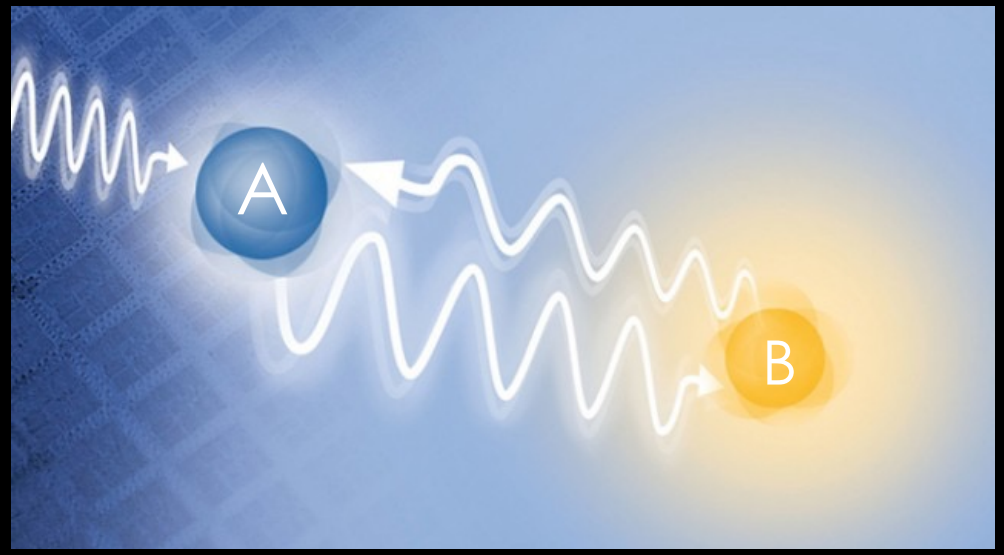
SPONTANEOUS PARAMETRIC DOWN-CONVERSION FROM MICRO- TO NANOSCALE

Alexander Solntsev
University of Technology Sydney

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)

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

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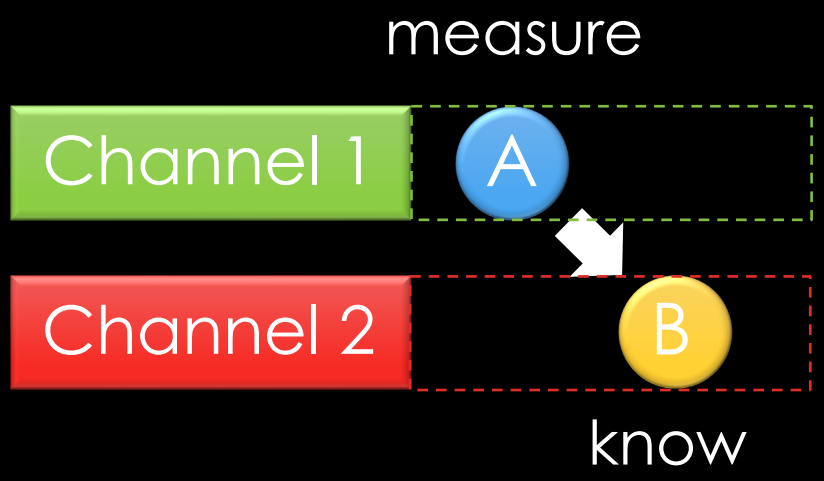

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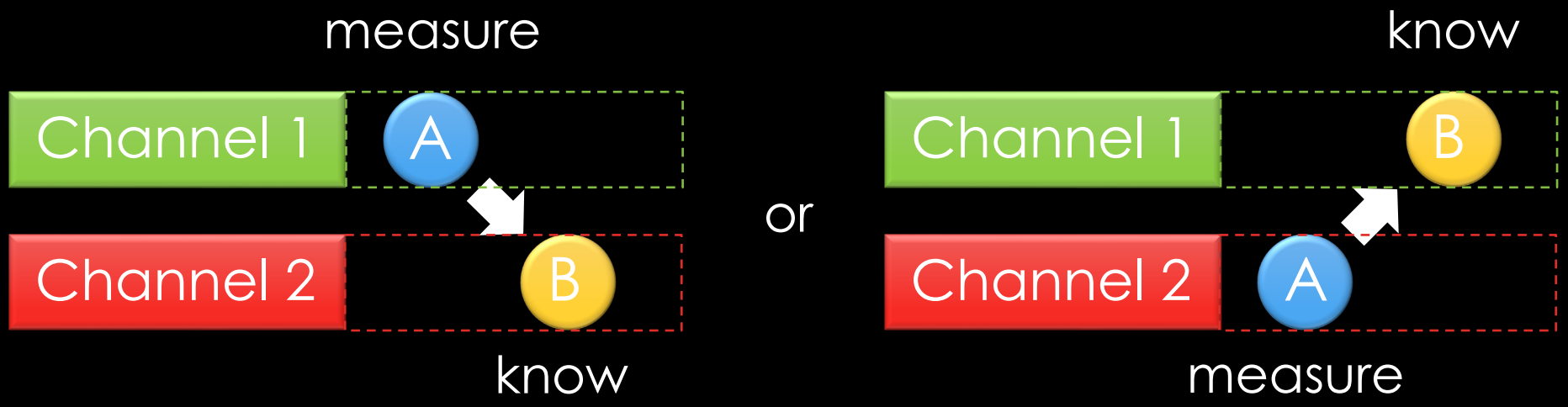


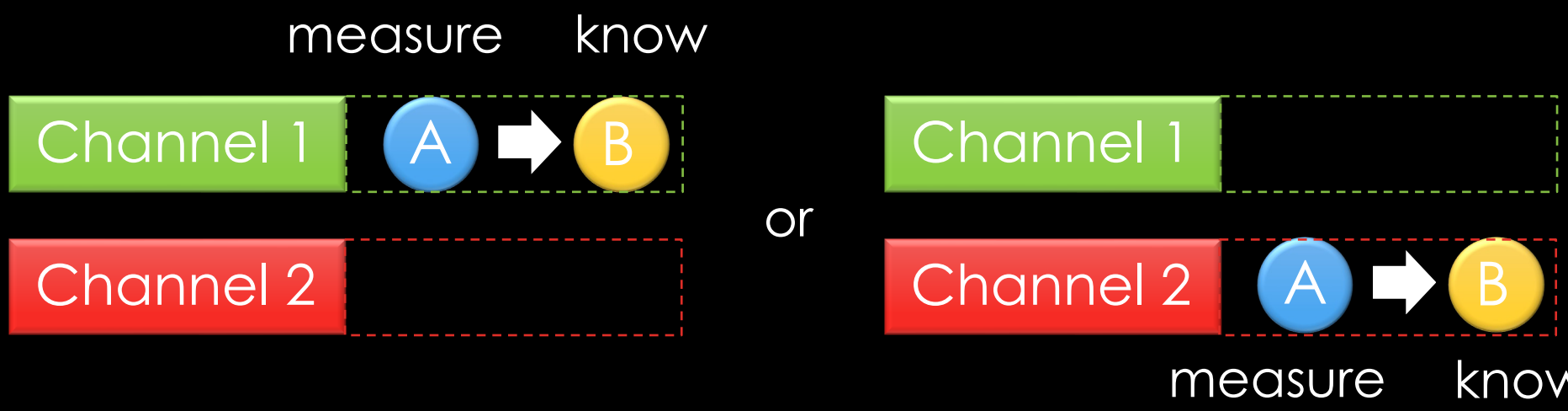
QUANTUM OPTICS

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)

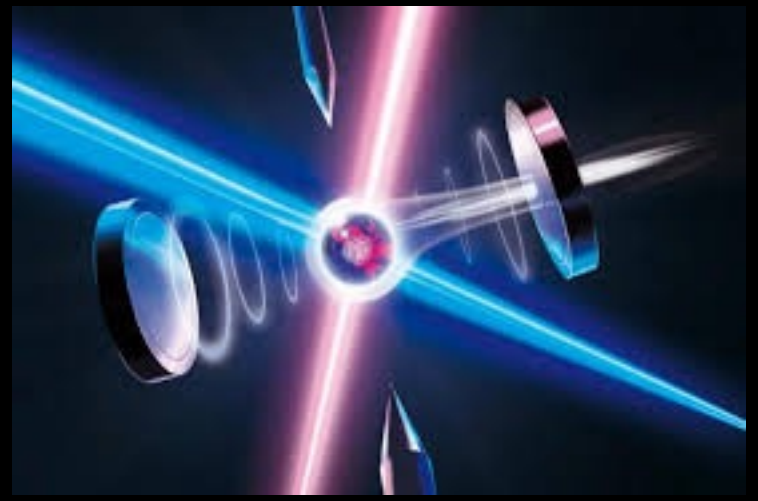


QUANTUM OPTICS

Applications of entanglement

Secure communication

Fast computation



Precise metrology

NONLINEAR OPTICS

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

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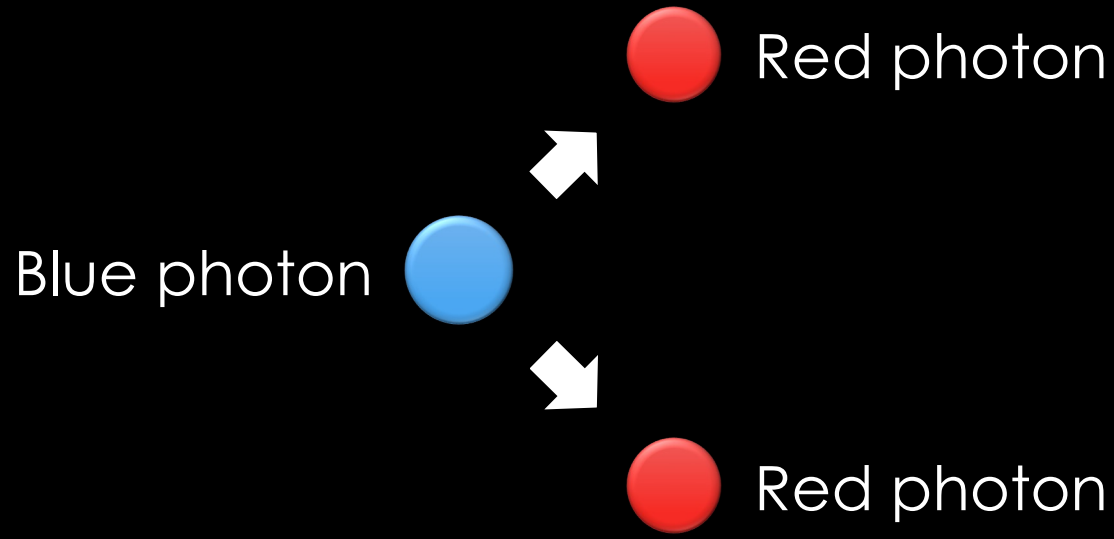

NONLINEAR OPTICS

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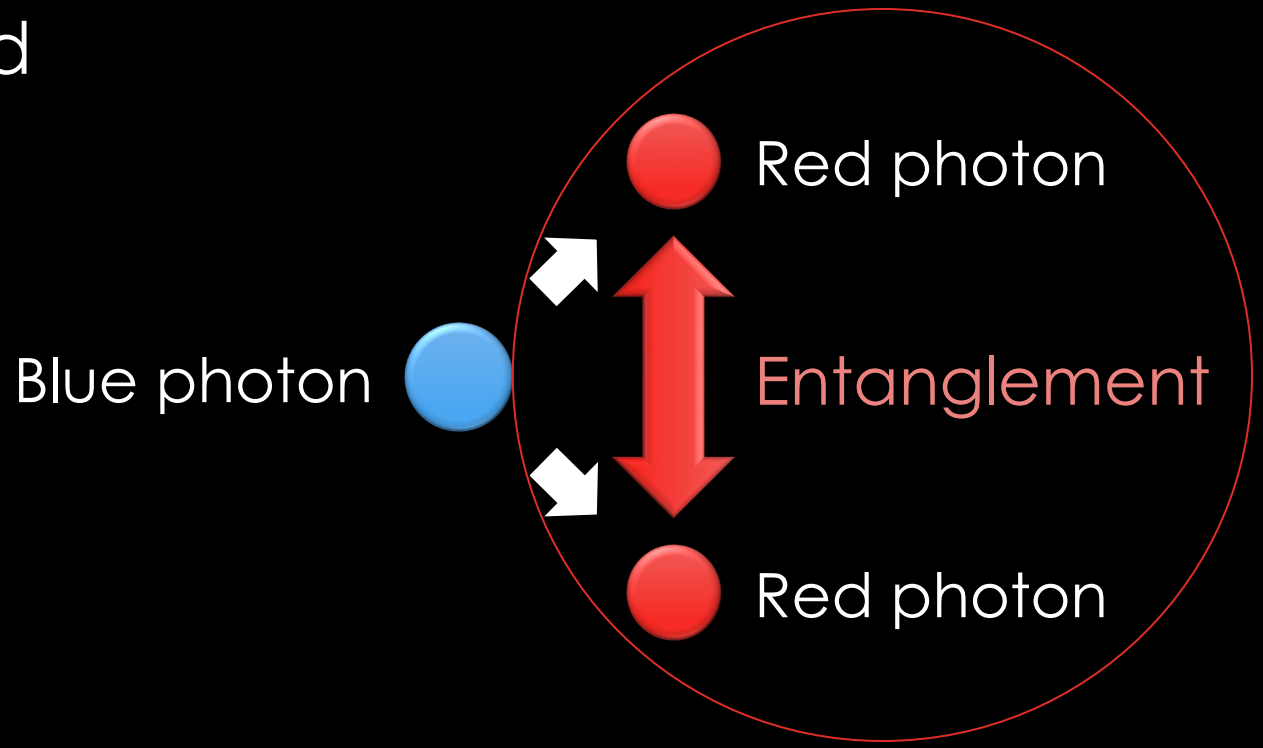
Creating a pair of entangled photons using nonlinearity (SPDC)



NONLINEAR QUANTUM OPTICS

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

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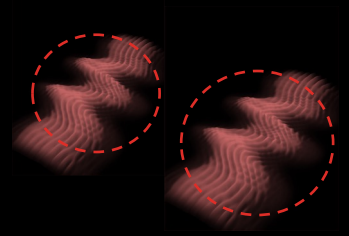
Powerful blue laser



Two red photons

Separated by color

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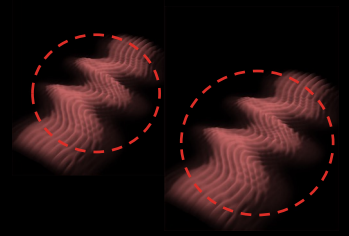

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Can we **control** entanglement with a laser though optical nonlinearity?

NONLINEAR QUANTUM OPTICS

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- On-chip integration

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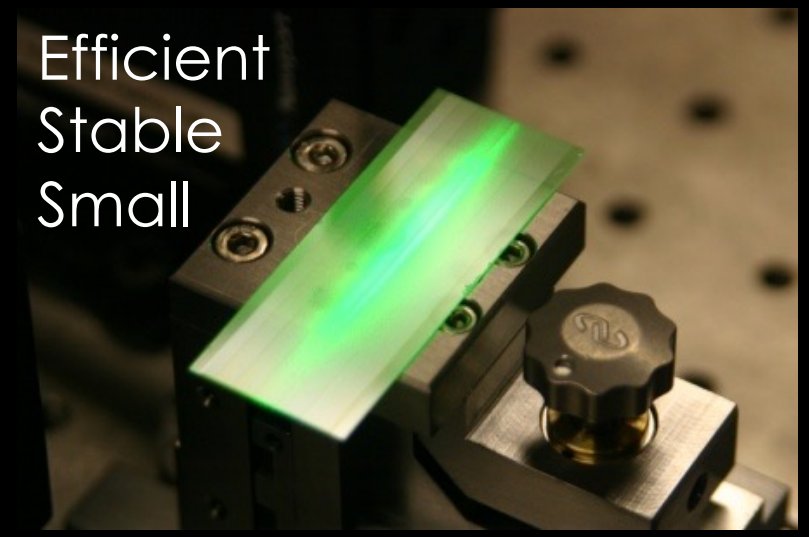
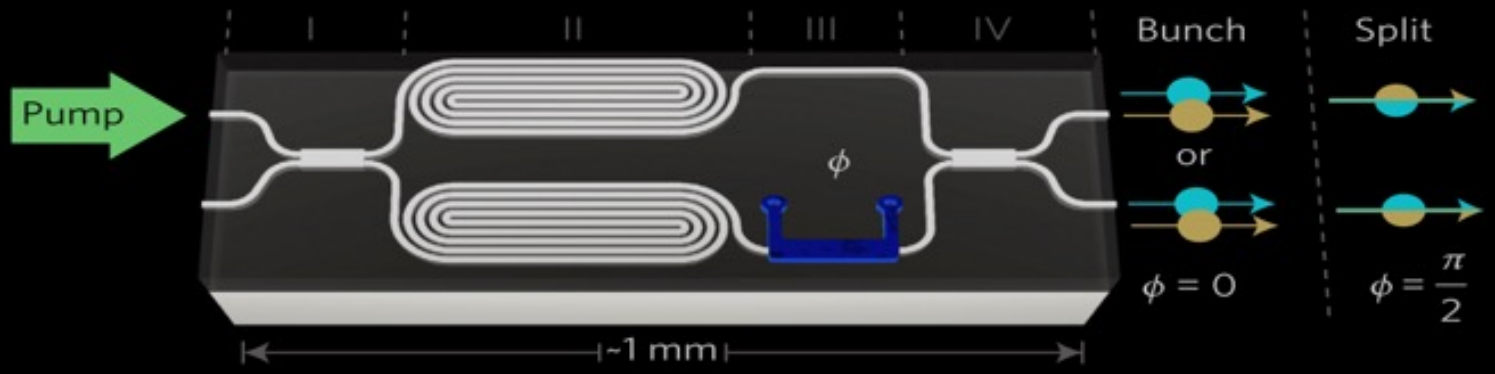
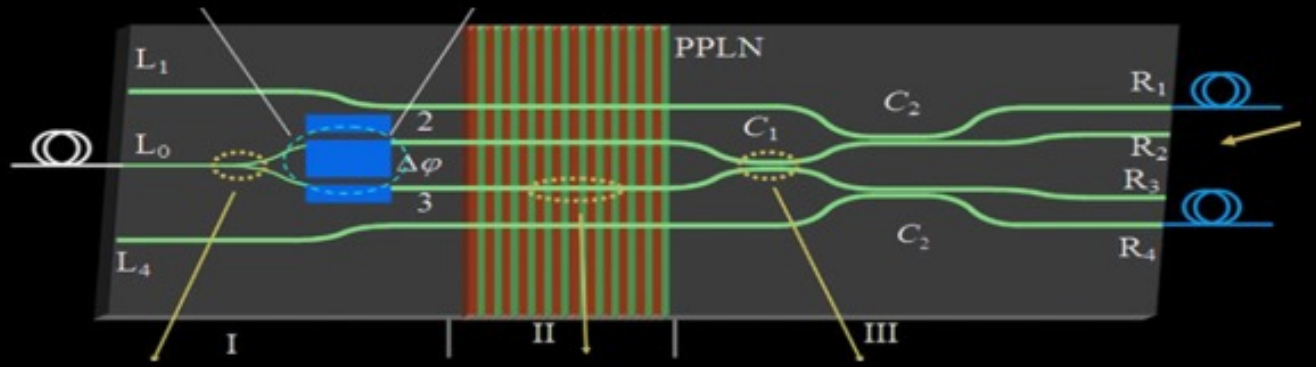


