Cosmology with the South Pole Telescope

Photo credit: Nicholas Huang

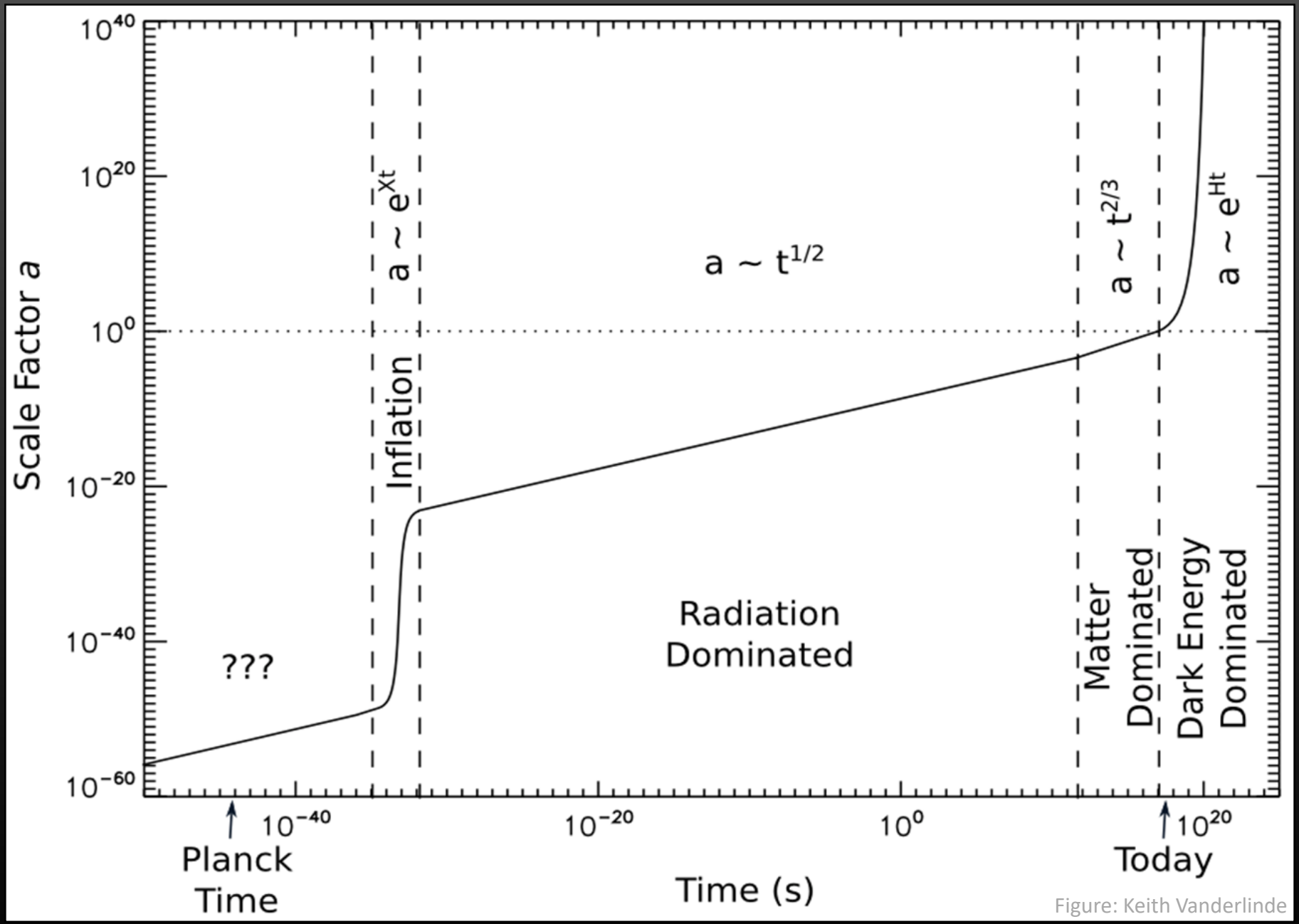
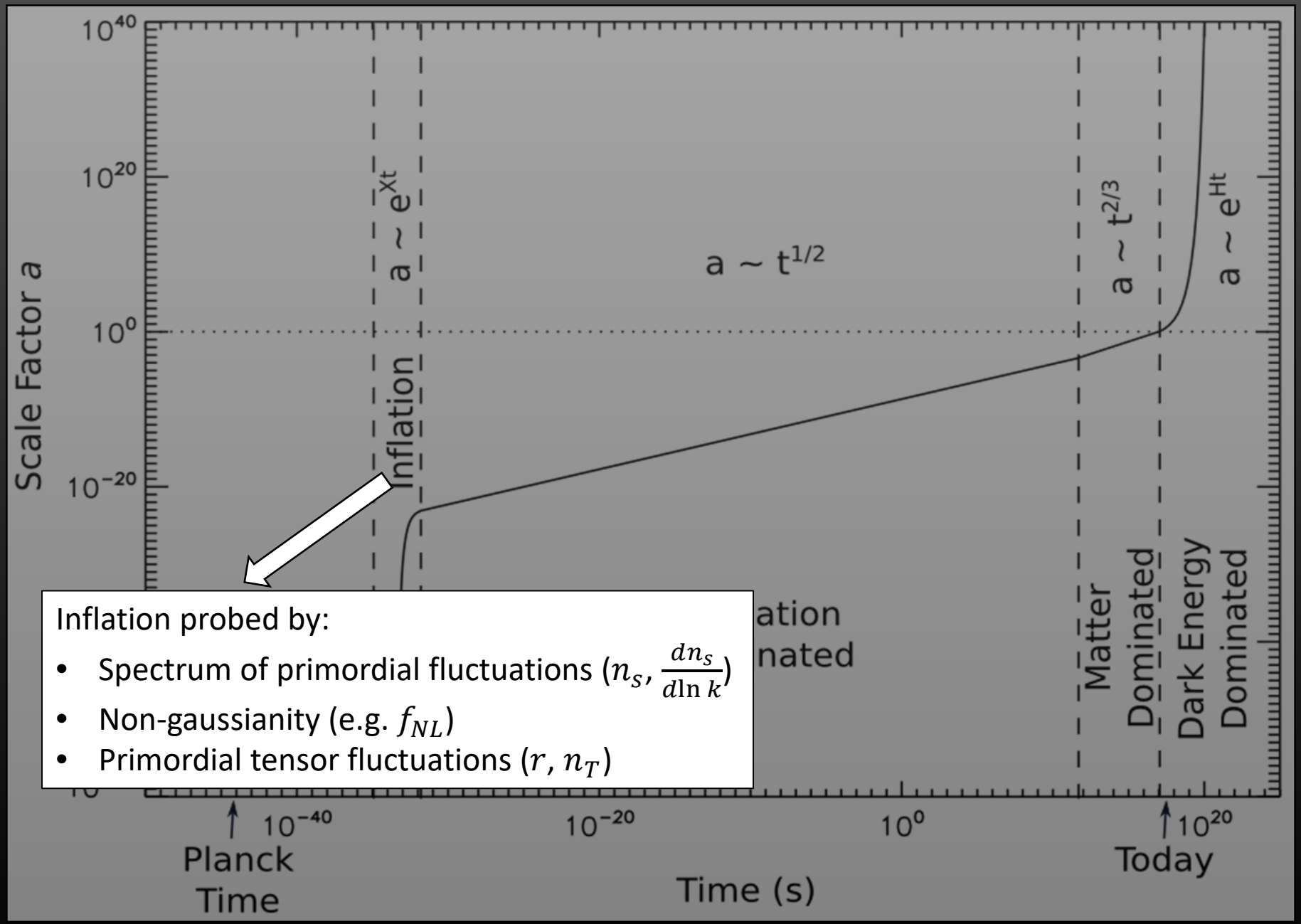
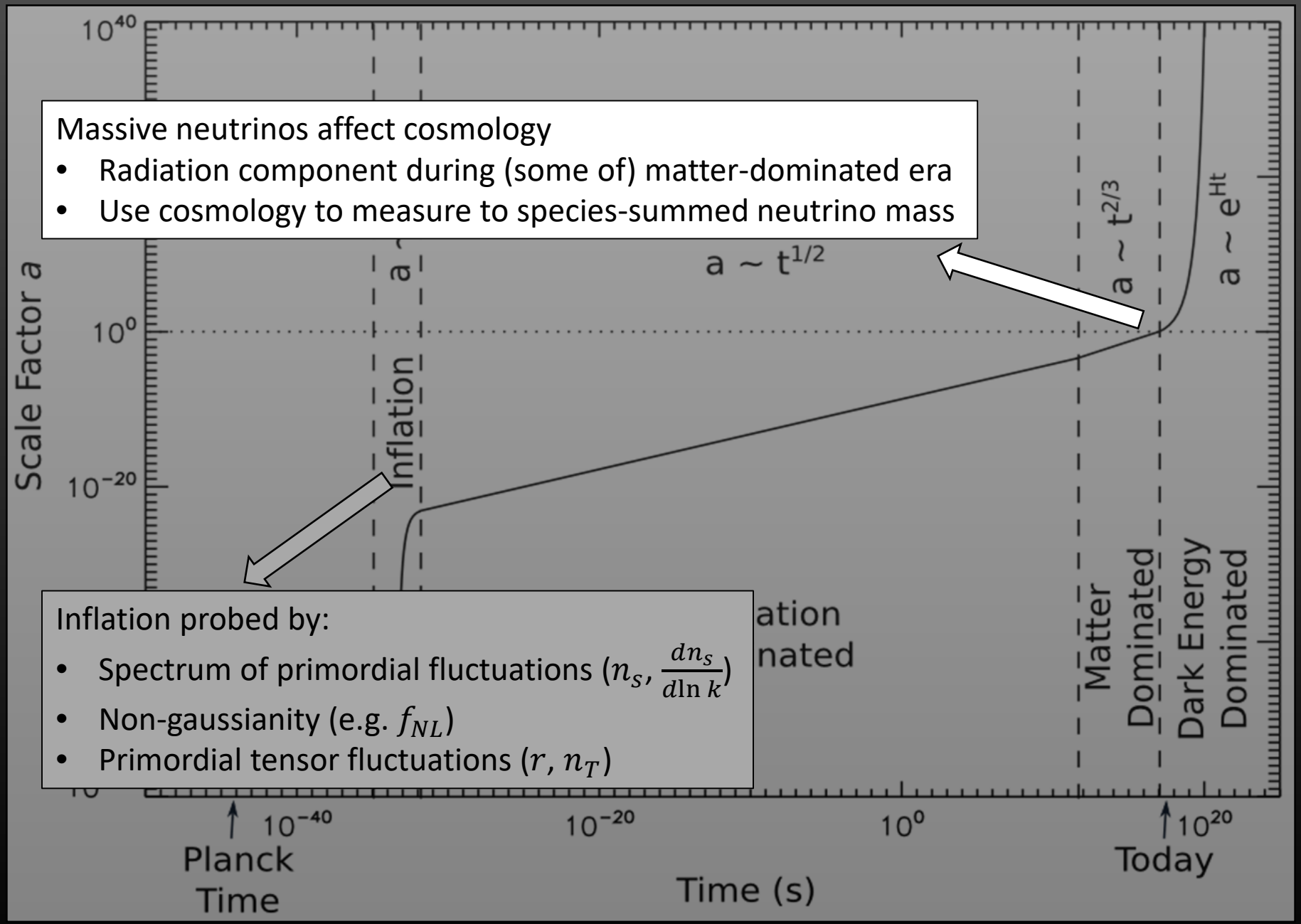


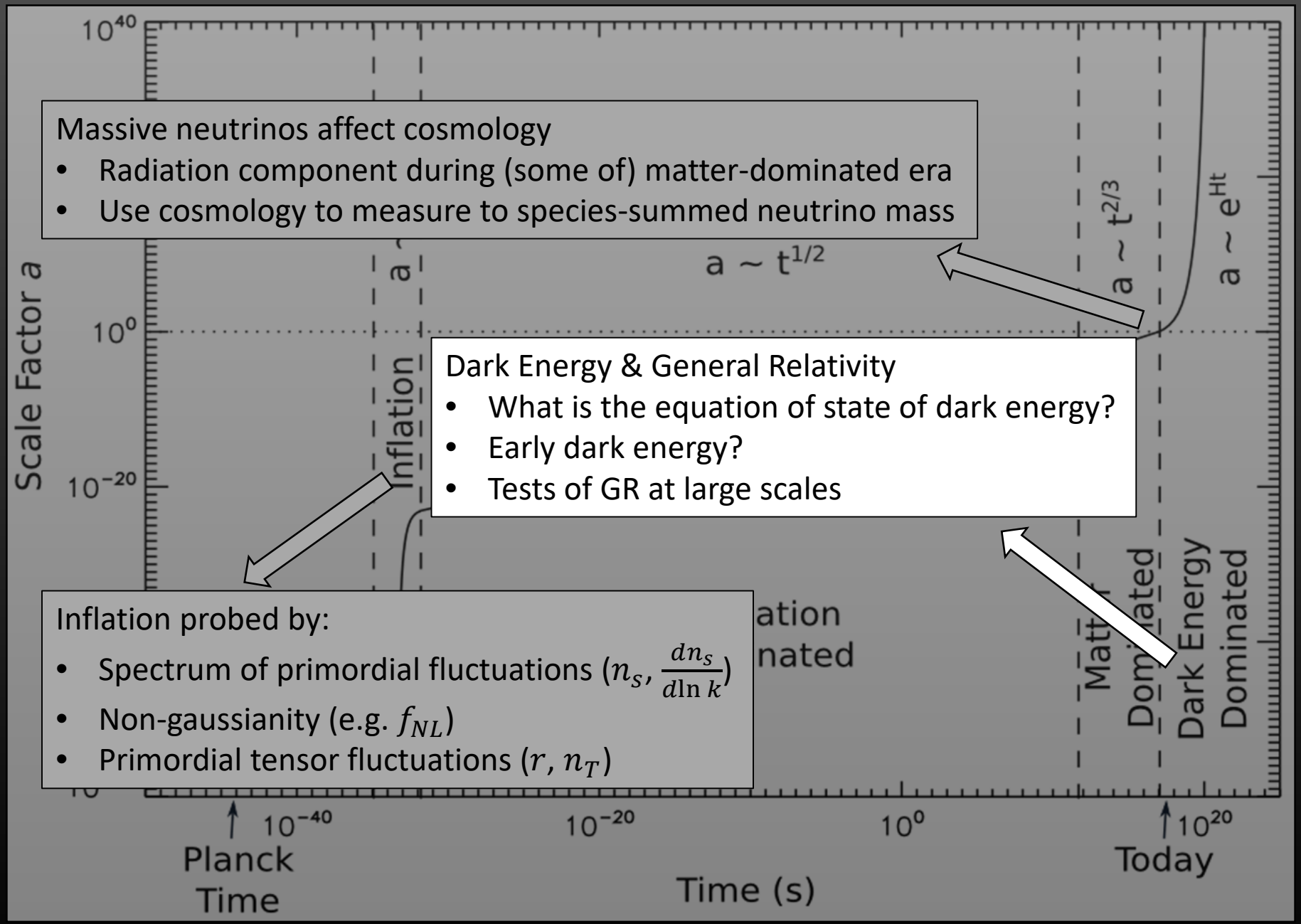
Figure: Keith Vanderlinde



Inflation probed by:

- Spectrum of primordial fluctuations (n_s, $\frac{dn_s}{d\ln k}$)
- Non-gaussianity (e.g. f_{NL})
- Primordial tensor fluctuations (r, n_T)


Massive neutrinos affect cosmology
• Radiation component during (some of) matter-dominated era
• Use cosmology to measure to species-summed neutrino mass
Inflation probed by:
• Spectrum of primordial fluctuations (n_s, $\frac{dn_s}{d\ln k}$)
• Non-gaussianity (e.g. f_{NL})
• Primordial tensor fluctuations (r, n_T)
Scale Factor a
10^{40}
10^{0}
10^{-20}
$a \sim t^{1/2}$
$a \sim t^{2/3}$
$a \sim e^{Ht}$
Inflation
Matter Dominated
Dark Energy Dominated
10^{-40}
10^{-20}
10^{0}
10^{20}
Planck Time
Time (s)
Today


Massive neutrinos affect cosmology
• Radiation component during (some of) matter-dominated era
• Use cosmology to measure to species-summed neutrino mass
Dark Energy & General Relativity
• What is the equation of state of dark energy?
• Early dark energy?
• Tests of GR at large scales
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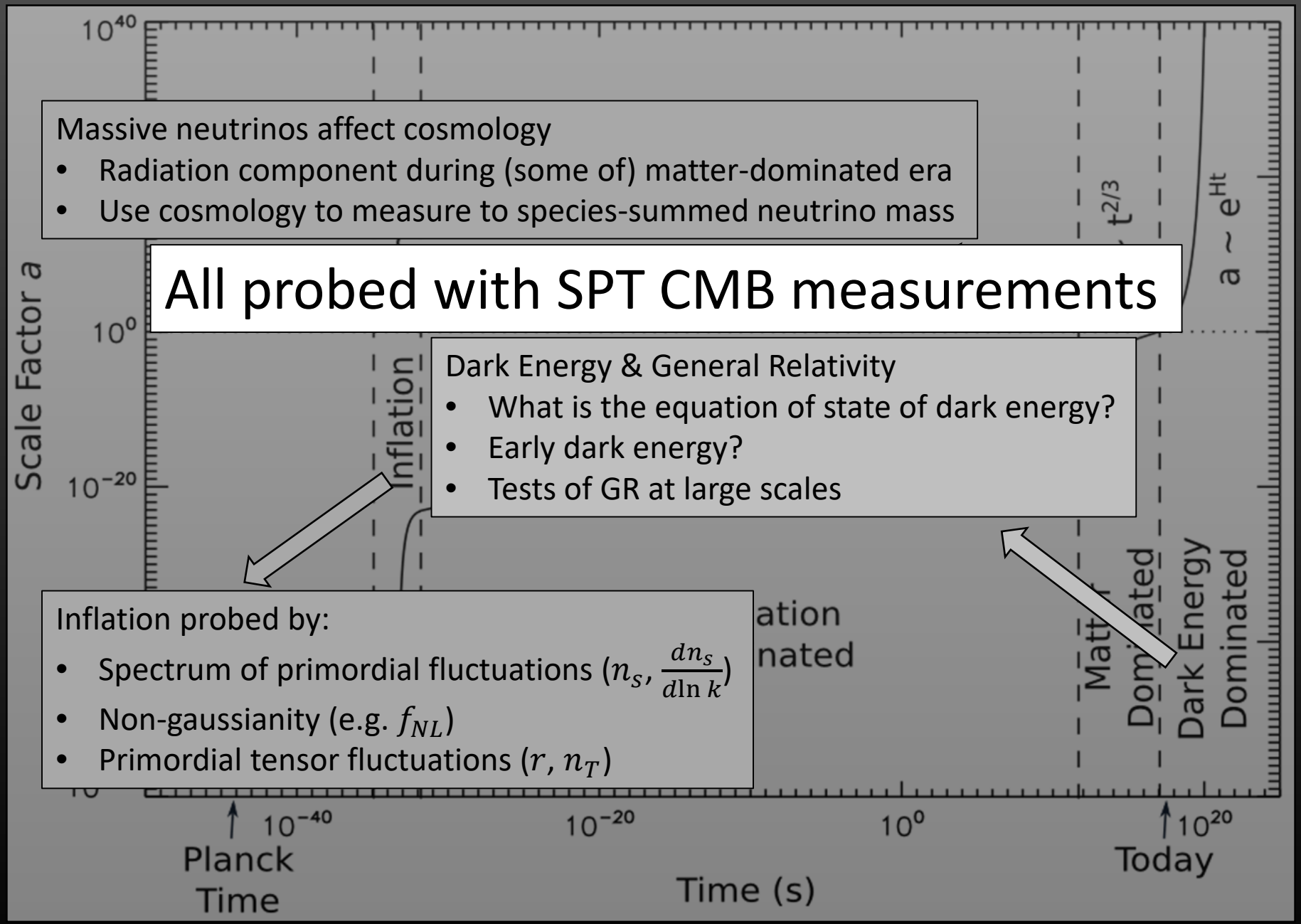
Massive neutrinos affect cosmology
• Radiation component during (some of) matter-dominated era
• Use cosmology to measure to species-summed neutrino mass
All probed with SPT CMB measurements
Dark Energy & General Relativity
• What is the equation of state of dark energy?
• Early dark energy?
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Inflation probed by:
• Spectrum of primordial fluctuations (n_s, $\frac{dn_s}{d\ln k}$)
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10^{40}
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10^{0}
10^{20}
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Today
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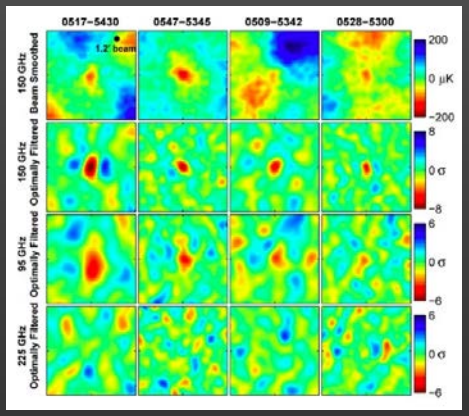
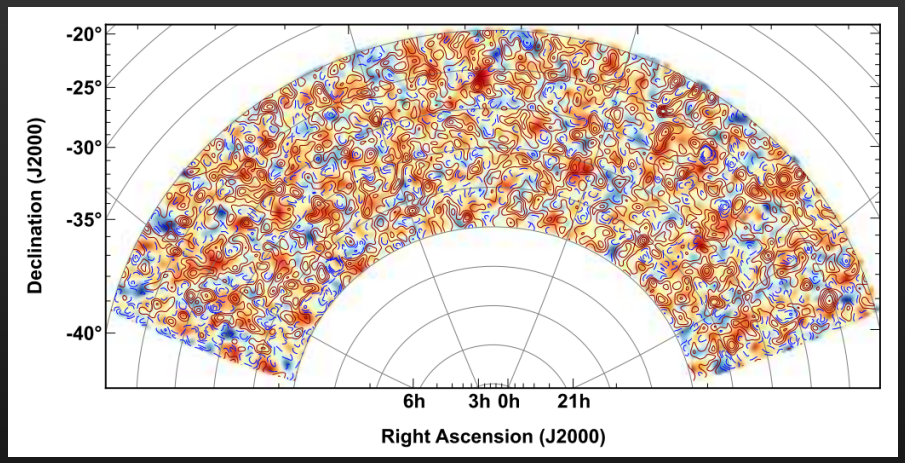
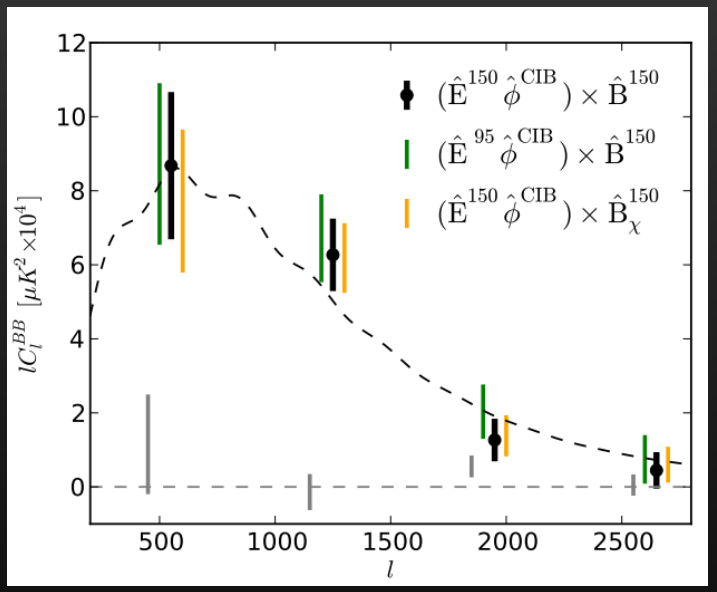
SPT Science Results

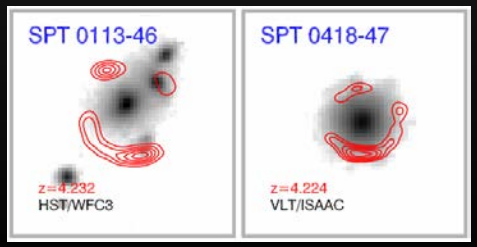


- First SZ-discovered clusters (Staniszewski+09)
- Best map of the projected mass in the universe over 2500 square degrees (Holder+13)



- First detection of B-mode polarization of the CMB (Hanson+13)
- New population of highly lensed dusty star-forming galaxies (Vieira+13)





The South Pole Telescope (SPT)

- 10m telescope -> 1 arcminute resolution
- 2007-2011 SPT-SZ survey
  - Observing at 90 GHz, 150 GHz, 220 GHz
- 2012-2016 SPTpol survey
  - Polarization-sensitive camera observing at 90 GHz, 150 GHz
- 2017-? SPT-3G survey
  - Polarization-sensitive camera observing at 90 GHz, 150 GHz, 220 GHz, ~20x faster than SPTpol

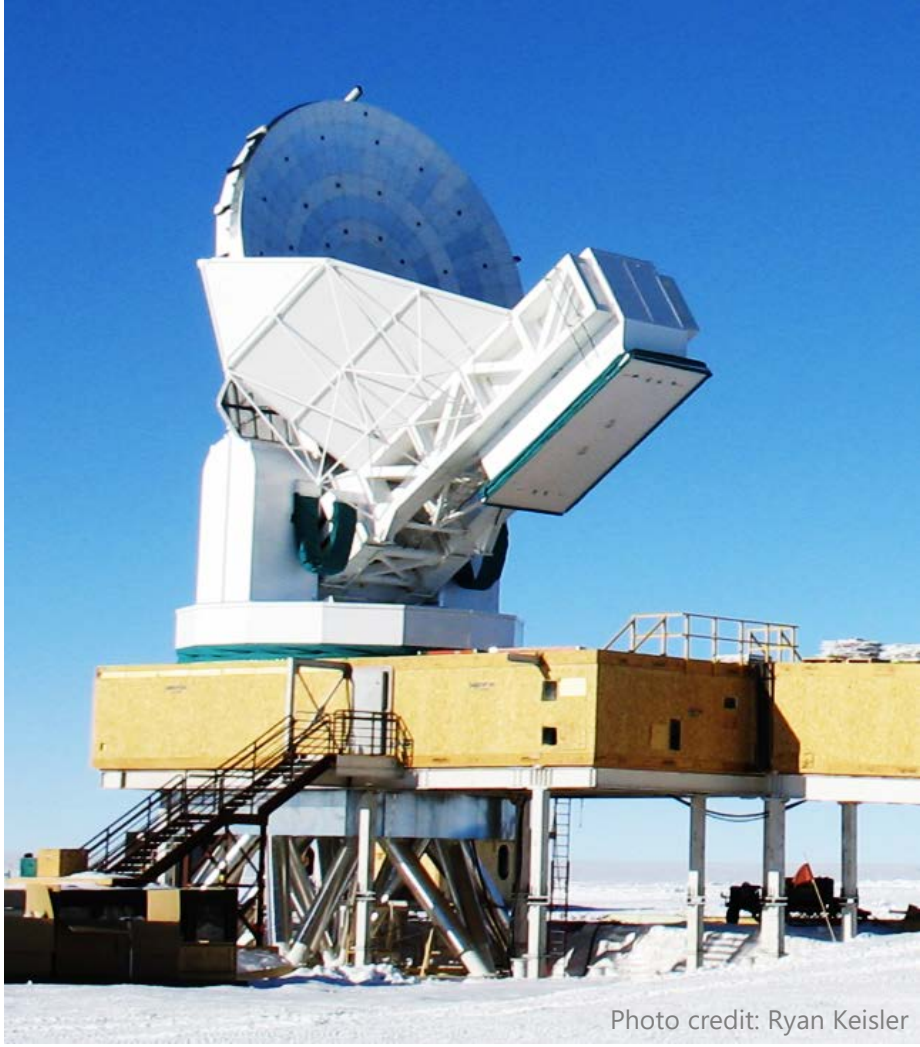
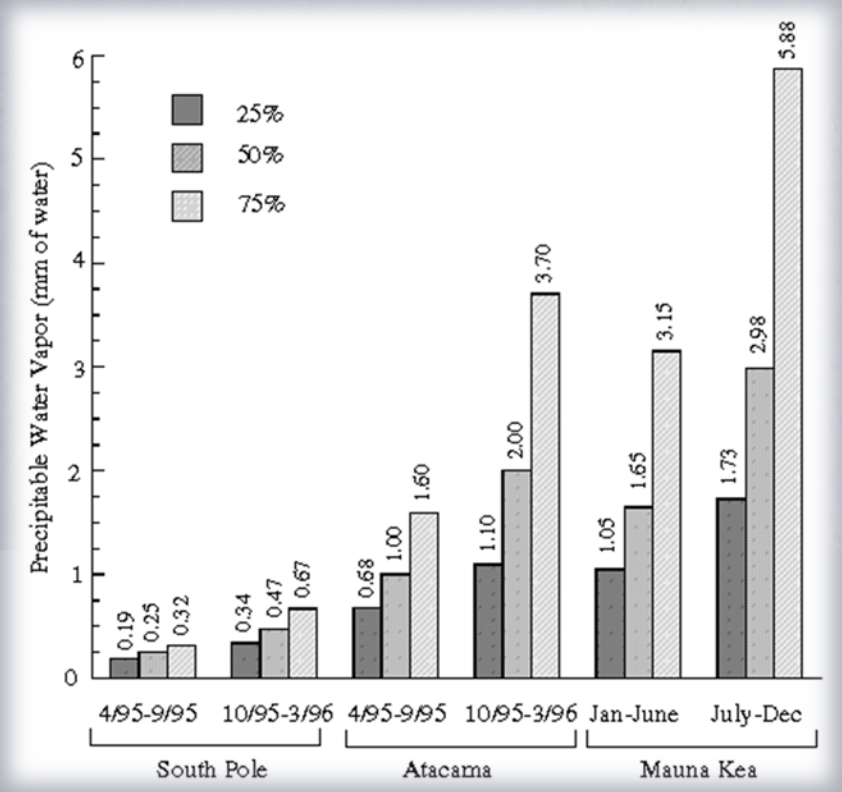


Photo credit: Ryan Keisler

Why the South Pole?



