Characterization of single-photon pulses

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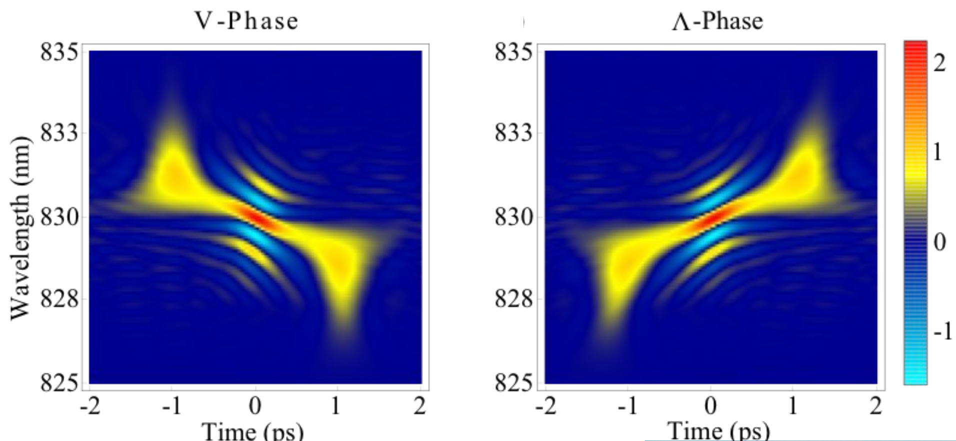
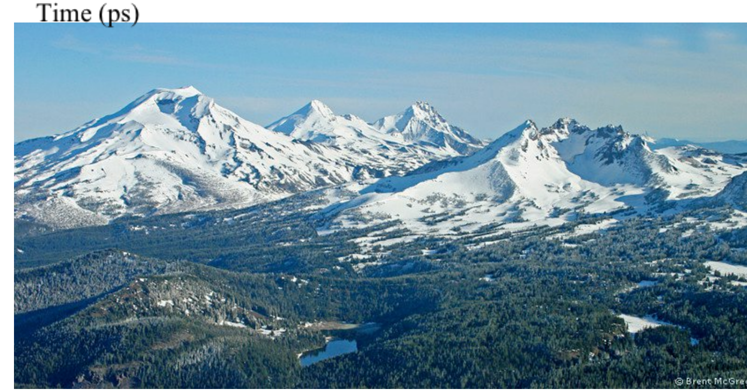




What is an ultrashort optical pulse?

- Solve Maxwell equations in free space to give wave equation

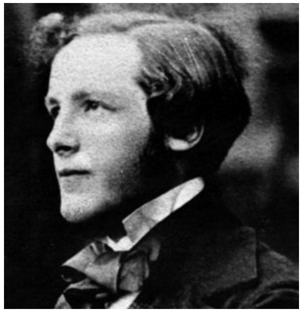
$$\oint \mathbf{E}\cdot d\mathbf{A} = \frac{q_{enc}}{\varepsilon_0}$$

$$\oint \mathbf{B}\cdot d\mathbf{A} = 0$$

$$\oint \mathbf{E}\cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

$$\oint \mathbf{B}\cdot d\mathbf{s} = \mu_0\varepsilon_0\frac{d\Phi_E}{dt} + \mu_0 i_{enc}$$

$$\left(\nabla^2 - \frac{1}{c^2}\partial_t^2\right)\mathbf{E}(\mathbf{x},t) = 0$$



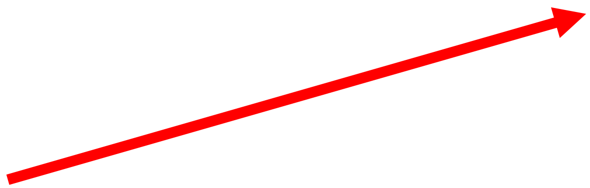
Paraxial approximation leads to beams

Carrier wave

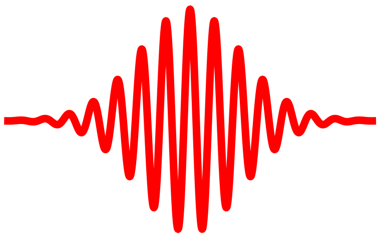
$$\mathbf{E}(\mathbf{x},t) = \hat{\mathbf{x}}\,\mathcal{E}_0\,\alpha(z/v - t)\,u(x,y;z)\exp(ik_0 z - \omega_0 t)$$

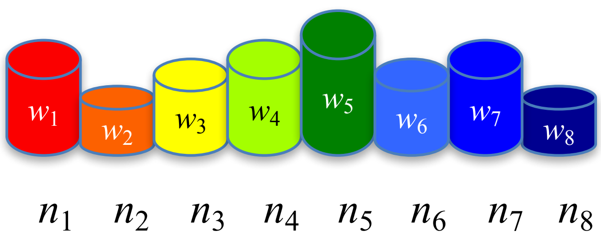
Slowly-varying envelope approximation leads to pulses

Linearity of Maxwell equations implies superpositions: **Wave packets**



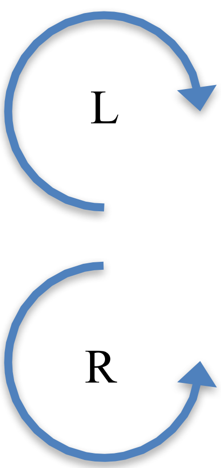
Direction of propagation





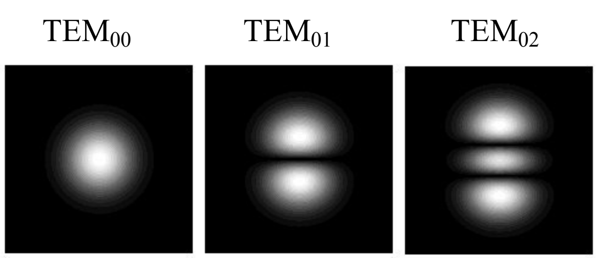
Spectral-temporal mode

Qutrit



Polarization mode

Qubit



Transverse spatial mode

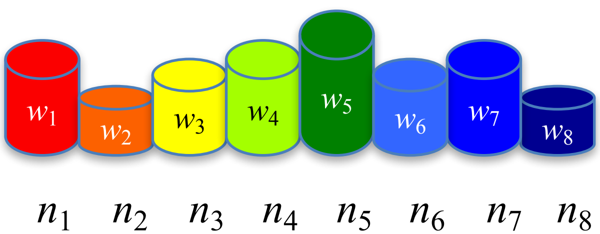
Qutrit

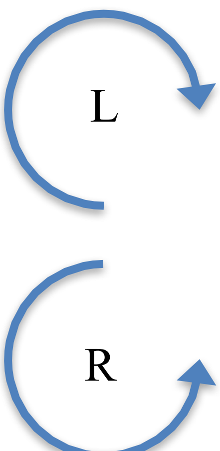
Photons and **modes**

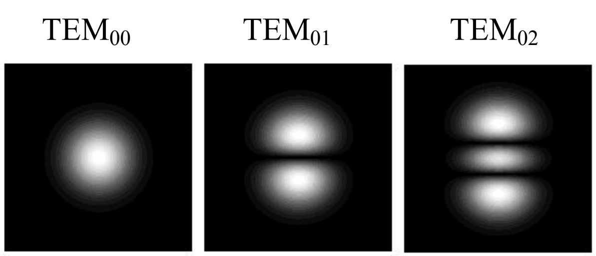
We tend to work at two extremes of the optical (quantum) state "spectrum"

Fixed ***photon*** number (say 1) we look at the *mode* distribution

Quantum state: Mode distribution of the photon and coherences between modes

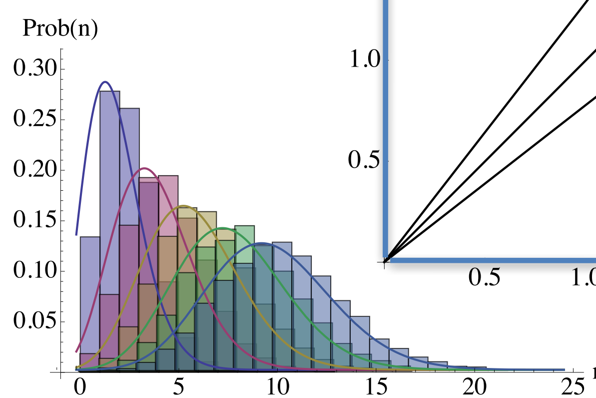


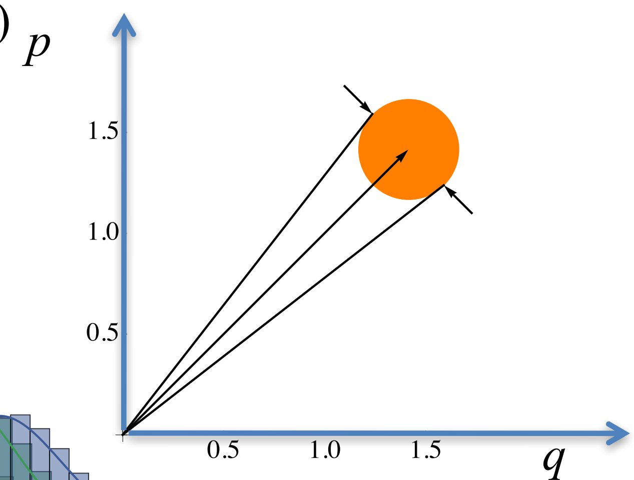




Fixed ***mode*** number (say 1) we look at the *photon* distribution

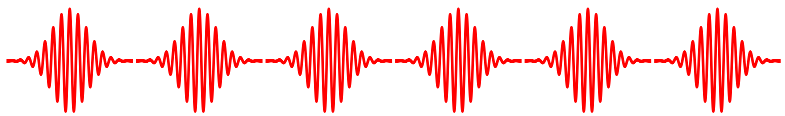
Quantum state: Photon number distribution and coherences between different photon numbers (amplitude and phase)



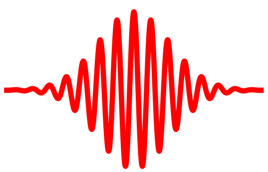
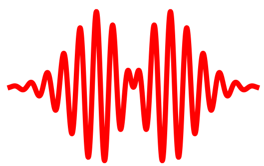


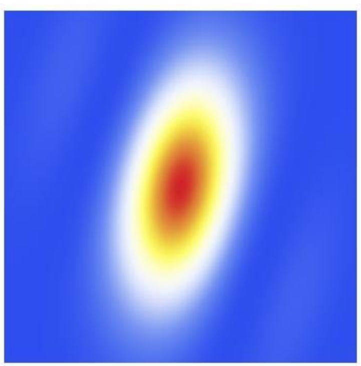
QCUMbER research explores both of these extremes

Focused on temporal-spectral pulsed modes of light (good for integrated optics)



Single- and two-photon states

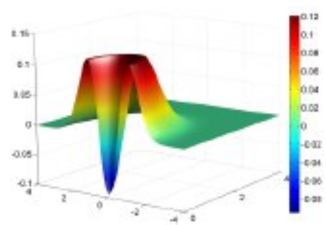
$\psi(t) =$  $+$ 



We will look at this today. . .

Single- and two-mode states

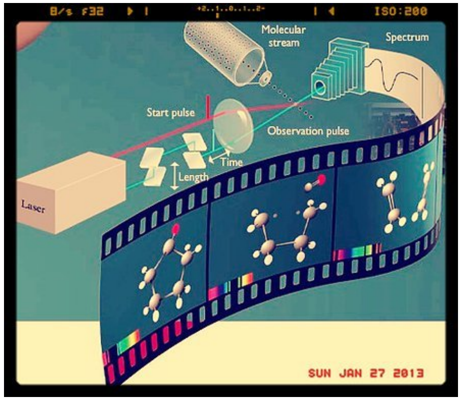
$$|\Psi\rangle = \sum_n c_n |n\rangle$$



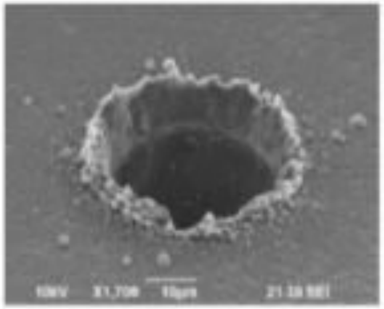
If you want to know more – ask me later. . .

Why short pulses?