ON-CHIP QUANTUM OPTICS

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



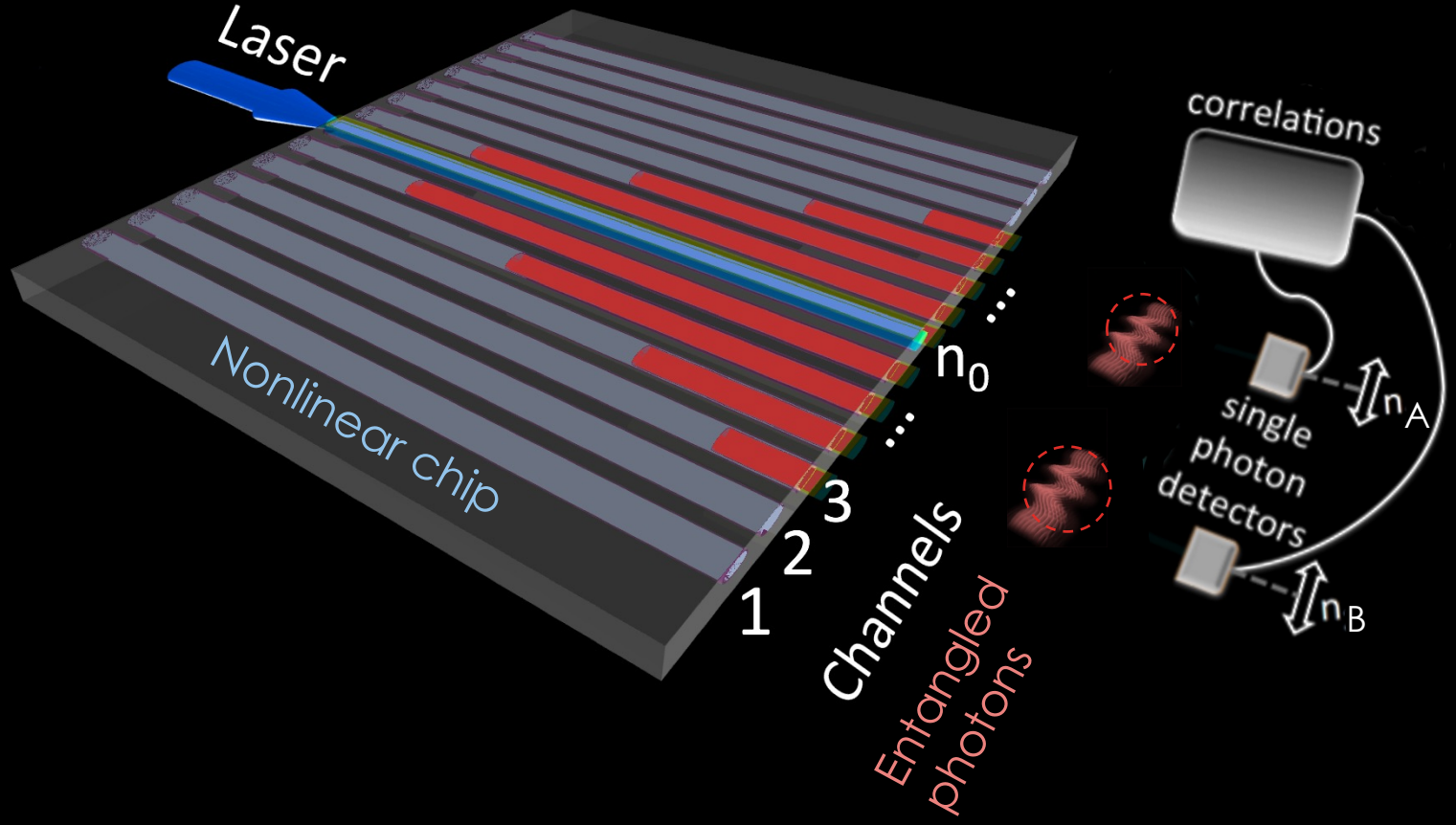
Silverstone et al., Nature Photonics **8**, 104 (2014)

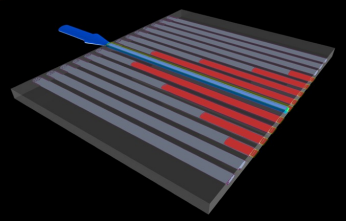


Jin et al., Phys. Rev. Lett, **113**, 103601 (2014)

LASER AND TWO PHOTONS ON A CHIP

Experiment

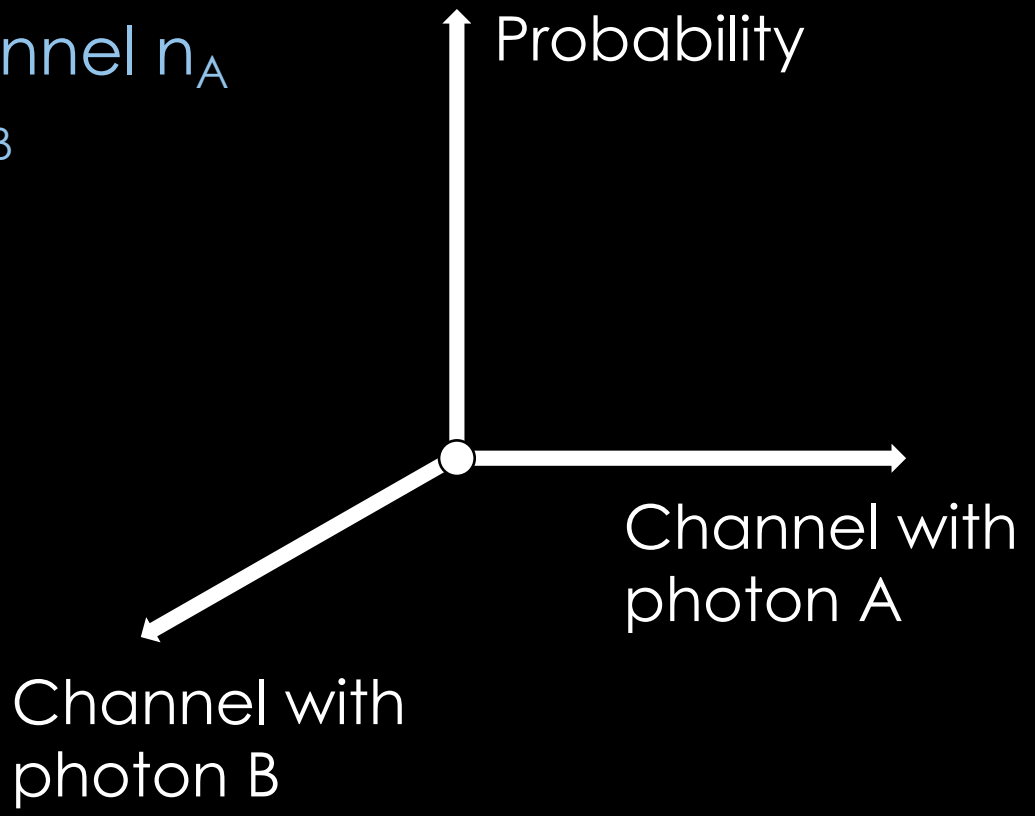


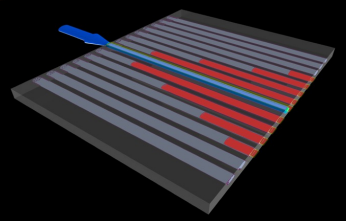


LASER AND TWO PHOTONS ON A CHIP

Correlations

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



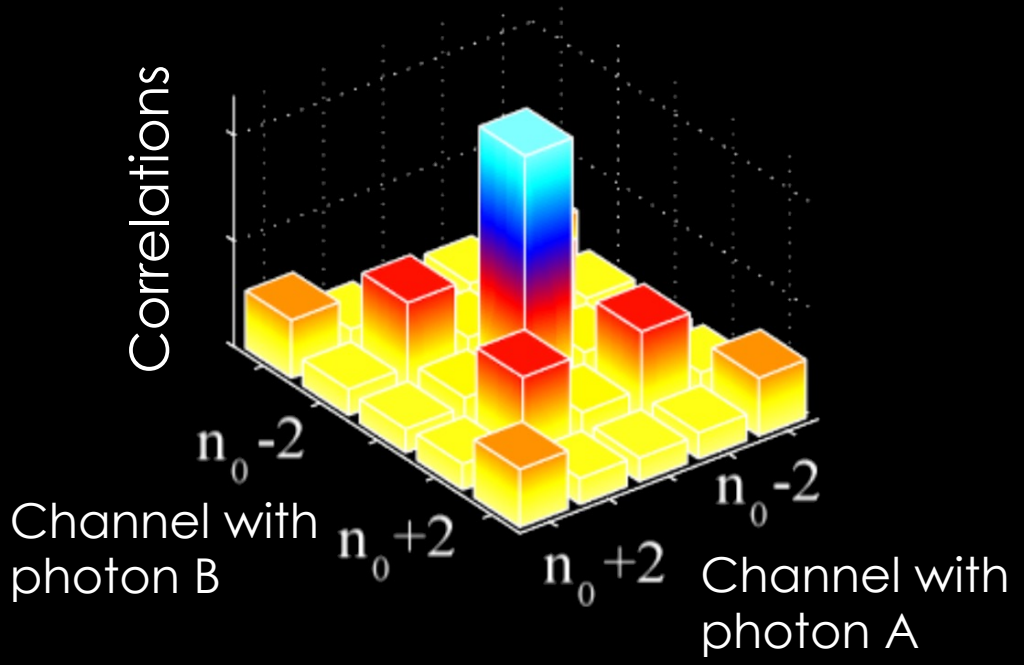


LASER AND TWO PHOTONS ON A CHIP

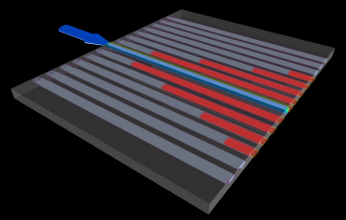
Results

Theory

Entanglement!



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



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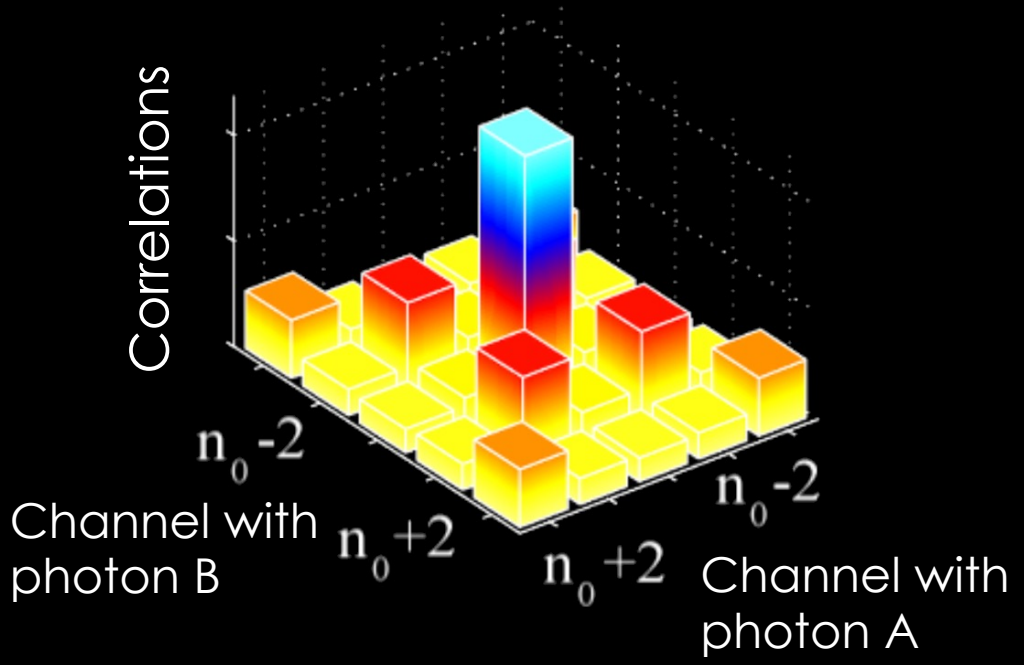

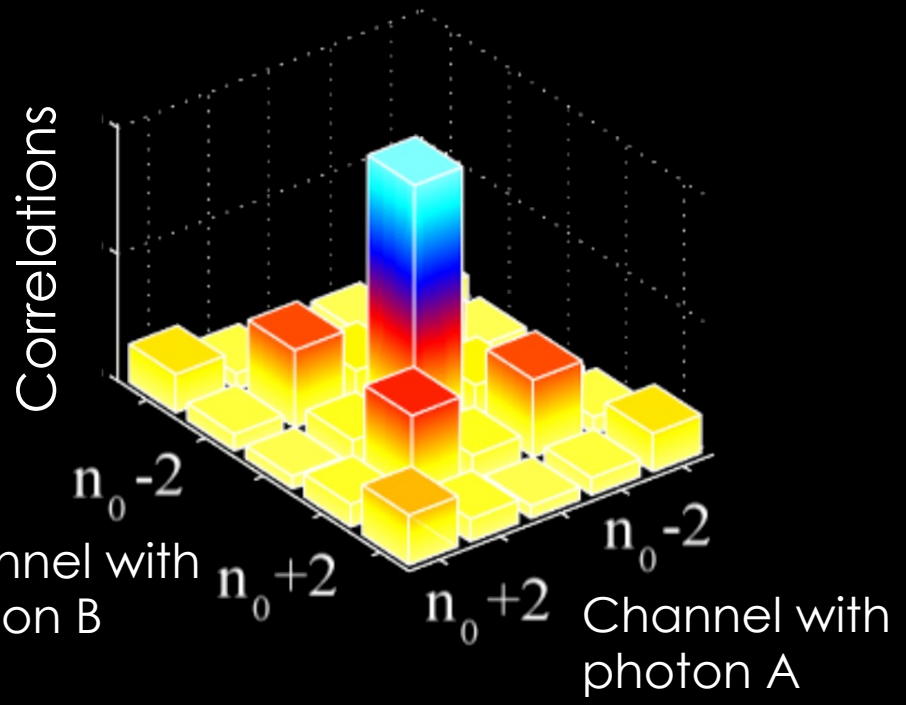

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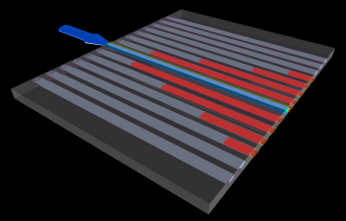
Solntsev et al., PRX 4, 031007 (2014)



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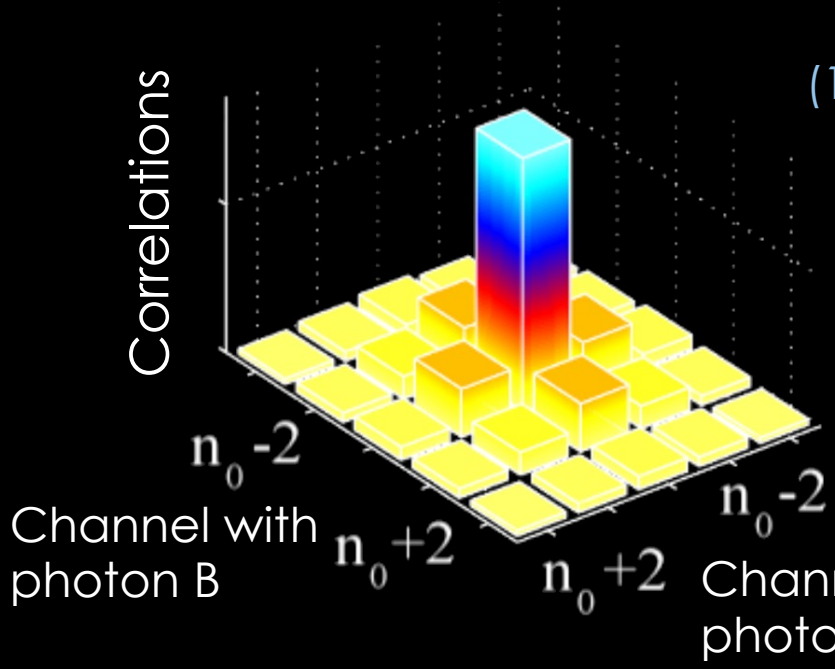
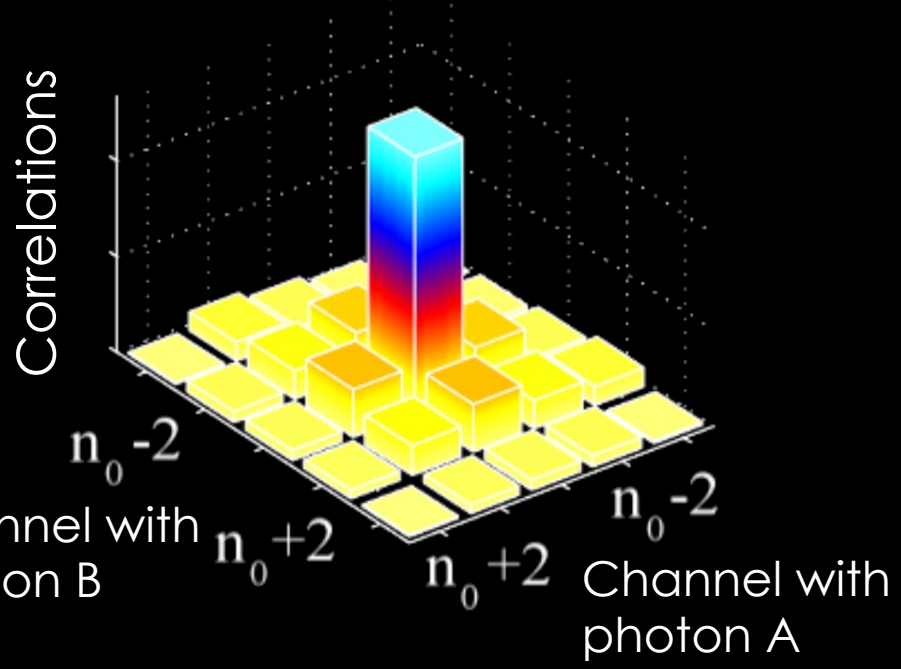


Slightly different laser colour

(1 nm wavelength shift)

Entanglement Suppressed!

