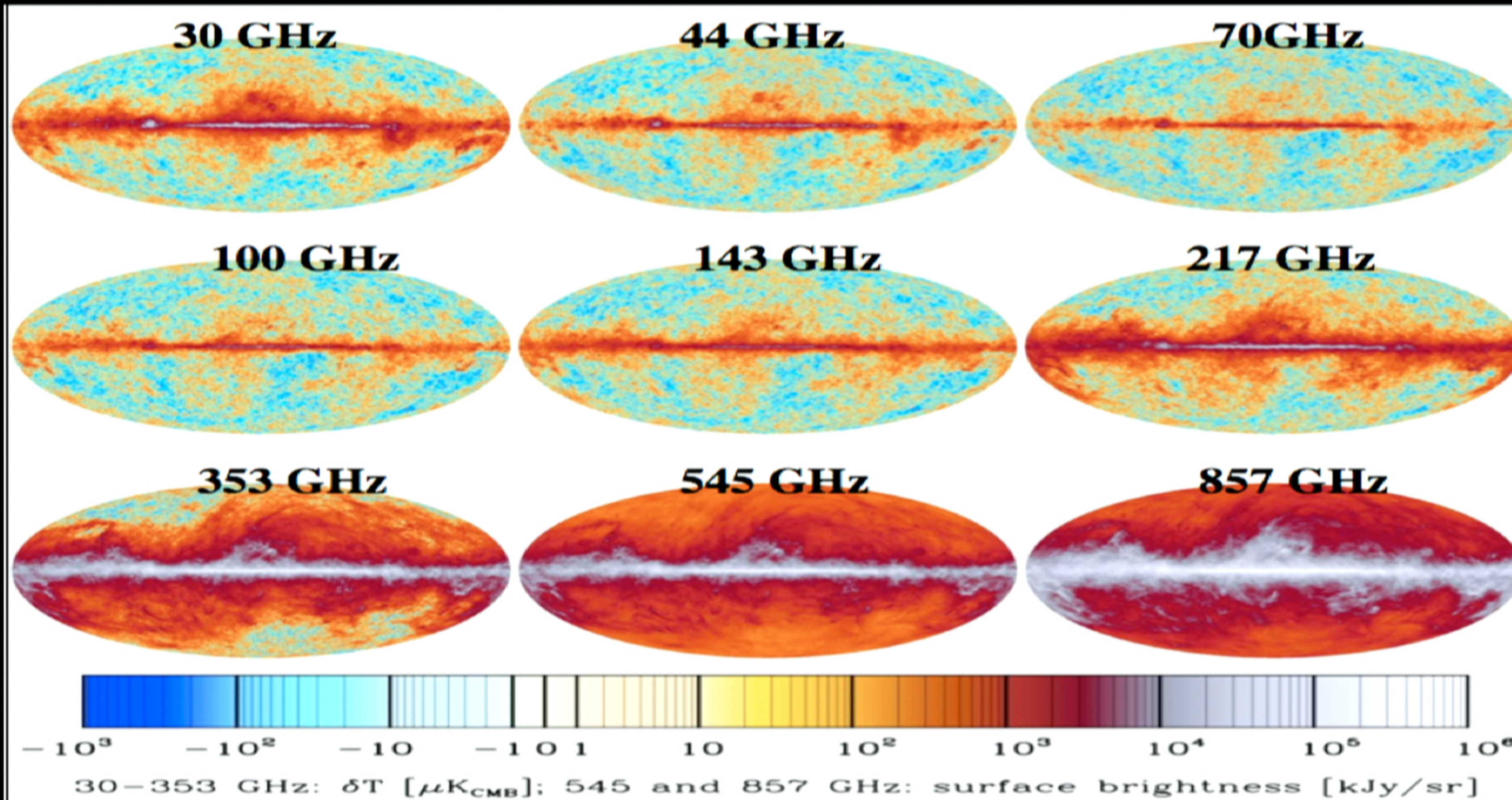
Title: Results and highlights from Planck

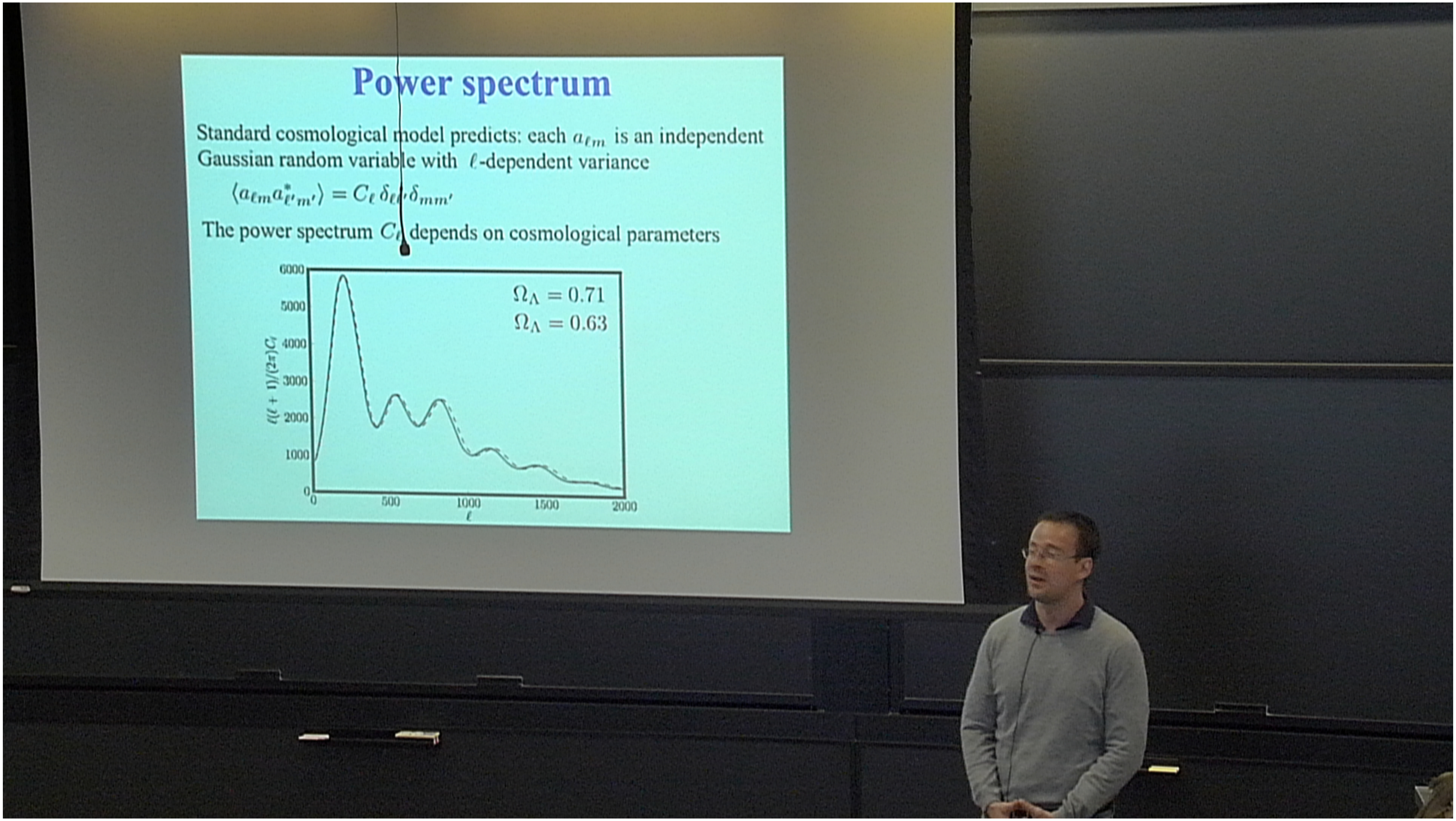
Date: Apr 16, 2013 11:00 AM

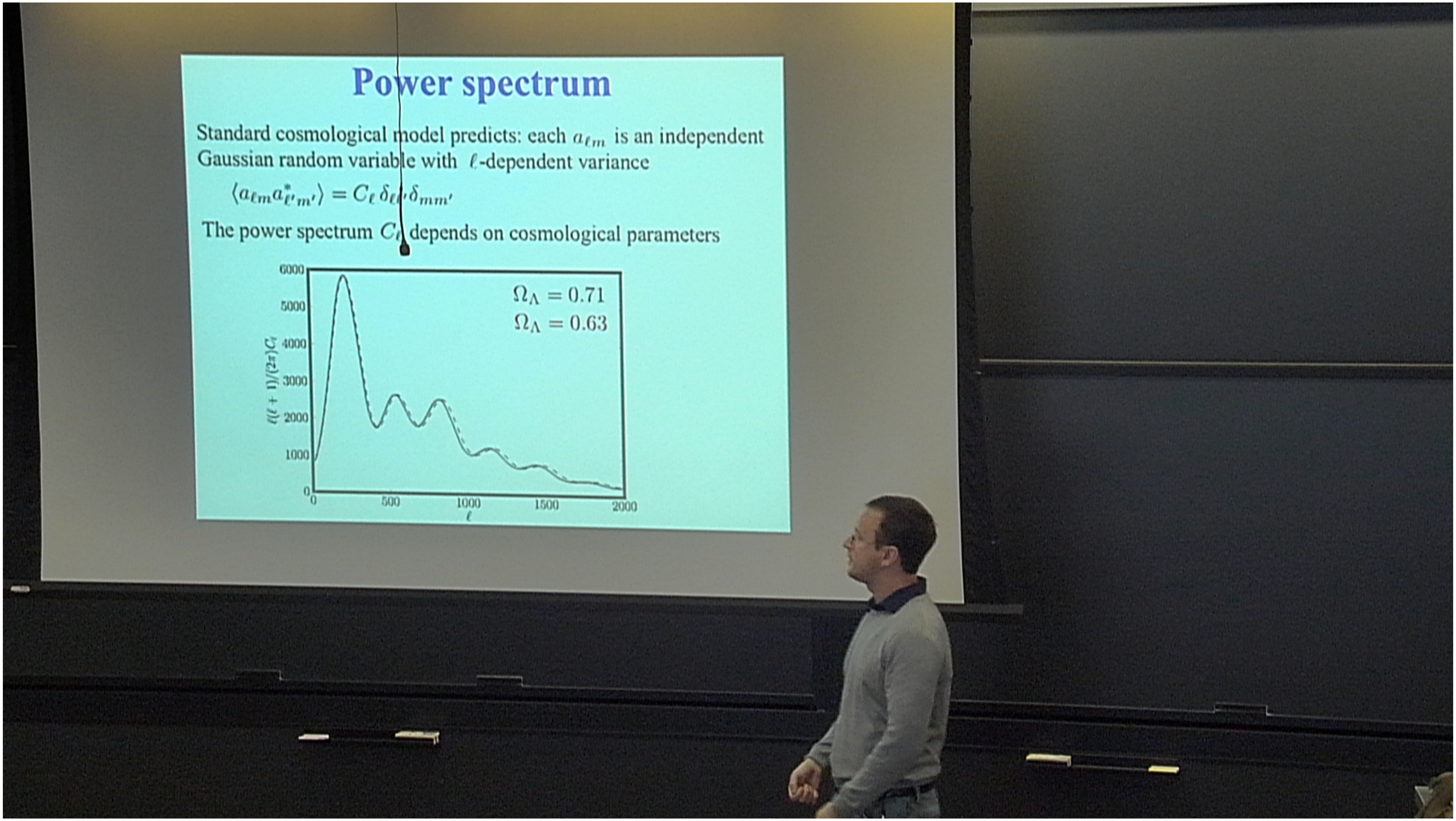
URL: http://pirsa.org/13040123

Abstract: Cosmological results
from Planck, a third-generation satellite mission to measure the cosmic
microwave background, have just been announced. These results improve
constraints on essentially all cosmological parameters, and have implications
for several preexisting sources of tension with the standard cosmological
model, while also raising new puzzles. I will discuss these results and
their significance, as well as the next steps forward.



30 GHz
44 GHz
70GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]


Power spectrum
Standard cosmological model predicts: each $a_{\ell m}$ is an independent Gaussian random variable with ℓ-dependent variance
$\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \, \delta_{\ell\ell'} \delta_{mm'}$
The power spectrum C_ℓ depends on cosmological parameters
$\Omega_\Lambda = 0.71$
$\Omega_\Lambda = 0.63$
$\ell(\ell+1)/(2\pi) C_\ell$
ℓ
0
1000
2000
3000
4000
5000
6000
500
1500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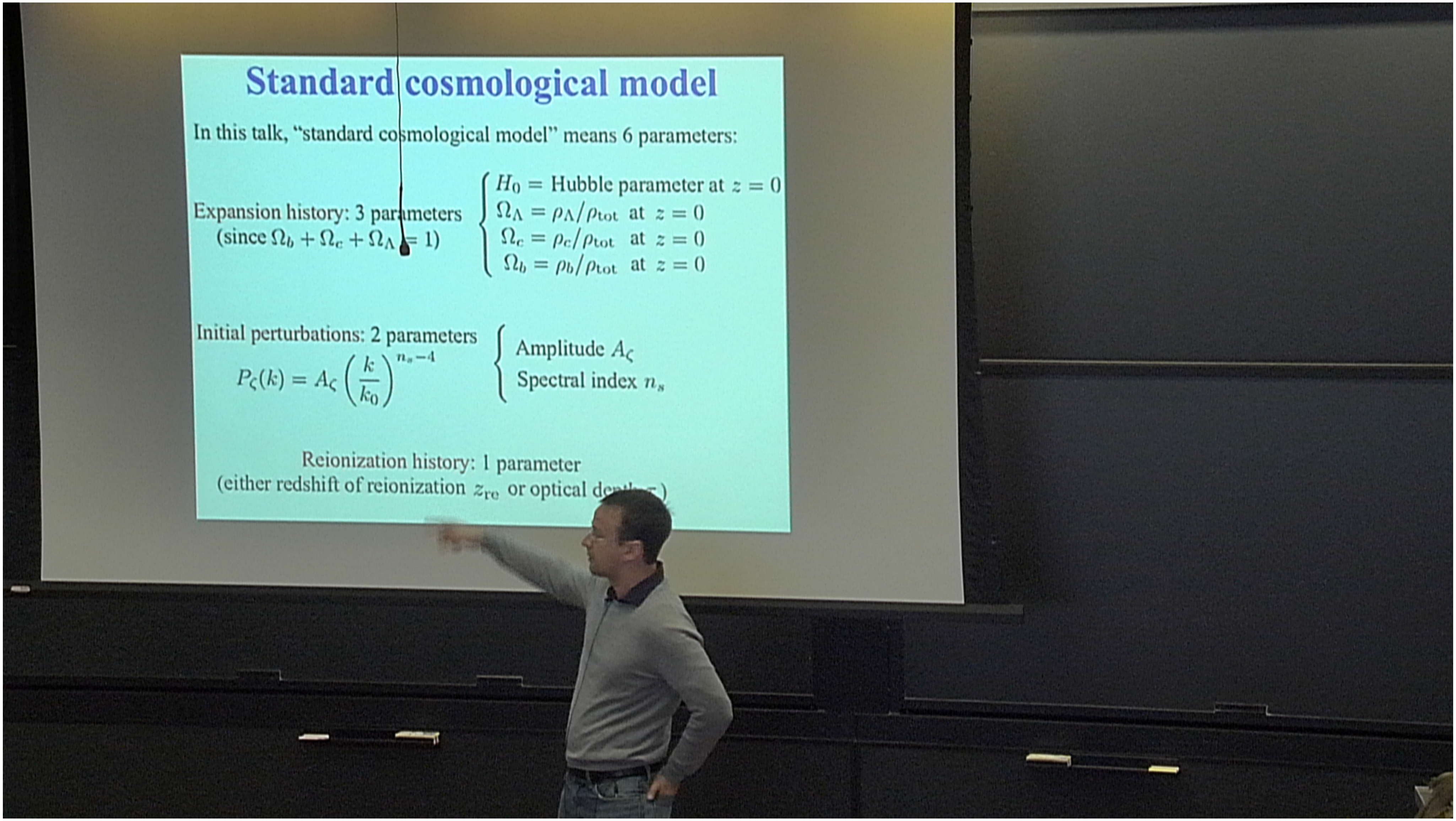
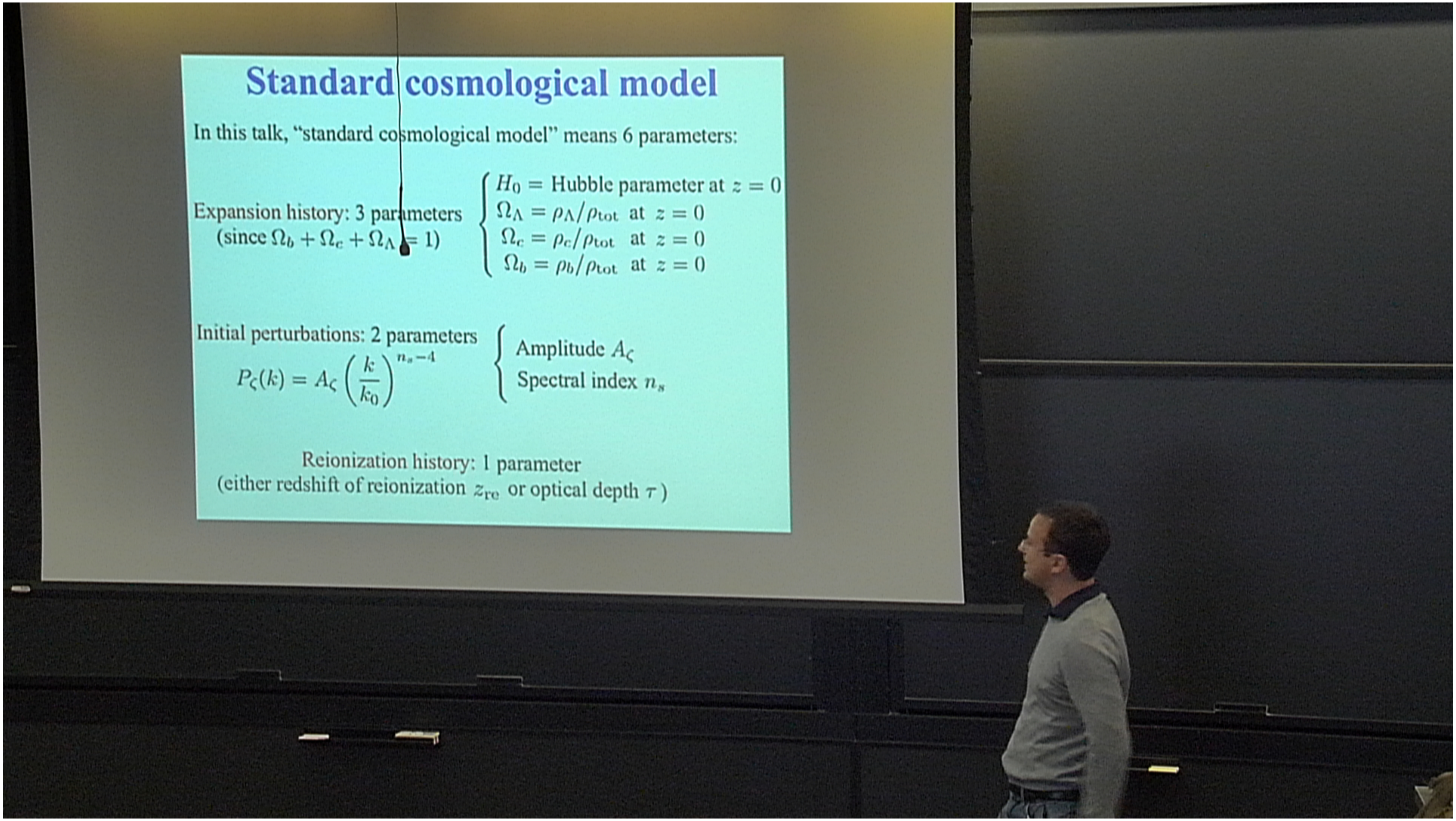

Standard cosmological model
In this talk, "standard cosmological model" means 6 parameters:
Expansion history: 3 parameters
(since $\Omega_b + \Omega_c + \Omega_\Lambda = 1$)
H_0 = Hubble parameter at $z = 0$
$\Omega_\Lambda = \rho_\Lambda/\rho_{\rm tot}$ at $z = 0$
$\Omega_c = \rho_c/\rho_{\rm tot}$ at $z = 0$
$\Omega_b = \rho_b/\rho_{\rm tot}$ at $z = 0$
Initial perturbations: 2 parameters
$P_\zeta(k) = A_\zeta \left(\frac{k}{k_0}\right)^{n_s - 4}$
Amplitude A_ζ
Spectral index n_s
Reionization history: 1 parameter
(either redshift of reionization $z_{\rm re}$ or optical de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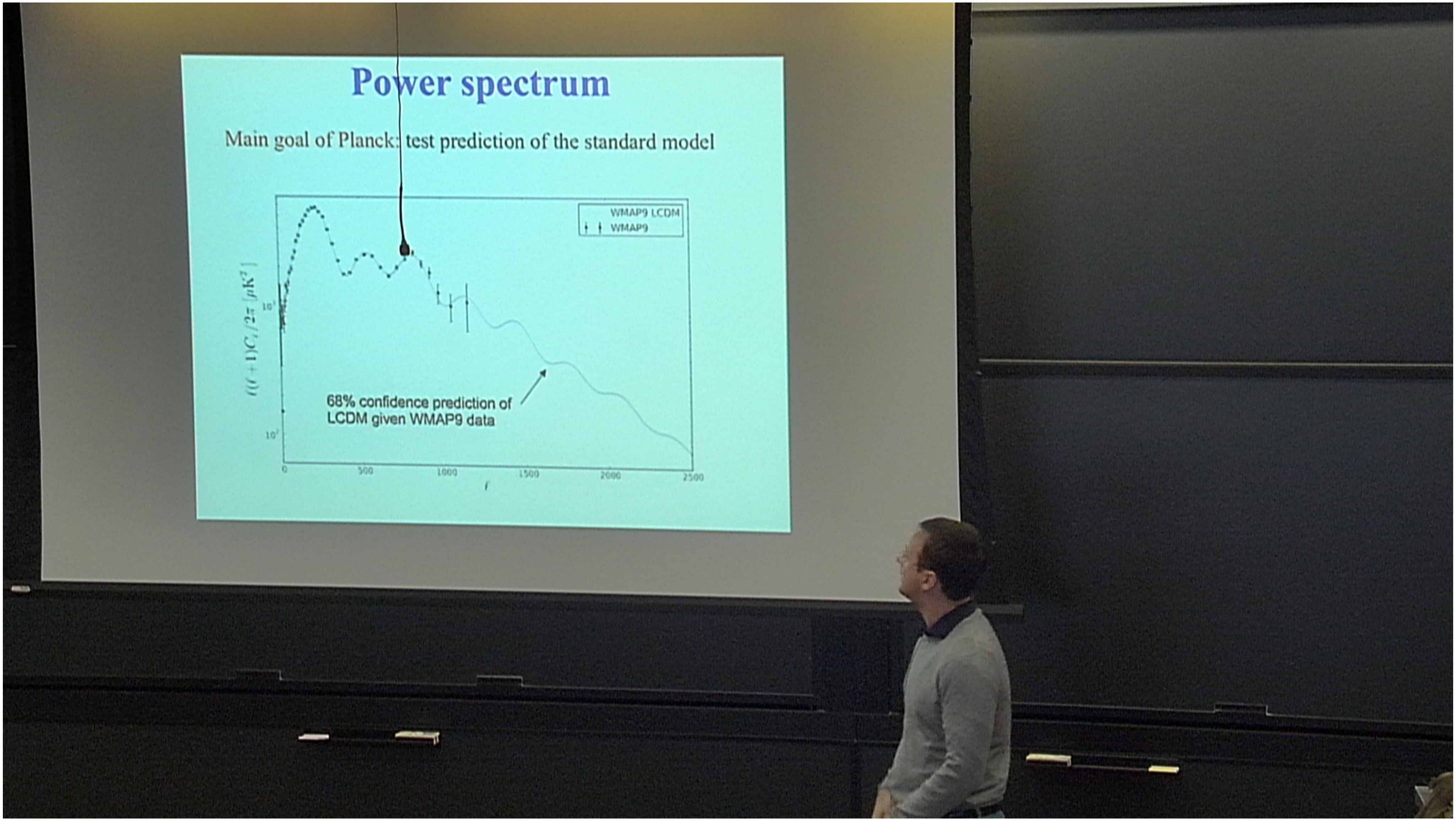
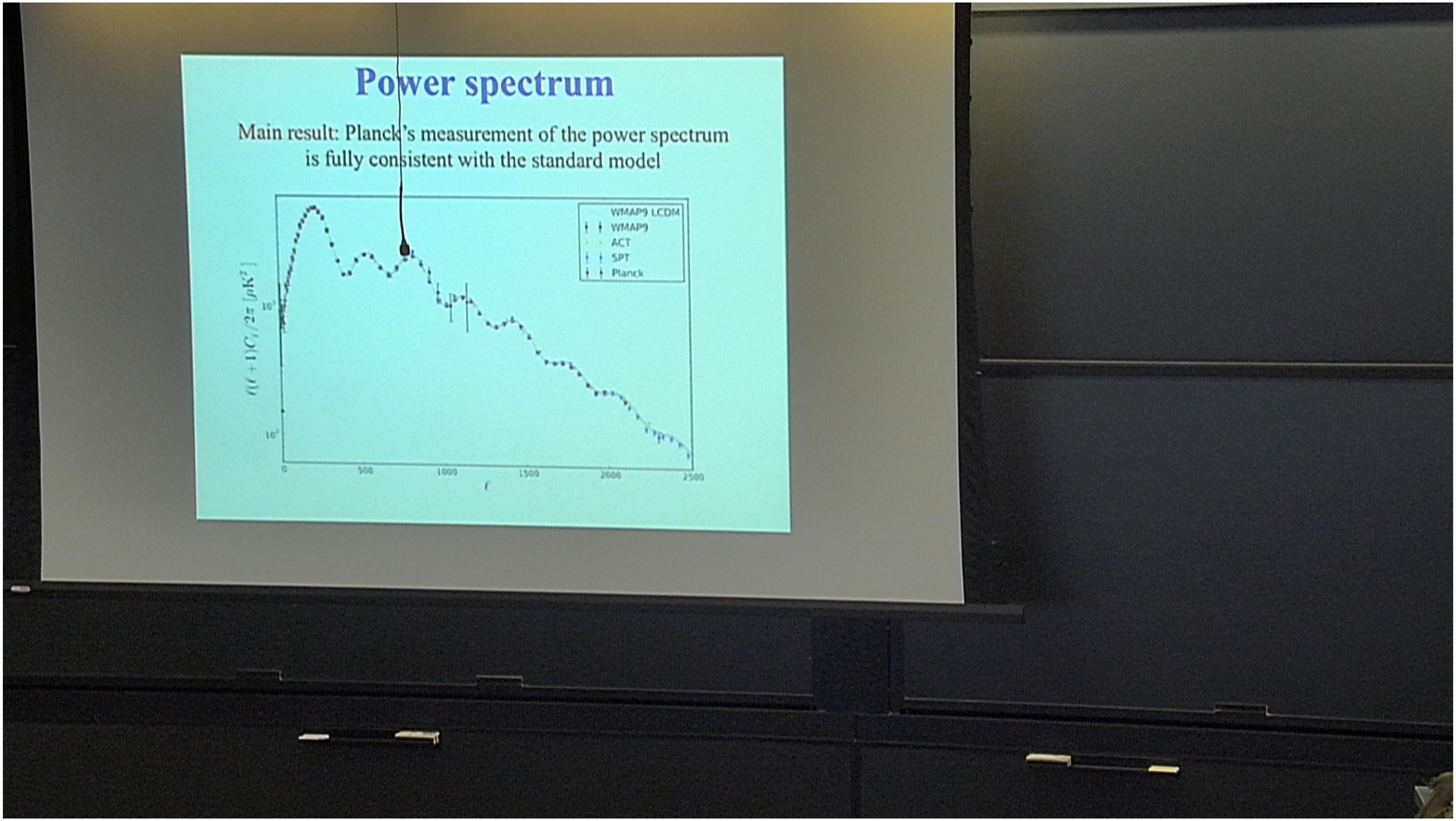
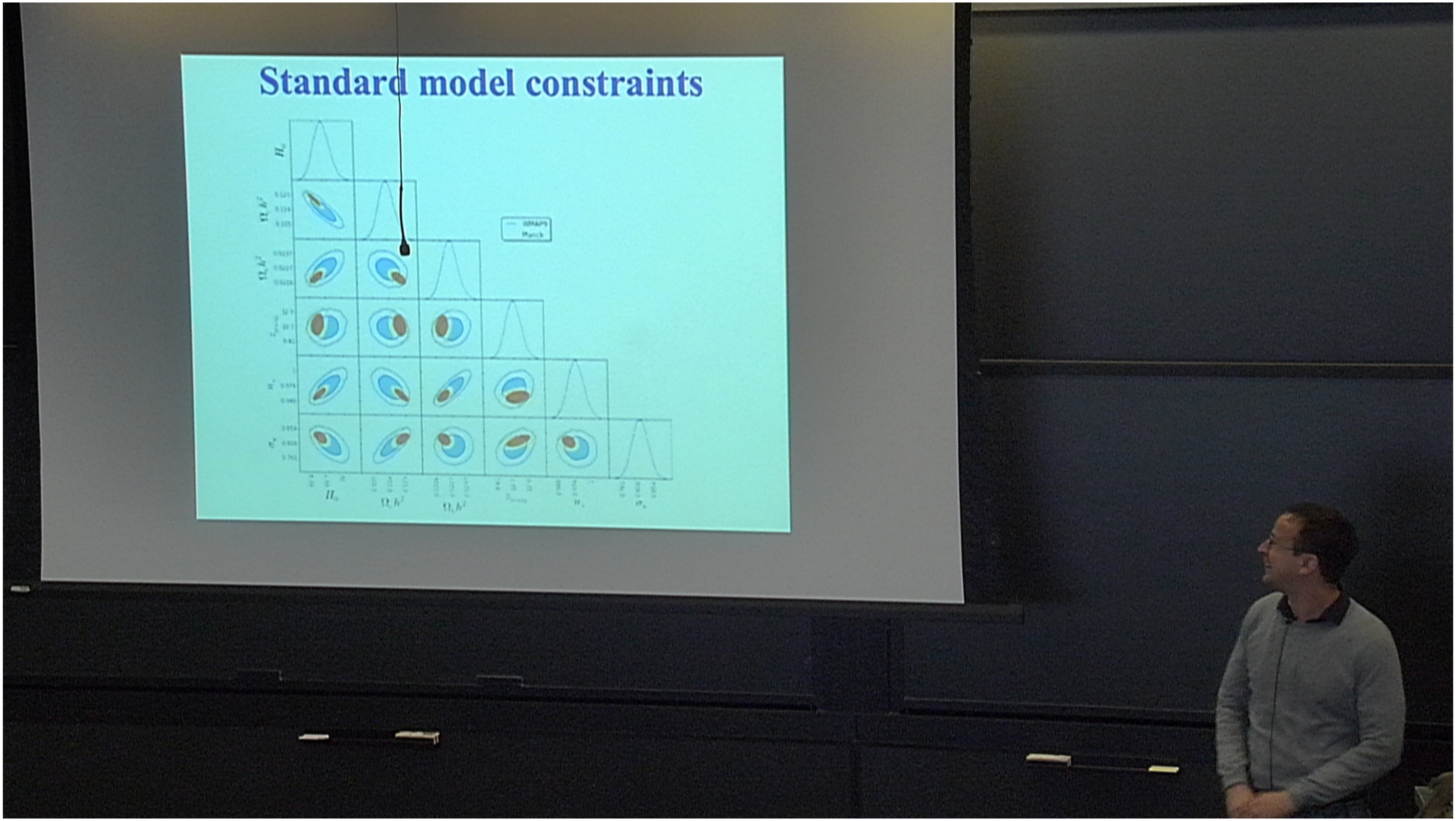
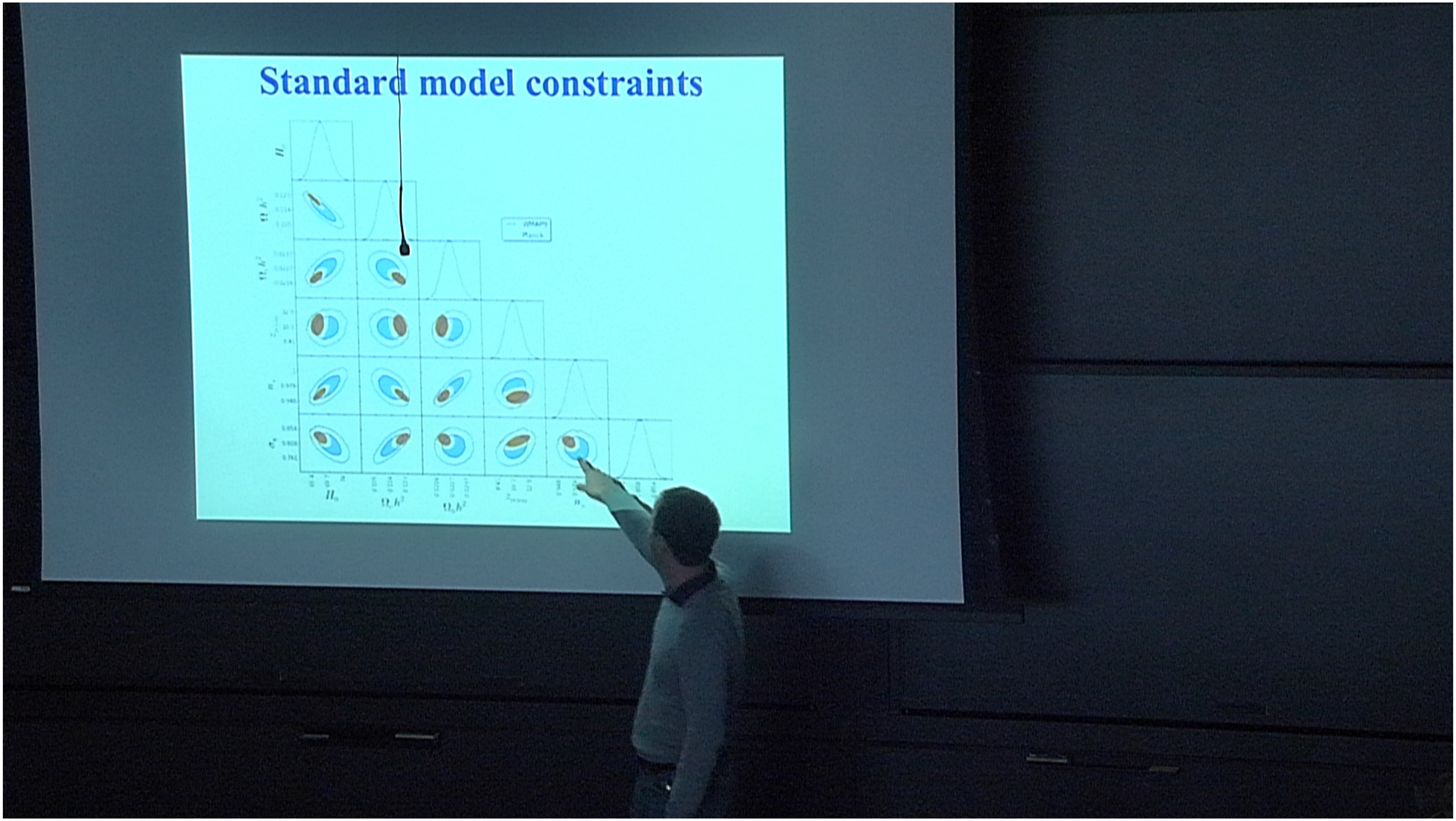

