LA-UR-24-22051
Approved for public release; distribution is unlimited.

Title: Space-Time Quantum Metasurfaces

Author(s): Dalvit, Diego Alejandro Roberto

Intended for: Invited talk at Korea University

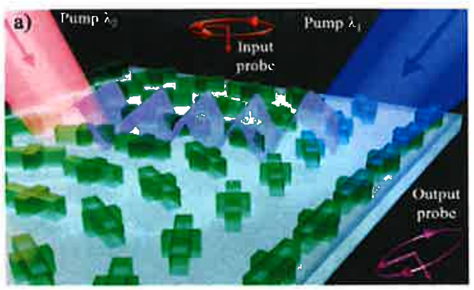
Issued: 2024-03-02

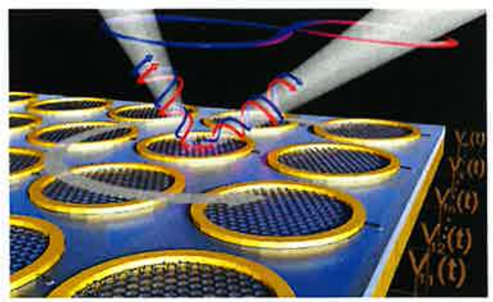
Space-Time Quantum Metasurfaces

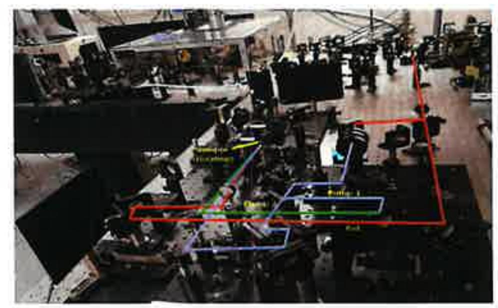
Diego Dalvit
Theoretical Division
Los Alamos National Laboratory

Outline

- **S**pace-**T**ime **Q**uantum **M**etasurfaces (**STQMs**)
- STQM manipulation of single photons
- STQM photon-pair production out of the quantum vacuum
- Brief description of ongoing experiments







PHYSICAL REVIEW LETTERS **127**, 043603 (2021)

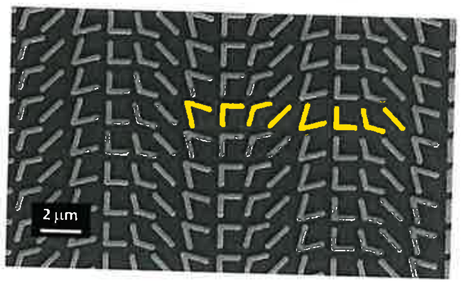
Editors' Suggestion | Featured in Physics

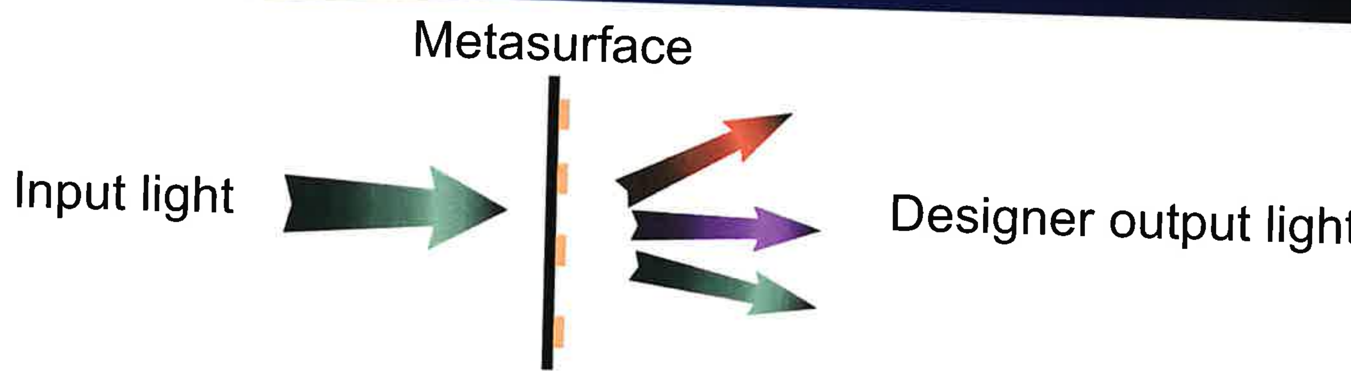
Space-Time Quantum Metasurfaces

Wilton J. M. Kort-Kamp, Abul K. Azad, and Diego A. R. Dalvit*

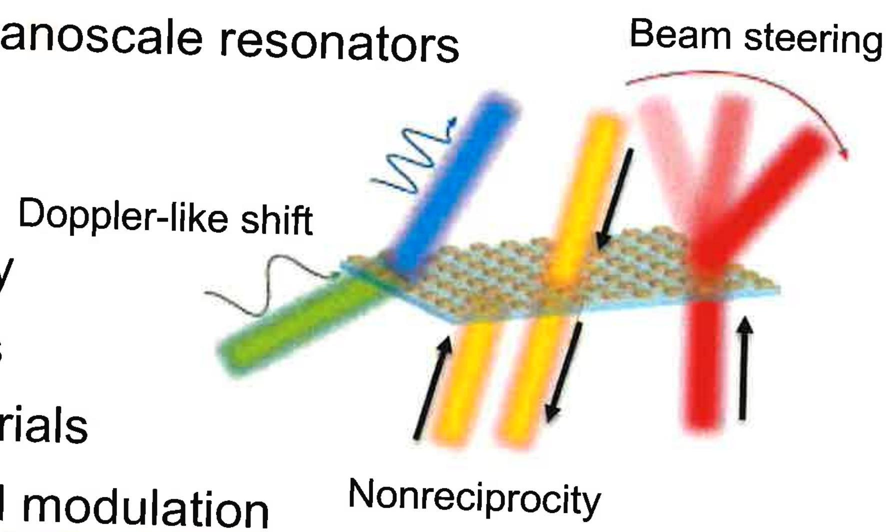
Electromagnetic Metasurfaces

Metasurface





- Arrays of suitably designed subwavelength nanoscale resonators
- Meta-atoms made of metals or dielectrics
- Full control of light
  - Static: functionalities tailored by geometry
  - Active: reconfigurable elements/materials
  - Dynamic: time-modulated elements/materials
- **"Space-time" metasurfaces**: spatiotemporal modulation



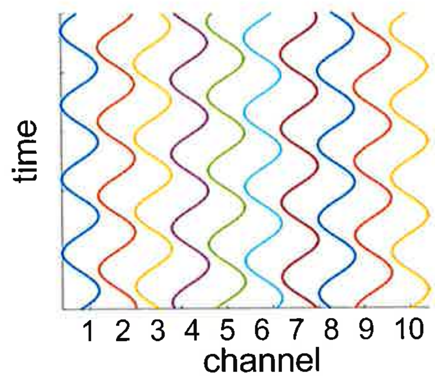
Space-Time Classical Metasurfaces

All-electric modulation

$V_i(t)=V_0 + \Delta V \cos(\Omega t - \Phi(\mathbf{r}_i))$

"synthetic" phase
(time-delay)

