

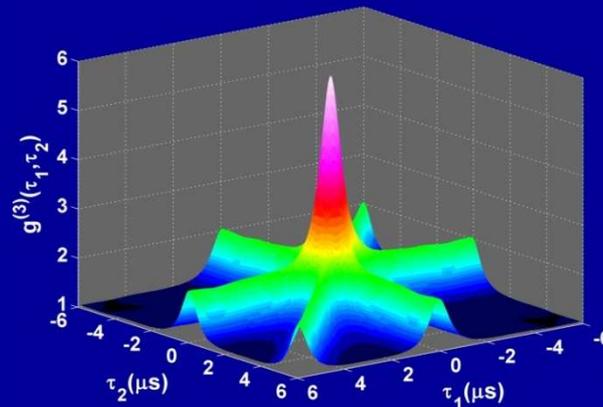
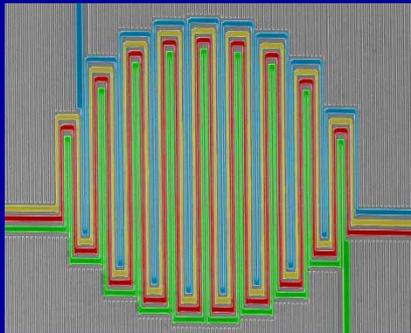
Measuring High-Order Coherences of Chaotic and Coherent Optical States

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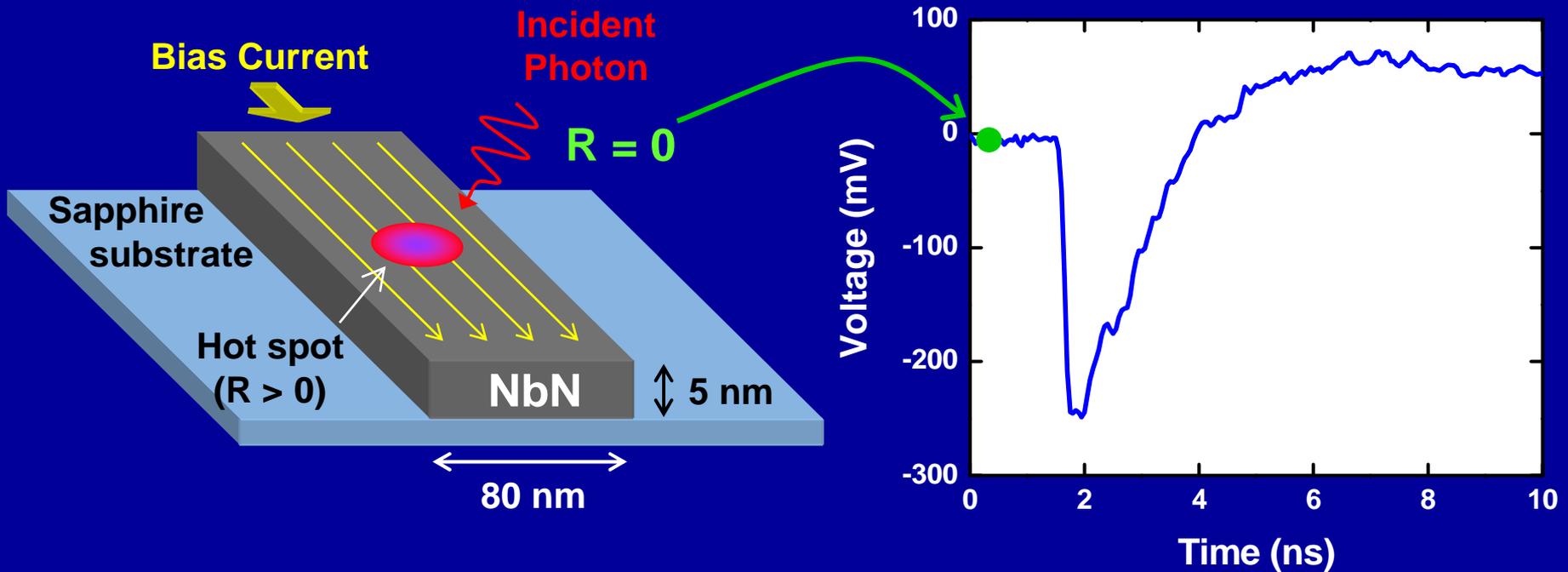
³MIT-Lincoln Labs, Lexington, MA



Outline

- Superconducting nanowire single-photon detectors (SNSPDs)
- Coherences: what, why, how?
- SNSPD with 4 interleaved elements
- Measuring 2nd, 3rd, 4th order coherences
 - Chaotic Source → High-order photon bunching
 - Coherent source → Control

Superconducting Nanowire Single-Photon Detector SNSPD



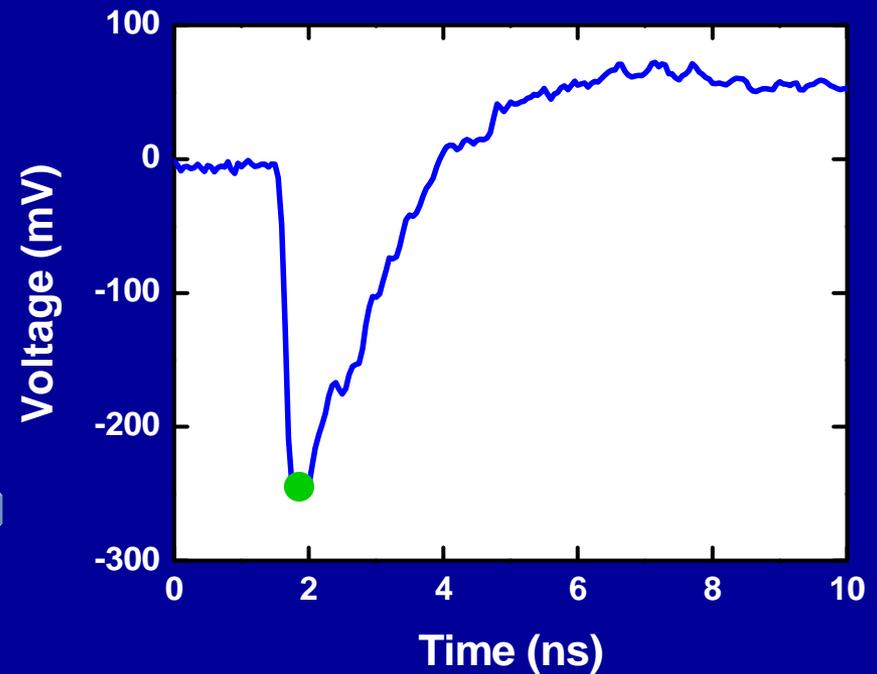
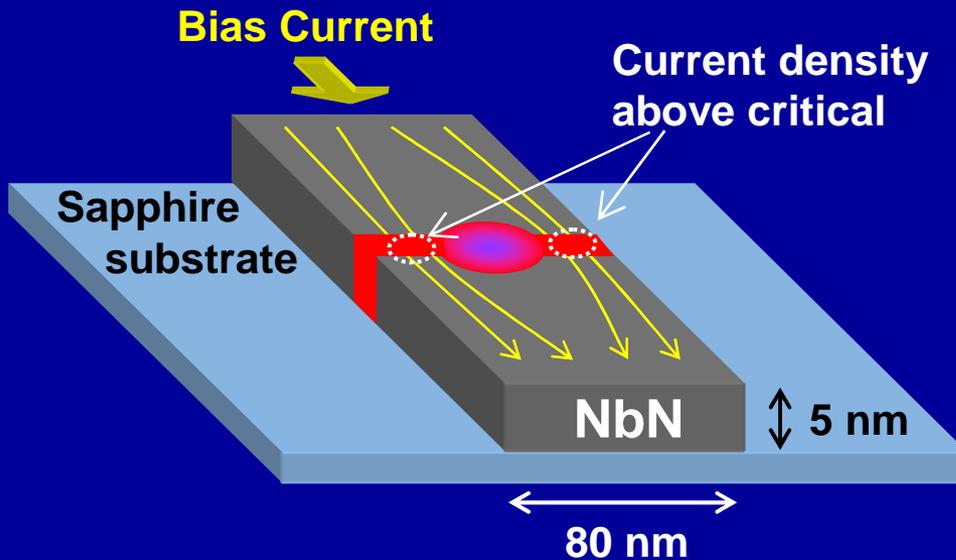
NbN Superconducts when:

- Temperature $< T_{\text{crit}}$ (~ 10 K)
- Current density $< J_{\text{crit}}$

• Gol'tsman *et al.*, APL 79, 705 (2001) • Verevkin *et al.*, J. Mod. Optics 51, 1447 (2004)

• Hadfield *et al.*, Opt. Expr. 13, 1086 (2005) • Rosfjord *et al.*, Opt. Expr. 14, 527 (2006)

Superconducting Nanowire Single-Photon Detector SNSPD



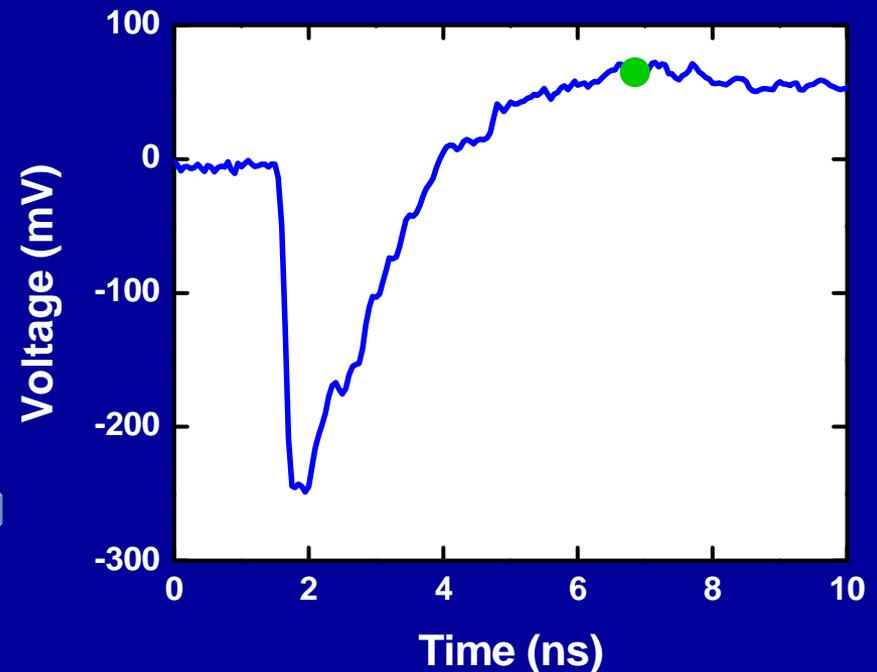
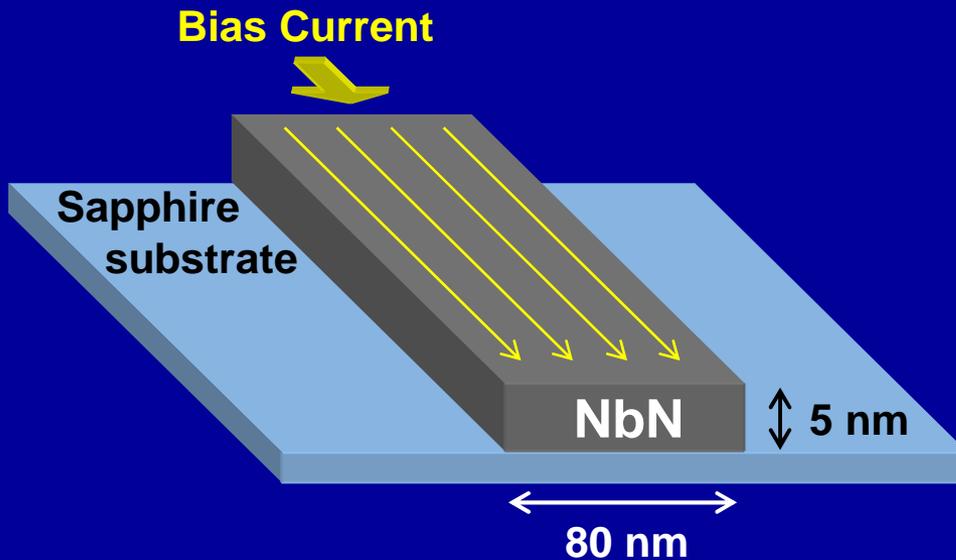
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Superconducting Nanowire Single-Photon Detector SNSPD



- Low jitter (<30 ps)
- Fast recovery (<5 ns)
- Detection Efficiencies >50%
- Dark Count Rate ~100 Hz

