Quantum Enhanced Imaging: LiDAR & Gravity Imaging using Microfabricated Devices

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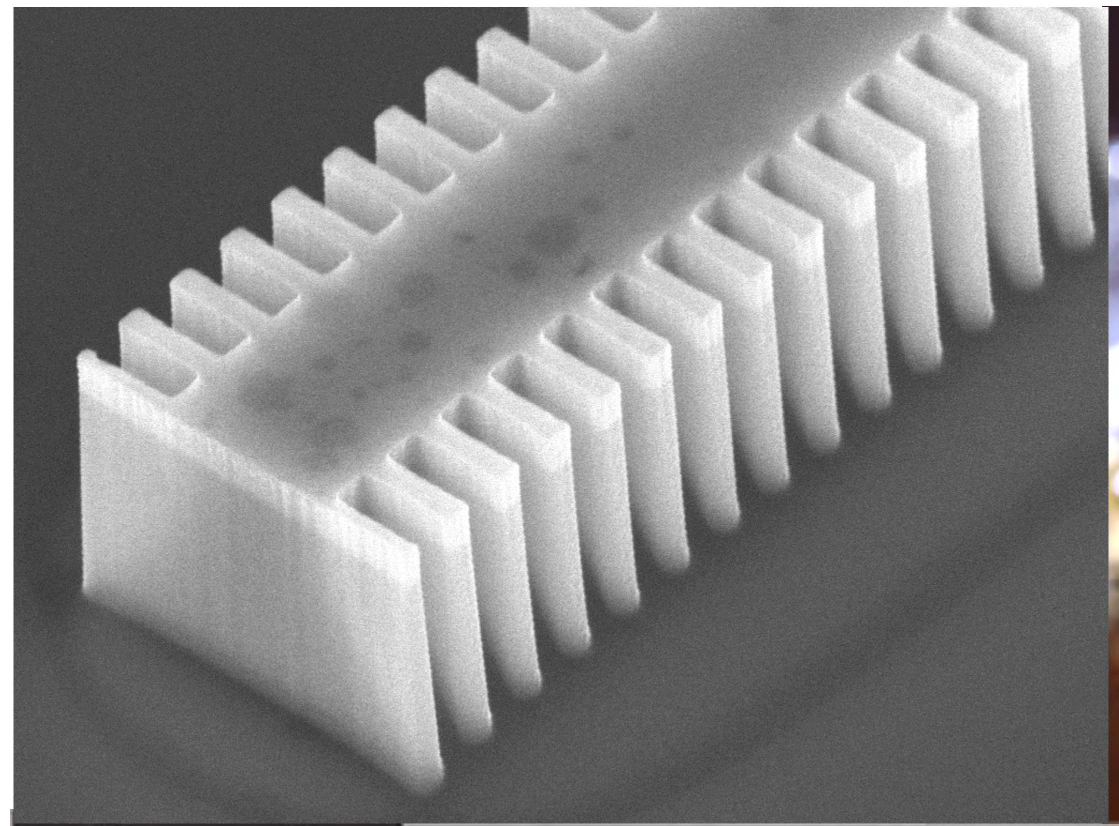
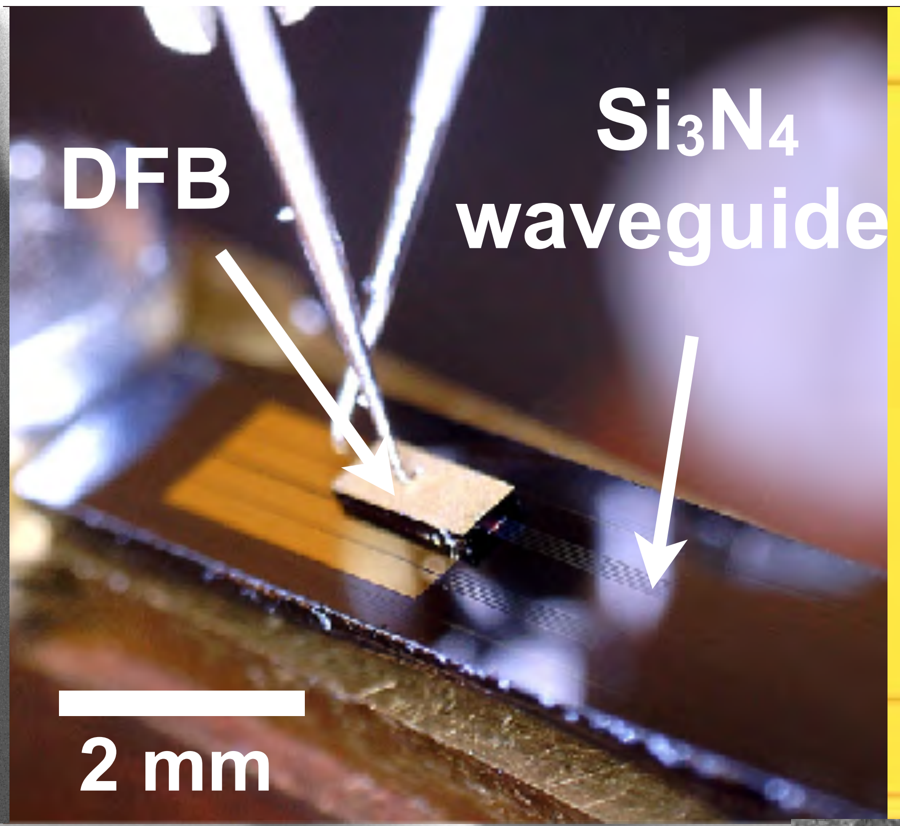
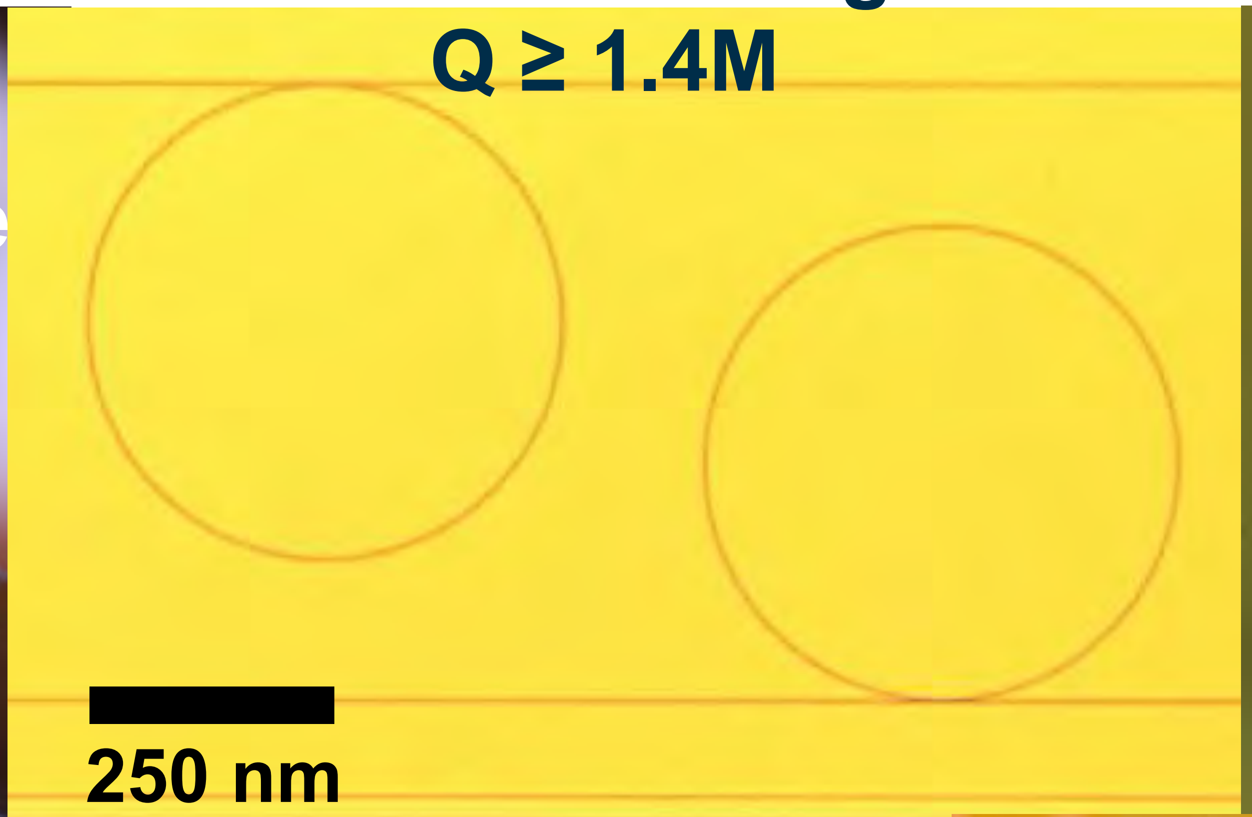
780 nm DFB laser



DFB laser on chip

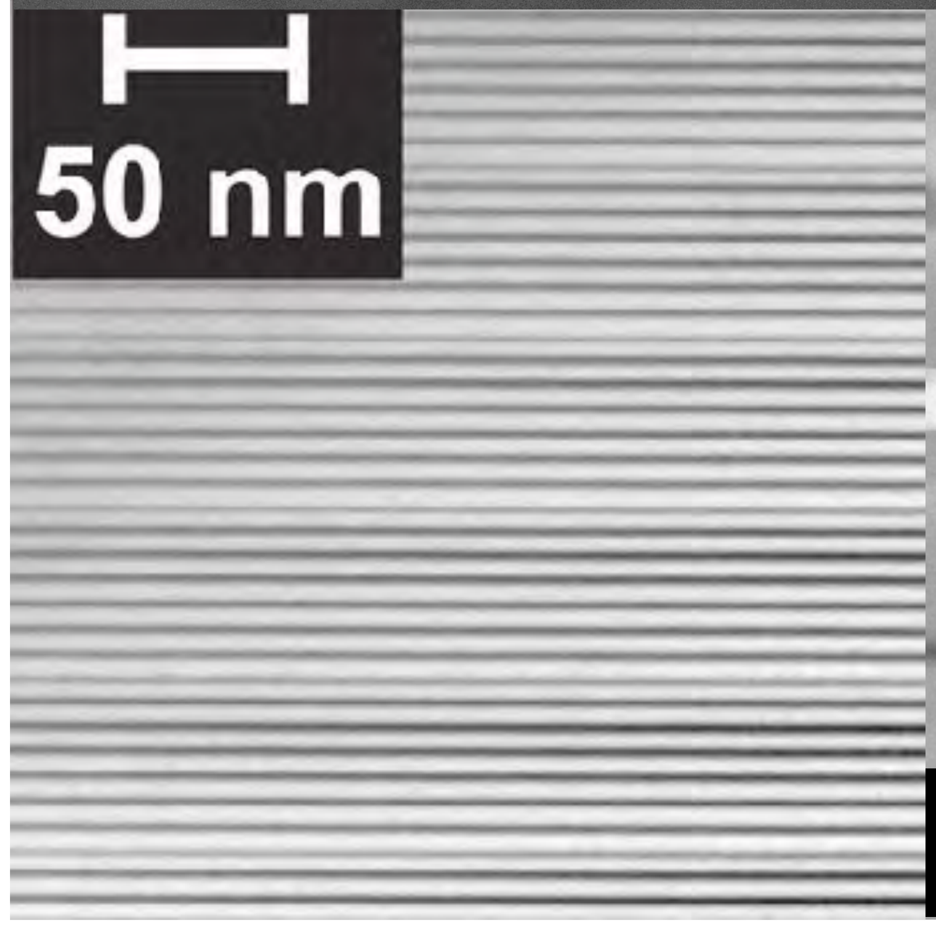


Si_3N_4 microrings

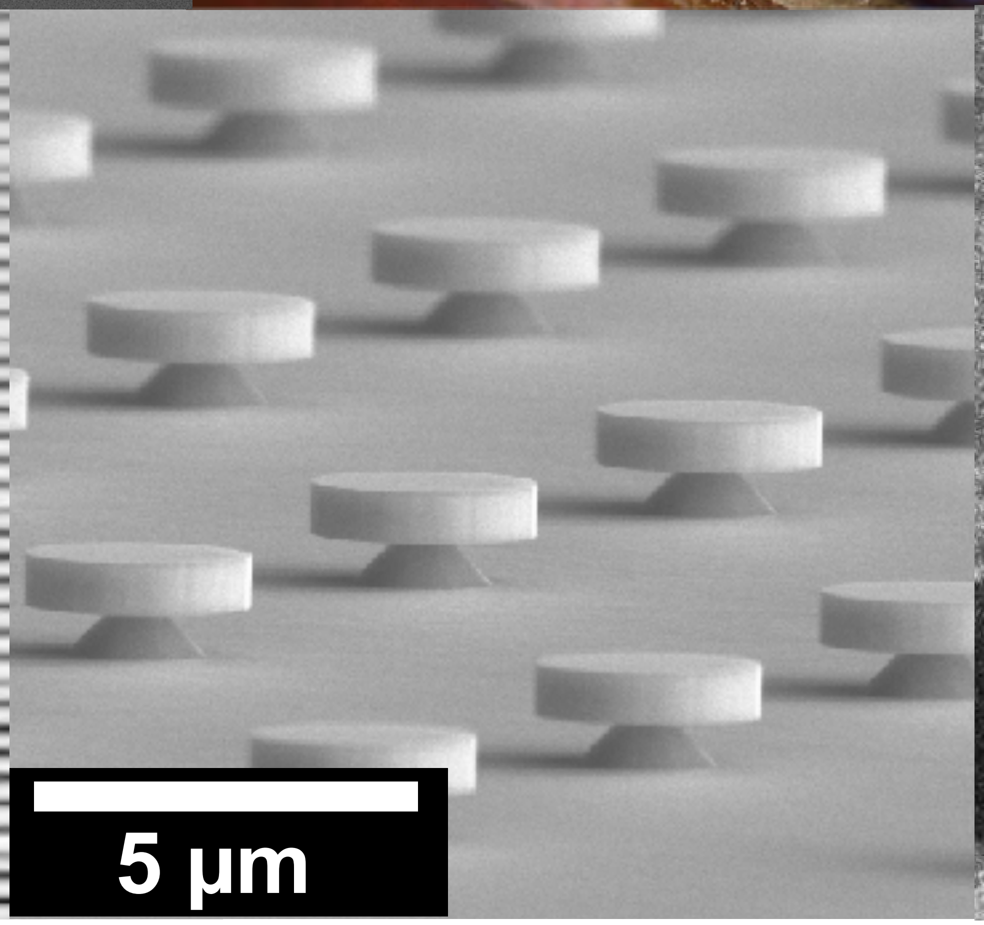


Rb MEMS cells

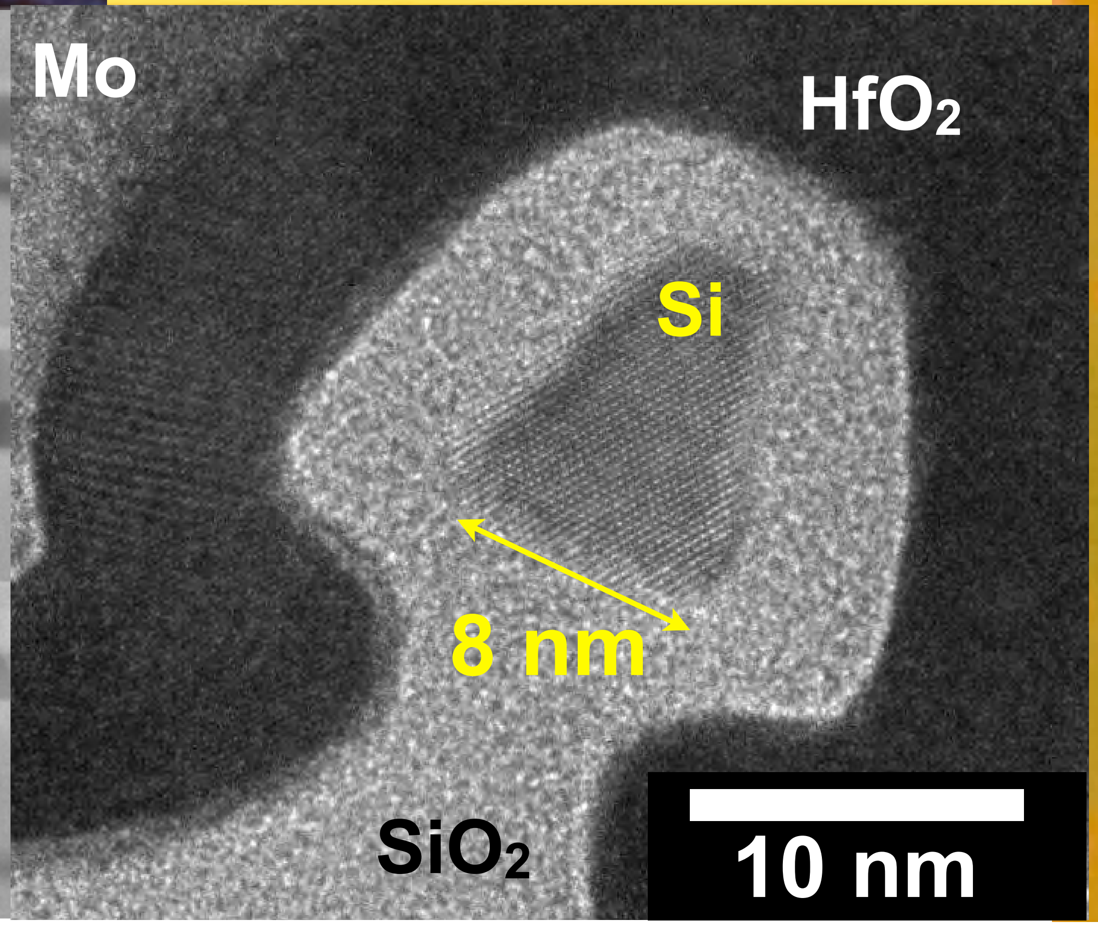
MEMS gravimeters



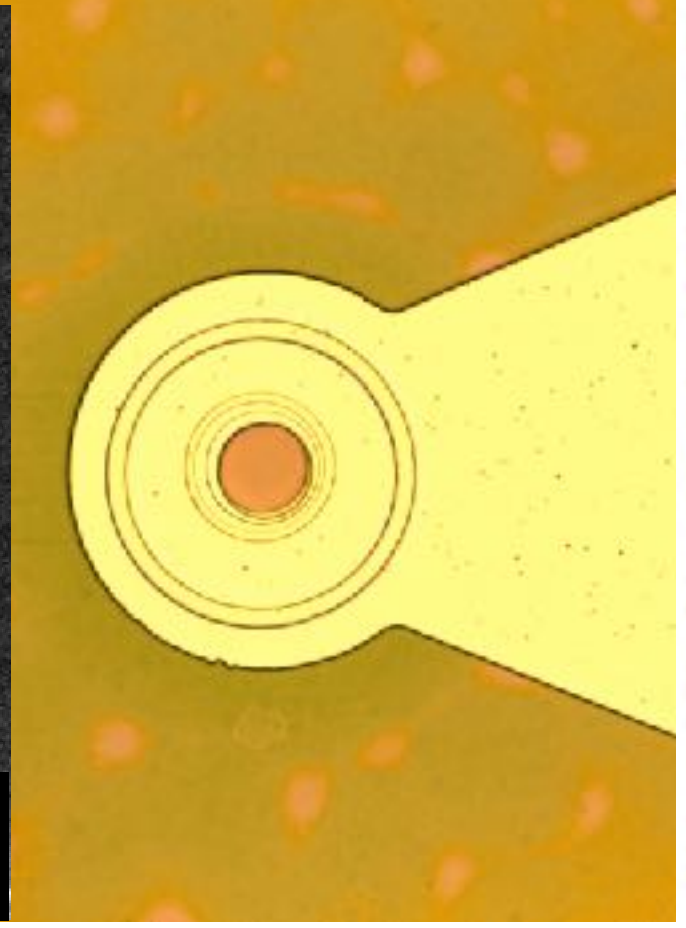
SiGe THz QCLs



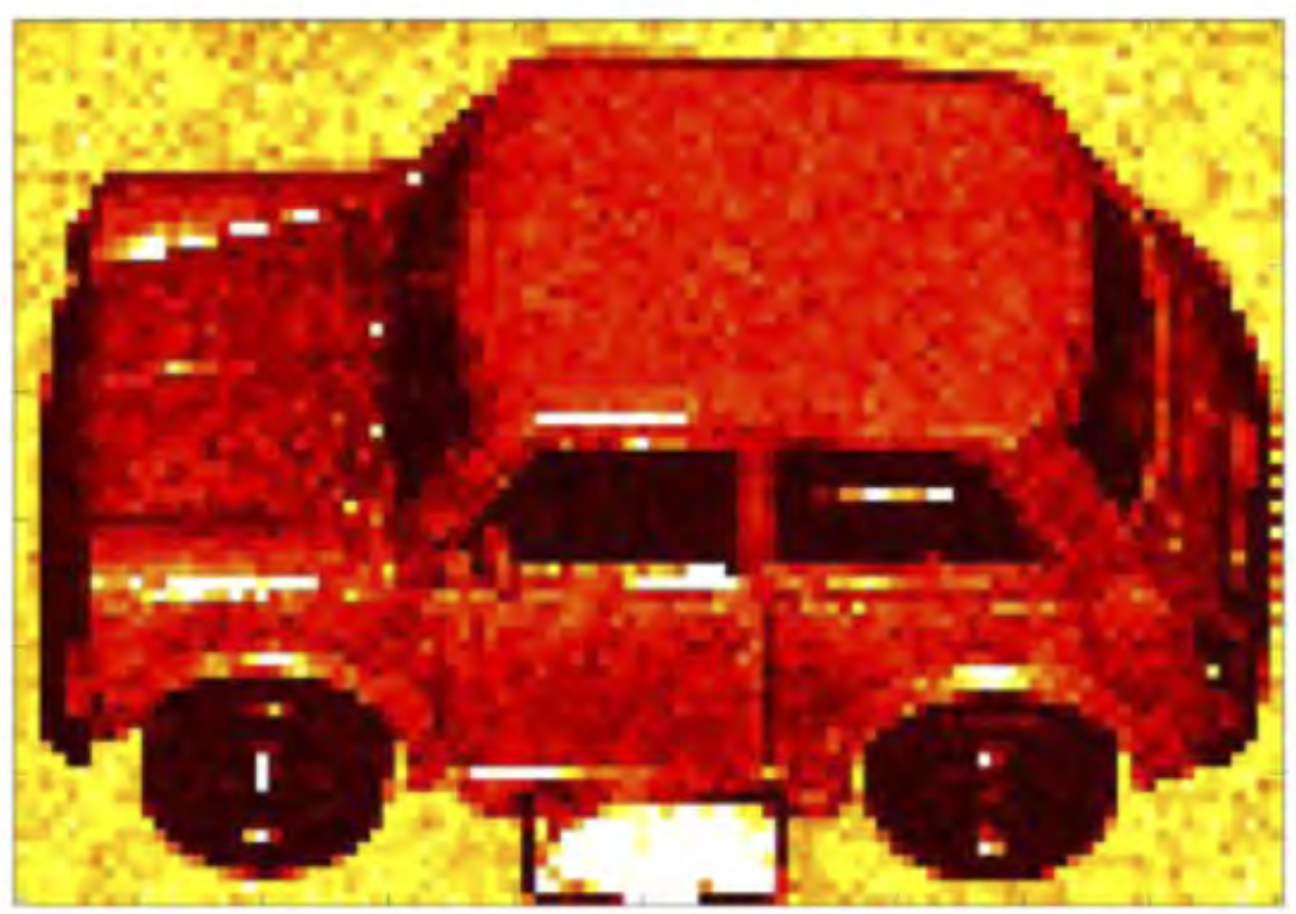
Ge on Si MIR Photonics



Si Nanowire SETs



Ge on Si SPADs



SWIR LIDAR

University of Glasgow

James Watt Nanofabrication Centre

QUANTIC

UK Quantum Technology Hub Sensors and Timing

QUANTUM COMMUNICATIONS HUB

- 1700 m^2 cleanroom - quasi-industrial operation with £35M equipment
- 23 technicians + 2 PhD research technologists, Director, Operations Director, CTO
- Processes include: MMICs, III-V, Si/SiGe/Ge, integrated photonics, metamaterials, MEMS (microfluidics), quantum technology
- STFC Kelvin-Rutherford Facility & DSTL strategic partner
- Commercial access through Kelvin NanoTechnology
- http://www.jwnc.gla.ac.uk/

Vistec VB6 & Nanobeam NB5

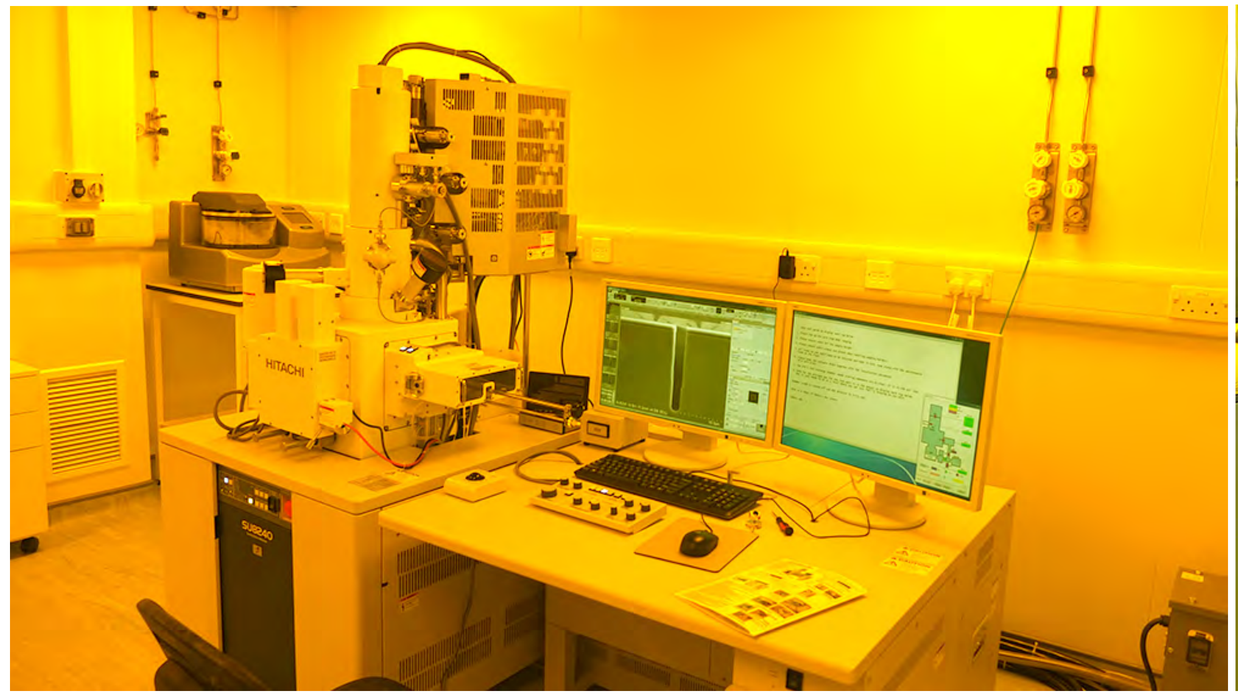
E-beam lithography

Süss MA8, MA6, MJB4 photolith

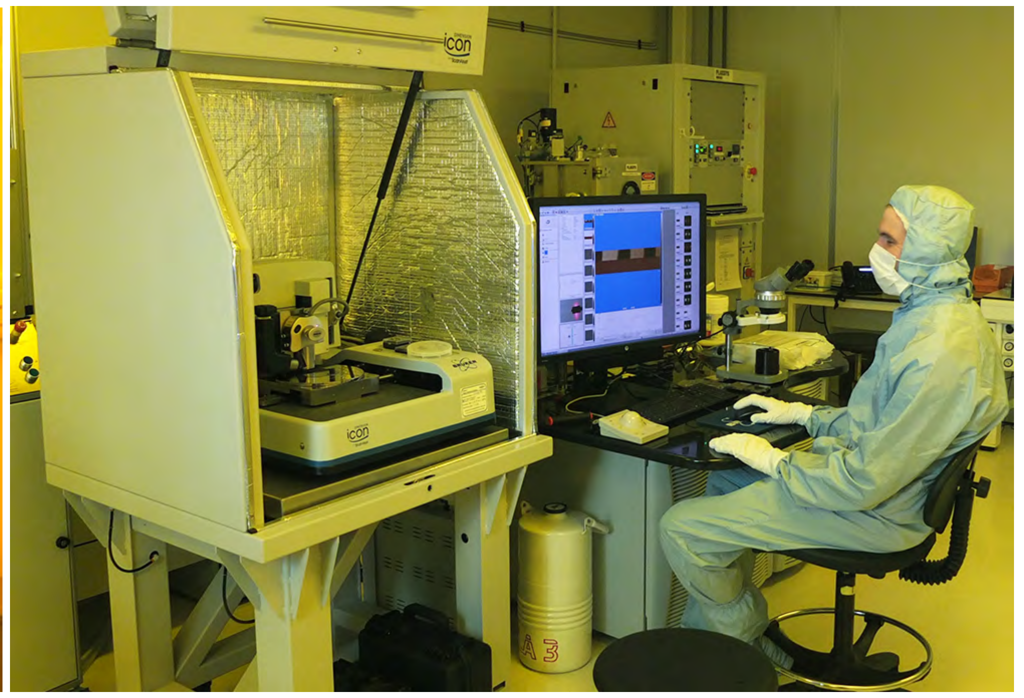
17 RIE / PECVD / ALD

6 Metal dep. tools

4 SEMs: Hitachi S8240 with EDX



Metrology



Ge on Si SPADs for LiDAR & Quantum Communications

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[1]James Watt School of Engineering, University of Glasgow, U.K
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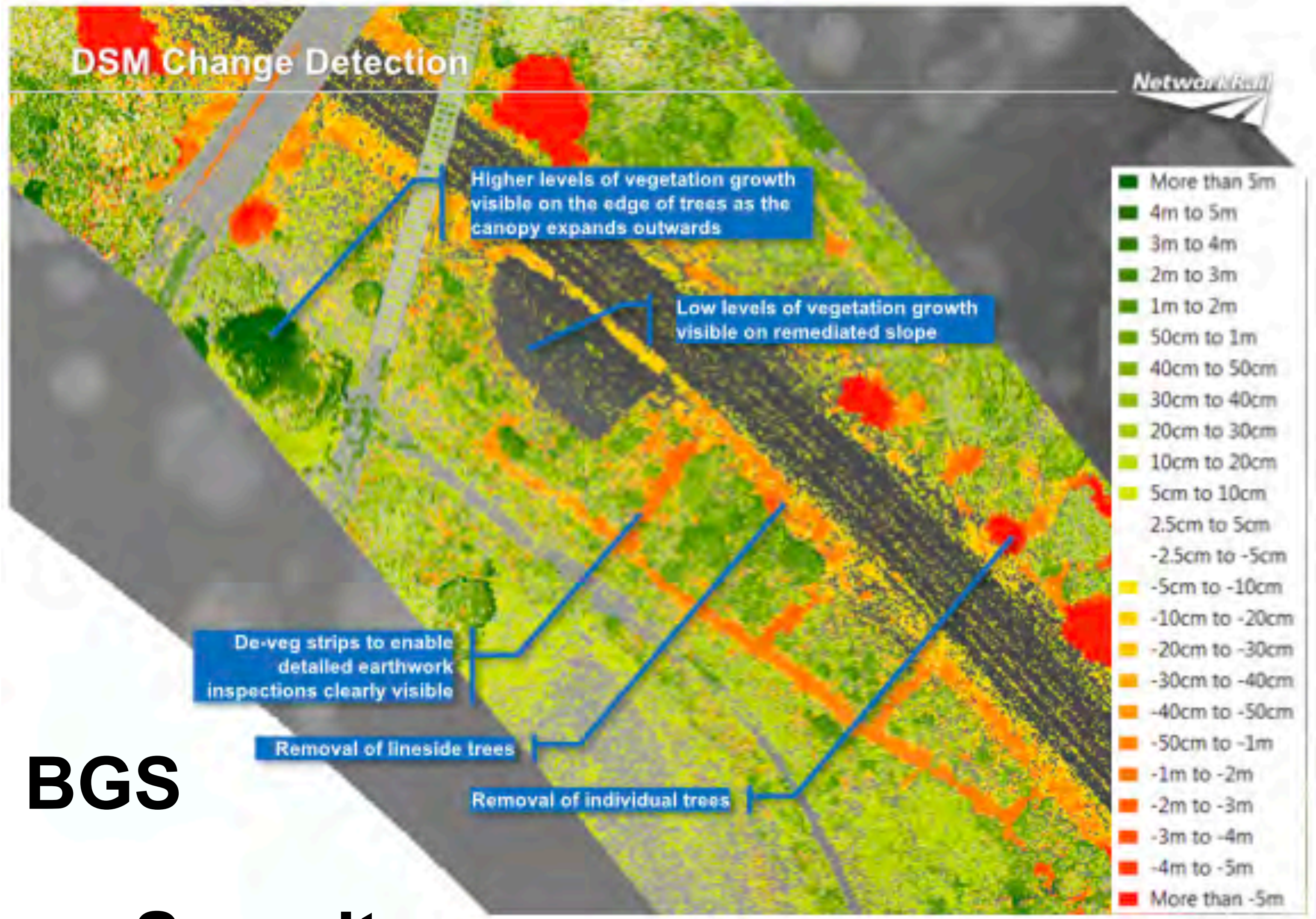
http://userweb.eng.gla.ac.uk/douglas.paul/

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME
QUANTIC
UKRI Engineering and Physical Sciences Research Council
QUANTUM COMMUNICATIONS HUB
[dstl]
UKRI Innovate UK