Varactor-loaded meta-atoms

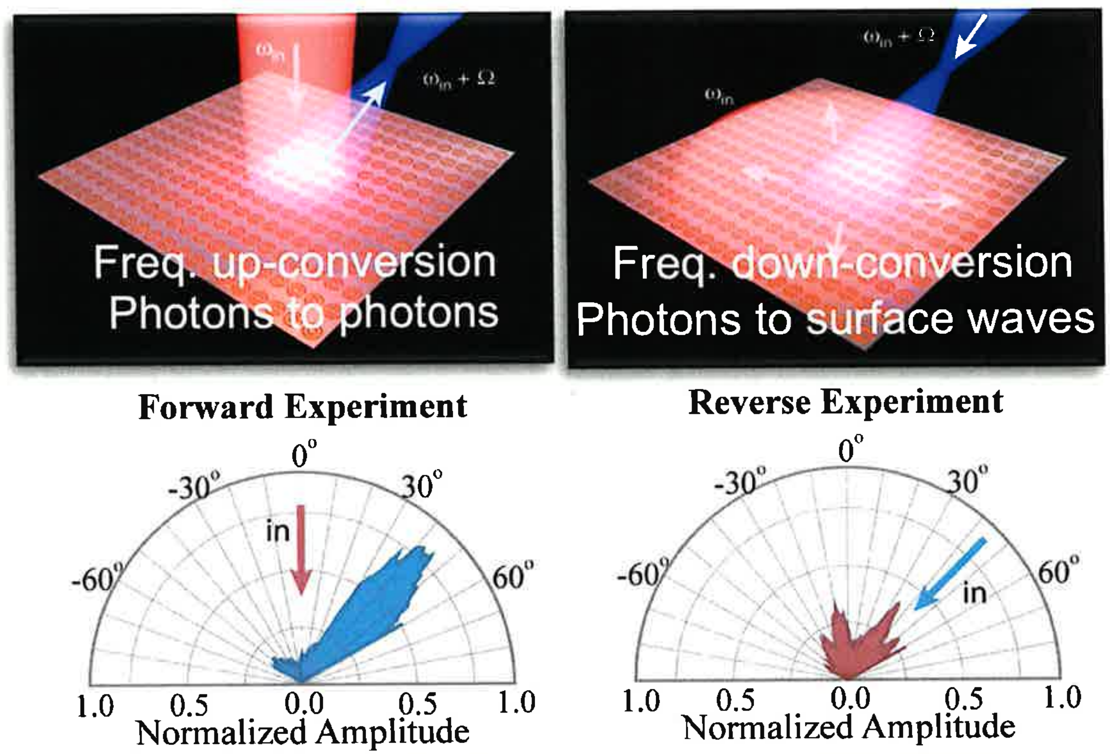


$\Omega/2\pi \sim 50$ kHz

$\beta \sim 1\ cm^{-1}$

Example: **Nonreciprocal steering**

$$\Phi_{steer}(x) = \beta x$$

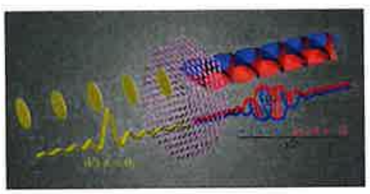


Cardin et al., Nat. Commun. **11**, 1469 (2020)

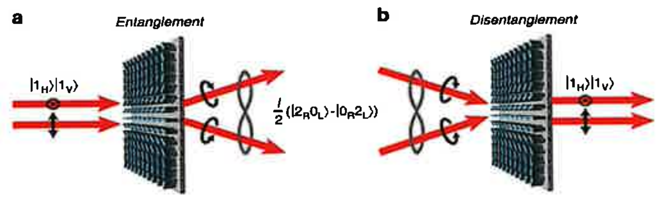
Quantum Metasurfaces

❑ **Quantum light + classical materials** (high-index linear/nonlinear dielectrics)

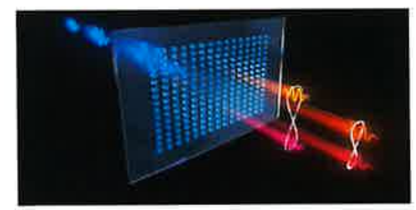
- Entanglement generation/manipulation
- Quantum sensors via metasurface interferometry
- Spontaneous parametric down-conversion (SPDC) and four-wave mixing (SFWM)



Stav et al., Science (2018)



Georgi et al., Light: Sci. & Appl. (2019)



Santiago-Cruz et al., Science (2022)

❑ **Quantum light + quantum materials** (QDs, NV centers, 2D quantum materials)

- Manipulation of spontaneous emission (SE):
  - near-deterministic emission sites
  - direction of emission
  - state of polarization

Proscia et al., Optica (2018)

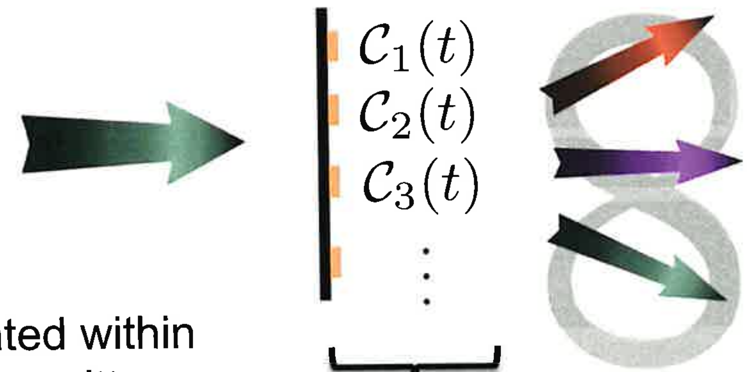
Kan et al., Adv. Mat. (2020)

Space-Time Quantum Metasurfaces (STQMs)

- Spatiotemporally modulated quantum metasurfaces
- Control all degrees of freedom of a single photon: polarization, frequency, direction of propagation, orbital angular momentum
- Dynamically generate and manipulate single- and multi-photon entanglement

Input quantum light

$|\Psi_{in}\rangle$



Distributed, time-dependent controls

Designer output quantum light

$$|\Psi_{out}\rangle = U(t)|\Psi_{in}\rangle$$

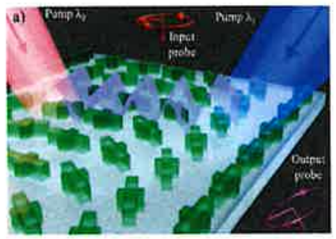
e.g., entangled light

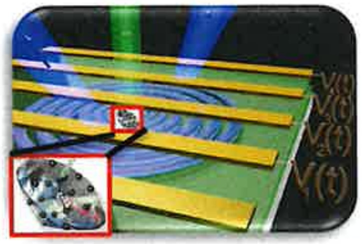
Note: $|\Psi_{in}\rangle$ could be generated within the STQM itself embedding q-emitters

Basic dipolar Hamiltonian: $H_{int}(t) = -\sum_i \mathbf{p}_i[\mathcal{C}_i(t)] \cdot \mathbf{E}(\mathbf{r}_i, t)$

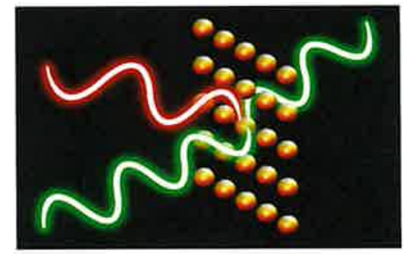
STQM "Flavors", Modulations, and Applications

- ❑ STQM "flavors"



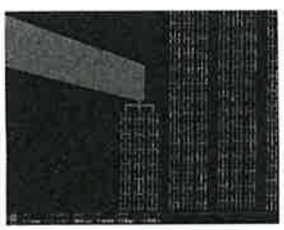


Solid-state quantum metasurfaces
Meta-atom 2D arrays



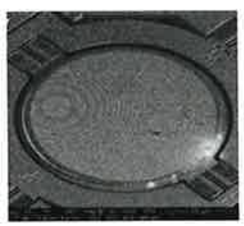
Cold-atom quantum metasurfaces
Single atoms trapped in 2D optical lattices

