Title: Some new things to do with the CMB and galaxy surveys

Date: Mar 20, 2012 11:00 AM

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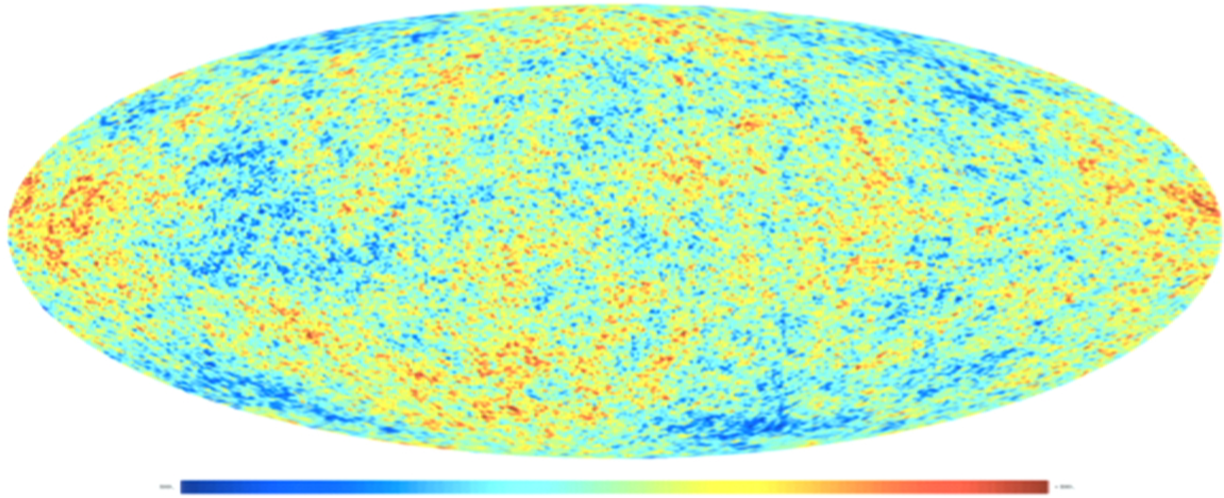
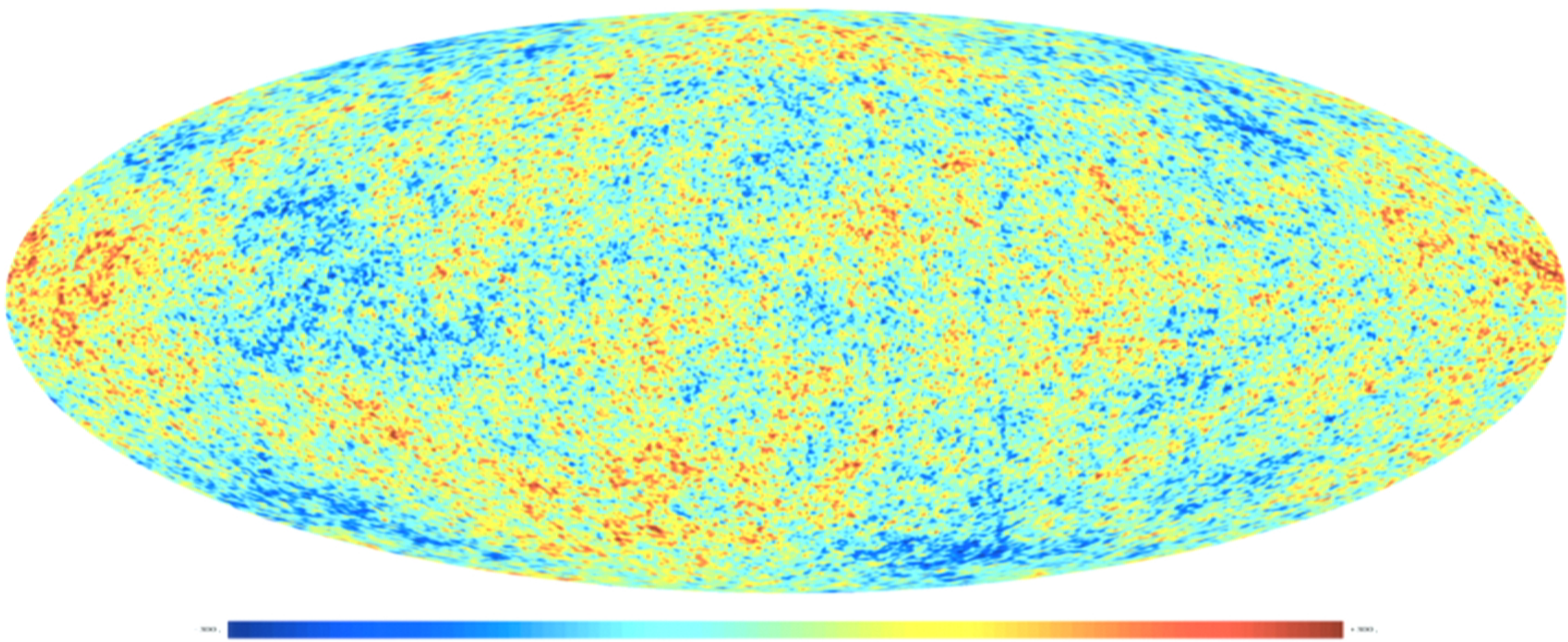
Abstract: Over the past several decades we have obtained increasingly precise data on the distribution of galaxies in the Universe and on the distribution of primordial perturbations via CMB measurements. This trend is likely to continue for the foreseeable future. In this talk I will discuss some new things to do with data from the CMB, galaxy surveys, and future 21-cm surveys look for new physics in the early and late Universe. Topics will include cosmic birefringence, new tests for parity violation, gravitational lensing, gravitational waves, and new inflationary physics.



The CMB, Galaxy Surveys (and 21-cm fluctuations): Beyond Power Spectra

Marc Kamionkowski
(Johns Hopkins University)

Perimeter Institute, 20 March 2012



$$T(\hat{n})$$

Here's how we quantify it:

$$a_{lm} = \int d^2\hat{n}\, T(\hat{n})\, Y^*_{lm}(\hat{n})$$

depends on coordinate system.

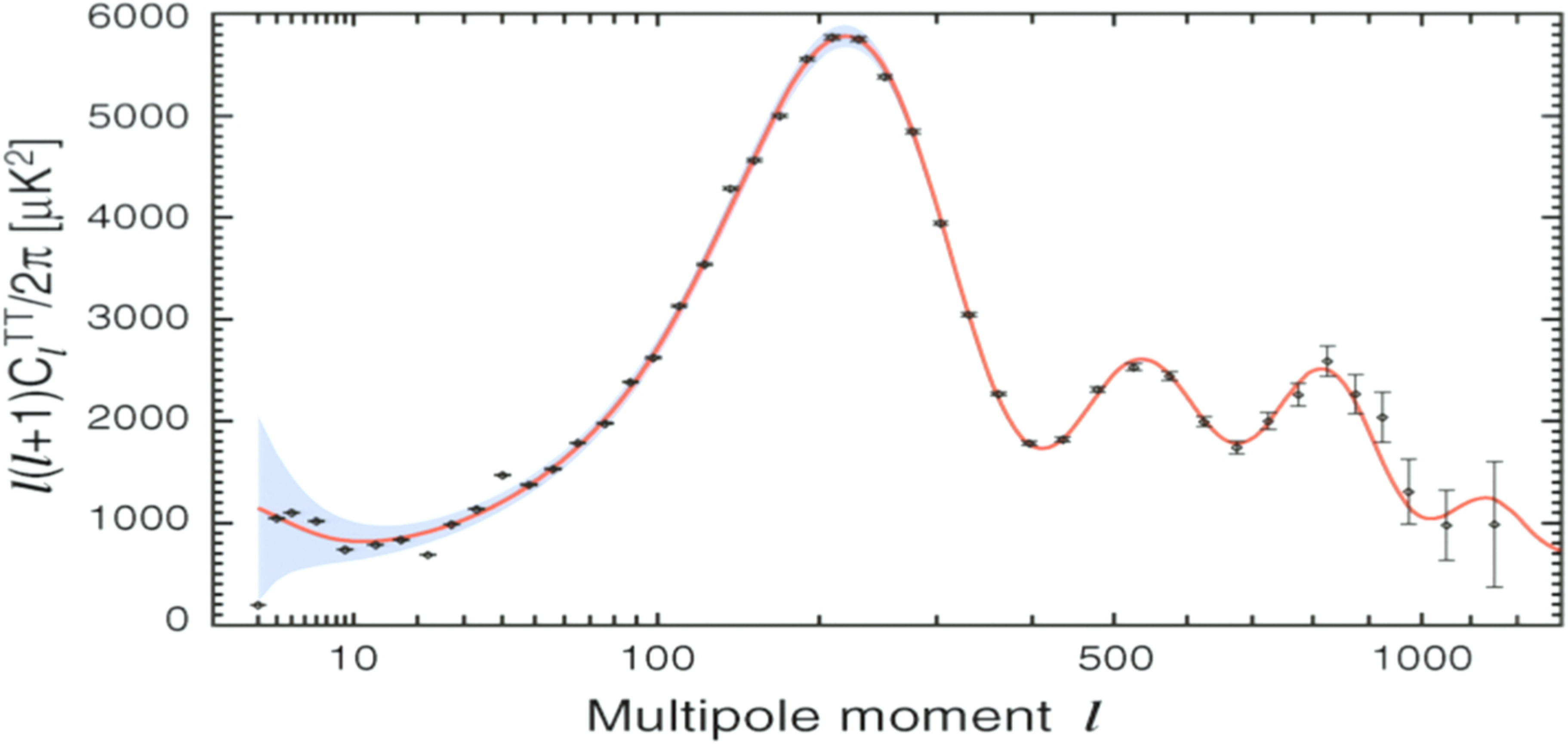
Power spectrum

$$C_l = \sum_m \frac{|a_{lm}|^2}{2l+1}$$

is rotational invariant.

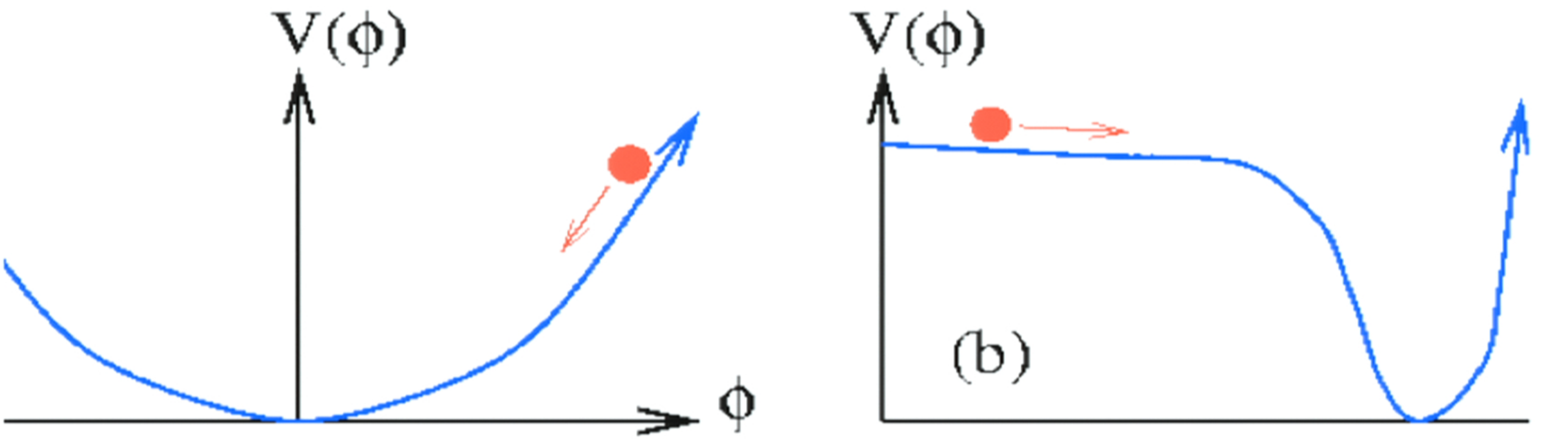
Variance of temperature distribution is

$$\langle (\Delta T)^2 \rangle = \sum_l \frac{2l+1}{4\pi} C_l$$


6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l^{TT}/2\pi\ [\mu K^2]$
10
100
500
1000
Multipole moment l

Interpretation: Temperature fluctuations from primordial density perturbations from inflation

The mechanism: Vacuum energy associated with new ultra-high-energy physics (e.g., grand unification, strings, supersymmetry, extra dimensions....)



Every Fourier mode of inflaton field satisfies SHO-like equation of motion:

$$\ddot{\phi}_{\vec{k}} + k^2 \phi_{\vec{k}} = 0$$

Then imprinted as primordial density perturbations

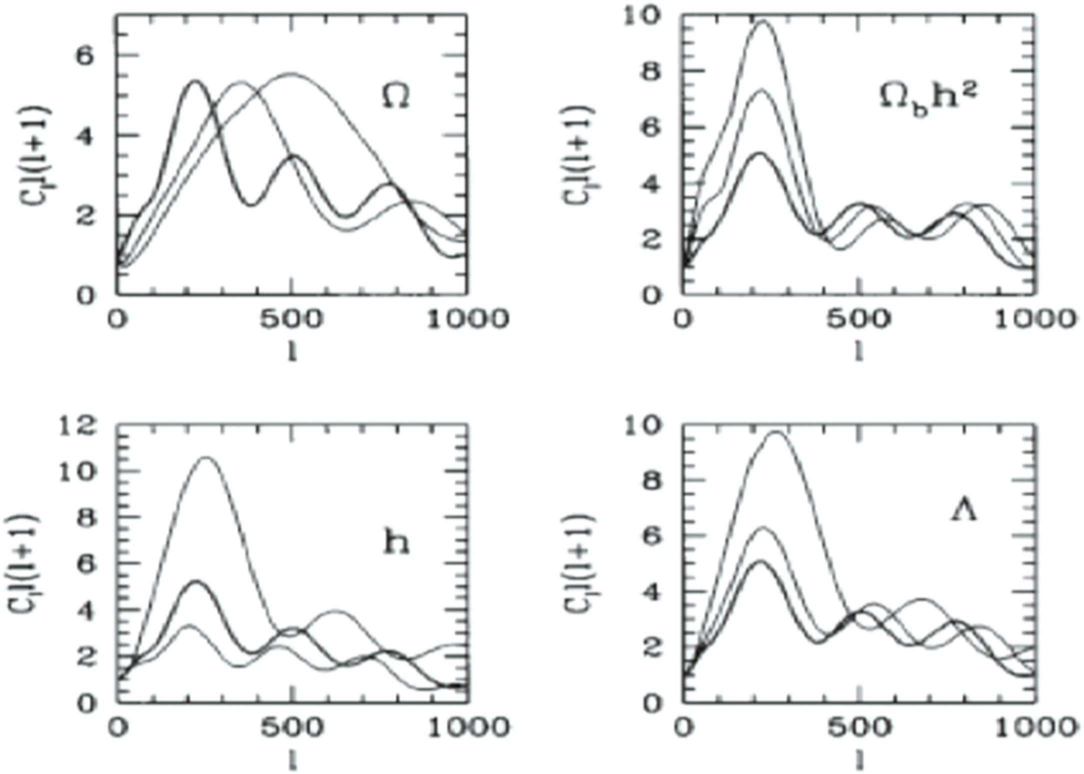
➔ Amplitude of each Fourier mode selected from Gaussian random distribution (the ground-state SHO wave function)

Inflationary prediction is that CMB is realization of statistically isotropic Gaussian random field: each a_{lm} is statistically independent and there is no m dependence

$$\langle a^*_{lm} a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

Power spectra depend on cosmological parameters, so measurement allows their determination (Jungman, MK, et al. 1996)

$$\{\Omega_{\rm m}, \Omega_{\rm de}, w, \Omega_{\rm b}, \Omega_{\nu}, H_0, \tau_{\rm reion}, n_s, \cdots\}$$



As has now been done......

FIVE-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE*[*] OBSERVATIONS: LIKELIHOODS AND PARAMETERS FROM THE *WMAP* DATA

J. Dunkley[1,2,3], E. Komatsu[4], M. R. Nolta[5], D. N. Spergel[2,6], D. Larson[7], G. Hinshaw[8], L. Page[1], C. L. Bennett[7], B. Gold[7], N. Jarosik[1], J. L. Weiland[9], M. Halpern[10], R. S. Hill[9], A. Kogut[8], M. Limon[11], S. S. Meyer[12], G. S. Tucker[13], E. Wollack[8], and E. L. Wright[14]

This paper focuses on cosmological constraints derived from analysis of *WMAP* data alone. A simple ΛCDM cosmological model fits the five-year *WMAP* temperature and polarization data. The basic parameters of the model are consistent with the three-year data and now better constrained: $\Omega_b h^2 = 0.02273 \pm 0.00062$, $\Omega_c h^2 = 0.1099 \pm 0.0062$, $\Omega_\Lambda = 0.742 \pm 0.030$, $n_s = 0.963^{+0.014}_{-0.015}$, $\tau = 0.087 \pm 0.017$, and $\sigma_8 = 0.796 \pm 0.036$, with $h = 0.719^{+0.026}_{-0.027}$. With five years of polarization data, we have measured the optical depth to reionization, $\tau > 0$, at 5σ significance. The redshift of an instantaneous reionization is constrained to be $z_{\rm reion} = 11.0 \pm 1.4$ with 68% confidence. The 2σ lower limit is $z_{\rm reion} > 8.2$, and the 3σ limit is $z_{\rm reion} > 6.7$. This excludes a sudden reionization of the universe at $z = 6$ at more than 3.5σ significance, suggesting that reionization was an extended process. Using two methods for polarized foreground cleaning we get consistent estimates for the optical depth, indicating an error due to the foreground treatment of $\tau \sim 0.01$. This cosmological model also fits small-scale cosmic microwave background (CMB) data, and a range of astronomical data measuring the expansion rate and clustering of matter in the universe. We find evidence for the first time in the CMB power spectrum for a nonzero cosmic neutrino background, or a background of relativistic species, with the standard three light neutrino species preferred over the best-fit ΛCDM model with $N_{\rm eff} = 0$ at $> 99.5\%$ confidence, and $N_{\rm eff} > 2.3$ (95% confidence limit (CL)) when varied. The five-year *WMAP* data improve the upper limit on the tensor-to-scalar ratio, $r < 0.43$ (95% CL), for power-law models, and halve the limit on r for models with a running index, $r < 0.58$ (95% CL). With longer integration we find no evidence for a running spectral index, with $dn_s/d\ln k = -0.037 \pm 0.028$, and find improved limits on isocurvature fluctuations. The current *WMAP*-only limit on the sum of the neutrino masses is $\sum m_\nu < 1.3$ eV (95% CL), which is robust, to within 10%, to a varying tensor amplitude, running spectral index, or dark energy equation of state.

What else can we do?

What else can we do?

1. Polarization

Detection of gravitational waves with CMB polarization

"E modes"

"B modes"

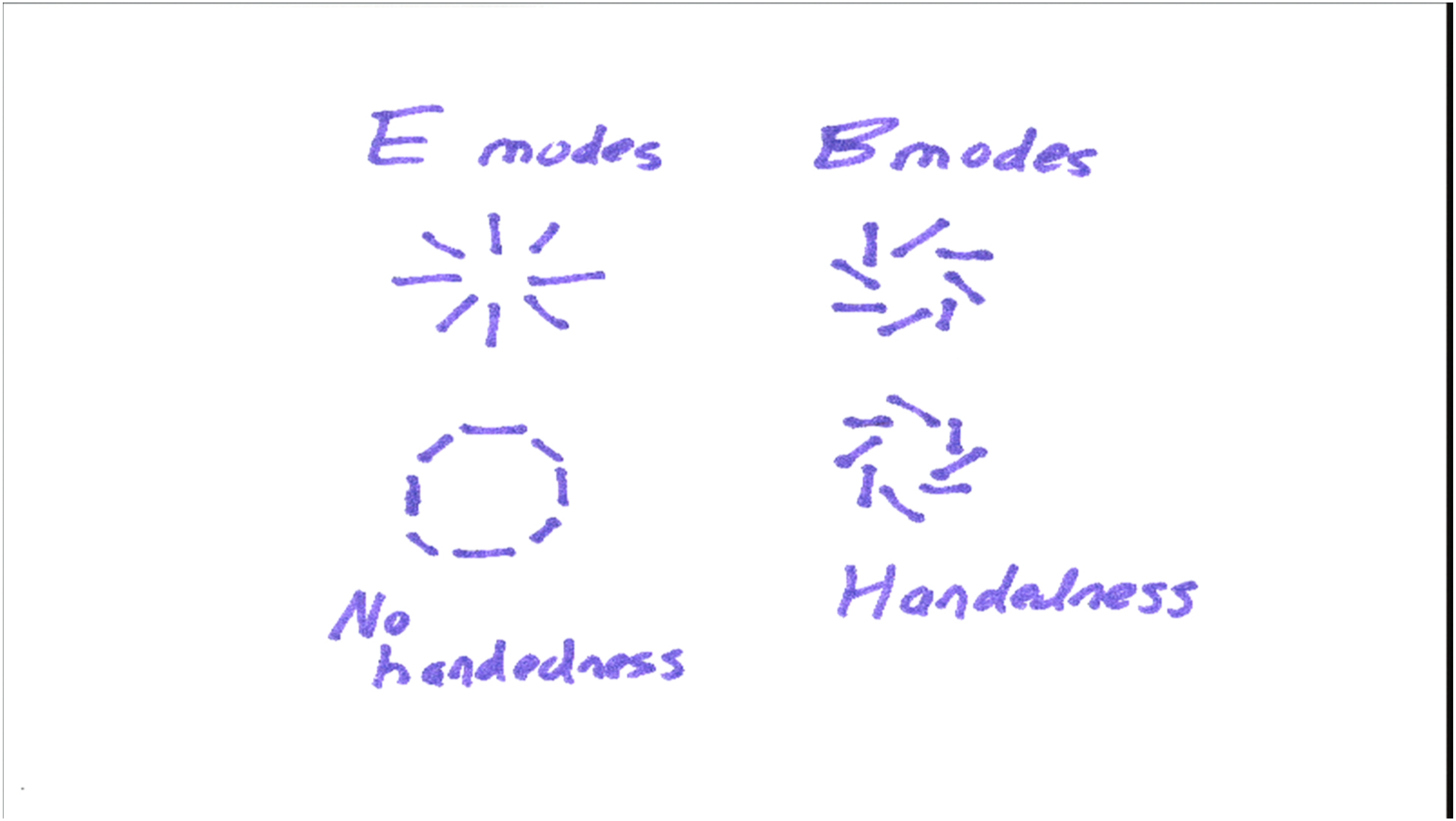
Temperature map: $T(\hat{n})$

Polarization Map: $\vec{P}(\hat{n}) = \vec{\nabla} A + \vec{\nabla} \times \vec{B}$

Density perturbations have no handedness"
so they can*not* produce a polarization with a curl

Gravitational waves do have a handedness, so they can (and do) produce a curl

(MK, Kosowsky, Stebbins 1996; Seljak, Zaldarriaga 1996)


E modes
B modes
No handedness
Handedness

Now SIX CMB power spectra

C_l^{TT} C_l^{EE} C_l^{BB}

C_l^{TE} C_l^{TB} C_l^{EB}

(parity breaking)

From three sets of temperature/polarization coefficients:

a_{lm}^{T} a_{lm}^{E} a_{lm}^{B}

Cosmological birefringence

- If some *Φ(t)* couples to E&M through:

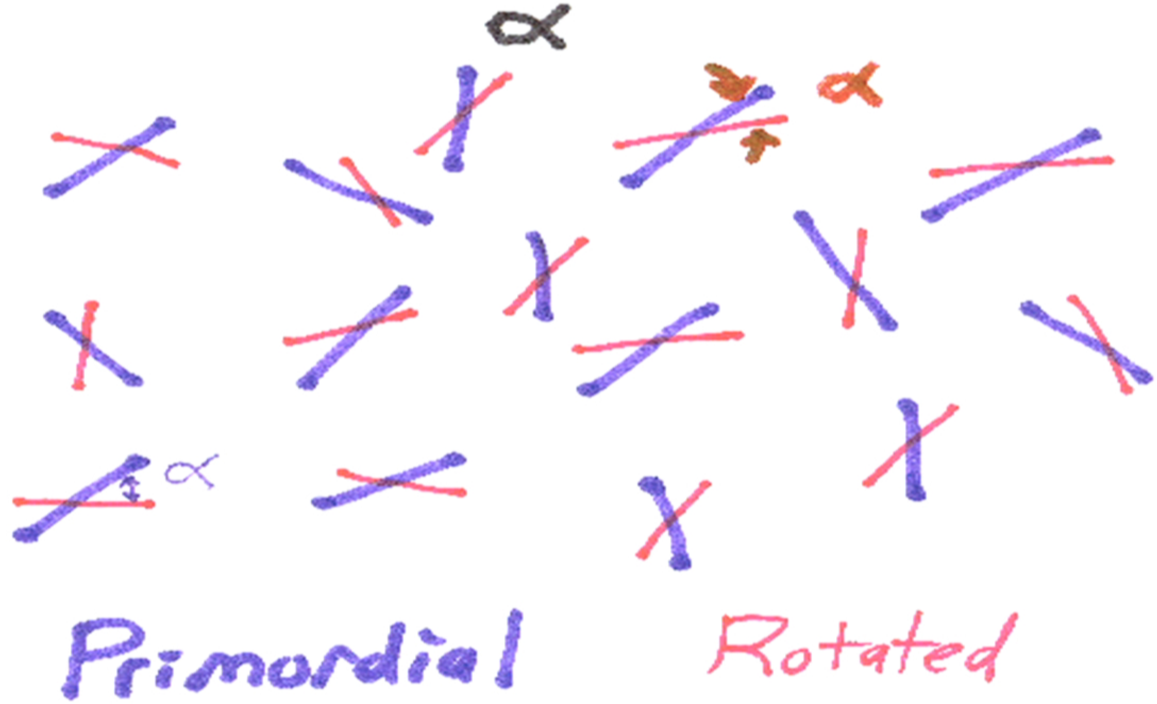
$$\mathcal{L} = \frac{1}{2}(\vec{E}^2 - \vec{B}^2) + \frac{\phi(t)}{M_*}\vec{E}\cdot\vec{B}$$

Φ(t) leads to rotation by $\alpha=\Delta\phi/M_*$, of polarization as photons propagate (Carroll, Field, Jackiw 1998)
Rotation induces EB cross-correlation (Lue, Wang, MK 1999)

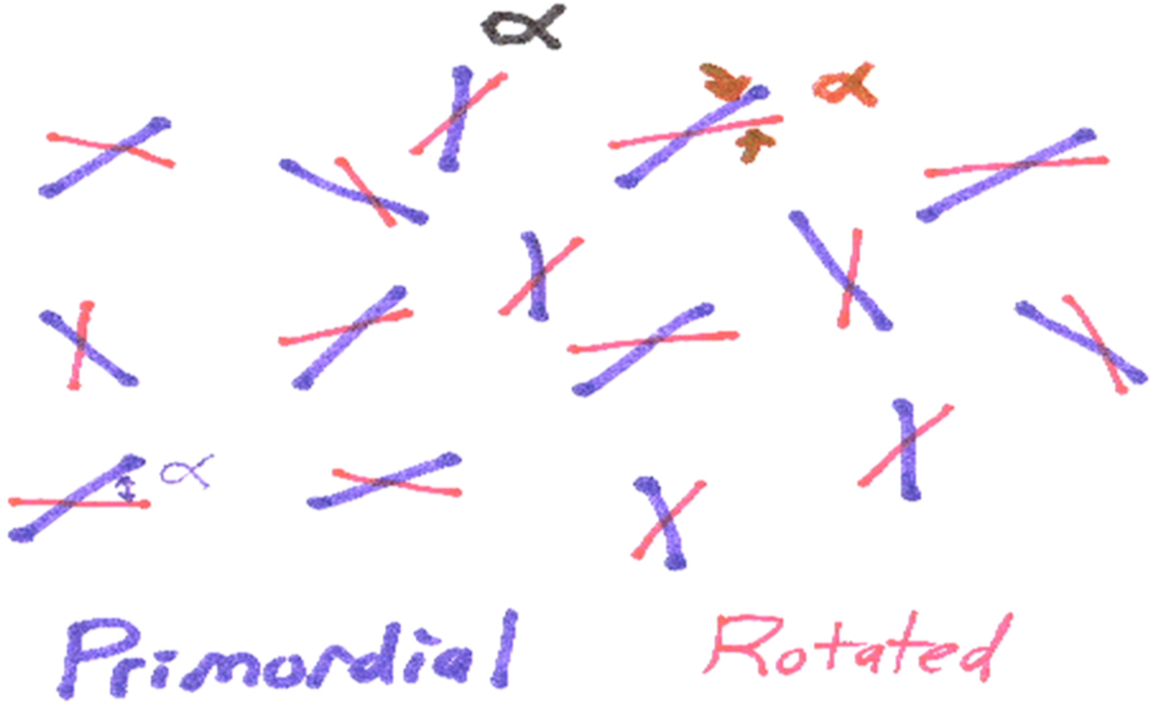
CMB searches: $\alpha<$few degrees (Feng et al., astro-ph/0601095; Komatsu et al. 2008; Wu et al. 2008.....)