- No afterpulsing or re-emission
- Broad λ range: UV to mid-IR
- Operate at ~3 K in closed-cycle fridge, fiber-coupled

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Temporal Coherence

Michelson Interferometer

$$g^{(1)}(\tau_1), g^{(2)}(\tau_1) \dots g^{(n)}(\tau_1, \tau_2, \dots) \dots$$

Intensity Interferometer

2nd Order:

$$g^{(2)}(\tau_1) = \frac{\langle \hat{a}^\dagger(t) \hat{a}^\dagger(t + \tau_1) \hat{a}(t + \tau_1) \hat{a}(t) \rangle}{\langle \hat{a}^\dagger(t) \hat{a}(t) \rangle^2}$$

Intensity Autocorrelation $\longrightarrow \langle : \hat{I}(t) \hat{I}(t + \tau_1) : \rangle$

(Symmetric about τ_1)

$$= \frac{\langle \hat{I}(t) \hat{I}(t + \tau_1) \rangle}{\langle \hat{I}(t) \rangle^2} = \frac{\int \eta I(t) \eta I(t + \tau_1) dt}{\left[\int \eta I(t) dt \right]^2}$$

Normalization

Loss doesn't change coherence!
(If same loss in all modes)

Study dynamics in:

Light sources

- "Thresholdless" lasers
- Single-photon sources
- Fluorescing molecules

Interaction media

- Time-dependent scattering

Known Aliases

- Intensity Interferometry
- Fluorescence Correlation Spectroscopy
- Dynamic Light Scattering

Temporal Coherence

Michelson Interferometer

$$g^{(1)}(\tau_1), g^{(2)}(\tau_1) \dots g^{(n)}(\tau_1, \tau_2, \dots) \dots$$

Intensity Interferometer

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Intensity Autocorrelation $\longrightarrow \langle : \hat{I}(t) \hat{I}(t + \tau_1) : \rangle = \frac{\int \eta I(t) \eta I(t + \tau_1) dt}{\langle \hat{I}(t) \rangle^2} = \frac{\int \eta I(t) \eta I(t + \tau_1) dt}{\left[\int \eta I(t) dt \right]^2}$

(Symmetric about τ_1)

Normalization

Loss doesn't change coherence!

(If same loss in all modes)

3rd Order:

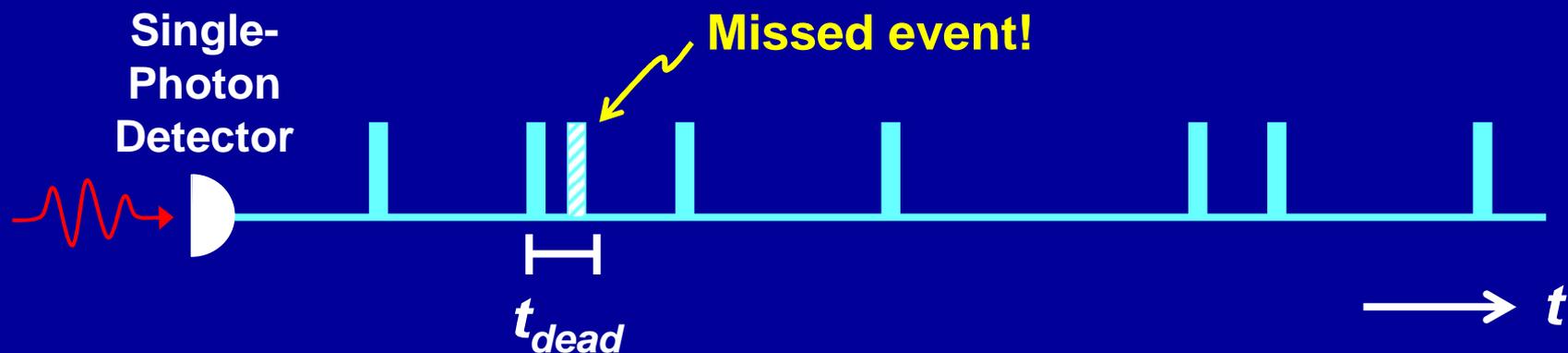
$$g^{(3)}(\tau_1, \tau_2) = \frac{\langle : \hat{I}(t) \hat{I}(t + \tau_1) \hat{I}(t + \tau_2) : \rangle}{\langle \hat{I}(t) \rangle^3}$$

4th Order:

$$g^{(4)}(\tau_1, \tau_2, \tau_3) = \frac{\langle : \hat{I}(t) \hat{I}(t + \tau_1) \hat{I}(t + \tau_2) \hat{I}(t + \tau_3) : \rangle}{\langle \hat{I}(t) \rangle^4}$$

>2nd Order: More τ 's \rightarrow Access more degrees of freedom
Asymmetry \rightarrow Irreversible processes

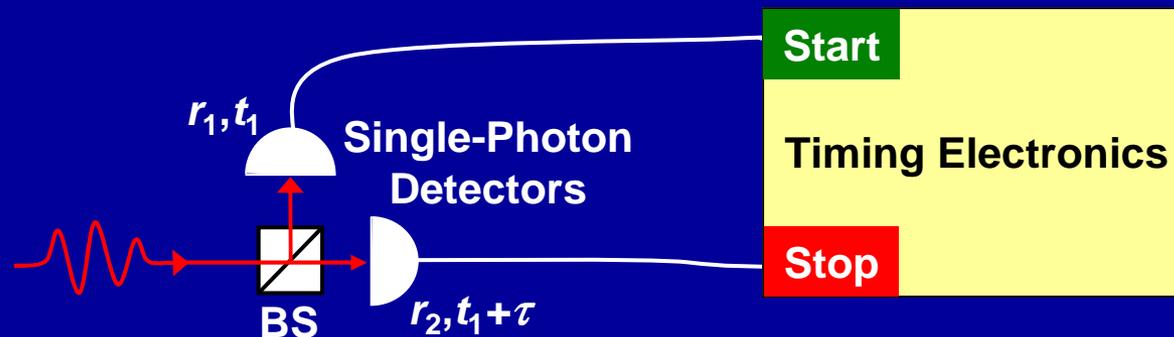
Measuring Intensity Correlations: 1 Detector



Electronics \rightarrow Compute Intensity Correlations

Can't access $\tau < t_{dead}$

Hanbury Brown-Twiss Interferometer



$$g^{(2)}(\tau) \approx g^{(2)}(r_1, t_1; r_2, t_1 + \tau)$$

Beamsplitter: Projects identical copies of input spatial mode(s) onto 2 detectors

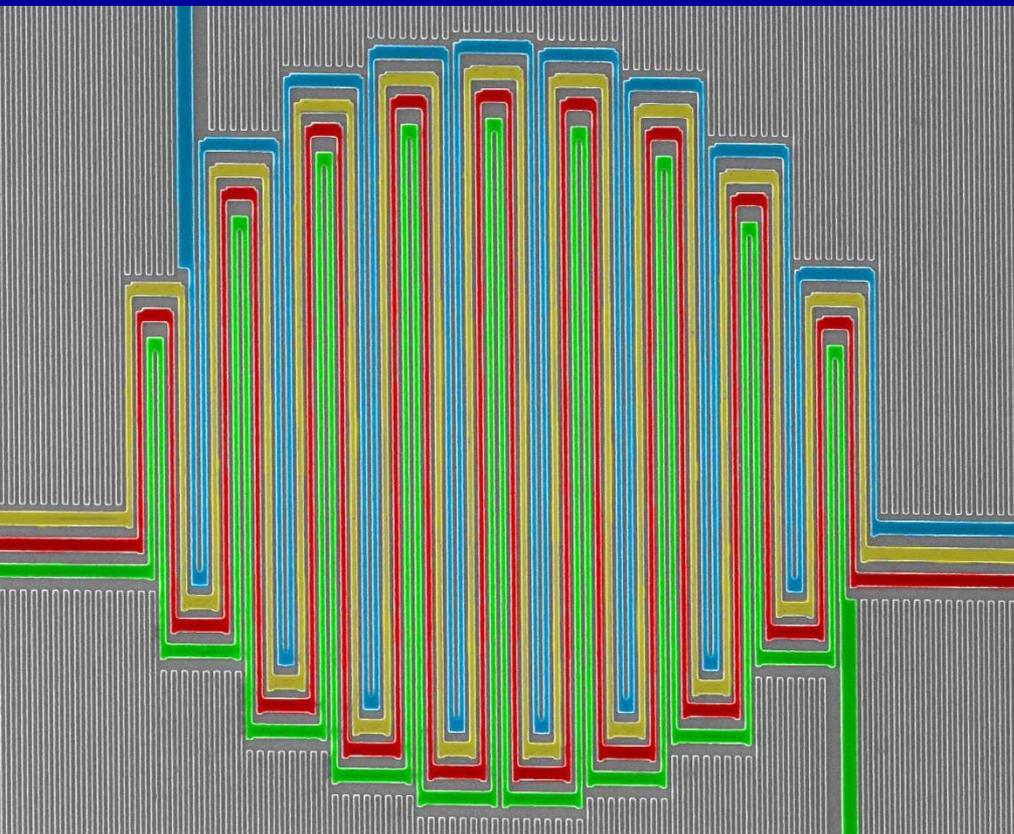
Potential pitfalls:

Imperfect beamsplitter, misalignment

Single-Photon Avalanche Diodes notorious for crosstalk via re-emission

Scaling to higher orders possible, but non-trivial

4-element interleaved SNSPD



10 μm

Independently bias and read out each element

Fiber-coupled: total **system** detection efficiency up to 46% @1550 nm

Device used here:

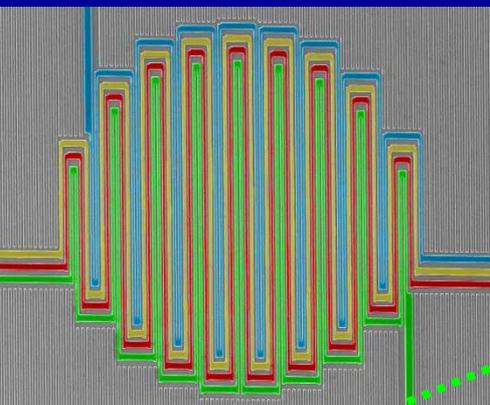
Efficiency ~4% @ 1070 nm

Dark Counts ~100 Hz each

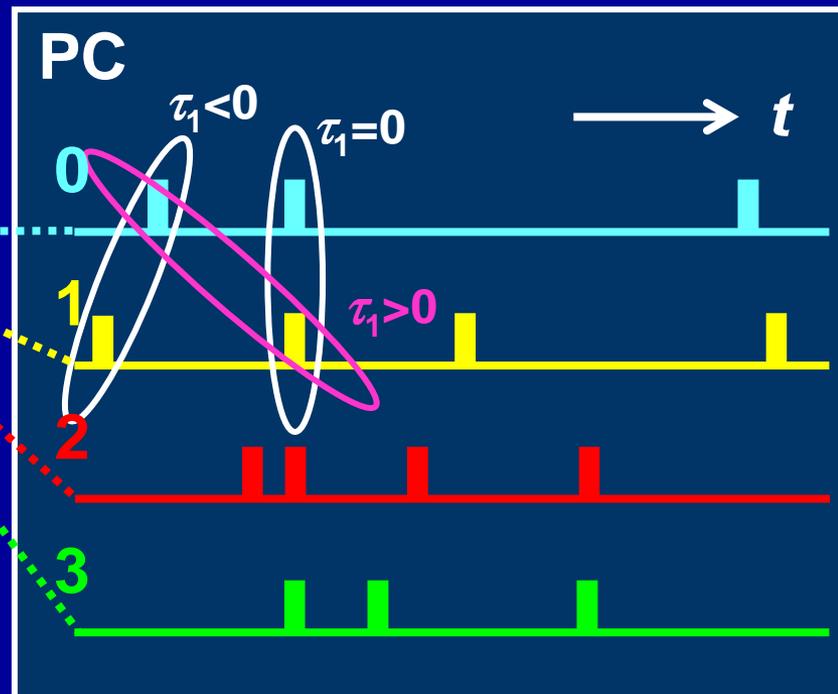
Light Counts ~100 kHz each

Dauler *et al.*, *J.Mod.Opt.* 56, 364 (2009)

