CMB Probes of LSS: Lensing & SZ

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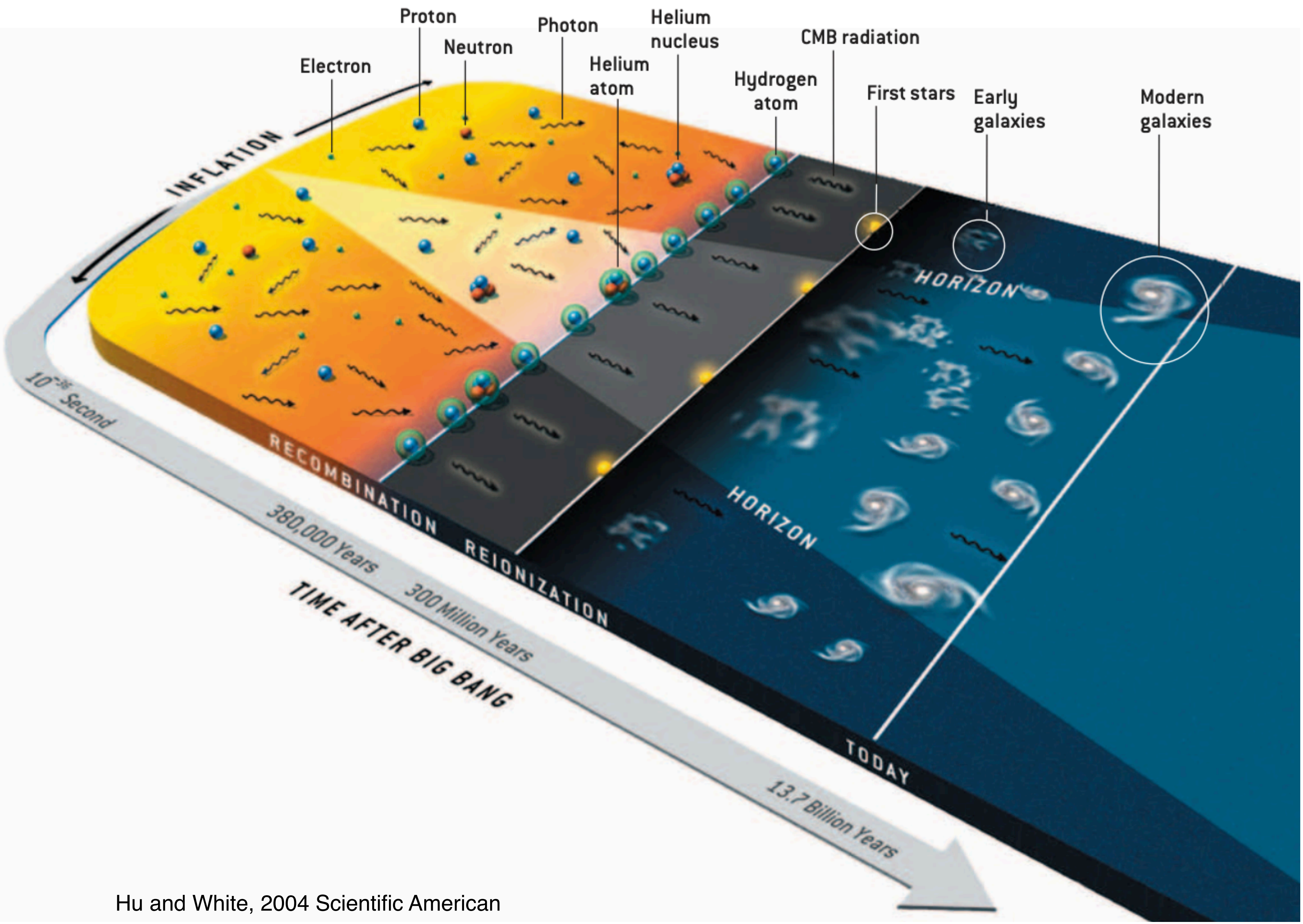
Outline

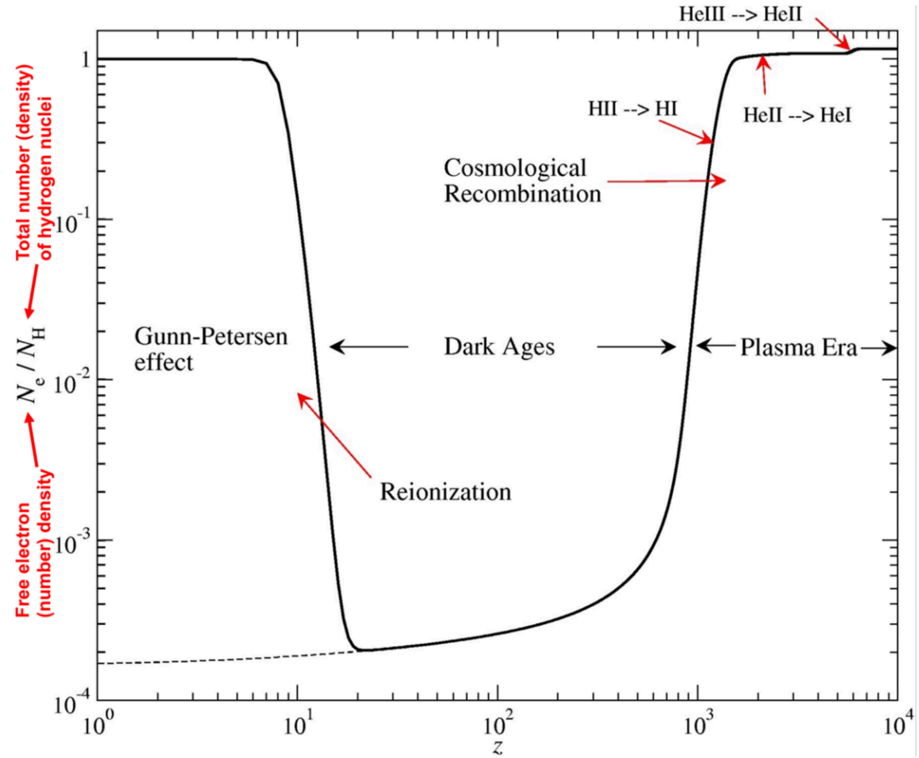
- the “surface of last scattering” is actually not the final word for lots of photons
  - ⋆ Thomson scattering
  - ⋆ lensing
  - ⋆ extragalactic foregrounds



Hu and White, 2004 Scientific American

Ionization non-equilibrium

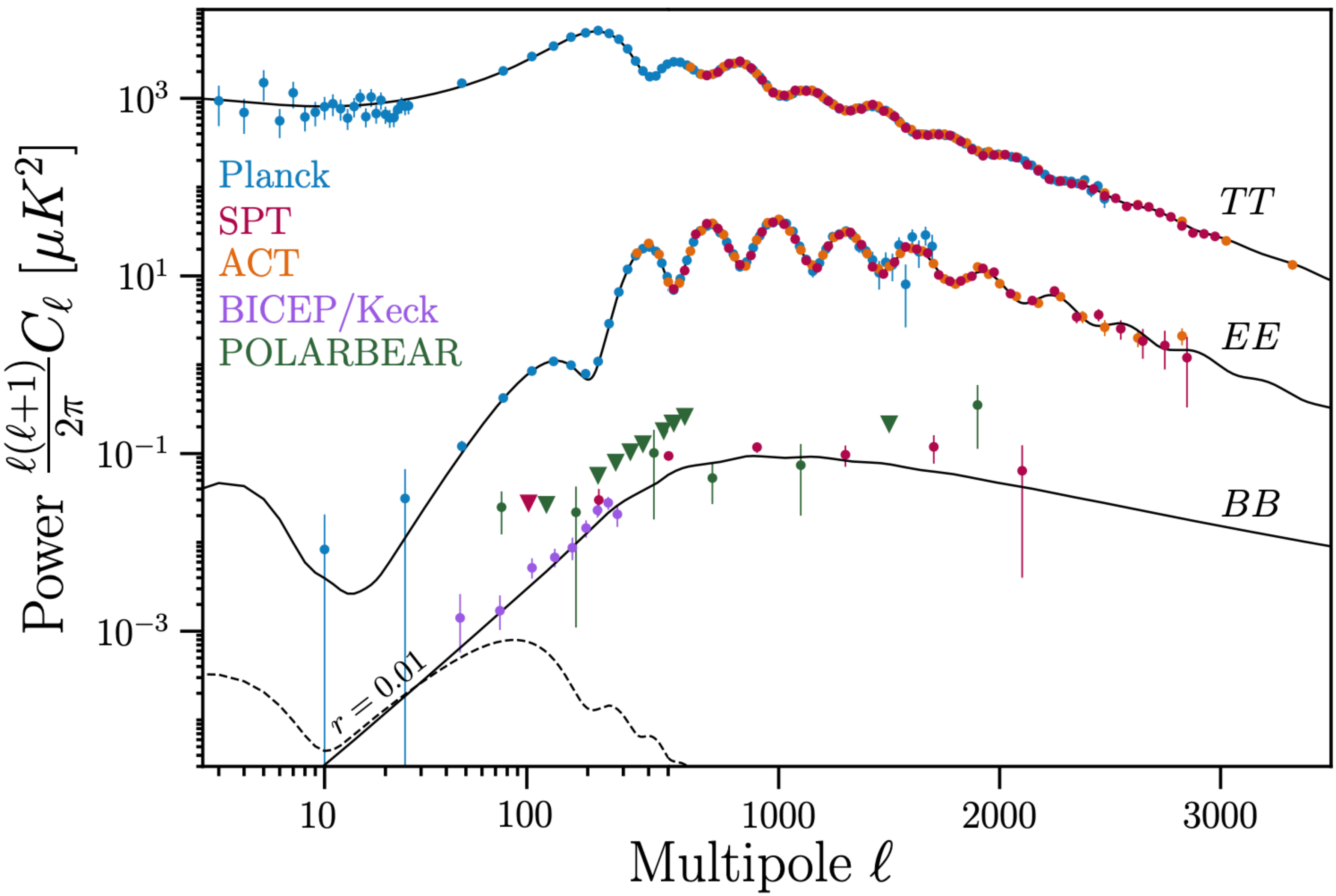
Hubble expansion causes recombinations to "freeze out" as e- and p+ can't find each other in the dilute universe



small residual ionization keeps gas and CMB thermally coupled for a surprisingly long time

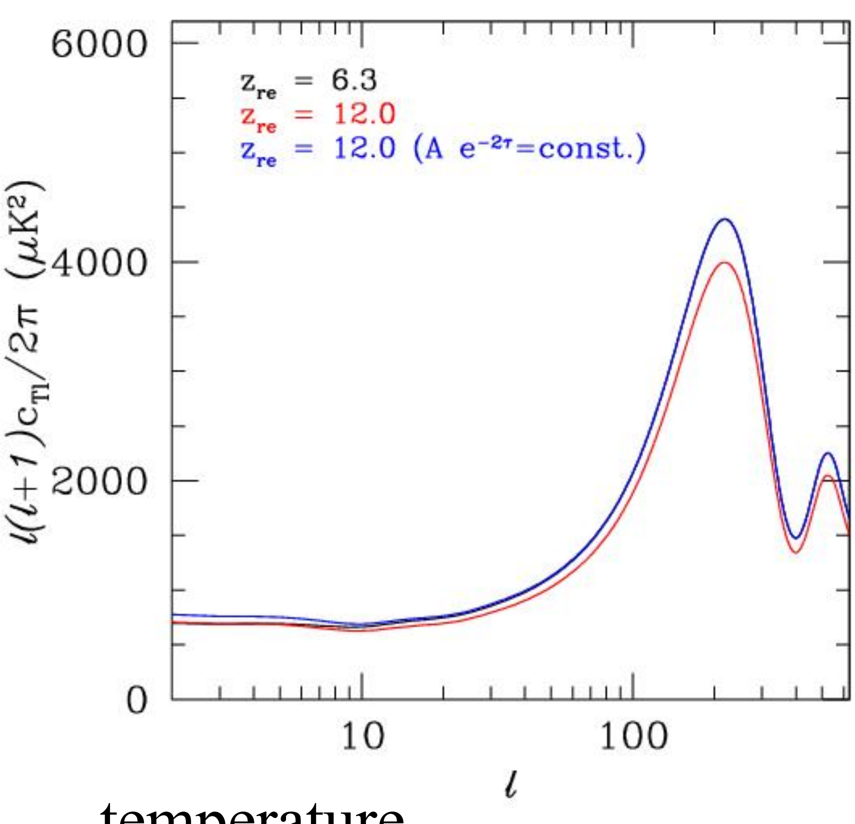
Sunyaev & Chluba 2009

reionization leads to unbinding of electrons from H atoms due to UV background ionizing field