Experiment

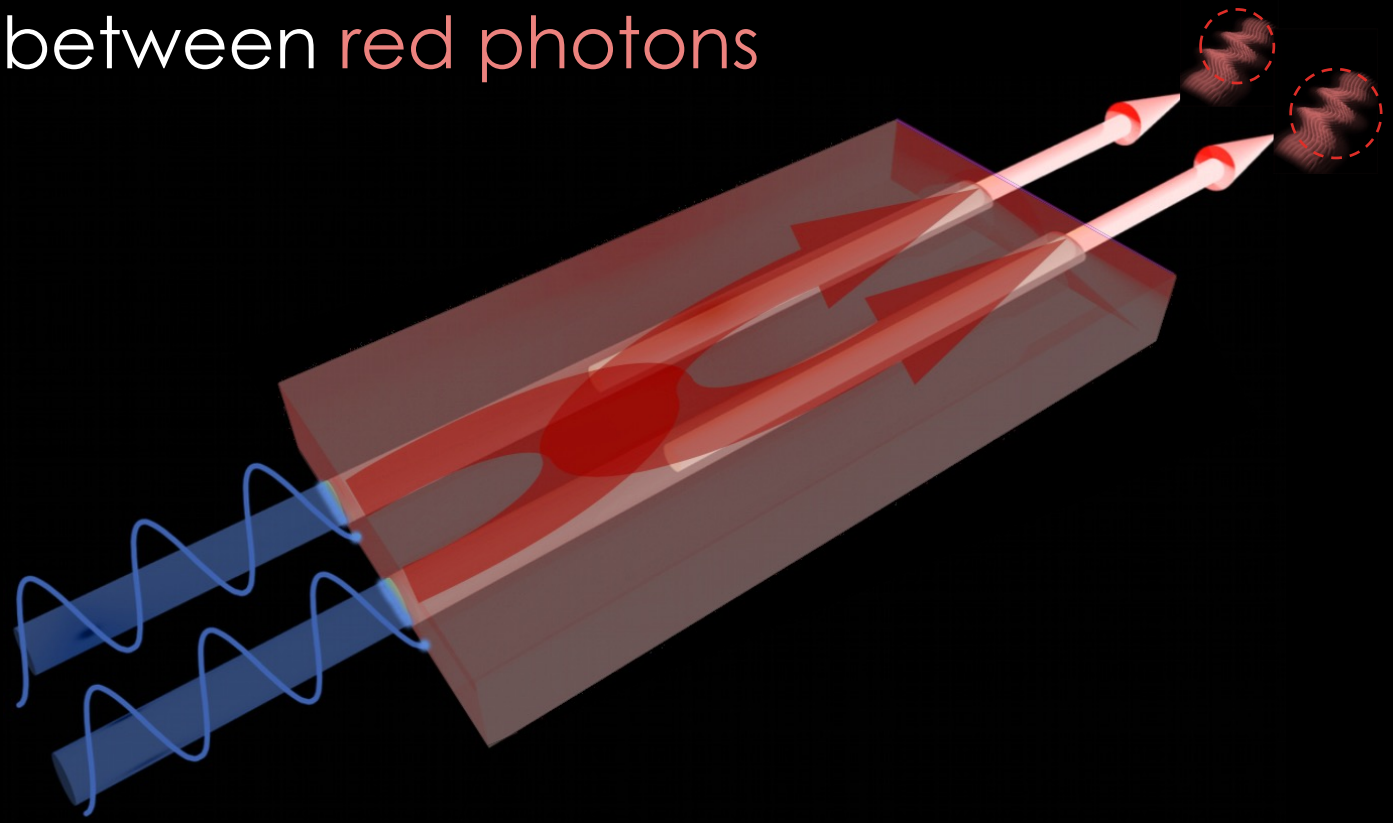


Solntsev et al., PRL 108, 023601 (2012)

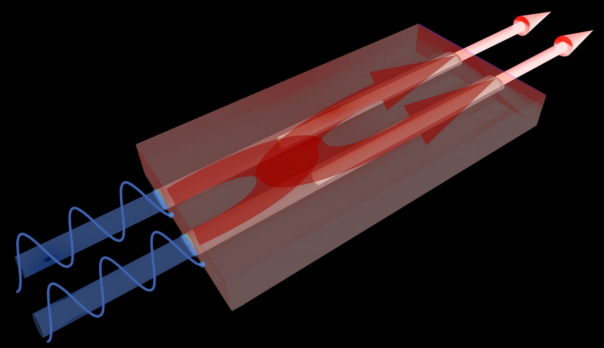
Solntsev et al., PRX 4, 031007 (2014)

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)



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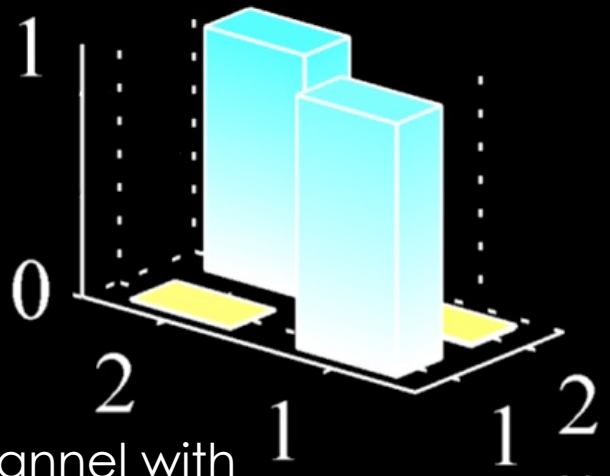
Experimental results

Counter-phase laser beams

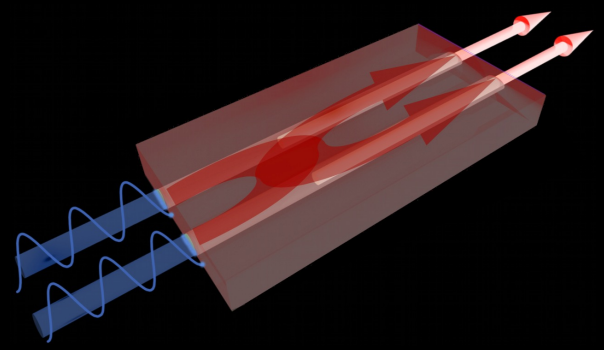
Entangled photons $|A_1,B_1\rangle + |A_2,B_2\rangle$



Channel with photon B

Channel with photon A

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



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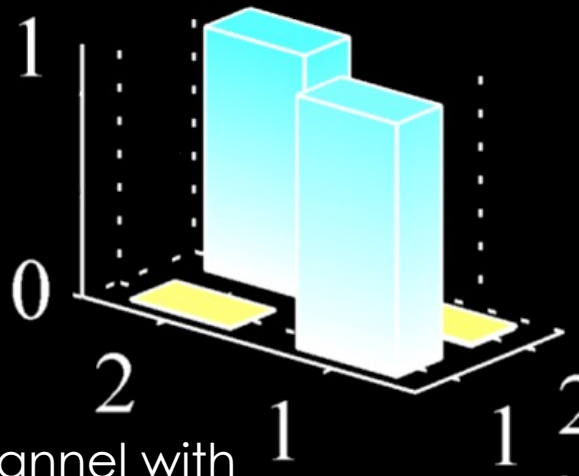

Channel with photon B

Channel with photon A

Tuning Entanglement!

In-phase laser beams

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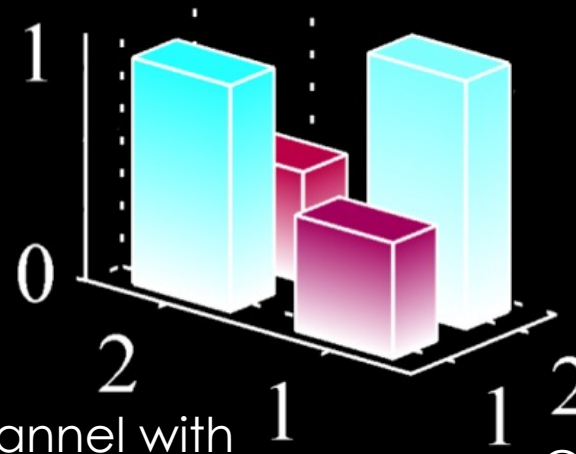


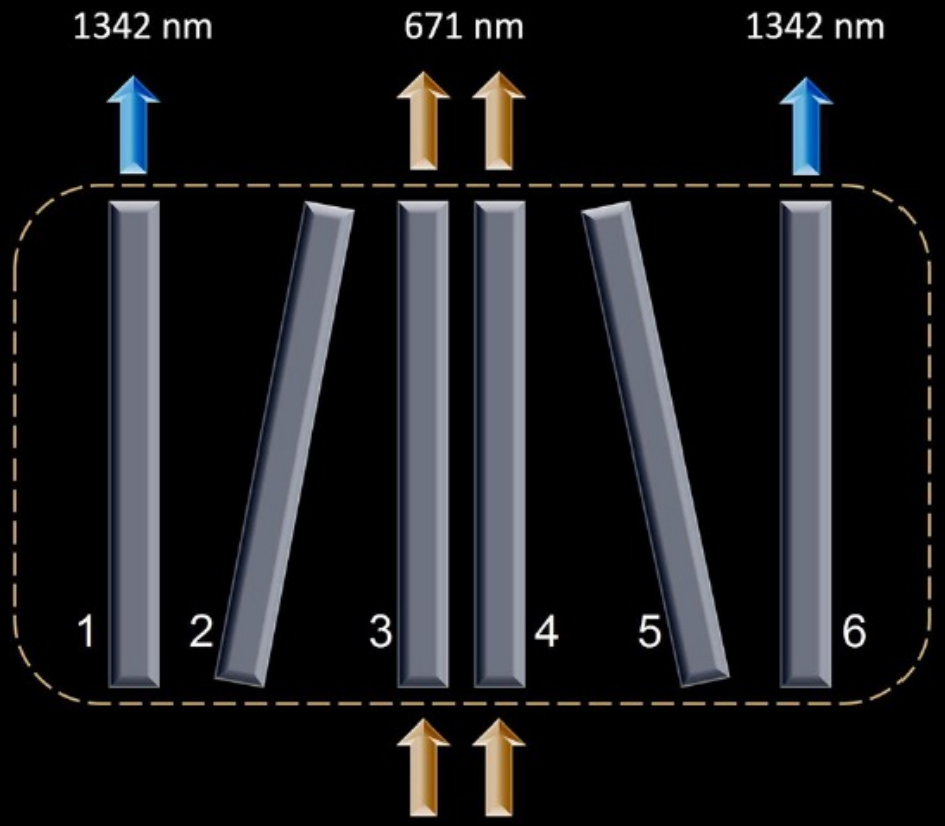
Channel with photon B

Channel with photon A

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

WAVEGUIDE ENGINEERING

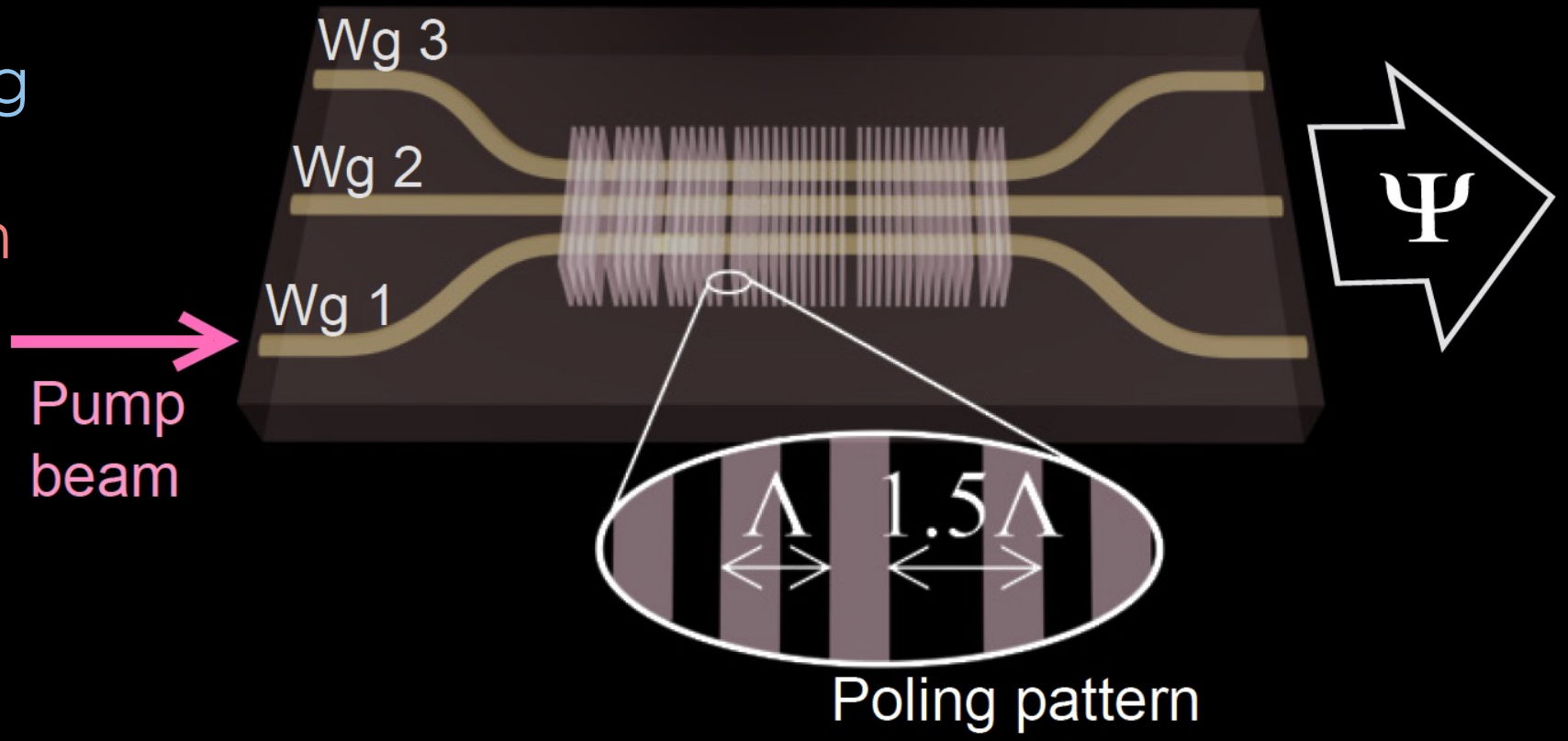
- Laser remains in central channels
- Pairs of photons couple to side channels
- Preserves Entanglement



Solntsev et al., APL 111, 261108 (2017)

POLING ENGINEERING

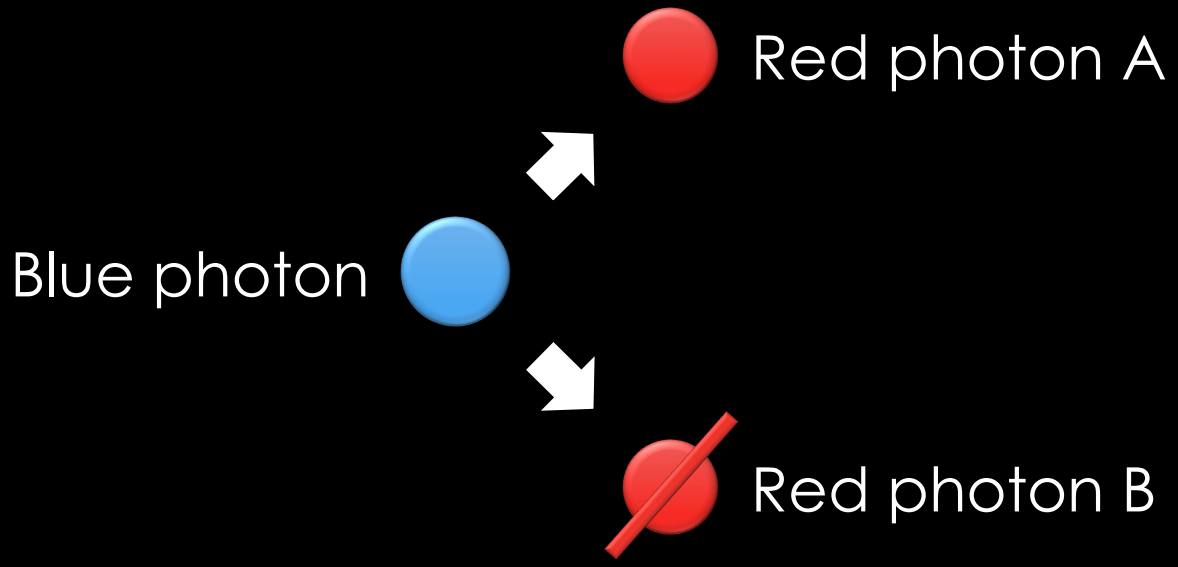
- Poling engineering allows generating arbitrary quantum states

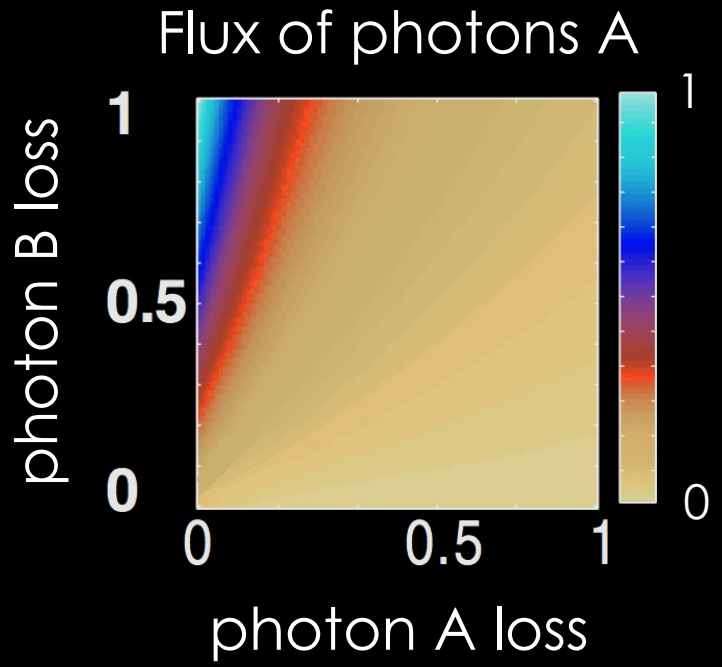


Lenzini, Titchener et al., LSA 7, 17143 (2018)
Titchener et al., PRA, 101, 023809 (2020)

LOSS ENGINEERING

- Plasmonics uses metals - optical loss is high
- Dialectics have scattering loss
- Tricks to make loss useful

