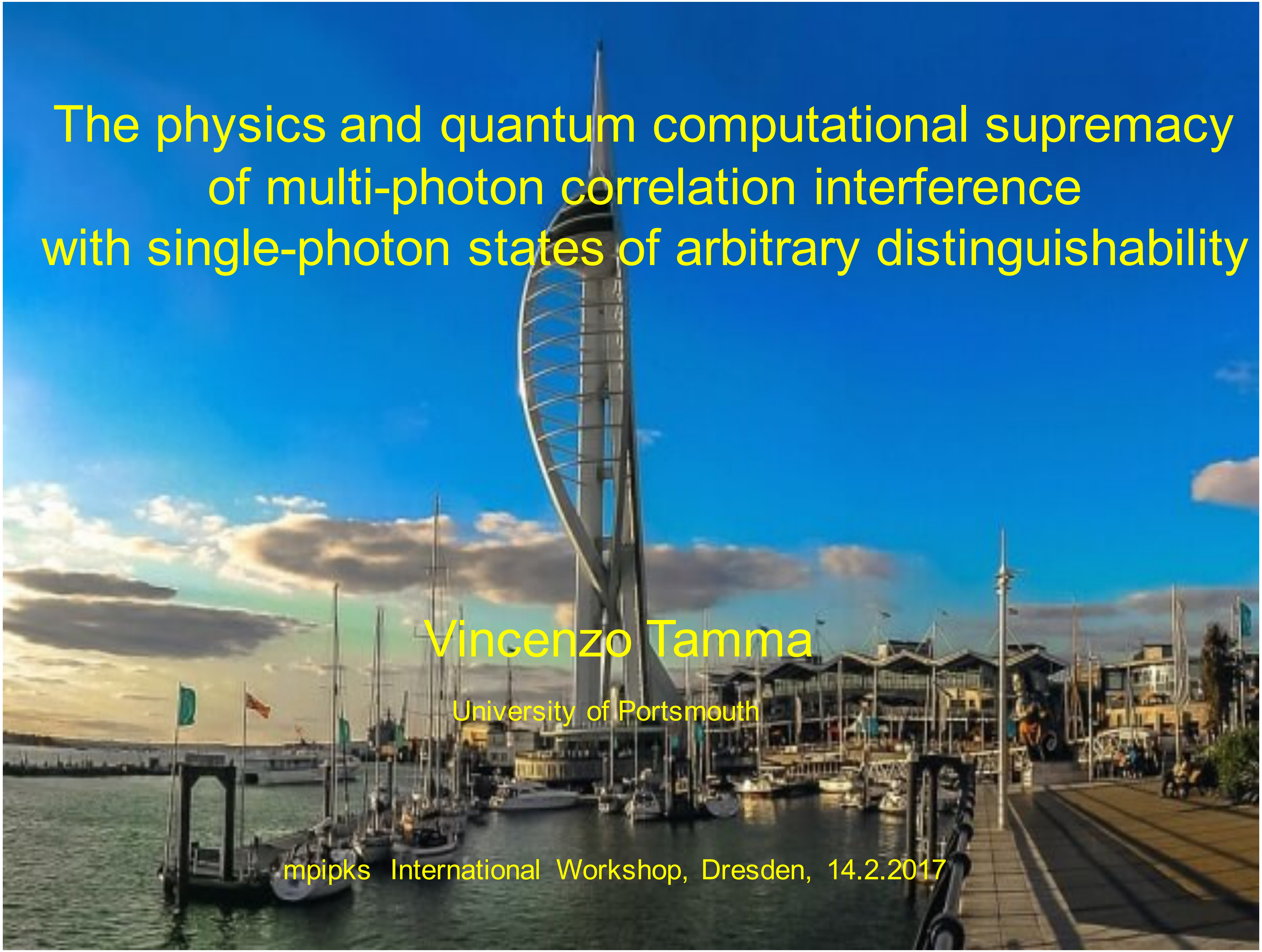


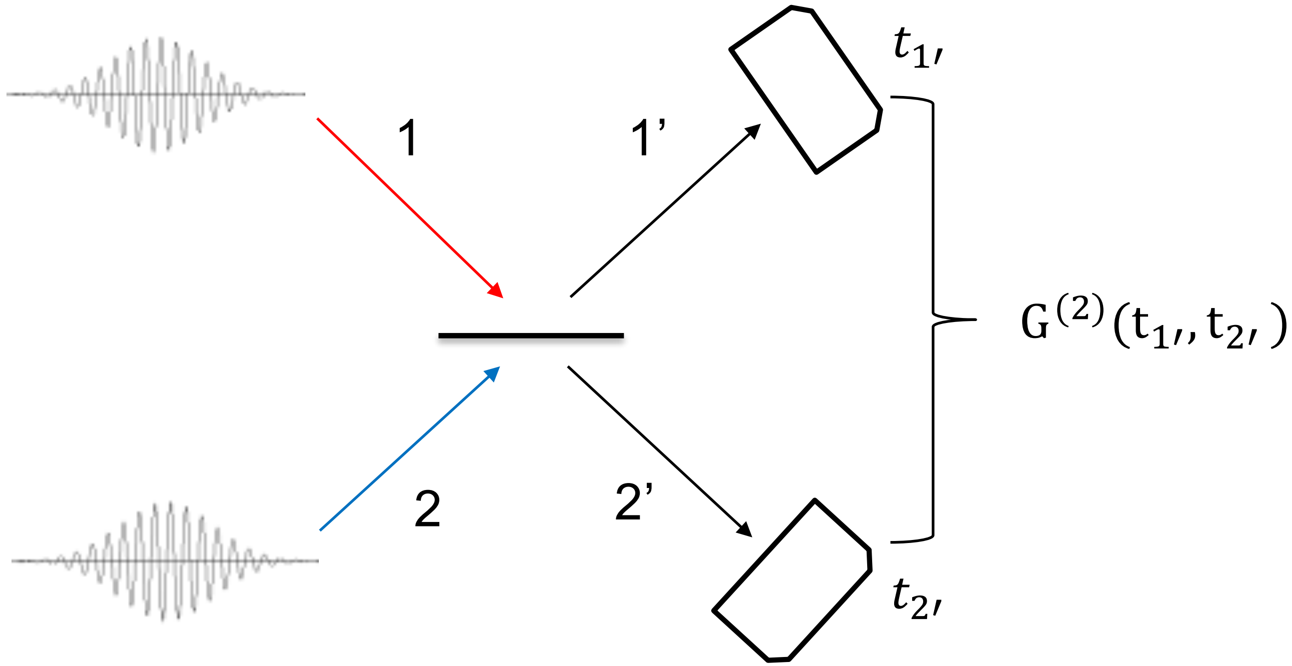
The physics and quantum computational supremacy of multi-photon correlation interference with single-photon states of arbitrary distinguishability

