Title: Measurements of Noice in Condensed Matter Systems Using Superconducting Qubits and Resonators

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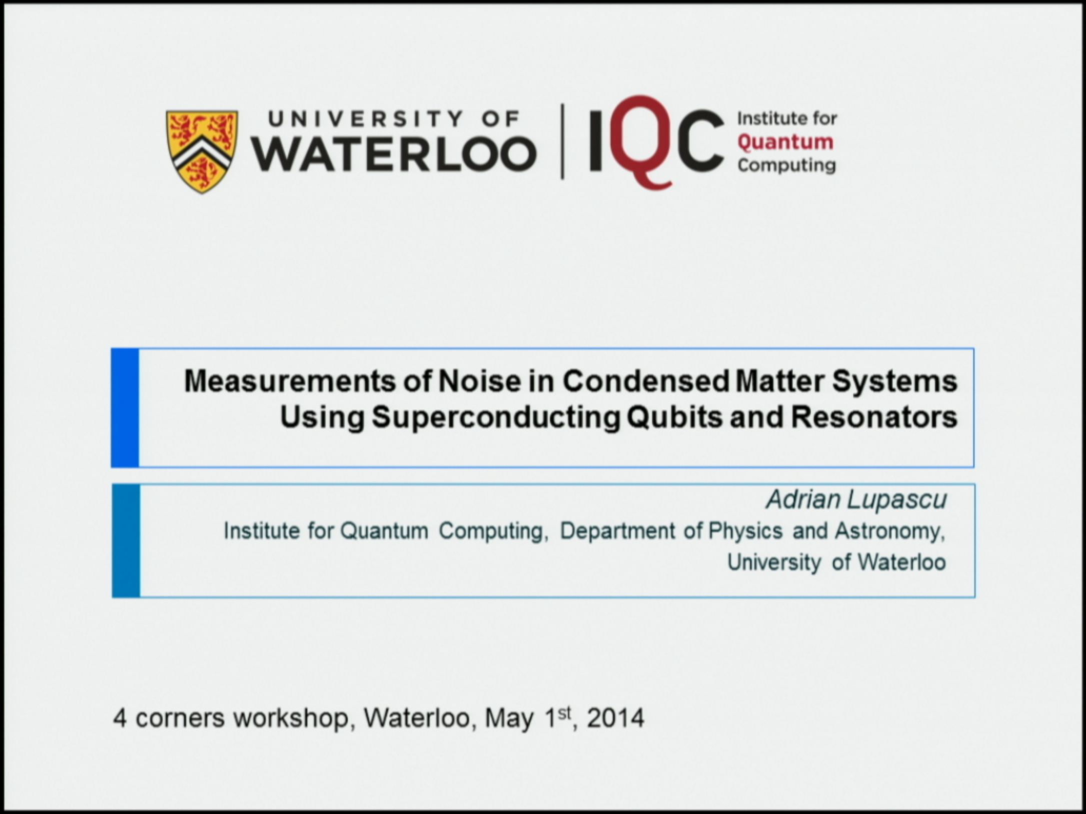
Abstract: Superconducting qubits based on Josephson junctions and resonators are presently leading candidates for the implementation of quantum computing. These systems couple strongly to their environment, which often makes preservation of coherence challenging. This strong coupling can be turned into an advantage: it enables the investigation of noise and loss at low temperatures. I will discuss two topics. The first topic is the use of superconducting flux qubits to measure magnetic flux noise. The second topic is the measurement of microwave loss in amorphous dielectric materials. Experiments with superconducting coherent systems can be used to extract new information on flux noise and dielectric loss, not accessible using other methods used in the past, providing useful input to theoretical developments.

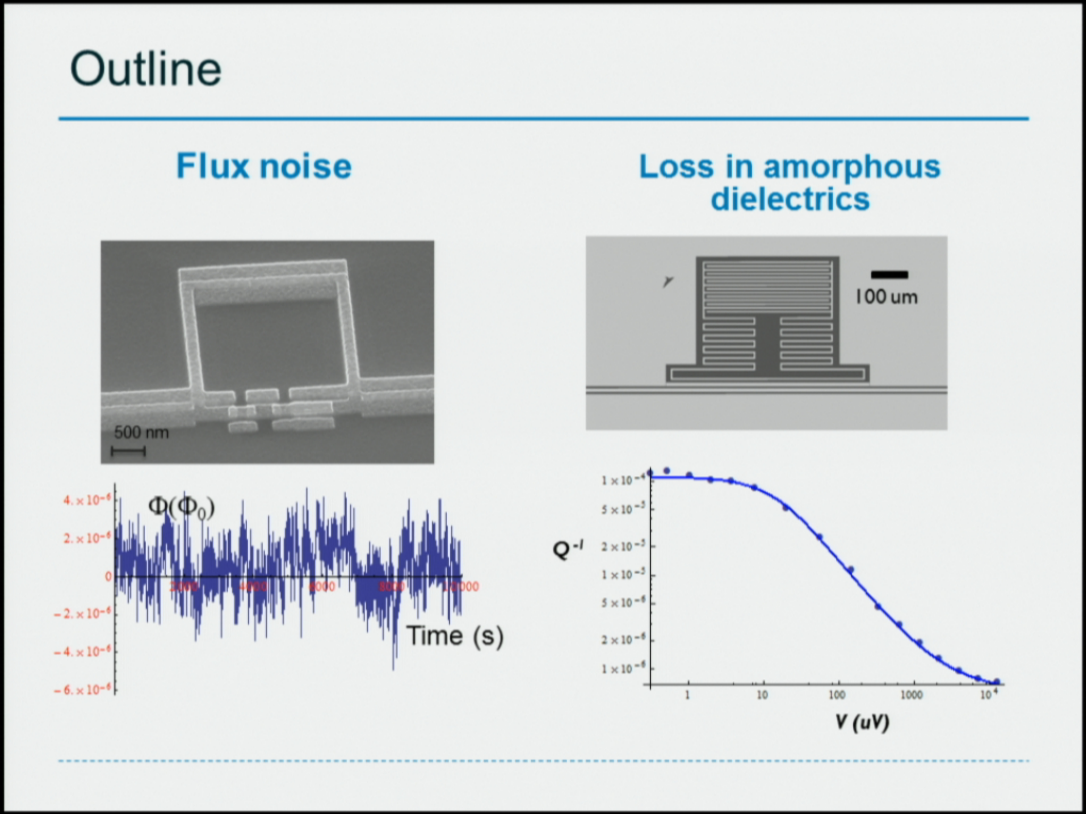


UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

Measurements of Noise in Condensed Matter Systems Using Superconducting Qubits and Resonators

Adrian Lupascu
Institute for Quantum Computing, Department of Physics and Astronomy,
University of Waterloo

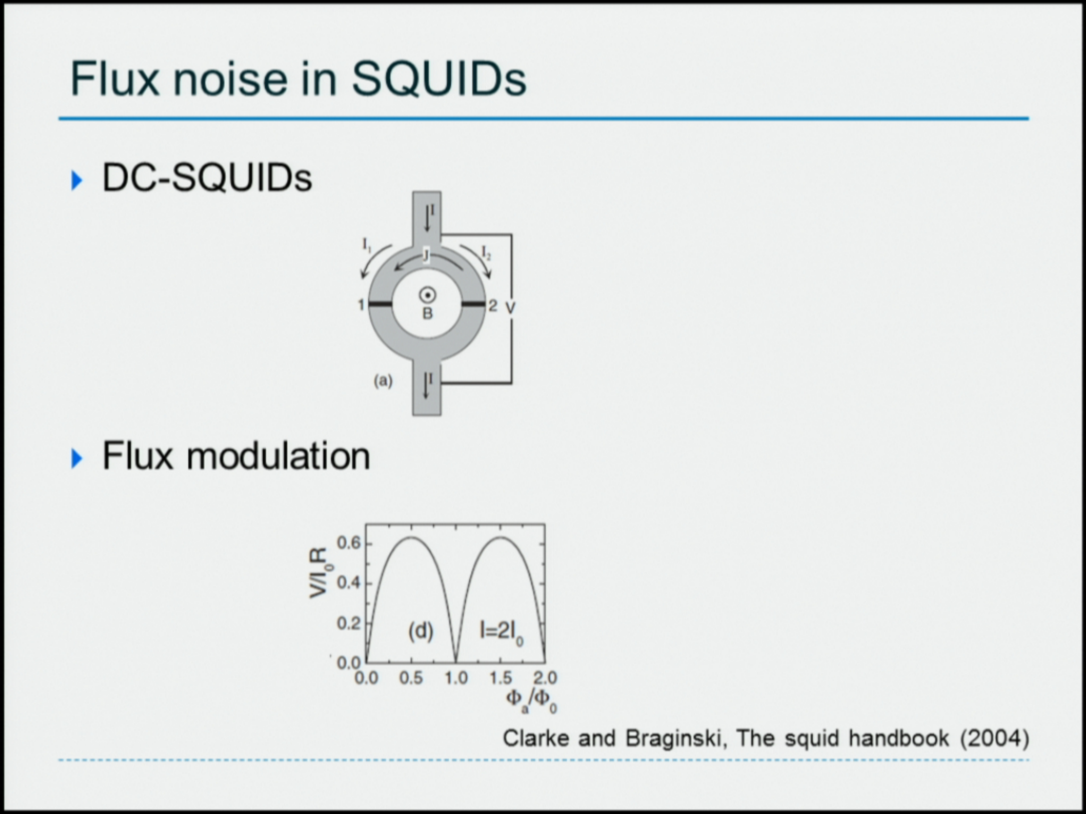
4 corners workshop, Waterloo, May 1st, 2014



Outline

Flux noise

Loss in amorphous dielectrics

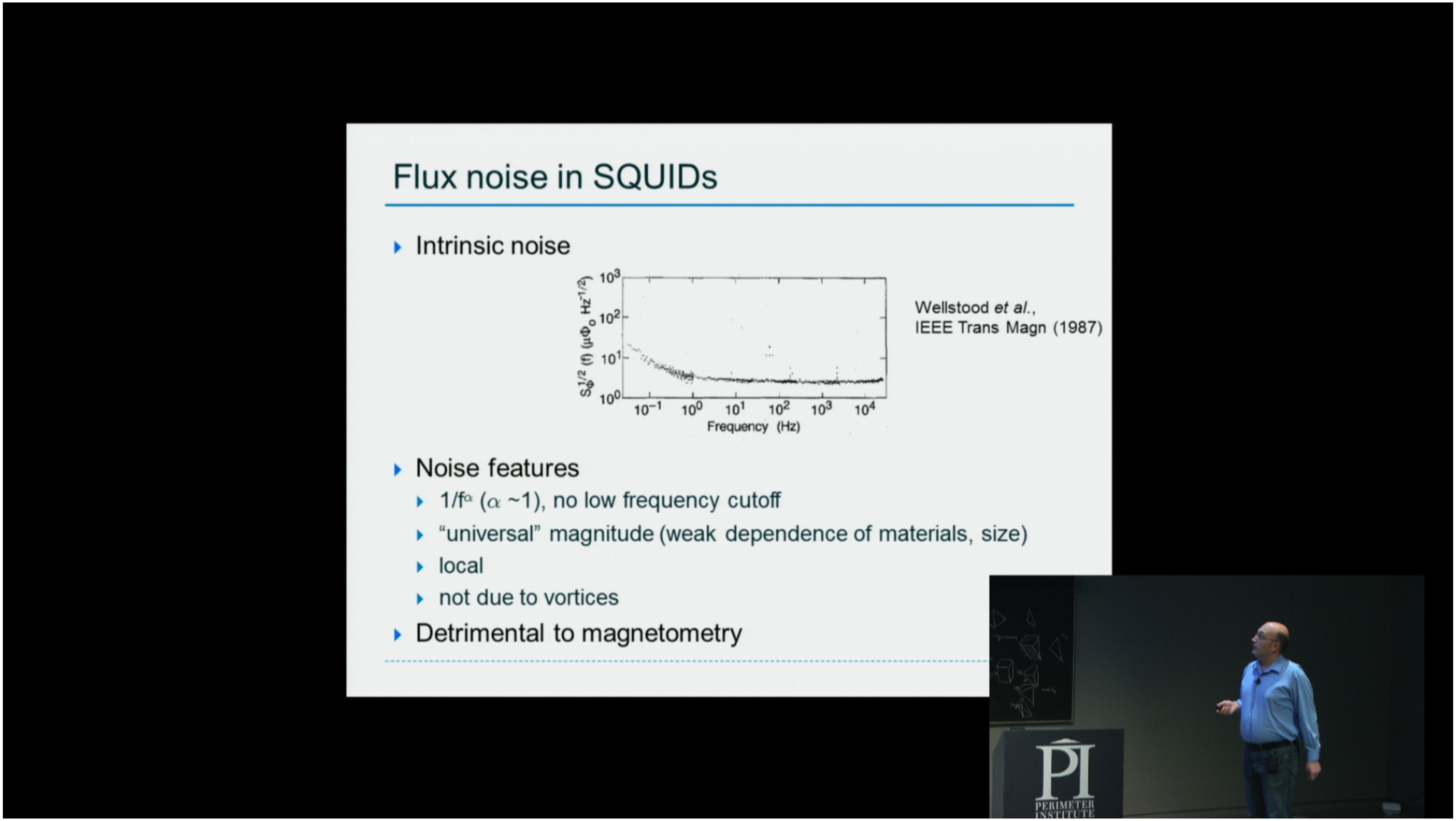


Flux noise in SQUIDs

- DC-SQUIDs

- Flux modulation

Clarke and Braginski, The squid handbook (2004)

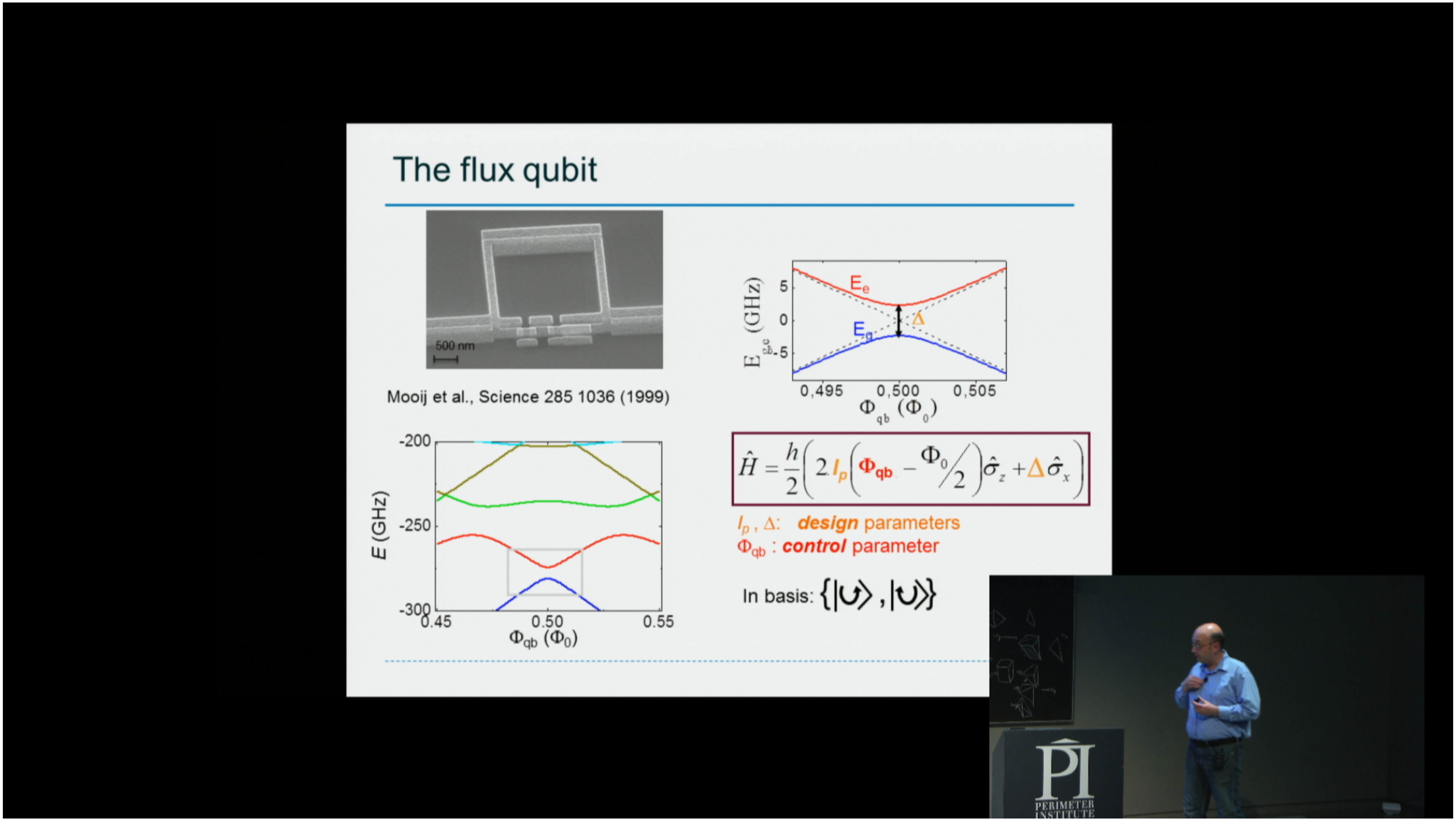


Flux noise in SQUIDs

- Intrinsic noise

Wellstood *et al.*,
IEEE Trans Magn (1987)