Power spectrum
Main goal of Planck: test prediction of the standard model
WMAP9 LCDM
WMAP9
68% confidence prediction of
LCDM given WMAP9 data
0
500
1000
1500
2000
2500


Power spectrum
Main result: Planck's measurement of the power spectrum is fully consistent with the standard model
WMAP9 LCDM
WMAP9
ACT
SPT
Planck
0
500
1000
1500
2000
2500


Standard model constraints
WMAP9
Planck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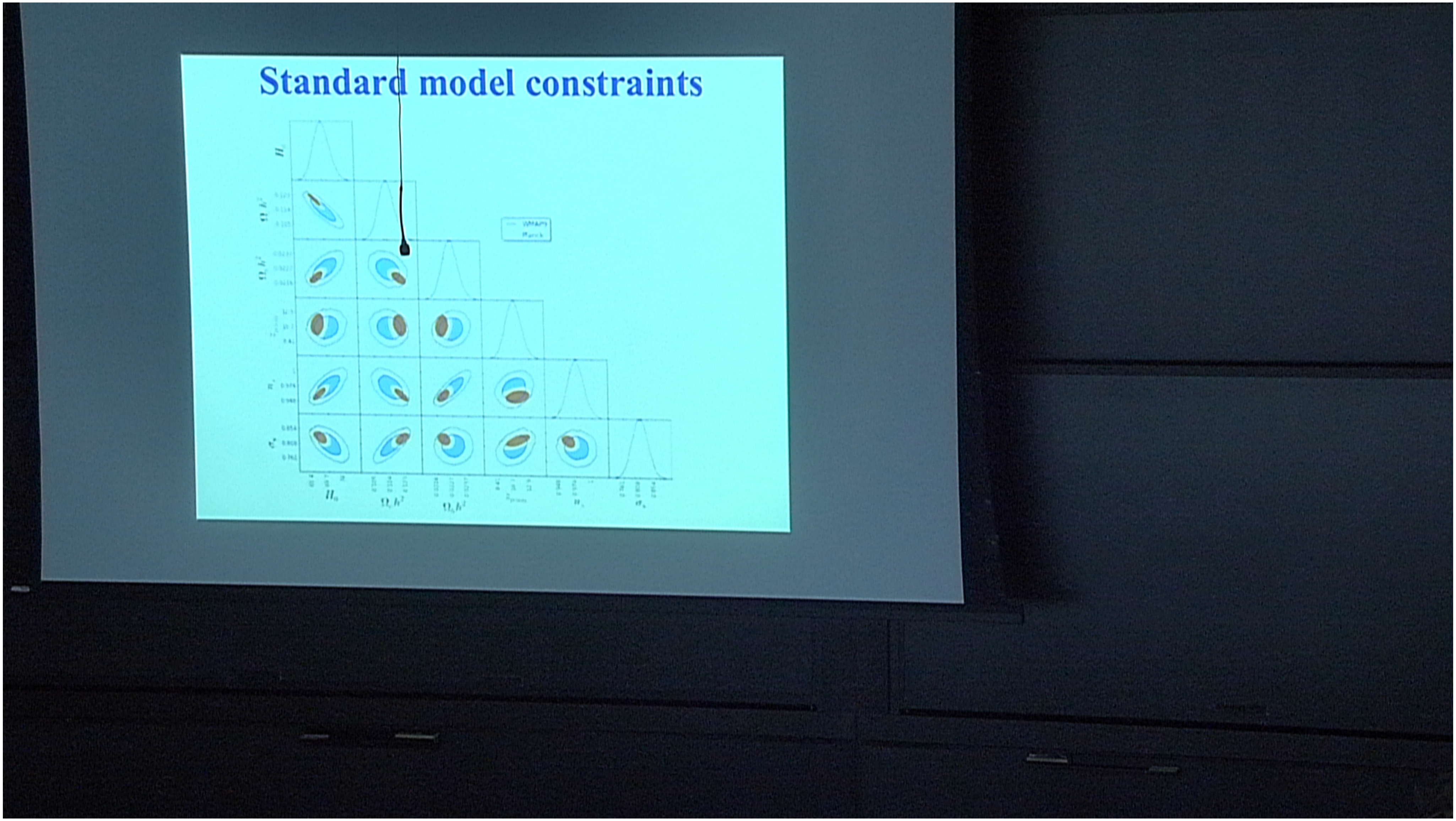
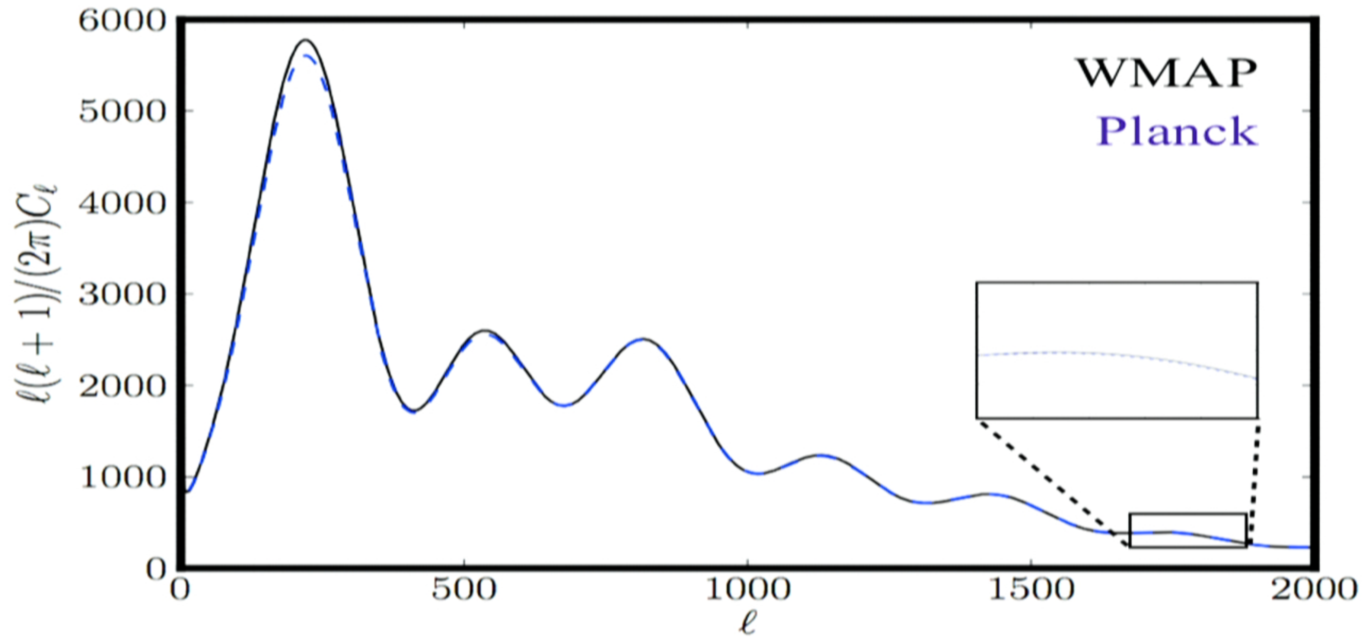
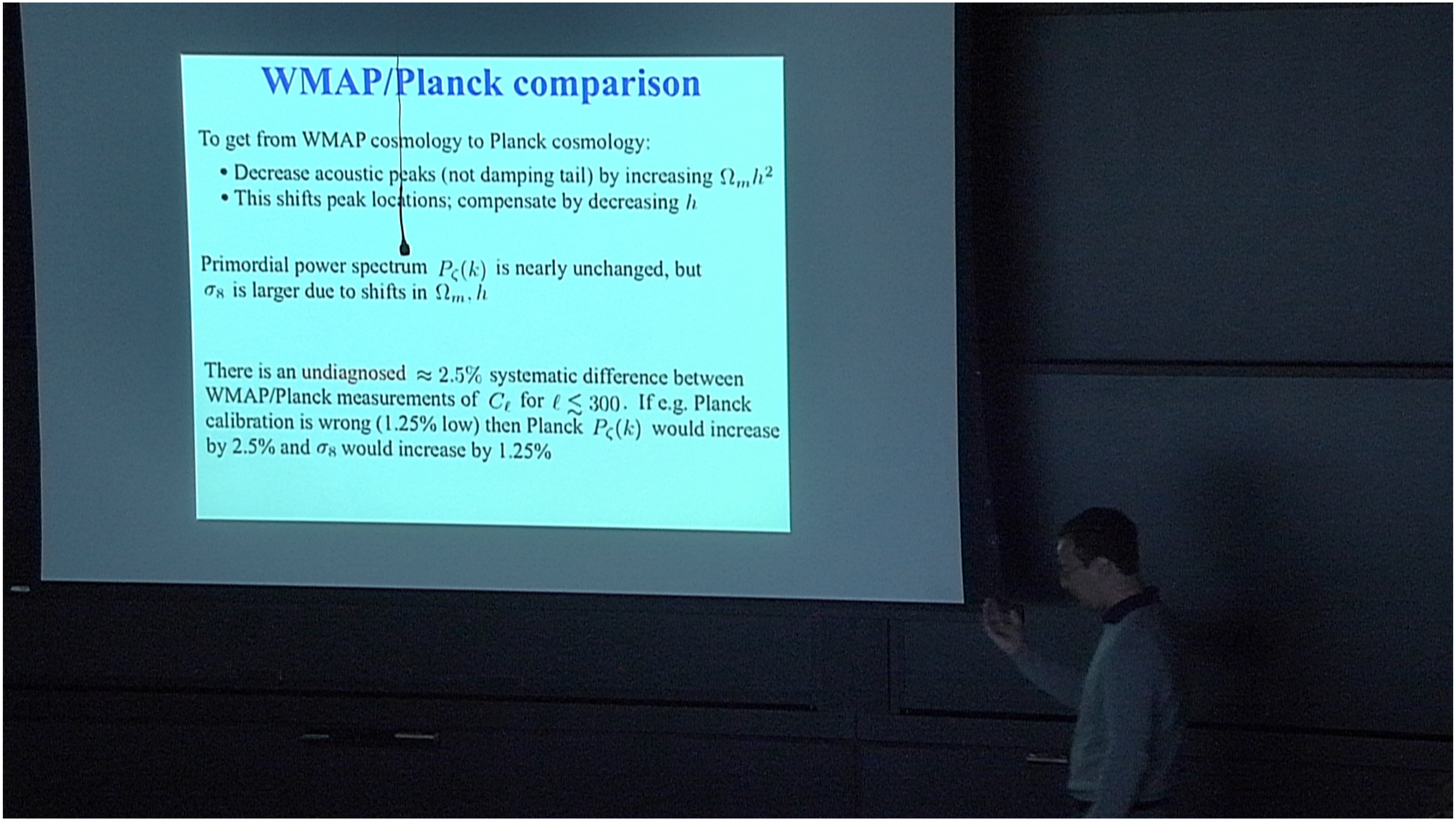
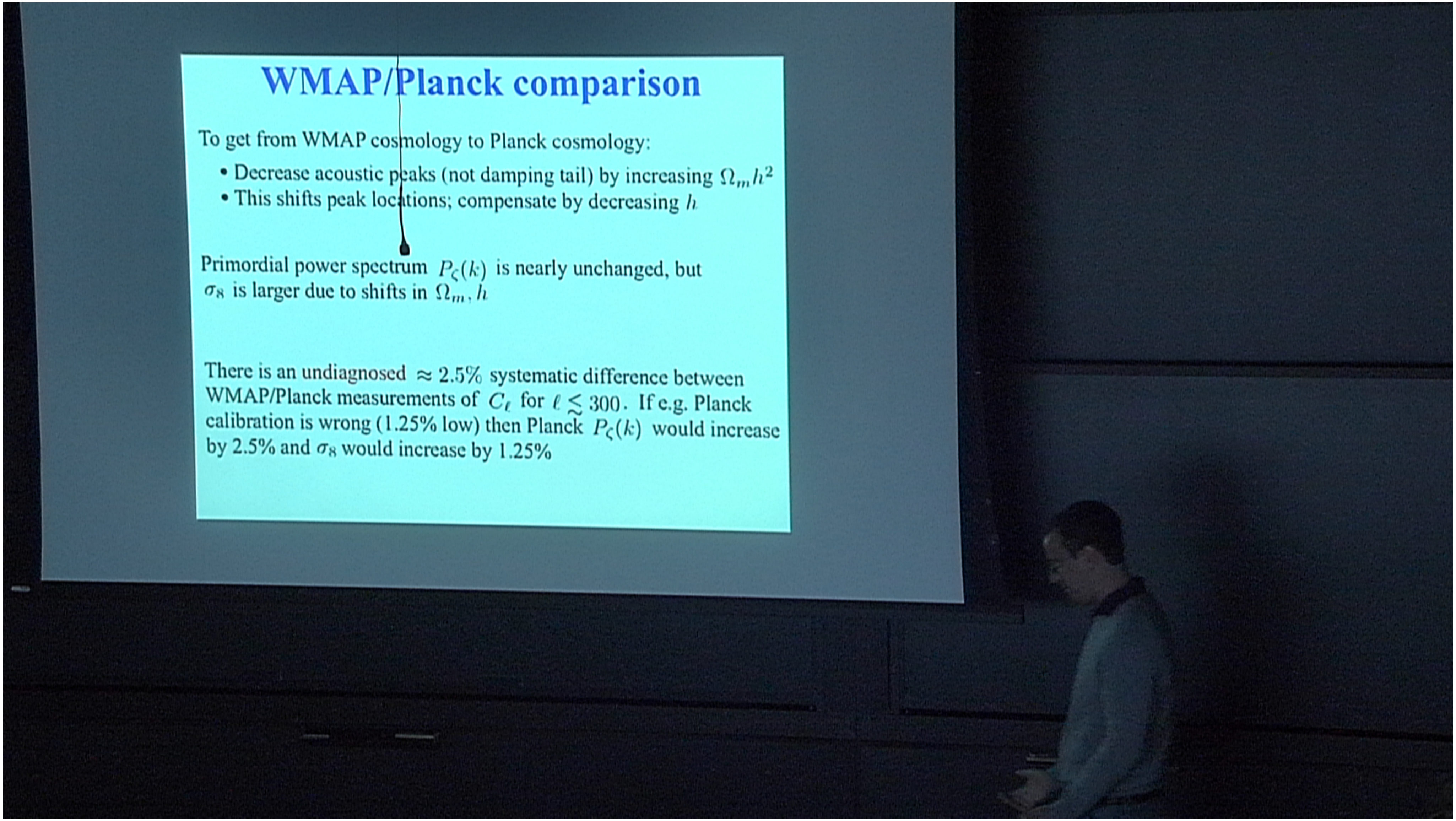

Standard model constraints

WMAP/Planck comparison

...but the same level of power in the damping tail




WMAP/Planck comparison
To get from WMAP cosmology to Planck cosmology:
• Decrease acoustic peaks (not damping tail) by increasing $\Omega_m h^2$
• This shifts peak locations; compensate by decreasing h
Primordial power spectrum $P_\zeta(k)$ is nearly unchanged, but σ_8 is larger due to shifts in Ω_m, h
There is an undiagnosed $\approx 2.5\%$ systematic difference between WMAP/Planck measurements of C_ℓ for $\ell \lesssim 300$. If e.g. Planck calibration is wrong (1.25% low) then Planck $P_\zeta(k)$ would increase by 2.5% and σ_8 would increase by 1.25%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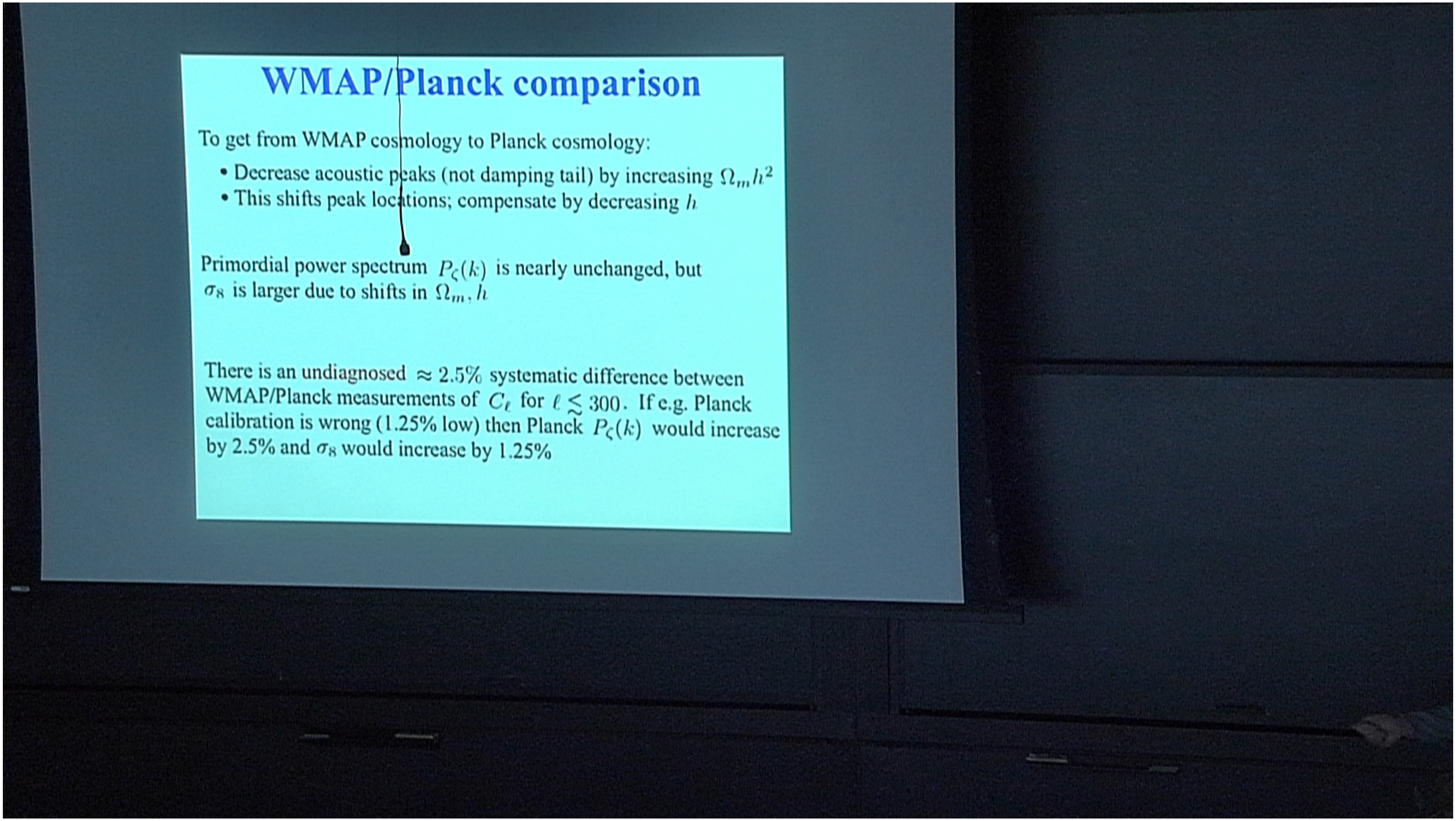
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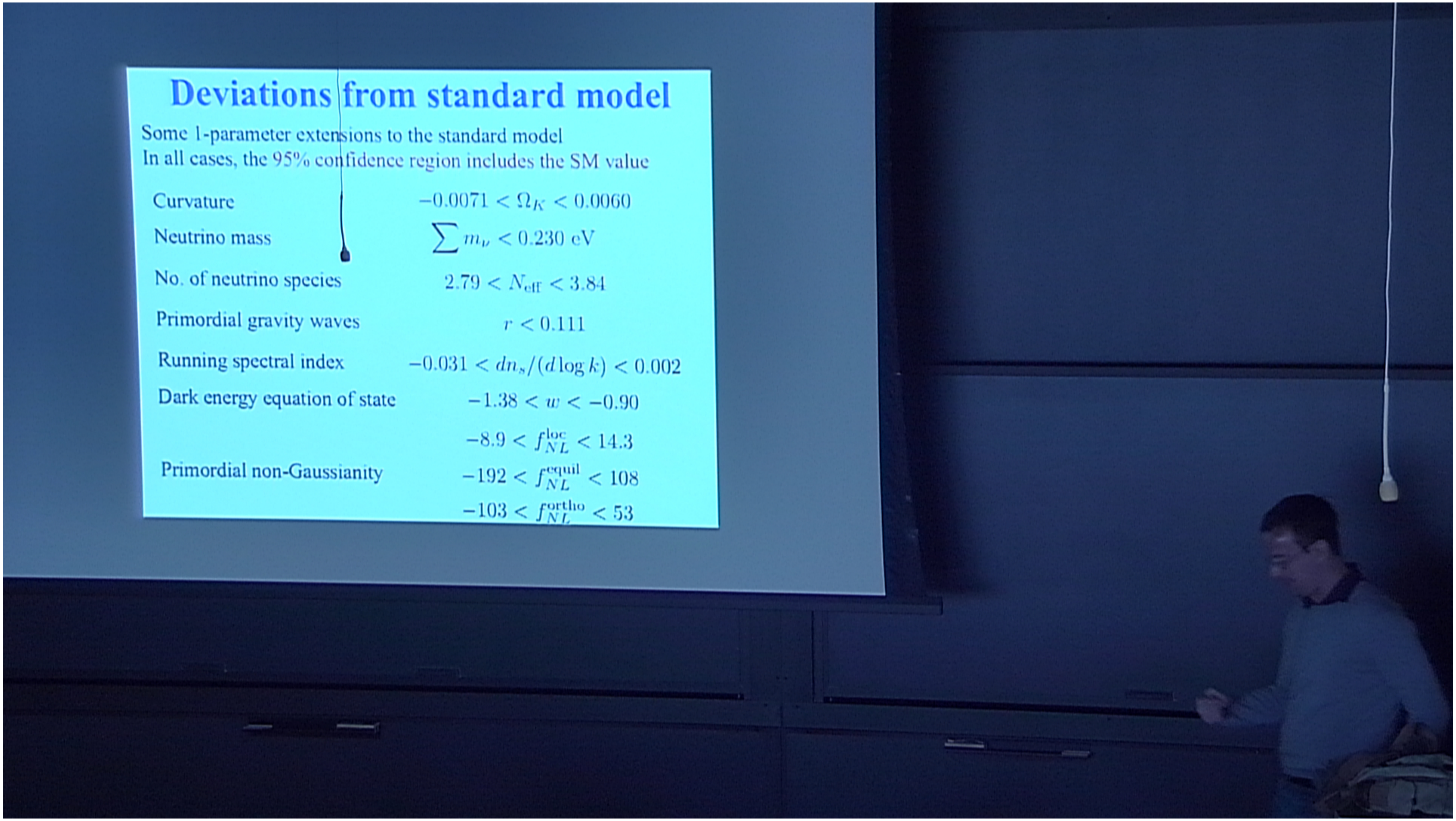
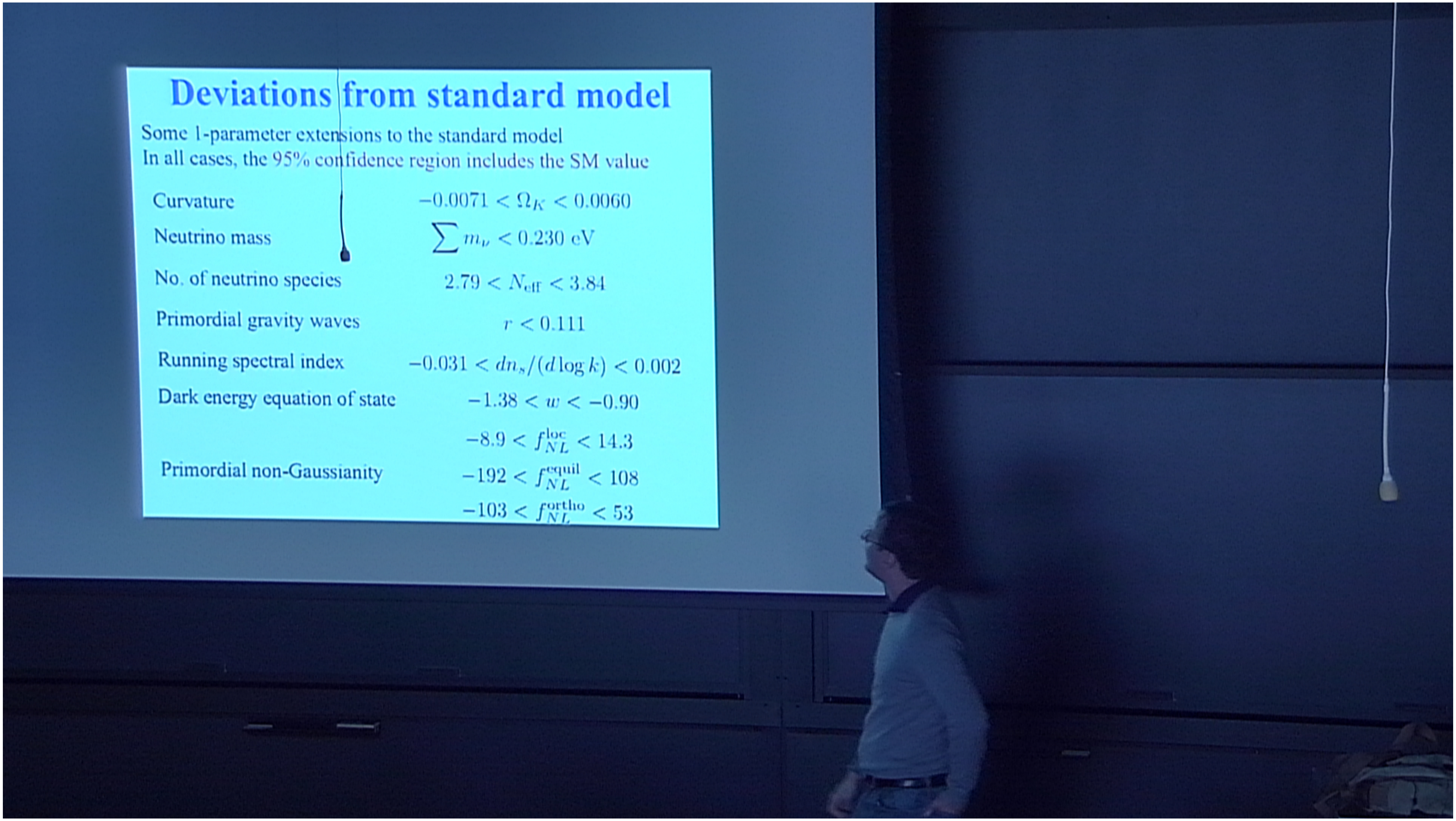

Deviations from standard model
Some 1-parameter extensions to the standard model
In all cases, the 95% confidence region includes the SM value
Curvature $-0.0071 < \Omega_K < 0.0060$
Neutrino mass $\sum m_\nu < 0.230$ eV
No. of neutrino species $2.79 < N_{\rm eff} < 3.84$
Primordial gravity waves $r < 0.111$
Running spectral index $-0.031 < dn_s/(d\log k) < 0.002$
Dark energy equation of state $-1.38 < w < -0.90$
$-8.9 < f_{NL}^{\rm loc} < 14.3$
Primordial non-Gaussianity $-192 < f_{NL}^{\rm equil} < 108$
$-103 < f_{NL}^{\rm ortho} < 53$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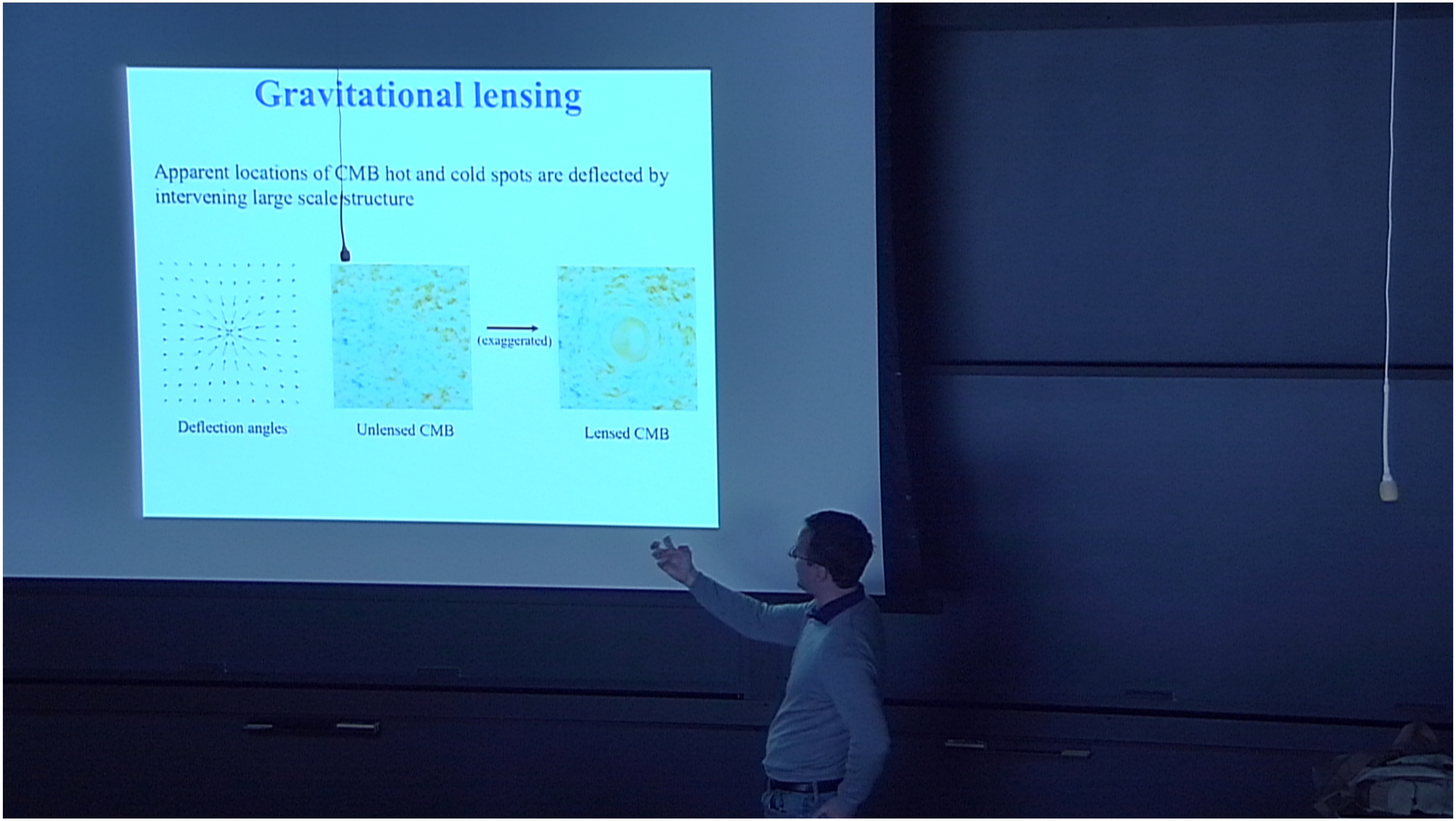
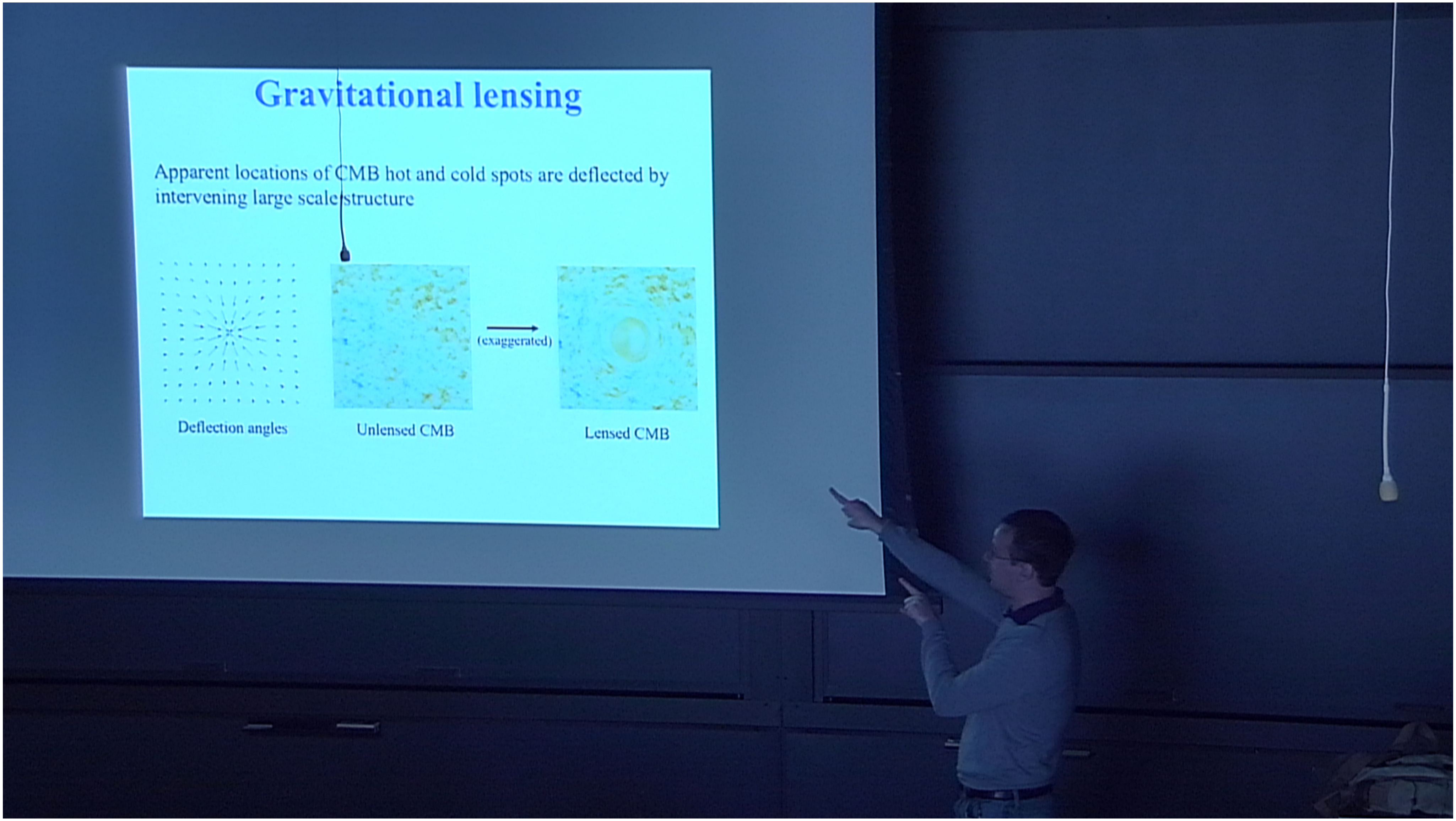