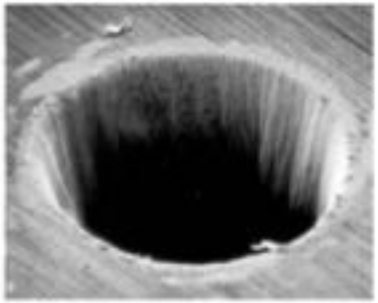
- Probe dynamics of material systems on ultrashort time scales (Chemistry Nobel Prize 1999)
- Nonlinear optical imaging (Chemistry Nobel Prize 2014)
- Machining and inscription (wave guide writing)



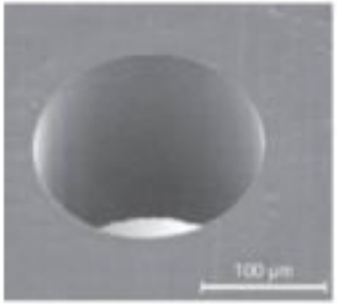
Femto-chemistry



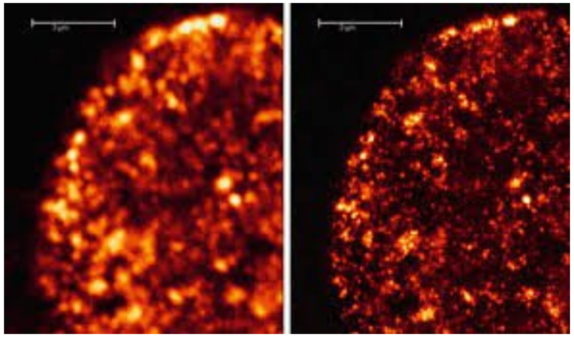
Nanosecond
HAZ (Heat Affected Zone)
Melt zone adds variability



Picosecond
Less HAZ
Rough surface adds variability



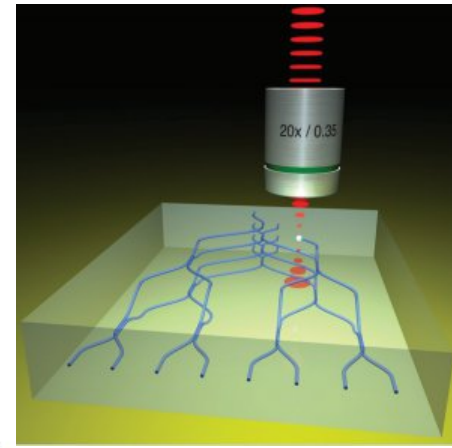
Femtosecond
No HAZ
Low variability

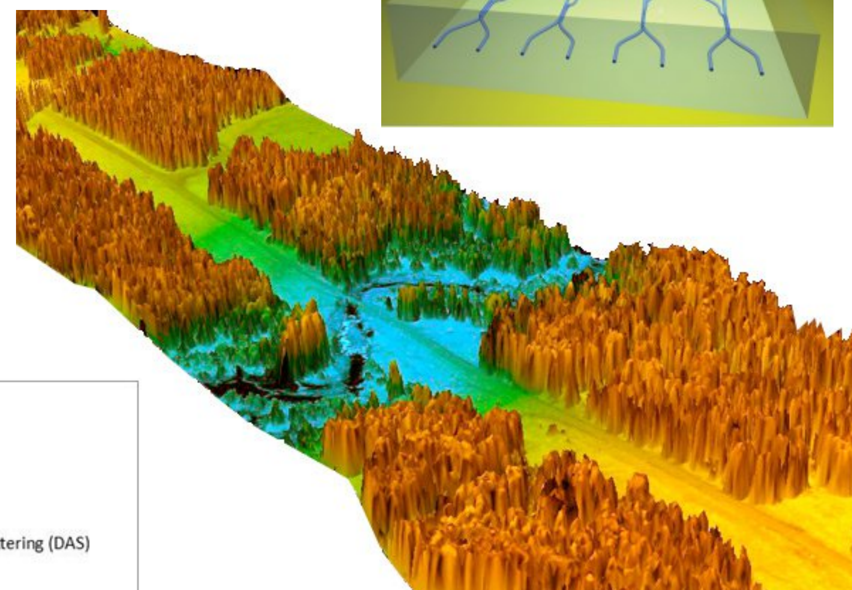


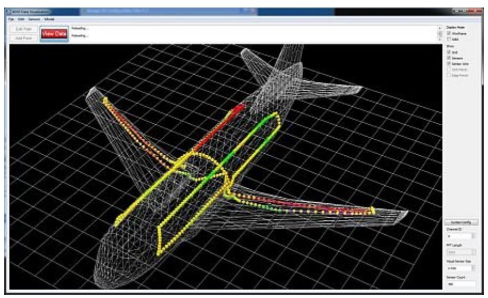
STED Microscopy

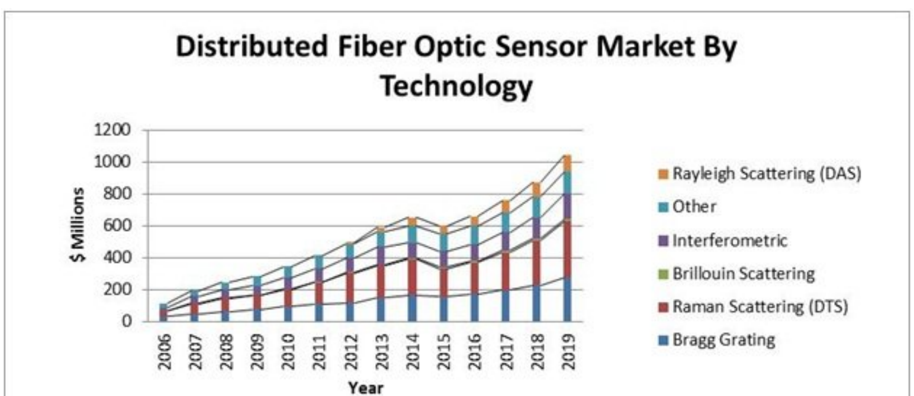
Why short pulses?

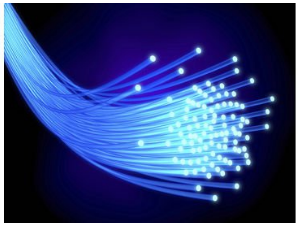
- Wave guide writing (fs inscription)
- Telecommunications (pulse mode encoding)
- Metrology (LiDAR)
- Distributed sensing





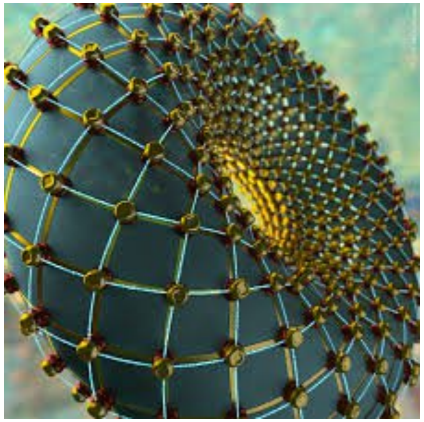


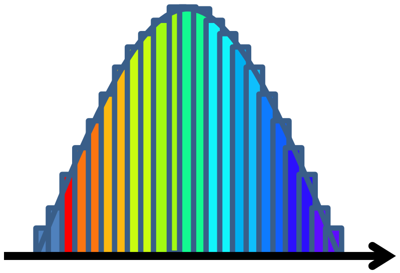




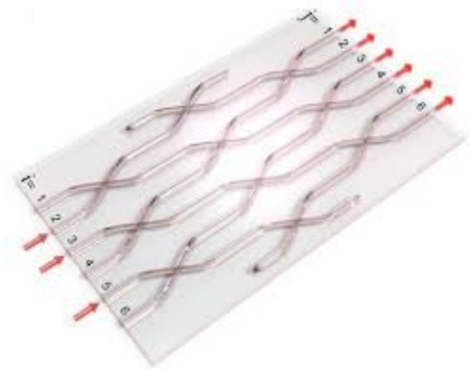
Why TF states for Q Info?

- Large information capacity
- Spectral-temporal modes used in classical telecom: well-suited to optical fiber and integrated-optics platforms (Take a hint from telecom industry!)
- Frequency translation between nodes of a hybrid quantum network (atoms, ions, NV centers, QDs)
- Natural choice to examine temporal evolution of quantum systems (e.g. energy transport in a network)



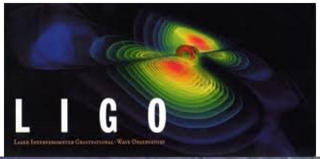


- Quantum computing (LOQC)

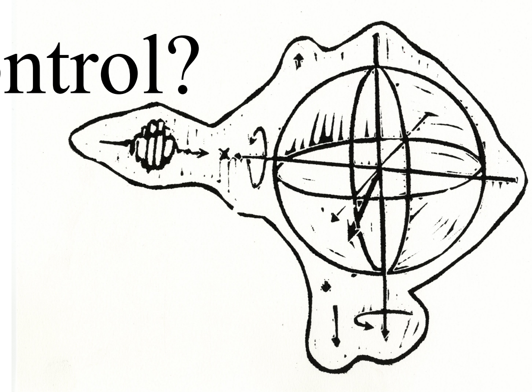


- Quantum communications

- Quantum-enhanced sensing



- Quantum control?



- "Single-particle" (excitation) superposition states: Being here and there at the same time!?
- Non-commuting observables
- Entanglement, steering, discord: Correlations between measurement outcomes that are "stronger than allowed classically"
- What is the "**Quantum*ness*?**"

Coherence is key!

Defining the precise resources / characteristics of quantum systems that enable non-classical protocols to surpass their classical counterparts is still an **open question**.

Ultracold

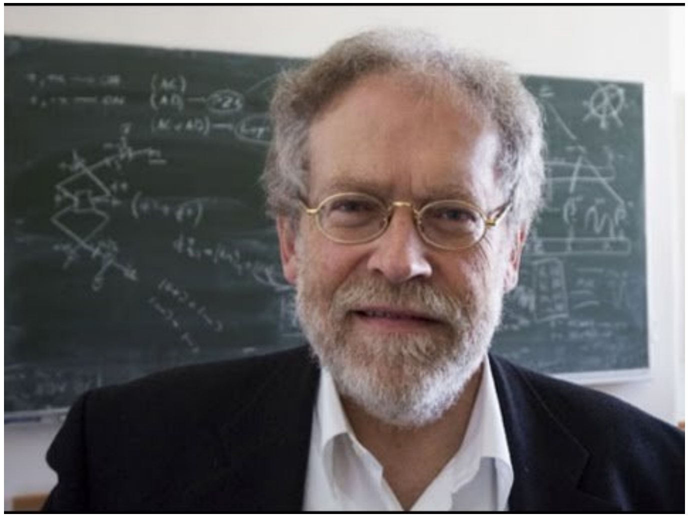
Ultrafast

Photons are Ultracool and Ultrafast!

Depends upon who you ask. . .

W. E. Lamb, "Anti-photon," Appl. Phys. B 60, 77-84 (1995).

A photon is an excitation of a quantum field mode.



A photon is what makes a detector click (photoelectric effect).

What is a click in a detector? That's for another day. . .

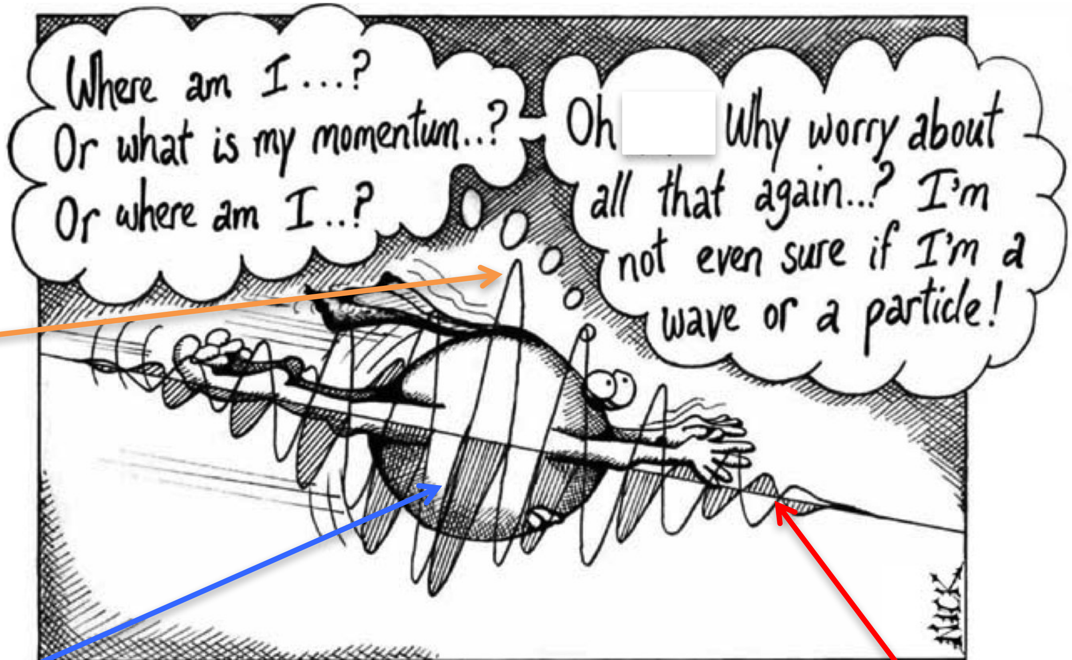
Quantum state of a single photon

What is the state of a single photon?