- Noise features
  - $1/f^\alpha$ (α ~1), no low frequency cutoff
  - "universal" magnitude (weak dependence of materials, size)
  - local
  - not due to vortices
- Detrimental to magnetometry



The flux qubit

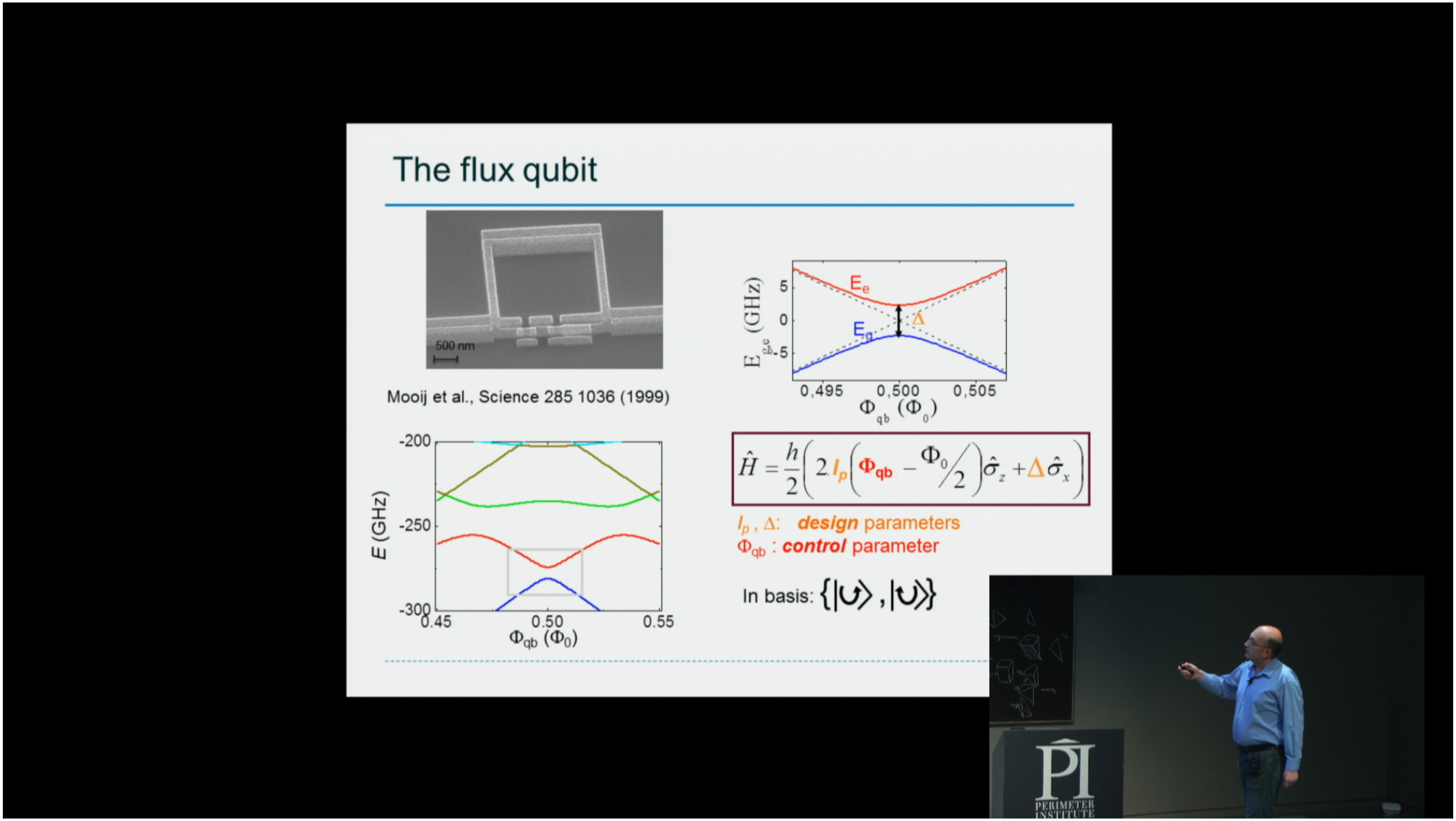
Mooij et al., Science 285 1036 (1999)

$$\hat{H} = \frac{h}{2}\left(2 I_p\left(\Phi_{qb} - \Phi_0/2\right)\hat{\sigma}_z + \Delta\hat{\sigma}_x\right)$$

I_p, Δ: ***design*** parameters

Φ_{qb} : ***control*** parameter

In basis: $\{|\circlearrowleft\rangle, |\circlearrowright\rangle\}$



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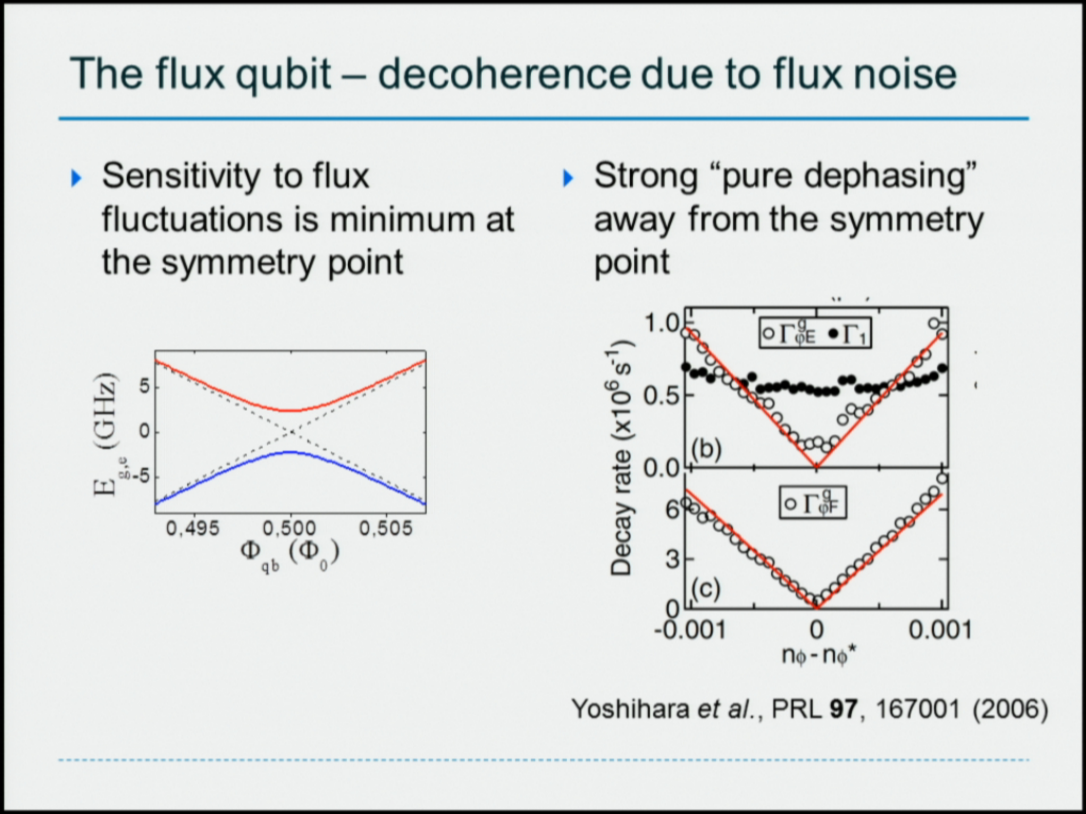
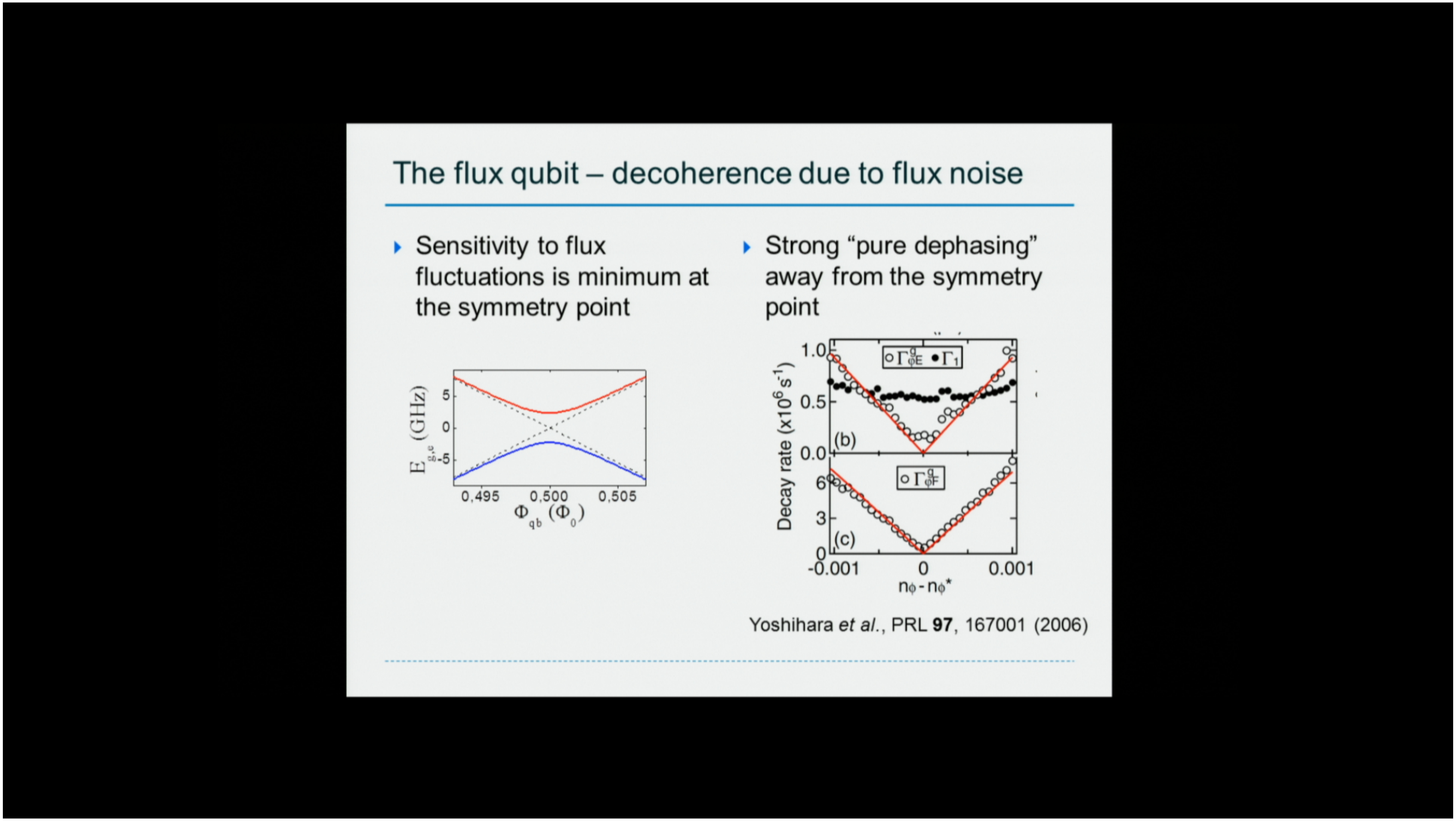


The flux qubit – decoherence due to flux noise

- Sensitivity to flux fluctuations is minimum at the symmetry point
- Strong "pure dephasing" away from the symmetry point

Yoshihara *et al.*, PRL **97**, 167001 (2006)



