Title: CMB anomalies from primordial gravitational waves

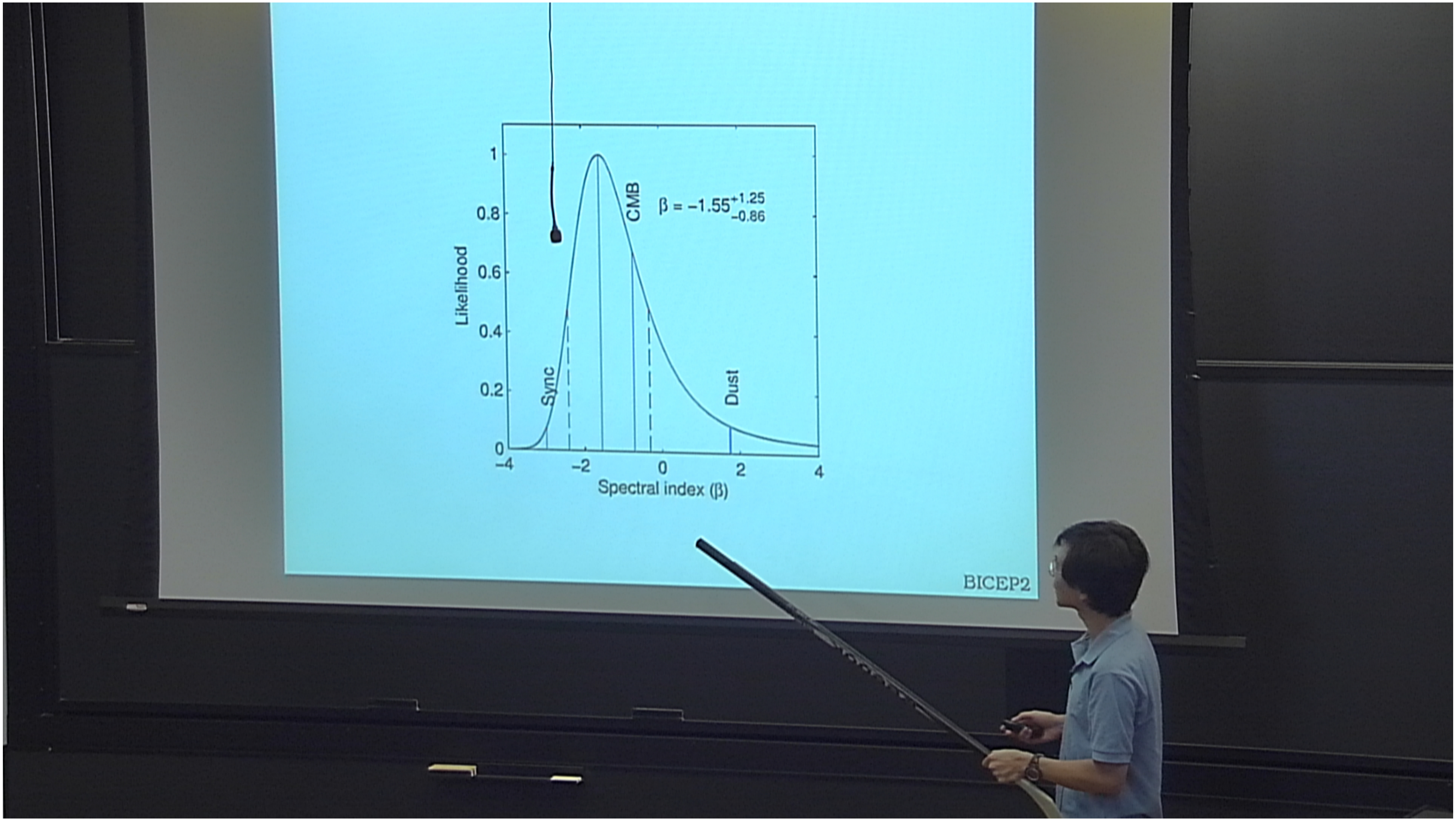
Date: Aug 13, 2014 01:00 PM

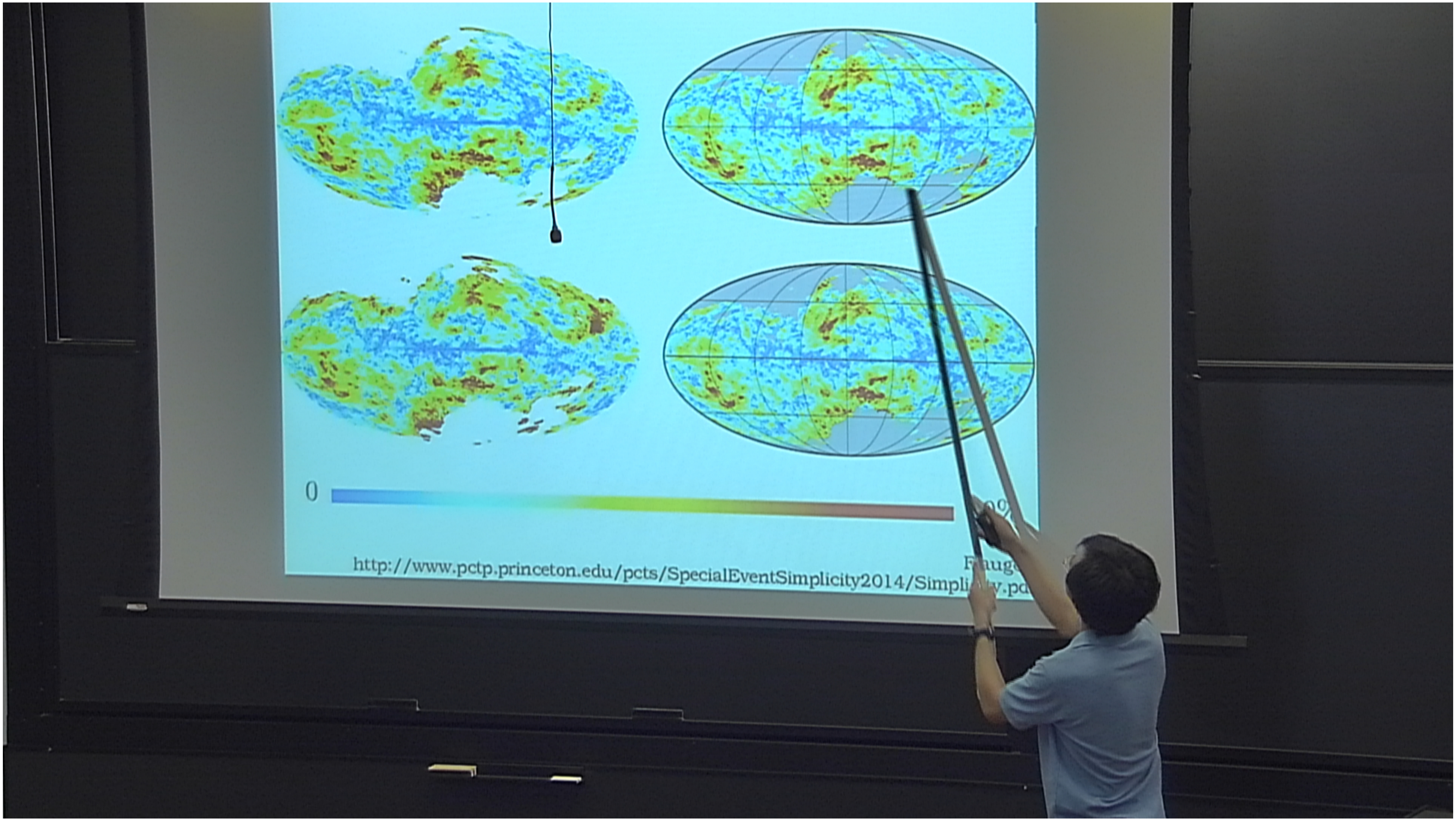
URL: http://pirsa.org/14080019

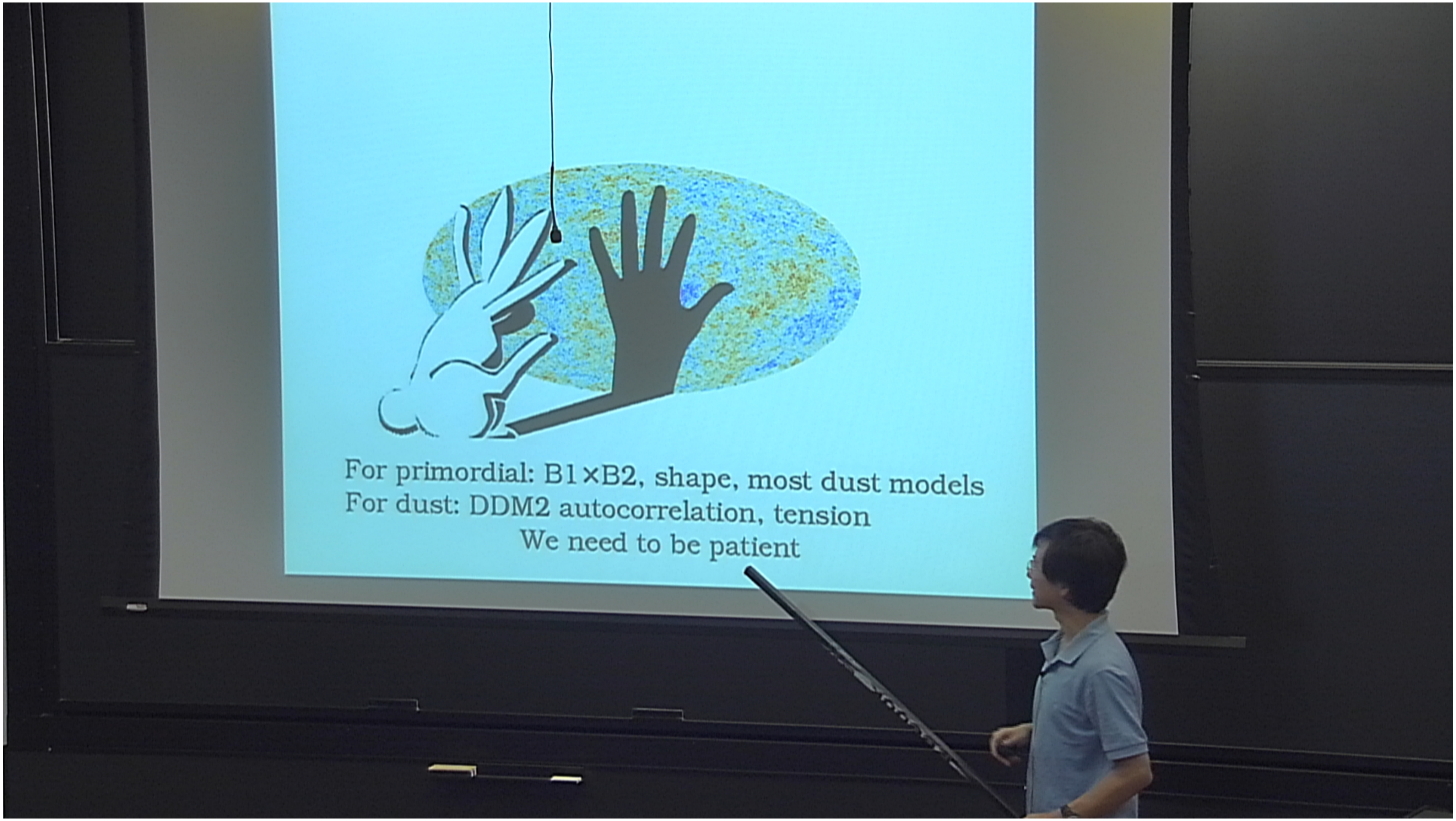
Abstract: We relate CMB anomalies and the recent observational evidence of primordial gravitational
 waves. Two aspects are investigated:

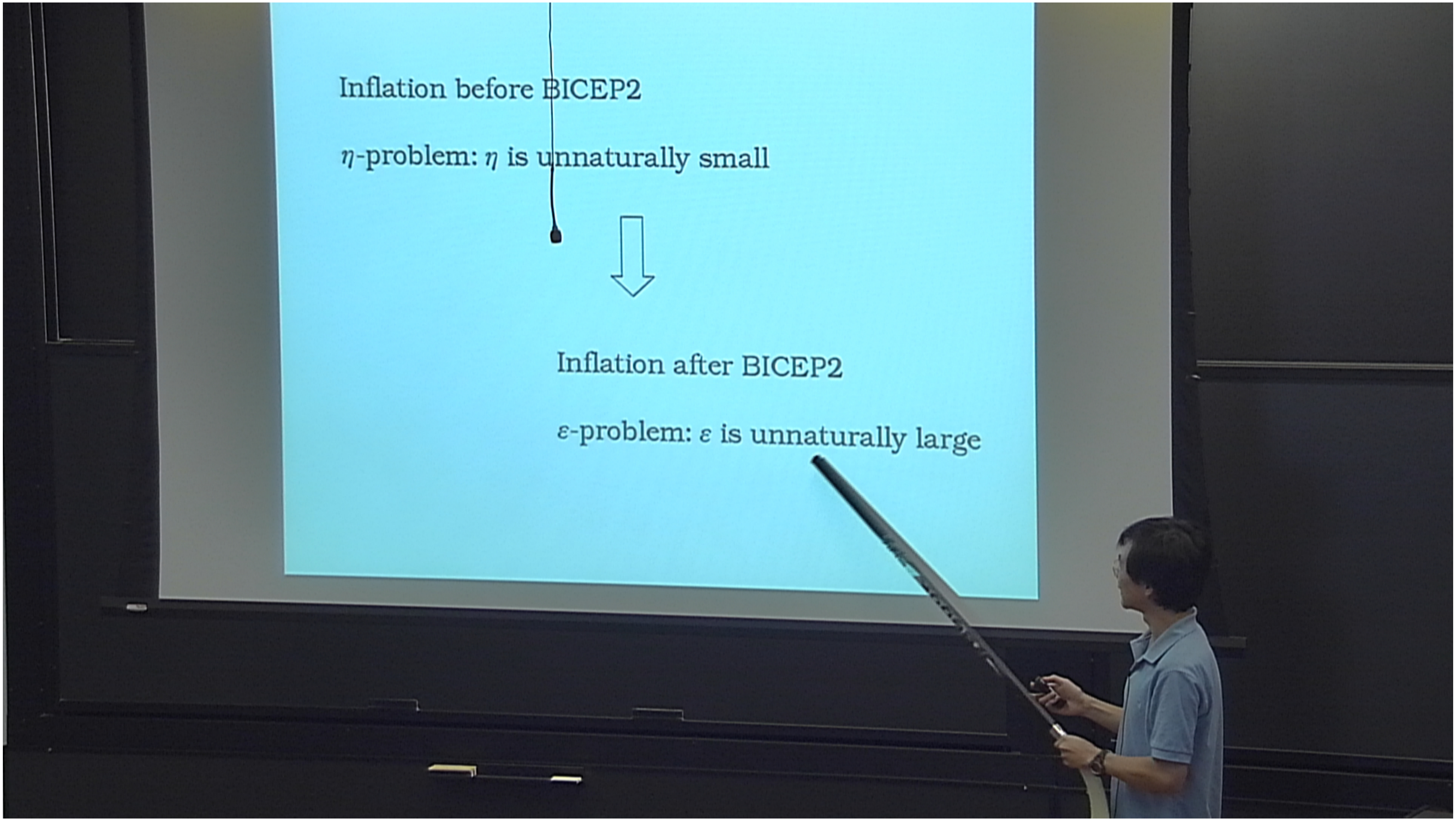
 (a) Several anomalies are spotted on the low ell temperature map of the WMAP and Planck
 experiments. However, those anomalies disappear at high ell. We propose that those low ell
 temperature anomalies may come from nearly scale invariant anomalies of the tensor sector.
 Those anomalies on the temperature map naturally decay towards small scales, characterized
 by the tensor-to-temperature radiation transfer function.

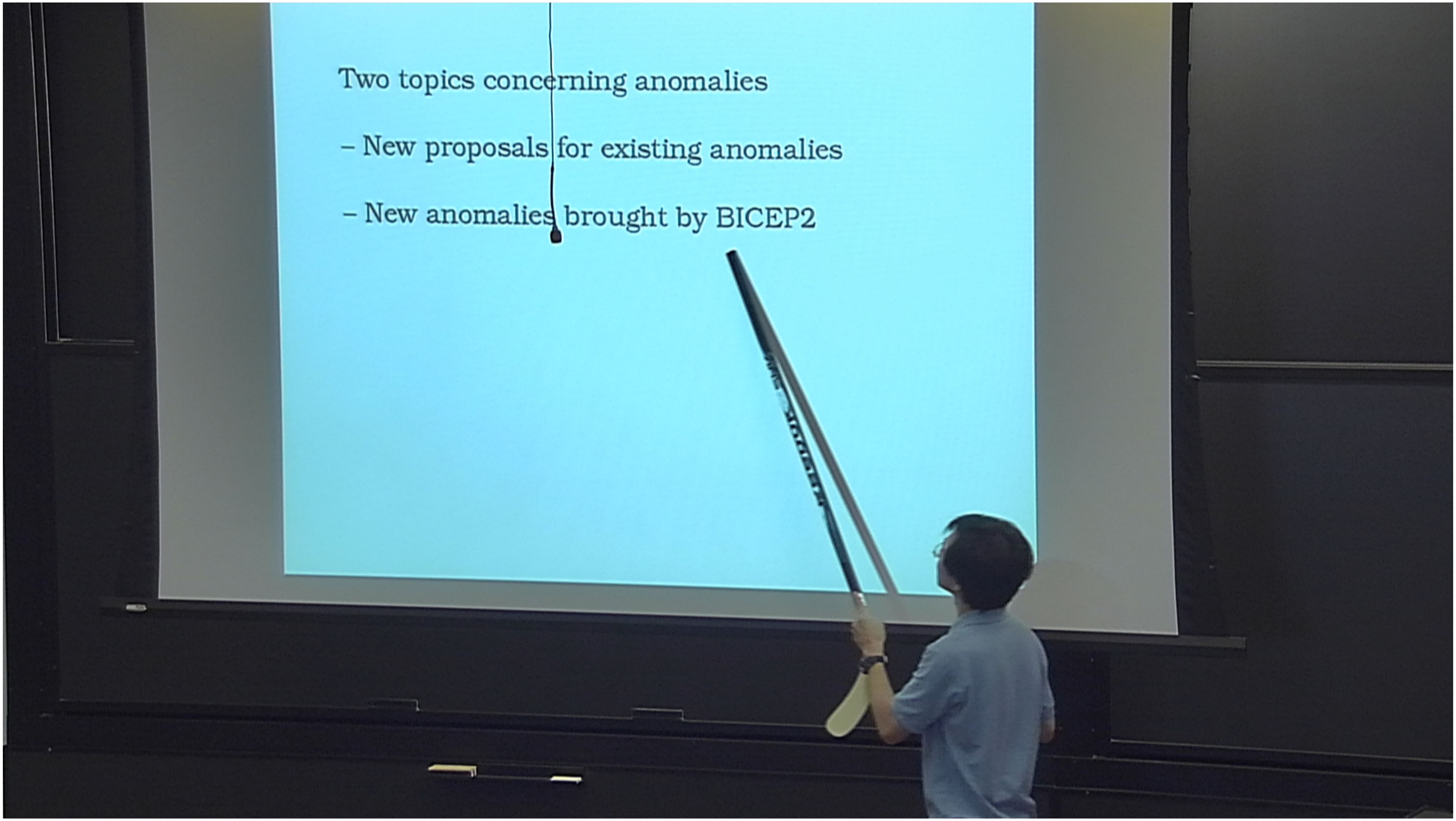
 (b) The anomalies introduced by the gravitational waves discovery. Strong tension is noticed
 between the BICEP2 and Planck data. We study in detail how blue tilt of the tensor spectrum
 reconciles the tension between those datasets.