The state of a single photon is the *mode function* that it occupies.*

Polarization (2D)

Qubit



Transverse-spatial-momentum (CV)

Qutrits

Time-frequency (CV)

* Details on the "Photon wave function"

B. J. Smith and M. G. Raymer, New J. Phys. **9**, 414 (2007)

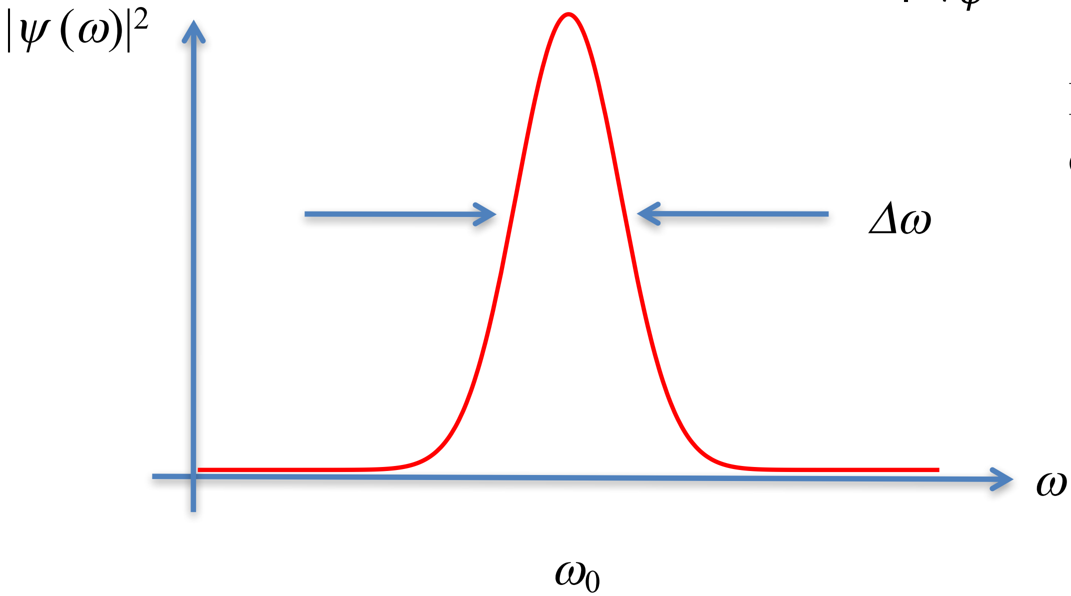
I. Bialynicki-Birula, *Progress in Optics XXXVI*, E. Wolf, ed. (1996)

J. E. Sipe, "Photon wave functions" Phys. Rev. A **52**, 1875-1883 (1995)

Single-photon state = mode function

- Pure states: Single-photon state = mode function

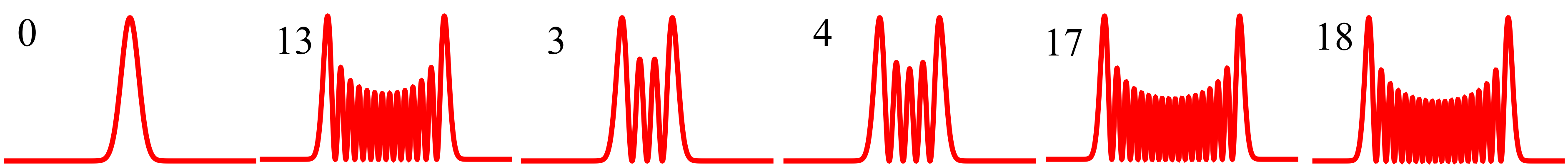
$$|1\rangle_\psi = a_\psi^\dagger |vac\rangle \qquad a_\psi^\dagger = \int a^\dagger(\omega)\psi(\omega)d\omega$$



Interpret as probability amplitude for detecting a single photon near frequency ω (analogous to spectrum)

B. Brecht, **Dileep V. Reddy**, C. Silberhorn, and **M. G. Raymer**, Phys. Rev. X **5**, 041017 (2015)

- Information can be encoded in the pulse mode shape of the photon (e.g. HG modes)

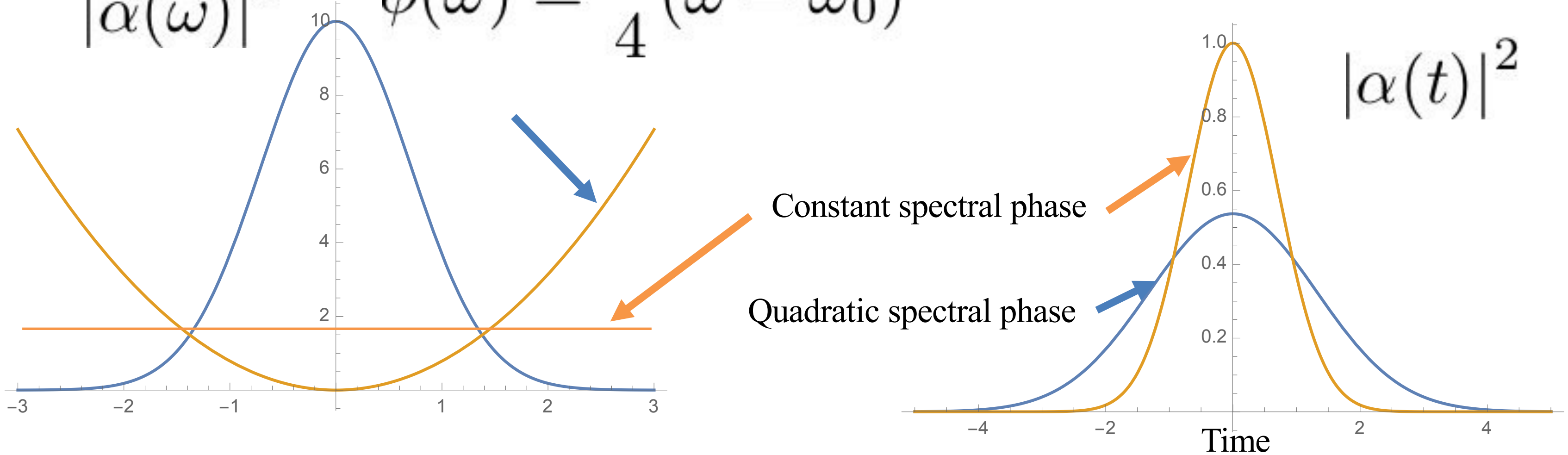


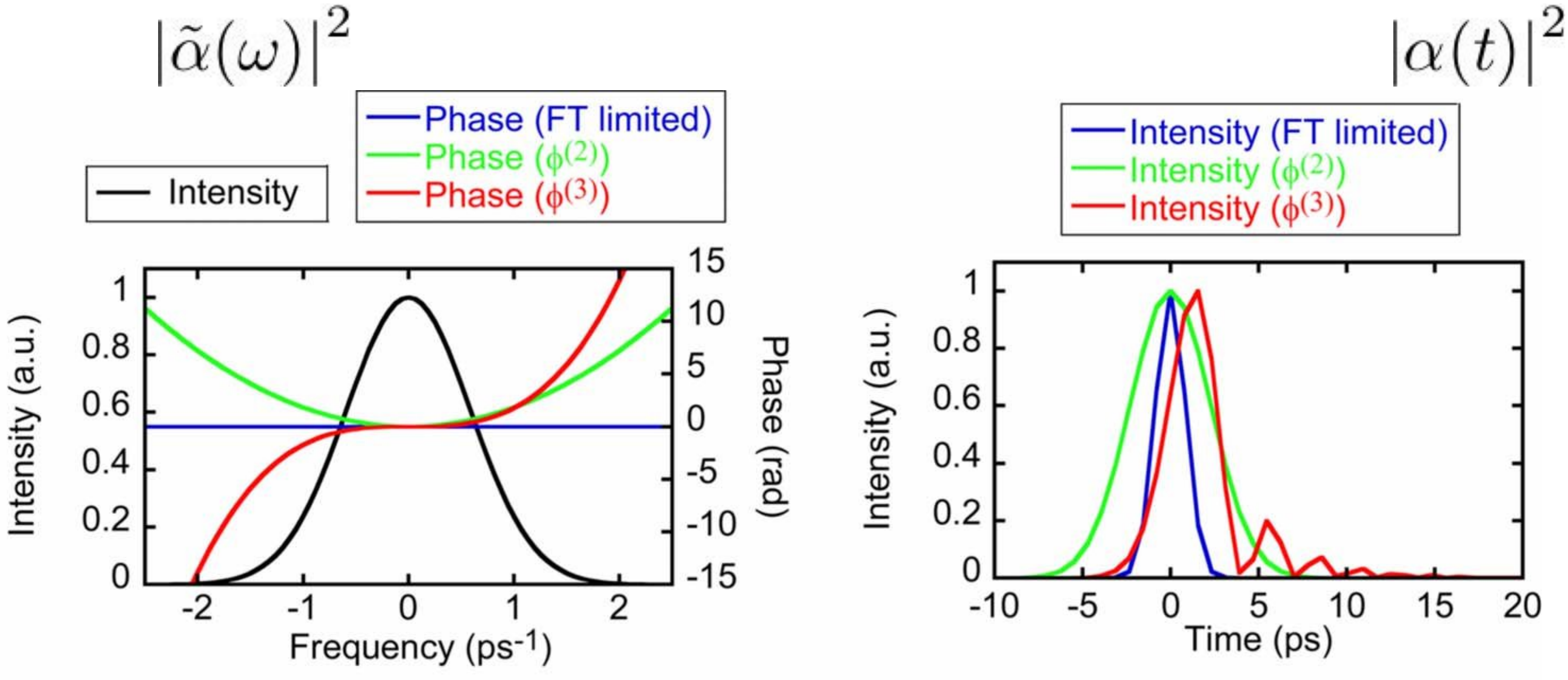
- Temporal envelope and phase $\alpha(t) = |\alpha(t)|\, e^{i\psi(t)}$

- Spectral envelope and phase $\tilde{\alpha}(\omega) = |\tilde{\alpha}(\omega)|\, e^{i\phi(\omega)}$

$|\tilde{\alpha}(\omega)|^2$ $\quad \phi(\omega) = \frac{\pi}{4}(\omega - \omega_0)^2$

$|\alpha(t)|^2$





From: I. A. Walmsley and C. Dorrer, "Characterization of ultrashort electromagnetic pulses," Advances in Optics and Photonics **1**, 308–437 (2009)

- Chrono-cyclic representations:

Wigner $$W\left(t,\omega\right)=\int_{-\infty}^{\infty}\alpha(t+t'/2)\alpha^{*}(t-t'/2)e^{i\omega t'}\mathrm{d}t'$$

$$W\left(t,\omega\right)=\frac{1}{2\pi}\int_{-\infty}^{\infty}\tilde{\alpha}(\omega+\omega'/2)\tilde{\alpha}^{*}(\omega-\omega'/2)e^{-i\omega' t}\mathrm{d}\omega'$$

Marginals give temporal and spectral intensities:

$$I\left(t\right)=\left|\alpha(t)\right|^{2}=\frac{1}{2\pi}\int_{-\infty}^{\infty}W\left(t,\omega\right)\mathrm{d}\omega$$

$$S\left(\omega\right)=\left|\tilde{\alpha}\left(\omega\right)\right|^{2}=\int_{-\infty}^{\infty}W\left(t,\omega\right)\mathrm{d}t$$

Wigner functions of

(a) Fourier-transform limited (FTL) Gaussian pulse

(b) pulse with Gaussian spectrum and quadratic spectral phase

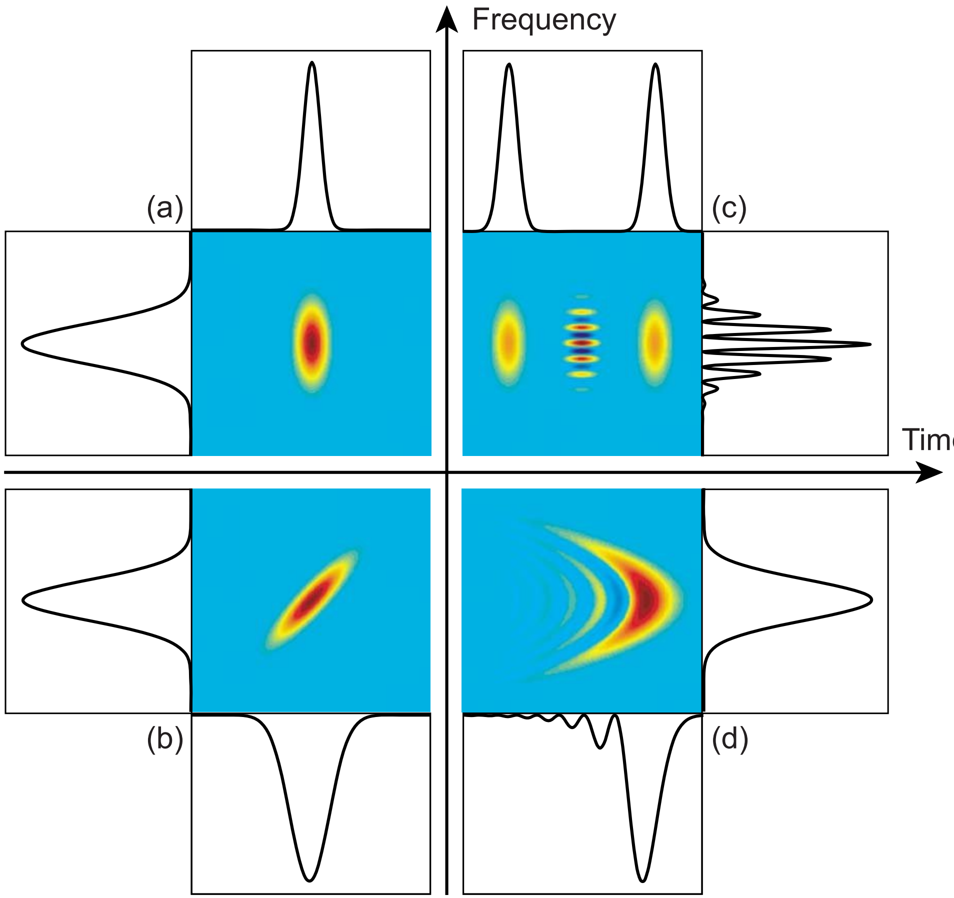
(c) pair of identical FTL Gaussian pulses

