Title: Photon sensors

Speakers: Sae Woo Nam

Collection: School on Table-Top Experiments for Fundamental Physics

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Single Photon Detectors

Sae Woo Nam

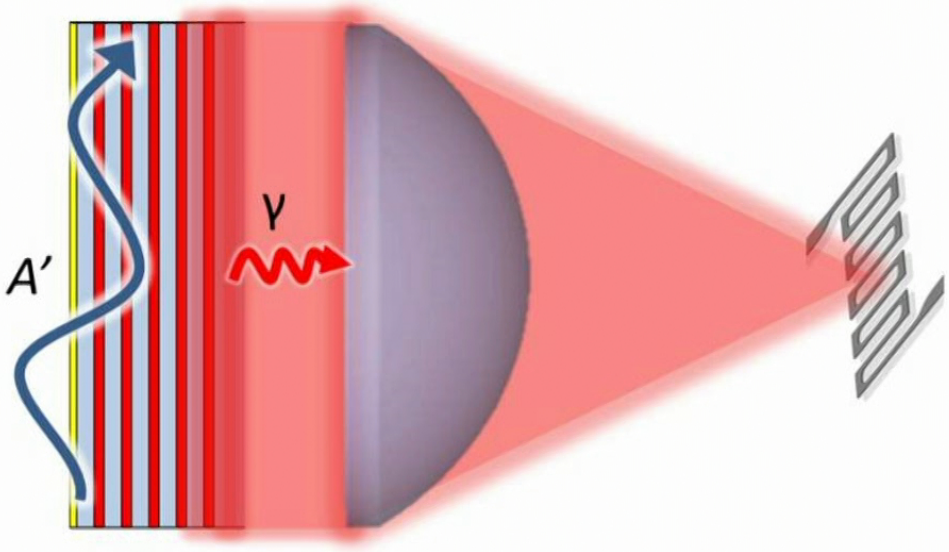
NIST - National Institute of Standards and Technology

Outline

- Lecture 2: Building LAMPOST
  - Cryogenics
  - Electronics
  - Optics
  - Detectors
  - Taking Data
  - What's next?
    - Veto backgrounds
    - Calibrations

LAMPOST: Dark Photons

- Absorb dark photon, convert to standard photon



- Requirements for Photon Detector:
  - Very low dark counts (false positives)
- Cryogenic Detectors:
  - SNSPD vs TES
  - SNSPD is simpler to use

Cryogenics / Cryostat

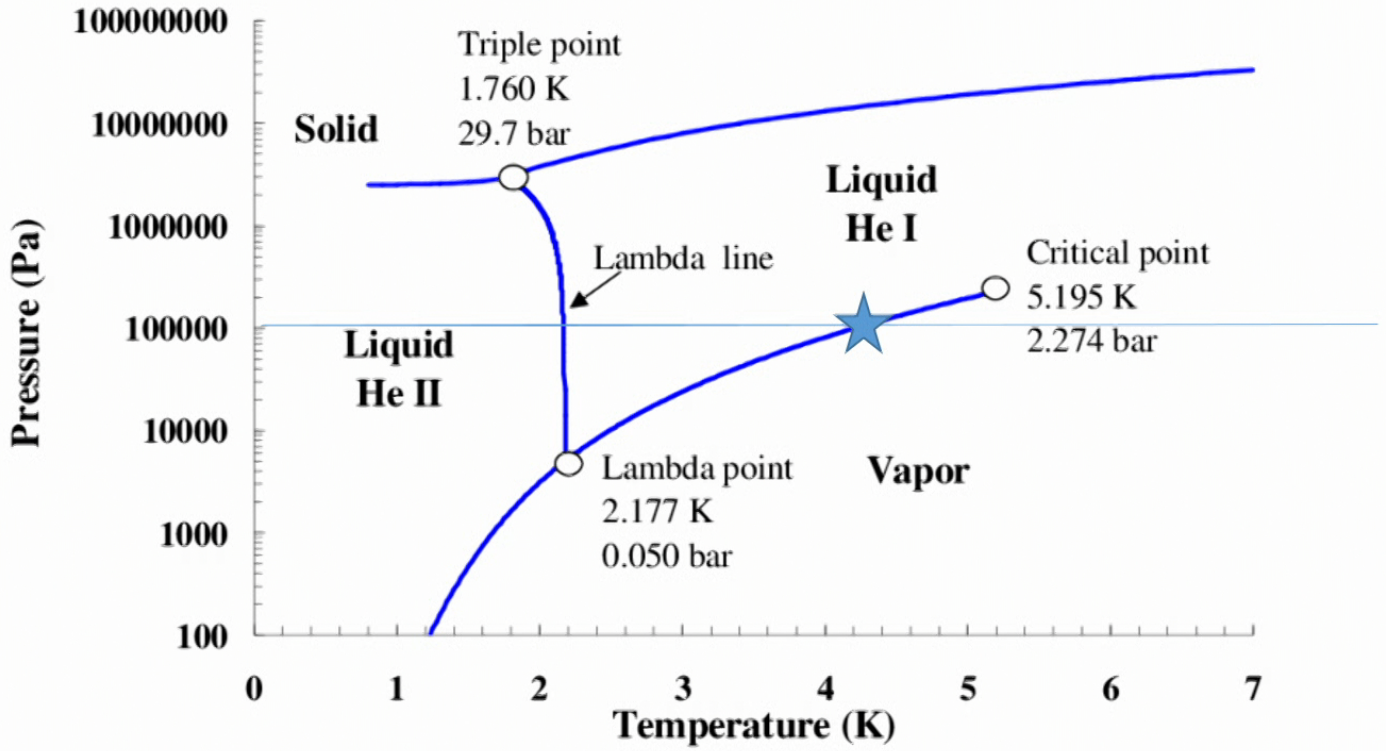
- Temperature as cold as possible, but easy to maintain
  - Target: 300 mK
- How do you get cold? …. Thermodynamic Properties
- How do you create an environment that holds cold stuff? …Mechanical Engineering
  - Sources of Heat
  - Materials

Properties of Gases

Cryogen	Triple point [K]	Normal boiling point [K]	Critical point [K]
Methane	90.7	111.6	190.5
Oxygen	54.4	90.2	154.6
Argon	83.8	87.3	150.9
Nitrogen	63.1	77.3	126.2
Neon	24.6	27.1	44.4
Hydrogen	13.8	20.4	33.2
Helium	2.2 (*)	4.2	5.2

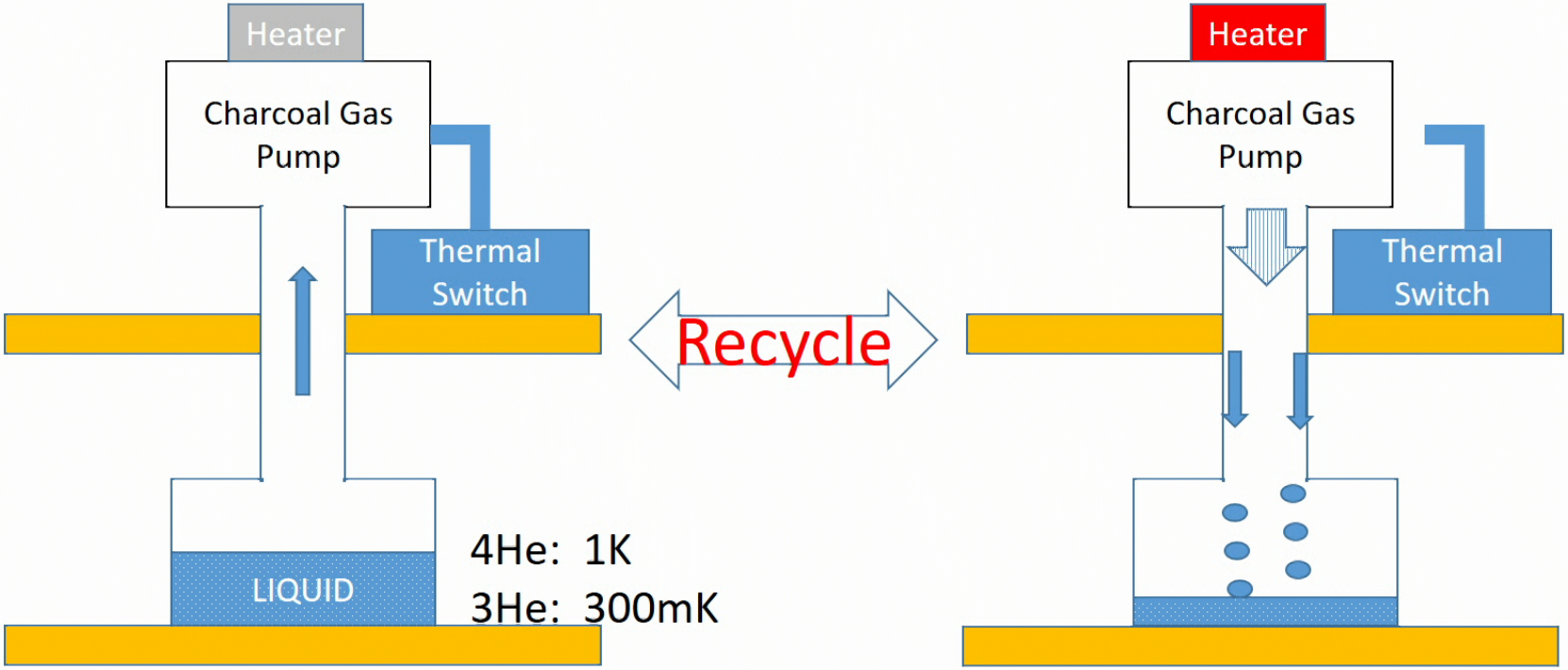
Slide 1 (semanticscholar.org)

Helium-4 Phase diagram

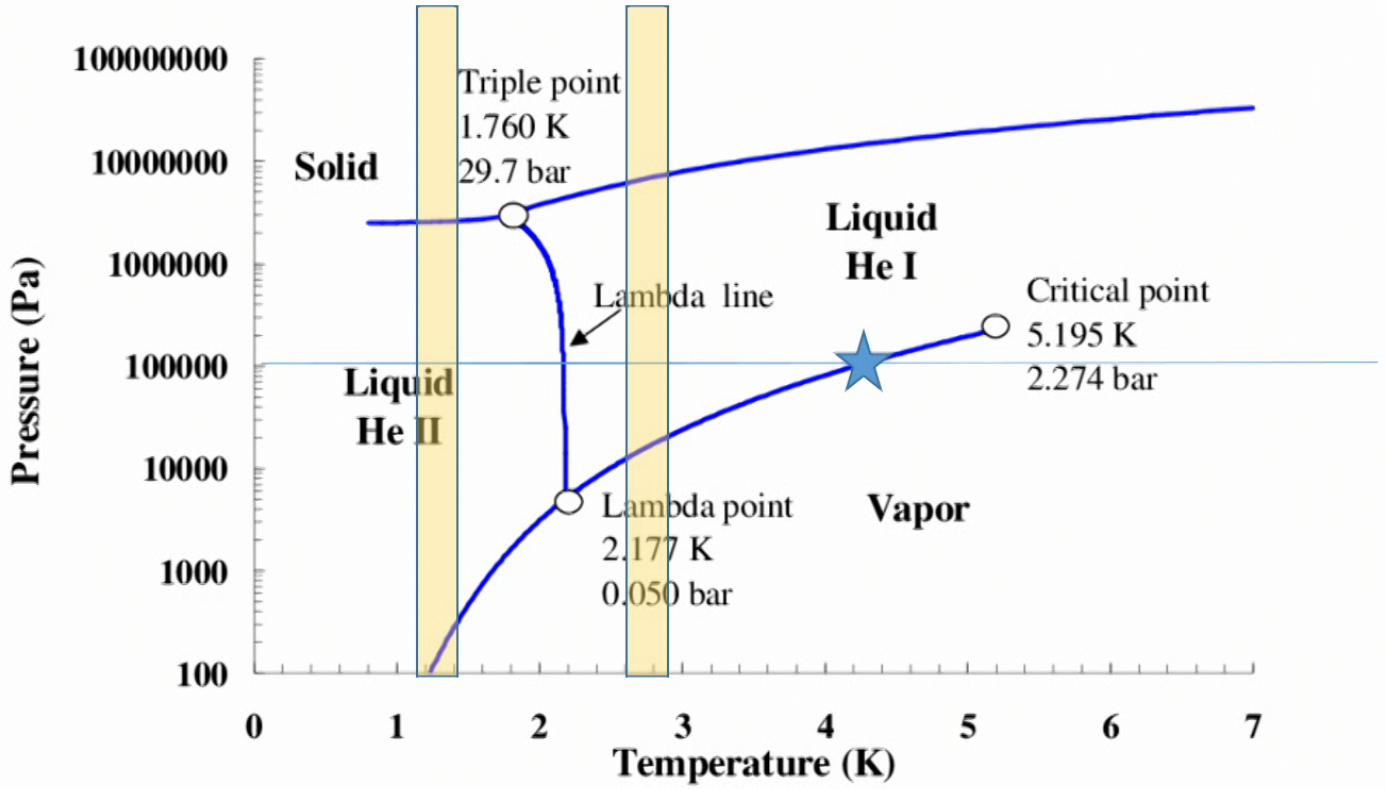


1: Phase diagram of 4 He | Download High-Resolution Scientific Diagram (researchgate.net)

Pumped (Evaporative) Helium cooling: Latent Heat of Vaporization

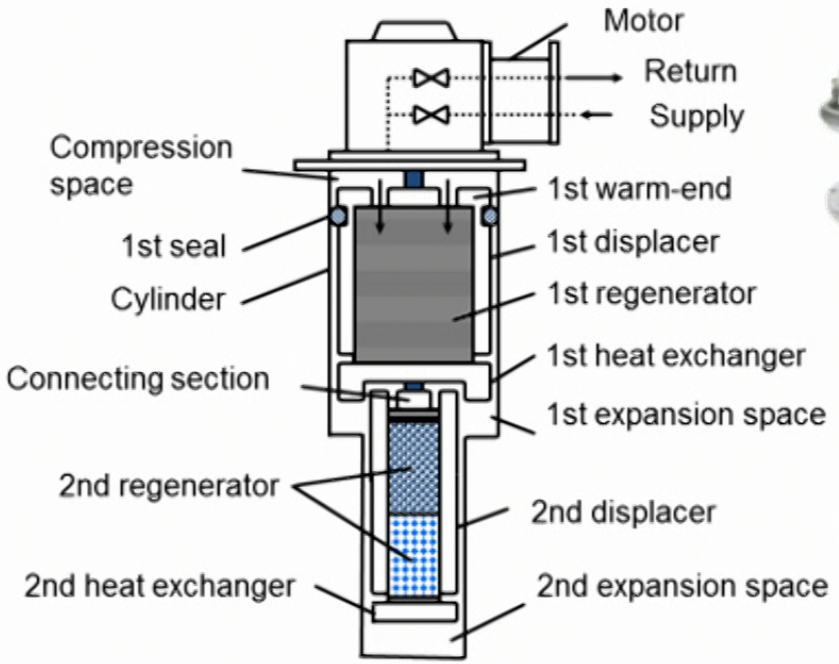


Helium-4 Phase diagram



1: Phase diagram of 4 He | Download High-Resolution Scientific Diagram (researchgate.net)

