Title: Quantum matter without quasiparticles

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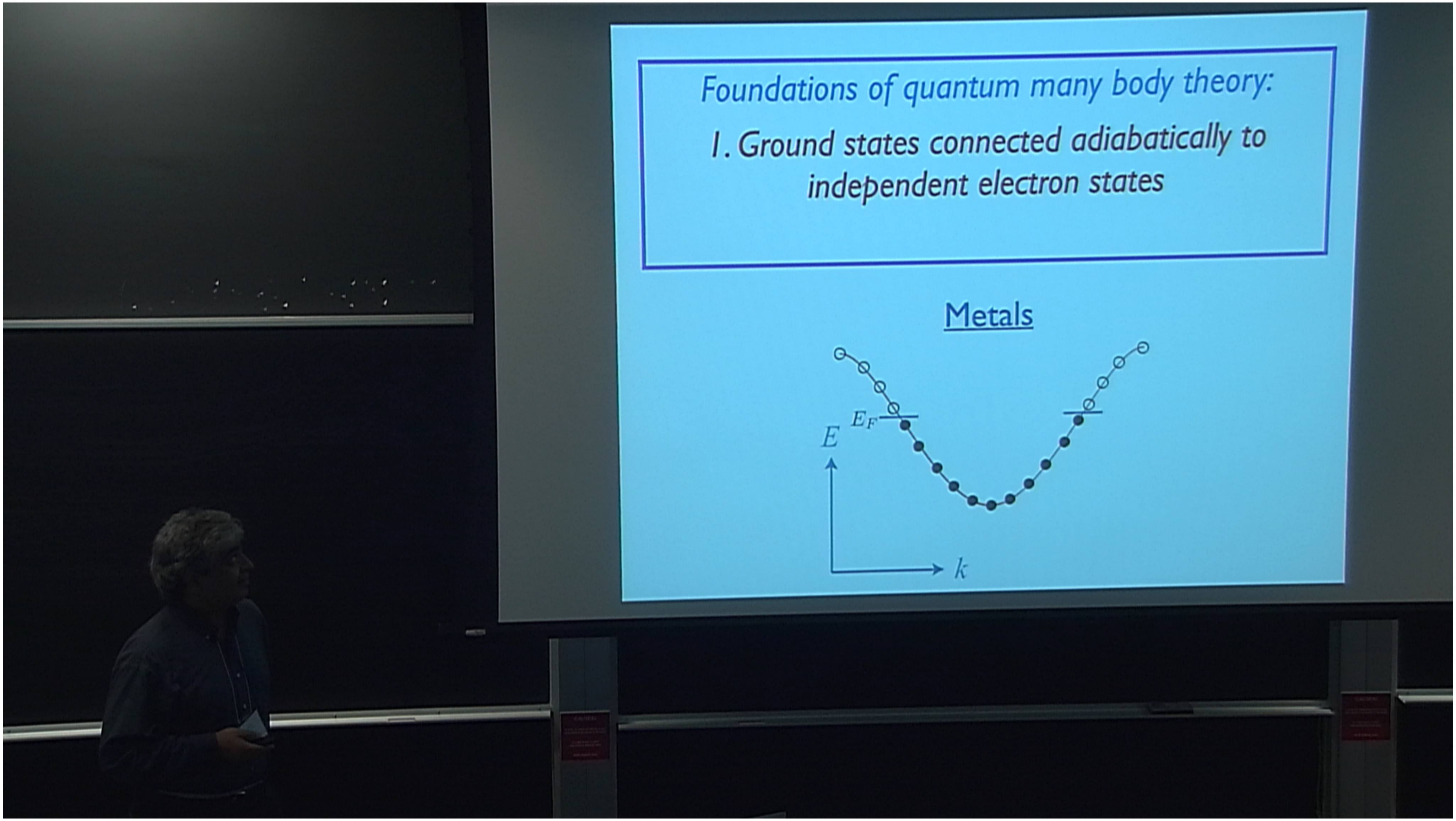
Abstract: Modern materials abound in systems to which the quasiparticle picture does not apply, and developing their theoretical description remains an important challenge in condensed matter physics. I will describe recent progress in understanding the dynamics of two systems without quasiparticles: (i) ultracold atoms in optical lattices, and (ii) the nematic quantum critical point of metals with applications to the `strange metalâ€™ found in the high temperature superconductors. A combination of field-theoretic, holographic, and numerical methods will be used.


Foundations of quantum many body theory:
1. Ground states connected adiabatically to independent electron states
Metals
E_F
E
k

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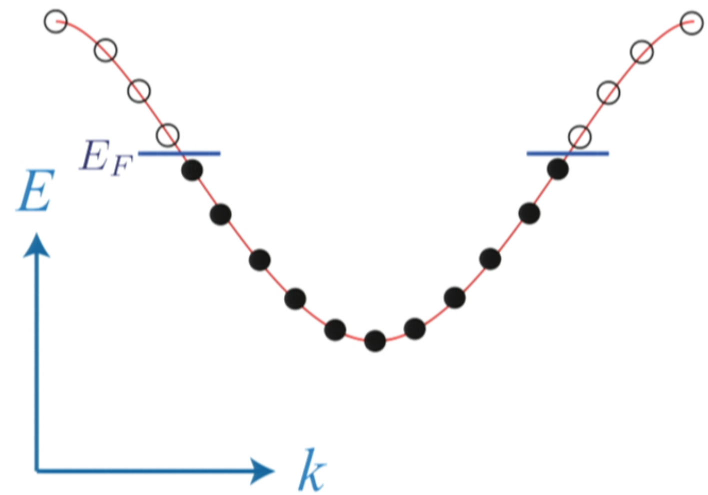
Metals



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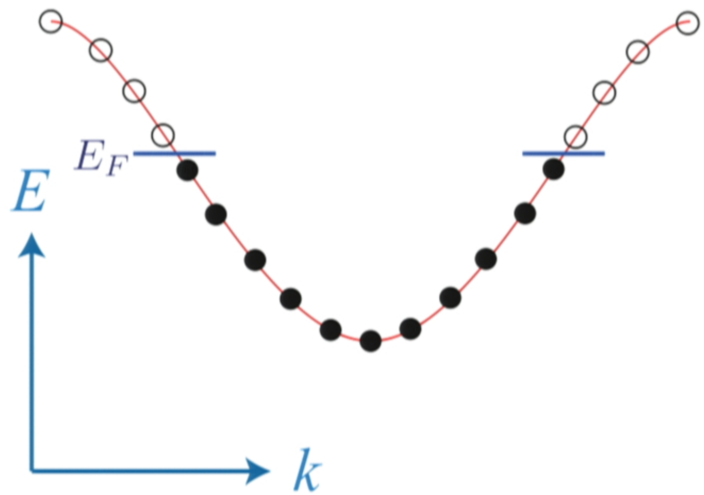

Modern phases of quantum matter:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. Boltzmann-Landau theory of quasiparticles

Famous examples:

The fractional quantum Hall effect of electrons in two dimensions (e.g. in graphene) in the presence of a strong magnetic field. The ground state is described by Laughlin's wavefunction, and the excitations are *quasiparticles* which carry fractional charge.

Modern phases of quantum matter:

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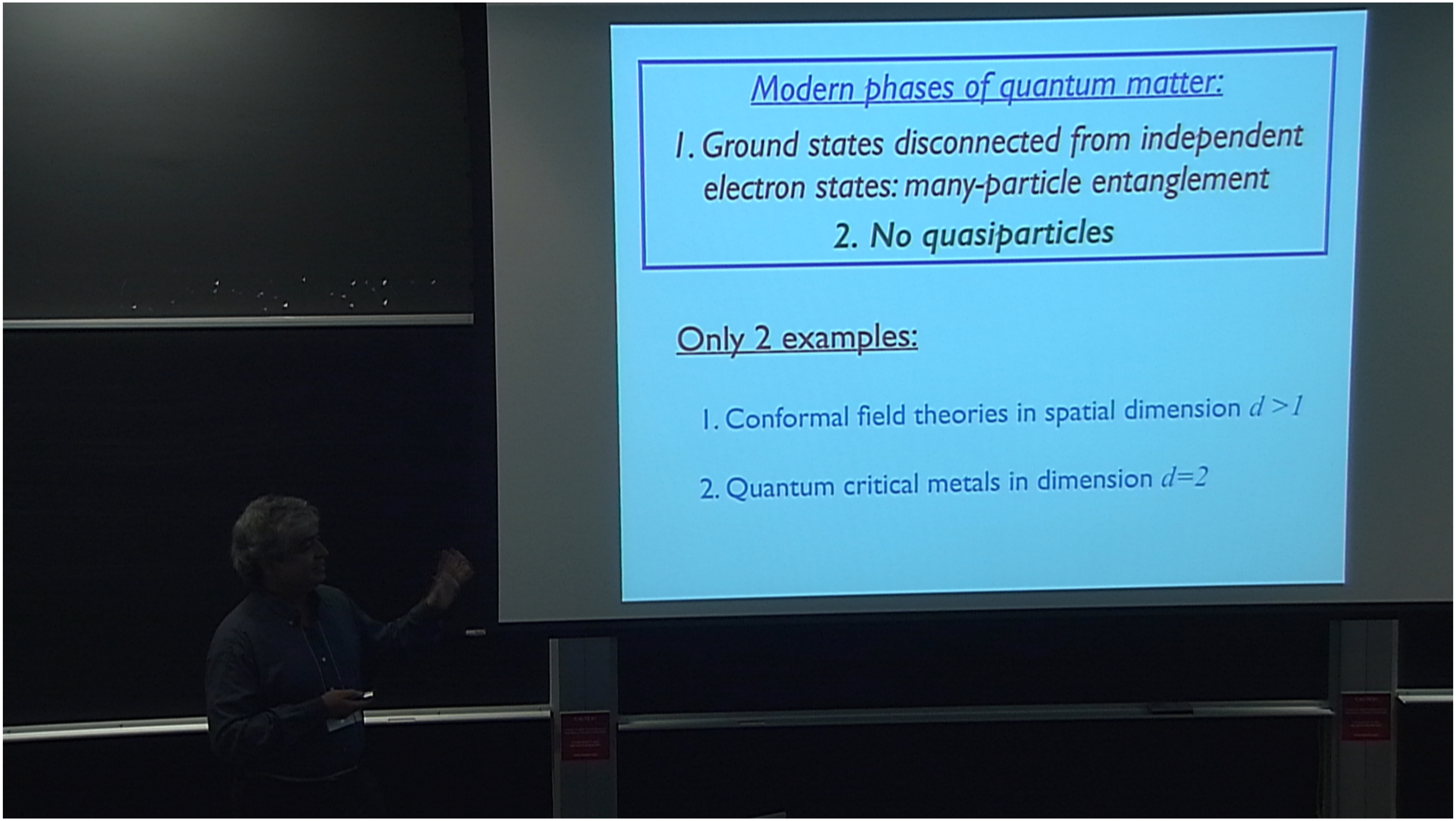
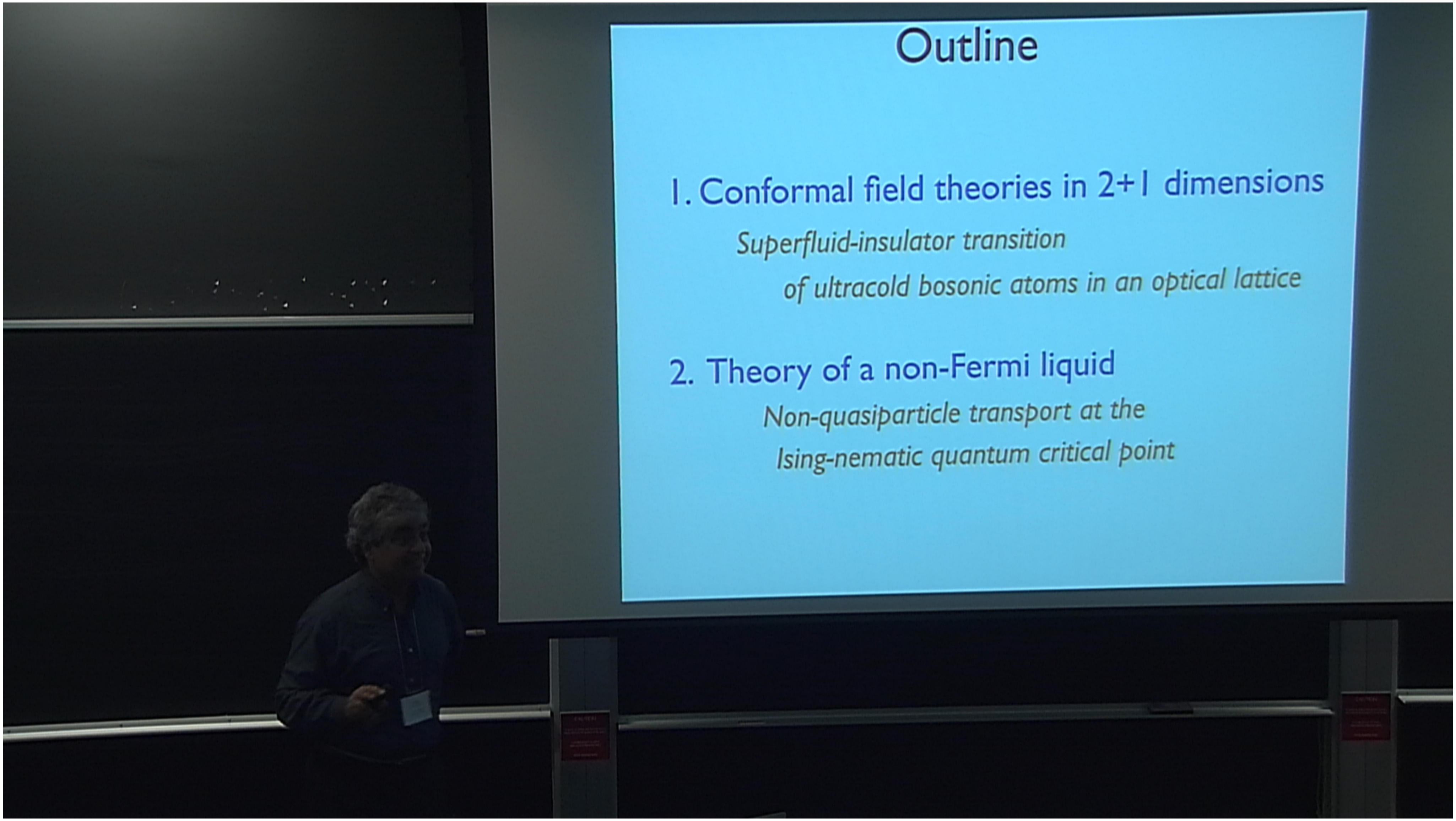
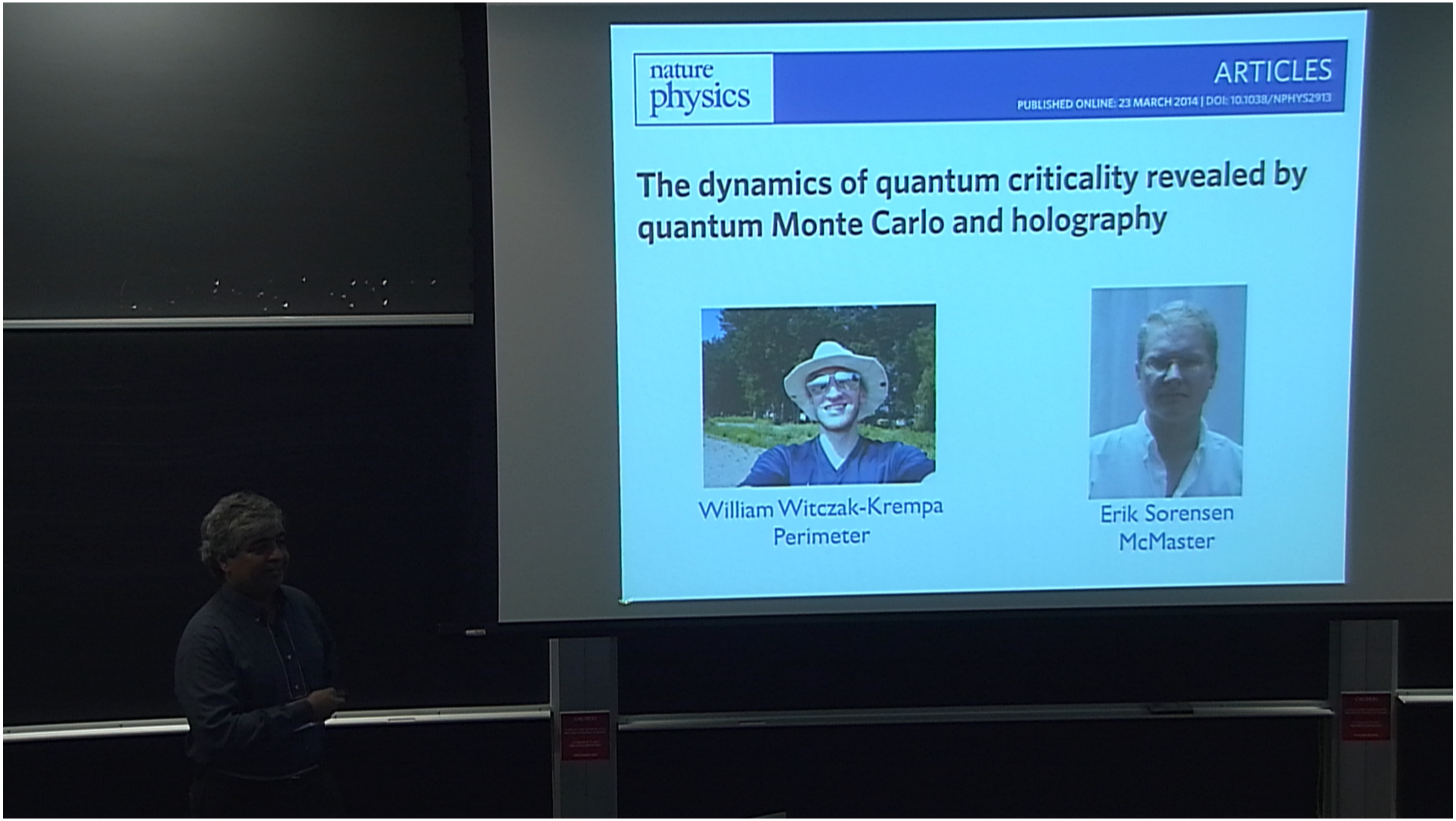
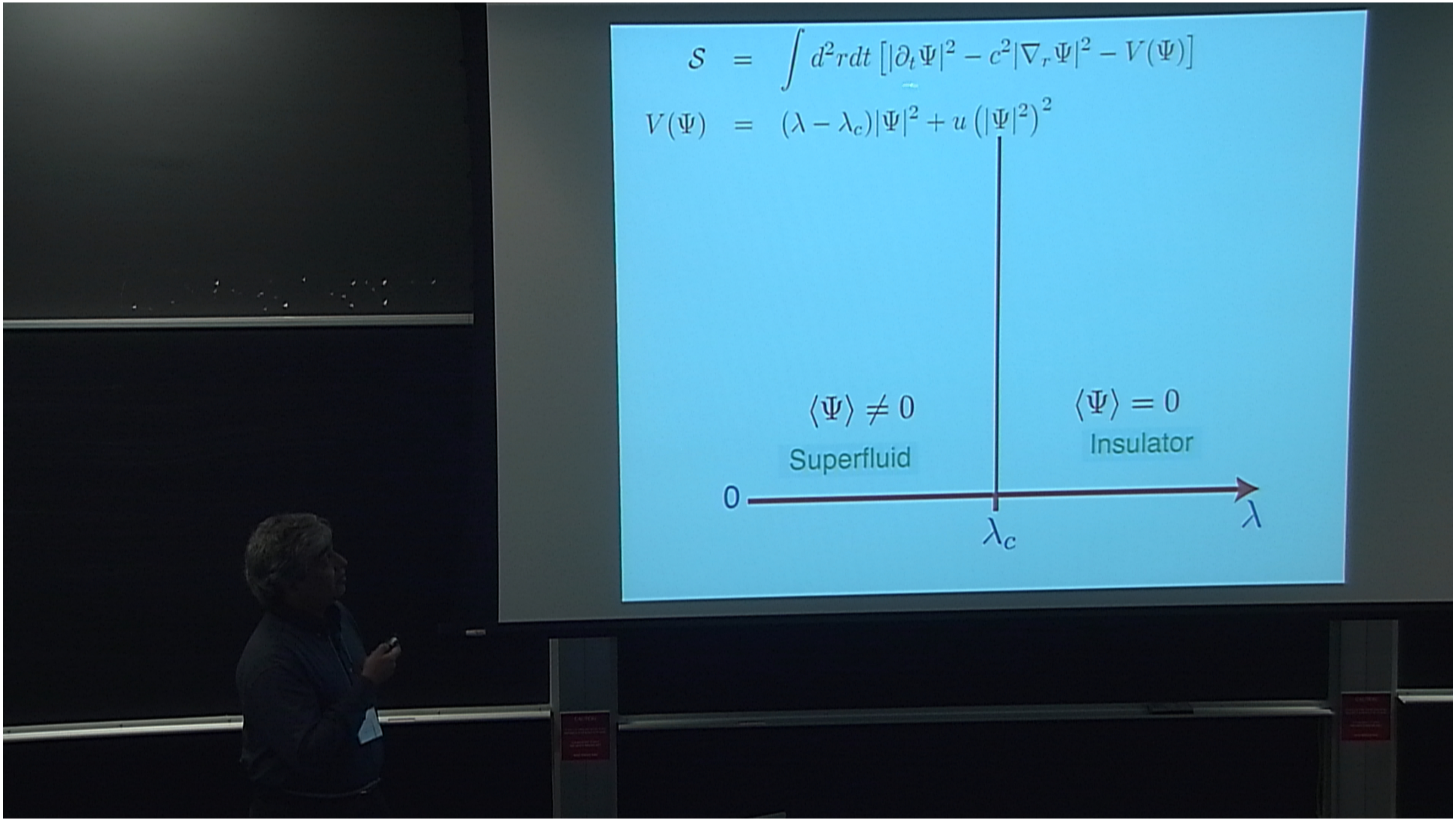
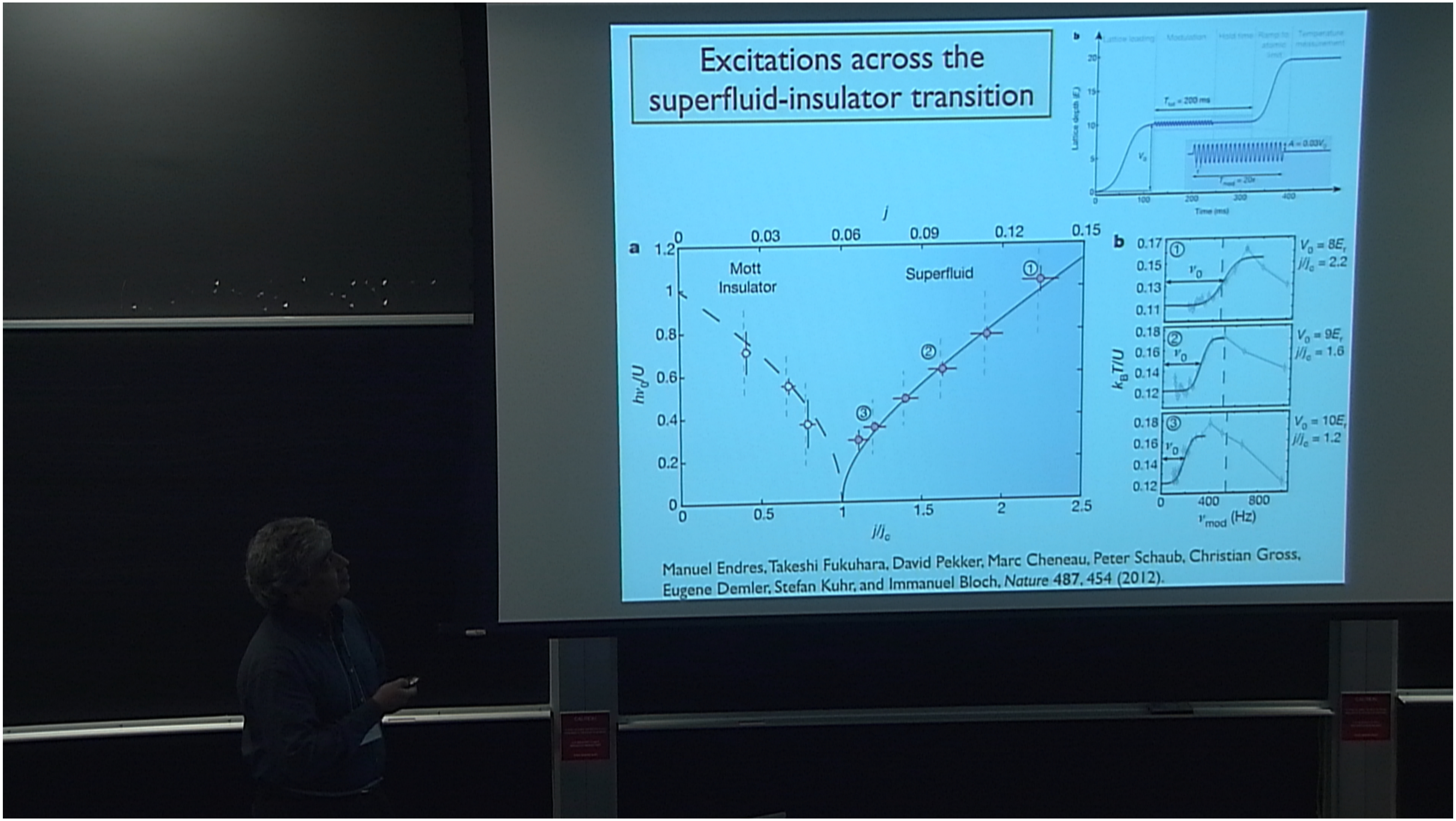
2. No quasiparticles

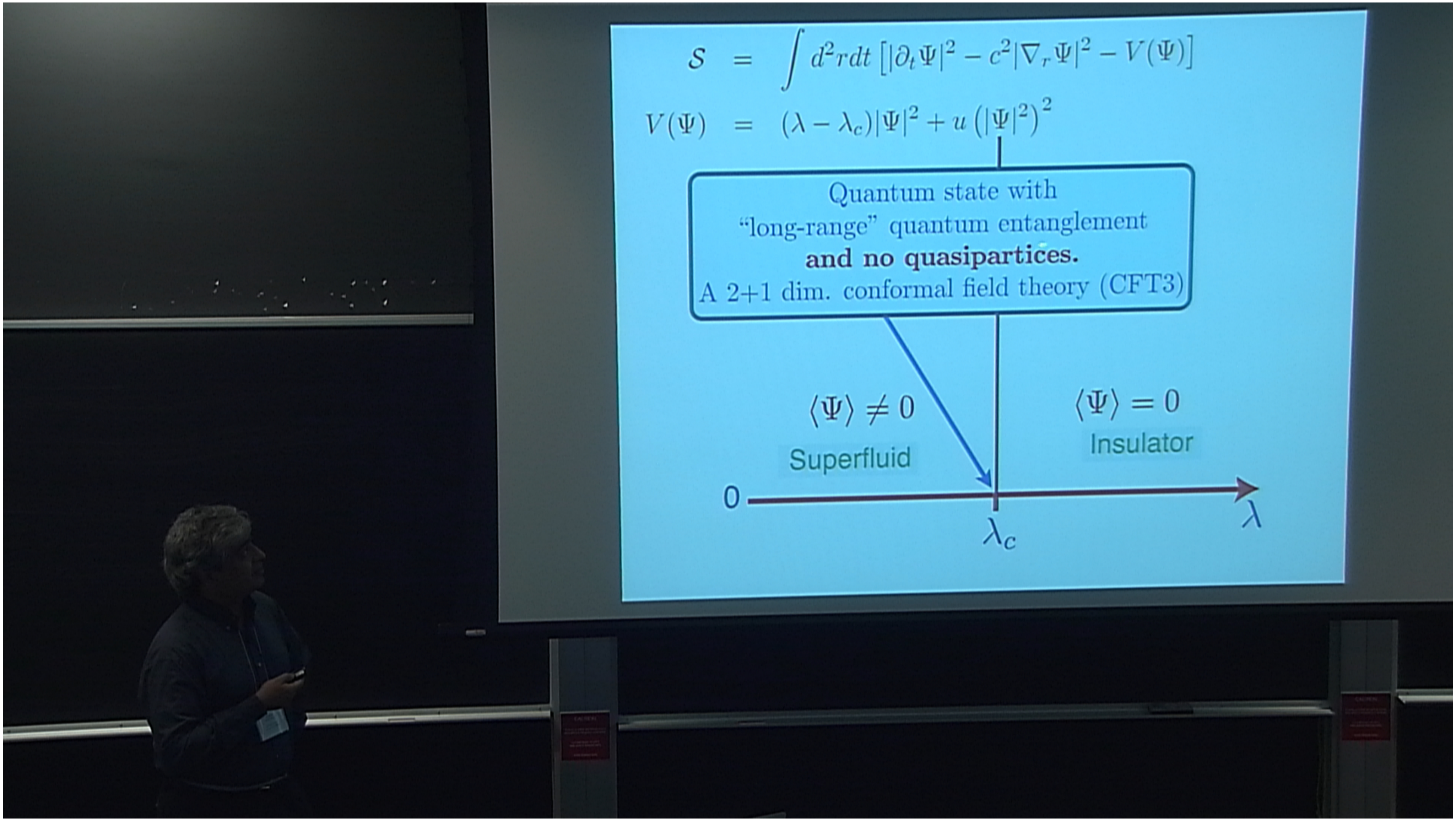

Modern phases of quantum matter:
1. Ground states disconnected from independent electron states: many-particle entanglement
2. No quasiparticles
Only 2 examples:
1. Conformal field theories in spatial dimension d >1
2. Quantum critical metals in dimension d=2


Outline
1. Conformal field theories in 2+1 dimensions
Superfluid-insulator transition
of ultracold bosonic atoms in an optical lattice
2. Theory of a non-Fermi liquid
Non-quasiparticle transport at the
Ising-nematic quantum critical point

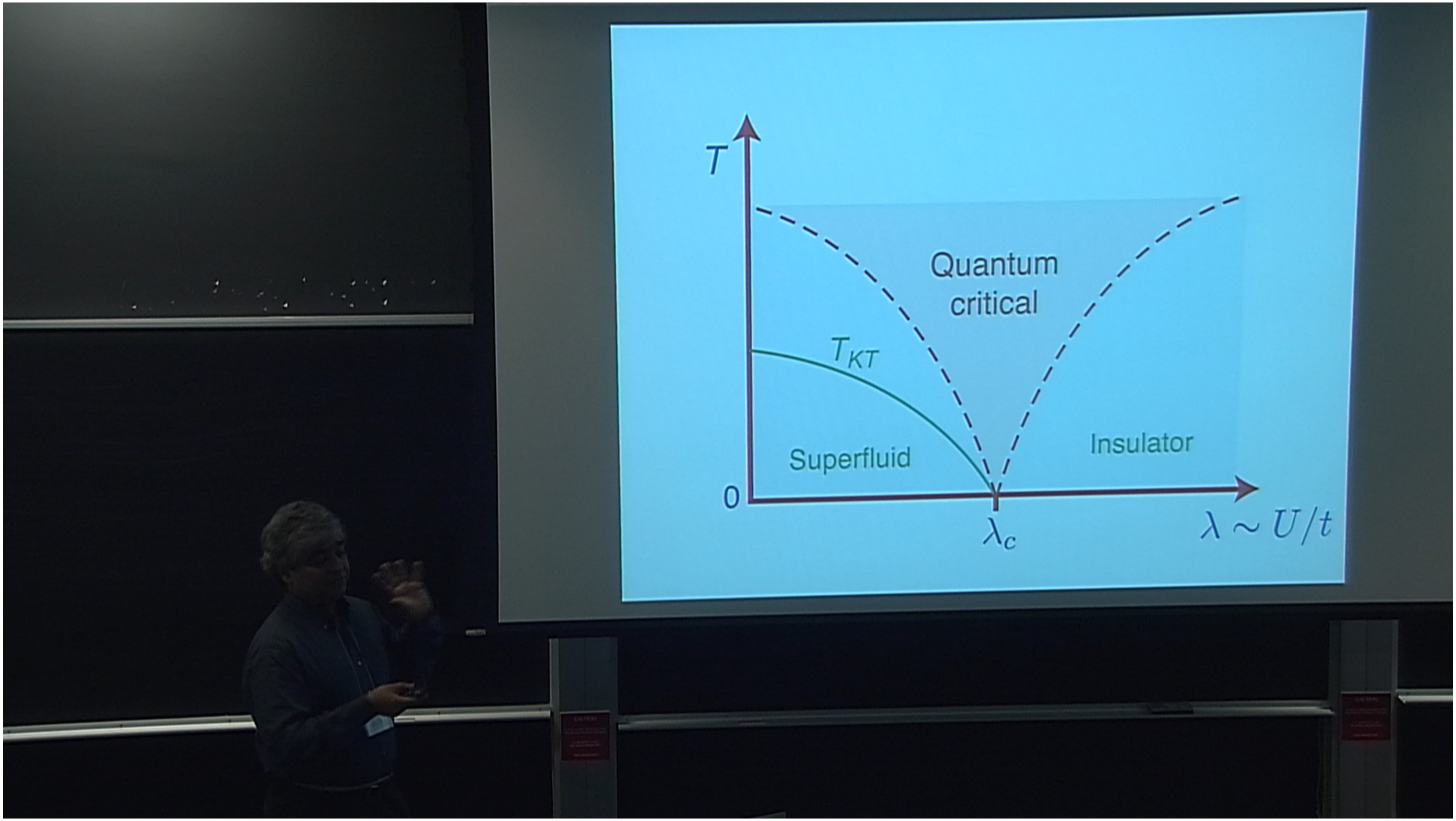

nature physics
ARTICLES
PUBLISHED ONLINE: 23 MARCH 2014 | DOI: 10.1038/NPHYS2913
The dynamics of quantum criticality revealed by quantum Monte Carlo and holography
William Witczak-Krempa
Perimeter
Erik Sorensen
McMaster