(d) pulse with Gaussian spectrum and third-order spectral phase.

temporal and spectral **marginals** are plotted

$I(t)$

$S(\omega)$



From: I. A. Walmsley and C. Dorrer,
Advances in Optics and Photonics **1**, 308–437 (2009)

- Direct measurement of temporal amplitude difficult to achieve below a few ps (using a 'streak camera')

$$I(t) = |\alpha(t)|^2$$

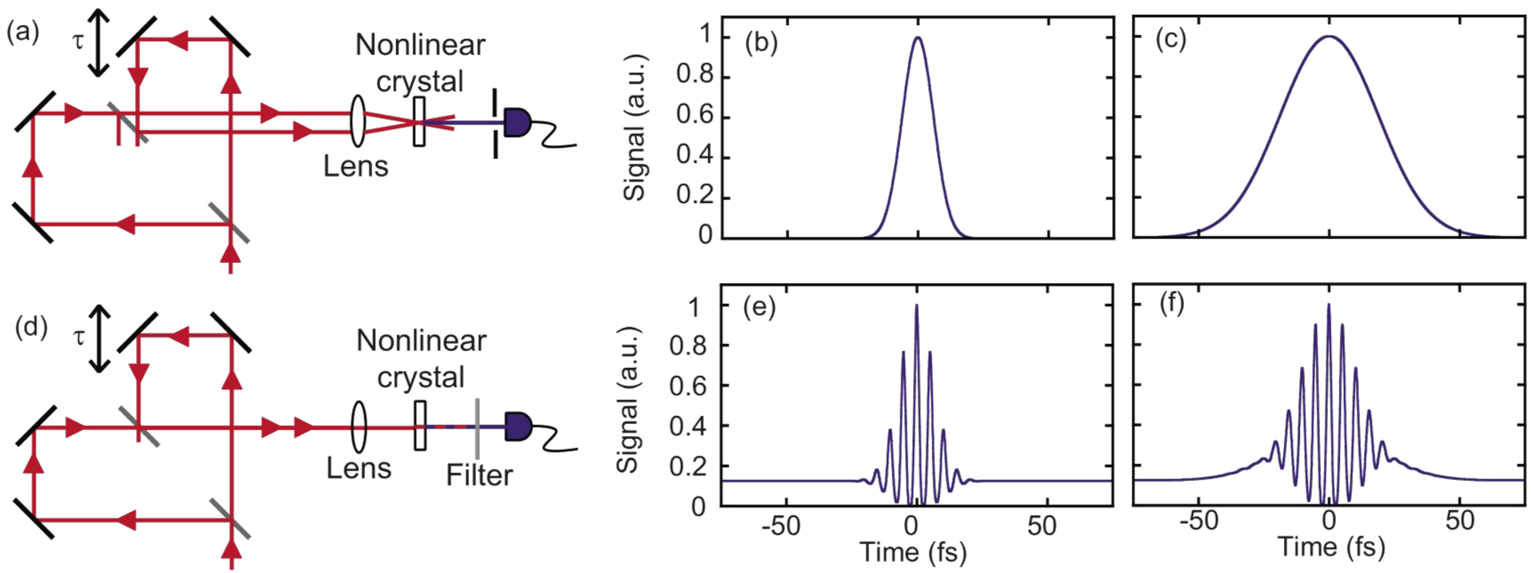
- Spectrum of pulses 'relatively' easy to achieve

$$S(\omega) = |\tilde{\alpha}(\omega)|^2$$
$$\mathcal{F}\{\alpha(t)\} = \tilde{\alpha}(\omega)$$

- In either case, still need to determine phase (either temporal or spectral)

- Need to have some kind of time-varying element (that changes on a similar time scale as the pulse itself)

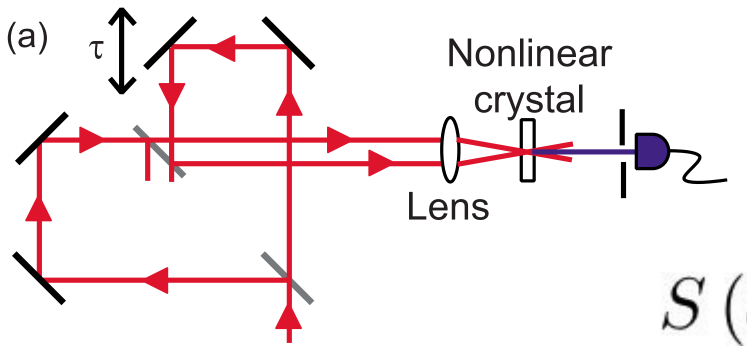
Use the pulse itself = **Intensity auto-correlation**



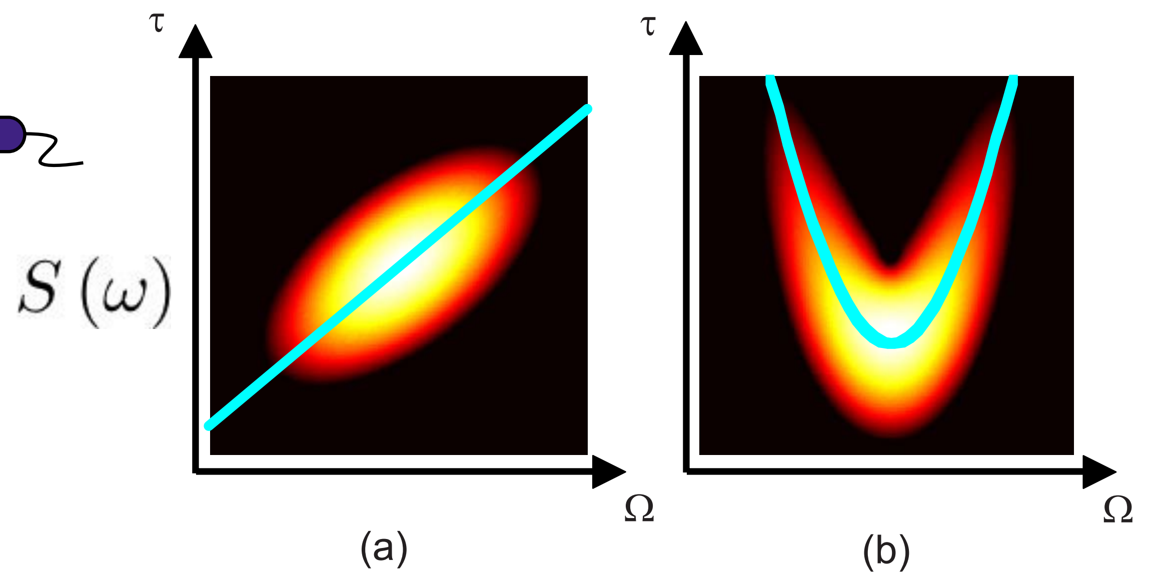
Can in principle try to determine temporal phase – but difficult in practice.

FROG: Frequency-resolved optical gating

Basically an intensity auto-correlator with a spectrometer



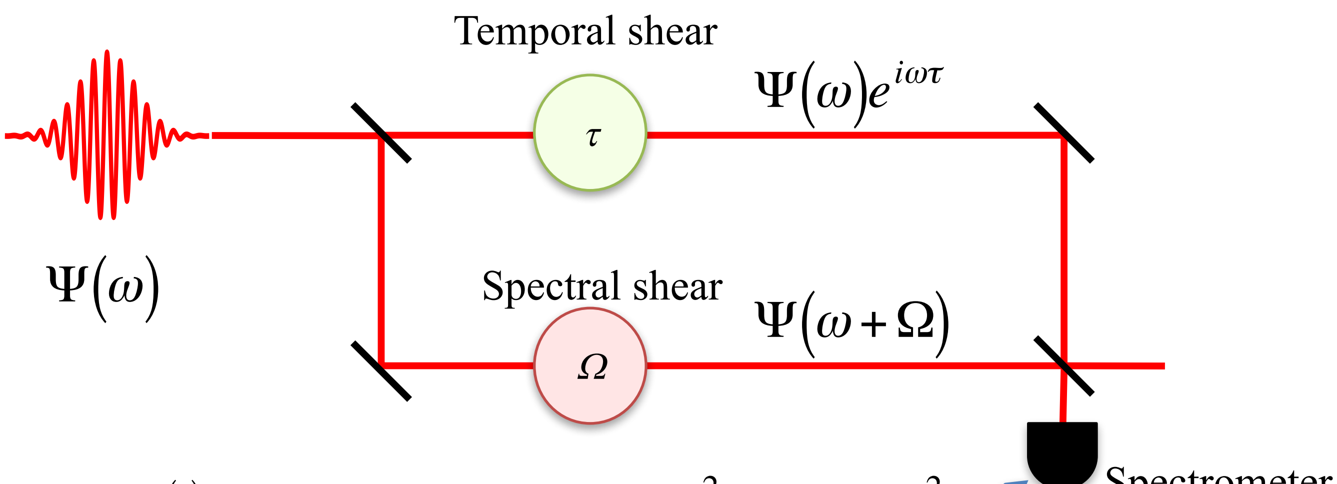
Spectrograms



second-order dispersion third-order dispersion

$$S_{\mathrm{FROG}}(\tau,\omega)=\left|\int_{-\infty}^{\infty}\alpha^2(t)\alpha^*(t-\tau)e^{-i\omega t}\mathrm{d}t\right|^2$$

SPIDER: Spectral-phase interferometry for direct electric-field reconstruction

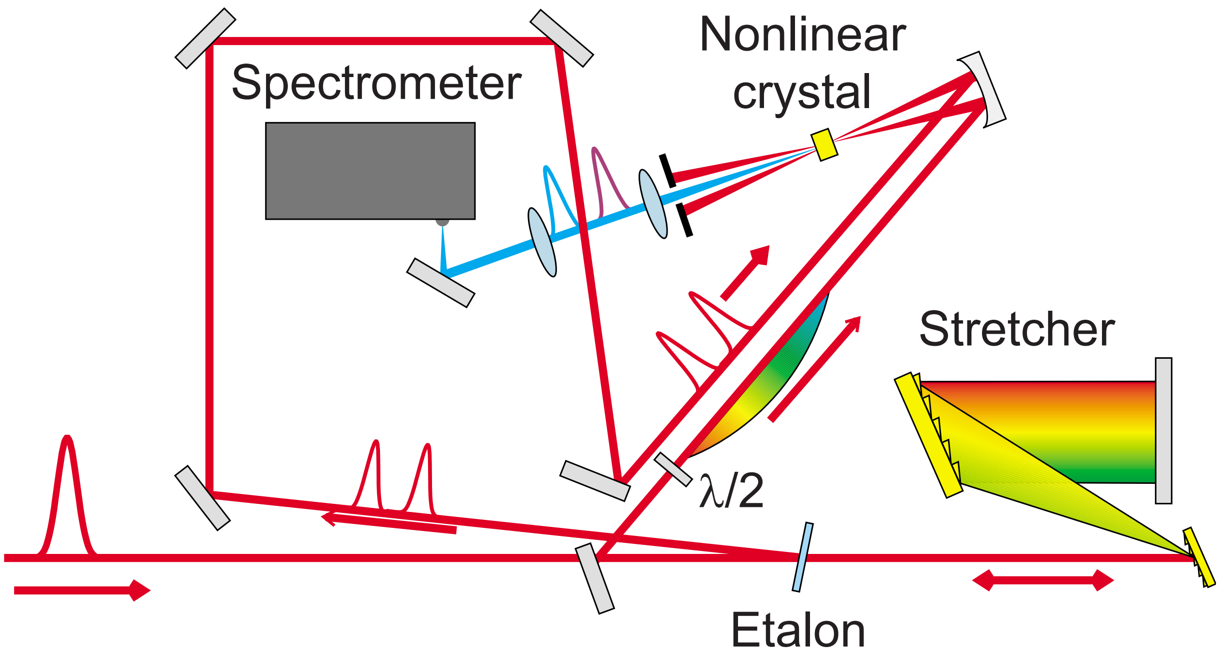


$$R^{(1)}(\omega;\Omega,\tau) \sim \left|\Psi(\omega+\Omega)\right|^2 + \left|\Psi(\omega)\right|^2$$
$$+ 2\,\mathrm{Re}\left\{\Psi^*(\omega)\Psi(\omega+\Omega)e^{-i\omega\tau}\right\}$$

Interference term contains spectral phase gradient: $\dfrac{d\varphi(\omega)}{d\omega} \approx \dfrac{\varphi(\omega+\Omega)-\varphi(\omega)}{\Omega}$

$$\varphi(\omega) = \mathrm{Arg}\{\Psi(\omega)\}$$

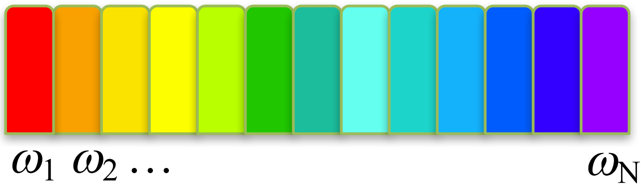
SPIDER: How to achieve spectral shear between two delayed replicas?
Nonlinear frequency conversion!