Gifford-McMahon Cooler



Cooling Power Specifications

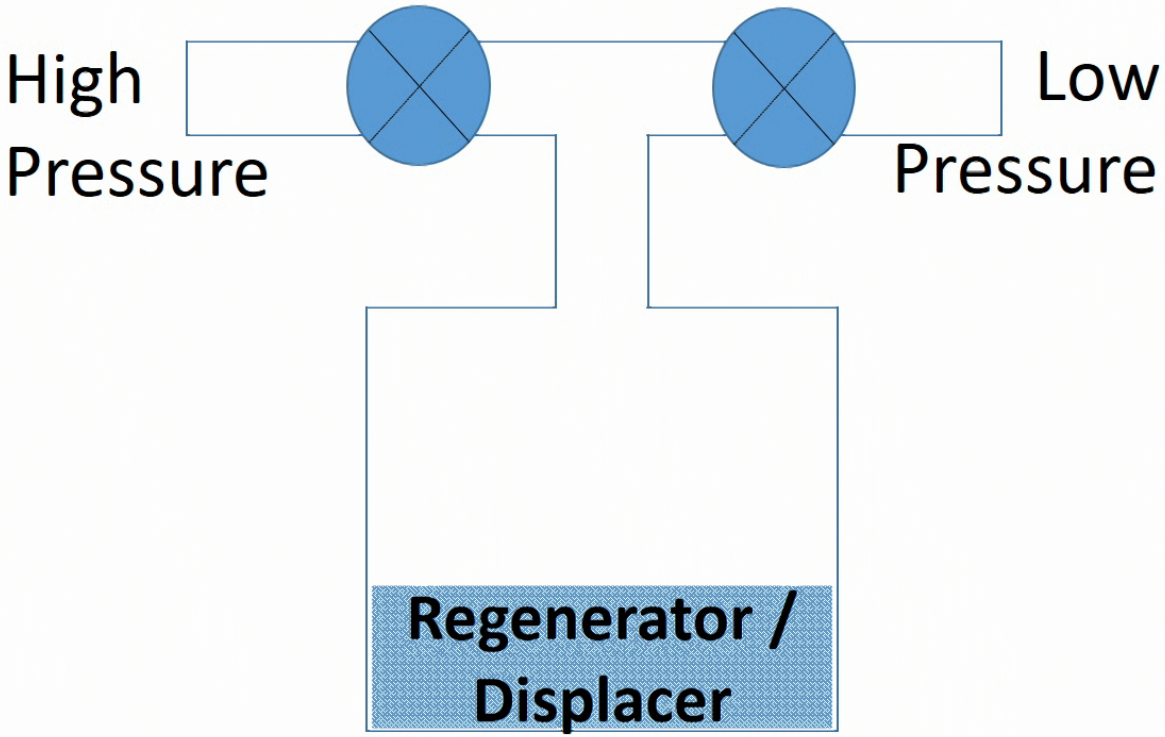
@60K: 5 Watts

@4.2K: 100mW

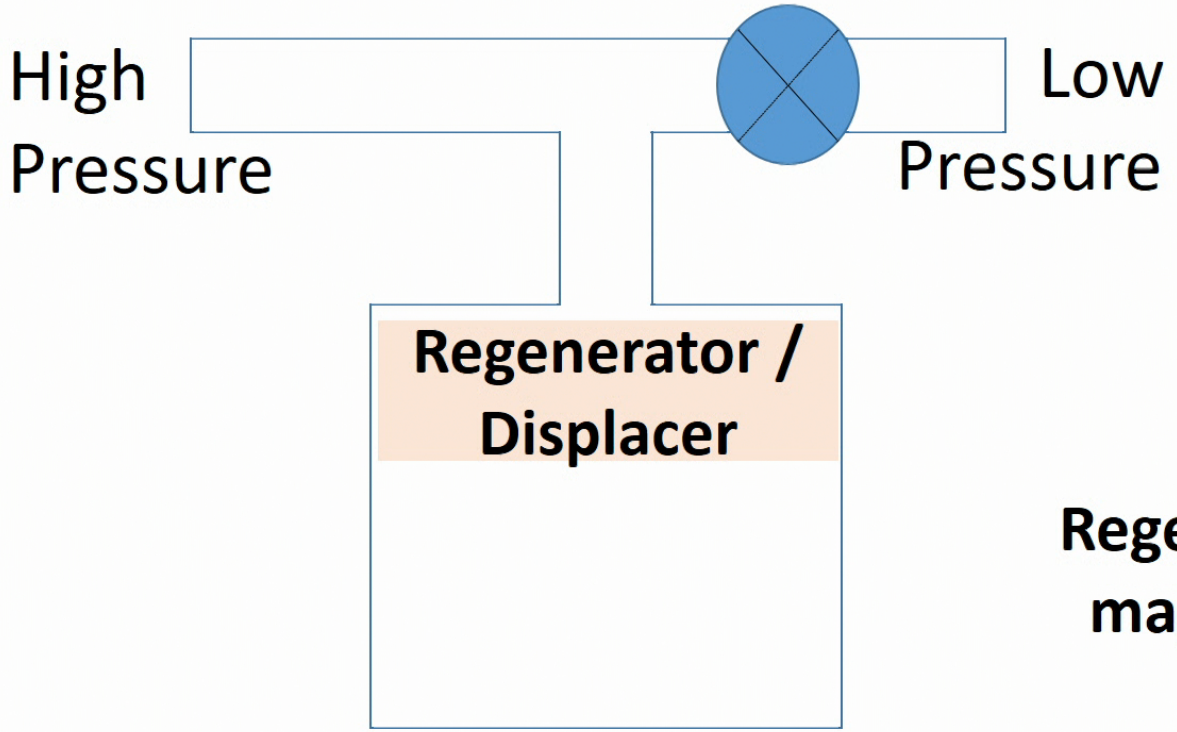
Requires a Helium compressor (1.5kW)

•IOP Conference Series Materials Science and Engineering 101(1):012136

GM-cooling (simple pictures):

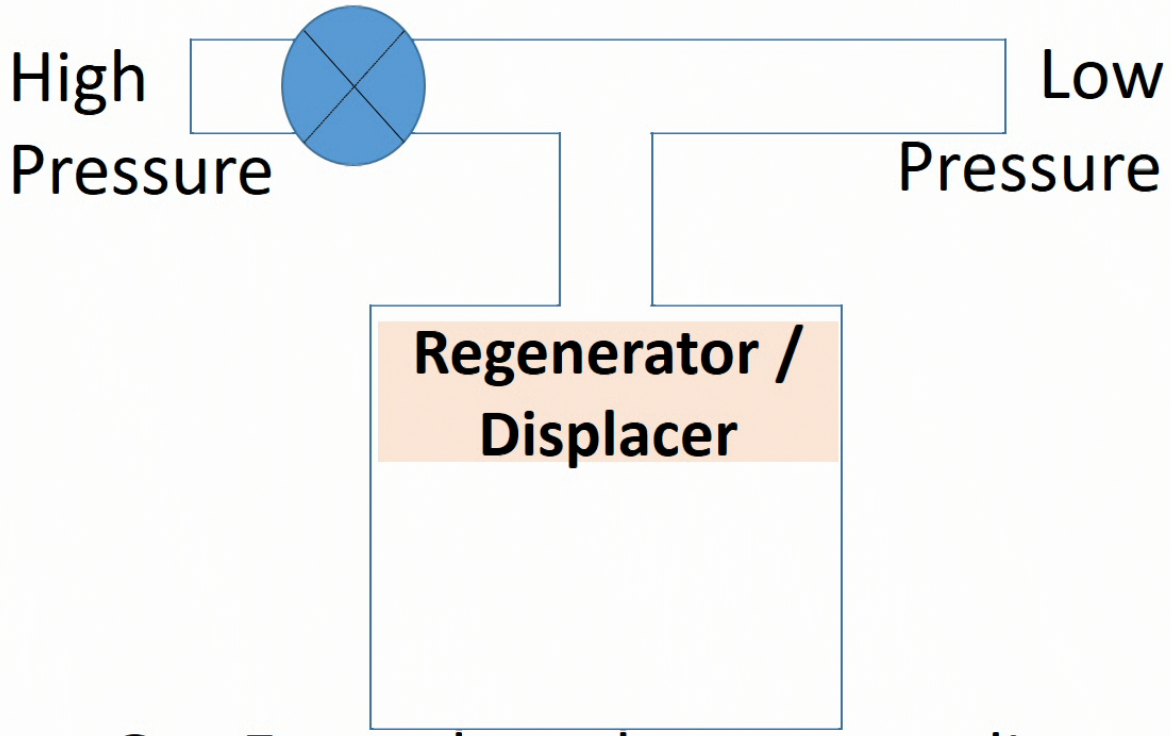


GM-cooling (simple pictures):



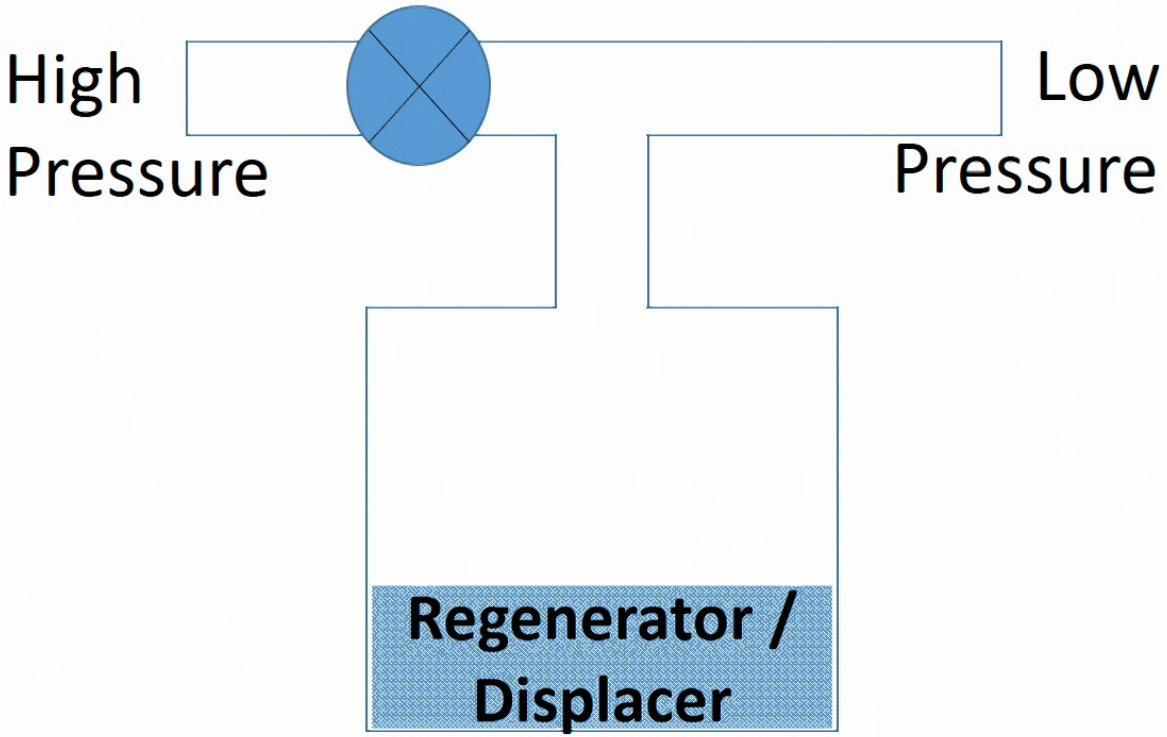
Regenerator is magic to me

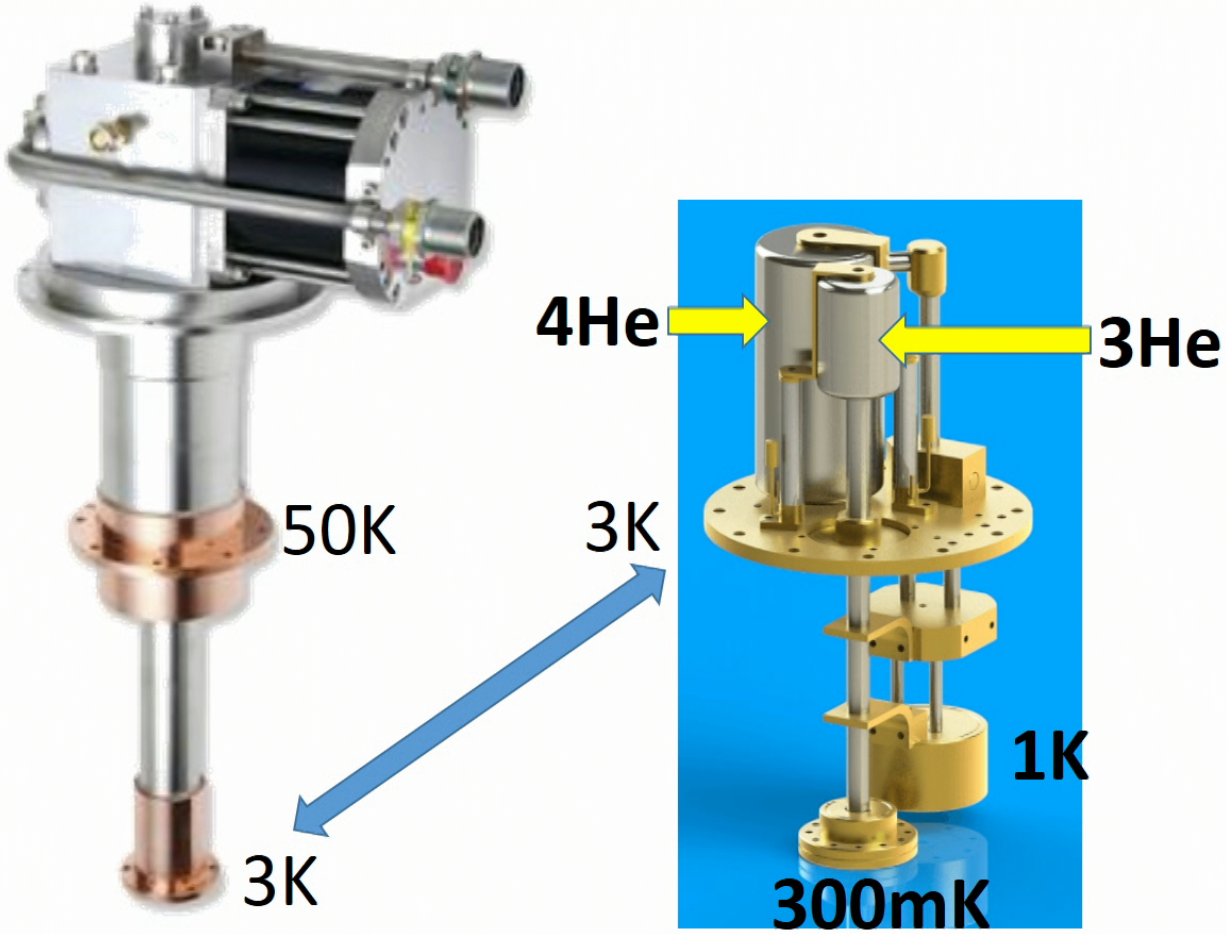
GM-cooling (simple pictures):



Gas Expands and we get cooling

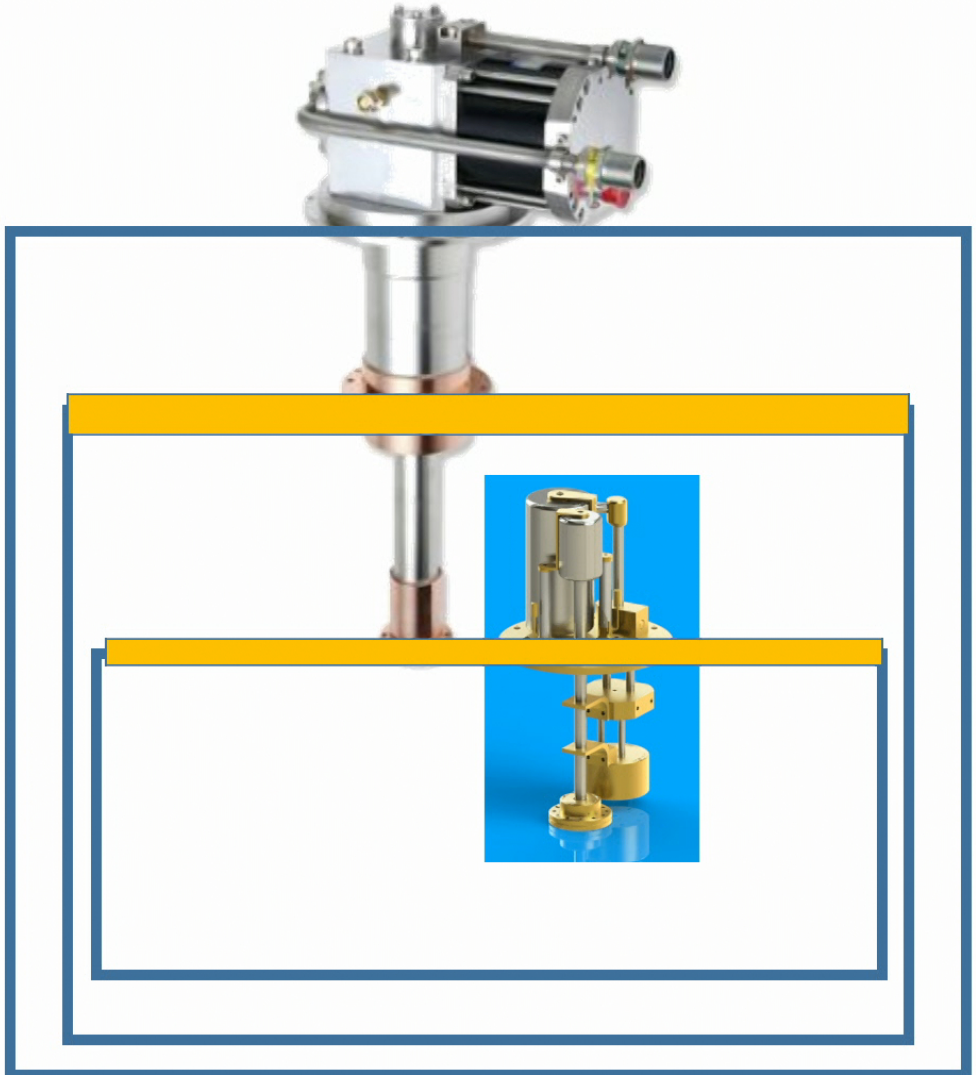
GM-cooling (simple pictures):