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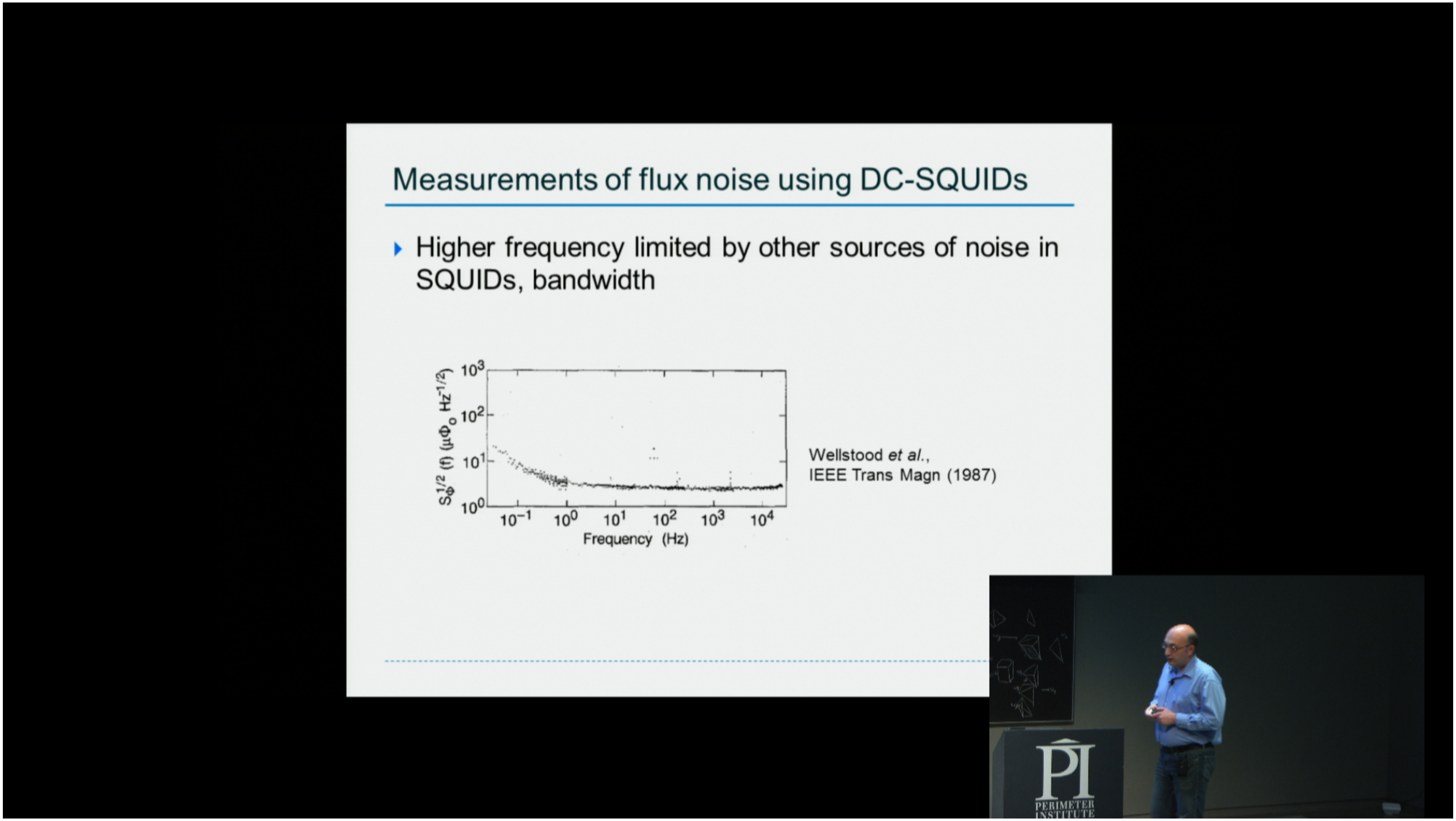
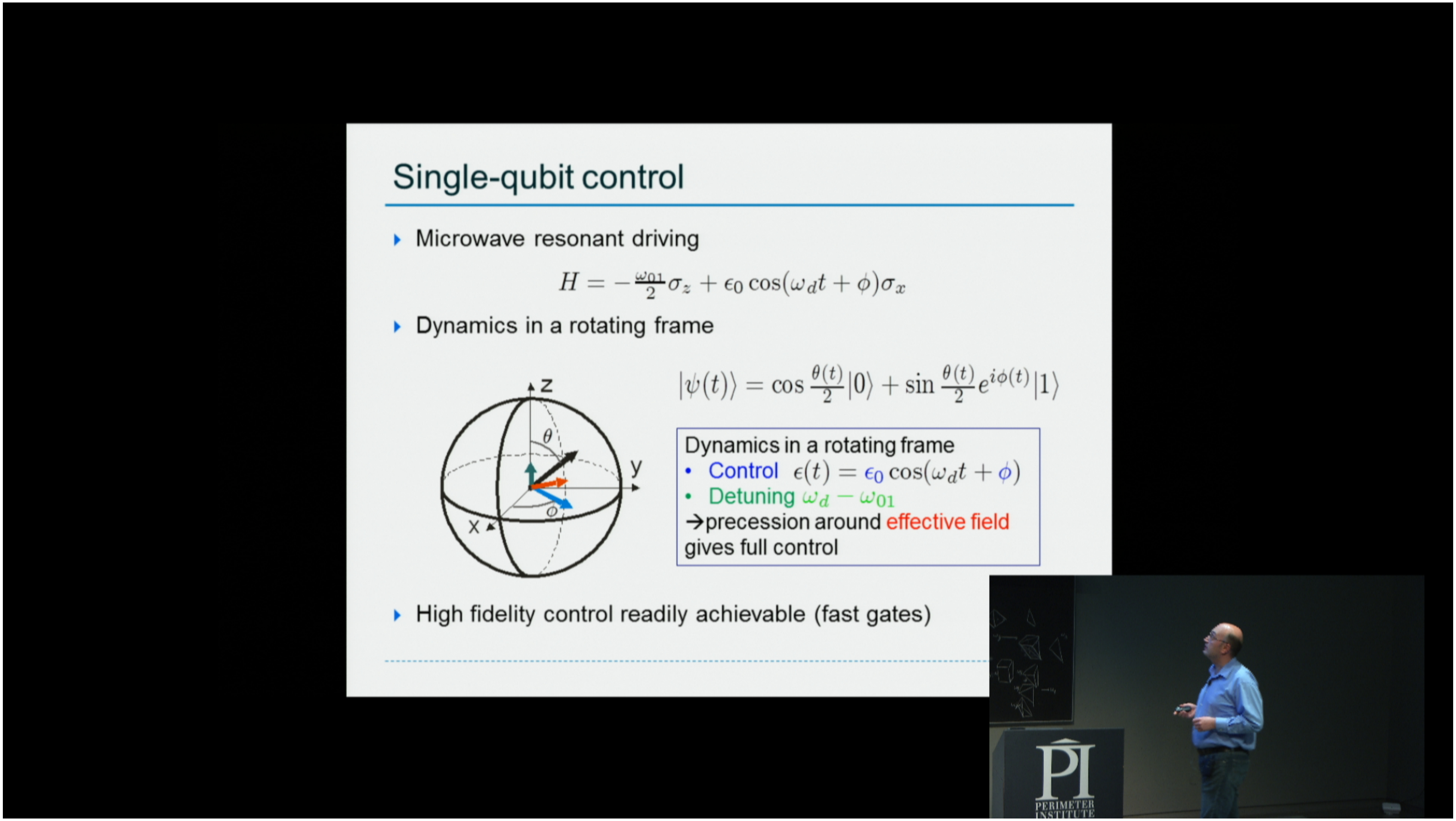


Measurements of flux noise using DC-SQUIDs

- Higher frequency limited by other sources of noise in SQUIDs, bandwidth

Wellstood *et al.*,
IEEE Trans Magn (1987)



Single-qubit control

- Microwave resonant driving

$$H = -\frac{\omega_{01}}{2}\sigma_z + \epsilon_0 \cos(\omega_d t + \phi)\sigma_x$$

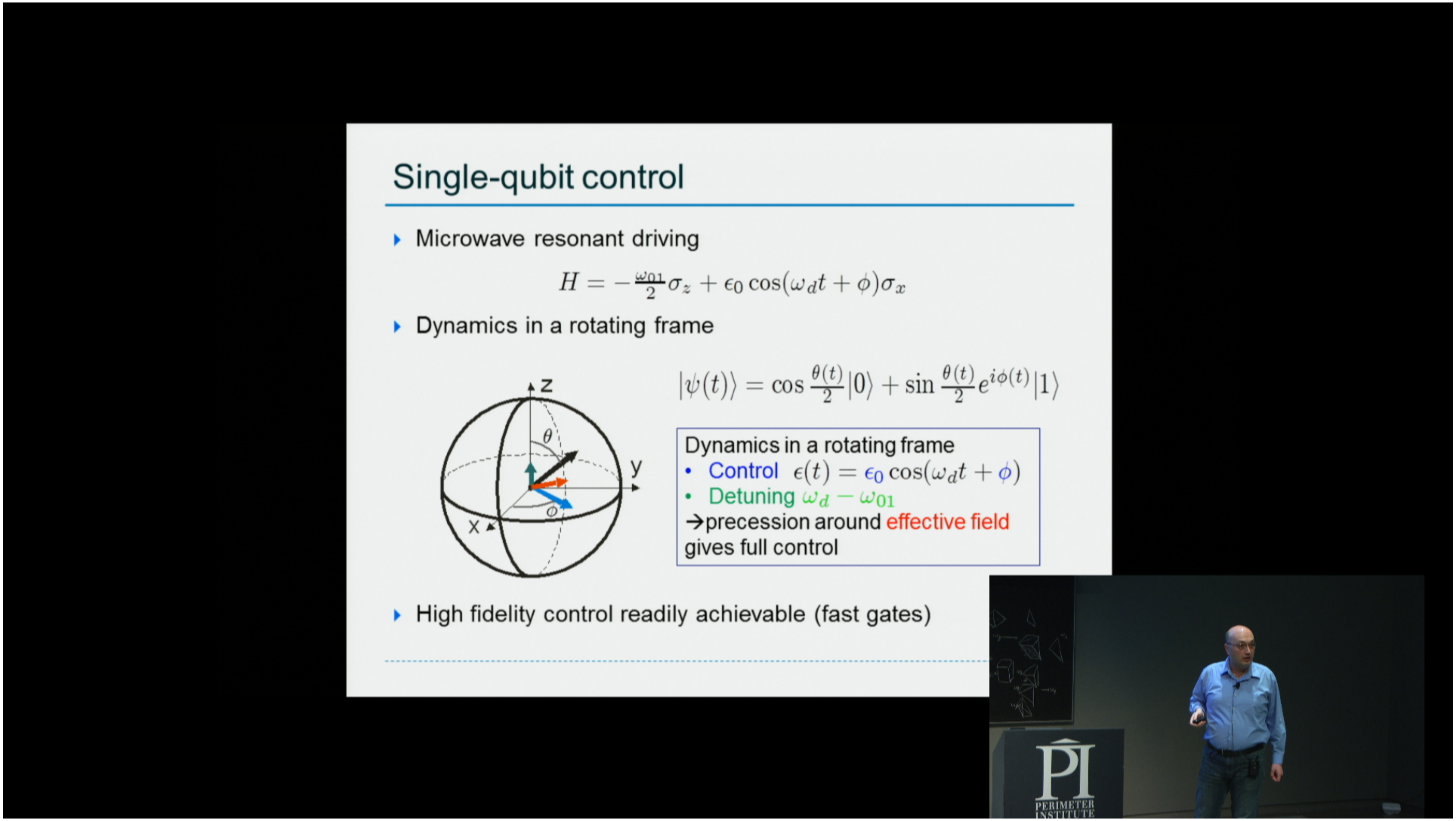
- Dynamics in a rotating frame

$$|\psi(t)\rangle = \cos\frac{\theta(t)}{2}|0\rangle + \sin\frac{\theta(t)}{2}e^{i\phi(t)}|1\rangle$$

Dynamics in a rotating frame
- Control $\epsilon(t) = \epsilon_0 \cos(\omega_d t + \phi)$
- Detuning $\omega_d - \omega_{01}$

→precession around effective field gives full control

- High fidelity control readily achievable (fast gates)



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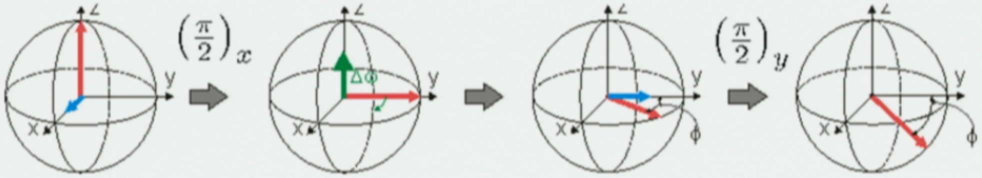
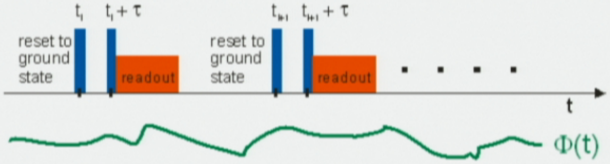
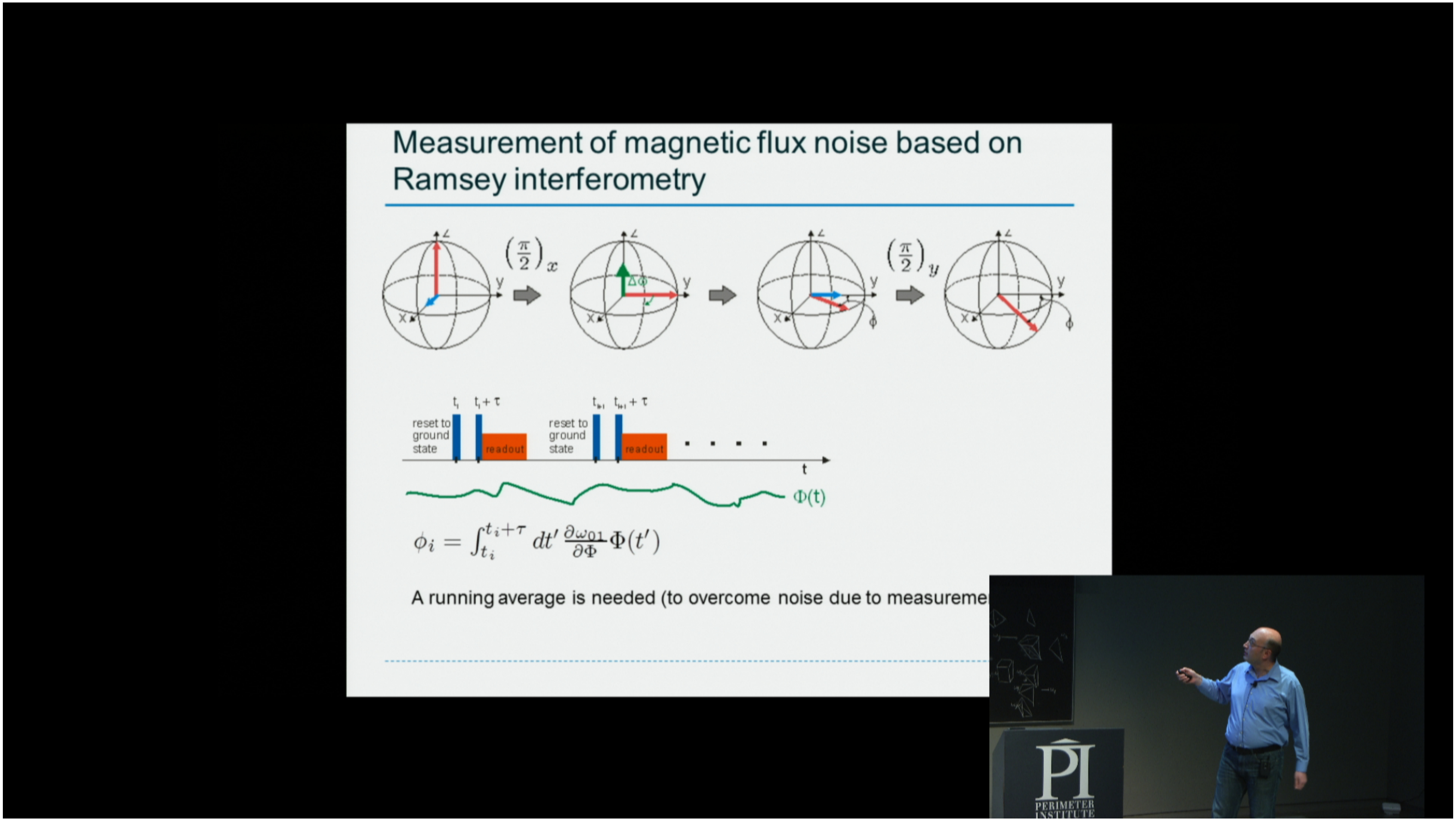
Measurement of magnetic flux noise based on Ramsey interferometry





$$\phi_i = \int_{t_i}^{t_i+\tau} dt' \, \frac{\partial \omega_{01}}{\partial \Phi} \Phi(t')$$

A running average is needed (to overcome noise due to measurement)