Gravitational lensing
Apparent locations of CMB hot and cold spots are deflected by intervening large scale structure
(exaggerated)
Deflection angles
Unlensed CMB
Lensed CMB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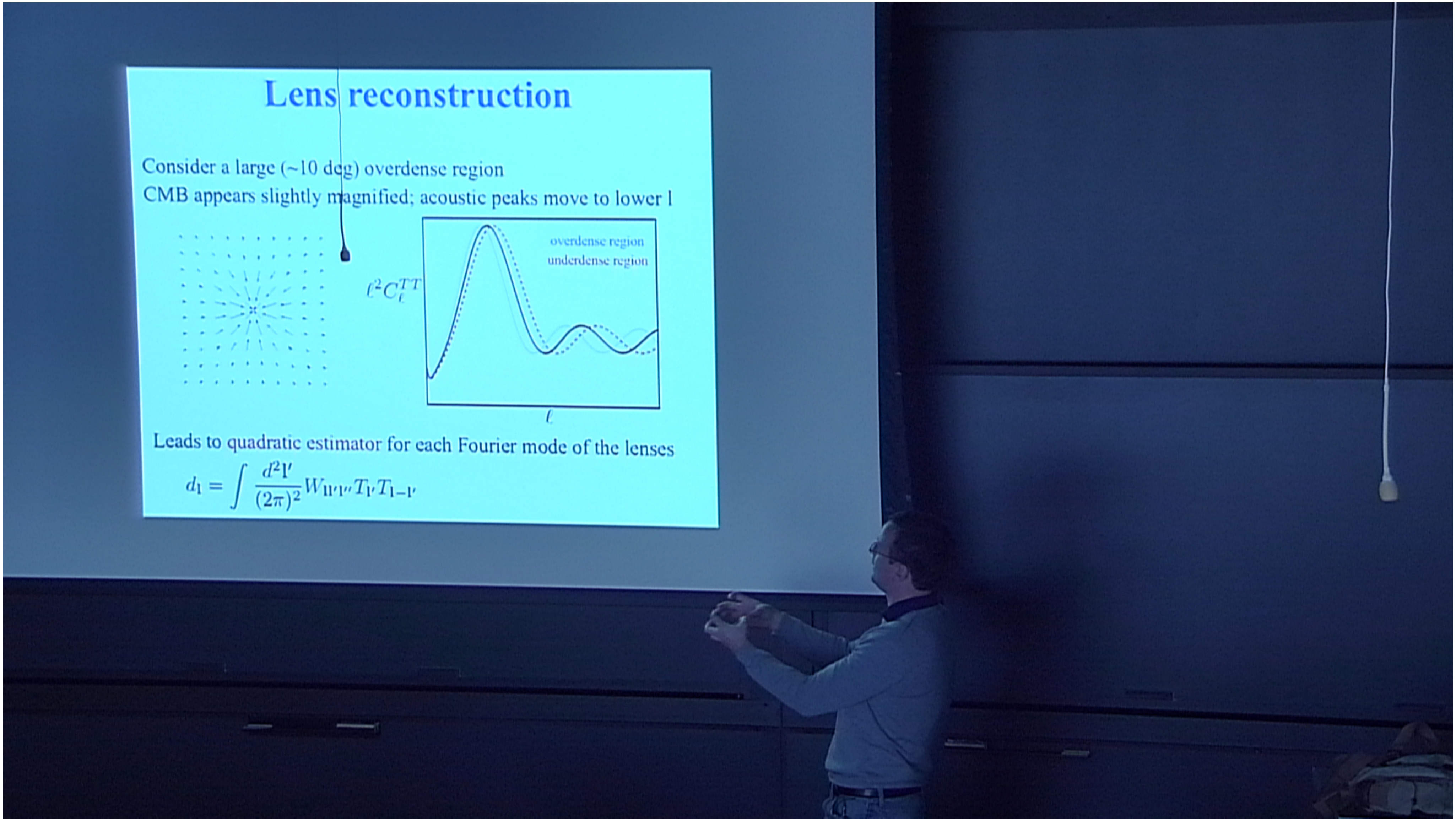
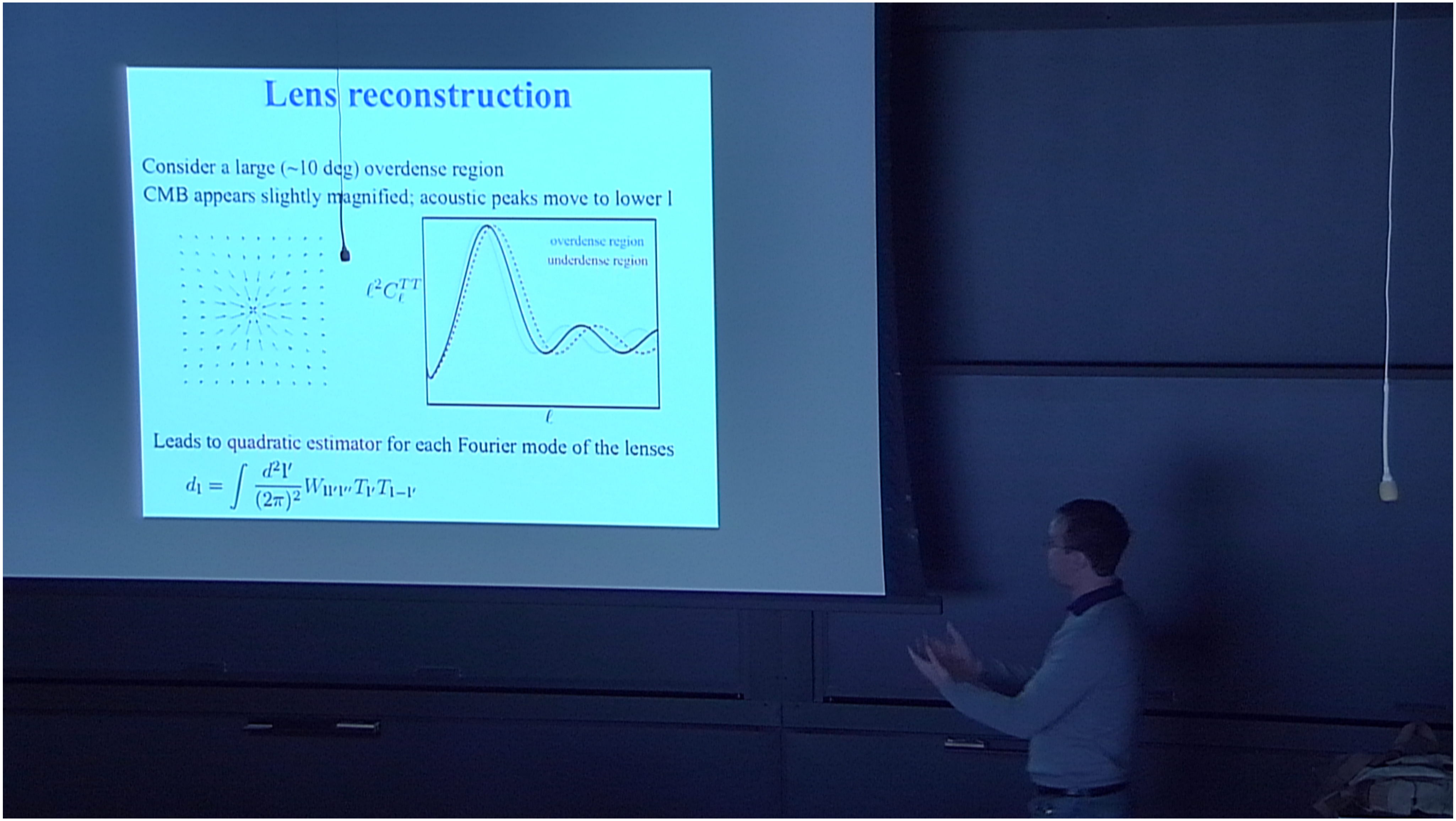

Lens reconstruction
Consider a large (~10 deg) overdense region
CMB appears slightly magnified; acoustic peaks move to lower l
overdense region
underdense region
$\ell^2 C_\ell^{TT}$
ℓ
Leads to quadratic estimator for each Fourier mode of the lenses
$d_{\mathbf{l}} = \int \frac{d^2\mathbf{l}'}{(2\pi)^2} W_{\mathbf{l}\mathbf{l}'\mathbf{l}''} T_{\mathbf{l}'} T_{\mathbf{l}-\mathbf{l}'}$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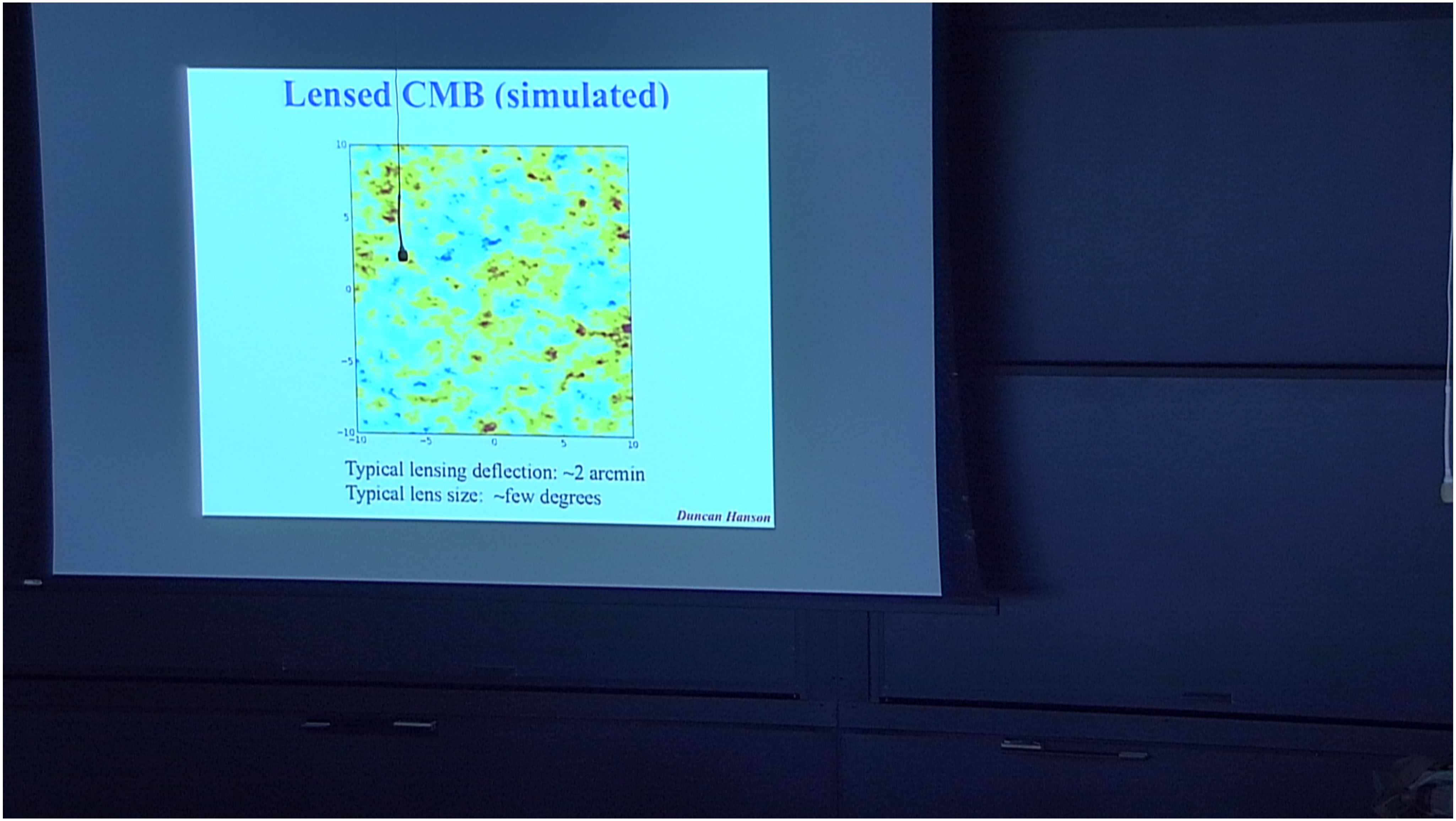
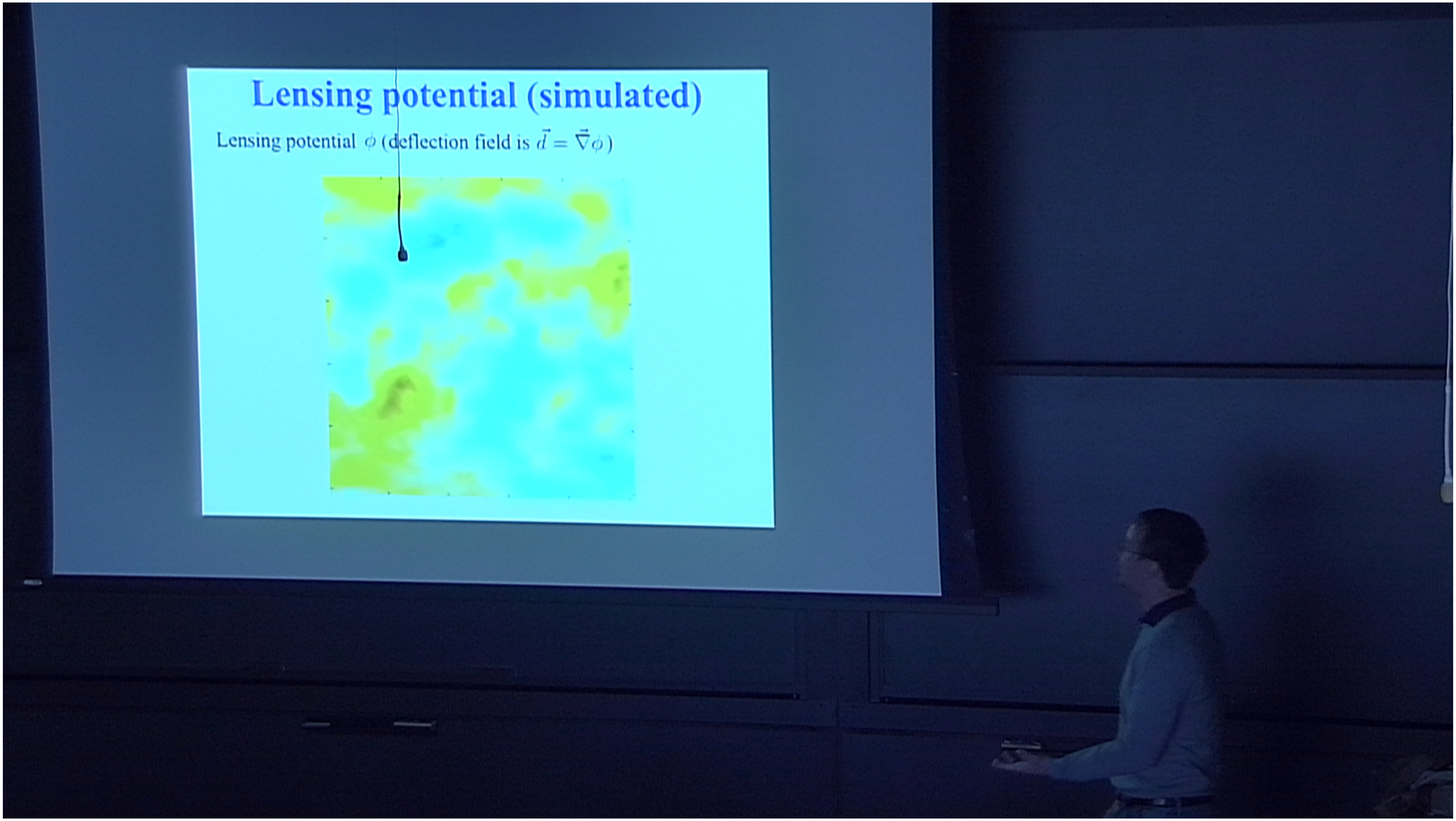

Lensed CMB (simulated)
Typical lensing deflection: ~2 arcmin
Typical lens size: ~few degrees
Duncan Hanson


Lensing potential (simulated)
Lensing potential ϕ (deflection field is $\vec{d} = \vec{\nabla}\phi$)

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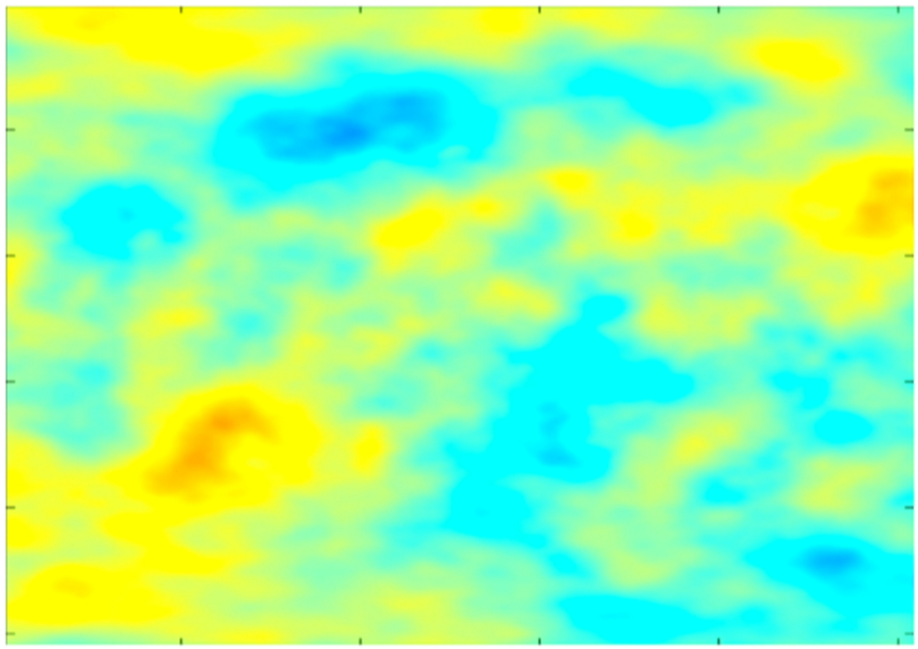
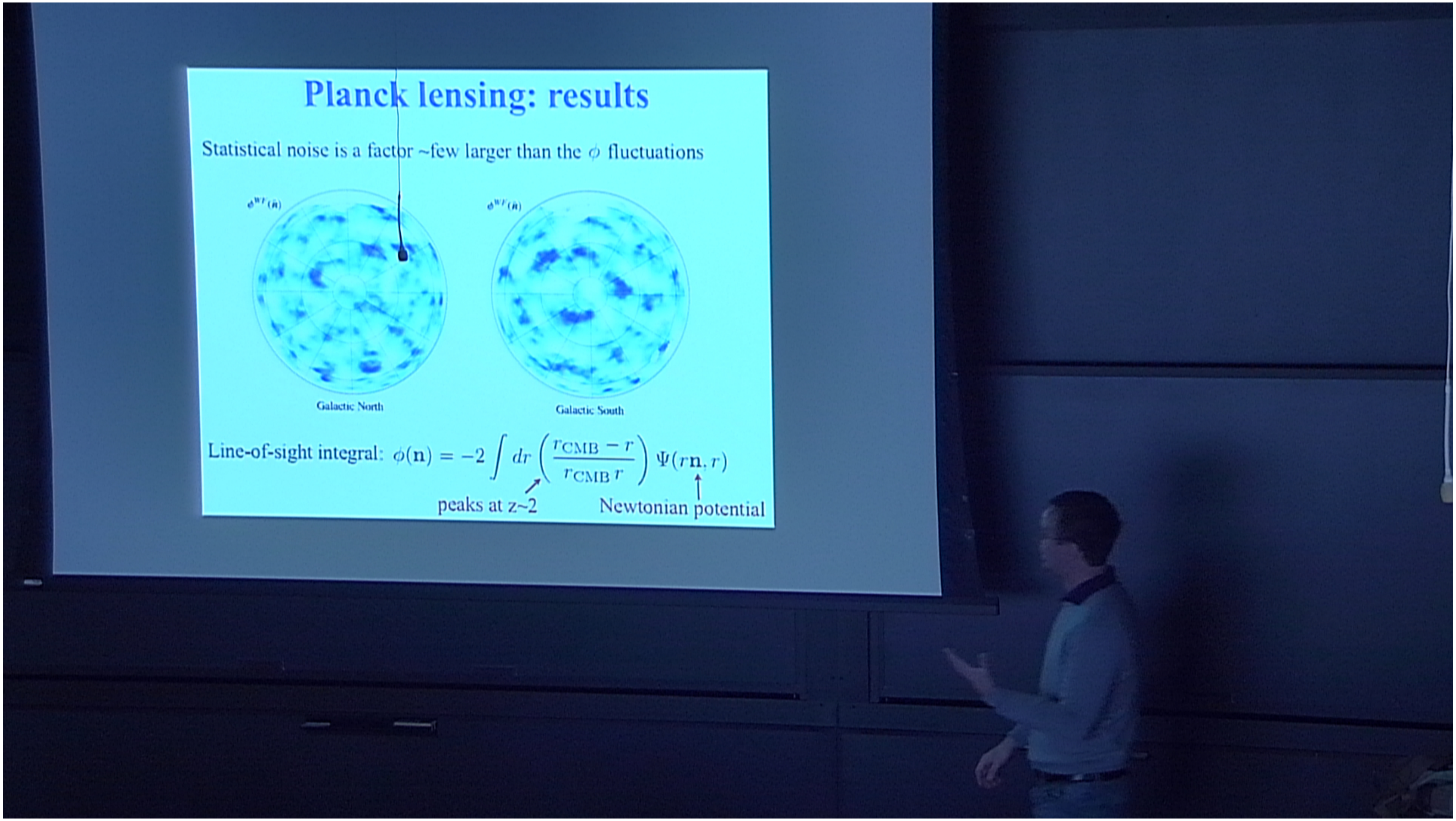
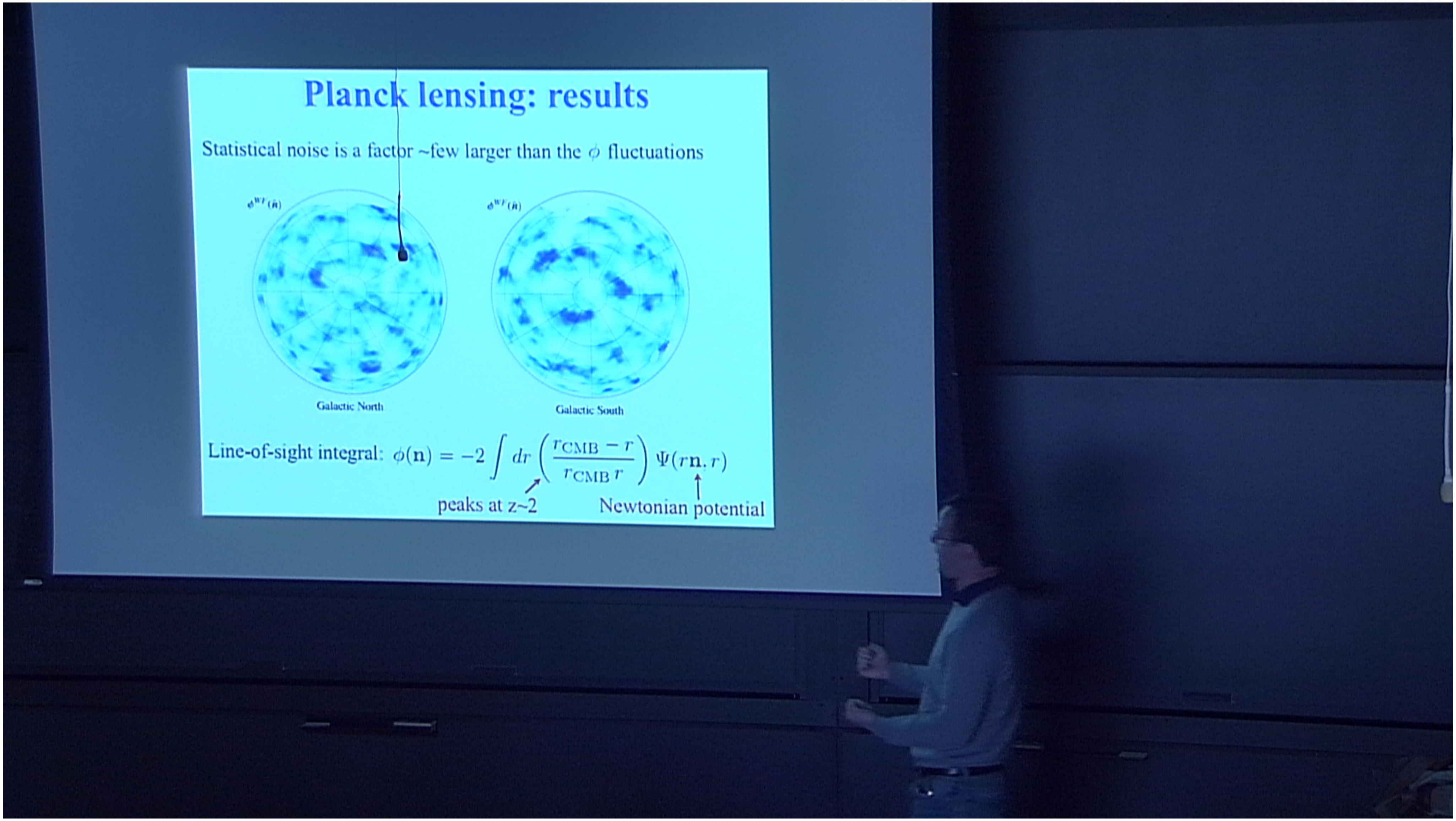




Planck lensing: results
Statistical noise is a factor ~few larger than the ϕ fluctuations
Galactic North
Galactic South
Line-of-sight integral: $\phi(\mathbf{n}) = -2 \int dr \left(\frac{r_{\rm CMB} - r}{r_{\rm CMB}\, r} \right) \Psi(r\mathbf{n}, r)$
peaks at z~2
Newtonian potential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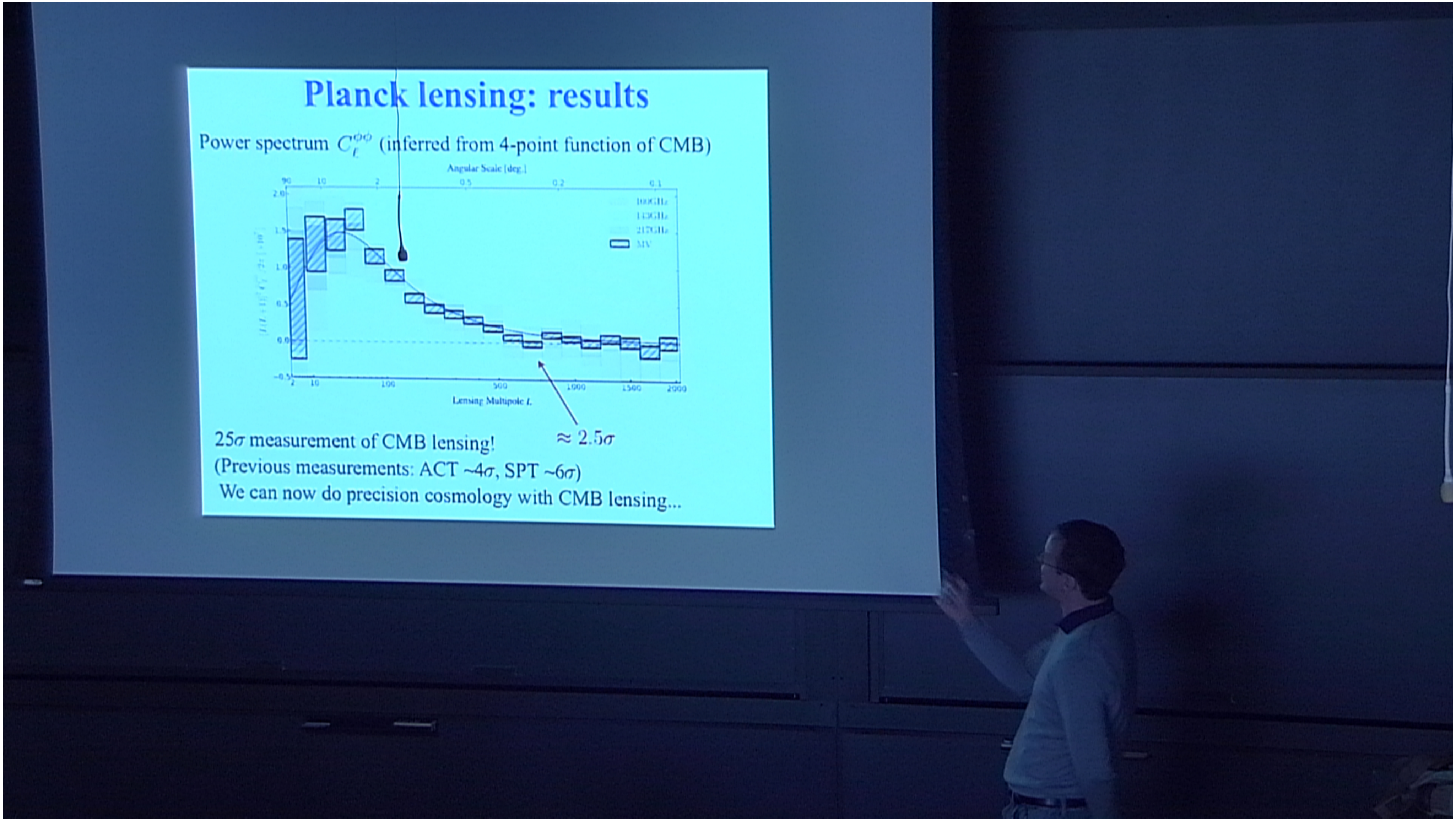
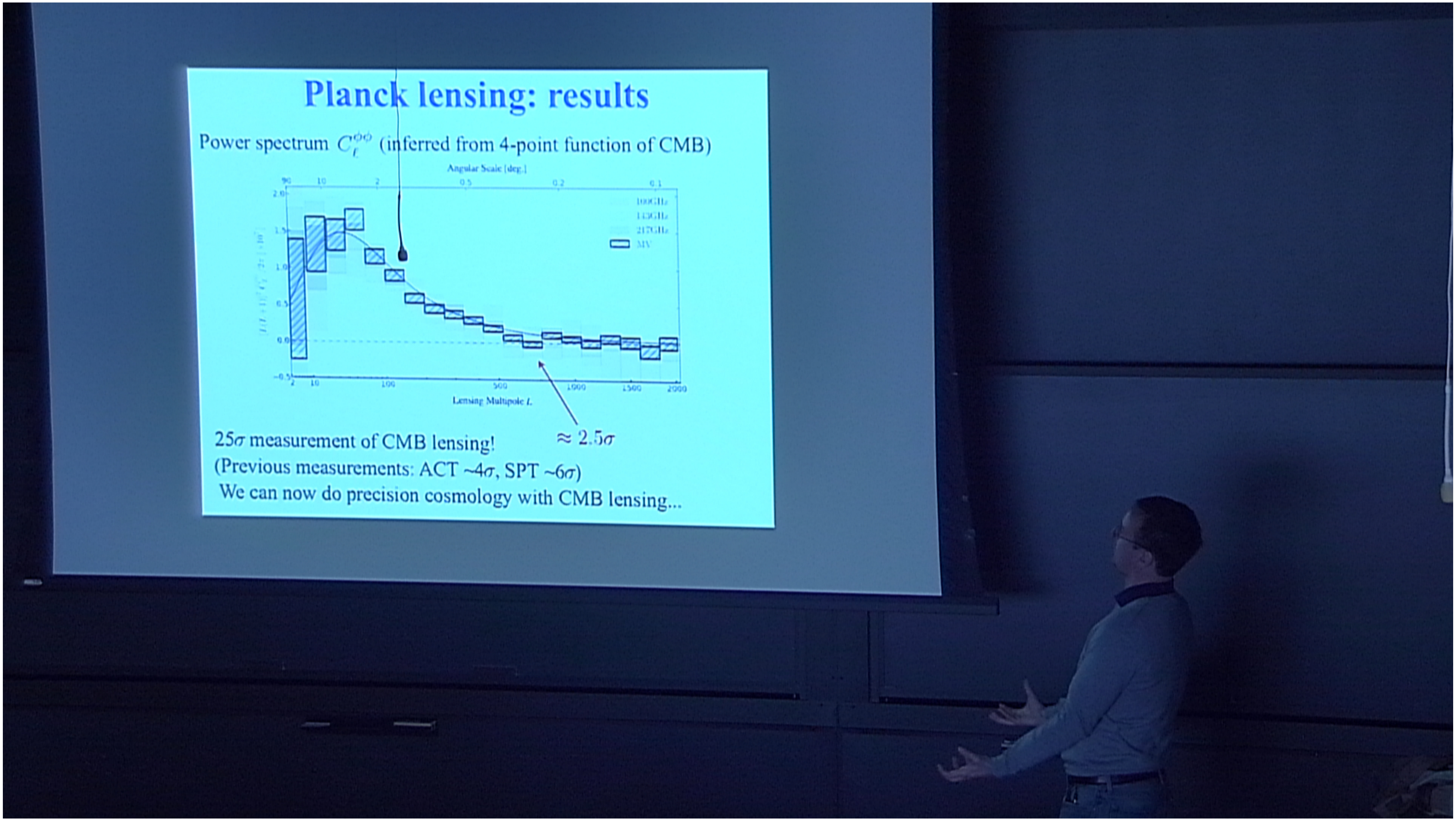

