QUANTUM OPTICS ON A NONLINEAR CHIP

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THE ART OF ENTANGLING LIGHT

Alexander Solntsev
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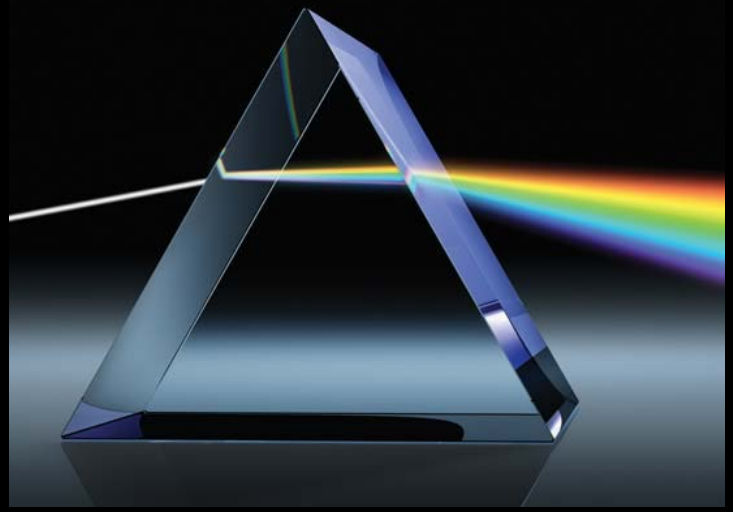
WHAT IS WELL KNOWN

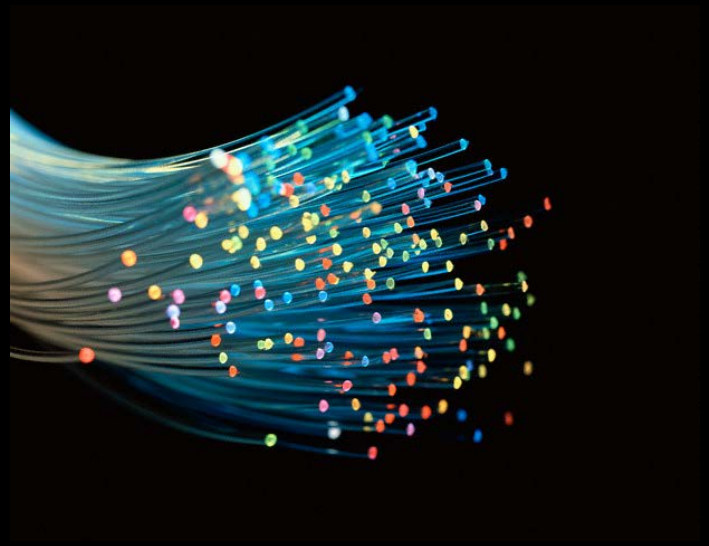
Moderate amount of light

- classical linear optics

diffraction



refraction

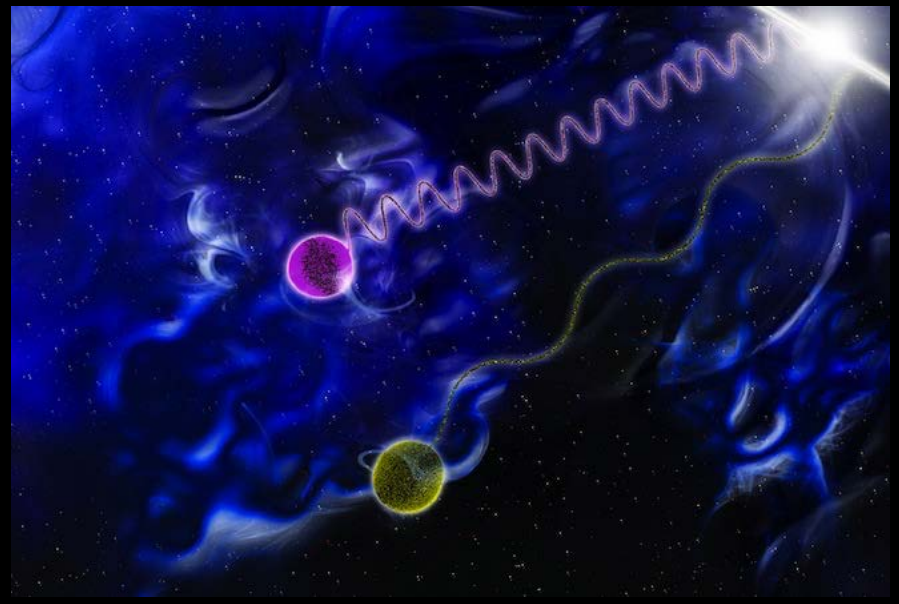


reflection

WHAT IS STUDIED NOW

Hardly any light (few photons)

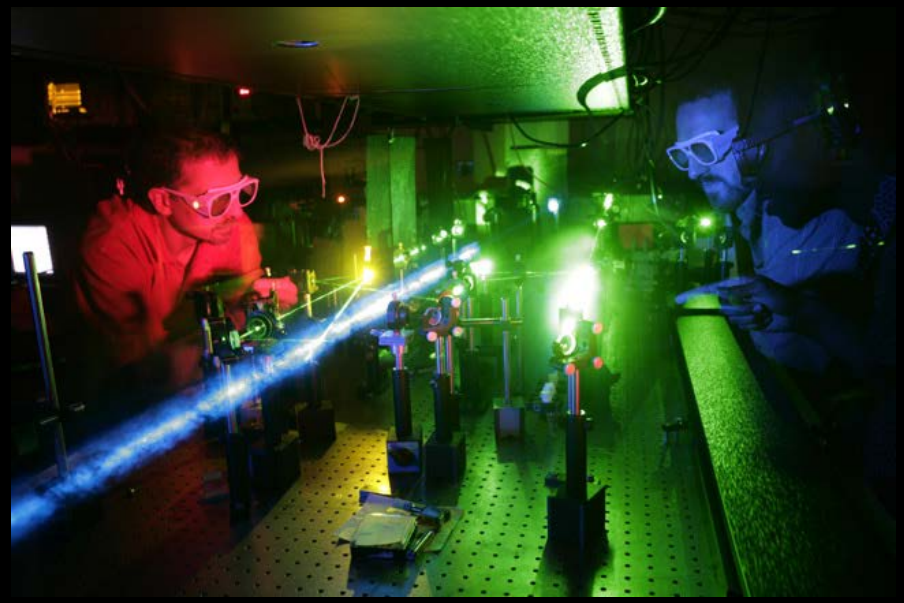
- quantum optics
  - Spooky quantum effects



+

A lot of light (intense lasers)

- nonlinear optics
  - Light changes matter

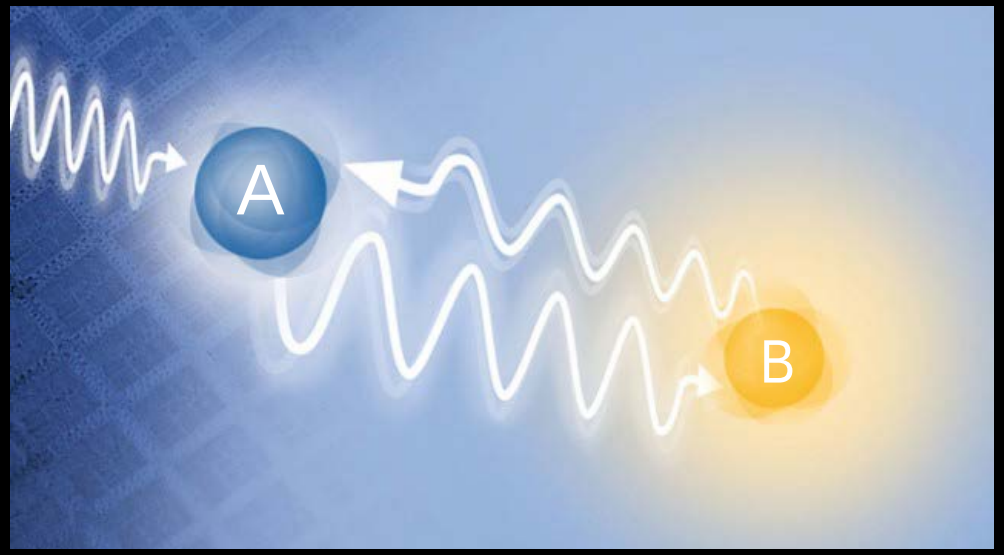


= ?

QUANTUM OPTICS

Entanglement – correlations without interaction

- Entangled photons are interconnected
- Measurement of one photon affects the other photon

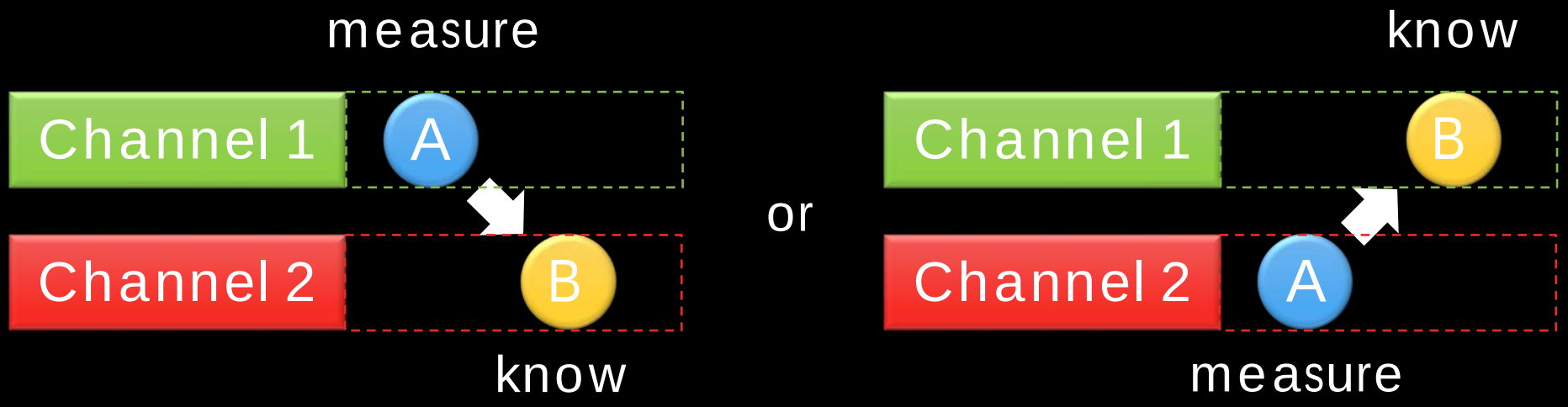


QUANTUM OPTICS

Entanglement – correlations without interaction

Two *photons* and two *channels*
(A and B) (1 and 2)

Entangled state #1: $|A_1,B_2\rangle + |A_2,B_1\rangle$ (one set of parameters)