Single Photon Detector Applications

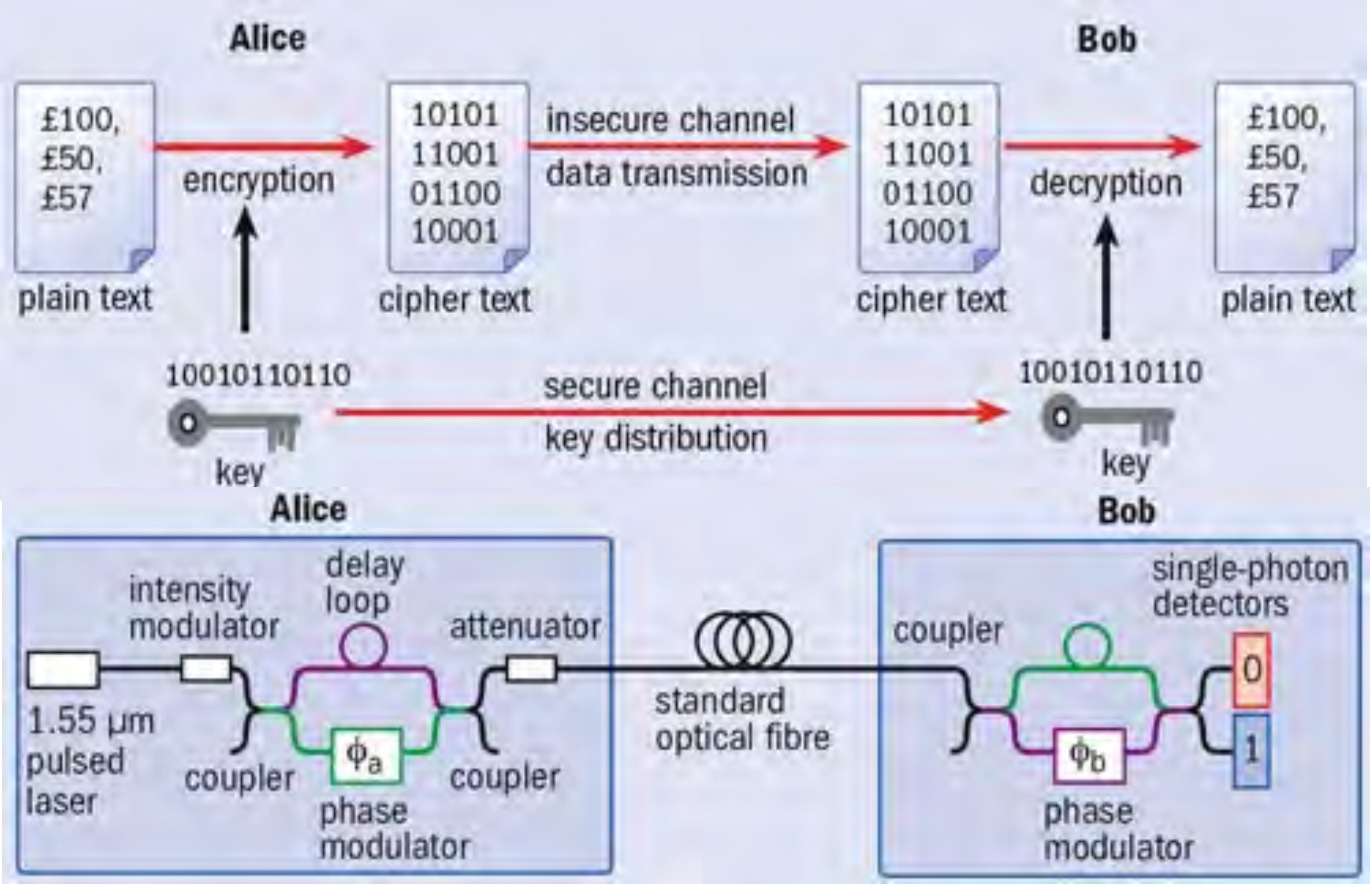
Erosion measurement



BGS

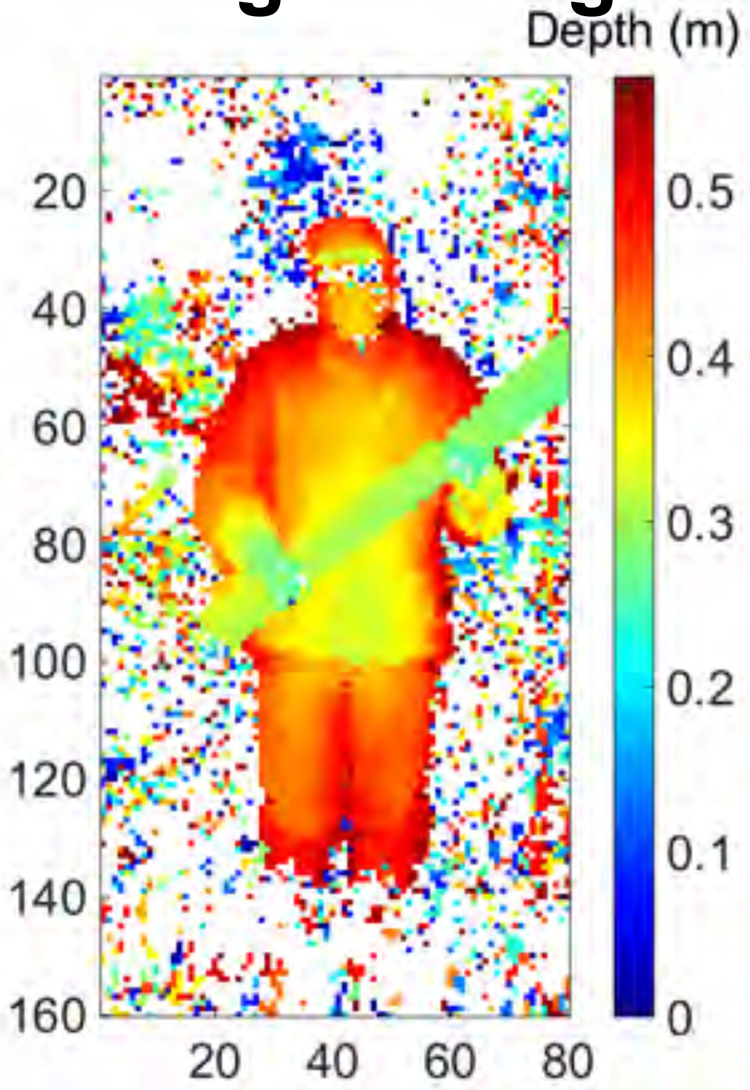
Automotive & autonomous vehicle lidar

Quantum key distribution

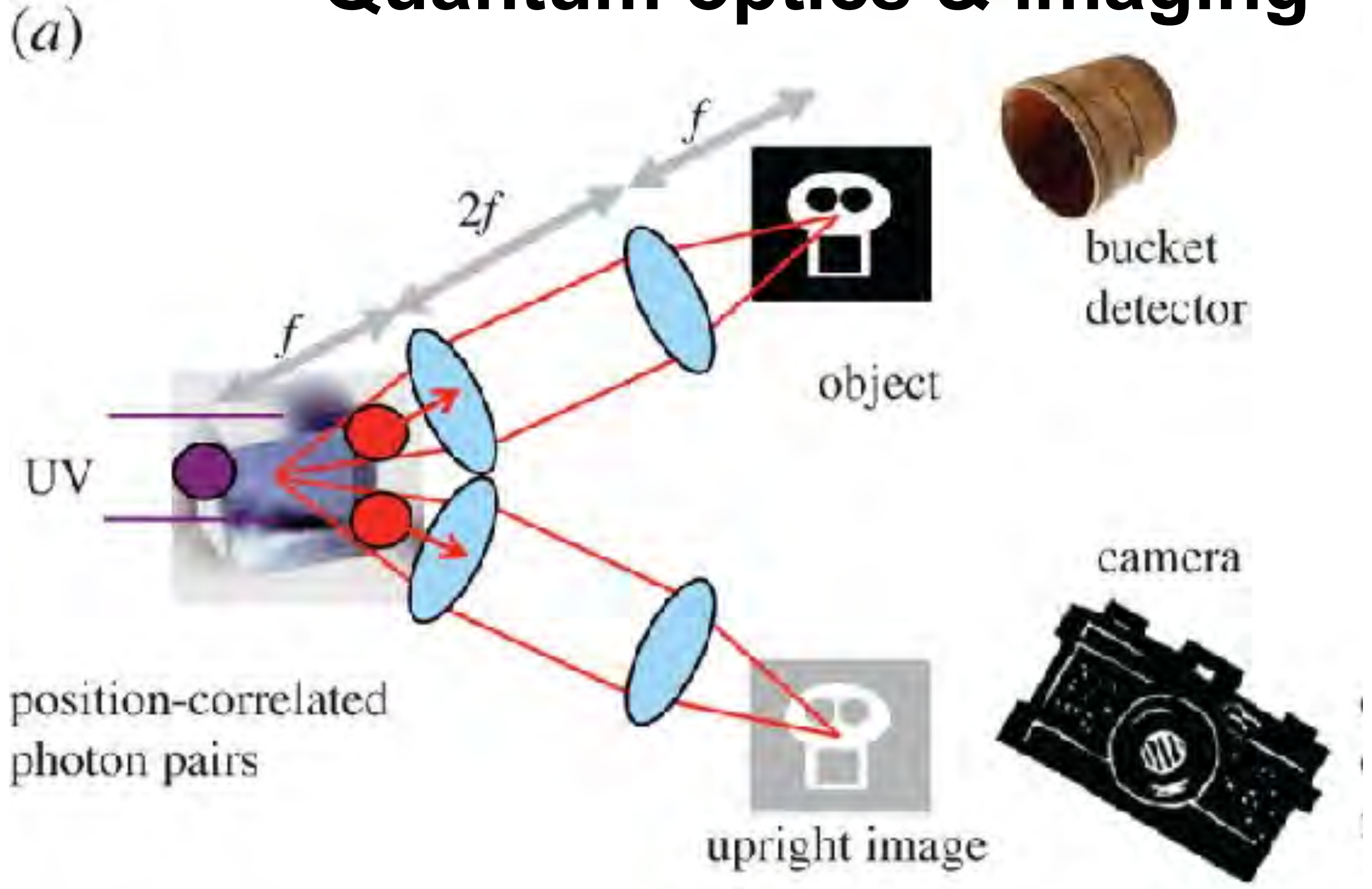


Andrew Shields, Phys. World (2007)

Security rangefinding

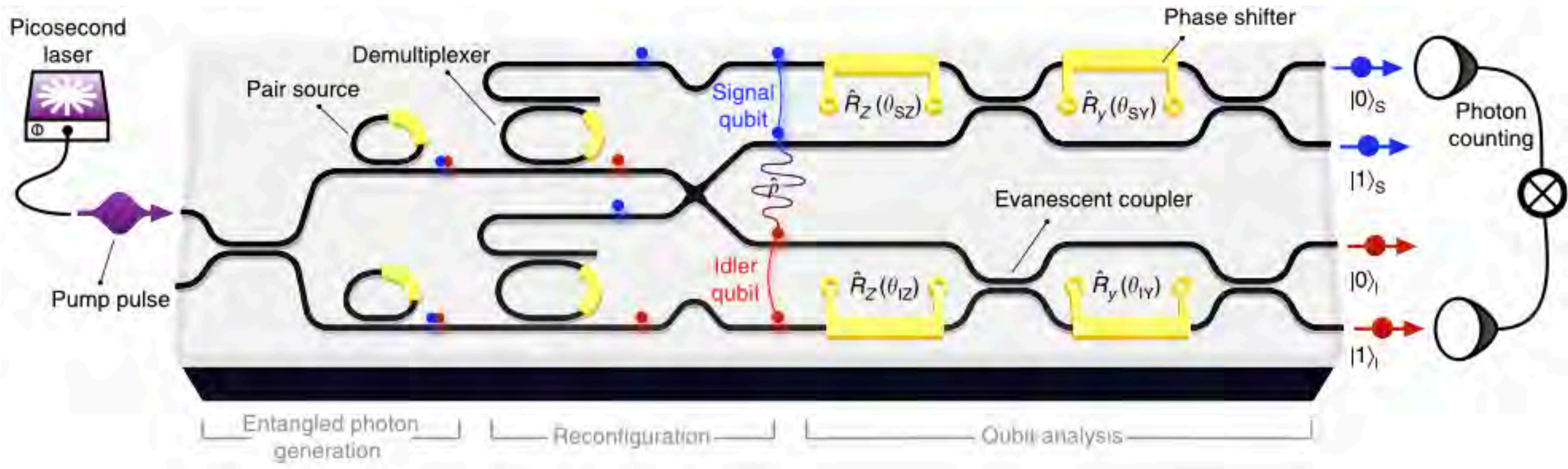


Quantum optics & imaging



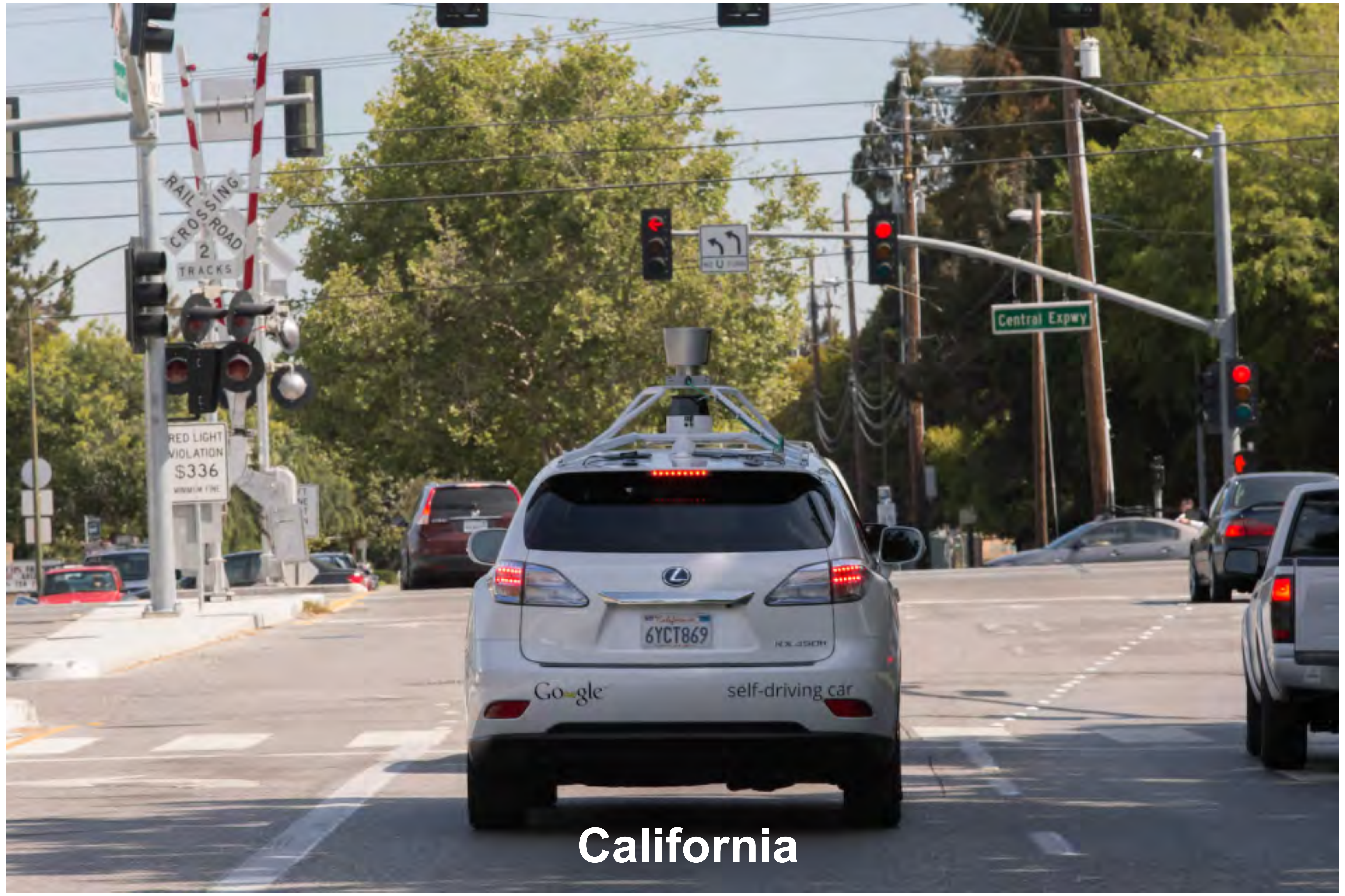
Padgett & Boyd, Phil. Trans. Roy. Soc. A 375, 20160233 (2017)

Photonic quantum simulation / computing



J.W. Singleton et al. Nature Comms. 6, 7948 (2015)

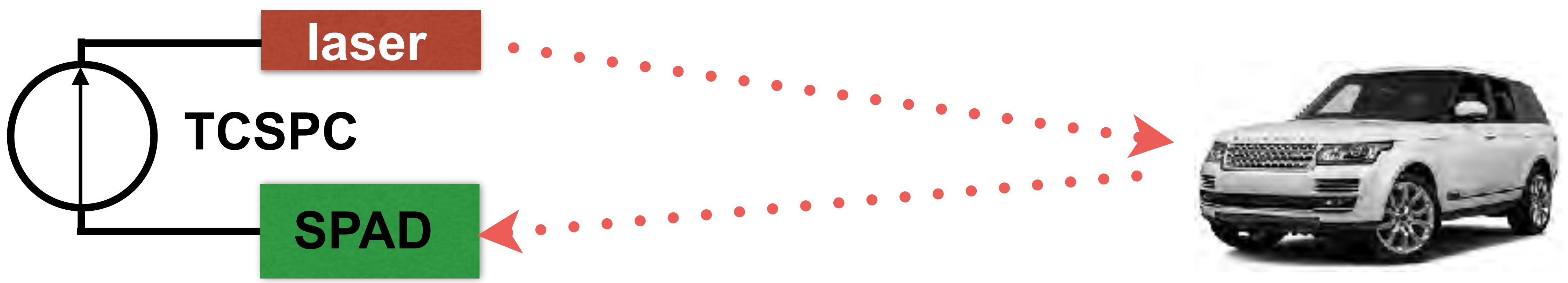
Practical LIDAR: Imaging Through Obscurants

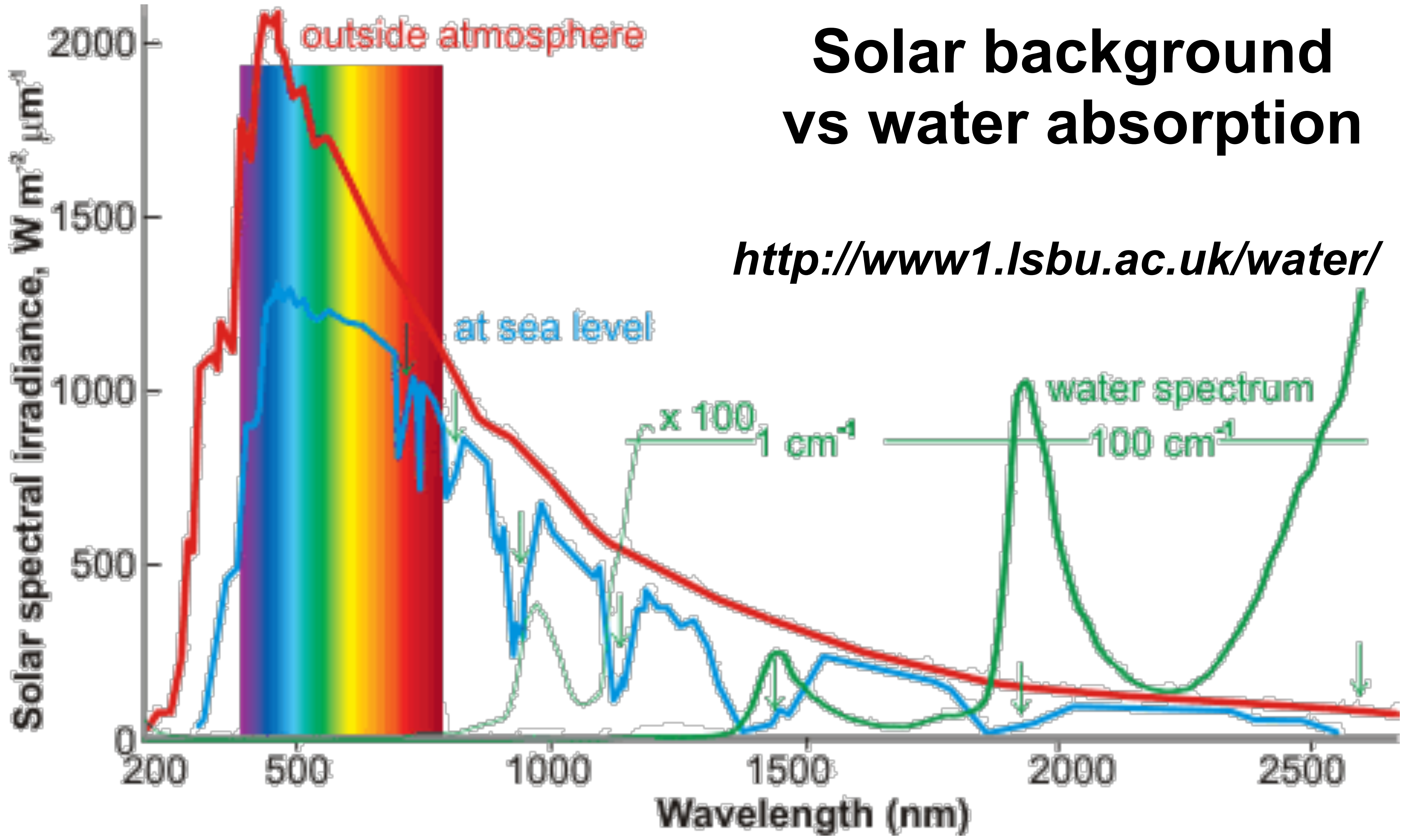


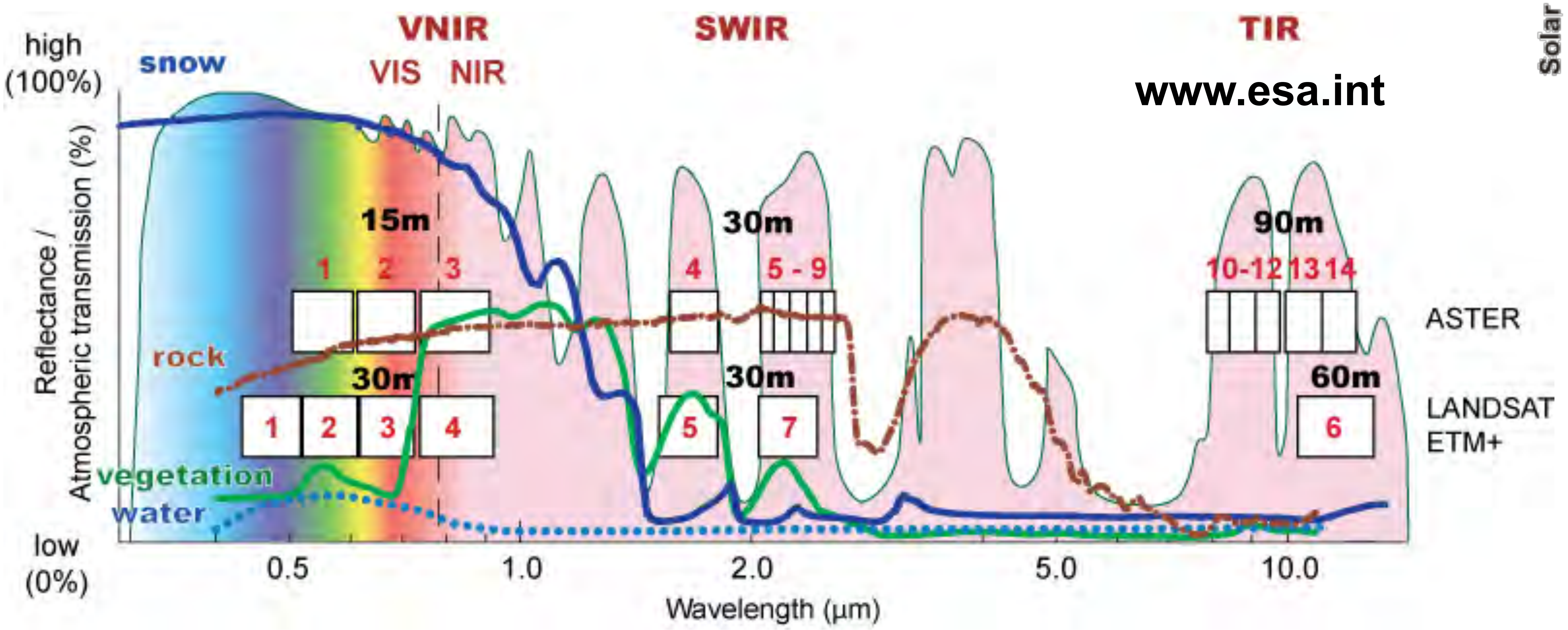
https://youngcardriver.com/driving/driving-in-heavy-rain/

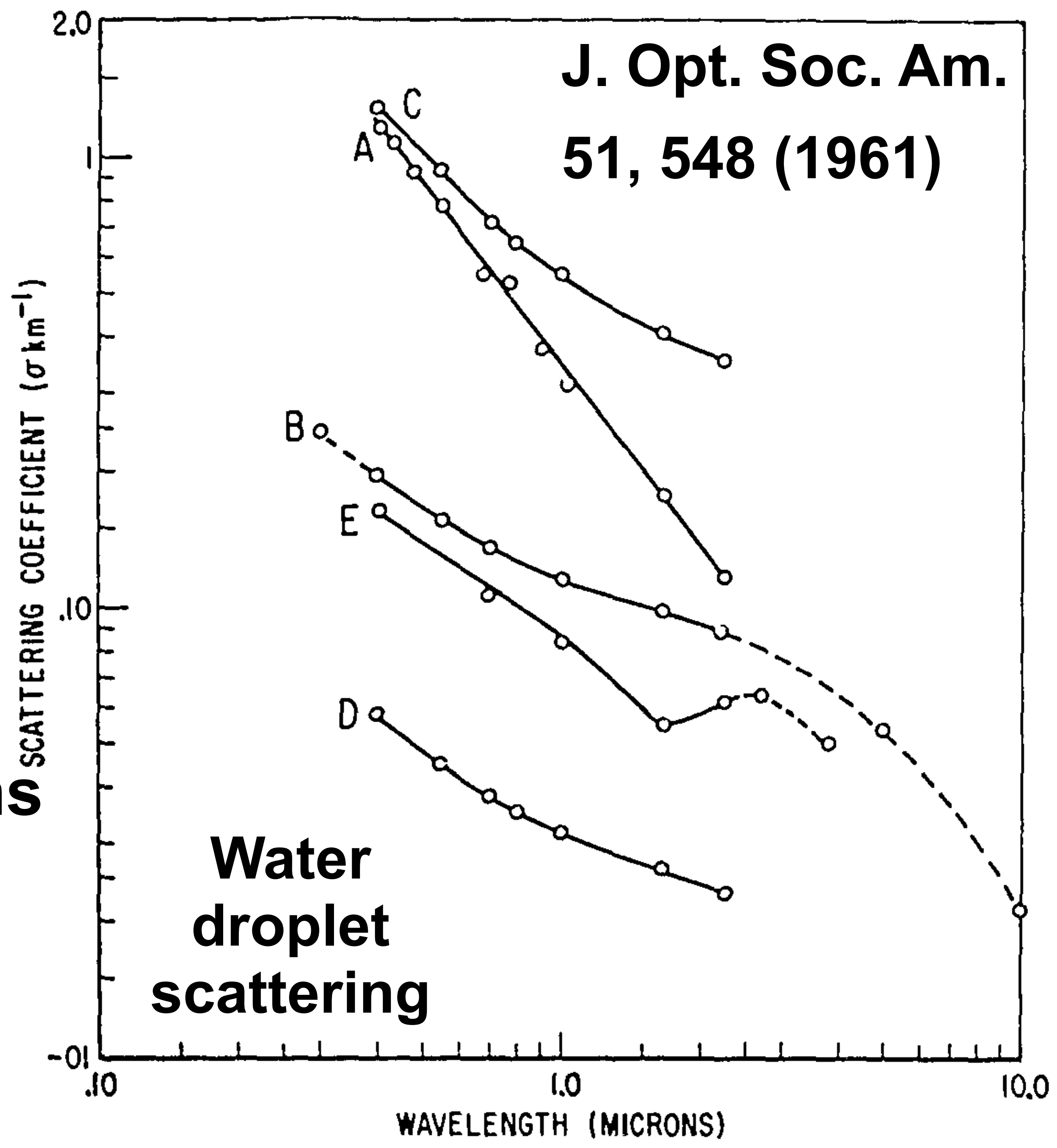
- UK motorway or A-class road requirement: Level 4 autonomy requires identification of objects in 10 ms at 300 m
- Military rangefinders & lidar $803.4M by 2023 with 6.29% CAGR (Reuters 2018)
- UK market for autonomous vehicle lidar, radar & GPS of £2.7Bn (£63Bn globally) by 2035 (UK Dept. Transport 2016)

Longer Wavelengths





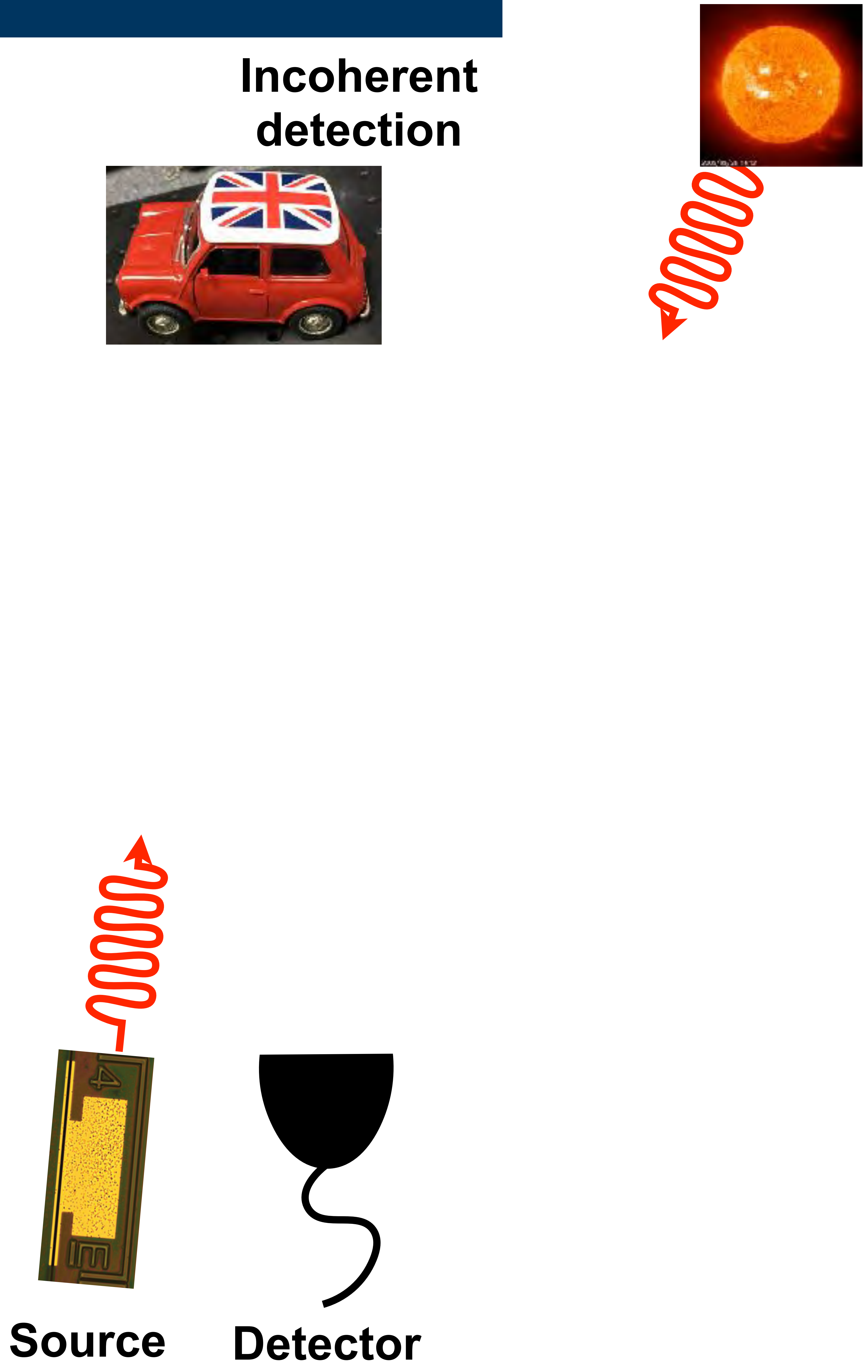




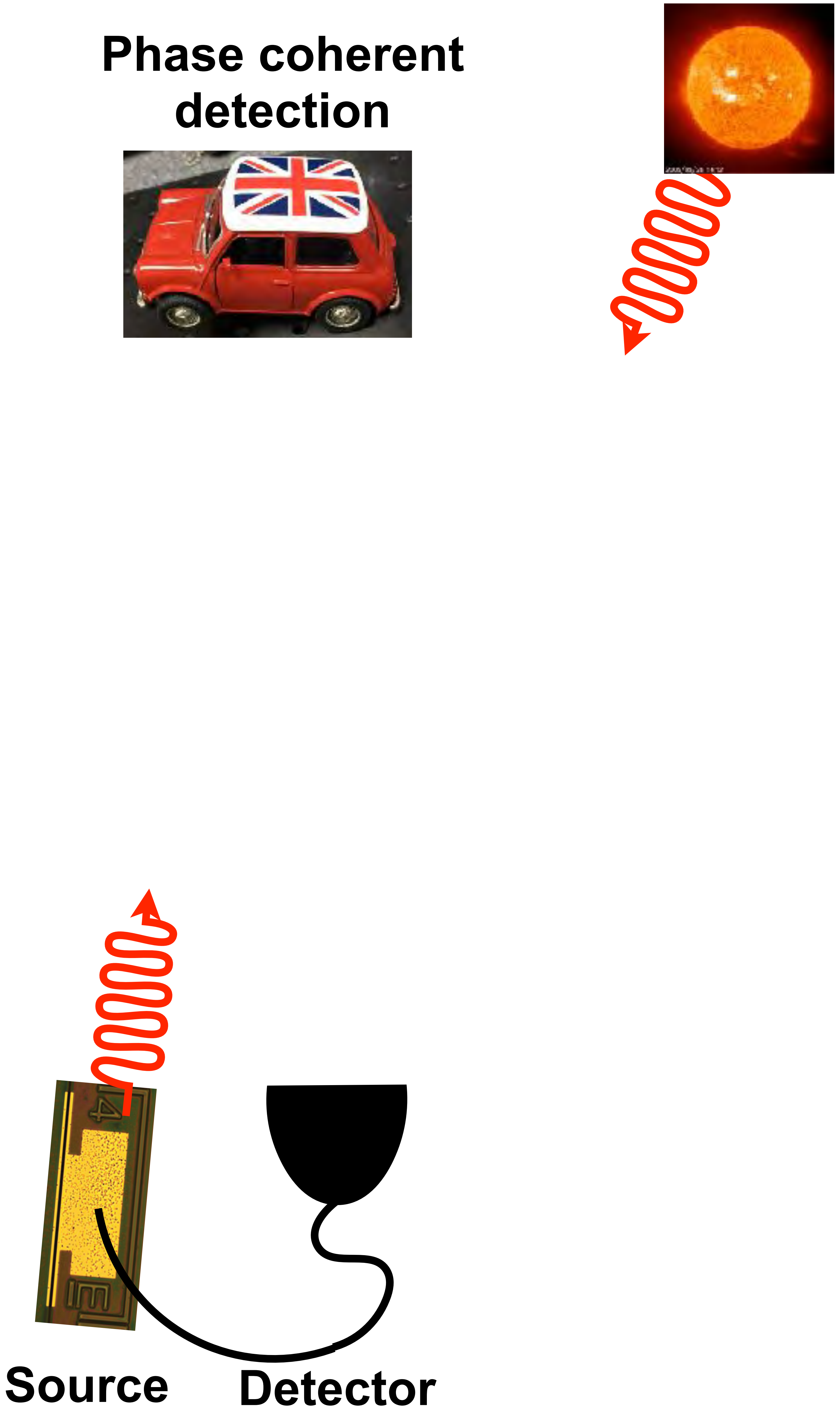
- Mie scattering from water droplets & solar background reduce at longer wavelengths
- IEC-60825-1 eye safe ~ 8 mW > 1400 nm wavelength – outside retina hazard region

