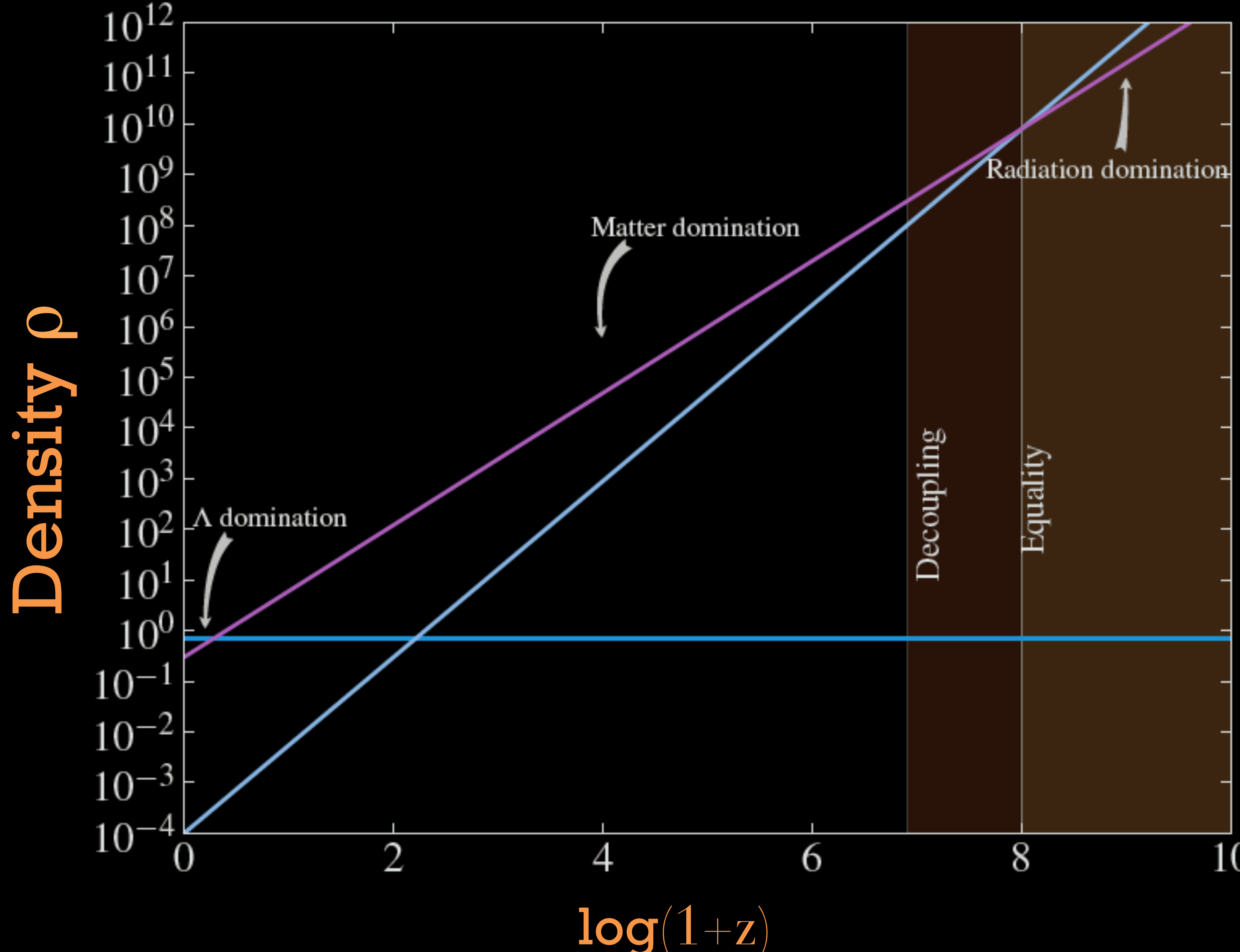
Constraining cosmology with the small-scale CMB

Renée Hložek
Lyman Spitzer Jr. Postdoctoral Fellow
Spitzer-Cotsen Fellow in the Society of Fellows of the Liberal Arts
TED 2014 Senior Fellow
Princeton University

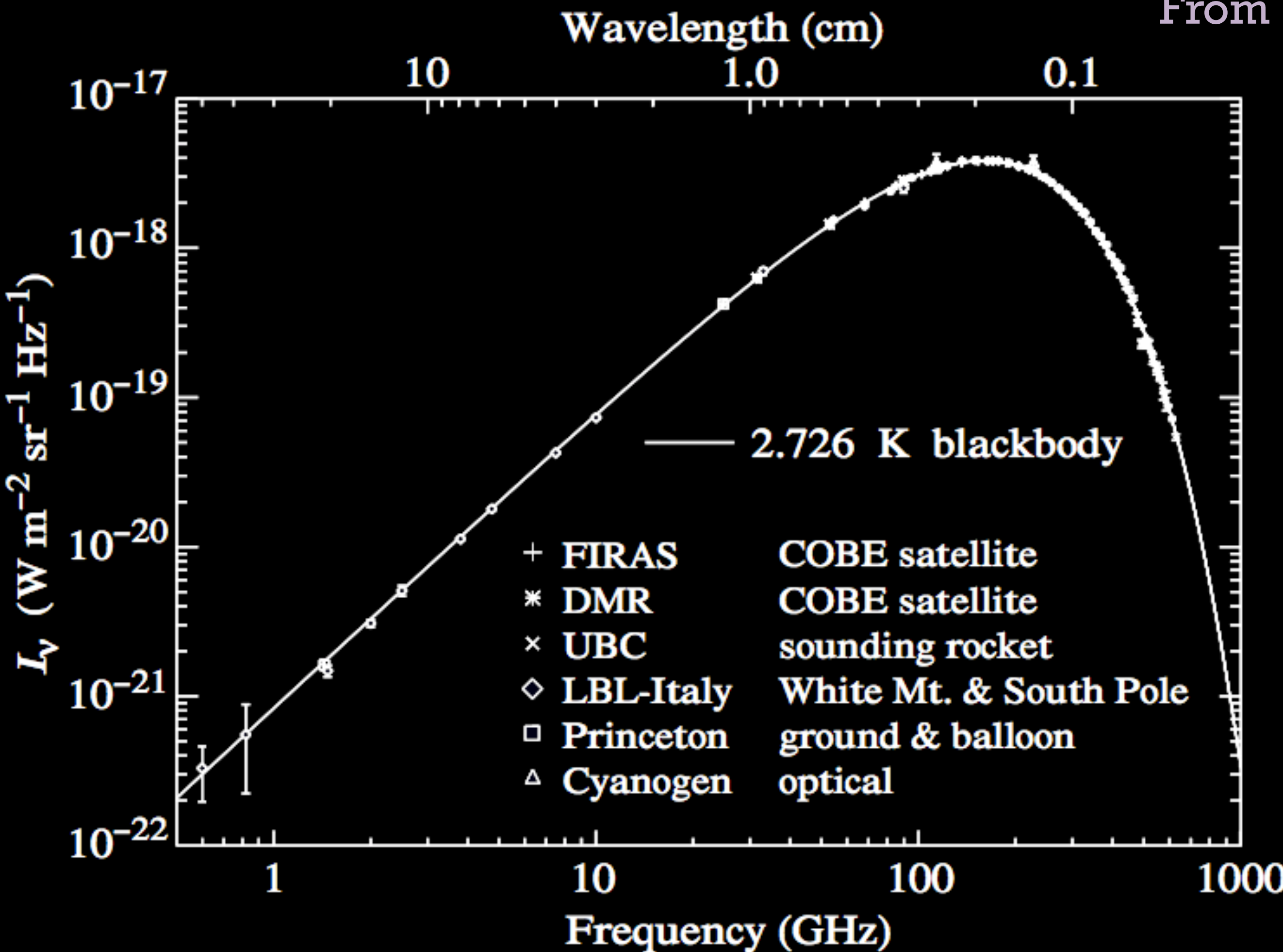
SLAC Summer Science Institute

The Cosmic Microwave Background



Fifty years of the CMB

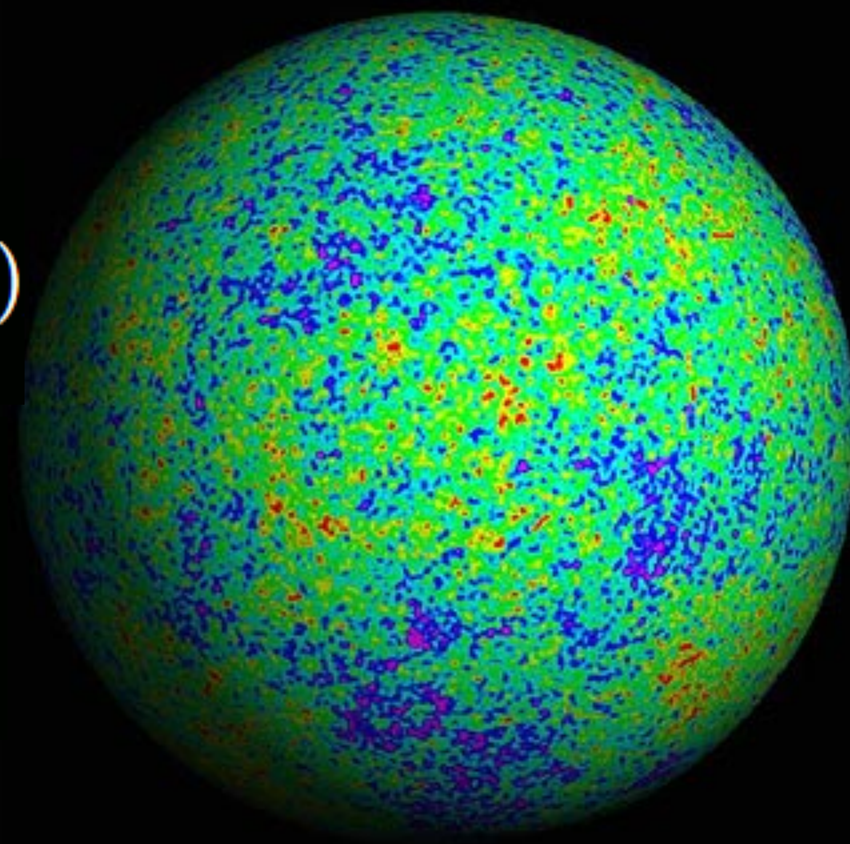
From George Smoot



The Cosmic Microwave Background

$$T(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}})$$

$$C_\ell = \frac{1}{(2\ell+1)} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}|^2 \rangle$$



CMB Power Spectrum

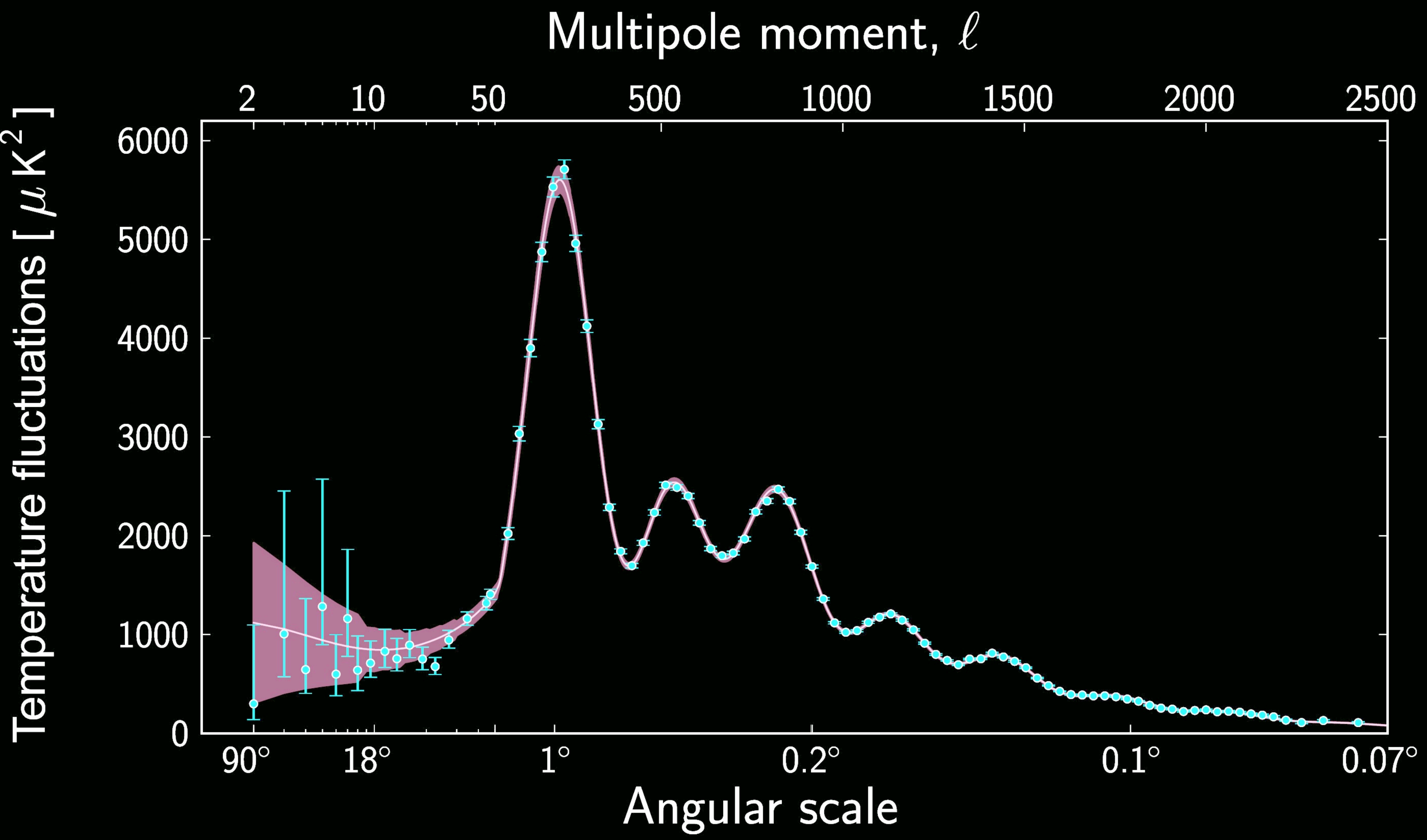
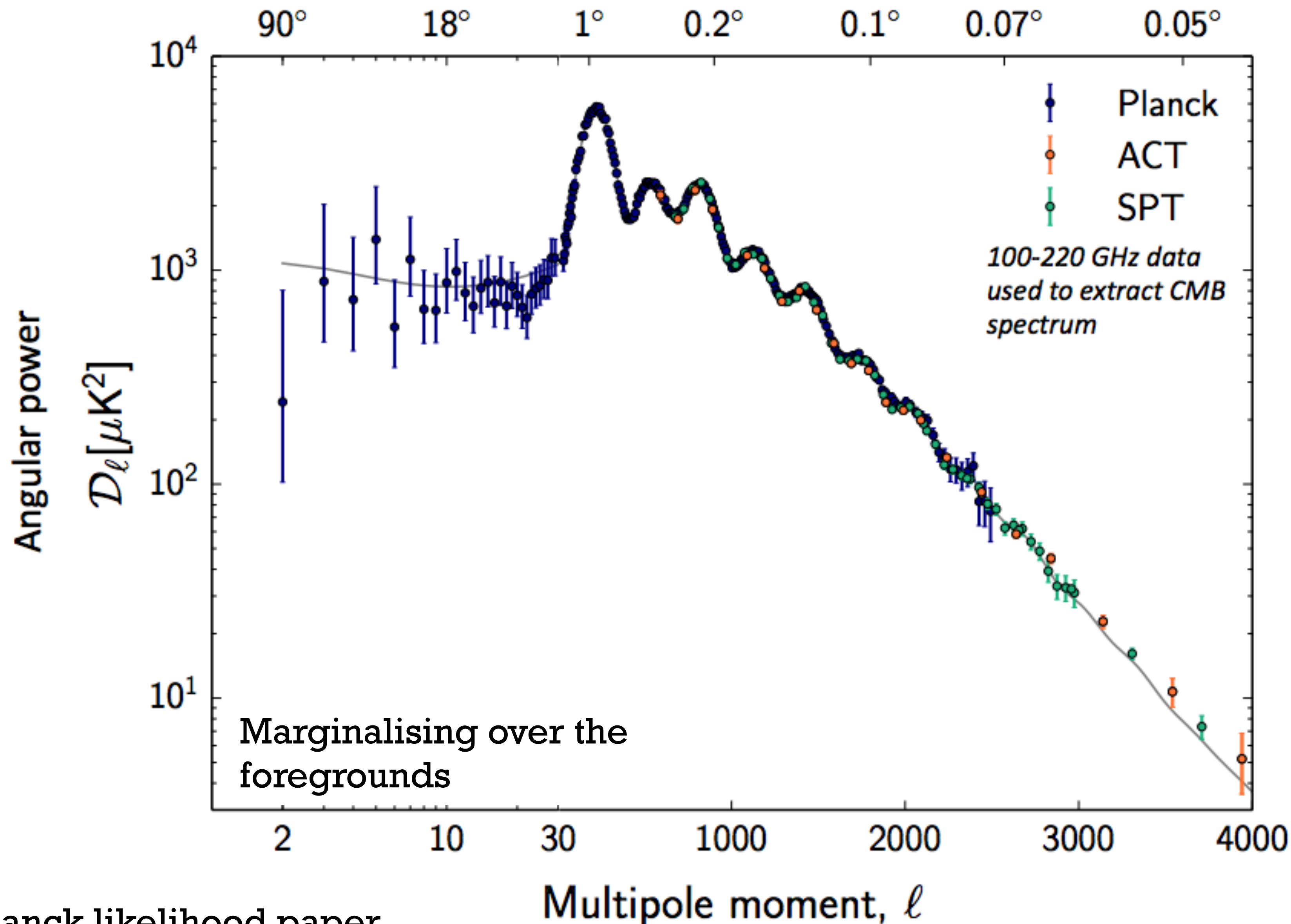


