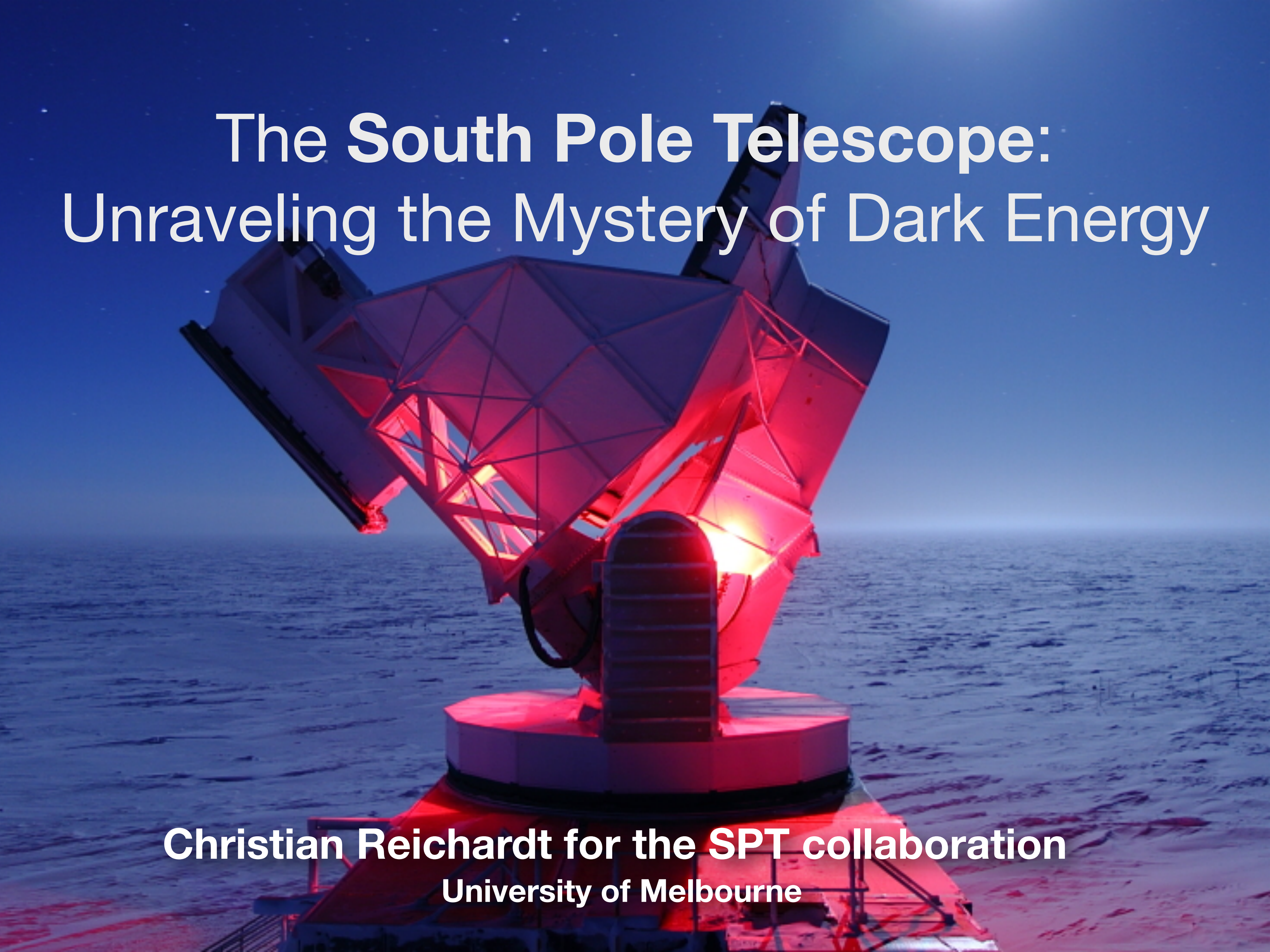
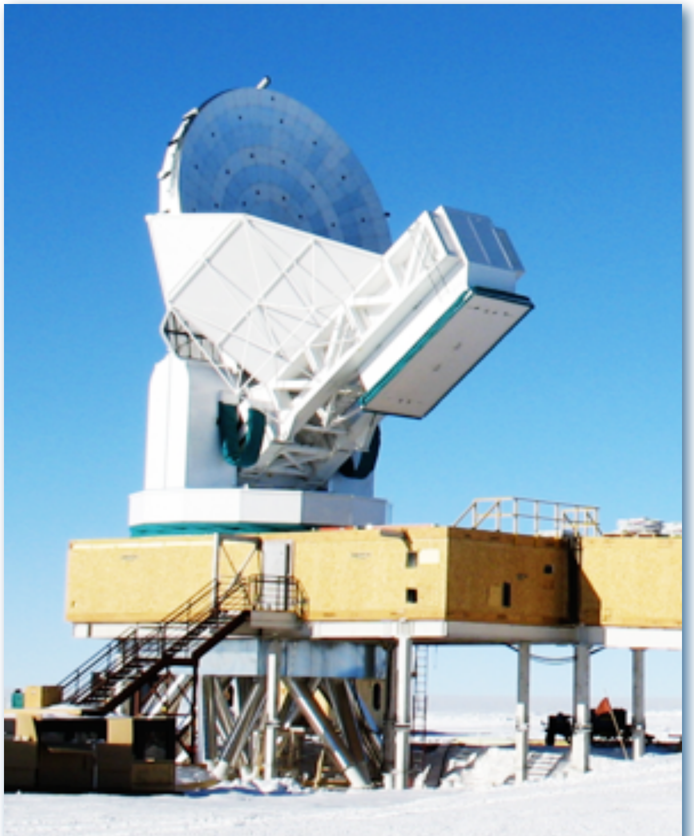


The **South Pole Telescope**: Unraveling the Mystery of Dark Energy

Christian Reichardt for the SPT collaboration
University of Melbourne

The South Pole Telescope (SPT)

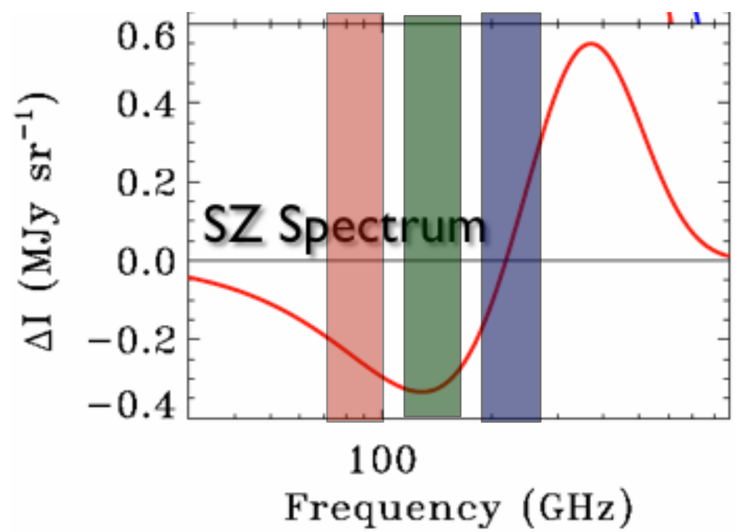


Site

- Best known mm-wave observing conditions

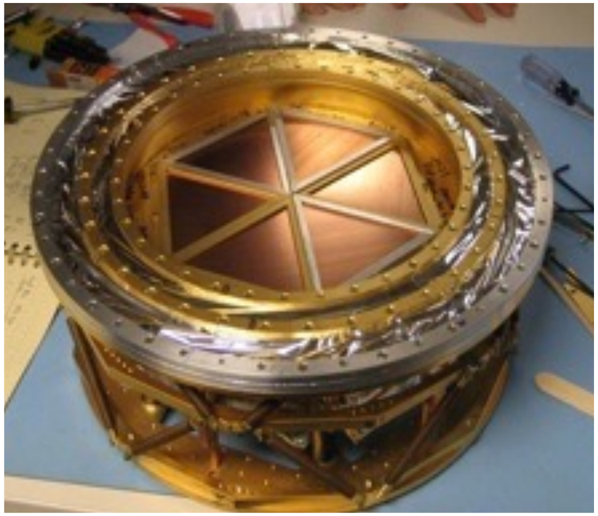
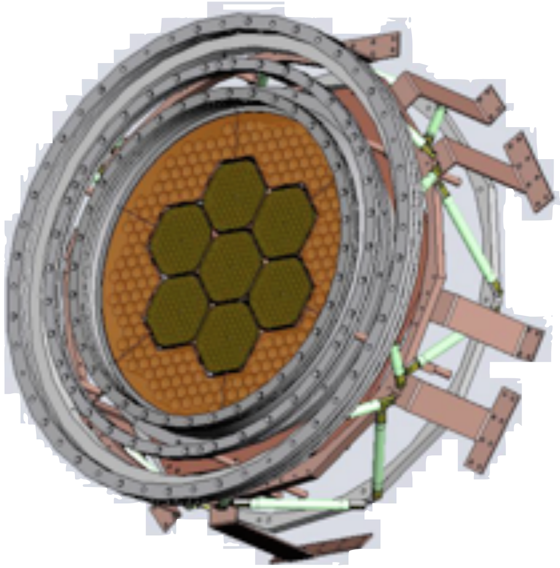
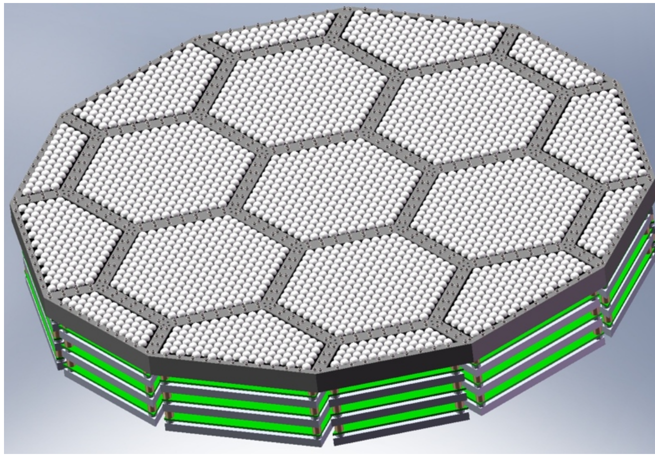
Telescope