- ❑ Modulation schemes



electrical

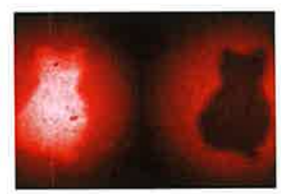
optical



MEMS

- ❑ Applications

Q-Communications

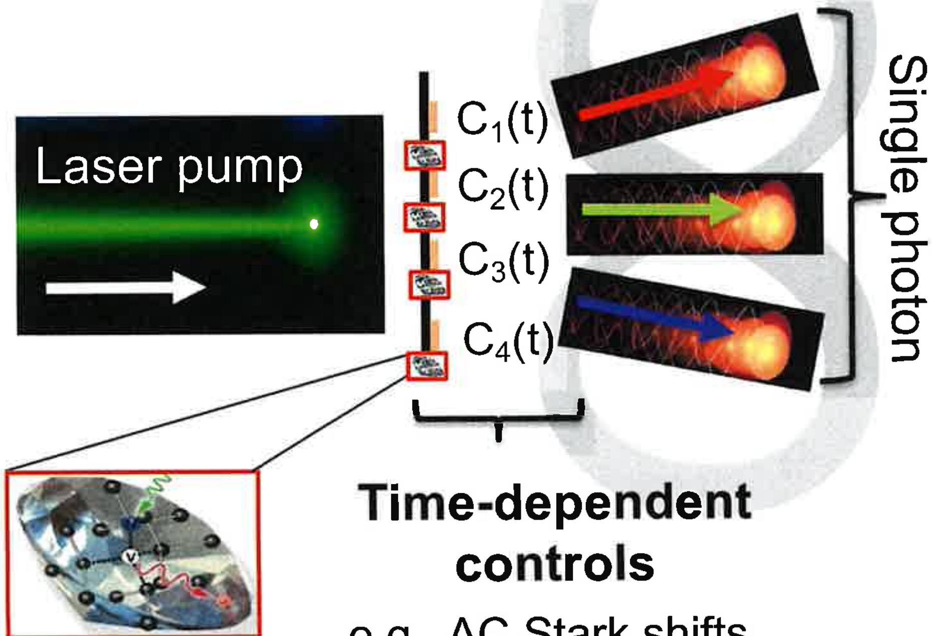


Q-Imaging

Q-Sensing

Shaping SE and SPDC/SFWM

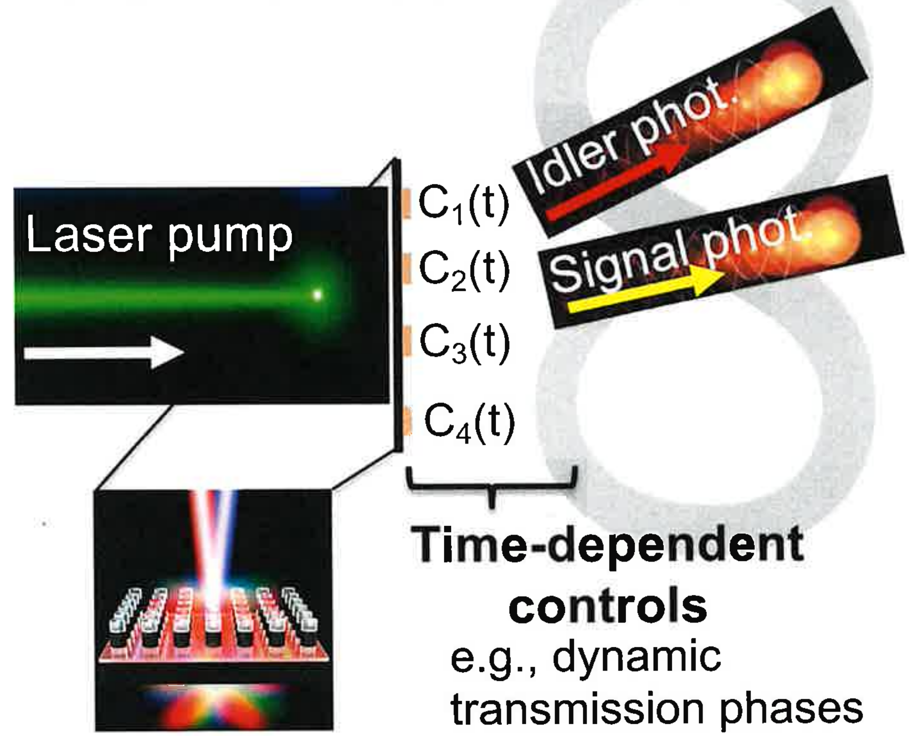
Space-Time SE
(e.g., single-photon color-path superposition)



Time-dependent controls
e.g., AC Stark shifts

Embedded quantum emitters

Space-Time SPDC/SFWM
(e.g., frequency-path entangled pairs)



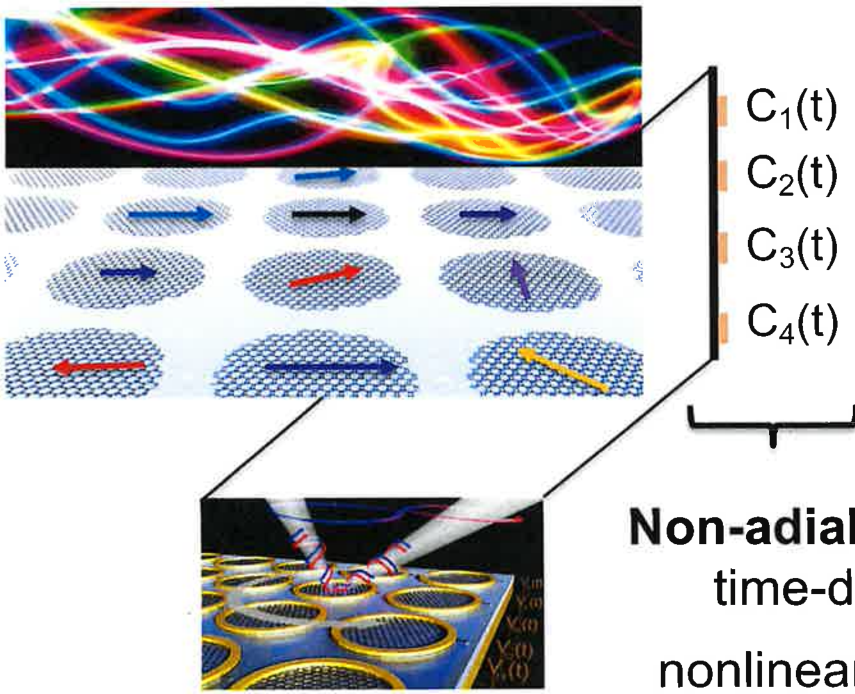
Time-dependent controls
e.g., dynamic transmission phases

nonlinear $\chi^{(2)}$ or $\chi^{(3)}$ meta-atoms

Shaping the Dynamical Casimir Effect (DCE)

The Quantum Vacuum

EM and matter quantum fluctuations (virtual photons, virtual dipoles)



Non-adiabatic (“accelerated”) time-dependent controls

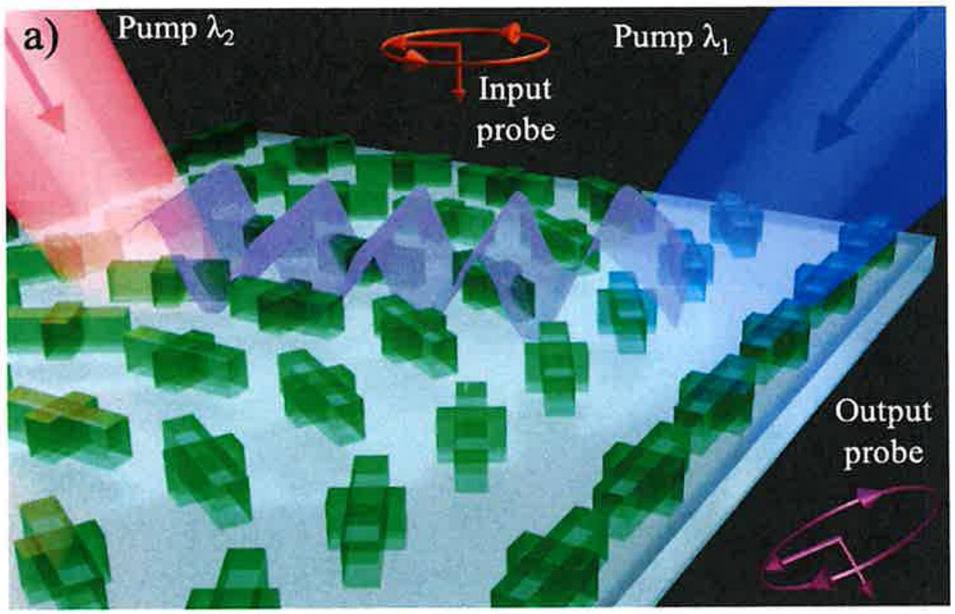
nonlinear $\chi^{(2)}$ or $\chi^{(3)}$ meta-atoms