Vincenzo Tamma

University of Portsmouth

mpipks International Workshop, Dresden, 14.2.2017

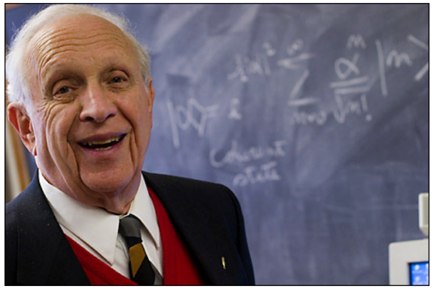
Two-photon interference at a beam splitter



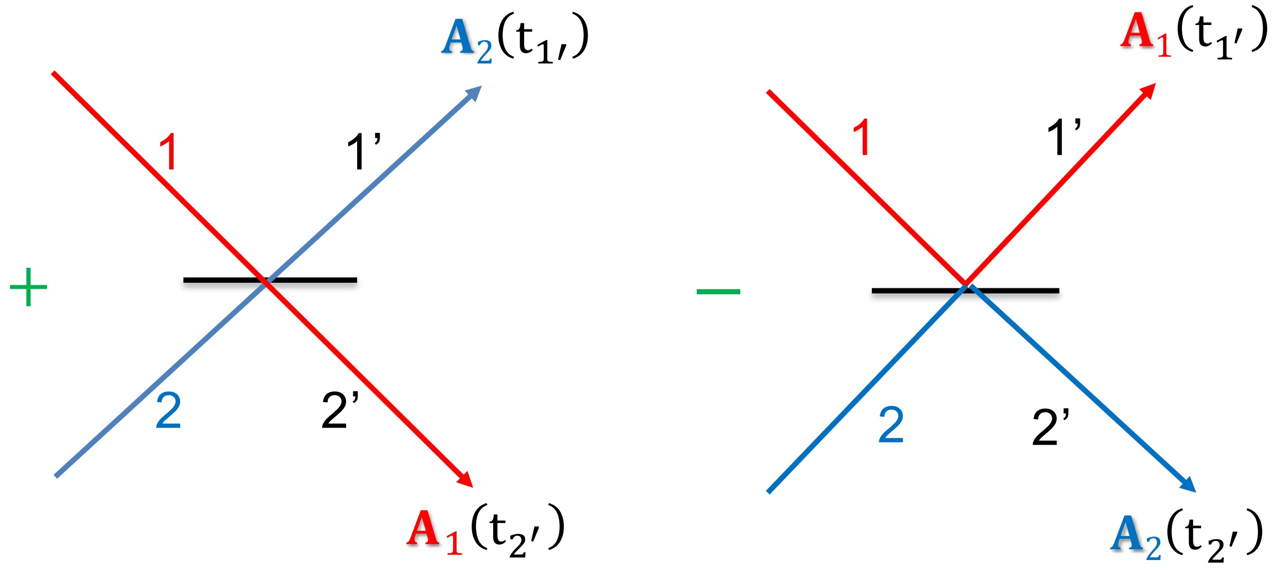
C. Hong, Z. Ou, and L. Mandel, PRL 59, 2044 (1987)
Y. H. Shih and C. O. Alley, PRL 61, 2921 (1988)
T. Legero, et al., PRL 93, 070503 (2004)

"It is not the photons that interfere physically, it is their probability amplitudes that interfere – and probability amplitudes can be defined equally well for arbitrary numbers of photons"

ONE HUNDRED YEARS OF LIGHT QUANTA Nobel Lecture, December 8, 2005 by Roy J. Glauber



