Quantum Physics & Quantum Information

Single-Photon LiDAR

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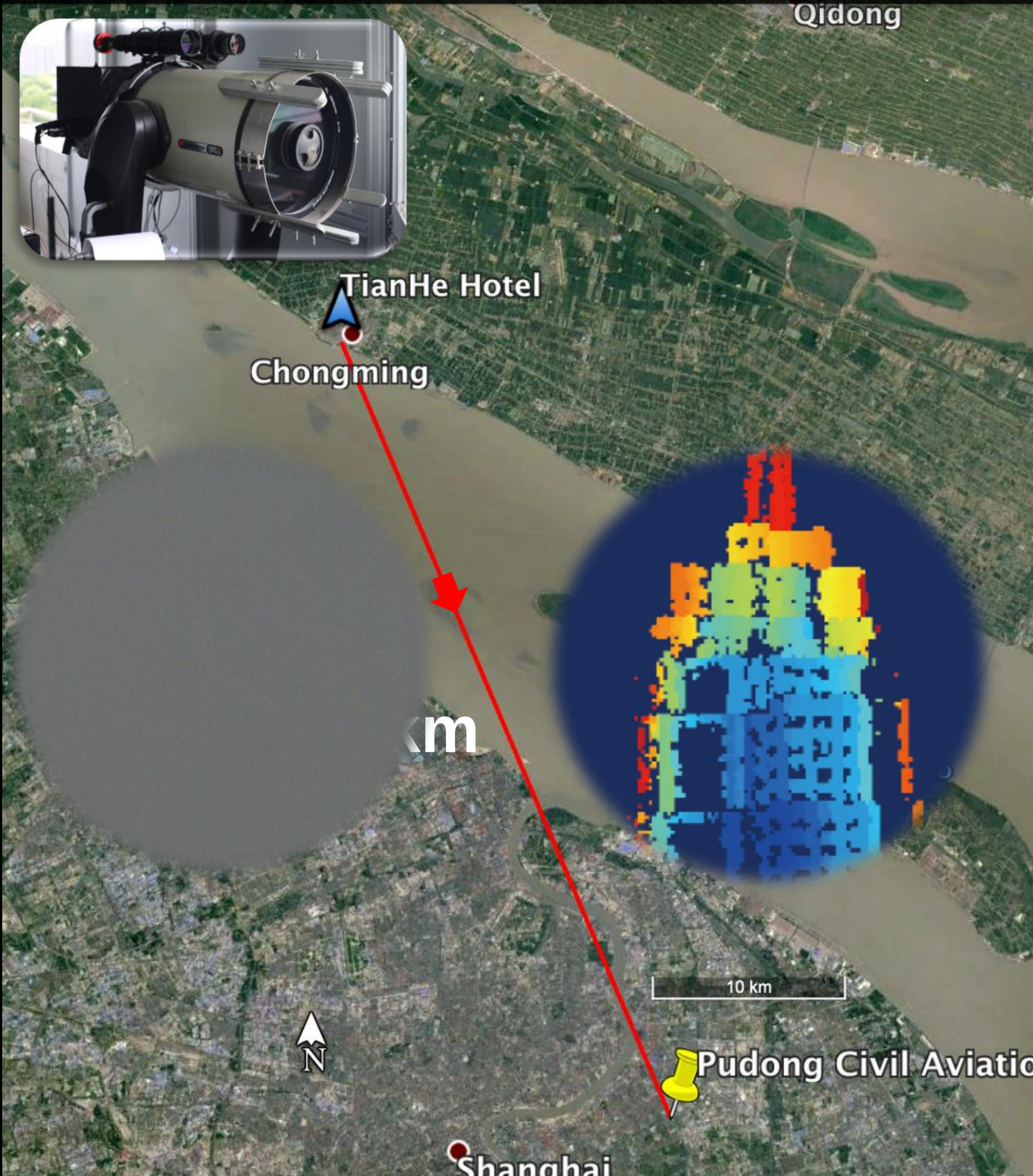
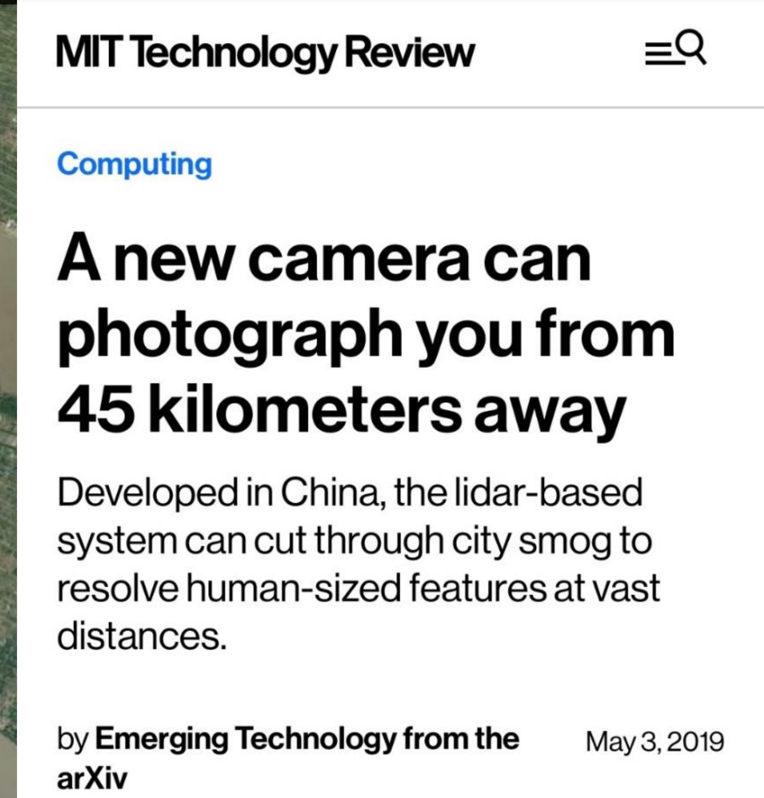