$\mathcal{S} = \int d^2r dt \left[|\partial_t \Psi|^2 - c^2 |\nabla_r \Psi|^2 - V(\Psi) \right]$
$V(\Psi) = (\lambda - \lambda_c)|\Psi|^2 + u \left(|\Psi|^2 \right)^2$
$\langle \Psi \rangle \neq 0$
Superfluid
$\langle \Psi \rangle = 0$
Insulator
0
λ_c
λ

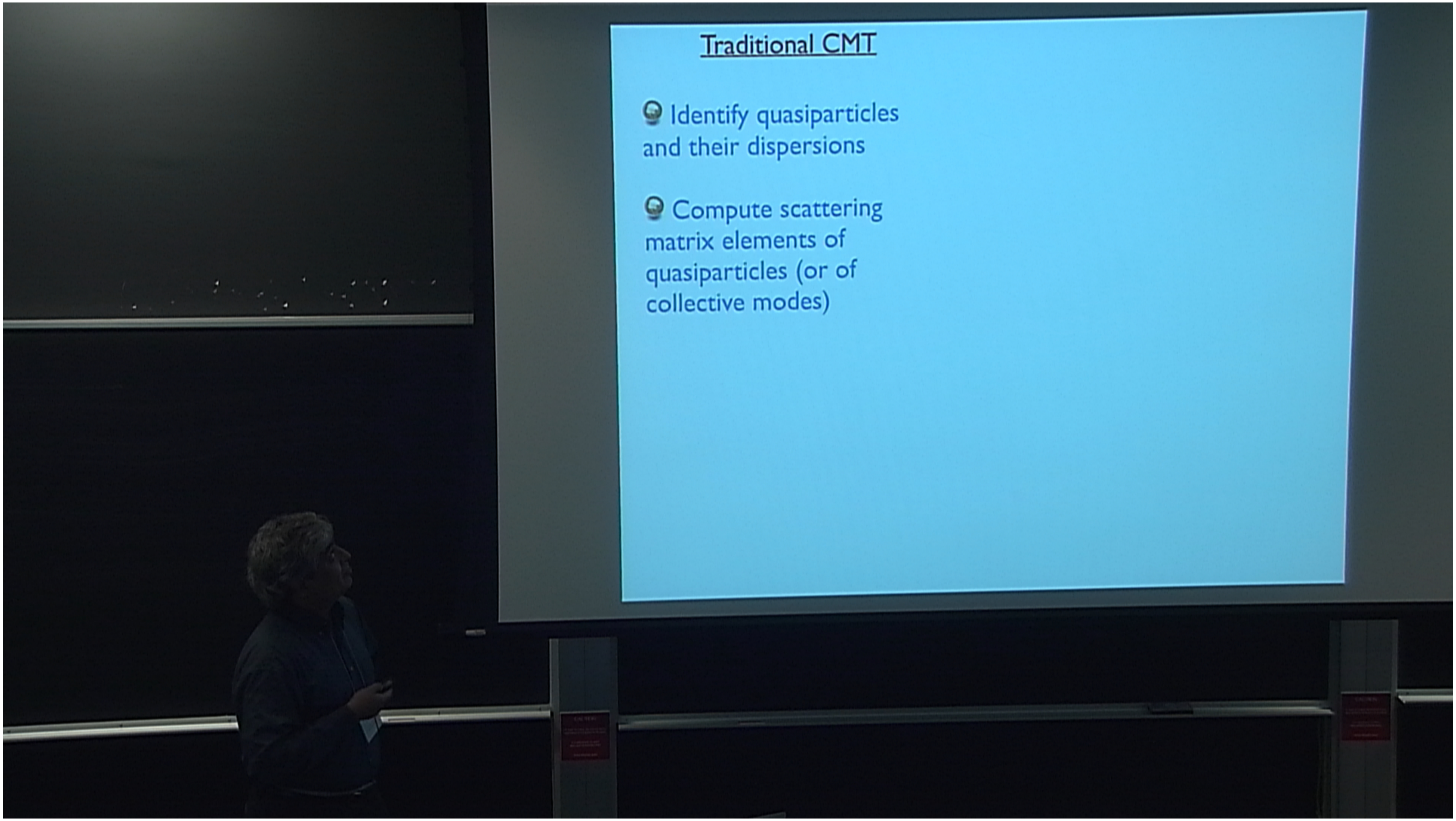

Excitations across the superfluid-insulator transition
Mott Insulator
Superfluid
j
j/j_c
$h\nu_0/U$
k_BT/U
$V_0 = 8E_r$
$j/j_c = 2.2$
$V_0 = 9E_r$
$j/j_c = 1.6$
$V_0 = 10E_r$
$j/j_c = 1.2$
ν_{mod} (Hz)
Manuel Endres, Takeshi Fukuhara, David Pekker, Marc Cheneau, Peter Schaub, Christian Gross, Eugene Demler, Stefan Kuhr, and Immanuel Bloch, *Nature* 487, 454 (2012).

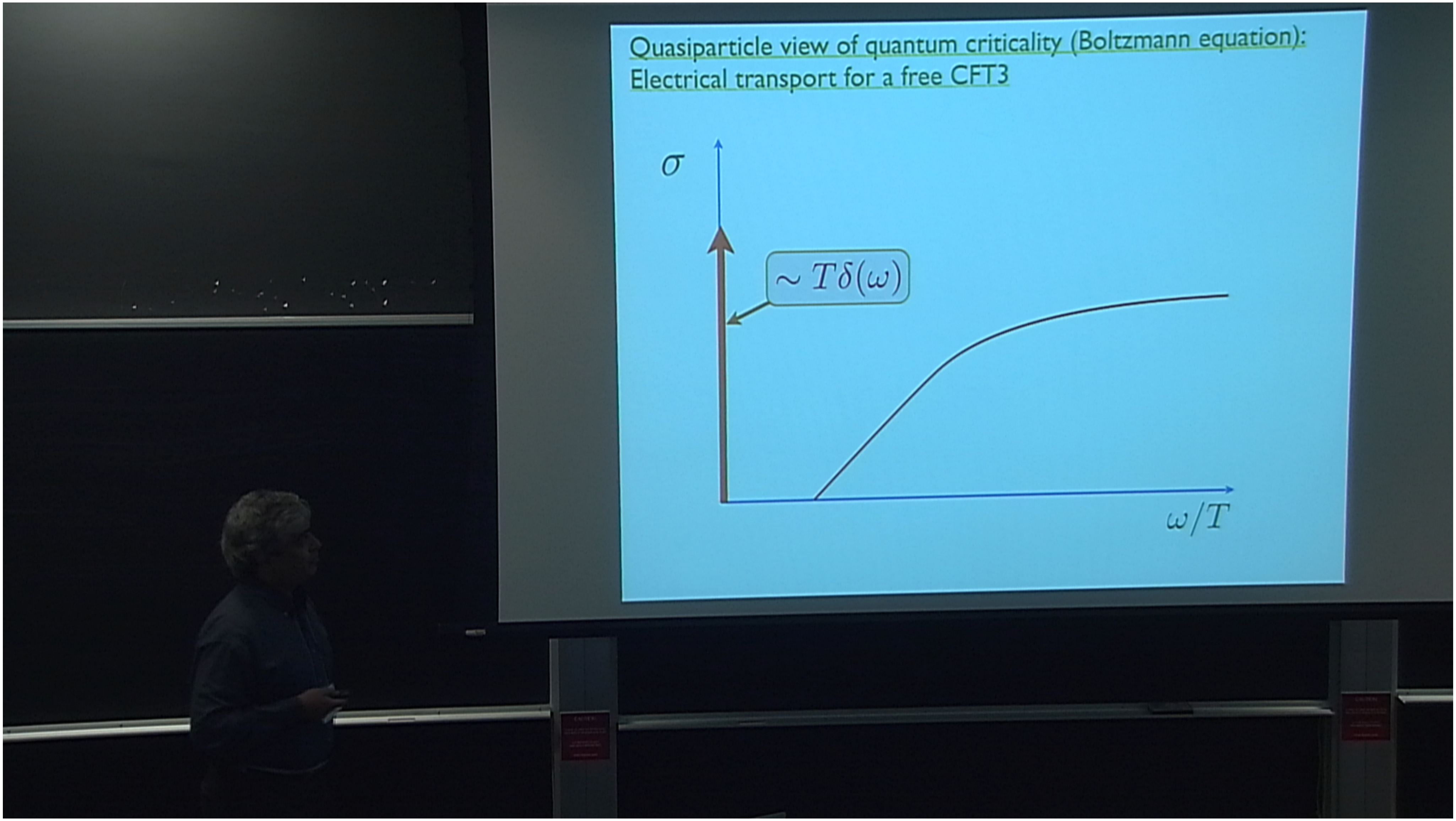


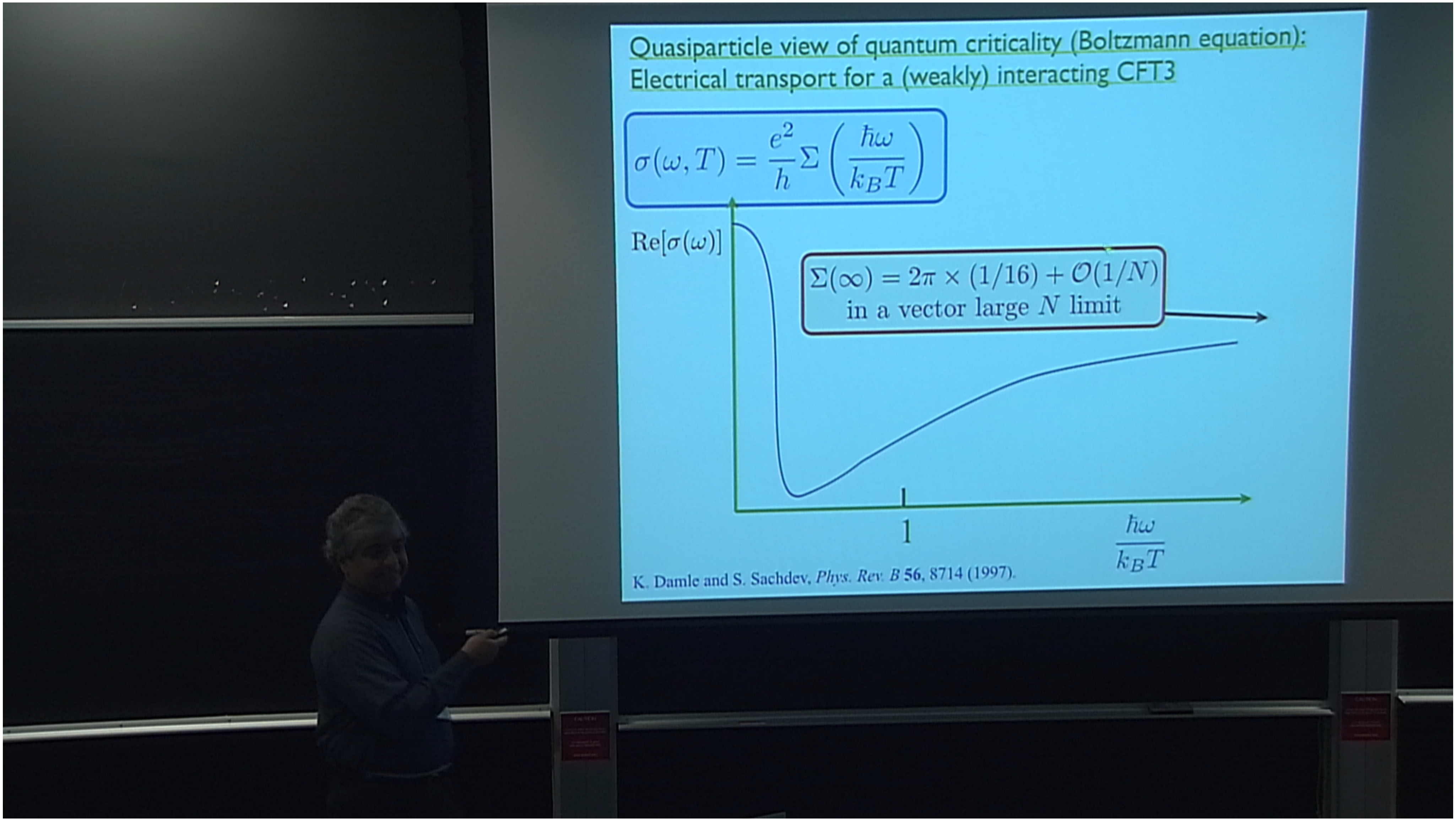
$$\mathcal{S} = \int d^2r dt \left[|\partial_t \Psi|^2 - c^2 |\nabla_r \Psi|^2 - V(\Psi) \right]$$
$$V(\Psi) = (\lambda - \lambda_c)|\Psi|^2 + u \left(|\Psi|^2 \right)^2$$
Quantum state with
"long-range" quantum entanglement
and no quasiparticces.
A 2+1 dim. conformal field theory (CFT3)
$\langle \Psi \rangle \neq 0$
Superfluid
$\langle \Psi \rangle = 0$
Insulator
0
λ_c
λ

