基于纠缠态光场的量子网络

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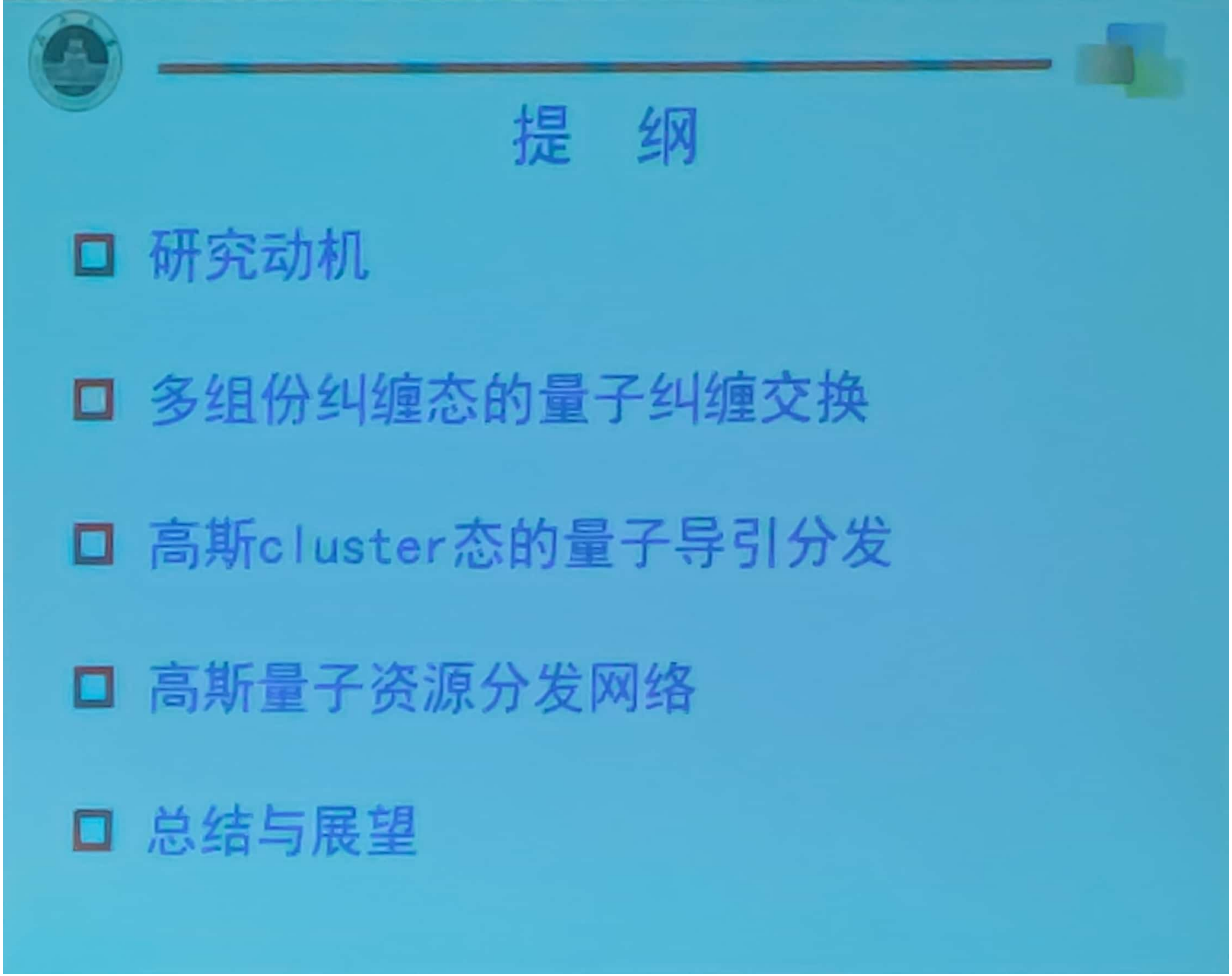
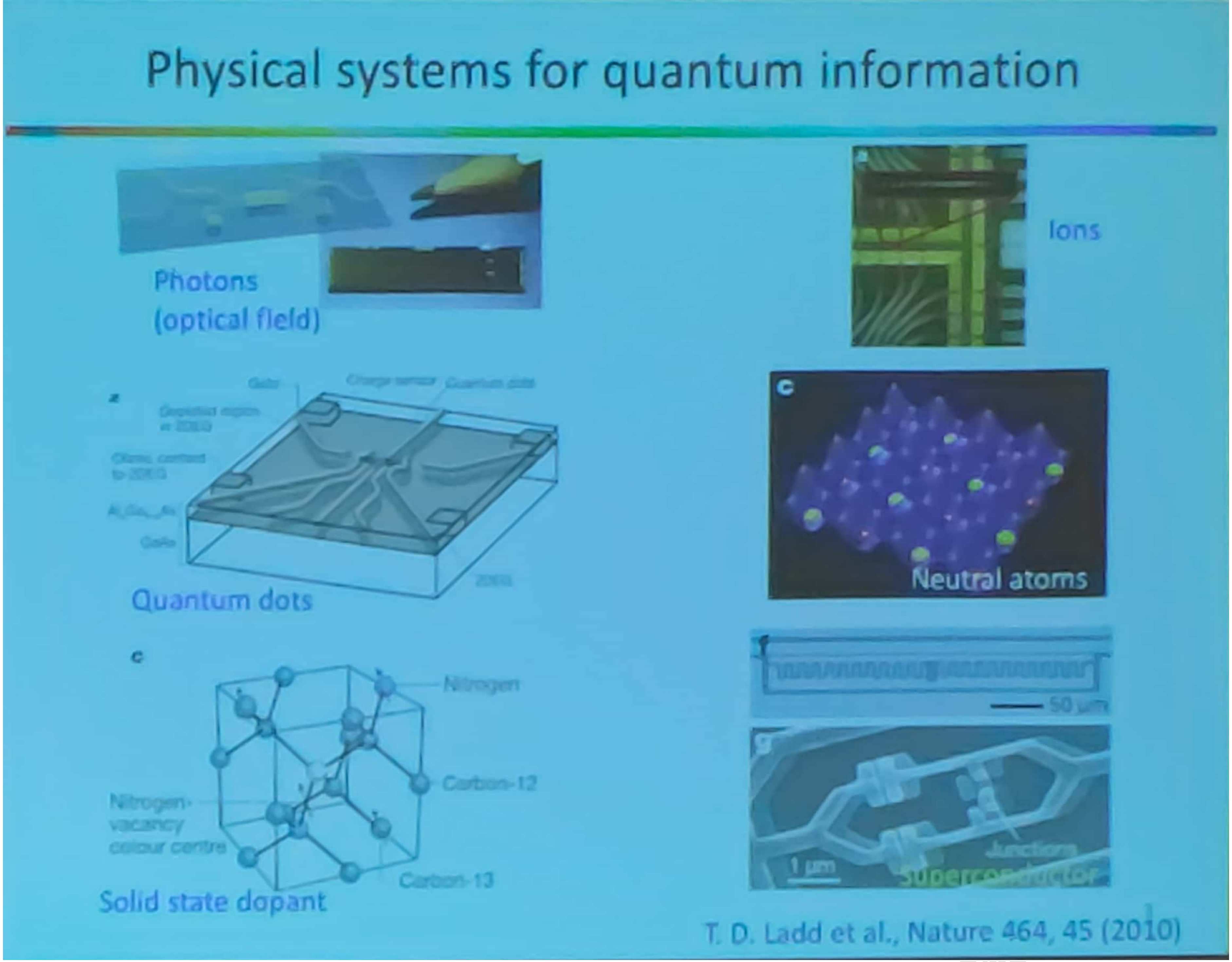
2021.5 重庆

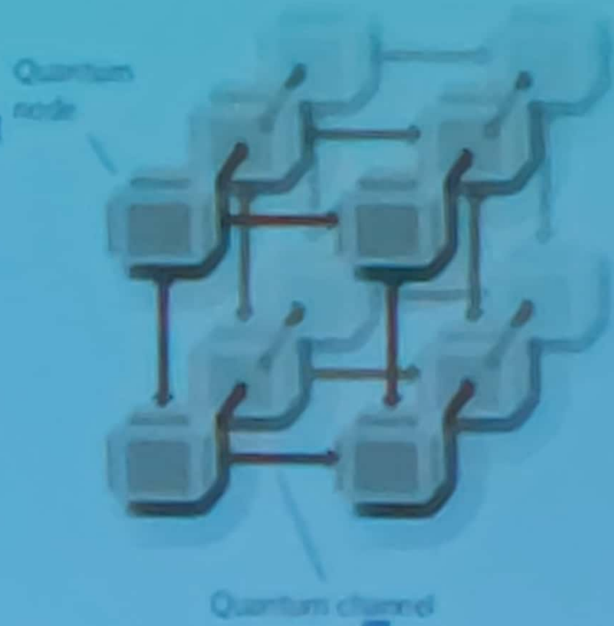
山西大学光电研究所


提 纲
研究动机
多组份纠缠态的量子纠缠交换
高斯cluster态的量子导引分发
高斯量子资源分发网络
总结与展望


Physical systems for quantum information
Photons
(optical field)
Ions
Quantum dots
Neutral atoms
Nitrogen
Carbon-12
Nitrogen-
vacancy
colour centre
Carbon-13
Solid state dopant
50 μm
1 μm
Junctions
Superconductor
T. D. Ladd et al., Nature 464, 45 (2010)

