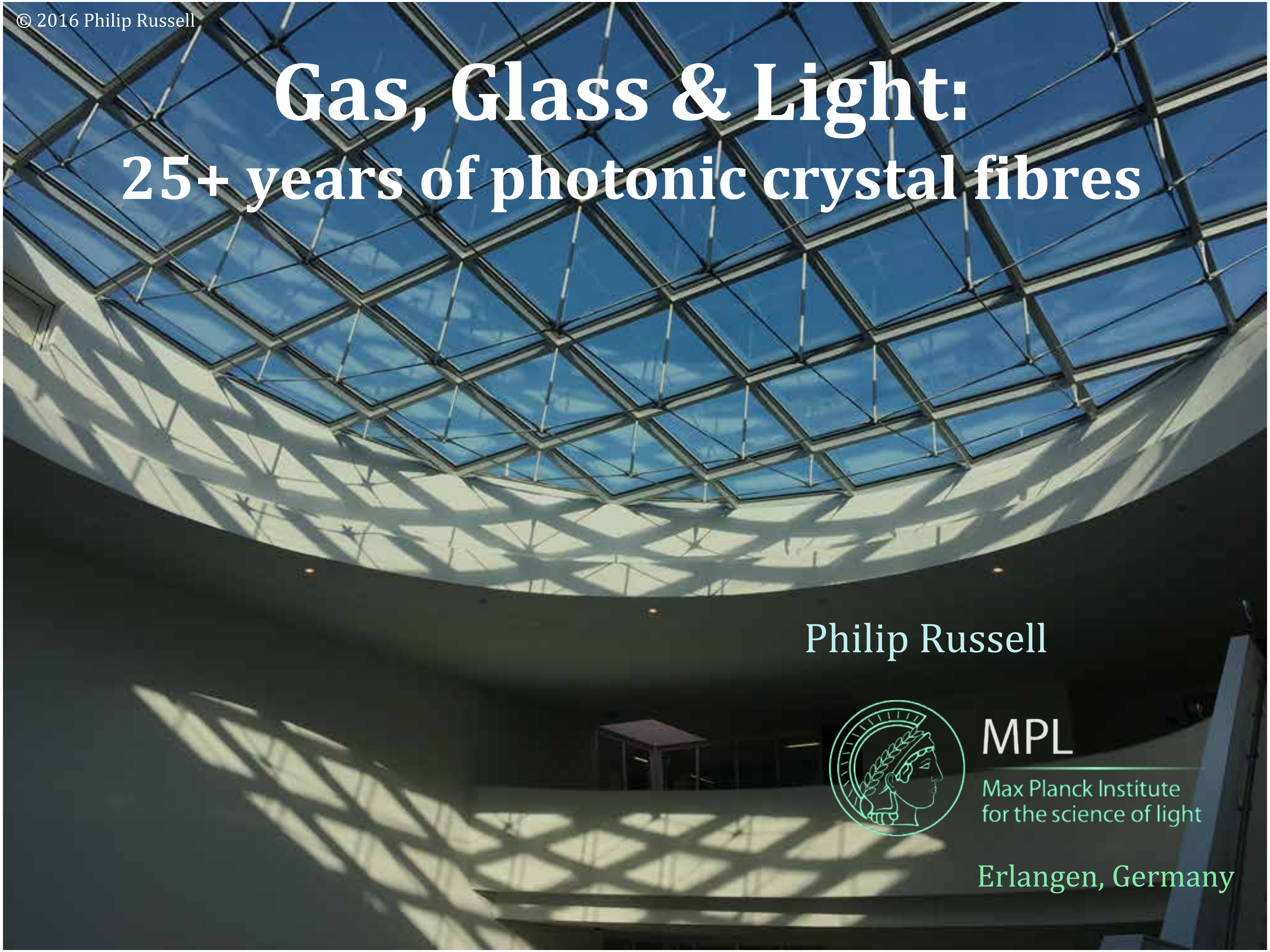
Gas, Glass & Light:
25+ years of photonic crystal fibres



