Title: Extended Path Intensity Correlation: Differential Astrometry with Microarcsecond Precision

Speakers: Marios Galanis

Series: Cosmology & Gravitation

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Abstract: The angular resolution of a stellar interferometer, as for a single telescope, becomes better at smaller wavelengths and larger baselines. The goal for ground detectors would then be optical interferometers with baselines as long as the Earth's diameter. The latter goal has been achieved in radio, but it becomes prohibitive in the optical, as the electromagnetic field oscillates too rapidly to record and analyze directly over km-long baselines. Intensity interferometry relying on second-order correlations can make this possible: rather than the amplitude and phase of incoming light, we need only count photons. This technique has a long history and to date the best measurements of nearby stellar radii, dating back to the 1950s. Its main limitations are the need for very bright sources and its narrow field of view, restricting kilometer-long baselines to sources only a few ?as away. In this talk, I will propose an optical-path modification of astronomical intensity interferometers, which introduces an effective time delay in the two-photon interference amplitude, splitting the main intensity correlation fringe into others at finite opening angles, allowing for differential astrometry of multiple compact sources such as stars or quasar images. Together with the exponential progress in the field of single photon detection, such a modification will immensely increase the scope of intensity interferometry beyond measurements of the optical emission region morphology. I will lay out the theory and technical requirements of time-delay intensity interferometry and, time permitting, I will talk about some promising applications, which include astrometric microlensing of stars and quasar images, binary-orbit characterization, exoplanet detection, Galactic acceleration measurements and calibration of the cosmic distance ladder, all at unprecedented relative astrometric precision.

Zoom link: https://pitp.zoom.us/j/92041231568?pwd=cWo2c0hwTEdmOTRCc042SHNxRWw5UT09

Extended Path Intensity Correlation:
Differential Astrometry with Microarcsecond Precision

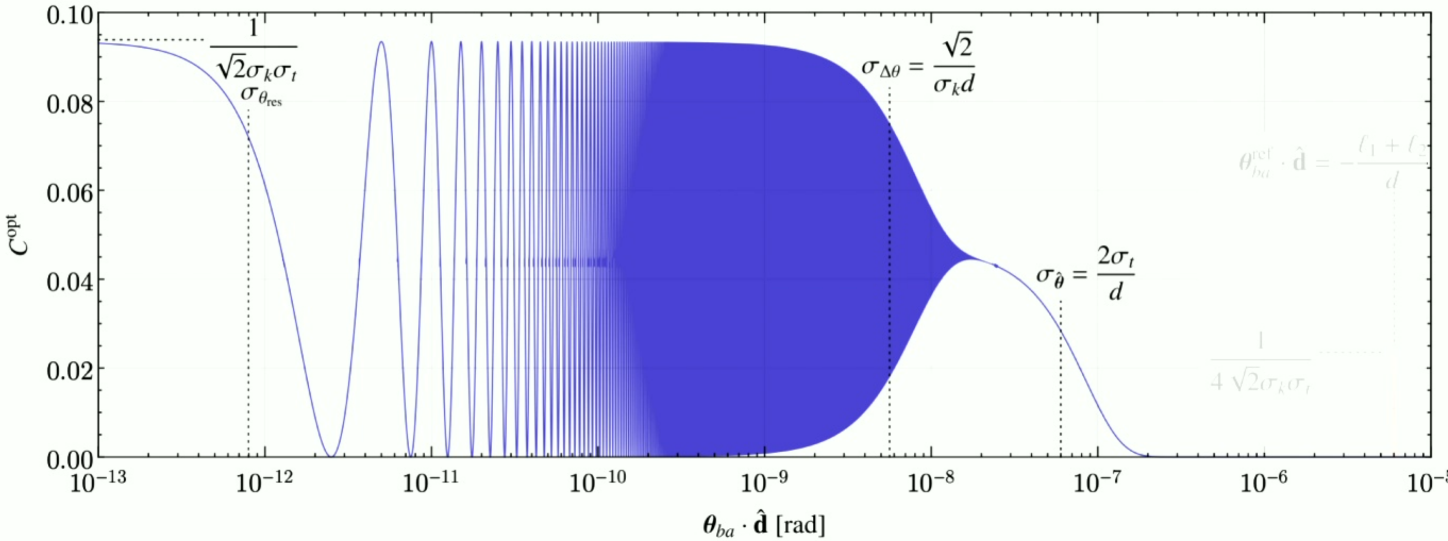
Marios Galanis
Perimeter Institute

In collaboration with: **Ken Van Tilburg** (NYU & CCA), **Masha Baryakhtar** (UW), **Neal Weiner** (NYU)

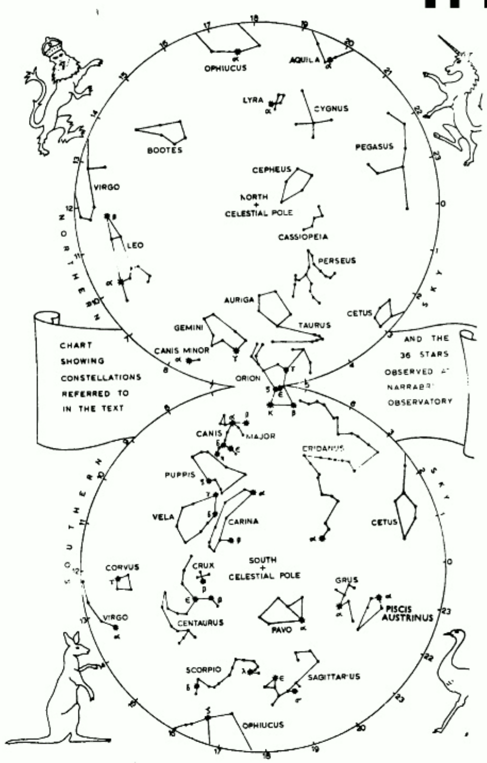
arXiv: 2304.xxxxx

Correlation

$d = 100\,\text{km},\ \bar{k} = \frac{2\pi}{500\,\text{nm}}, \sigma_k = \bar{k}/5000,\ \sigma_t = 10\,\text{ps}$



