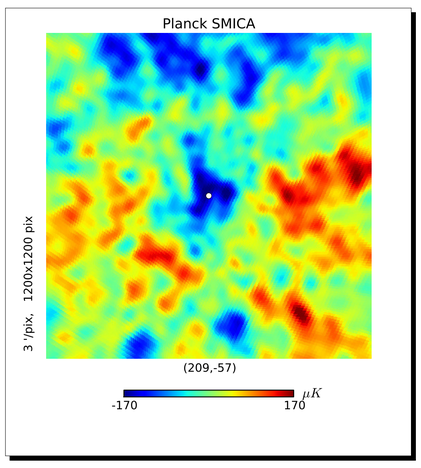

Detection of a Supervoid Aligned with the Cold Spot of the Cosmic Microwave Background

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and the Pan-STARRS1 collaboration

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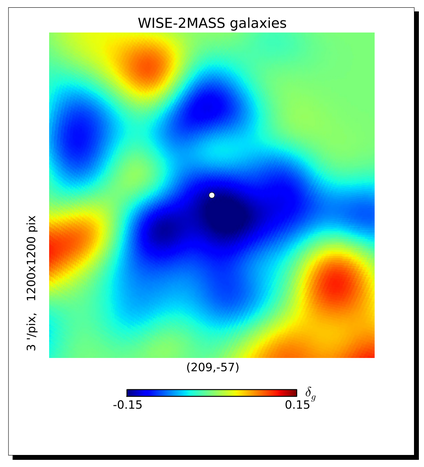

The Cold Spot anomaly

The Cold Spot is perhaps the most significant among the "anomalies" in the WMAP and *Planck* maps of the Cosmic Microwave Background. This exceptionally cold region of $\Delta T \approx -70$ μK, and of size $R \approx 5^\circ$ could be of primordial origin, or caused e.g. by a foreground supervoid via the Integrated Sachs-Wolfe effect (ISW). While so far no supervoid was found that could fully explain the CS, there is strong, $\gtrsim 4.4\sigma$, statistical evidence that superstructures imprint on the CMB as cold and hot spots. Targeted redshift and imaging surveys in the area excluded the presence of a large underdensity of $\delta \simeq -0.3$ between redshifts of $0.3 < z < 1.0$. These surveys, however, ran out of volume at low redshifts due to their small survey area, although their observations are consistent with the presence of a void at $z < 0.3$ with low significance. The Wide-field Infrared Survey Explorer all-sky survey effectively probes low redshift $z \leq 0.3$ unconstrained by previous studies.

WISE-2MASS-PS1 galaxy map

Map making and preparation:

1. effective star-galaxy separation based on WISE and 2MASS photometry
2. cross matching with Pan-STARRS1 optical observations in g, r, and i in a 50° x 50° box
3. estimation of photometric redshifts with support vector machine algorithms

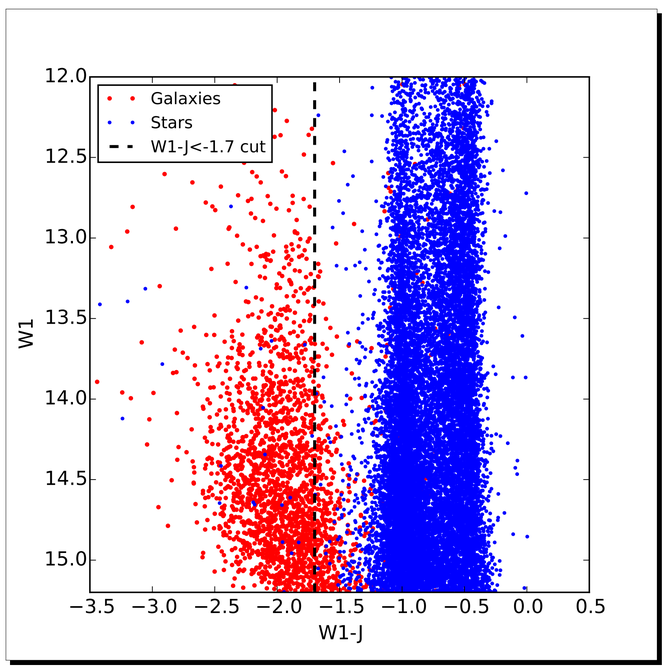

Figure: Selection of galaxies using WISE and 2MASS photometry and colors based on SDSS training.