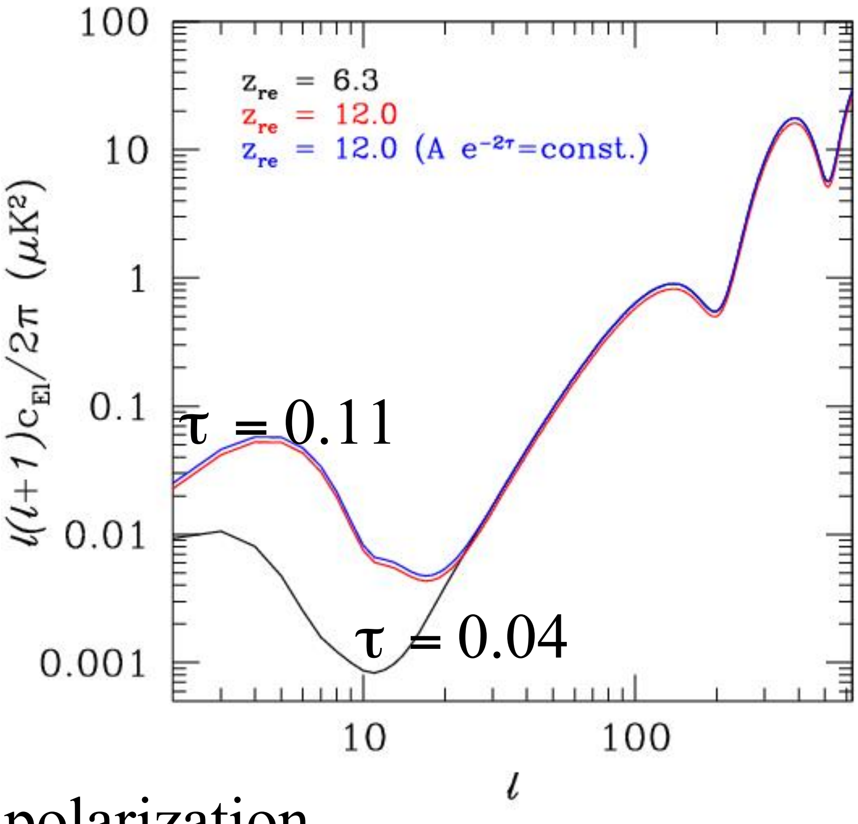


Snowmass CMB Measurements white paper 2203.07638

WMAP: +- 0.015 ; Planck: +-0.005 ; ???: +-0.002



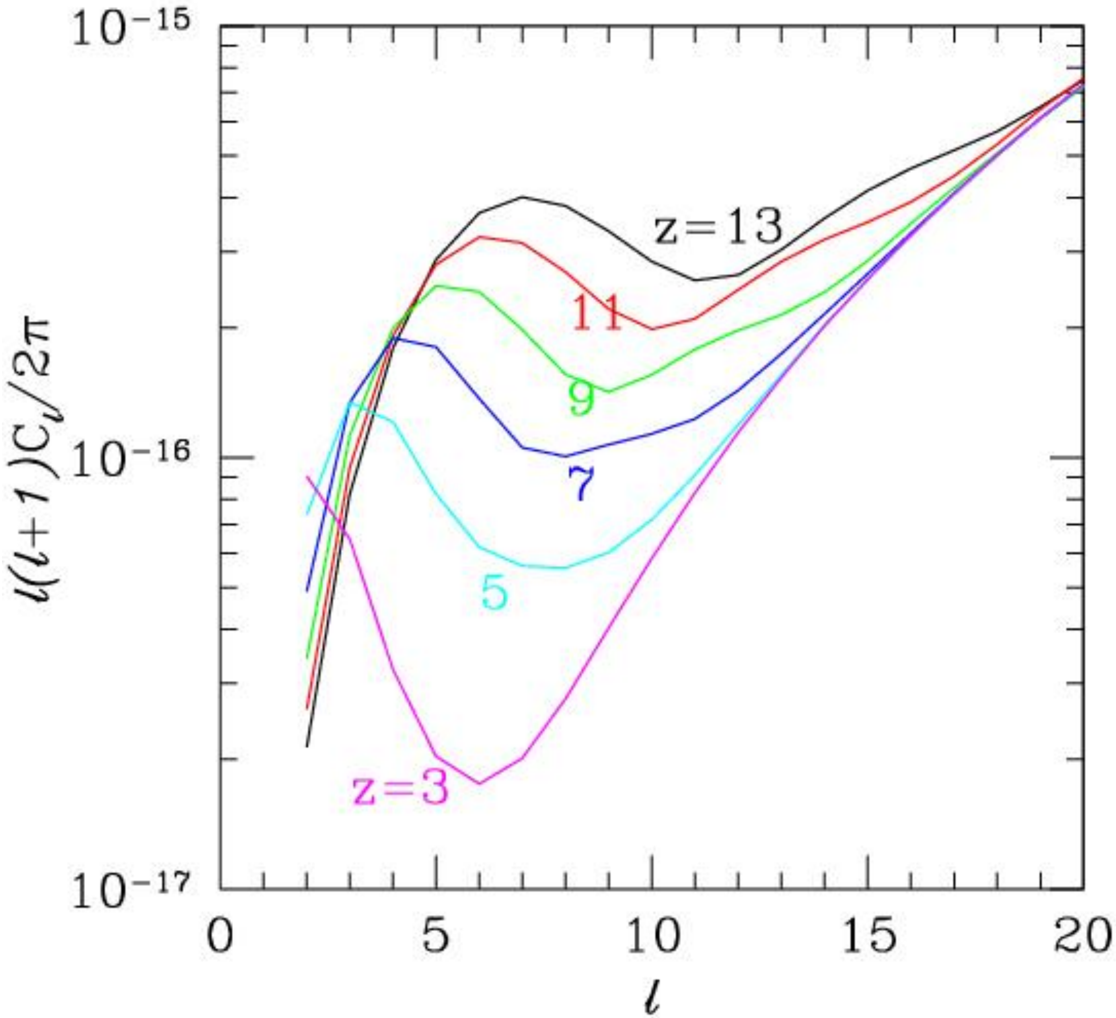
temperature



polarization

Ionization and CMB Polarization

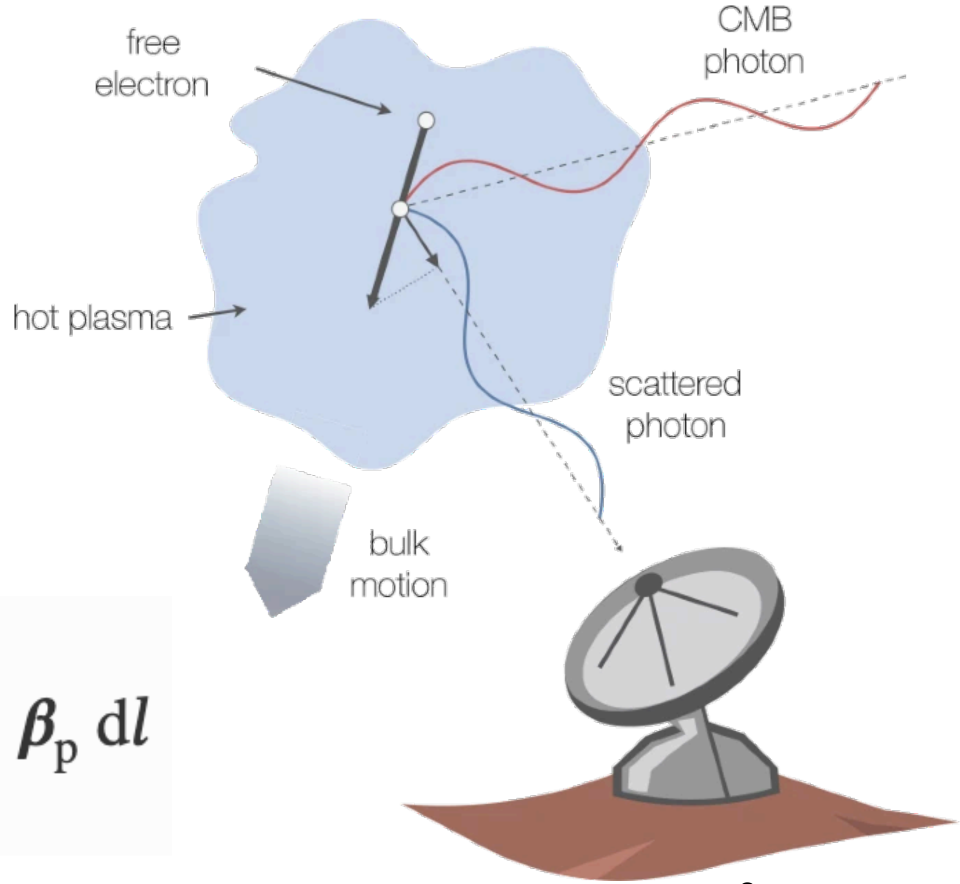
“Pulse” of ionization dz=1



Scattering on moving electrons: kSZ

- kinetic Sunyaev-Zeldovich effect: Thomson scattering by bulk flow of electrons

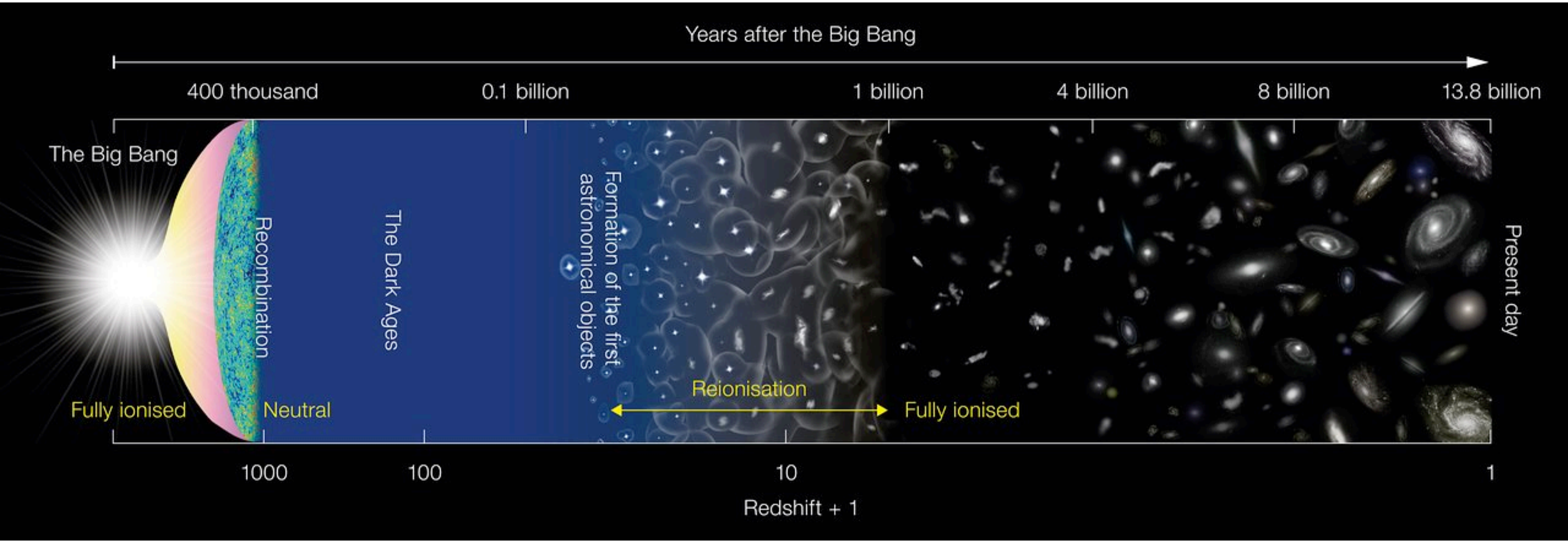
$$\frac{\Delta T_{\rm CMB}}{T_{\rm CMB}} \approx -\int \sigma_{\rm T} n_{\rm e}\, n \cdot \boldsymbol{\beta}_{\rm p}\, {\rm d}l$$



Mroczkowski et al 2019

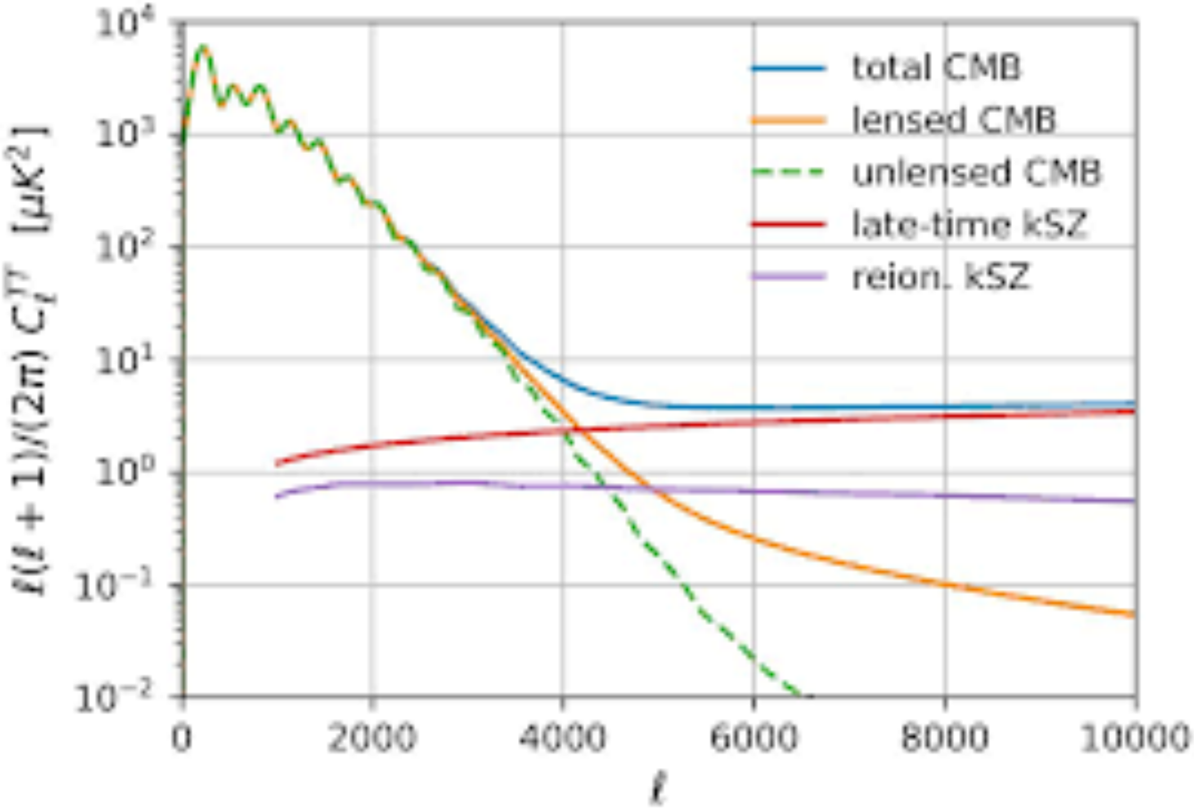
Scattering on moving electrons: kSZ

clumps of moving electrons at reionization, and at late times



ESA

Scattering on moving electrons: kSZ



Madhavacheril

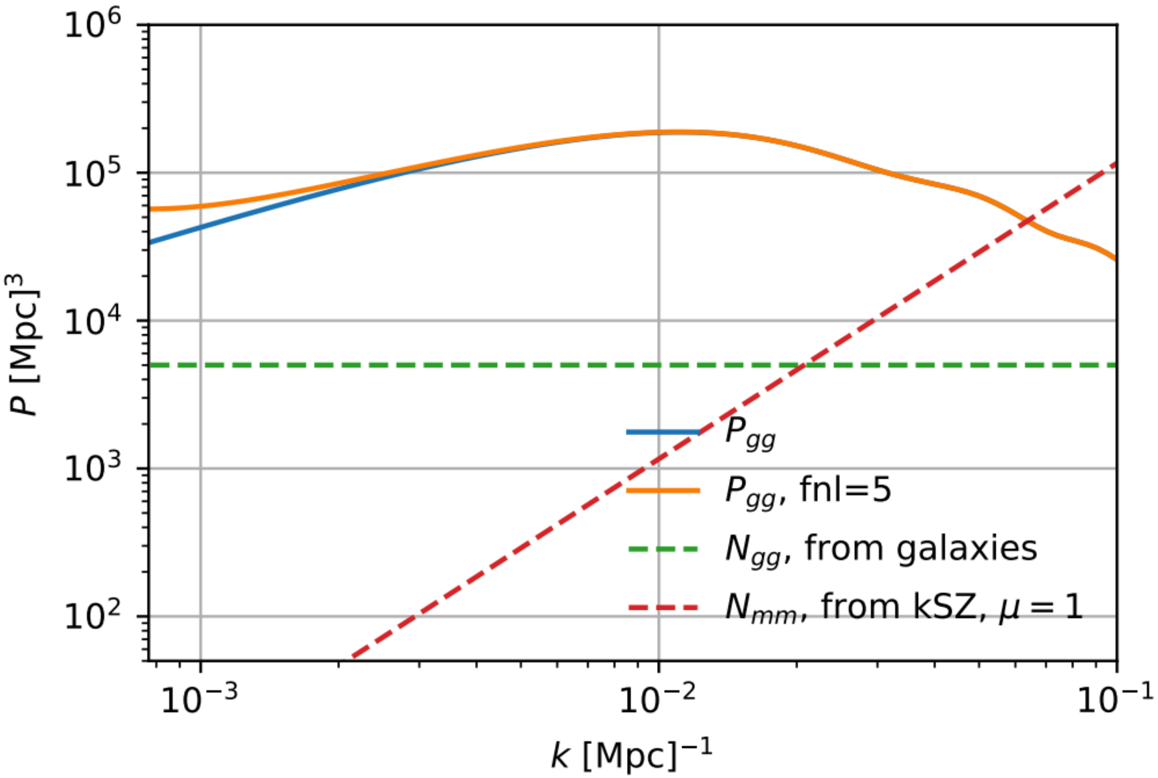
Scattering on moving electrons: kSZ

current status:

detected in cross-correlation with galaxies/clusters

forecast:

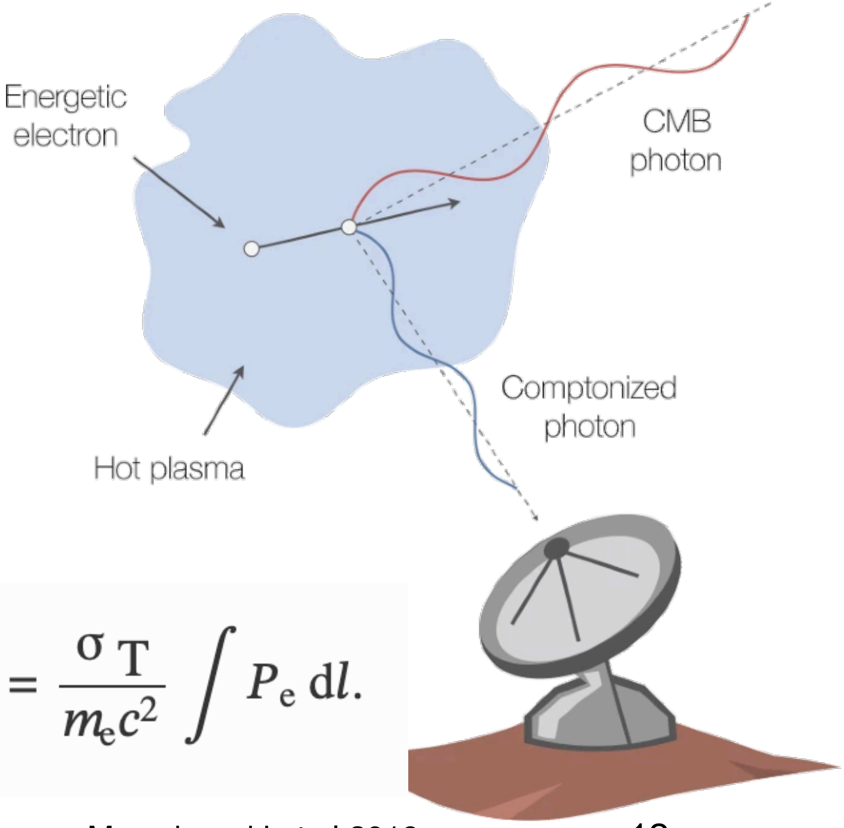
soon to be detected in auto-spectrum, higher order correlations could be very powerful for largest scales



Munchmeyer et al 2018

Scattering on moving electrons: tSZ

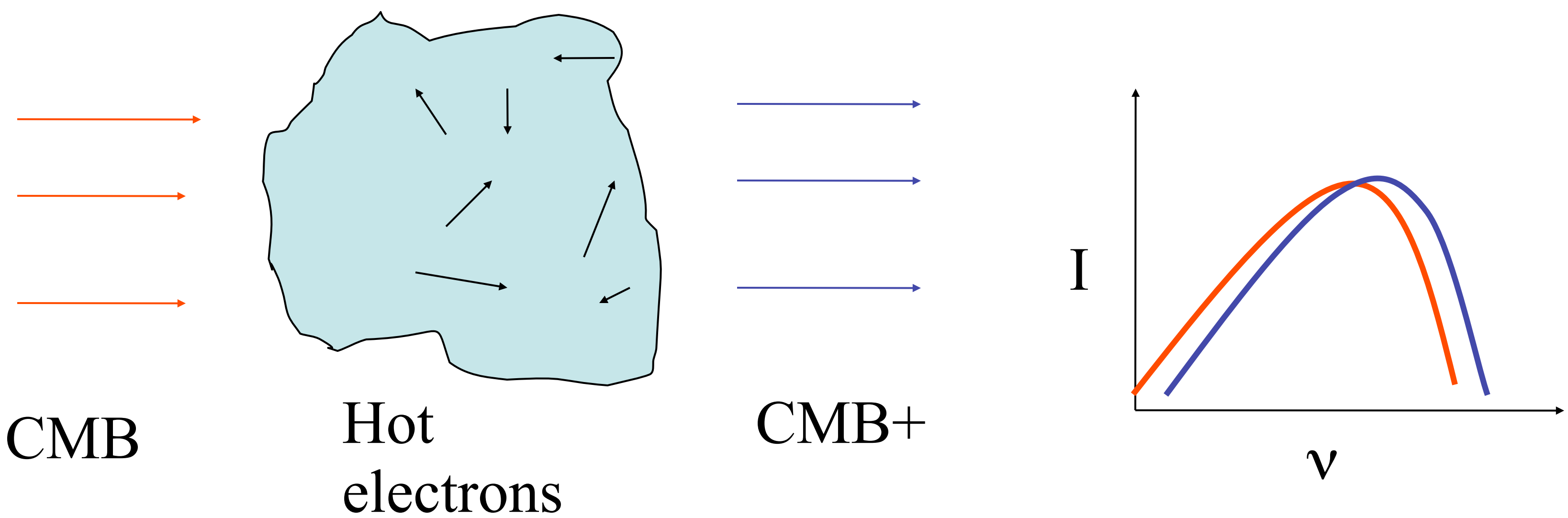
- thermal Sunyaev-Zeldovich effect: Thomson scattering by thermal motions of electrons



$$y \equiv \int \frac{k_B T_e}{m_e c^2} \, d\tau_e = \int \frac{k_B T_e}{m_e c^2} n_e \sigma_T dl = \frac{\sigma_T}{m_e c^2} \int P_e \, dl.$$