Methods to Improve Imaging Signal to Noise

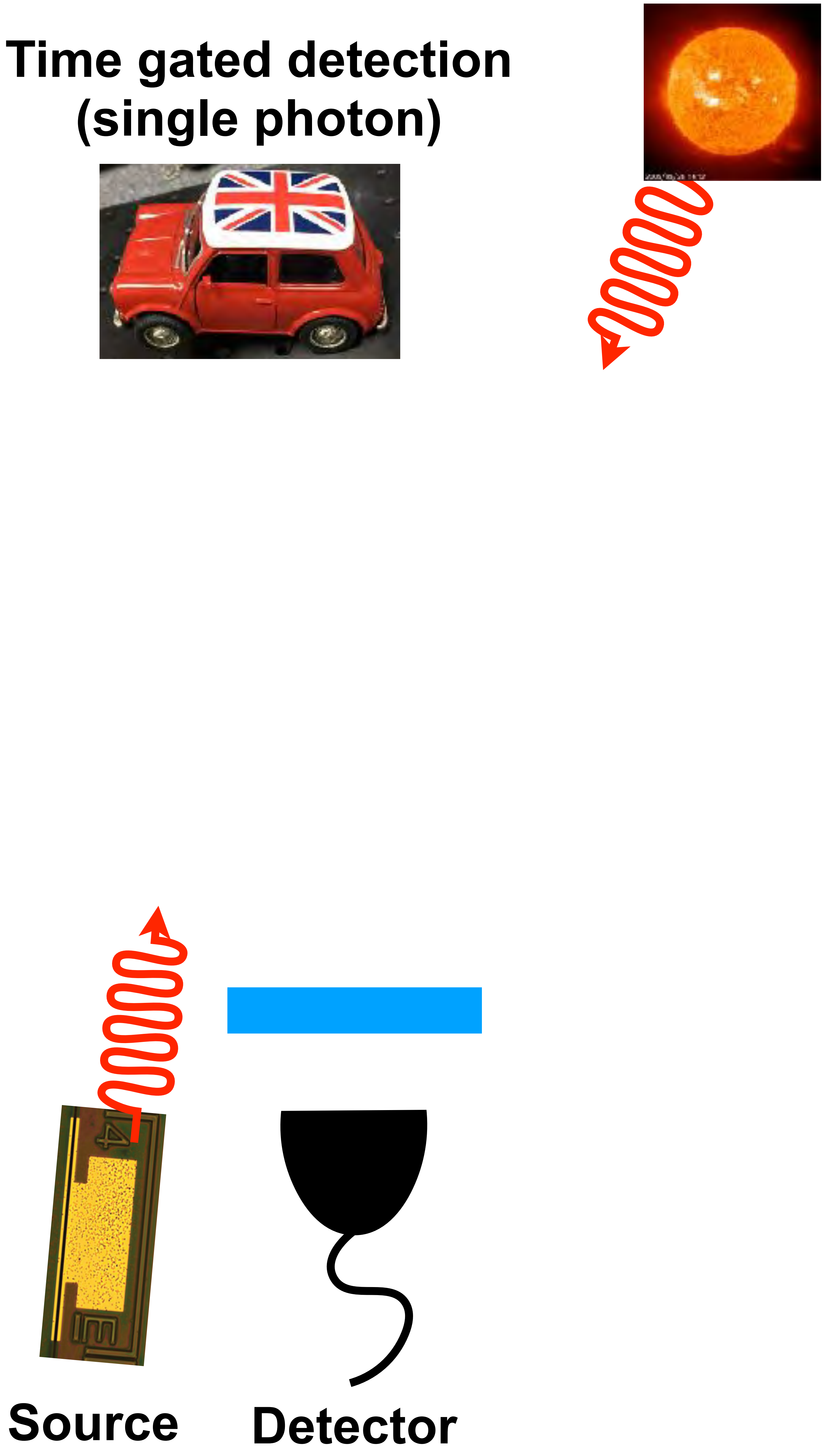
Incoherent detection



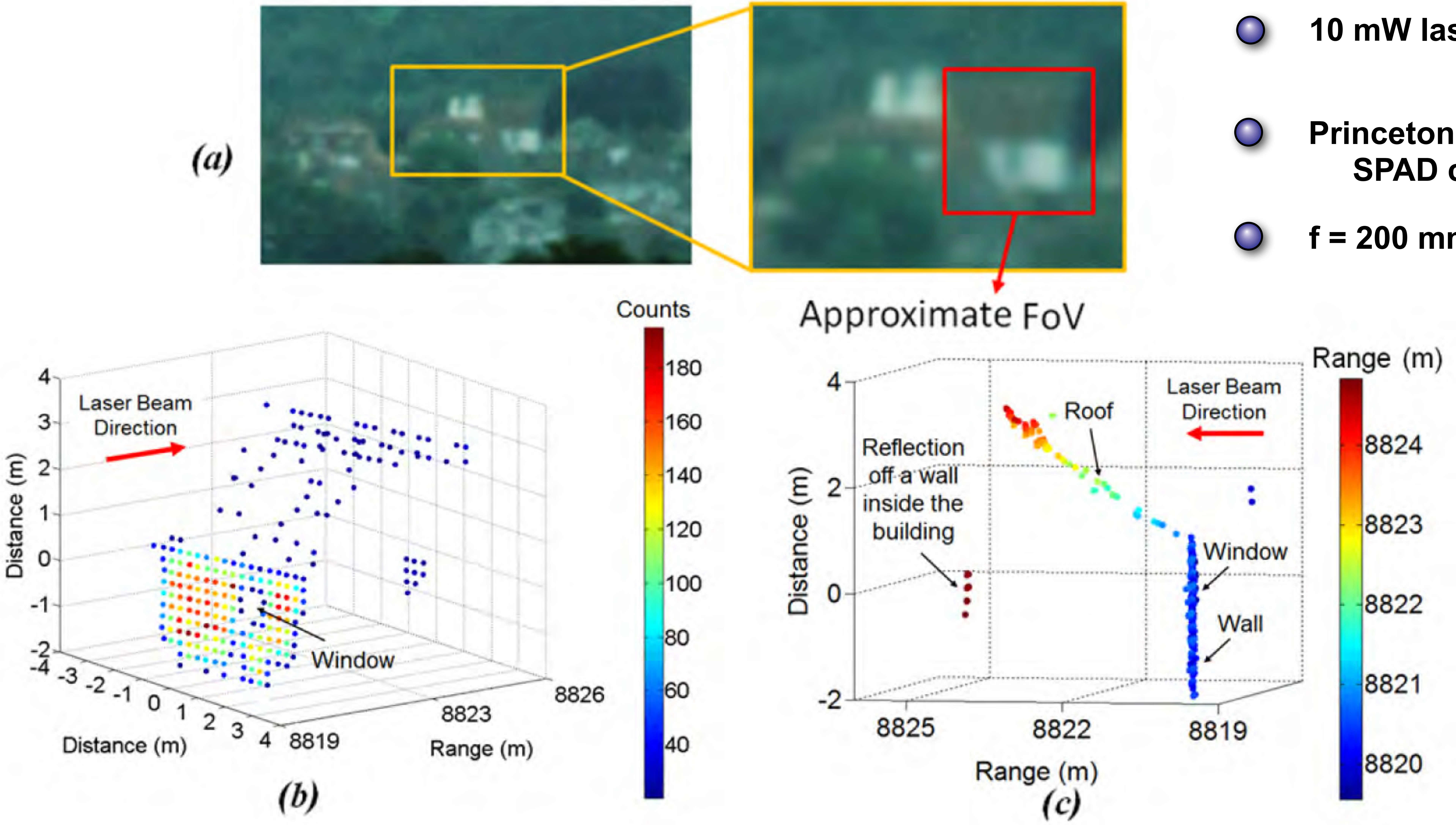
Phase coherent detection



Time gated detection (single photon)



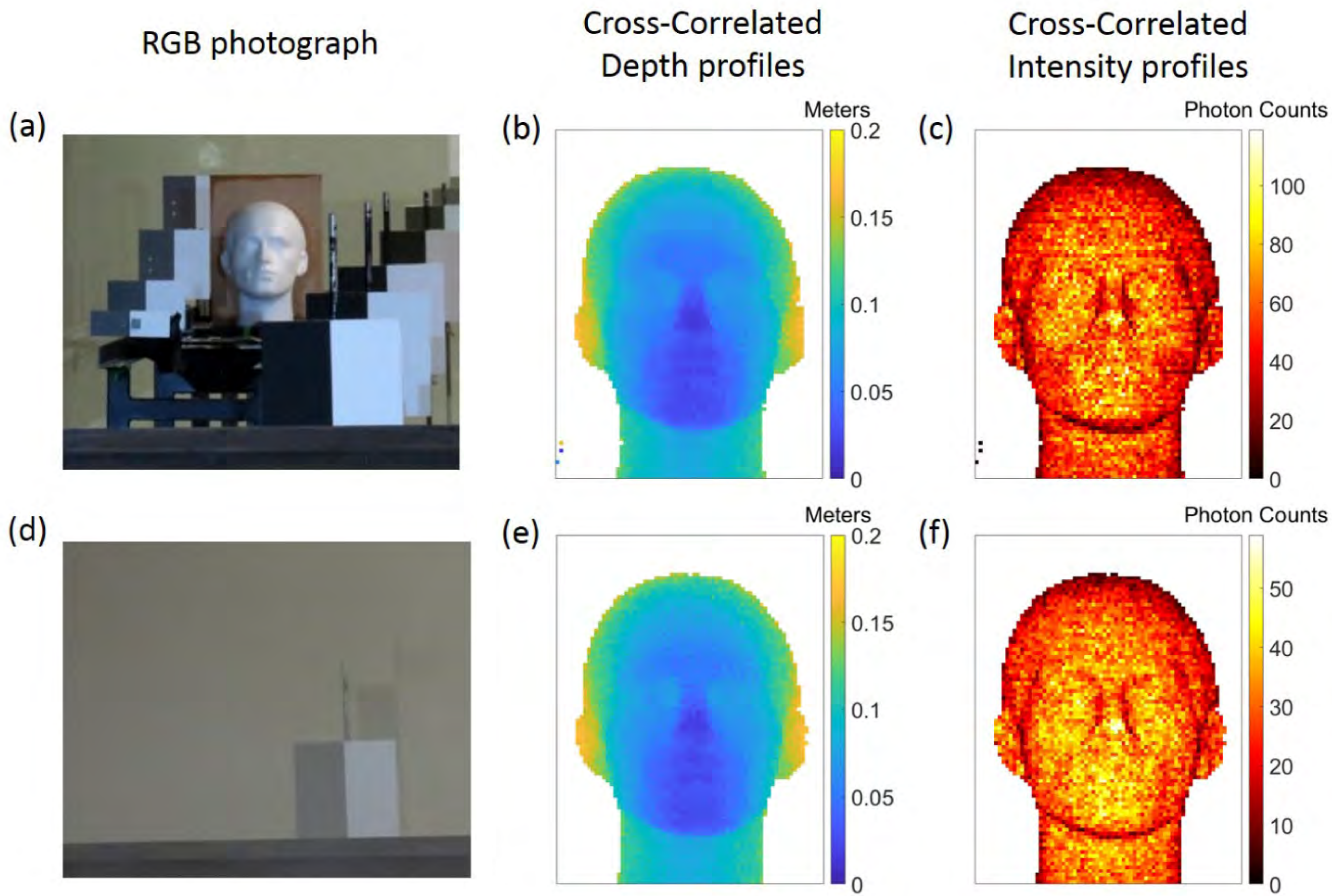
SWIR Single Photon Avalanche Detector InGaAs Camera



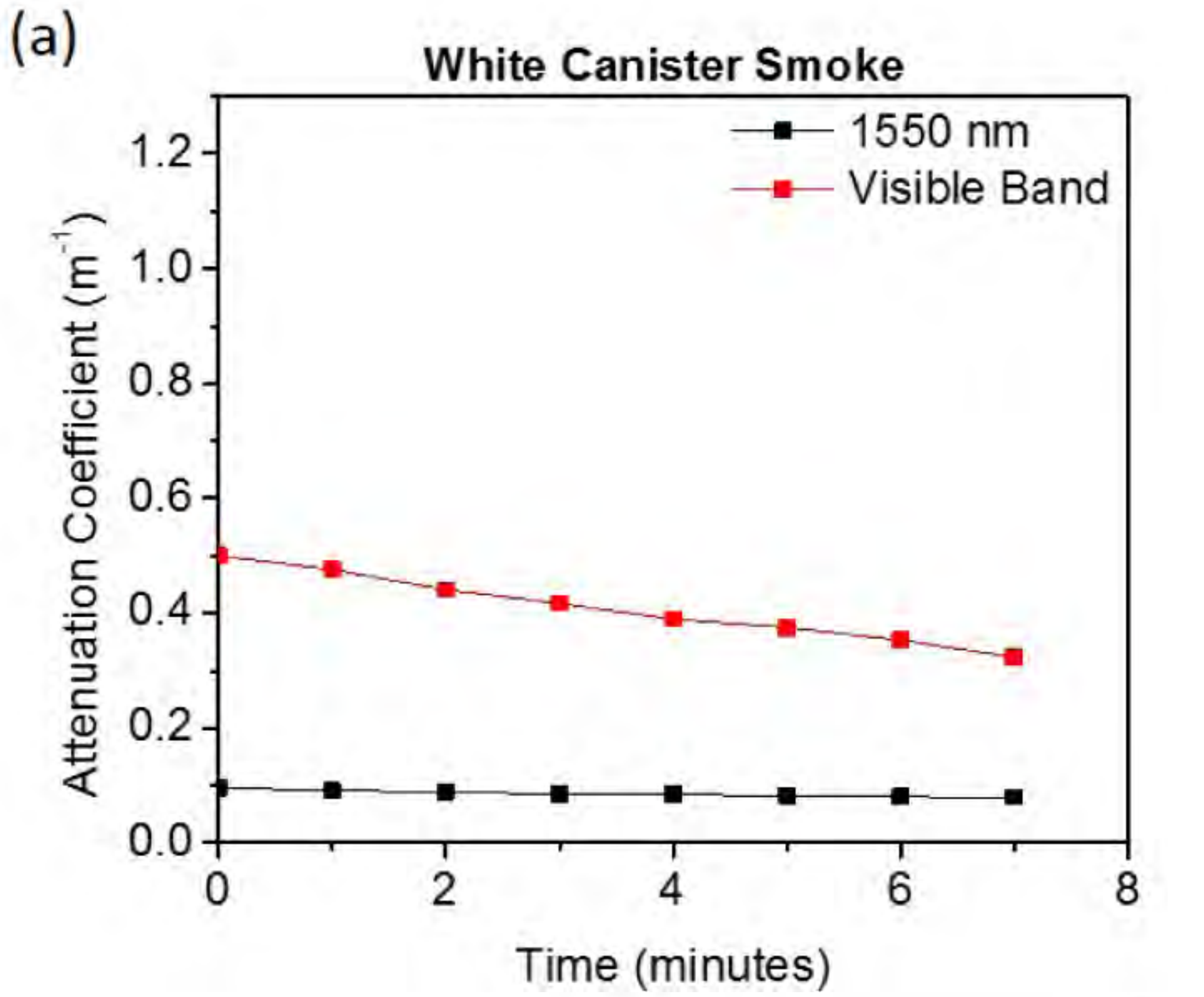
- 10 mW laser at 1550 nm
- Princeton Lightwave SWIR SPAD camera at £150k
- f = 200 mm lens

A.G. Pawlikowska et al. Opt. Exp. 25, 11919 (2017)

Imaging Through Obscurants



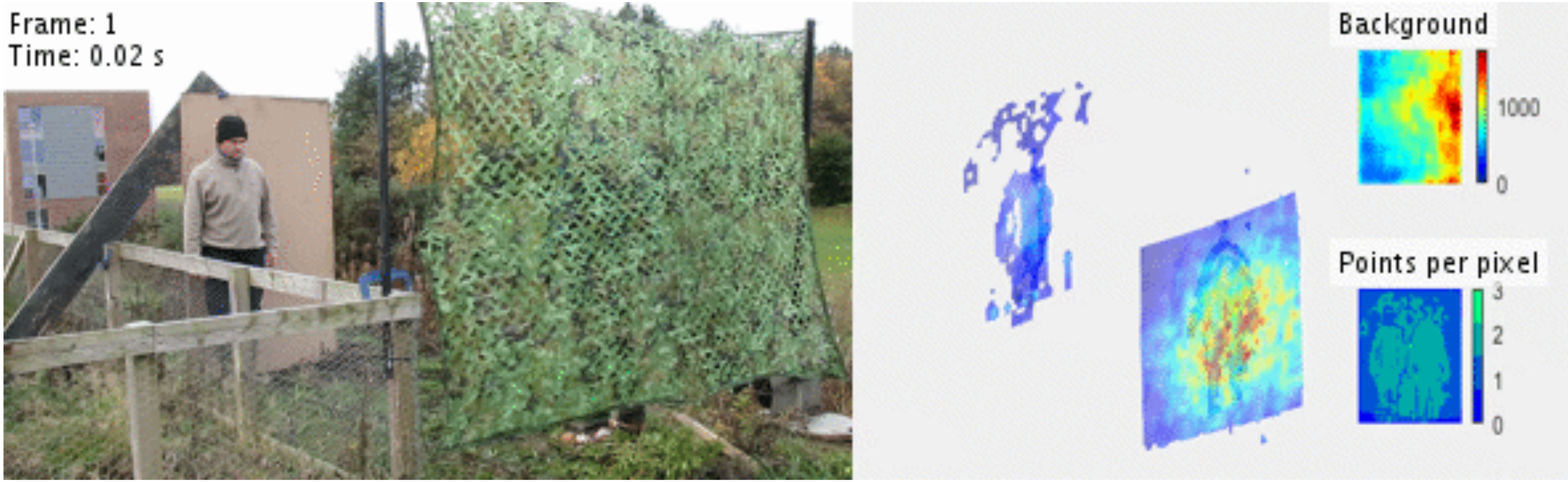
1550 nm 3D images at 24 m through smoke



- **1.5 mW laser at 1550 nm**
- **Princeton Lightwave SWIR SPAD camera at £150k**
- **f = 200 mm lens, 3 ms / pixel**
- **12 attenuation lengths in visible**
  2.4 attenuation lengths at 1550 nm

R. Tobin, Opt. Exp. 27, 4590 (2019)

Real Time Reconstruction of Multi-Surface Moving Scenes using Single-Photon Detection at 330 Meters Range

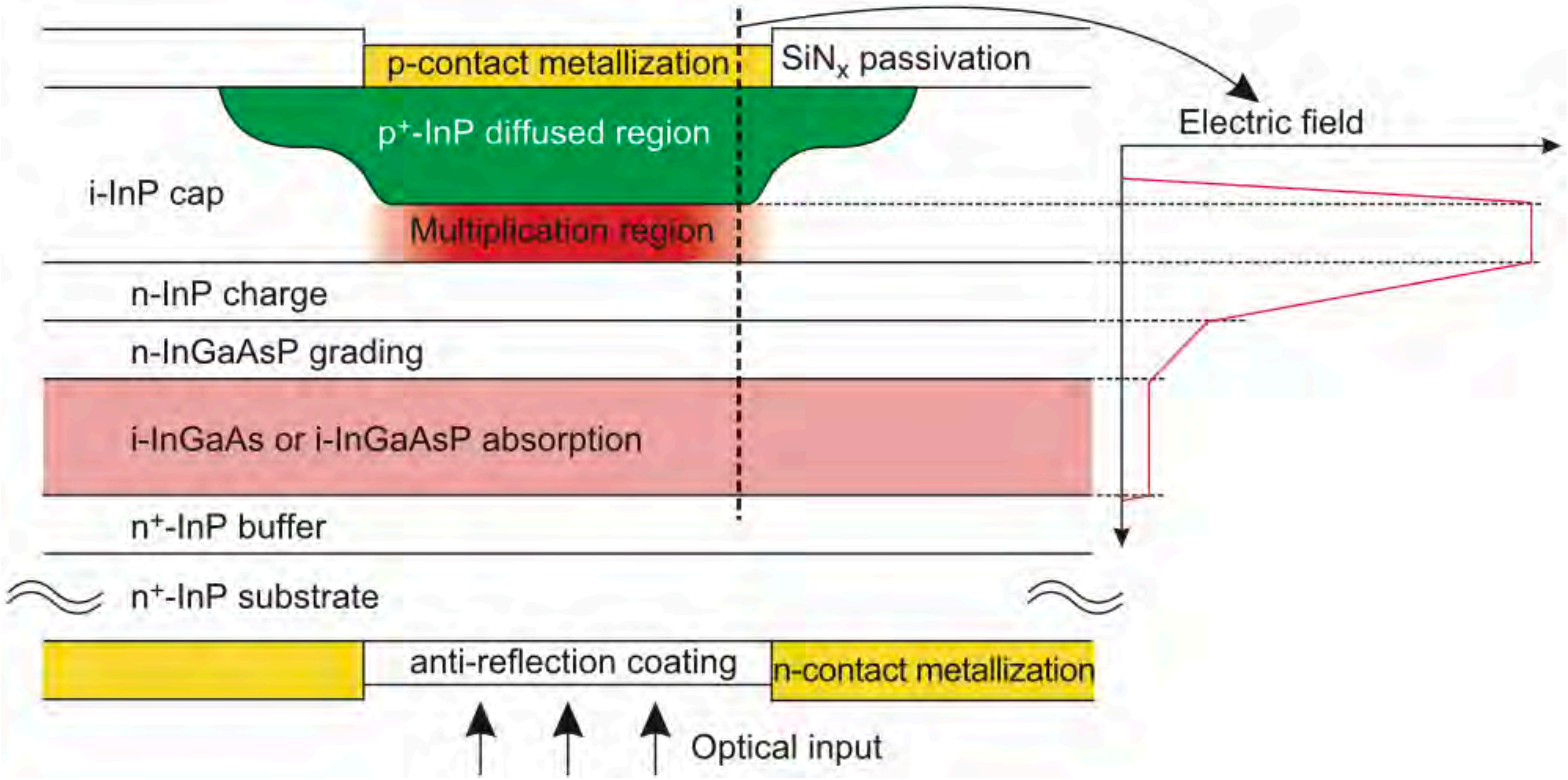


- **Multiple surfaces resolved – more than one surface per pixel, on average**
- **50 grayscale frames per second of 32 x 32 pixels at 1550 nm**
- **Real-time processing**
- **Eye-safe illumination in presence of solar background**

J. Tachella, et al."Real-time 3D reconstruction of complex scenes using single-photon lidar: when image processing meets computer graphics" Nature Comms. 10, 4984 (2019)

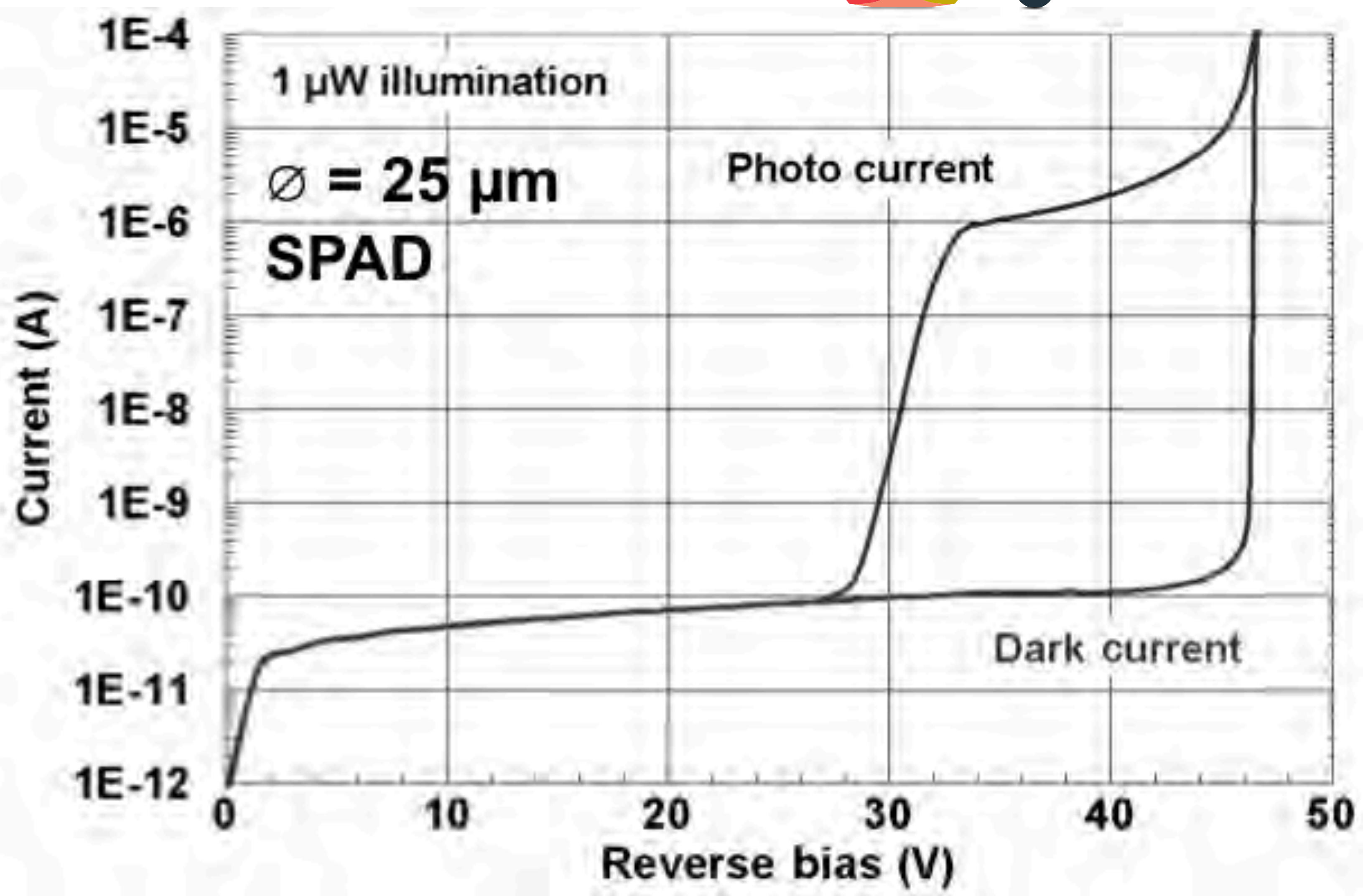
InGaAs SPADs

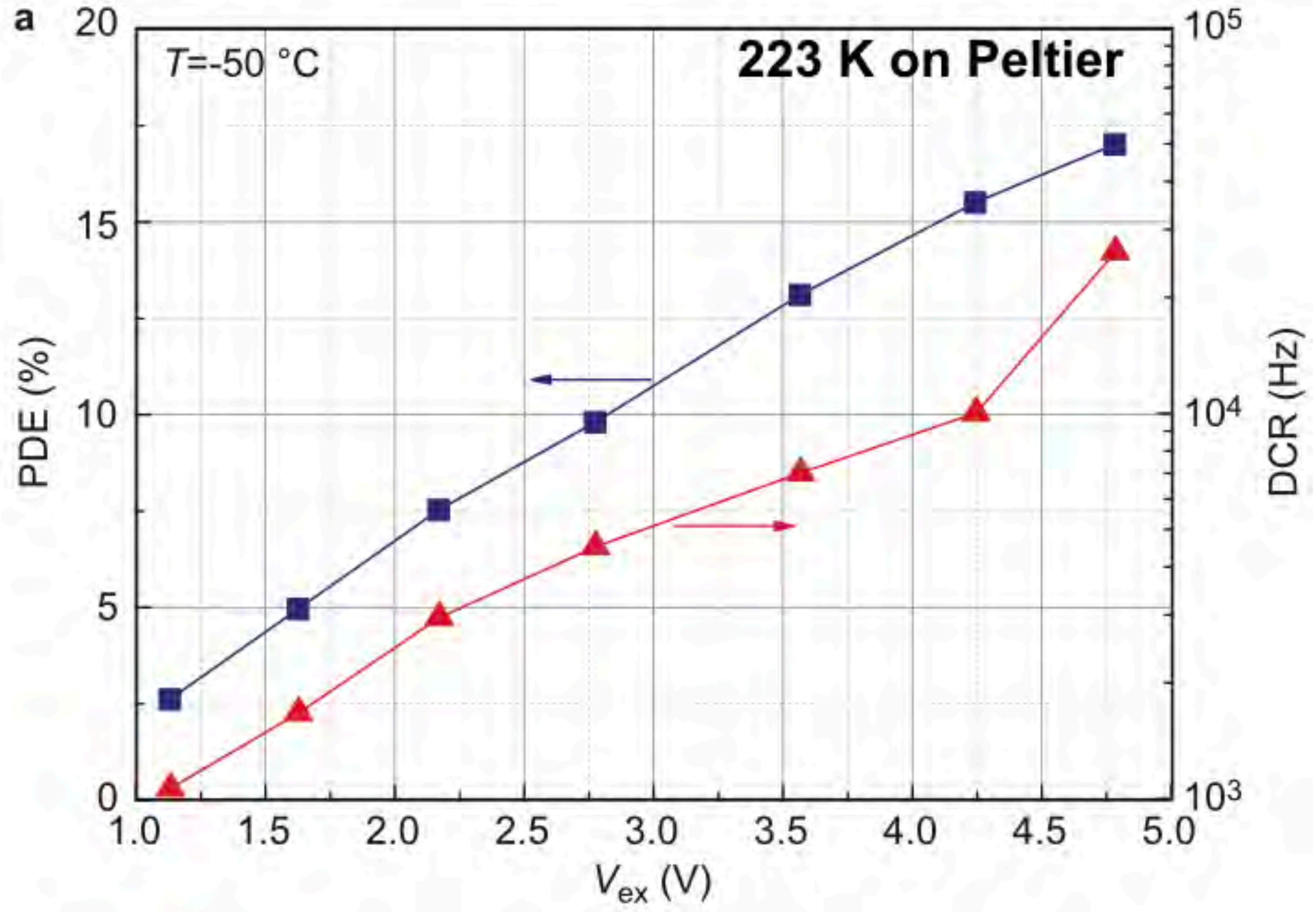
- **Princeton Lightwave (now Argo AI): significant funding over decades & commercial leader in InGaAs SPADs on InP**