Right- and left-circularly polarized EM waves propagate with same speed to 10^{-30} !!!

Uniform Rotation



Uniform Rotation



What else can we do?

2. Departures from Gaussianity and Statistical Isotropy

Inflationary prediction,

$$\langle a_{lm}^* a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

can be modified by

- late-time effects (e.g., gravitational lensing)
- Inflationary physics beyond vanilla inflation
- Exotica

Any such effects can be parametrized as

$$\langle a_{lm}^* a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'} + \sum_{L \geq 0} \sum_{M=-L}^{L} \mathcal{C}_{lml'm'}^{LM} A_{ll'}^{LM}$$

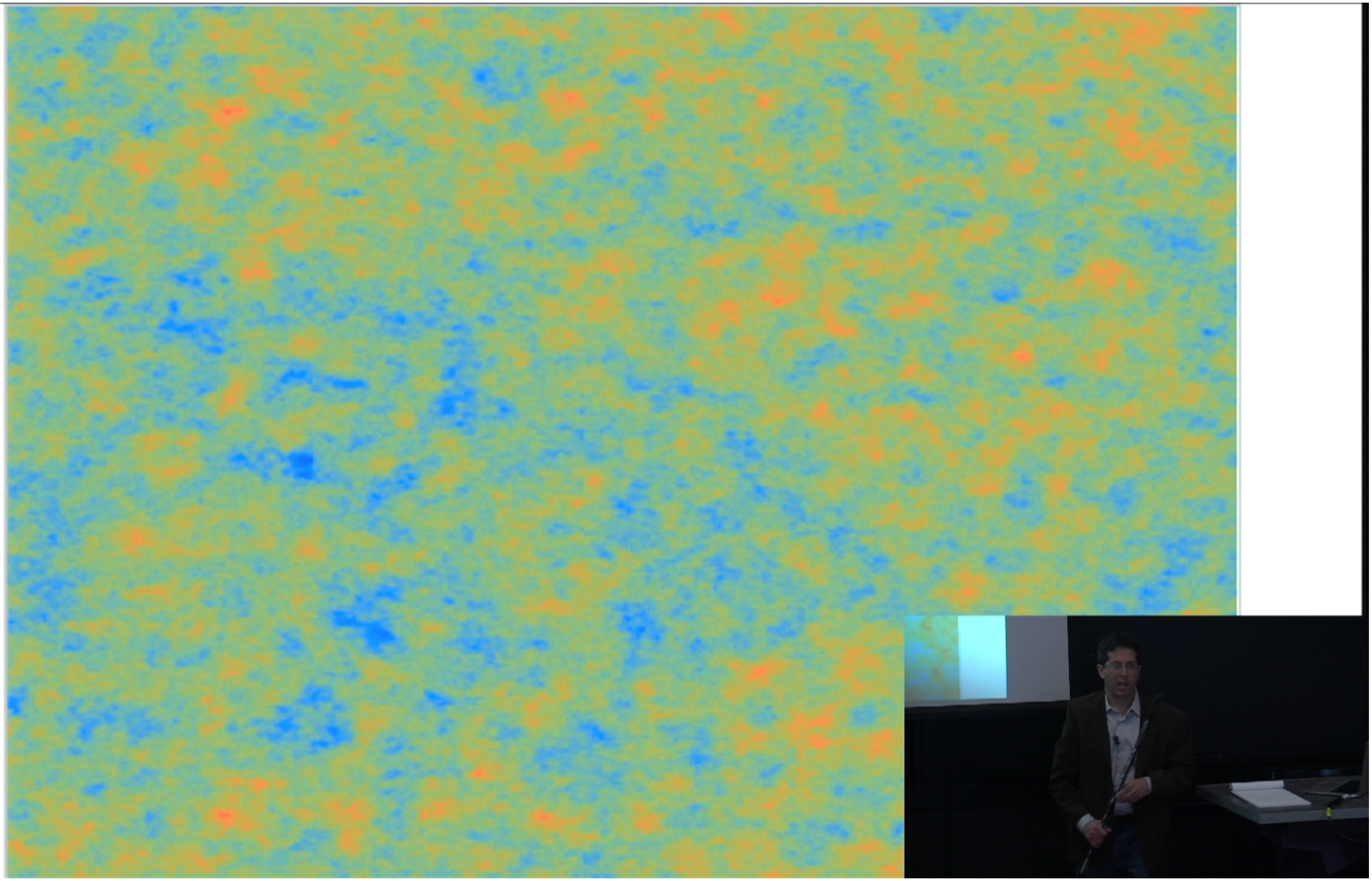
Clebsch-Gordan coefficients

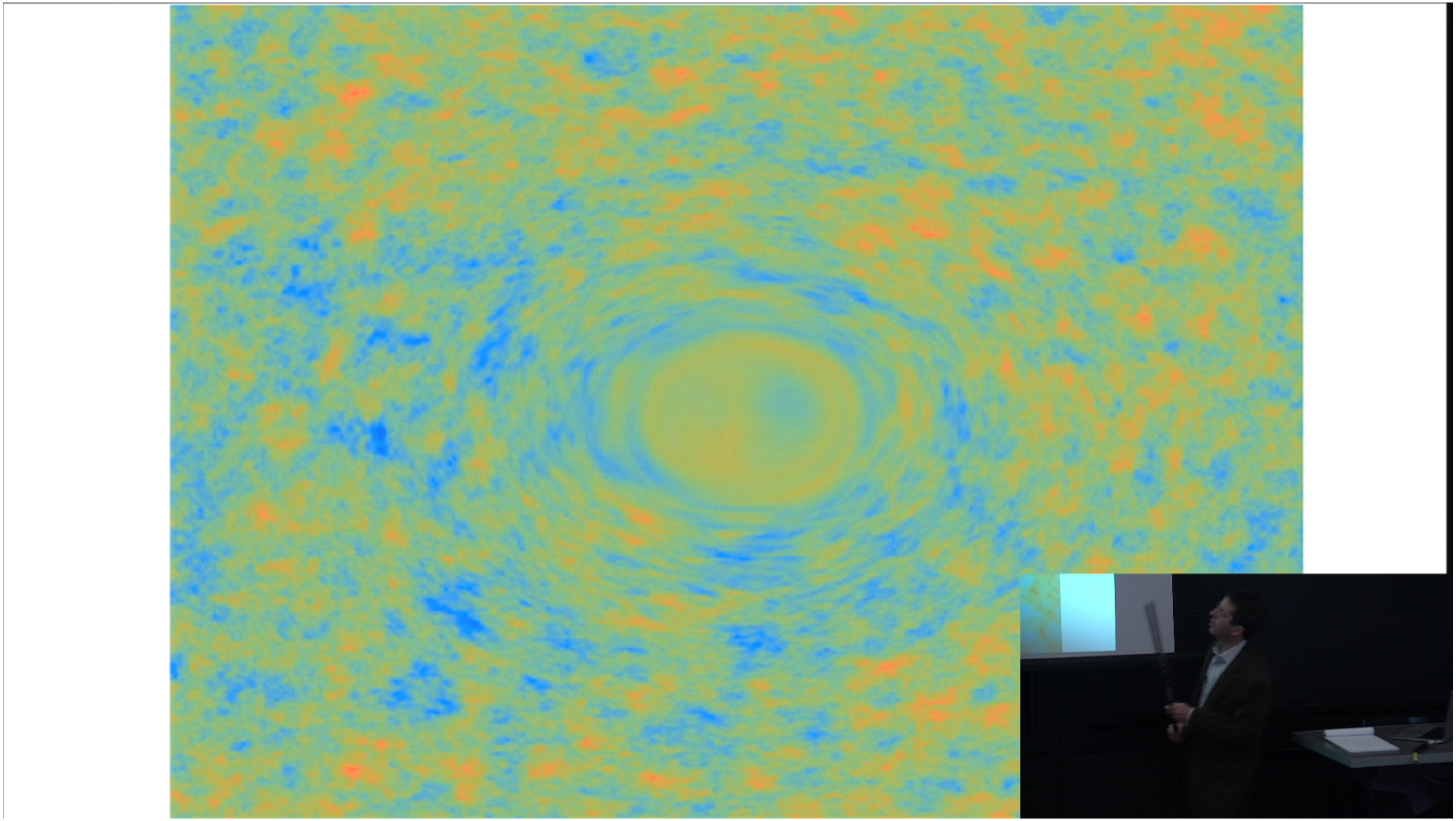
Bipolar spherical harmonics (BiPoSHs)
(Hajian & Souradeep 2004; Book, MK, Souradeep 2011)

Recipe for measuring BiPoSHs (generalizations of power spectrum to direction-dependent fluctuations):

$$\widehat{A_{ll'}^{LM}} = \sum_{lml'm'} \mathcal{C}_{lml'm'}^{LM} a_{lm}^{*} a_{l'm'}$$

Example 1: Weak gravitational lensing of CMB





$$A^{\oplus}{}^{LM}_{ll'} = \frac{\phi_{LM}}{\sqrt{2L+1}} \left[\frac{C_l G^L_{l'l}}{\sqrt{l'(l'+1)}} + \frac{C_{l'} G^L_{ll'}}{\sqrt{l(l+1)}} \right] = Q^{\oplus L}_{ll'} \phi_{LM}$$

where deflection angle is $\vec{\alpha} = \vec{\nabla}\phi$

Lensing of CMB recently detected!
through cross-correlation with galaxy surveys

(Smith, Zahn, Dore 2007; Hirata et al. 2008)

And now without galaxies (Das et al. (ACT) 2010)

Example II (Exotica): Departures from Statistical Isotropy (Pullen,MK, 2007)

- Inflation: Universe statistically isotropic and homogeneous
- Statistical isotropy: Power spectrum does not depend on direction

To test….

- Require family of models that violate statistical isotropy and/or homogeneity, with departure from SI/SH parametrized by quantity that can be dialed to zero (e.g., inflationary models of Ackerman, Carroll, Wise predict power quadrupole)
- Develop estimators that measure SI/SH-violating parameters from observables

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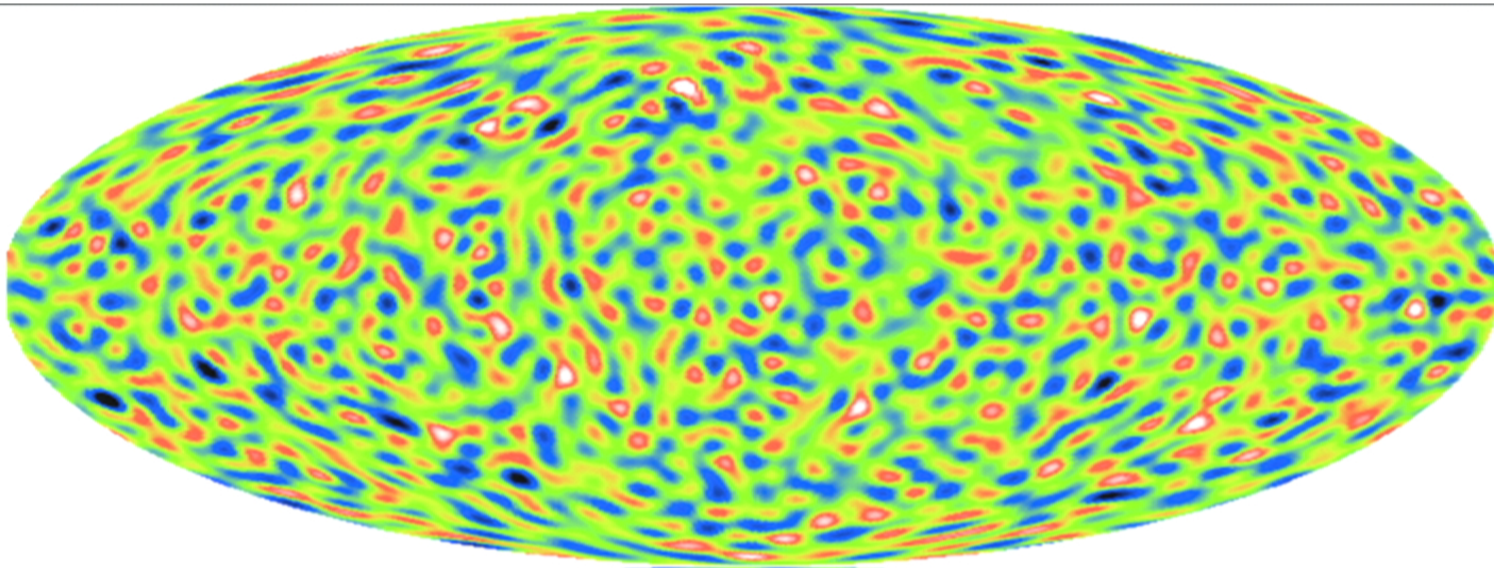
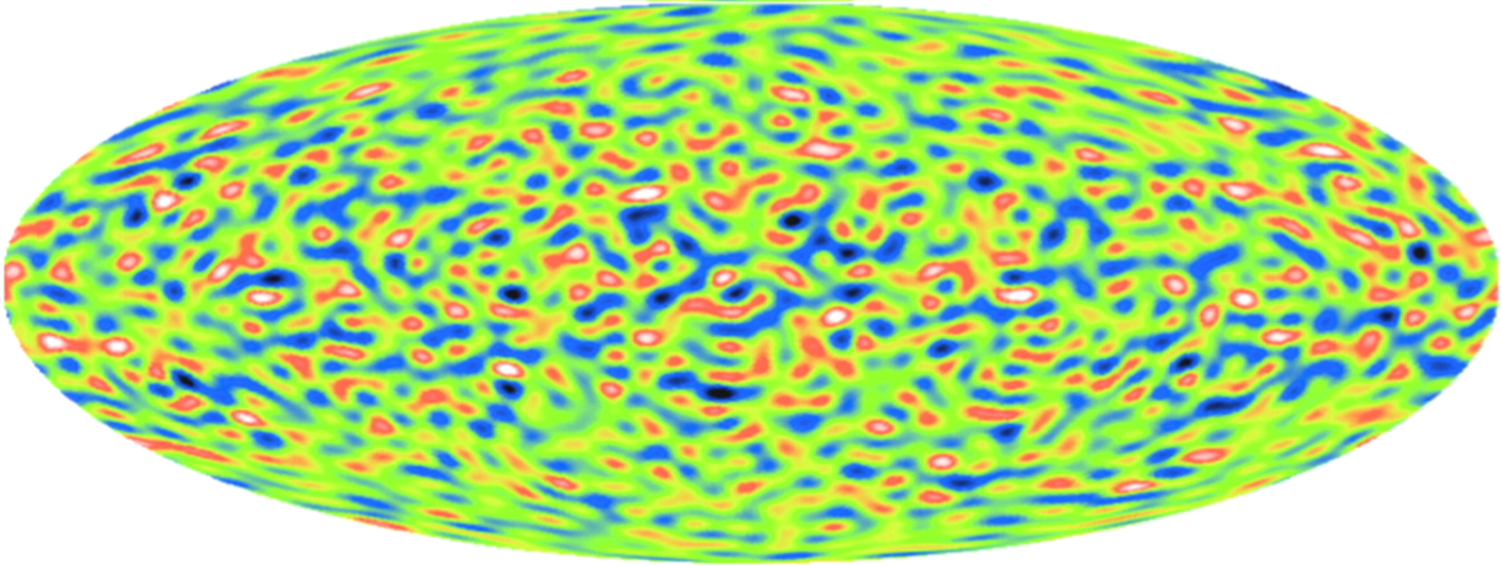
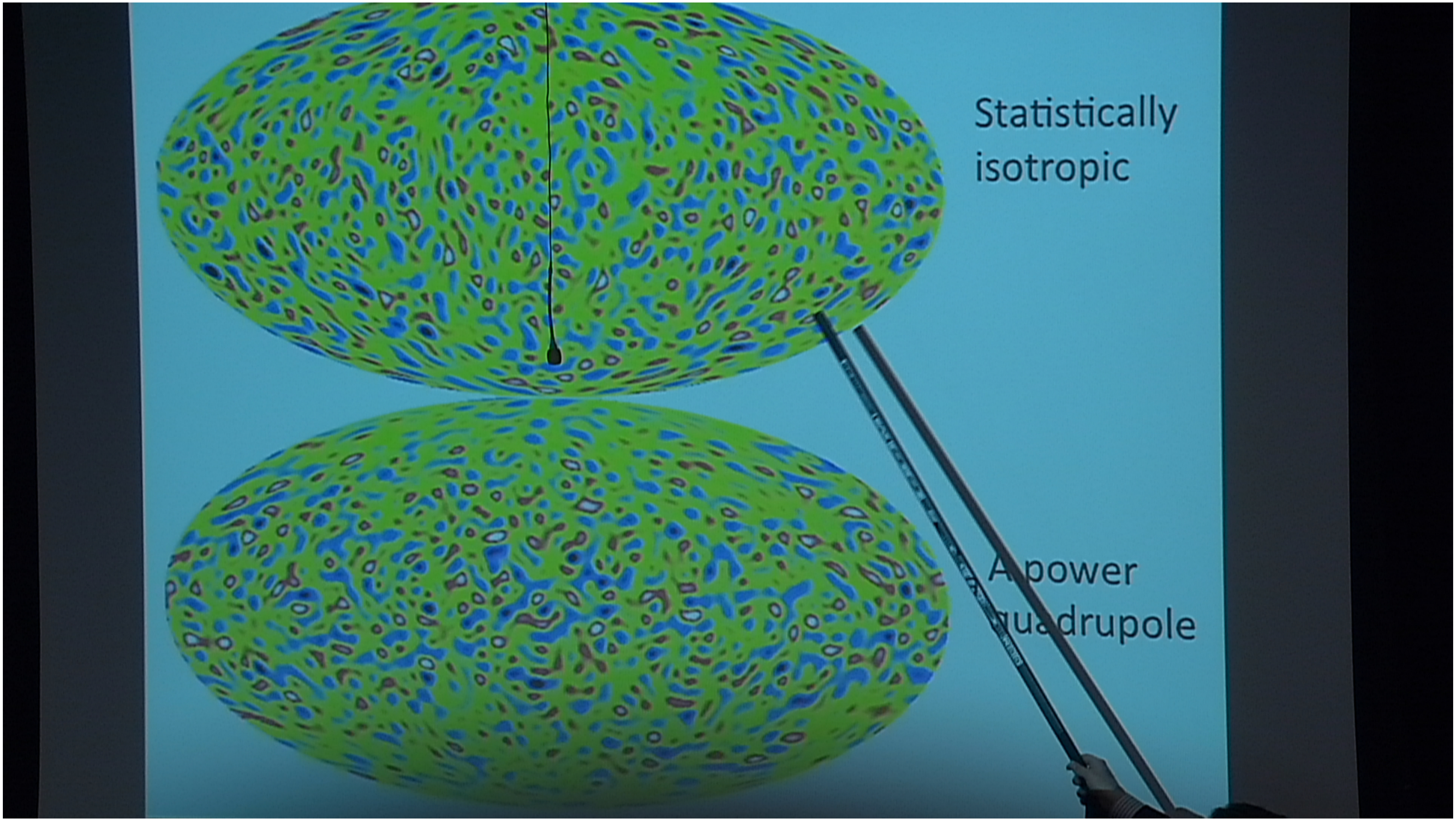