- 10 m with 1 deg^2 field of view
- 3-colors: **100**, **150**, **220** GHz
- Resolution of **1.6**, **1.2**, **1.0** arcmin (well-matched to high-*z* clusters, r_{500} ~ 2 arcmin at z=1)

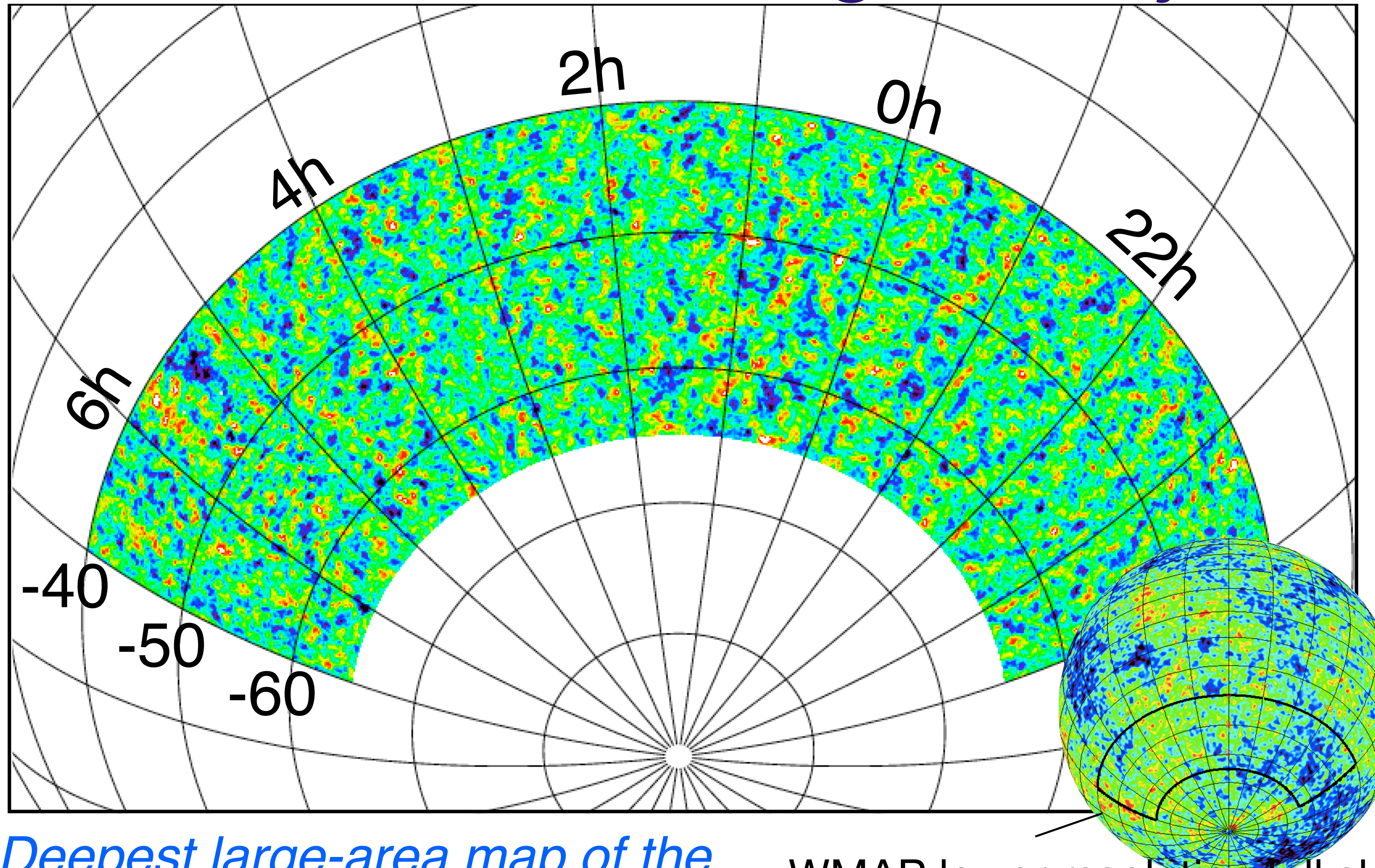


Australian Government
Australian Research Council

Receivers

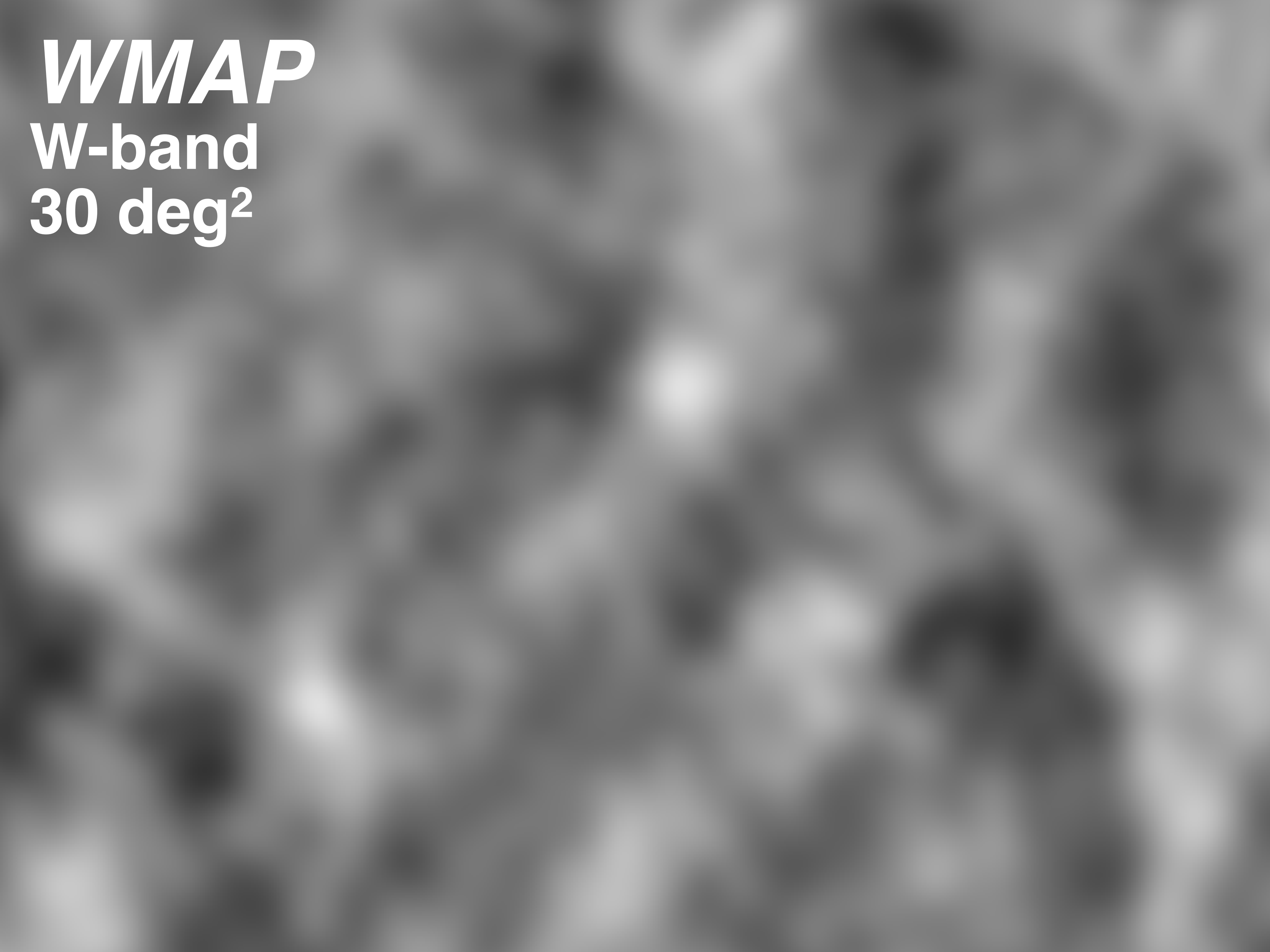
SPT-SZ (2007-2011)	**SPT-Pol (2012-)**	**SPT-3G (2016?)**
		
• 960 bolometers	• 1536 polarization-sensitive bolometers	• 15,234 polarization-sensitive bolometers
• Surveyed 2500 deg^2	• Surveying 500 deg^2	• Plan 2500 deg^2 survey
• Final map depths of	• Exp. map depths of	• Exp. map depths of
40 μK-arcmin @ 95 GHz	8 μK-arcmin @ 95 GHz	4.2 μK-arcmin @ 95 GHz
18 μK-arcmin @ 150 GHz	5 μK-arcmin @ 150 GHz	2.5 μK-arcmin @ 150 GHz
70 μK-arcmin @ 220 GHz		4.0 μK-arcmin @ 220 GHz