Image credit: Erminia Calabrese for Planck



Planck likelihood paper
1507.02704

Basic cosmological model

"Just 6 numbers":

$\Omega_b h^2$ $\Omega_c h^2$ Ω_Λ

$\Delta^2_{\mathcal{R}}$ n_s

Densities of the universe

Initial conditions

τ Reionization physics

The CMB on small scales allows us to test for deviations from the vanilla model

Neutrino constraints

Either parameterise via the effective number of neutrino species:

$$n_\nu = N_{\rm eff}\left(\frac{3}{4}\right)\left(\frac{4}{11}\right)n_\gamma;$$

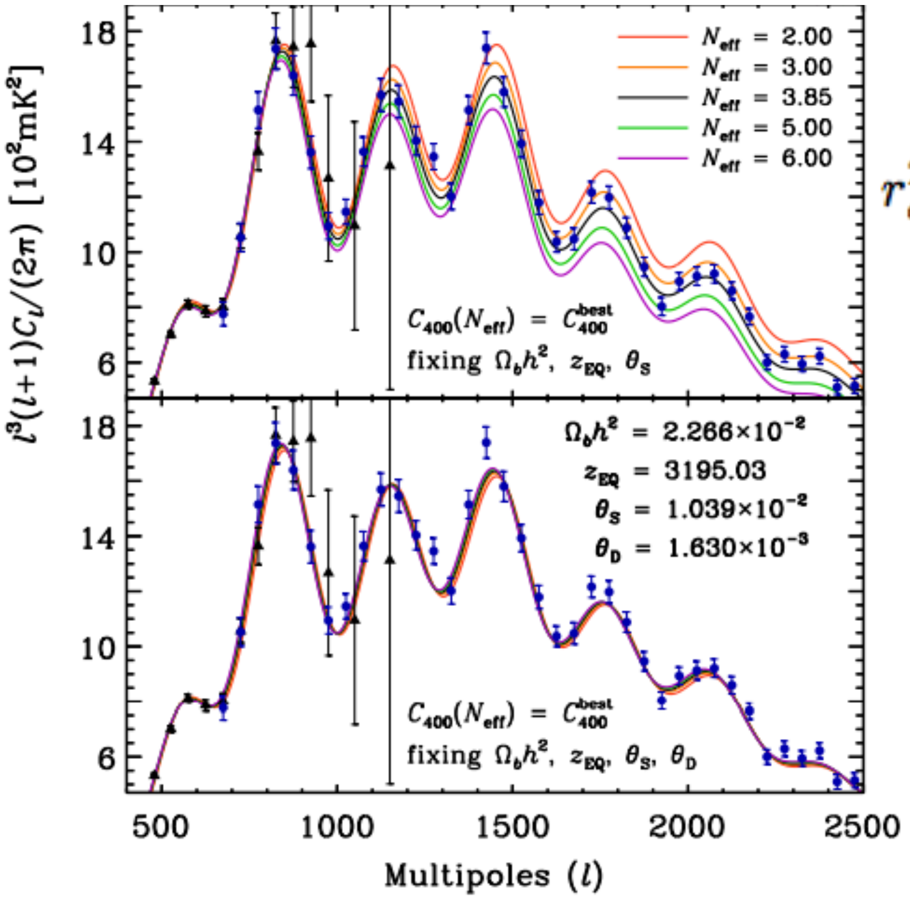
$$\rho_R = \left(1 + N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right)\rho_\gamma$$

or consider sum of the masses of the neutrino species (again through the energy density):

$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{93\ \text{eV}}$$

Largest effect is to change the expansion rate

Effective relativistic species



$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H} \left[\frac{R^2 + \frac{16}{15}(1+R)}{6(1+R^2)} \right]$$

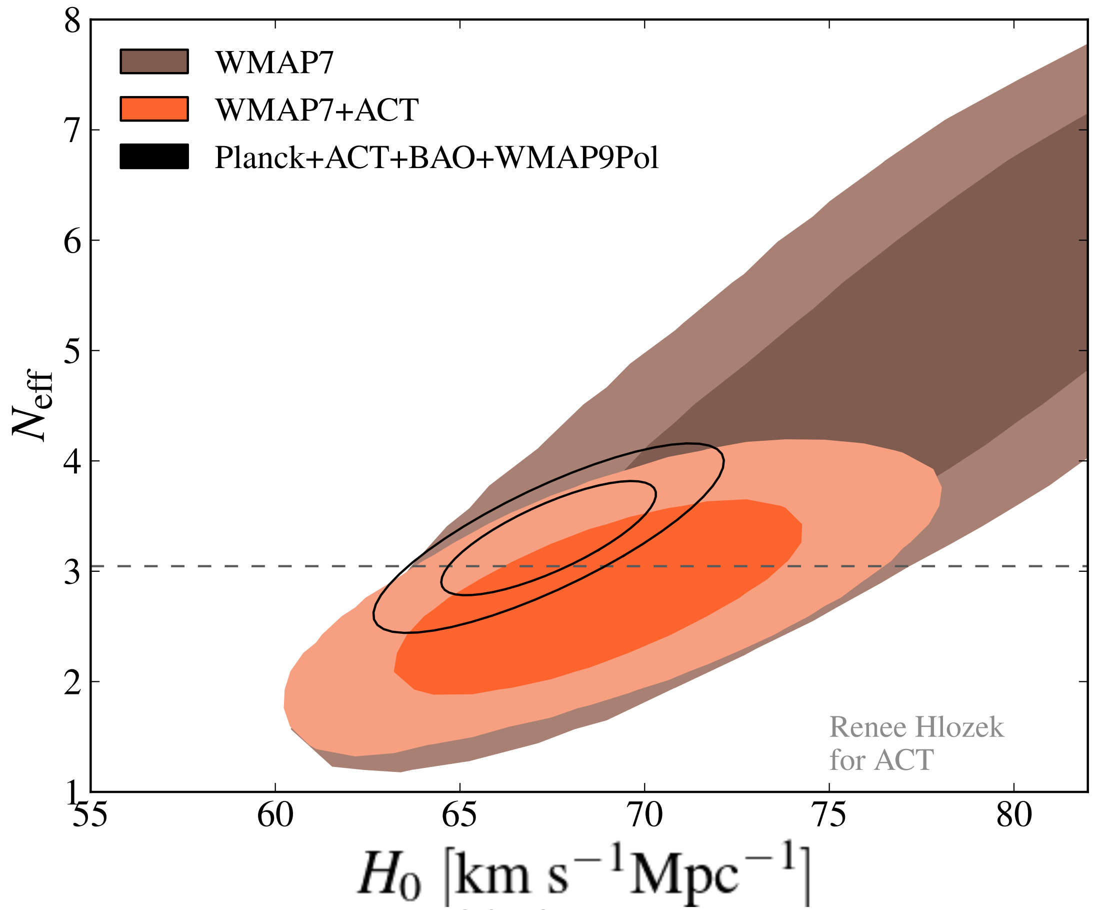
$$r_s = \int_0^{t_*} c_s\, dt/a = \int_0^{a_*} \frac{c_s\, da}{a^2 H}$$

$$R = 3\rho_b/(4\rho_\gamma)$$

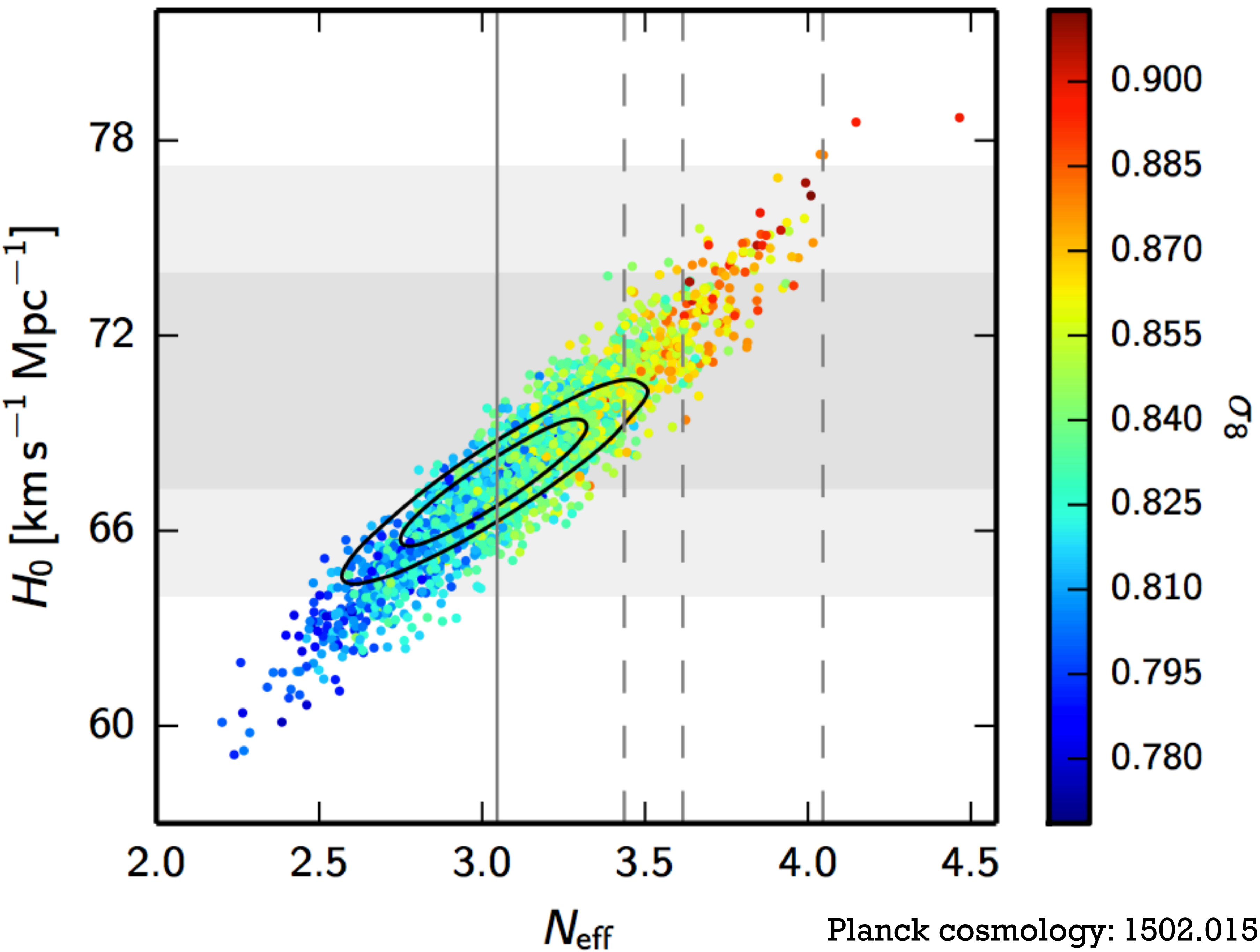
Hou, Keisler, Knox et al. 2011

Effective relativistic species

Consistent with 3 neutrino model.

