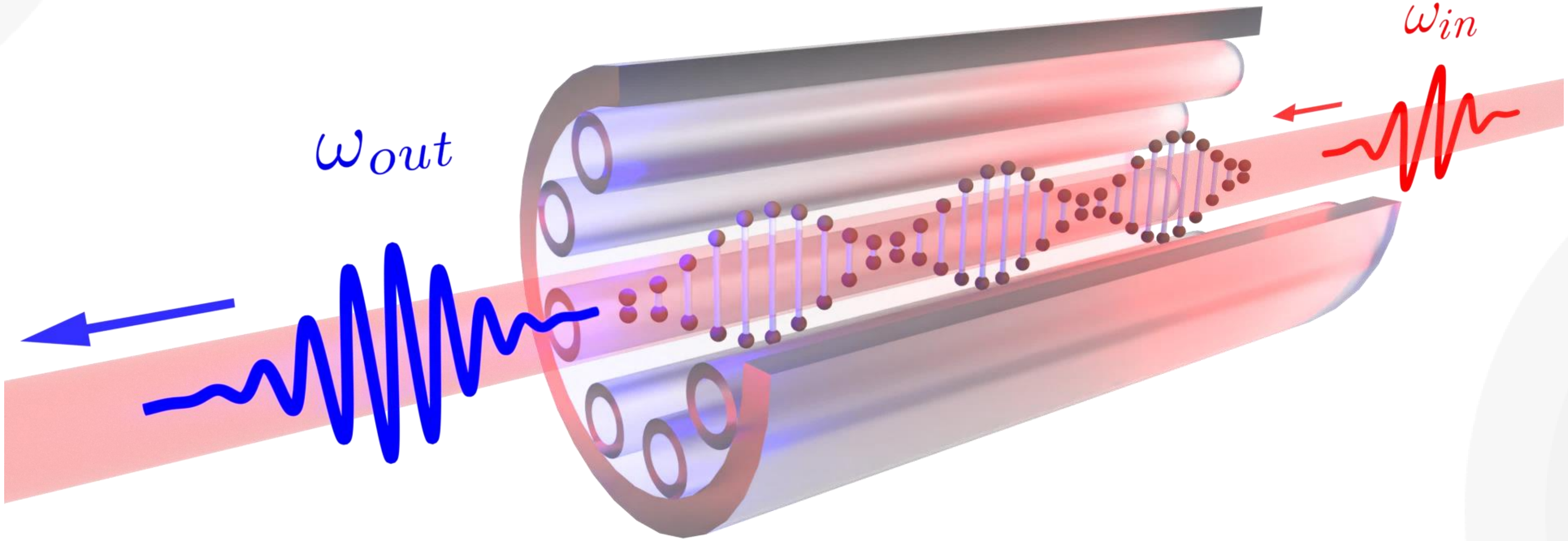
Coloring light quanta with synchronous molecular motion

David Novoa



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EFO·LAB EXTREME FIBRE OPTICS LABORATORY
APG APPLIED PHOTONICS GROUP
ikerbasque Basque Foundation for Science

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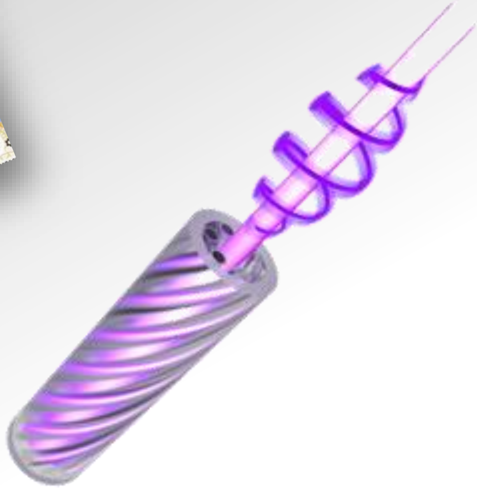
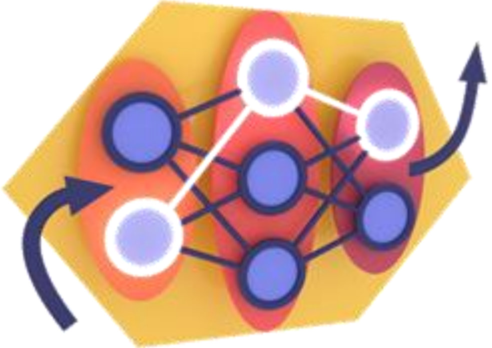
Extreme Fibre Optics Lab



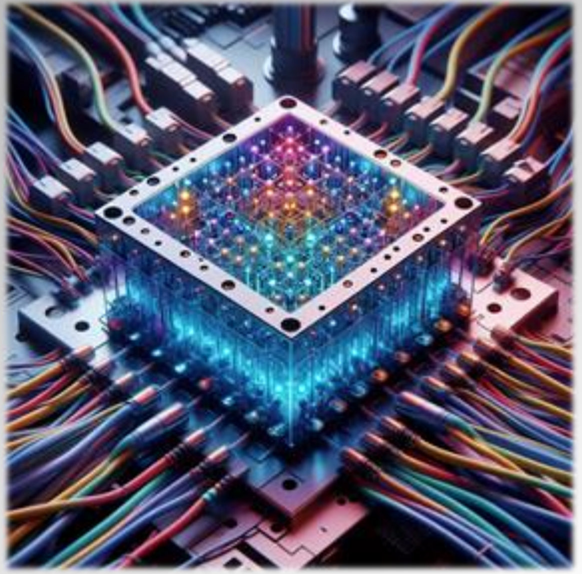
Exotic light sources

Nonlinear quantum optics



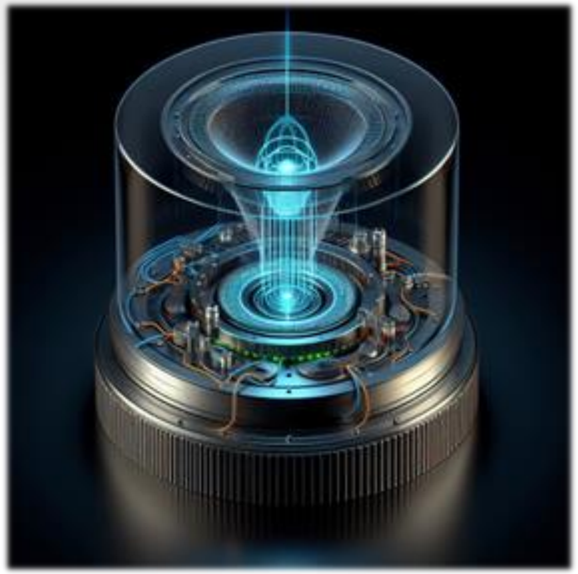
Smart photonics

Quantum technologies



Q-Computing

Q-Simulation

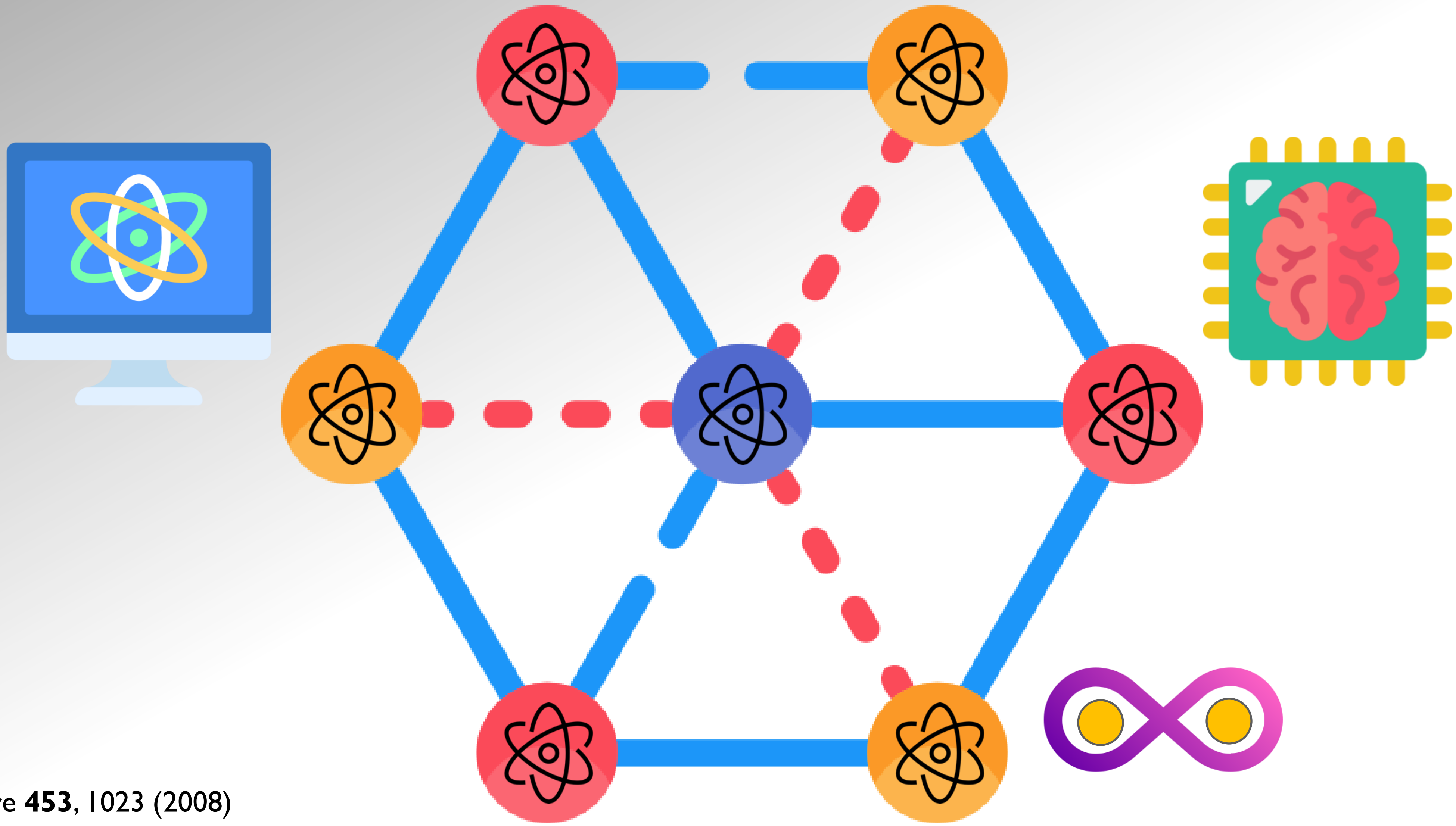


Q-Sensing

Q-Communications

Images generated by OpenAI's DALL-E & Microsoft Designer

Boosting hybrid quantum networks



Kimble, Nature **453**, 1023 (2008)

