The Cold Spot on the Cosmic Microwave Background

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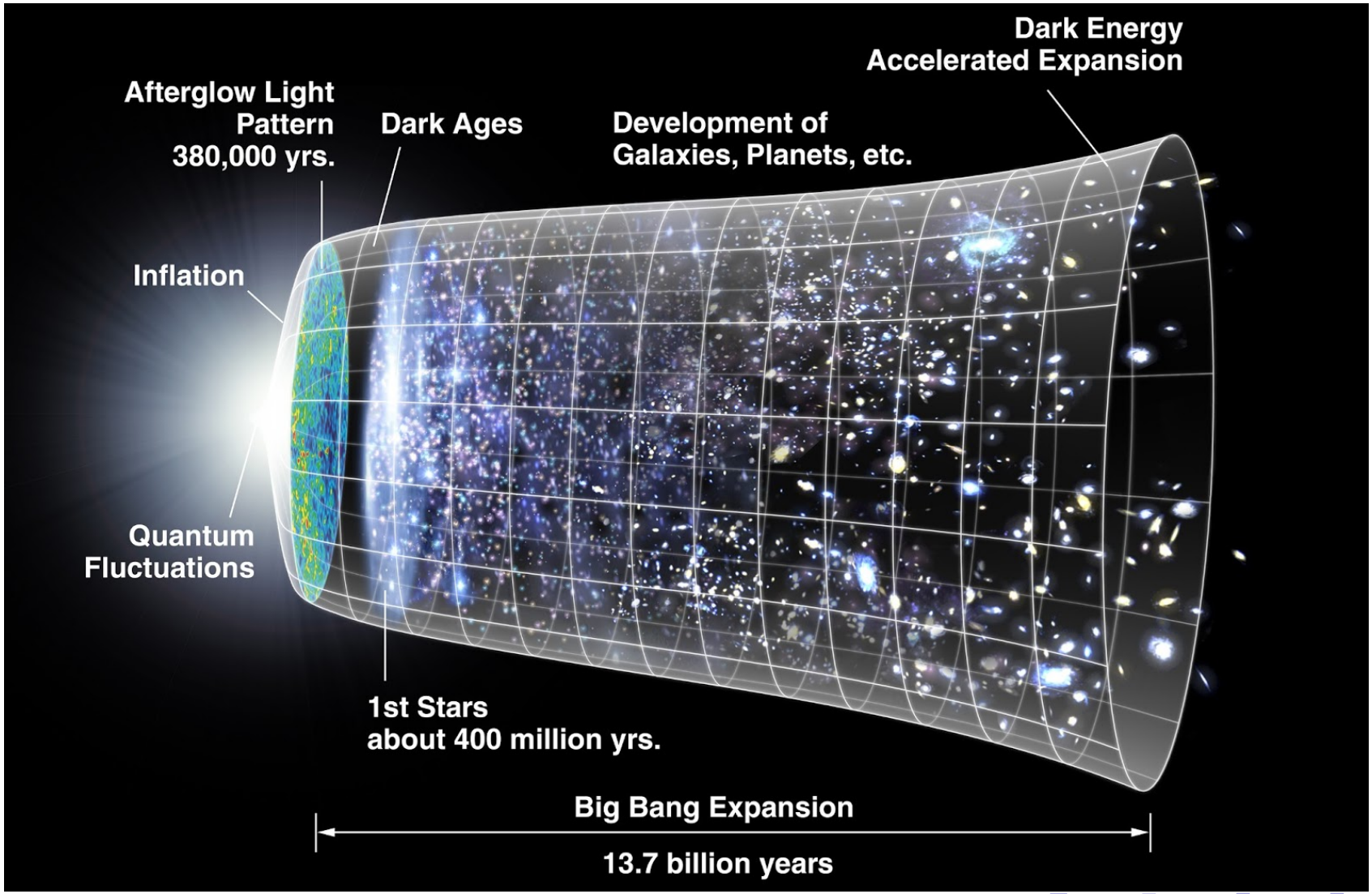
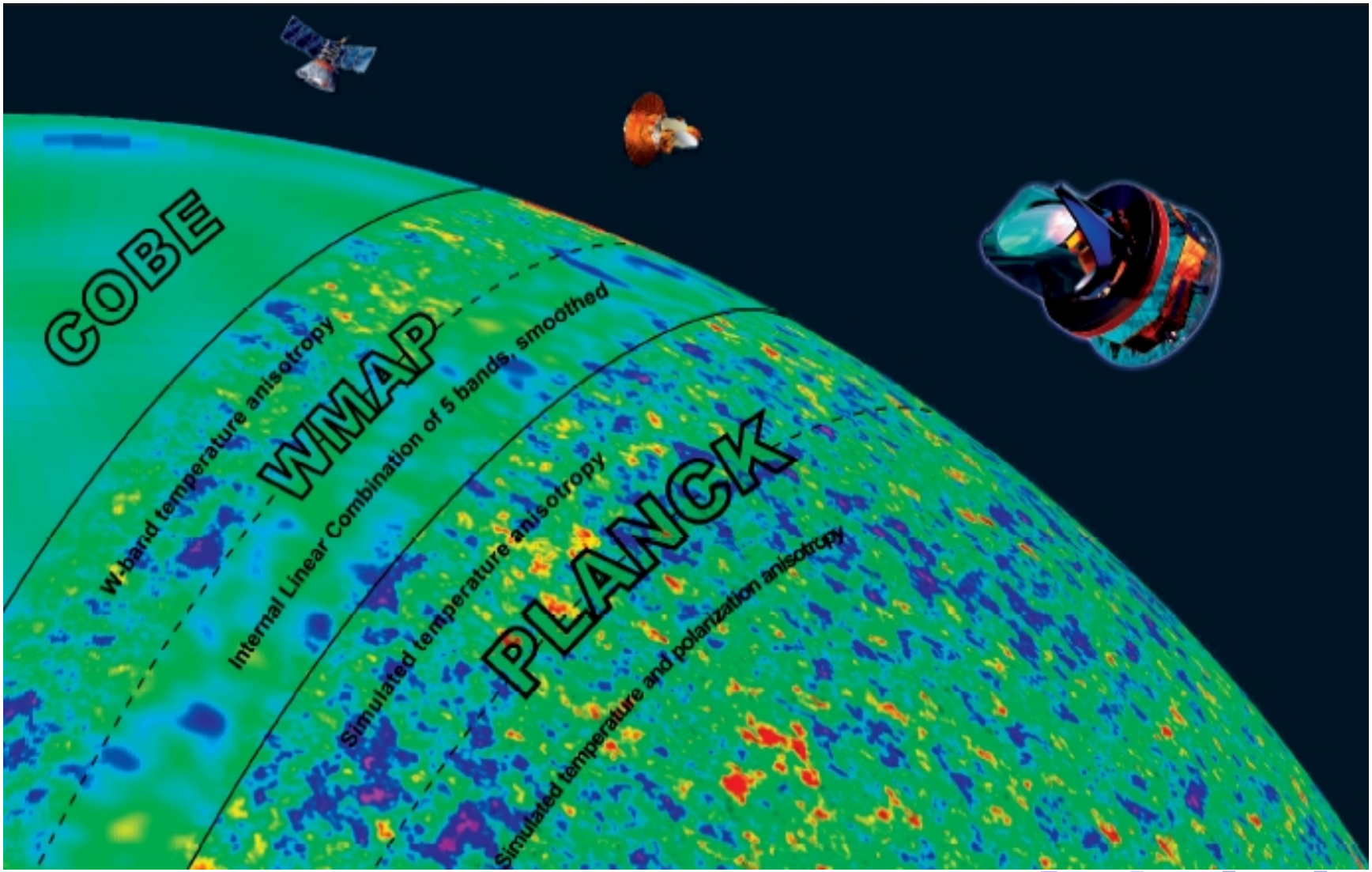
Outline