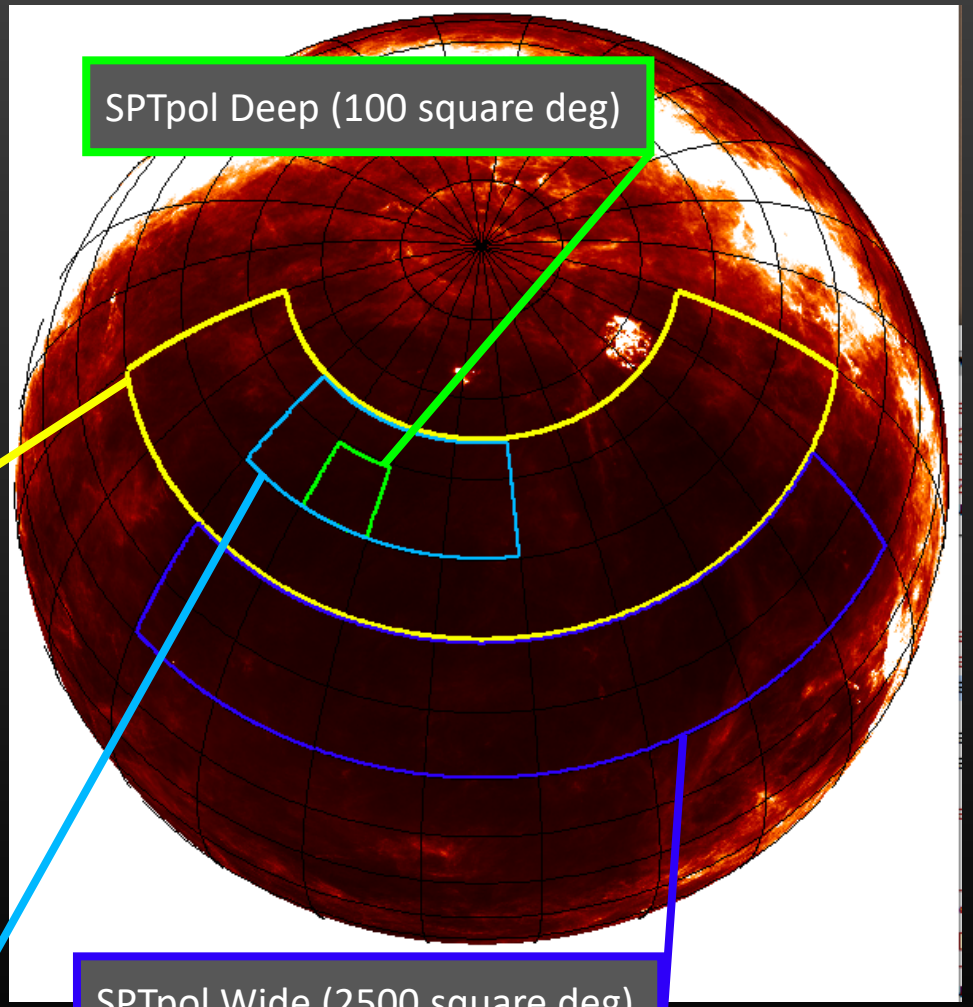
- The level of precipitable water vapor (PWV) is key in ground-based mm-wave experiments

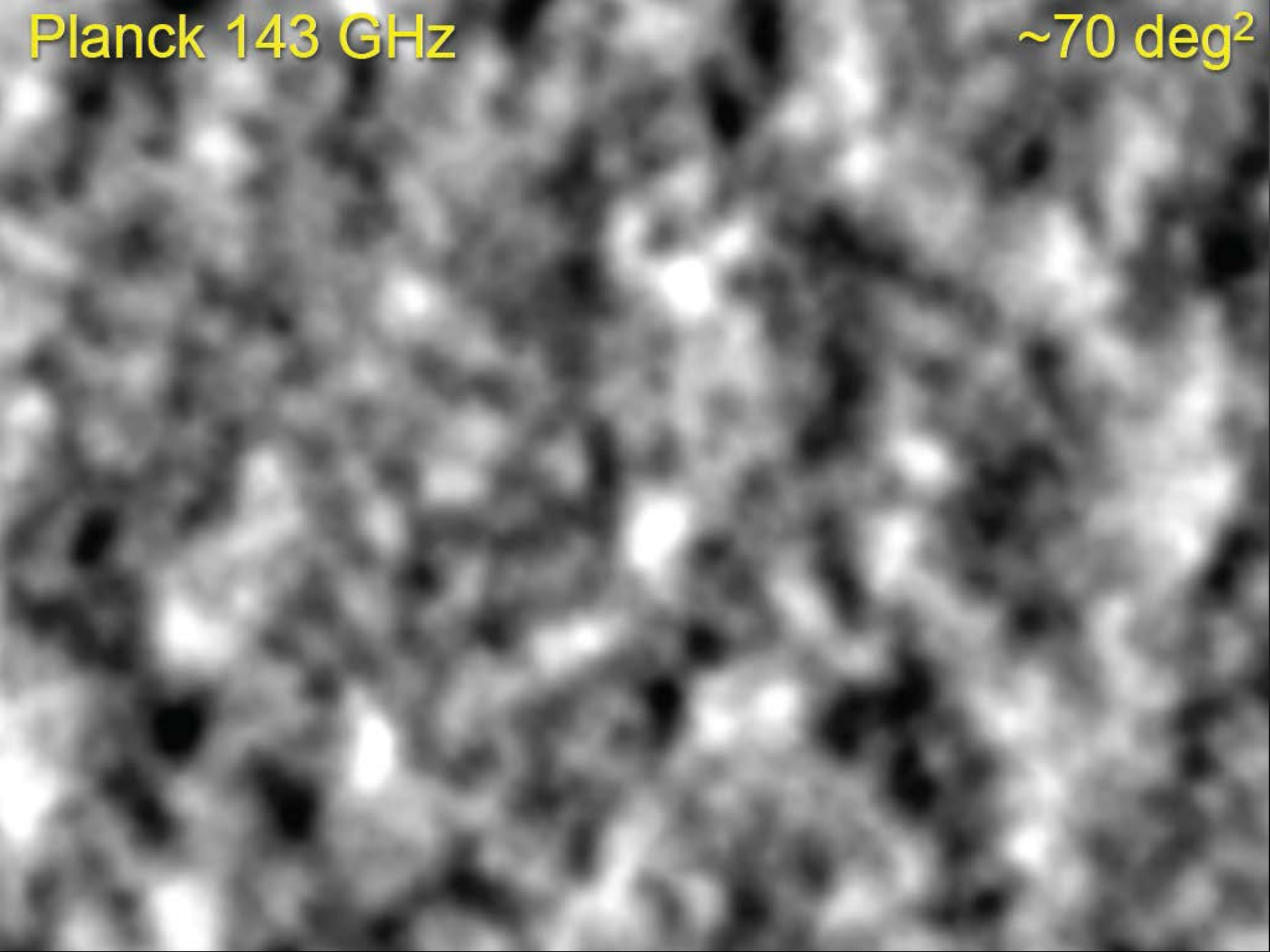
SPT Surveys

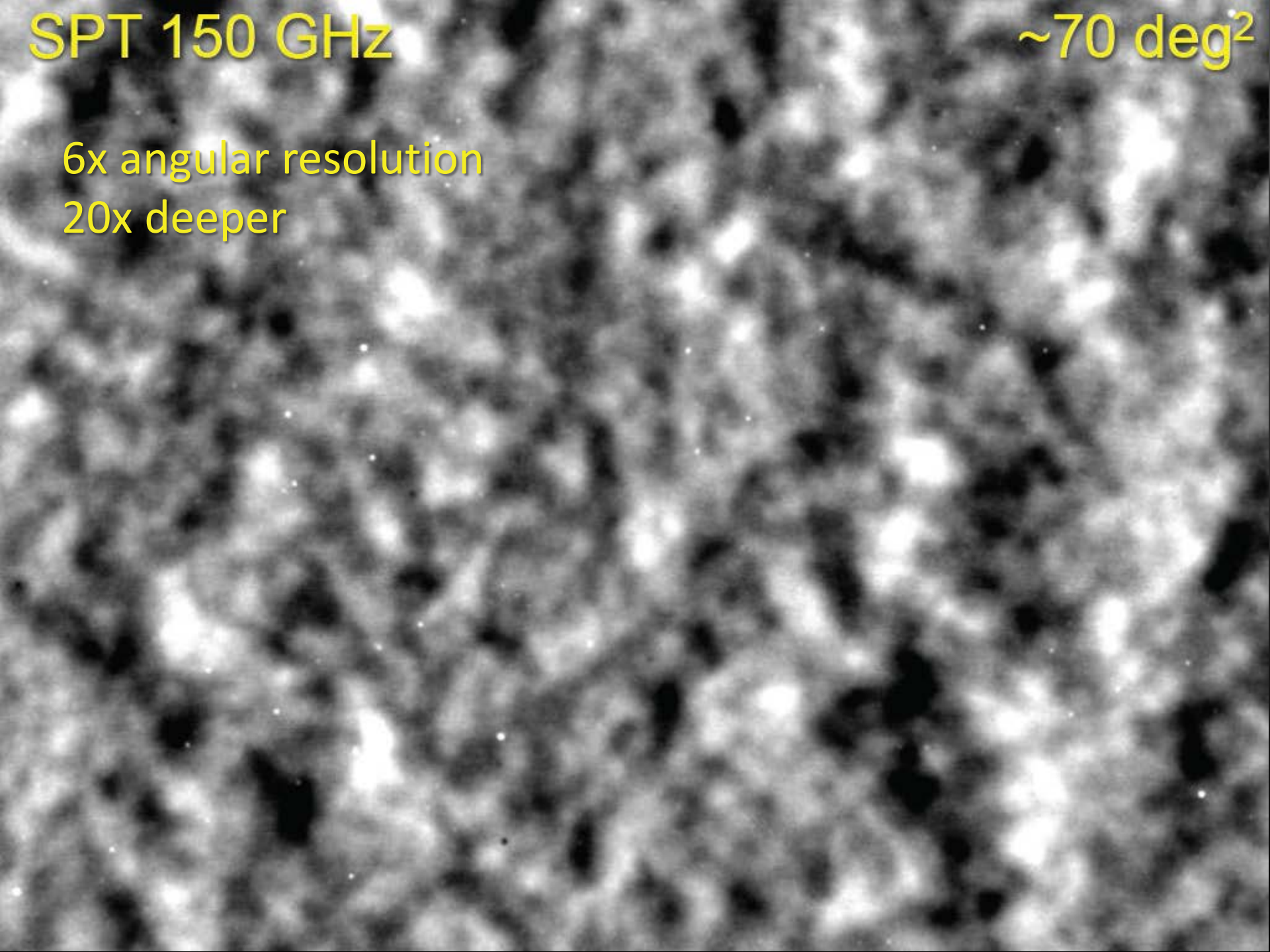
SPT-SZ (2007-2011):
- 2500 square degree survey
- 18 μK-arcmin at 150 GHz
- Winterovers: Stephen Padin, Zak Staniszewski, Keith Vanderlinde, Dana Hrubes, Erik Shirokoff, Ross Williamson, Daniel Luong-Van

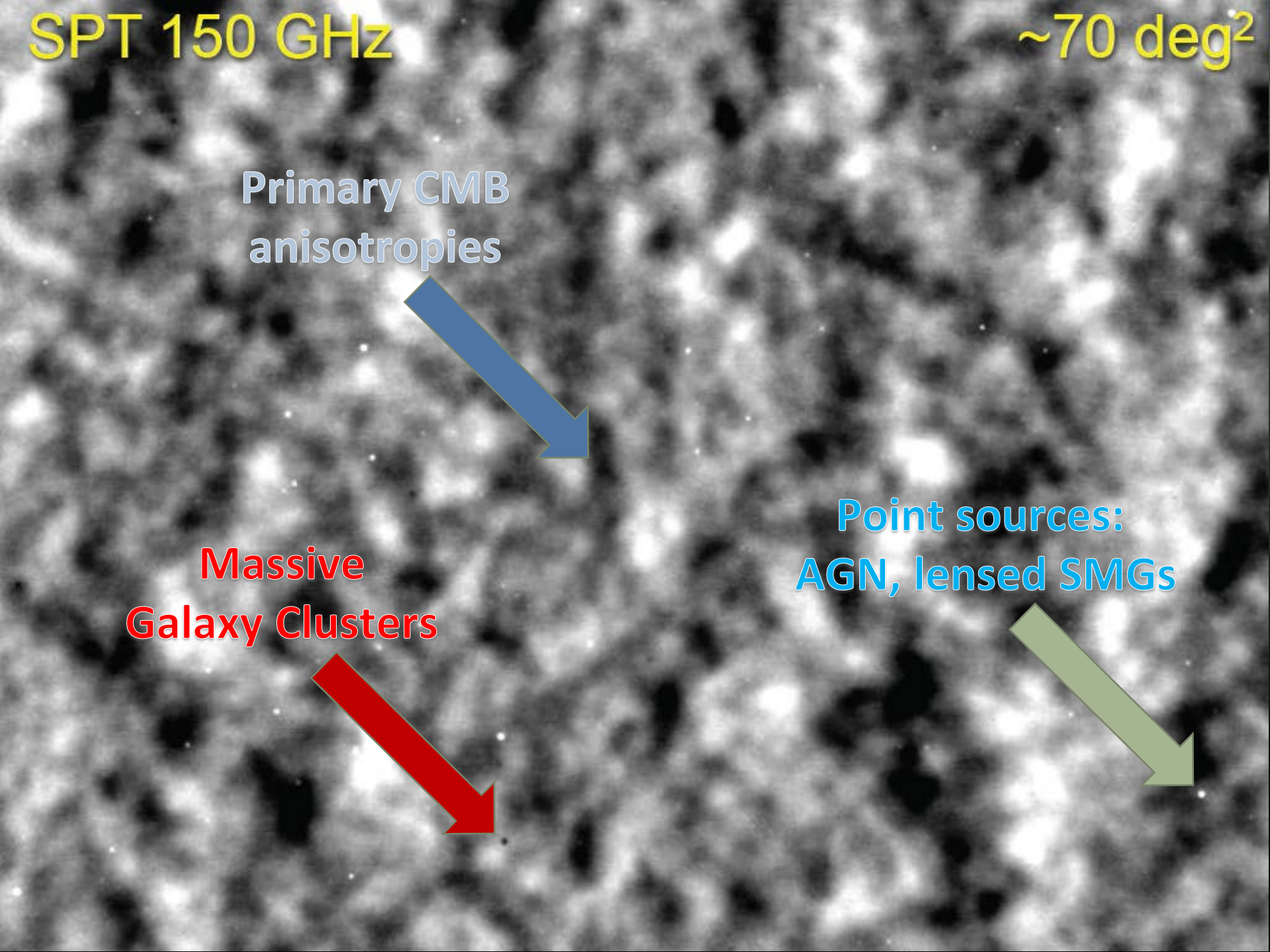
SPT-3G (2017+)
- Currently deployed in engineering mode
- Expected to achieve 2 μK-arcmin at 150 GHz
- Winterovers: Daniel Michalik, Andrew Nadolski