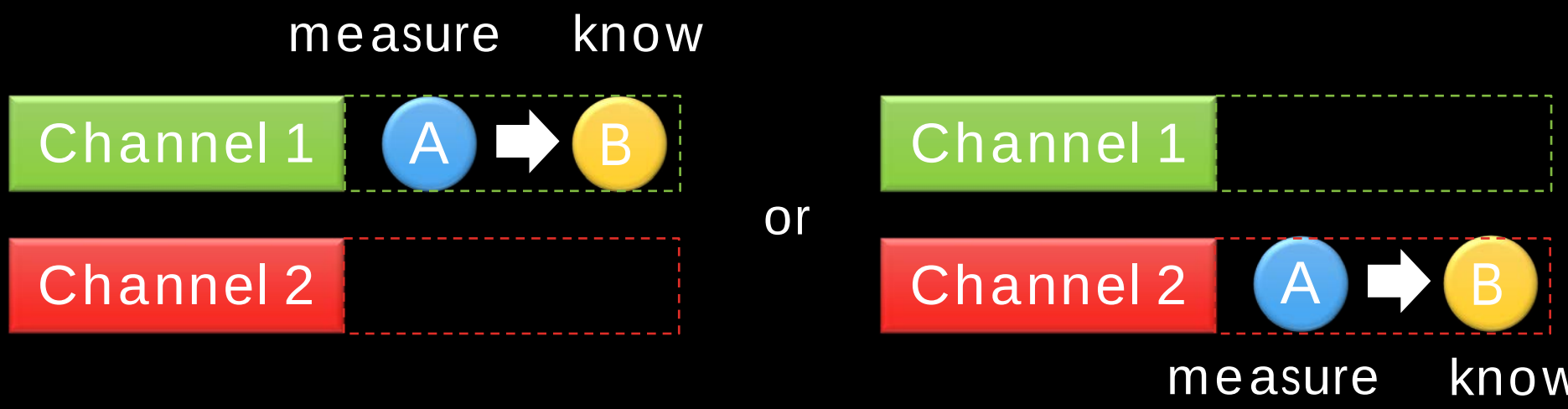


QUANTUM OPTICS

Entanglement – correlations without interaction

Two *photons* and two *channels*
(A and B) (1 and 2)

Entangled state #2: $|A_1,B_1\rangle + |A_2,B_2\rangle$ (another set of parameters)

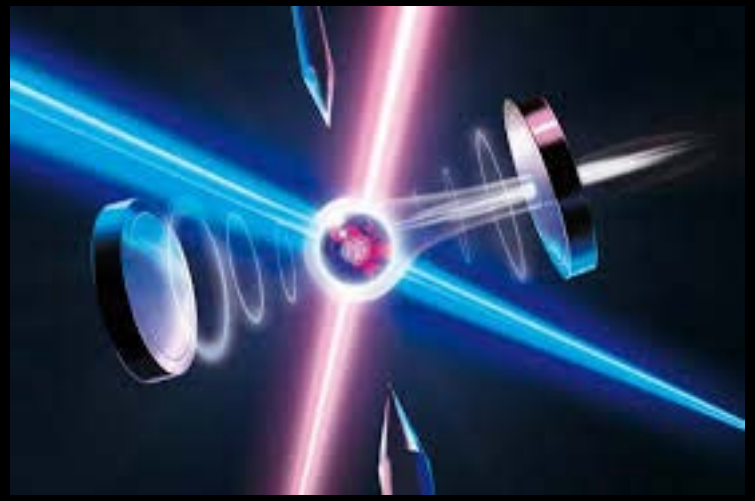


QUANTUM OPTICS

Applications of entanglement

Secure communication

Fast computation



Precise metrology

NONLINEAR OPTICS

Applications

Green laser pointer

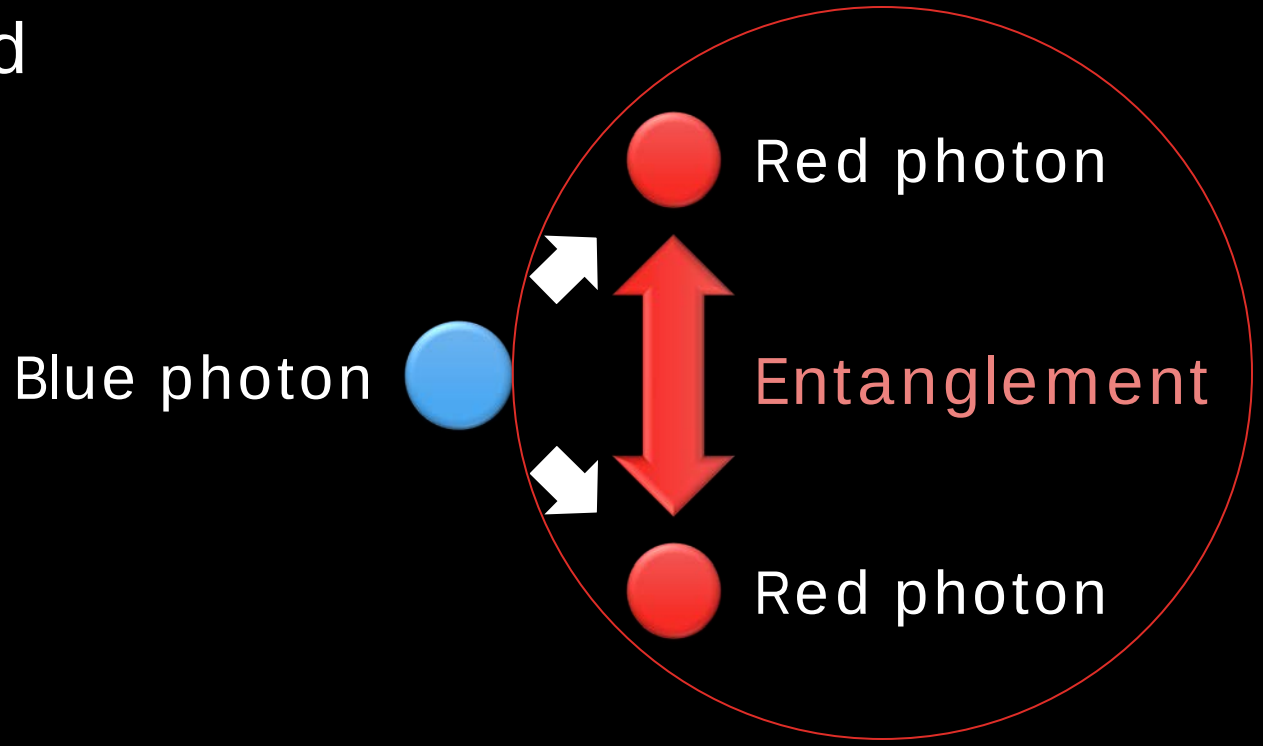
Telecommunications

Microscopy

NONLINEAR OPTICS

- Intense light changes matter
- Different colors of light interact through matter
- Light color can be changed

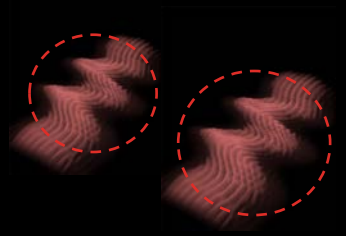
Creating a pair of entangled photons using nonlinearity (SPDC)



WHAT WE STUDY

- A lot of light + hardly any light
  - Integrated nonlinear quantum optics

Powerful blue laser



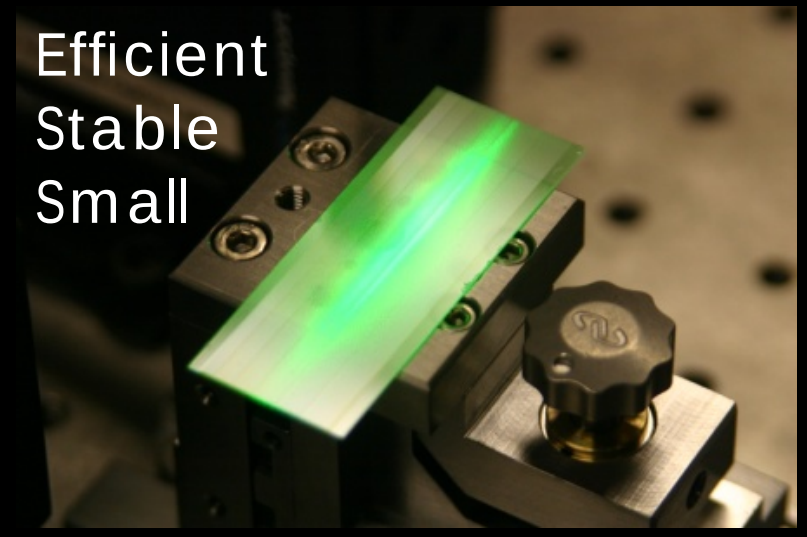
Two red photons

Separated by color

Can we **control** entanglement with a laser though optical nonlinearity?

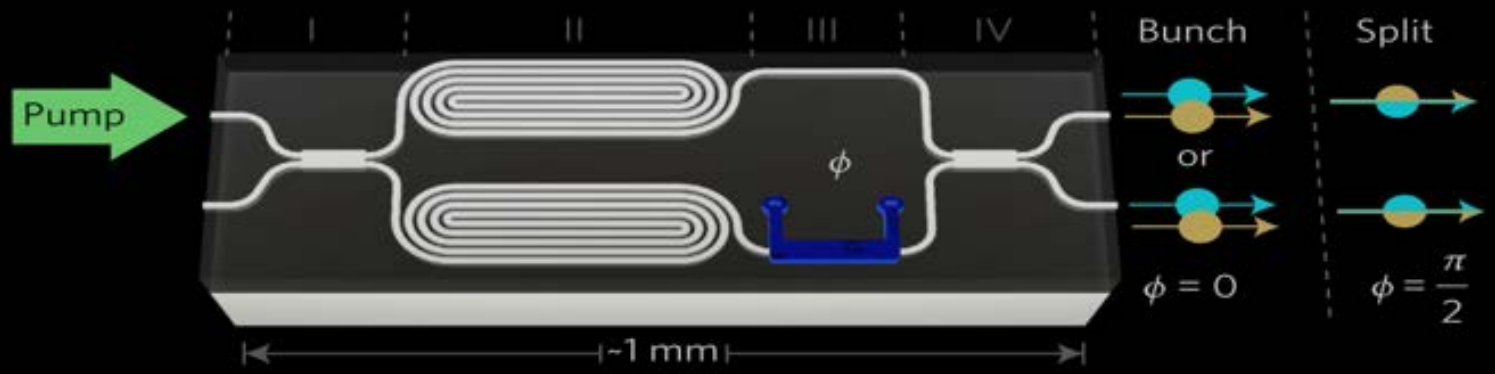
WHAT WE STUDY

- A lot of light + hardly any light
  - Integrated nonlinear quantum optics
- On-chip integration