MIT Technology Review

Computing

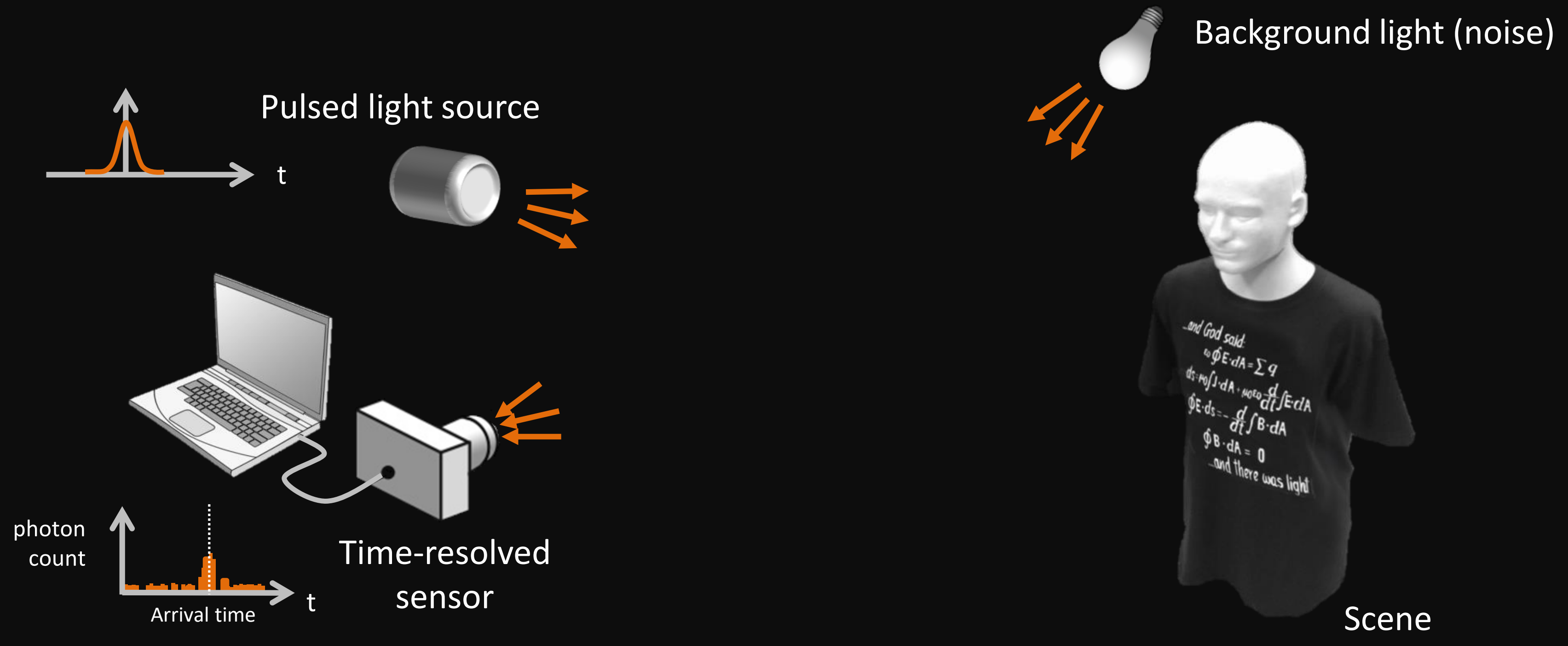
A new camera can photograph you from 45 kilometers away

Developed in China, the lidar-based system can cut through city smog to resolve human-sized features at vast distances.

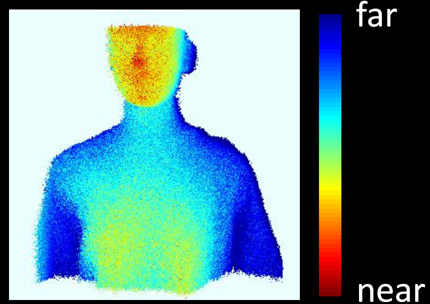
by **Emerging Technology from the arXiv** May 3, 2019

Li et al., arXiv:1904.10341 (2019)

Traditional active optical imaging



Reflectivity



3D structure

Using a <u>large</u> number of photon detections (thousands per pixel), we obtain

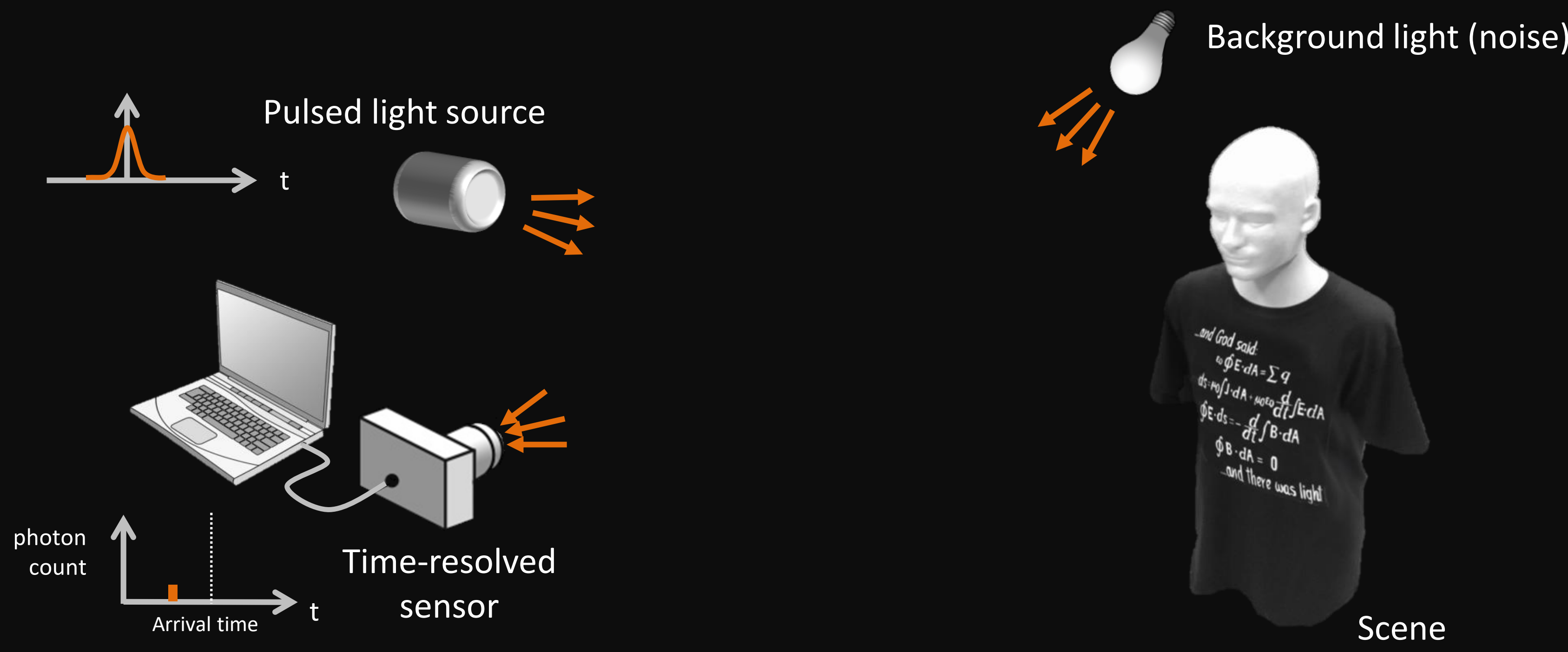
Detecting fewer photons (hundreds per pixel) leads to image degradation due to shot noise

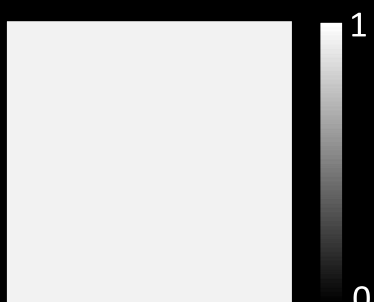
Reflectivity from number of detected photons at each pixel

Degradation is traditionally modeled as additive Gaussian noise

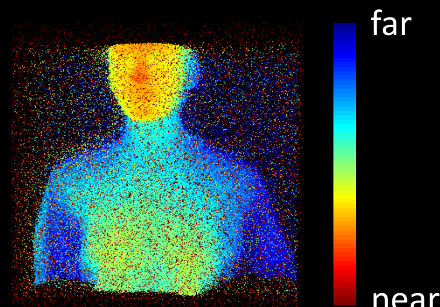
3D from time-of-flight info (shift of photon-count histogram's peak) at each pixel

Active imaging with 1 photon per pixel??