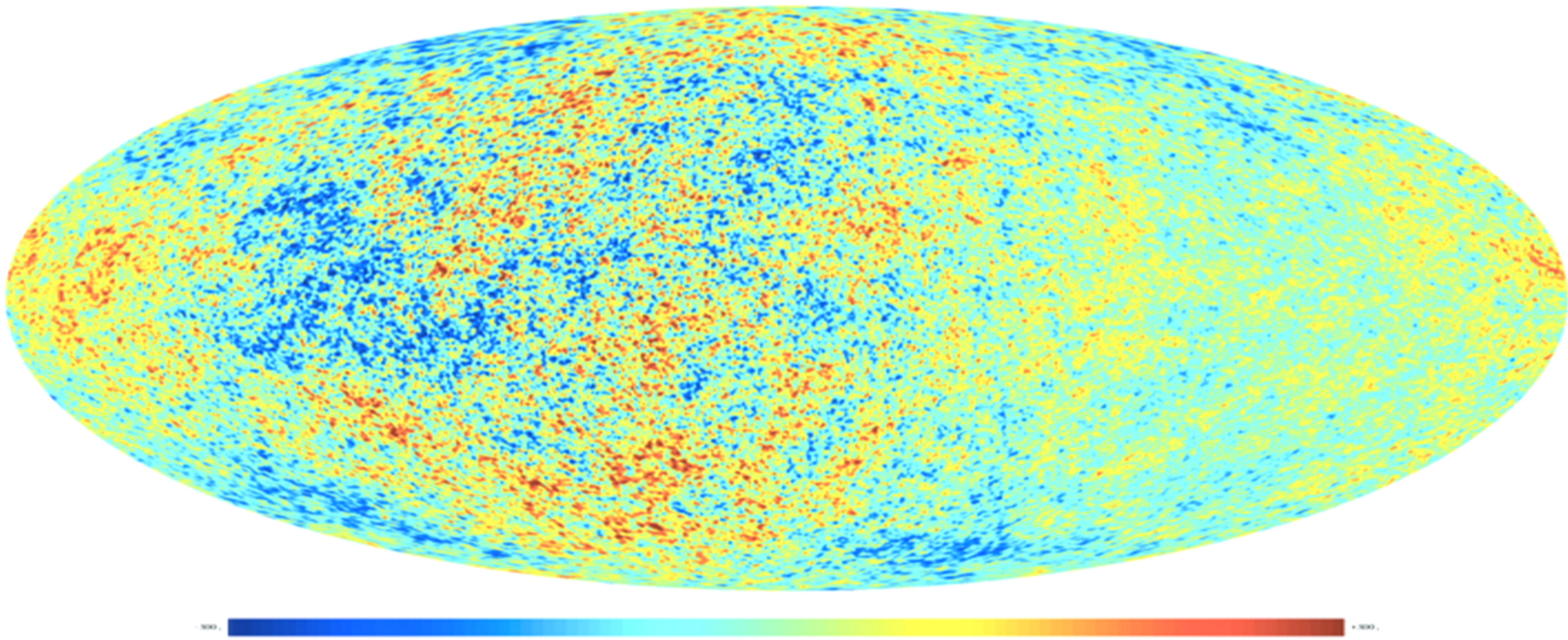
Statistically isotropic



A power quadrupole

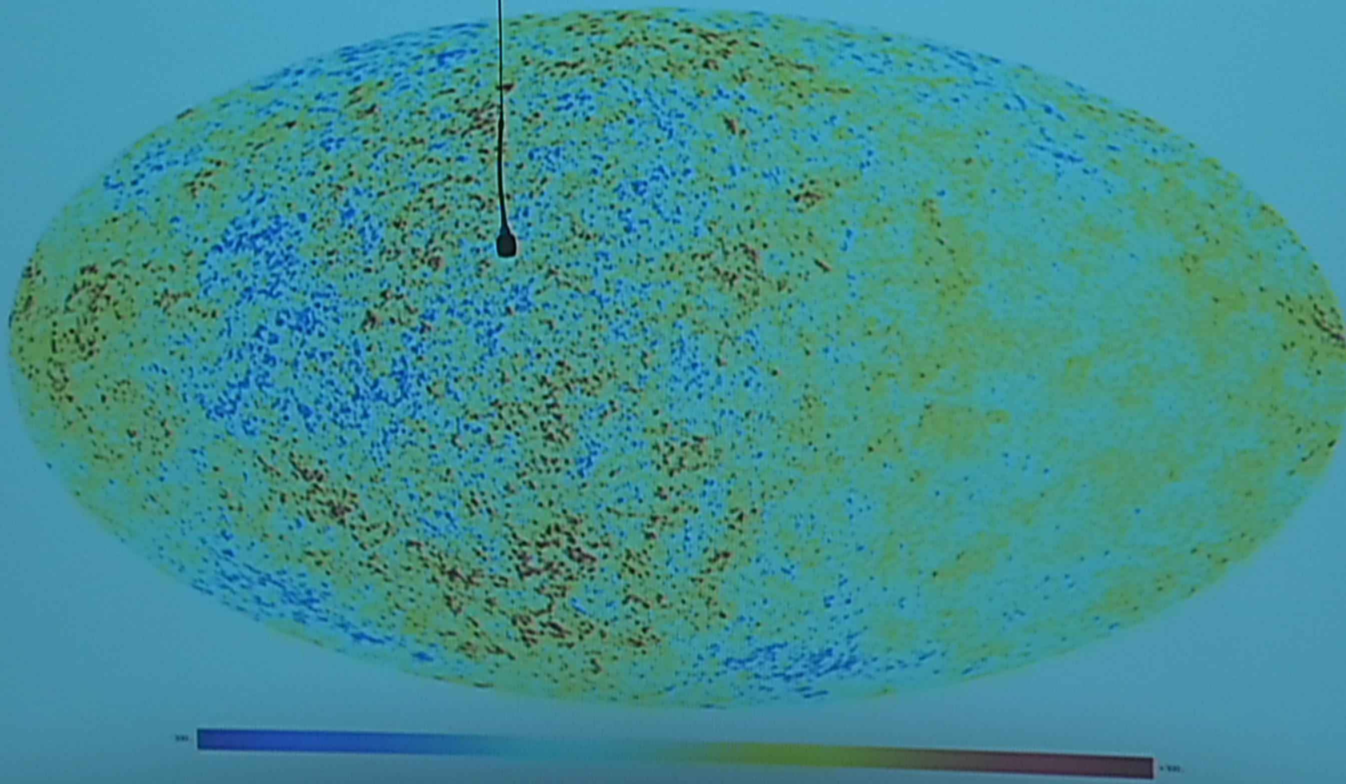

Statistically
isotropic
A power
quadrupole

A power dipole



Erickcek, MK, Carroll 2008; Erickcek, Carroll, MK 2008; Erickcek, Hirata, MK 2009

A power dipole



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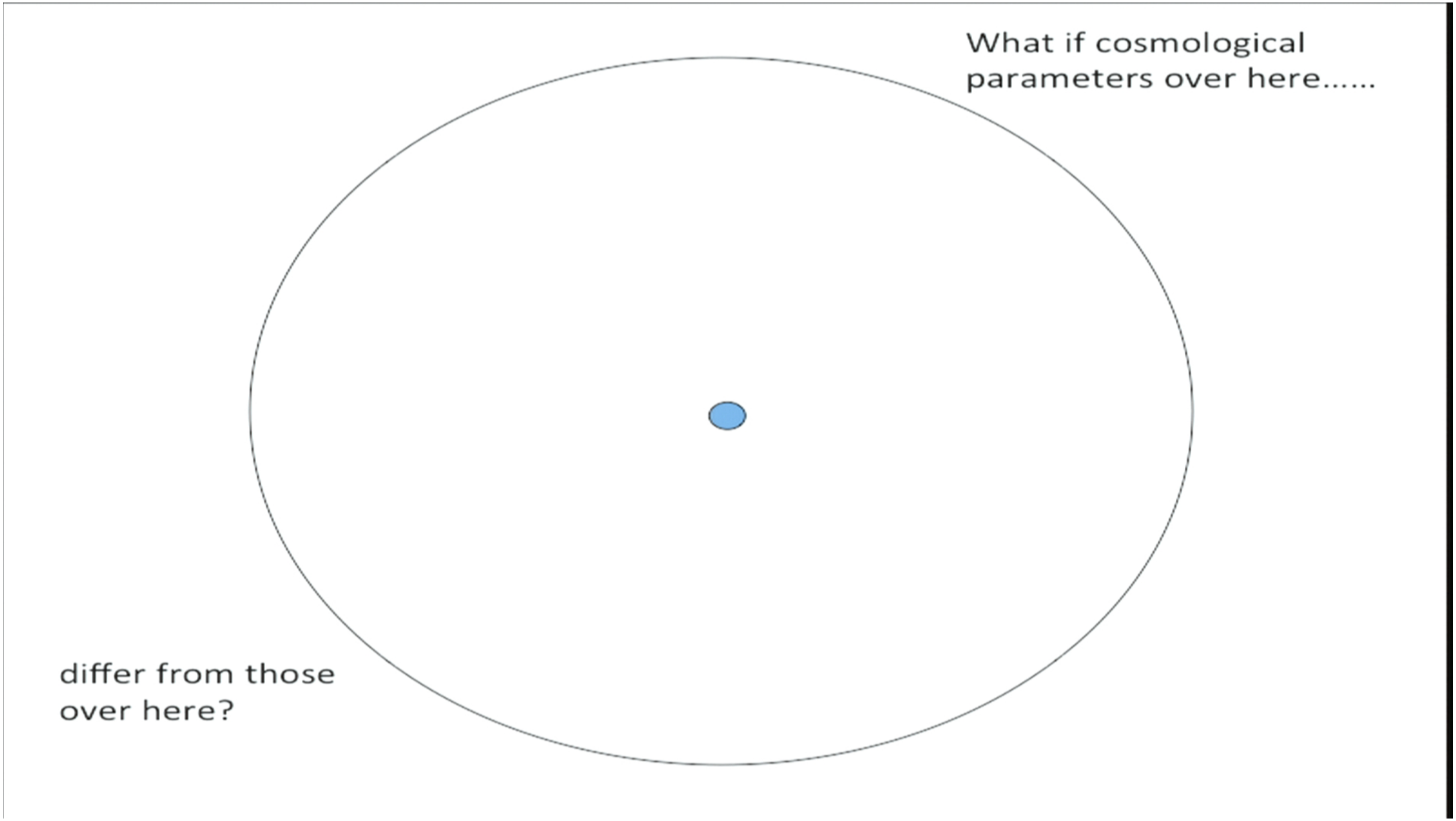
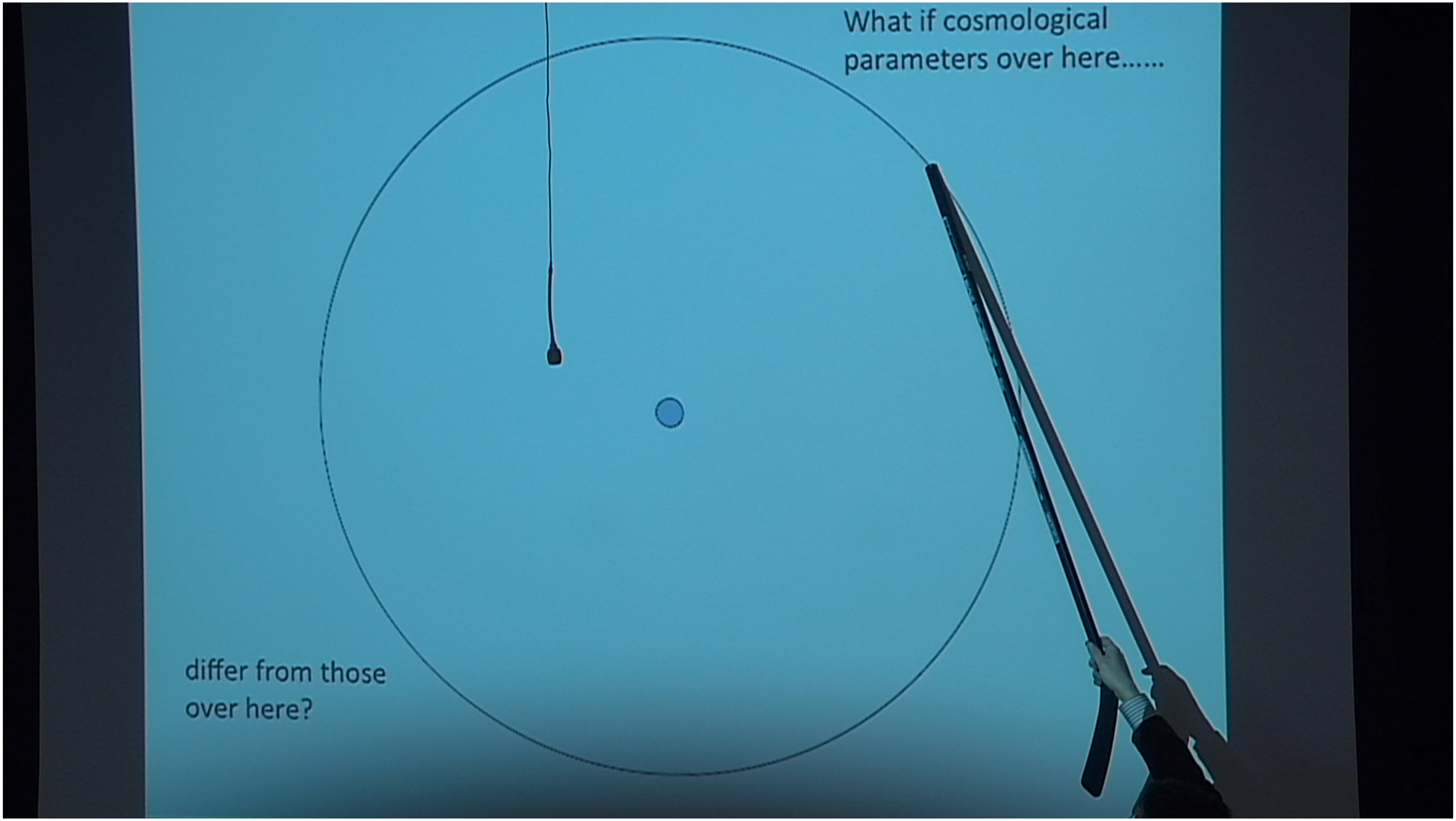

What if cosmological
parameters over here……
differ from those
over here?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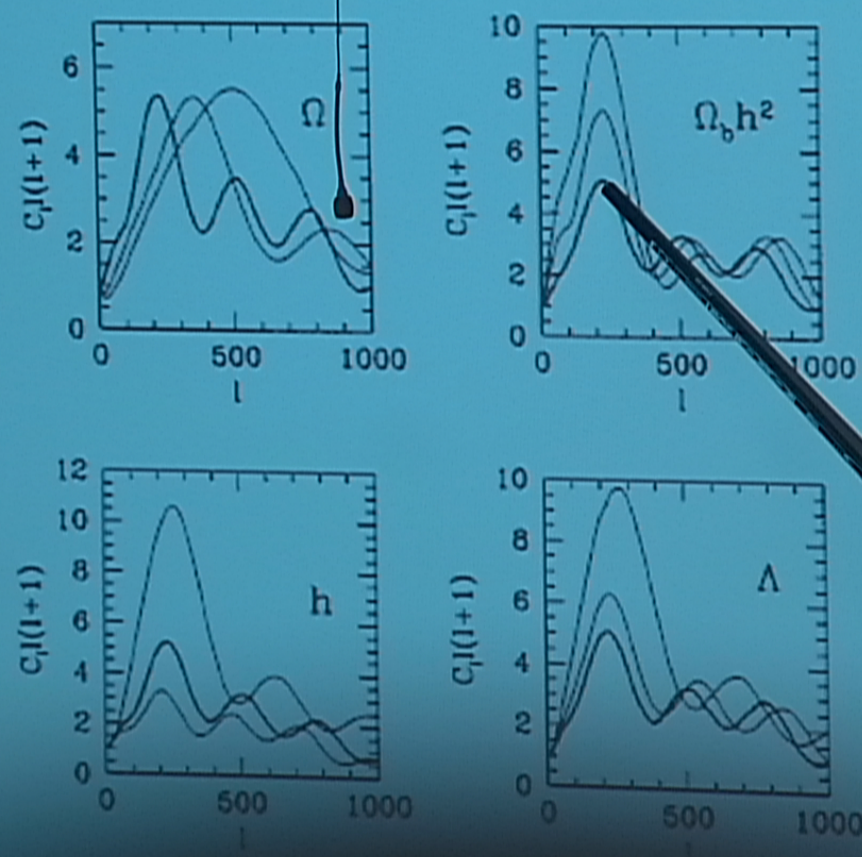
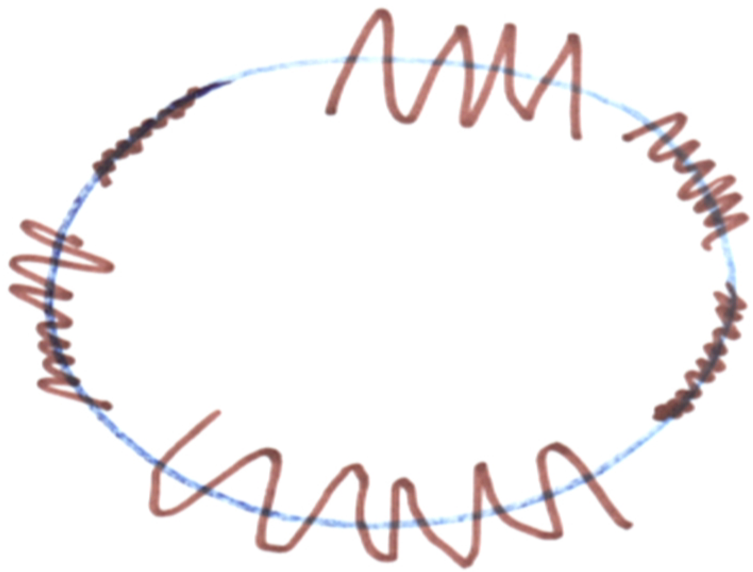
over here?

Then power spectra will differ from one point on sky to another:

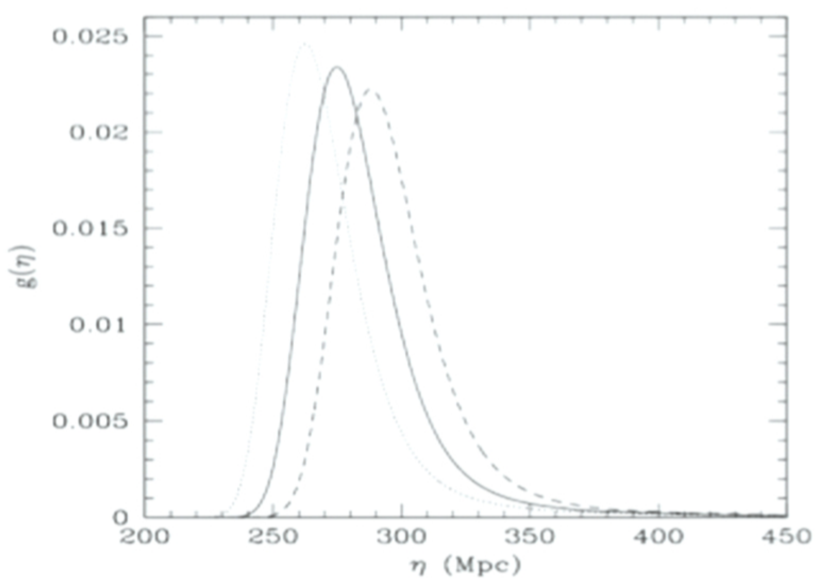


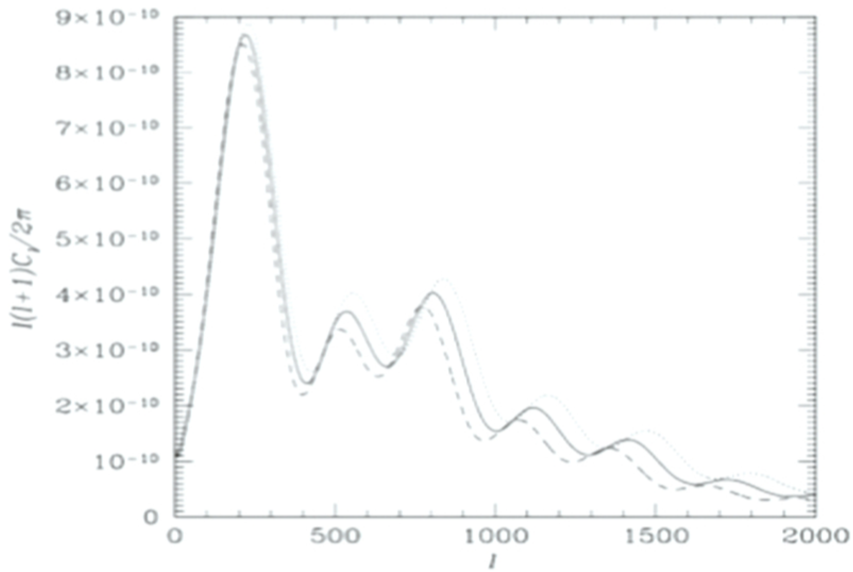
So T fluctuations may vary across sky……



This is described by BiPoSHs

E.g., suppose fine-structure constant varied





Visibility function — Power spectrum

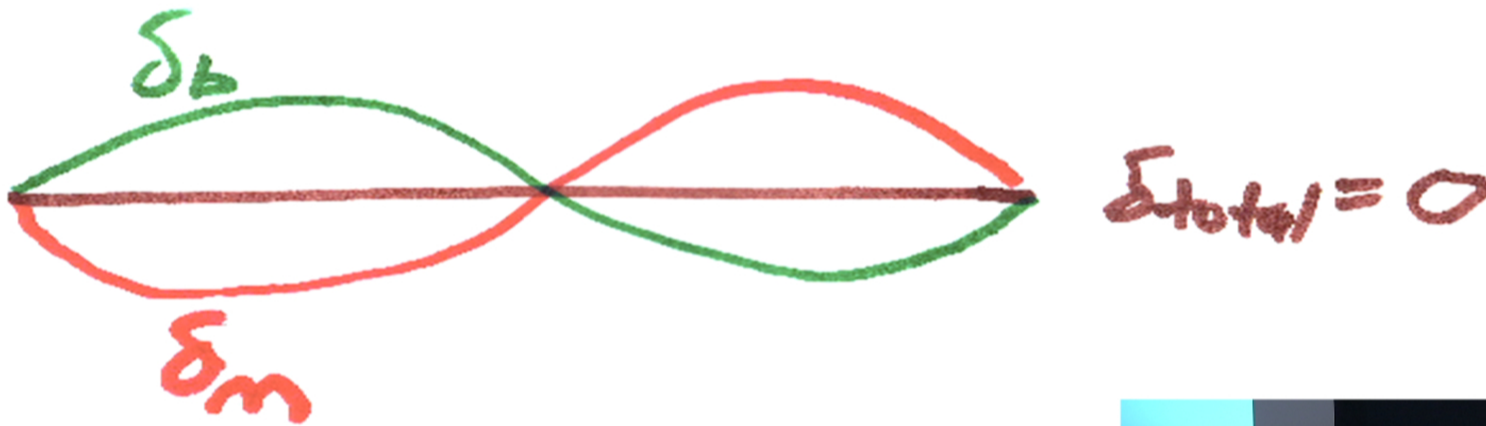
Can be sought with BiPoSHs (Sigurdson, MK, Kurylov 2003)

Another example: Compensated isocurvature perturbations

Baryon-density fluctuation compensated by dark-matter fluctuation of equal magnitude (Pritchard and Gordon 2009; Holder, Nollett, van Engelen 2009)

Strongest current constraint, from baryon-DM ratios measured in galaxy clusters: $\lesssim 10\%$

Compensated isocurvature perturbation



Polarization BiPoSHs: Spatially-varying cosmological birefringence (MK, 2008; Gluscevic, MK, Cooray 2009; Yadav et al. 2009; MK 2010; Gluscevic, MK, Caldwell 2011)

- What if CB rotation angle varies from one point on sky to another?? (e.g., Pospelov, Ritz, Skordis 2008; Caldwell et al., in preparation)
- Then observed polarization has nothing to do with primordial polarization!!!
- Develop technique to measure rotation as function of angle, and thus to infer primordial polarization pattern

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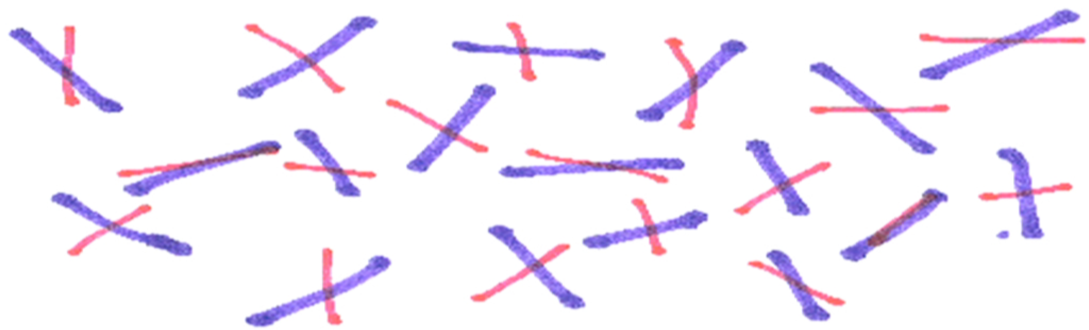
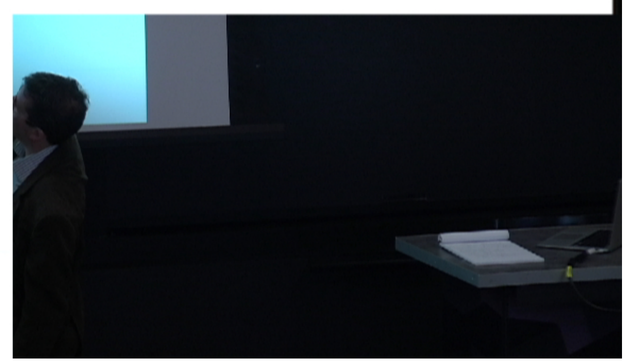
Rotation $\alpha(\hat{n})$ depends on position $\hat{n}$



Primordial   Rotated

? ? ?



Odd-Parity BiPoSHs (Book, MK, Souradeep 2011)

- Lensing, SI violations, patchy reionization, variable cosmological parms all induce only BiPoSHs with L+l+l'=even.
- But BiPoSHs can have L+l+l'=odd
- Odd/even split ~ E/B decomposition for CMB polarization
- Odd-parity BiPoSHs may be induced by lensing by GWs or by pointing errors, asymmetric beams, etc.

New probes of parity violation

- Cross-correlation between even- and odd-parity BiPoSHs are parity breaking. May be induced by chiral GW background

Odd-parity bispectrum (MK, Souradeep 2010)

- Three-pt functions from inflation have

$$\langle a_{l_1 m_1} a_{l_2 m_2} a_{l_3 m_3} \rangle \neq 0 \quad \text{for} \quad l_1 + l_2 + l_3 = \text{even}$$

but odd-parity bispectrum, with

$$l_1 + l_2 + l_3 = \text{odd}$$

is also allowed mathematically and can be measured from data.