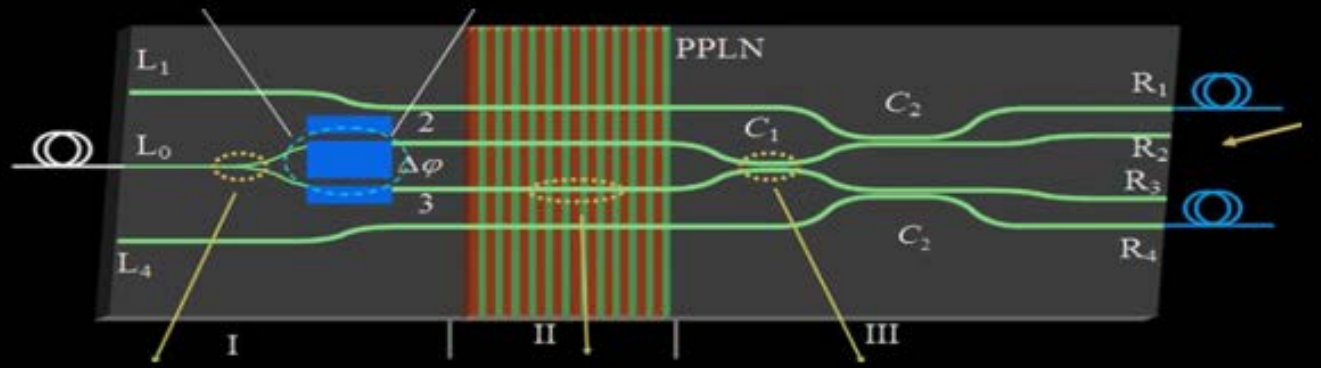


ON-CHIP QUANTUM OPTICS

- Generating entangled photons on a nonlinear chip
- Control is complex, requires thermo-optical or electro-optical tuning



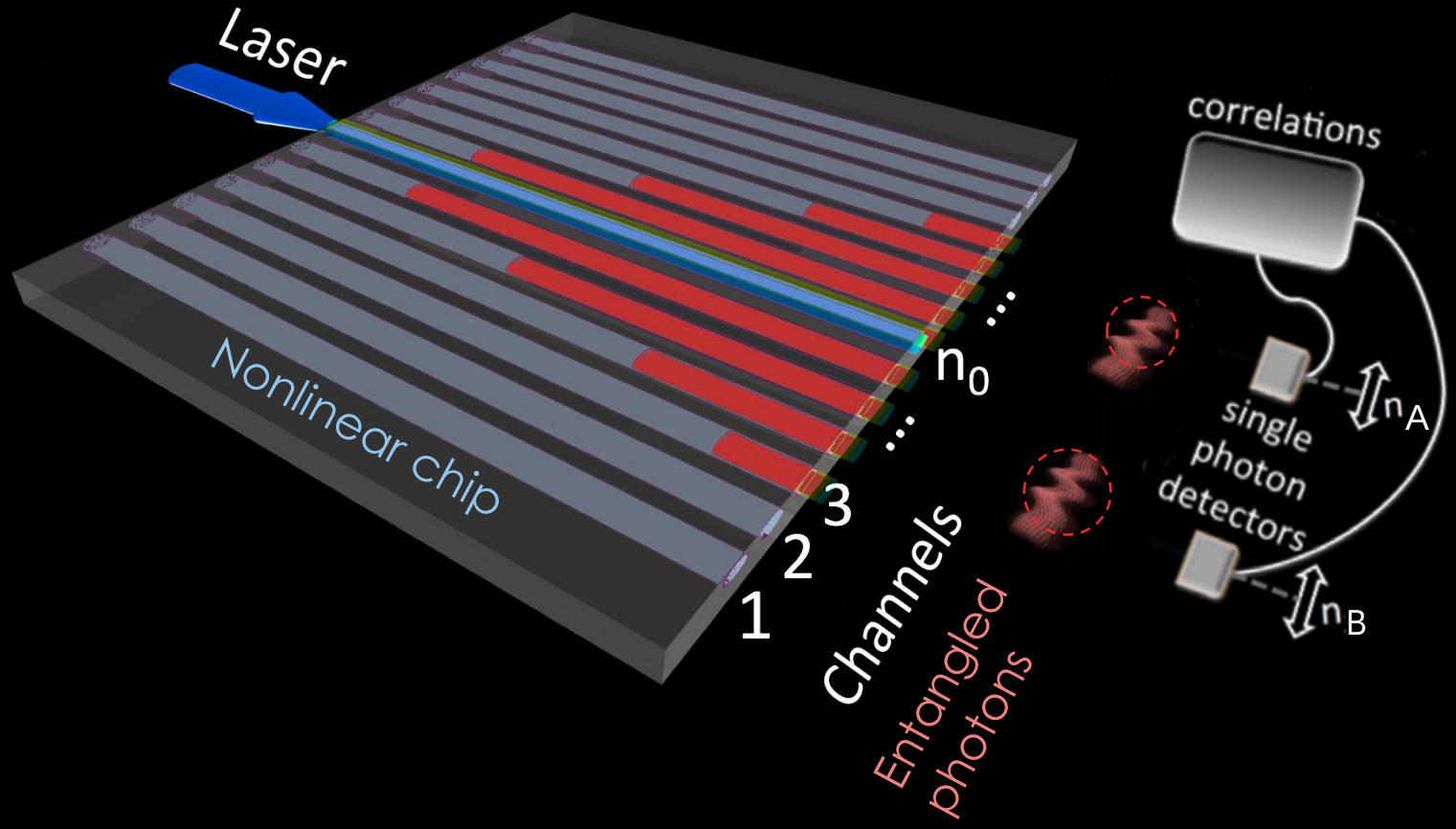
Silverstone et al., Nature Photonics **8**, 104 (2014)

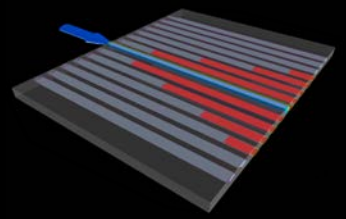


Jin et al., Phys. Rev. Lett, **113**, 103601 (2014)

LASER AND TWO PHOTONS ON A CHIP

Experiment

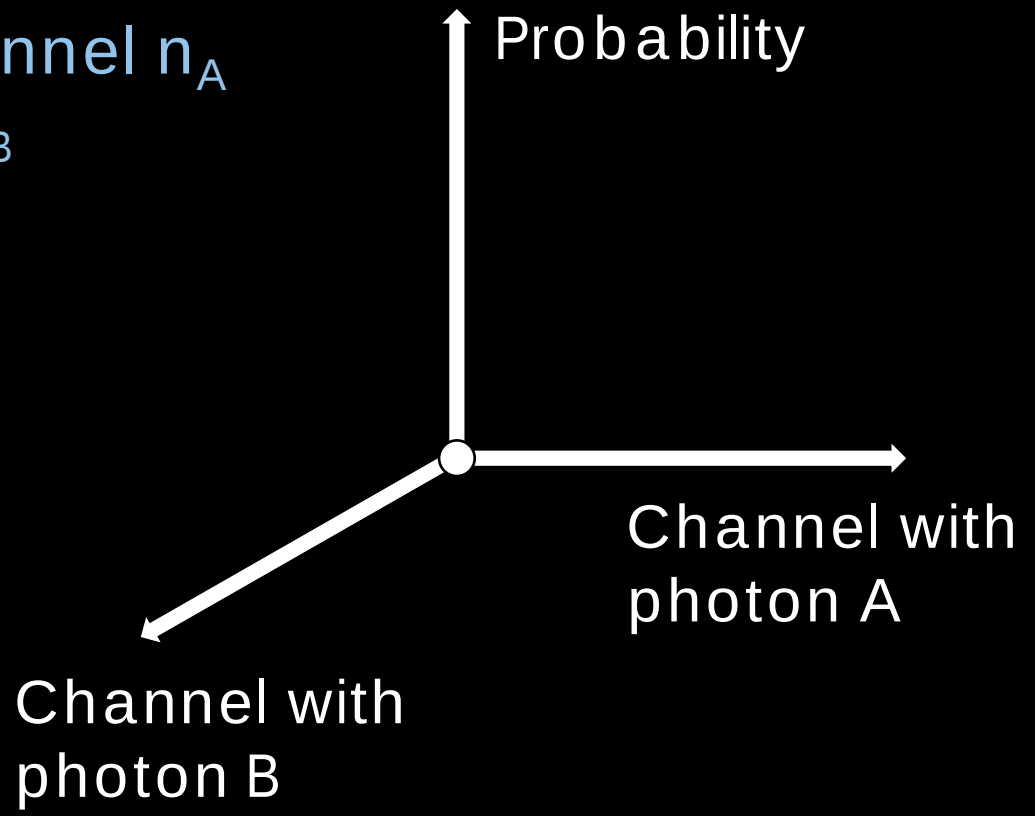


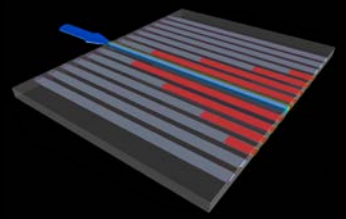


LASER AND TWO PHOTONS ON A CHIP

Correlations

- Probability of photon A in the channel n_A while photon B is in the channel n_B





