# Measuring a Mole of Photons

*Redefining Optical Power Traceability at NIST*

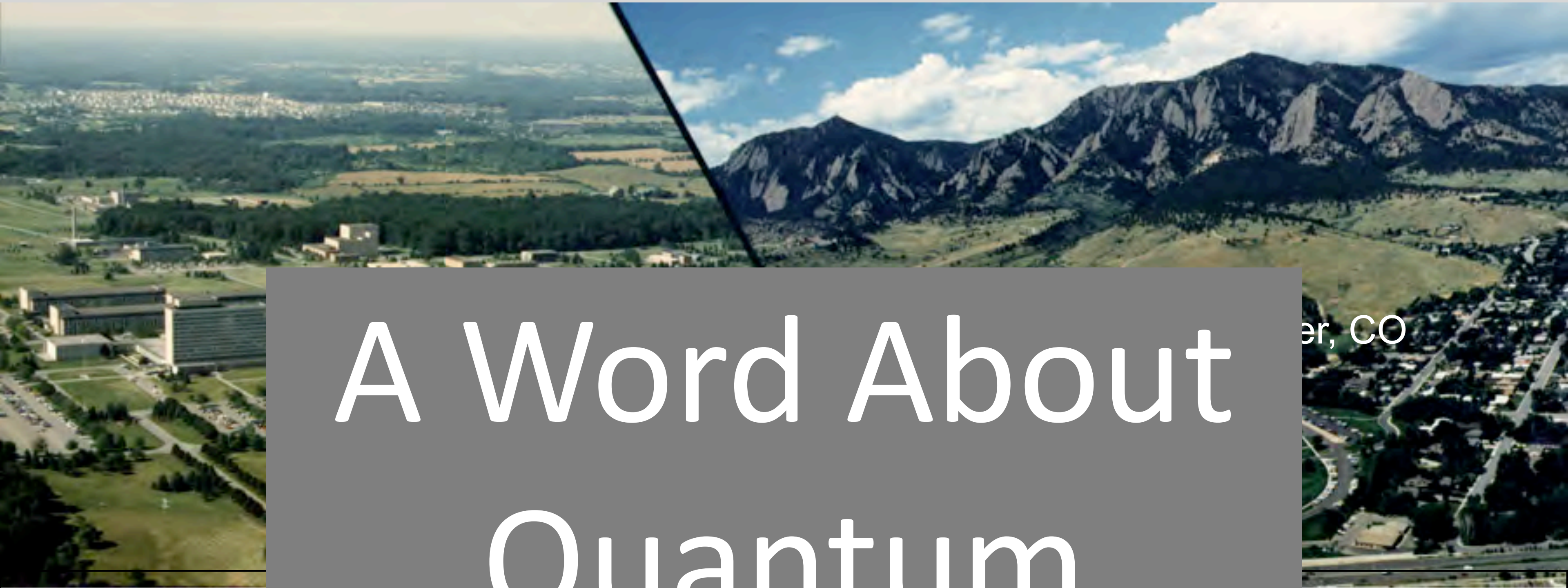
**John Lehman, NIST**
**Sources and Detectors, Applied Physics,**
**Boulder, Colorado**

# Where and Who


*Physical Measurement Laboratory*
*Applied Physics Division*
*Sources and Detectors*

*Please visit!*

# Where and Who




# A Word About Quantum Metrology

*Physical Me*
*Applied Phys*
*Sources and*

*Please visit!*

A quantum standard or measurement:

1. is based upon unchanging, universal, fundamental constants or macroscopic quantum phenomena;

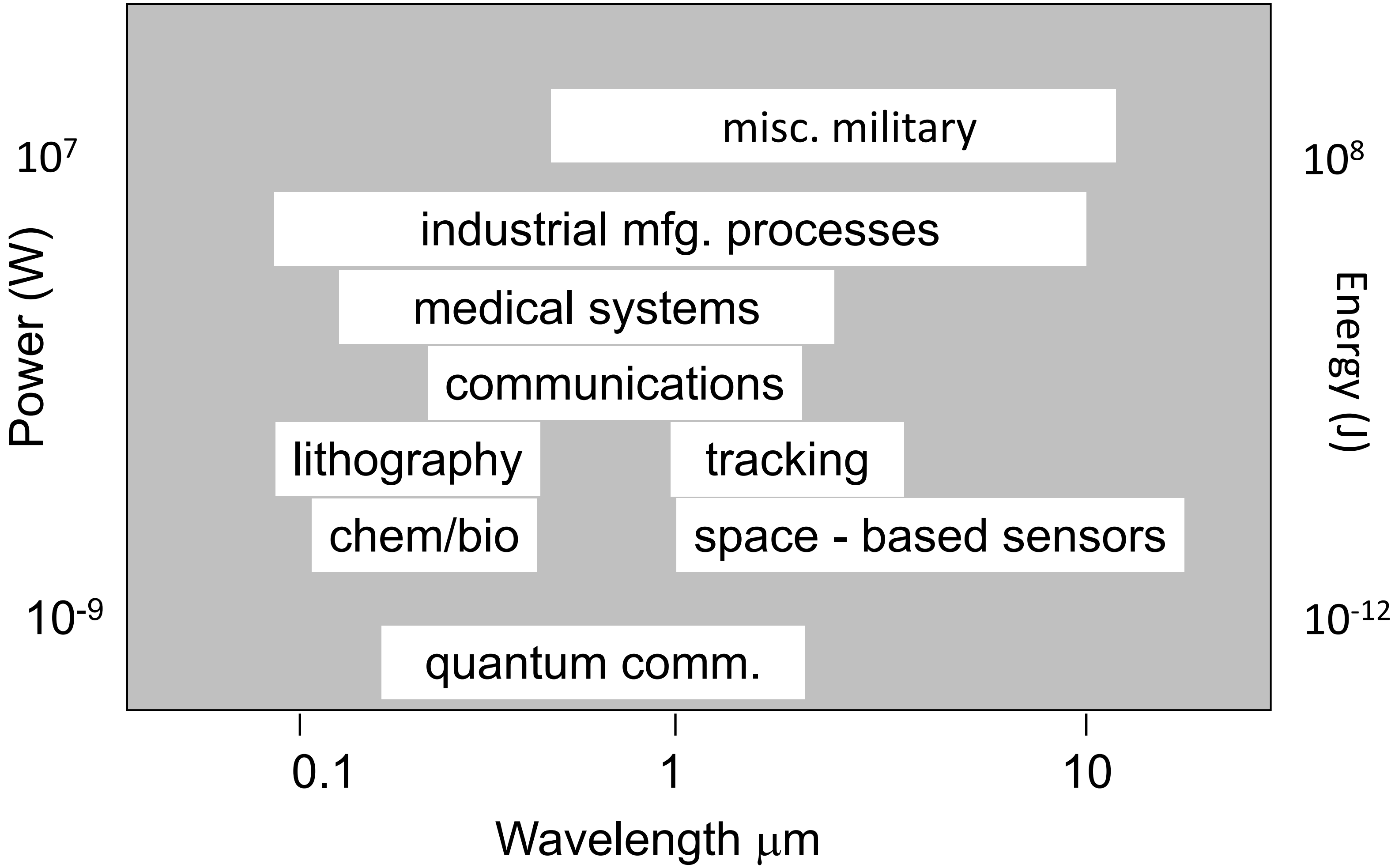
2. provides a true value of the realization or measurement or no value at all; and

3. has a known uncertainty that is characterized quantitatively and is fit for purpose.

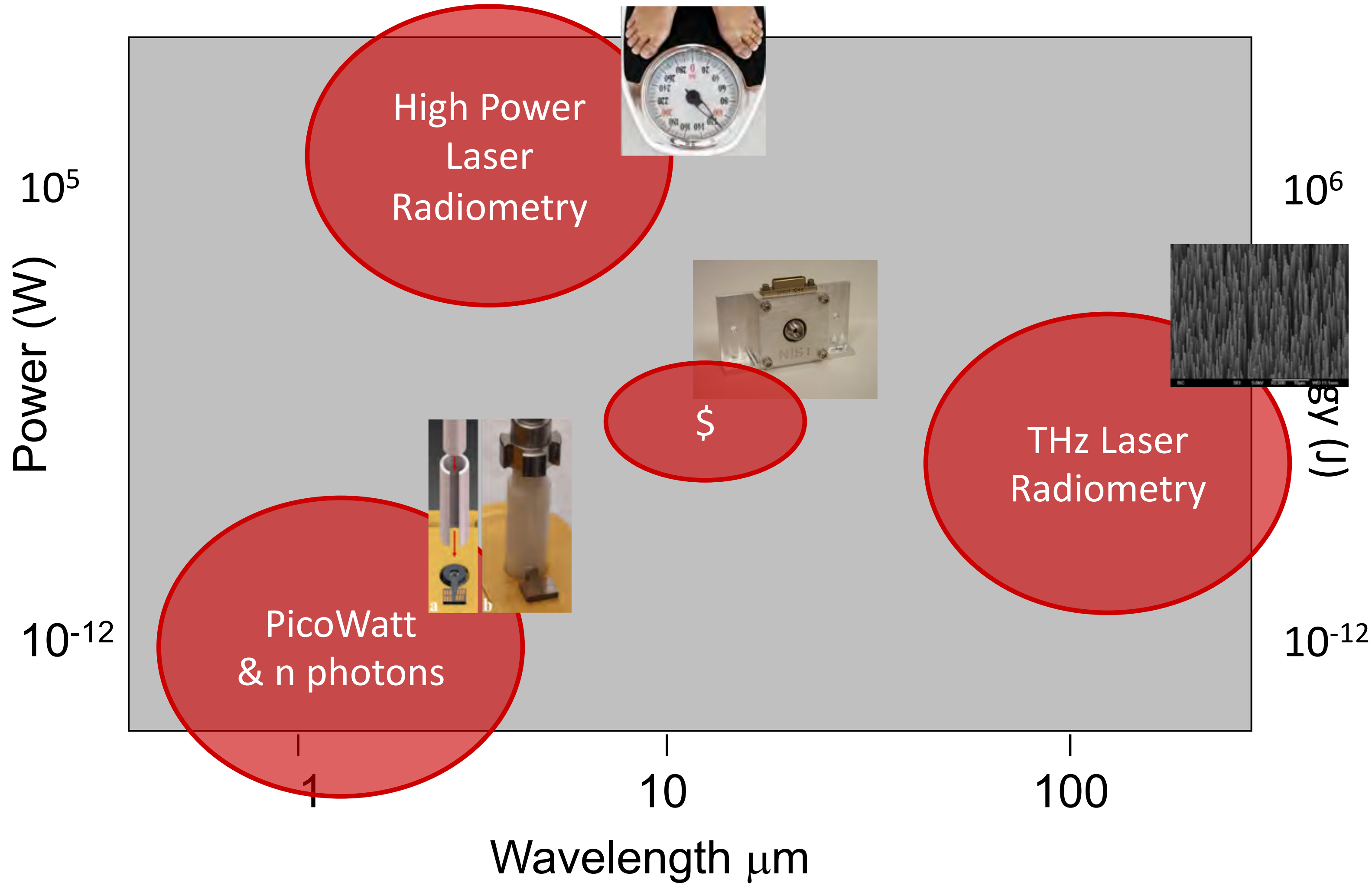
1. NIST (context)
2. Classical Radiometry
3. Quantum Radiometry (?)

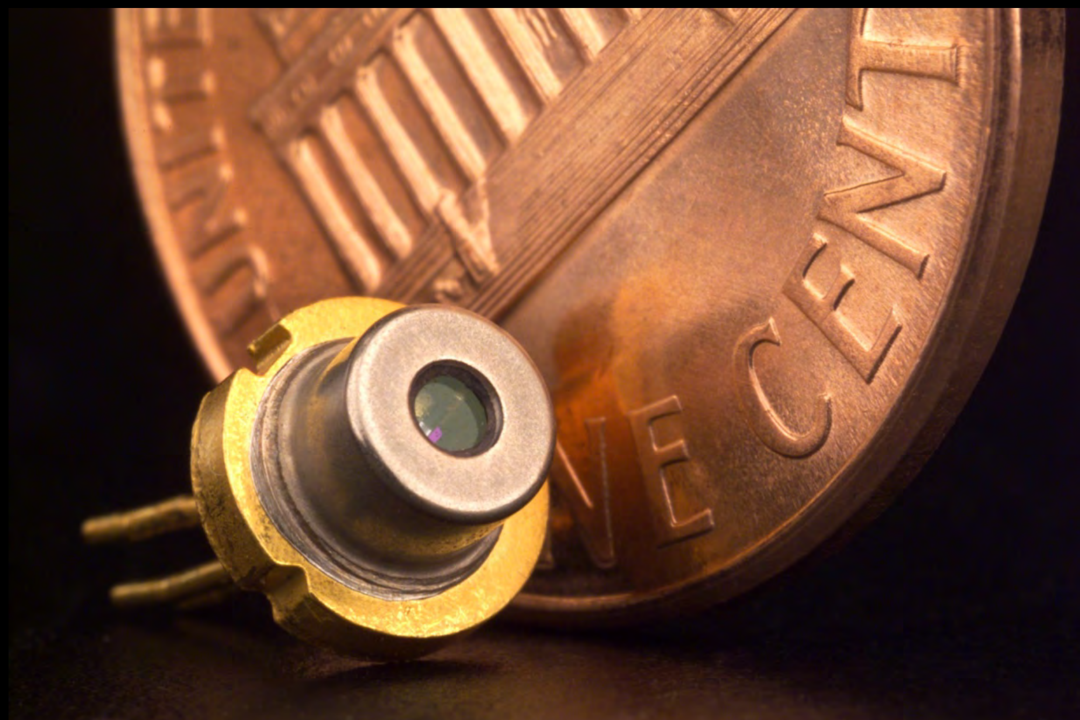
# Major Goals (drive our research)

*The next generation of sources and detectors for laser power and energy measurements traceable to NIST*



# Major Goals

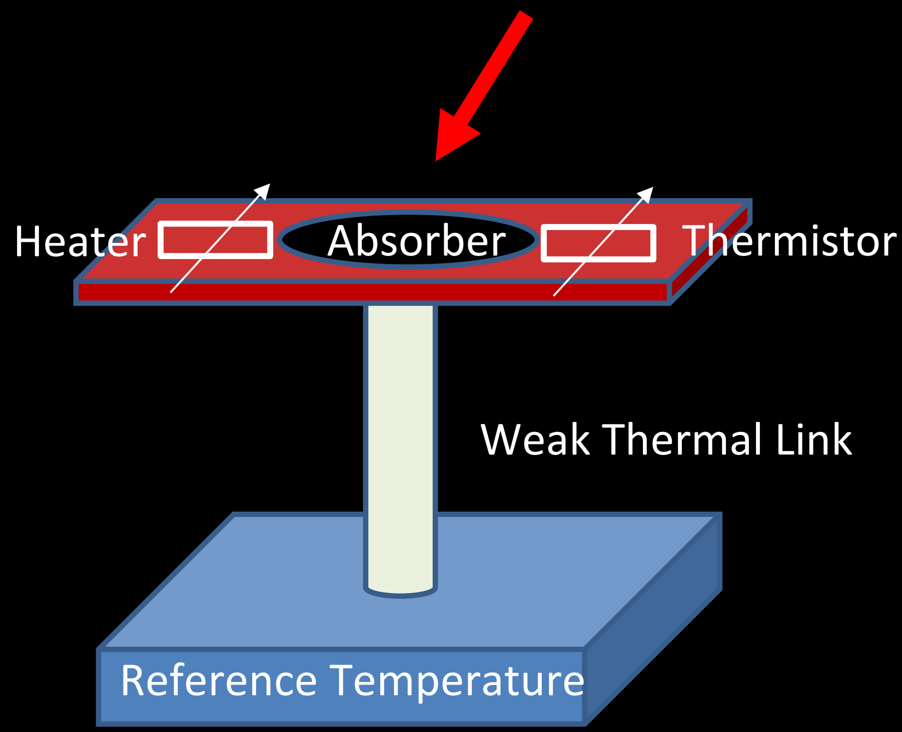

High Power
Laser
Radiometry
$
THz Laser
Radiometry
PicoWatt
& n photons
NIST
a
b
$10^5$
$10^{-12}$
$10^6$
$10^{-12}$
Power (W)
gy (J)
1
10
100
Wavelength μm




U.S. AIR FORCE
ED
USAF

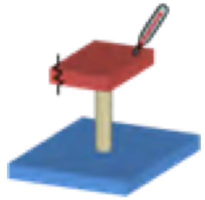

(not a commodity)

# Present Primary Standardization




Optical Power Traceable to the SI by Electrical Measurements
resistance, current, voltage