Planck lensing: results
Power spectrum $C_\ell^{\phi\phi}$ (inferred from 4-point function of CMB)
Angular Scale [deg.]
100GHz
143GHz
217GHz
MV
Lensing Multipole L
$\approx 2.5\sigma$
25σ measurement of CMB lensing!
(Previous measurements: ACT ~4σ, SPT ~6σ)
We can now do precision cosmology with CMB lensing...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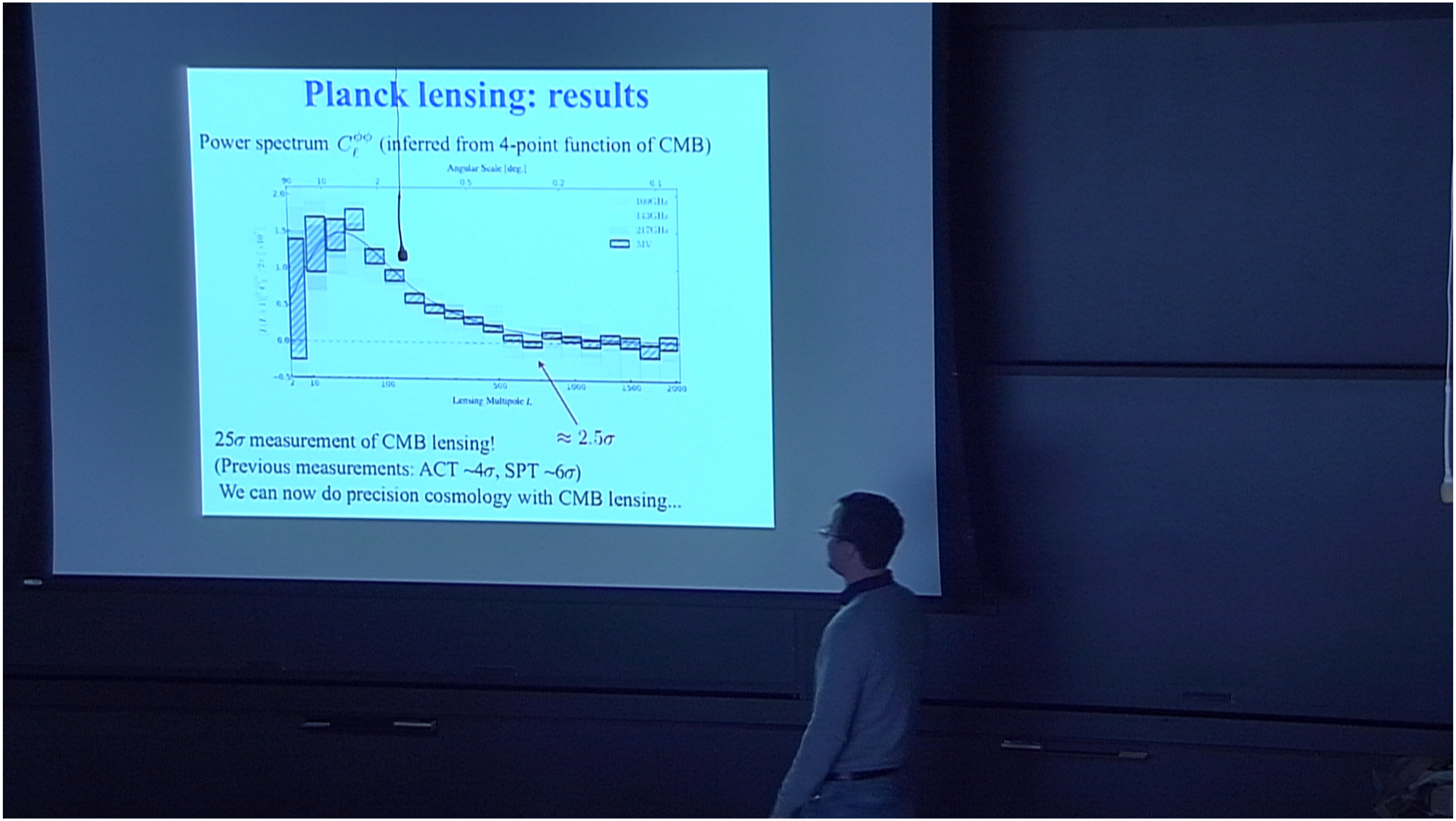
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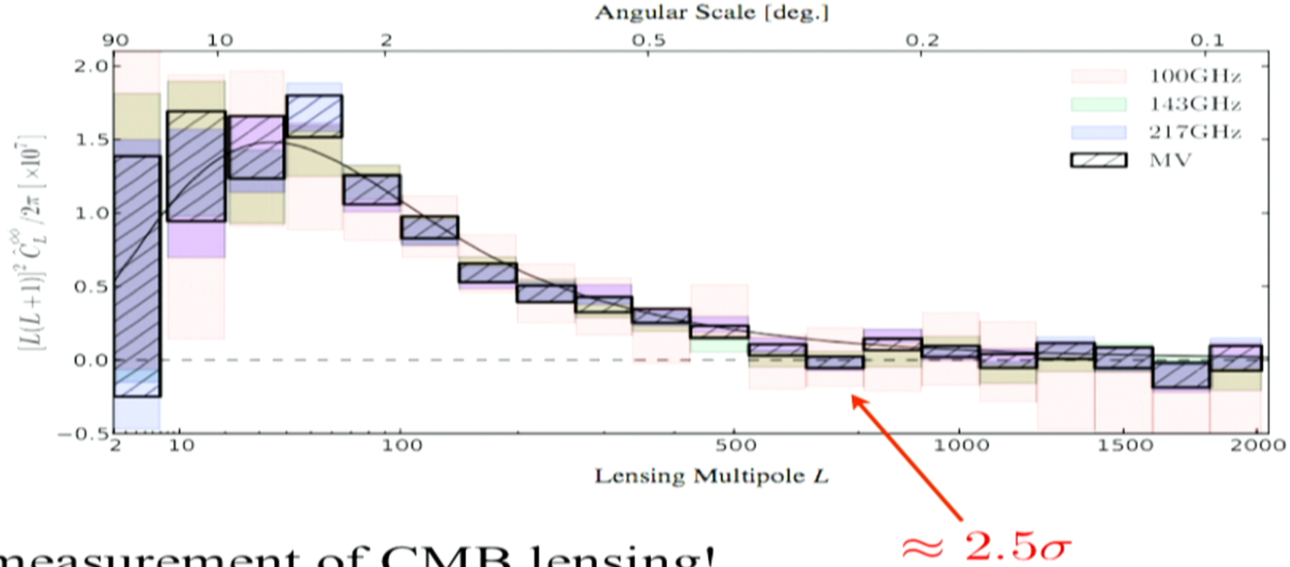

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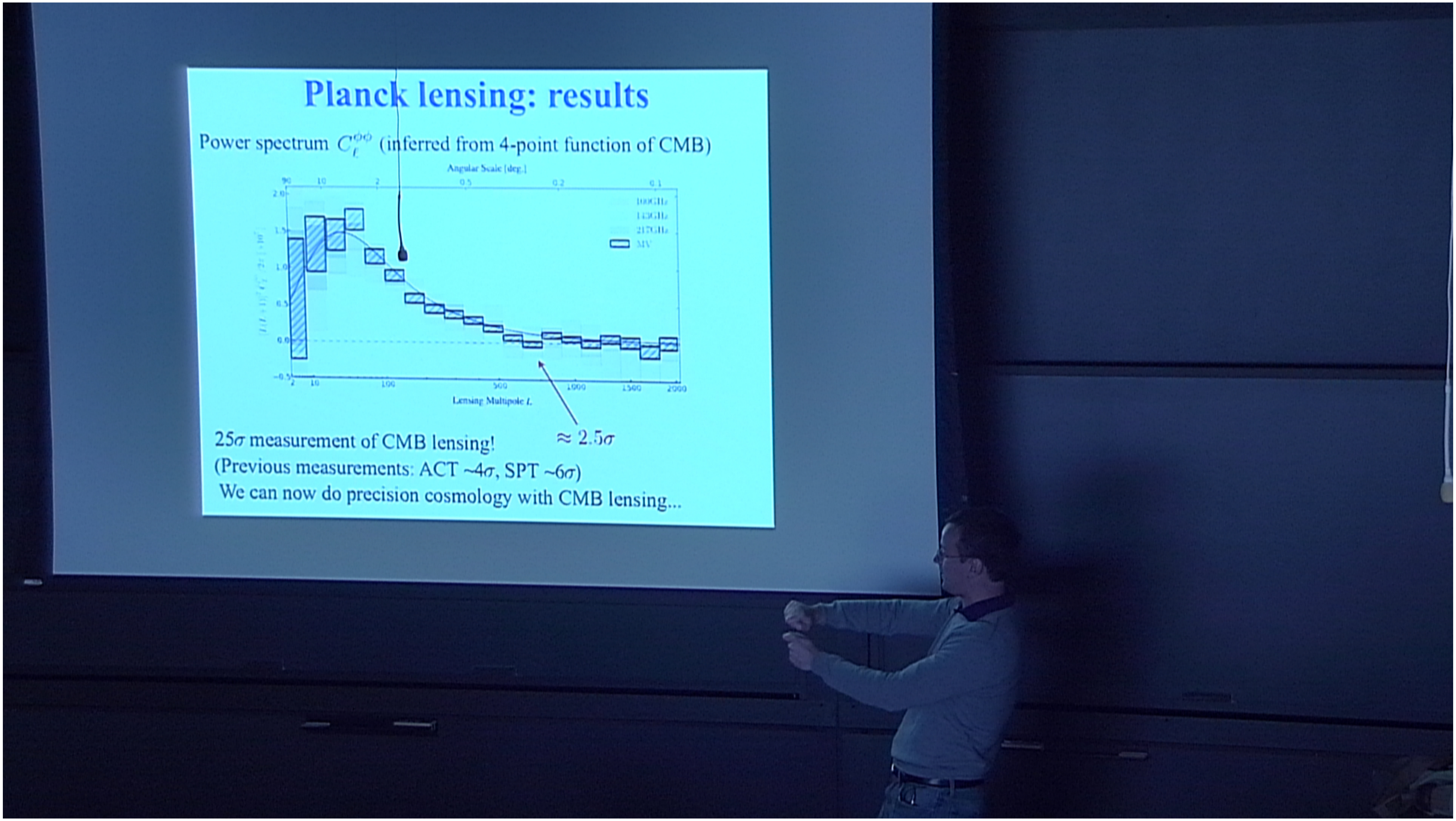
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Power spectrum $C_L^{\phi\phi}$ (inferred from 4-point function of CMB)
Angular Scale [deg.]
MV
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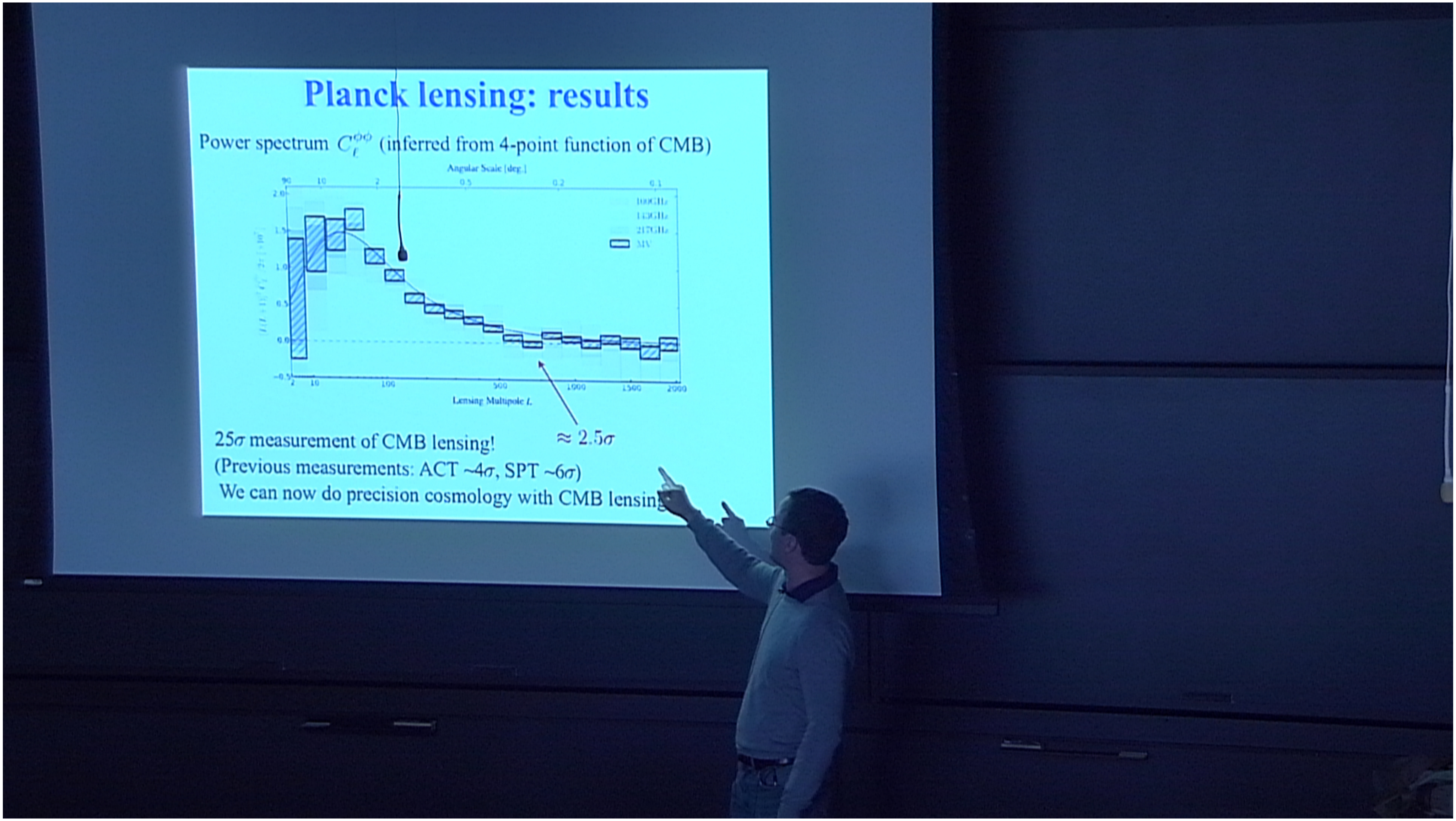
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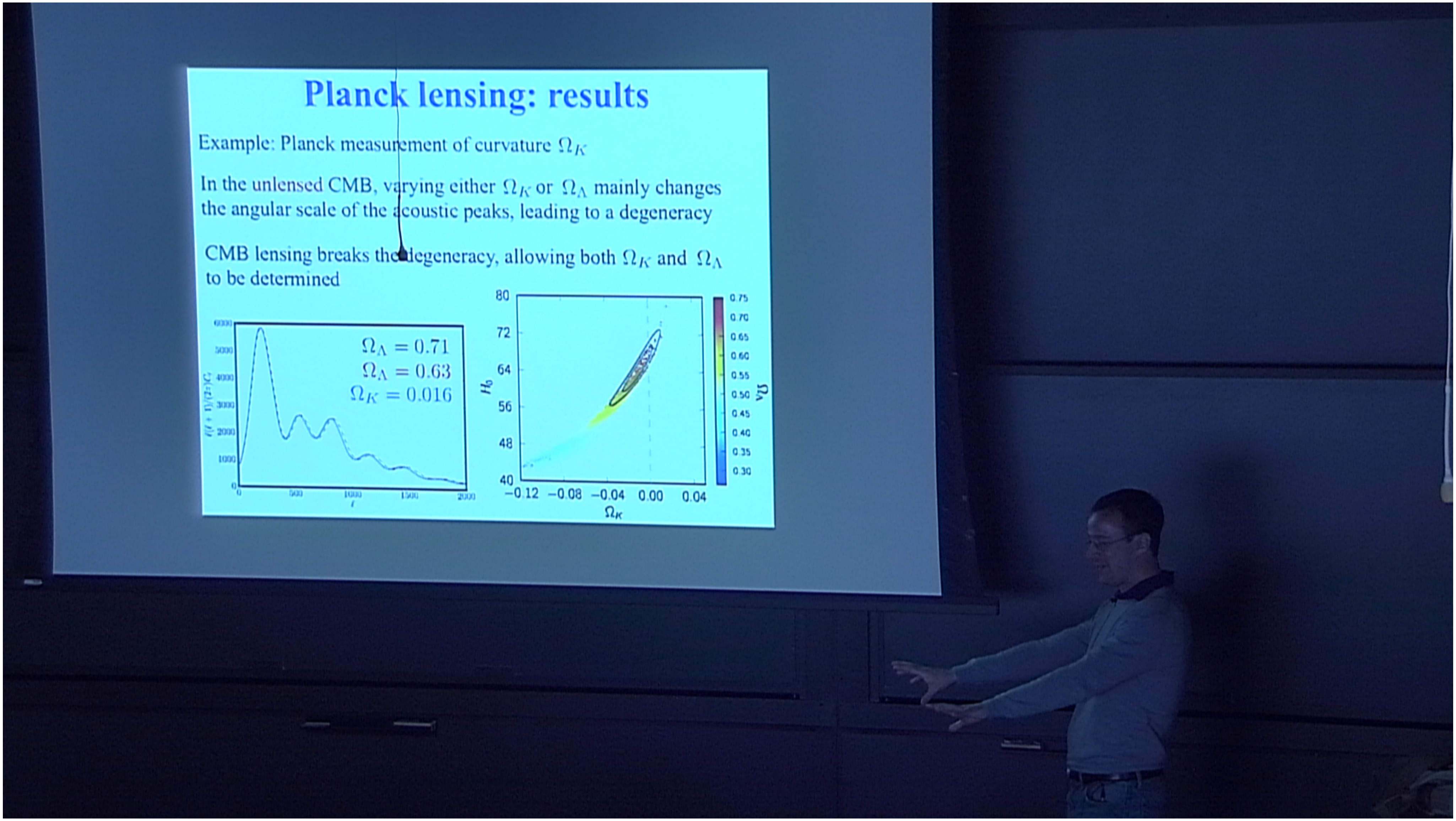
Planck lensing: results
Example: Planck measurement of curvature Ω_K
In the unlensed CMB, varying either Ω_K or Ω_Λ mainly changes the angular scale of the acoustic peaks, leading to a degeneracy
CMB lensing breaks the degeneracy, allowing both Ω_K and Ω_Λ to be determined
$\Omega_\Lambda = 0.71$
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$\Omega_K = 0.016$
H_0
Ω_K
Ω_Λ
80
72
64
56
48
40
−0.12
−0.08
−0.04
0.00
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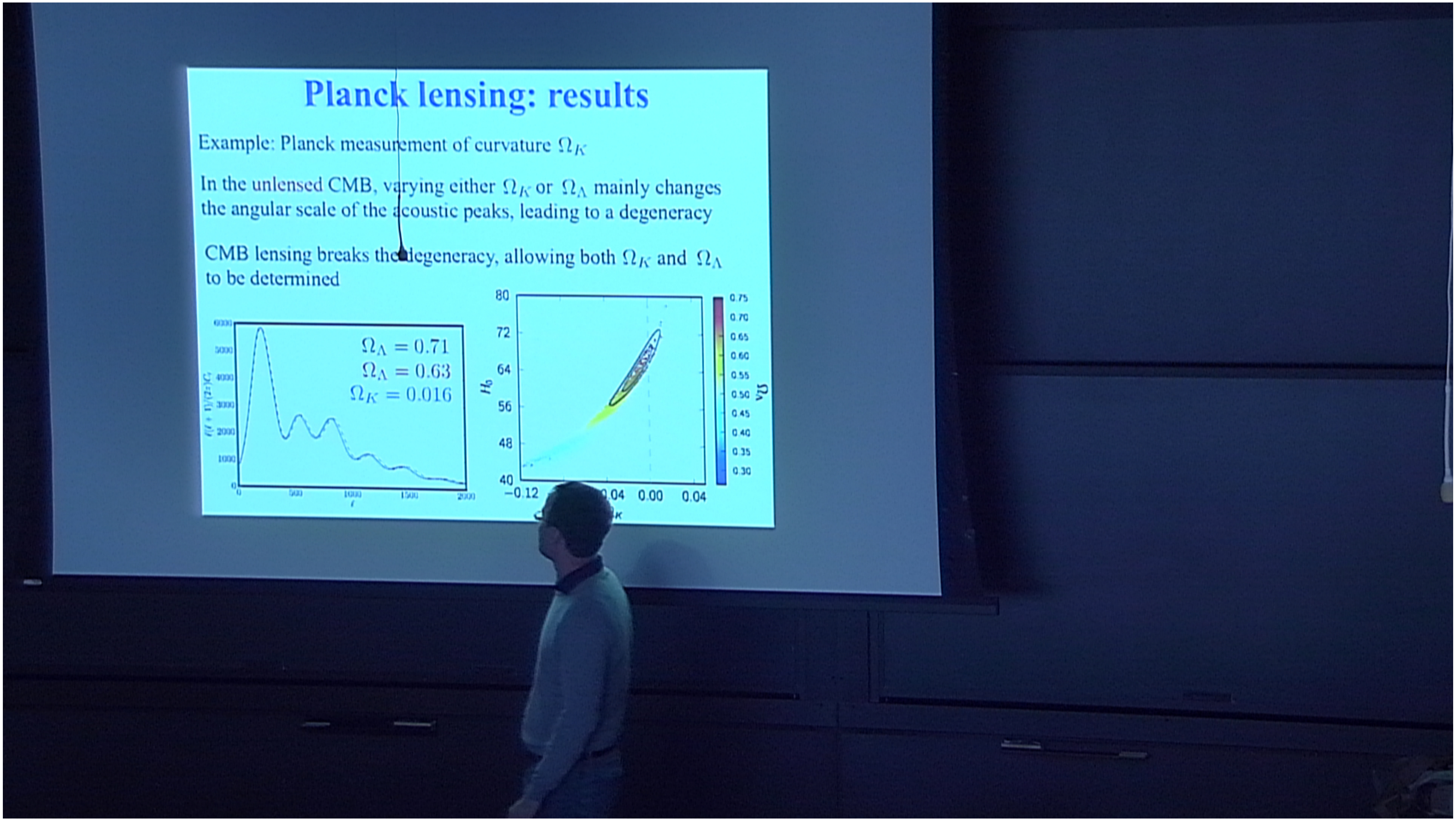
0.35
0.30



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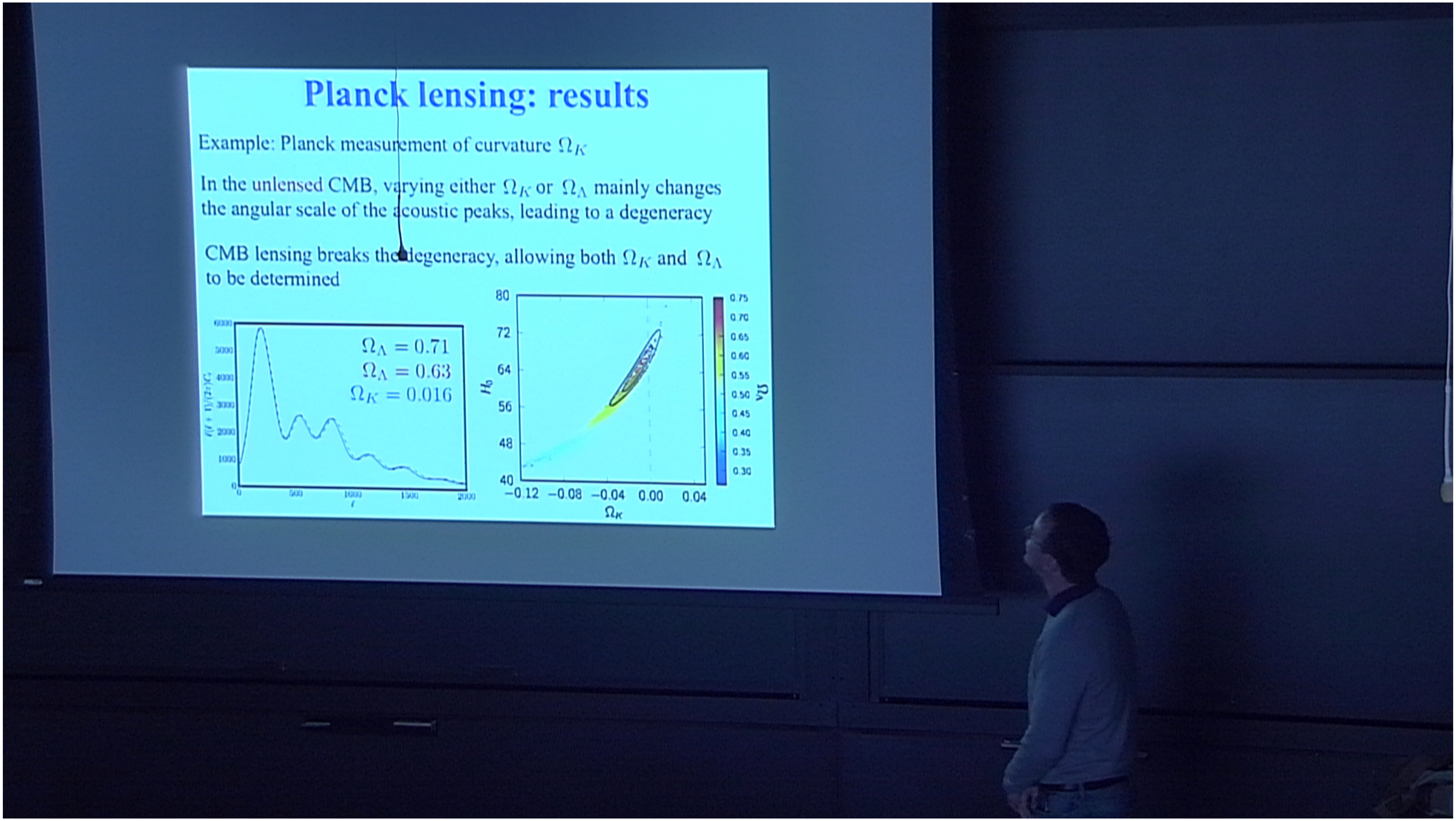
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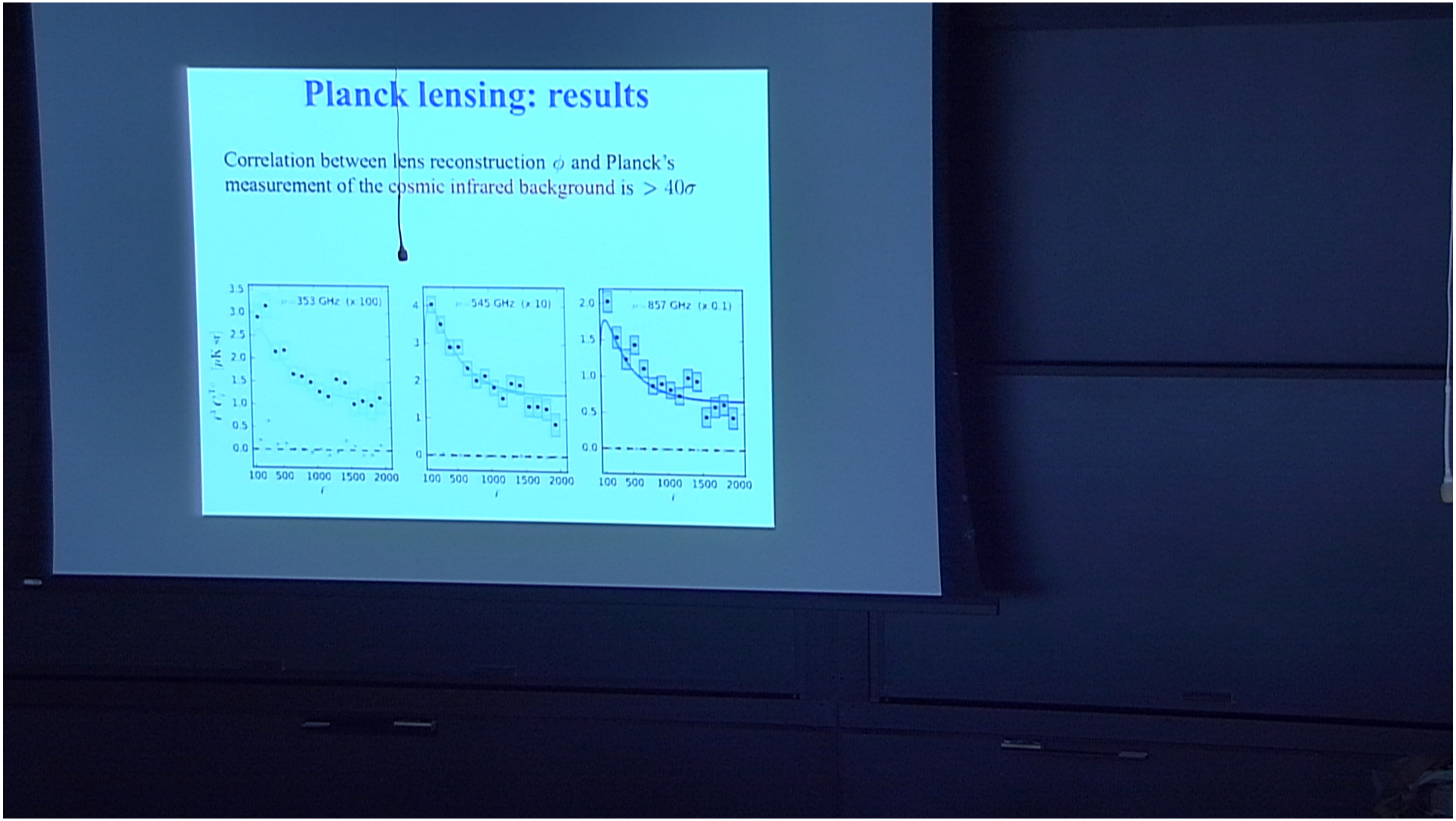
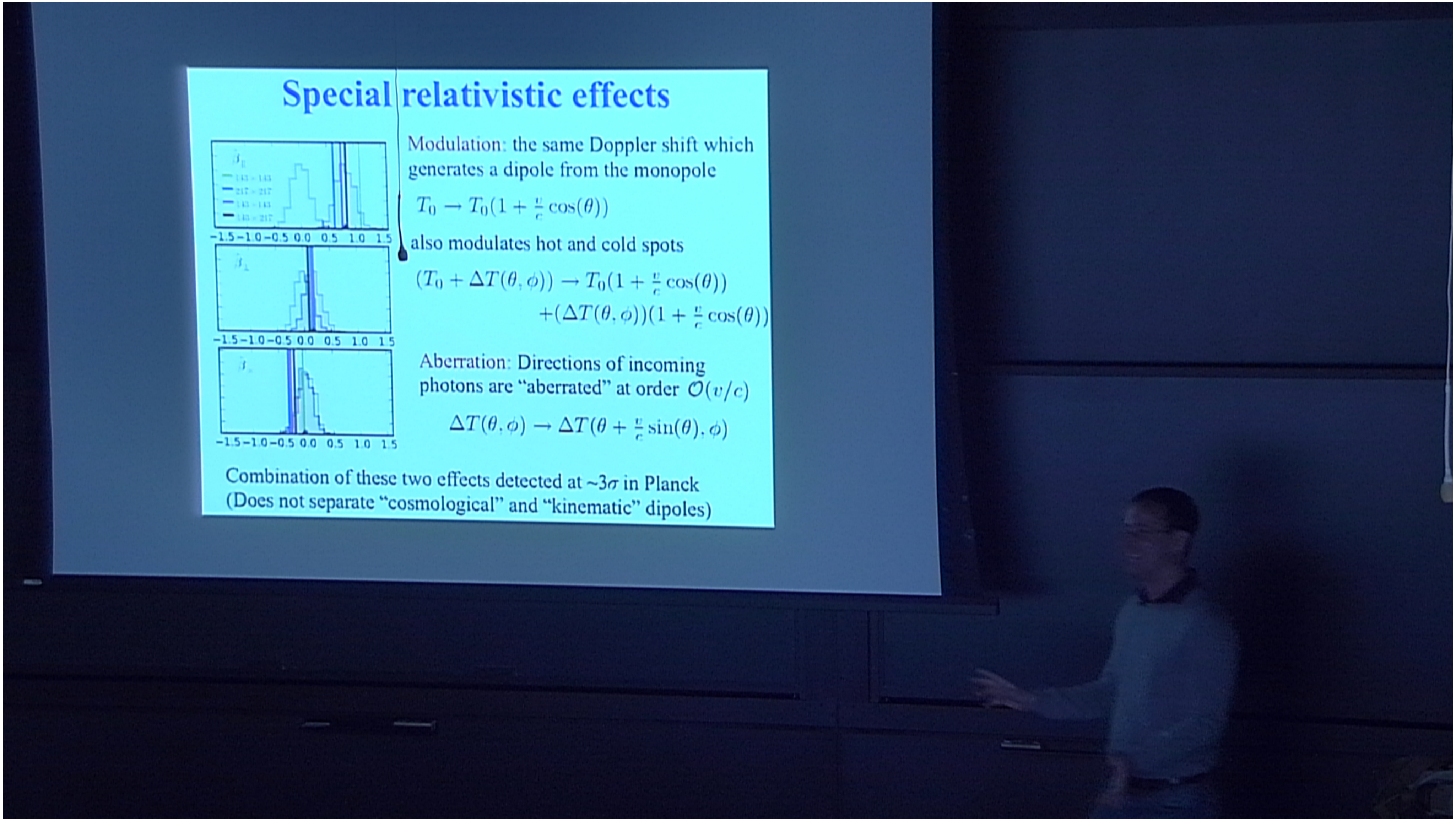
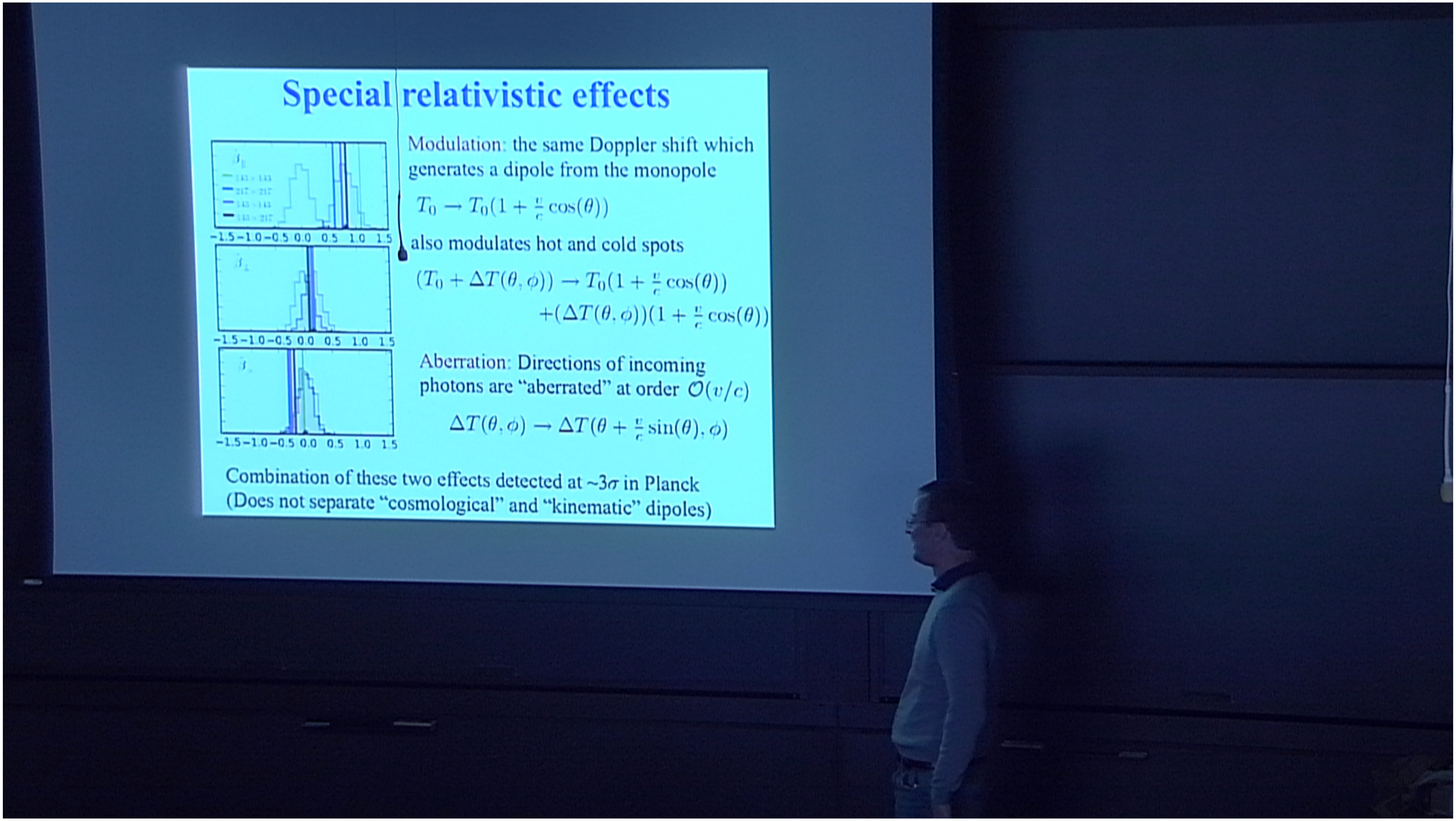