Philip Russell

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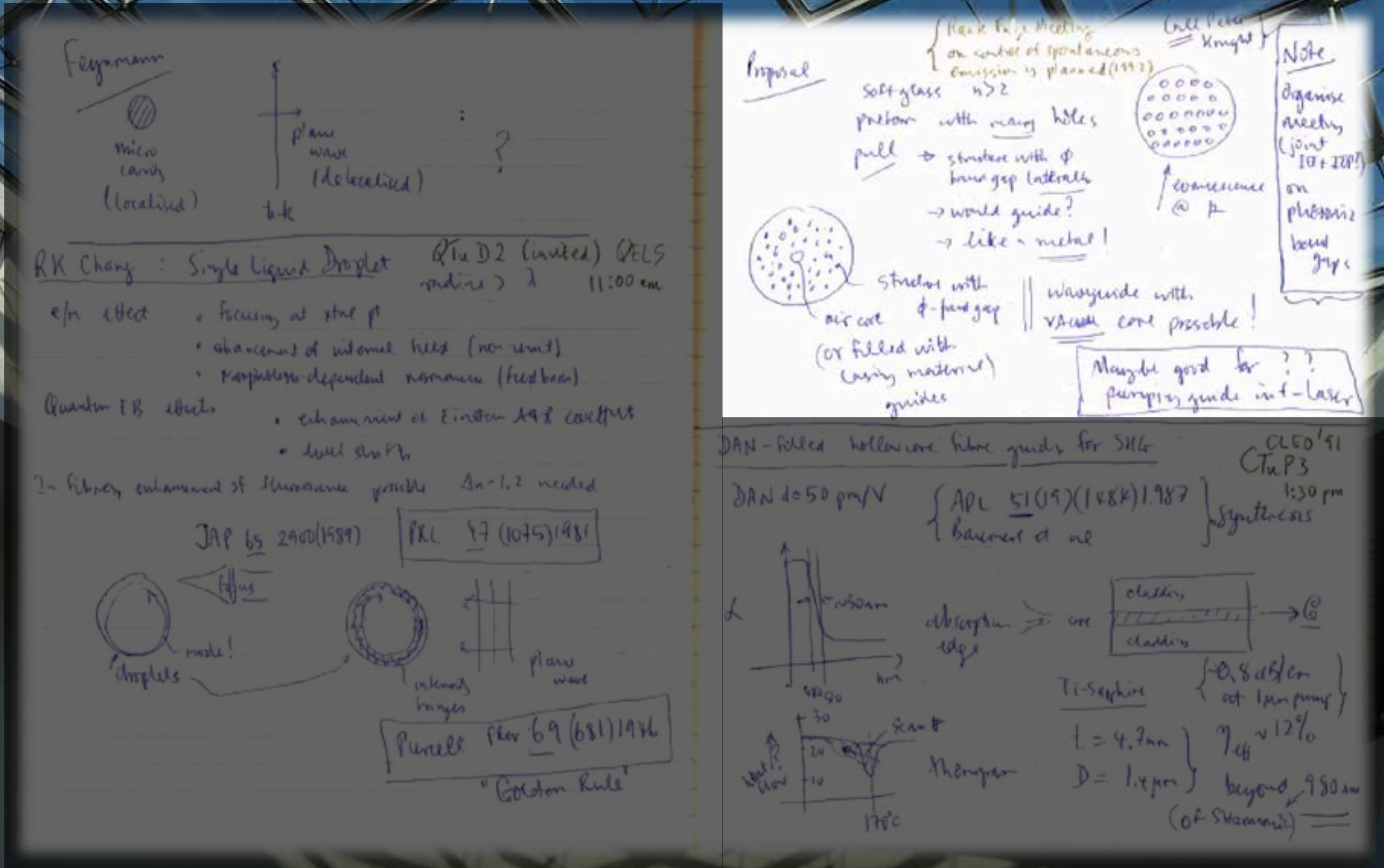
Erlangen, Germany

