

量子成像科学与技术

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合肥国家实验室



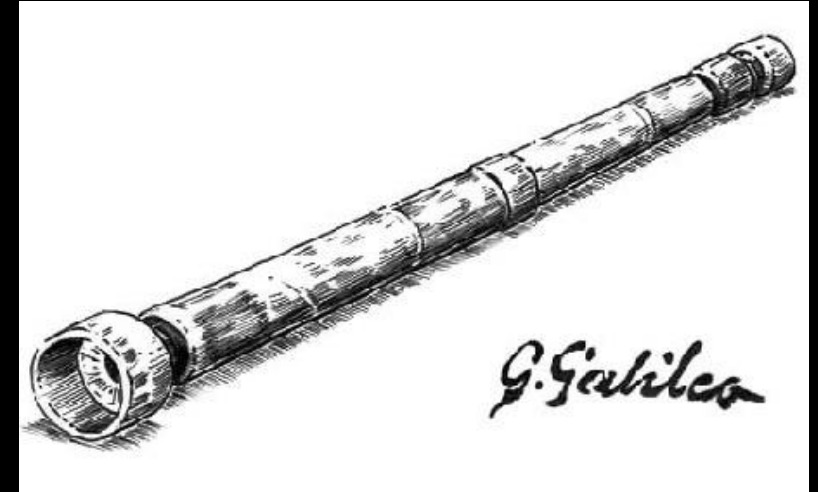
2026年9月

feihuxu@ustc.edu.cn

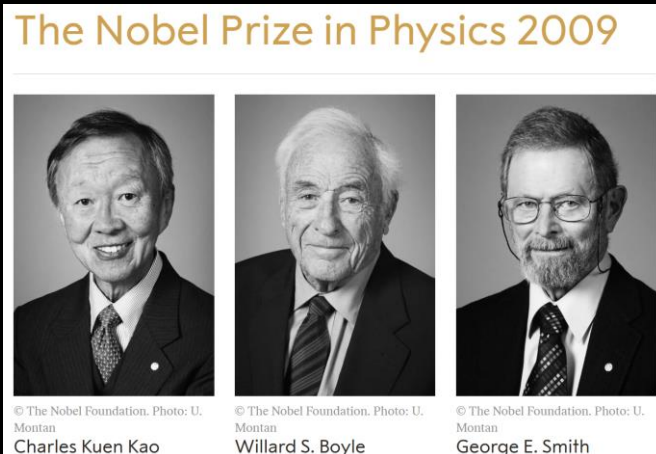
成像科学



墨子的小孔成像



伽利略的望远镜



CCD的发明



超分辨显微镜

夜视红外成像（热成像）

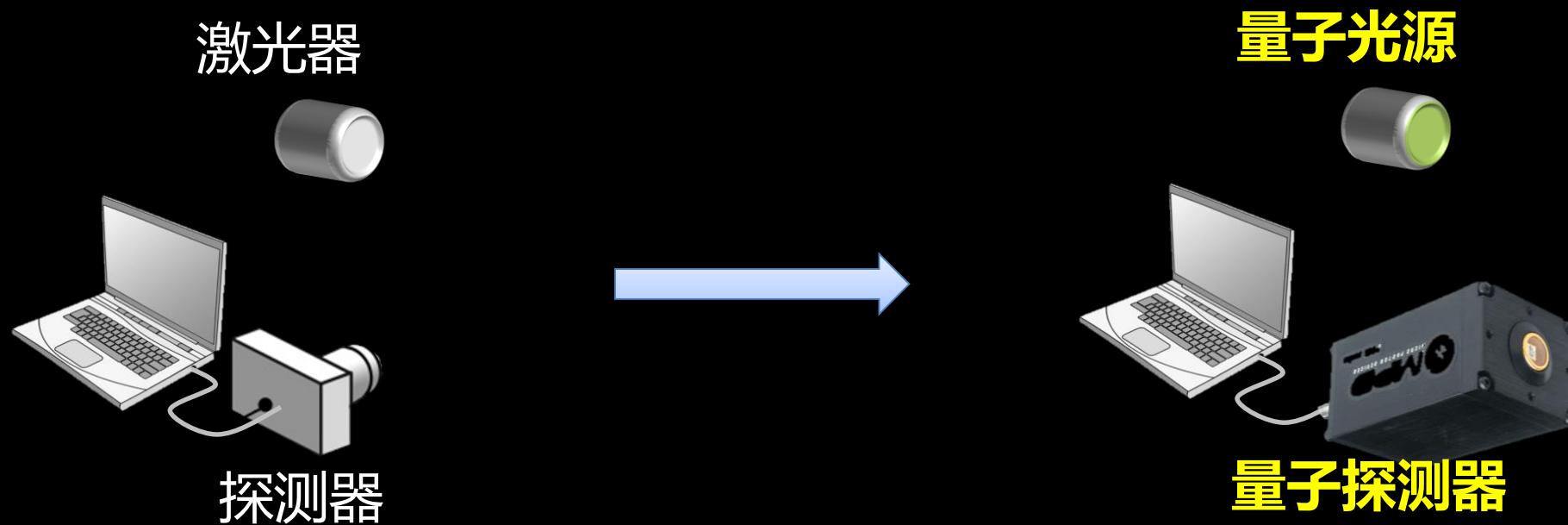


激光雷达主动成像



主动发射激光，进行飞行时间测量，实现目标场景的三维成像

量子成像



将量子光源、量子探测等量子技术应用于成像科学，突破传统成像技术在灵敏度、距离、分辨率等方面的极限



什么是量子成像？



量子成像是一种利用量子力学原理进行成像的技术。与传统成像技术不同，量子成像利用光子（如光的粒子）和量子态的特性，以实现更高的成像精度和灵敏度。

主要特点

- 1. **量子纠缠**：通过纠缠态光子对，量子成像可以提高成像的信噪比，从而获取更清晰的图像。
- 2. **亚光子数成像**：量子成像可以在低光条件下工作，甚至在光子数极少的情况下进行成像，这在生物医学和夜视成像中有重要应用。
- 3. **量子干涉**：利用量子干涉效应，可以增强成像系统的分辨率，获得更细微的结构信息。

应用领域

- **医学成像**：如在活体组织成像中提高分辨率。
- **材料科学**：分析材料的微观结构。
- **安全监控**：提高探测灵敏度。

量子成像的研究仍在不断发展，未来可能会带来更多创新的应用和技术突破。

deepseek

什么是量子成像？



量子成像是一种利用量子力学原理（如纠缠光子对、单光子探测等）实现超越经典光学极限的新型成像技术。其核心是通过量子态的特性获取传统成像无法实现的信息，主要分为以下两类：

1. 量子关联成像（鬼成像）

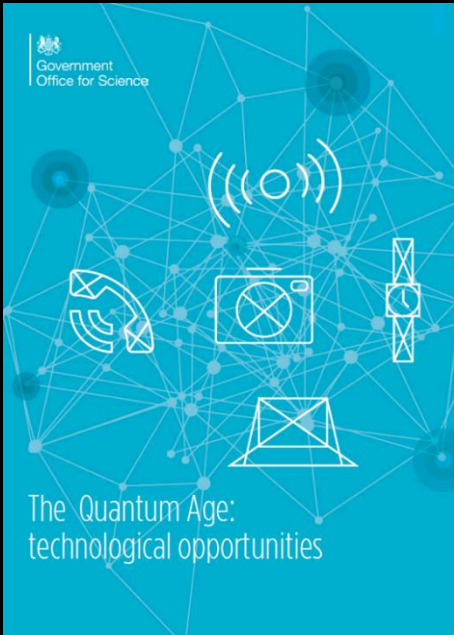
- **原理**：利用纠缠光子对的量子关联性，即使物体仅被其中一个光子照射，也能通过另一个未接触物体的光子重建图像。
- **特点**：
 - **非局域成像**：成像不依赖直接探测物体的光路，适用于恶劣环境（如雾霾、强散射介质）。
 - **抗干扰性强**：在低光或噪声环境下仍能清晰成像。

2. 单光子成像

- **原理**：通过单光子级别的超灵敏探测，实现极弱光条件下的成像。
- **特点**：
 - **超高灵敏度**：可探测单个光子，适用于极暗环境。
 - **时间分辨率高**：皮秒级精度，用于动态过程捕捉（如荧光寿命成像）。

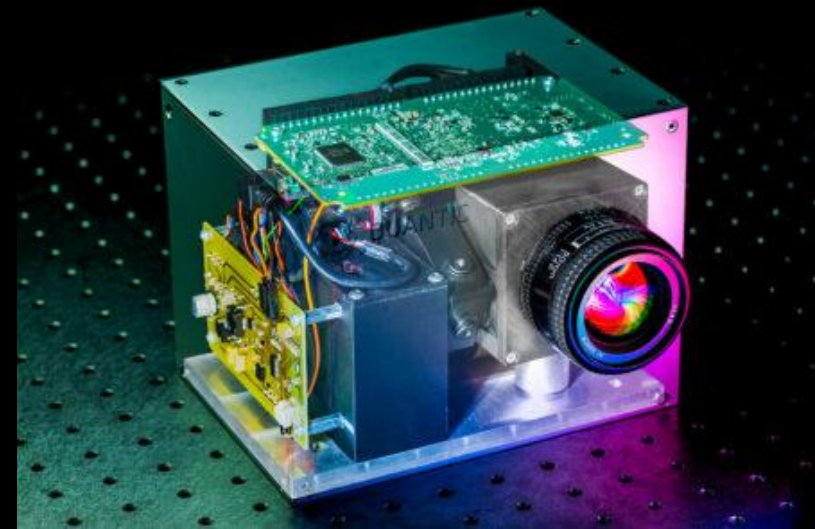
量子成像的国内外布局

- ▶ 英国，2016年启动国家量子专项成立“量子增强成像研究中心”，延续资助
- ▶ 美国，2018年启动国家量子行动计划支持“光量子成像在生物、环境、遥感等研究领域的应用”，近期延续资助
- ▶ 中国，科技创新-2030“量子通信与量子计算机”重大项目、基金委“高精度量子操控与探测”重大研究计划、科技部“地球观测与导航”重点研发计划等



UK Quantum Technology Hubs

- Quantum Computing and Simulation
- Quantum Communication
- Quantum Sensors and Timing
- Quantum Enhanced Imaging



1. 量子增强成像
Quantum-enhanced Imaging

2. 量子启发成像
Quantum-inspired Imaging

量子增强成像

利用量子特性，突破经典物理极限，提升传统成像能力

Science

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HOME > SCIENCE > VOL. 306, NO. 5700 > QUANTUM-ENHANCED MEASUREMENTS: BEATING THE STANDARD QUANTUM LIMIT

🔒 | SPECIAL REVIEWS

Quantum-Enhanced Measurements: Beating the Standard Quantum Limit

VITTORIO GIOVANNETTI, SETH LLOYD, AND LORENZO MACCONE [Authors Info & Affiliations](#)

SCIENCE • 19 Nov 2004 • Vol 306, Issue 5700 • pp. 1330-1336 • DOI: 10.1126/science.1104149

9,536 1,908

🔒 c

nature photonics

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Review Article | Published: 30 September 2024

Advances in quantum imaging

[Hugo Defienne](#) ✉, [Warwick P. Bowen](#), [Maria Chekhova](#), [Gabriela Barreto Lemos](#), [Dan Oron](#), [Sven Ramelow](#), [Nicolas Treps](#) & [Daniele Faccio](#)

[Nature Photonics](#) 18, 1024–1036 (2024) | [Cite this article](#)

Diagram illustrating a quantum radar system:

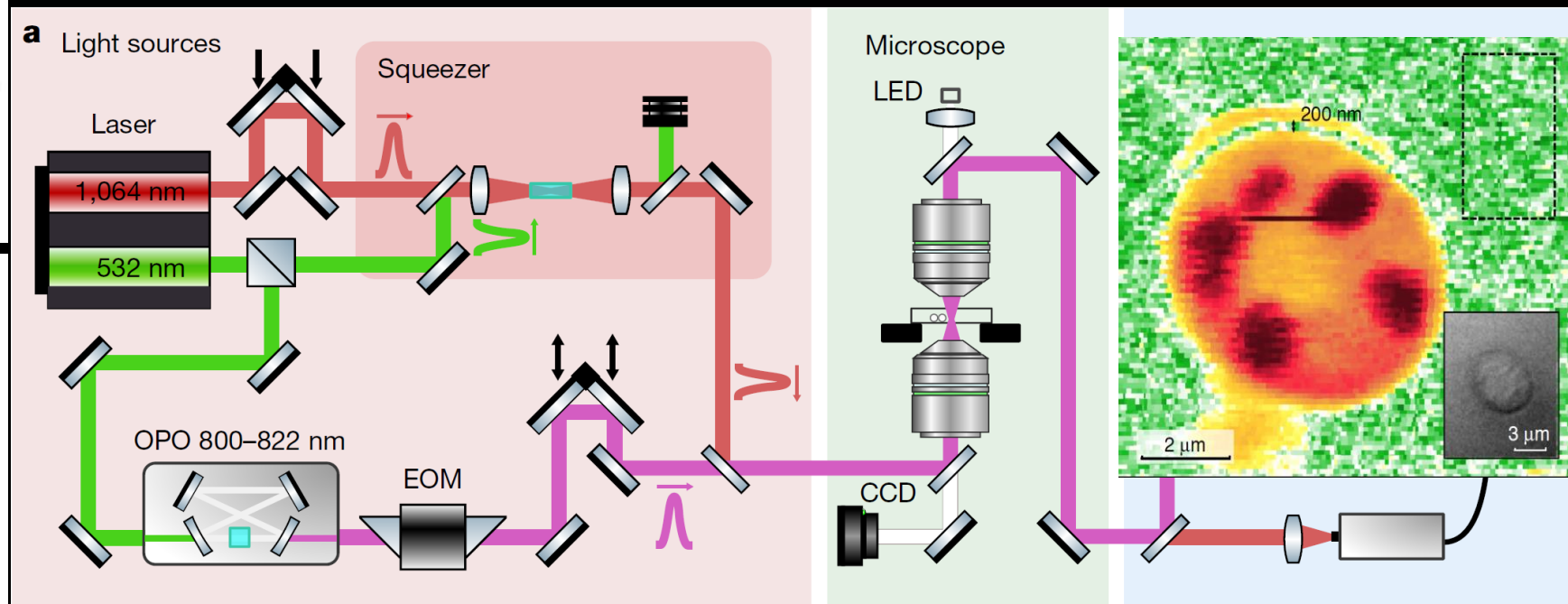
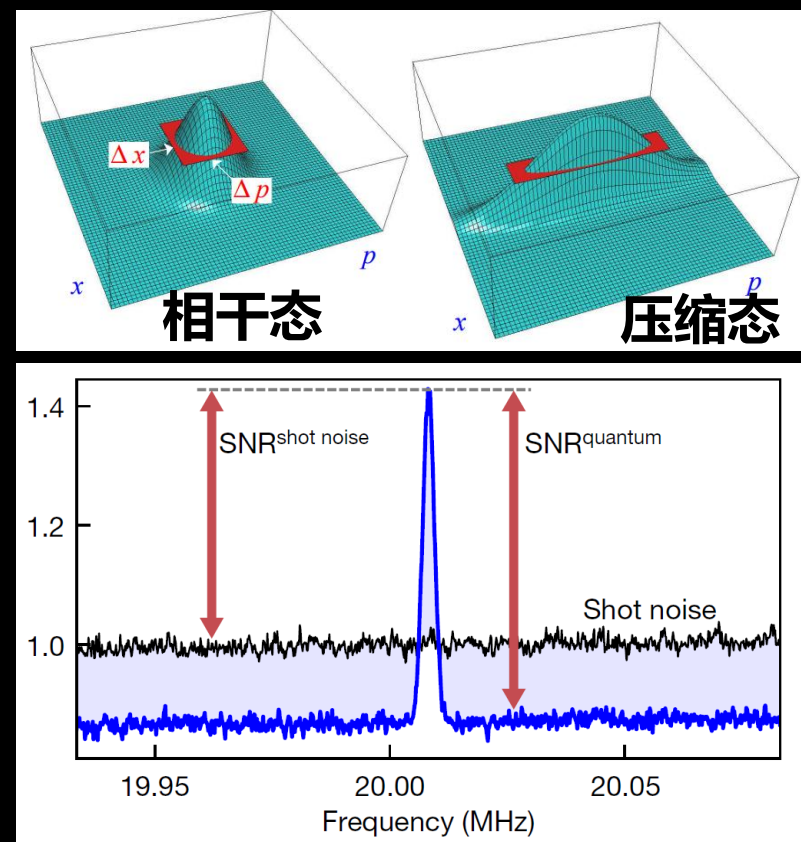
- Entangled photons** are generated and split into two paths.
- The **Image-forming photon** path leads to **Quantum memory**.
- The **Detection photon** path leads to a circular detector.
- The detector is directed towards a target (jet), reflecting photons.
- The detector is connected to **Quantum computation**.
- Quantum memory** is also connected to **Quantum computation**.

S. Lloyd, Science 321, 1463 (2008)
J. Shapiro et al., PRL 101, 253601 (2008)



J. Shapiro et al., PRL 114, 110506 (2015)
Barzanjeh et al., Sci. Adv. 6 eabb0451 (2020)
Lijian Zhang et al., PRL 127, 040504 (2021)
Dawei Wang et al., PRL 131, 033603 (2023)

例2：量子压缩态(Squeezed State)

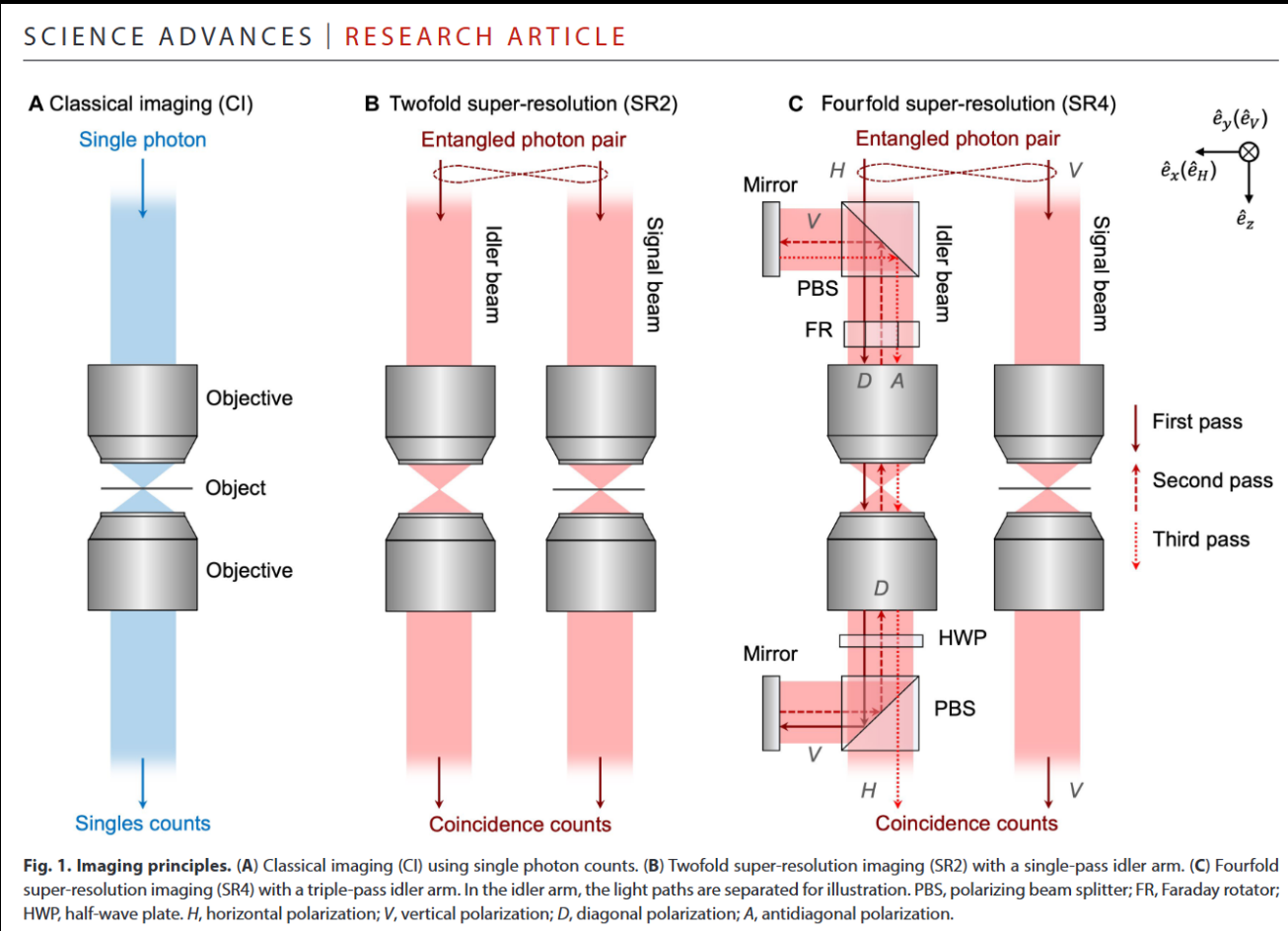


“The quantum squeezing allows imaging of molecular bonds within a cell with a 35% improved SNR compared with conventional microscopy.”