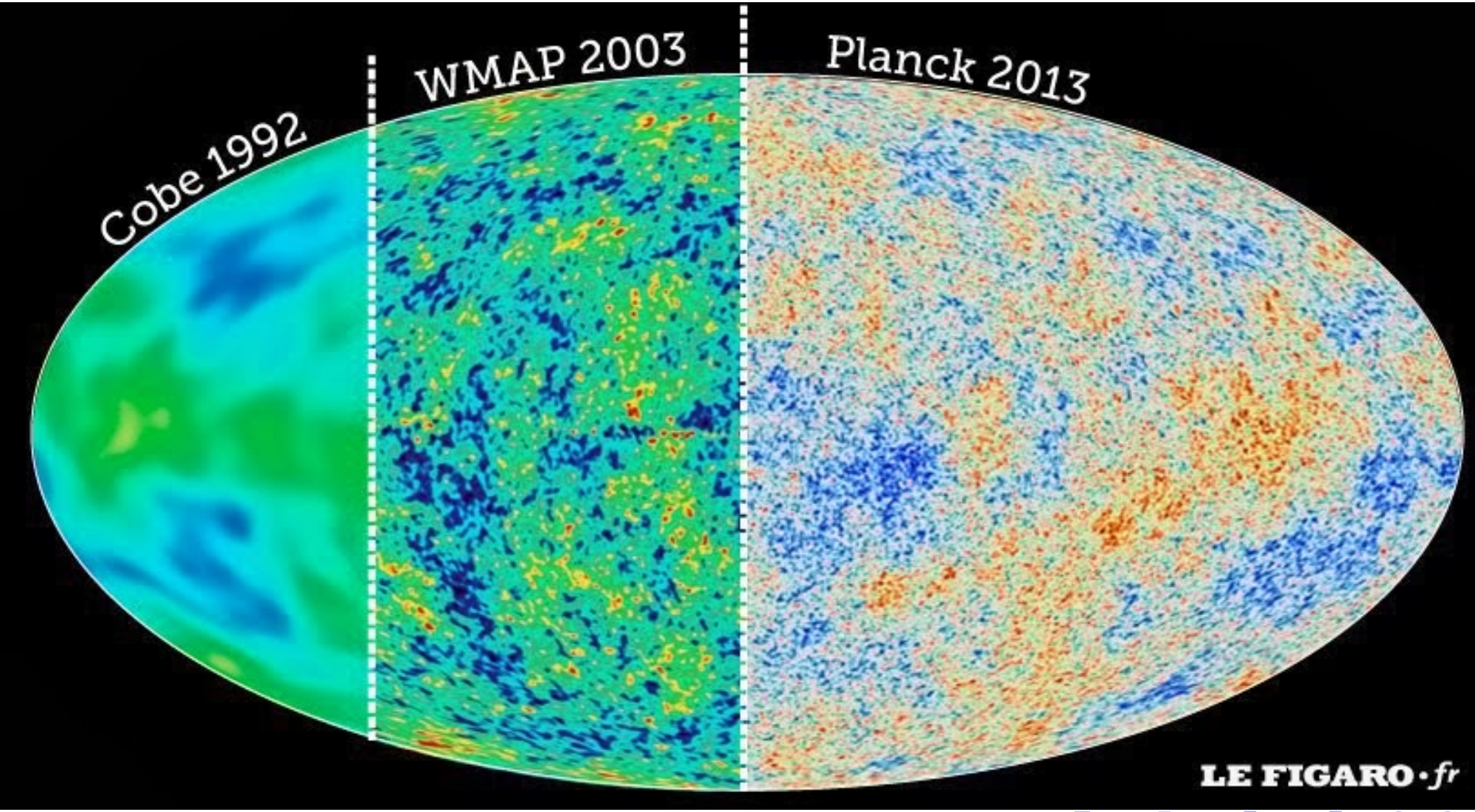
From Big Bang to Present



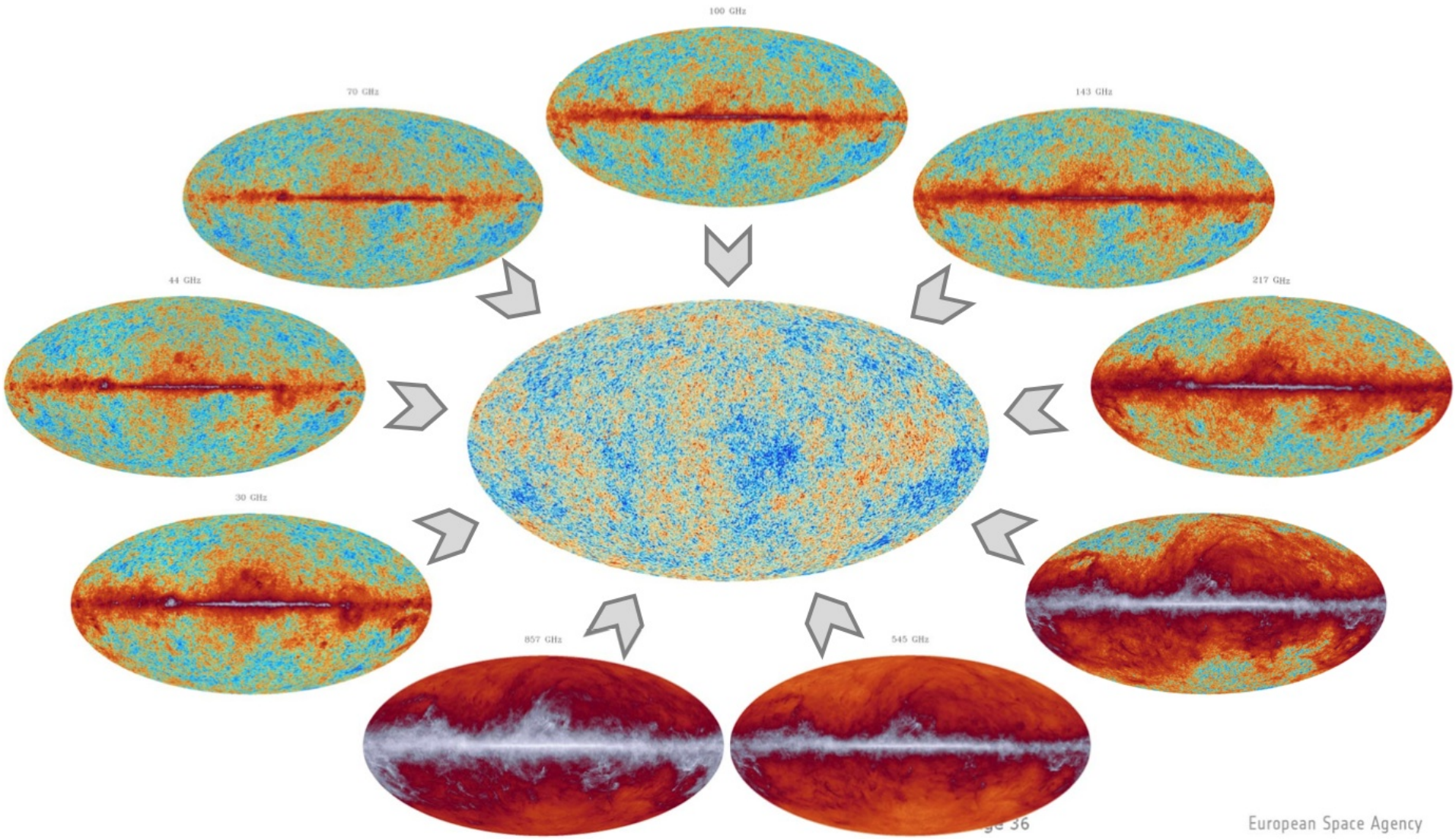
From COBE To Planck



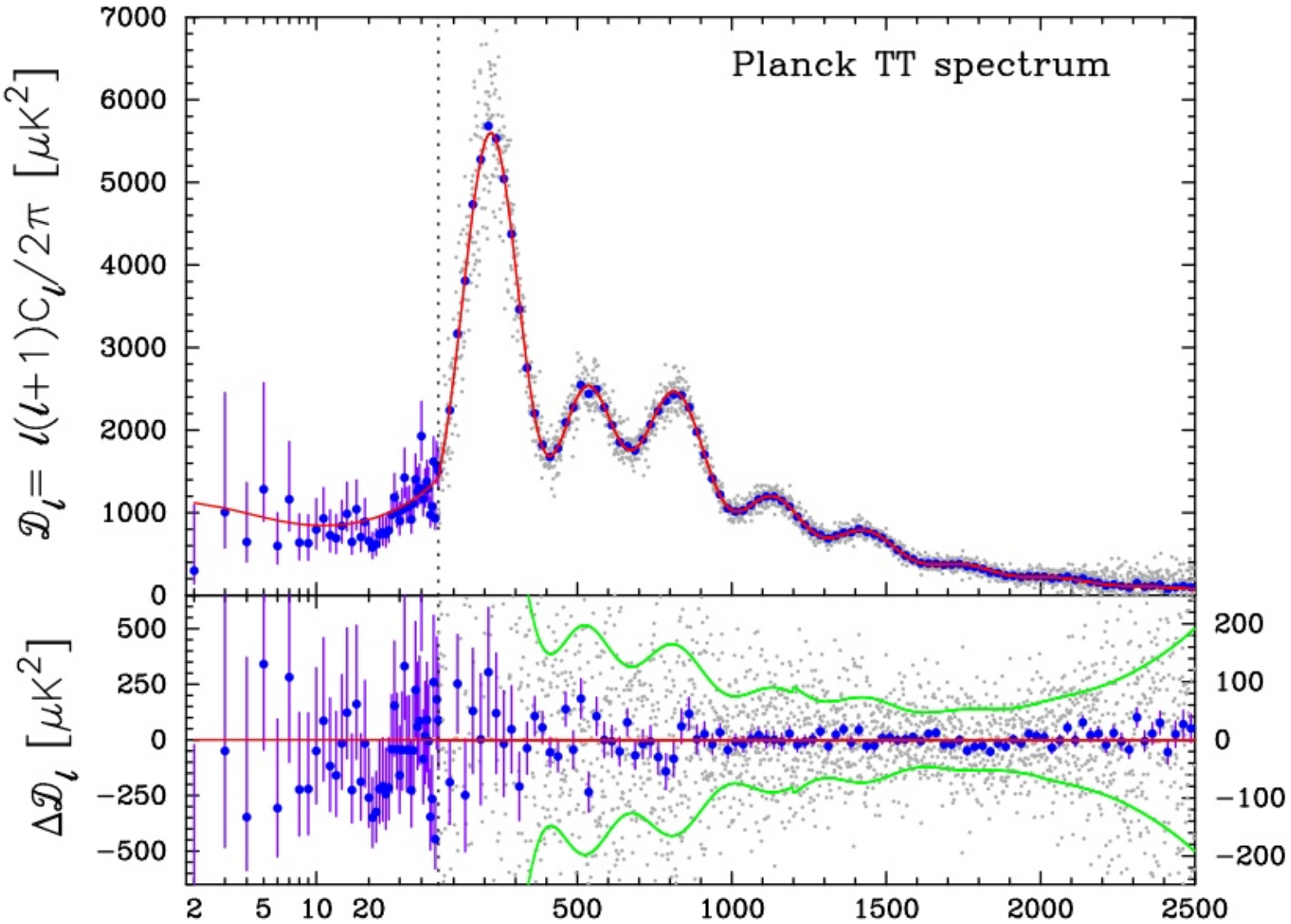
Increasing Resolution



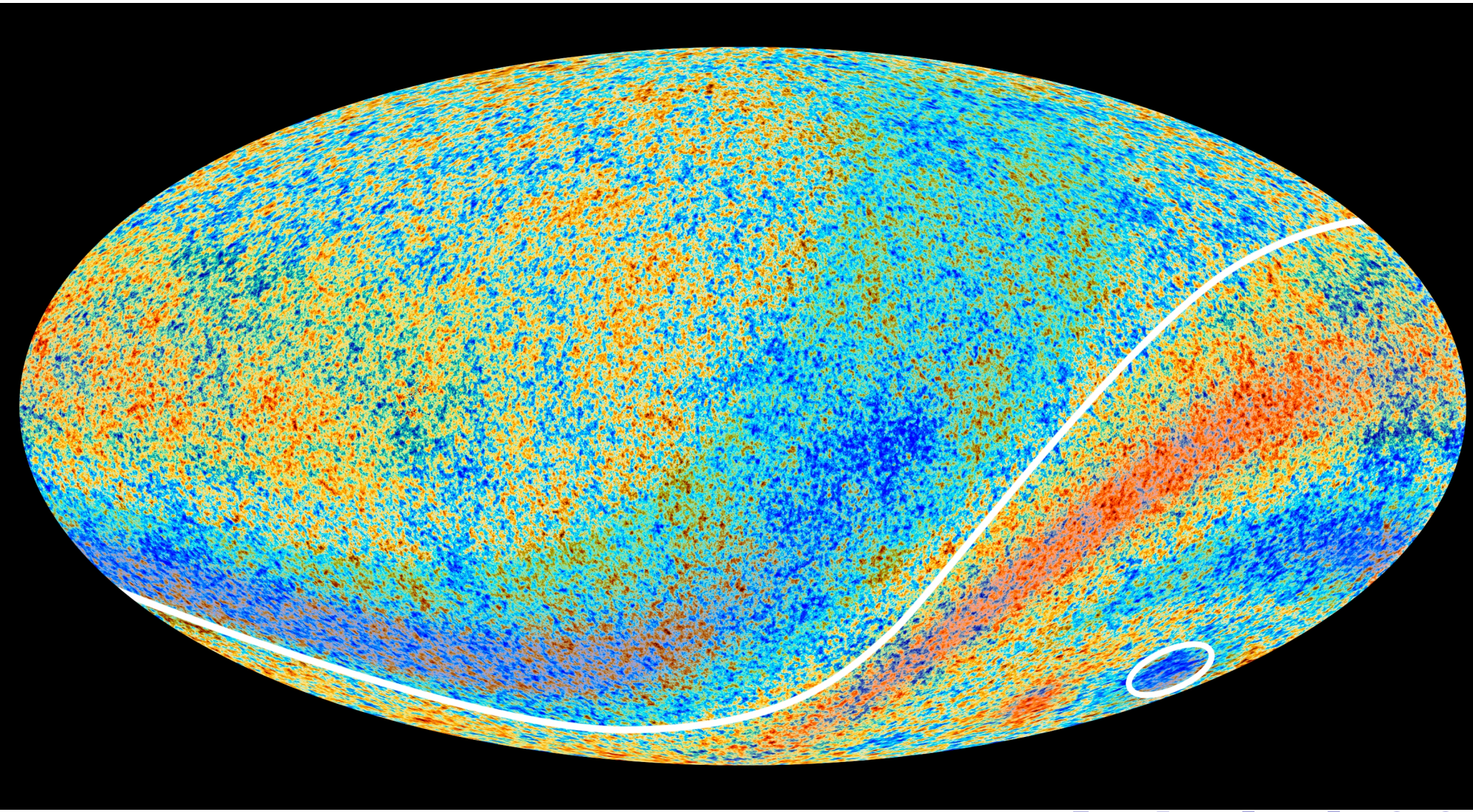
Frequency Coverage



Power Spectrum



Anomalies in Planck



Anomalies

- Discovered in WMAP and confirmed by Planck
- 2-3σ deviations from isotropic Gaussian statistics from LCDM
- explanation ranges from exotic physics (textures) to statistical fluke
- Cold Spot 0.5% unlikely (Cruz etal 2006): one of the most significant
- Zhang & Huterer (2009): skeptical view
- $\Delta T \simeq -70\ \mu K$
- extends at least 5°, and up to 15° on the CMB
- Inoue & Silk (2007): $200\mathrm{h}^{-1}\mathrm{Mpc}$ void with $\delta = -0.3$ via ISW

Integrated Sachs-Wolf Effect

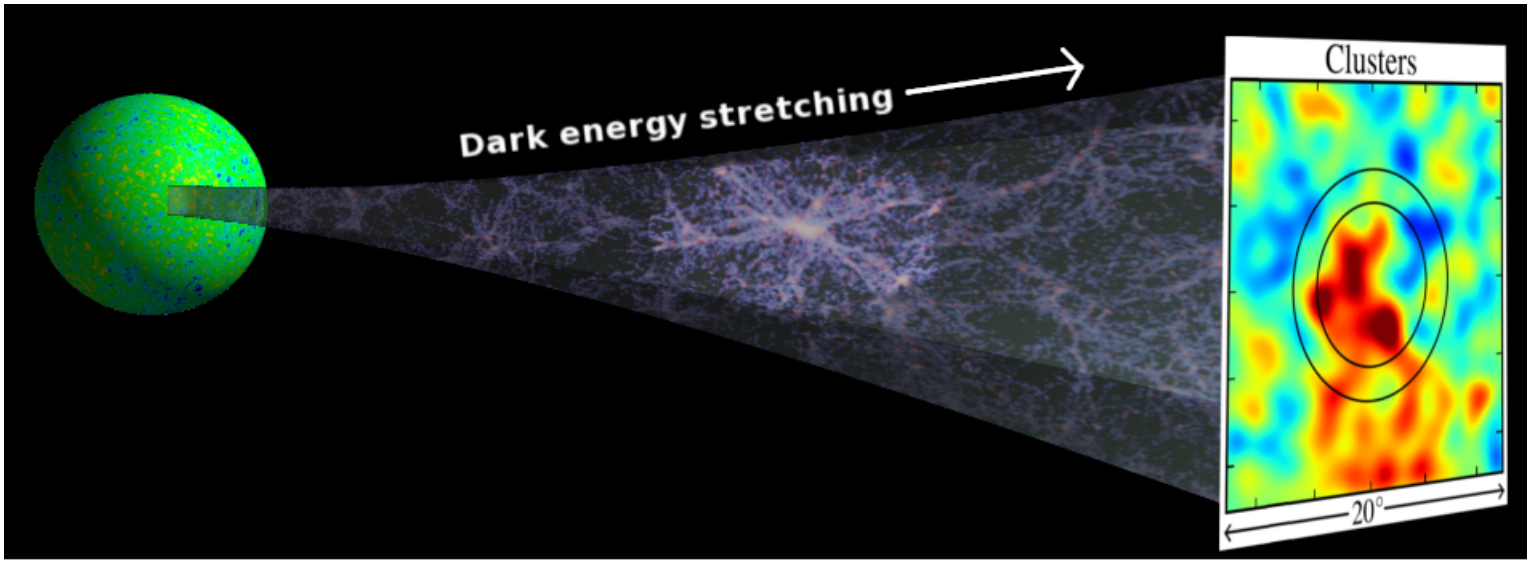
- Photons passing through changing gravitational potentials are becoming slightly hotter or colder

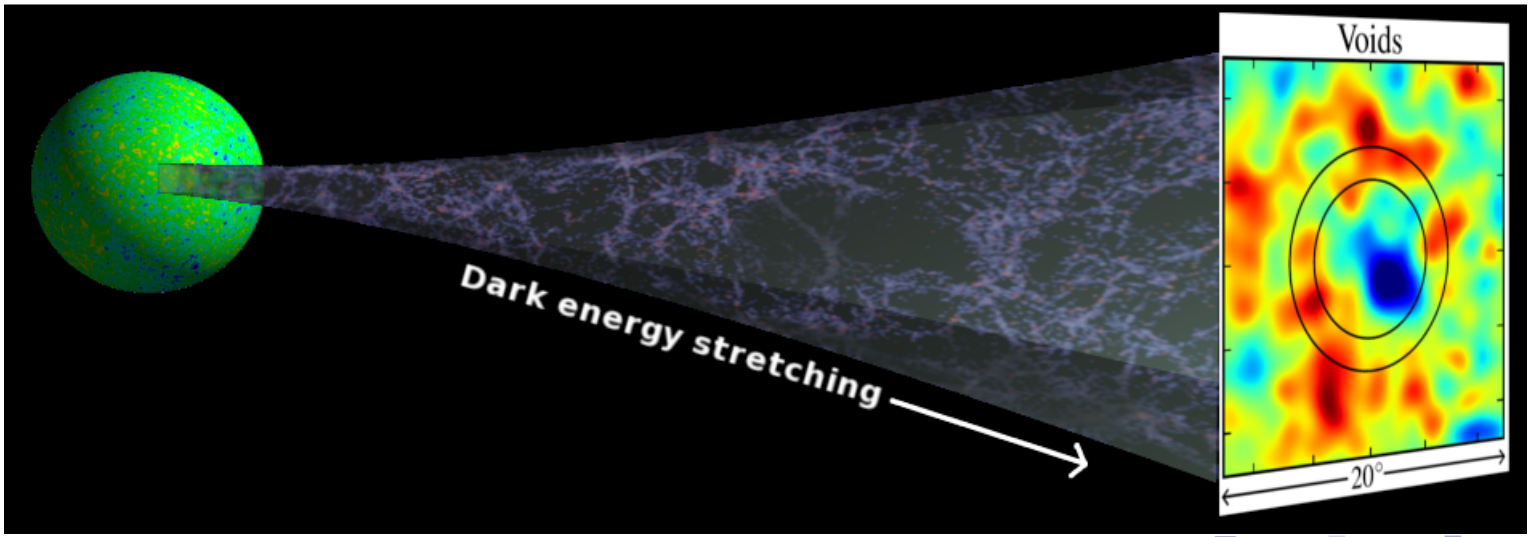
$$\Delta T_{\rm ISW} \simeq \int d\tau \frac{d\Phi}{d\tau},$$

- where

$$\frac{d\Phi(\mathbf{x})}{d\tau} = \frac{\Phi(\mathbf{x})}{(1+z)} \frac{d}{d\tau} \left[(1+z) D_1(z)\right]$$

The Integrated Sachs-Wolfe effect





Linear ISW as a Signature of DE

- In a flat, matter dominated universe $D_1 = 1/(1+z)$,
- There is a linear effect if $\Omega_M \neq 1$, e.g., ΛCDM
- If the universe is flat (e.g., from CMB), linear ISW effect signals Dark Energy
- Caviat: there can be a non-linear effect as well