# Cryogenic Radiometer Design

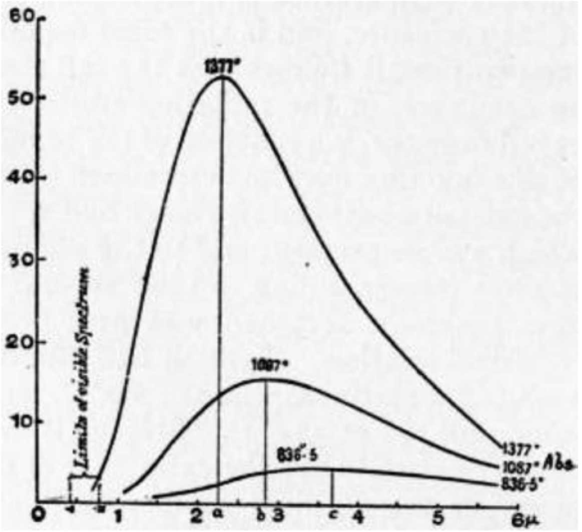


weak thermal link

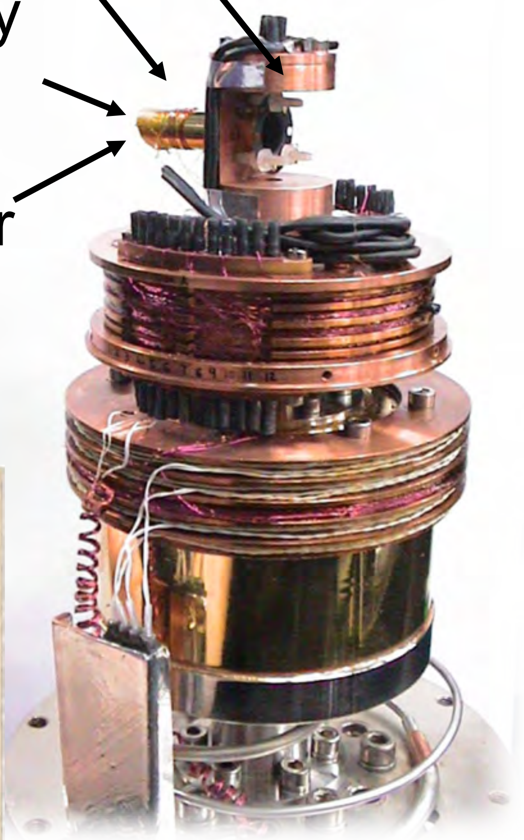
heater

blackened cavity
and absorber

thermometer





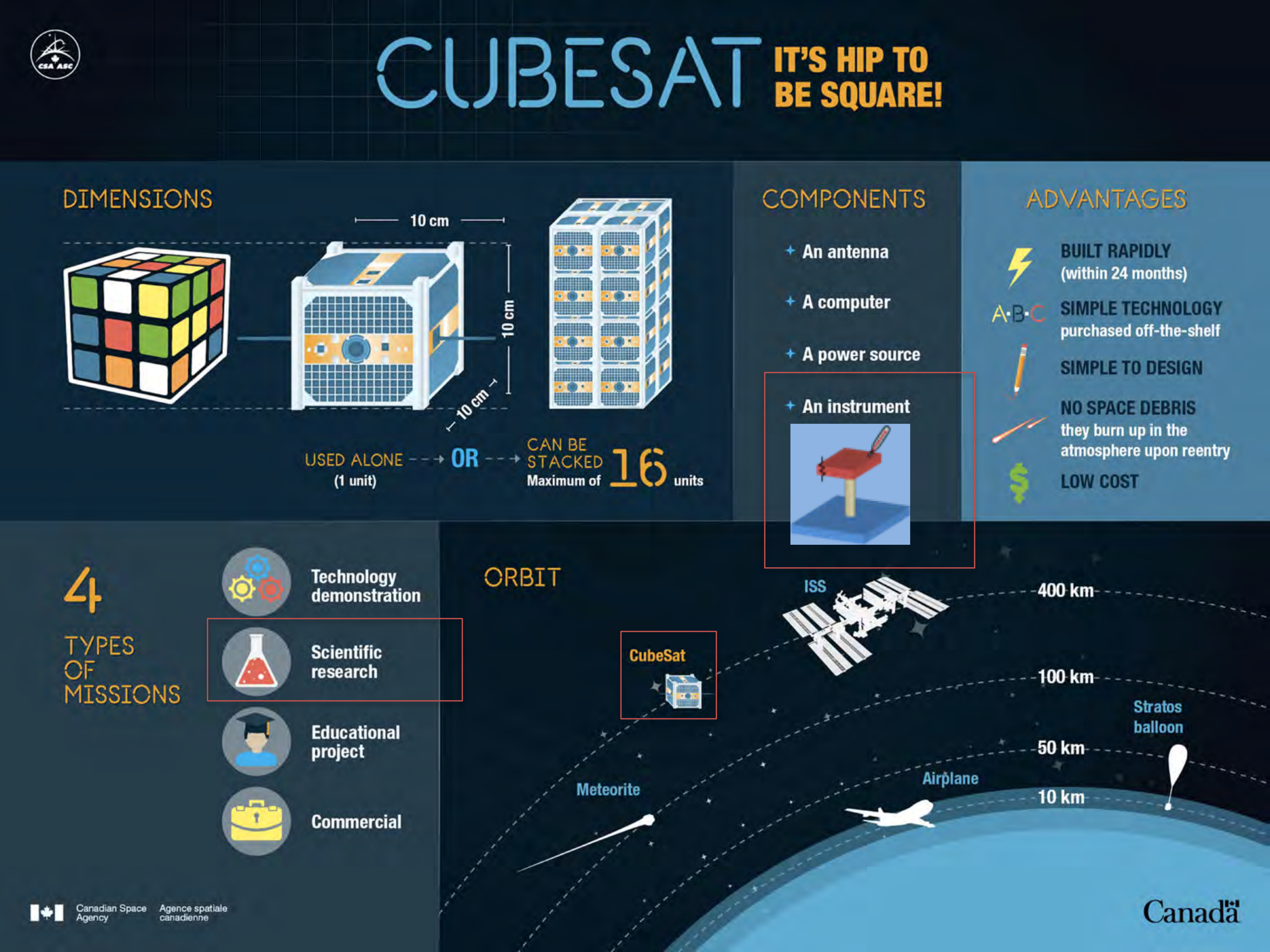


Kurlbaum, Wied. Ann. V. 65, p. 746, 1898

photo: courtesy Malcolm White

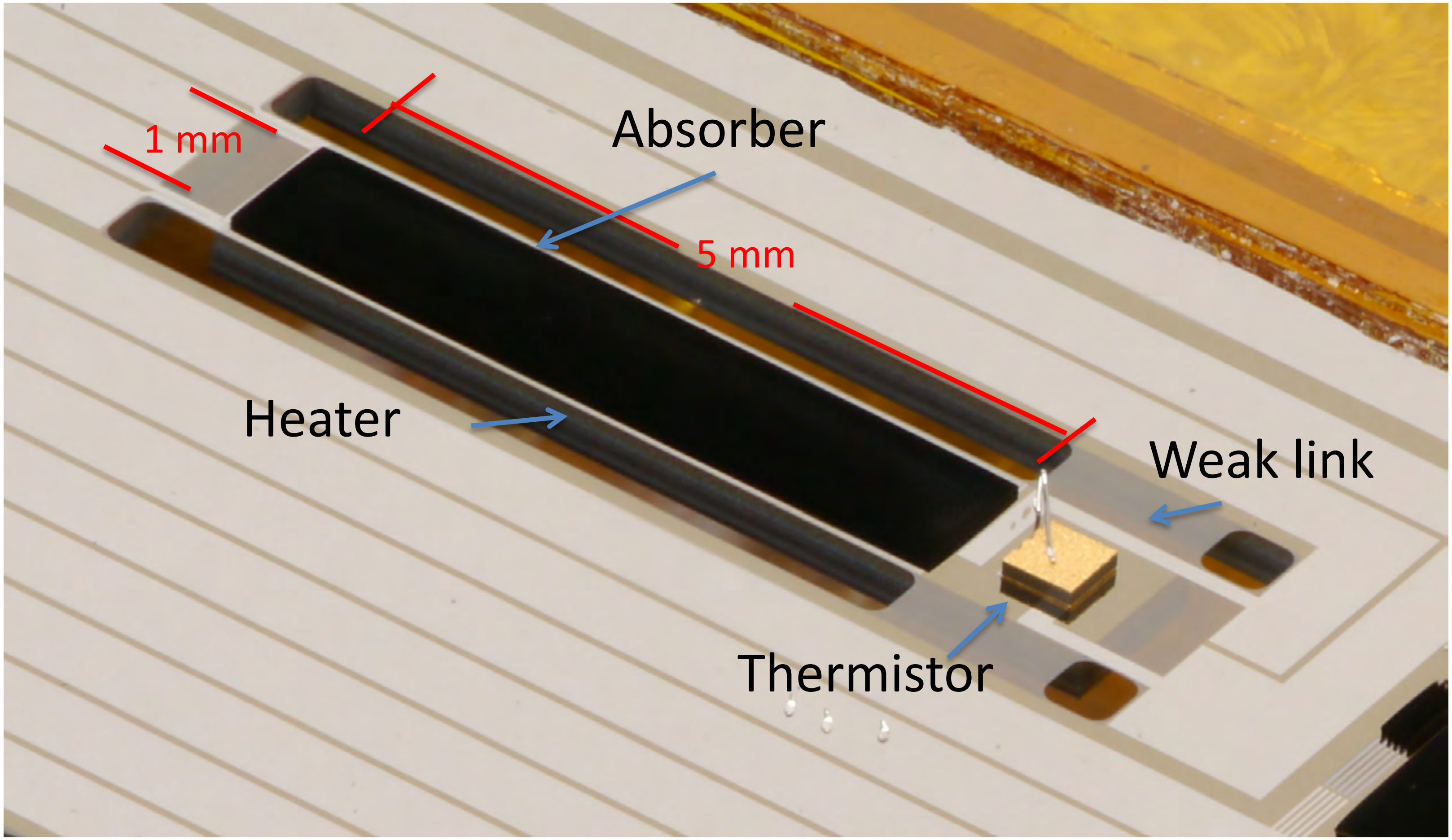
Martin, et al., , Metrologia, 21, 1985

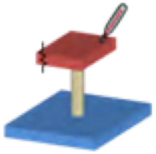
# Some classical Radiometry Applications


CSA ASC
CUBESAT
IT'S HIP TO BE SQUARE!
DIMENSIONS
10 cm
10 cm
10 cm
USED ALONE
(1 unit)
OR
CAN BE STACKED
Maximum of 16 units
COMPONENTS
An antenna
A computer
A power source
An instrument
ADVANTAGES
BUILT RAPIDLY
(within 24 months)
A·B·C
SIMPLE TECHNOLOGY
purchased off-the-shelf
SIMPLE TO DESIGN
NO SPACE DEBRIS
they burn up in the atmosphere upon reentry
LOW COST
4 TYPES OF MISSIONS
Technology demonstration
Scientific research
Educational project
Commercial
ORBIT
ISS
400 km
CubeSat
100 km
Stratos balloon
50 km
Airplane
Meteorite
10 km
Canadian Space Agency
Agence spatiale canadienne
Canada

# Spectral Irradiance, NIST on a Chip

"NIST on a Space Ship, LASP/NASA"



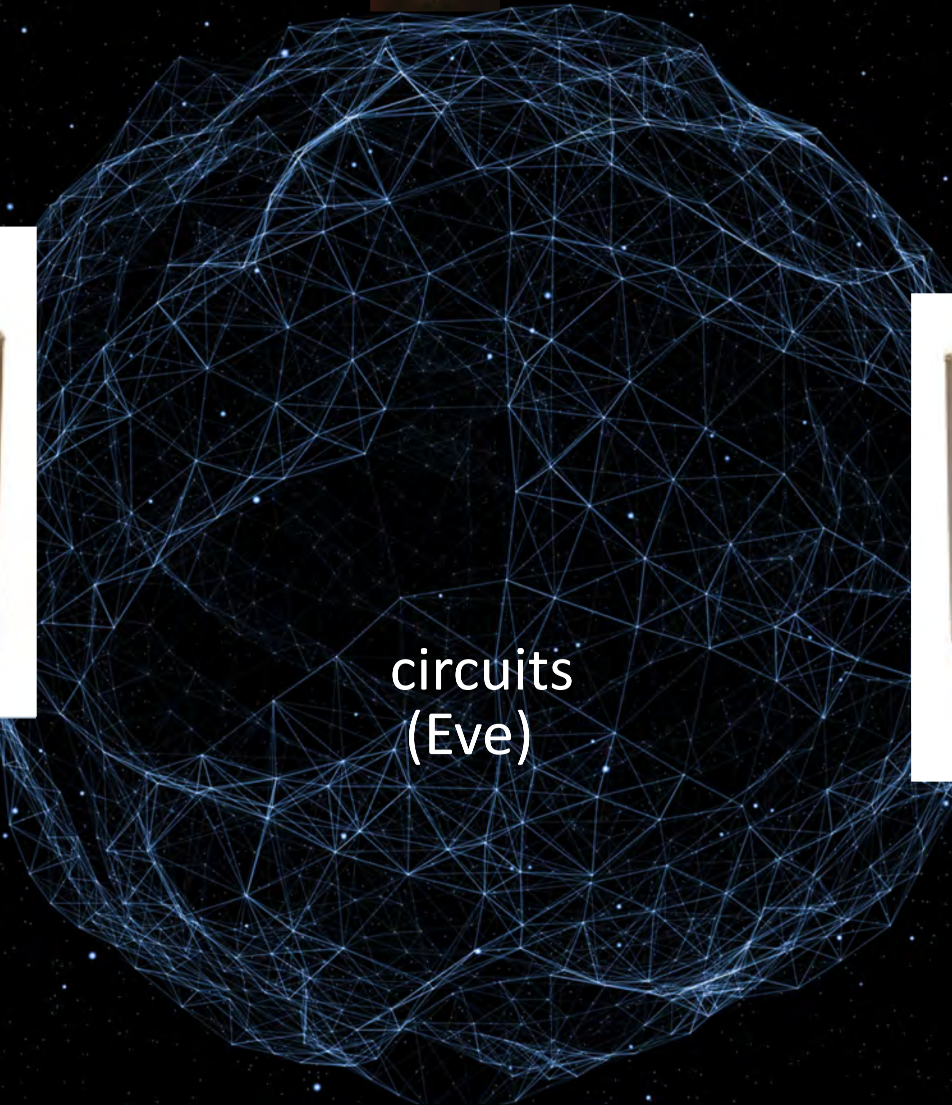



Carbon nanotube absolute radiometer

## Quantum Internet Conveyed by Photons

Bob

single photon sources




Alice

single photon detectors



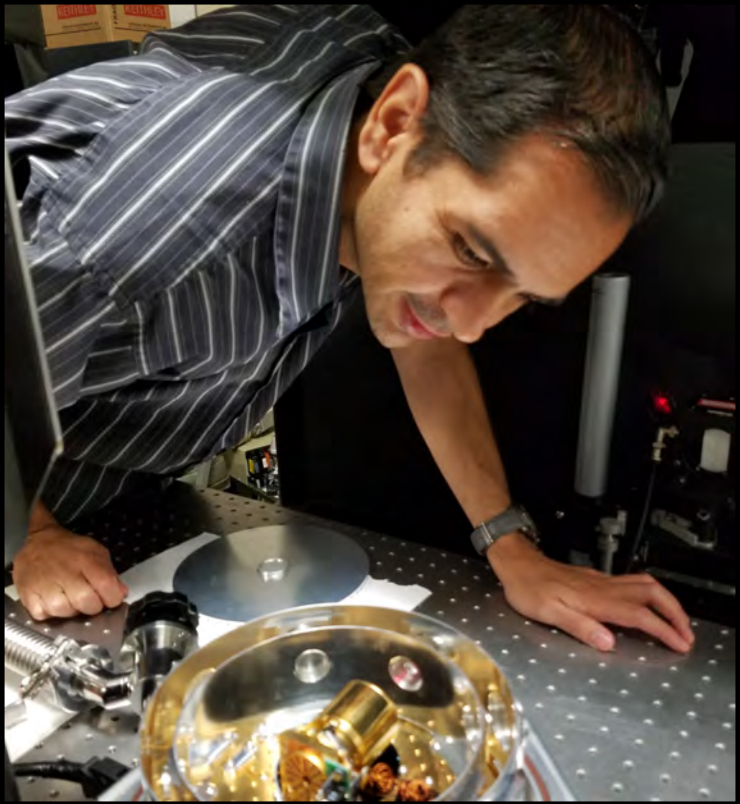
Not just cat videos, but Schrödinger Cat videos.

# Development with SIM and CENAM

Zues Gutierrez of CENAM spent twelve months with the Sources and Detectors Group in Boulder undertaking implementation of the Carbon Nanotube Radiometer for optical fiber power metrology.

