dots\\ \Omega_{m,N}\end{matrix} \Rightarrow \boxed{\text{Friedmann eq.}} \Rightarrow \left\langle \begin{matrix}\Delta V_1\\ \Delta V_2\\ \dots\\ \Delta V_N\end{matrix}\right\rangle \Rightarrow a(t+\delta t) \tag{2}$$

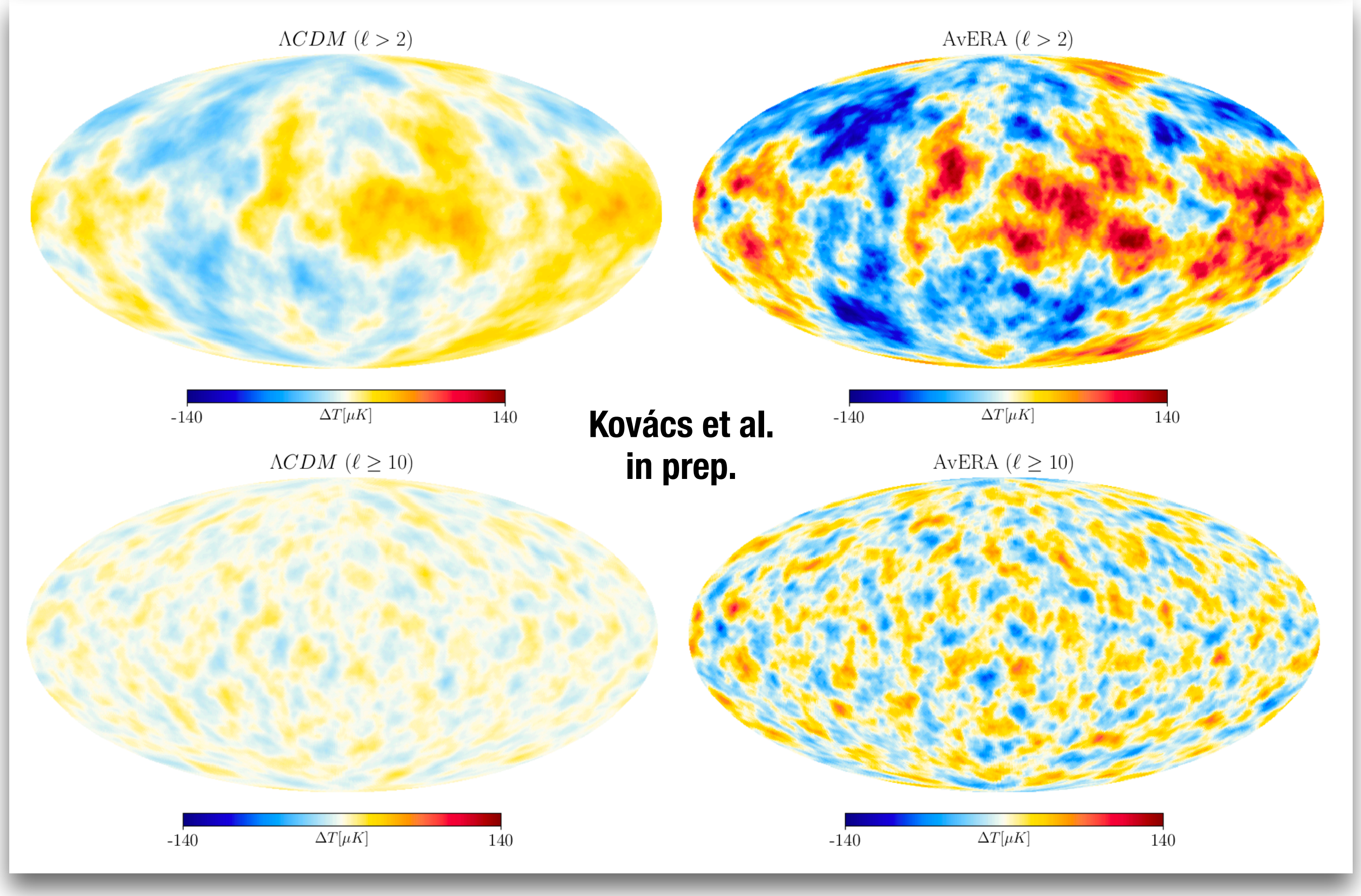
Figure 1. Top: Standard cosmological N-body simulations evolve the Friedmann equations using the average density. Since the total mass is constant the scale factor increment is independent of density fluctuations. Bottom: We calculate the expansion rate of local mini-universes and average the volume increment spatially to get the global scale factor increment.