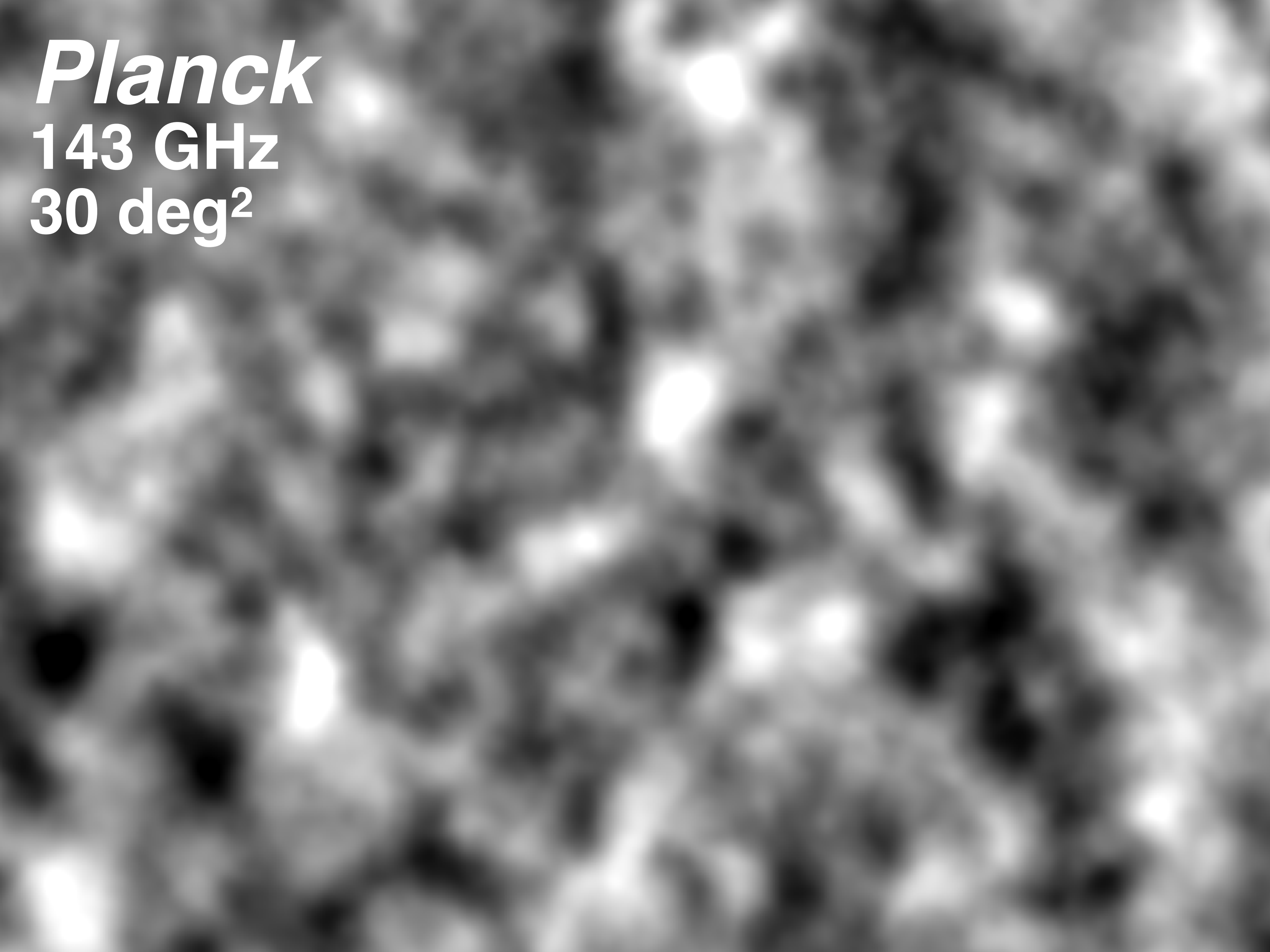
SPT-SZ 2500 deg^2 survey

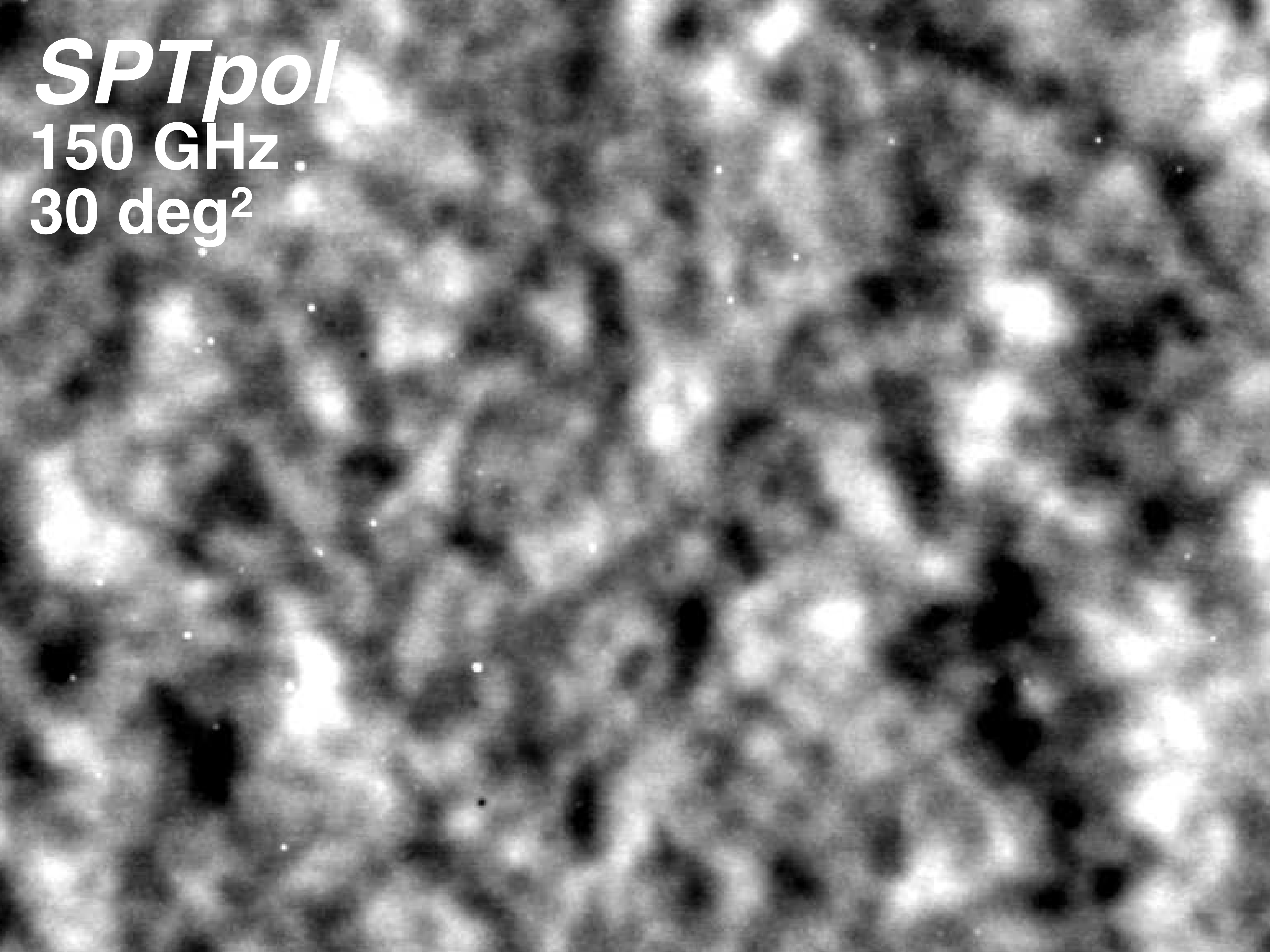


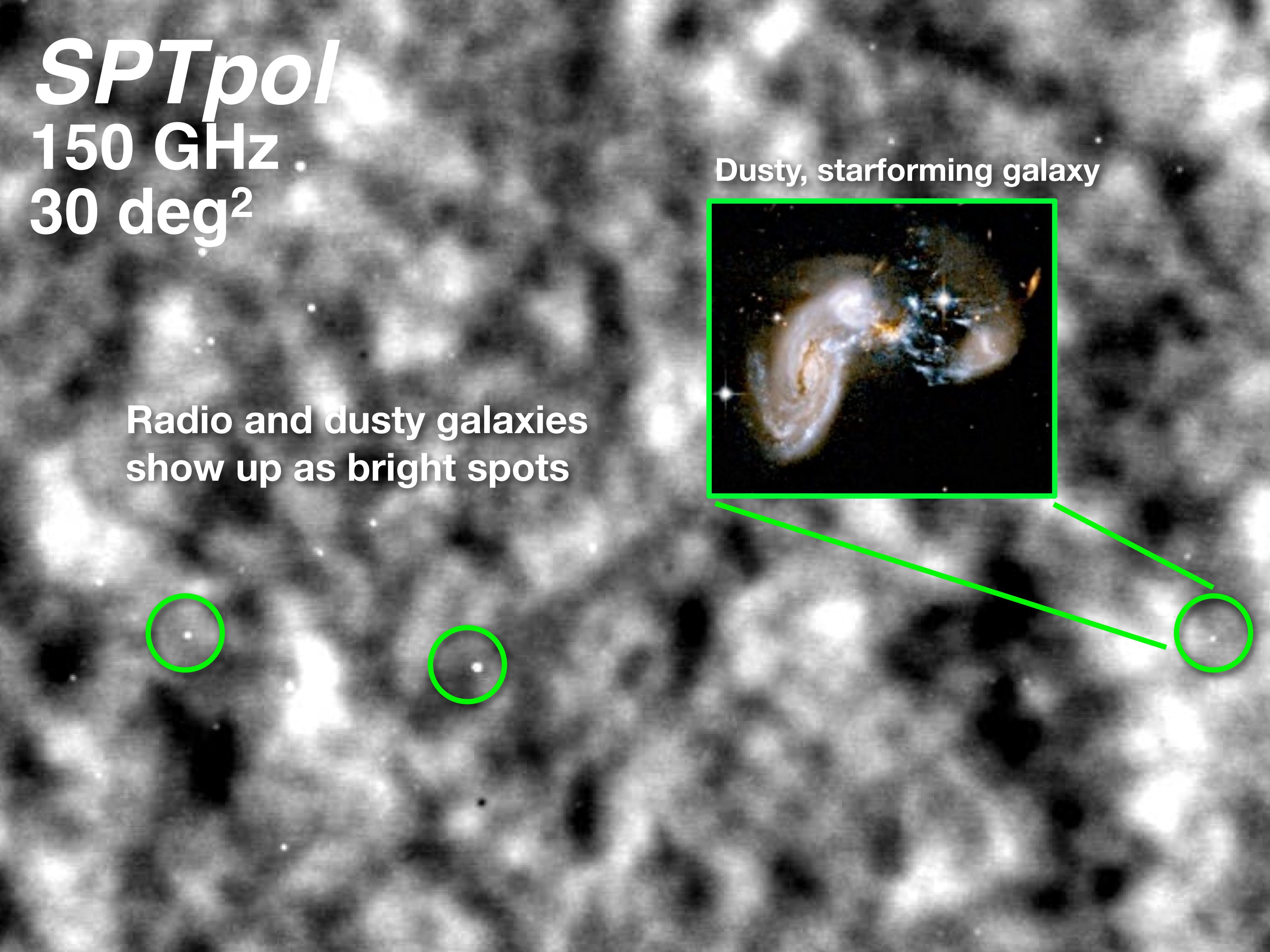
Deepest large-area map of the cosmic microwave background

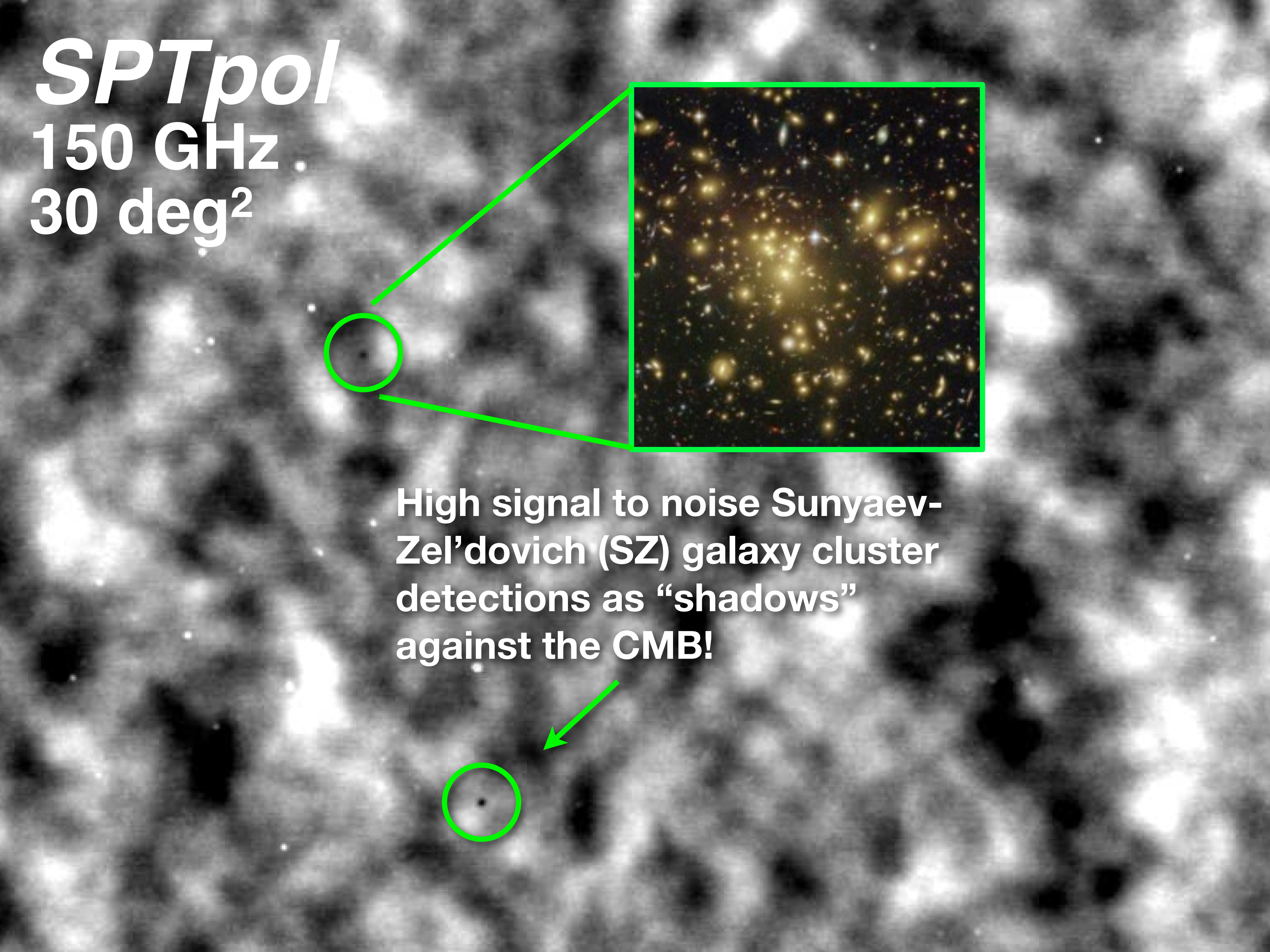
WMAP lower resolution full sky map with SPT area marked


WMAP
W-band