Narrabri Stellar Intensity Interferometer

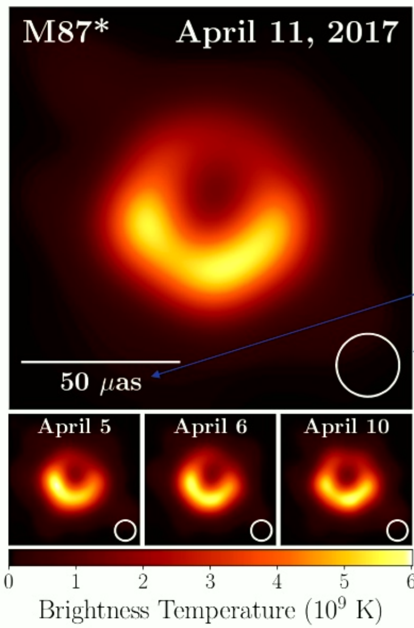


Star number	Star name	Type	Zero-baseline correlation $c_N \pm \sigma$	Angular diameter $\times 10^{-3}$ sec of arc $\theta_{UD} \pm \sigma$	$\theta_{LD} \pm \sigma$	Temperature $[T_e(F) \pm \sigma]$/K
472	α Eri	B 3 (Vp)	0·98 ± 0·05	1·85 ± 0·07	1·92 ± 0·07	13 700 ± 600
1713	β Ori	B 8 (Ia)	0·98 ± 0·08	2·43 ± 0·05	2·55 ± 0·05	11 500 ± 700
1790	γ Ori	B 2 (III)	1·03 ± 0·07	0·70 ± 0·04	0·72 ± 0·04	20 800 ± 1300
1903	ε Ori	B O (Ia)	0·86 ± 0·07	0·67 ± 0·04	0·69 ± 0·04	24 500 ± 2000
1948	ζ Ori	O 9·5 (Ib)	0·60 ± 0·06	0·47 ± 0·04	0·48 ± 0·04	26 100 ± 2200
2004	κ Ori	B 0·5 (Ia)	1·18 ± 0·09	0·44 ± 0·03	0·45 ± 0·03	30 400 ± 2000
2294	β CMa	B 1 (II–III)	1·07 ± 0·08	0·50 ± 0·03	0·52 ± 0·03	25 300 ± 1500
2326	α Car	F 0 (Ib–II)	0·75 ± 0·22	6·1 ± 0·7	6·6 ± 0·8	7500 ± 250
2421	γ Gem	A 0 (IV)	1·17 ± 0·09	1·32 ± 0·09	1·39 ± 0·09	9600 ± 500
2491	α CMa	A 1 (V)	0·91 ± 0·06	5·60 ± 0·15	5·89 ± 0·16	10 250 ± 150
2618	ε CMa	B 2 (II)	0·89 ± 0·06	0·77 ± 0·05	0·80 ± 0·05	20 800 ± 1300
2693	δ CMa	F 8 (Ia)	0·93 ± 0·18	3·29 ± 0·46	3·60 ± 0·50	— —
2827	η CMa	B 5 (Ia)	0·99 ± 0·09	0·72 ± 0·06	0·75 ± 0·06	14 200 ± 1300
2943	α CMi	F 5 (IV–V)	0·98 ± 0·10	5·10 ± 0·16	5·50 ± 0·17	6500 ± 200
3165	ζ Pup	O 5 (f)	1·04 ± 0·08	0·41 ± 0·03	0·42 ± 0·03	30 700 ± 2500
3207	γ^2 Vel	WC 8 + O 9 (I)	—	0·43 ± 0·05	0·44 ± 0·05	29 000 ± 3000
3685	β Car	A 1 (IV)	1·01 ± 0·06	1·51 ± 0·07	1·59 ± 0·07	9500 ± 350
3982	α Leo	B 7 (V)	1·12 ± 0·07	1·32 ± 0·06	1·37 ± 0·06	12 700 ± 800
4534	β Leo	A 3 (V)	1·17 ± 0·10	1·25 ± 0·09	1·33 ± 0·10	9050 ± 450
4662	γ Crv	B 8 (III)	0·97 ± 0·10	0·72 ± 0·06	0·75 ± 0·06	13 100 ± 1200
4853	β Cru	B 0·5 (III)	0·88 ± 0·03	0·702 ± 0·022	0·722 ± 0·023	27 900 ± 1200
5056	α Vir	B 1 (IV)	—	0·85 ± 0·04	0·87 ± 0·04	22 400 ± 1000
5132	ε Cen	B 1 (III)	1·02 ± 0·07	0·47 ± 0·03	0·48 ± 0·03	26 000 ± 1800
5953	δ Sco	B 0·5 (IV)	0·75 ± 0·07	0·45 ± 0·04	0·46 ± 0·04	— —
6175	ζ Oph	O 9·5 (V)	1·01 ± 0·12	0·50 ± 0·05	0·51 ± 0·05	— —
6556	α Oph	A 5 (III)	0·94 ± 0·09	1·53 ± 0·12	1·63 ± 0·13	8150 ± 400
6879	ε Sgr	A 0 (V)	1·02 ± 0·06	1·37 ± 0·06	1·44 ± 0·06	9650 ± 400
7001	α Lyr	A 0 (V)	0·99 ± 0·04	3·08 ± 0·07	3·24 ± 0·07	9250 ± 350
7557	α Aql	A 7 (IV, V)	0·94 ± 0·06	2·78 ± 0·13	2·98 ± 0·14	8250 ± 250
7790	α Pav	B 2·5 (V)	1·01 ± 0·07	0·77 ± 0·05	0·80 ± 0·05	17 100 ± 1400
8425	α Gru	B 7 (IV)	1·11 ± 0·08	0·98 ± 0·07	1·02 ± 0·07	14 800 ± 1200
8728	α PsA	A 3 (V)	1·02 ± 0·08	1·98 ± 0·13	2·10 ± 0·14	9200 ± 500