area = 4.91 x 10^{-10} m^{-2}
= x16 smaller than Ge on Si

J. Zhang et al., Light Sci. App. 4, e286 (2015)



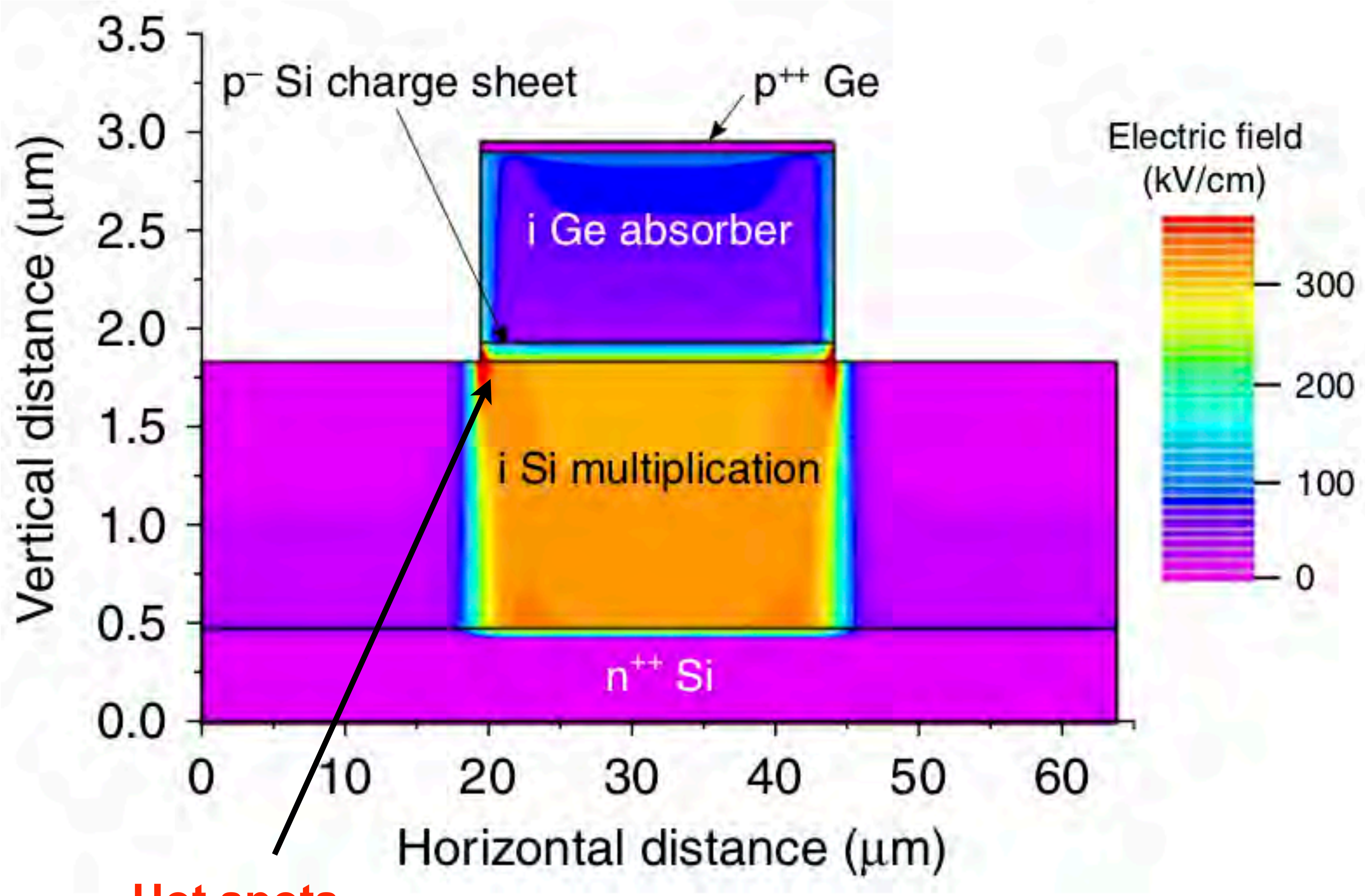


$20k single pixel, $150k for 32 x 32 camera

Electric Field Profiles

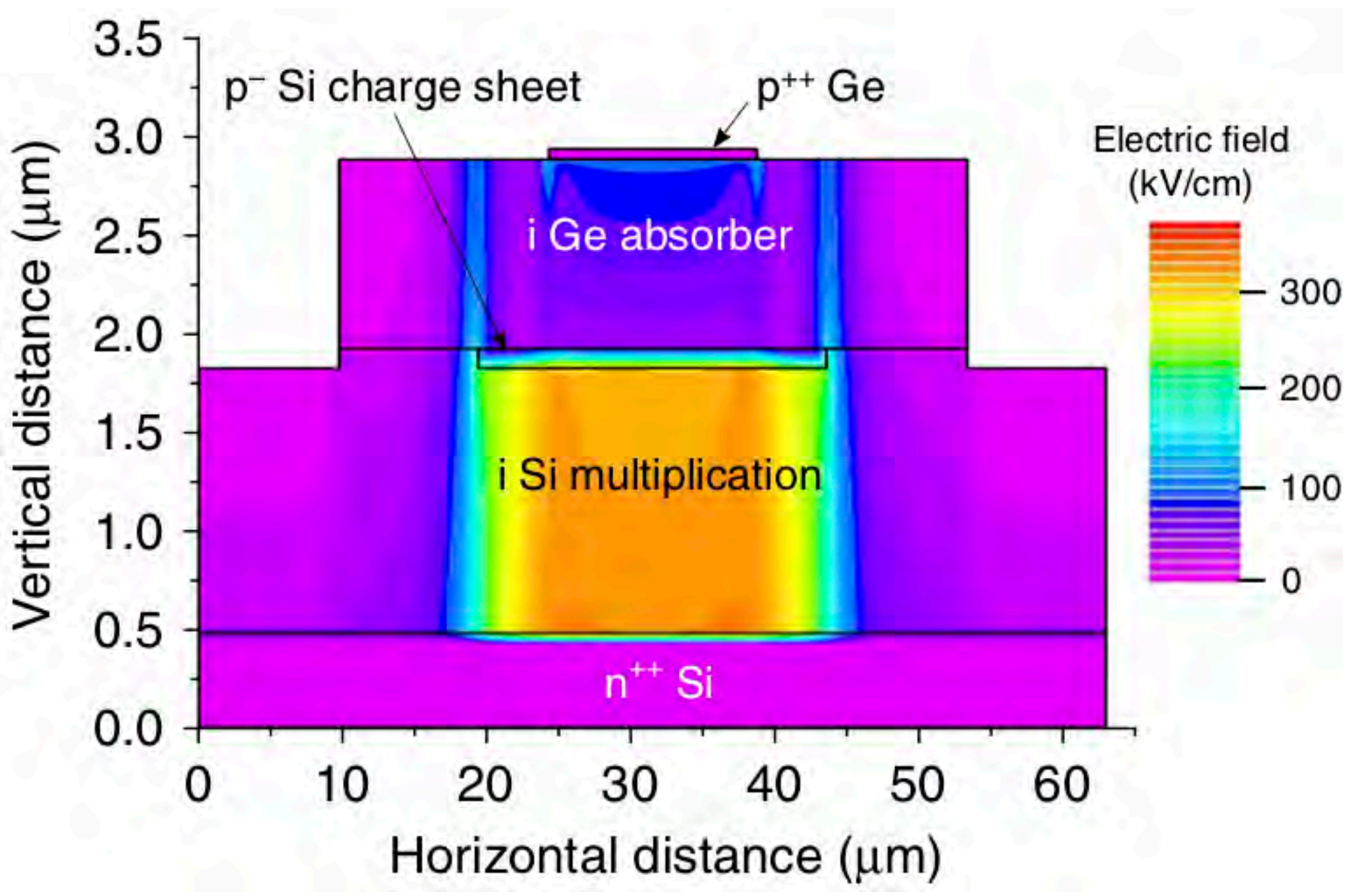
Silvaco Athena TCAD

Mesa device



Hot spots increase DCR

Planar device

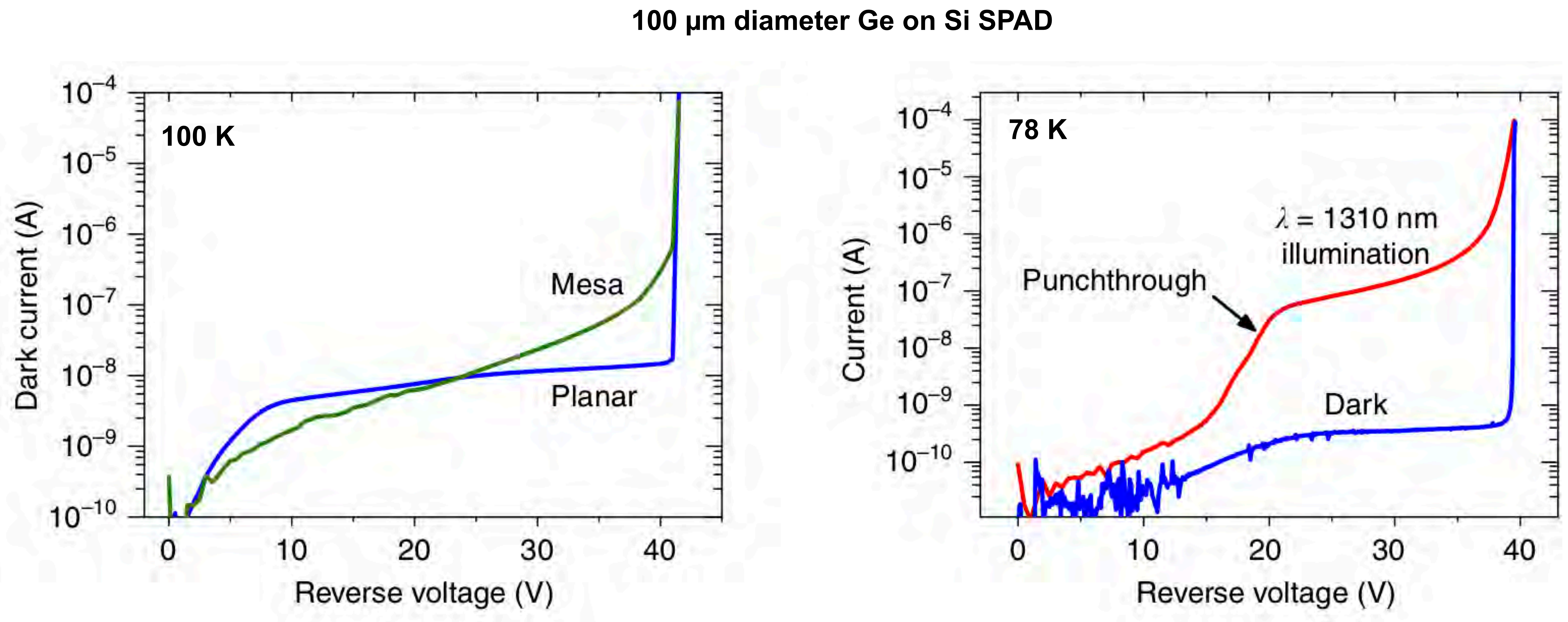


GB Patent application no. 1814688.6 (10th September 2018)

R.E. Warburton et al., IEEE Trans. Elec. Dev. 60, 3807 (2013)

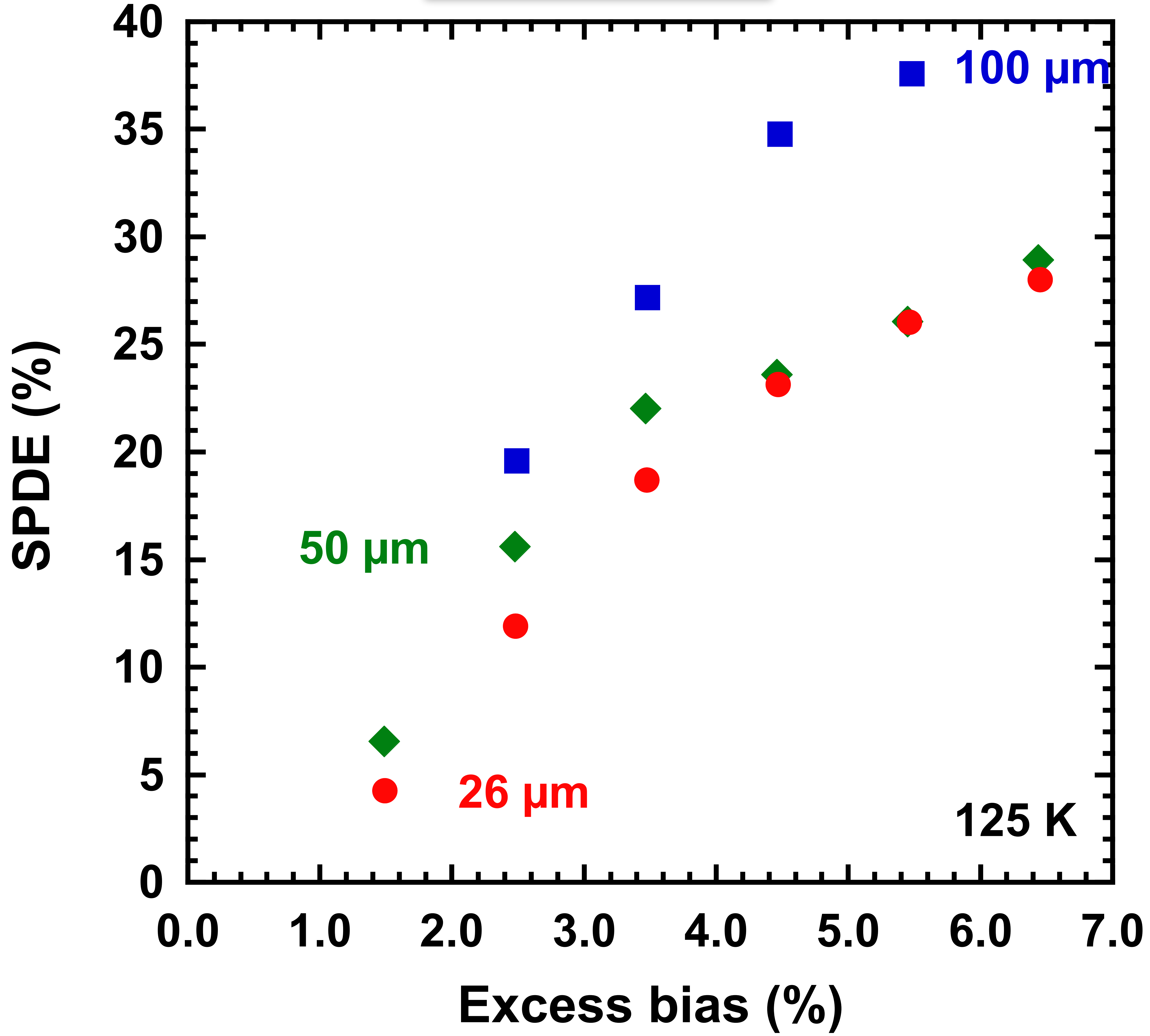
P. Vines et al., Nature Comms. 10, 1086 (2019)

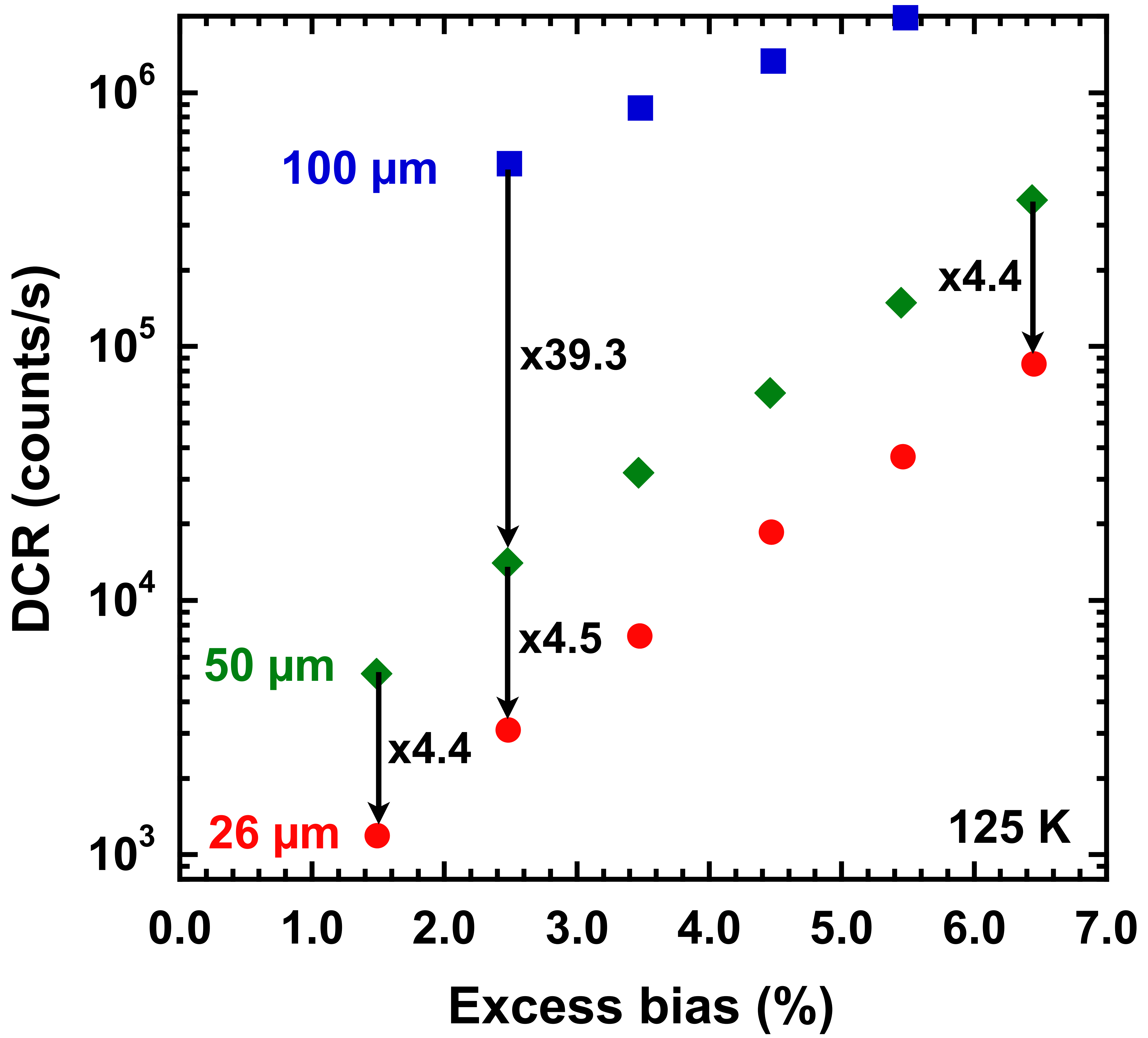
Ge SPADs Planar vs Mesa



P. Vines et al., Nature Comms. 10, 1086 (2019)

Device Scaling



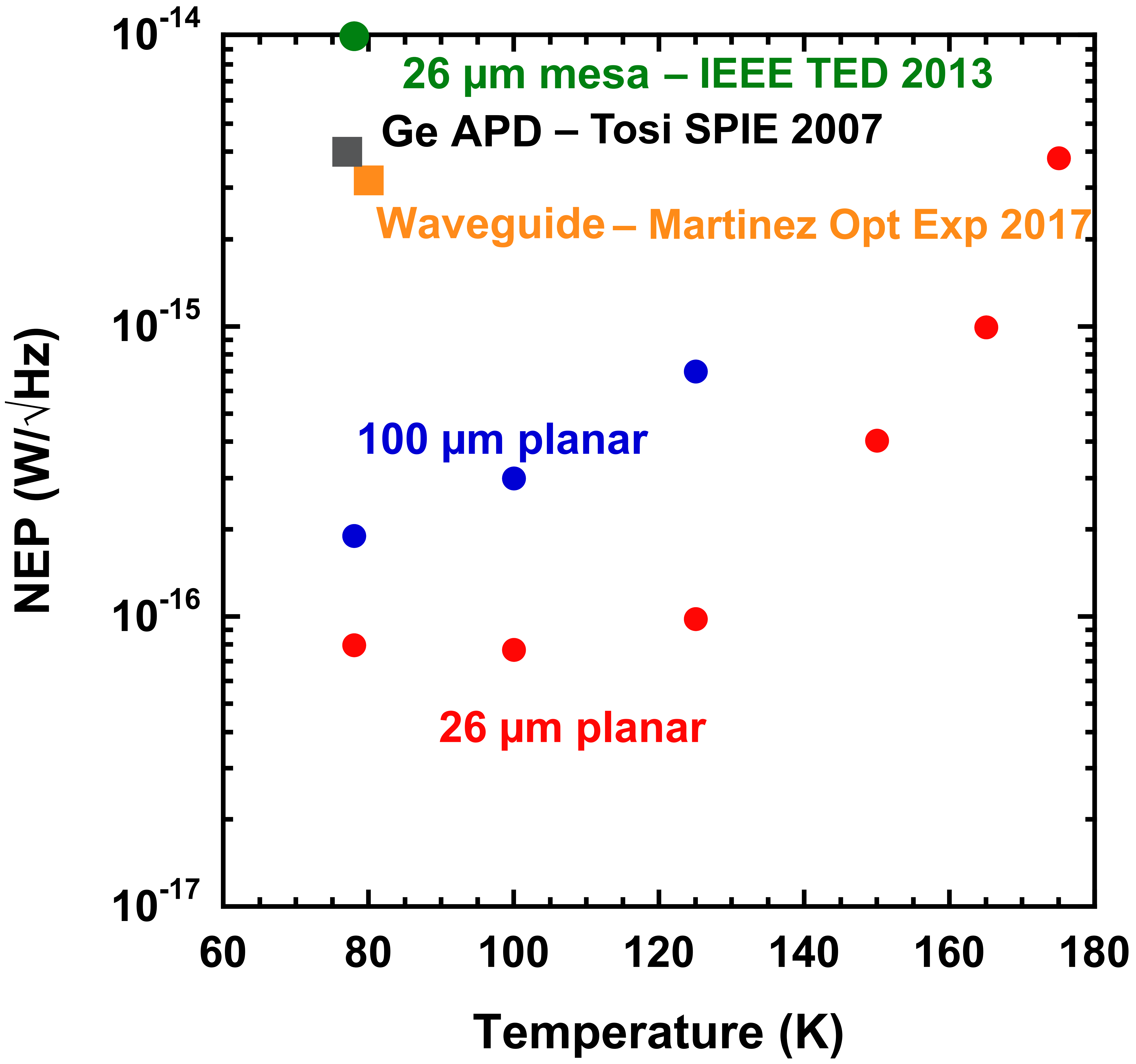


- DCR for 50 & 26 µm devices scales with Ge volume

P. Vines et al., Nature Comms. 10, 1086 (2019)

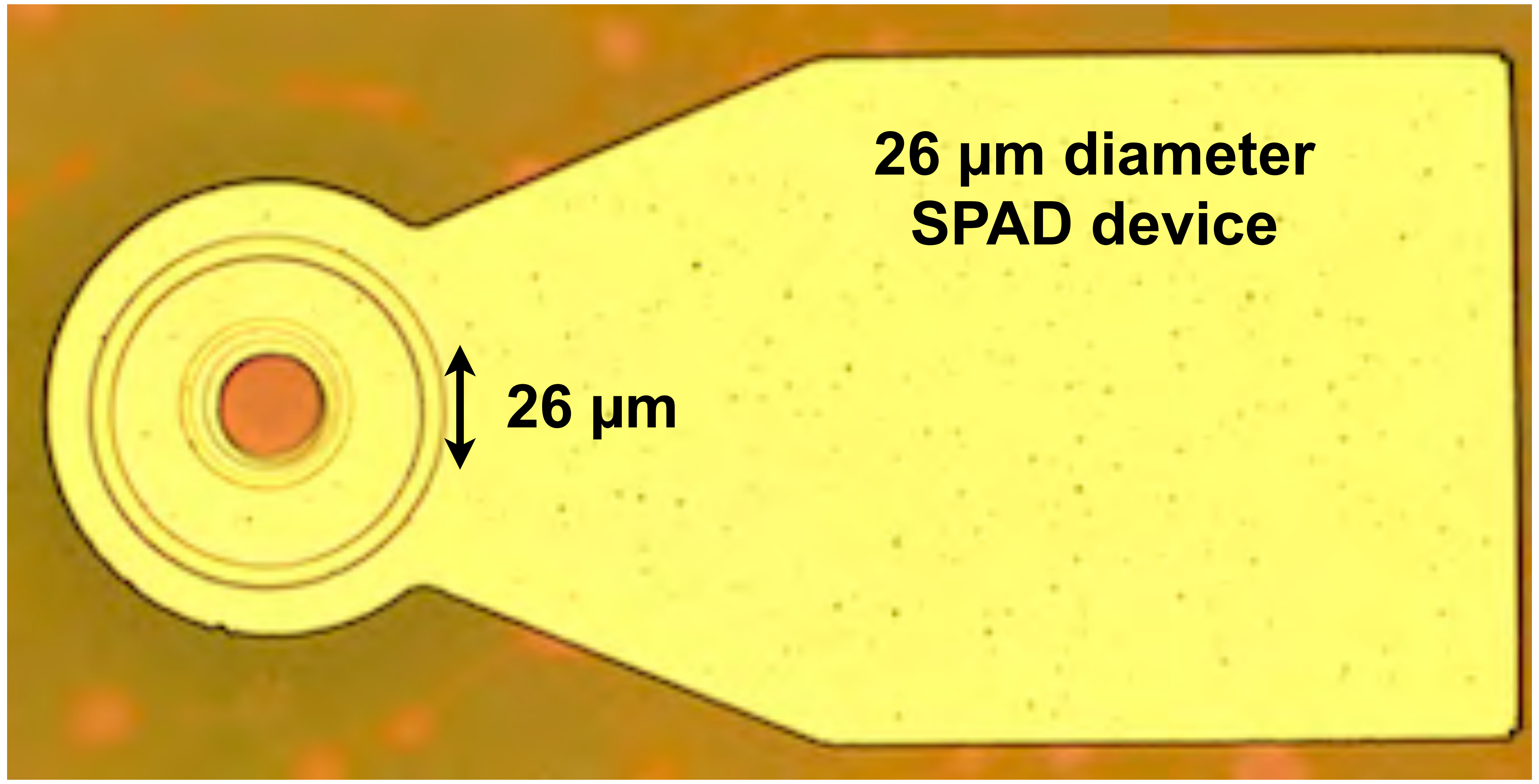
F.E. Thorburn et al. Proc. SPIE 11386, 113860N (2020)

Performance @ 1310 nm



$$\mathrm{NEP} = \frac{h\nu}{\mathrm{SPDE}}\sqrt{2\mathrm{DCR}}$$

- 310 ± 10 ps jitter for 100 µm diameter SPAD @ 78 K
- 134 ± 10 ps jitter for 26 µm diameter SPAD @ 100 K

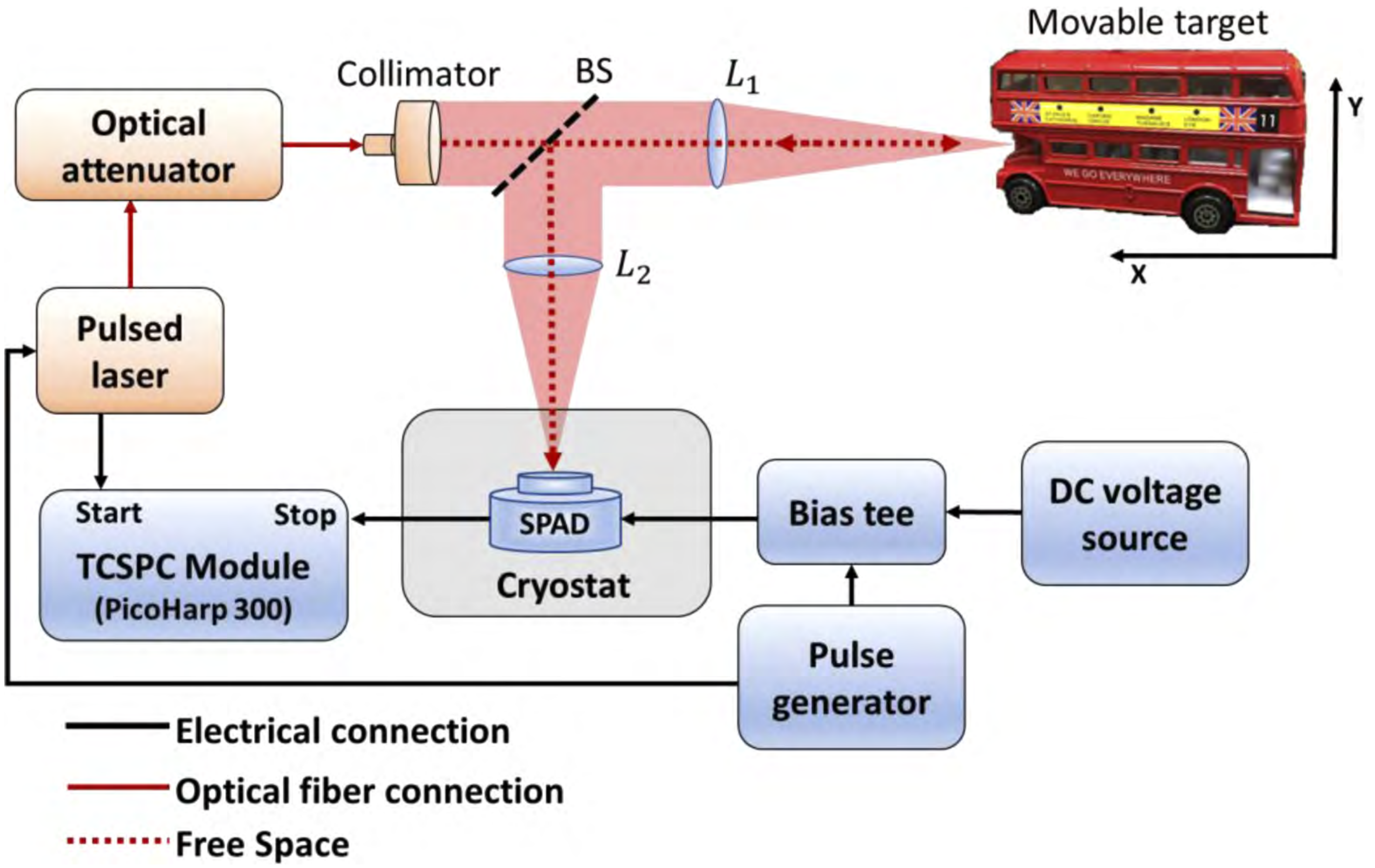


19.5 ps timing bin for jitter measurements

- 26 µm InGaAs NEP = 1 x 10^{-17} W/√Hz at 223 K and 1550 nm

LIDAR Imaging

- 912 pW laser after attenuation
- λ = 1450 nm
- Repetition rate 104 kHz
- 100 μm diameter SPAD at 100 K
- V_{ex} = 1.5%, SPDE = 10%
- DCR = 4.7 MHz
- 23 mm aperture
- Mechanical raster of single pixel
- 100 x 70 pixel raster for images

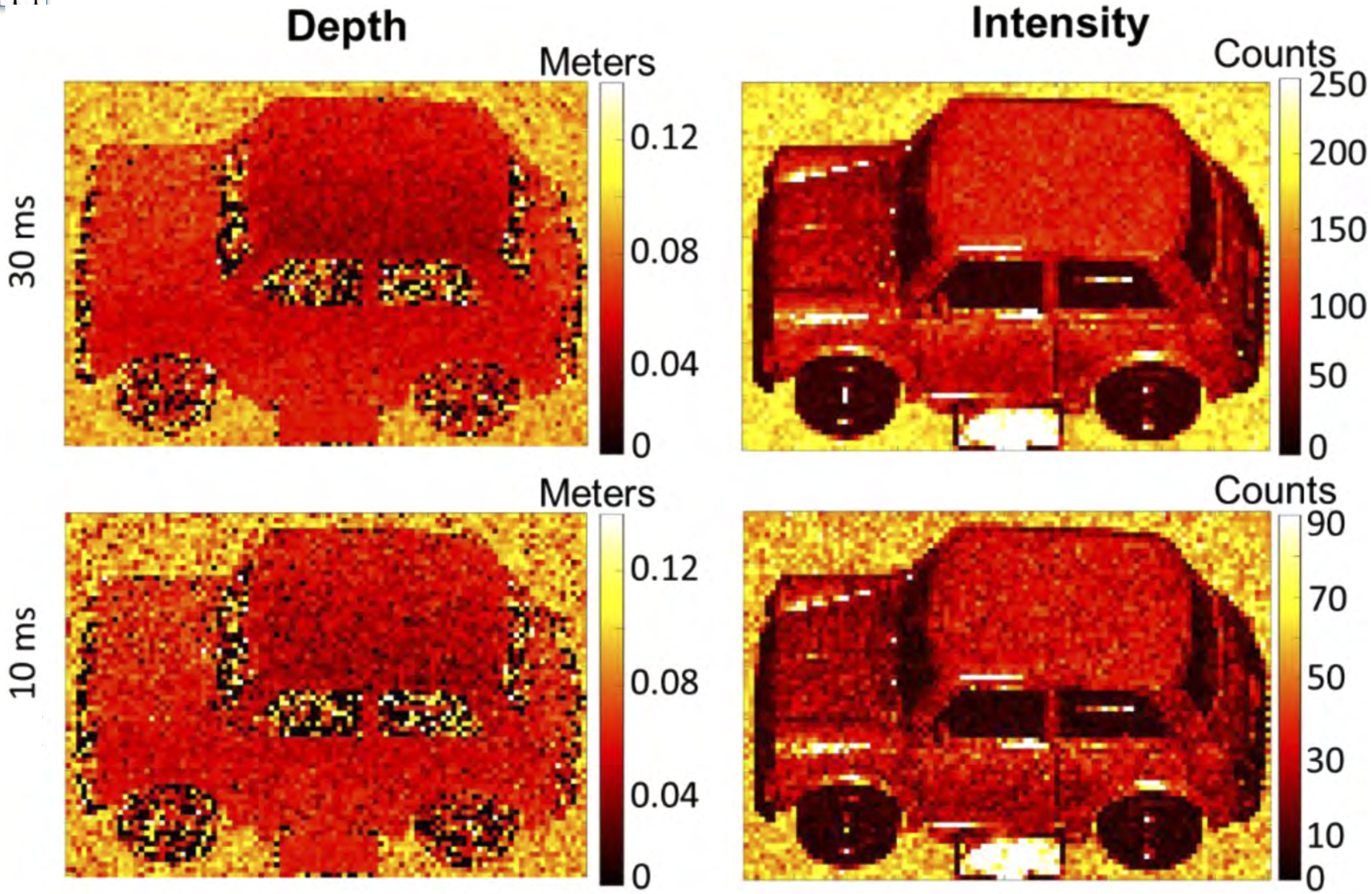


K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

LIDAR with Ge on Si SPADs

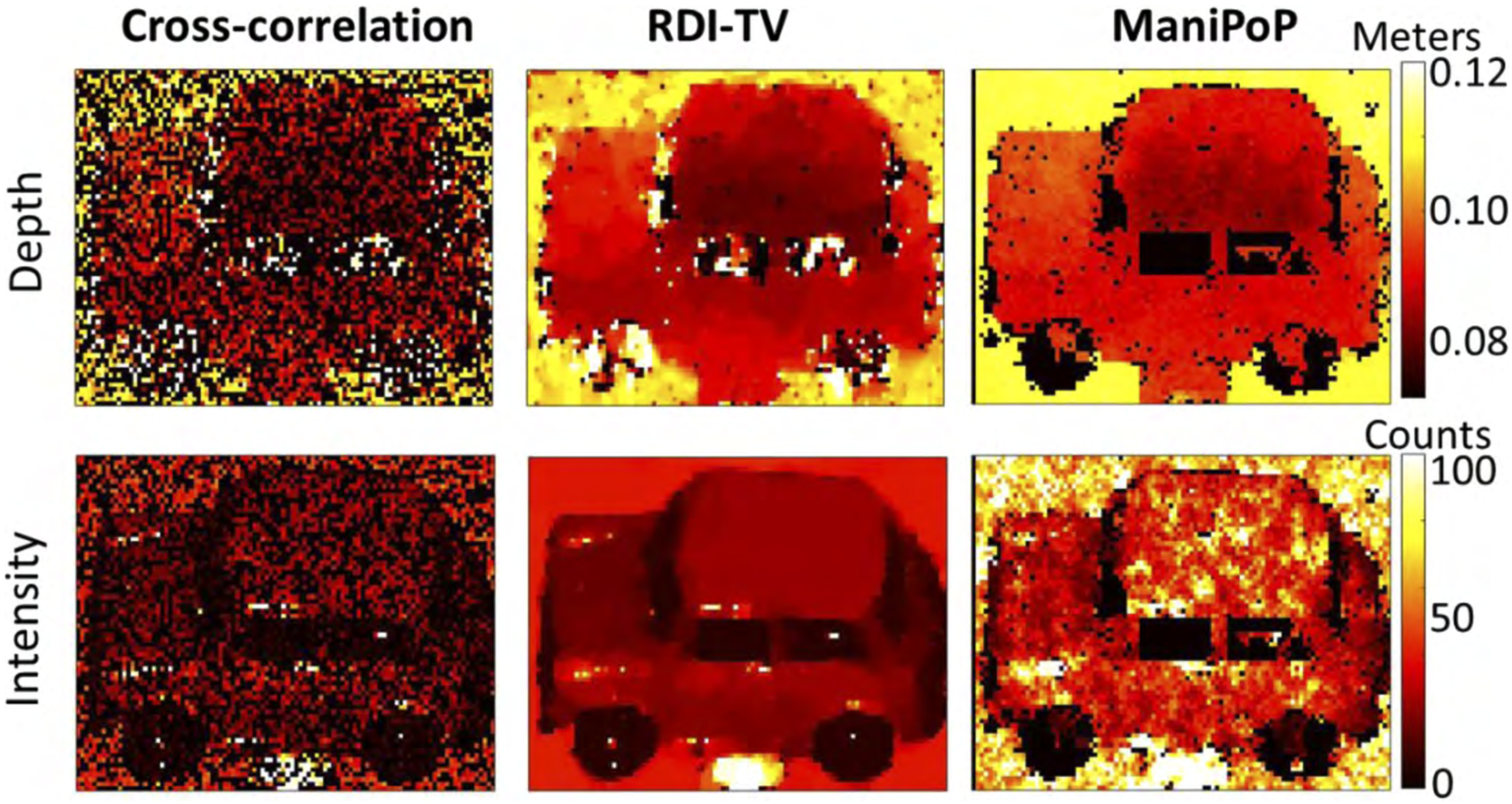
95mm x 60mm x 45mm (L x W x H)

