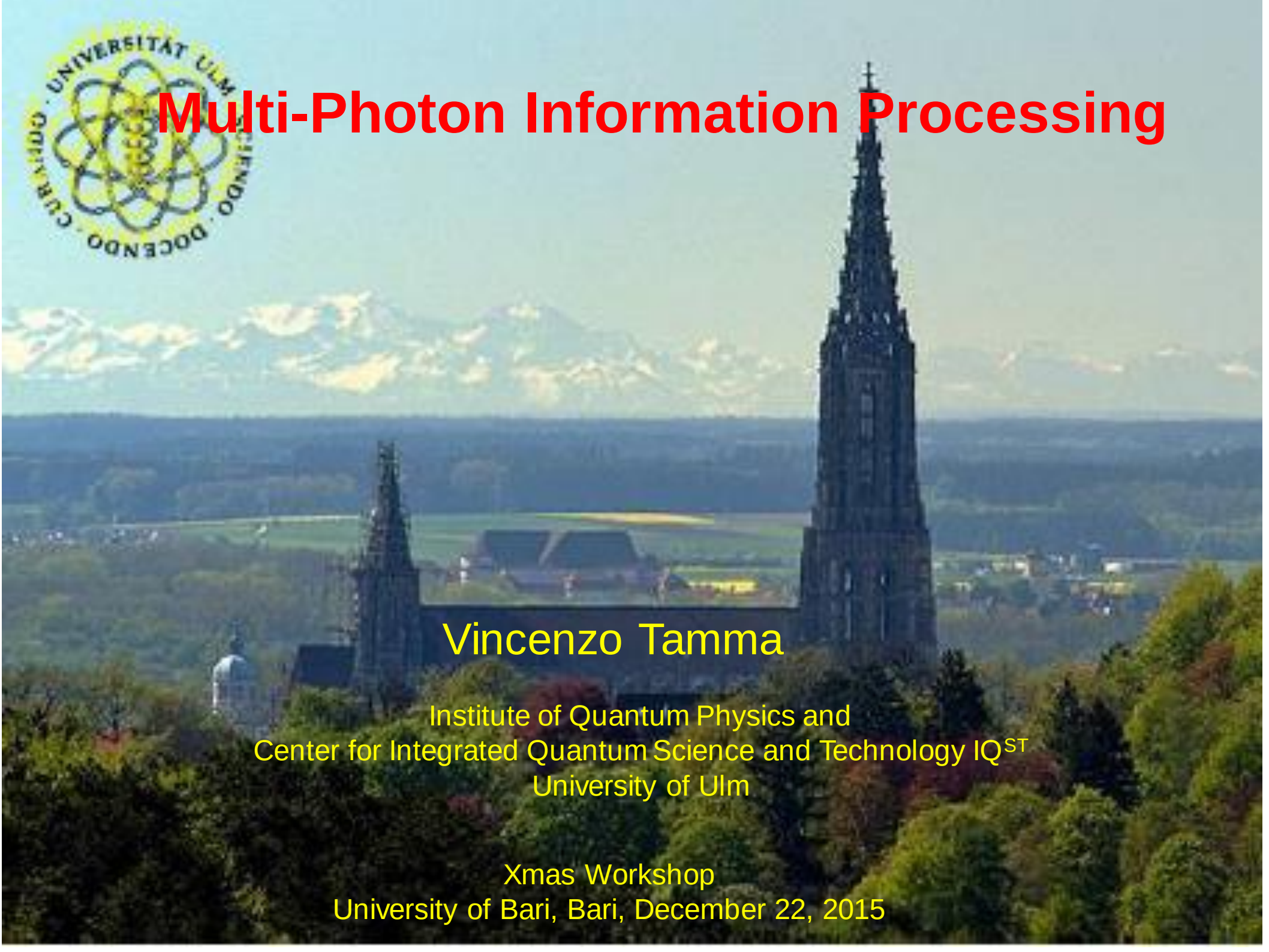


Multi-Photon Information Processing

Vincenzo Tamma

Institute of Quantum Physics and
Center for Integrated Quantum Science and Technology IQST
University of Ulm

Xmas Workshop
University of Bari, Bari, December 22, 2015

Overview

Multi-Photon Information Processing

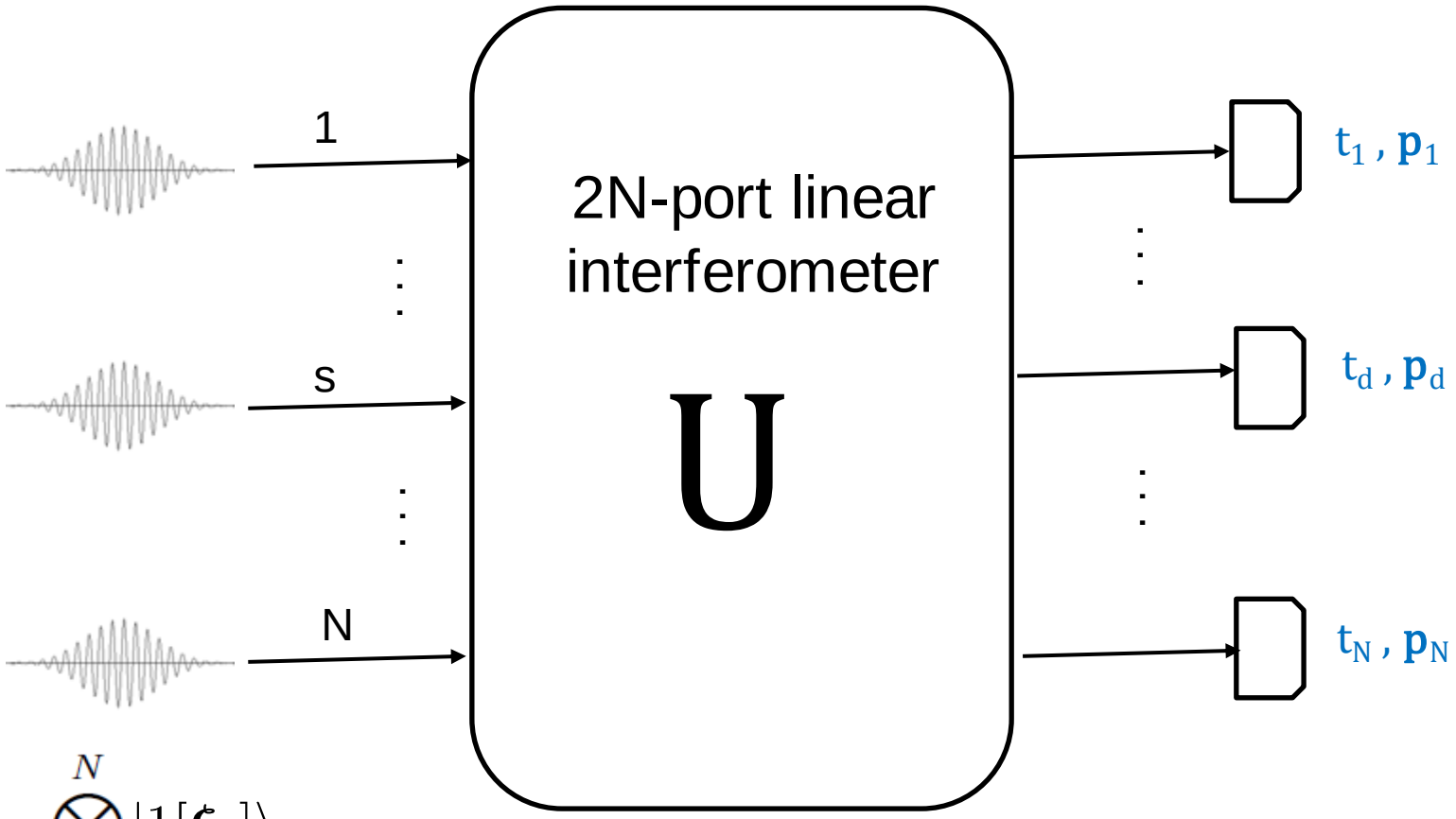
- ✓ Quantum Sensors
- ✓ Super-Resolution Imaging
- ✓ Quantum Computing
- ✓ Secure Quantum Communications