4-element interleaved SNSPD



4-Channel
Time-Tagging
Electronics

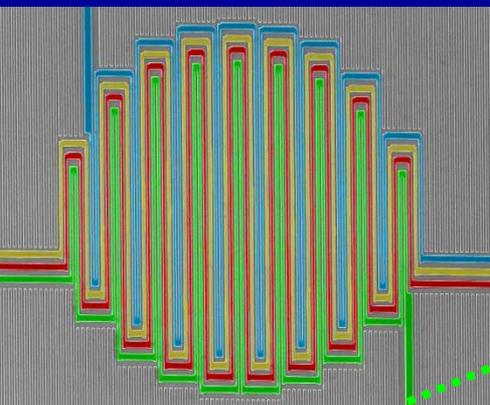


Post-processing → Multi-start, multi-stop histograms

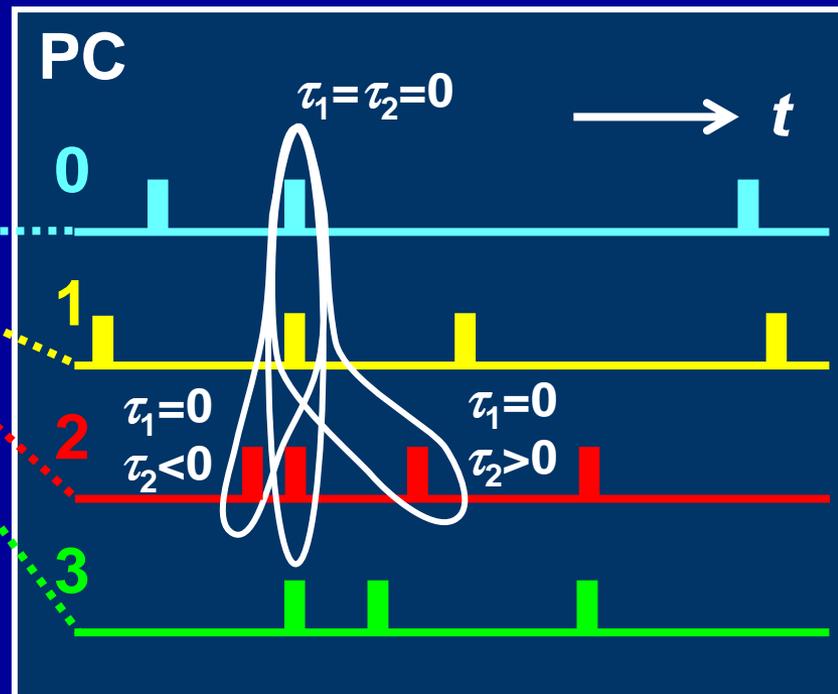
$$g^{(2)}(\tau_1) = \frac{\langle : \hat{I}(t) \hat{I}(t + \tau_1) : \rangle}{\langle \hat{I}(t) \rangle^2} \approx \frac{\langle P_0(t) \& P_1(t + \tau_1) \rangle}{\langle P_0 \rangle \langle P_1 \rangle} = \frac{\text{Raw Histogram}}{R_0 R_1 \Delta \tau T}$$

Uncorrelated Probability
 Count Rates
 Bin Width
 Run Time

4-element interleaved SNSPD



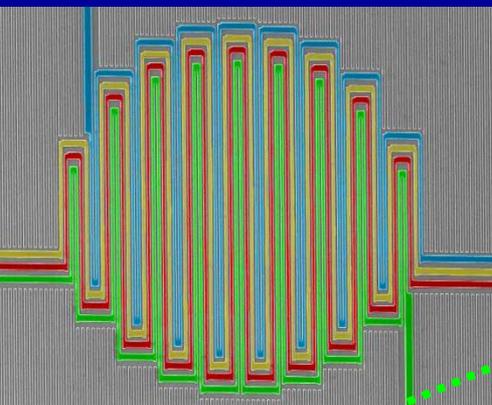
4-Channel
Time-Tagging
Electronics



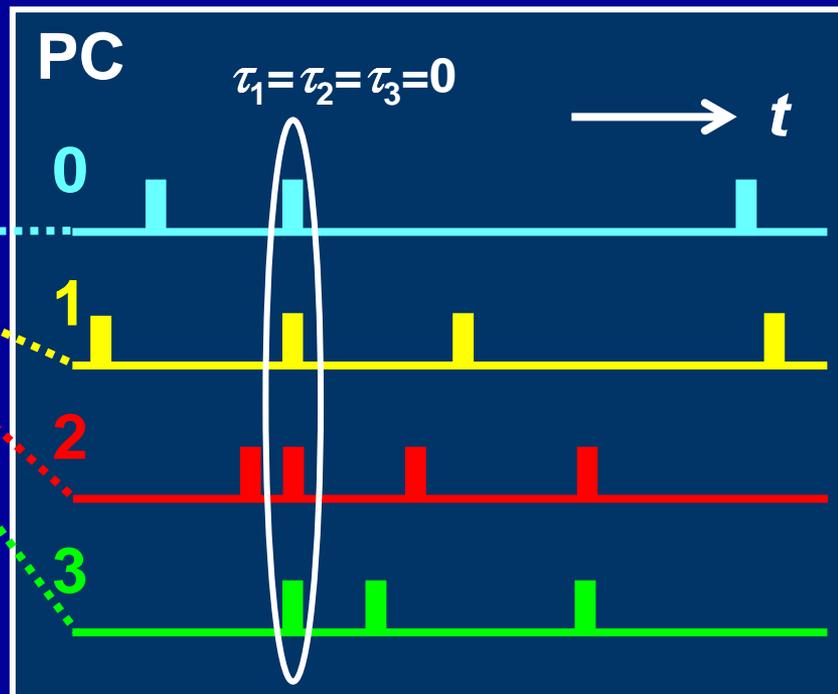
Post-processing → Multi-start, multi-stop histograms

$$g^{(3)}(\tau_1, \tau_2) = \frac{\langle : \hat{I}(t) \hat{I}(t + \tau_1) \hat{I}(t + \tau_2) : \rangle}{\langle \hat{I}(t) \rangle^3} \approx \frac{\langle P_0(t) \& P_1(t + \tau_1) \& P_2(t + \tau_2) \rangle}{\langle P_0 \rangle \langle P_1 \rangle \langle P_2 \rangle} = \frac{\text{Raw Histogram}}{R_0 R_1 R_2 (\Delta\tau)^2 T}$$

4-element interleaved SNSPD



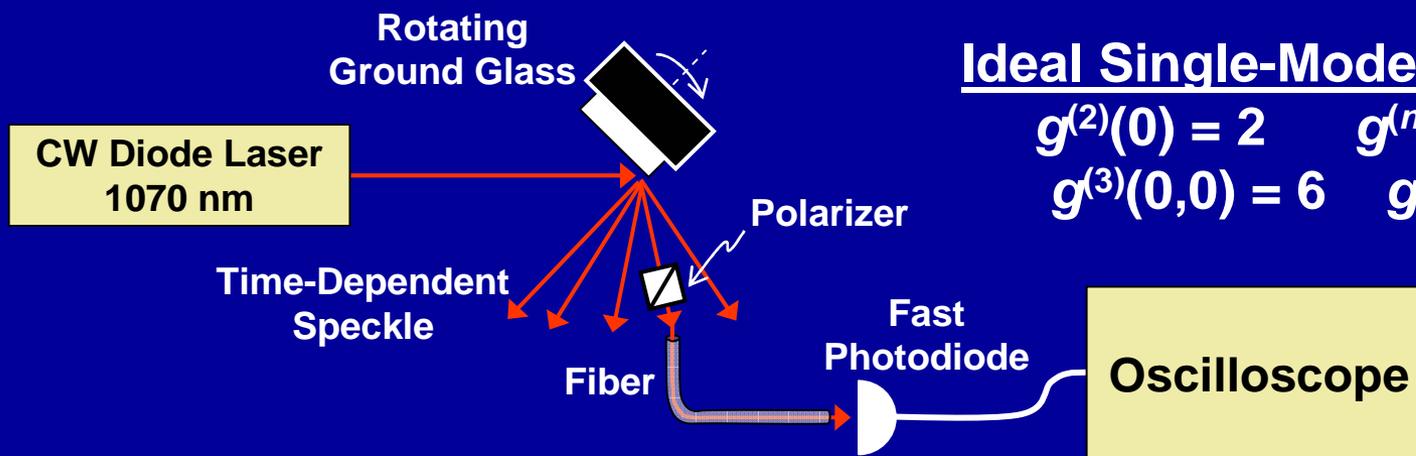
4-Channel
Time-Tagging
Electronics



Post-processing → Multi-start, multi-stop histograms

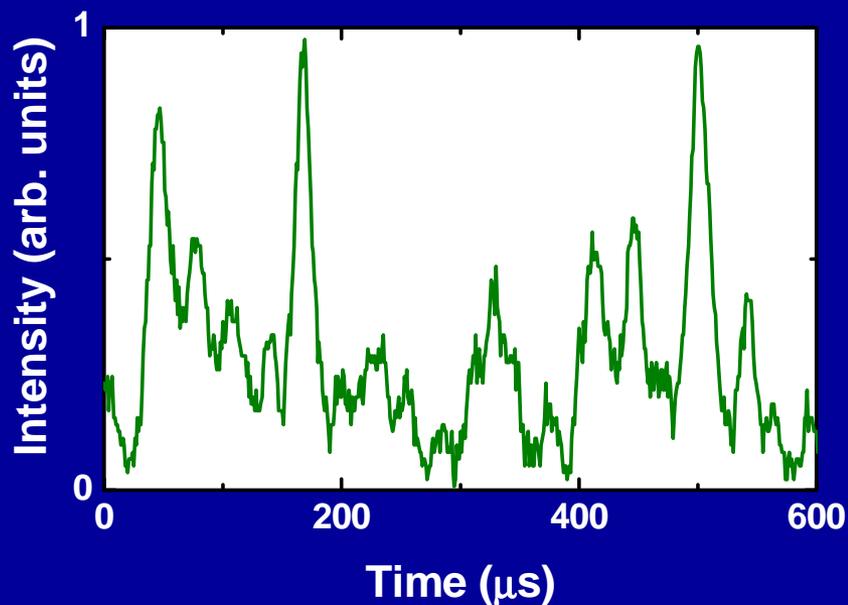
$$g^{(4)}(\tau_1, \tau_2, \tau_3) = \frac{\langle : \hat{I}(t) \hat{I}(t + \tau_1) \hat{I}(t + \tau_2) \hat{I}(t + \tau_3) : \rangle}{\langle \hat{I}(t) \rangle^4} \approx \frac{\langle P_0(t) \& P_1(t + \tau_1) \& P_2(t + \tau_2) \& P_3(t + \tau_3) \rangle}{\langle P_0 \rangle \langle P_1 \rangle \langle P_2 \rangle \langle P_3 \rangle}$$

Chaotic, Pseudo-Thermal Source

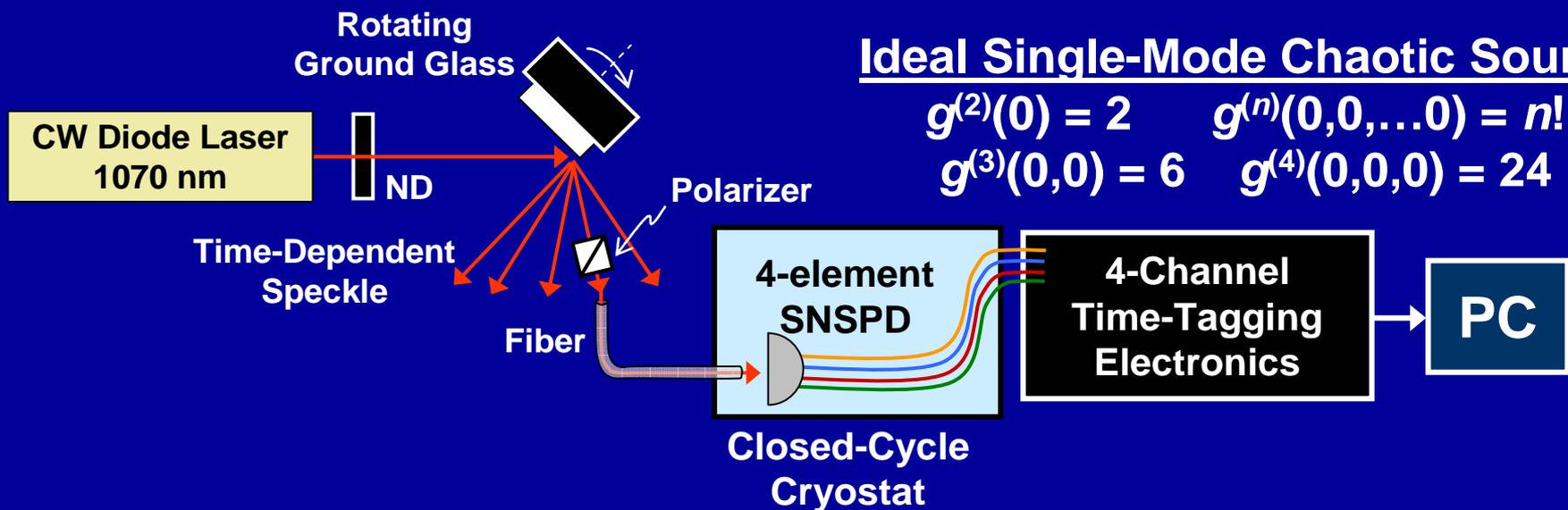


Ideal Single-Mode Chaotic Source

$$g^{(2)}(0) = 2 \quad g^{(n)}(0,0,\dots,0) = n!$$
$$g^{(3)}(0,0) = 6 \quad g^{(4)}(0,0,0) = 24$$