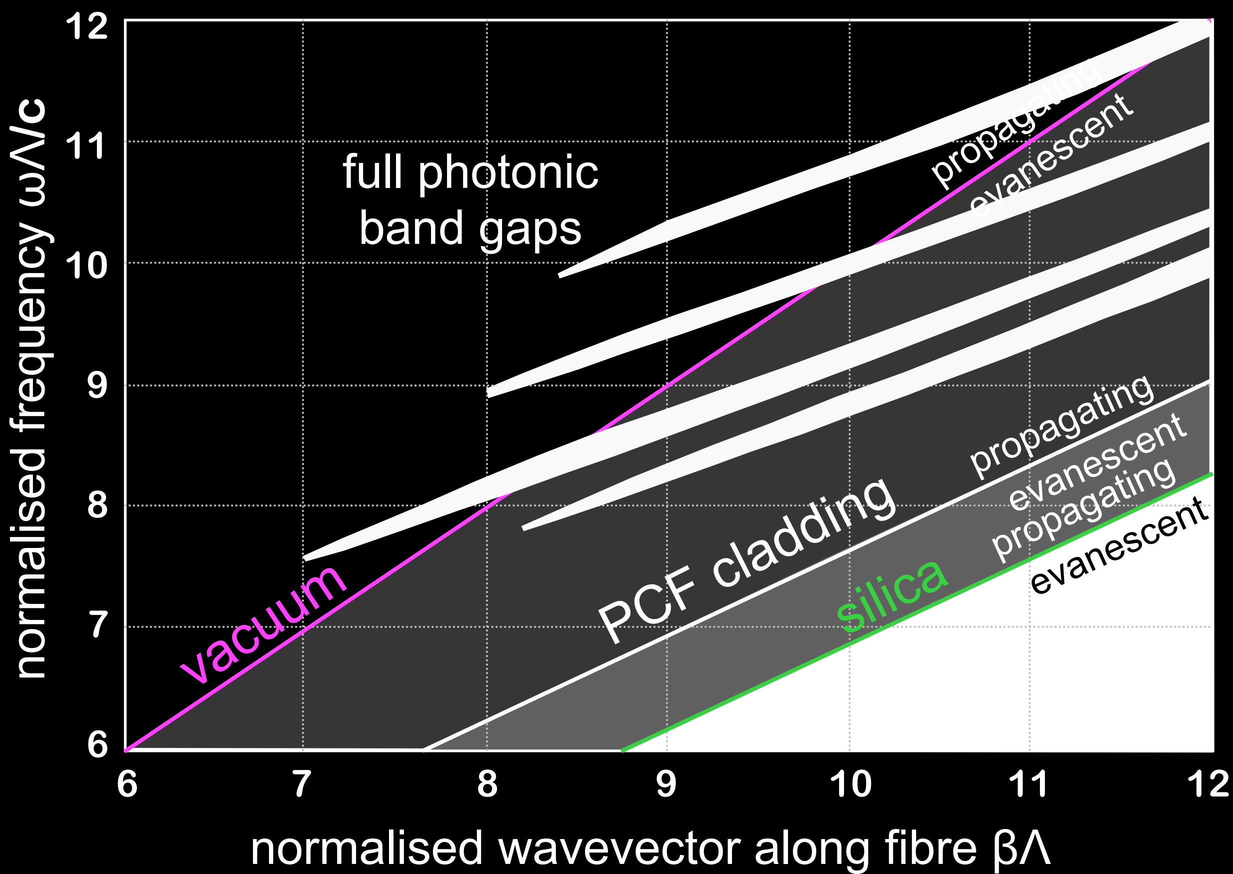
26 years ago at CLEO-US

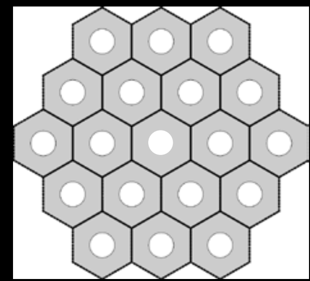


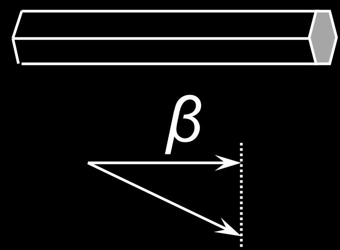
2D photonic bandgaps in silica/air PCF

Birks et al, Electron. Lett. **31**, 1941 (1995)