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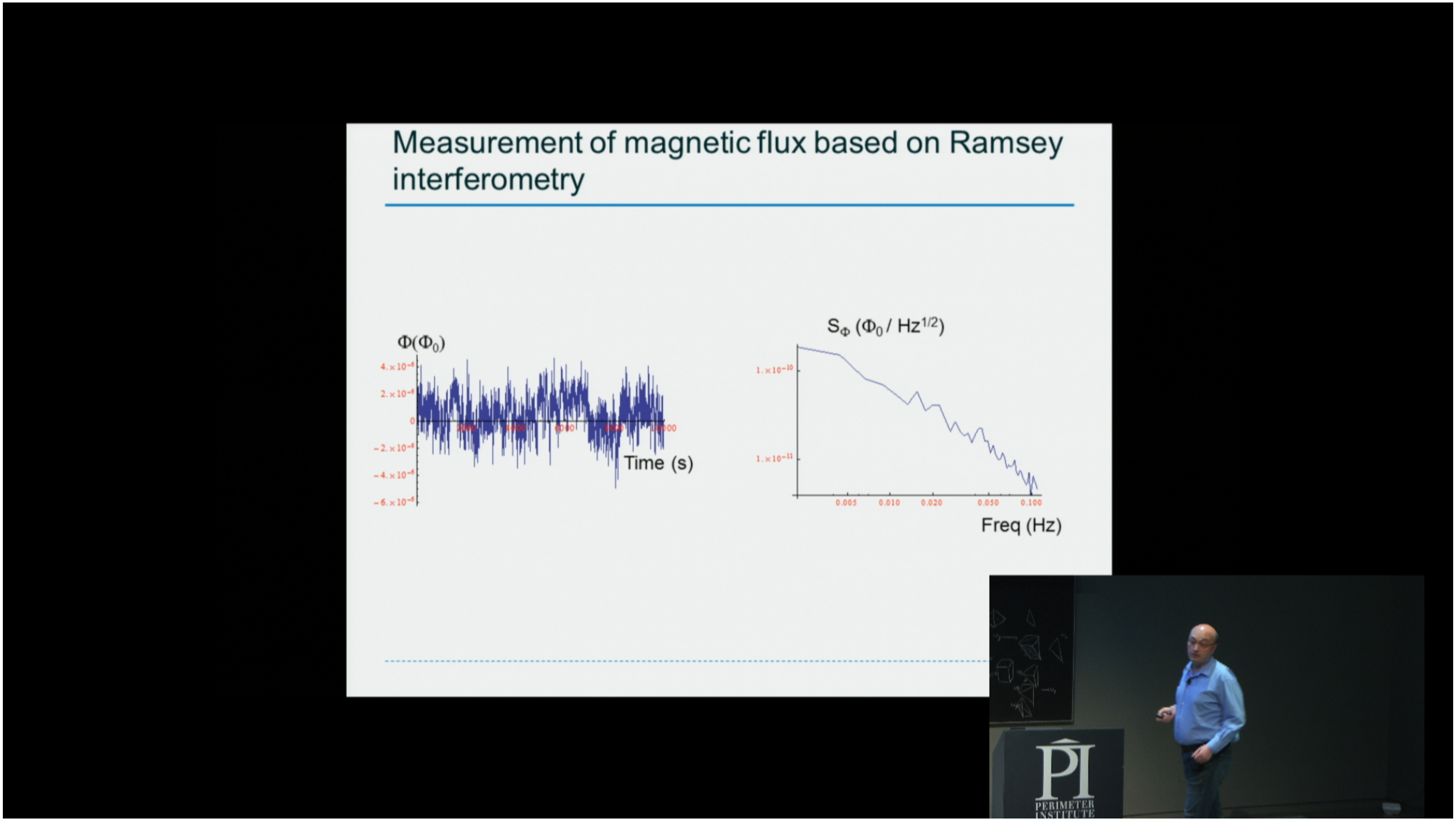

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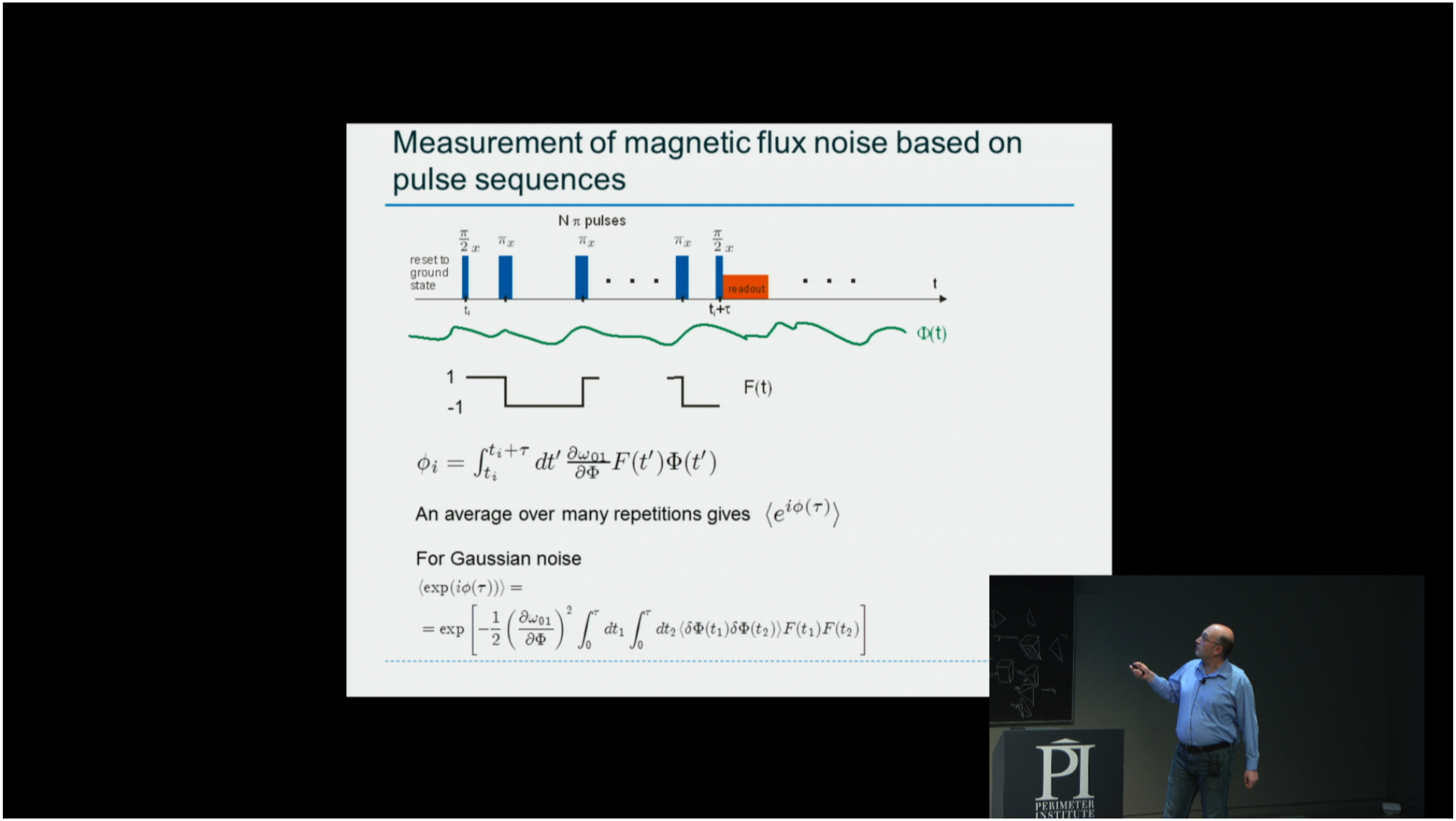


Measurement of magnetic flux noise based on pulse sequences

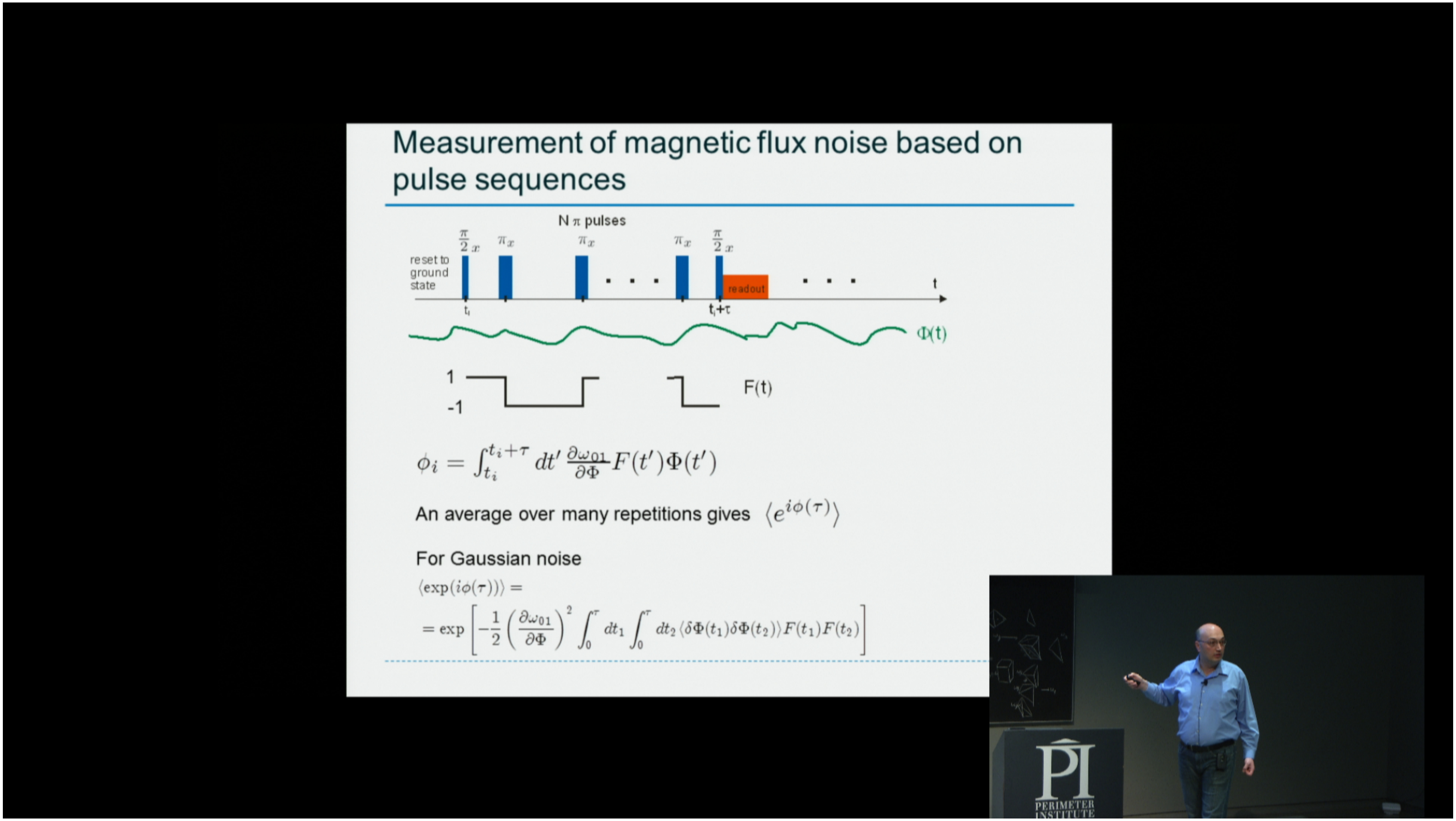
$$\phi_i = \int_{t_i}^{t_i+\tau} dt' \, \frac{\partial \omega_{01}}{\partial \Phi} F(t')\Phi(t')$$

An average over many repetitions gives $\langle e^{i\phi(\tau)} \rangle$

For Gaussian noise

$$\langle \exp(i\phi(\tau)) \rangle =$$

$$= \exp\left[-\frac{1}{2} \left(\frac{\partial \omega_{01}}{\partial \Phi} \right)^2 \int_0^\tau dt_1 \int_0^\tau dt_2 \, \langle \delta\Phi(t_1)\delta\Phi(t_2) \rangle F(t_1)F(t_2) \right]$$



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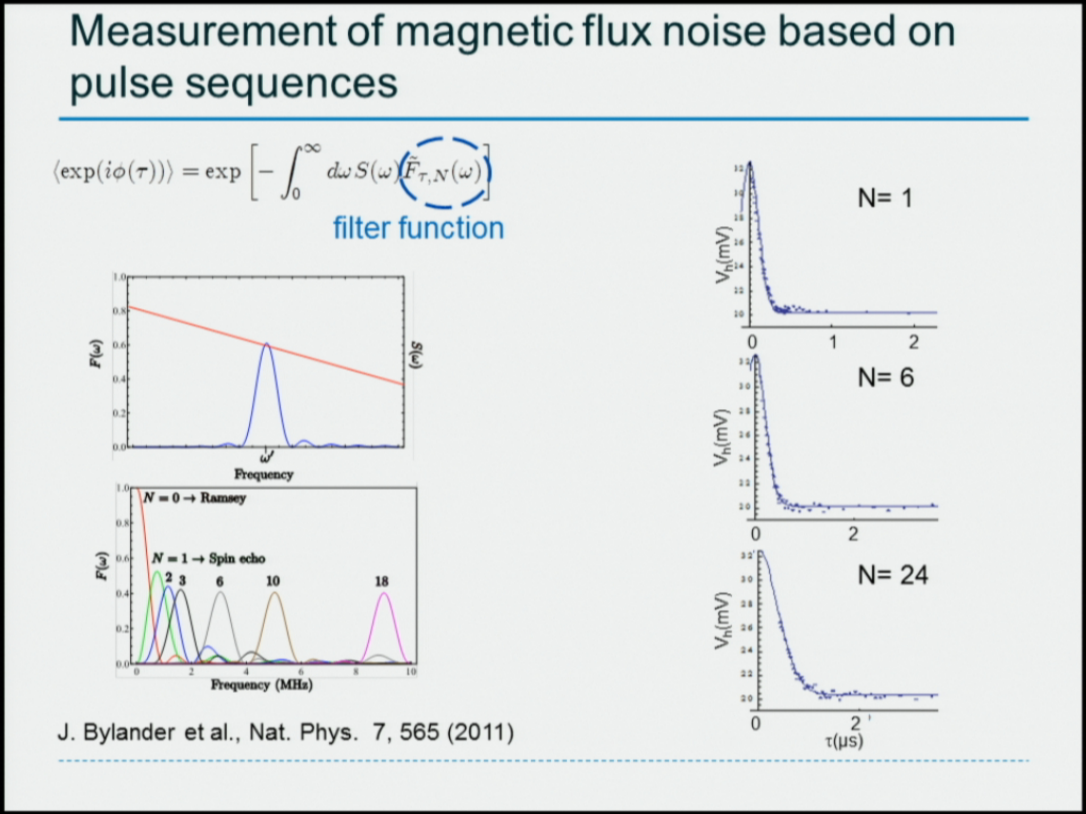
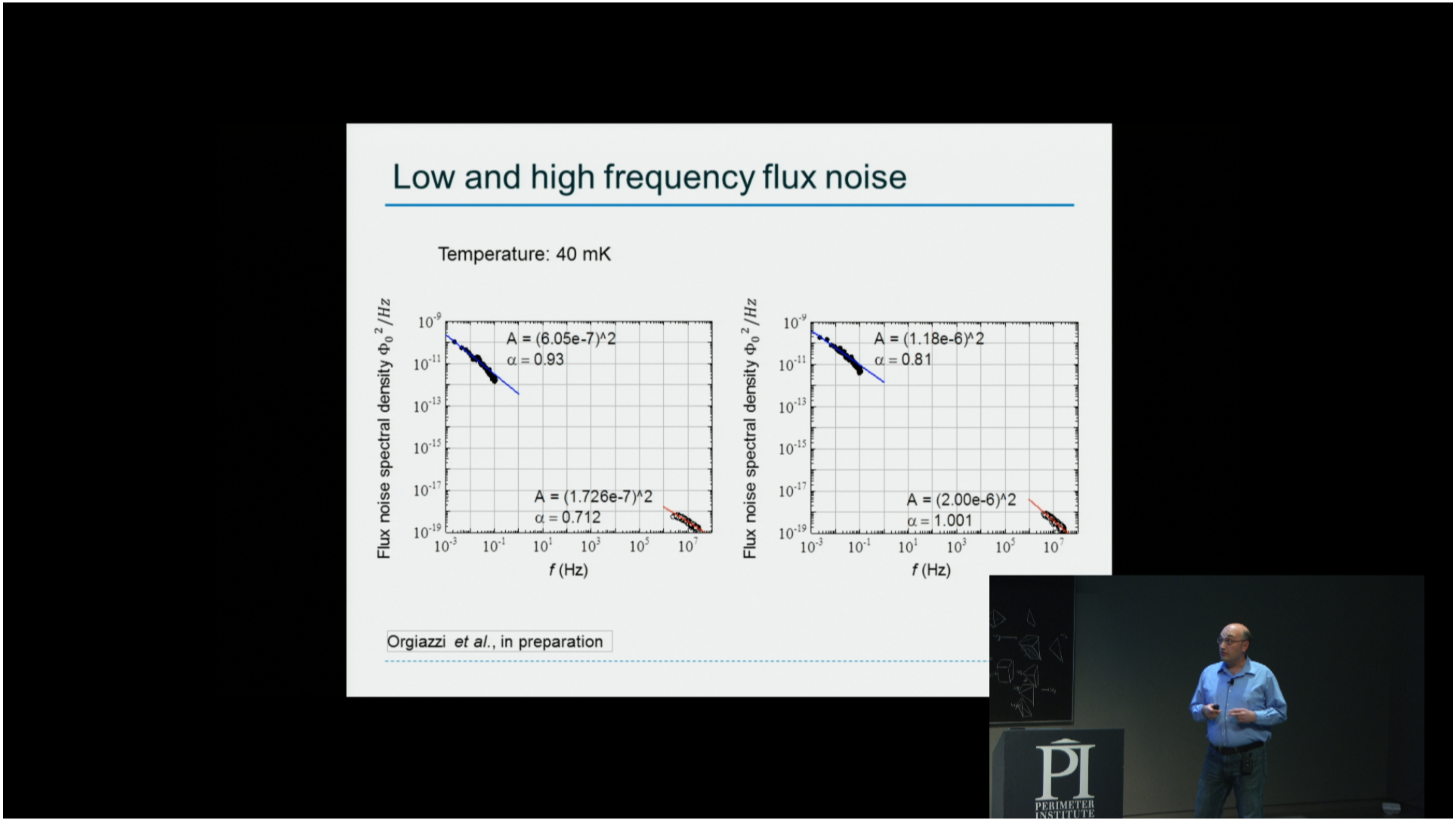