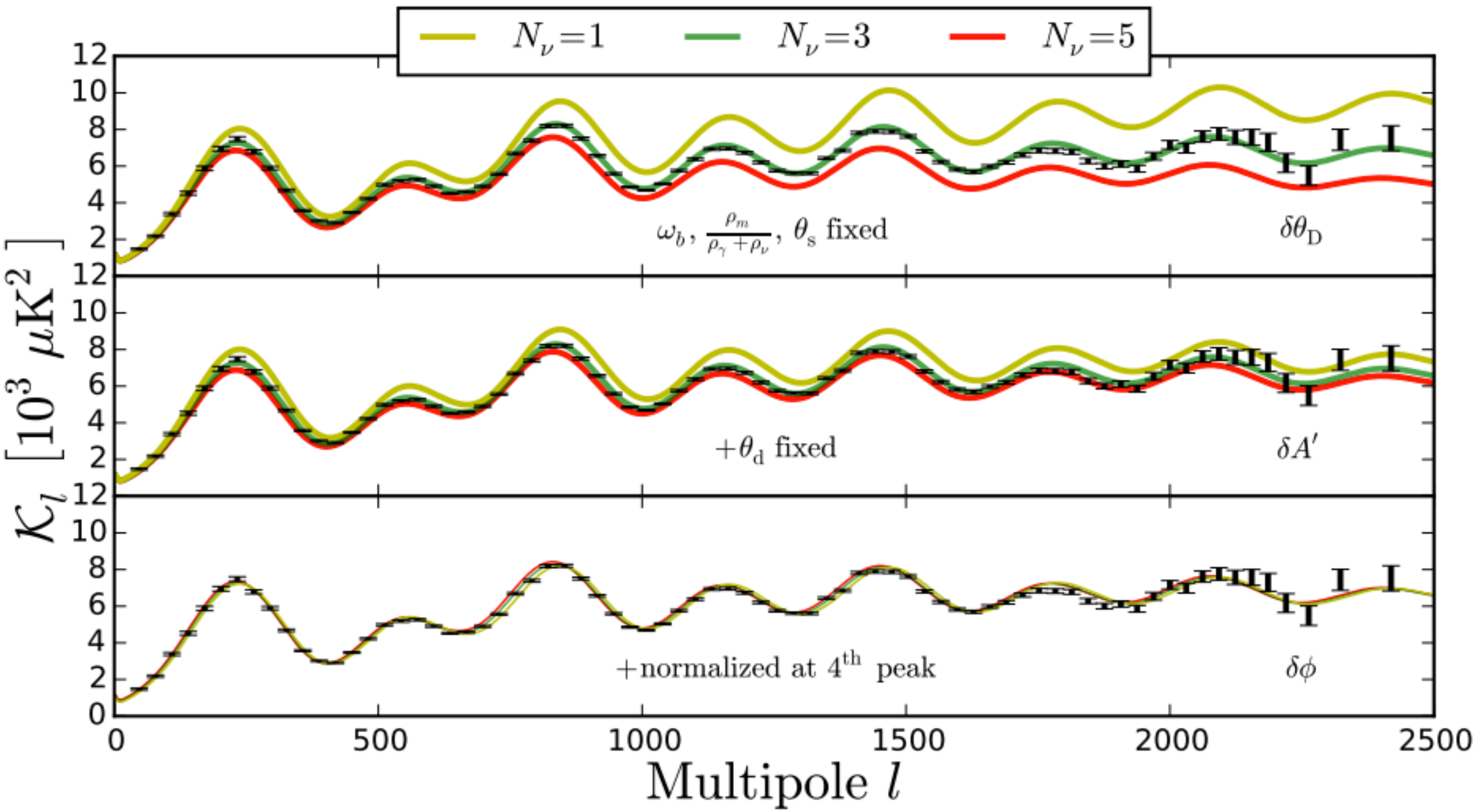


Sievers, Hlozek, Nolta et al. 2013

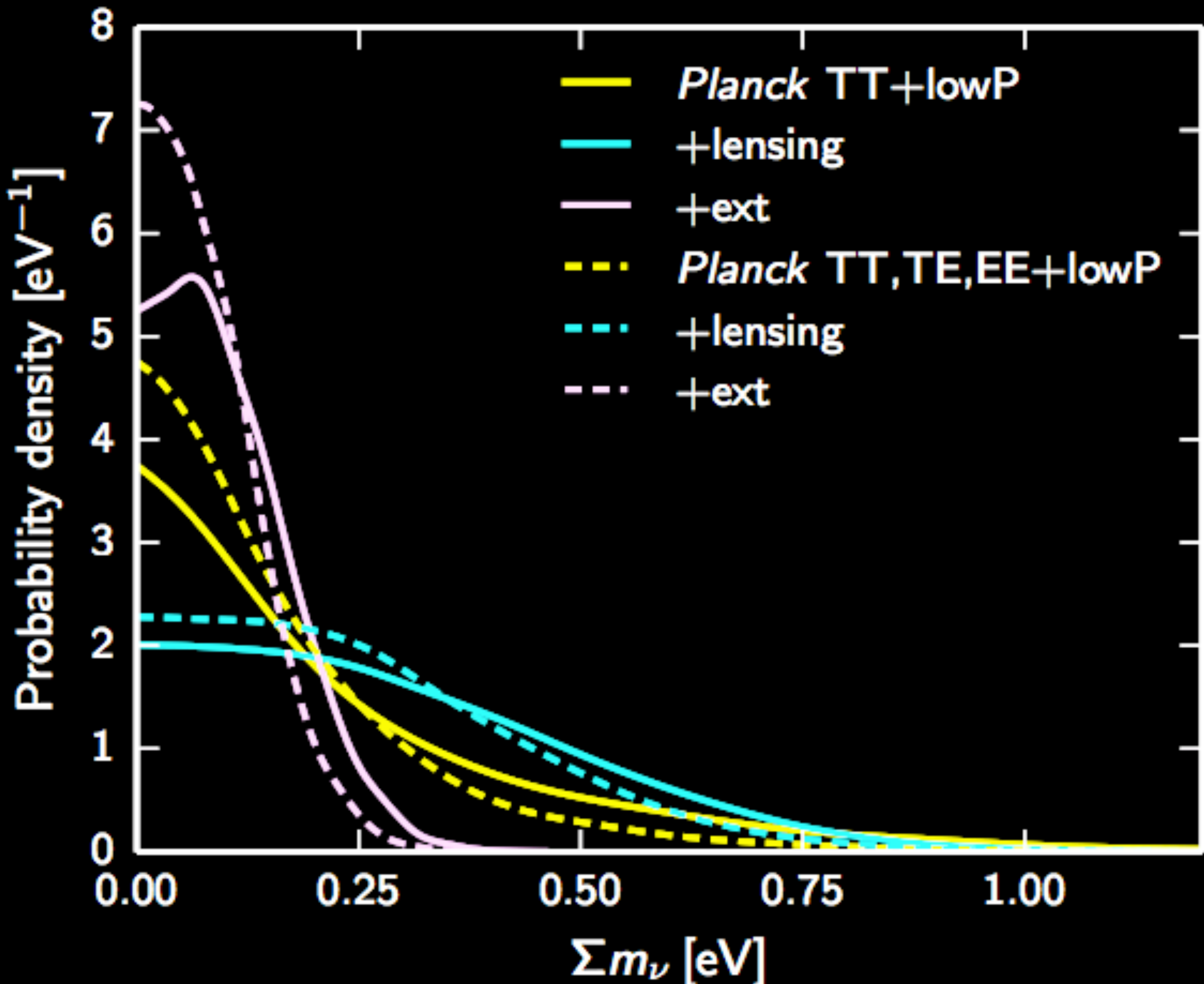


Planck cosmology: 1502.01589

Phase shift introduced at higher order



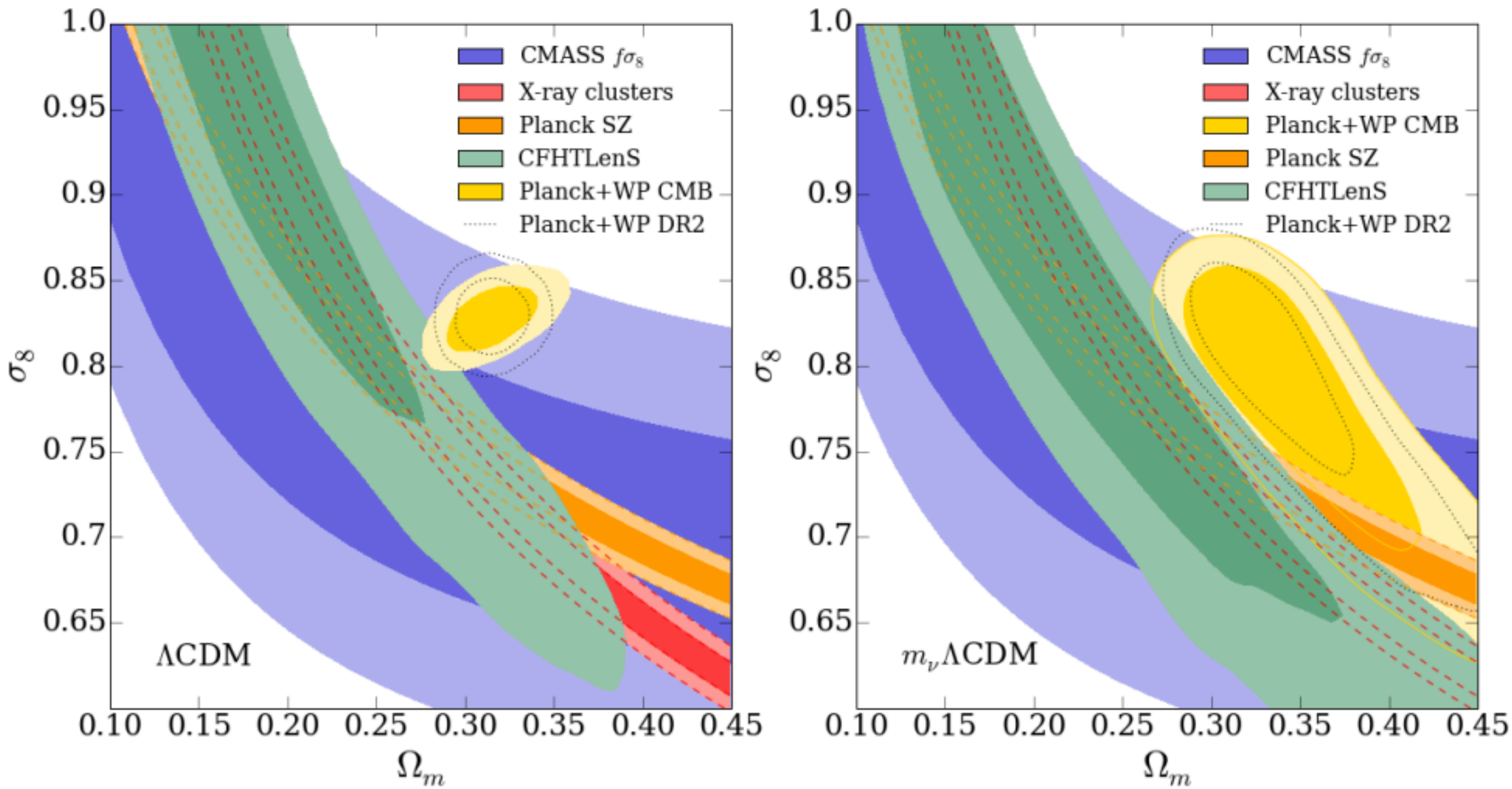
Frollin, Knox, Millea, Pan 2015



$$\sum m_\nu < 0.68 \text{ eV} \quad (95\%, \textit{Planck} \text{ TT+lowP+lensing}).$$

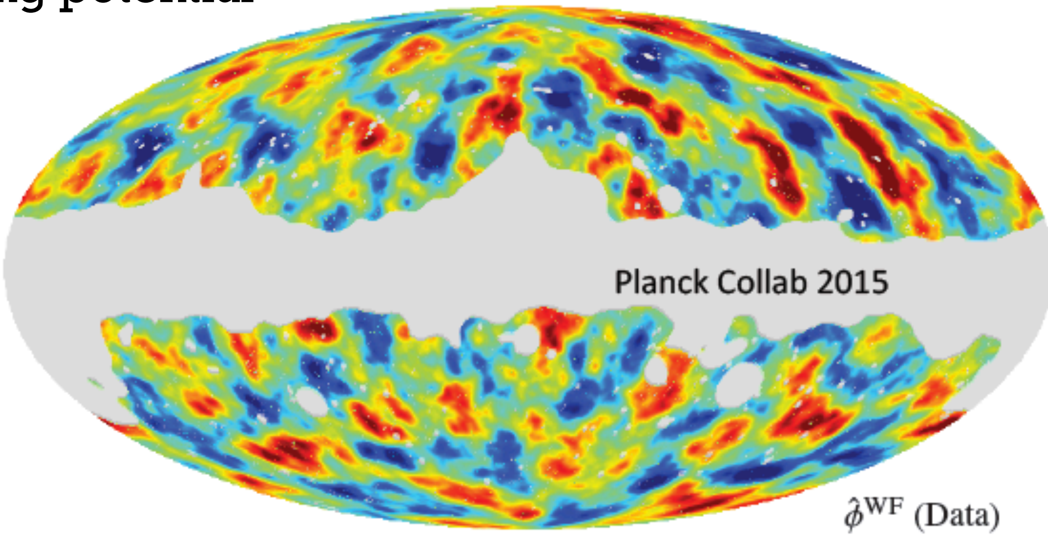
$$\left.\begin{aligned} \sum m_\nu &< 0.23 \text{ eV} \\ \Omega_\nu h^2 &< 0.0025 \end{aligned}\right\} \quad 95\%, \textit{Planck} \text{ TT+lowP+lensing+ext}.$$