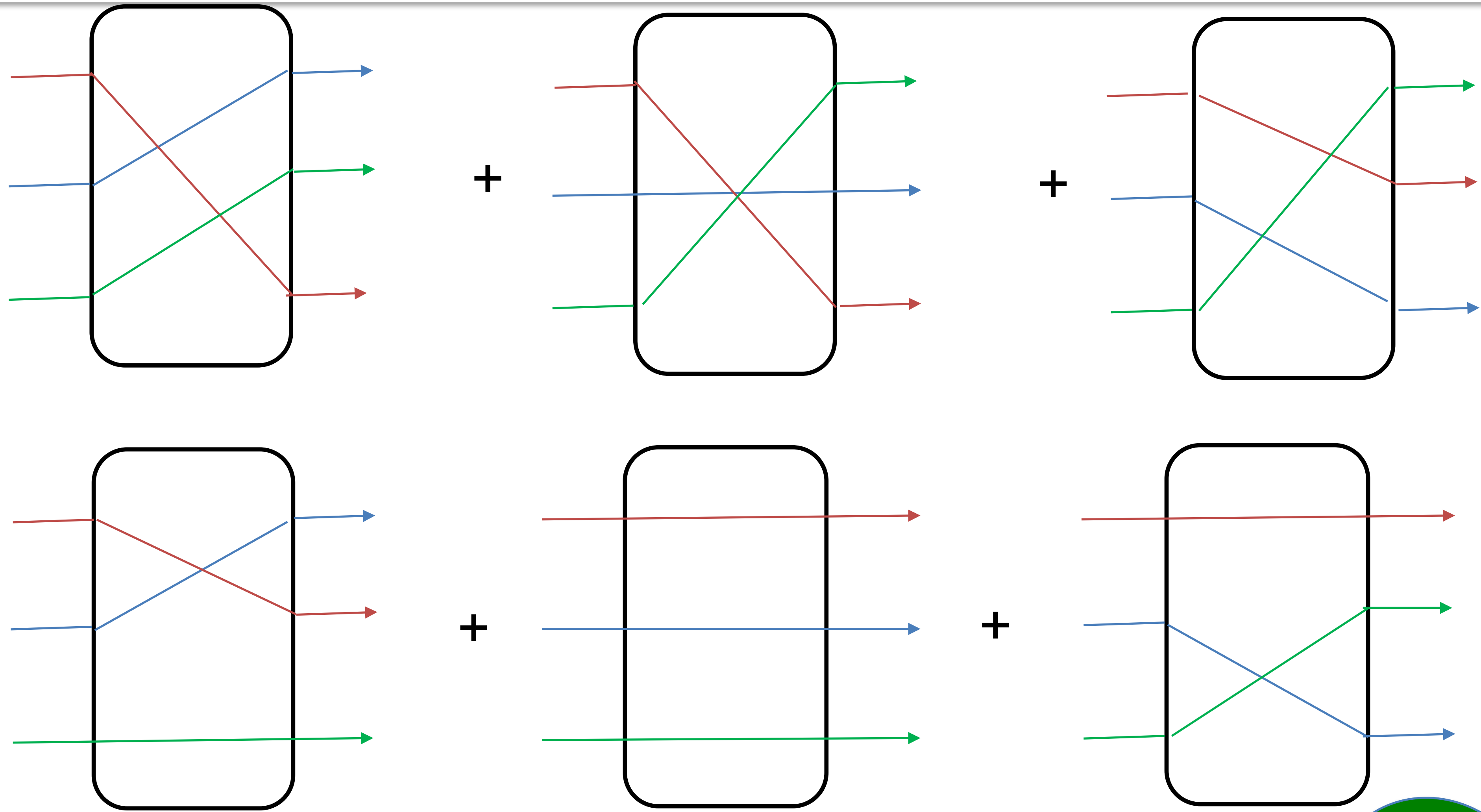
Interference of probability amplitudes



$$G^{(2)}(t_{1'}, t_{2'}) = \frac{1}{2}\left| + \ \mathbf{A}_1(t_{2'})\,\mathbf{A}_2(t_{1'}) \quad - \ \mathbf{A}_1(t_{1'})\,\mathbf{A}_2(t_{2'}) \right|^2$$

$$= \frac{1}{2}\left| perm \begin{pmatrix} -\ \mathbf{A}_1(t_{1'}) & \mathbf{A}_2(t_{1'}) \\ \mathbf{A}_1(t_{2'}) & \mathbf{A}_2(t_{2'}) \end{pmatrix} \right|^2$$

Three-photon interference

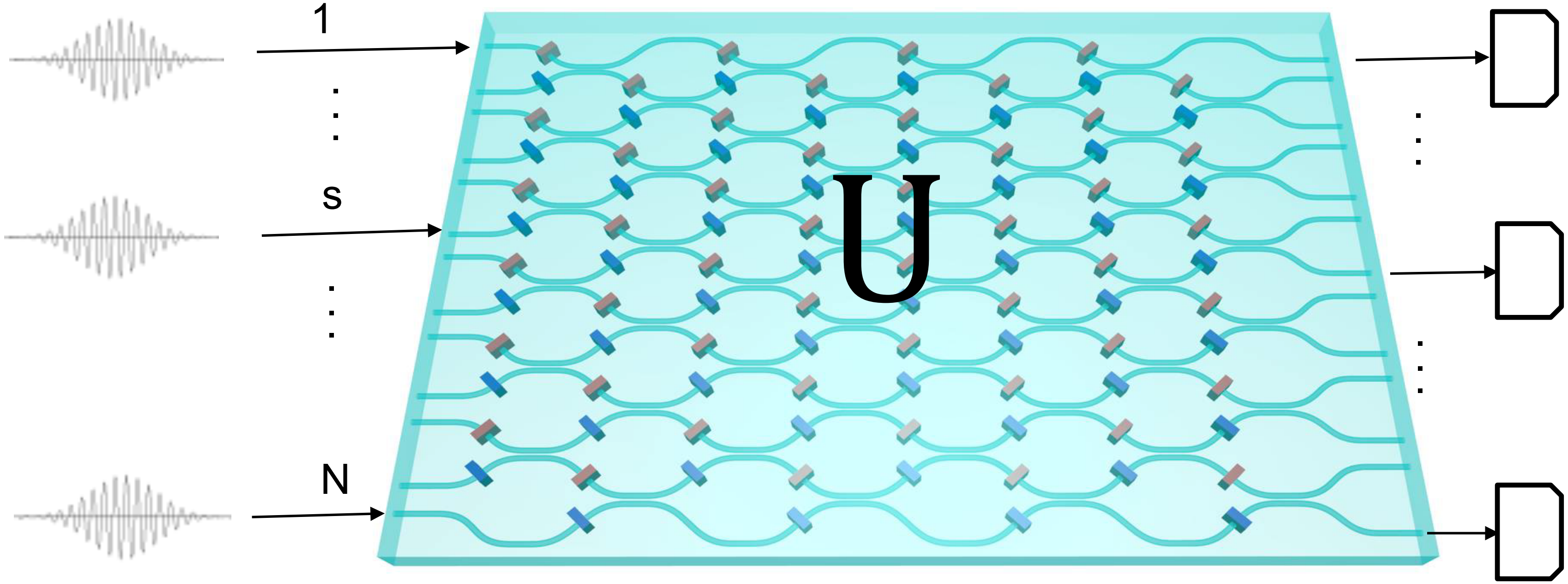


3!=6 interfering 3-photon probability amplitudes

PRL 114, 243601 (2015) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2015

Multiboson Correlation Interferometry with Arbitrary Single-Photon Pure States

Vincenzo Tamma,* and Simon Laibacher



N! interfering N-photon probability amplitudes:

N! simultaneous computational tasks!