Awschalom *et al.*, PRX Quantum **2**, 017002 (2021)

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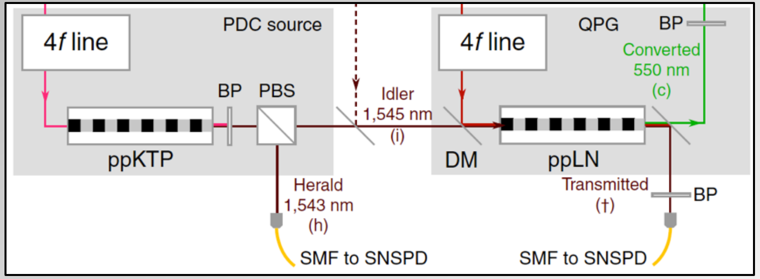
Approaches to quantum frequency conversion

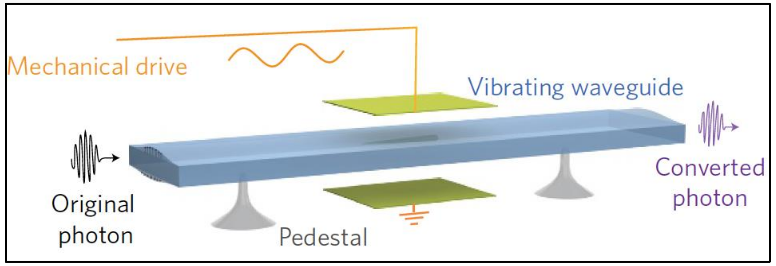
A good quantum convertor must (ideally) be

- Efficient
- Broadband
- Tunable
- Low noise & decoherence



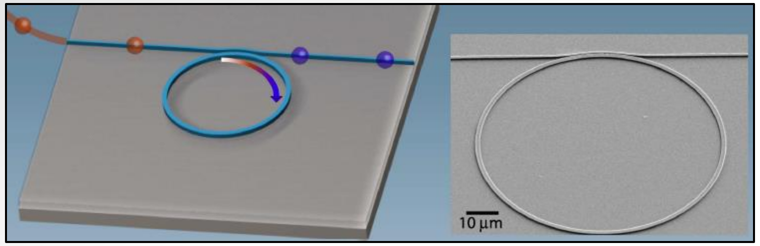
Nonlinear crystals

Allgaier *et al.*, Nat. Comms. **8**, 14288 (2017)



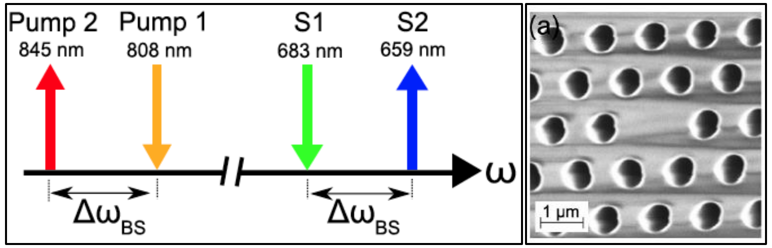
Opto-mechanical systems

Fan *et al.*, Nat. Photonics **10**, 766 (2016)



Microresonators on chip

Singh *et al.*, Optica **6**, 563 (2019)



Optical fibers

McGuinness *et al.*, Phys. Rev. Lett. **105**, 093604 (2010)

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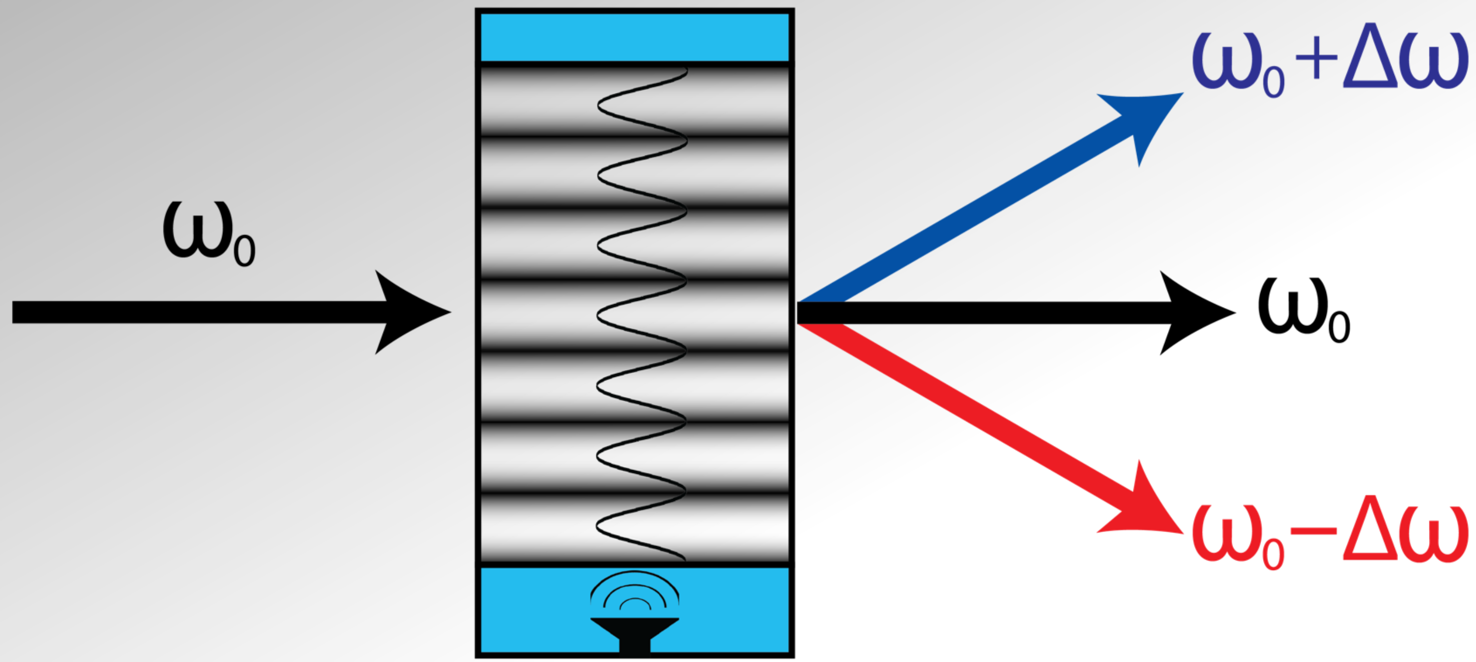
Optical modulation of quantum light

"Acousto-optic" modulation at optical frequencies?



Wish list

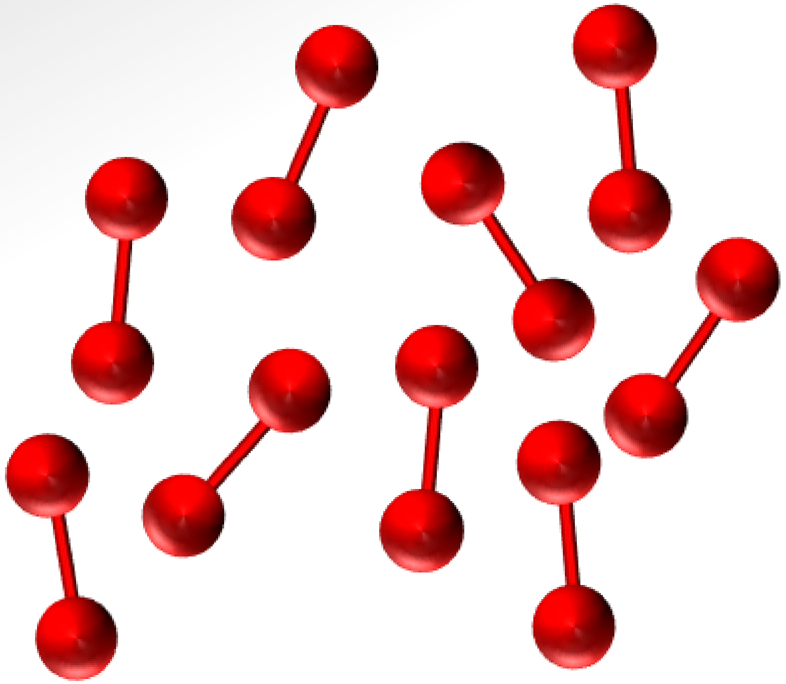
- **Near-unity efficiency**
- **Tunable & Broadband**
- **Low (noise & loss)**
- **High spatial quality**
- **Thresholdless**

Hydrogen as a molecular modulator

- Large shift ~ 125 THz

- Near-unity efficiency
- Tunable & Broadband
- Low (noise & loss)
- High spatial quality
- Thresholdless

- Highly dispersive
- Weak nonlinear response



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Hydrogen as a molecular modulator

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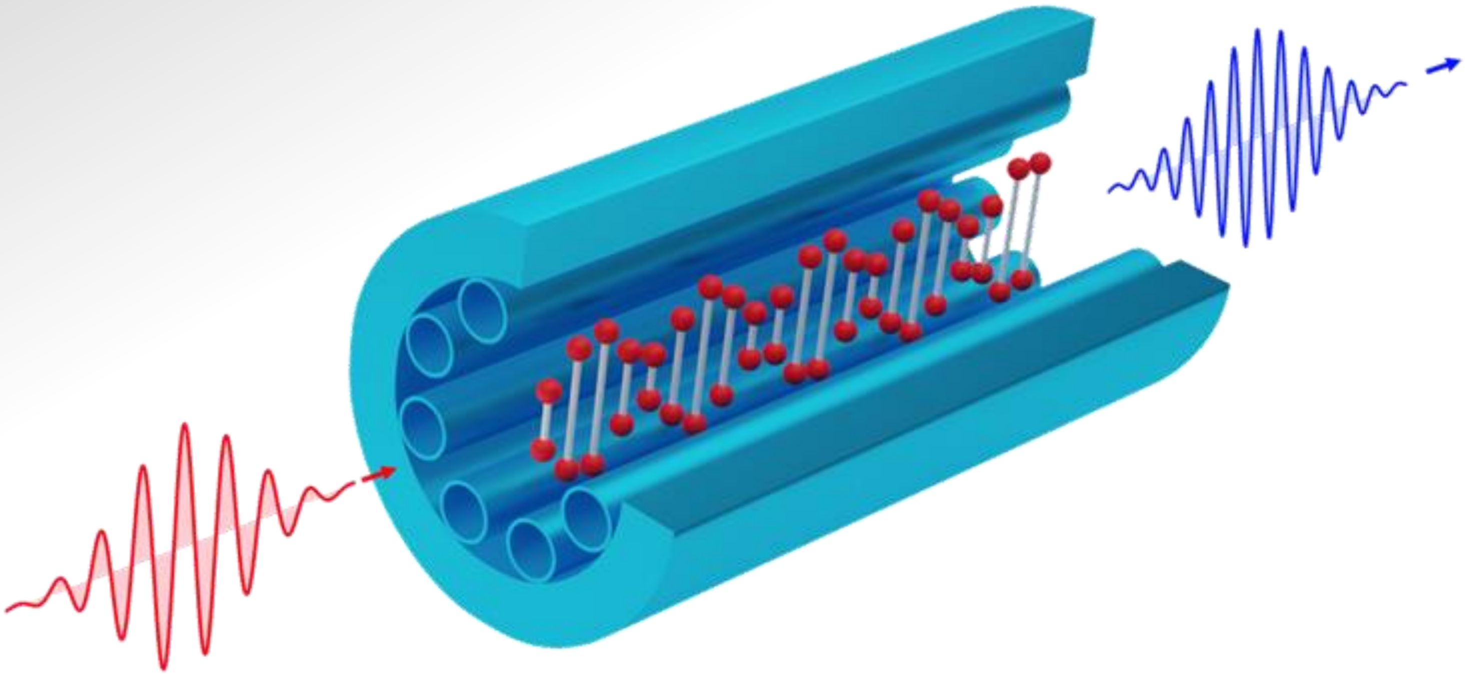