Planck lensing: results
Correlation between lens reconstruction ϕ and Planck's measurement of the cosmic infrared background is $> 40\sigma$
353 GHz (x 100)
545 GHz (x 10)
857 GHz (x 0.1)
100 500 1000 1500 2000


Special relativistic effects
Modulation: the same Doppler shift which generates a dipole from the monopole
$T_0 \rightarrow T_0(1 + \frac{v}{c}\cos(\theta))$
also modulates hot and cold spots
$(T_0 + \Delta T(\theta, \phi)) \rightarrow T_0(1 + \frac{v}{c}\cos(\theta)) + (\Delta T(\theta, \phi))(1 + \frac{v}{c}\cos(\theta))$
Aberration: Directions of incoming photons are "aberrated" at order $\mathcal{O}(v/c)$
$\Delta T(\theta, \phi) \rightarrow \Delta T(\theta + \frac{v}{c}\sin(\theta), \phi)$
Combination of these two effects detected at ~3σ in Planck
(Does not separate "cosmological" and "kinematic" dipoles)
-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5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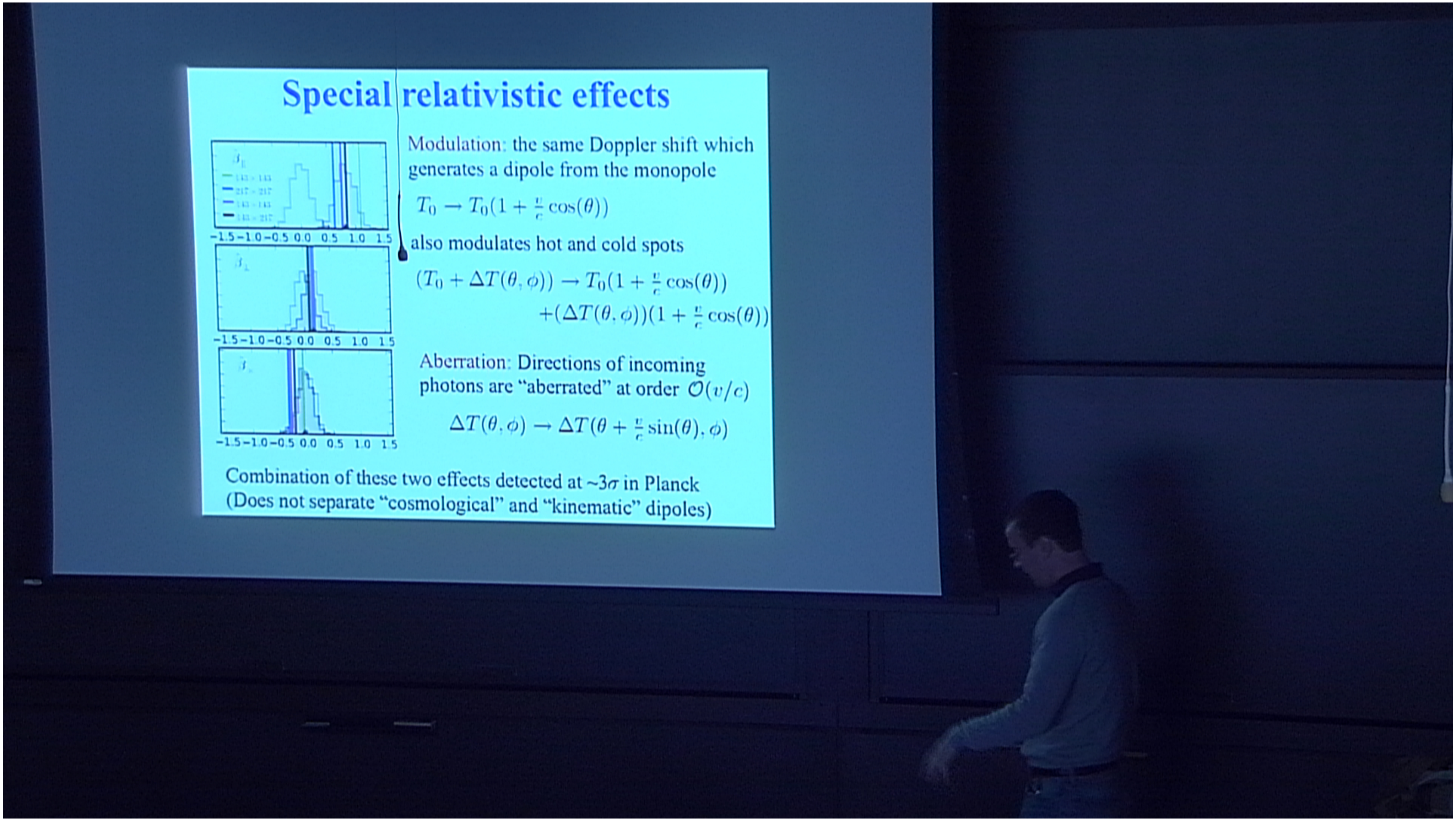
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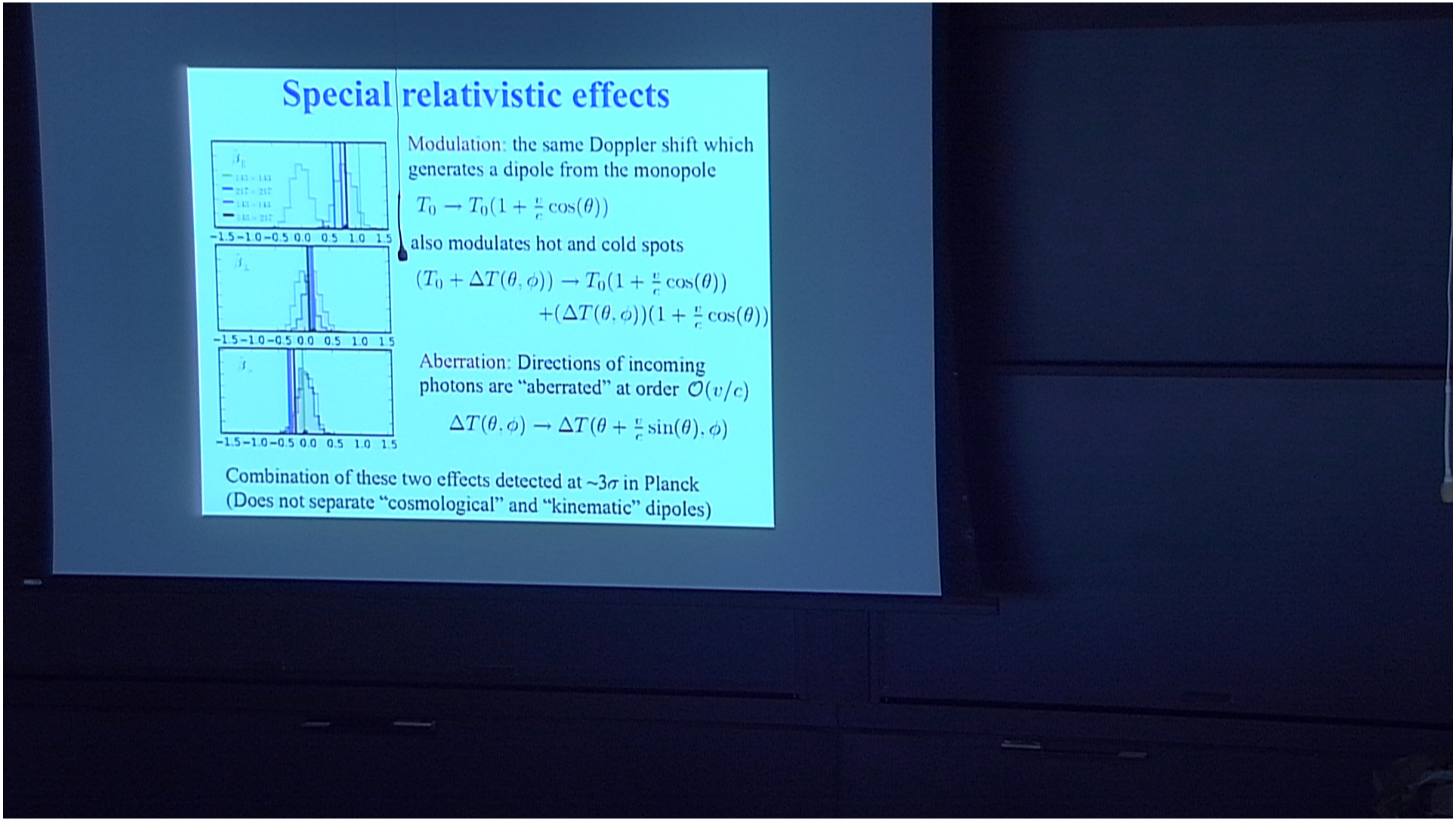
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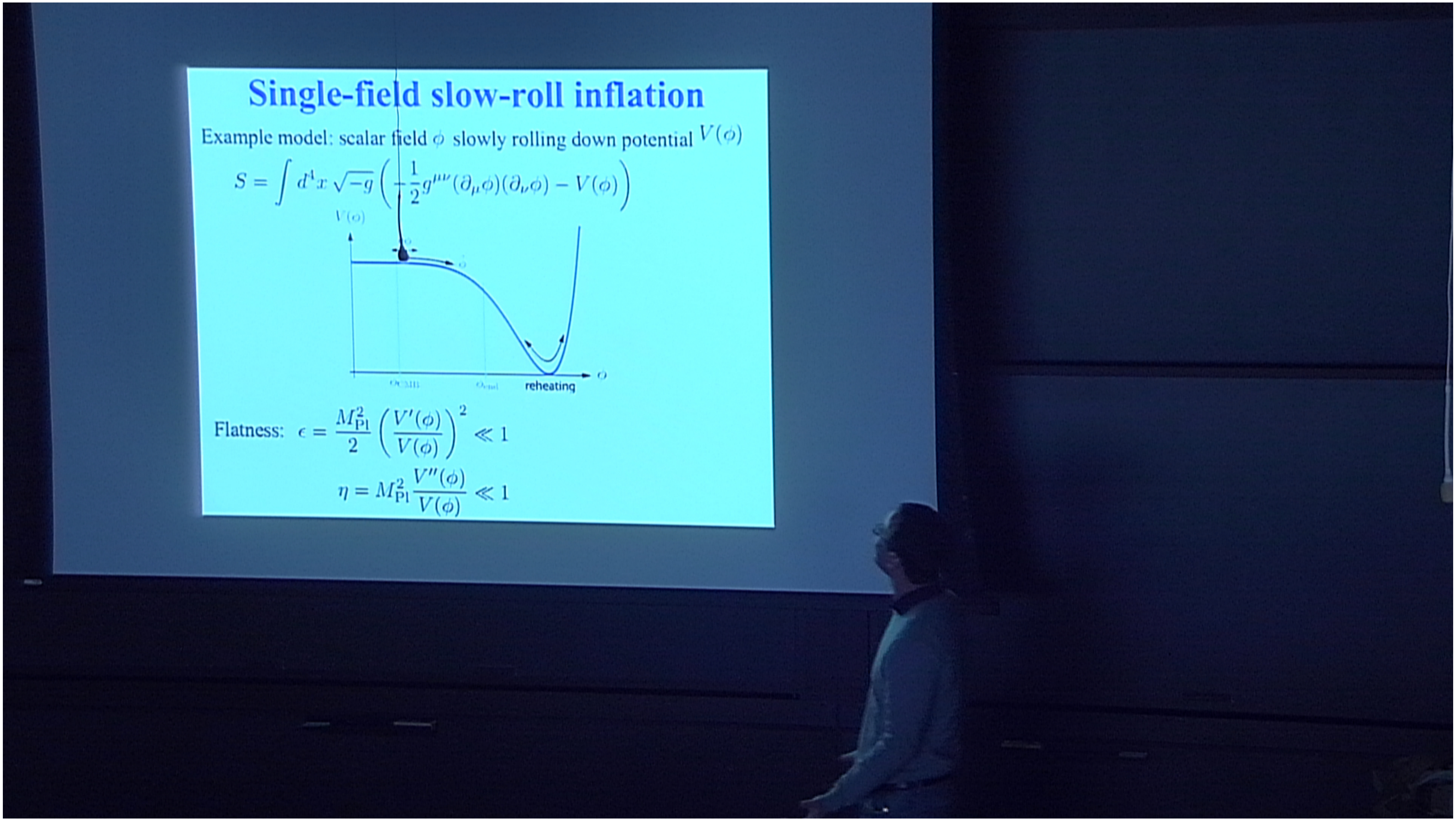
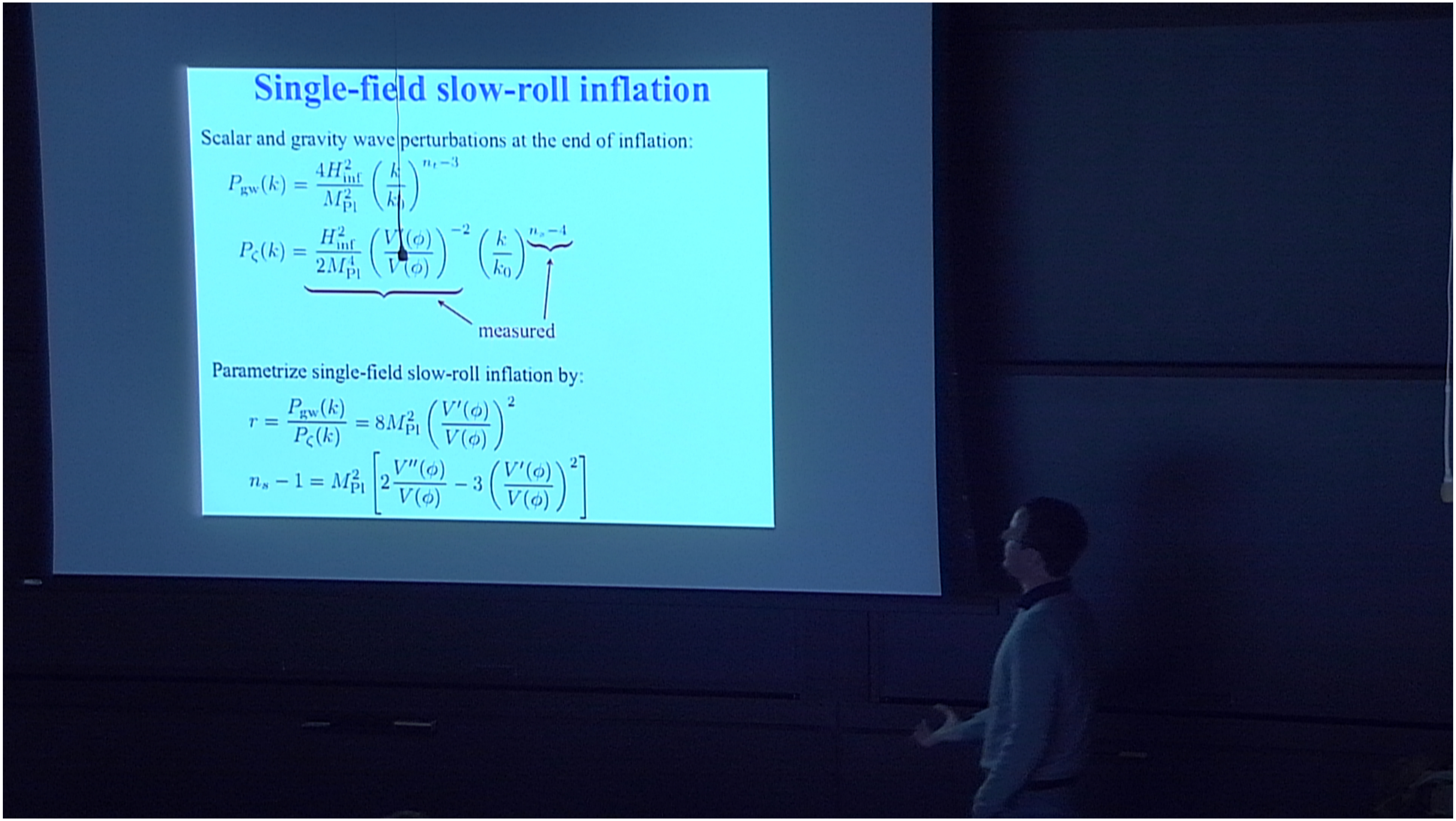

Single-field slow-roll inflation
Example model: scalar field ϕ slowly rolling down potential $V(\phi)$
$S = \int d^4x \sqrt{-g} \left(-\frac{1}{2} g^{\mu\nu} (\partial_\mu \phi)(\partial_\nu \phi) - V(\phi) \right)$
$V(\phi)$
ϕ_{CMB}
ϕ_{end}
reheating
ϕ
Flatness: $\epsilon = \frac{M_{Pl}^2}{2} \left(\frac{V'(\phi)}{V(\phi)} \right)^2 \ll 1$
$\eta = M_{Pl}^2 \frac{V''(\phi)}{V(\phi)} \ll 1$


Single-field slow-roll inflation
Scalar and gravity wave perturbations at the end of inflation:
$P_{\rm gw}(k) = \frac{4H_{\rm inf}^2}{M_{\rm Pl}^2}\left(\frac{k}{k_0}\right)^{n_t-3}$
$P_\zeta(k) = \frac{H_{\rm inf}^2}{2M_{\rm Pl}^4}\left(\frac{V'(\phi)}{V(\phi)}\right)^{-2}\left(\frac{k}{k_0}\right)^{n_s-4}$
measured
Parametrize single-field slow-roll inflation by:
$r = \frac{P_{\rm gw}(k)}{P_\zeta(k)} = 8M_{\rm Pl}^2\left(\frac{V'(\phi)}{V(\phi)}\right)^2$
$n_s - 1 = M_{\rm Pl}^2\left[2\frac{V''(\phi)}{V(\phi)} - 3\left(\frac{V'(\phi)}{V(\phi)}\right)^2\right]$

Single-field slow-roll inflation

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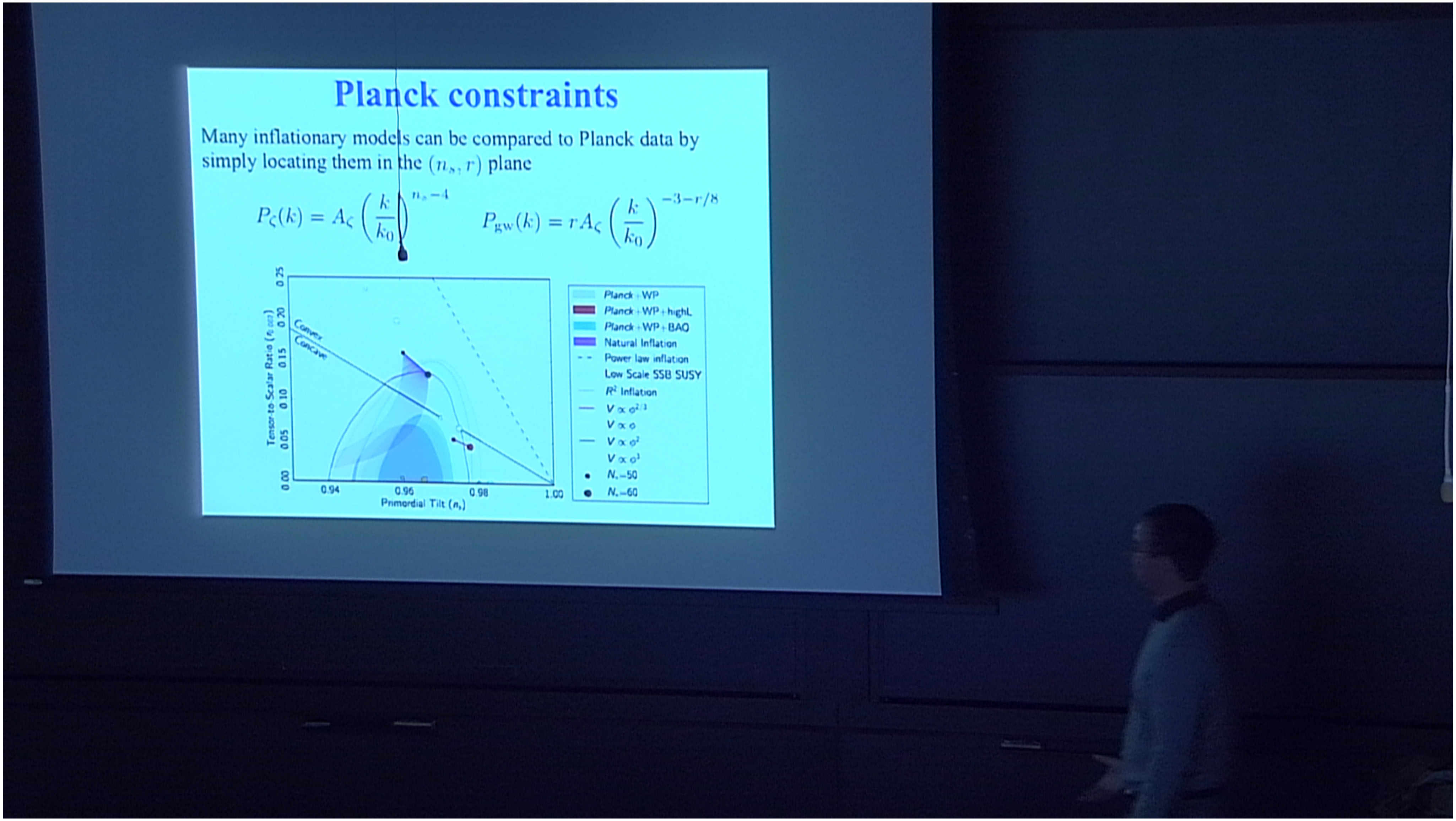
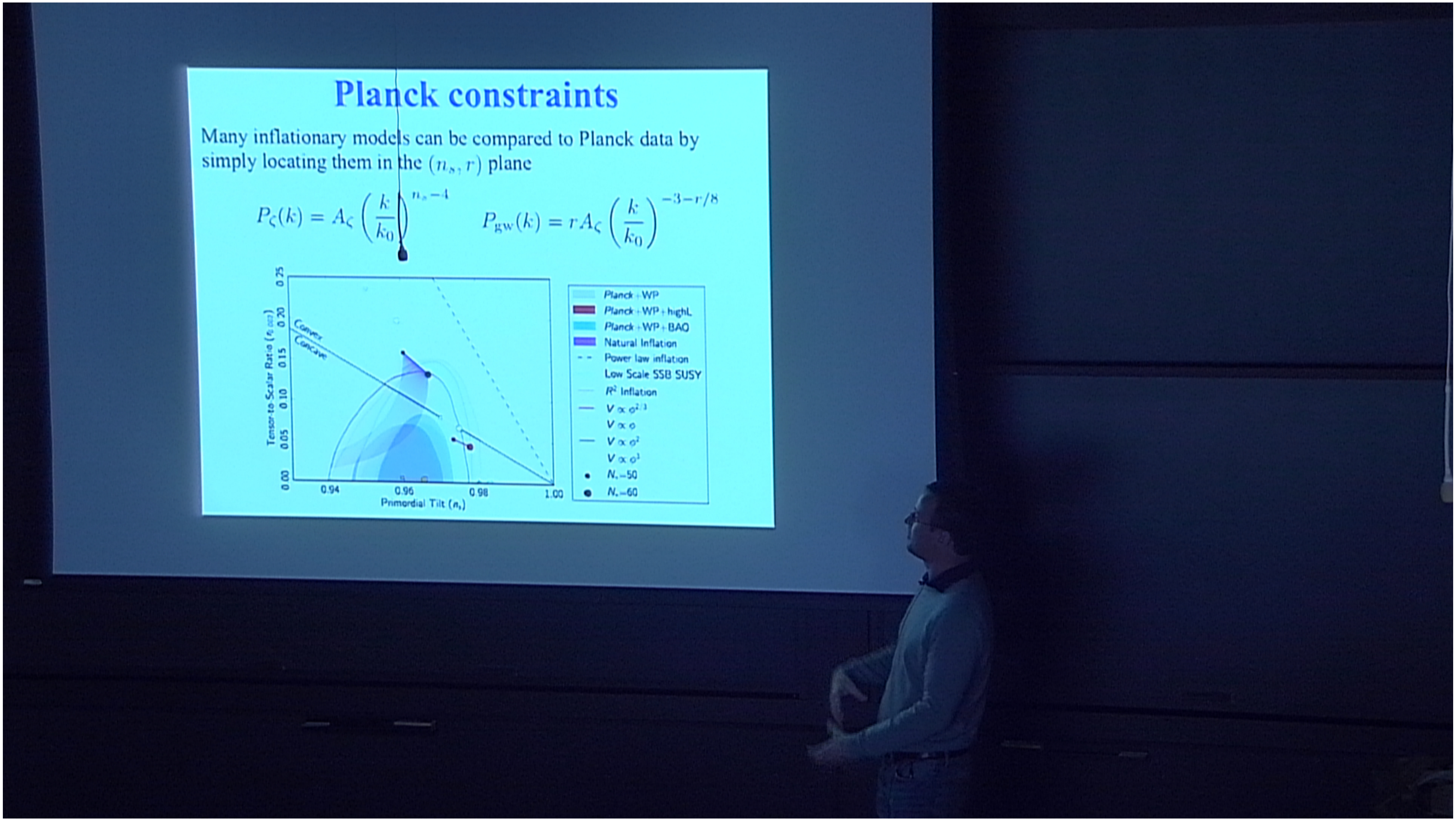

Planck constraints
Many inflationary models can be compared to Planck data by simply locating them in the (n_s, r) plane
$P_\zeta(k) = A_\zeta \left(\frac{k}{k_0}\right)^{n_s-4}$ $P_{\rm gw}(k) = rA_\zeta \left(\frac{k}{k_0}\right)^{-3-r/8}$
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
Convex
Concave
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
$N_*=50$
$N_*=60$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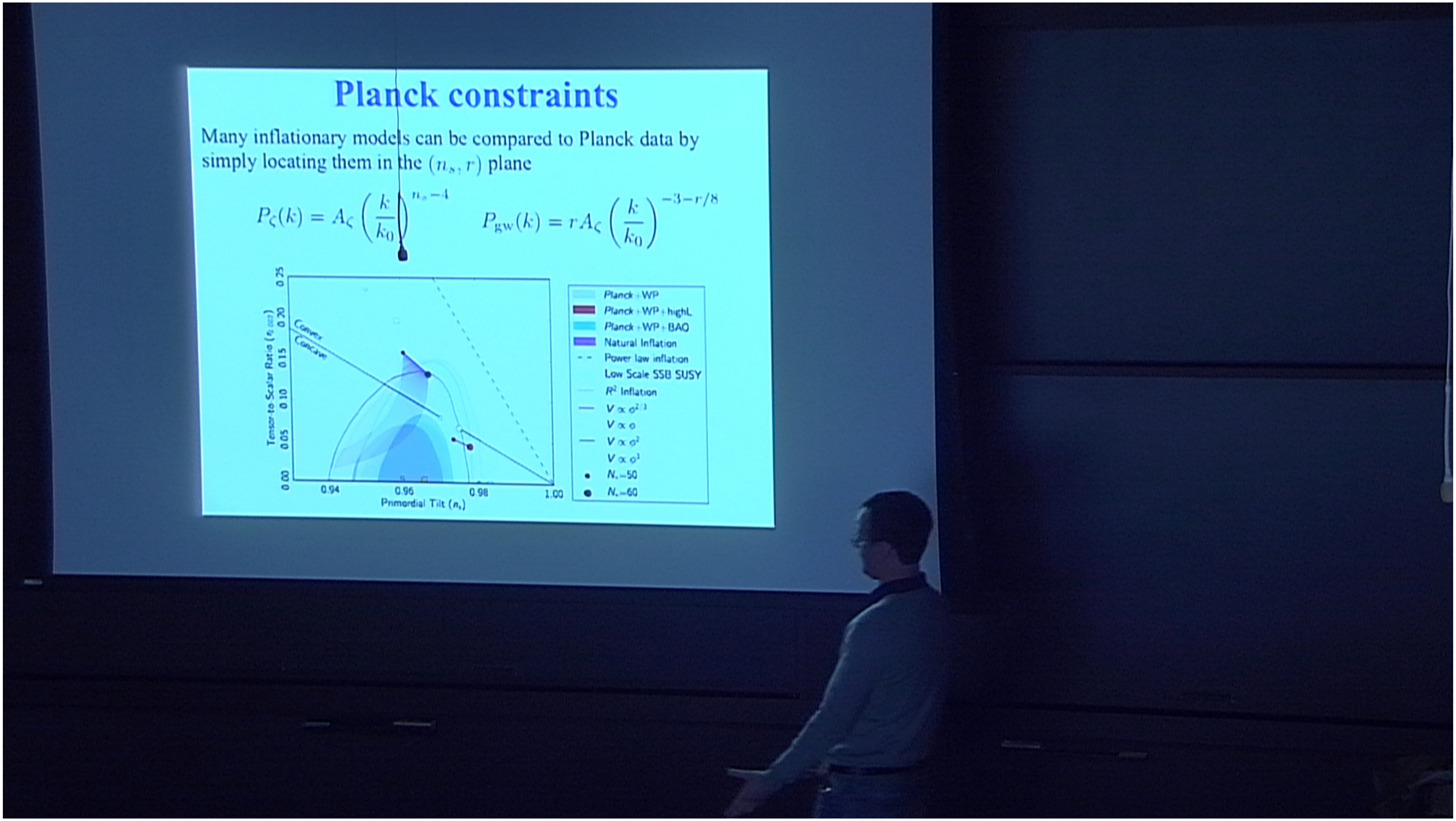