45% air filling fraction
index contrast 1:1.46







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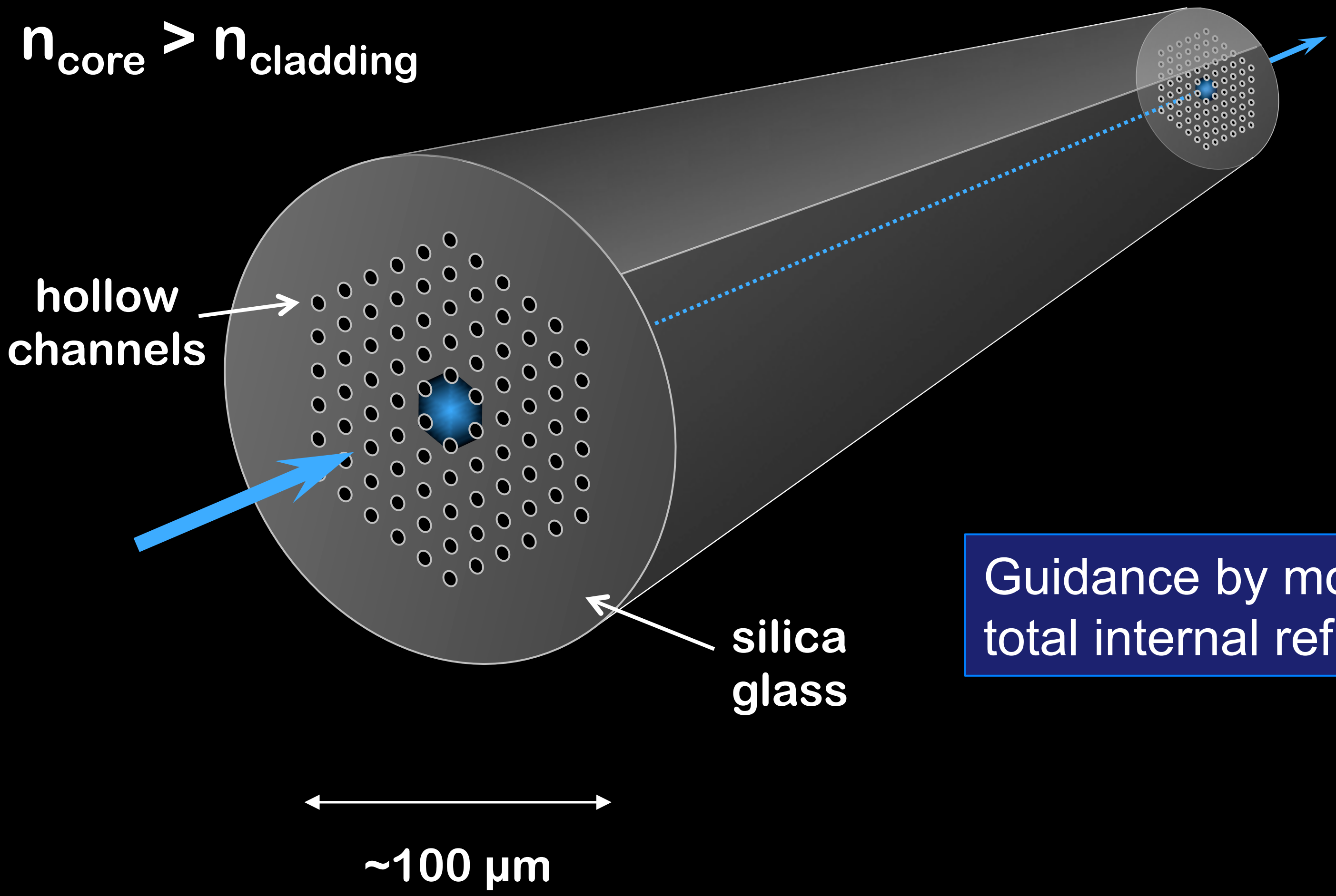
Solid core photonic crystal fibre (1995)

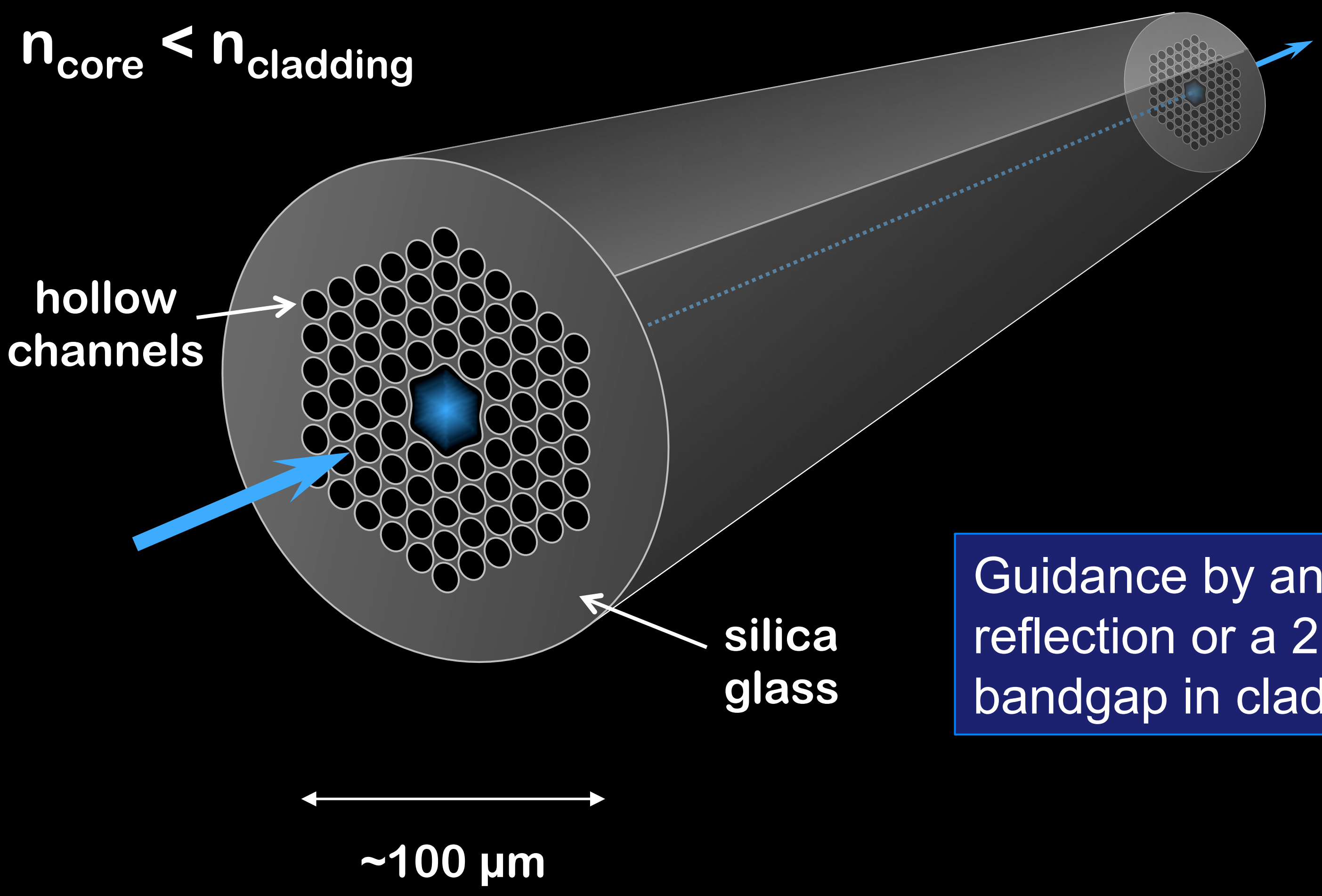
Knight et al: Opt. Lett. **21**, 1547 (1996)