Mroczkowski et al 2019

Thermal Sunyaev-Zel'dovich Effect



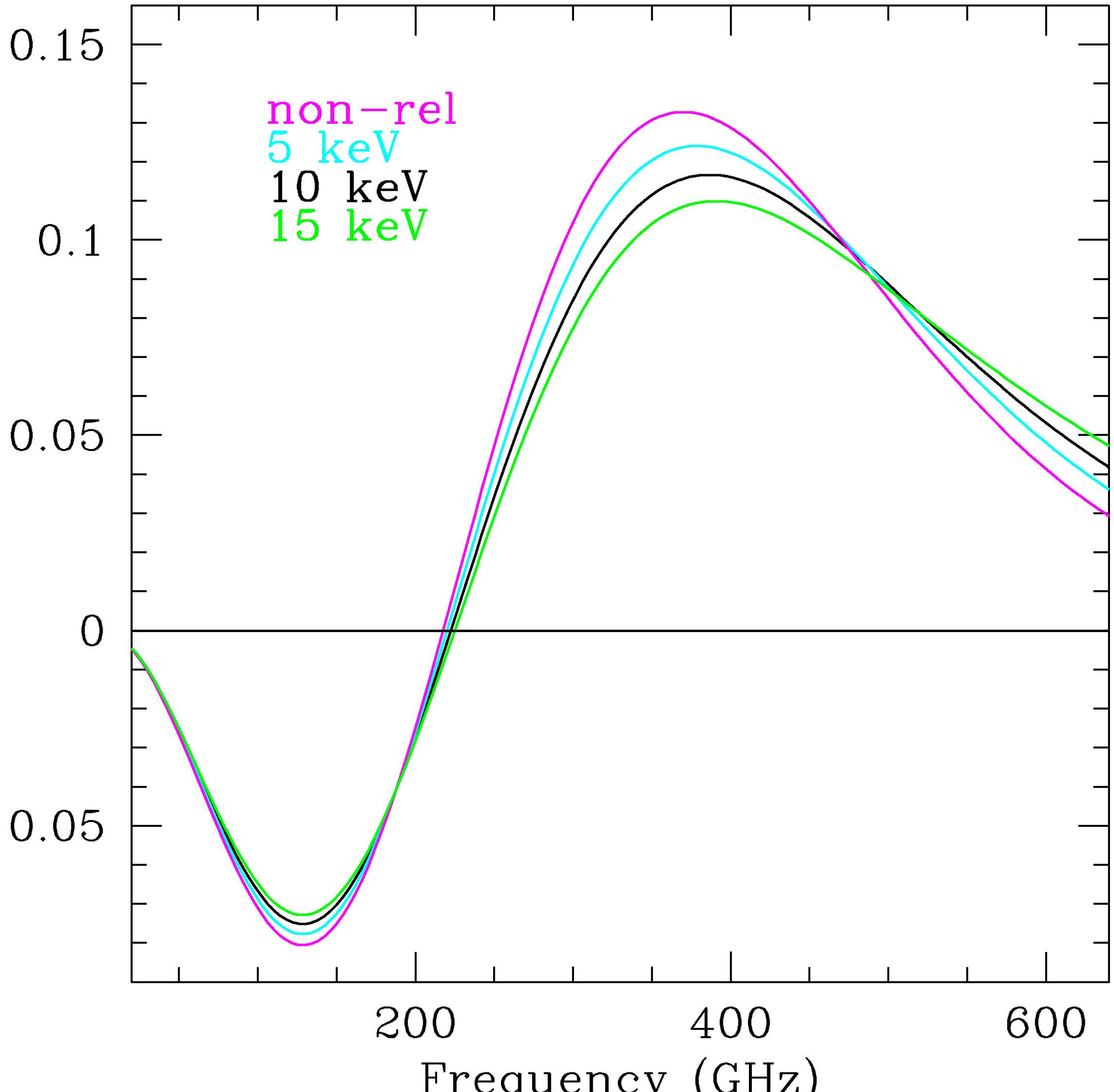
Optical depth: $\tau \sim 0.01$

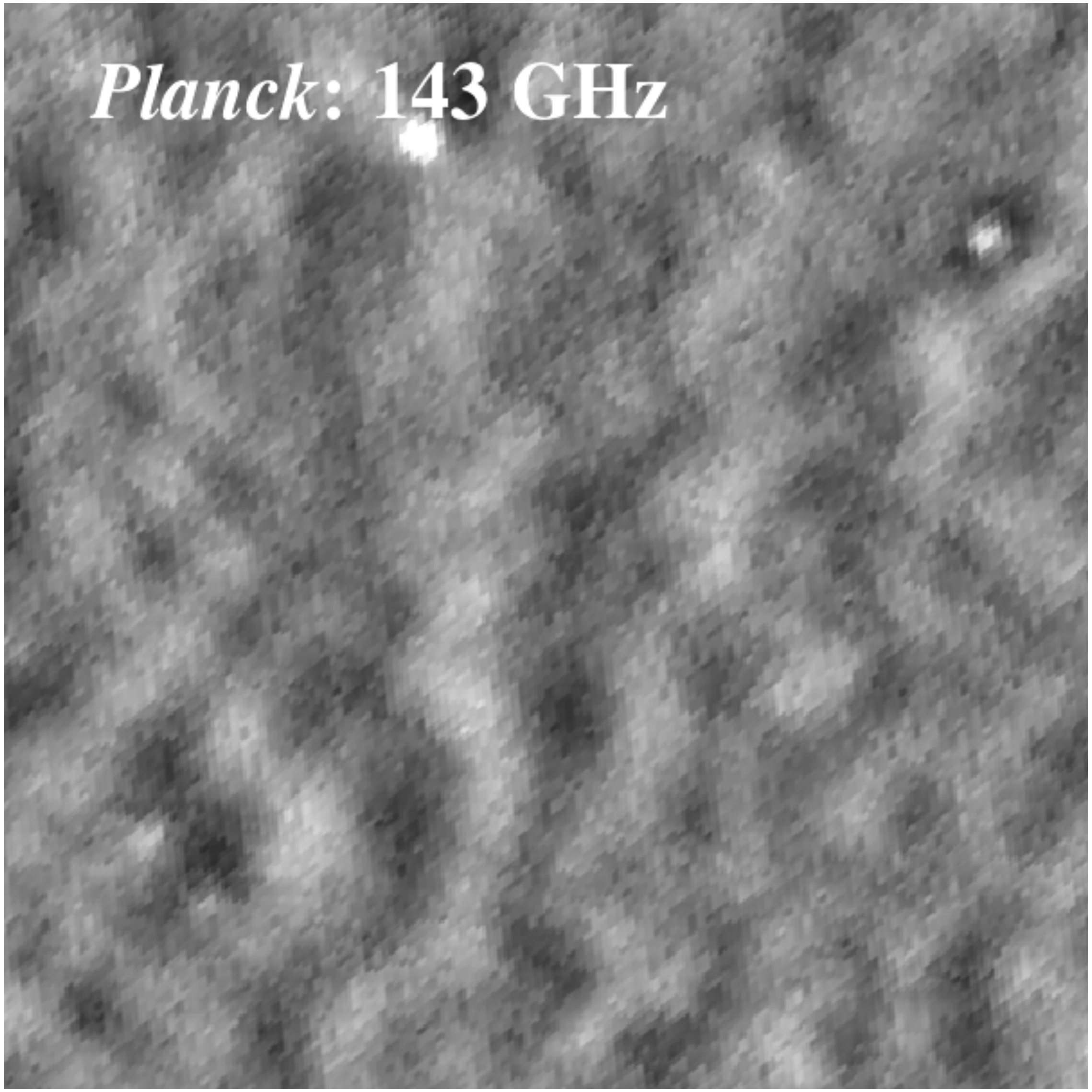
Fractional energy gain per scatter: $\frac{kT}{m_e c^2} \sim 0.01$

Typical cluster signal: ~500 uK

Thermal SZ Effect
(and relativistic corrections)

uK imaging would allow 1 kev accuracy in ***SZ temperature***

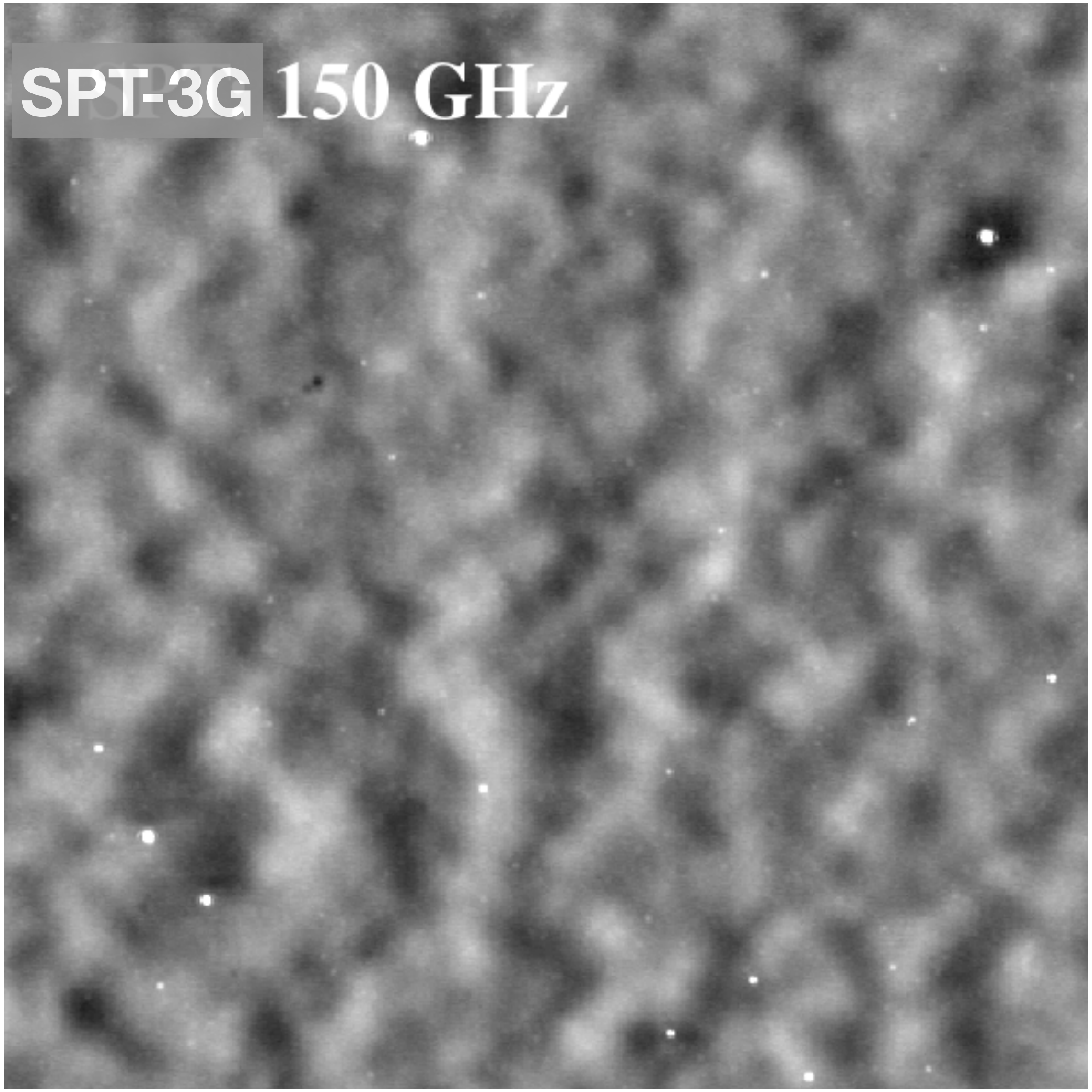




3 degrees

3 degrees

Srini Raghunathan



3 degrees

3 degrees

Srini Raghunathan

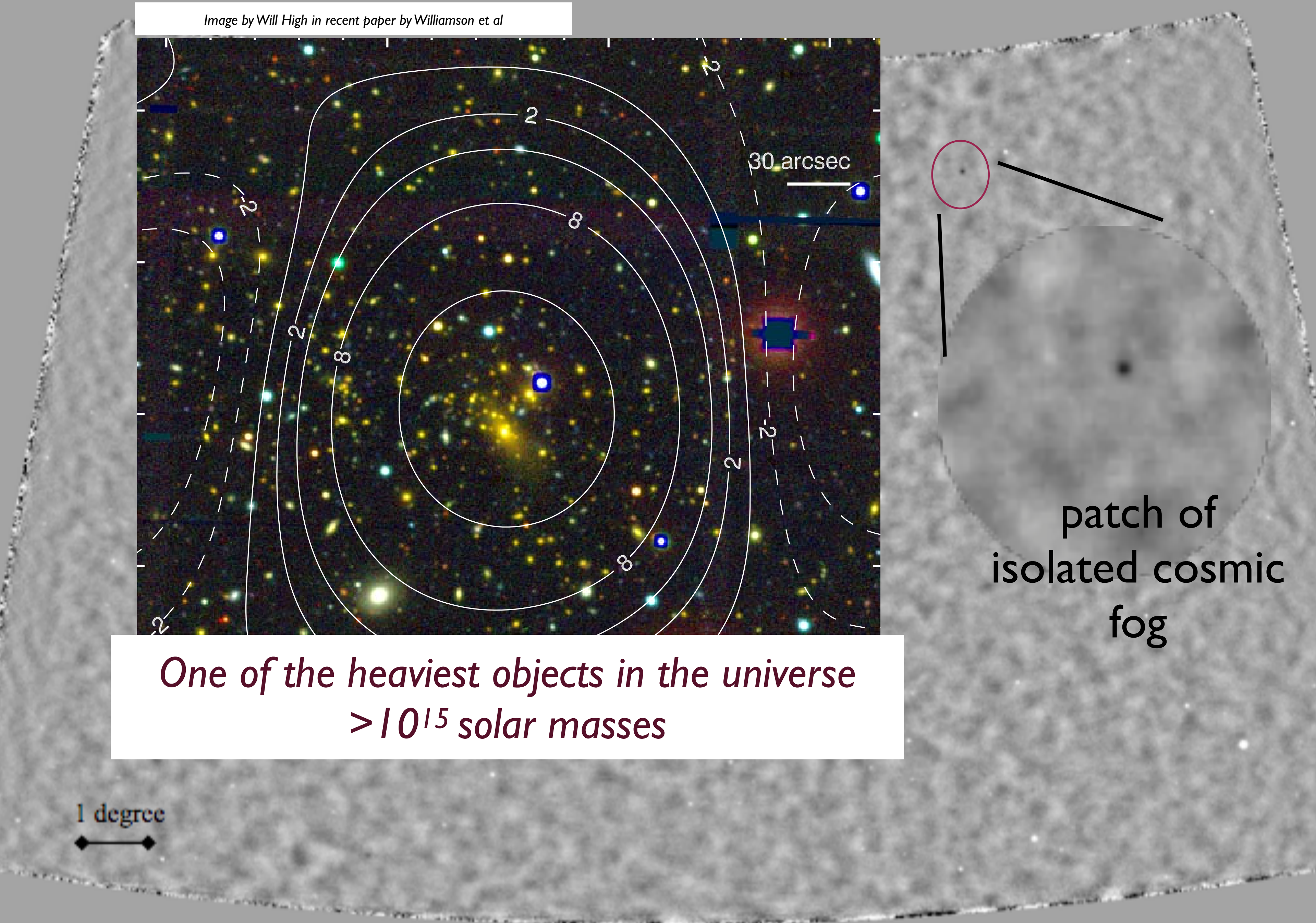
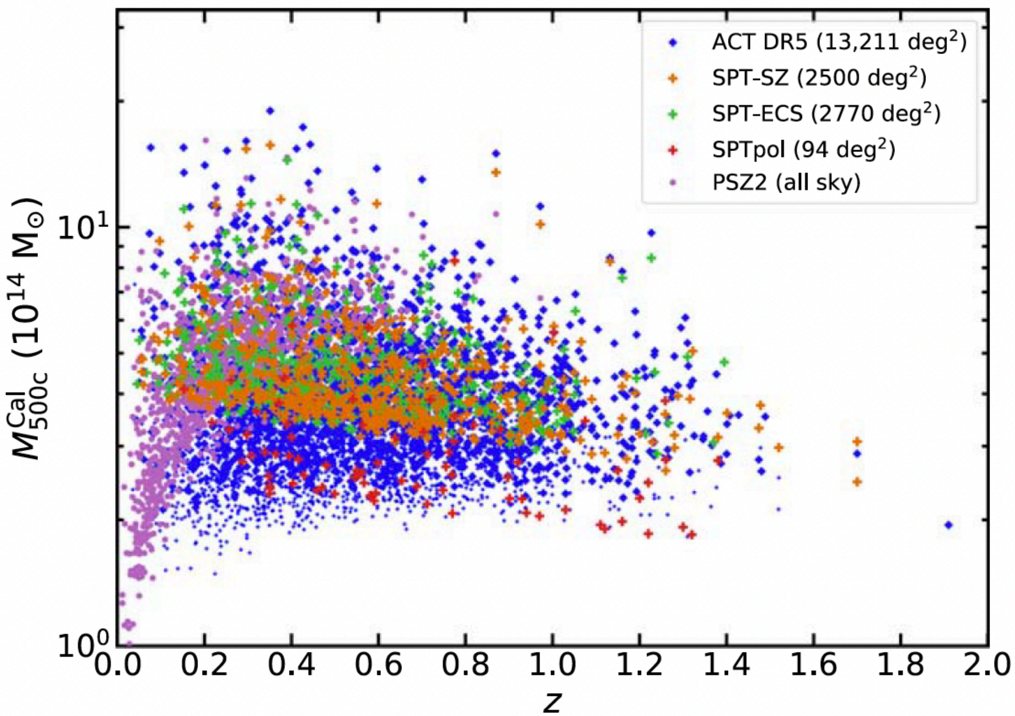