研究动机：构建量子网络

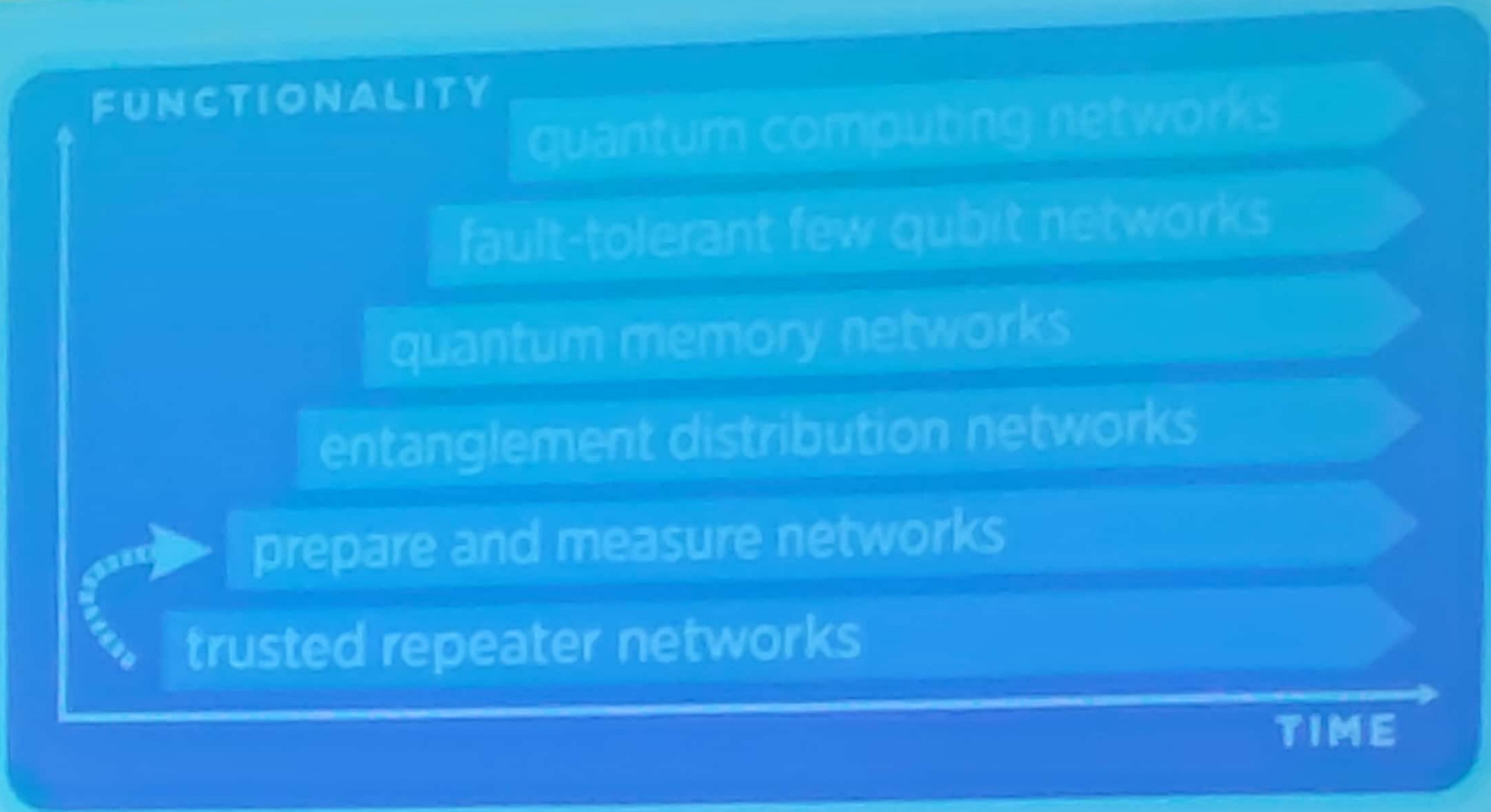
量子信息处理
量子计算
量子模拟
量子纠错
量子存储
量子接口
… …



H. J. Kimble,
Nature **453**, 1023 (2008).

量子通信（量子态的传输）
量子纠缠分发
量子密钥分发
量子纠错
… …

Stages of quantum internet



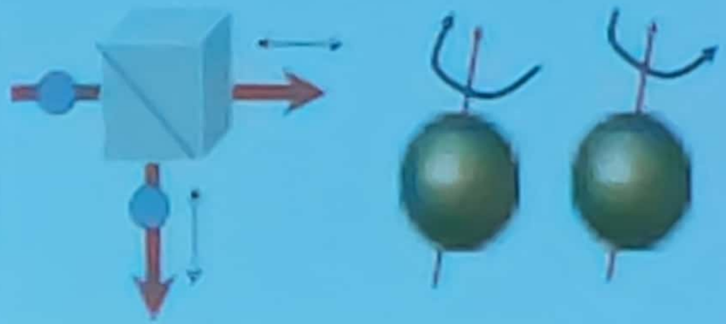
Quantum internet: A vision for the road ahead, **Science** 362, 303 (2018)

Motivation and background

Optical Quantum information

Discrete variables

Qubit $\boxed{\alpha|0\rangle + \beta|1\rangle}$

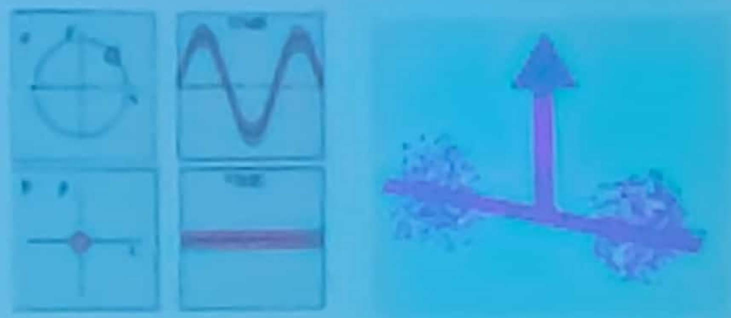


Polarization   Spin

- 🙂 Maximum entanglement
- ☹ Probabilistic

Continuous variables

Qumode $\boxed{\hat{X},\ \hat{Y}}$



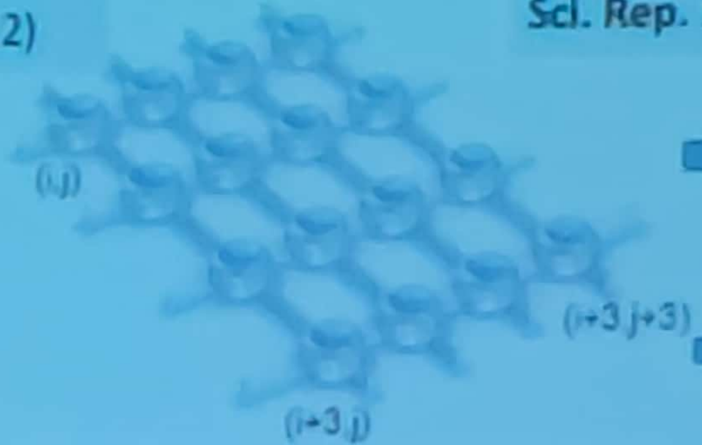
Amplitude and phase quadratutes   Position and Momentum

- 🙂 Deterministic
- ☹ Finite entanglement

Quantum information with continuous variables

Preparation of Cluster state
Four-mode CV cluster state
PRL, 98,070502 (2007)
Eight-mode CV cluster state
Opt. Lett. 37, 5178 (2012)

One-way quantum computation
Gate sequence for CV one-way QC
Nat. Commun. 4, 2828 (2013)
Five-wavepacket QEC
Sci. Rep. 5, 15462 (2015)



Multipartite entangled state

Quantum network
Swapping between multipartite states
PRL 117, 240503 (2016)
Distribution of Gaussian EPR steering
PRL 118, 230501 (2017)
PRL 125, 250506 (2020)
npj Quantum Information 7, 65 (2021)

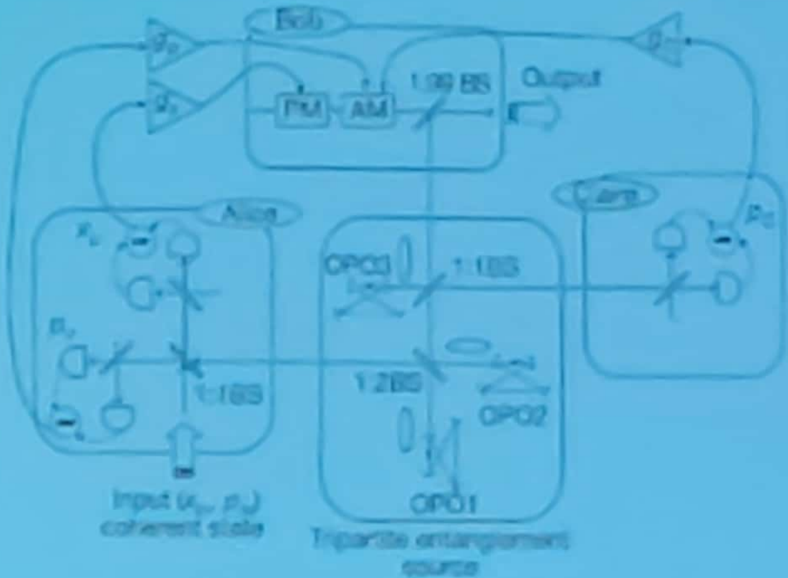
Fundamental physics
Characterizing multipartite entanglement
npj Quantum Information 5, 3 (2019)
Test of error-disturbance uncertainty relation
npj Quantum Information 5, 68 (2019)

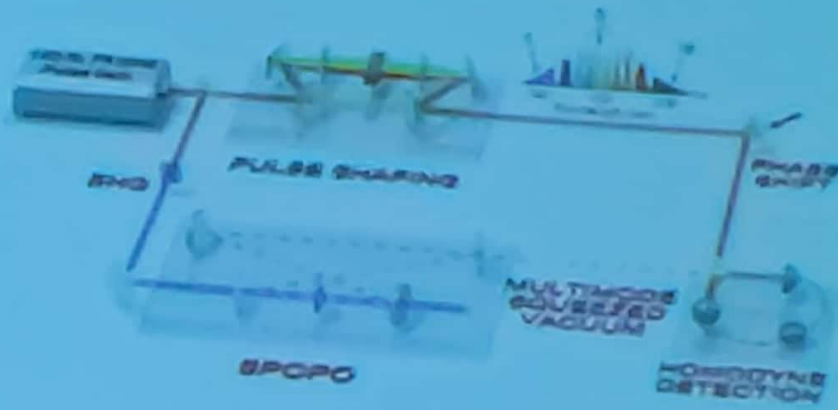
- 多组份纠缠态的量子纠缠交换

多组份纠缠态的量子纠缠交换

Distribute multipartite entangled state to quantum nodes

Local quantum network





Quantum teleportation network, Nature 431, 430-433 (2004)

Wavelength-multiplexed quantum networks with ultrafast frequency combs *Nat. Photon.* 8, 109-112 (2014)

多组份纠缠态的量子纠缠交换

Distribute multipartite entangled state to quantum nodes

⬇

Local quantum network

A global quantum network can be built by connecting several space-separated local quantum networks.