Average Expansion Rate Approximation

ISW in the Millennium XXL: AvERA vs. ΛCDM

- **MXXL halo mock on a lightcone out to z=2.2 (Smith et al. 2017)**
- **Beck et al. 2018 constructed a ray-traced ISW map for this simulation (but using a different starting point)**
- **My idea: use the lightcone mock's center for the ISW ray tracing**
- **Then find supervoids and stack**
- **The AvERA ISW signal is not directly accessible**
- **Scaled growth history as seen in other AvERA simulation runs**





Kovács et al. in prep.

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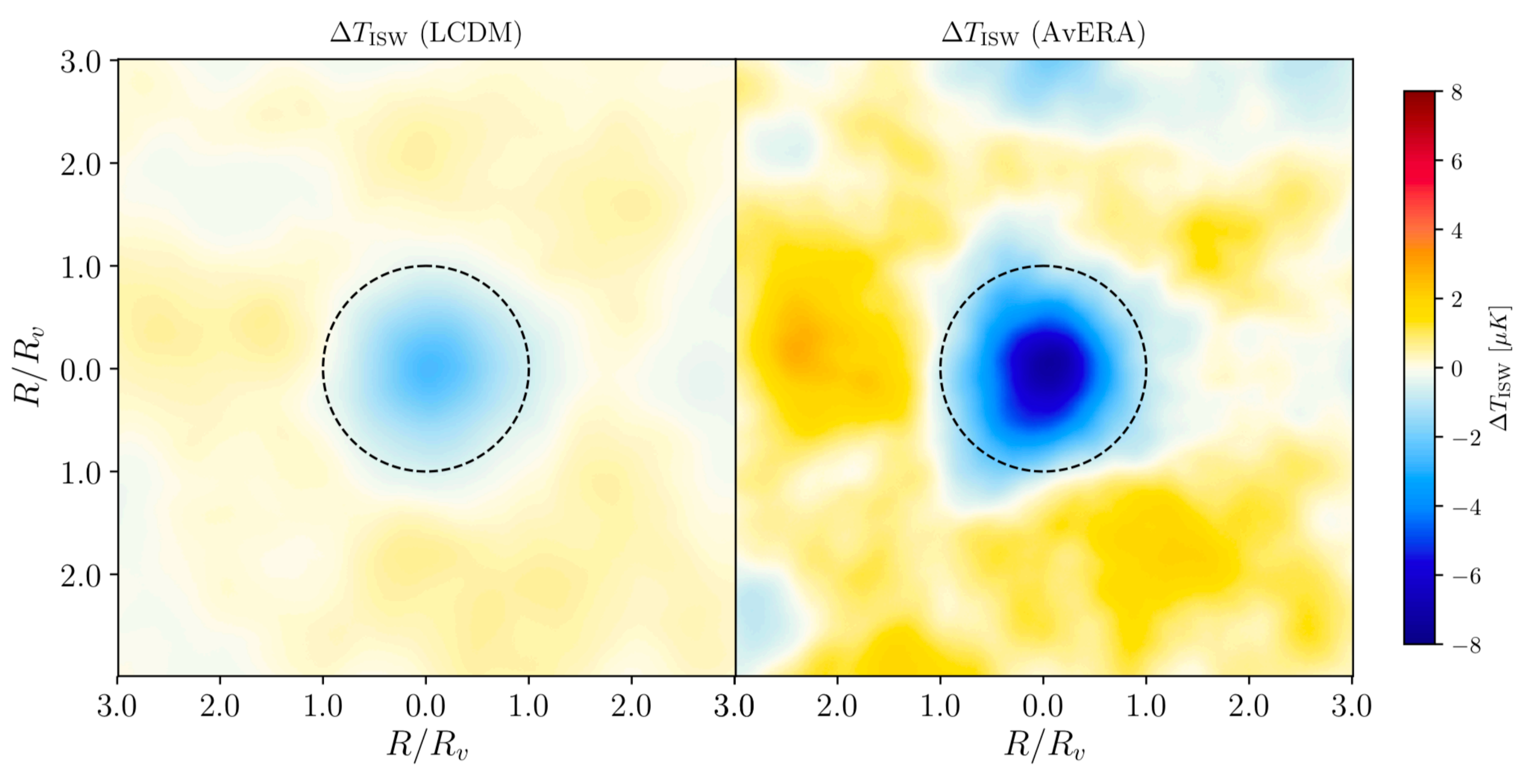
AvERA vs. ΛCDM