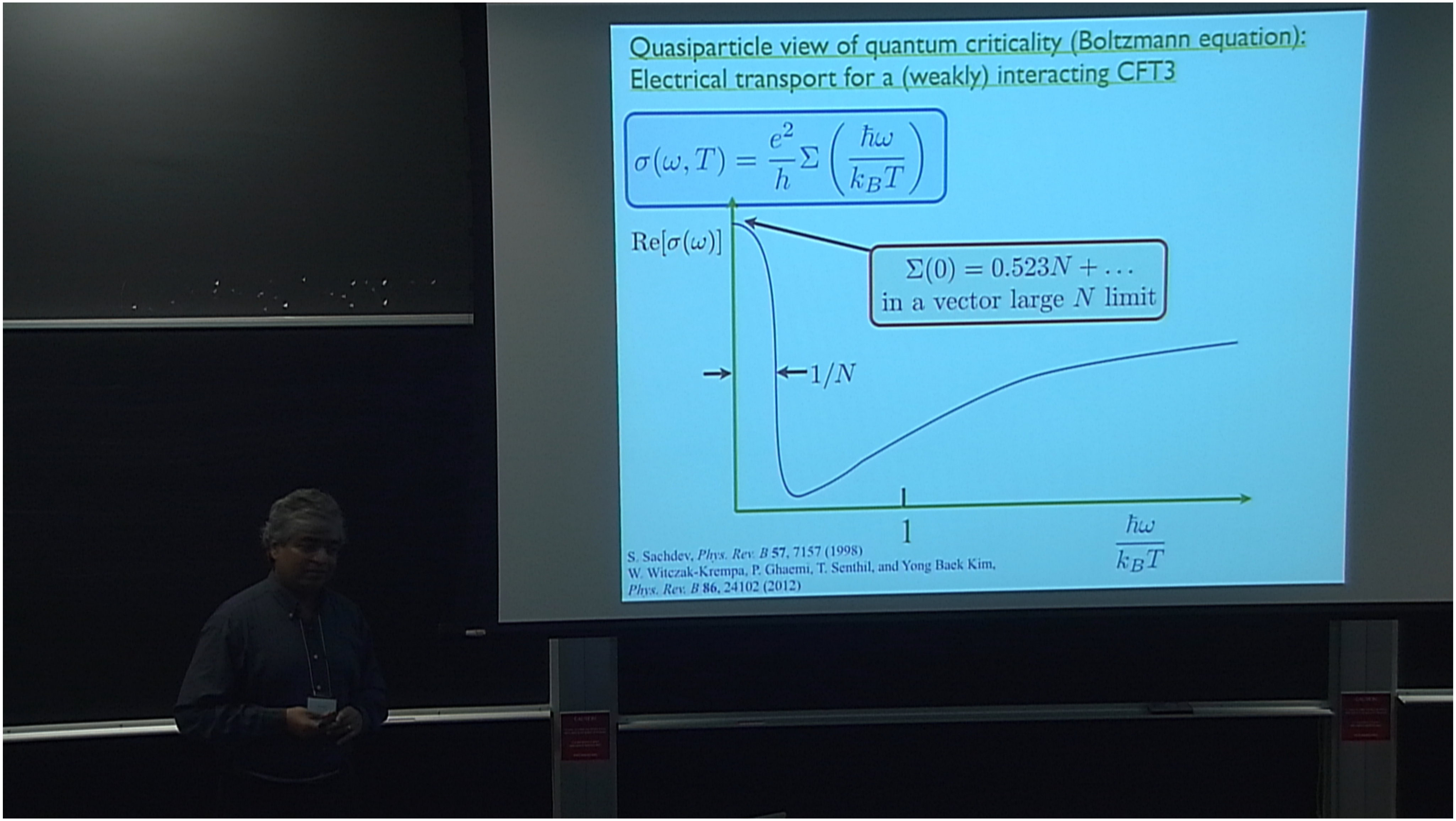


T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$


Traditional CMT
Identify quasiparticles and their dispersions
Compute scattering matrix elements of quasiparticles (or of collective modes)


Quasiparticle view of quantum criticality (Boltzmann equation):
Electrical transport for a free CFT3
σ
$\sim T\delta(\omega)$
ω/T


Quasiparticle view of quantum criticality (Boltzmann equation):
Electrical transport for a (weakly) interacting CFT3
$\sigma(\omega, T) = \frac{e^2}{h}\Sigma\left(\frac{\hbar\omega}{k_B T}\right)$
$\mathrm{Re}[\sigma(\omega)]$
$\Sigma(\infty) = 2\pi \times (1/16) + \mathcal{O}(1/N)$
in a vector large N limit
1
$\frac{\hbar\omega}{k_B T}$
K. Damle and S. Sachdev, Phys. Rev. B 56, 8714 (1997).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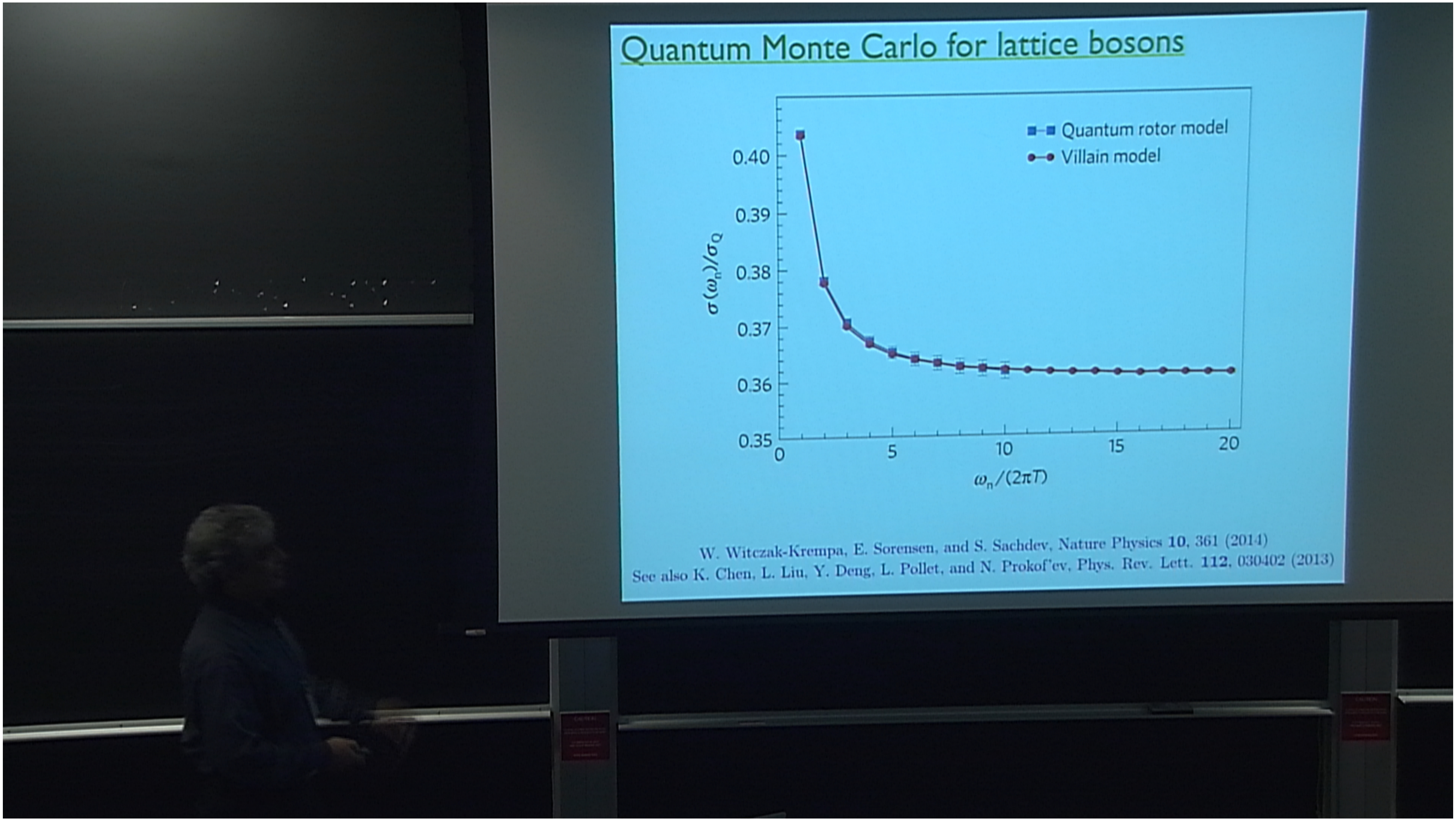
S. Sachdev, Phys. Rev. B 57, 7157 (1998)
W. Witczak-Krempa, P. Ghaemi, T. Senthil, and Yong Baek Kim,
Phys. Rev. B 86, 24102 (2012)



Quantum Monte Carlo for lattice bosons
Quantum rotor model
Villain model
$\sigma(\omega_n)/\sigma_Q$
0.40
0.39
0.38
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0.36
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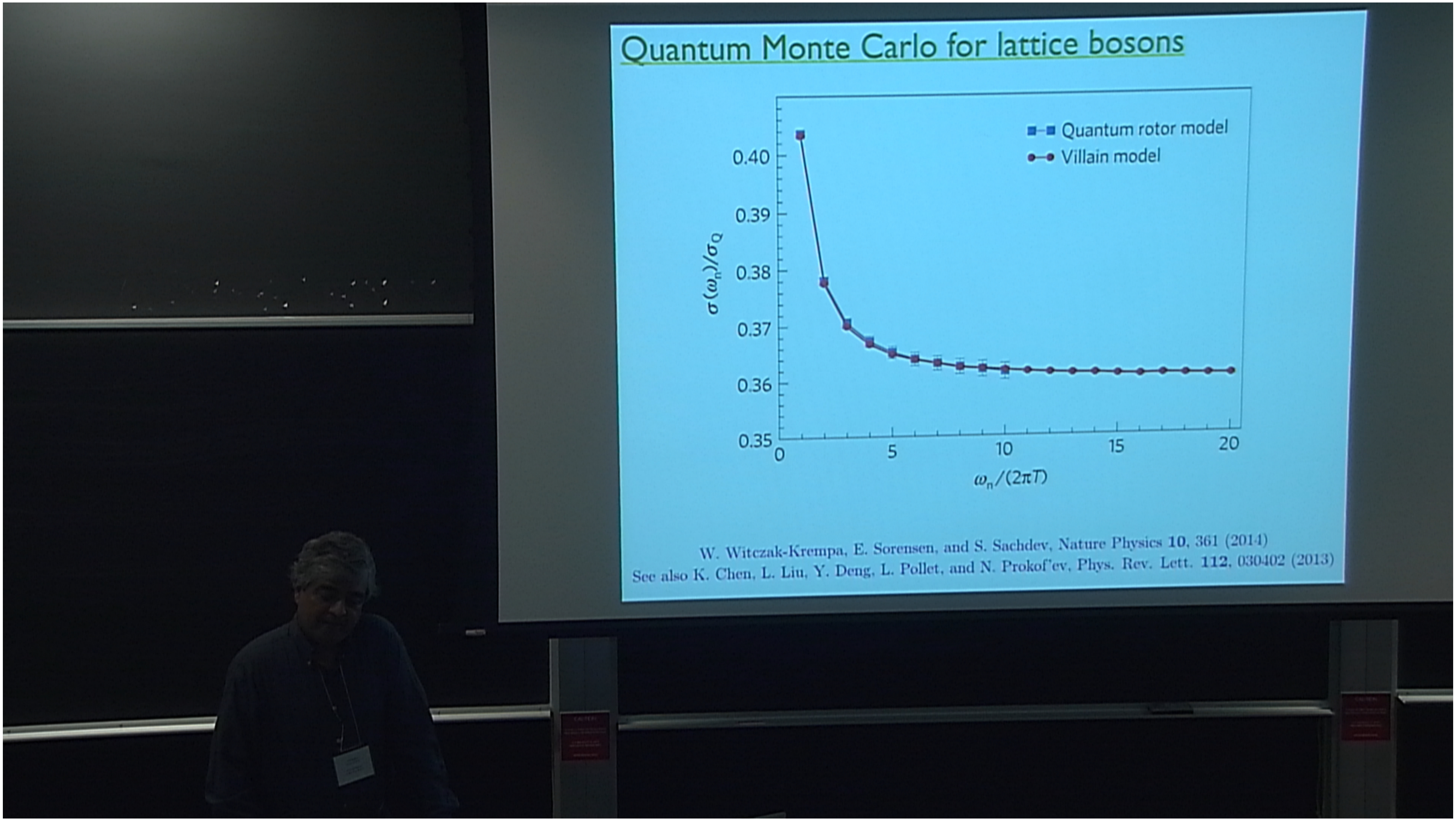
$\omega_n/(2\pi T)$
W. Witczak-Krempa, E. Sorensen, and S. Sachdev, Nature Physics 10, 361 (2014)
See also K. Chen, L. Liu, Y. Deng, L. Pollet, and N. Prokof'ev, Phys. Rev. Lett. 112, 030402 (2013)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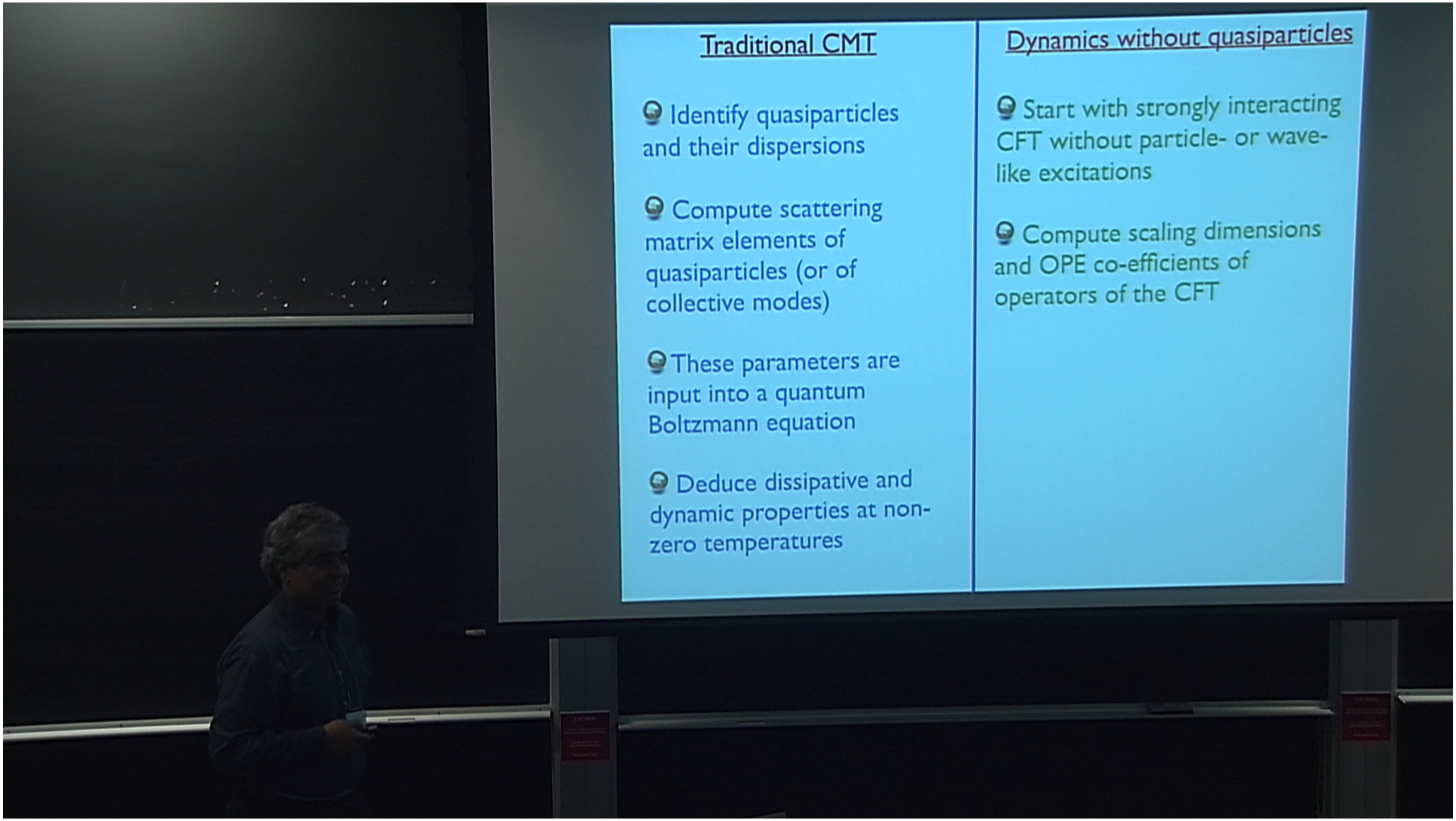
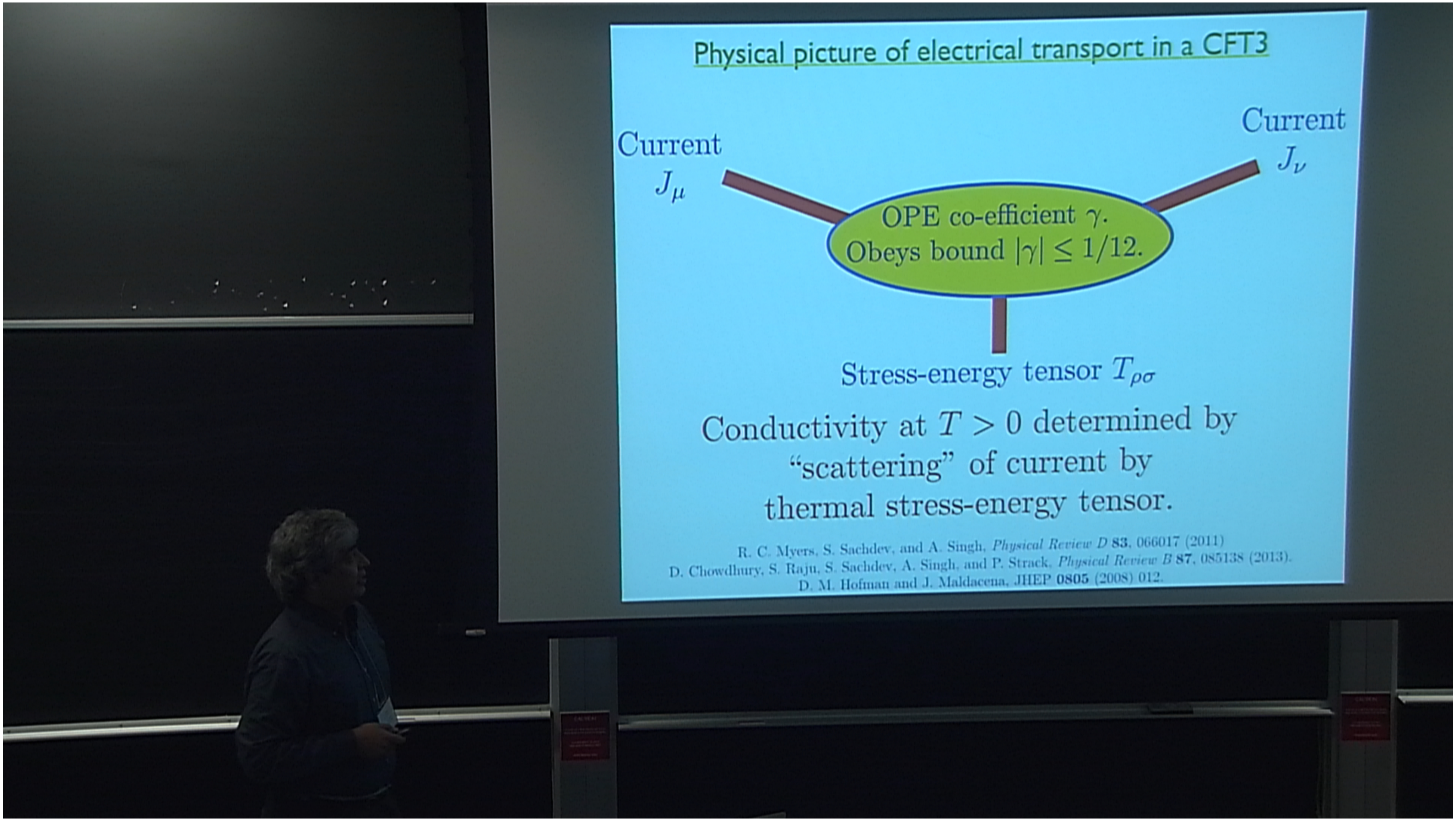