Quantum Computational Supremacy

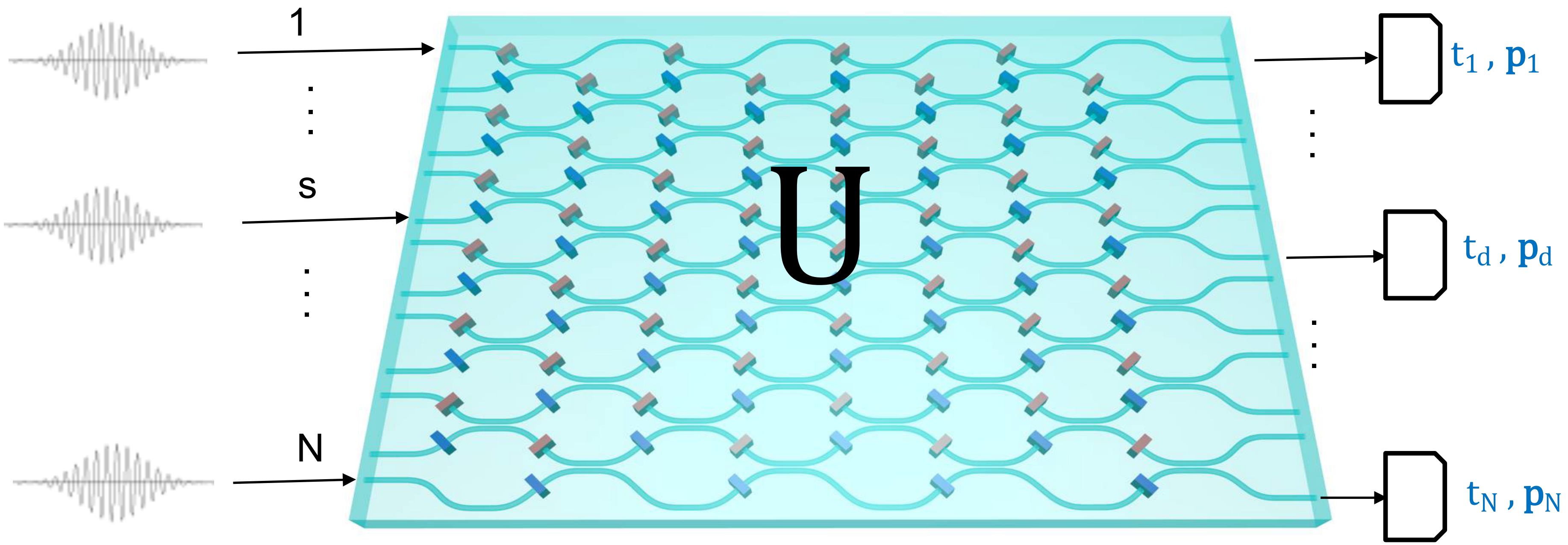
- Zooming in on arbitrary
  N-Photon State Evolutions
- N-Photon Entanglement Generation
- Multi-Boson Computational Speed-Up

Quantum Computational Supremacy

- Zooming in on arbitrary N-Photon State Evolutions

Multi-Photon Correlation Landscapes

$$|\mathcal{S}\rangle := \bigotimes_{s=1}^{N} |1[\boldsymbol{\xi}_s]\rangle_s$$



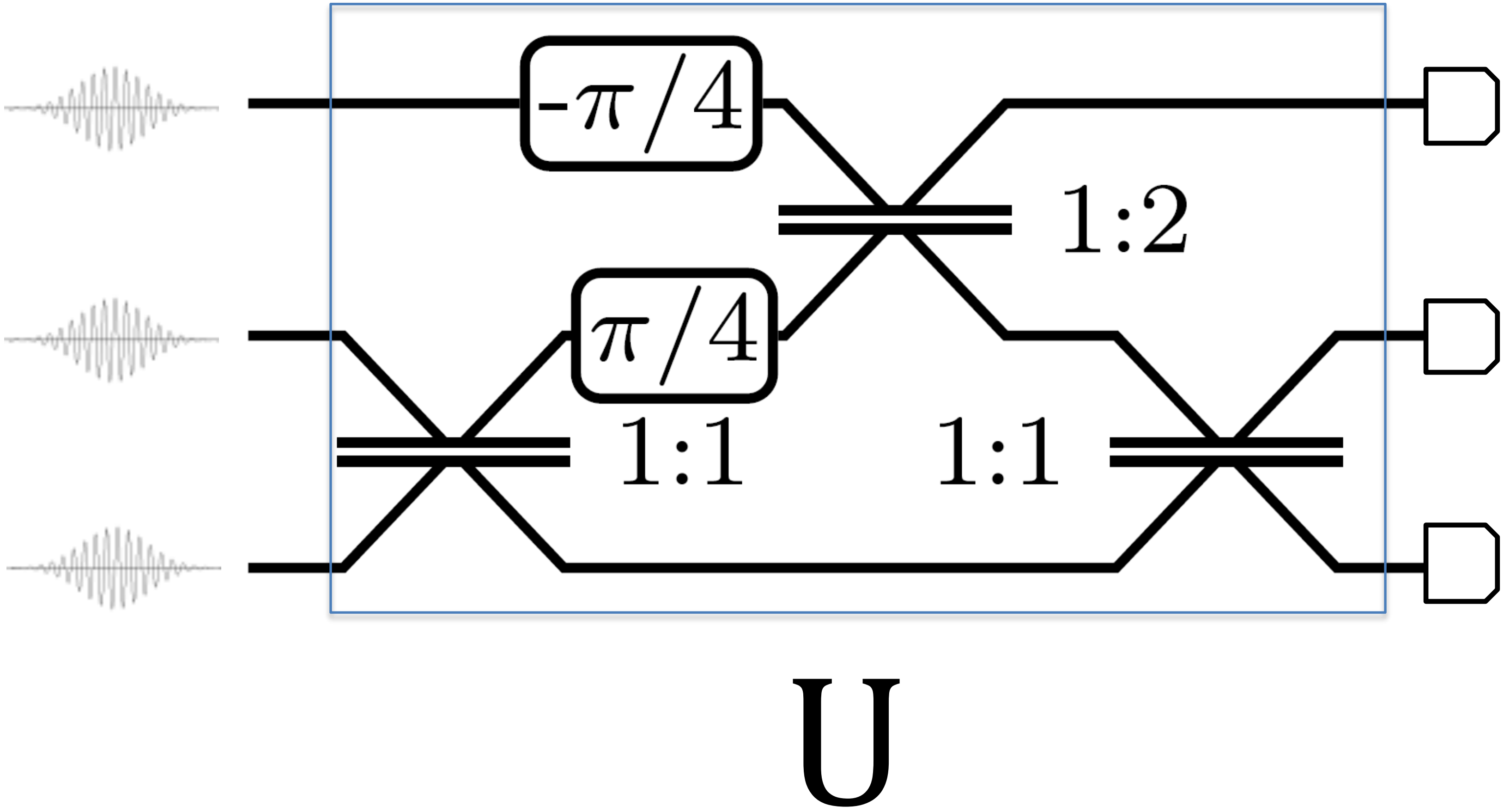
N! interfering N-photon detection amplitudes

$$G^{(N)}_{\{t_d,\boldsymbol{p}_d\}} = \left|\mathrm{perm}\, \mathcal{T}_{\{t_d,\boldsymbol{p}_d\}}\right|^2 \quad \text{with} \quad \mathcal{T}_{\{t_d,\boldsymbol{p}_d\}} := \left[\mathcal{U}_{d,s}\,(\boldsymbol{p}_d \cdot \boldsymbol{\chi}_s(t_d))\right]_{\substack{d=1,\ldots,N \\ s=1,\ldots,N}}$$