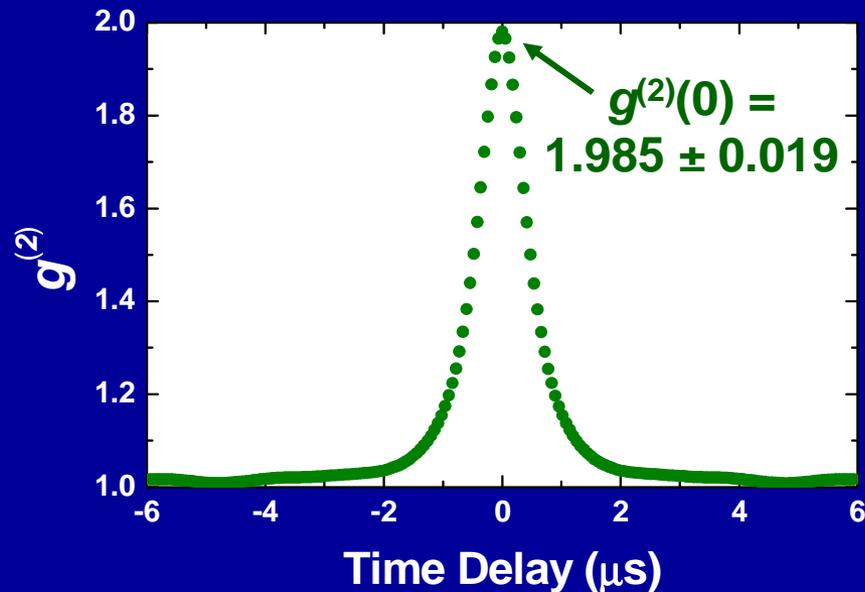
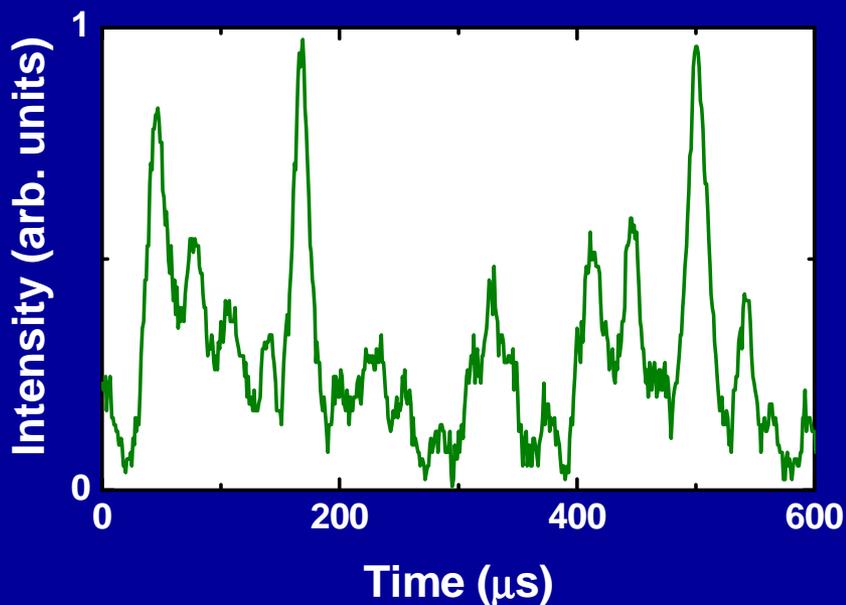
2nd-Order Coherence



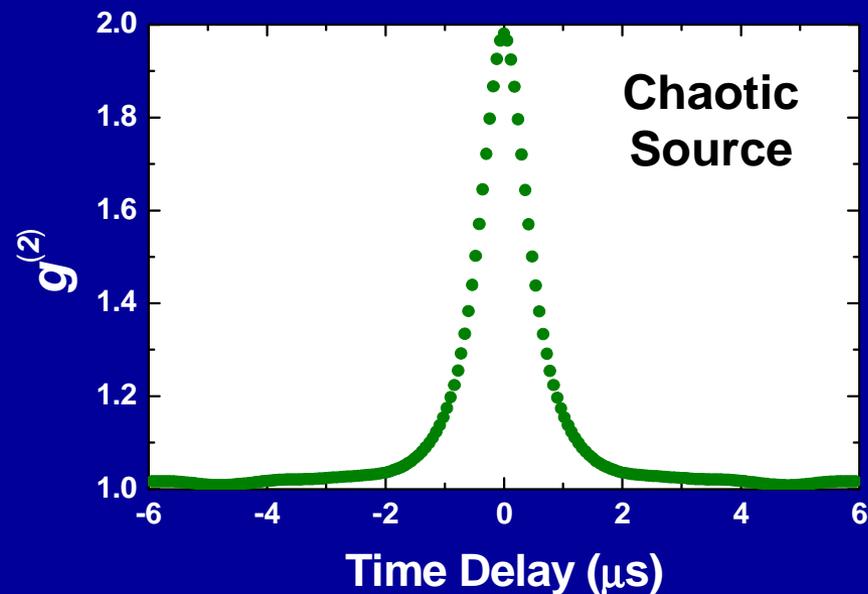
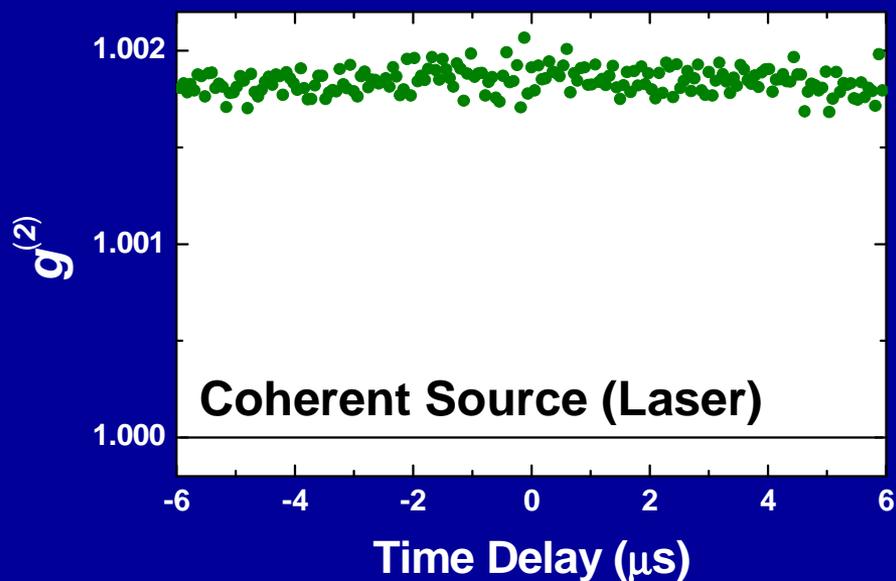
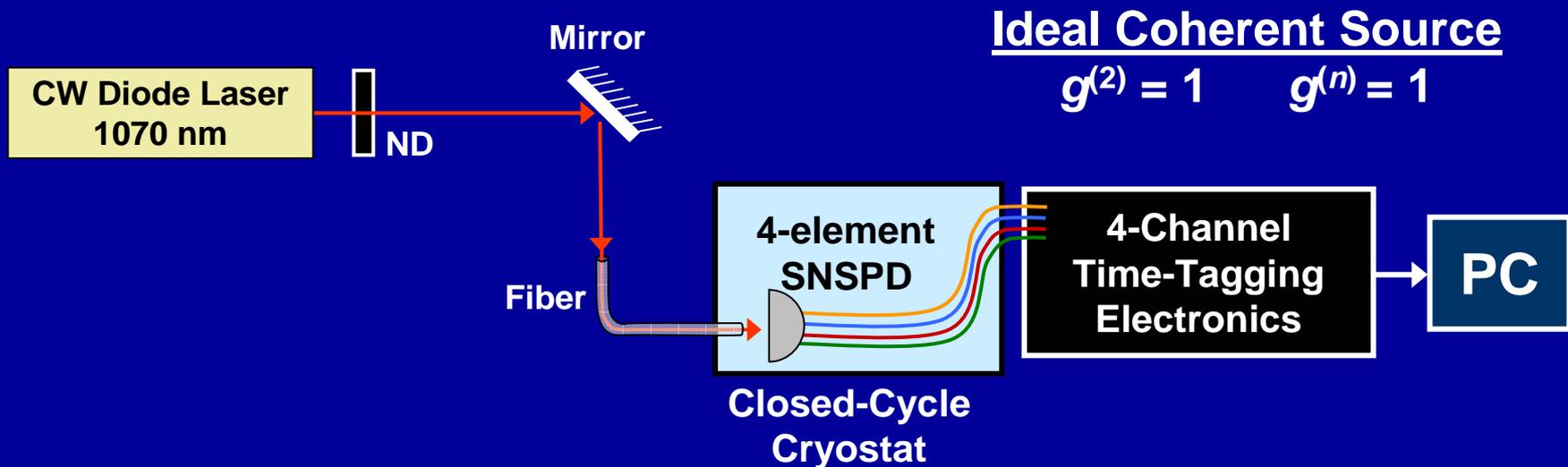
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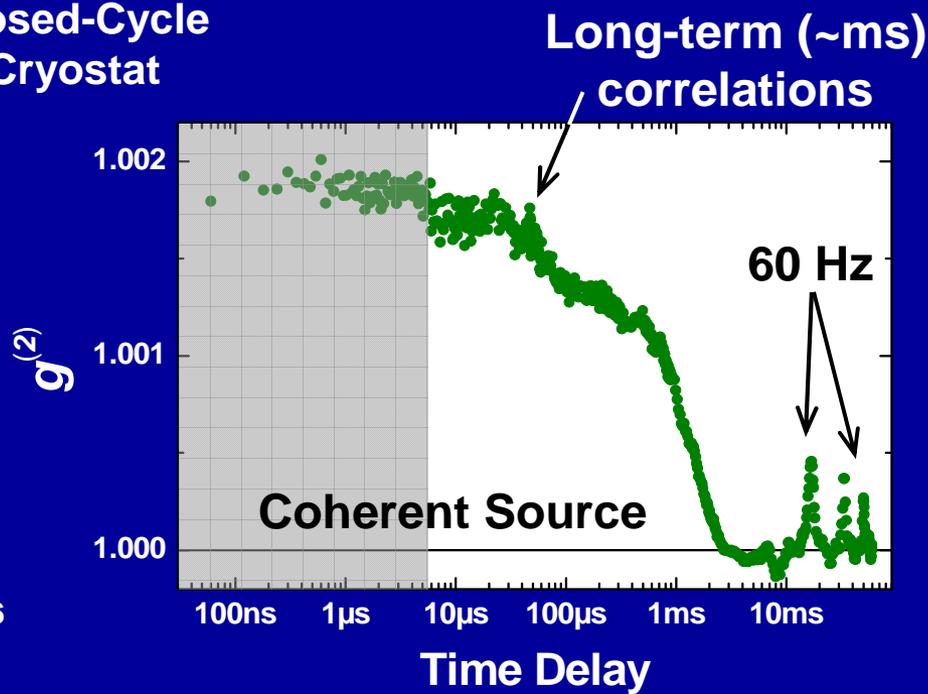
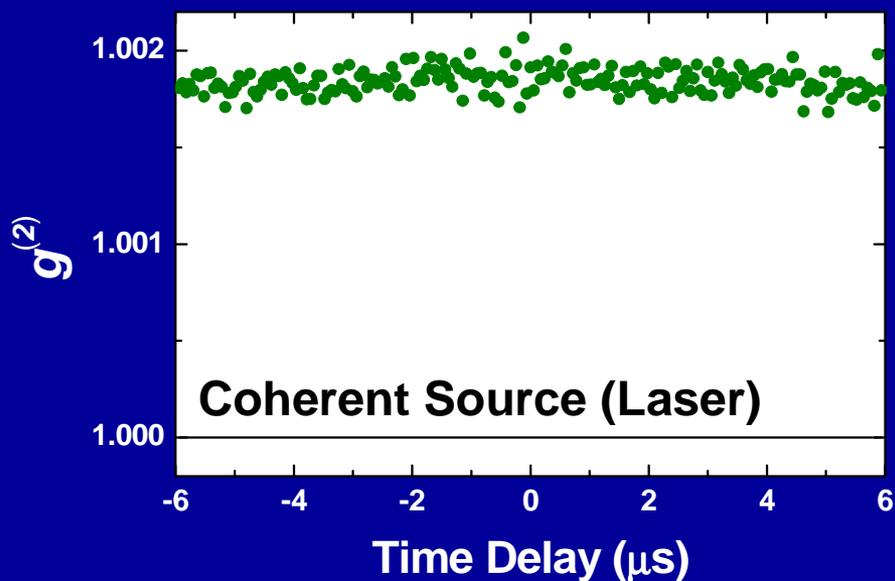
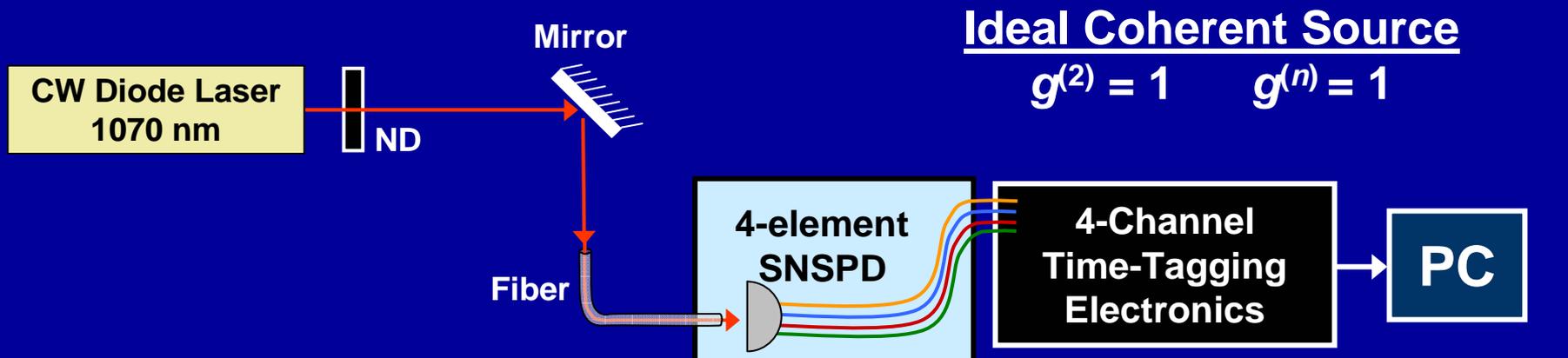
$$g^{(3)}(0,0) = 6 \quad g^{(4)}(0,0,0) = 24$$