The stacked imprint of Millennium XXL supervoids



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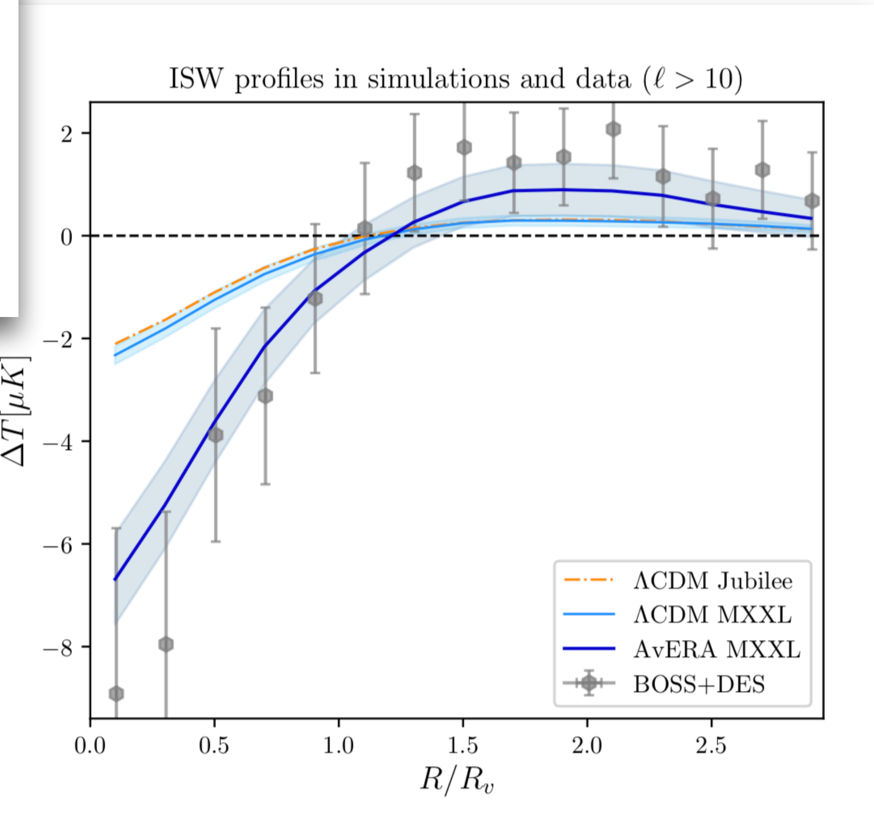
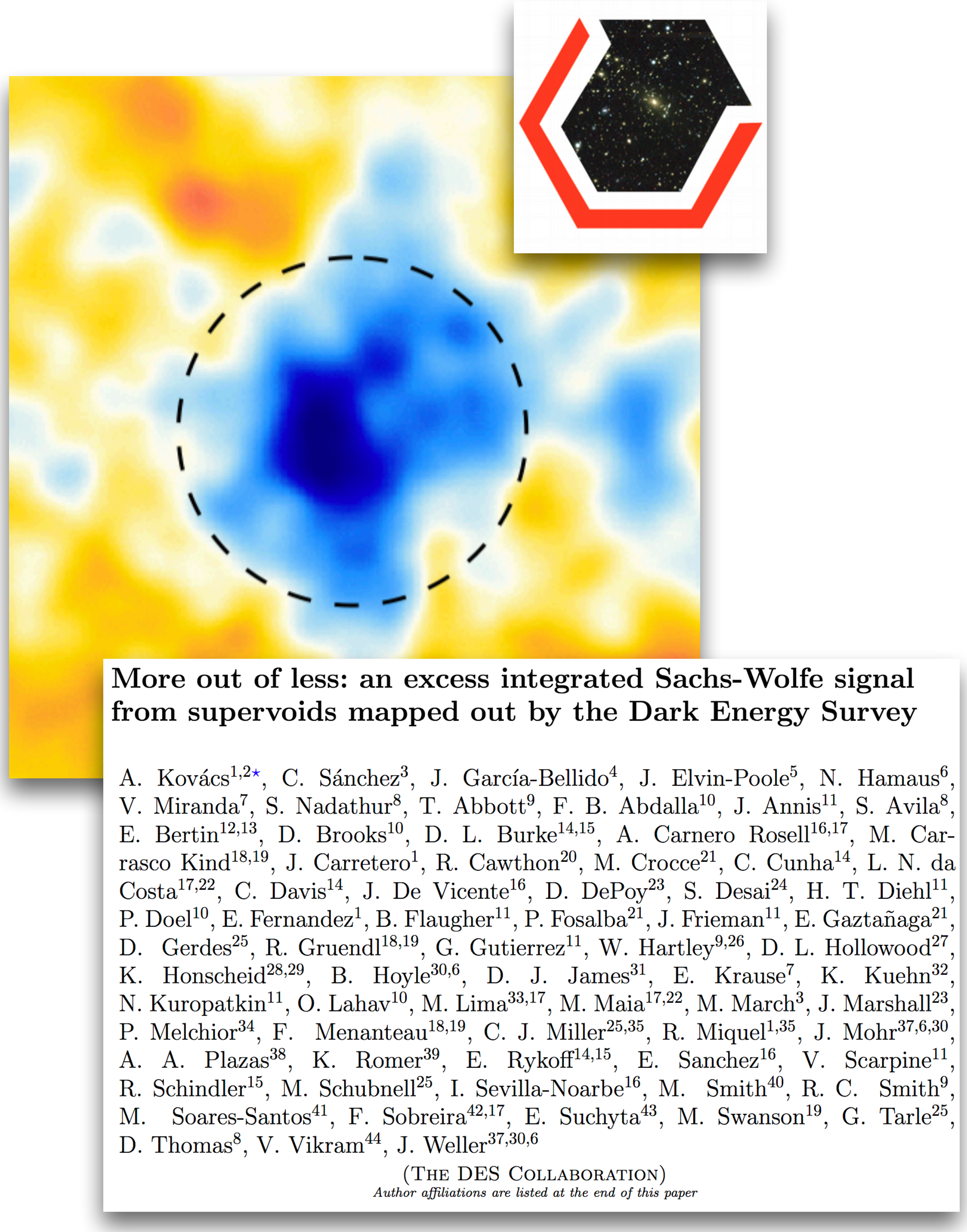