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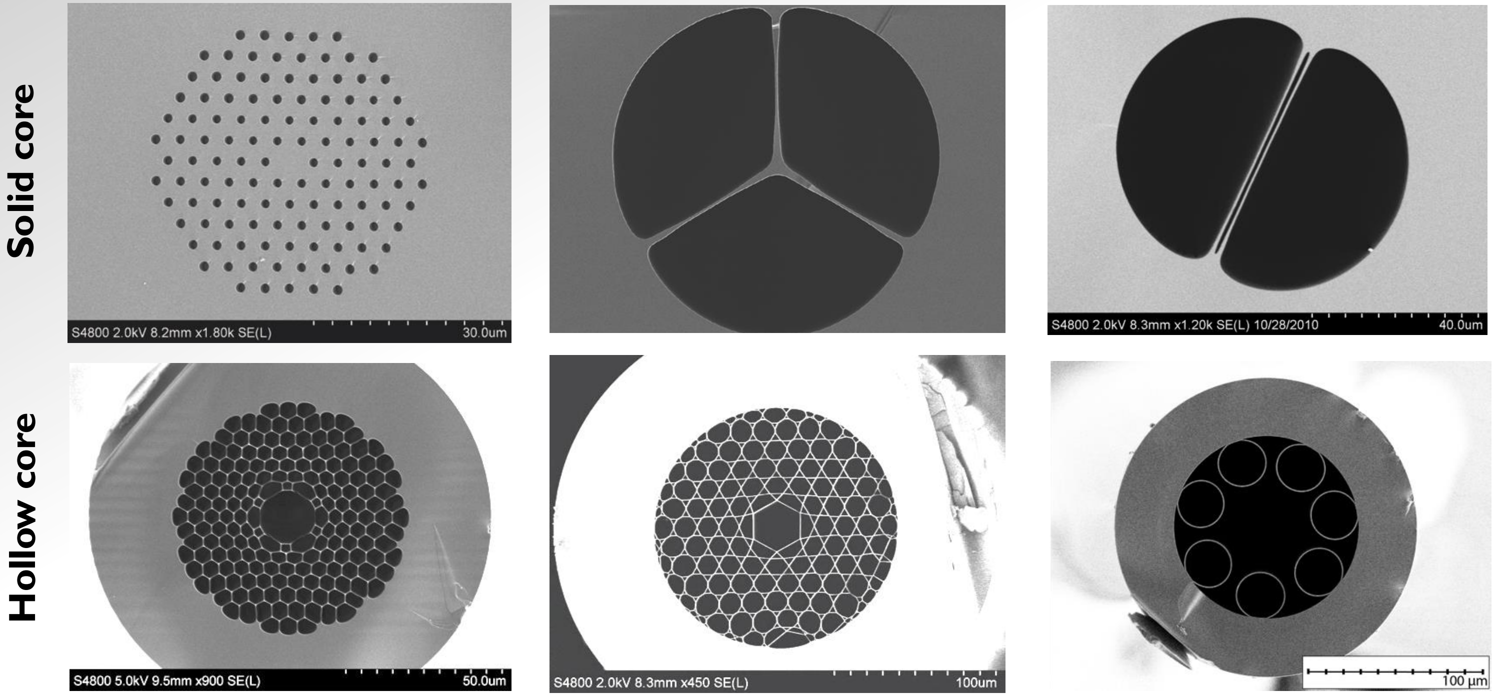
Photonic crystal fibers

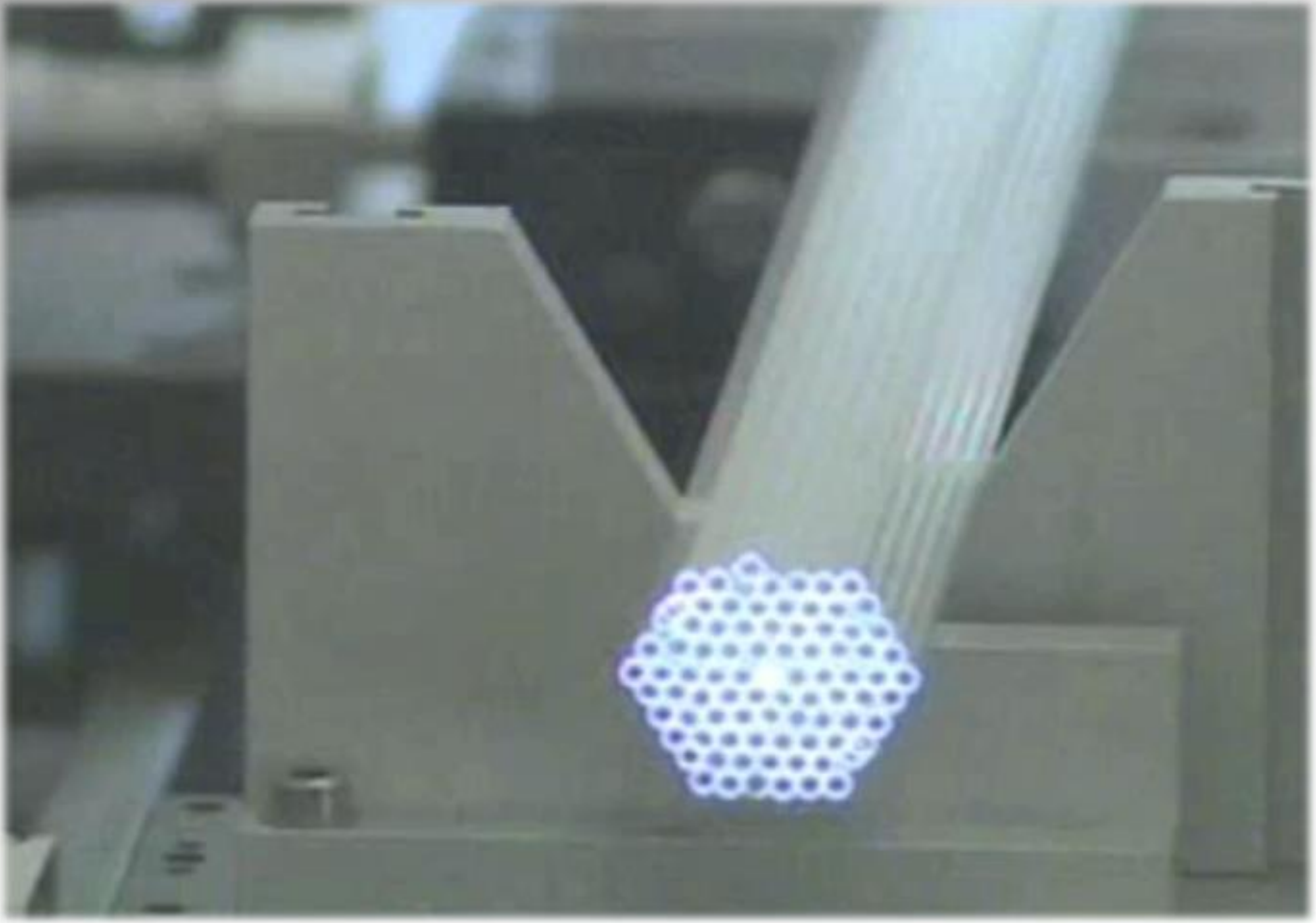
- Philip Russell introduced the concept of PCF in the 90's
- Micro-structured optical fibers with a periodic cladding
- Capable of guiding light in either solid or hollow channels

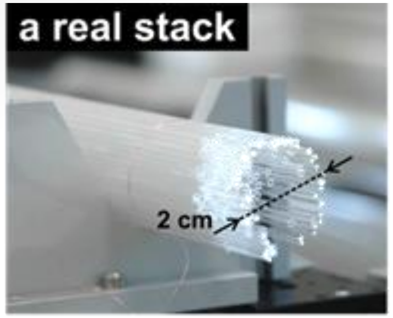


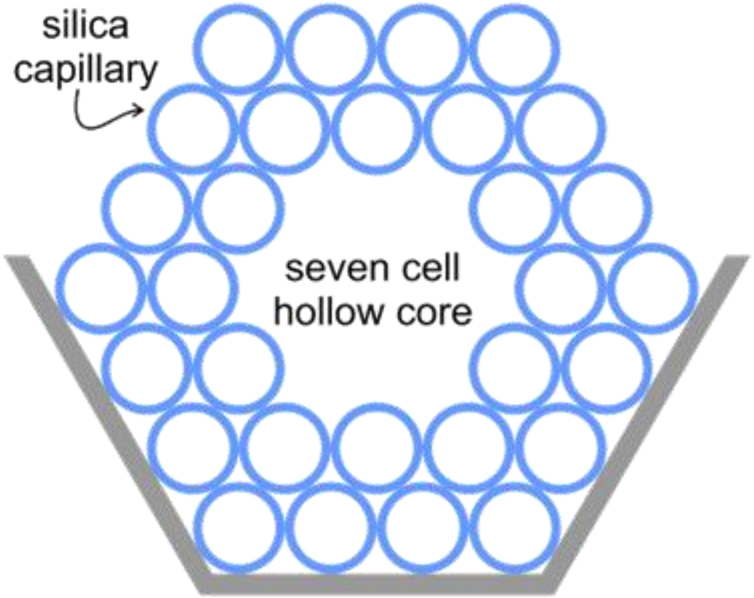
Knight *et al.*, Opt. Lett. **21**, 1547 (1996)