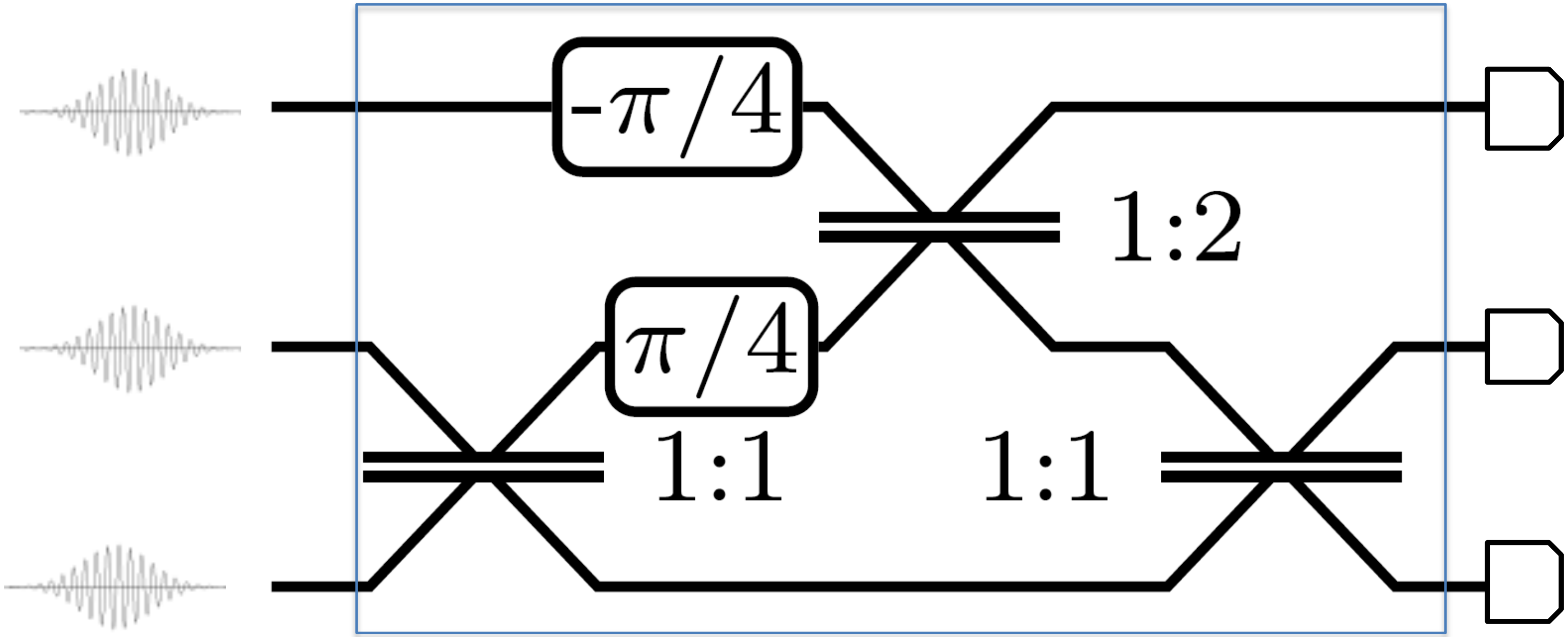
$$\boldsymbol{\chi}_s(t) := \mathcal{F}[\boldsymbol{\xi}_s](t-\Delta t)$$

Quantum interference with identical photons

Identical photons, perm $U = 0$ → Destructive Quantum Interference



Photons of different colors: no time-resolved detections



Different colors:

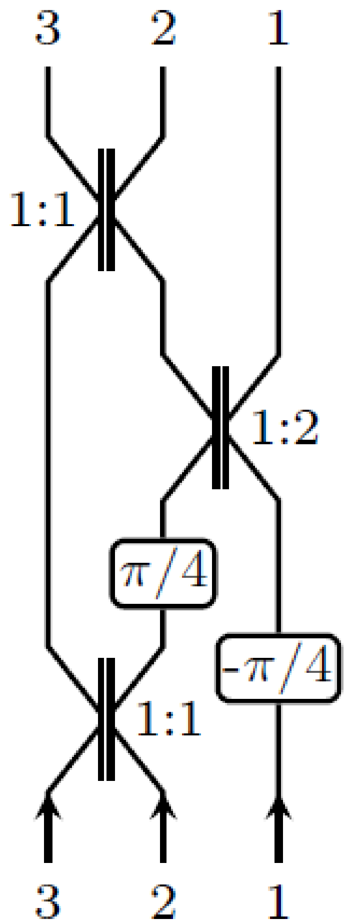
$\omega_s - \omega_{s'} \gg \Delta\omega \ \forall s \neq s'$ $\longrightarrow$ No multiphoton interference