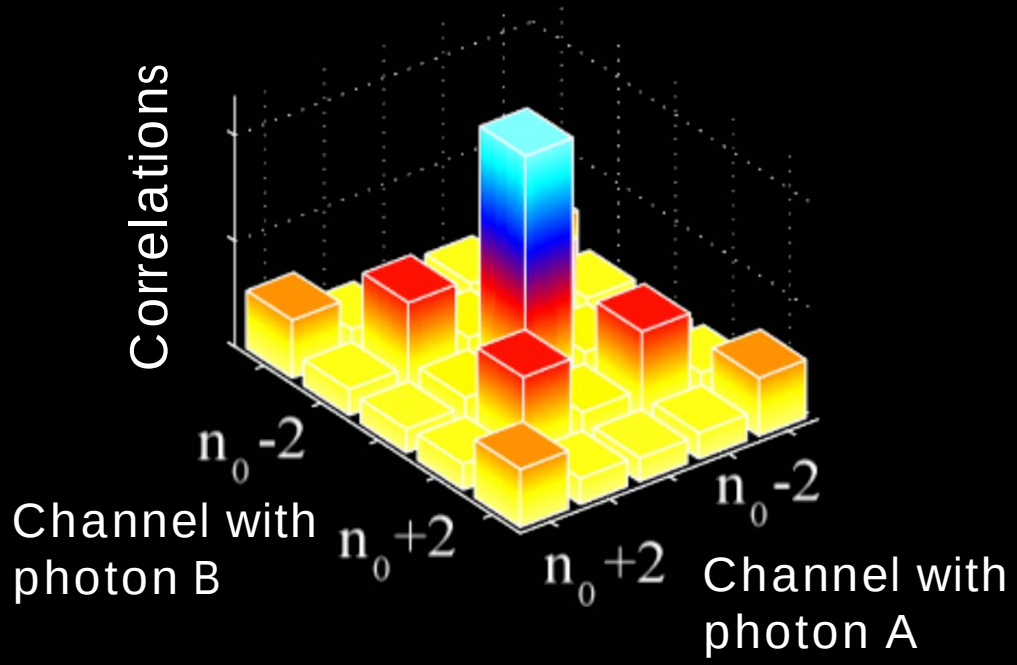
LASER AND TWO PHOTONS ON A CHIP

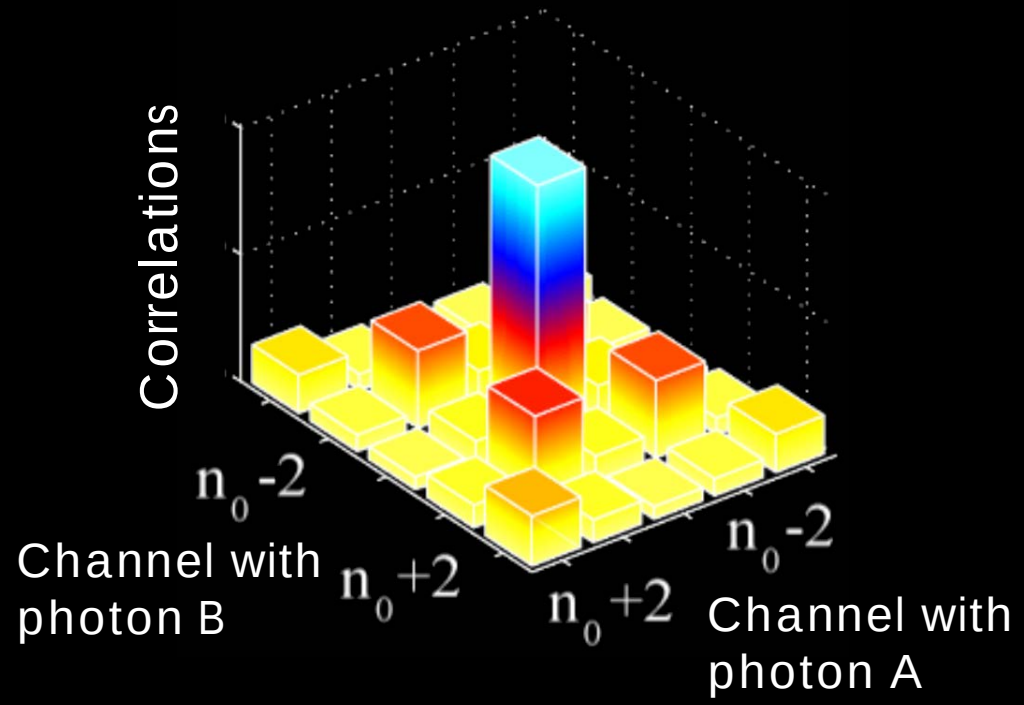
Results

Theory

Entanglement!

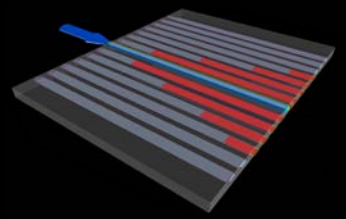
Experiment





Solntsev et al., PRL 108, 023601 (2012)

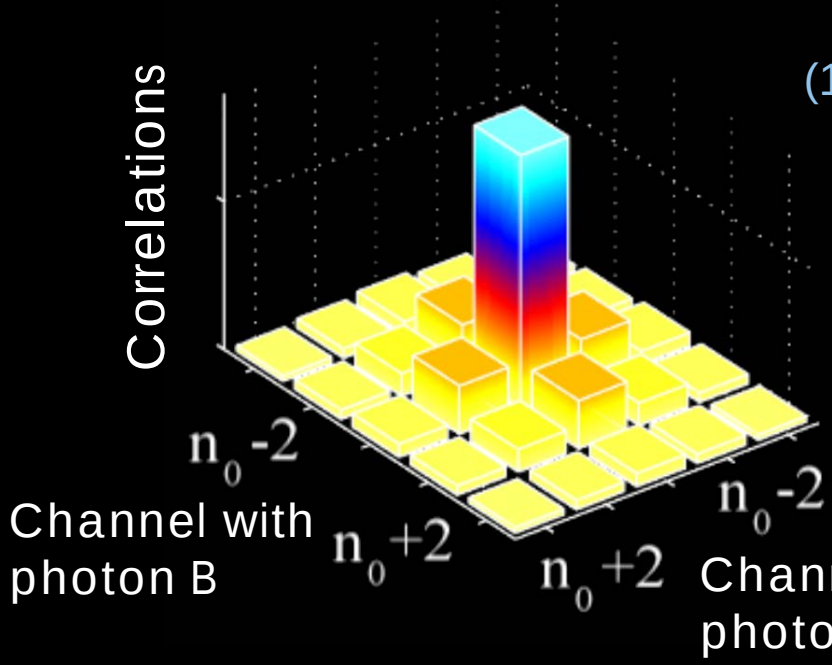
Solntsev et al., PRX 4, 031007 (2014)



LASER AND TWO PHOTONS ON A CHIP

Results

Theory

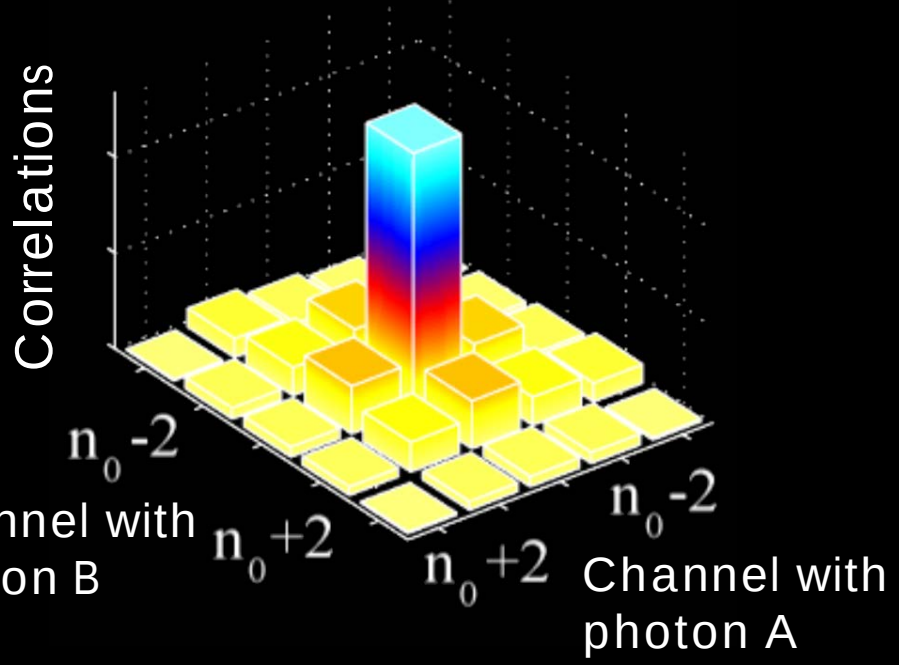


Slightly different laser colour

(1 nm wavelength shift)

Entanglement Suppressed!

Experiment

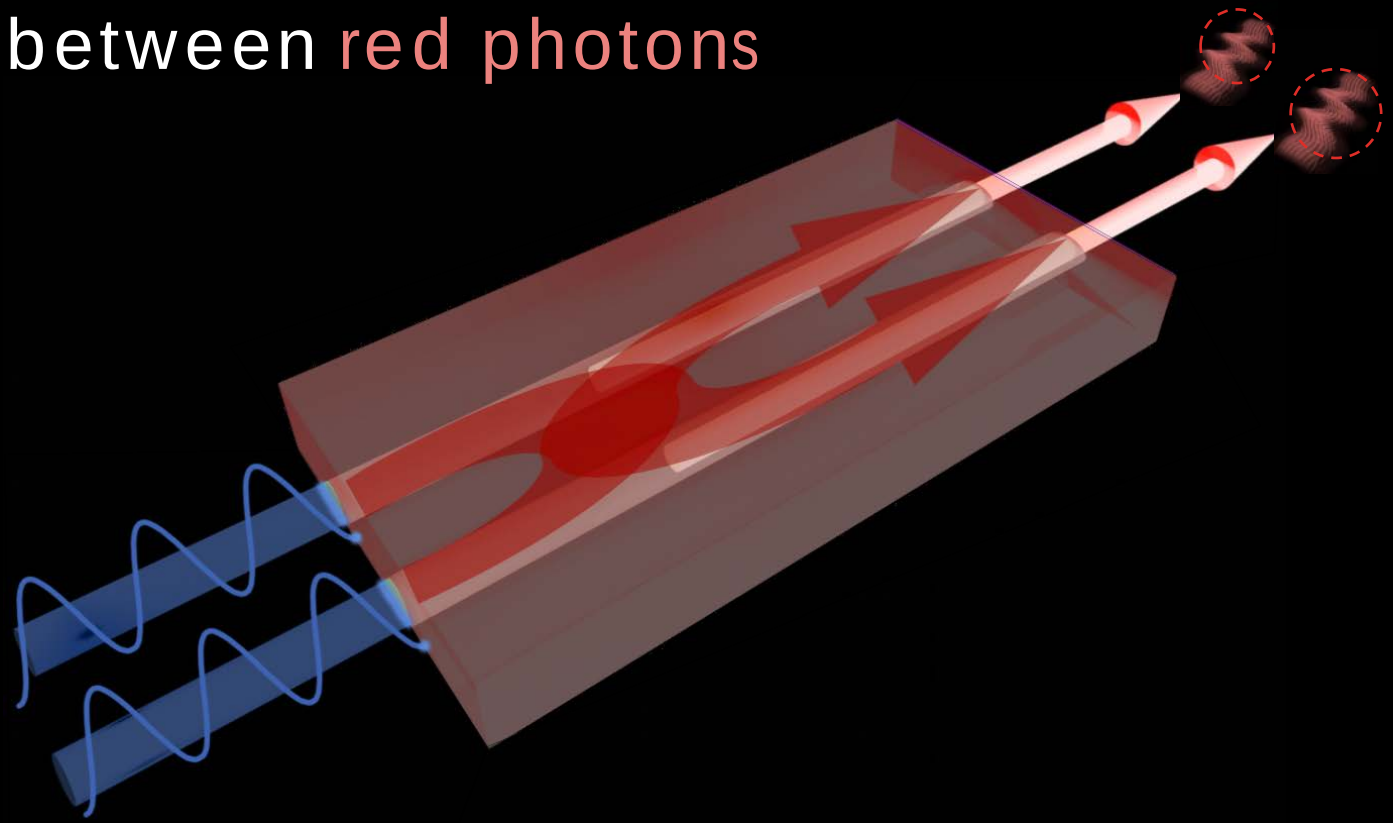


Solntsev et al., PRL 108, 023601 (2012)

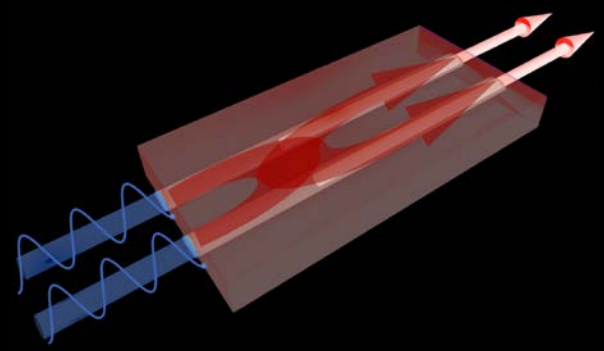
Solntsev et al., PRX 4, 031007 (2014)

2 LASER BEAMS
2 CHANNELS
2 PHOTONS

Controlling the phase between blue laser beams
to tune entanglement between red photons