Russell, Science **299**, 358 (2003)

PCF Fabrication: Stack and Draw

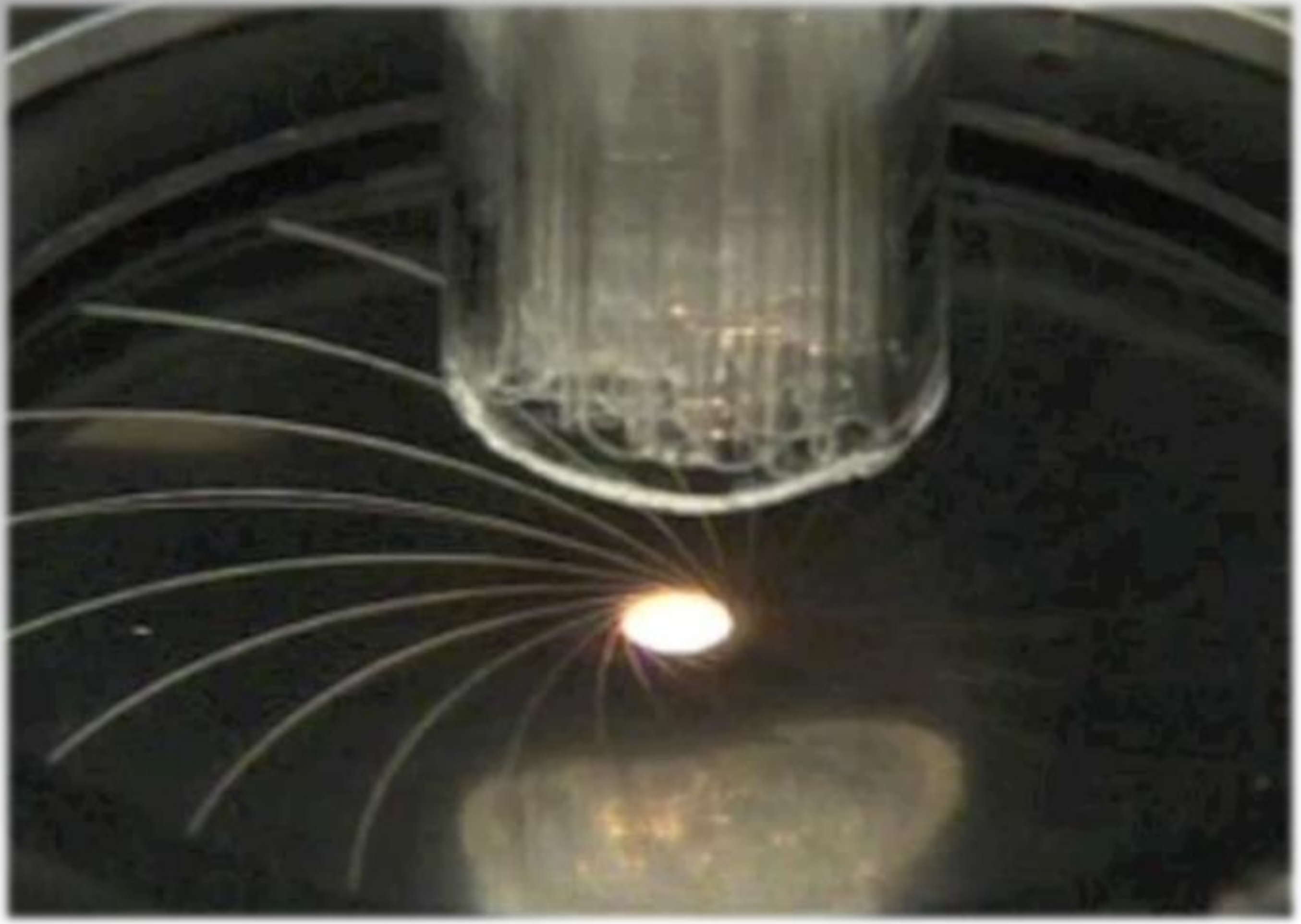


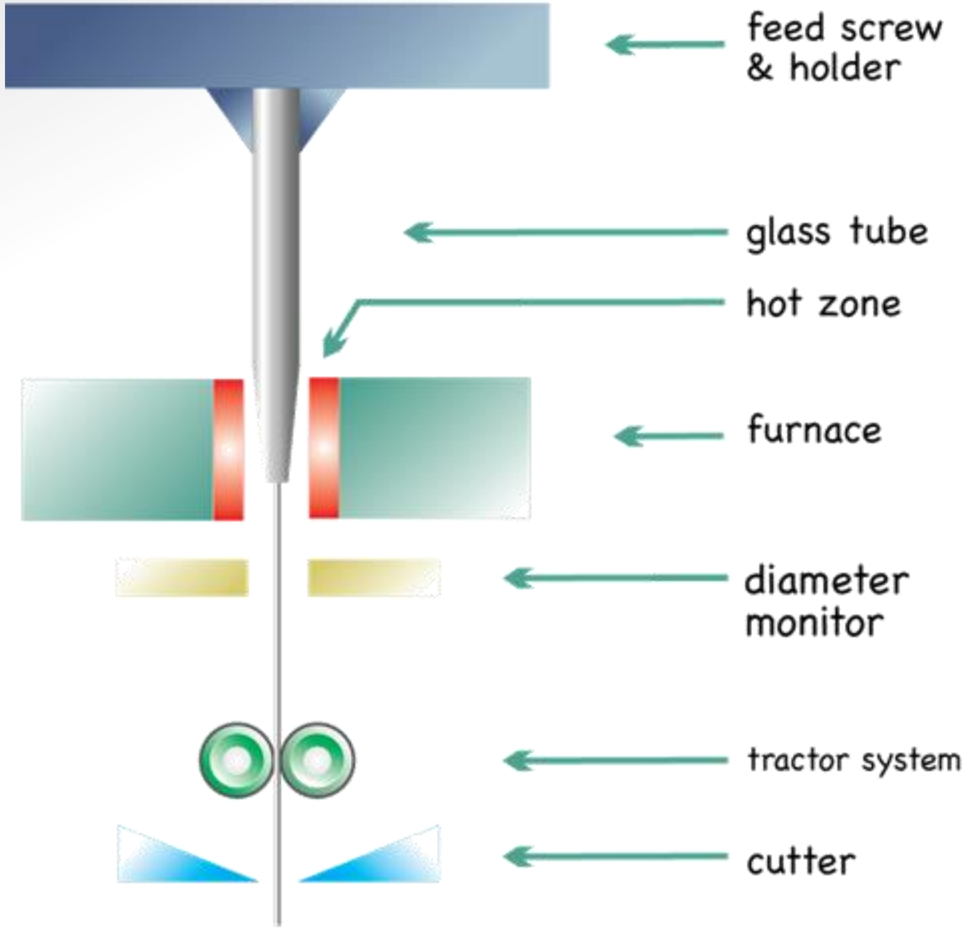




Stacking

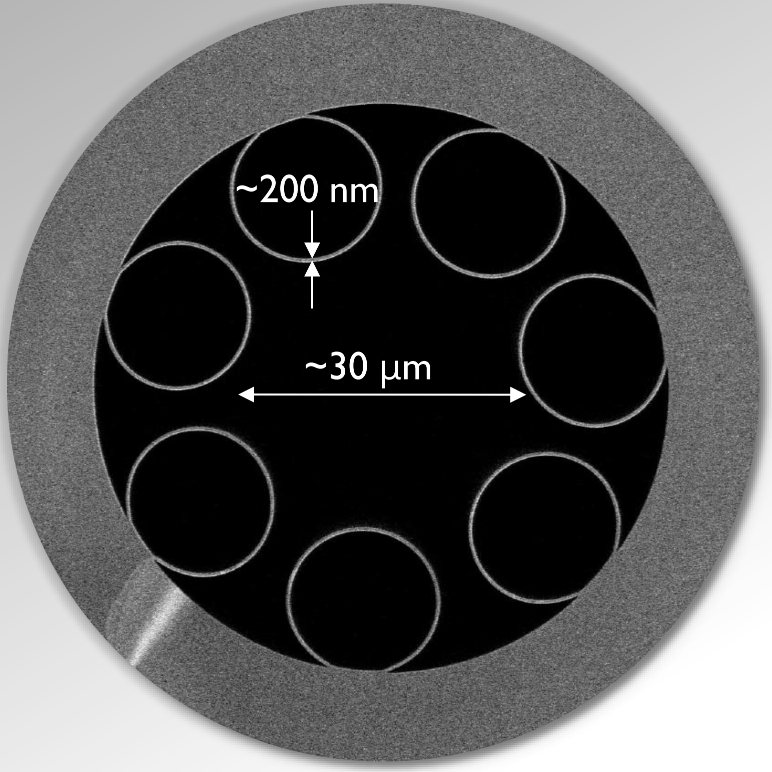
PCF Fabrication: Stack and Draw





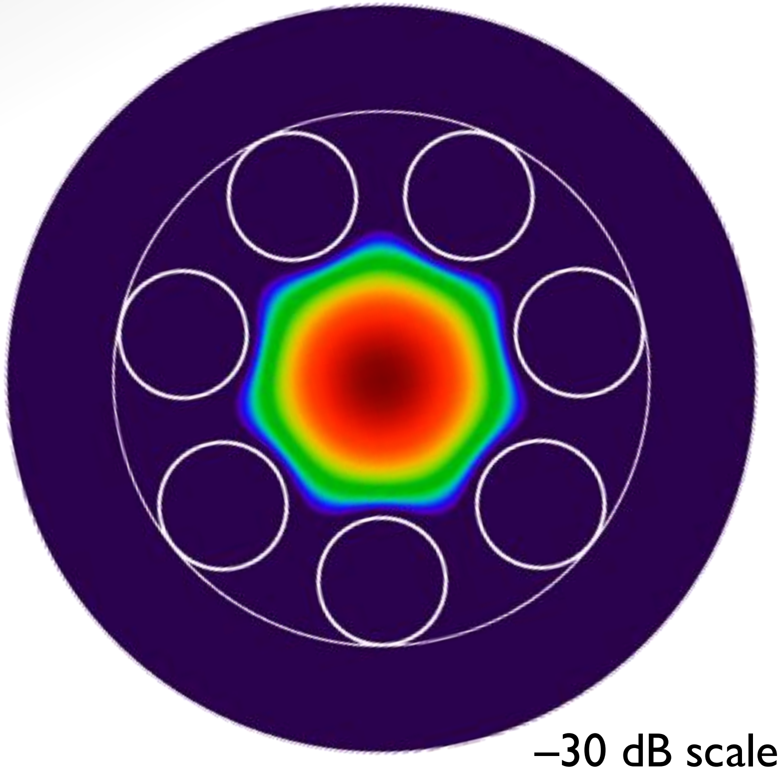
Hollow-core anti-resonant fibers

Scanning electron micrograph



- “Faster” speed of light
- Ultralow attenuation
- Broad transmission windows
- High damage threshold
- Adjustable dispersion & nonlinearity