“量子增强相干拉曼显微镜对细胞内的分子键成像提升35%信噪比”

Bowen et al., Nature 594, 201 (2021)

例3：量子显微成像

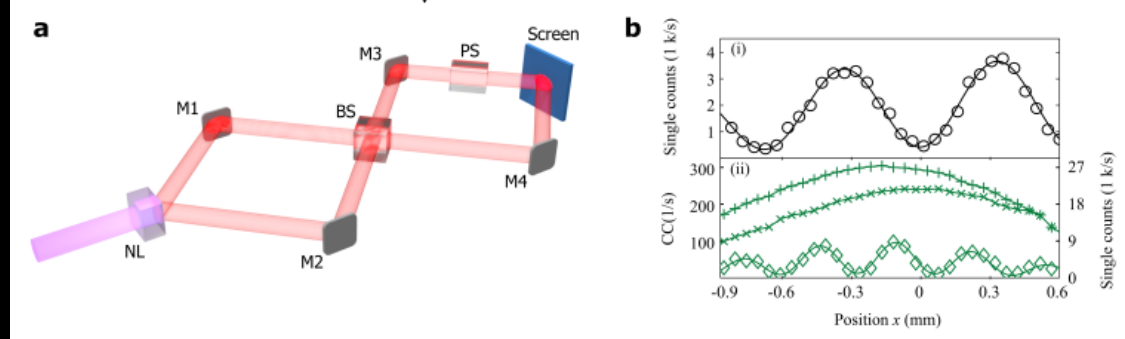


Above-twofold quantum super-resolution microscopy enabled by multiple idler passes with entangled biphotons

<https://www.science.org/doi/full/10.1126/sciadv.aea9457>

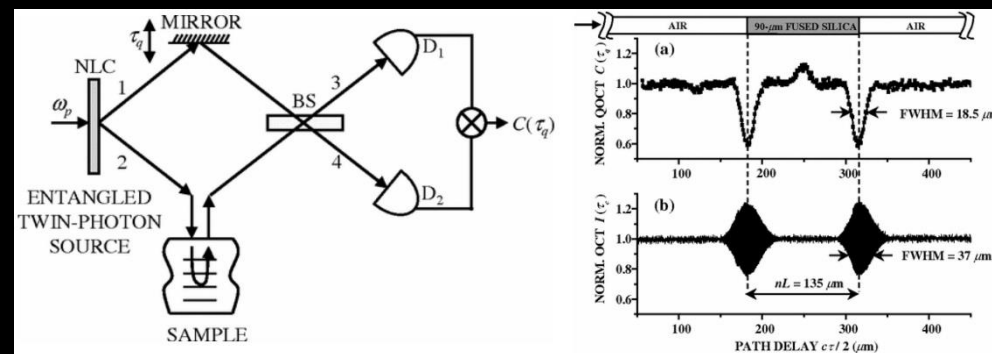
例4：量子纠缠态

$$|\text{NOON}\rangle = \frac{|N\rangle_a |0\rangle_b + e^{iN\theta} |0\rangle_a |N\rangle_b}{\sqrt{2}}$$



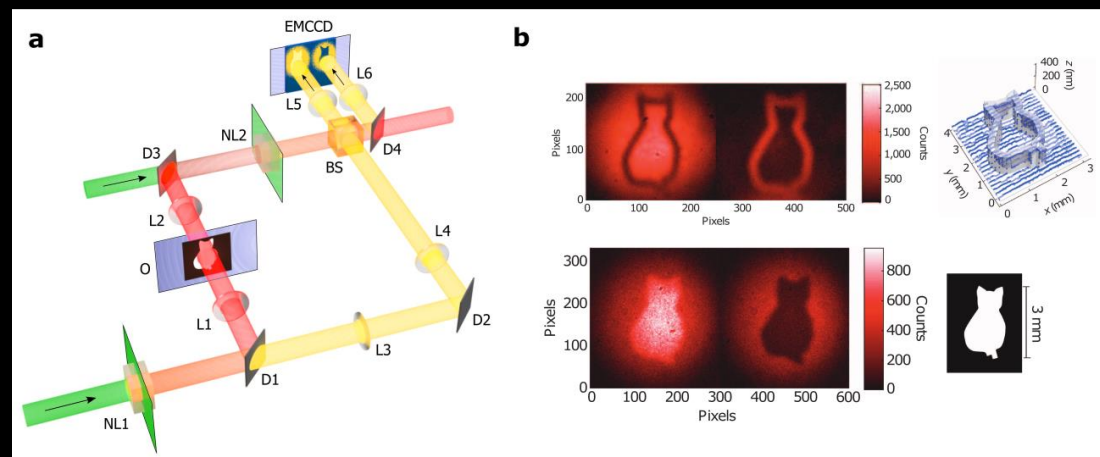
“NOON纠缠态” 超分辨成像

Dowling et al., Phys. Rev. Lett. 85, 2733 (2000)



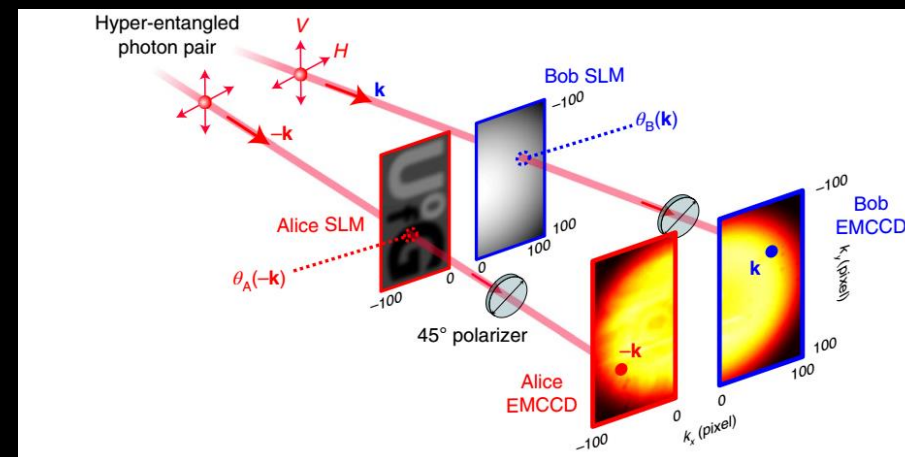
量子光学相干层析成像(QOCT)

Nasr et al., Phys. Rev. Lett. 91, 083601 (2003)



量子诱导相干探测

Zeilinger et al., Nature 512, 409 (2014)



量子全息成像

Faccio et al., Nature Physics 17, 591 (2021)

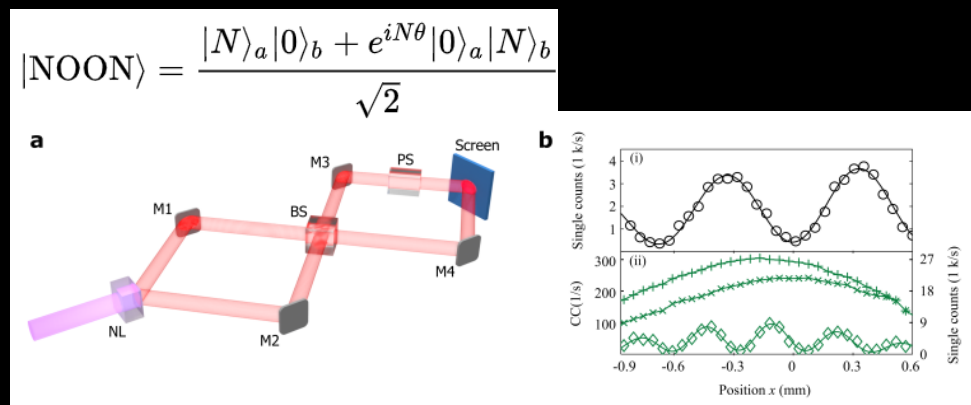
量子增强成像技术

研究现状：基础研究和原理验证



“There ‘s just a lot of problems that make QI hard for me to believe that this system is going to be of any use,” Jeff Shapiro (MIT) says in 2020.

“有很多问题使我很难相信量子照明现在会有实用性”



“The NOON states are known to be very sensitive to photon losses and rather hard to produce experimentally” Miles Padgett et al. in Nat Rev Phys

“NOON态对于损坏非常敏感、实验难以制备”

在量子显微成像方面，具体潜在实用价值

量子启发成像

受量子物理启发而发展的全新成像技术，提升传统成像能力

REVIEW

Science 361, 660 (2018)

OPTICAL IMAGING

Quantum-inspired computational imaging

Yoann Altmann¹, Stephen McLaughlin¹, Miles J. Padgett², Vivek K Goyal³,
Alfred O. Hero⁴, Daniele Faccio^{2*}

Ghost and Single-pixel Imaging

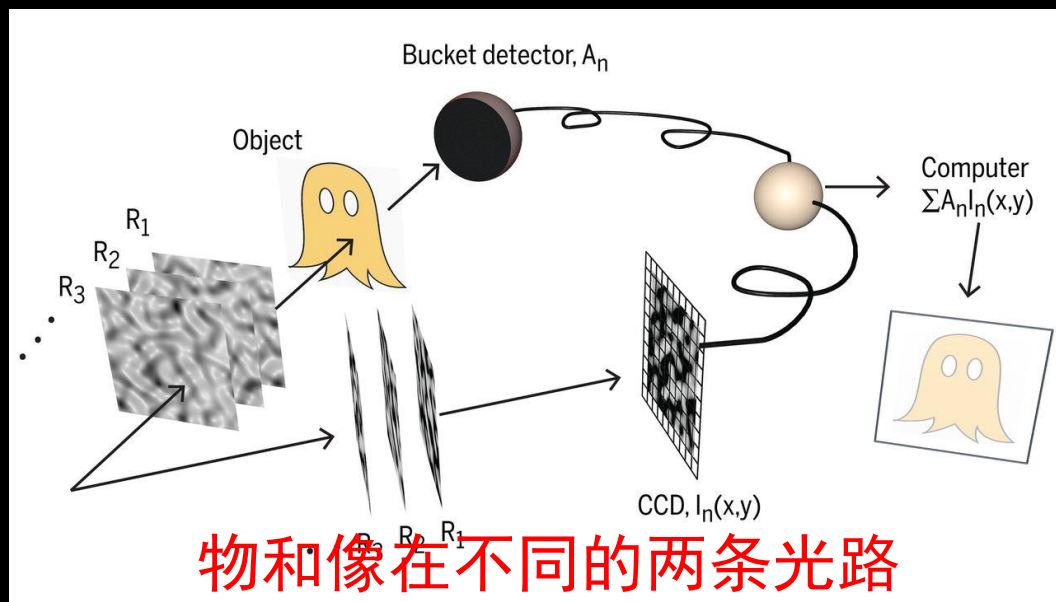
Single-photon Imaging

Non-line-of-sight Imaging

Imaging in Scattering Media

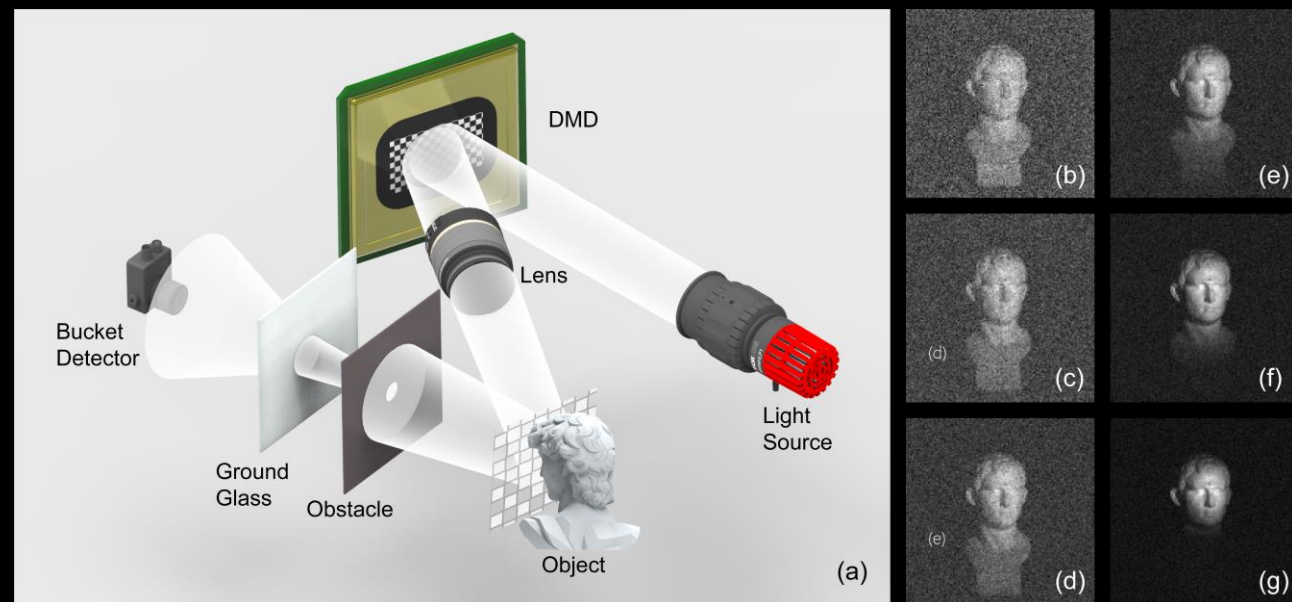
Super-resolution Imaging, e.g., SPADE

例1：关联成像、鬼成像、单像素成像



关联成像（或鬼成像）是由量子纠缠发展而来的高阶关联成像技术

Klyshko, Sov. Phys. Usp. 31, 74 (1988)
Pittman, Shih et al. PRA 52, R3429 (1995)



单像素成像（或计算鬼成像）基于结构光场调控与算法实现图像重构

Duarte et al. IEEE Sig. Proc. Mag. (2008)
Shapiro PRA 78, 061802 (2008)

例1：关联成像、鬼成像、单像素成像

nature
photonics

REVIEW ARTICLE

<https://doi.org/10.1038/s41566-018-0300-7>

Principles and prospects for single-pixel imaging

Matthew P. Edgar^{1,2}, Graham M. Gibson^{1,2} and Miles J. Padgett^{1,2*}

“单光子和单像素成像” 专题

激光与光电子学进展, 2021年58卷第10期

———— 韩申生、吴令安、尤立星携手组织 “单光子和单像素成像” 专题 ————

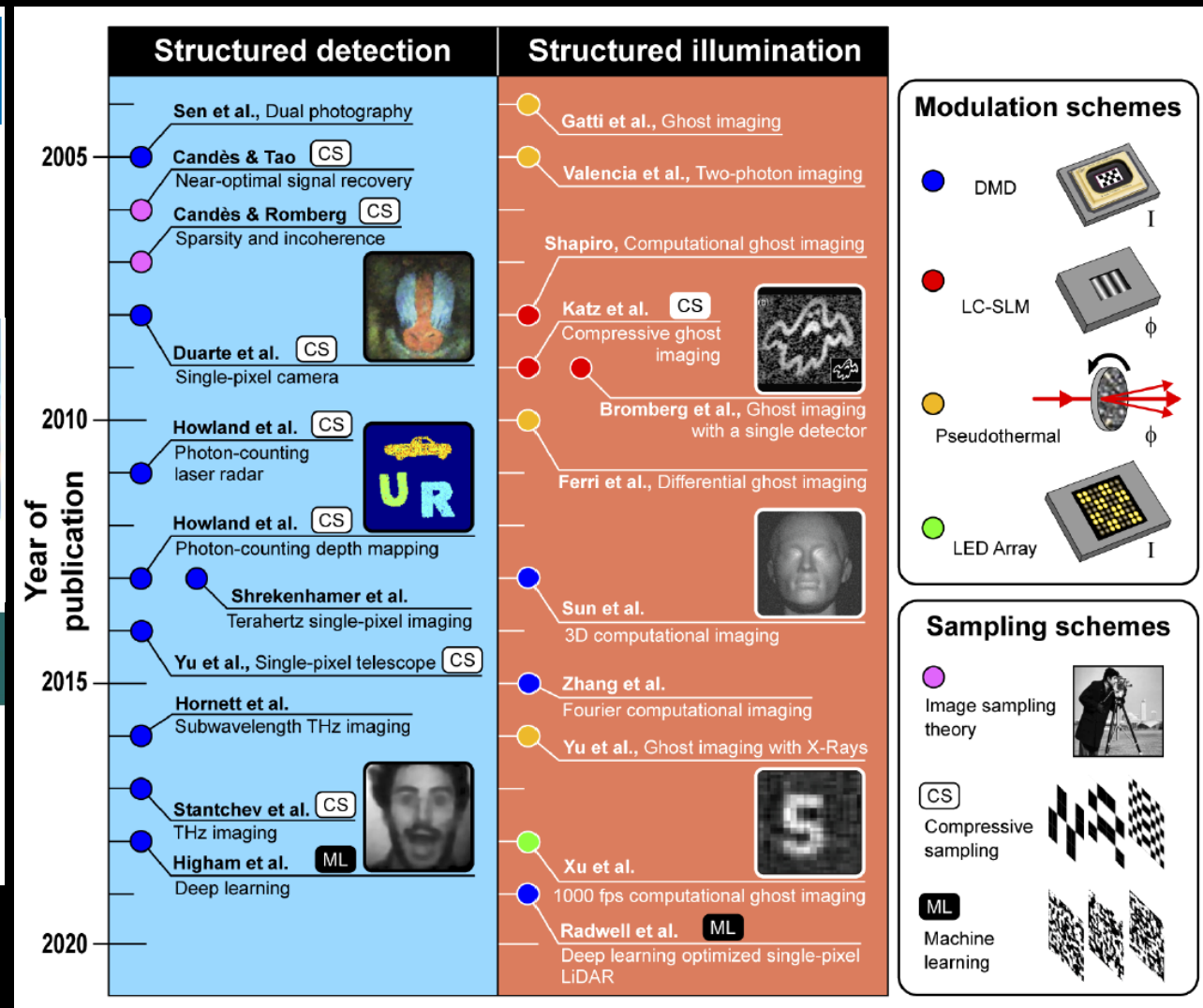
CHINESE OPTICS LETTERS

Vol. 22, No. 11 | November 2024

Ghost imaging, development, and recent advances [Invited]