Warning: neutrino mass 'mops' up systematics

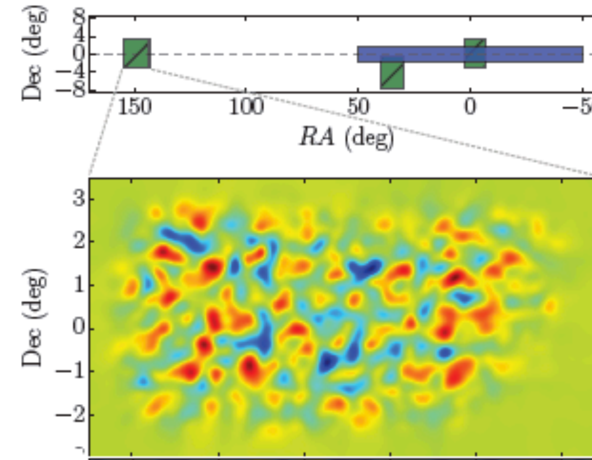


MacCrann et al. 2014

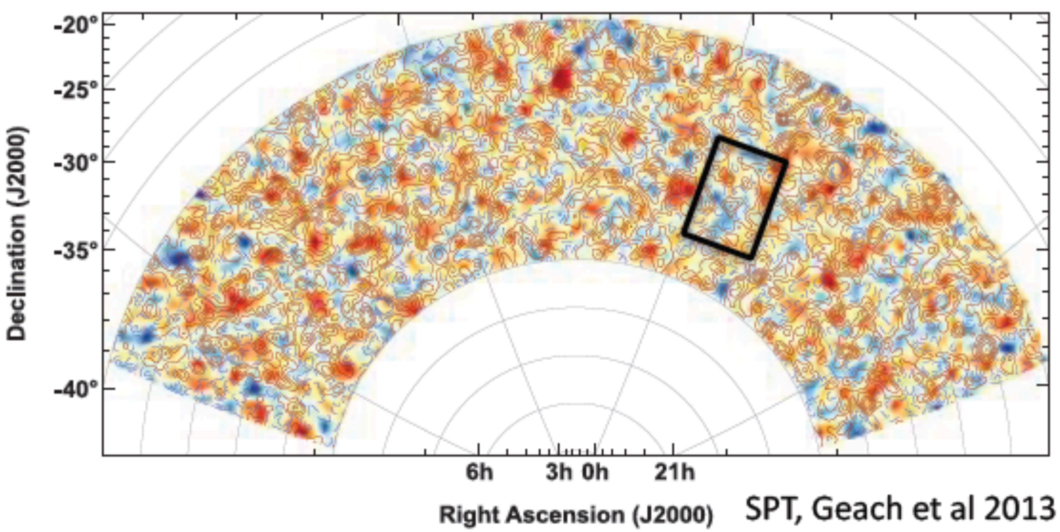
Lensing potential



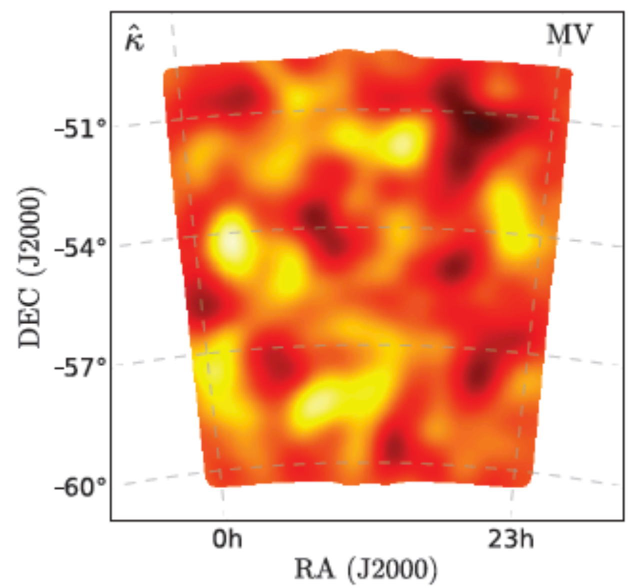
Planck Collab 2015



ACTPol, Allison et al 2015



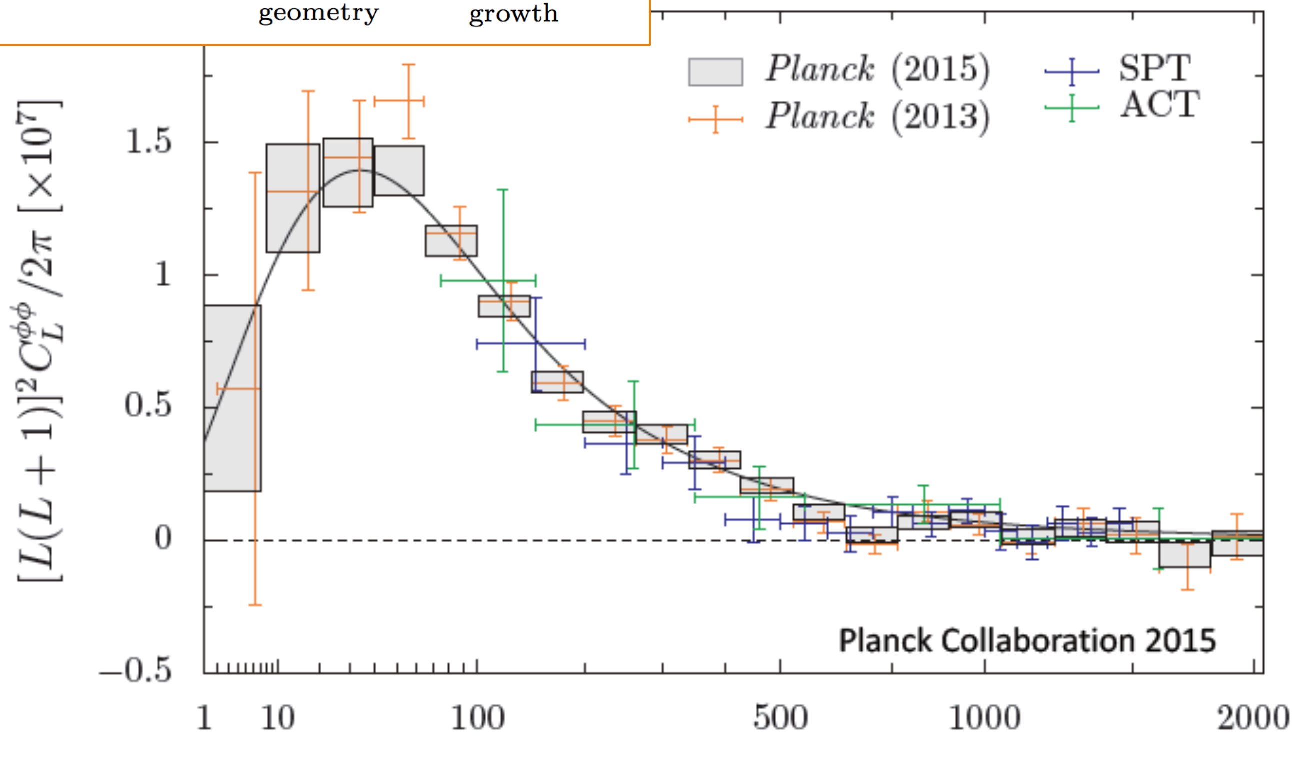
SPT, Geach et al 2013



SPTPol, Story et al 2015

$$\delta T(\mathbf{n}) = \delta\tilde{T}(\mathbf{n}+\mathbf{d})$$

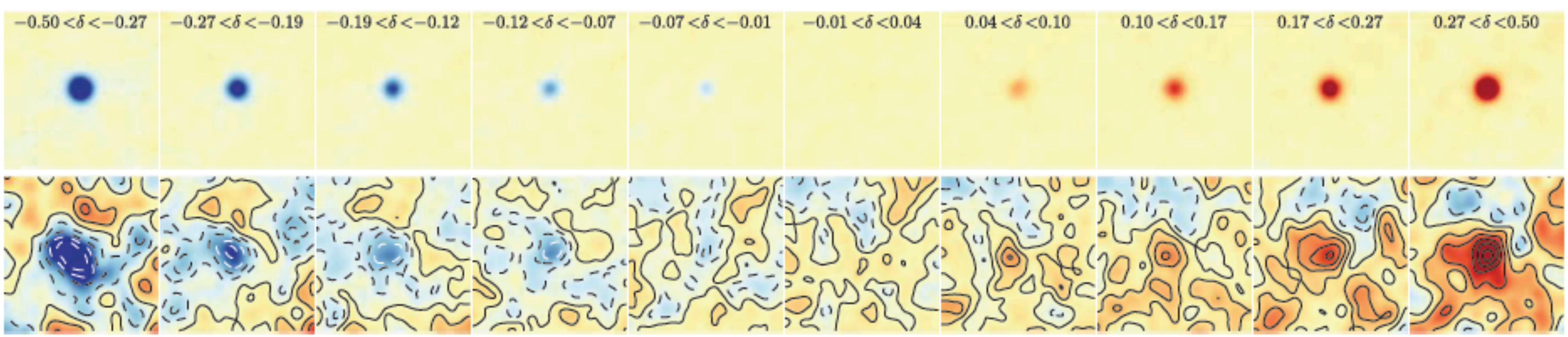
$$\frac{\ell^2}{4} C_\ell^{dd} = \int_0^{\eta_*} d\eta \underbrace{W^2(\eta)}_{\text{geometry}} \underbrace{\left[D(\eta)/a(\eta)\right]^2}_{\text{growth}}$$



CMB lensing constrains neutrino mass to < 0.7 eV

POLARBEAR detected EE/EB lensing a 4 sigma (2014)

4-pt reconstruction but also in cross-correlation



WISE quasars: $b_{\rm fixed} = 1.61 \pm 0.22$

One example: SPTPol (Greach et al. 2015)

Anisotropies to Polarisation

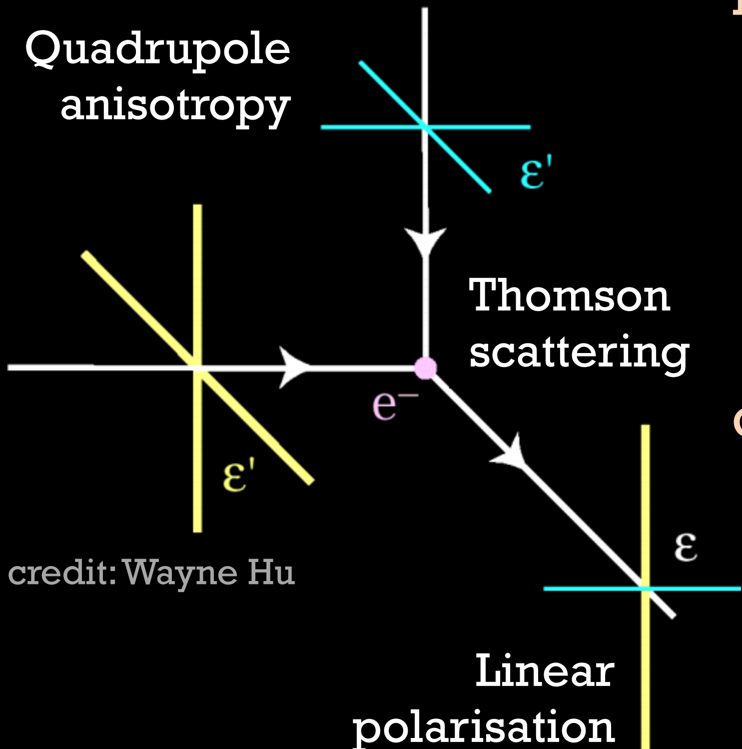
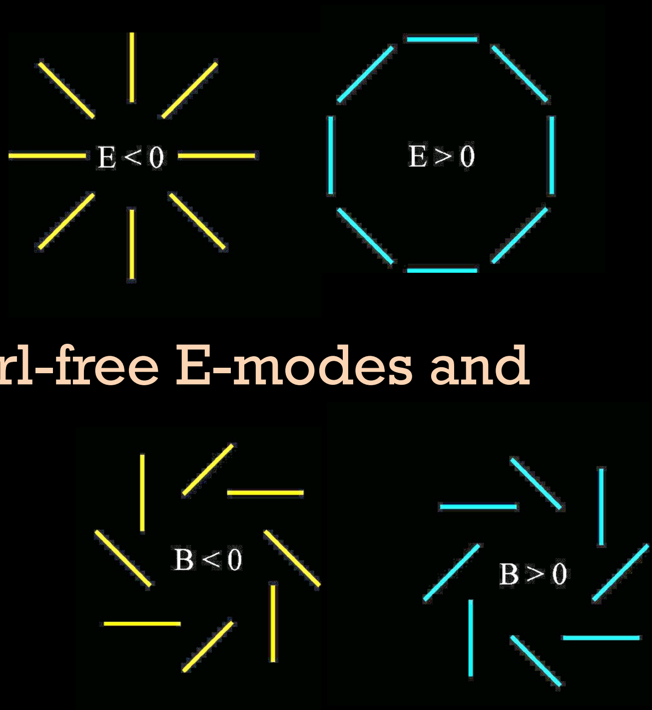


Image credit: Wayne Hu

Polarisation pattern decomposed into:

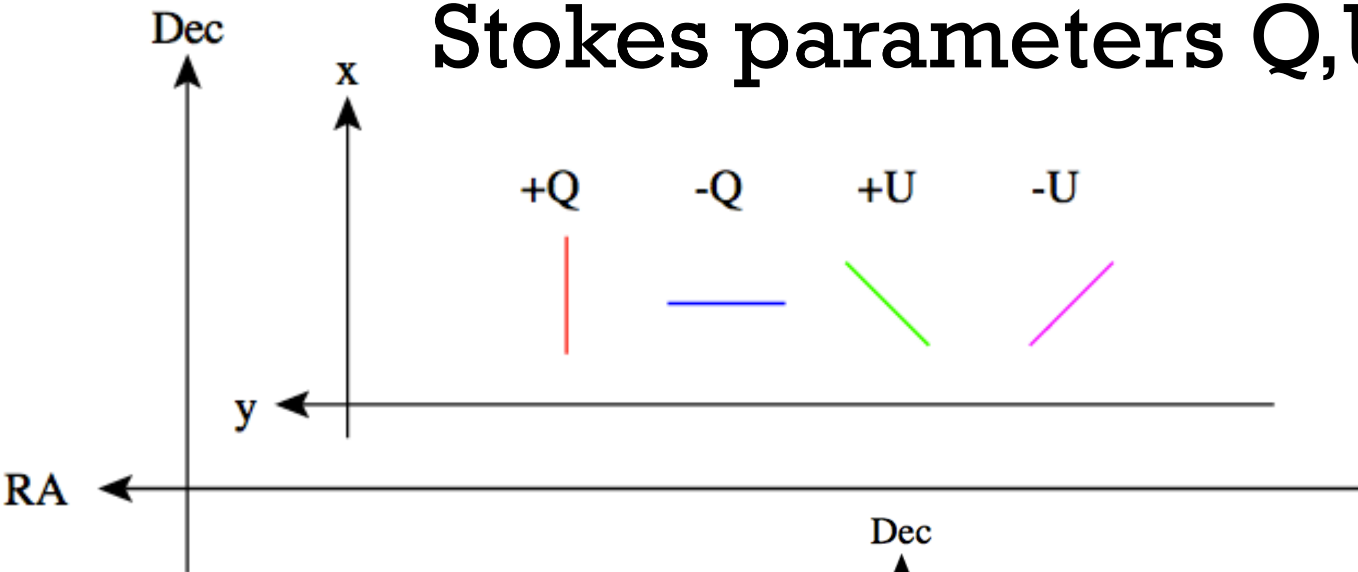


curl-free E-modes and

divergence-free B modes

$$\mathcal{P}_{ab} = \nabla_{\langle a}\nabla_{b\rangle} P_E - \epsilon^{c}{}_{(a}\nabla_{b)}\nabla_c P_B$$

Relating E, B to Stokes parameters Q,U



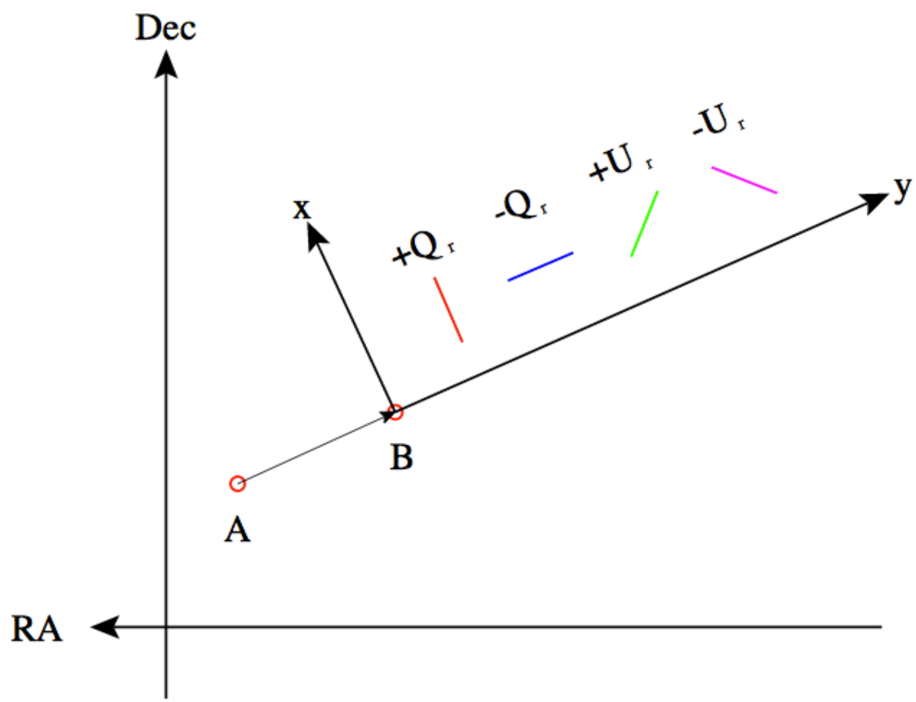
Express linear polarisation with a basis
$\underline{\mathbf{E}} = \mathbf{E}_x \, \underline{\mathbf{e}_x} + \mathbf{E}_y \, \underline{\mathbf{e}_y}$