Finite-element modelling



–30 dB scale

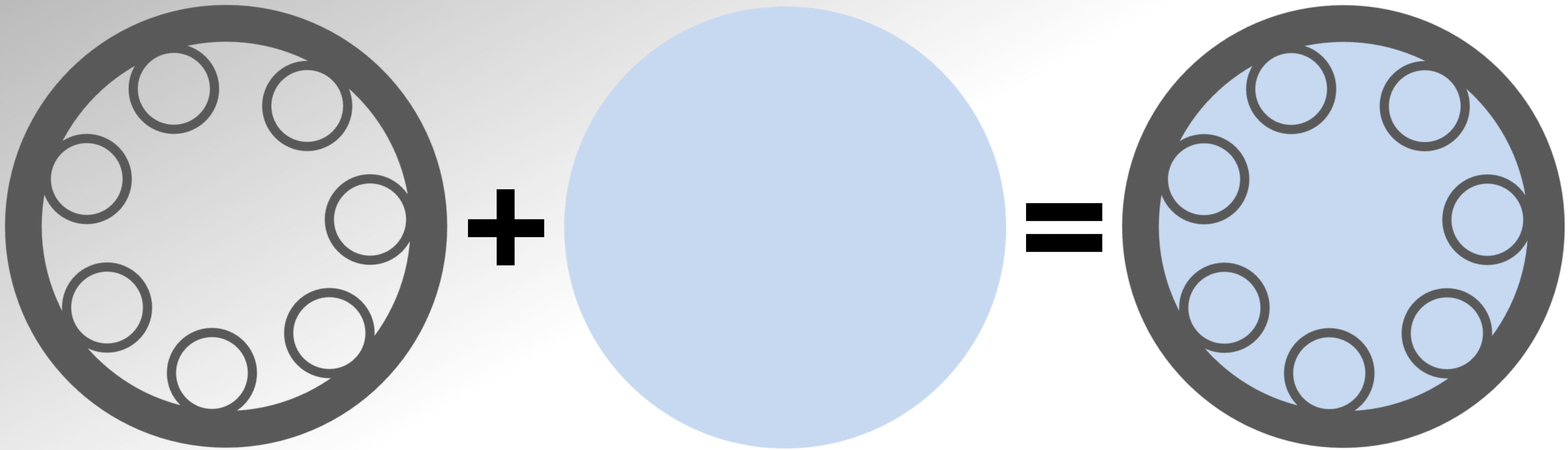
Benabid *et al.*, Science **298**, 399 (2002)
Pryamikov *et al.*, Opt. Express **19**, 1441 (2011)
Numkam-Fokoua *et al.*, Adv. Opt. Phot. **15**, 1 (2023)

Pressure-tunable dispersion

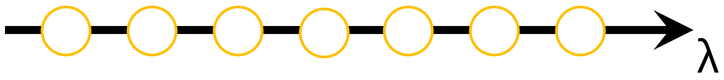
Waveguide dispersion
(Anomalous)

Gas dispersion
(Normal)

Combined dispersion
(Tunable)



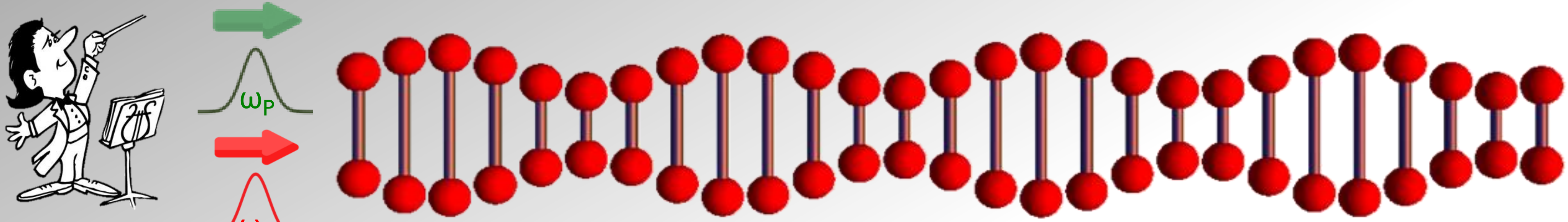
Zero-dispersion wavelength

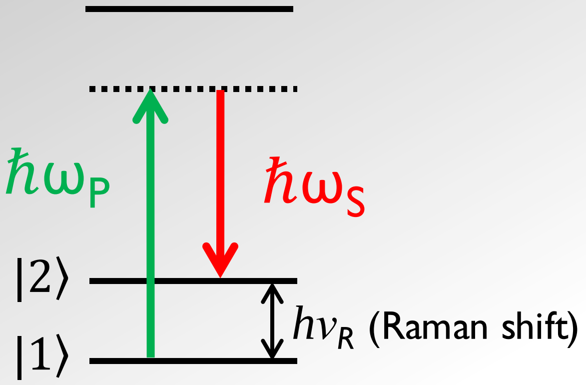


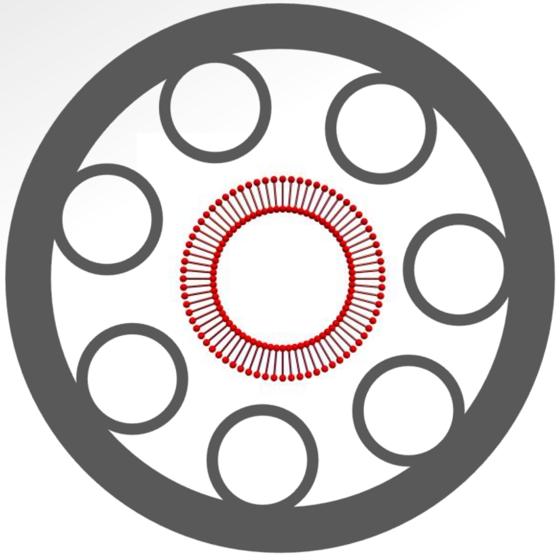
$P_1 > P_2 > P_3 \cdots$

Marcatili *et al.*, Bell. Sys. Tech. J. **43**, 1783 (1964)
Russell *et al.*, Nat. Photonics **8**, 278 (2014)

Raman scattering & molecular modulation







Synchronous molecular motion

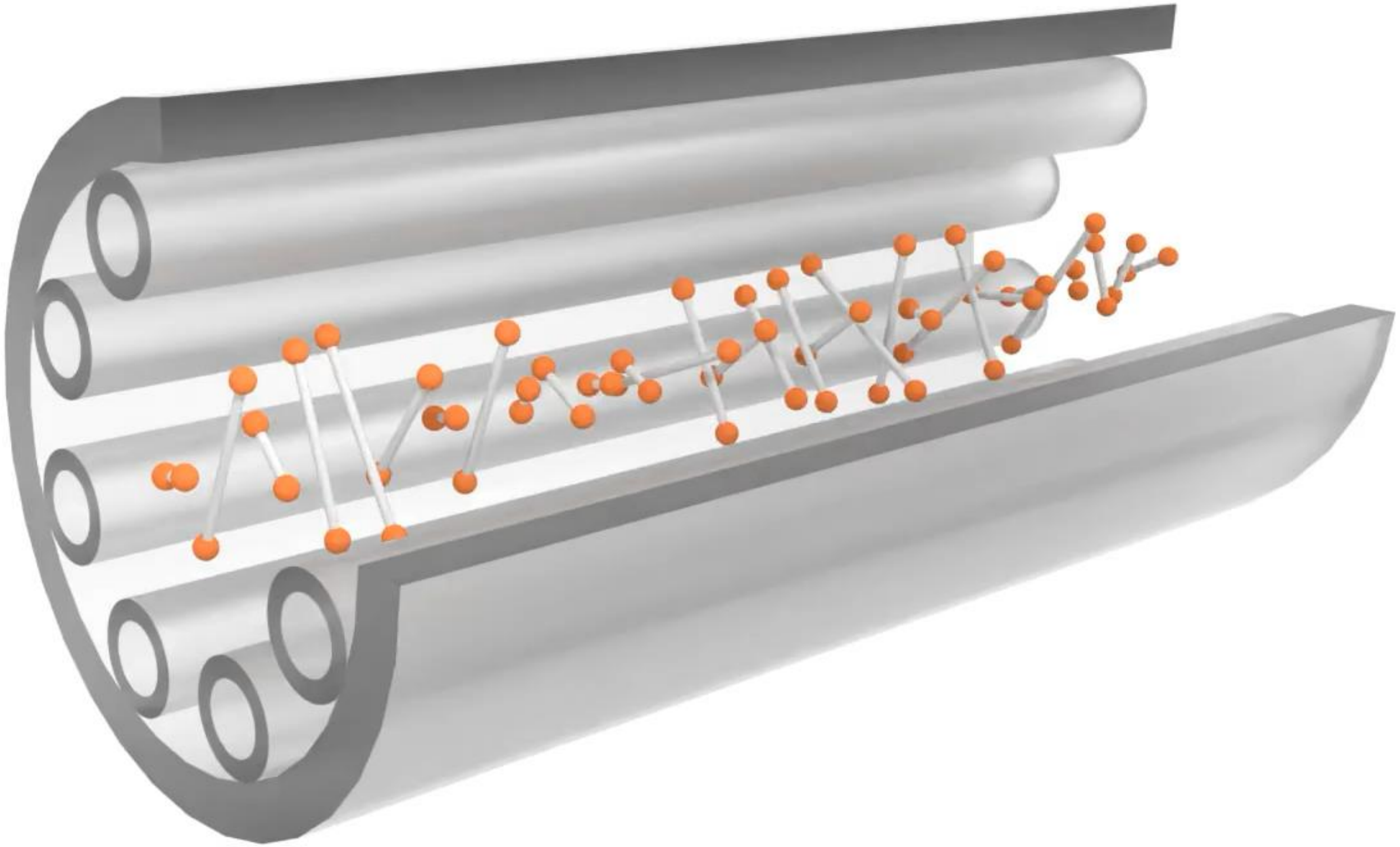
⇩

Travelling refractive-index pattern

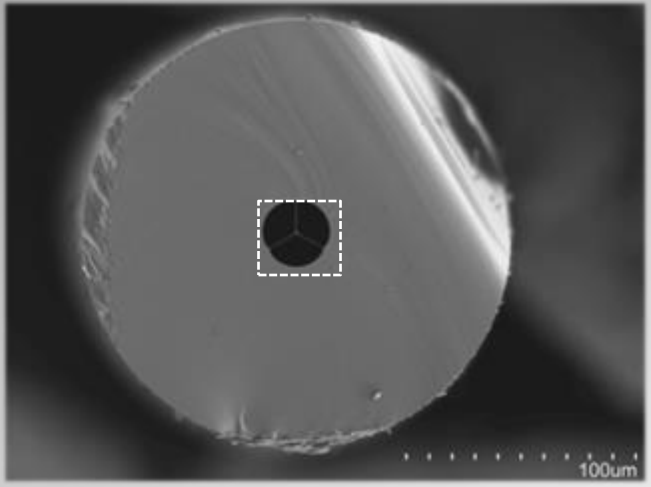
Hosseini *et al.*, Phys. Rev. Lett. **119**, 253903 (2017)
Mridha *et al.*, Optica **6**, 731 (2019)
Tyumenev *et al.*, ACS Photonics **7**, 1989 (2020)
Arcos *et al.*, EPL, *in press* (2024)

