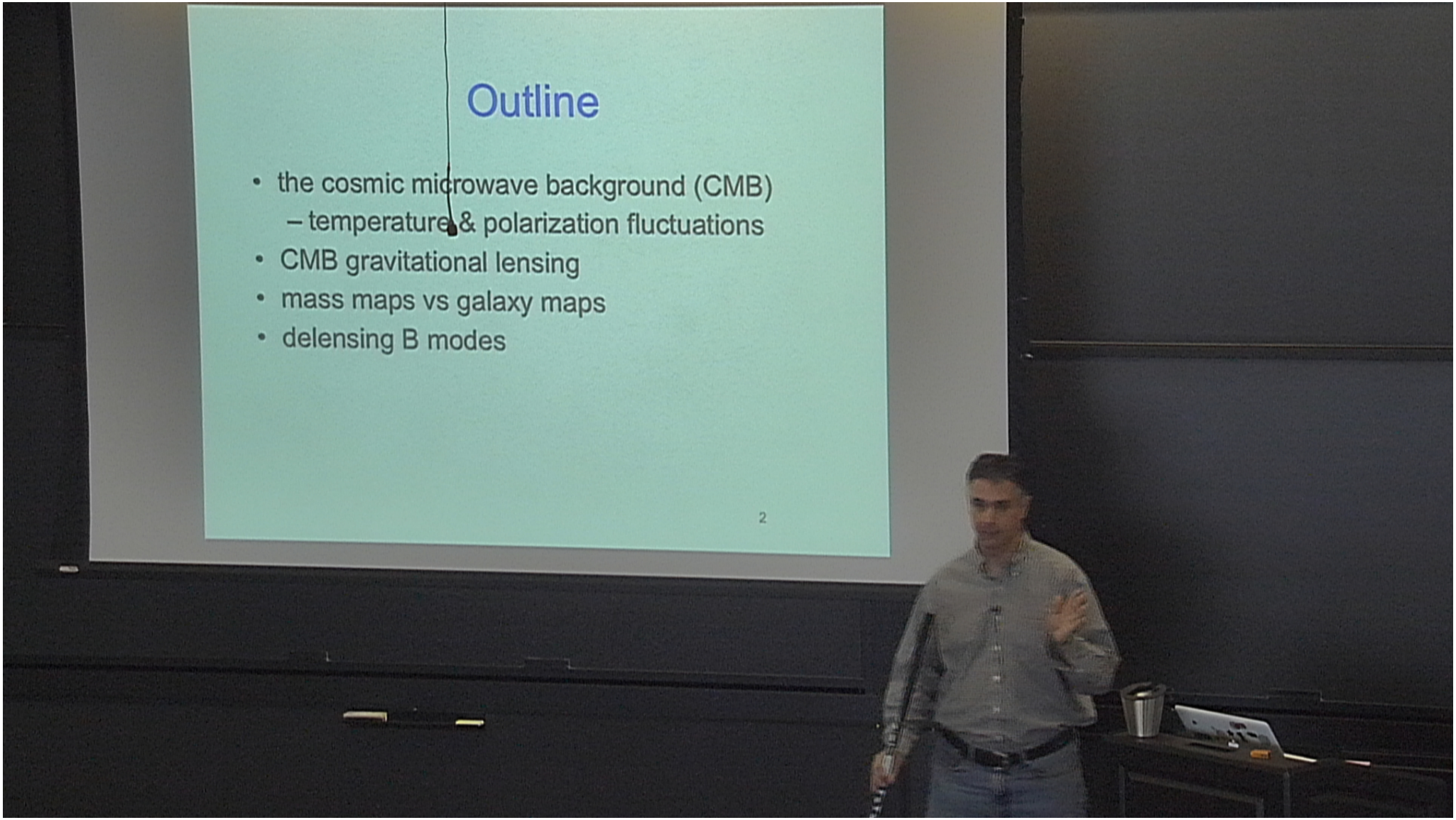
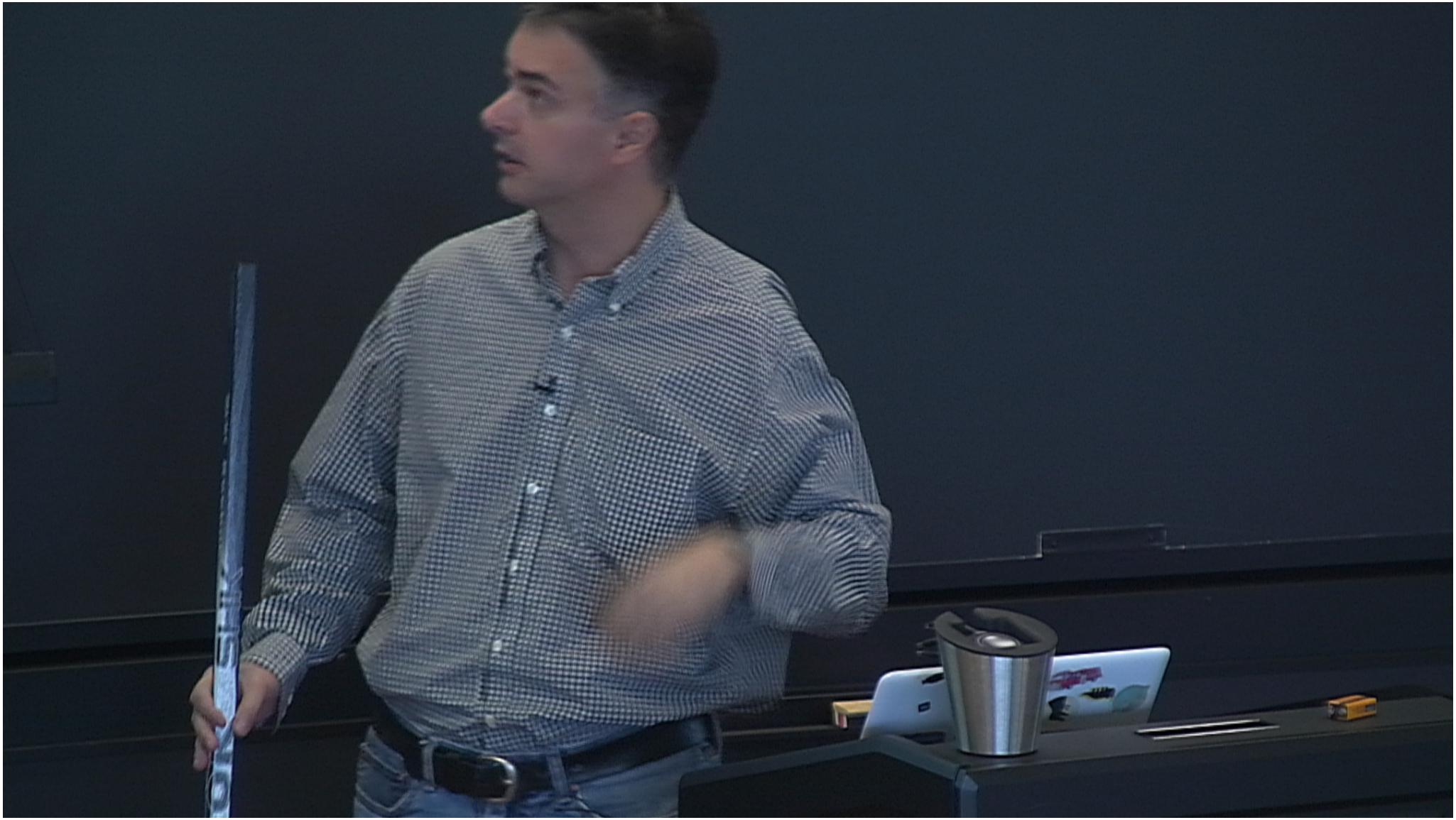
Title: Gravitational lensing of the CMB

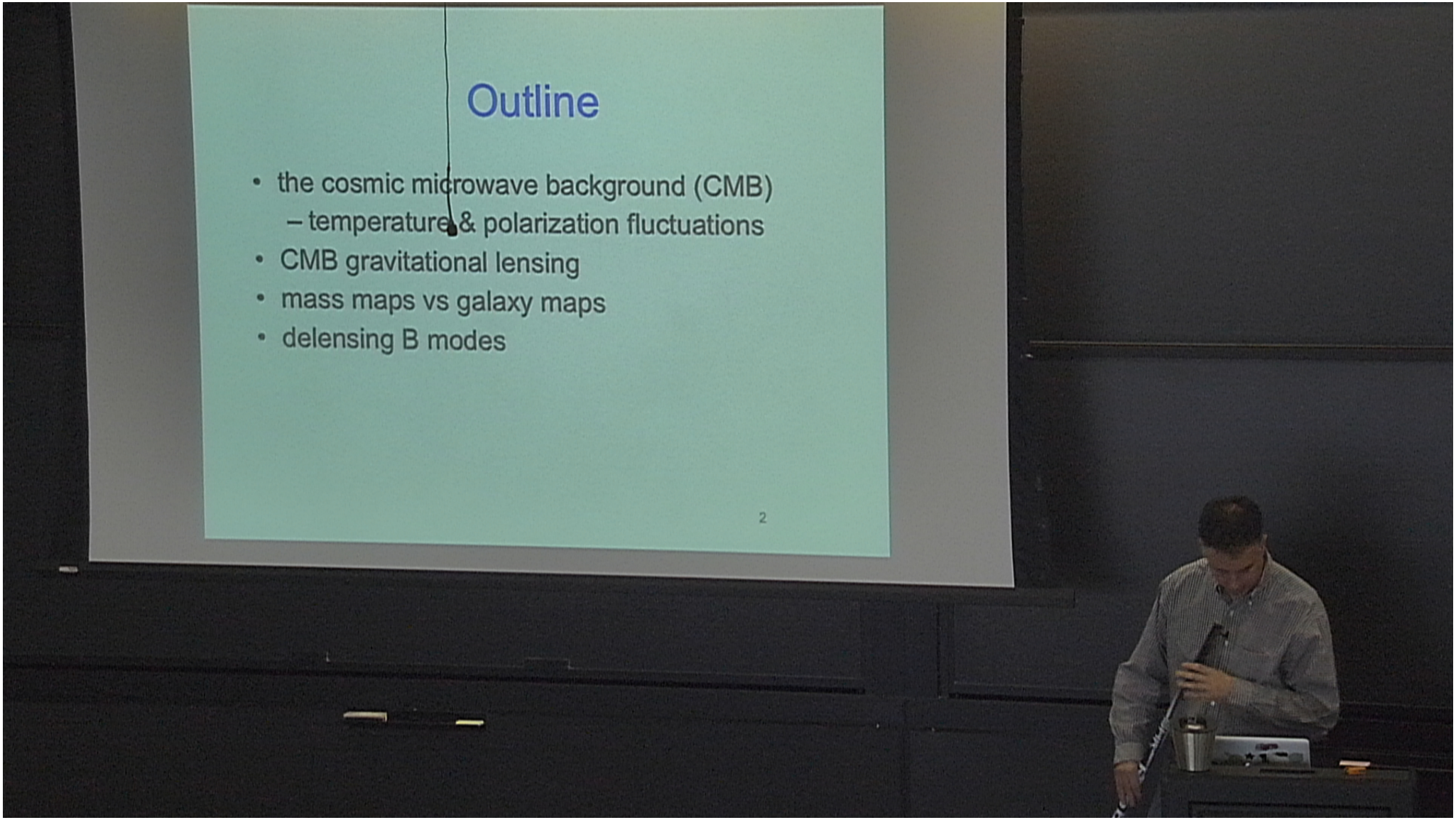
Date: Oct 14, 2014 11:00 AM

URL: http://pirsa.org/14100084

Abstract: Gravitational lensing of the cosmic microwave background is emerging as a useful cosmological tool. Recent measurements have been made by several experiments (including the South Pole Telescope, which will be featured), with rapidly improving precision. These measurements can be used for many purposes, including studying the connection between dark matter and galaxies on large scales, measuring the clustering of matter at z~3, and improving the precision of possible measurements of gravitational radiation from inflation.


Outline
• the cosmic microwave background (CMB)
– temperature & polarization fluctuations
• CMB gravitational lensing
• mass maps vs galaxy maps
• delensing B modes
2

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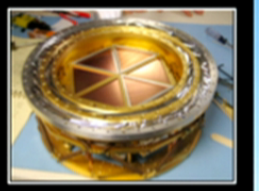
The South Pole Telescope (SPT)

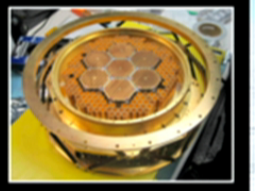
10-meter sub-mm quality wavelength telescope

100, **150**, **220** GHz and
1.6, **1.2**, **1.0** arcmin resolution

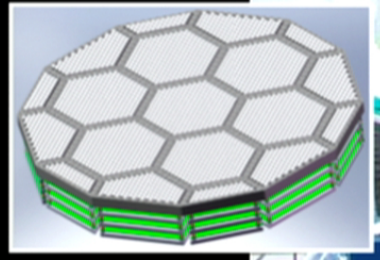
2007: SPT-SZ
960 detectors
100,150,220 GHz

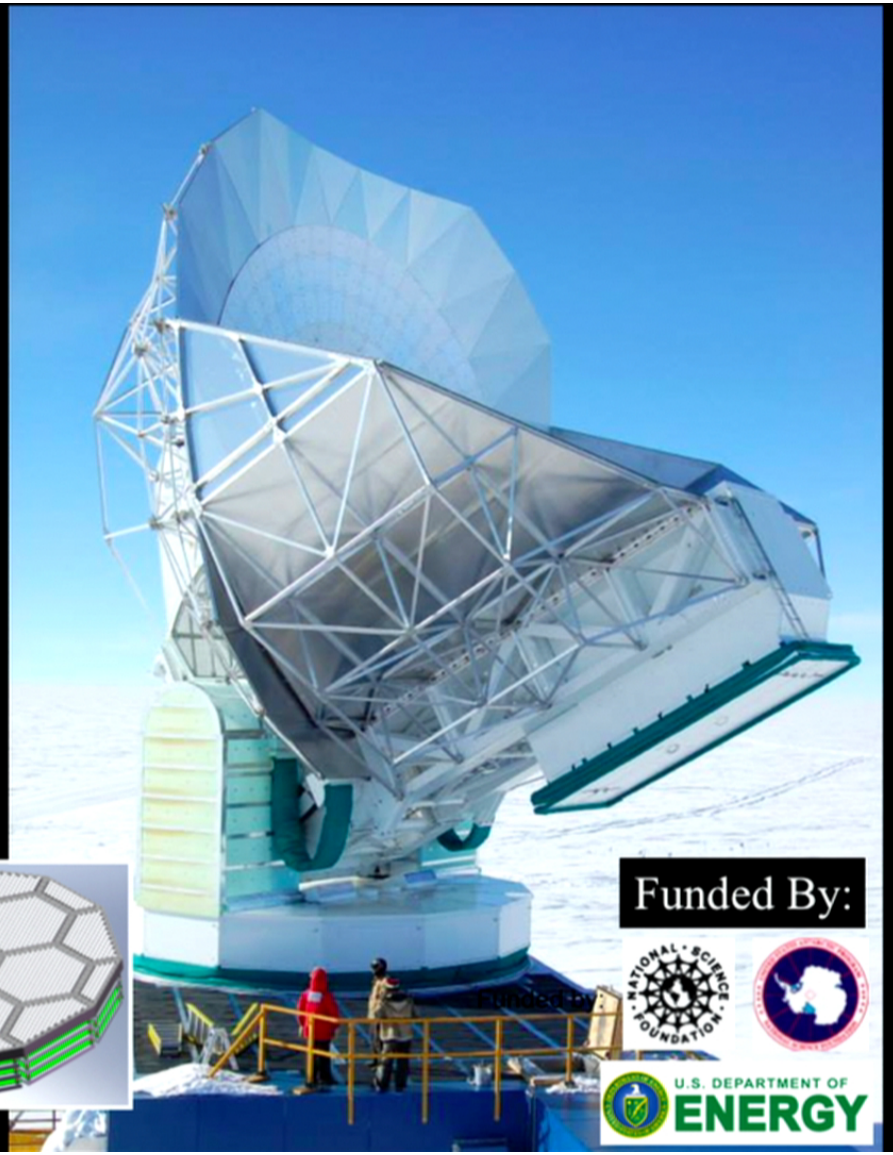


2012: SPTpol
1600 detectors
100,150 GHz
+Polarization

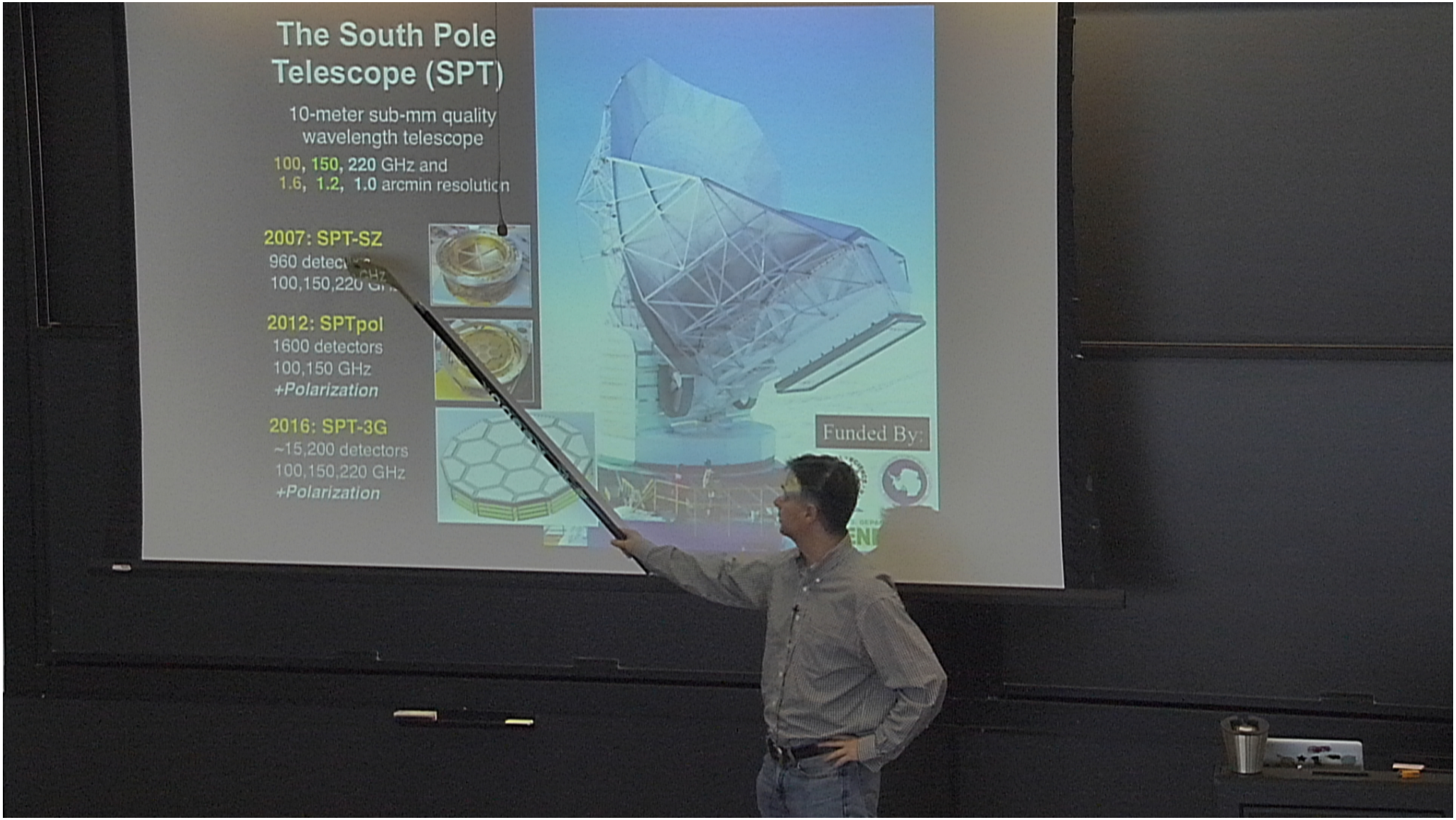


2016: SPT-3G
~15,200 detectors
100,150,220 GHz
+Polarization





Funded By:


The South Pole Telescope (SPT)
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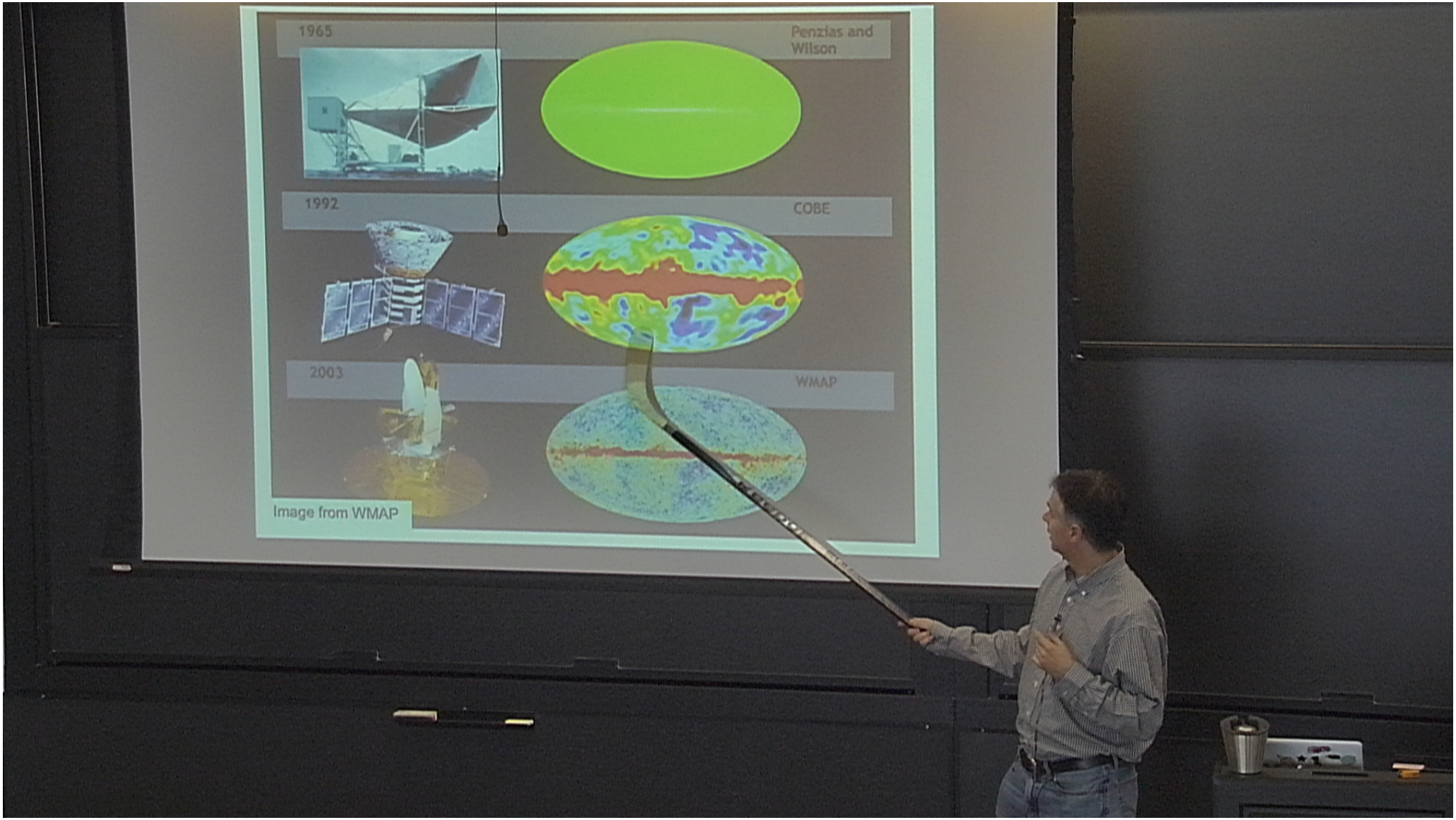