Allows probe of novel parity-breaking early-Universe physics and new set of null tests for systematics in experiments

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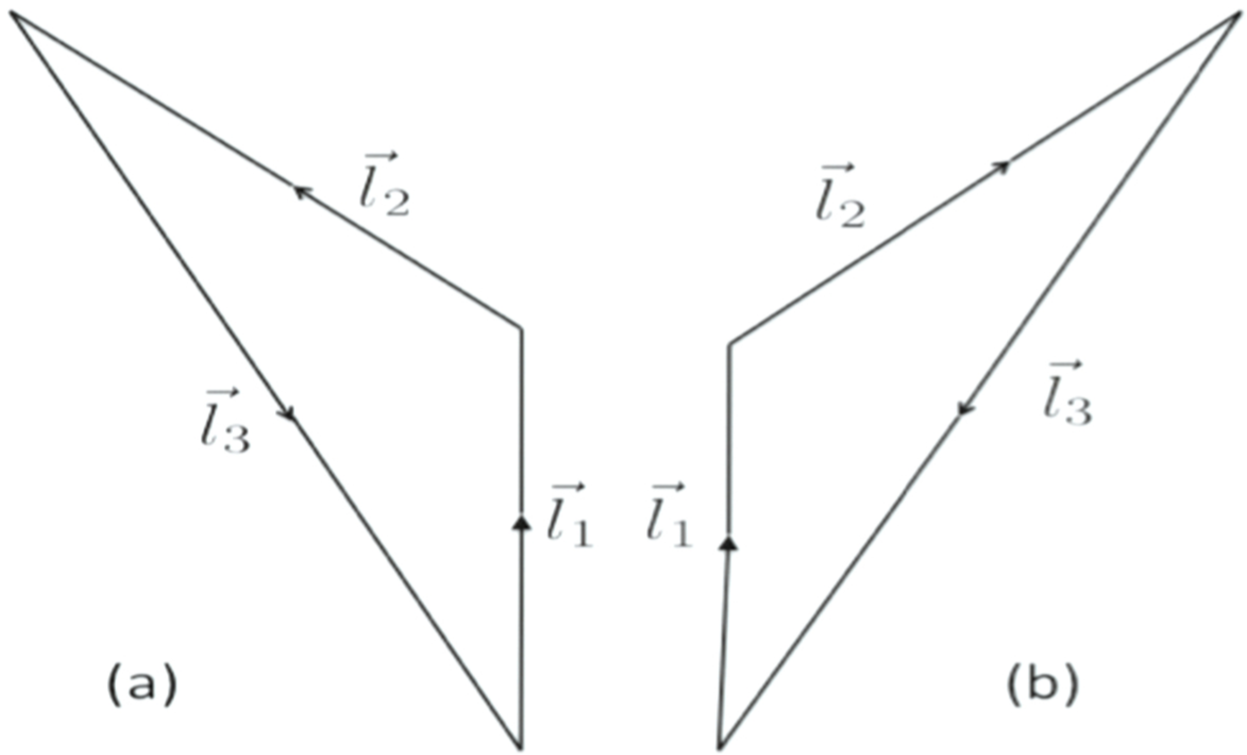
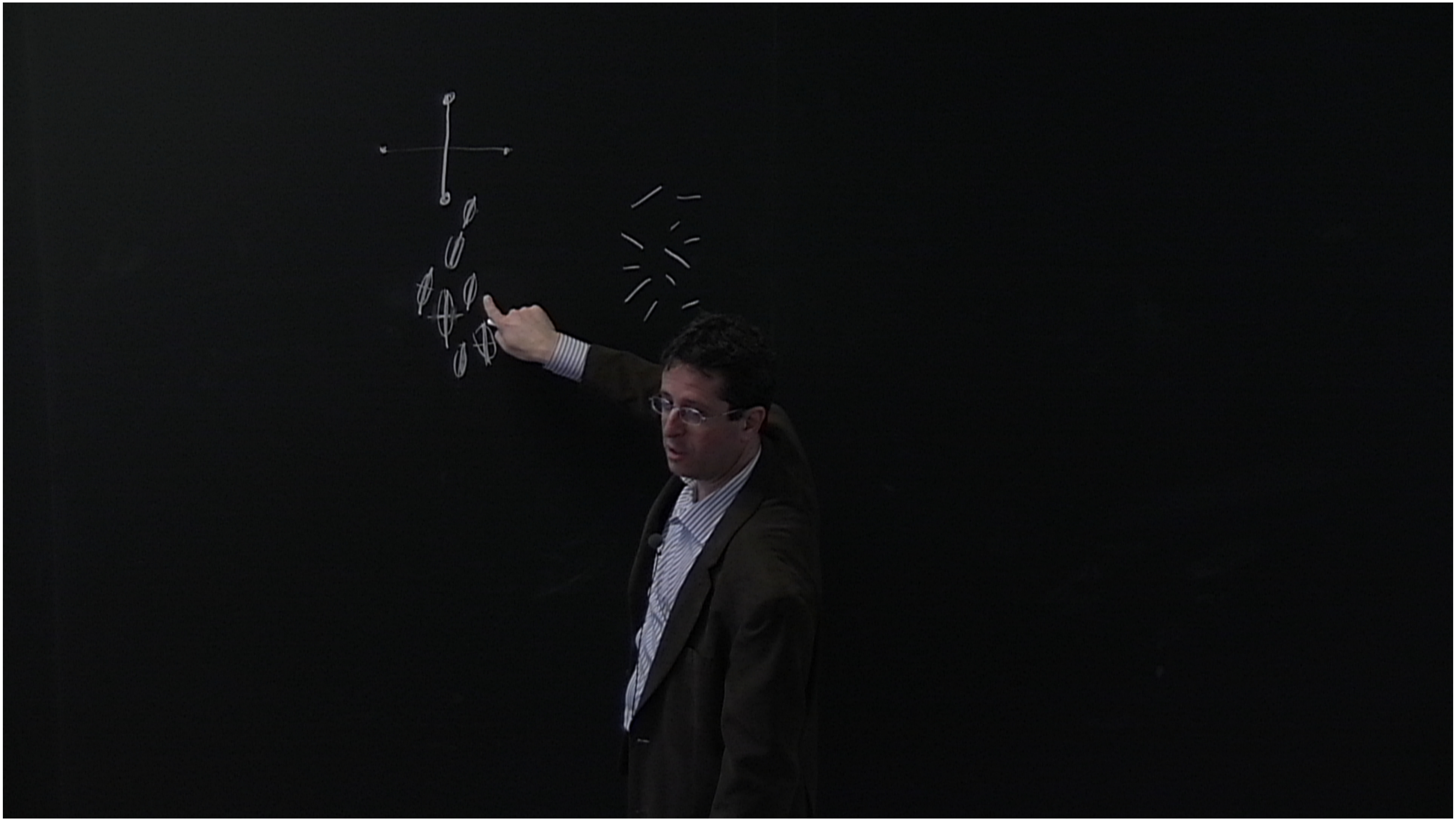
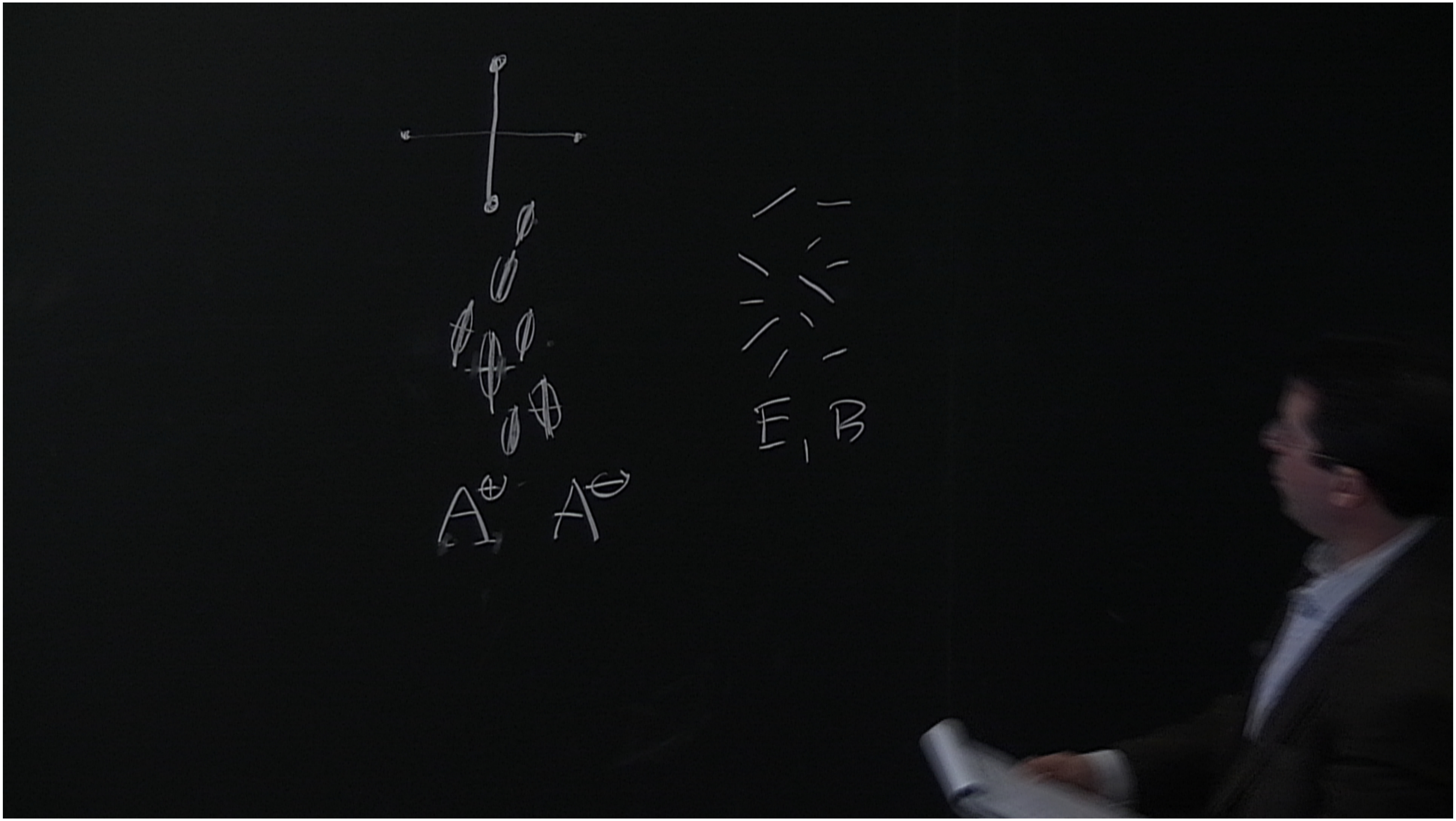
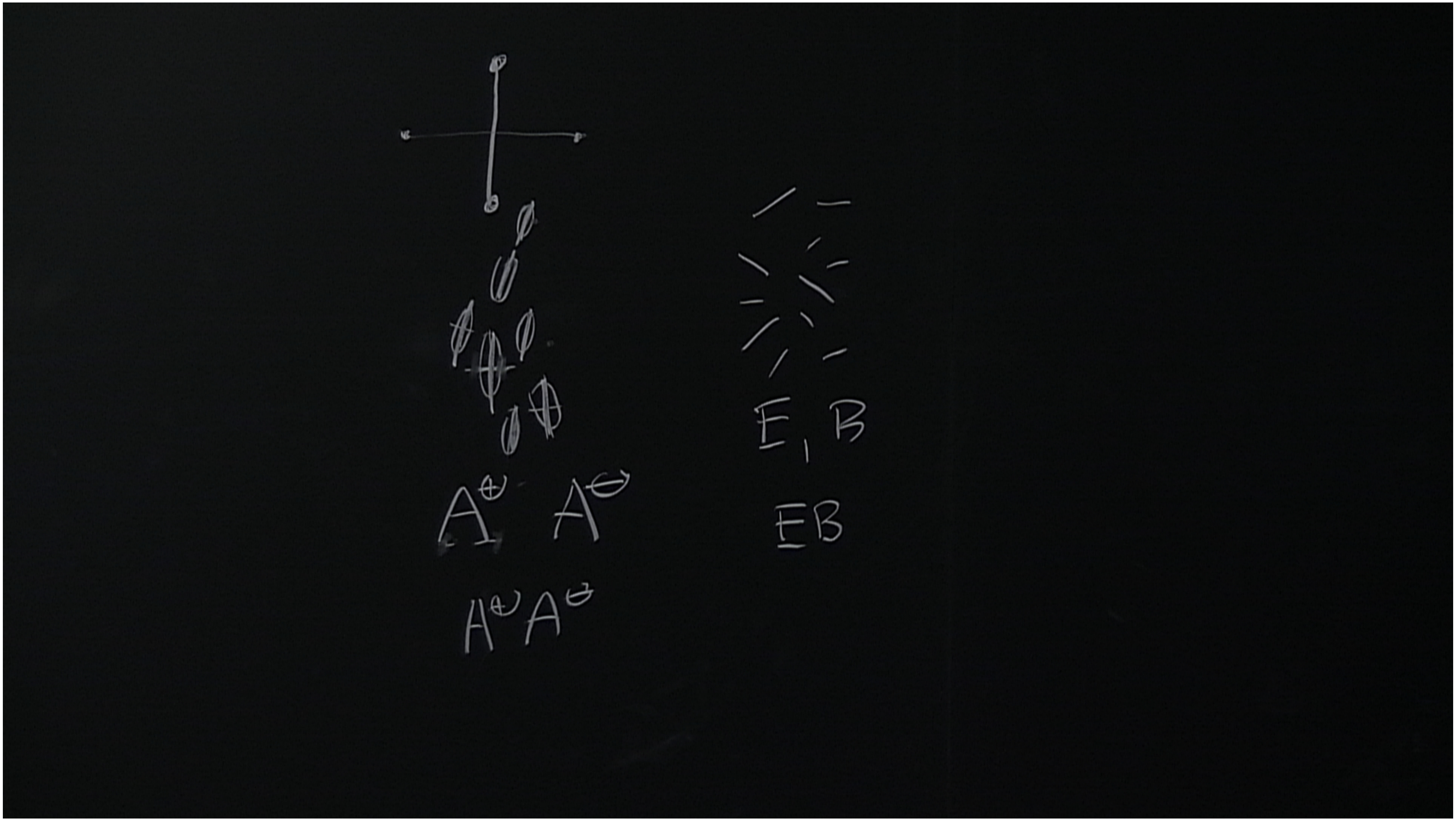


Odd-parity bispectrum differences, rather than sums, contributions from mirror-image triangles




$A^{\oplus}$ $A^{\ominus}$
E, B


$A^{\oplus}$ $A^{\ominus}$
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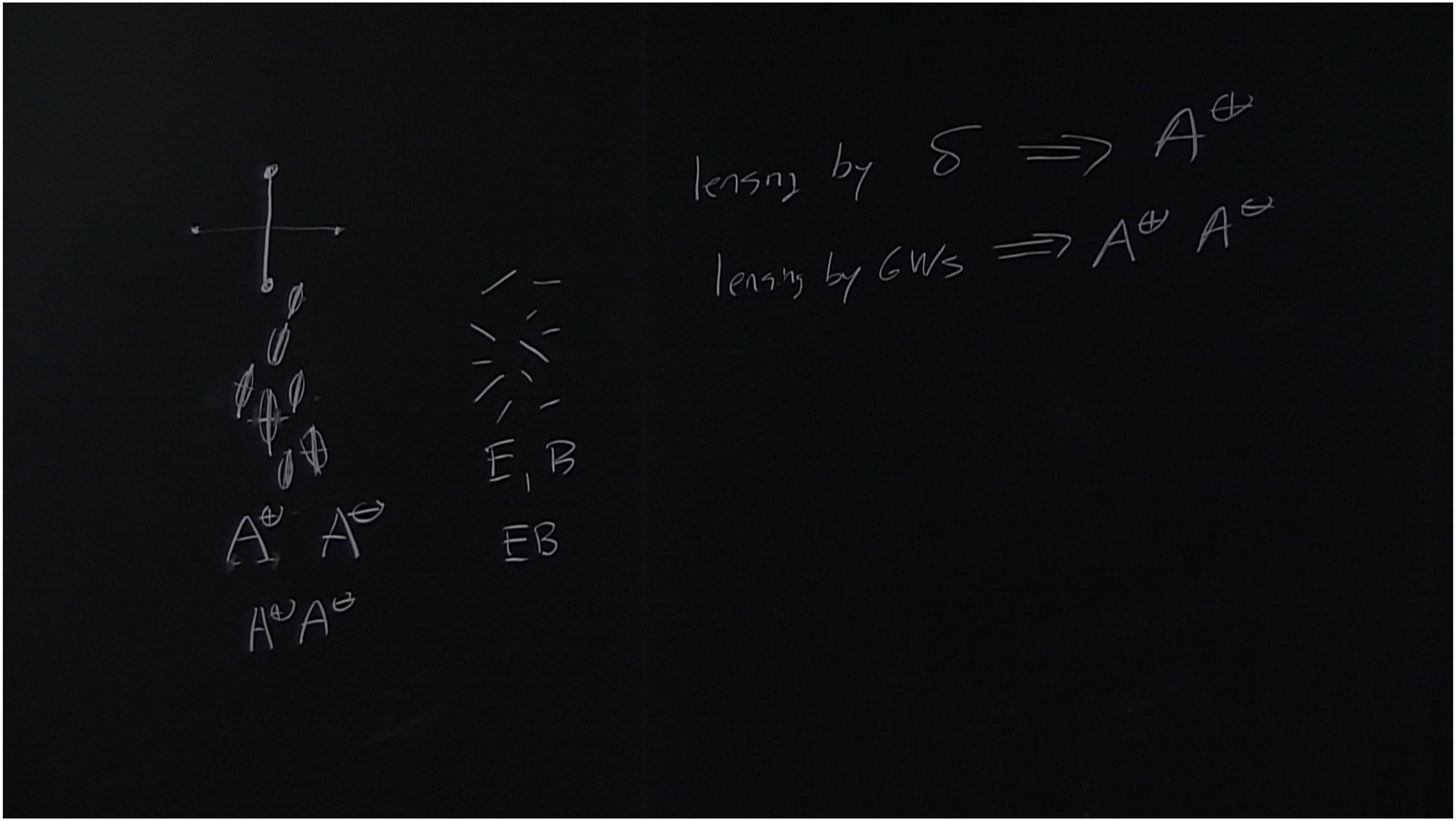
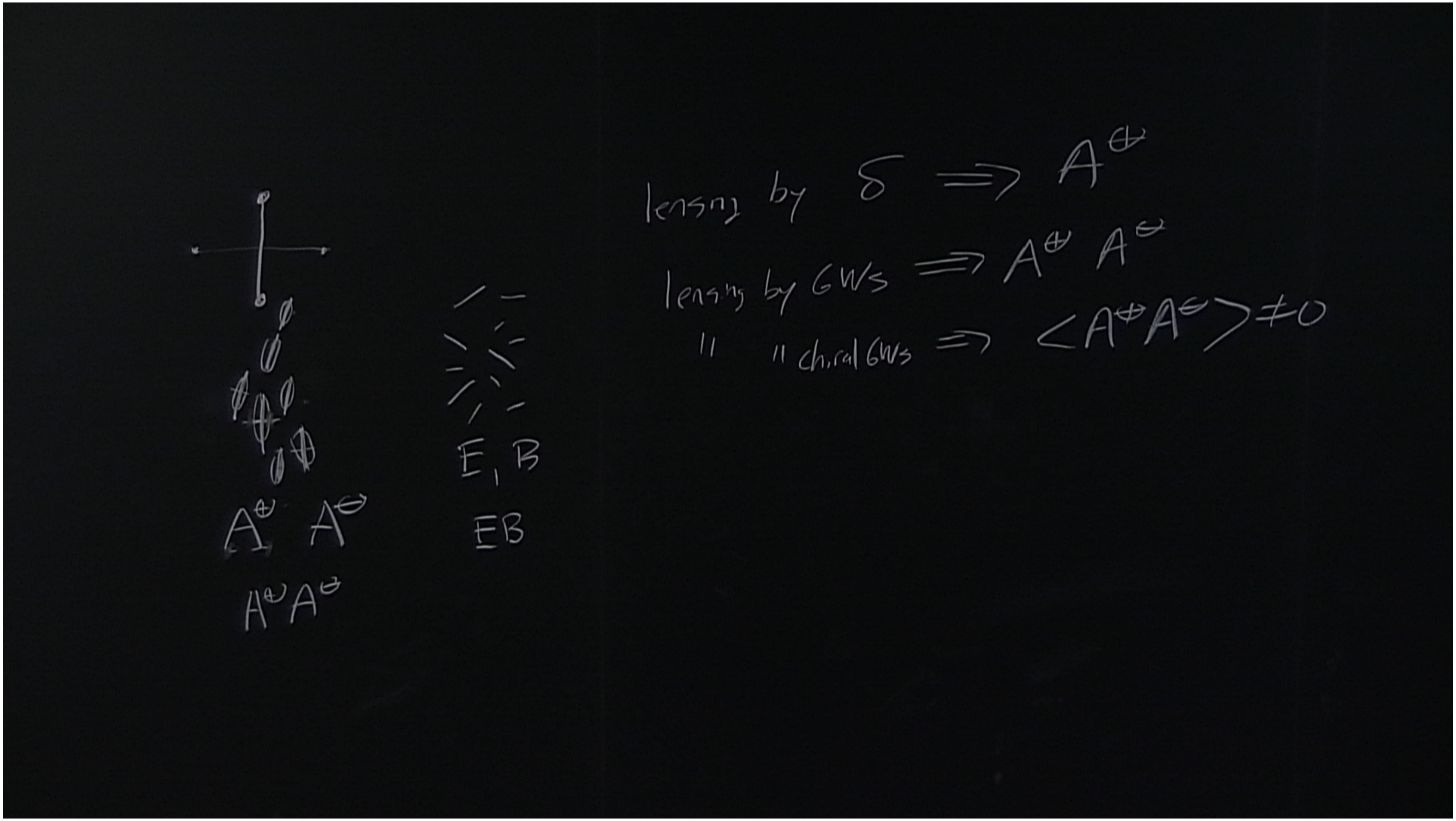
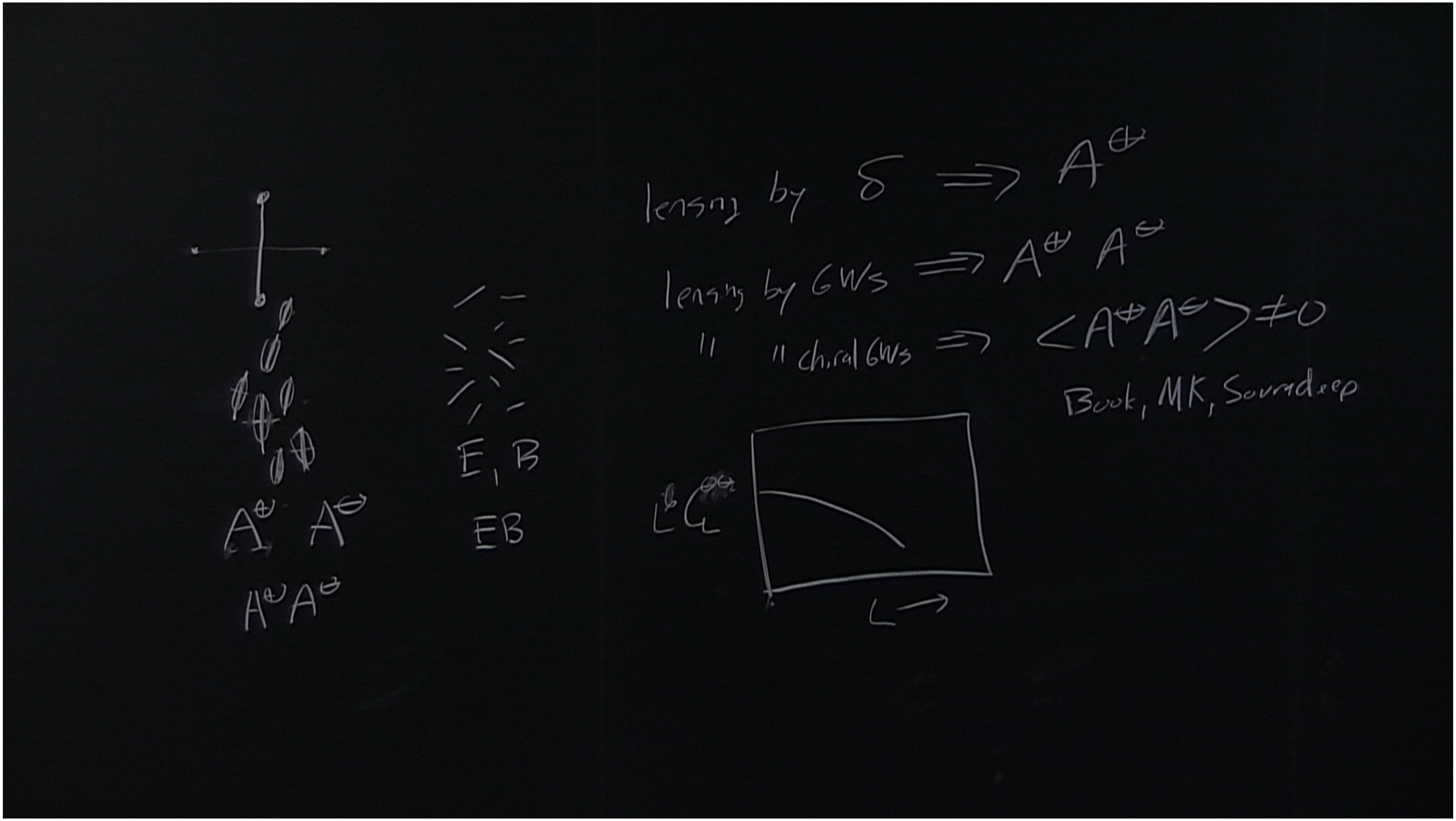
E, B
EB


$A^{\oplus}$ $A^{\ominus}$
$A^{\oplus} A^{\ominus}$
E, B
EB
lensing by $\delta \Longrightarrow A^{\oplus}$
lensing by GWs $\Longrightarrow A^{\oplus} A^{\ominus}$