- **The AvERA models shows good agreement with BOSS+DES observations**
- **More work is needed to figure out the role of void definition**

Summary

- the DES Y3 data probes the ISW effect in a new window
- previous excess signal in BOSS is confirmed with more data
- New simulation results indicate that the ISW tension is plausibly related to the Hubble tension
- The AvERA model offers an interesting new way to test these hypotheses
- Future: opposite-sign ISW at z>1.4 in AvERA (eBOSS, DESI, Euclid)



More out of less: an excess integrated Sachs-Wolfe signal from supervoids mapped out by the Dark Energy Survey

A. Kovács[1,2⋆], C. Sánchez[3], J. García-Bellido[4], J. Elvin-Poole[5], N. Hamaus[6], V. Miranda[7], S. Nadathur[8], T. Abbott[9], F. B. Abdalla[10], J. Annis[11], S. Avila[8], E. Bertin[12,13], D. Brooks[10], D. L. Burke[14,15], A. Carnero Rosell[16,17], M. Carrasco Kind[18,19], J. Carretero[1], R. Cawthon[20], M. Crocce[21], C. Cunha[14], L. N. da Costa[17,22], C. Davis[14], J. De Vicente[16], D. DePoy[23], S. Desai[24], H. T. Diehl[11], P. Doel[10], E. Fernandez[1], B. Flaugher[11], P. Fosalba[21], J. Frieman[11], E. Gaztañaga[21], D. Gerdes[25], R. Gruendl[18,19], G. Gutierrez[11], W. Hartley[9,26], D. L. Hollowood[27], K. Honscheid[28,29], B. Hoyle[30,6], D. J. James[31], E. Krause[7], K. Kuehn[32], N. Kuropatkin[11], O. Lahav[10], M. Lima[33,17], M. Maia[17,22], M. March[3], J. Marshall[23], P. Melchior[34], F. Menanteau[18,19], C. J. Miller[25,35], R. Miquel[1,35], J. Mohr[37,6,30], A. A. Plazas[38], K. Romer[39], E. Rykoff[14,15], E. Sanchez[16], V. Scarpine[11], R. Schindler[15], M. Schubnell[25], I. Sevilla-Noarbe[16], M. Smith[40], R. C. Smith[9], M. Soares-Santos[41], F. Sobreira[42,17], E. Suchyta[43], M. Swanson[19], G. Tarle[25], D. Thomas[8], V. Vikram[44], J. Weller[37,30,6]

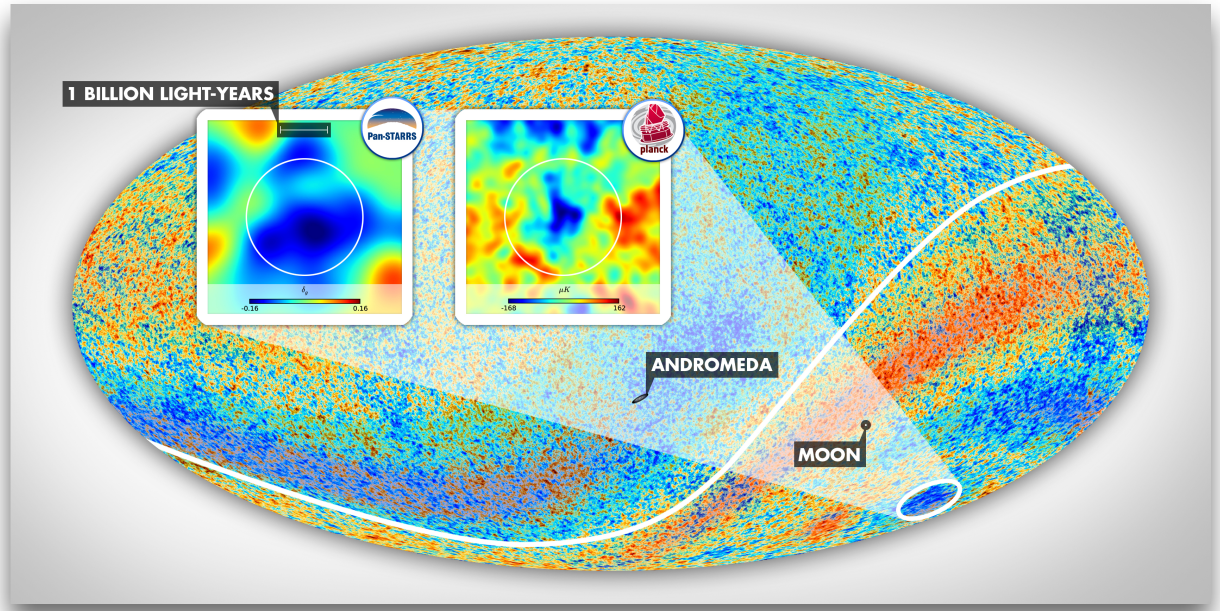
(The DES Collaboration)