SPTpol (2012-2016):
- Main survey: 500 square degrees
- 5 μK-arcmin at 150 GHz
- Winterovers: Nicholas Huang, Cynthia Chiang, Jason Gallicchio, Dana Hrubes, Robert Citron, Charlie Sievers, Todd Veach, Amy Lowitz, Christine Corbett Moran




Planck 143 GHz
~70 deg²

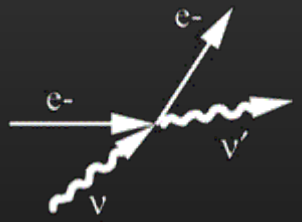

SPT 150 GHz
~70 deg²
6x angular resolution
20x deeper

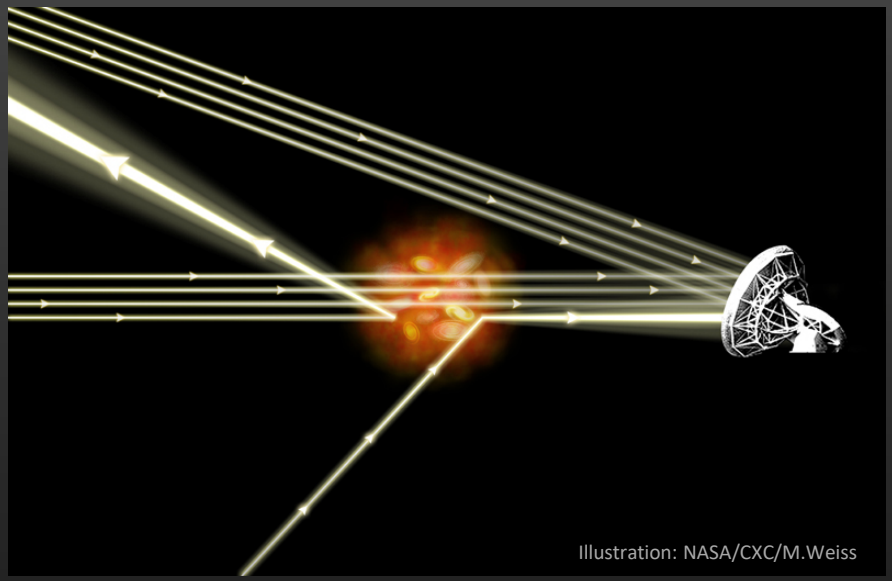

SPT 150 GHz
~70 deg²
Primary CMB anisotropies
Massive Galaxy Clusters
Point sources: AGN, lensed SMGs

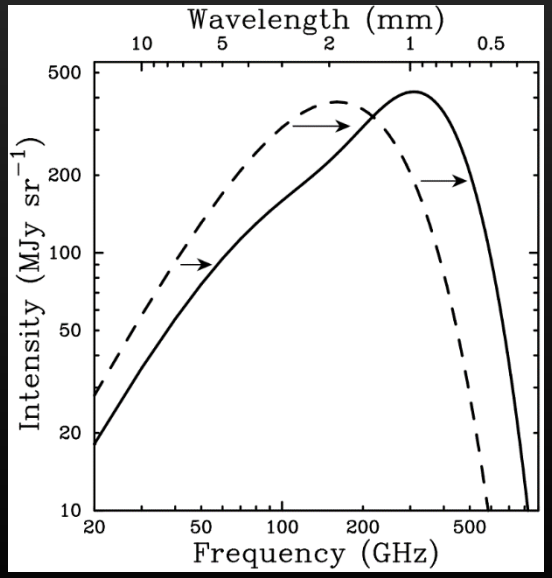
Sunyaev-Zel'dovich Effect

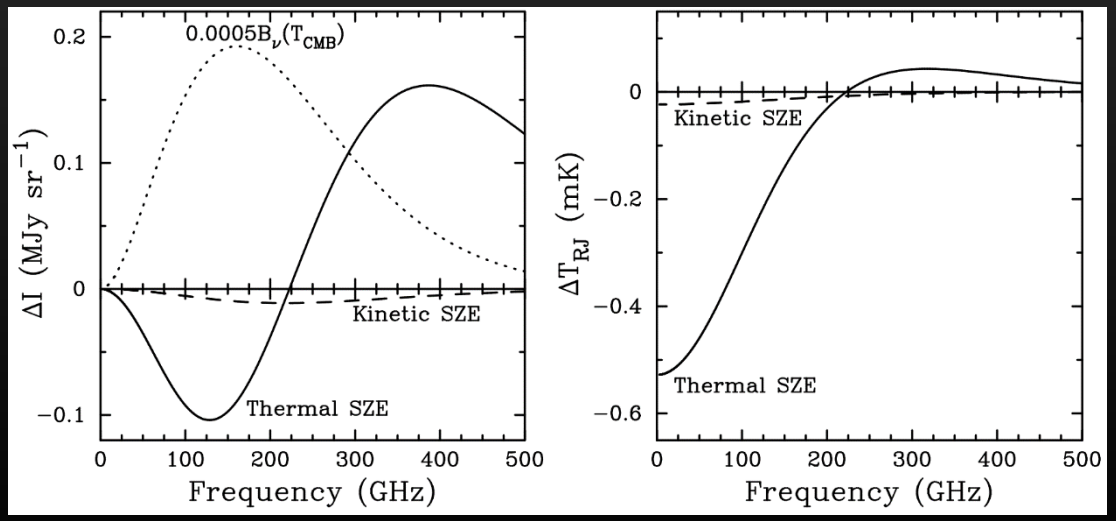
- Distortion of the Cosmic Microwave Background from inverse Compton scattering due to high energy electrons
- Measure Compton y-parameter

y = (optical depth) * (fractional energy gain per scattering)





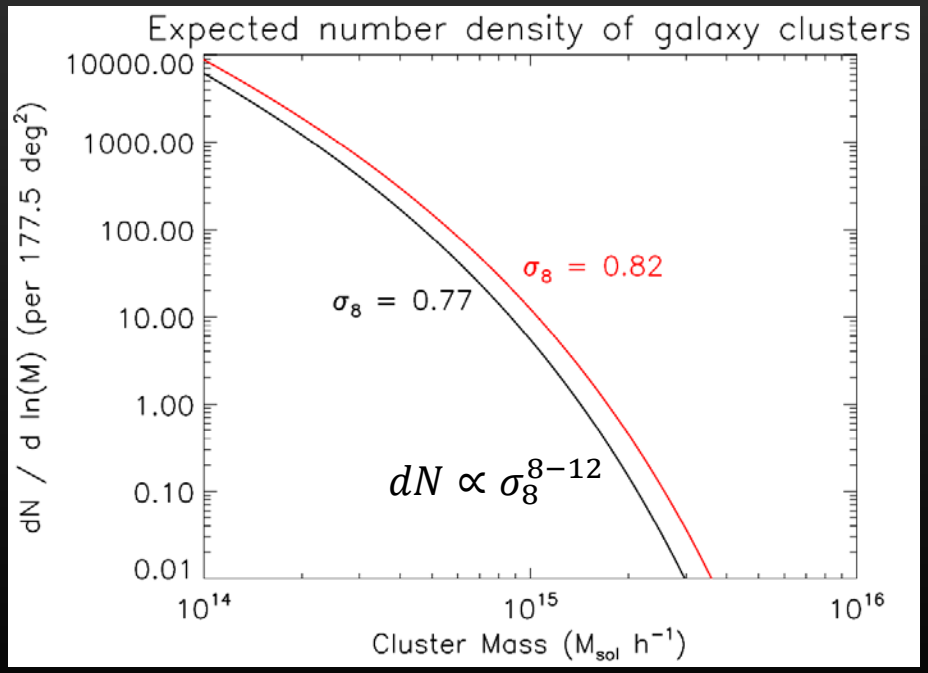


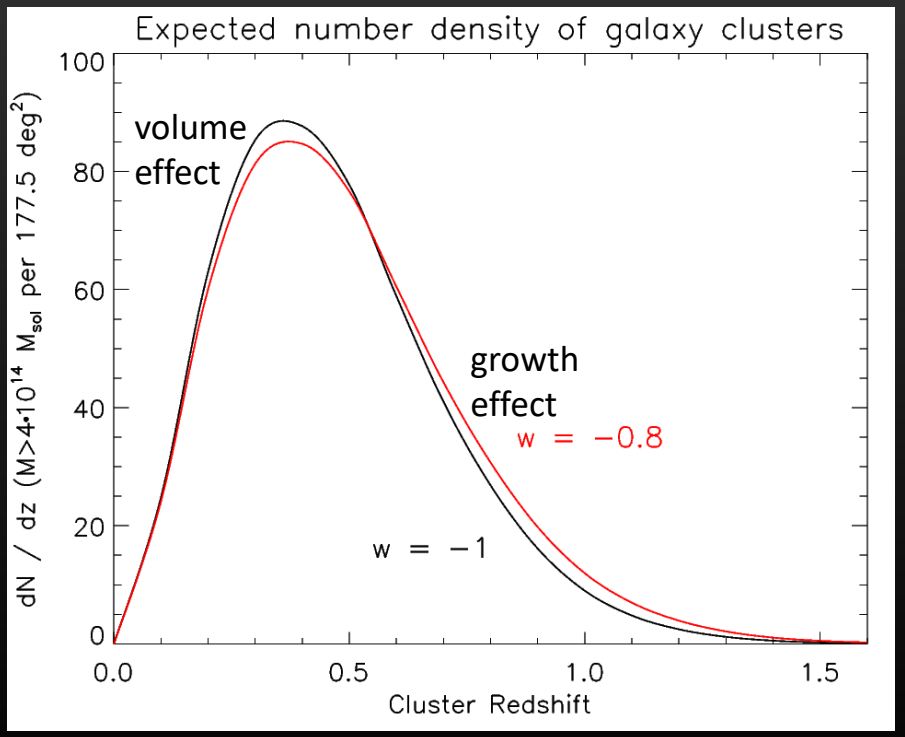


Figures from Carlstrom, Holder, Reese (2002)

Counting Galaxy Clusters

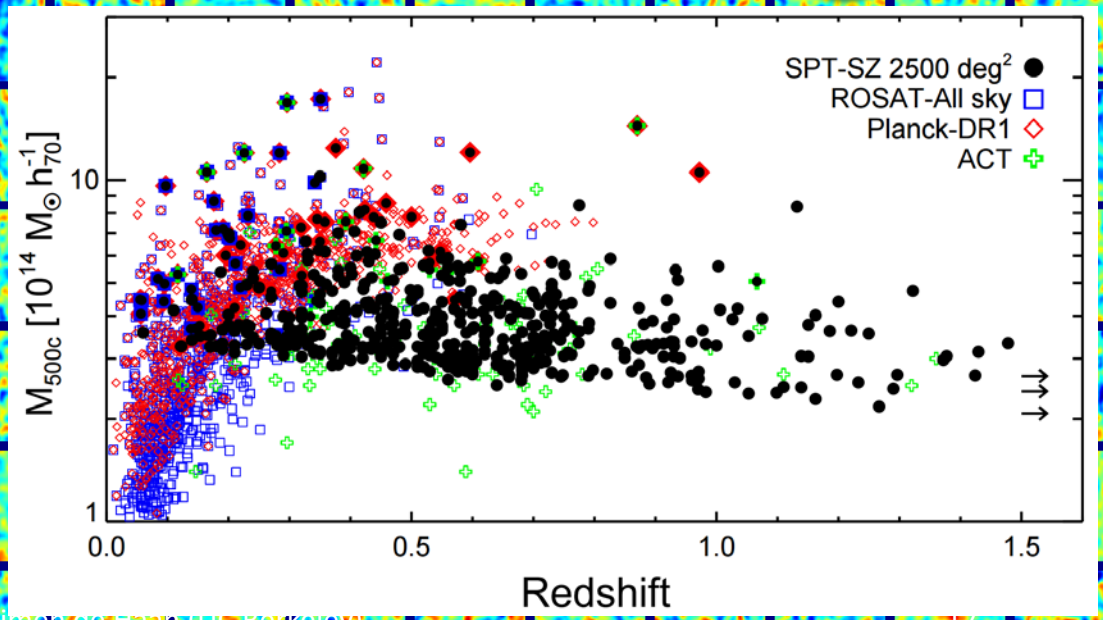
- Abundance as a function of mass and redshift ("mass function") is robustly predicted from N-body simulations
- Mass function is extremely sensitive to cosmological parameters
  - ΛCDM $\sigma_8(\Omega_M/0.27)^{0.3}$
  - Dark energy (w, w_a)
  - Neutrino Mass $\sum m_\nu$





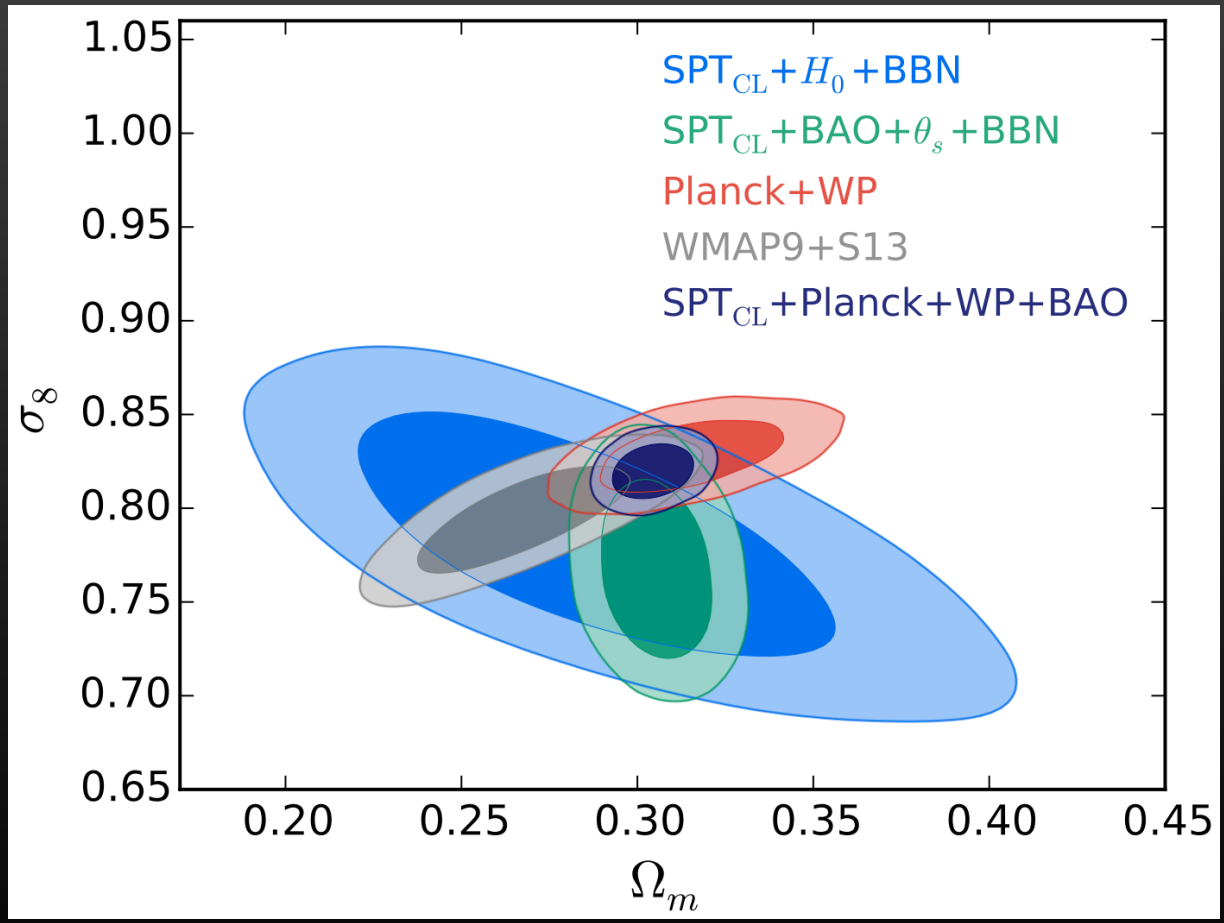
SPT-SZ Cluster Catalog

~400 clusters in cosmology sample (95% purity)