2nd-Order Coherence

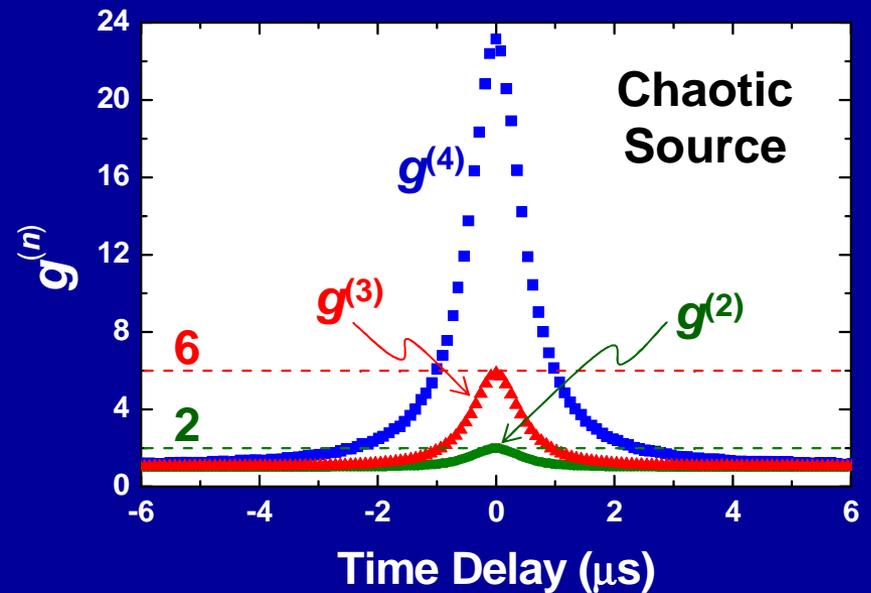
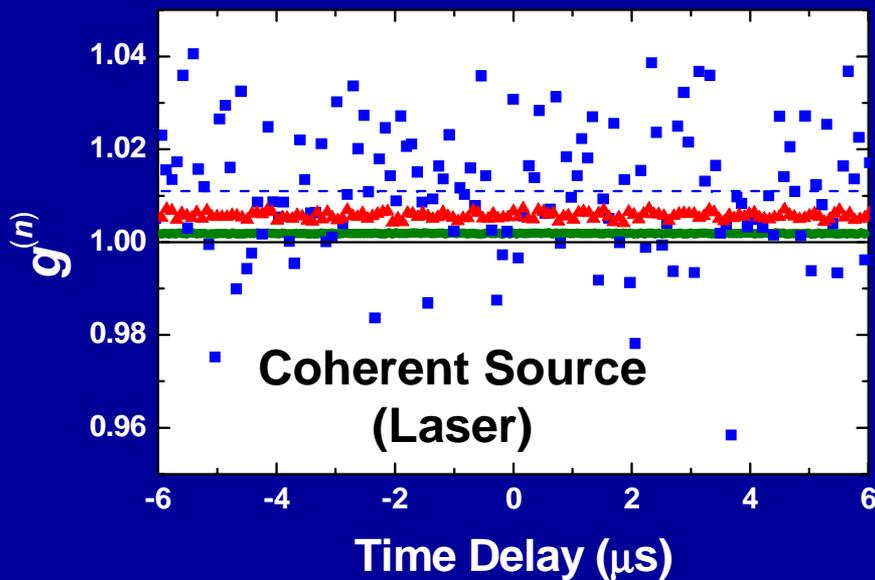


2nd-Order Coherence

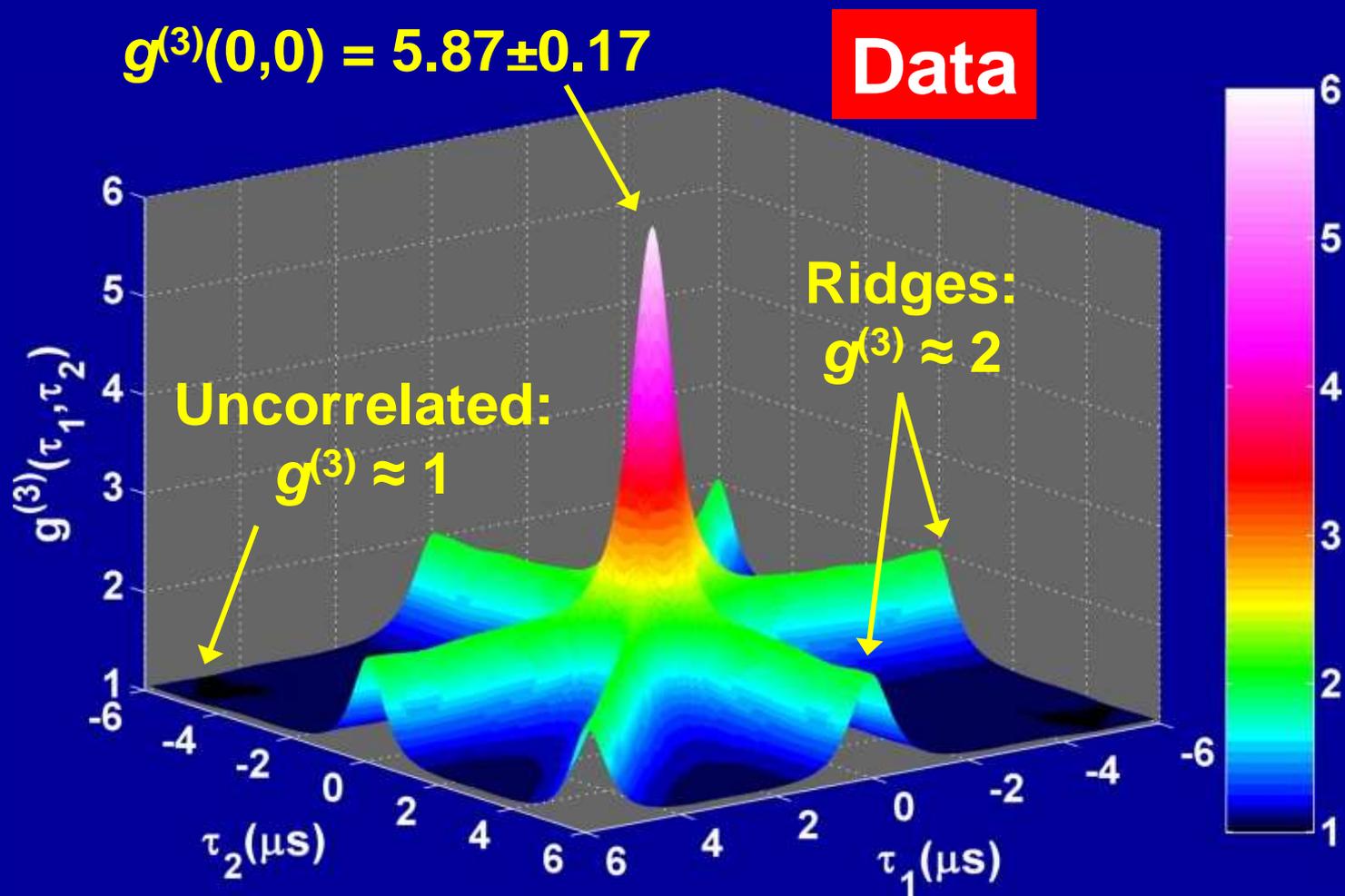


Higher-Order Coherence

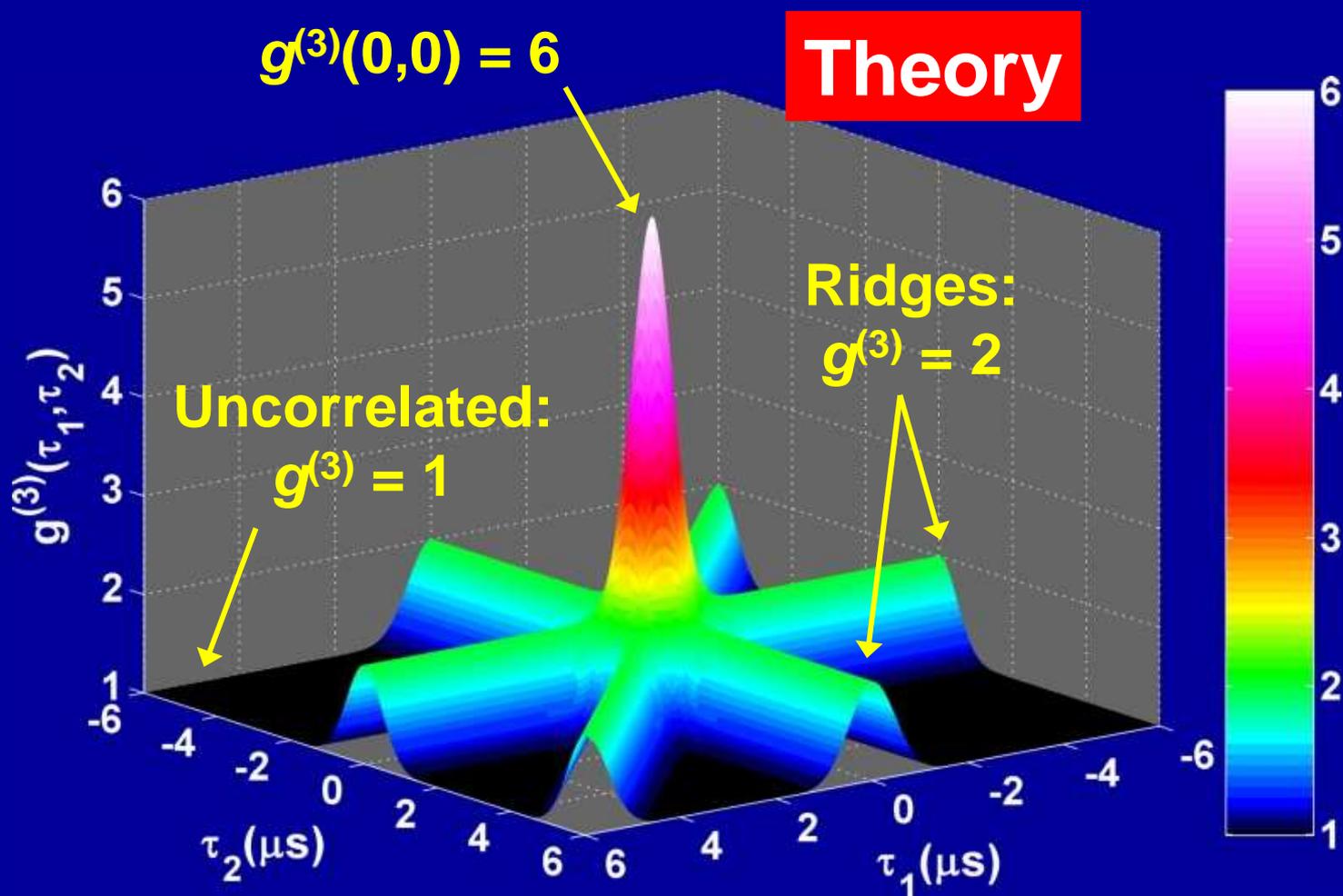
	Coherent (Avg)		Chaotic (All $\tau_i = 0$)	
	Expected	Result	Expected	Result
$g^{(2)}$	1	1.0018 ± 0.0008	2	1.99 ± 0.02
$g^{(3)}$	1	1.006 ± 0.002	6	5.9 ± 0.2
$g^{(4)}$	1	1.011 ± 0.005	24	23 ± 2