Outline:

- ➢ N-Photon Correlation Landscapes
- ➢ N-Photon Entanglement Correlations
- ➢ Complexity of Multi-Boson Correlation Interference
- ➢ Multipath Correlation Interference with a Thermal Source

Multiboson Correlation Interferometry with Arbitrary Single-Photon Pure States

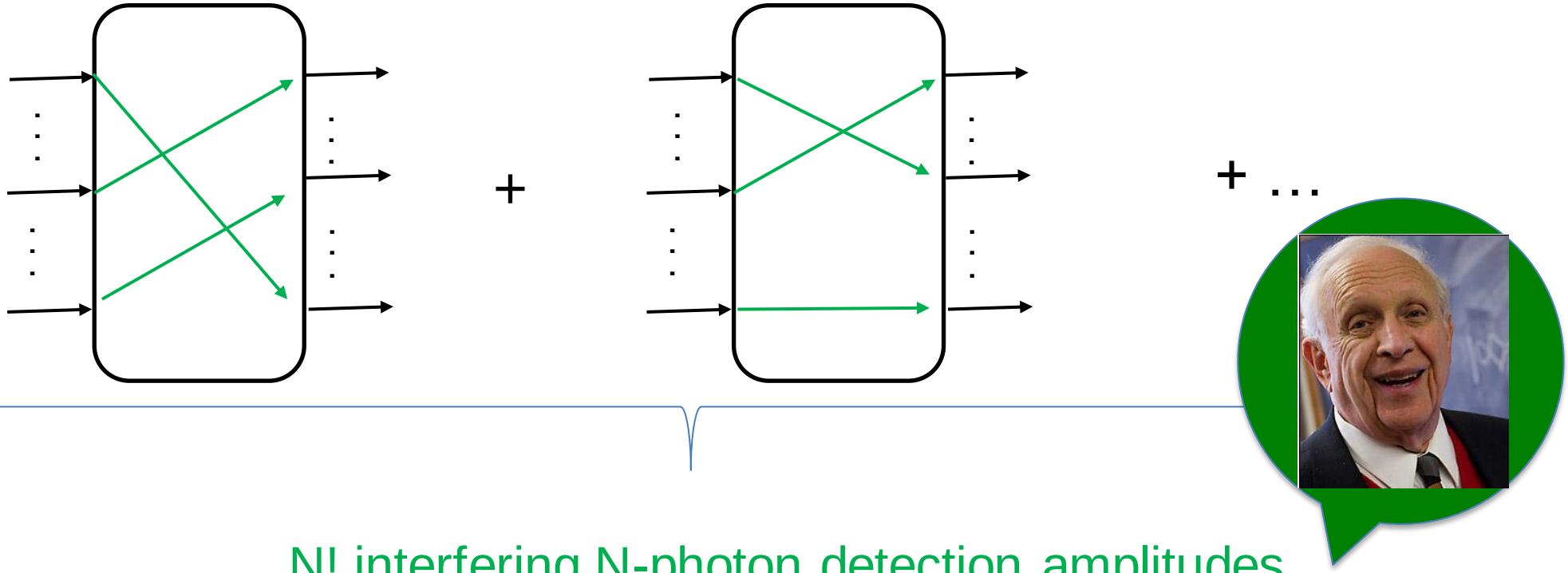
Vincenzo Tamma* and Simon Laibacher
Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQ^{ST}), Universität Ulm,



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

$$G^{(N)}_{\{t_d,\boldsymbol{p}_d\}} := \langle \mathcal{S}| \prod_{d=1}^{N} \left(\boldsymbol{p}_d^{*} \cdot \hat{\mathbf{E}}_d^{(-)}(t_d)\right) \left(\boldsymbol{p}_d \cdot \hat{\mathbf{E}}_d^{(+)}(t_d)\right) |\mathcal{S}\rangle$$