Typically use Stokes parameters Q, U

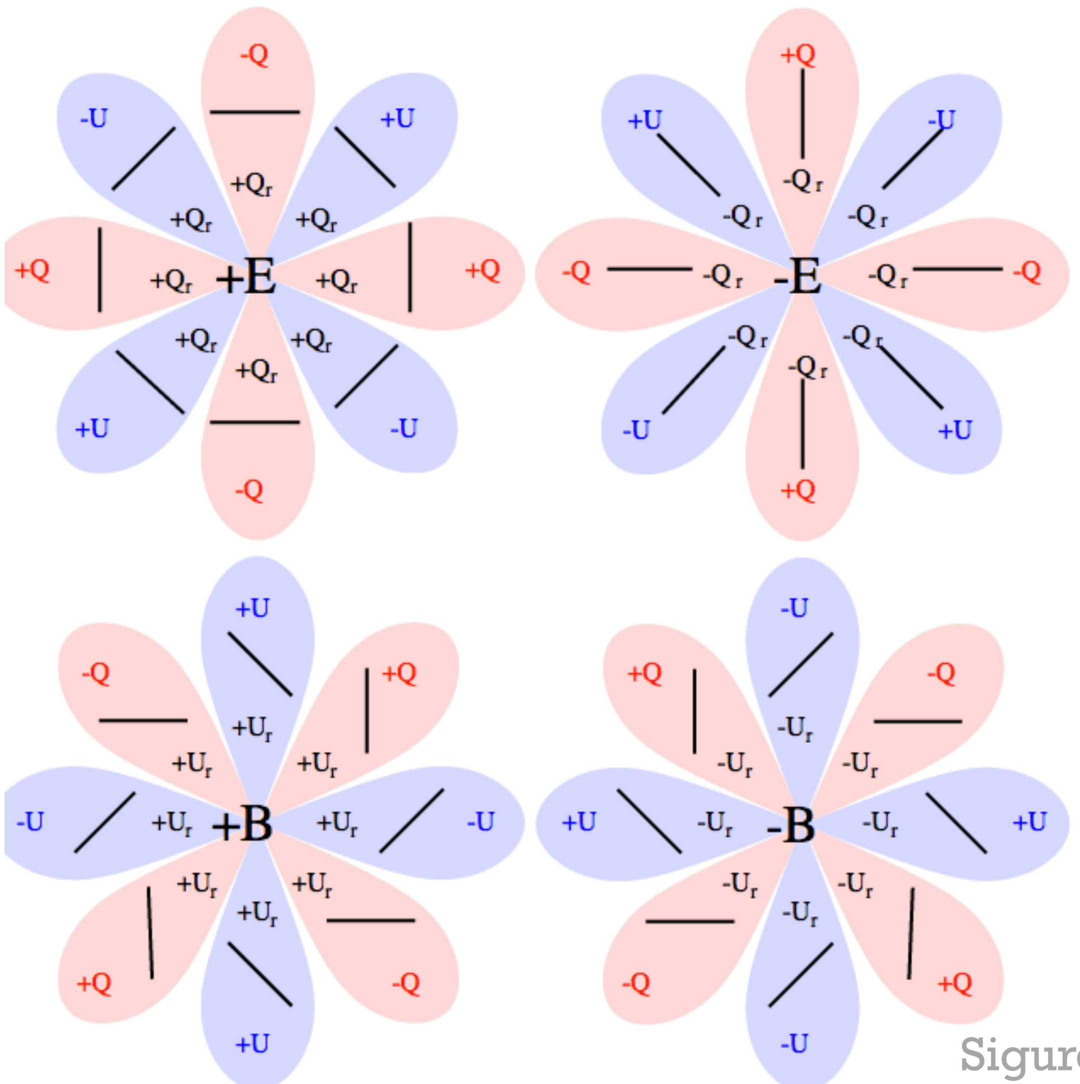
Stokes parameters at a point A (in polar coords)

$$E(A) \equiv \langle Q_{r(A)}(B) \rangle_B$$
$$B(A) \equiv \langle U_{r(A)}(B) \rangle_B$$

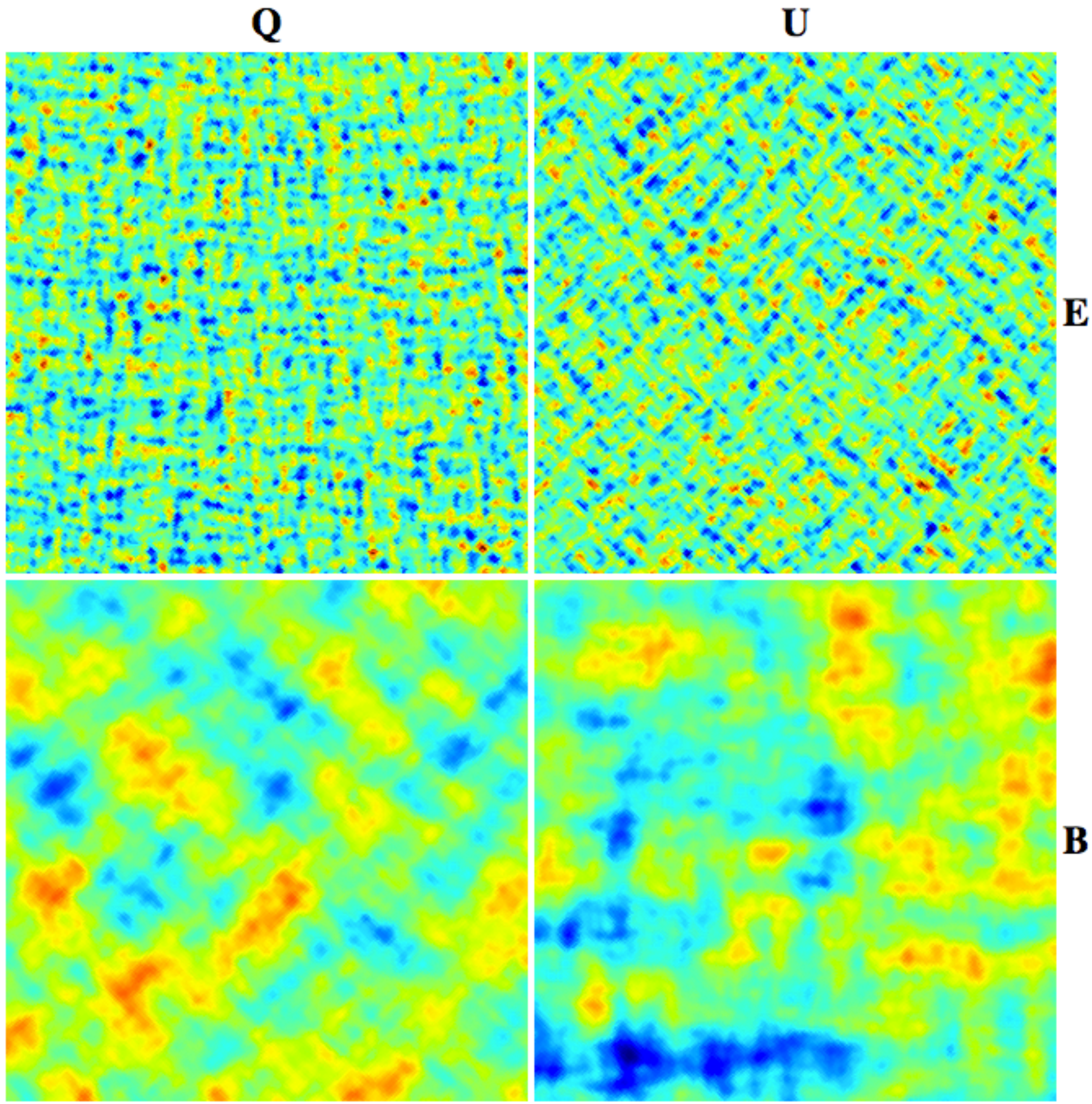
Brackets = radially weighed average over all points B



Relating E, B to Stokes parameters Q,U



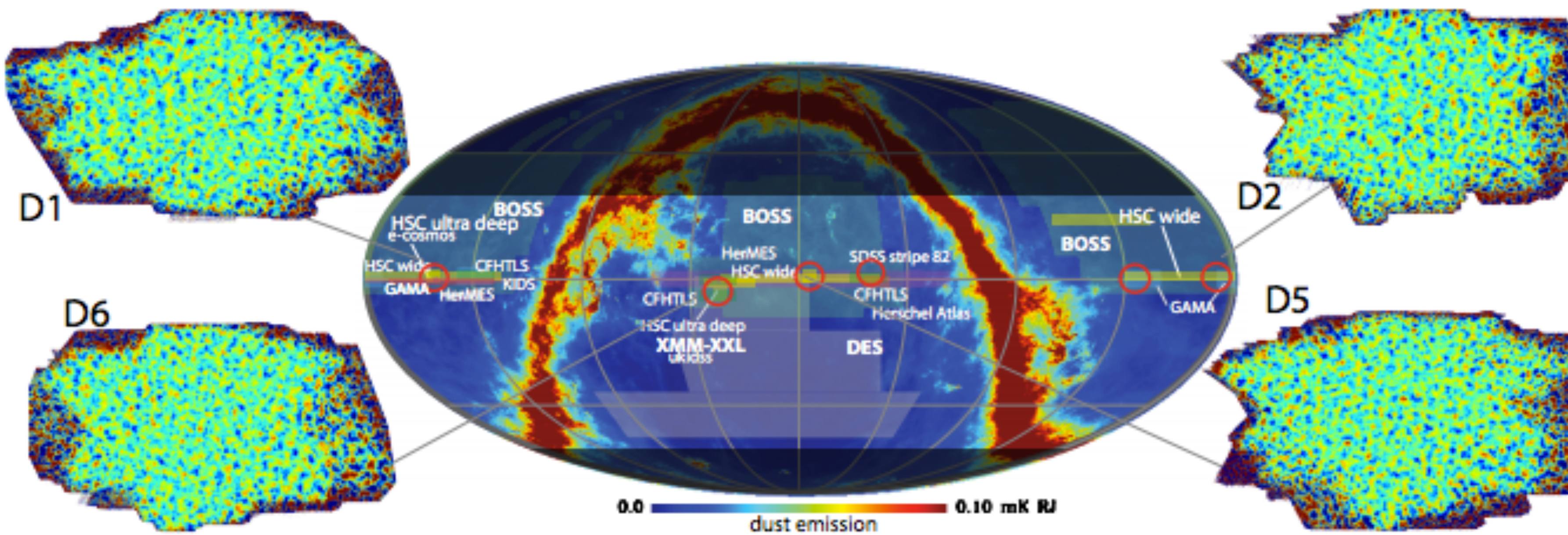
Sigurd Naess for ACTPol


Q
U
E
B

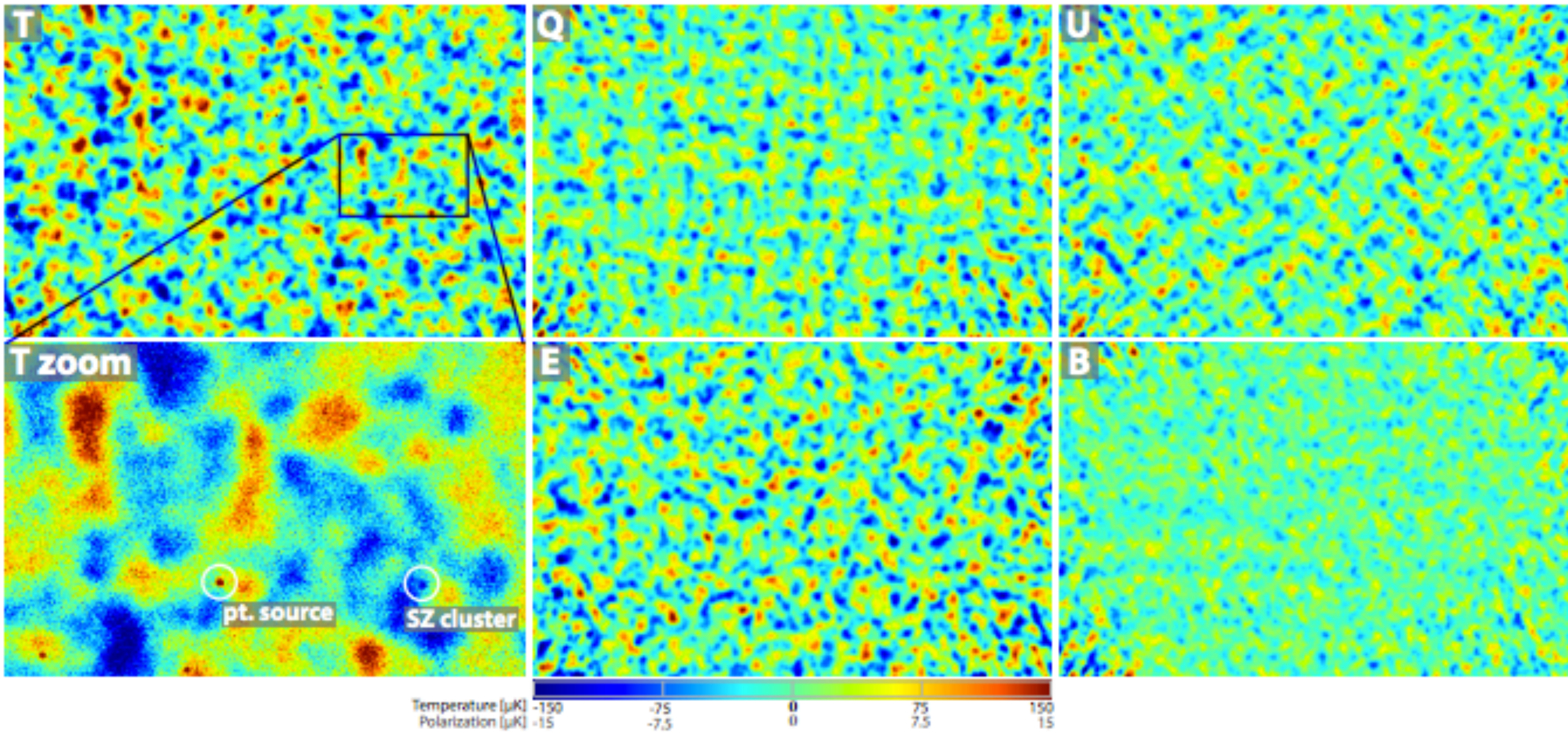
THE ATACAMA COSMOLOGY TELESCOPE: CMB POLARIZATION AT $200 < \ell < 9000$

Sigurd Naess[1], Matthew Hasselfield[2,3], Jeff McMahon[4], Michael D. Niemack[5], Graeme E. Addison[3], Peter A. R. Ade[6], Rupert Allison[1], Mandana Amiri[3], Andrew Baker[7], Nick Battaglia[8], James A. Beall[9], Francesco de Bernardis[5], J Richard Bond[10], Joe Britton[9], Erminia Calabrese[1], Hsiao-mei Cho[9], Kevin Coughlin[4], Devin Crichton[11], Sudeep Das[12], Rahul Datta[4], Mark J. Devlin[13], Simon R. Dicker[13], Joanna Dunkley[1], Rolando Dünner[14], Joseph W. Fowler[9], Anna E. Fox[9], Patricio Gallardo[5,14], Emily Grace[15], Megan Gralla[11], Amir Hajian[10], Mark Halpern[3], Shawn Henderson[5], J. Colin Hill[2], Gene C. Hilton[9], Matt Hilton[16], Adam D. Hincks[3], Renée Hlozek[2], Patty Ho[15], Johannes Hubmayr[9], Kevin M. Huffenberger[17], John P. Hughes[7], Leopoldo Infante[14], Kent Irwin[18], Rebecca Jackson[4,19], Jeff Klein[13], Brian Koopman[5], Arthur Kosowsky[20], Dale Li[9], Thibaut Louis[1], Marius Lungu[13], Mathew Madhavacheril[21], Tobias A. Marriage[11], Loïc Maurin[14], Felipe Menanteau[22,23], Kavilan Moodley[16], Charles Munson[4], Laura Newburgh[15], John Nibarger[9], Michael R. Nolta[10], Lyman A. Page[15], Christine Pappas[15], Bruce Partridge[24], Felipe Rojas[14], Benjamin Schmitt[13], Neelima Sehgal[21], Blake D. Sherwin[25], Jon Sievers[26,10], Sara Simon[15], David N. Spergel[2], Suzanne T. Staggs[15], Eric R. Switzer[27,10], Robert Thornton[28,13], Hy Trac[8], Carole Tucker[6], Alexander Van Engelen[21], Jon Ward[13], Edward J. Wollack[27]