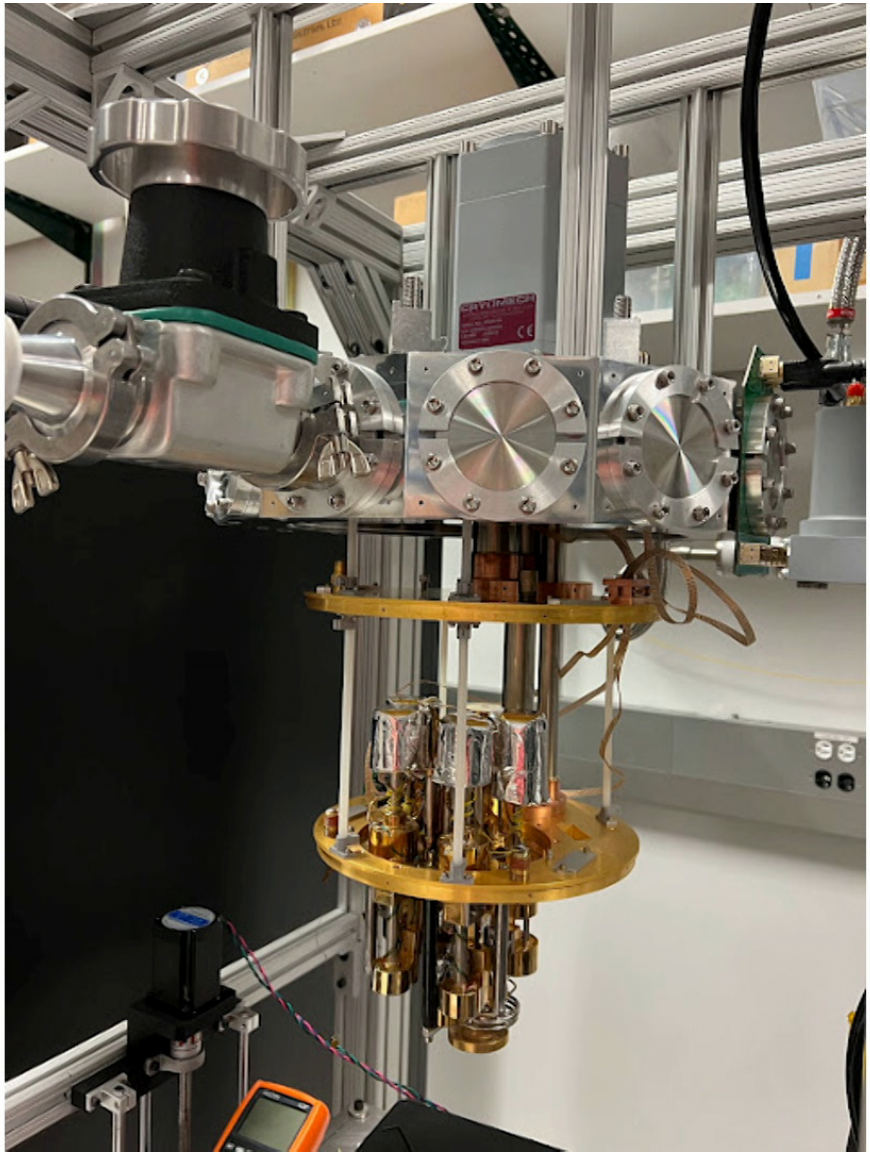


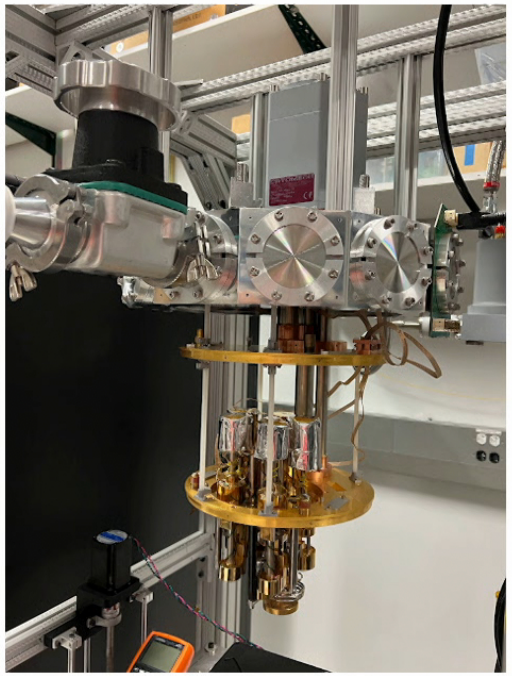

4He
3He
50K
3K
3K
1K
300mK

How do you hold the refrigeration together?

- We do not have infinite cooling power….
  - Reduce sources of heat as much as possible
    - Vacuum
    - Radiation
    - Thermal conduction (materials we can use)







Fits in a standard instrumentation rack

How do we know the temperature?

- 300K to 2K…. Diode thermometers
- 1K and lower: Resistive therometers
- How much heat does wiring add?
  - We can estimate using Fourier's Law and Wiedemann-Franz Law

$$\dot{Q} = -k(T)A\nabla T$$

$$k(T) = \mathcal{L}T\sigma = \frac{\mathcal{L}T}{\rho} \qquad \mathcal{L} = 24.4\frac{nW\Omega}{K^2}$$

Heatload from a wire

$$\dot{Q} = -k(T)A\nabla T$$

$$k(T) = \mathcal{L}T\sigma = \frac{\mathcal{L}T}{\rho}$$

$$\dot{Q} = -\mathcal{L}T\frac{A}{\rho}\frac{dT}{dx}$$

$$\int_0^l \dot{Q}dx = -\int_{T_{hot}}^{T_{cold}} \mathcal{L}T\frac{A}{\rho}\frac{dT}{dx}$$

Assume resistance is not Temperature dependent

$$\dot{Q}l = \mathcal{L}\frac{A}{\rho}\int_{T_{cold}}^{T_{hot}} T\frac{dT}{dx}$$

$$\dot{Q} = \mathcal{L}\frac{A}{\rho l}\frac{T_{hot}^2 - T_{cold}^2}{2}$$

$$\dot{Q} = \mathcal{L}\frac{T_{hot}^2 - T_{cold}^2}{2R}$$

Heatload from a wire

$$\dot{Q} = \mathcal{L}\frac{T_{hot}^2 - T_{cold}^2}{2R}$$

T_hot = 300K, T_cold = 50K, R=1
Heatload = 24.4 nW * 300^2 = 2.2 mW

T_hot = 50K, T_cold = 4K, R=1
Heatload = 24.4nW * 50^2 = 61 μW

Measuring Temperature:

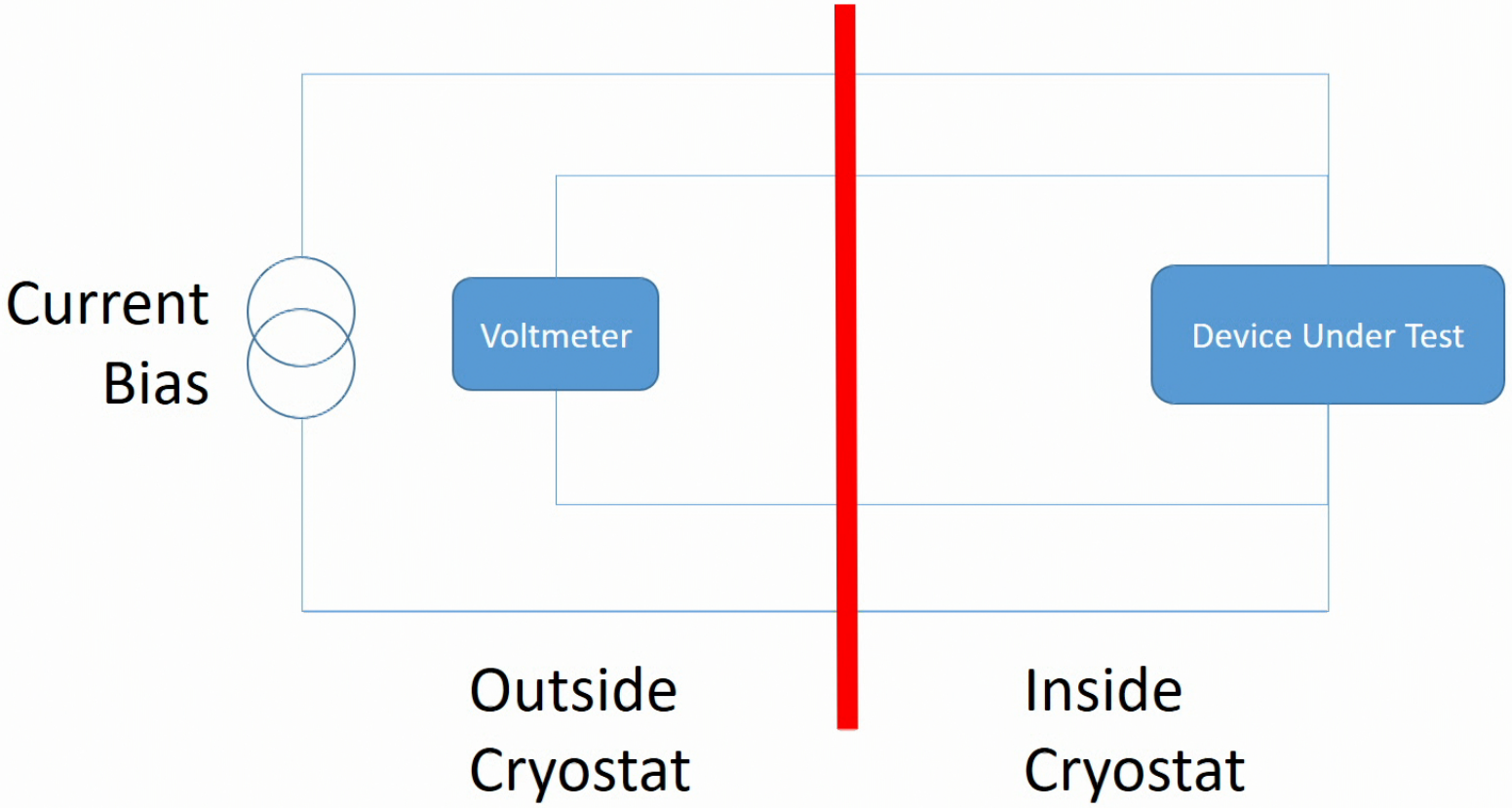
- Diodes:
  - Bias at a fixed current, measure voltage…

$$I_D = I_o\left(e^{\frac{qV_D}{nkT}} - 1\right)$$

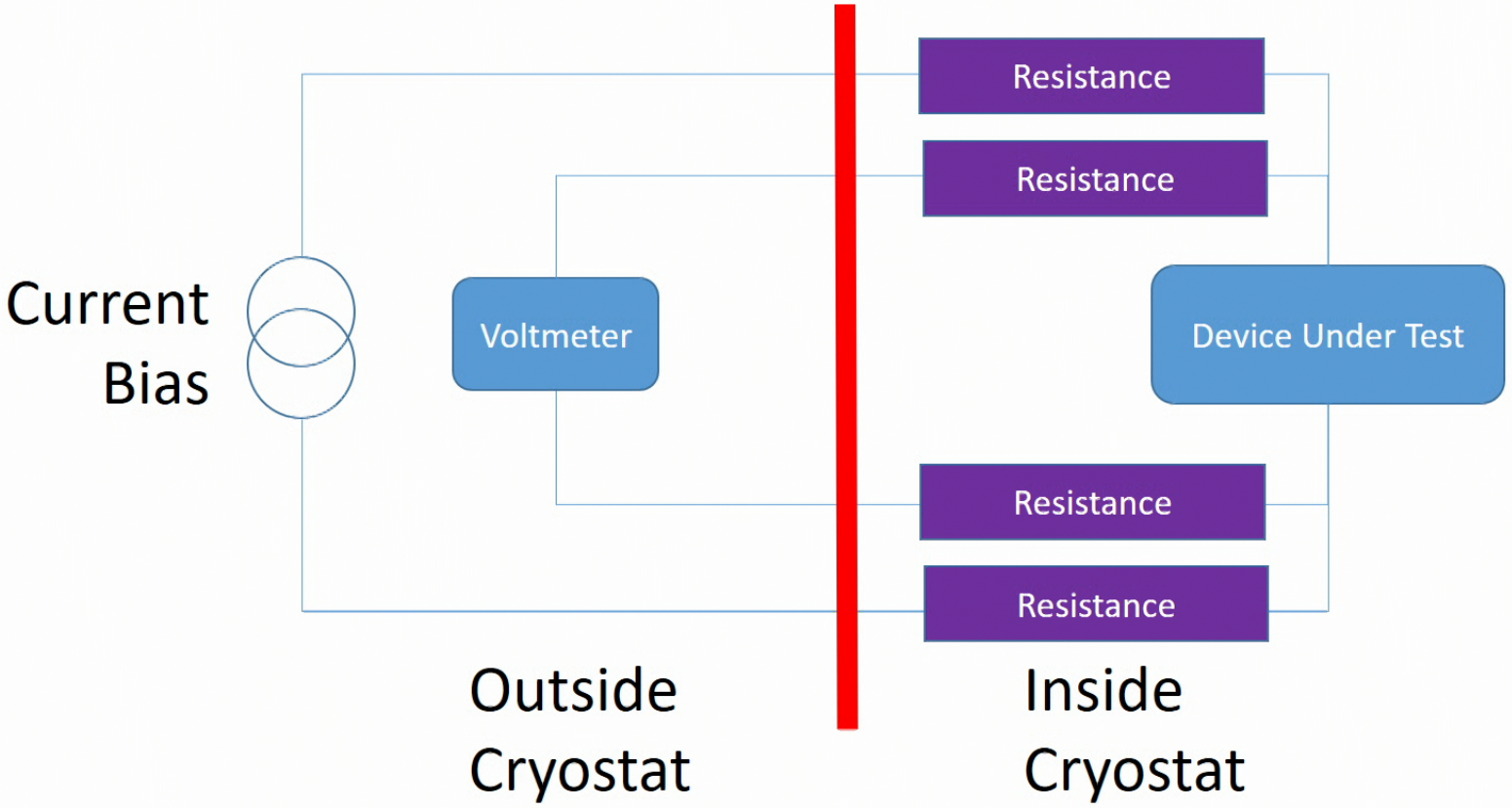
- Resistors:
  - Temperature dependence

- Four wire technique:
  - Why?

Four-Wire measurements

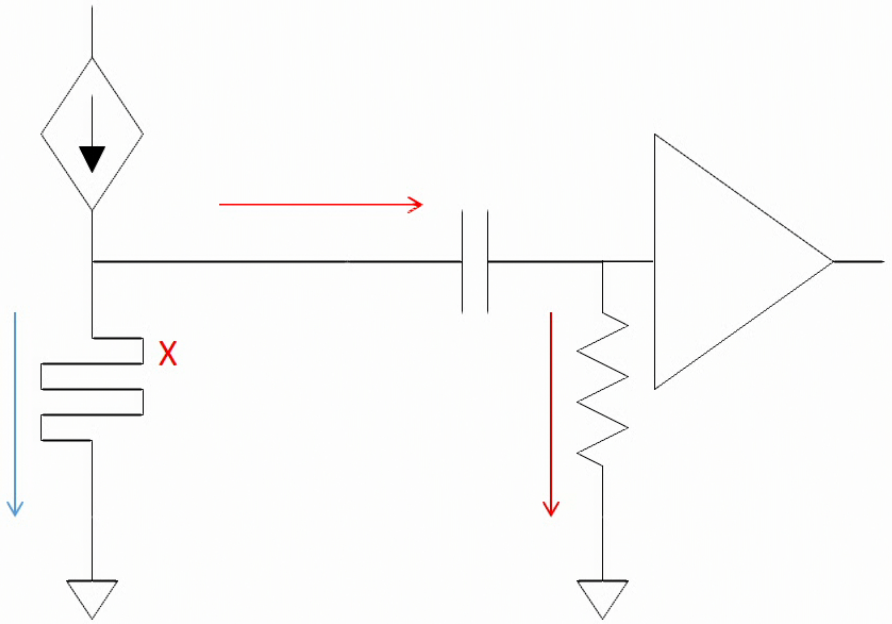


Four-Wire measurements



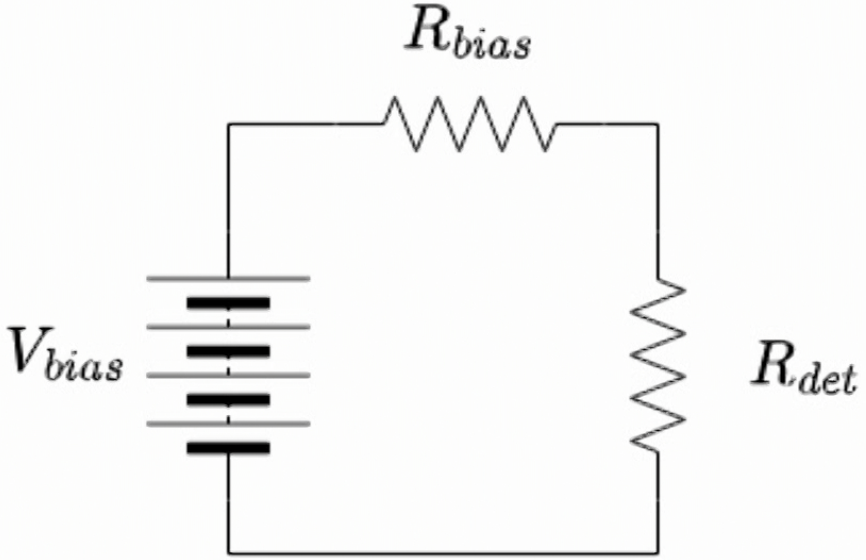
Detector Electronics

- Detector Bias
- RF-amplifier



Current Bias:

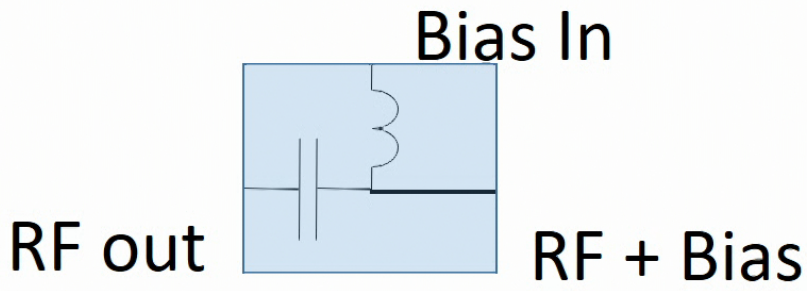
- KISS
- Simple and approximate



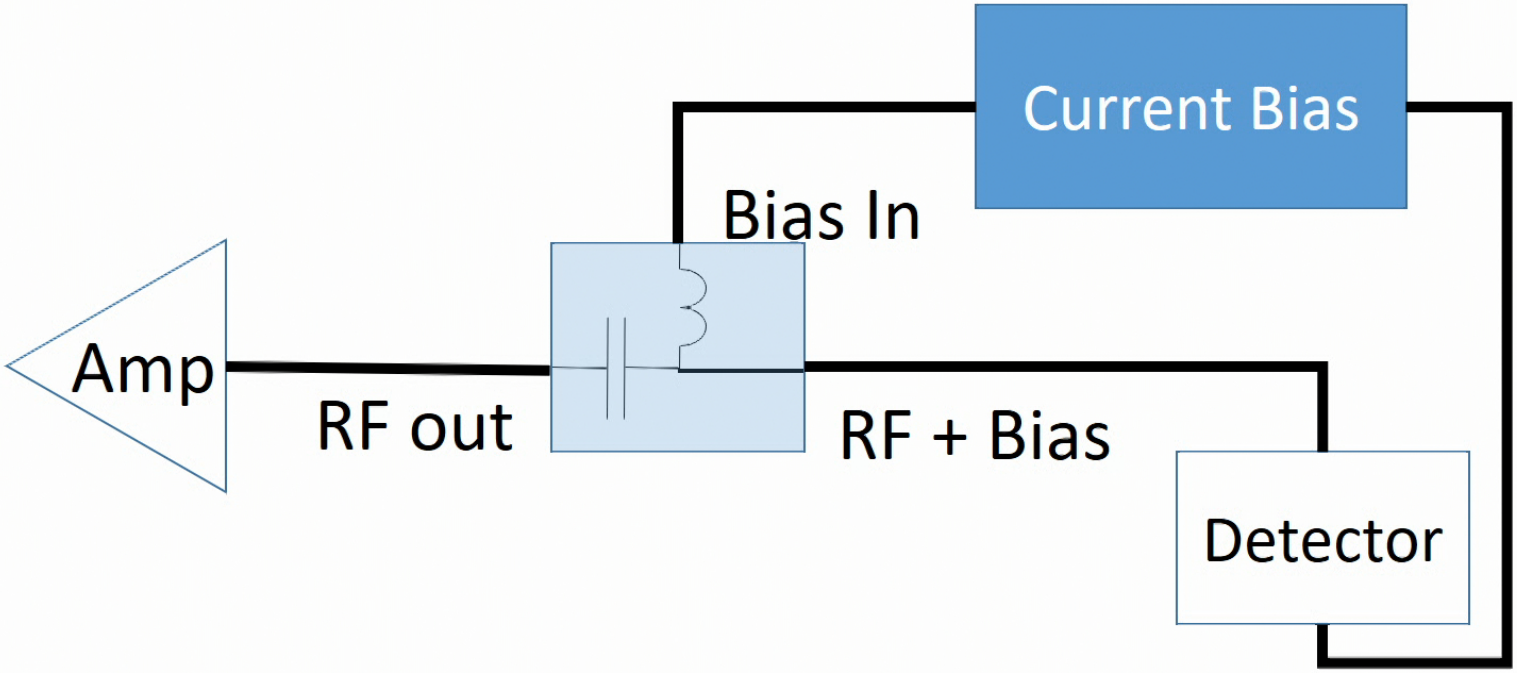
$$I_{bias} = \frac{V_{bias}}{R_{bias} + R_{det}} = \frac{V_{bias}}{R_{bias}(1 + \frac{R_{bias}}{R_{det}})}$$

Bias + signal from the detector:

- “BIAS TEE”
- Three Terminal device



More complete circuit for the detector

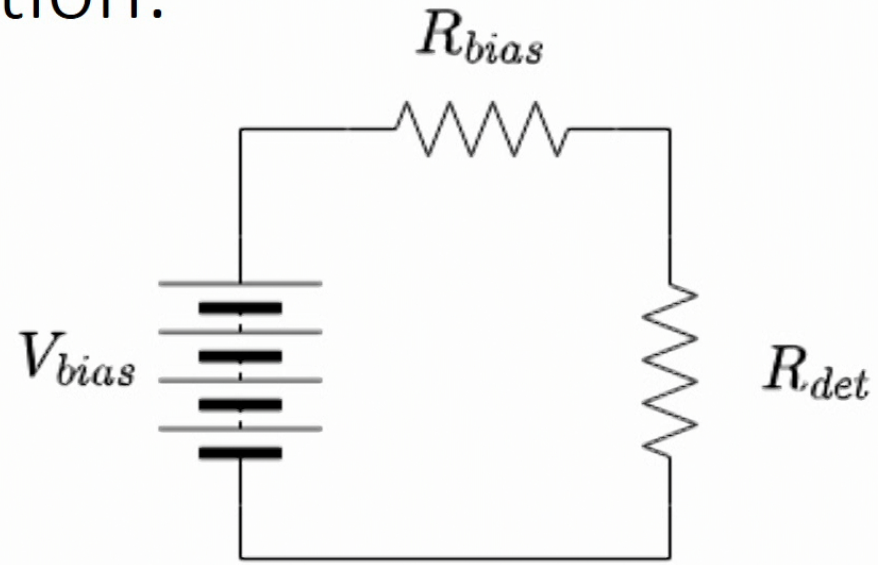


How much current noise comes from the bias circuit?

- We don’t live in an environment where the temperature = 0.
- We need a few microamps of current to bias the nanowire detector.
  - The current source will introduce noise/fluctuations in the bias current.
  - How much will this fluctuation be?

Need more information:

- Vbias noise ~ 10nV/rtHz
- Bias Tee filters the noise
  - Bandwidth = 100kHz
- R_bias ~ 100 kOhm



Comments about Noise

- Noise is unpredictable in amplitude and phase
- “60Hz” pickup… => not “random noise”
- Random noise:
  - Quantify by looking at the < noise^2 > because <noise> = 0

$$\left\langle n^2 \right\rangle = \frac{1}{T}\int_0^T n(t)^2 dt$$

- Parseval’s Theorem:

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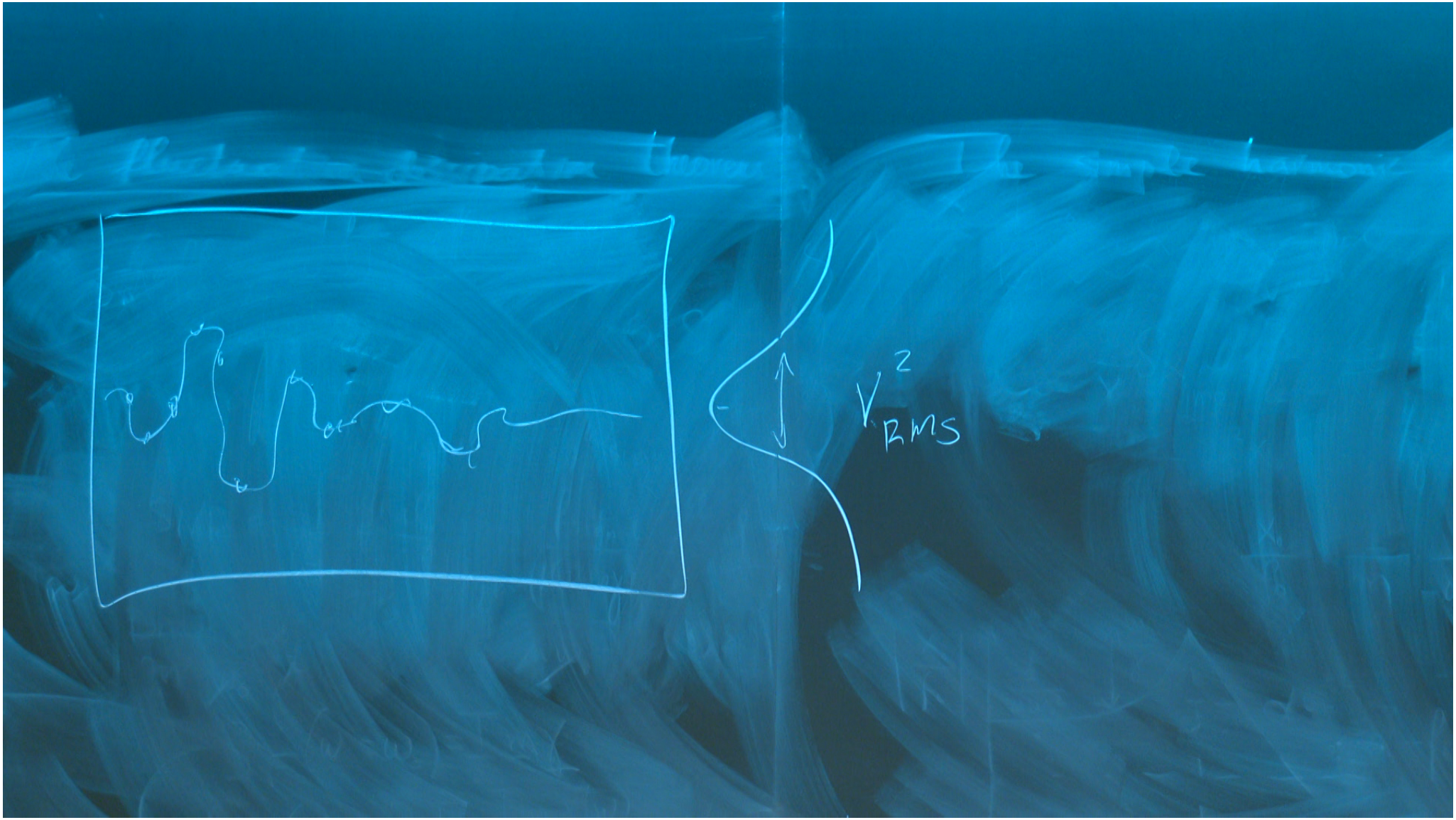
V_{RMS}^2

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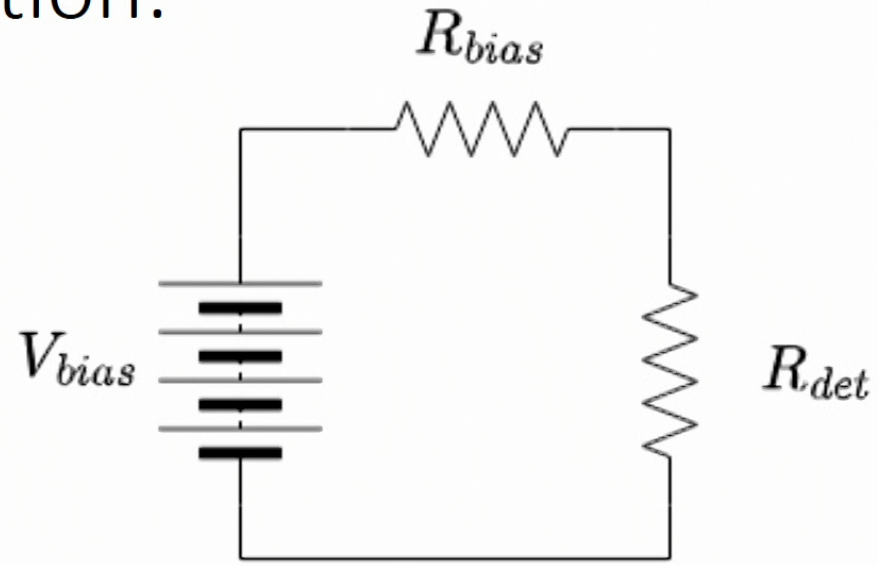
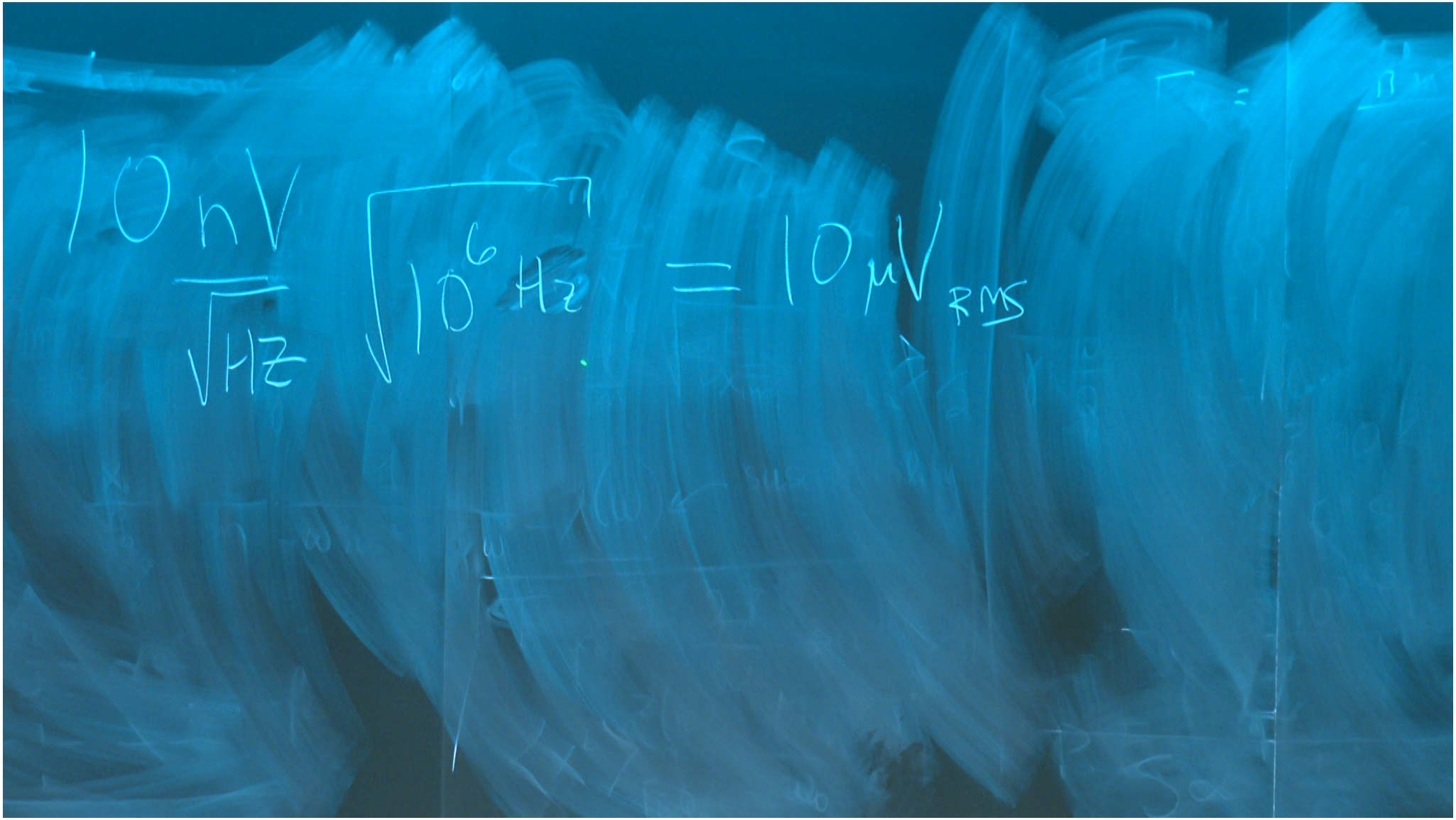
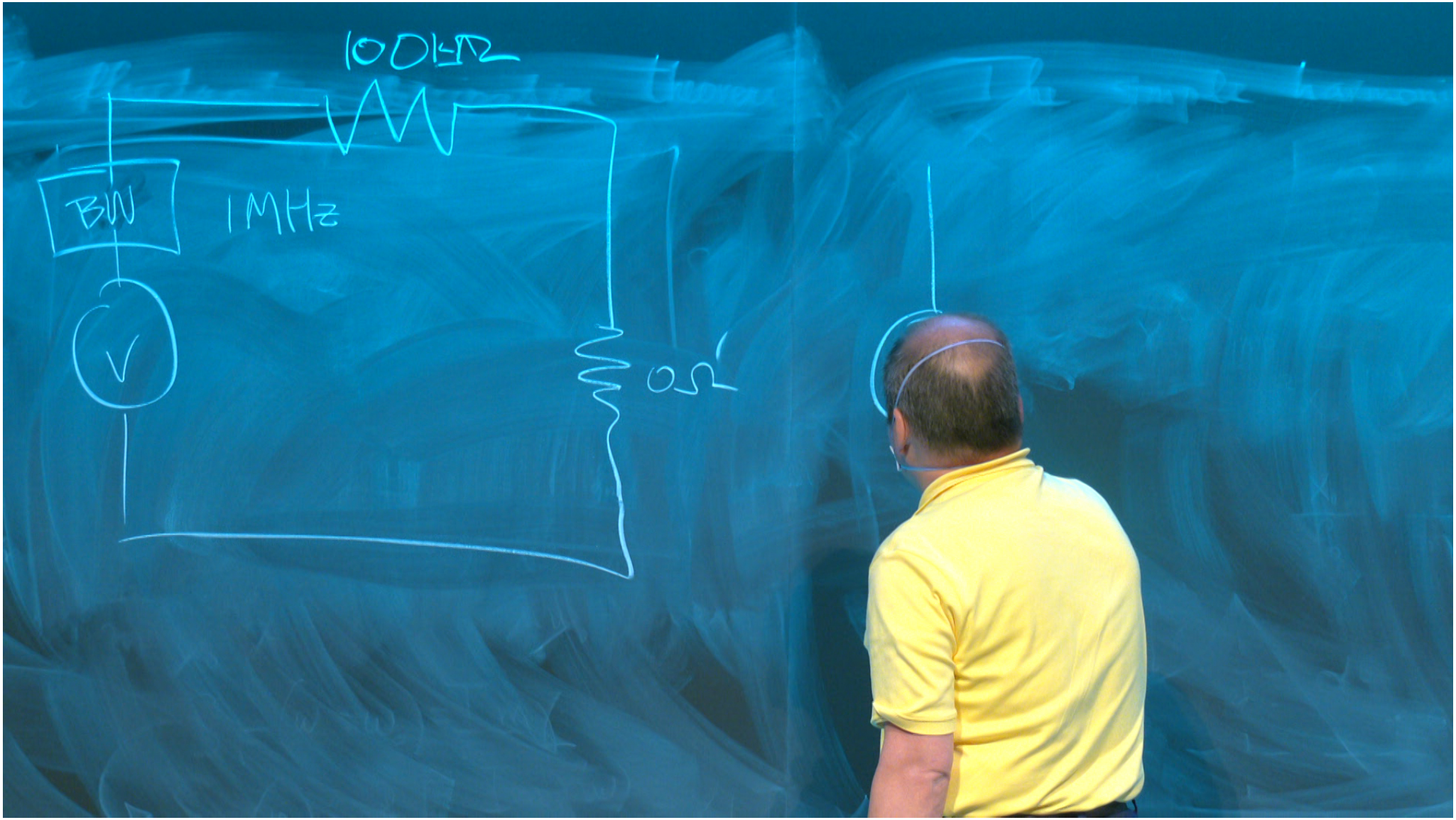
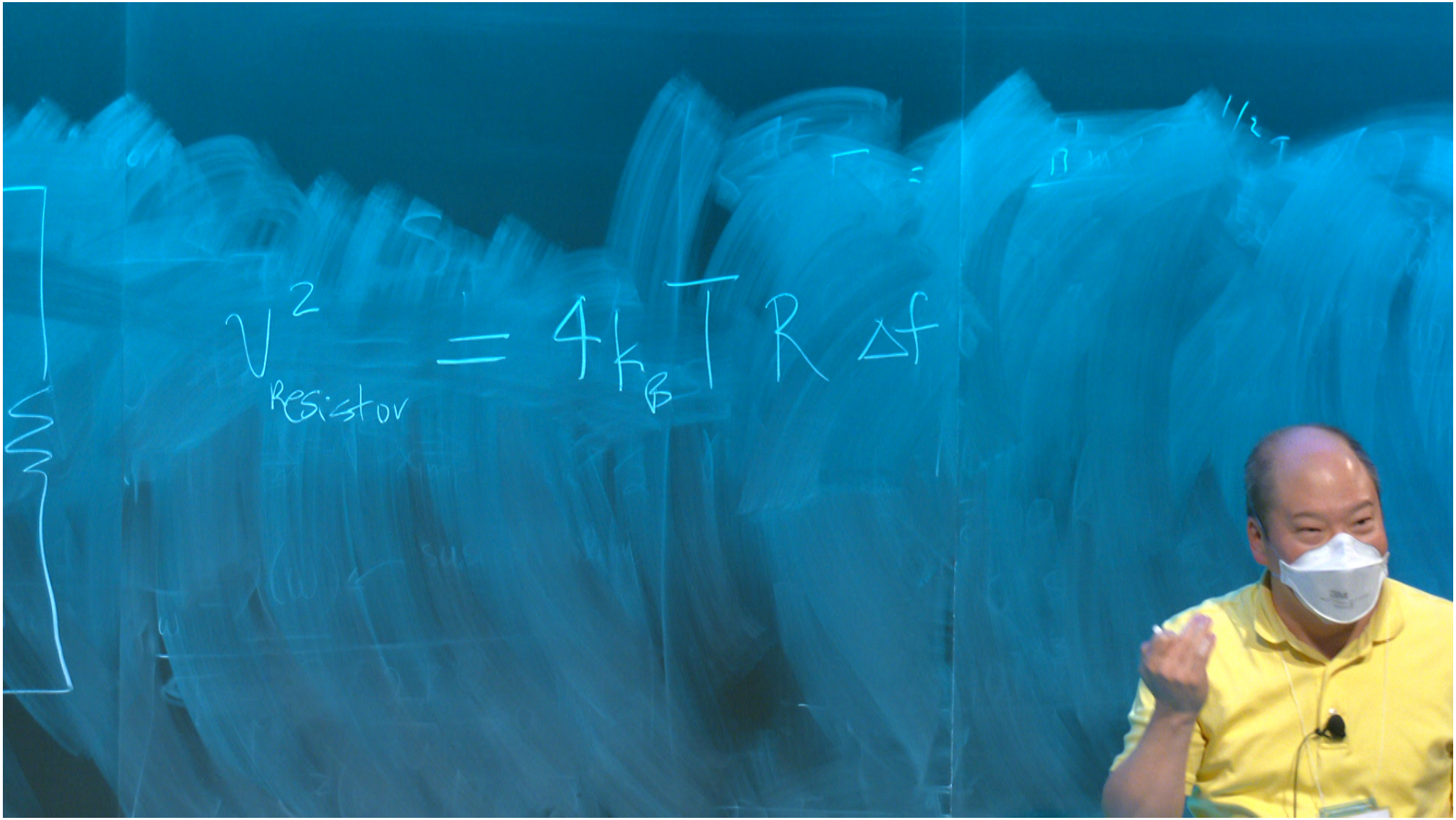