1965
Penzias and Wilson
1992
COBE
2003
WMAP
Image from WMAP

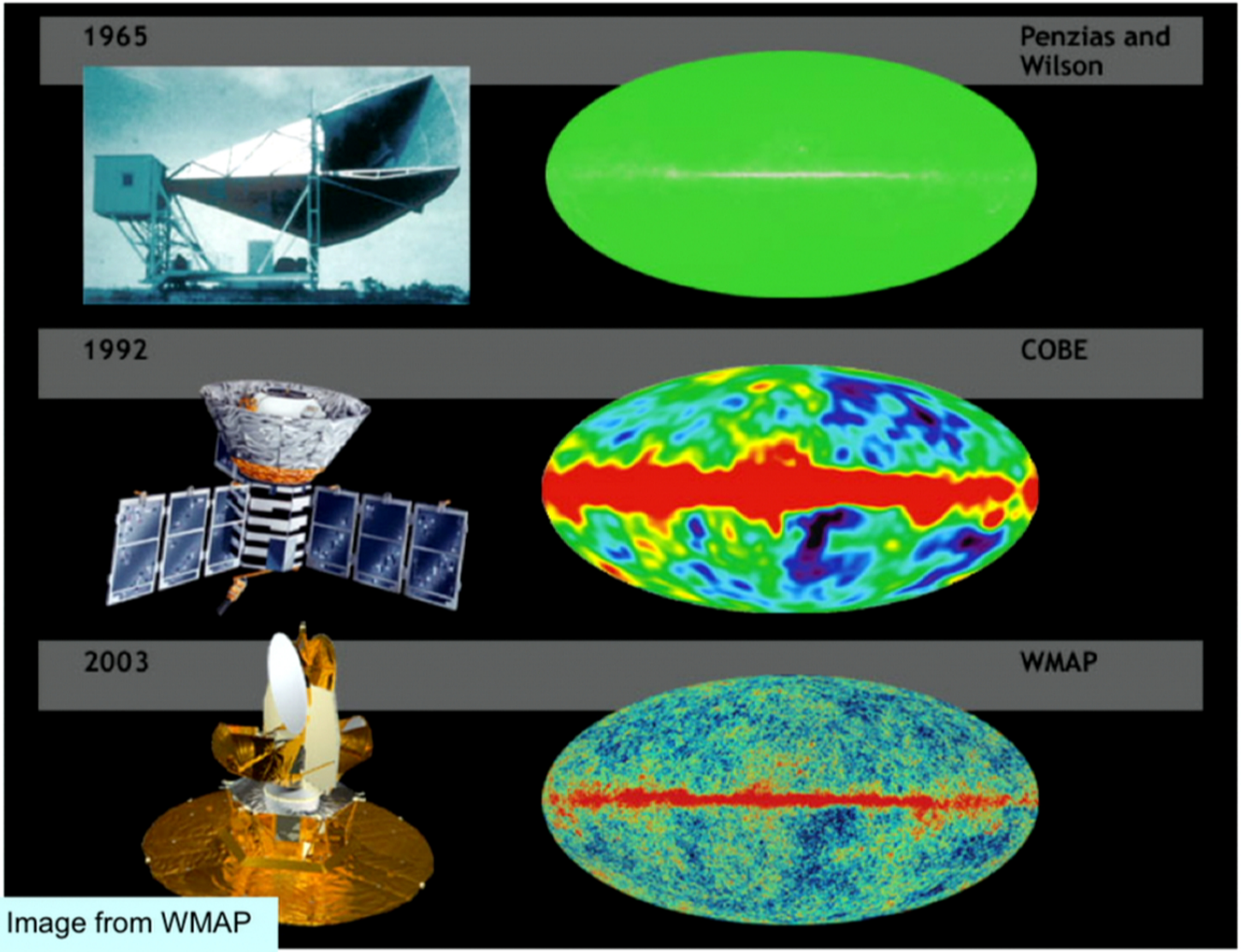
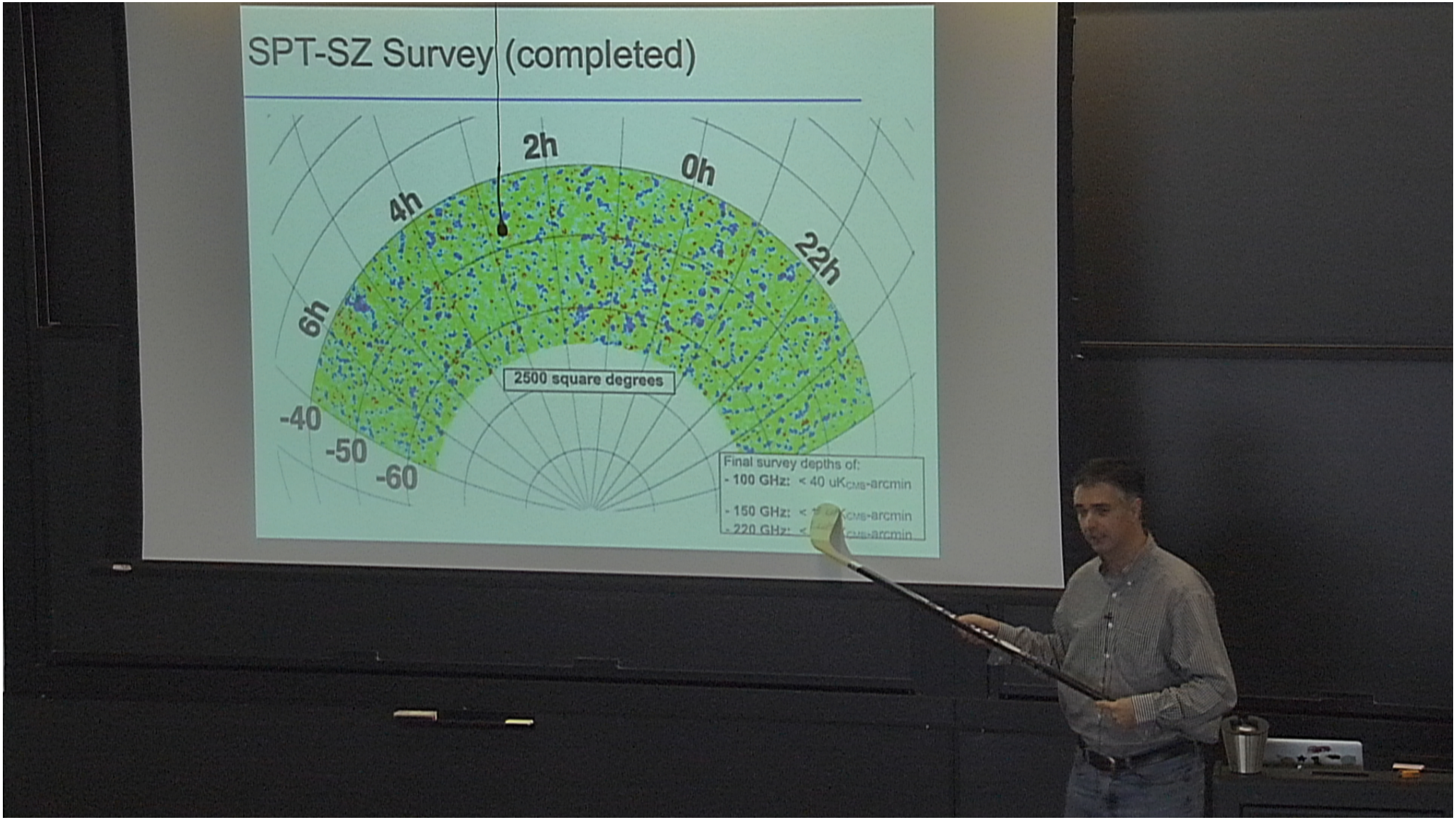
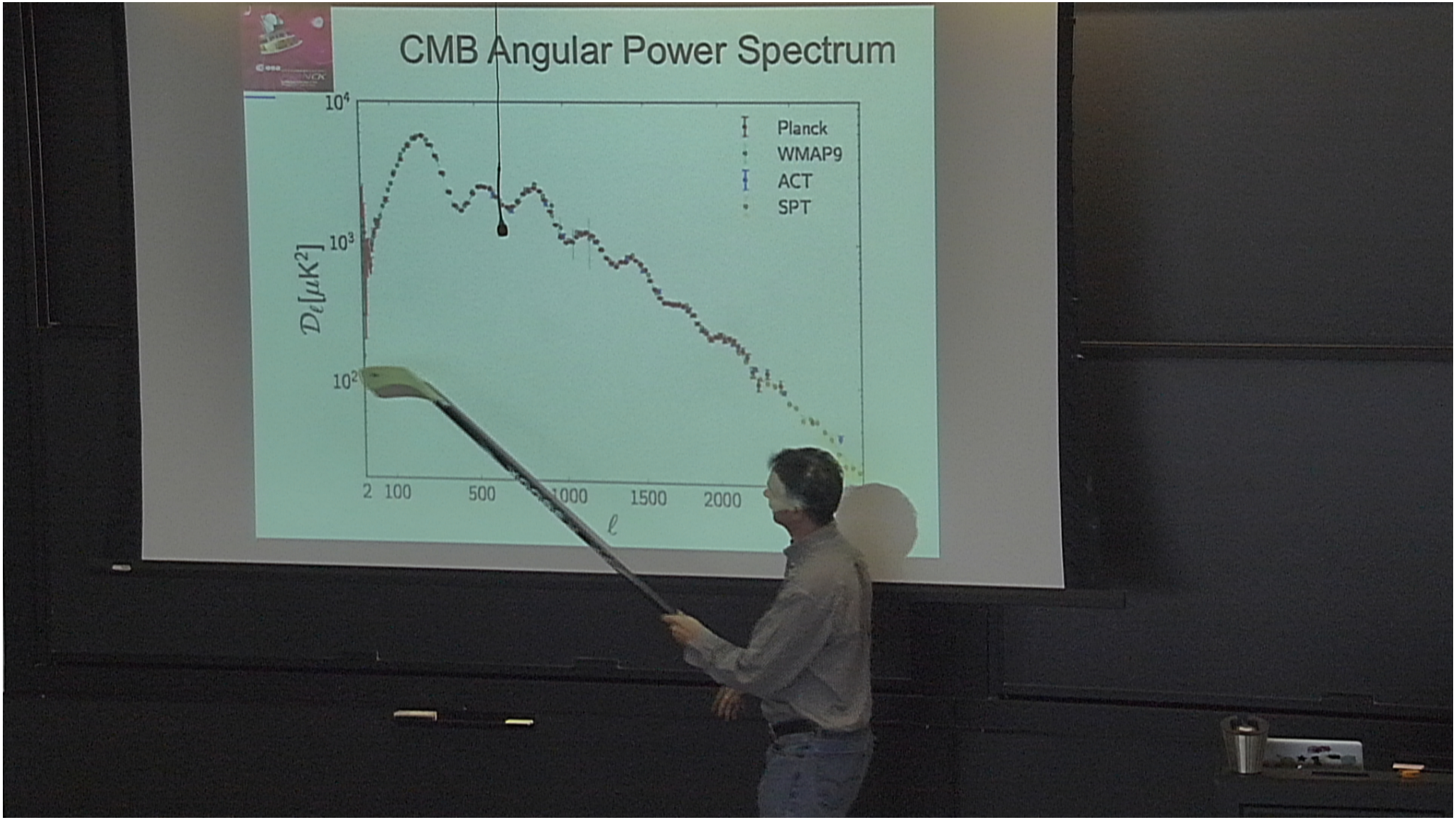
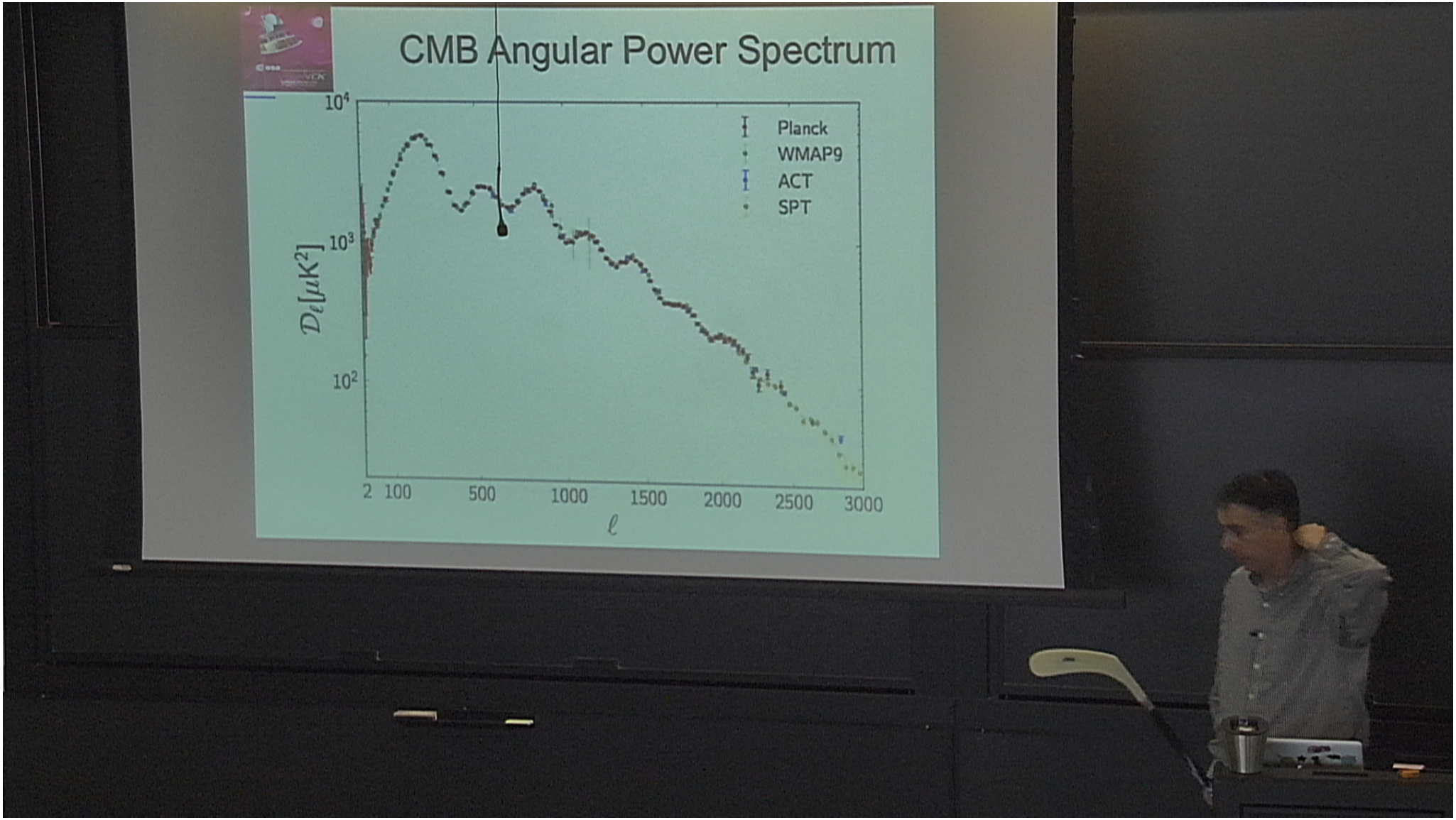
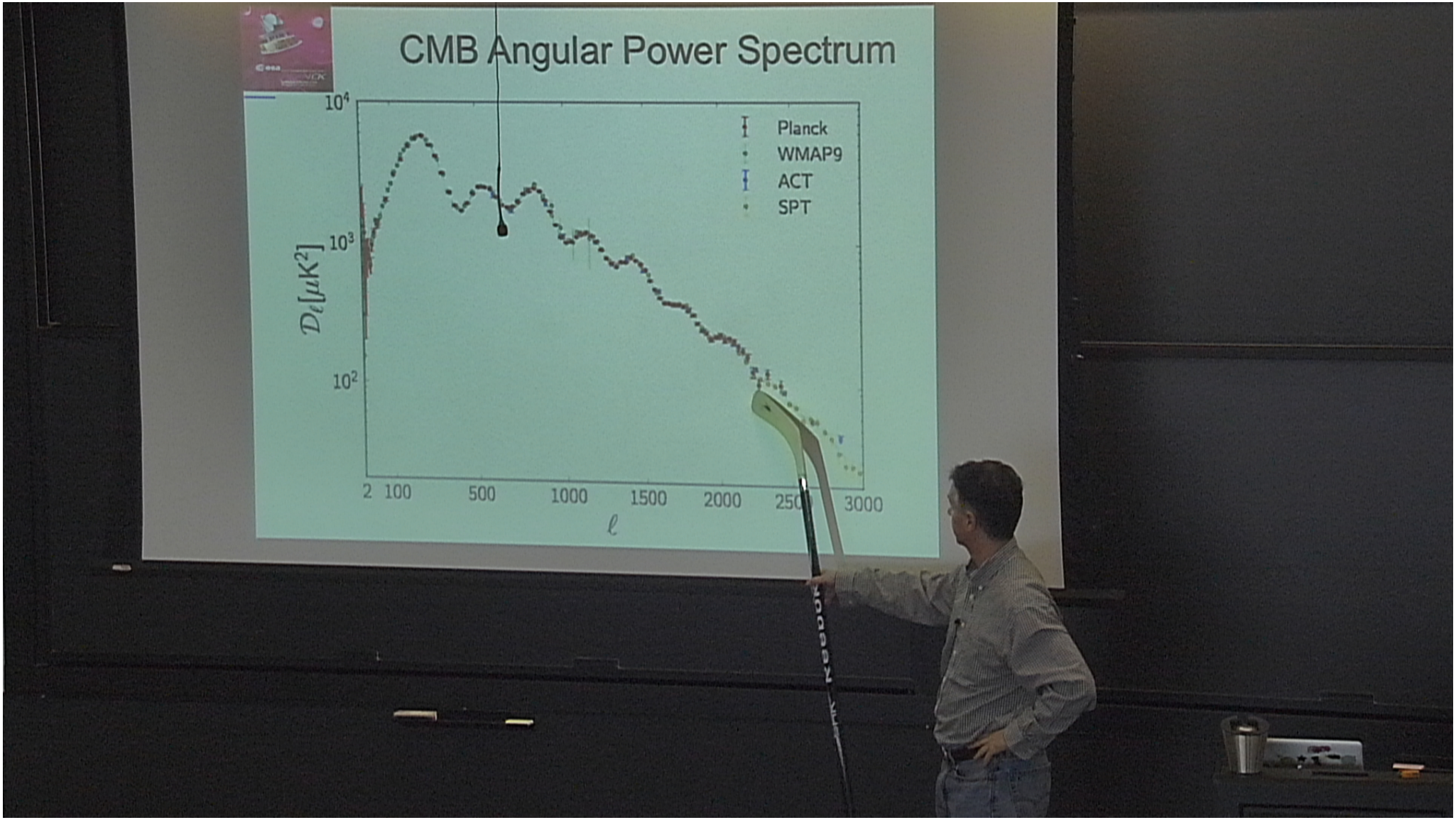


Image from WMAP


SPT-SZ Survey (completed)
2h
0h
4h
22h
6h
2500 square degrees
-40
-50
-60
Final survey depths of:
- 100 GHz: < 40 uKCMB-arcmin
- 150 GHz: <
- 220 GHz: <


CMB Angular Power Spectrum
Planck
WMAP9
ACT
SPT
10^4
10^3
10^2
$\mathcal{D}_\ell[\mu K^2]$
2
100
500
1000
1500
2000
ℓ


CMB Angular Power Spectrum
Planck
WMAP9
ACT
SPT
10^4
10^3
10^2
$\mathcal{D}_\ell[\mu K^2]$
2 100 500 1000 1500 2000 2500 3000
ℓ


CMB Angular Power Spectrum
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10^3
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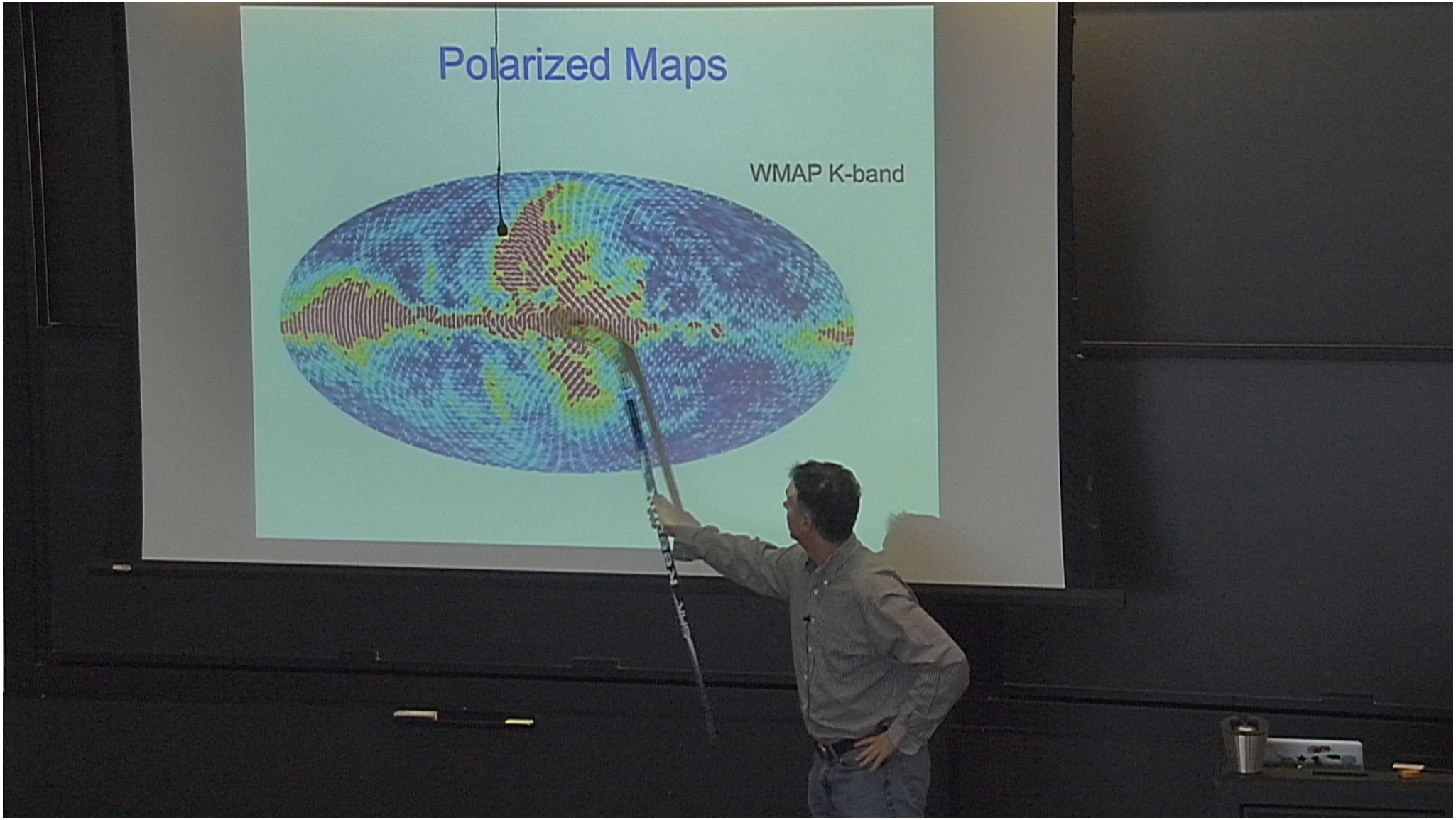
$\mathcal{D}_\ell[\mu K^2]$
2
100
500
1000
1500
2000
3000
ℓ