Measurement of magnetic flux noise based on pulse sequences

$$\langle \exp(i\phi(\tau))\rangle = \exp\left[-\int_0^\infty d\omega\, S(\omega)\, \tilde{F}_{\tau,N}(\omega)\right]$$

filter function

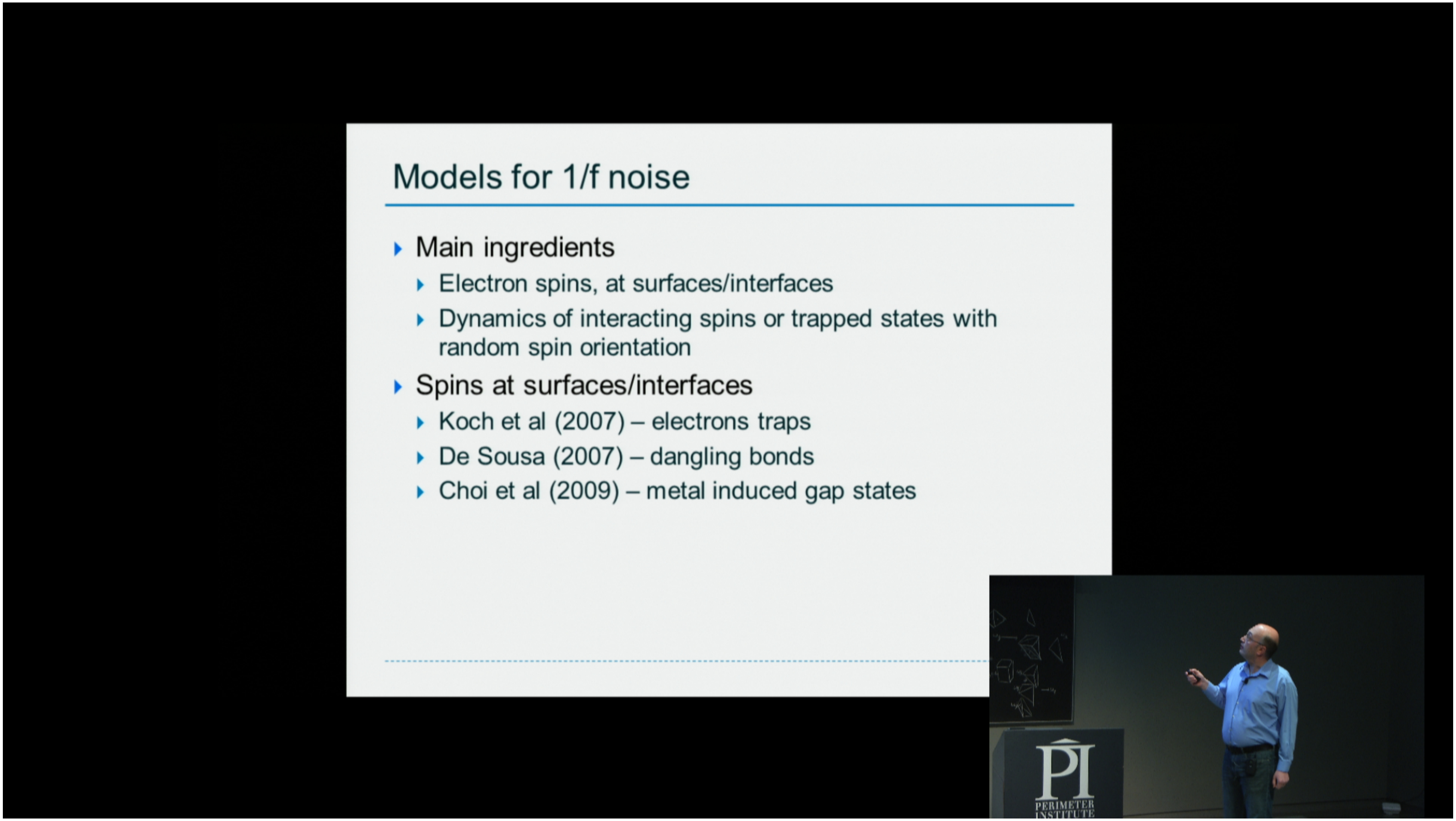
J. Bylander et al., Nat. Phys. 7, 565 (2011)



Low and high frequency flux noise

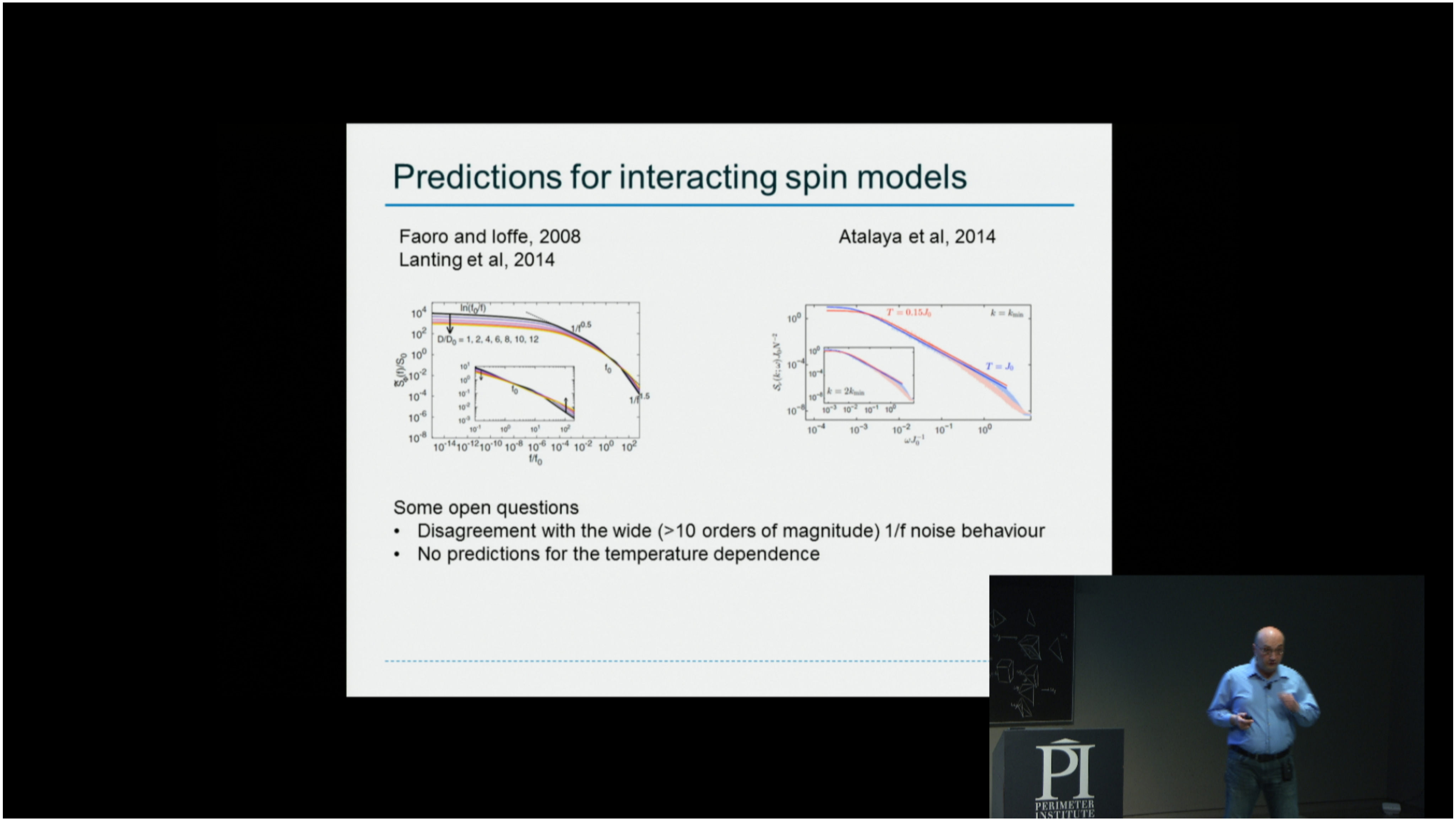
Temperature: 40 mK

Orgiazzi *et al.*, in preparation



Models for 1/f noise

- Main ingredients
  - Electron spins, at surfaces/interfaces
  - Dynamics of interacting spins or trapped states with random spin orientation
- Spins at surfaces/interfaces
  - Koch et al (2007) – electrons traps
  - De Sousa (2007) – dangling bonds
  - Choi et al (2009) – metal induced gap states



Predictions for interacting spin models

Faoro and Ioffe, 2008
Lanting et al, 2014

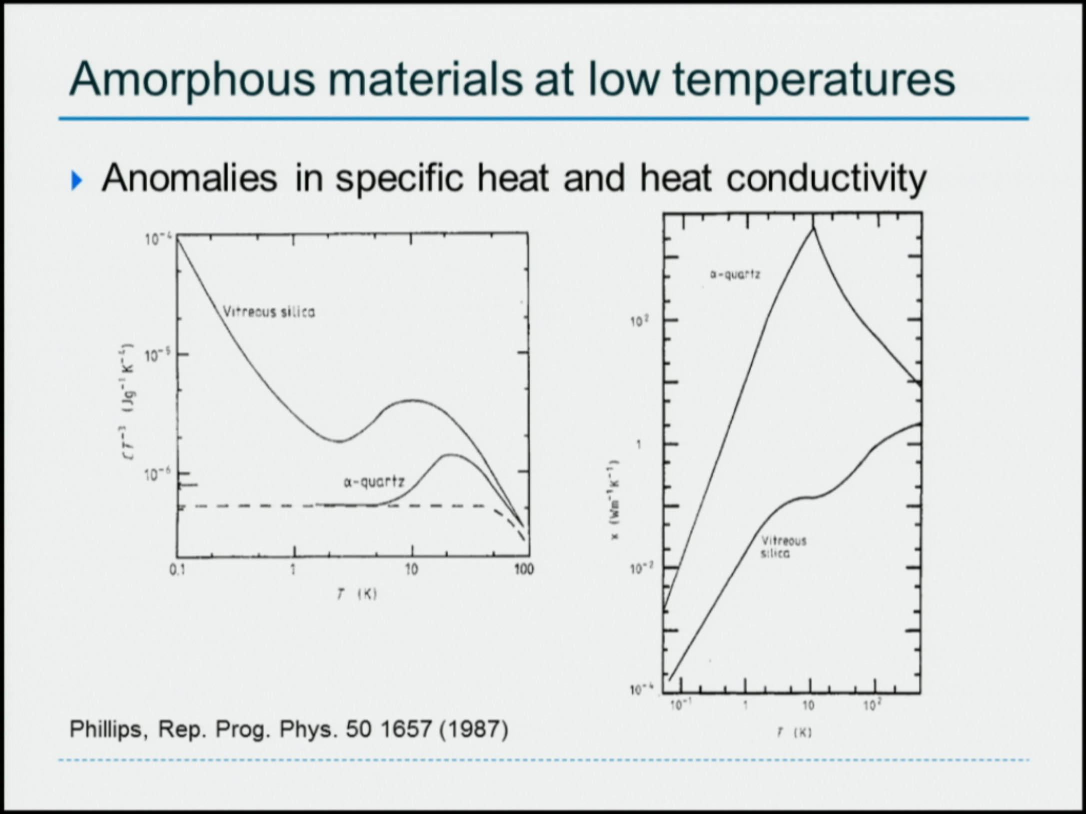
Atalaya et al, 2014

Some open questions

- Disagreement with the wide (>10 orders of magnitude) 1/f noise behaviour
- No predictions for the temperature dependence

Prospects

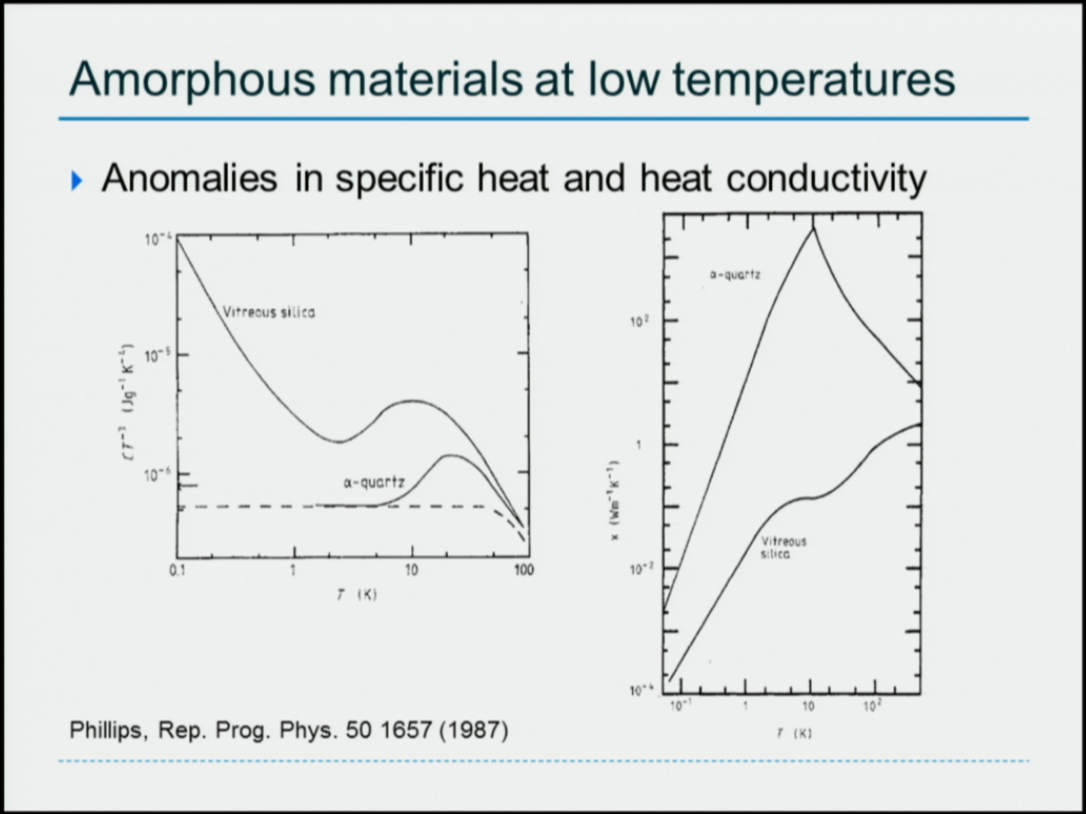
- Measurements based on qubits give access to wider spectral information, better sensitivity; input to theory
- Systematic experiments: verify scaling, dependence on materials
- Reduction of magnetic field noise will have a major impact on quantum information and magnetic field detection