量子纠缠交换

ARTICLES
PUBLISHED ONLINE: 15 JUNE 2014 | DOI: 10.1038/NPHYS3000
nature physics

A quantum network of clocks

P. Kómár[1], E. M. Kessler[1,2], M. Bishof[3], L. Jiang[4], A. S. Sørensen[5], J. Ye[3] and M. D. Lukin[1*]

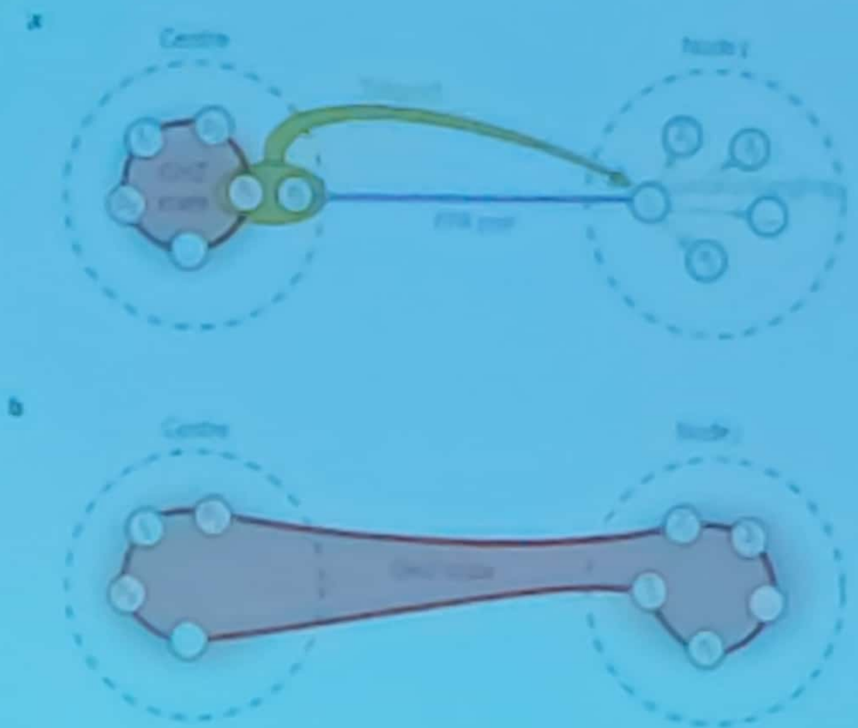
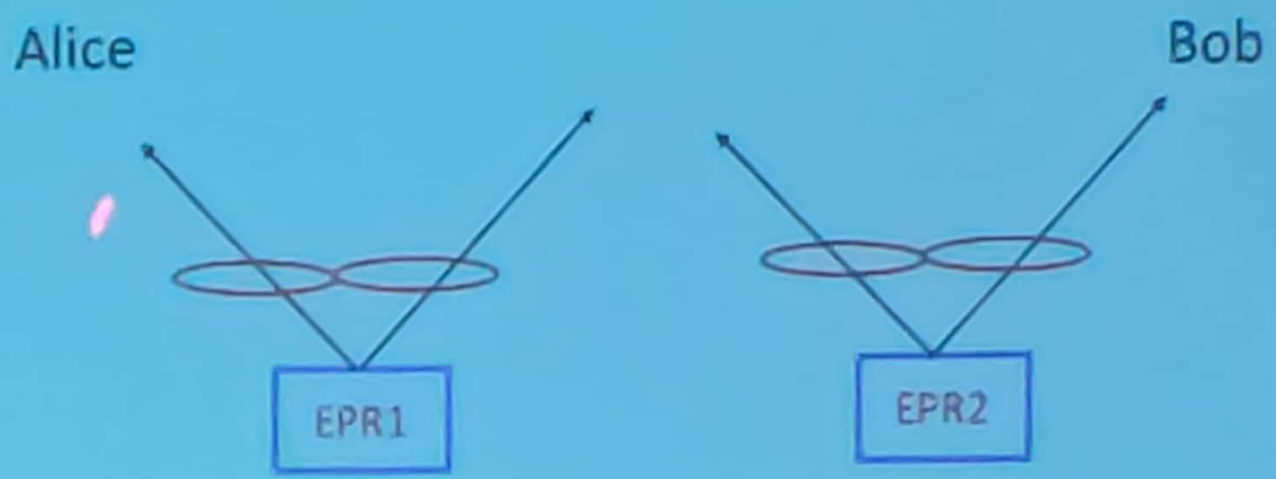


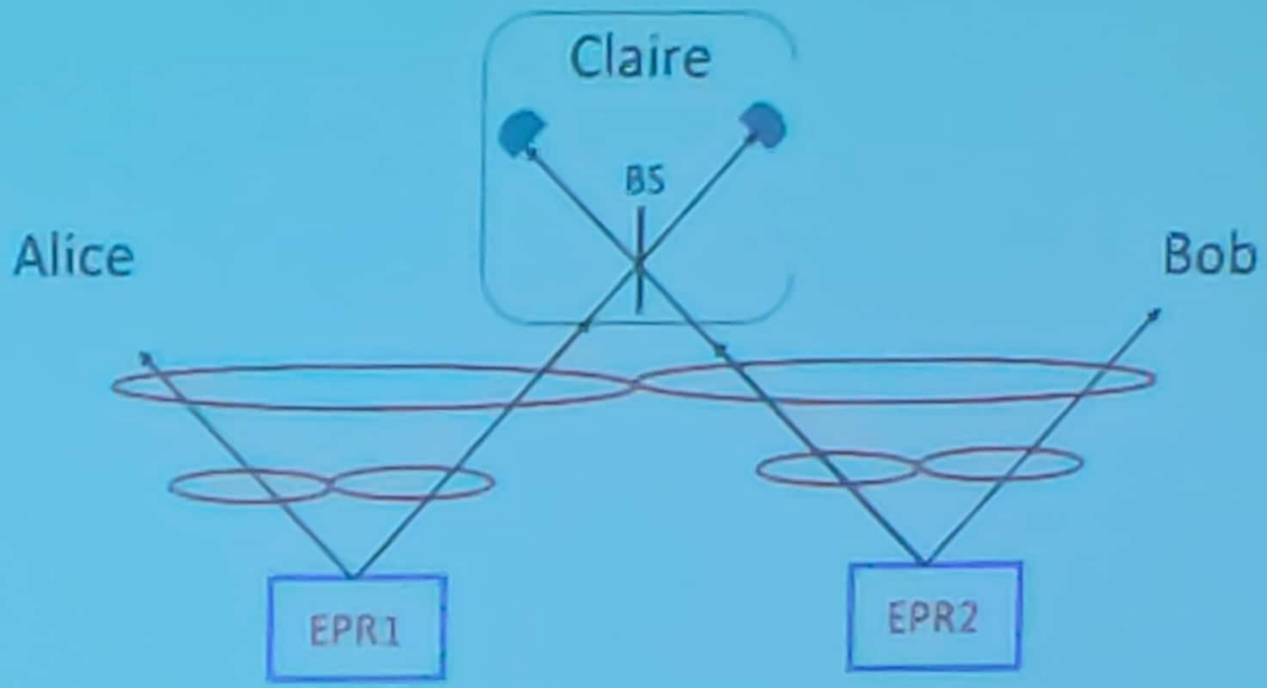
Figure 2 | Entangled state preparation between distant nodes.