1965–1974

Narrabri Stellar Intensity Interferometer

EHT



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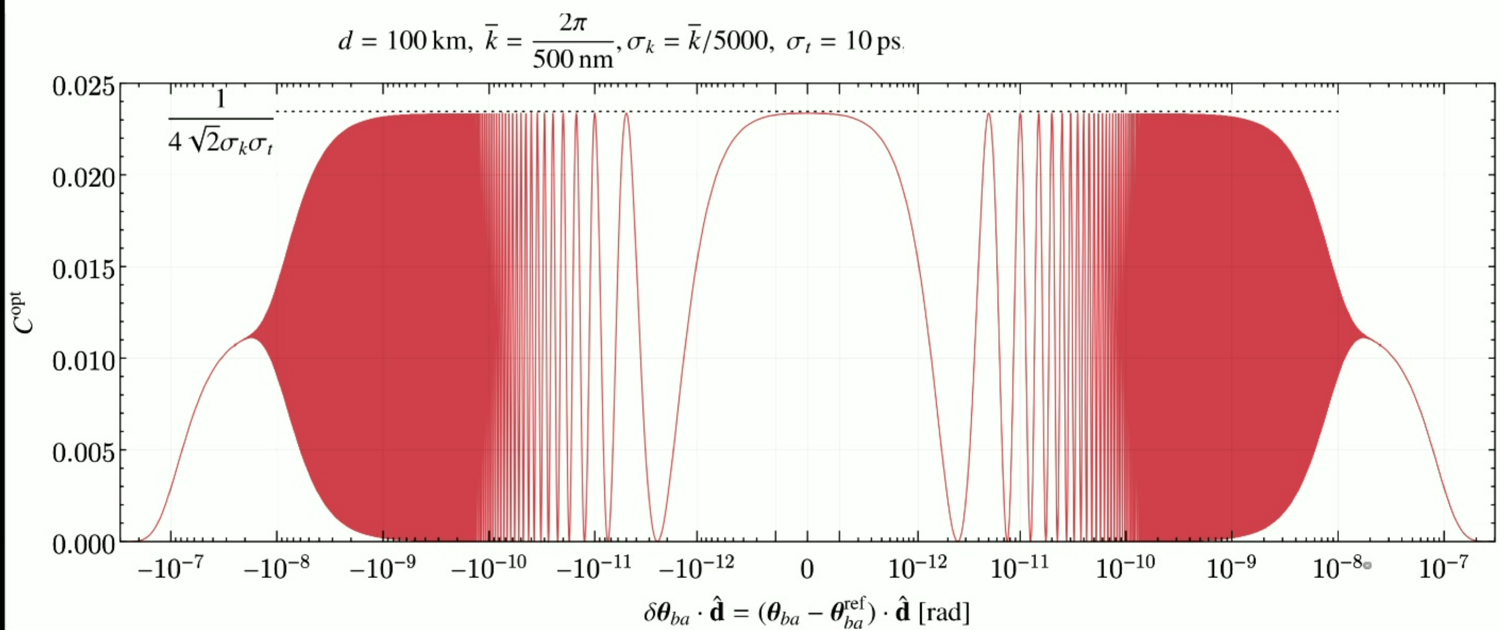
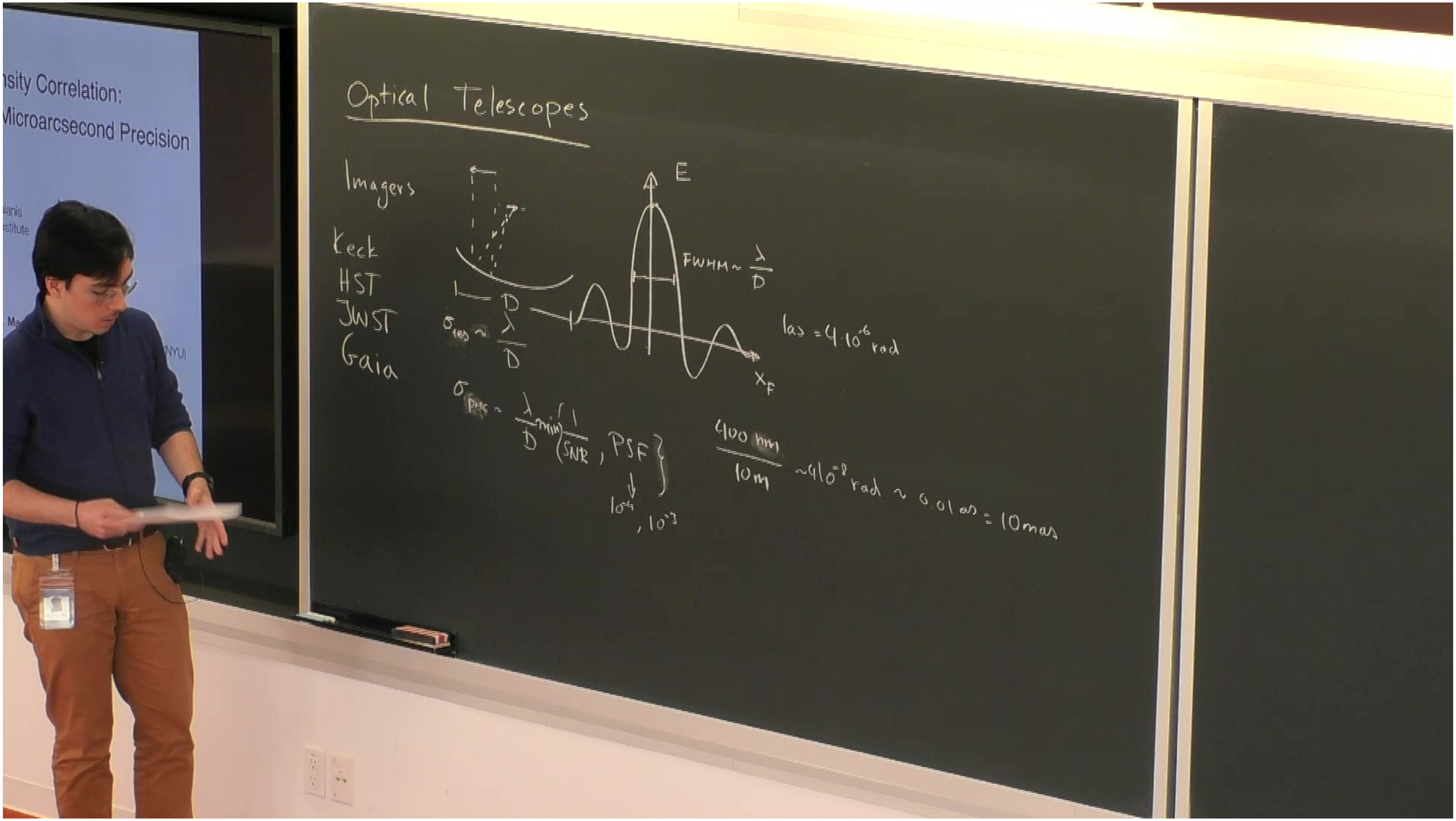
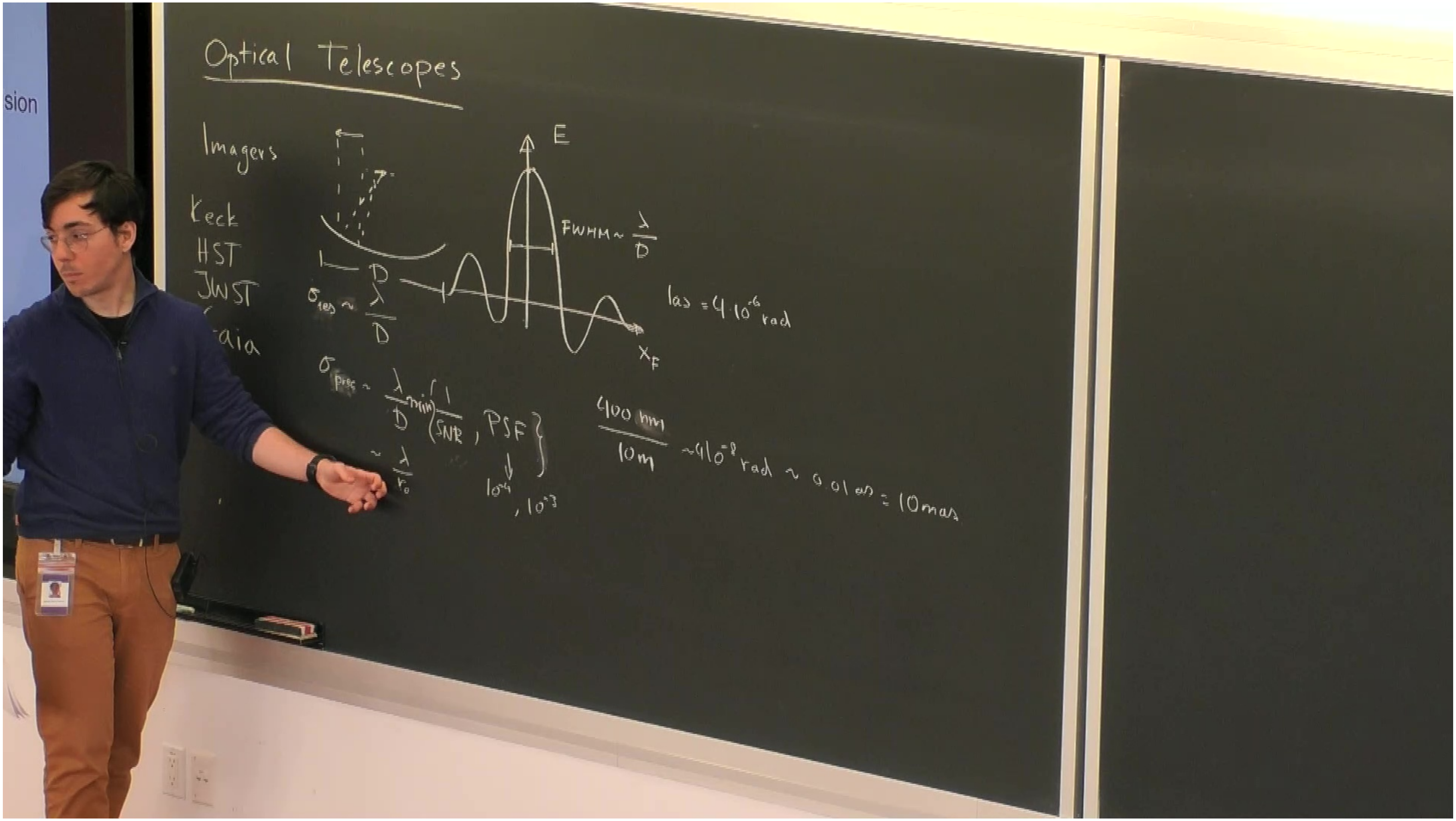
1965–1974