30 deg²


Planck
143 GHz
30 deg²


SPTpol
150 GHz
30 deg²

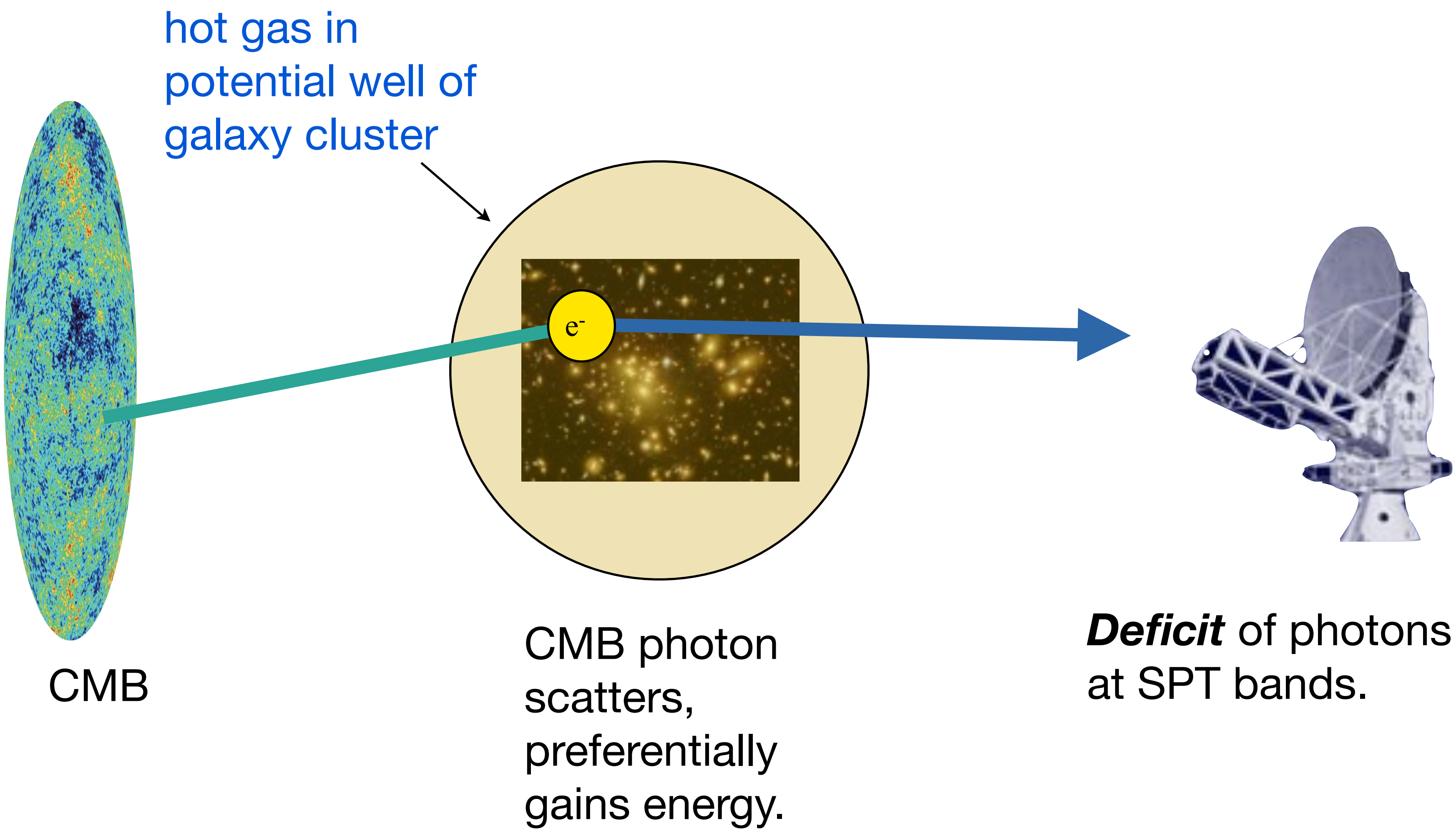

SPTpol
150 GHz
30 deg²
Dusty, starforming galaxy
Radio and dusty galaxies
show up as bright spots


SPTpol
150 GHz
30 deg²
High signal to noise Sunyaev-Zel'dovich (SZ) galaxy cluster detections as "shadows" against the CMB!