Reflectivity



3D structure

Reflectivity image is featureless

3D image is severely degraded by background light

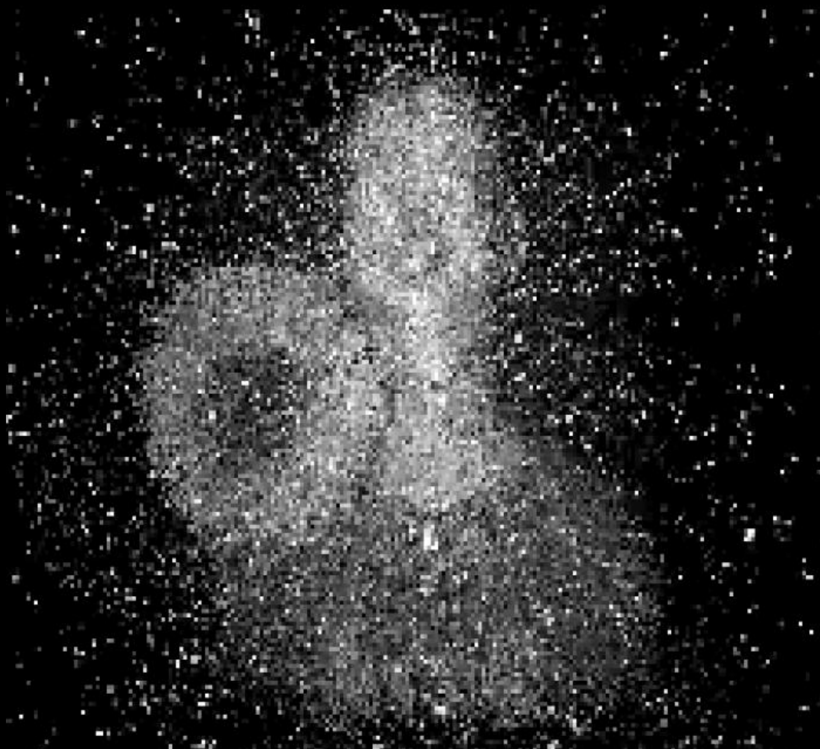
Single-Photon VS Conventional

	Conventional LiDAR	Single photon LiDAR
Sensitivity	~1 nW (10^9 photons)	**~1 photon**
Power	High	**Low**
Range	~10 kilometers	**> 100 kilometers**
Accuracy	~10 cm (ns)	**~mm (ps)**

How to do it?

- New software: Computational Algorithm
- New hardware: Single-Photon Imaging System

Results with 1 photon per pixel

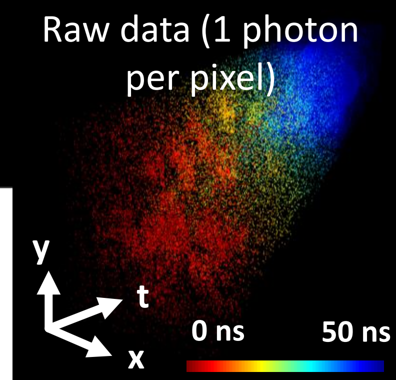


Conventional algorithm

Our algorithm

Nat. Commun. **7**, 12046 (2016); see also *Science* 343, 58 (2014)

Computational algorithm



Step 0: calibration

- Calibrate $\mathbf{B}$ and also identify set of "hot pixels" $\mathcal{H}$

✓ **Filter noise in time domain**

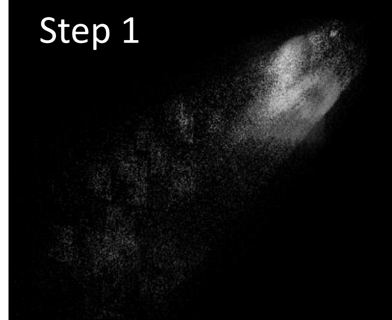
✓ **Spatial correlations**

Step 1: estimate scene reflectivity

Combine photon-count likelihood with spatial correlation to solve regularized ML estimation (convex)

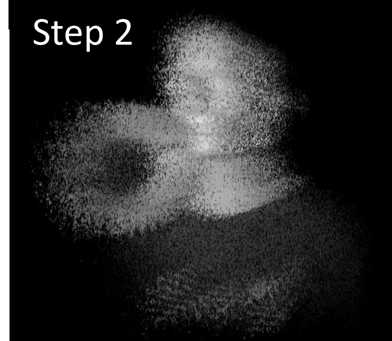
$$\underset{\mathbf{A}}{\text{minimize}} \quad \Bigg[\underbrace{\sum_{(i,j)\notin\mathcal{H}} \mathcal{L}(\mathbf{A}_{i,j};\mathbf{C}_{i,j},\mathbf{B}_{i,j})}_{\text{data fidelity of photon counts}} \Bigg] + \underbrace{\tau_A \,\text{pen}(\mathbf{A})}_{\text{spatial correlations of scene reflectivity}}$$

$$\text{subject to} \quad \mathbf{A}_{i,j} \geq 0$$



Step 2: censor noise photons

Use $\text{OMP}(\mathbf{T}_k, N_k)$ to locate photon clusters and reject photon arrival times not near to them by pulsewidth



Step 3: estimate scene depth

Combine arrival-time likelihood with spatial correlation to solve regularized ML estimation (convex)

$$\underset{\mathbf{D}}{\text{minimize}} \quad \Bigg[\underbrace{\sum_{(i,j)\notin\mathcal{H}} \sum_{T_{i,j}\in\mathbf{U}_{i,j}} \mathcal{L}(\mathbf{D}_{i,j};T_{i,j})}_{\text{data fidelity of filtered arrival times}} \Bigg] + \underbrace{\tau_D \,\text{pen}(\mathbf{D})}_{\text{spatial correlations of scene depth}}$$

$$\text{subject to} \quad \mathbf{D}_{i,j} \geq 0$$

Nat. Commun. **7**, 12046 (2016); see also *Science* 343, 58 (2014)

Push the range limit

$$R_{limit} \propto SNR \cdot \eta_a = \frac{PA\eta_s}{R^2 h\nu\bar{n}} \cdot \eta_a$$

Laser power (*P*)
Telescope aperture (*A*)