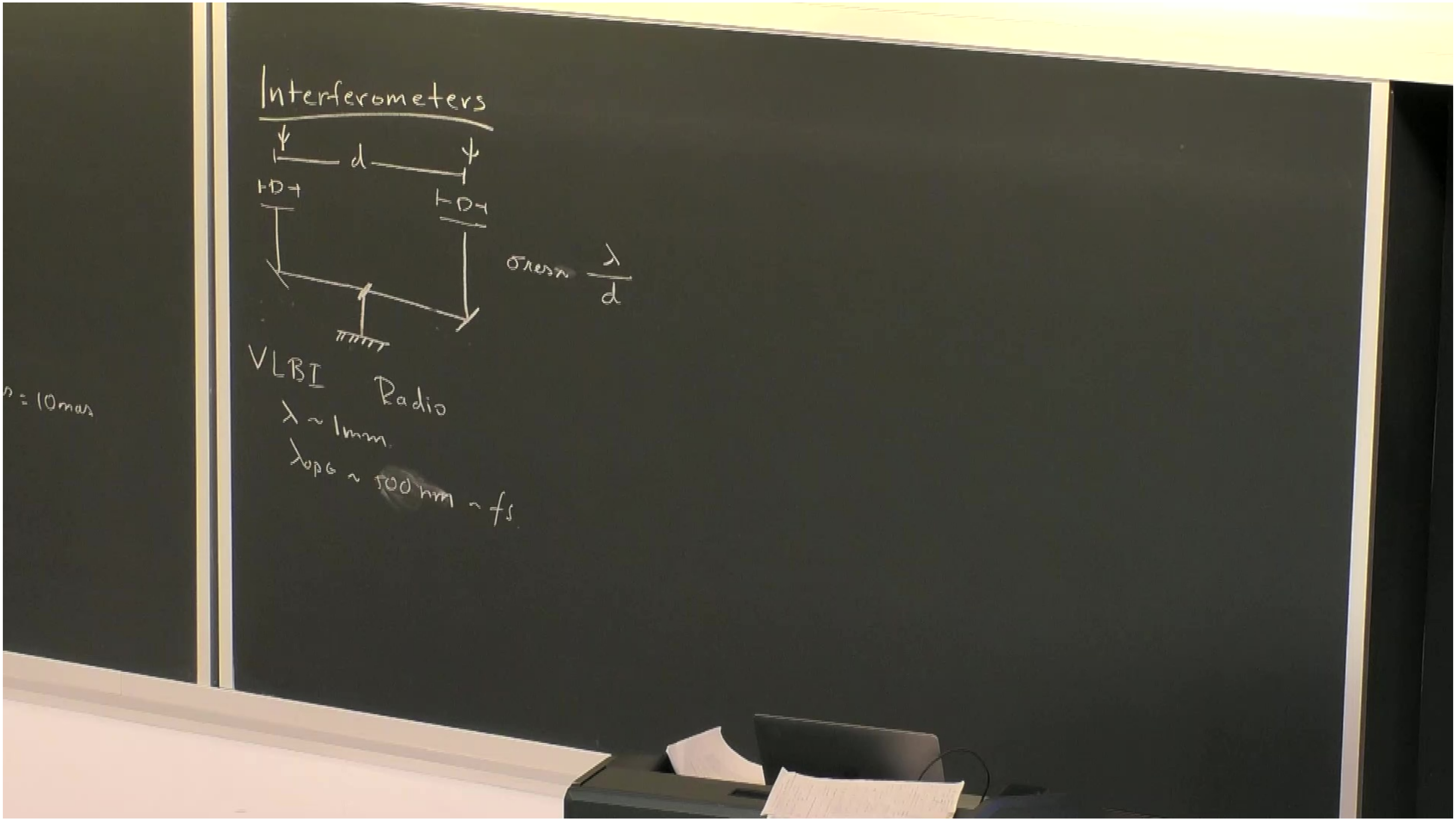
Correlation - Extended FOV

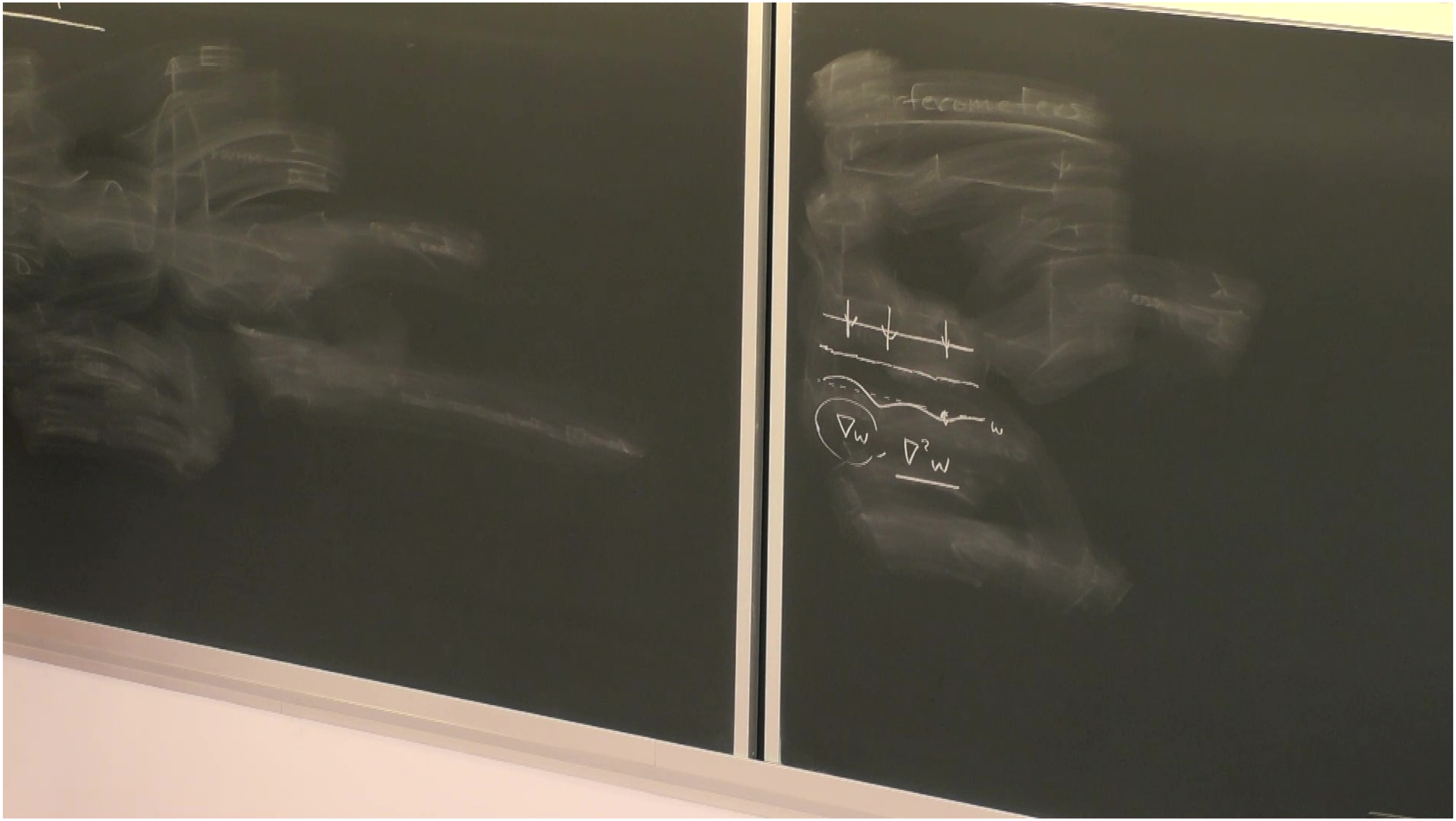


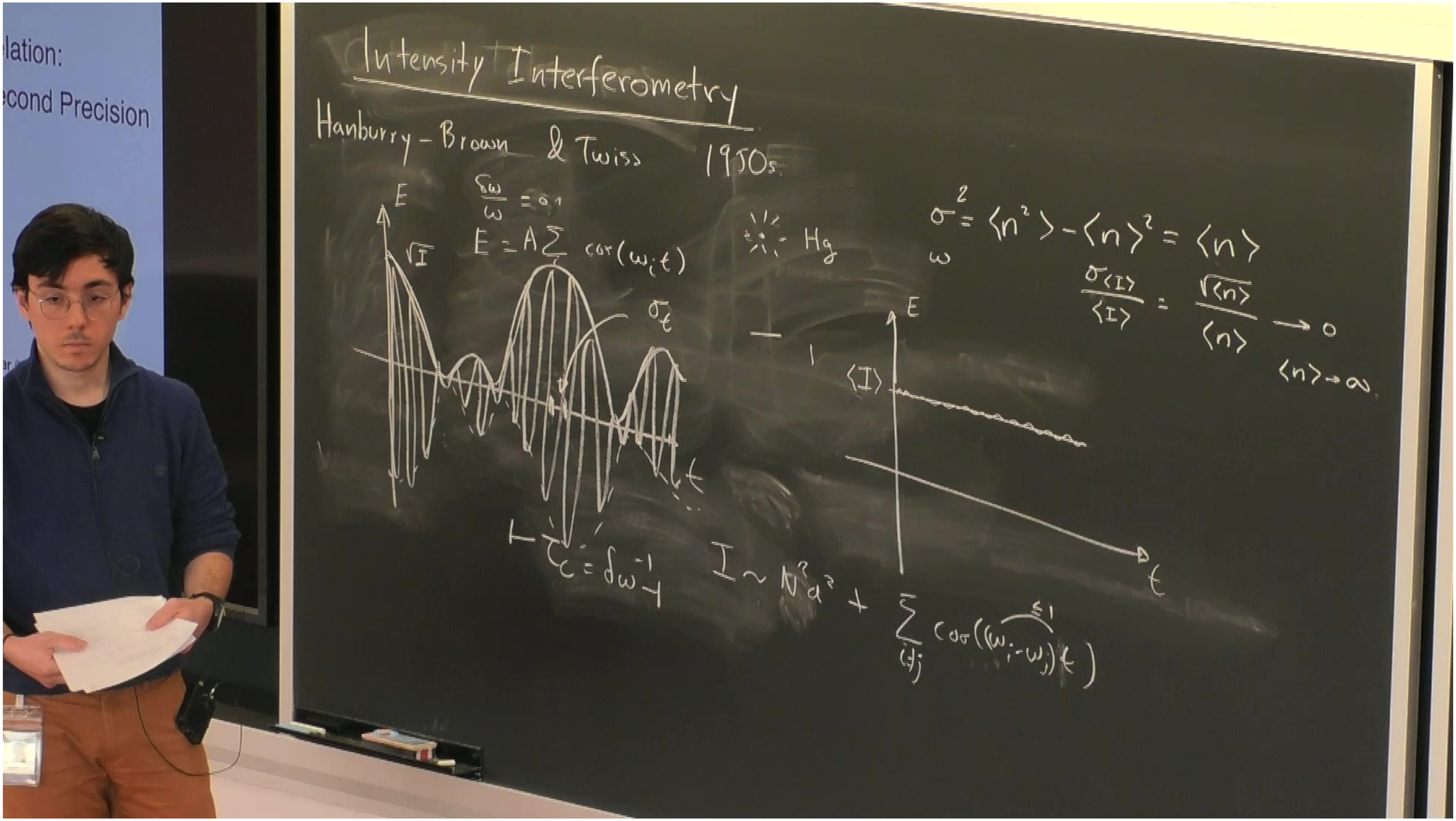


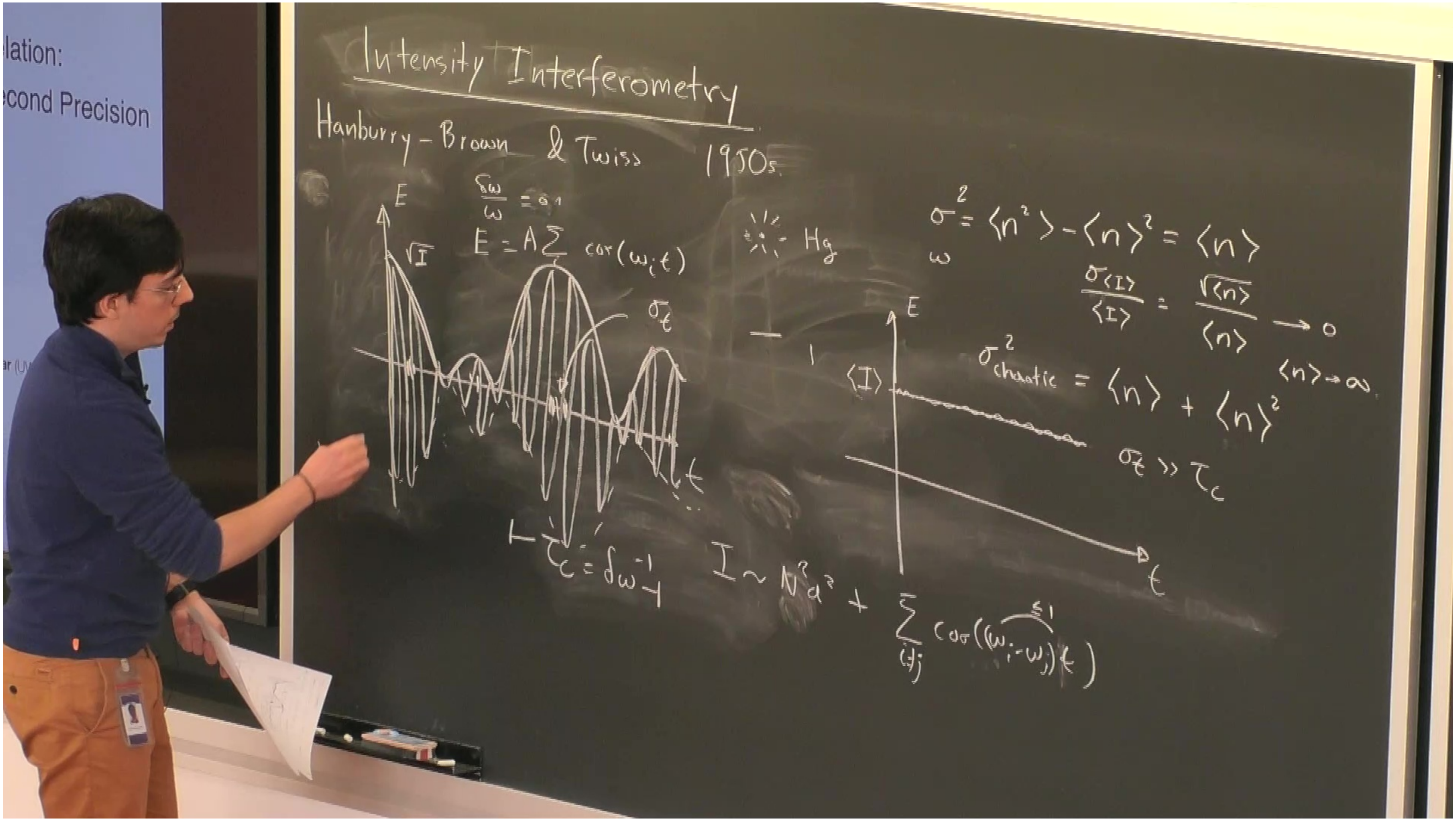
Microarcsecond Precision
Optical Telescopes
Imagers
Keck
HST
JWST
Gaia
E
FWHM ~ λ/D
D


sion
Optical Telescopes
Imagers
Keck
HST
JWST
Gaia
E
FWHM ~ λ/D
D
σ_res ~ λ/D
x_F
1as = 4·10^-6 rad
σ_prec ~ λ/D min{1/SNR, PSF}
~ λ/r_0
10^-4, 10^-3
400 nm / 10 m ~ 4·10^-8 rad ~ 0.01 as = 10 mas