Multi-Photon Correlation Landscapes



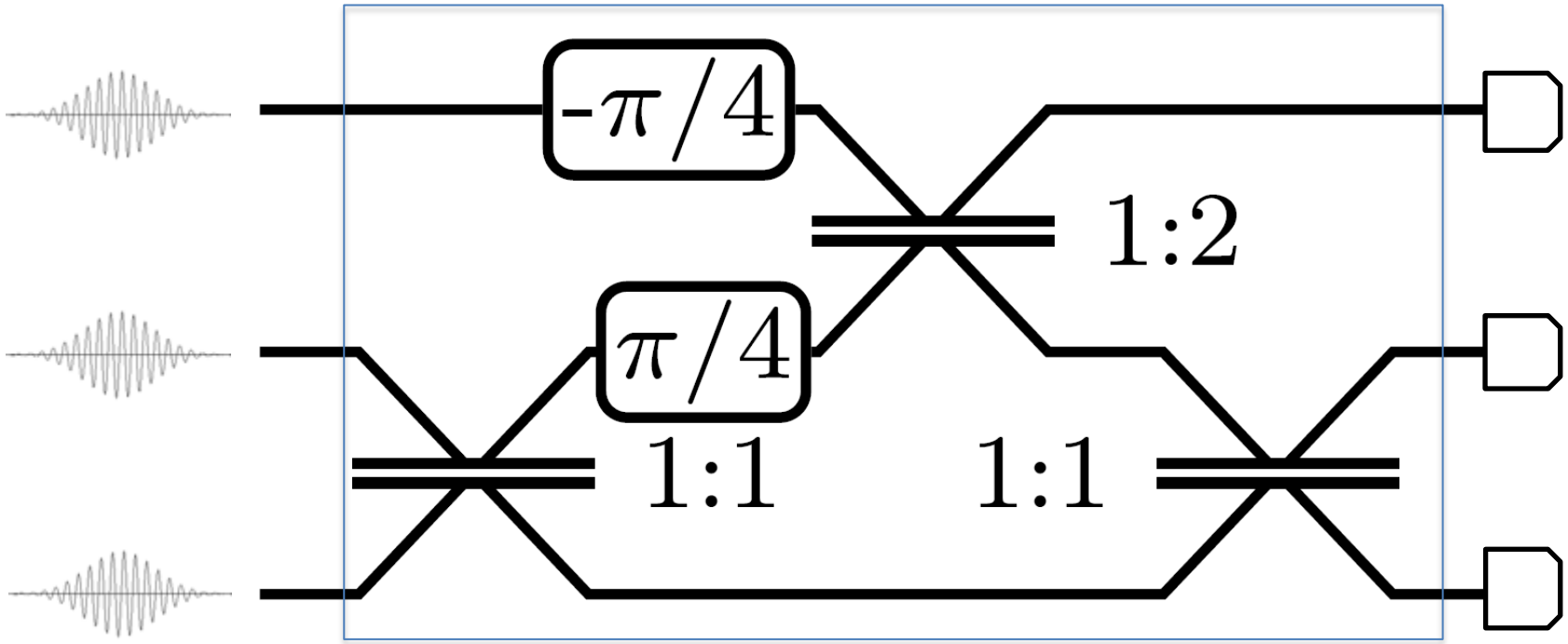
N! interfering N-photon detection amplitudes

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

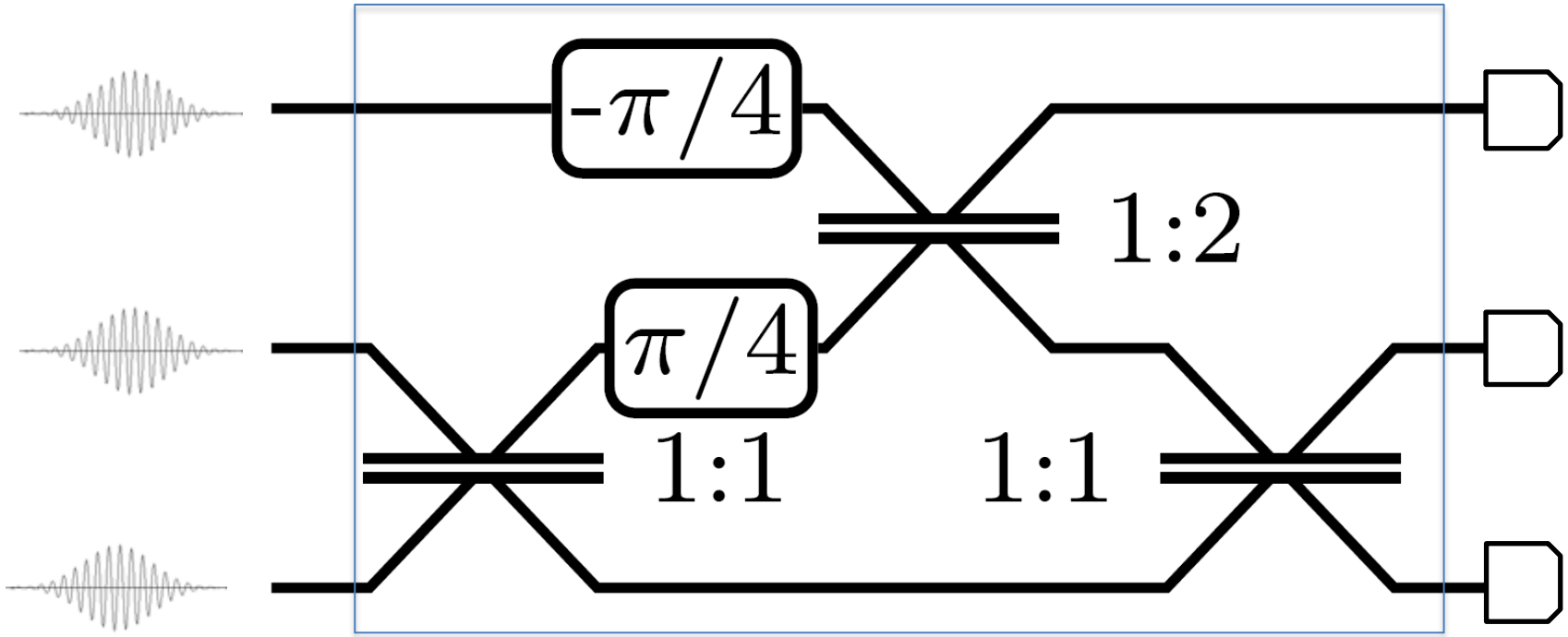
$$\boldsymbol{\chi}_s(t) := \mathcal{F}[\boldsymbol{\xi}_s](t-\Delta t)$$

Quantum interference with identical photons

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



Photons of different colors: no time-resolved detections



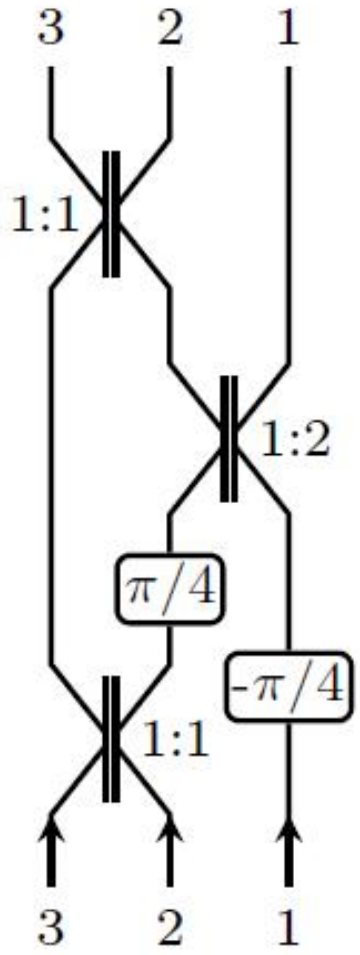
Different colors:

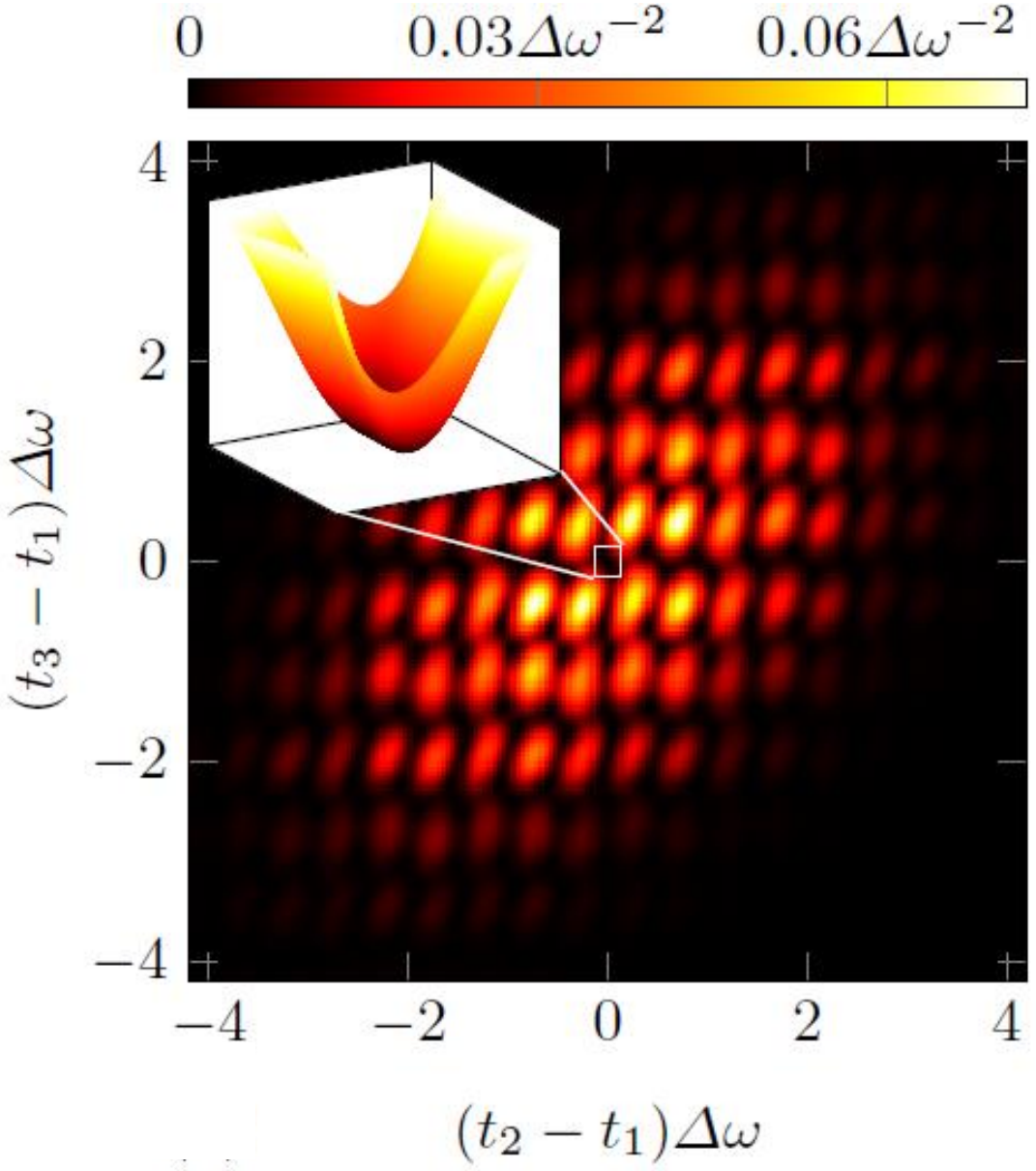
$$\omega_s - \omega_{s'} \gg \Delta\omega \;\forall s \neq s'$$ ⟶ No multi-photon interference

Photons of different colors: time-resolved detections

Detection integration time:

$$T_I \ll |\omega_s - \omega_{s'}|^{-1} \quad \forall s, s' \in \mathcal{S}$$



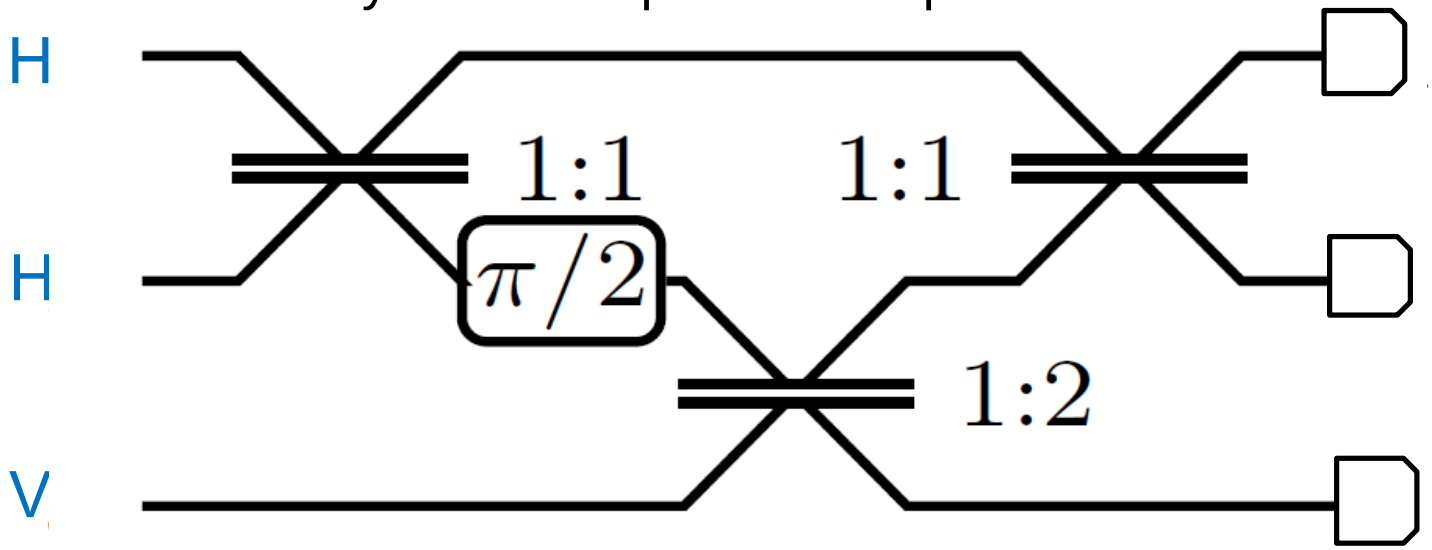


- Three-Photon "Dip"
- Quantum Beats

→ **Zooming in on N-photon quantum states and their interferometric evolution**

Entanglement correlations: identical photons

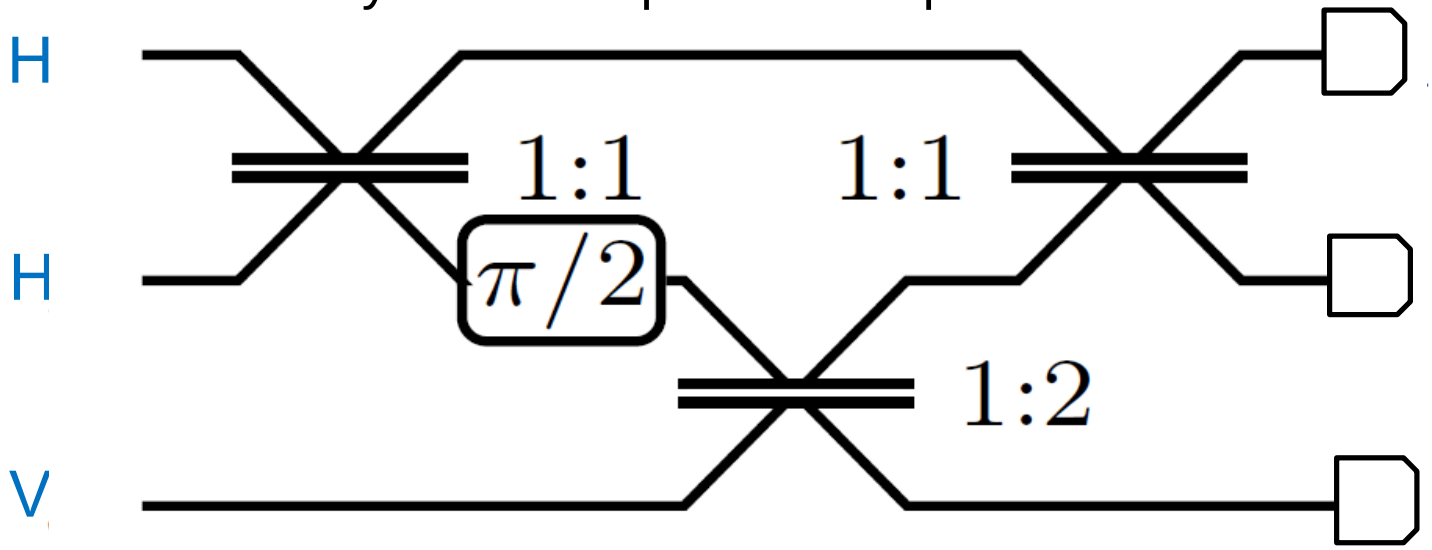
Symmetric 3-port beam splitter



$$|W\rangle = \frac{1}{\sqrt{3}}\left(|H\rangle\,|H\rangle|V\rangle + |V\rangle|H\rangle|H\rangle + |H\rangle|V\rangle|H\rangle \right)$$

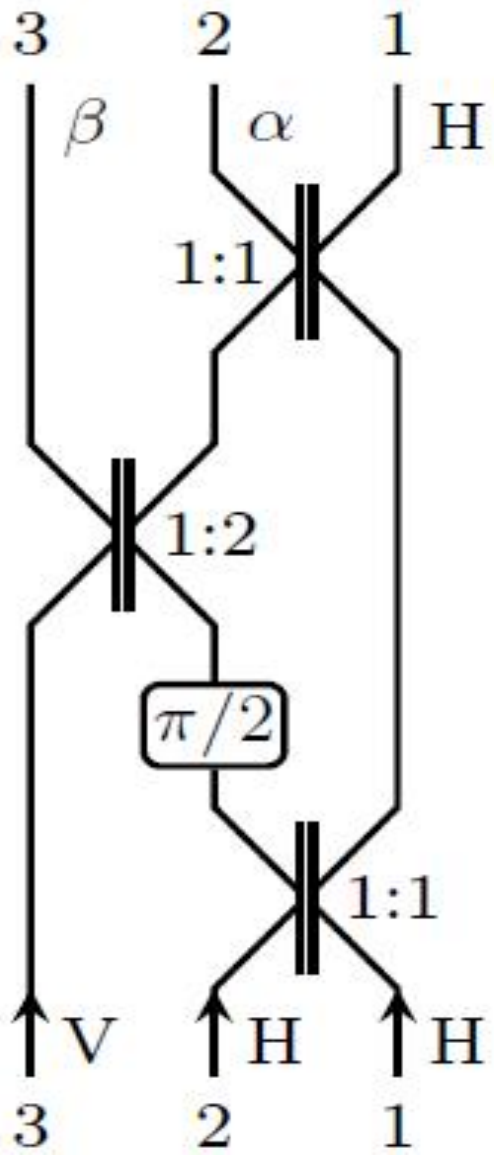
Photons of different colors: no time-resolved detections