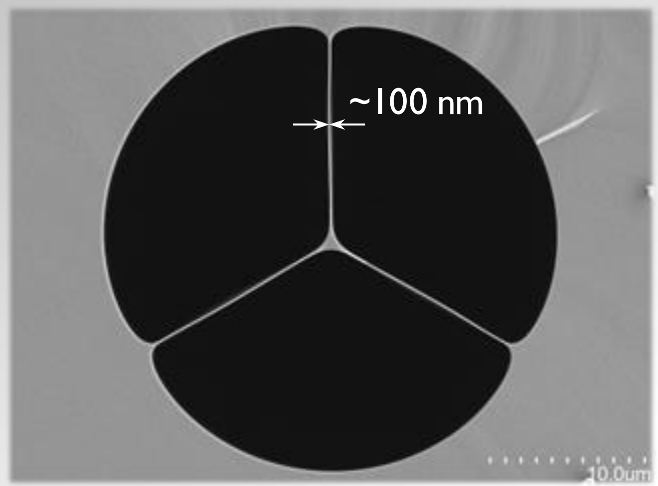
Quantum frequency conversion of single photons

Tyumenev, Hammer, Joly, Russell, DN, Science **376**, 621 (2022)

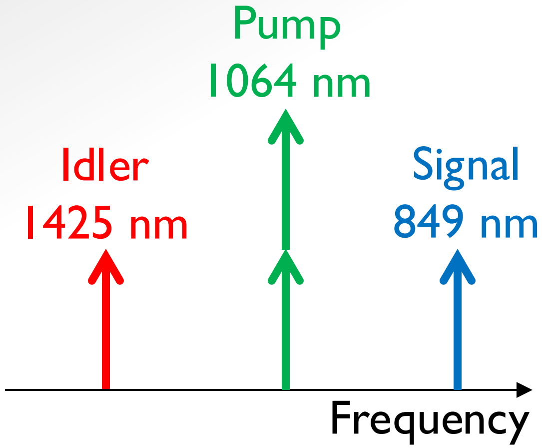


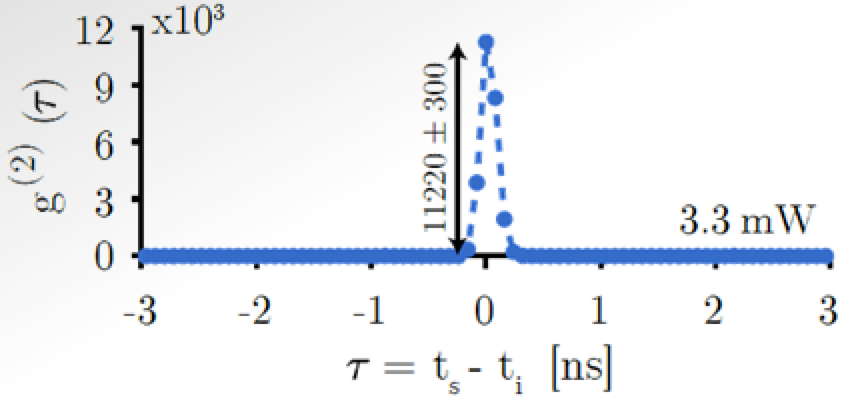
Source of entangled biphotons



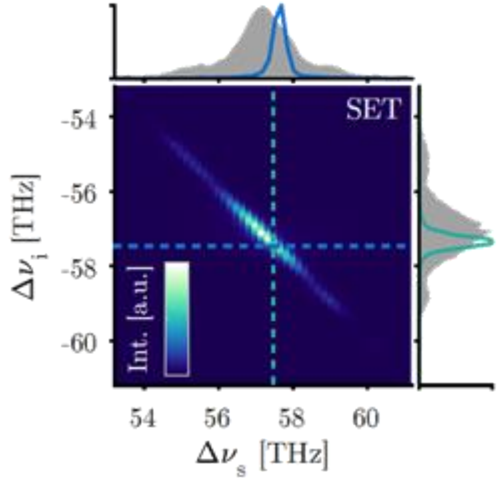


Spontaneous four-wave mixing





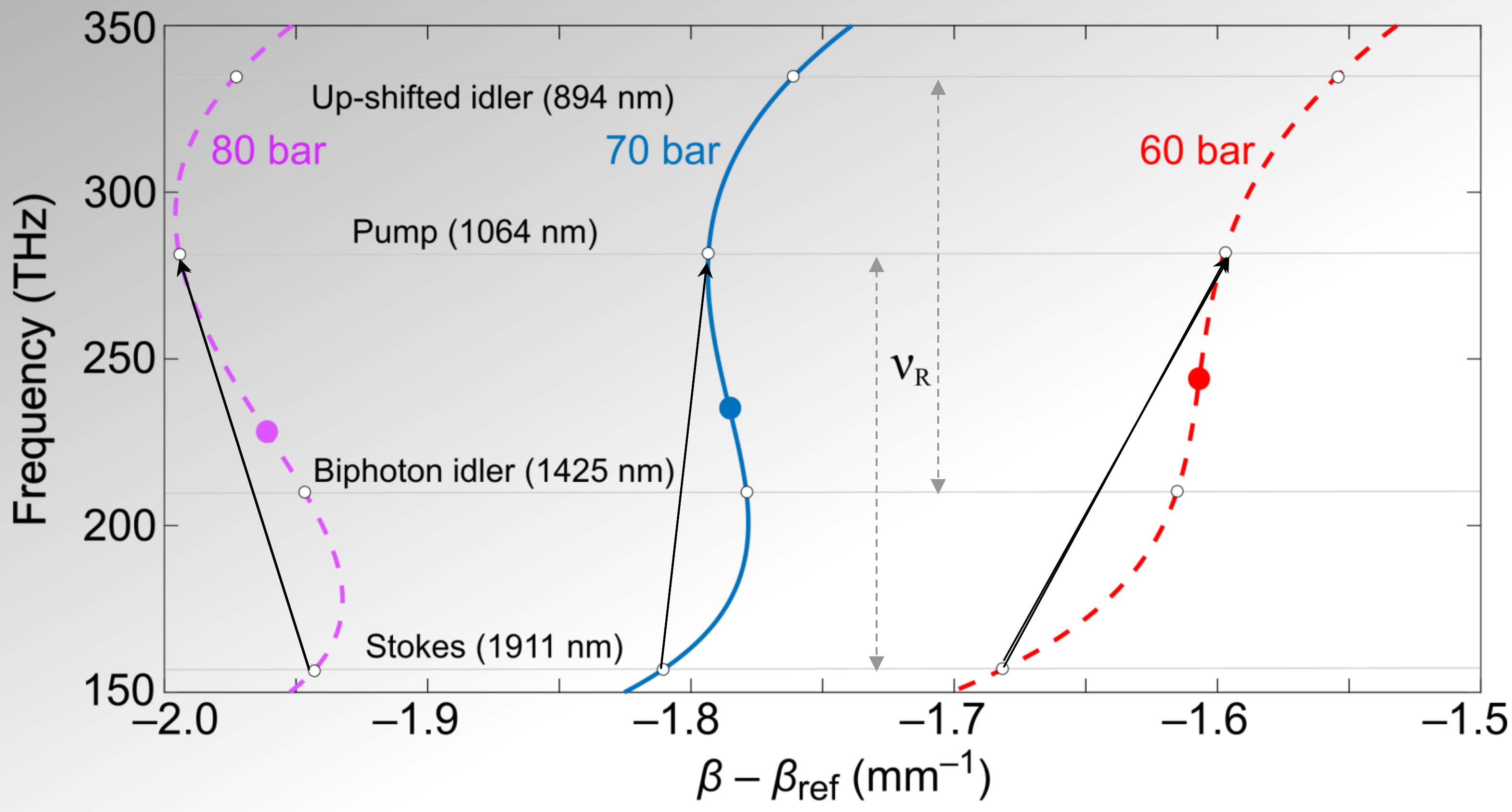
Stimulated emission tomography

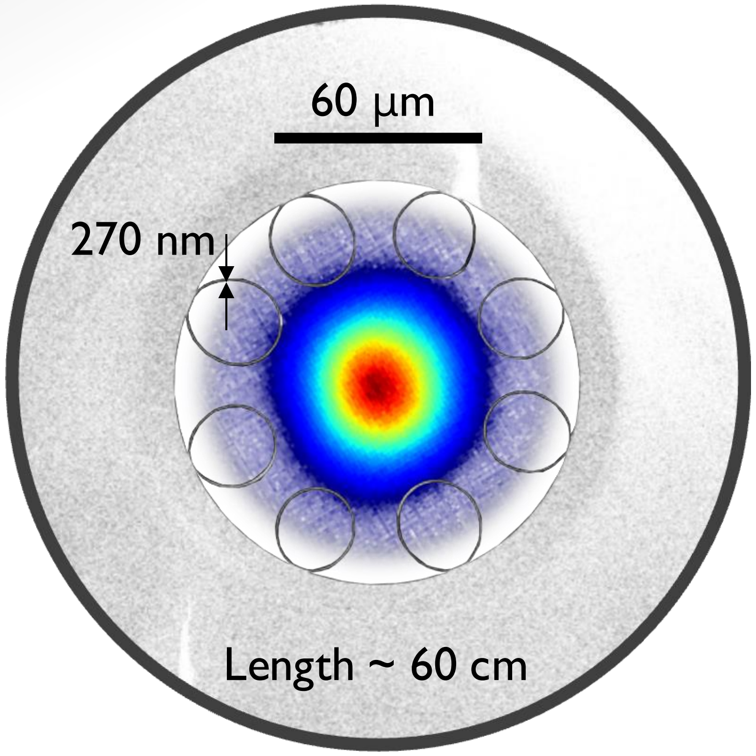


Hammer *et al*., Phys. Rev. Res. **2**, 012079 (2020)