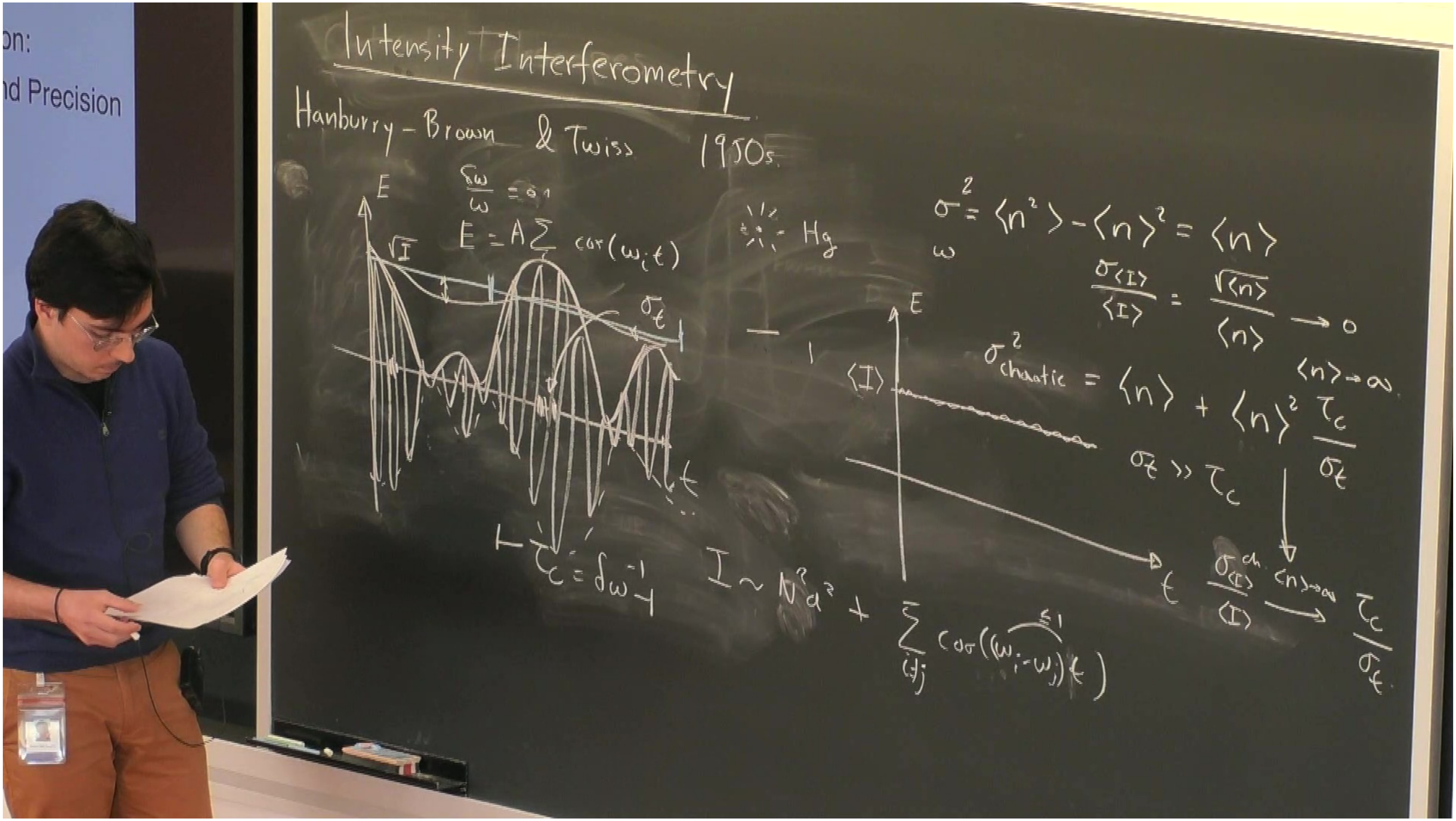

Interferometers
d
D
D
σres ~ λ/d
VLBI
Radio
λ ~ 1mm
λopt ~ 500 nm ~ fs
= 10mas


∇w
∇²w
w


lation:
cond Precision
Intensity Interferometry
Hanburry-Brown & Twiss 1950s
δω/ω
E = A Σ cos(ω_i t)
√I
σ_t
τ_c = δω^-1
Hg
I ~ N²a² + Σ cos((ω_i - ω_j) t)
σ² = ⟨n²⟩ - ⟨n⟩² = ⟨n⟩
σ⟨I⟩ / ⟨I⟩ = √⟨n⟩ / ⟨n⟩ → 0
⟨n⟩ → ∞
⟨I⟩



lation:
econd Precision
Intensity Interferometry
Hanburry - Brown & Twiss 1950s
E
√I
t
E = A Σ cos(ω_i t)
σ_t
τ_c = δω^-1
I ~ N²a² + Σ_{i,j} cos((ω_i - ω_j) t)
Hg
σ²_ω = ⟨n²⟩ - ⟨n⟩² = ⟨n⟩
σ⟨I⟩ / ⟨I⟩ = √⟨n⟩ / ⟨n⟩ → 0
⟨n⟩ → ∞
σ²_chaotic = ⟨n⟩ + ⟨n⟩²
⟨I⟩
σ_t >> τ_c


on:
nd Precision
Intensity Interferometry
Hanburry - Brown & Twiss 1950s
Hg
E = A Σ cos(ω_i t)
δω/ω = 0.1
√I
σ_t
t
E
⟨I⟩
τ_c = δω^-1
I ~ N^2 a^2 + Σ_{i≠j} cos((ω_i - ω_j) t)
σ^2 = ⟨n^2⟩ - ⟨n⟩^2 = ⟨n⟩
σ⟨I⟩ / ⟨I⟩ = √⟨n⟩ / ⟨n⟩ → 0
⟨n⟩ → ∞
σ^2 chaotic = ⟨n⟩ + ⟨n⟩^2 τ_c / σ_t
σ_t >> τ_c
σ^ch_⟨I⟩ / ⟨I⟩ → τ_c / σ_t