3rd-Order: Chaotic Source



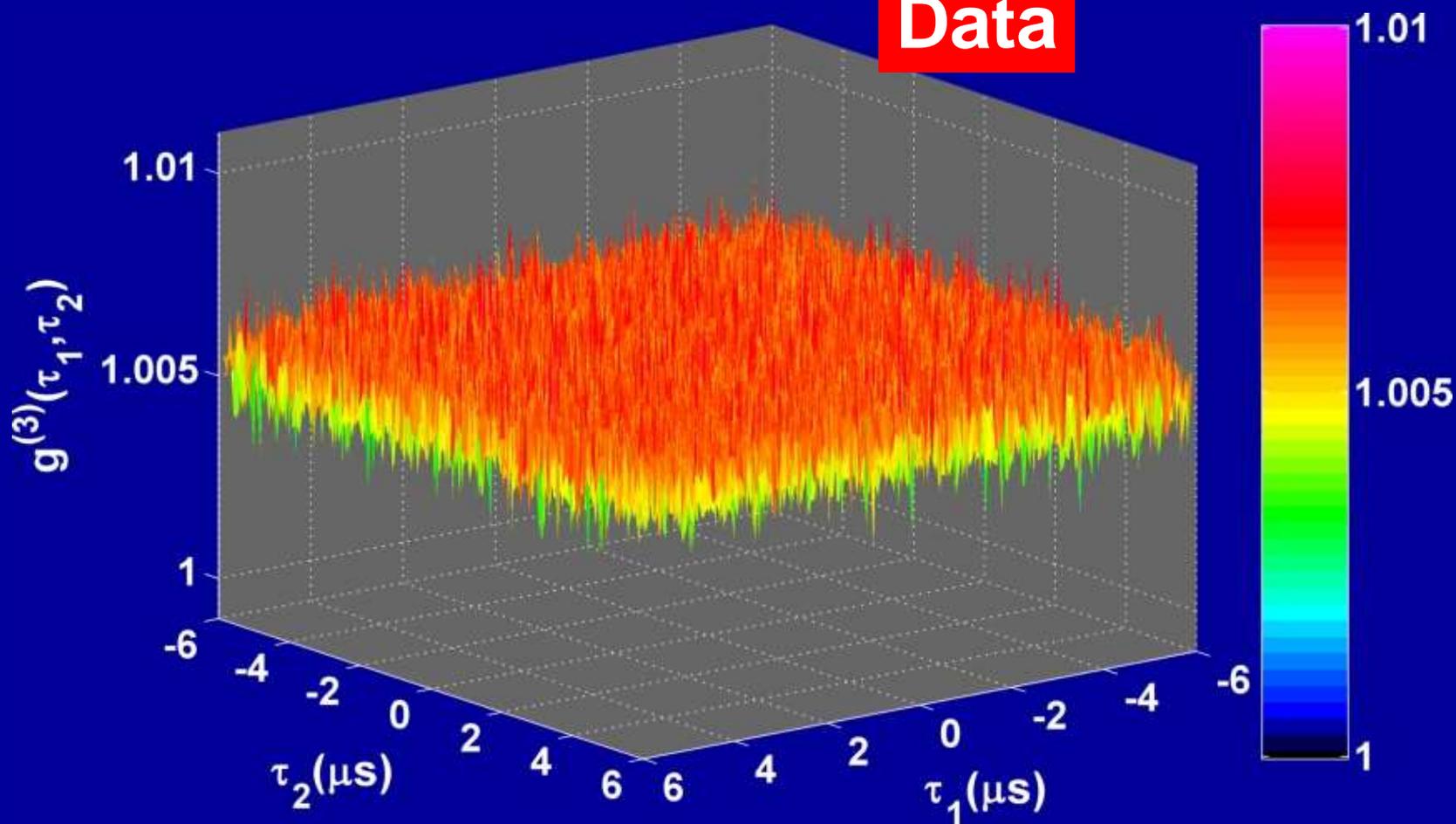
3rd-Order: Chaotic Source



Calculation assumes ideal Gaussian scattering process:
P.-A. Lemieux and D. J. Durian, *JOSA A* 16, 1651 (1999)