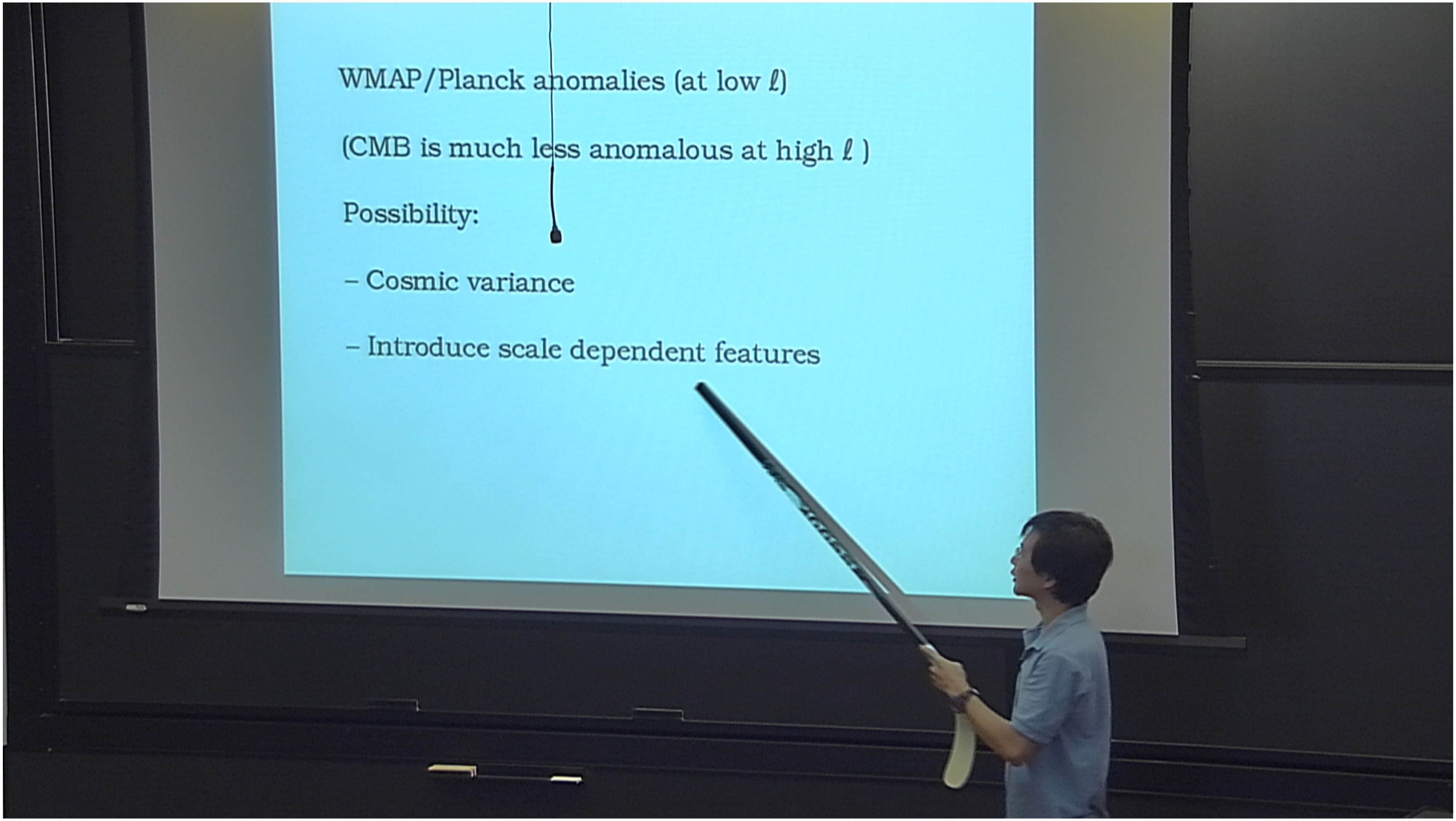

Likelihood
Spectral index (β)
Sync
CMB
Dust
β = −1.55^{+1.25}_{−0.86}
BICEP2

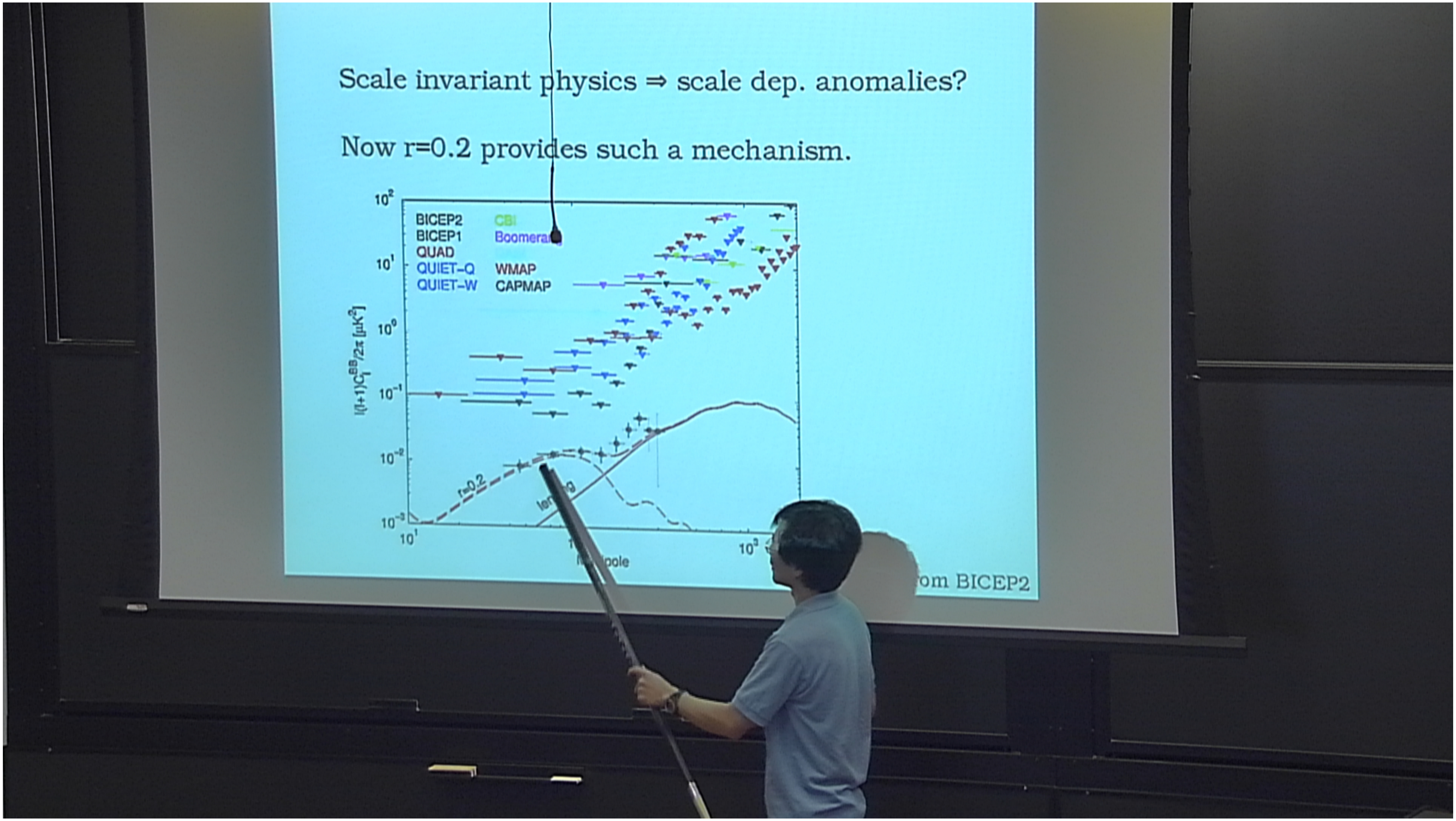

0
http://www.pctp.princeton.edu/pcts/SpecialEventSimplicity2014/Simpli

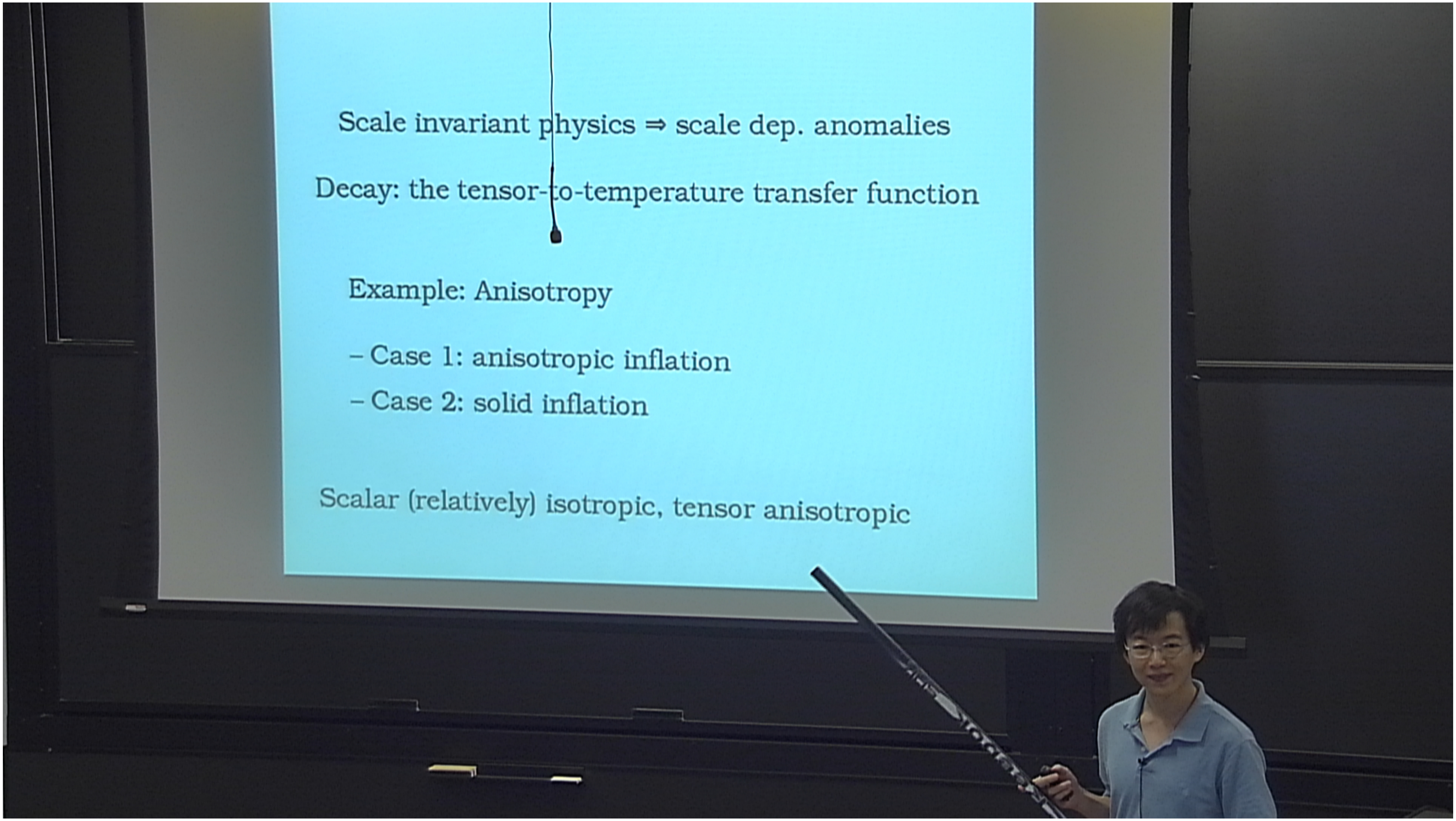

For primordial: B1×B2, shape, most dust models
For dust: DDM2 autocorrelation, tension
We need to be patient


Inflation before BICEP2
η-problem: η is unnaturally small
Inflation after BICEP2
ε-problem: ε is unnaturally large

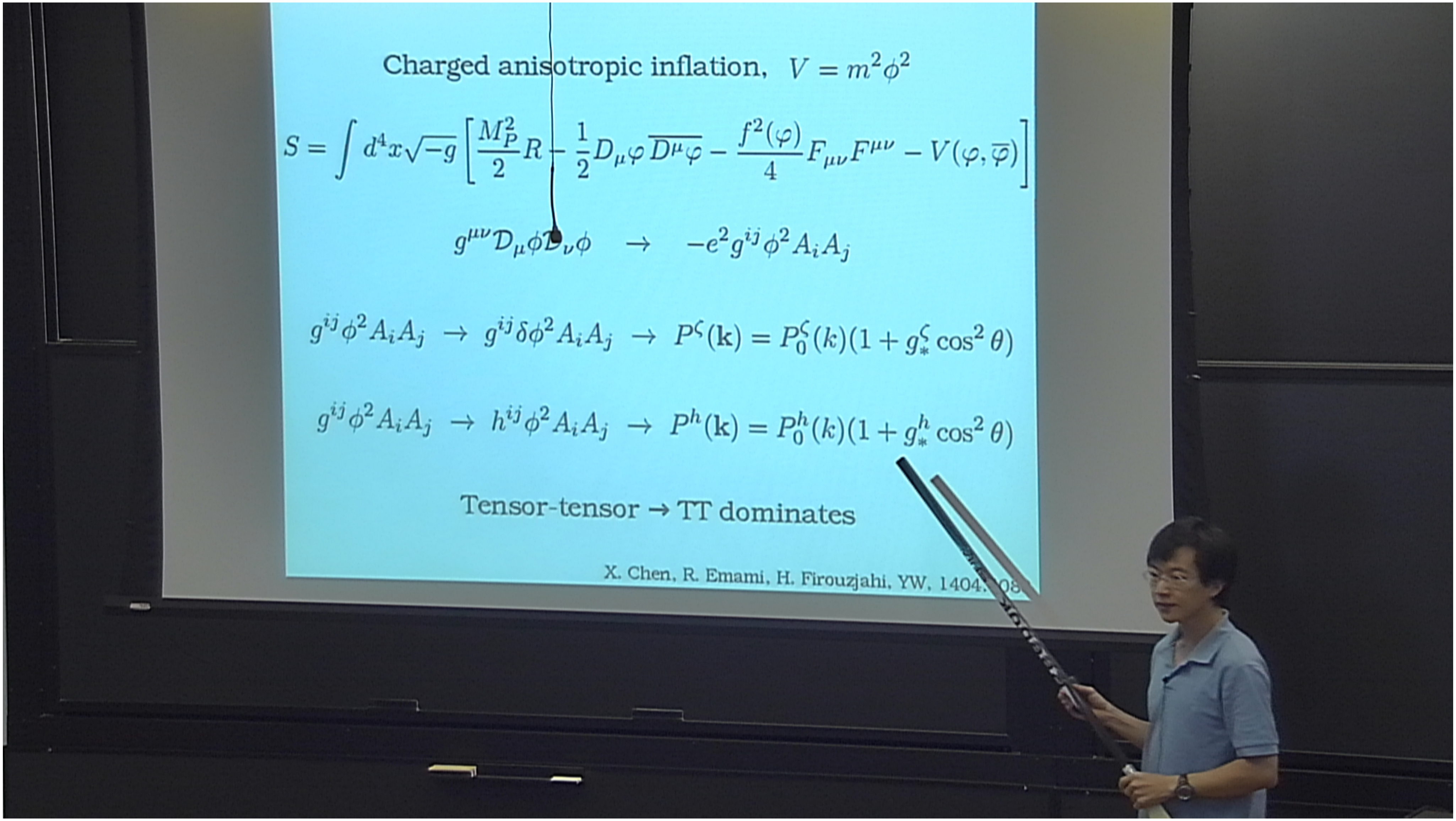

Two topics concerning anomalies
– New proposals for existing anomalies
– New anomalies brought by BICEP2

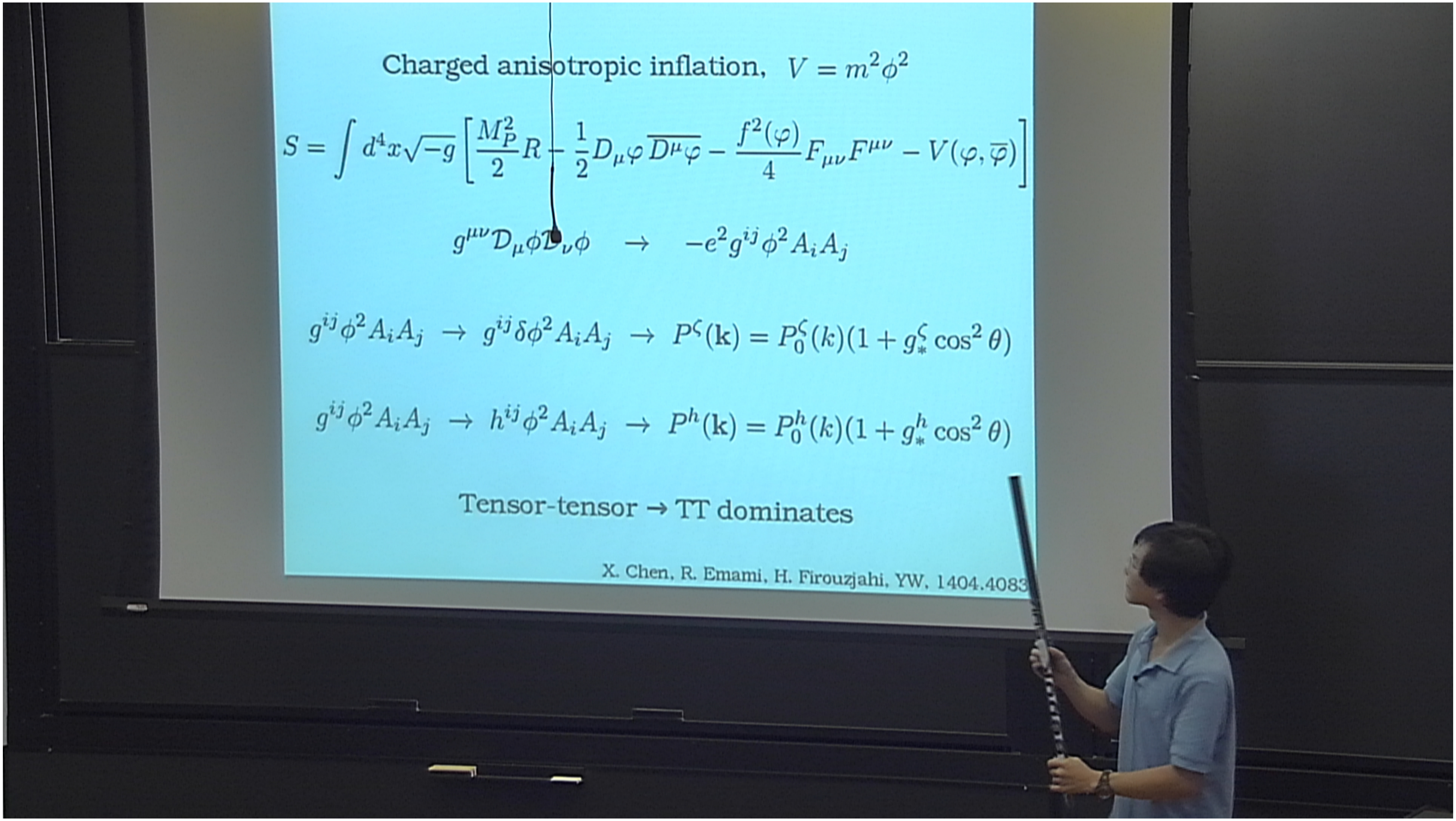

WMAP/Planck anomalies (at low ℓ)
(CMB is much less anomalous at high ℓ)
Possibility:
– Cosmic variance
– Introduce scale dependent features


Scale invariant physics ⇒ scale dep. anomalies?
Now r=0.2 provides such a mechanism.
BICEP2
BICEP1
QUAD
QUIET-Q
QUIET-W
CBI
WMAP
CAPMAP
r=0.2
om BICEP2



Scale invariant physics ⇒ scale dep. anomalies
Decay: the tensor-to-temperature transfer function
Example: Anisotropy
– Case 1: anisotropic inflation
– Case 2: solid inflation
Scalar (relatively) isotropic, tensor anisotropic


Charged anisotropic inflation, $V = m^2\phi^2$
$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}D_\mu\varphi\overline{D^\mu\varphi} - \frac{f^2(\varphi)}{4}F_{\mu\nu}F^{\mu\nu} - V(\varphi,\overline{\varphi})\right]$
$g^{\mu\nu}\mathcal{D}_\mu\phi\mathcal{D}_\nu\phi \quad \rightarrow \quad -e^2 g^{ij}\phi^2 A_i A_j$
$g^{ij}\phi^2 A_i A_j \rightarrow g^{ij}\delta\phi^2 A_i A_j \rightarrow P^\zeta(\mathbf{k}) = P_0^\zeta(k)(1 + g_*^\zeta \cos^2\theta)$
$g^{ij}\phi^2 A_i A_j \rightarrow h^{ij}\phi^2 A_i A_j \rightarrow P^h(\mathbf{k}) = P_0^h(k)(1 + g_*^h \cos^2\theta)$
Tensor-tensor → TT dominates
X. Chen, R. Emami, H. Firouzjahi, YW, 1404.