- 912 pW laser
- λ = 1450 nm
- Repetition rate 104 kHz
- V_{ex} = 1.5%, SPDE = 10%
- DCR = 4.7 MHz
- 23 mm aperture
- 100 x 70 pixel raster



K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

Noisy LIDAR Reconstruction



- 10 ms acquisition time with 50% of pixels removed

K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

LIDAR Performance Estimations

- Estimate of photon events recorded in timing bin corresponding to peak of photo return histogram:

$$n_p = \frac{E_{pulse} F \lambda}{hc} t \frac{A_{lens} \rho}{2\pi R^2} e^{-2\alpha R} C_{in} C_{det} \eta$$

- Background counts per bin:

$$n_b = t \mathrm{DCR} \tau_b F$$

26 µm SPAD
DCR = 2.6kc/s

- Signal–to–noise

$$\mathrm{SNR} = \frac{n_p}{\sqrt{n_p + n_b}}$$

- Average laser power required for successful imaging at distance R:

$$P_{out} = \frac{hc}{\lambda} \frac{2\pi R^2 n_p}{A_{lens} \rho t \eta C_{in} C_{det}}$$

E_{pulse} = laser pulse energy

F = laser rep. rate

λ = wavelength

t = acquisition time

A_{lens} = collection area of lens

ρ = reflectivity of target (= 10%)

R = distance to target

α = attenuation coefficient of environment

C_{in} = internal loss of system (= 10 dB)

C_{det} = temporal response of detector

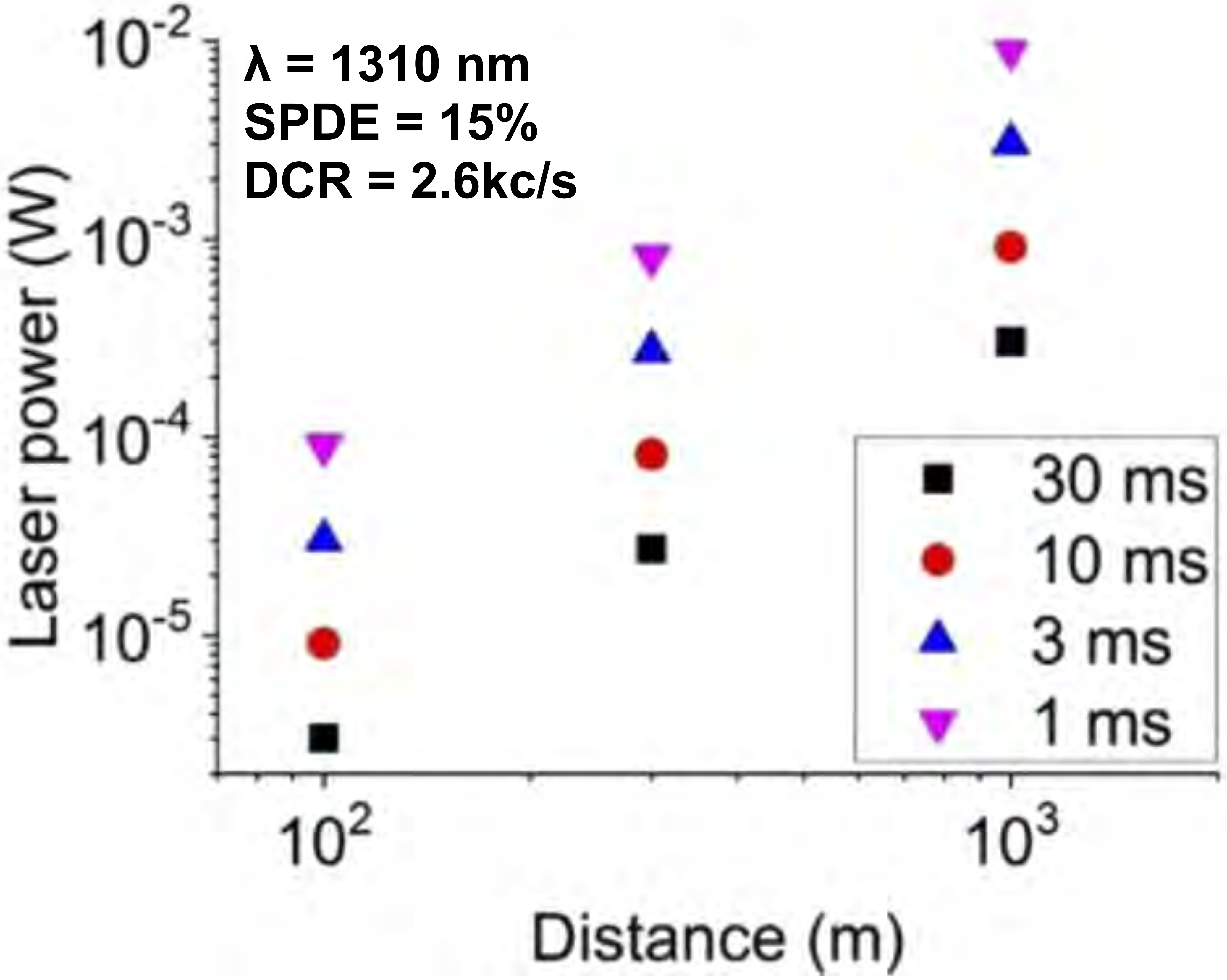
η = detector SPDE (= 15% or 9%)

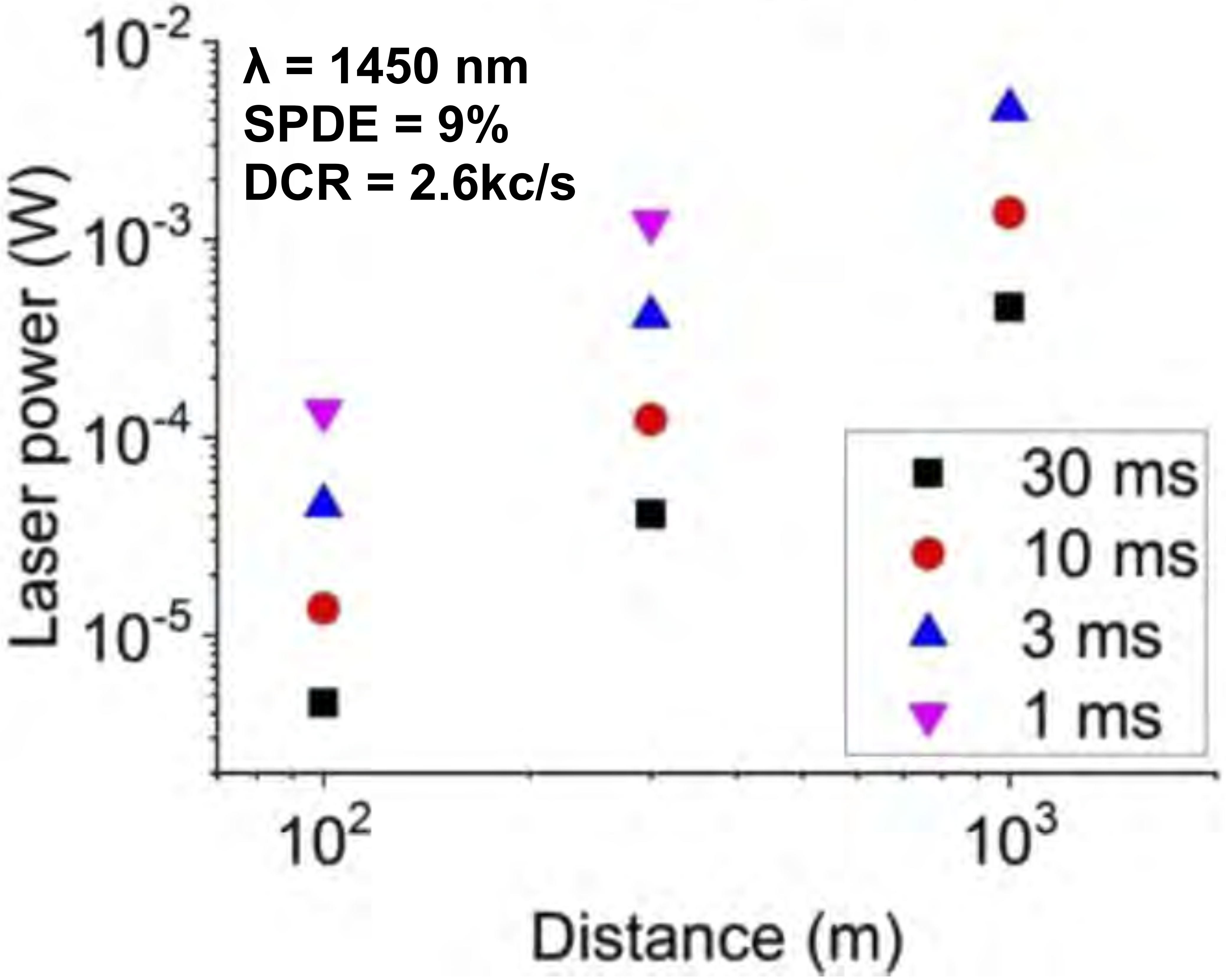
τ_b = bin size (= 50 ns)

K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

LIDAR Range

- 23 mm aperture lens with 26 μm Ge-on-Si SPAD operating at 125 K, 2.5% excess bias & 100 kHz rep. rate
- SNR = 1.4, internal system loss = 10 dB, reflectivity of target is Lambertian with 10% back-scatter



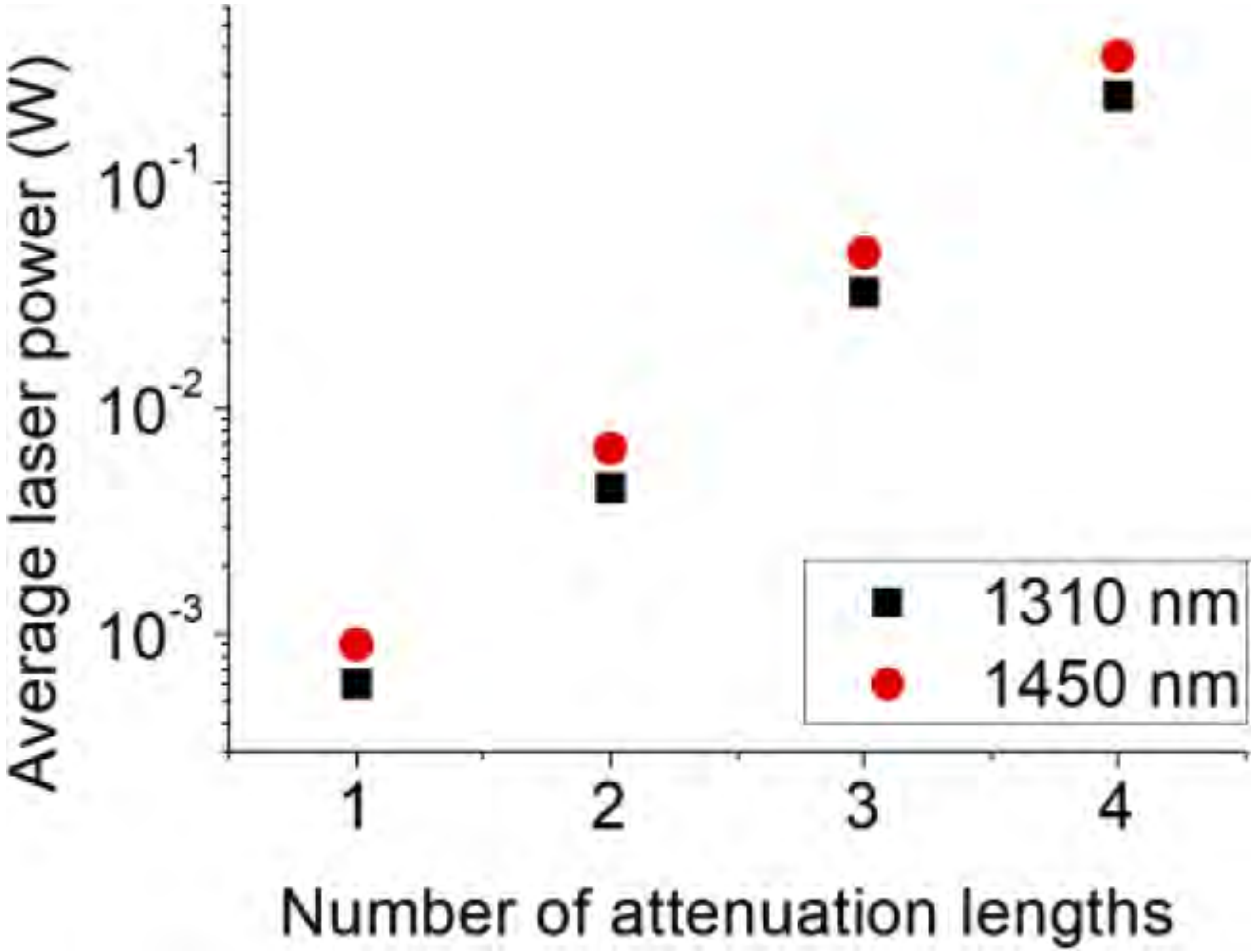


- ≥ 1 km range for LIDAR for eye-safe laser powers (IEC-60825-1) for ≥ 1 ms averaging per pixel

K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

300 m Through Obscurants

- 23 mm aperture lens with 26 μm Ge-on-Si SPAD operating at 125 K, 2.5% excess bias & 100 kHz rep. rate



(to the target)

- 10 ms acquisition time per pixel
- Eye-safe lidar feasible for automotive motorway driving in weakly attenuating media
- Reconstruction algorithms & improved SPDE at longer λ will improve performance in obscurant media

K. Kuzmenko et al., Opt. Exp. 28, 1330 (2020)

Agile Quantum Safe Communications

InnovateUK Project no. 104615 – AQuaSeC

Quantum Cryptography

TREL (TOSHIBA Leading Innovation)
Characterisation of components
High performance prototype
Security evaluation
User trials

KETS
QRNG
Low SWaP prototype
Security evaluation
User trials

Post-Quantum Cryptography

Queen's University Belfast
Hardware modules for QRA

Royal Holloway Uni. London
Security design
Software implementations of QRA

Component Developers

IQE
Commercial growth of wafers

Uni. of Glasgow
Processing of Ge on Si APDs

Uni. of Sheffield
Growth of InGaAs/InP APDs and placed dot wafers

Uni. of Cambridge (Physics)
Processing of InGaAs/InP APDs and emitters

Heriot-Watt Uni.
Characterisation of APDs

National Facilities

National Physical Laboratory
Security evaluation & certification

System Integrators

British Telecom
Demonstrations with end users

Senetas
Link encryption system and QKD integration

Uni. of Cambridge (Eng.)
Field trials in Cambridge and NDFIS

Dashboard
Integration with IoT system

TDS
Integration with tethered drone system

End Users

BT Radianz
Developing use-cases in financial sector

British Petroleum
Corporate network / Oil & Gas sectors

Ministry of Defence
Use cases in defence sector

CRUK - Cambridge Institute
Use cases in healthcare sector

AQuaSeC solutions to present QKD technology limits:

1. reduce cost with PICs & modules
   - shrink QKD onto photonic integrated circuits (PIC)
   - PIC integrated into standardised pluggables

2. Network integration
   - use WDM to operate QKD on data network
   - PIC modules allow wavelength & routing flexibility

3. Crypto integration
   - collaboration of "classical" & quantum crypto
   - integrate necessary QRAs into QKD hardware & software
   - provide hybrid "quantum-safe" solution combining QKD and QRAs

4. Create security assurance procedure
   - setup security evaluation test-bed at NPL
   - establish certification process for quantum security products

Single Photon Imaging, Detection & Ranging

InnovateUK project no. 191217 (SPIDAR)

Industry supply chain

- TOSHIBA — UK system manufacture
- IQE — laser & SPAD epi material
- Compound Semiconductor Technologies — laser & SPAD fabrication
- bay photonics — packaging

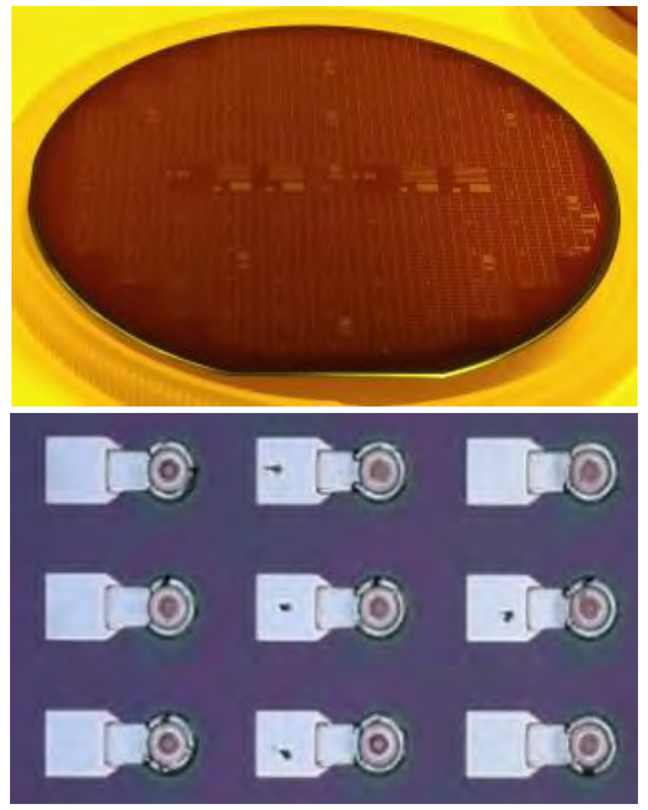
Academia

- University of Glasgow — Ge on Si SPAD arrays
- Heriot Watt University — Imaging algorithms & user trials
- The University of Edinburgh — ROIC
- University of Cambridge — InGaAs SPAD arrays

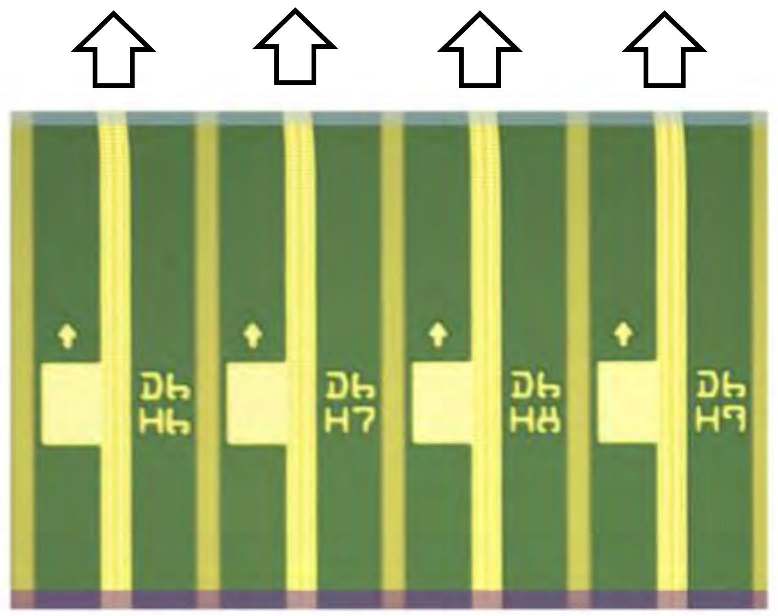
Industrial end users

- Jaguar Land Rover — automotive use cases & trials
- Thales — defence use cases & trials
- MIRA (A HORIBA COMPANY) — CAV test facilities
- NetworkRail — rail infrastructure use cases & trials

WP1: SPAD imaging arrays



WP2: Diode laser arrays



CST DFB Laser Diode Array

WP3: Quantum imaging systems

WP4: End user trials

Summary

- Planar design key resulting in 3 orders of magnitude reduction of DCR
- SPDE up to 38% at 1310 nm & 125 K
- NEP = 7.8×10^{-17} W/$\sqrt{\text{Hz}}$ and 134 ± 10 ps jitter for 26 μm SPAD at 100 K
- Afterpulsing at least x5 lower than InGaAs under identical conditions
- Initial LIDAR demonstration at eye-safe wavelengths
- Aim for telecoms wavelengths on Si at Peltier cooler temperatures

- EPSRC QuantiC
- EPSRC Quantum Comms Hub
- EPSRC SPEXS Programme Grant
- InnovateUK AquaSec
- InnovateUK SPIDAR
- Dstl PhD scholarship

P. Vines et al., "High performance Ge-on-Si SPAD detectors" Nature Comms. 10, 1086 (2019)

K. Kuzmenko et al., "3D LIDAR imaging using Ge-on-Si SPAD detectors" Opt. Exp. 28, 1330 (2020)

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Further details:
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Douglas.Paul@glasgow.ac.uk

Engineering and Physical Sciences Research Council

MEMS Gravimeters & Gradiometers

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Institute for Gravitational Waves

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Royal Academy of Engineering Chair in Emerging Technologies

DSTL Visiting Fellow

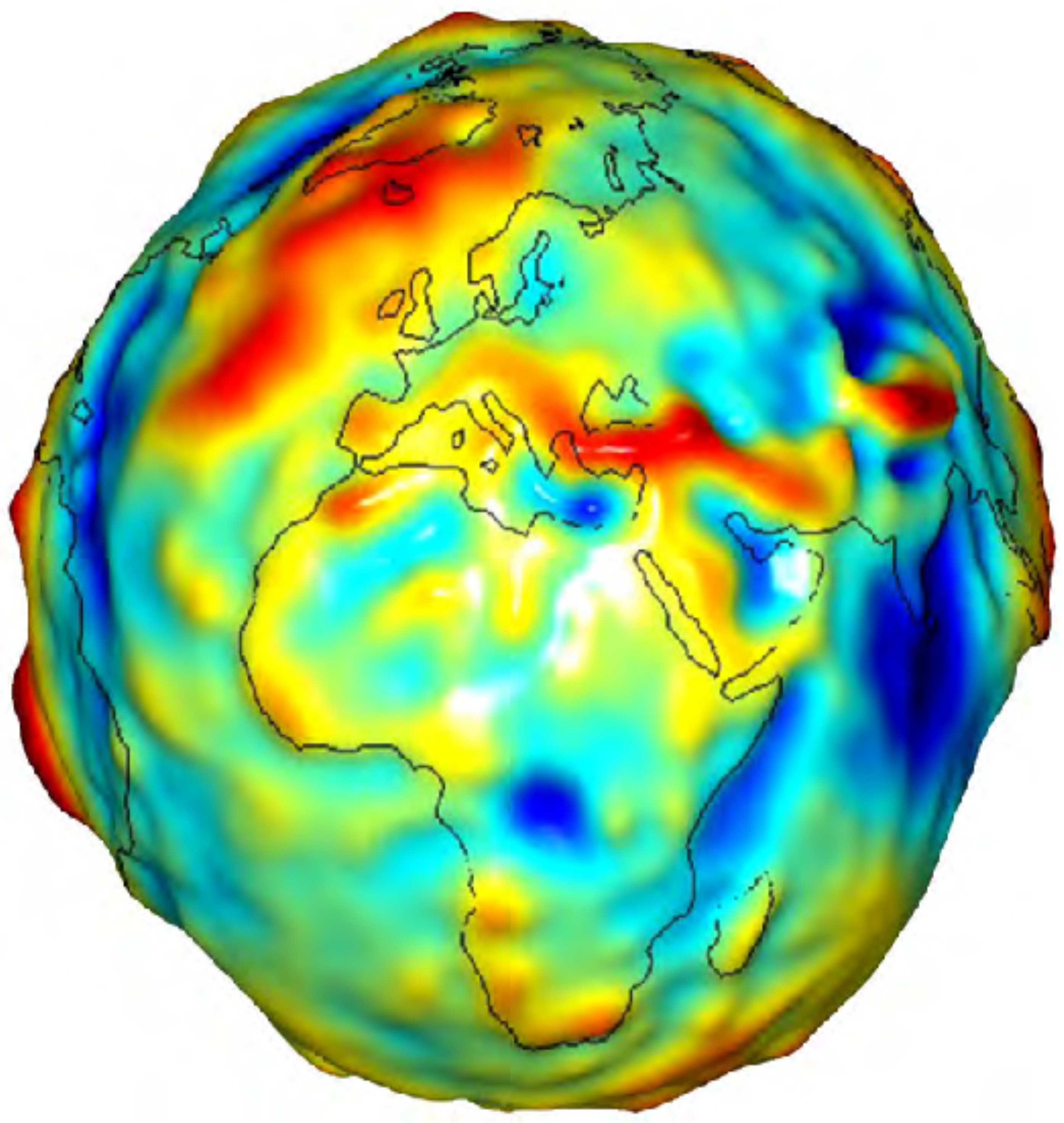
School of Engineering, University of Glasgow, U.K.

Marc Aftalion, Steven Brampsie, Jim Hough, Giovanna Marocco, Richard Middlemiss, Andreas Noack, Elizabeth Passey, Abhinav Prasad, Shelia Rowan, Karl Towland