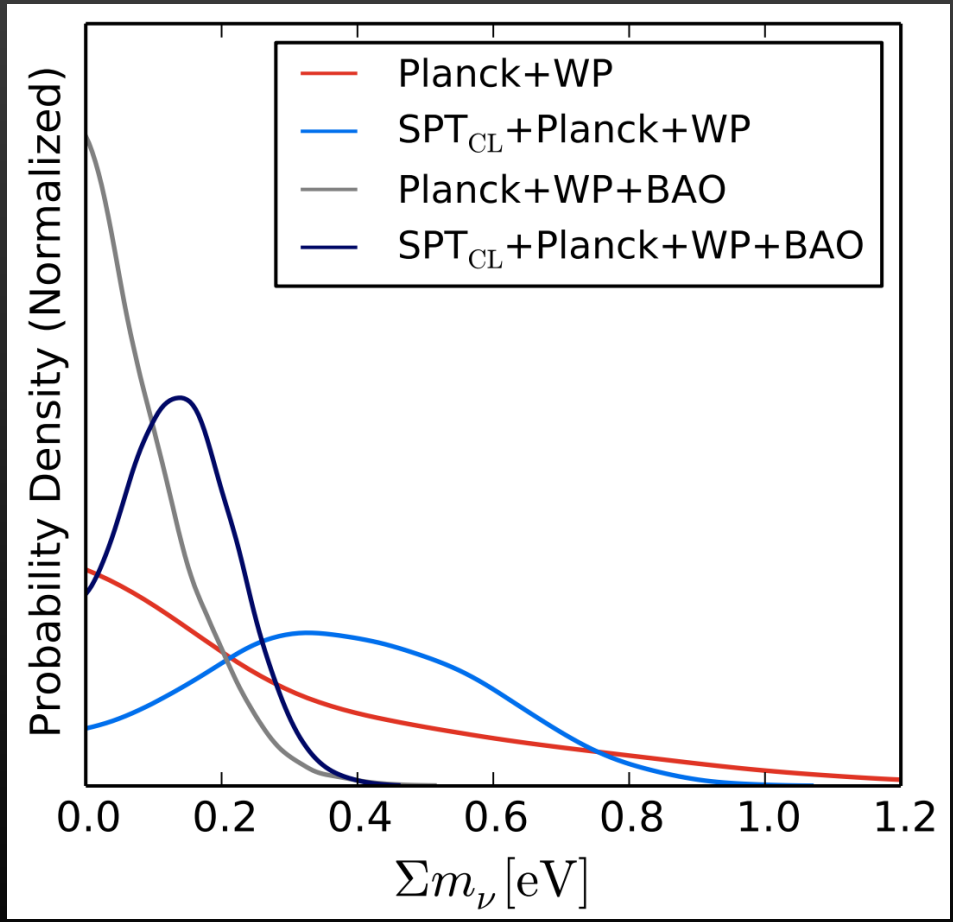
ΛCDM Results

- Consistent with ΛCDM parameters from CMB power spectrum measurements



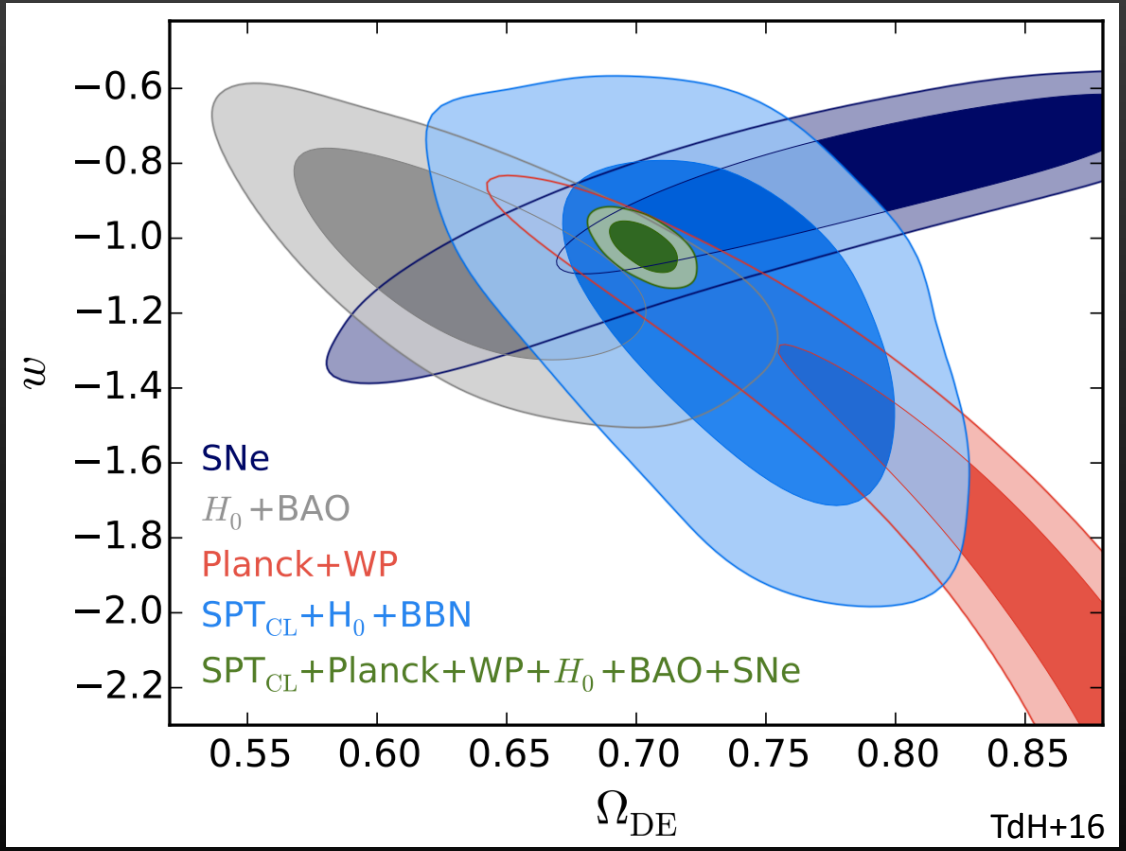
Constraints on the Species-summed Neutrino Mass

- Addition of cluster count information causes the posterior to peak at positive values
- Consistent with minimal allowed value of $\Sigma m_\nu = 0.06$ eV from atmospheric neutrino oscillation experiments

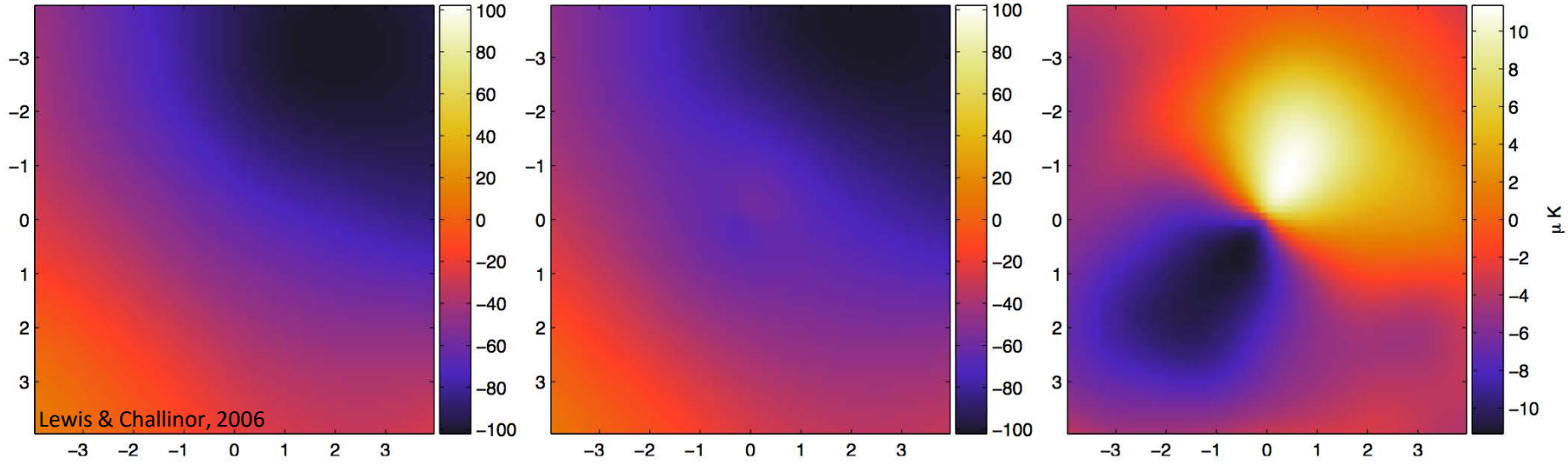


Dark Energy

- Consistent with other probes
- Clusters are a growth-based probe, providing a powerful complementary probe of dark energy
- Consistent with ΛCDM where $w = -1$
- Small, but non-negligible improvement (14%) on w from $\sigma_8 - w$ degeneracy breaking



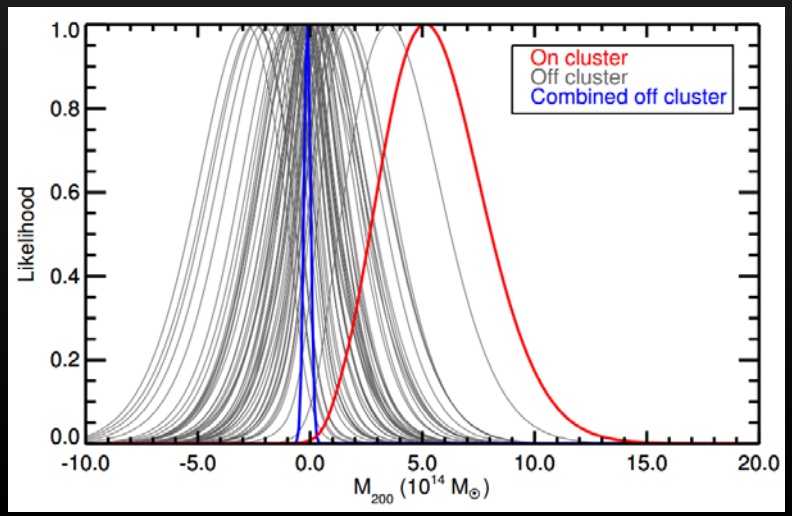
CMB-halo lensing will enable the next generation of cluster cosmology (e.g. with SPT-3G)