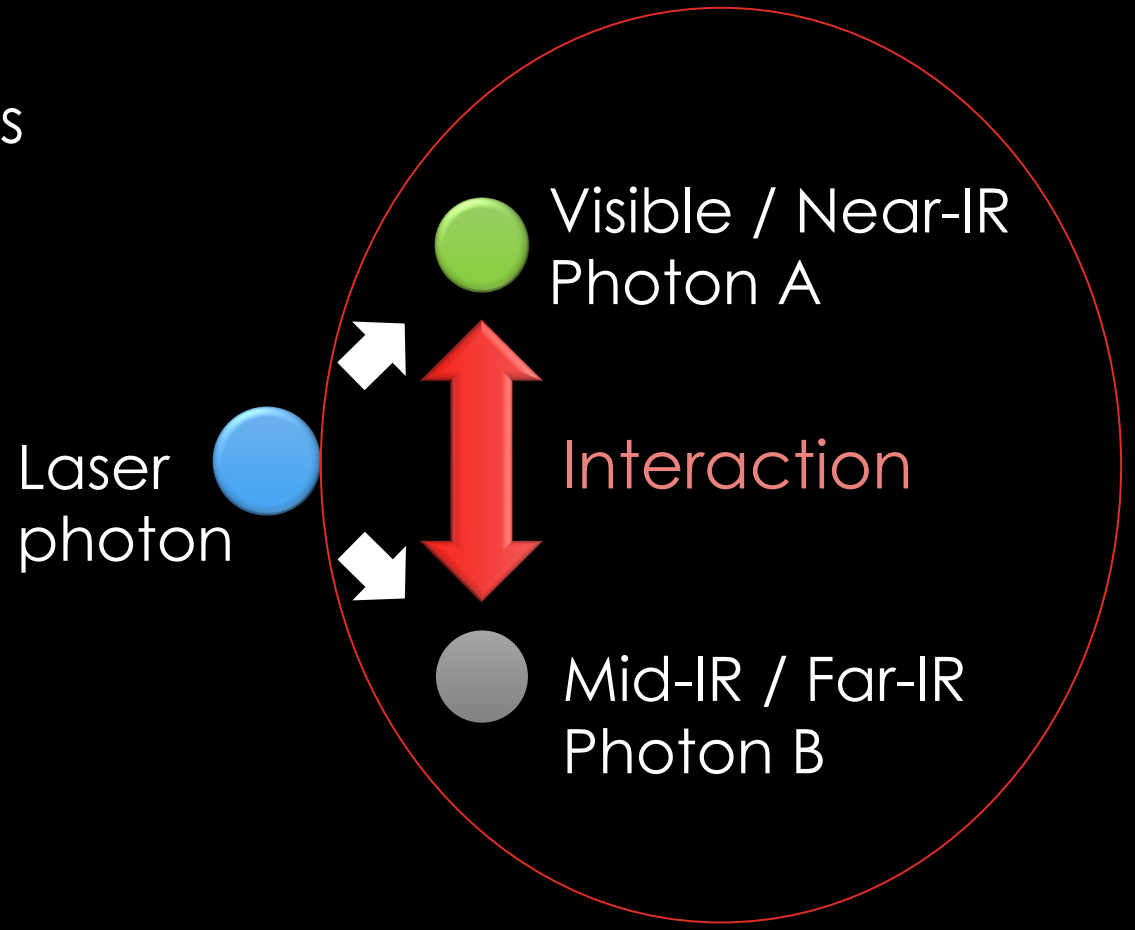




Antonosyan, Solntsev, Sukhorukov
PRA 90, 043845 (2014)
Photonics Research 6, A6-A9 (2018)

SPDC SPECTROSCOPY

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



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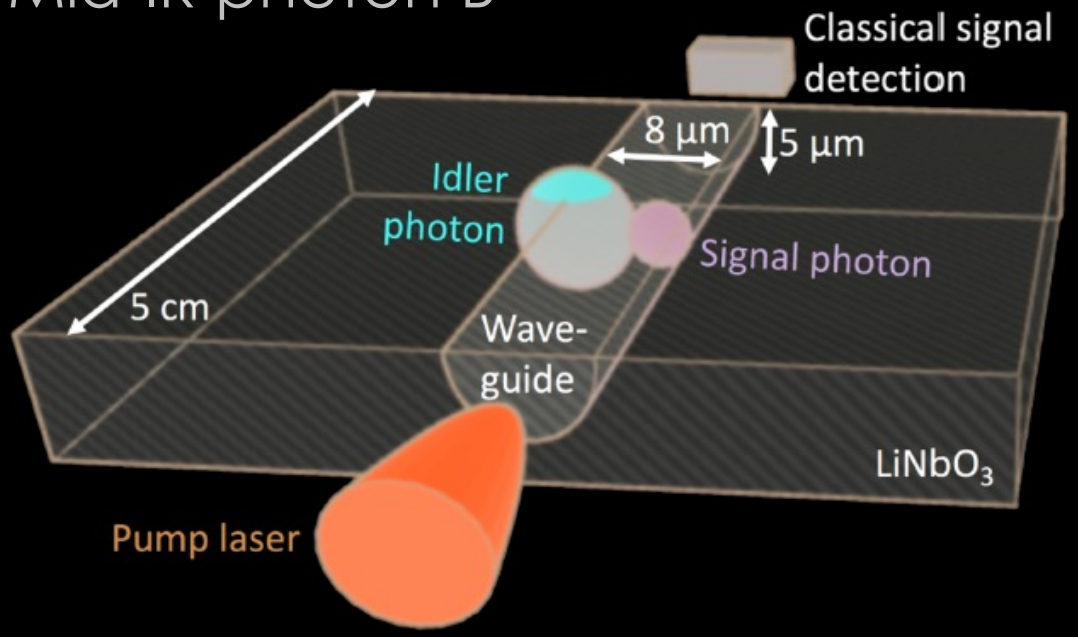
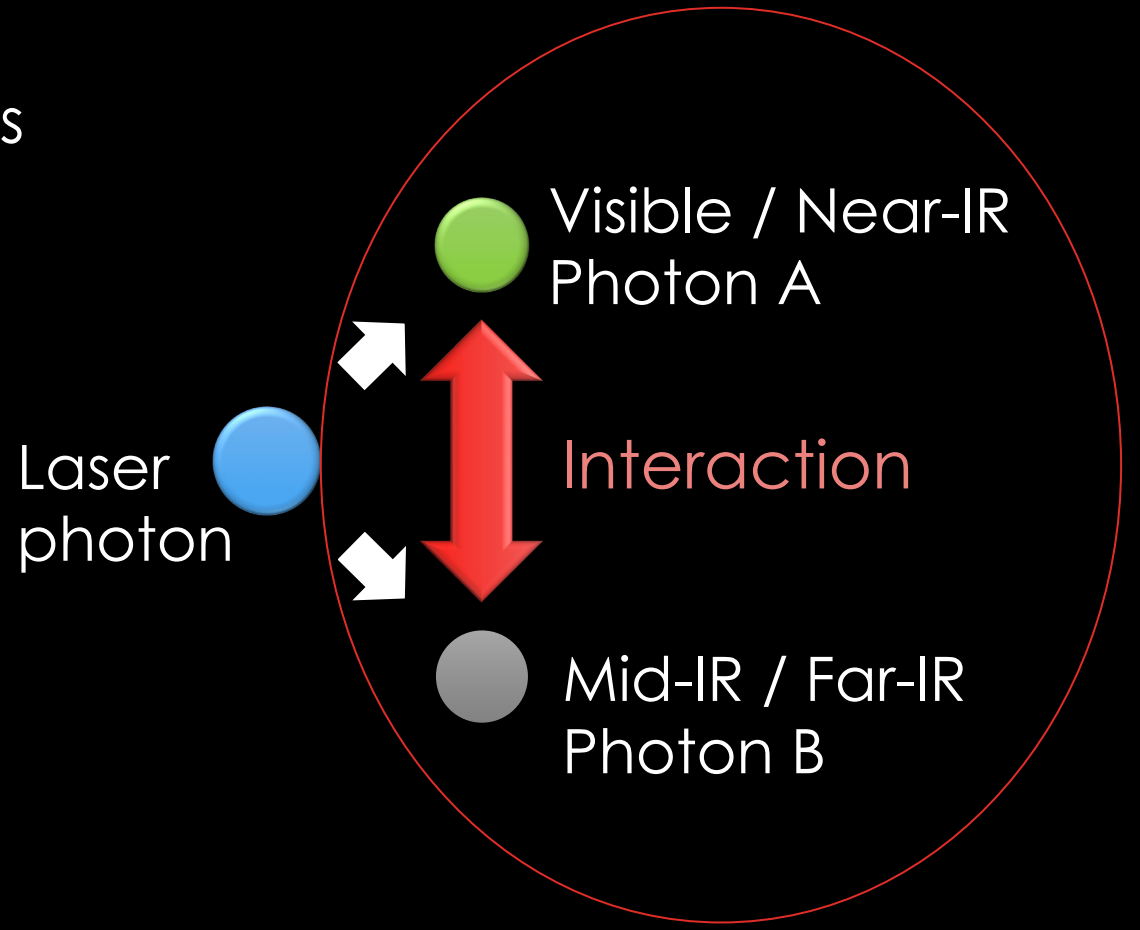
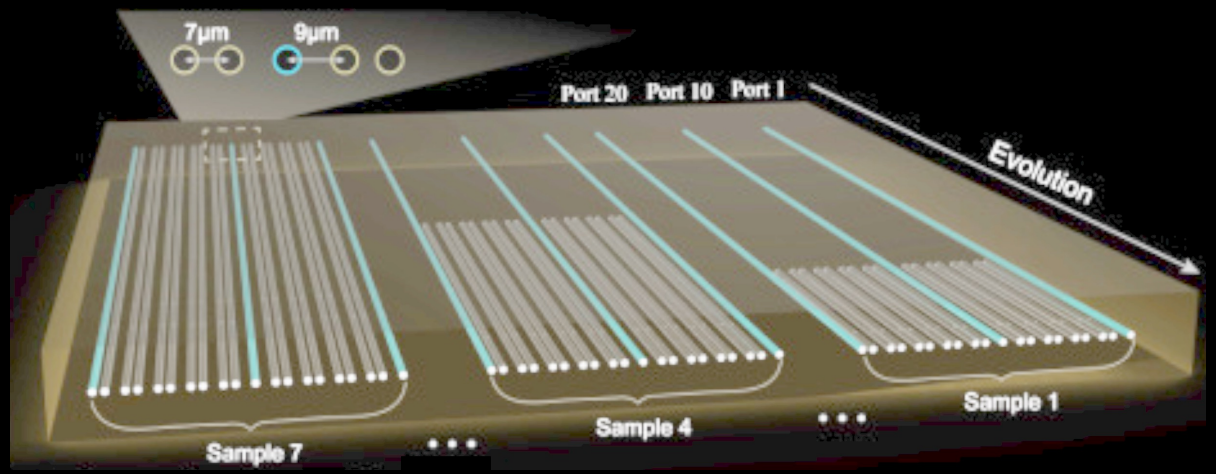




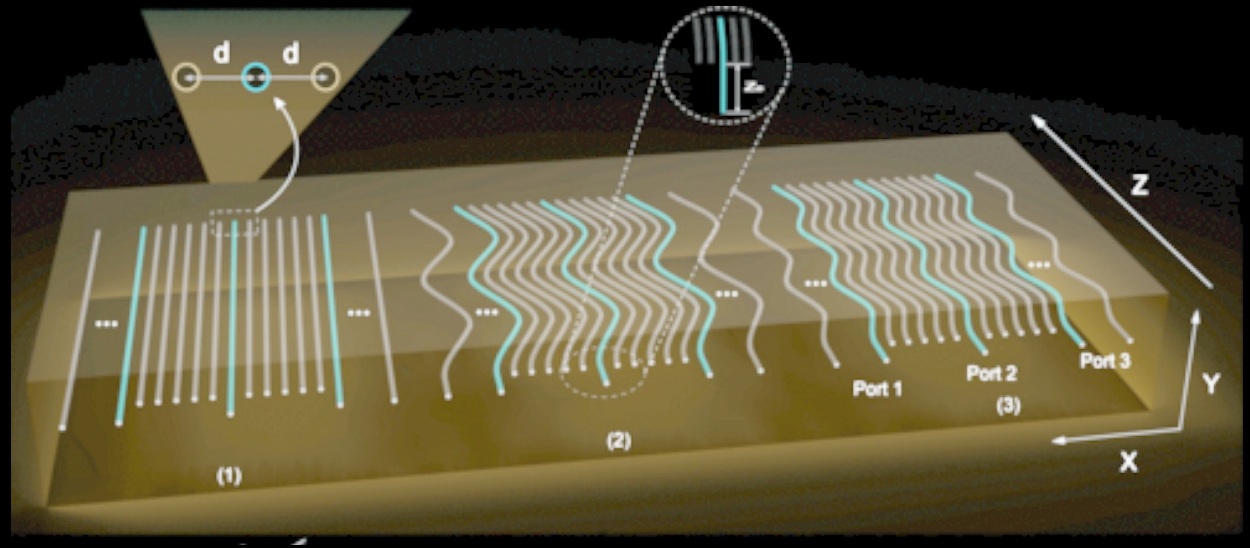
Solntsev et al., APL Photonics 3, 021301 (2018)

TOPOLOGY

- Topological protection of the generated entanglement



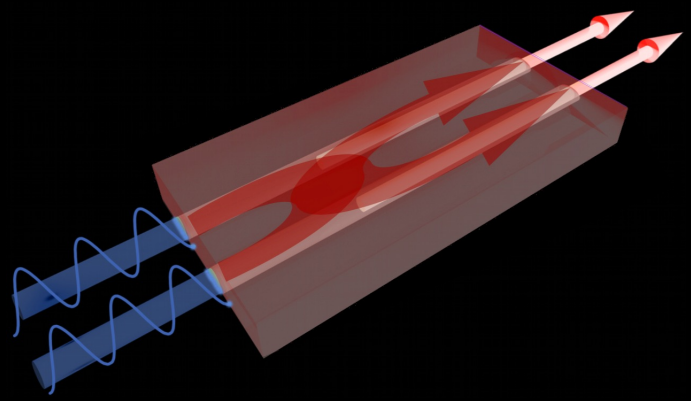
R. J. Ren et al., Phot. Research 10, 456-464 (2022)



Z.-K. Jiang et al., PRL 129, 173602 (2022)

NONLINEAR QUANTUM OPTICS

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

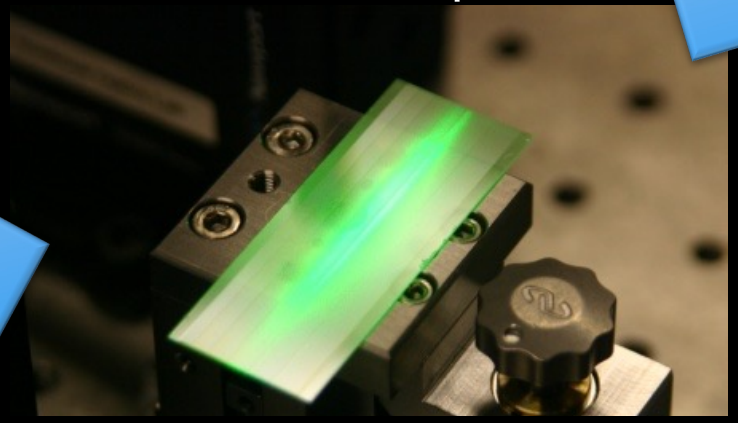


Solntsev et al., Reviews in Physics 2, 19 (2017)