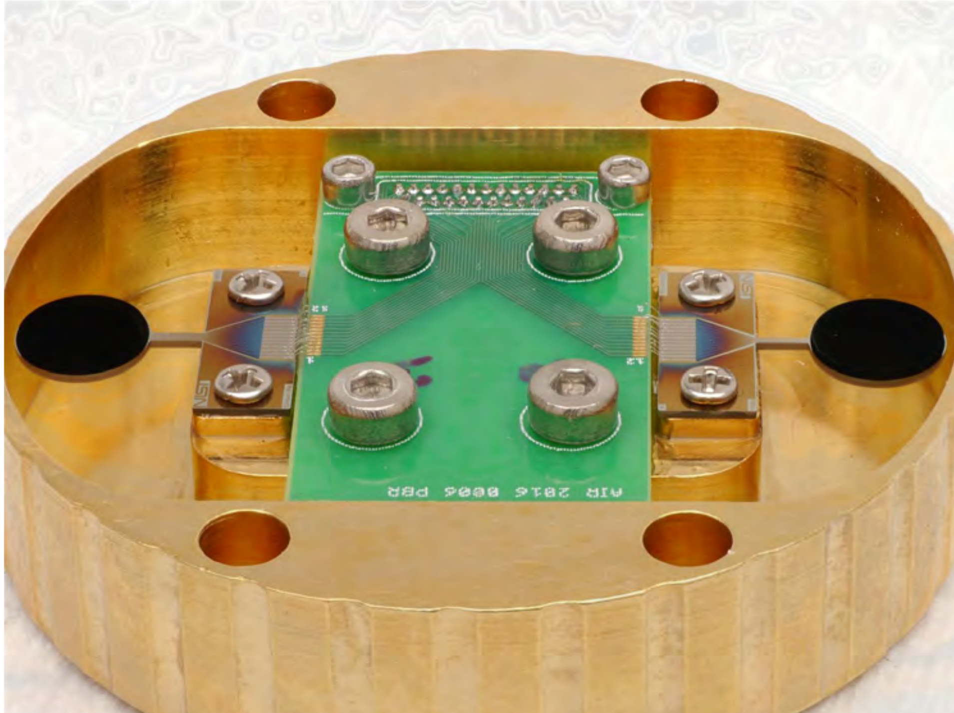
- Instrumentation
- Documentation
- Fiber-system design
- Protocol

*Continuing in 2018 and beyond*

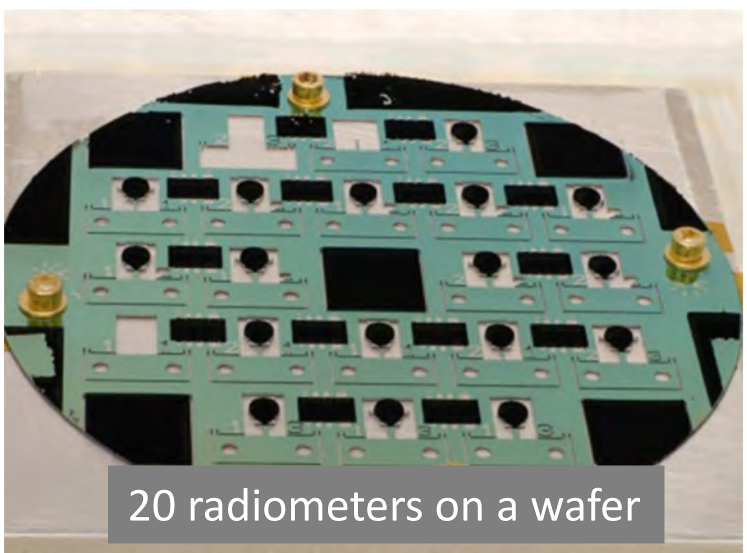


Thanks to NIST OIAA
NIST Cal Service Development $ (G. Strouse)
C. Matamoros, CENAM

# Carbon Nanotube-based Chip-scale Radiometers



Packaged radiometer for ‘embedded’ standard

20 radiometers on a wafer

# Output (NMI-Grade radiometer)

Temperature controlled stage for thermal bias and stability (complete for any fridge)

mechanically cooled

FPGA electronics either/or "COTS"

Carbon nanotube radiometer
Shipping to CENAM in 2017
for intercomparison

ca. 1985

=

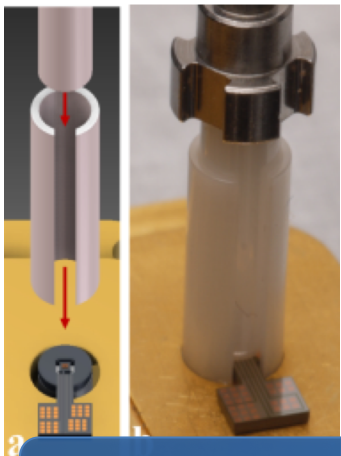

5 μK pk/pk stability (for days)

Cost reduced ~ $750k to $150k

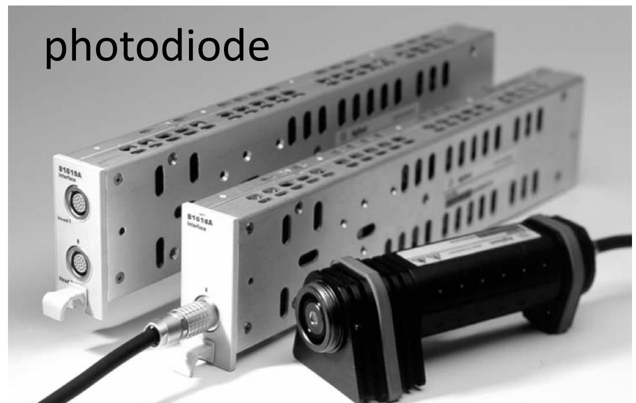
With
Malcolm White
Igor Vayshenker
Michelle Stephens
Nathan Tomlin
Chris Yung

# Single Photon Traceability

Defining traceability by means of
- synchrotron source linearity
- classical radiometry
- with PTB et al.



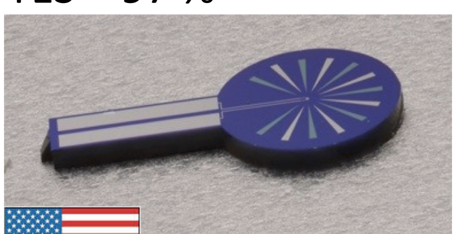
photodiode

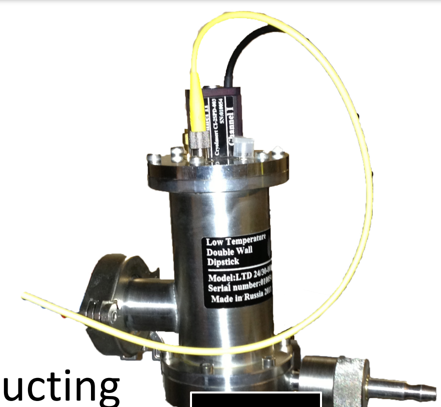


fiber radiometer

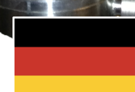
Few photons — — — — — — picowatts — — — — — microwatts

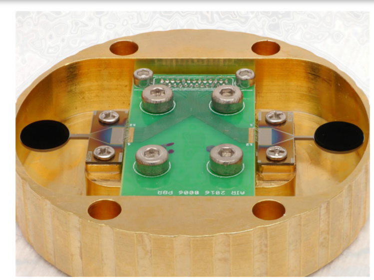
Superconducting TES ~ 97 %



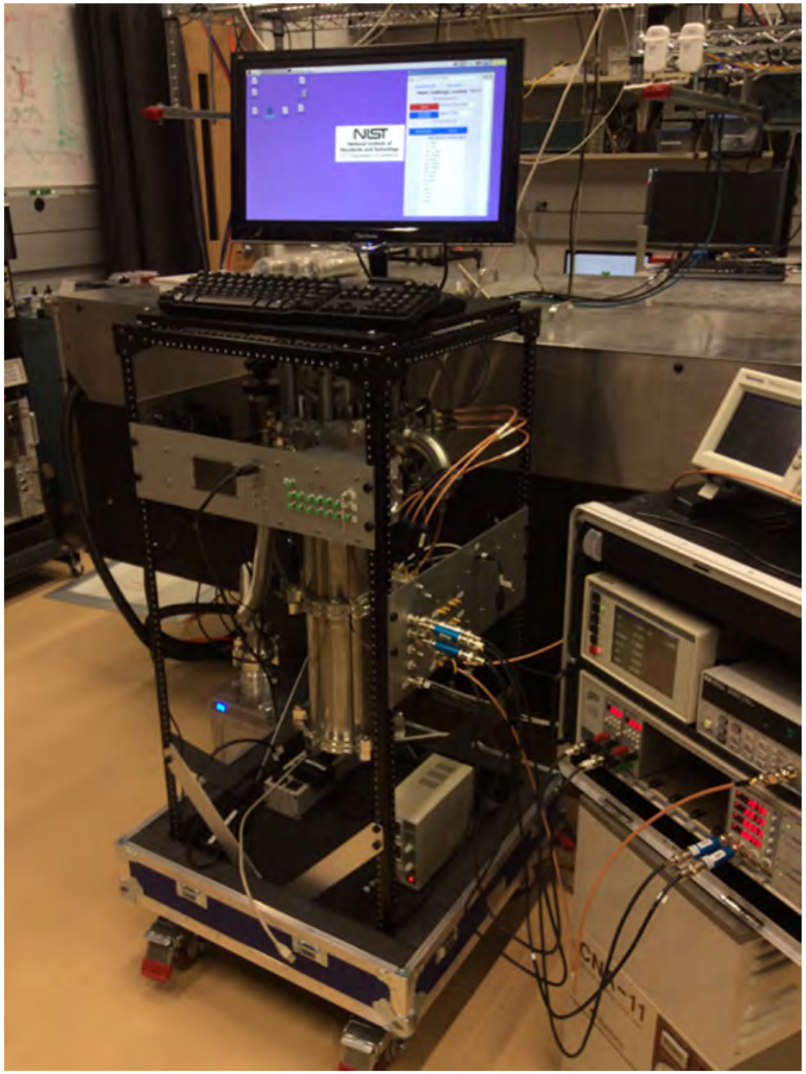


superconducting nanowire ~ 13 %

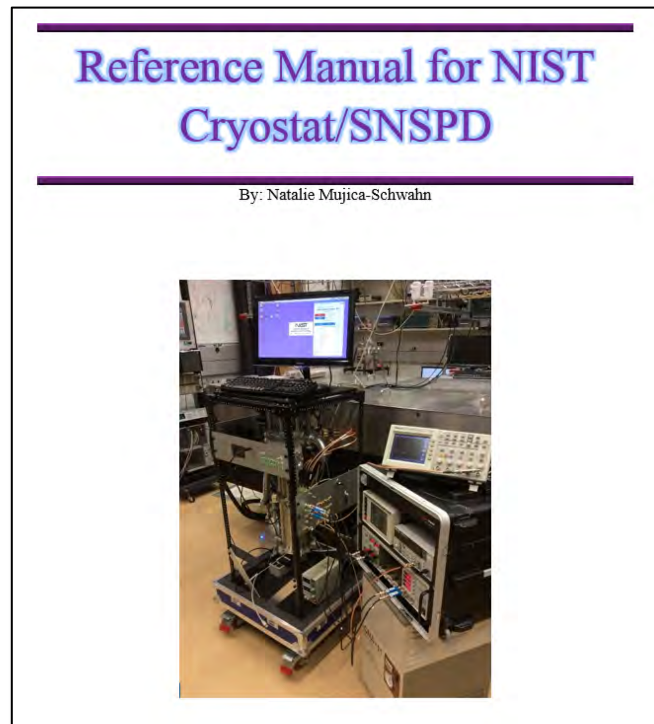




# Portable Single-Photon Detector Calibration System

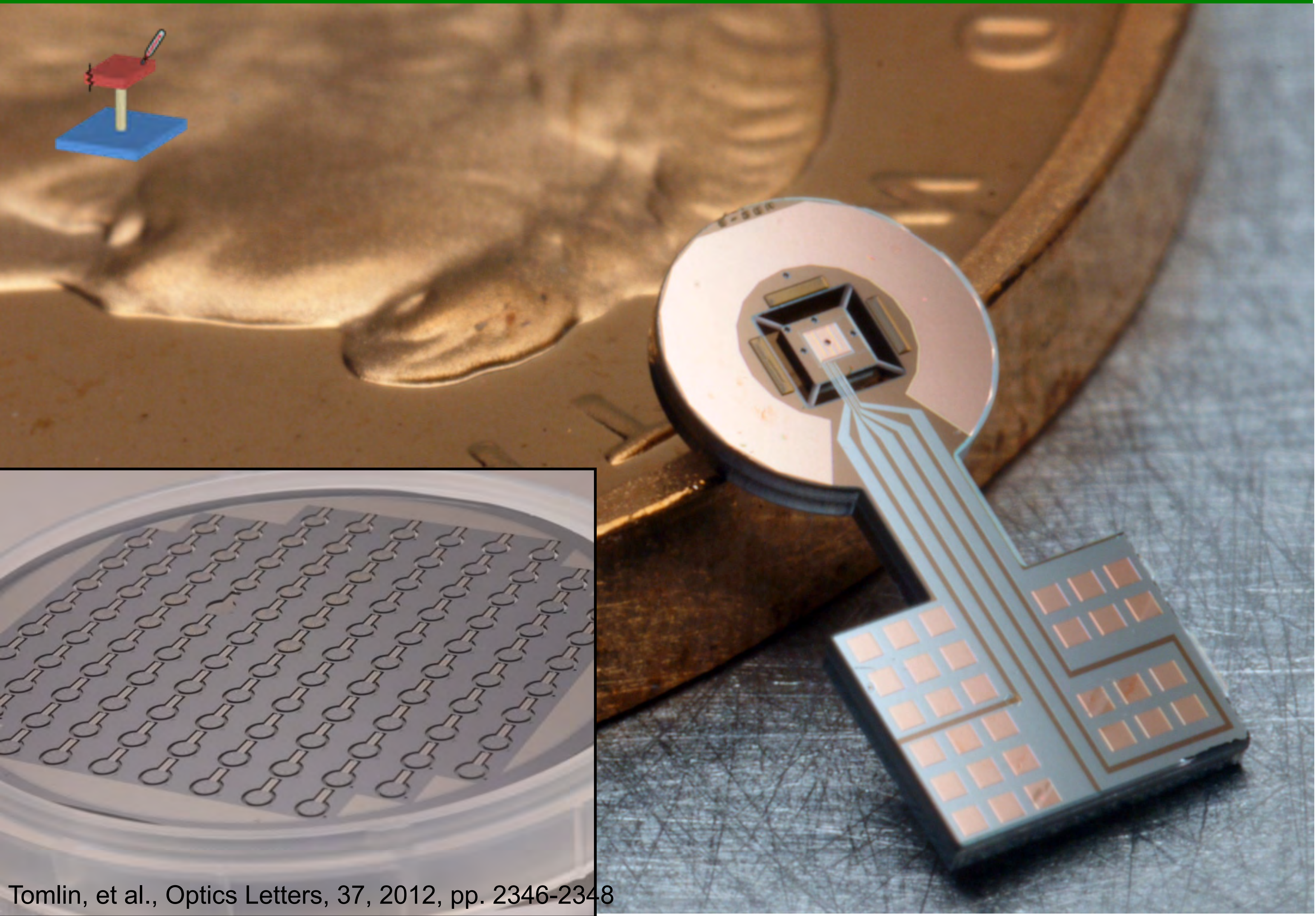


- *Portable/shippable*
- *International Comparison 2018*
- *First Nanowire calibration system*
- *NIST Calibration Service 2017*


Reference Manual for NIST Cryostat/SNSPD

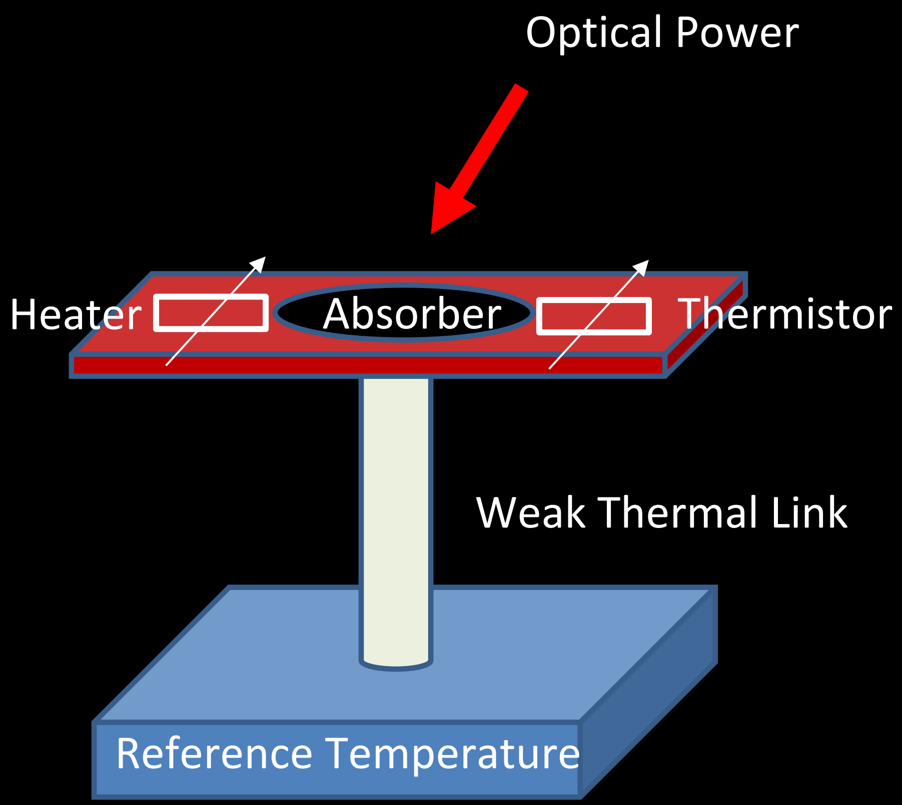
By: Natalie Mujica-Schwahn

# Fully lithographic superconducting transition radiometer



Tomlin, et al., Optics Letters, 37, 2012, pp. 2346-2348

# Present Primary Standardization



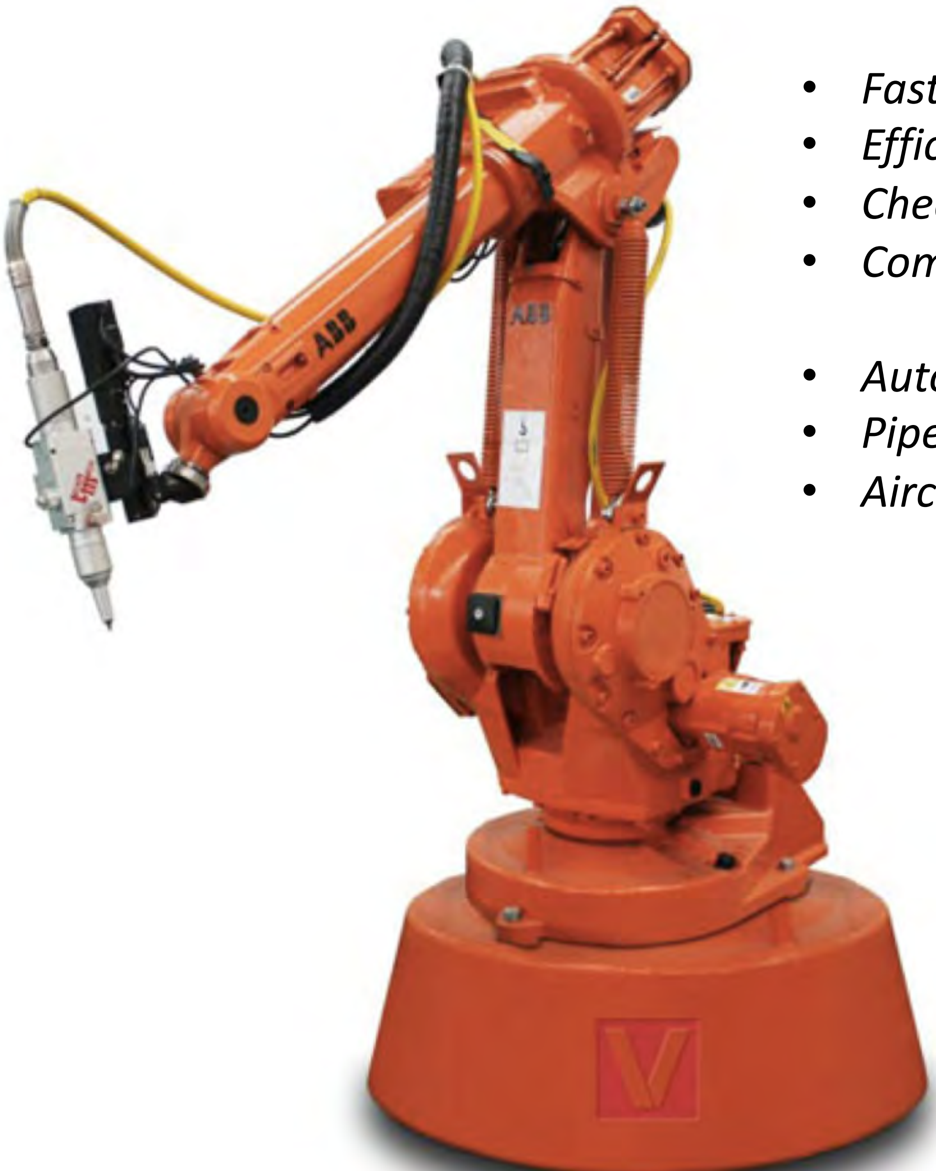

This is difficult to scale to kilowatts!