$\tau_c \sim \lambda \sim fs$ $\quad\quad$ $\tau_c \sim \Delta\lambda$

$\sigma_t \approx ns$ $\quad$ 1950s $\quad$ PMTs

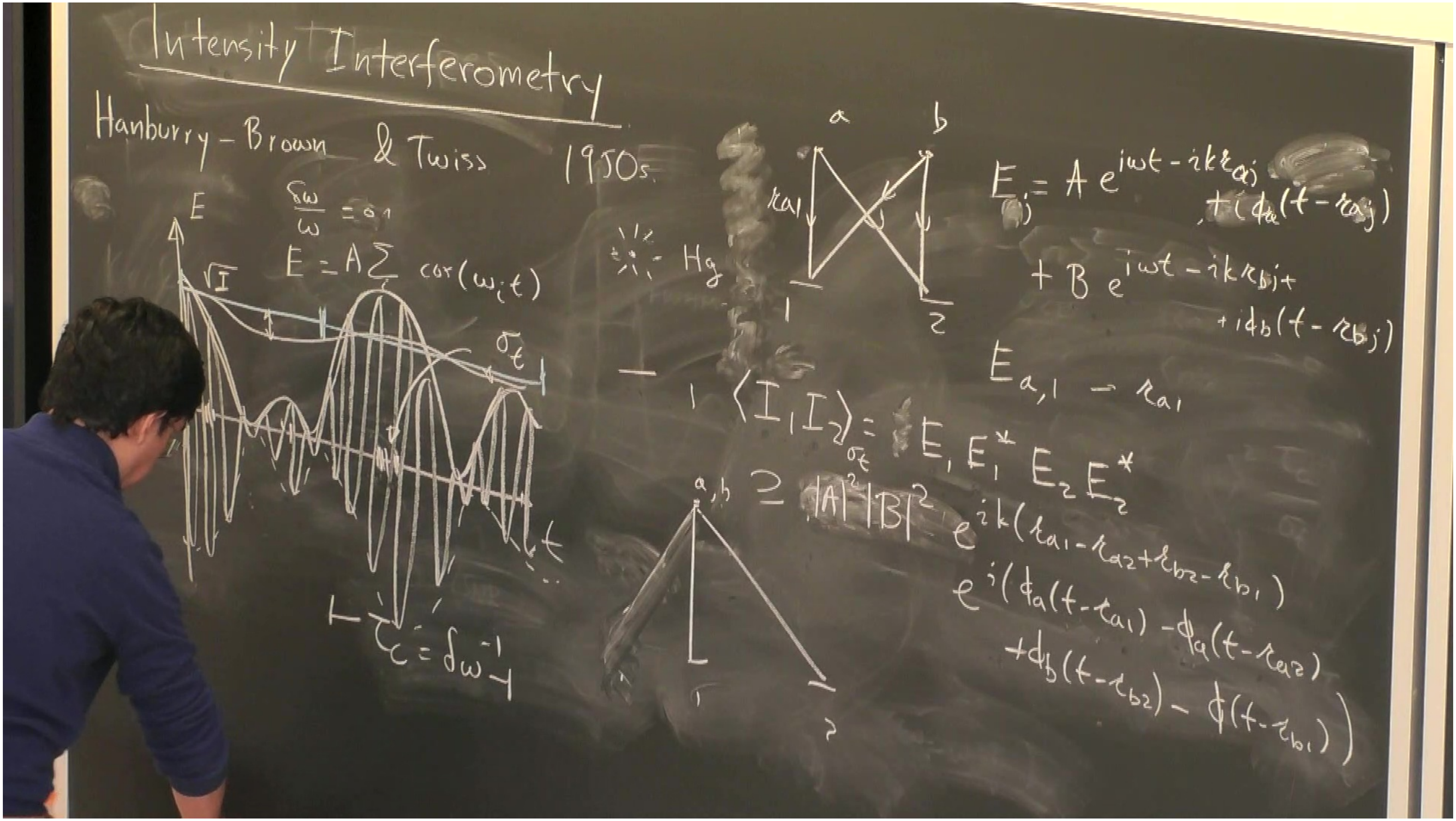
$\lesssim 10ps$ $\quad$ SNSPDs

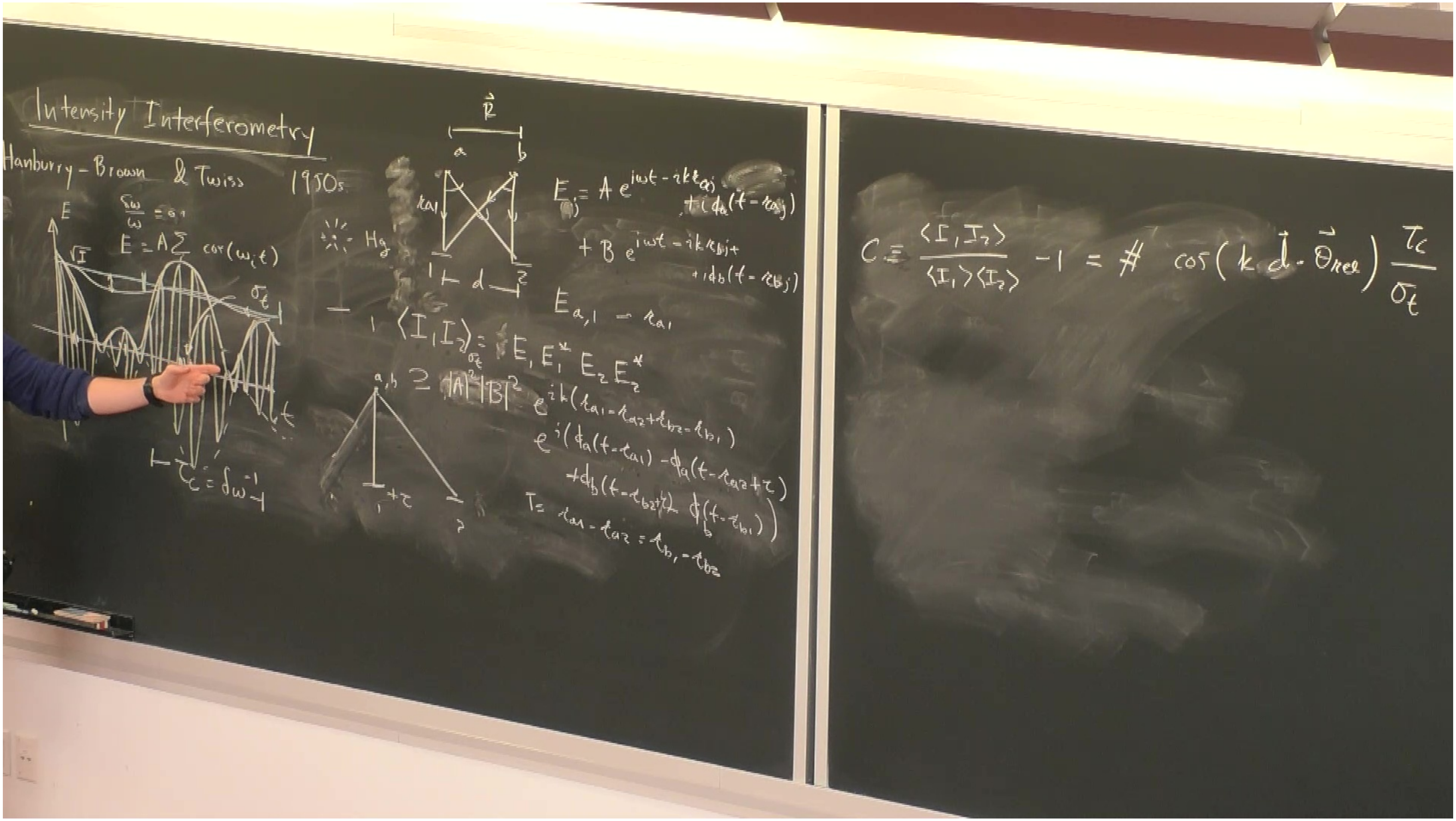
SPADs

$$E = A \sum_i e^{i\omega_i t + \phi_i}$$

$$\langle |E|^2 \rangle = \left\langle \sum_i \sum_j A_i A_j^* e^{i(\omega_i - \omega_j)t + (\phi_i - \phi_j)} \right\rangle \quad \delta_{ij}$$

$$= \sum_i |A_i|^2 \longrightarrow \int dk \, f(k)$$


Intensity Interferometry
Hanburry-Brown & Twiss 1950s
δω/ω = 0.1
E = A Σ cos(ω_i t)
√I
σ_t
τ_c = δω^-1
Hg
a b
1 2
E_j = A e^{iωt - ikr_aj + iφ_a(t - r_aj)}
+ B e^{iωt - ikr_bj + iφ_b(t - r_bj)}
E_a,1 → r_a1
⟨I_1 I_2⟩_σt = E_1 E_1* E_2 E_2*
a,b ⊇ |A|^2 |B|^2 e^{ik(r_a1 - r_a2 + r_b2 - r_b1)}
e^{i(φ_a(t - r_a1) - φ_a(t - r_a2) + φ_b(t - r_b2) - φ(t - r_b1))}


Intensity Interferometry
Hanburry-Brown & Twiss 1950s
E = A Σ cos(ω_i t)
Hg
τ_c = δω^-1
⟨I_1 I_2⟩ = E_1 E_1* E_2 E_2*
C = ⟨I_1 I_2⟩ / ⟨I_1⟩⟨I_2⟩ − 1 = # cos(k d · θ_rel) τ_c / σ_t

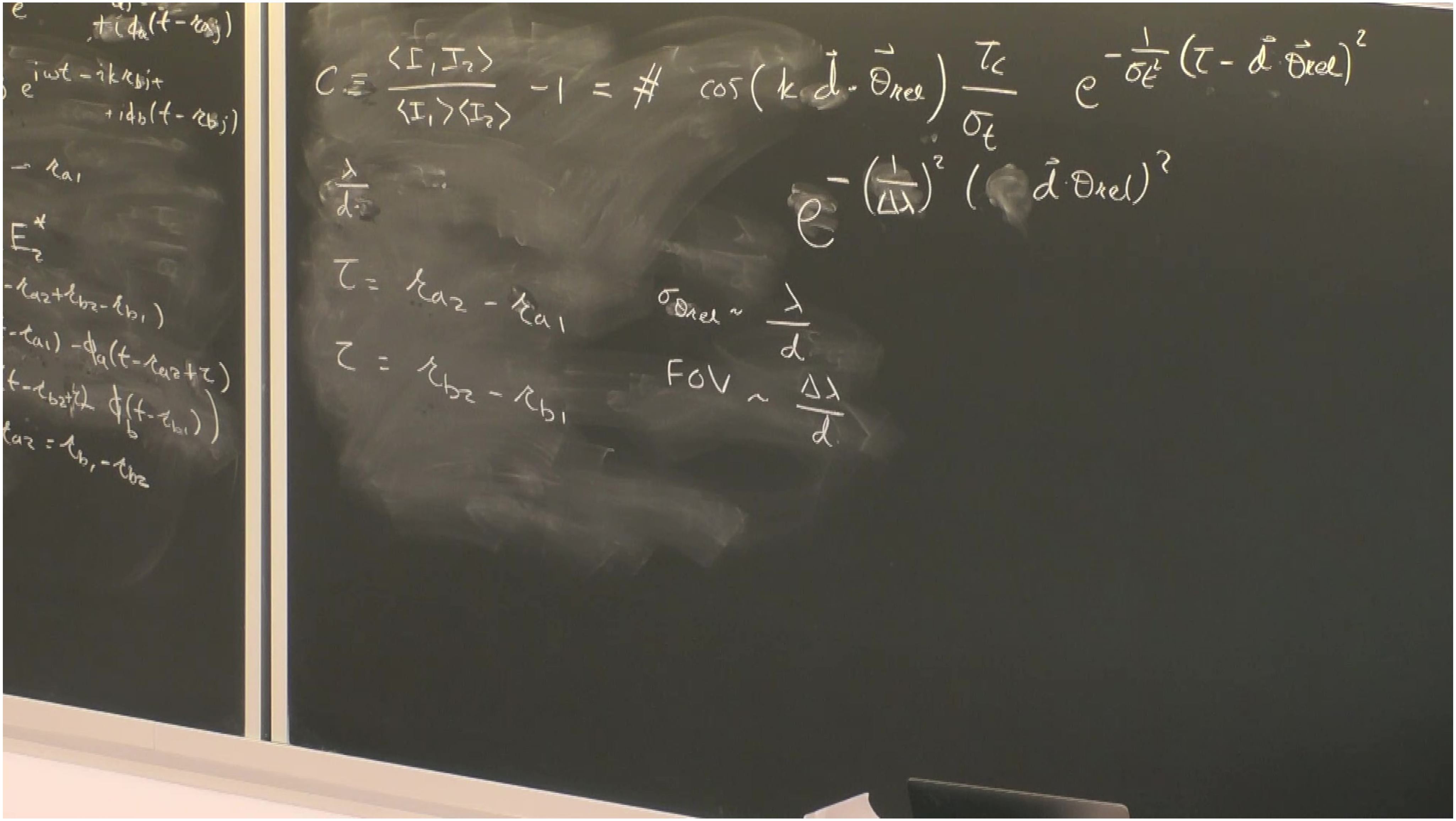
$$C \equiv \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} - 1 = \# \cos\left(k\, \vec{d} \cdot \vec{\theta}_{rel}\right) \frac{\tau_c}{\sigma_t}\, e^{-\frac{1}{\sigma_t^2}\left(\tau - \vec{d}\cdot\vec{\theta}_{rel}\right)^2}$$

$$e^{-\left(\frac{1}{\Delta\lambda}\right)^2 \left(k\, \vec{d}\, \theta_{rel}\right)^2}$$