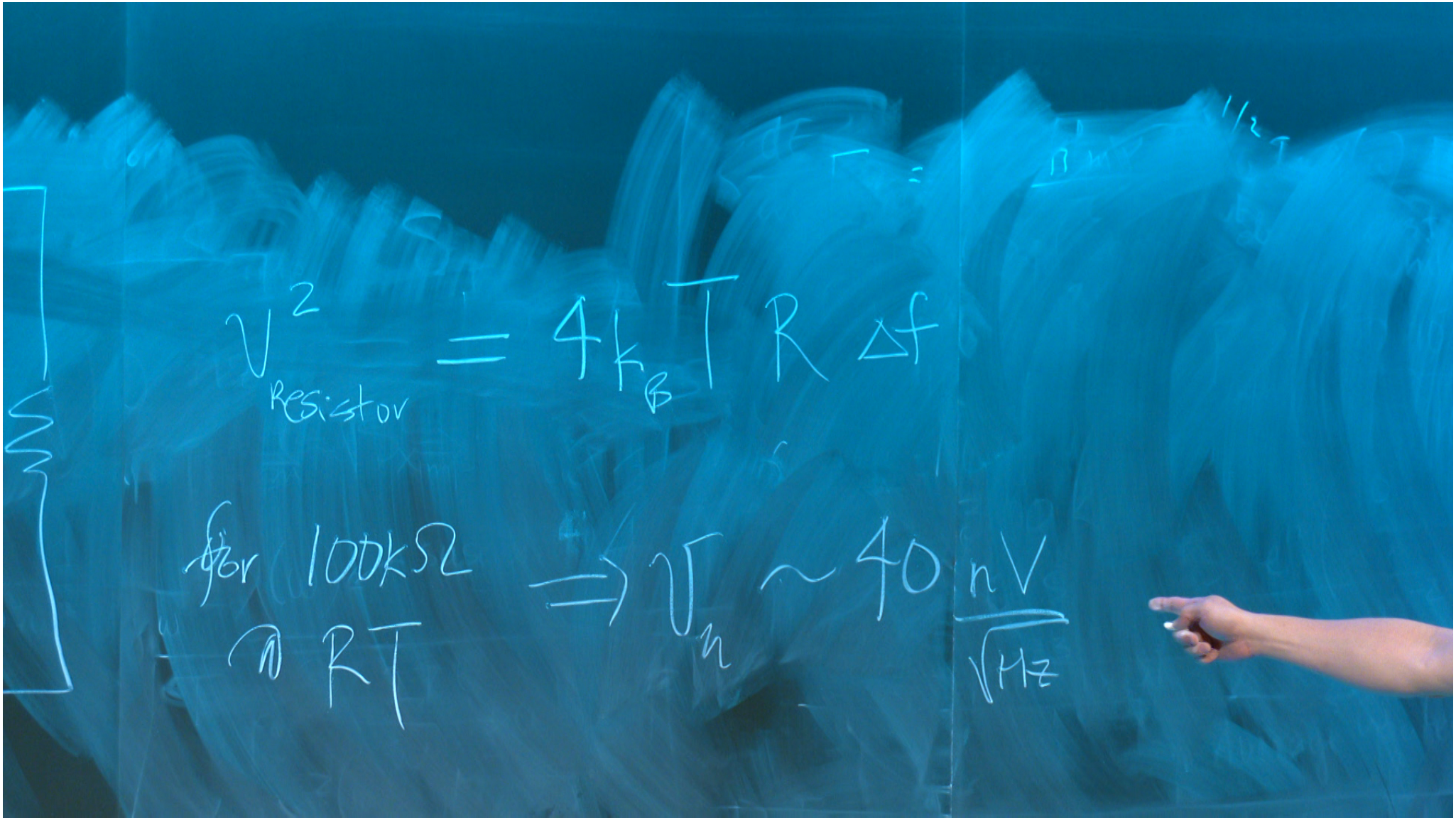

10 nV/√Hz √10^6 Hz = 10 μV RMS

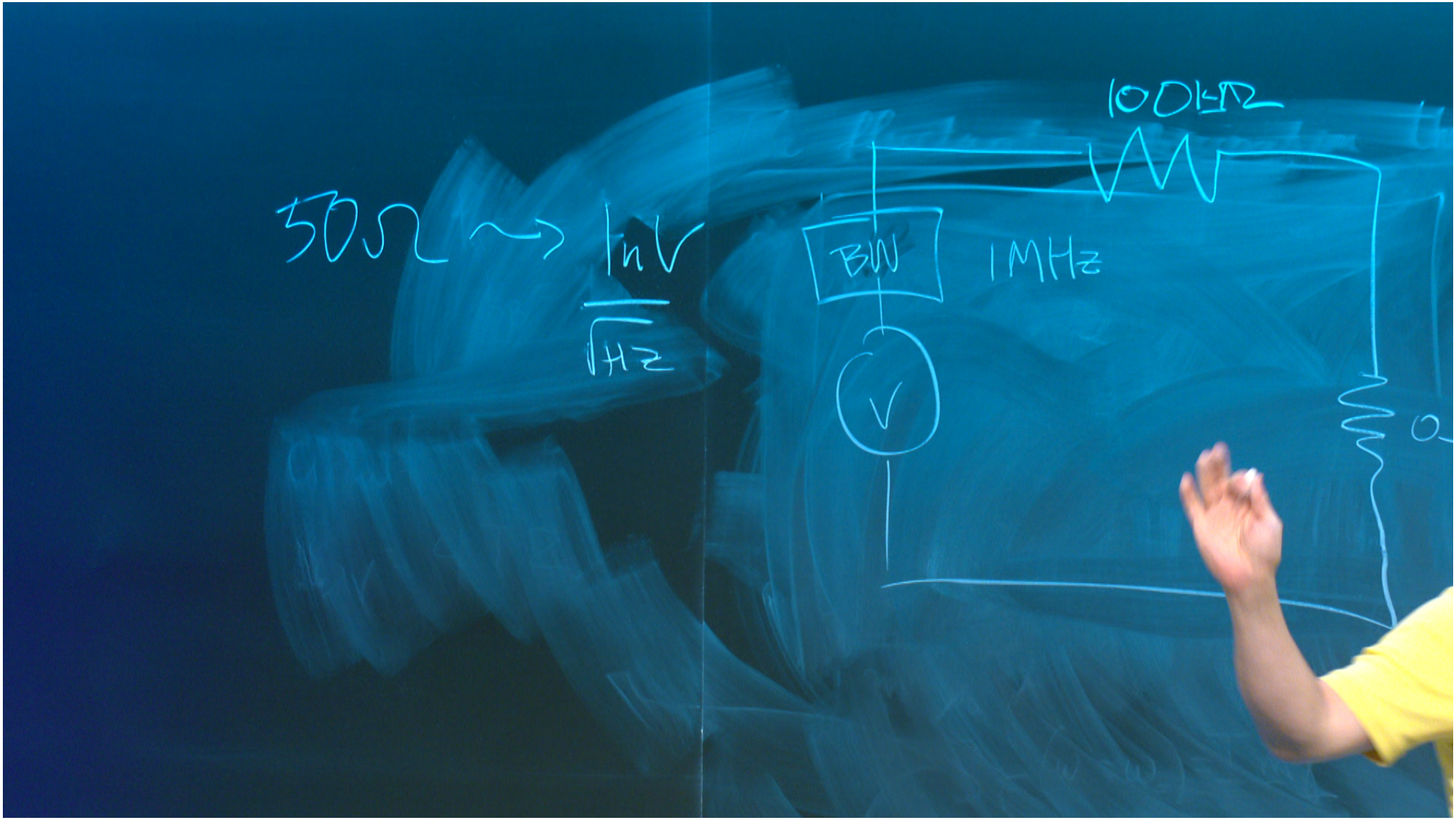

100kΩ
BW
1MHz
V
0Ω

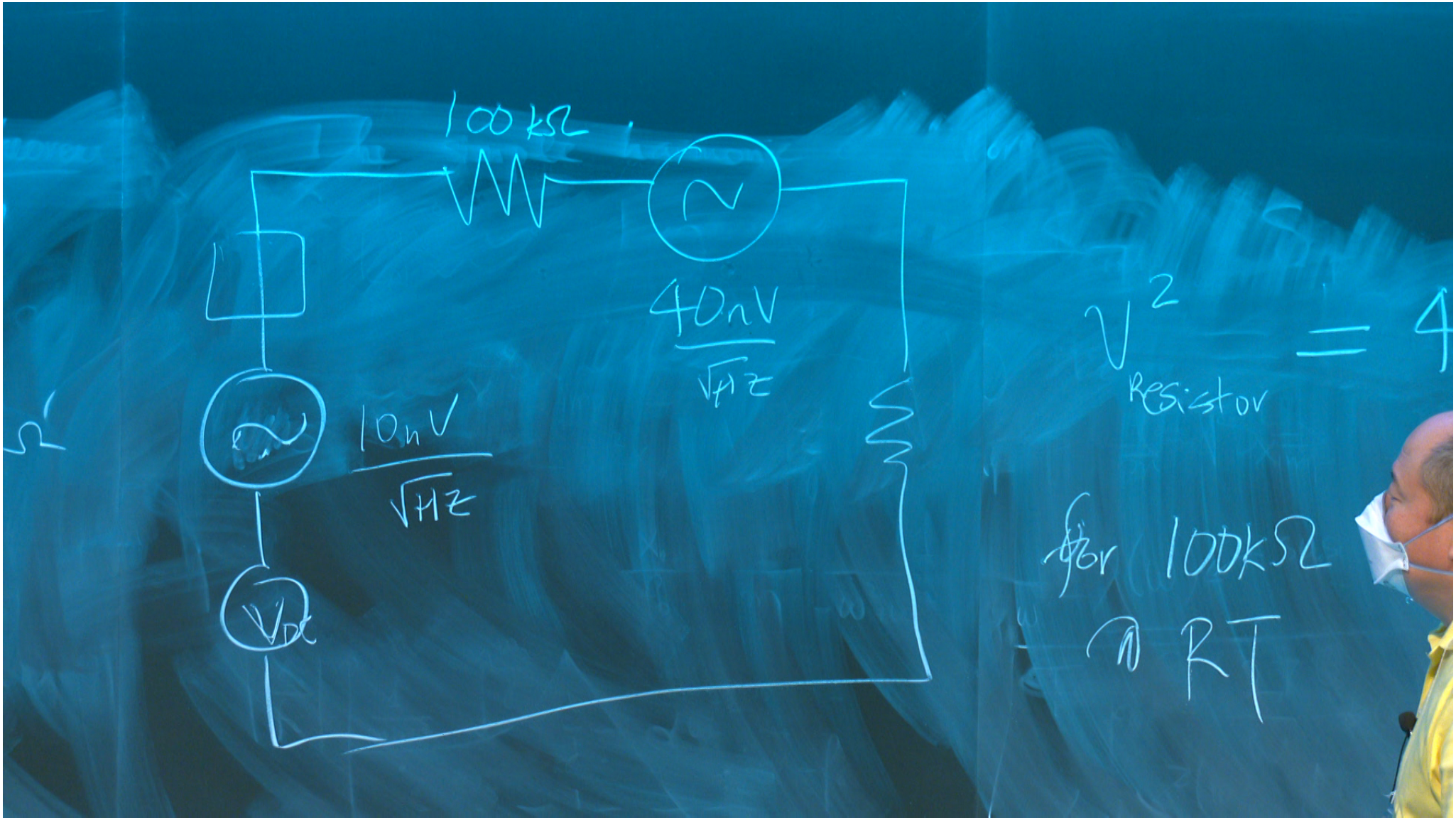
10nV
√Hz

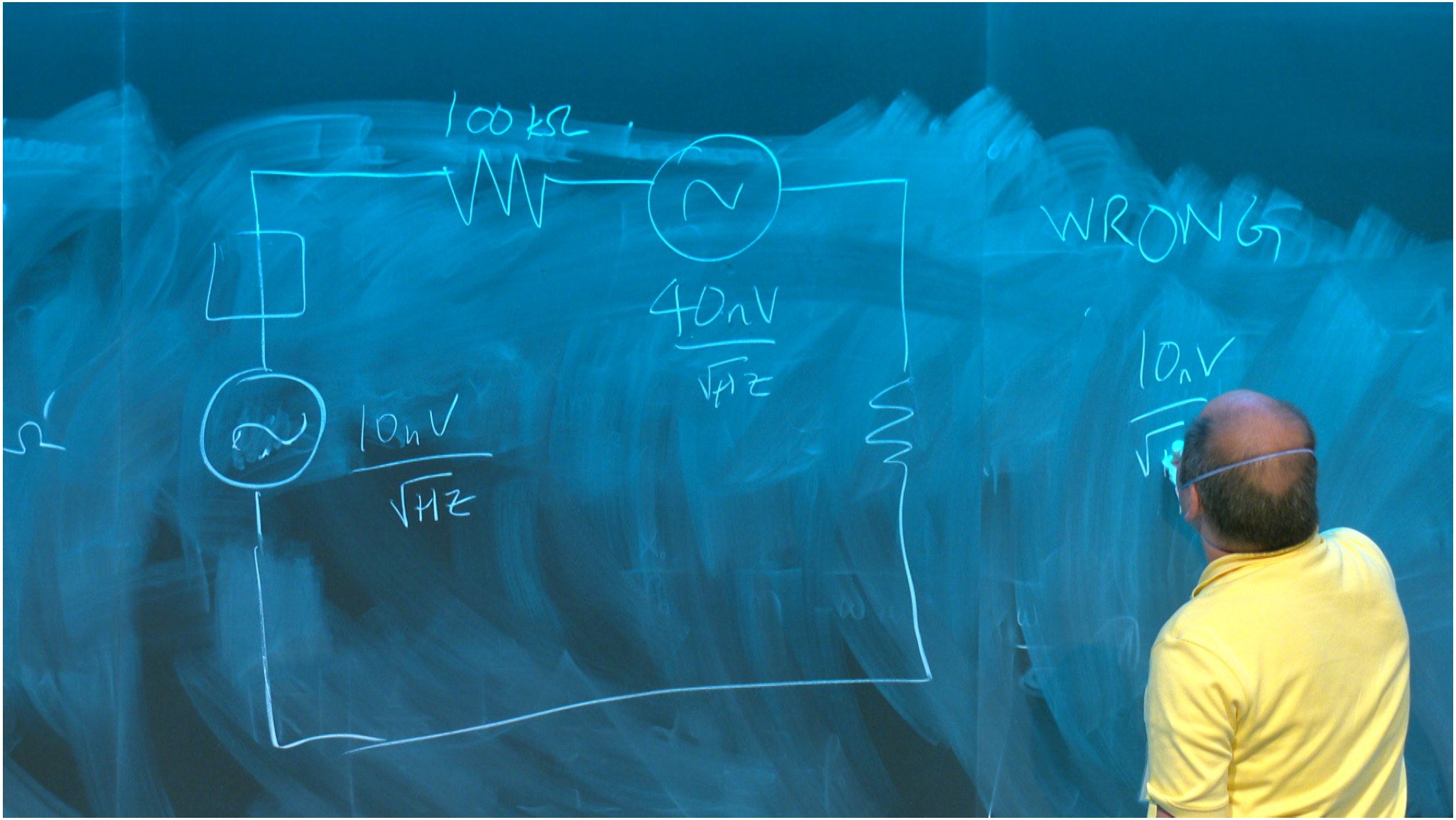

$V^2_{Resistor} = 4 k_B T R \Delta f$

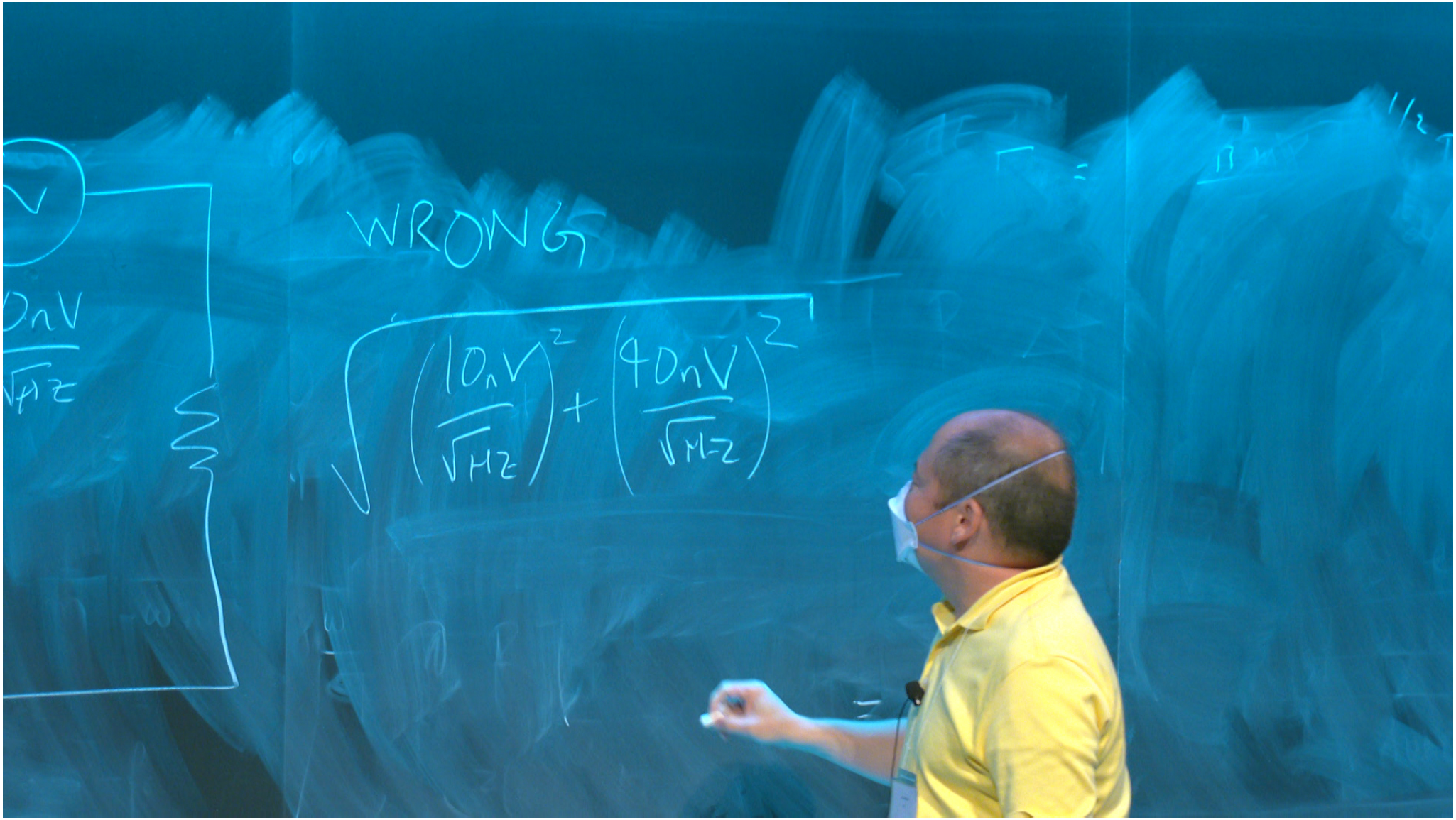
$V^2_{Resi} = 4 k_B T R \Delta f$

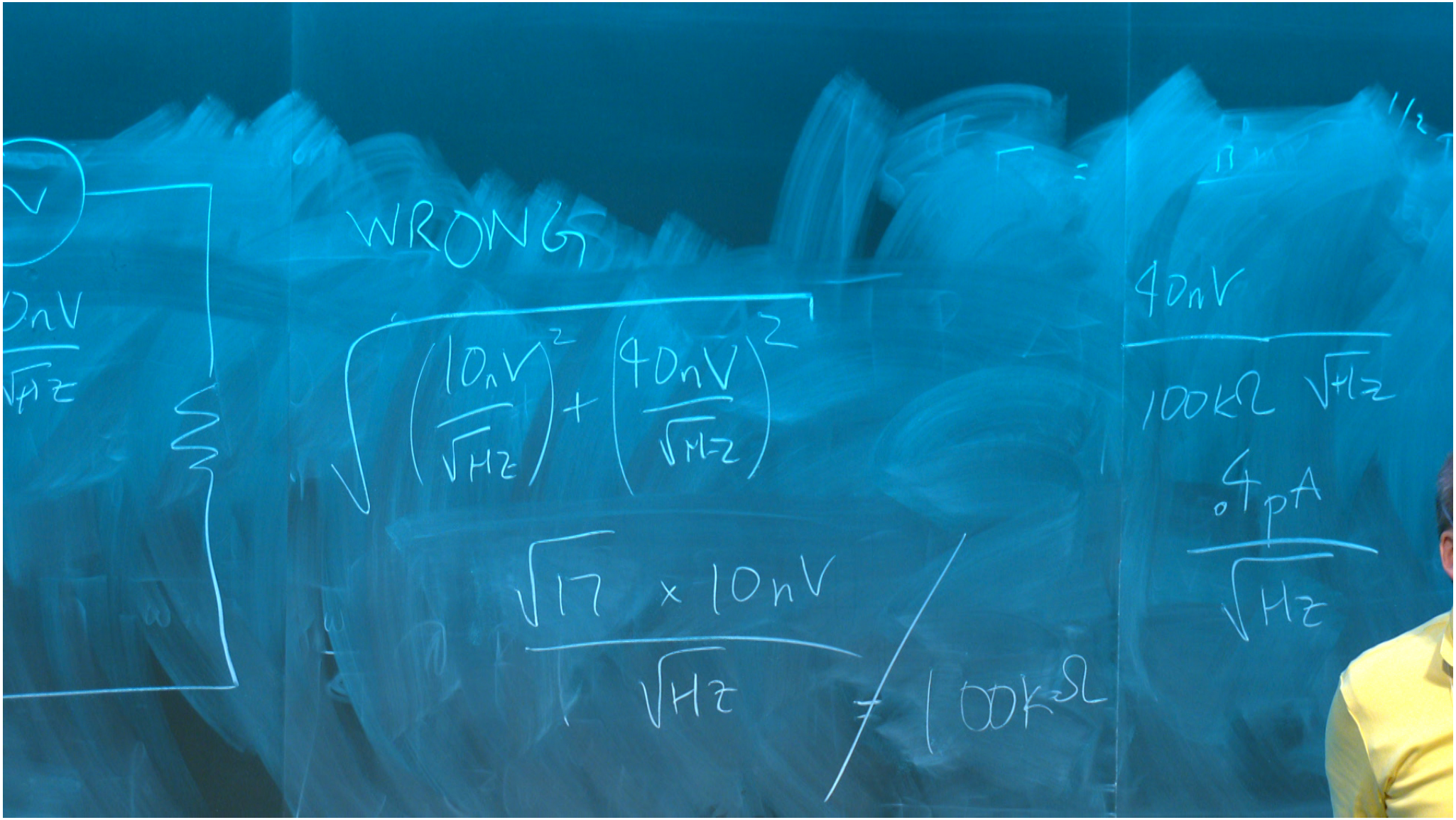

$V^2_{Resistor} = 4 k_B T R \Delta f$
for 100kΩ @ RT
$\Rightarrow V_n \sim 40 \frac{nV}{\sqrt{Hz}}$