Cold Spot in WMAP

Vielva Etal 2004, Cruz etal 2005

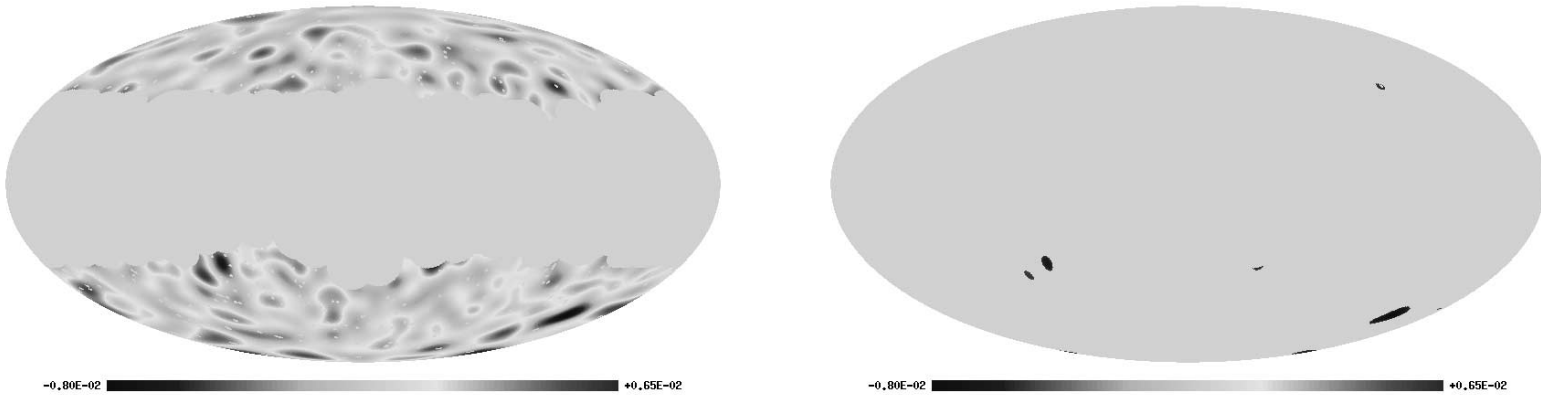
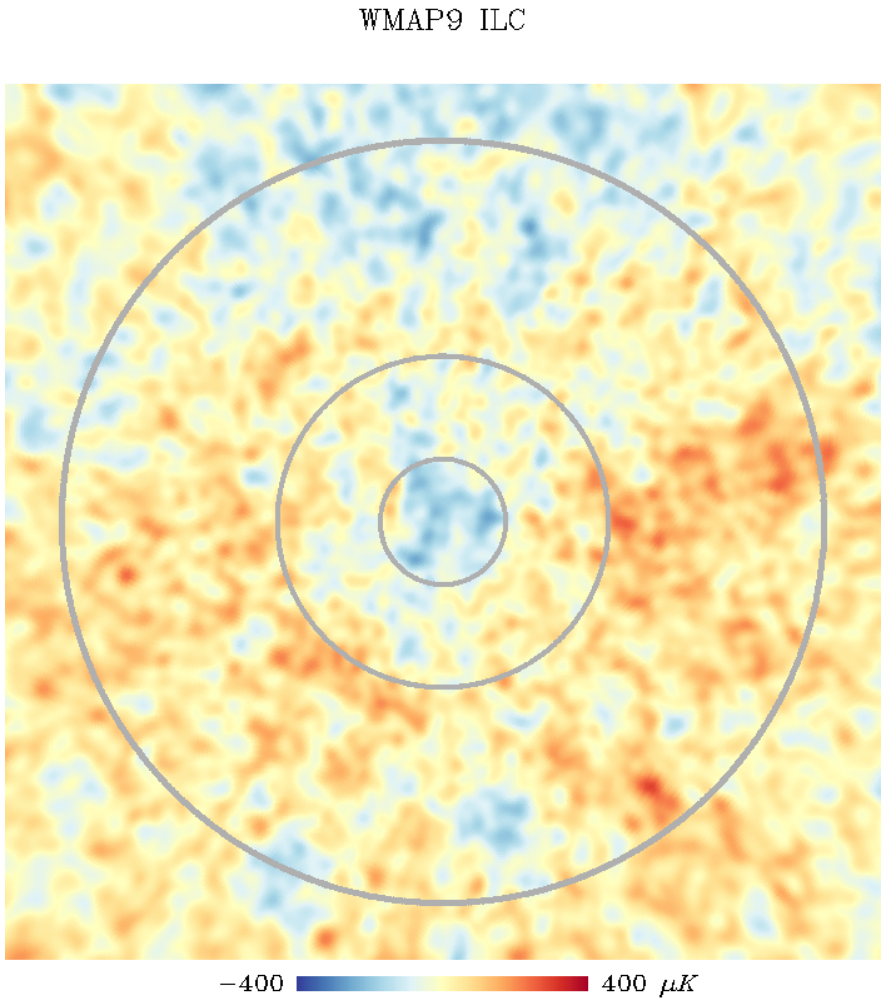
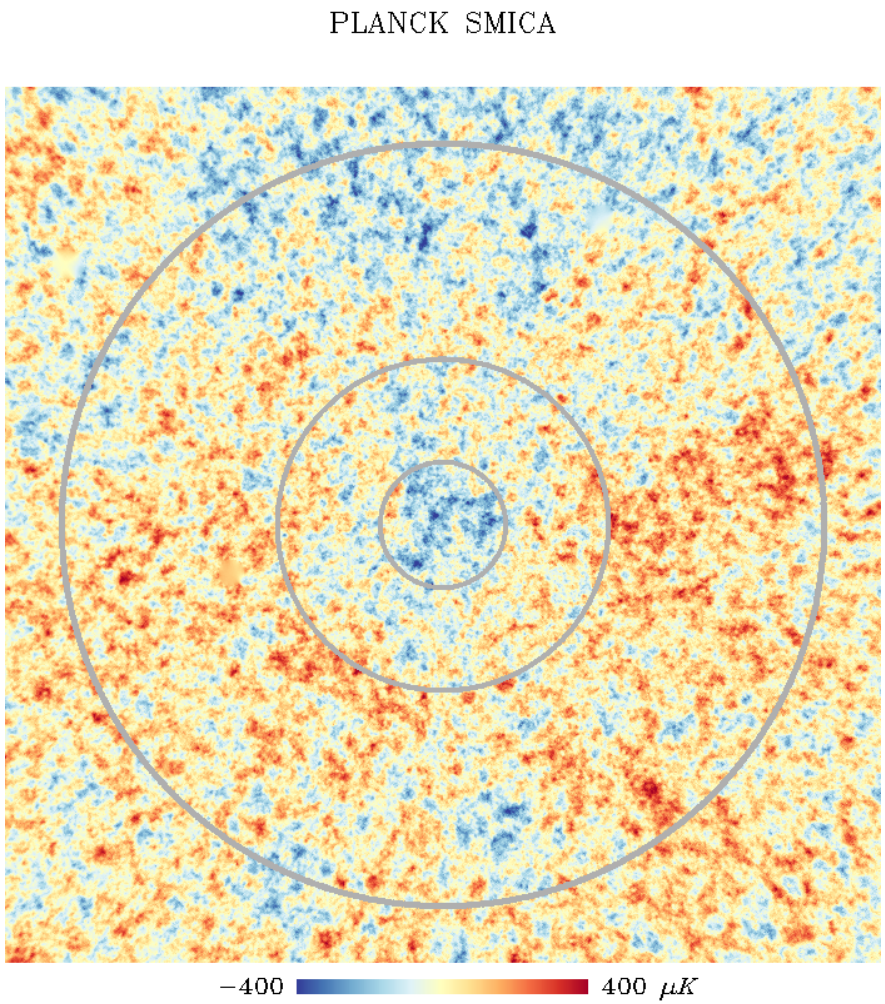


FIG. 12.—In the left panel, the SMHW coefficients at $R_8 = 250.'0$ outside the exclusion mask $M(R_8)$ are presented. In the right panel, only those coefficients above 3 $\sigma(R_8)$ are plotted. If these coefficients are not considered, the kurtosis of the remaining ones is completely compatible with the Gaussian model. The coldest spot (shown in black) at $b = -57^\circ$, $l = 209^\circ$ has a minimum value equal to -4.57 $\sigma(R_8)$. The simulations indicate that the probability of this value is $\approx$1%. [*See the electronic edition of the Journal for a color version of this figure.*]

Cold Spot
WMAP 9-year data



Cold Spot
Planck-Smica



Void in the NVSS near the Cold Spot

Rudnick Etal 2007

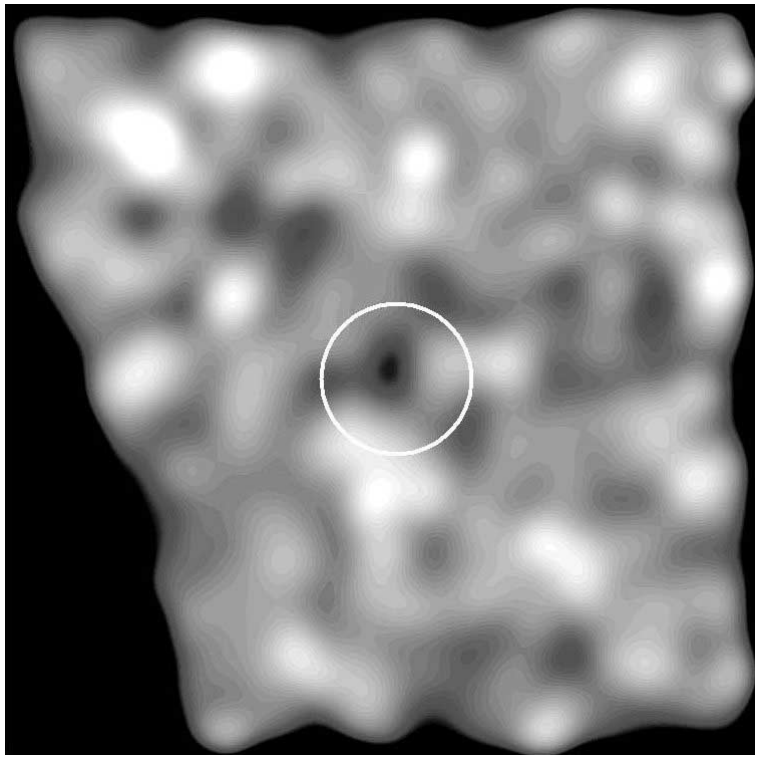
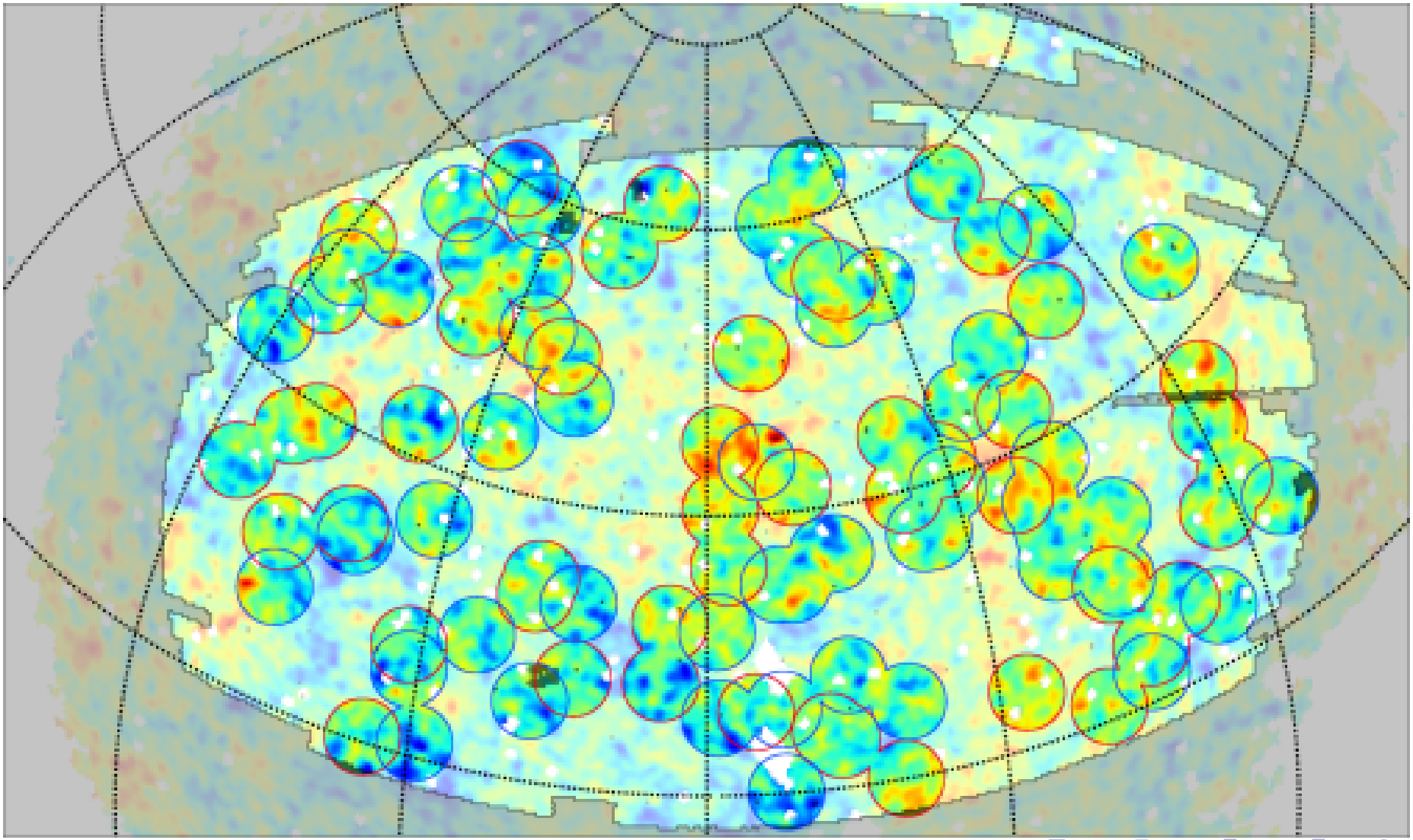


FIG. 1.—50° field from smoothed NVSS at 3.4° resolution, centered at $l = 209^\circ$, $b = -57^\circ$. Values range from 9.3 mJy beam^{-1} (*black*) to 21.5 mJy beam^{-1} (*white*). A 10° diameter circle indicates the position and size of the *WMAP* cold spot.