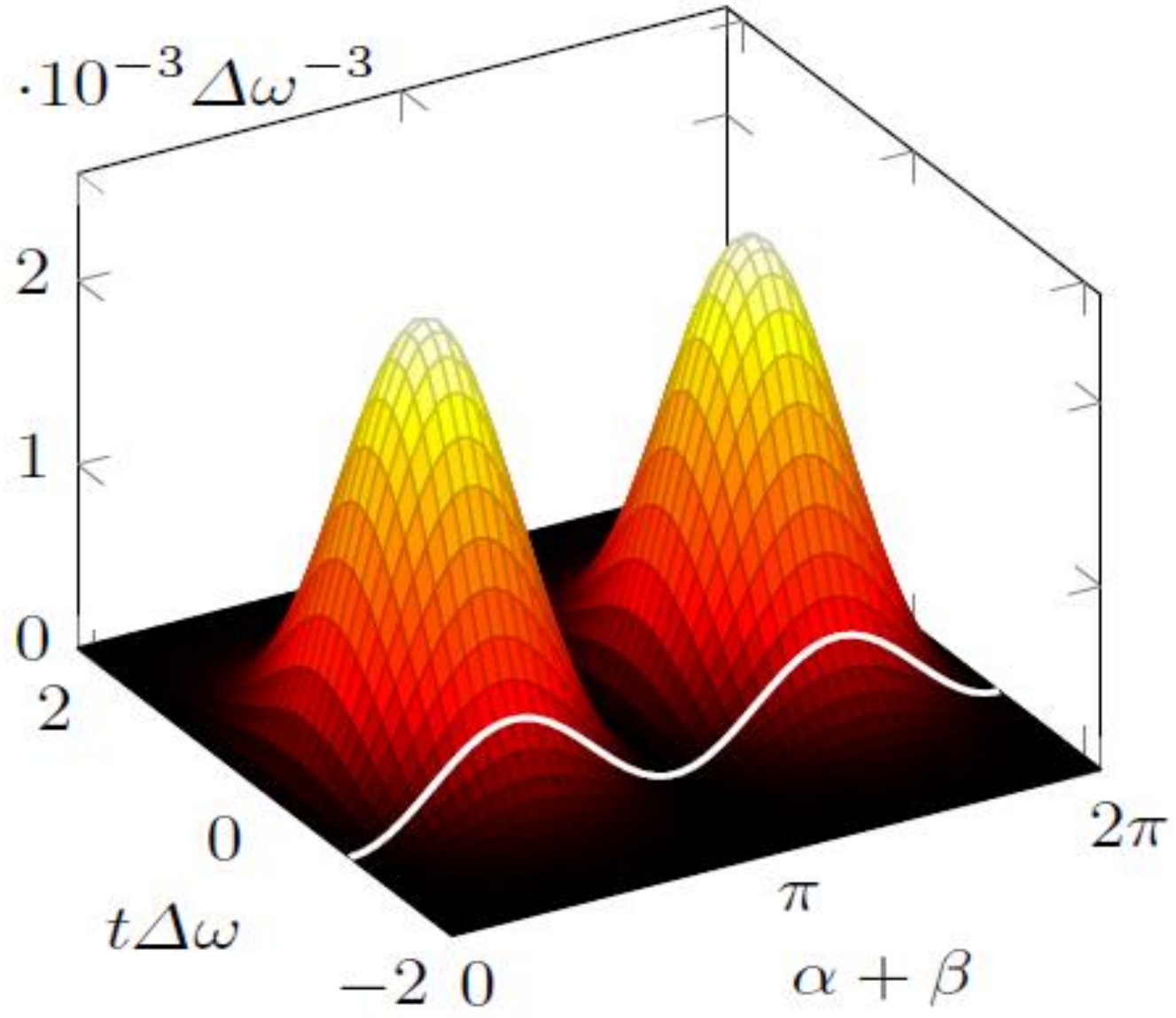
Symmetric 3-port beam splitter



$\omega_s - \omega_{s'} \gg \Delta\omega \;\forall s \neq s'$ ⟶ No entanglement correlations

Time-resolved detections





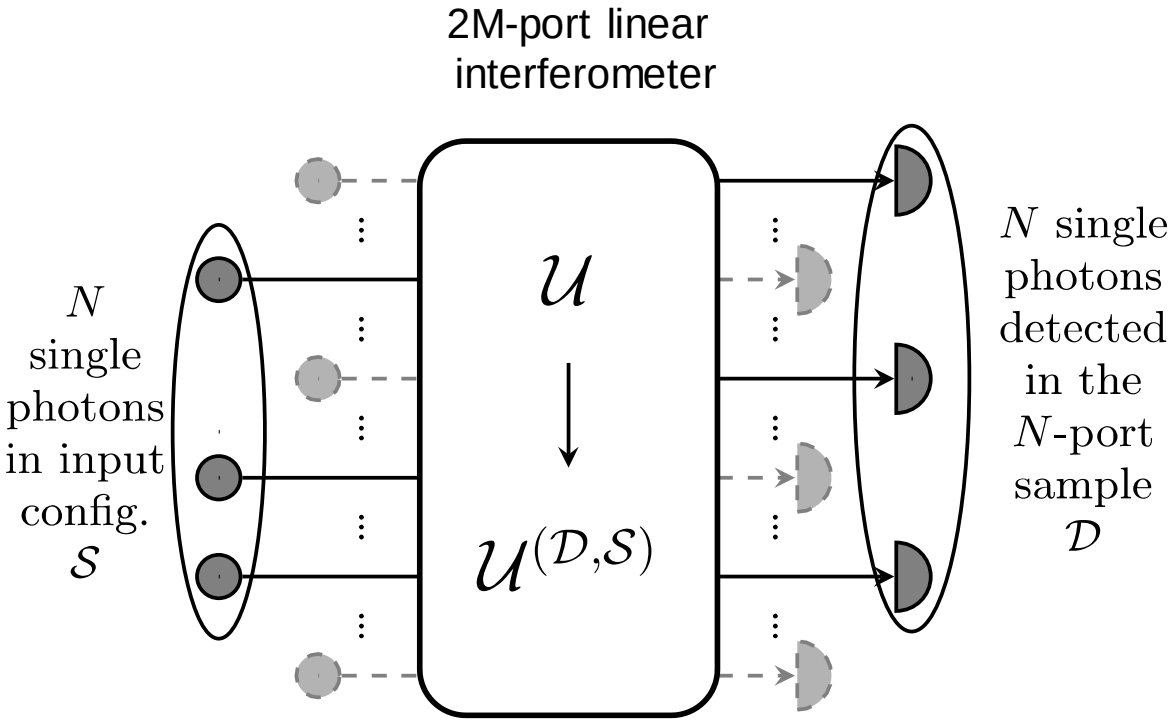
100 % Bell correlations
at equal detection times

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

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

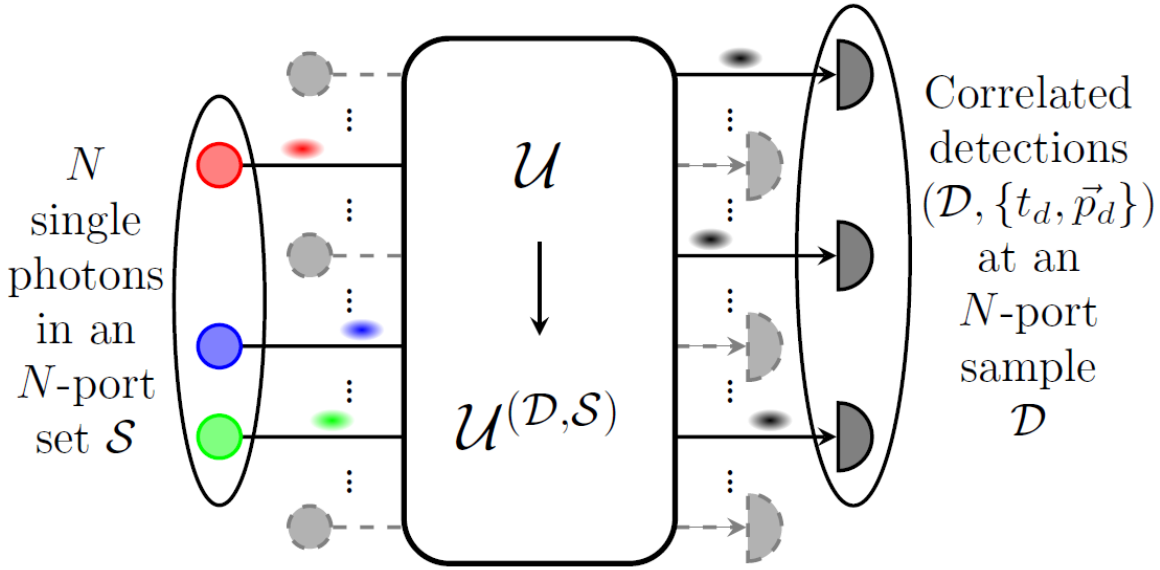
Computing permanents harder than factoring large numbers! (Valiant, 1979)