$\eta_s, \bar{n}$

Experiment

High coupling efficiency
Low distortion
High transmittance
Noise reduce

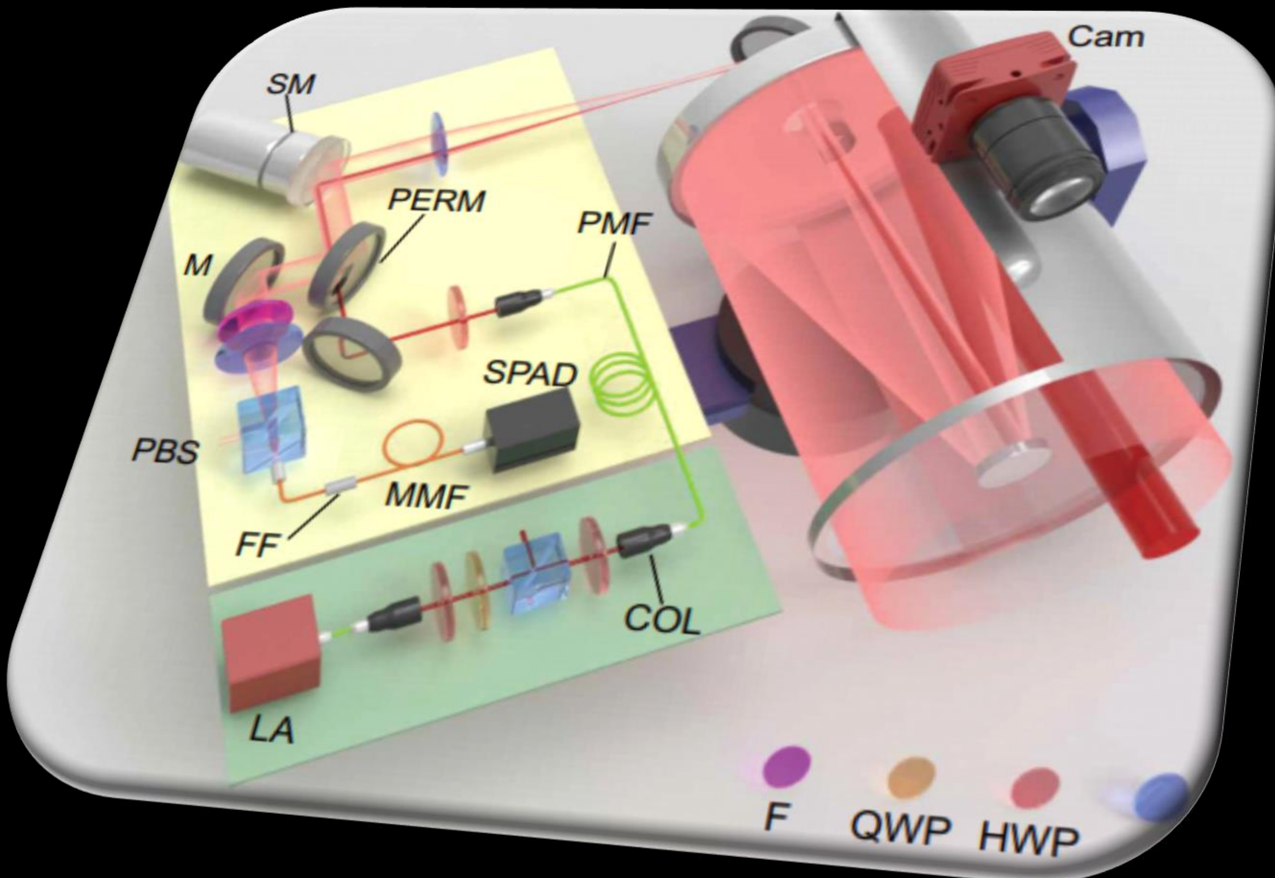
η_a

Algorithm

Denoise ~ 1 PPP
Low SNR reconstruction

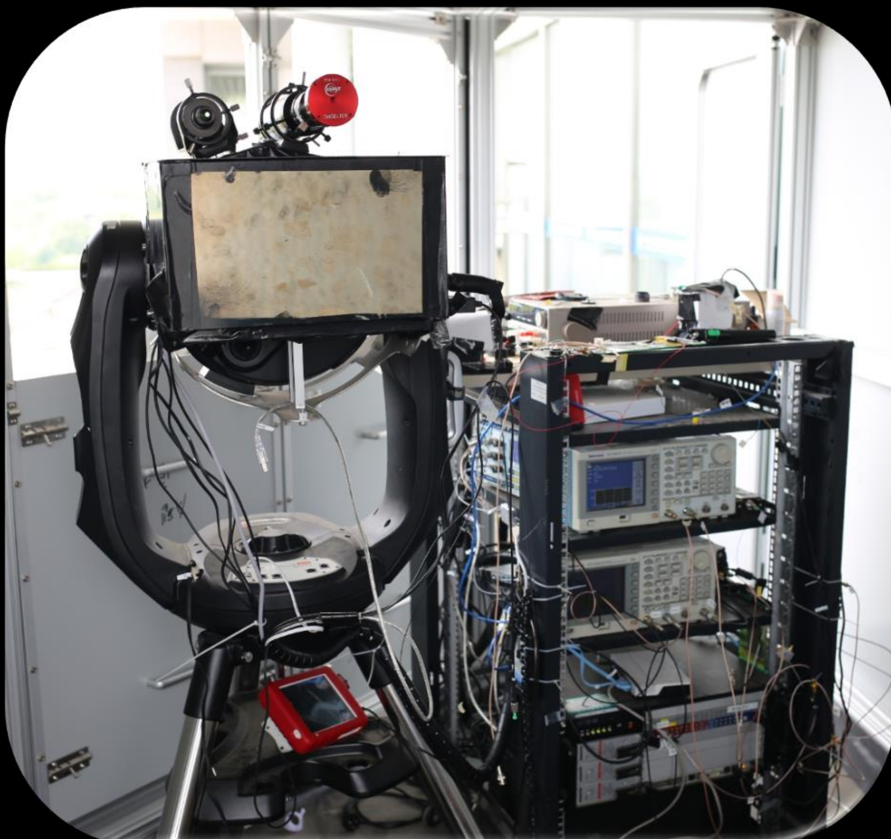
- Optimize the optical design of the hardware system
- Propose a new algorithm for outdoor environments

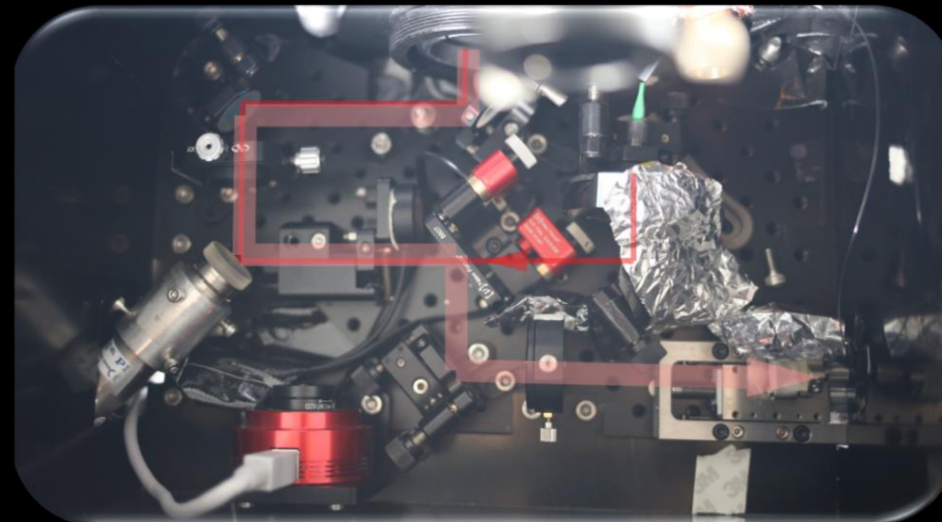
Single-Photon Imaging



- 1550 nm: eye safe, reduced solar, low loss
- Use polarization to reduce the noise (x100)
- High coupling efficiency (50%)
- Compact, dual-axis scanning

arXiv:1904.10341



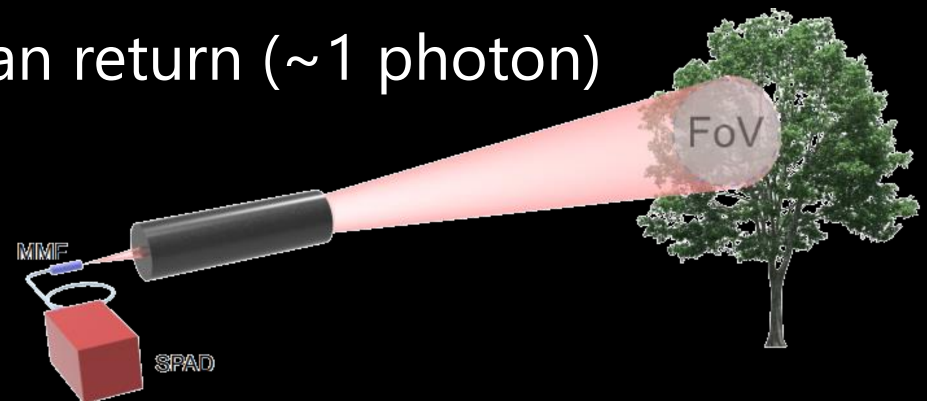



CELESTRON
EDGE HD OPTICS

Algorithm

Challenges

- A large FoV in far field covers multiple reflectors
- A strong background noise in outdoor environment
- Only few signal photons can return (~1 photon)



Solutions

- G**lobal gating** to unmix signal from noise
- Modified SPIRAL-TAP solver to solve **the deconvolution** problem with **3D matrix**
- Impose a transverse-smoothness using the **3D TV norm**