Phase-matched molecular modulation

Energy & momentum must be conserved in the interaction



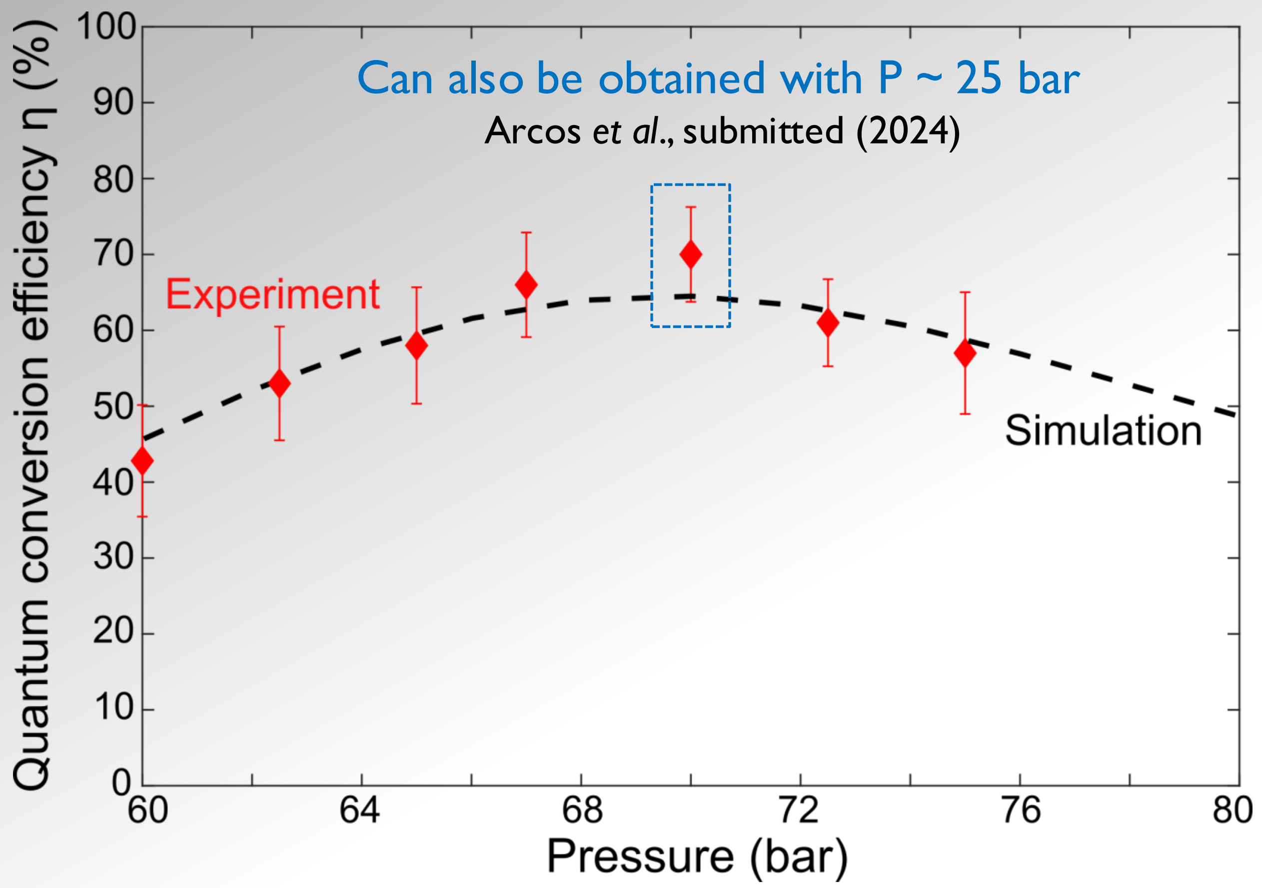


Record-high launching efficiency ~ **96%**

Tyumenev *et al*., Science **376**, 621 (2022)

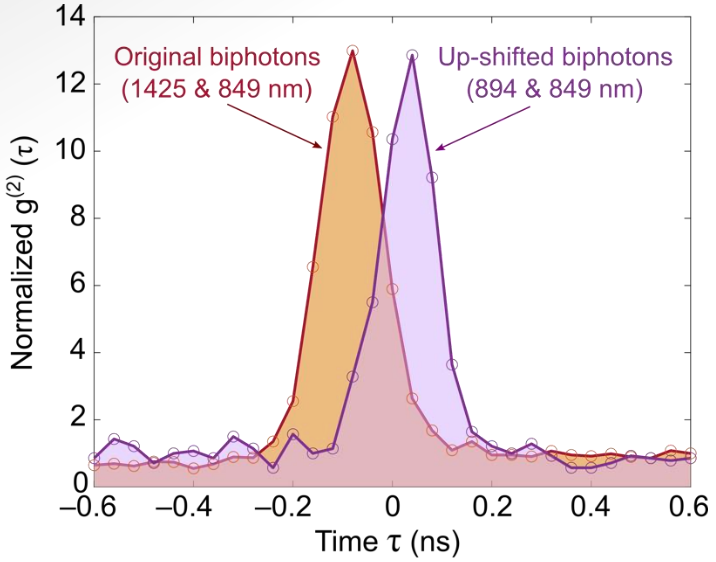
Quantum frequency conversion of single photons

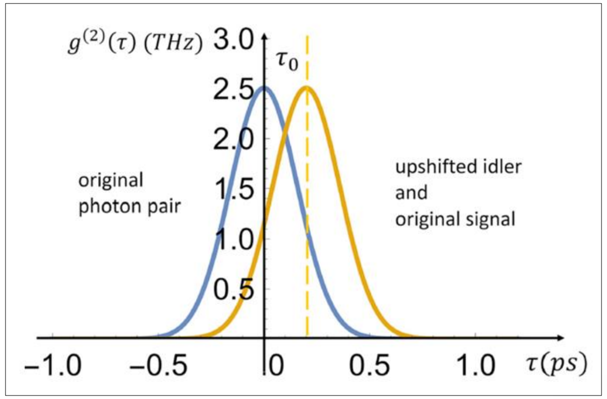
Highly efficient conversion at the quantum level



Tyumenev *et al.*, Science **376**, 621 (2022)

Preservation of nonclassical correlations





Wang *et al.*, Phys. Rev. A **108**, 063706 (2023)

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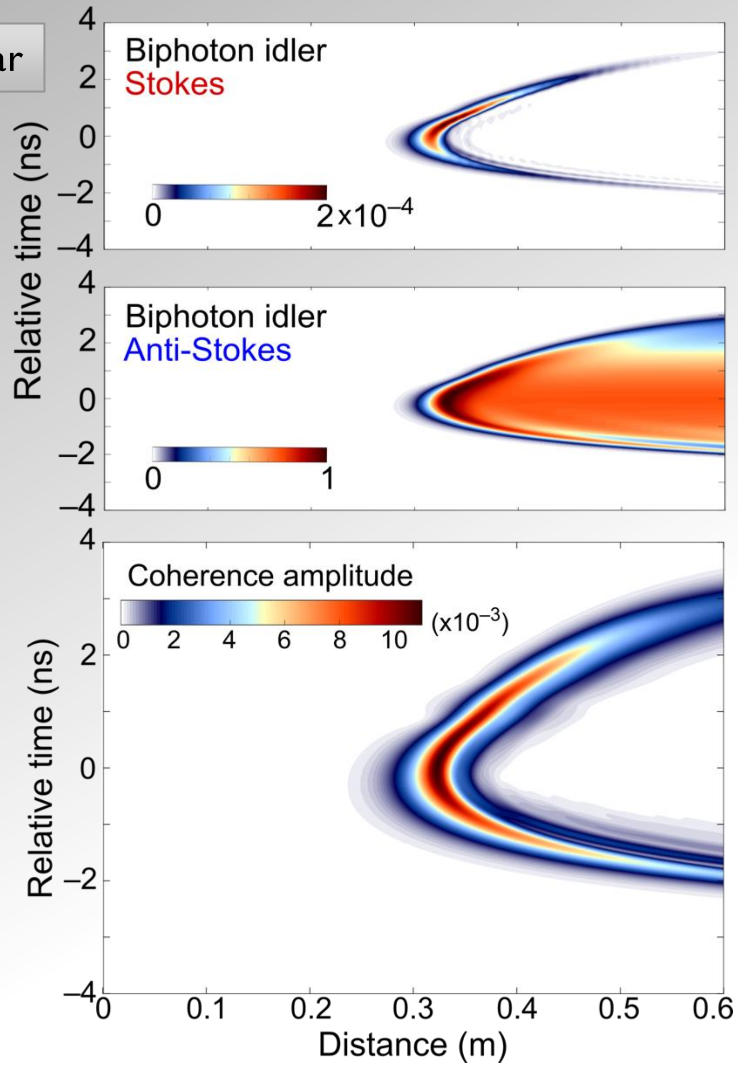
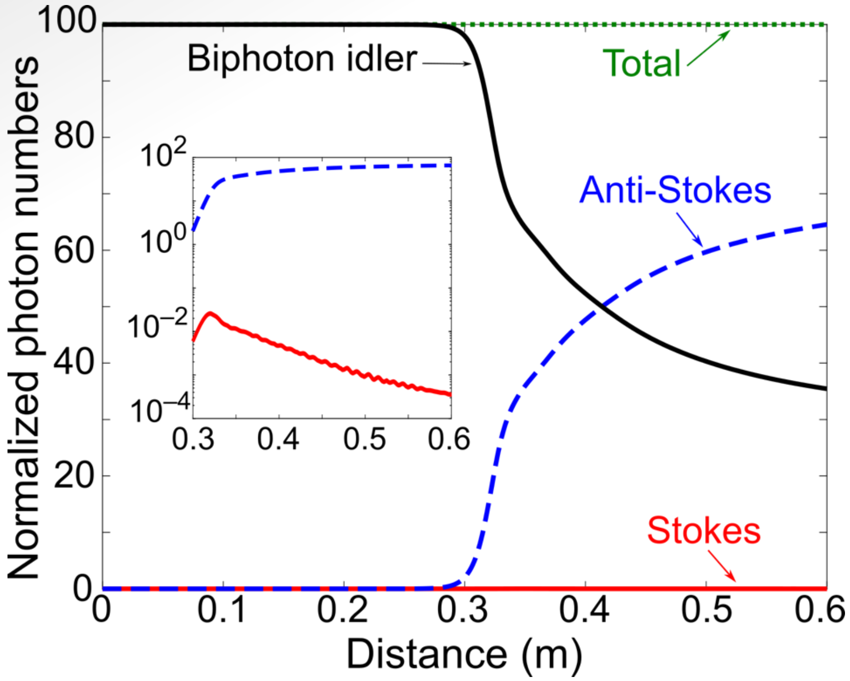
Modelling of the quantum conversion process