Image by Will High in recent paper by Williamson et al
30 arcsec
2
8
-2
patch of
isolated cosmic
fog
One of the heaviest objects in the universe
>10^15 solar masses
1 degree

tSZ-selected Galaxy Clusters

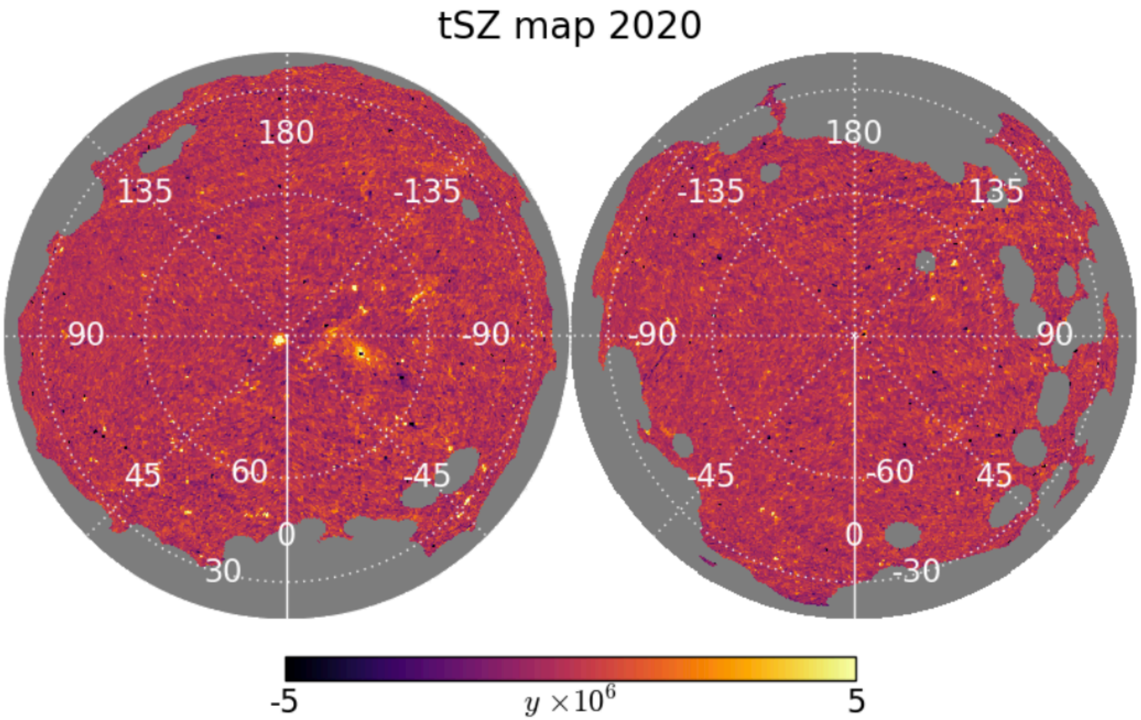
- now many thousands of galaxy clusters have been discovered by their CMB signatures



Hilton et al 2021

Compton y maps

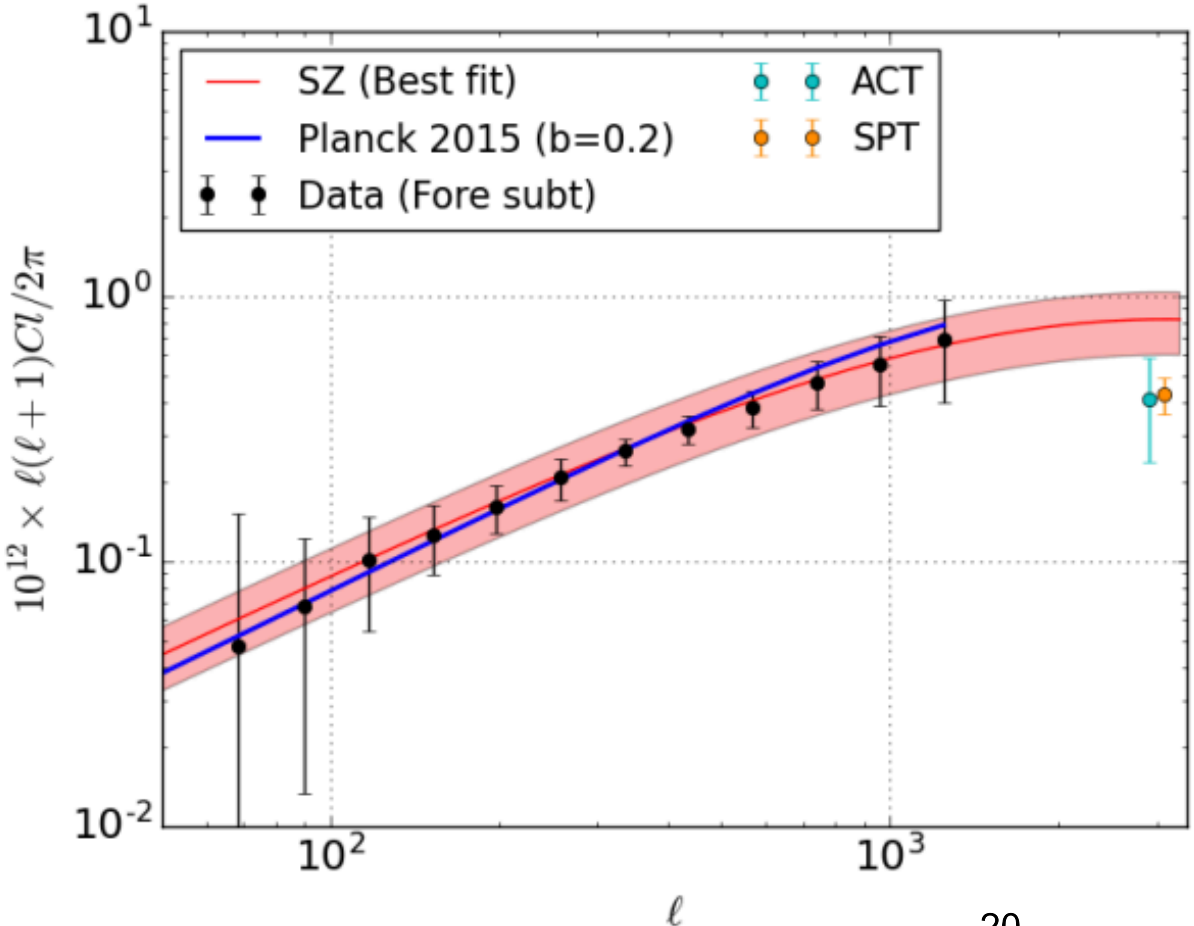
Tanimura et al.



Compton y power spectrum

Hint that maybe tSZ power is low at high ell

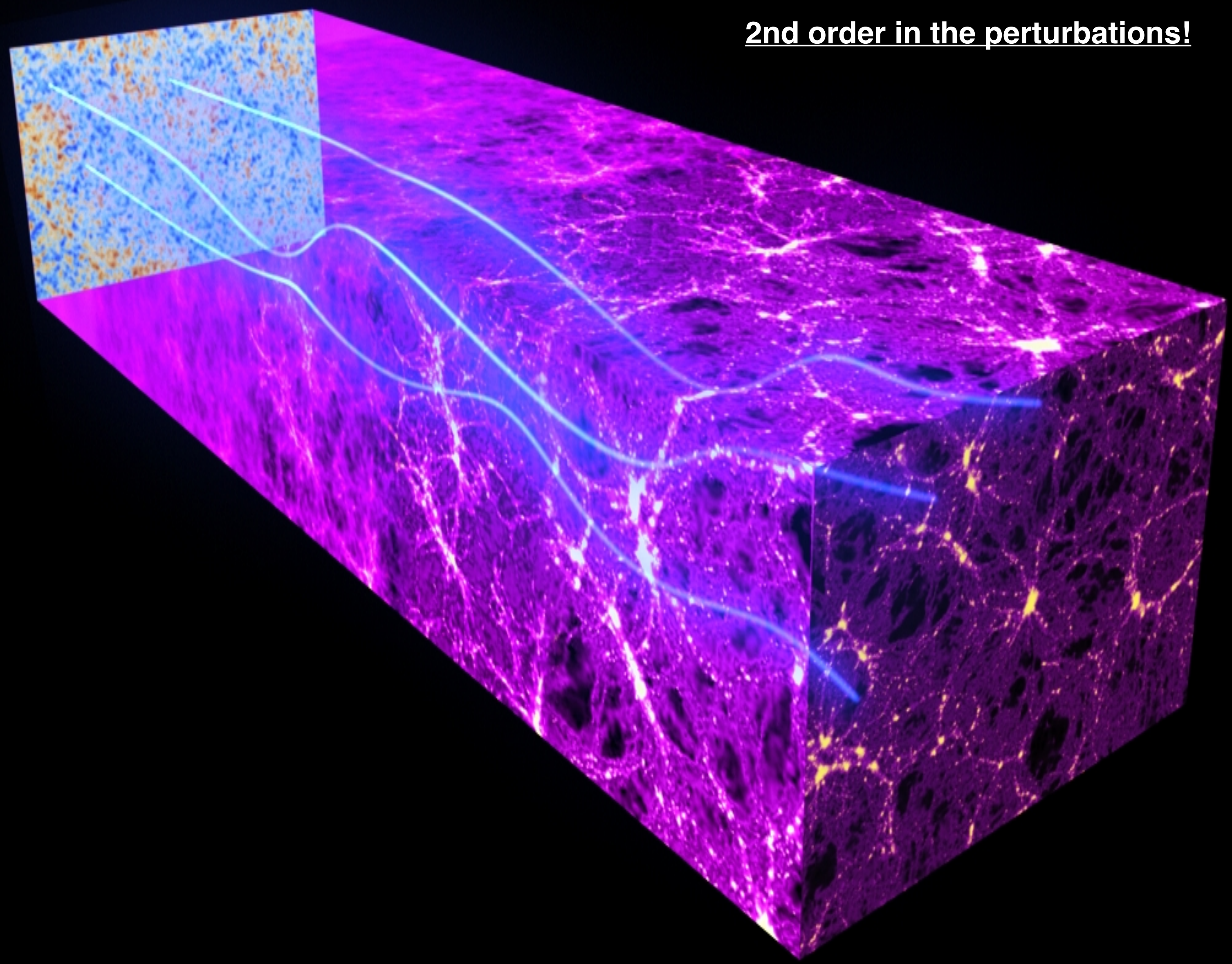
Almost entirely just 1-halo term



Tanimura et al 2021

lensing of primordial fluctuations by intervening fluctuations

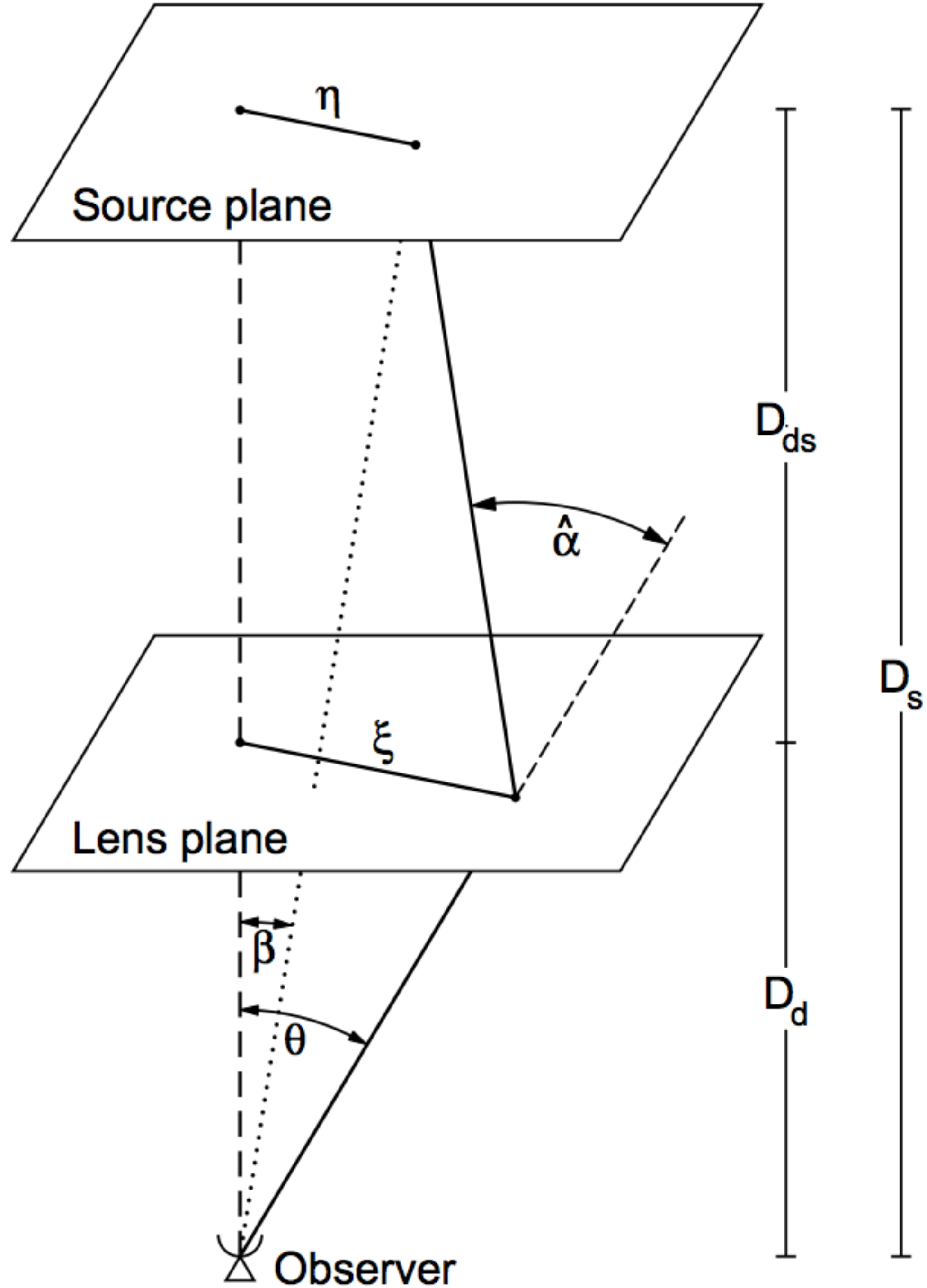
2nd order in the perturbations!



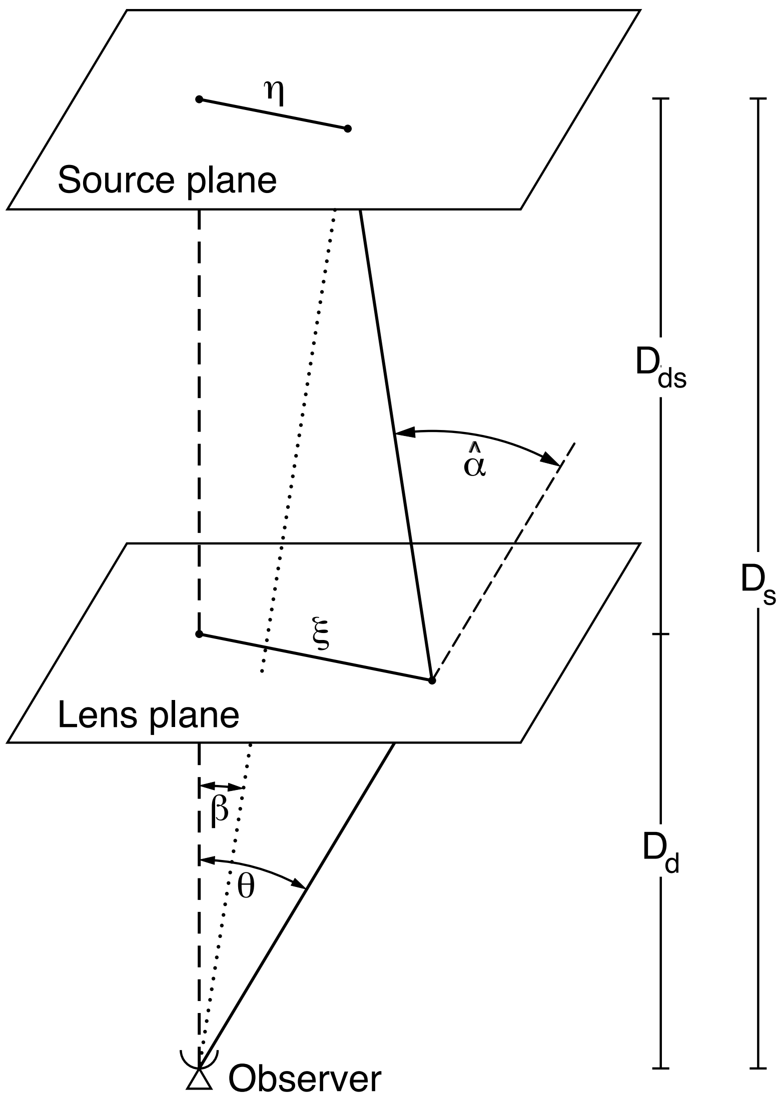
ESA and the Planck Collaboration

Gravitational lensing

$$\hat{\alpha} = \frac{4GM}{c^2 \xi}$$



Bartelmann & Schneider
http://arxiv.org/abs/astro-ph/9912508



source position — image position — deflection angle

$$\vec{\beta} = \vec{\theta} - \frac{D_{\mathrm{ds}}}{D_{\mathrm{s}}}\,\hat{\vec{\alpha}}(D_{\mathrm{d}}\vec{\theta}) \equiv \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

$$\vec{\alpha}(\vec{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta'\,\kappa(\vec{\theta}')\,\frac{\vec{\theta}-\vec{\theta}'}{|\vec{\theta}-\vec{\theta}'|^2}$$

$$\psi(\vec{\theta}) = \frac{1}{\pi}\int_{\mathbb{R}^2} \mathrm{d}^2\theta'\,\kappa(\vec{\theta}')\,\ln|\vec{\theta}-\vec{\theta}'|$$

lensing potential — convergence

$$\mathcal{A}(\vec{\theta}) = \frac{\partial\vec{\beta}}{\partial\vec{\theta}} = \left(\delta_{ij} - \frac{\partial^2\psi(\vec{\theta})}{\partial\theta_i\partial\theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} ,$$

where we have introduced the components of the shear $\gamma \equiv \gamma_1 + i\gamma_2 = |\gamma| e^{2i\varphi}$

$$\gamma_1 = \frac{1}{2}(\psi_{,11} - \psi_{,22}) , \quad \gamma_2 = \psi_{,12} ,$$

$$\mathcal{A} = (1-\kappa) \begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$$

distortion has overall magnification

image gets bigger (or smaller), not **brighter** (dimmer)