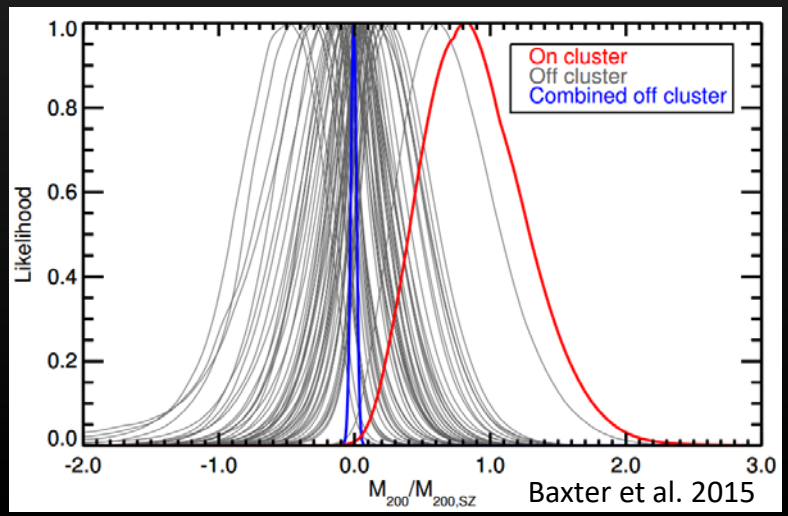


Unlensed CMB

Lensed CMB

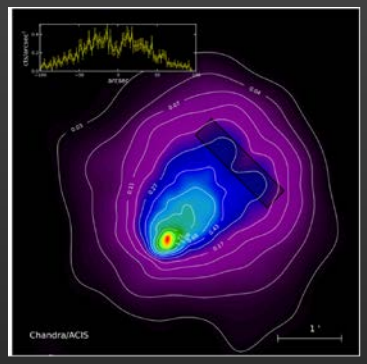
Difference

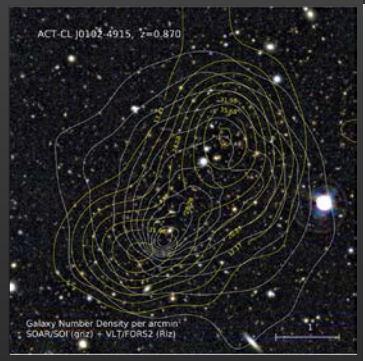




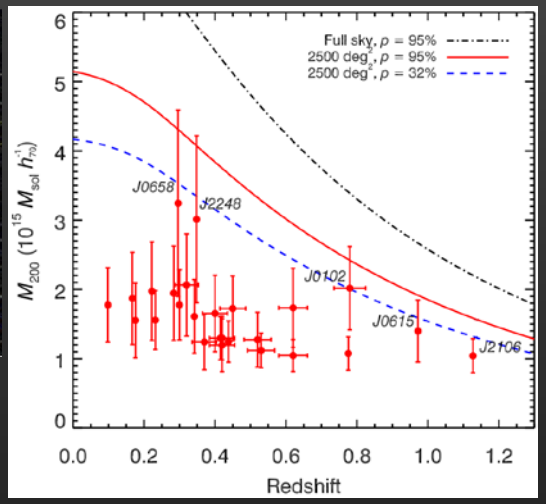
Baxter et al. 2015

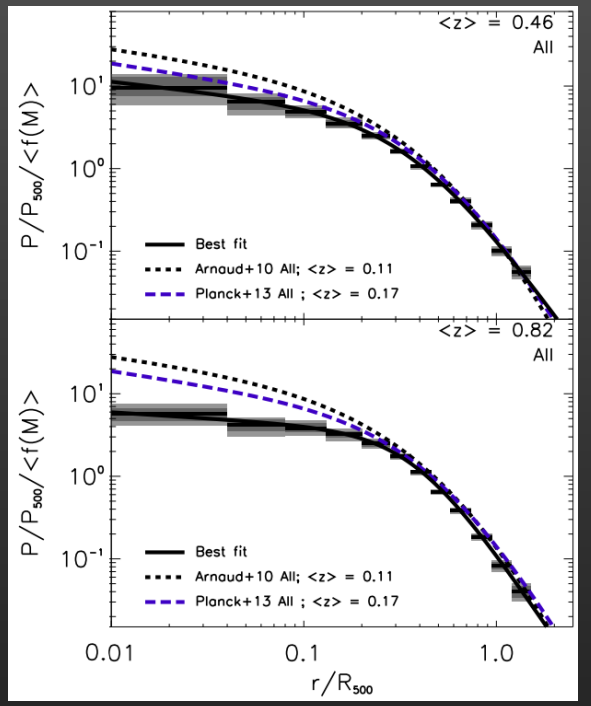
More Cluster Science



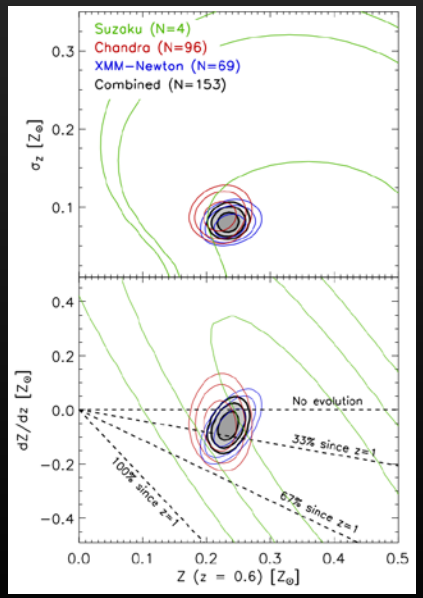


ACT-CL/SPT-CL J0102-4915: "El-Gordo": under ΛCDM, only 1% chance of finding such an extreme/rare cluster in the 2500 square degree SPT-SZ survey





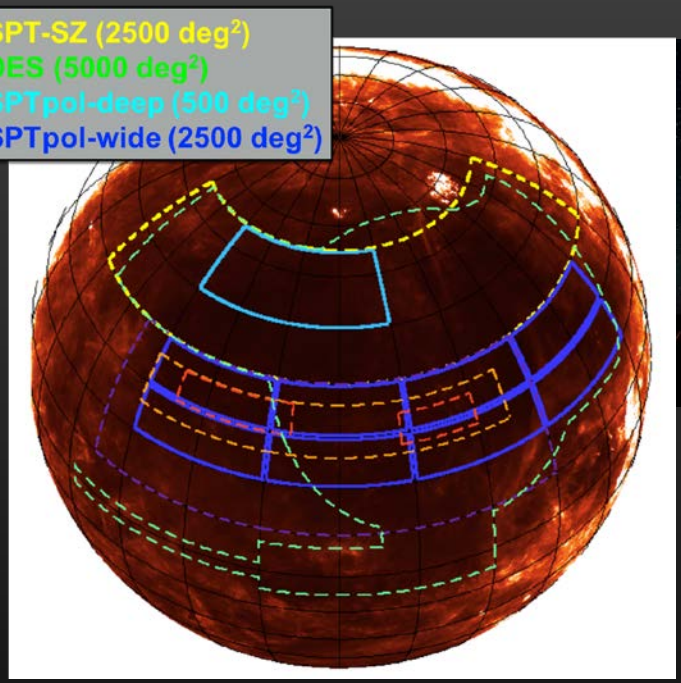
Cluster pressure profiles (McDonald+14)



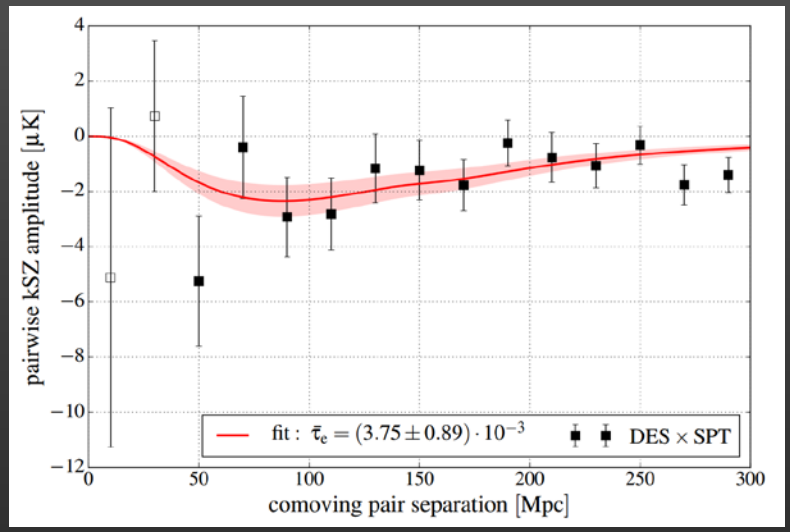
Constraints on average cluster metallicity , its evolution with redshift, and its intrinsic scatter (McDonald+16)

- Aside from cluster counting cosmology, lots of cluster science with SPT+follow-up data
- Not shown: cool cores, X-ray morphology, fine structure constant evolution, the Phoenix cluster, etc., etc.
- More coming: tests of GR through the growth of structure, cluster pressure profiles out to large radius from SZ data, AGN populations, etc.

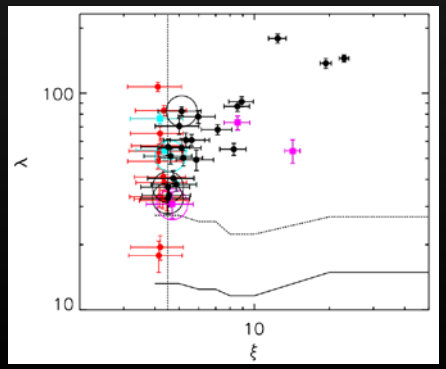
Cross-correlation science with e.g. DES



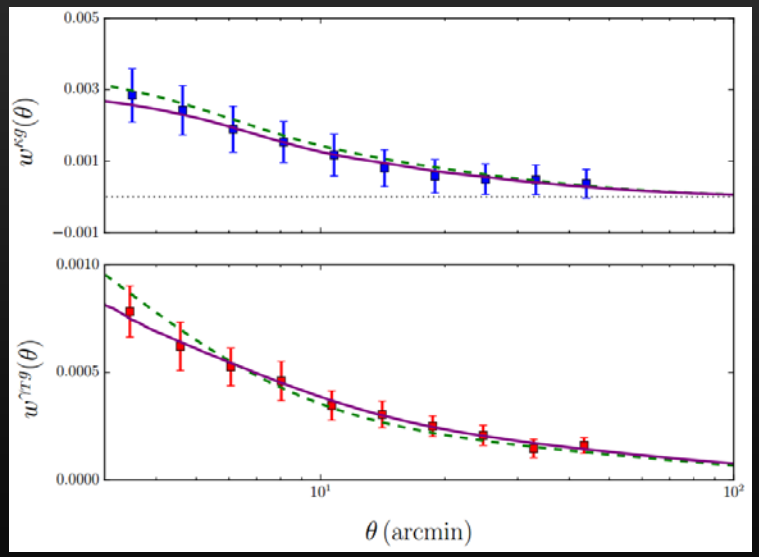
Excellent overlap (3200 square degrees) between the Dark Energy Survey and SPT footprints



Pairwise estimator uses 3D DES cluster catalog to measure kSZ signal in SPT maps: sensitive to total electron density and could be used as a test of gravity on large scales (Soergel+16)



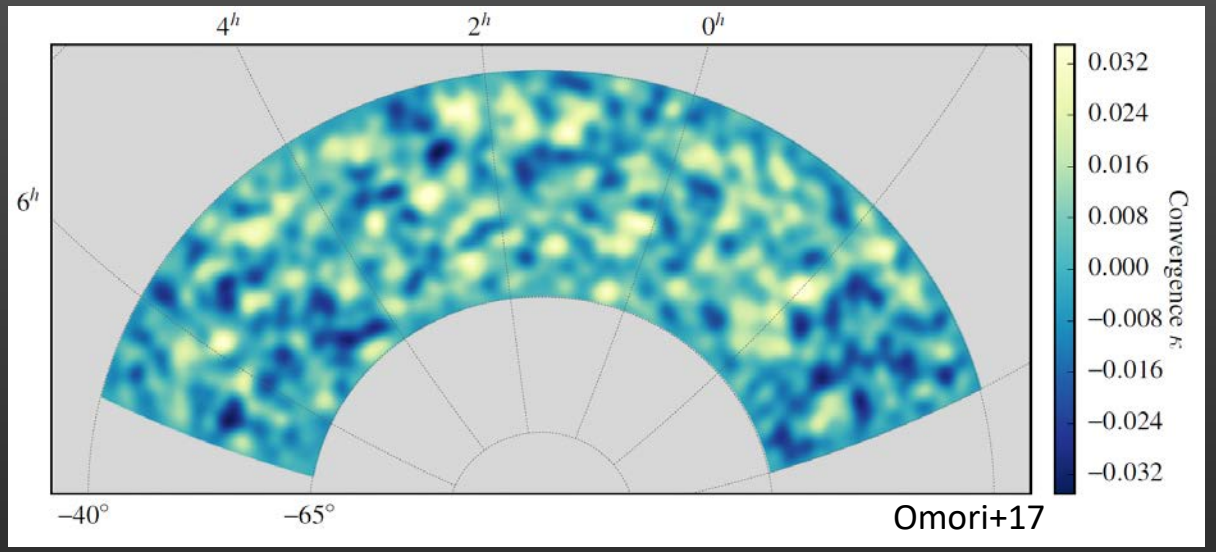
Use SPT scaling relations to calibrate DES observables e.g. cluster richness (Saro+15)



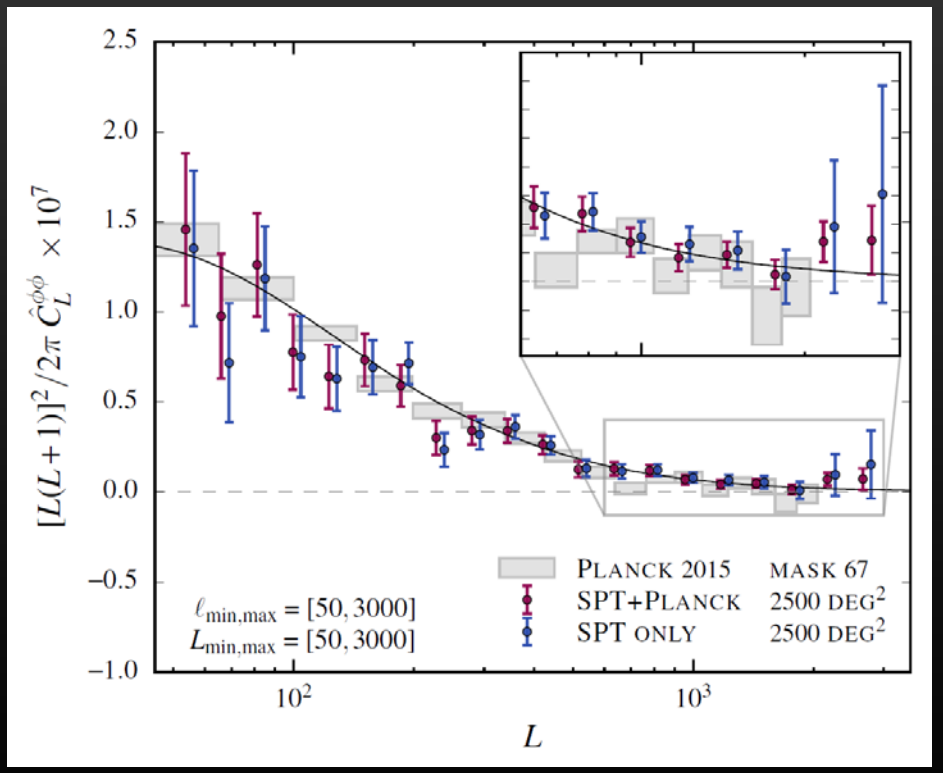
Use CMB lensing map to weigh DES galaxies (Baxter+16). Will CMB lensing provide the ultimate shear calibration for optical surveys?