Entanglement swapping

量子纠缠交换

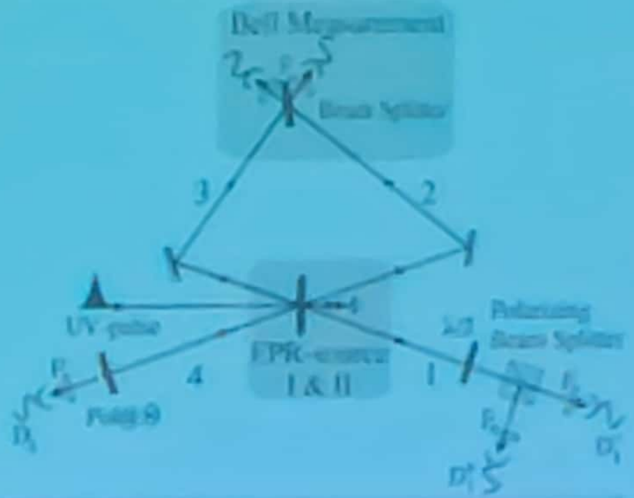


量子纠缠交换



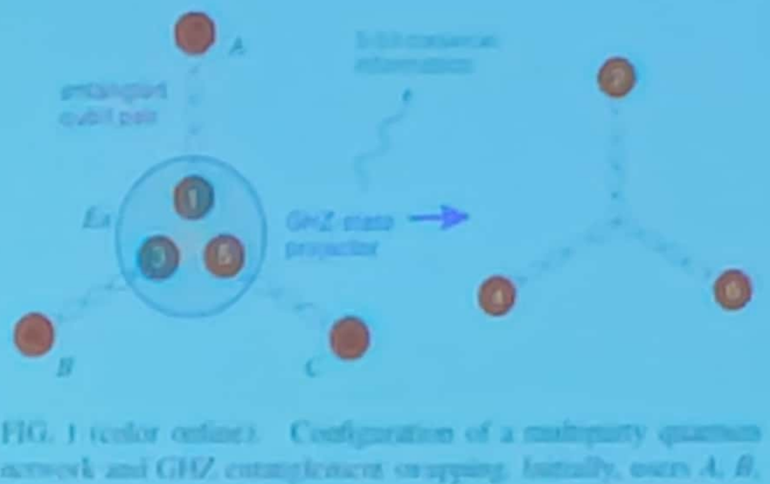
Joint measurement + feedforward of measurement results

量子纠缠交换实验进展



Phys. Rev. Lett. 80, 3891 (1998)

Phys. Rev. Lett. 93, 250503 (2004)

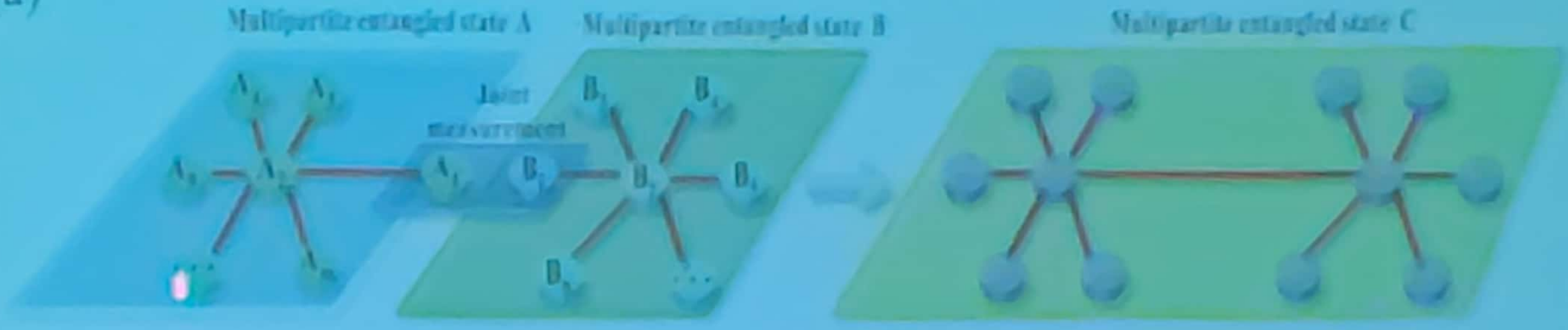


Phys. Rev. Lett. 103, 020501 (2009)

Phys. Rev. Lett. 114, 100501 (2015)

The principle of experiment

(a)



n+m	⟶	n+m-2
3+3	⟶	4
3+2	⟶	3

Xiaolong Su et al. PRL 117, 240503 (2016)

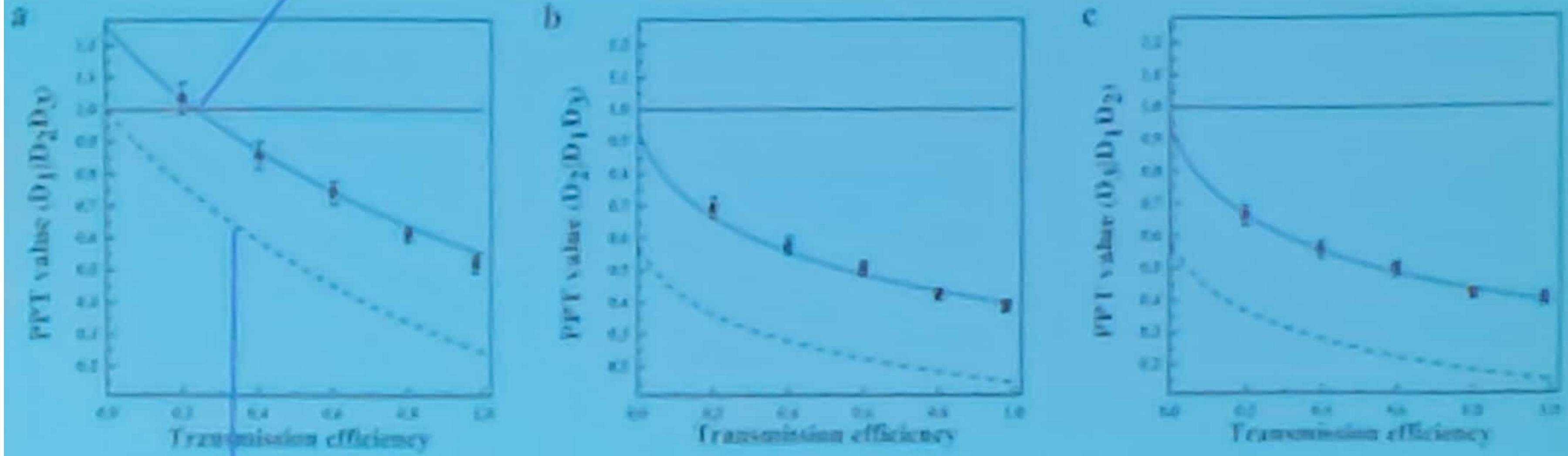
损耗信道中的量子纠缠

Necessary and sufficient condition

→ The positive partial transposition (PPT) criterion

Phys. Rev. Lett. **86**, 3658-3661 (2001)
Phys. Rev. A **73**, 032345 (2006)