Setzpfandt, Solntsev et al., Laser & Photonics Reviews 10, 131-136 (2016)

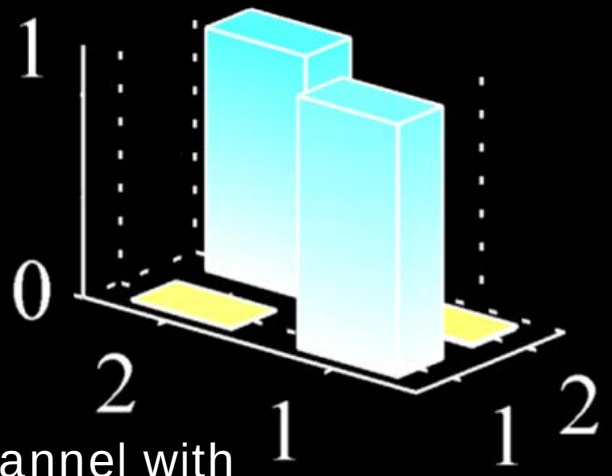


2 LASER BEAMS
2 CHANNELS
2 PHOTONS

Experimental results

Counter-phase laser beams

Entangled photons $|A_1,B_1\rangle + |A_2,B_2\rangle$



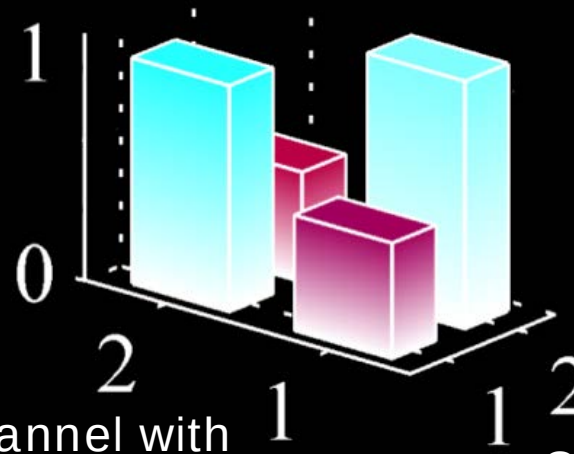
Channel with photon B

Channel with photon A

Tuning Entanglement!

In-phase laser beams

Entangled photons $|A_1,B_2\rangle + |A_2,B_1\rangle$



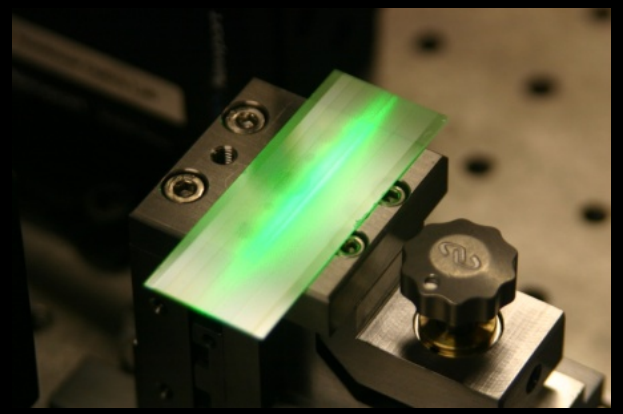
Channel with photon B

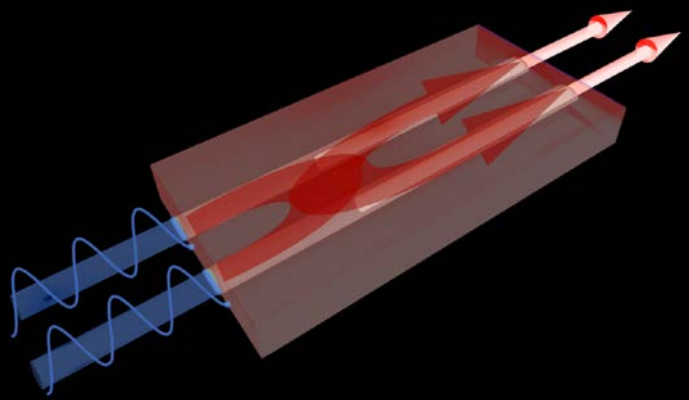
Channel with photon A

Setzpfandt, Solntsev et al., Laser & Photonics Reviews 10, 131-136 (2016)

THE ART OF ENTANGLING LIGHT

- Entanglement is a fantastic resource!
- Tunable source of entangled photons on a nonlinear chip
- Nonlinearity creates and controls entanglement





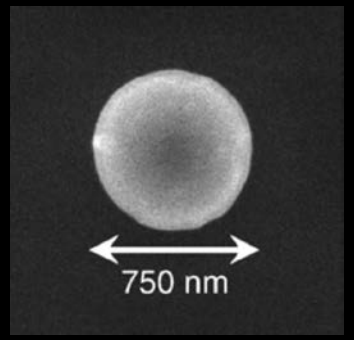
Solntsev et al., Reviews in Physics 2, 19 (2017)

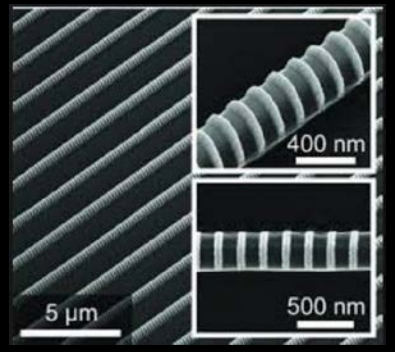
THE ART OF ENTANGLING LIGHT

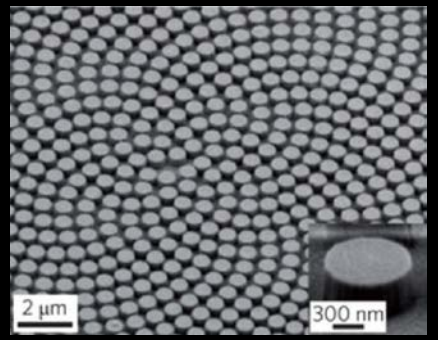
Entanglement and nonlinearity in

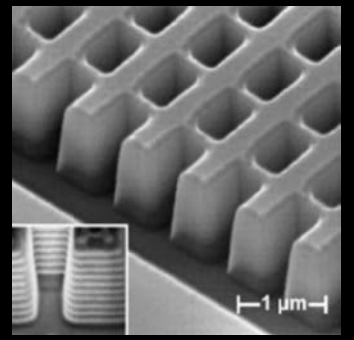
- Nanoparticles
- Nanostructures
- Metasurfaces
- Metamaterials

Quantum light control on the nanoscale



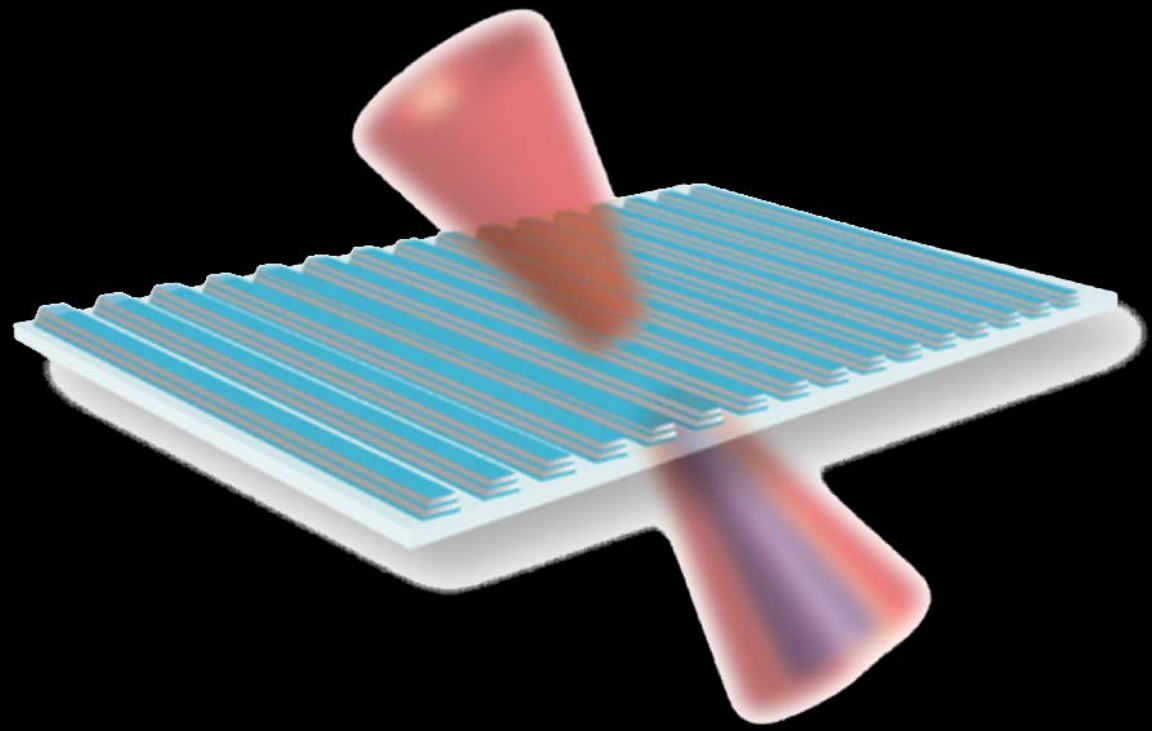






NONLINEAR NANO-PHOTONICS

- Frequency doubling in plasmonic nanostructures
- Changing the colour of light on a tiny scale
- Interplay of Electric and Magnetic Resonances
- Controlling the properties of emitted light



Courtesy of Vladimir Shalaev

NONLINEAR NANO-RESONATORS

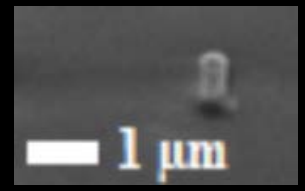
- Nonlinear optical frequency doubling in AlGaAs nanodisks

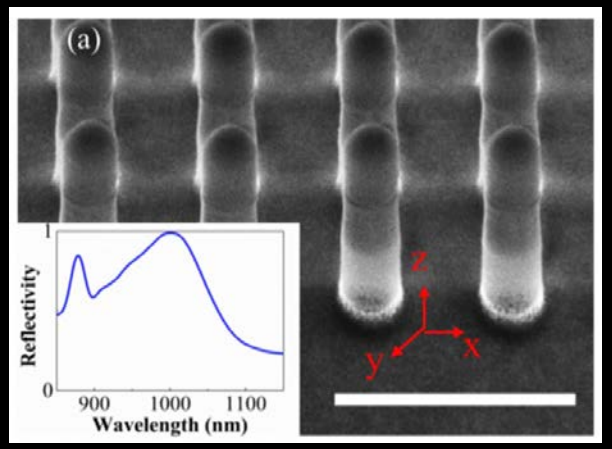
Research Article | Vol. 24, No. 14 | 11 Jul 2016 | OPTICS EXPRESS 15965
Optics EXPRESS