Traditional CMT
Identify quasiparticles and their dispersions
Compute scattering matrix elements of quasiparticles (or of collective modes)
These parameters are input into a quantum Boltzmann equation
Deduce dissipative and dynamic properties at non-zero temperatures
Dynamics without quasiparticles
Start with strongly interacting CFT without particle- or wave-like excitations
Compute scaling dimensions and OPE co-efficients of operators of the CFT


Physical picture of electrical transport in a CFT3
Current
J_μ
Current
J_ν
OPE co-efficient γ.
Obeys bound $|\gamma| \leq 1/12$.
Stress-energy tensor $T_{\rho\sigma}$
Conductivity at $T > 0$ determined by
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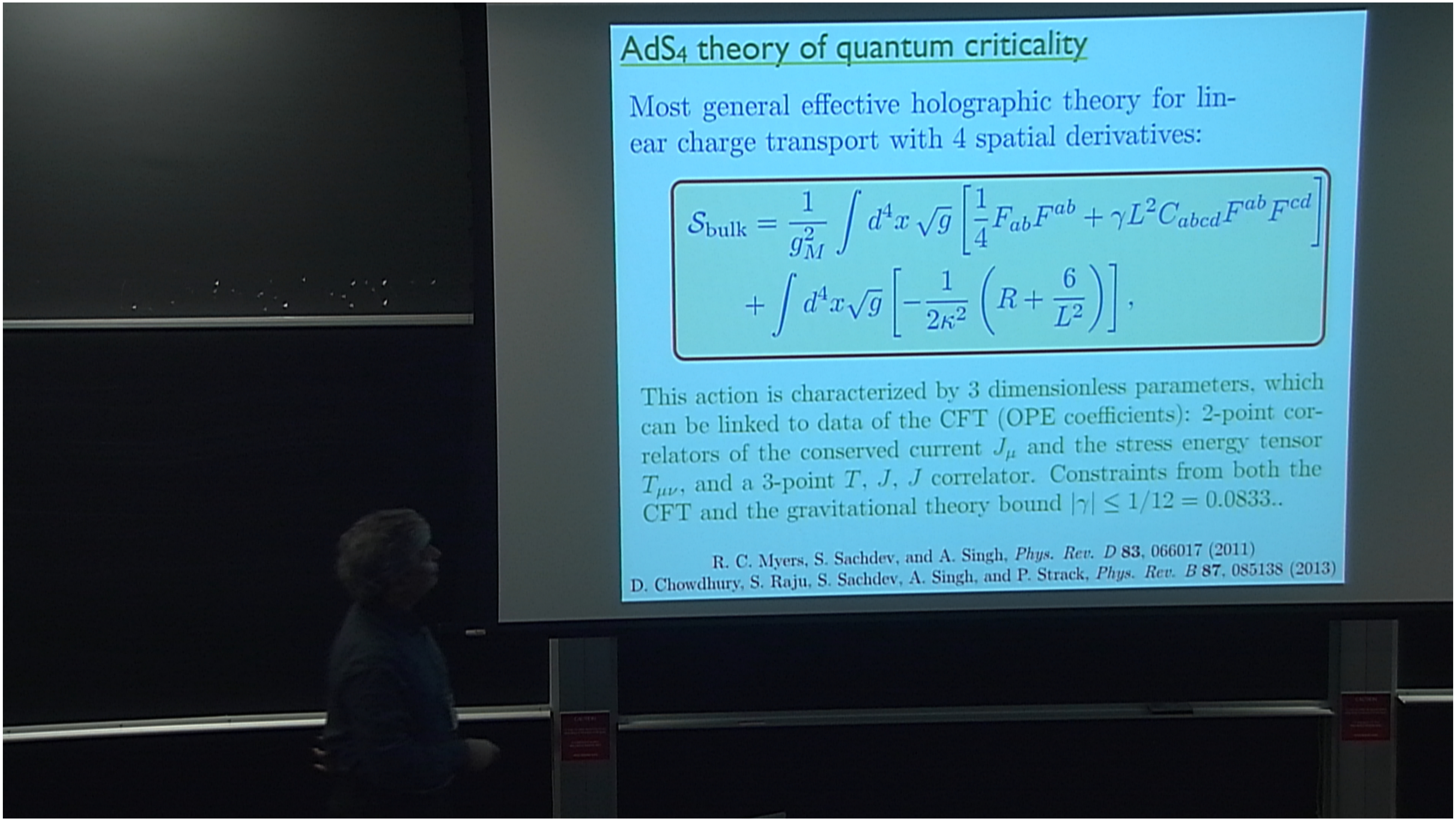
thermal stress-energy tensor.
R. C. Myers, S. Sachdev, and A. Singh, Physical Review D 83, 066017 (2011)
D. Chowdhury, S. Raju, S. Sachdev, A. Singh, and P. Strack, Physical Review B 87, 085138 (2013).
D. M. Hofman and J. Maldacena, JHEP 0805 (2008) 012.


AdS$_4$ theory of quantum criticality
Most general effective holographic theory for linear charge transport with 4 spatial derivatives:
$$S_{\rm bulk} = \frac{1}{g_M^2}\int d^4x\,\sqrt{g}\left[\frac{1}{4}F_{ab}F^{ab} + \gamma L^2 C_{abcd}F^{ab}F^{cd}\right] + \int d^4x\sqrt{g}\left[-\frac{1}{2\kappa^2}\left(R+\frac{6}{L^2}\right)\right],$$
This action is characterized by 3 dimensionless parameters, which can be linked to data of the CFT (OPE coefficients): 2-point correlators of the conserved current J_μ and the stress energy tensor $T_{\mu\nu}$, and a 3-point T, J, J correlator. Constraints from both the CFT and the gravitational theory bound $|\gamma| \leq 1/12 = 0.0833$..
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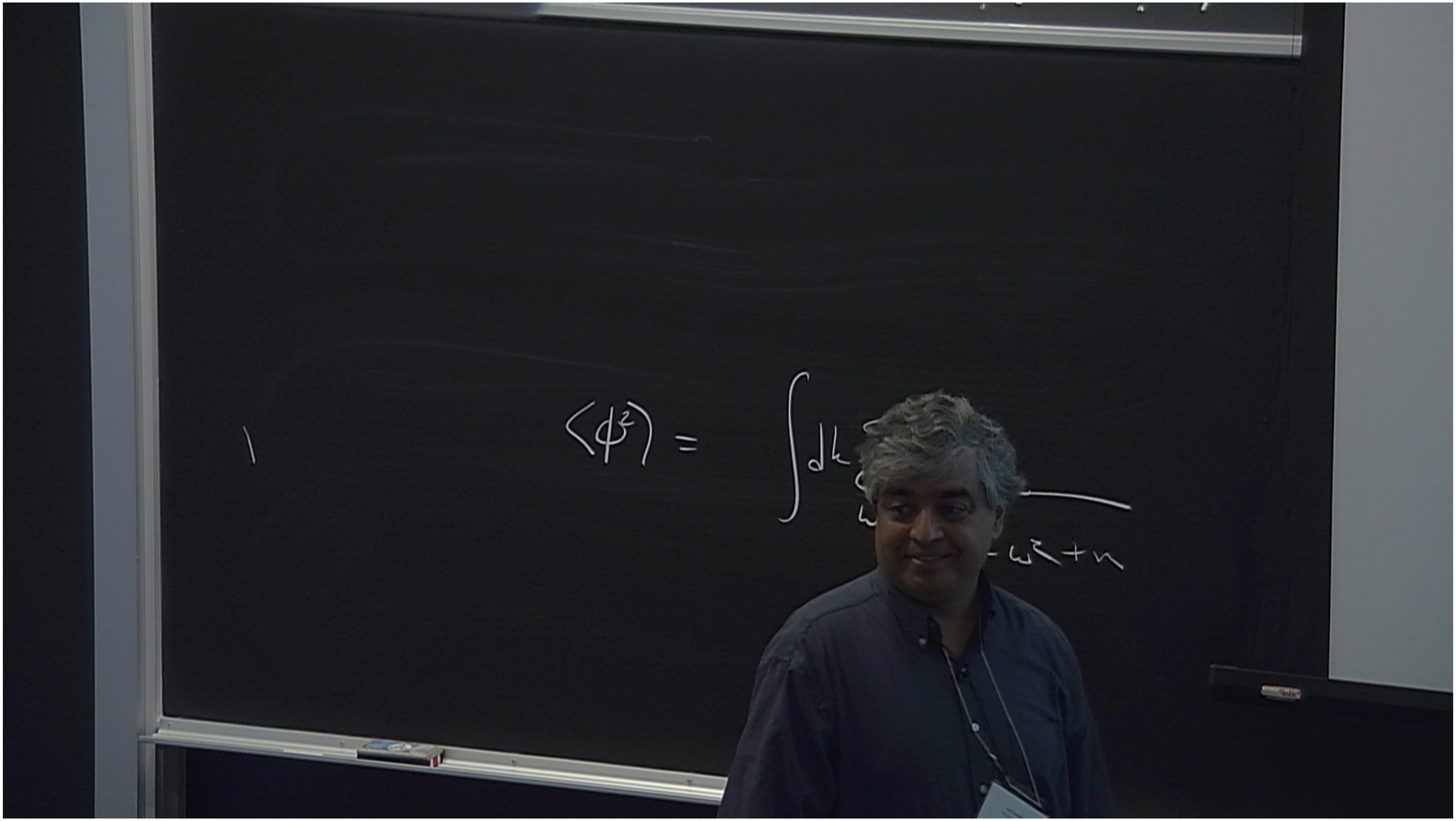
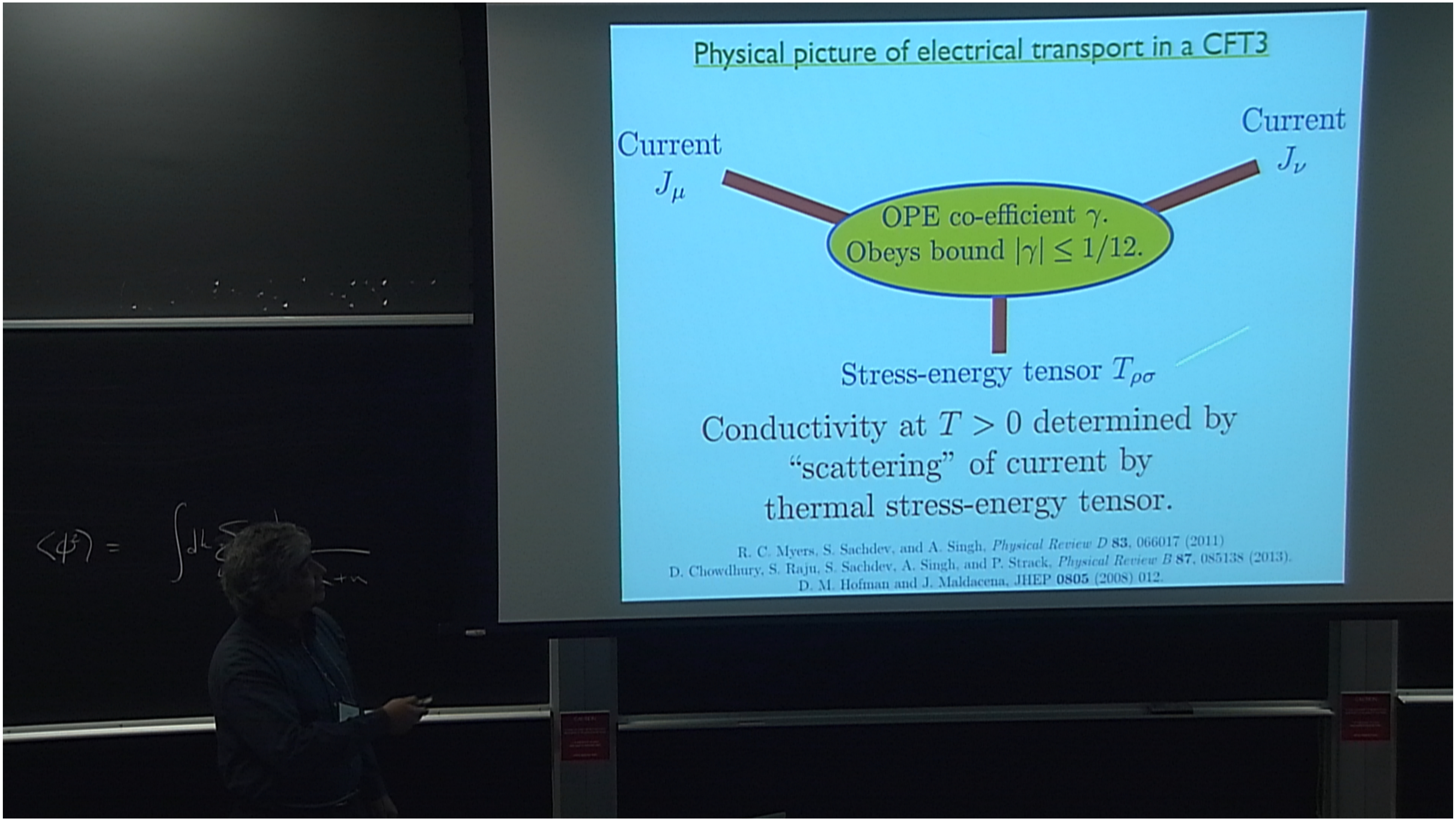