Polarized Maps
WMAP K-band

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!***

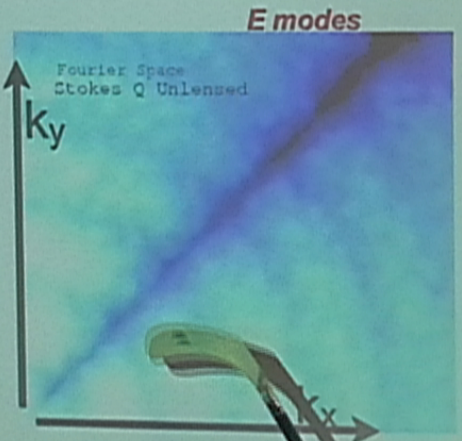


Image of positive kx/positive ky Fourier transform of a 10x10 deg patch of Stokes Q CMB map [simulated, nothing clever done to it]

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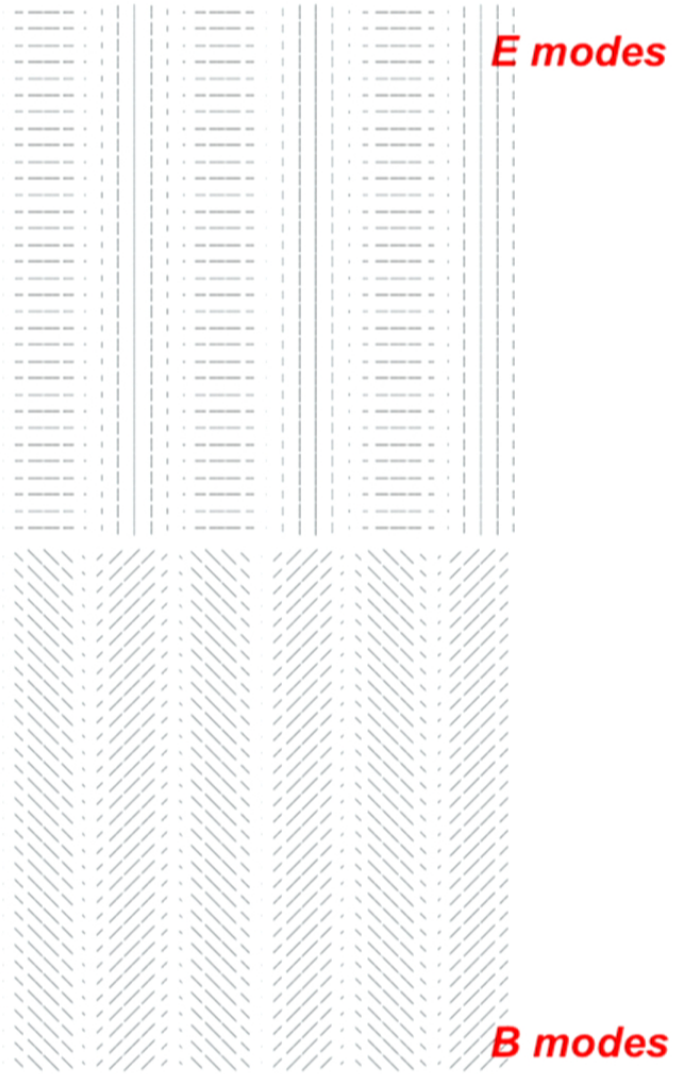
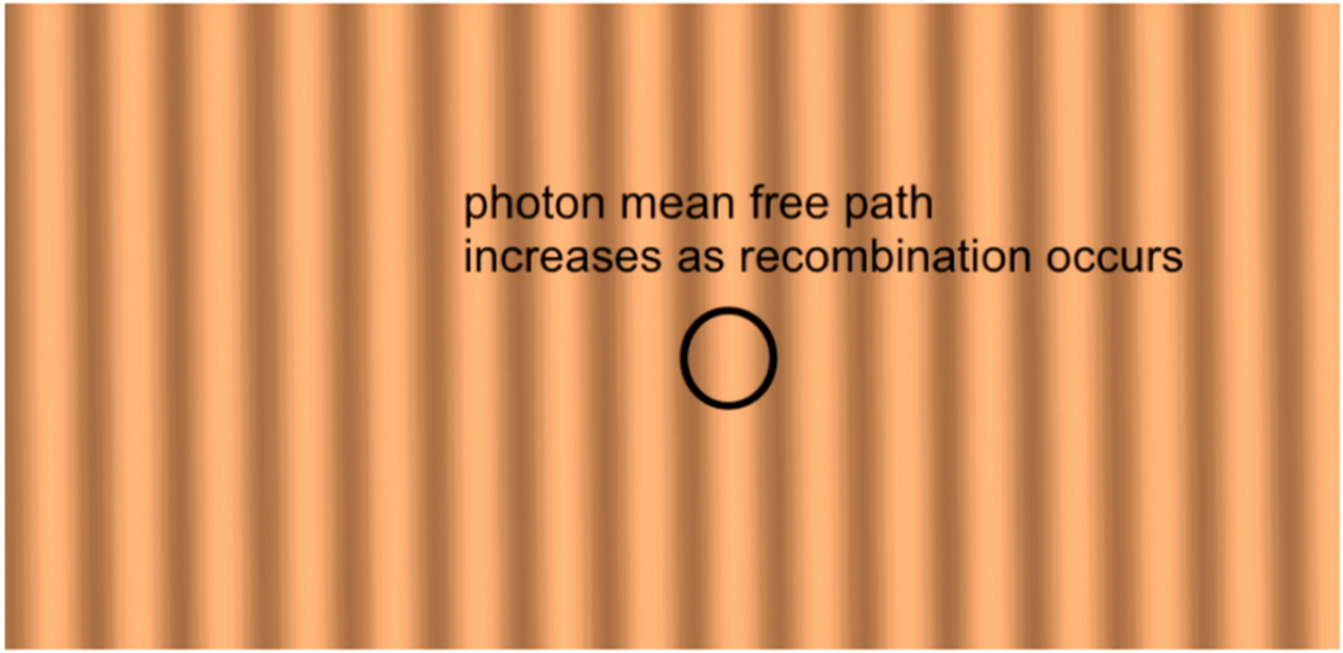


Bunn

Density fluctuations generate pure E mode



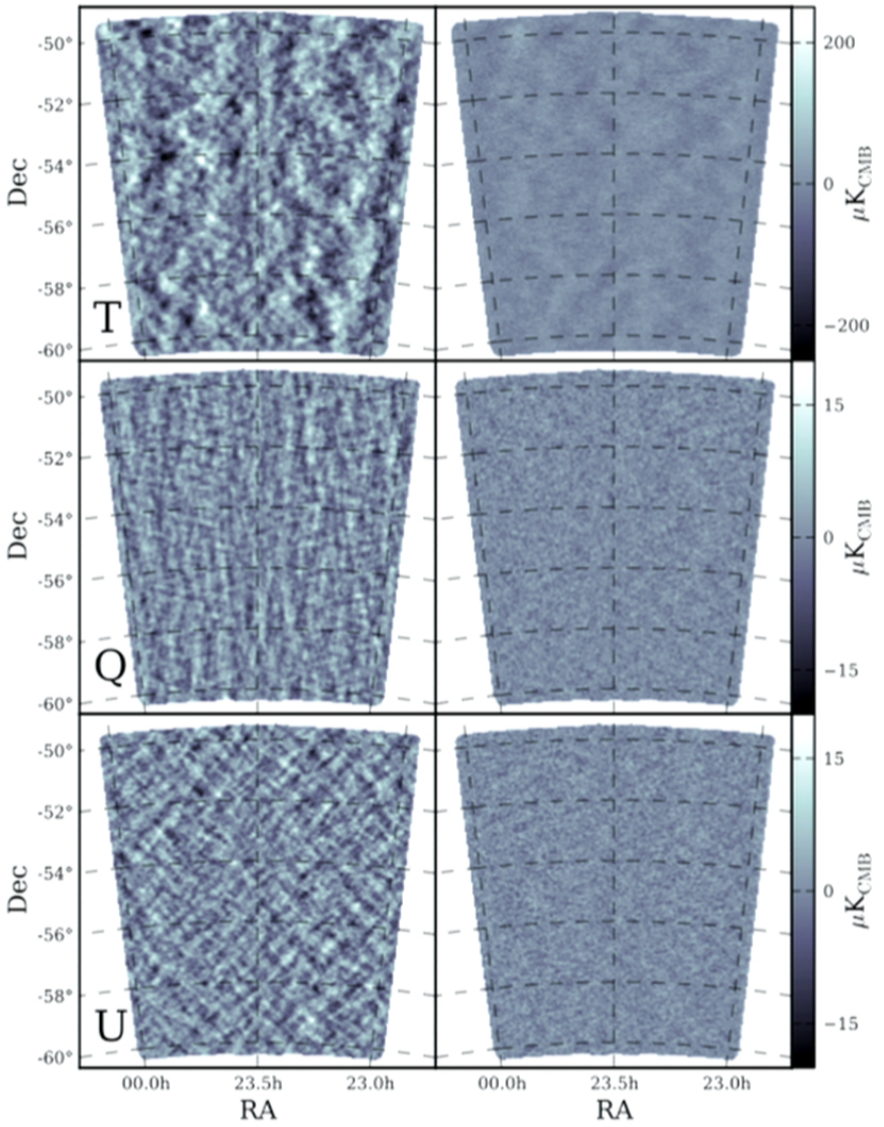
- E-modes <=> polarization
- lensing convergence <=> shear

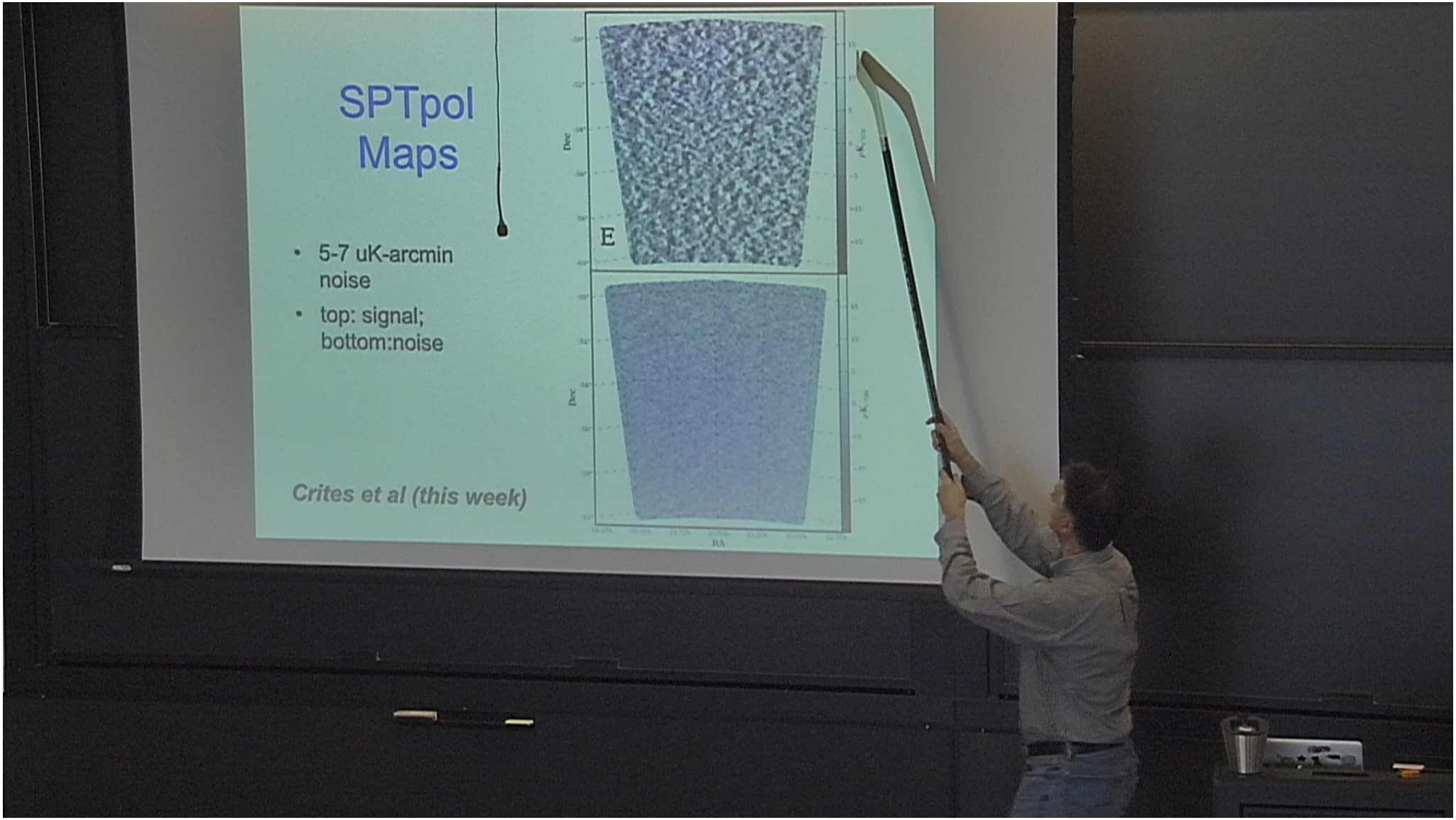
21

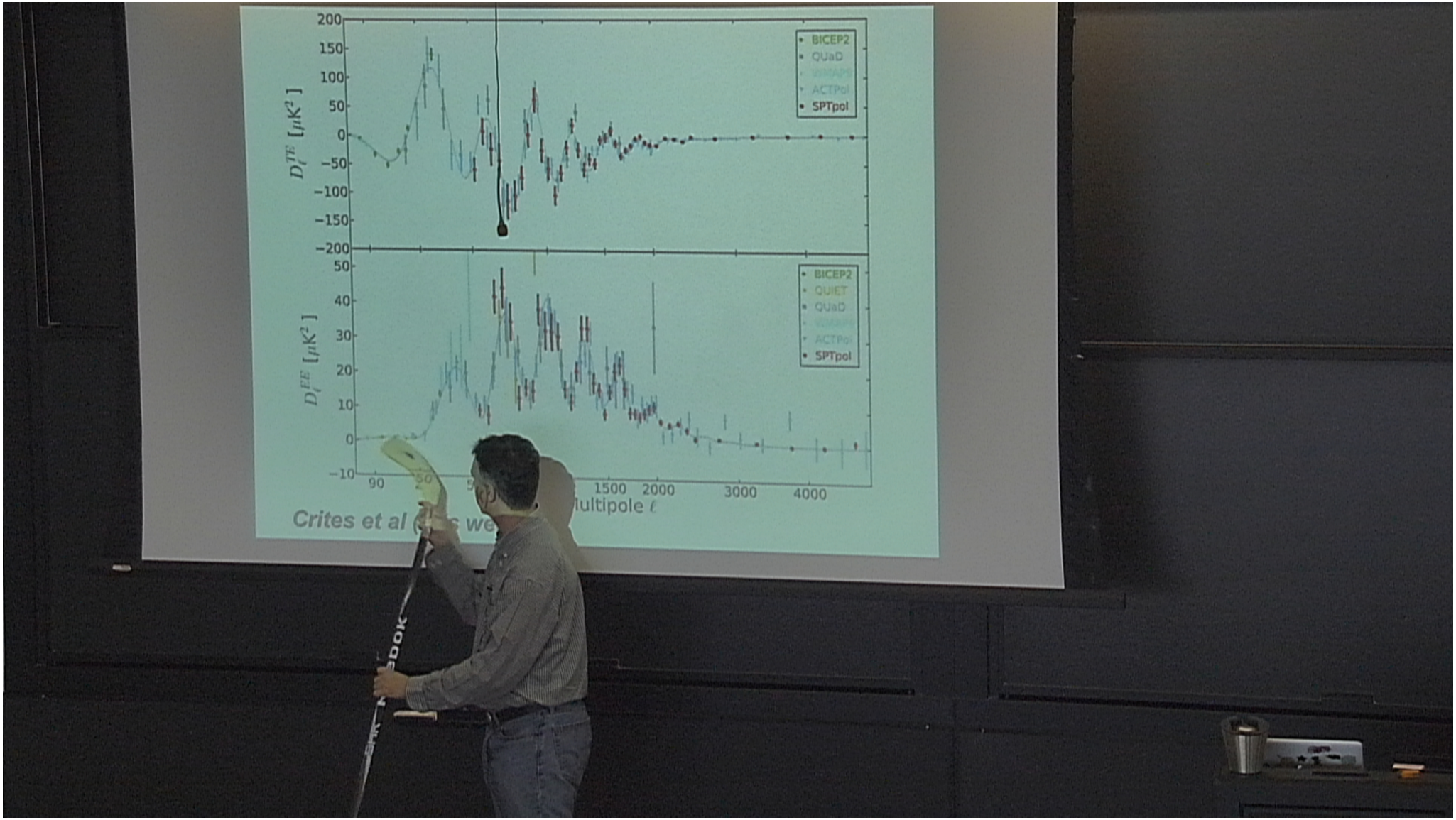
SPTpol Maps

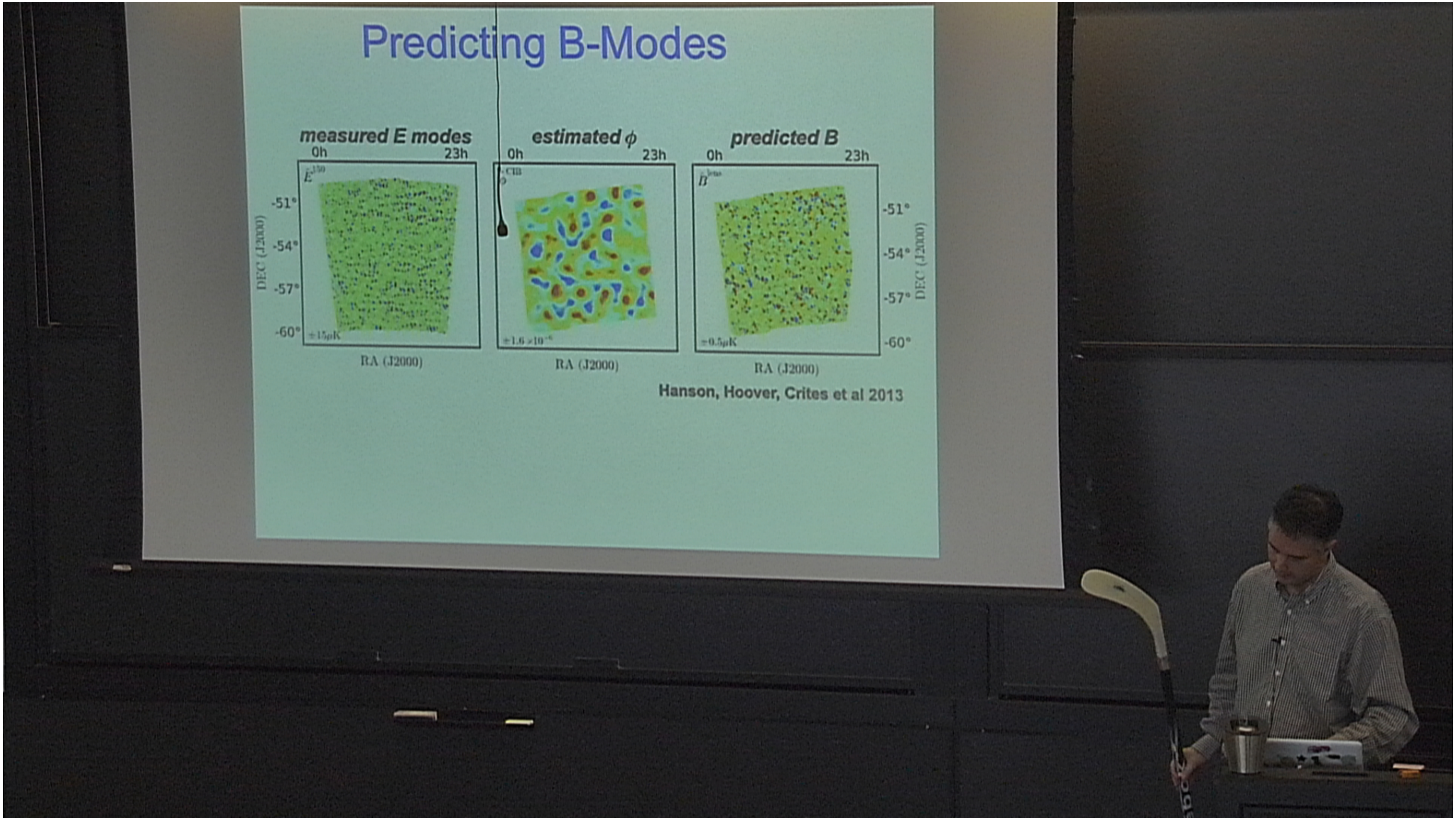
- 5-7 uK-arcmin noise
- left: signal; right:noise

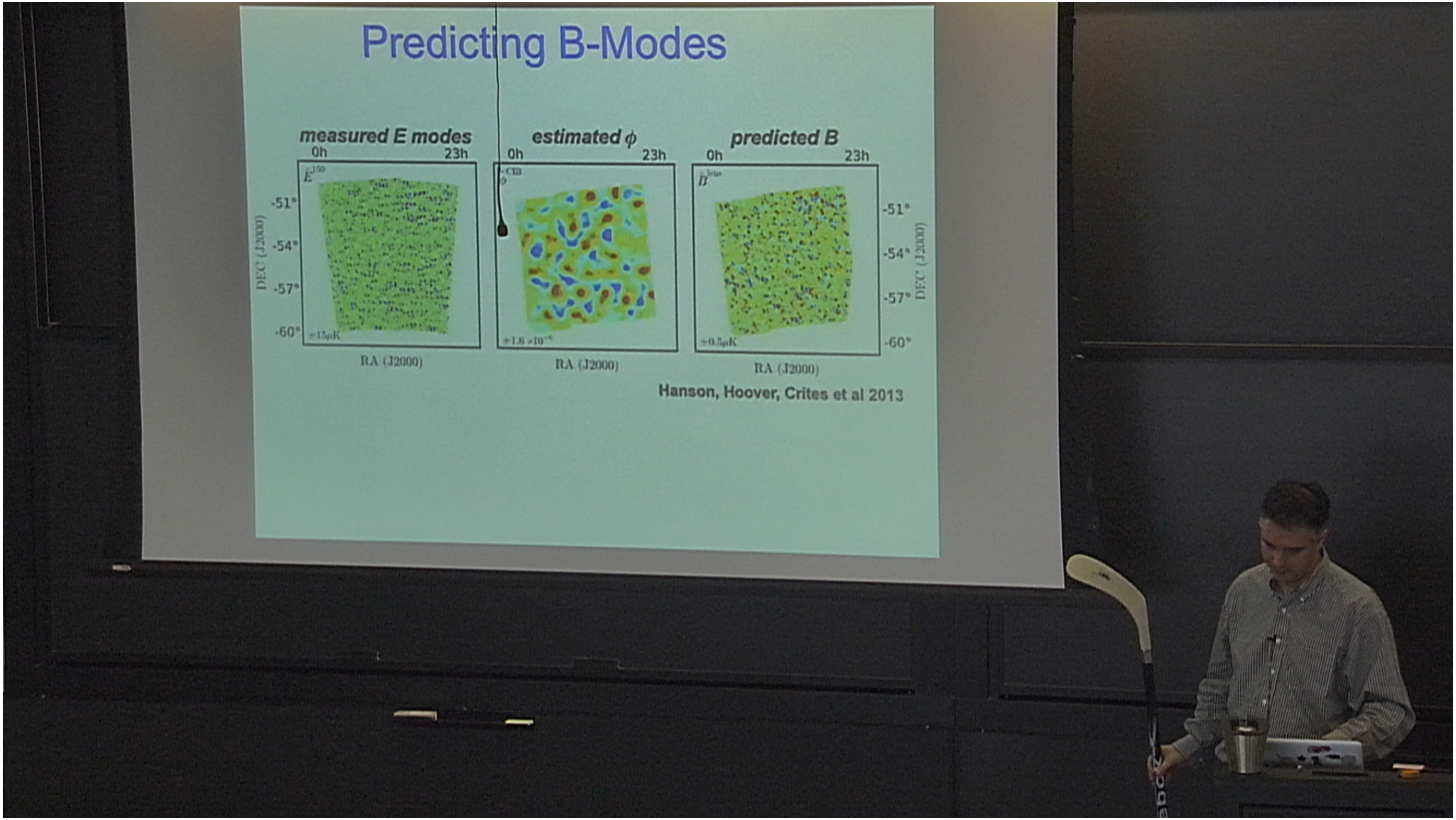
Crites et al (this week)