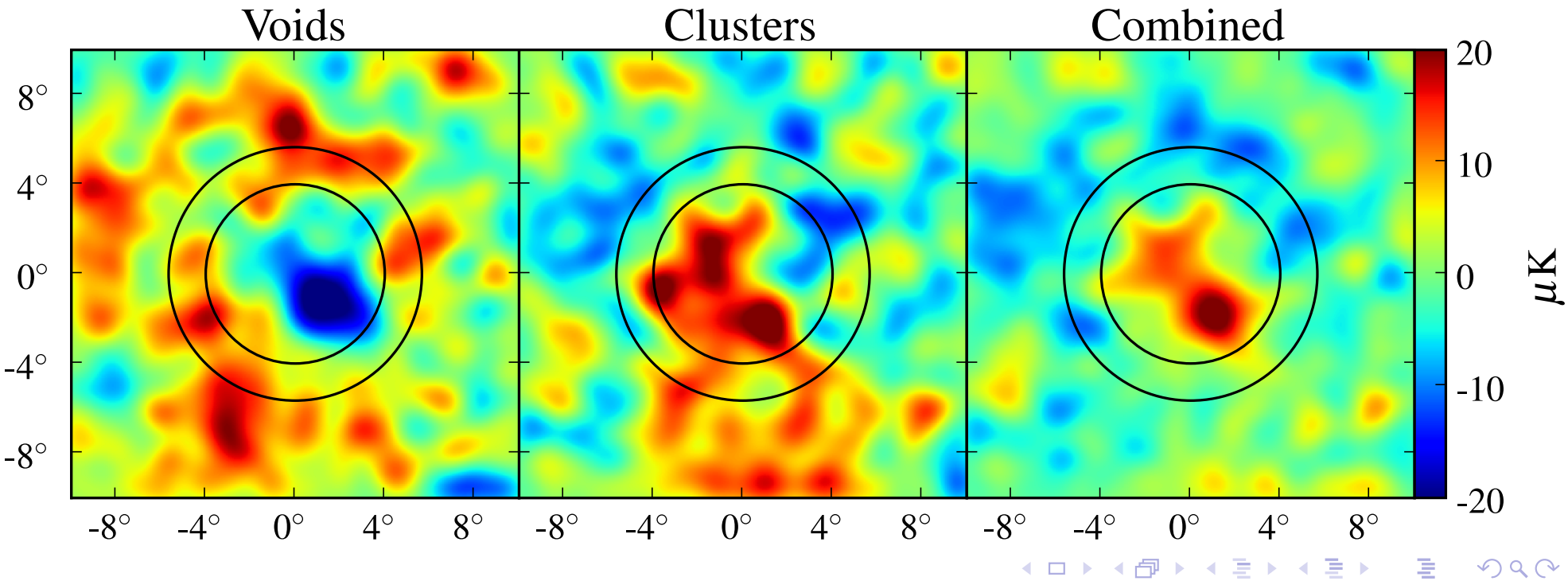
Superstructures from SDSS LRGs



Granett Etal 2009

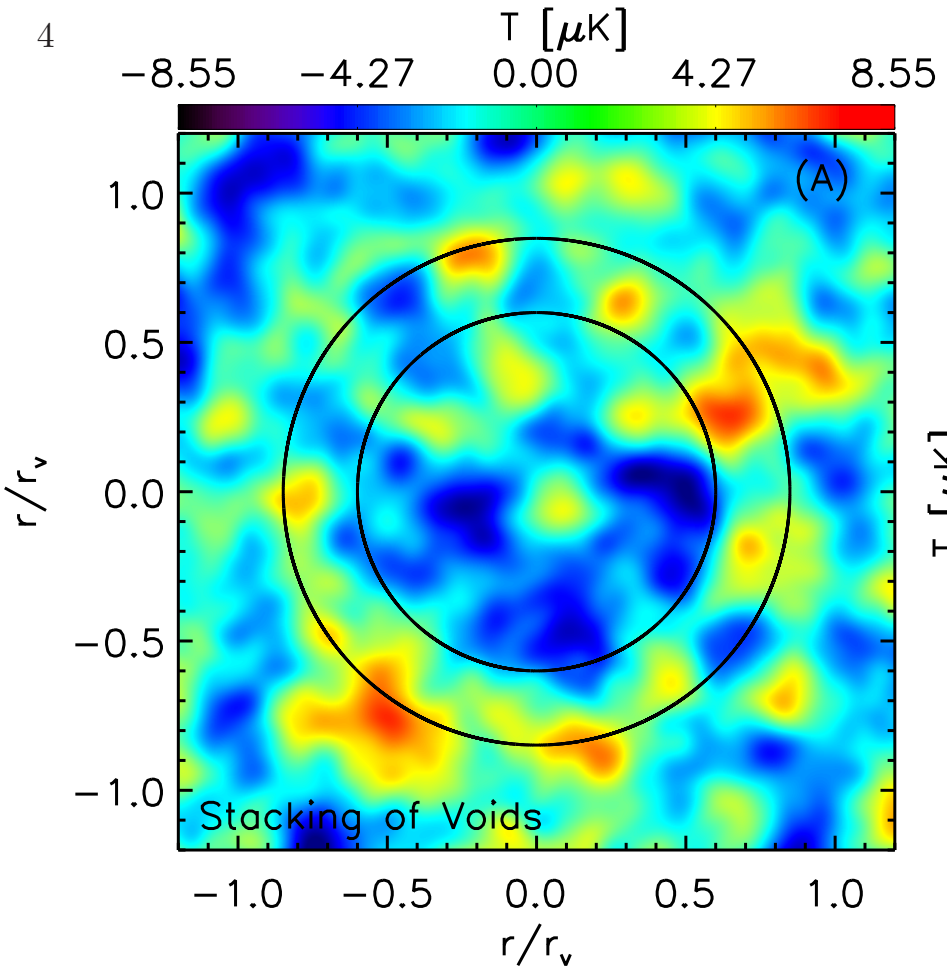
Superstructures from SDSS LRGs

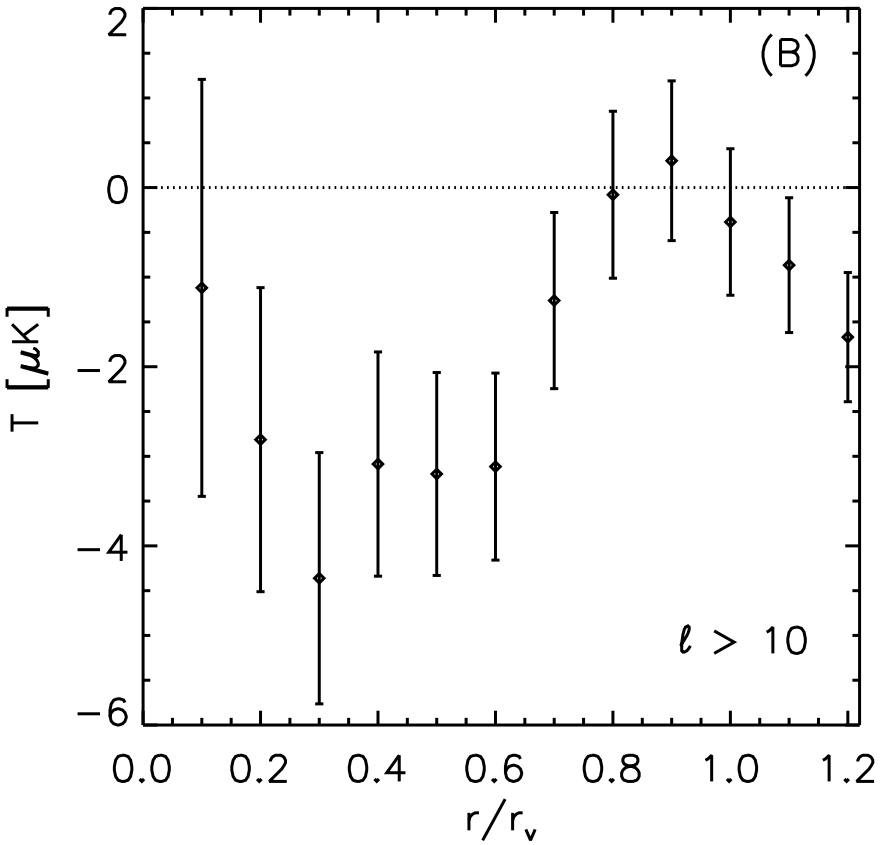
- superstructures imprint on the CMB
- strong statistical evidence 4.4σ
- ISW is plausible, although $\simeq 10\mu K$ higher than expected



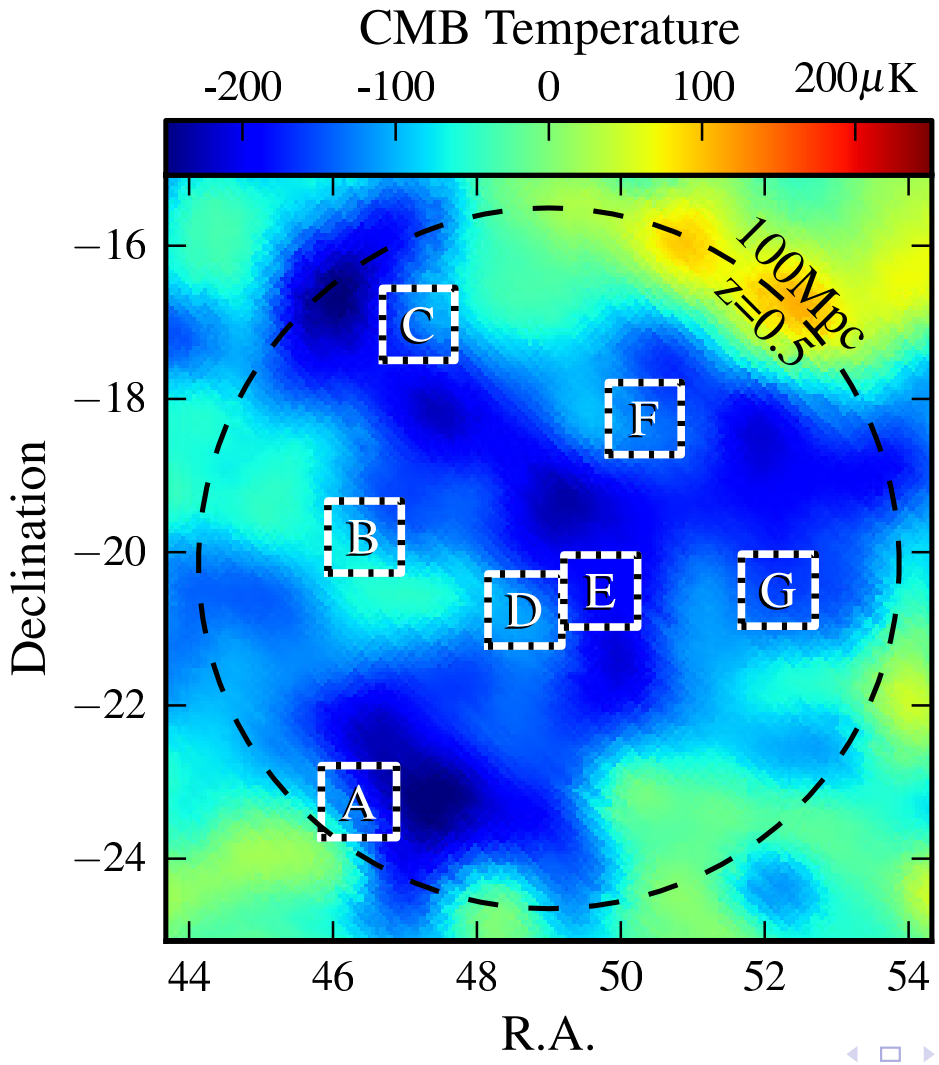
Cai etal 2013

Supersvoids from SDSS spectroscopic survey $\simeq 3\sigma$, again higher then simulation