Peiming Li (李珮明)^{1,†}, Xiaojin Chen (陈孝金)^{1,†}, Xiaodong Qiu (邱晓东)^{2,3,†}, Binglin Chen (陈炳霖)¹, Lixiang Chen (陈理想)^{2*}, and Baoqing Sun (孙宝清)^{1,4**}

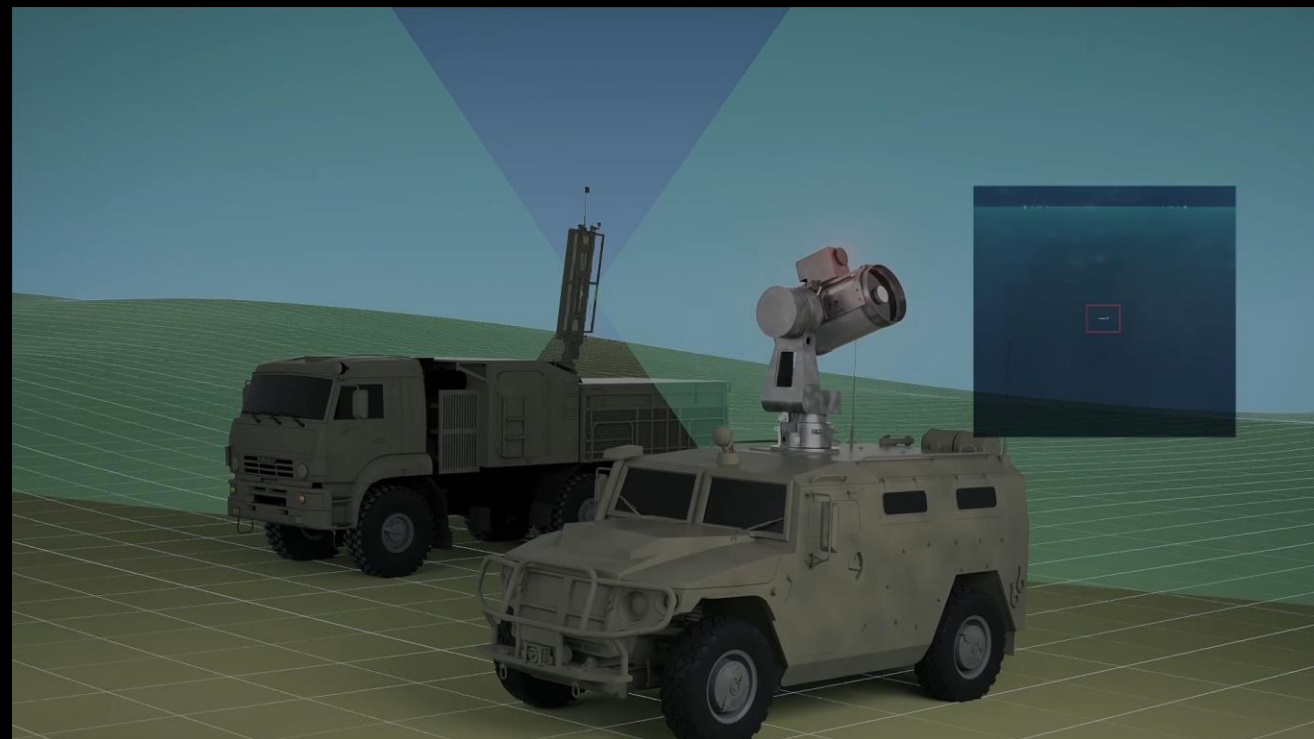
- 计算关联的方法用于其他领域
- 具有一定的实用化价值



单光子成像

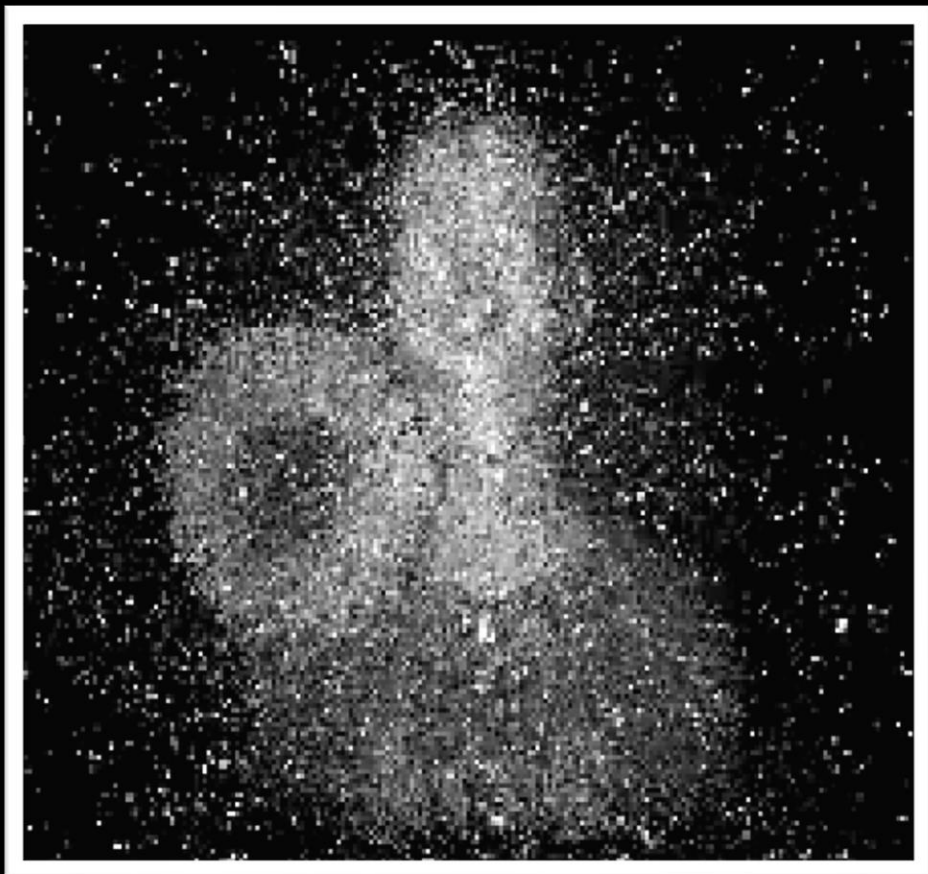
单光子成像

主动发射激光，接收端利用**单光子探测器件、光学设计、成像算法**，
提升激光雷达的灵敏度和距离

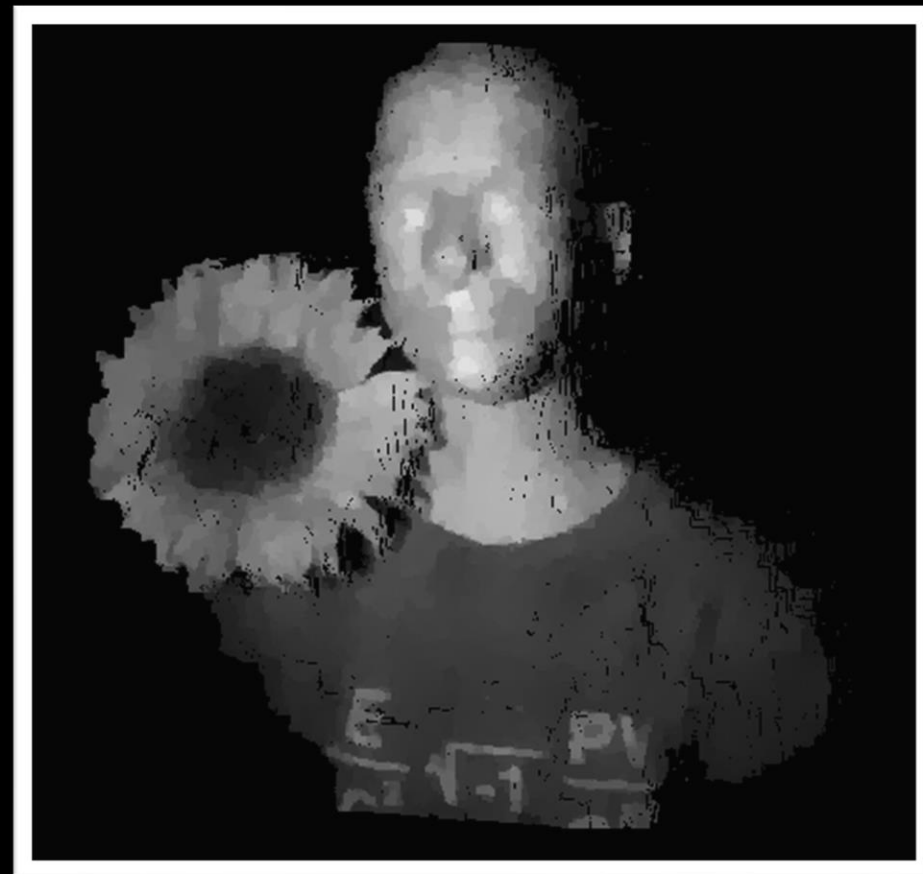


	激光雷达	单光子雷达
灵敏度	10^9 光子/像素	1光子/像素
探测距离	<10公里	>100公里
分辨率	$1.22\lambda/D$	突破光学口径

计算成像算法(1光子/像素)



传统算法



新算法

计算成像算法

Raw data (1 photon per pixel)

Step 0: calibration

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

- ✓ 单光子探测物理模型
- ✓ 时域滤波
- ✓ 压缩感知

Step 1: estimate scene reflectivity

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

$$\begin{array}{ll} \underset{\mathbf{A}}{\text{minimize}} & \left[\sum_{(i,j) \notin \mathcal{H}} \mathcal{L}(\mathbf{A}_{i,j}; \mathbf{C}_{i,j}, \mathbf{B}_{i,j}) \right] + \tau_A \text{pen}(\mathbf{A}) \\ \text{subject to} & \mathbf{A}_{i,j} \geq 0 \end{array}$$

$\uparrow$ data fidelity of photon counts $\uparrow$ spatial correlations of scene reflectivity

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

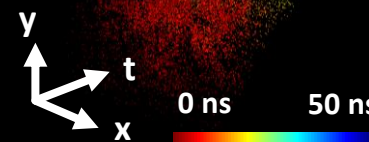
Step 3: estimate scene depth

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

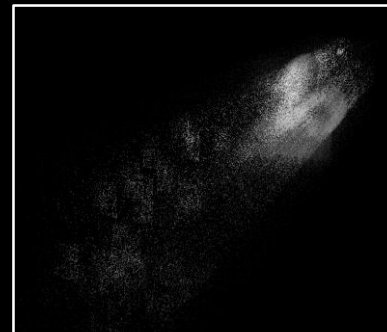
$$\begin{array}{ll} \underset{\mathbf{D}}{\text{minimize}} & \left[\sum_{(i,j) \notin \mathcal{H}} \sum_{T_{i,j} \in \mathbf{U}_{i,j}} \mathcal{L}(\mathbf{D}_{i,j}; T_{i,j}) \right] + \tau_D \text{pen}(\mathbf{D}) \\ \text{subject to} & \mathbf{D}_{i,j} \geq 0 \end{array}$$

$\uparrow$ data fidelity of filtered arrival times $\uparrow$ spatial correlations of scene depth

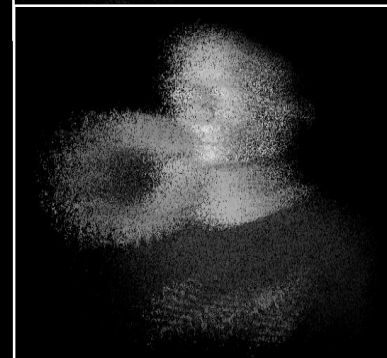
Nat Commun 7, 12046 (2016)



Step 1



Step 2

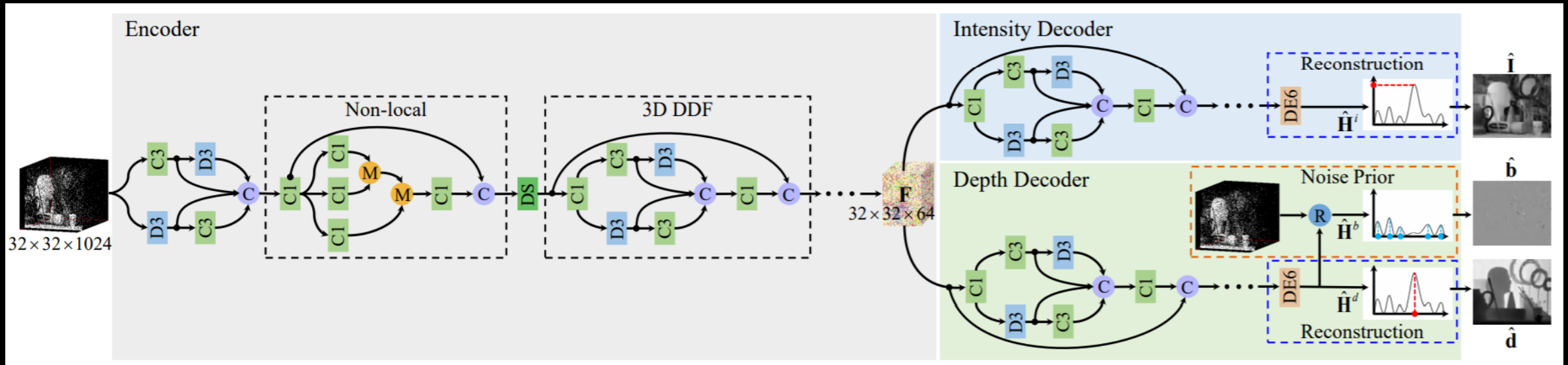
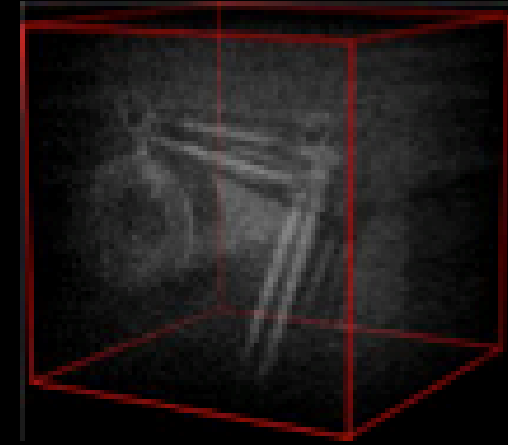


Step 3



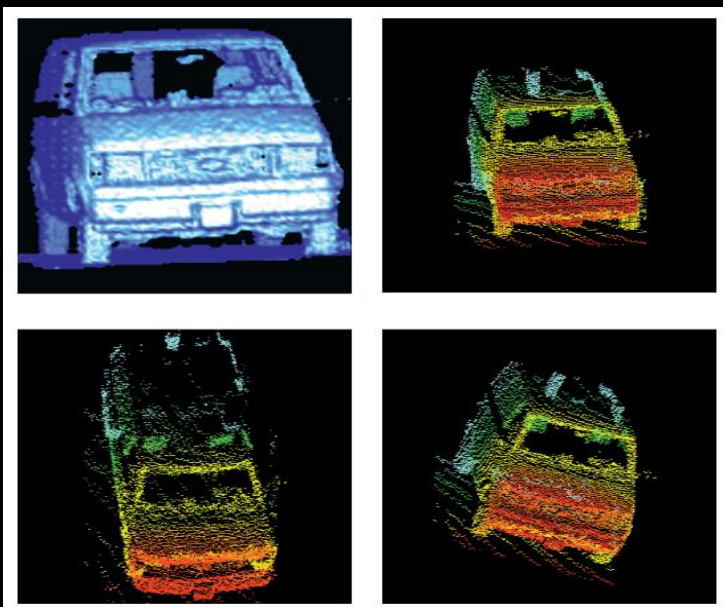
Deep-learning method

- Depth reconstruction -> Denoising
- 3D Dilated Dense Fusion (DDF)
- Speed: **0.1 second/frame**
- Sensitivity: < 1 photon/pixel

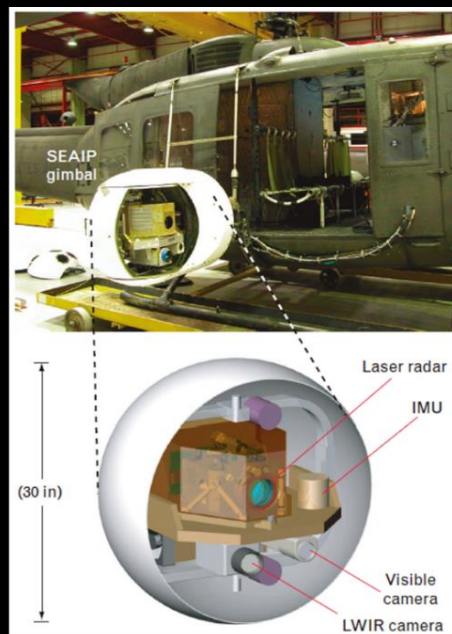


单光子成像实验进展

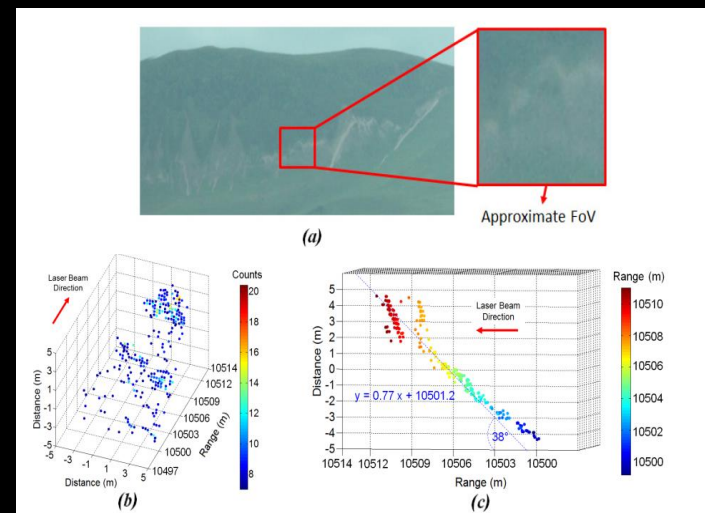
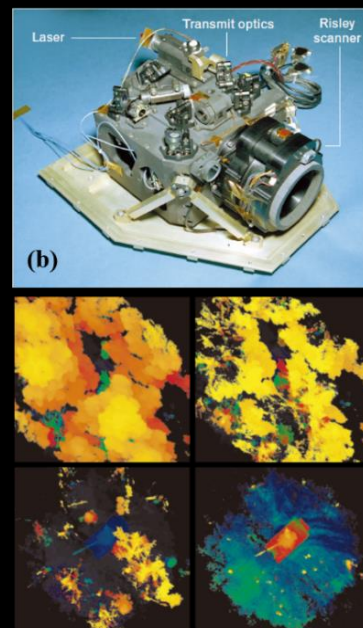
- 美国DARPA资助，麻省理工学院林肯实验室(MIT LL) 最早开始研究
- 英国、美国、意大利、中国等科研院所随后取得系列成果



MIT LL单光子探测激光雷达
(2000)

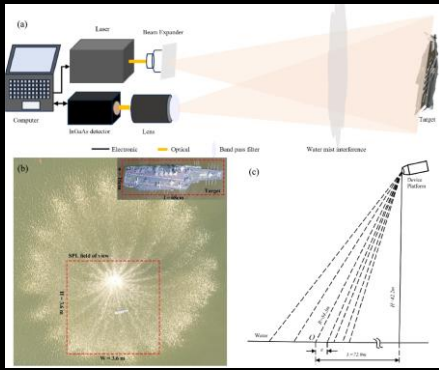


美国Jigsaw获取目标3D图像
(2007)