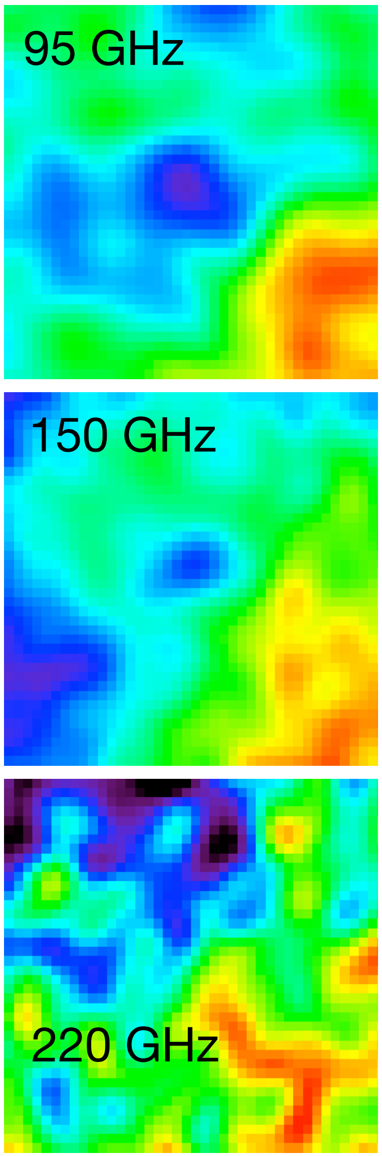
Galaxy clusters

- Most massive (and rare) objects in the Universe
  - Can contain thousands of galaxies
  - Most baryons in gas not stars
- Take billions of years to form
  - Form late enough to "feel" dark energy

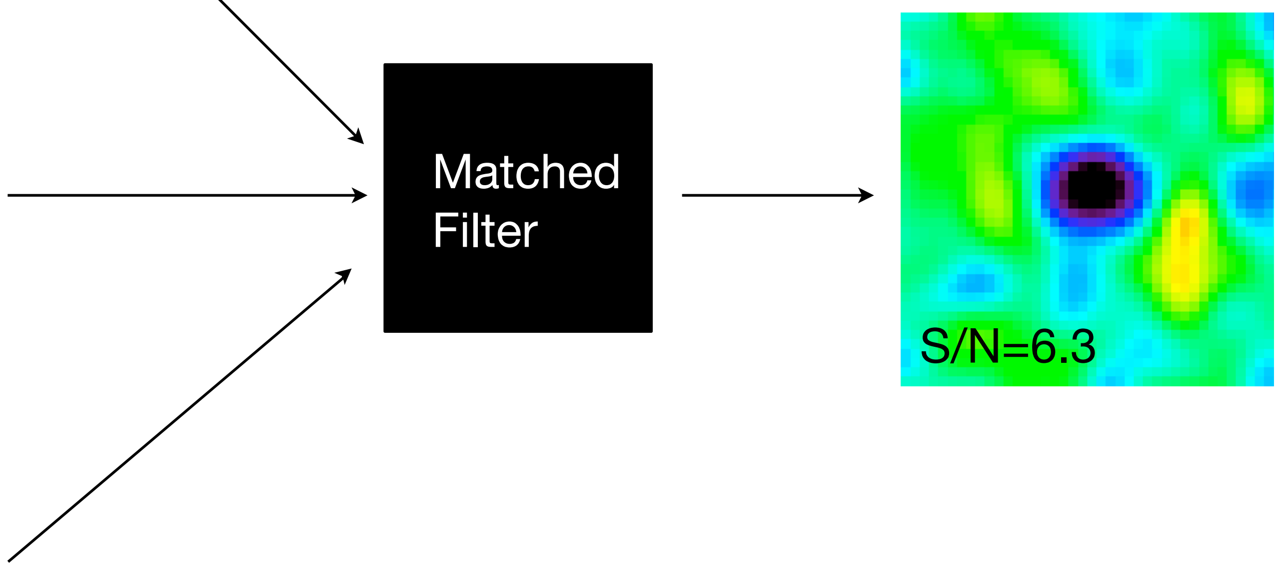
thermal Sunyaev Zel'dovich (SZ) effect



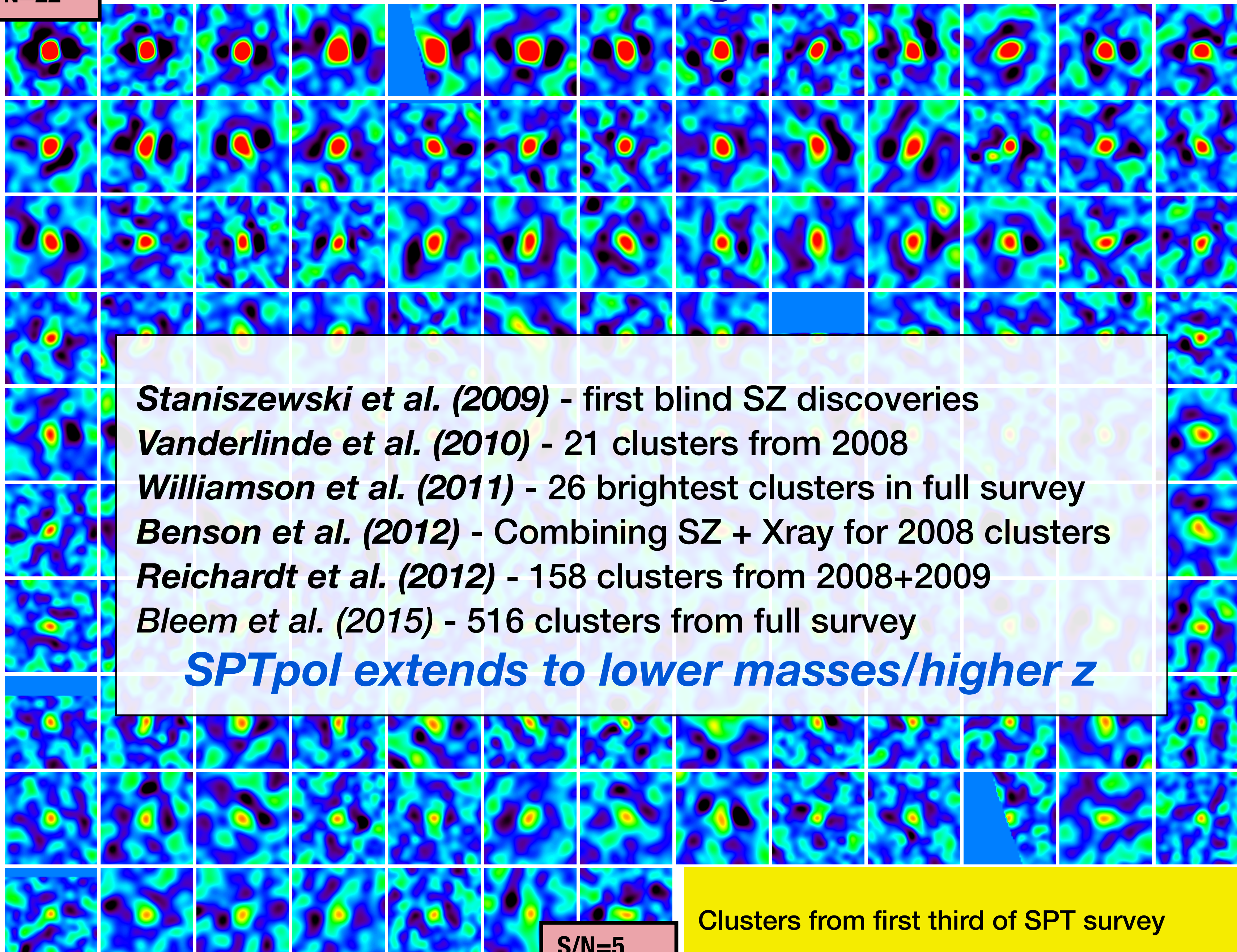
Finding clusters in the SPT survey



- Combine maps at different frequencies into a synthesized thermal SZ map, and find significant objects in that map
- [OR: these steps can be combined into a single spatial-spectral filter (e.g. Tegmark 2000, Herranz et al. 2002, Melin et al. 2006).]