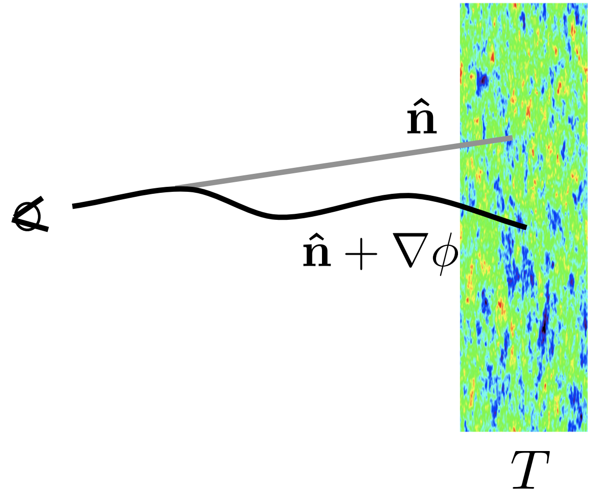
$$g(\vec{\theta}) \equiv \frac{\gamma(\vec{\theta})}{1-\kappa(\vec{\theta})}$$

reduced shear

CMB Lensing

Photons get shifted

$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}}))$$



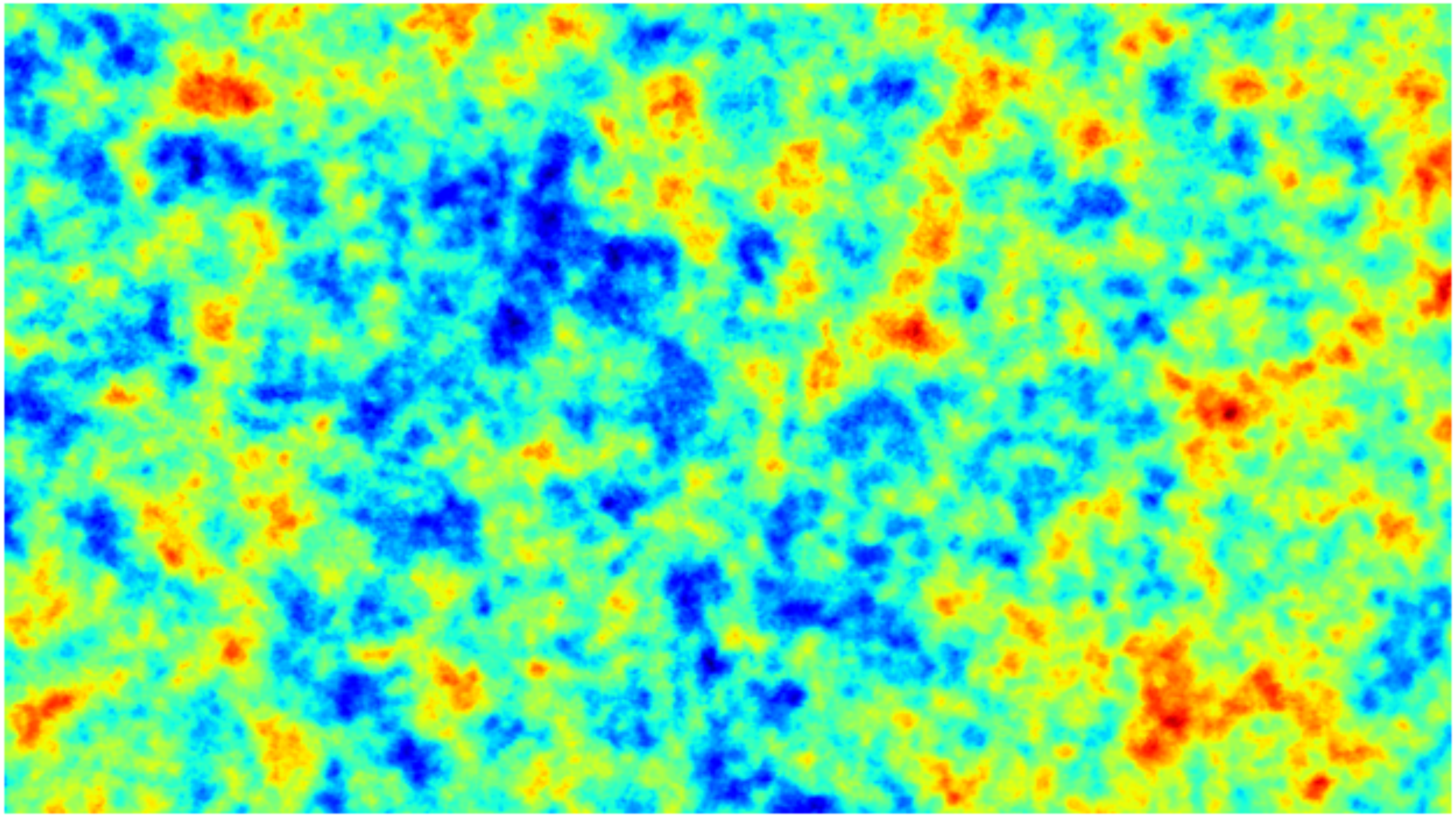
In WL limit, add many deflections along line of sight

$$\nabla\phi(\hat{\mathbf{n}}) = -2\int_0^{\chi_\star} d\chi\, \frac{\chi_\star - \chi}{\chi_\star \chi} \nabla_\perp \Phi(\chi\hat{\mathbf{n}}, \chi)$$

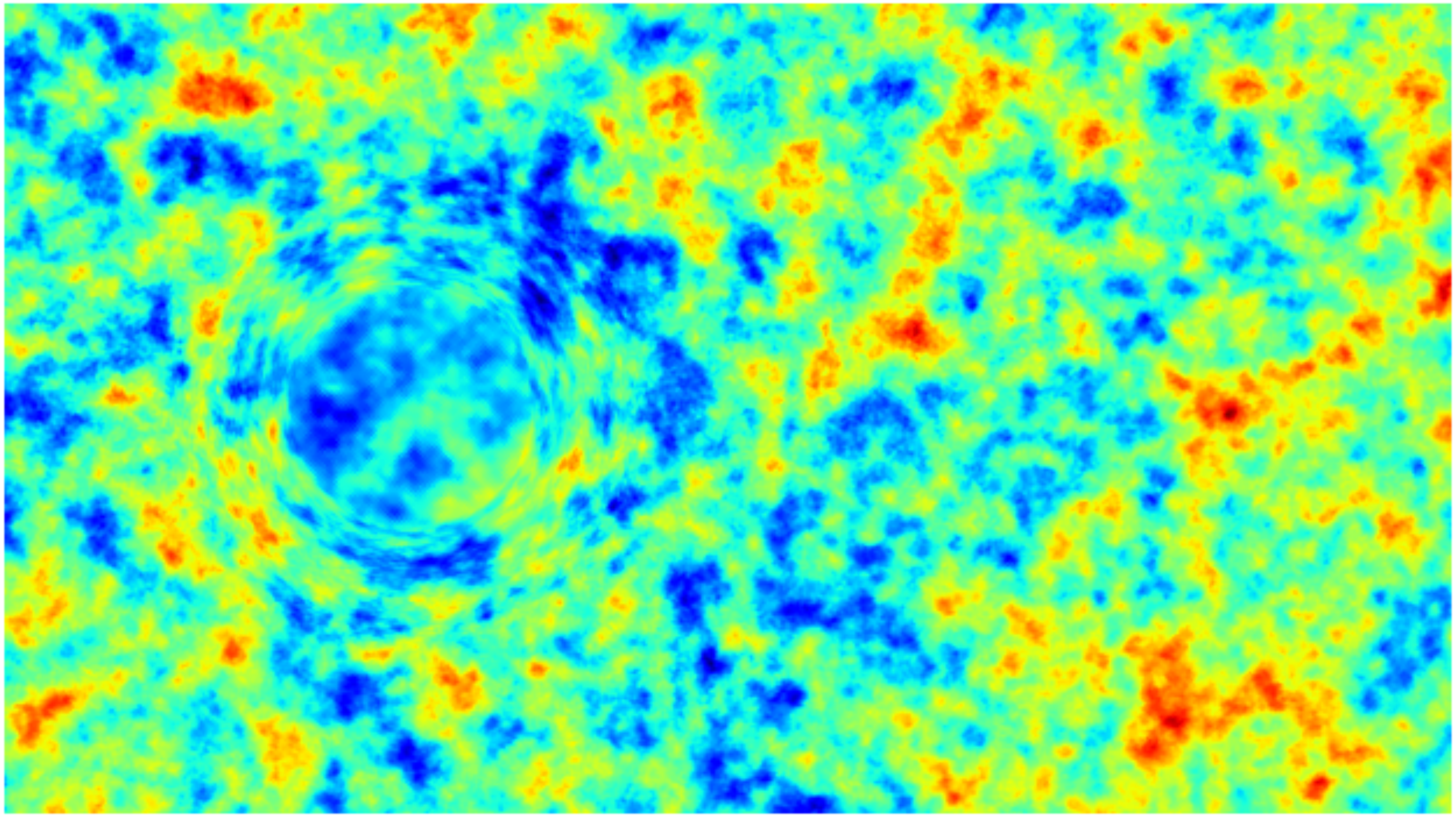
Broad kernel, peaks at z ~ 2

- CMB is a unique source for lensing
  - Gaussian, with well-understood power spectrum (contains all info)
  - At redshift which is (a) unique, (b) known, and (c) highest

patch of sky (the North pole) as seen by Planck (17x10 degrees)

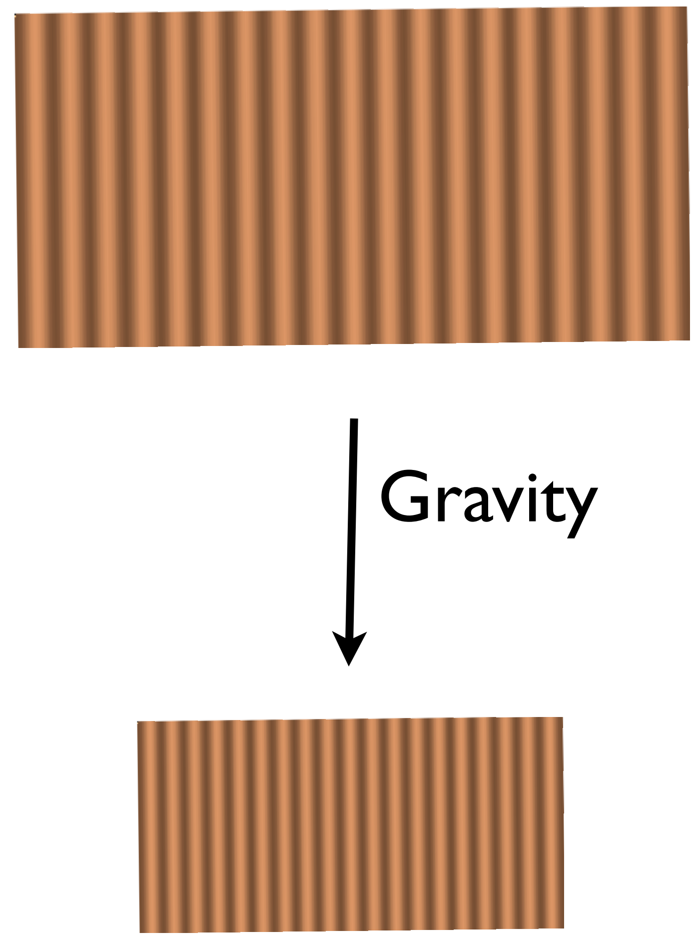


SIMULATED lensing effect (20x larger than typical)