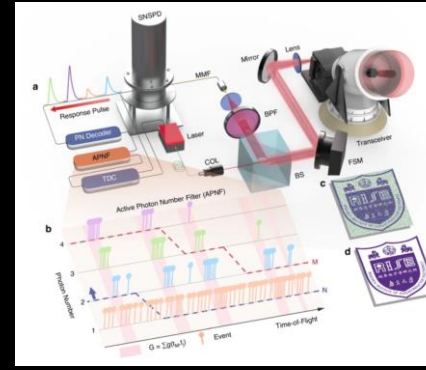


英国赫瑞瓦特大学10km成像
(2017)

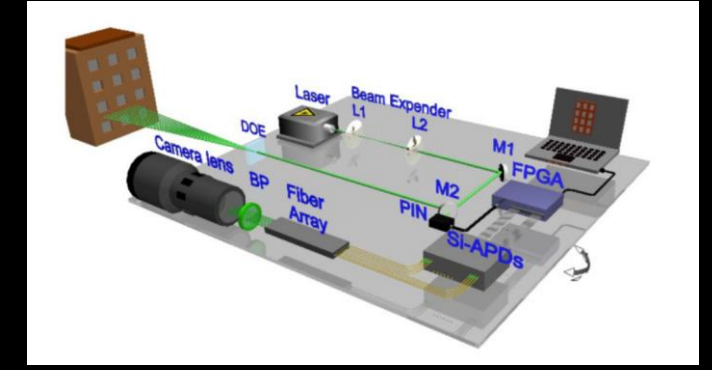
➤ 探测距离小于10公里



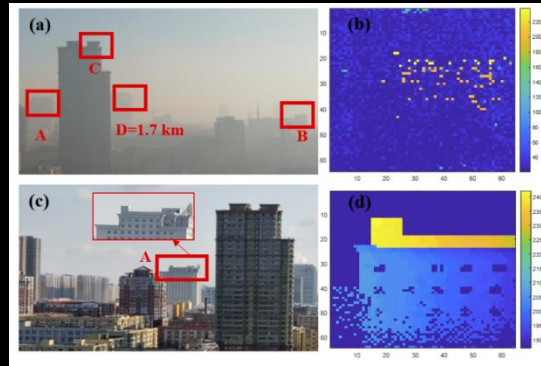
Liantuan Xiao@SXU
Light: Sci & App 14, 244 (2025)



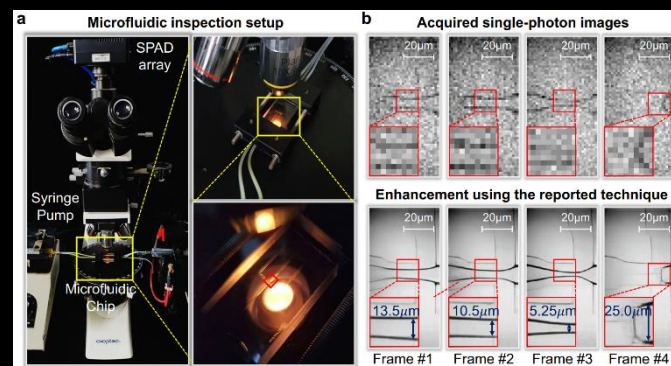
Weiji He, Qian Chen@NUST
Light: Sci & App 14, 138 (2025)



G. Wu, H. Zeng@ECNU
Optics Express 25, 10189 (2017)



Jianfeng Sun@HIT
Optics Express 30, 34497 (2022)



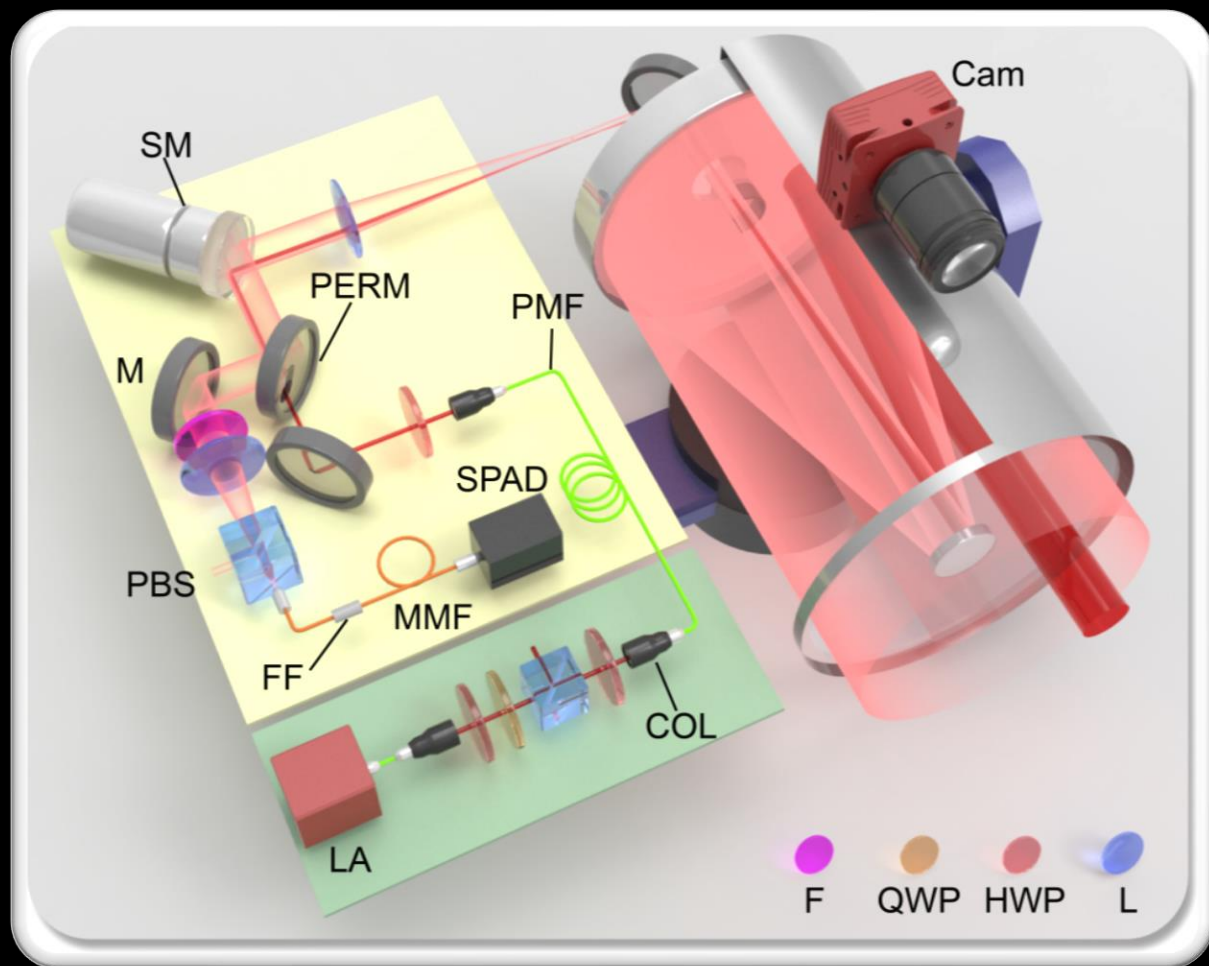
Liheng Bian, Jun Zhang@BIT
Nat. Commun. 14, 5902 (2023)



Labao Zhang@NJU
Supercond. Sci. Technol. (2021)

Chinese teams in USTC, SITP, HIT, ECNU, NJU, NUST, BIT, NUDT, SXU etc
International teams in MIT LL, Heriot-Watt, Stanford, BU, Toronto, EPFL, Milano etc

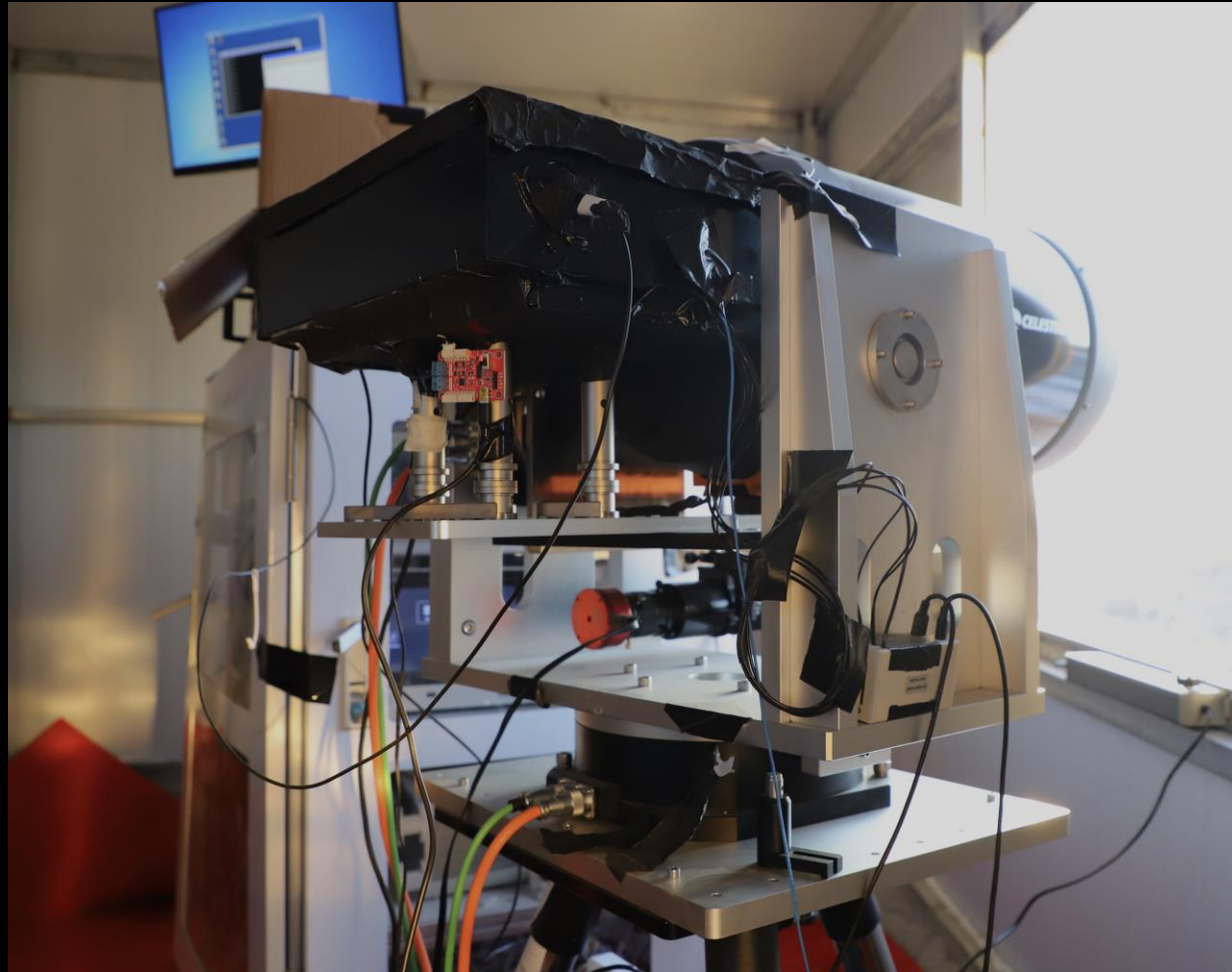
高效率、低噪声单光子成像系统



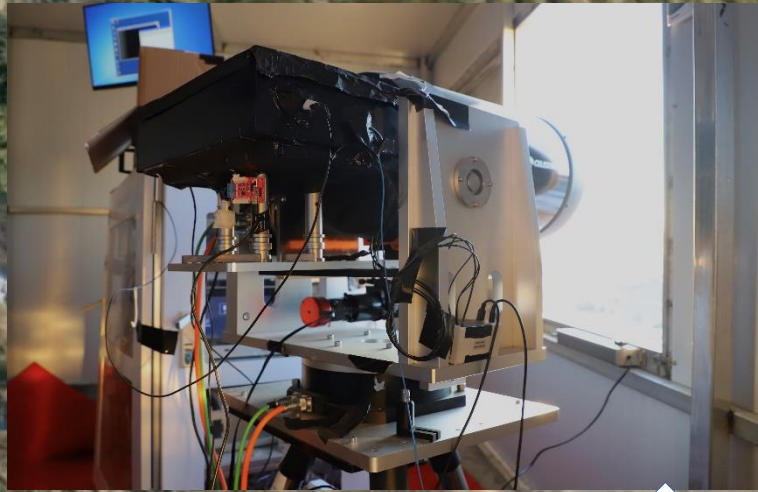
- 短波红外波段 (SWIR1550nm)
- 小型化InGaAs单光子探测器 (40%, 0.1KHz)
- 高耦合效率、光学镀膜
- 时域和偏振维度滤波抑制噪声 (x50倍信噪比提升)
- 集成化光学设计, 双轴扫描