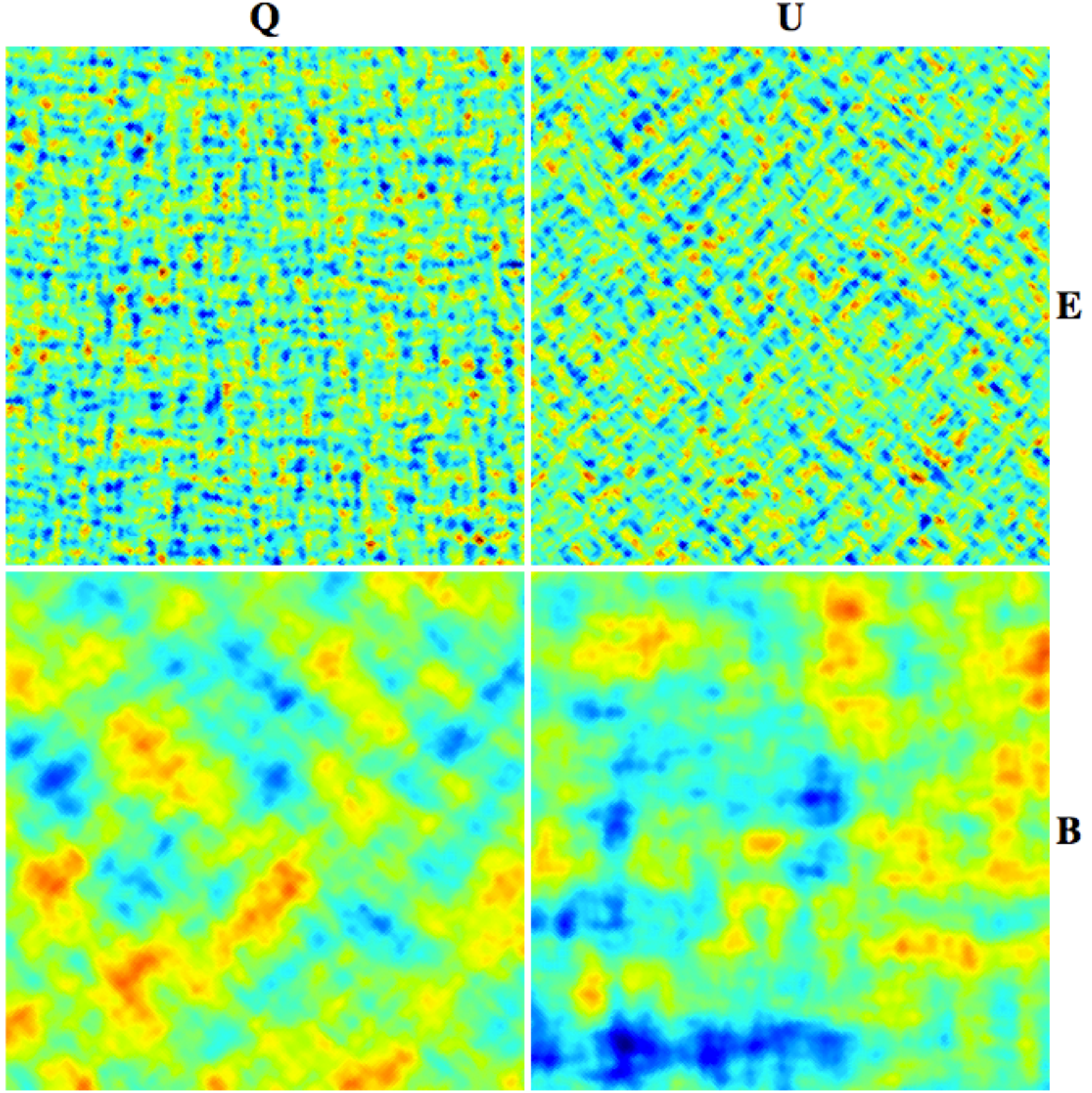
Draft: May 22, 2014



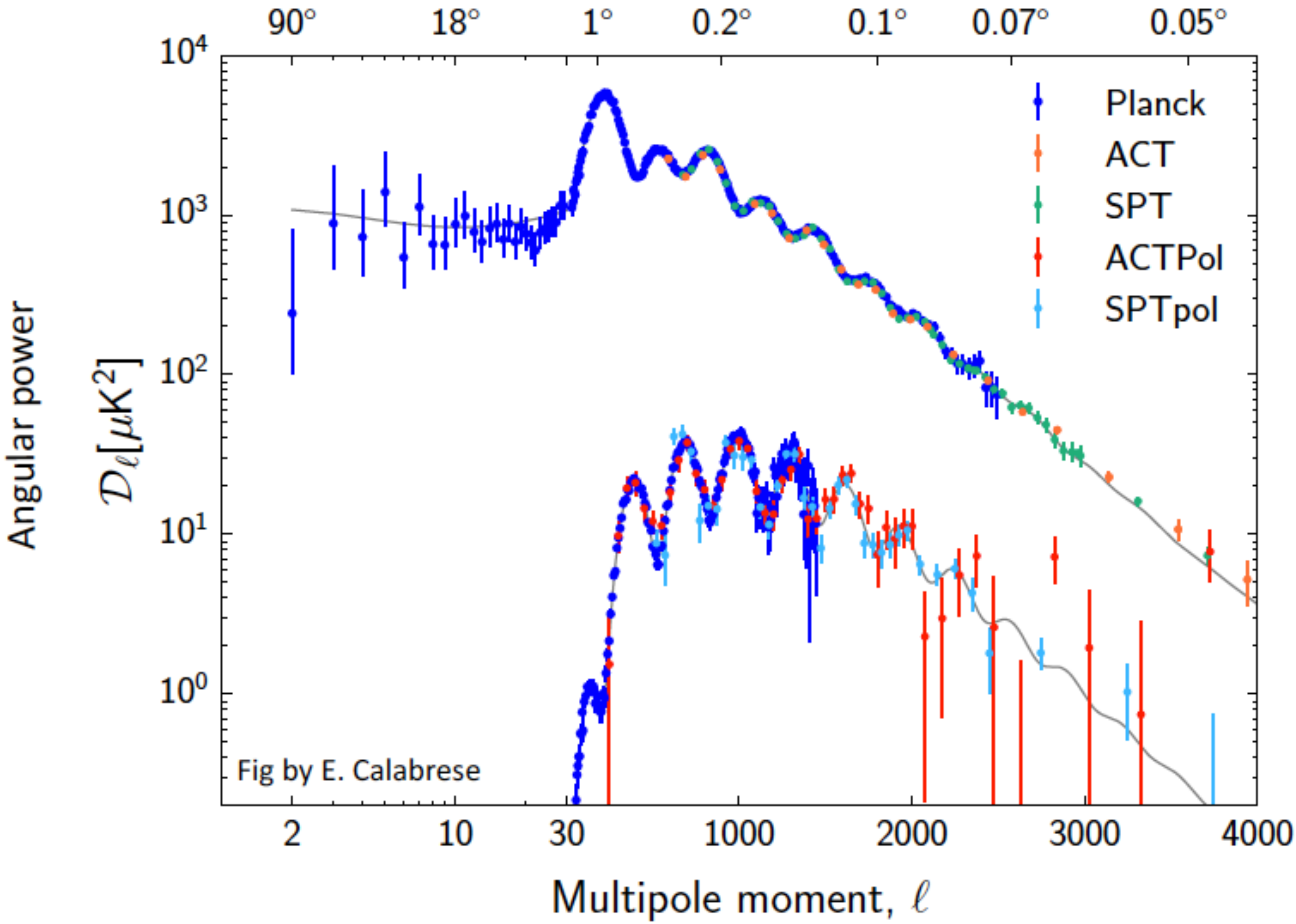
What the data look like



Naess et al. 2014

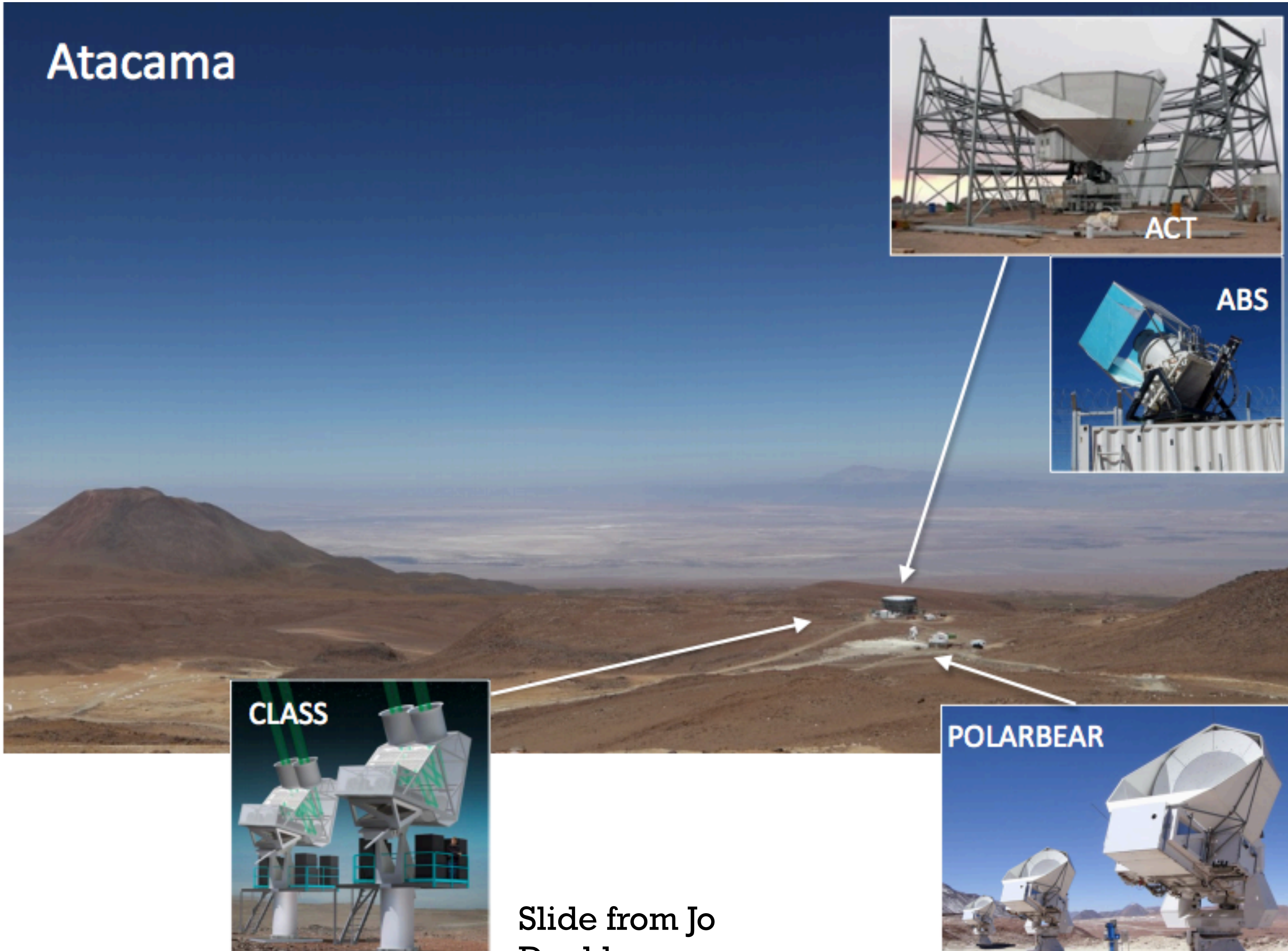


Q
U
E
B

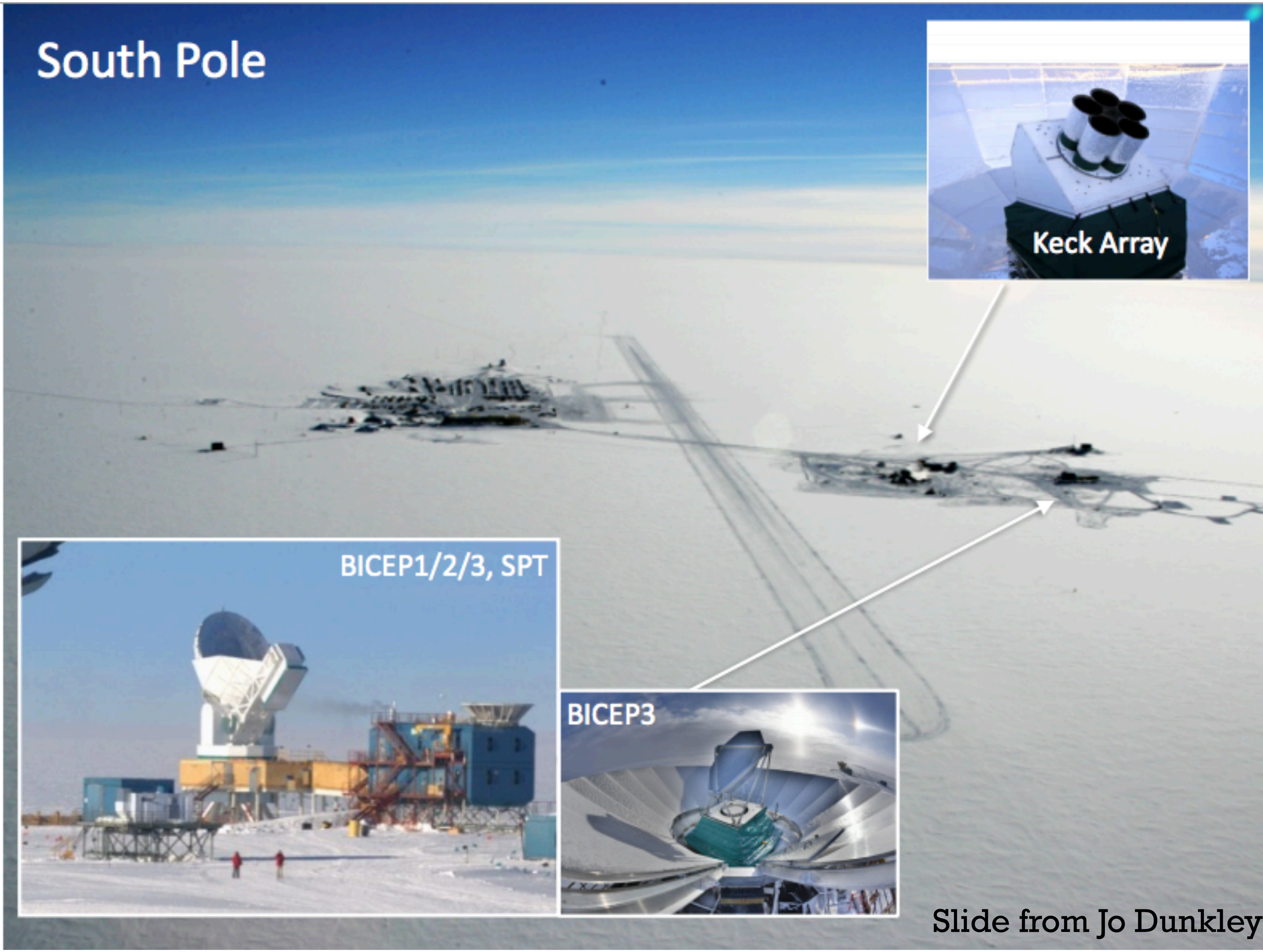


90°
18°
1°
0.2°
0.1°
0.07°
0.05°
10^4
10^3
10^2
10^1
10^0
Angular power
$\mathcal{D}_\ell [\mu K^2]$
Planck
ACT
SPT
ACTPol
SPTpol
Fig by E. Calabrese
2
10
30
1000
2000
3000
4000
Multipole moment, ℓ