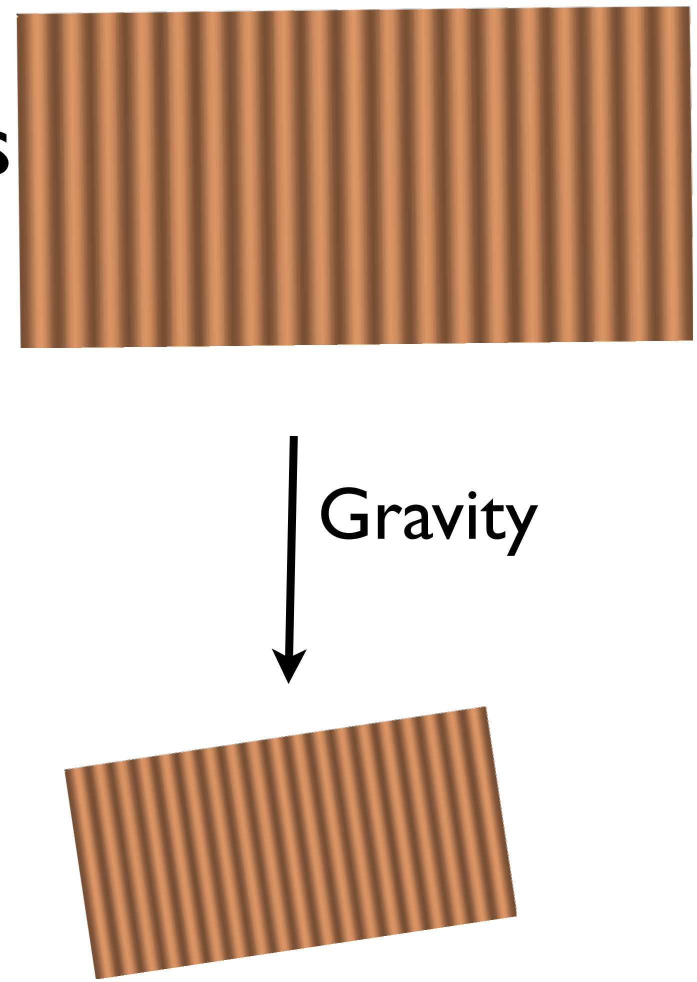
Lensing simplified

- gravitational potentials distort images by stretching, squeezing, shearing

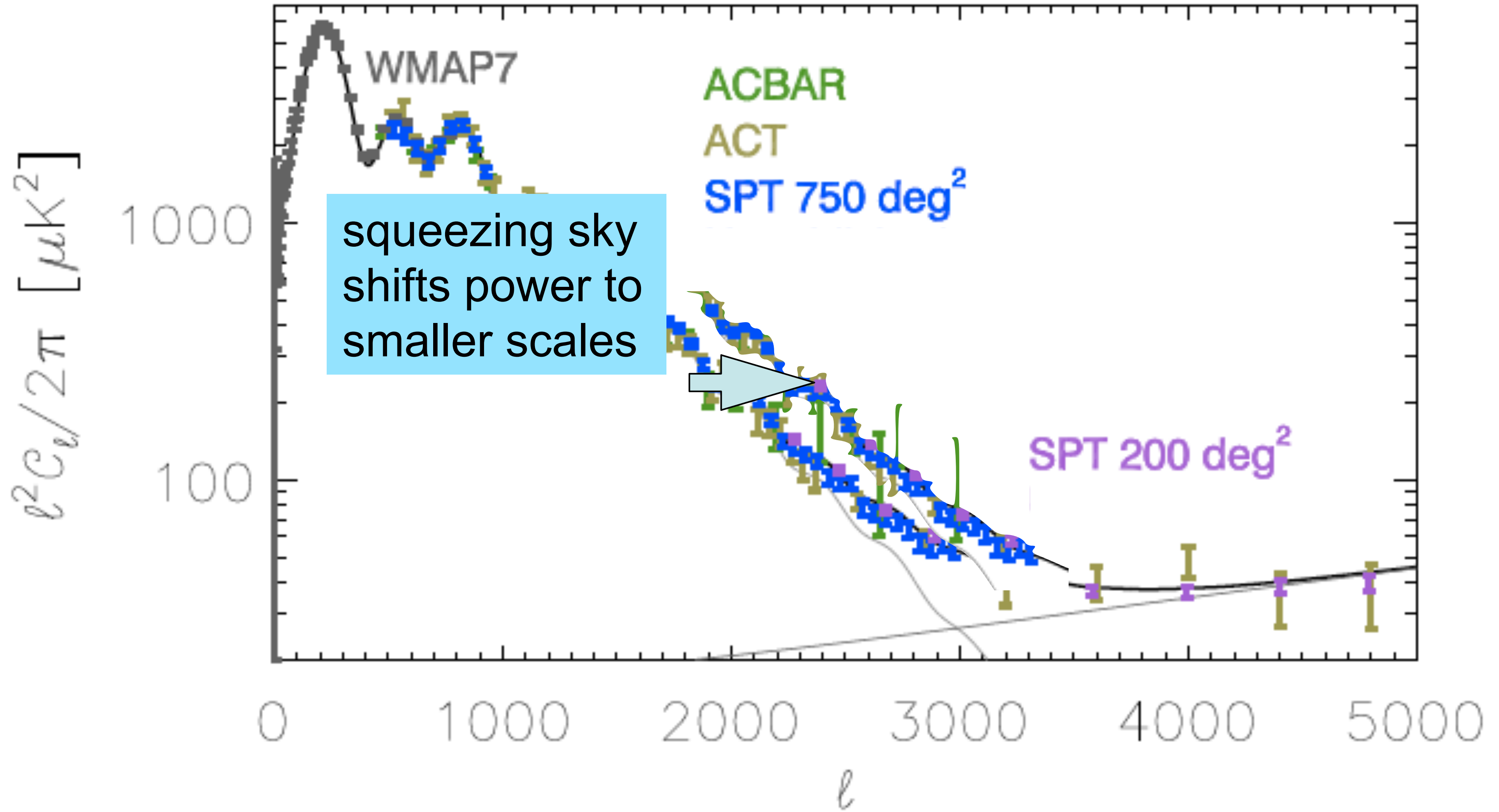


Lensing simplified

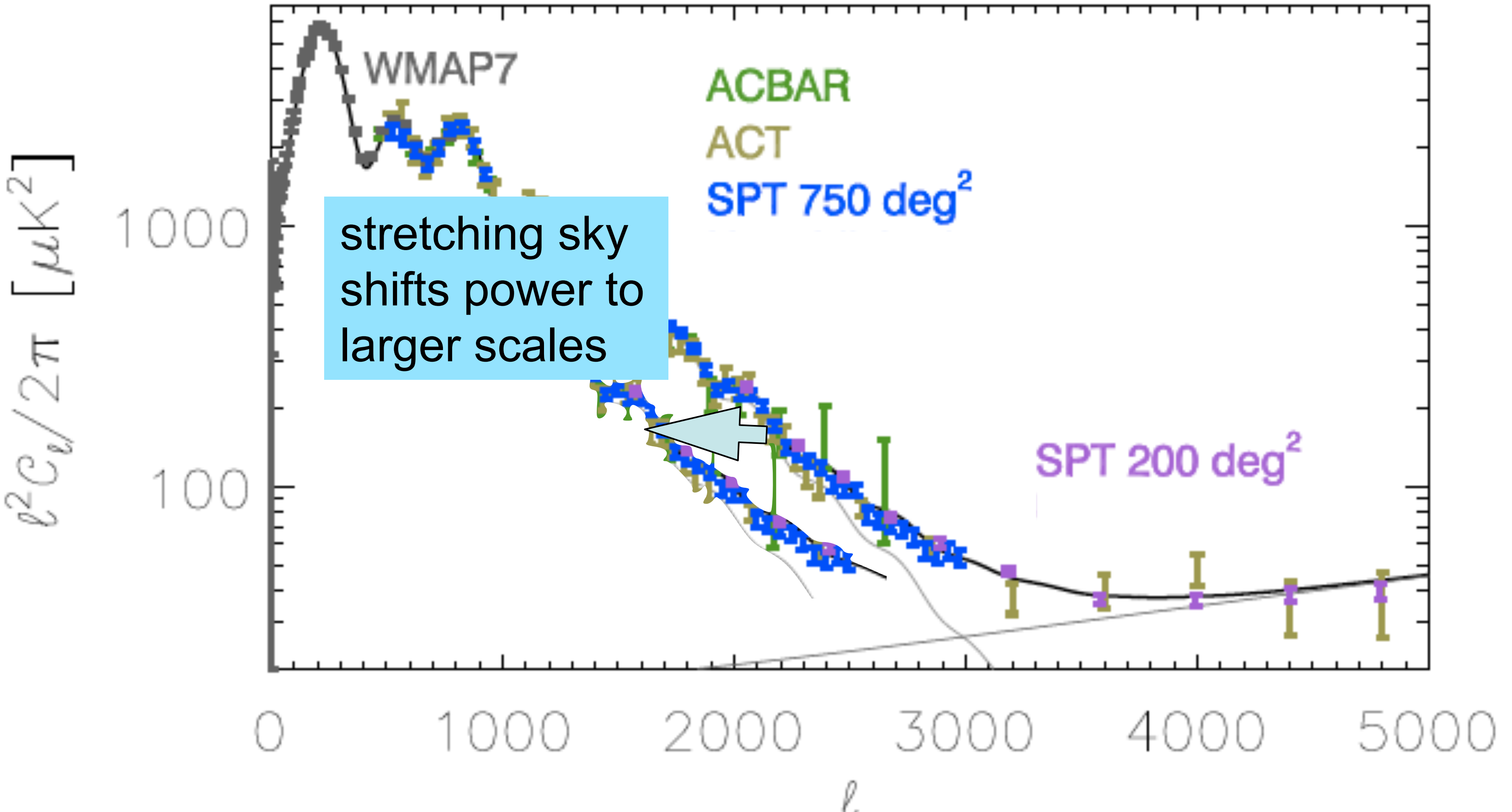
- where gravity stretches, gradients become smaller
- where gravity compresses, gradients are larger
- shear changes ***direction***



CMB Power Spectrum



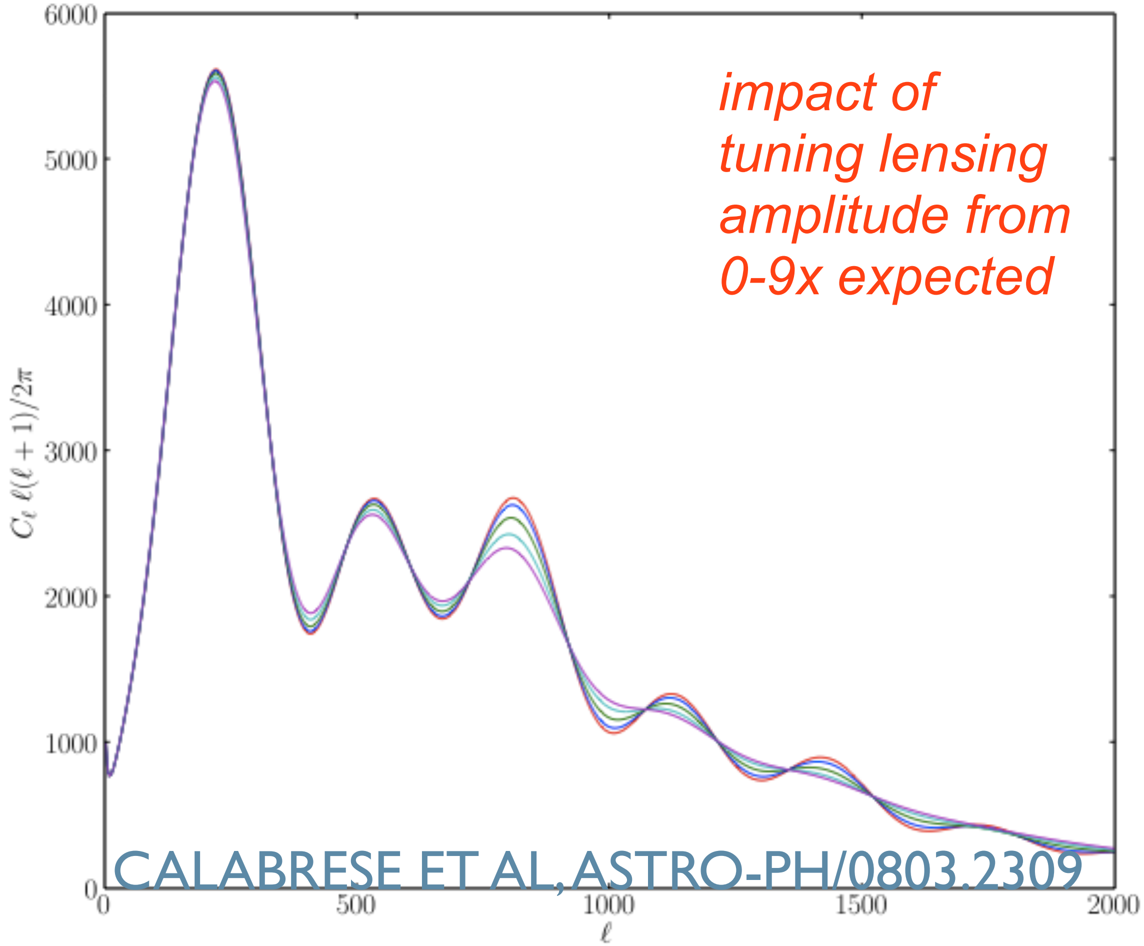
CMB Power Spectrum



Spatially varying power spectrum!!

Effect on CMB Power Spectrum

- mixing of power leads to smoothing of acoustic peaks
- small effect but data is really good



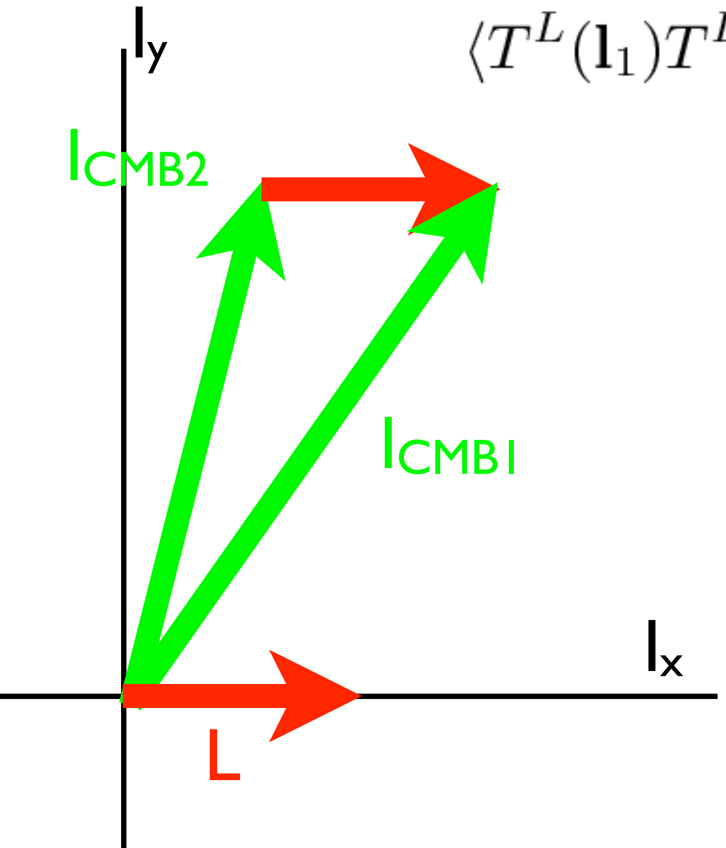
Mode Coupling from Lensing

$$T^L(\hat{\mathbf{n}}) = T^U(\hat{\mathbf{n}} + \nabla\phi(\hat{\mathbf{n}})) = T^U(\hat{\mathbf{n}}) + \nabla T^U(\hat{\mathbf{n}}) \cdot \nabla\phi(\hat{\mathbf{n}}) + O(\phi^2),$$

- Non-gaussian mode coupling for $\mathbf{l_1} \neq -\mathbf{l_2}$:

$$\langle T^L(\mathbf{l}_1) T^L(\mathbf{l}_2)\rangle = \mathbf{L} \cdot (\mathbf{l}_1 C^T_{l_1} + \mathbf{l}_2 C^T_{l_2})\phi(\mathbf{L}) + O(\phi^2)$$

$$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$$



- We extract φ by taking a suitable average over CMB multipoles separated by a distance L
- We use the standard Hu quadratic estimator.

E-modes and B-modes

$$Q(\boldsymbol{l}) = [E(\boldsymbol{l})\cos(2\phi_l) - B(\boldsymbol{l})\sin(2\phi_l)]$$
$$U(\boldsymbol{l}) = [E(\boldsymbol{l})\sin(2\phi_l) + B(\boldsymbol{l})\cos(2\phi_l)].$$

- E/B is a different way to express polarization field
- easy to understand in flat-sky limit (i.e. Fourier modes)

E-modes/B-modes

- E-modes vary spatially parallel or perpedicular to polarization direction
- B-modes vary spatially at 45 degrees
- CMB
  - scalar perturbations only generate *only* E
- ***Lensing of CMB is much more obvious in polarization!***

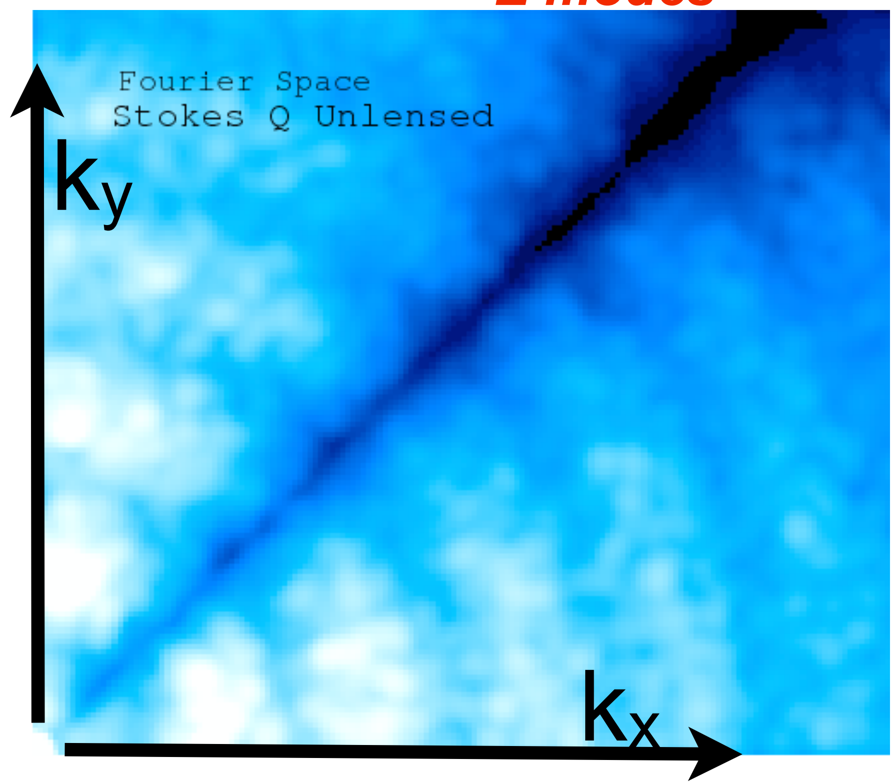
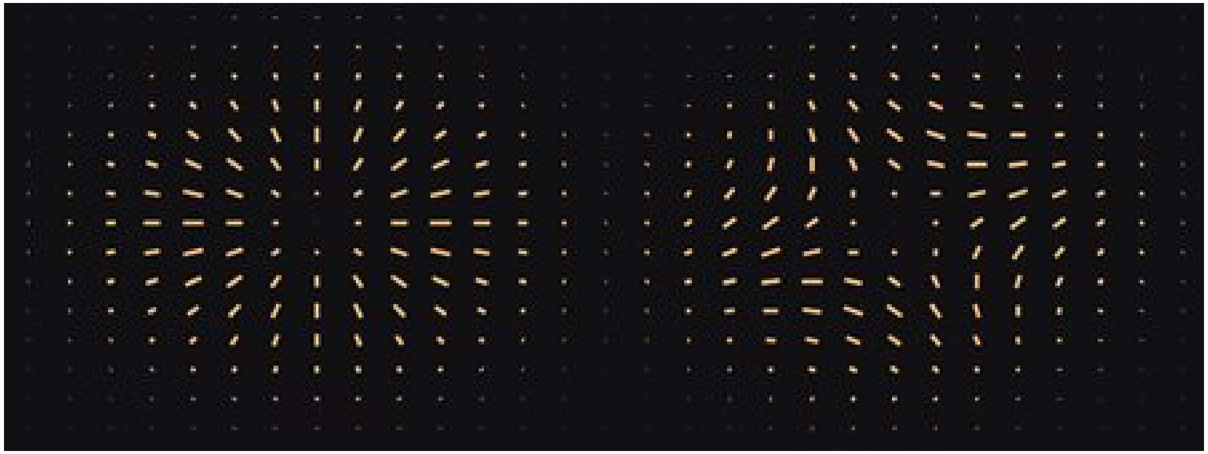


Image of positive kx/positive ky Fourier transform of a 10x10 deg chunk of Stokes Q CMB map [simulated; nothing clever done to it]

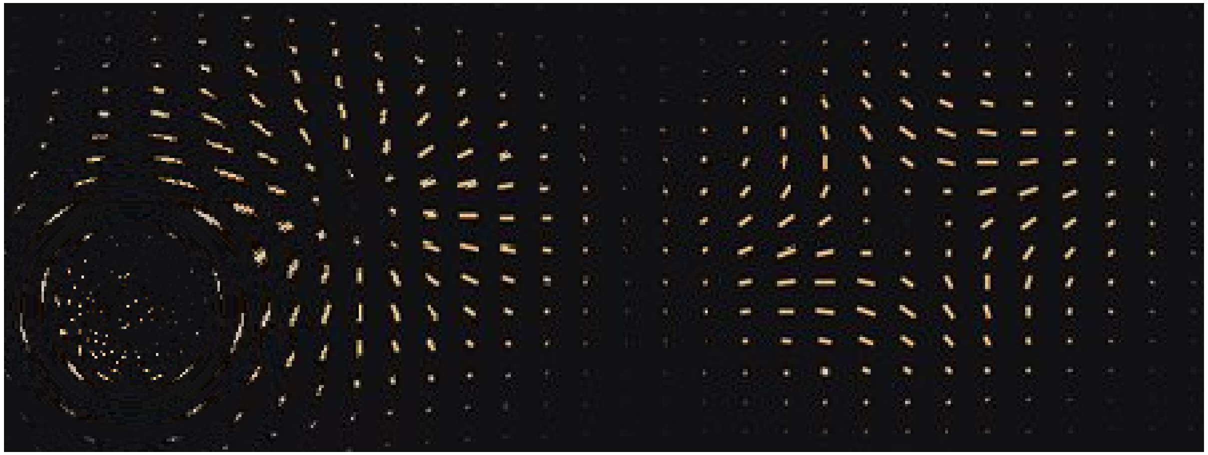
B Modes from E Modes

Before: pure E mode (left) and pure B mode (right)

