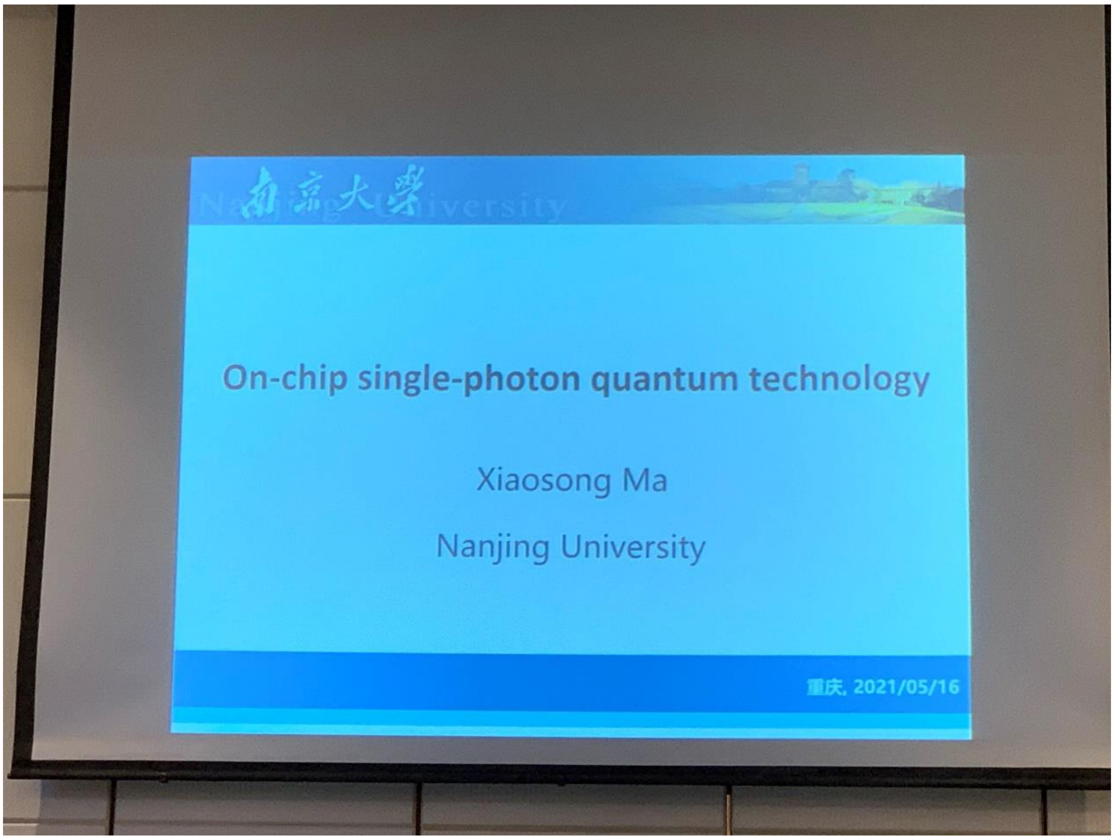
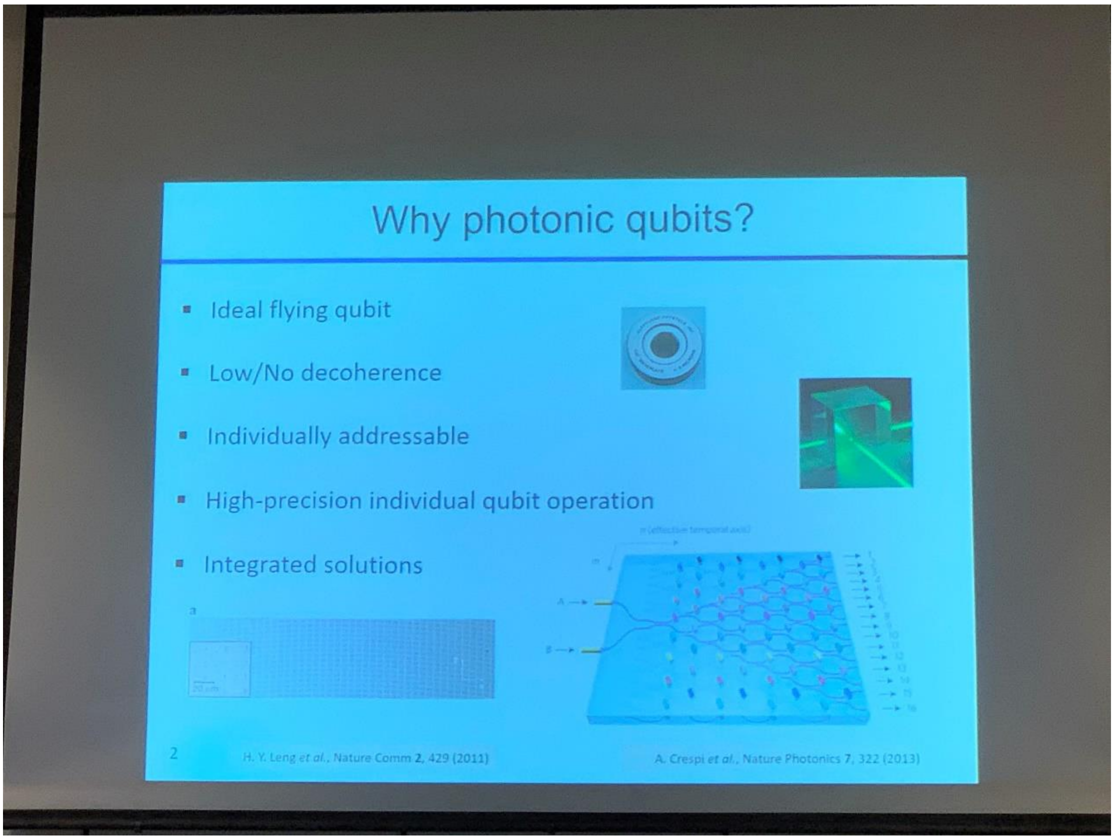
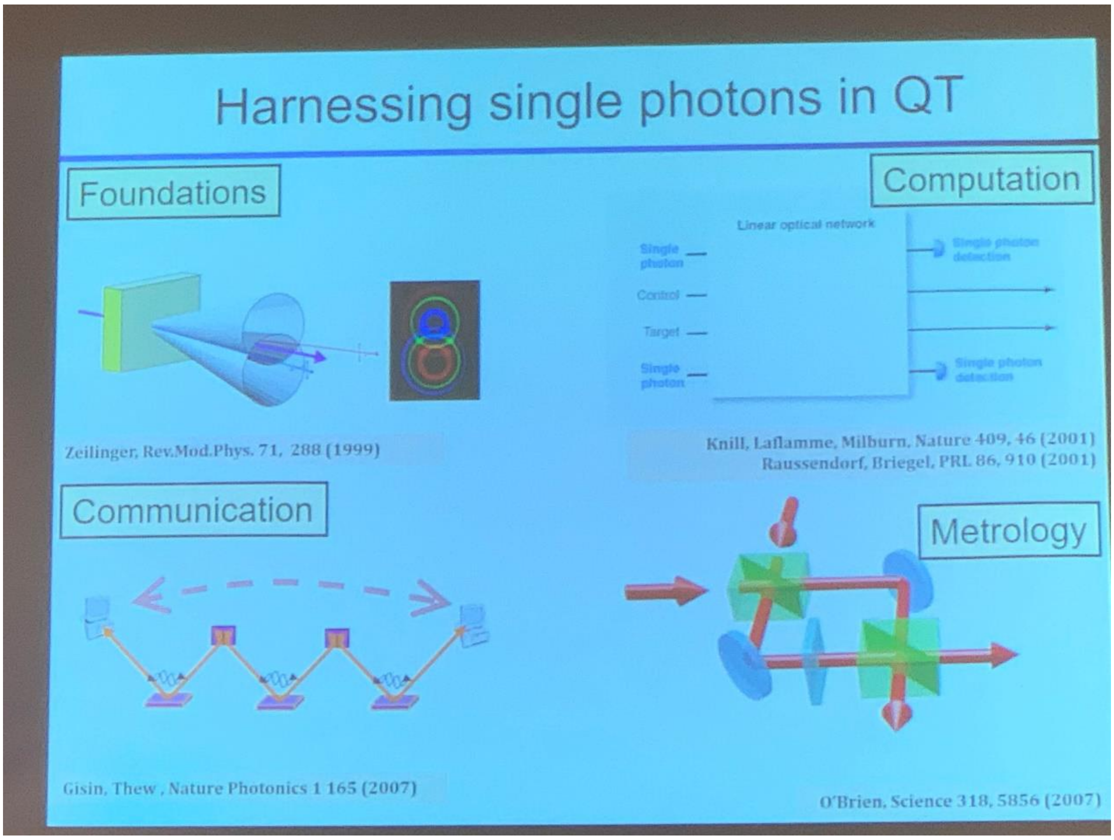
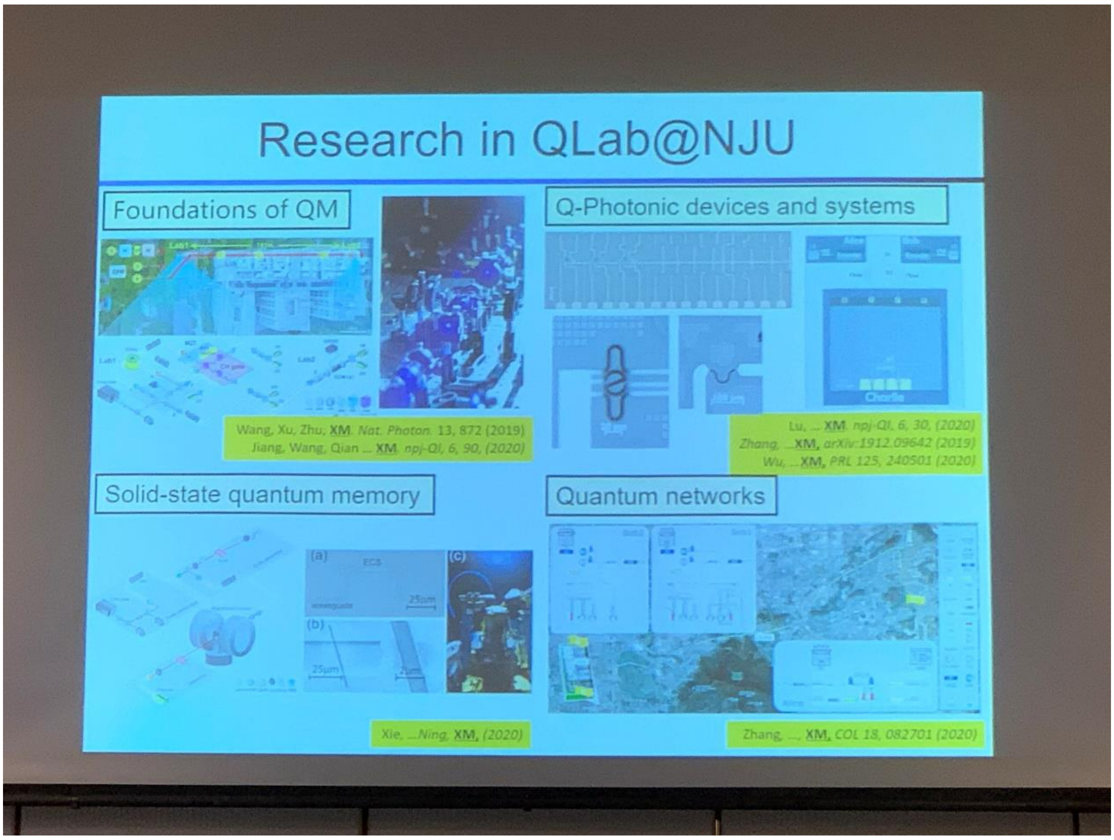
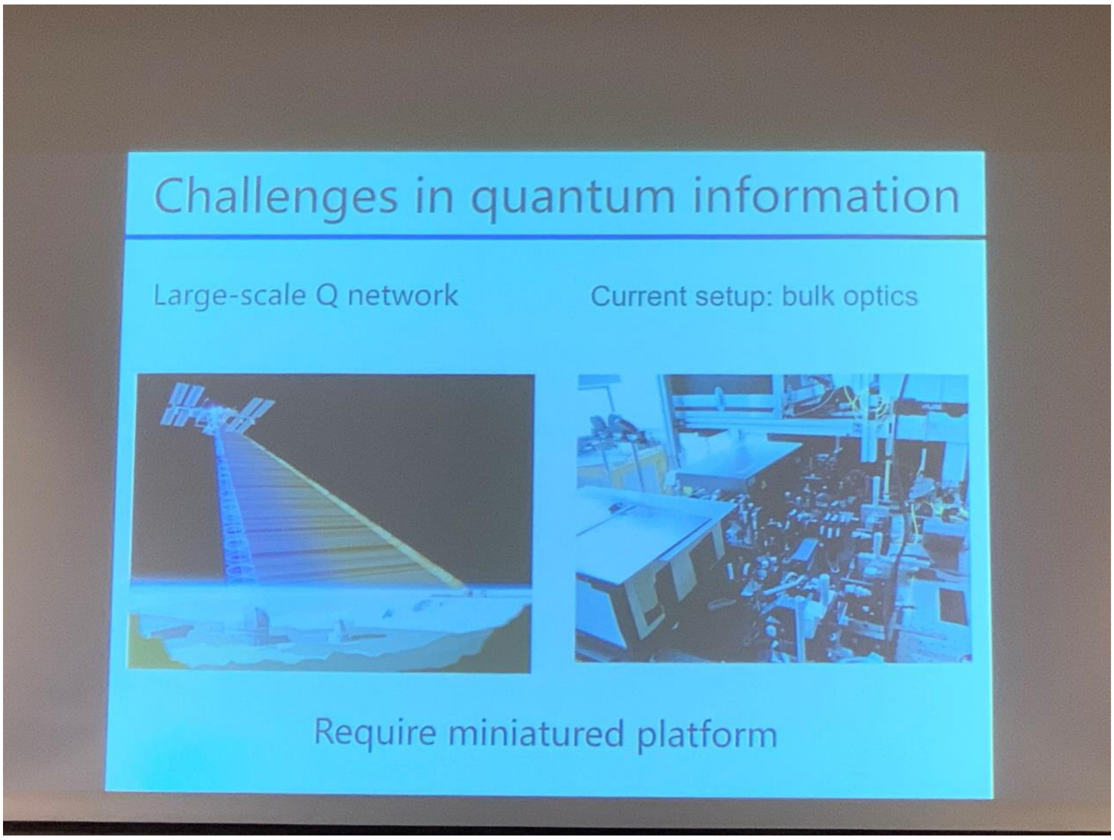