Charged anisotropic inflation, $V = m^2\phi^2$
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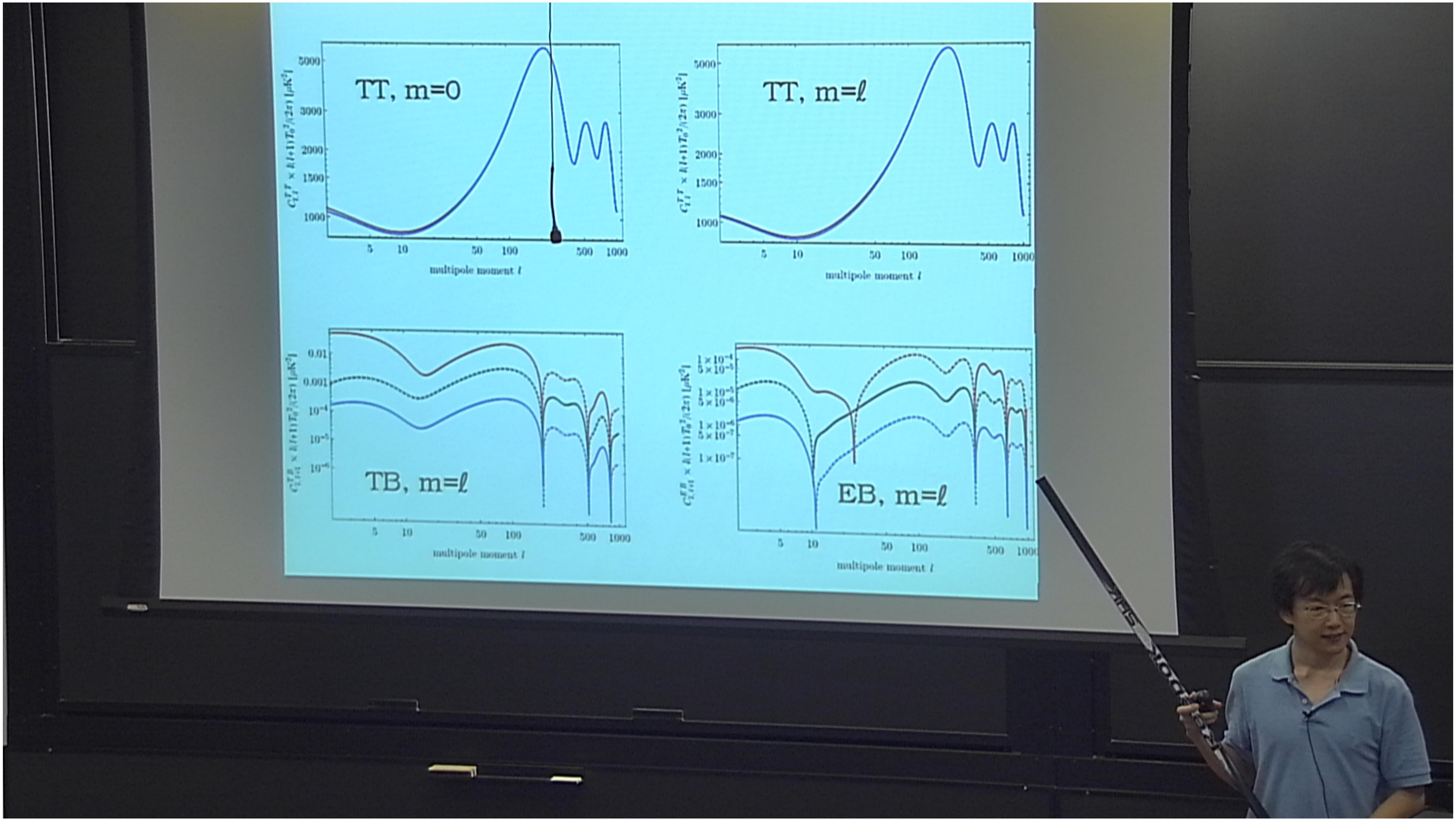
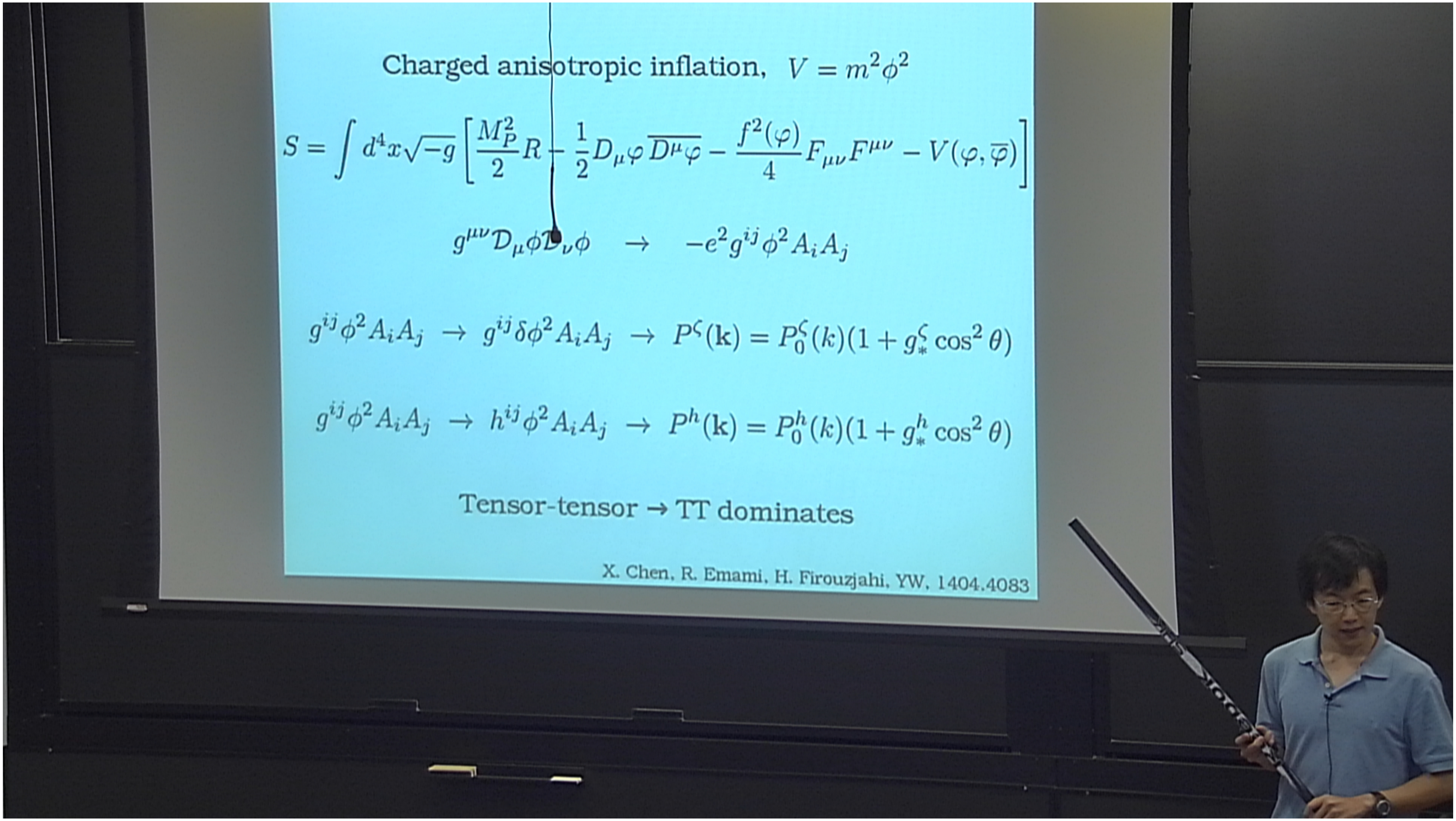
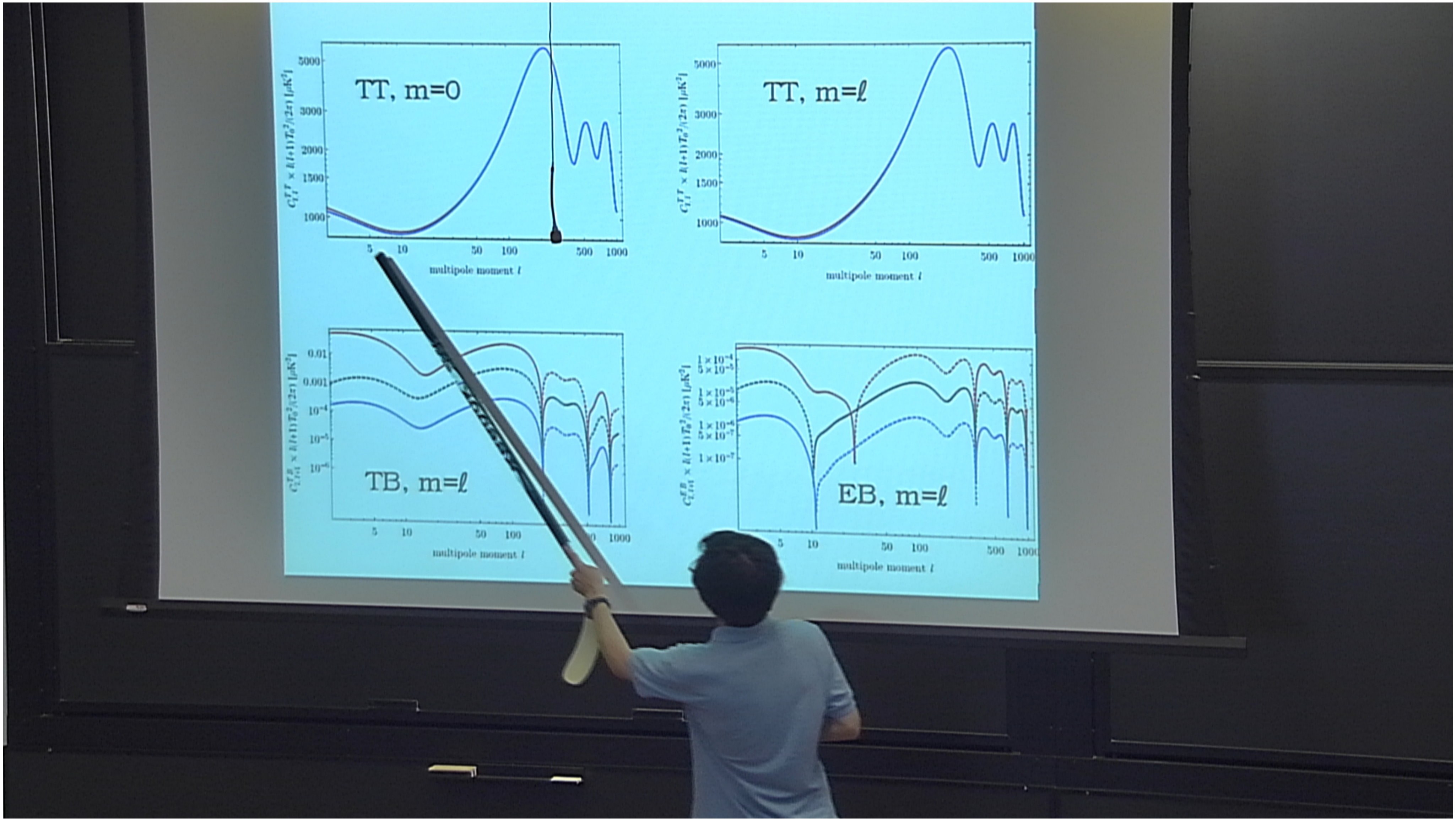
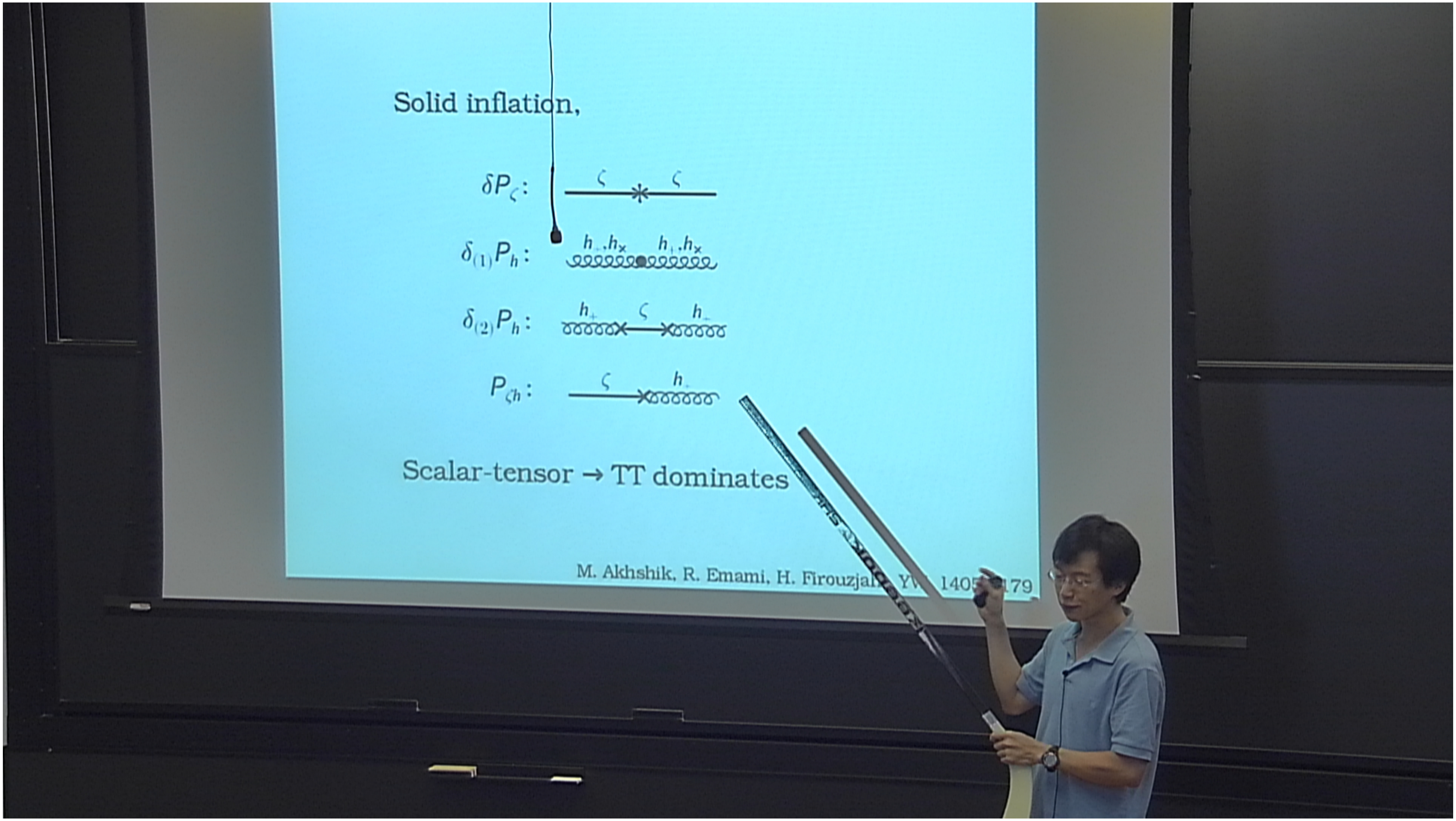
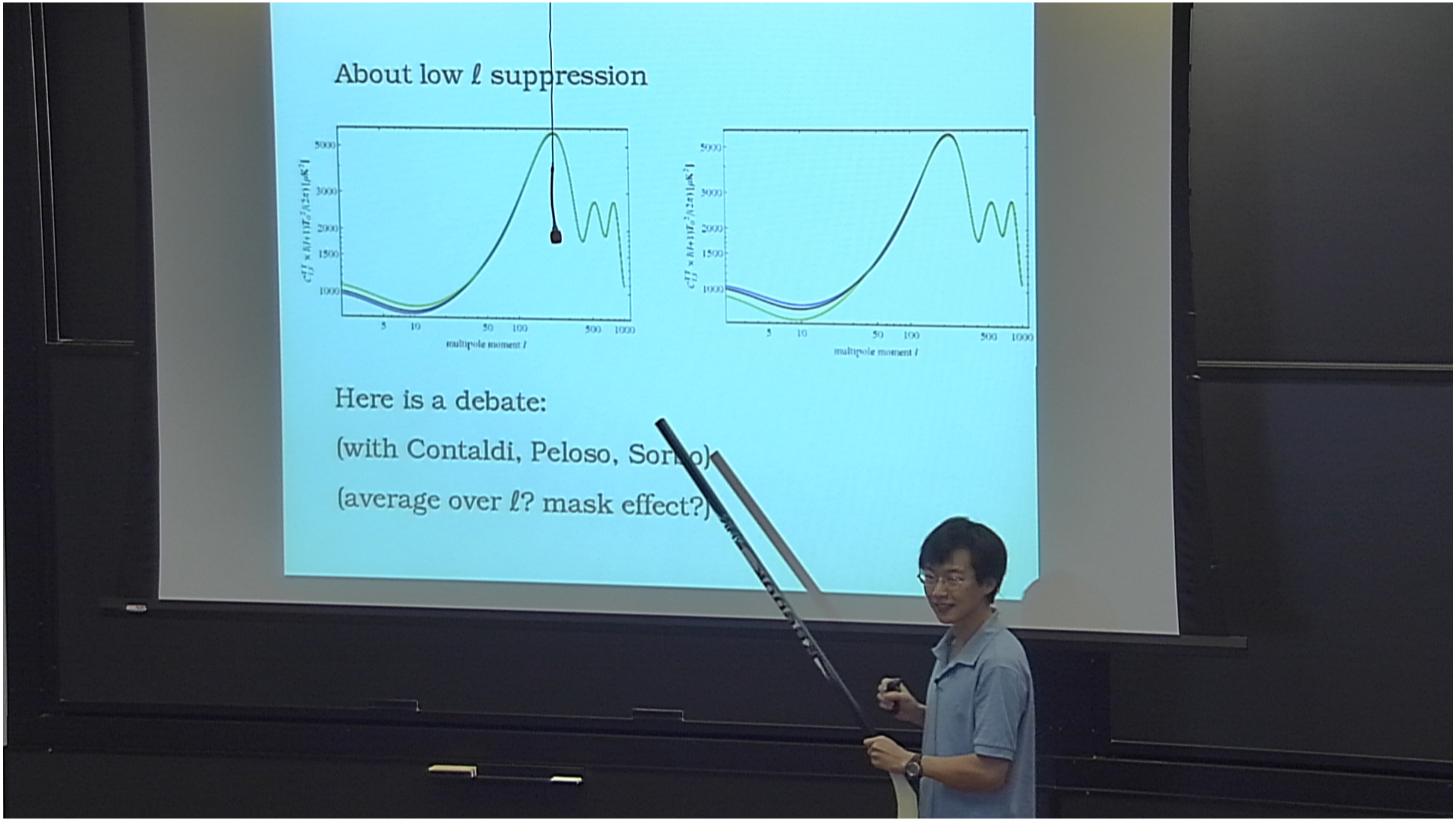
$g^{\mu\nu}\mathcal{D}_\mu\phi\mathcal{D}_\nu\phi \quad \rightarrow \quad -e^2 g^{ij}\phi^2 A_i A_j$
$g^{ij}\phi^2 A_i A_j \ \rightarrow \ g^{ij}\delta\phi^2 A_i A_j \ \rightarrow \ P^\zeta(\mathbf{k}) = P_0^\zeta(k)(1 + g_*^\zeta \cos^2\theta)$
$g^{ij}\phi^2 A_i A_j \ \rightarrow \ h^{ij}\phi^2 A_i A_j \ \rightarrow \ P^h(\mathbf{k}) = P_0^h(k)(1 + g_*^h \cos^2\theta)$
Tensor-tensor → TT dominates
X. Chen, R. Emami, H. Firouzjahi, YW, 1404.4083