Main steps in the analysis:

1. galaxy counting in circles of size $R = 15^\circ$ and $R = 5^\circ$ based on previous size estimates for the Cold Spot with and without its outer hot ring
2. measurement of the galaxy bias to estimate the real dark matter underdensity
3. tomographic imaging of the Cold Spot region in $\Delta z = 0.07$ photo-z slices
4. estimation of statistical and systematic errors using Gaussian simulations
5. comparisons to theory, and search for similar voids in the WISE-2MASS galaxy map

The supervoid at the Cold Spot

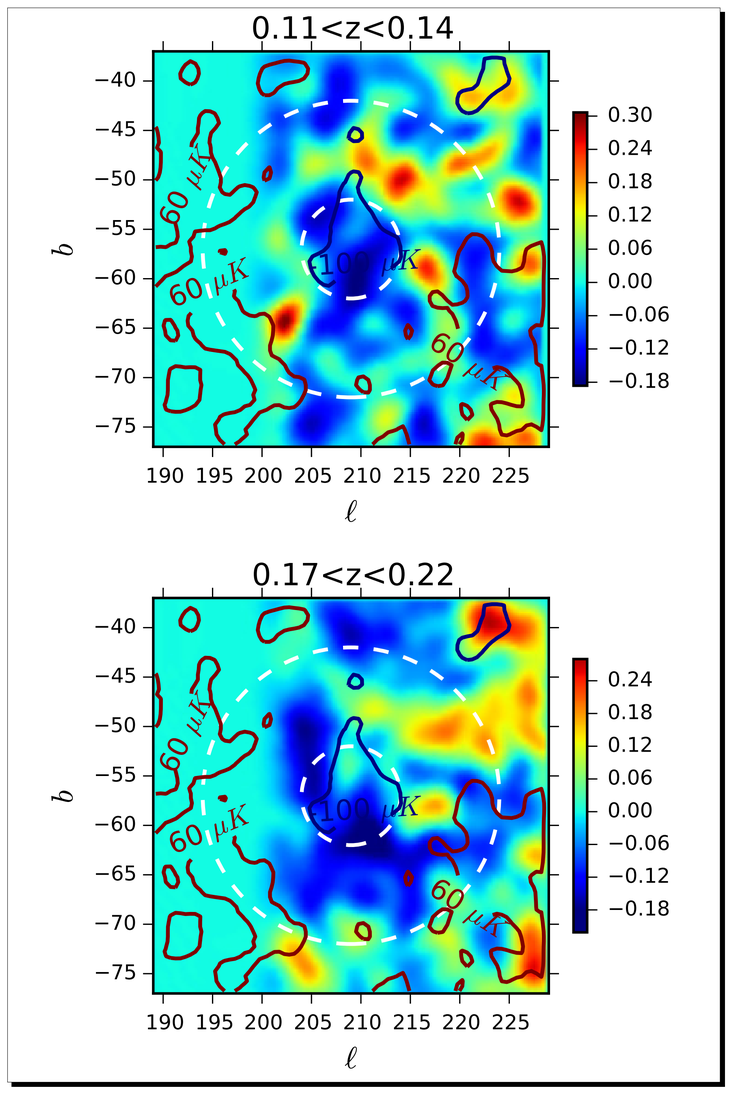

Figure: Tomographic imaging of the Cold Spot region using photo-z information provided by Pan-STARRS1. Contours mark the CMB temperature levels.

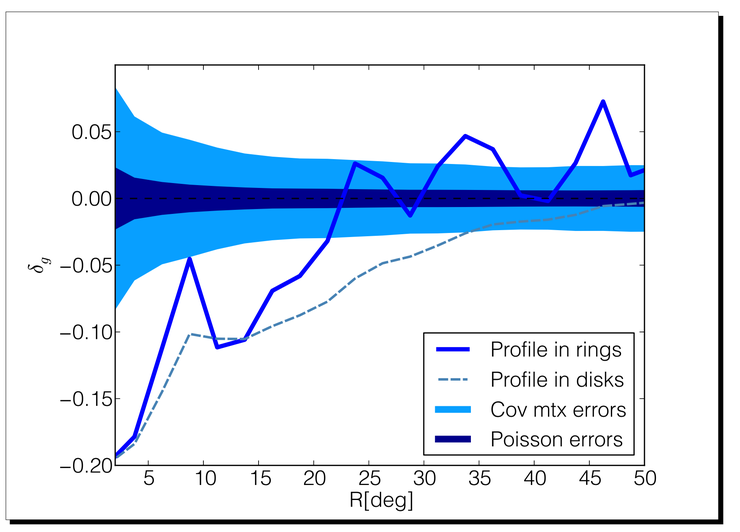

Figure: The radial galaxy density profile measured in the WISE-2MASS catalogue, and a comparison to error levels.