SPT finds massive, high-redshift clusters



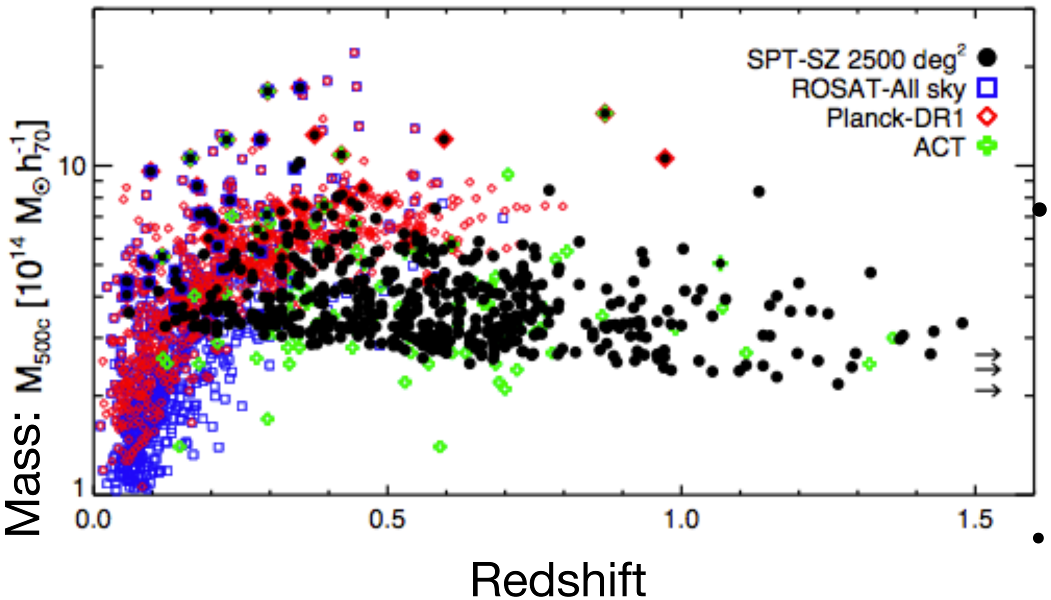
Staniszewski et al. (2009) - first blind SZ discoveries
Vanderlinde et al. (2010) - 21 clusters from 2008
Williamson et al. (2011) - 26 brightest clusters in full survey
Benson et al. (2012) - Combining SZ + Xray for 2008 clusters
Reichardt et al. (2012) - 158 clusters from 2008+2009
Bleem et al. (2015) - 516 clusters from full survey

SPTpol extends to lower masses/higher z

Clusters from first third of SPT survey

SPT Cluster Sample Properties

Cluster Mass vs Redshift



See, **Bleem et al. ApJS 2015**

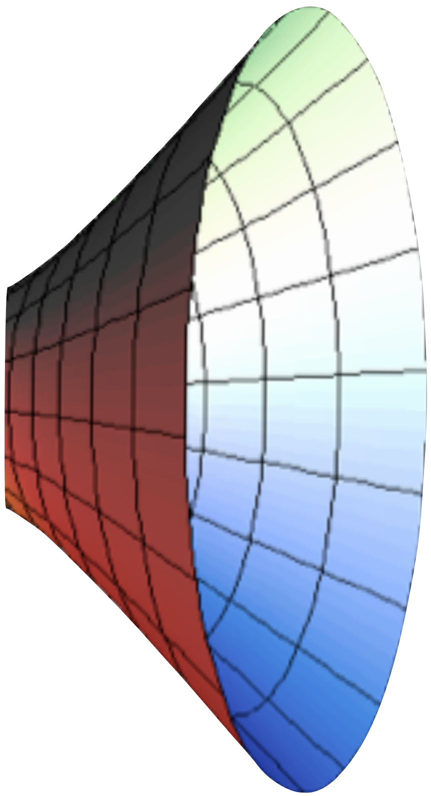
- **~677 candidates** in SPT 2500 deg^2 catalog
  - 516 have measured redshifts
  - 80% are new discoveries
  - 95% purity at S/N > 5 (409 candidates)
- **High redshift**:
  - Median z ~ 0.55
  - Three at z > 1.5 (highest w. spec-z is 1.478)
- **Massive**:
  - median M_{500}=3.5x10^{14} M_o/h_{70}
  - M_{500} > 2x10^{14} M_o/h_{70}
  - ~100% complete above 5x10^{14} M_o/h_{70}

Cosmology with Clusters

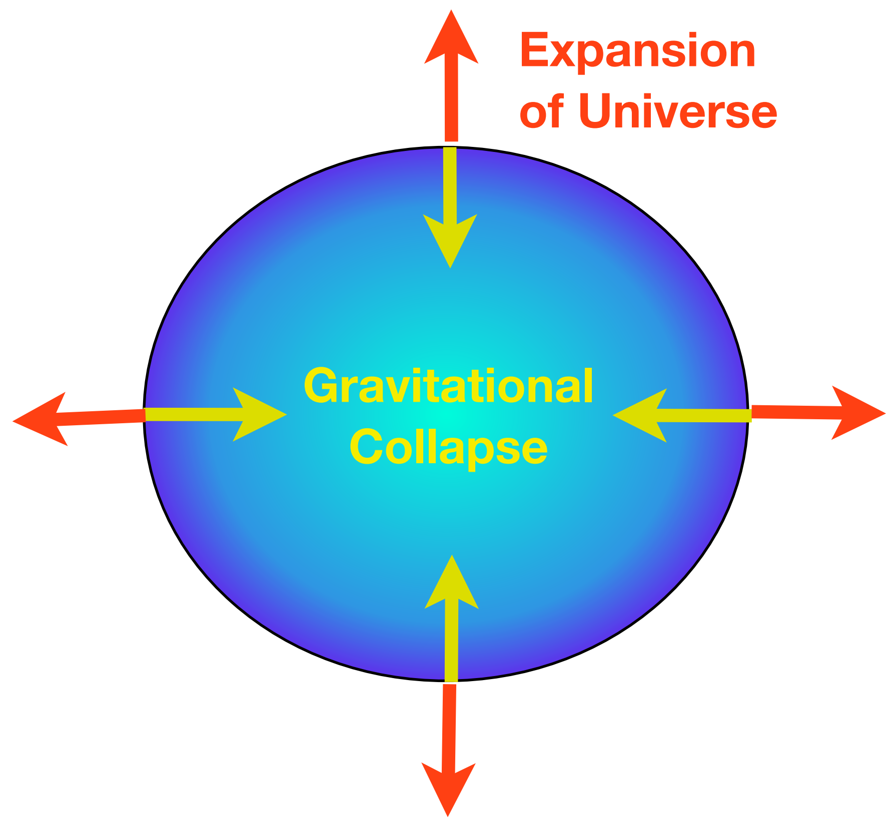
Tijmen de Haan, et al. In prep.

Observational signatures of Dark Energy

Geometry: Distance-redshift



Growth of Structure: G(z)



Cosmology with Galaxy clusters

Joe Mohr

Cluster Abundance, dN/dz

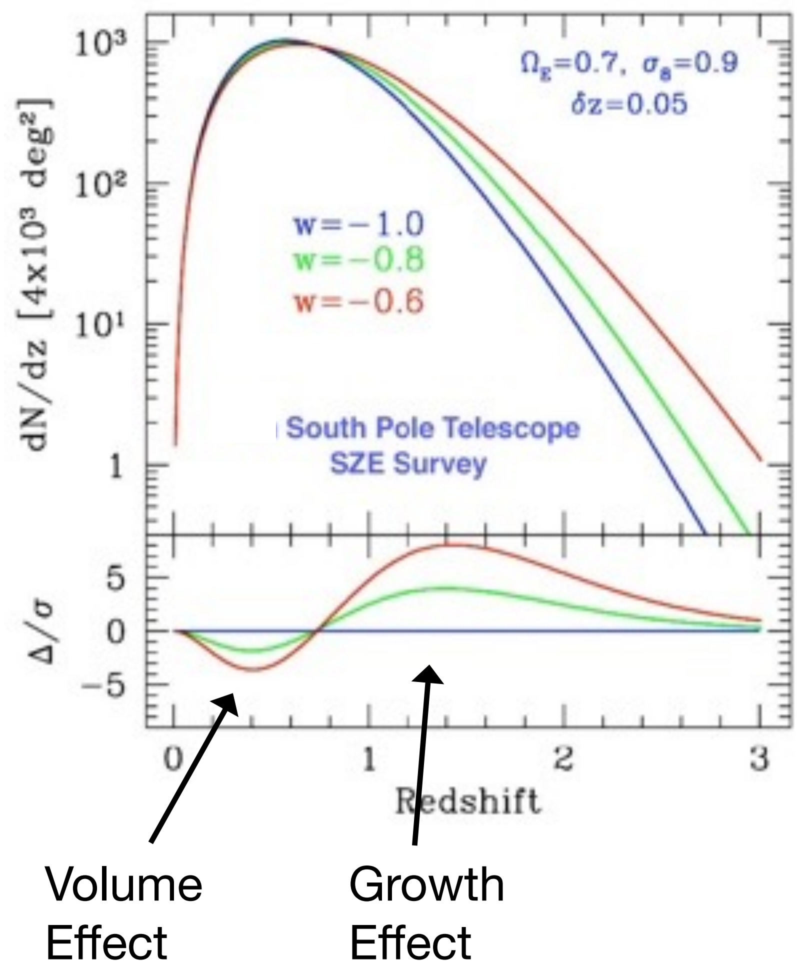
$$\frac{dN}{d\Omega dz} = n(z)\frac{dV}{d\Omega dz}$$