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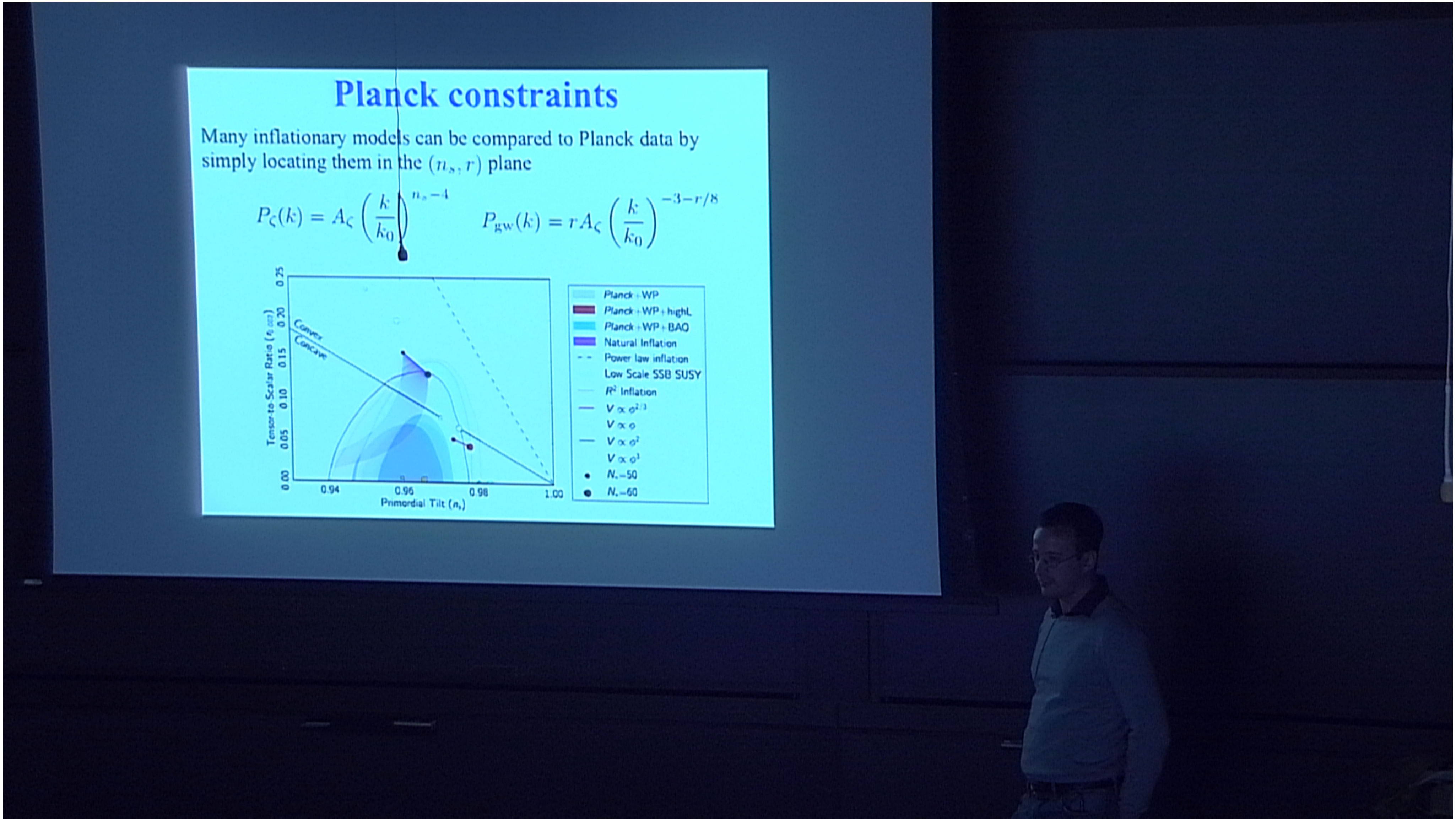
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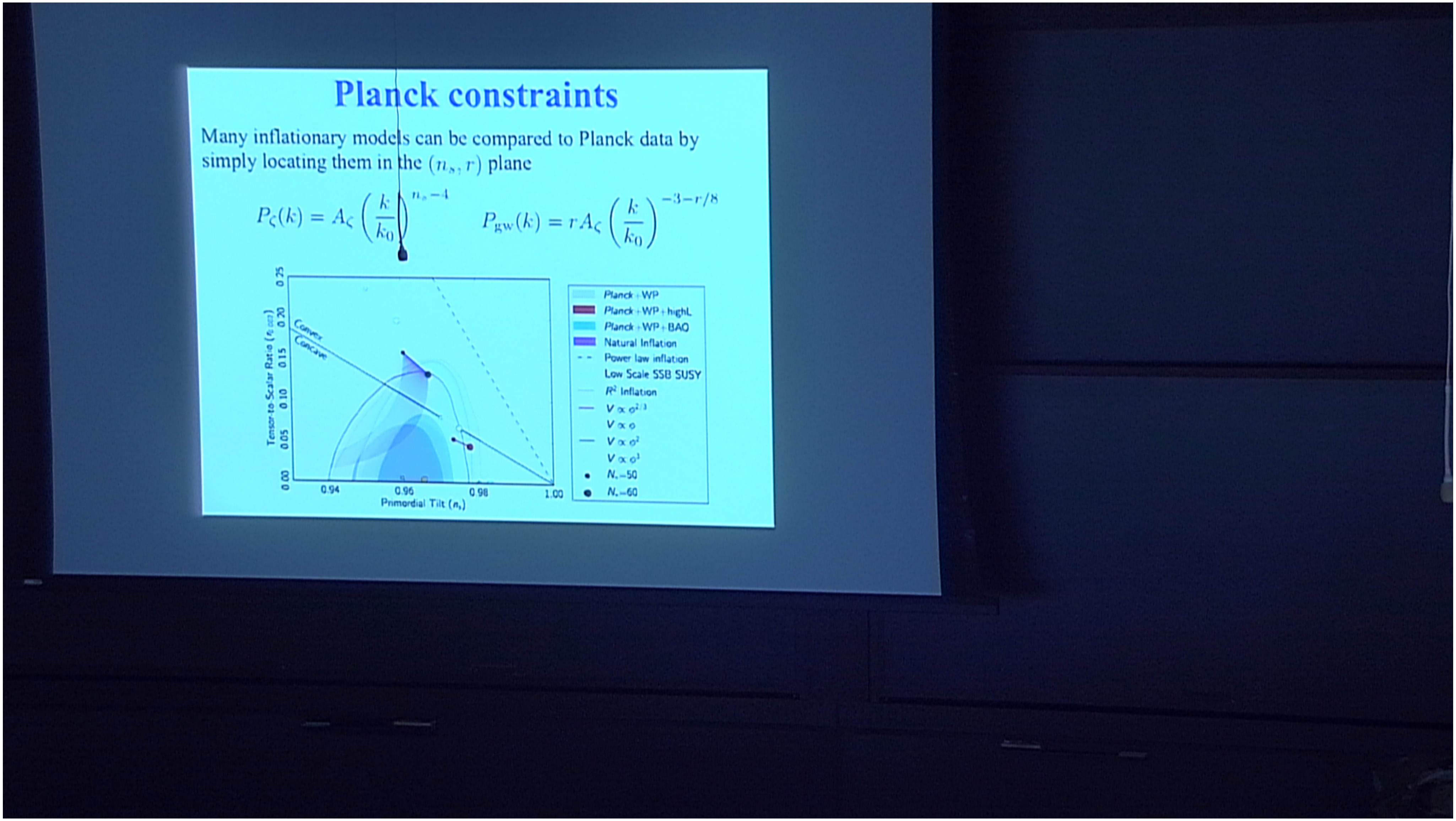
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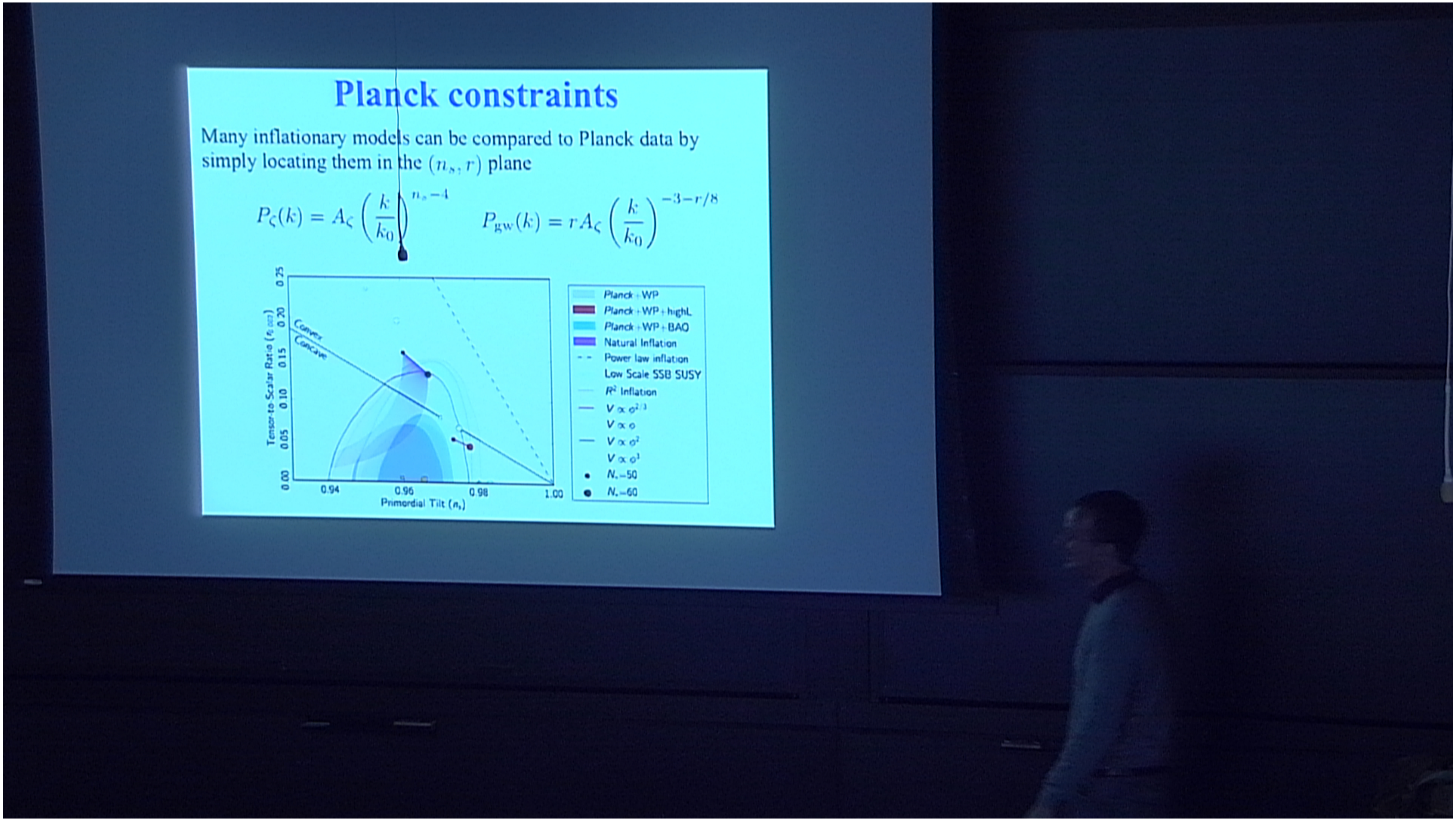
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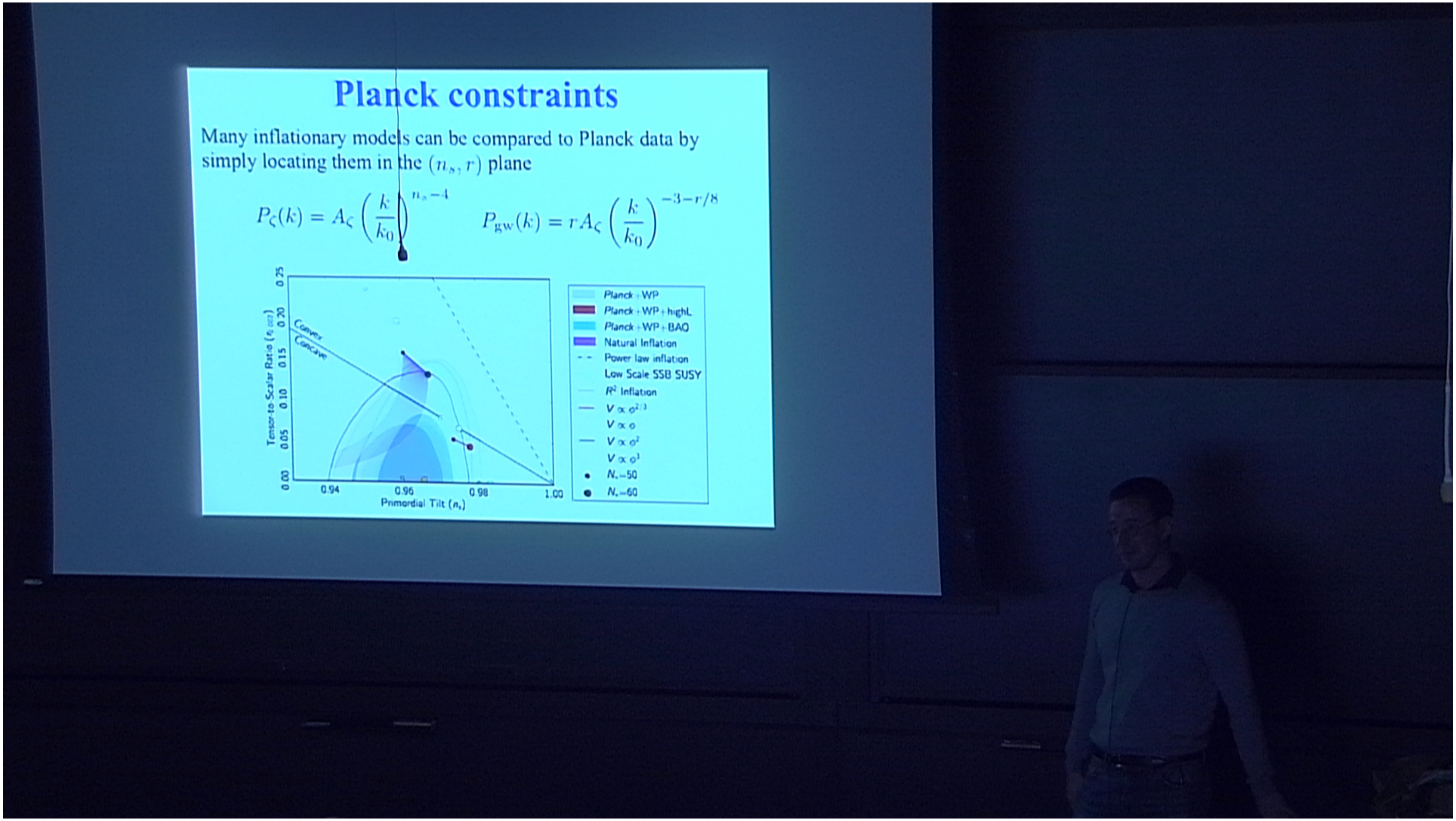
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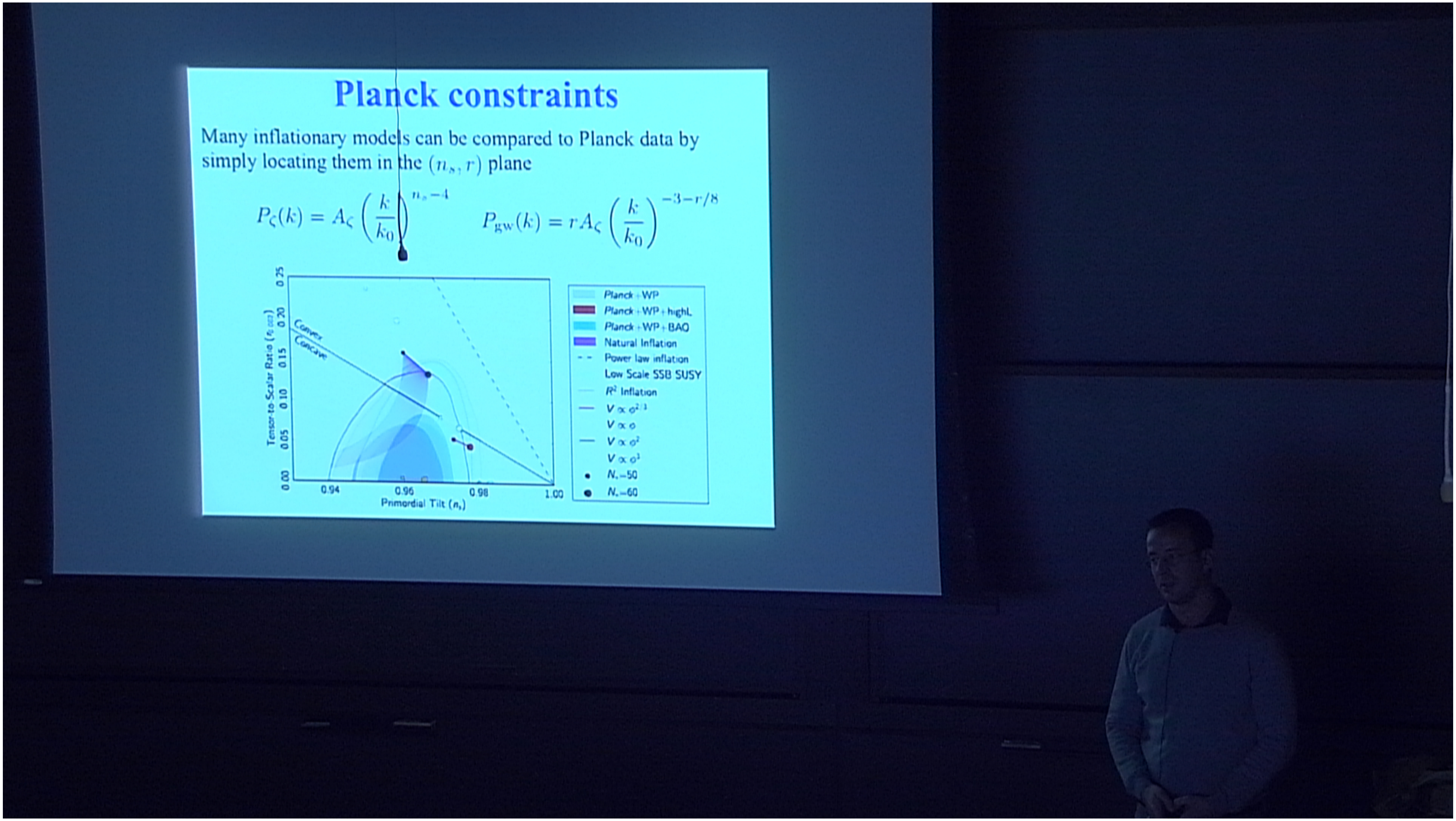
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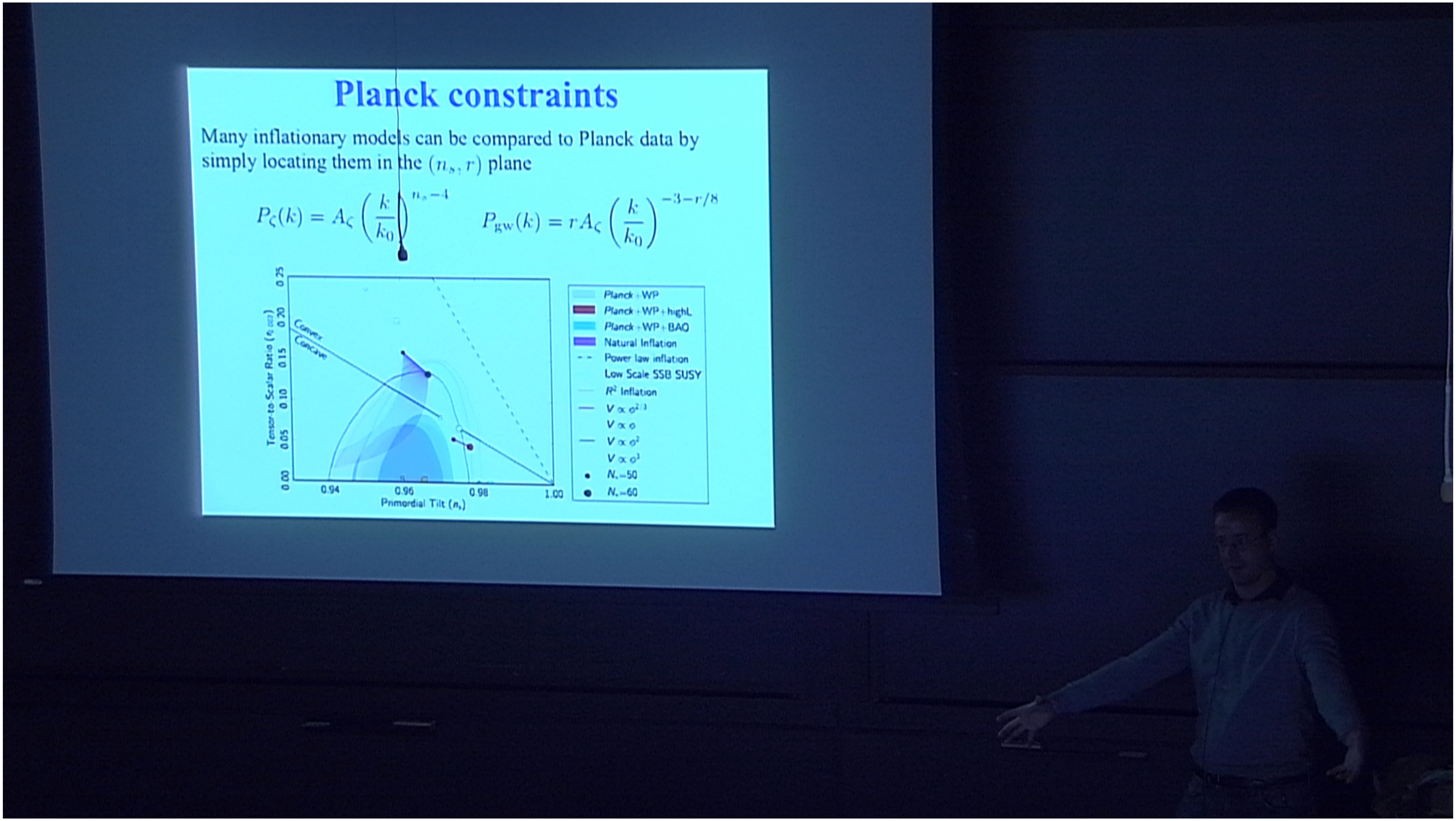
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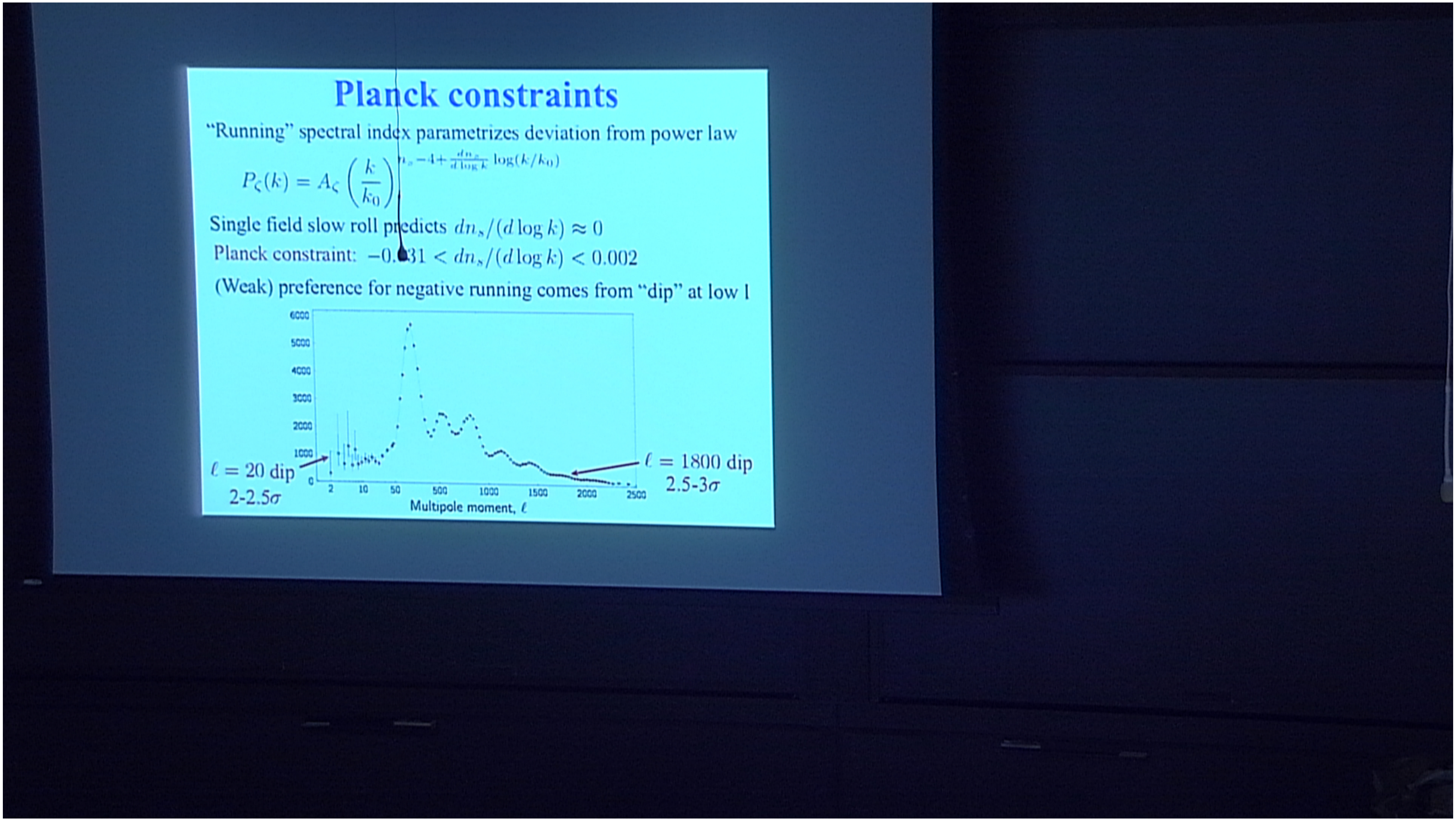
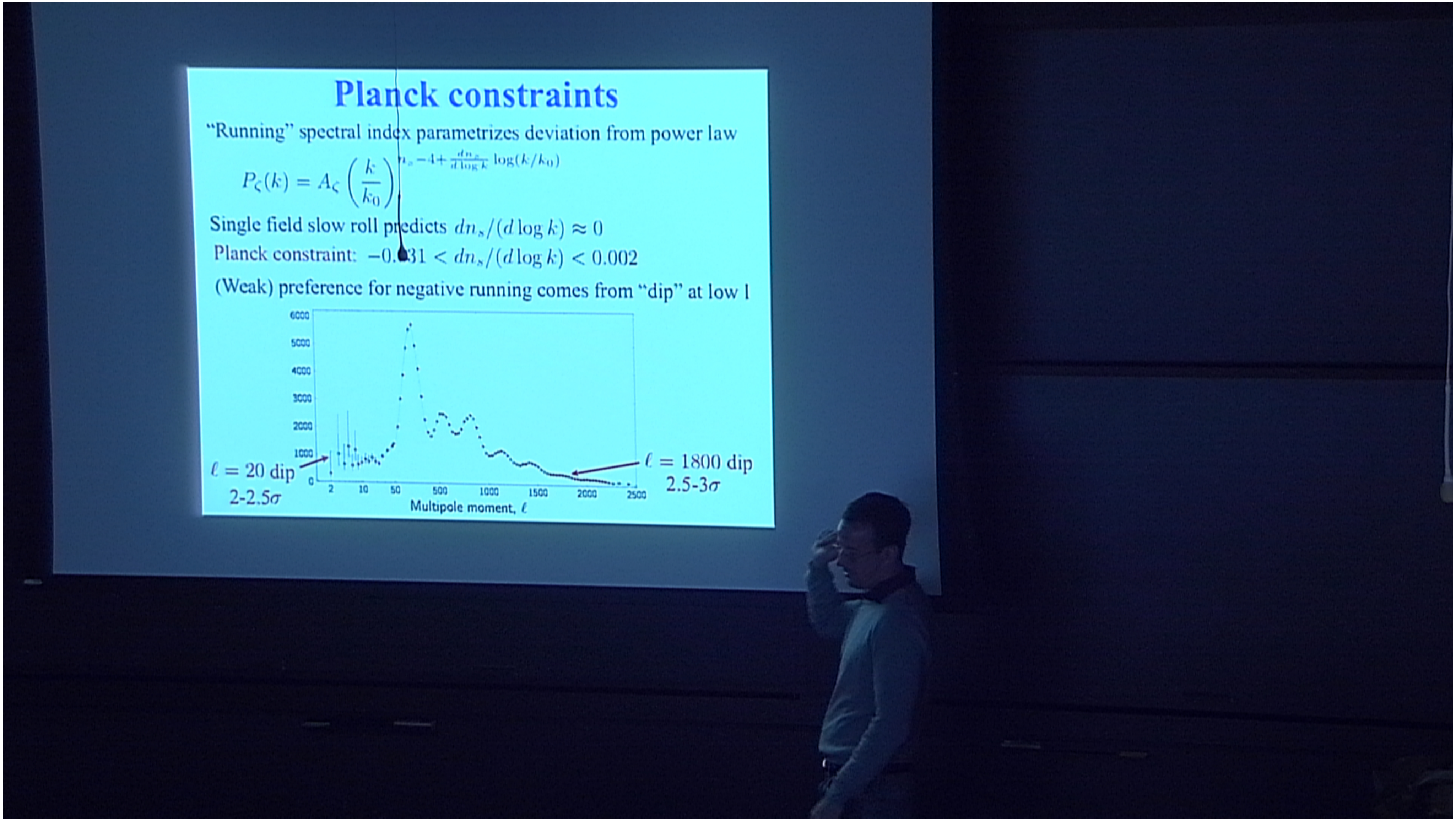

Planck constraints
"Running" spectral index parametrizes deviation from power law
$P_\zeta(k) = A_\zeta \left(\frac{k}{k_0}\right)^{n_s - 4 + \frac{dn_s}{d\log k}\log(k/k_0)}$
Single field slow roll predicts $dn_s/(d\log k) \approx 0$
Planck constraint: $-0.031 < dn_s/(d\log k) < 0.002$
(Weak) preference for negative running comes from "dip" at low l
$\ell = 20$ dip
2-2.5σ
$\ell = 1800$ dip
2.5-3σ
Multipole moment, ℓ