Modelling: Maxwell-Bloch equations

P = 70 bar



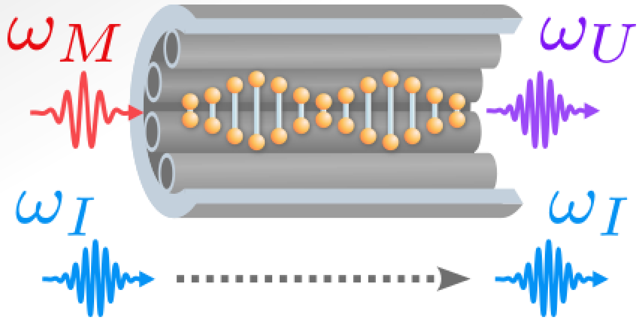
Selectivity: Down-conversion is 5 orders of magnitude weaker



Quantum model of fibre-based molecular modulation

Does this approach preserve other quantum properties such as entanglement?

Formalism	Light	Matter
Maxwell-Bloch		
G. Tavis-Cummings		



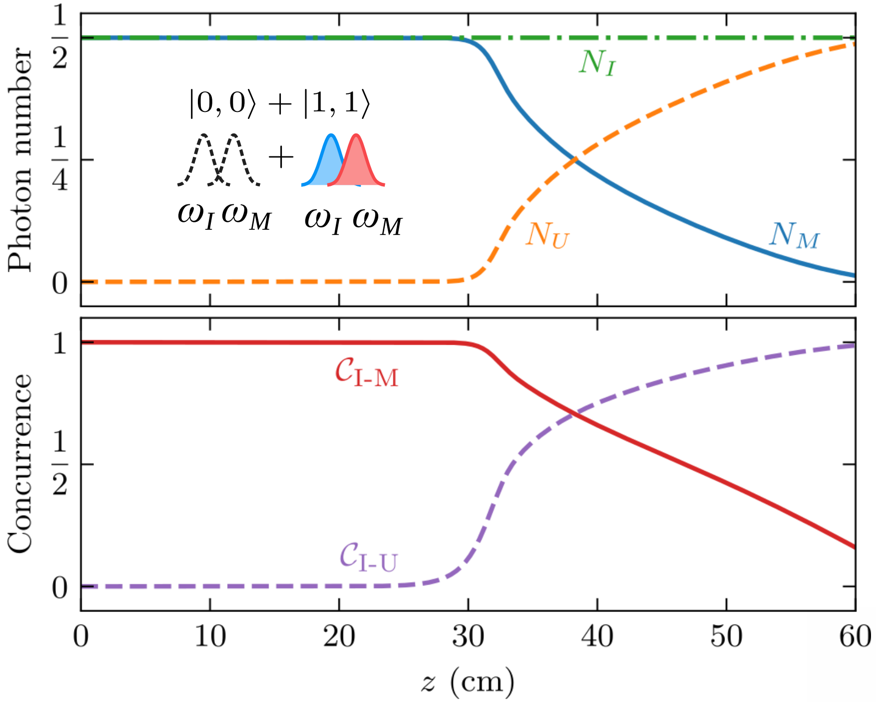
Two-stage model:

(I) Preparation of the molecular quantum coherence

$$\hat{H}^I_\alpha = \hbar G_S\left(e^{i\Delta\beta z}\alpha_P\alpha_S^*\hat{J}^+ + e^{-i\Delta\beta z}\alpha_P^*\alpha_S\hat{J}^-\right)$$

(II) Molecular modulation of arbitrary quantum states

$$\hat{H}^I_\xi = \hbar G_U\left(\xi^* e^{i\Delta\beta z}\hat{a}_M^\dagger\hat{a}_U + \xi e^{-i\Delta\beta z}\hat{a}_M\hat{a}_U^\dagger\right)$$



Tavis and Cummings, Phys. Rev. **170**, 379 (1968)

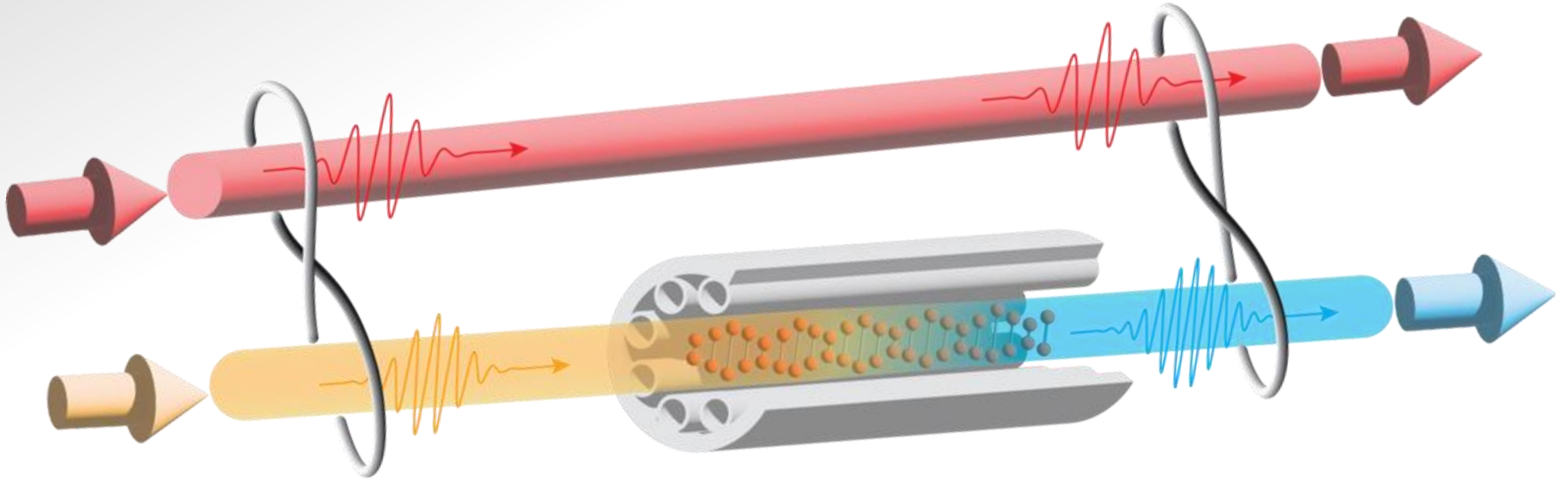
González-Raya *et al.*, submitted (2024)

Conclusions

✓ Anti-resonant fibers are excellent platforms for quantum nonlinear photonics

✓ Efficient quantum frequency conversion achieved in H_2-filled anti-resonant fibers

✓ A full quantum framework predicts the transfer of entanglement during molecular modulation



Thank you for your attention!

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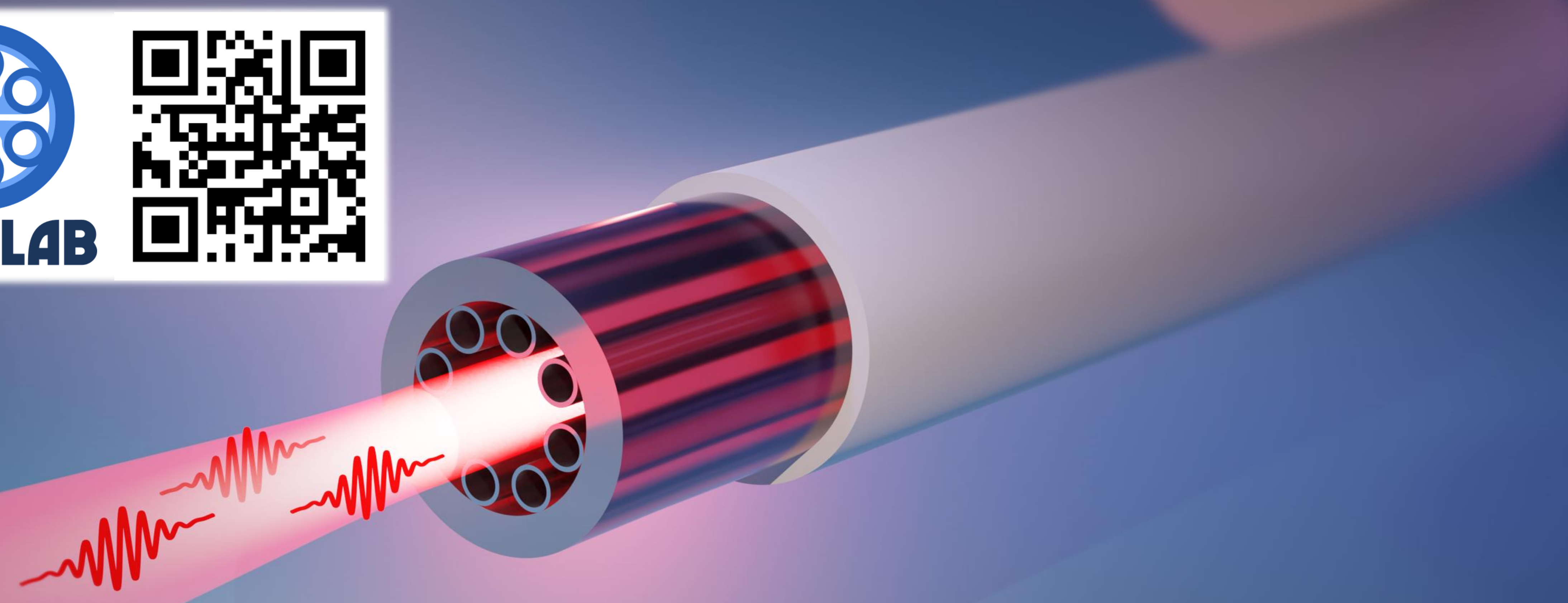

eman ta zabal zazu
UPV EHU
ikerbasque
Basque Foundation for Science
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