SPTpol Maps
• 5-7 uK-arcmin noise
• top: signal; bottom:noise
Crites et al (this week)
E
Dec
RA


200
150
100
50
0
−50
−100
−150
−200
D_ℓ^{TE} [μK^2]
BICEP2
QUaD
ACTPol
SPTpol
50
40
30
20
10
0
−10
D_ℓ^{EE} [μK^2]
BICEP2
QUIET
QUaD
ACTPol
SPTpol
90
1500
2000
3000
4000
ultipole ℓ
Crites et al


Predicting B-Modes
measured E modes
estimated ϕ
predicted B
0h
23h
-51°
-54°
-57°
-60°
DEC (J2000)
RA (J2000)
$\pm 15\mu$K
$\pm 1.6 \times 10^{-5}$
$\pm 0.5\mu$K
Hanson, Hoover, Crites et al 2013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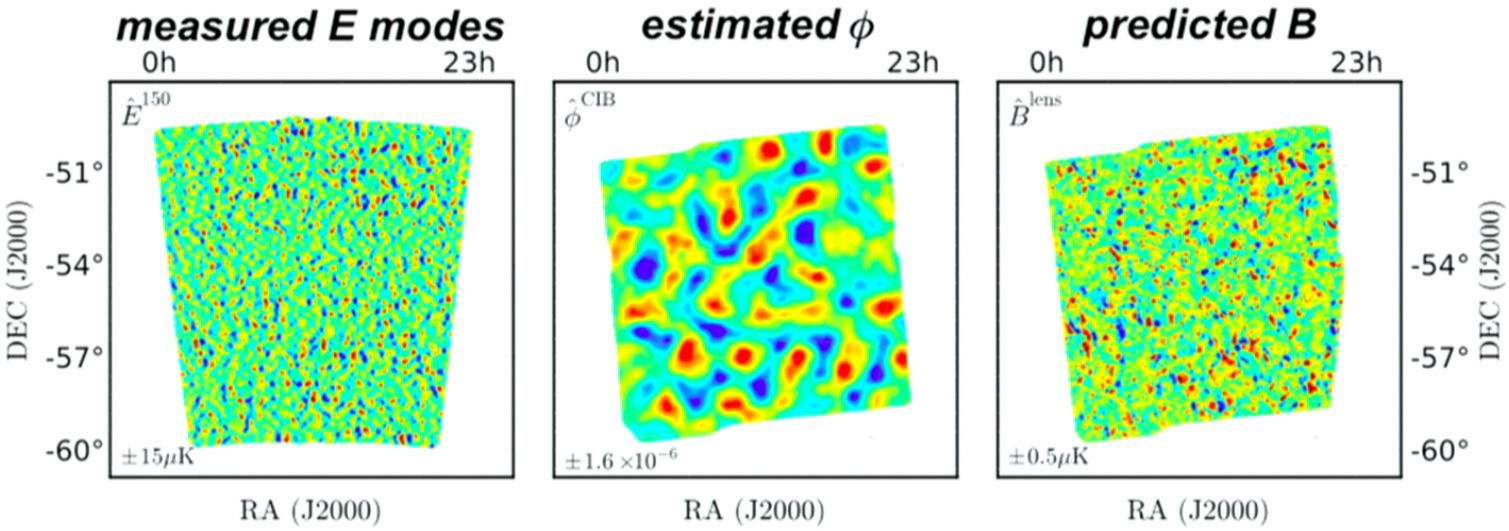
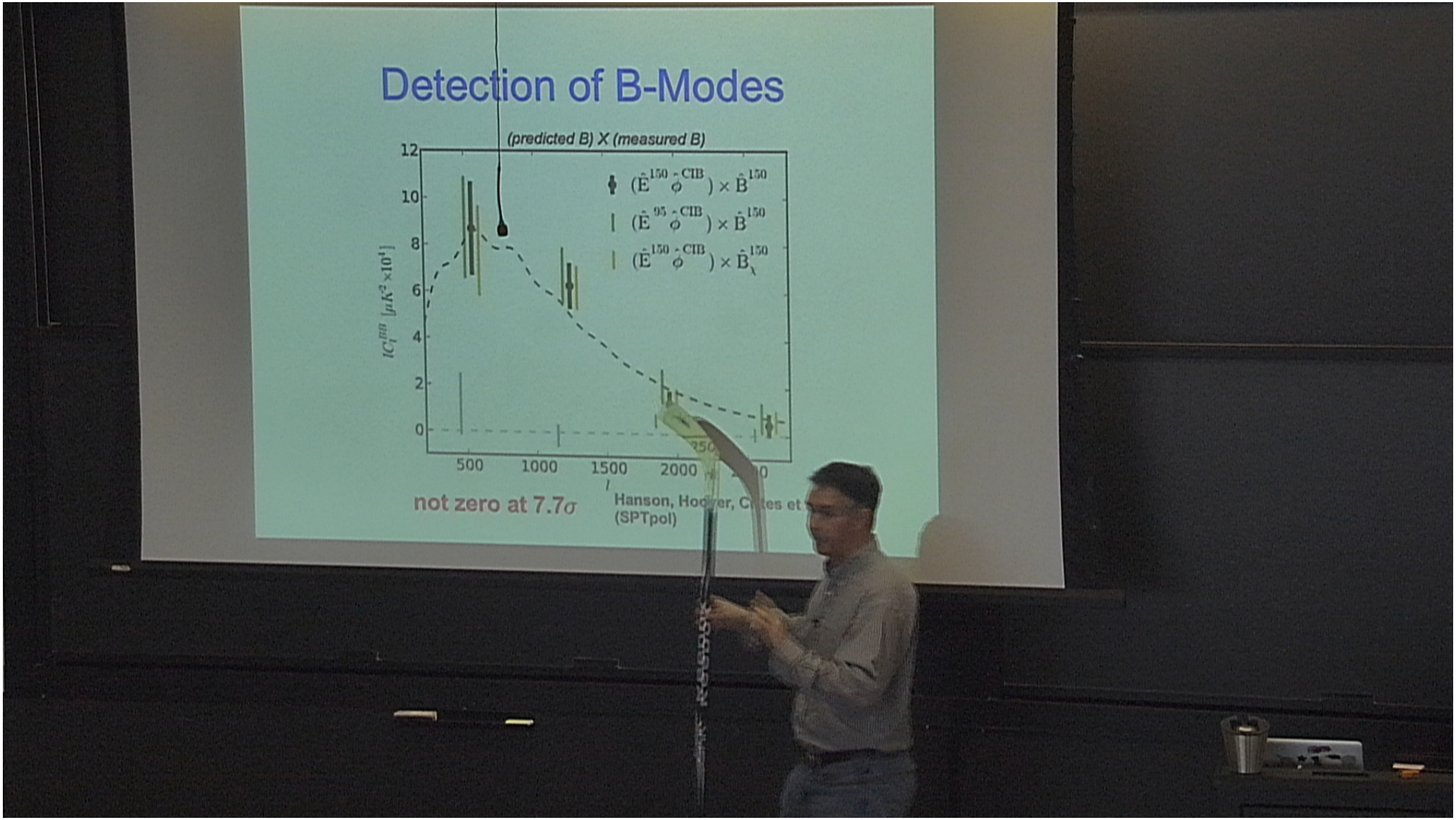
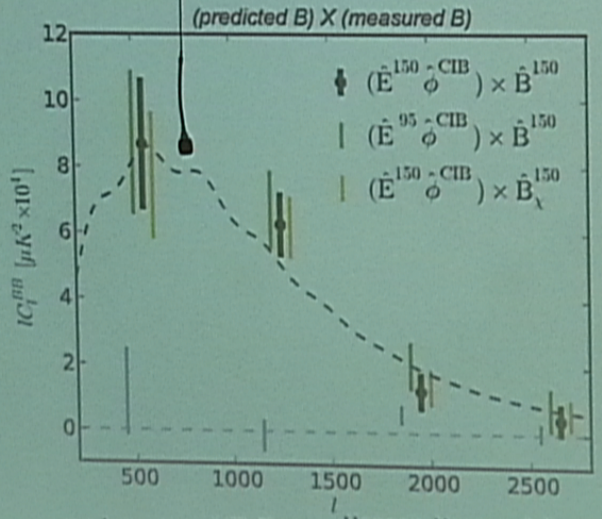


Hanson, Hoover, Crites et al 2013

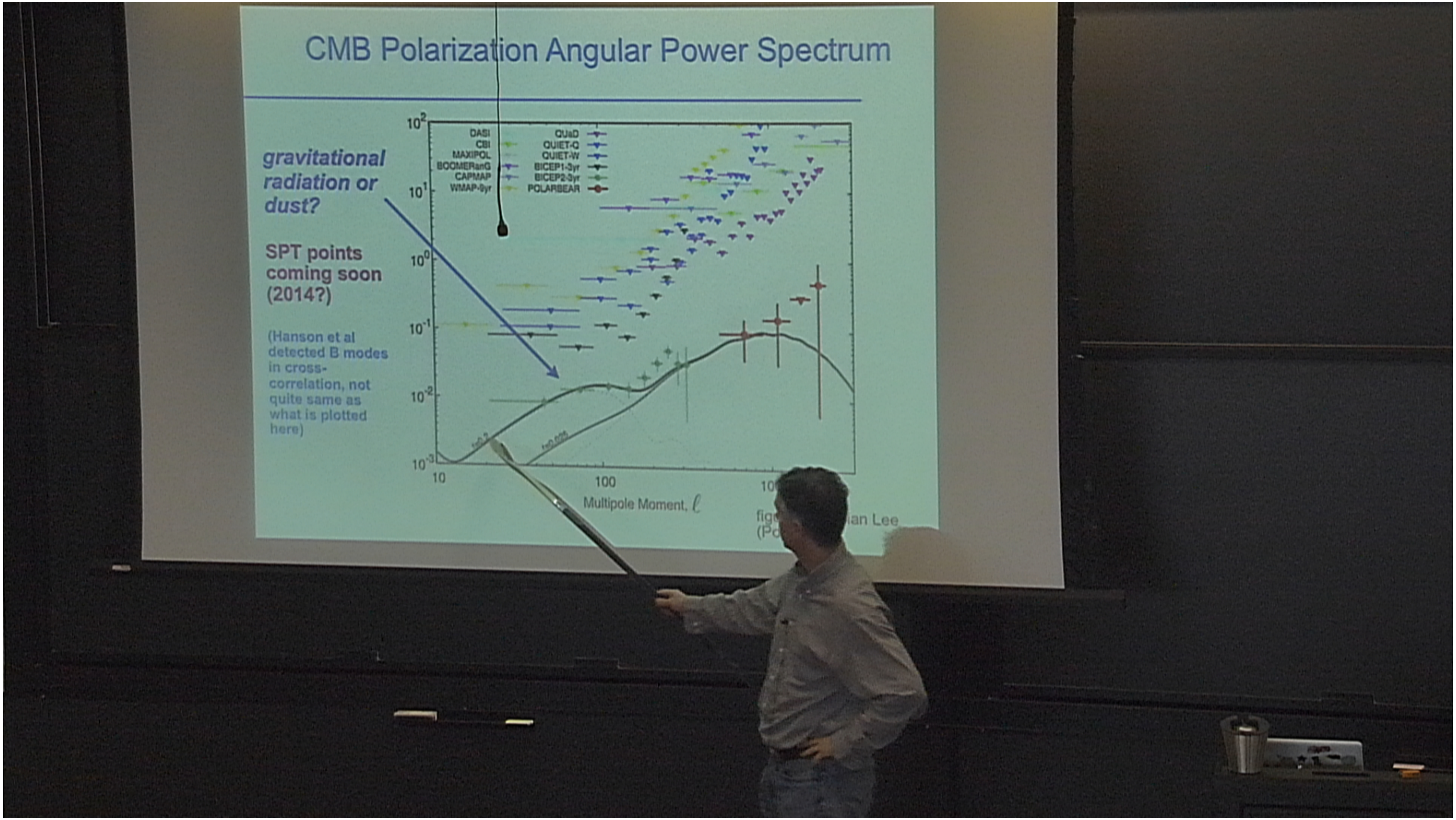

Detection of B-Modes
(predicted B) X (measured B)
12
10
8
6
4
2
0
500
1000
1500
2000
lC_l^{BB} [$\mu K^2 \times 10^4$]
$(\hat{E}^{150} \hat{\phi}^{CIB}) \times \hat{B}^{150}$
$(\hat{E}^{95} \hat{\phi}^{CIB}) \times \hat{B}^{150}$
$(\hat{E}^{150} \hat{\phi}^{CIB}) \times \hat{B}^{150}_{\lambda}$
not zero at 7.7σ
Hanson, Hoover, C
(SPTpol)

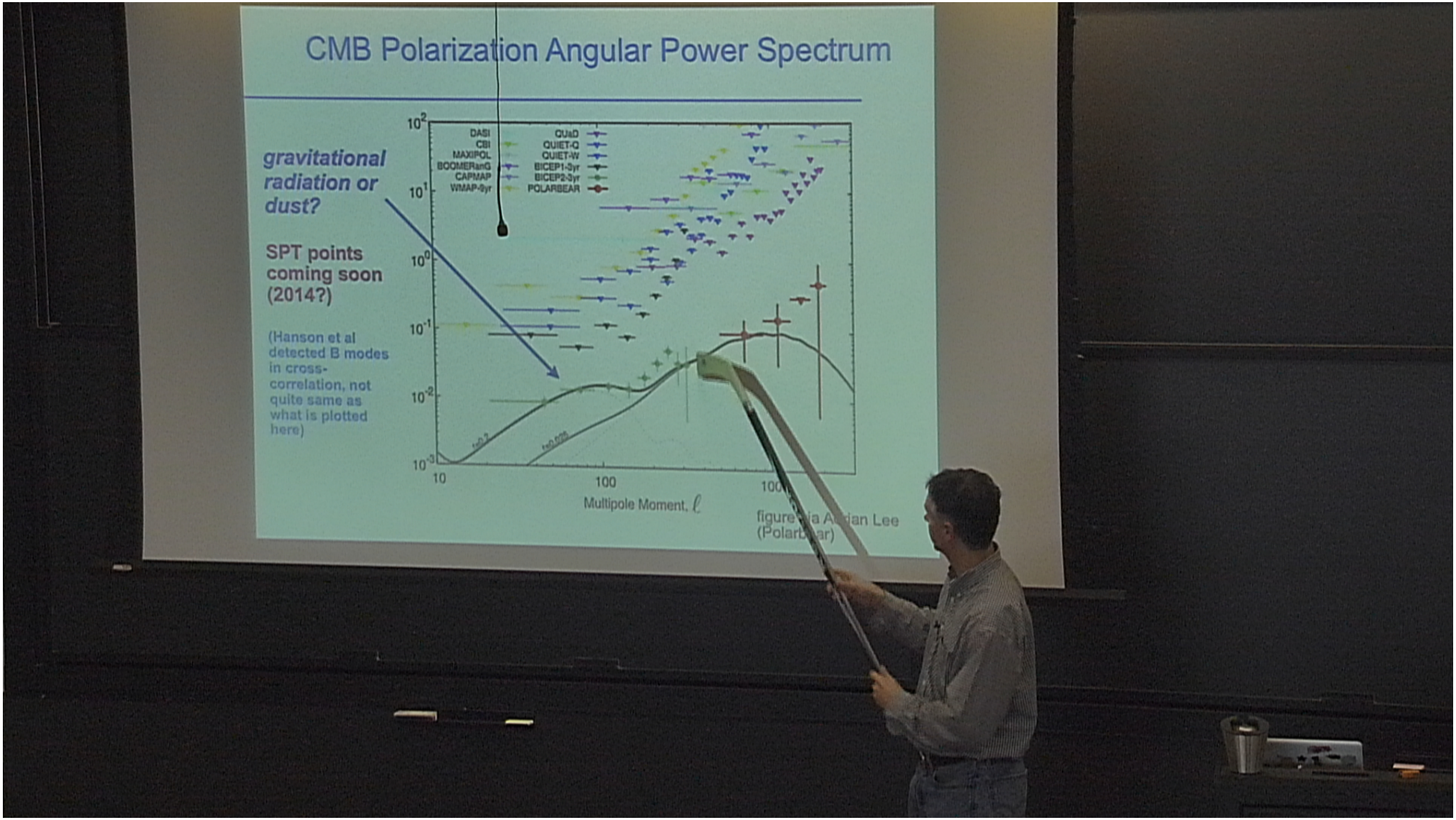
Detection of B-Modes



not zero at 7.7σ

Hanson, Hoover, Crites et al 2013 (SPTpol)


CMB Polarization Angular Power Spectrum
gravitational radiation or dust?
SPT points coming soon (2014?)
(Hanson et al detected B modes in cross-correlation, not quite same as what is plotted here)
DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
BICEP2-3yr
POLARBEAR
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10
100
Multipole Moment, ℓ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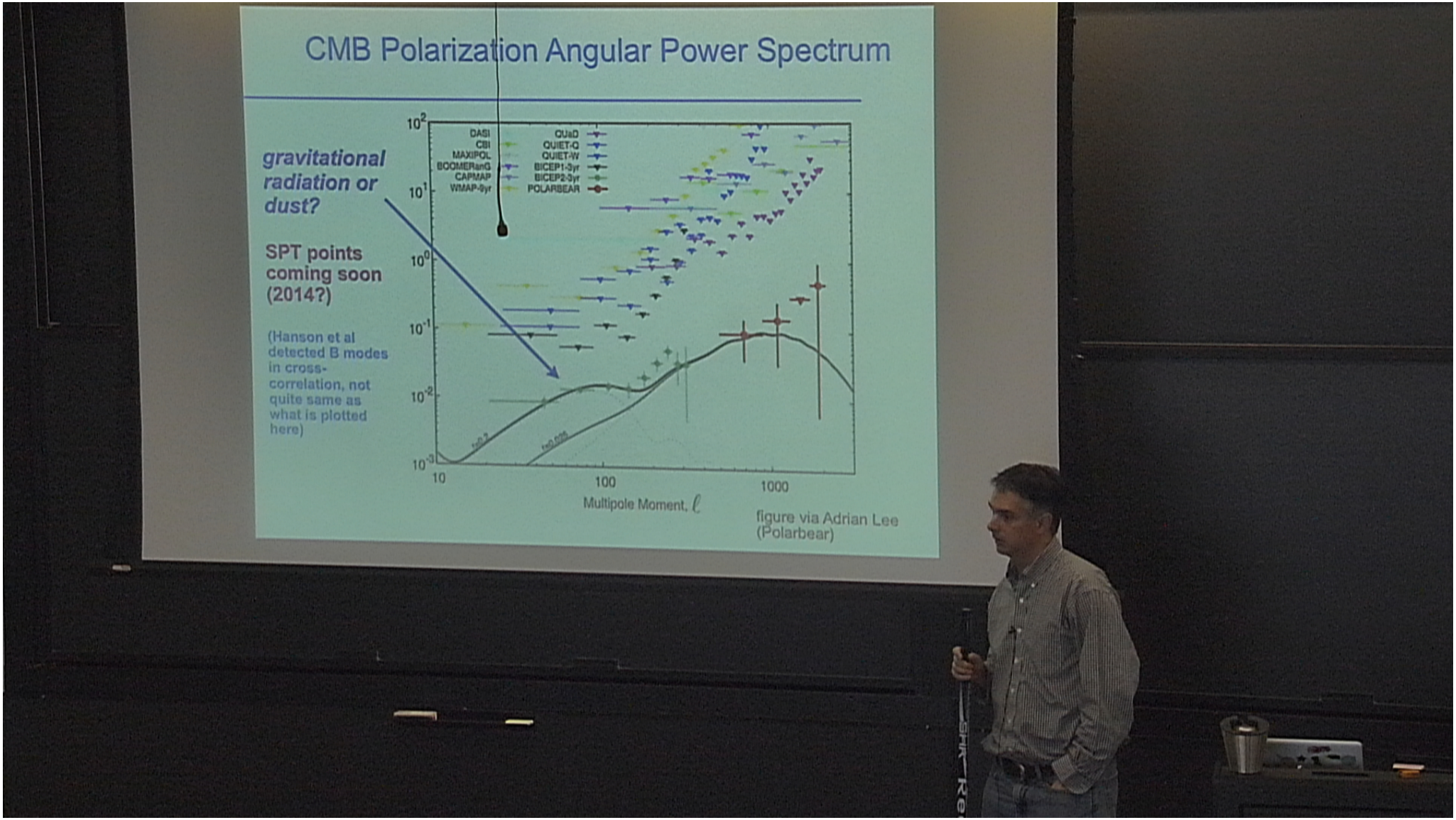
BICEP2-3yr
POLARBEAR
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10
100
Multipole Moment, ℓ
figure via Adrian Lee (Polarbear)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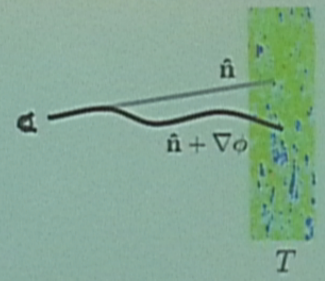
BICEP2-3yr
POLARBEAR
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10
100
1000
Multipole Moment, ℓ
figure via Adrian Lee (Polarbear)

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

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

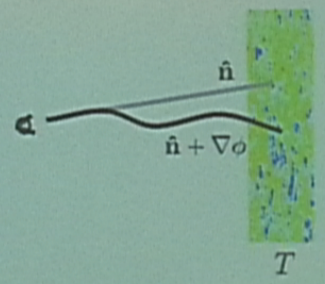
Broad kernel, peaks at $z \sim 2$

- 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

CMB Lensing

Photons get shifted

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



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- CMB is a unique source for lensing
  - Gaussian, with well-understood power spectrum (contains all info)
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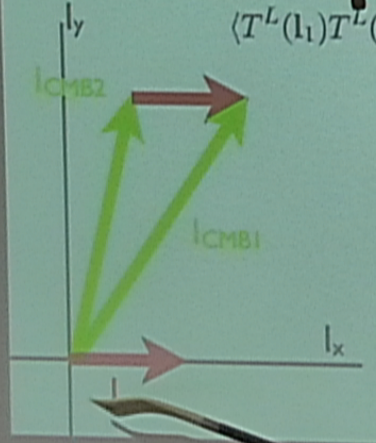
Mode Coupling from Lensing