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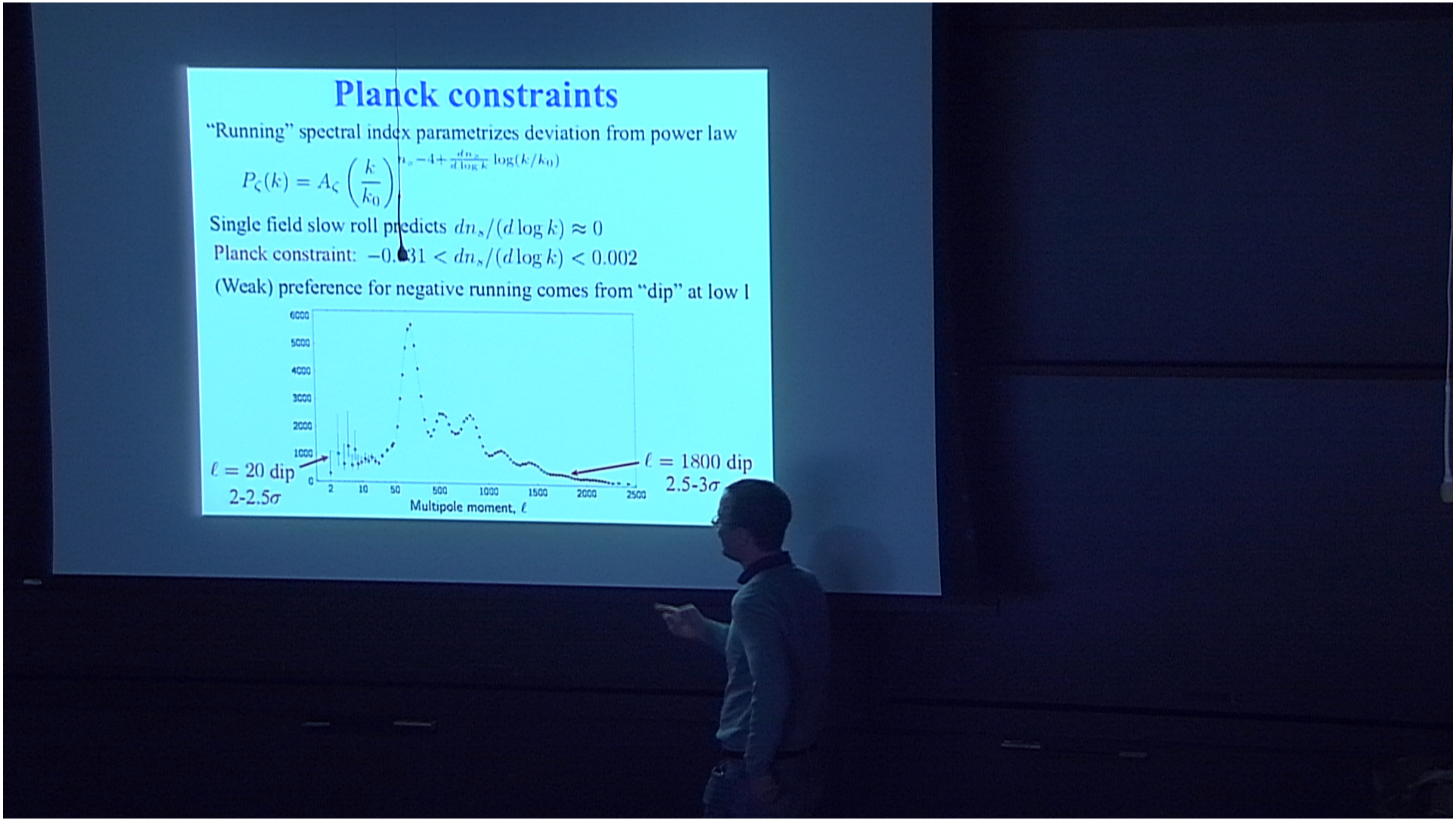
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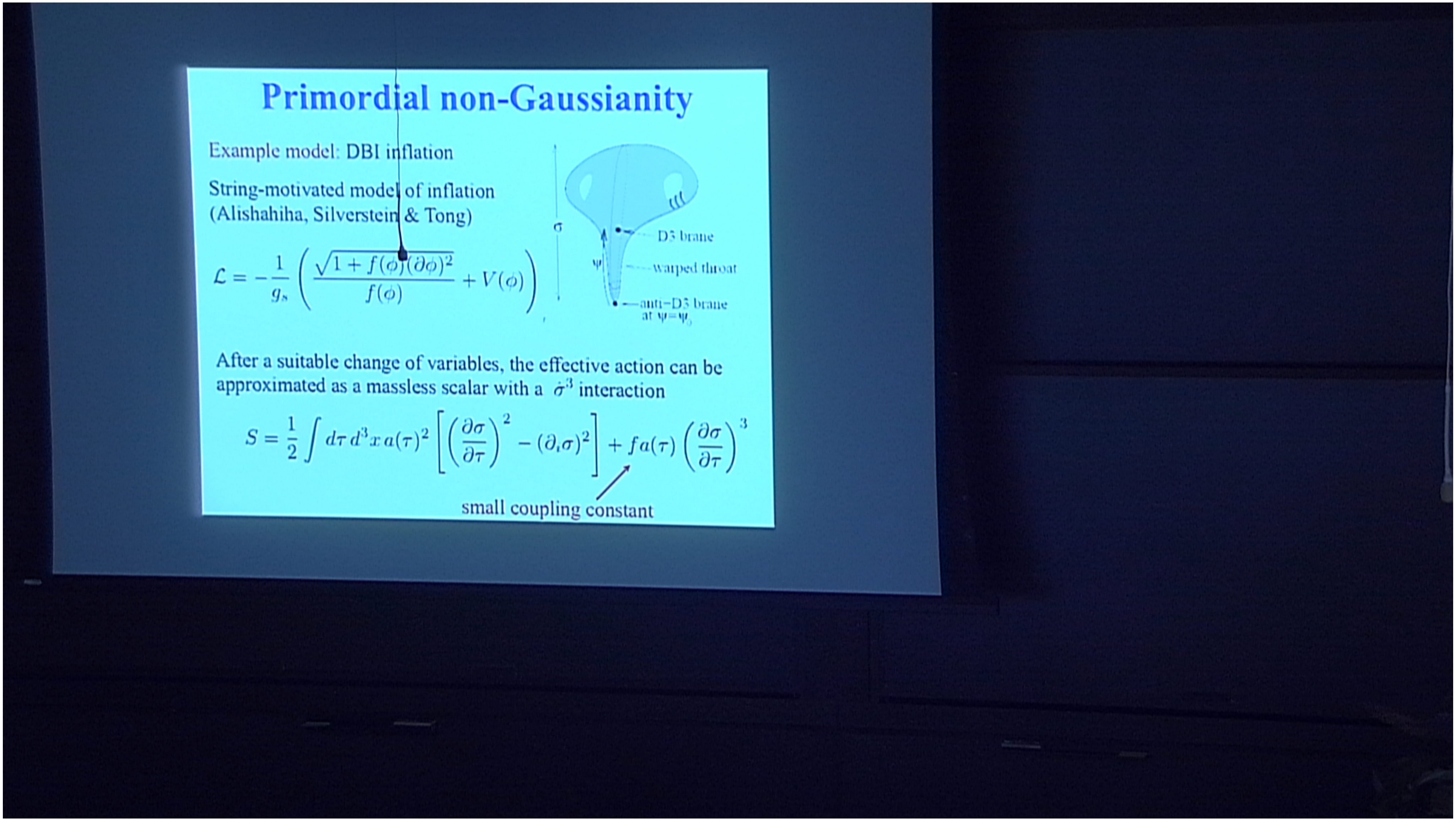
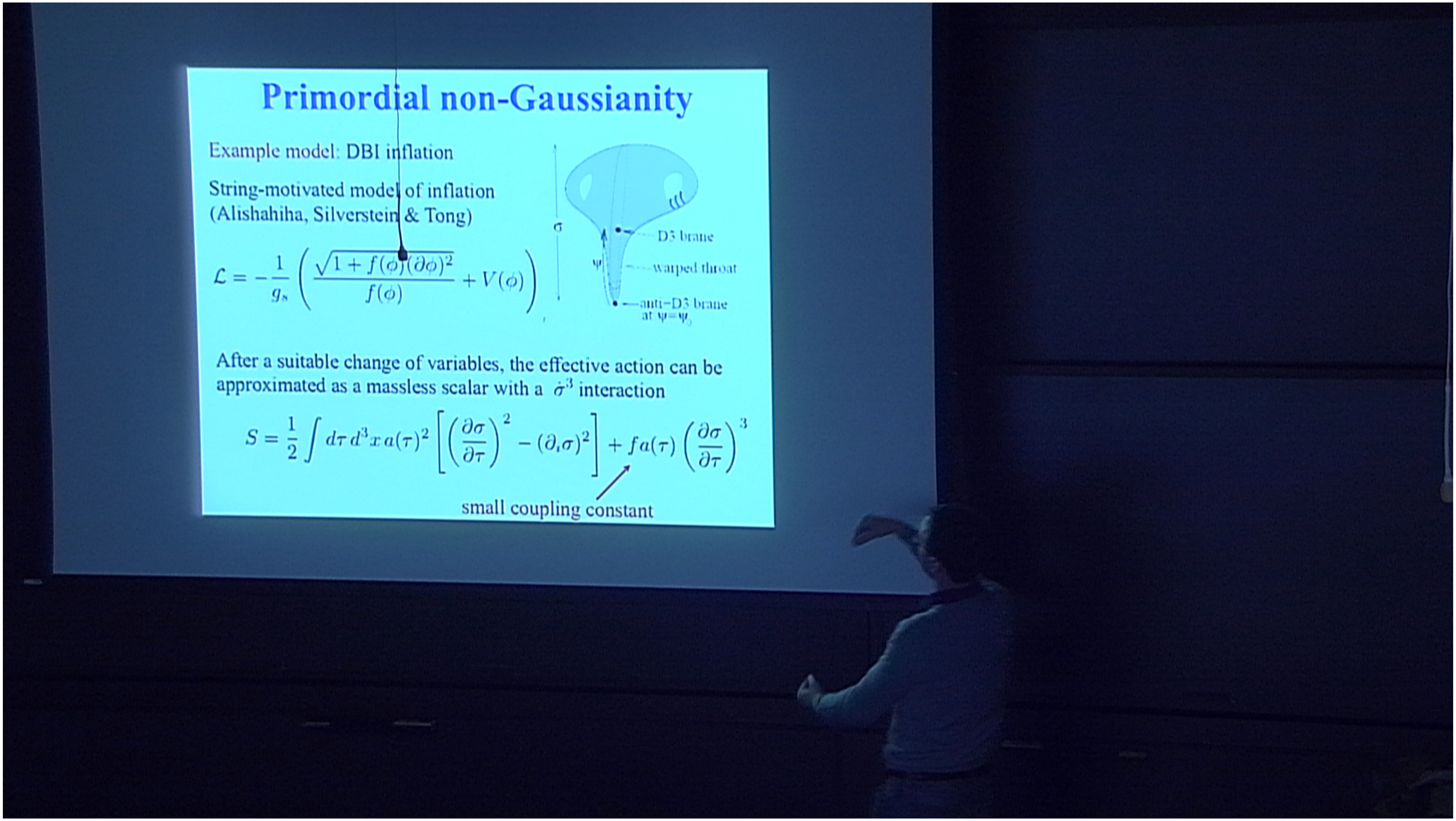

Primordial non-Gaussianity
Example model: DBI inflation
String-motivated model of inflation
(Alishahiha, Silverstein & Tong)
$\mathcal{L} = -\frac{1}{g_s}\left(\frac{\sqrt{1+f(\phi)(\partial\phi)^2}}{f(\phi)} + V(\phi)\right)$
σ
ψ
D3 brane
warped throat
anti-D3 brane
at ψ=ψ0
After a suitable change of variables, the effective action can be approximated as a massless scalar with a $\dot{\sigma}^3$ interaction
$S = \frac{1}{2}\int d\tau\, d^3x\, a(\tau)^2\left[\left(\frac{\partial\sigma}{\partial\tau}\right)^2 - (\partial_i\sigma)^2\right] + f a(\tau)\left(\frac{\partial\sigma}{\partial\tau}\right)^3$
small coupling constant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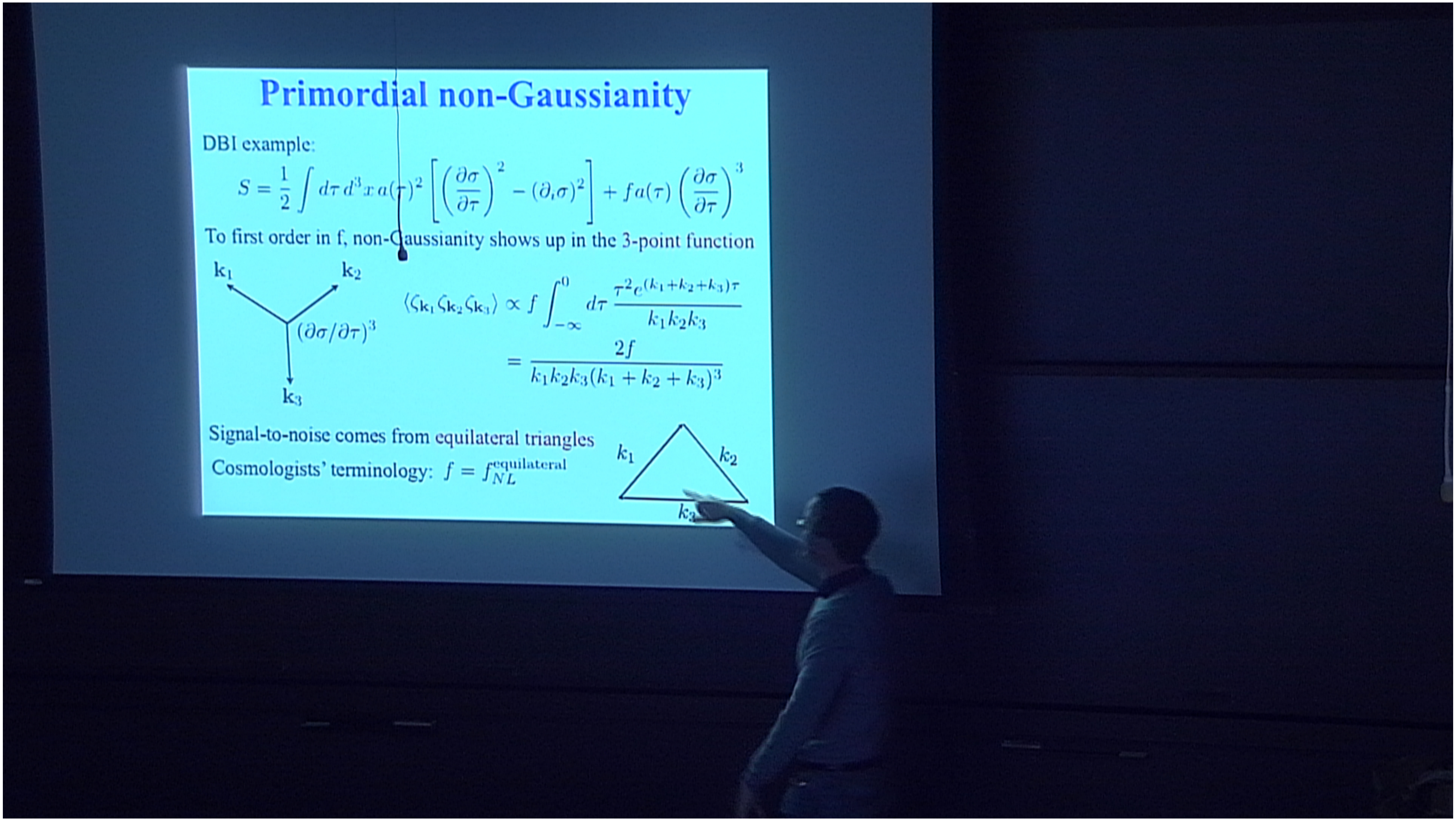
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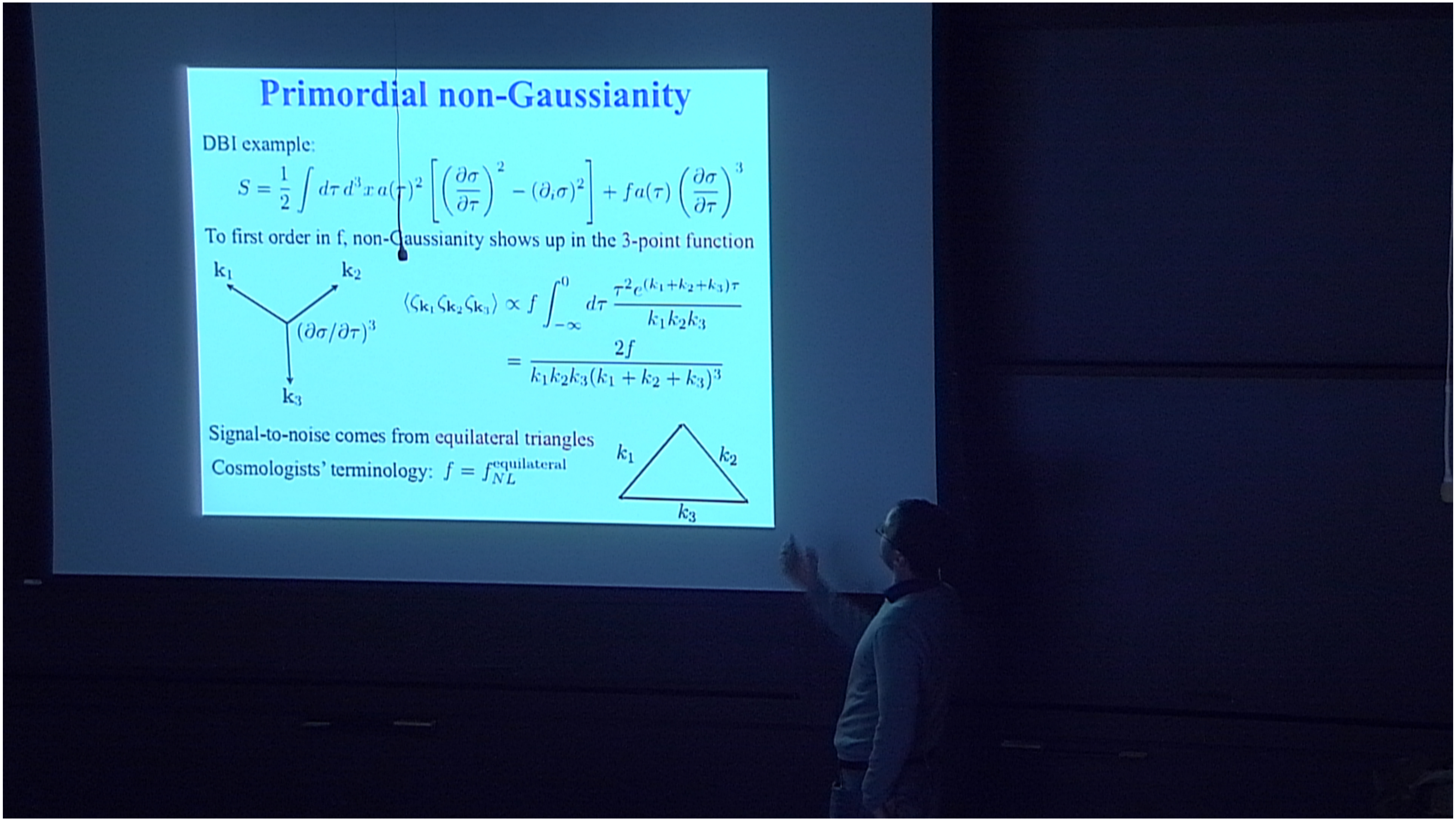
To first order in f, non-Gaussianity shows up in the 3-point function
$\mathbf{k}_1$
$\mathbf{k}_2$
$(\partial\sigma/\partial\tau)^3$
$\mathbf{k}_3$
$\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle \propto f\int_{-\infty}^{0} d\tau\, \frac{\tau^2 e^{(k_1+k_2+k_3)\tau}}{k_1k_2k_3}$
$= \frac{2f}{k_1k_2k_3(k_1+k_2+k_3)^3}$
Signal-to-noise comes from equilateral triangles
Cosmologists' terminology: $f = f_{NL}^{\mathrm{equilateral}}$
k_1
k_2
k_3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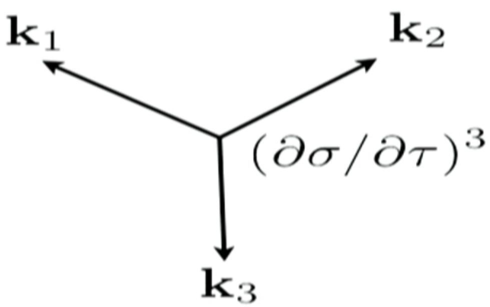

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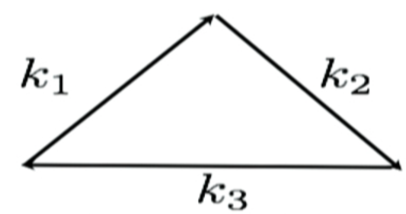
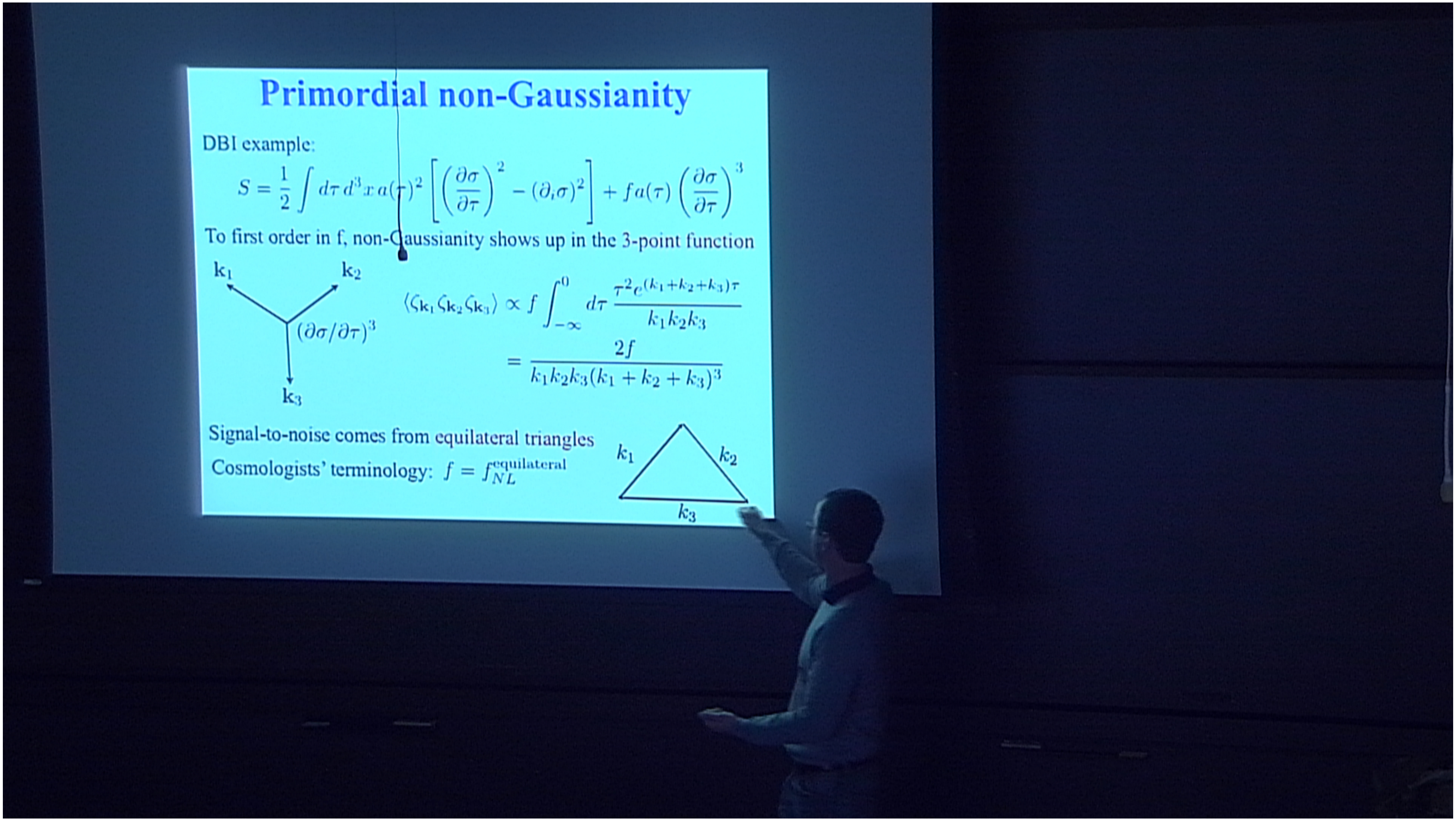
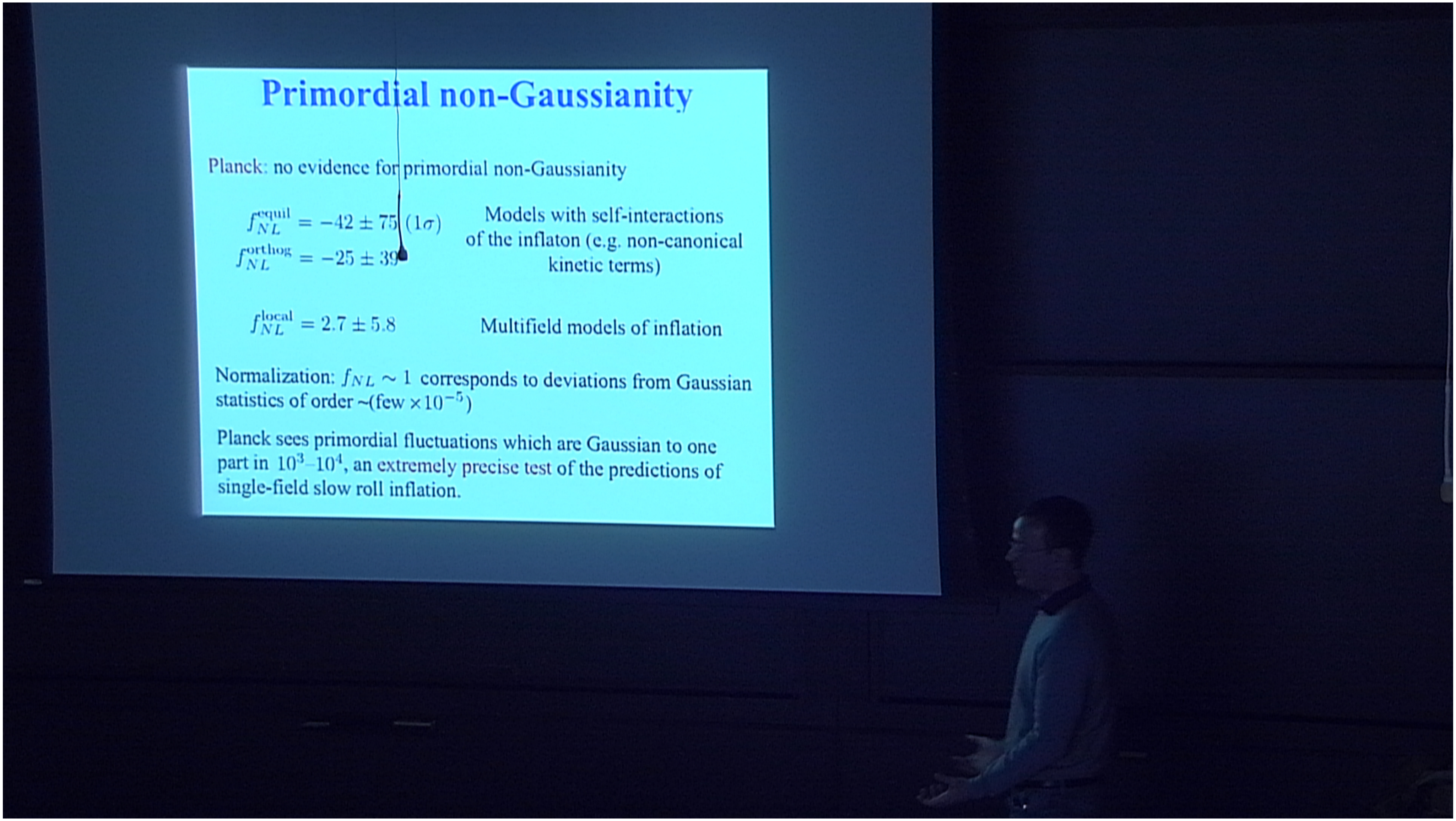
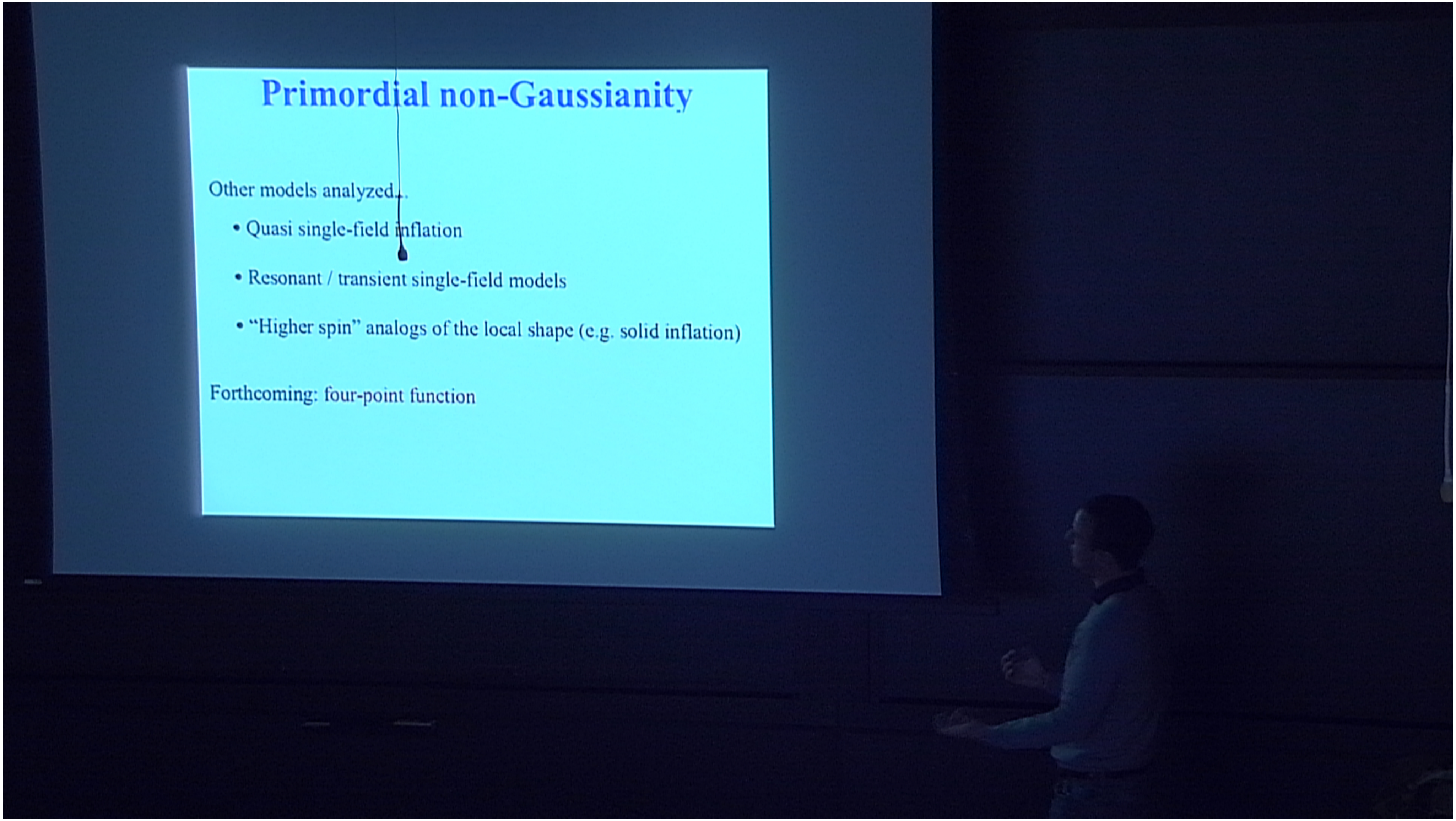
Cosmologists' terminology: $f = f_{NL}^{\text{equilateral}}$




Primordial non-Gaussianity
DBI example:
$S = \frac{1}{2}\int d\tau\, d^3x\, a(\tau)^2 \left[\left(\frac{\partial\sigma}{\partial\tau}\right)^2 - (\partial_i\sigma)^2\right] + f a(\tau)\left(\frac{\partial\sigma}{\partial\tau}\right)^3$
To first order in f, non-Gaussianity shows up in the 3-point function
$\mathbf{k}_1$
$\mathbf{k}_2$
$(\partial\sigma/\partial\tau)^3$
$\mathbf{k}_3$
$\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle \propto f\int_{-\infty}^{0} d\tau\, \frac{\tau^2 e^{(k_1+k_2+k_3)\tau}}{k_1k_2k_3}$
$= \frac{2f}{k_1k_2k_3(k_1+k_2+k_3)^3}$
Signal-to-noise comes from equilateral triangles
Cosmologists' terminology: $f = f_{NL}^{\text{equilateral}}$
k_1
k_2
k_3


Primordial non-Gaussianity
Planck: no evidence for primordial non-Gaussianity
$f_{NL}^{\rm equil} = -42 \pm 75\ (1\sigma)$
$f_{NL}^{\rm orthog} = -25 \pm 39$
Models with self-interactions of the inflaton (e.g. non-canonical kinetic terms)
$f_{NL}^{\rm local} = 2.7 \pm 5.8$
Multifield models of inflation
Normalization: $f_{NL} \sim 1$ corresponds to deviations from Gaussian statistics of order ~(few $\times 10^{-5}$)
Planck sees primordial fluctuations which are Gaussian to one part in 10^3–10^4, an extremely precise test of the predictions of single-field slow roll inflation.


Primordial non-Gaussianity
Other models analyzed...
• Quasi single-field inflation
• Resonant / transient single-field models
• "Higher spin" analogs of the local shape (e.g. solid inflation)
Forthcoming: four-point function

Early universe: where do we stand?

WMAP and Planck constraints in (n_s, r) plane are qualitatively similar, but Planck constraints on primordial non-Gaussianity are much better.

In the near future, Planck and other experiments will improve constraints on r by at least a factor of 10. Does single field slow roll inflation predict detectable r?

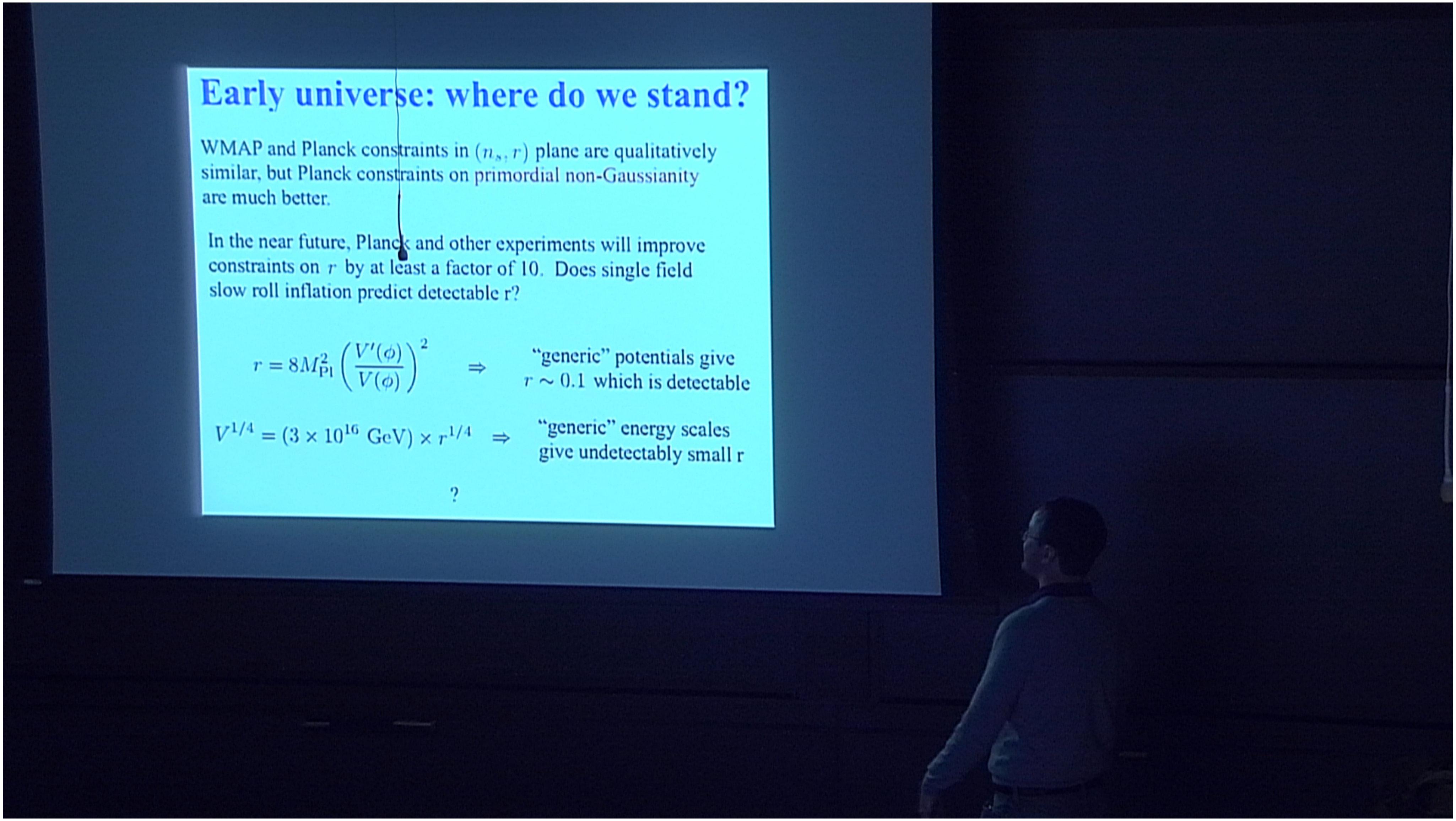
$$r = 8M_{\rm Pl}^2 \left(\frac{V'(\phi)}{V(\phi)}\right)^2 \quad \Rightarrow$$