单光子成像样机

@2019

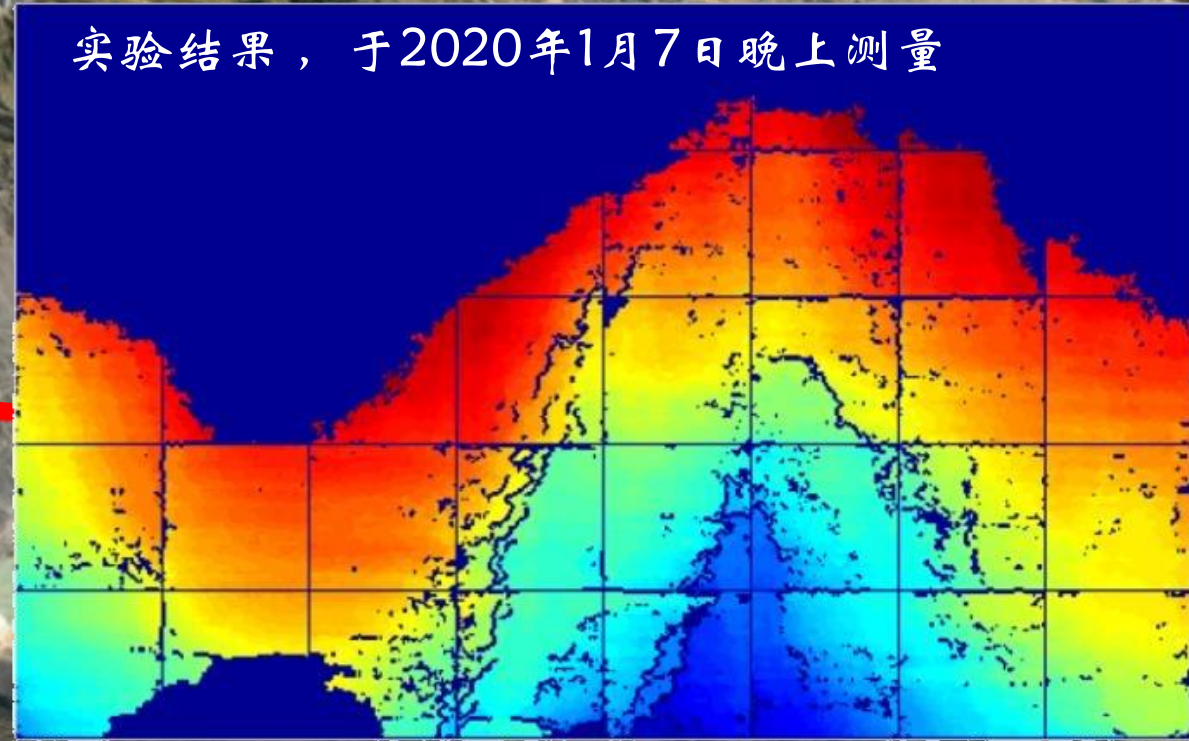


200km单光子成像实验



setup

实验结果，于2020年1月7日晚上测量



target



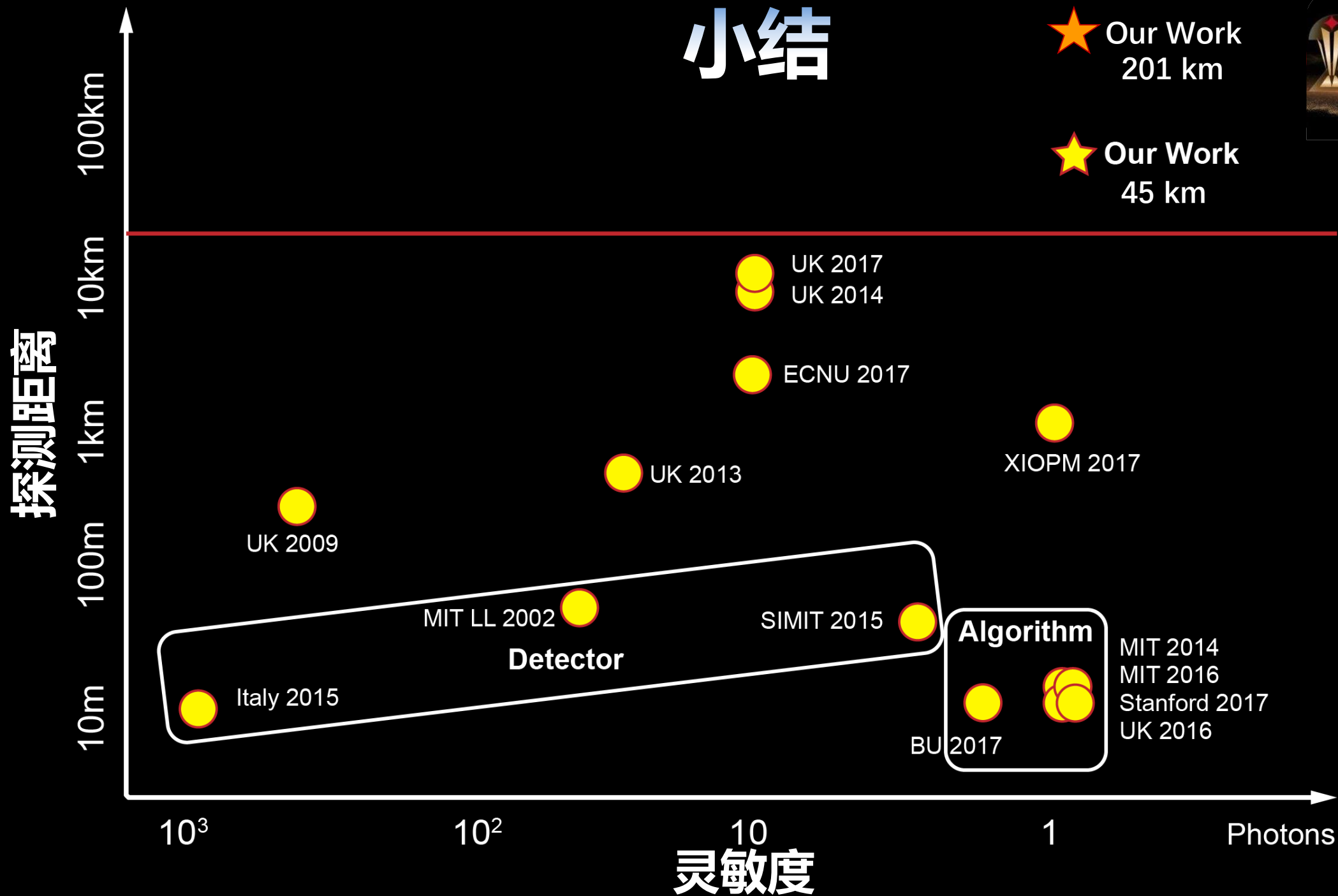
小结

★ Our Work
201 km

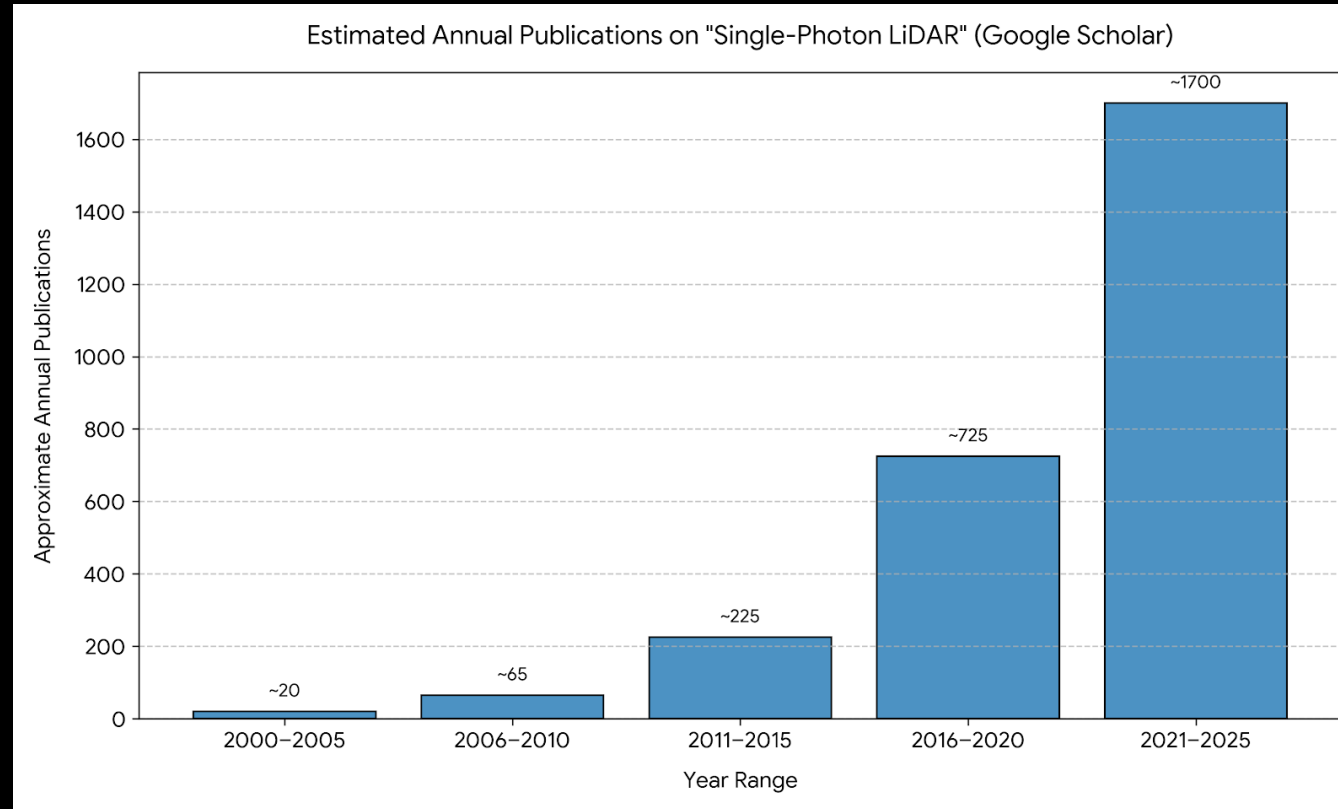
★ Our Work
45 km



Optics in
2020



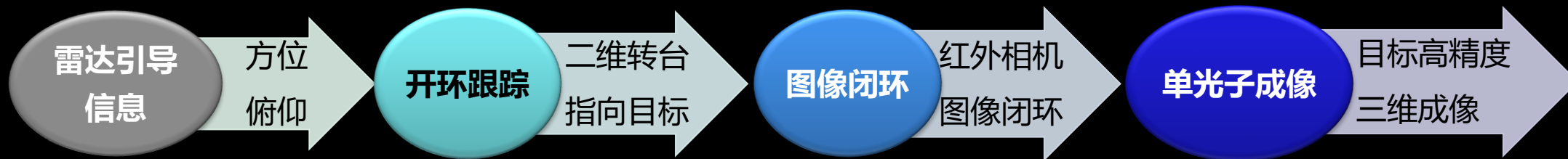
小结



Major Growth Drivers (by Gemini)

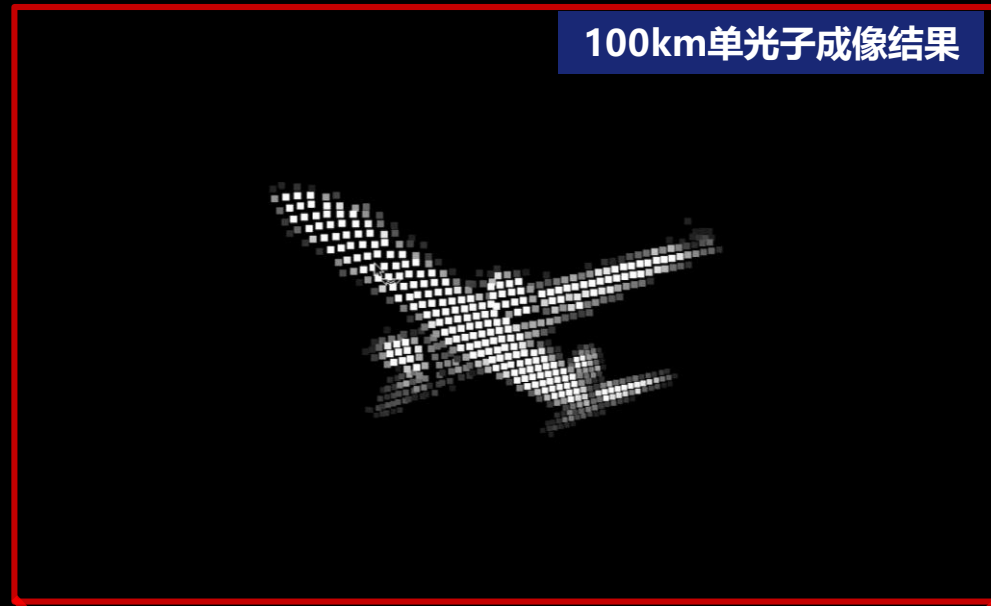
- 2014–2016: Breakthroughs in **photon-efficient computational algorithms** allowed 3D reconstruction using less than 1 photon per pixel on average.
- 2020–2025: Proliferation of SPAD arrays and solid-state single-photon sensors for **automotive** and **long-range remote sensing** research.

单光子-面阵-实时-成像系统



- 面阵实时成像
- 自动跟踪捕获
- 工程样机研制

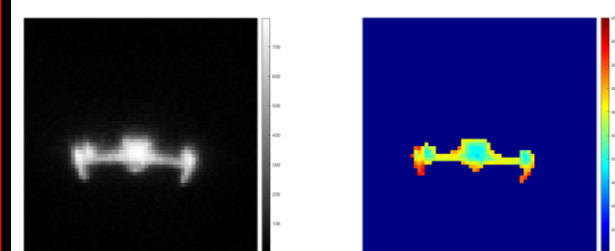
远距离民航飞机成像和识别



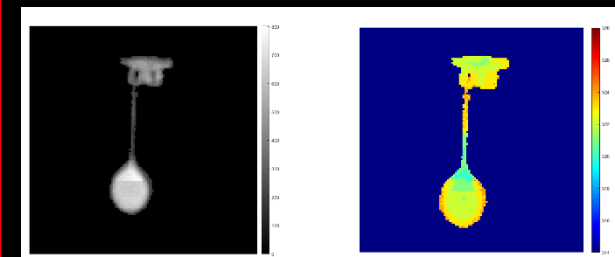
低慢小目标成像与识别



单光子成像结果



大疆 无人机



精灵4无人机+气球

7km范围内无人机成像结果

Track and image various UAVs in real time at 6.25 fps over distances >7 km

单光子雷达产品

2024年起以知识产权“授权”的形式，交由科大国盾量子山东公司进行成果转化

<https://www.quantum-sd.com>



小型化单光子雷达

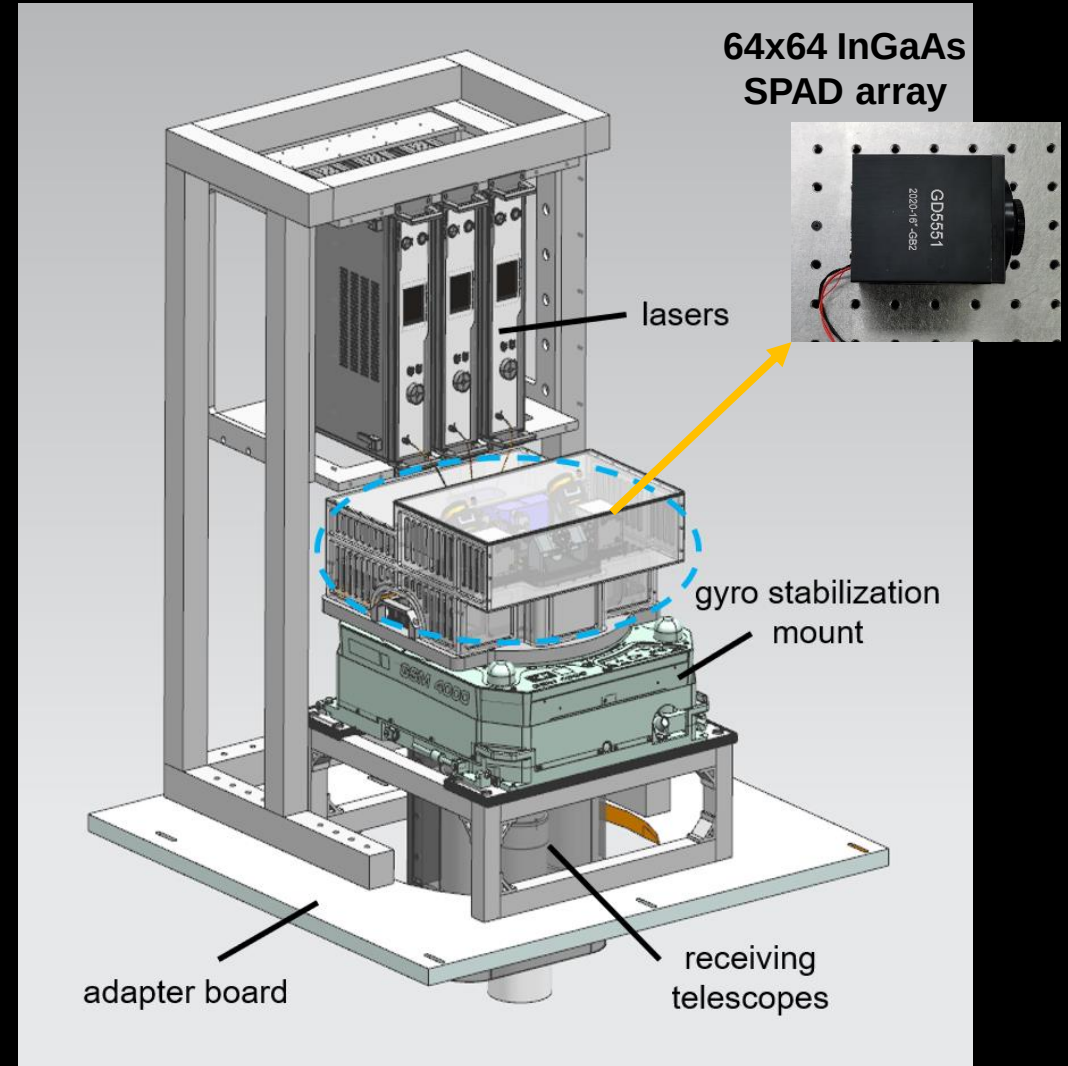
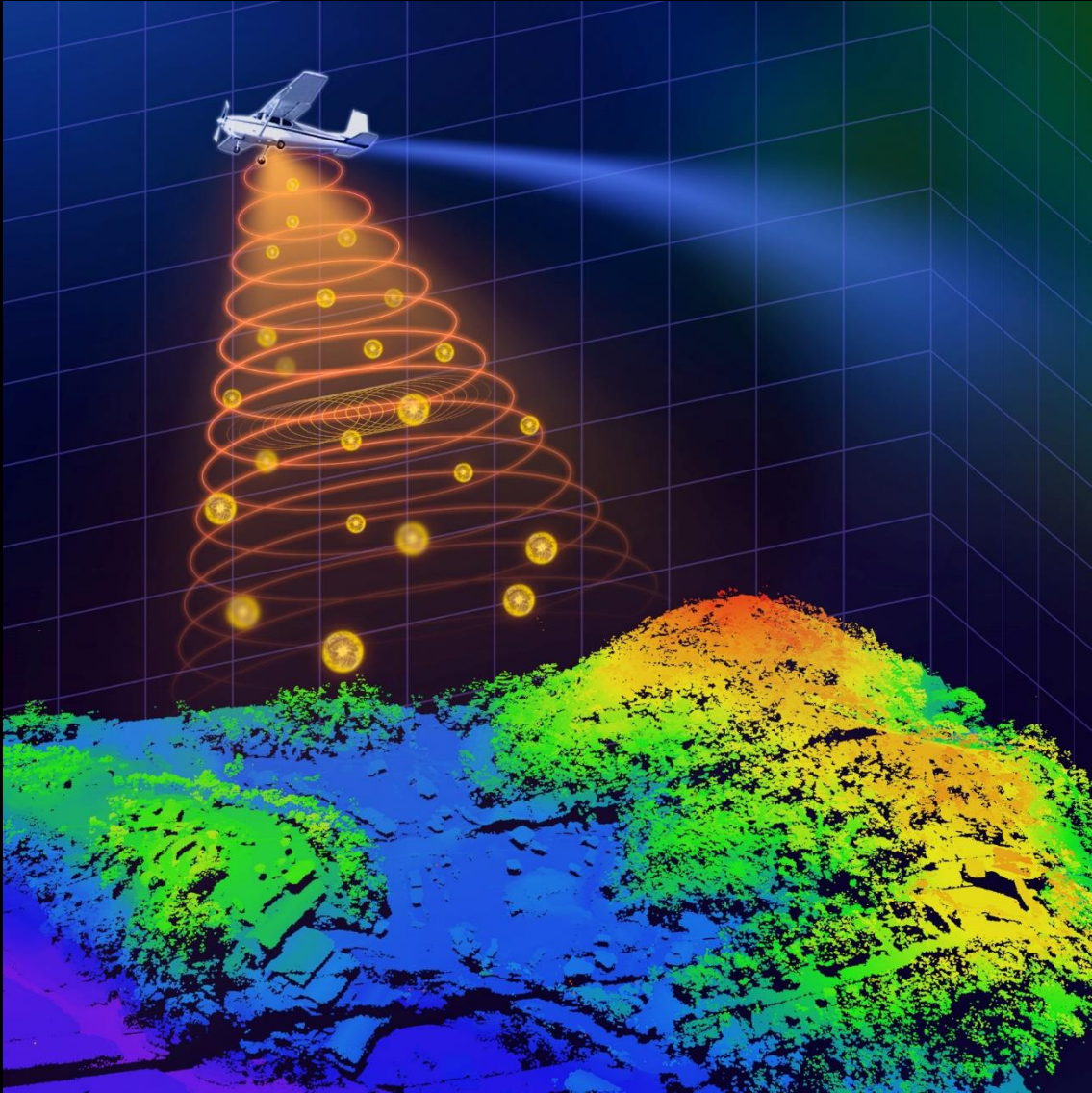