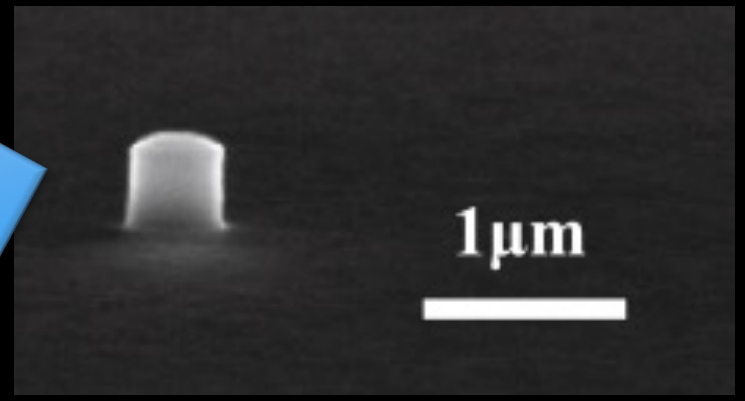
MINIATURIZATION

Bulk

Photonic chip



Nanoscale



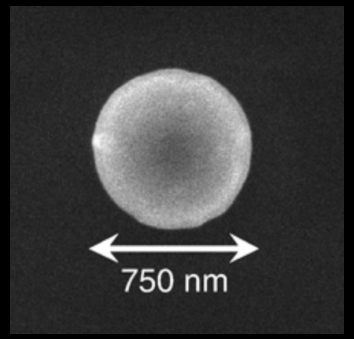
NONLINEAR QUANTUM OPTICS

Entanglement and nonlinearity

NONLINEAR QUANTUM OPTICS

Entanglement and nonlinearity in

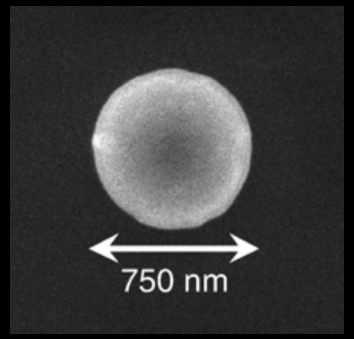
- Nanoparticles

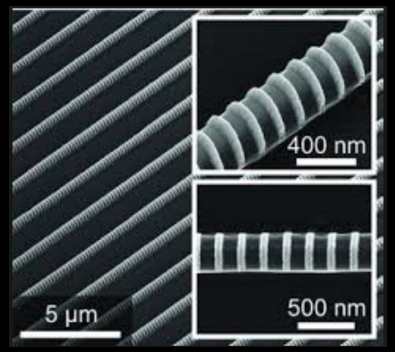


NONLINEAR QUANTUM OPTICS

Entanglement and nonlinearity in

- Nanoparticles
- Nanostructures

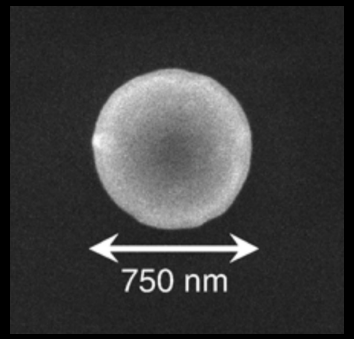


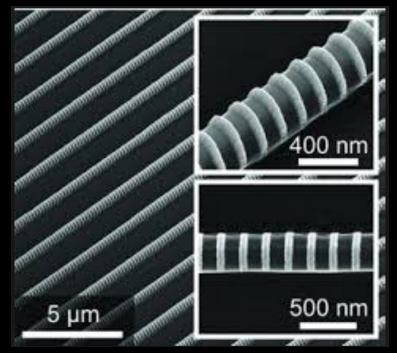


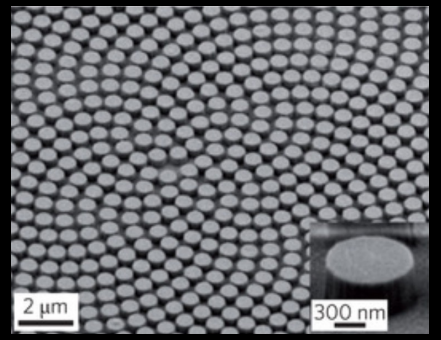
NONLINEAR QUANTUM OPTICS

Entanglement and nonlinearity in

- Nanoparticles
- Nanostructures
- Metasurfaces



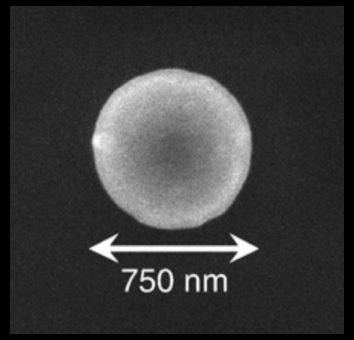


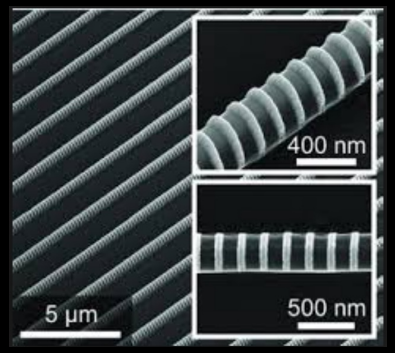


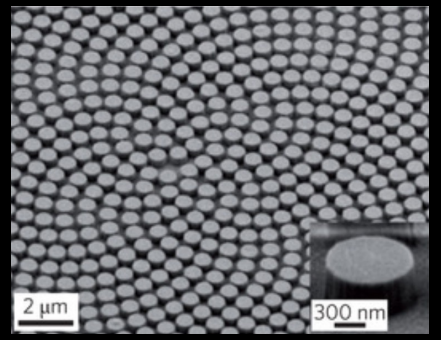
NONLINEAR QUANTUM OPTICS

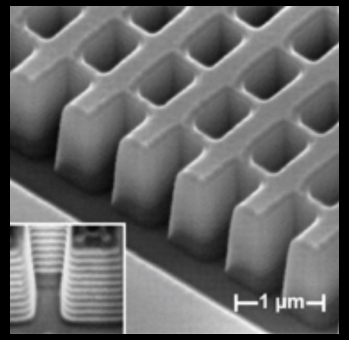
Entanglement and nonlinearity in

- Nanoparticles
- Nanostructures
- Metasurfaces
- Metamaterials





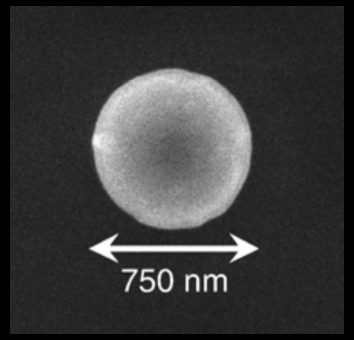


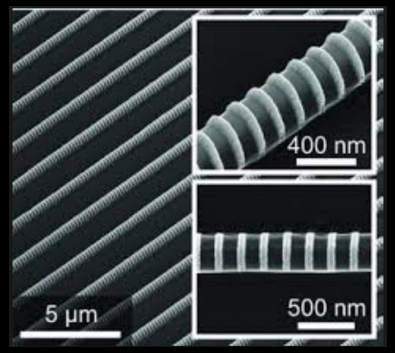


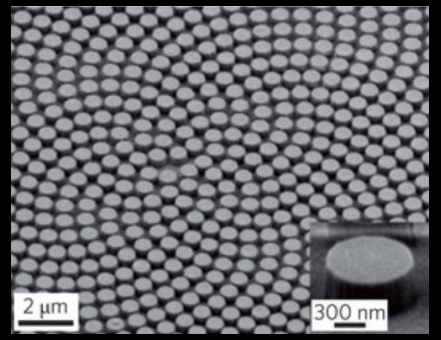
NONLINEAR QUANTUM OPTICS

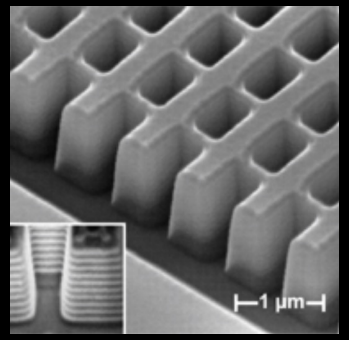
Entanglement and nonlinearity in

- Nanoparticles
- Nanostructures
- Metasurfaces
- Metamaterials
- 2D materials







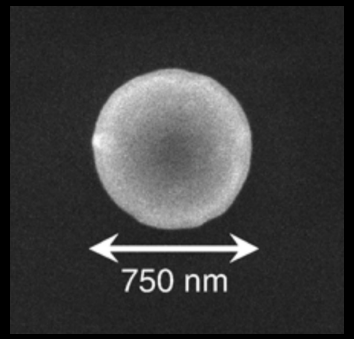


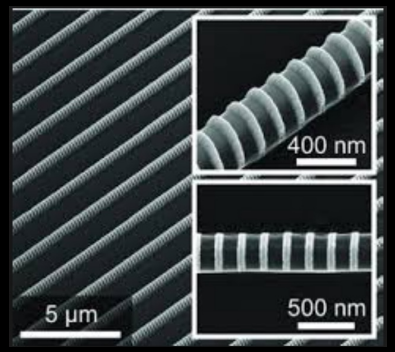
NONLINEAR QUANTUM OPTICS

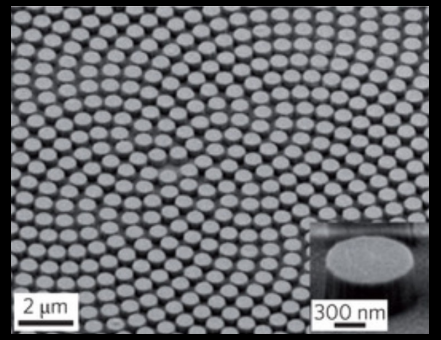
Entanglement and nonlinearity in

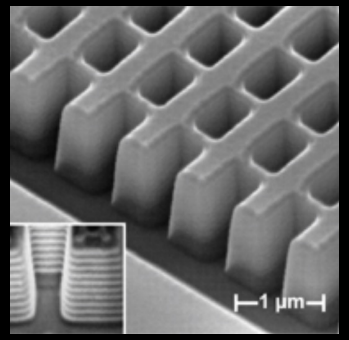
- Nanoparticles
- Nanostructures
- Metasurfaces
- Metamaterials
- 2D materials

Quantum light control on the nanoscale









WHY NONLINEARITY?

Single-photon sources

- quantum dots
- color centers
- etc.

WHY NONLINEARITY?

Single-photon sources

- quantum dots
- color centers
- etc.

Either helium cooled or low indistinguishability

NONLINEAR NANO-RESONATORS

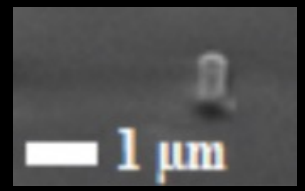
- Nonlinear optical frequency doubling in AlGaAs nanodisks

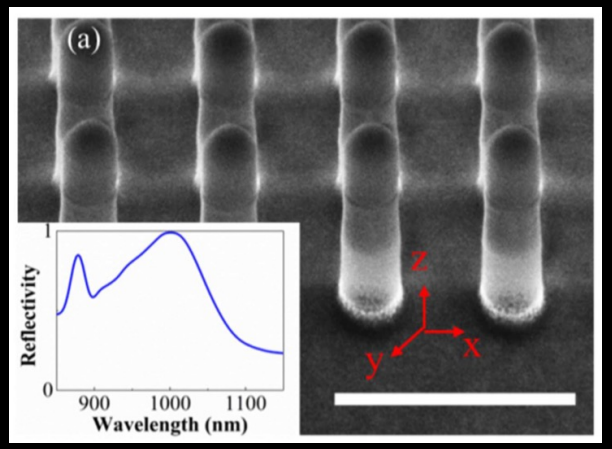
Research Article | Vol. 24, No. 14 | 11 Jul 2016 | OPTICS EXPRESS 15965
Optics EXPRESS

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





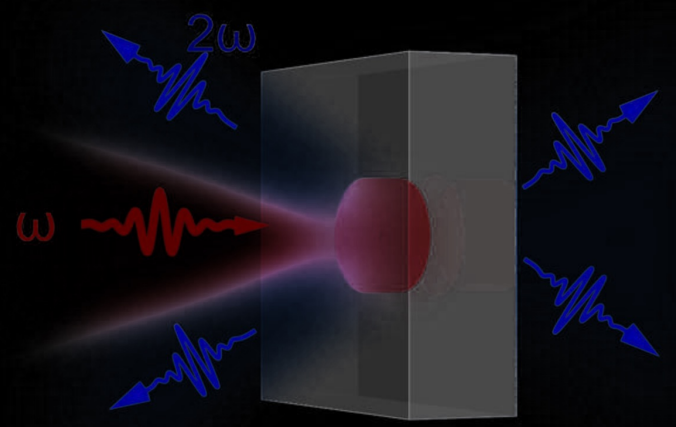
Nano Lett., **2016**, *16* (9), pp 5426–5432

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

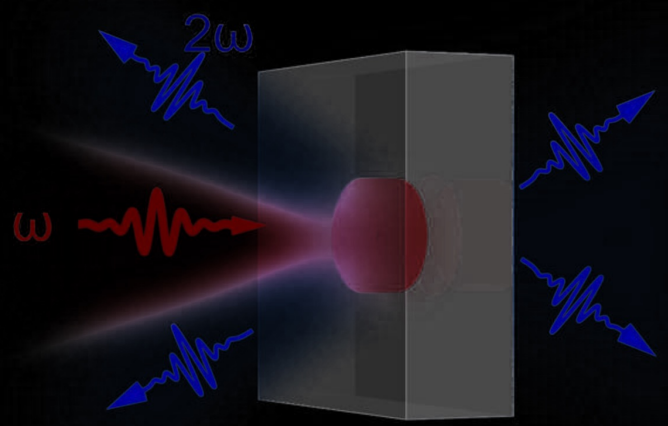
- Nonlinear optical frequency doubling in AlGaAs nano-disk

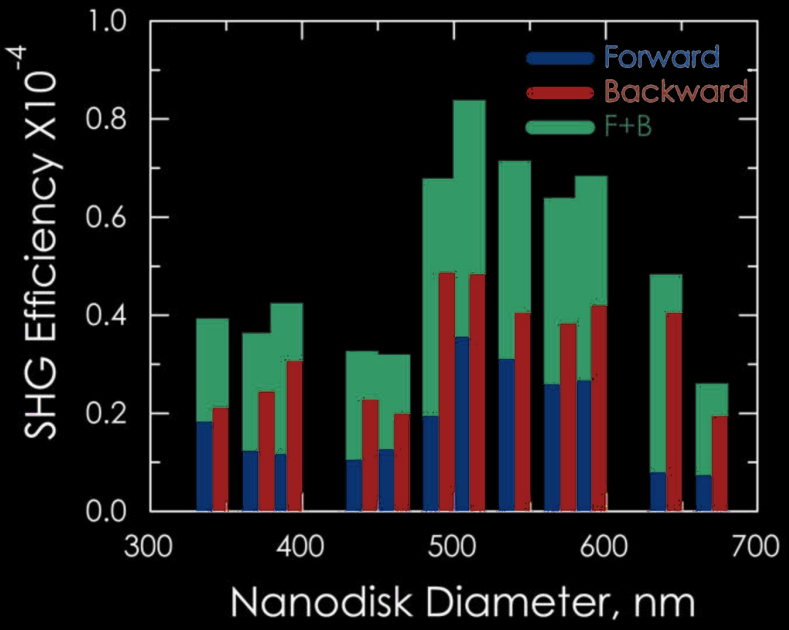


Camacho et al., Nano Lett. 16, 7191−7197 (2016)

NONLINEAR NANO-RESONATORS

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

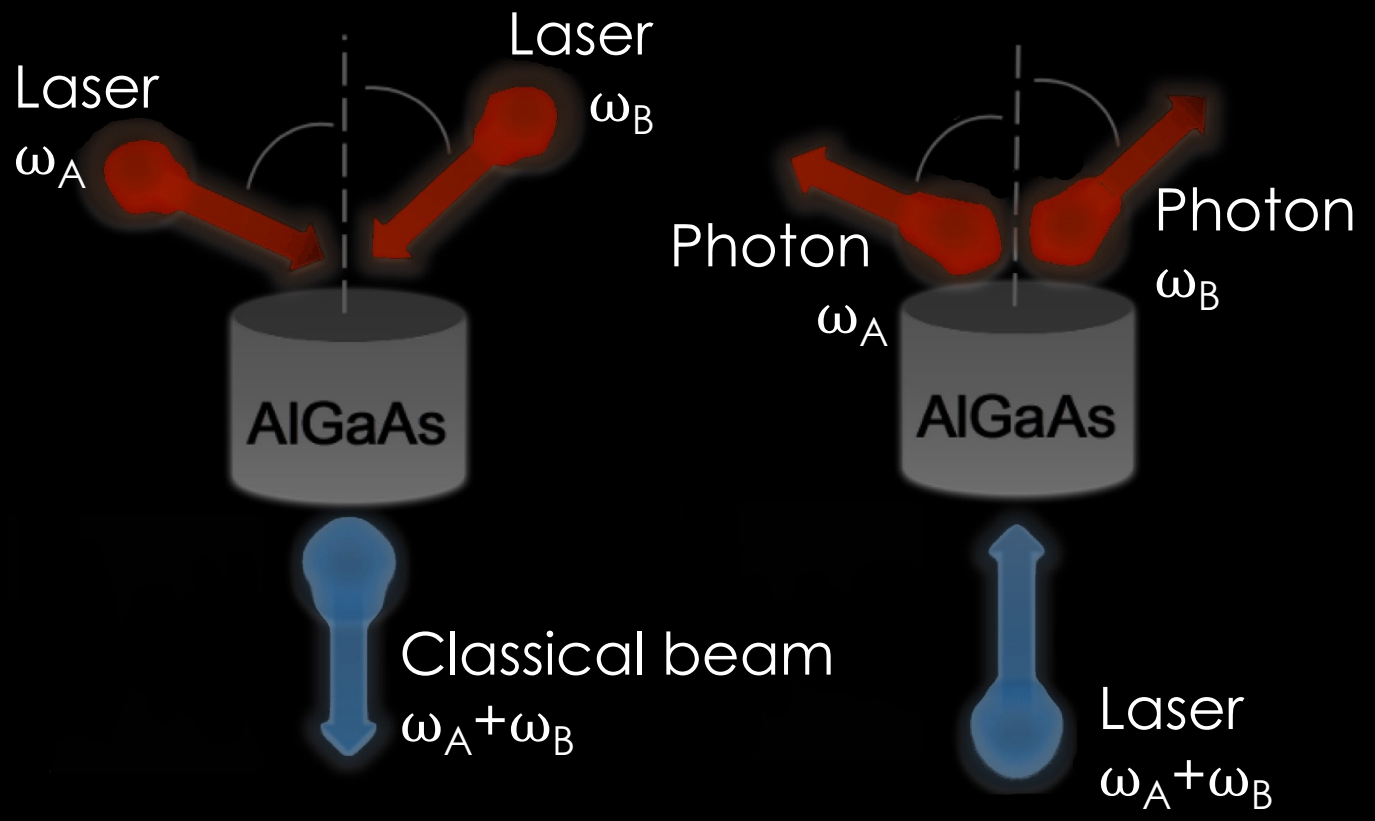




Camacho et al., Nano Lett. 16, 7191−7197 (2016)

NONLINEAR NANO-RESONATORS

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

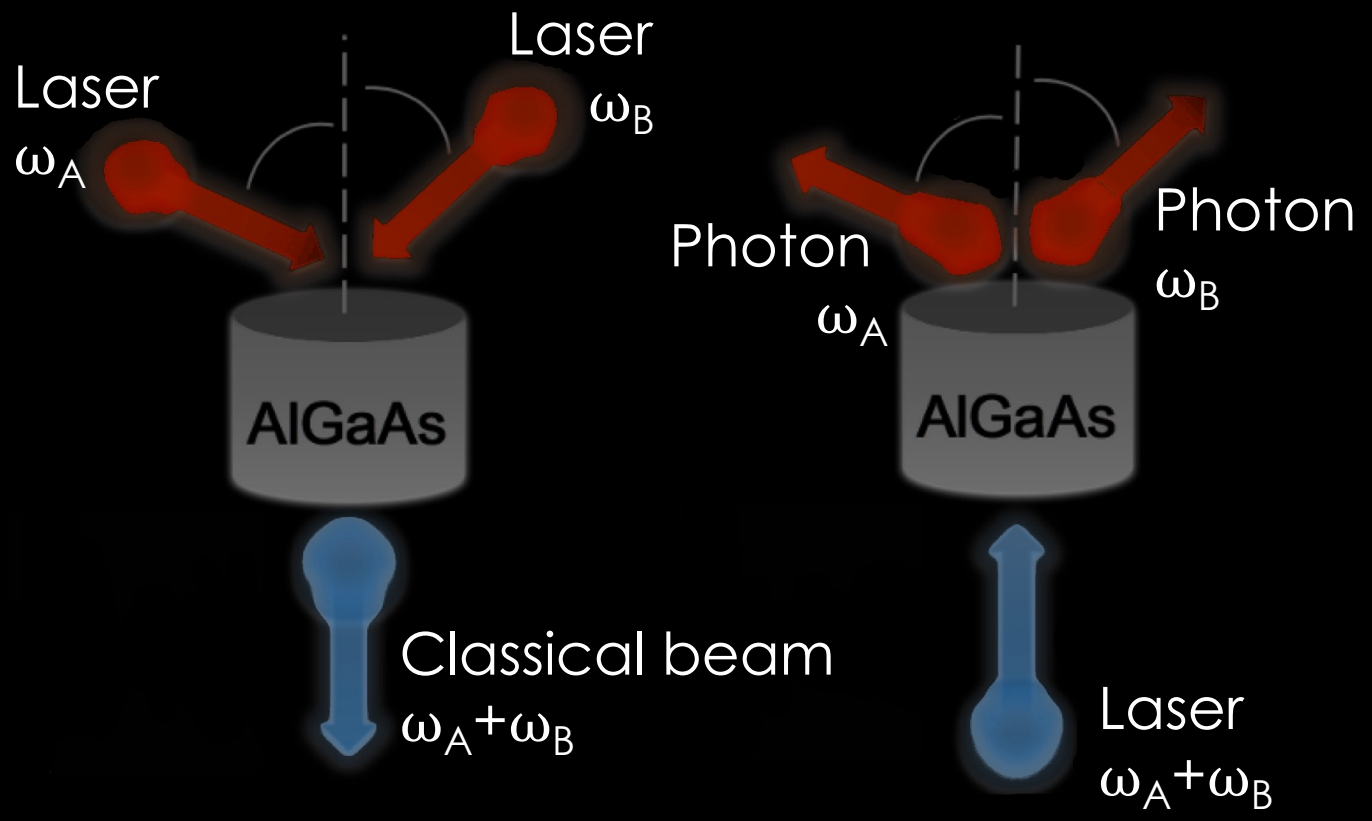


SoIntsev et al., Frontiers in Optics, FF1C.5 (2016)