Hardware + Software

Conventional LiDAR
~10 kilometers [OE, 2017]

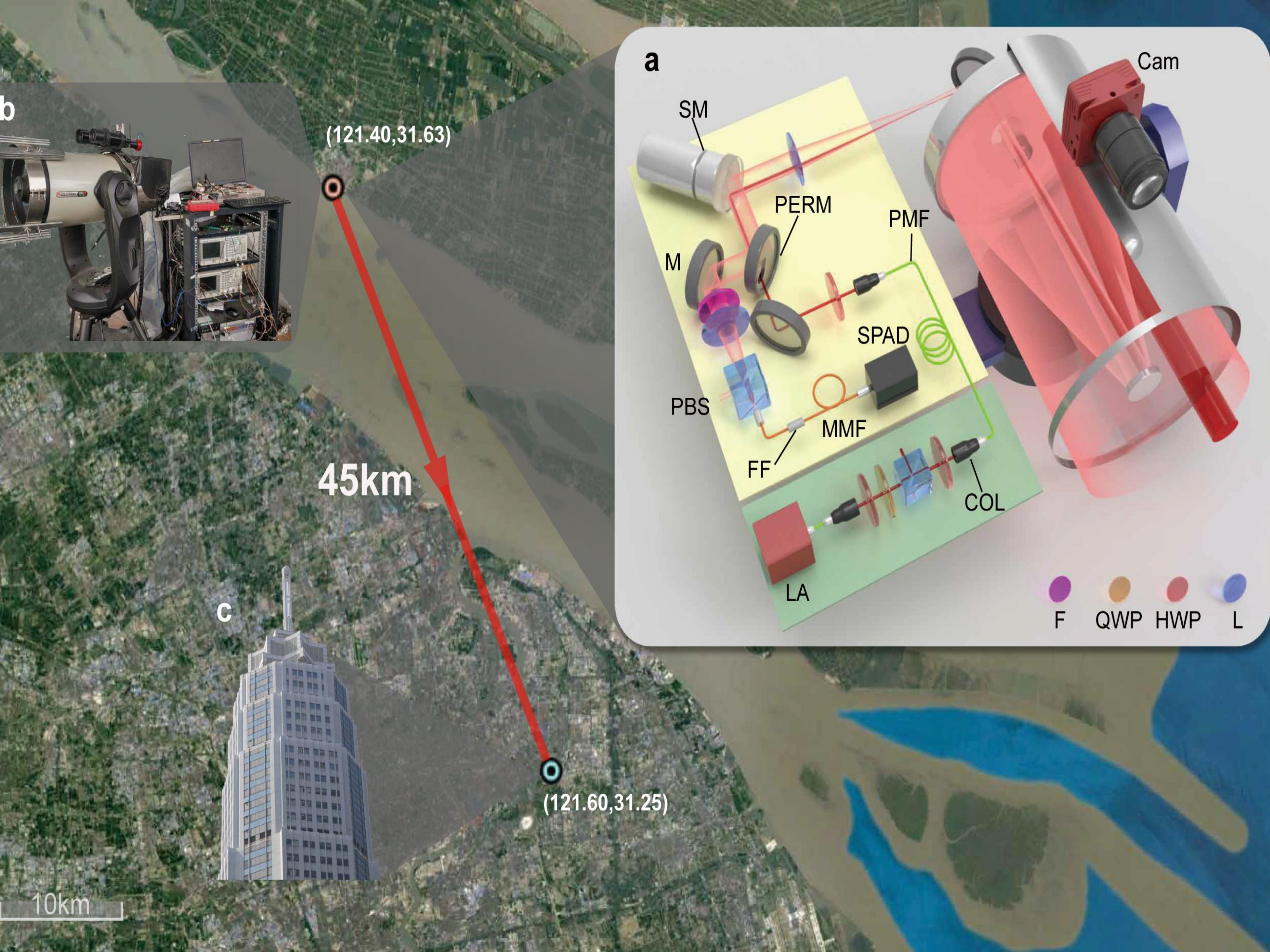
New hardware:
Single Photon detection
High coupling and detection
Advanced noise-suppression

Conventional algorithm:
100 photon/pixel [pixelwise ML]

New algorithm:
Sensitivity ~1 photon per pixel
SNR = 0.031 (200ns time gate)

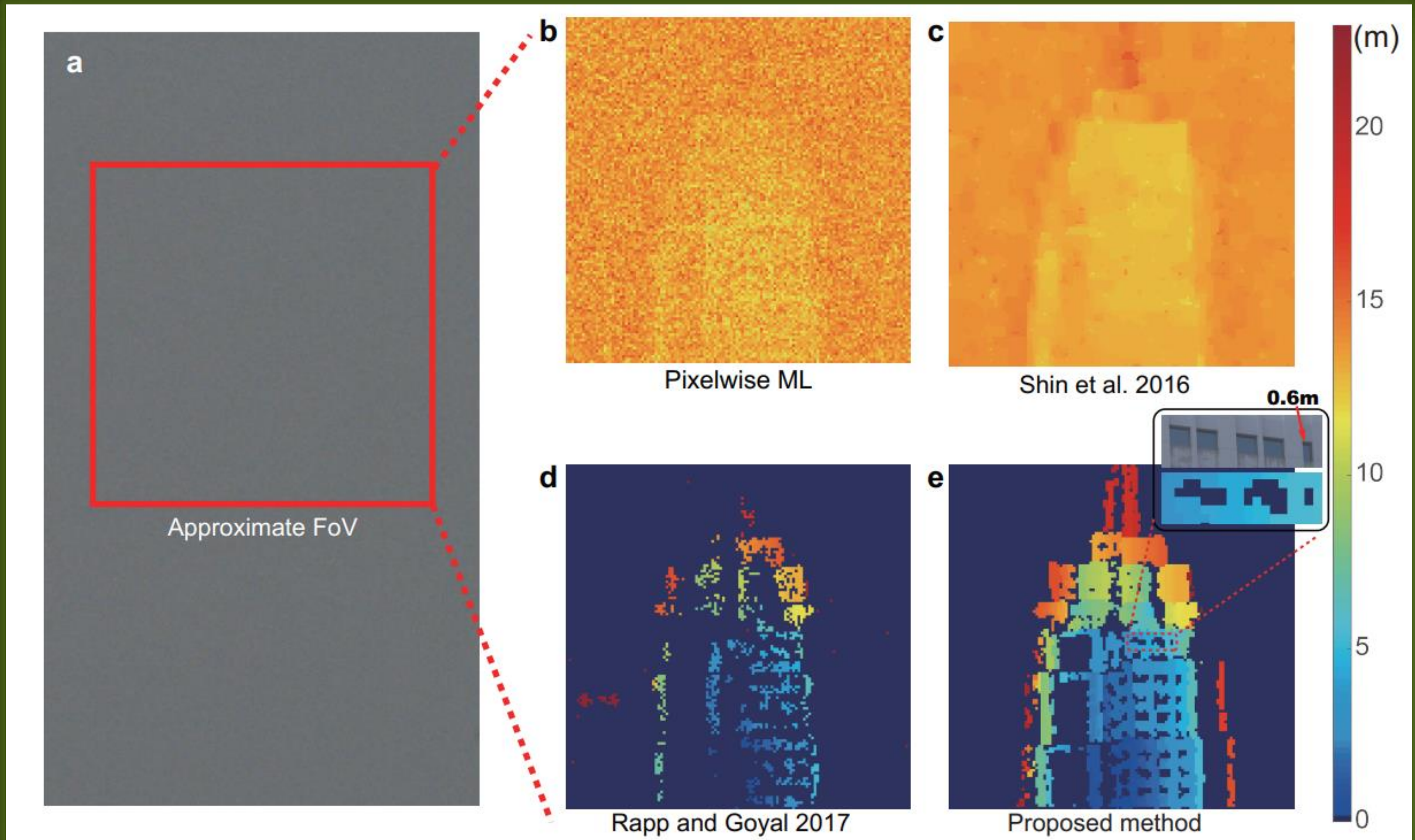
Laser power: reduced by ~100 times
Imaging distance: extended by ~10 times