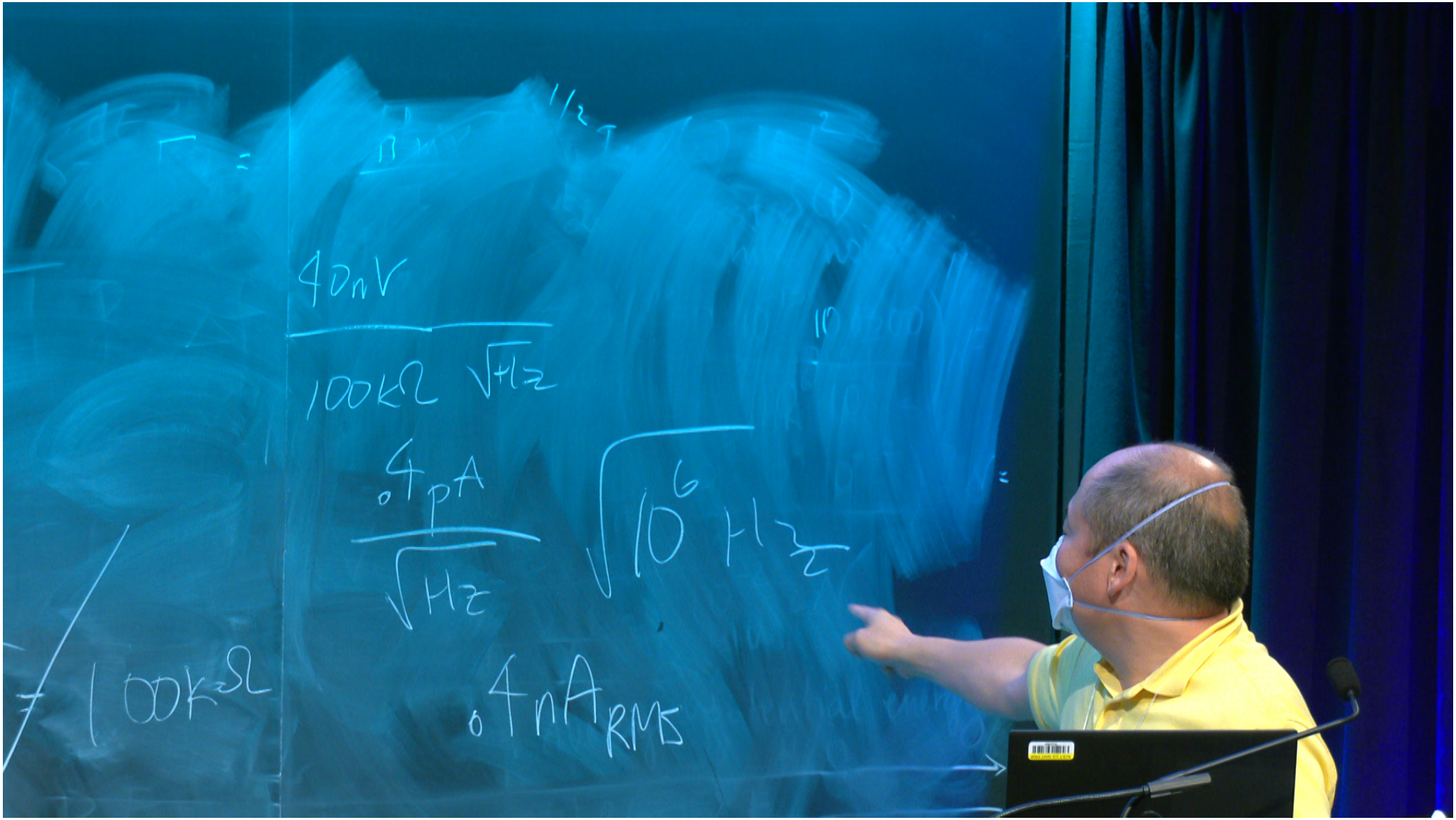

50Ω
1nV
√Hz
BW
1MHz
100kΩ
V


100 kΩ
40nV
√Hz
10nV
√Hz
V_{DC}
V^2
Resistor
=
for 100kΩ
RT

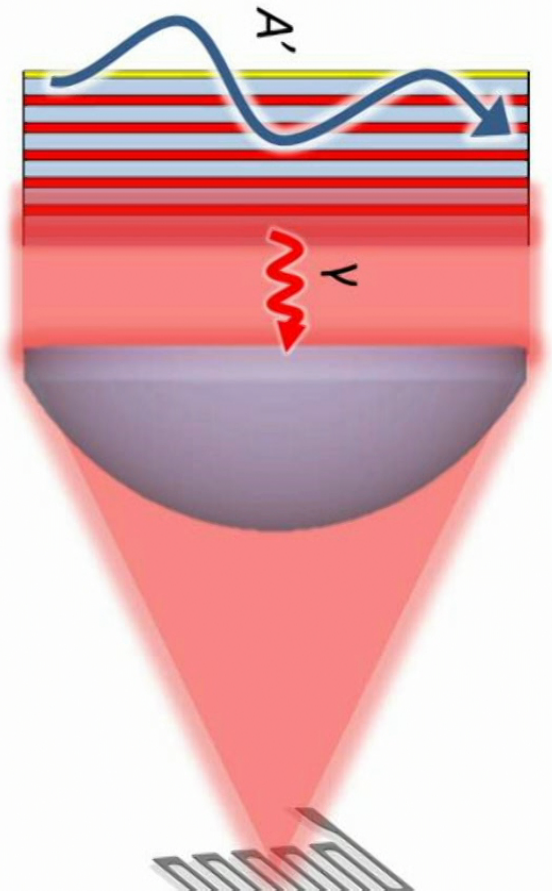

100 kΩ
40nV
√Hz
10nV
√Hz
WRONG
10nV

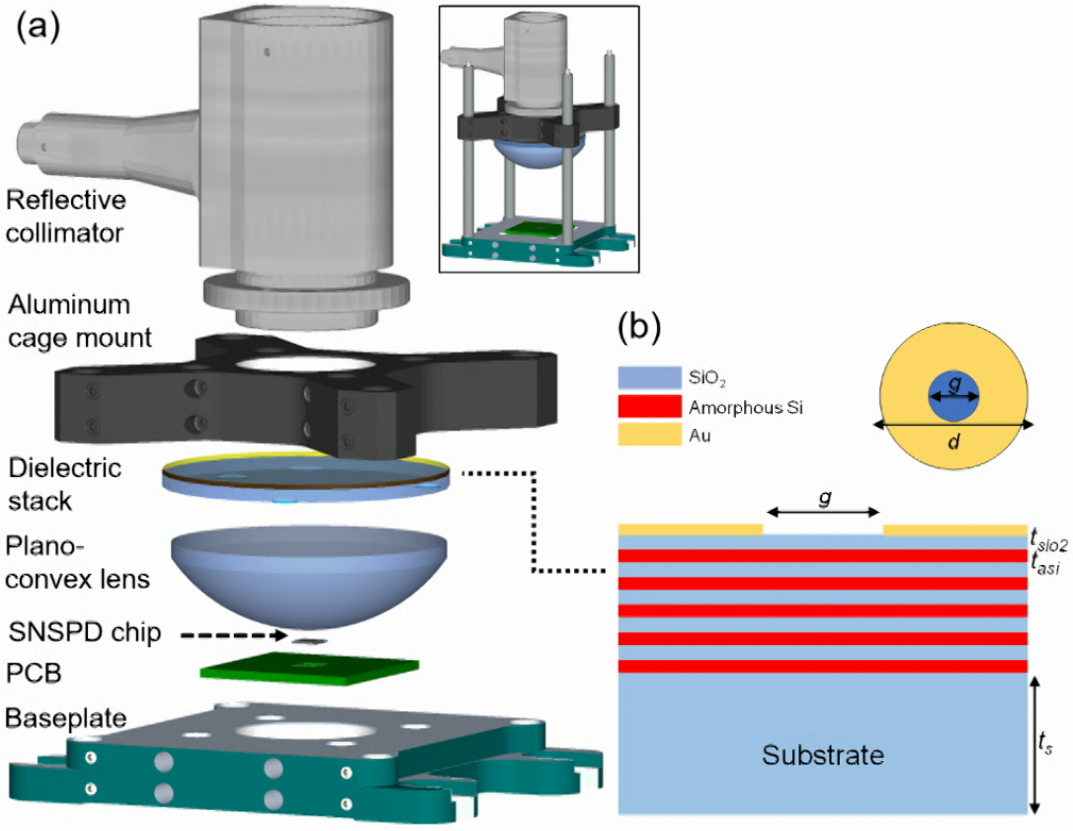

WRONG
$\sqrt{\left(\frac{10nV}{\sqrt{Hz}}\right)^2 + \left(\frac{40nV}{\sqrt{Hz}}\right)^2}$


WRONG
$\sqrt{\left(\frac{10nV}{\sqrt{Hz}}\right)^2 + \left(\frac{40nV}{\sqrt{Hz}}\right)^2}$
$\frac{\sqrt{17} \times 10nV}{\sqrt{Hz}} \neq 100k\Omega$
$\frac{40nV}{100k\Omega\sqrt{Hz}}$
$0.4pA$
$\sqrt{Hz}$


40nV
100kΩ √Hz
4pA
√Hz
√10^6 Hz
100kΩ
4nA RMS

Optics


A
V


(a)
Reflective collimator
Aluminum cage mount
Dielectric stack
Plano-convex lens
SNSPD chip
PCB
Baseplate
(b)
SiO2
Amorphous Si
Au
g
d
g
tslo2
tasi
Substrate
ts

Comments about Noise

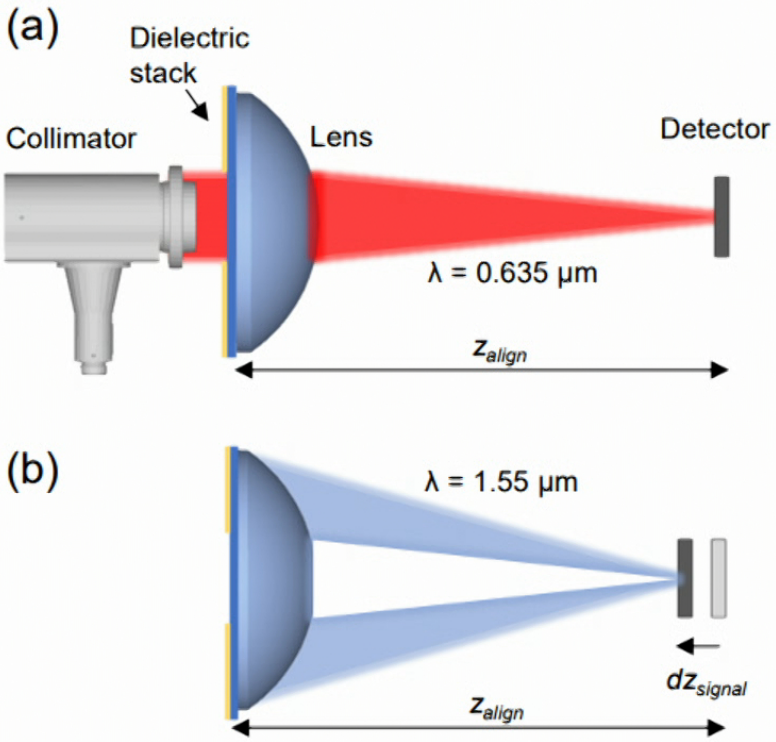
- Noise is unpredictable in amplitude and phase
- “60Hz” pickup… => not “random noise”
- Random noise:
  - Quantify by looking at the < noise^2 > because <noise> = 0

$$\left\langle n^2 \right\rangle = \frac{1}{T}\int_0^T n(t)^2 dt$$

- Parseval’s Theorem:

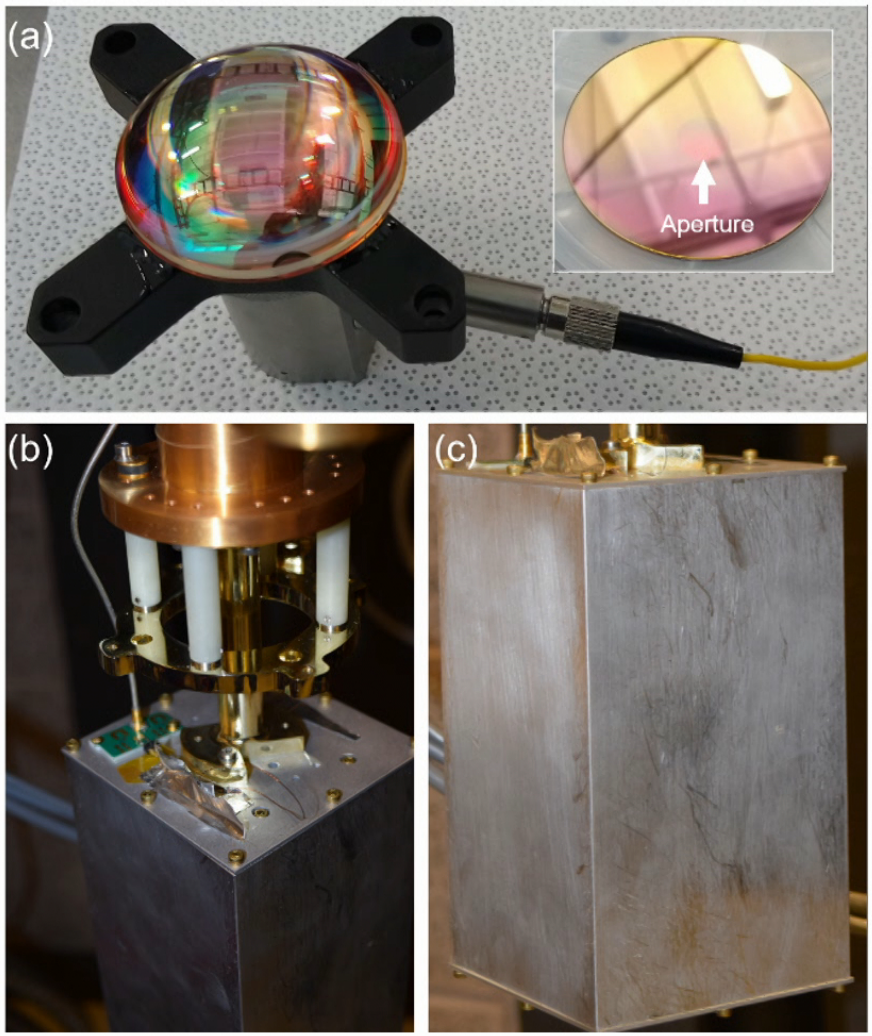
$$\left\langle n^2 \right\rangle = \frac{1}{T}\int_0^T n(t)^2 dt = \int \left\| \mathcal{N}(f) \right\|^2 df$$

How do align the lens to the device?

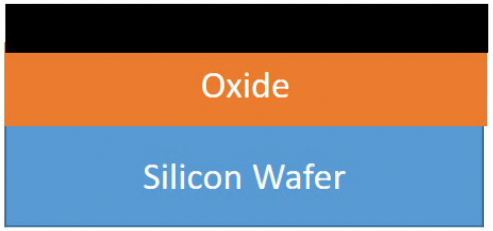


- Hole in Au mirror lets us put in a collimated red laser beam.
- Unfortunately focus for the red beam is not the same as for light from 1550 nm.
- Adjusted the distance after focusing with the red laser beam.
- Did not explicitly design the mechanics to account for thermal contraction… large uncertainty in collection efficiency