Photon pairs out of the quantum vacuum

DCE is related to

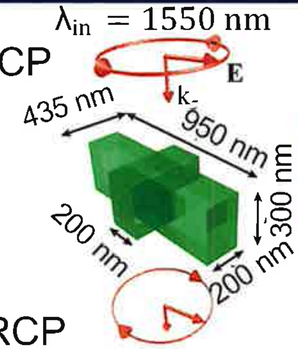
- SPDC/SFWM
- Hawking radiation
- Unruh effect
- Schwinger effect

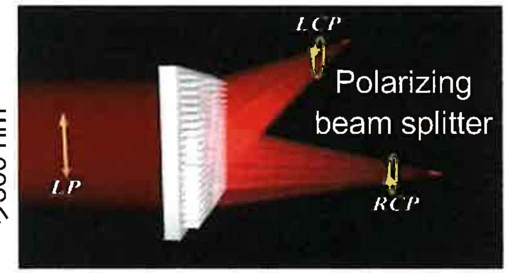
Example #1: Single-Photon Manipulation via STQMs



All-Optical Spatiotemporal Modulation

- Metasurface
  - **High-index dielectrics** (a-Si): low-loss, minimized decoherence
  - Modeled using Mie theory (e-, m- dipoles)
  - Anisotropic and rotated meta-atoms for spin-orbit coupling: geometric (Berry) phase

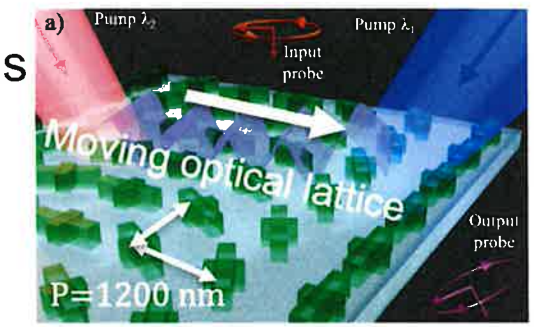




$\mathbf{k}_{out,RCP} = \mathbf{k}_{in} + \boldsymbol{\beta}_g$

$\mathbf{k}_{out,LCP} = \mathbf{k}_{in} - \boldsymbol{\beta}_g$

- Spatiotemporal modulation
  - **Moving optical lattice** from two interfering detuned pumps
  - Travelling-wave modulation of dielectric constant via third-order nonlinear susceptibility of a-Si



$$C_j(t) \sim \Delta n_j(t) = \Delta n \cos(\Omega t - \boldsymbol{\beta} \mathbf{r}_j)$$

$$\sim |E_p|^2 \chi^{(3)} \qquad \Omega = \omega_{P1} - \omega_{P2} \qquad \boldsymbol{\beta} = \mathbf{k}_{P1} - \mathbf{k}_{P2}$$

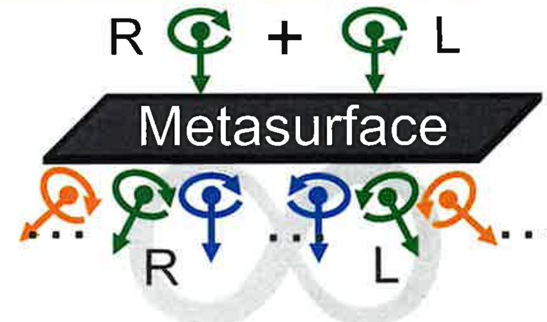
$\Omega/2\pi \sim 10$ THz $\quad \beta \sim \beta_g \sim 0.01\, \omega_{in}/c$

$I_P \sim 1$ GW/cm^2 $\quad \Delta n/n_{\alpha\text{-}Si} \sim 1\%$

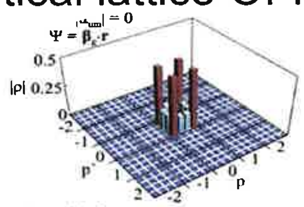
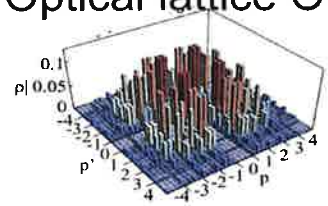
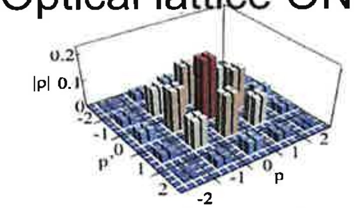
Single-Photon Entanglement Generation and Manipulation

$$|\omega_{in}, \mathbf{0}, H\rangle \rightarrow \sum_{p} \sum_{q=0,1} [C_{pq}^{(R)} |\omega_{in} + p\Omega; p\boldsymbol{\beta} + q\boldsymbol{\beta}_g; R\rangle + C_{pq}^{(L)} |\omega_{in} + p\Omega; p\boldsymbol{\beta} - q\boldsymbol{\beta}_g; L\rangle]$$

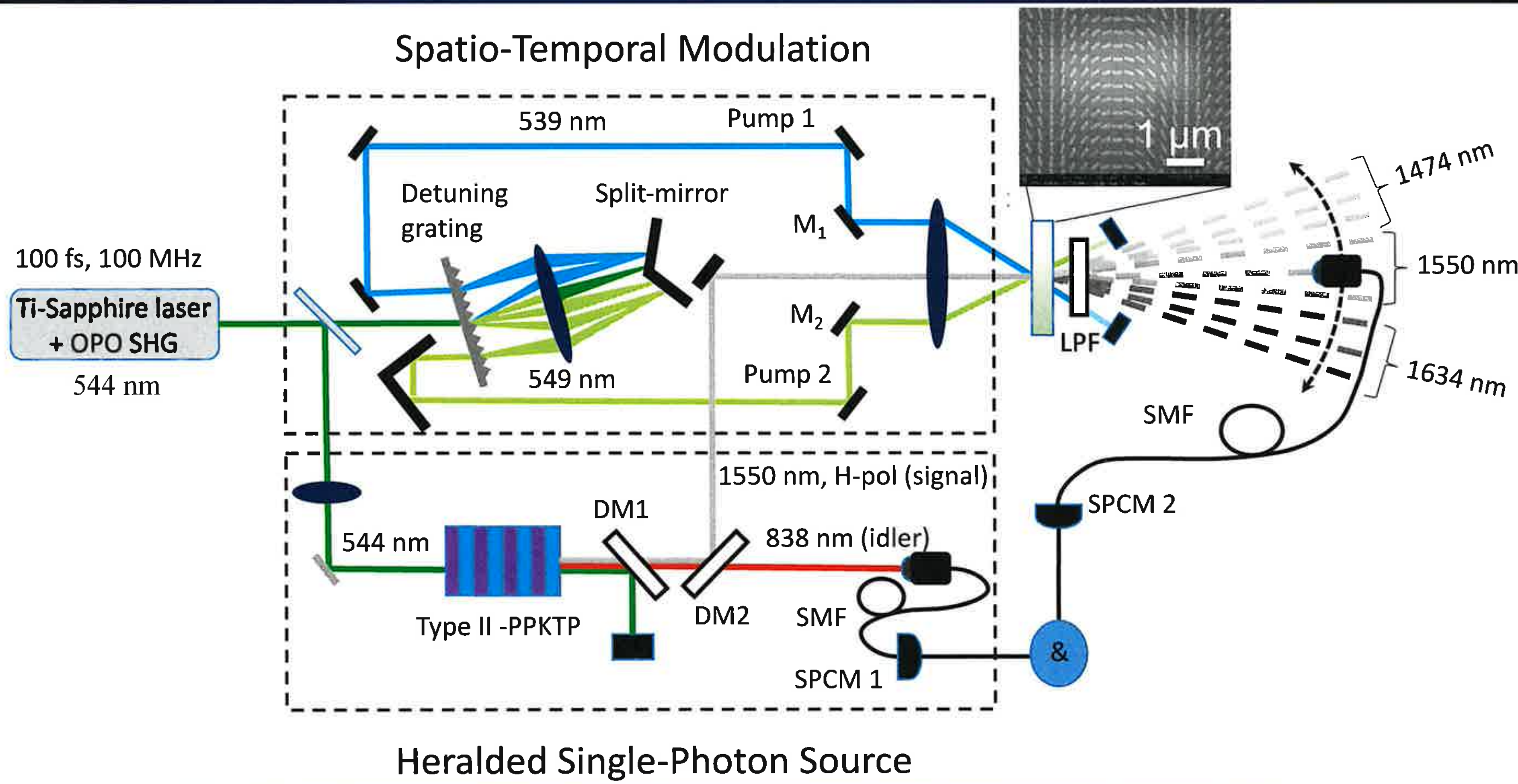
- Frequency-path-spin quantum superposition
- Frequency comb – diffraction orders
- Correlations: spin-path (Berry) and path-color (optical lattice)