CMB Lensing

- S/N>1 CMB lensing map of the 2D κ field (integrated mass in the universe)
- Improved lensing power spectrum over Planck at $\ell > 1000$
- Useful for cross-correlation analyses



Omori+17



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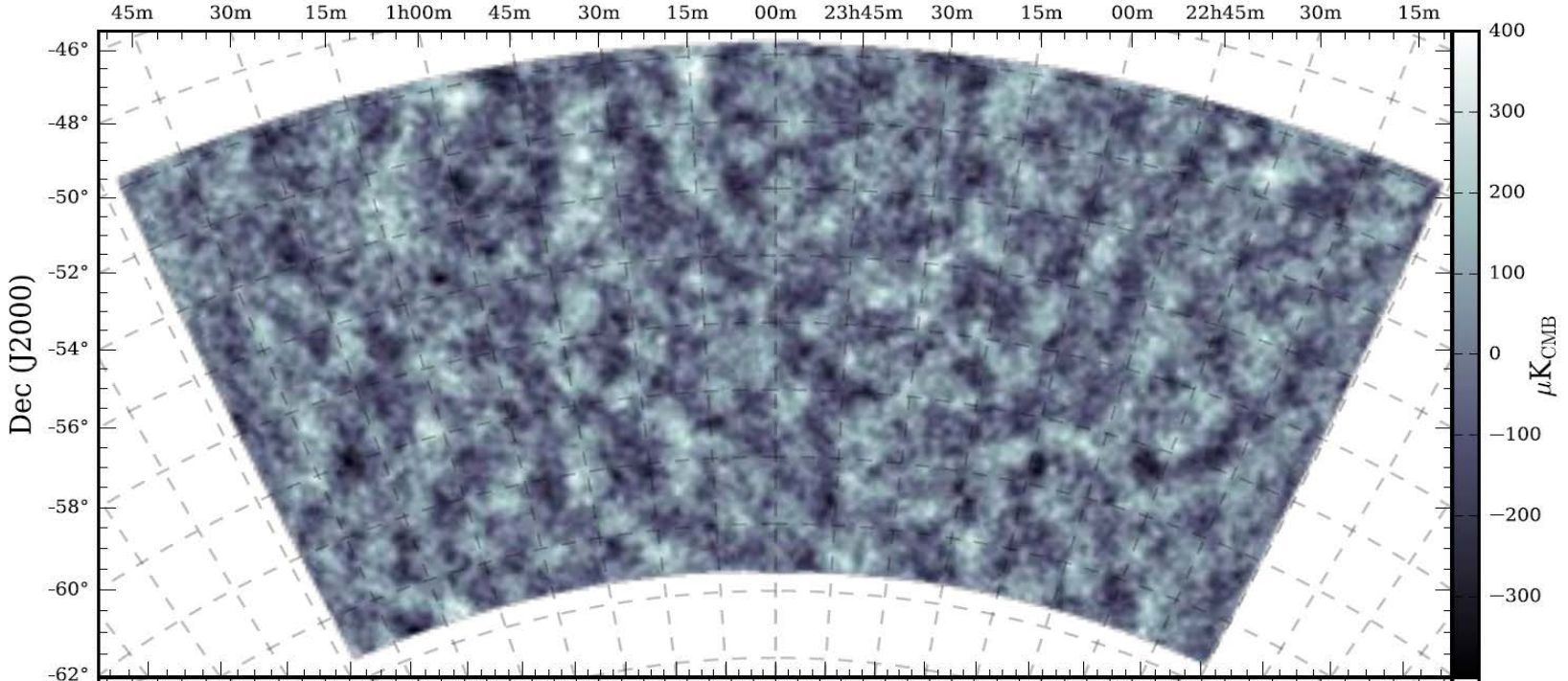
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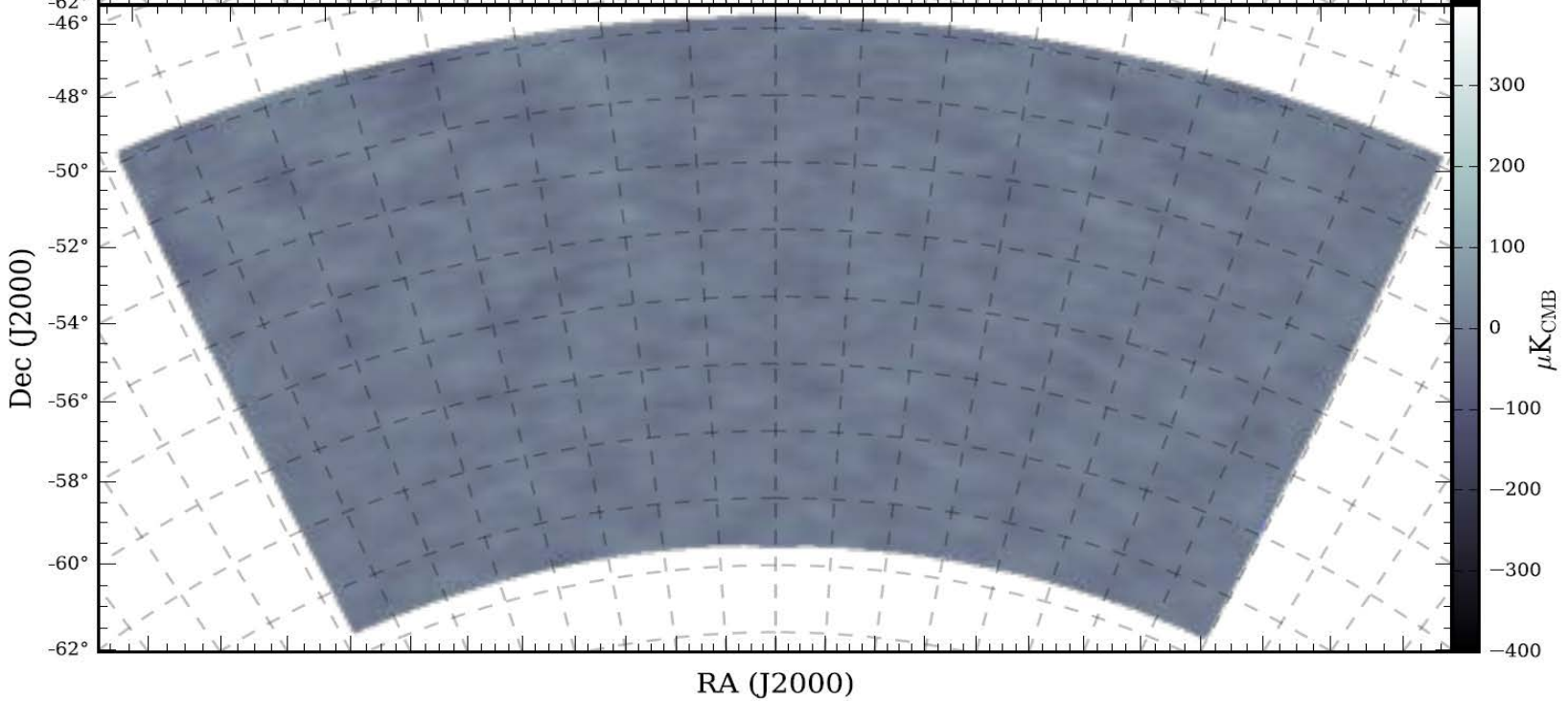
μK_{CMB}

Noise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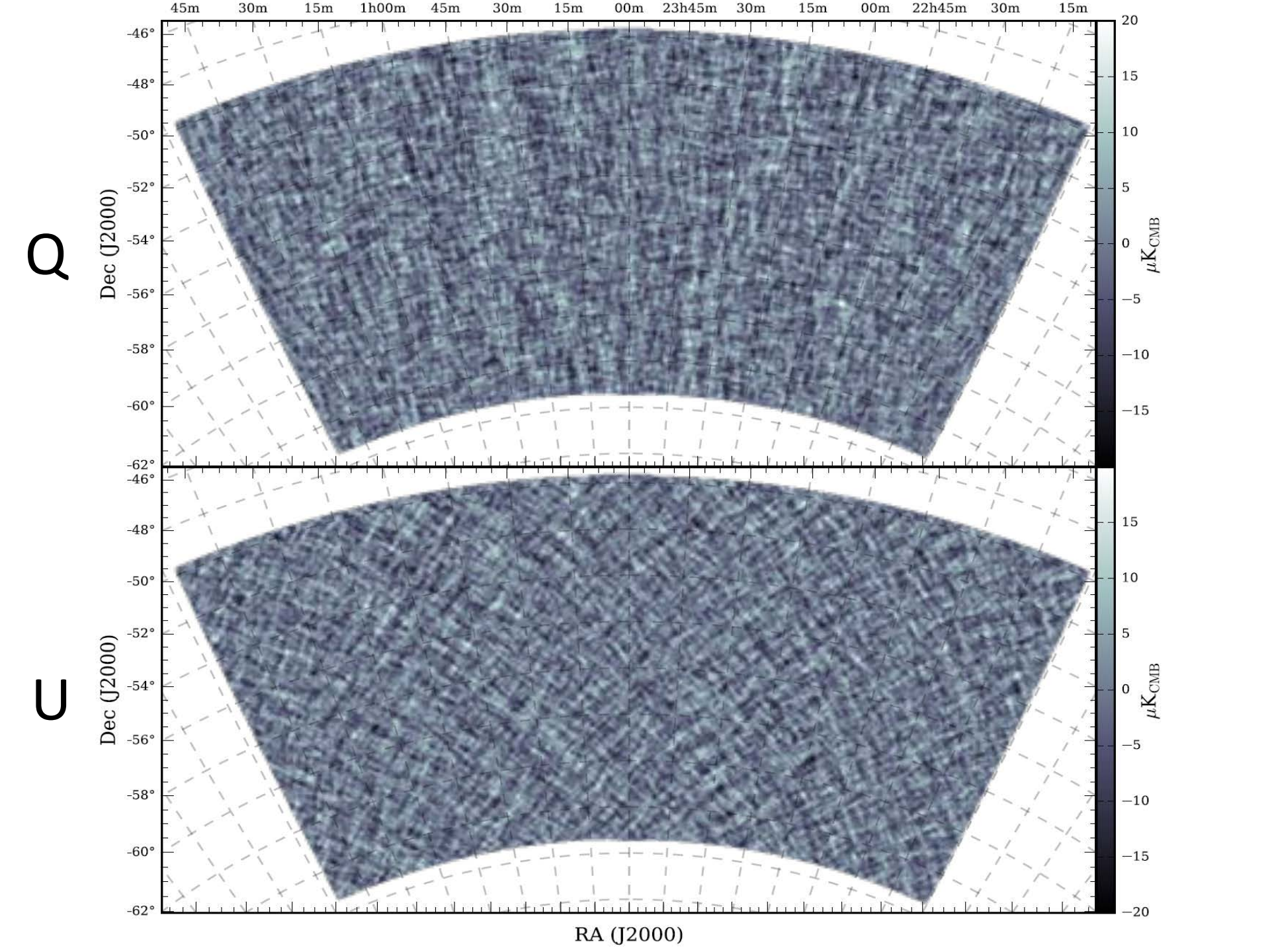
μK_{CMB}
RA (J2000)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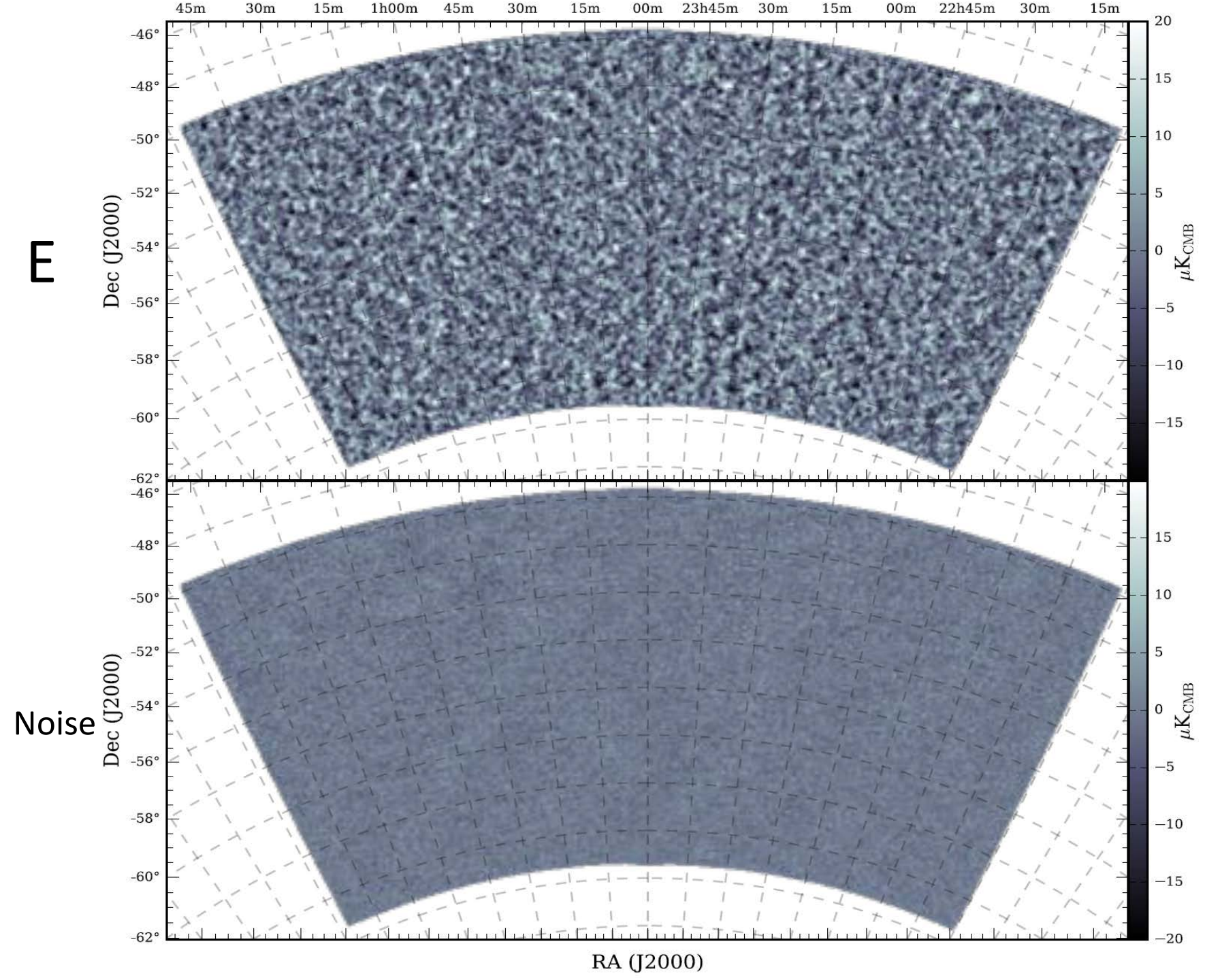
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Noise
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Dec (J2000)
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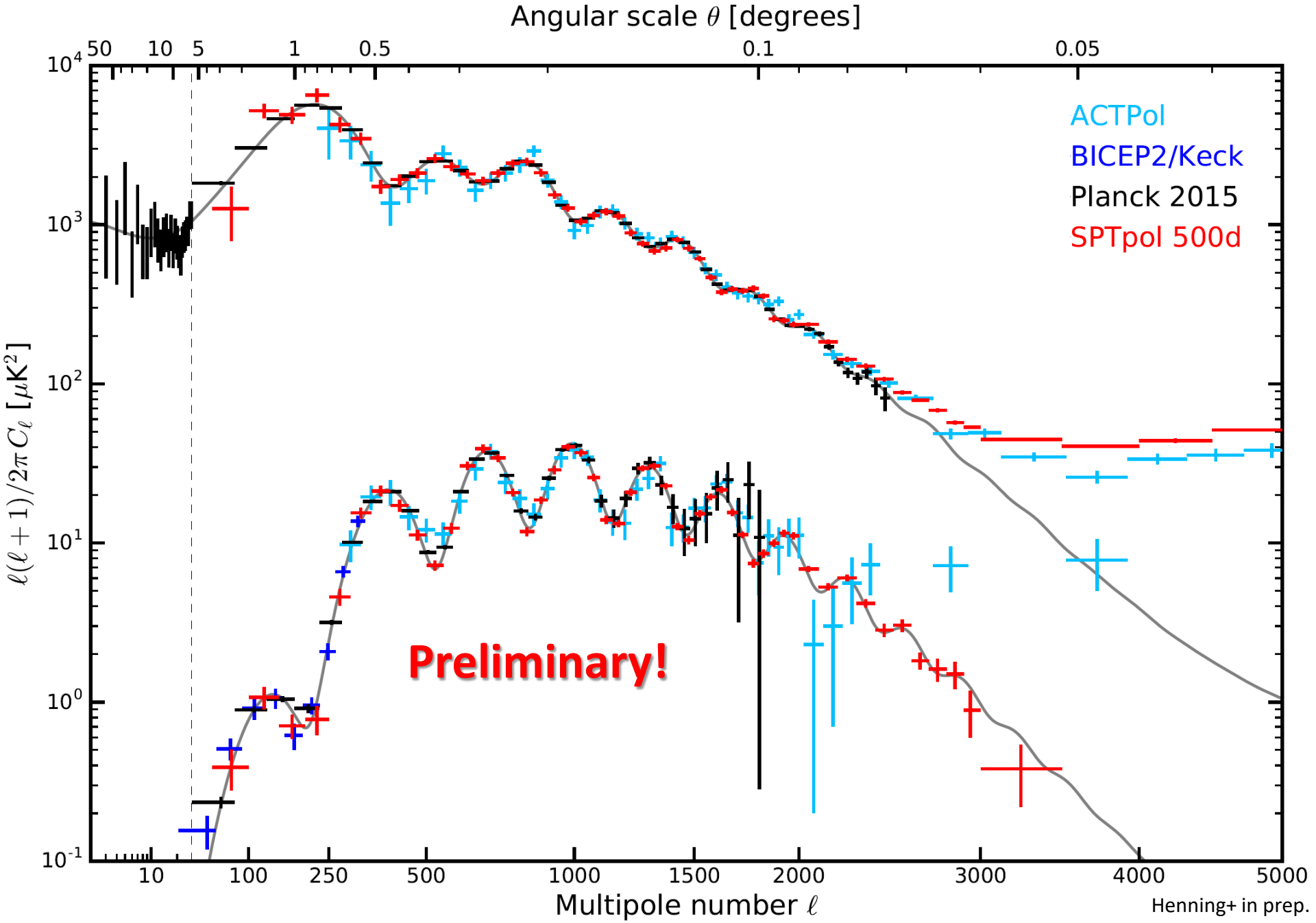
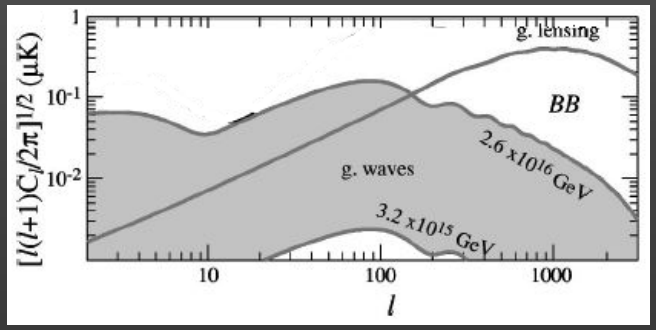
−20
μK_{CMB}