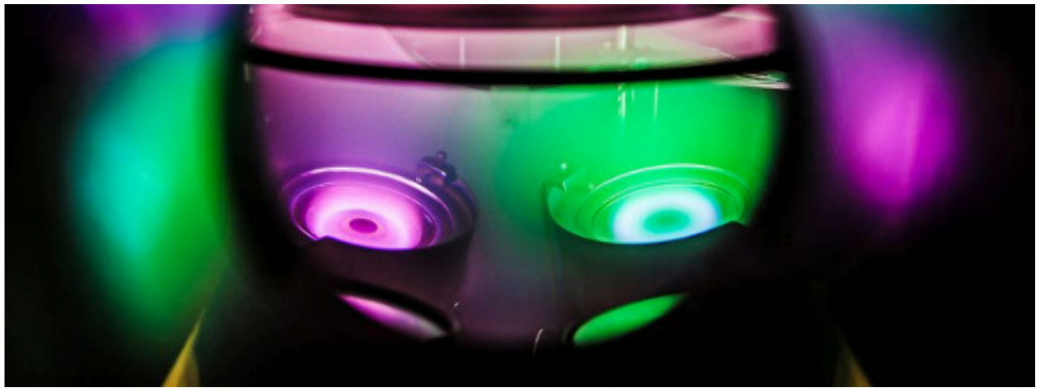
Light tight box…

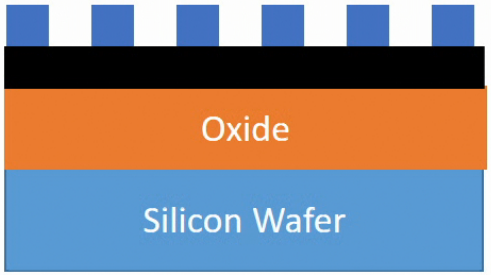


Detector Fabrication

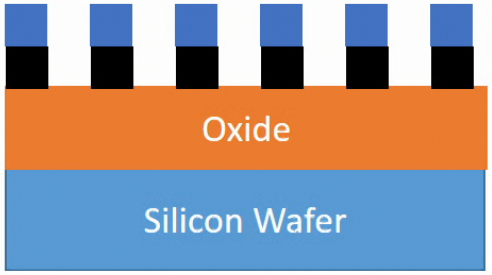


Sputter WSi

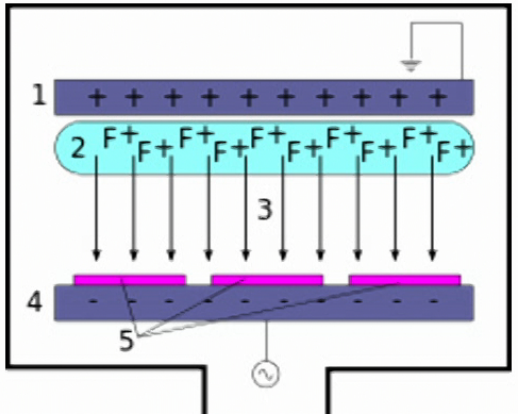




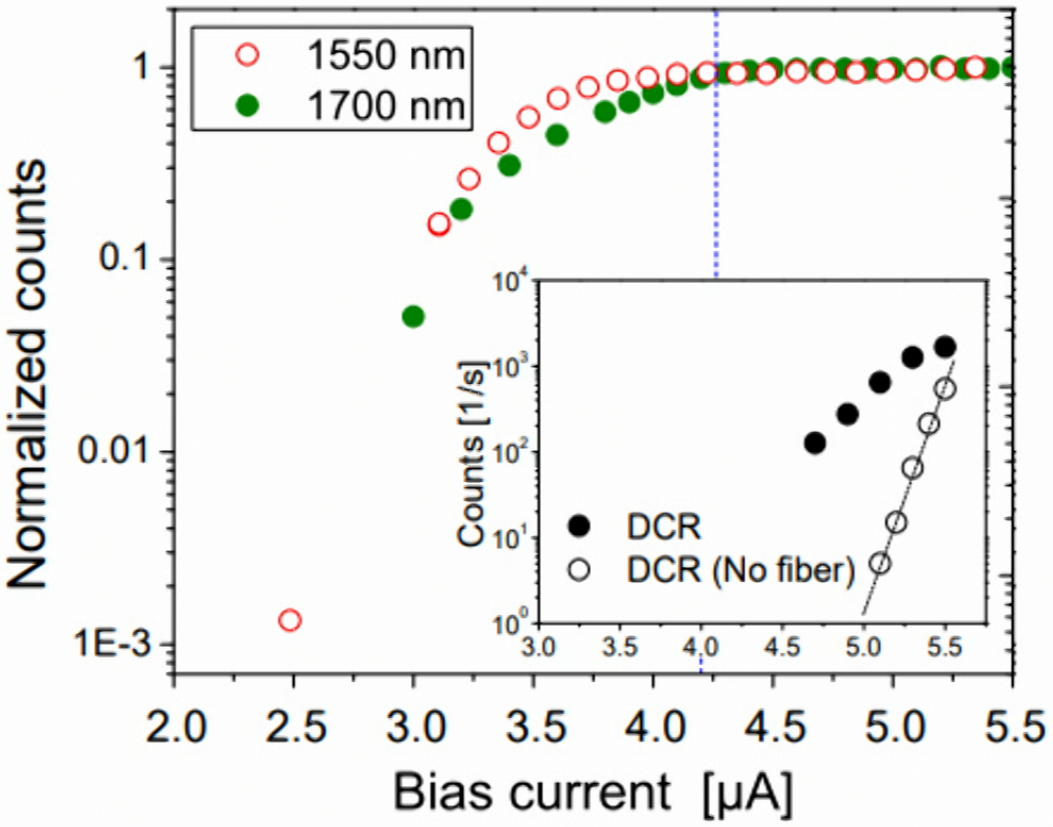
Coat and pattern e-beam resist



Etch WSi



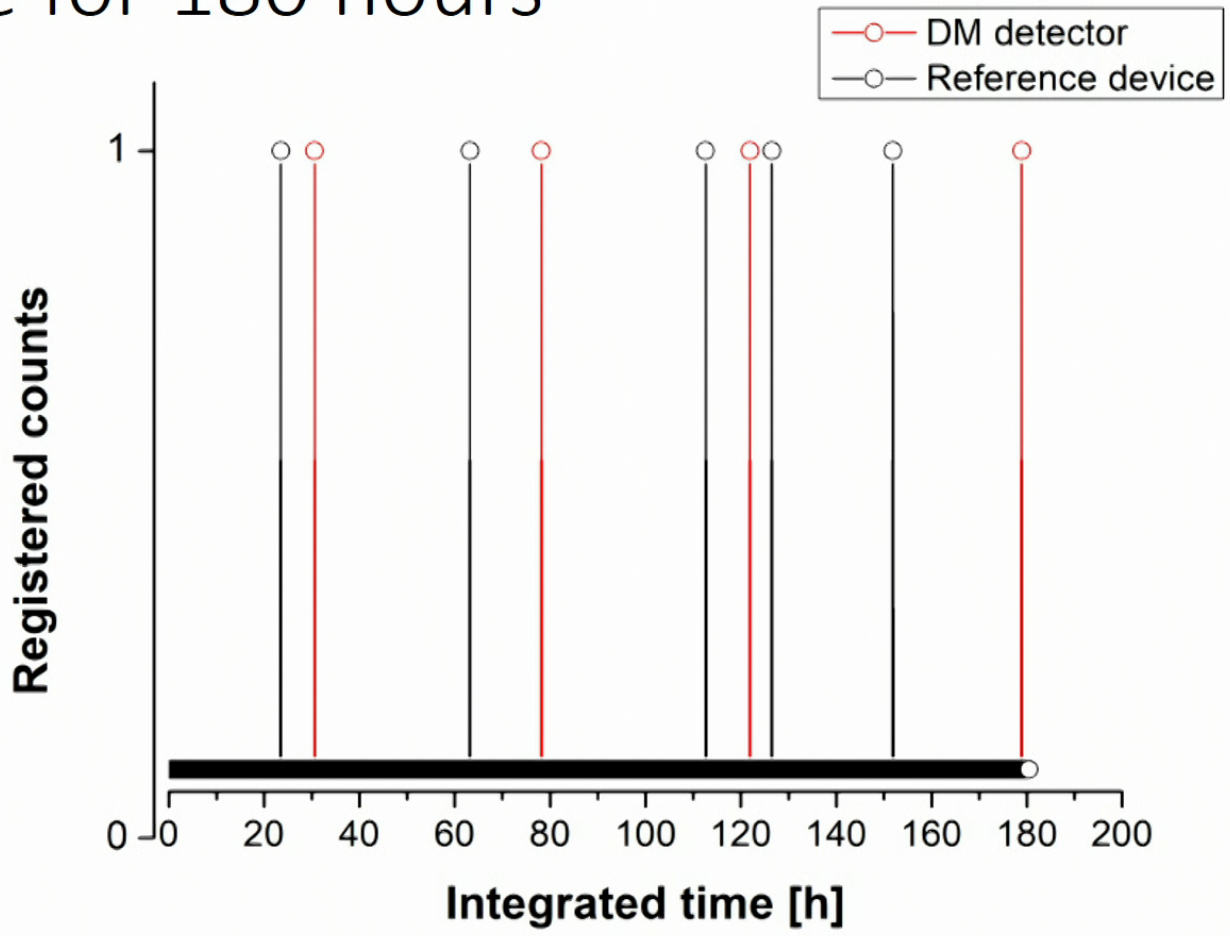
Picking the bias point / Calibration

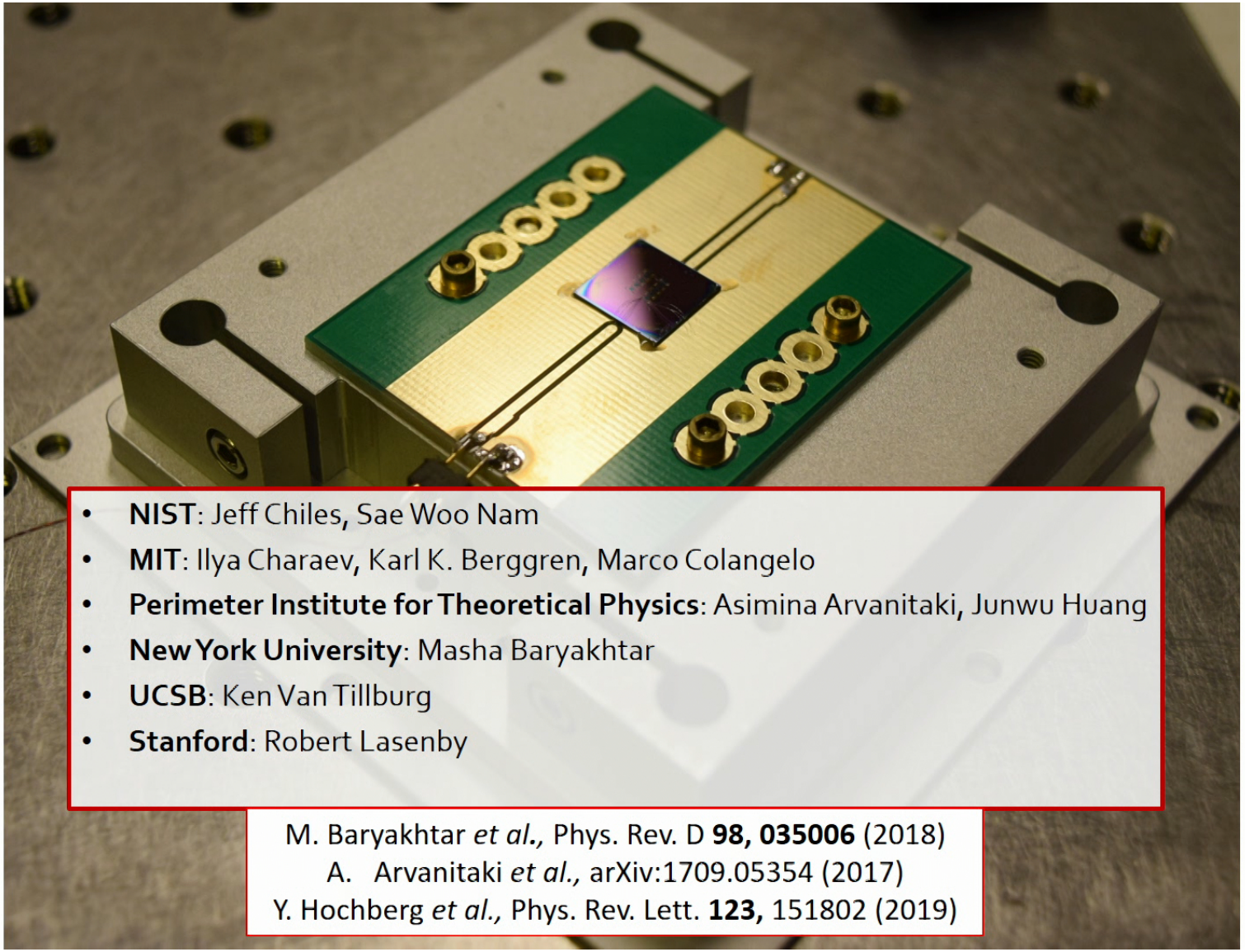


Two different laser colors to get an estimate of the difference in efficiency as a function of wavelength

So that exponentially disappearing dark counts will not occur at 1 count per day

Observe for 180 hours





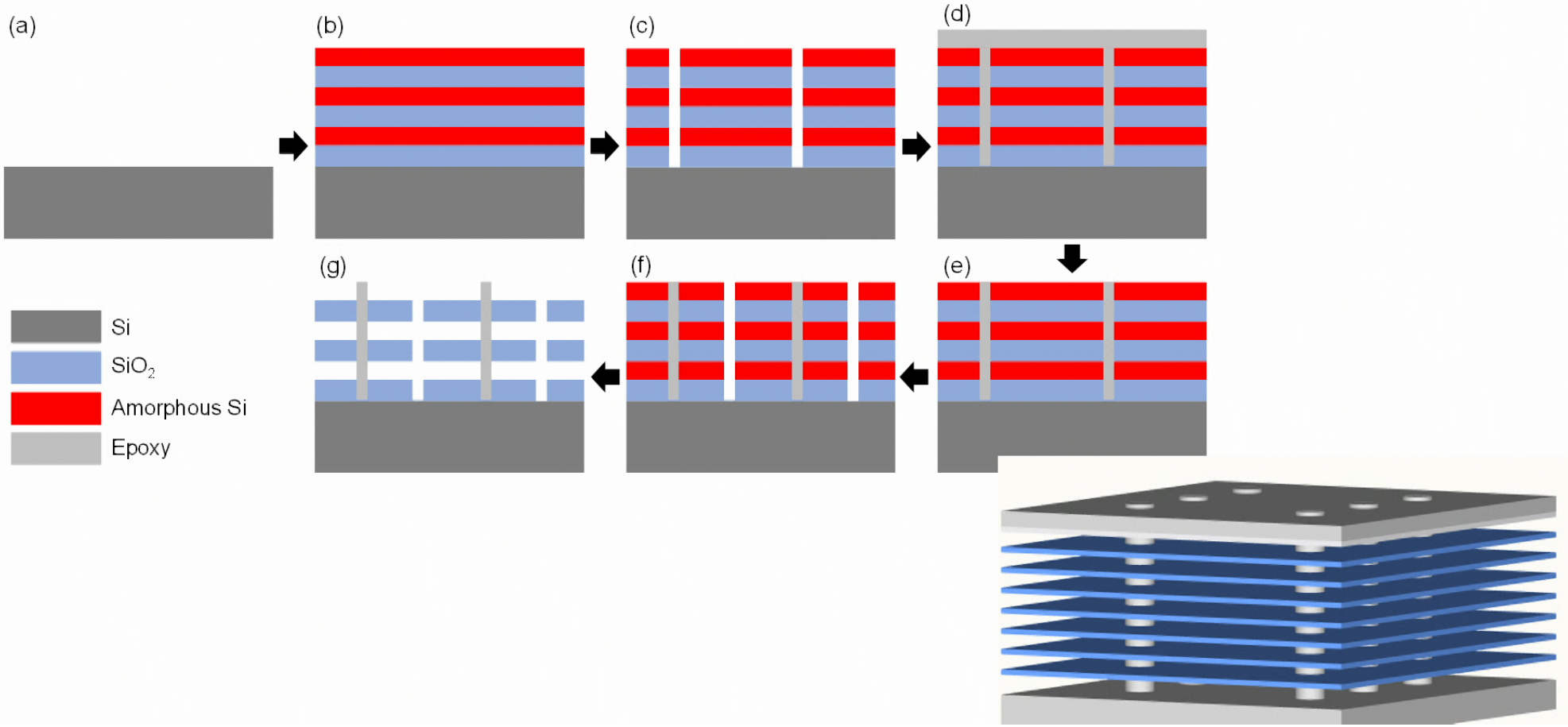
- **NIST**: Jeff Chiles, Sae Woo Nam
- **MIT**: Ilya Charaev, Karl K. Berggren, Marco Colangelo
- **Perimeter Institute for Theoretical Physics**: Asimina Arvanitaki, Junwu Huang
- **New York University**: Masha Baryakhtar
- **UCSB**: Ken Van Tillburg
- **Stanford**: Robert Lasenby

M. Baryakhtar *et al.,* Phys. Rev. D **98, 035006** (2018)
A. Arvanitaki *et al.,* arXiv:1709.05354 (2017)
Y. Hochberg *et al.,* Phys. Rev. Lett. **123,** 151802 (2019)