❑ (Hyper-) entanglement generation and manipulation

	Linearly polarized input Optical lattice OFF	Linearly polarized input Optical lattice ON	Circularly polarized input Optical lattice ON
			
Entang. type:	**Spin-Path** (bipartite, dim=2)	**Color-Spin-Path** (multipartite, dim>2)	**Color-Path** (bipartite, dim>2)
Concurrence:	$C = \sqrt{2(1 - \mathrm{Tr}\rho_{spin}^2)} = 0.99$	C' = 1.26 ($C_{max}=\sqrt{2}$)	C' = 1.38 ($C'_{max}=\sqrt{2}$)

Ongoing Experiment: Color-Spin-Path Hyperentangled Single-Photon

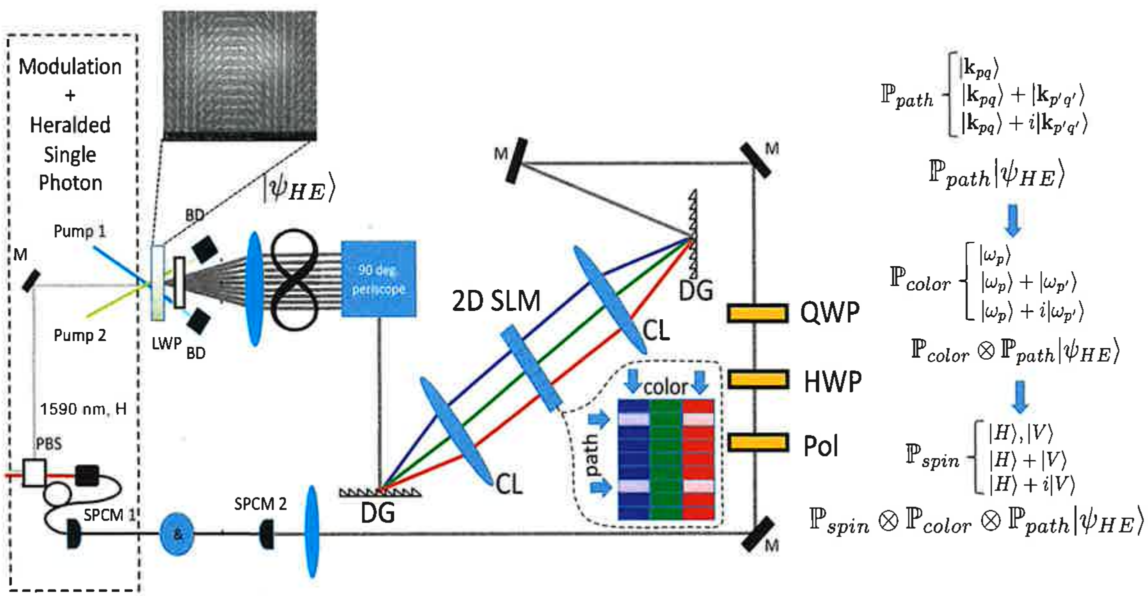


Quantum State Tomography: Measuring Color-Spin-Path Entangl.

- **Measure density matrix** $\rho = |\Psi_{HE}\rangle\langle\Psi_{HE}| = \sum_\alpha r_\alpha \Gamma_\alpha$ ← $SU(2) \otimes SU(3) \otimes SU(9)$ generators

2 spins	3 colors	9 paths
Pauli matrices	Gell-Mann matrices	No special name

Complex coefficients to be measured



$s_\alpha = \langle\psi_{HE}|\mathbb{P}_\alpha|\psi_{HE}\rangle$ (2916 independent measurements)

1. **Implement projectors**

$$P_\alpha = P_{spin} P_{color} P_{path}$$

2. **Measure expectation values**

$$s_\alpha = \langle P_\alpha \rangle$$

3. **Calculate r_α via Maximum Likelihood Estimation**

$$\mathrm{Min}_{r_\alpha} ||\mathbf{s} - \mathbf{B}\,\mathbf{r}|| \qquad B_{\alpha\beta} = \mathrm{Tr}[\Gamma_\alpha P_\beta]$$

$$\rho = \sum_\alpha r_\alpha \Gamma_\alpha$$

$\mathrm{Tr}\rho = 1$

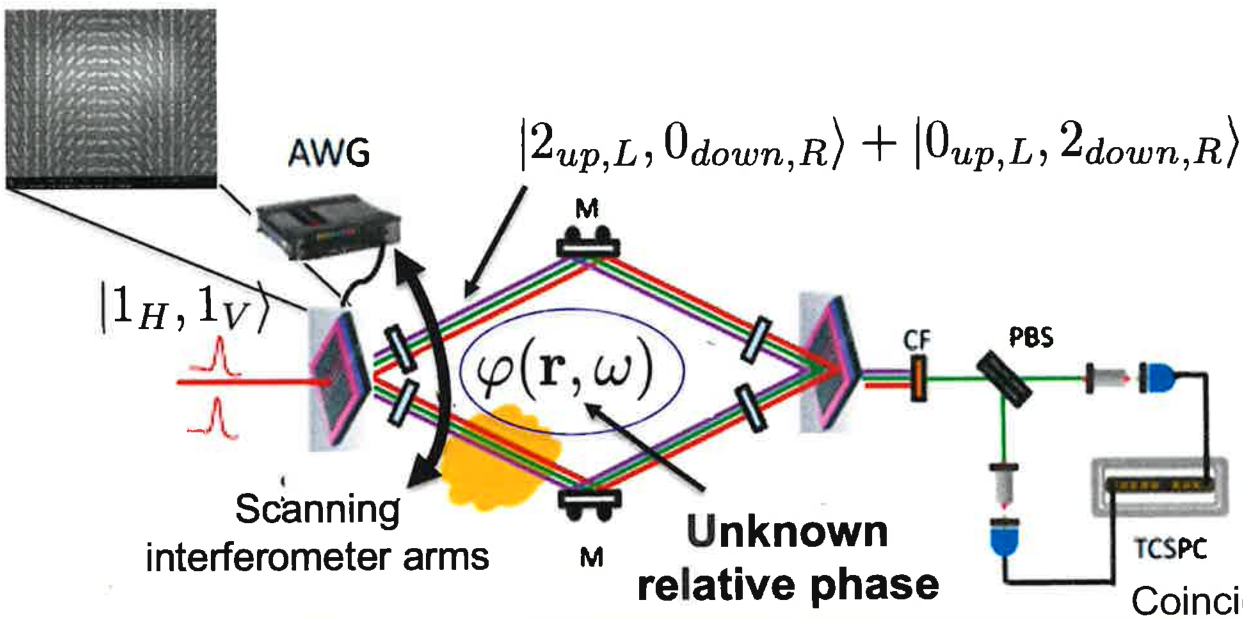
$\rho = \rho^\dagger$

$\rho^2 \geq 0$

Another Ongoing Experiment: Active/Dynamic Quantum Sensing

- Multicolor/multipath quantum interferometry (sensing dispersive and spatial properties)
- Travelling-wave modulation: color-spin-path entangled probe
- Ultimate quantum precision (Heisenberg limit) via "NOON" states $|N,0\rangle + |0,N\rangle$