南京大學
On-chip single-photon quantum technology
Xiaosong Ma
Nanjing University
重庆, 2021/05/16

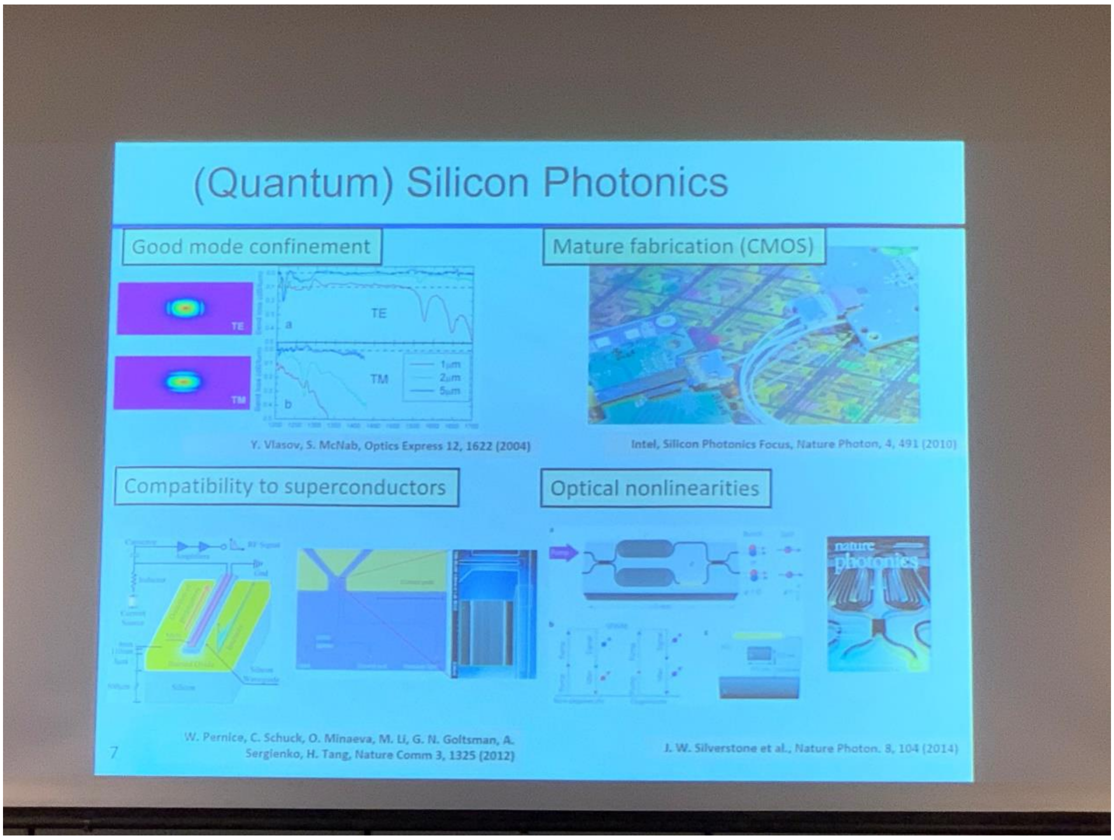

Why photonic qubits?
Ideal flying qubit
Low/No decoherence
Individually addressable
High-precision individual qubit operation
Integrated solutions
2
H. Y. Leng et al., Nature Comm 2, 429 (2011)
A. Crespi et al., Nature Photonics 7, 322 (2013)


Harnessing single photons in QT
Foundations
Computation
Linear optical network
Single photon
Control
Target
Single photon
Single photon detection
Single photon detection
Zeilinger, Rev.Mod.Phys. 71, 288 (1999)
Knill, Laflamme, Milburn, Nature 409, 46 (2001)
Raussendorf, Briegel, PRL 86, 910 (2001)
Communication
Metrology
Gisin, Thew , Nature Photonics 1 165 (2007)
O'Brien, Science 318, 5856 (2007)

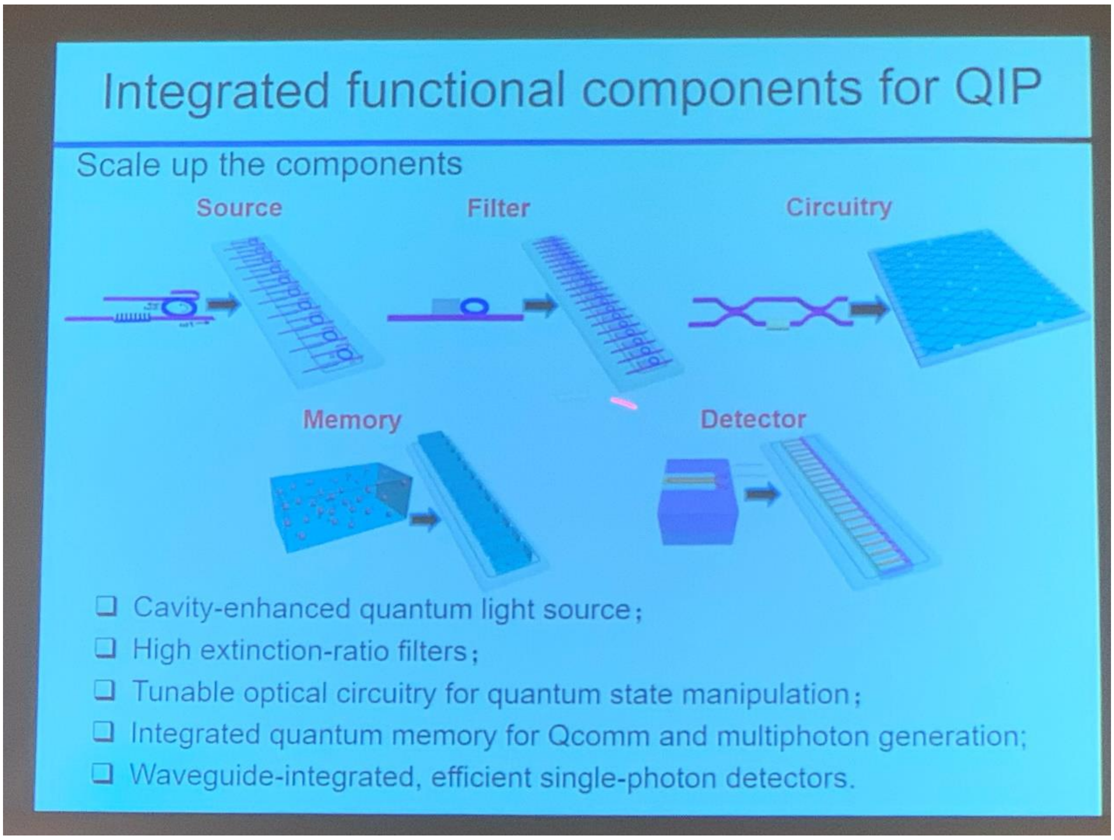

Research in QLab@NJU
Foundations of QM
Q-Photonic devices and systems
Wang, Xu, Zhu, XM. Nat. Photon. 13, 872 (2019)
Jiang, Wang, Qian ... XM. npj-QI, 6, 90, (2020)
Lu, ... XM. npj-QI, 6, 30, (2020)
Zhang, ...XM, arXiv:1912.09642 (2019)
Wu, ...XM, PRL 125, 240501 (2020)
Solid-state quantum memory
Quantum networks
(a)
(b)
(c)
25μm
Xie, ...Ning, XM, (2020)
Zhang, ..., XM, COL 18, 082701 (2020)