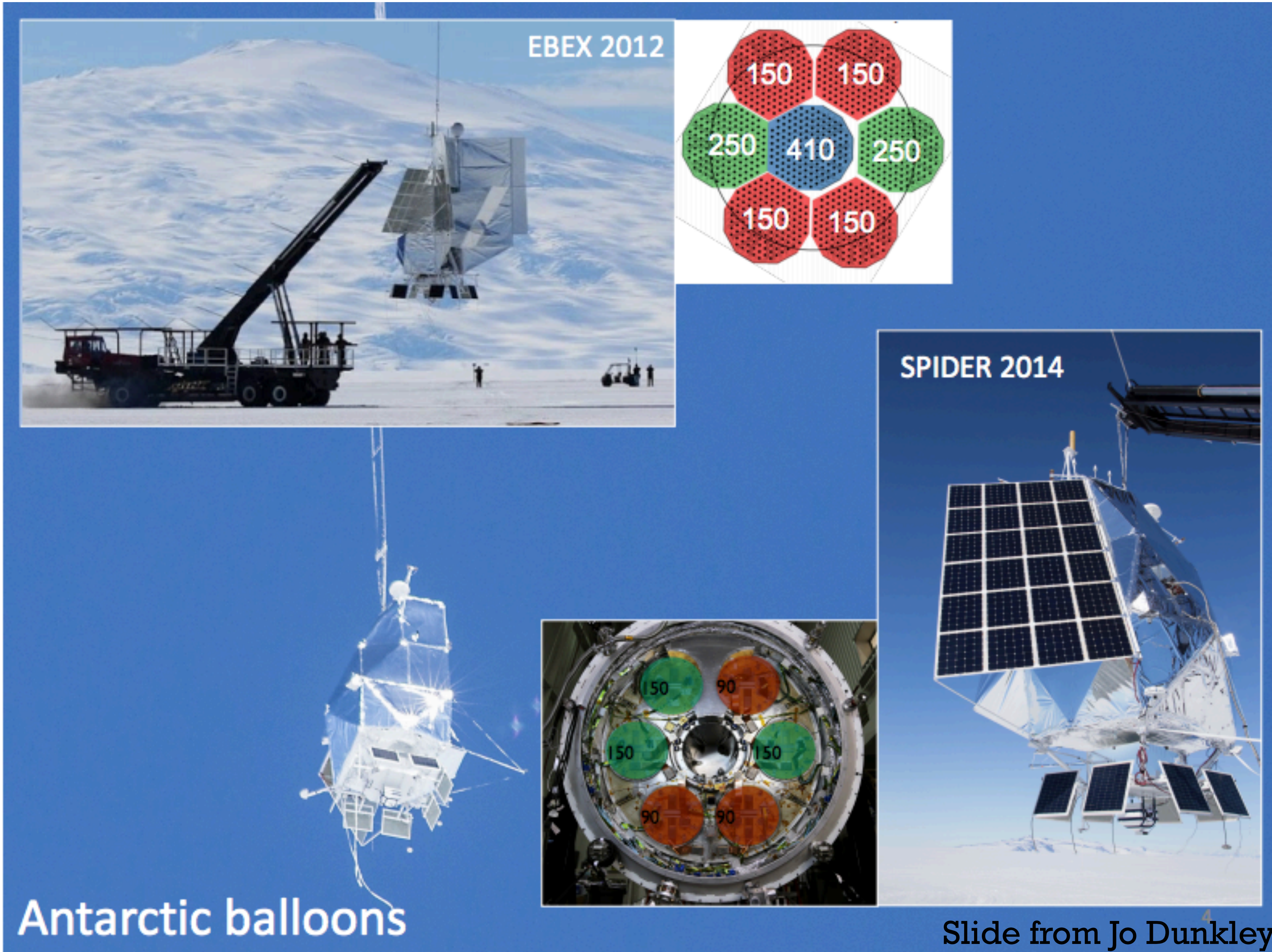
Neutrino constraints will improve greatly with future small-scale experiments



Slide from Jo Dunkley



Slide from Jo Dunkley

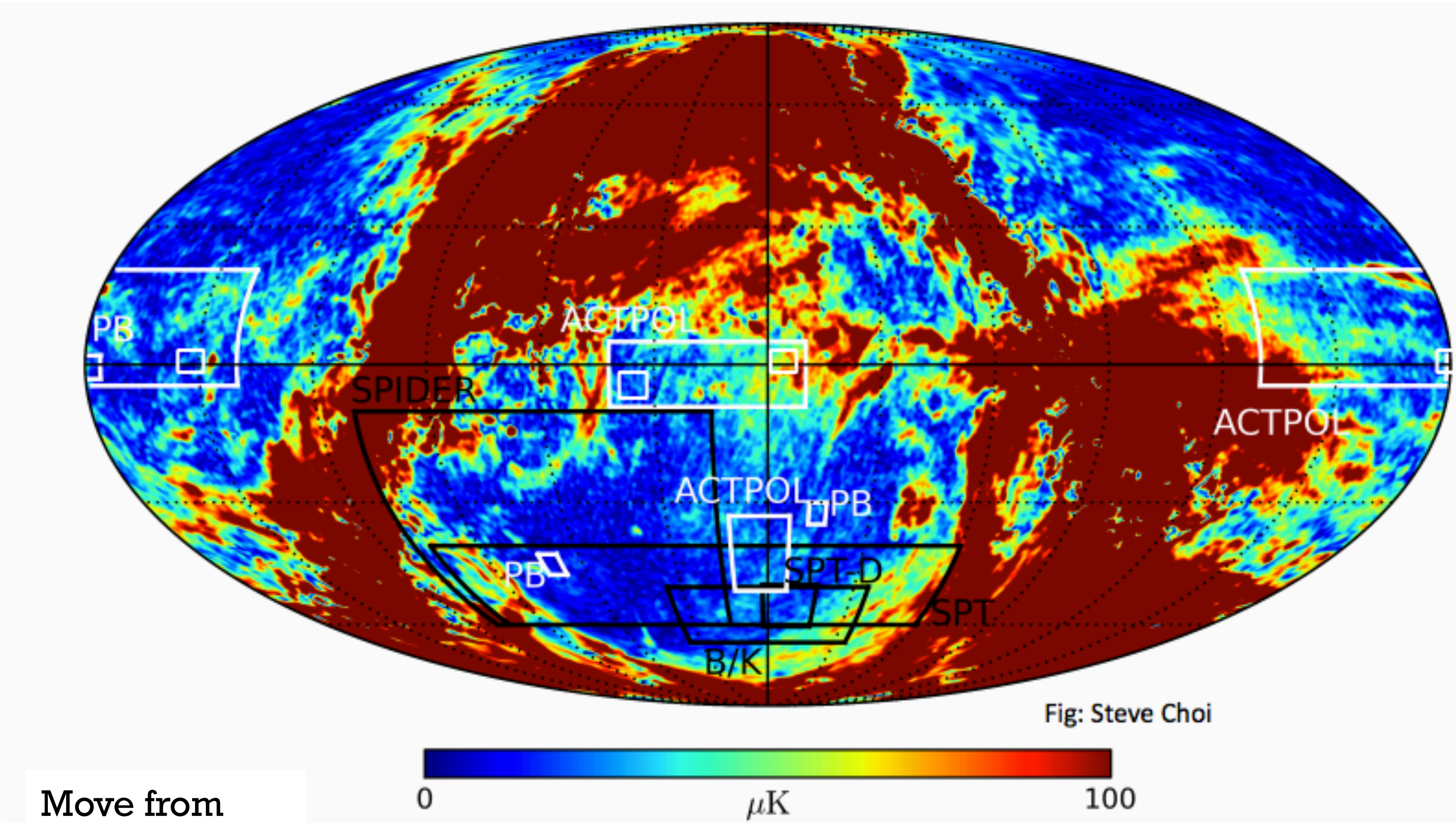

EBEX 2012
150
150
250
410
250
150
150
SPIDER 2014
150
90
150
150
90
90
Antarctic balloons
Slide from Jo Dunkley

California+
South Africa
C-BASS 5 GHz

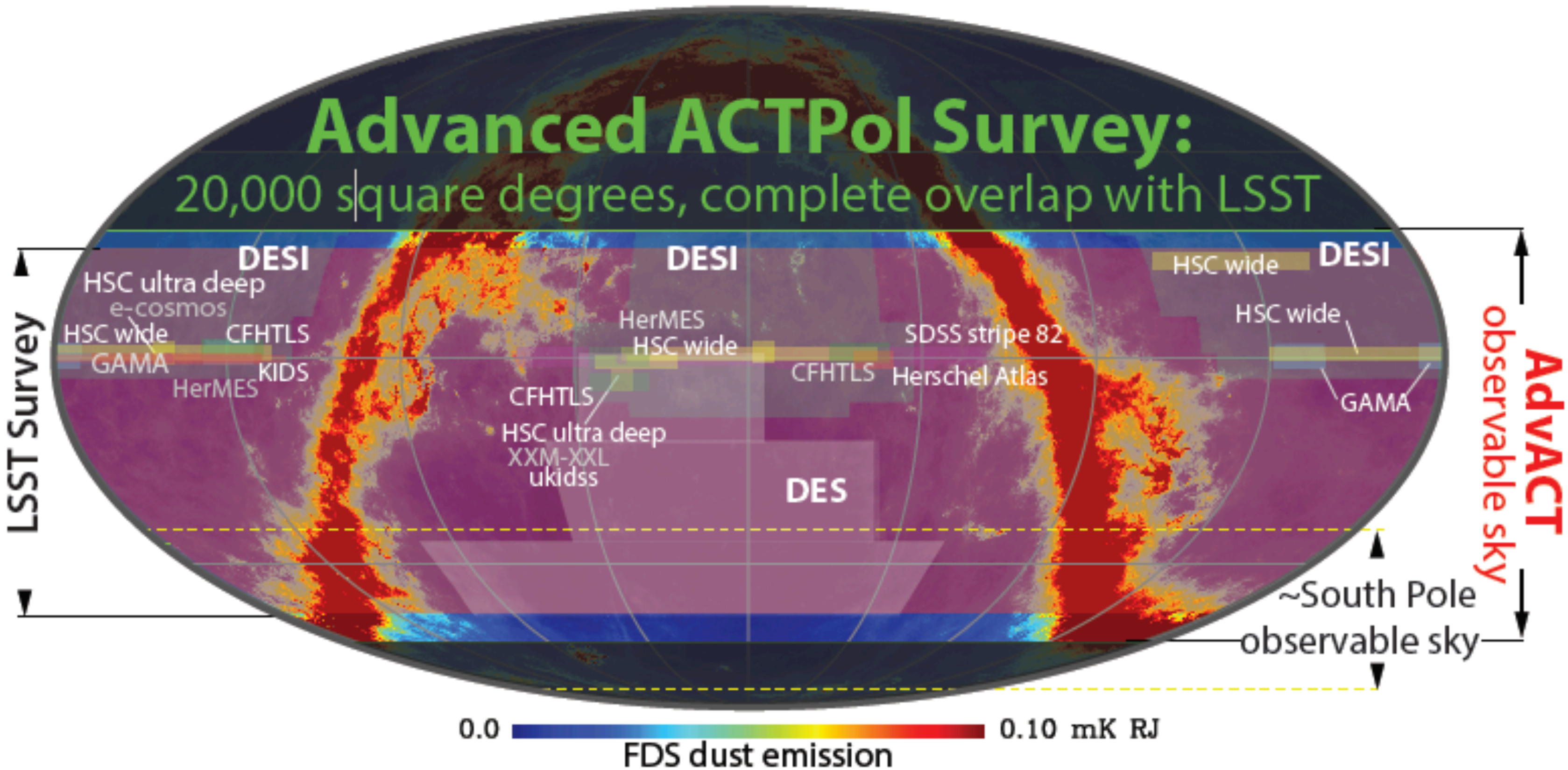
Tenerife (+South Africa?)
QUIJOTE 11, 13, 17, 19 GHz
(2015/16 - 30, 40 GHz)