Long-range 3D imaging



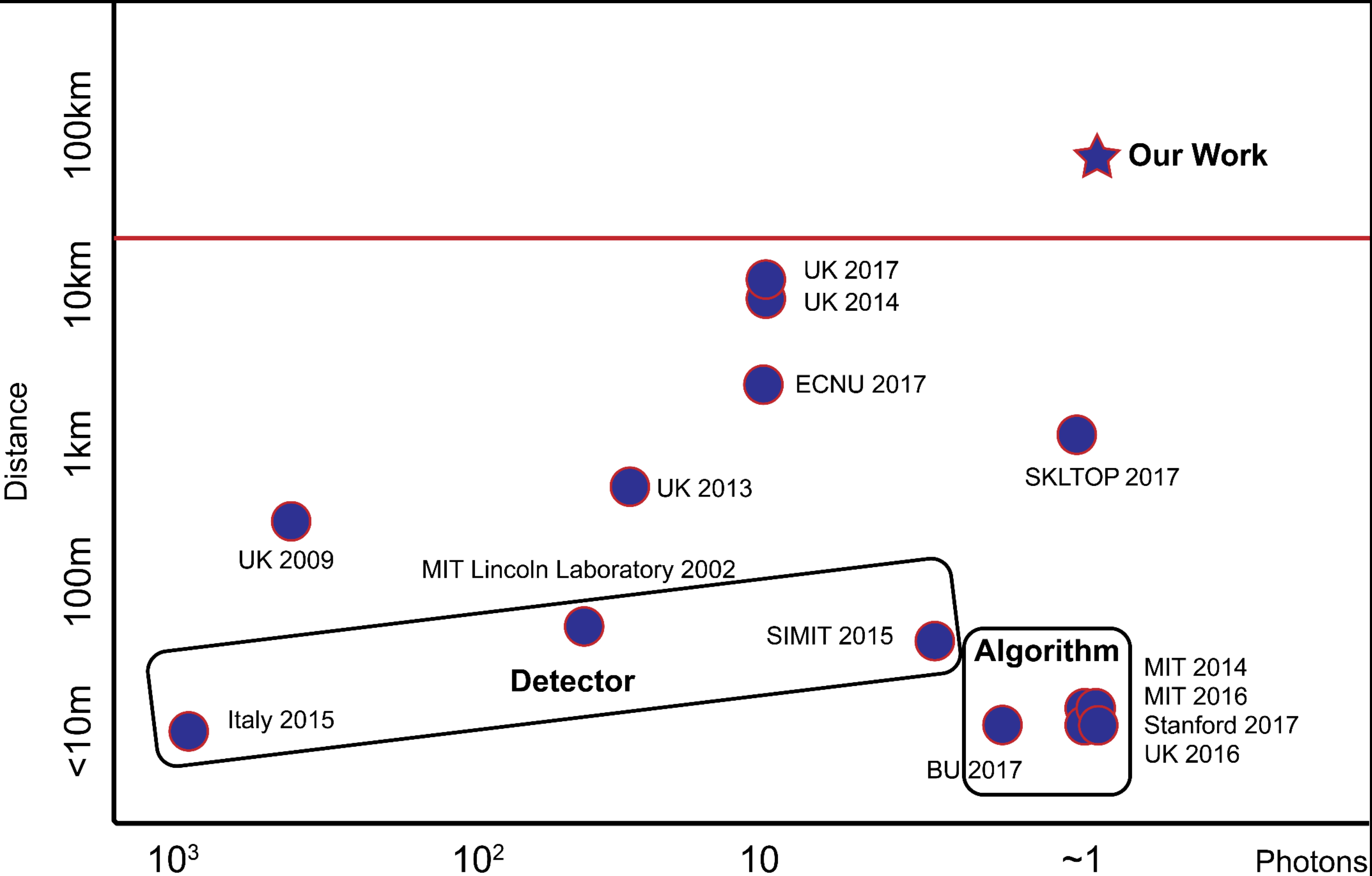
a
Cam
SM
PERM
PMF
M
SPAD
PBS
MMF
FF
COL
LA
F
QWP
HWP
L
b
(121.40,31.63)
45km
c
(121.60,31.25)
10km

45-km results



Range	45 km	Sensitivity	2.59 photon/pixel
Pixels	16 k	Spatial resolution	0.6 m

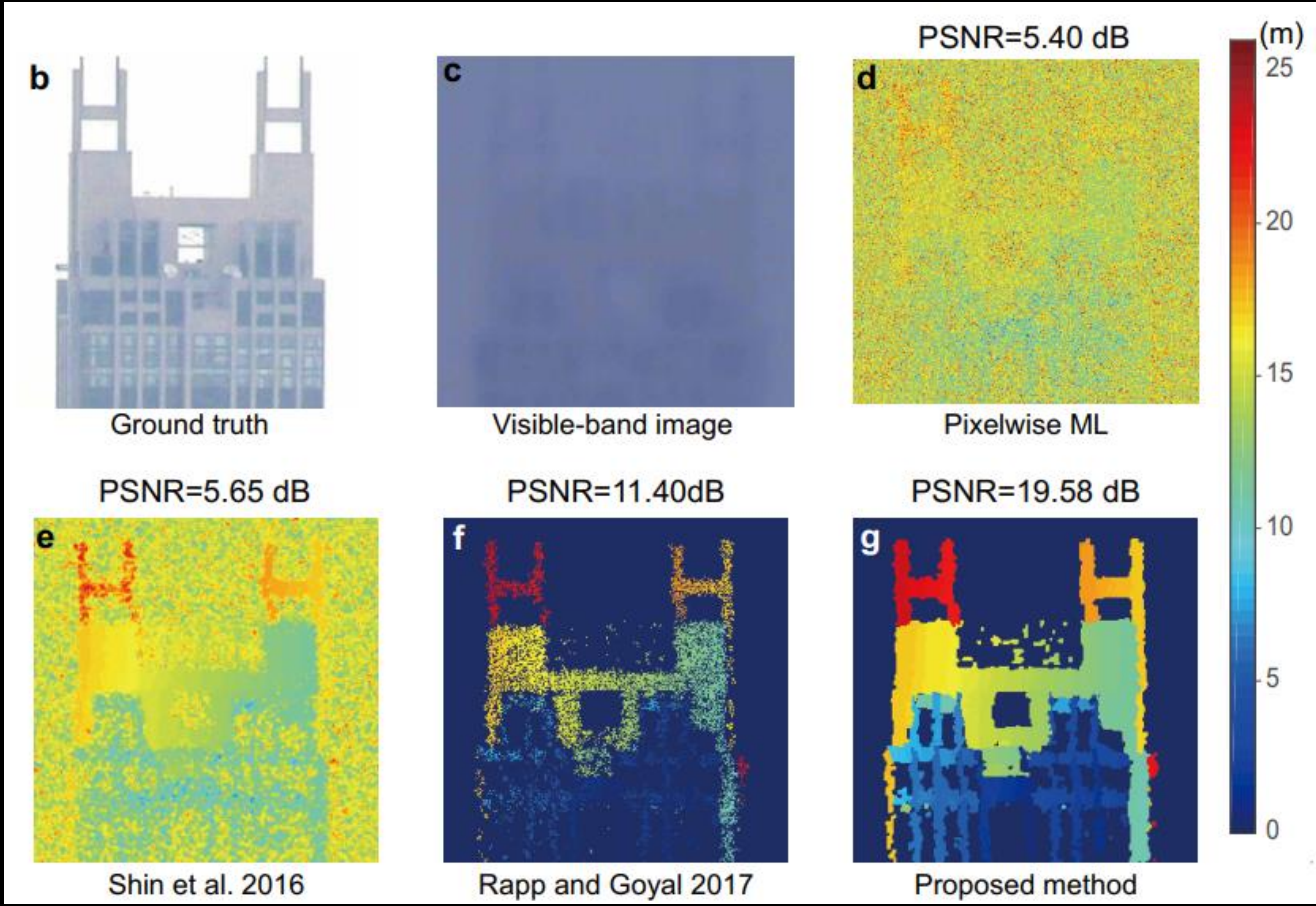
Li et al., arXiv:1904.10341 (2019)