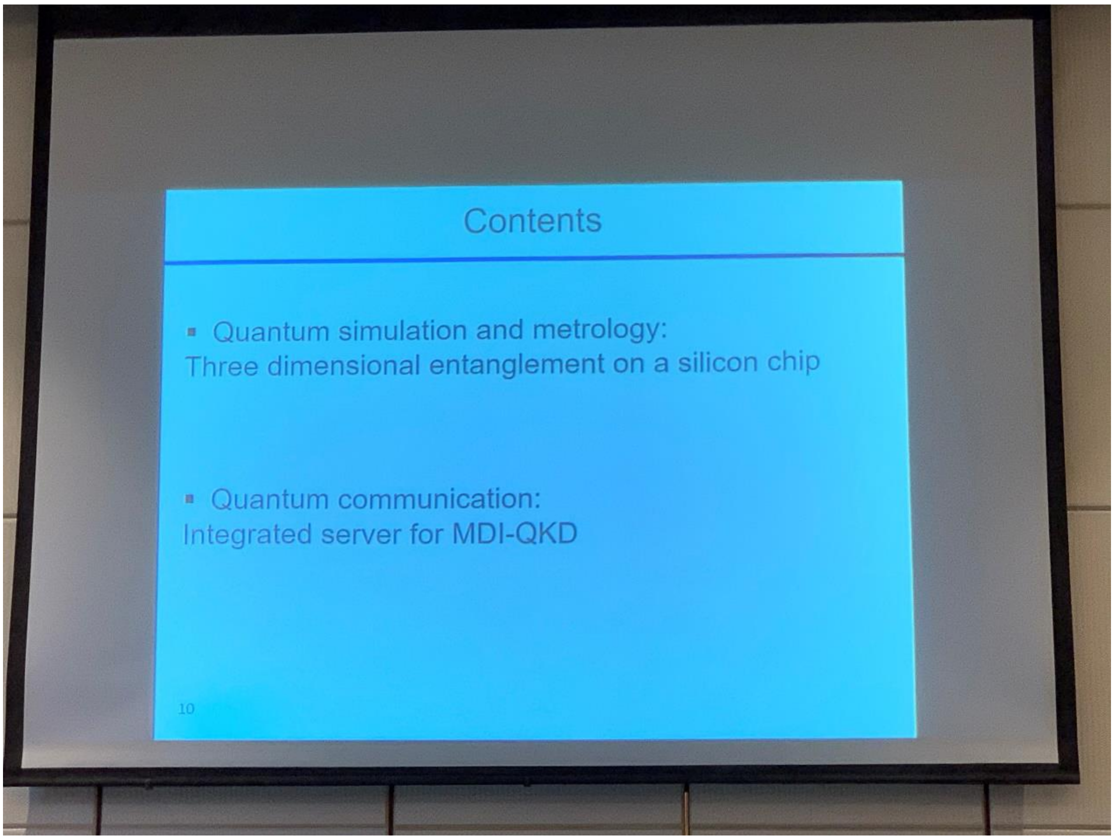


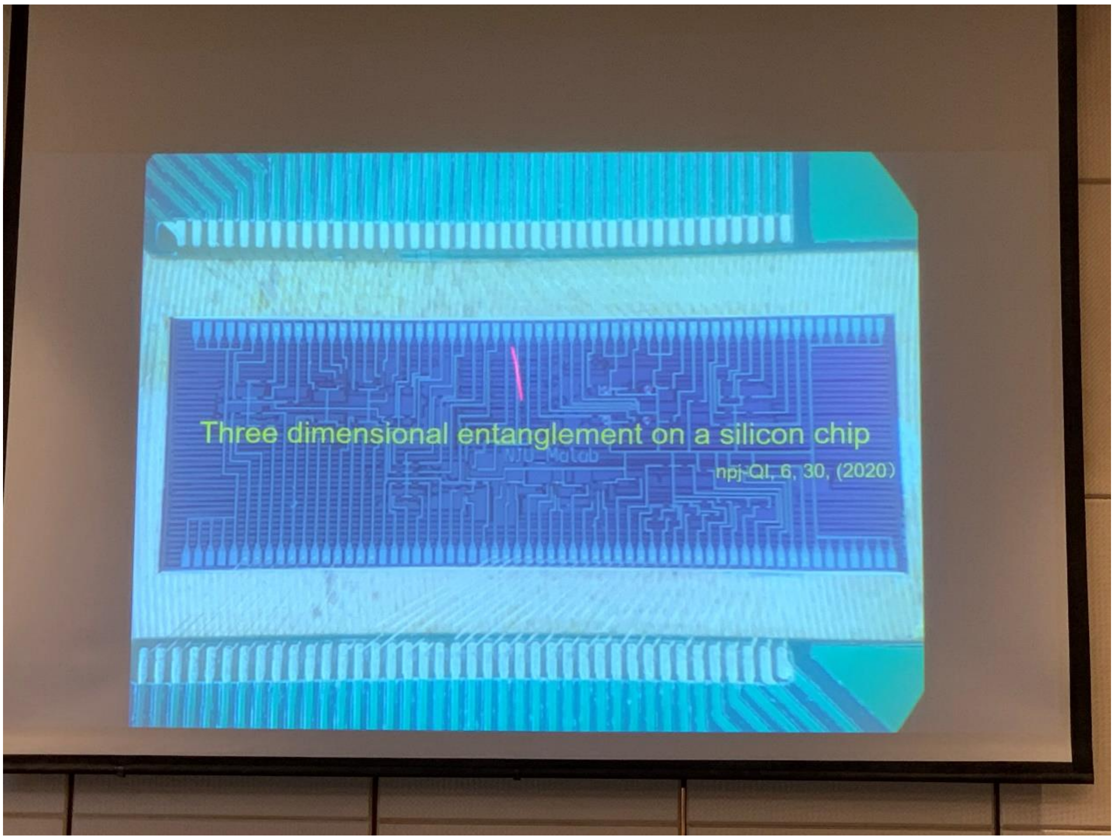
Challenges in quantum information
Large-scale Q network
Current setup: bulk optics
Require miniatured platform

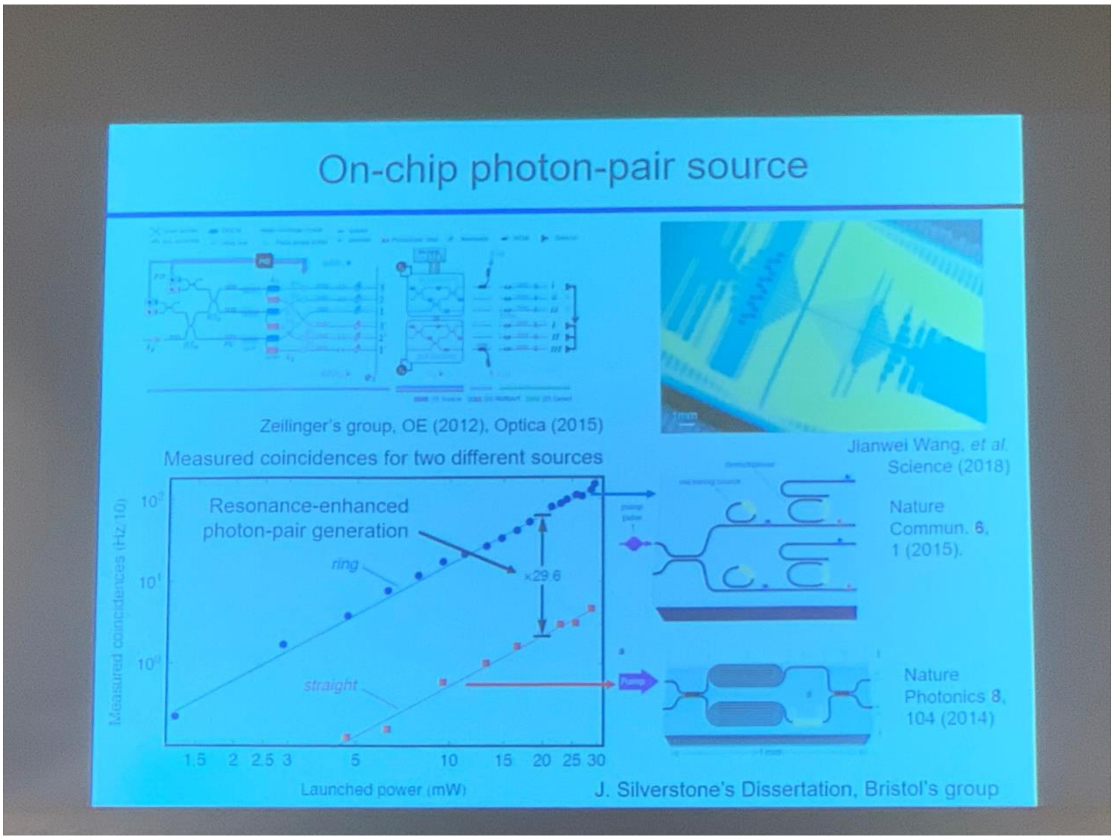



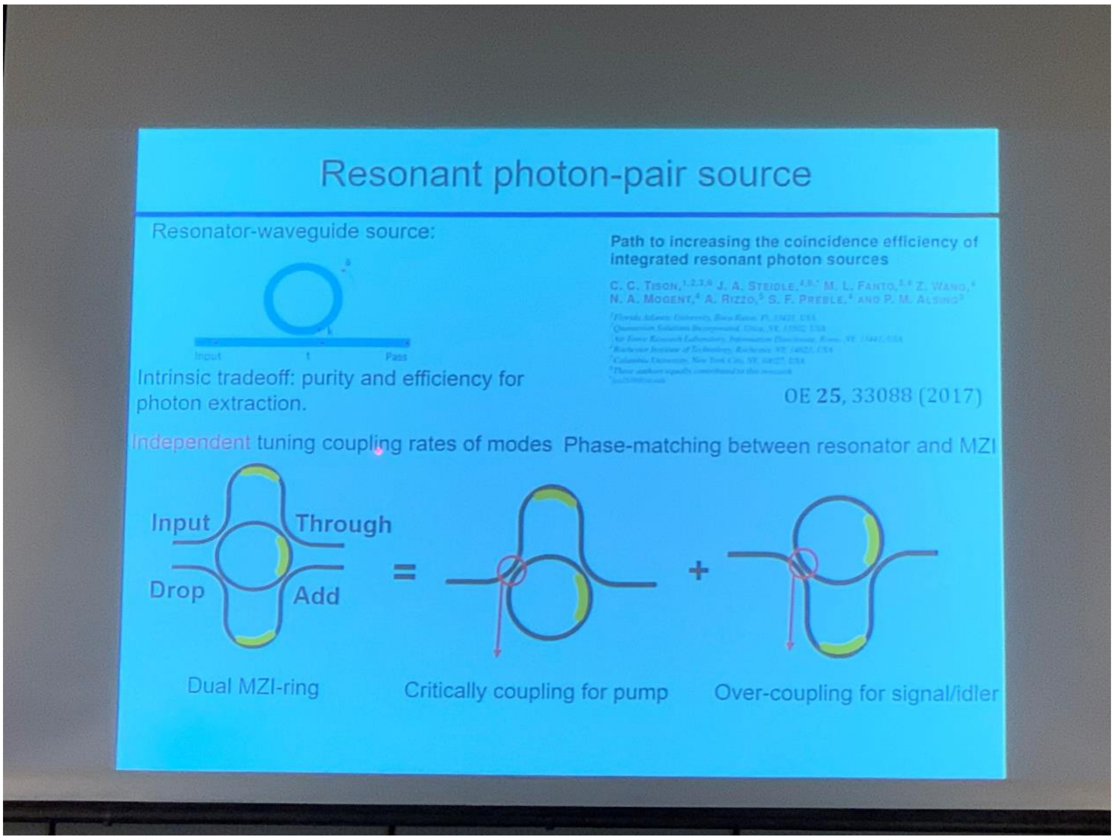
(Quantum) Silicon Photonics
Good mode confinement
TE
TM
a
b
1μm
2μm
5μm
Y. Vlasov, S. McNab, Optics Express 12, 1622 (2004)
Mature fabrication (CMOS)
Intel, Silicon Photonics Focus, Nature Photon, 4, 491 (2010)
Compatibility to superconductors
W. Pernice, C. Schuck, O. Minaeva, M. Li, G. N. Goltsman, A. Sergienko, H. Tang, Nature Comm 3, 1325 (2012)
Optical nonlinearities
nature photonics
J. W. Silverstone et al., Nature Photon. 8, 104 (2014)
7

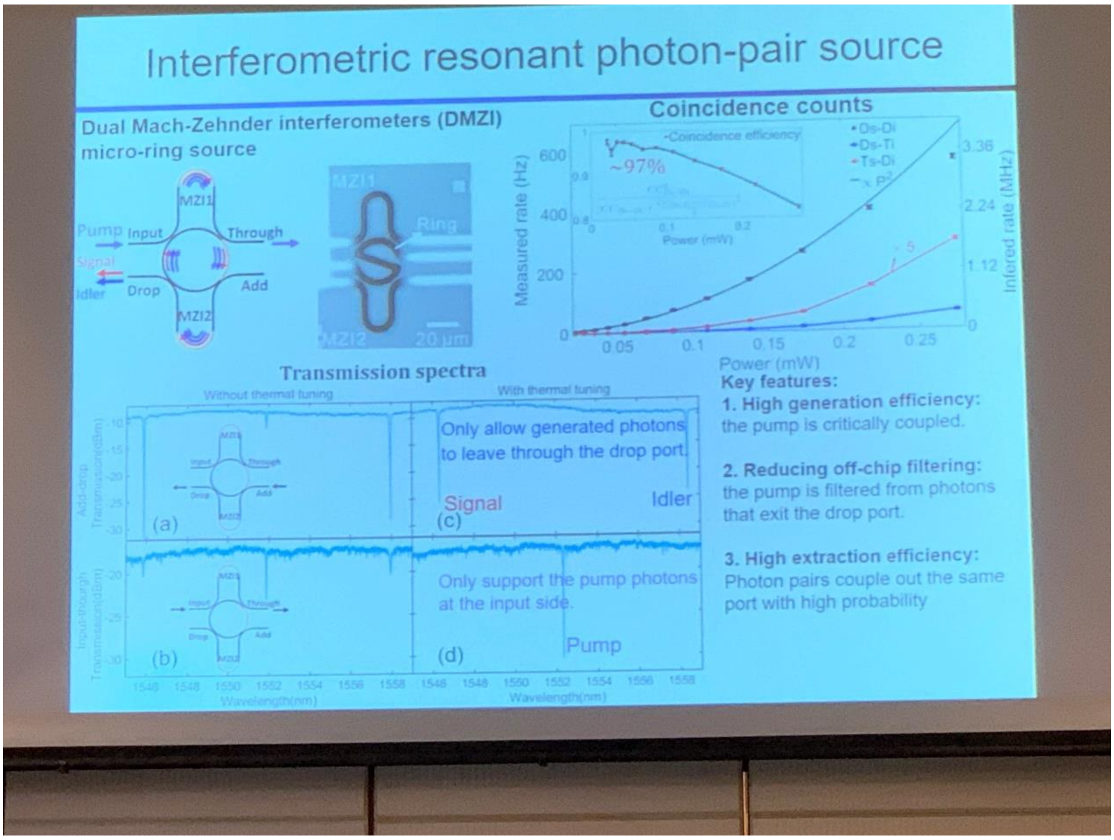

Integrated functional components for QIP
Scale up the components
Source
Filter
Circuitry
Memory
Detector
Cavity-enhanced quantum light source;
High extinction-ratio filters;
Tunable optical circuitry for quantum state manipulation;
Integrated quantum memory for Qcomm and multiphoton generation;
Waveguide-integrated, efficient single-photon detectors.