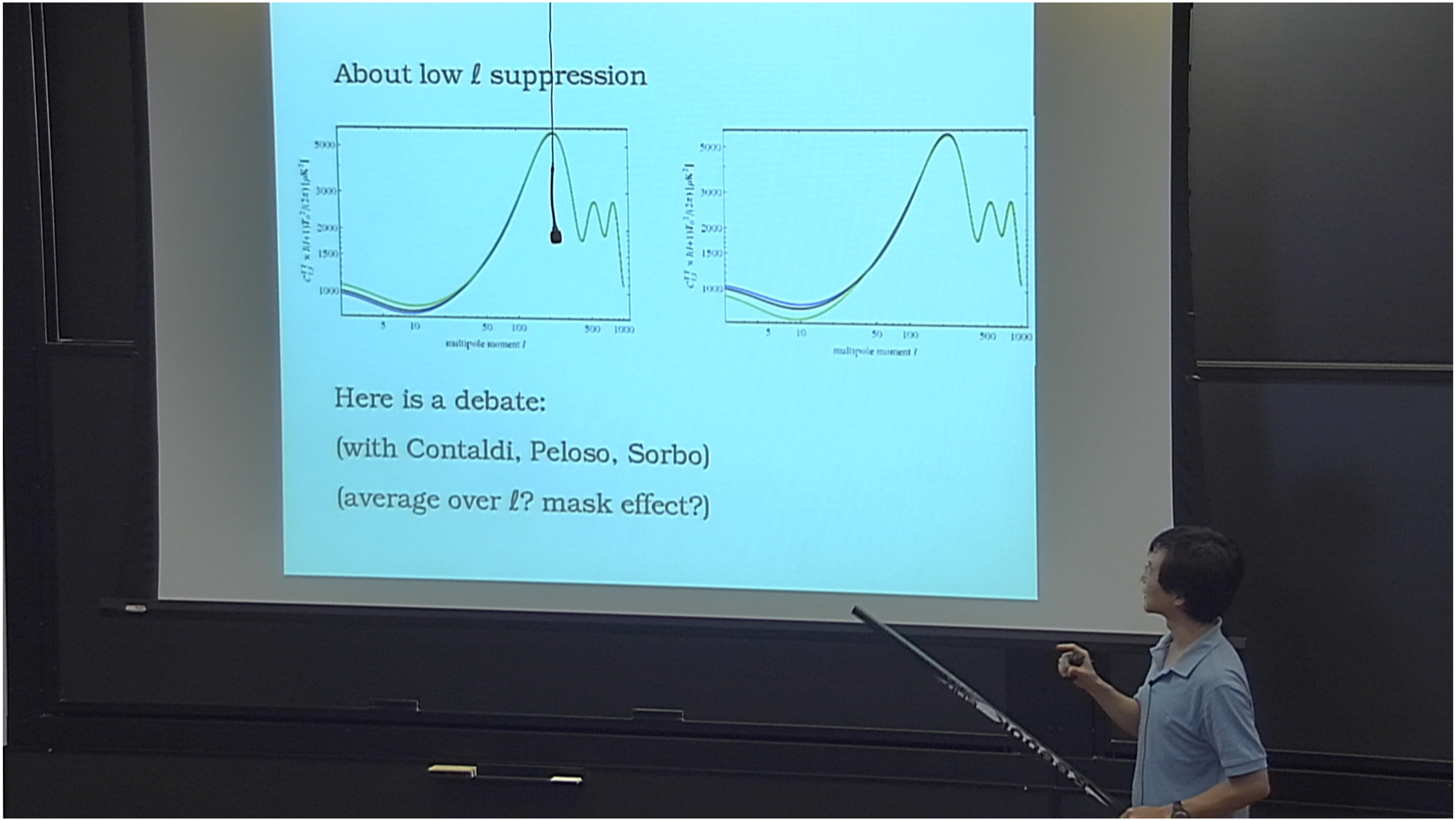

TT, m=0
TT, m=ℓ
TB, m=ℓ
EB, m=ℓ
multipole moment l
multipole moment l
multipole moment l
multipole moment l

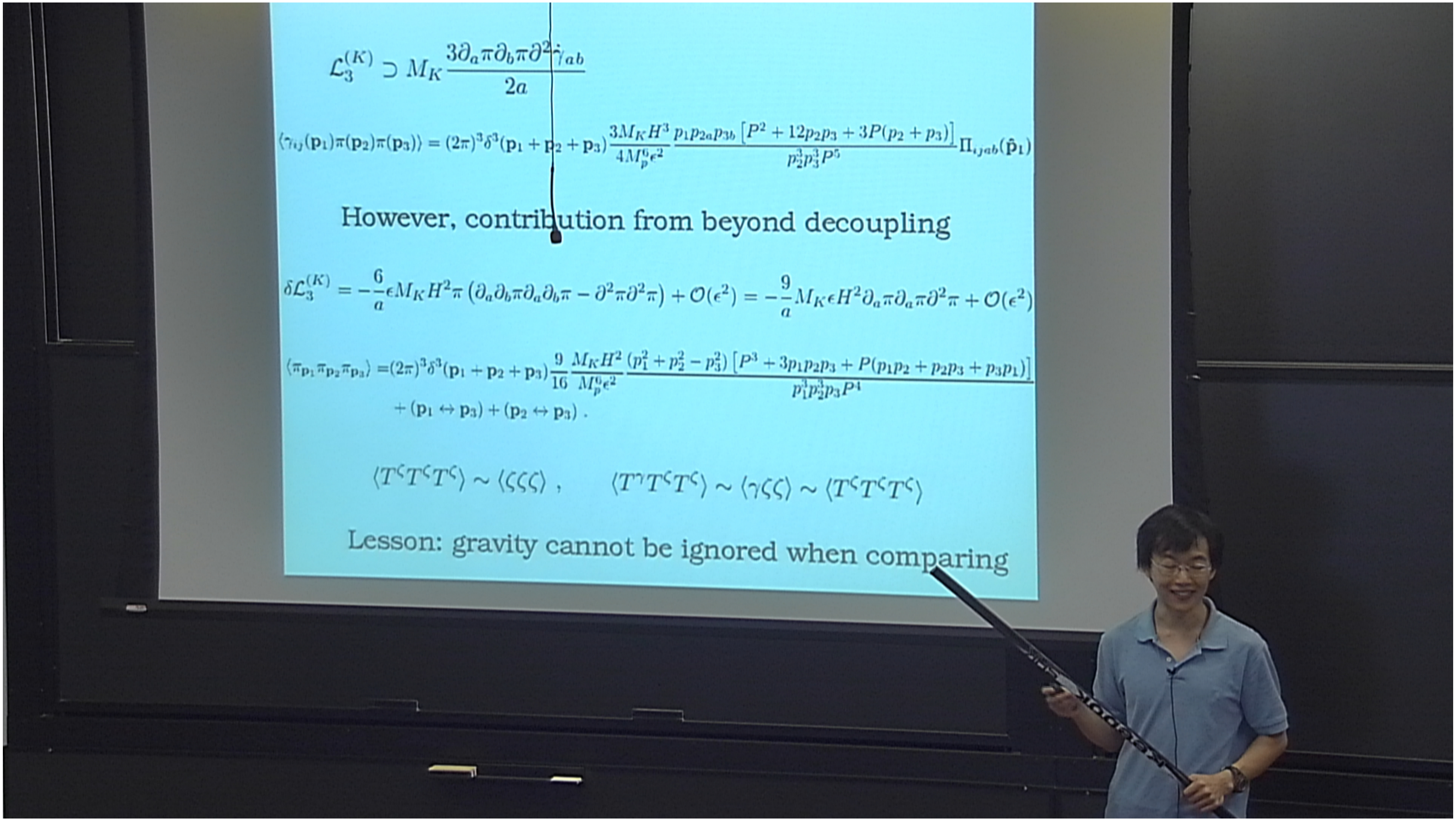

Charged anisotropic inflation, $V = m^2\phi^2$
$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}D_\mu\varphi\overline{D^\mu\varphi} - \frac{f^2(\varphi)}{4}F_{\mu\nu}F^{\mu\nu} - V(\varphi,\overline{\varphi})\right]$
$g^{\mu\nu}\mathcal{D}_\mu\phi\mathcal{D}_\nu\phi \quad \rightarrow \quad -e^2g^{ij}\phi^2A_iA_j$
$g^{ij}\phi^2A_iA_j \;\rightarrow\; g^{ij}\delta\phi^2A_iA_j \;\rightarrow\; P^\zeta(\mathbf{k}) = P_0^\zeta(k)(1+g_*^\zeta\cos^2\theta)$
$g^{ij}\phi^2A_iA_j \;\rightarrow\; h^{ij}\phi^2A_iA_j \;\rightarrow\; P^h(\mathbf{k}) = P_0^h(k)(1+g_*^h\cos^2\theta)$
Tensor-tensor → TT dominates
X. Chen, R. Emami, H. Firouzjahi, YW, 1404.4083

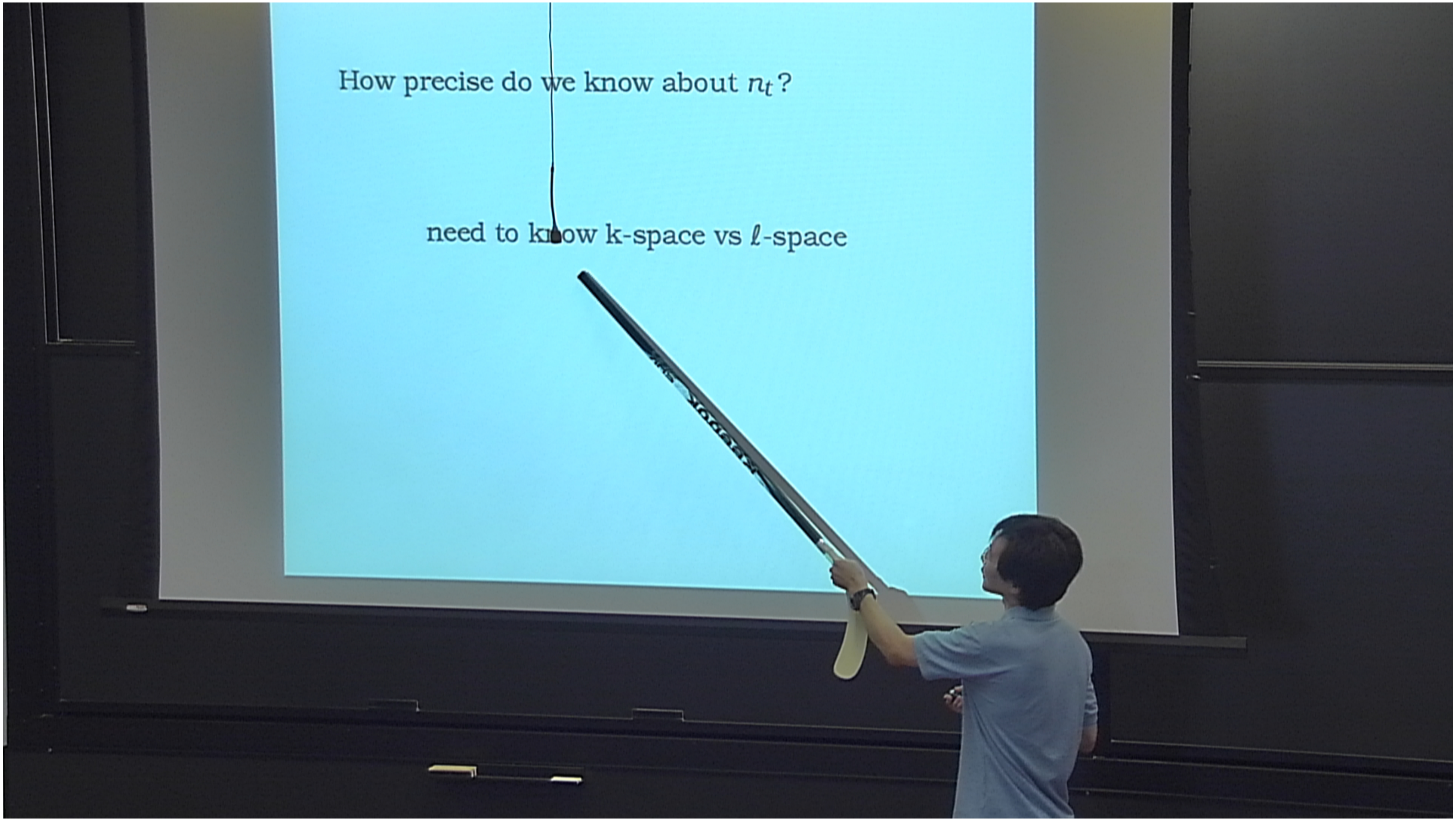

TT, m=0
TT, m=ℓ
TB, m=ℓ
EB, m=ℓ
multipole moment l
multipole moment l
multipole moment l
multipole moment l

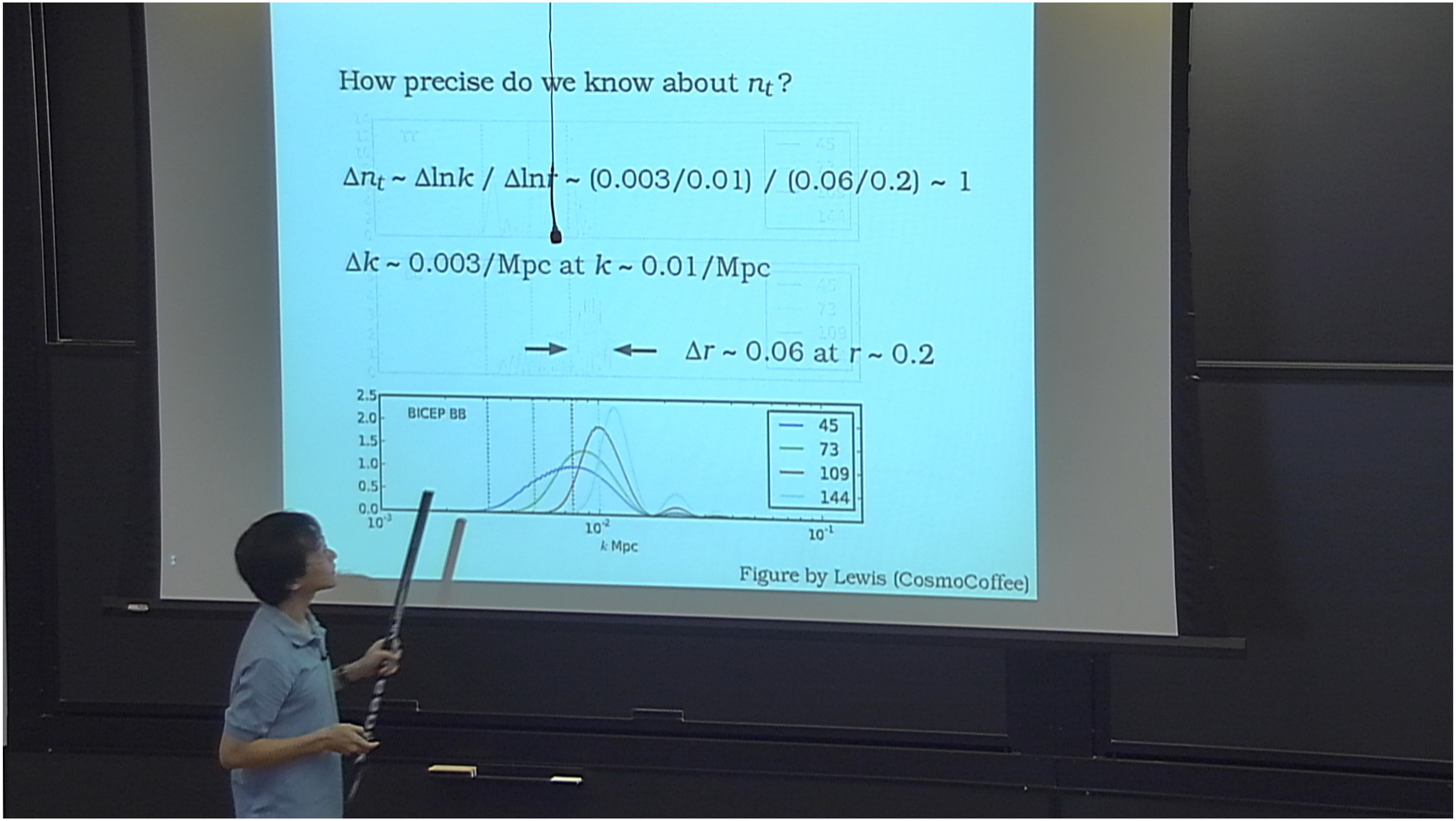

Solid inflation,
δP_ζ :
ζ ζ
$\delta_{(1)} P_h$:
$h_+, h_\times$ $h_+, h_\times$
$\delta_{(2)} P_h$:
h_+ ζ h_-
$P_{\zeta h}$:
ζ h_+
Scalar-tensor → TT dominates
M. Akhshik, R. Emami, H. Firouzjah

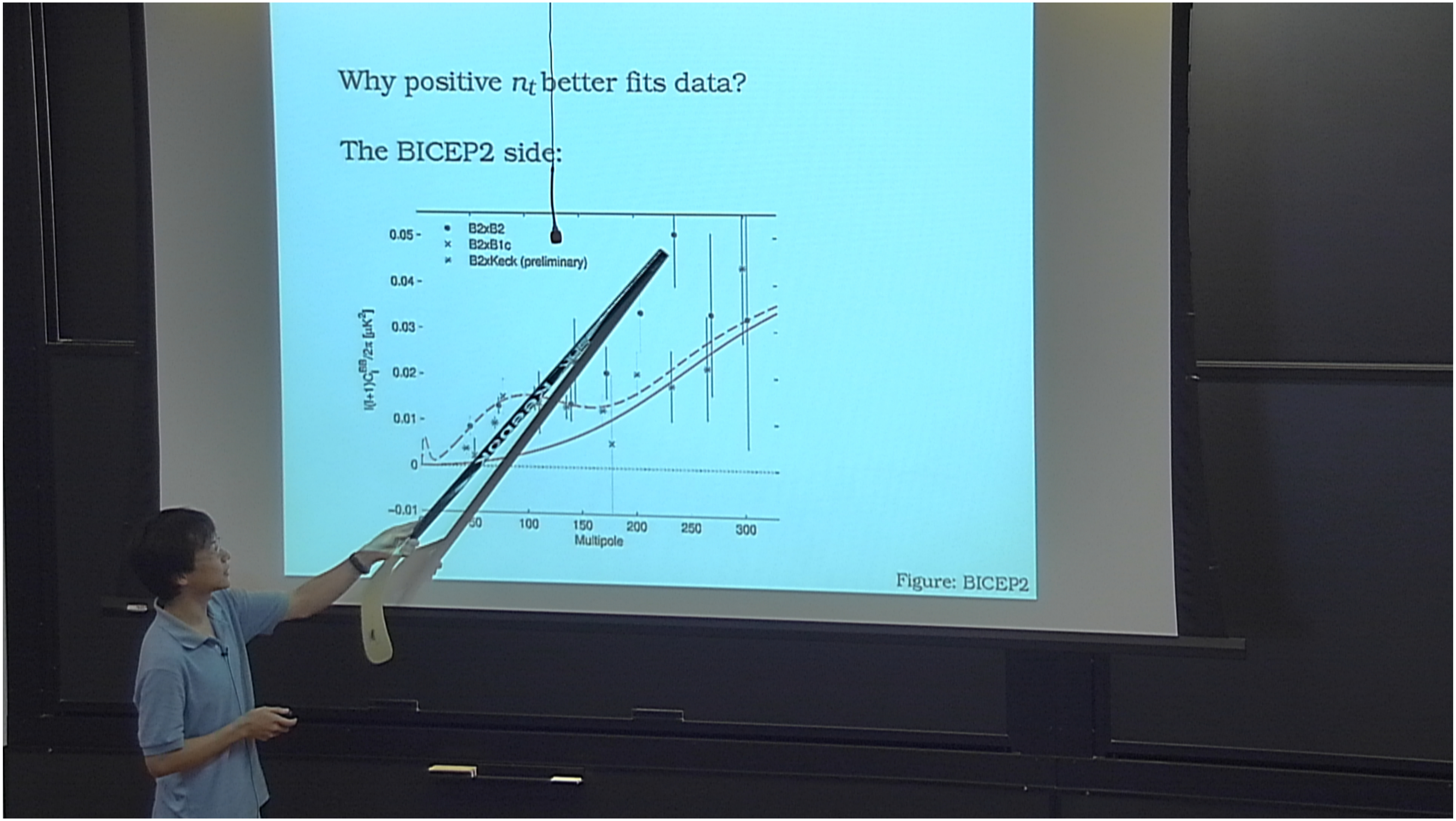

About low ℓ suppression
5000
3000
2000
1500
1000
5
10
50
100
500
1000
multipole moment l
Here is a debate:
(with Contaldi, Peloso, Sor
(average over ℓ? mask effect?)