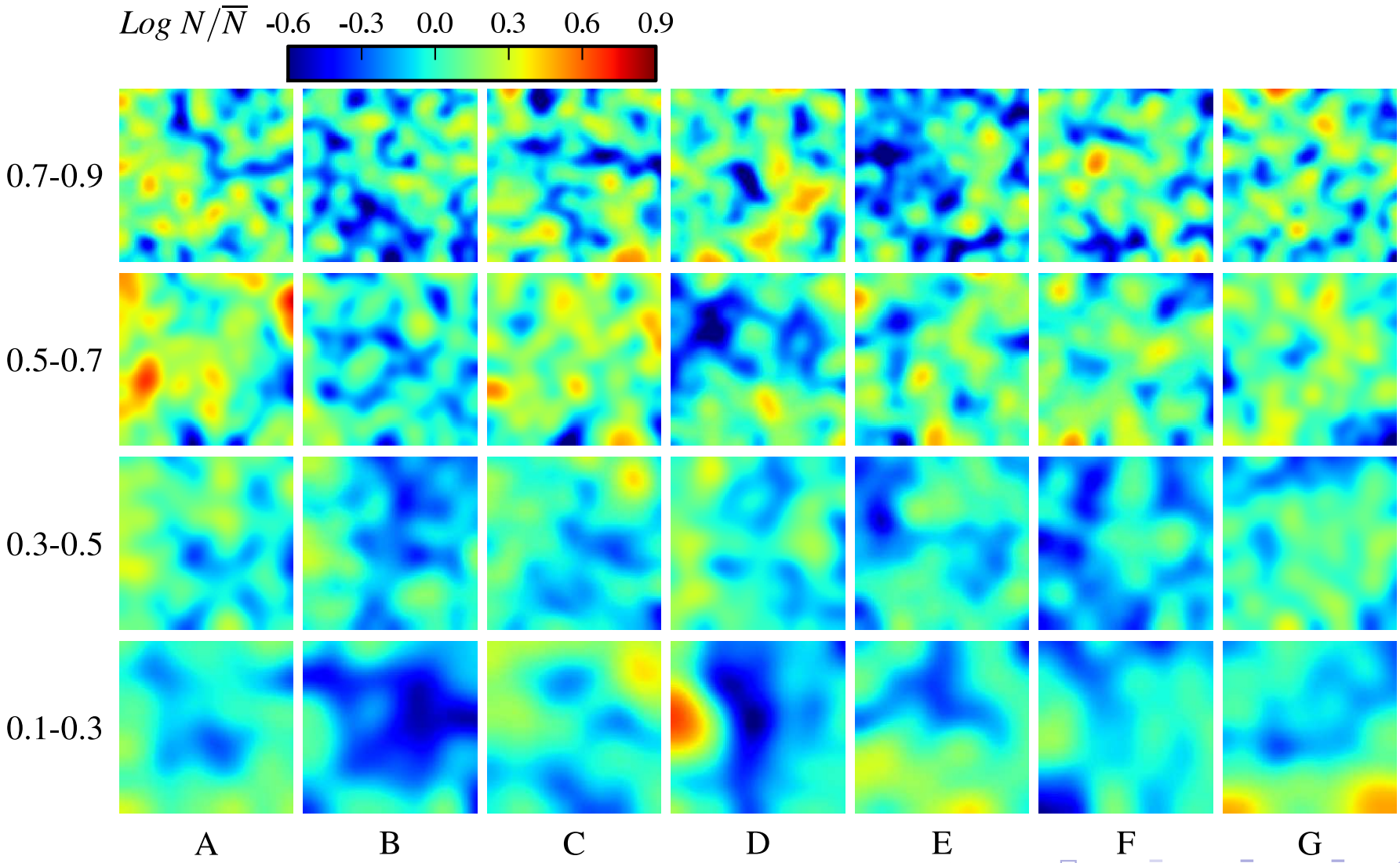




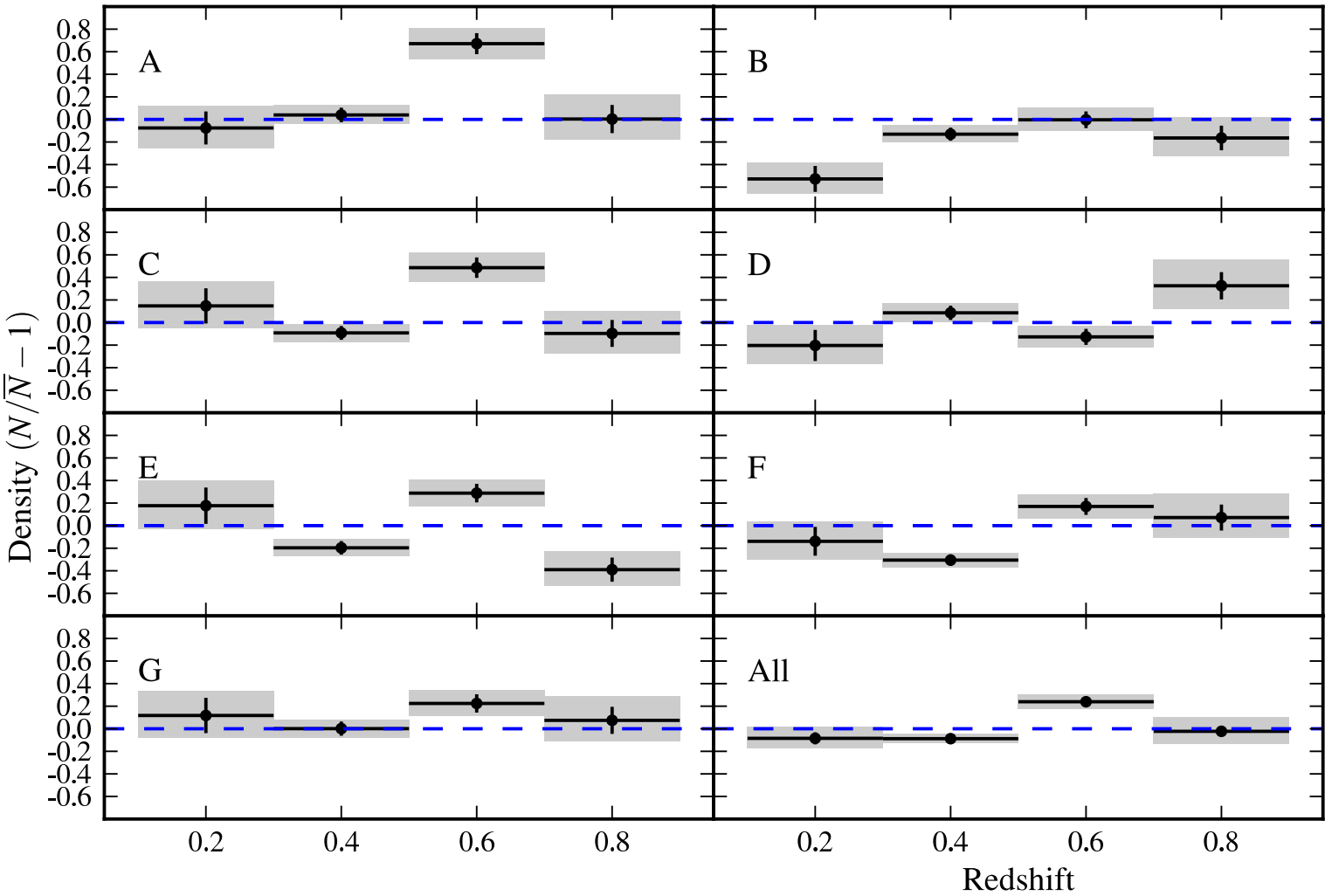
Granett etal (2010)
Imaging survey



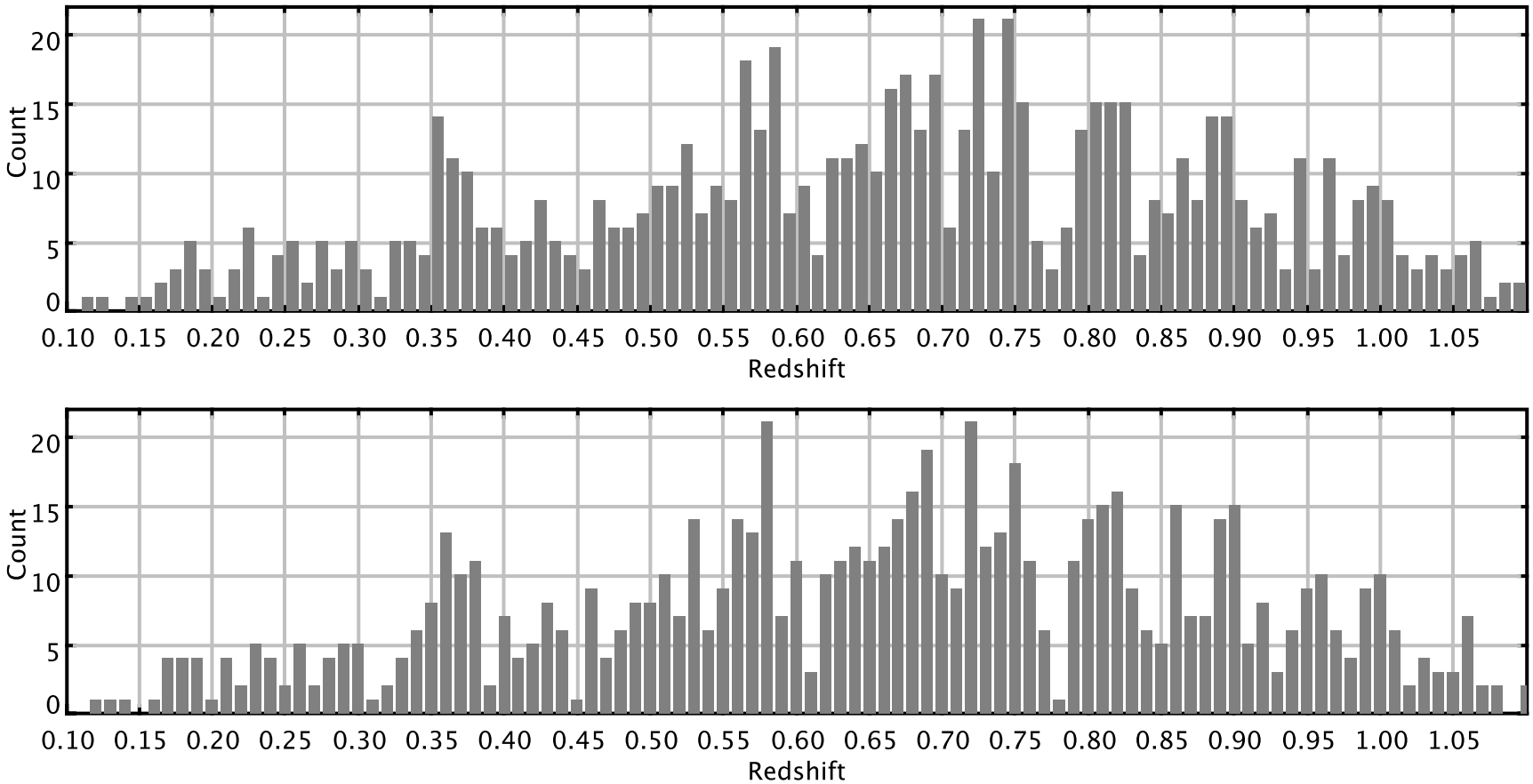
Density Maps in Redshift



Constraints



Bremer etal (2010)
redshift survey



Search Summary

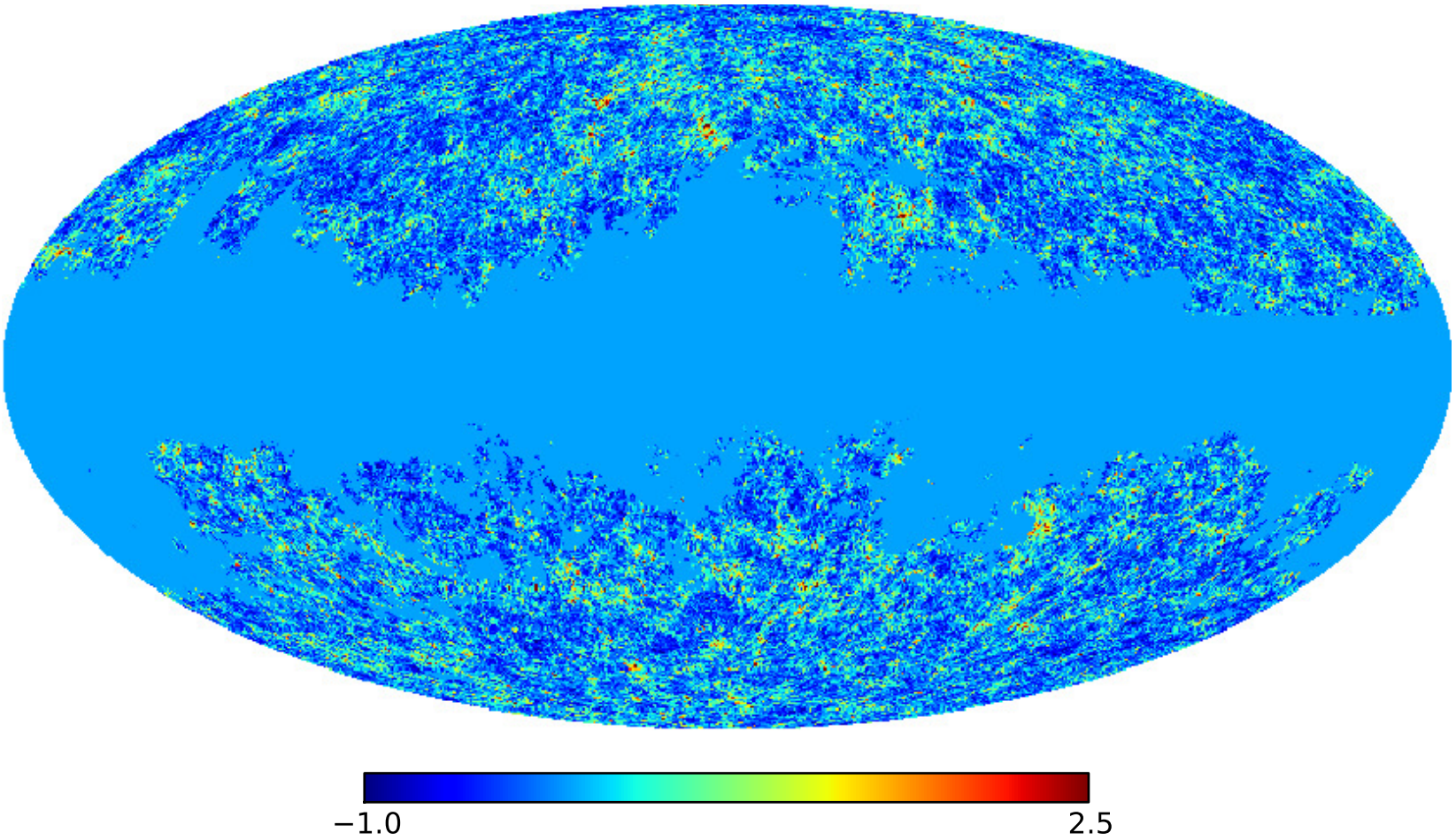
- Bremer etal found no evidence of a void at $0.35 < z < 1$
- Granett etal could exclude $\gtrsim 100 h^{-1} \mathrm{Mpc}$ void for $0.5 < z < 1$
- no evidence for $0.3 < z < 0.5$
- data consistent with a void at $z < 0.3$ with low significance
- both surveys ran out of volume at low z
- wide area shallow survey need to test for the presence of a large void at $z < 0.3$
- Francis & Peacock (2010) found an under-density in 2MASS corresponding to up to $7 \mu K$ signal

The WISE-2MASS catalog

- matched the WISE and 2MASS catalogs (Kovacs & Szapudi 2014)
- $W1 \leq 15.2$ and $J \leq 16.5$
- clean star galaxy separation
- $\lesssim$2% stellar contamination
- removes artifacts present in WISE alone
- 2.5 million objects
- significantly deeper than 2MASS $z_{med} \simeq 0.14$
- galactic cut of 20° and $E(B-V) \geq 0.1$ (Schlegel etal 2011) mask
- 21,200 square degrees

Photometric Redshifts

SVM classification

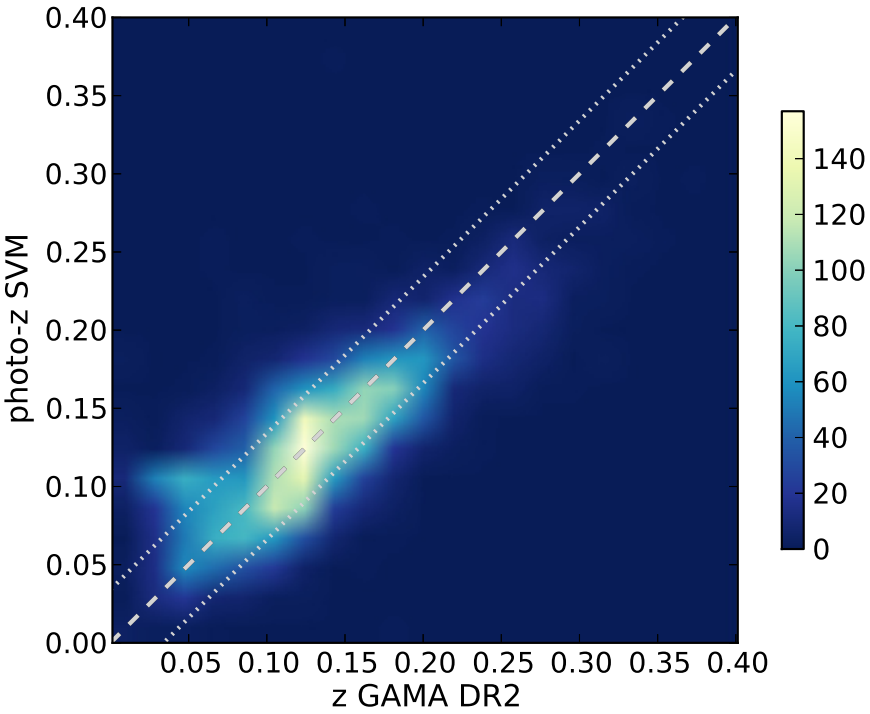


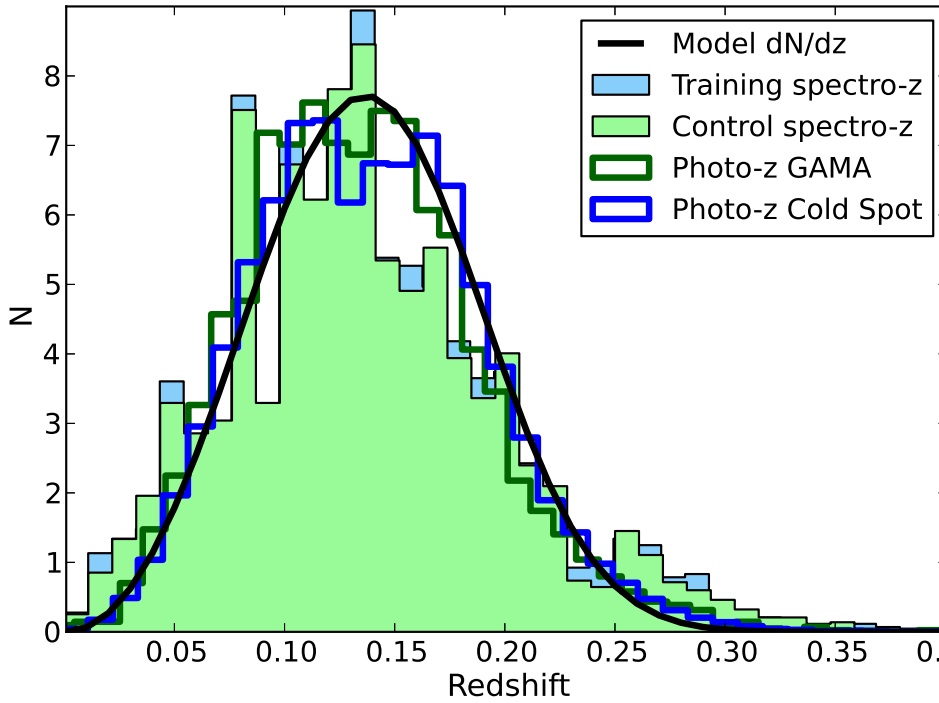
PS1 matching

- Cold Spot center $(l, b) \simeq (209^\circ, -57^\circ)$
- matching a $50^\circ \times 50^\circ$ with Pan-STARRS1 around it
- Dec $\geq -28^\circ$ due to PS1 mask
- 73,100 objects with matching rate 86% in 1500 square degrees
- Kron and PSF magnitudes g, r, i
- photo-z's with SVM
- GAMA matching (96%) for teaching and control set
- $\sigma_z = 0.034$