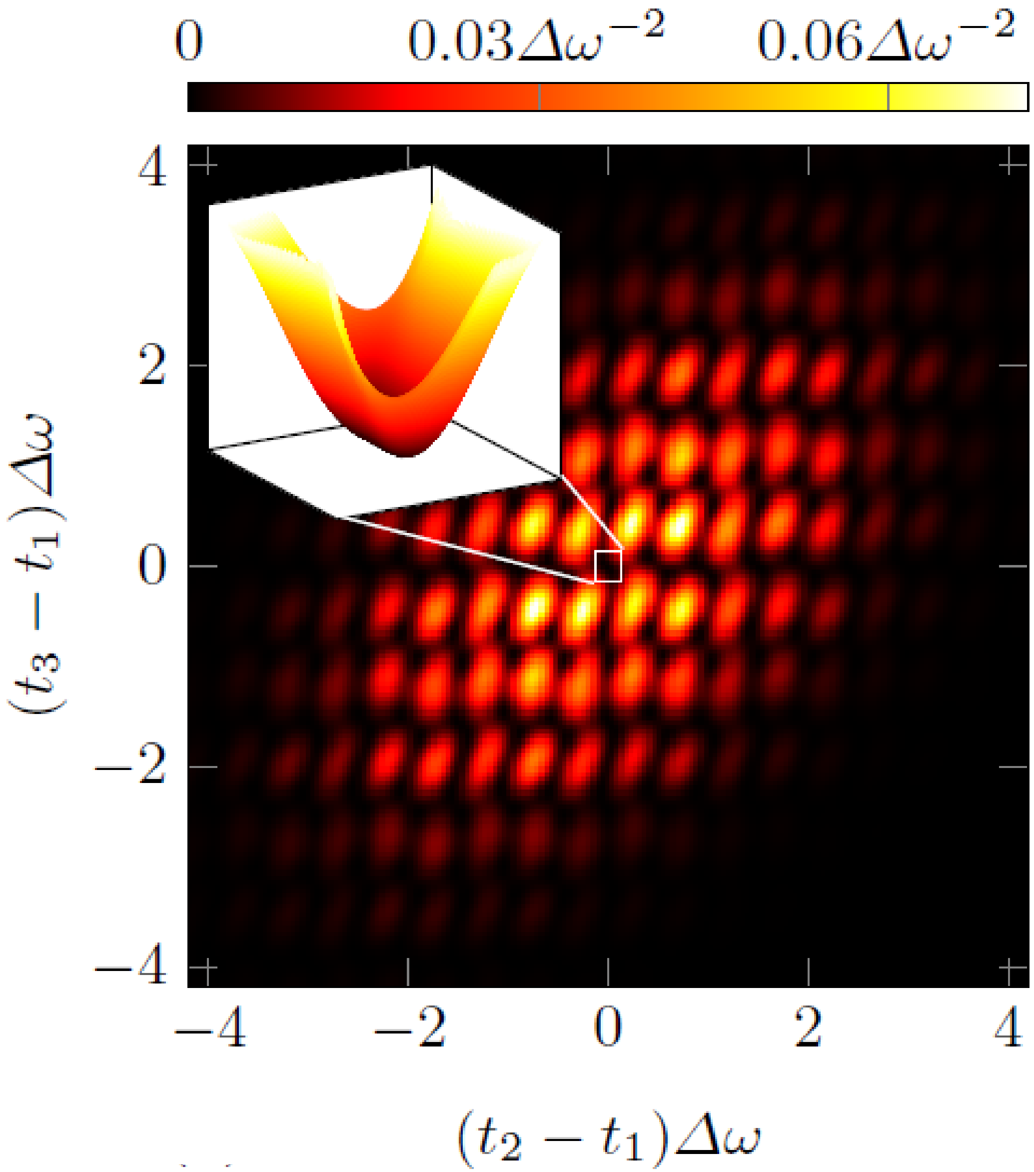
Photons of different colors: time-resolved detections

V. Tamma and S. Laibacher, Phys. Rev. Lett. **114**, 243601 (2015)

Detection integration time:

$T_I \ll |\omega_s - \omega_{s'}|^{-1}$





- Three-Photon "Dip"
- Quantum Beats

→ **Zooming in on arbitrary N-photon state evolution**

Quantum Computational Supremacy

- Zooming in on arbitrary
  N-photon State Evolutions

- N-Photon Entanglement Generation

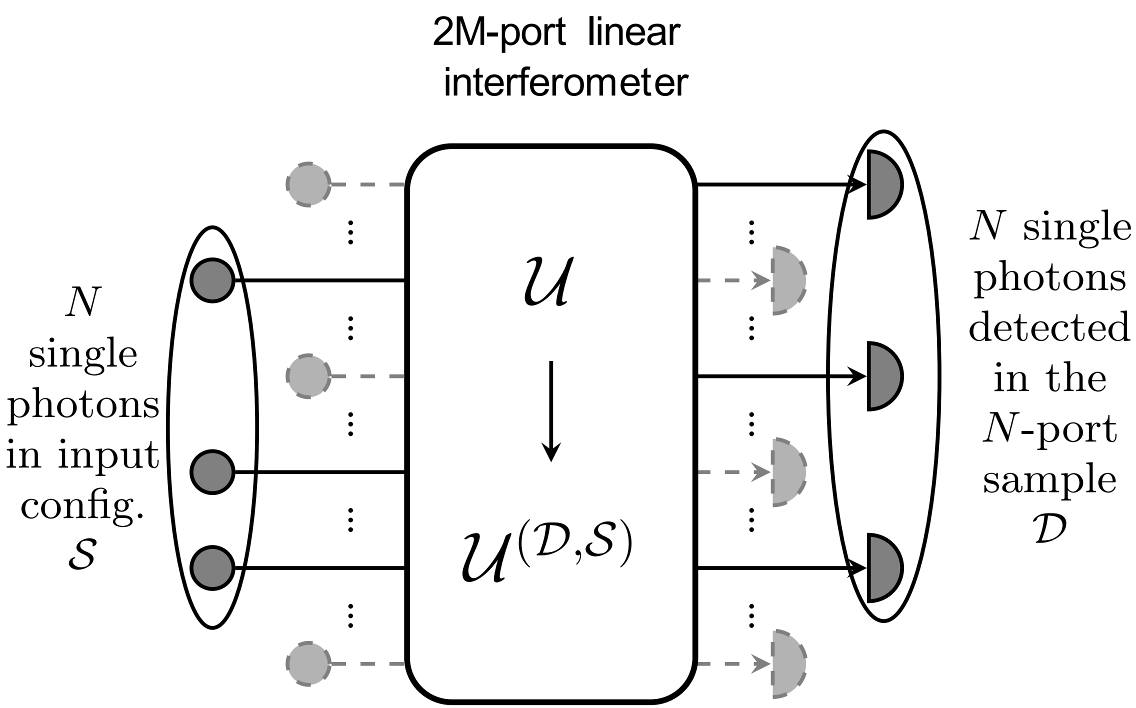
- Multi-Boson Computational Speed-Up

THEORY OF COMPUTING, Volume 9 (4), 2013, pp. 143–252

The Computational Complexity of Linear Optics

Scott Aaronson†
MIT

Alex Arkhipov‡
MIT



$$\mathrm{P}(\mathcal{D};\mathcal{S}) = \left|\mathrm{per}\,\mathcal{U}^{(\mathcal{D},\mathcal{S})}\right|^2$$