This is NOT compatible with single photons
(single-photon nonlinearity is 'hard')

- Single-photon density matrix (focus on ω-τ DOF)

$$\hat{\rho} = \sum_{\omega_1, \omega_1'} \rho^{(1)}(\omega_1, \omega_1') |\omega_1\rangle\langle\omega_1'|$$



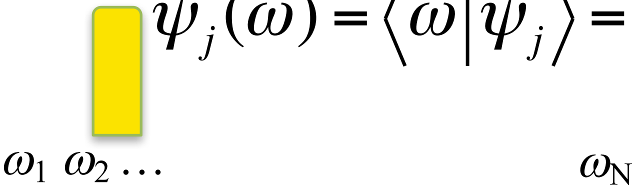
(a classical mixture of pure states)

$$\hat{\rho} = \sum_{m,n} \rho_{mn} |\phi_m\rangle\langle\phi_n|$$

- Pure states (only one mode)

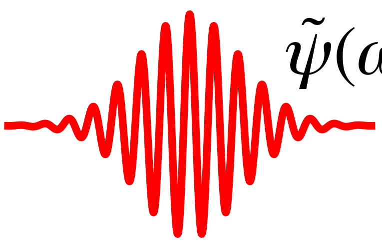
$$\hat{\rho} = |\psi\rangle\langle\psi|$$

Frequency eigenstate



$$\tilde{\psi}_j(\omega) = \langle\omega|\psi_j\rangle = \delta_{\omega\omega_j}$$

Wavepacket eigenstate



$$\tilde{\psi}(\omega) = \langle\omega|\psi\rangle$$

- If we know a priori that a source emits only one photon at a time then…

  the state of a single photon source describes how the photon is distributed across all the modes of the field (polarization, spatial, frequency).
- Single-photon density matrix is equivalent to classical field correlation function

$$g^{(1)}(\omega_1, \omega_1') = \frac{\left\langle \hat{a}^\dagger(\omega_1)\hat{a}(\omega_1')\right\rangle}{\sqrt{\left\langle \hat{a}^\dagger(\omega_1)\hat{a}(\omega_1)\right\rangle\left\langle \hat{a}^\dagger(\omega_1')\hat{a}(\omega_1')\right\rangle}} = \rho^{(1)}(\omega_1, \omega_1')$$

- Two-photon density matrix is equivalent to the fourth-order field correlation function

$$g^{(2)}\left(\omega_1,\omega_2;\omega_1',\omega_2'\right)$$

$$=\frac{\left\langle \hat{a}^{\dagger}\left(\omega_1\right)\hat{a}^{\dagger}\left(\omega_2\right)\hat{a}\left(\omega_2'\right)\hat{a}\left(\omega'\right)\right\rangle}{\sqrt{\left\langle \hat{a}^{\dagger}\left(\omega_1\right)\hat{a}\left(\omega_1\right)\right\rangle\left\langle \hat{a}^{\dagger}\left(\omega_2\right)\hat{a}\left(\omega_2\right)\right\rangle\left\langle \hat{a}^{\dagger}\left(\omega_1'\right)\hat{a}\left(\omega_1'\right)\right\rangle\left\langle \hat{a}^{\dagger}\left(\omega_2'\right)\hat{a}\left(\omega_2'\right)\right\rangle}}$$

$$=\rho^{(2)}\left(\omega_1,\omega_2;\omega_1',\omega_2'\right)$$

$$\rho^{(2)}\left(\omega_1,\omega_2;\omega_1',\omega_2'\right)=\left\langle \omega_1,\omega_2\left|\hat{\rho}^{(2)}\right|\omega_1',\omega_2'\right\rangle$$

Generalizes to N-photon states!

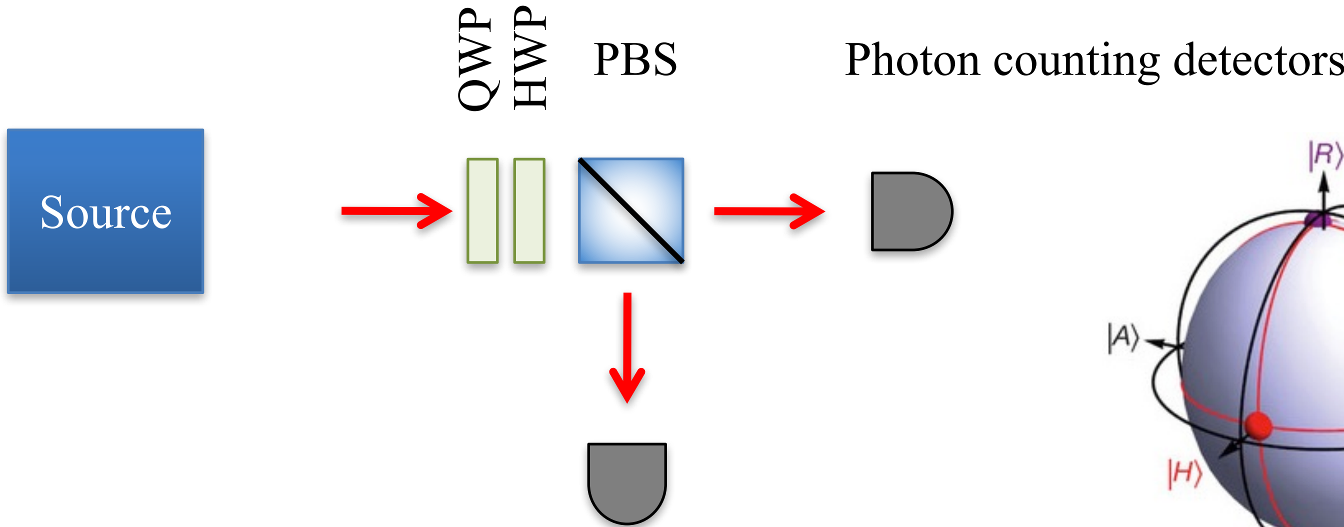
- Quantum optics becomes "classical" optics:
  - Techniques to measure $g^{(1)}$ and $g^{(2)}$ for classical fields are sufficient to completely characterize quantum states!

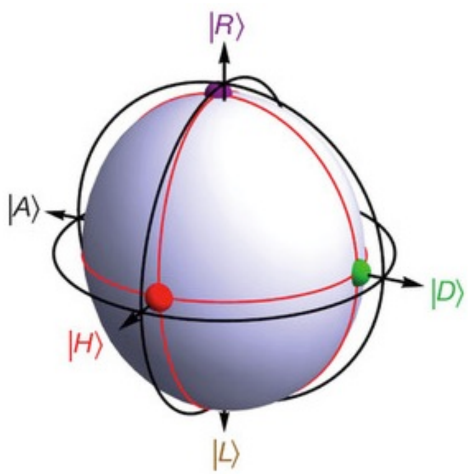
$$g^{(1)}(\omega_1,\omega_1') = \rho^{(1)}(\omega_1,\omega_1') = \langle \omega_1 | \hat{\rho}^{(1)} | \omega_1' \rangle$$

$$g^{(2)}(\omega_1,\omega_2;\omega_1',\omega_2') = \rho^{(2)}(\omega_1,\omega_2;\omega_1',\omega_2') = \langle \omega_1,\omega_2 | \hat{\rho}^{(2)} | \omega_1',\omega_2' \rangle$$

Single-photon characterization = Interferometry
Two-photon characterization = Coincidence interferometry

• Polarization interferometry: Polarimetry





- QWP and HWP shift phases between different polarization components
- PBS analyzes in the HV basis

Setting the QWP and HWP so that we measure in three bases:

$\{|H\rangle, |V\rangle\}$

$\{|D\rangle, |A\rangle\}$

$\{|R\rangle, |L\rangle\}$

James et al PRA **64**, 052312 (2001)
G. G. Stokes, Trans. Cambridge Philos. Soc. **9**, 399 (1852)

Characterizing single-photon pulses?

Interference with 'known' reference pulse (Scan reference)

Homodyne

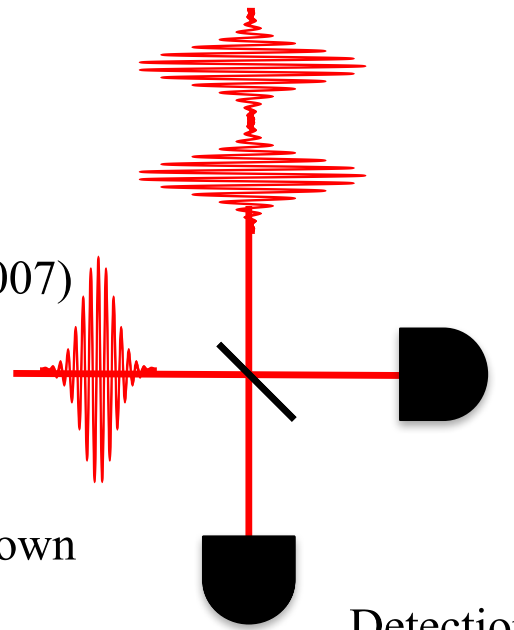
Poloycarpou et al, PRL **109**, 053602 (2012)
Morin et al, PRL **111**, 213602 (2013)
Z. Qin et al, Light: Sci. Appl. **4**, e298 (2015)

Hong-Ou-Mandel interference

Wasilewski, Kolenderski, and Frankowski, PRL **99**, 123601 (2007)

Nonlinear pulse gate

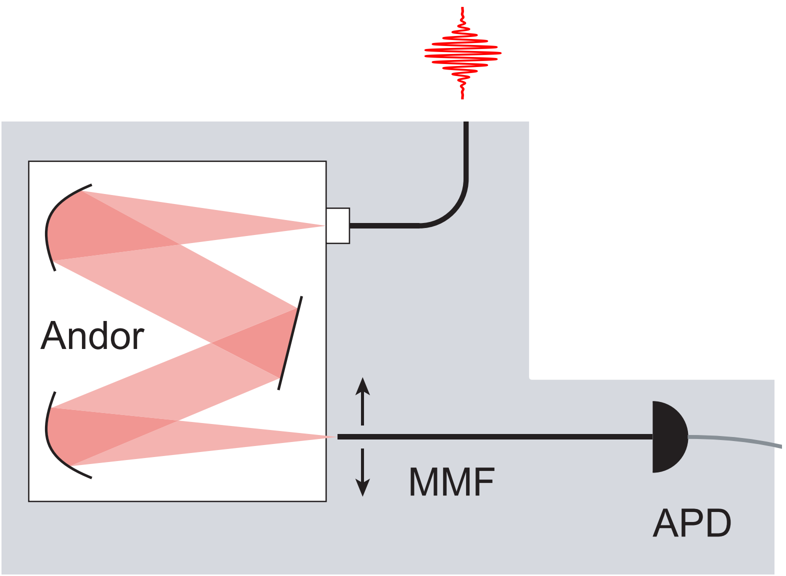
V. Ansari et al., PRL **120**, 213601 (2018)



Requires tunable reference pulses matched to the source to be characterized.
Is there another way?