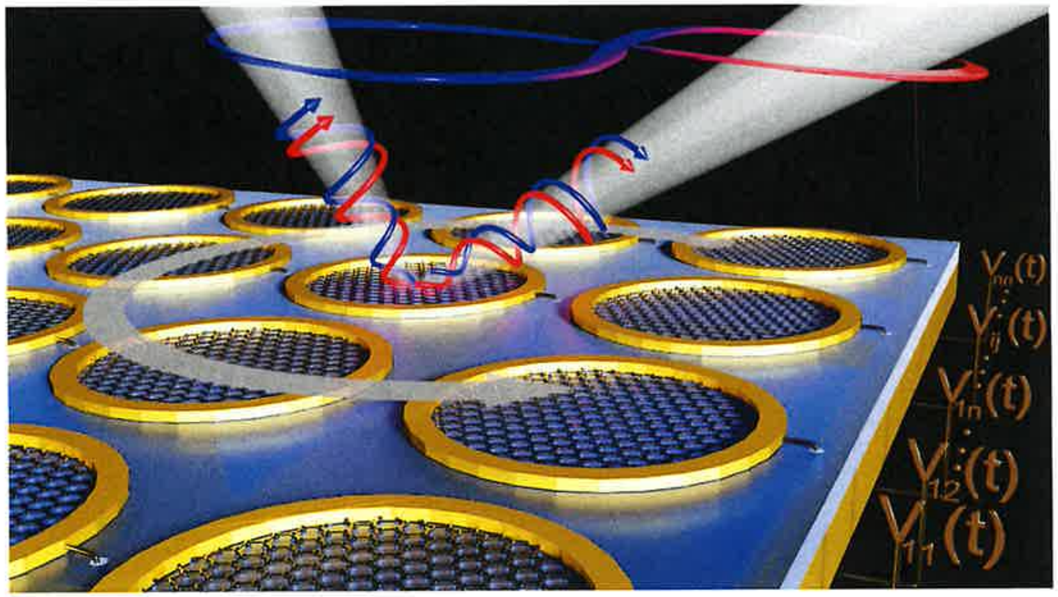
Heisenberg limit: $\Delta\varphi_{HL} \sim 1/N$ Better than shot-noise limit: $\Delta\varphi_{SN\,(SQL)} \sim 1/\mathrm{sqrt}(N)$



N=2 NOON state
Photon bunching
Frequency comb

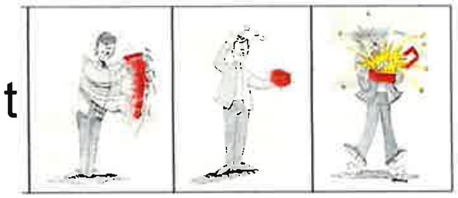
Phase estimation
$\Delta\varphi_{HL} \sim 1/N$

Example #2: Quantum Vacuum Manipulation via STQMs



Dynamical Casimir Effect (DCE), aka "Casimir Light"

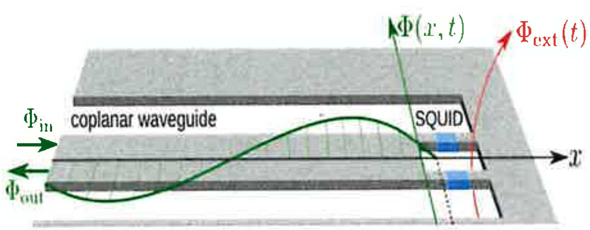
❑ **Mechanical DCE** (predicted in 1970's)



- "Shaking" the quantum vacuum by a moving mirror generates light
- Mechanical oscillation cannot be fast & large (few GHz, 100s nm)
- Mechanical DCE rate: << 1 photon-pair/year. Not detectable…

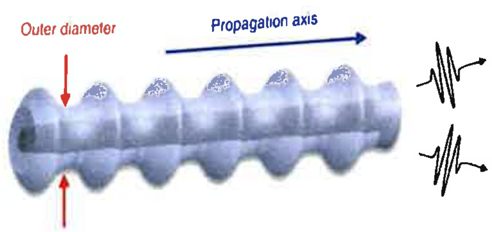
❑ **Analogs of mechanical DCE:** Modulate material properties (measured in 2000's)

Oscillating magnetic flux $\Phi(t)$ in SQUID



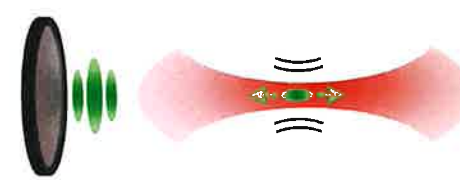
Ω ~ 5 GHz 10^6 photon pairs/s

Light propagating in nonlinear optical fiber of periodic diameter D(x)=D(x+L)



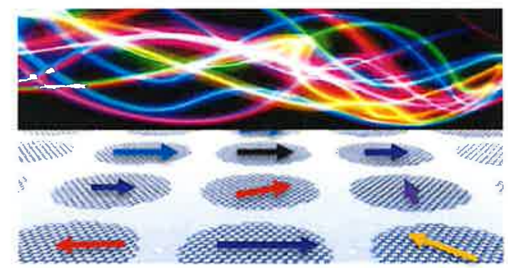
Ω_{eff}=c/nL~ 50 MHz 10^6 photon pairs/s

BEC with modulated trap stiffness $V_{trap}(t)$: Acoustic DCE



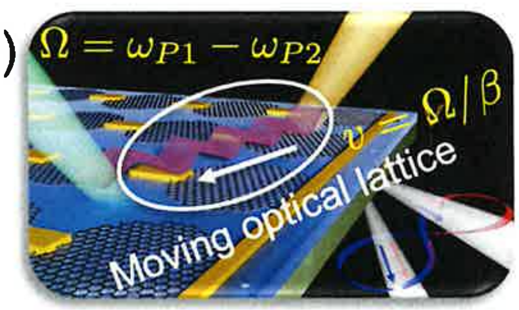
Ω ~ 2 kHz, 10^3 Bogoliubov pairs/s

A "Quantum Antenna" Emitting Casimir Light



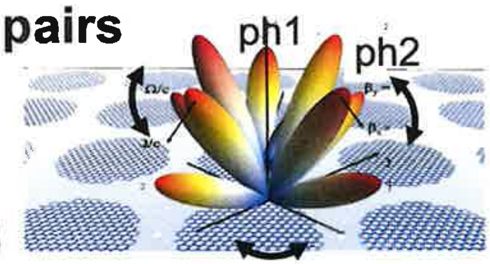
- EM field and matter quantum vacuum fluctuations

$$\langle \mathbf{p}_i^{(fl)} \rangle = \langle \mathbf{E}_i^{(fl)} \rangle = \langle \mathbf{p}_i^{(fl)} \mathbf{E}_j^{(fl)} \rangle = 0 \quad \text{but} \quad \begin{matrix} \langle \mathbf{E}_i^{(fl)} \mathbf{E}_j^{(fl)} \rangle \sim \delta_{ij} \\ \langle \mathbf{p}_i^{(fl)} \mathbf{p}_j^{(fl)} \rangle \sim \delta_{ij} \end{matrix}$$



- **Parametric amplification of quantum fluctuations**
  - Graphene disks (tunable, localized plasmons, nonlinear $\chi^{(3)}$)
  - Spatiotemporal modulation: Moving optical lattice

$$\alpha_i \rightarrow \alpha_i + \Delta\alpha \cos(\Omega t - \boldsymbol{\beta} \cdot \mathbf{r}_i) \qquad \Delta\alpha \sim \frac{|E_P|^2 \sigma^{(3)}}{\omega^2 - \omega_{disk}^2 + i\omega\gamma}$$