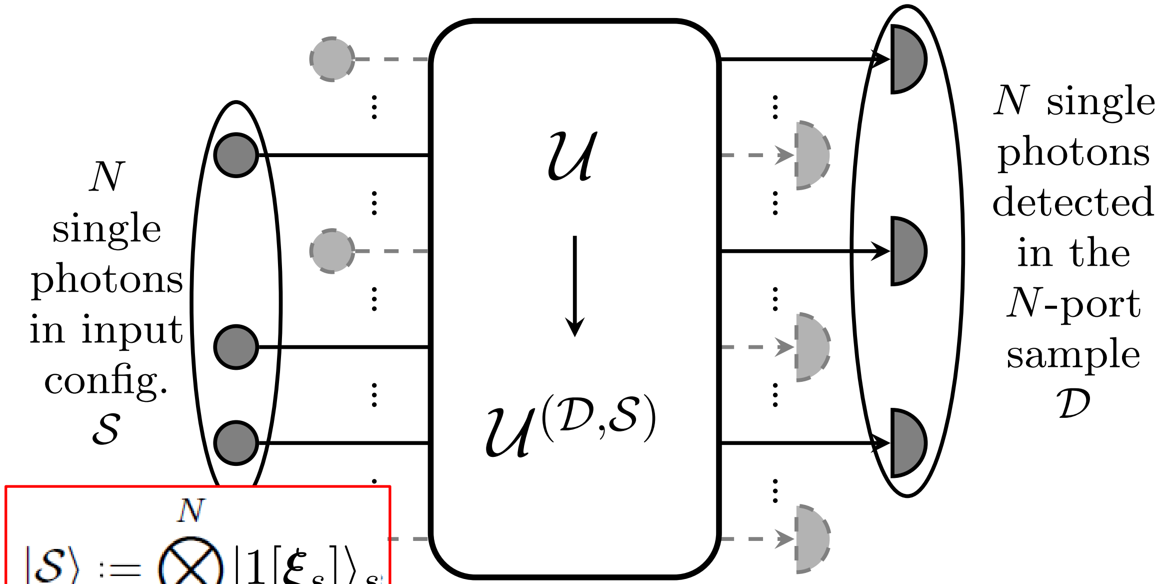
with

$$\mathcal{U}^{(\mathcal{D},\mathcal{S})} := [\mathcal{U}_{d,s}]_{\substack{d\in\mathcal{D}\\ s\in\mathcal{S}}}$$

- Identical photons
- Random unitary transformation U
- M >> N ≥ 30
- Sampling measurements
  (no time-resolved detections)

Boson sampling
with identical bosons
hard to simulate classically

Partially distinguishable input photon states



$$|\mathcal{S}\rangle := \bigotimes_{s=1}^{N} |1[\boldsymbol{\xi}_s]\rangle_s$$

$$P_{av}(\mathcal{D};\mathcal{S}) = \sum_{\rho\in\Sigma_N} f_\rho(\mathcal{S})\,\mathrm{per}\,\mathcal{A}_\rho^{(\mathcal{D},\mathcal{S})}$$

V. Tamma and S. Laibacher, Phys. Rev. Lett. **114**, 243601 (2015)

Interference-type matrices:

$$\mathcal{A}_\rho^{(\mathcal{D},\mathcal{S})} := \left[\mathcal{U}^*_{d,s}\mathcal{U}_{d,\rho(s)}\right]_{\substack{d\in\mathcal{D}\\ s\in\mathcal{S}}}$$

N-boson indistinguishability factors:

$$f_\rho(\mathcal{S}) := \prod_{s\in\mathcal{S}} g(s,\rho(s))$$

with

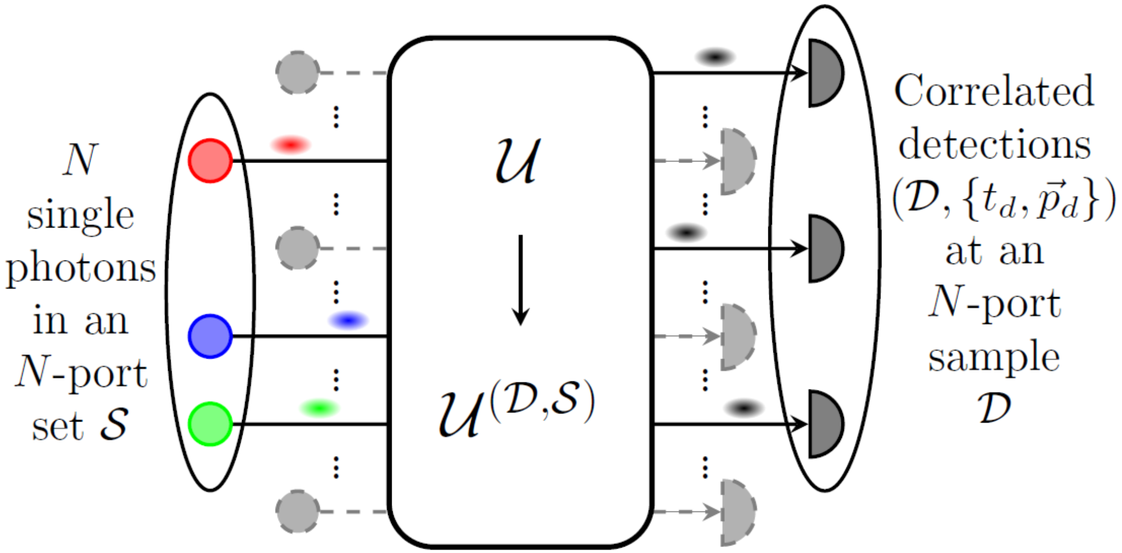
$$g(s,s') = \int_{-\infty}^{\infty} \mathrm{d}\omega\, \boldsymbol{\xi}_s(\omega)\cdot\boldsymbol{\xi}_{s'}(\omega)$$