University of Glasgow

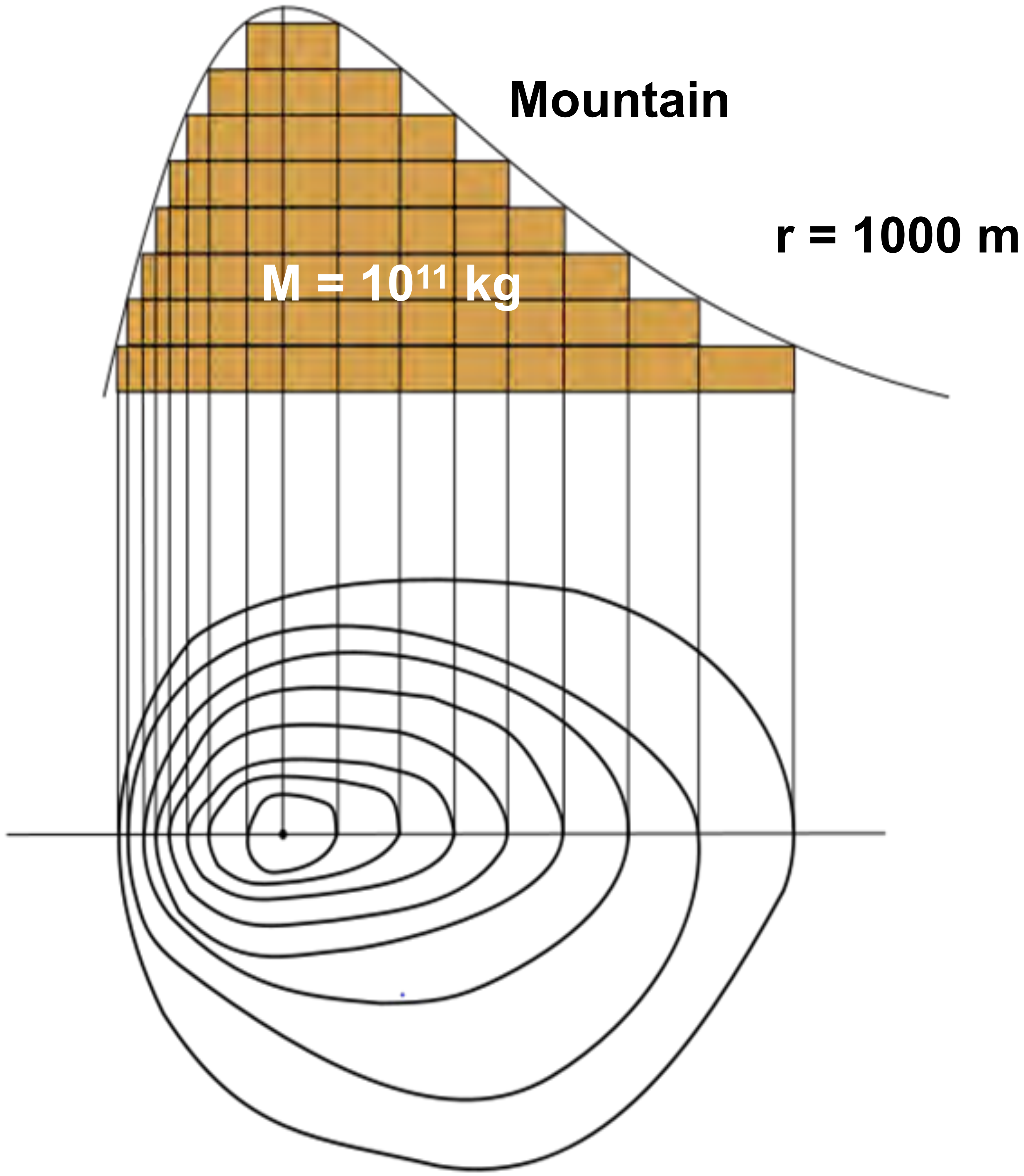
Gravity

- Gravity cannot be shielded



a_{earth} = 1 g = 9.81 ms^{-2}

$$F = \frac{GMm}{r^2} \quad \text{or} \quad a = \frac{GM}{r^2}$$



$a_{mountain}$ = 0.7 μg = 700 μGal

1 ng ~ 9.81 x 10^{-9} m s^{-2} = 1 μGal

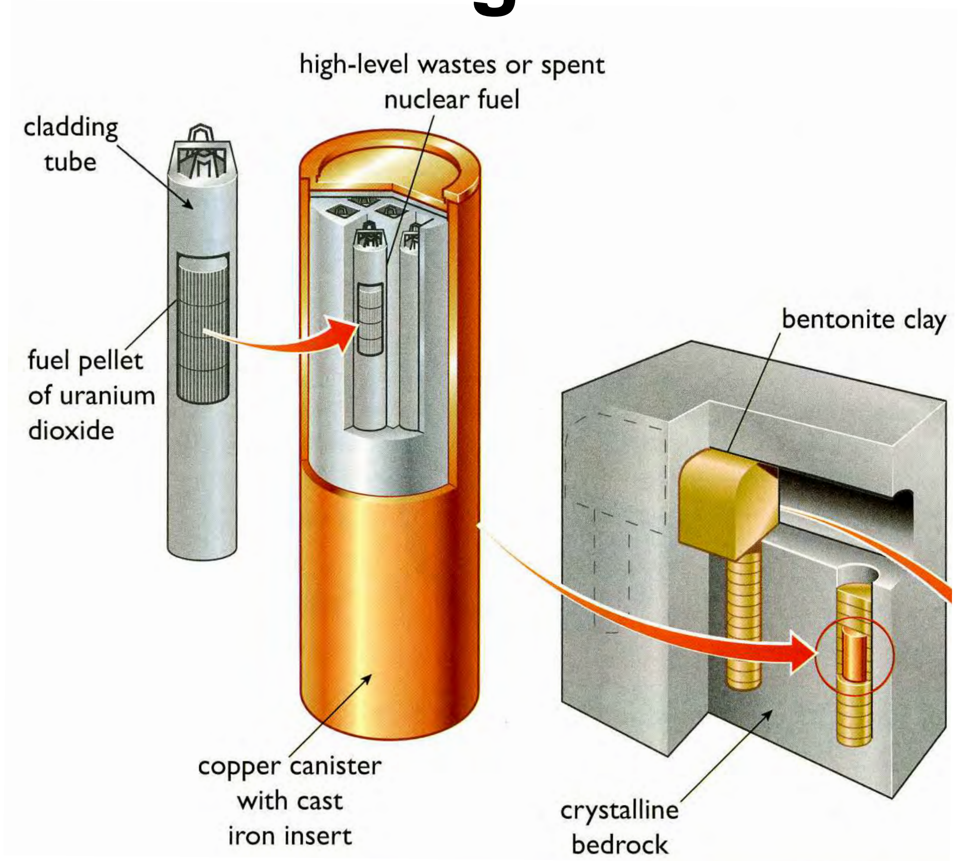
120 kg soldier 1m behind a wall

$a_{soldier}$ = 8 ng = 8 μGal

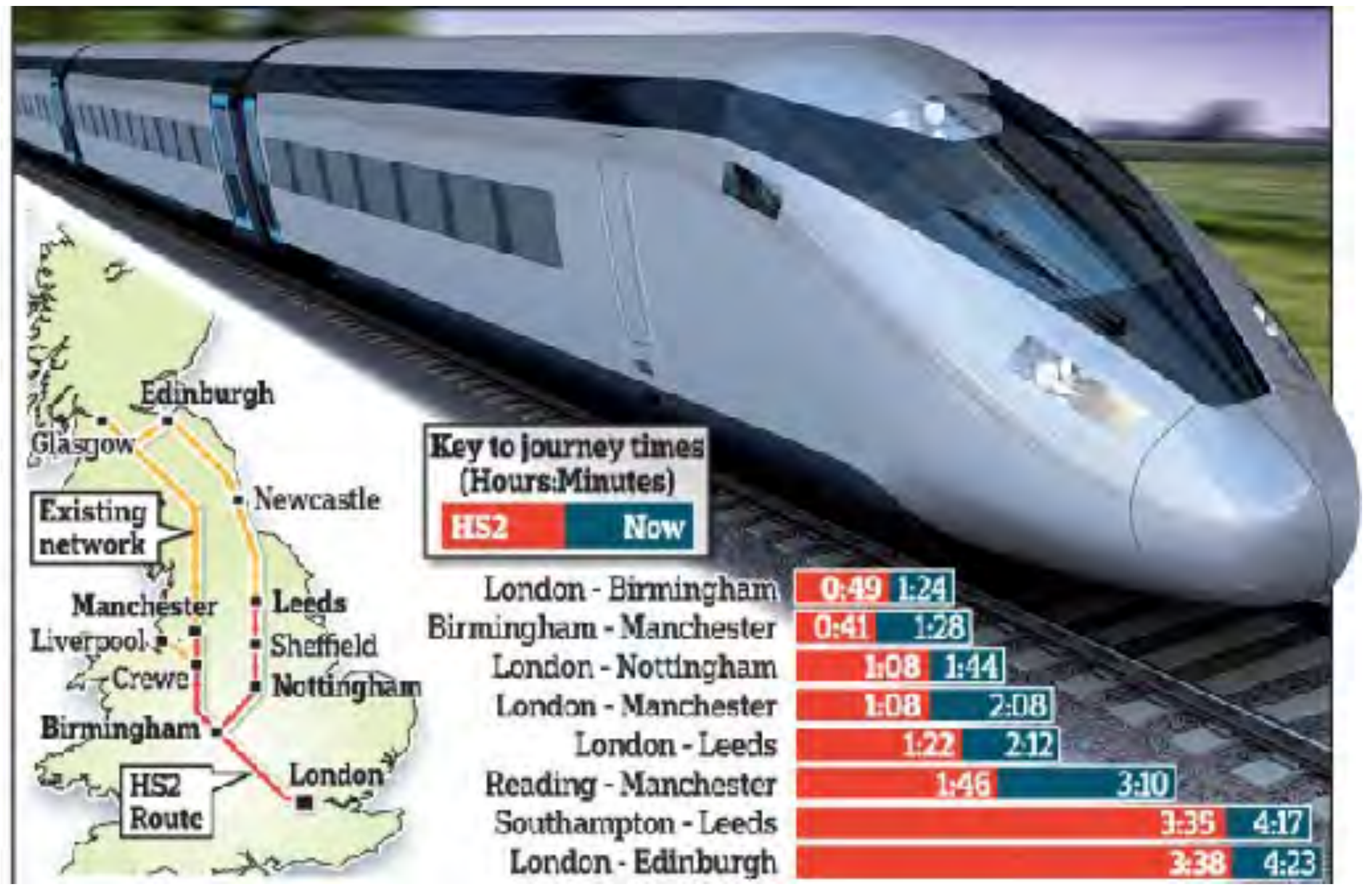
Gravity Markets

Oil & gas prospecting

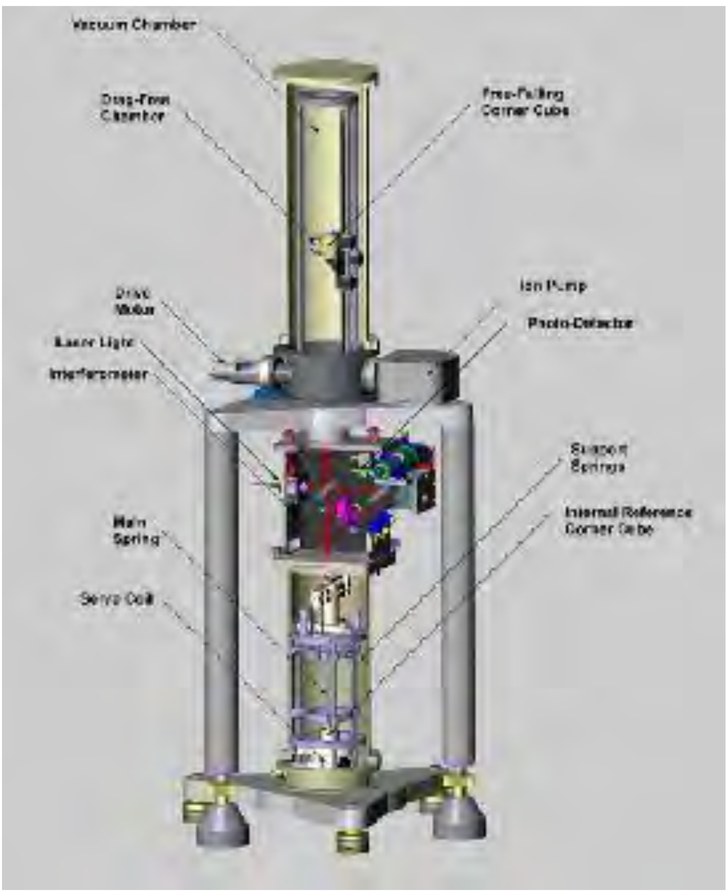
Environmental monitoring



HS2 survey



GPS time correction (satellite g correction)

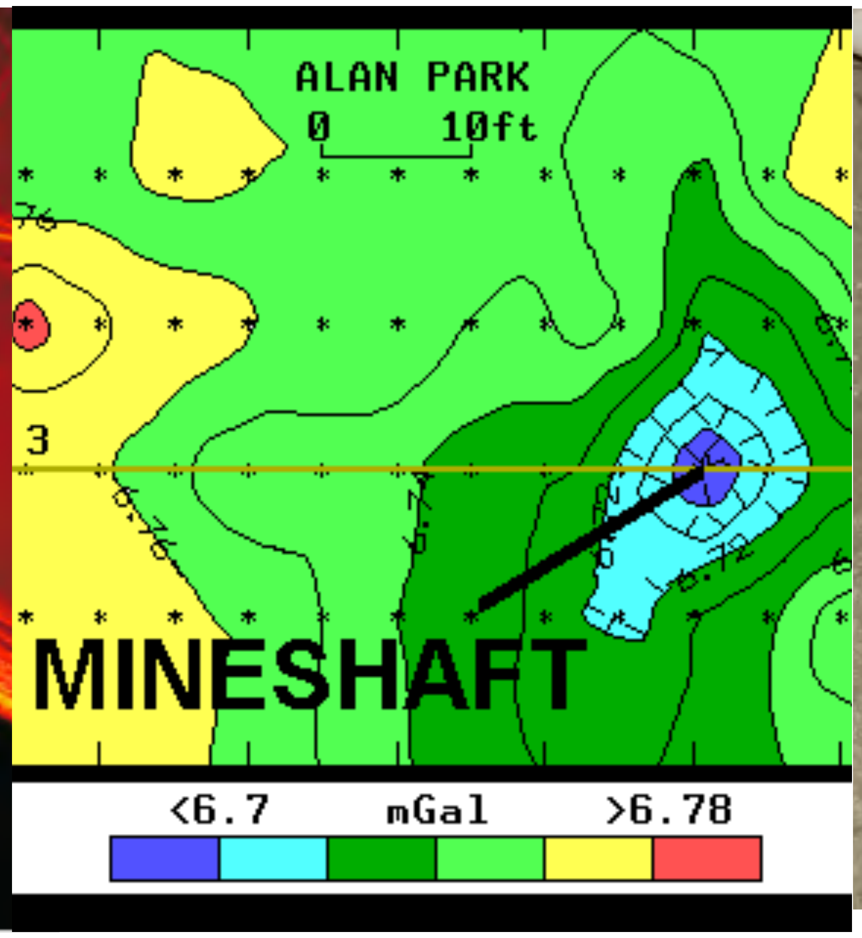


Buried utilities / brown field site

Security & Defence

Volcano eruption

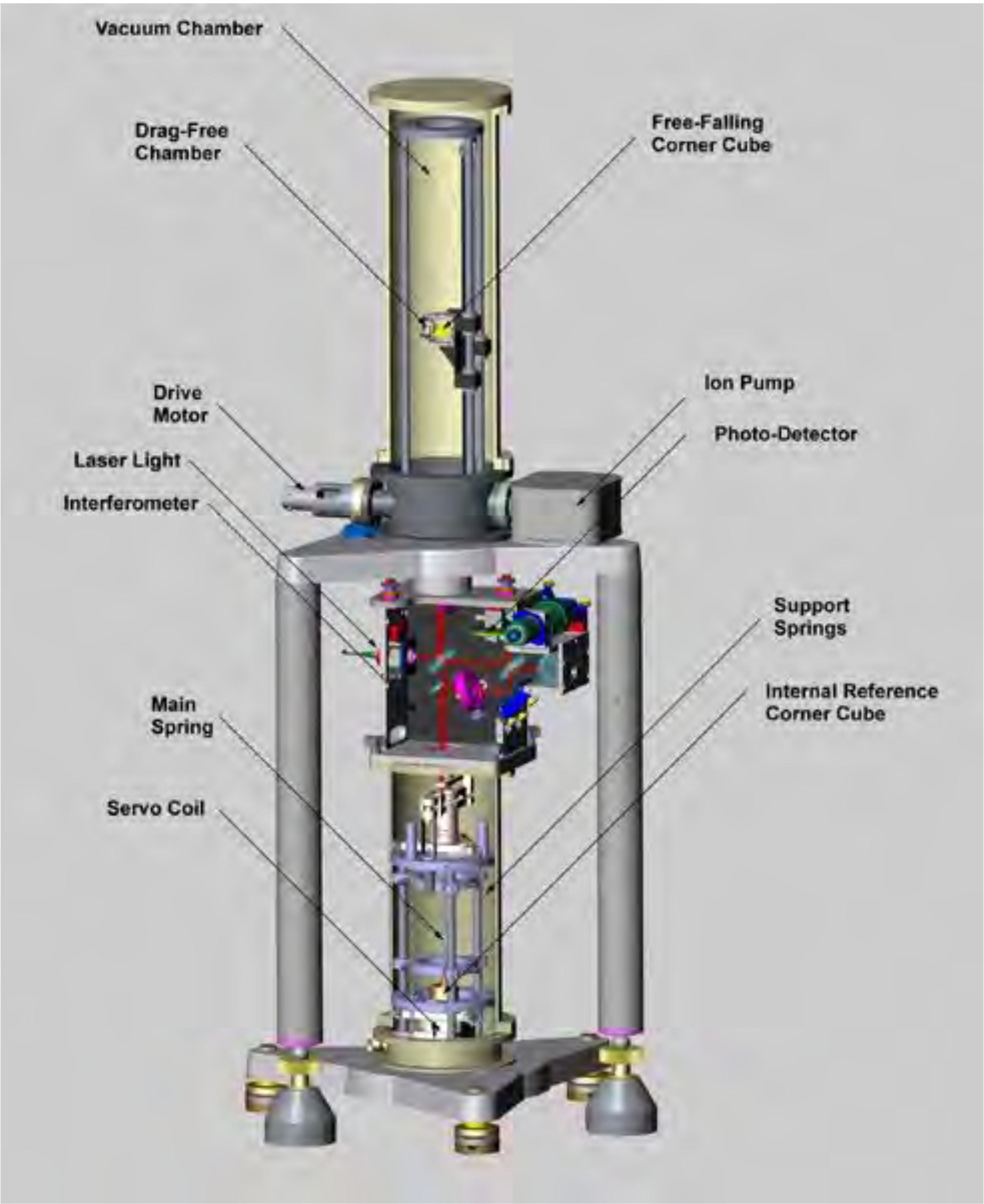
Geological hazard detection



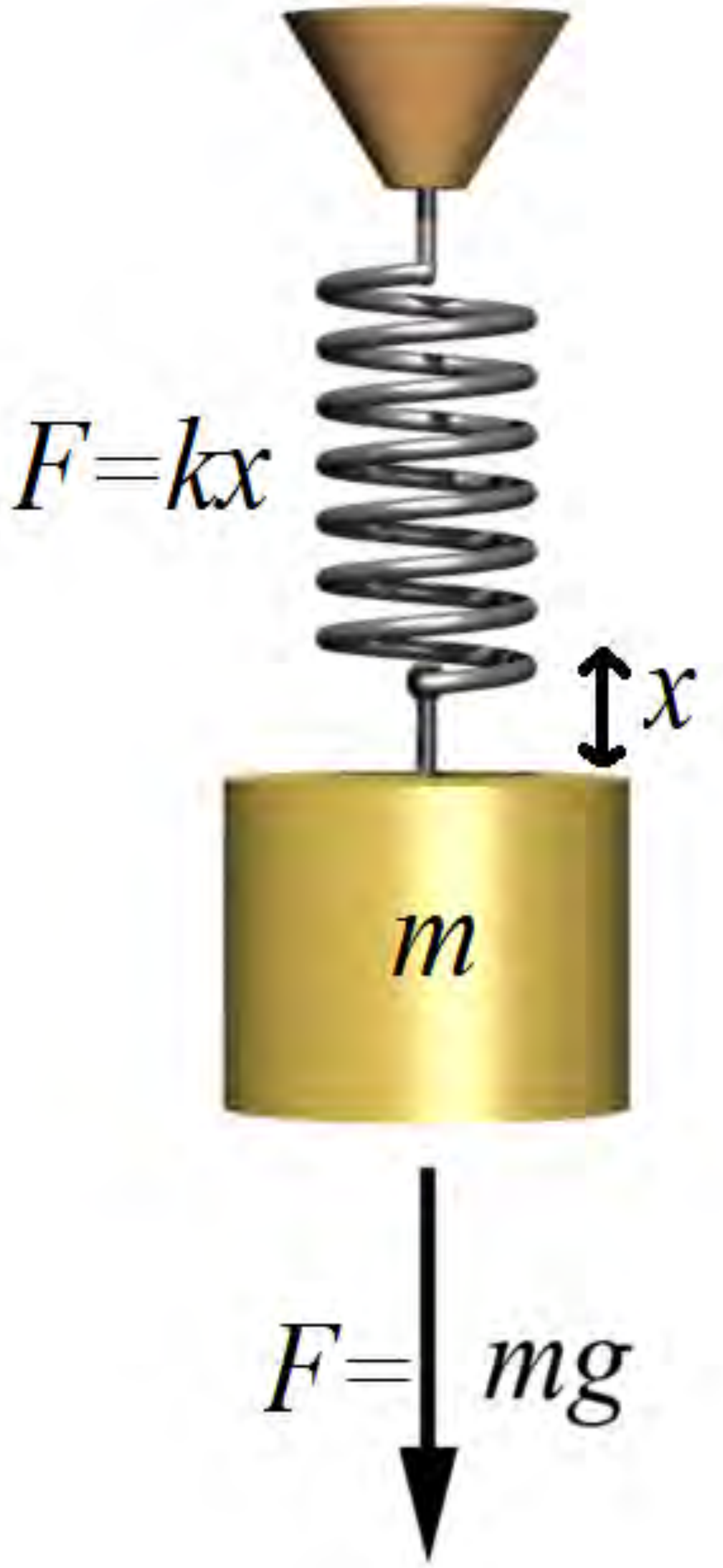
Security tunnel detection

Satellite navigation

Present Absolute and Relative Gravimeters

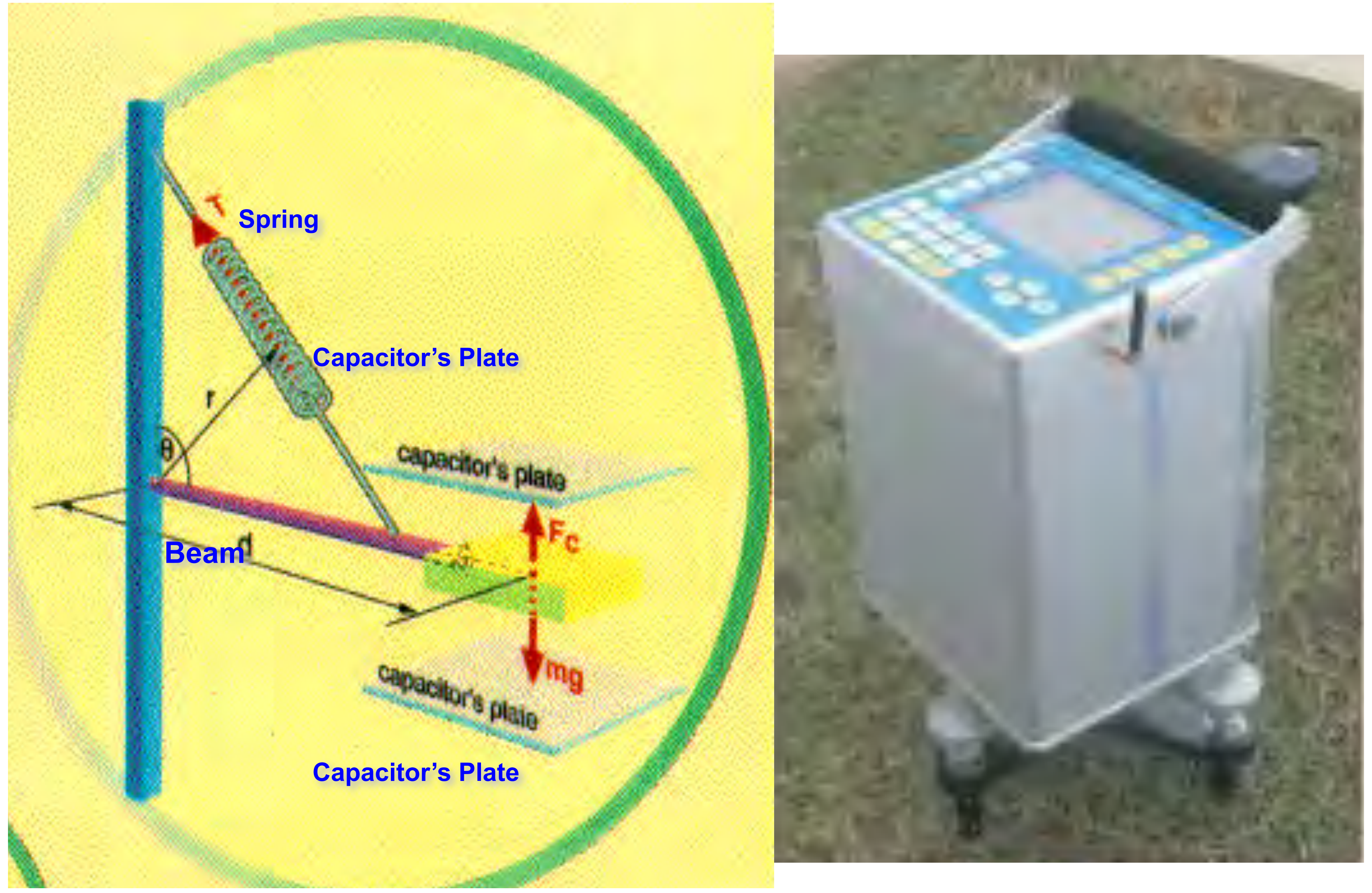


Absolute: free fall mass e.g. FG5



$$\mathbf{a} = \frac{\mathbf{k}}{\mathbf{m}}\mathbf{x}$$

$$\mathbf{a} = 4\pi^2\mathbf{f}^2\mathbf{x}$$



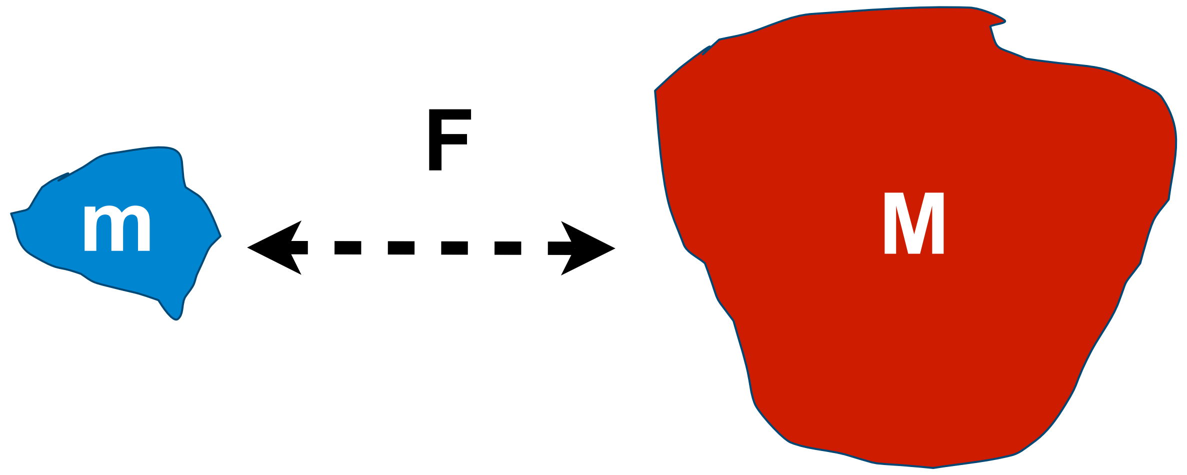
Relative: mass on a spring e.g. CG5

University of Glasgow

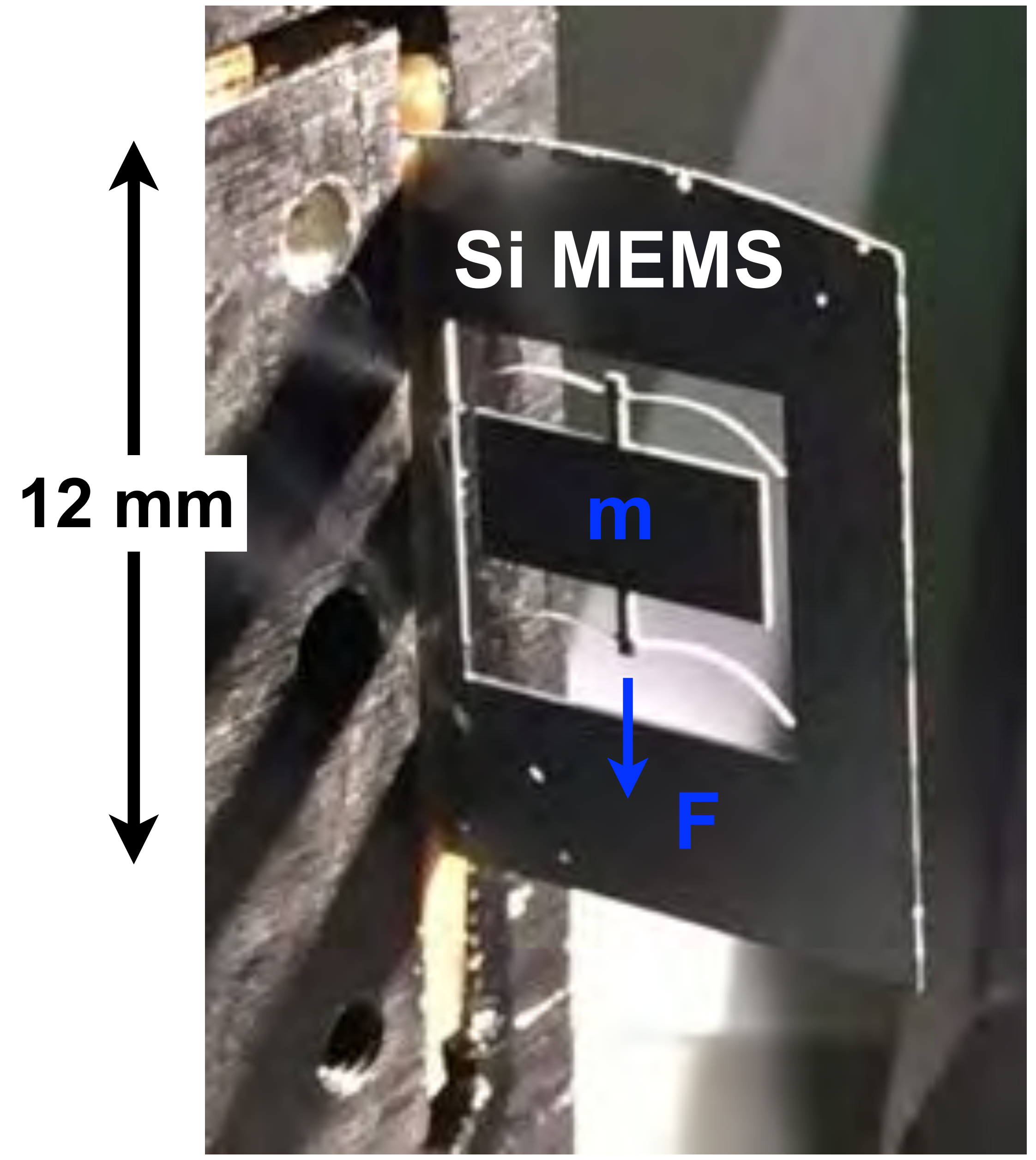
MEMS Gravimeter

QUANTIC

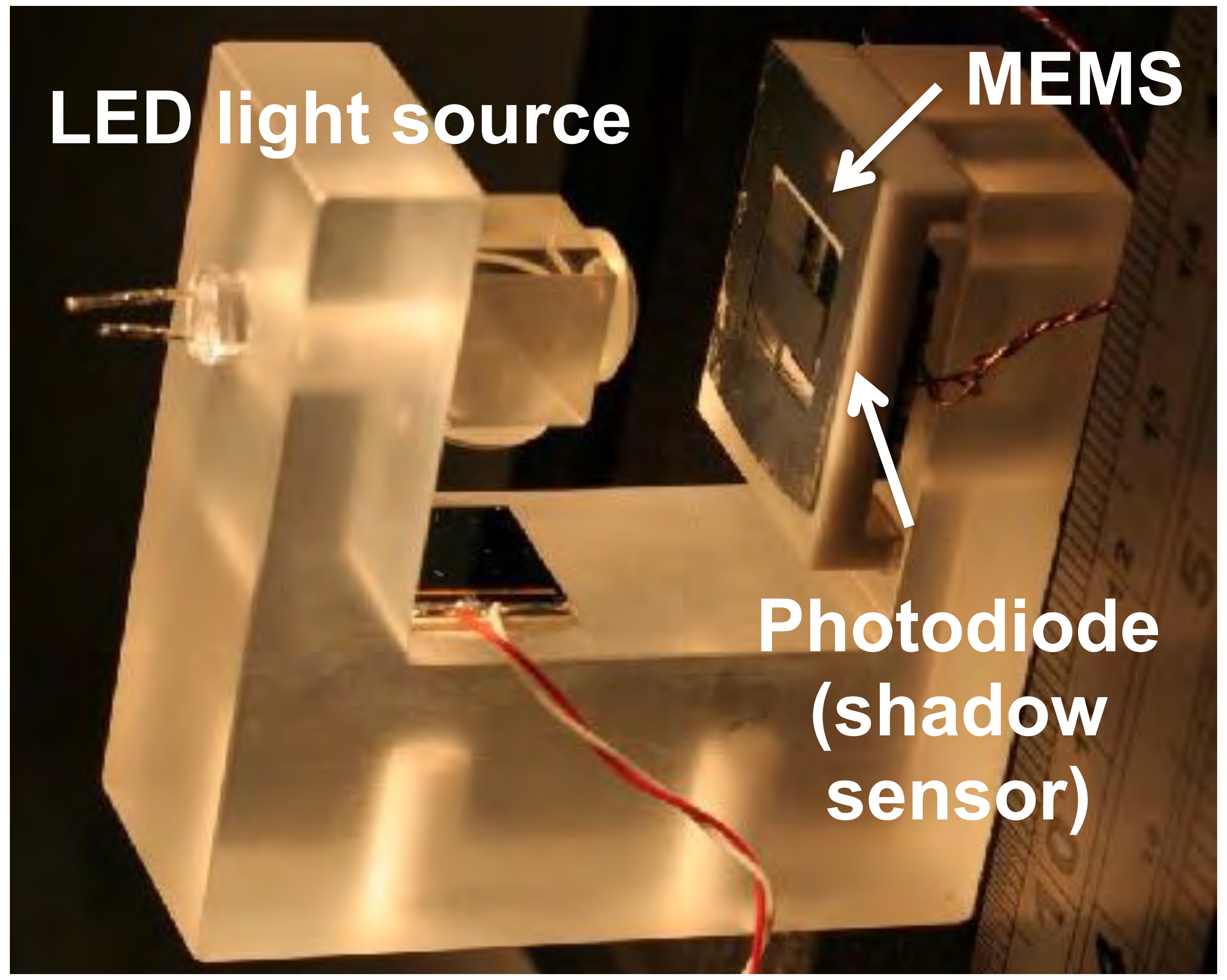
- MEMS geometrical anti-spring flexures produce 2.2 Hz resonance

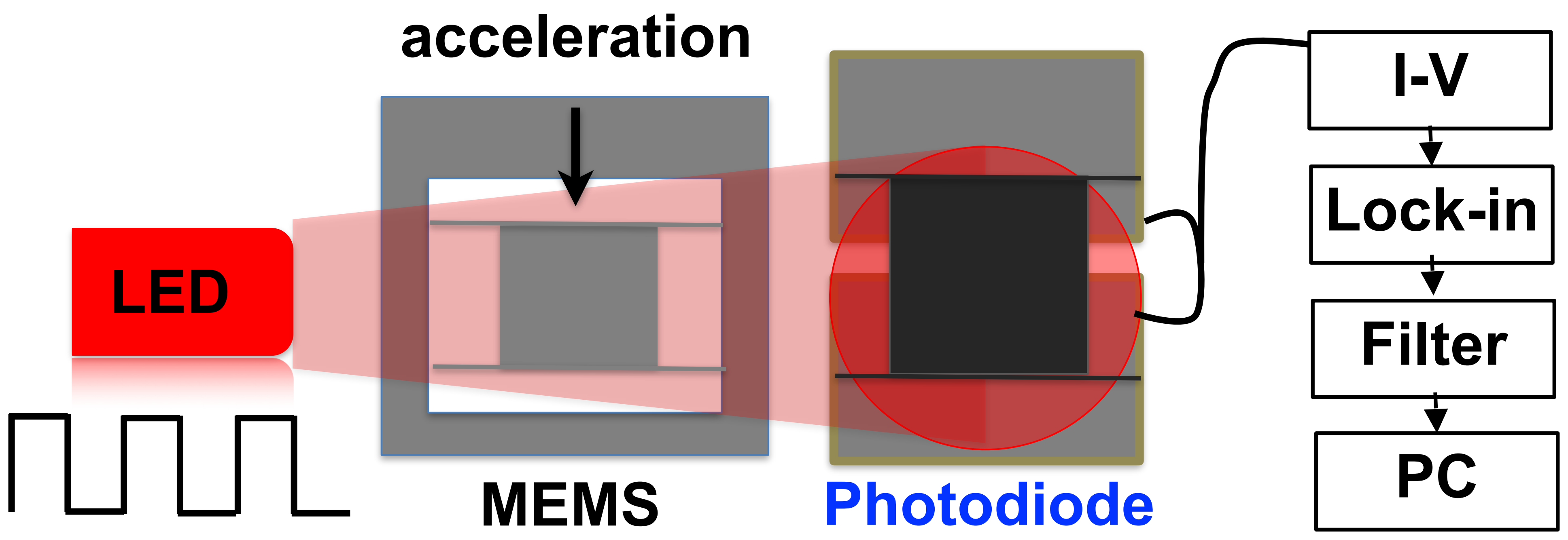


$$\boxed{F = \frac{GMm}{r^2}}$$



- Split photodiode sensor –> integrated interferometer in development
  - ≤ 2 nm/√Hz over 60 s
  - ≤ 5 nm/√Hz over 2 days