Monolithic AlGaAs second-harmonic nanoantennas

V. F. Gili,[1] L. Carletti,[2] A. Locatelli,[2] D. Rocco,[2] M. Finazzi,[3] L. Ghirardini,[3] I. Favero,[1] C. Gomez,[4] A. Lemaître,[4] M. Celebrano,[3] C. De Angelis,[2] and G. Leo[1,*]

10^{-4} SHG efficiency





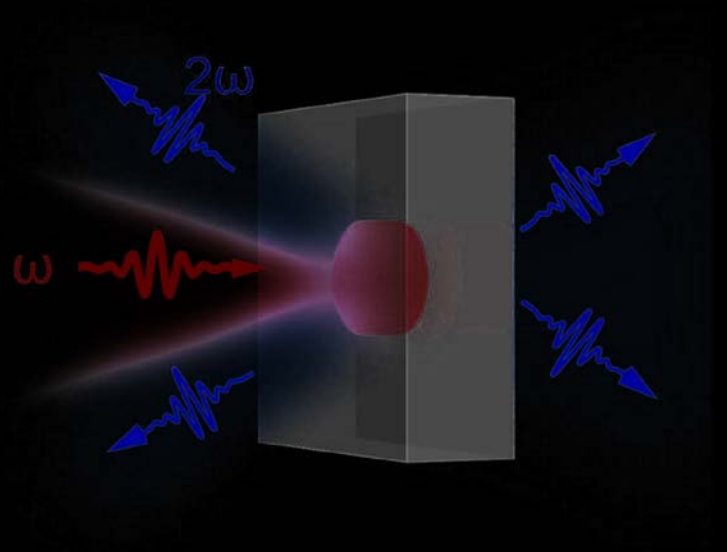
Nano Lett., **2016**, *16* (9), pp 5426–5432

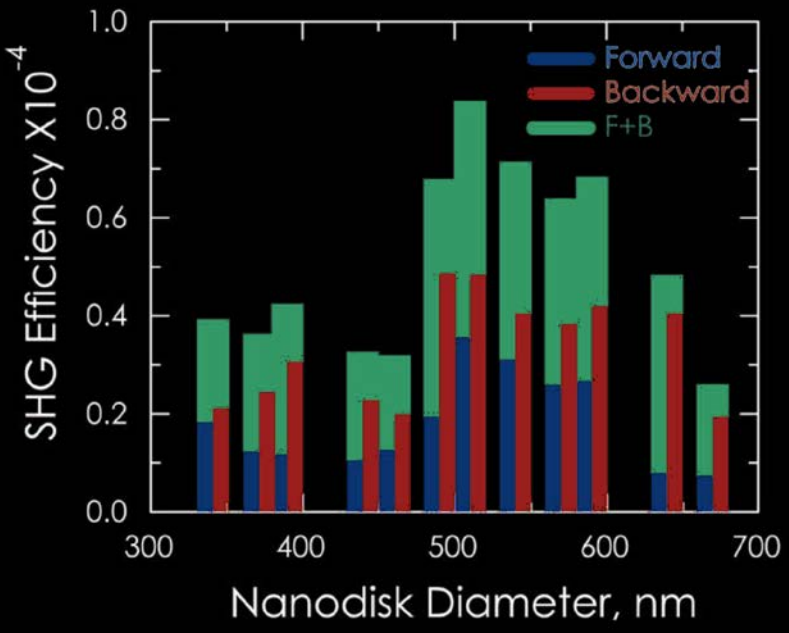
Resonantly Enhanced Second-Harmonic Generation Using III–V Semiconductor All-Dielectric Metasurfaces

Sheng Liu*†, Michael B. Sinclair†, Sina Saravi§, Gordon A. Keeler†, Yuanmu Yang†‡, John Reno†‡, Gregory M. Peake†, Frank Setzpfandt§, Isabelle Staude§, Thomas Pertsch§, and Igal Brener*†‡

NONLINEAR NANO-RESONATORS

- Nonlinear optical frequency doubling in AlGaAs nano-disk
- 10^{-4} efficiency
- Control of direction and polarization



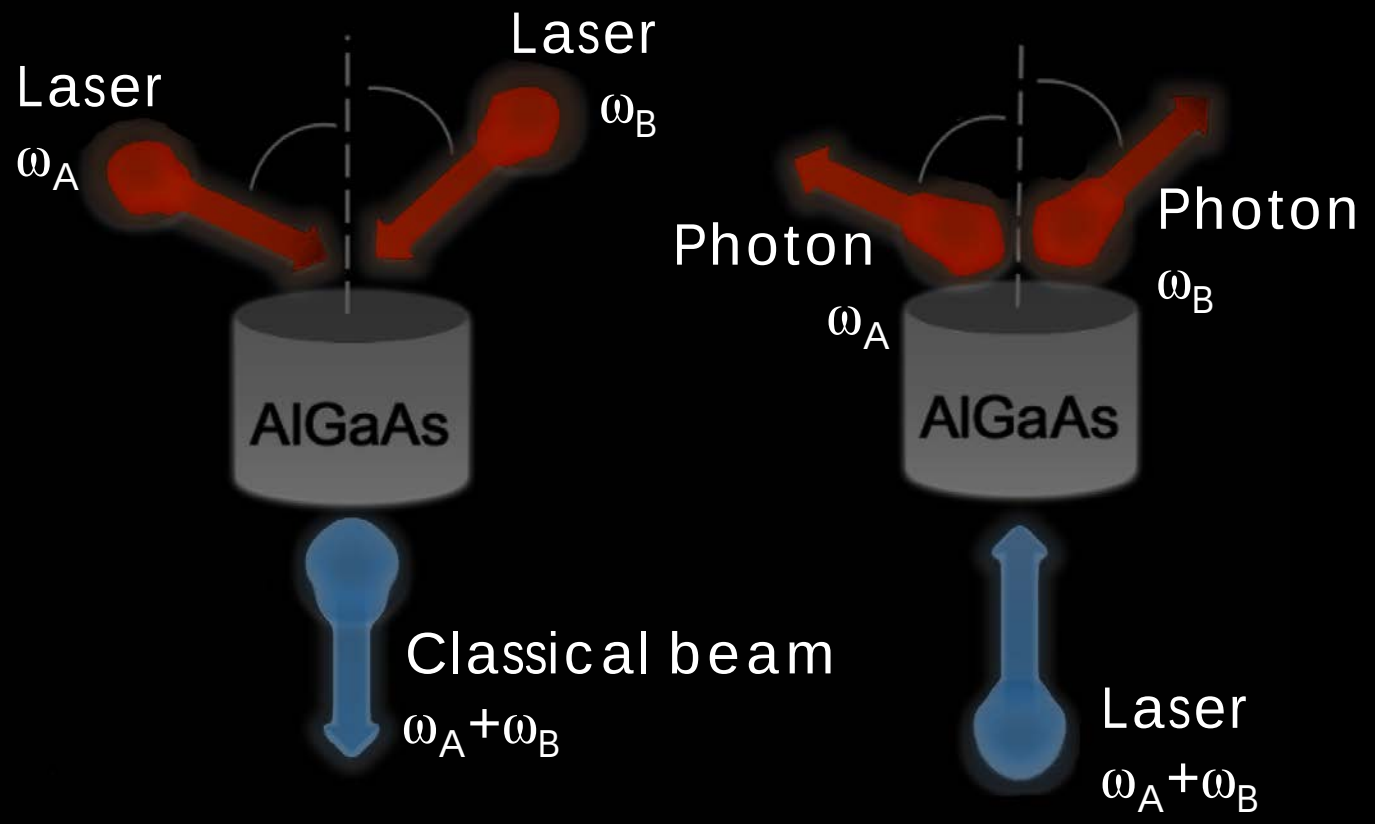


Nano Lett. 16, 7191−7197 (2016)

NONLINEAR NANO-RESONATORS

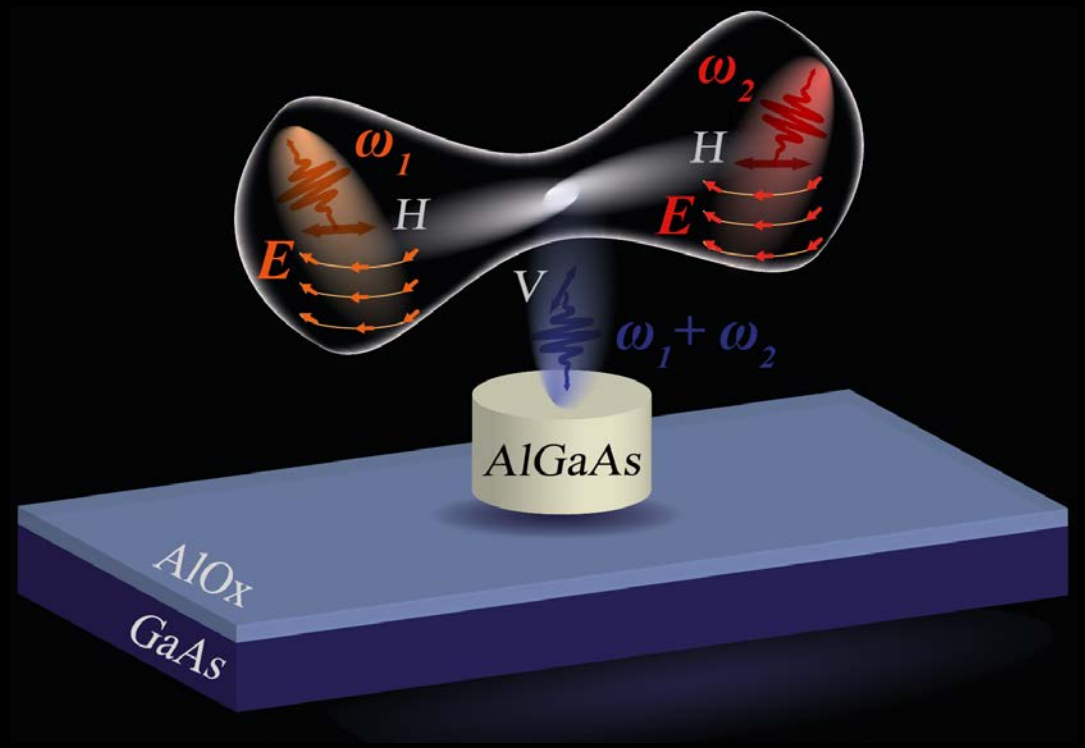
- Classical nonlinear processes can be used to predict quantum photon-pair generation