"generic" potentials give $r \sim 0.1$ which is detectable

$$V^{1/4} = (3 \times 10^{16}\ \text{GeV}) \times r^{1/4} \quad \Rightarrow$$

"generic" energy scales give undetectably small r

?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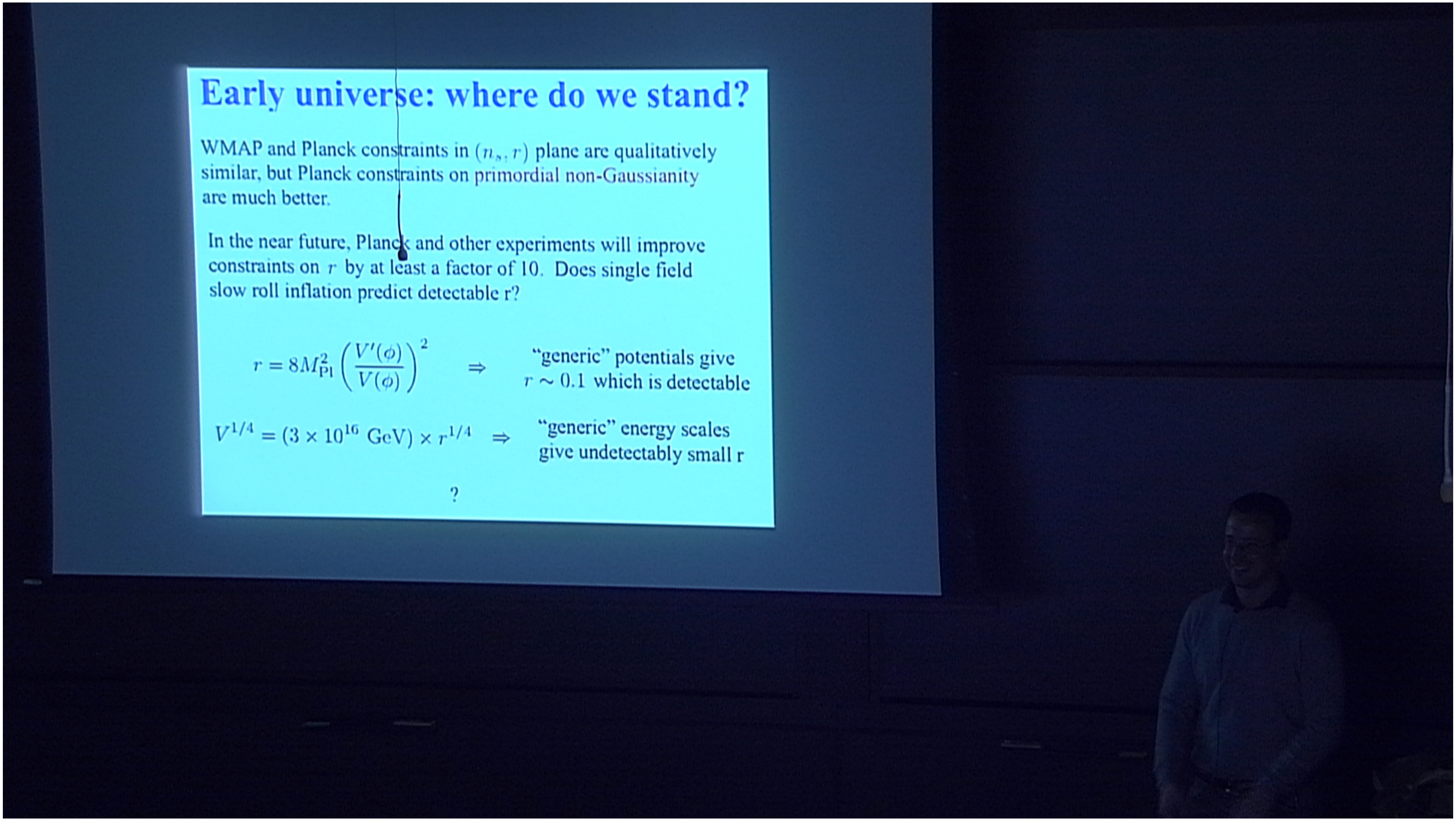
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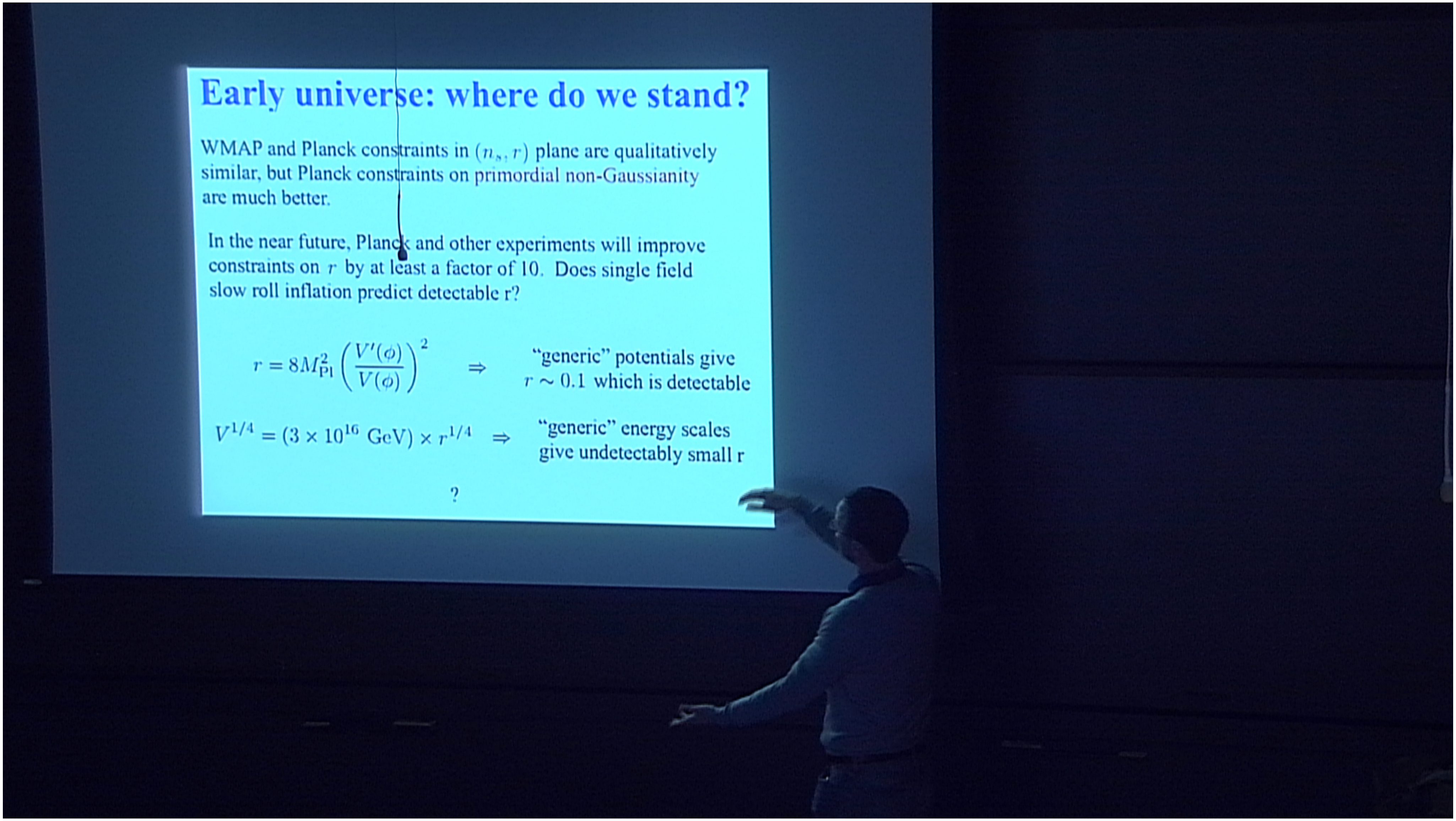
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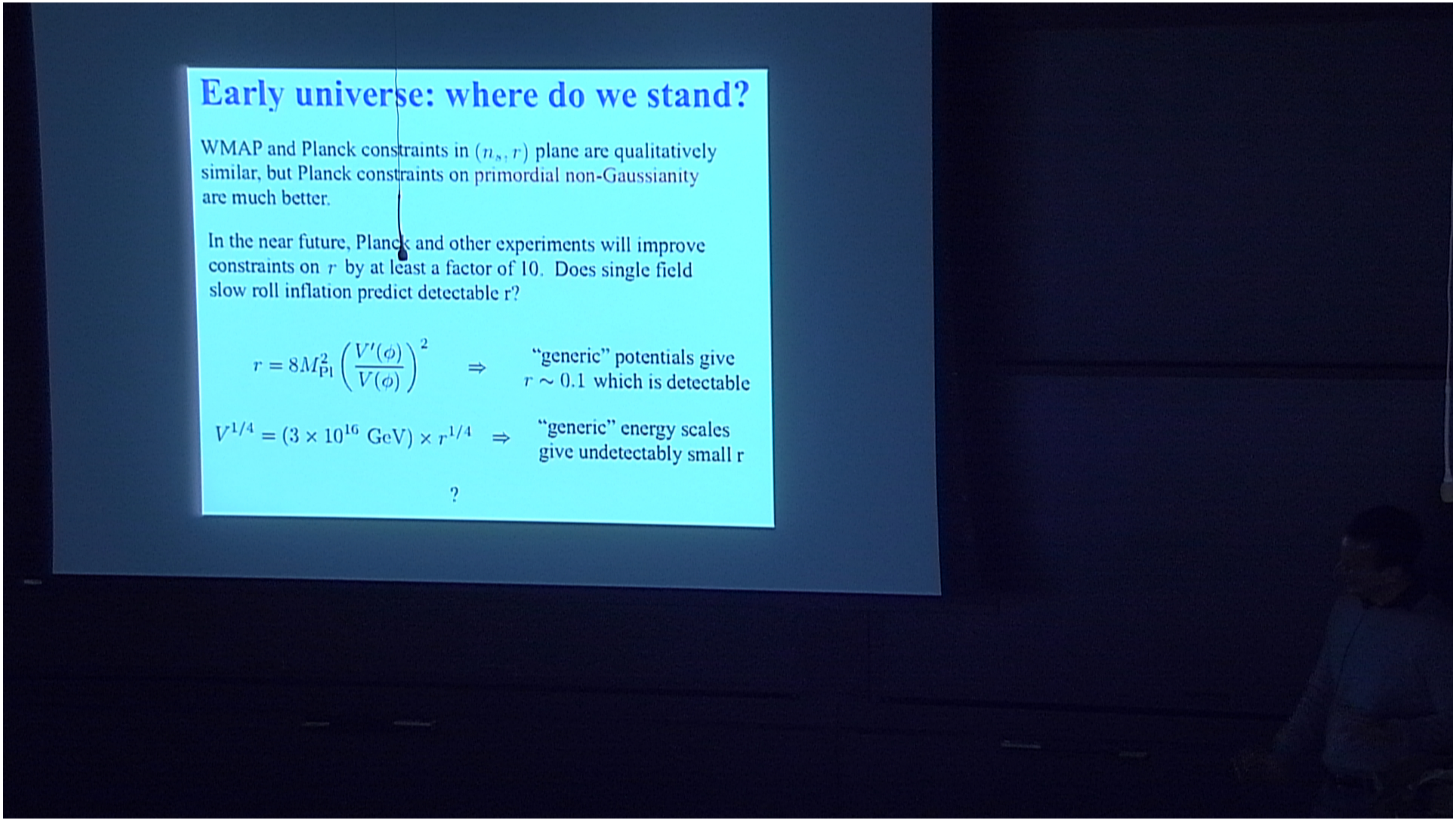
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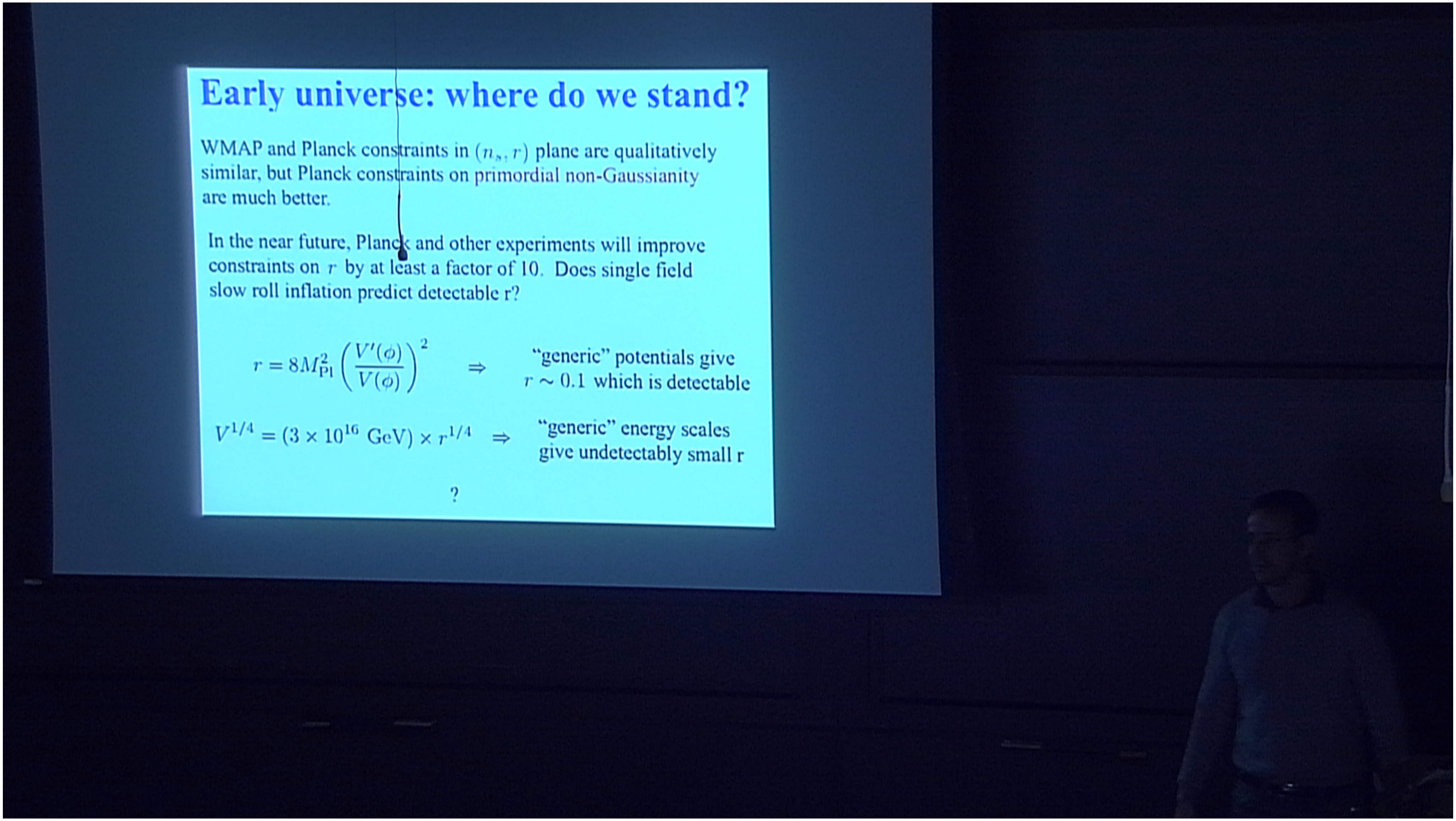
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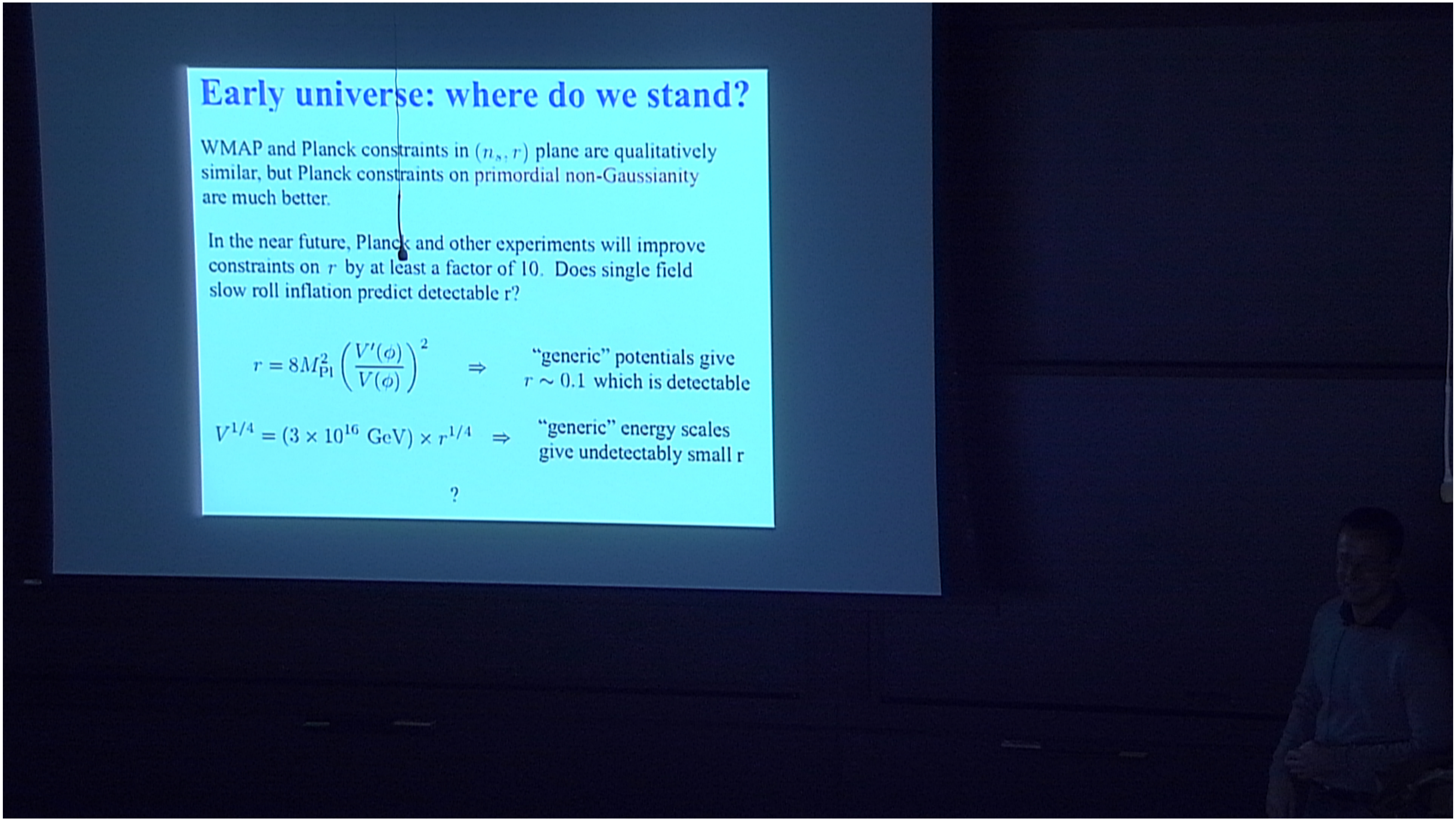
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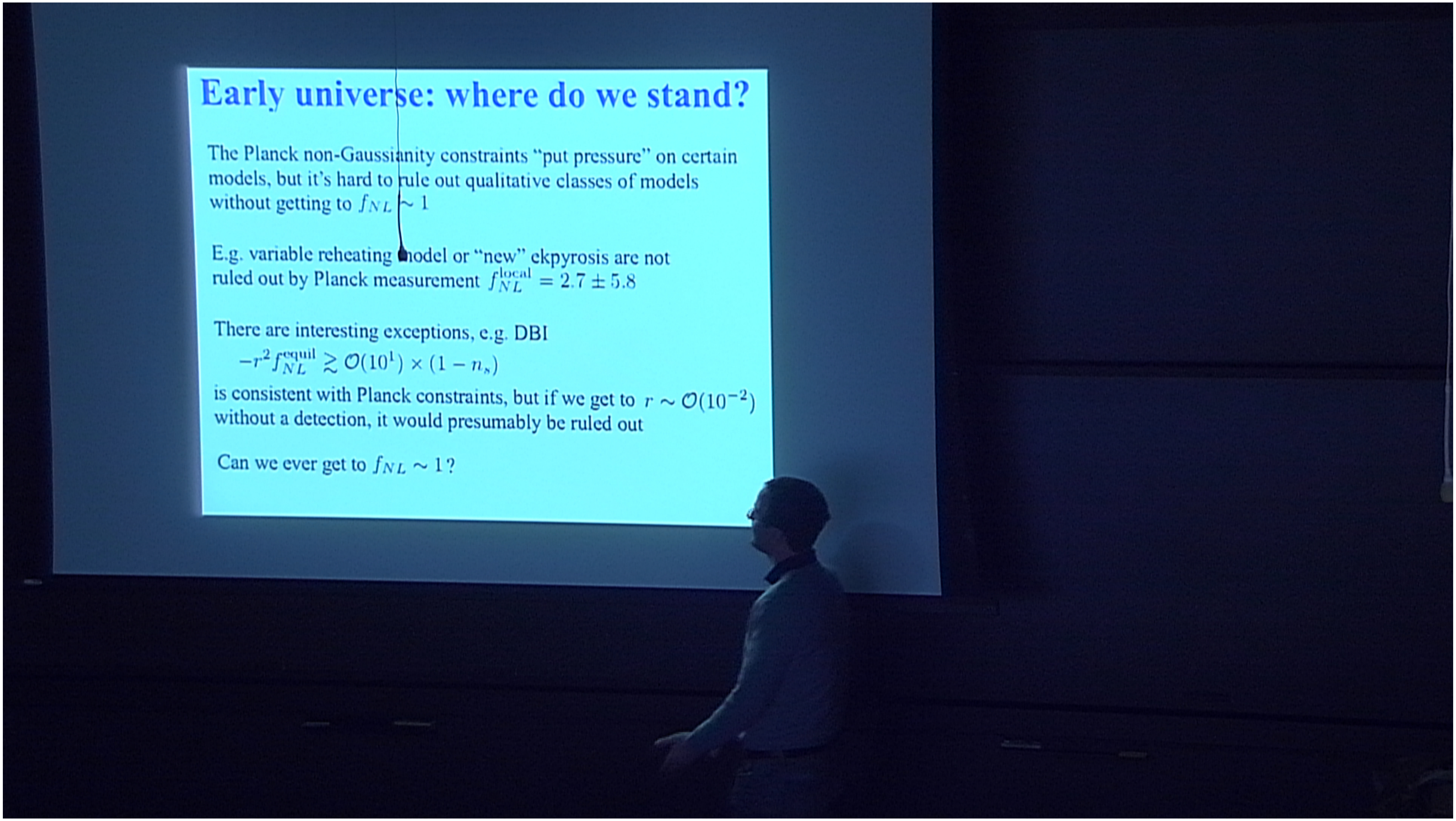
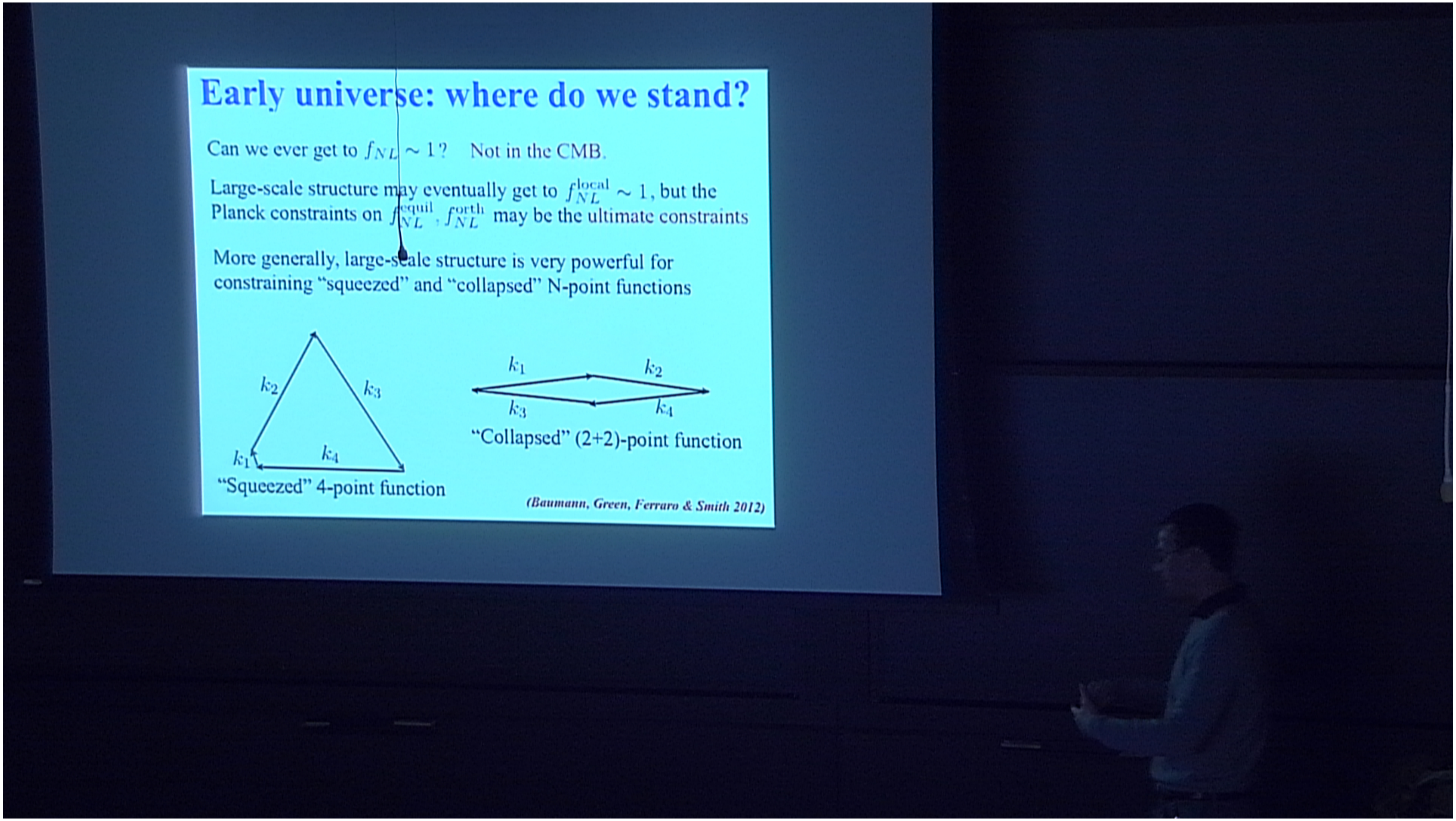
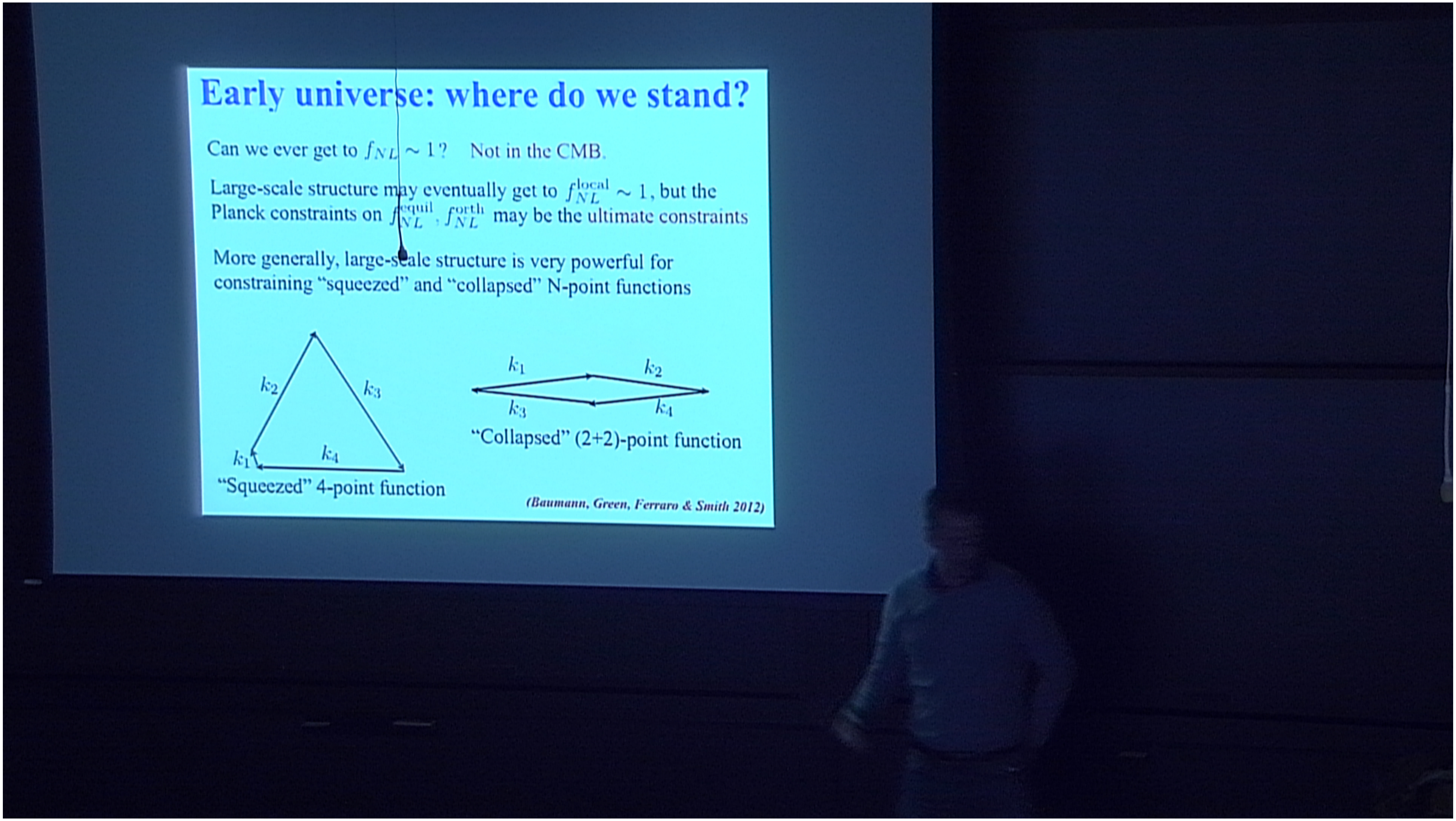

Early universe: where do we stand?
The Planck non-Gaussianity constraints "put pressure" on certain models, but it's hard to rule out qualitative classes of models without getting to $f_{NL} \sim 1$
E.g. variable reheating model or "new" ekpyrosis are not ruled out by Planck measurement $f_{NL}^{\mathrm{local}} = 2.7 \pm 5.8$
There are interesting exceptions, e.g. DBI
$-r^2 f_{NL}^{\mathrm{equil}} \gtrsim \mathcal{O}(10^1) \times (1 - n_s)$
is consistent with Planck constraints, but if we get to $r \sim \mathcal{O}(10^{-2})$ without a detection, it would presumably be ruled out
Can we ever get to $f_{NL} \sim 1$?


Early universe: where do we stand?
Can we ever get to $f_{NL} \sim 1$? Not in the CMB.
Large-scale structure may eventually get to $f_{NL}^{\rm local} \sim 1$, but the Planck constraints on $f_{NL}^{\rm equil}, f_{NL}^{\rm orth}$ may be the ultimate constraints
More generally, large-scale structure is very powerful for constraining "squeezed" and "collapsed" N-point functions
k_1
k_2
k_3
k_4
"Squeezed" 4-point function
"Collapsed" (2+2)-point function
(Baumann, Green, Ferraro & Smith 2012)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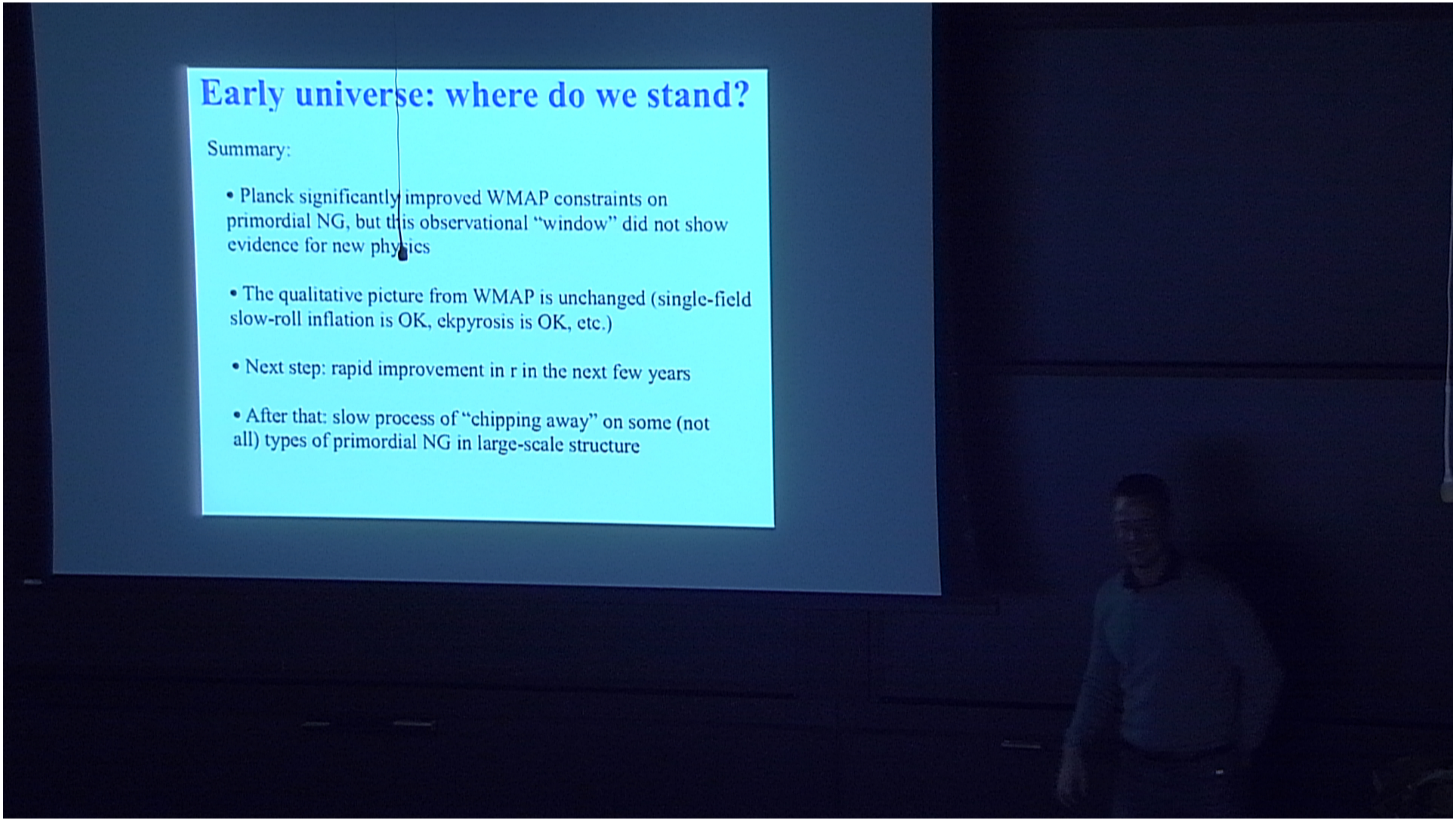
Early universe: where do we stand?
Summary:
• Planck significantly improved WMAP constraints on primordial NG, but this observational "window" did not show evidence for new physics
• The qualitative picture from WMAP is unchanged (single-field slow-roll inflation is OK, ekpyrosis is OK, etc.)
• Next step: rapid improvement in r in the next few years
• After that: slow process of "chipping away" on some (not all) types of primordial NG in large-scale structure