Main observations:

1. an underdensity of $\delta \approx -20\%$ in the center in the 2D WISE-2MASS galaxy map
2. no evidence for an underdensity at low redshift
3. deepening in the center at $0.10 < z < 0.15$
4. $\delta \approx -15\%$ underdensity at $0.10 < z < 0.30$
5. extra deepening in the central $R < 5^\circ$ region at $0.10 < z < 0.15$
6. inner compensation around the deepest central region at $0.10 < z < 0.15$

Model for the supervoid and its effect in the CMB

Galaxy counts versus a simple top-hat void profile including the photo-z smearing effect:

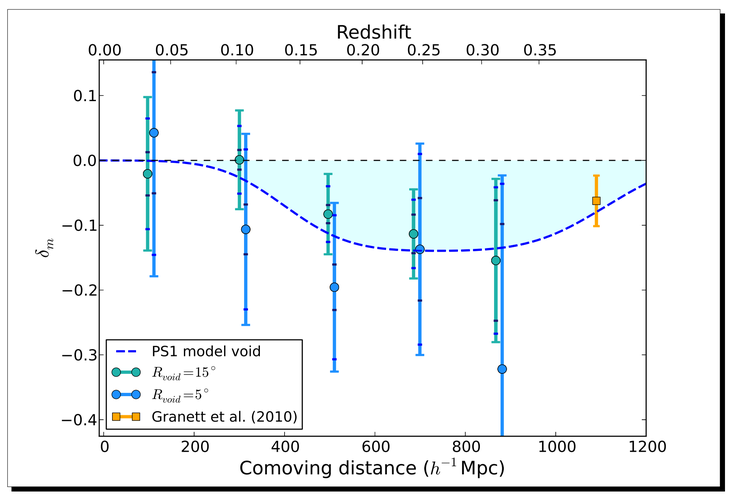

Figure: Galaxy density measurements in photo-z slices along the line-of-sight, marking out the supervoid.

Best fit supervoid parameters:

	Finelli et al. LTB	Szapudi et al. Top-hat
R [h^{-1}Mpc]	198 ± 90	220 ± 50
Redshift	-	0.22 ± 0.03
Depth	-0.29 ± 0.19	-0.14 ± 0.04

The simple model of Rudnick et al. for the CMB temperature effect caused by the supervoid:

$$\Delta T_{ISW} = -\left(\frac{R}{c/H_0}\right)^3 (1+2z)^{1/2} (1+z)^{-2} \delta \, T_{CMB}$$

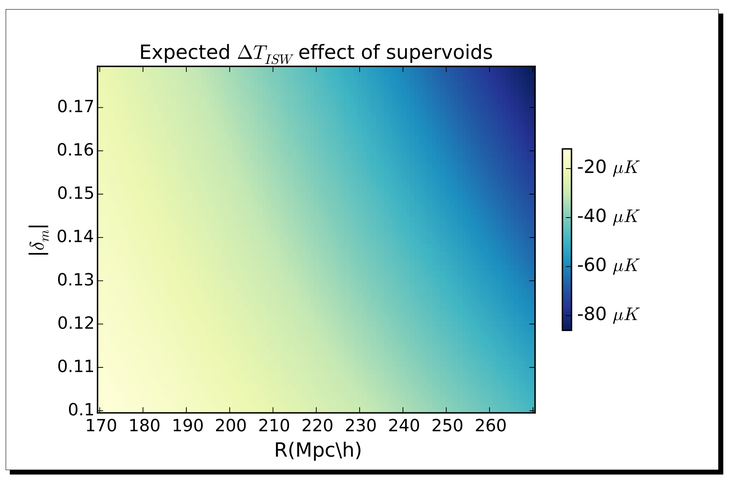

Figure: Estimated CMB temperature shift caused by model supervoids in the $\pm 1\sigma$ parameter space of the best-fit supervoid.

The temperature depression for a supervoid with the best-fit parameters is $\Delta T_{ISW} \approx -30$ μK.

Conclusions

1. A supervoid of size $R \approx 220\, h^{-1}$Mpc and $\delta \approx -0.15$ was discovered aligned with the Cold Spot
2. In ΛCDM, the supervoid cannot fully account for the Cold Spot as an ISW imprint
3. Chance alignment of a $\sim 3\sigma$ fluctuation in the CMB and a $\sim 3\sigma$ fluctuation in the LSS is not plausible, and their causal connection is strongly preferred, even without a clear physical picture
4. We found *one more* similarly large supervoid in the WISE-2MASS catalog, aligned with a depression of $\Delta T_{ISW} \approx -20$ μK in the CMB, in agreement with the predictions of the model