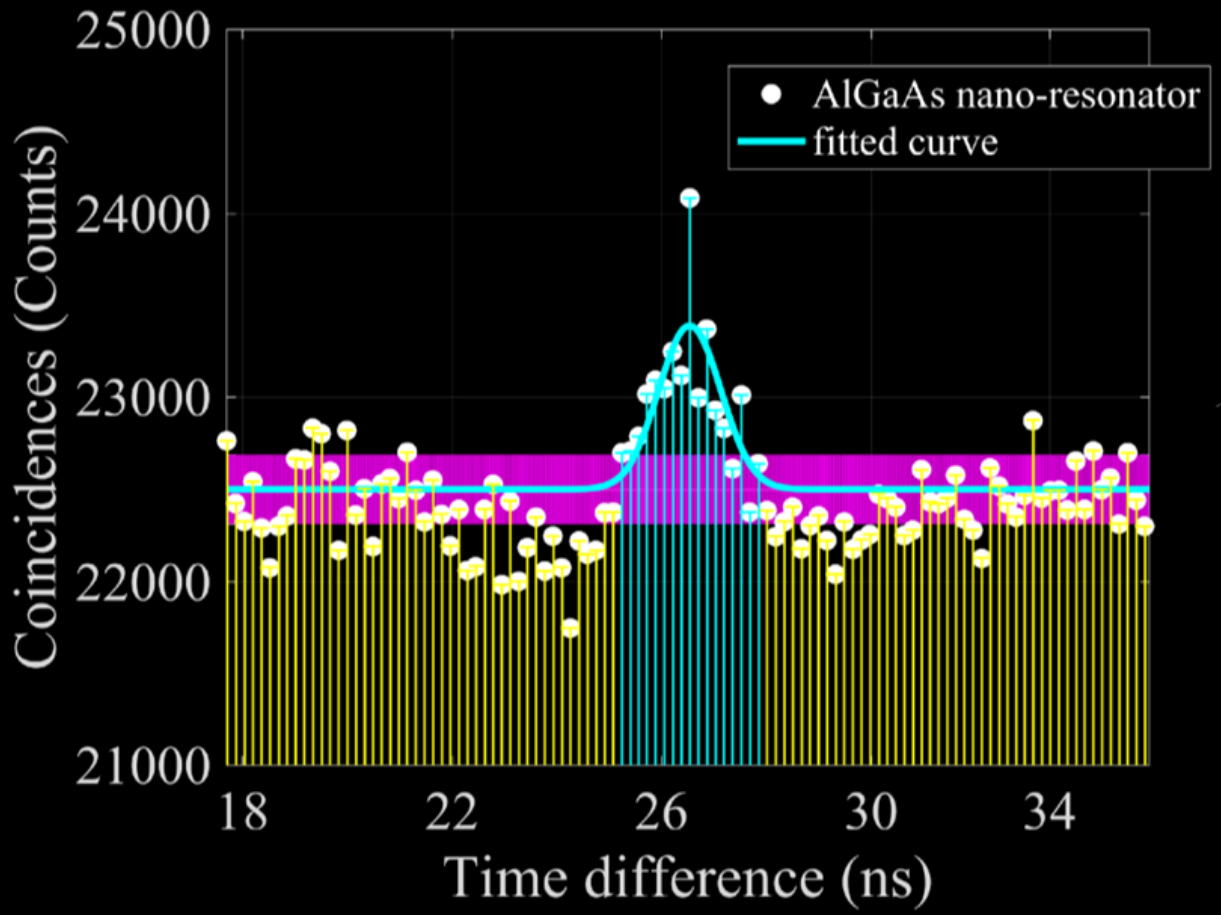
- Predicting up to 10^5 Hz photon-pair rate
- First nanoscale nonlinear entangled photon generator



Solntsev et al., Frontiers in Optics, FF1C.5 (2016)

NONLINEAR NANO-RESONATORS



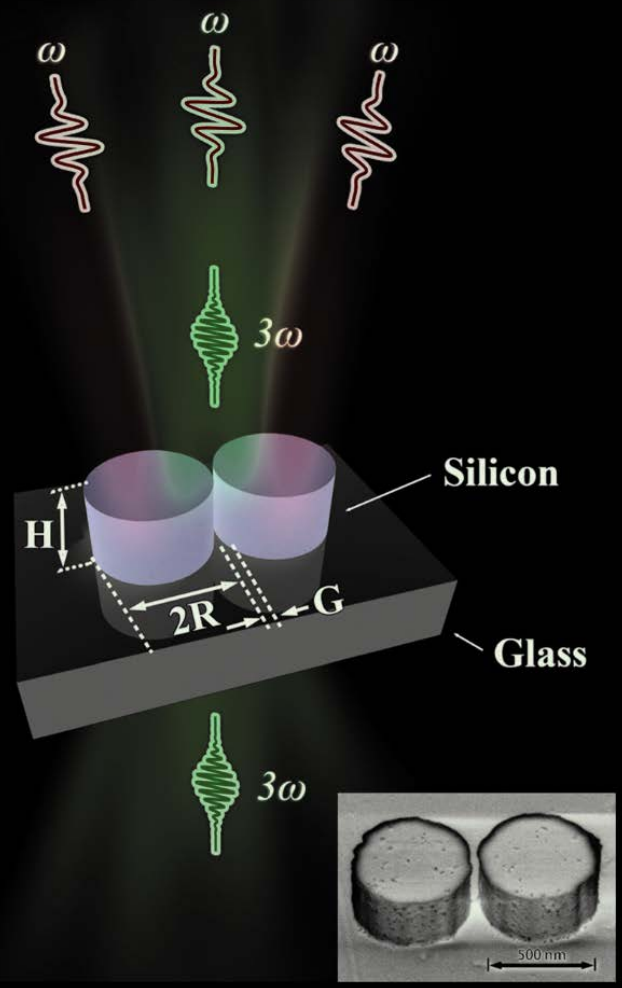


Marino, Solntsev et al., CLEO accepted (2018)

NONLINEAR NANO-RESONATORS

- Nonlinear optical frequency tripling in silicon nano-disks
- 10^{-6} efficiency
- Control of direction and polarization

- Uses much more common type of optical nonlinearity
- Can photon pairs be efficiently generated here?

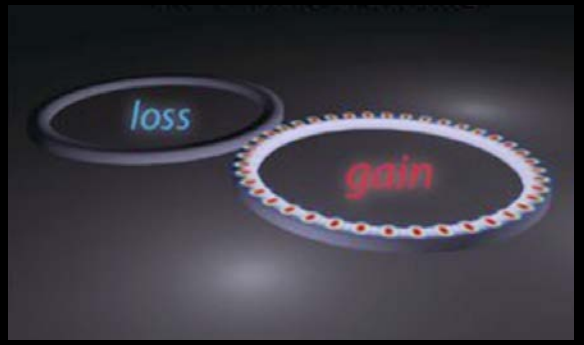


Nanoscale .1039/c6nr09702b (2017)

PLASMONICS

- Plasmonics uses metals
- Optical loss is high
- Tricks to make loss useful

Optical loss can help get single-mode lasing



Science 346, 975–978 (2014)

PLASMONICS

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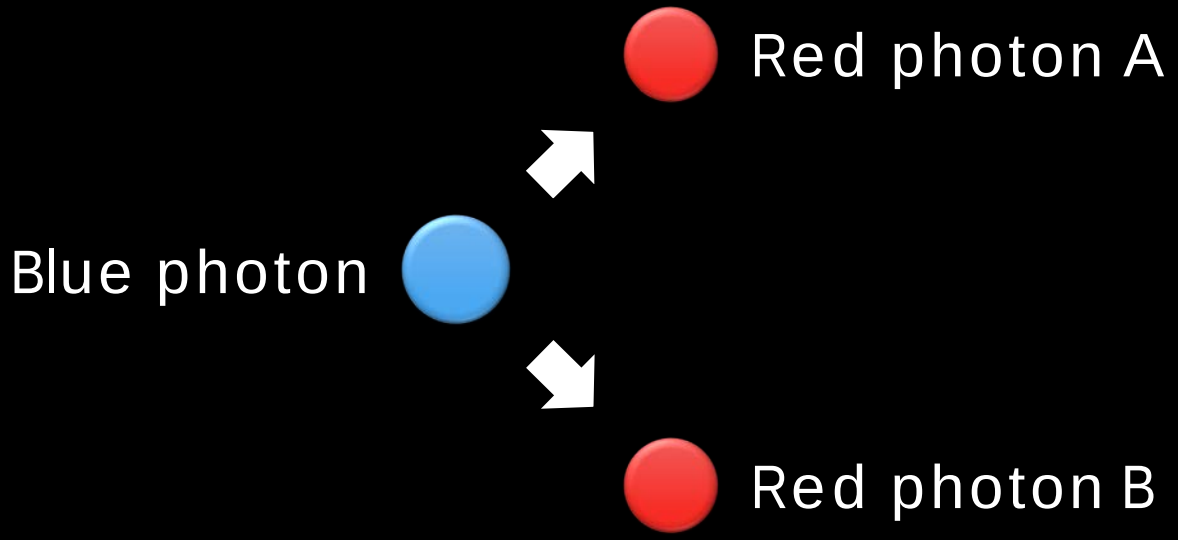
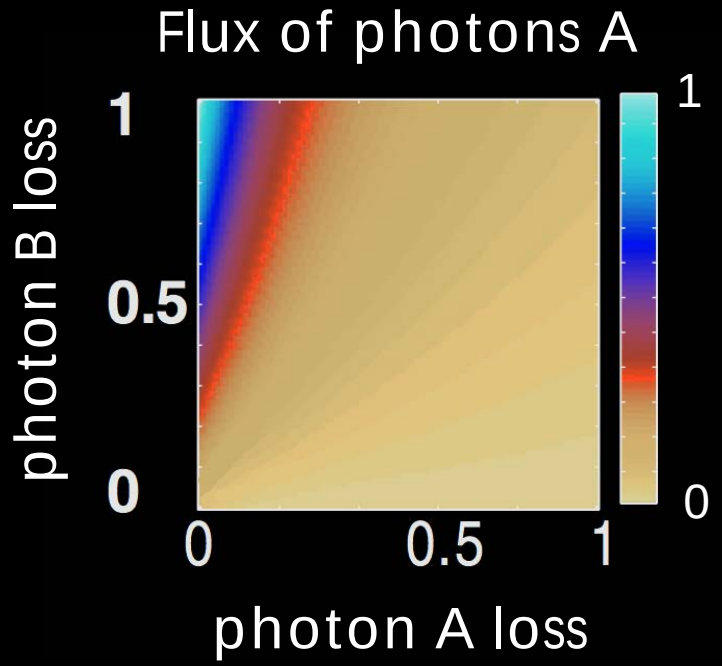
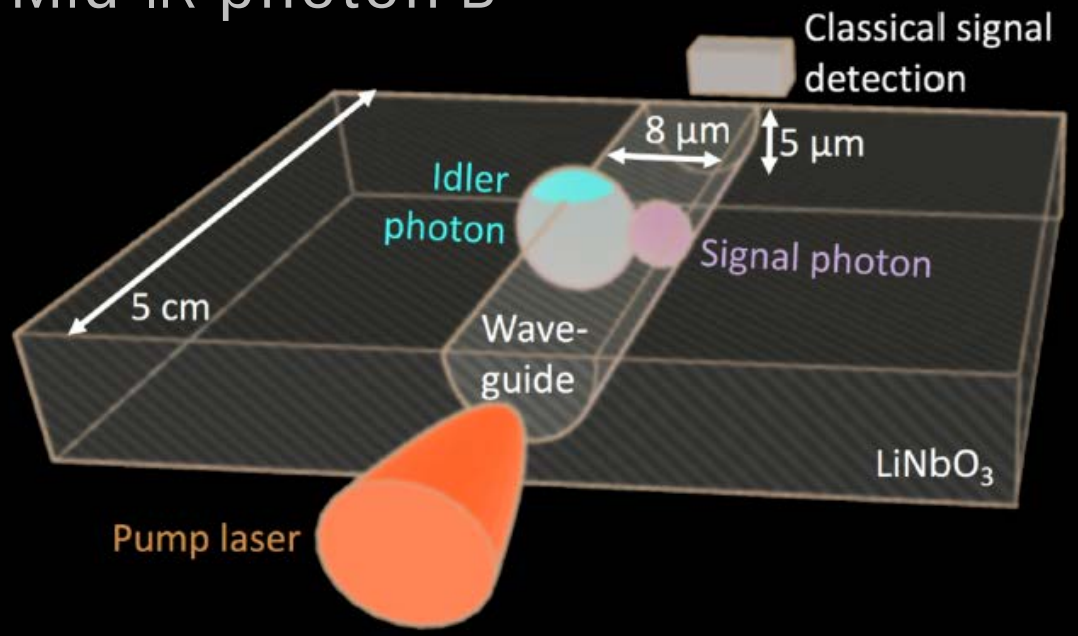