Amorphous materials at low temperatures

- Anomalies in specific heat and heat conductivity

Phillips, Rep. Prog. Phys. 50 1657 (1987)



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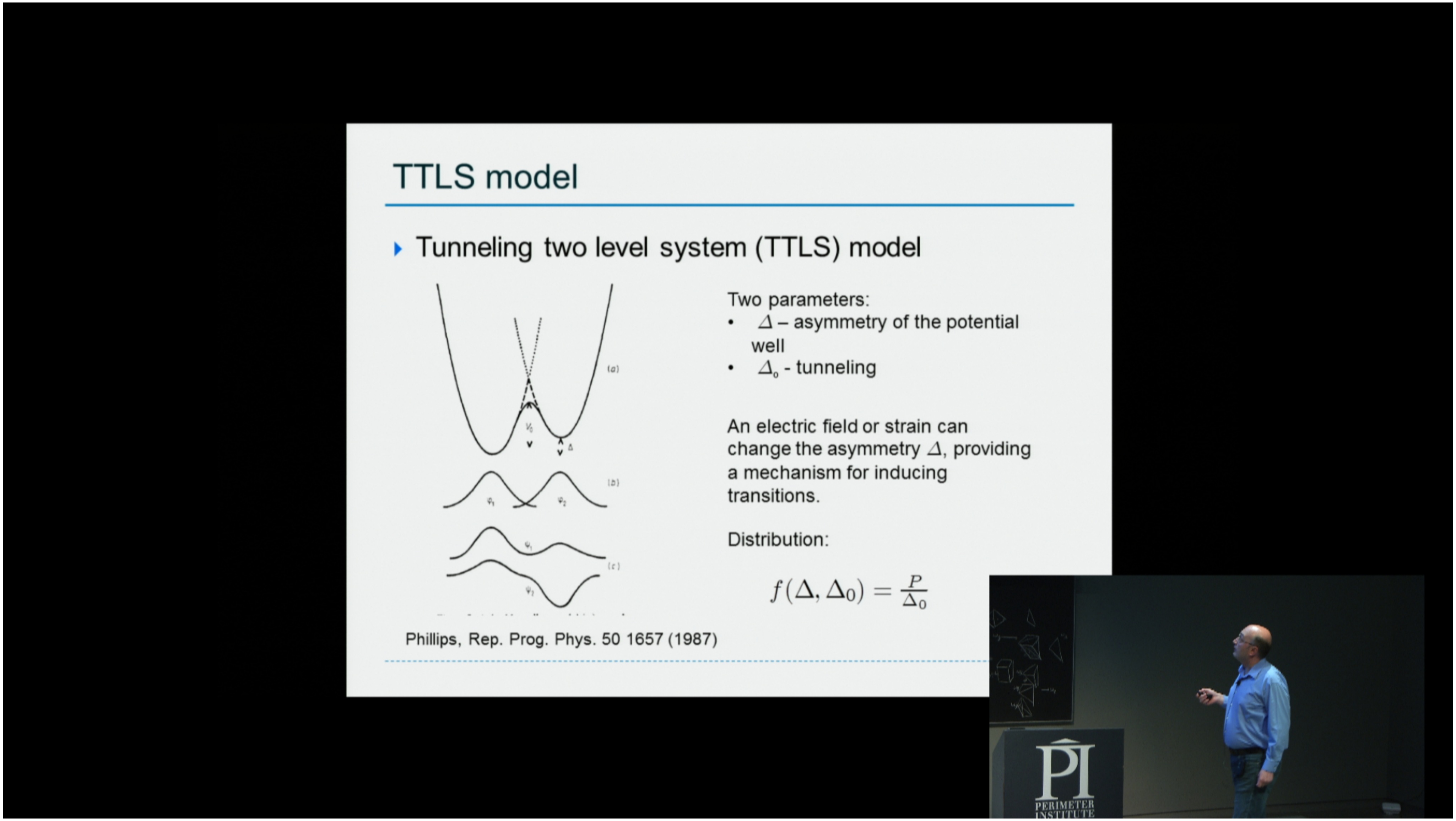


TTLS model

- Tunneling two level system (TTLS) model

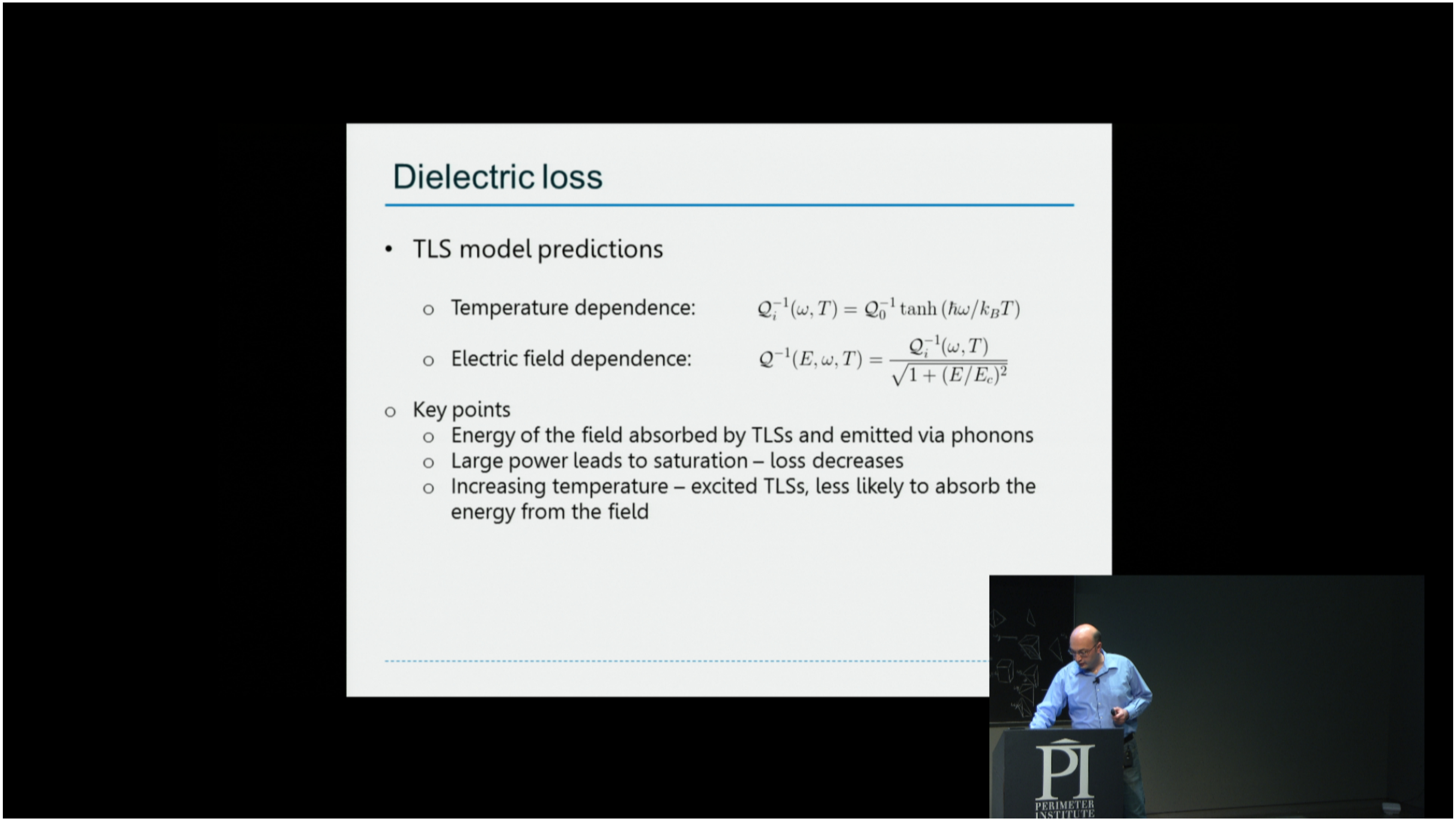
Two parameters:
- Δ – asymmetry of the potential well
- Δ_0 - tunneling

An electric field or strain can change the asymmetry Δ, providing a mechanism for inducing transitions.

Distribution:

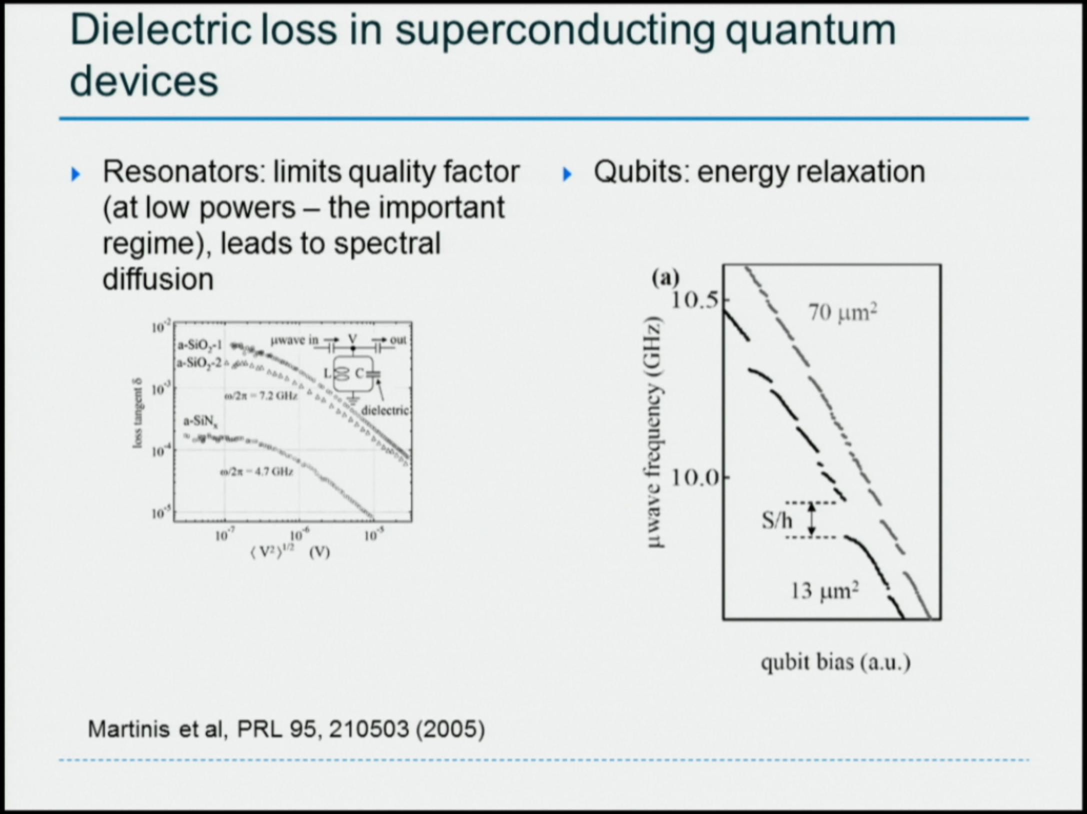
$$f(\Delta, \Delta_0) = \frac{P}{\Delta_0}$$

Phillips, Rep. Prog. Phys. 50 1657 (1987)



Dielectric loss

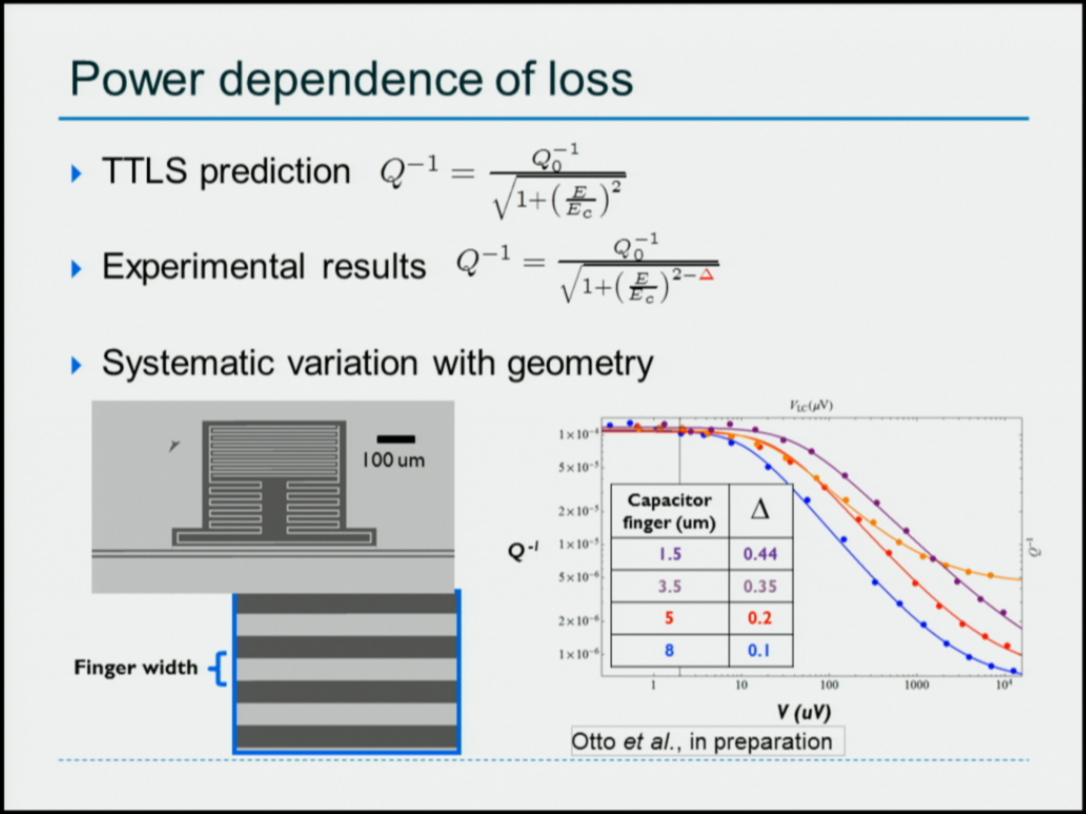
- TLS model predictions
  - Temperature dependence: $Q_i^{-1}(\omega, T) = Q_0^{-1} \tanh\left(\hbar\omega / k_B T\right)$
  - Electric field dependence: $Q^{-1}(E, \omega, T) = \dfrac{Q_i^{-1}(\omega, T)}{\sqrt{1 + (E/E_c)^2}}$
- Key points
  - Energy of the field absorbed by TLSs and emitted via phonons
  - Large power leads to saturation – loss decreases
  - Increasing temperature – excited TLSs, less likely to absorb the energy from the field



Dielectric loss in superconducting quantum devices

- Resonators: limits quality factor (at low powers – the important regime), leads to spectral diffusion
- Qubits: energy relaxation

Martinis et al, PRL 95, 210503 (2005)