California
B-Machine 40 GHz

Slide from Jo Dunkley

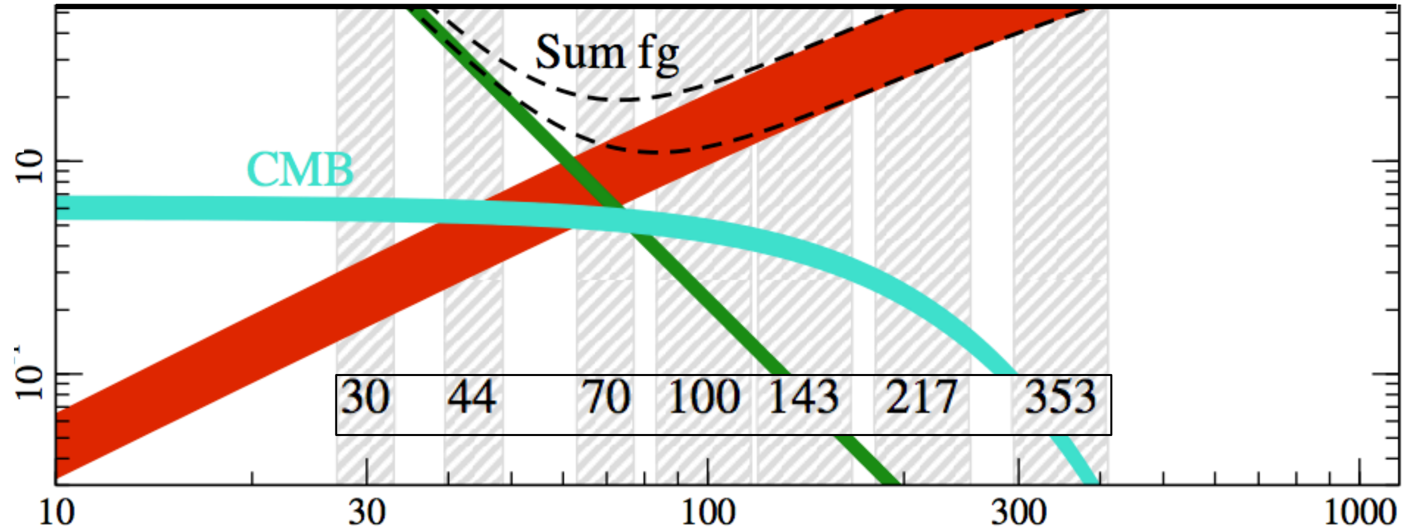


Move from smaller patches currently



To larger surveys over much of the sky

2016 - 2019



30’ CLASS
3’ Simons Array
1’ AdvACT
Atacama

30’ BICEP3
3’ SPT-3G
1’ QUBIC
Antarctica

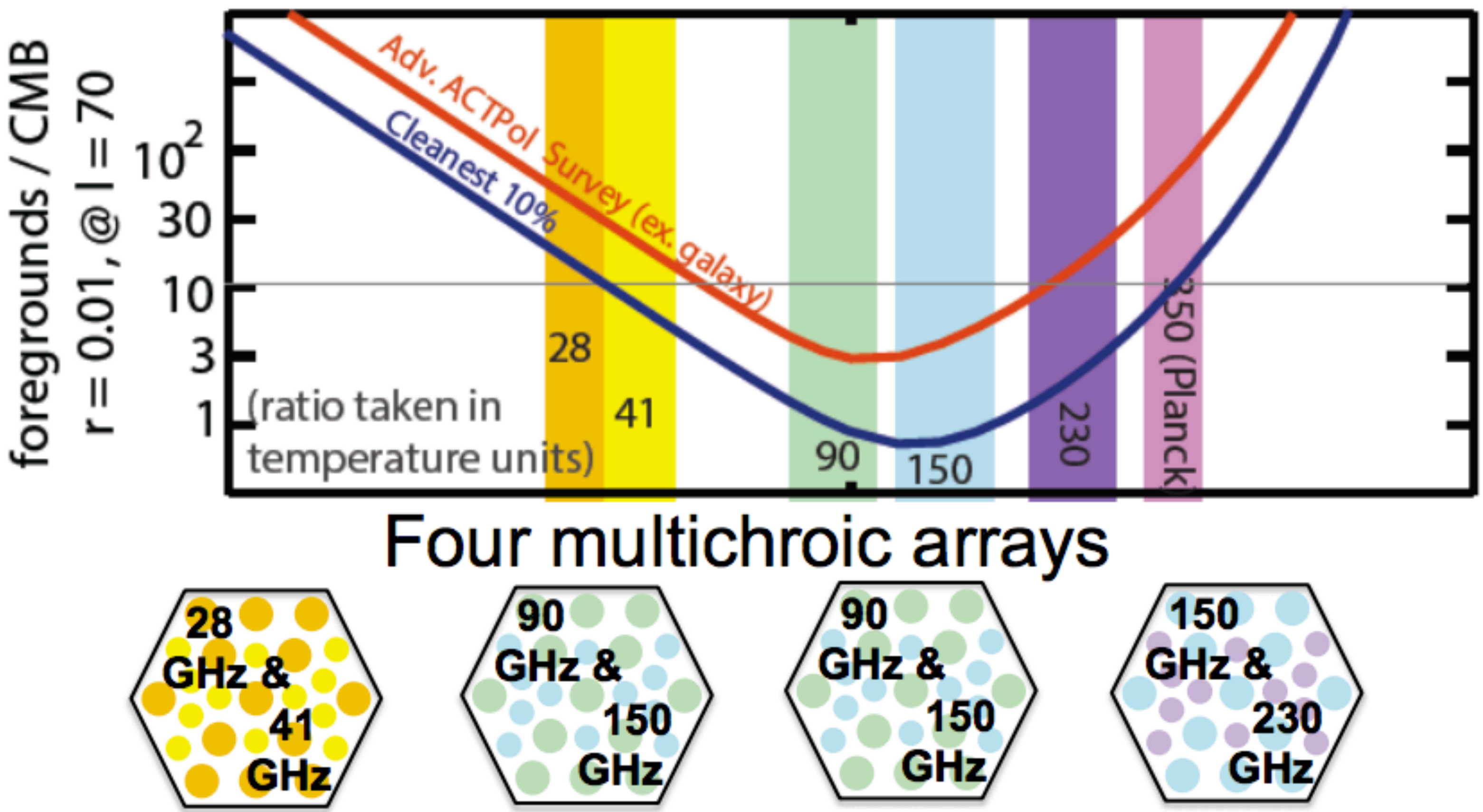
60’ QUIJOTE
Tenerife
20’ B-machine
California

20’ PIPER
60’ SPIDER-2
90’ LSPE
Balloon

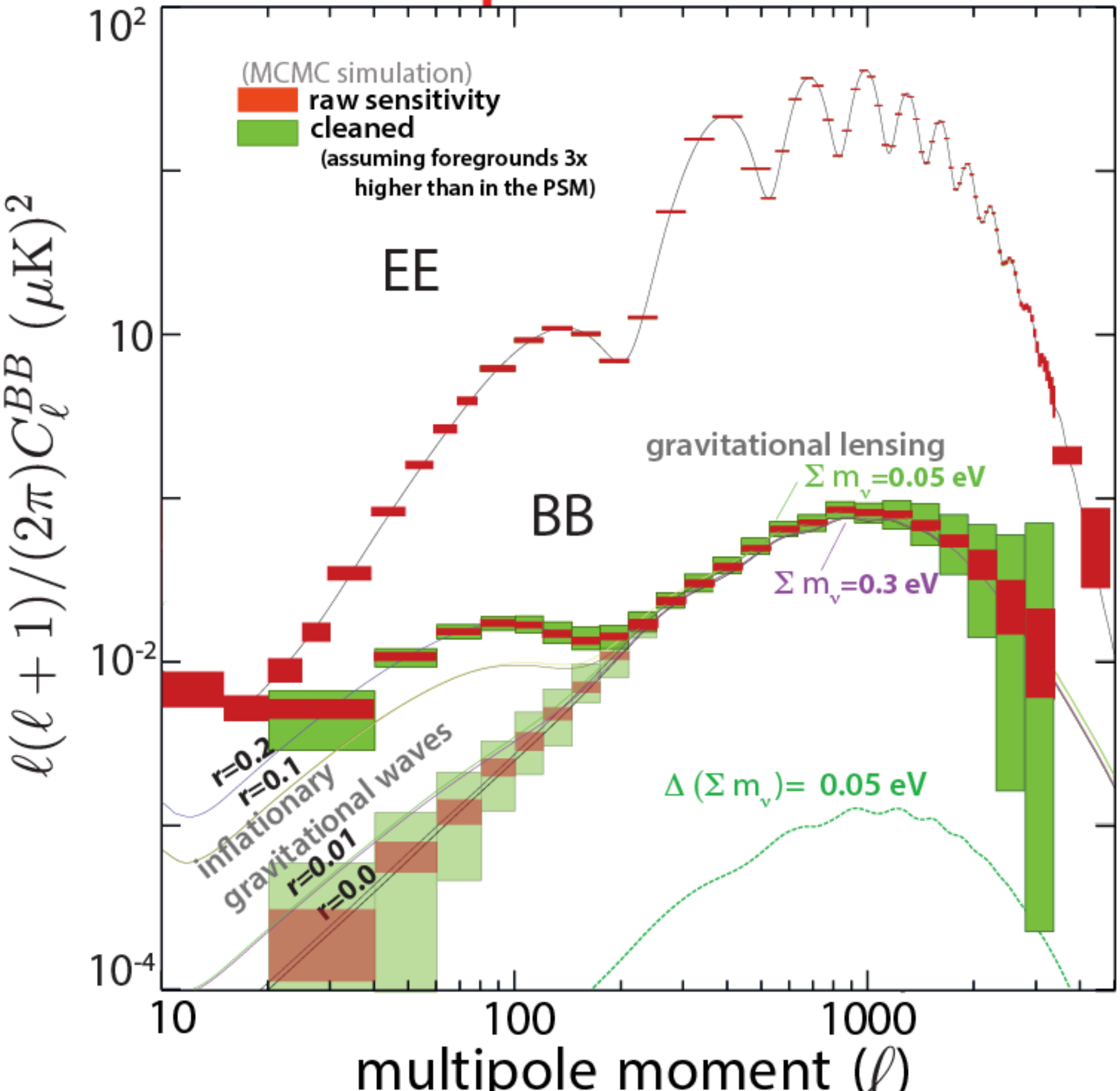
Slide adapted from Jo Dunkley

AdvACT

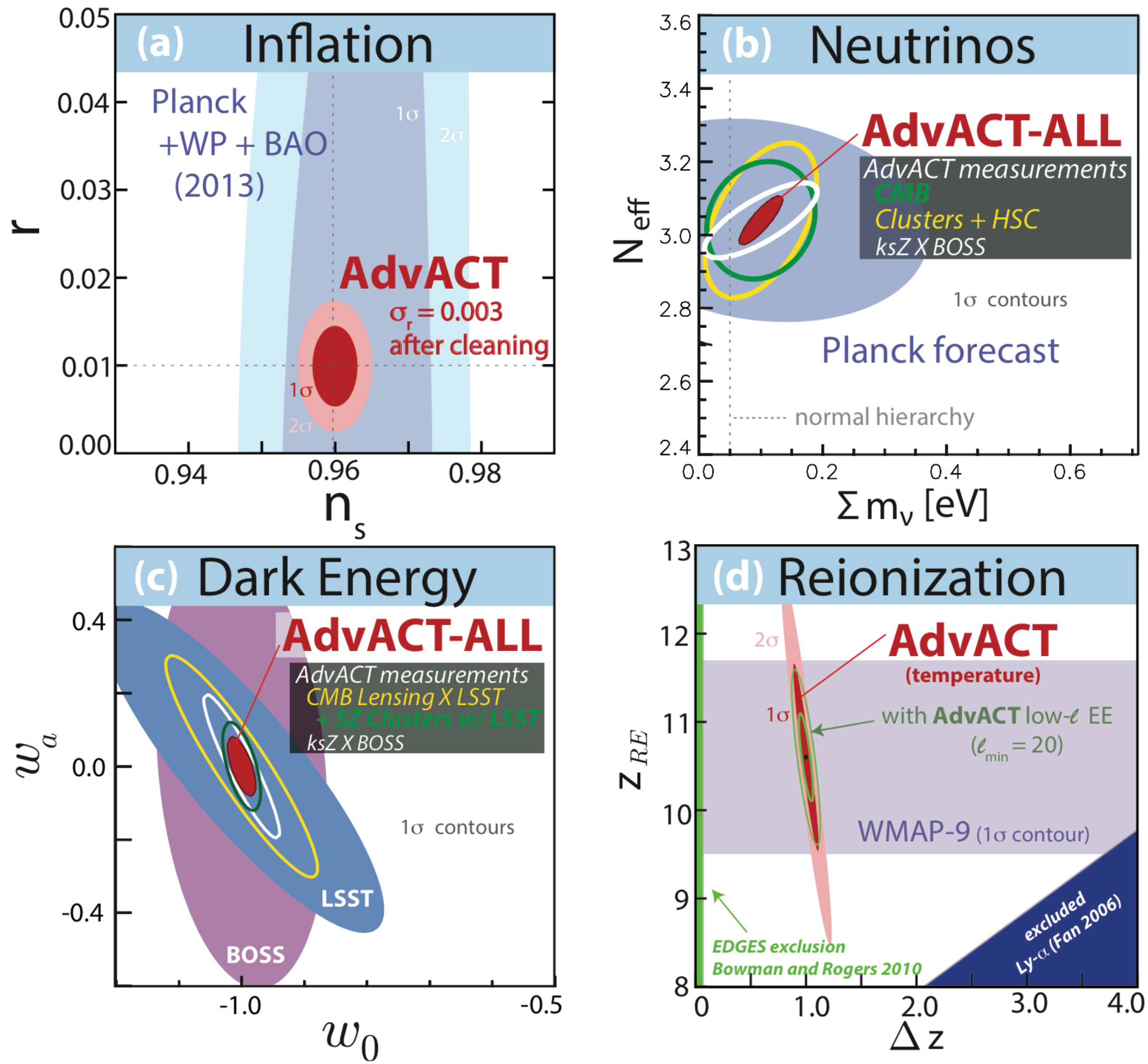
Four multichroic detector arrays with five bands – 30 → 230 GHz



AdvACT polarization forecast

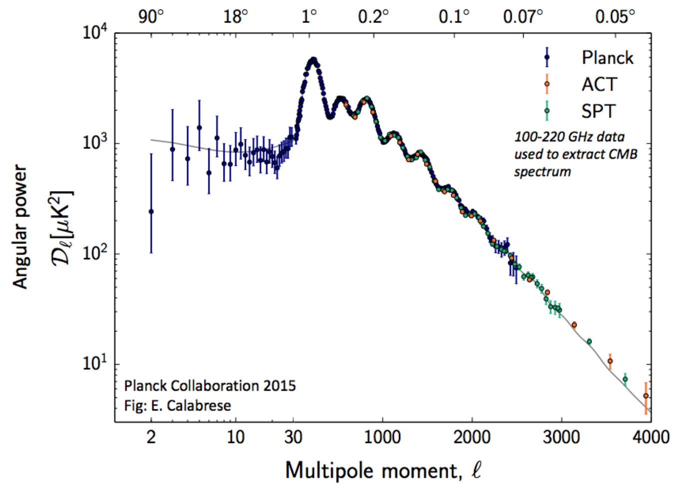


AdvACT: Cosmological Forecasts

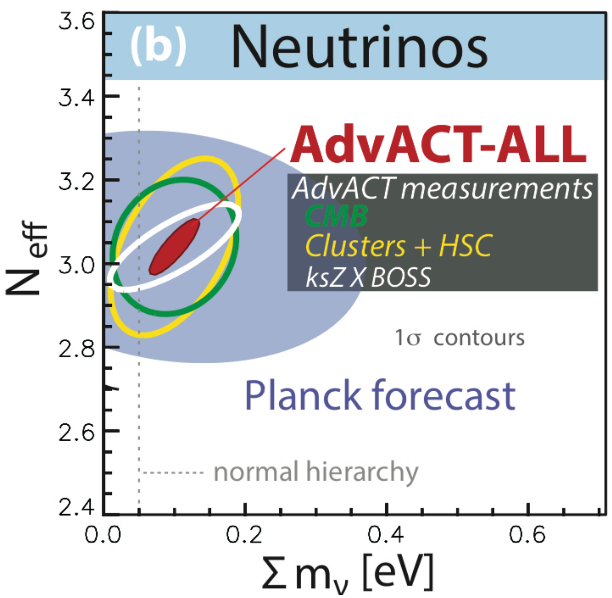


Uncertainty on sum of neutrino mass of ~0.04 eV
10x improvement over Planck!

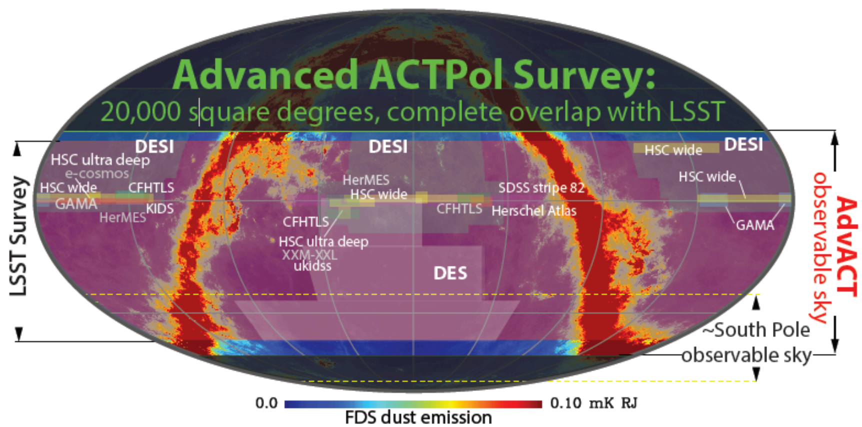
Summary



90°
18°
1°
0.2°
0.1°
0.07°
0.05°
Planck
ACT
SPT
100-220 GHz data used to extract CMB spectrum
Angular power
$\mathcal{D}_\ell [\mu K^2]$
Planck Collaboration 2015
Fig: E. Calabrese
Multipole moment, ℓ



(b) Neutrinos
AdvACT-ALL
AdvACT measurements
CMB
Clusters + HSC
ksZ X BOSS
1σ contours
Planck forecast
normal hierarchy
N_{eff}
Σm_ν [eV]



Advanced ACTPol Survey:
20,000 square degrees, complete overlap with LSST
DESI
DESI
DESI
HSC ultra deep
HSC wide
GAMA
CFHTLS
KIDS
HerMES
HSC wide
SDSS stripe 82
Herschel Atlas
HSC wide
HSC wide
GAMA
CFHTLS
HSC ultra deep
DES
LSST Survey
AdvACT observable sky
~South Pole observable sky
0.0
0.10 mK RJ
FDS dust emission