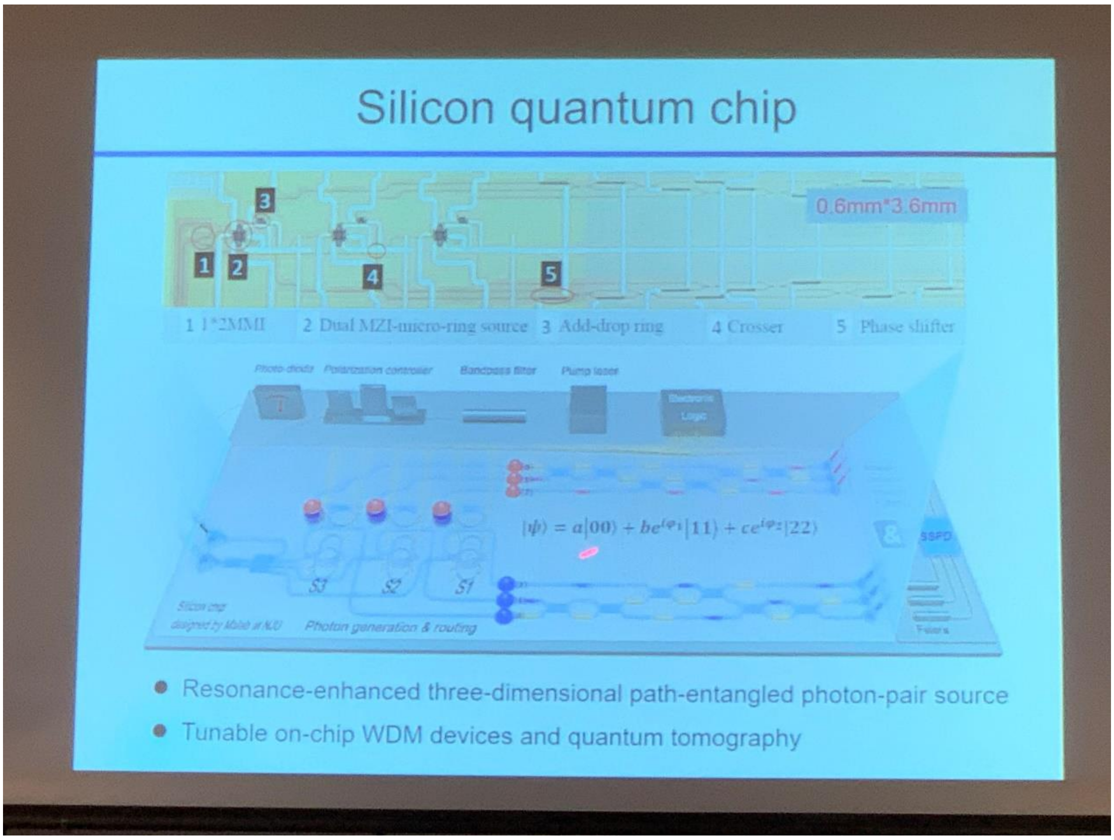

Contents
Quantum simulation and metrology:
Three dimensional entanglement on a silicon chip
Quantum communication:
Integrated server for MDI-QKD
10

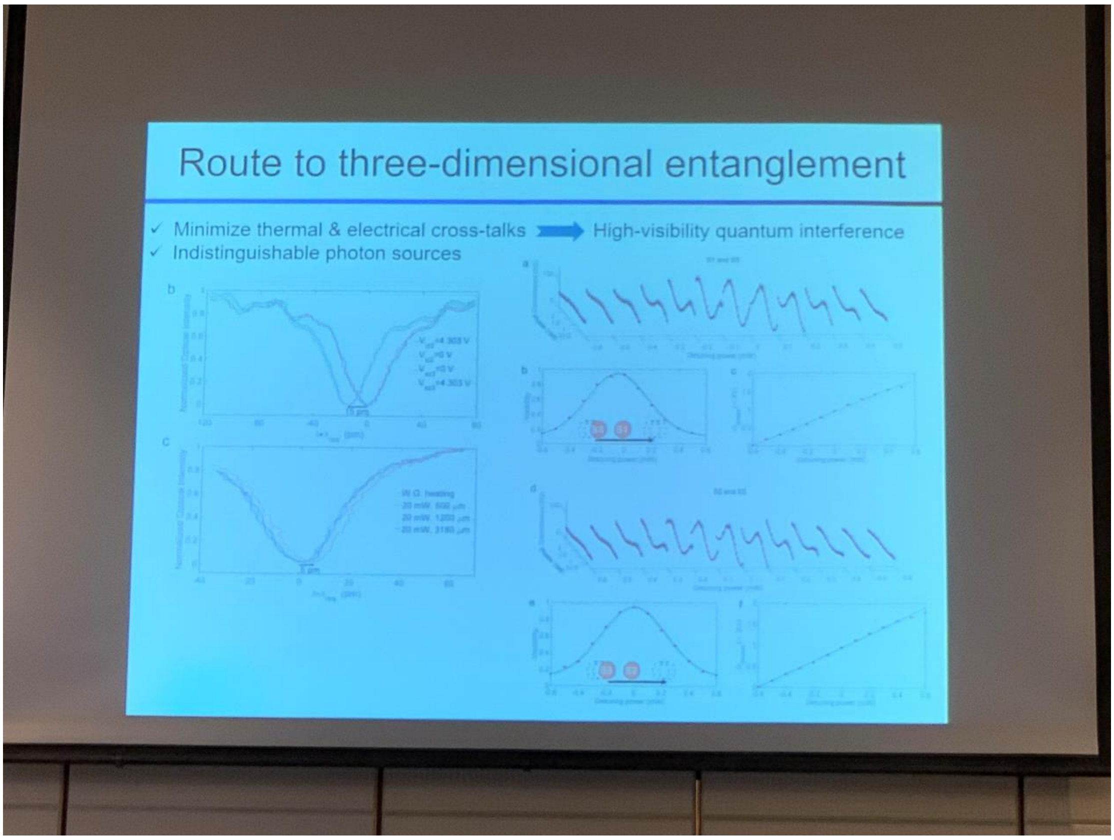

Three dimensional entanglement on a silicon chip
npj-QI, 6, 30, (2020)

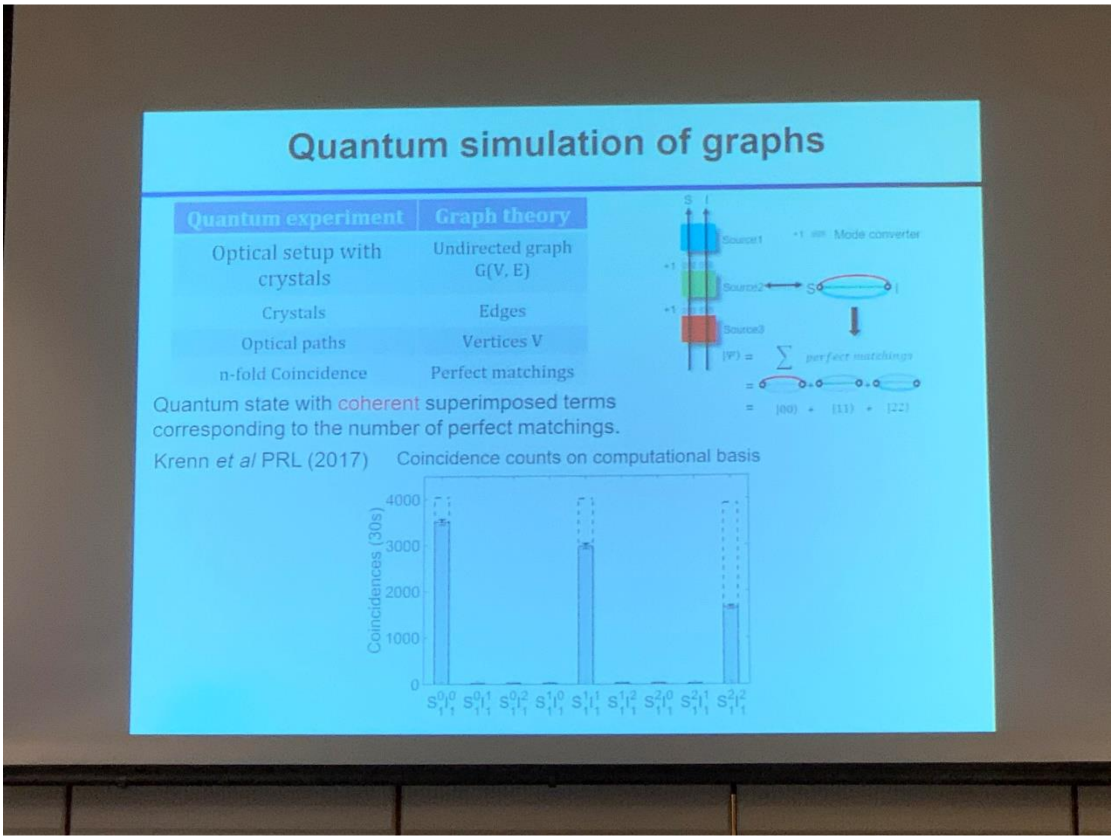

On-chip photon-pair source
Zeilinger's group, OE (2012), Optica (2015)
Jianwei Wang, et al. Science (2018)
Measured coincidences for two different sources
Resonance-enhanced photon-pair generation
ring
straight
×29.6
Measured coincidences (Hz/10)
Launched power (mW)
1.5 2 2.5 3 5 10 15 20 25 30
Nature Commun. 6, 1 (2015).
Nature Photonics 8, 104 (2014)
J. Silverstone's Dissertation, Bristol's group

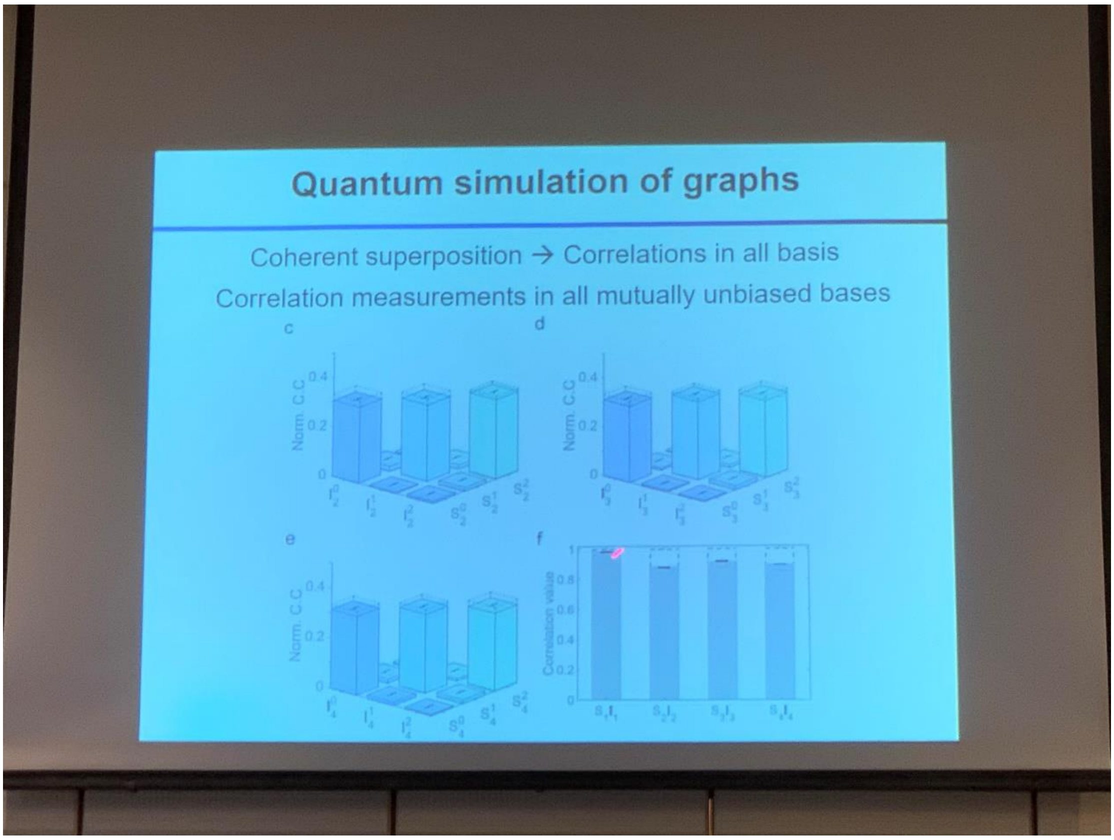

Resonant photon-pair source
Resonator-waveguide source:
Input
Pass
Intrinsic tradeoff: purity and efficiency for photon extraction.
Path to increasing the coincidence efficiency of integrated resonant photon sources
OE 25, 33088 (2017)
Independent tuning coupling rates of modes
Phase-matching between resonator and MZI
Input
Through
Drop
Add
=
+
Dual MZI-ring
Critically coupling for pump
Over-coupling for signal/idler