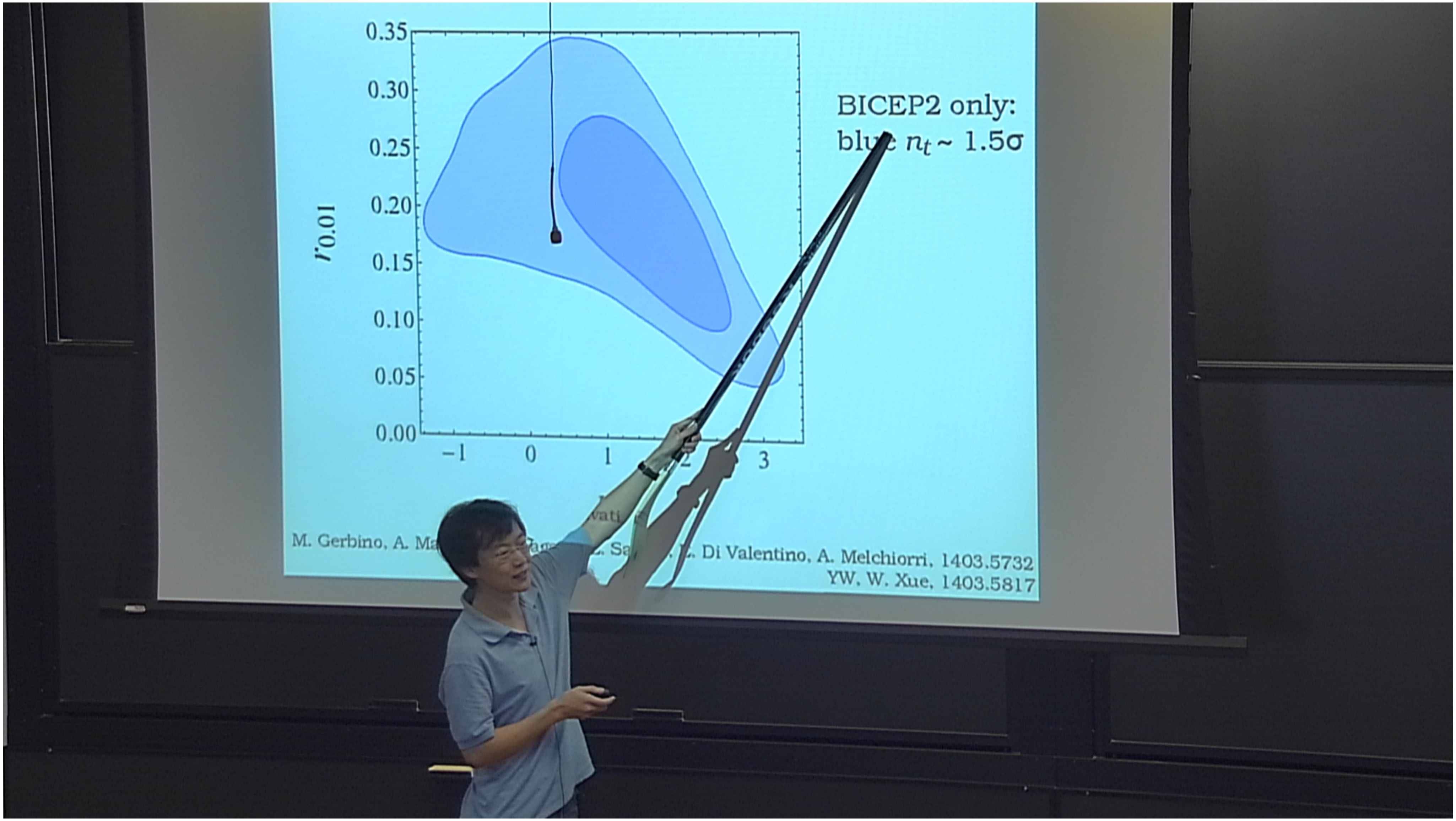

About low ℓ suppression
5000
3000
2000
1500
1000
5
10
50
100
500
1000
multipole moment l
Here is a debate:
(with Contaldi, Peloso, Sorbo)
(average over ℓ? mask effect?)

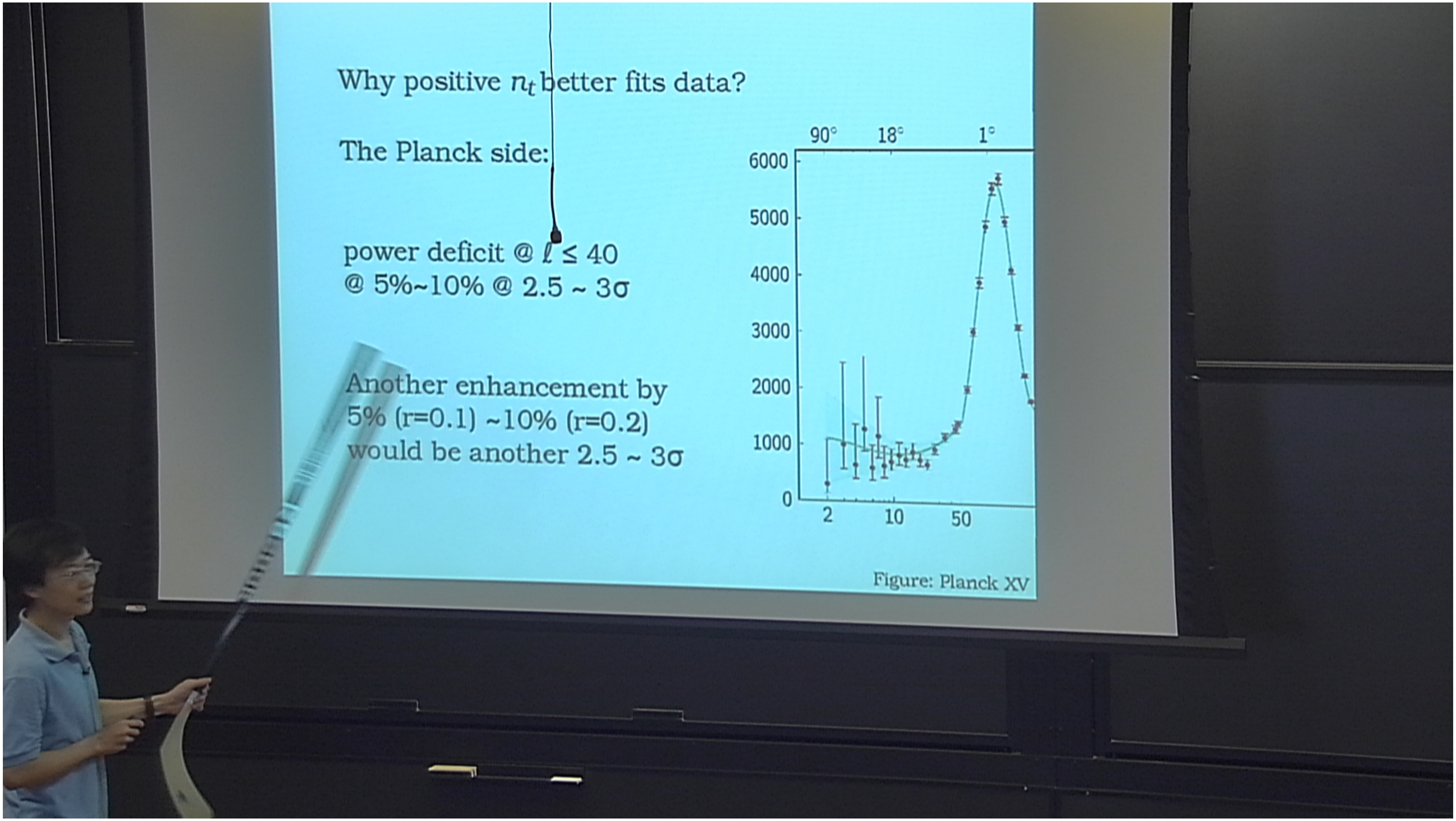

$\mathcal{L}_3^{(K)} \supset M_K \frac{3\partial_a\pi\partial_b\pi\partial^2\dot{\gamma}_{ab}}{2a}$
$\langle\gamma_{ij}(\mathbf{p}_1)\pi(\mathbf{p}_2)\pi(\mathbf{p}_3)\rangle = (2\pi)^3\delta^3(\mathbf{p}_1+\mathbf{p}_2+\mathbf{p}_3)\frac{3M_K H^3}{4M_p^6\epsilon^2}\frac{p_1 p_{2a} p_{3b}\left[P^2+12p_2p_3+3P(p_2+p_3)\right]}{p_2^3 p_3^3 P^5}\Pi_{ijab}(\hat{\mathbf{p}}_1)$
However, contribution from beyond decoupling
$\delta\mathcal{L}_3^{(K)} = -\frac{6}{a}\epsilon M_K H^2\pi\left(\partial_a\partial_b\pi\partial_a\partial_b\pi - \partial^2\pi\partial^2\pi\right) + \mathcal{O}(\epsilon^2) = -\frac{9}{a}M_K\epsilon H^2\partial_a\pi\partial_a\pi\partial^2\pi + \mathcal{O}(\epsilon^2)$
$\langle\pi_{\mathbf{p}_1}\pi_{\mathbf{p}_2}\pi_{\mathbf{p}_3}\rangle = (2\pi)^3\delta^3(\mathbf{p}_1+\mathbf{p}_2+\mathbf{p}_3)\frac{9}{16}\frac{M_K H^2}{M_p^6\epsilon^2}\frac{(p_1^2+p_2^2-p_3^2)\left[P^3+3p_1p_2p_3+P(p_1p_2+p_2p_3+p_3p_1)\right]}{p_1^3p_2^3p_3P^4}$
$+(\mathbf{p}_1\leftrightarrow\mathbf{p}_3)+(\mathbf{p}_2\leftrightarrow\mathbf{p}_3)$.
$\langle T^\zeta T^\zeta T^\zeta\rangle \sim \langle\zeta\zeta\zeta\rangle$, $\langle T^\gamma T^\zeta T^\zeta\rangle \sim \langle\gamma\zeta\zeta\rangle \sim \langle T^\zeta T^\zeta T^\zeta\rangle$
Lesson: gravity cannot be ignored when comparing

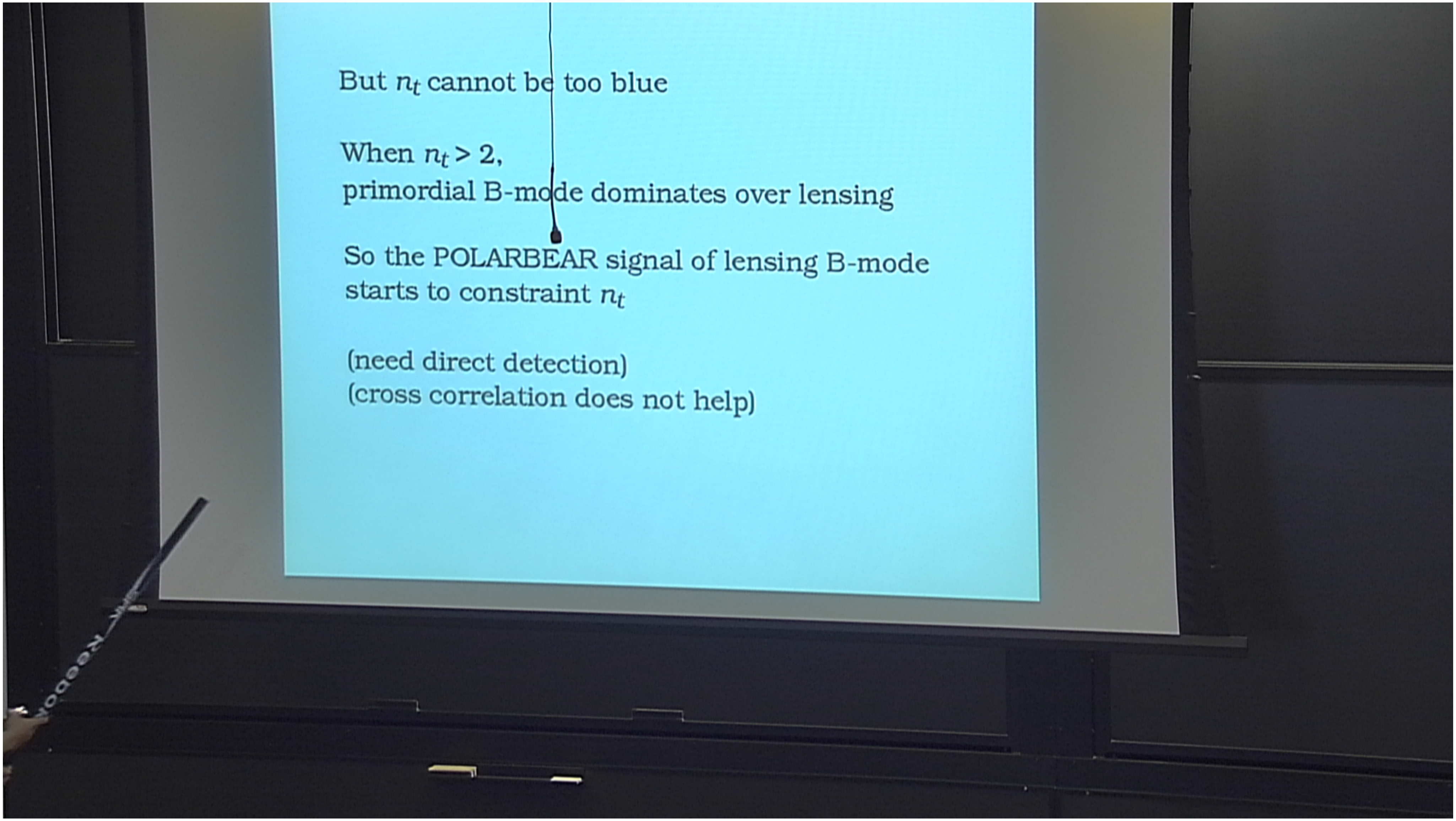

How precise do we know about n_t ?
need to know k-space vs ℓ-space

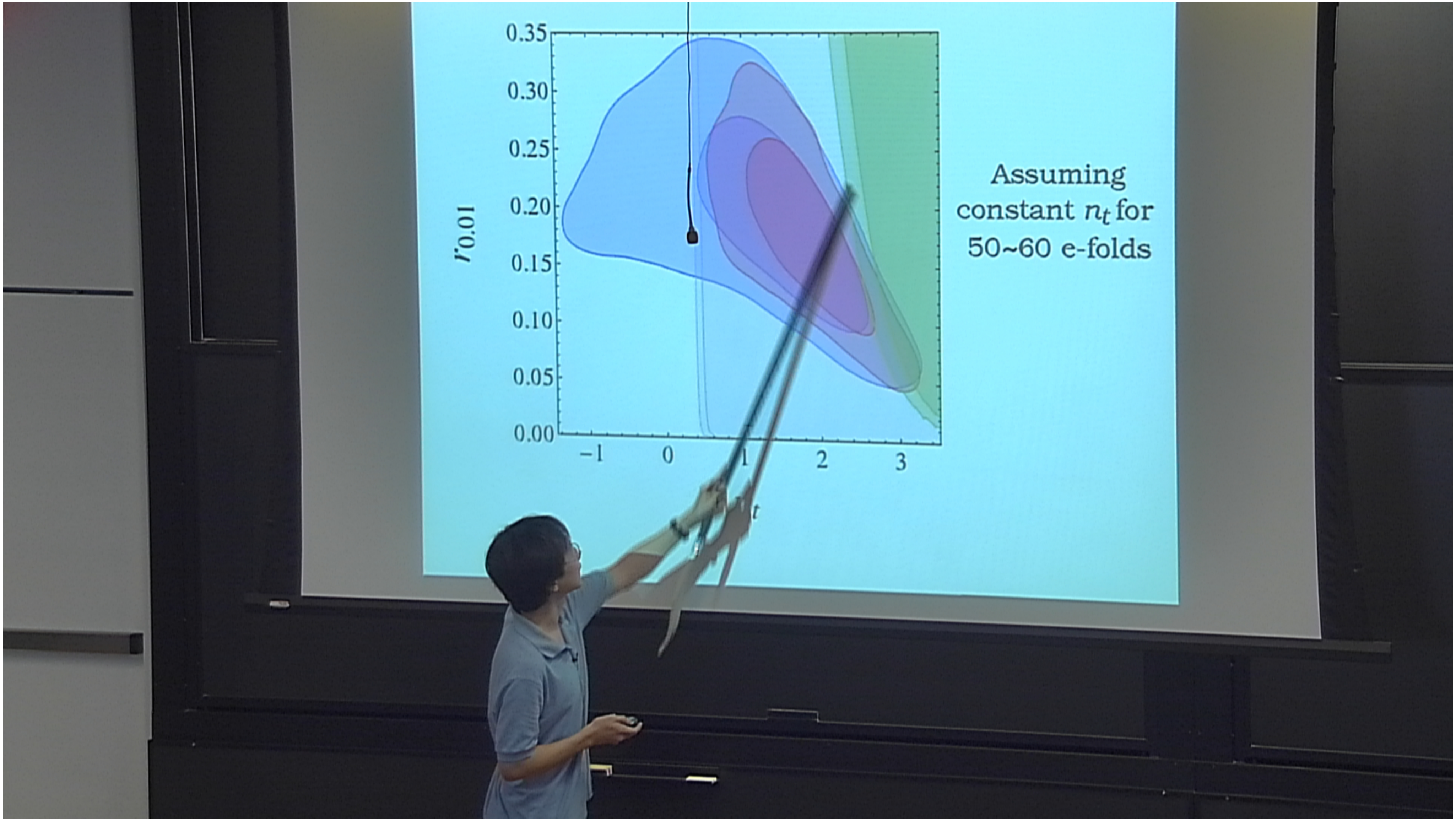

How precise do we know about n_t ?
Δn_t ~ Δlnk / Δlnr ~ (0.003/0.01) / (0.06/0.2) ~ 1
Δk ~ 0.003/Mpc at k ~ 0.01/Mpc
Δr ~ 0.06 at r ~ 0.2
BICEP BB
45
73
109
144
k Mpc
Figure by Lewis (CosmoCoffee)