$$\frac{\lambda}{d}$$

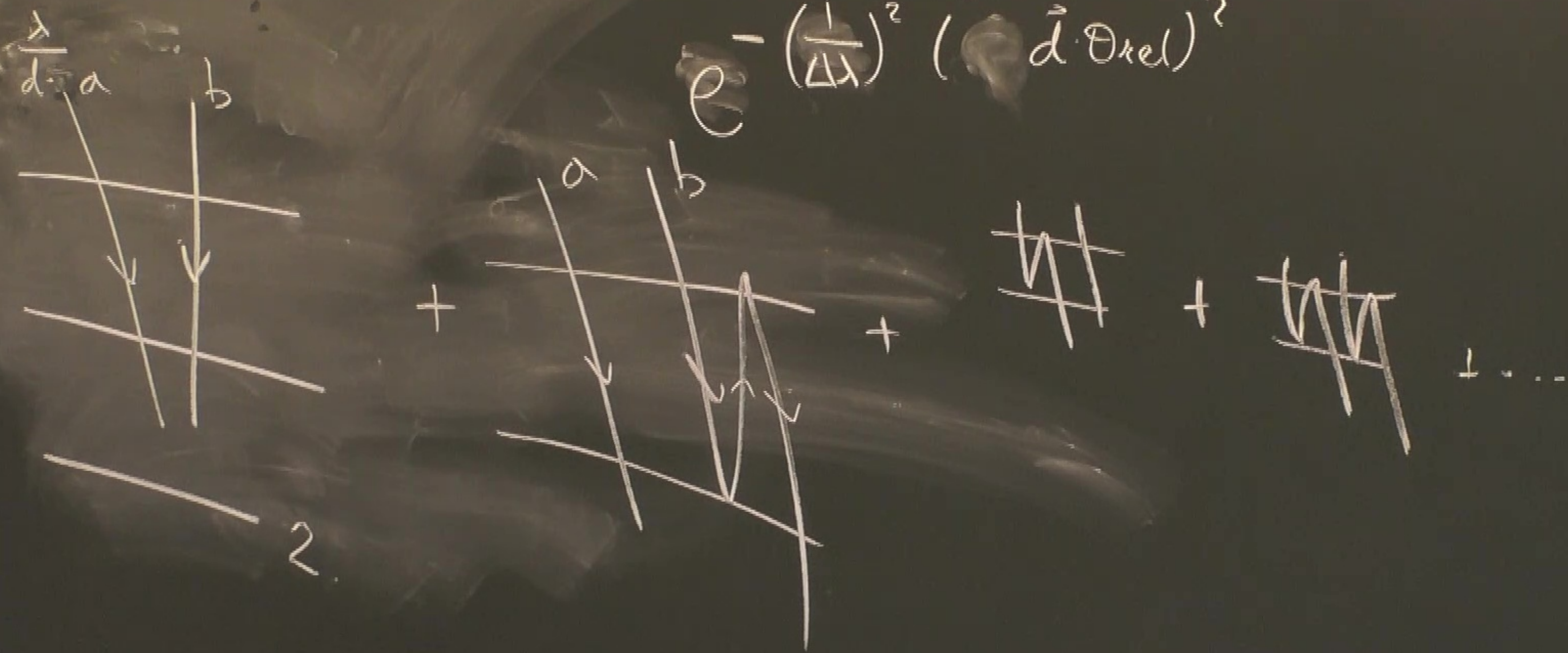
$$\tau = r_{a2} - r_{a1}$$

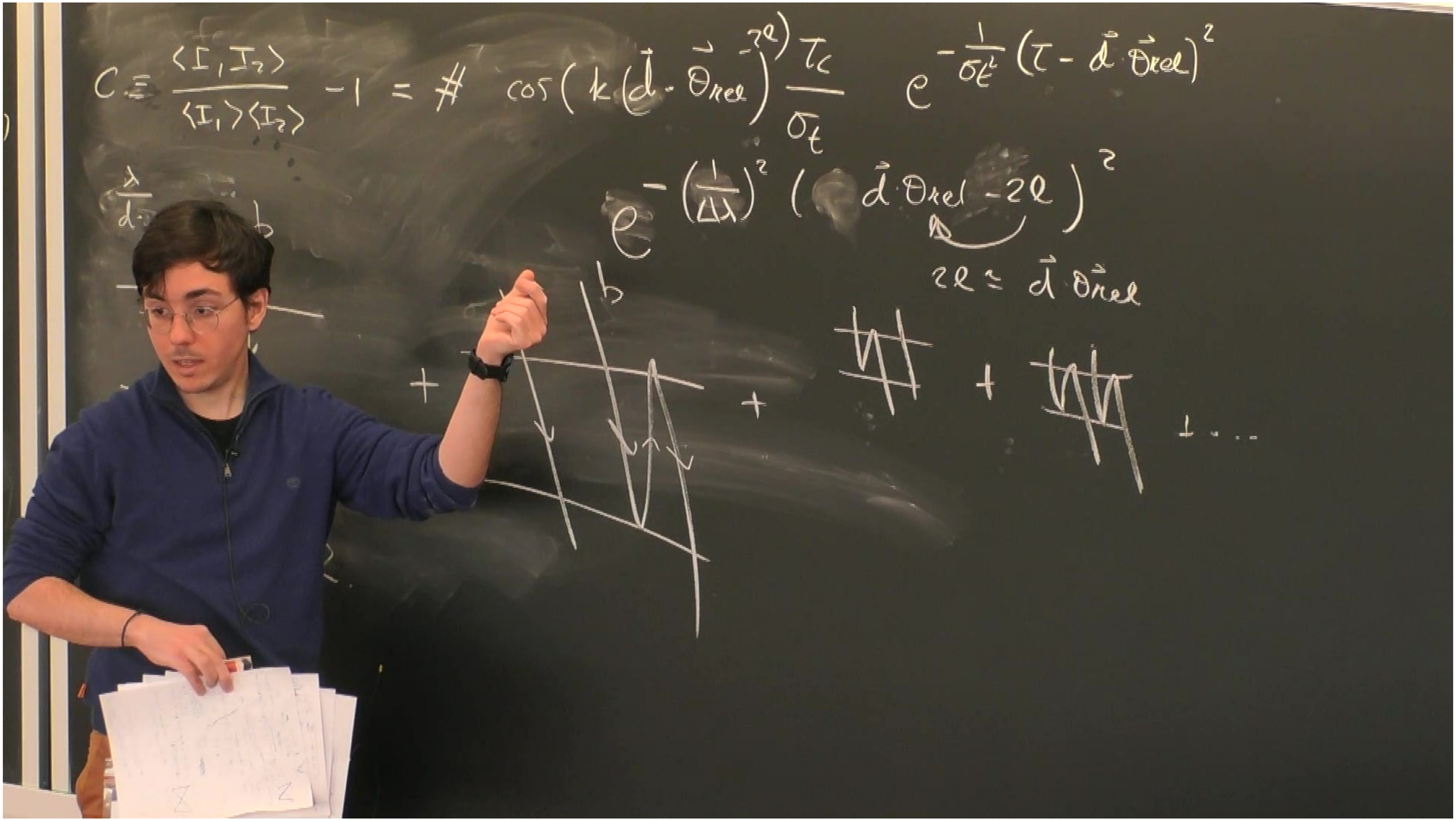
$$\tau = r_{b2} - r_{b1}$$


C ≡ ⟨I1 I2⟩ / ⟨I1⟩⟨I2⟩ − 1 = # cos(k d · θrel) τc/σt e^(−1/σt² (τ − d · θrel)²)
e^(−(1/Δλ)² (d · θrel)²)
λ/d
τ = ta2 − ta1
τ = tb2 − tb1
σθrel ~ λ/d
FOV ~ Δλ/d

$$C \equiv \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} - 1 = \# \cos\left(k \vec{d} \cdot \vec{\theta}_{rel}\right) \frac{\tau_c}{\sigma_t} e^{-\frac{1}{\sigma_t^2}\left(\tau - \vec{d} \cdot \vec{\theta}_{rel}\right)^2}$$

$$e^{-\left(\frac{1}{\Delta\lambda}\right)^2 \left(\vec{d} \cdot \theta_{rel}\right)^2}$$




C ≡ ⟨I1 I2⟩ / ⟨I1⟩⟨I2⟩ − 1 = # cos(k(d · θrel − 2ℓ)) τc/σt e^(−1/σt² (τ − d · θrel)²)
e^(−(1/Δλ)² (d · θrel − 2ℓ)²)
2ℓ ≈ d θrel