⟨ϕ²⟩ =
∫dk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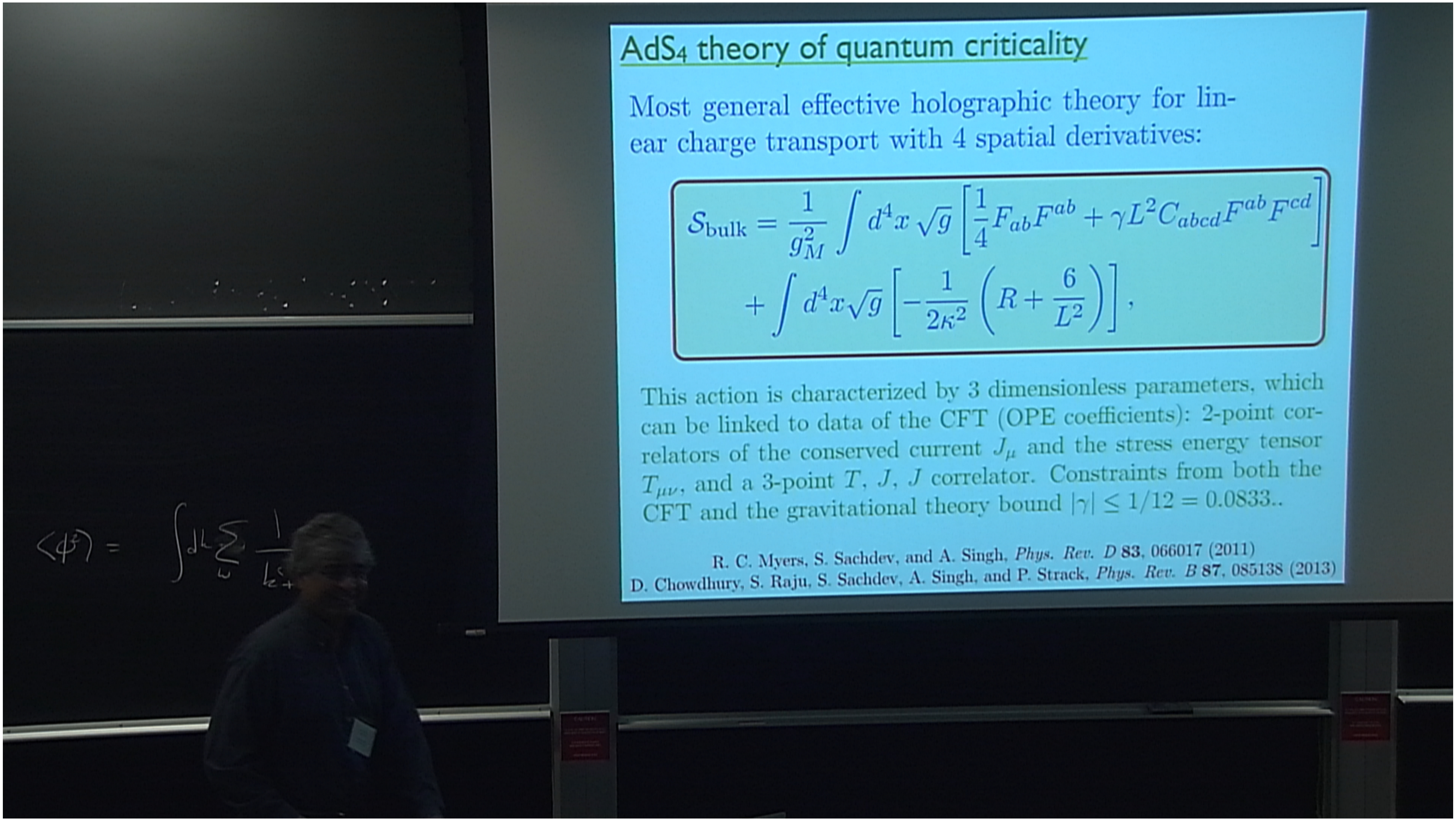
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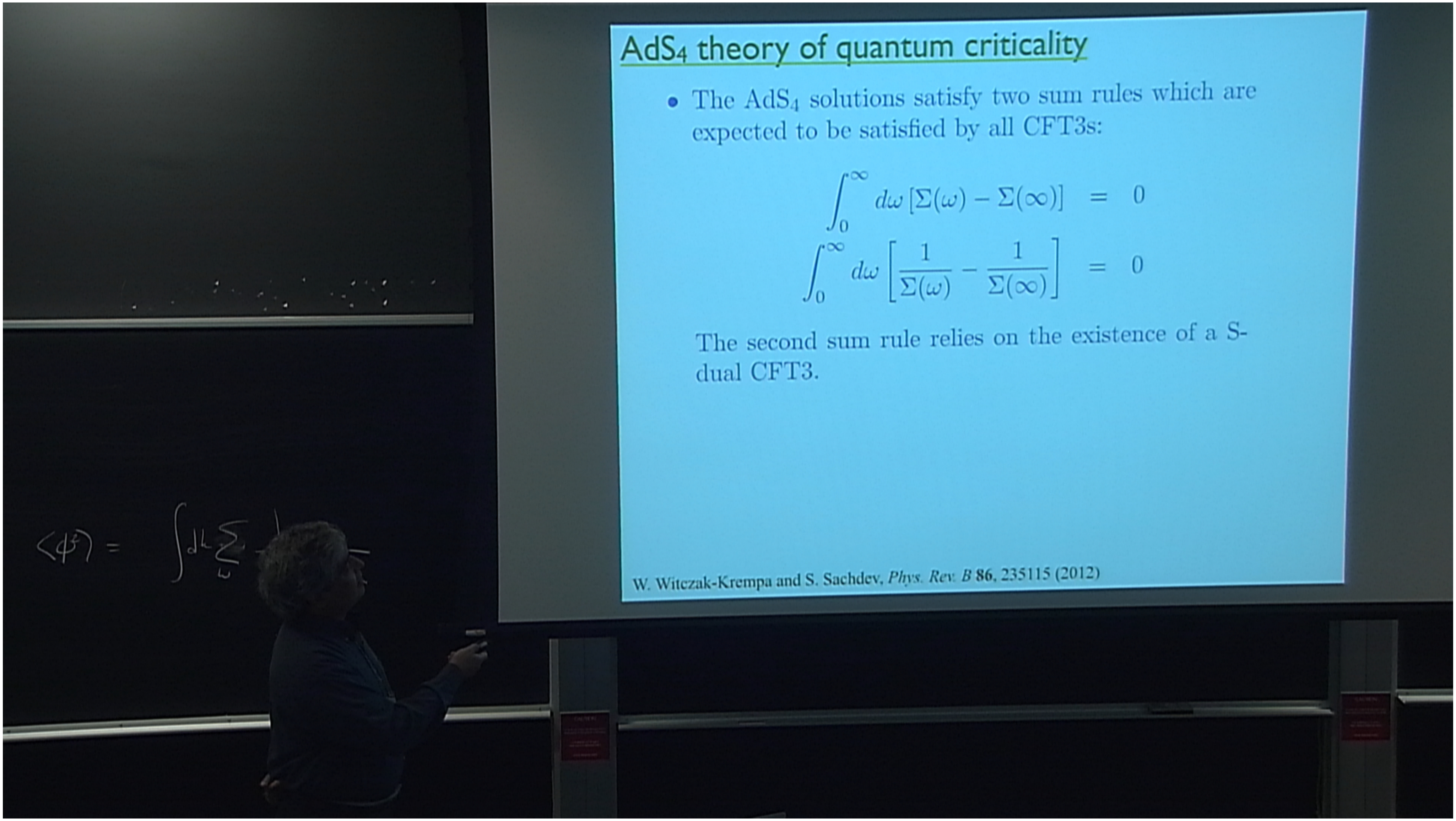
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The second sum rule relies on the existence of a S-dual CFT3.
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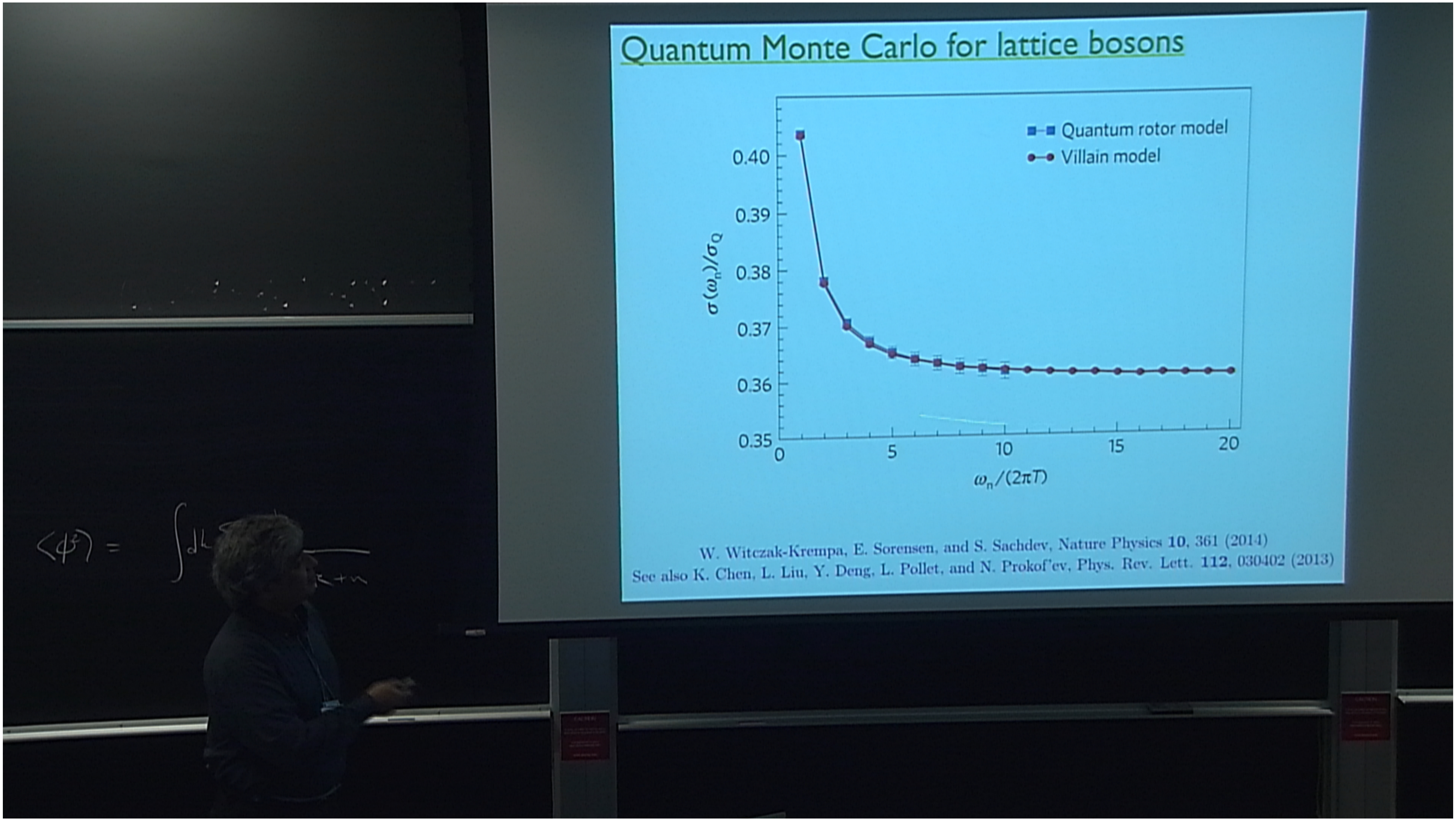
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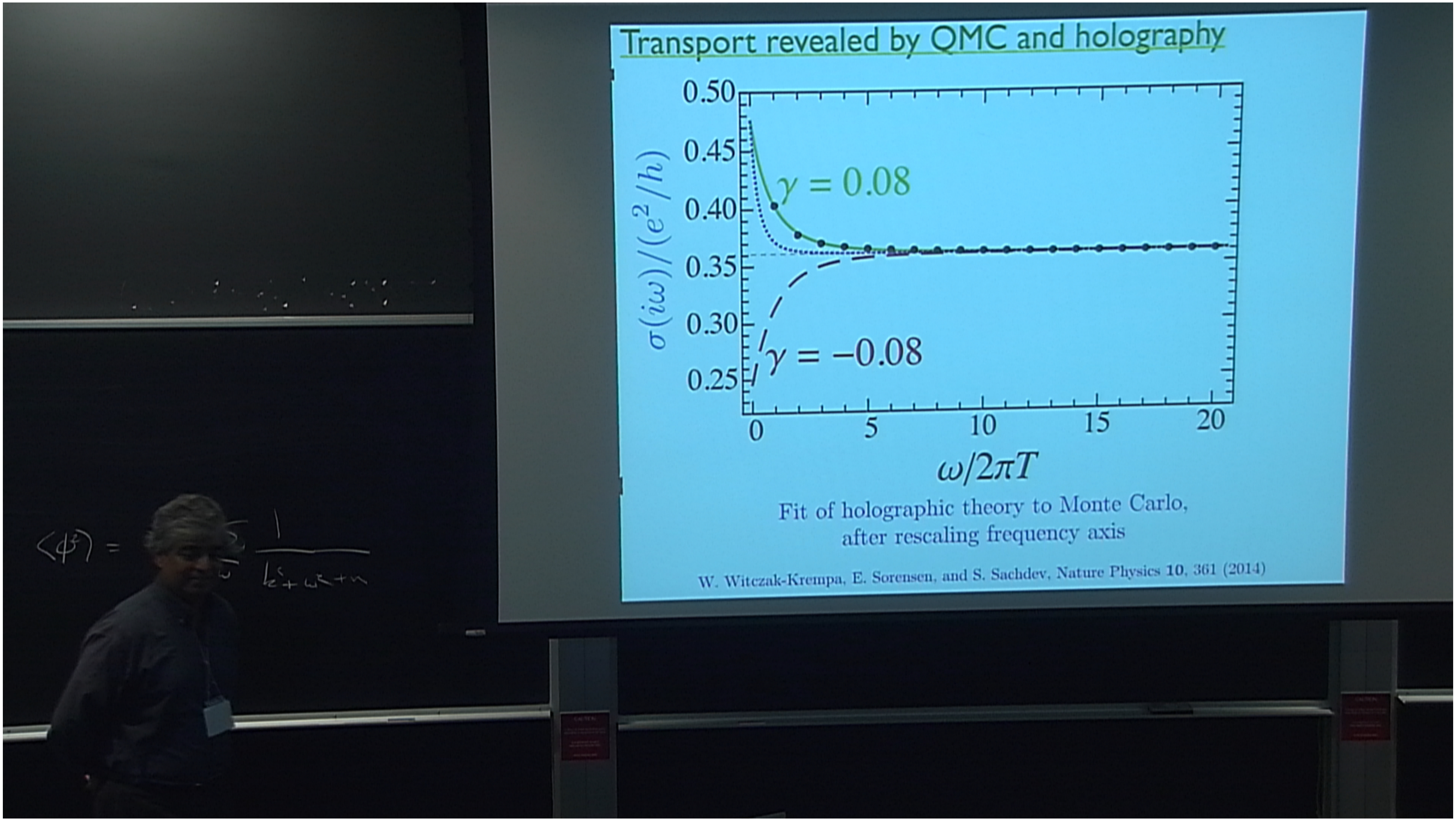
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γ = 0.08
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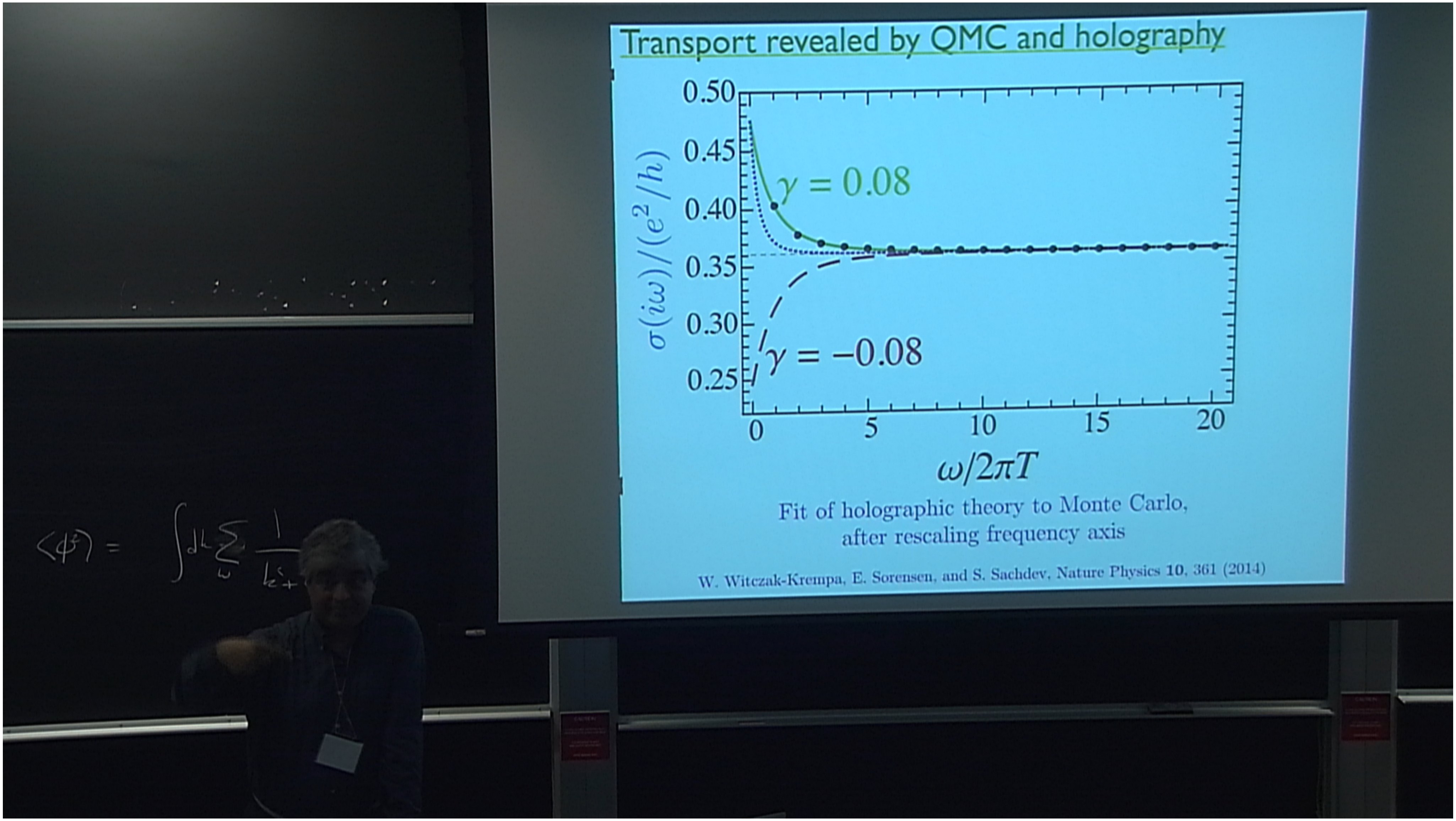
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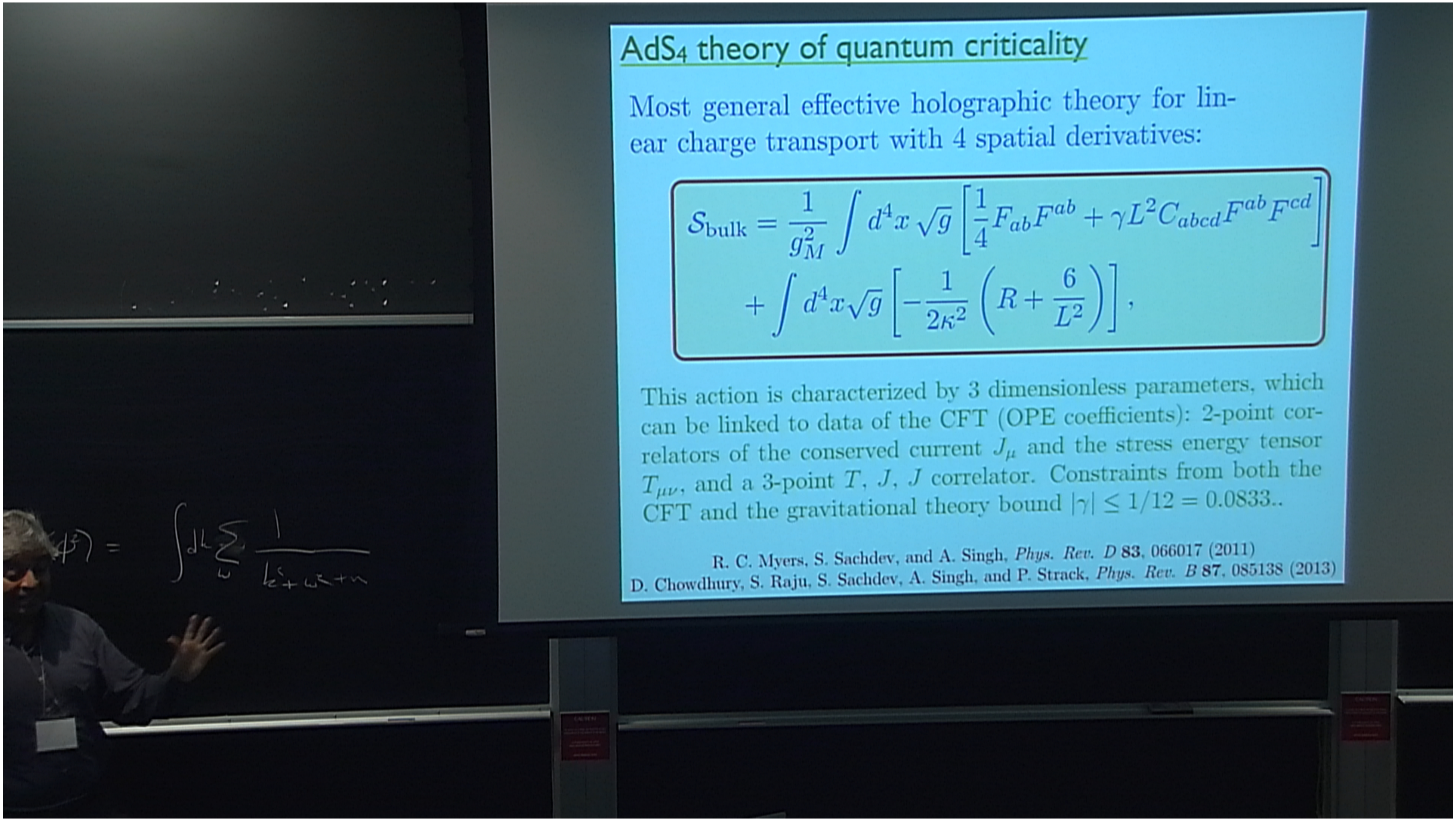
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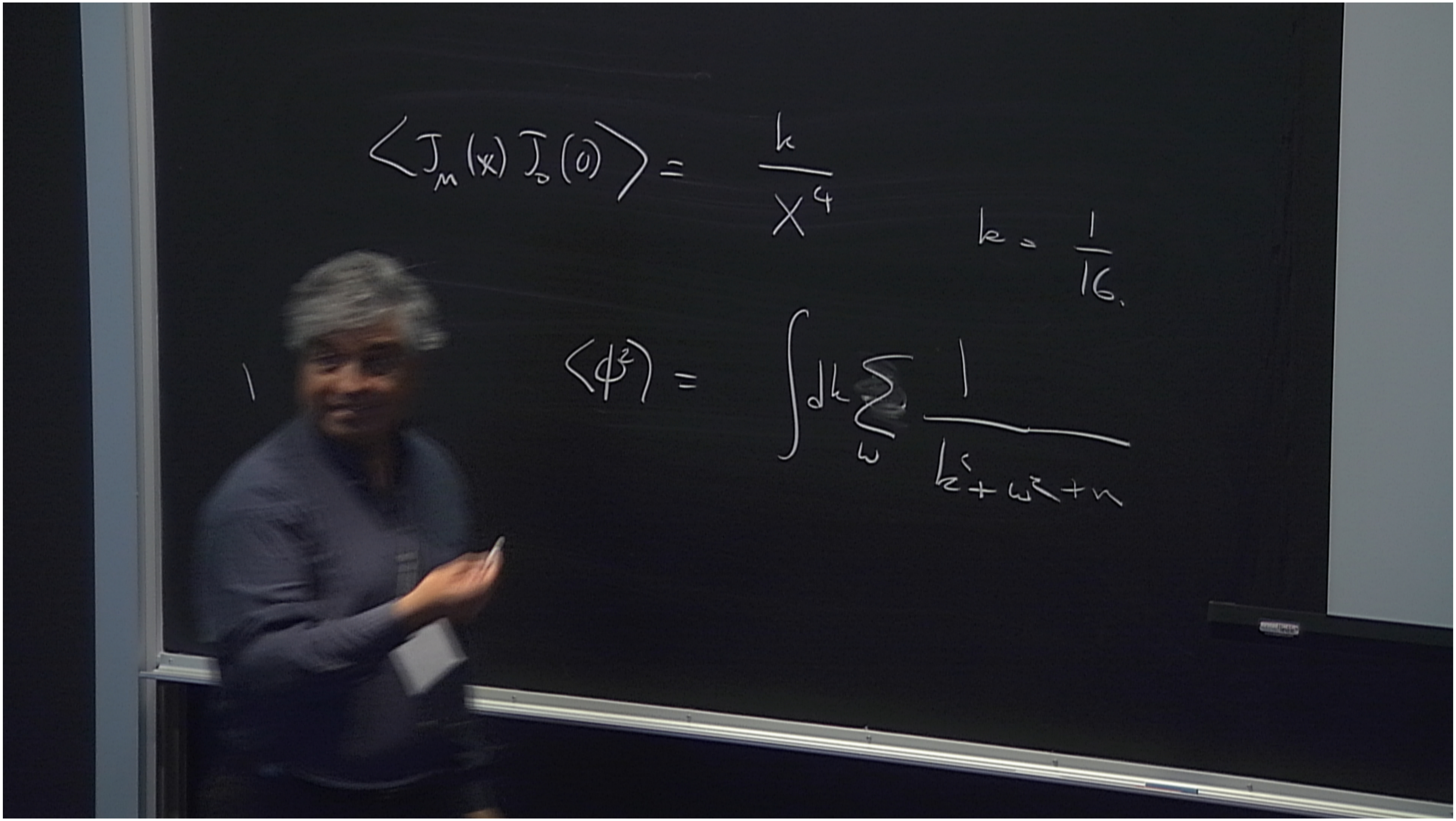
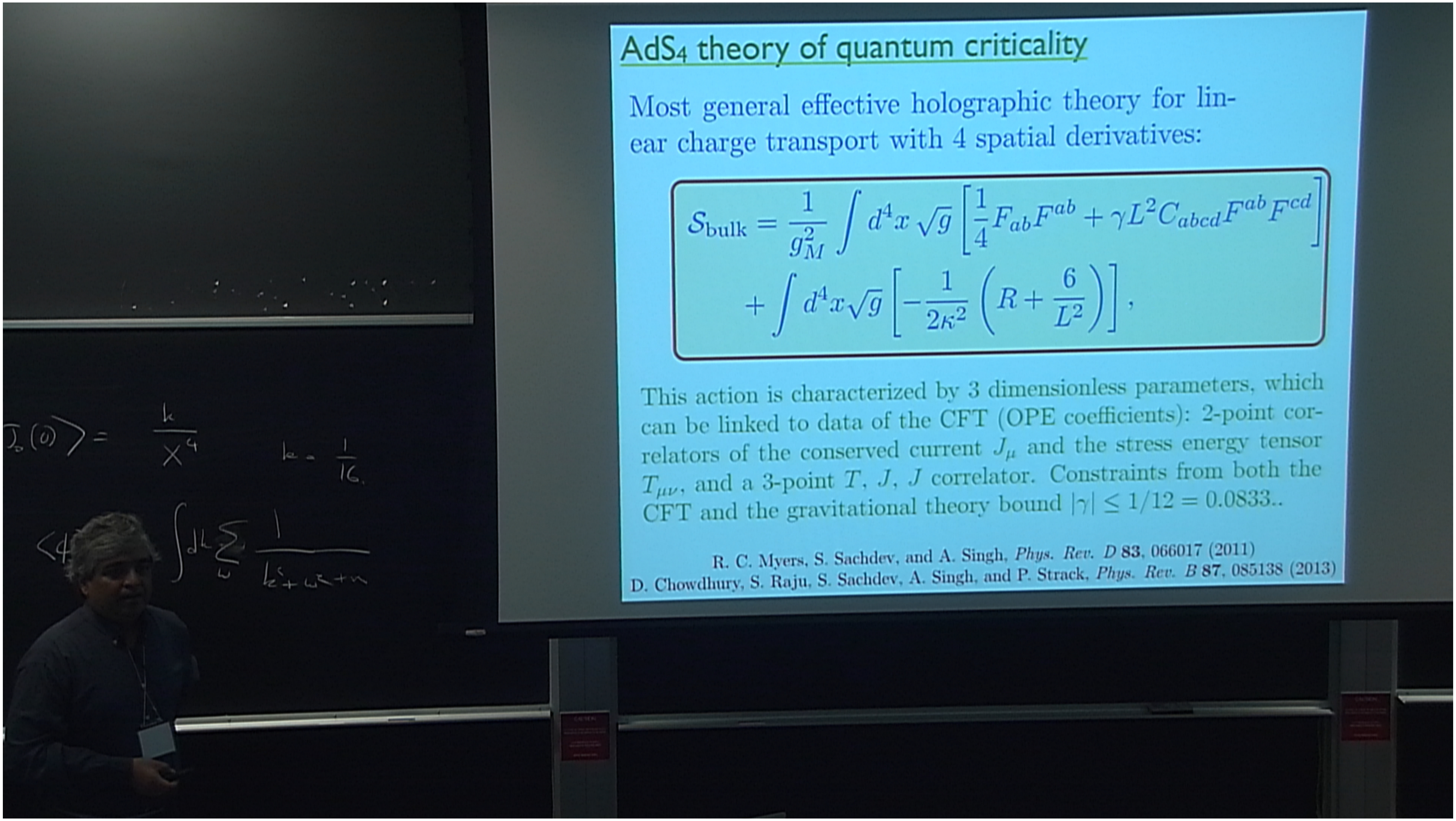