# Commercially Available High Power Lasers


To meet the needs of DoD and manufacturing

Diode Pumped Fiber Lasers
~ $50/W

# A new era in – laser-based manufacturing




- *Fast*
- *Efficient*
- *Cheap*
- *Competitive*

- *Automobiles*
- *Pipelines*
- *Aircraft quality assurance*

> $1E9 industry

*How (and why) do we serve the multi-kW industry?*

# Laser-Based Manufacturing (Welding)

32 m of Laser Welds in a Jetta (Fraunhofer, Dresden)

# No more rivets

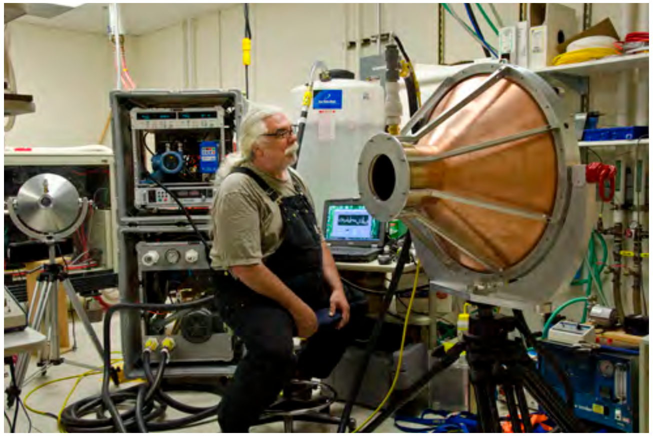
*1 % Laser power variation is the difference between a cut and a weld in thin materials*

# Additive Manufacturing (3D Laser Printing)

GE Jet engine nozzle
$3M/aircraft savings

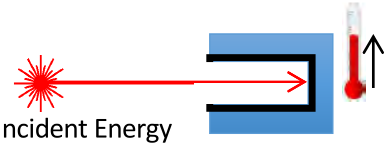
# High Power Laser Radiometry: State-of-the-Art

***Calibration at ~10s of kW***



**Traditional approach:**

Energy meter
Absorption-based
Energy $\propto \Delta T$

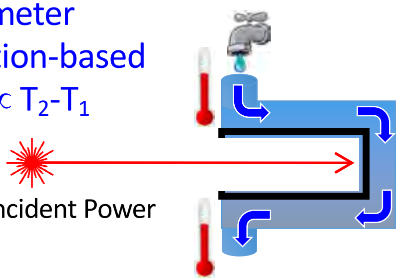



**Calorimeter:**

Energy range: > *300 kJ*
Response time: *minutes*
Size: *cubic meters*
Weight: *hundreds of pounds*
~1% uncertainty

**Current State-of-the-Art:**

Power meter
Absorption-based
Power $\propto T_2$-$T_1$




**Flowing water power meter:**

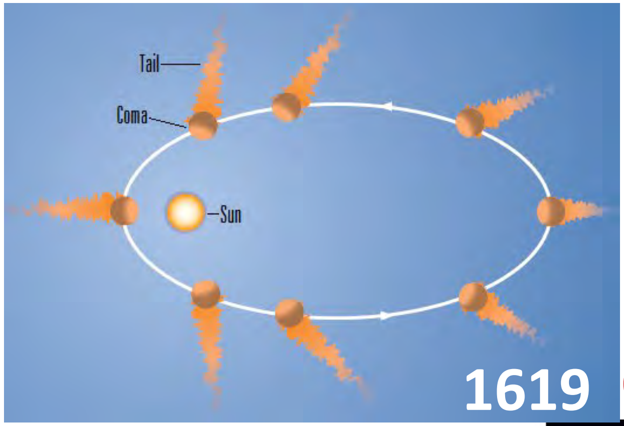
Power range: *1 - 100 kW*
Response time: *tens of seconds*
Size: *cubic meters*
Weight: *hundreds of pounds*
~1% uncertainty

**???**

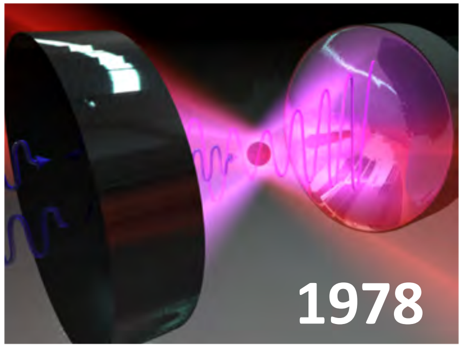
- Sub-second response
- "small" and portable
- ~1% uncertainty

# Photons have energy *and* momentum

(Comet tail)

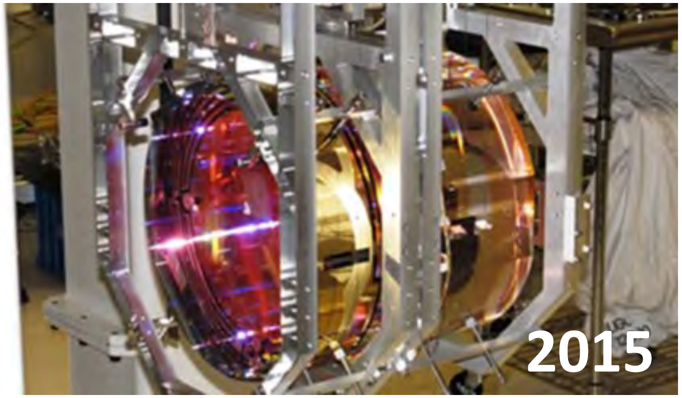



(Optical tweezers)




(Viking Spacecraft)


(LIGO mirrors)



# How much does a photon weigh?

# Radiation Pressure (photonic mole)

$6.023 \times 10^{23}$ Photons (for example)

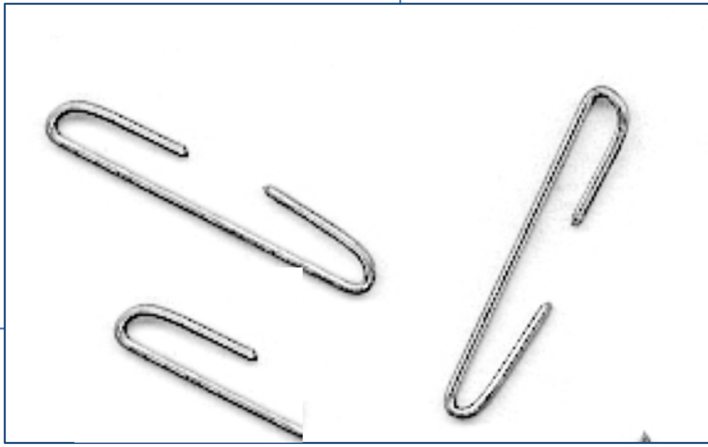
$$Wavelength = \lambda = 1\mu m$$

$$Energy_{photon} = \frac{hc}{\lambda(1.6 \cdot 10^{-19}\ \mathrm{J/ev})}$$

$$Power = mole(E_{ph}(1.6 \cdot 10^{-19}\ \mathrm{J/eV}))$$

$$Pressure = 2\frac{mole}{Area}\frac{h}{\lambda}$$ reflected

$$Staples = \frac{mass}{33\ mg}$$



1 mole ≈ 2.5 staples ≈ 119 kW

# Mass calibration

**Conversion factor (normal incidence, perfectly reflecting mirror):**

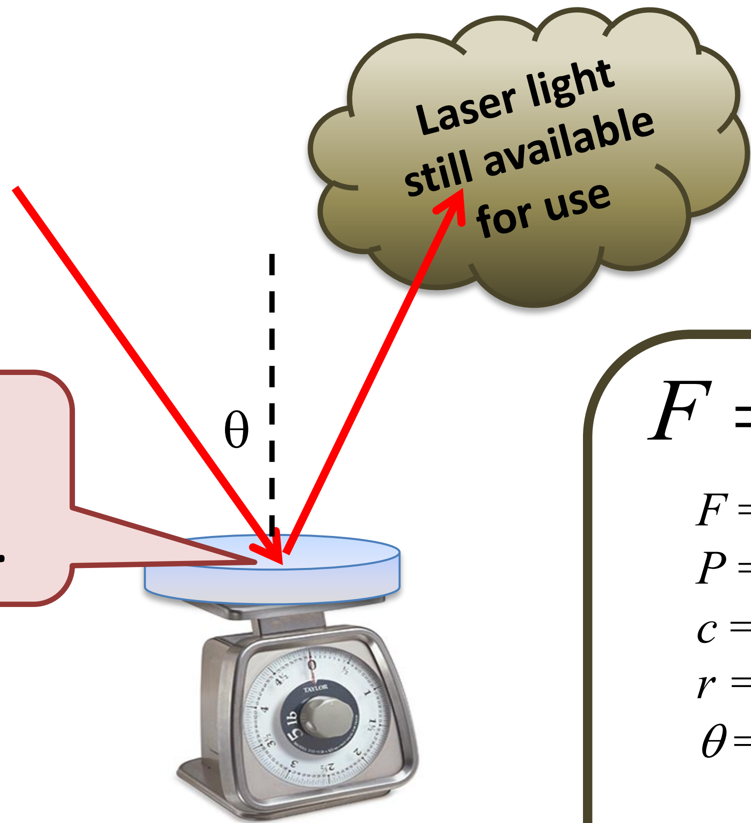
$$k = 6.67\times10^{-9}\ \mathrm{N/W} \longrightarrow 670\ \mu\mathrm{g}\ /\ \mathrm{kW}$$

| Laser power | Application | Equivalent mass | Object |
|---|---|---|---|
| **10 W** | Marking | 6.7 microgram | eyelash |
| **1 kW** | Welding/Cutting | 670 microgram | grain of sand |
| **100 kW** | Research / Defense | 67 milligrams | two staples |

Pressure = Irradiance/(speed of light)

# Optical Watt Traceable to the kilogram?

**Concept:** A precision scale with a mirror attached can measure the radiation force of light.




**Minimal absorption, power-scalable, no thermal recovery time.**

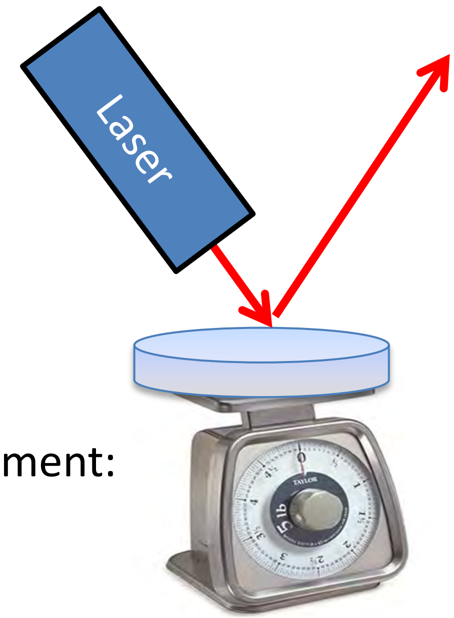
$$F = (2P / c) r \cos\theta$$

$F$ = Force (Newtons)
$P$ = optical power (Watts)
$c$ = speed of light (m/s)
$r = R+(1\text{-}R)\alpha/2 \rightarrow$ reflectivity
$\theta$ = angle of incidence

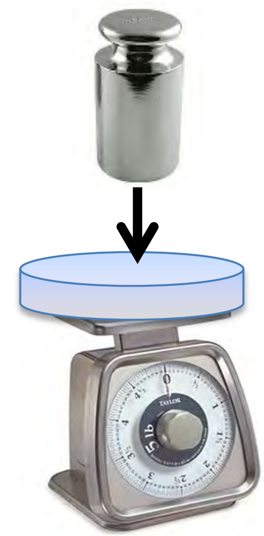
$$P = F \cdot (c / 2r\cos\theta)$$

# Optical Watt Traceable to the kilogram?

Measurement:

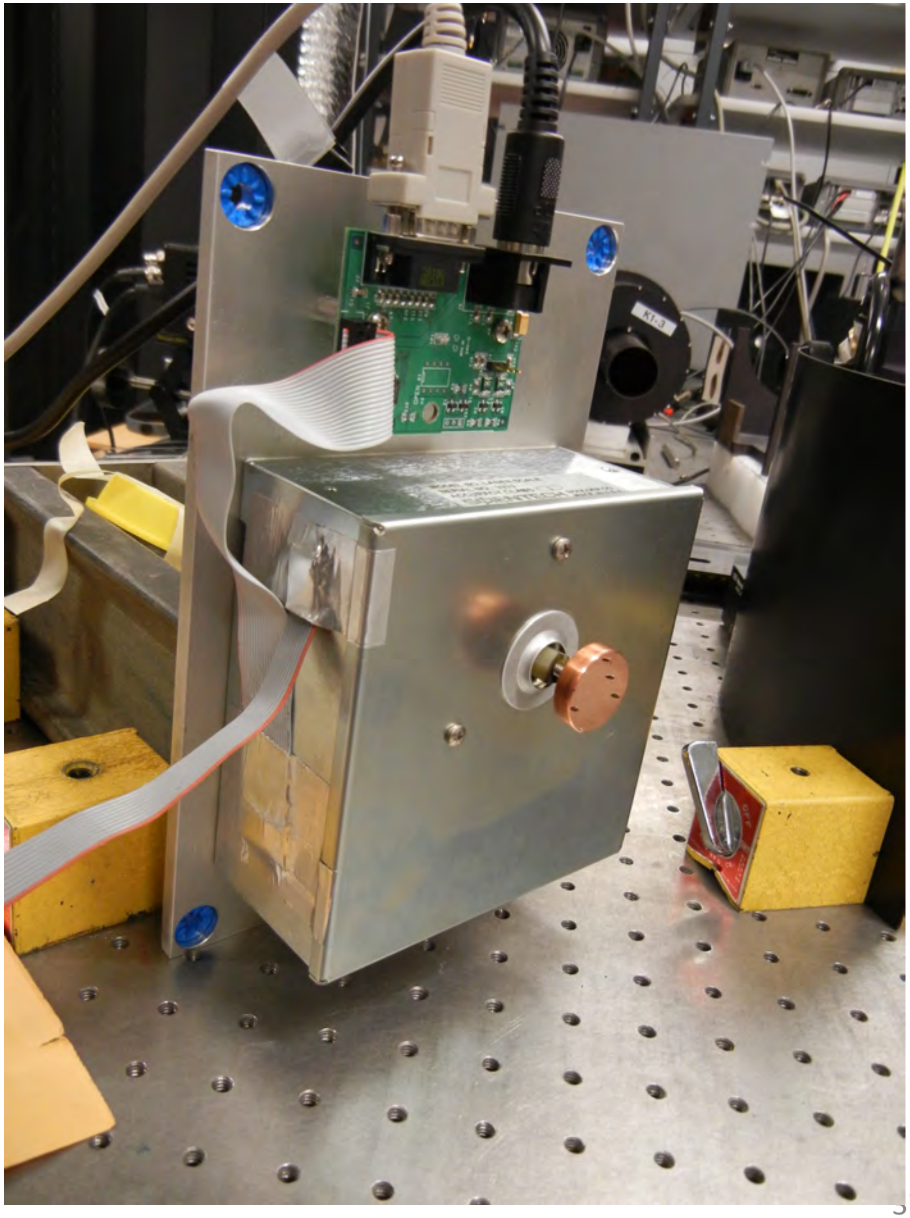



Calibration:

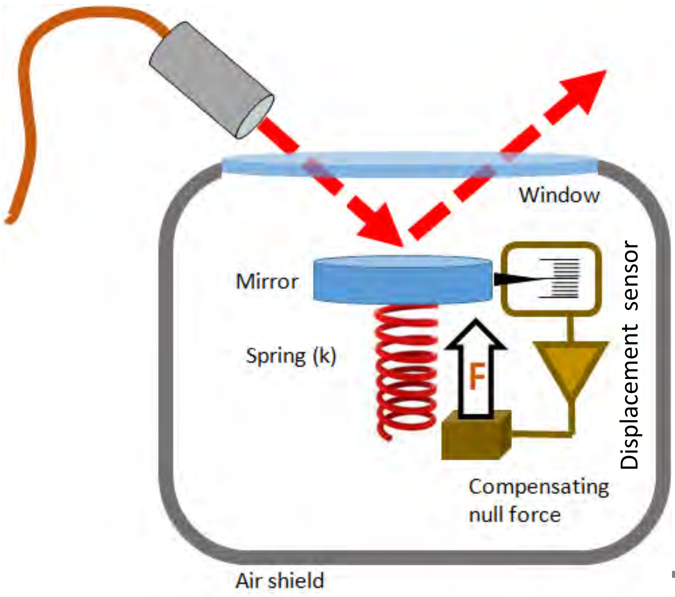


# How?

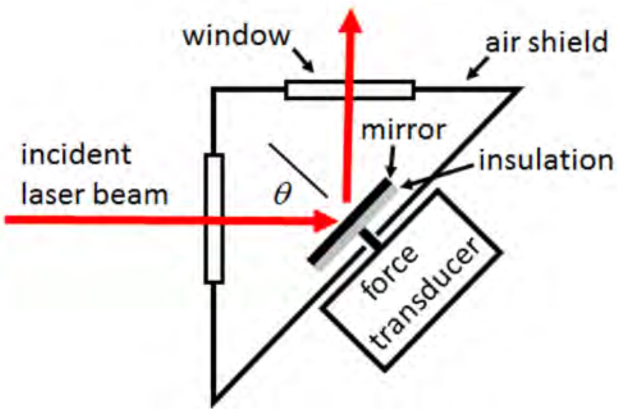
# Tech Transfer

# Radiation pressure power meter (RPPM) design



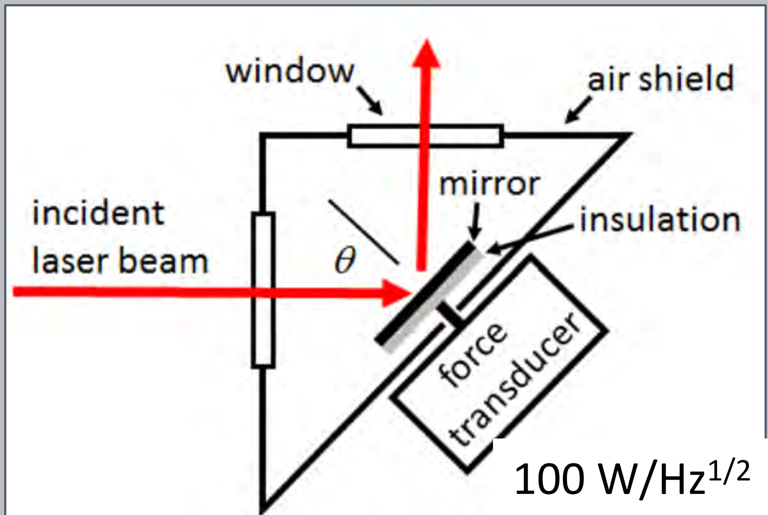

*With Scientech, Inc., Boulder, Colorado*



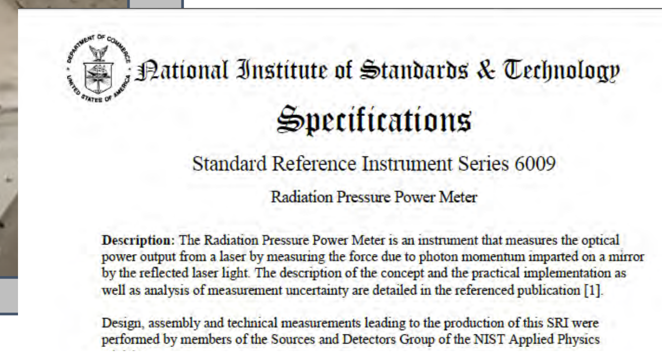

## Specifications

| | |
|---|---|
| Dimensions: | 30x30x30 $cm^3$ |
| **Power:** | |
| Noise-equivalent power | 100 W/√Hz |
| *Calibrated and validated* (1.6 %, 2U) | 1 – 10 kW |
| *Early prototype measurement* | 92 kW |
| *Non-NIST intracavity measurement* | 500 kW |
| **Response time:** | |
| *Settling time* | 5 s |

# Photon Momentum: Standard Reference Instrument




**Radiation Pressure Power Meter (RPPM)**


National Institute of Standards & Technology

Specifications

Standard Reference Instrument Series 6009

Radiation Pressure Power Meter

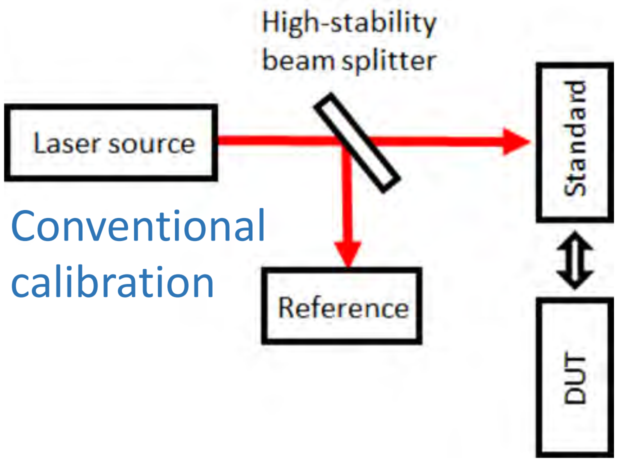
**Description:** The Radiation Pressure Power Meter is an instrument that measures the optical power output from a laser by measuring the force due to photon momentum imparted on a mirror by the reflected laser light. The description of the concept and the practical implementation as well as analysis of measurement uncertainty are detailed in the referenced publication [1].

Design, assembly and technical measurements leading to the production of this SRI were performed by members of the Sources and Detectors Group of the NIST Applied Physics

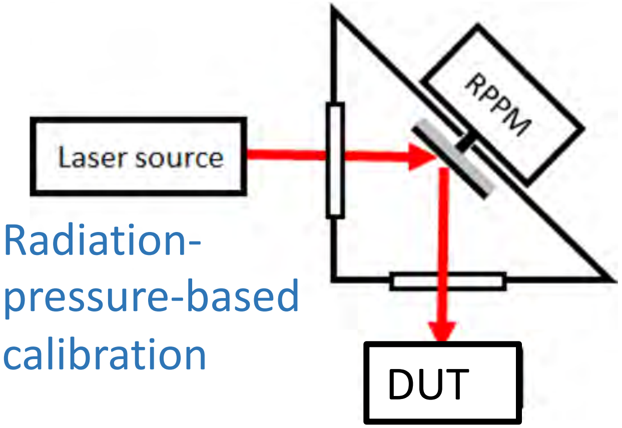
P. Williams, et al., *Optics Express*, **25**, 4382 (2017), Patent 9,625,313

- *Standard established 2017*
- *Disseminated to DoD up to 50 kW*

# Measurements, calibration, and validation

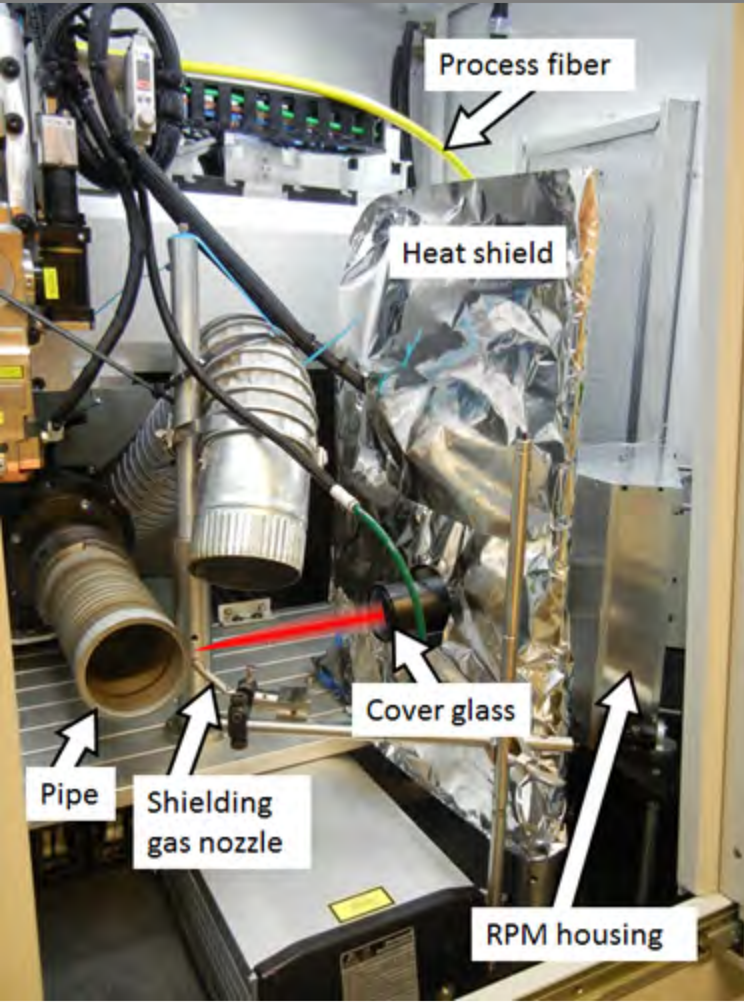


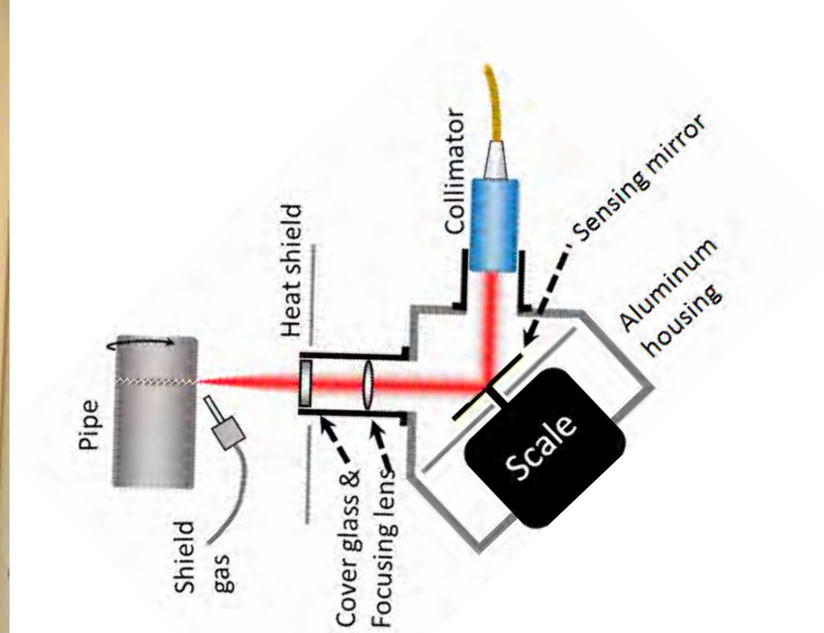

Conventional calibration

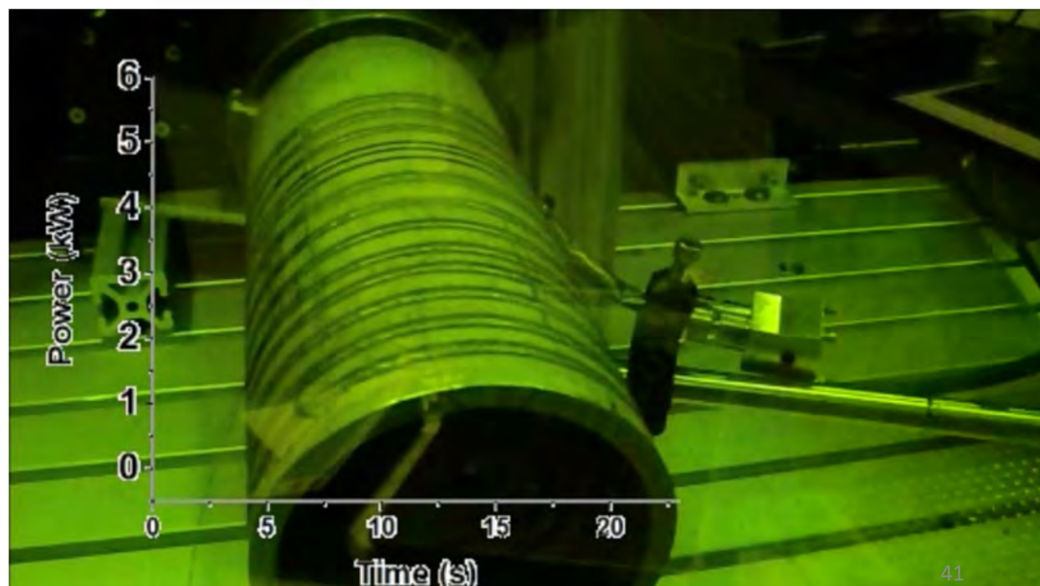


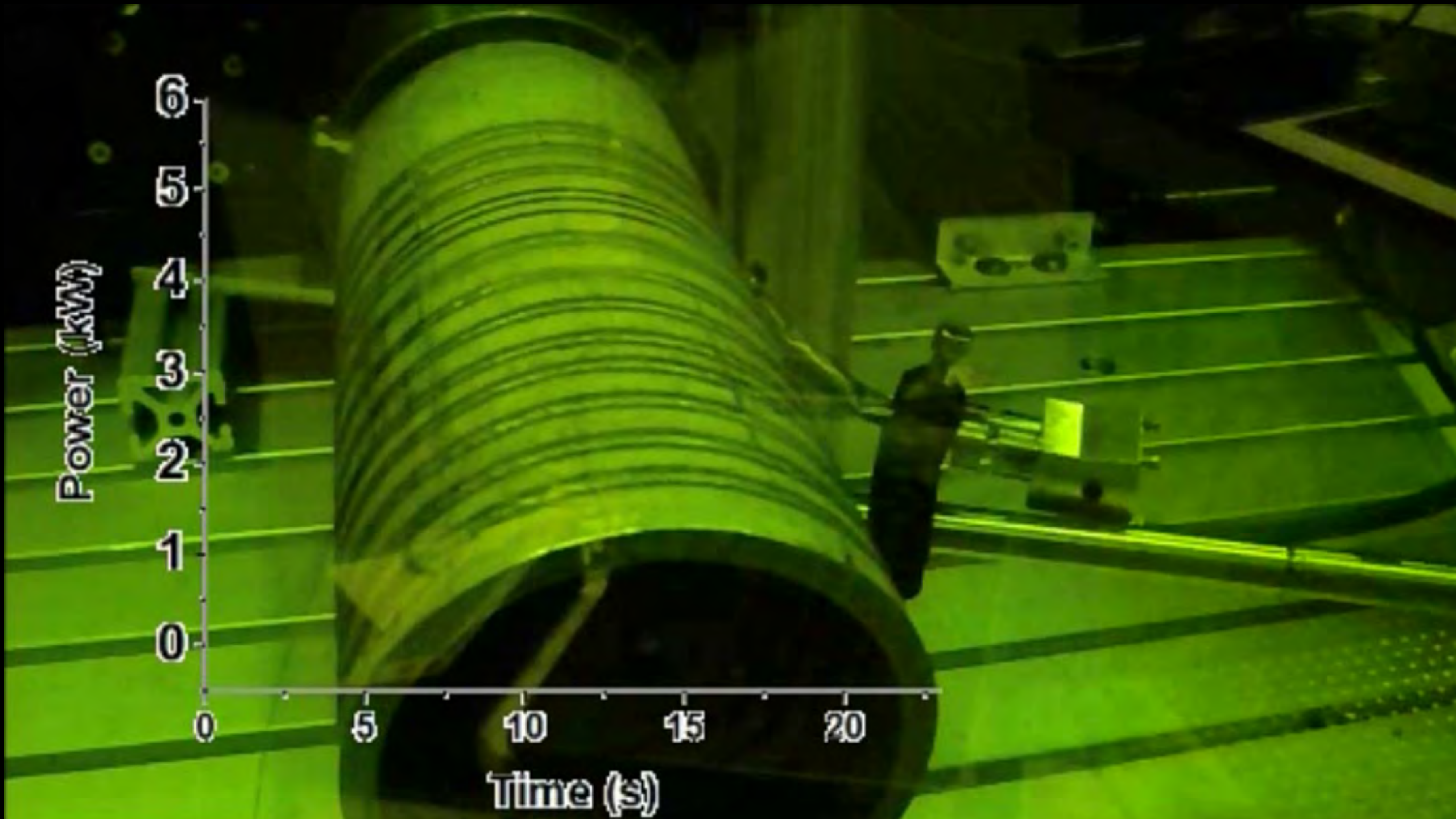

Radiation-pressure-based calibration

# *In-situ* power measurement



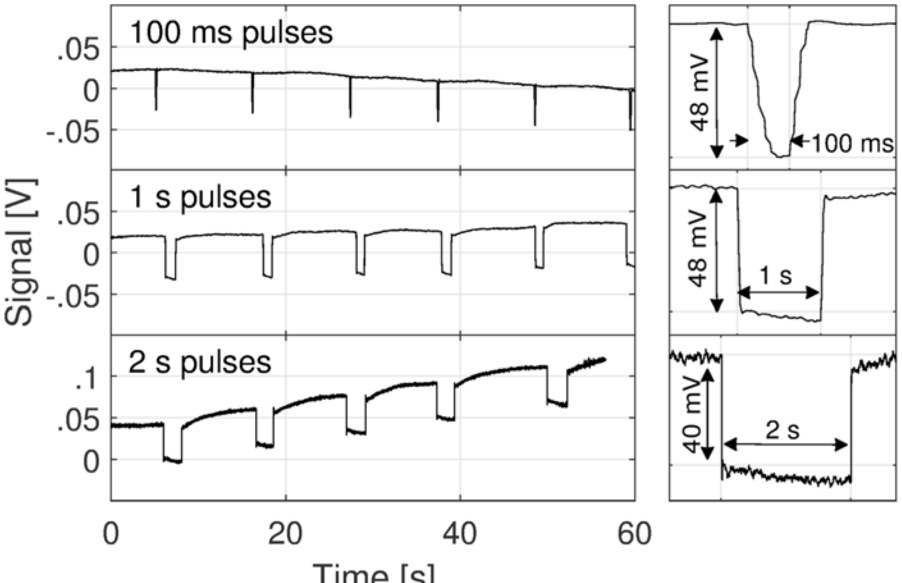

Power (kW)
6
5
4
3
2
1
0
0
5
10
15
20
Time (s)