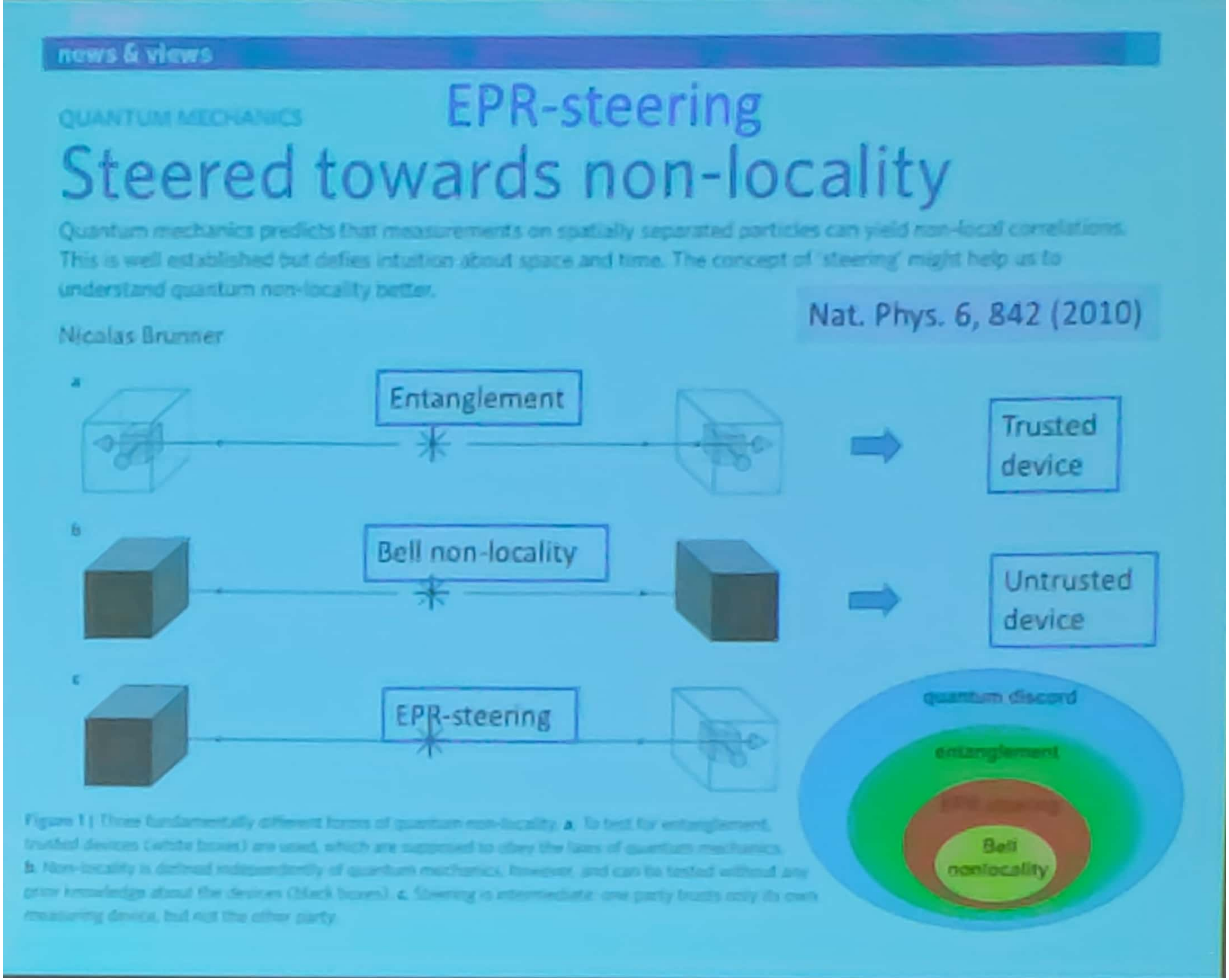
0.24



-10.9 dB squeezing

3+2 → 3

- 高斯cluster态的量子导引分发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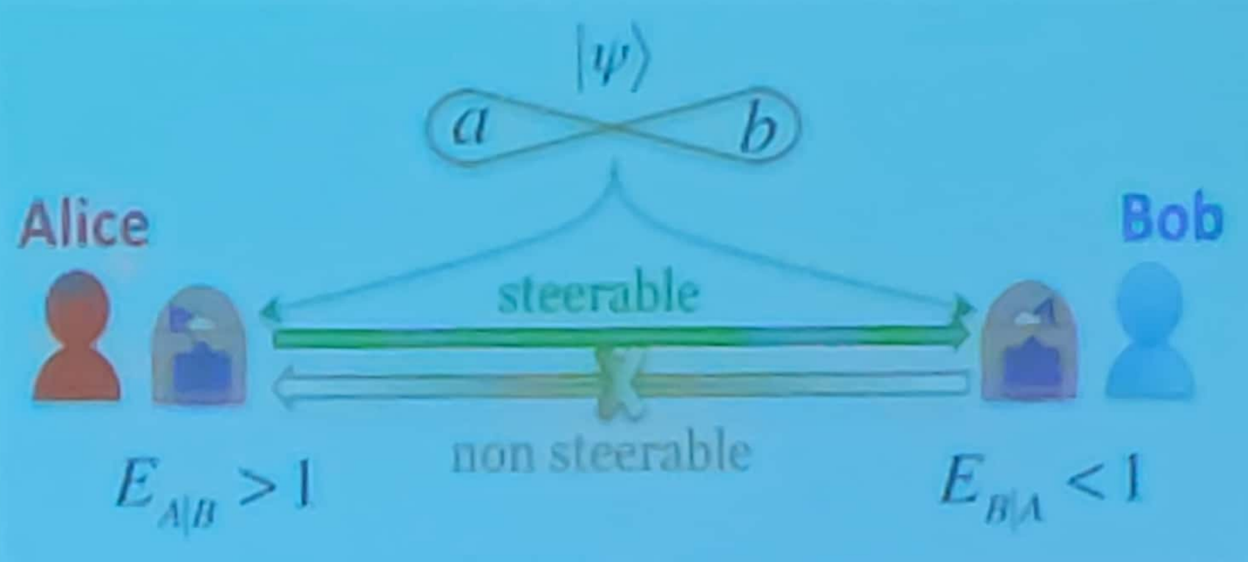
QUANTUM MECHANICS
EPR-steering
Steered towards non-locality
Quantum mechanics predicts that measurements on spatially separated particles can yield non-local correlations. This is well established but defies intuition about space and time. The concept of 'steering' might help us to understand quantum non-locality better.
Nicolas Brunner
Nat. Phys. 6, 842 (2010)
a
Entanglement
Trusted device
b
Bell non-locality
Untrusted device
c
EPR-steering
quantum discord
entanglement
Bell nonlocality

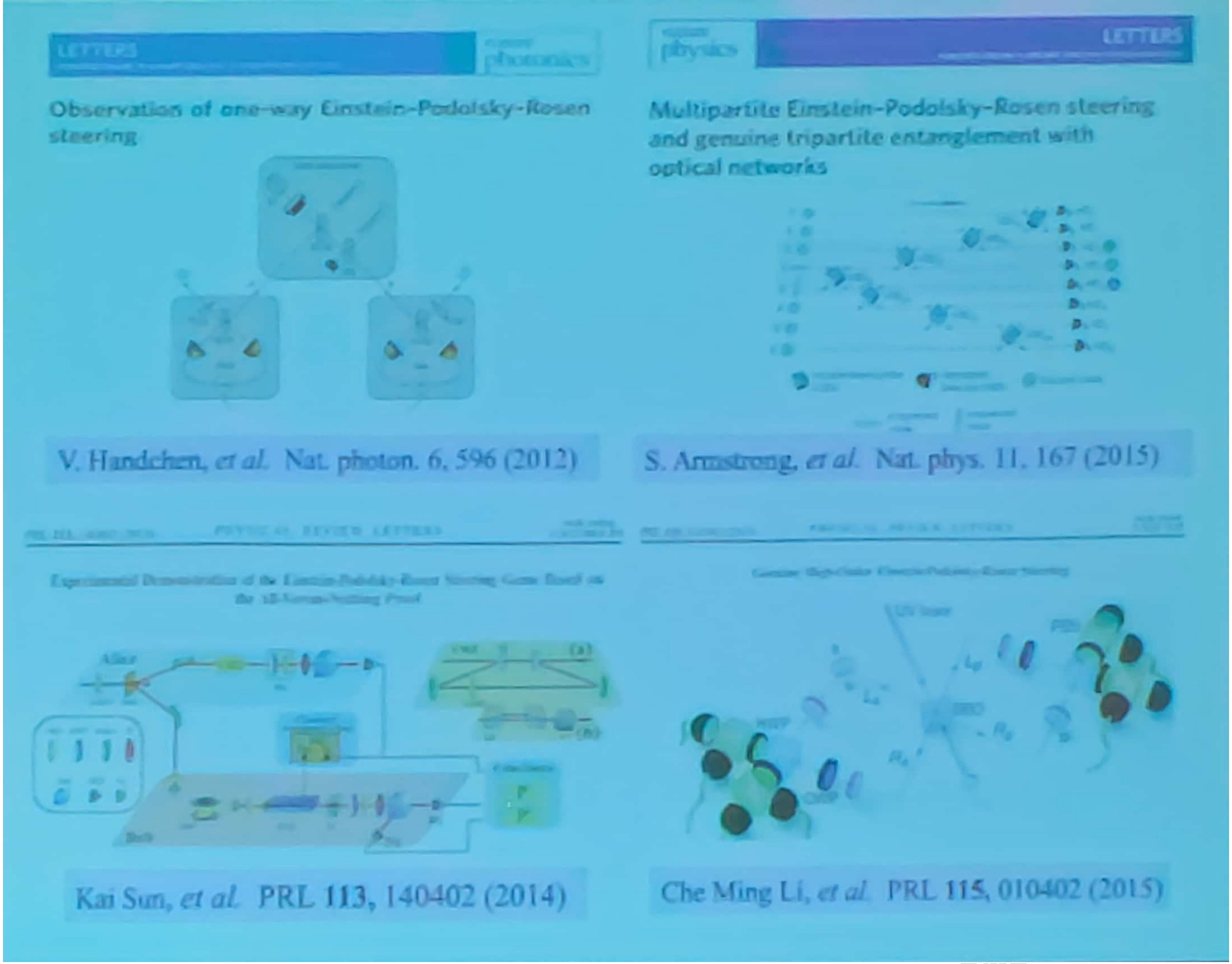
Verify the one-way EPR steering

One-way EPR steering

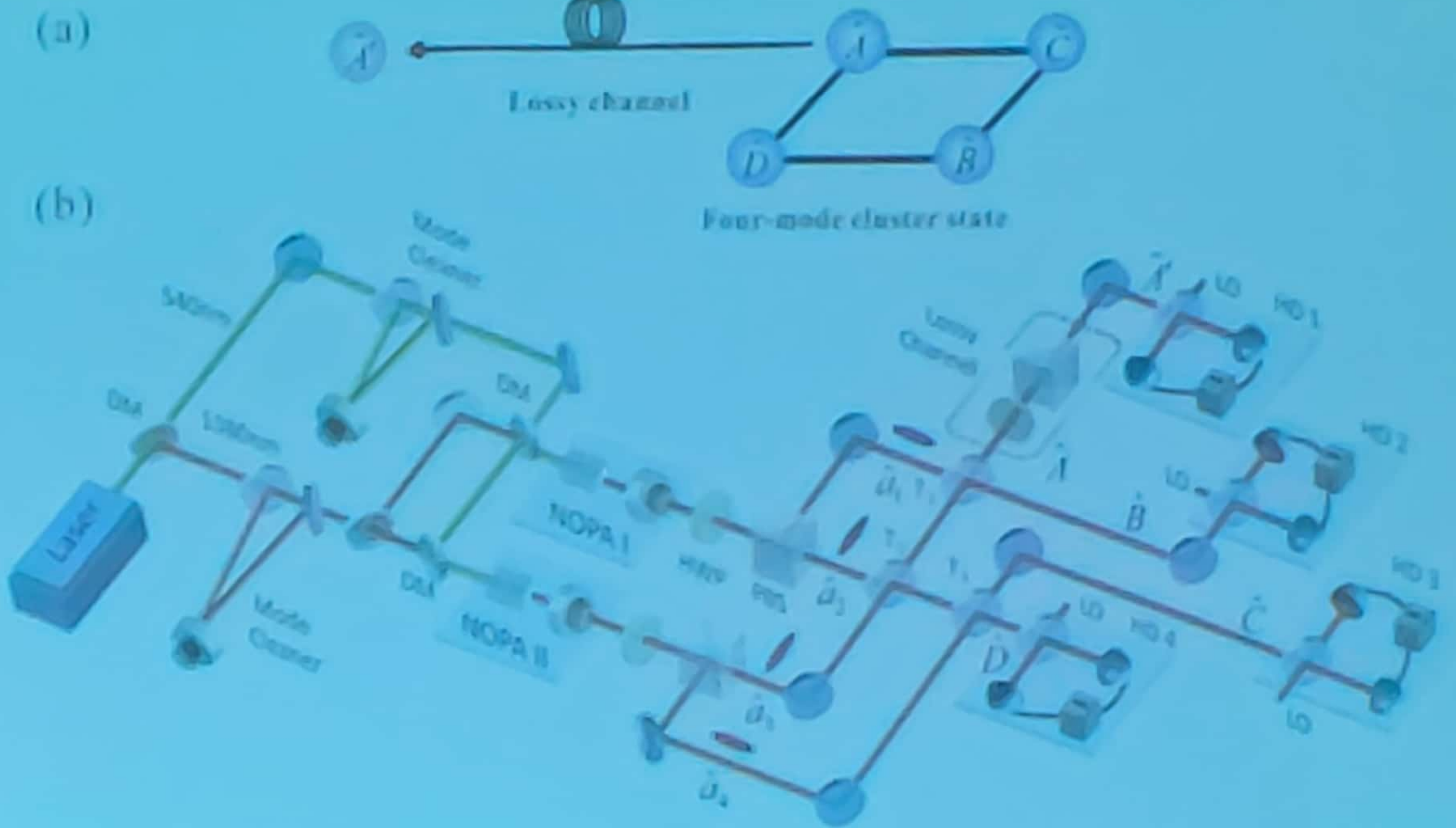


One side device independent QKD
PRA 85, 010301(R) (2012)