3rd-Order: Coherent Source

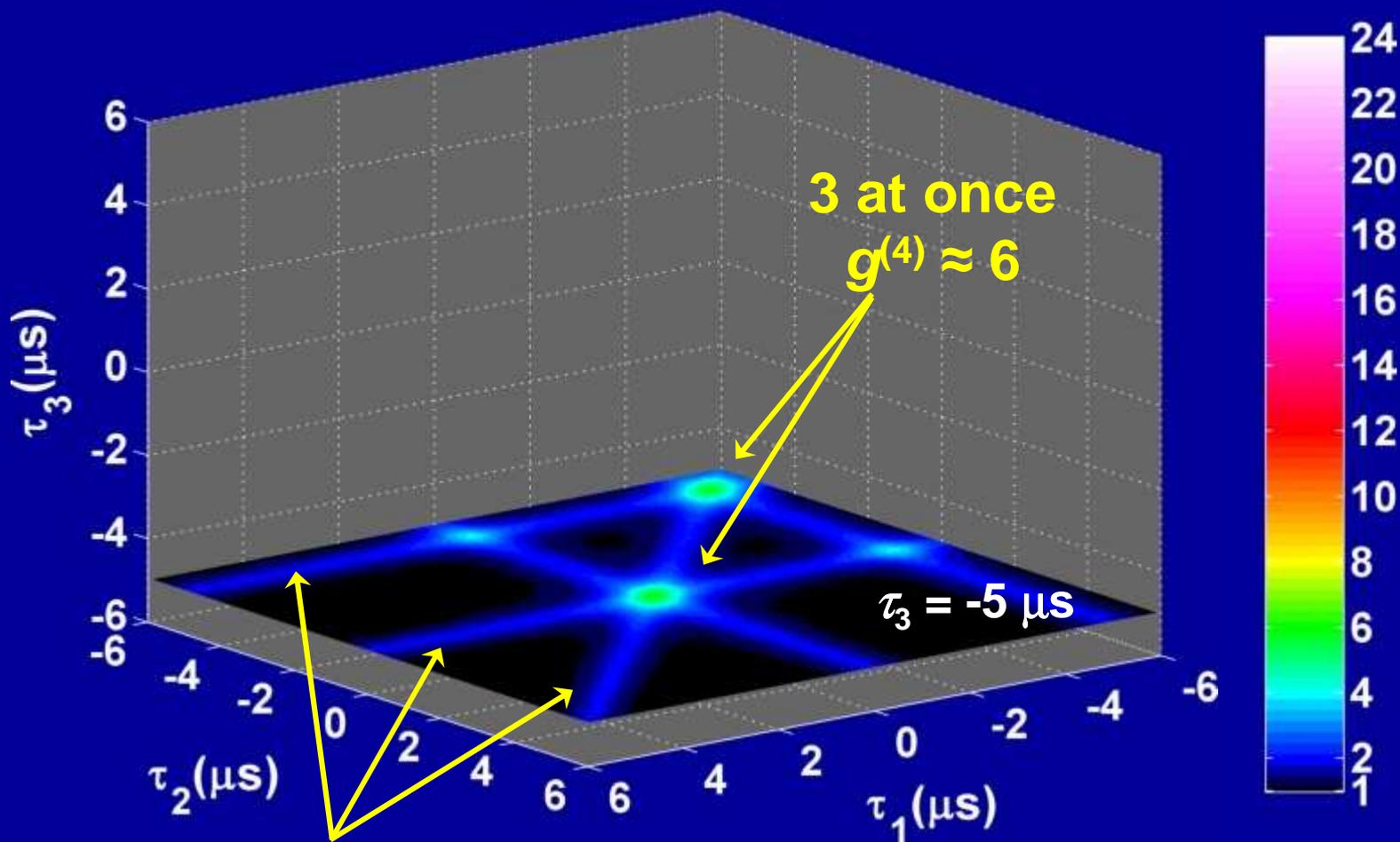
Data



Mean value: $\langle g^{(3)} \rangle = 1.006 \pm 0.002$

→ Precision measurement of weak cross-correlation

4th-Order: Chaotic Source

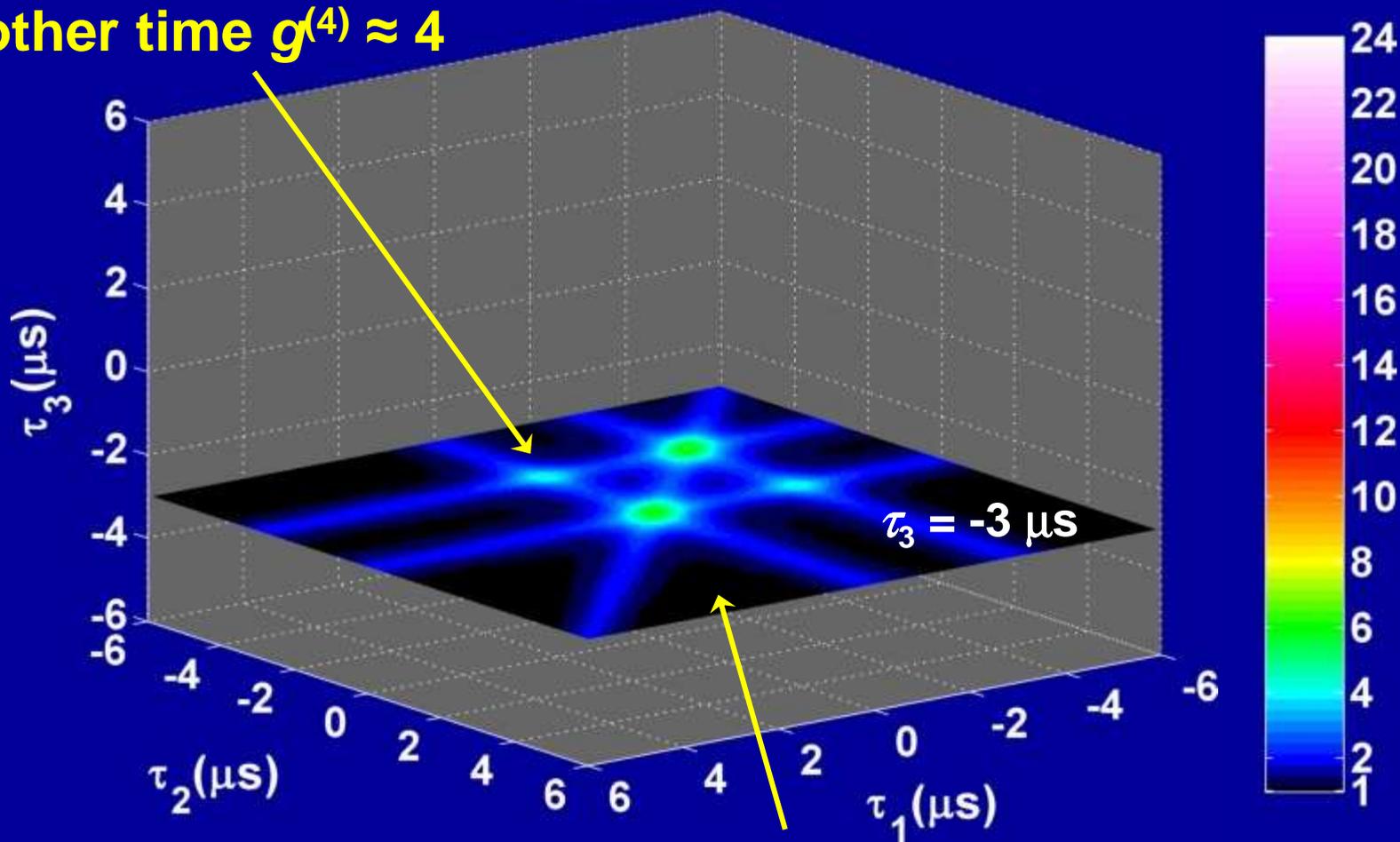


2 Elements fire simultaneously

$$g^{(4)} \approx 2$$

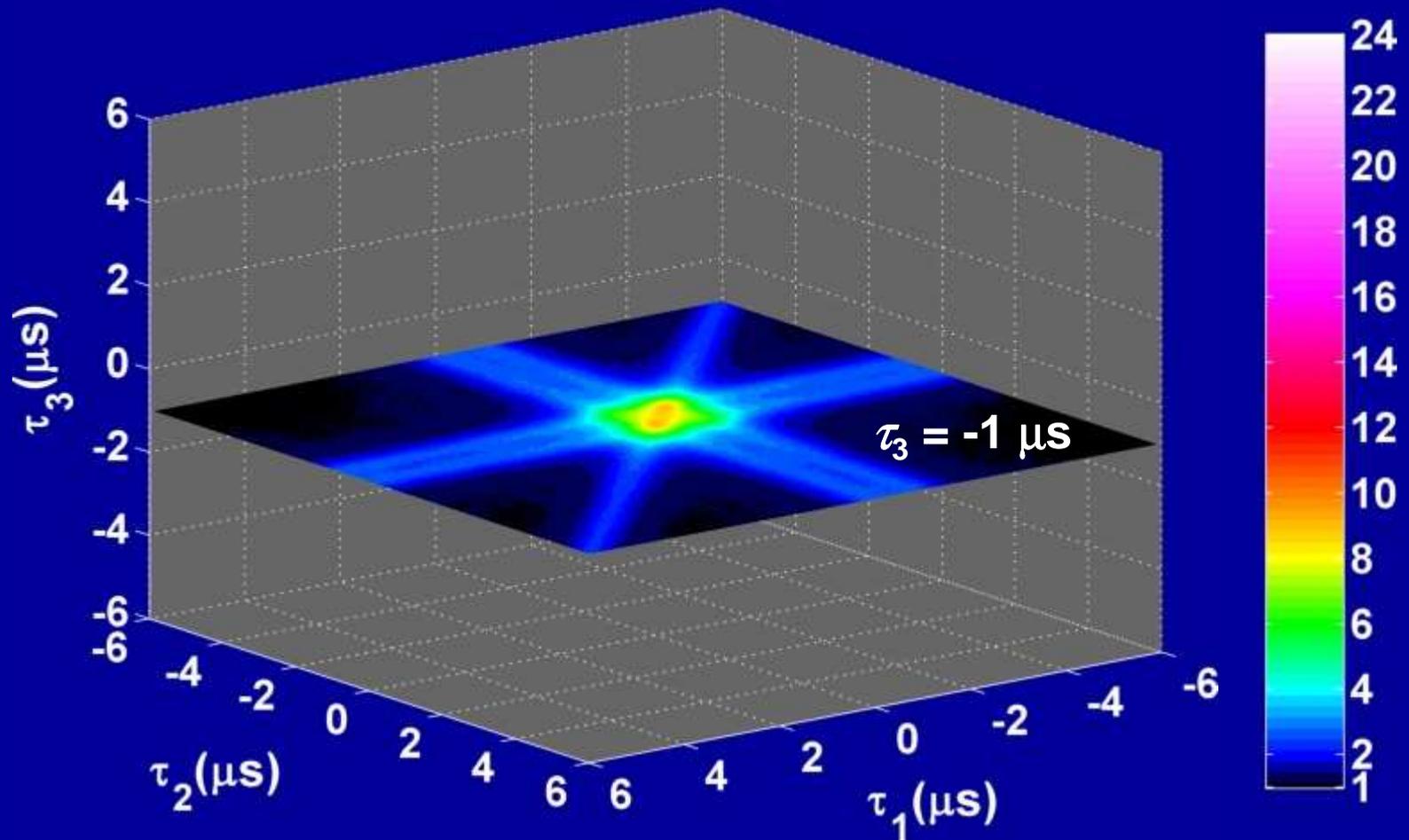
4th-Order: Chaotic Source

2 at one time, 2 at another time $g^{(4)} \approx 4$



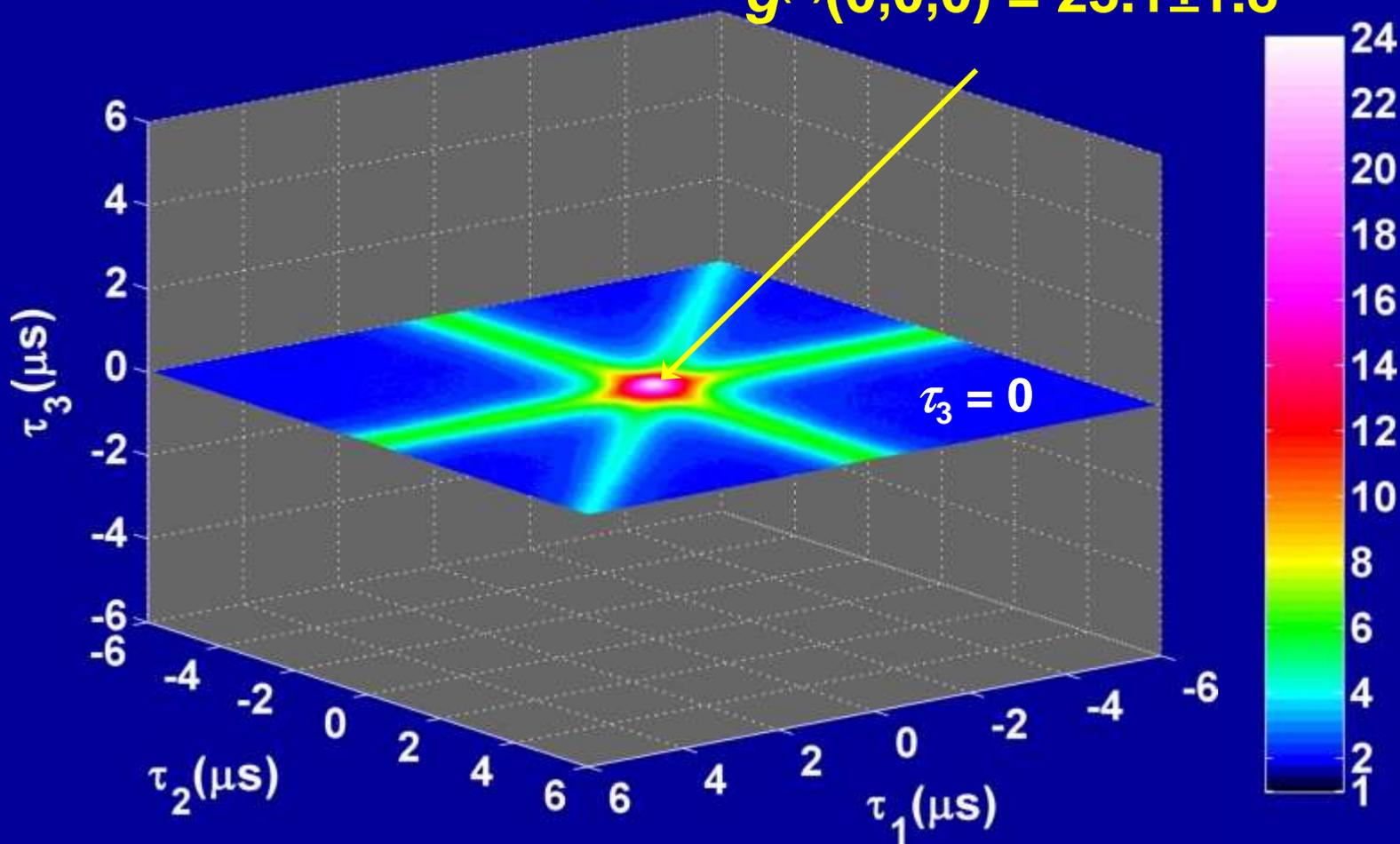
All 4 at different times $g^{(4)} \approx 1$