Why positive n_t better fits data?
The BICEP2 side:
B2xB2
B2xB1c
B2xKeck (preliminary)
0.05
0.04
0.03
0.02
0.01
0
−0.01
100
150
200
250
300
Multipole
Figure: BICEP2

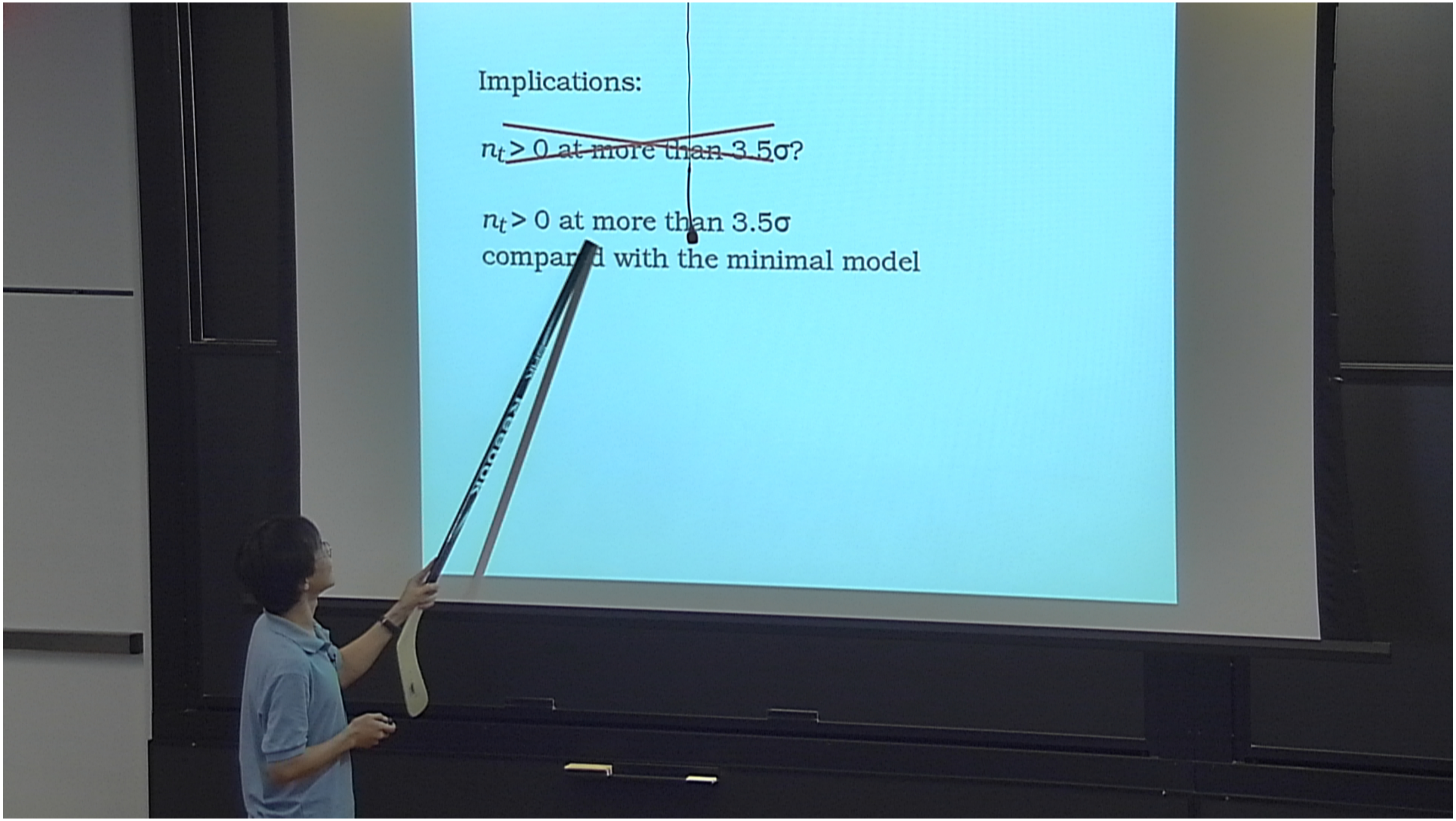

0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
$r_{0.01}$
−1
0
1
2
3
BICEP2 only:
blue n_t ~ 1.5σ
M. Gerbino, A. Ma
. Di Valentino, A. Melchiorri, 1403.5732
YW, W. Xue, 1403.5817

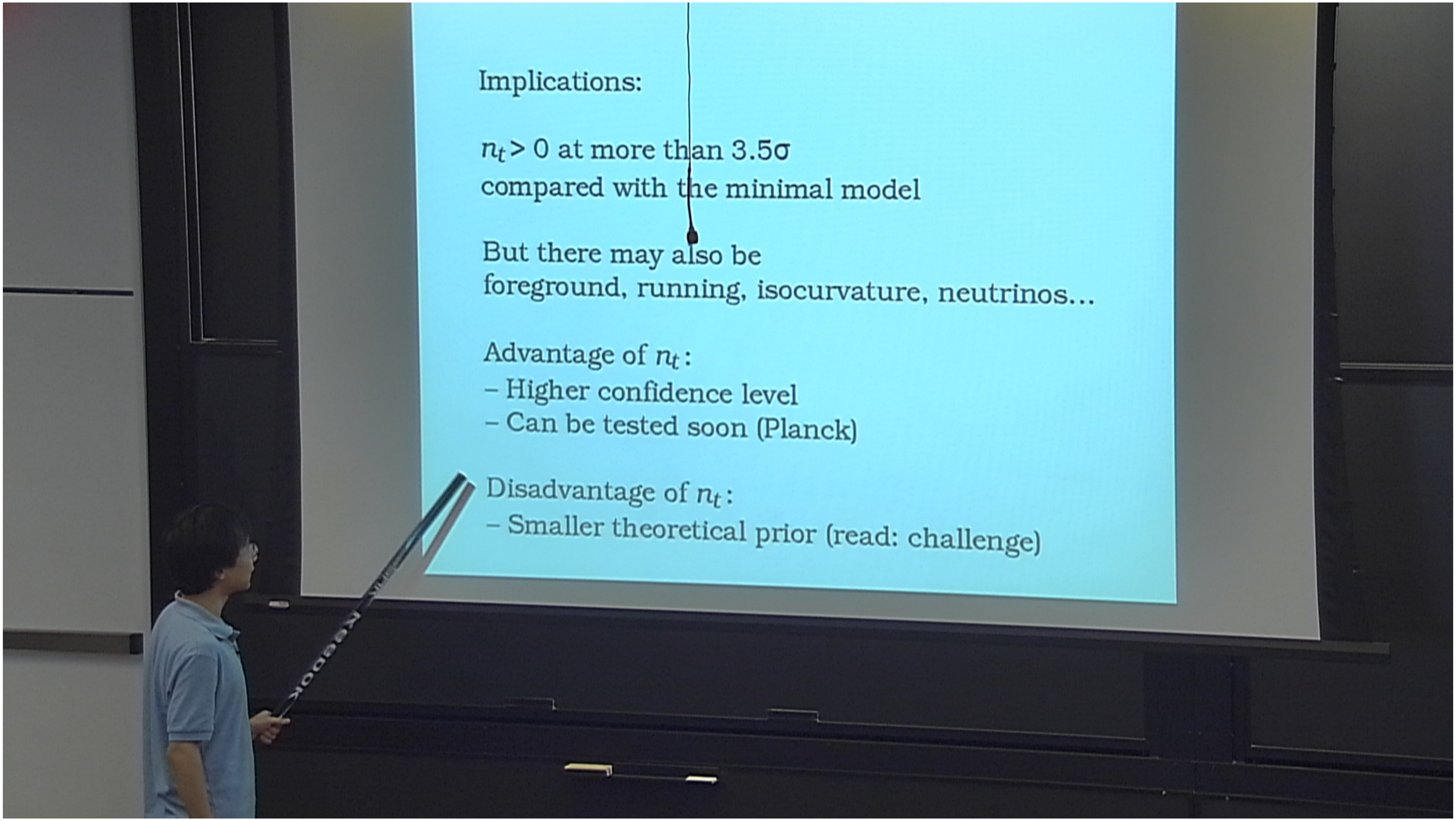

Why positive n_t better fits data?
The Planck side:
power deficit @ $\ell \leq 40$
@ 5%~10% @ 2.5 ~ 3σ
Another enhancement by
5% (r=0.1) ~10% (r=0.2)
would be another 2.5 ~ 3σ
90°
18°
1°
6000
5000
4000
3000
2000
1000
0
2
10
50
Figure: Planck XV

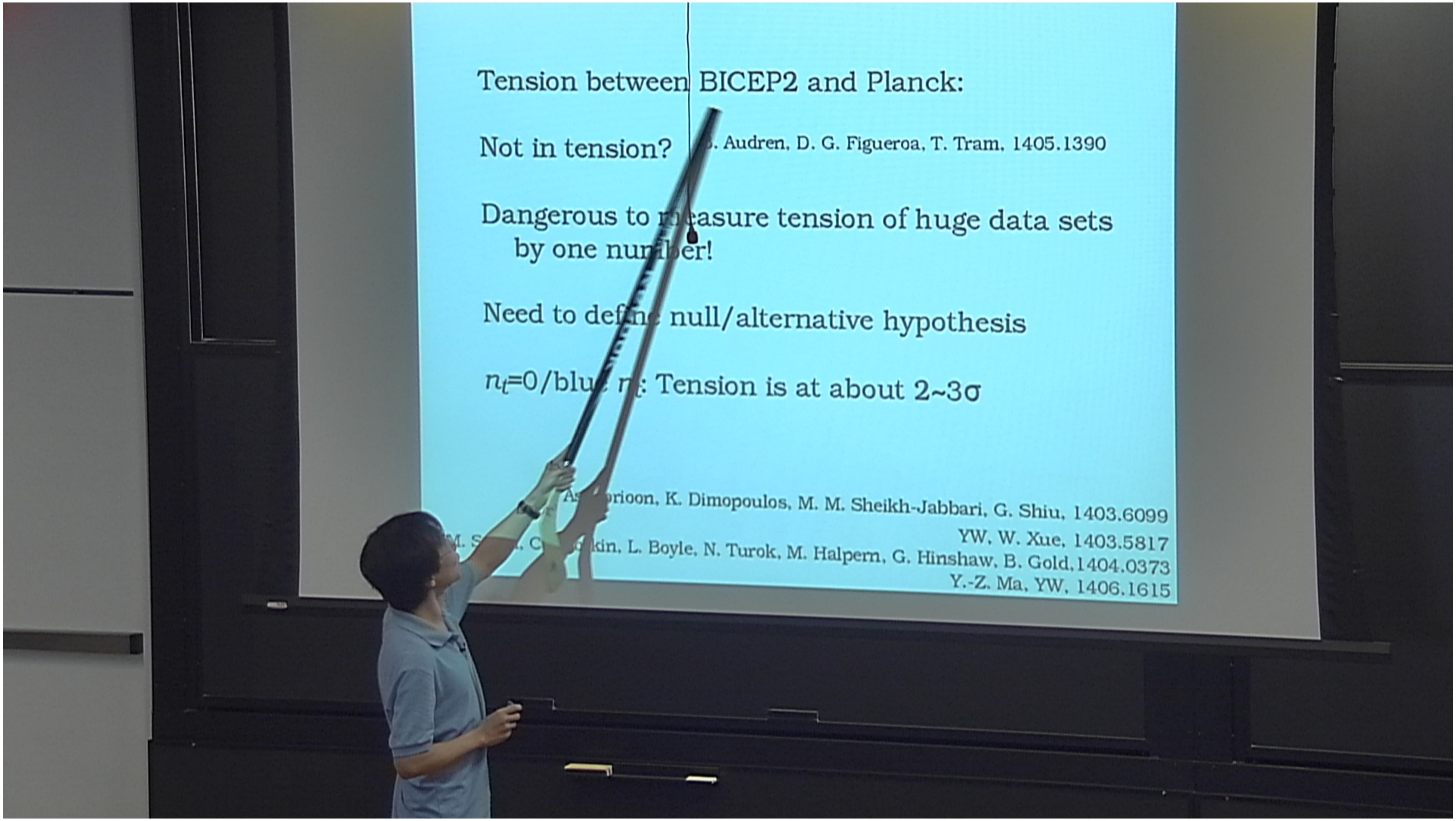

But n_t cannot be too blue
When $n_t > 2$,
primordial B-mode dominates over lensing
So the POLARBEAR signal of lensing B-mode
starts to constraint n_t
(need direct detection)
(cross correlation does not help)

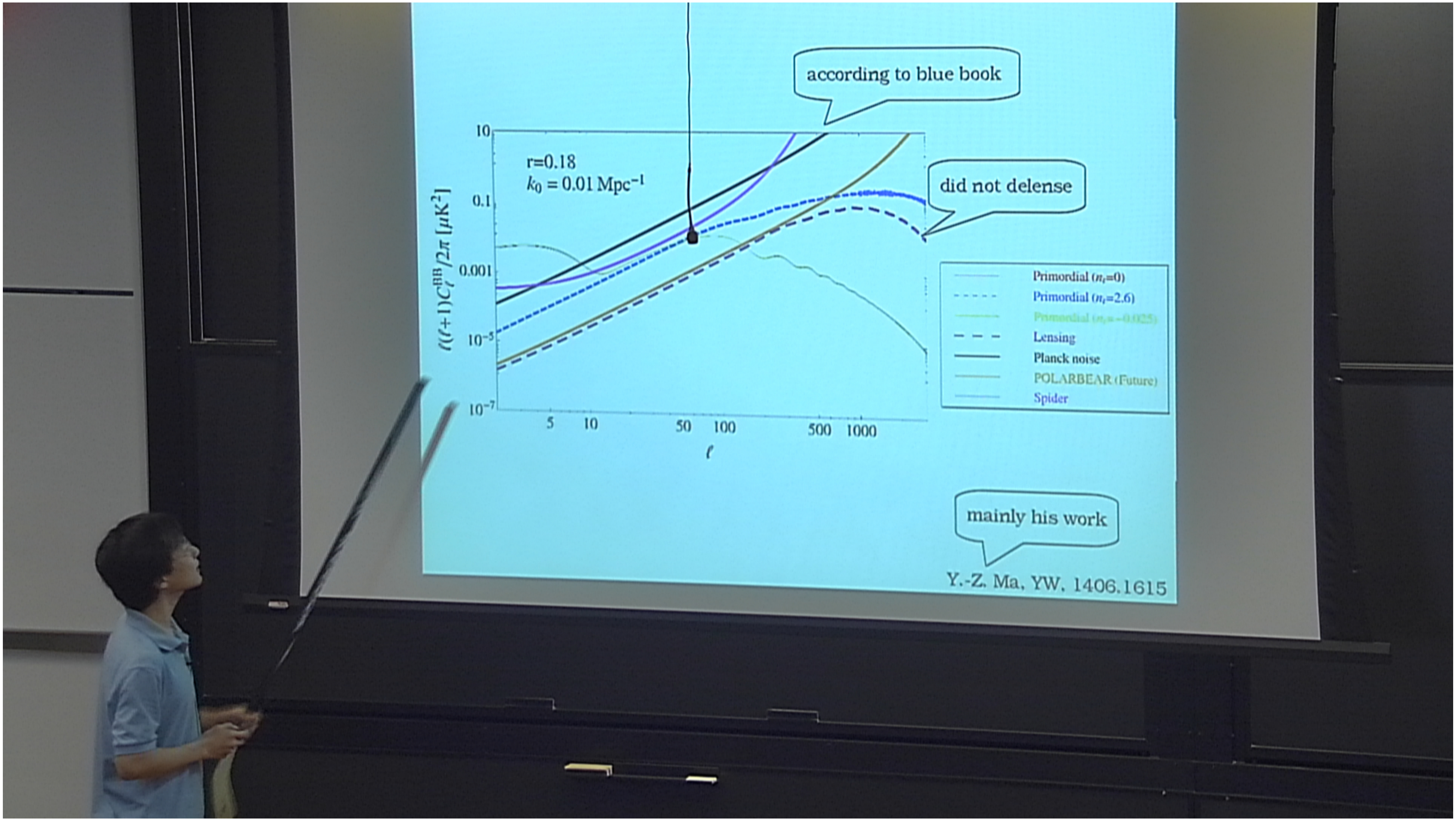


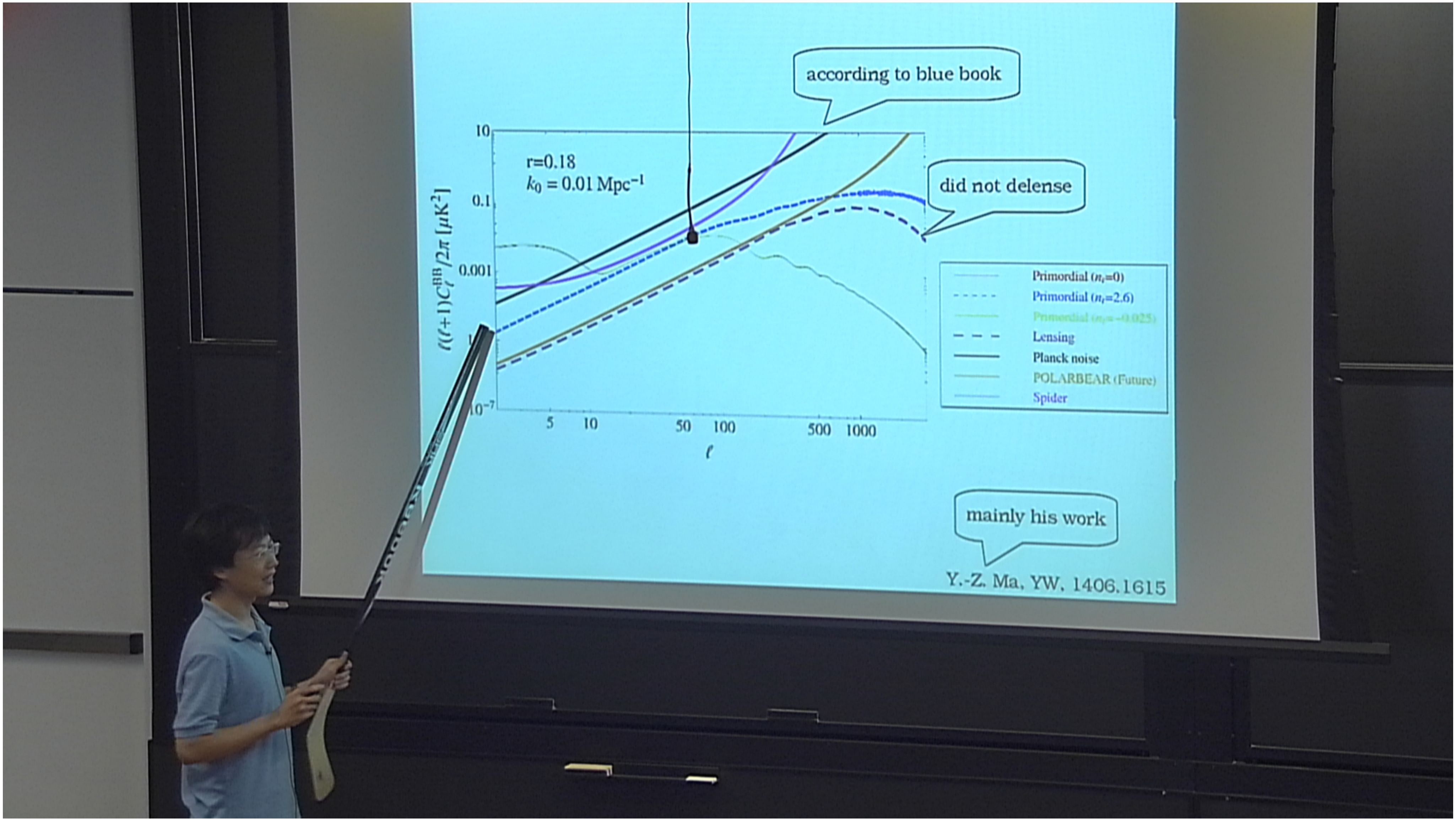
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
$r_{0.01}$
−1
0
1
2
3
Assuming
constant n_t for
50~60 e-folds