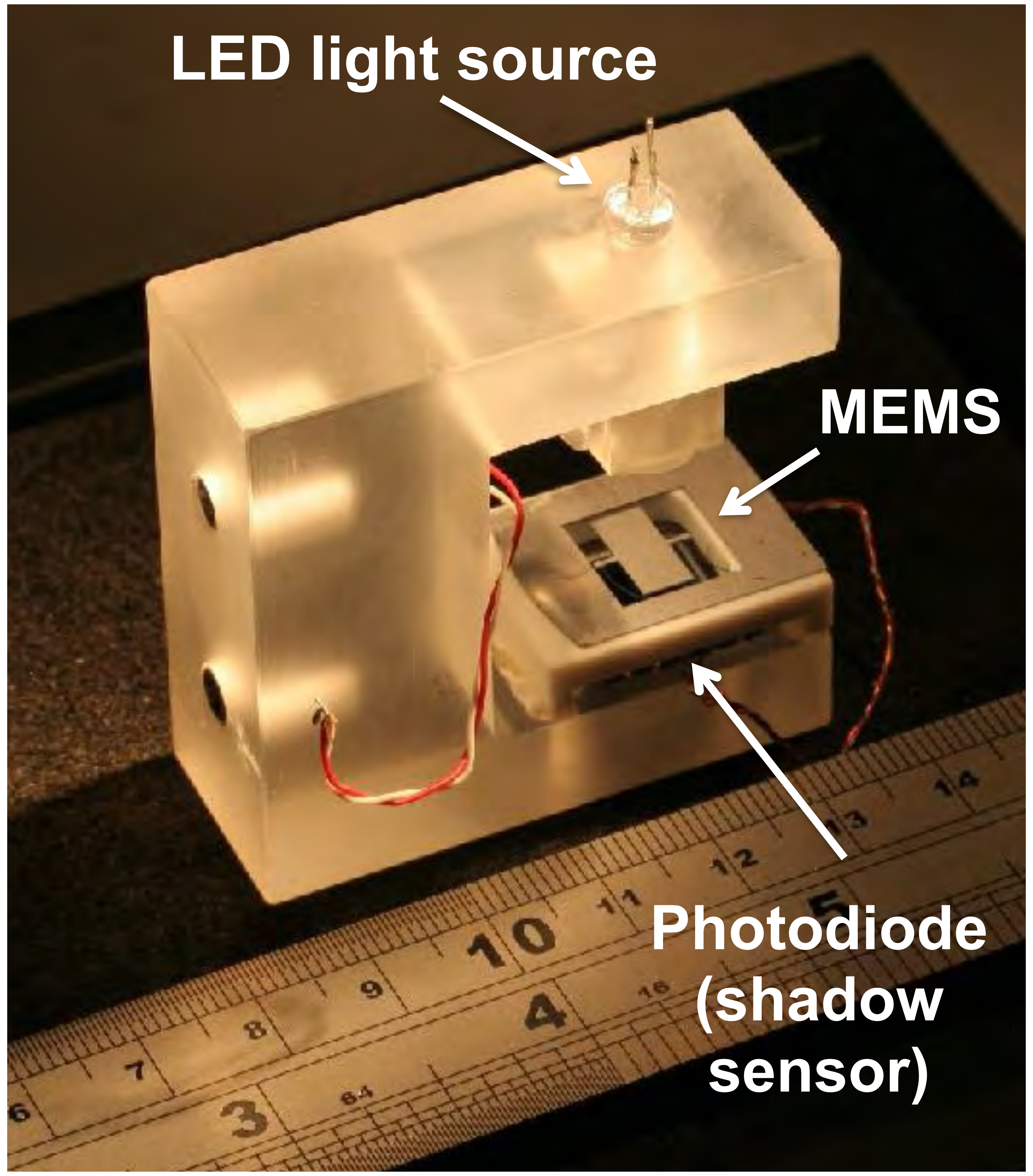


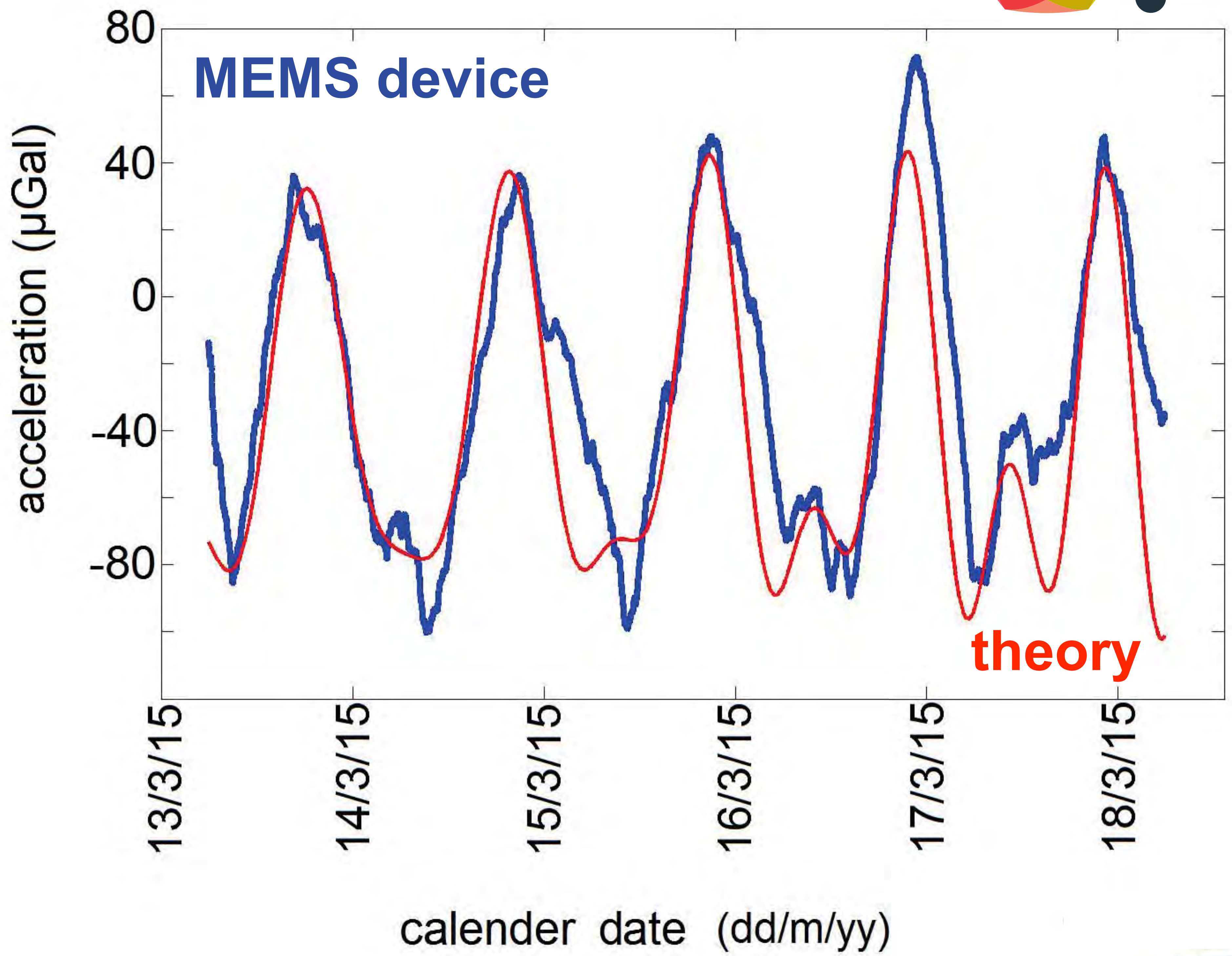


Patent Application: WO2016030435

R.P. Middlemiss et al. Nature 531, 614 (2016)

MEMS Gravimeter



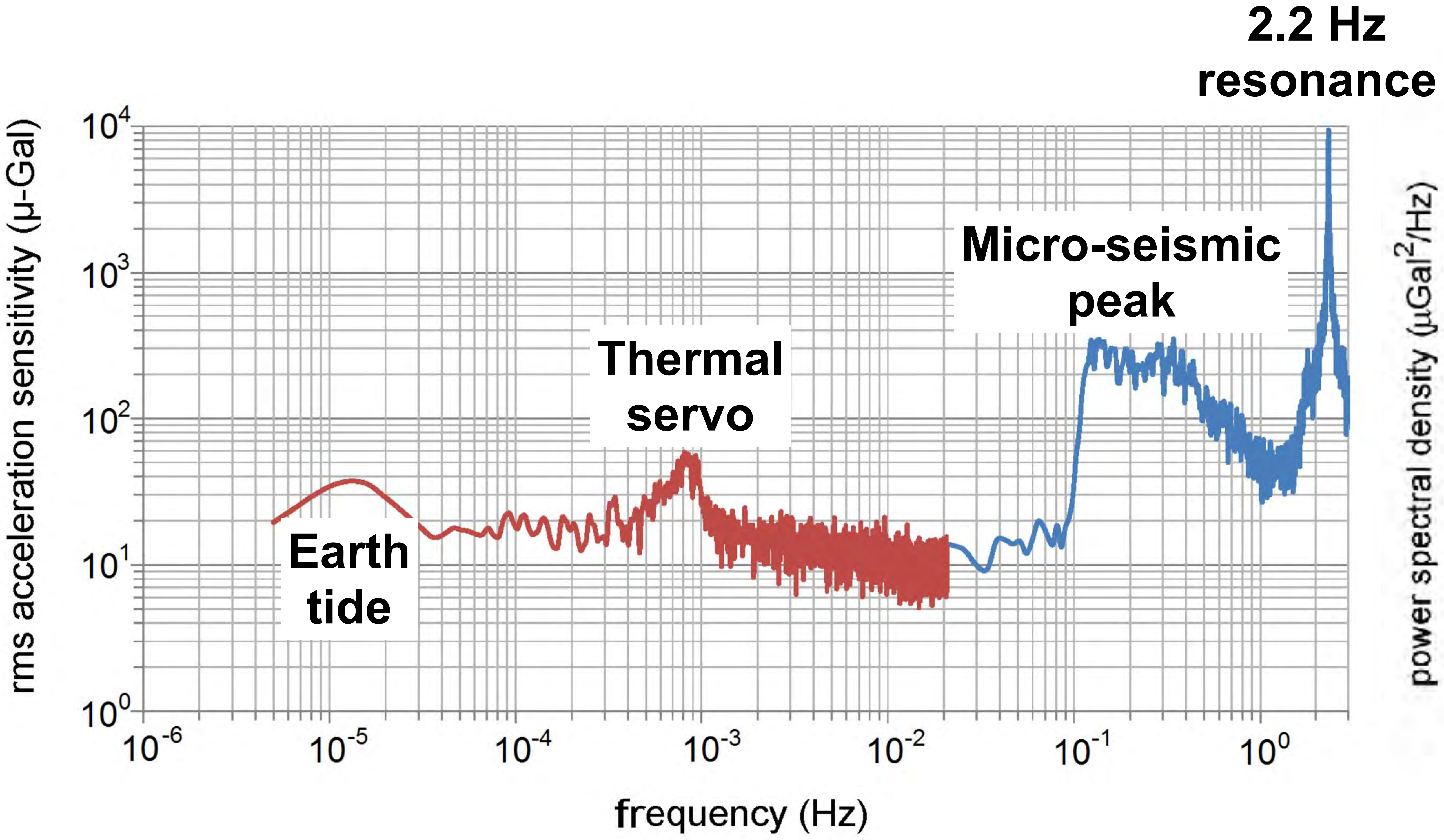


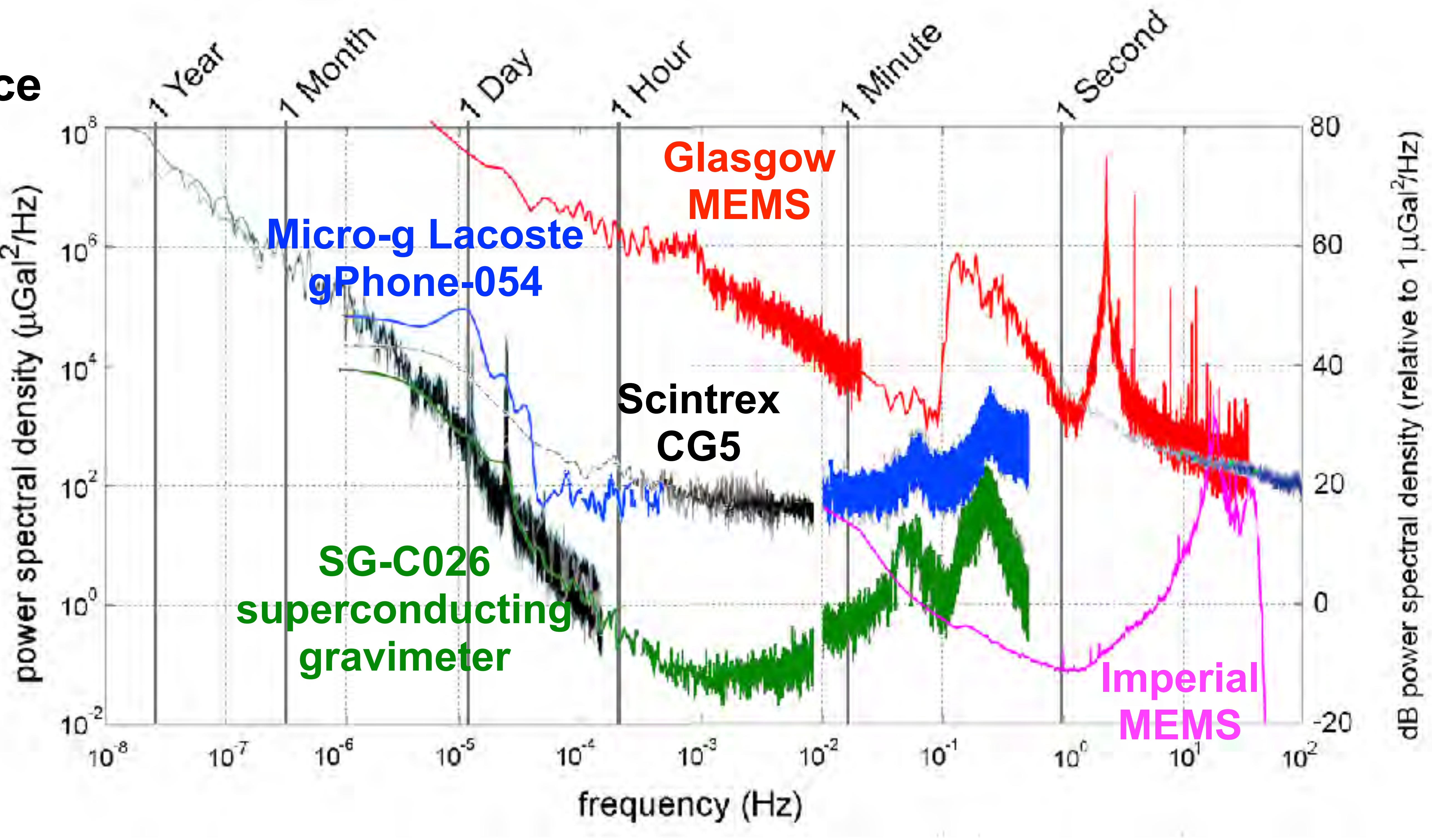
- Industry requirement: ≤10 µGal/√Hz gravimeter
- 40 µGal/√Hz gravimeter achieved

R.P. Middlemiss et al. Nature 531, 614 (2016)

Gravimeter – Seismometer – Accelerometer

- **5 orders of magnitude measurements: accelerometer – seismometer – gravimeter**



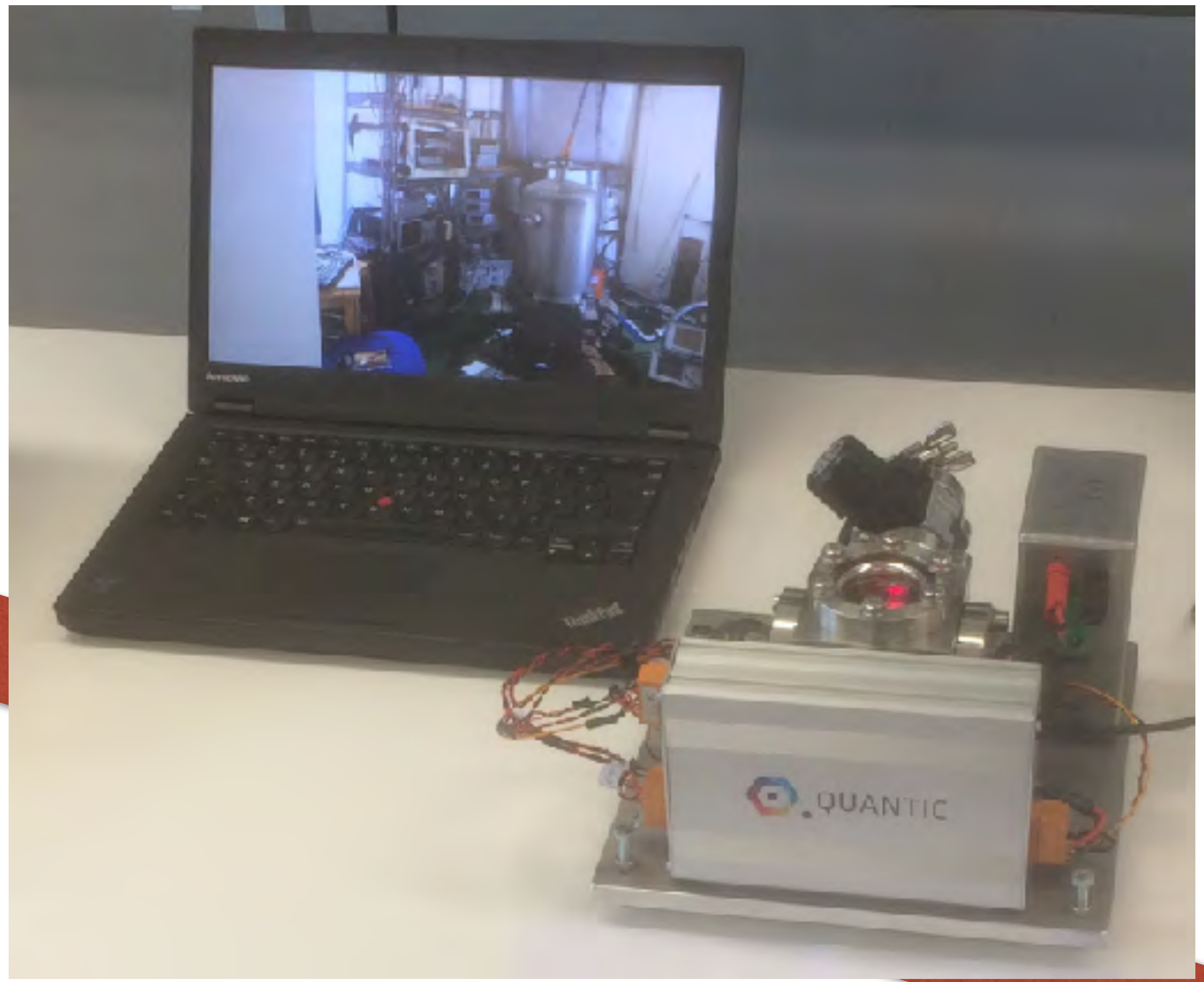


R.P. Middlemiss et al., Nature 531, 614 (2016)

Miniaturising the Gravimeter

Old: Nature publication

2017/18: Shoebox sized field demonstrator

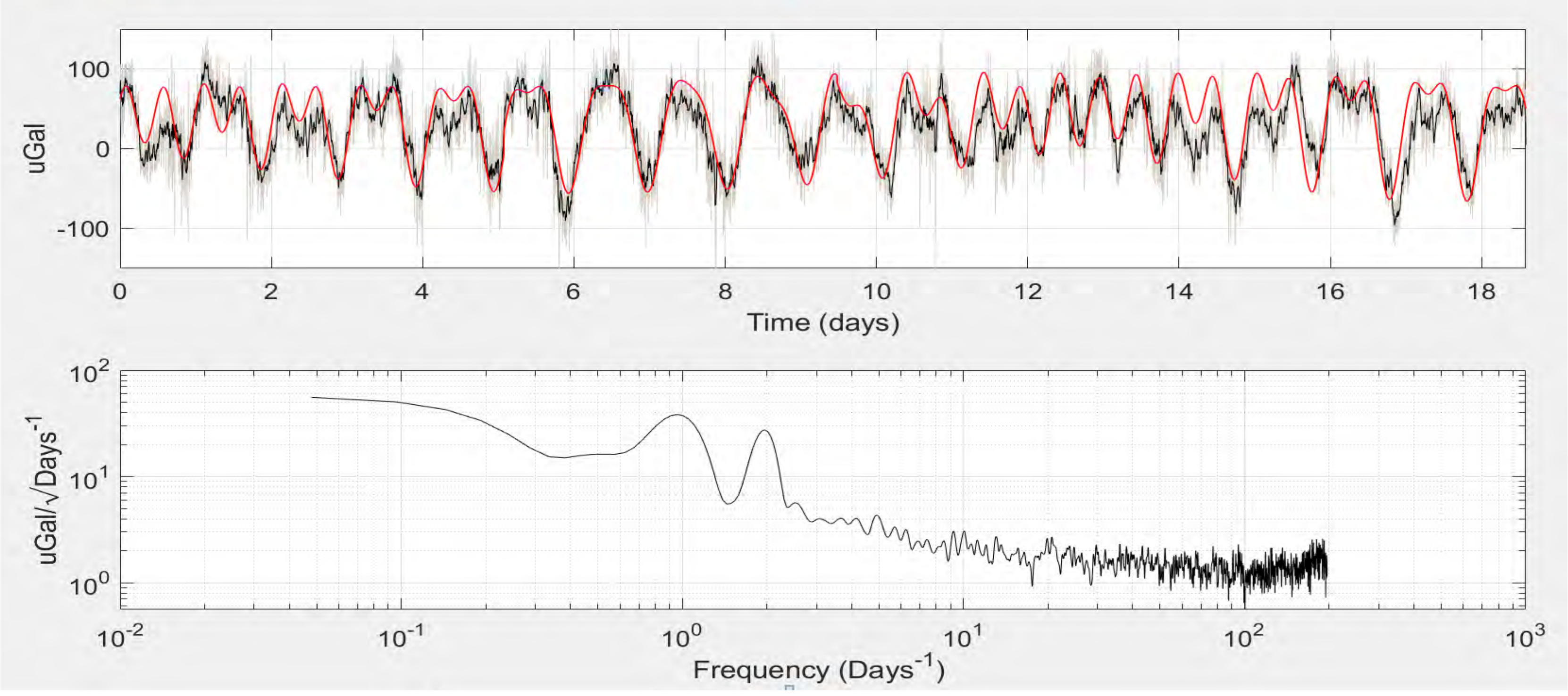


10 kg, 3.2 W, 15 hours battery
± 2 mK temperature control,
dsPIC µcontroller & SD card

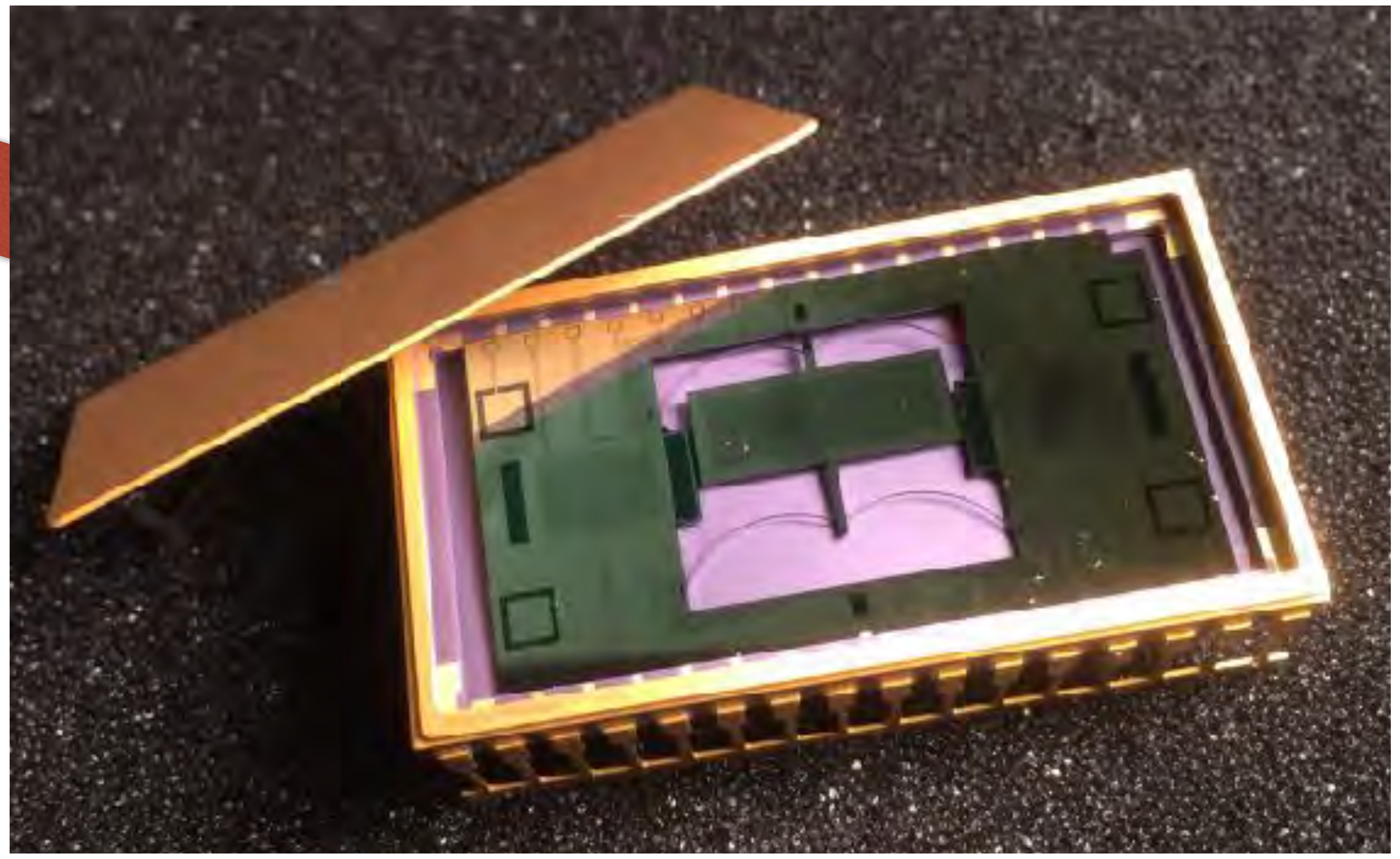
R.P. Middlemiss et al., Sensors 17, 2571 (2017)

8 µGal/√Hz

16th Feb to 5th March 2019



Now: Standard MEMS vacuum package

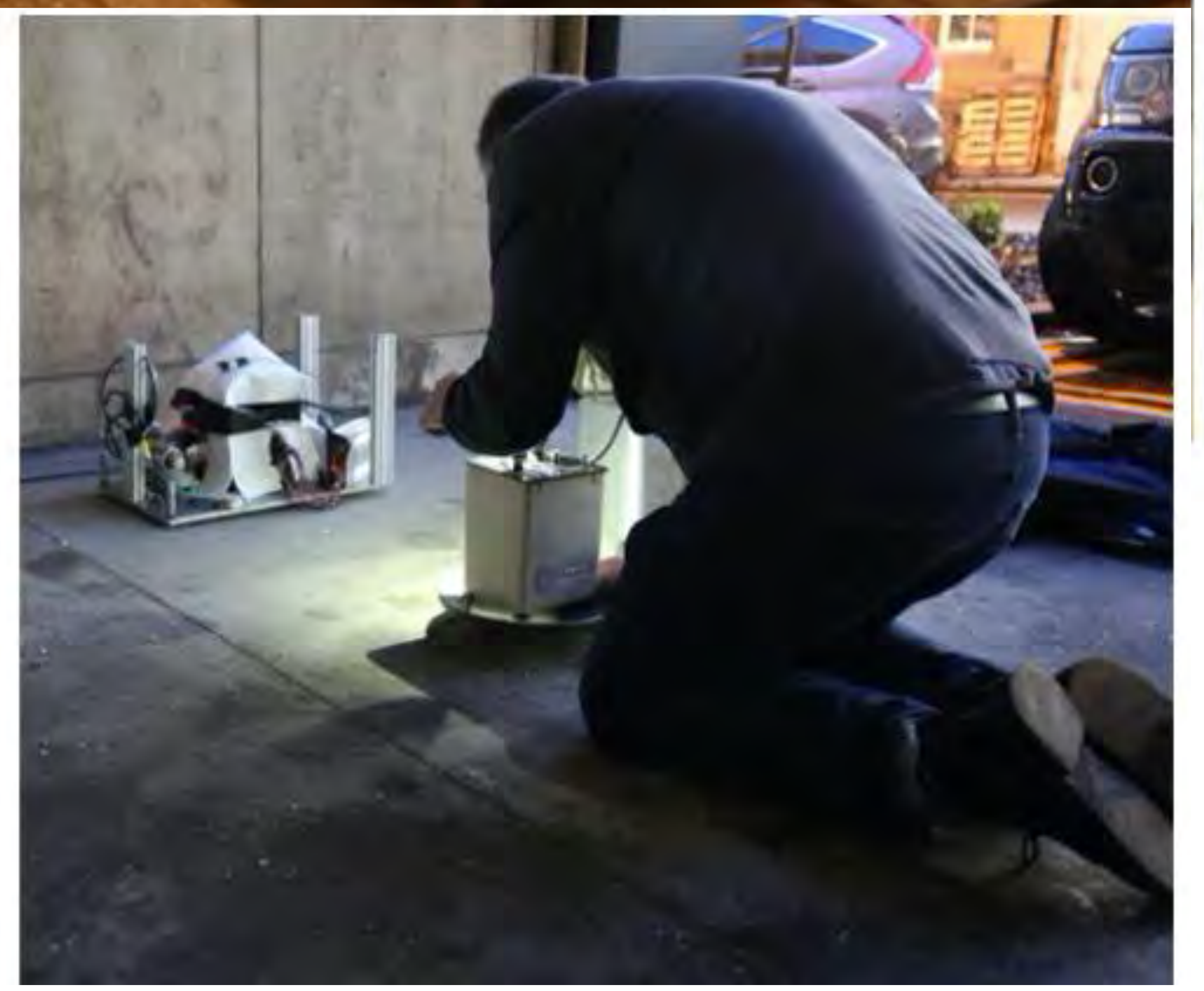


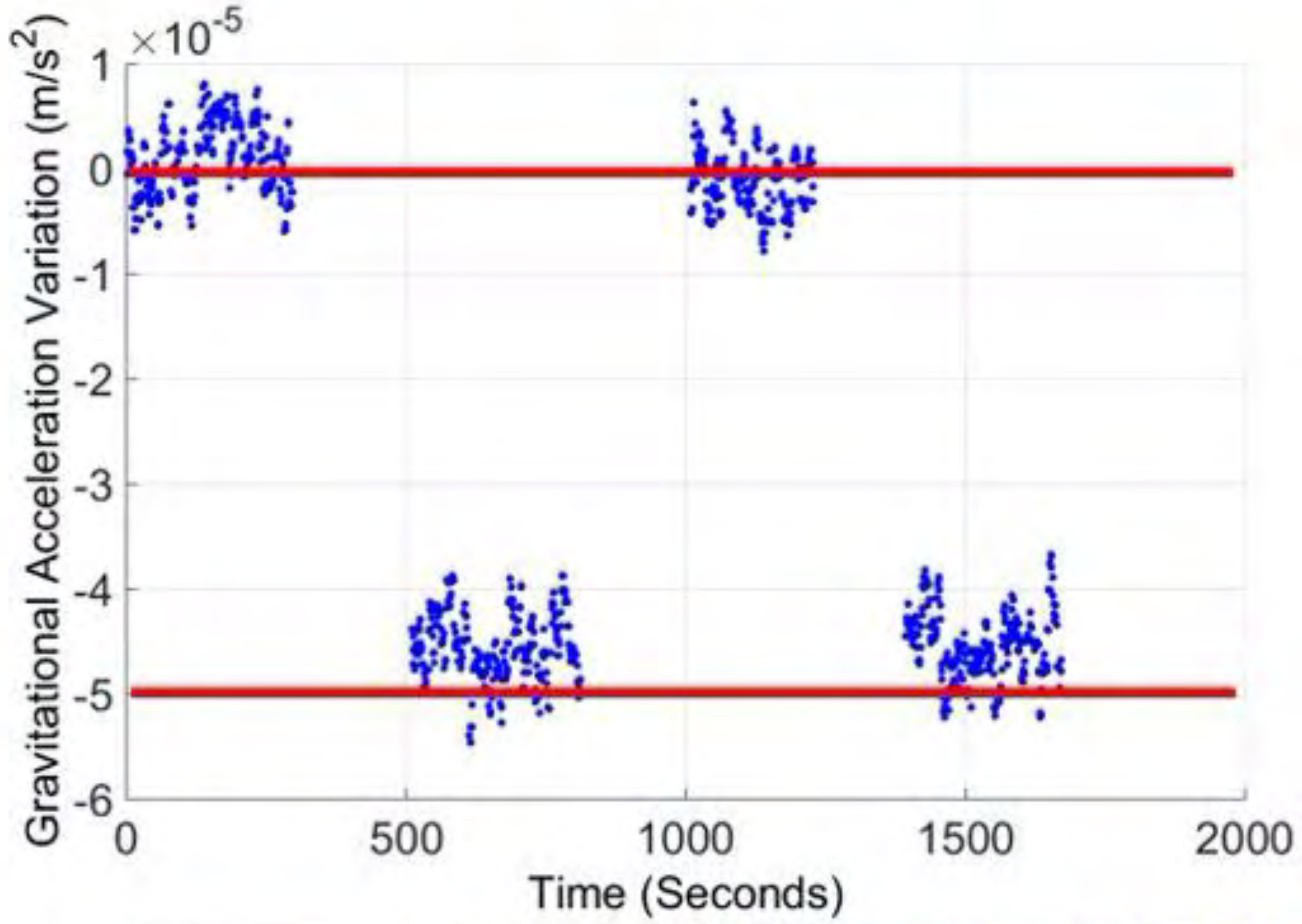
Now: system ~5 kg, < 3.2 W
15 hours battery, 5 µGal/√Hz

Demonstrator requests from industry:

- oil & gas prospecting
- volcano eruptions
- geophysics (sink holes…….)
- nuclear waste, SNM detection
- security & defence
- navigation