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

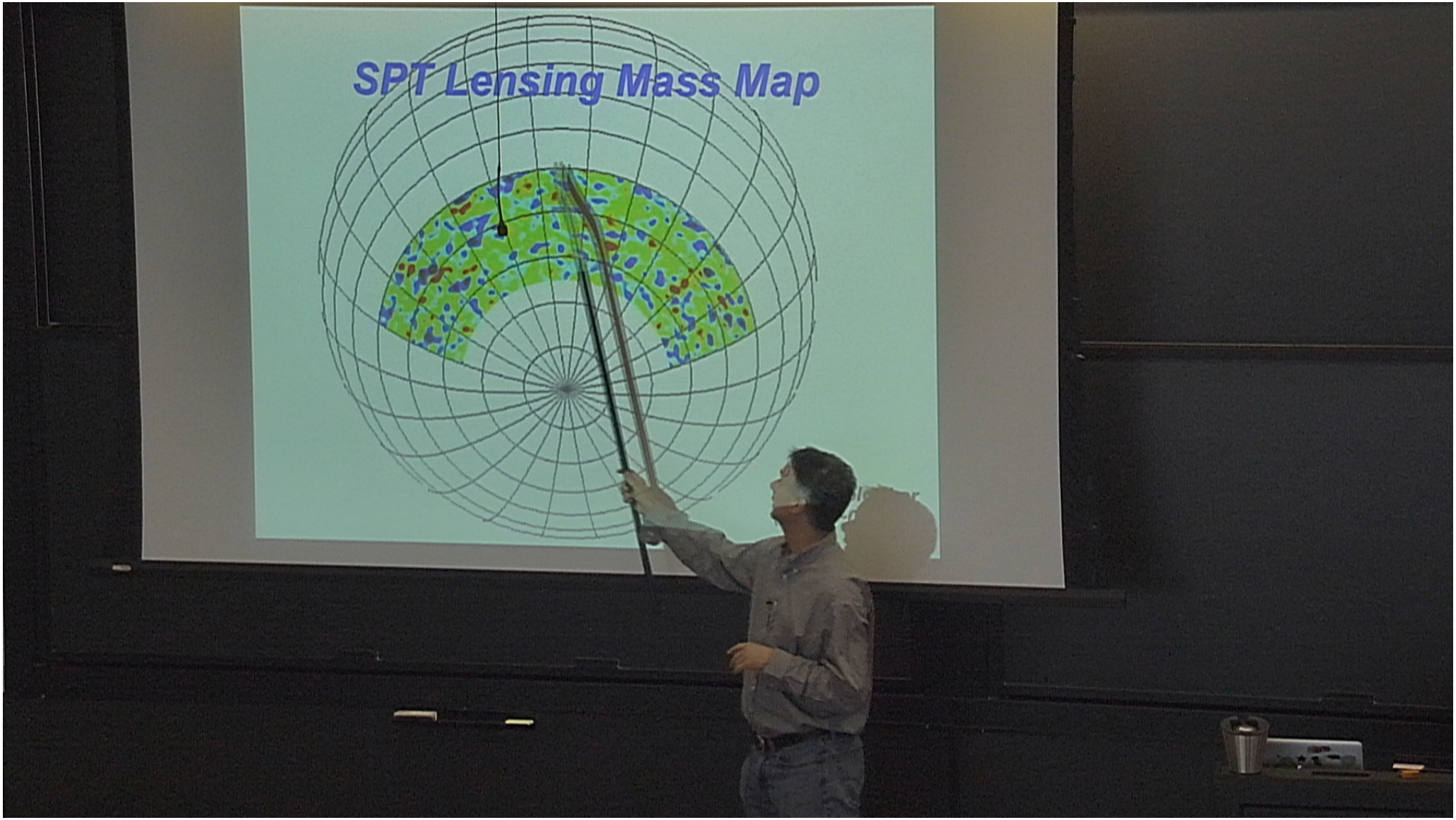
- Non-gaussian mode coupling for $\mathbf{l}_1 \neq -\mathbf{l}_2$:

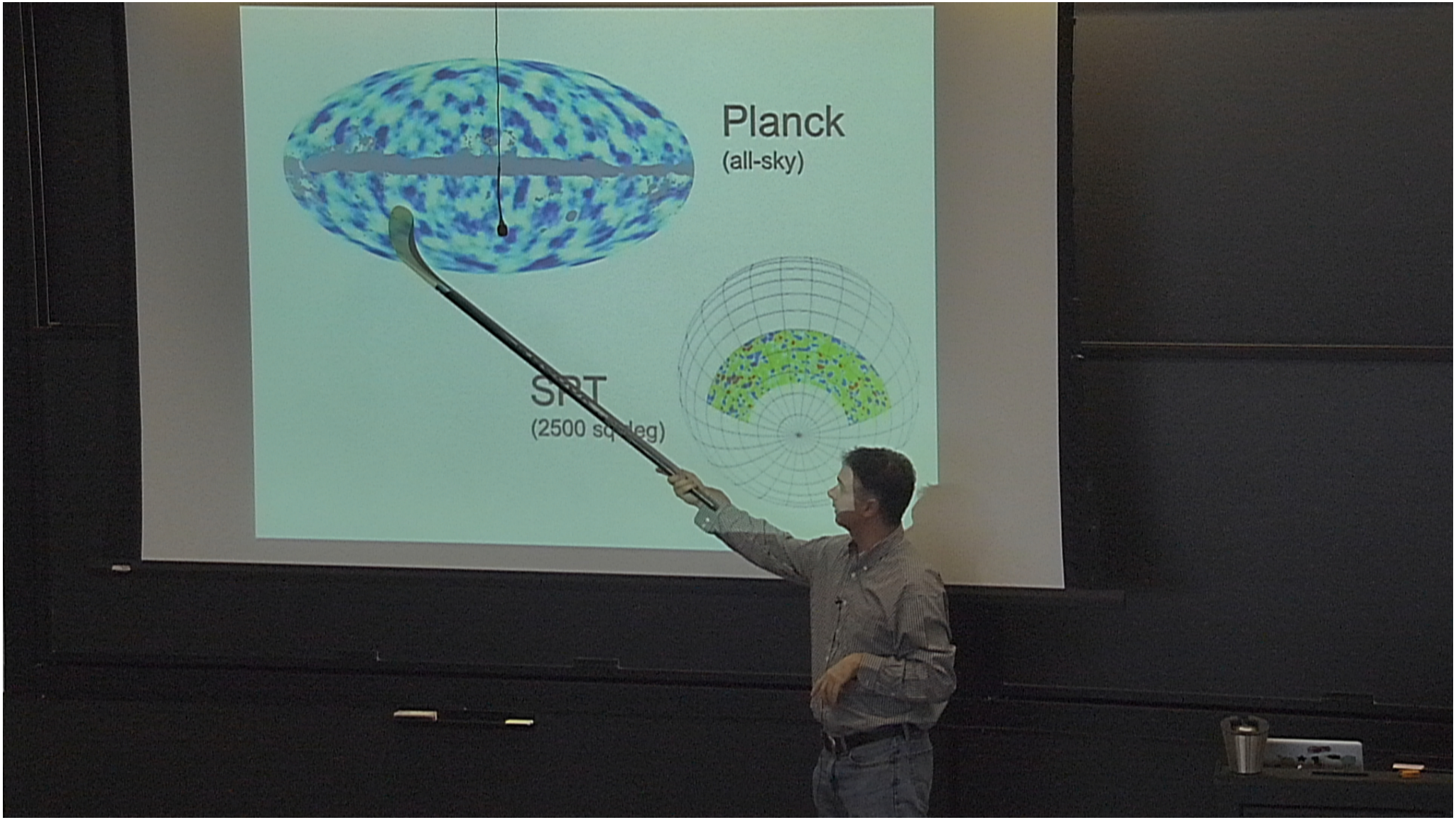
$$\langle T^L(\mathbf{l}_1) T^L(\mathbf{l}_2)\rangle = \mathbf{L}\cdot(\mathbf{l}_1 C^T_{l_1} + \mathbf{l}_2 C^T_{l_2})\phi(\mathbf{L}) + O(\phi^2)$$

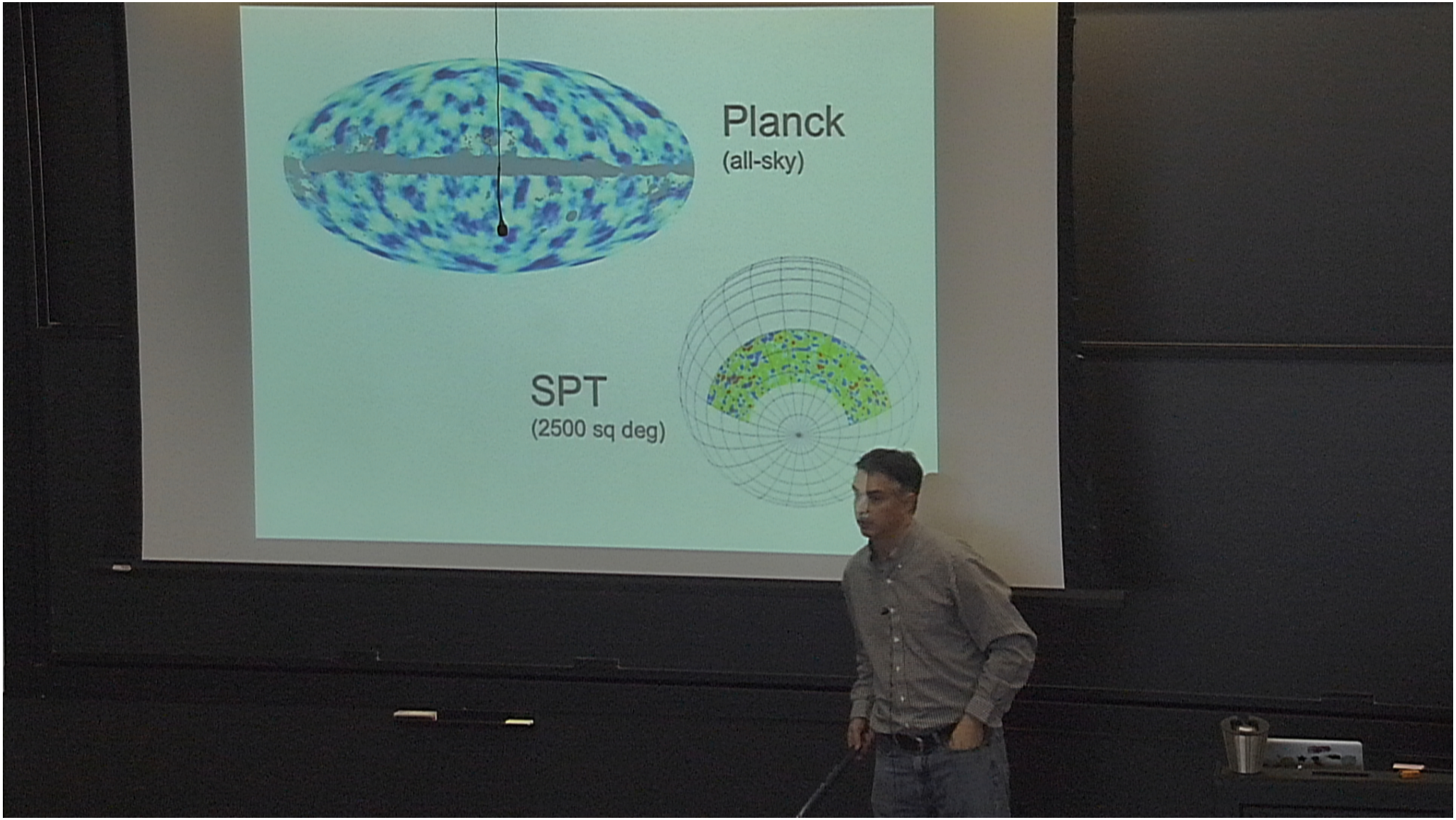
$$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$$

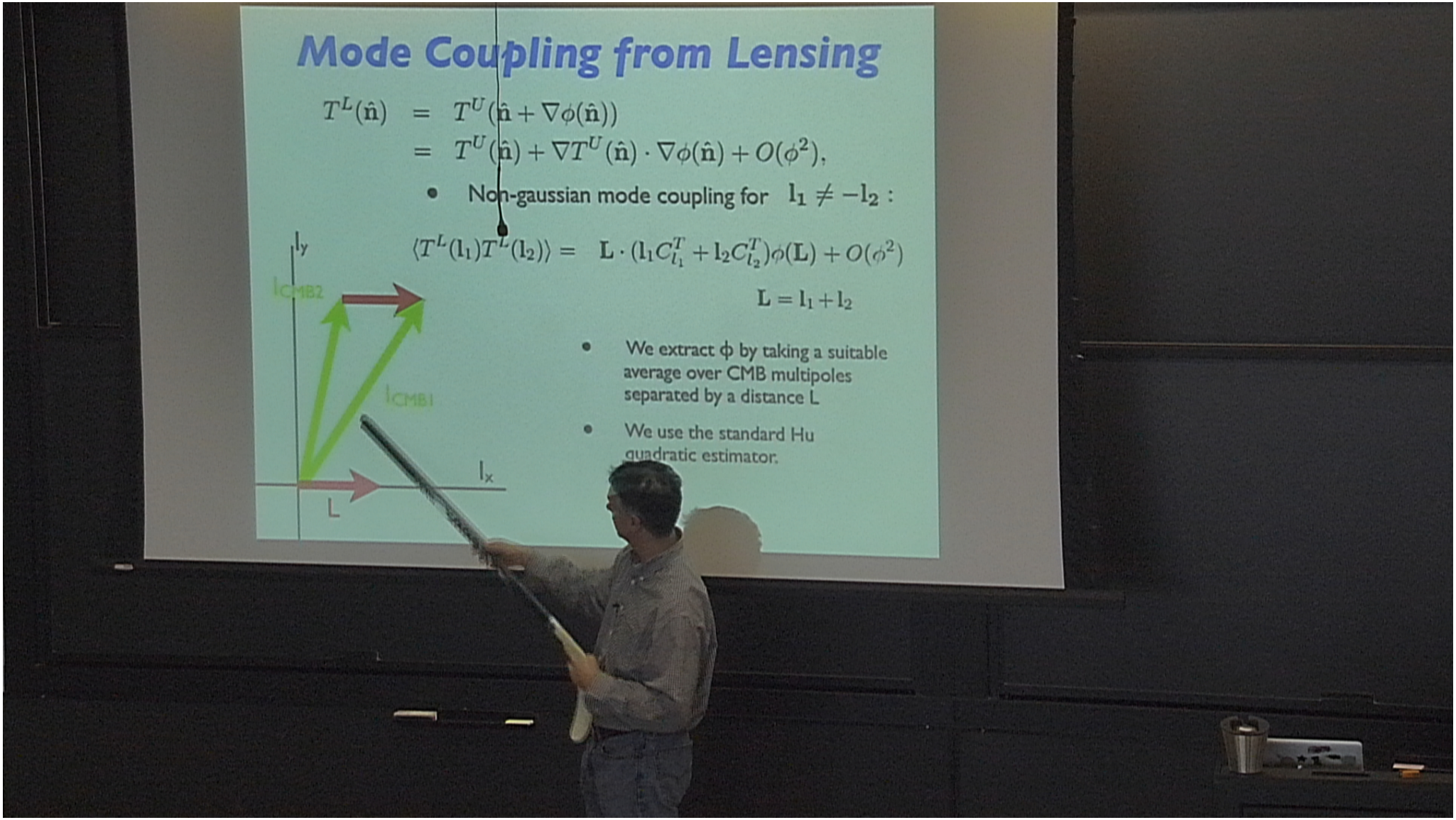


- We extract ϕ by taking a suitable average over CMB multipoles separated by a distance L
- We use the standard Hu quadratic estimator.


SPT Lensing Mass Map


Planck
(all-sky)
SPT
(2500 sq deg)


Planck
(all-sky)
SPT
(2500 sq deg)