# Photon Momentum: SRI & "Smart Mirror"

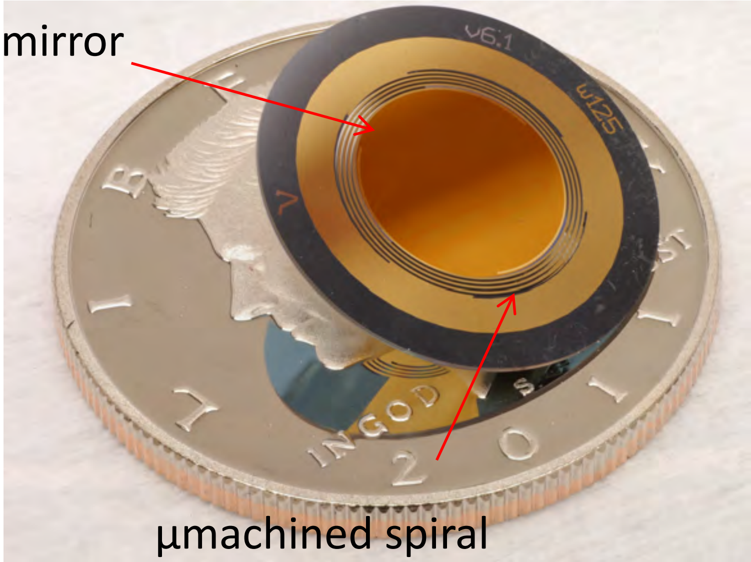
**Smart Mirror**


1 W/Hz$^{1/2}$

- *Optical power traceable to the kilogram*
- *Smart Mirror int'l patent allowed 2018*




Bragg mirror



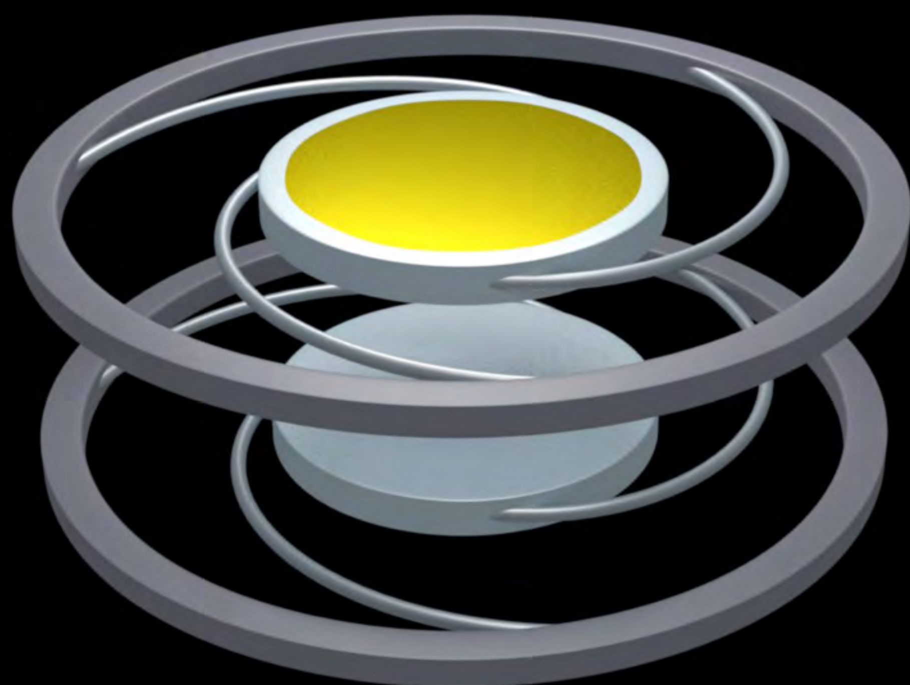
µmachined spiral legs



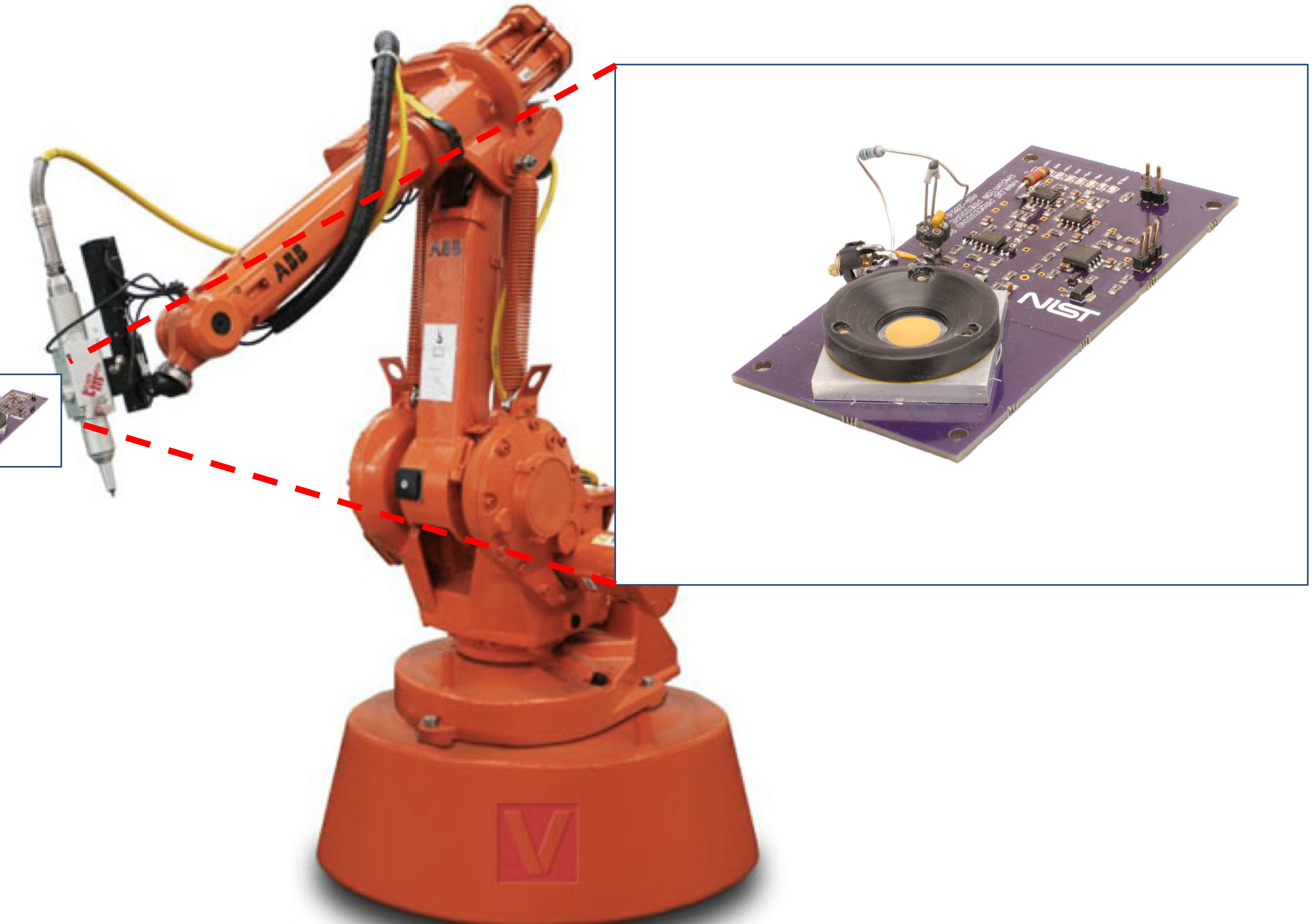
www.nist.gov/programs-projects/photoforce-project

# Smart Mirror Refresher

## Miniaturized Radiation Pressure Sensor

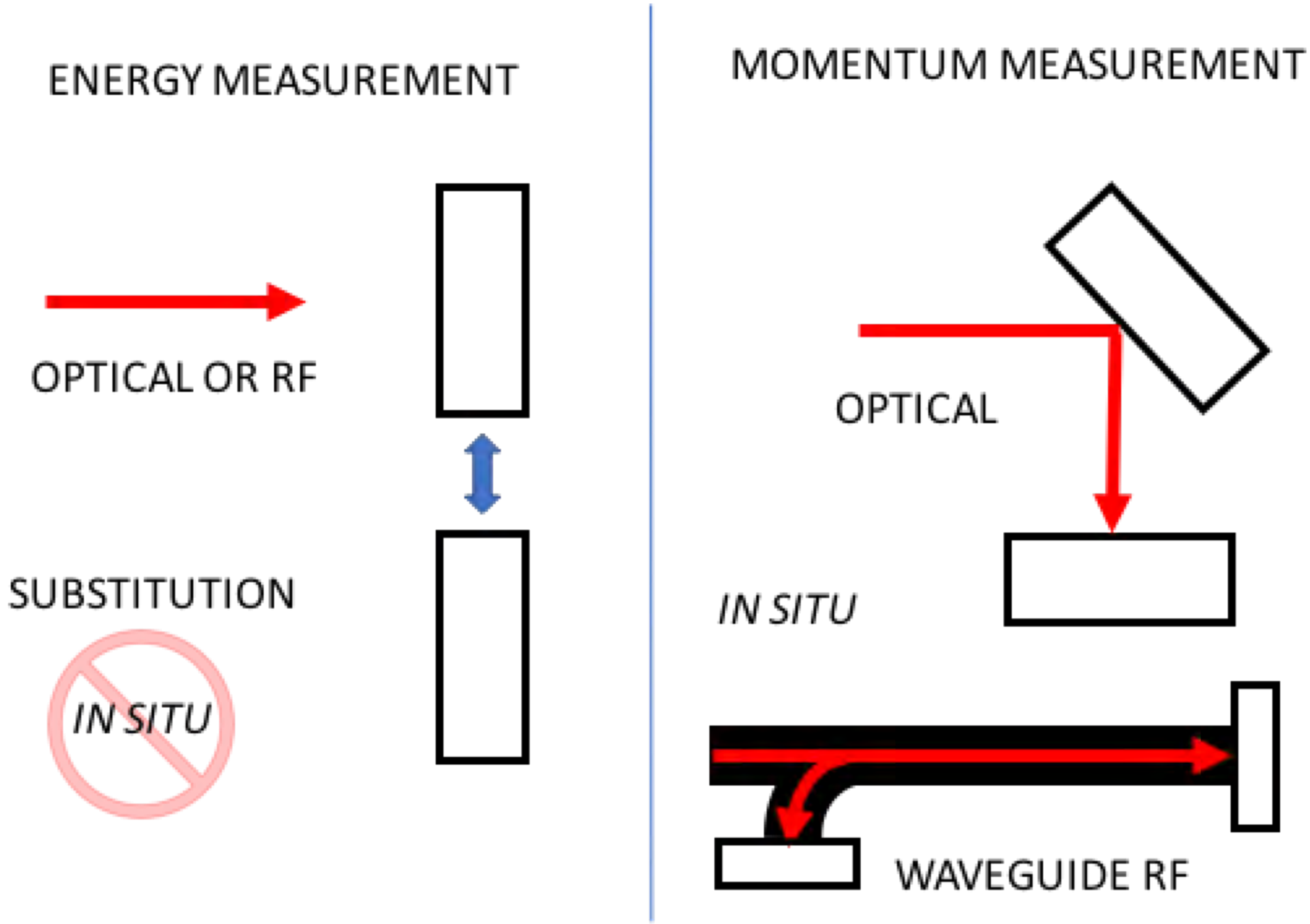


# A new era in – laser-based manufacturing

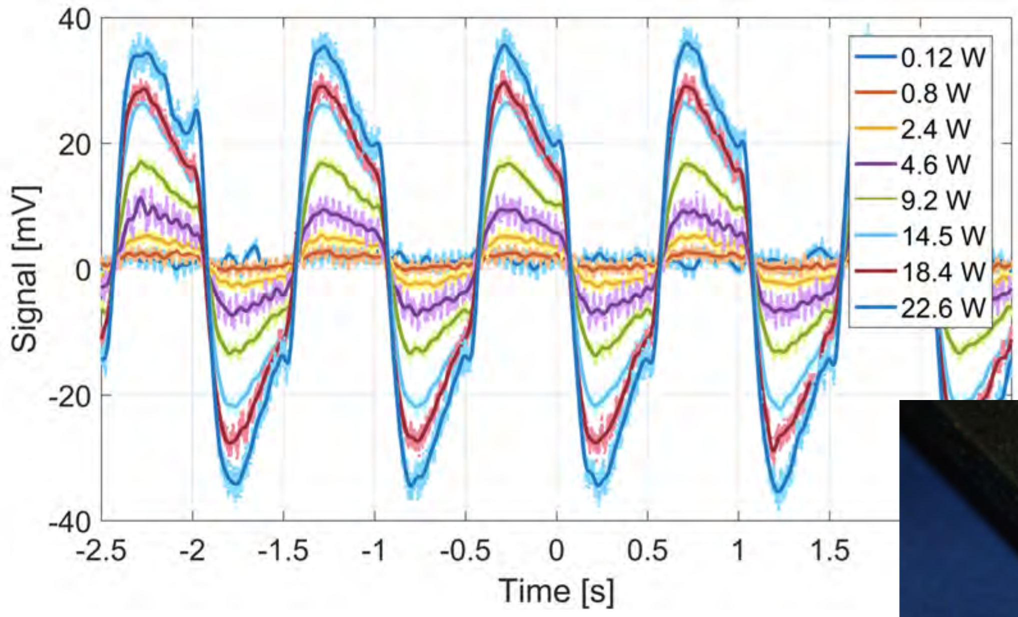



*How (and why) do we serve the multi-kW industry?*

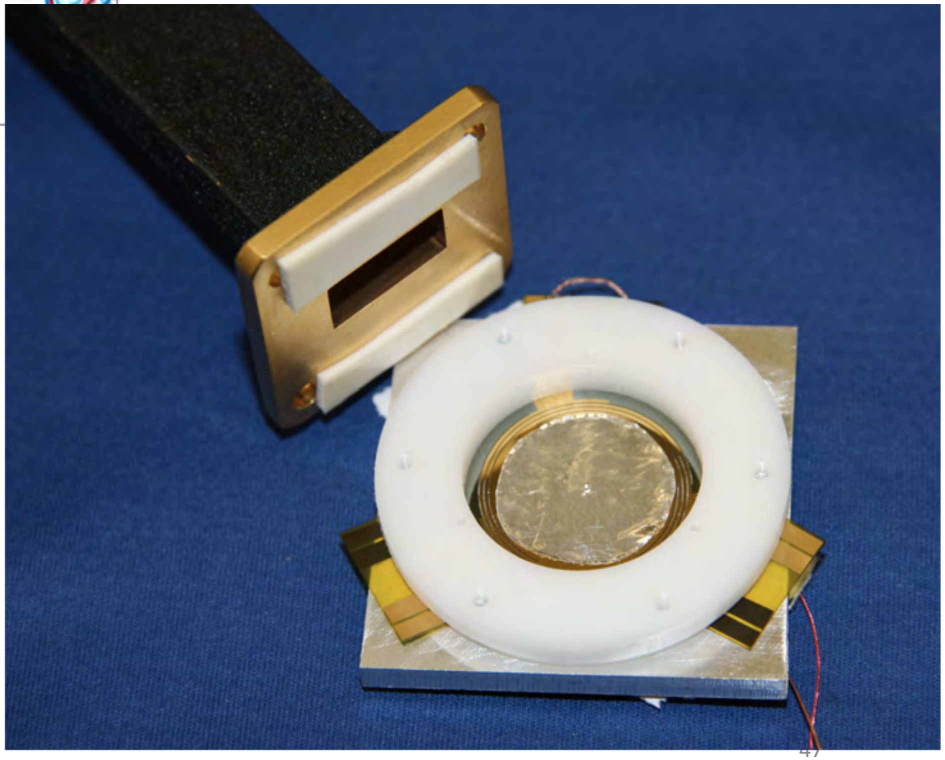
# *In-situ* power measurement for *RF and Microwave*