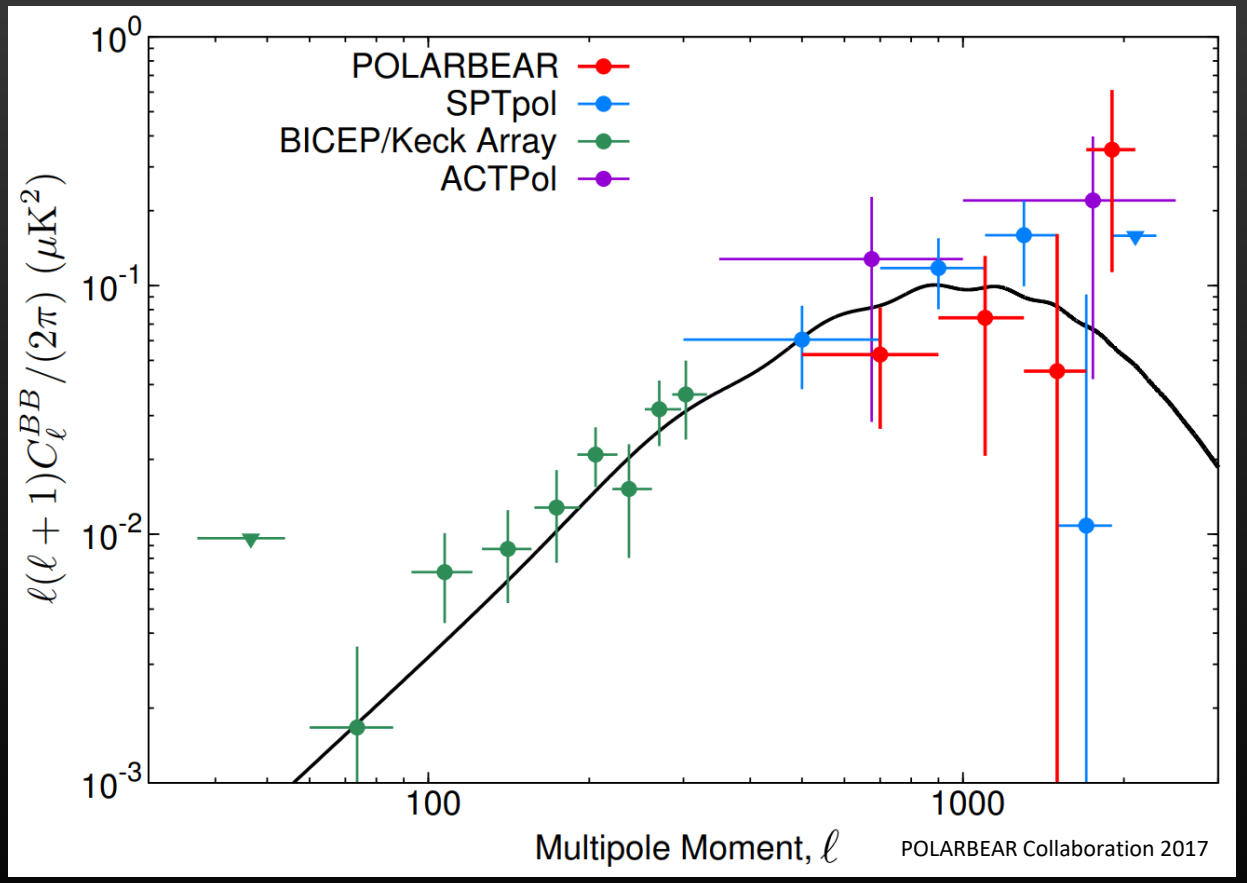

Angular scale θ [degrees]
50
10
5
1
0.5
0.1
0.05
ACTPol
BICEP2/Keck
Planck 2015
SPTpol 500d
Preliminary!
$\ell(\ell+1)/2\pi C_\ell$ [μK^2]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10
100
250
500
1000
1500
2000
3000
4000
5000
Multipole number ℓ
Henning+ in prep.

B-mode Polarization



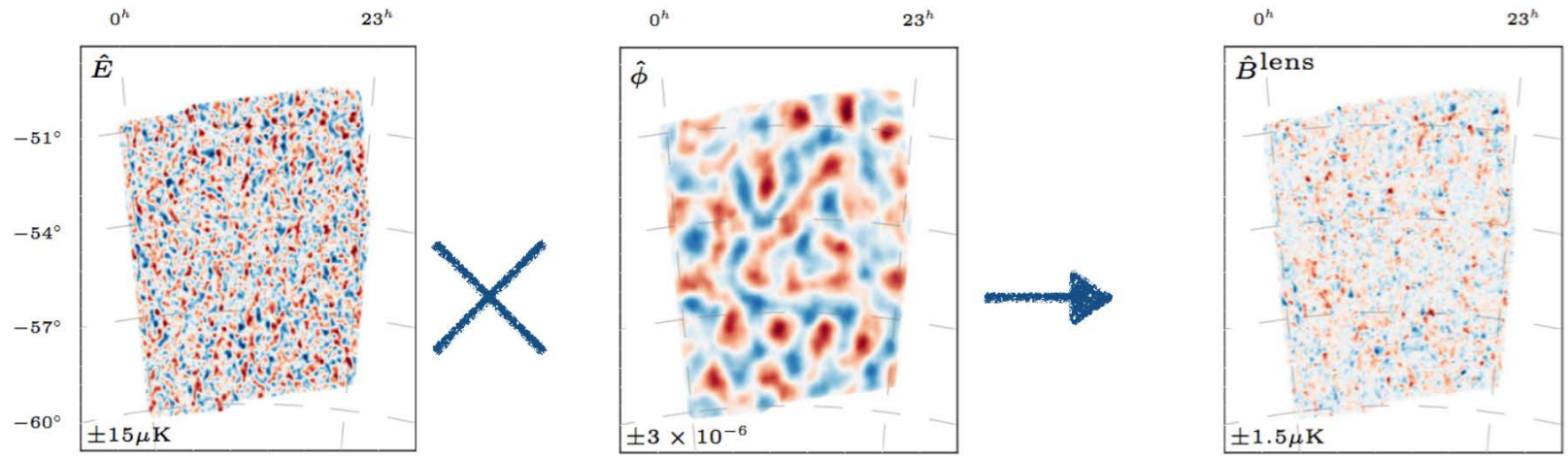
Adapted from Hu03

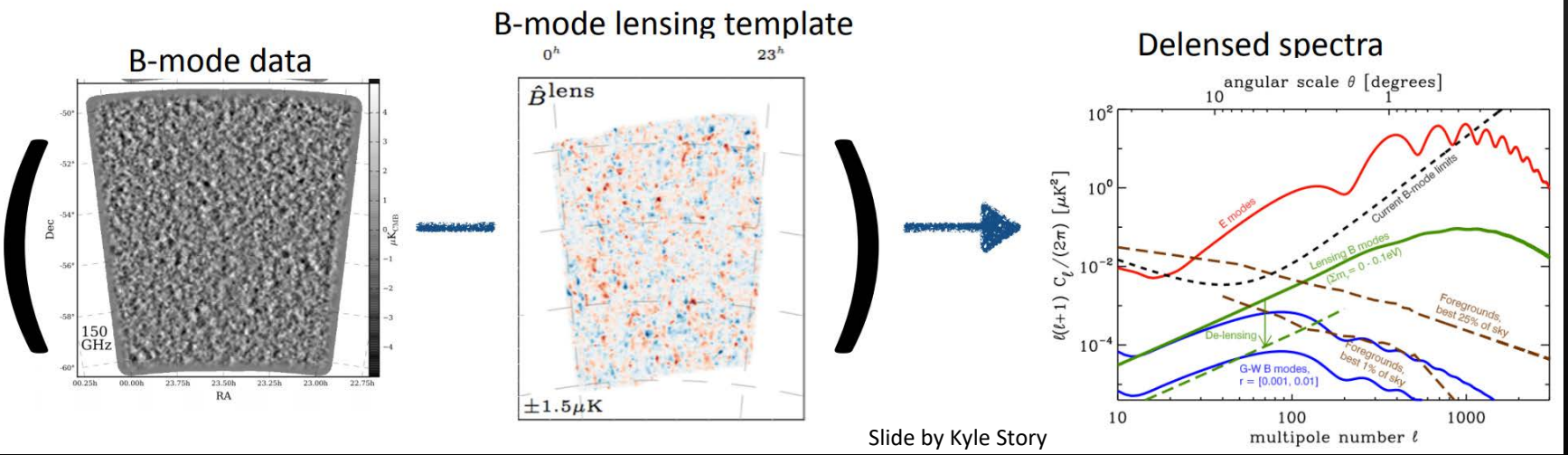
- High-ell B-modes sourced by lensing
  - Best constraints from SPTpol Deep ->
  - SPTpol main survey analysis in progress
- Low-ell B-modes sourced by primordial gravitational waves
  - SPTpol main survey analysis in progress



POLARBEAR Collaboration 2017

Delensing

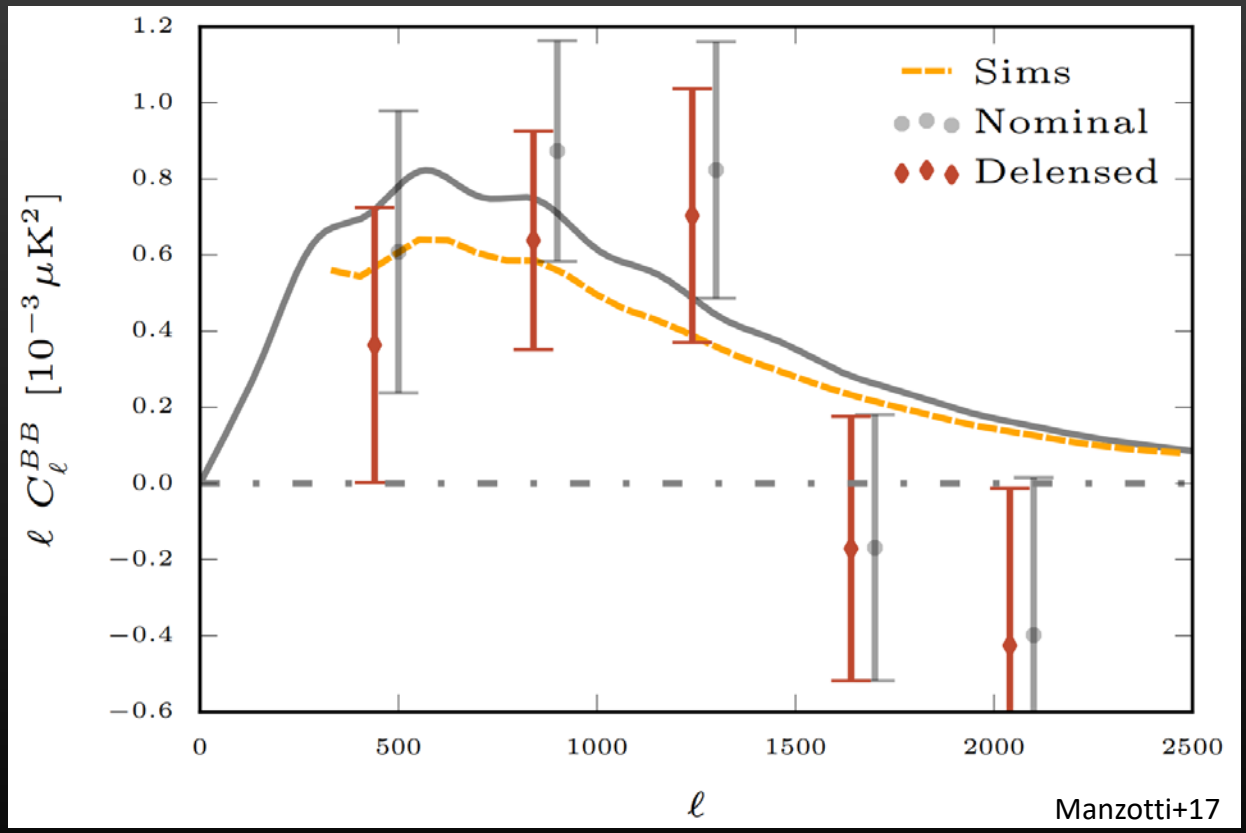




Slide by Kyle Story

Delensing: proof of concept with SPTpol

- It works (6.9 σ)
- 28% reduction of B-mode power



Manzotti+17

Summary

- SPT is performing an amazingly broad spectrum of astrophysics and cosmology
- Cluster cosmology: improved constraints on ΛCDM and extensions involving dark energy and neutrinos
  - Big improvements expected from SPT-3G: an order of magnitude more clusters and precise CMB-halo lensing
- CMB power spectrum (TT, TE, EE, BB, lensing)
- Cross-correlation science
- Inflation science with BB power spectrum + delensing