4th-Order: Chaotic Source

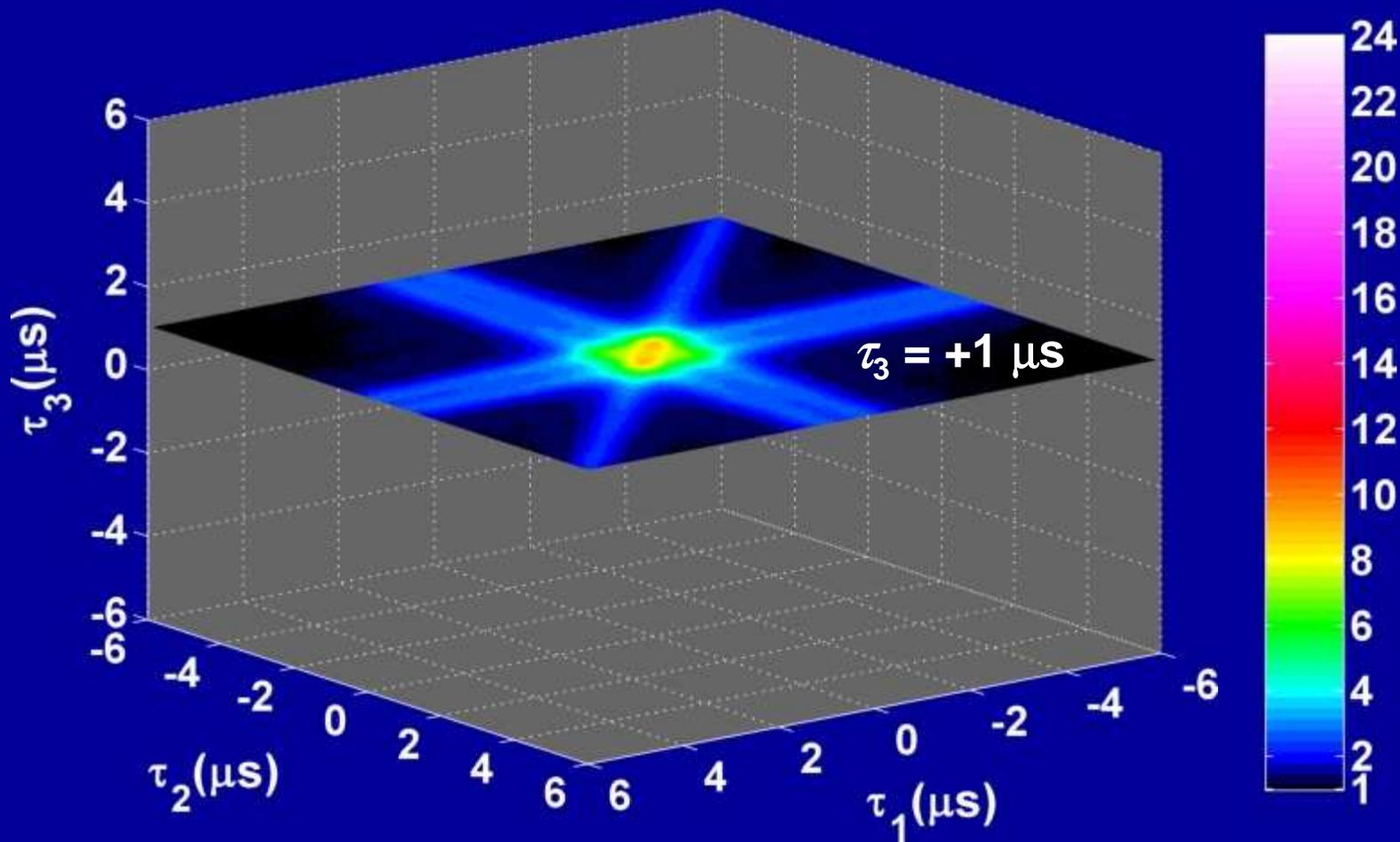


4th-Order: Chaotic Source

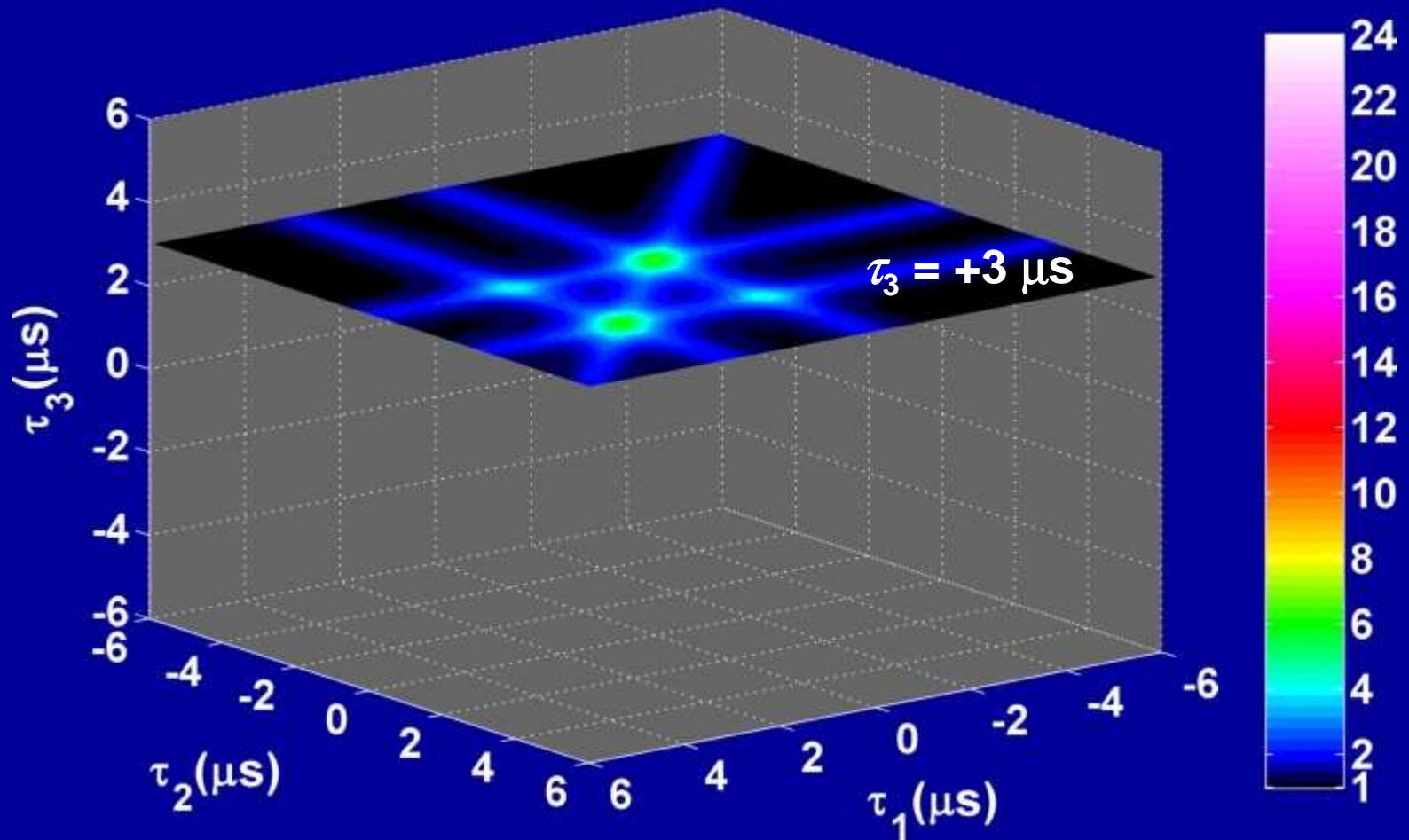
All 4 at once:
 $g^{(4)}(0,0,0) = 23.1 \pm 1.8$



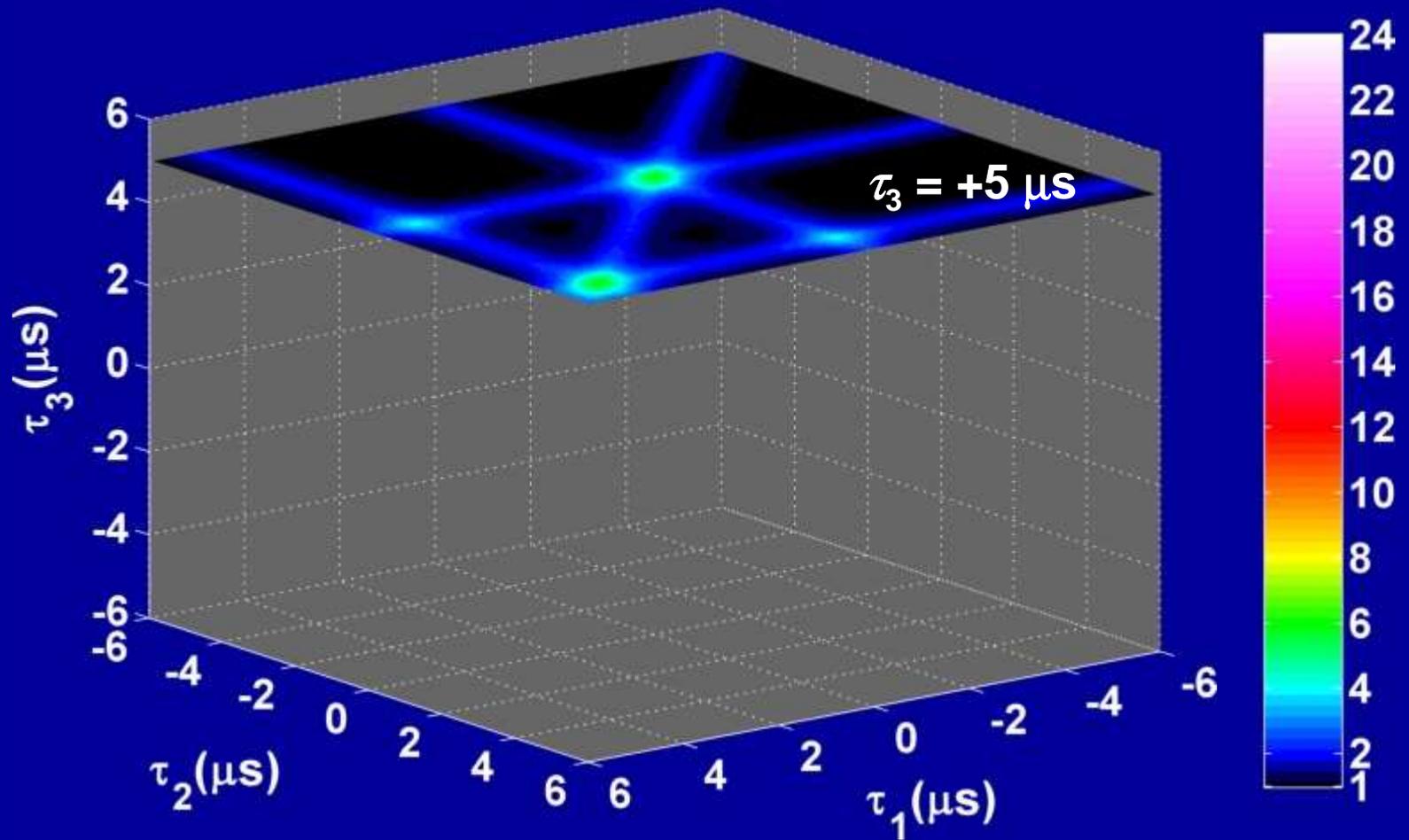
4th-Order: Chaotic Source



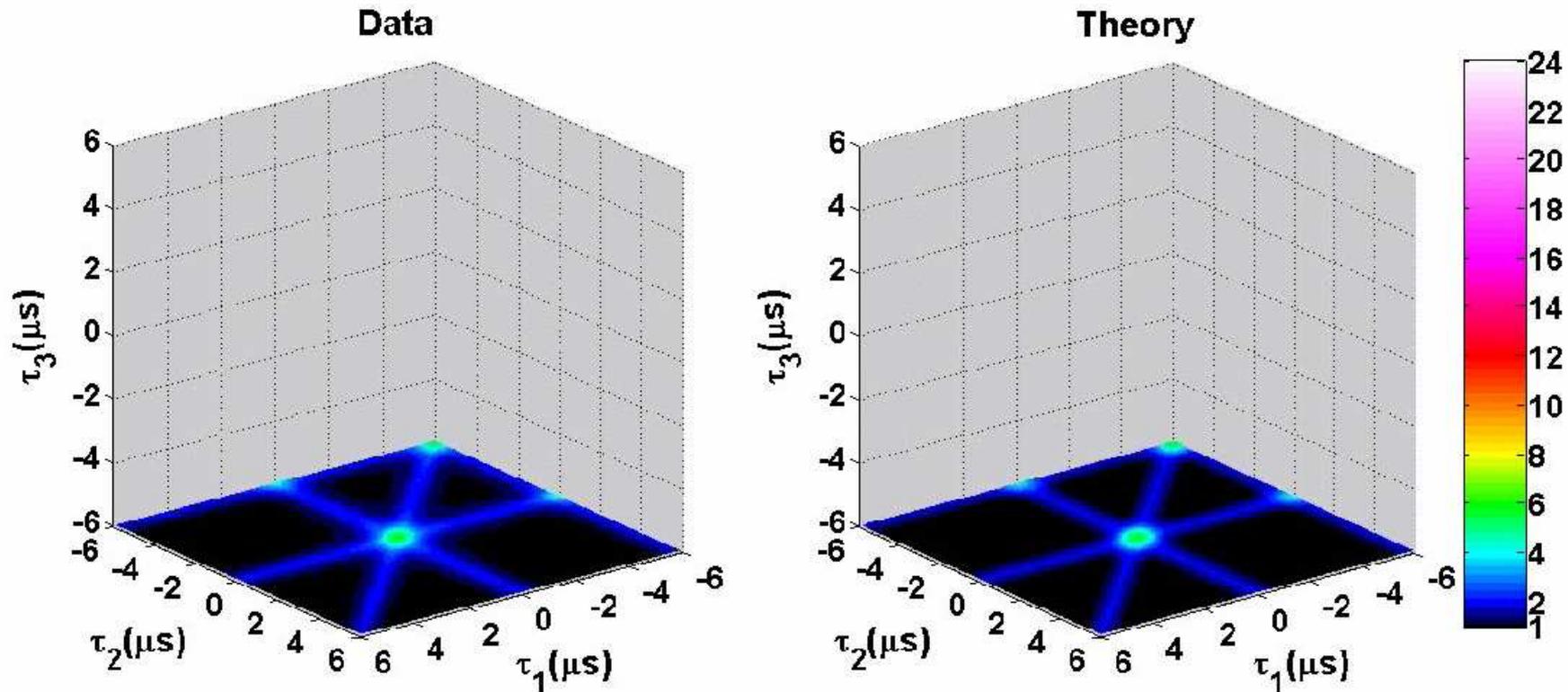
4th-Order: Chaotic Source



4th-Order: Chaotic Source



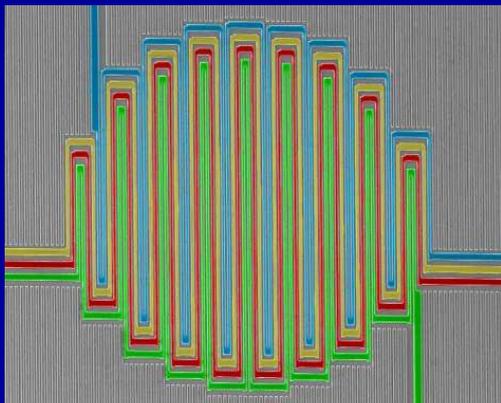
4th-Order: Chaotic Source



g4datatheory.avi

Summary

- **Superconducting Nanowire Single-Photon Detectors (SNSPDs)**
- **4-Element interleaved SNSPD + Time-stamping electronics**
 - Multi-channel, multi-start, multi-stop correlation histograms: $g^{(2)}, g^{(3)}, g^{(4)}$
 - Chaotic source: High-order photon bunching: $g^{(n)}(0,0,\dots) = n!$
 - Coherent source: $g^{(n)} \approx 1$
- **High-Order Coherence Measurement To-Do List**
 - Single-photon sources
 - Condensates (atomic, excitonic)
 - Non-equilibrium steady-state vs. equilibrium in biochemical reactions
 - Thresholdless lasers
 - Molecular aggregates



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