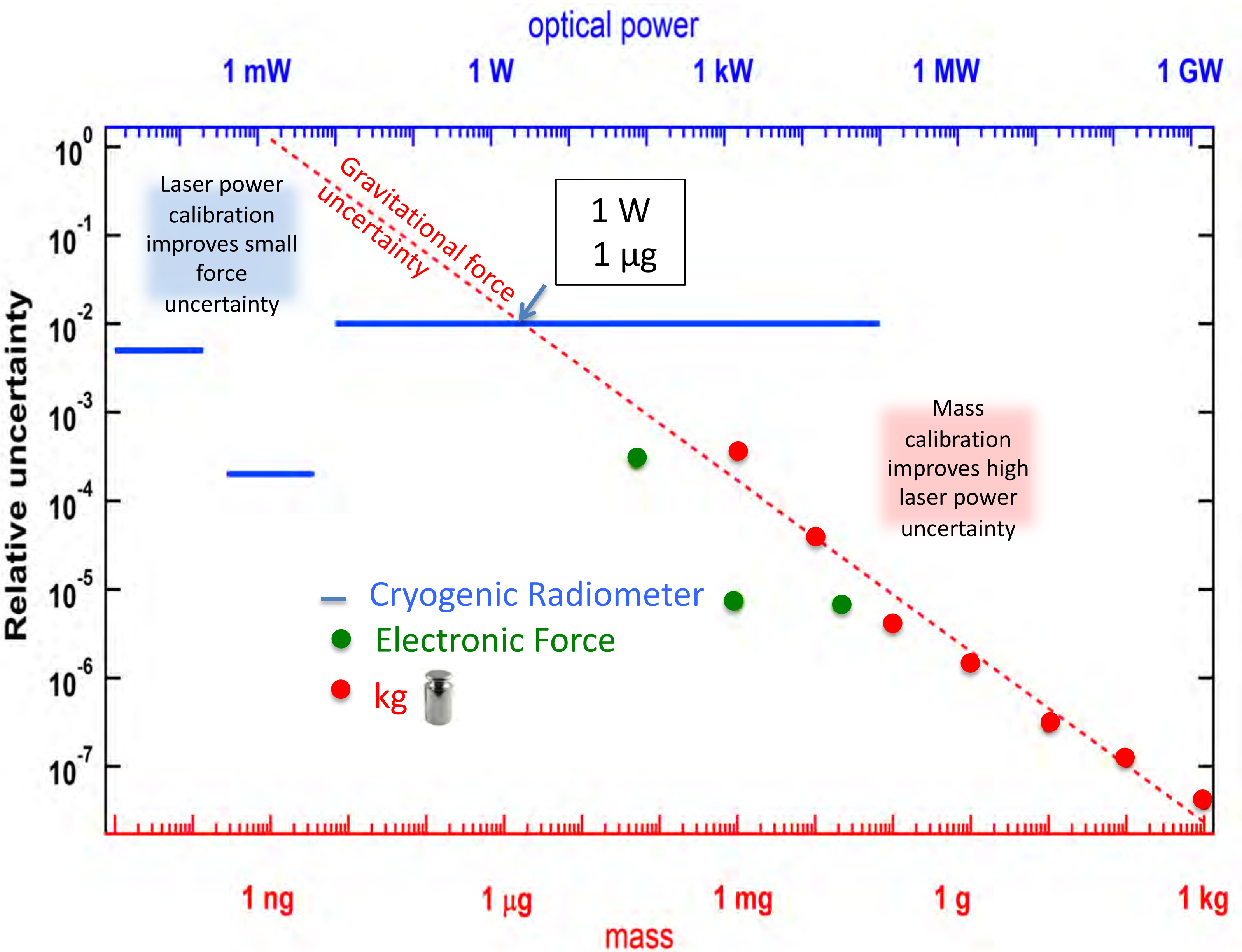
# *In-situ* power measurement



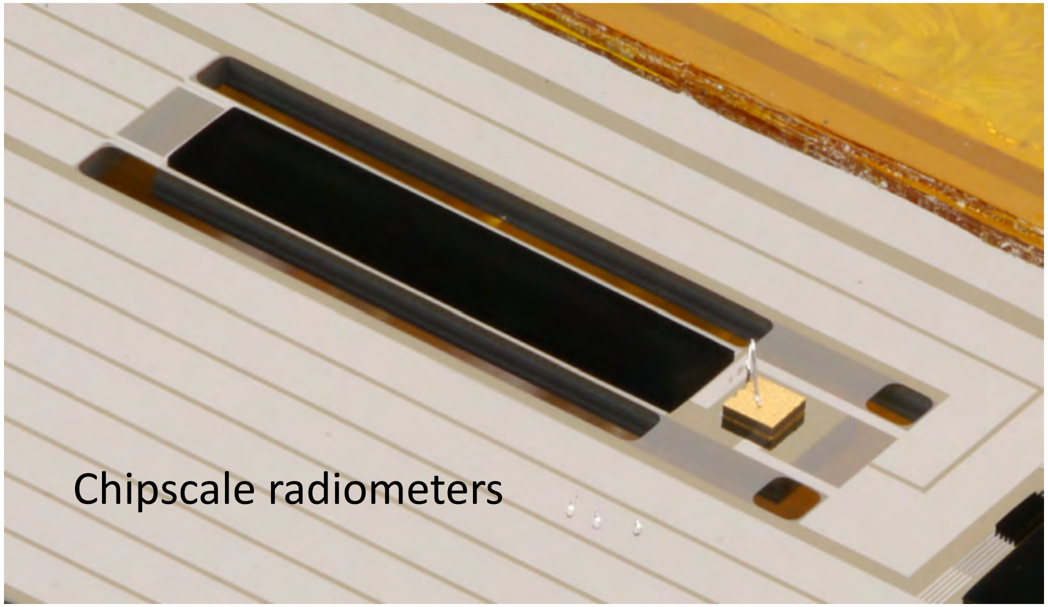

15 GHz



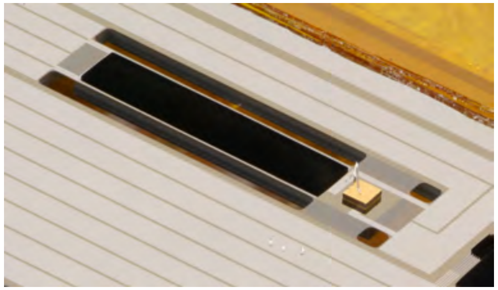
# Using Force to Measure Light and Vice Versa

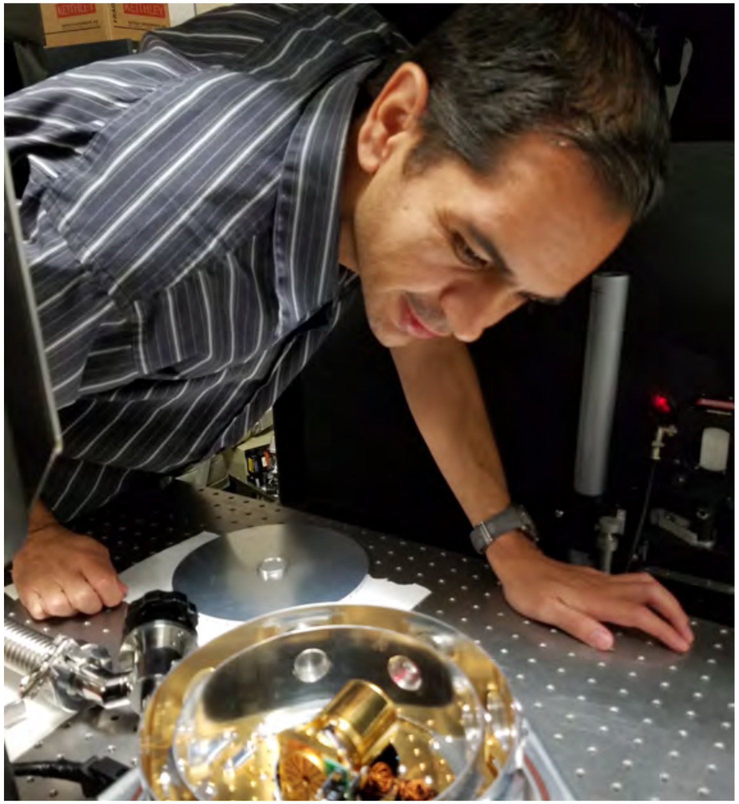


# Summary

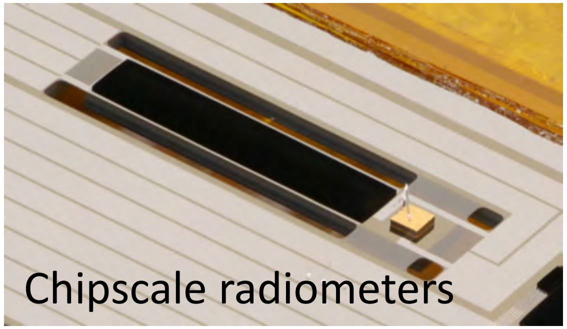


# Summary





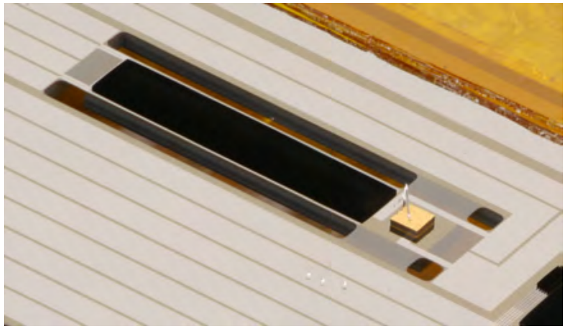
# Summary

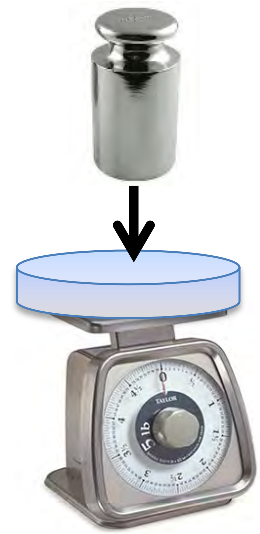




Optical Power Traceable to the $h$ by way of kg

# Summary



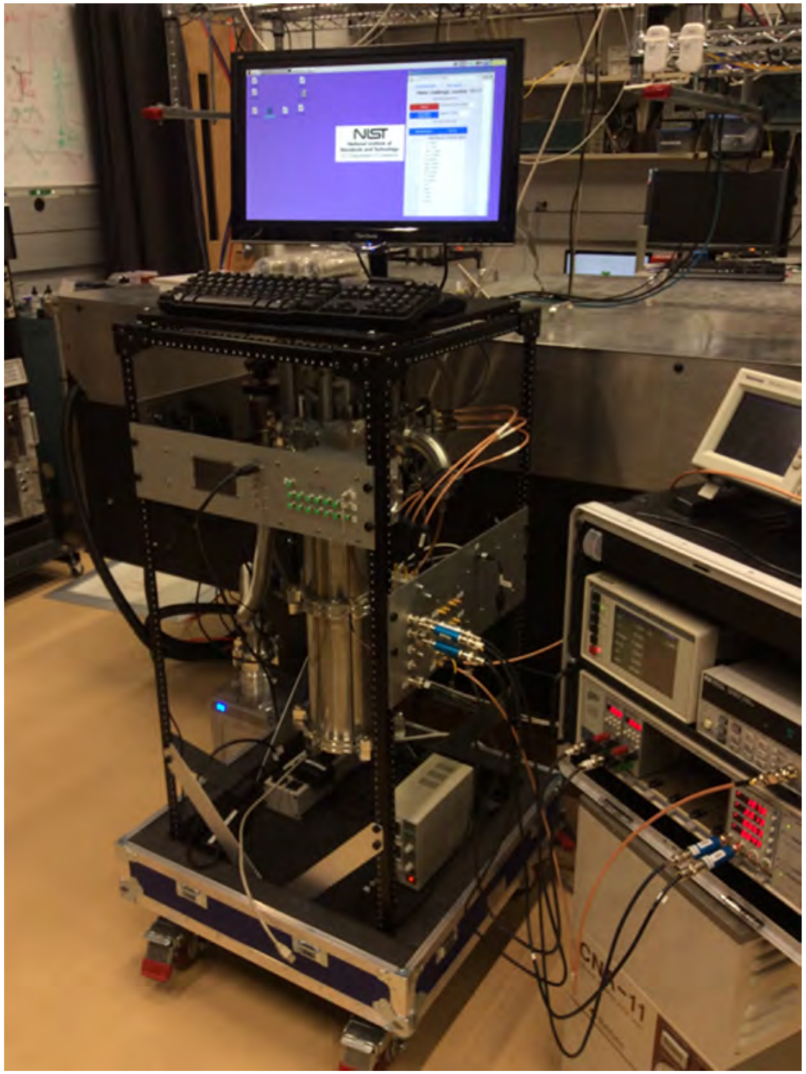


Chipscale photonic force sensors
“UV to 5G”

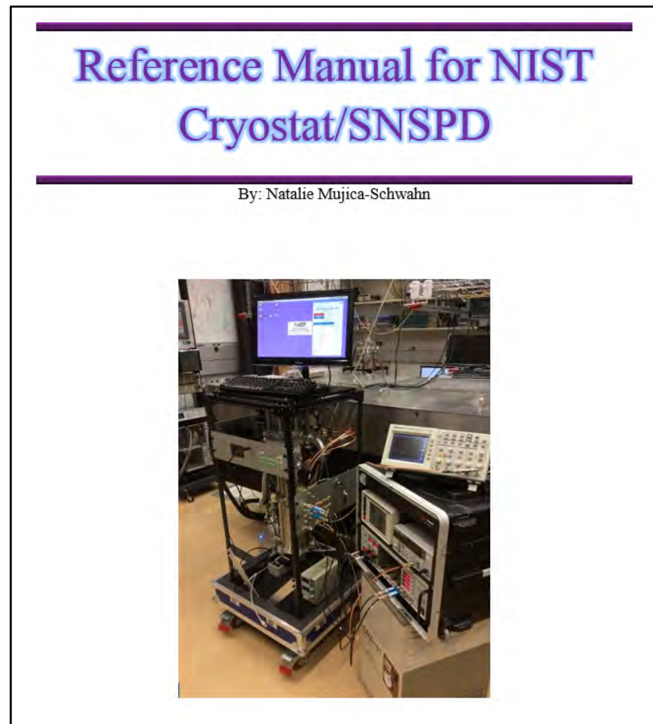
# People

Paul Williams
Michelle Stephens
Nathan Tomlin
Chris Yung
Alexandra Artusio Glimpse
Ivan Ryger
Brian Simonds
Malcolm White
Zeus Gutierrez
Thomas Gerrits
Kyle Rogers
Sae Woo Nam
Marla Dowell
Gordie Shaw
Greg Strouse

# Portable Single-Photon Detector Calibration System




- *Portable/shippable*
- *International Comparison 2018*
- *First Nanowire calibration system*
- *NIST Calibration Service 2017*
- *Tour stop*



Reference Manual for NIST Cryostat/SNSPD

By: Natalie Mujica-Schwahn

Extra Material

# Laser Manufacturing, Background

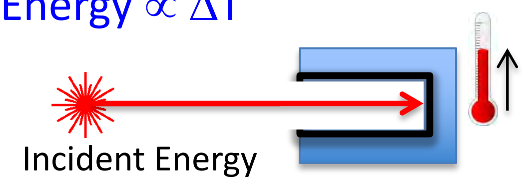
Existing techniques for fundamental laser power/energy calibration involve absorbing all the light and measuring the resulting temperature change.

**Traditional approach:**

Energy meter

Absorption-based

Energy $\propto \Delta T$




**Calorimeter:**

Energy range: > *300 kJ*

Response time: *minutes*

Size: *cubic meters*

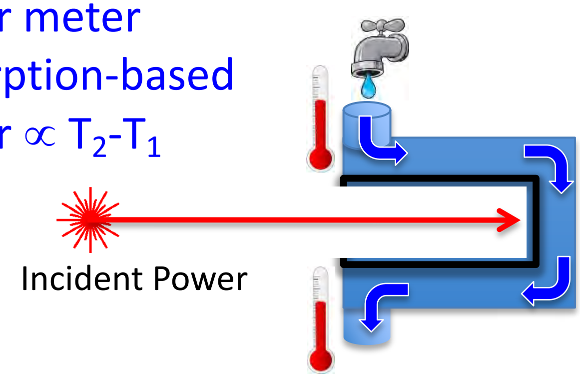
Weight: *hundreds of pounds*

**Current approach:**

Power meter

Absorption-based

Power $\propto T_2\text{-}T_1$




**Flowing water power meter:**

**Best Uncertainty**

Power range: *1 - 100 kW*

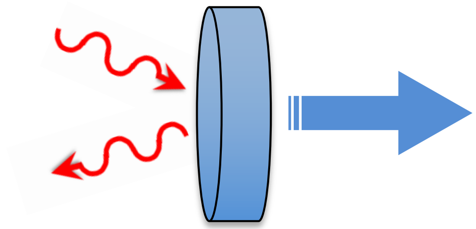
Response time: *tens of seconds*

Size: *cubic meters*

Weight: *hundreds of pounds*

# Laser Manufacturing, In-situ Power

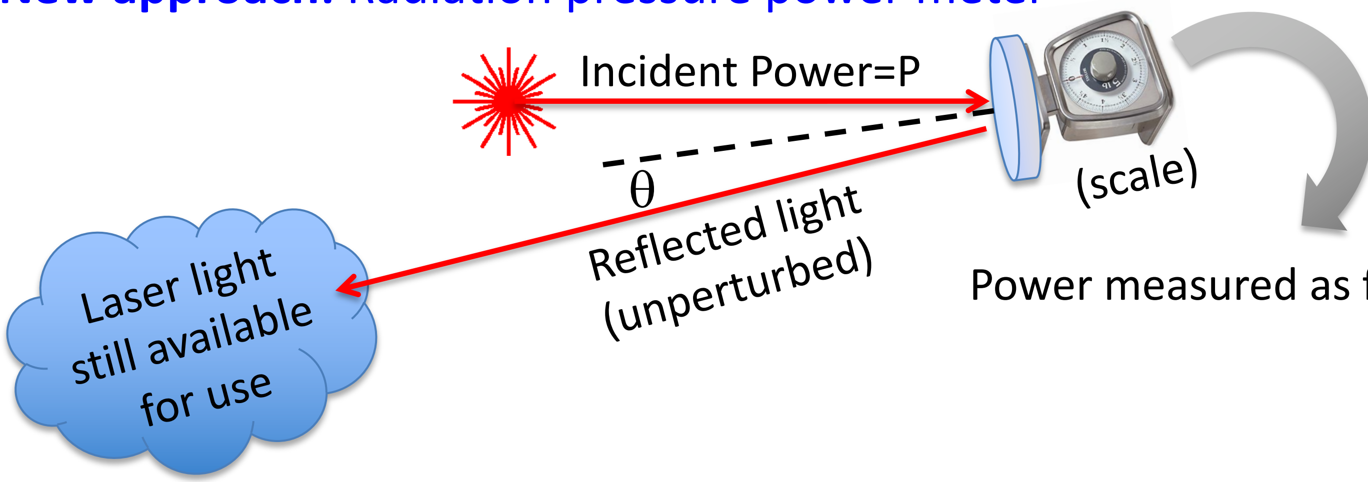
Enabling physics:



Light has momentum,
(photons push things).