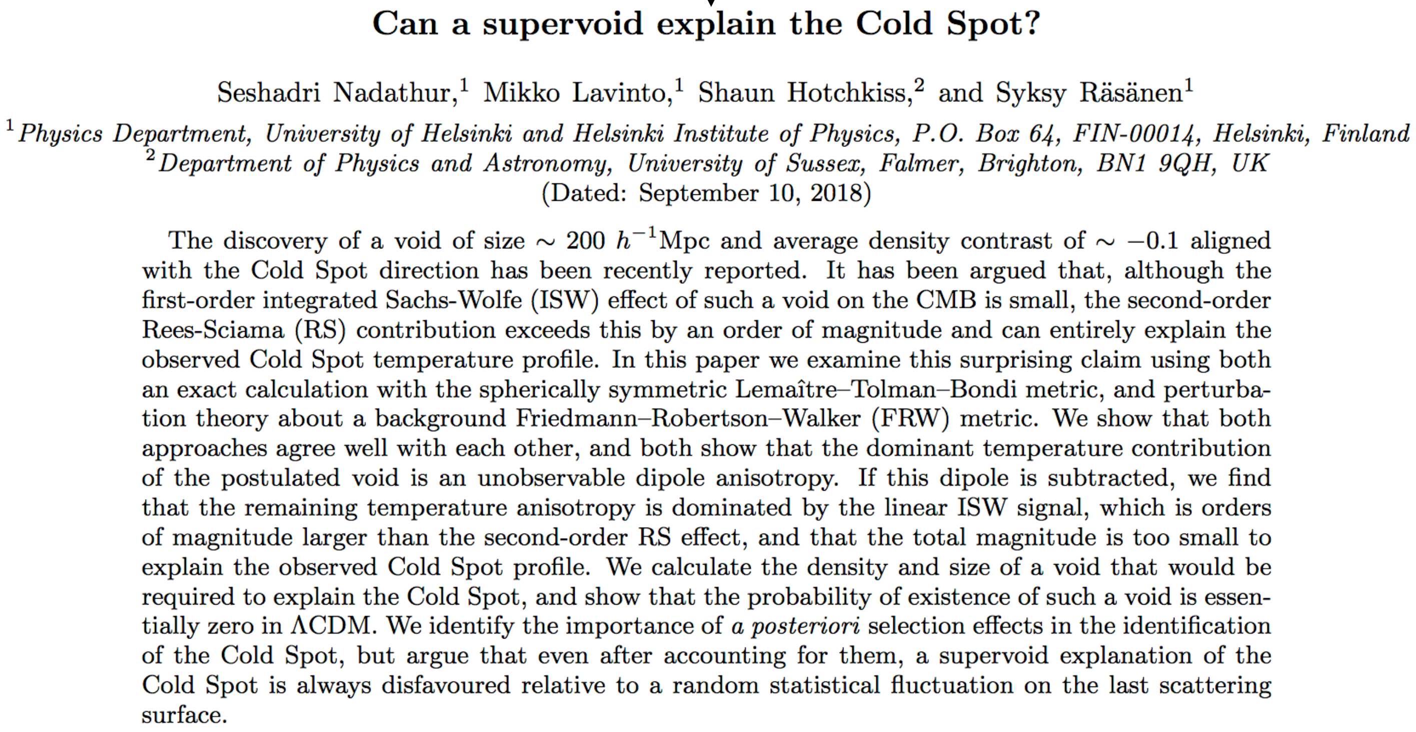
Author affiliations are listed at the end of this paper

Thanks to collaborators: the DES team, especially Carles Sánchez (void finding) and Juan García-Bellido (theory)

AvERA and the CMB Cold Spot - a bonus

- debate if the CMB Cold Spot and the Eridanus supervoid are in causal relation
- Same problem: ΛCDM models predict 4-5 times smaller signal than the observed CMB profile
- the CMB Cold Spot is consistent with the coldest spot in the AvERA ISW map





Can a supervoid explain the Cold Spot?

Seshadri Nadathur,[1] Mikko Lavinto,[1] Shaun Hotchkiss,[2] and Syksy Räsänen[1]
[1] *Physics Department, University of Helsinki and Helsinki Institute of Physics, P.O. Box 64, FIN-00014, Helsinki, Finland*
[2] *Department of Physics and Astronomy, University of Sussex, Falmer, Brighton, BN1 9QH, UK*

(Dated: September 10, 2018)