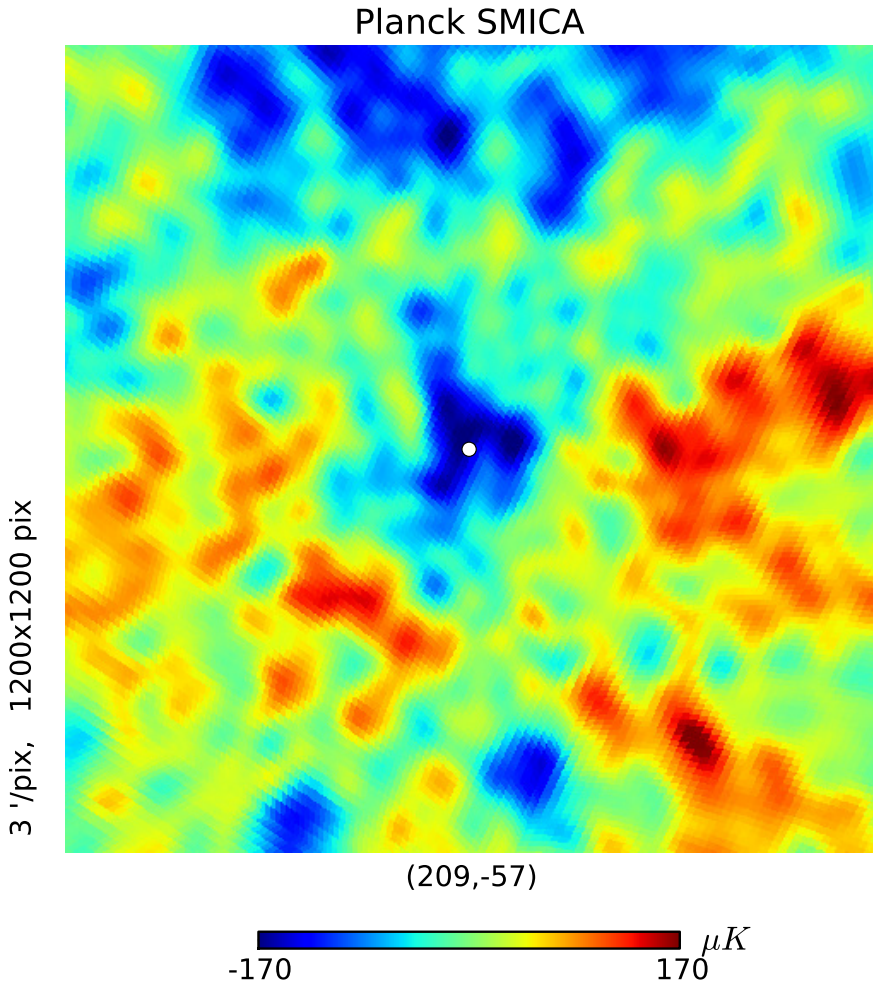
Photometric Redshifts

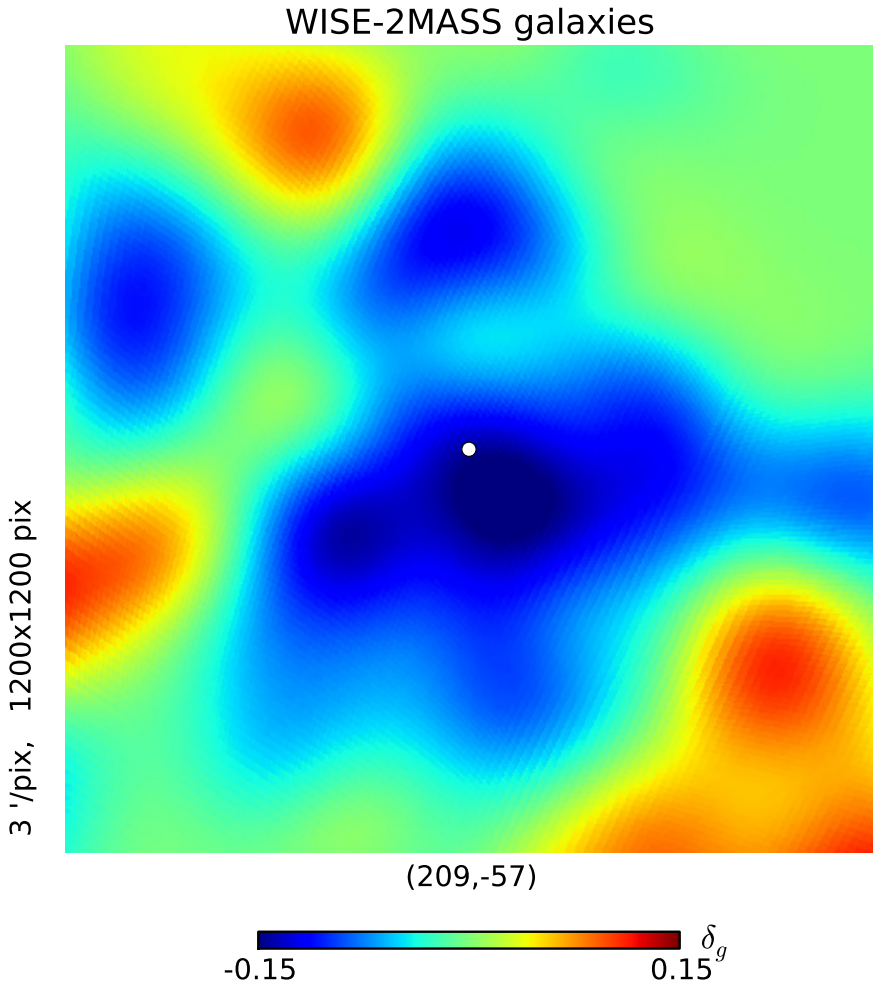
SVM classification



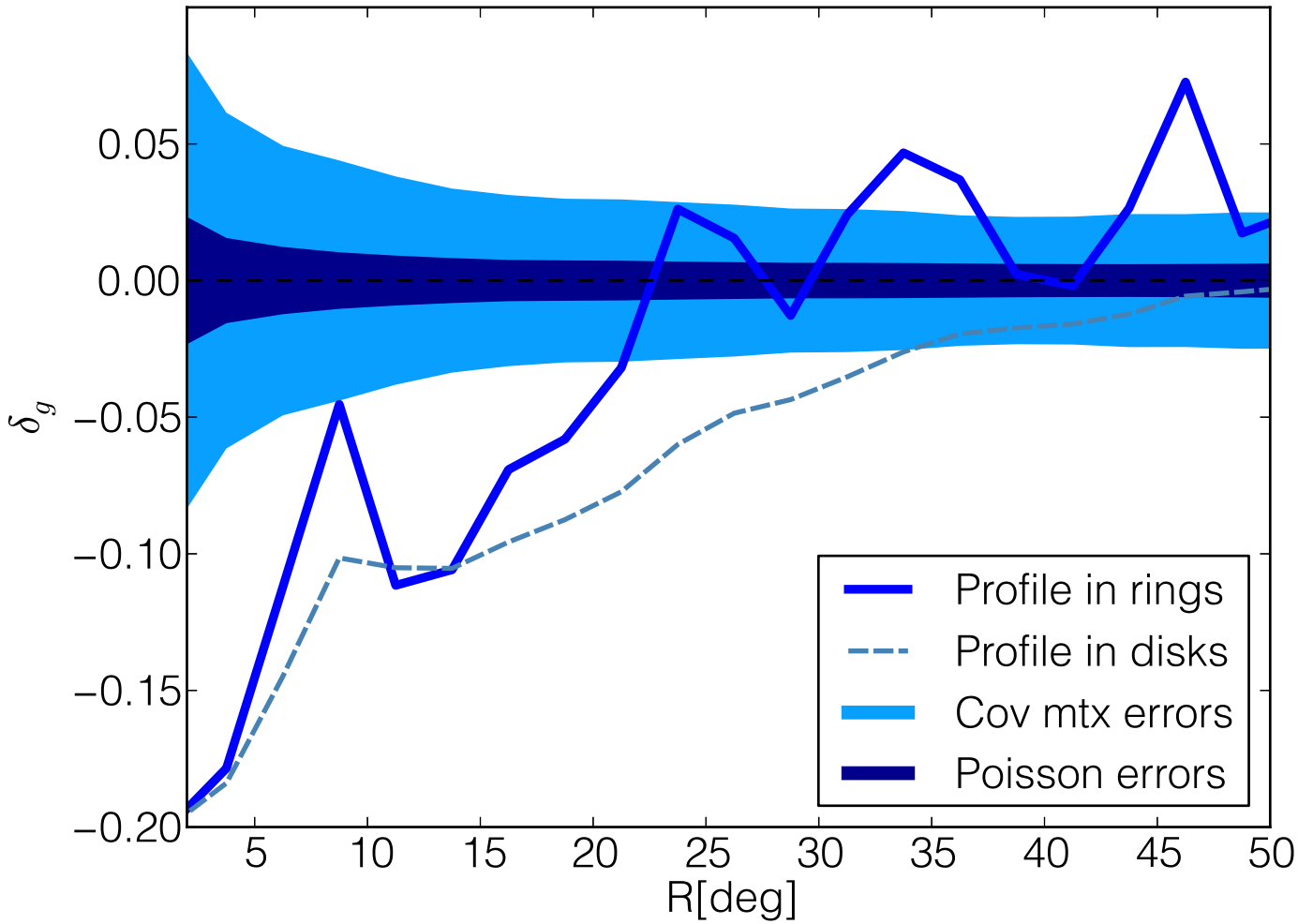


Coldspot Area in WISE-2MASS

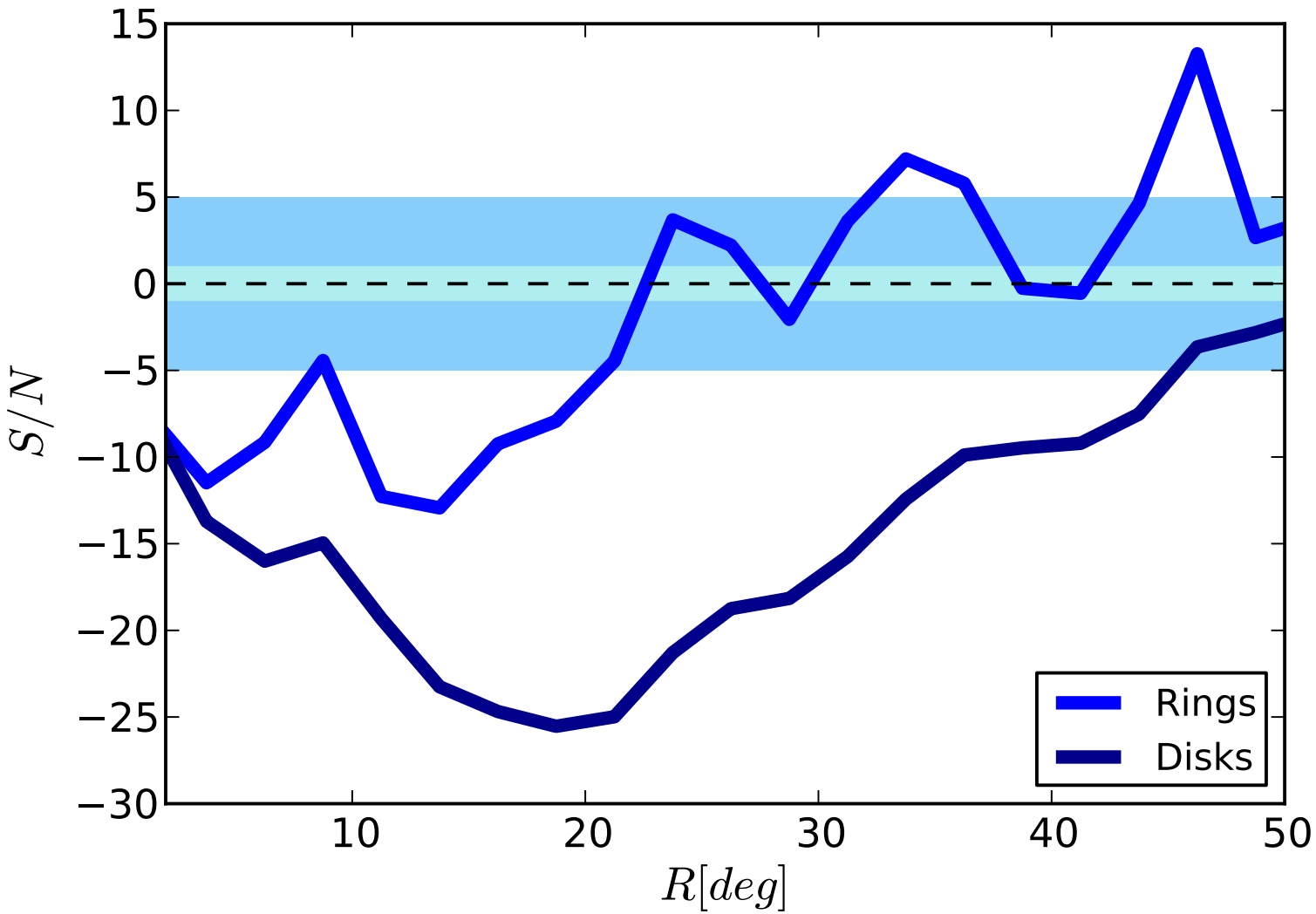




Radial Profile
Density



Radial Profile
Significance

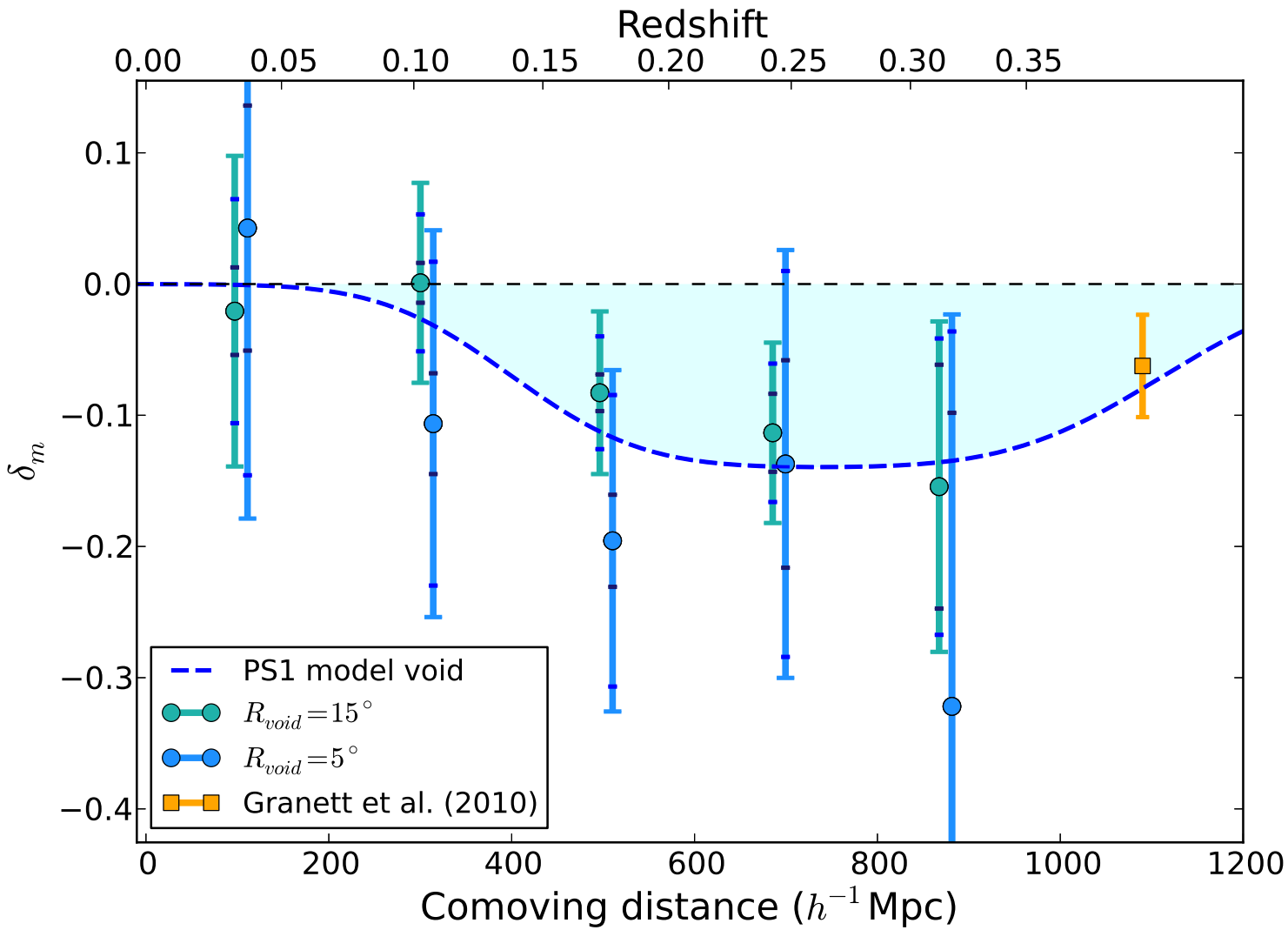


2D results

- We decided in advance to test for 5° and 15° radii based on literature of the Cold Spot
- S/N is 12 in rings, and 13, and 23 for disks, respectively
- Though under density detected at 5σ to 20° in rings