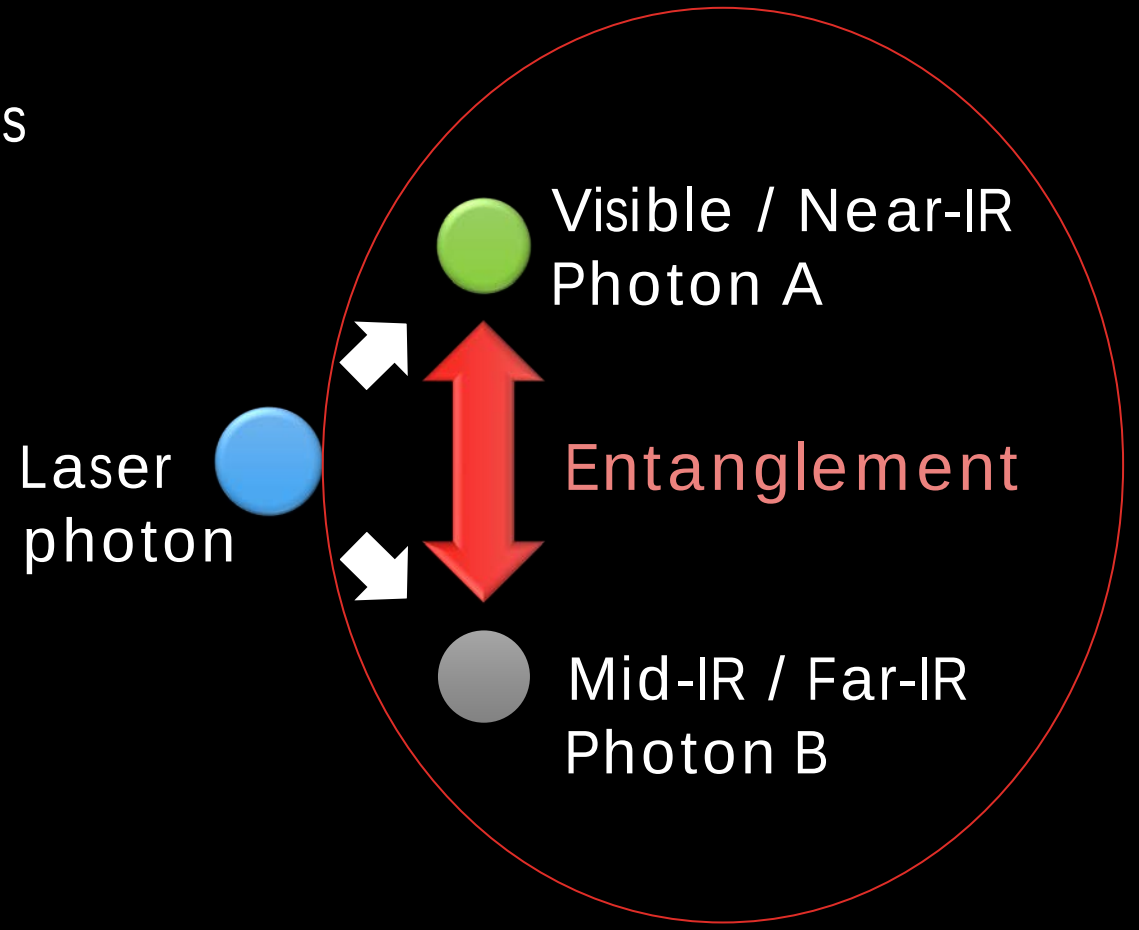


Antonosyan, Solntsev, Sukhorukov
PRA 90 043845 (2014)
Photonics Research 6, A6-A9 (2018)

SPDC SPECTROSCOPY

- Measuring easy-to-detect photon A to figure out how environment affects Mid-IR photon B





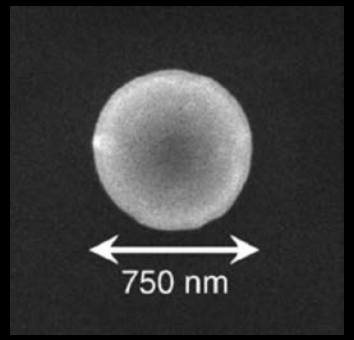
Solntsev et al., APL Photonics 3, 021301 (2018)

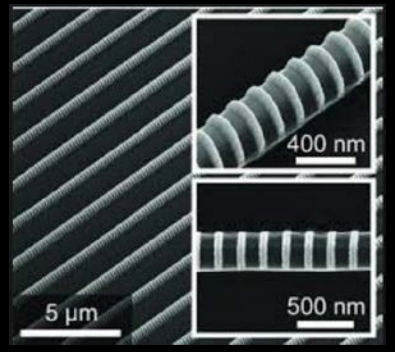
THE ART OF ENTANGLING LIGHT

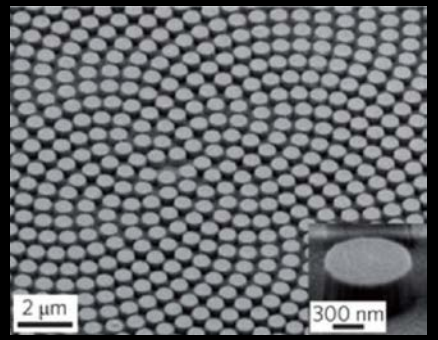
Entanglement and nonlinearity in

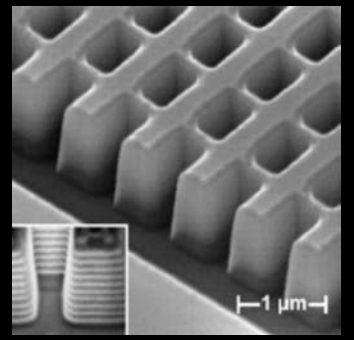
- Nanoparticles
- Nanostructures
- Metasurfaces
- Metamaterials

➢ Quantum light control on the nanoscale
➢ Quantum nonlinear spectroscopy










A A Sukhorukov


Y S Kivshar


D N Neshev


T Persch


A Szameit


G Leo


M Rahmani


C Xiong


C De Angelis

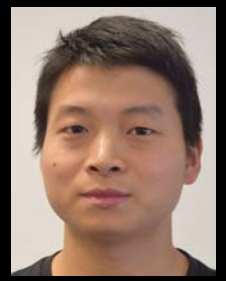

F Setzpfandt


D Antonosyan


J Titchener


K Wang

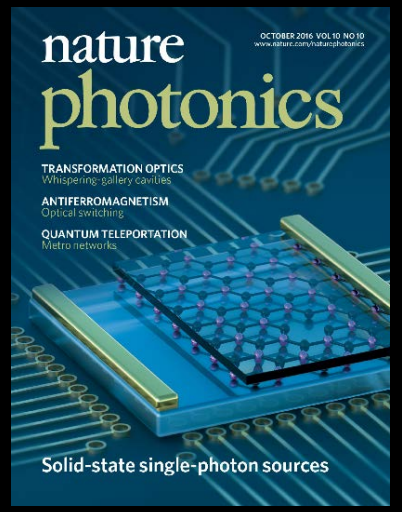

G Marino


H Chen

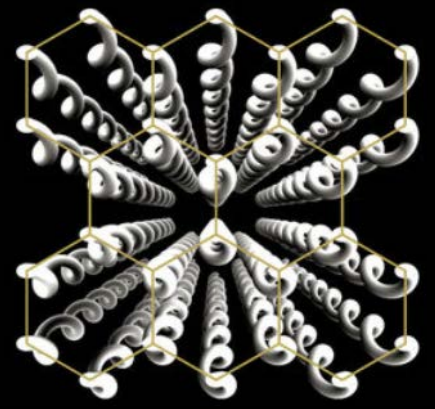
Thank you!

PHOTONIC CIRCUITS FOR DETERMINISTIC PHOTON SOURCES BASED ON 2D MATERIALS

I Aharonovich



- New emitters in 2D materials – hexagonal Boron Nitride
- Promising applications:
  - Quantum emission at high temp (Kianinia et al., ACS Phot 2016)
  - Integration with tapered fibers (Schell et al., ACS Photon 2017)
  - Plasmonic cavity arrays (Tran, Wang, Xu et al., Nanolett 2017)

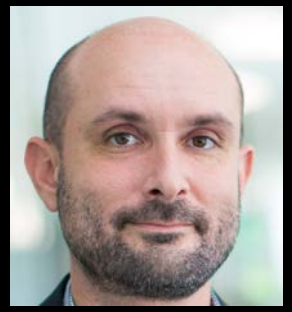


Nature 496, 196–200 (2014)

A Szameit

Vision: a fully integrated 2D quantum system on a single chip

METASURFACES FOR APPLICATIONS IN TELECOM AND MEDICINE



C Poulton

M Lapine

- Novel designs and concepts
- Effective medium theory / modelling
- Tunable (reconfigurable) metamaterials

cylite

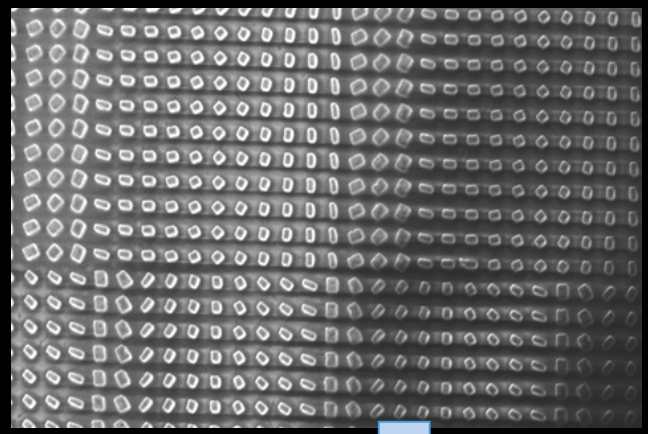
Designing and testing metasurfaces with required response

METASURFACES FOR QUANTUM OPTICS


A A Sukhorukov


Y S Kivshar


D N Neshev



- A metasurface that will allow EM-CCD cameras to see multiphoton quantum light
- Full quantum tomography: entanglement, purity etc.

Wang et al., arXiv:1804.03494 (2018)

Thank you!

PhD scholarships available