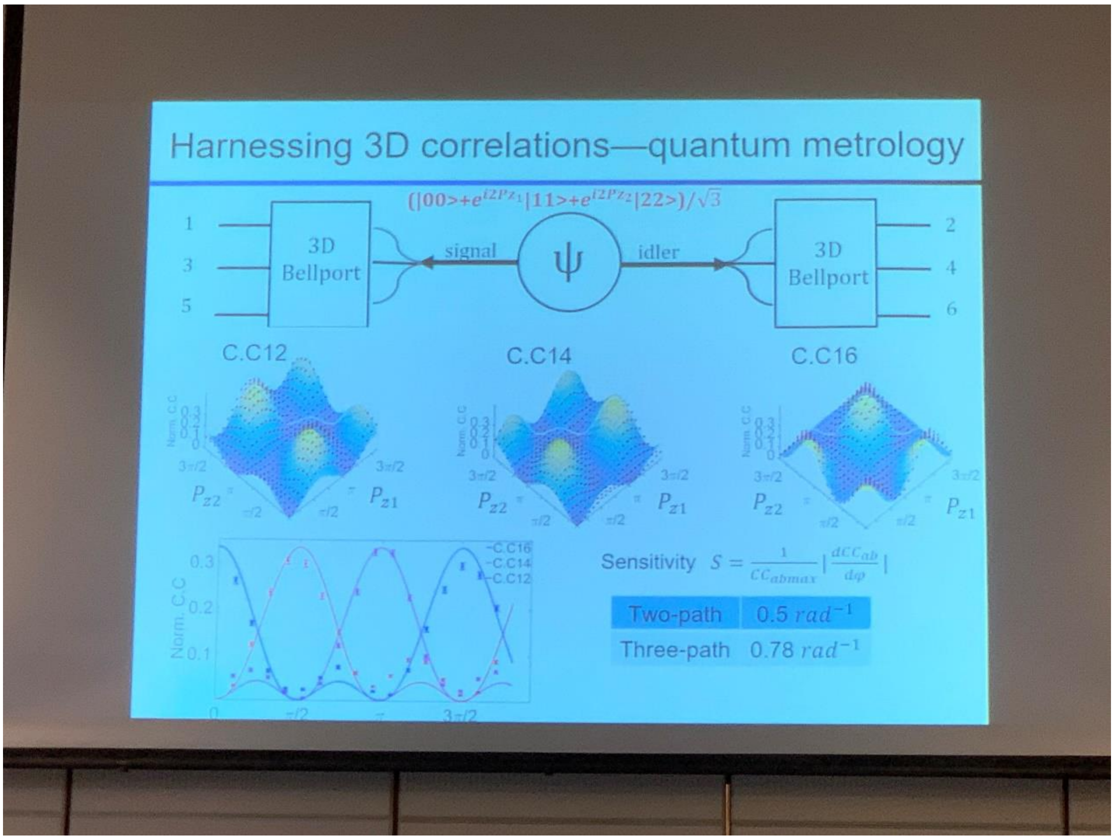

Interferometric resonant photon-pair source
Dual Mach-Zehnder interferometers (DMZI) micro-ring source
MZI1
MZI2
Pump
Signal
Idler
Input
Through
Drop
Add
Ring
20 μm
Coincidence counts
Coincidence efficiency
~97%
Ds-Di
Ds-Ti
Ts-Di
P²
Measured rate (Hz)
Infered rate (MHz)
Power (mW)
Transmission spectra
Without thermal tuning
With thermal tuning
Only allow generated photons to leave through the drop port.
Signal
Idler
Only support the pump photons at the input side.
Pump
Wavelength(nm)
Key features:
1. High generation efficiency: the pump is critically coupled.
2. Reducing off-chip filtering: the pump is filtered from photons that exit the drop port.
3. High extraction efficiency: Photon pairs couple out the same port with high probability

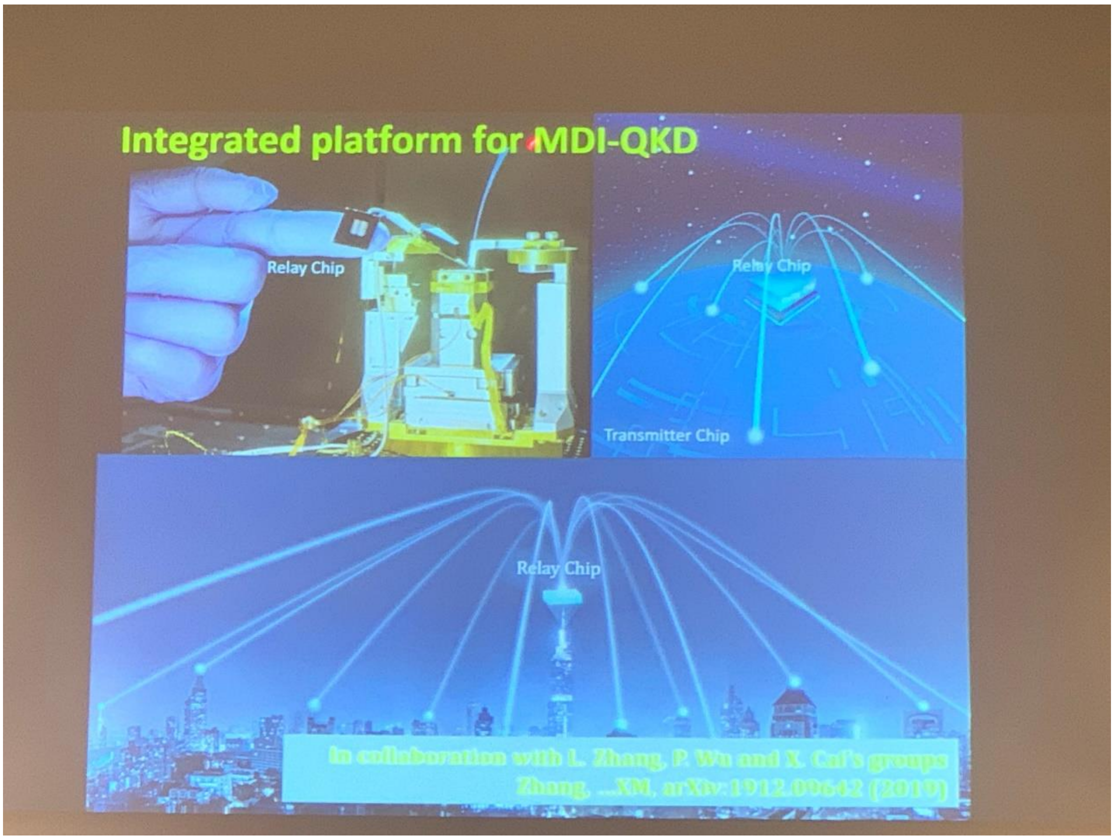

Silicon quantum chip
0.6mm*3.6mm
1 1*2MMI
2 Dual MZI-micro-ring source
3 Add-drop ring
4 Crosser
5 Phase shifter
Photon generation & routing
$|\psi\rangle = a|00\rangle + be^{i\varphi_1}|11\rangle + ce^{i\varphi_2}|22\rangle$
Resonance-enhanced three-dimensional path-entangled photon-pair source
Tunable on-chip WDM devices and quantum tomography

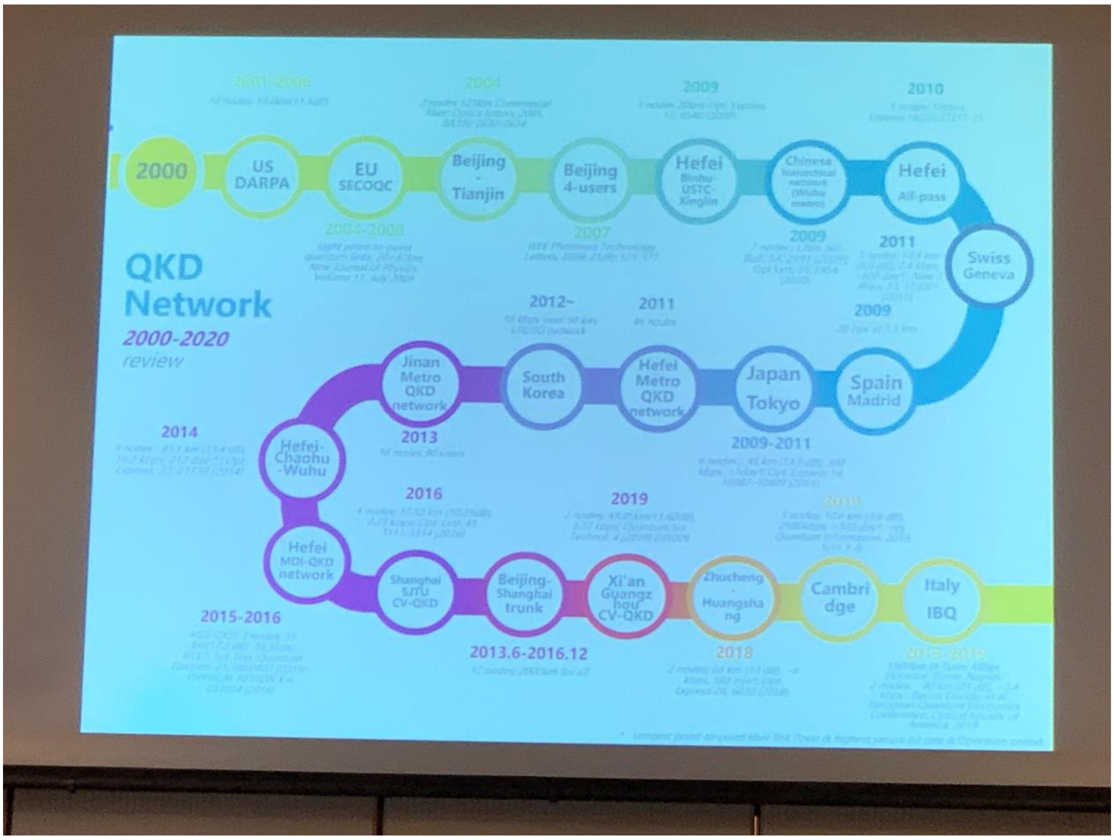

Route to three-dimensional entanglement
✓ Minimize thermal & electrical cross-talks
High-visibility quantum interference
✓ Indistinguishable photon sources

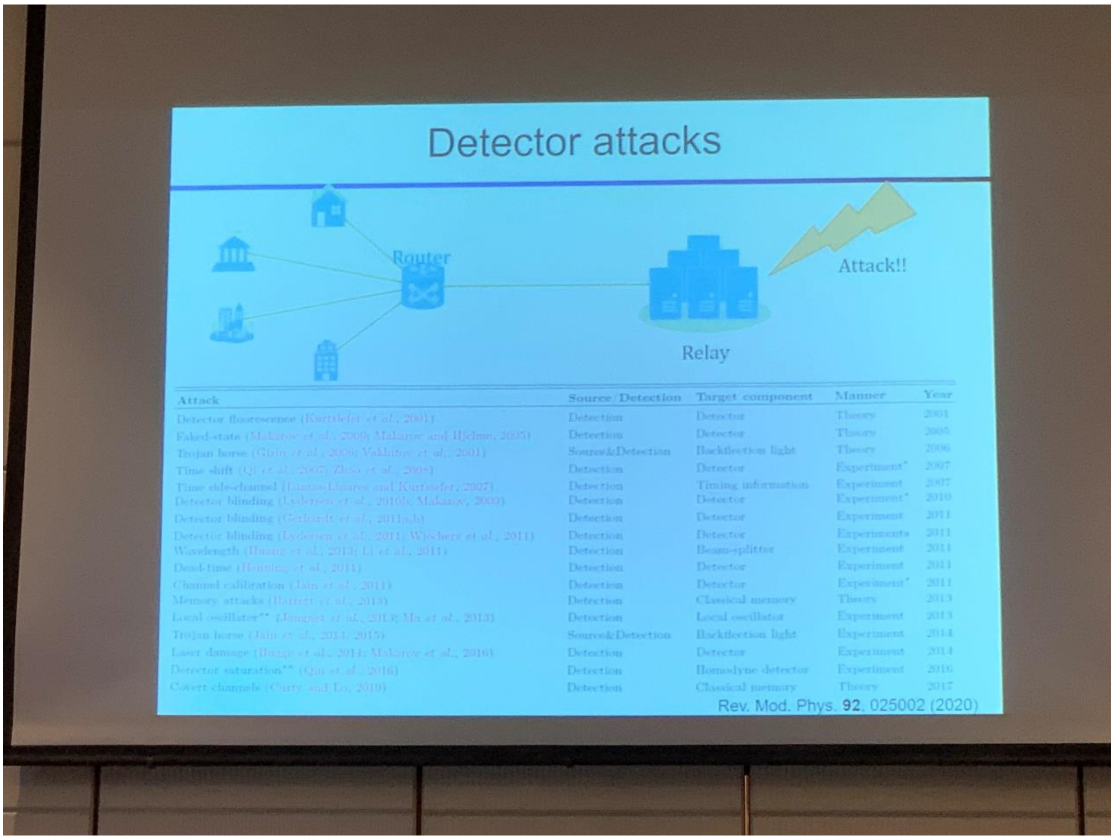

Quantum simulation of graphs
Quantum experiment
Graph theory
Optical setup with crystals
Undirected graph G(V, E)
Crystals
Edges
Optical paths
Vertices V
n-fold Coincidence
Perfect matchings
Mode converter
Source1
Source2
Source3
perfect matchings
|00⟩ + |11⟩ + |22⟩
Quantum state with coherent superimposed terms corresponding to the number of perfect matchings.
Krenn et al PRL (2017)
Coincidence counts on computational basis
Coincidences (30s)
4000
3000
2000
1000
0