NONLINEAR NANO-RESONATORS

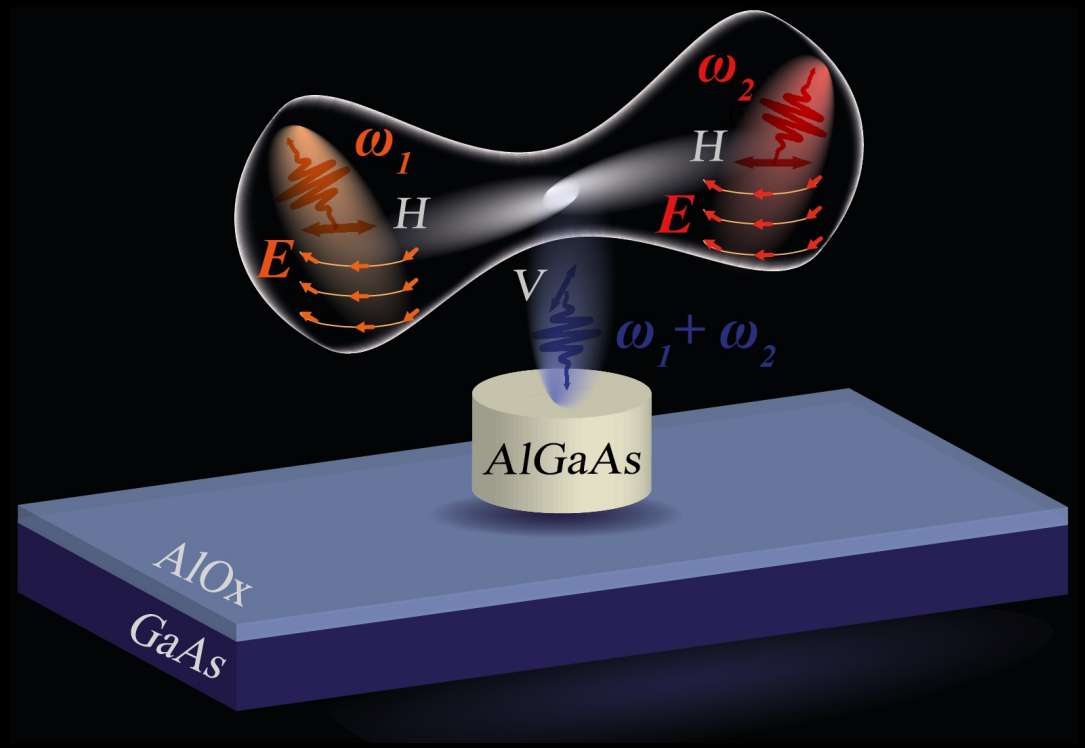
- Classical nonlinear processes can be used to predict quantum photon-pair generation

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



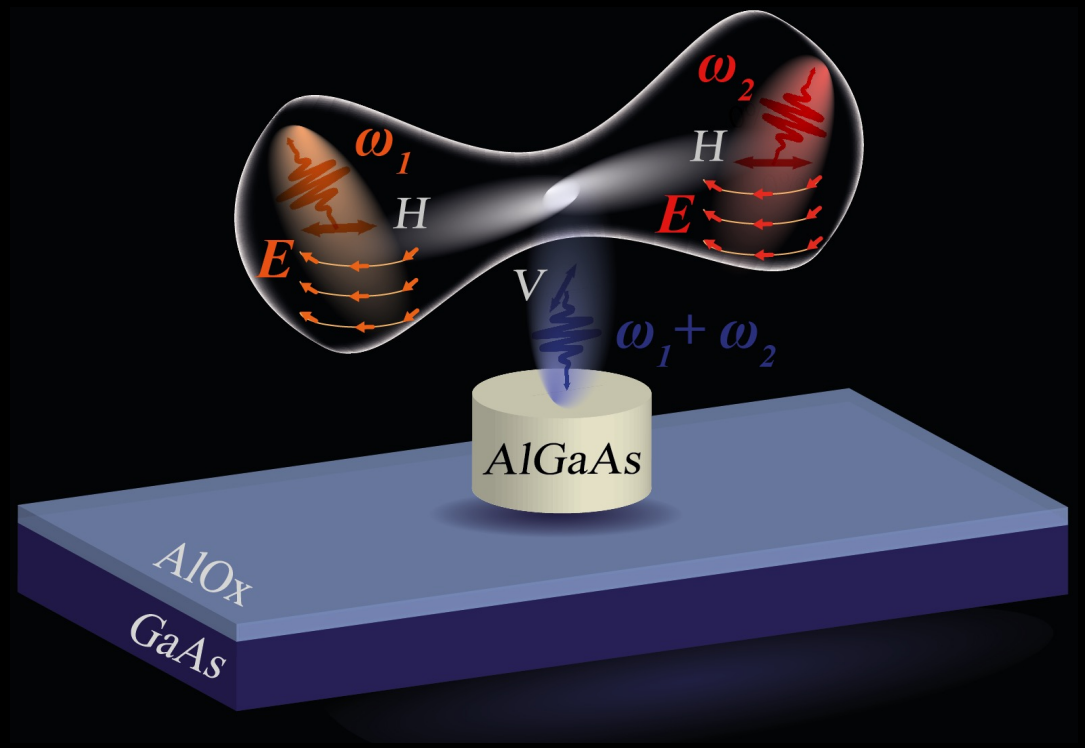
Solntsev et al., Frontiers in Optics, FF1C.5 (2016)

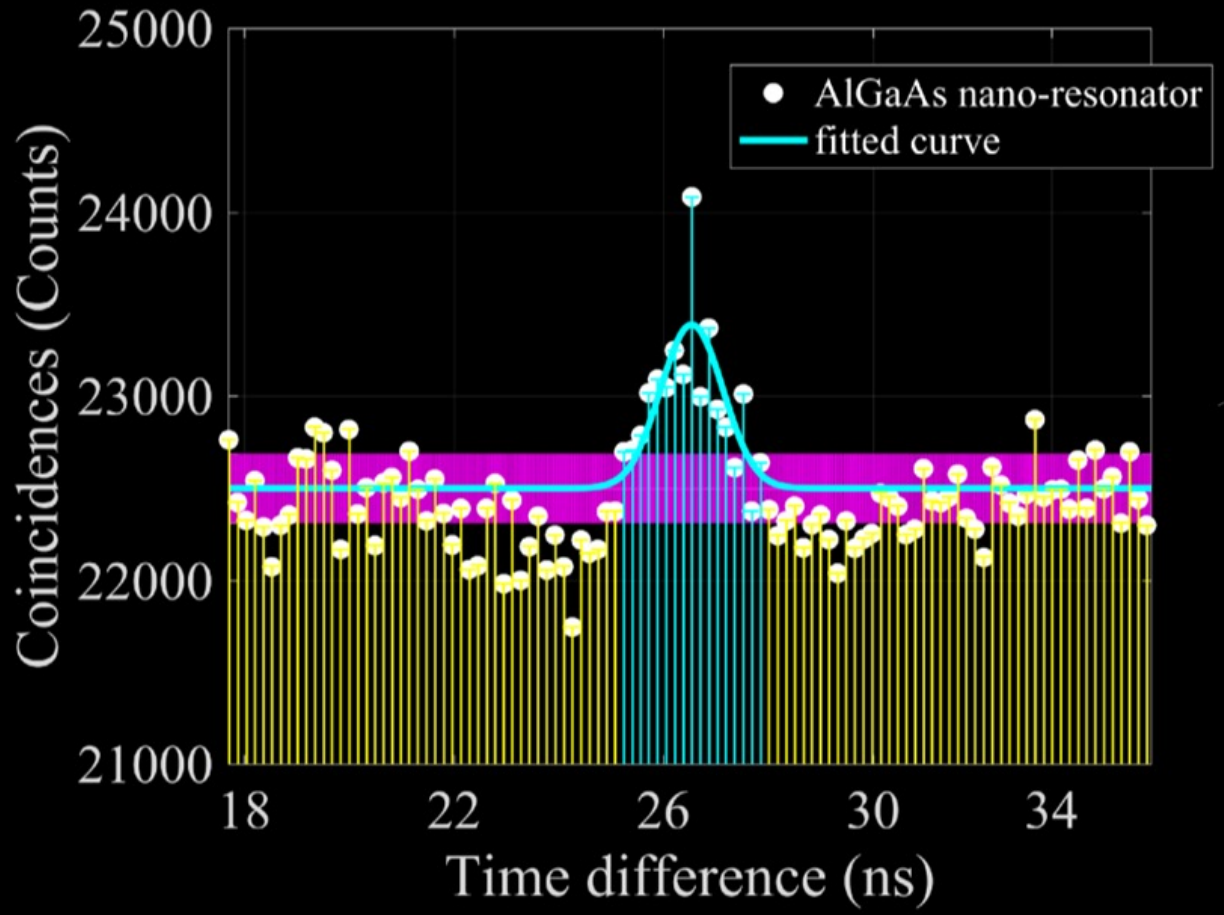
NONLINEAR NANO-RESONATORS



Marino, Solntsev et al., Optica, 6 1416-1422 (2019)

NONLINEAR NANO-RESONATORS

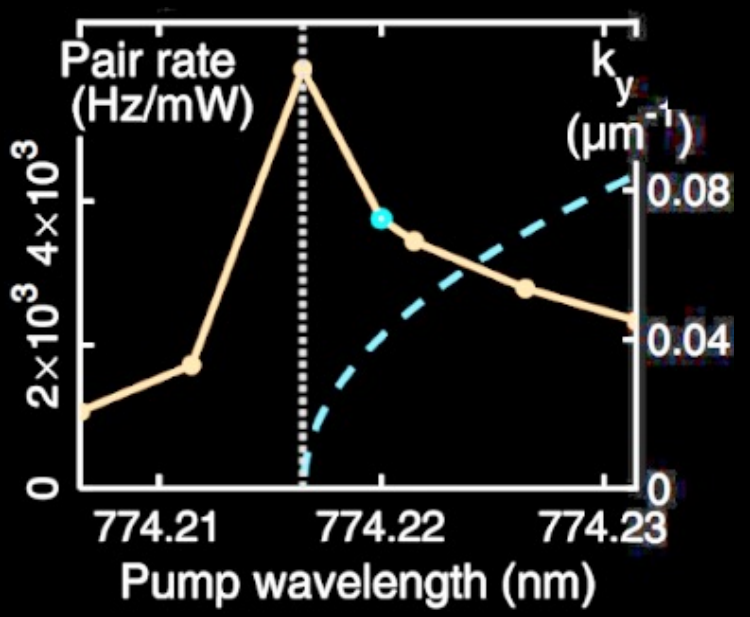




Marino, Solntsev et al., Optica, 6 1416-1422 (2019)

ENHANCEMENT

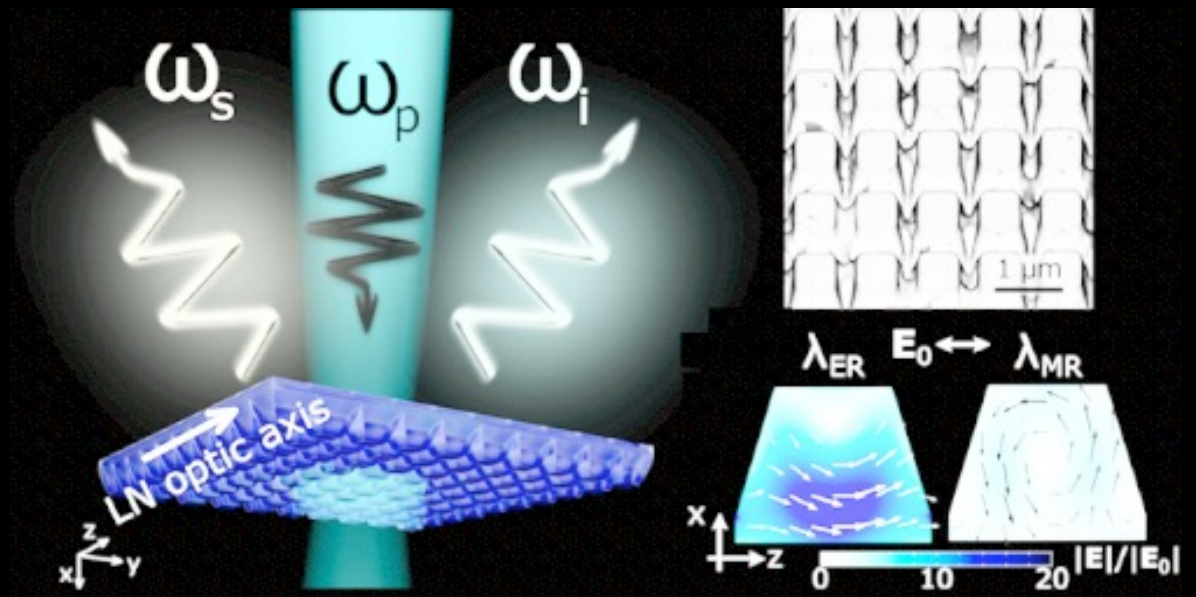
- AlGaAs metasurface design supporting BIC resonances
- Generation rate ~ 1.75 kHz mW^{-1}



M. Parry et al., Adv. Photonics 3, 055001 (2021)

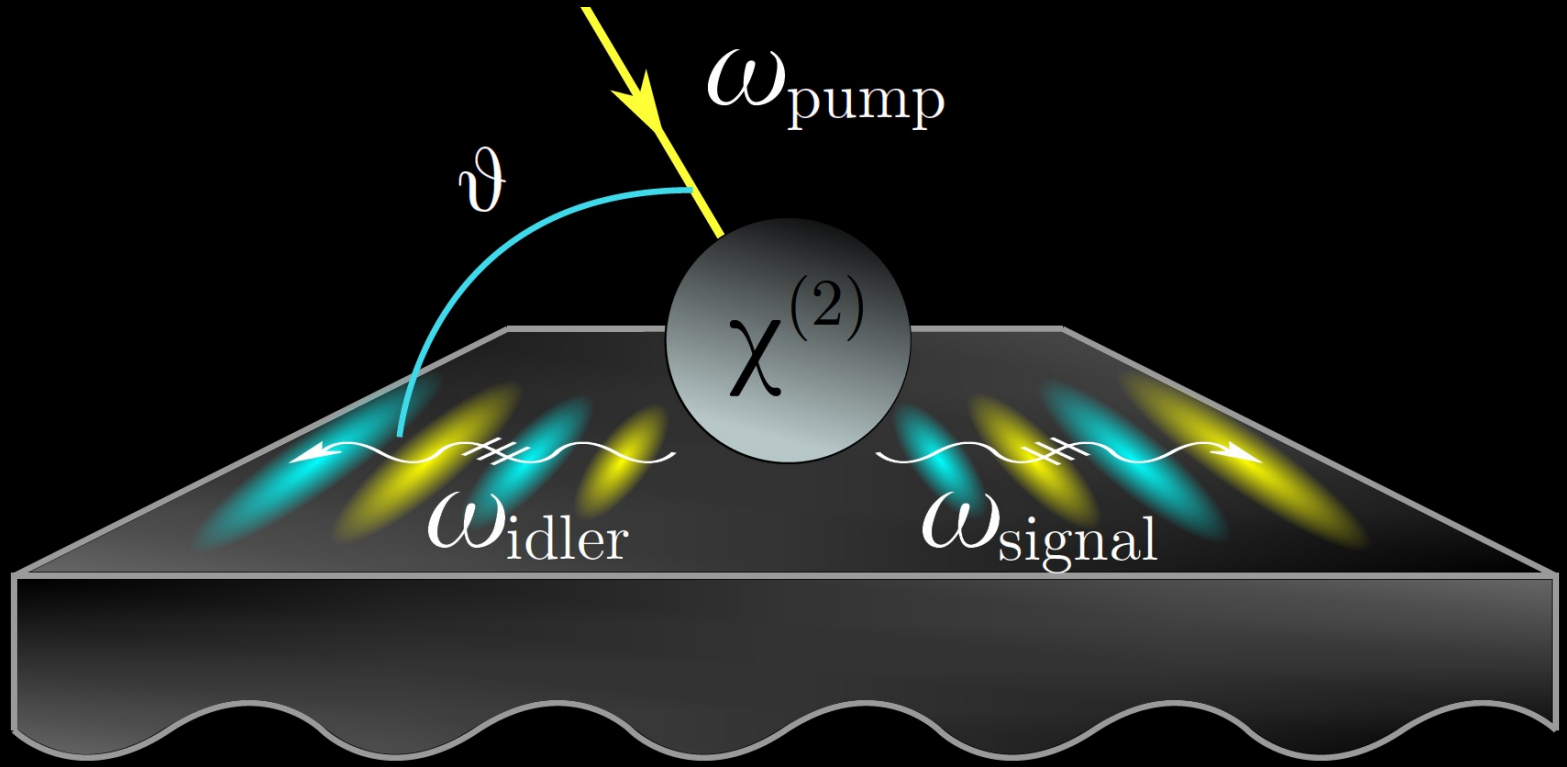
ENHANCEMENT

- $LiNbO_3$ metasurface
- 2 orders of magnitude enhancement



Santiago-Cruz et al., Nano Lett. 21, 4423–4429 (2021)