The discovery of a void of size $\sim 200\ h^{-1}$Mpc and average density contrast of ~ -0.1 aligned with the Cold Spot direction has been recently reported. It has been argued that, although the first-order integrated Sachs-Wolfe (ISW) effect of such a void on the CMB is small, the second-order Rees-Sciama (RS) contribution exceeds this by an order of magnitude and can entirely explain the observed Cold Spot temperature profile. In this paper we examine this surprising claim using both an exact calculation with the spherically symmetric Lemaître–Tolman–Bondi metric, and perturbation theory about a background Friedmann–Robertson–Walker (FRW) metric. We show that both approaches agree well with each other, and both show that the dominant temperature contribution of the postulated void is an unobservable dipole anisotropy. If this dipole is subtracted, we find that the remaining temperature anisotropy is dominated by the linear ISW signal, which is orders of magnitude larger than the second-order RS effect, and that the total magnitude is too small to explain the observed Cold Spot profile. We calculate the density and size of a void that would be required to explain the Cold Spot, and show that the probability of existence of such a void is essentially zero in ΛCDM. We identify the importance of *a posteriori* selection effects in the identification of the Cold Spot, but argue that even after accounting for them, a supervoid explanation of the Cold Spot is always disfavoured relative to a random statistical fluctuation on the last scattering surface.