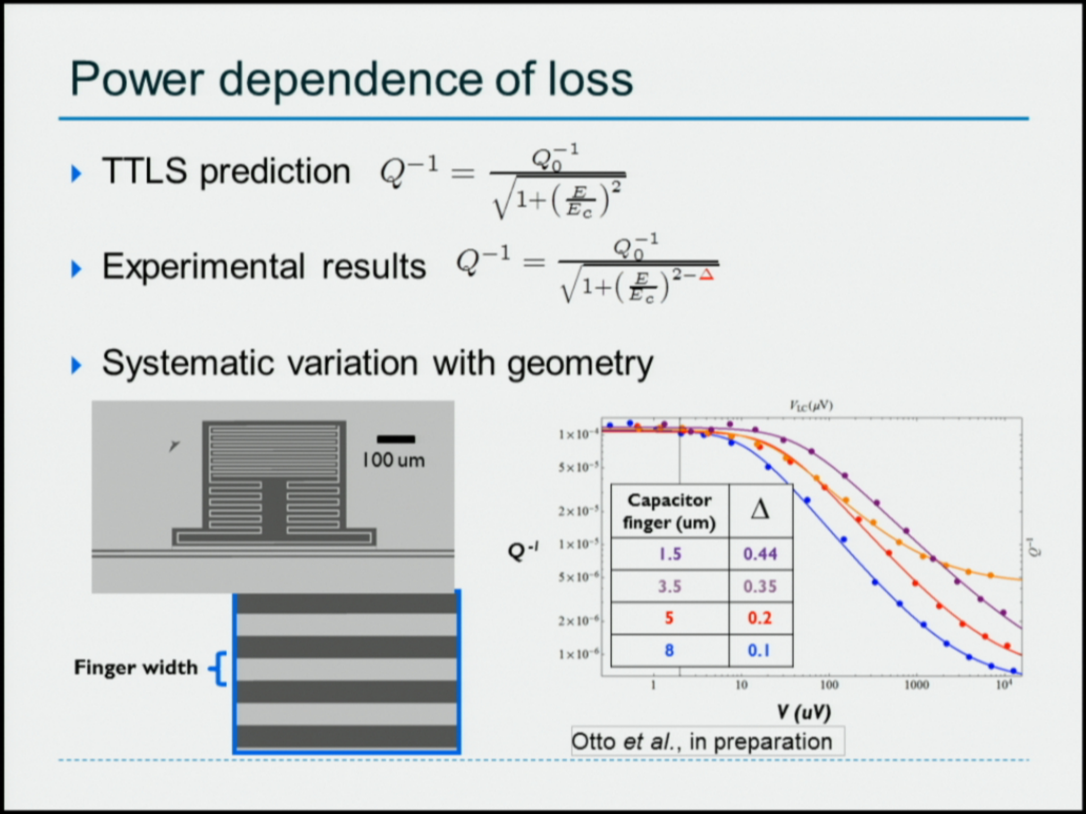


Power dependence of loss

- TTLS prediction $Q^{-1} = \frac{Q_0^{-1}}{\sqrt{1+\left(\frac{E}{E_c}\right)^2}}$
- Experimental results $Q^{-1} = \frac{Q_0^{-1}}{\sqrt{1+\left(\frac{E}{E_c}\right)^{2-\Delta}}}$
- Systematic variation with geometry

Capacitor finger (um)	Δ
1.5	0.44
3.5	0.35
5	0.2
8	0.1

Otto *et al.*, in preparation



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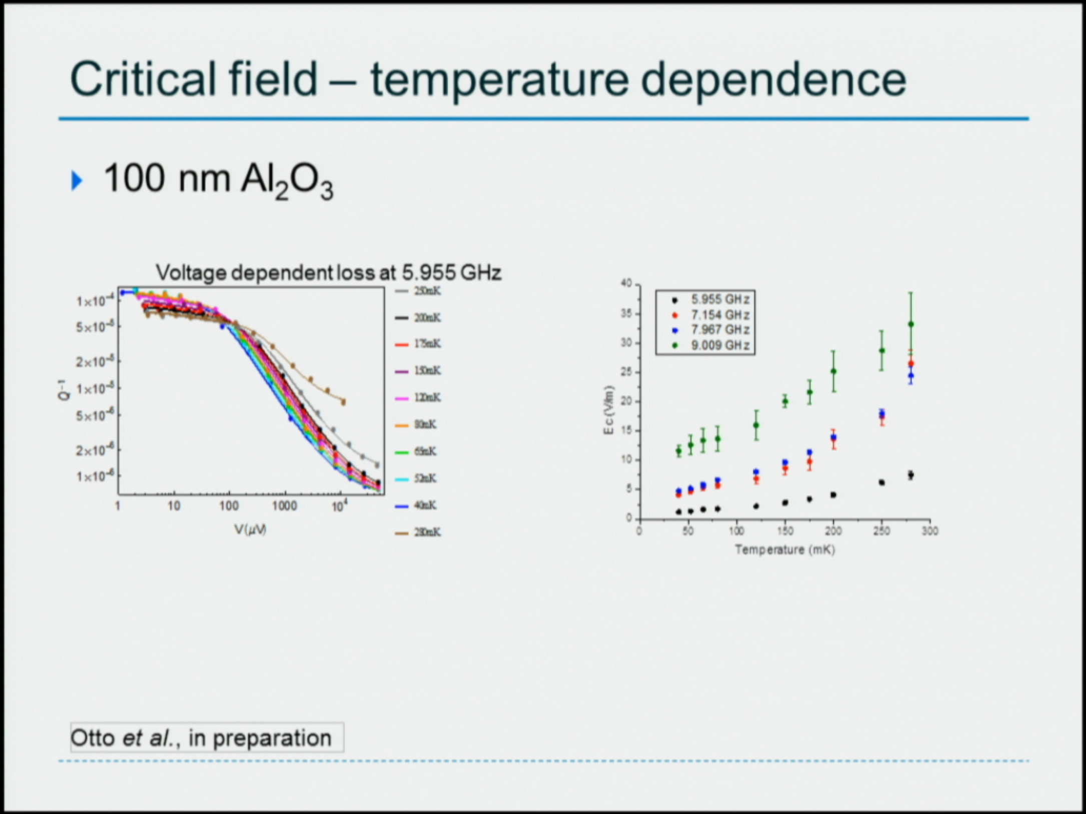
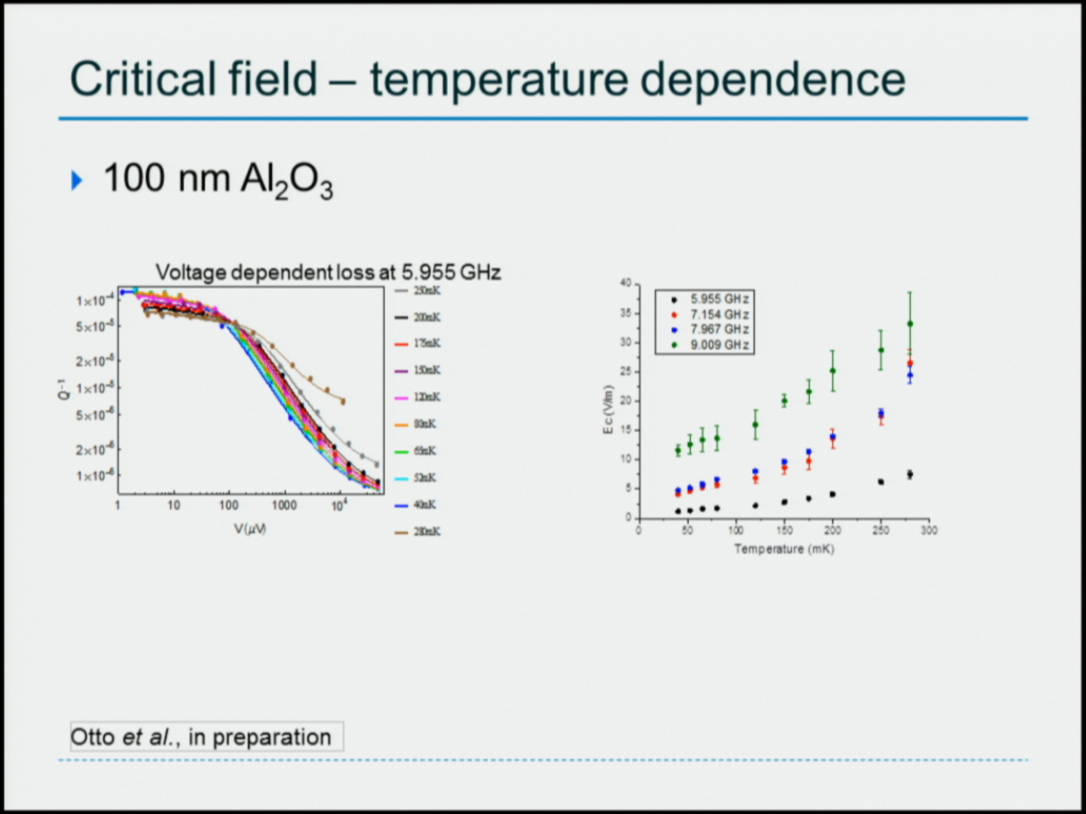


Critical field – temperature dependence

- 100 nm Al_2O_3

Otto *et al.*, in preparation



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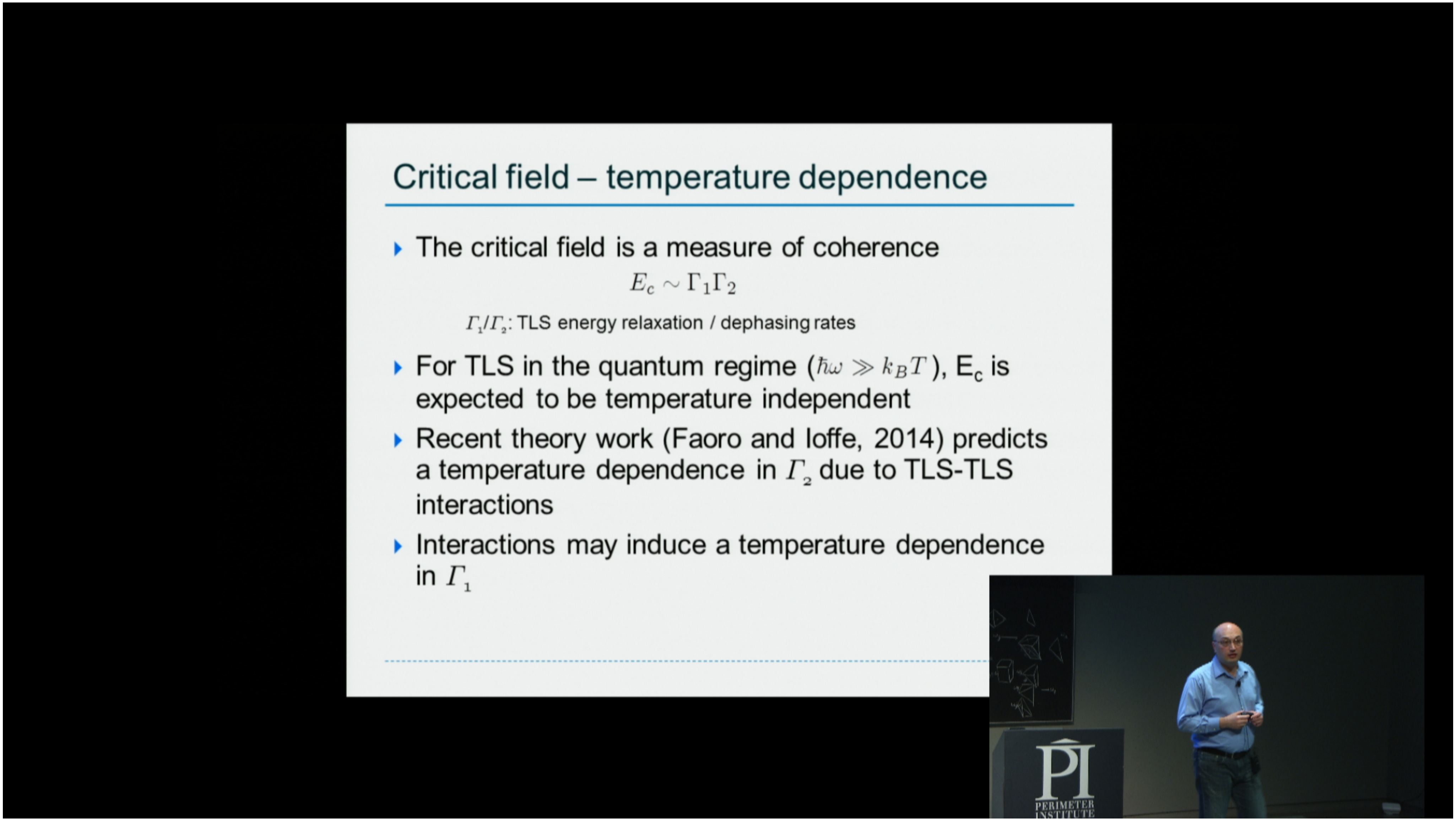


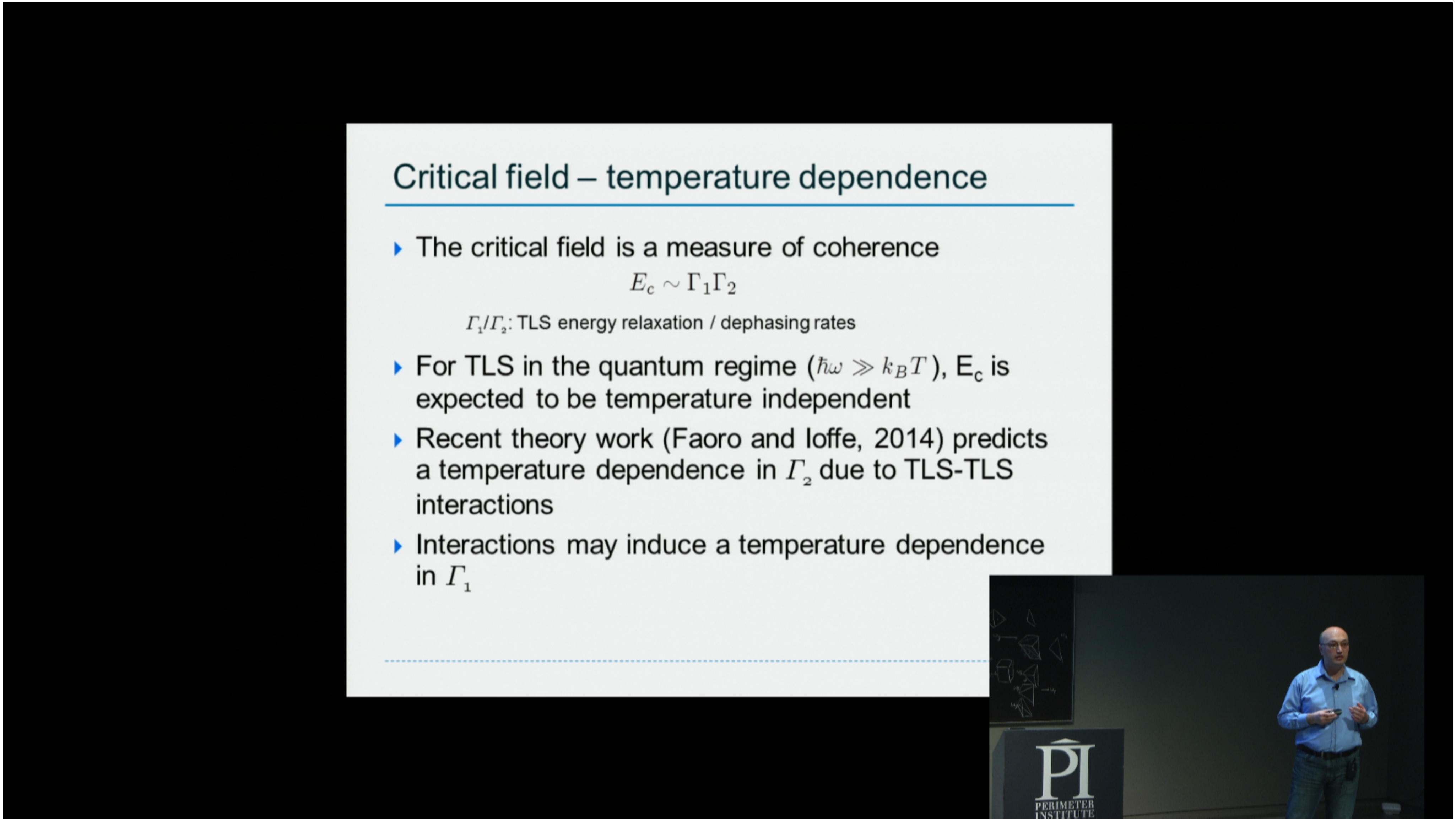
Critical field – temperature dependence

- The critical field is a measure of coherence

$$E_c \sim \Gamma_1 \Gamma_2$$

Γ_1/Γ_2: TLS energy relaxation / dephasing rates

- For TLS in the quantum regime ($\hbar\omega \gg k_B T$), E_c is expected to be temperature independent
- Recent theory work (Faoro and Ioffe, 2014) predicts a temperature dependence in Γ_2 due to TLS-TLS interactions
- Interactions may induce a temperature dependence in Γ_1