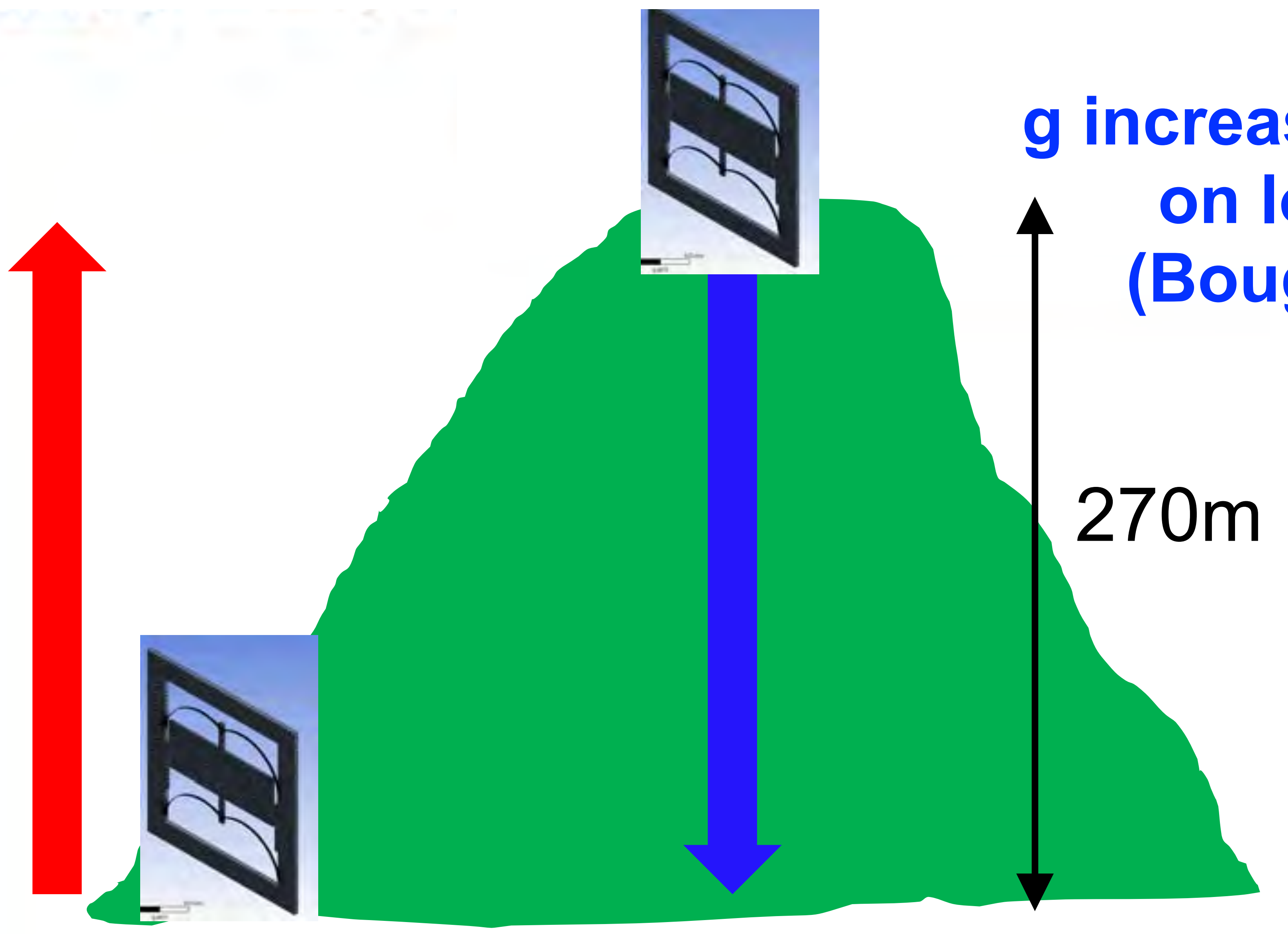
Initial Lift Trials & Comparison with Commercial Gravimeter





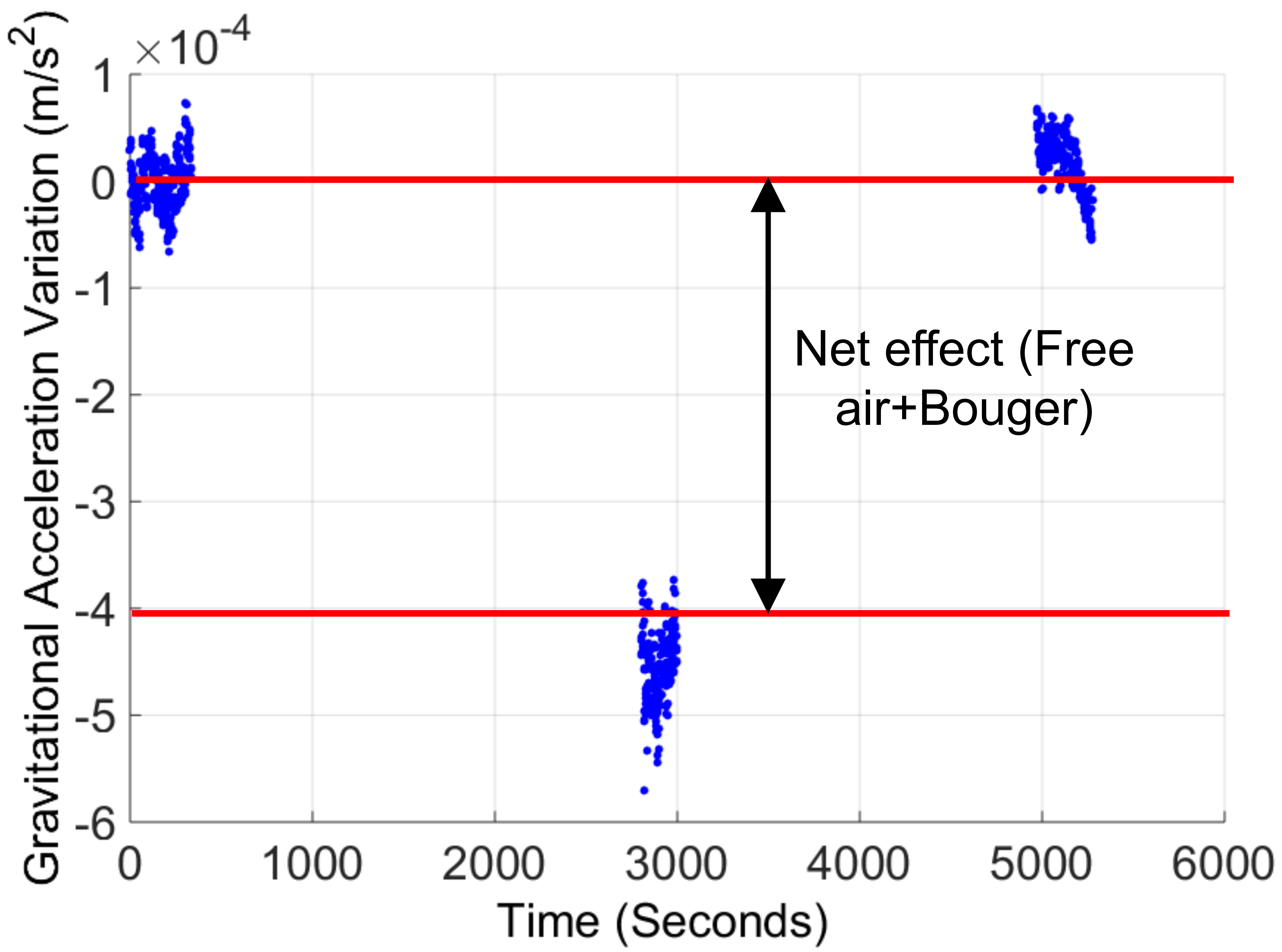
Field Tests 2017: Campsie Fells

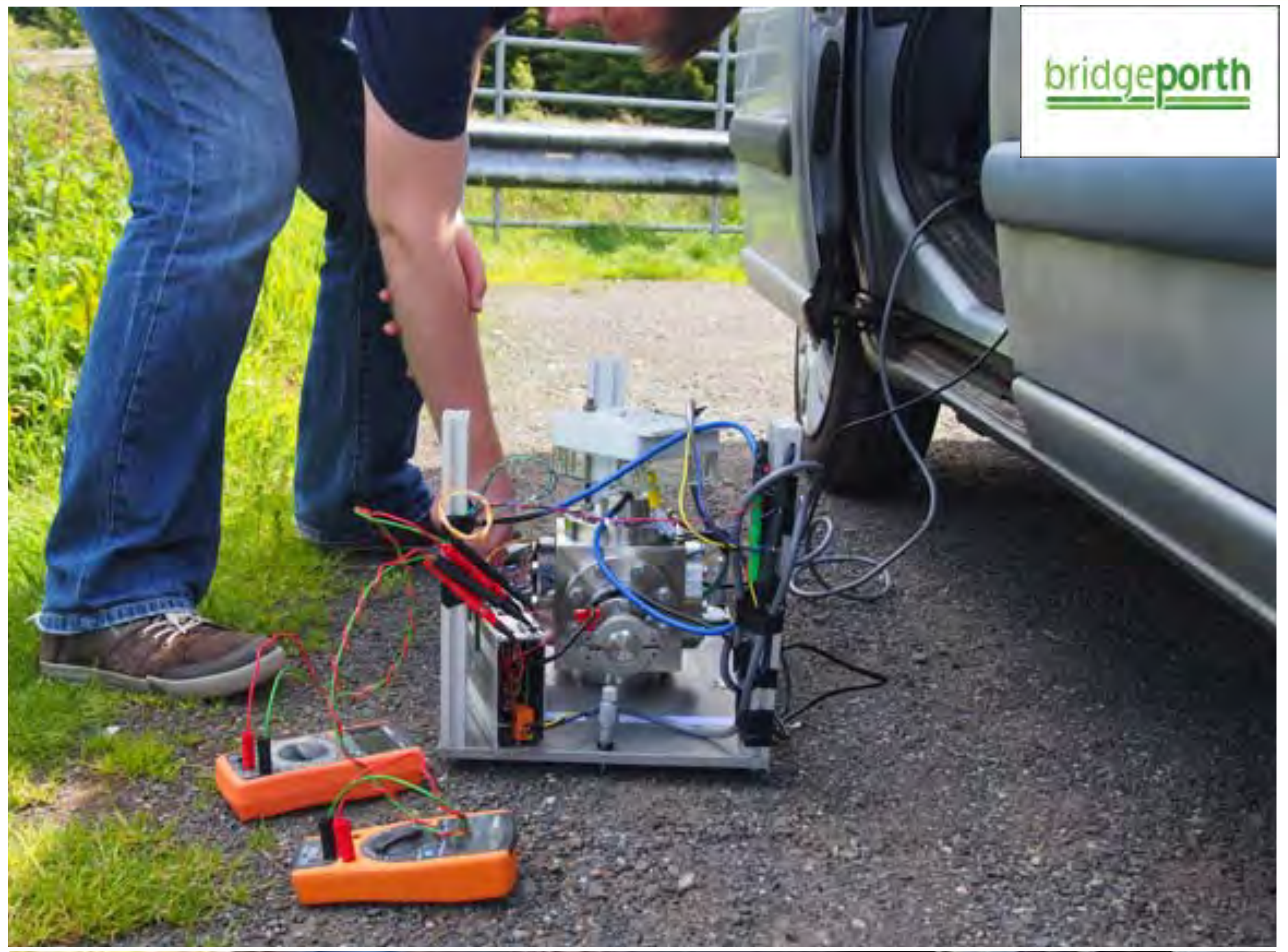
g reduces as moving away from earth (free air effect)

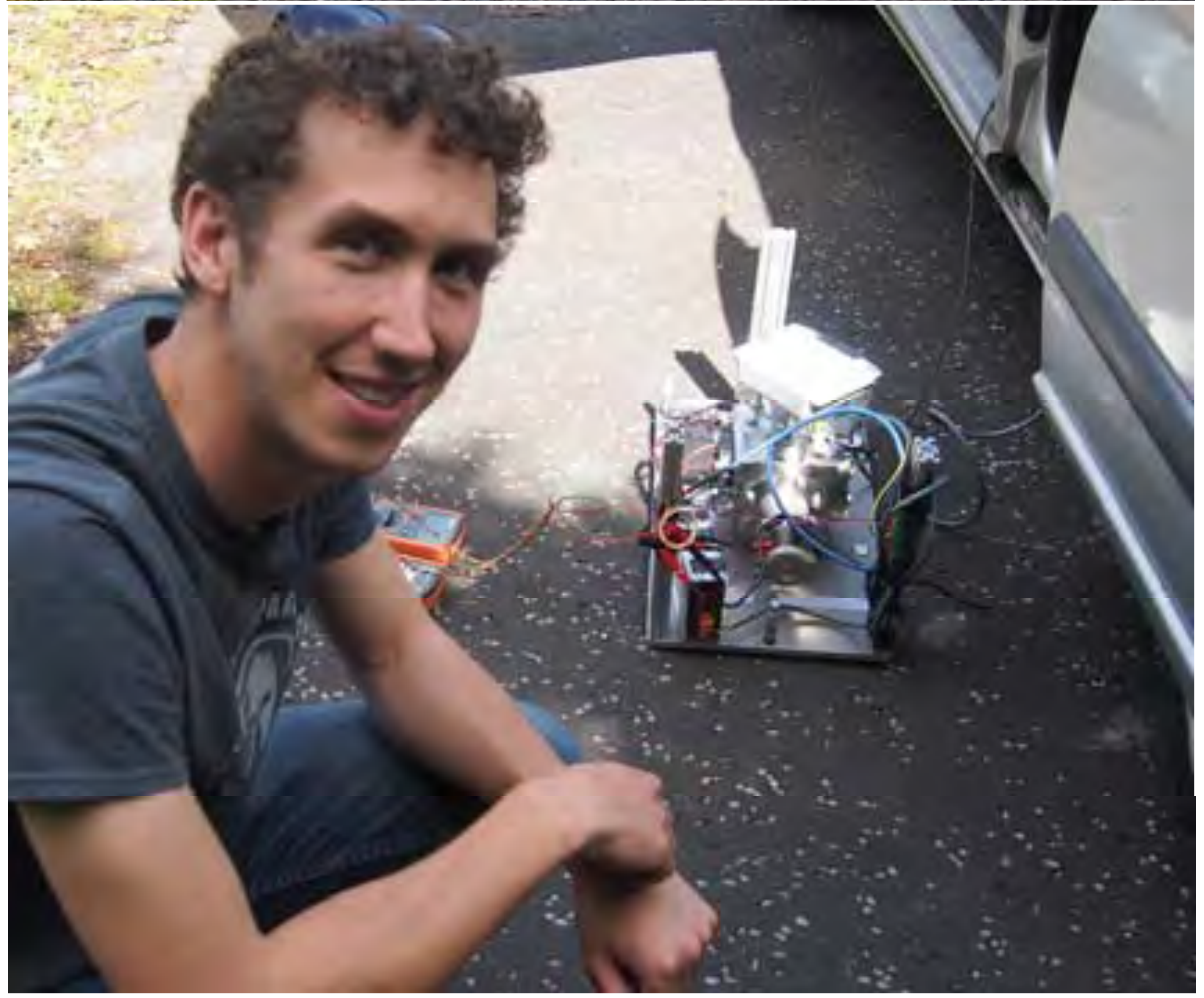


g increases as sitting on local rock (Bouger effect)

270 m altitude change (Campsie Fells)

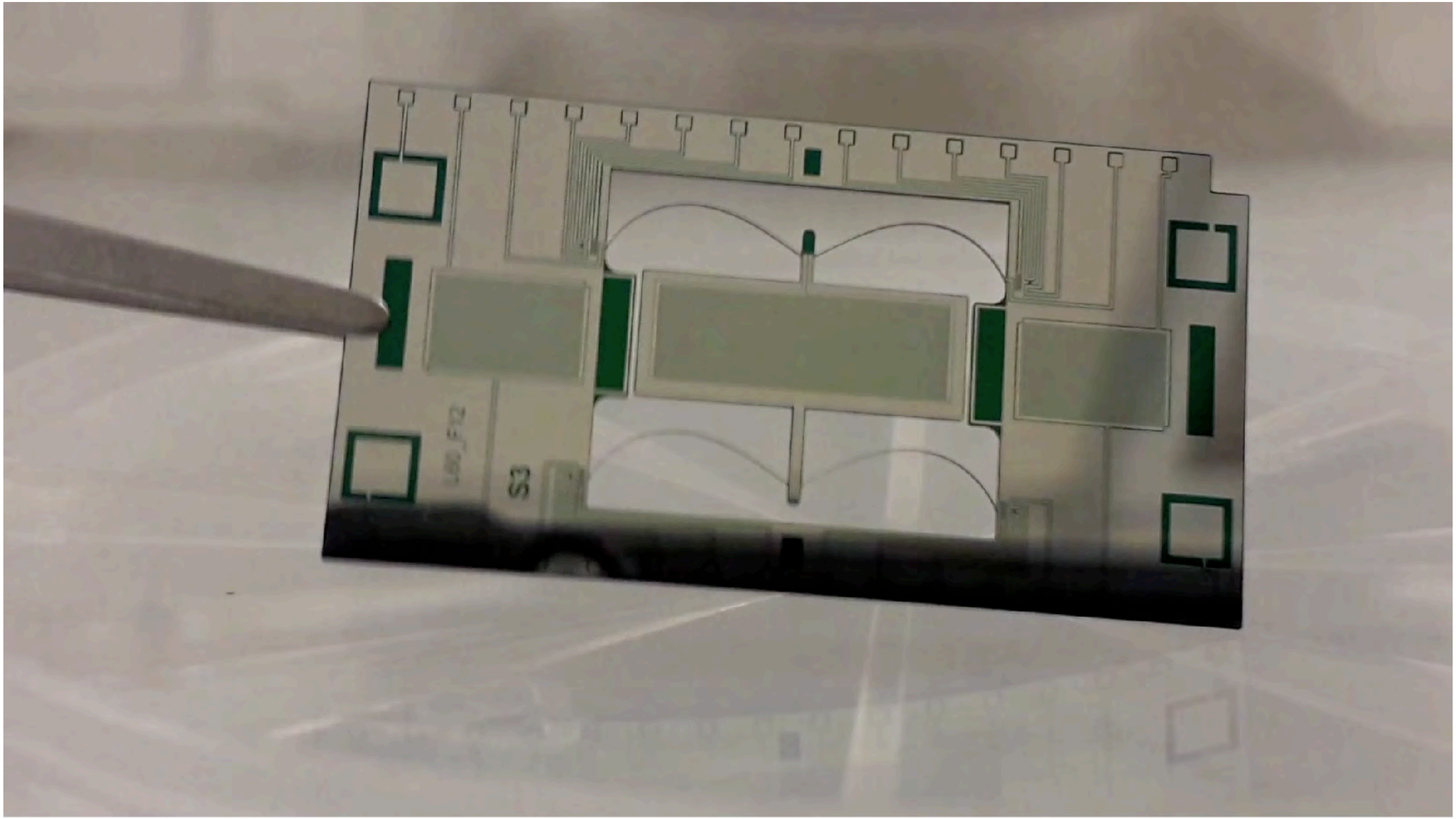




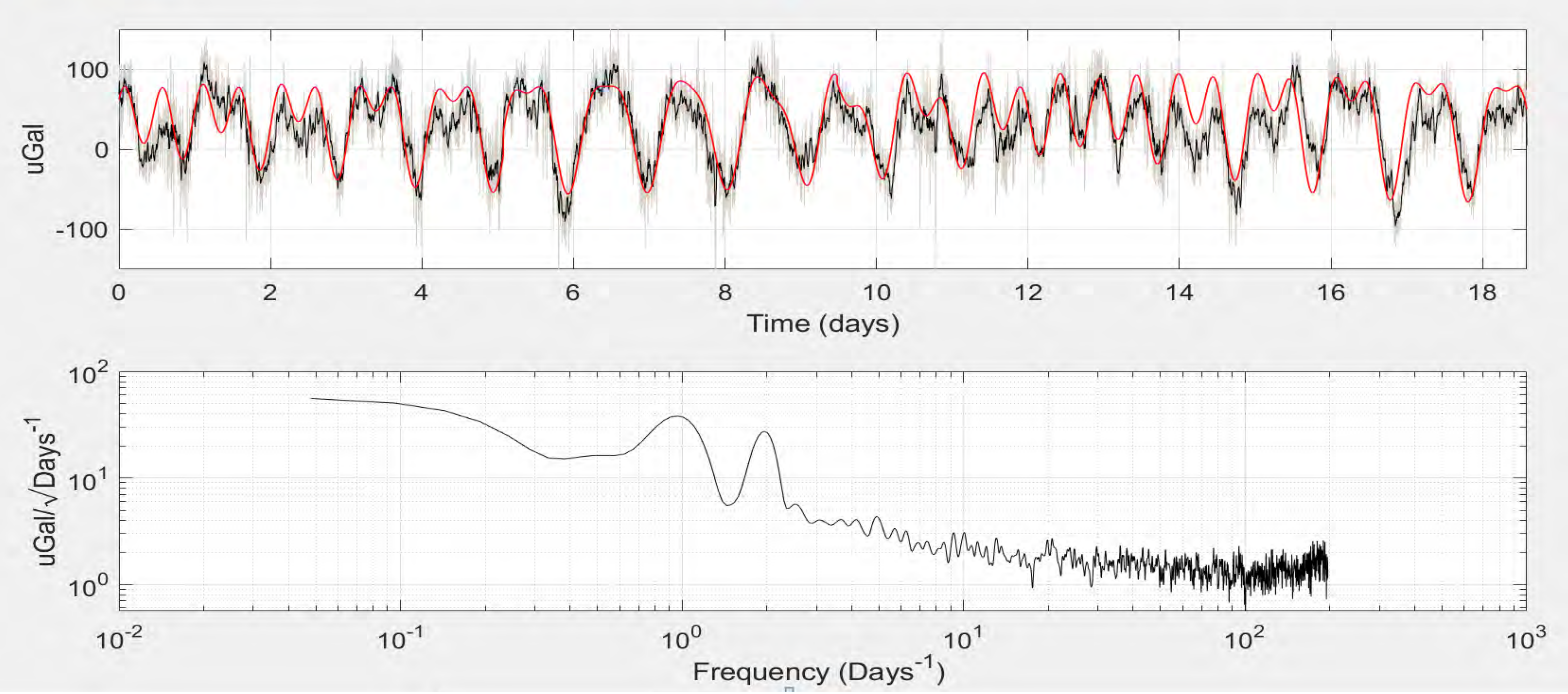


R.P. Middlemiss et al., Sensors 17, 2571 (2017)

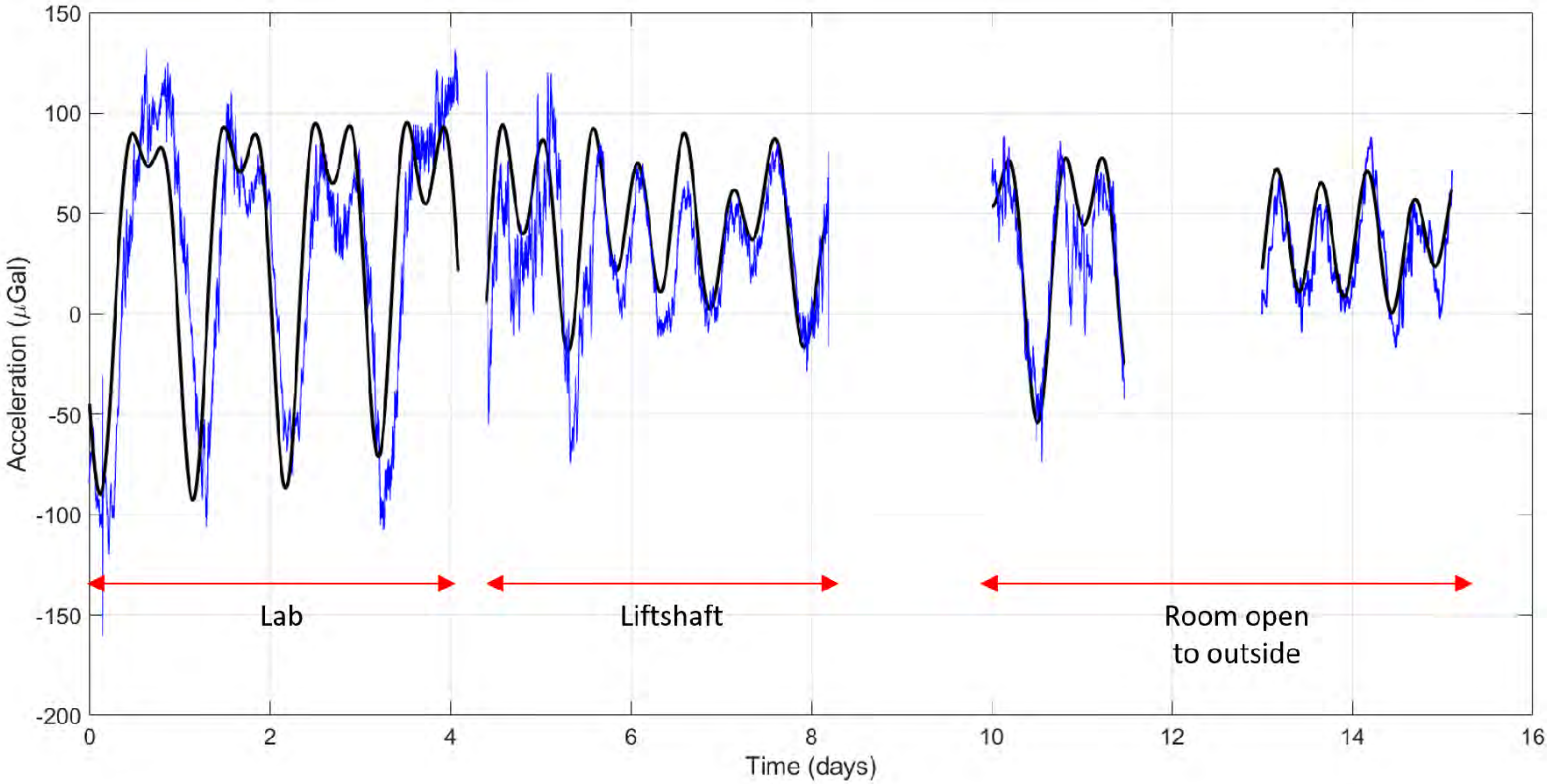
Capacitive Readout Wee-g Wafer Scale



18 Days of Earth Tide Measurements



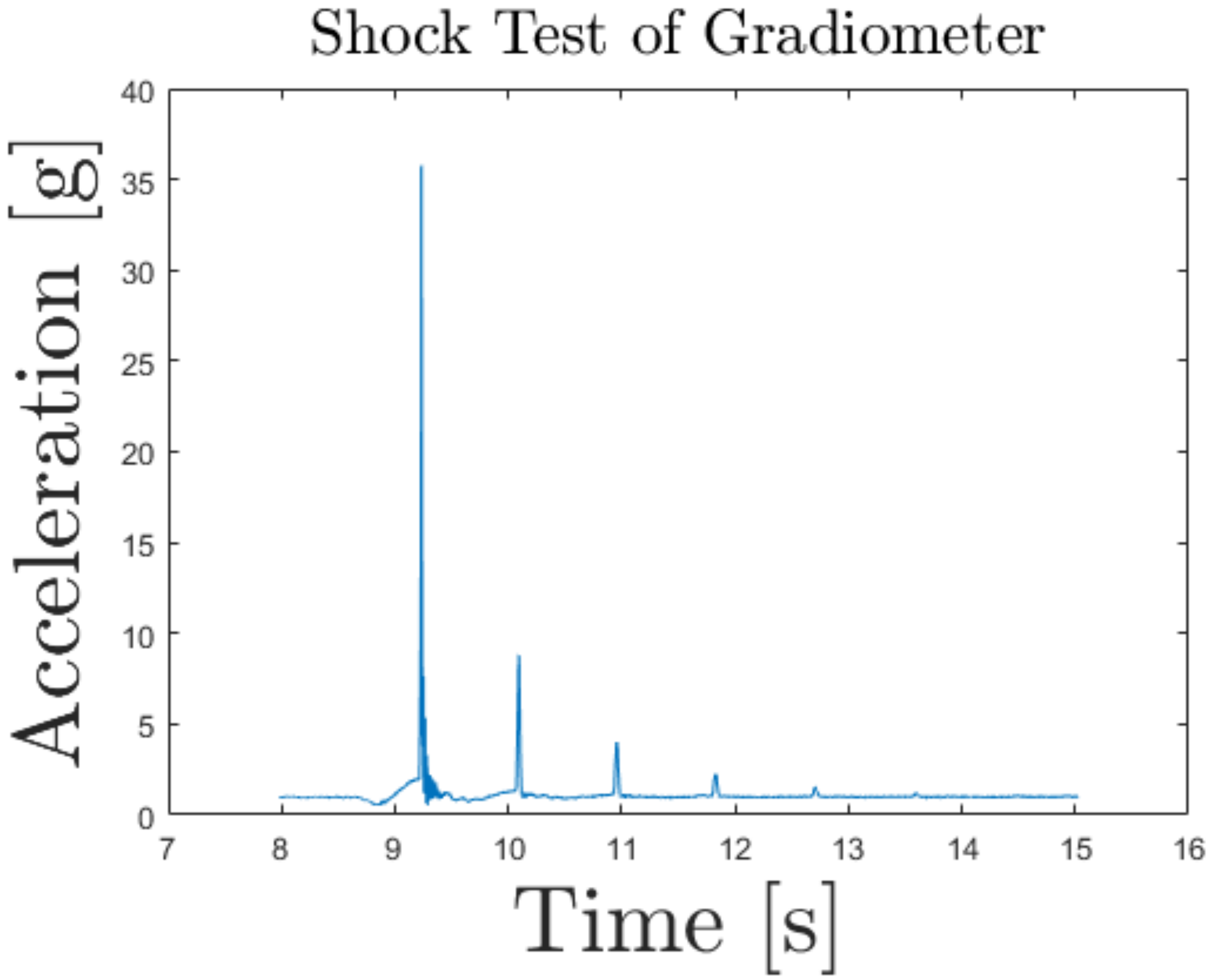
Field Environment Operation

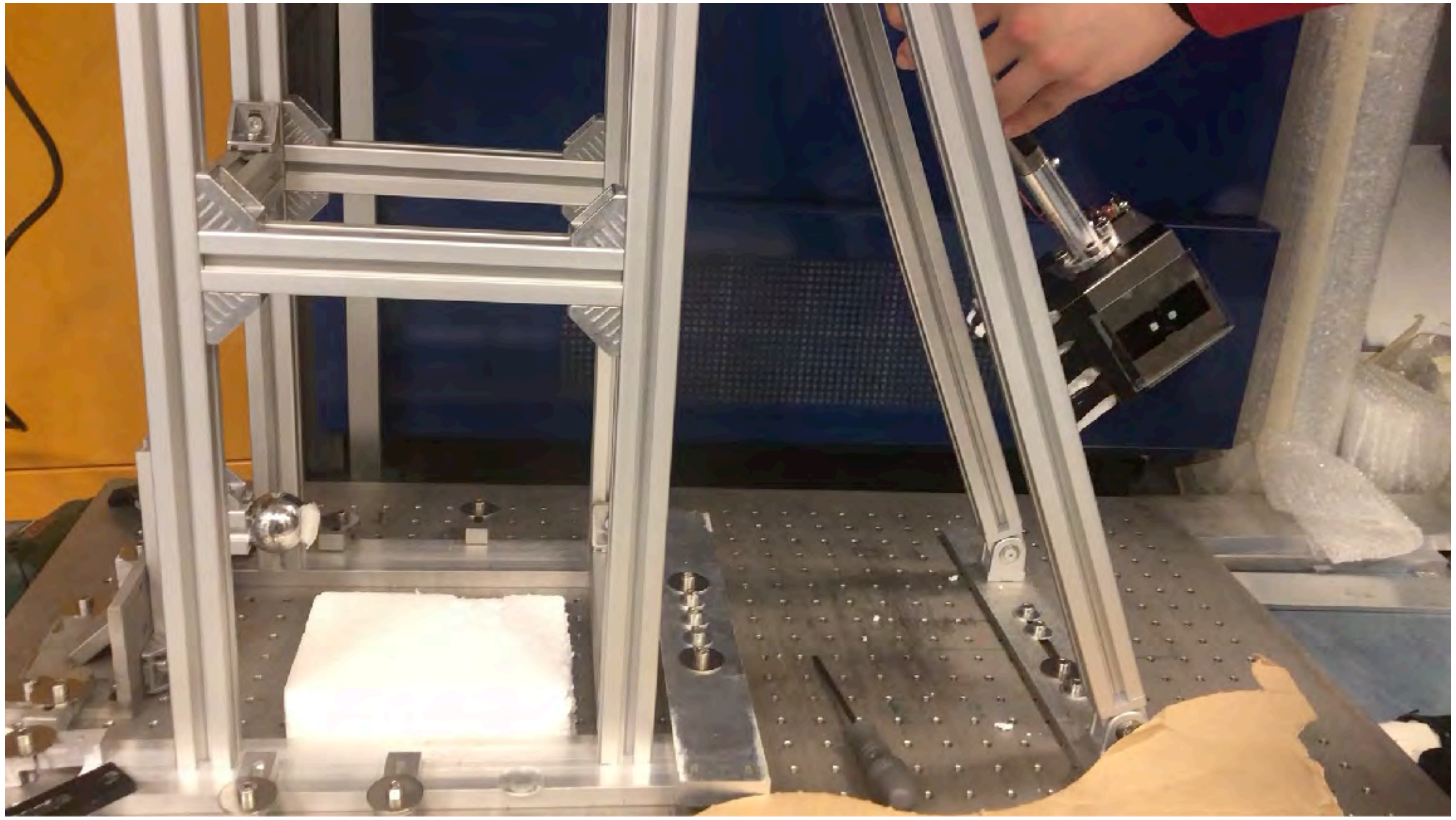


Gradiometer Packaging/Testing - Shock Testing

Successful shock tests of both gradiometer and gravimeter up to 43 g

Video shows a test using the gradiometer





Thermal and Mechanical Housing

height 225 mm

diameter 250 mm

- **Mechanical and thermal enclosure to IP67 for MEMS gravimeters & gradiometers developed by Wideblue**

Summary

- 5 μGal/√Hz performance for land survey applications
- EC Project NEWTON-g using 30 MEMS gravimeters to image magma flow on Mt Etna volcano
- Two industrial funded projects to run MEMS gradiometer on a drone
- Field trials organised for a range of applications from November 2020
- In process of spinning out technology with aim for first products late 2021

Further details:
http://userweb.eng.gla.ac.uk/douglas.paul/index.html
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Engineering and Physical Sciences Research Council
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UK Quantum Technology Hub Sensors and Timing
Innovate UK
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