- The disk is under dense up to 50°
- The presence of the under density is firmly established in WISE-2MASS
- Next we produce counts in photo-z bins at the two fiducial radii

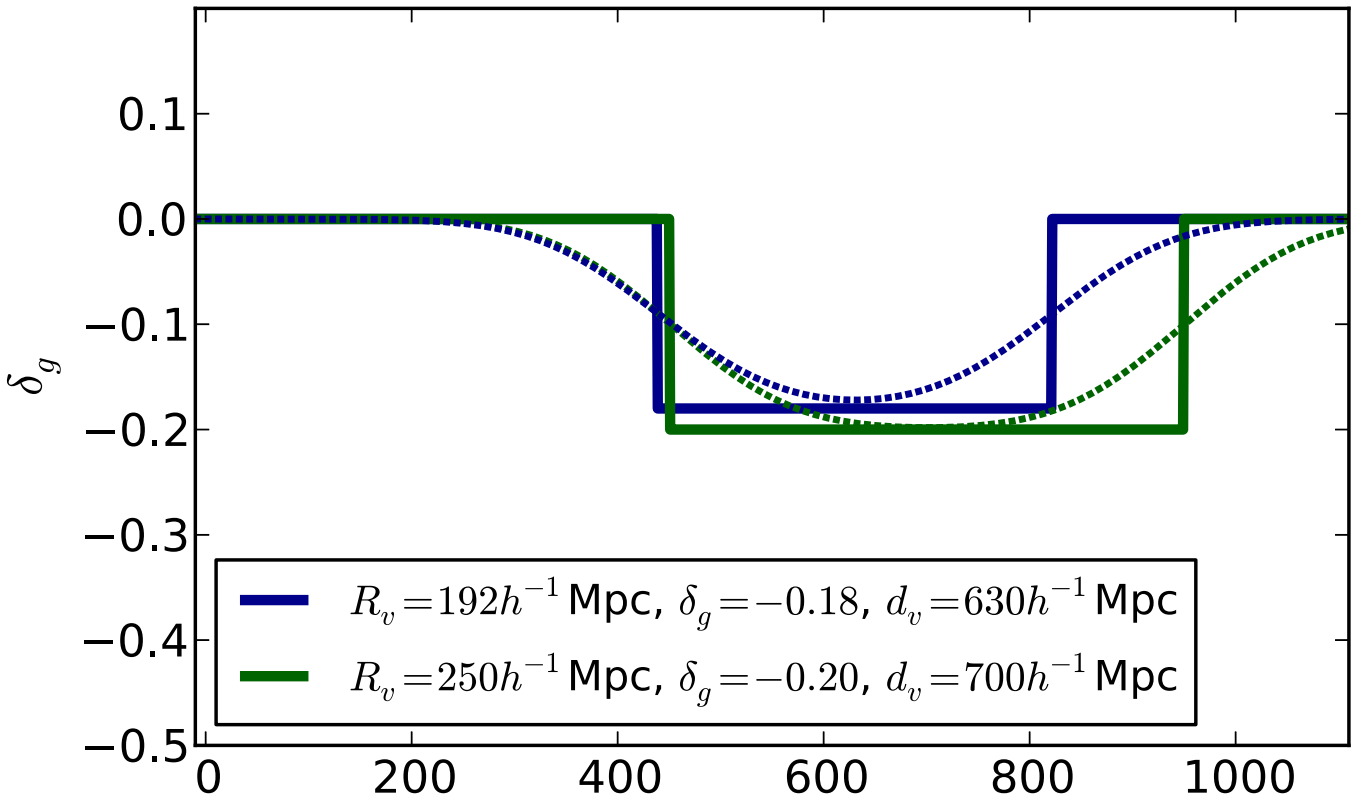
Redshift Profile

Szapudi etal + PS1 (2014)

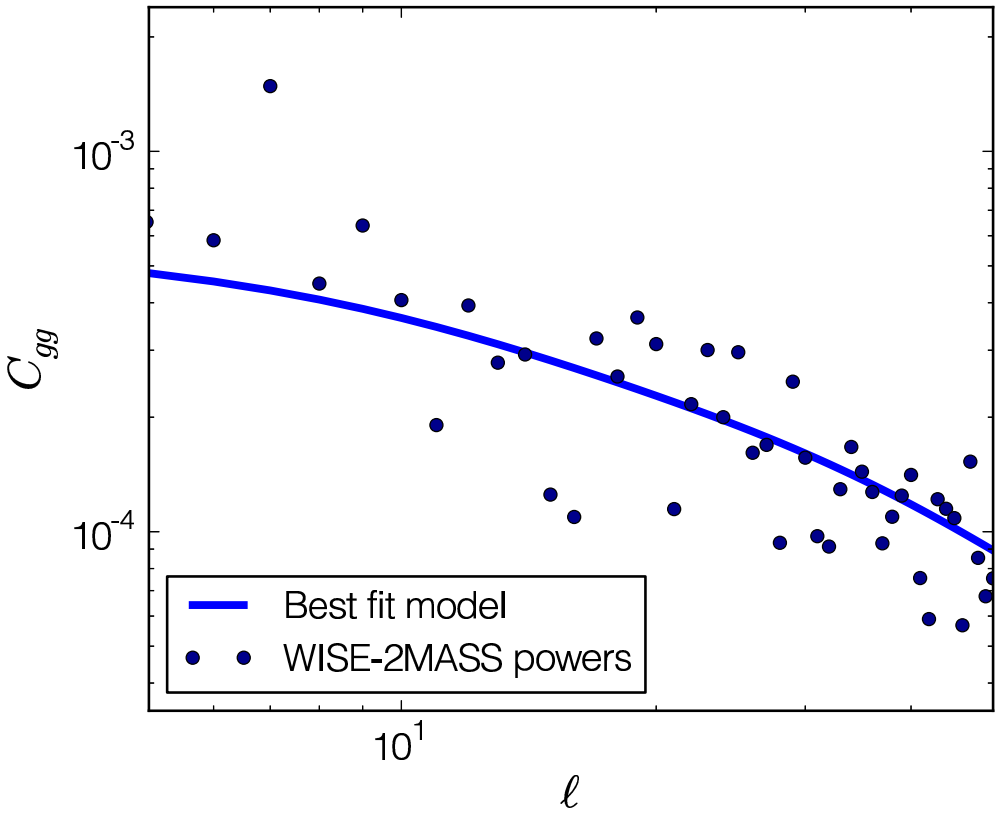


Toy Model
Tophat in z

- A simple top hat: good fit $\chi^2 = 3.55/3 d.o.f.$ vs $\chi^2_0 = 7.74$.
- $R = 220 \pm 50 \mathrm{h}^{-1}\mathrm{Mpc}$, $\delta_m = -0.14 \pm 0.04$, and $z_{void} = 0.22 \pm 0.03$