$\langle J_\mu(x) J_0(0) \rangle = \frac{k}{X^4}$
$k = \frac{1}{16}$
$\langle \phi^2 \rangle = \int dk \sum_\omega \frac{1}{k^2 + \omega^2 + m}$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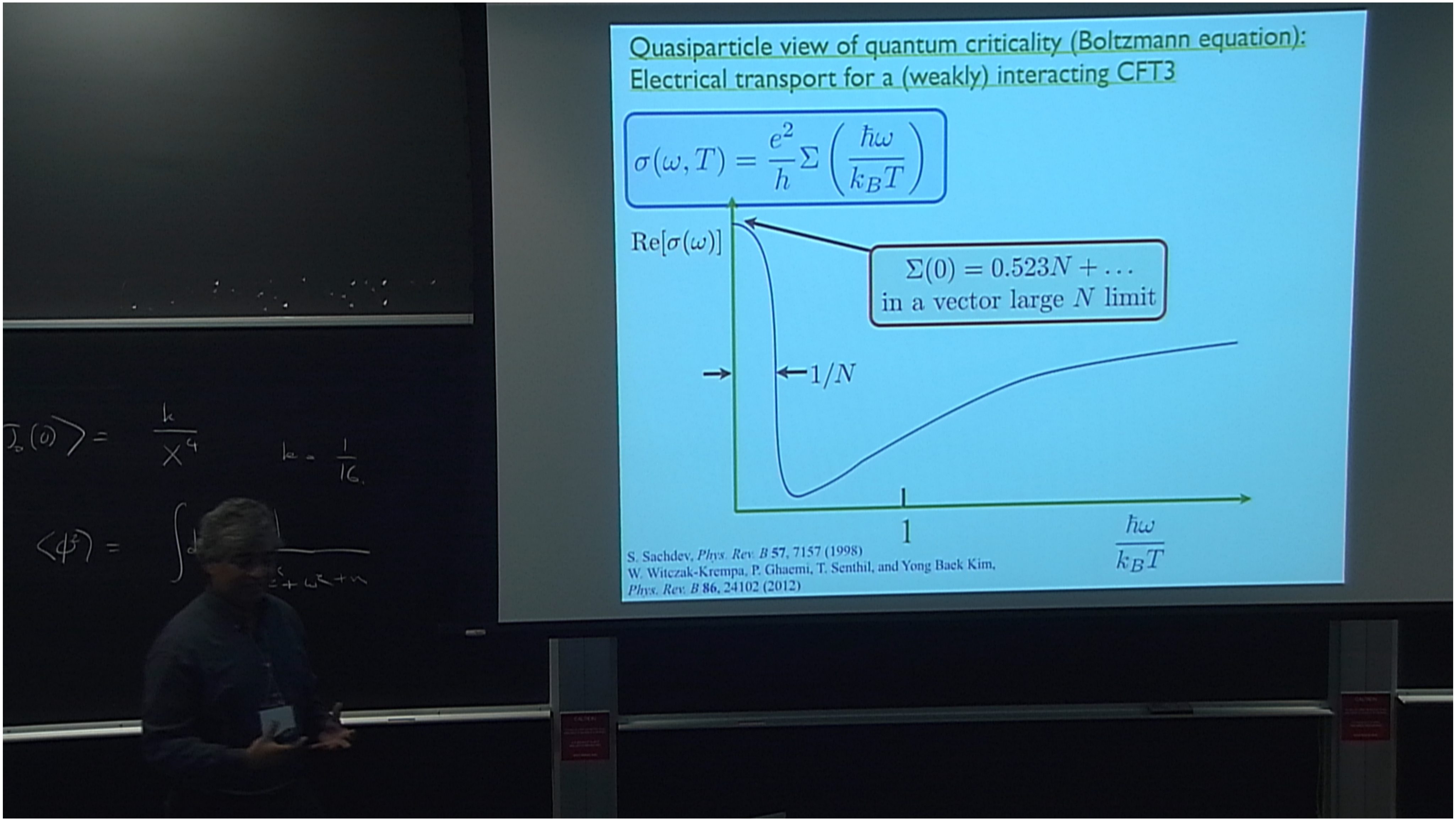
Quasiparticle view of quantum criticality (Boltzmann equation):
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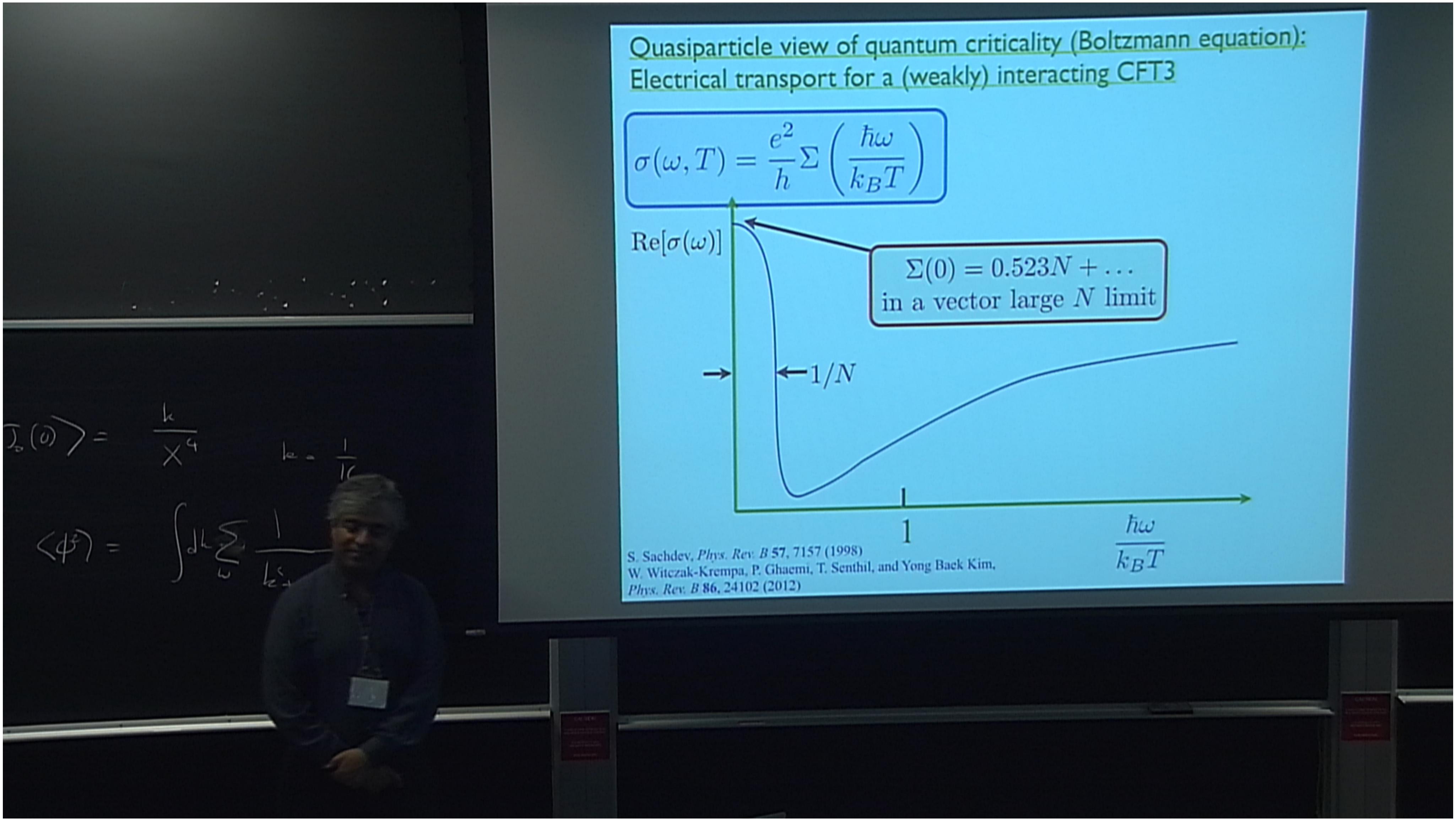