2M-port linear interferometer

Pairwise state distinguishability

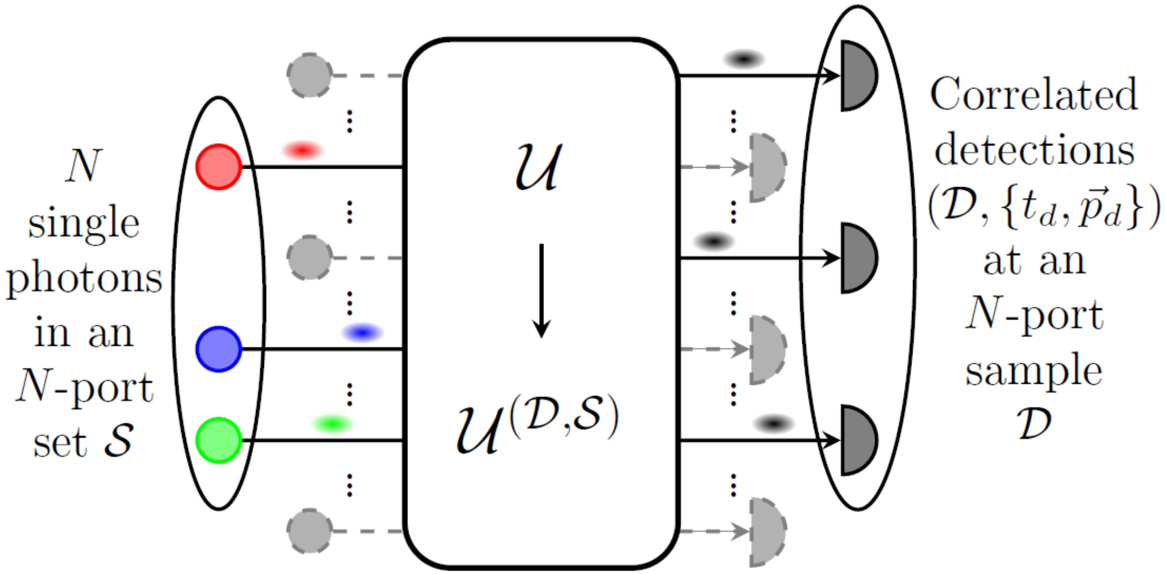
From the Physics to the Computational Complexity of Multiboson Correlation Interference

Simon Laibacher and Vincenzo Tamma*



Multiboson Correlation Sampling:

- Arbitrary single-photon pure states $|\mathcal{S}\rangle := \bigotimes_{s\in\mathcal{S}} |1[\xi_s]\rangle_s \bigotimes_{s\notin\mathcal{S}} |0\rangle_s$
- Sampling measurements based on time and polarization-resolving detections



$$\boxed{G^{(\mathcal{D},\mathcal{S})}_{\{t_d,\boldsymbol{p}_d\}} = \left|\mathrm{perm}\,\mathcal{T}^{(\mathcal{D},\mathcal{S})}_{\{t_d,\boldsymbol{p}_d\}}\right|^2}$$

with

$$\mathcal{T}^{(\mathcal{D},\mathcal{S})}_{\{t_d,\boldsymbol{p}_d\}} := \left[\mathcal{U}_{d,s}\,\left(\boldsymbol{p}_d \cdot \boldsymbol{\chi}_s(t_d)\right)\right]_{\substack{d\in\mathcal{D}\\ s\in\mathcal{S}}}$$

$$\boldsymbol{\chi}_s(t) := \mathcal{F}[\boldsymbol{\xi}_s](t-\Delta t)$$

Photons of different colors

Different colors: $\omega_s - \omega_{s'} \gg \Delta\omega \; \forall s \neq s'$

- Boson Sampling Trivial

Multiboson Correlation Sampling

Different colors: $\omega_s - \omega_{s'} \gg \Delta\omega \; \forall s \neq s'$

Detection integration time: $T_I \ll |\omega_s - \omega_{s'}|^{-1}$

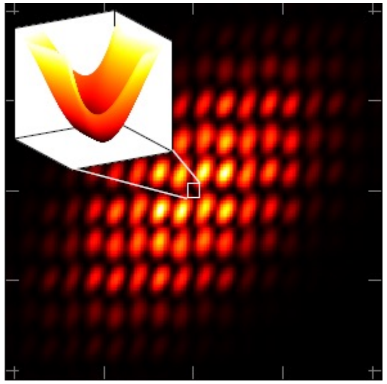
N-photon interference at any detection time:

$$G^{(\mathcal{D},\mathcal{S})}_{\{t_d,\mathbf{p}_d\}} \propto \left| \text{perm}\left(\left[\mathcal{U}^{(\mathcal{D},\mathcal{S})}_{d,s} \, \mathrm{e}^{i\omega_s t_d} \right]_{\substack{d\in\mathcal{D} \\ s\in\mathcal{S}}} \right) \right|^2$$

- Multi-Boson Correlation Sampling Hard even in the Approximate case

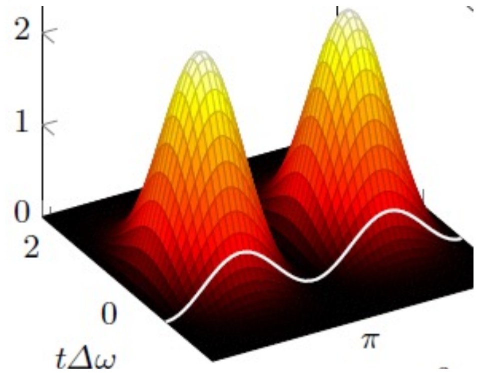
Summary

➢ Zooming in on N-photon state evolution

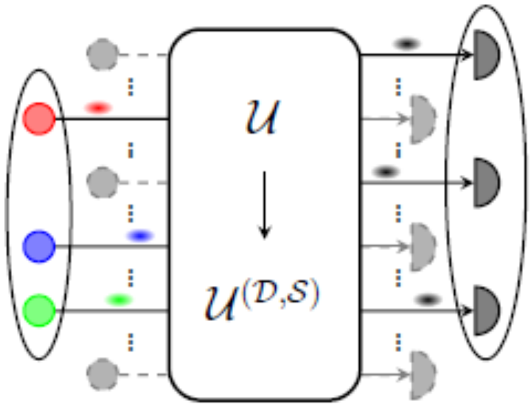


V. Tamma and S. Laibacher, Phys. Rev. Lett. **114**, 243601 (2015)

➢ N-photon Entanglement Generation



➢ Multi-Boson Computational Speed-Up



S. Laibacher and V. Tamma, Phys. Rev. Lett. **115**, 243605 (2015)
V. Tamma and S. Laibacher, Phys. Rev. A **90**, 063836 (2014)
V. Tamma and S. Laibacher, Quantum Inf. Process. **15**(3), 1241-1262 (2015)
V. Tamma and S. Laibacher, J. Mod. Opt. **63** 1 (2015)