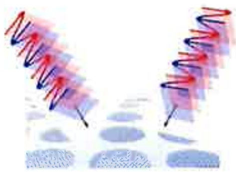
- **Hamiltonian: akin to a "quantum antenna" emitting photon pairs**

$$H_{DCE}(t) \sim a_1^\dagger a_2^\dagger \, \Delta\alpha \; e^{i(\omega_1 + \omega_2 - \Omega)t} \sum_i e^{i(\mathbf{k}_1 + \mathbf{k}_2 - \boldsymbol{\beta}) \cdot \mathbf{r}_i} + c.c.$$

- **Energy-momentum conservation:** $\omega_1 + \omega_2 = \Omega \quad \mathbf{k}_1 + \mathbf{k}_2 = \boldsymbol{\beta}$

Full Spatiotemporal Control over Casimir Light

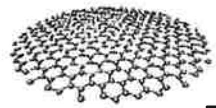
Frequency



$\Omega = \omega_{P1} - \omega_{P2}$

Detuning

+



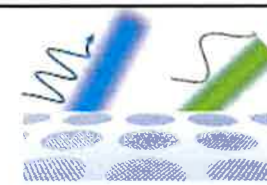
$\omega_{disk} \sim \sqrt{E_F/d}$

Plasmon resonance

→

$\omega_1 \approx \omega_{disk}$

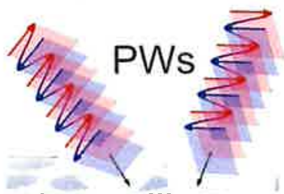
$\omega_2 \approx \Omega - \omega_{disk}$



Wavefront

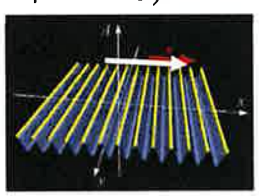
$\beta \neq 0$

$\alpha_i(t) \sim \cos(\Omega t - \boldsymbol{\beta} \cdot \mathbf{r}_i) \rightarrow \mathbf{k}_1 + \mathbf{k}_2 = \boldsymbol{\beta}$



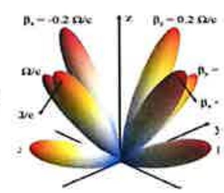
Non-collinear $\beta \neq 0$

→



Travelling optical lattice

→



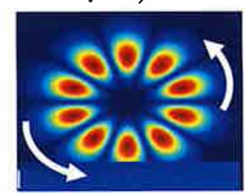
Steered DCE

$\ell \neq 0$

$\alpha_i(t) \sim \cos(\Omega t - \ell \varphi_i) \rightarrow m_1 + m_2 = \ell$

Counter-rotating $\ell = 2p \neq 0$

→



Spinning optical lattice

→

Vortex DCE

Entanglement

$\beta \neq 0$

Energy LM $|\Psi\rangle = \sum_{\mathbf{k}} c_{\mathbf{k}} \, |\omega_{disk}, \mathbf{k}\rangle_1 |\Omega - \omega_{disk}, \boldsymbol{\beta} - \mathbf{k}\rangle_2$

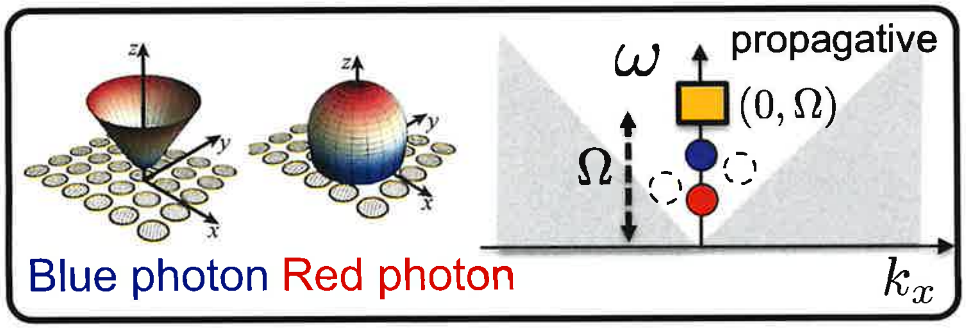
$\ell \neq 0$

Energy AM $|\Psi\rangle = \sum_{m} c_m \, |\omega_{disk}, m\rangle_1 |\Omega - \omega_{disk}, \ell - m\rangle_2$

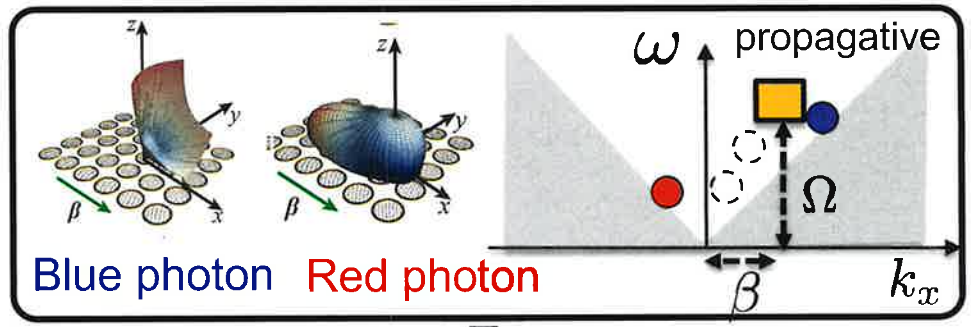
Steering: Two-Photon Angular Distribution and Dispersion Relation

$\bullet\ (\mathbf{k}_1, \omega_1) + \bullet\ (\mathbf{k}_2, \omega_2) = \blacksquare\ (\beta, \Omega)$

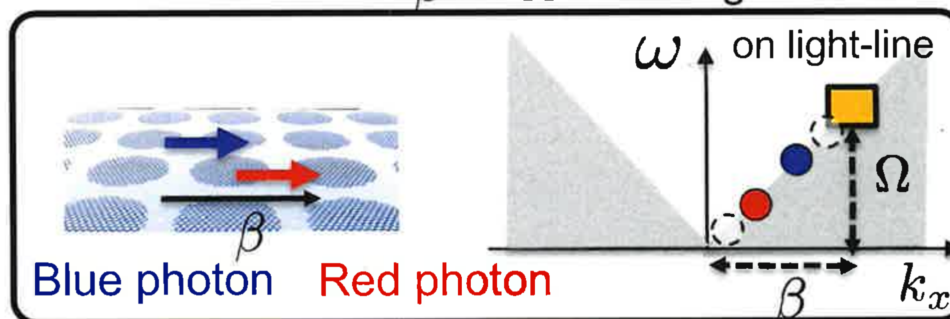
$\beta = 0$ Time-only modulation



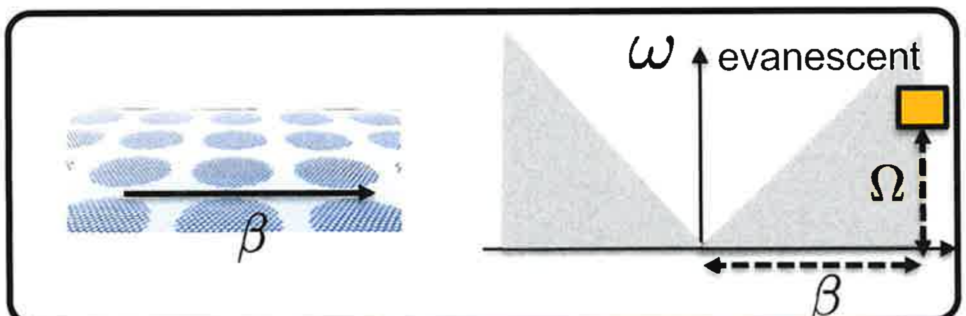
$0 < \beta < \Omega$ Space-time modulation. Steering