H. M. Wiseman, PRL.98,140402, (2007), E. G. Cavalcanti.., PRA.80.032112 (2009)
V. Handchen.2012, Nature Photonics,10.1038


LETTERS
photonics
Observation of one-way Einstein-Podolsky-Rosen steering
V. Handchen, et al. Nat. photon. 6, 596 (2012)
physics
LETTERS
Multipartite Einstein-Podolsky-Rosen steering and genuine tripartite entanglement with optical networks
S. Armstrong, et al. Nat. phys. 11, 167 (2015)
PHYSICAL REVIEW LETTERS
Alice
Bob
Kai Sun, et al. PRL 113, 140402 (2014)
PHYSICAL REVIEW LETTERS
UV laser
PBS
BBO
Che Ming Li, et al. PRL 115, 010402 (2015)

Demonstration of monogamy relations for EPR steering in Gaussian cluster state



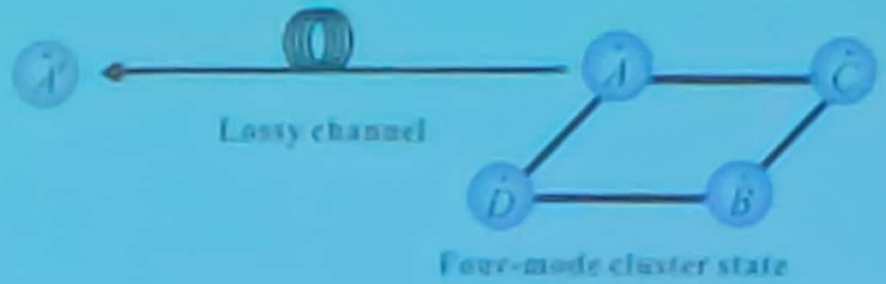
Xiaowei Deng et al. PRL 118, 230501 (2017)

Monogamy relations of Gaussian EPR steerability

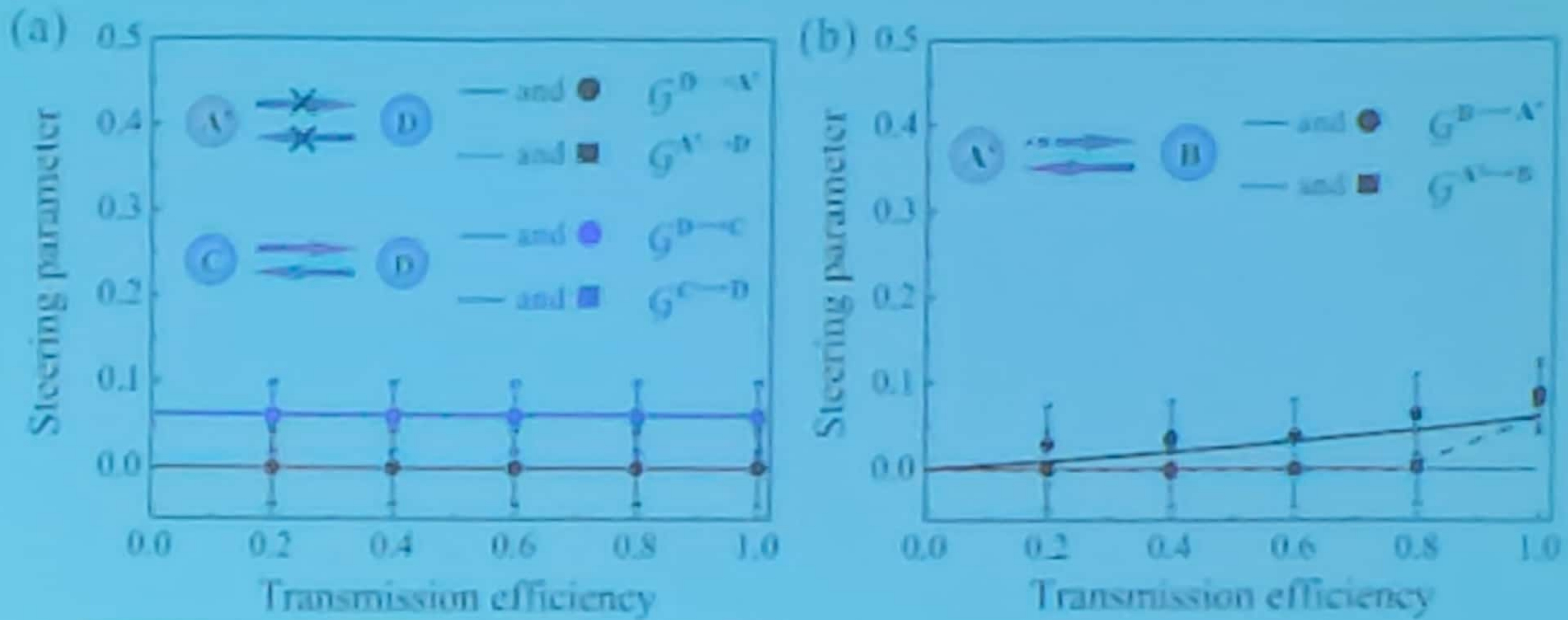
Type	Inequality	Specifications	
I	$\mathcal{G}^{A\to C} > 0 \;\Rightarrow\; \mathcal{G}^{B\to C} = 0$	$n_A = n_B = n_C = 1$	PRA, 88,062108
II	$\mathcal{G}^{A\to C} > 0 \;\Rightarrow\; \mathcal{G}^{B\to C} = 0$	$n_A, n_B \geq 1; n_C = 1$	JPA, 49, 34LT02
IIIa	$\mathcal{G}^{C\to(AB)} - \mathcal{G}^{C\to A} - \mathcal{G}^{C\to B} \geq 0$	$n_A = n_B = n_C = 1$	PRA, 95,010101
IIIb	$\mathcal{G}^{(AB)\to C} - \mathcal{G}^{A\to C} - \mathcal{G}^{B\to C} \geq 0$	$n_A = n_B = n_C = 1$	PRA, 95,010101
IVa	$\mathcal{G}^{C\to(AB)} - \mathcal{G}^{C\to A} - \mathcal{G}^{C\to B} \geq 0$	$n_A, n_B, n_C \geq 1$	PRL, 117,220502
IVb	$\mathcal{G}^{(AB)\to C} - \mathcal{G}^{A\to C} - \mathcal{G}^{B\to C} \geq 0$	$n_A, n_B \geq 1; n_C = 1$	PRL, 117,220502

TABLE I: Classification of monogamy relations for the bipartite quantifier $\mathcal{G}^{j\to k}$ of EPR steerability of party k by party j under Gaussian measurements, in a tripartite $(n_A + n_B + n_C)$-mode system ABC. Note: I $\sqsubseteq$ II and III $\sqsubseteq$ IV, where "$\sqsubseteq$" indicates being generalized by; the relations in types II and IVb can be violated for $n_C > 1$.