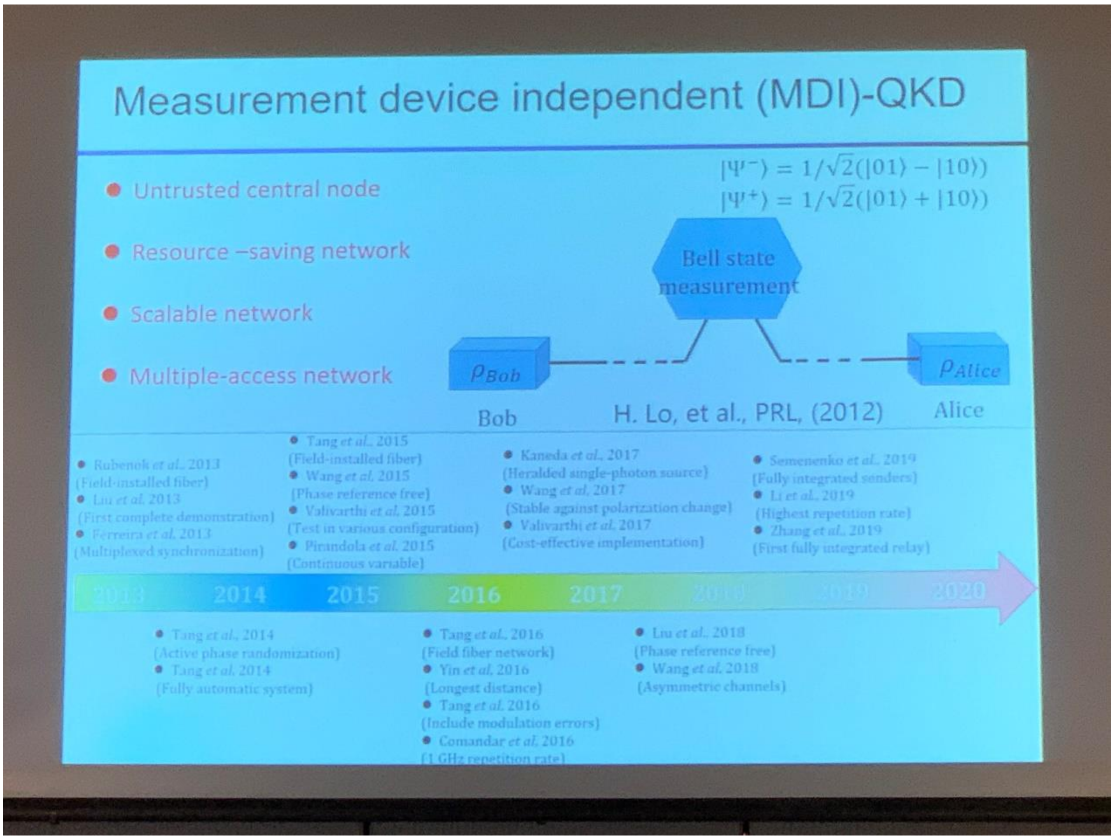

Quantum simulation of graphs
Coherent superposition → Correlations in all basis
Correlation measurements in all mutually unbiased bases
c
d
e
f
Norm. C.C
0.4
0.2
0
Correlation value
1
0.8
0.6
0.4
0.2
0

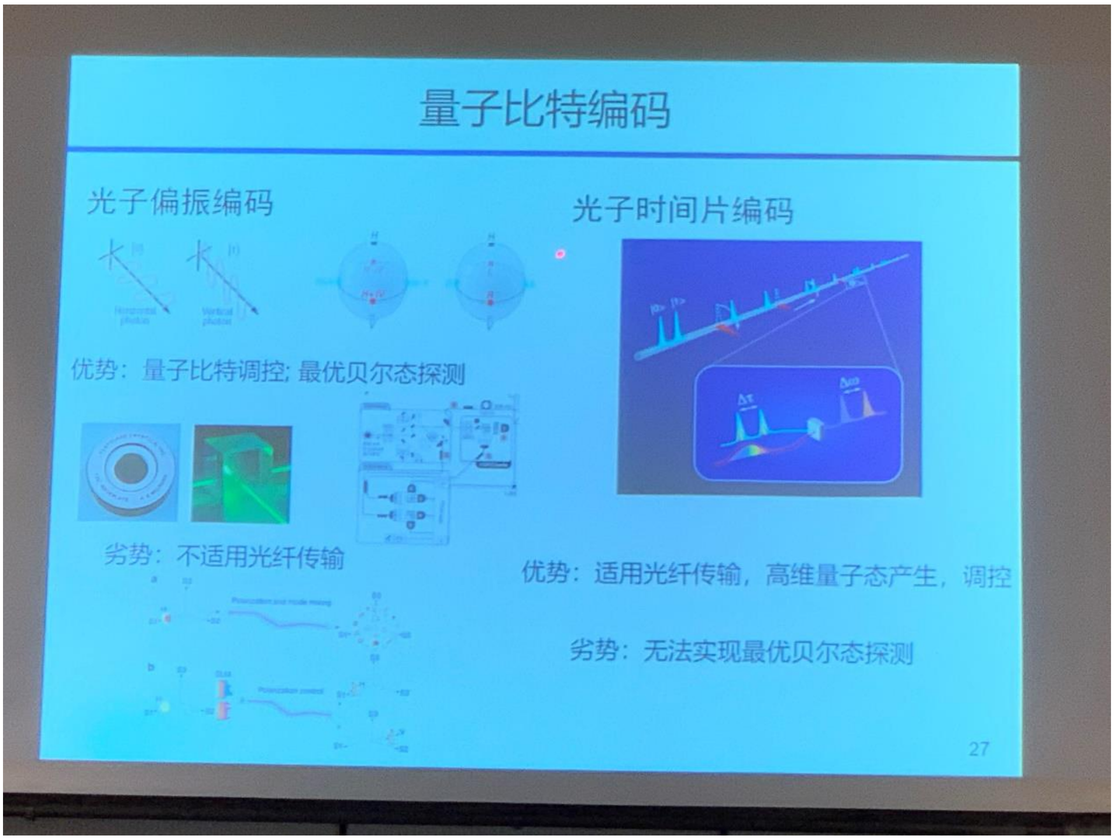

Harnessing 3D correlations—quantum metrology
$(|00\rangle + e^{i2P_{z1}}|11\rangle + e^{i2P_{z2}}|22\rangle)/\sqrt{3}$
1
3
5
3D Bellport
signal
ψ
idler
3D Bellport
2
4
6
C.C12
C.C14
C.C16
$P_{z2}$
$P_{z1}$
Norm. C.C
C.C16
C.C14
C.C12
Sensitivity $S = \frac{1}{CC_{abmax}} \left| \frac{dCC_{ab}}{d\varphi} \right|$
Two-path 0.5 $rad^{-1}$
Three-path 0.78 $rad^{-1}$

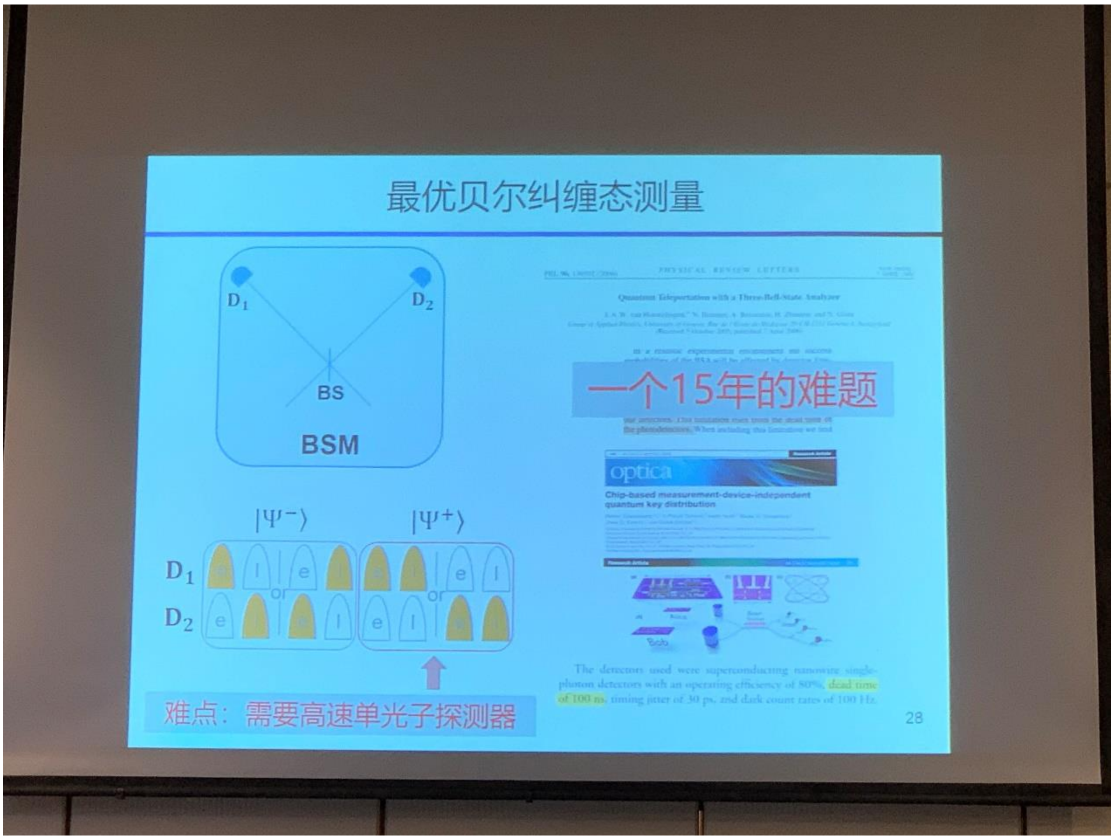

Integrated platform for MDI-QKD
Relay Chip
Relay Chip
Transmitter Chip
Relay Chip
In collaboration with L. Zhang, P. Wu and X. Cai's groups
Zhang, ...XM, arXiv:1912.09642 (2019)

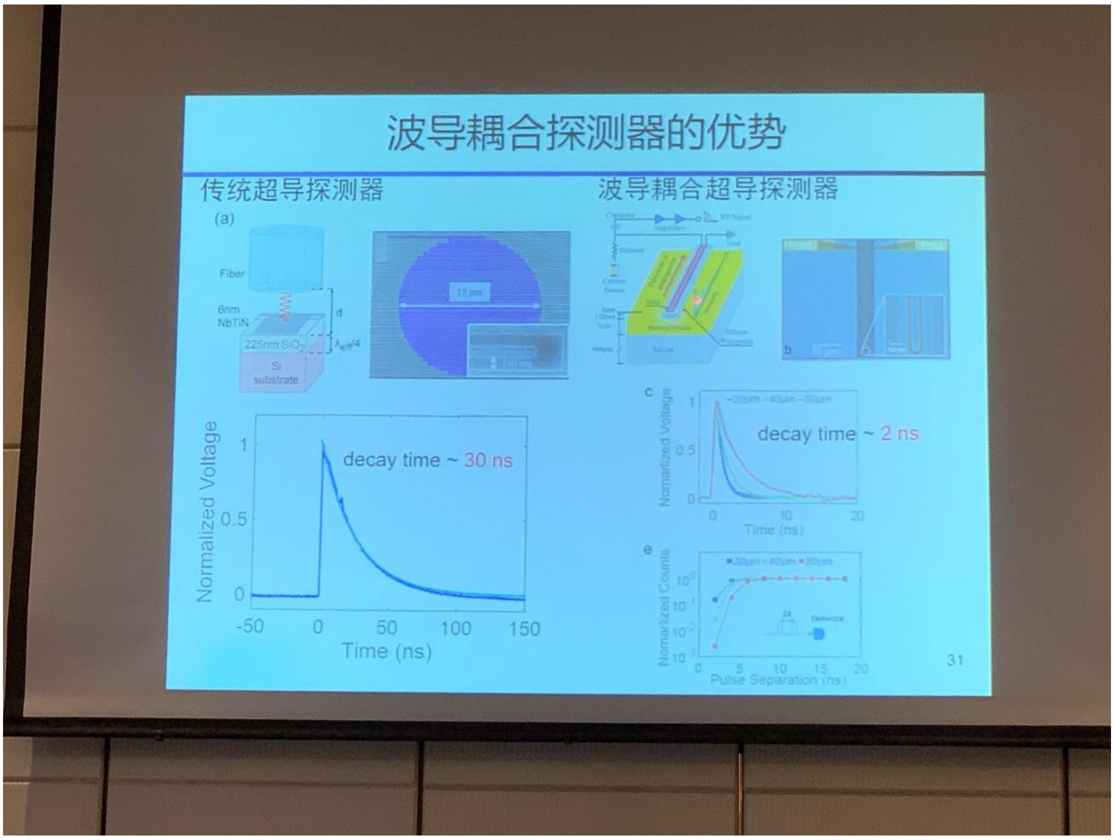

2000
US DARPA
EU SECOQC
Beijing - Tianjin
Beijing 4-users
Hefei
Chinese
Hefei All-pass
Swiss Geneva
Spain Madrid
Japan Tokyo
Hefei Metro QKD network
South Korea
Jinan Metro QKD network
Hefei-Chaohu-Wuhu
Hefei MDI-QKD network
Shanghai SJTU CV-QKD
Beijing-Shanghai trunk
Xi'an Guangzhou CV-QKD
Zhucheng - Huangshang
Cambridge
Italy IBQ
QKD Network
2000-2020
review
2004-2008
2007
2009
2010
2011
2009
2012~
2011
2013
2014
2016
2019
2009-2011
2015-2016
2013.6-2016.12
2018
2019