一代低空目标探测仪

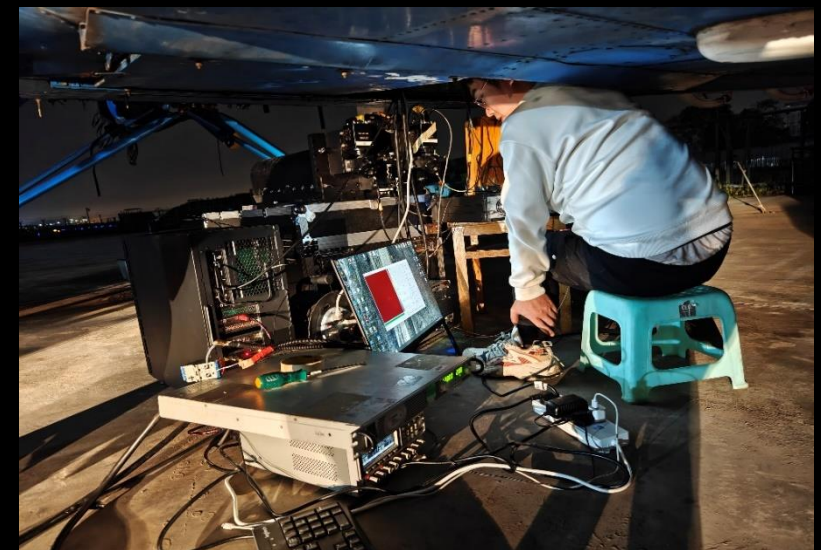


二代低空目标探测仪

Airborne single-photon LiDAR



Airborne single-photon LiDAR



Airborne single-photon LiDAR

Total imaging area: 250m x 10km

Lateral resolution: 16 cm

Depth resolution: 15 cm

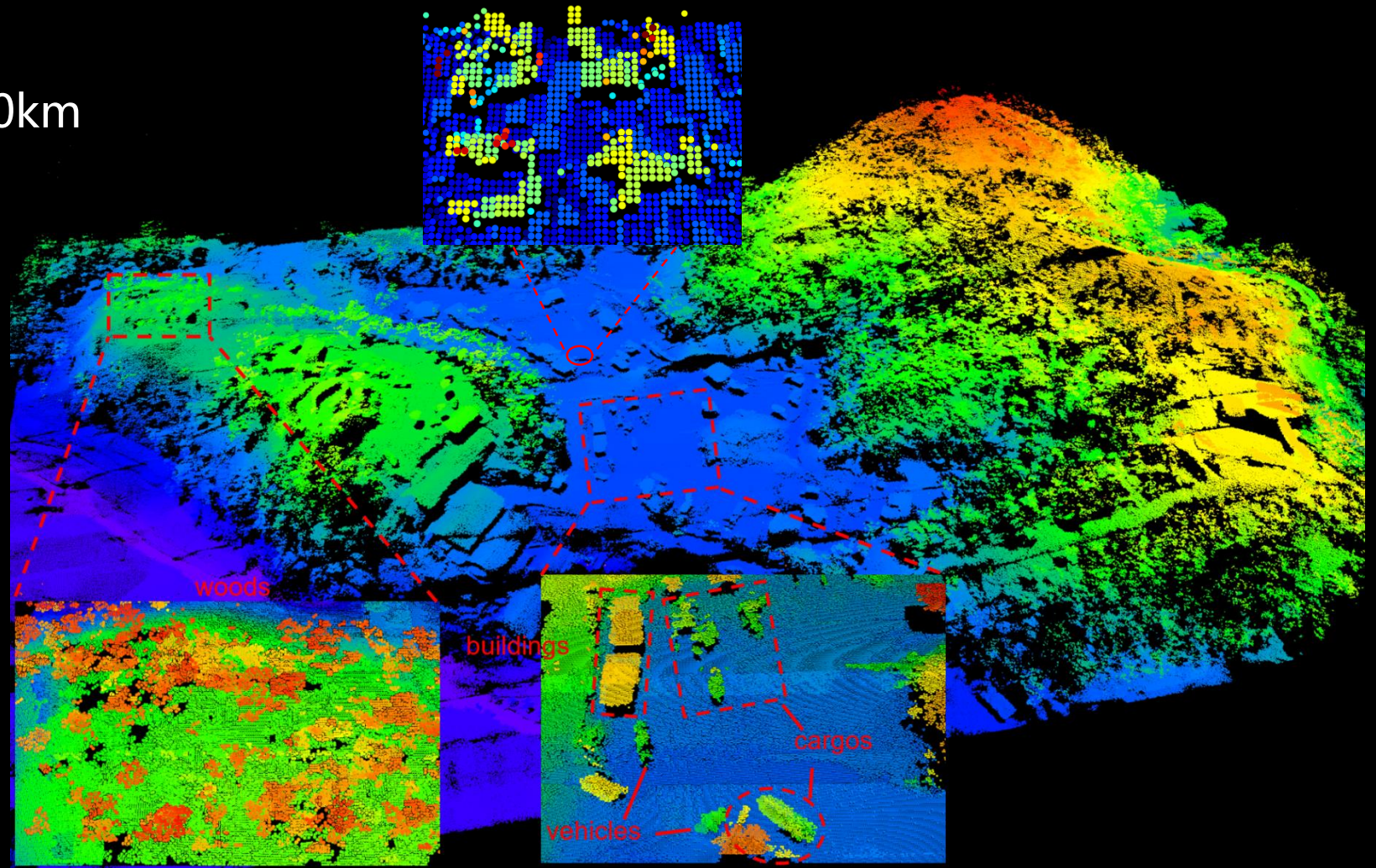
Speed: 50 m/s

Altitude : 2 km

Telescope: 47 mm

Resolution: ~32 urad

Sensitivity: 2 photons/pixel

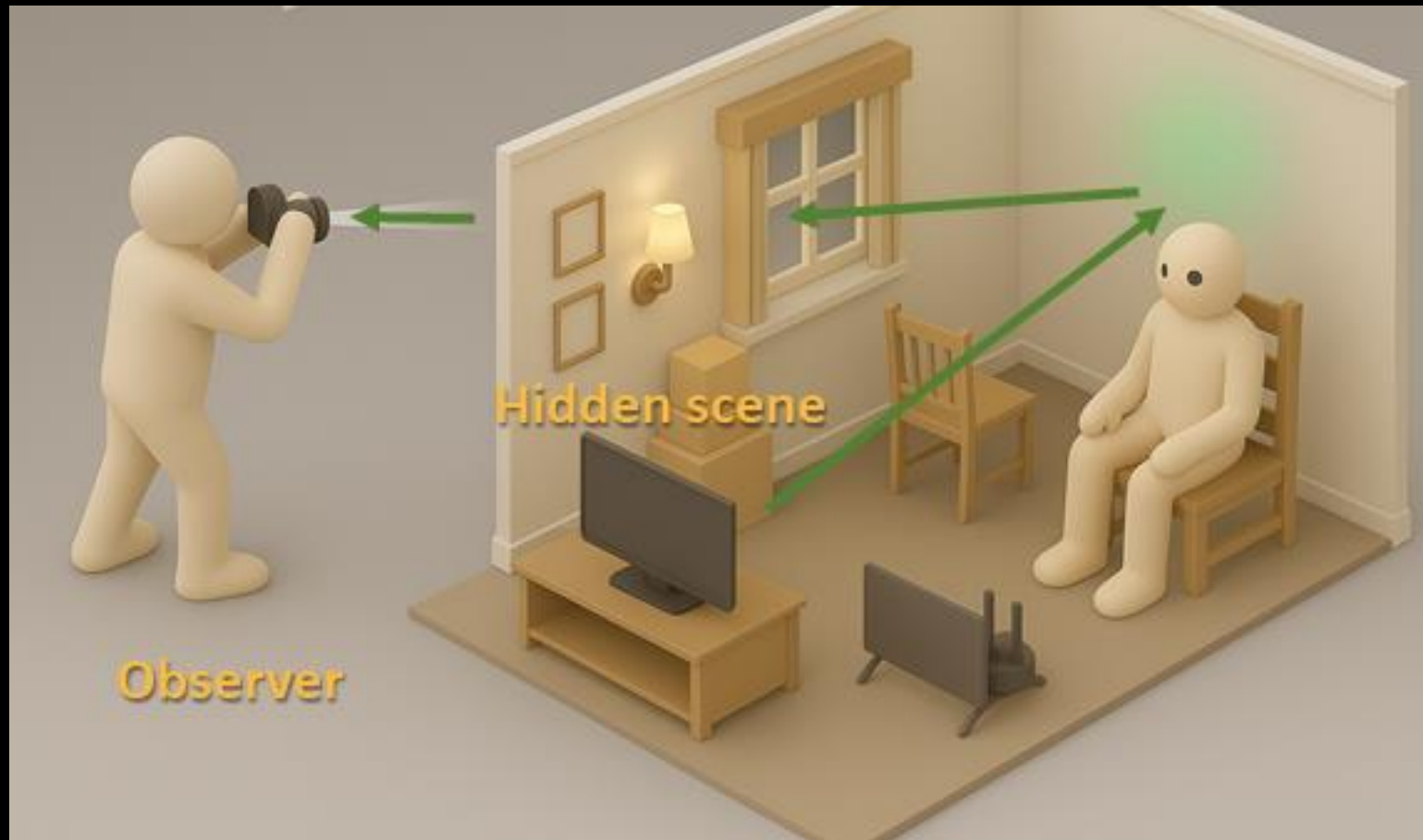


See also related works by MIT Lincoln Laboratory, SIOM etc.

Hong et al., Optica 11, 612 (2024)

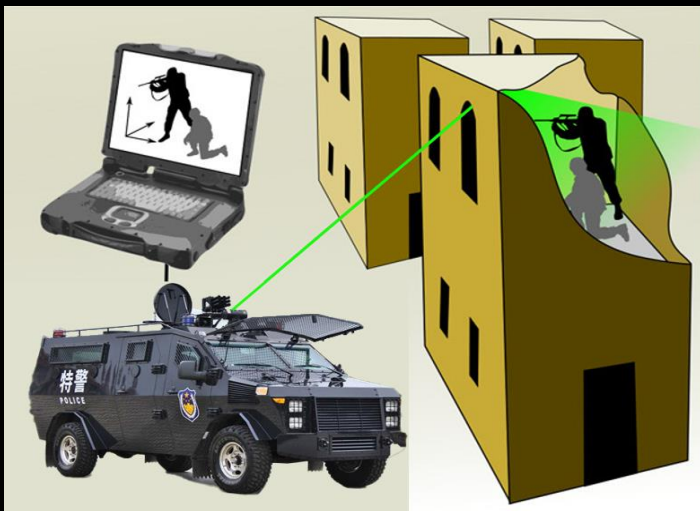
非视域成像

非视域（非视距、绕视、拐角）成像

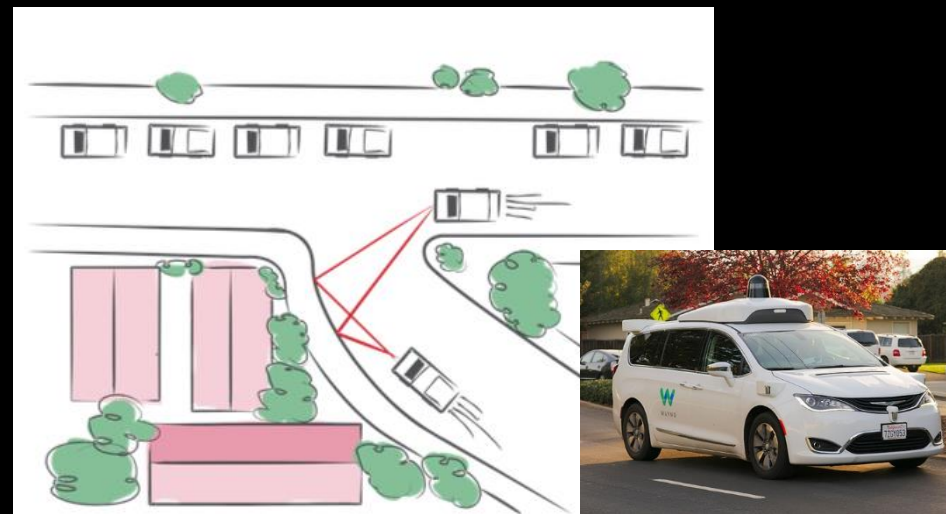


能否拍摄出肉眼看不到的场景？

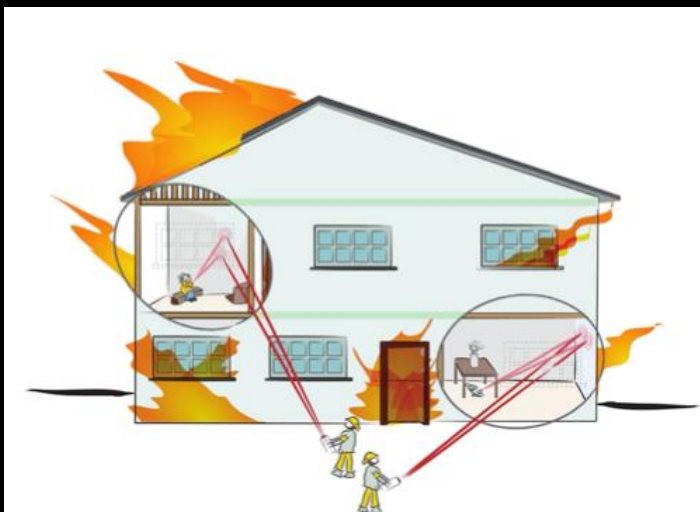
应用



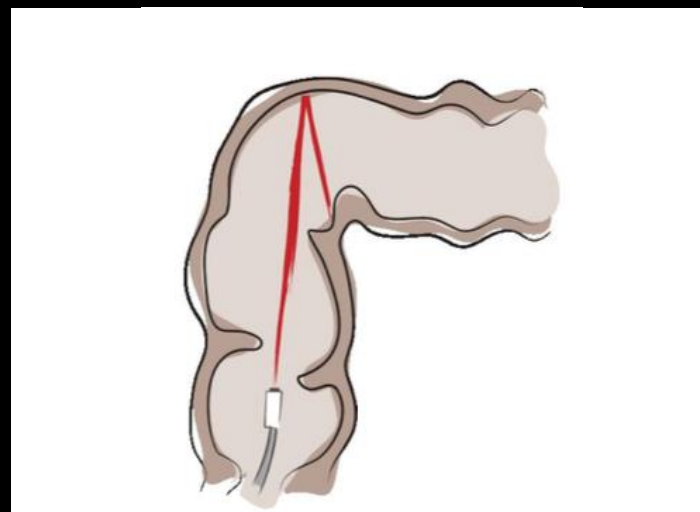
国防应用



自动驾驶



灾害救援



医学检测

非视域成像原理

墙面

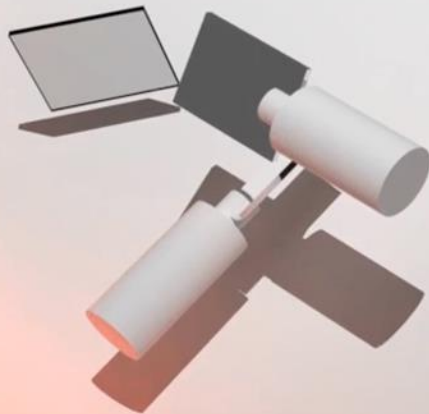
探测器



脉冲激
光器



扫描
振镜

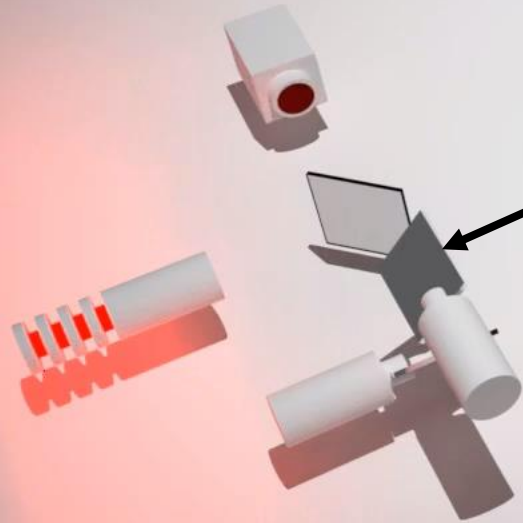


隐藏场景

04.800 ns

1st bounce: 2.7 ns

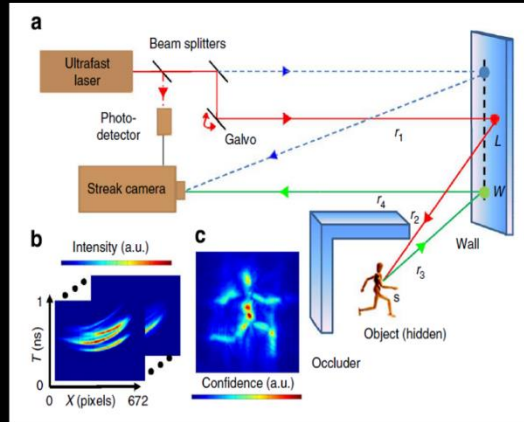
3rd bounce: 4.3 ns



40 cm (2.7 ns)

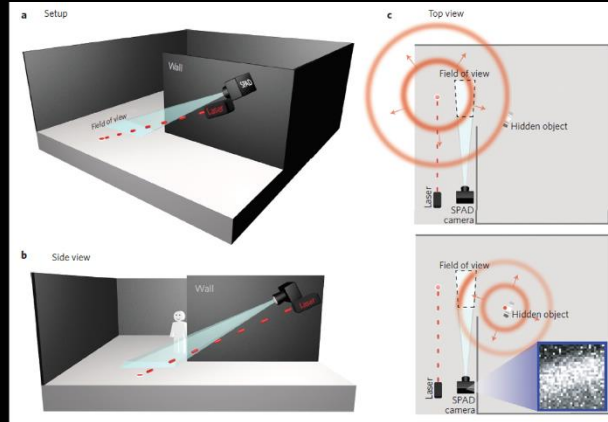
24 cm
(4.3 ns - 2.7 ns)

Some recent progress



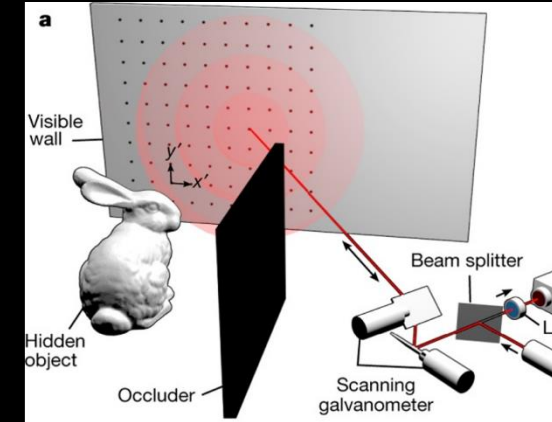
MIT

Velten et al. Nat. Commun. **3**, 745 (2012)
Raskar et al. Nature **653**, 693 (2026)



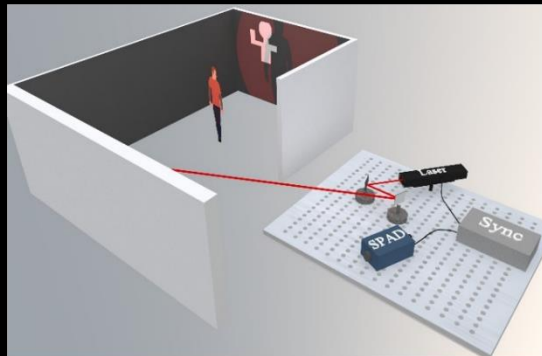
Glasgow

Gariepy et al. Nat. Photon. **10**, 23 (2016)



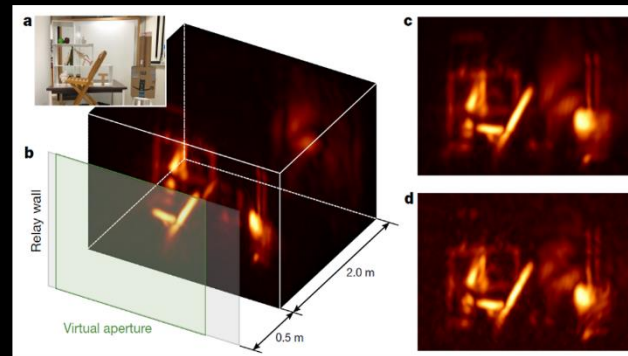
Stanford

O'Toole et al., Nature **555**, 338 (2018)



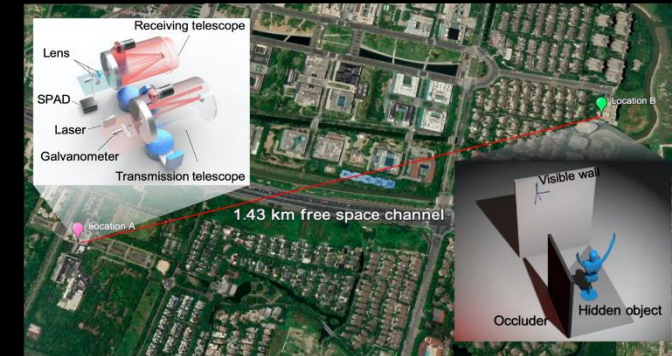
Boston

Sanders et al., Nature **565**, 472 (2019)



Wisconsin

Liu et al. Nature **572**, 620 (2019)

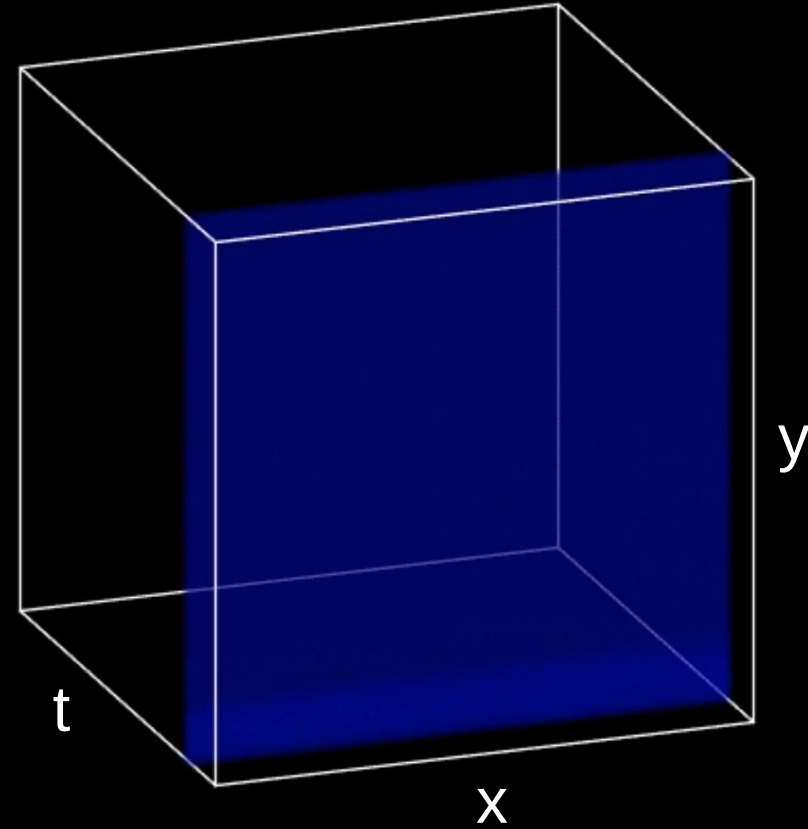
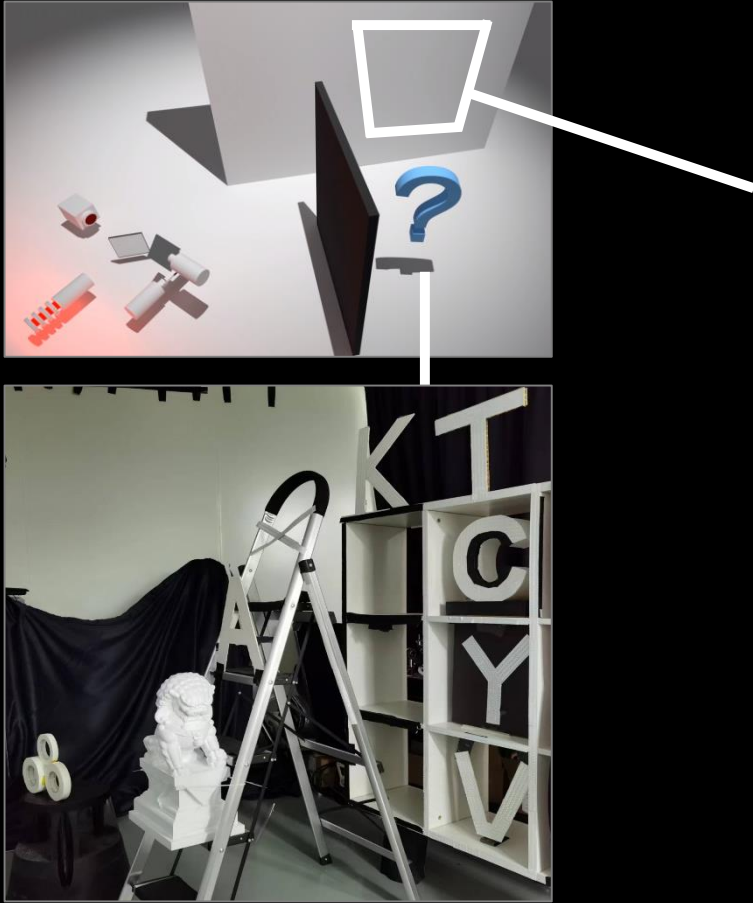