A⊕ A⊖
A⊕A⊖
E, B
EB
lensing by δ ⟹ A⊕
lensing by GWs ⟹ A⊕ A⊖
" " chiral GWs ⟹ <A⊕A⊖> ≠ 0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Book, MK, Souradeep
$A^{\oplus}\ A^{\ominus}$
$A^{\oplus} A^{\ominus}$
E, B
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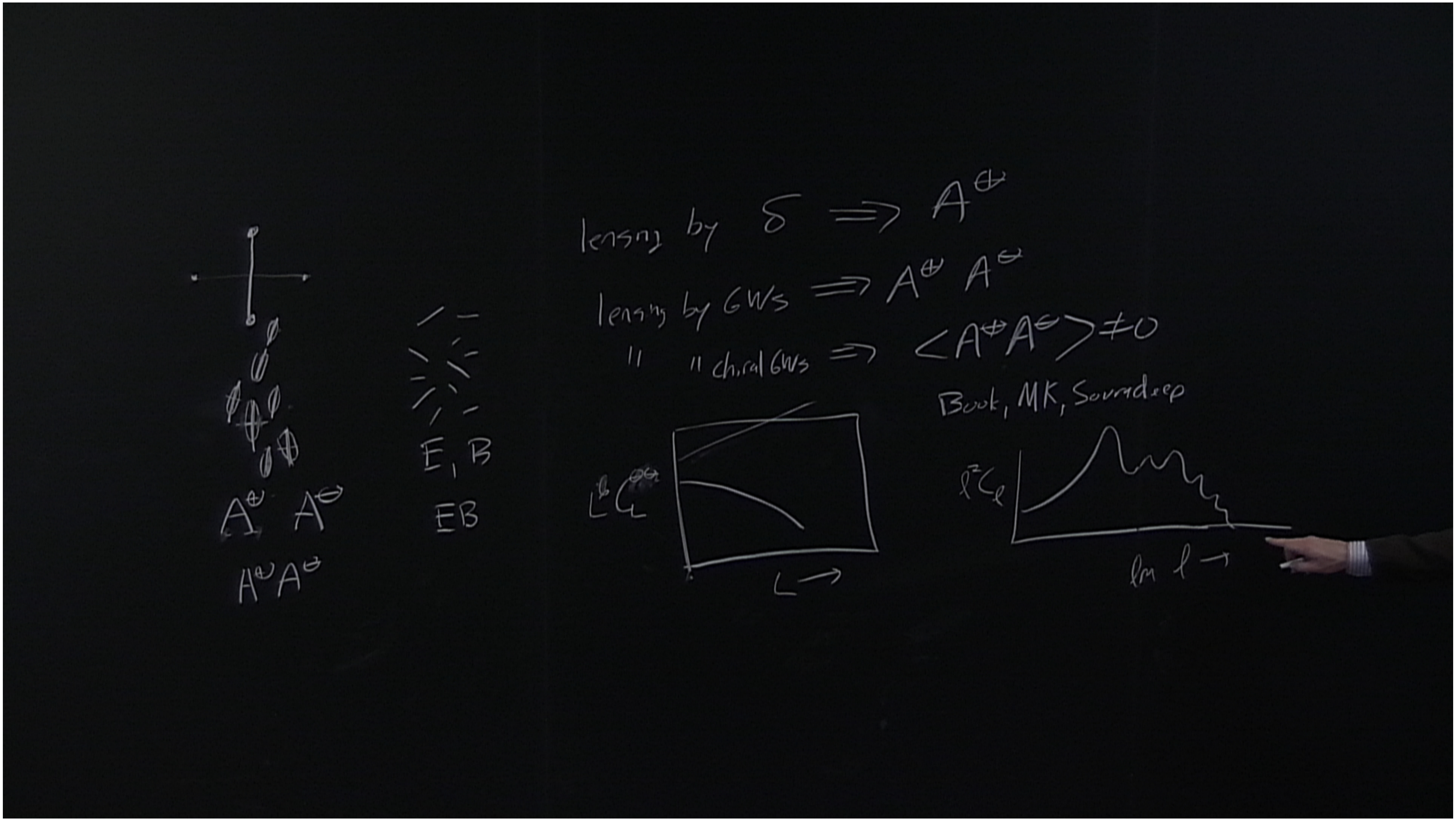
lensing by δ ⟹ A⊕
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A⊕ A⊖
A⊕A⊖
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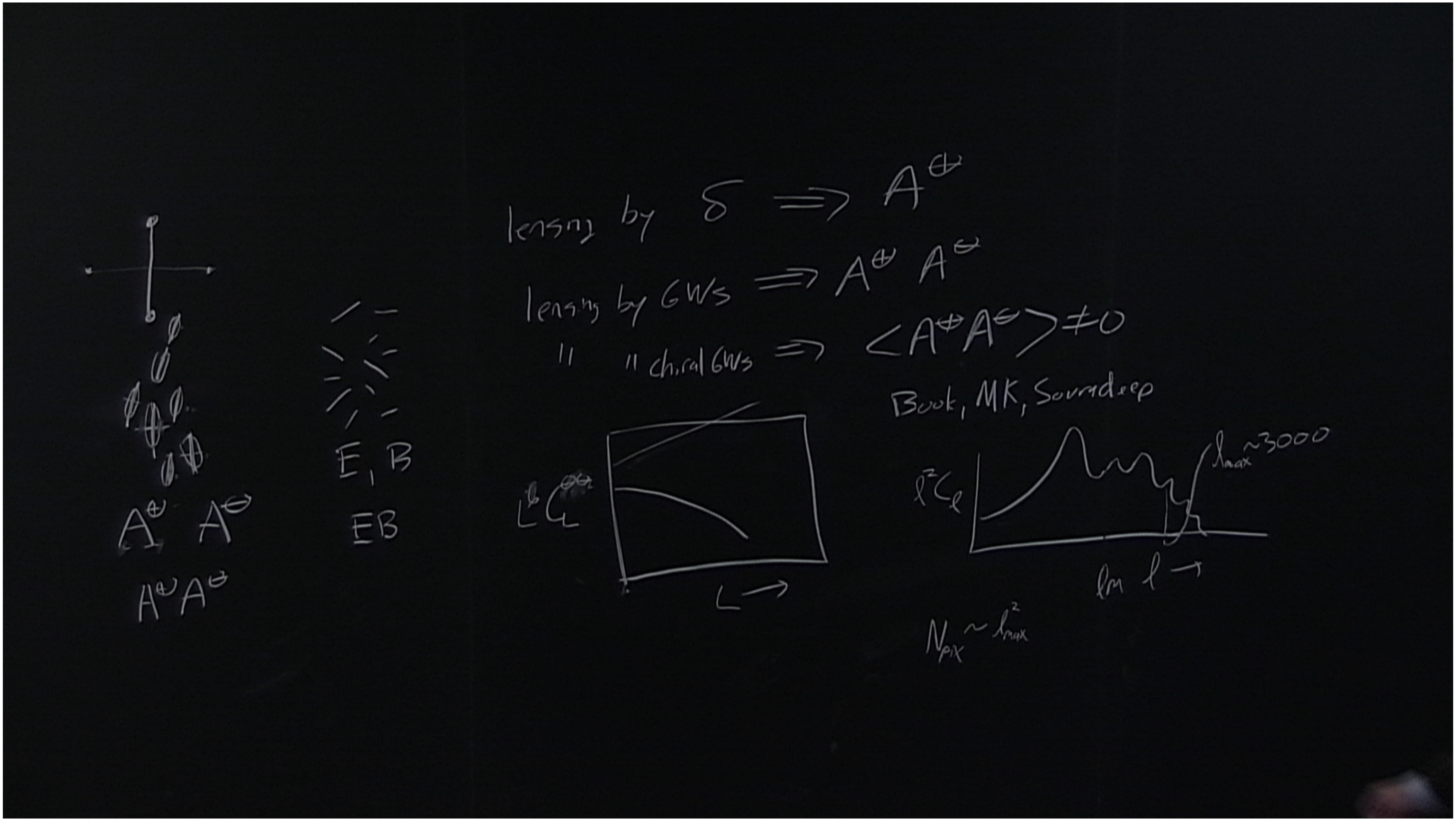
L² C_L⊕⊖
L →
l²C_l
ln l →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Book, MK, Souradeep
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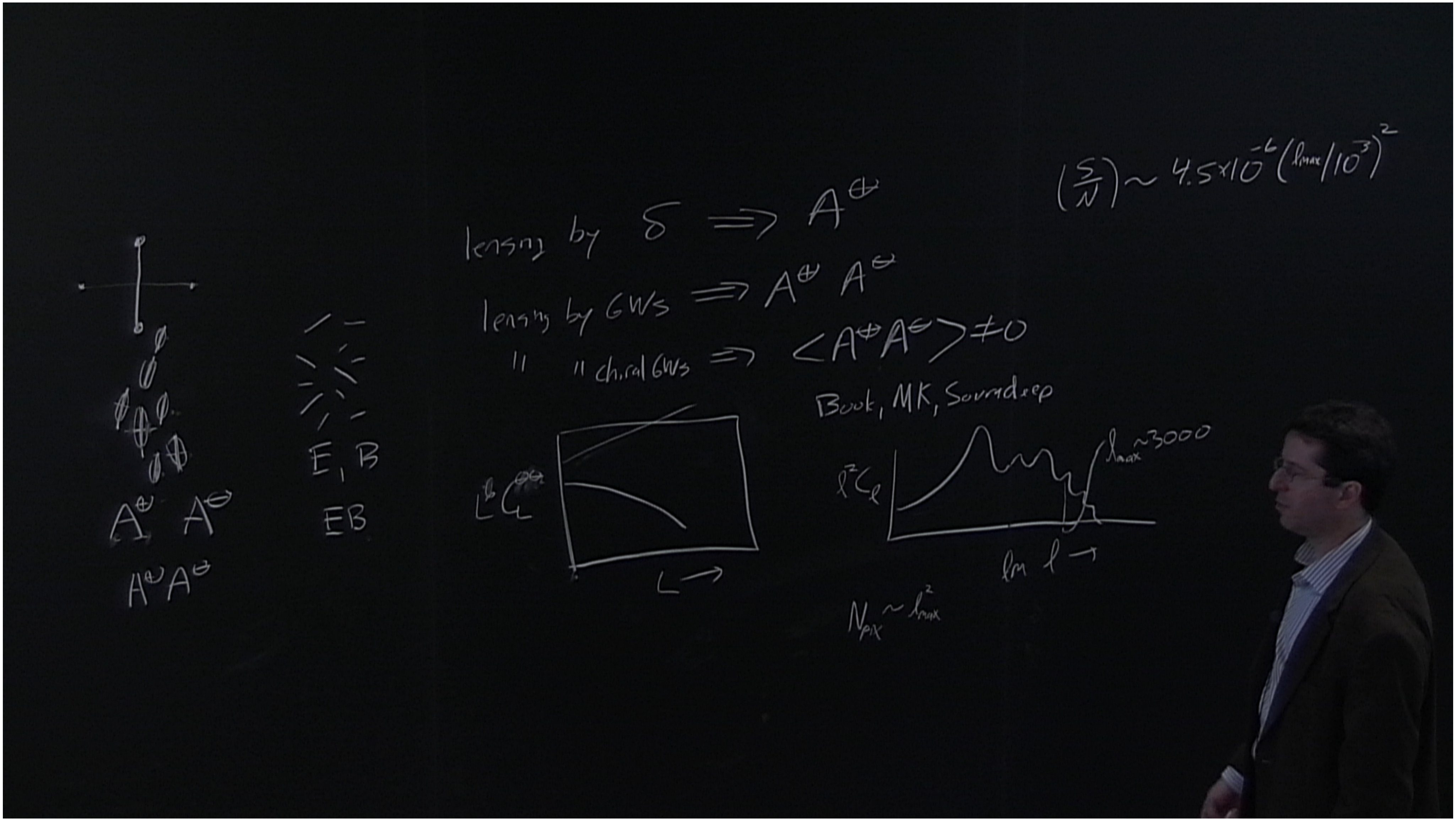
A⊕ A⊖
A⊕A⊖
ℓmax ~3000
Npix ~ ℓmax²


(S/N) ~ 4.5×10^-6 (lmax/10^3)^2
lensing by δ ⟹ A⊕
lensing by GWs ⟹ A⊕ A⊖
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A⊕ A⊖
A⊕A⊖
E, B
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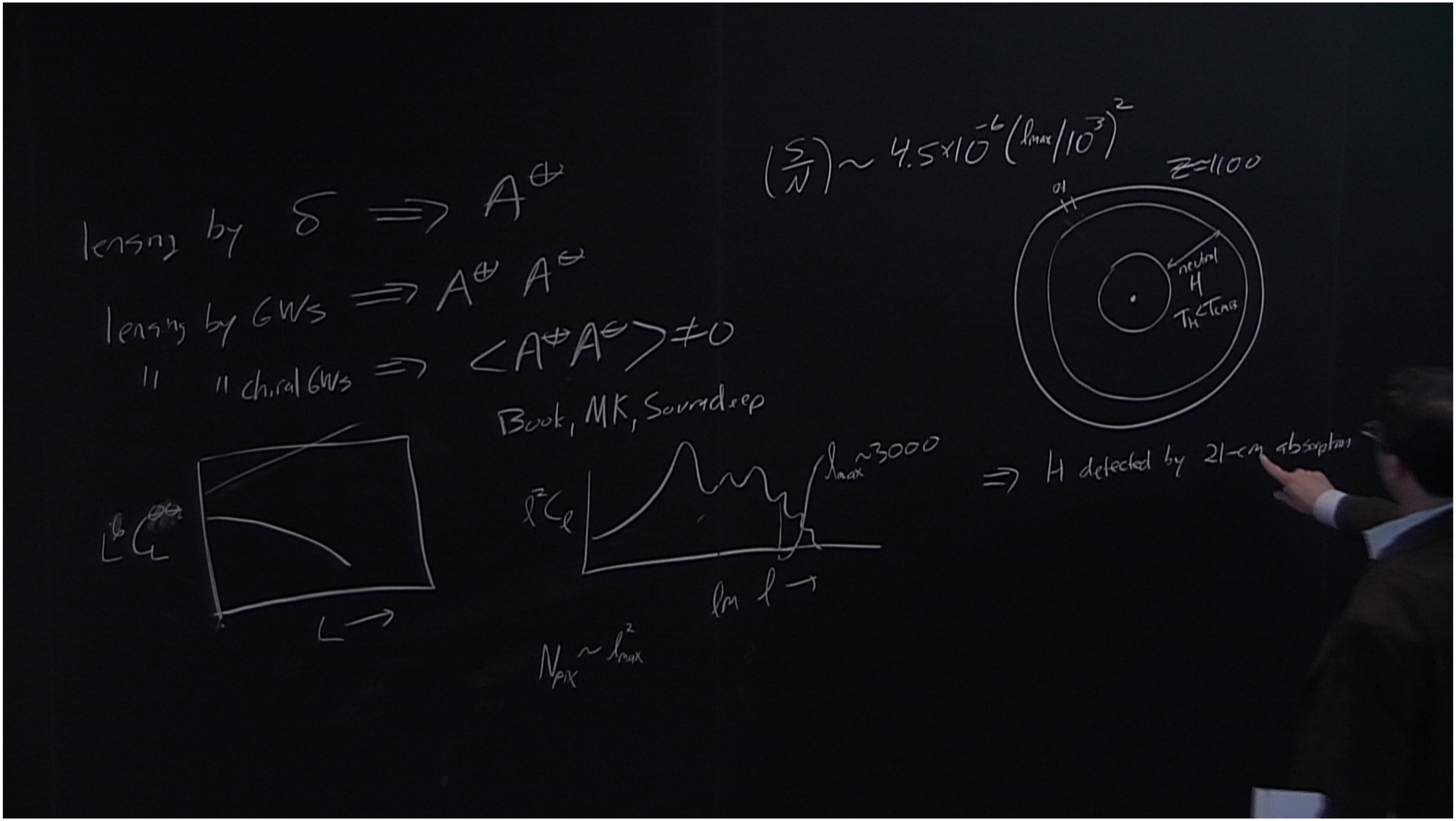
L →
lmax ~3000
l²Cl
l →
Npix ~ lmax²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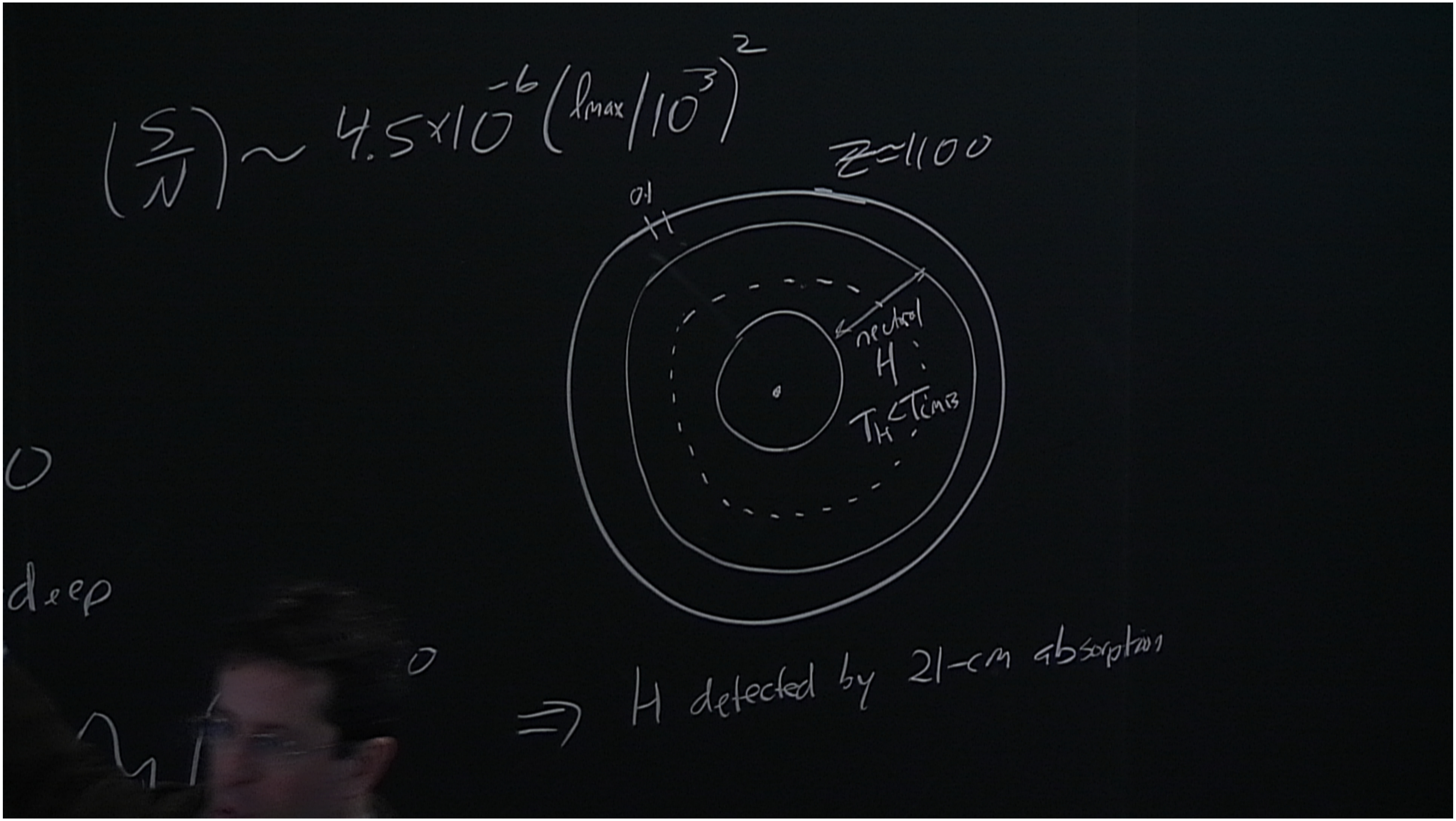
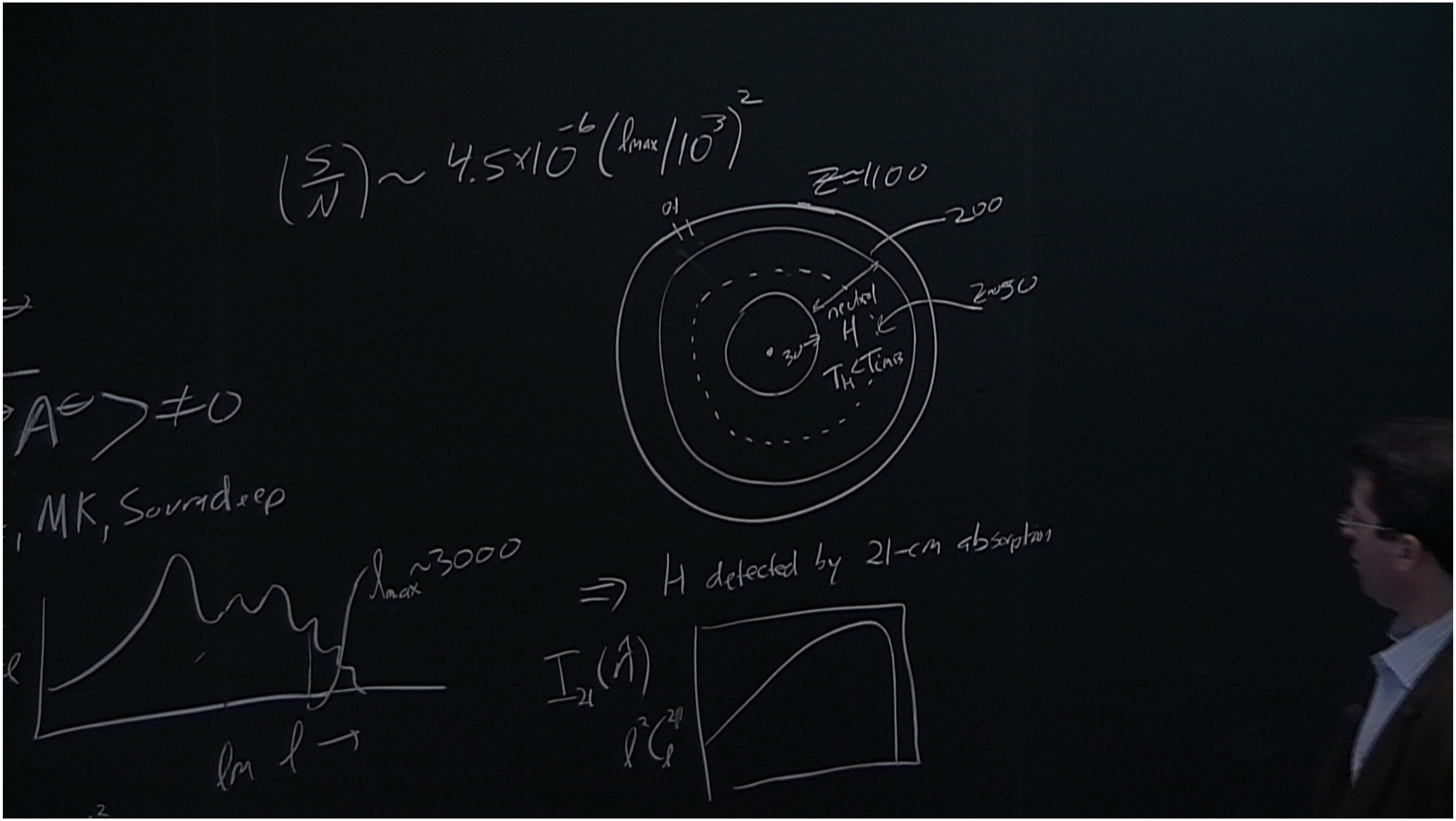
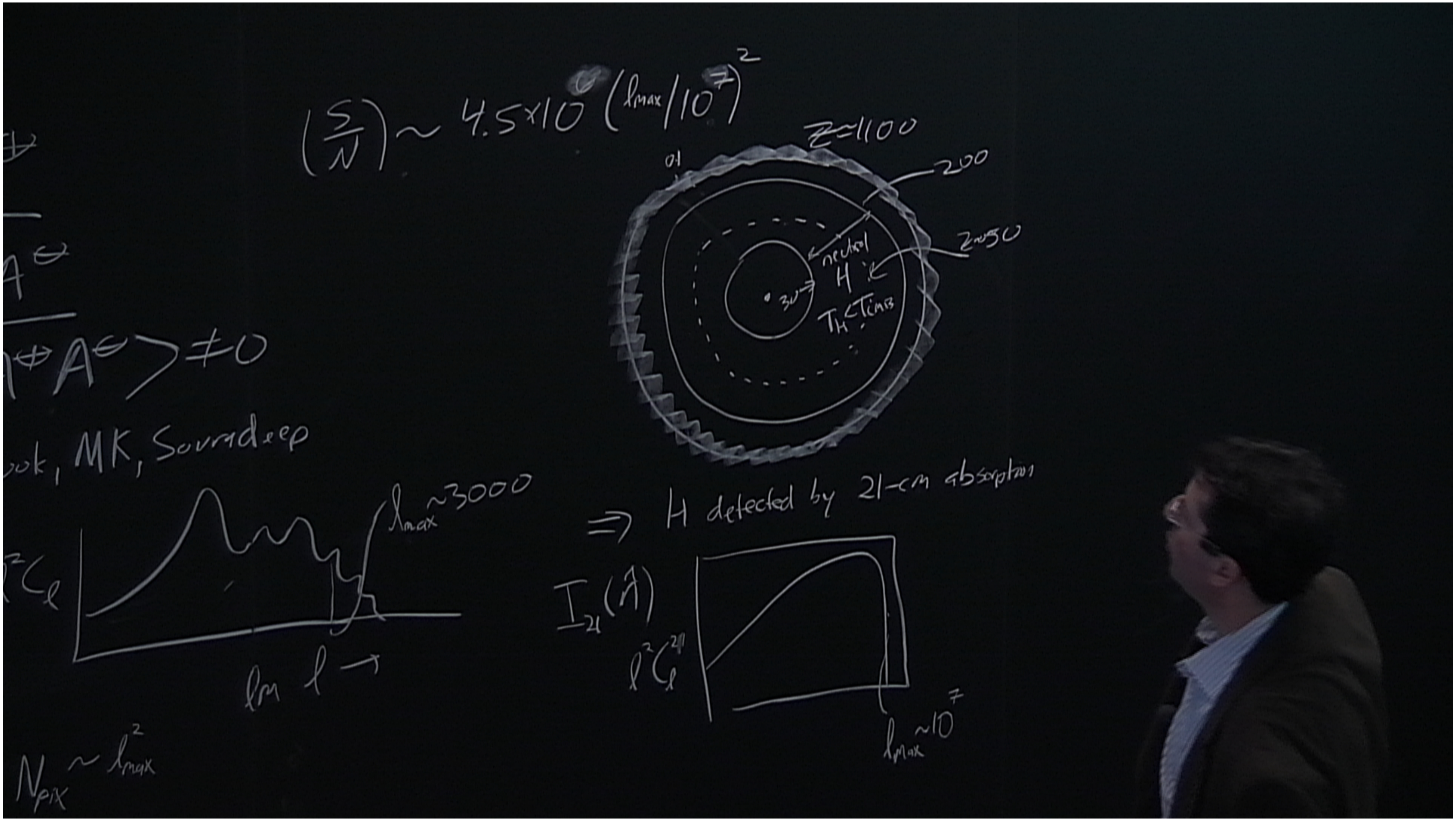
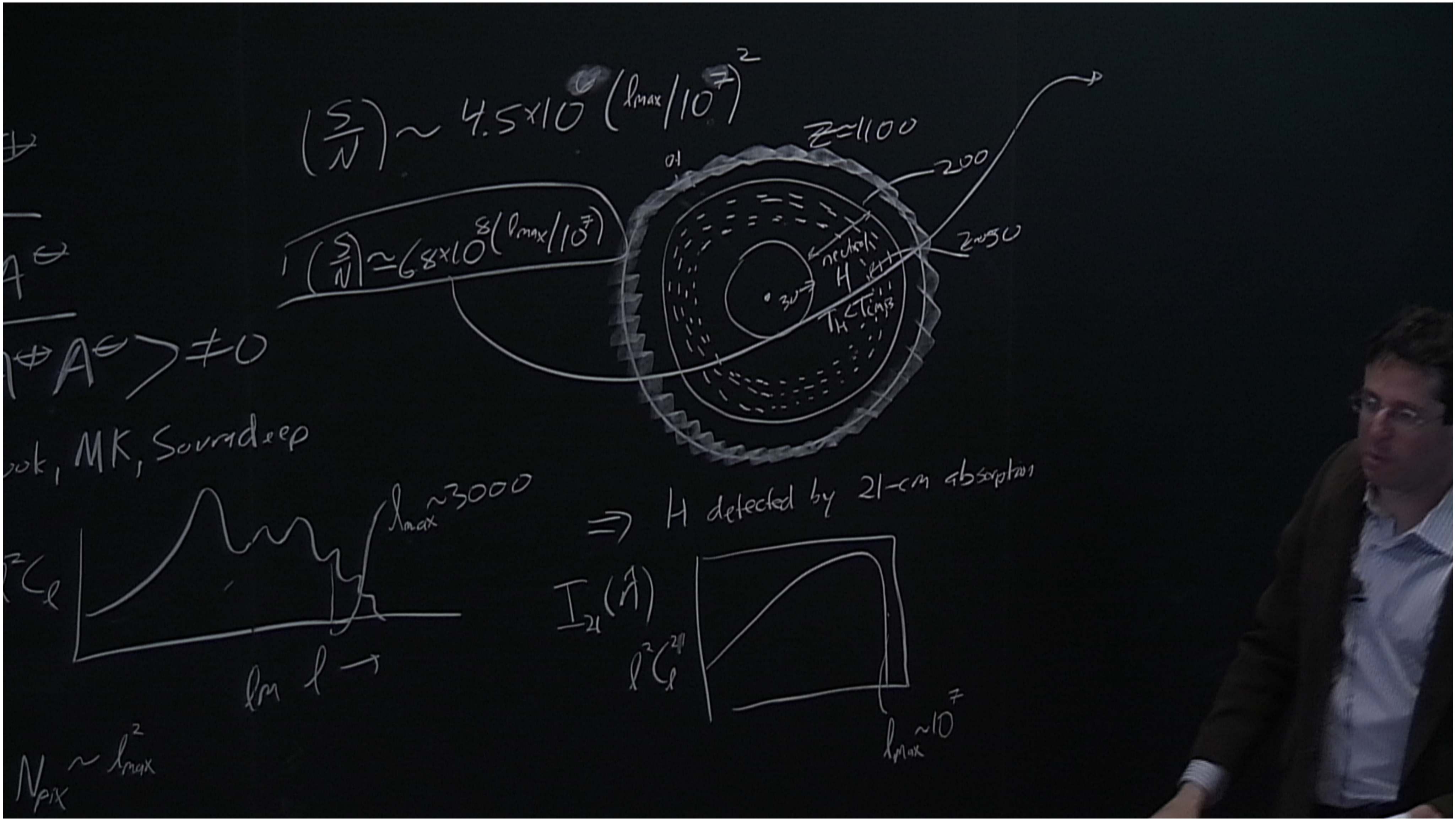
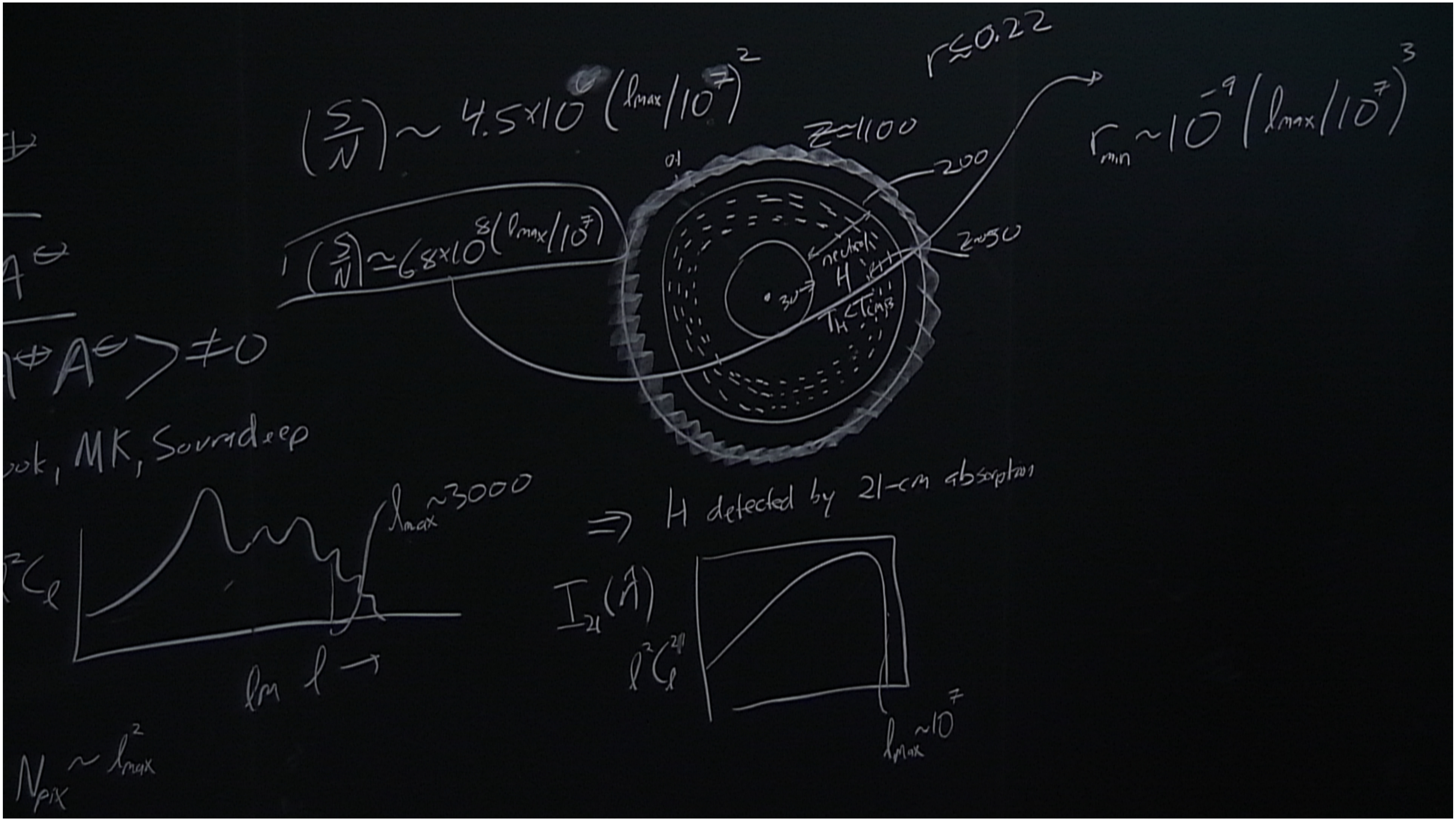
(S/N) ~ 4.5×10⁻⁶ (lmax/10³)²
z≈1100
neutral H
lmax~3000
Npix ~ lmax²
⟹ H detected by 21-cm absorption