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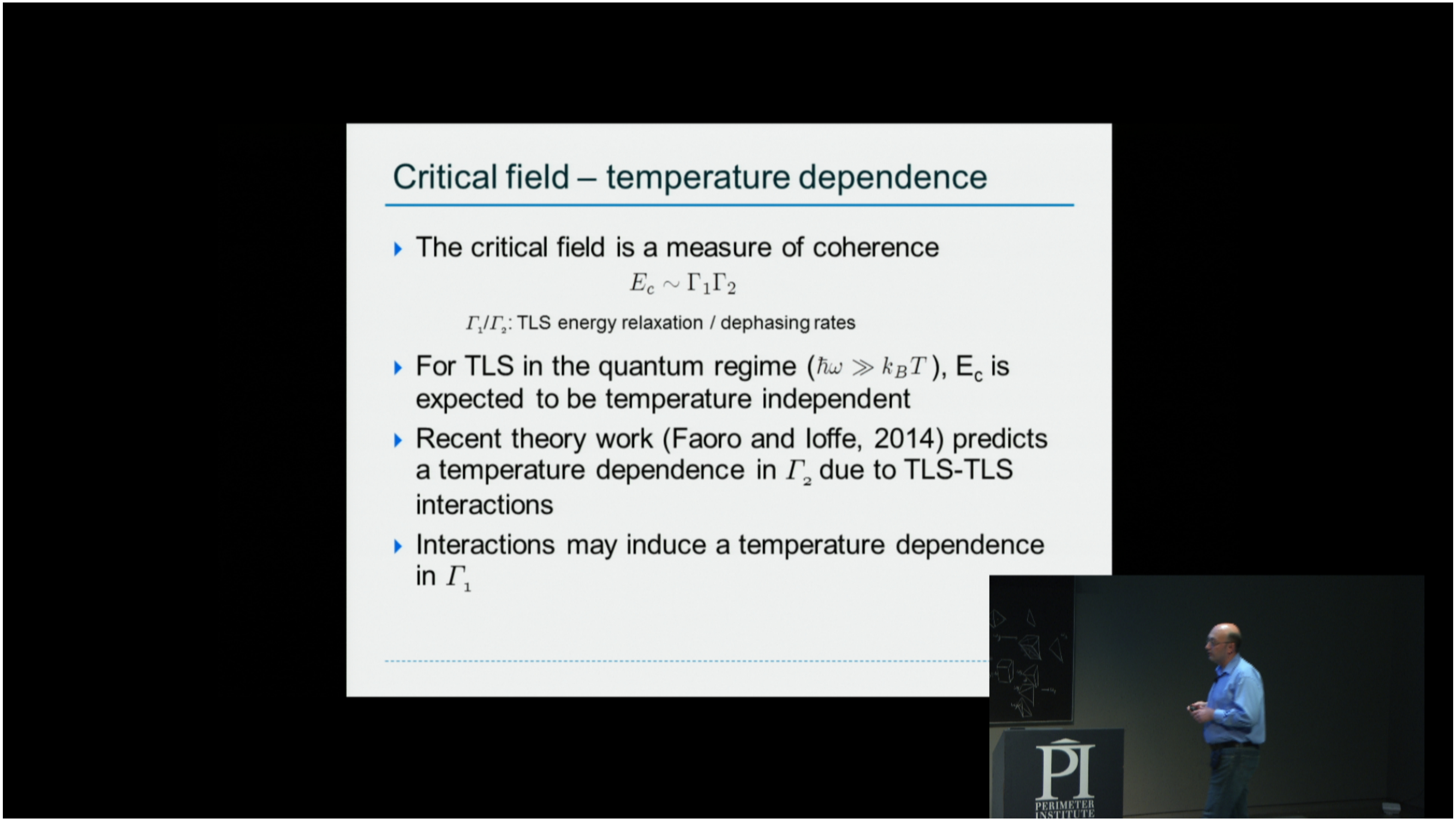

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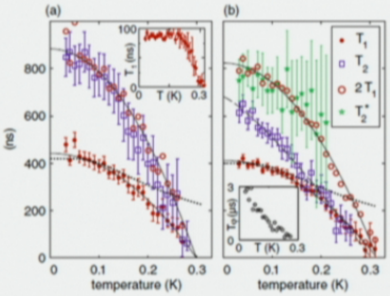
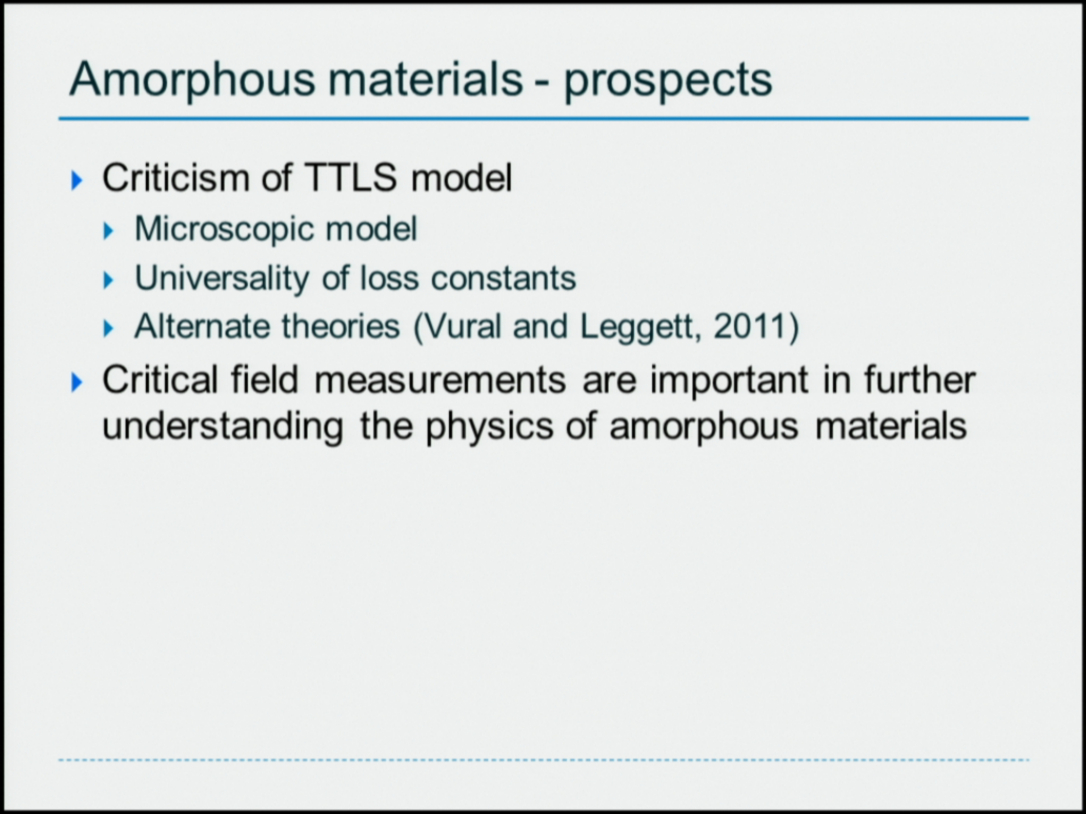
Measurements of TLS decohrence using qubits

- Measurements in thin AlOx layers



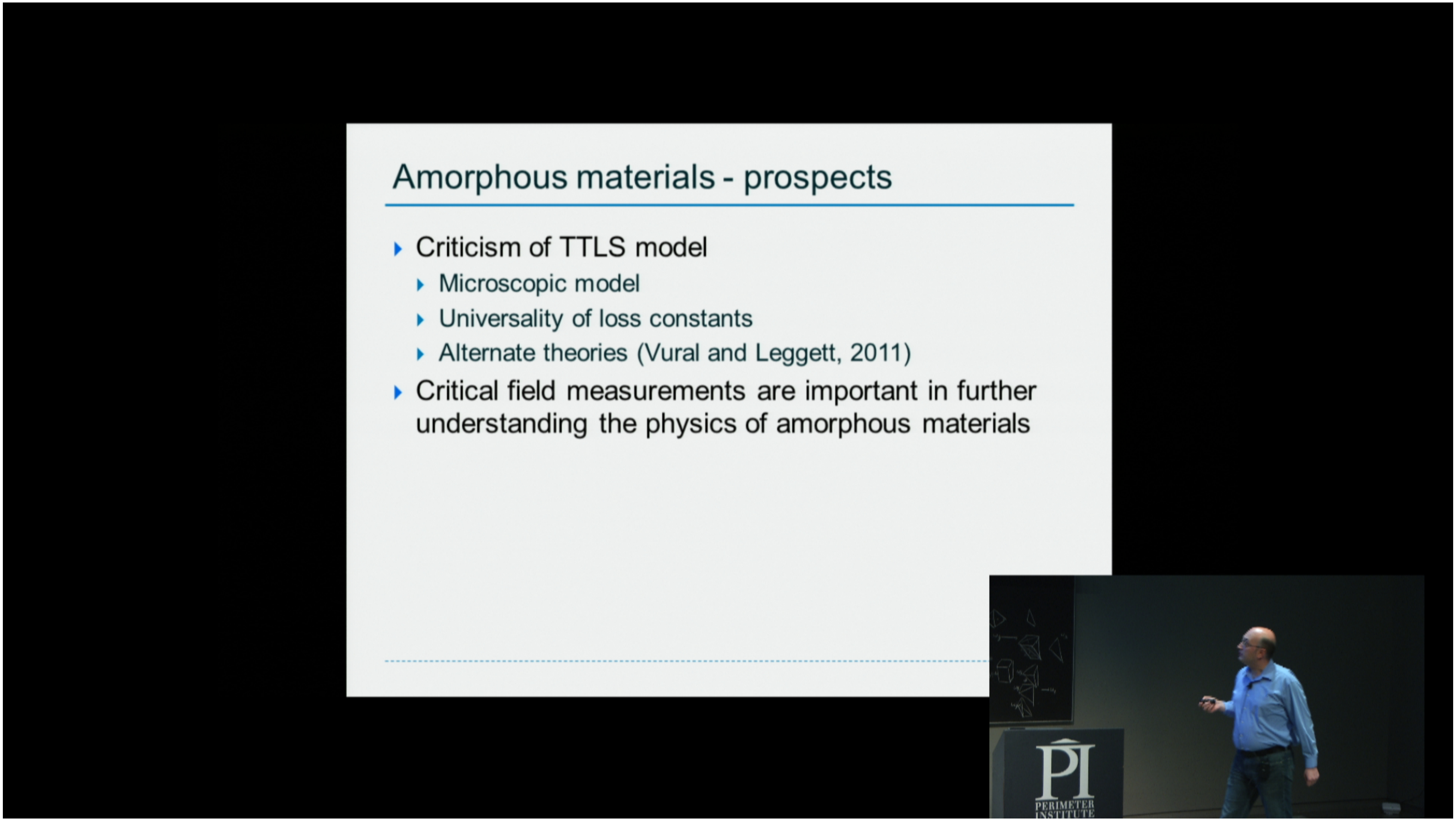
Lisenfeld et al, PRL 105, 230504 (2010).

- Temperature dependence is different of what we find (are measurements on individual TLSs biased?)



Amorphous materials - prospects

- Criticism of TTLS model
  - Microscopic model
  - Universality of loss constants
  - Alternate theories (Vural and Leggett, 2011)
- Critical field measurements are important in further understanding the physics of amorphous materials



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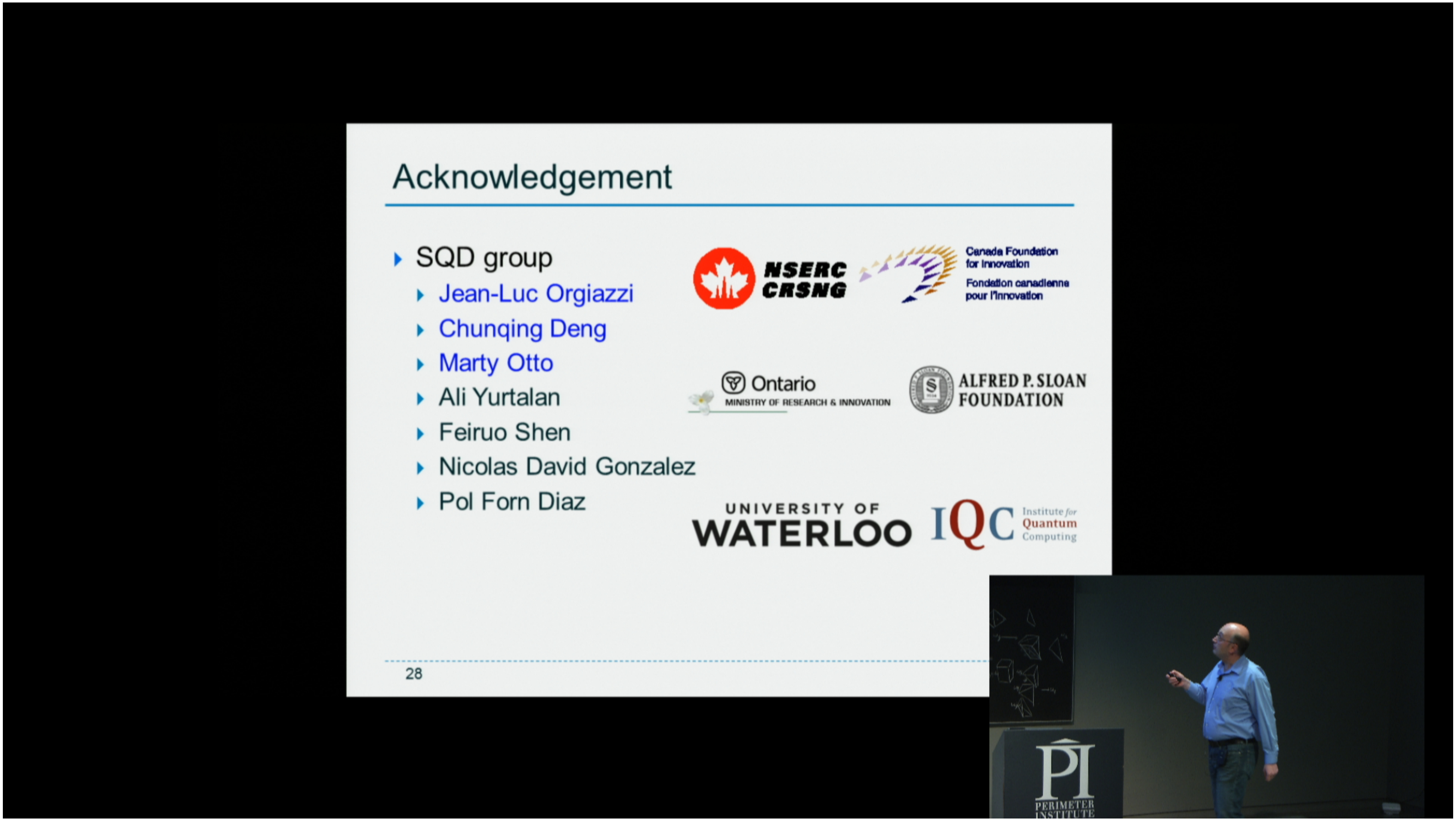

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