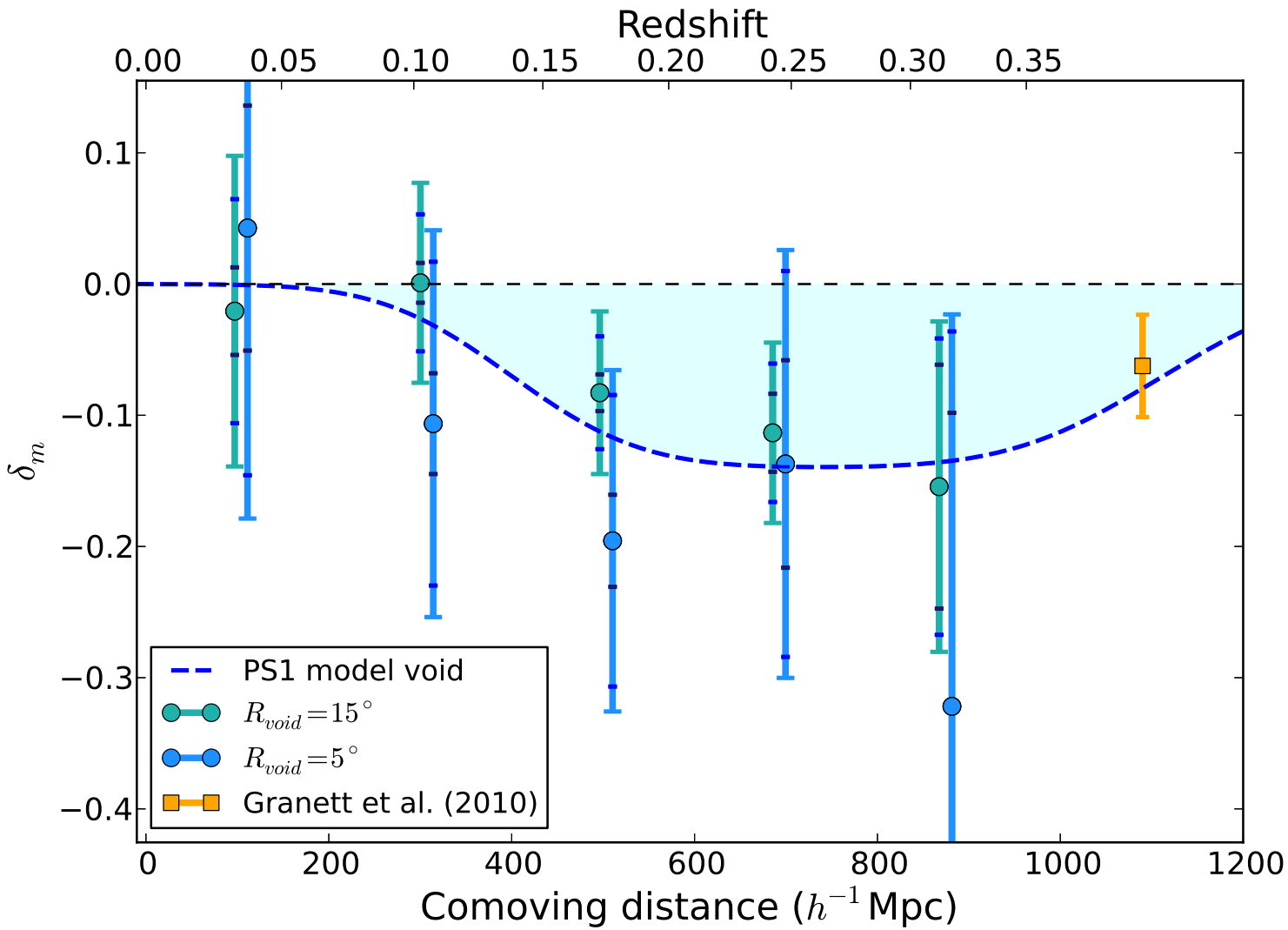
Galaxy bias



- Simple model $\delta_g = b\delta_m$
- Best fit $b = 1.41 \pm 0.07$

Redshift Profile

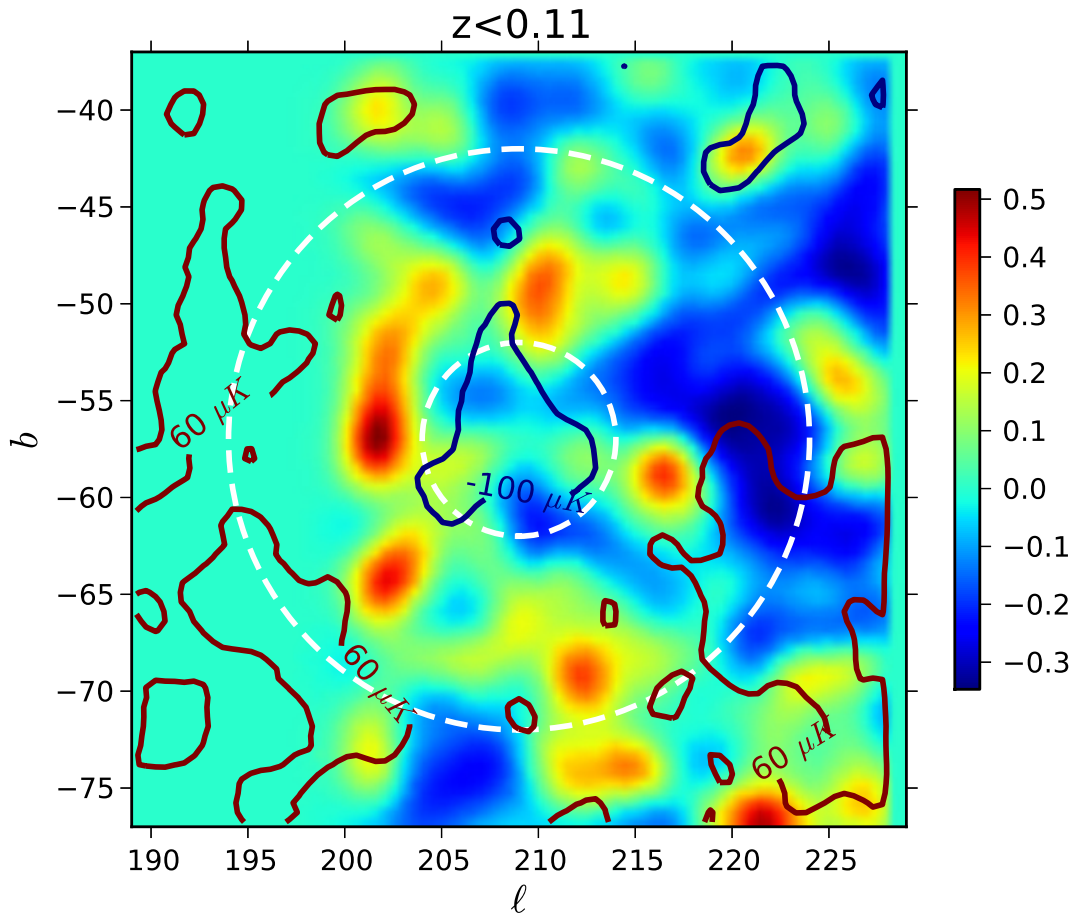
Szapudi etal + PS1 (2014)



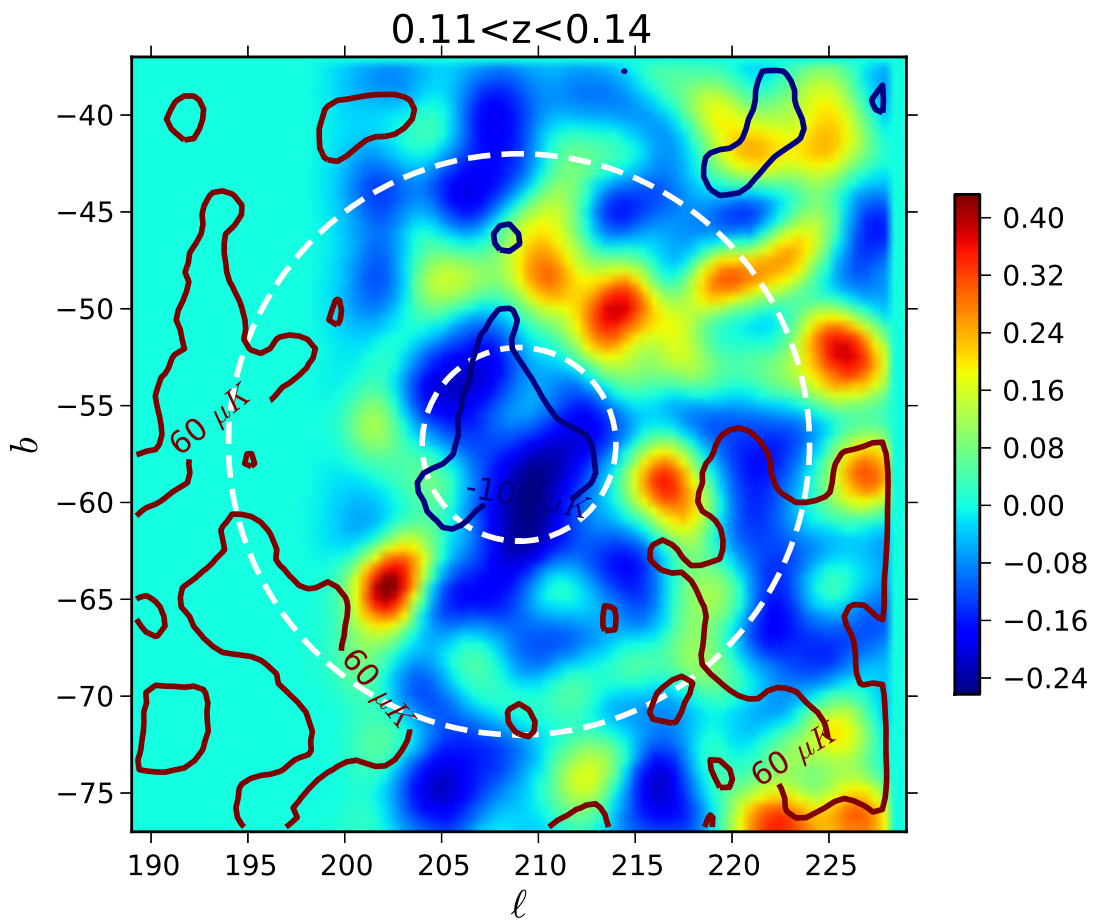
3D Results

- S/N is 5 and 6σ, respectively
- From power spectrum $b = 1.41 \pm 0.07 \rightarrow \delta_m = 0.14 \pm 0.04$
- with $R = 220 \pm 50 \mathrm{h}^{-1}\mathrm{Mpc}$ $z_{void} = 0.22 \pm 0.03$
- $3.3 + \sigma$ void in LCDM
- H_1: two random structures with random alignment: probability $p_{CS} \times p_{void} \times p_{align}$
- H_2: supervoid causing the CS: probability p_{void}
- ratio $p_{CS} \times p_{align} \simeq 1 : 200,000$
- linear ISW from this void up to $\simeq 20 - 40 \mu K$
- caveats: toy model and uncertainties in parameters, and non-linearities

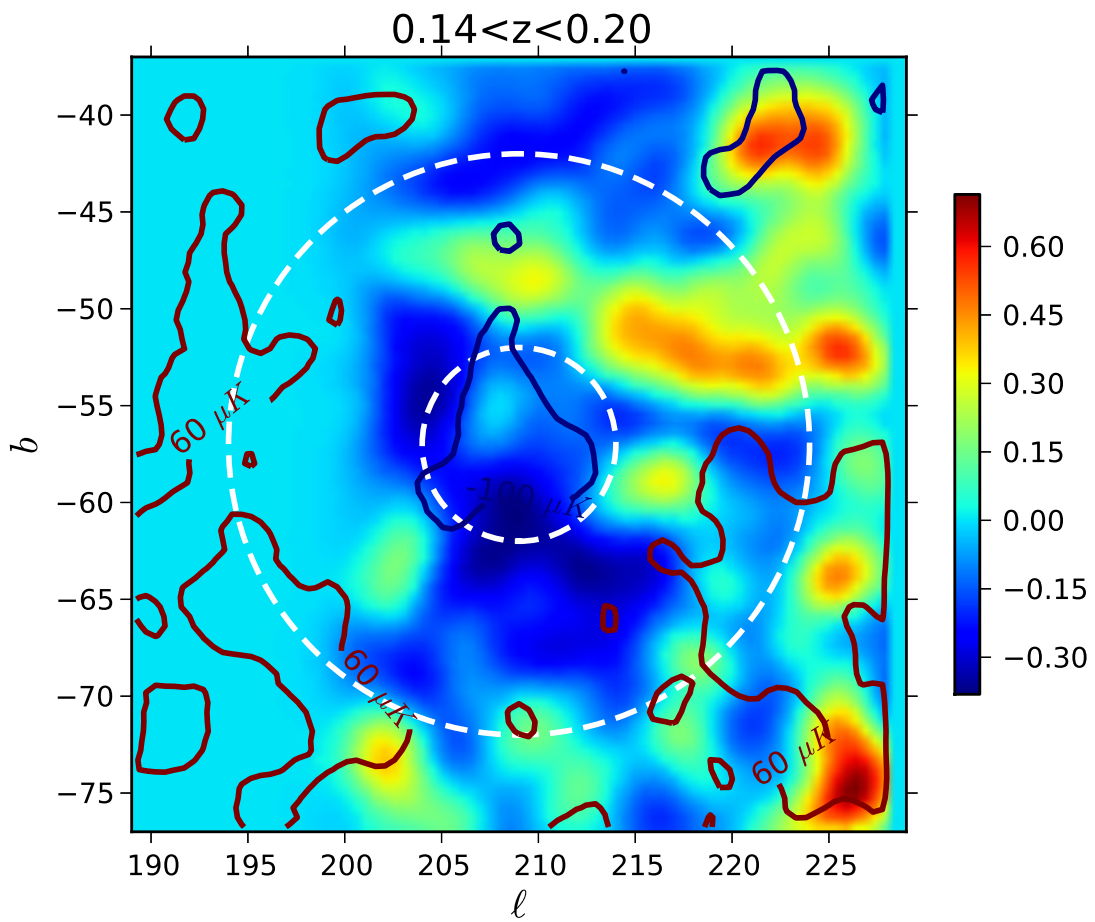
Tomography


z<0.11
−40
−45
−50
−55
−60
−65
−70
−75
b
190
195
200
205
210
215
220
225
ℓ
60 μK
-100 μK
60 μK
60 μK
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3

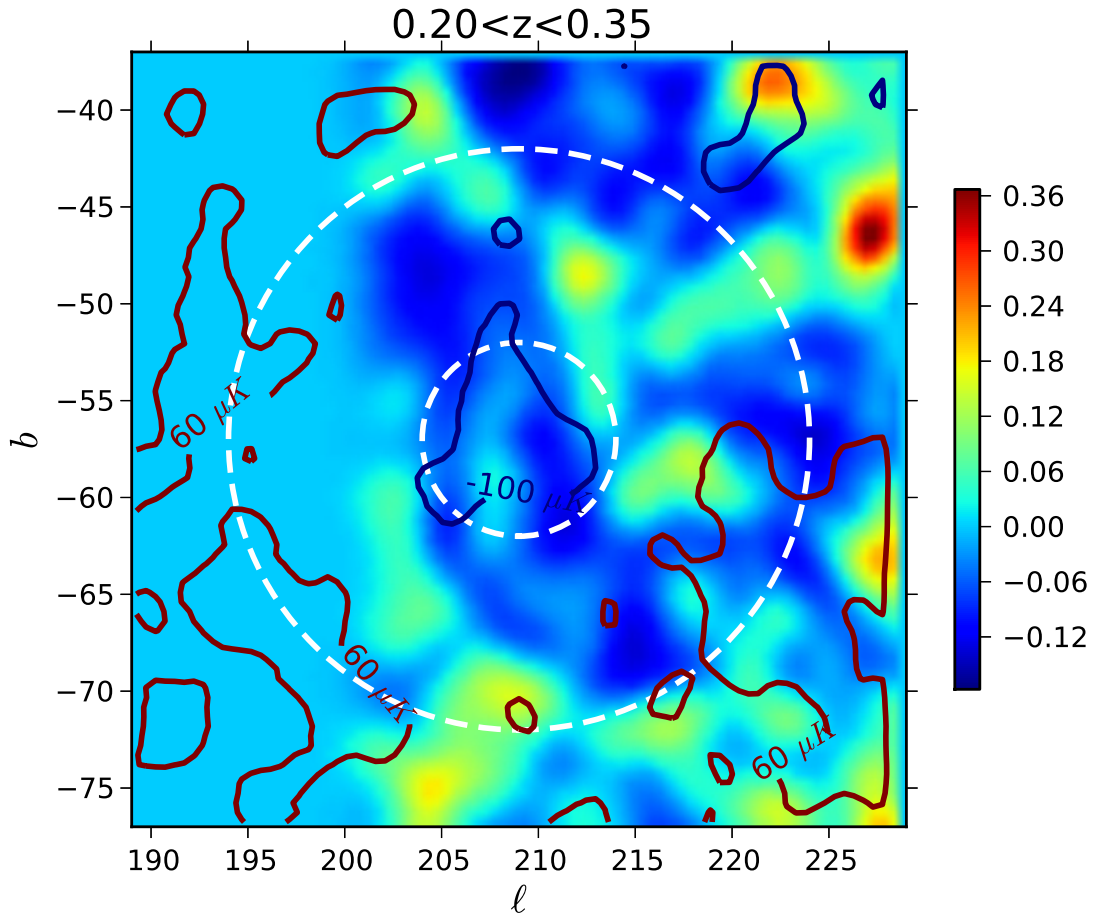
Tomography


0.11<z<0.14
−40
−45
−50
−55
−60
−65
−70
−75
b
190
195
200
205
210
215
220
225
ℓ
60 μK
-10 μK
60 μK
60 μK
0.40
0.32
0.24
0.16
0.08
0.00
−0.08
−0.16
−0.24

Tomography


0.14<z<0.20
−40
−45
−50
−55
−60
−65
−70
−75
b
190
195
200
205
210
215
220
225
ℓ
60 μK
−100 μK
60 μK
60 μK
0.60
0.45
0.30
0.15
0.00
−0.15
−0.30

Tomography


0.20<z<0.35
−40
−45
−50
−55
−60
−65
−70
−75
b
190
195
200
205
210
215
220
225
ℓ
60 μK
-100 μK
60 μK
60 μK
0.36
0.30
0.24
0.18
0.12
0.06
0.00
−0.06
−0.12

Summary

- A supervoid was detected in both WISE-2MASS and WISE-2MASS-PS1 in counts centered on the Cold Spot
- In 2D: $\delta_g \lesssim 0.2$, $r \simeq 20^\circ$
- 3D toy model: $R = 220 \pm 50 \mathrm{h}^{-1}\mathrm{Mpc}$, $\delta_m = -0.14 \pm 0.04$, and $z_{void} = 0.22 \pm 0.03$
- A rare but not impossible void, at least 3.3σ in LCDM
- Chance alignment unlikely
- linear ISW up to $\simeq 20 - 40 \mu K$, but could be larger when non-linearities and uncertainties are taken into account
- most previous ISW measurements are a factor of $2 - 4$ higher than theory
- Possibly the first anomaly with plausible explanation
- A rare event but not on the CMB