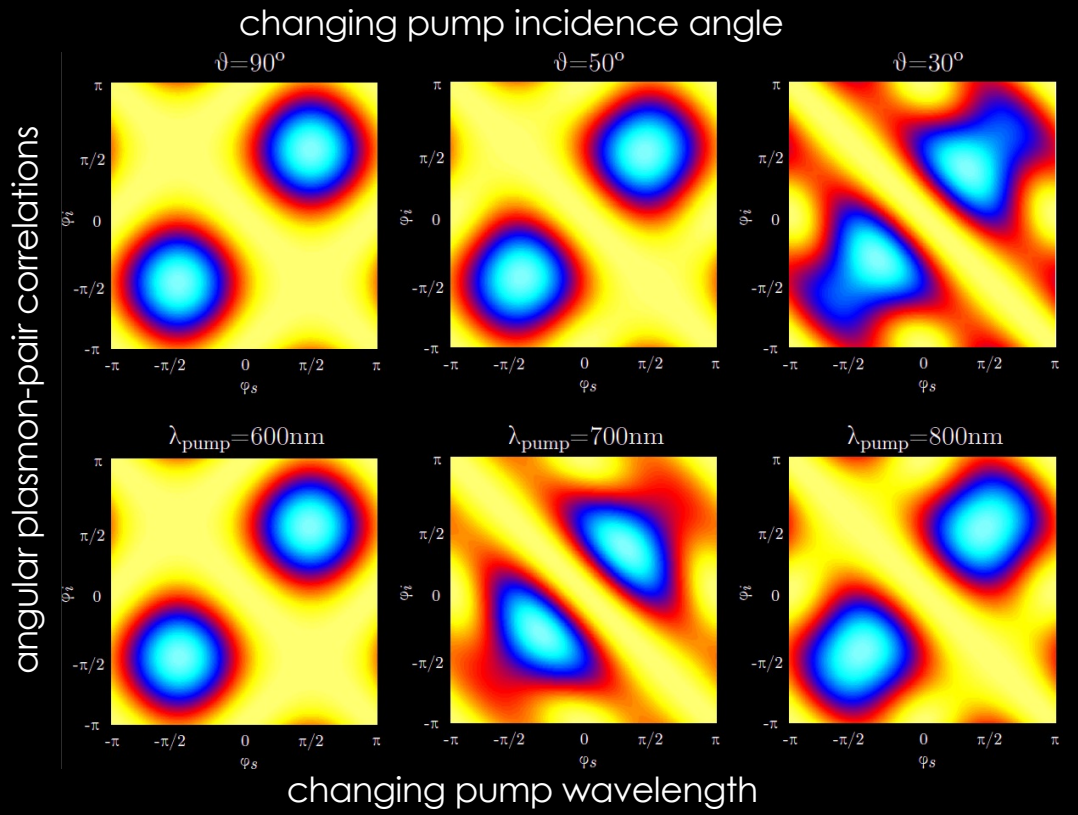
NANO-RESONATOR ON METAL



Olekhno et al., International Conference on Laser Optics (2022)

PLASMONIC ENTANGLEMENT GENERATION

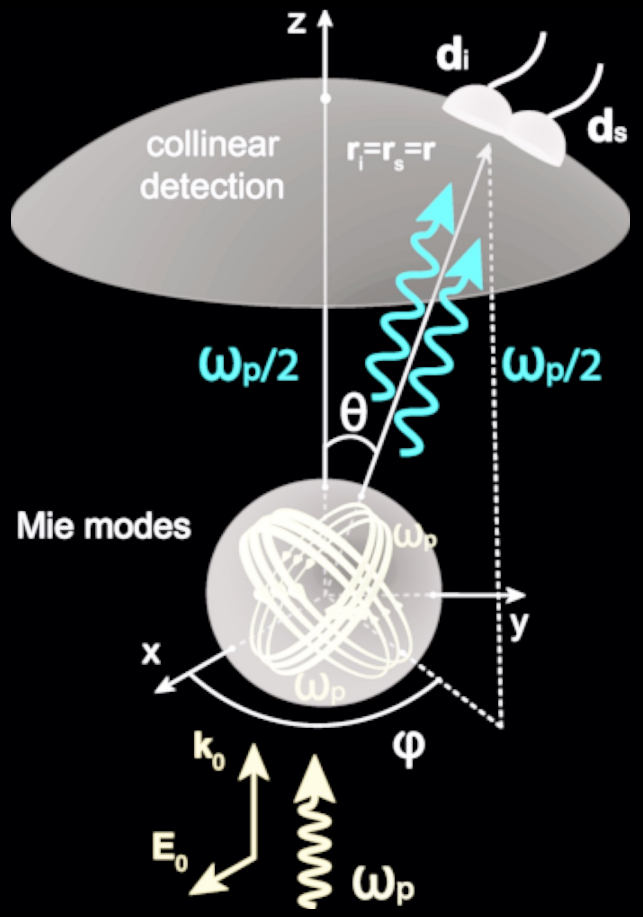
- At the right pump frequency, generation is strongly enhanced
- Entangled plasmons $|A_1,B_1\rangle + |A_2,B_2\rangle$
- Robust for pump wavelengths and incidence angles



Olekhno et al., International Conference on Laser Optics (2022)

DIRECTIONALITY CONTROL

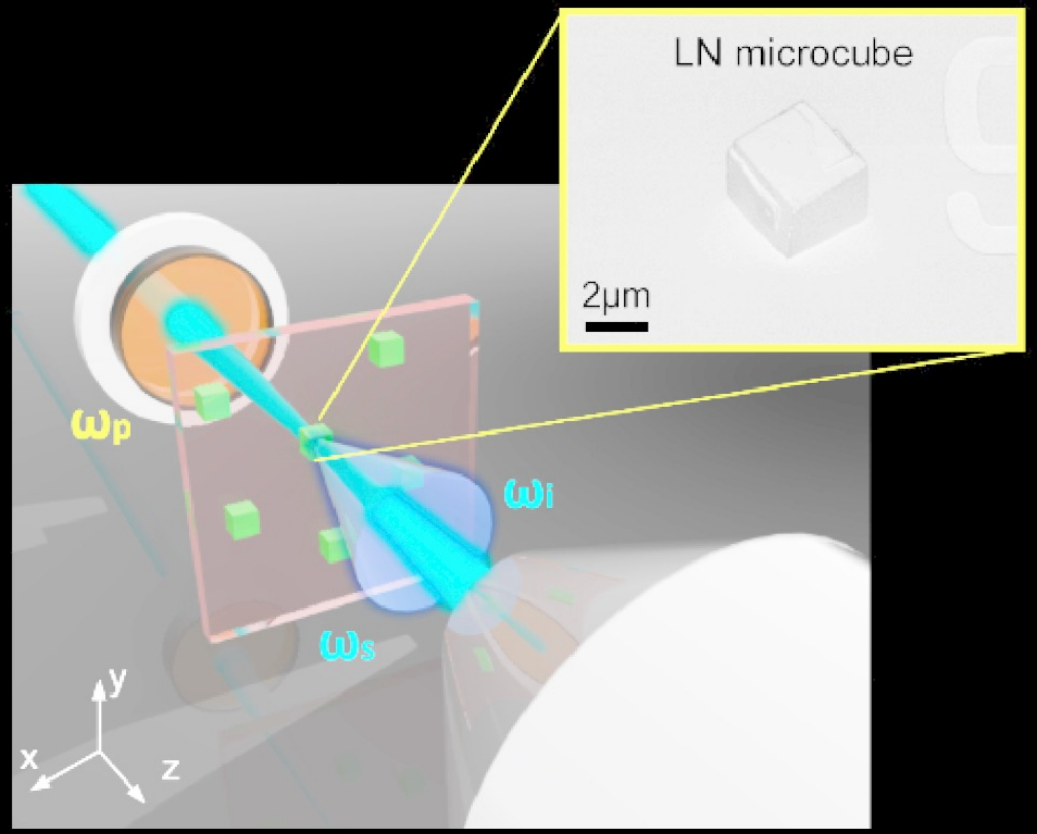
- Enhancement via Mie resonances
- Nonlinear Kerker effect
- Highly directional photon-pair generation



Nikolaeva et al., Phys. Rev. A 103, 043703 (2021)

LINBO3 MICROCUBES

- 20.6 GHz/Wm
- 3 orders of magnitude more than the efficiency of biphoton generation in bulk nonlinear crystals

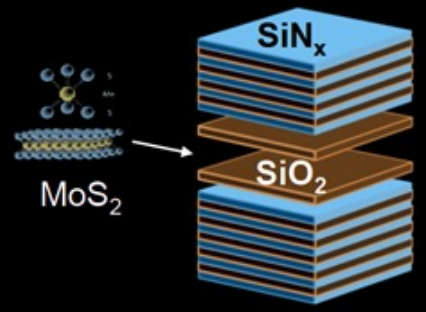


N. M. H. Duong et al., Opt. Mat. Expr. 12, 3696-3704 (2022)

2D MATERIAL NONLINEAR OPTICS

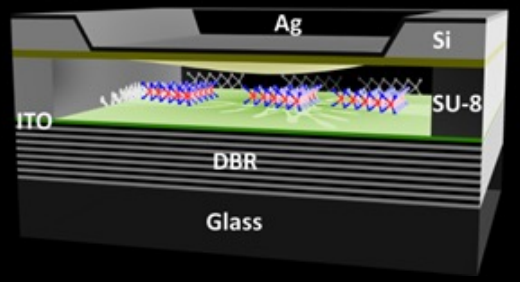
- Frequency doubling in 2D materials
- Can be enhanced by integration with photonic structures

Microcavity



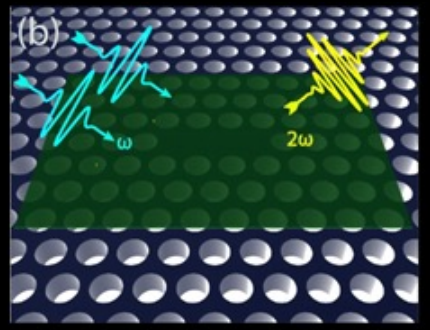
J. Day et al., Opt. Mater. Express 2360-2365(2016)

Optomechanical platform



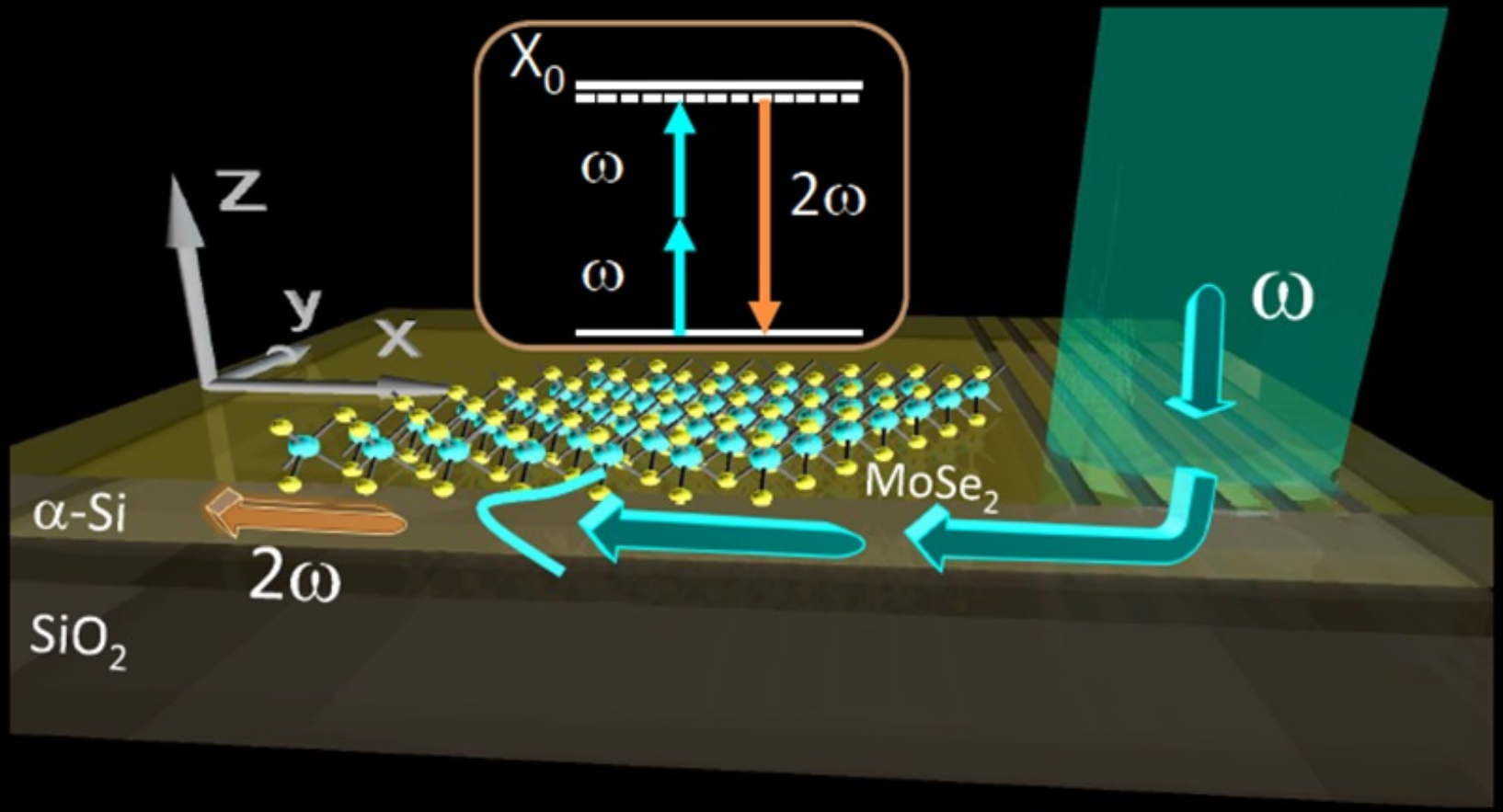
Y Li et al., Nano Lett. 16, 1631-1636 (2016)

Photonics cyrstal



T. K. Fryett et al., 2D Mater. 4, 1(2016)

2D MATERIAL NONLINEAR OPTICS

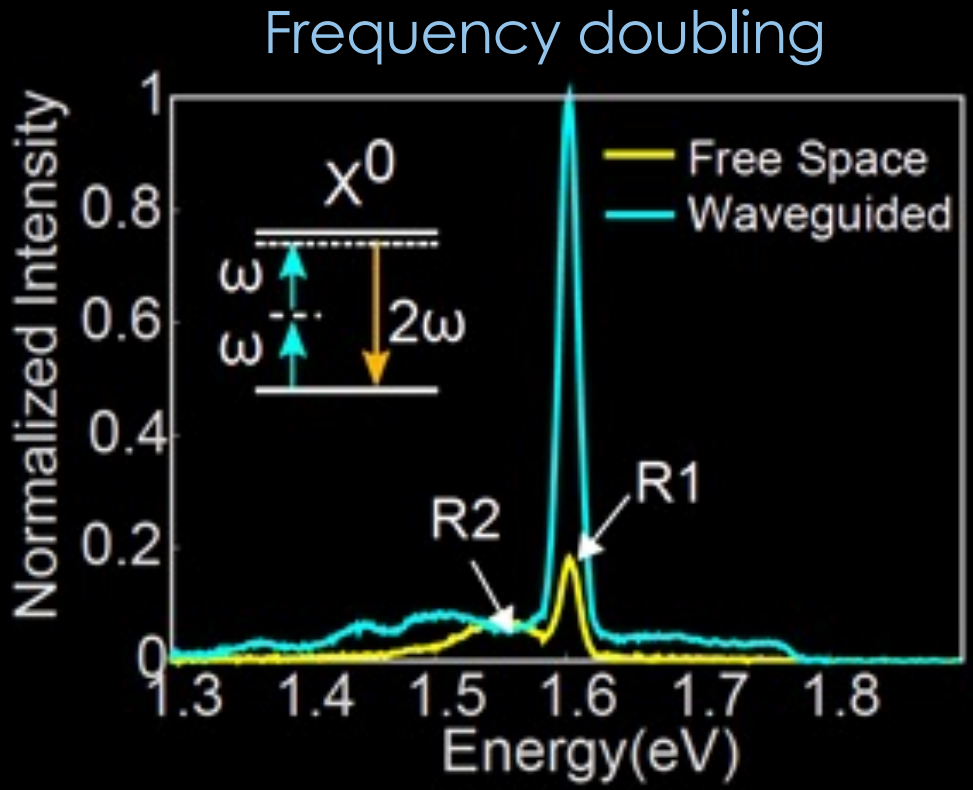


Chen et al., LSA 6, e17060 (2017)

2D MATERIAL NONLINEAR OPTICS

- 2D materials can add 2^d order nonlinearity
- Nanophotonics enhances nonlinearity in 2D materials

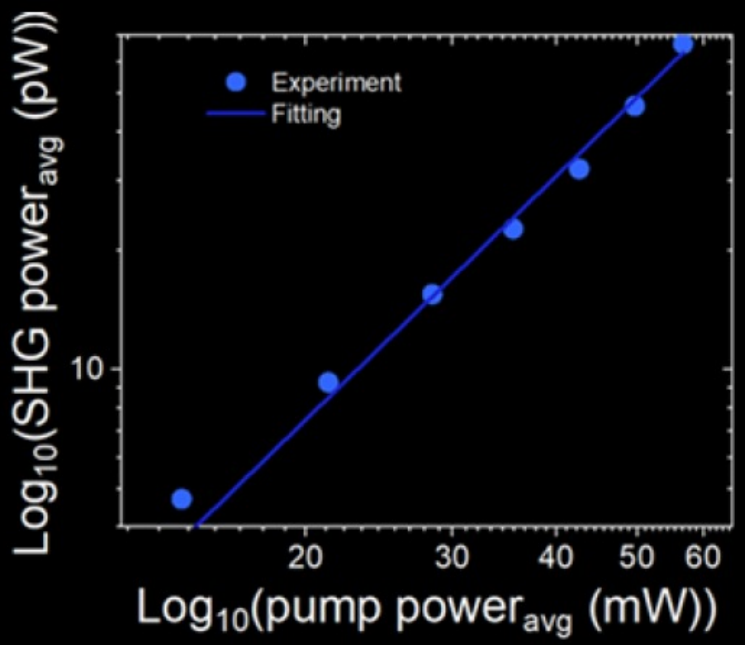
- Next: quantum light



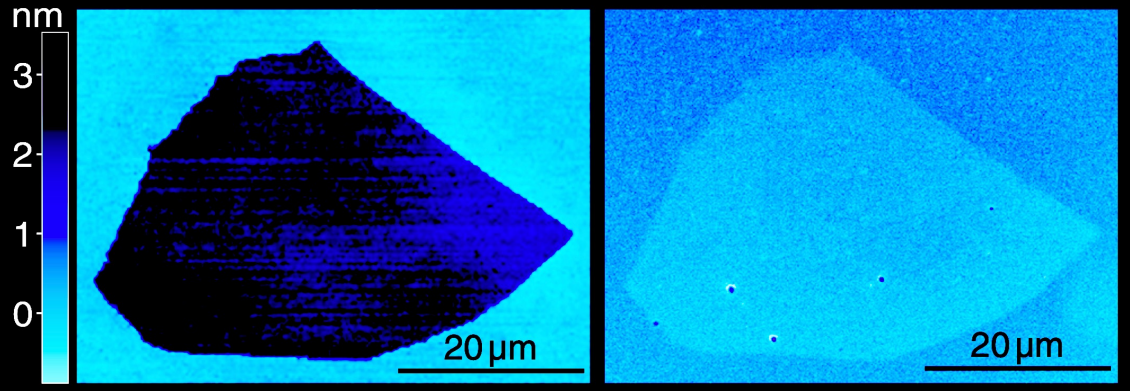
Chen et al., LSA 6, e17060 (2017)