From B-pol.org

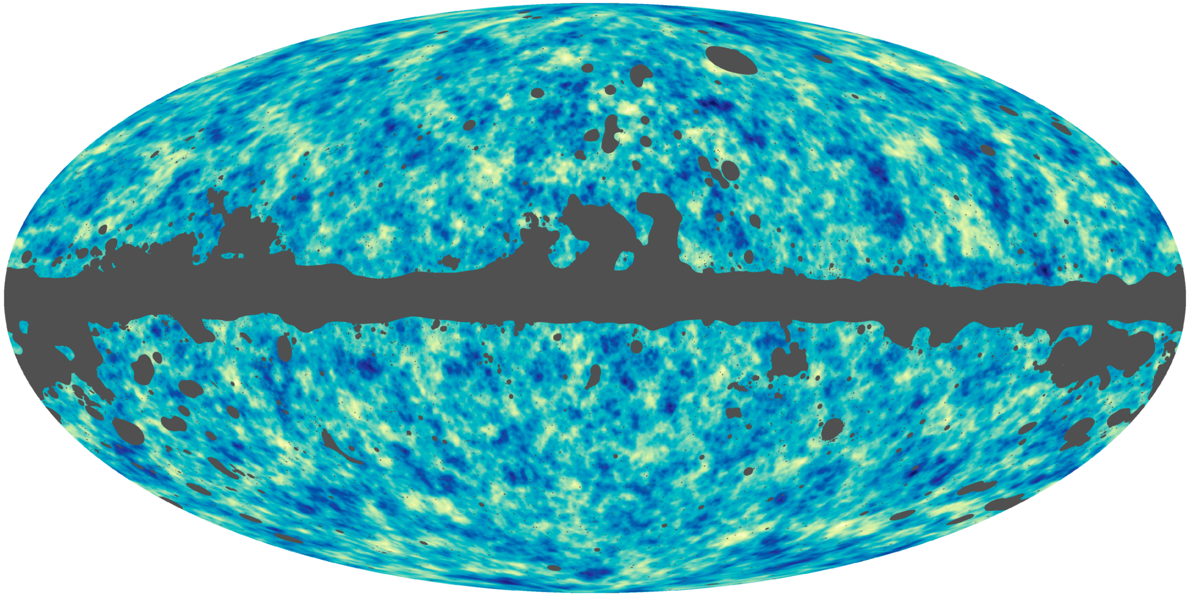


After: large point mass lenses image



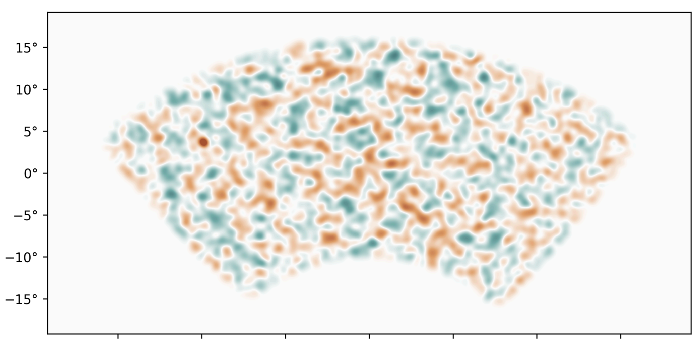
Lensing done with "Lens an astrophysicist"

http://theory2.phys.cwru.edu/~pete/GravitationalLens/



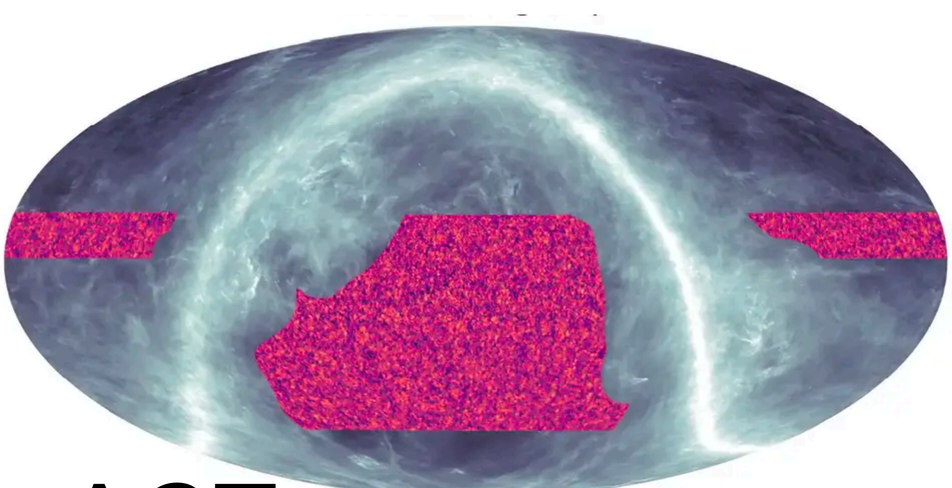
Planck

(~all-sky)



SPT-3G

(1500 square degrees)

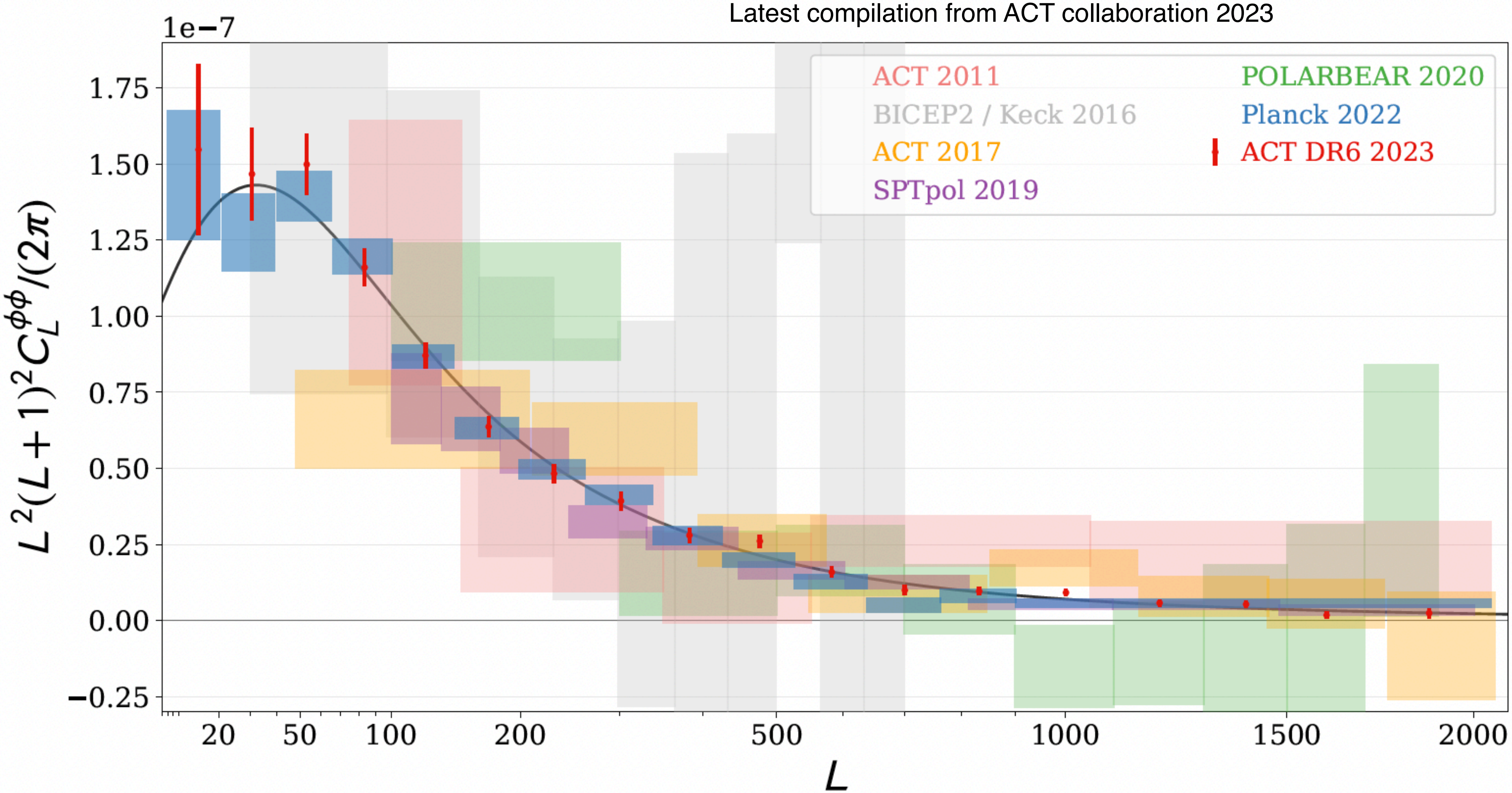


ACT

(9400 square degrees)

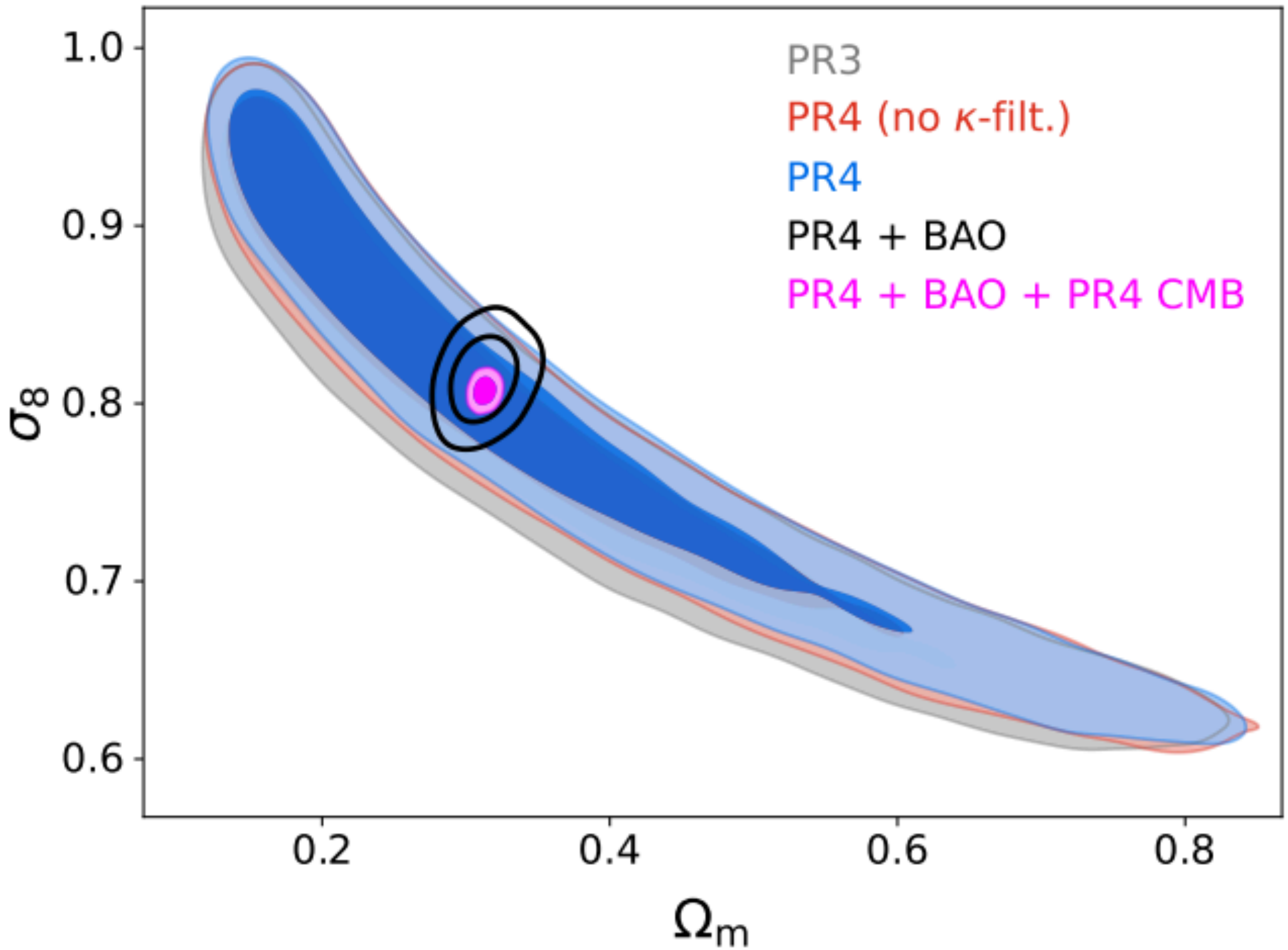
CMB Lensing Power Spectra

Latest compilation from ACT collaboration 2023



Qu et al 2023

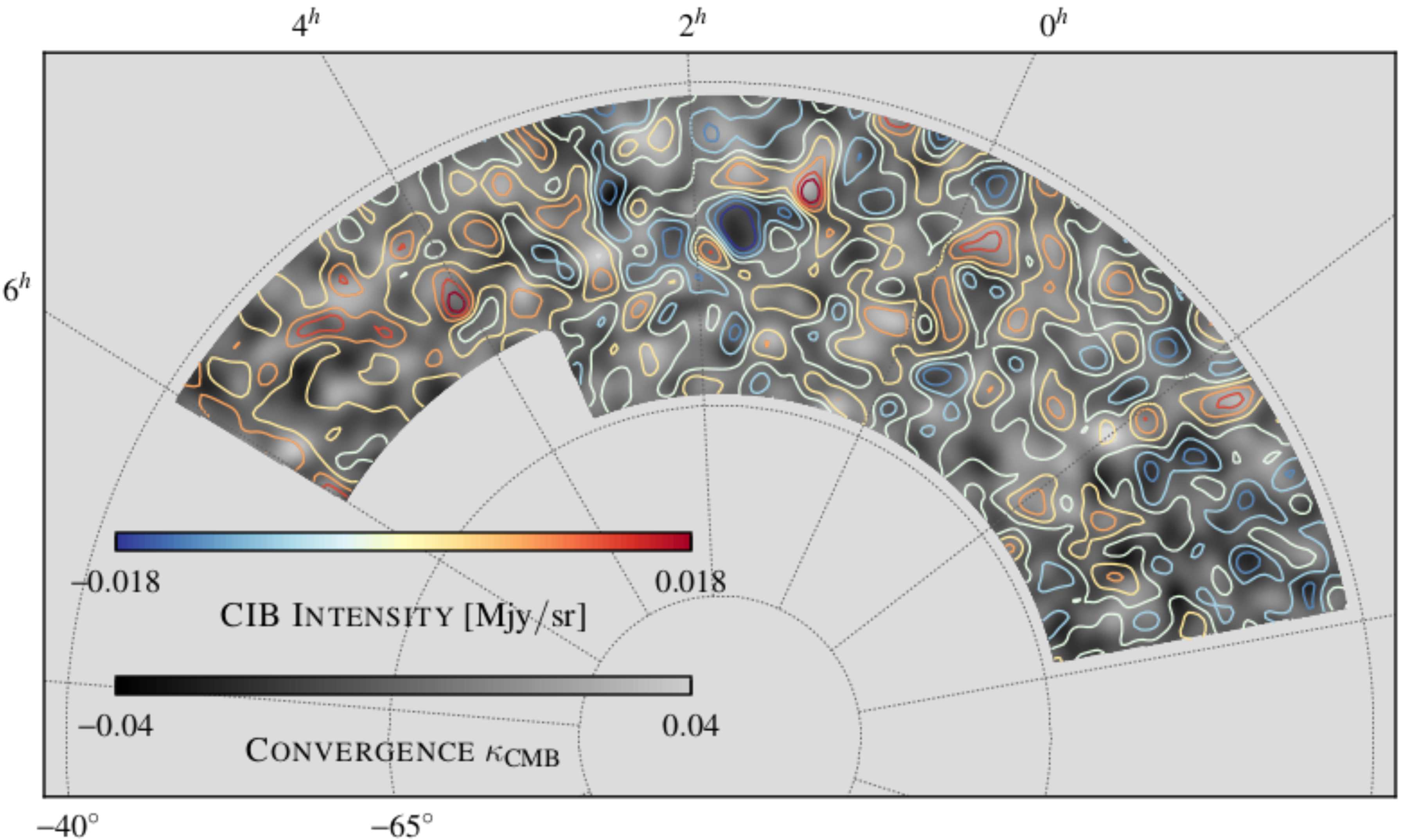
Cosmological contraints on structure formation



Planck: Carron 2022

see also Madhavacheril 2023

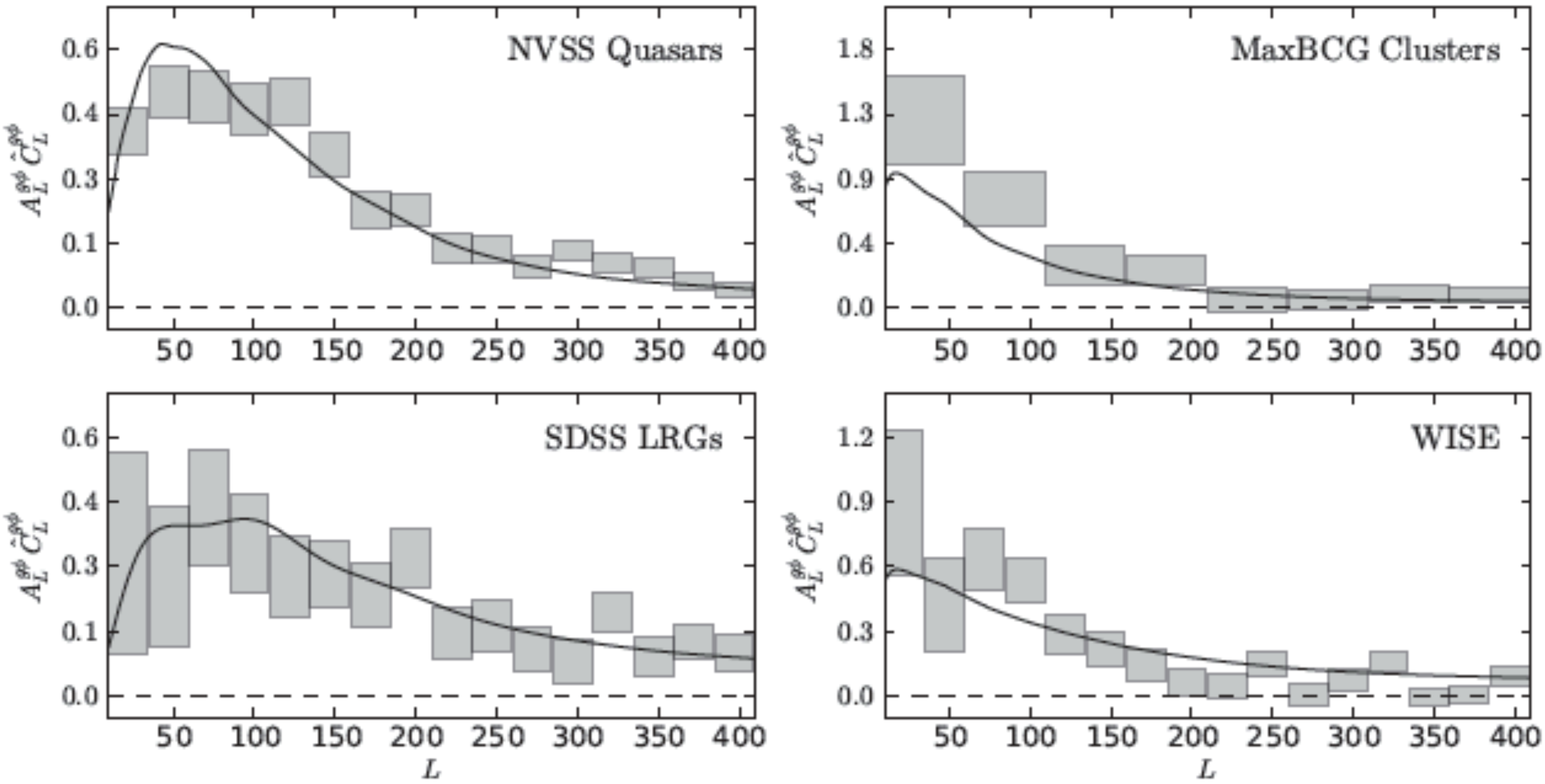
CMB-LSS cross-correlation: CIB



CIB map from Planck GNLIC 545 GHz

Omori, Chown, Simard, KTS, et. al (arXv:1705.00743)

Planck X Galaxies, etc.