EPR steering between any two modes



位于对角位置的模式可以相互导引
位于相邻位置的模式不能相互导引

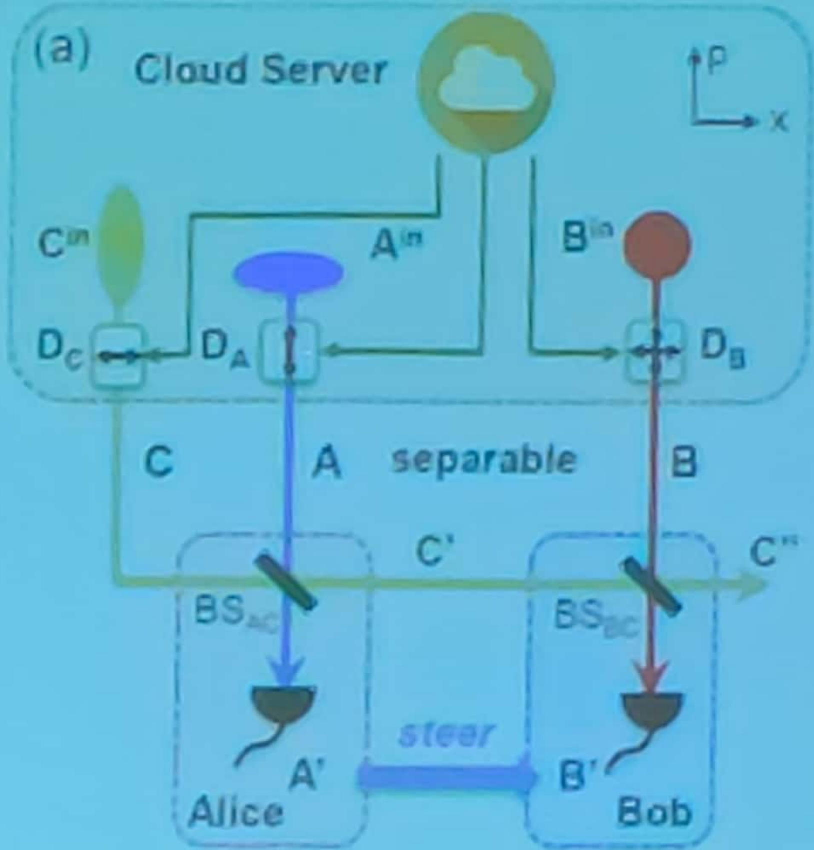


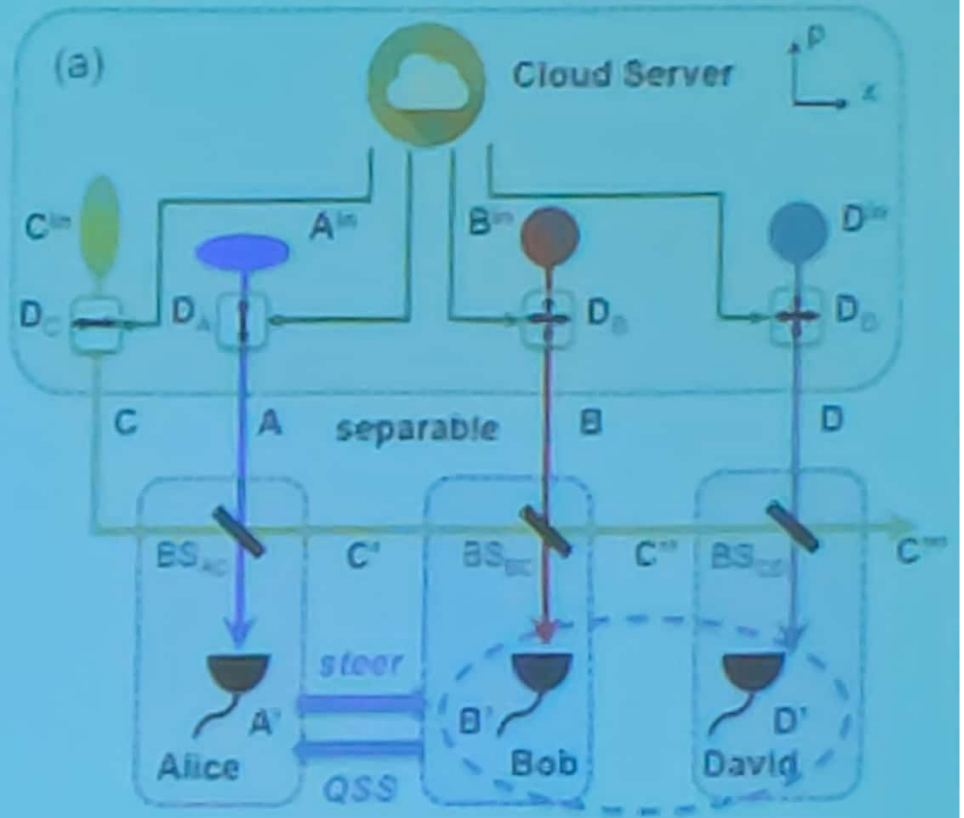
Type-I monogamy relation $\quad \mathcal{G}^{A\to C} > 0 \;\Rightarrow\; \mathcal{G}^{B\to C} = 0$

Xiaowei Deng et al. PRL 118, 230501 (2017)

- 高斯量子资源分发网络

Distribution of Gaussian EPR steering with separable states in a quantum network

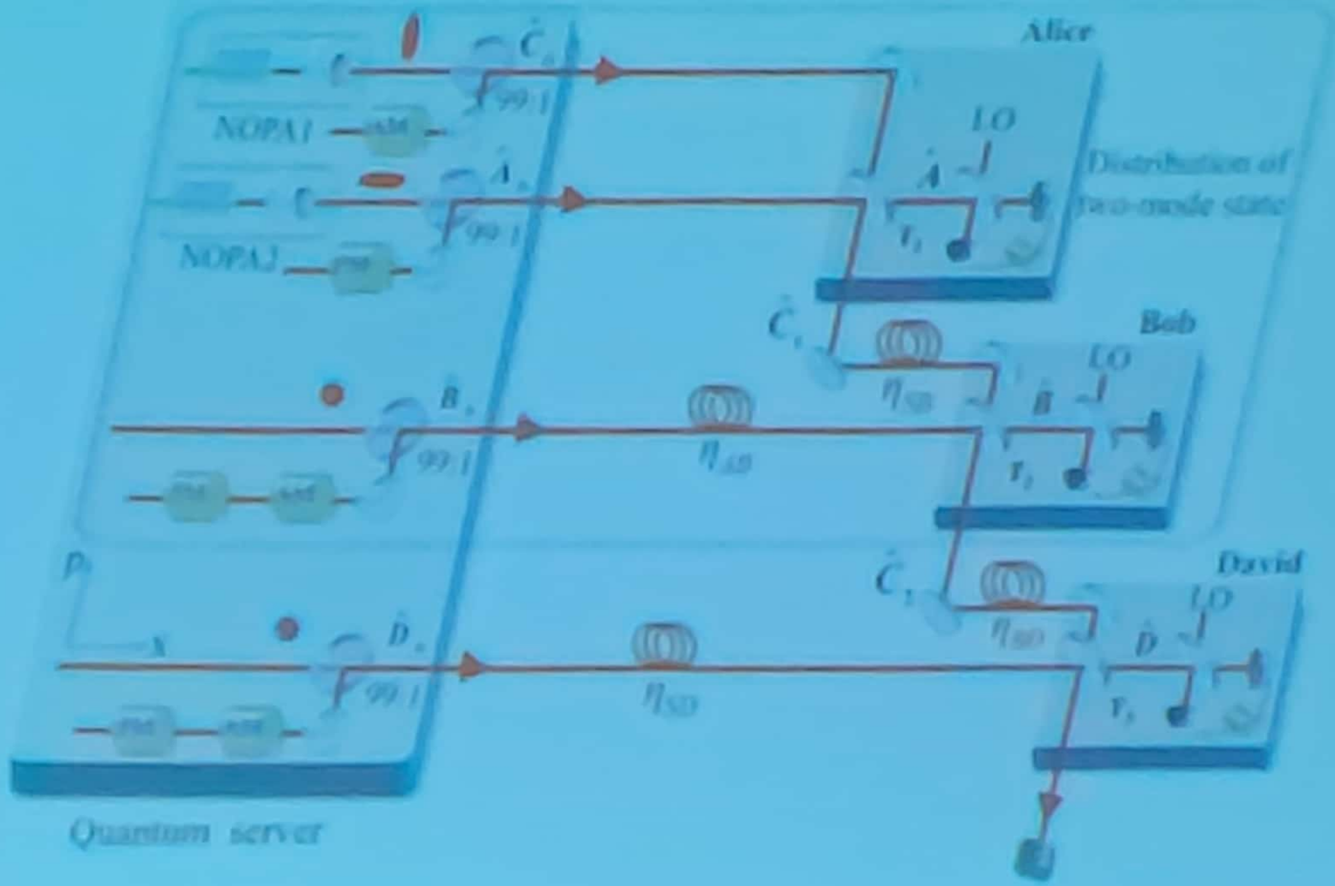




Quantum network for distribution of Gaussian quantum resource

Y. Xiang, X. Su, L. Mišta, Jr., G. Adesso and Q. He, Phys. Rev. A(R) 99, 010104 (2019)

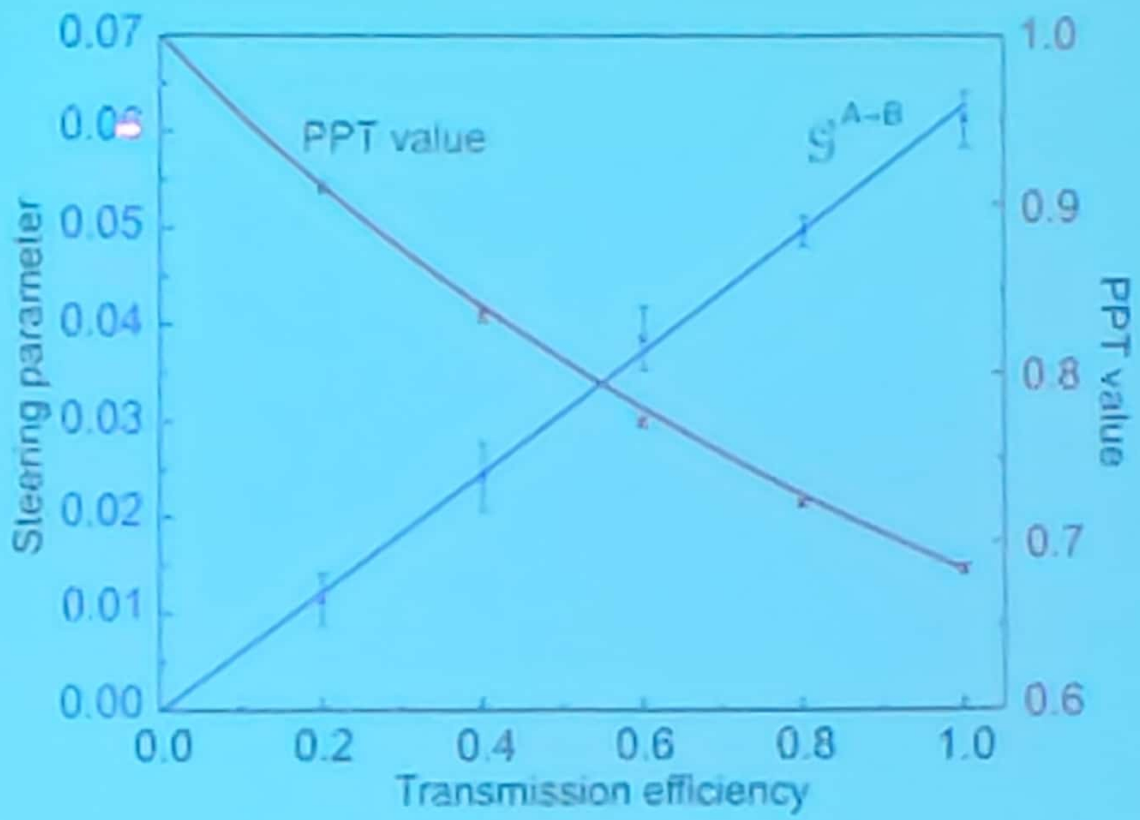
Experimental set-up



Meihong Wang et al. PRL 125, 260506 (2020)