Pulse characterization: Spectral measurements

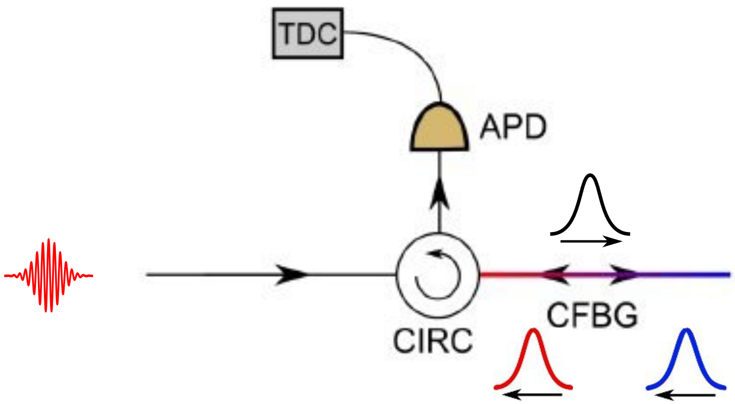
Scanning with a single pixel detector



Map frequency onto position

Kim Y H and Grice W P, *Opt. Lett.* **30** 908 (2005)

Simultaneous monitoring all spectral bins



* Dispersion ~ 950ps/nm over 10 nm range centered on 830 nm

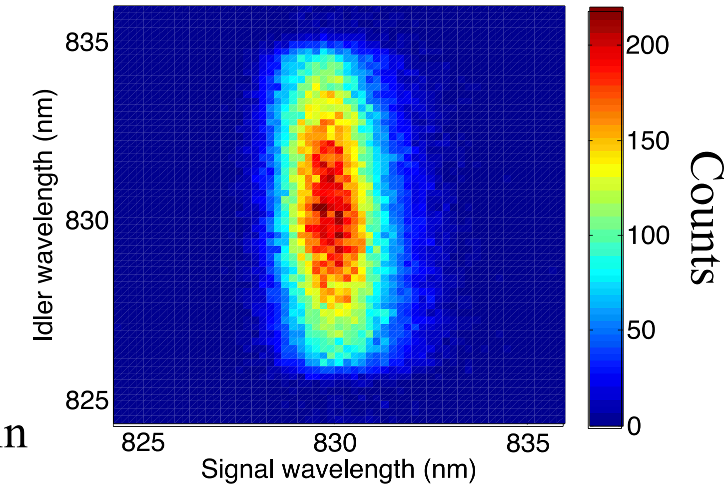
* FT of ~ 10^3 modes

Map frequency onto time (Fourier transform)

M. A. Muriel, J. Azaña, and A. Carballar, Opt. Lett. **24**, 1 (1999).

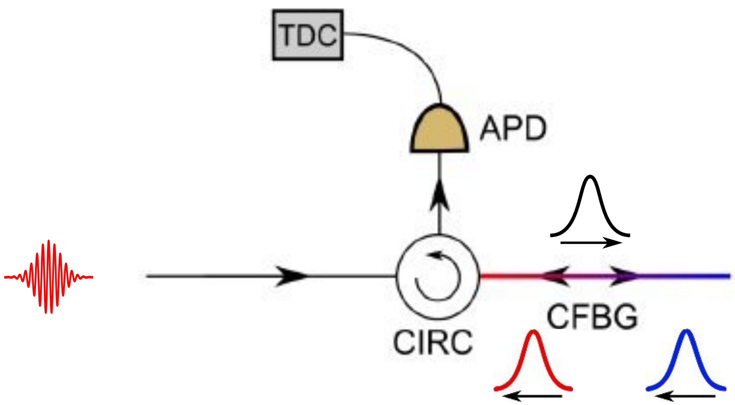
M. Avenhaus, A. Eckstein, P. J. Mosley, and C. Silberhorn, Opt. Lett. **34**, 2873 (2009).

Two-photon joint spectrum

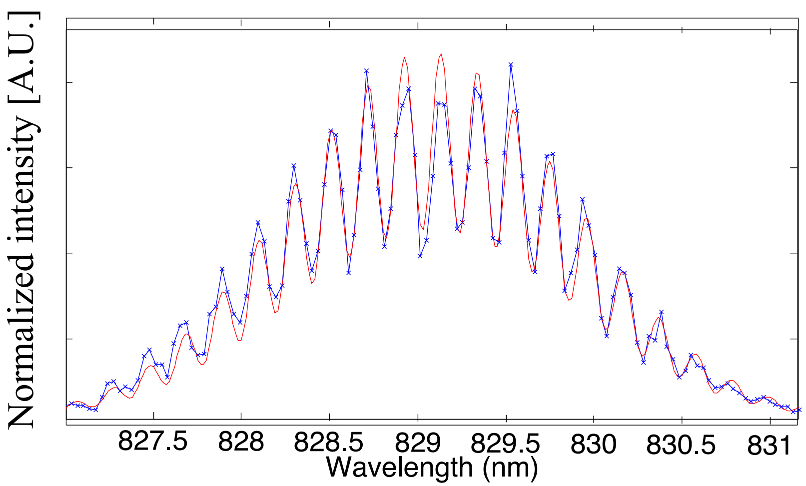


10 min

Simultaneous monitoring all spectral bins



Double pulse with spectral fringes



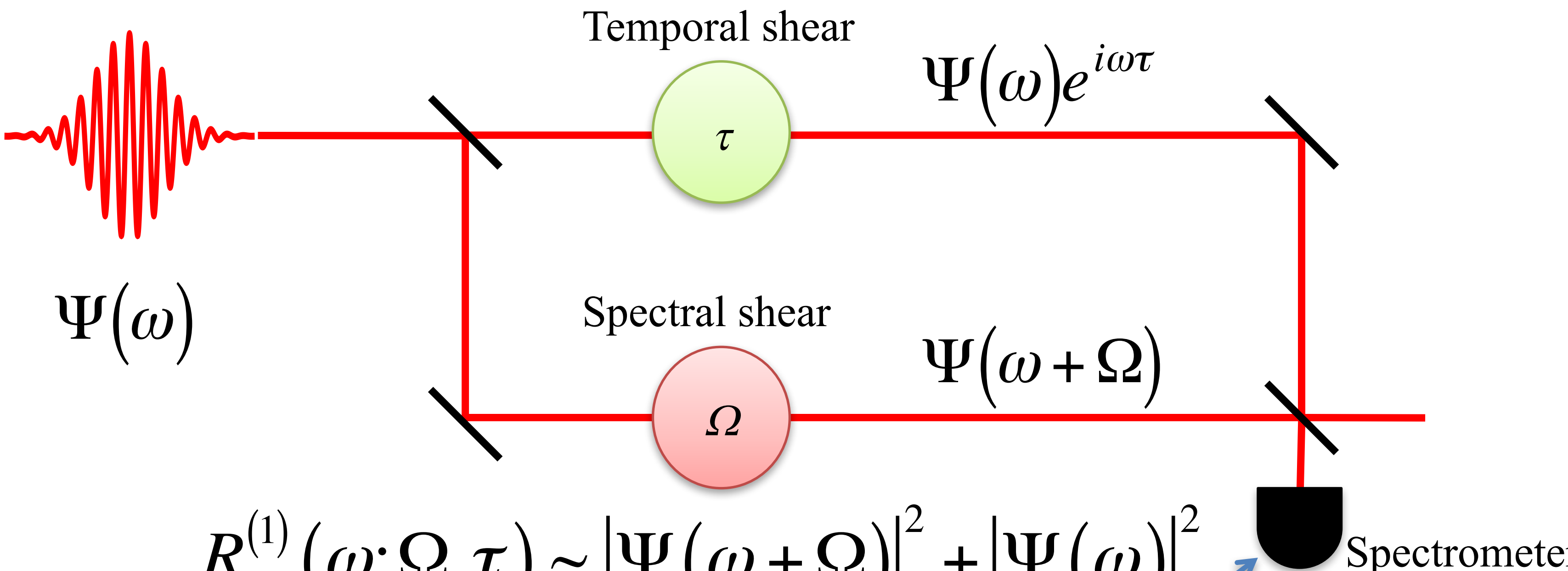
* Dispersion ~ 950ps/nm
over 10 nm range centered on 830 nm
* FT of ~ 10^3 modes

Map frequency onto time (Fourier transform)

* Spectral resolution ~ 0.05 nm (23 GHz)
limited by detector timing jitter
(~ 200 spectral bins)
* Can be improved at telecom wavelengths

A. O. C. Davis et al, Optics Express **25**, 12804 – 12811 (2017).

Single-photon state reconstruction | Spectral shearing interferometry



$$R^{(1)}(\omega;\Omega,\tau) \sim \left|\Psi(\omega+\Omega)\right|^2 + \left|\Psi(\omega)\right|^2 + 2\,\mathrm{Re}\left\{\Psi^*(\omega)\Psi(\omega+\Omega)e^{-i\omega\tau}\right\}$$

A. O. C. D. et al, arXiv 1709.05248 and 1802.07208

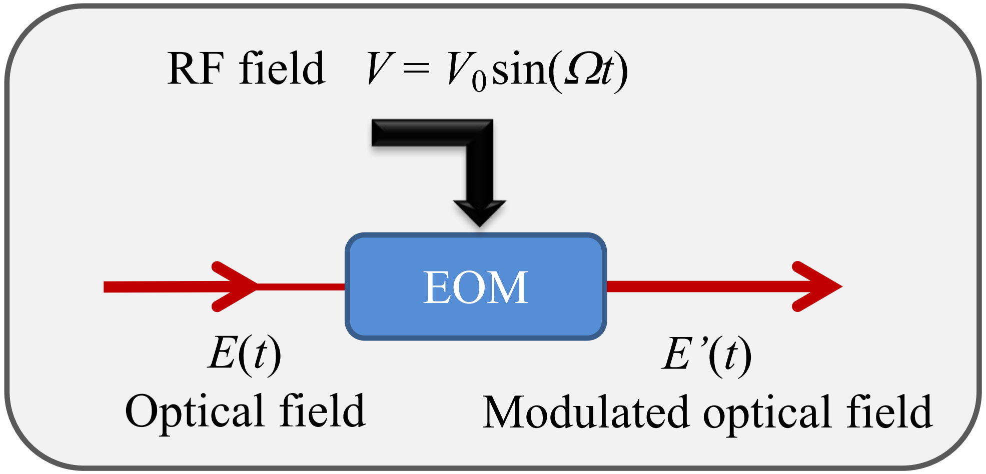
Scan spectral shear to map out single-photon state

How to achieve SPECTRAL SHEAR for single photon?

Spectral control by electro-optic phase modulation: CW field

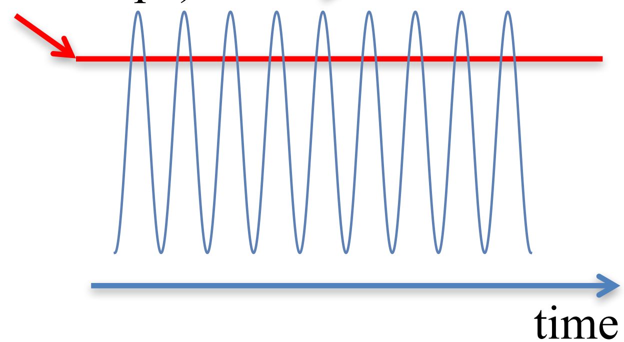
Common use of EOM – Add “sidebands” to continuous-wave beam

$$\phi(t) = \phi_0 \sin(\Omega t)$$



$$E(t) \approx E_0 e^{-i\omega_0 t}$$

(Constant envelope)

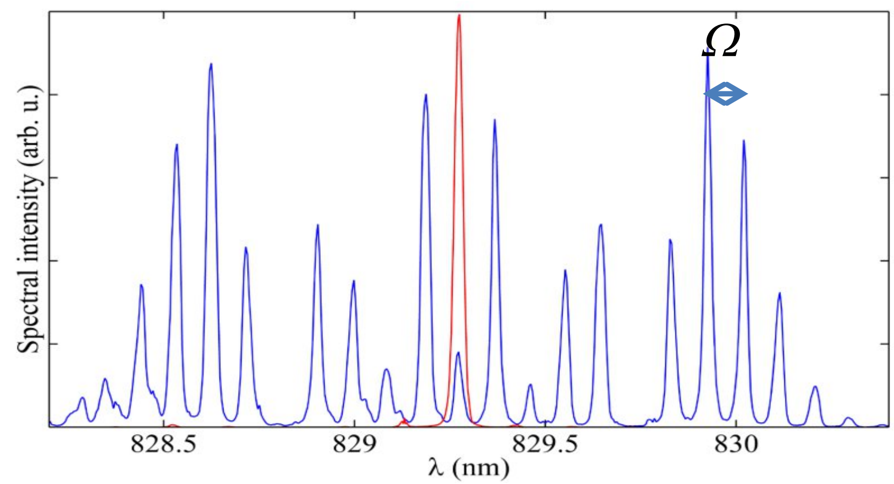


$$E'(t) \approx E_0 e^{-i\omega_0 t} \exp\left[i\phi_0 \sin(\Omega t)\right]$$

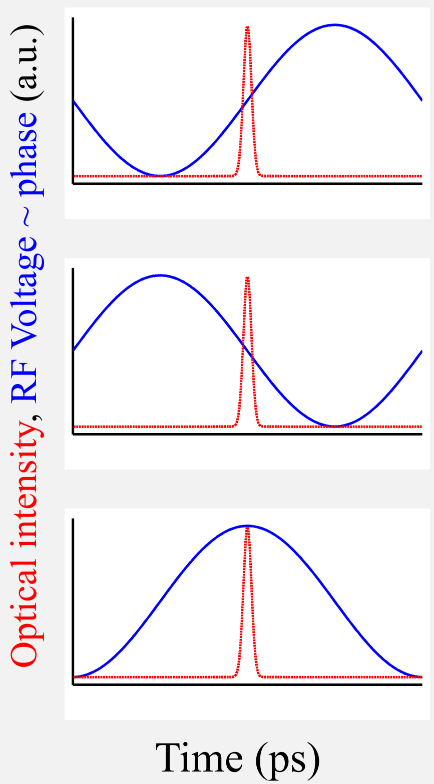
$$\approx E_0 e^{-i\omega_0 t}\left[1 + i\phi_0 \sin(\Omega t)\right]$$

$$\approx E_0 \left[e^{-i\omega_0 t} - \frac{\phi_0}{2}\left(e^{-i(\omega_0+\Omega)t} - e^{-i(\omega_0-\Omega)t}\right)\right]$$