Mode Coupling from Lensing
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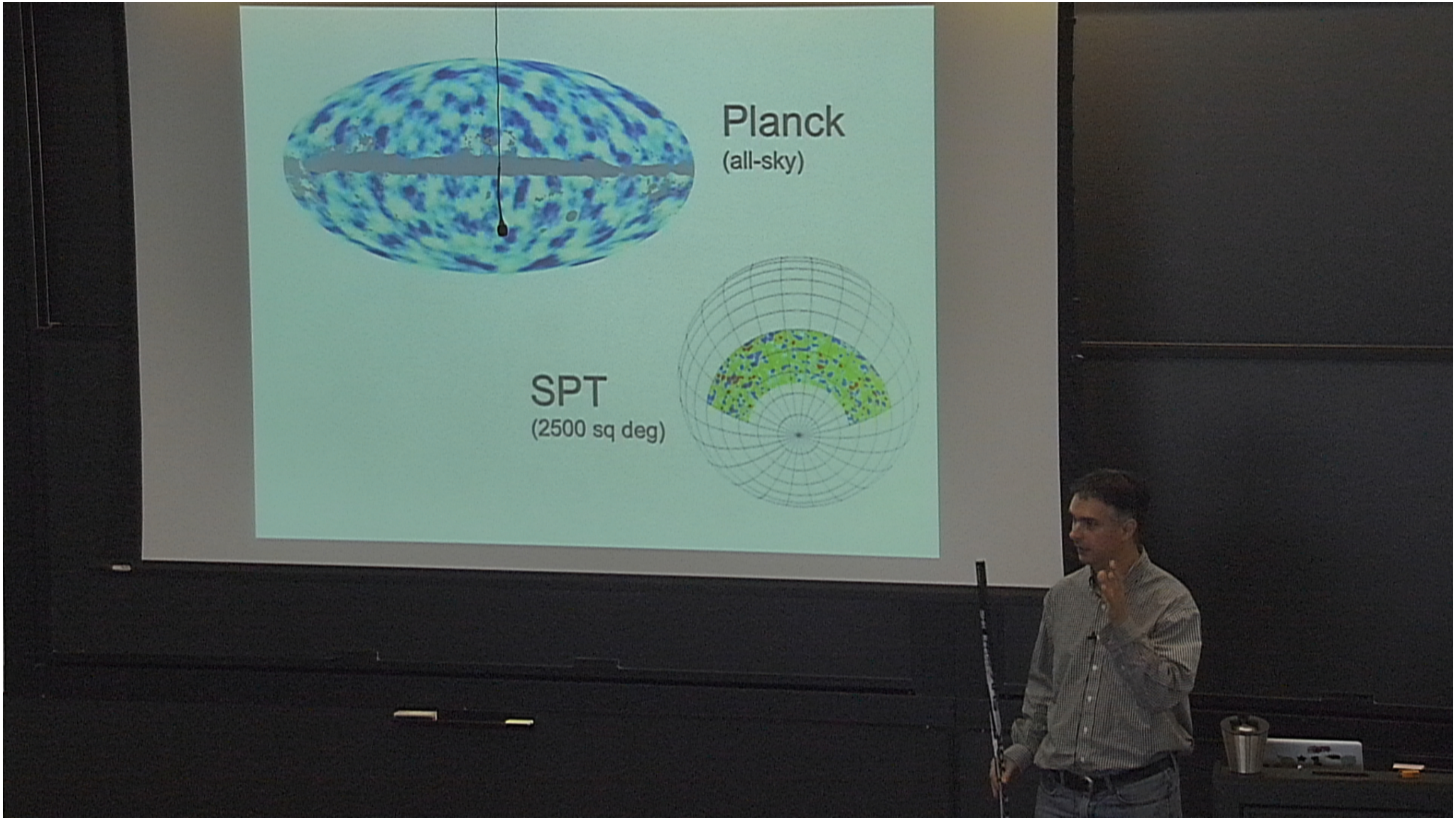
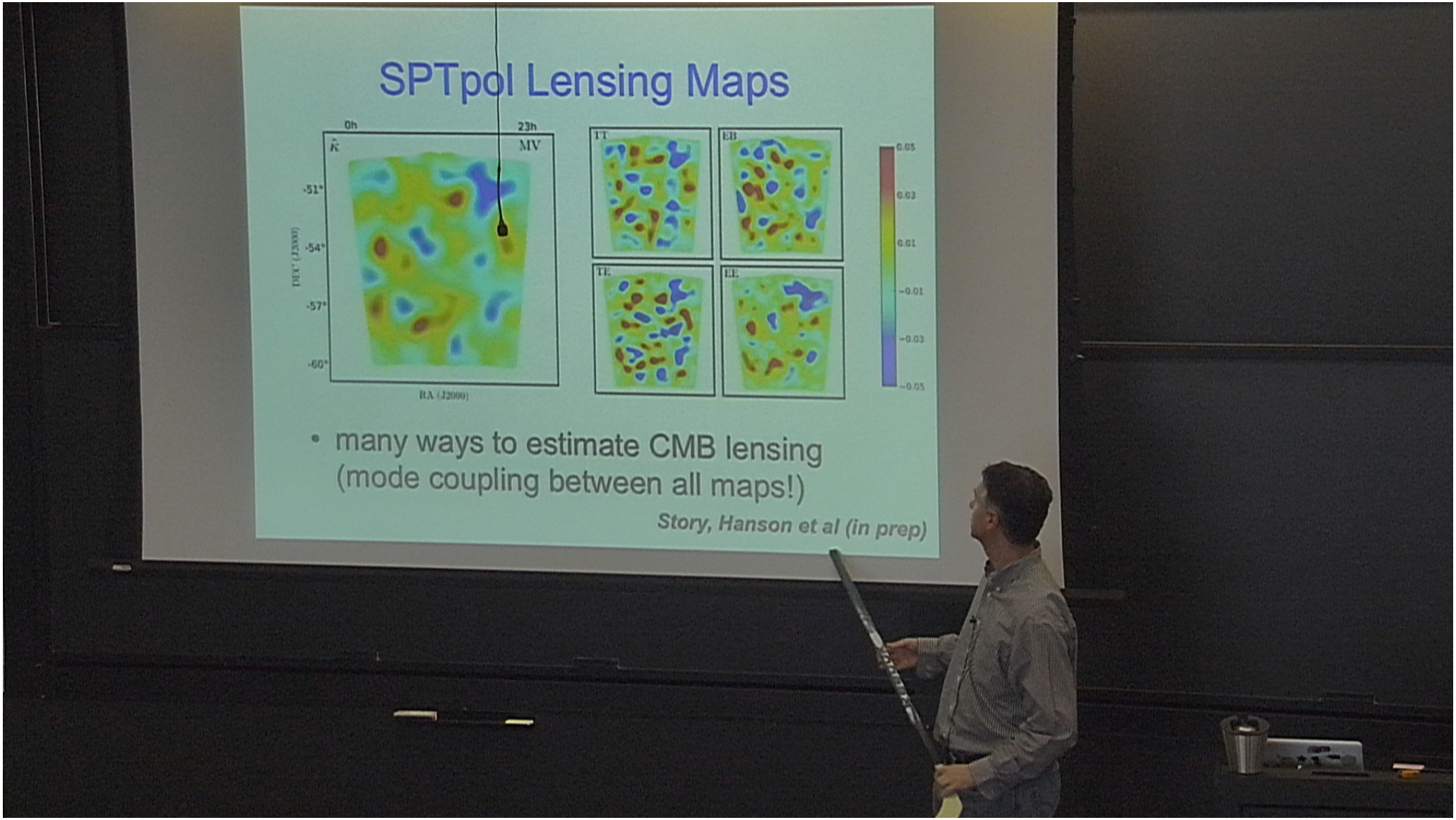
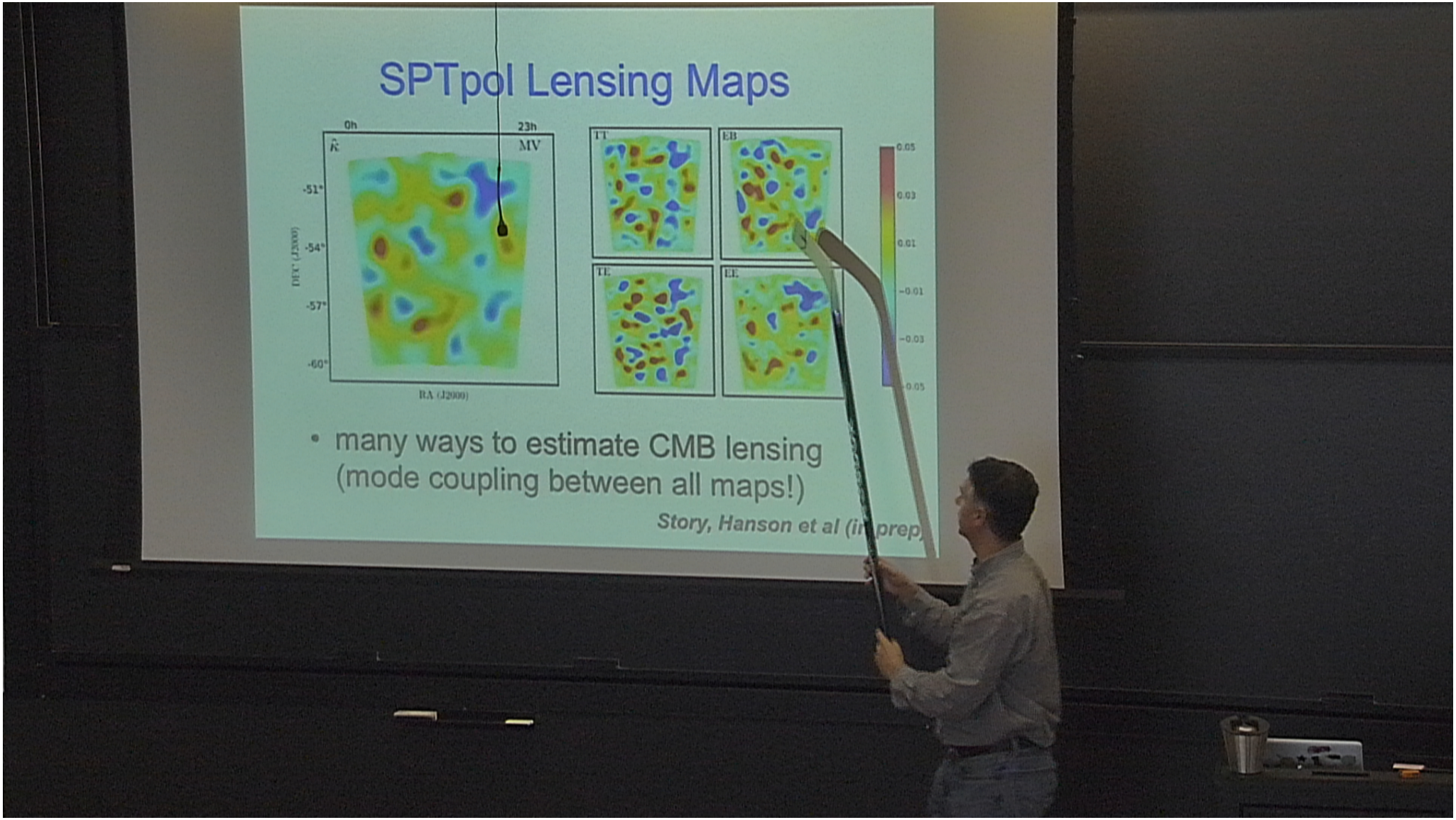
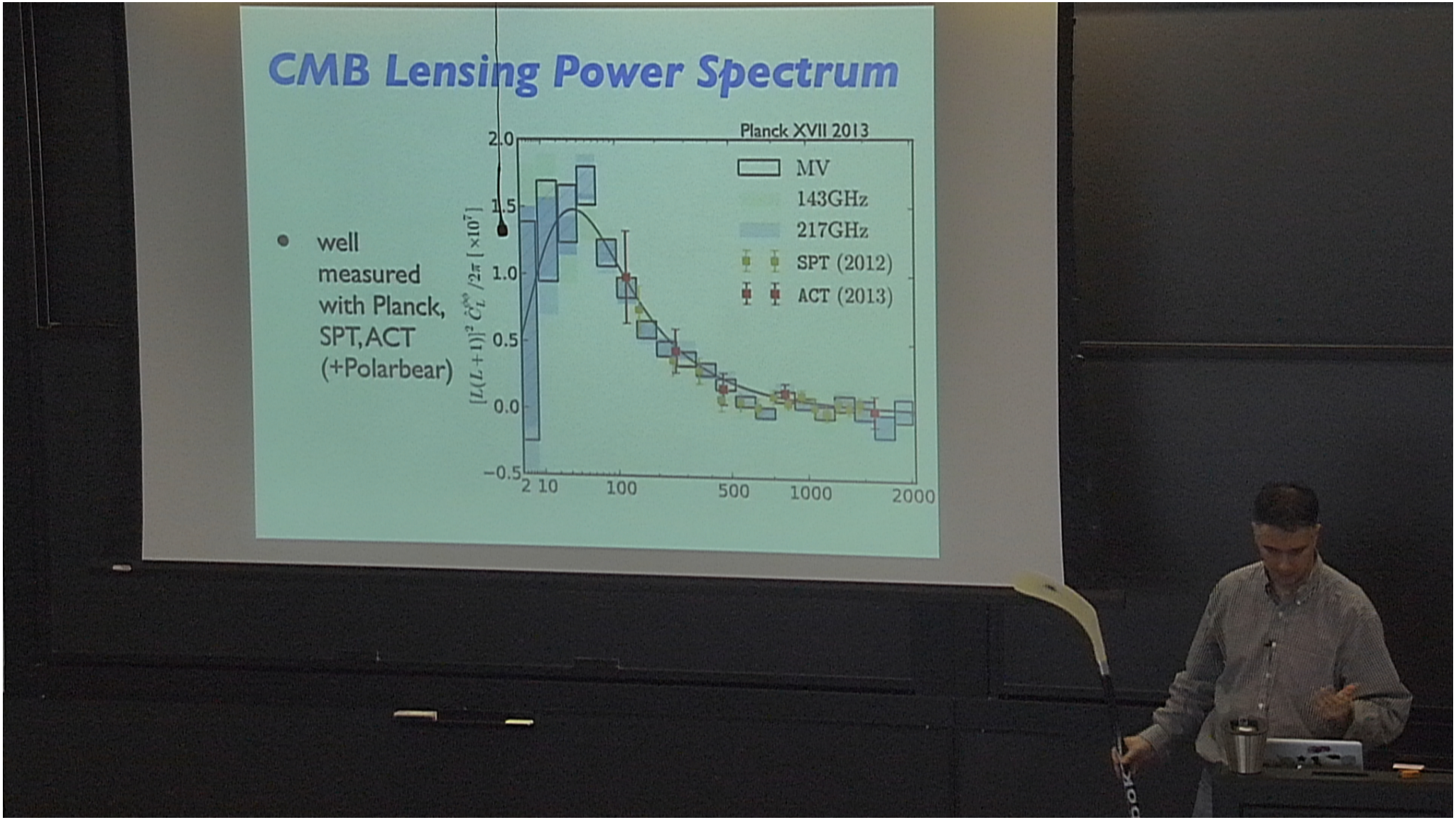
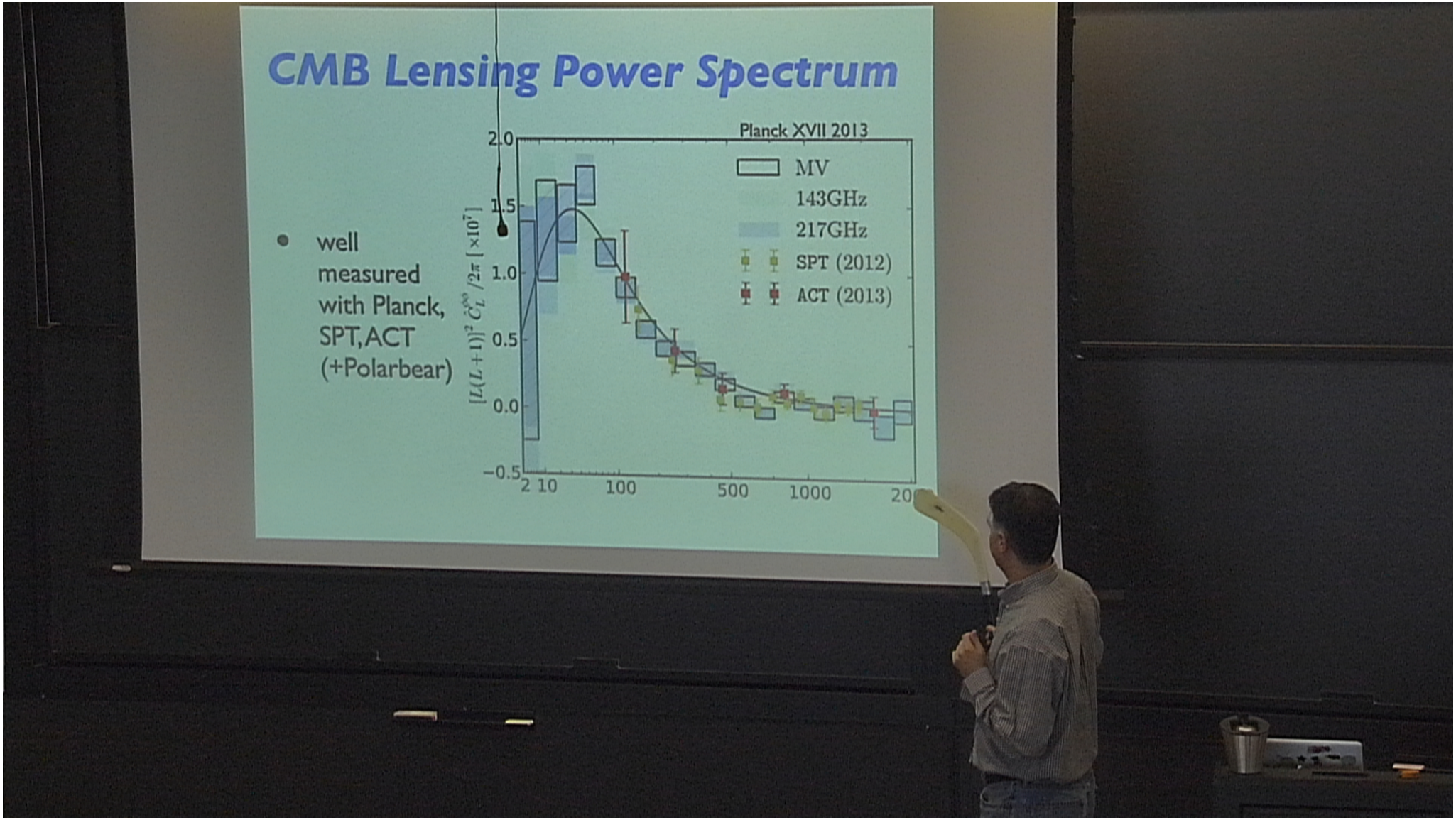
$= T^U(\hat{\mathbf{n}}) + \nabla T^U(\hat{\mathbf{n}}) \cdot \nabla\phi(\hat{\mathbf{n}}) + O(\phi^2),$
• Non-gaussian mode coupling for $\mathbf{l}_1 \neq -\mathbf{l}_2$:
$\langle T^L(\mathbf{l}_1) T^L(\mathbf{l}_2) \rangle = \mathbf{L} \cdot (\mathbf{l}_1 C^T_{l_1} + \mathbf{l}_2 C^T_{l_2}) \phi(\mathbf{L}) + O(\phi^2)$
$\mathbf{L} = \mathbf{l}_1 + \mathbf{l}_2$
l_y
l_{CMB2}
l_{CMB1}
l_x
L
• We extract ϕ by taking a suitable average over CMB multipoles separated by a distance L
• We use the standard Hu quadratic estimator.

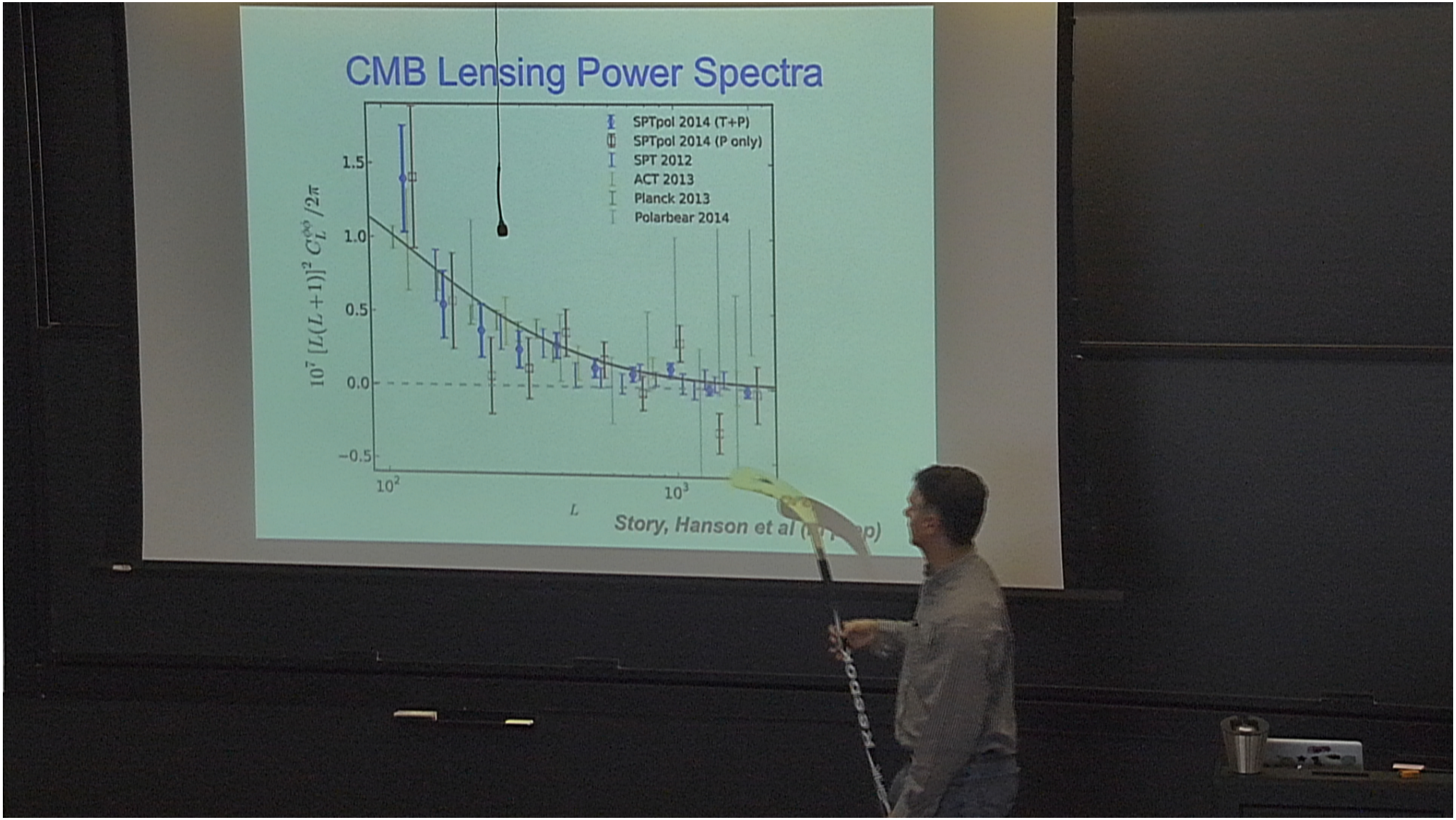

Planck
(all-sky)
SPT
(2500 sq deg)

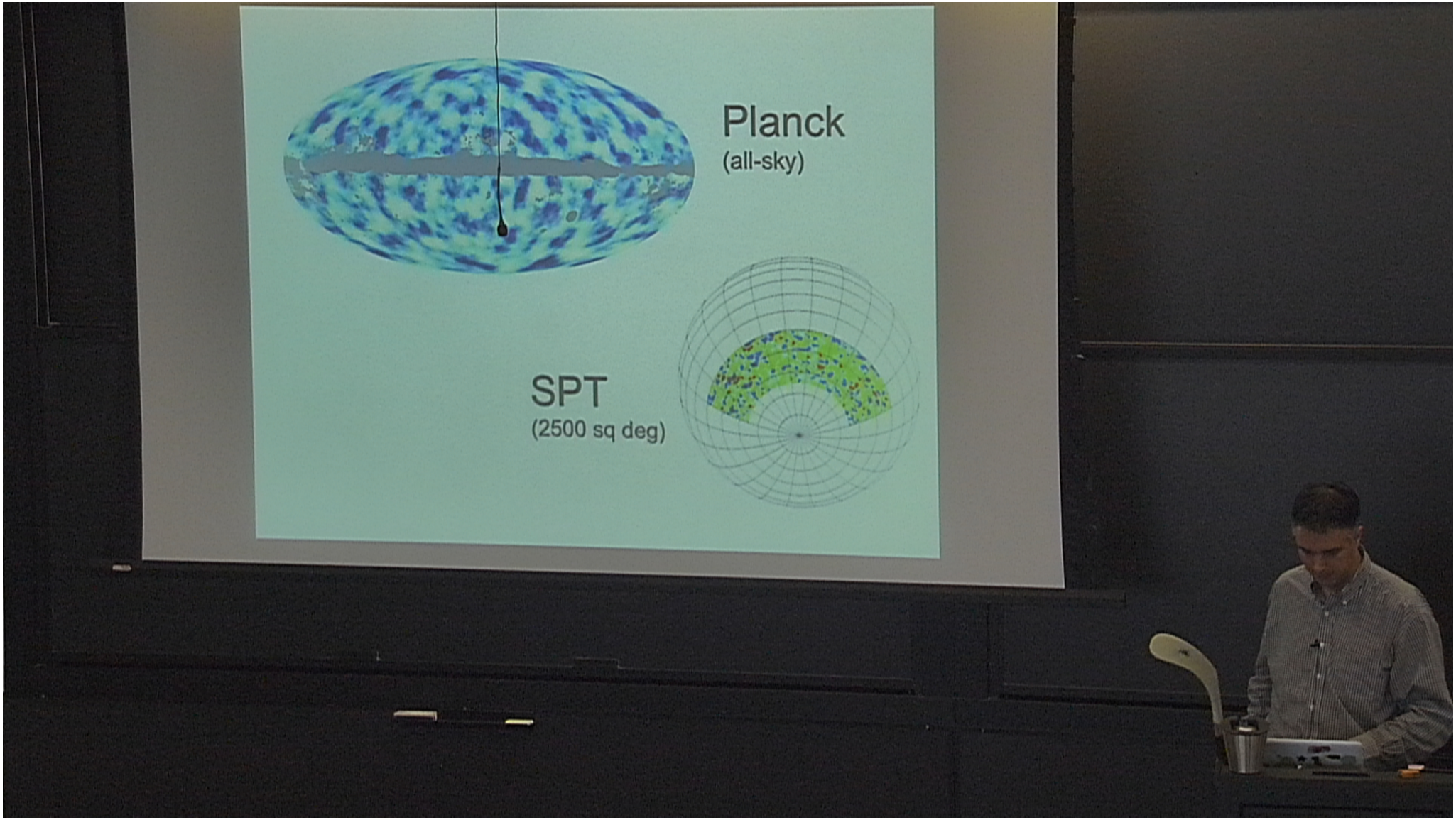

SPTpol Lensing Maps
0h
23h
$\hat{\kappa}$
MV
-51°
-54°
-57°
-60°
DEC (J2000)
RA (J2000)
TT
EB
TE
EE
0.05
0.03
0.01
-0.01
-0.03
-0.05
• many ways to estimate CMB lensing (mode coupling between all maps!)
Story, Hanson et al (in prep)

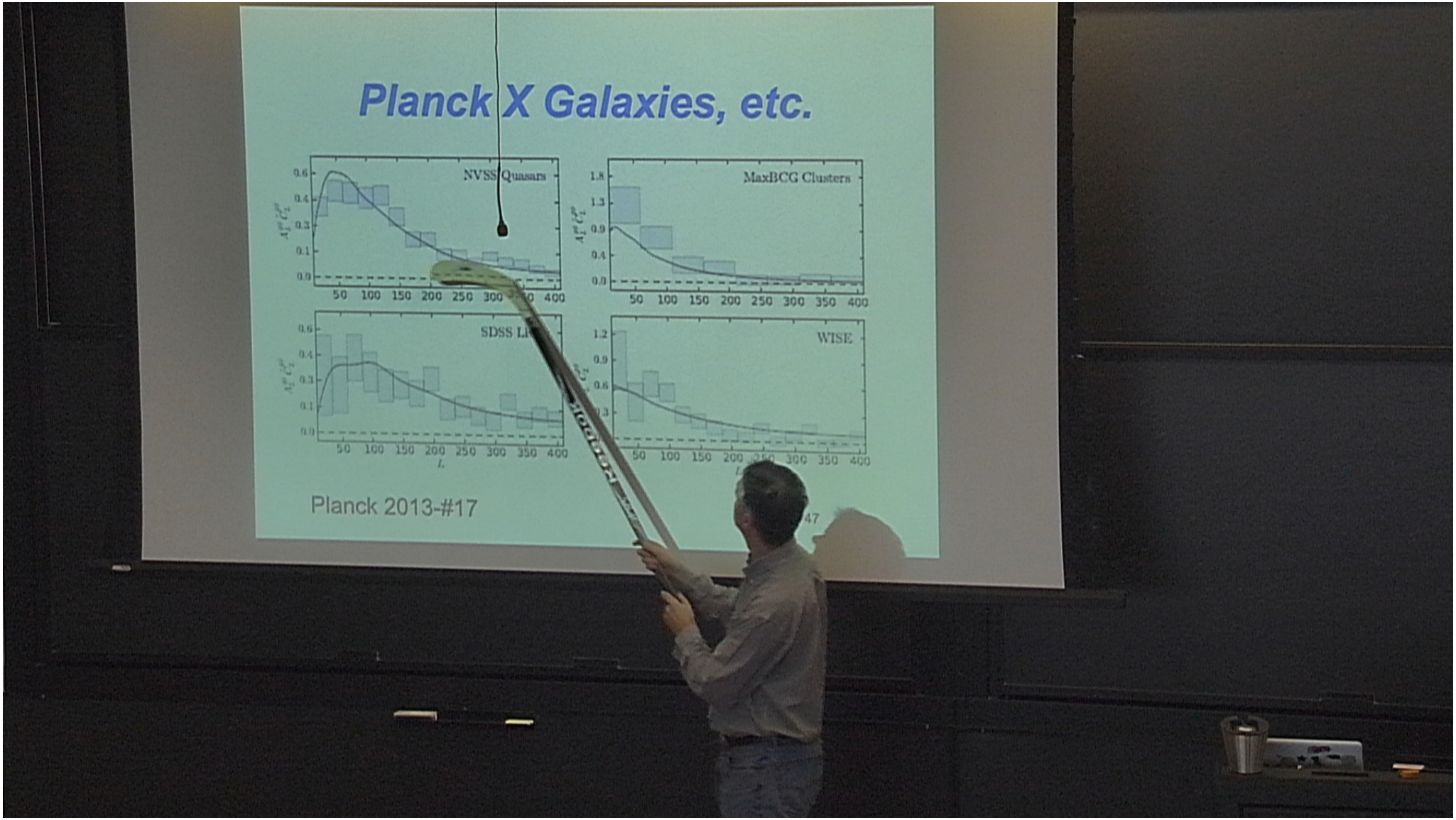

SPTpol Lensing Maps
0h
23h
$\hat{\kappa}$
MV
-51°
-54°
-57°
-60°
DEC (J2000)
RA (J2000)
TT
EB
TE
EE
0.05
0.03
0.01
-0.01
-0.03
-0.05
• many ways to estimate CMB lensing (mode coupling between all maps!)
Story, Hanson et al (in prep)