(S/N) ~ 4.5×10^-6 (l_max/10^3)^2
z≃1100
0.1
neutral H
T_H < T_CMB
deep
⇒ H detected by 21-cm absorption


(S/N) ~ 4.5×10^-6 (lmax/10^3)^2
z≈1100
200
z≈30
neutral H
TH<TCMB
MK, Souradeep
lmax~3000
ln l →
⇒ H detected by 21-cm absorption
I21(λ)
l^2 C_l^21


neutral
H
H detected by 21-cm absorption

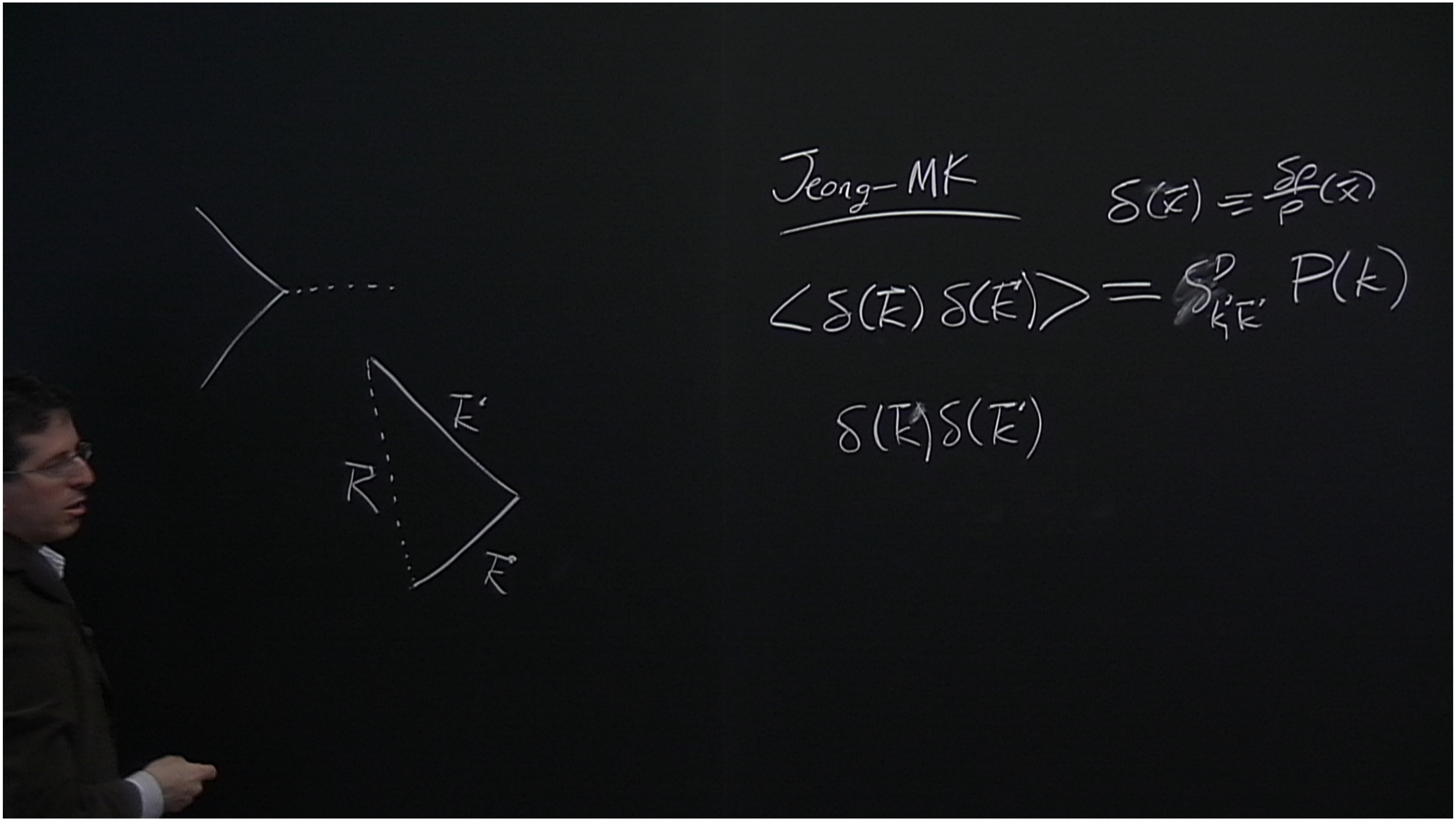

(S/N) ~ 4.5×10^6 (lmax/10^7)^2
(S/N) ≃ 6.8×10^8 (lmax/10^7)
z≈1100
200
z≈50
neutral H
T_H < T_CMB
MK, Sovradeep
lmax ~3000
ln l →
⇒ H detected by 21-cm absorption
I_21(n̂)
l^2 C_l^21
lmax ~10^7
N_pix ~ lmax^2


r ≲ 0.22
z ≃ 1100
200
z ≃ 50
30
neutral H
T_H < T_CMB
MK, Souradeep
l_max ~ 3000
⇒ H detected by 21-cm absorption
l_max ~ 10^7
N_pix ~ l_max^2

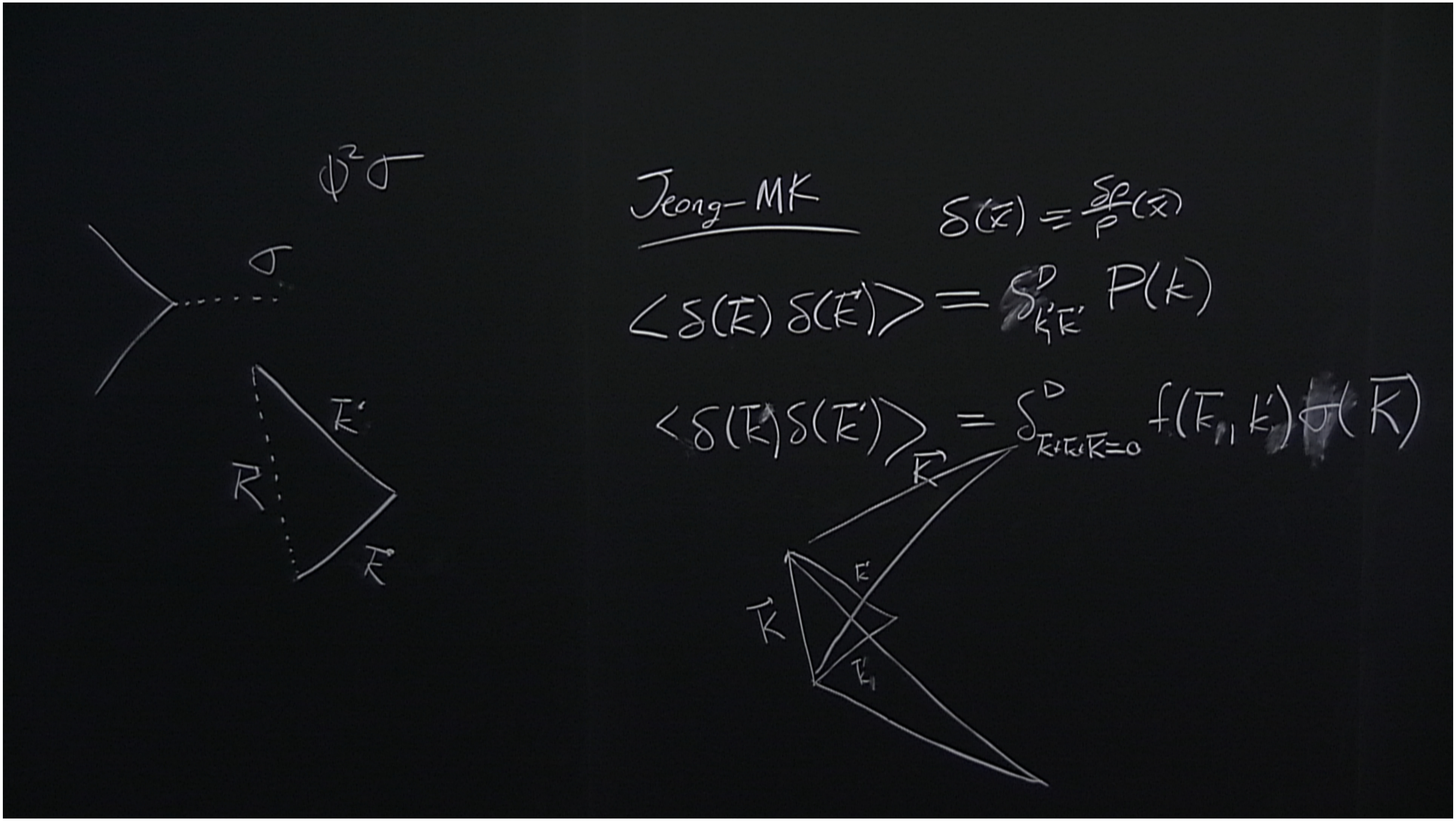
Jeong–MK

$$\delta(\vec{x}) = \frac{\delta\rho}{\rho}(\vec{x})$$

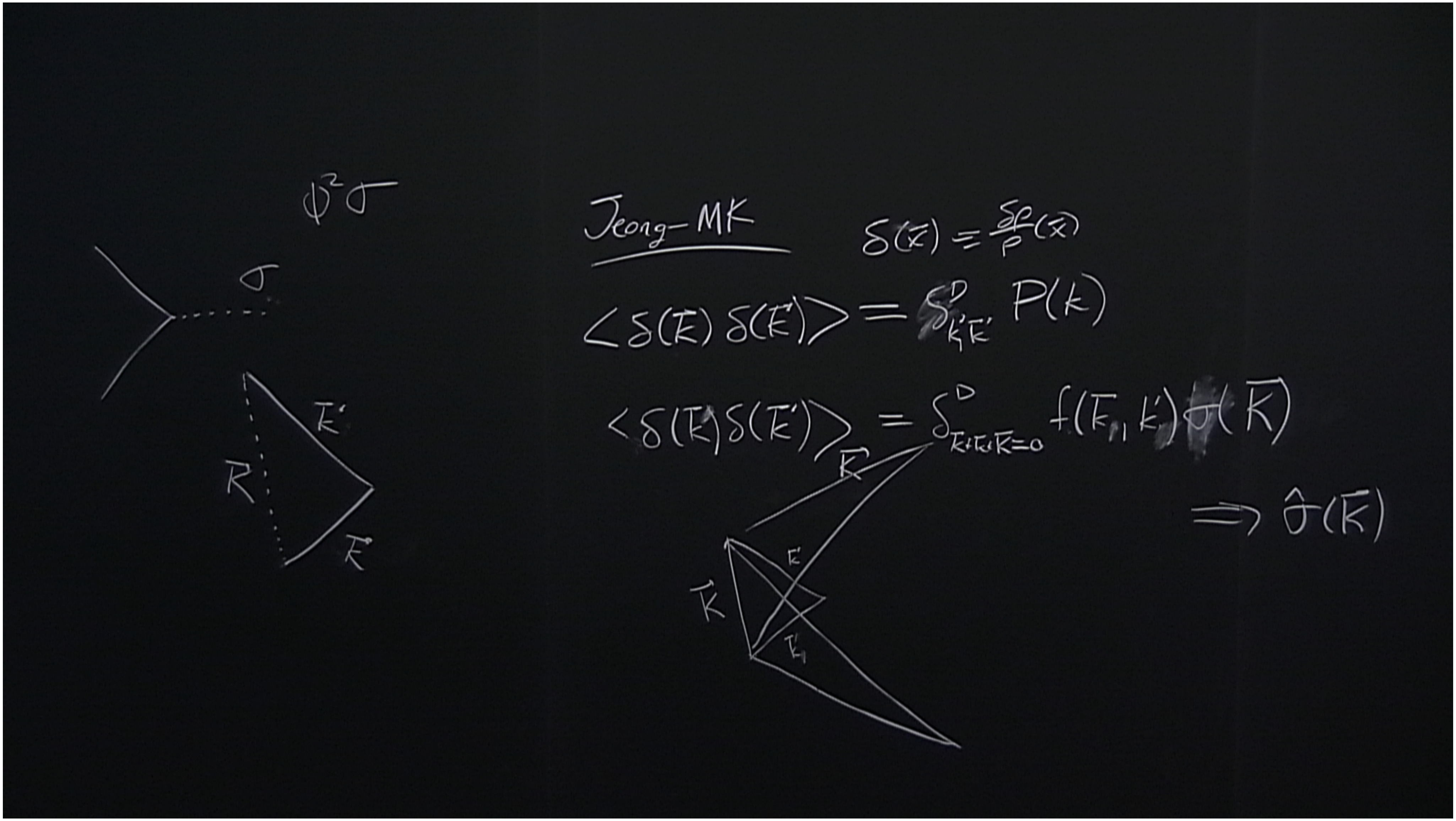
$$\langle \delta(\vec{k})\,\delta(\vec{k}')\rangle = \delta^{D}_{\vec{k},\vec{k}'}\,P(k)$$



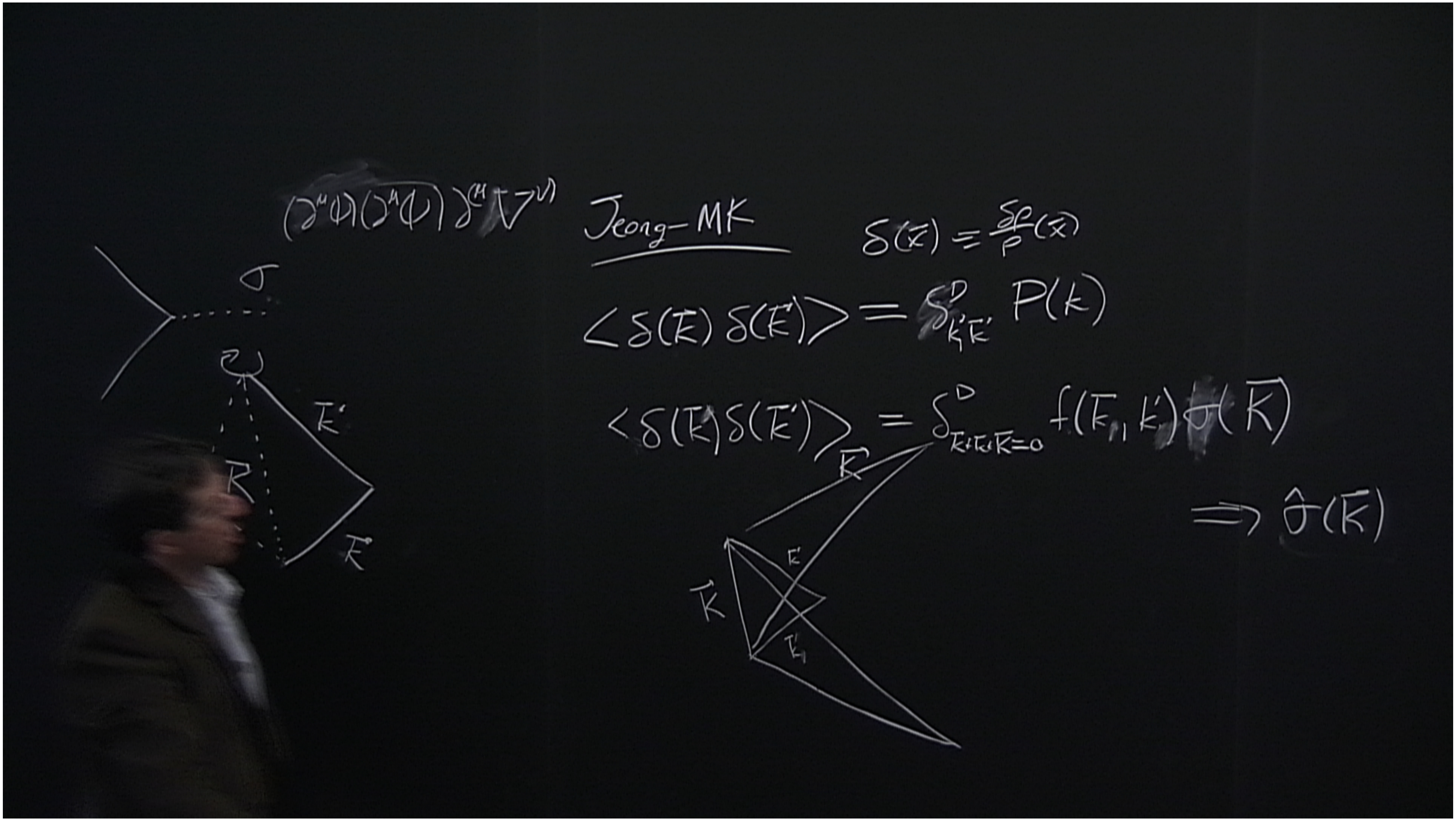
Jeong–MK
δ(x) = δρ/ρ (x)
<δ(k) δ(k')> = δ^D_{k,k'} P(k)
δ(k) δ(k')
k'
R
k