Planck 2013-#17

Angular Clustering

Angular power spectrum of power spectrum between two maps X & Y (could be same map!)

$$C_\ell^{XY} = \frac{2}{\pi} \int_0^\infty d\chi_1 \, d\chi_2 \; W^X(\chi_1) W^Y(\chi_2) \int_0^\infty k^2 \, dk \; P_{XY}(k; z_1, z_2) j_\ell(k\chi_1) j_\ell(k\chi_2)$$

Limber approximation, which generally works pretty well except for really large scales

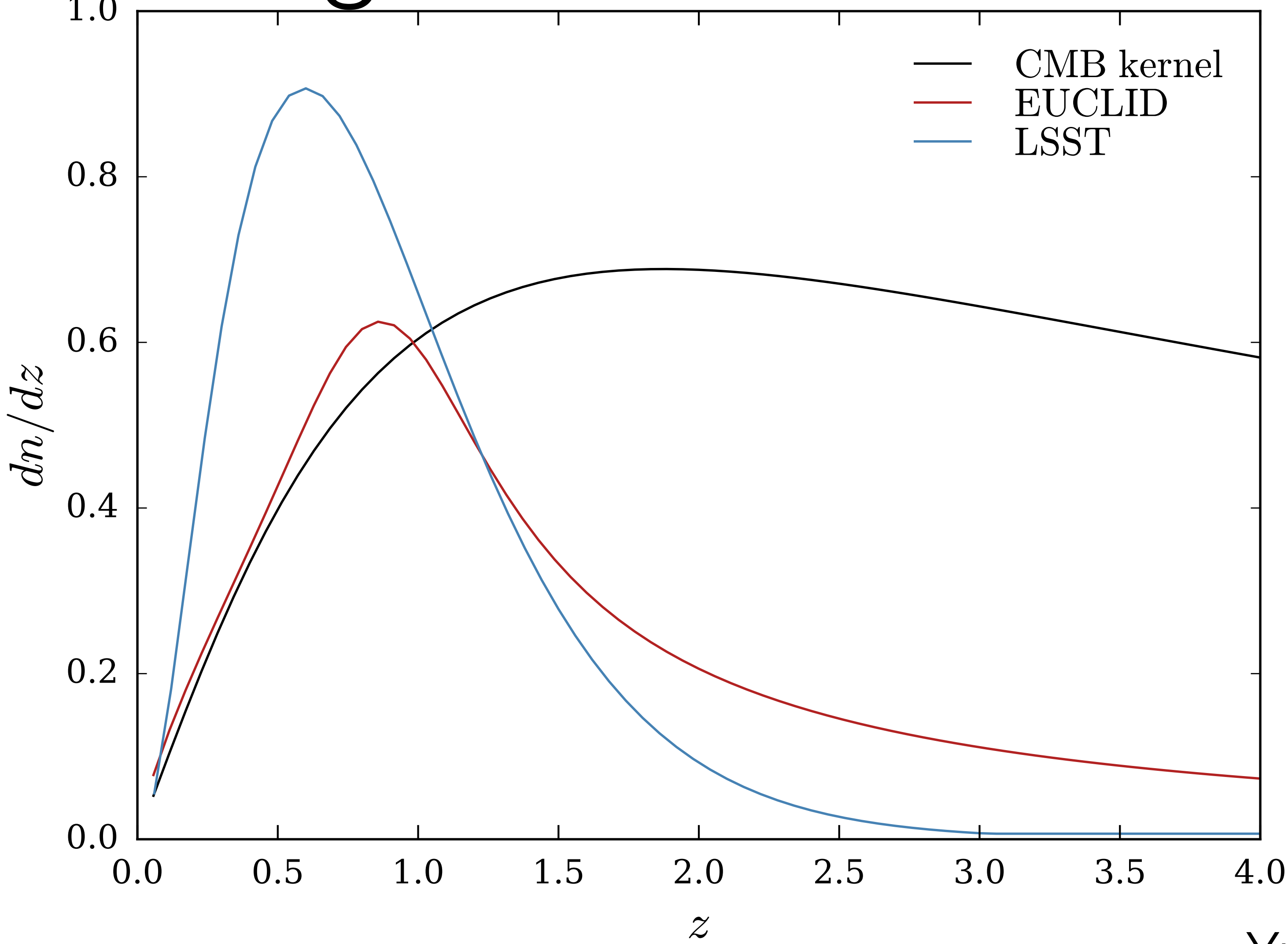
$$C_\ell^{XY} = \int d\chi \; \frac{W^X(\chi) W^Y(\chi)}{\chi^2} \; P_{XY}\left(k_\perp = \frac{\ell + 1/2}{\chi}, k_z = 0\right)$$

weights for CMB lensing or some galaxy tracer

$$W^\kappa(\chi) = \frac{3}{2}(\Omega_m + \Omega_\nu) H_0^2 (1+z) \; \frac{\chi(\chi_\star - \chi)}{\chi_\star} \quad , \quad W^g(\chi) = b(z) H(z) \; \frac{dN}{dz}$$

Krolewski et al 1909.07412

CMB lensing is sensitive to higher z sources



Yuuki Omori

Angular Clustering

$$C_\ell^{\kappa g} = b^{\mathrm{eff}} \int d\chi \frac{W^\kappa(\chi)}{\chi^2} H(z) \left[f(z) \frac{dN_p}{dz} \right] P(k\chi = \ell + 1/2)$$

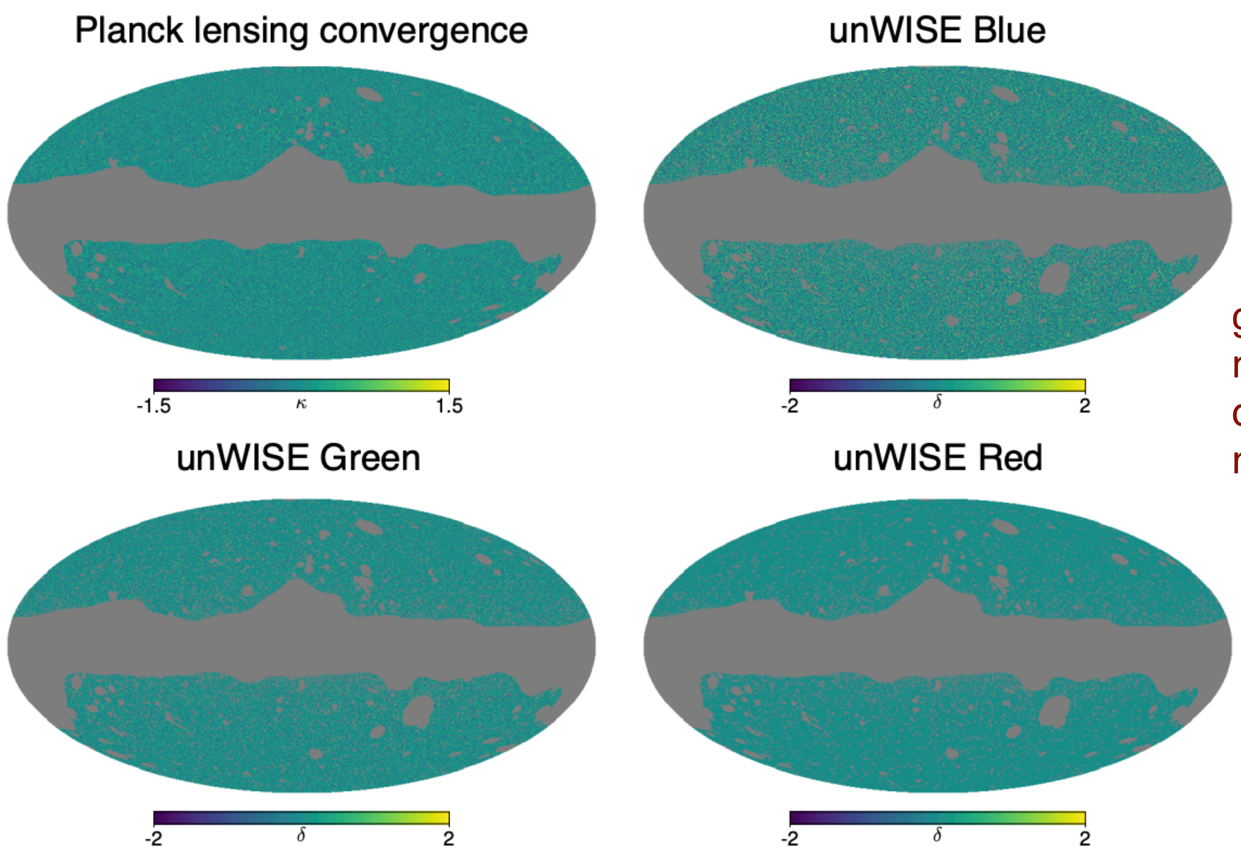
$$C_\ell^{gg} = (b^{\mathrm{eff}})^2 \int d\chi \frac{1}{\chi^2} H(z)^2 \left[f(z) \frac{dN_p}{dz} \right]^2 P(k\chi = \ell + 1/2)$$

$$W^\kappa(\chi) = \frac{3}{2}(\Omega_m + \Omega_\nu) H_0^2 (1+z) \, \frac{\chi(\chi_\star - \chi)}{\chi_\star} \quad , \quad W^g(\chi) = b(z) H(z) \, \frac{dN}{dz}$$

- CMB lensing power measures projected power of all matter **(no b)**
- galaxy clustering measures projected power of biased tracers **(b dN/dz)^2**
- CMB lensing X galaxies measures projected power in common **(b dN/dz)**

Krolewski et al 1909.07412

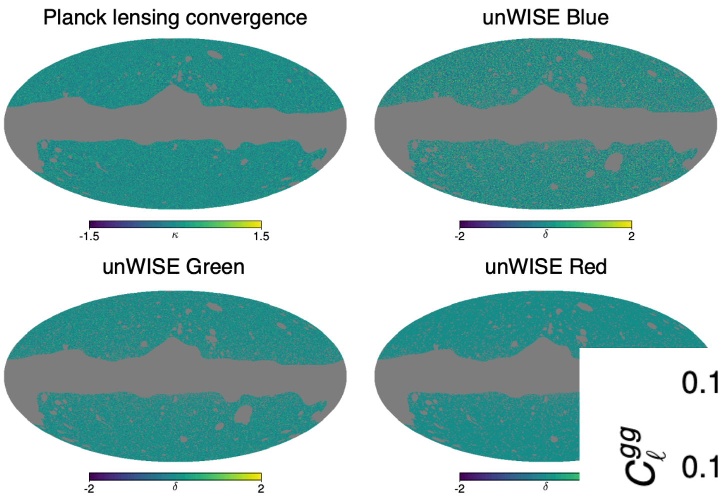
Example: WISE X Planck lensing

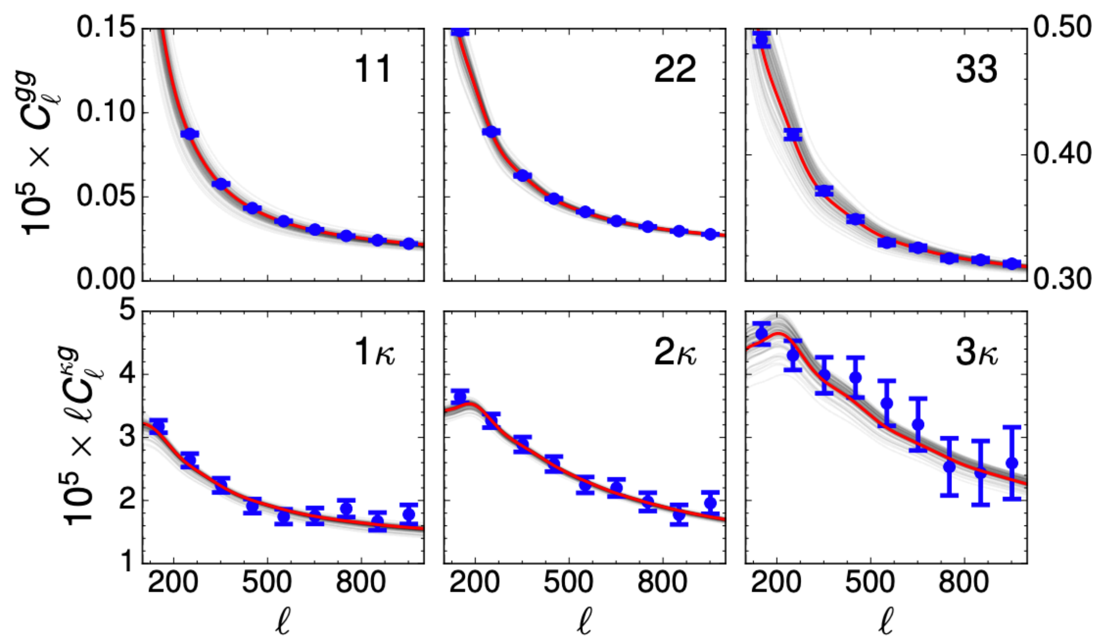


galaxy number density maps

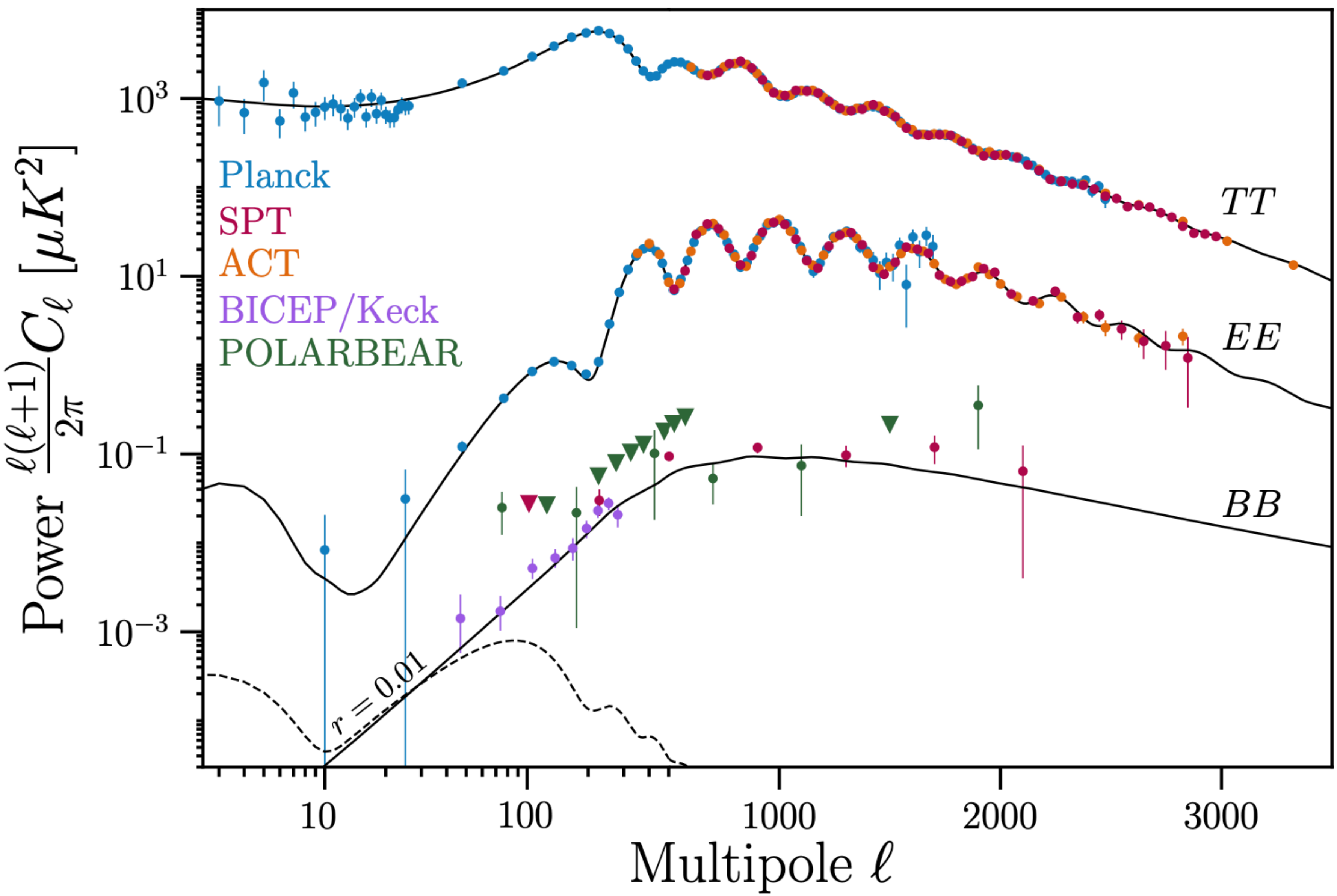
Krolewski et al 1909.07412

Example: WISE X Planck lensing





Krolewski et al 1909.07412



Snowmass CMB Measurements white paper 2203.07638

Power spectrum Uncertainties

- fundamentally limited by number of independent measurements, noise
- $C_{l;meas}=C_{l;true}+C_{l;noise}$ *in any single map you can't tell the difference*
- $Var(C_l) \sim (2/n_{meas})C_l^2$ ***"sample variance"***
- more modes means better measurement of $C_{l;true}+C_{l;noise}$
- lower noise gives better measure of $C_{l;true}$

Delensing lowers sample variance for B-mode searches

SPT-3G + external tracers (galaxies+CIB) can remove 80% of lensing power

BICEP/Keck is signal-dominated, so
delensing directly reduces the error bar for constraints on tensors
(also true for SPT-3G, for however low in l can be reached)