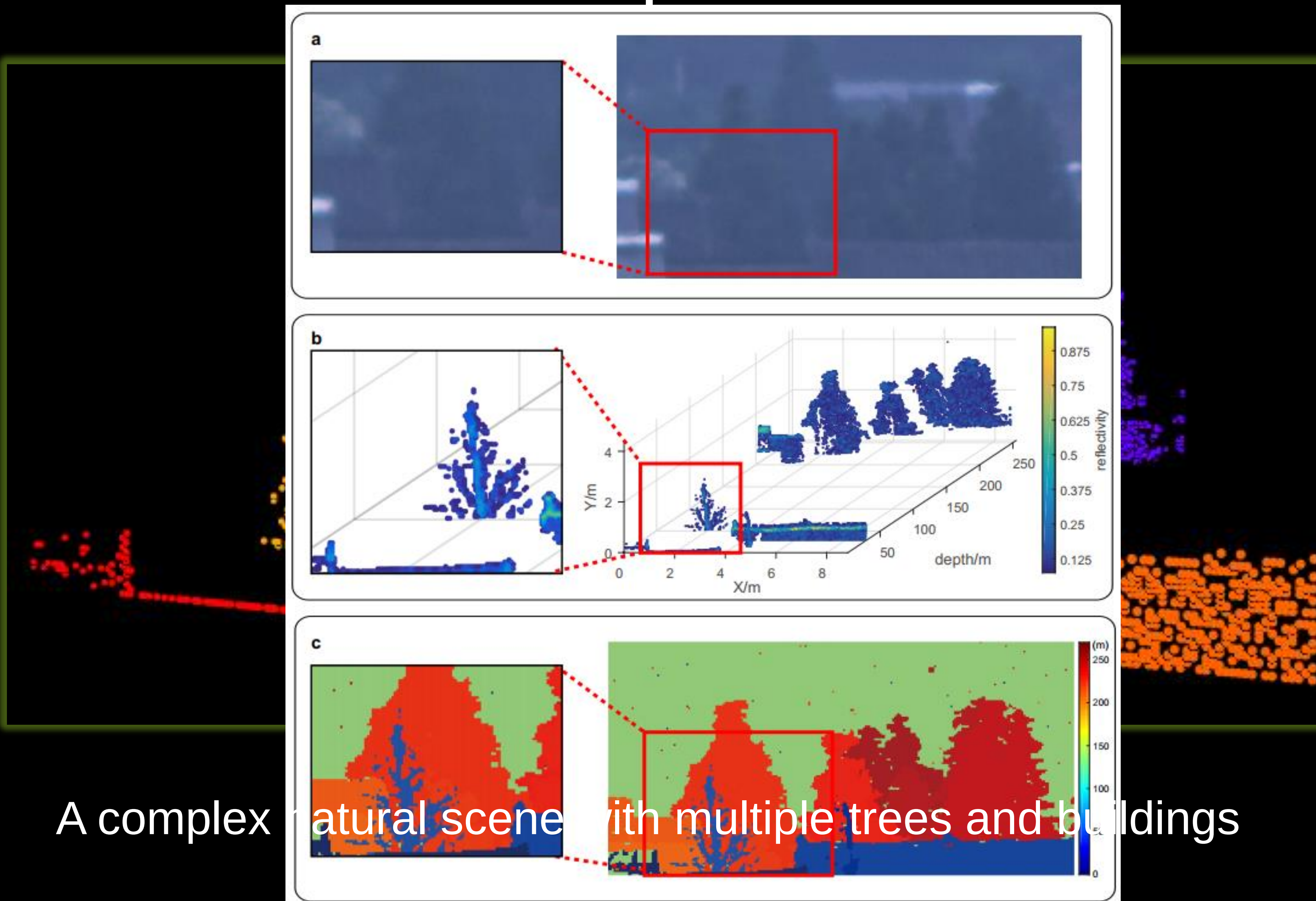
Distance
100km
10km
1km
100m
<10m
Our Work
UK 2017
UK 2014
ECNU 2017
SKLTOP 2017
UK 2013
UK 2009
MIT Lincoln Laboratory 2002
SIMIT 2015
Detector
Italy 2015
Algorithm
MIT 2014
MIT 2016
Stanford 2017
UK 2016
BU 2017
10^3
10^2
10
~1
Photons

Caoluzhen
Oriental Pearl TV Tower
Putuo
K11
Shanghai
You are here
USTC
10 km
Minhang
22 km
Liuzaozhen
Whilte dome
Utility pole
3 km
N
Vienna Hotel