Growth

Depends on:
Matter Power Spectrum, *P(k)*
Growth Rate of Structure, *D(z)*

Geometry

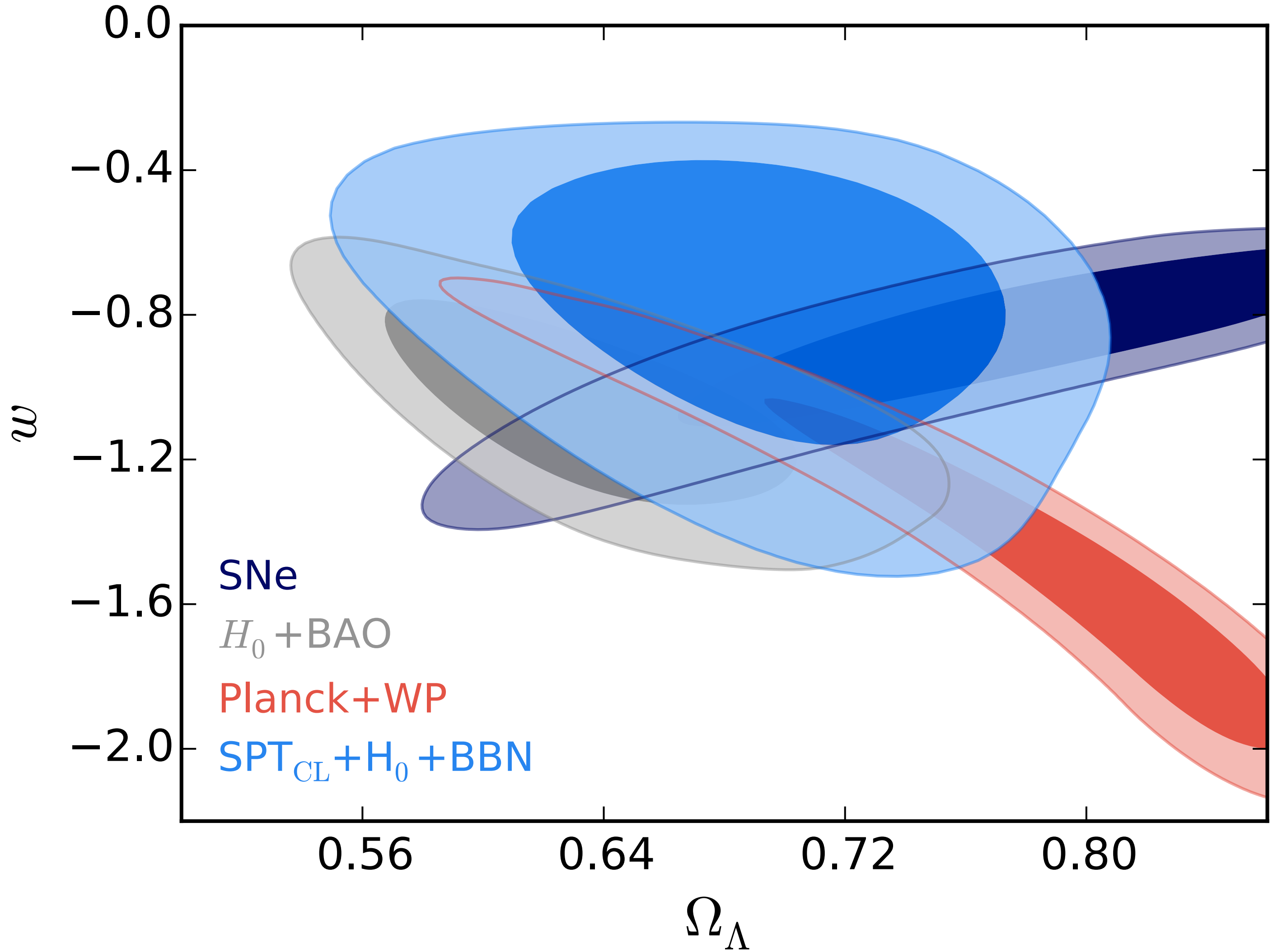
Depends on:
Rate of Expansion, *H(z)*



$\rho(z) = \rho_0(1+z)^{3(1+w)}$
where w = ρ/p is dark energy eqn. of state

Preliminary!

Dark Energy



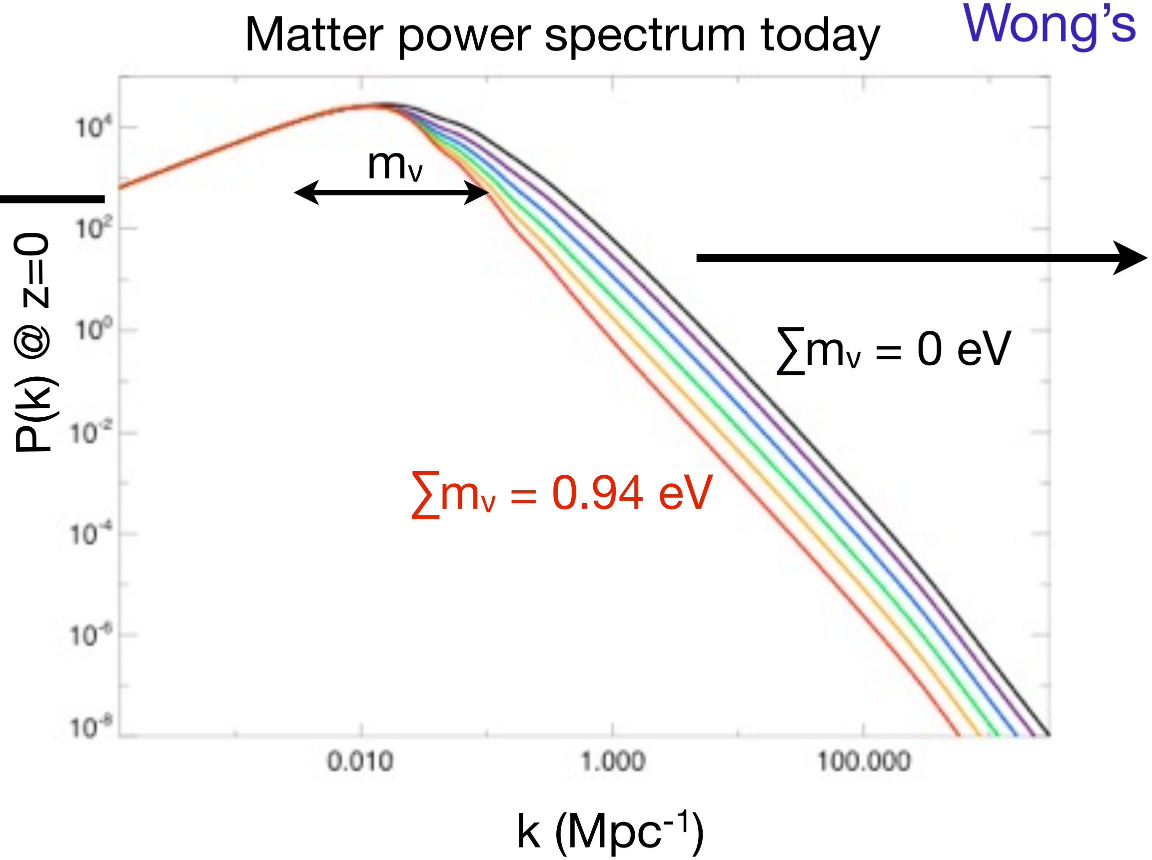
Planck + WP + H0 + BAO + SNe:
w = -1.06±0.05

Add clusters:
w = -1.03±0.04

Neutrinos as seen by LSS

As discussed in Yvonne Wong's talk this morning

Long scales: Faster expansion & clustering cancel (no net change)

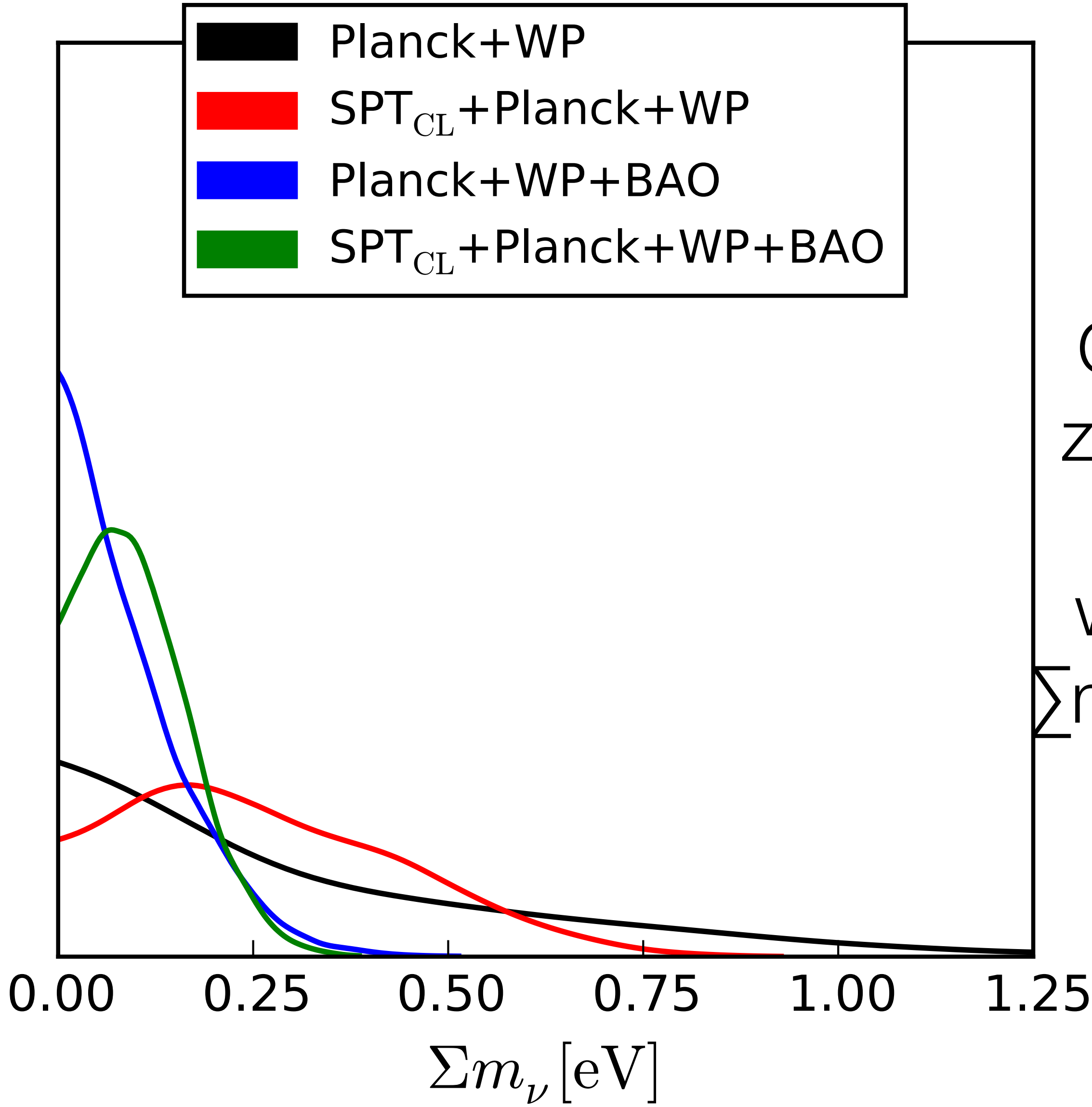


Short scales: Faster expansion suppresses structure

0.1 eV changes cluster abundance by 25%

Neutrino masses

Preliminary!