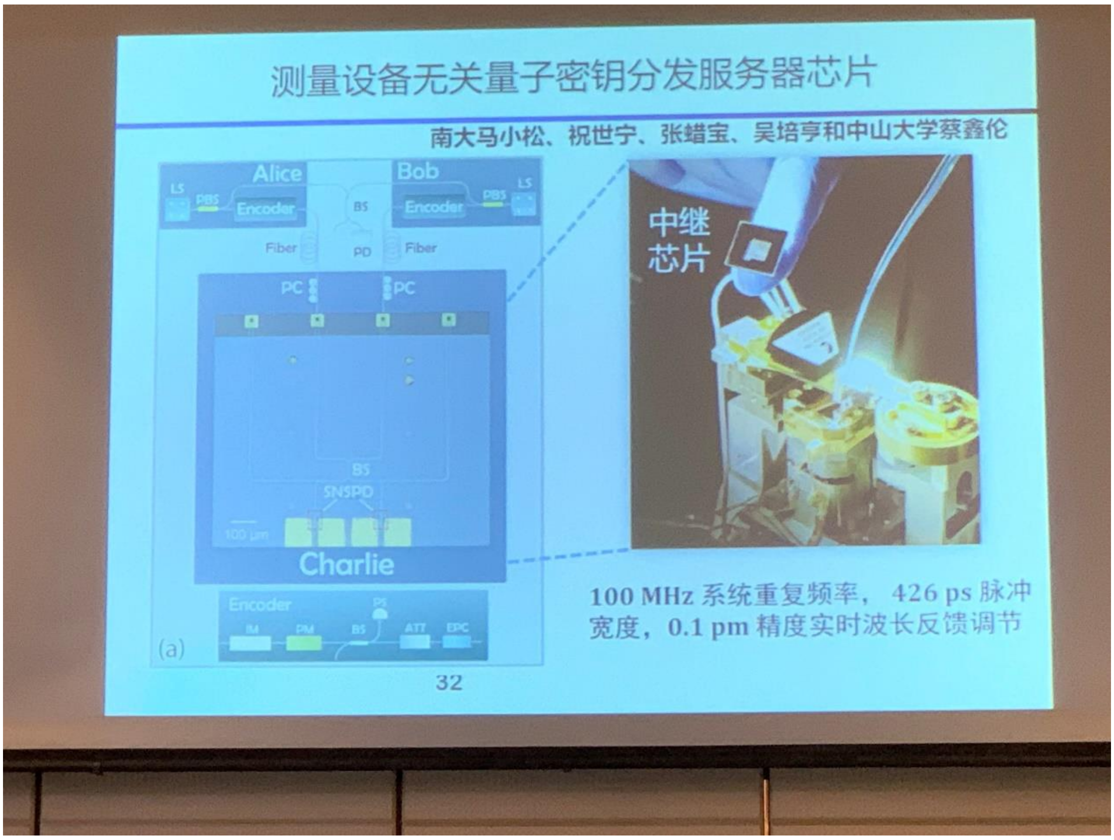

Detector attacks
Router
Attack!!
Relay
Attack | Source/Detection | Target component | Manner | Year
Detector fluorescence (Kurtsiefer et al., 2001) | Detection | Detector | Theory | 2001
Faked-state (Makarov et al., 2000; Makarov and Hjelme, 2005) | Detection | Detector | Theory | 2005
Trojan horse (Gisin et al., 2006; Vakhitov et al., 2001) | Source&Detection | Backflection light | Theory | 2006
Time shift (Qi et al., 2007; Zhao et al., 2008) | Detection | Detector | Experiment* | 2007
Time side-channel (Lamas-Linares and Kurtsiefer, 2007) | Detection | Timing information | Experiment | 2007
Detector blinding (Lydersen et al., 2010b; Makarov, 2009) | Detection | Detector | Experiment* | 2010
Detector blinding (Gerhardt et al., 2011a,b) | Detection | Detector | Experiment | 2011
Detector blinding (Lydersen et al., 2011; Wiechers et al., 2011) | Detection | Detector | Experiments | 2011
Wavelength (Huang et al., 2013; Li et al., 2011) | Detection | Beam-splitter | Experiment | 2011
Dead-time (Henning et al., 2011) | Detection | Detector | Experiment | 2011
Channel calibration (Jain et al., 2011) | Detection | Detector | Experiment* | 2011
Memory attacks (Barrett et al., 2013) | Detection | Classical memory | Theory | 2013
Local oscillator** (Jouguet et al., 2013; Ma et al., 2013) | Detection | Local oscillator | Experiment | 2013
Trojan horse (Jain et al., 2014, 2015) | Source&Detection | Backflection light | Experiment | 2014
Laser damage (Bugge et al., 2014; Makarov et al., 2016) | Detection | Detector | Experiment | 2014
Detector saturation** (Qin et al., 2016) | Detection | Homodyne detector | Experiment | 2016
Covert channels (Curty and Lo, 2019) | Detection | Classical memory | Theory | 2017
Rev. Mod. Phys. 92, 025002 (2020)


Measurement device independent (MDI)-QKD
$|\Psi^-\rangle = 1/\sqrt{2}(|01\rangle - |10\rangle)$
$|\Psi^+\rangle = 1/\sqrt{2}(|01\rangle + |10\rangle)$
Untrusted central node
Resource –saving network
Scalable network
Multiple-access network
Bell state measurement
$\rho_{Bob}$
$\rho_{Alice}$
Bob
H. Lo, et al., PRL, (2012)
Alice
Rubenok et al., 2013 (Field-installed fiber)
Liu et al. 2013 (First complete demonstration)
Ferreira et al. 2013 (Multiplexed synchronization)
Tang et al., 2015 (Field-installed fiber)
Wang et al. 2015 (Phase reference free)
Valivarthi et al. 2015 (Test in various configuration)
Pirandola et al. 2015 (Continuous variable)
Kaneda et al., 2017 (Heralded single-photon source)
Wang et al. 2017 (Stable against polarization change)
Valivarthi et al. 2017 (Cost-effective implementation)
Semenenko et al., 2019 (Fully integrated senders)
Li et al., 2019 (Highest repetition rate)
Zhang et al., 2019 (First fully integrated relay)
2014
2015
2016
2017
2020
Tang et al., 2014 (Active phase randomization)
Tang et al. 2014 (Fully automatic system)
Tang et al., 2016 (Field fiber network)
Yin et al. 2016 (Longest distance)
Tang et al. 2016 (Include modulation errors)
Comandar et al. 2016 (1 GHz repetition rate)
Liu et al., 2018 (Phase reference free)
Wang et al. 2018 (Asymmetric channels)

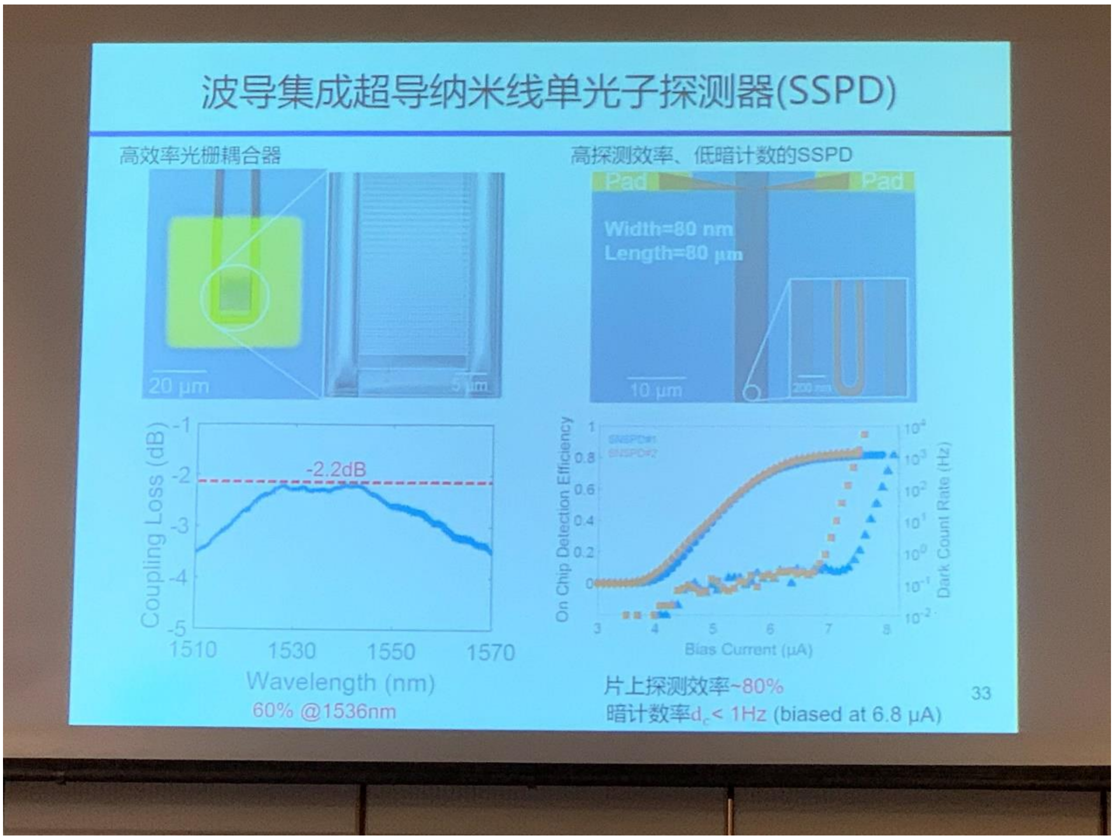

量子比特编码
光子偏振编码
优势：量子比特调控; 最优贝尔态探测
劣势：不适用光纤传输
光子时间片编码
优势：适用光纤传输，高维量子态产生，调控
劣势：无法实现最优贝尔态探测
27


最优贝尔纠缠态测量
D1
D2
BS
BSM
|Ψ⁻⟩
|Ψ⁺⟩
D1
D2
or
or
一个15年的难题
PHYSICAL REVIEW LETTERS
Quantum Teleportation with a Three-Bell-State Analyzer
optica
Chip-based measurement-device-independent quantum key distribution
难点：需要高速单光子探测器
The detectors used were superconducting nanowire single-photon detectors with an operating efficiency of 80%, dead time of 100 ns, timing jitter of 30 ps, and dark count rates of 100 Hz.
28

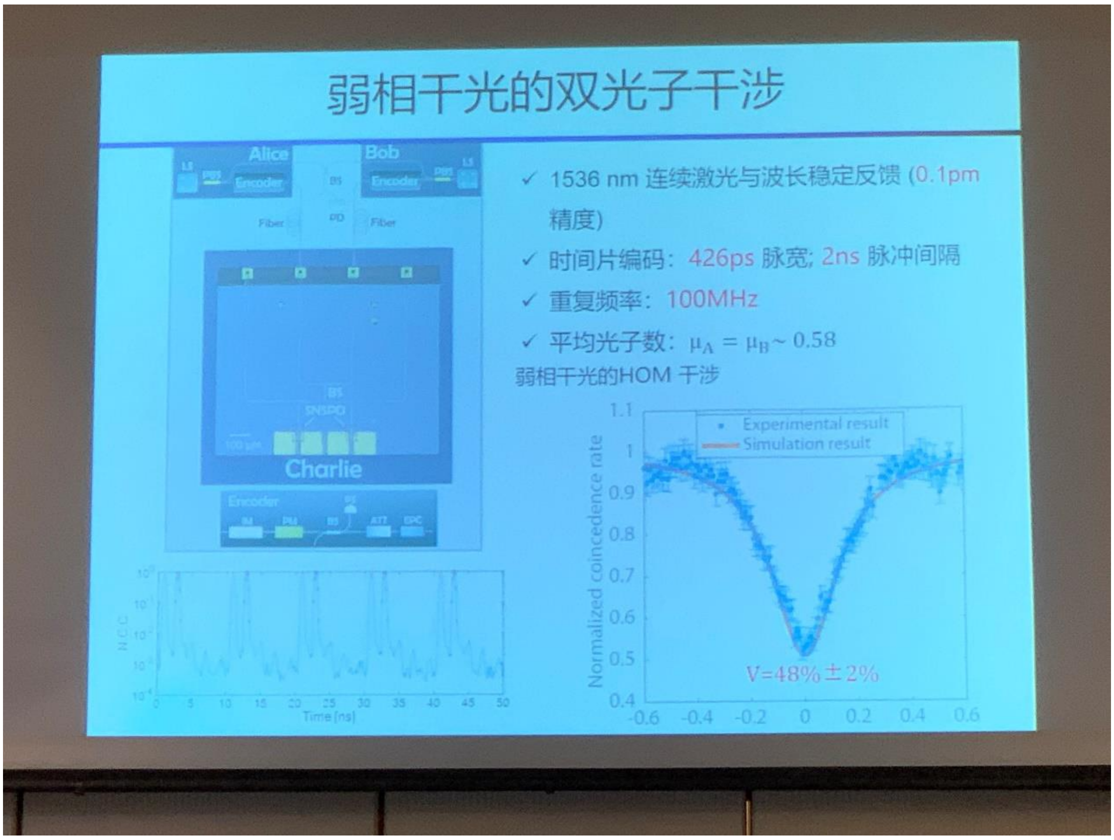

波导耦合探测器的优势
传统超导探测器
波导耦合超导探测器
(a)
Fiber
6nm NbTiN
225nm SiO2
Si substrate
15 μm
decay time ~ 30 ns
Normalized Voltage
Time (ns)
decay time ~ 2 ns
Normalized Voltage
Time (ns)
Normalized Counts
Pulse Separation (ns)
Detector
31