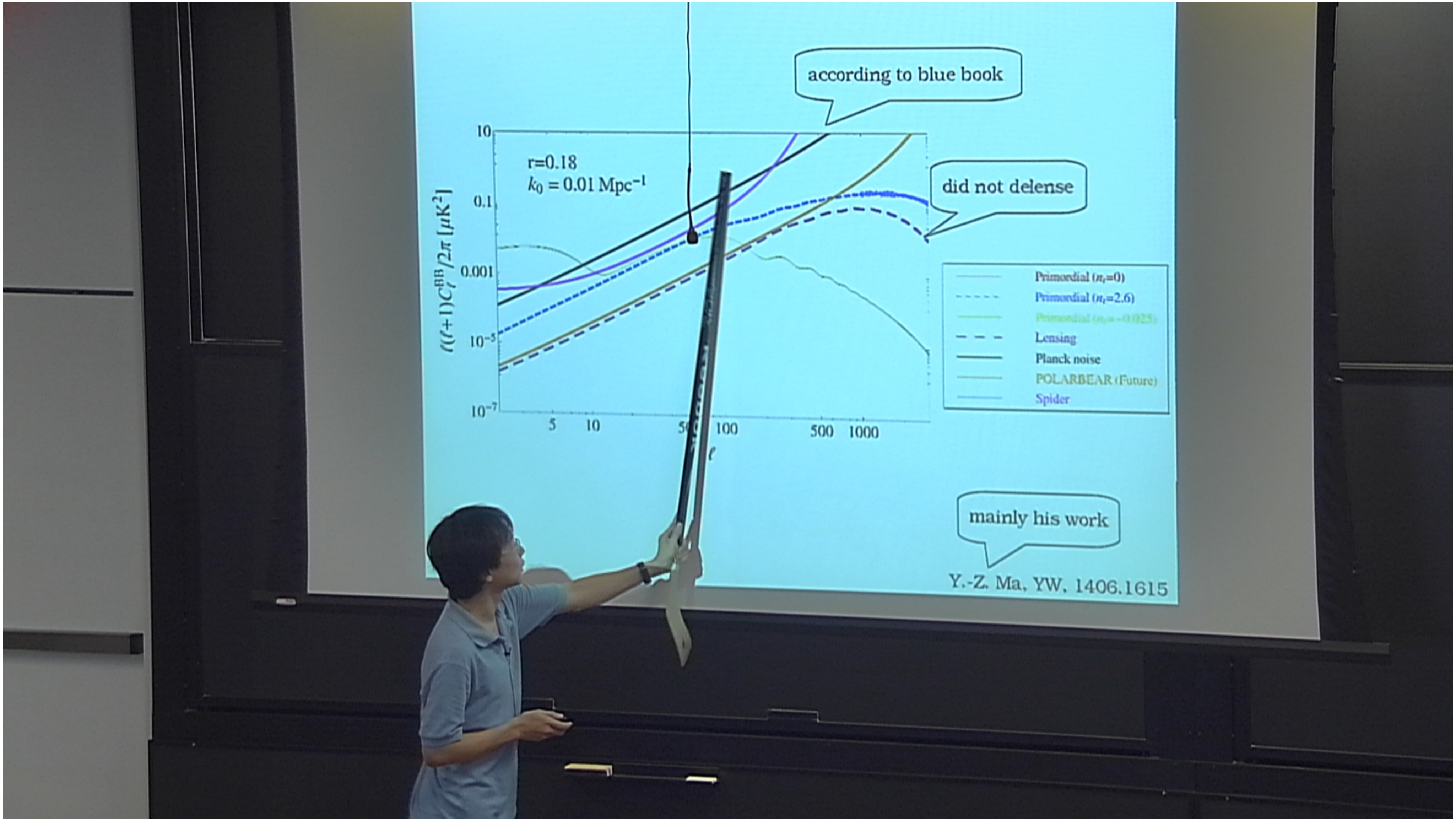

Implications:
$n_t > 0$ at more than 3.5σ?
$n_t > 0$ at more than 3.5σ
compar d with the minimal model

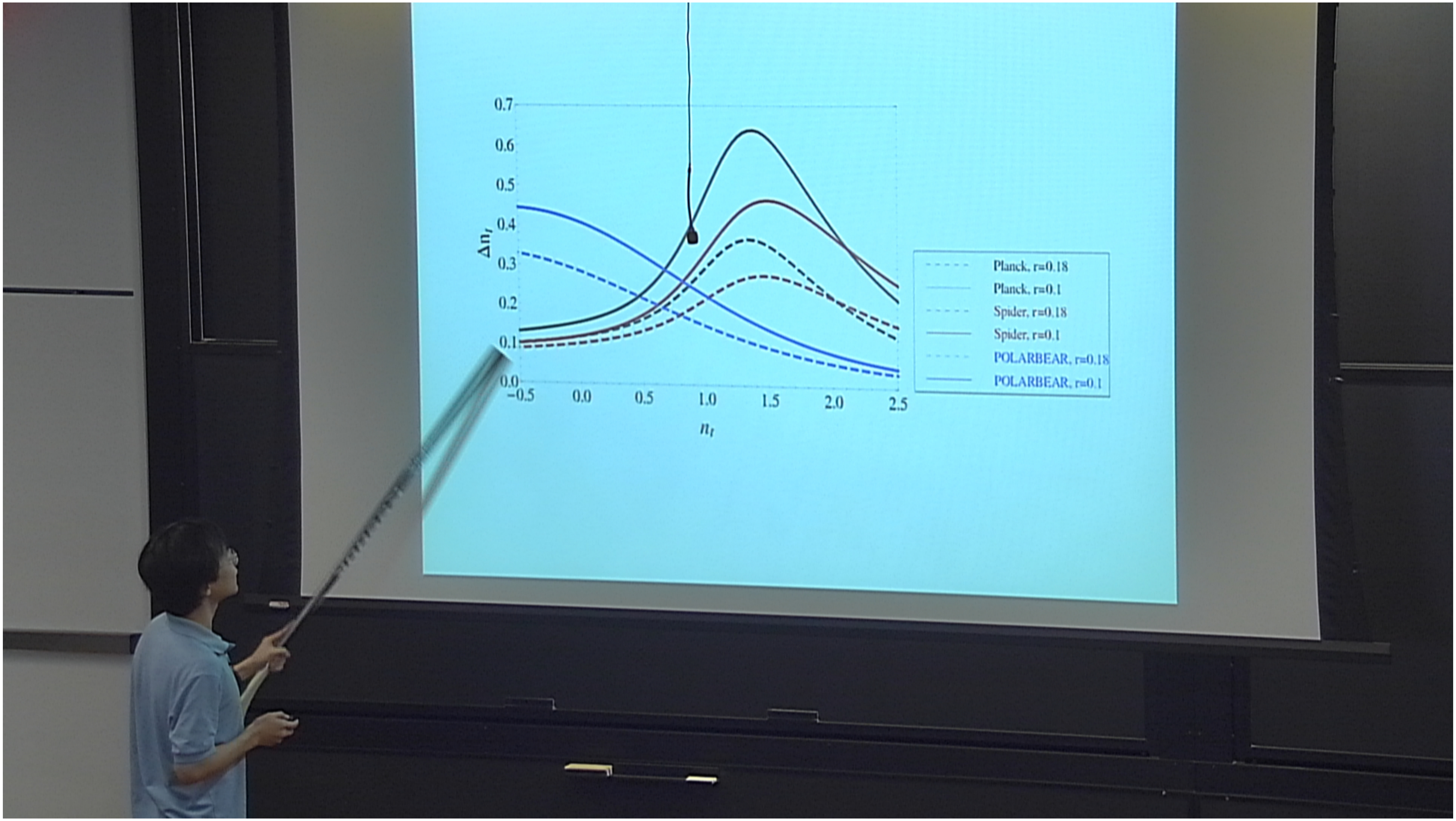

Implications:
$n_t > 0$ at more than 3.5σ
compared with the minimal model
But there may also be
foreground, running, isocurvature, neutrinos...
Advantage of n_t:
– Higher confidence level
– Can be tested soon (Planck)
Disadvantage of n_t:
– Smaller theoretical prior (read: challenge)


Tension between BICEP2 and Planck:
Not in tension?
. Audren, D. G. Figueroa, T. Tram, 1405.1390
Dangerous to measure tension of huge data sets
by one number!
Need to define null/alternative hypothesis
n_t=0/blue n_t: Tension is at about 2~3σ
orioon, K. Dimopoulos, M. M. Sheikh-Jabbari, G. Shiu, 1403.6099
YW, W. Xue, 1403.5817
kin, L. Boyle, N. Turok, M. Halpern, G. Hinshaw, B. Gold,1404.0373
Y.-Z. Ma, YW, 1406.1615

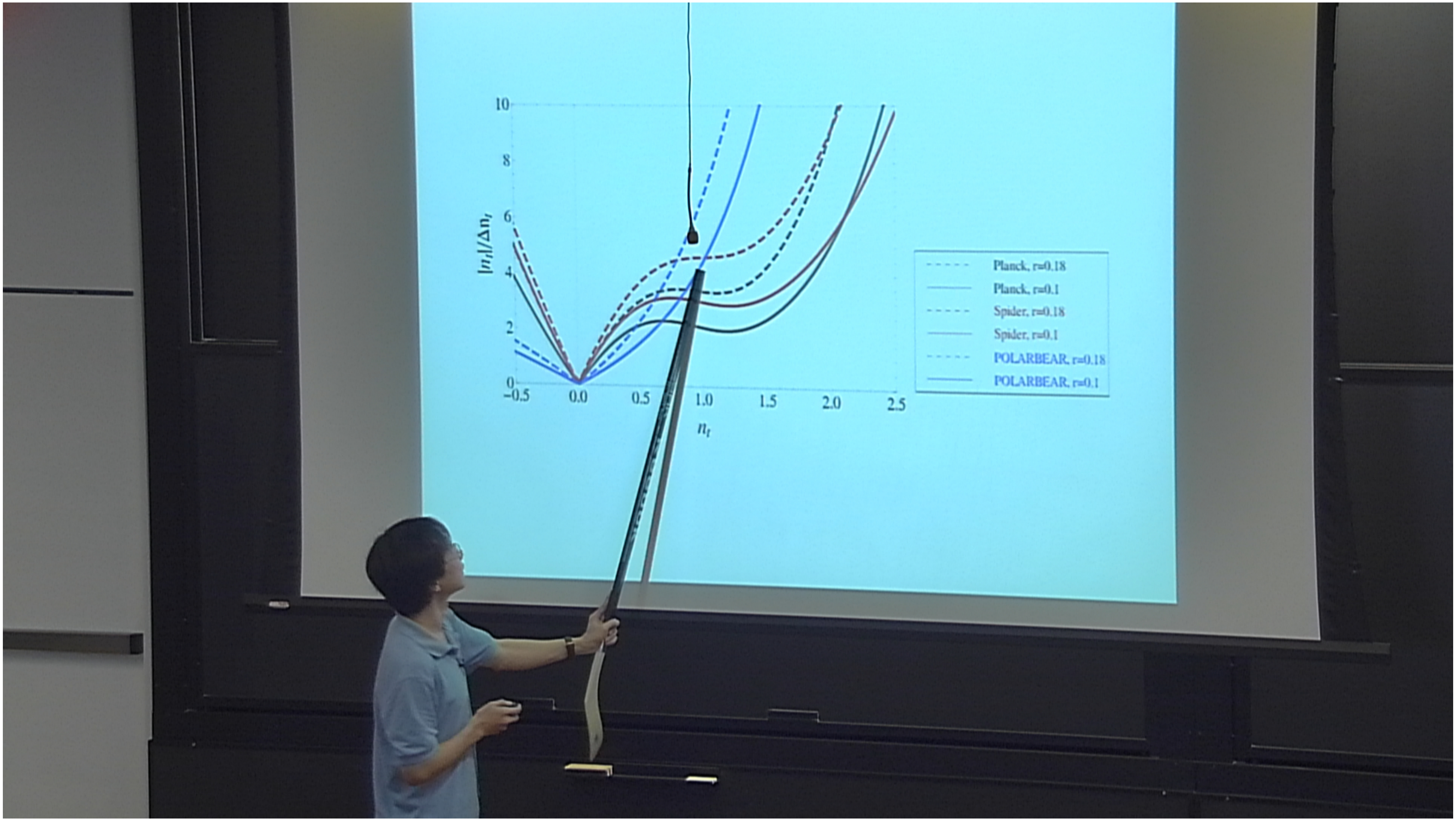

according to blue book
did not delense
mainly his work
r=0.18
k0 = 0.01 Mpc-1
l(l+1)C_l^BB/2π [μK²]
10
0.1
0.001
10-5
10-7
5 10 50 100 500 1000
l
Primordial (nt=0)
Primordial (nt=2.6)
Lensing
Planck noise
POLARBEAR (Future)
Spider
Y.-Z. Ma, YW, 1406.1615


according to blue book
did not delense
mainly his work
r=0.18
$k_0 = 0.01\,\mathrm{Mpc}^{-1}$
$\ell(\ell+1)C_\ell^{BB}/2\pi\ [\mu K^2]$
10
0.1
0.001
10^{-7}
5
10
50
100
500
1000
ℓ
Primordial (n_t=0)
Primordial (n_t=2.6)
Primordial (n_t=−0.025)
Lensing
Planck noise
POLARBEAR (Future)
Spider
Y.-Z. Ma, YW, 1406.1615

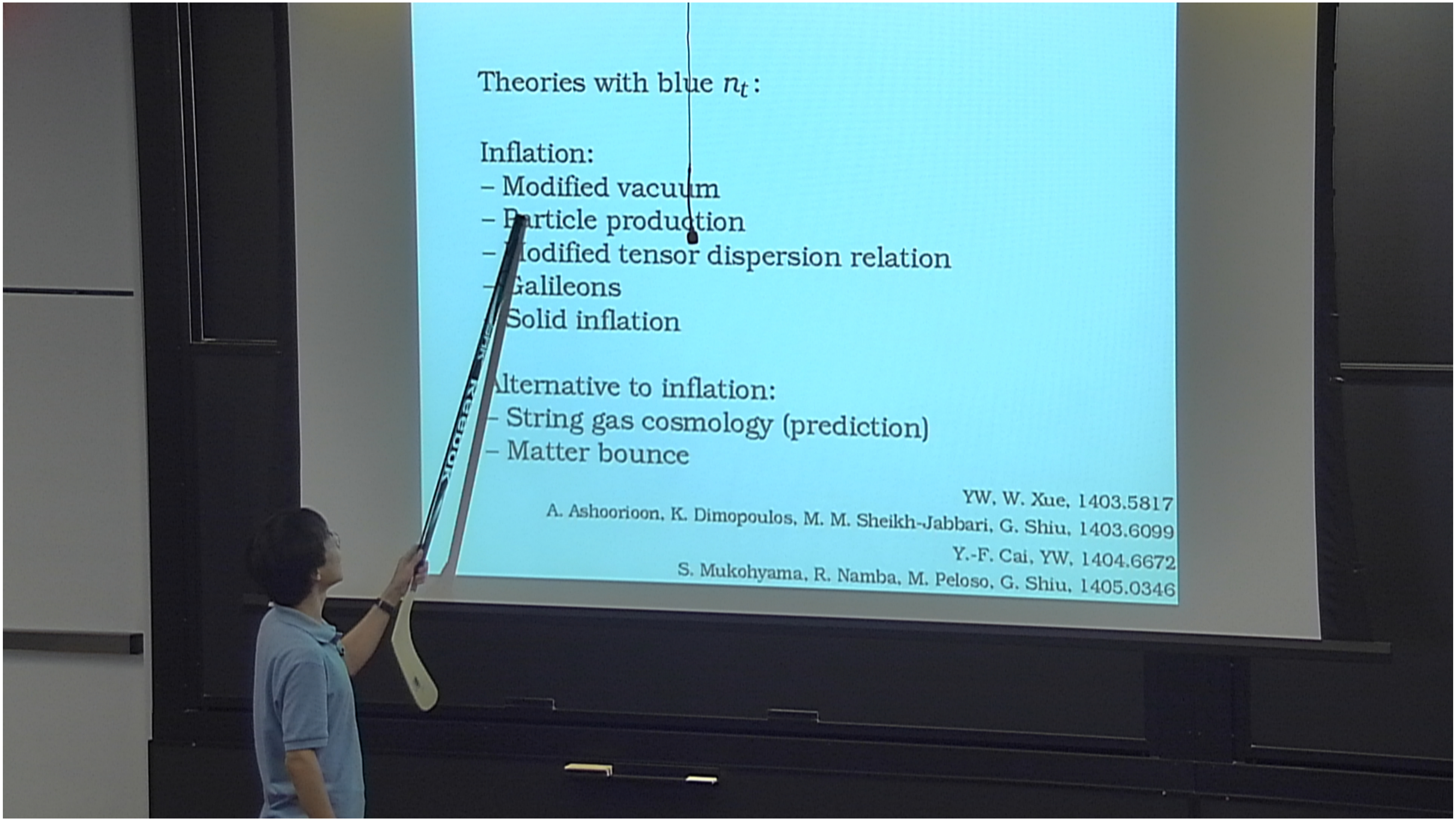

according to blue book
did not delense
mainly his work
r=0.18
$k_0 = 0.01\,\mathrm{Mpc}^{-1}$
$\ell(\ell+1)C_\ell^{BB}/2\pi\ [\mu K^2]$
10
0.1
0.001
10^{-5}
10^{-7}
5
10
100
500
1000
ℓ
Primordial (n_t=0)
Primordial (n_t=2.6)
Lensing
Planck noise
POLARBEAR (Future)
Spider
Y.-Z. Ma, YW, 1406.1615