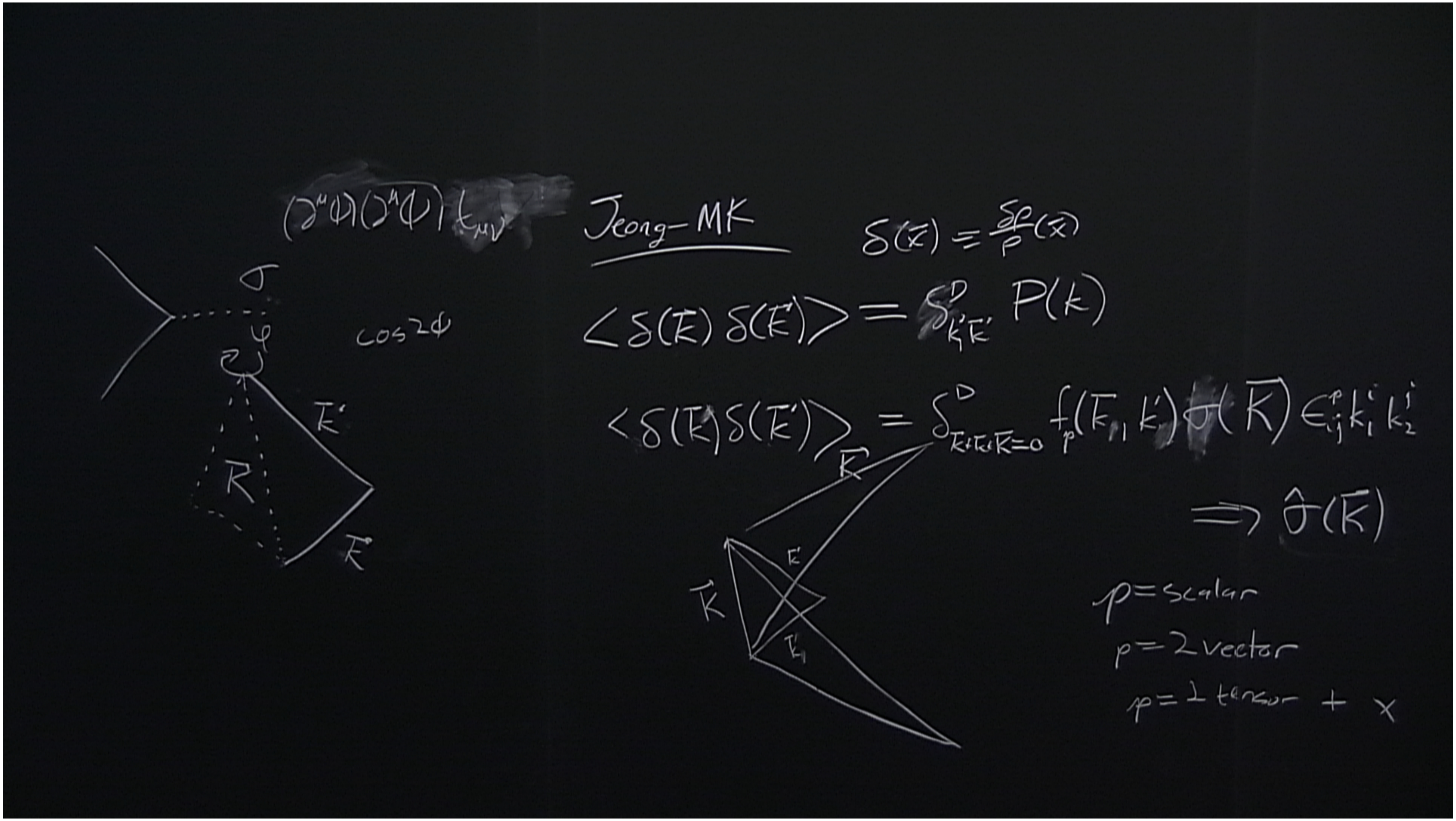
φ²σ
σ
Jeong–MK
δ(x) ≡ δρ/ρ (x)
⟨δ(k) δ(k')⟩ = δ^D_{k,k'} P(k)
⟨δ(k) δ(k')⟩_K = δ^D_{k+k'+K=0} f(k, k') σ(K)

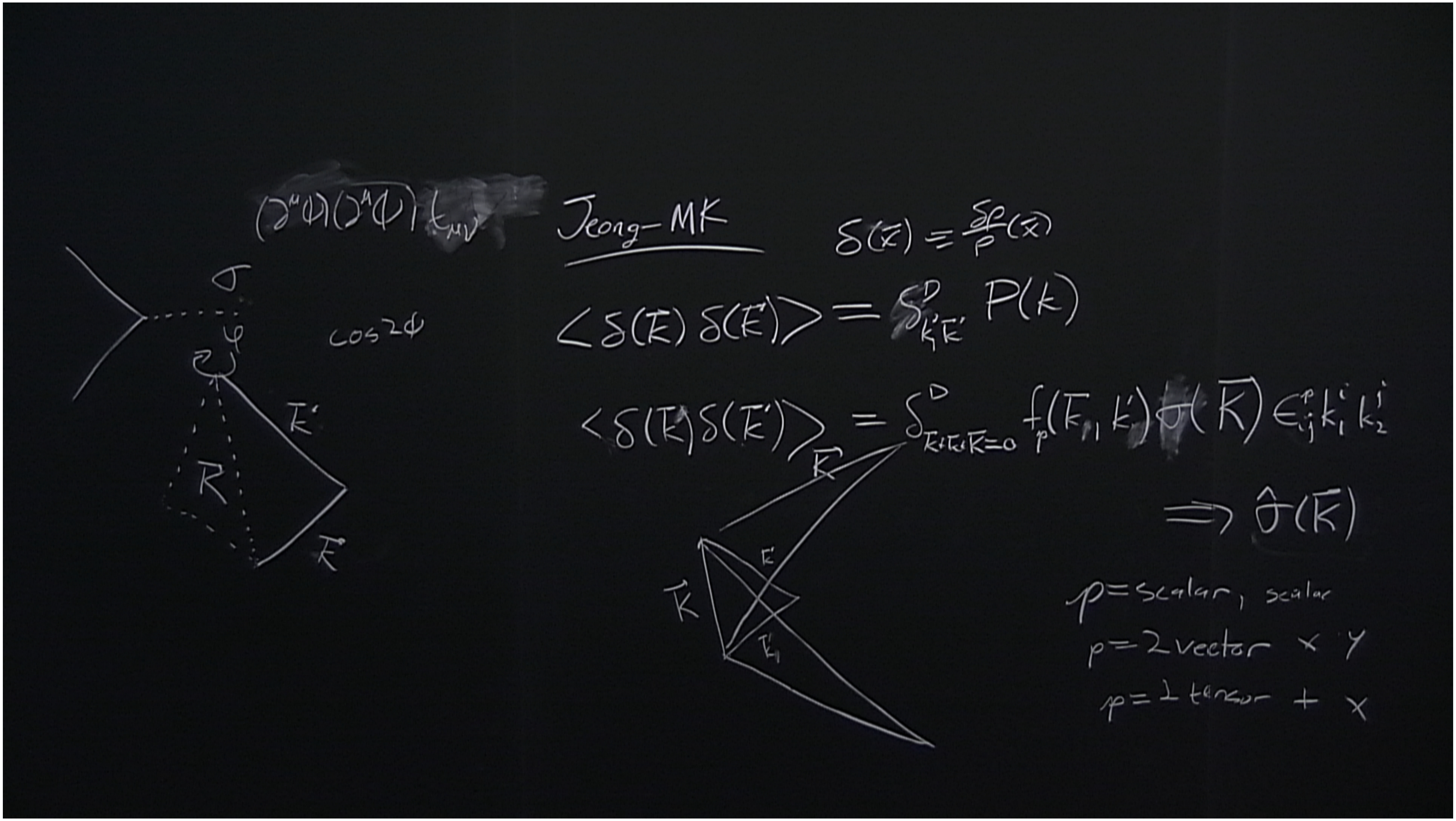


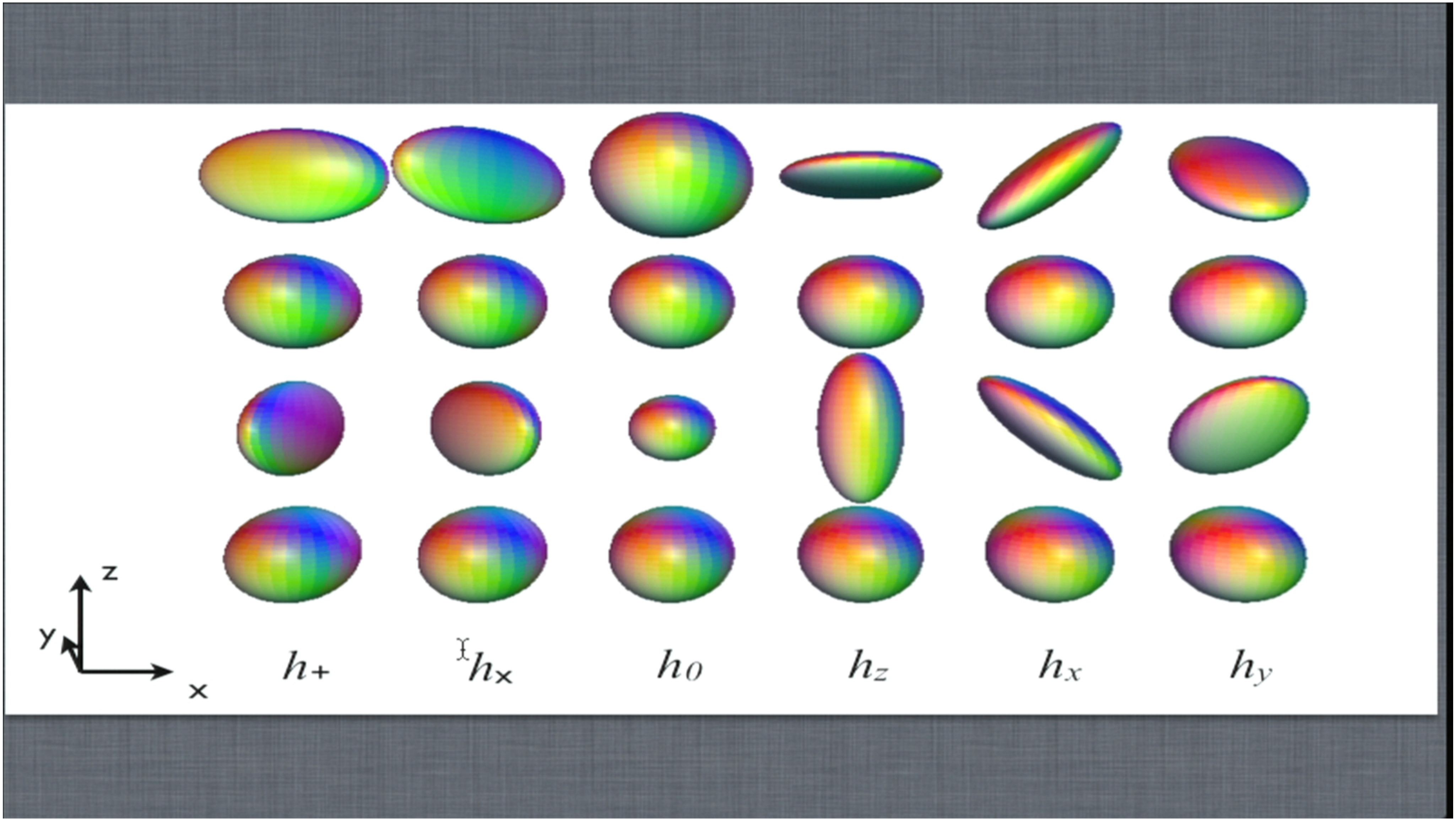
$\phi^2\sigma$
σ
Jeong–MK
$\delta(\vec{x}) = \frac{\delta\rho}{\rho}(\vec{x})$
$\langle \delta(\vec{k})\delta(\vec{k}')\rangle = \delta^D_{\vec{k},\vec{k}'} P(k)$
$\langle \delta(\vec{k})\delta(\vec{k}')\rangle_{\vec{K}} = \delta^D_{\vec{k}+\vec{k}'+\vec{K}=0} f(\vec{k},\vec{k}')\sigma(\vec{K})$
$\Rightarrow \hat{\sigma}(\vec{K})$

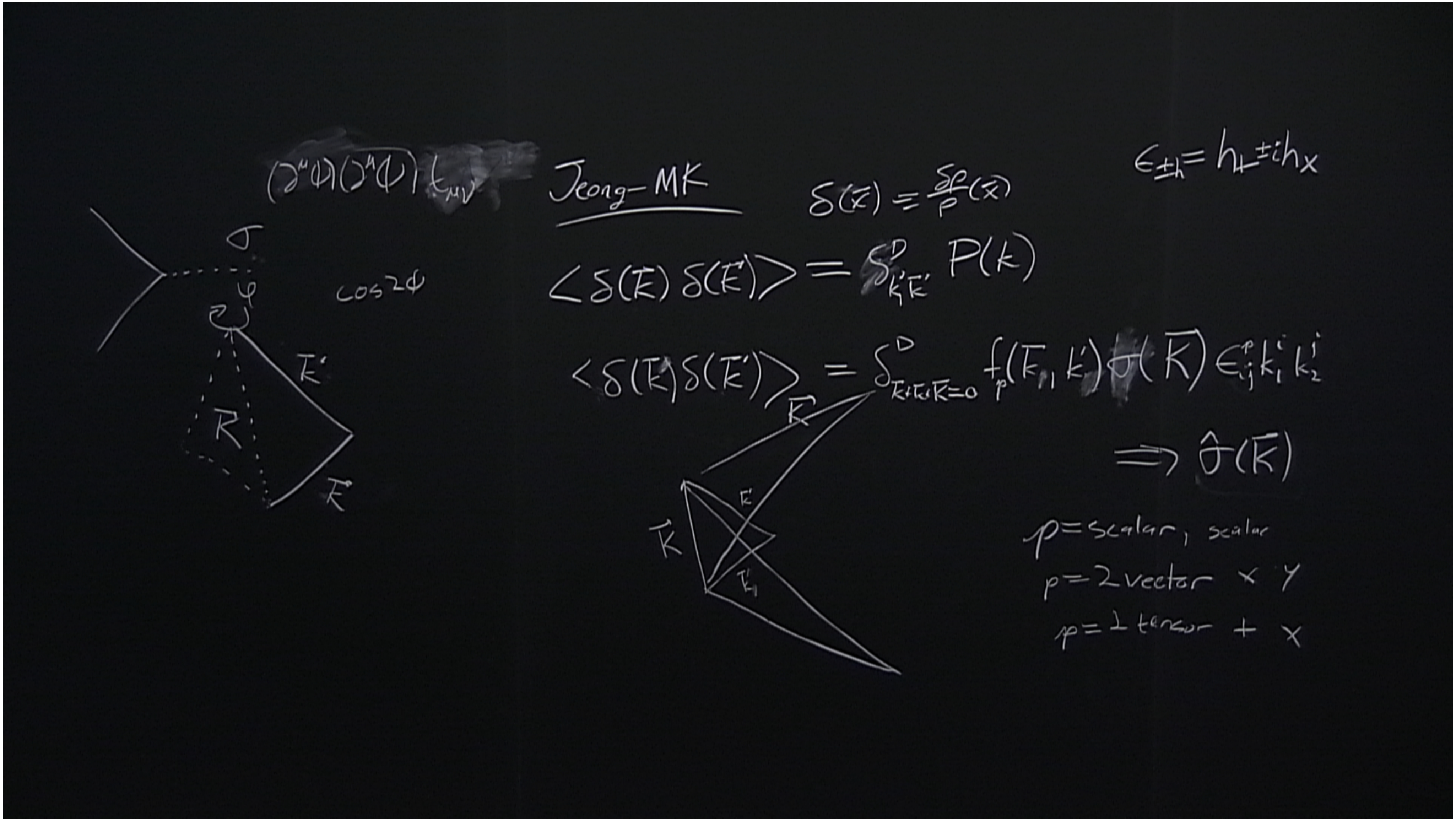


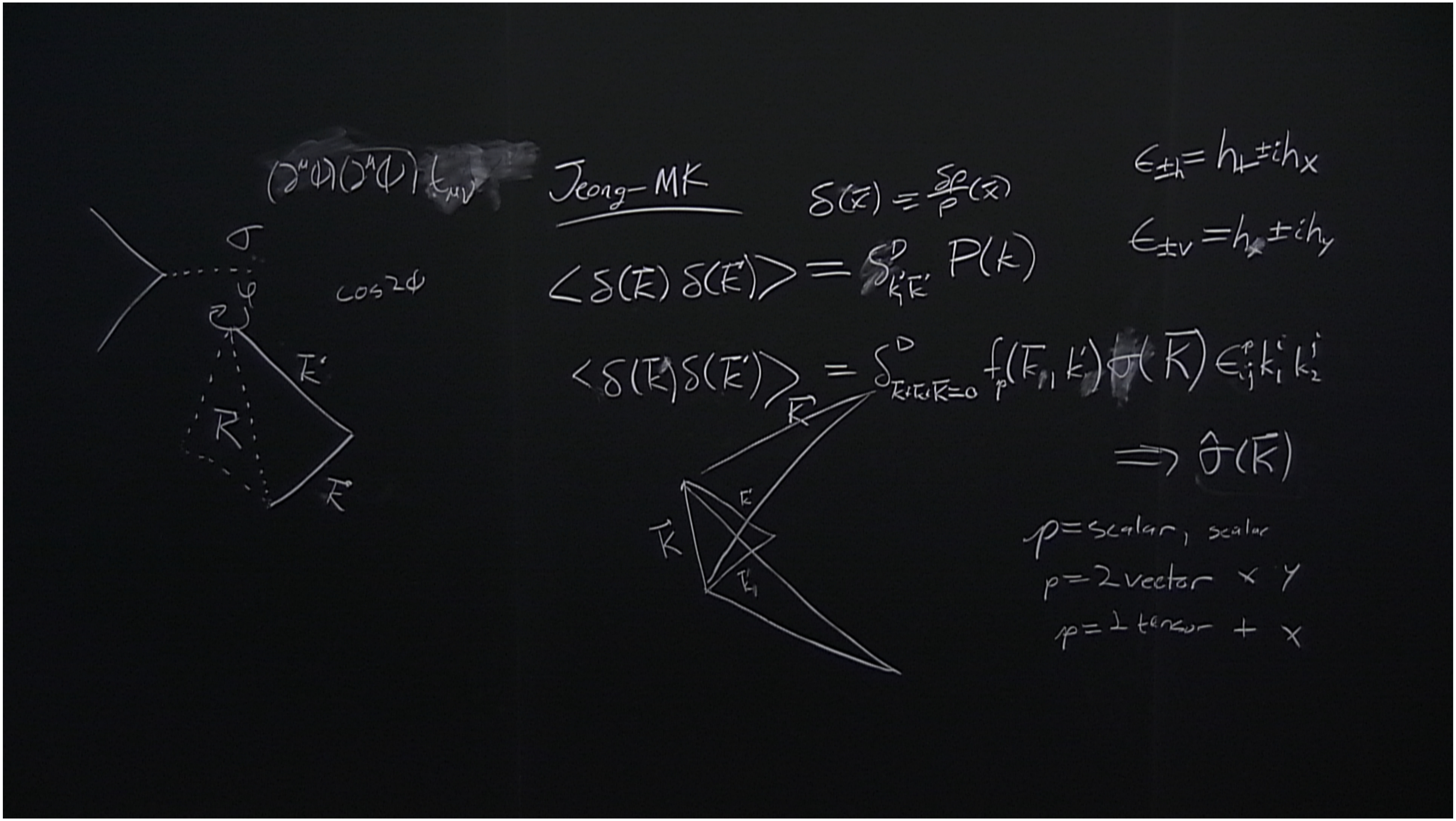
Jeong-MK
$\delta(\vec{x}) = \frac{\delta\rho}{\rho}(\vec{x})$
$\langle \delta(\vec{k})\,\delta(\vec{k}')\rangle = \delta^D_{k+k'}\,P(k)$

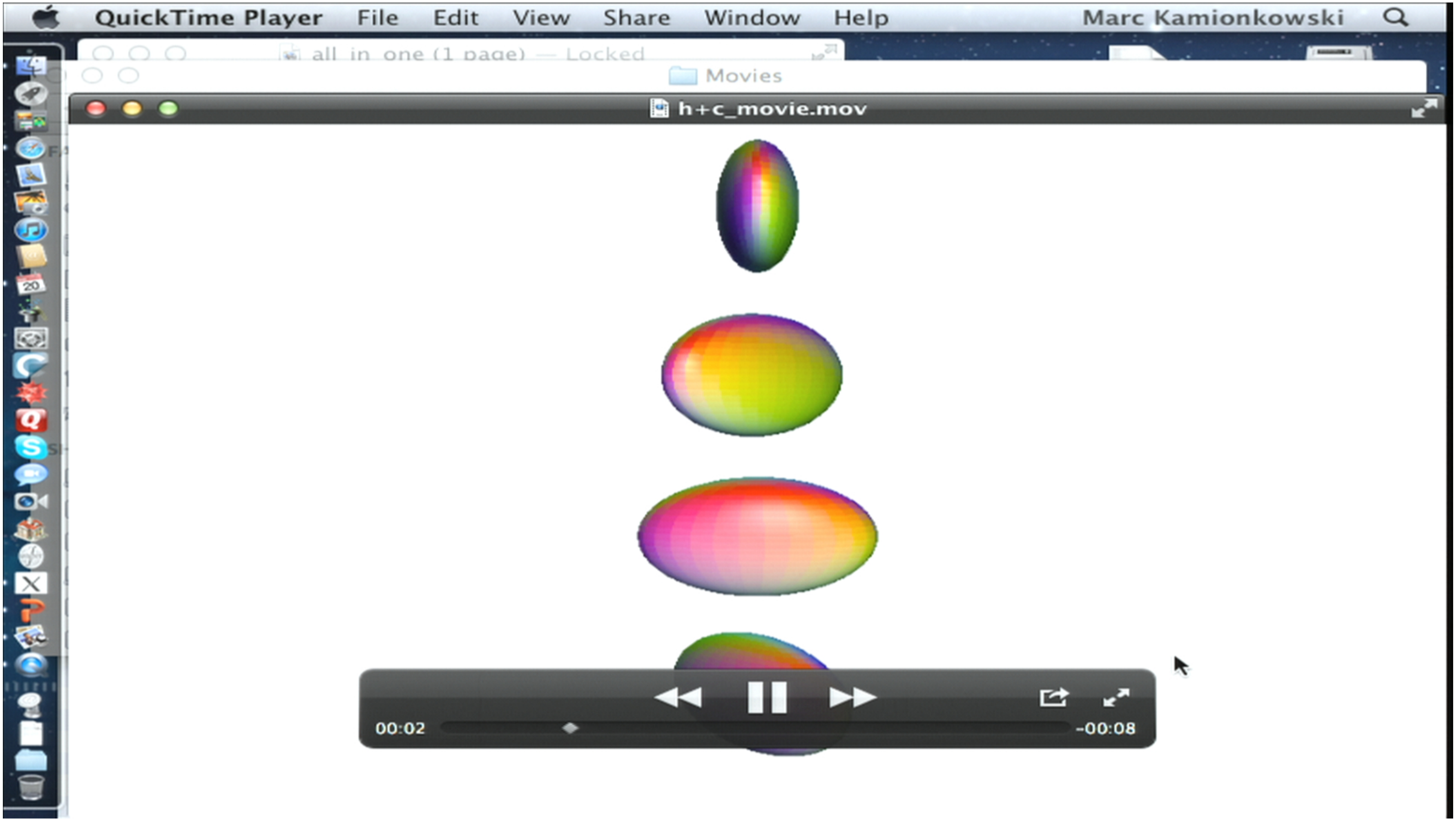

Jeong–MK
δ(x) = δρ/ρ (x)
⟨δ(k) δ(k')⟩ = δ^D_{k,k'} P(k)
⟨δ(k) δ(k')⟩_K = δ^D_{k+k'+K=0} f_p(k, k') σ(K) ε^p_{ij} k^i_1 k^j_2
⇒ σ̂(K)
p = scalar
p = 2 vector
p = 2 tensor + ×
cos 2φ
R