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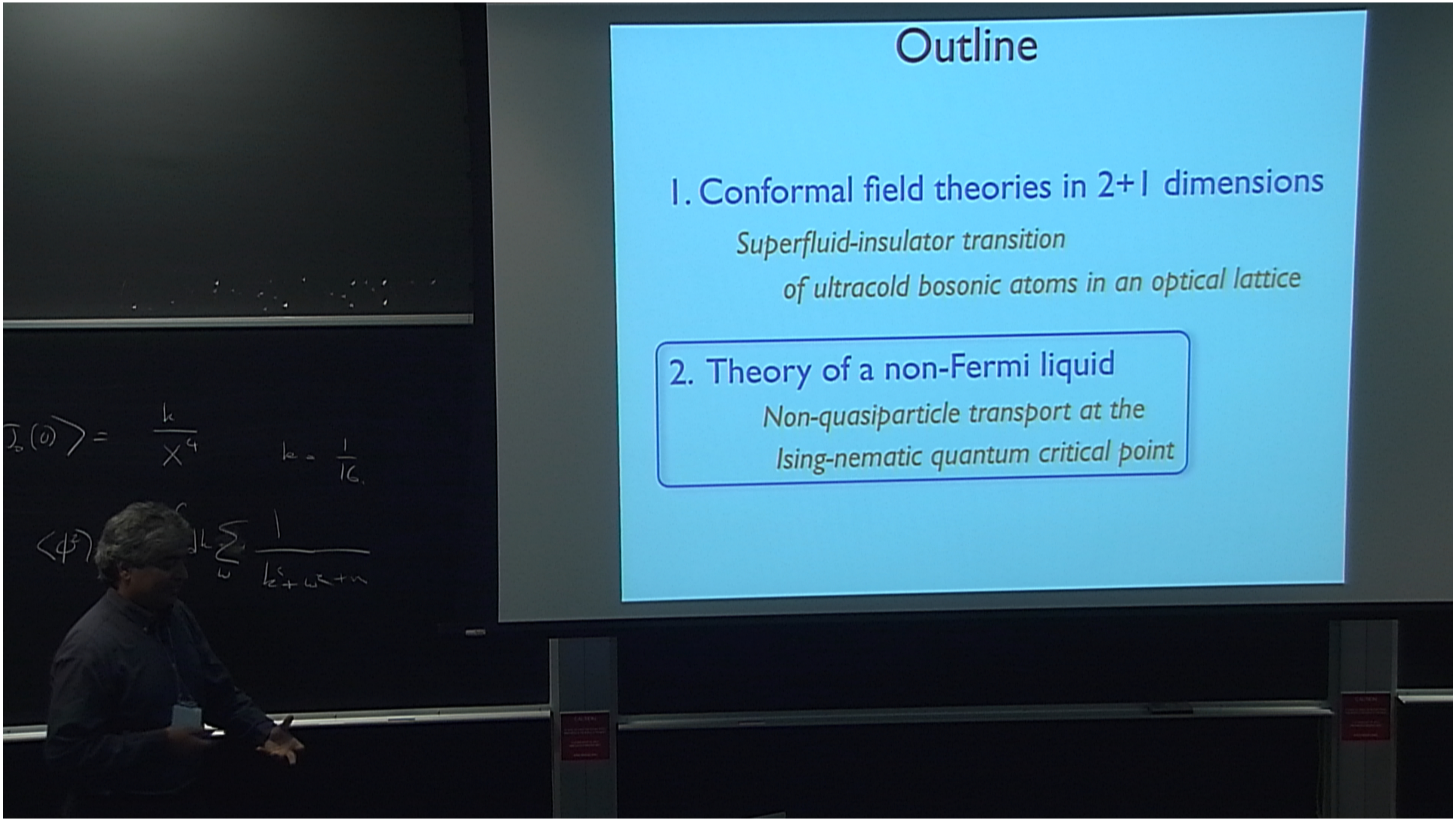

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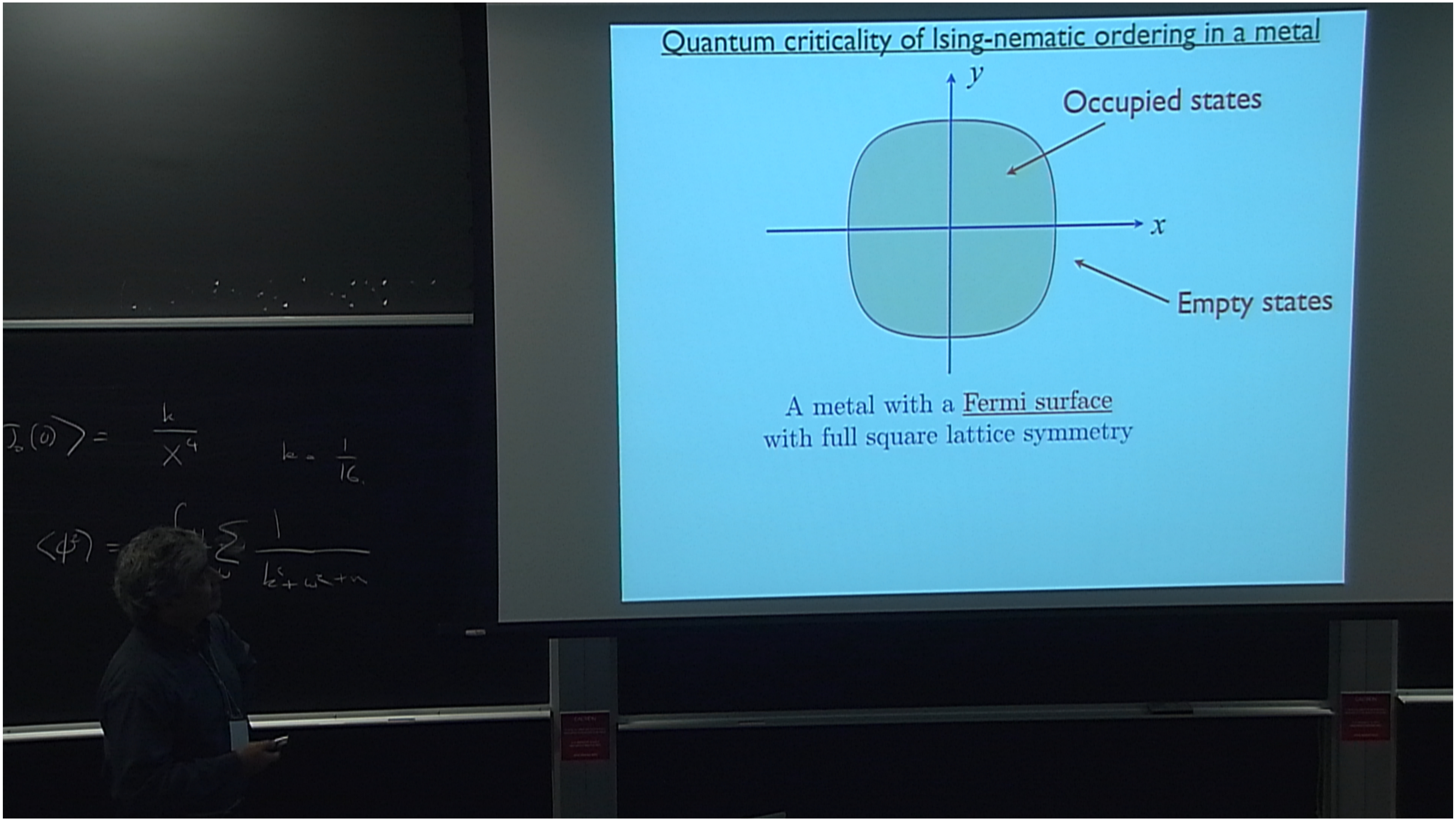
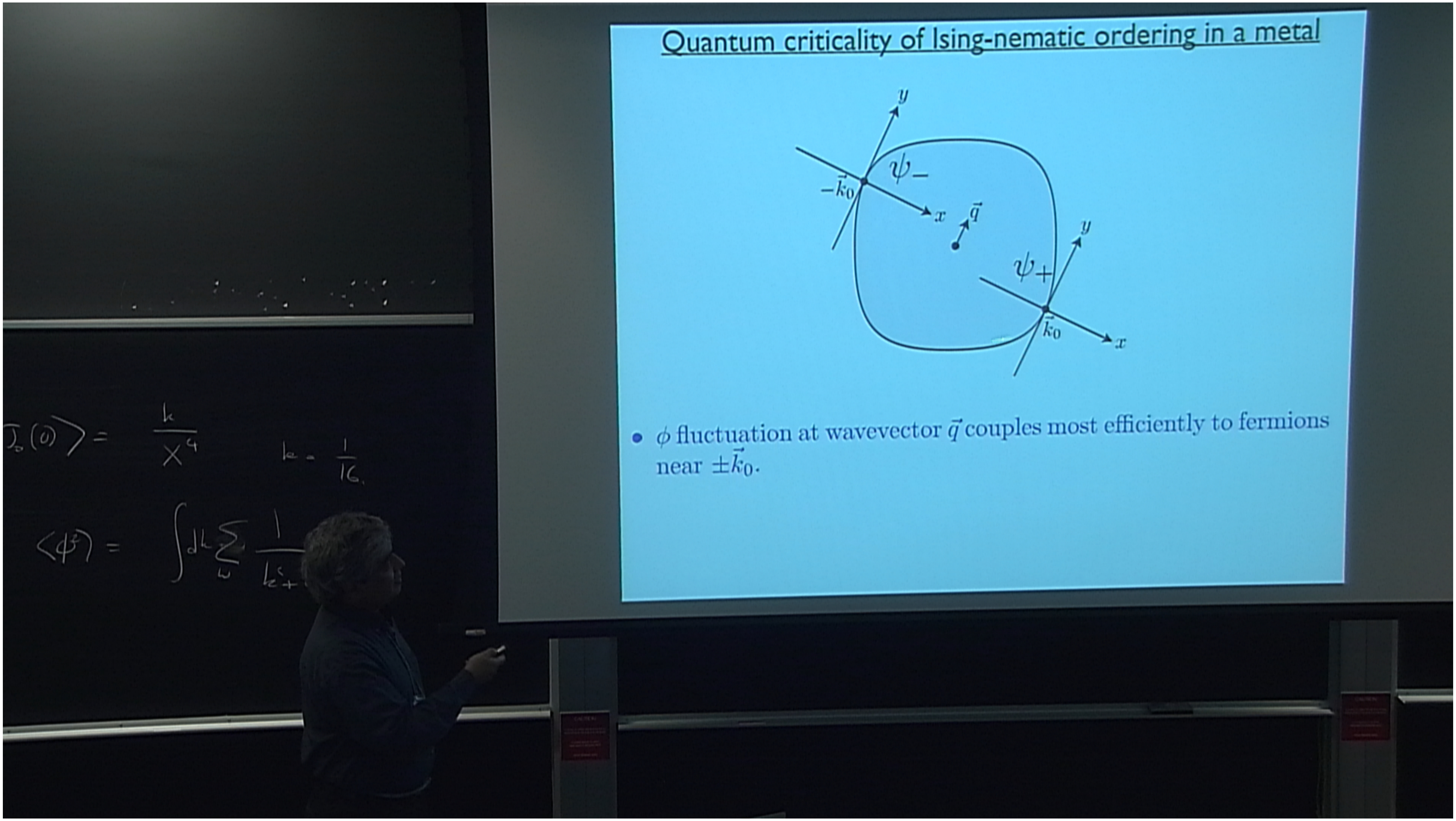
Non-quasiparticle transport at the
Ising-nematic quantum critical point


Quantum criticality of Ising-nematic ordering in a metal
y
Occupied states
x
Empty states
A metal with a Fermi surface
with full square lattice symmetry


Quantum criticality of Ising-nematic ordering in a metal
y
ψ_-
$-\vec{k}_0$
x
$\vec{q}$
y
ψ_+
$\vec{k}_0$
x
• ϕ fluctuation at wavevector $\vec{q}$ couples most efficiently to fermions near $\pm\vec{k}_0$.