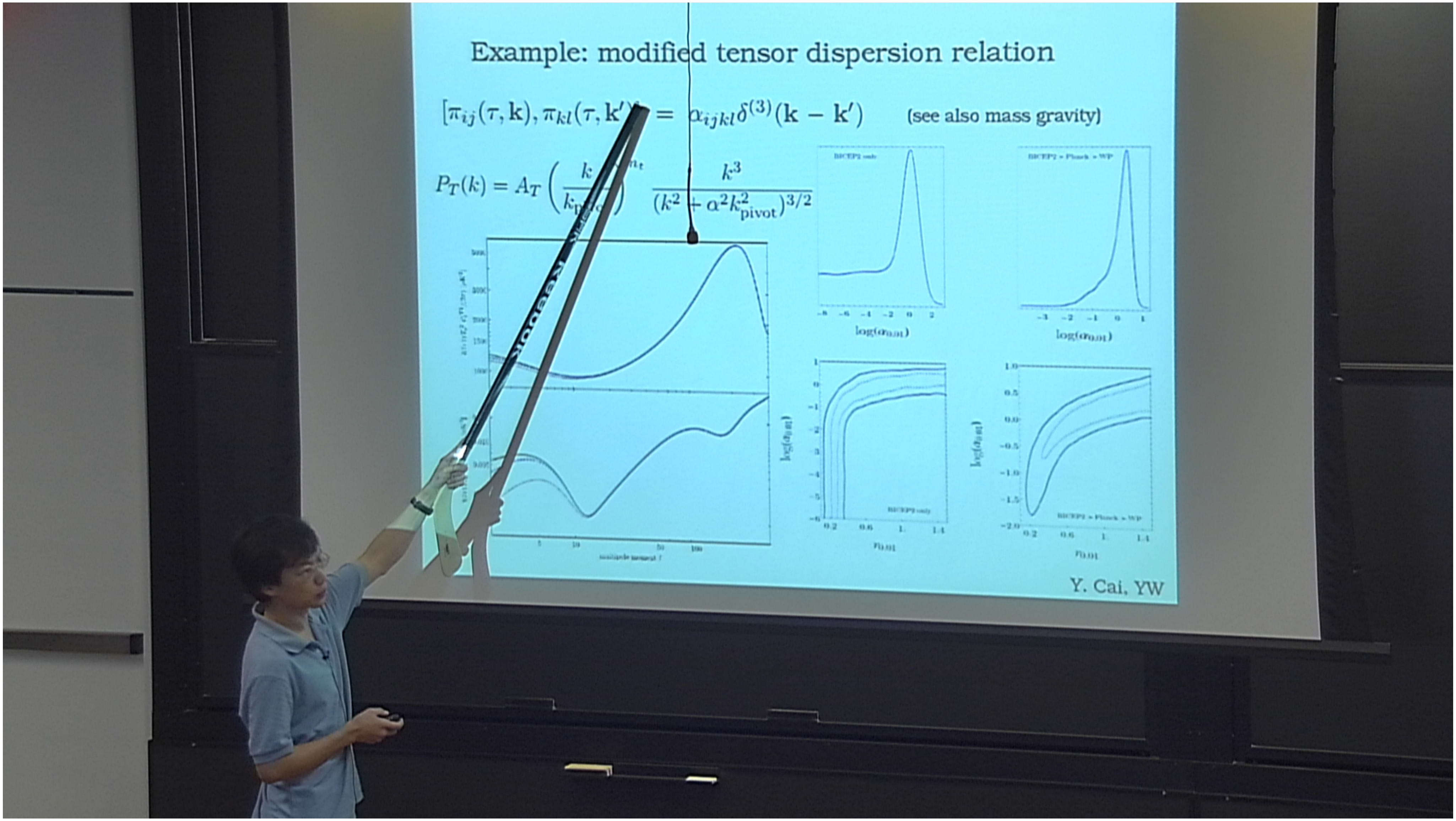


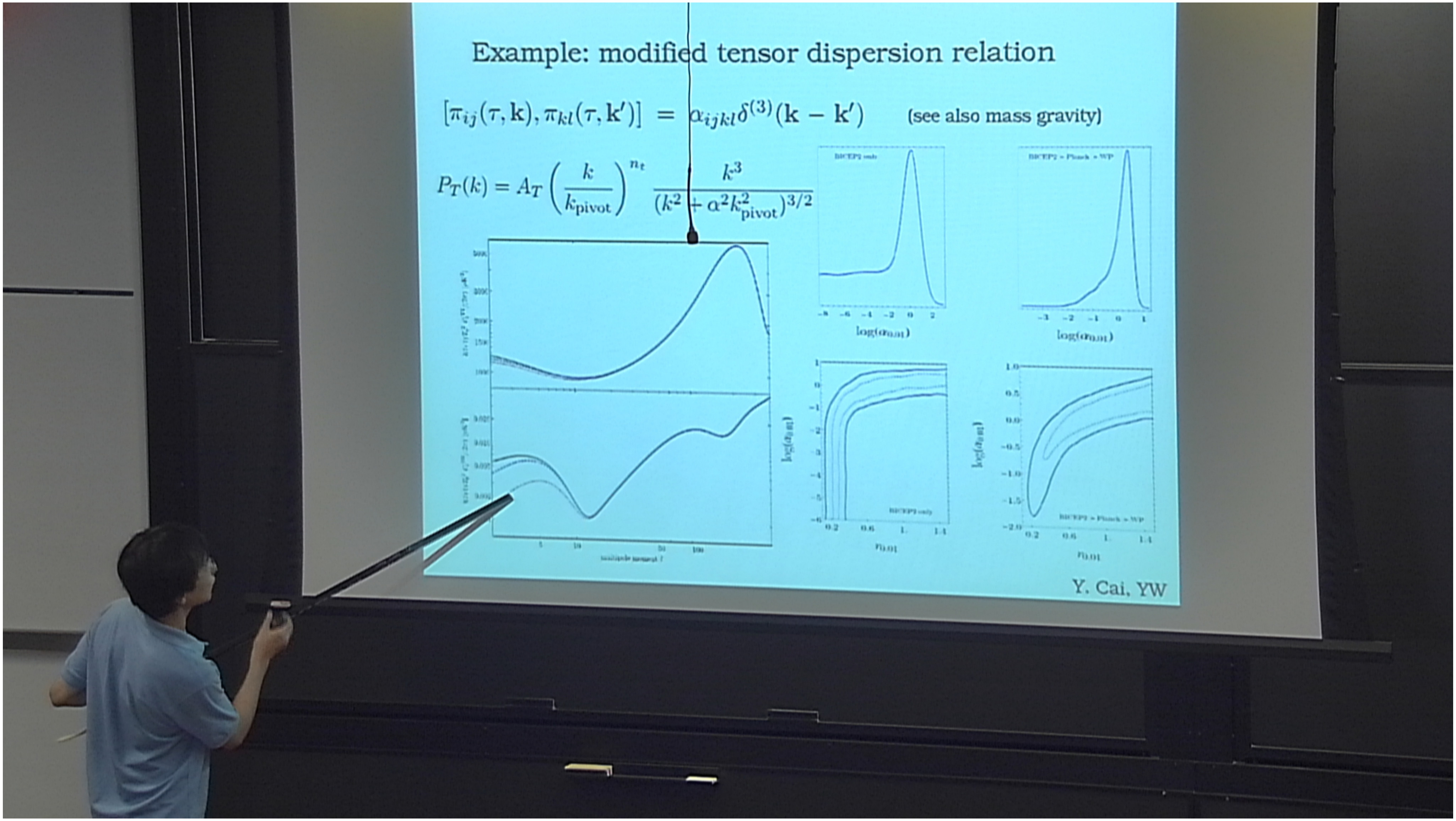
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Δn_t
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
n_t
Planck, r=0.18
Planck, r=0.1
Spider, r=0.18
Spider, r=0.1
POLARBEAR, r=0.18
POLARBEAR, r=0.1

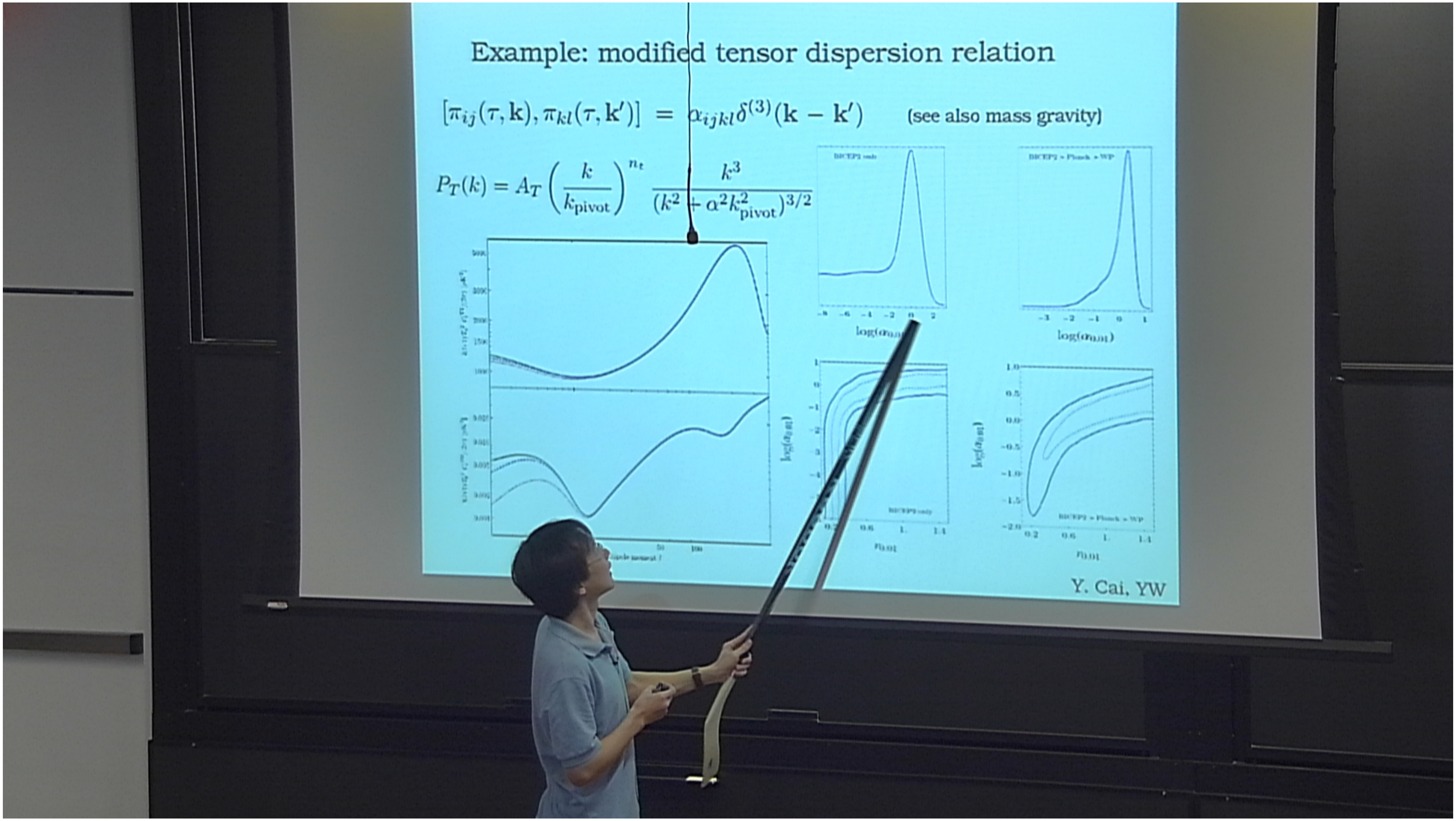


$|n_t|/\Delta n_t$
10
8
6
4
2
0
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
n_t
Planck, r=0.18
Planck, r=0.1
Spider, r=0.18
Spider, r=0.1
POLARBEAR, r=0.18
POLARBEAR, r=0.1


Theories with blue n_t:
Inflation:
– Modified vacuum
– Particle production
– Modified tensor dispersion relation
– Galileons
– Solid inflation
Alternative to inflation:
– String gas cosmology (prediction)
– Matter bounce
YW, W. Xue, 1403.5817
A. Ashoorioon, K. Dimopoulos, M. M. Sheikh-Jabbari, G. Shiu, 1403.6099
Y.-F. Cai, YW, 1404.6672
S. Mukohyama, R. Namba, M. Peloso, G. Shiu, 1405.0346


Example: modified tensor dispersion relation
(see also mass gravity)
BICEP2 only
BICEP2 + Planck + WP
log(α0.01)
r0.01
Y. Cai, YW


Example: modified tensor dispersion relation
$[\pi_{ij}(\tau,\mathbf{k}),\pi_{kl}(\tau,\mathbf{k}')] = \alpha_{ijkl}\delta^{(3)}(\mathbf{k}-\mathbf{k}')$
(see also mass gravity)
$P_T(k) = A_T\left(\frac{k}{k_{\rm pivot}}\right)^{n_t}\frac{k^3}{(k^2+\alpha^2k^2_{\rm pivot})^{3/2}}$
Y. Cai, YW



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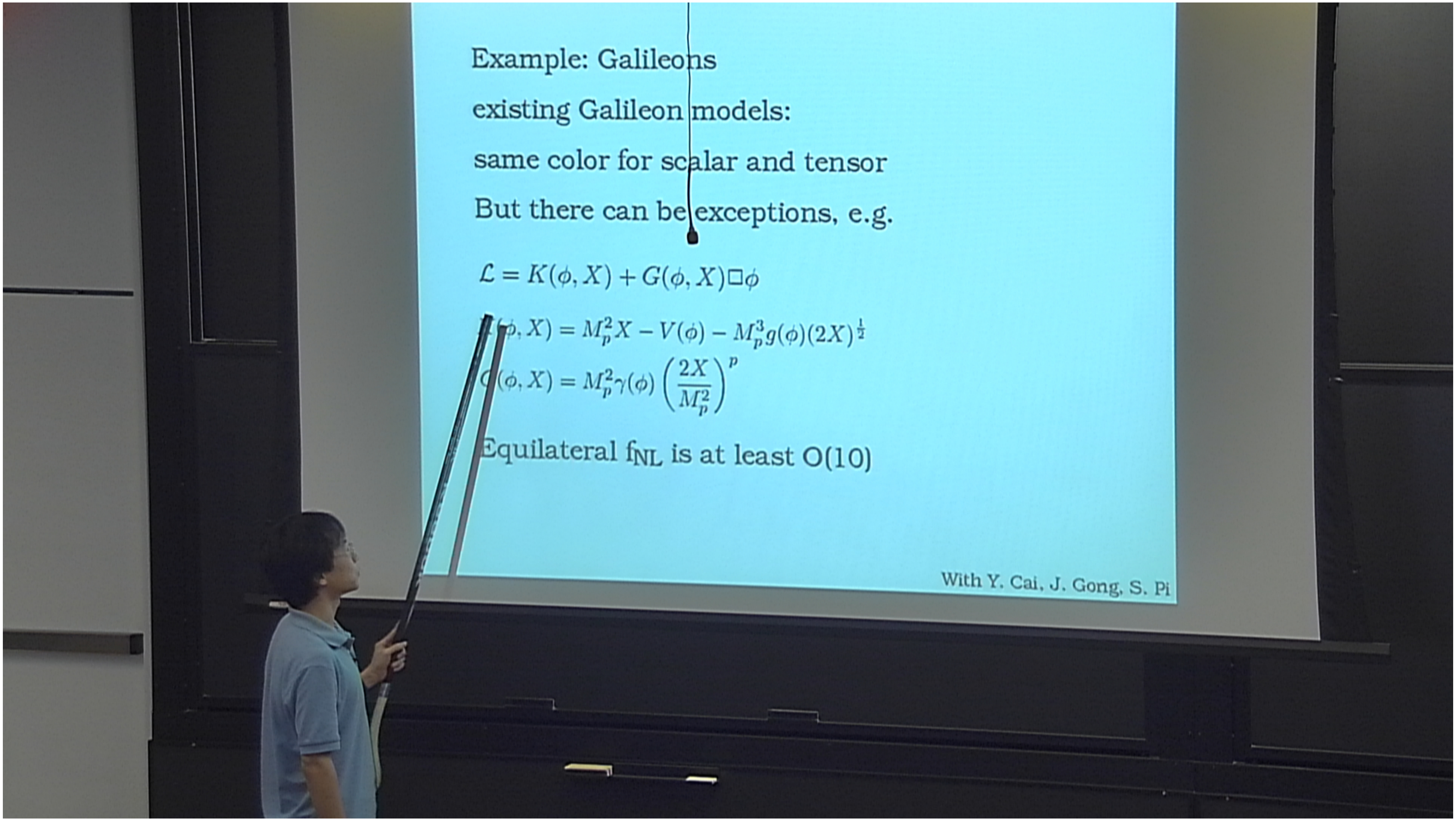
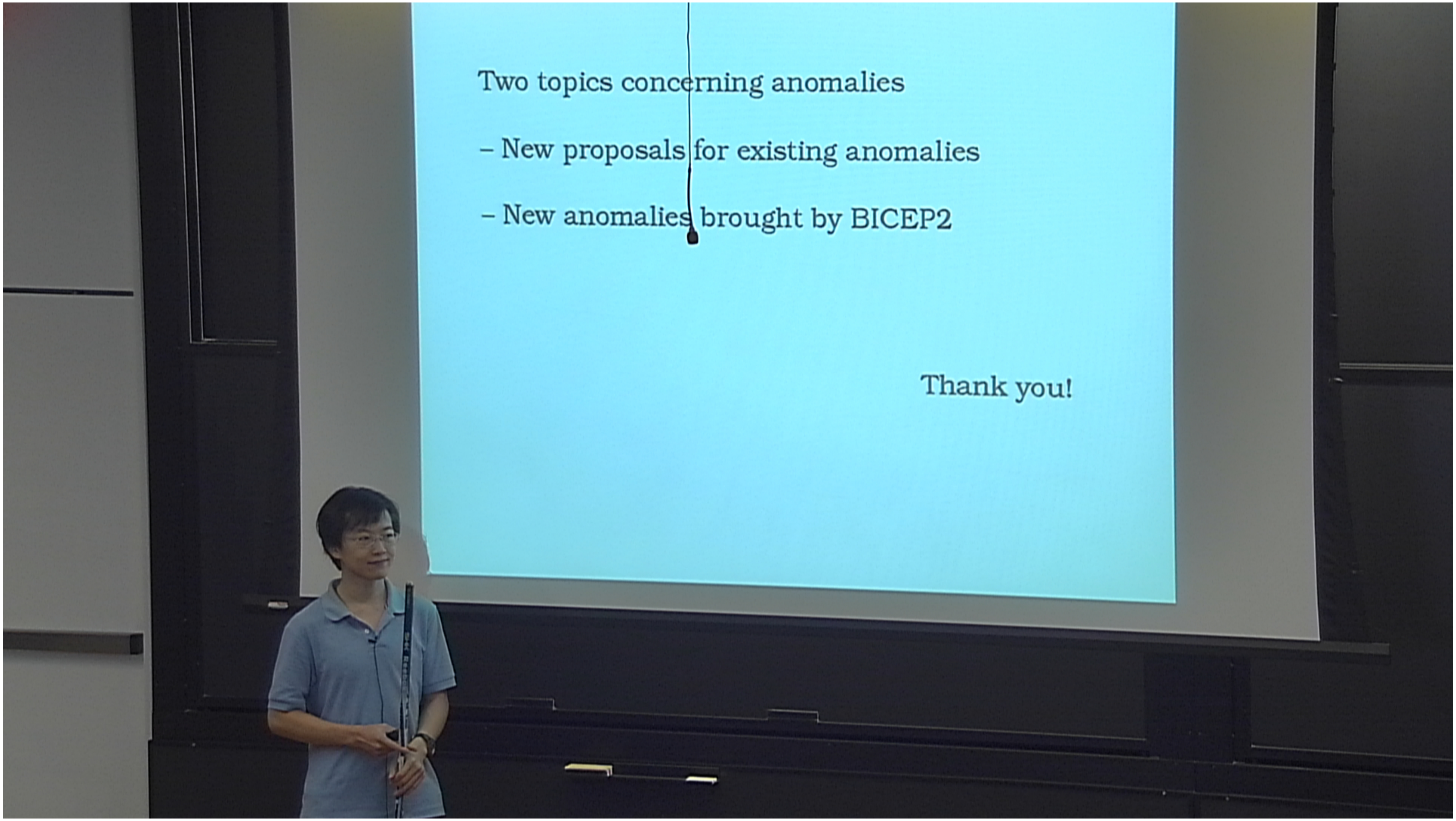

Example: Galileons
existing Galileon models:
same color for scalar and tensor
But there can be exceptions, e.g.
$\mathcal{L} = K(\phi, X) + G(\phi, X)\Box\phi$
$(\phi, X) = M_p^2 X - V(\phi) - M_p^3 g(\phi)(2X)^{\frac{1}{2}}$
$(\phi, X) = M_p^2 \gamma(\phi) \left(\frac{2X}{M_p^2}\right)^p$
quilateral f_{NL} is at least O(10)
With Y. Cai, J. Gong, S. Pi


Two topics concerning anomalies
– New proposals for existing anomalies
– New anomalies brought by BICEP2
Thank you!