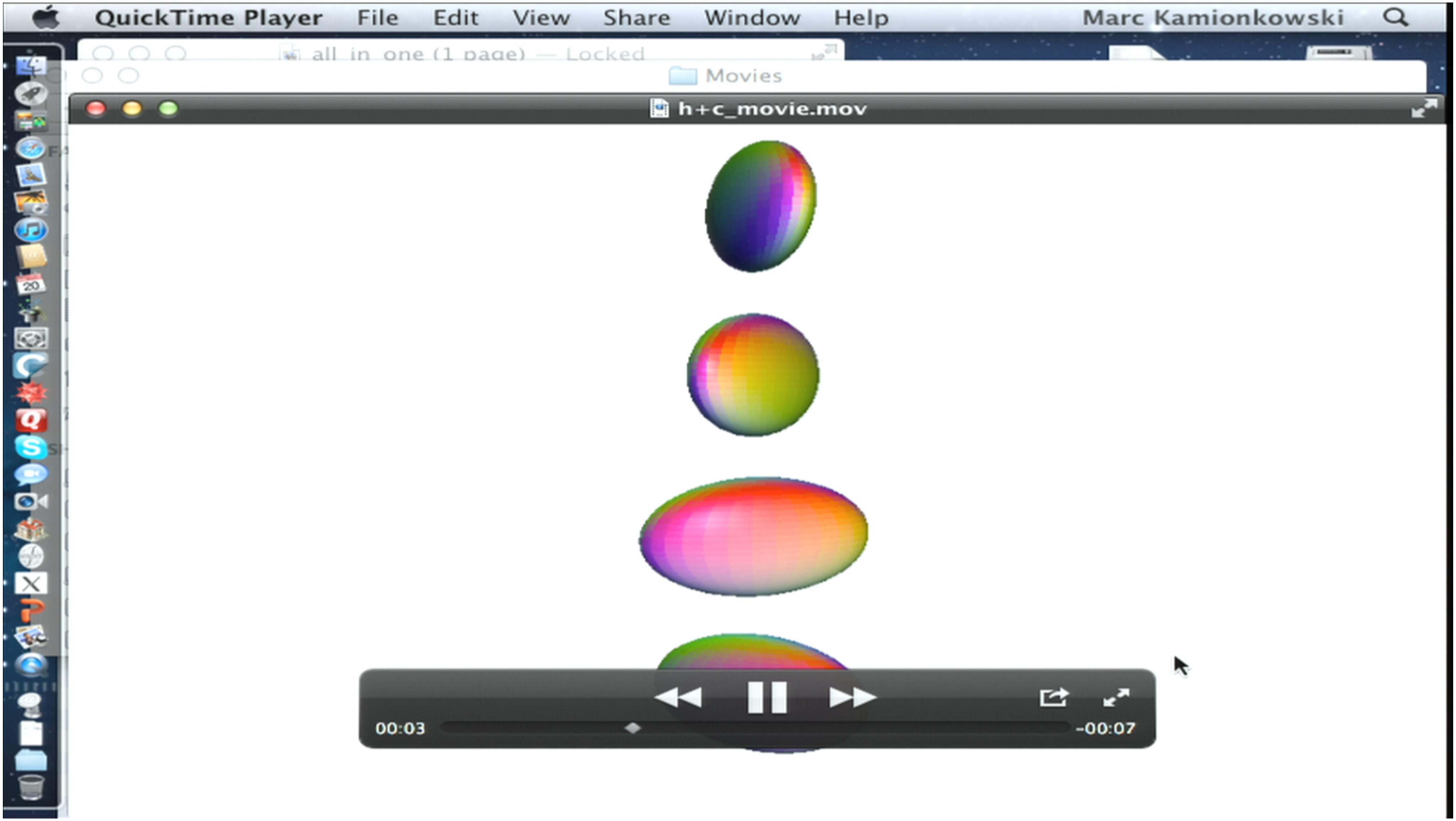

Jeong–MK
cos 2φ
p = scalar, scalar
p = 2 vector × Y
p = 2 tensor + X


z
y
x
h_+
$h_\times$
h_0
h_z
h_x
h_y


Jeong–MK
cos 2ϕ
p = scalar, scalar
p = 2 vector × y
p = 2 tensor + ×


Jeong-MK
cos 2φ
p = scalar, scalar
p = 2 vector × y
p = 2 tensor + ×


QuickTime Player File Edit View Share Window Help
Marc Kamionkowski
all in one (1 page) — Locked
Movies
h+c_movie.mov
00:02
-00:08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Marc Kamionkowski
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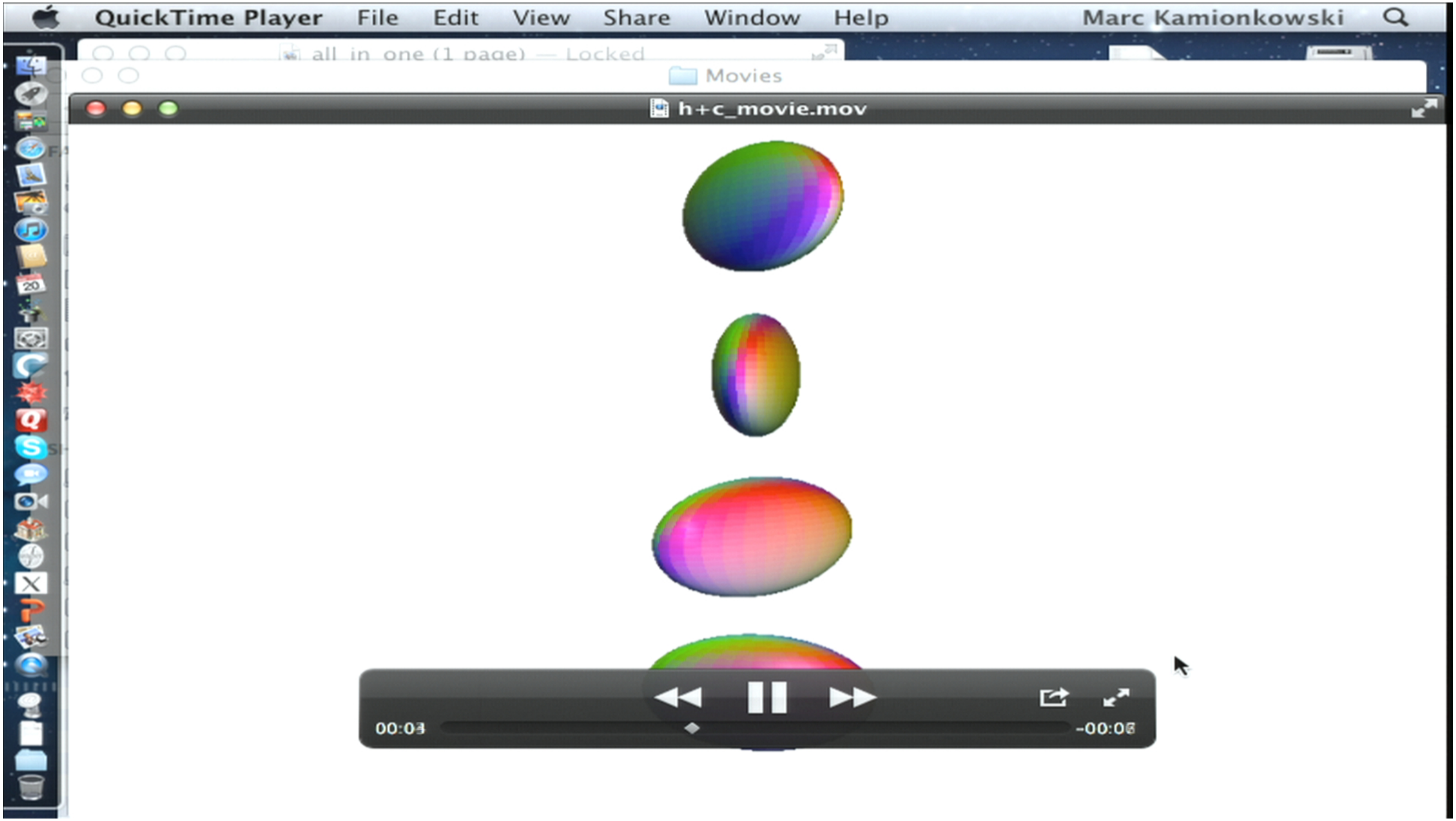
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Marc Kamionkowski
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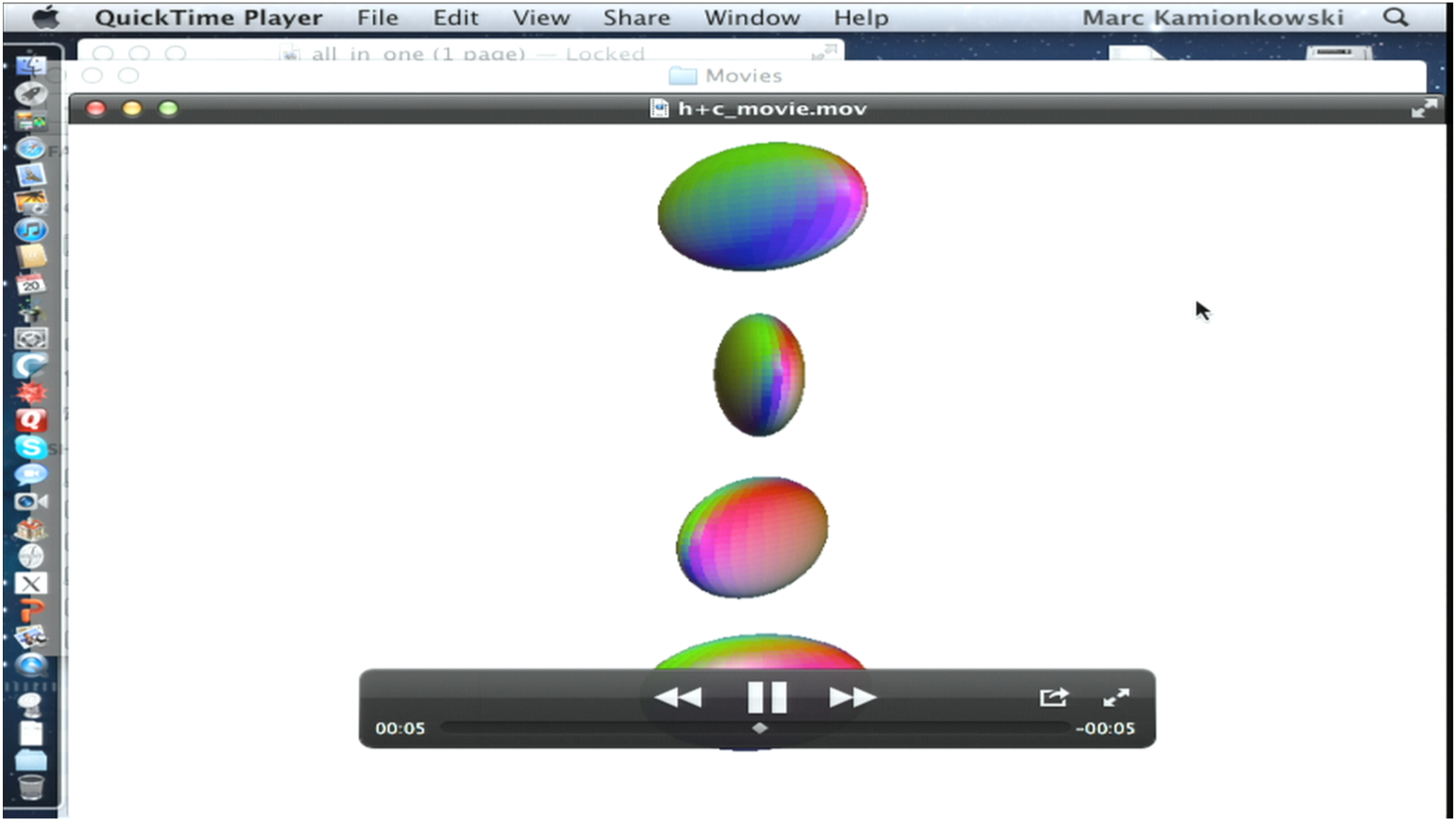
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Marc Kamionkowski
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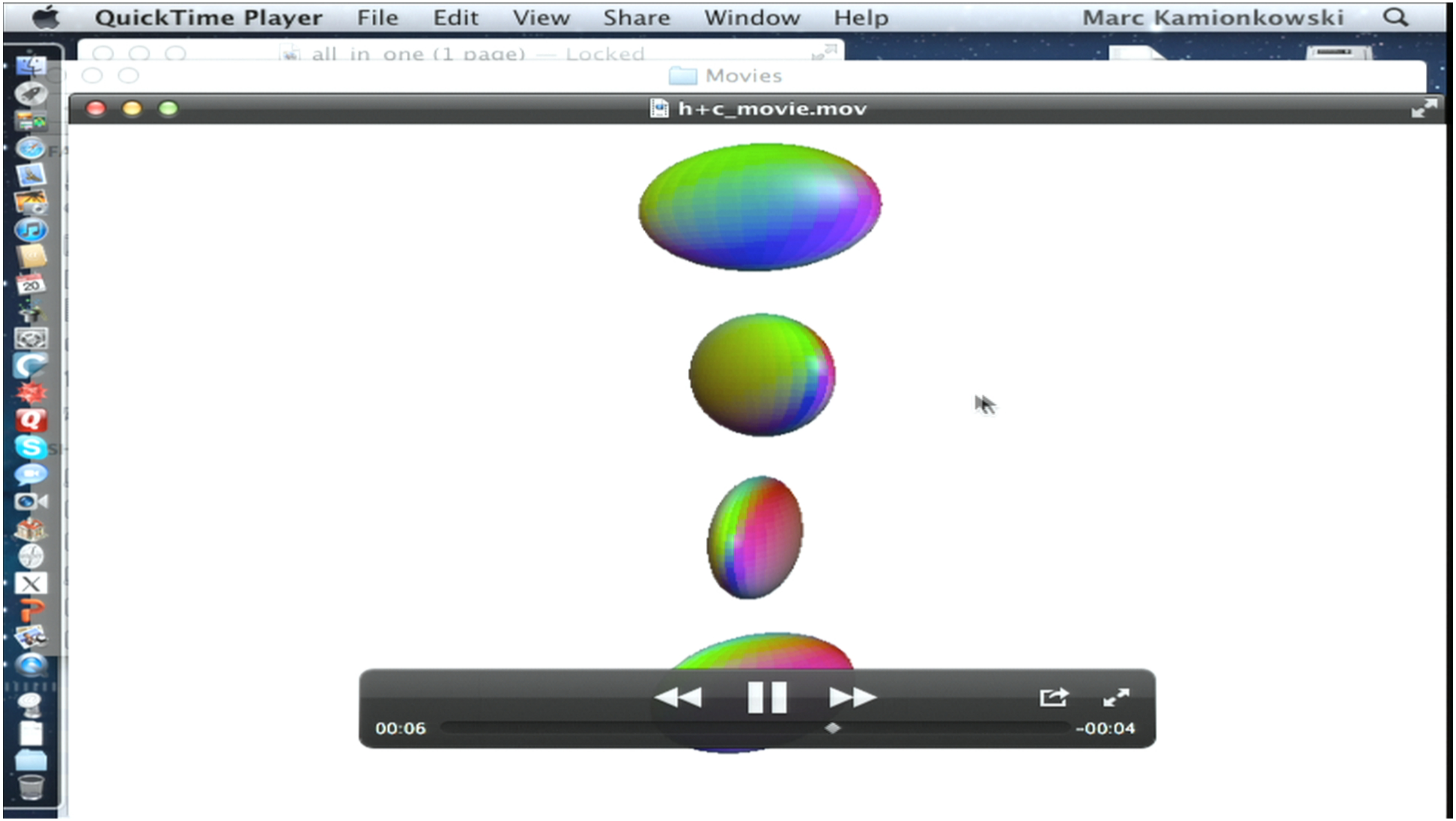
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Marc Kamionkowski
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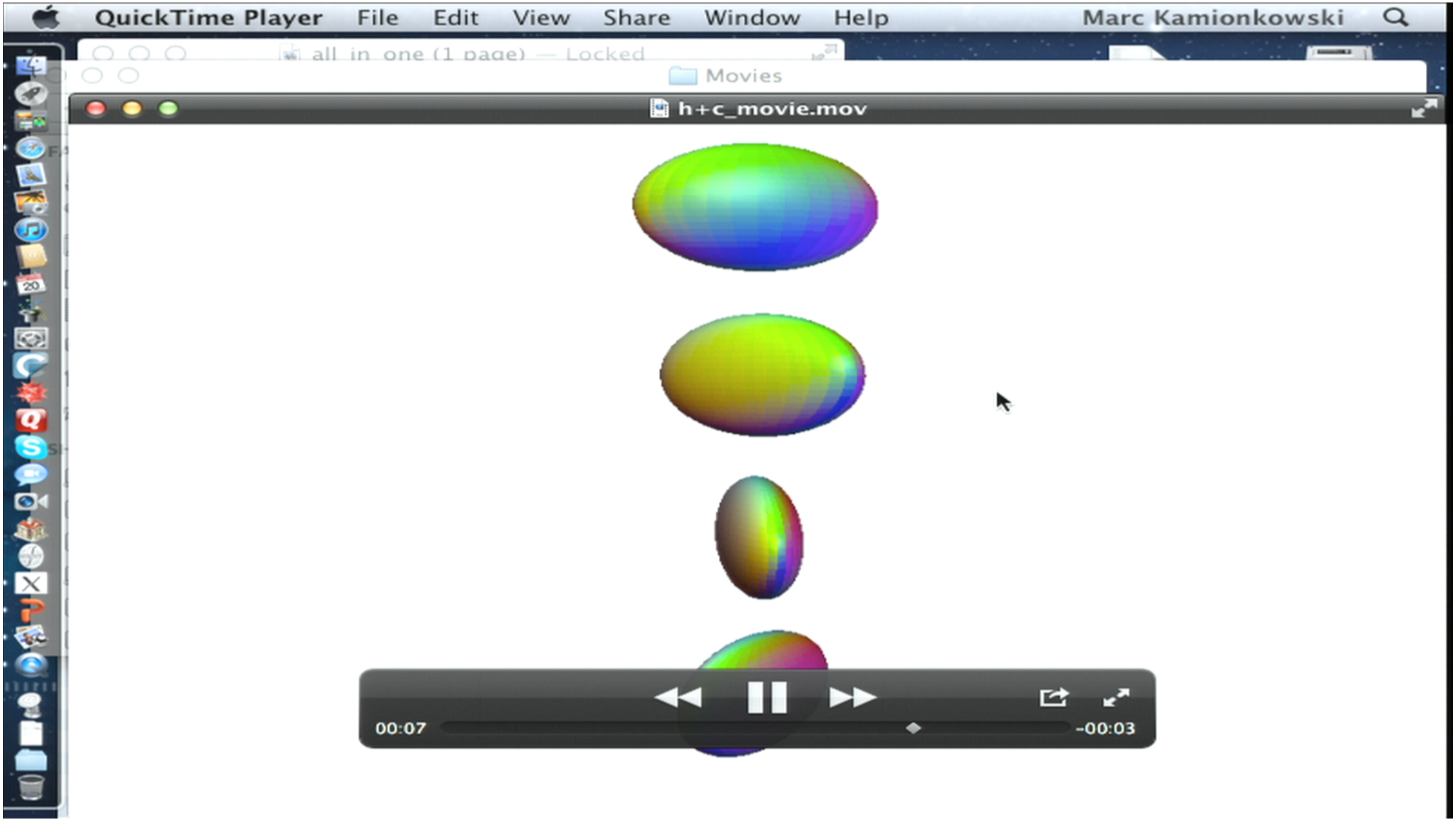
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Help
Marc Kamionkowski
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Movies
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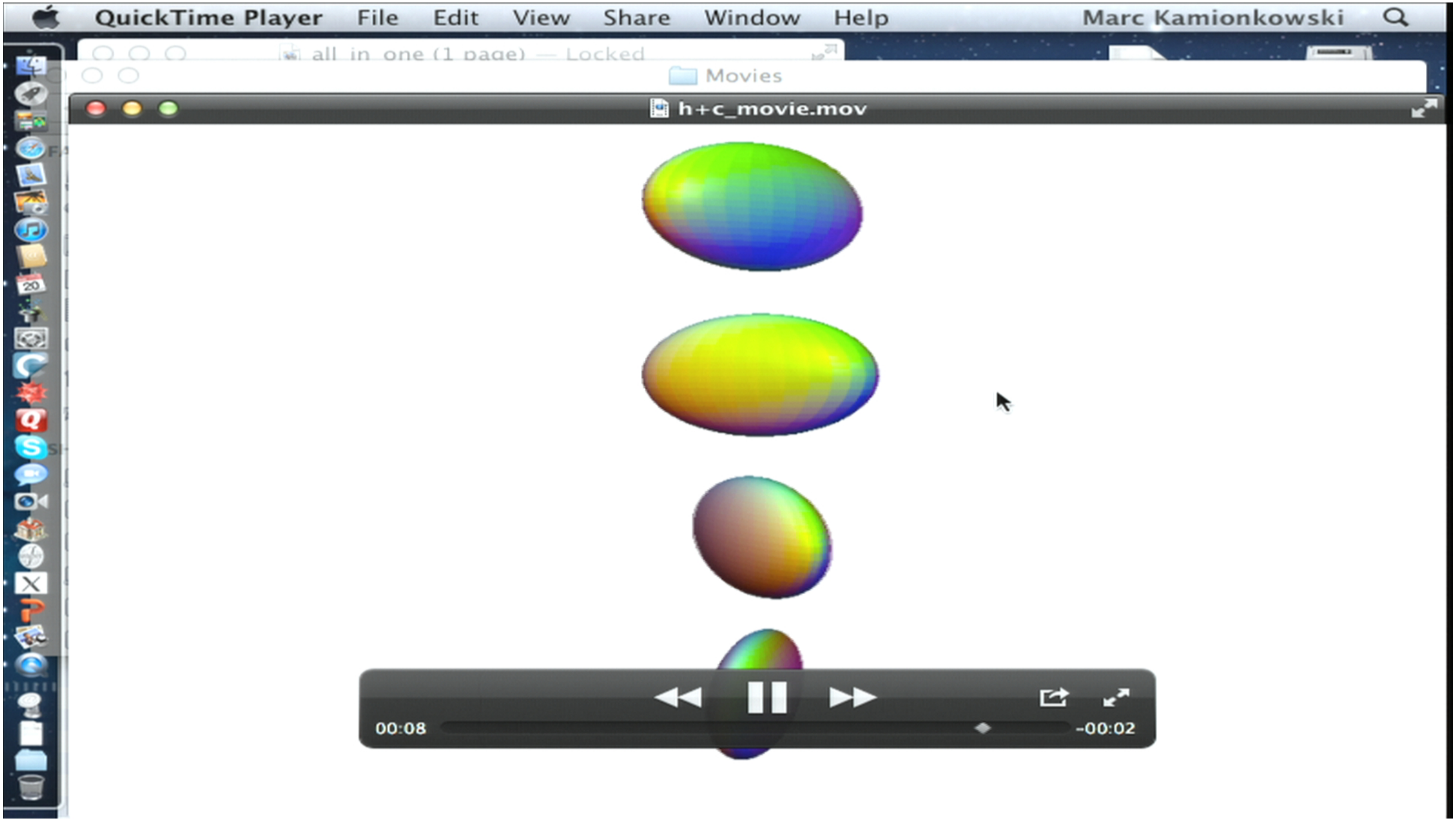
QuickTime Player
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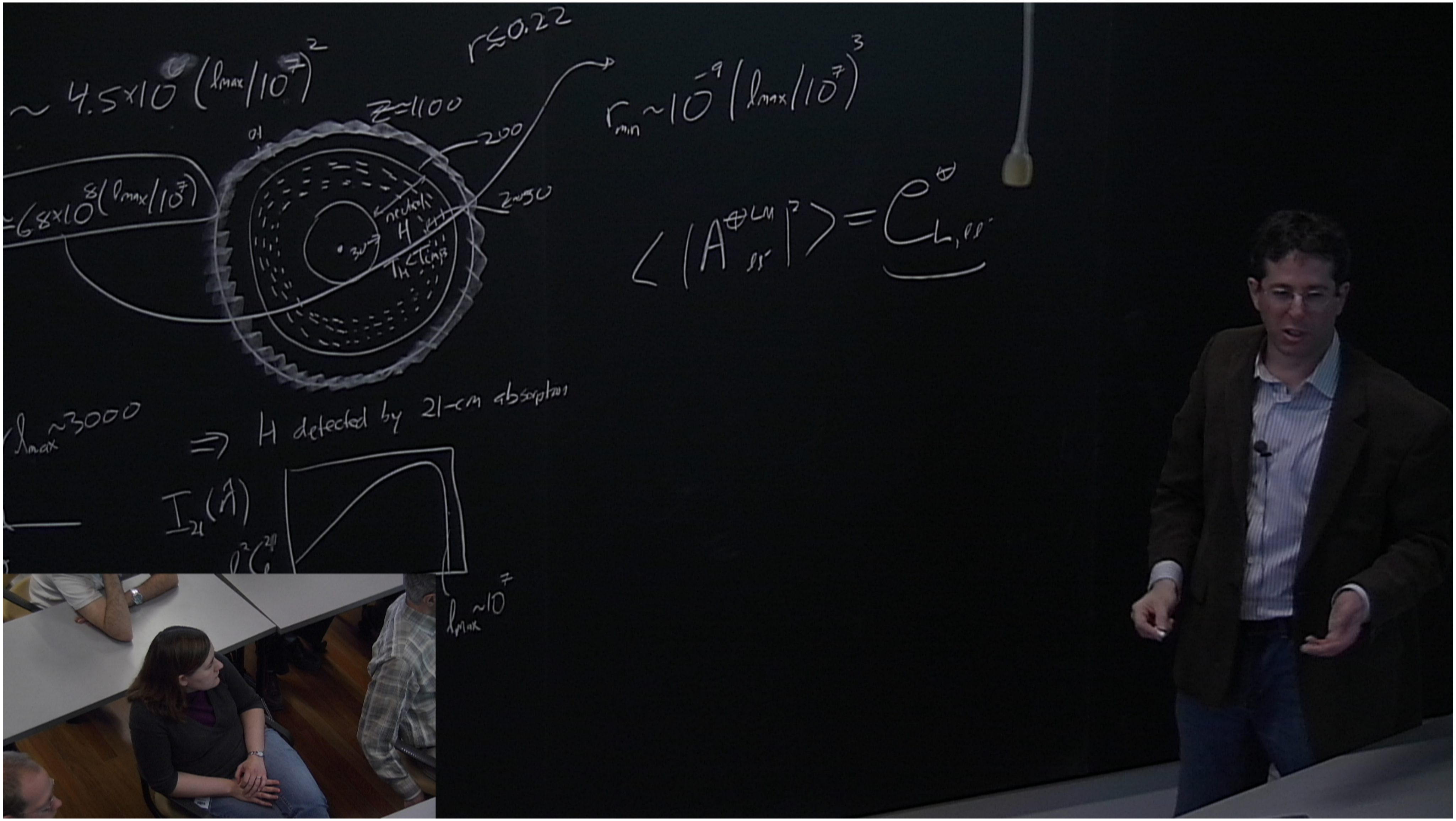
Help
Marc Kamionkowski
all in one (1 page) — Locked
Movies
h+c_movie.mov
00:08
-00:02

Conclusions

- Current CMB measurements provide precise determination of cosmological parameters and provide strong evidence in support of inflation
- Planck will make these measurements even more precise, and active suborbital search for inflationary gravitational waves under way
- But there is more that can be done with these and future experiments


r≲0.22
z≃1100
z≃50
H detected by 21-cm absorption