What's next

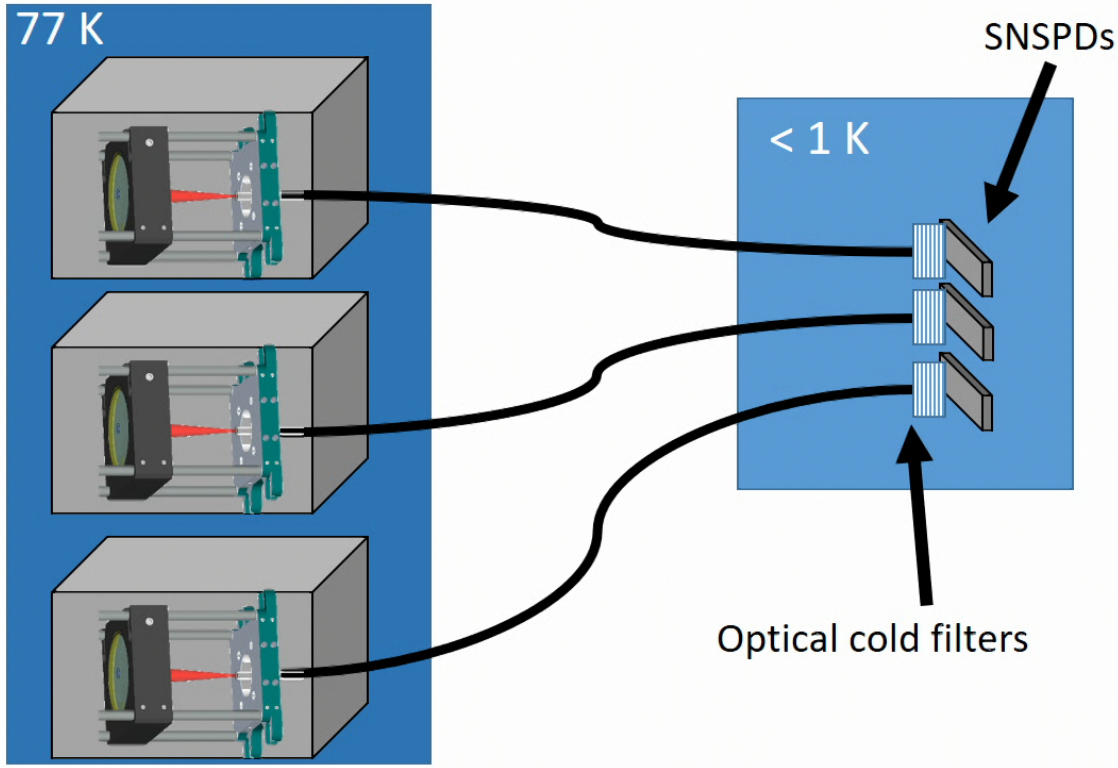
- Are the observed events an unwanted background signal
  - Muon veto
  - Local muon veto using a scintillator with SNSPD patterned on top
- Other mediators
- Axion
- Scaling up

Other Dark Matter Targets, Gas + Dielectrics:



Future work: Axions, scaling to larger coverage

- Separate Dark Matter target from detectors
  - Could add B-field to detect Axions



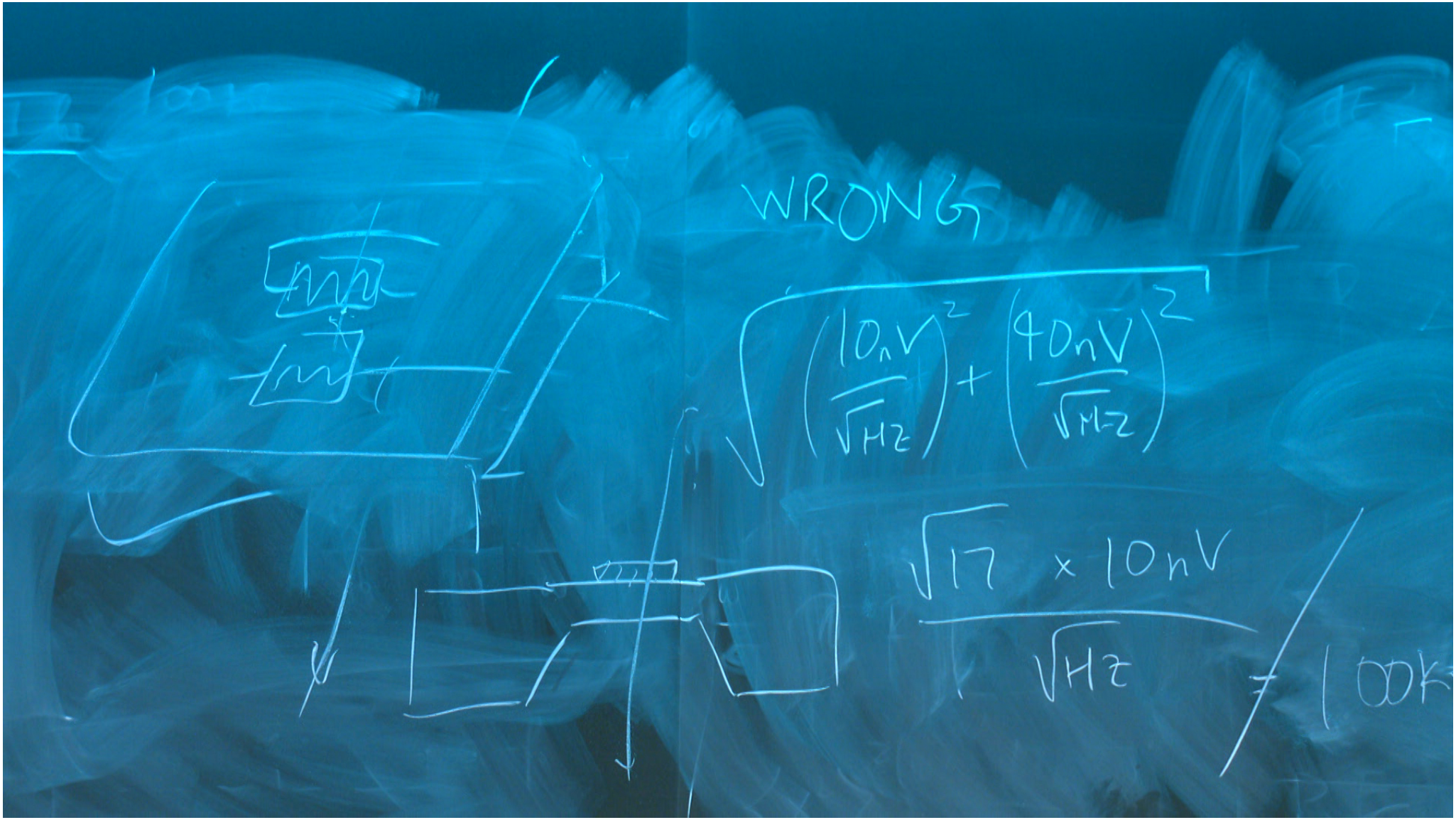
Closing thoughts

- Superconducting devices / amplifiers enable detection of single photons from mm-waves to UV photons.
- Cryogenics has improved significantly in the last ten years…. It is slowly becoming “invisible”
- The ultimate performance of superconducting based single photon detectors is an open area of research.

1nV
√Hz

WRONG
$\sqrt{\left(\frac{10nV}{\sqrt{Hz}}\right)^2+\left(\frac{40nV}{\sqrt{Hz}}\right)^2}$
$\frac{\sqrt{17}\times 10n}{\sqrt{Hz}}$

$\sim \frac{\ln V}{\sqrt{Hz}}$


WRONG
$\sqrt{\left(\frac{10nV}{\sqrt{Hz}}\right)^2+\left(\frac{40nV}{\sqrt{Hz}}\right)^2}$
$\frac{\sqrt{17}\times 10nV}{\sqrt{Hz}}$