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

Boson sampling with identical bosons hard to simulate classically

From the Physics to the Computational Complexity of Multiboson Correlation Interference

Simon Laibacher and Vincenzo Tamma*



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

with

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

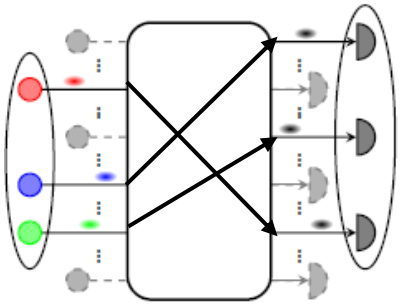
$$\boldsymbol{\chi}_s(t) := \mathcal{F}[\boldsymbol{\xi}_s](t-\Delta t)$$

Multi-Boson Correlation Sampling:

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

Multiphoton Interference and Complexity

- N photons distinguishable at the detectors at any time

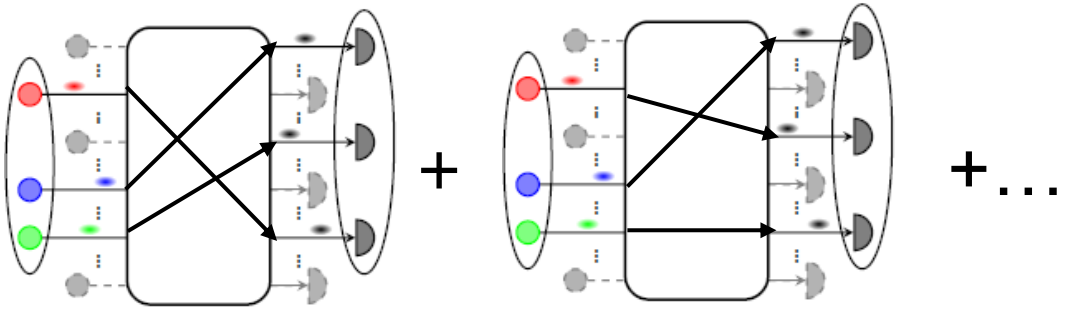


$$G^{(\mathcal{D},\mathcal{S})}_{\{t_d,\boldsymbol{p}_d\}} = \left| \prod_{s\in\mathcal{S}} \mathcal{U}_{\sigma(s),s}\left(\boldsymbol{p}_{\sigma(s)} \cdot \boldsymbol{\chi}_s(t_{\sigma(s)})\right) \right|^2$$

No N-photon interference

Multi-Boson Correlation Sampling Trivial!

- N photons indistinguishable at the detectors at given time intervals and polarizations



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

Occurrence of N-photon interference

Exact Multi-Boson Correlation Sampling Hard!

Photons of different colors

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

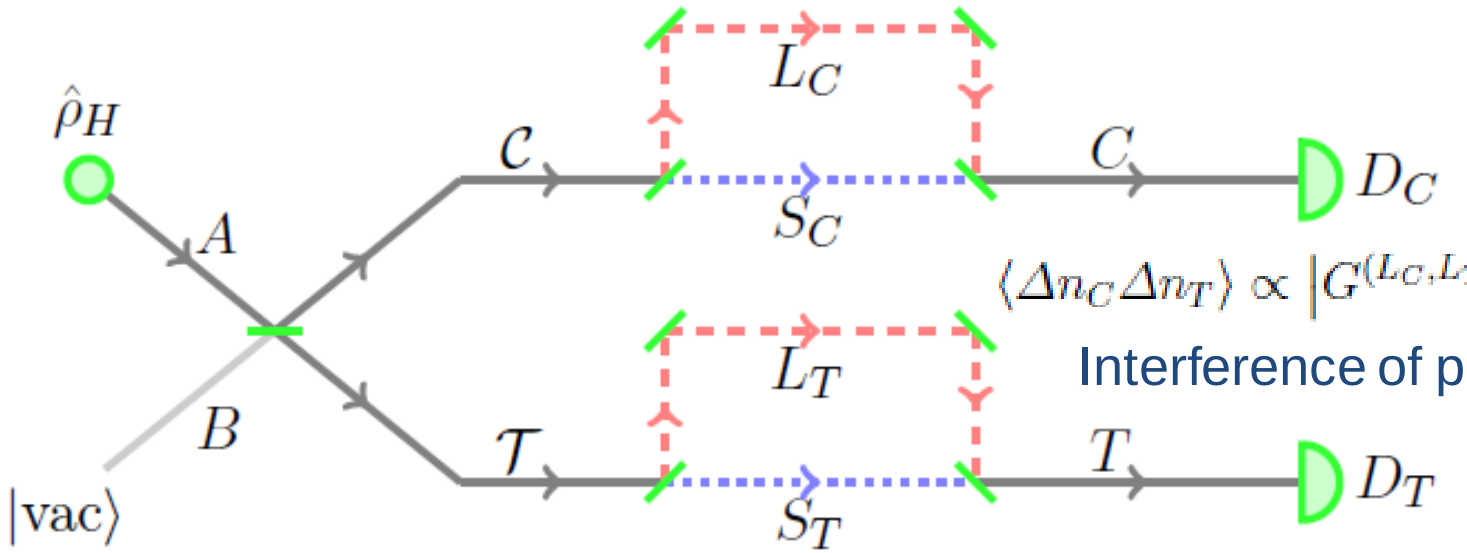
Detection integration time: $T_I \ll |\omega_s - \omega_{s'}|^{-1}$

N-photon interference at any detection time:

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

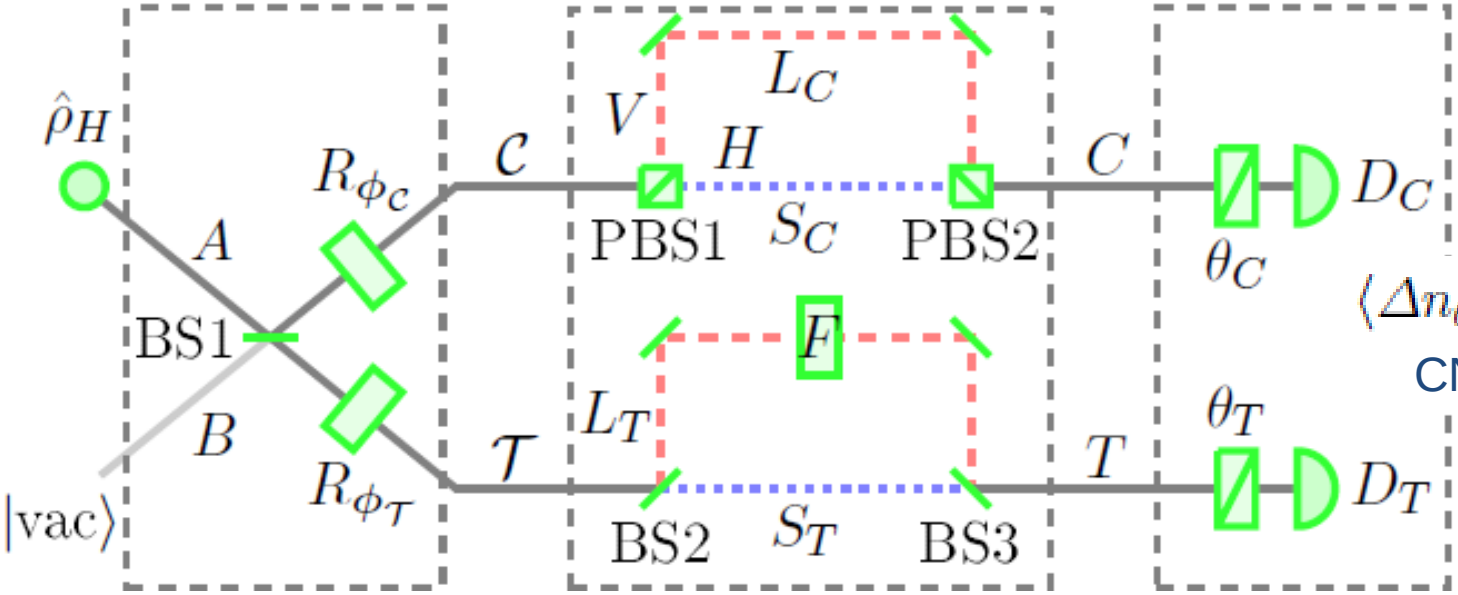
- Even Approximate Multi-Boson Correlation Sampling Hard
- Boson Sampling Trivial

Multipath Correlation Interference with a Thermal Source



$$\langle \Delta n_C \Delta n_T \rangle \propto \left| G^{(L_C,L_T)}(t_C,t_T) + G^{(S_C,S_T)}(t_C,t_T) \right|^2$$

Interference of pairs of correlated paths



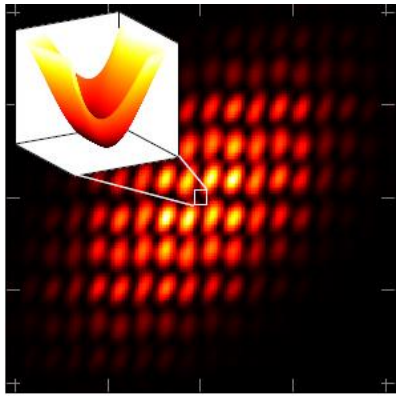
$$\langle \Delta n_{\theta_C} \Delta n_{\theta_T} \rangle \propto \overline{\tau}^2 P_{\mathrm{CNOT}}$$

CNOT gate simulation

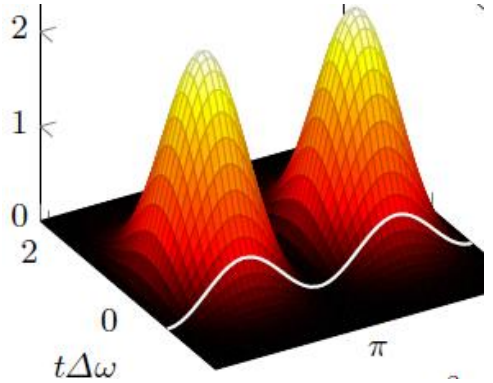
V. Tamma and J. Seiler: arXiv:1503.07369

Summary

- N-photon Interference Landscapes

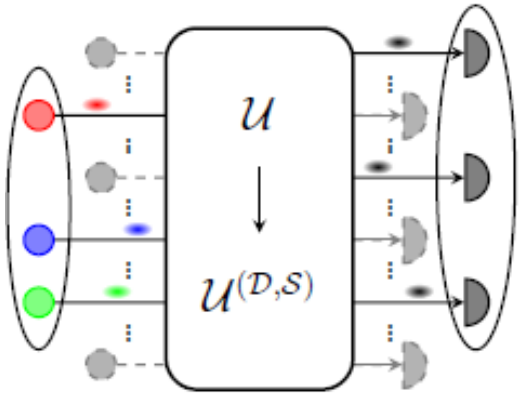


- Entanglement Correlations



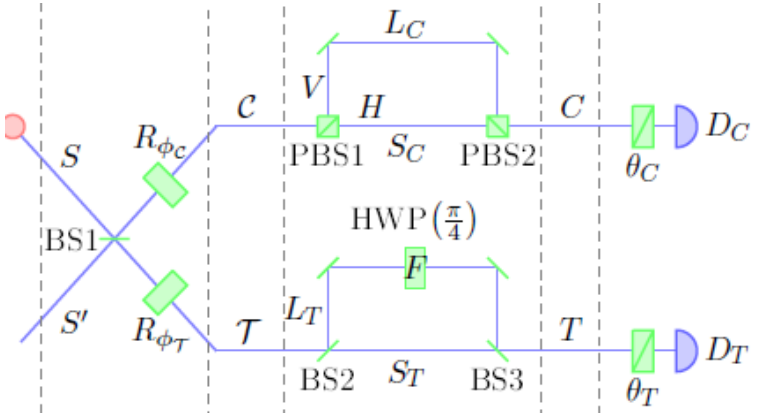
V. Tamma and S. Laibacher, Phys. Rev. Lett. **114**, 243601 (2015)

- Complexity of Multi-Boson Correlation Interference



S. Laibacher and V. Tamma Phys. Rev. Lett. **115**, 243605 (2015)
V. Tamma and S. Laibacher, Phys. Rev. A **90**, 063836 (2014)

- Multipath Correlation Interference with a Thermal Source



V. Tamma and J. Seiler: arXiv:1503.07369