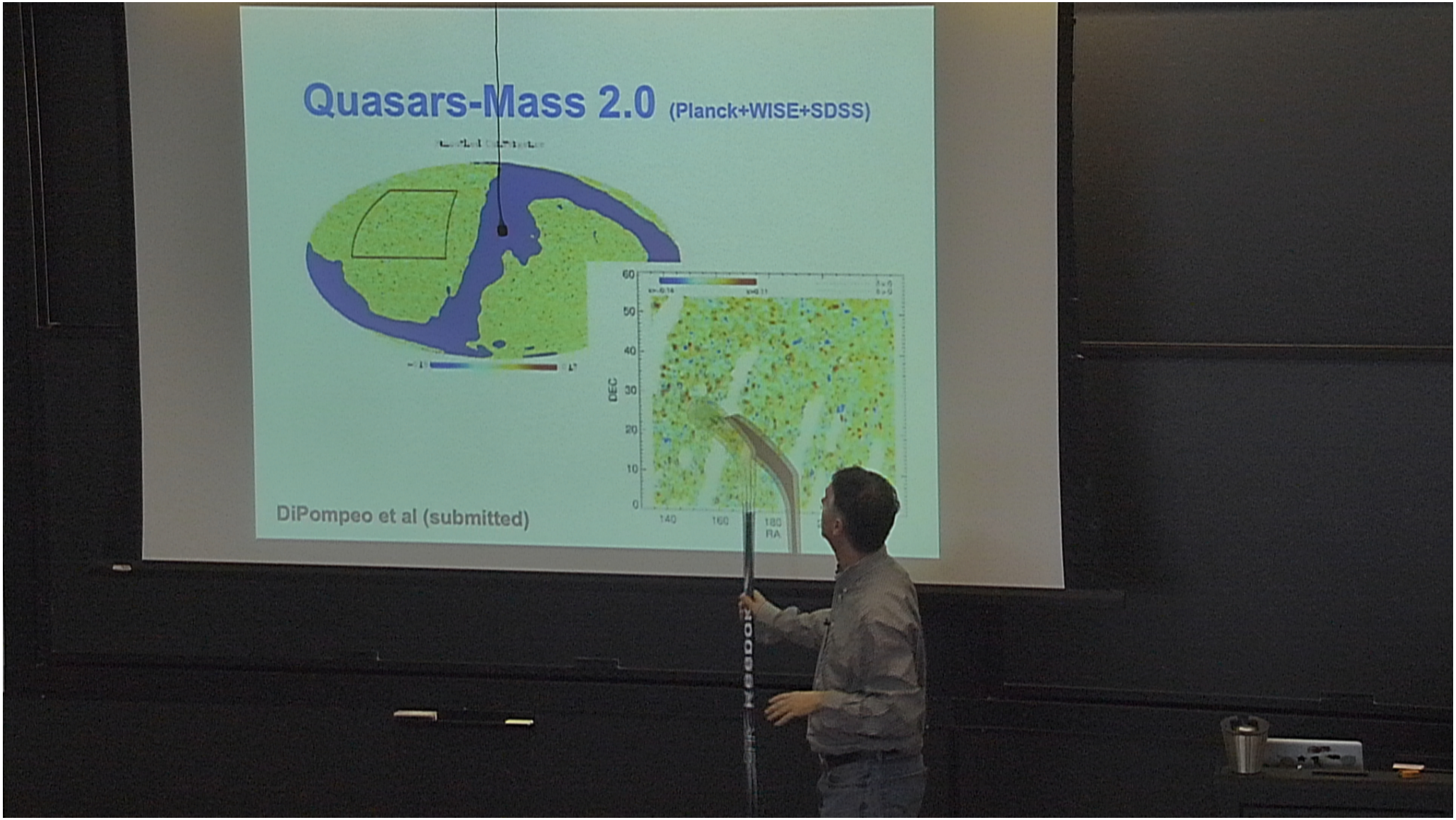

CMB Lensing Power Spectrum
well measured with Planck, SPT,ACT (+Polarbear)
Planck XVII 2013
MV
143GHz
217GHz
SPT (2012)
ACT (2013)
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
2.0
1.5
1.0
0.5
0.0
−0.5
2
10
100
500
1000
2000

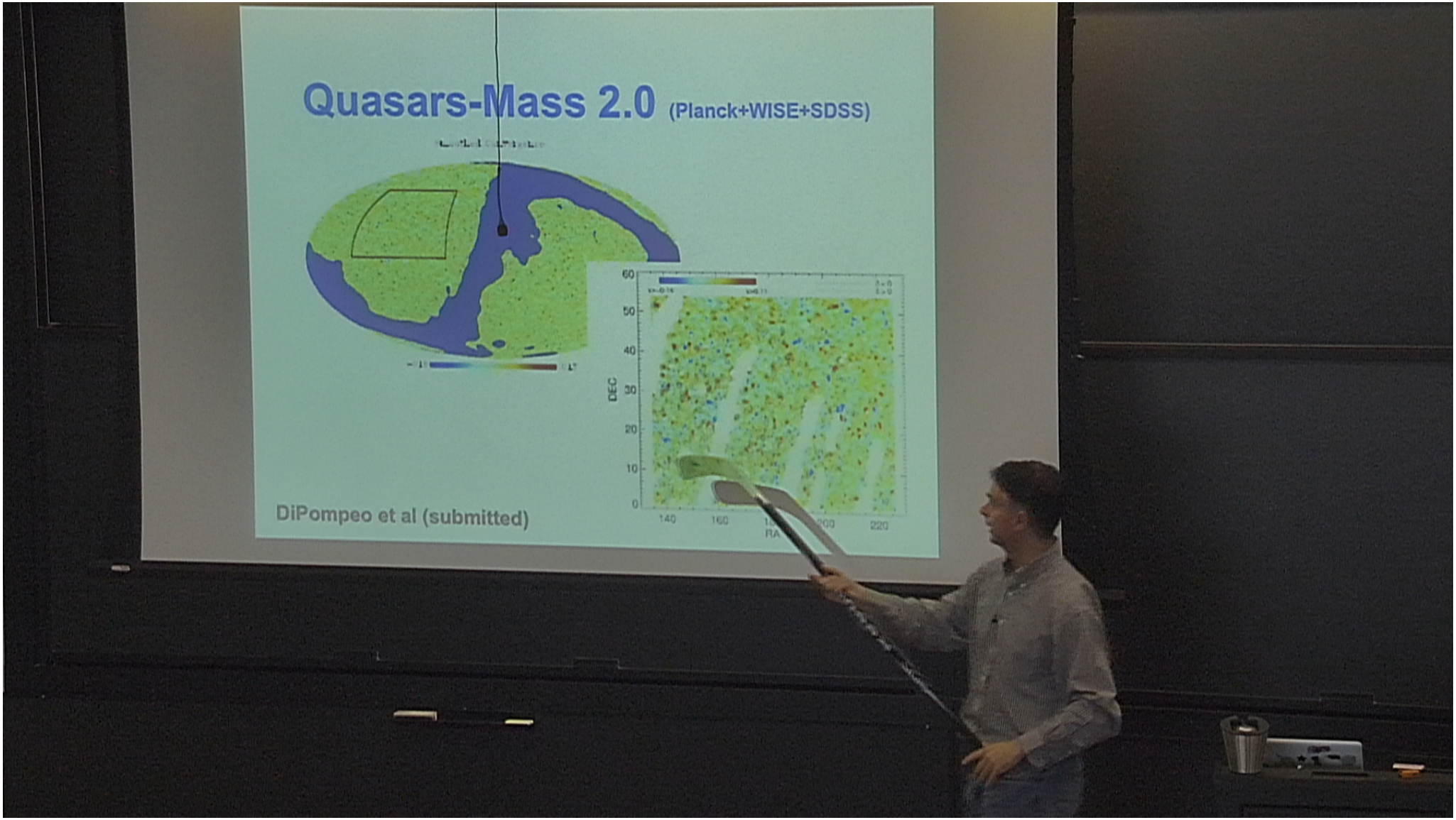

CMB Lensing Power Spectrum
well measured with Planck, SPT,ACT (+Polarbear)
Planck XVII 2013
MV
143GHz
217GHz
SPT (2012)
ACT (2013)
2.0
1.5
1.0
0.5
0.0
−0.5
2 10
100
500
1000

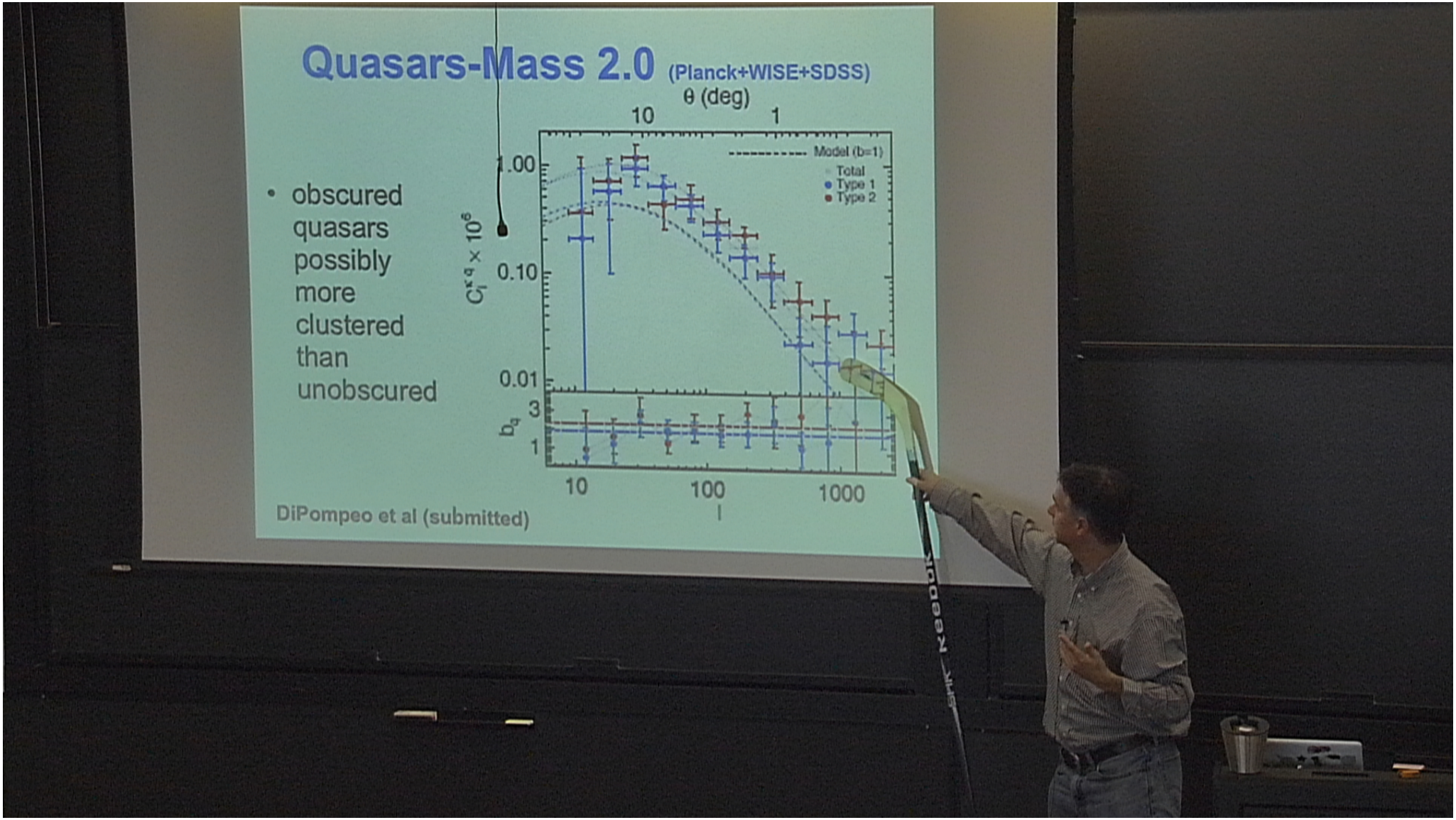

CMB Lensing Power Spectra
SPTpol 2014 (T+P)
SPTpol 2014 (P only)
SPT 2012
ACT 2013
Planck 2013
Polarbear 2014
$10^7\,[L(L+1)]^2\,C_L^{\phi\phi}/2\pi$
1.5
1.0
0.5
0.0
−0.5
10^2
10^3
L
Story, Hanson et al

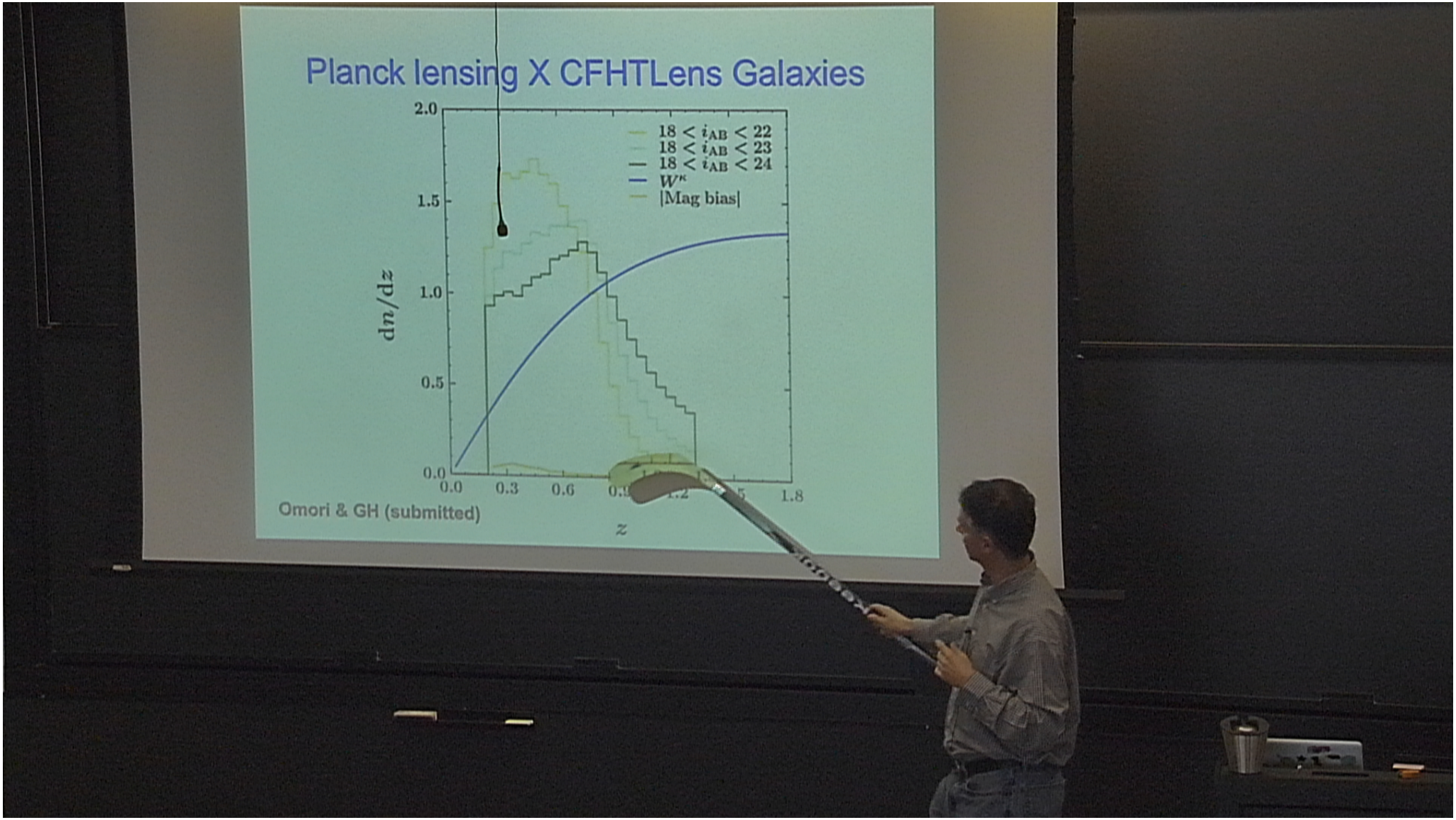

Planck
(all-sky)
SPT
(2500 sq deg)

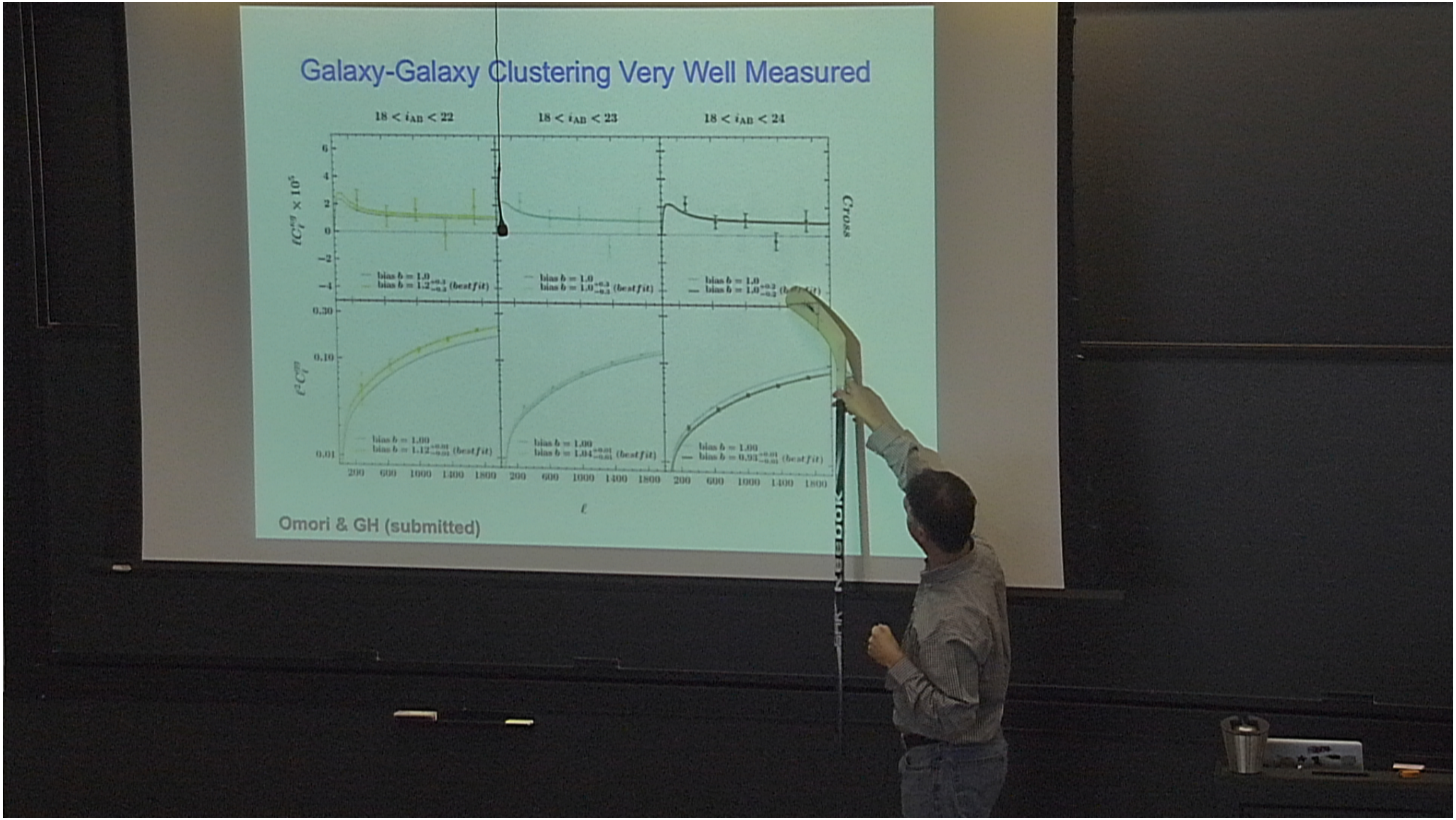

Planck X Galaxies, etc.
NVSS Quasars
MaxBCG Clusters
SDSS LR
WISE
Planck 2013-#17

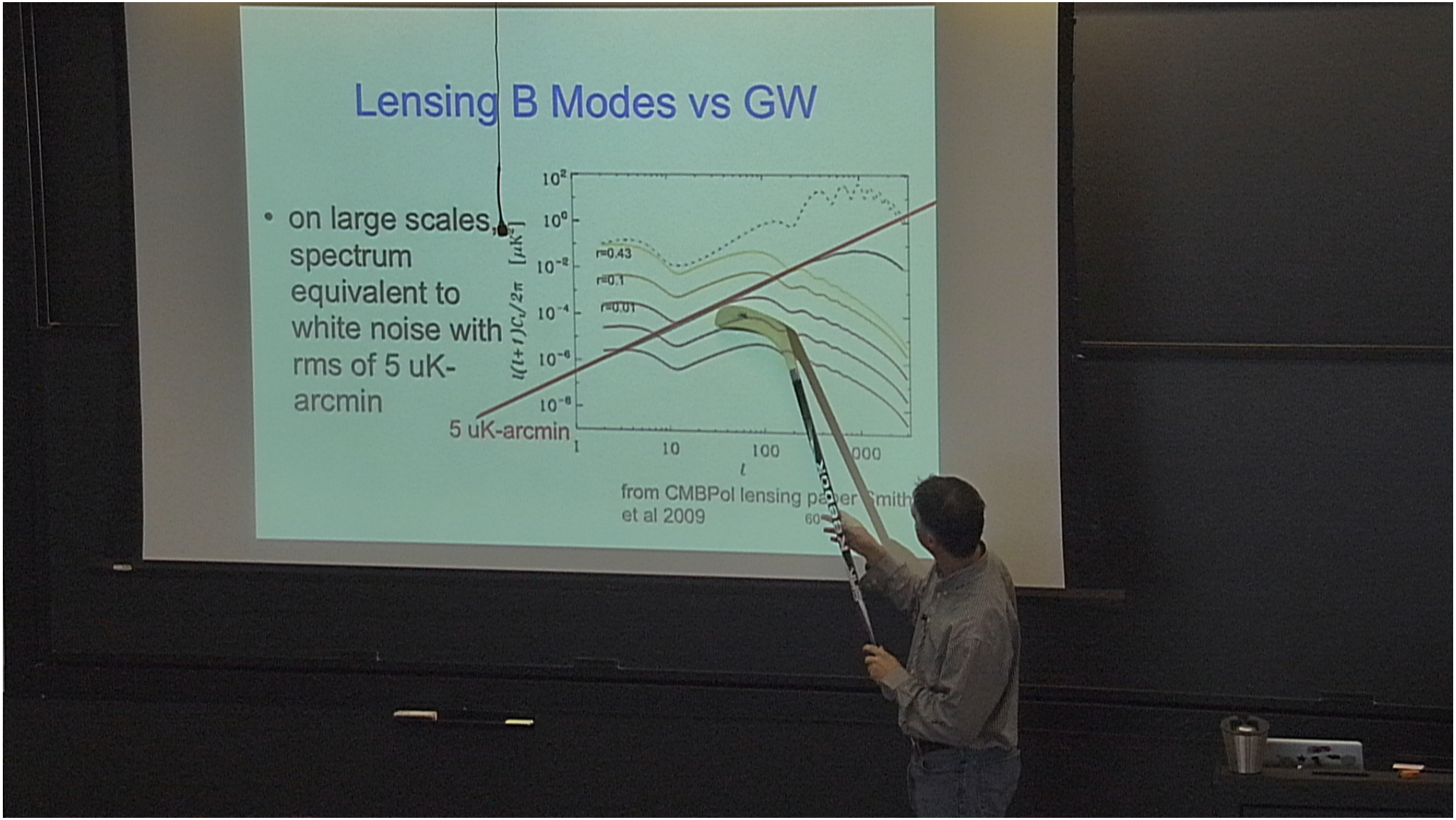

Quasars-Mass 2.0 (Planck+WISE+SDSS)
DiPompeo et al (submitted)
DEC
RA
60
50
40
30
20
10
0
140
160
180