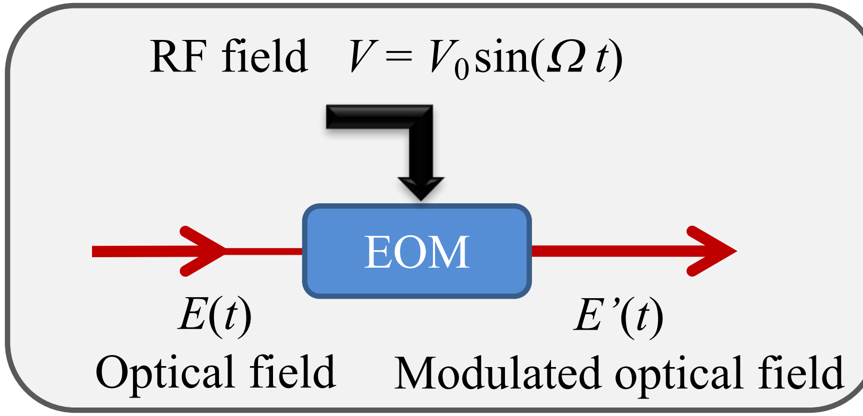
First-order side bands



Electro-optic phase modulation: pulsed regime



$V = V_0 \sin(\Omega t)$



RF field introduces a temporally varying phase

- Linear temporal phase:

  $E'(t) = E(t)\, \mathbf{e}^{\mathbf{i}\boldsymbol{\Omega t}}$ $\Longrightarrow$ **frequency shear**

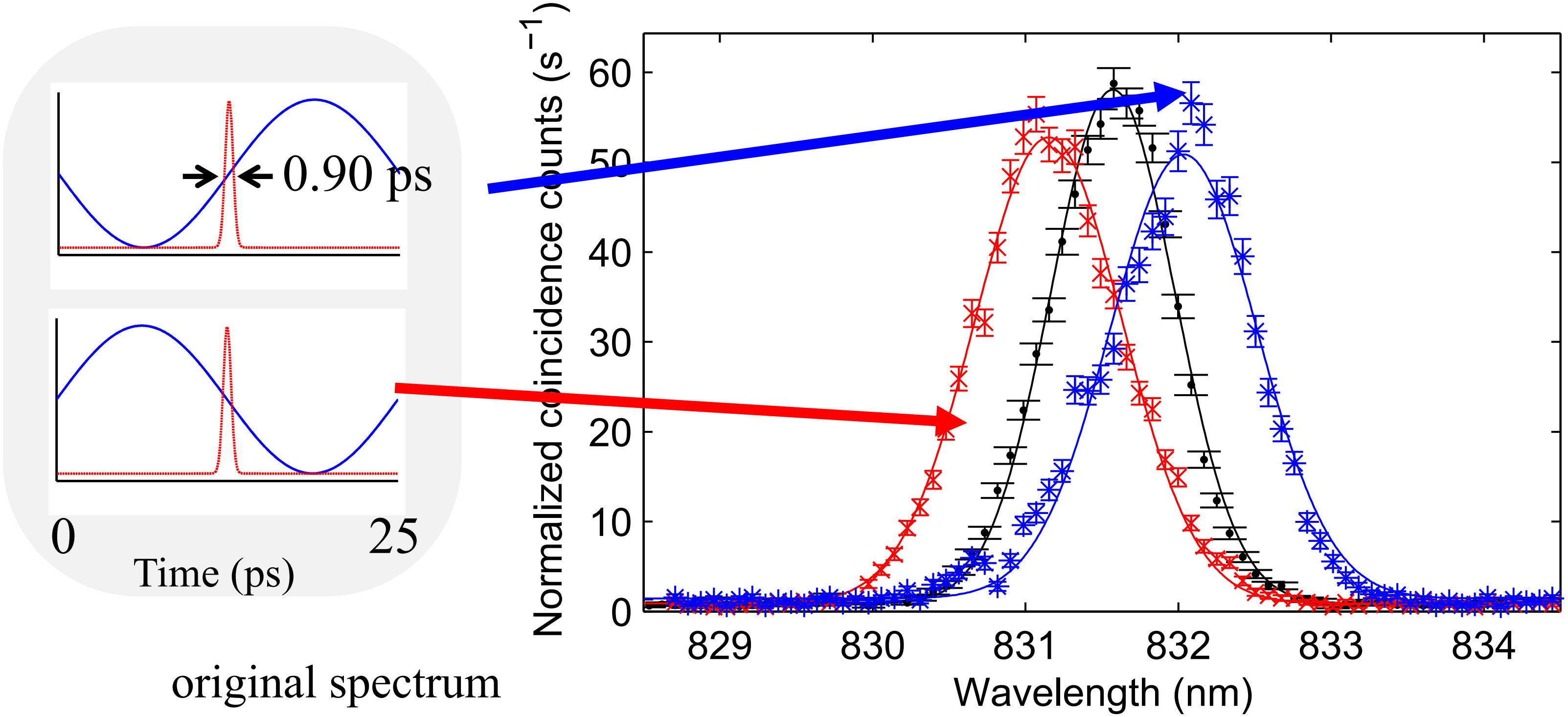
  (in analogy to linear spectral phase corresponding to a temporal shear)

- Quadratic temporal phase:

  $E'(t) = \mathrm{E}(t)\, \mathbf{e}^{\mathbf{i}\boldsymbol{At^2}}$ $\Longrightarrow$ **spectral broadening** (for a Fourier limited pulse)

  (in analogy to quadratic spectral phase causing temporal dispersion)

Spectral shear of single-photon pulses



original spectrum
modified spectrum

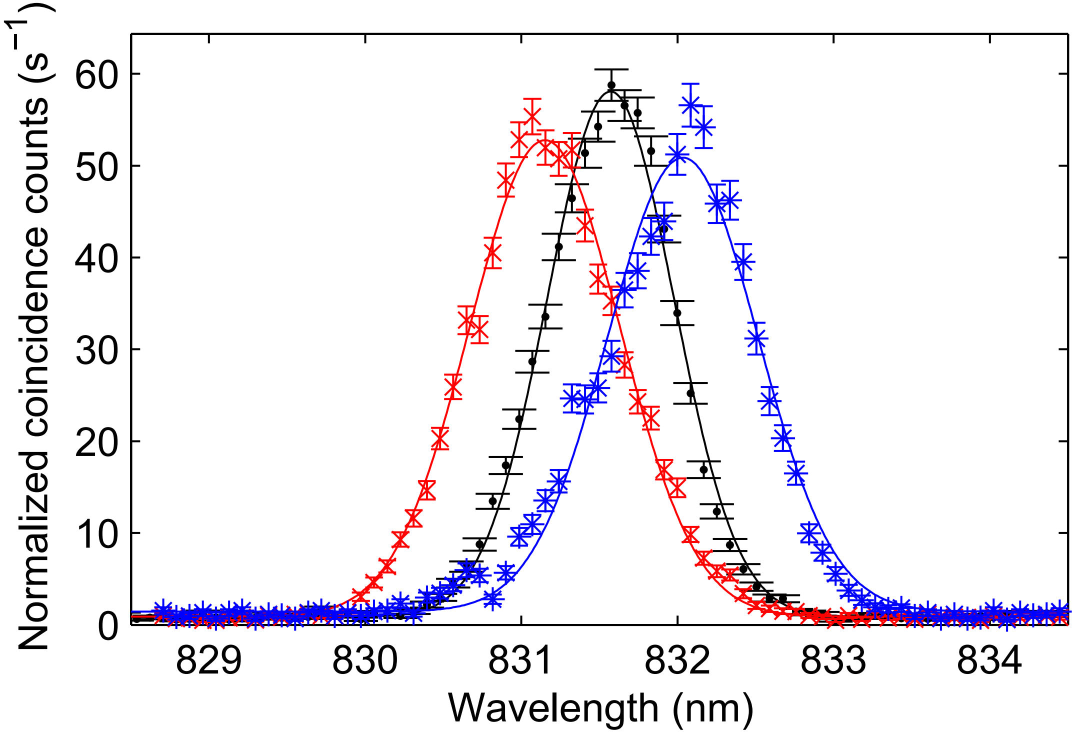
L. J. Wright et al, Phys. Rev. Lett. **118**, 023601 (2017)

Linear temporal phase = spectral shear

- **Deterministic** spectral manipulation – every photon is frequency shifted!
- Shift comparable to the bandwidth
- No strong optical fields involved (no filtering or added noise)
- Preserves single-photon character: $g^{(2)}(0)$ unchanged (0.040 ± 0.001)

Linear temporal phase:
Frequency shift by ±0.6 nm
(over 200 GHz)

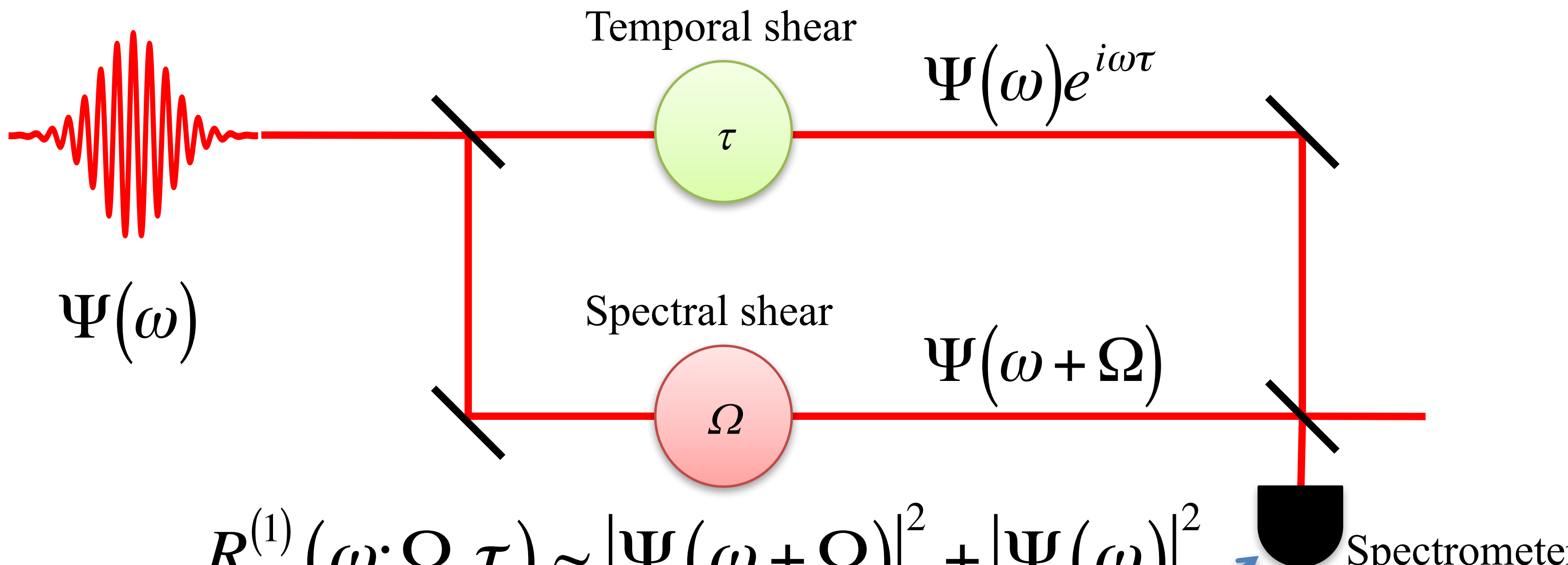
original spectrum
modified spectrum



L. J. Wright et al, Phys. Rev. Lett. **118**, 023601 (2017)

Single-photon state reconstruction

Spectral shearing interferometry



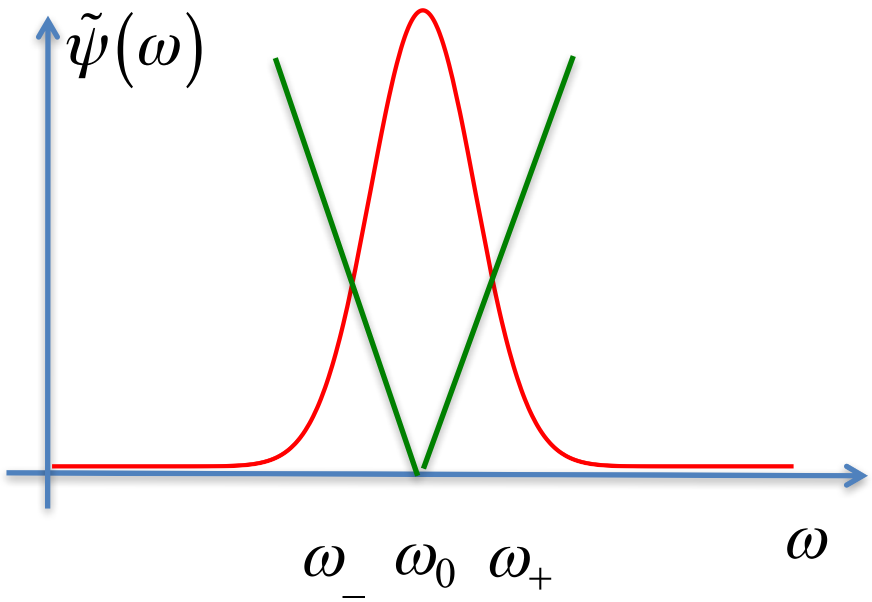
$$R^{(1)}(\omega;\Omega,\tau) \sim \left|\Psi(\omega+\Omega)\right|^2 + \left|\Psi(\omega)\right|^2 + 2\,\mathrm{Re}\left\{\Psi^*(\omega)\Psi(\omega+\Omega)e^{-i\omega\tau}\right\}$$