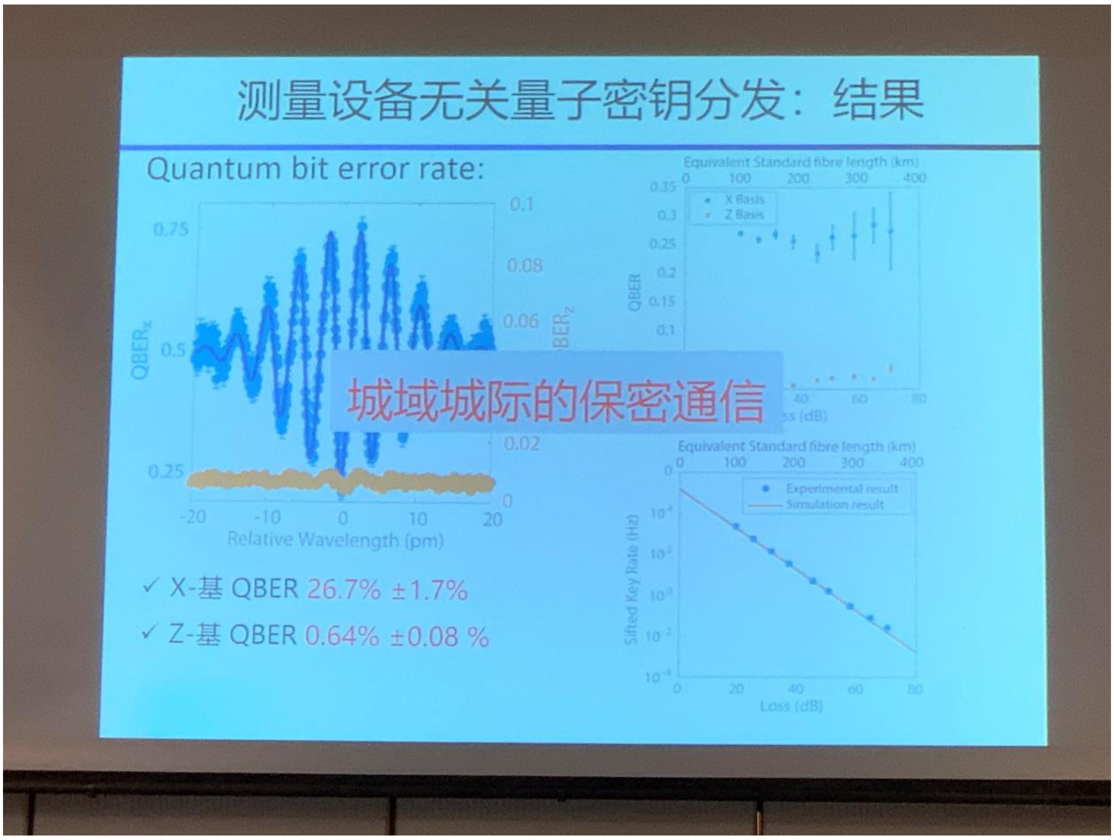
测量设备无关量子密钥分发服务器芯片
南大马小松、祝世宁、张蜡宝、吴培亨和中山大学蔡鑫伦
Alice
Bob
LS
PBS
Encoder
BS
Fiber
PD
PC
SNSPD
100 μm
Charlie
IM
PM
ATT
EPC
(a)
中继
芯片
100 MHz 系统重复频率， 426 ps 脉冲宽度，0.1 pm 精度实时波长反馈调节
32

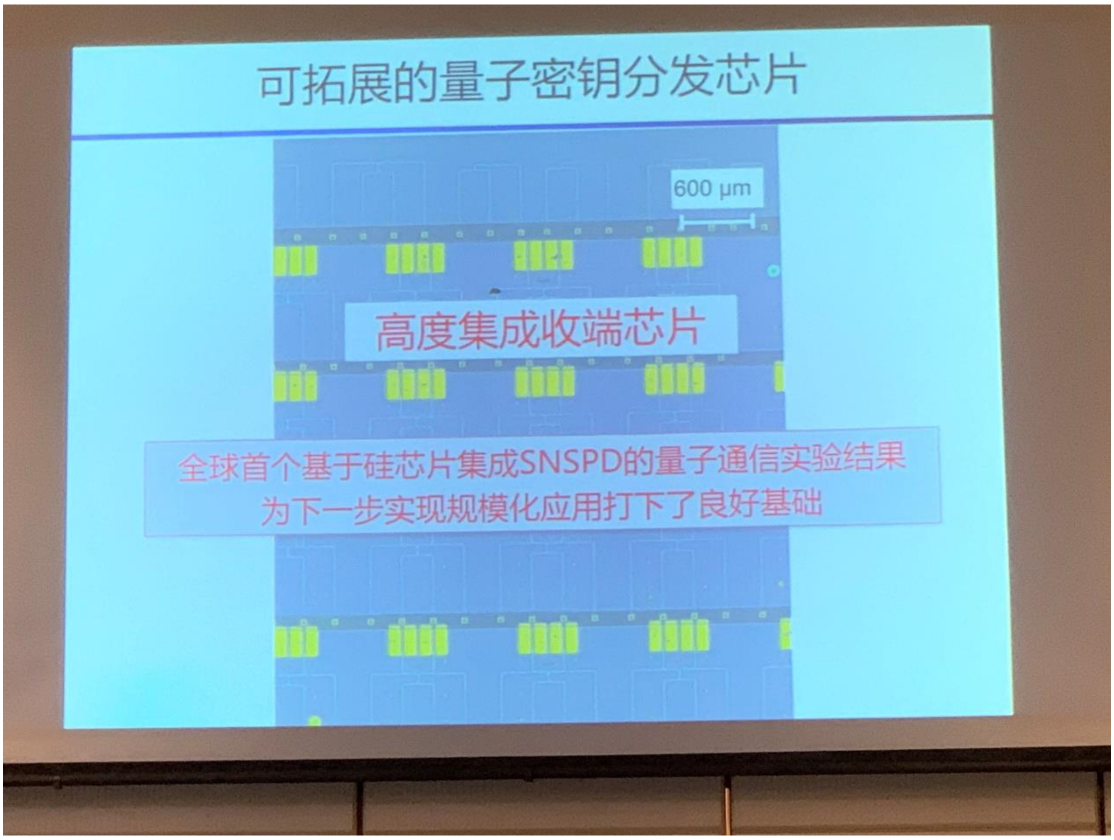
波导集成超导纳米线单光子探测器(SSPD)
高效率光栅耦合器
20 μm
高探测效率、低暗计数的SSPD
Pad
Width=80 nm
Length=80 μm
10 μm
Coupling Loss (dB)
-2.2dB
Wavelength (nm)
1510
1530
1550
1570
60% @1536nm
On Chip Detection Efficiency
Dark Count Rate (Hz)
Bias Current (μA)
片上探测效率~80%
暗计数率$d_c$< 1Hz (biased at 6.8 μA)
33



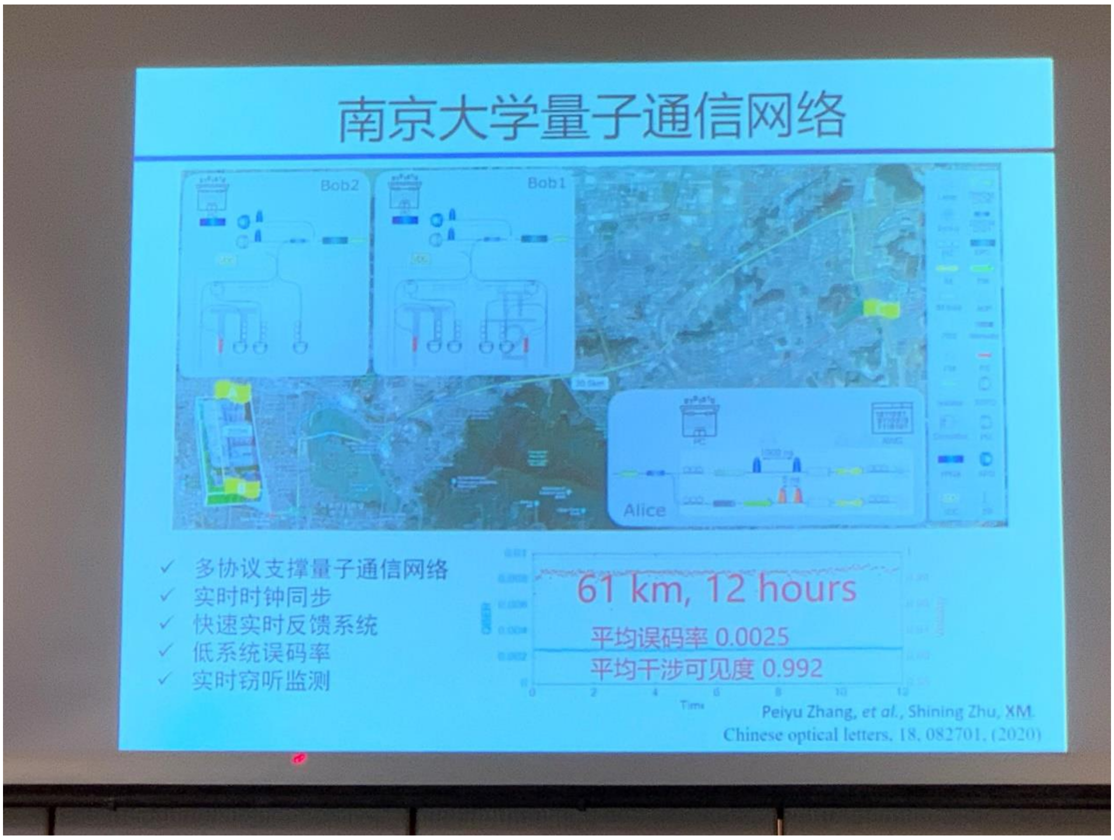
弱相干光的双光子干涉
Alice
Bob
Encoder
Charlie
✓ 1536 nm 连续激光与波长稳定反馈 (0.1pm 精度)
✓ 时间片编码：426ps 脉宽; 2ns 脉冲间隔
✓ 重复频率：100MHz
✓ 平均光子数：μA = μB ~ 0.58
弱相干光的HOM 干涉
Experimental result
Simulation result
Normalized coincidence rate
V=48%±2%
Time (ns)

测量设备无关量子密钥分发：结果
Quantum bit error rate:
Relative Wavelength (pm)
✓ X-基 QBER 26.7% ±1.7%
✓ Z-基 QBER 0.64% ±0.08 %
城域城际的保密通信
Equivalent Standard fibre length (km)
X Basis
Z Basis
QBER
Experimental result
Simulation result
Sifted Key Rate (Hz)
Loss (dB)



可拓展的量子密钥分发芯片
600 μm
高度集成收端芯片
全球首个基于硅芯片集成SNSPD的量子通信实验结果
为下一步实现规模化应用打下了良好基础

南京大学量子通信网络
Bob2
Bob1
Alice
✓ 多协议支撑量子通信网络
✓ 实时时钟同步
✓ 快速实时反馈系统
✓ 低系统误码率
✓ 实时窃听监测
61 km, 12 hours
平均误码率 0.0025
平均干涉可见度 0.992
Peiyu Zhang, et al., Shining Zhu, XM
Chinese optical letters, 18, 082701, (2020)

Quantum optics group @ Nanjing University
Postdoctoral Fellows
Yubo Xie
Liangliang Lu
Xinhe Jiang
Zhaozhong Chen
Ph.D Students
Kai Wang
Wenchao Ma
Yiquan Yang
Master Students
Lijun Xia
Peng Chen
Peiyu Zhang
Tong Wu
Zhiyu Chen
Fangchao Qu
Kaiyi Qian
Wenjun wen
Xiaodong Zheng