Experimental results for two users

Dependence of quantum correlations on transmission efficiency in lossy channels



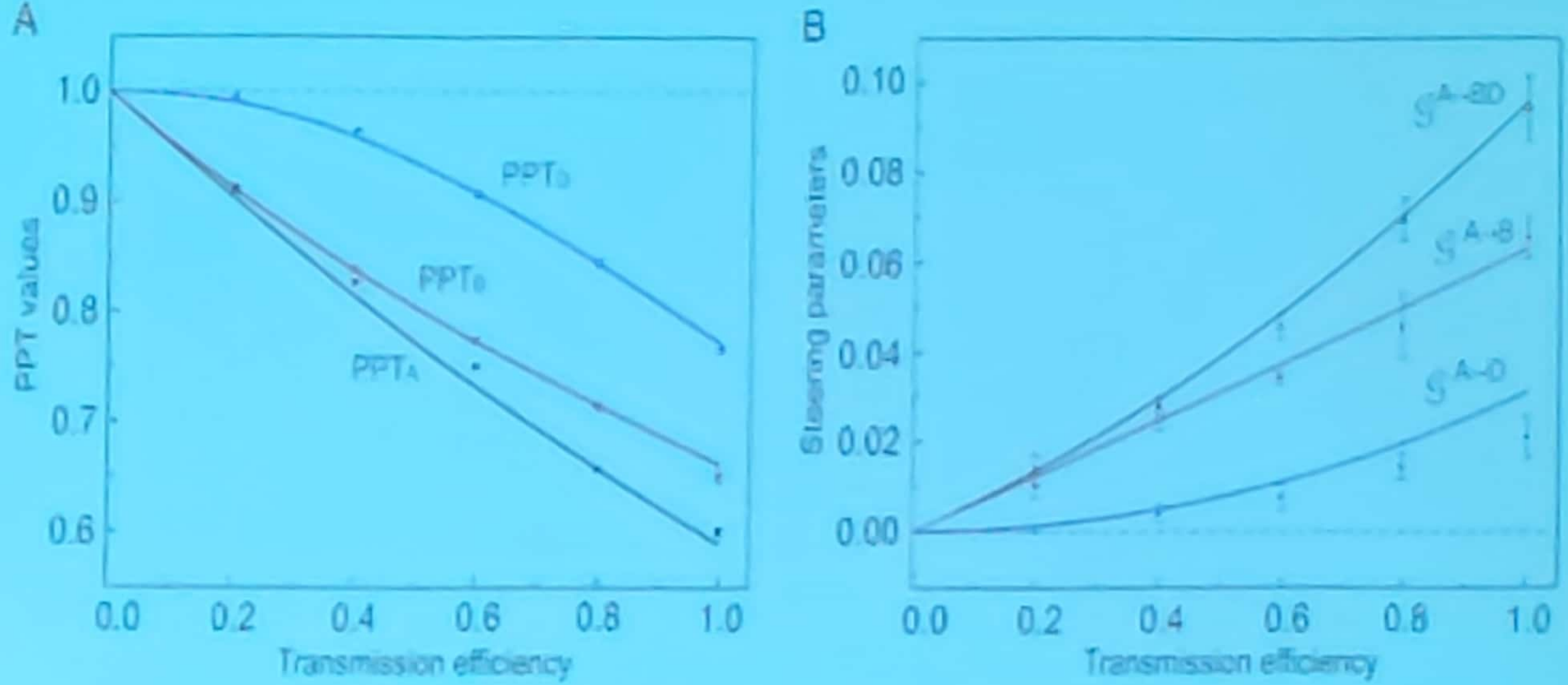
Optimized displacement $D_B' = \sqrt{\frac{\eta(1-T_2)}{T_2}} D_s$

The transmission efficiencies from Alice to Bob and Quantum server to Bob are equal in our experiment.

Meihong Wang et al.
PRL 125, 260506 (2020)

Experimental results for three users

Dependences of quantum correlations (A) quantum entanglement (B) EPR steering on transmission efficiency in lossy channels

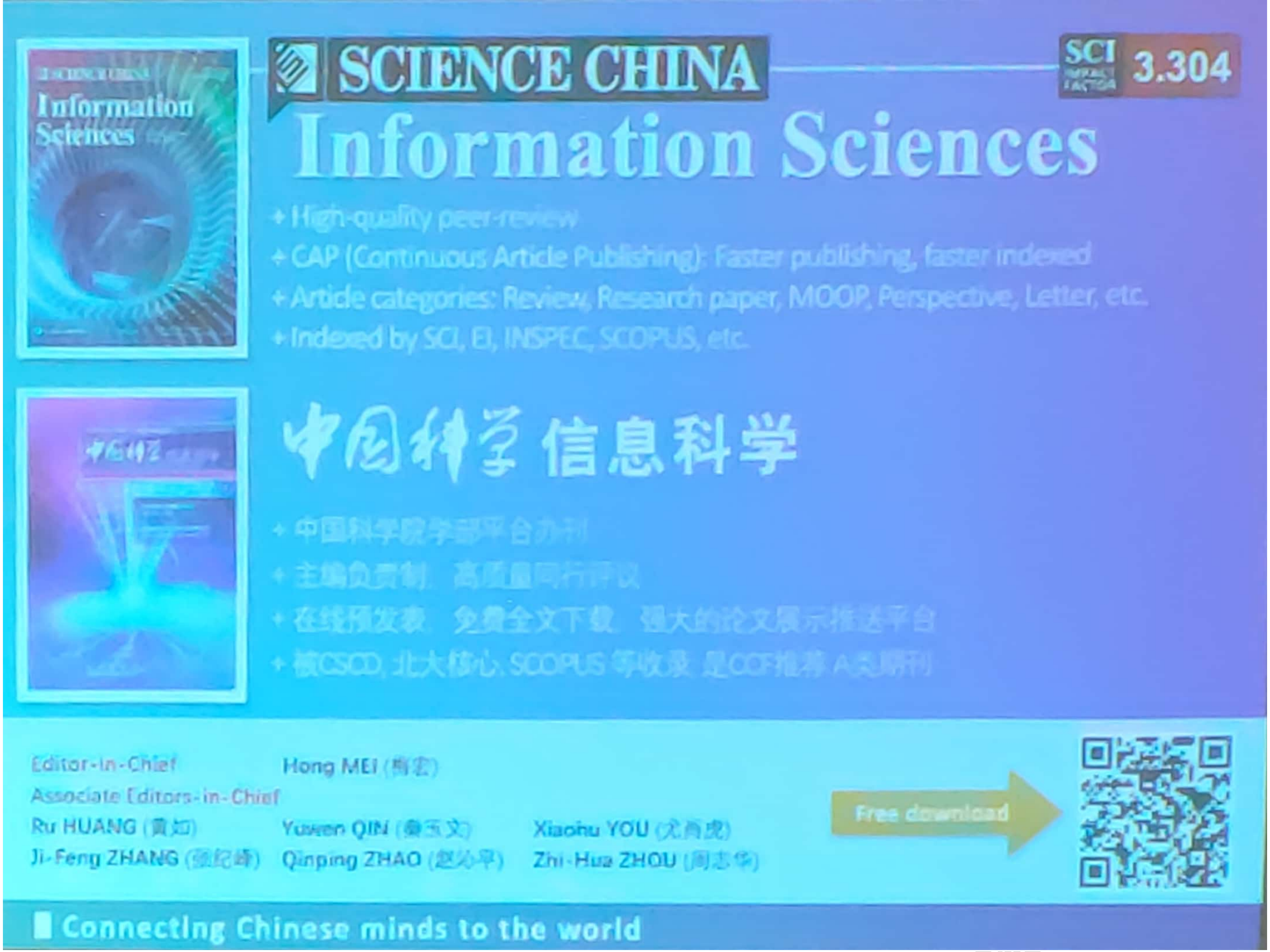


Optimized displacements $D_a' = D_a, D_b' = \sqrt{\eta}D_a = \sqrt{2\eta}D_a$

Meihong Wang et al. PRL 125, 260506 (2020)

总结与展望

- We experimentally demonstrate quantum entanglement swapping between two multipartite entangled states.
- We experimentally demonstrate the monogamy relations for EPR steering in Gaussian cluster state.
- We experimentally demonstrate distribution of Gaussian EPR-steering in a quantum network.
- Toward practical quantum internet.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