2D MATERIAL NONLINEAR OPTICS

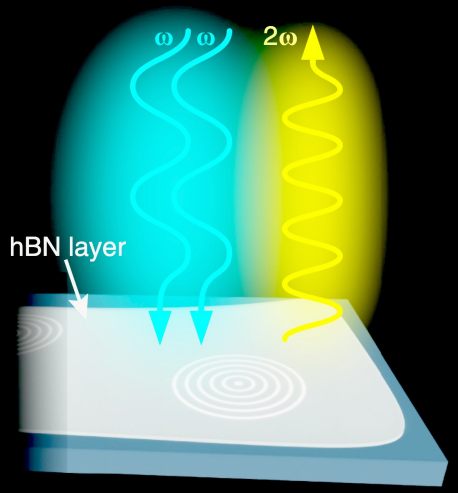
- hBN – transparent 2D dielectric, highly nonlinear



Kim et al., Opt. Lett. 44, 5792-5795 (2019)

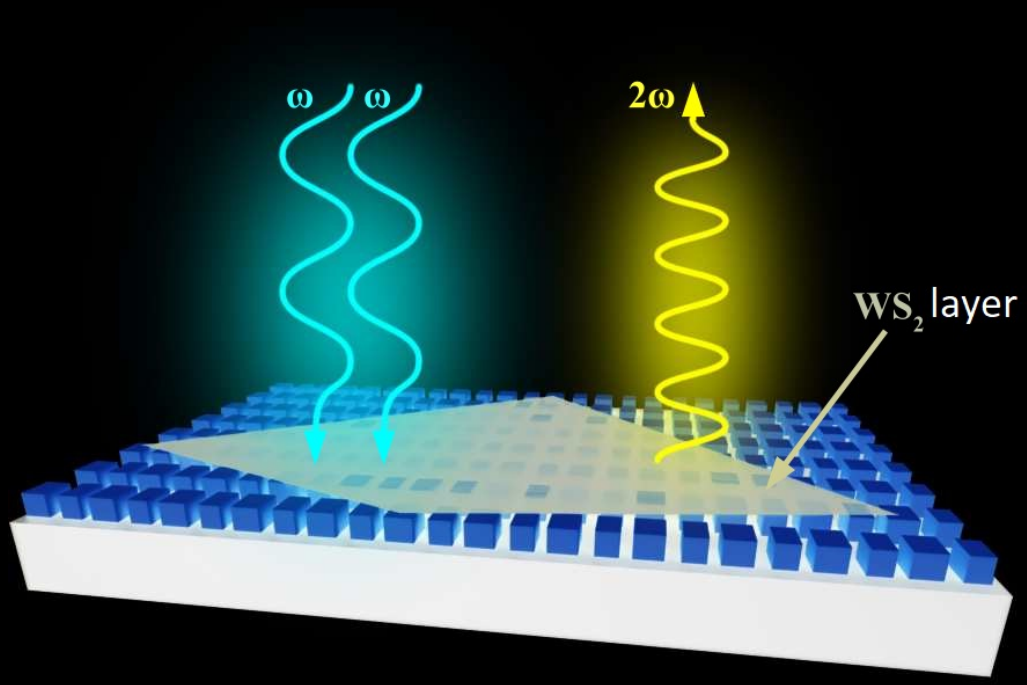


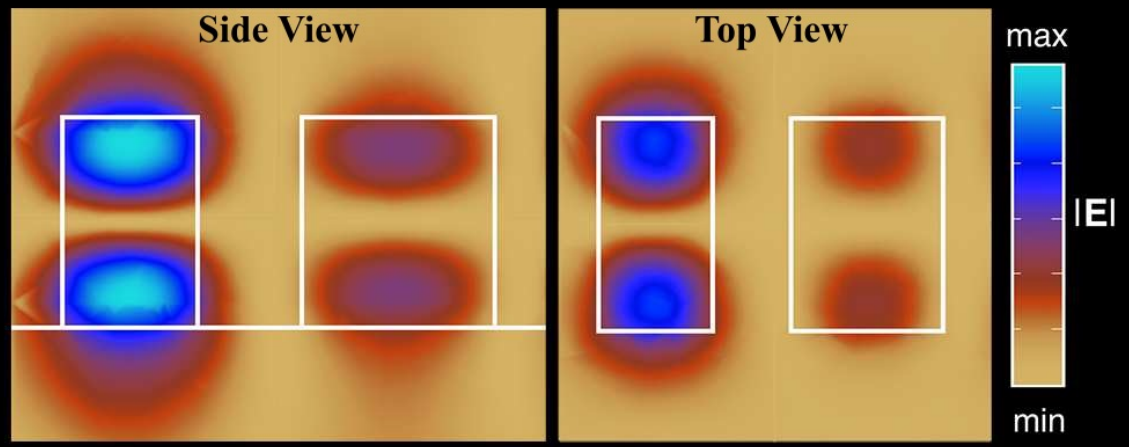
- 10000 µm^2 hBN flakes
- Integration with circular Bragg gratings

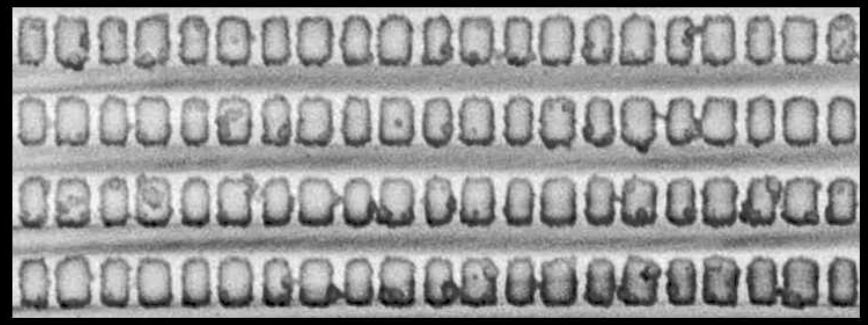


Bernhardt et al., Opt. Lett. 46, 564-567 (2021)

ENHANCING 2D MATERIAL SHG WITH A BIC METASURFACE







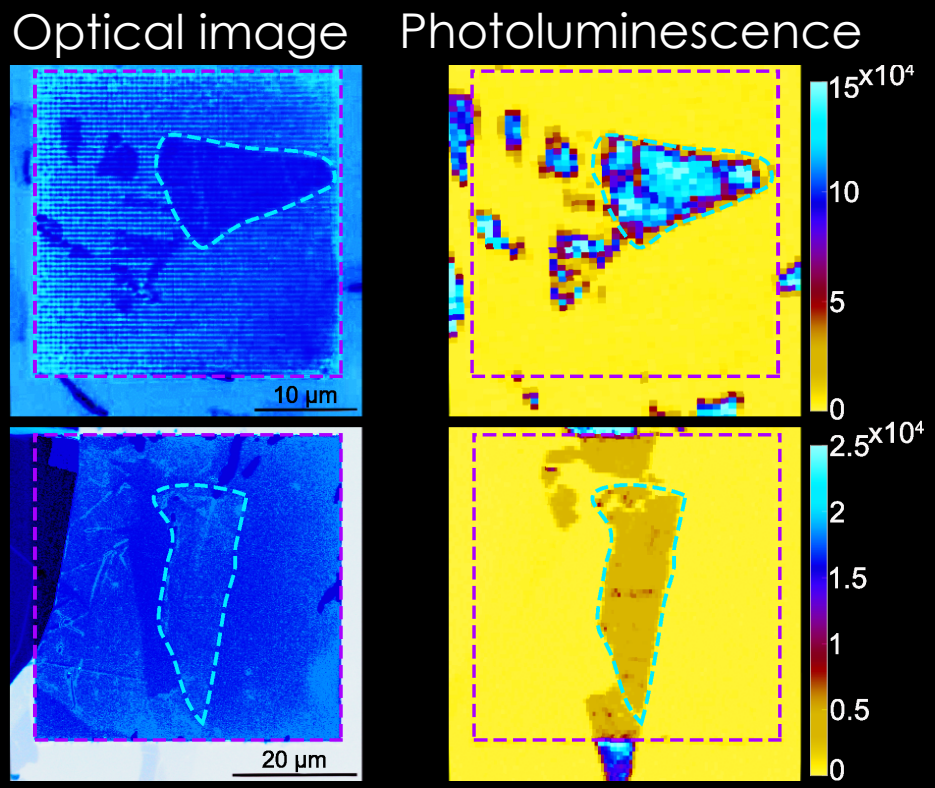
- Sharp BIC resonance
- Field is concentrated on the top of the metasurface

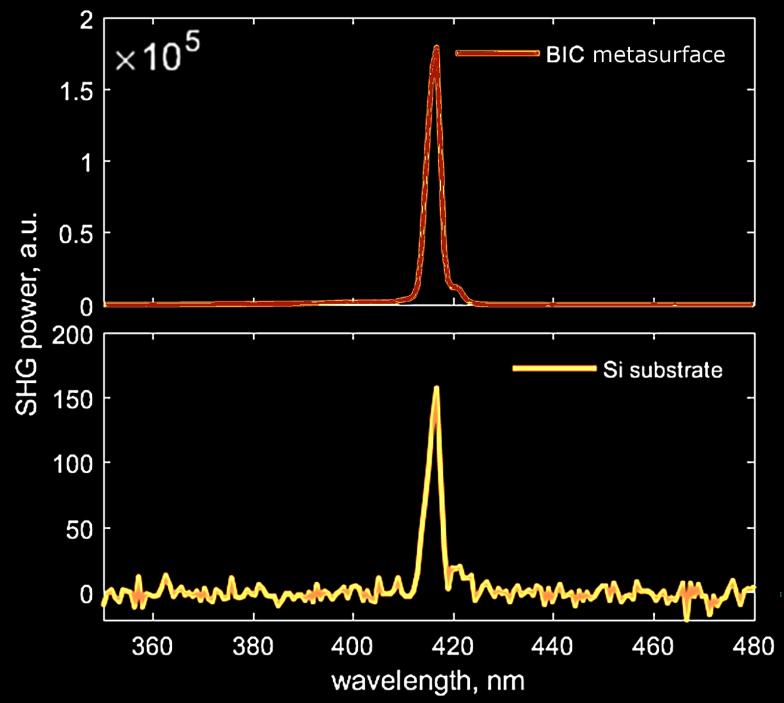
Bernhardt et al., Nano Letters, 20, 5309-5314 (2020)

ENHANCING 2D MATERIAL SHG WITH A BIC METASURFACE

WS_2 flake on BIC metasurface

WS_2 flake on Si substrate

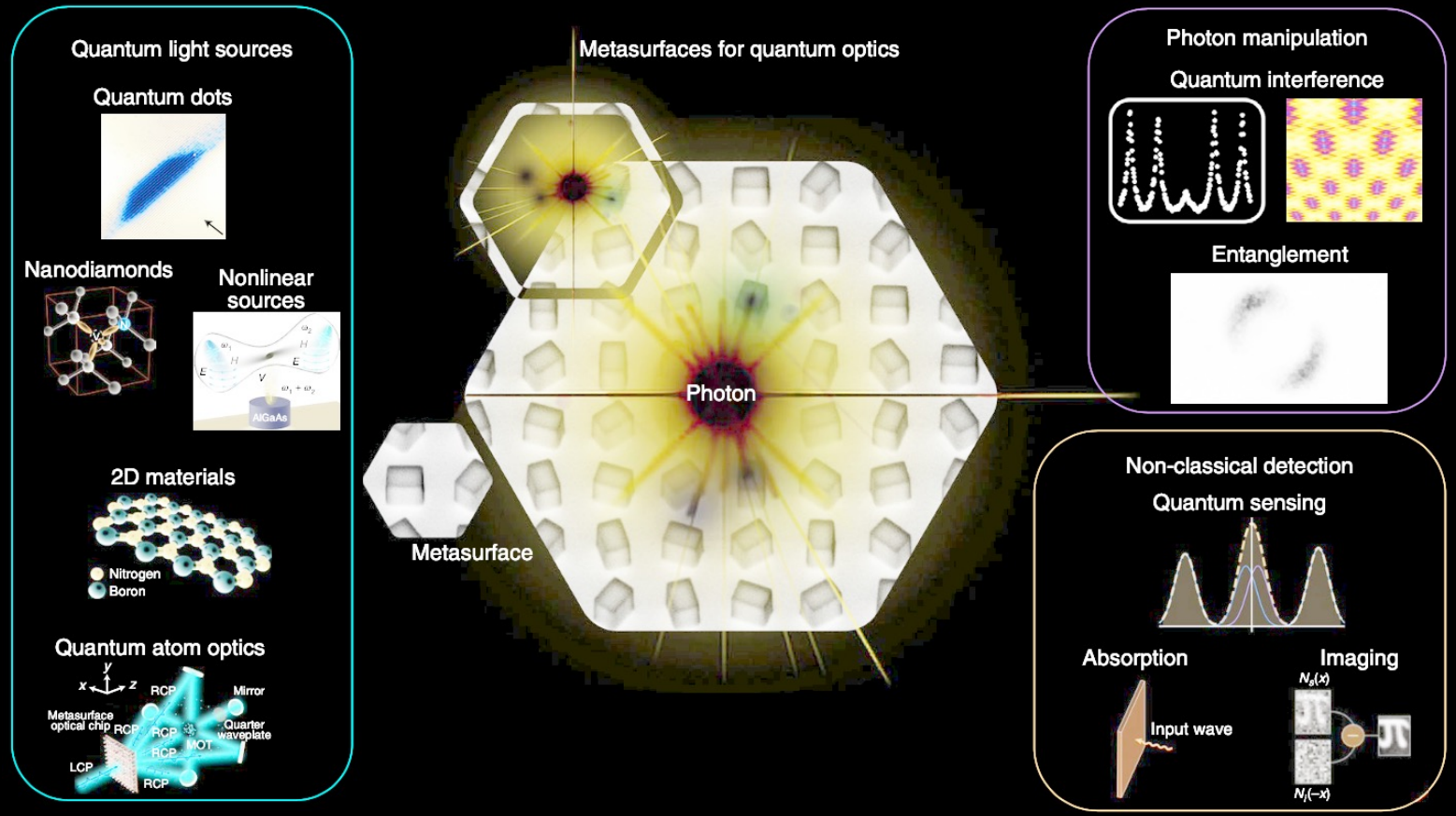




- Over 1200 times SHG enhancement!
- Next: quantum light

Bernhardt et al., Nano Letters, 20, 5309-5314 (2020)

METASURFACES FOR QUANTUM OPTICS

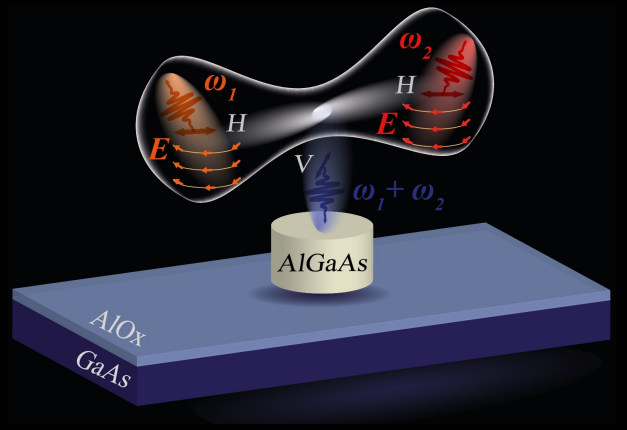


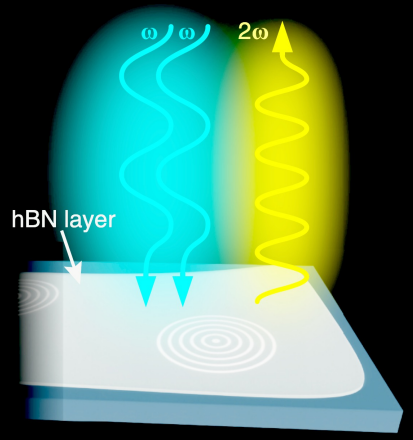
Solntsev et al., Nature Phot. 15, 327–336 (2021)

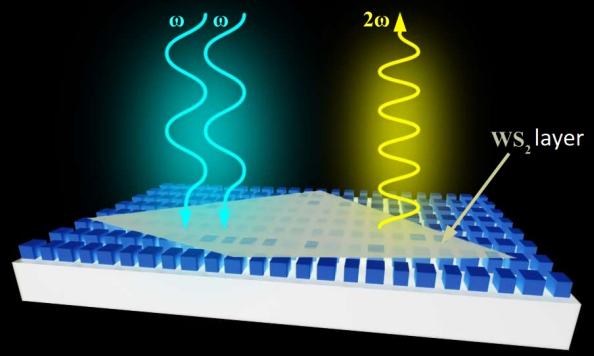
CONCLUSION

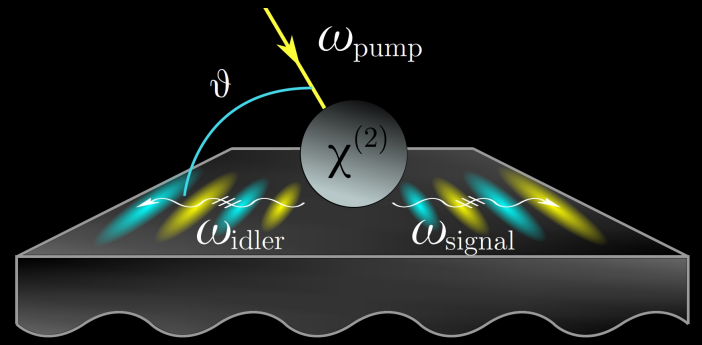
- Nonlinearity creates and controls entanglement
- Works on the nano-scale and at room temperature
- Now the quest is on for

2D / meta / nano










X M Jin


R Grange


M Lobino


T Persch


A A Sukhorukov


I Aharonovich


Y S Kivshar


D N Neshev


D Antonosyan


G Leo


T Tran


M Rahmani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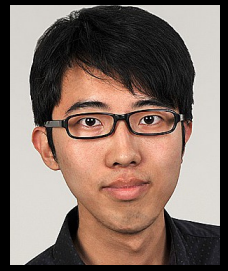
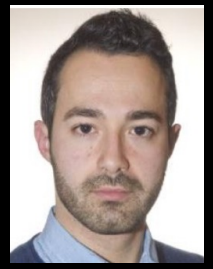
F Setzpfandt

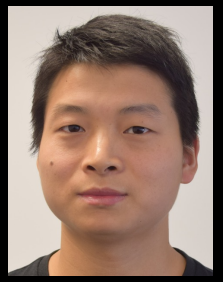

M Petrov


N M HDuong


K Wang


G Marino


S White


H Chen


J Titchener


N Olekhno

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