USTC

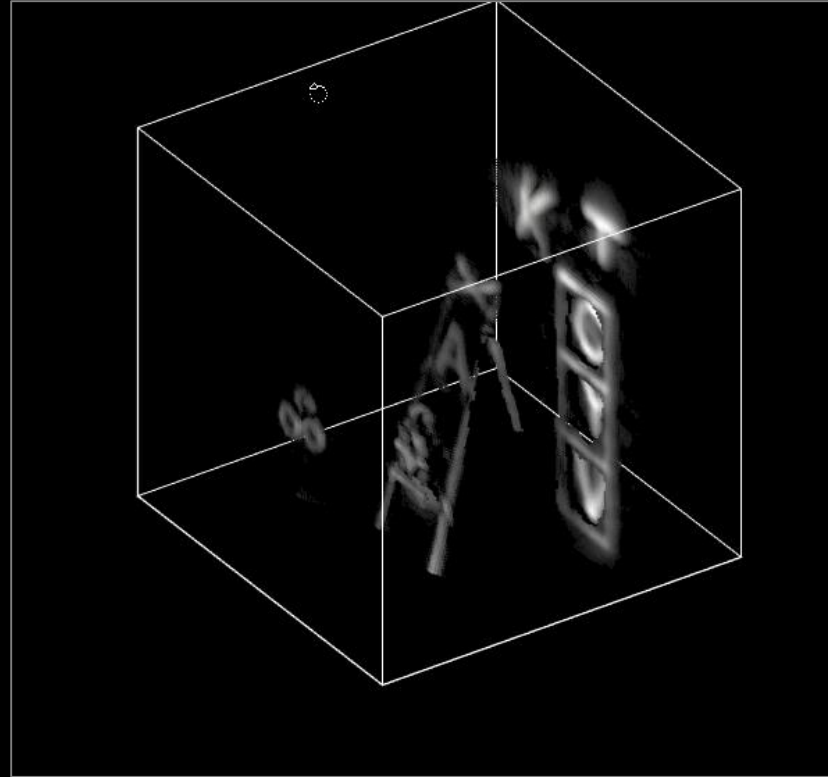
Wu et al., PNAS **118**, e2024468118 (2021)
Huang et al., PRL **132**, 233802 (2024)
Ye et al., Nat Comput Sci **4**, 920 (2024)

Chinese teams in USTC, Tsinghua, NUST, IOE-Chengdu, HIT, Tianjing, NUDT etc

Data for complex scene



Processing result



4帧/秒复杂场景实时成像

Ye et al., *Nature Computational Science* 4, 920 (2024)

公里级非视域成像实验

林语溪小区
(上海浦东康桥镇)

Location 2



1430 m free space channel

Location 1

中科大上海研究院
(上海浦东康桥镇)



隐藏场景



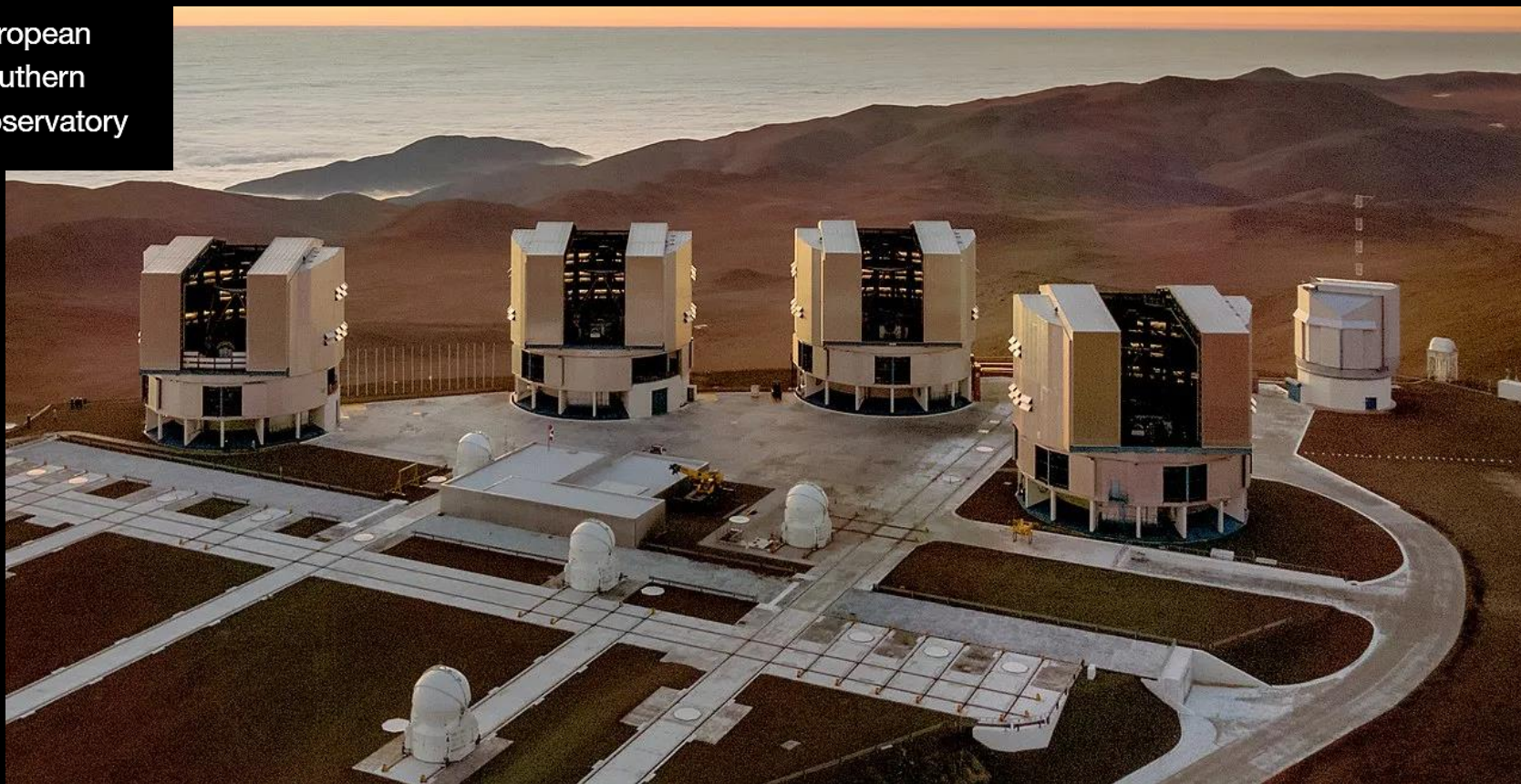
光学合成孔径

光学合成孔径干涉阵列

VLTI (Very Large Telescope Interferometer)



European
Southern
Observatory



智利阿塔卡马沙漠

4个8.2m主望远镜

4个1.8m可移动望远镜

最长基线: 130m

最高分辨率: 2mas

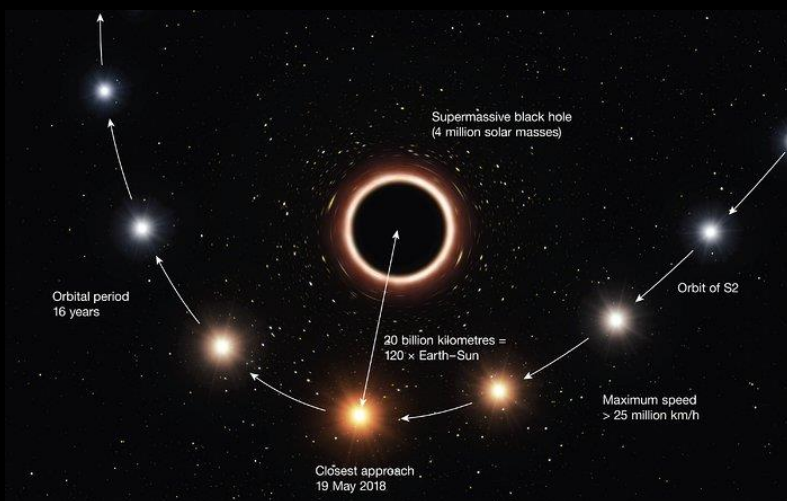
探测波段: 1.5-13 μ m

关键科学问题:

- 恒星物理与演化
- 活动星系核与黑洞
- 系外行星与行星系统

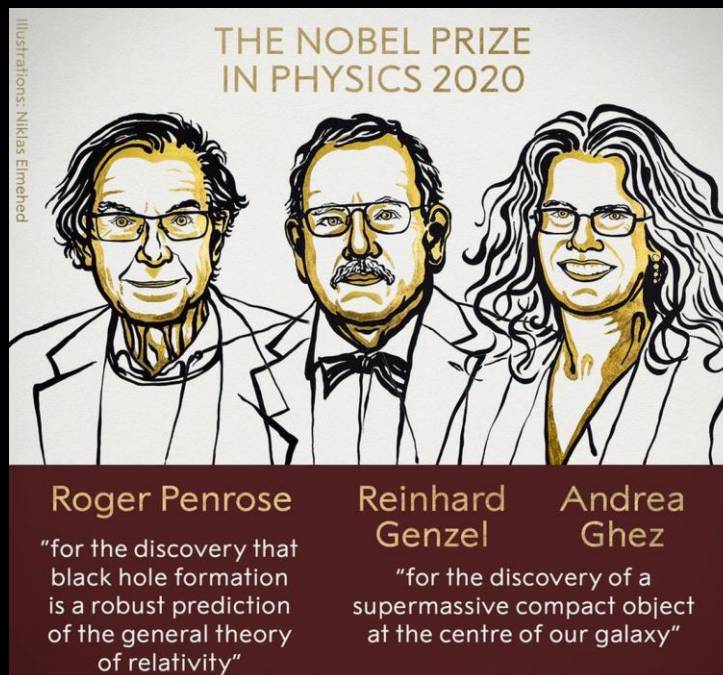
光学合成孔径干涉阵列

VLTI (Very Large Telescope Interferometer)



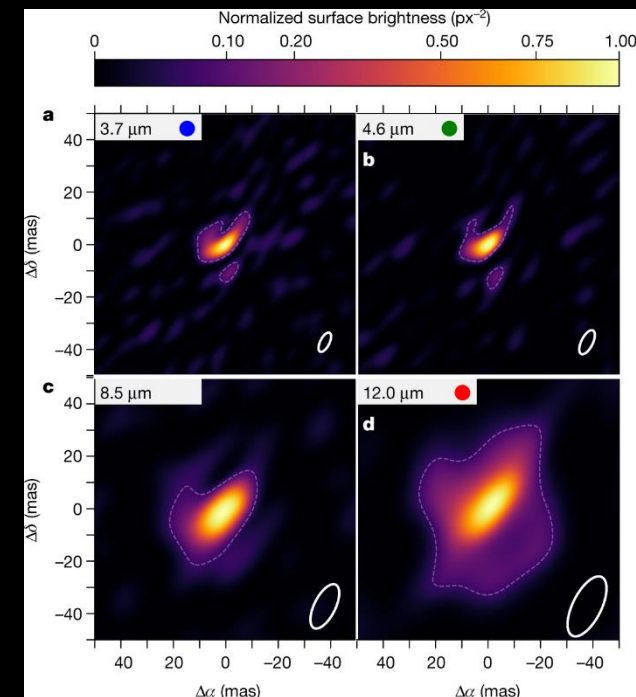
- 首次观测到银河系中心恒星S2的引力红移，验证了广义相对论

A & A L15, 615 (2018)



- 2020诺奖：利用合成孔径干涉成像技术“发现银河系中心超大质量天体”

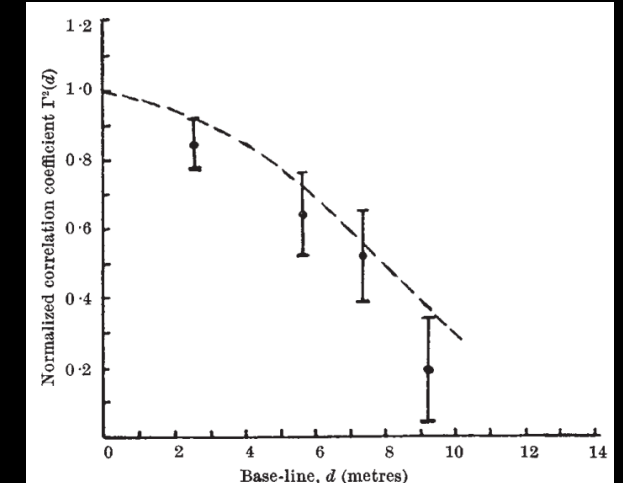
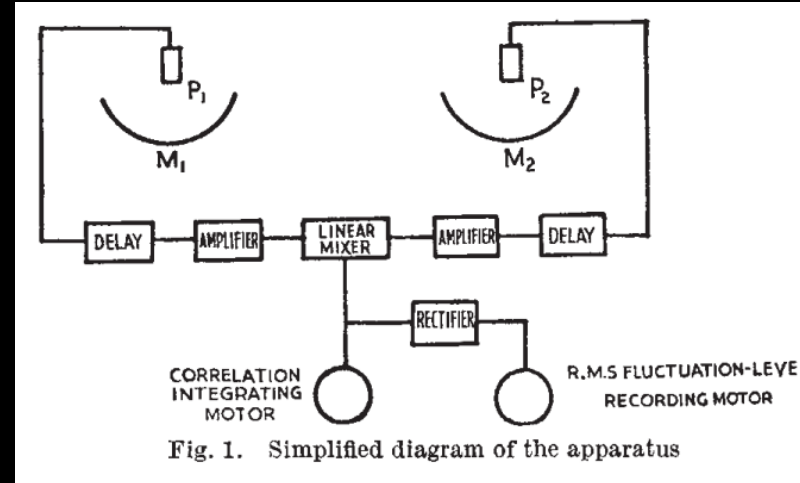
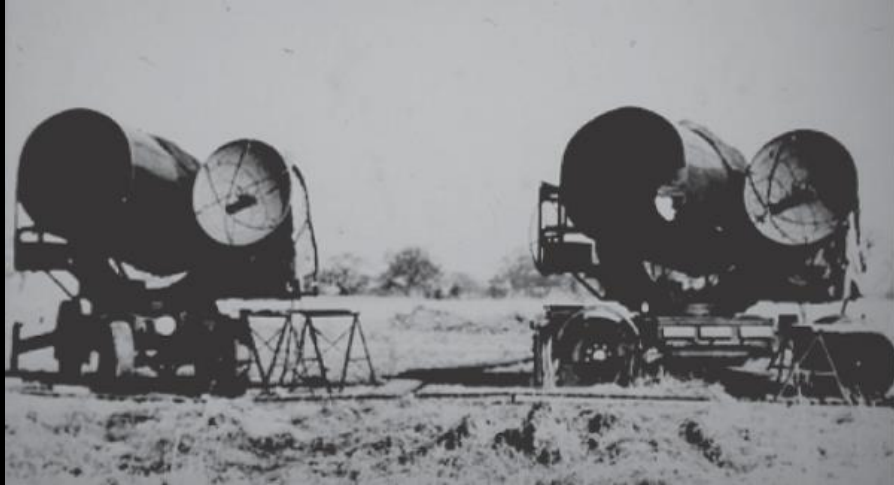
A & A L11, 623 (2019)



- 对活动星系核中心区域的尘埃分布的详细观测

Nature 403, 602 (2022)

强度干涉合成孔径成像



- In 1956, Hanbury-Brown-Twiss (HBT) used two reflectors to measure the angular diameter of Sirius.