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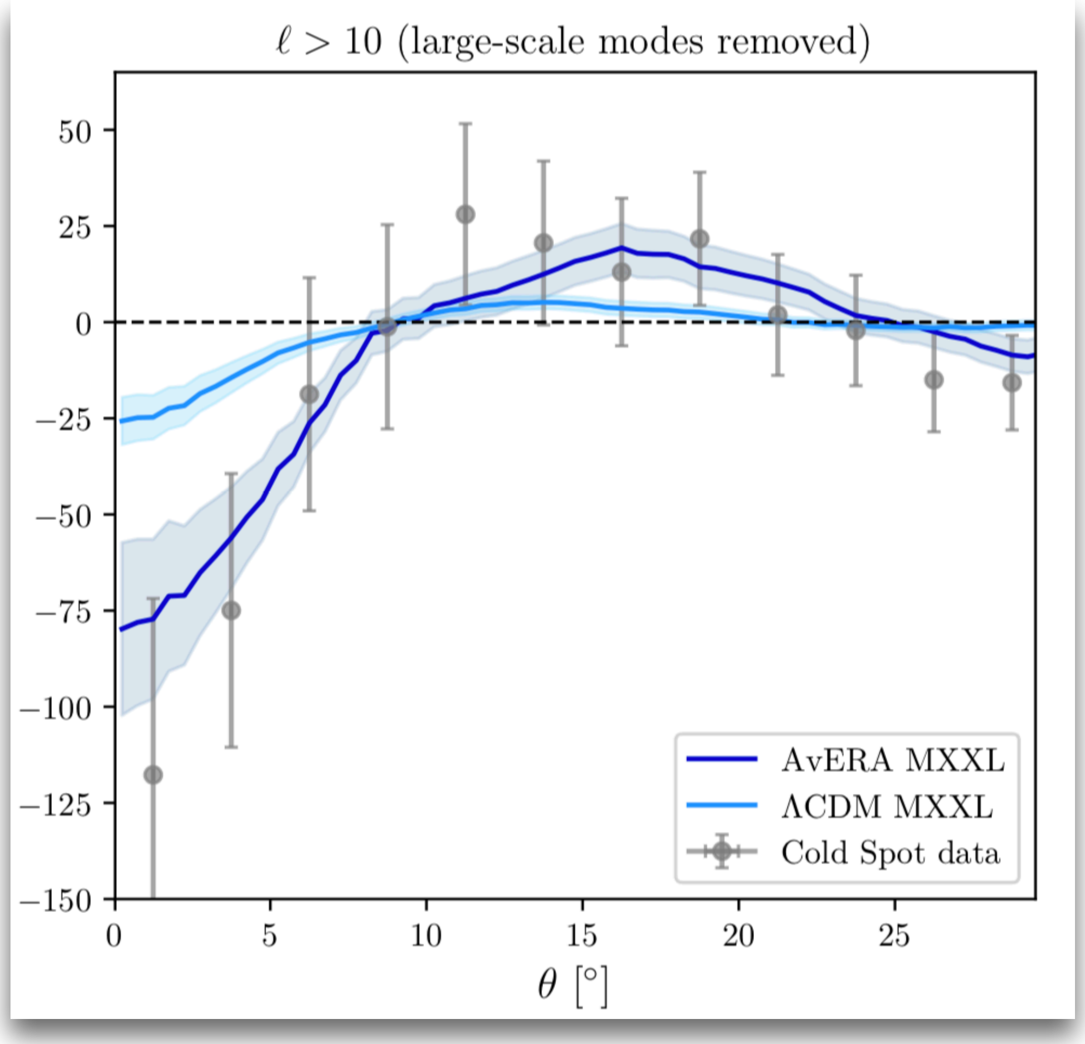
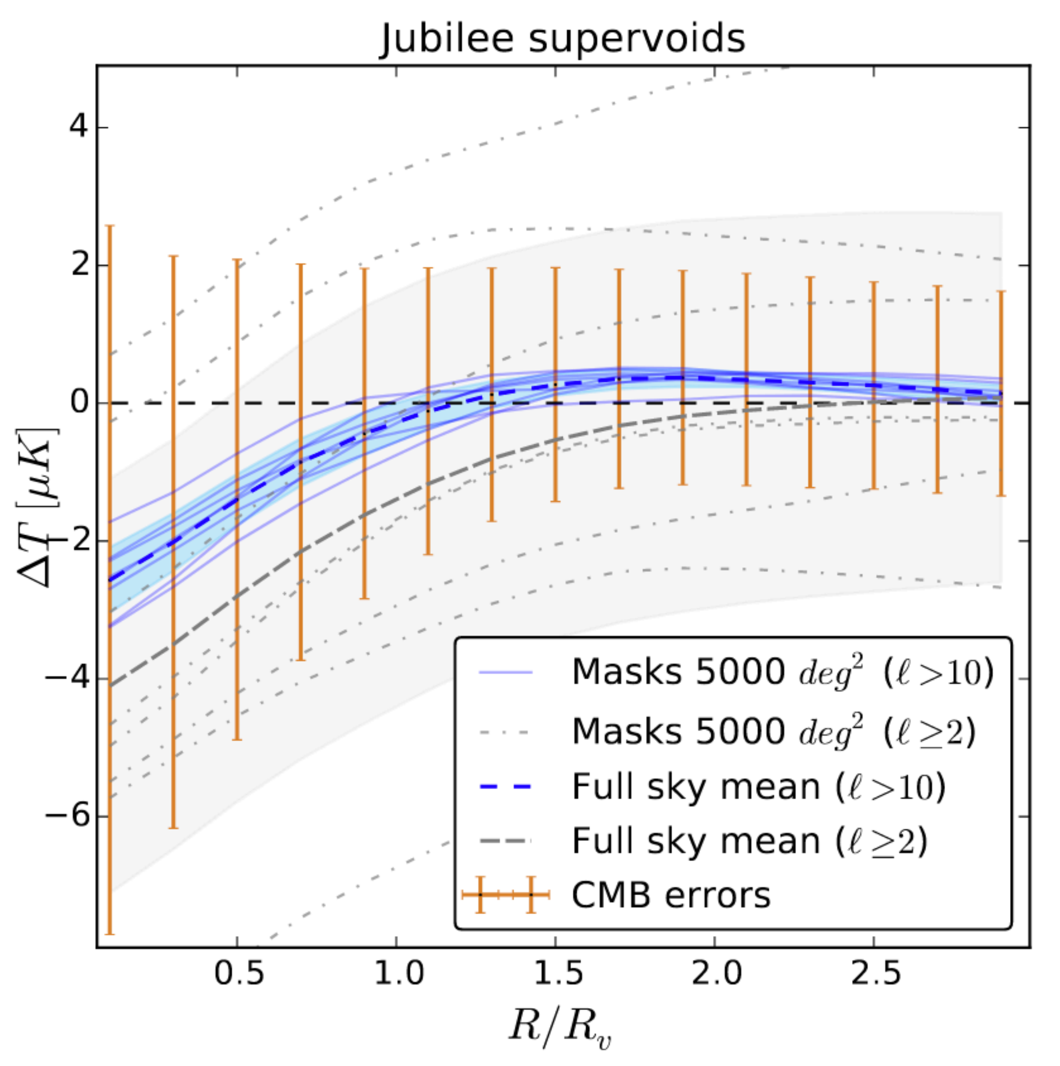
- the CMB Cold Spot is consistent with the coldest spot in the AvERA ISW map



Kovács et al. in prep.

Extra slide - covariance matrices and map filtering



Kovács et al. 2019