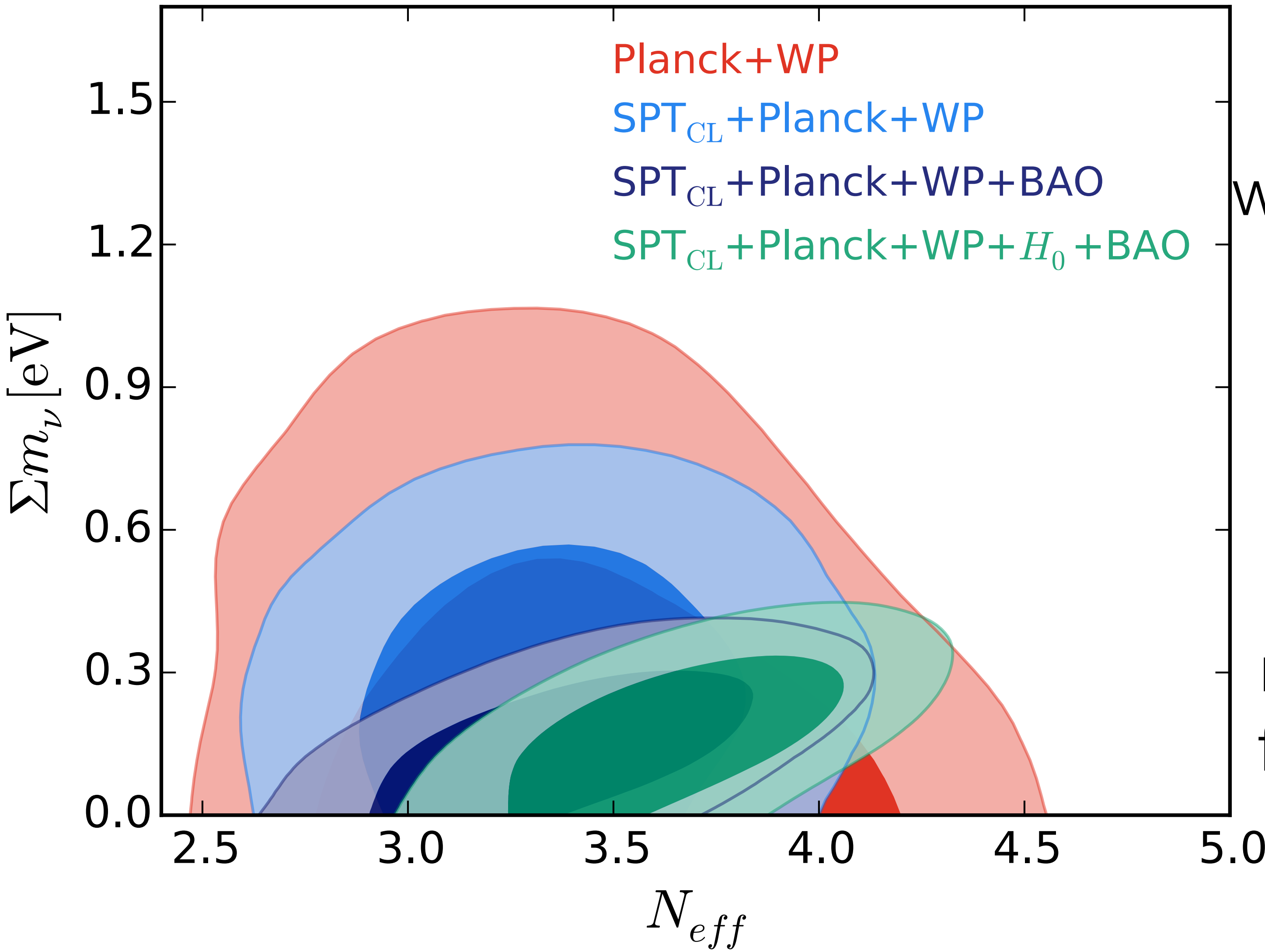
Consistent with zero in all cases.

with everything:

$\sum m_\nu = 0.10 \pm 0.07$

Preliminary!

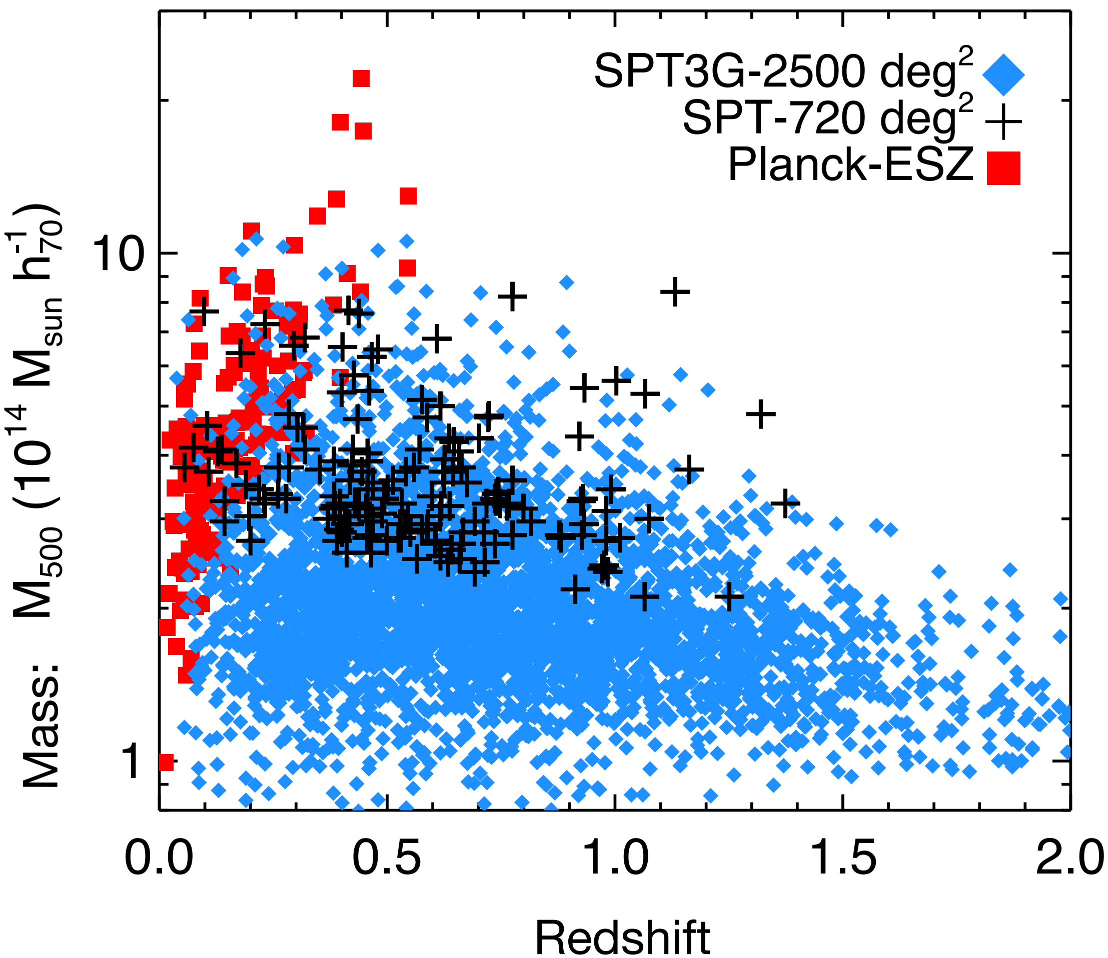
Sterile neutrino constraints



with everything:
N_{eff} = 3.68 ± 0.25
$\sum m_\nu$ = 0.19 ± 0.10

marginal pref. for something new

SPT-3G will have 10x more clusters!



- 8000 clusters
- Improves DES dark energy figure of merit by x4 (Wu et al 2010)
- 2% cluster mass calibration from CMB-cluster lensing

In conclusion

- The SPT, Planck and ACT SZ surveys have found hundreds of massive galaxy clusters

  Bleem et al., 2015

  de Haan et al., In prep.

  - Active followup program underway + Dark Energy Survey
  - Search for deviations from the standard model:
    - Dark energy
    - Neutrino masses
    - and others like running of the scalar index.
- Next generation of experiments will find thousands of galaxy clusters and substantially improve mass calibration