$\beta = \Omega$ Grazing emission

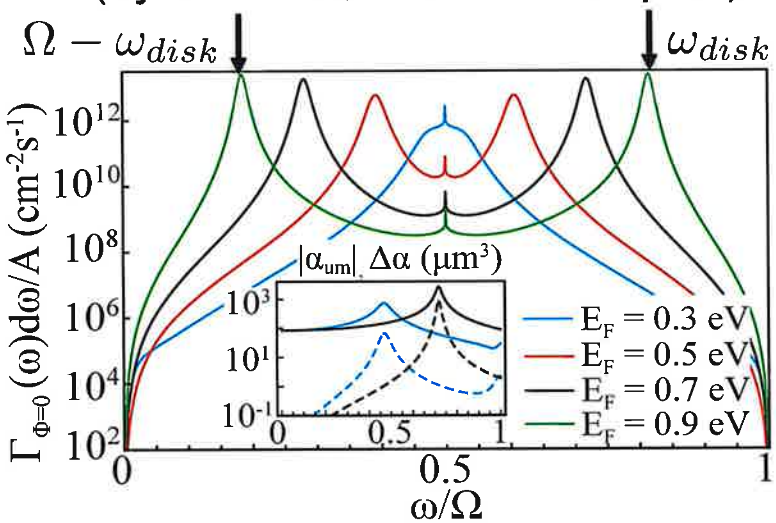


$\beta > \Omega$ Emission of plasmon pairs



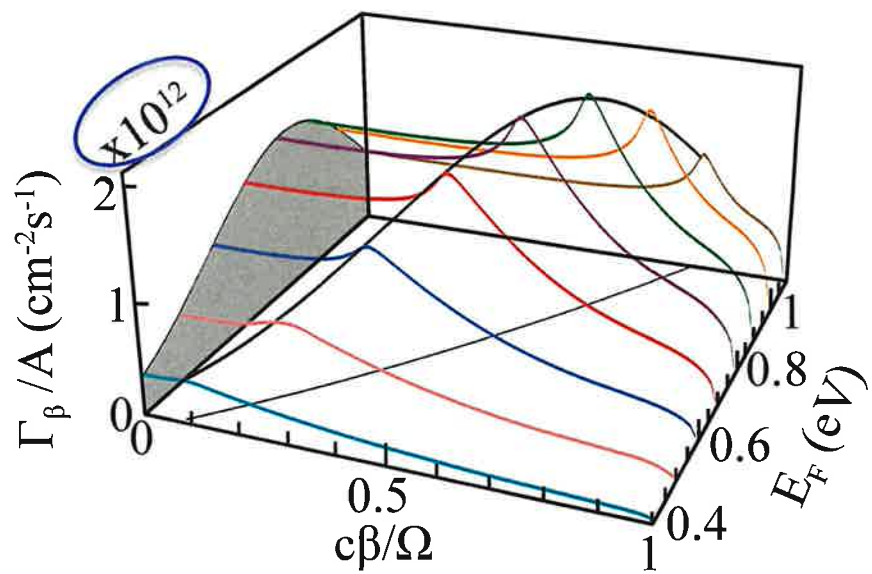
Spectra and Total Rates

DCE emission spectrum
(symmetric, double-humped)



- Pumps: 193 THz and 93 THz
- Ultrafast modulation: Ω/2π ~ 100 THz
- Intensity: ~ 1 GW/cm^2
- Modulation amplitude ~ 1%

Giant total emission rate



- Graphene relaxation time: ~ 50 fs
- Graphene disks diameter: d ~ 50 nm
- Metasurface period: a ~ 500 nm

Ongoing Experiment: DCE Generation at THz Frequencies

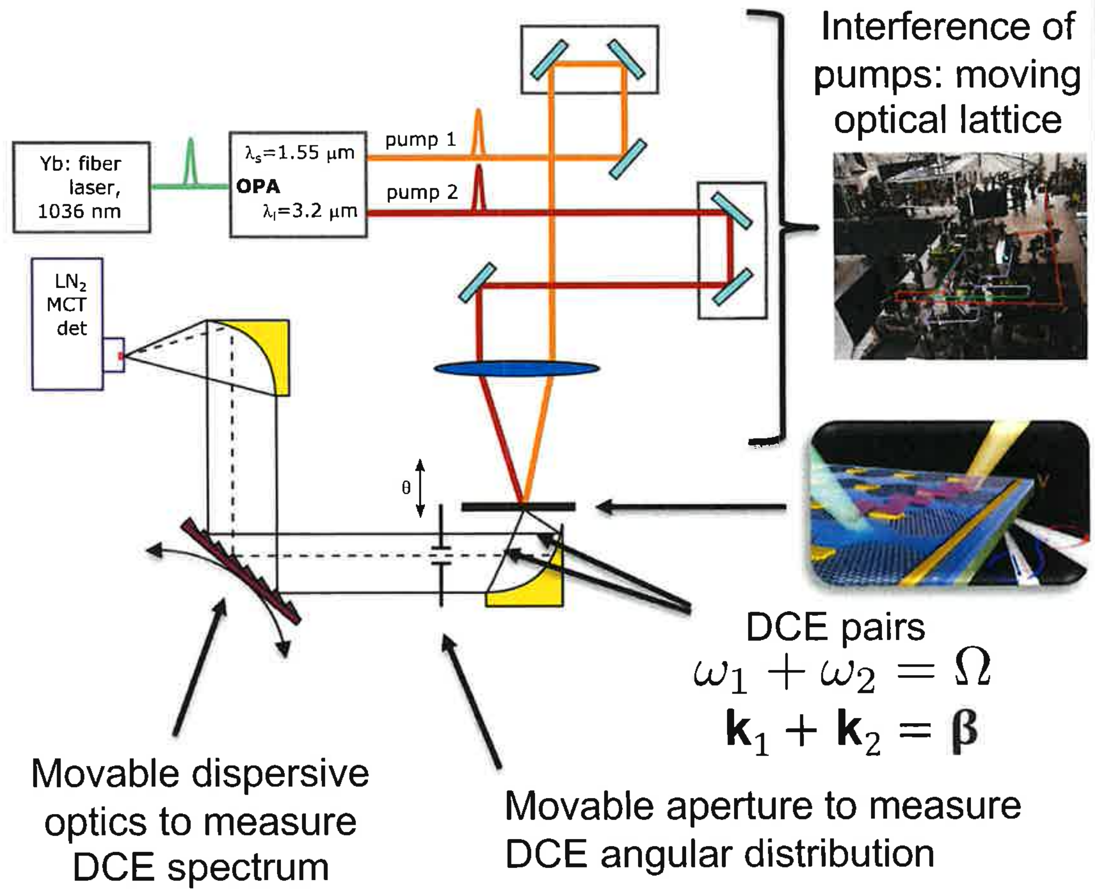
- Ultra-fast modulation frequency

  $$\Omega/2\pi \sim 100\ \mathrm{THz}$$

- Laser: Yb:fiber laser (1036 nm)
  - Pulse duration: 250 fs
  - Repetition rate: 80 MHz
  - Peak power → ~ GW/cm^2

- OPO
  - Signal→ 1.55 µm, Idler→ 3.2 µm
  - Detuning of signal/idler pumps is tunable with OPO

- All-optical ultrafast modulation of graphene (approaching graphene time response)



$$\omega_1 + \omega_2 = \Omega$$

$$\mathbf{k}_1 + \mathbf{k}_2 = \boldsymbol{\beta}$$

Summary

✓ Introduced STQM concept

PHYSICAL REVIEW LETTERS **127,** 043603 (2021)

Editors' Suggestion | Featured in Physics

Space-Time Quantum Metasurfaces

Wilton J. M. Kort-Kamp, Abul K. Azad, and Diego A. R. Dalvit*

- Spatiotemporal manipulation of quantum light
- Quantum light + classical/quantum matter
- Solid-state and cold-atom platforms

✓ Ongoing LANL experiments to realize STQMs

- Dynamic generation/manipulation of entanglement
- Active STQM quantum sensing
- Active STQM spontaneous emission
- Steered DCE photon pairs