A. O. C. D. et al, arXiv 1709.05248 and 1802.07208

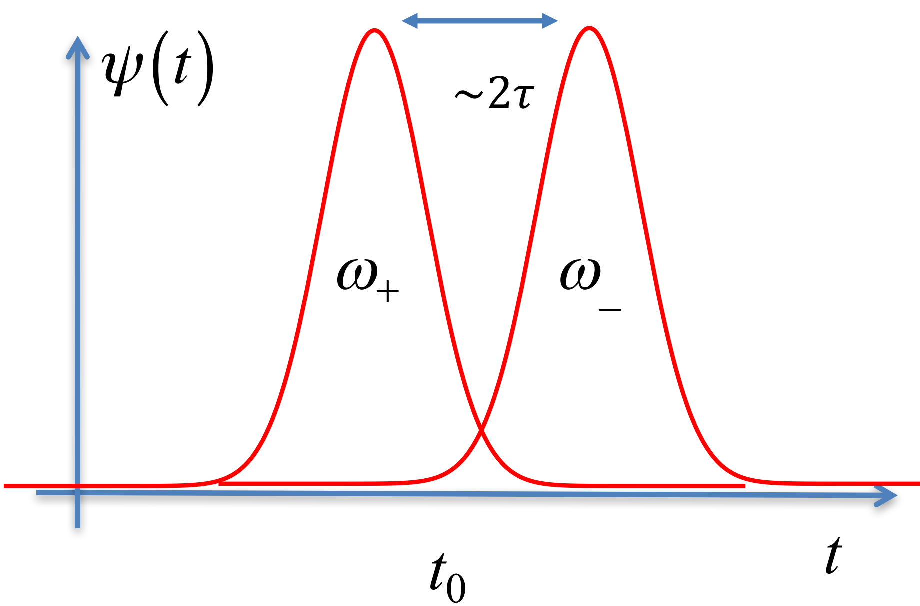
Scan spectral shear to map out single-photon state

Single-photon states with V-spectral phase: Double pulse

Spectral domain



Temporal domain

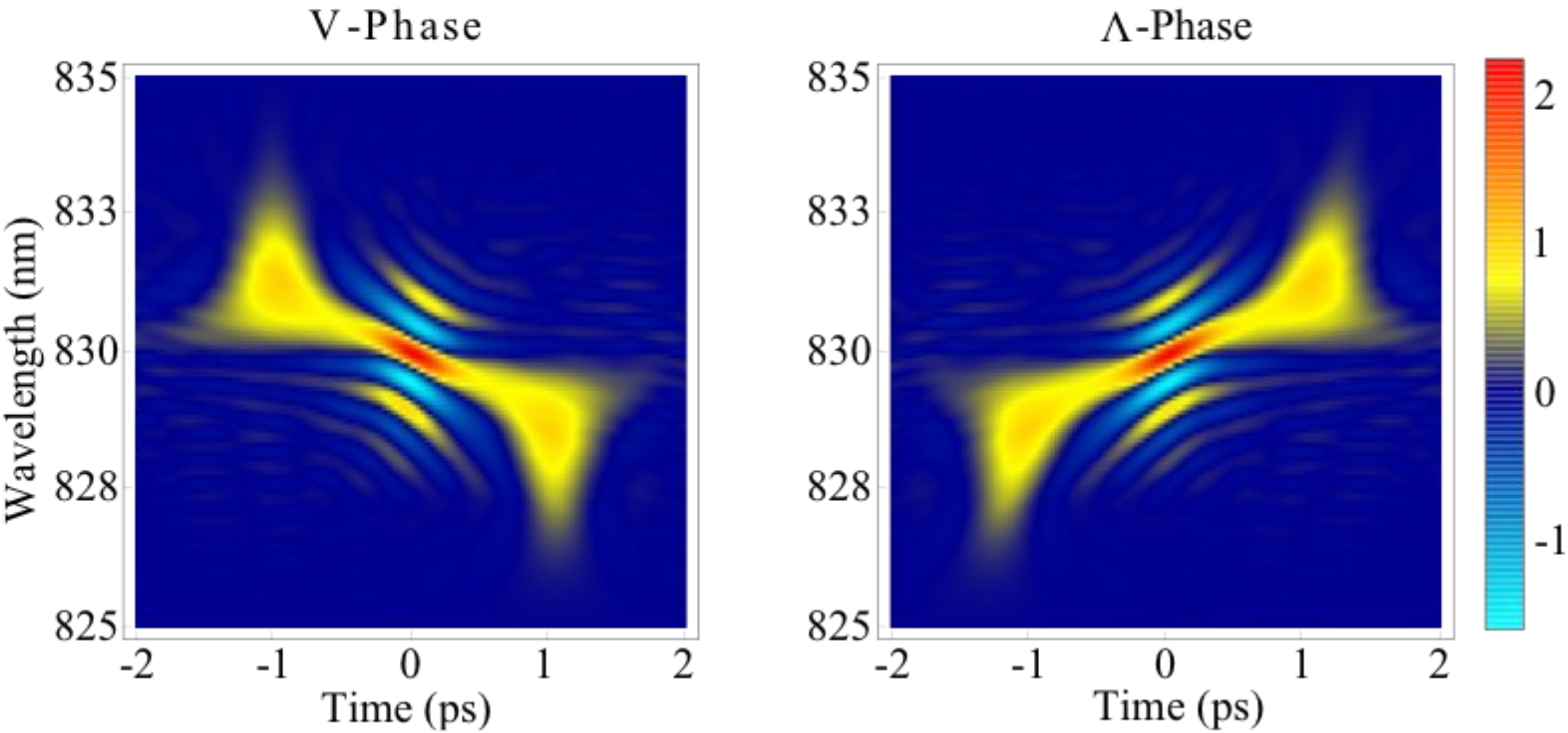


V-phase: $\varphi(\omega) = |\omega - \omega_0|\tau$

Two pulses separated by $\sim 2\tau$ with different central frequencies

A. O. C. D. et al, arXiv 1709.05248 and 1802.07208

Reconstructed single-photon states with Λ- and V-spectral phase



A. O. C. D. et al, arXiv 1709.05248 and 1802.07208

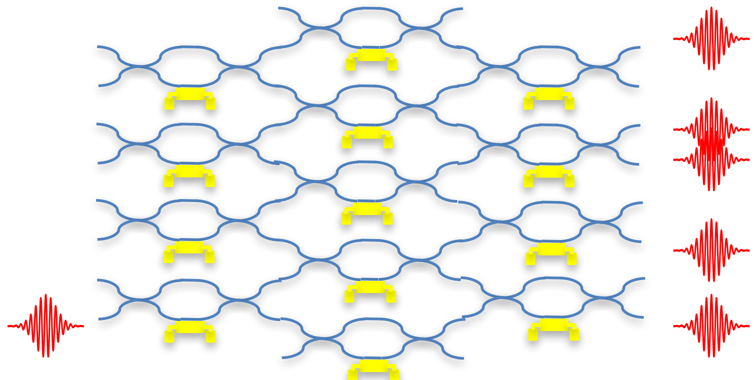
Outlook: Arbitrary Time-frequency mode unitary operations

Arbitrary unitary operations on many modes is required for OQTs

“Standard” spatial-mode unitary operation

Used in:
* LOQC
* Boson sampling
* QRW
* Machine learning

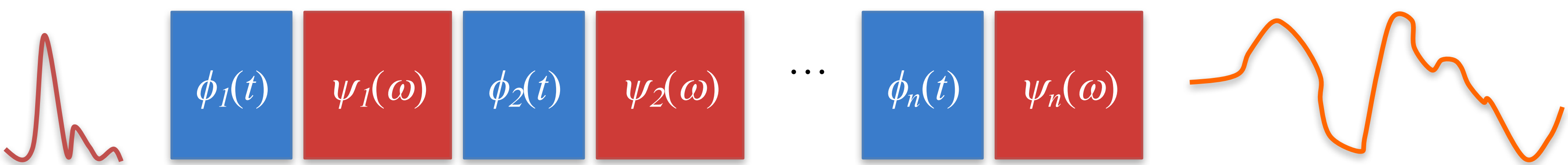
$\psi_{in}(x)$



$\psi_{out}(x) = U\psi_{in}(x)$

Time-frequency mode operations

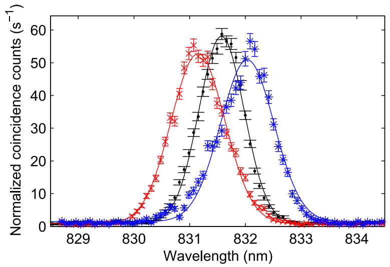
$\psi_{in}(t)$ Requires both spectral and temporal mode unitary operations $\psi_{out}(t) = U\psi_{in}(t)$

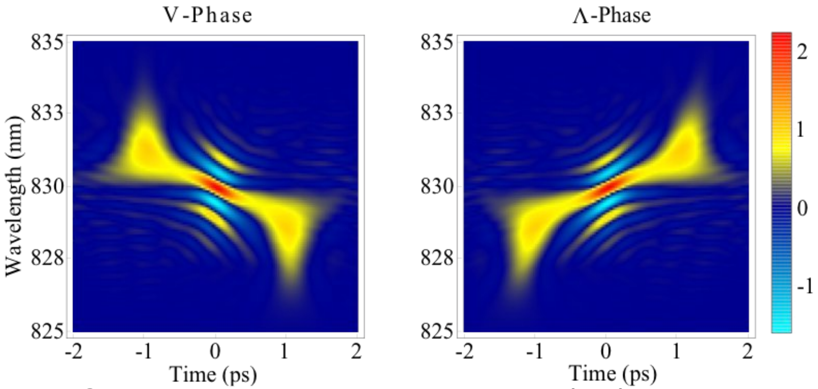


Can be realized with electro-optic temporal phase modulation and spectral phase

Ask **James Ashby** at poster session!

Summary: pulsed modes





- Modes and photons: A tale of two communities
- Temporal-spectral pulsed modes: Good for spelling (information encoding)
- Manipulation by phase only operation (shear and more!)
- Frequency shear, time lens, entanglement swapping, pulse measurement, and MORE TO COME!!

Thanks to those who have contributed!

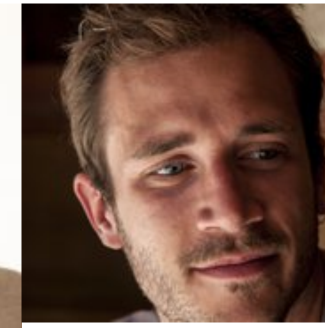
Michał Jachura

Christoph Söller

Michał Karpiński

Laura Wright

Alex Davis



Valerian Thiel

[dstl]

John Fell OUP fund

QCUMbER

Peru D'Ornellas

MARIE CURIE ACTIONS

EPSRC
Pioneering research and skills

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

NQIT Networked Quantum Information Technologies

Current Oregon Group!

See posters from Sofiane and James!

Sofiane
Merkouche

James
Ashby

Hannes
Sobattka

Mostafa
El Demery

National Science Foundation
WHERE DISCOVERIES BEGIN

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"Quantum" research at Oregon

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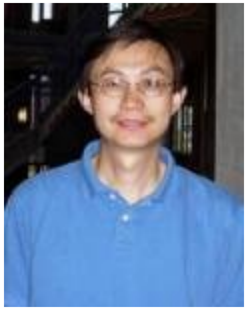
S. van Enk



H. Wang

D. Wineland

PhD and postdoc positions available: Contact bjsmith@uoregon.edu

THANKS!

National Science Foundation
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Oregon Center for Optical Molecular & Quantum Science

John Templeton Foundation