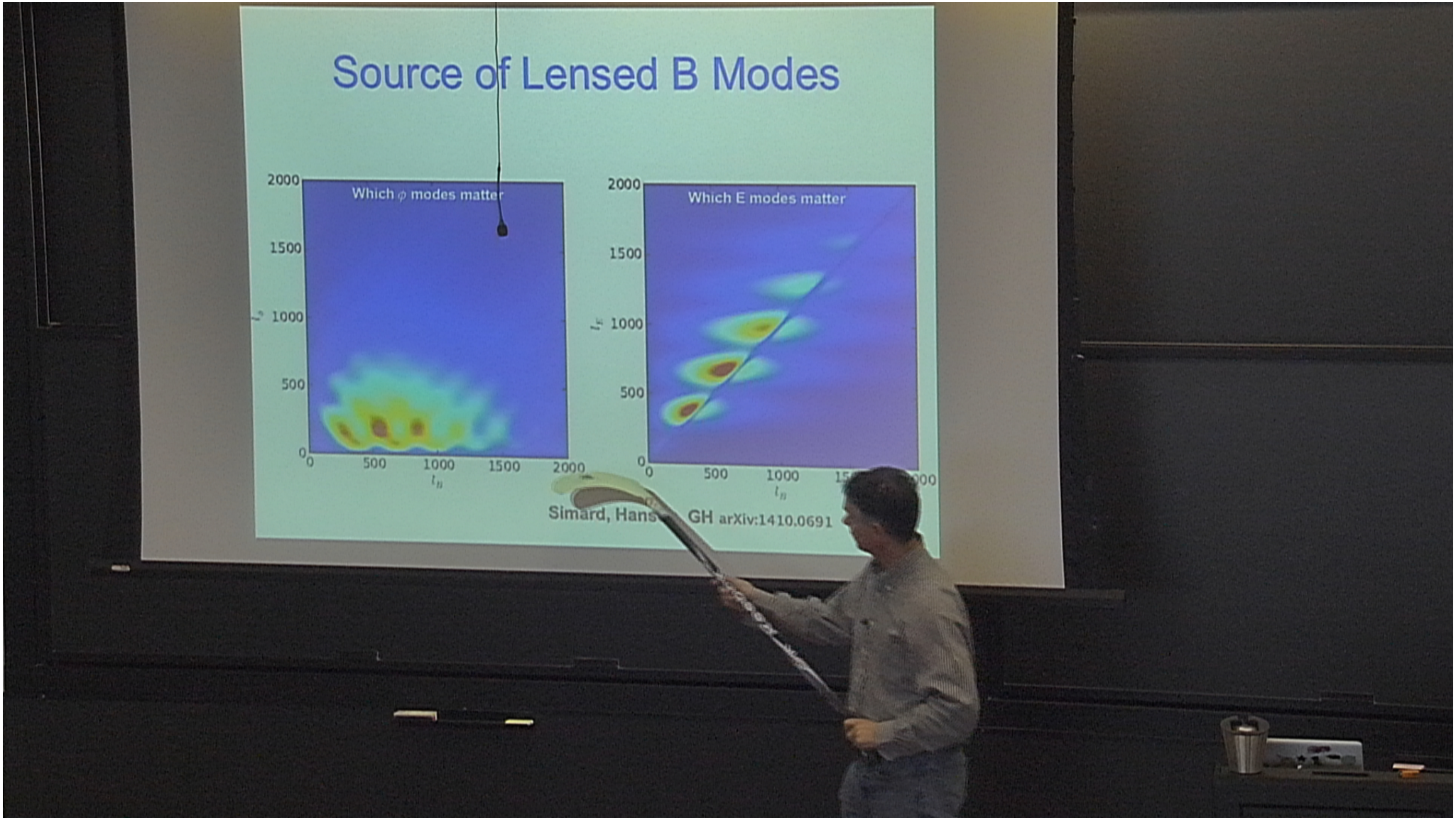

Quasars-Mass 2.0 (Planck+WISE+SDSS)
DiPompeo et al (submitted)
DEC
RA
60
50
40
30
20
10
0
140
160
220

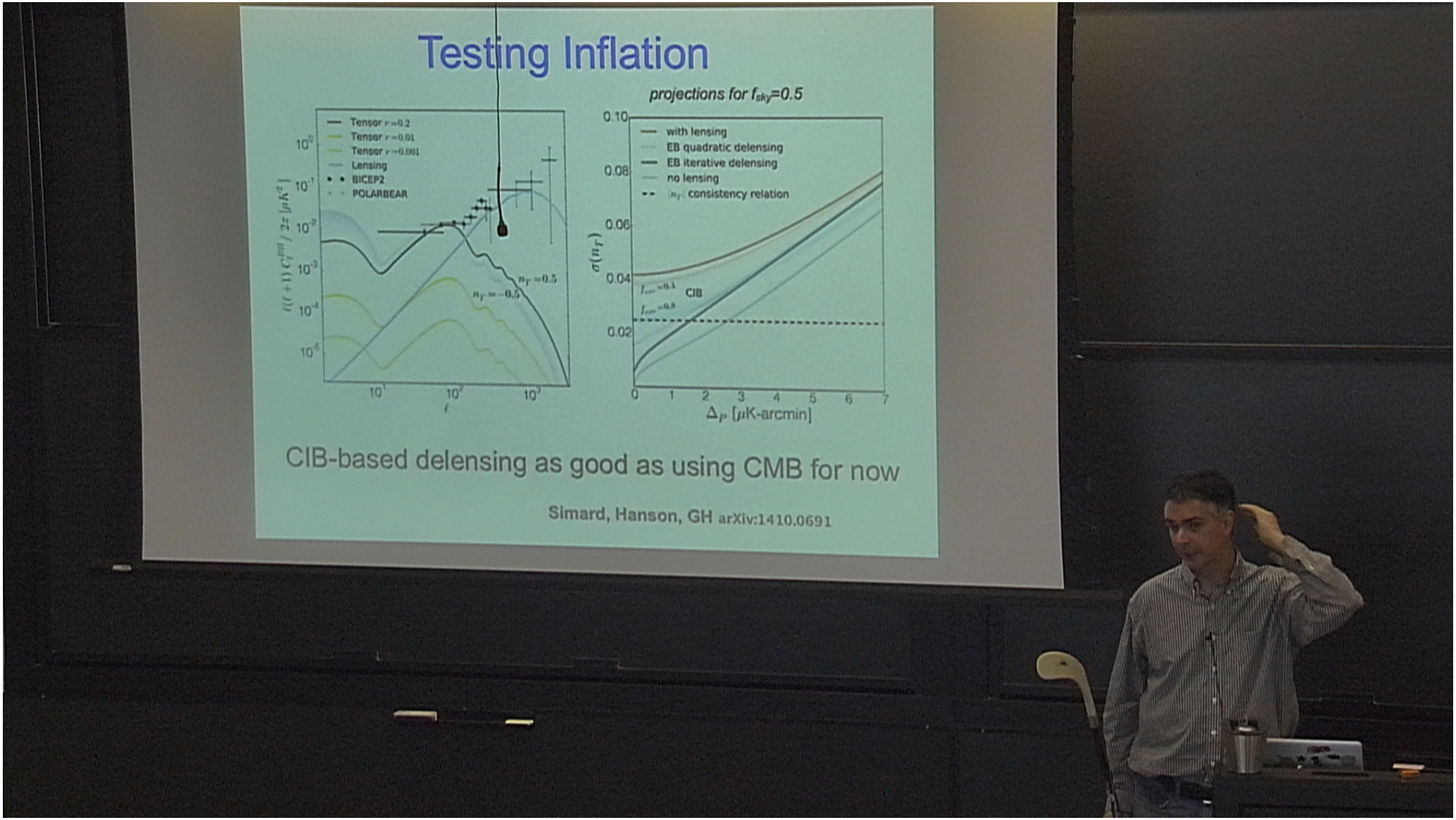

Quasars-Mass 2.0 (Planck+WISE+SDSS)
θ (deg)
10
1
Model (b=1)
Total
Type 1
Type 2
1.00
0.10
0.01
$C_l^{\kappa q} \times 10^6$
3
1
b_q
10
100
1000
l
• obscured quasars possibly more clustered than unobscured
DiPompeo et al (submitted)

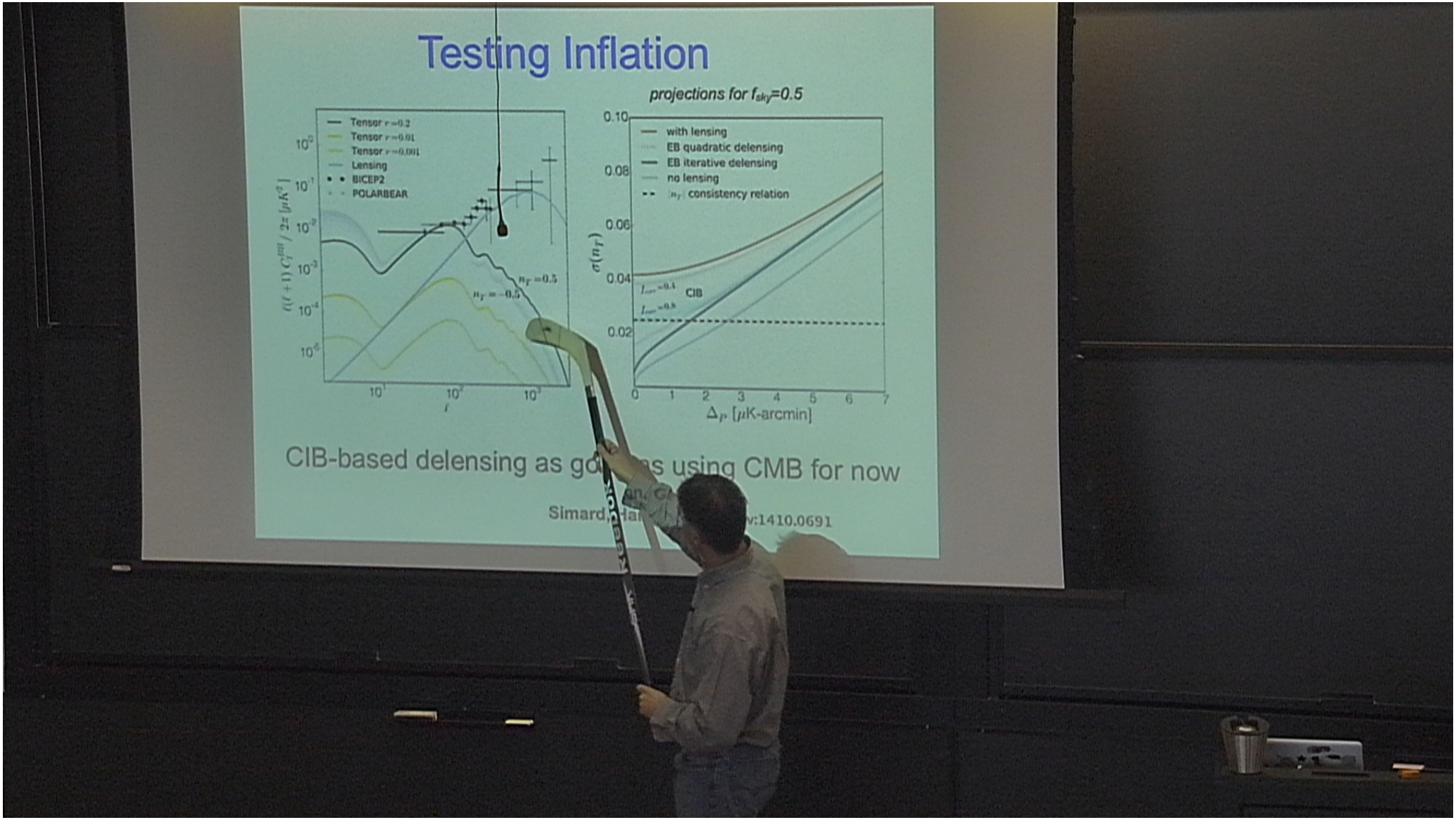

Planck lensing X CFHTLens Galaxies
2.0
1.5
1.0
0.5
0.0
dn/dz
0.0
0.3
0.6
1.8
z
$18 < i_{AB} < 22$
$18 < i_{AB} < 23$
$18 < i_{AB} < 24$
W^κ
|Mag bias|
Omori & GH (submitted)

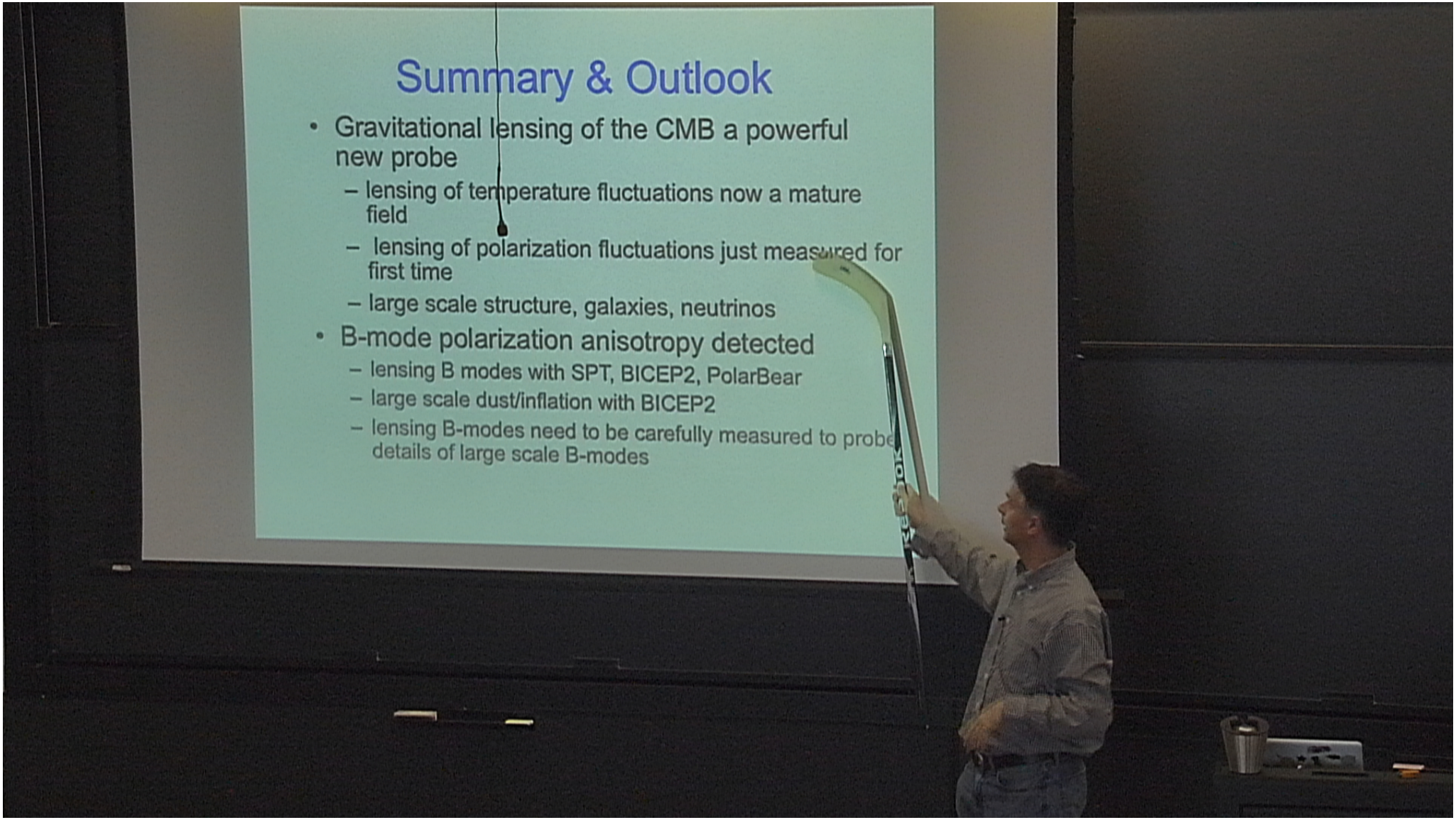

Galaxy-Galaxy Clustering Very Well Measured
$18 < i_{AB} < 22$
$18 < i_{AB} < 23$
$18 < i_{AB} < 24$
$\ell C_\ell^{gg} \times 10^5$
Cross
bias $b = 1.0$
bias $b = 1.2^{+0.2}_{-0.2}$ (best fit)
bias $b = 1.0$
bias $b = 1.0^{+0.3}_{-0.3}$ (best fit)
bias $b = 1.0$
bias $b = 1.0^{+0.2}_{-0.2}$ (best fit)
$\ell^2 C_\ell^{gg}$
bias $b = 1.00$
bias $b = 1.12^{+0.01}_{-0.01}$ (best fit)
bias $b = 1.00$
bias $b = 1.04^{+0.01}_{-0.01}$ (best fit)
bias $b = 1.00$
bias $b = 0.93^{+0.01}_{-0.01}$ (best fit)
200 600 1000 1400 1800
ℓ
Omori & GH (submitted)

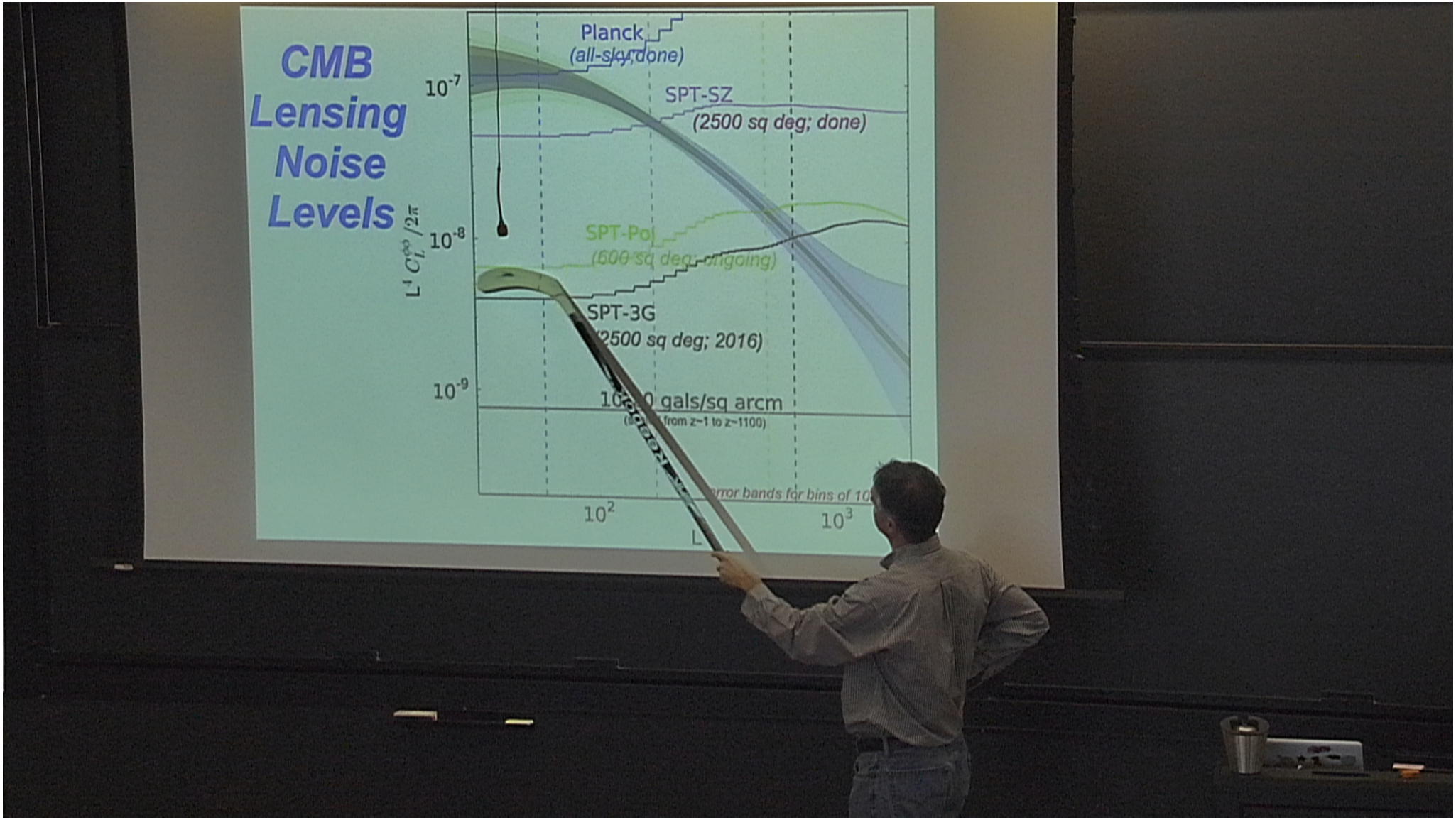

Lensing B Modes vs GW
on large scales, spectrum equivalent to white noise with rms of 5 uK-arcmin
5 uK-arcmin
r=0.43
r=0.1
r=0.01
l
from CMBPol lensing paper Smith et al 2009


Source of Lensed B Modes
Which ϕ modes matter
Which E modes matter
2000
1500
1000
500
0
0
500
1000
1500
2000
L^ϕ
L_E
l_B
Simard, Hans GH arXiv:1410.0691


Testing Inflation
projections for f_{sky}=0.5
Tensor r=0.2
Tensor r=0.01
Tensor r=0.001
Lensing
BICEP2
POLARBEAR
n_T=0.5
n_T=−0.5
ℓ
with lensing
EB quadratic delensing
EB iterative delensing
no lensing
n_T consistency relation
CIB
$\sigma(n_T)$
Δ_P [μK-arcmin]
CIB-based delensing as good as using CMB for now
Simard, Hanson, GH arXiv:1410.0691


Testing Inflation
projections for f_{sky}=0.5
Tensor r=0.2
Tensor r=0.01
Tensor r=0.001
Lensing
BICEP2
POLARBEAR
n_T=0.5
n_T=−0.5
$\ell(\ell+1)C_\ell^{BB}/2\pi$ [μK^2]
ℓ
with lensing
EB quadratic delensing
EB iterative delensing
no lensing
n_T consistency relation
CIB
$\sigma(n_T)$
Δ_P [μK-arcmin]
CIB-based delensing as go
s using CMB for now
Simard
v:1410.0691


Summary & Outlook
• Gravitational lensing of the CMB a powerful new probe
– lensing of temperature fluctuations now a mature field
– lensing of polarization fluctuations just measured for first time
– large scale structure, galaxies, neutrinos
• B-mode polarization anisotropy detected
– lensing B modes with SPT, BICEP2, PolarBear
– large scale dust/inflation with BICEP2
– lensing B-modes need to be carefully measured to probe details of large scale B-modes


CMB Lensing Noise Levels
Planck
(all-sky; done)
SPT-SZ
(2500 sq deg; done)
SPT-Pol
(600 sq deg; ongoing)
SPT-3G
(2500 sq deg; 2016)
gals/sq arcm
from z~1 to z~1100)
10^{-7}
10^{-8}
10^{-9}
10^2
10^3
$L^4 C_L^{\phi\phi}/2\pi$
L