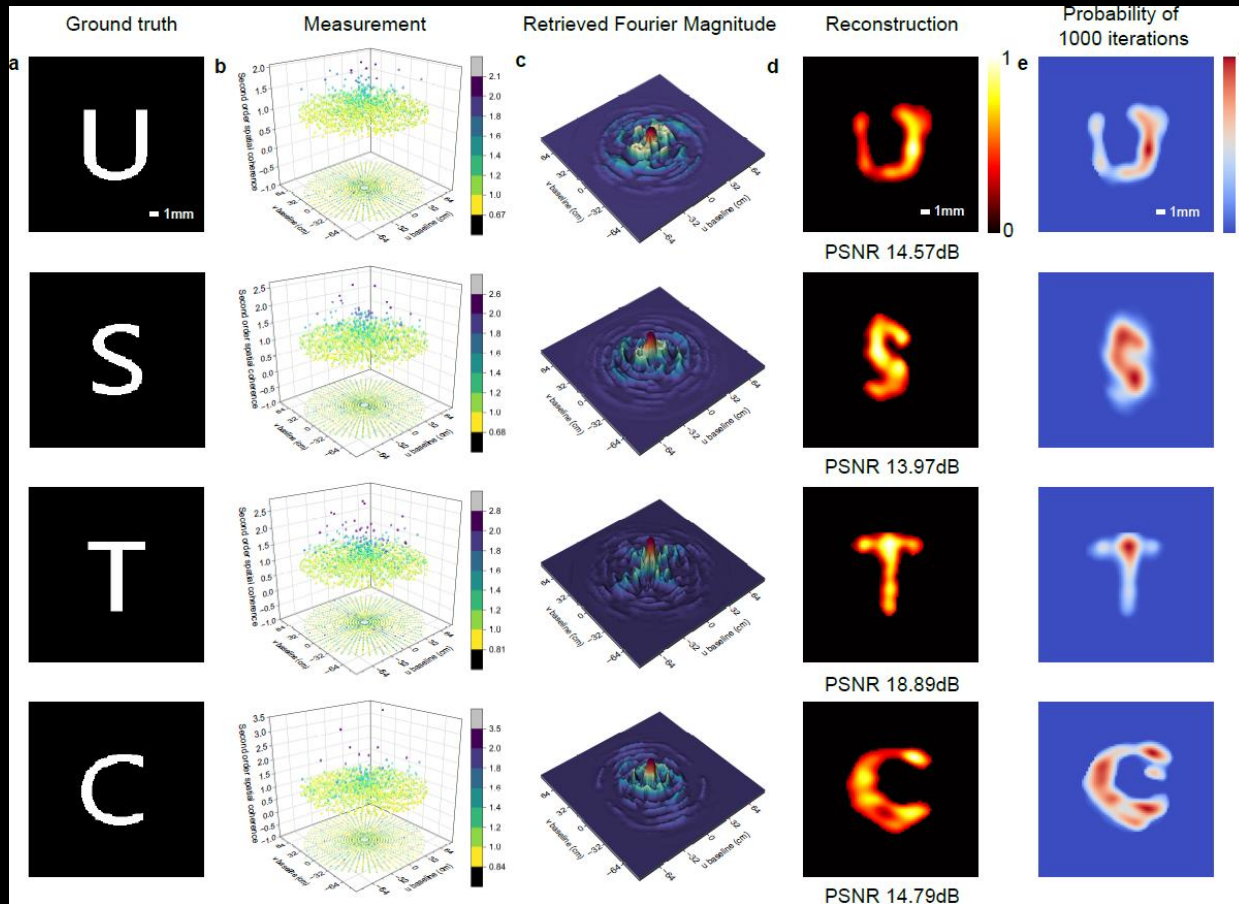
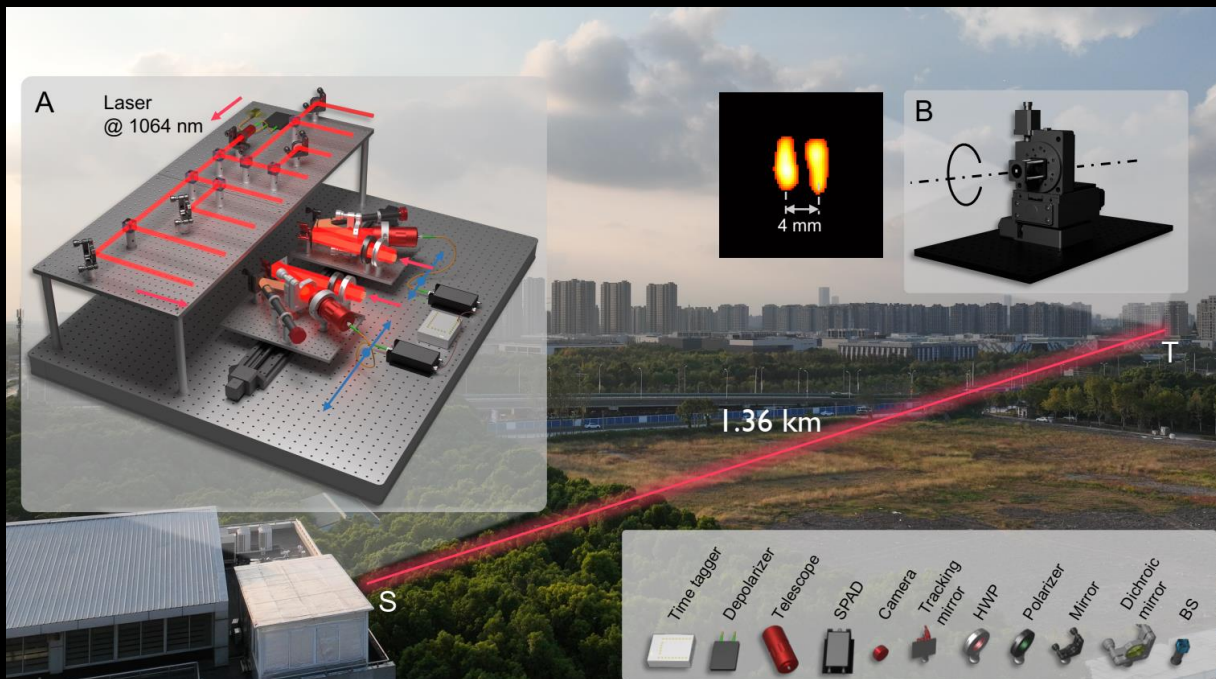
Second-order correlation function

$$g^{(2)} = \frac{\langle I(r_a, t) I(r_b, t + \tau) \rangle}{\langle I(r_a, t) \rangle \langle I(r_b, t) \rangle} = 1 + \underline{|g^{(1)}(r_a, r_b, t)|^2}$$

Nature 178, 1046 (1956)

- ✓ Independent optical measurements → without optical phase control
- ✓ Easily expandable baseline → Higher angular resolution
- ✓ Insensitive to atmospheric turbulence and optical imperfections
- × SNR lower than amplitude interferometer

主动强度干涉合成孔径成像



成像分辨率 < 3 mm @ 1.36 km, 超越单个子口径衍射极限 14 倍

未来展望

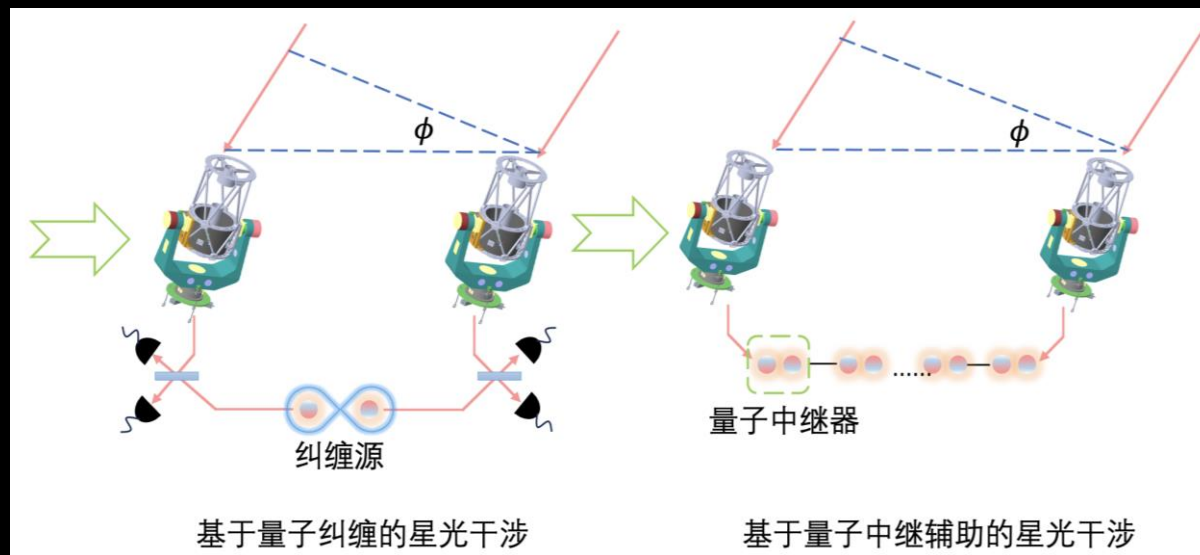
量子成像+天文观测

- 光学合成孔径技术路线已接近极限：百米级的真空管与高精度光学延迟线
- ✓ **量子隐形传态**可以不直接传光量子本身，大幅提升“一阶干涉”光学合成孔径望远镜的基线长度 [E. Gibney, Nature 535, 478 (2016)]
- ✓ 基于**强度干涉**的“二阶干涉”光学合成孔径技术[PRL 134, 180201 (2026)]

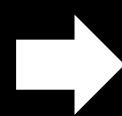
VLT装置图



2020年诺奖：利用大口径望远镜的合成孔径干涉成像技术“发现银河系中心超大质量天体”



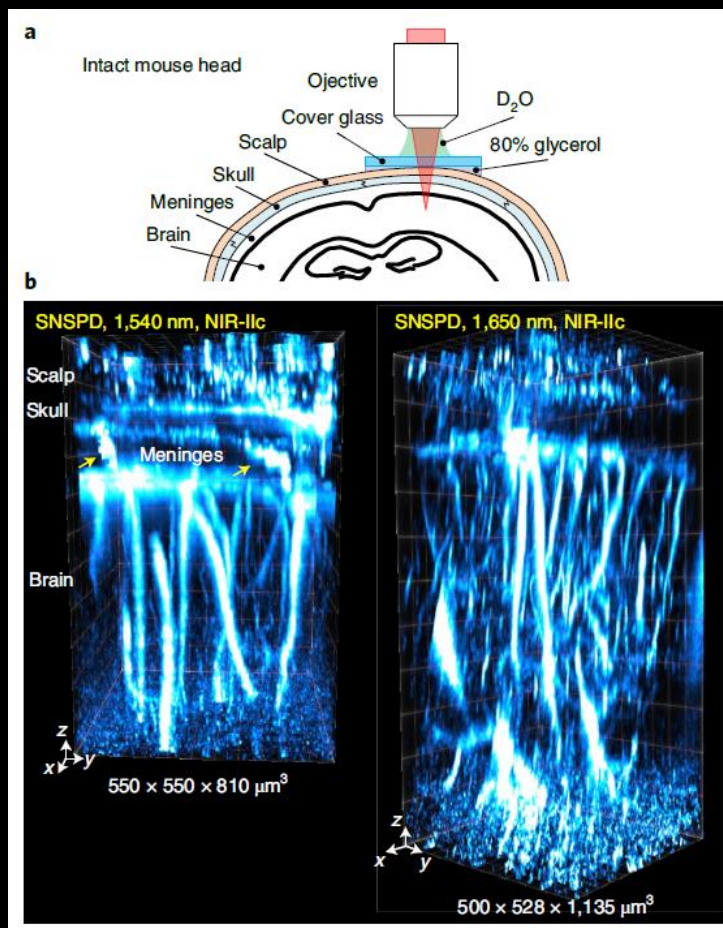
基线长度: 100 m
角分辨率: 10 nrad



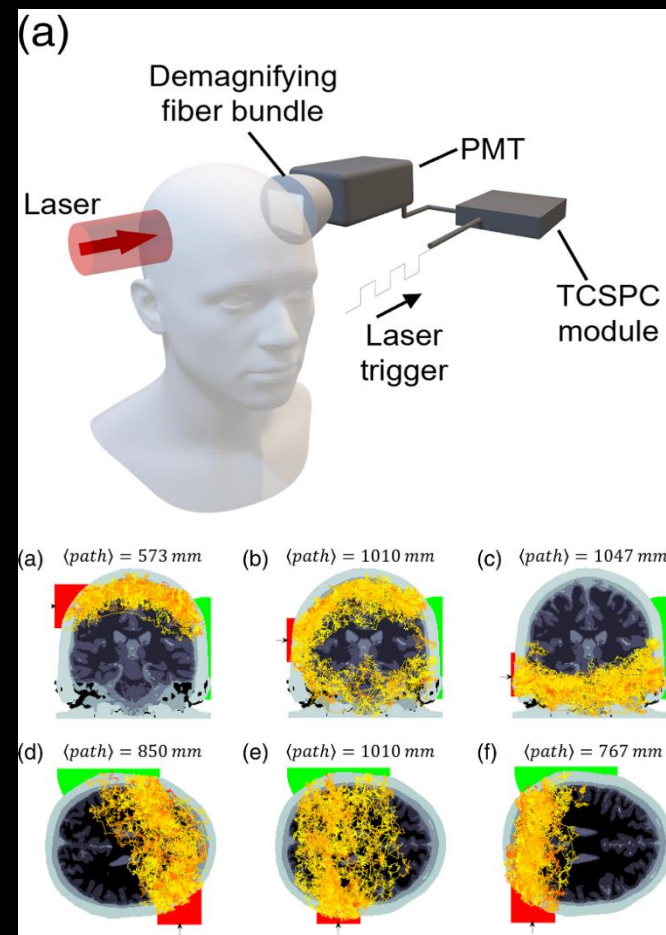
基线长度: 1 km – 1000 km
角分辨率: nrad – 0.1 prad

单光子成像+生物医学、人体健康

生物医学成像：近红外II区更深的穿透，应用于肿瘤诊断、神经科学等



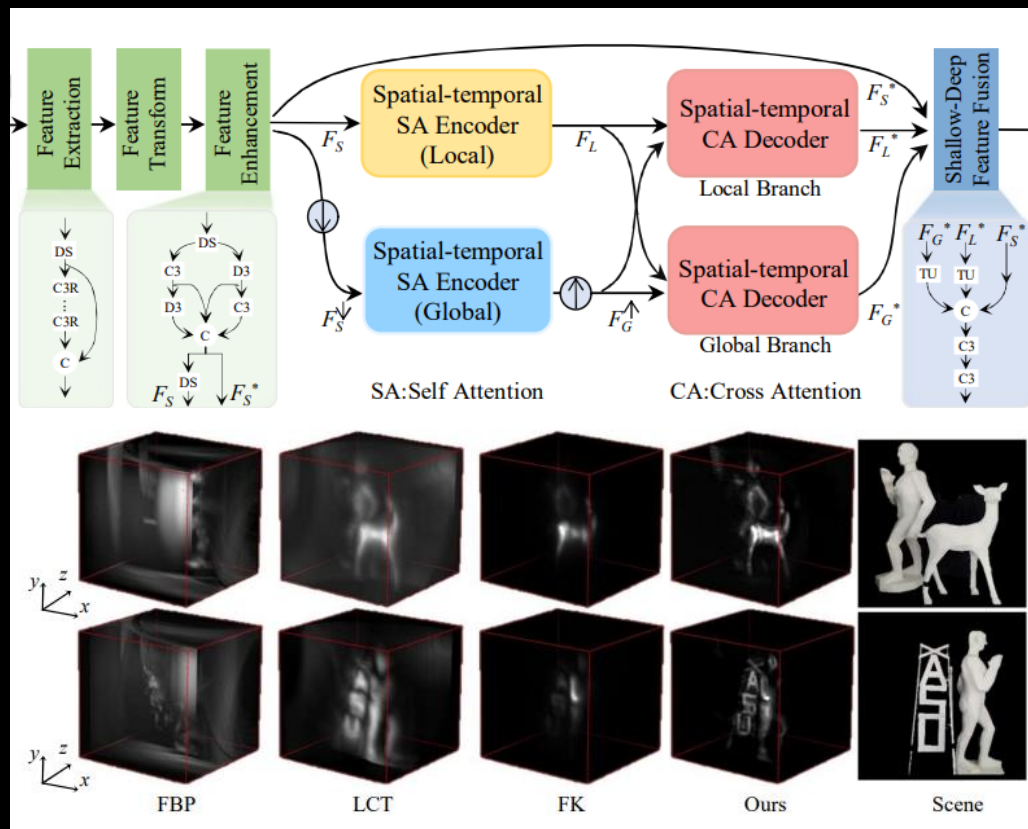
Hongjie Dai et al., Nat Nanotechnology 17, 653 (2022)



D. Faccio et al., Neurophotonics 12, 025014 (2025)

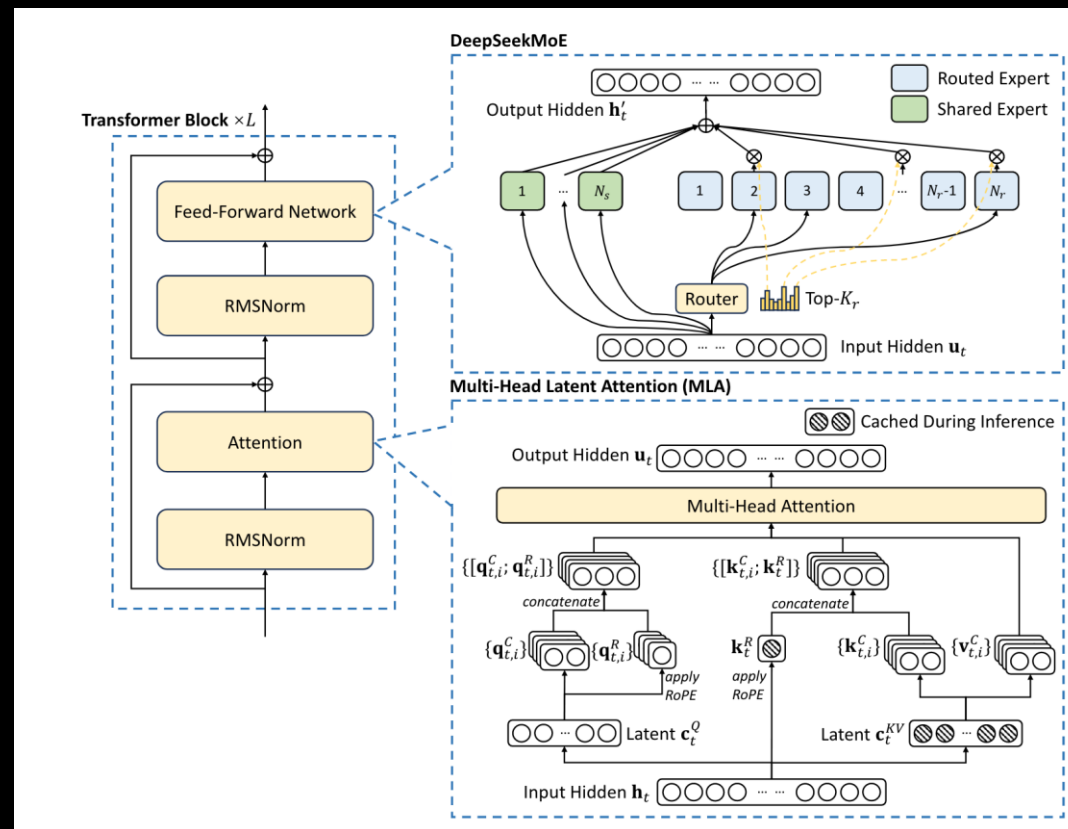
量子成像+人工智能

In collaboration with Xin Yuan, David Brady et al.



Transformer for NLOS imaging

Xiong, Xu et al., CVPR-2023; NeurIPS-2024



LLM for optical imaging

Liu et al. "Deepseek-v3 technical report"
arXiv:2412.19437 (2024)

总结：单光子成像、非视域成像等

➤ Long-range LiDAR Imaging

- SPI algorithms
- SPI techniques
- Airborne remote sensing

➤ NLOS Imaging

- NLOS algorithms
- NLOS techniques

➤ Optical Synthetic Aperture

- Active HBT

- Li et al., *Nat Photonics* 17, 416 (2023)
- Liu et al., *Nat Photonics* 15, 137 (2021)
- Li et al., *Nat Photonics* 13, 644 (2019)
- Ye et al., *Nat Comp Sci* 4, 920 (2024)
- Wu et al., *PNAS* 118, e2024468118 (2021)
- Zhou et al., *PRL* 136, 143801 (2026)
- Huang et al., *PRL* 132, 233802 (2024)
- Wang et al., *PRL* 127, 053602 (2021)
- Li et al., *Optica* 12, 626 (2025)
- Hong et al., *Optica* 11, 612 (2024)
- Li et al., *Optica* 8, 344 (2021)
- Peng et al., *IEEE TPAMI* 45, 4180 (2023)

Exploit the ToF of single photons

Thanks to my colleagues, students, collaborators



- **Colleague:** Jian-Wei Pan, Xian-Kang Dou, Jian-Yu Wang, Cheng-Zhi Peng, Qiang Zhang, Jun Zhang, Yuan Cao, Zhiwei Xiong
- **Postdoc:** Zheng-Ping Li (AP), Wenwen Li, Wei Li, Yutao Chen
- **PhD:** Xin Huang, Jun-Tian Ye, Rui-Lin Ye, Yijun Zhou, Likang Zhang, Bin Wang, Pengyu Jiang, Hao Tan, Jianjiang Liu, Yu Hong, Chen Dai
- **Collaborator:** Jeff Shapiro (MIT), Vivek Goyal (BU), Xin Yuan (Westlake), Frank Wilczek (MIT), Franco Zappa (Milano), Gerald Buller (HWU)



Thank you!



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