**Concept:** The novelty of this approach is that it does not absorb the light.

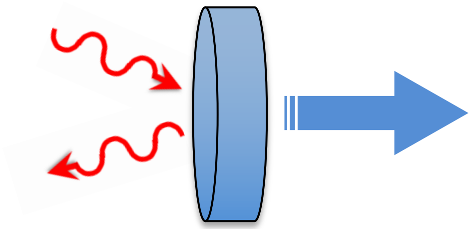
**New approach:** Radiation pressure power meter




Power measured as force:

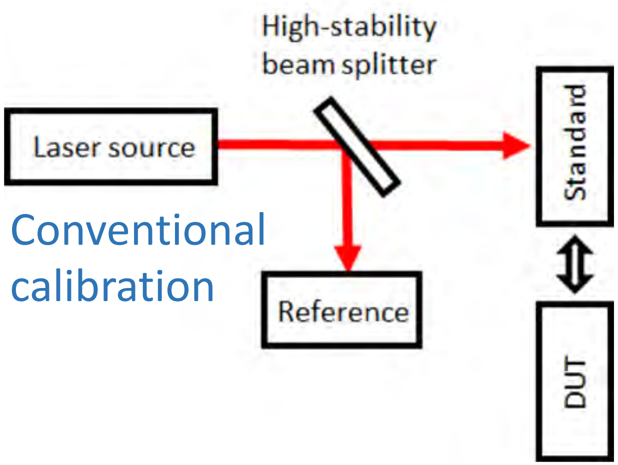
# Laser Manufacturing, In-situ Power

Enabling physics:

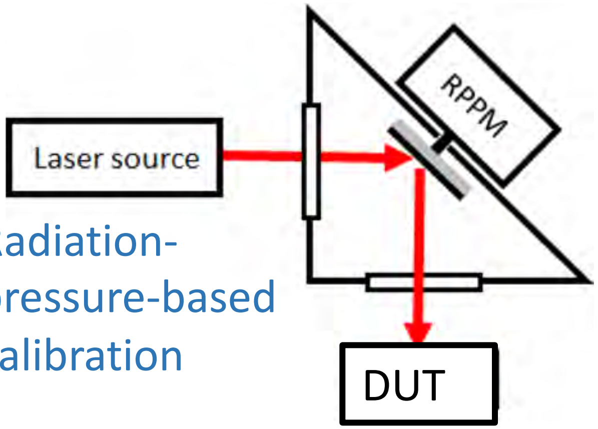


Light has momentum,
(photons push things).

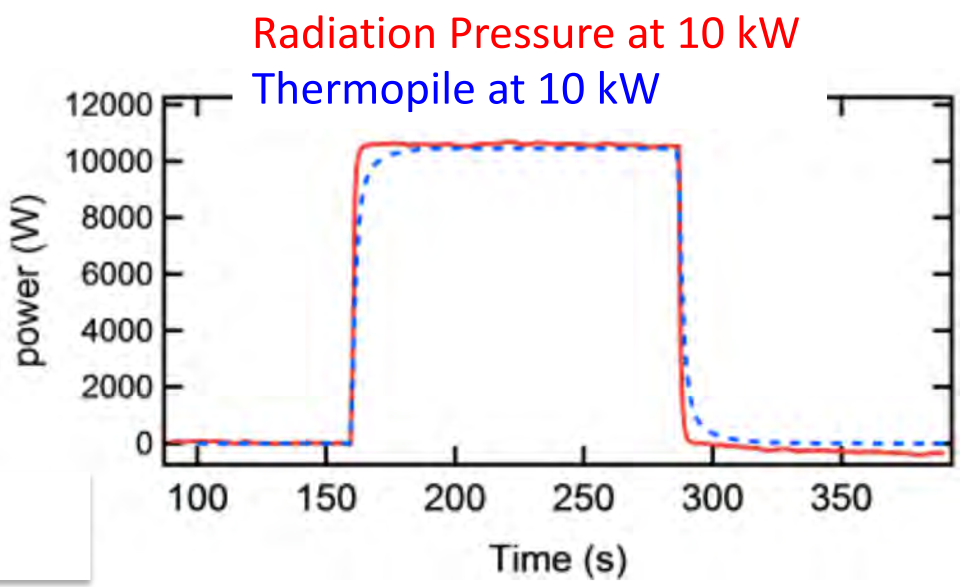
# Measurements, calibration, and validation

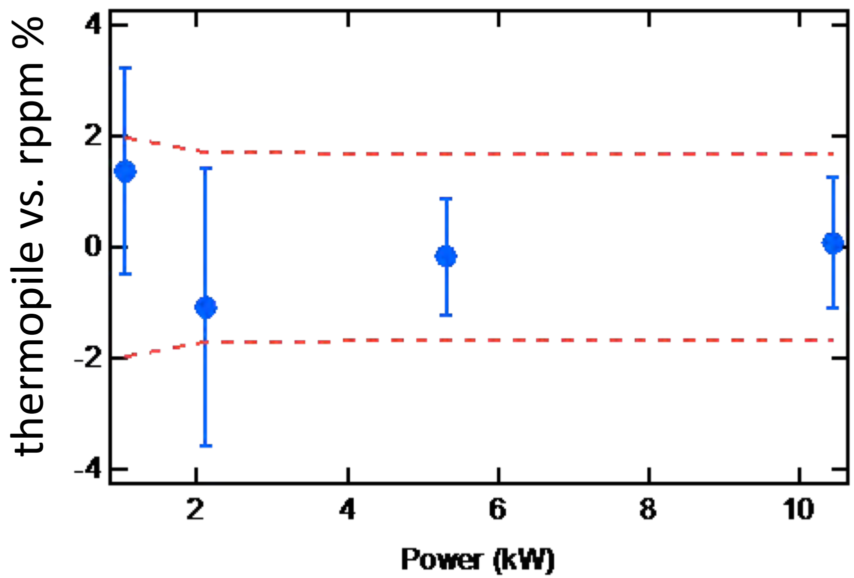



Conventional calibration




Radiation-pressure-based calibration

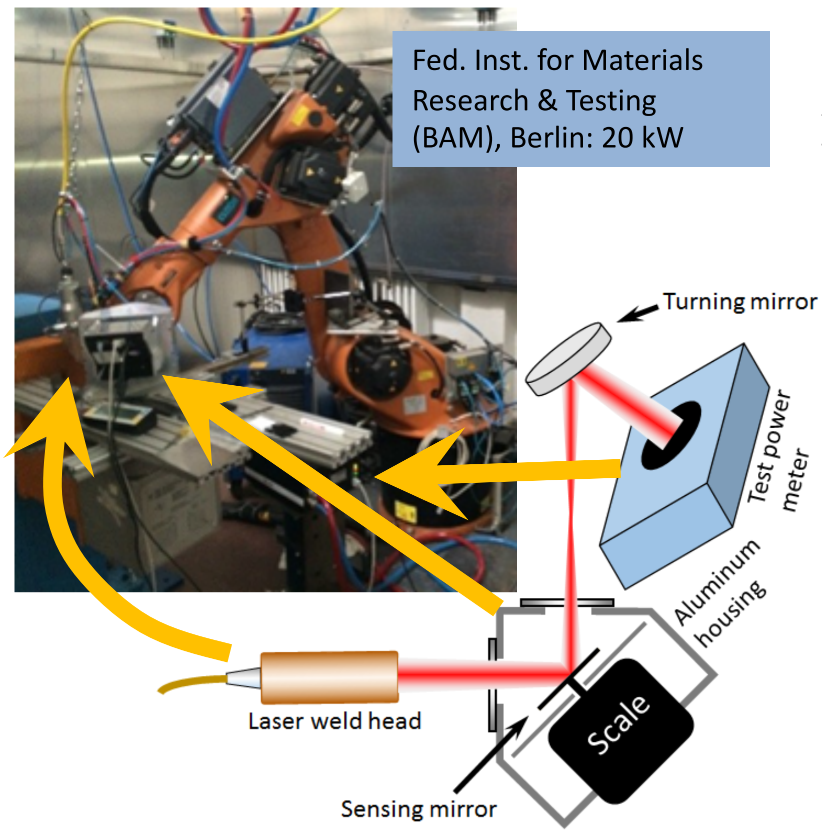


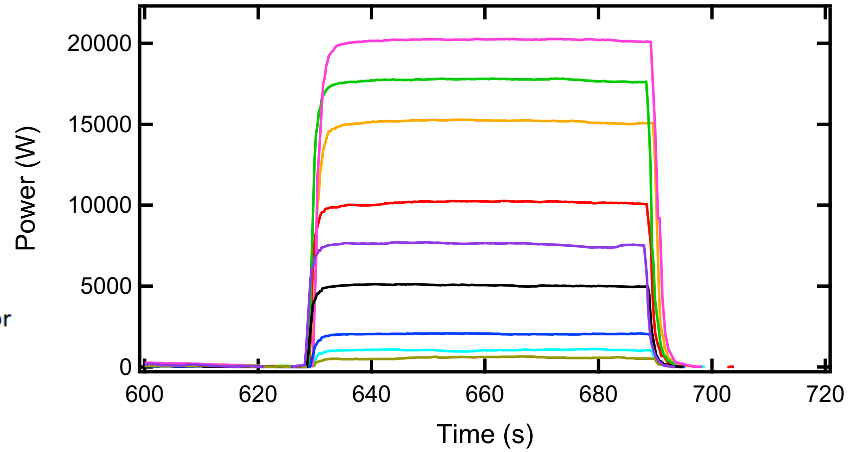




Williams et al., OPTICS EXPRESS, Vol. 25, No. 4 | 20 Feb 2017 | 4382

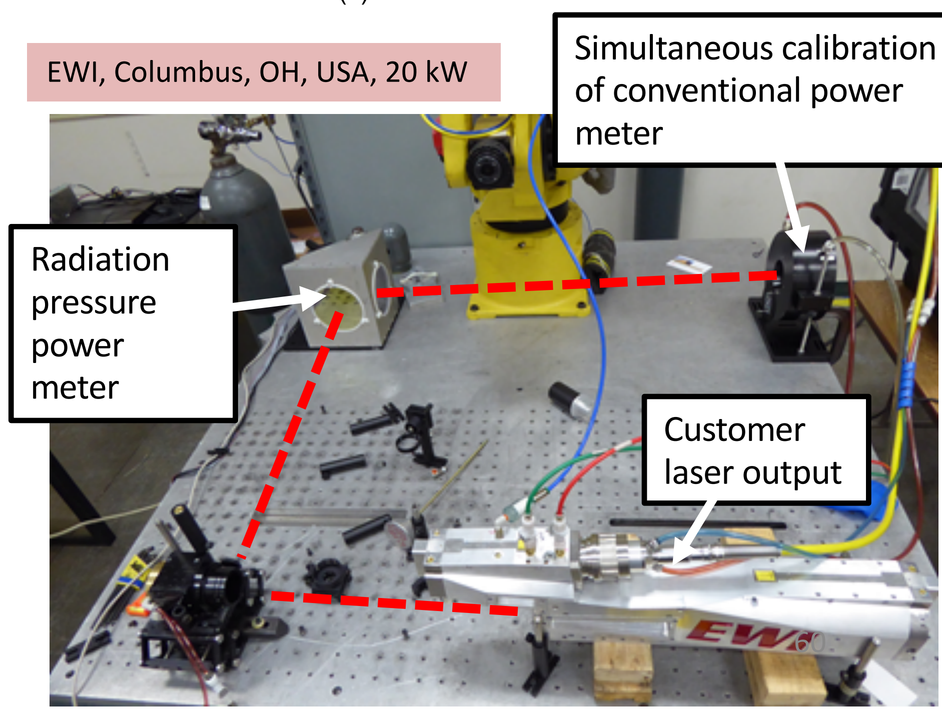
# On-site primary standard high power calibrations

As a truly portable primary standard, the radiation pressure power meter allows on-site calibrating measurements of high power lasers



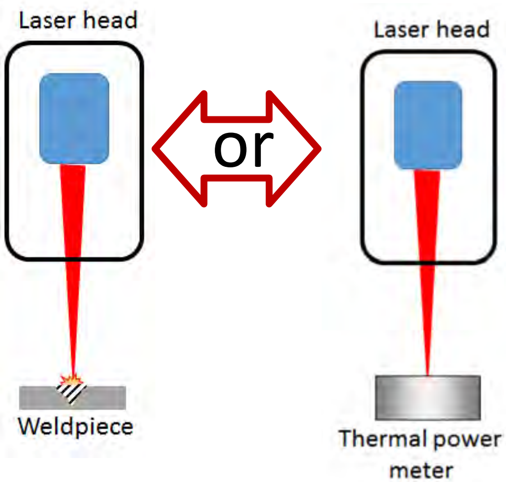




EWI, Columbus, OH, USA, 20 kW

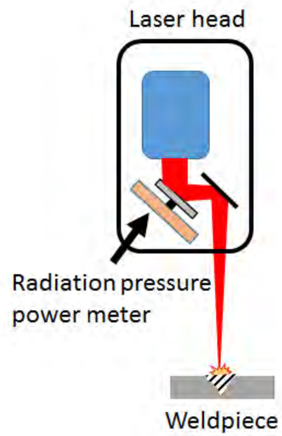


# *In-situ* power measurement

## Example: Measure laser power during a laser weld operation

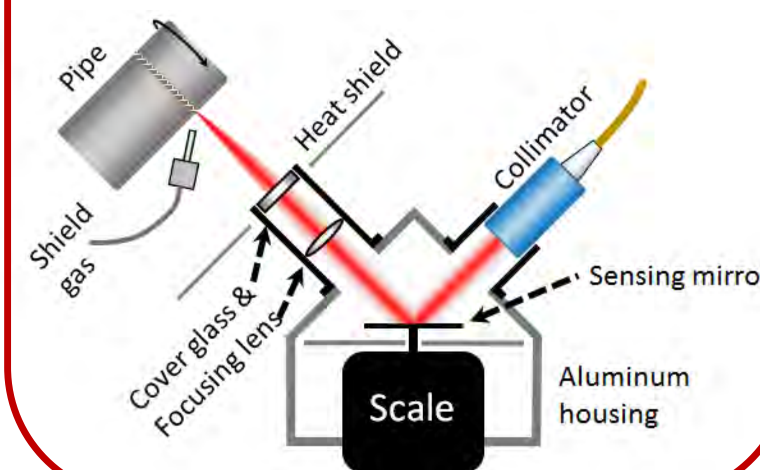



Traditional approach




**Prototype Radiation pressure power meter setup:**

- Not miniaturized
- Still using commercial scale



# Current performance limitations

## Dominant uncertainty sources

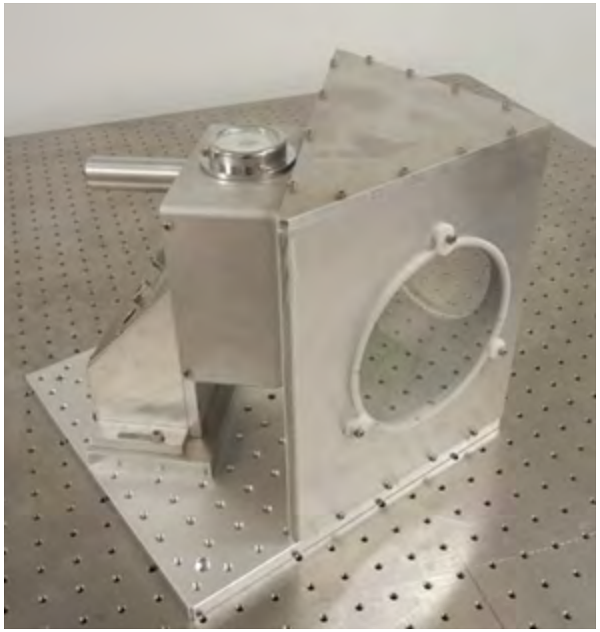
**Low powers (< 2 kW):** Acoustic vibrations

*Reduce with averaging*

**High powers (> 2 kW):** Nonlinearity in thermal drift

*Use at shorter injection times*

***Highest powers (>10 kW):*** No primary-standard comparisons




acumenlabware

# What If…