22-km imaging in daylight

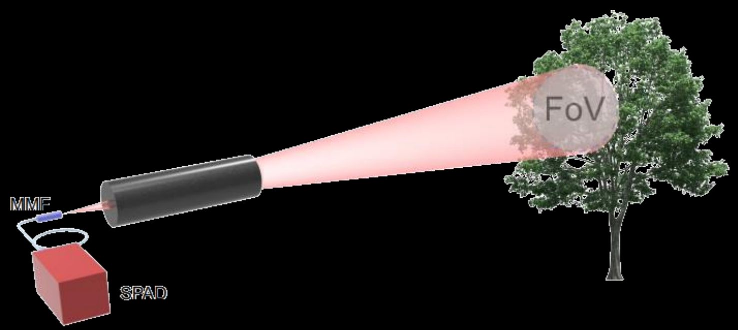


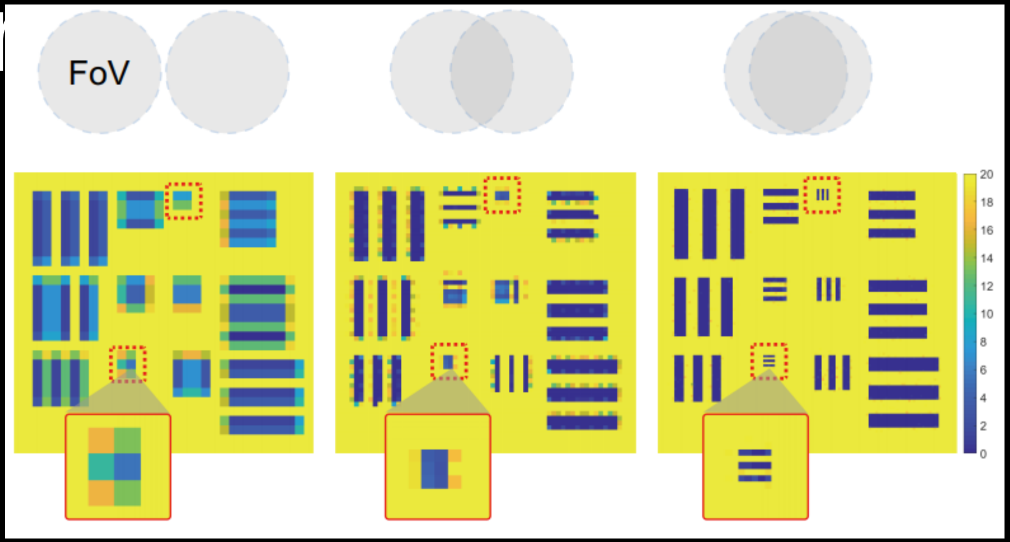
3-km Complex Scenes

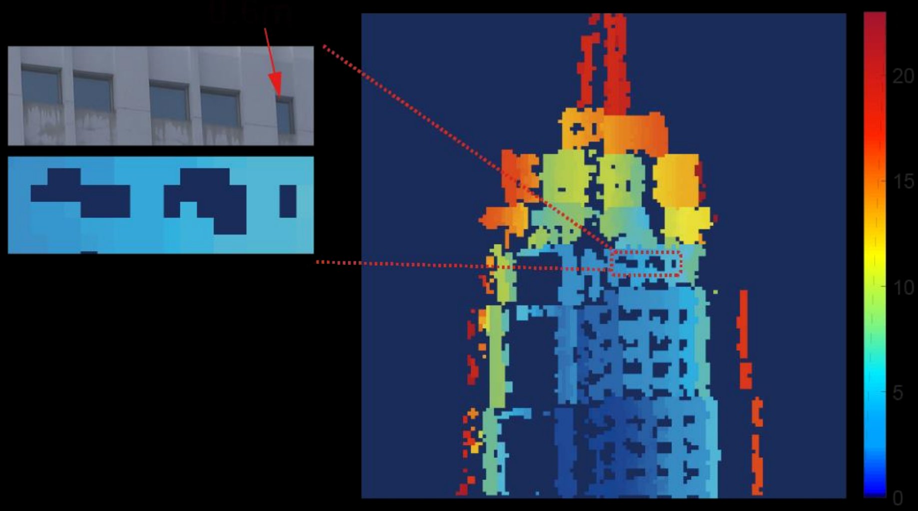


A complex natural scene with multiple trees and buildings

Super-Resolution in long





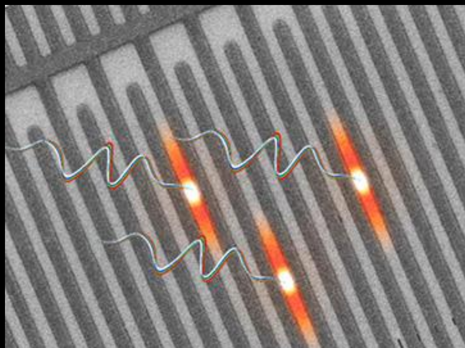


At 45 km:

- **Diffraction limit: ~ 1 m**
- **Our resolution: ~ 0.6 m**

Motivated by the Nobel Prize in Chemistry 2014 for "super-resolved fluorescence microscopy"

Future work



SNSPD

Laser without ASE

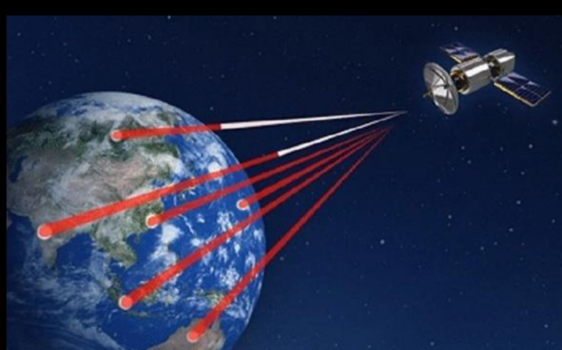
Longer

~200-km stand-off distance

Faster

Speed up the imaging and provide ***real-time*** imaging for rapid moving targets

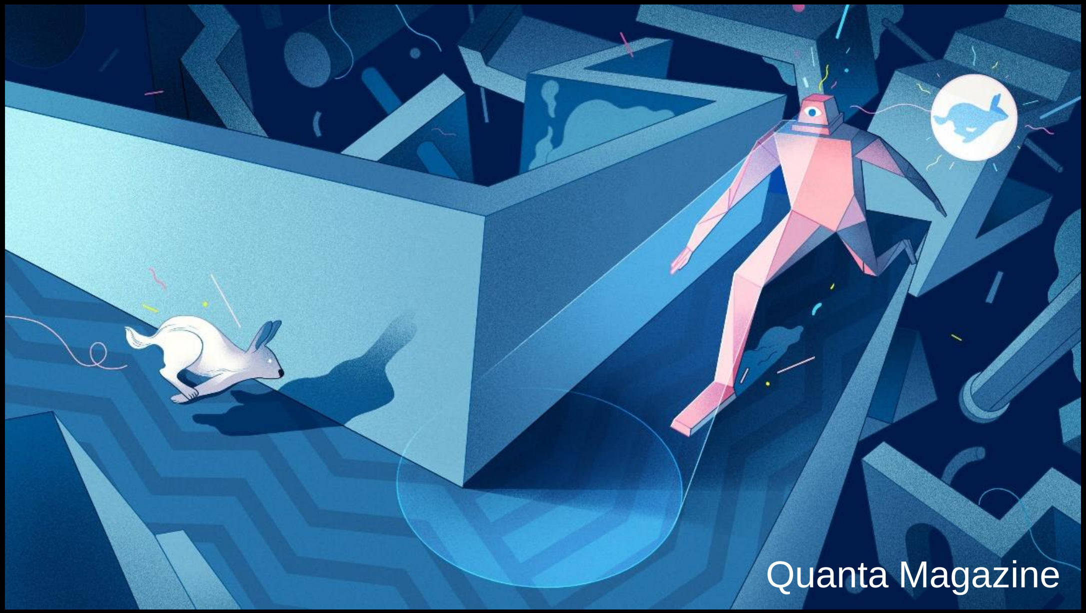
Geiger-mode SPAD arrays



Satellite 3D imaging

Low-power single-photon LiDAR mounted on LEO satellites

Other on-going research



- Non-line-of-sight imaging
- Diffuse imaging at near-infrared wavelength
- Advanced algorithms, e.g., machine learning

Xu et al., Opt. Express 26, 9945 (2018); Xu et al., in preparation (2019)

Non-Line-of-Sight Tracking over 1.4 km

People


Kejin Wei


Wei Li


Zhengping Li


Yuzhe Zhang


Bin Wang


Xin Huang


Juntian Ye


Hao Tan


Yu Hong


Jinjian Han


Pengyu Jiang

Director: Jian-Wei Pan

Collaborators: Cheng-Zhi Peng, Qiang Zhang, Jun Zhang, Yuan Cao & Hai-Yun Xia, Xian-Kang Dou

Keep smiling, our LiDAR may be watching you ☺.

Thank you!

Li et al., arXiv:1904.10341 (2019)

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Parameter	Our system
Distance	45 km
Scene	Building
Size	128×128, 64m×64m
Average Photon Number/Pixel	2.59
SNR	0.031 (a time gate of 200 ns, 30 m)
Detector	InGaAs, 15%, 500-ps jitter, 2200 dark count
Wavelength	1550 nm
Objective Lens	f=2800 mm, D=280 mm
Laser Repetition Rate	100 kHz
Laser Pulse Width	0.5 ns
Average Output Power	120 mW, 1.2 μJ per pulse
Angular Resolution	11.3 μrad
TDC	Tailored, 50-ps jitter
Optical Box Size	30×30×35 cm^3
Coupling Fiber	62.5 μm