Guidance by modified total internal reflection

Hollow core PCF (1999)

Cregan et al: Science **285**, 1537 (1999)



Guidance by anti-resonant reflection or a 2D photonic bandgap in cladding

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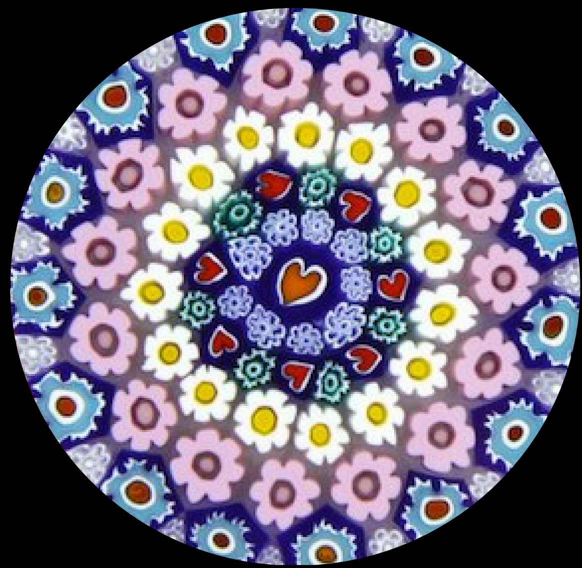
MAKING PCF



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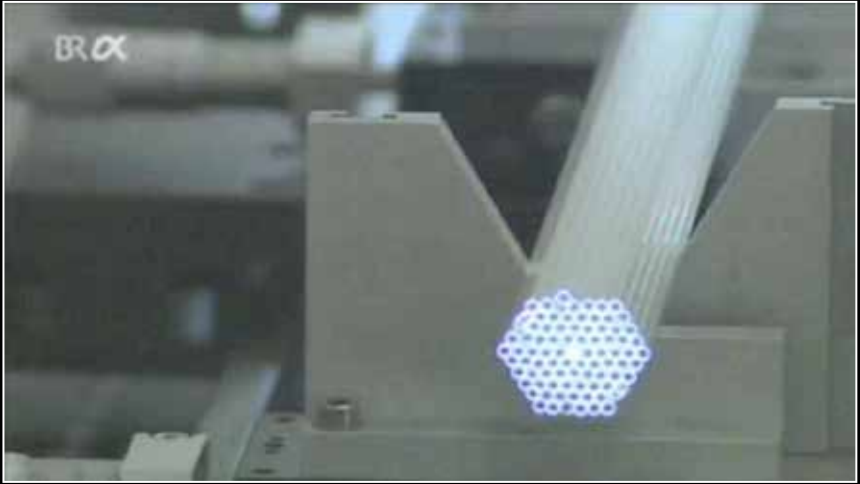
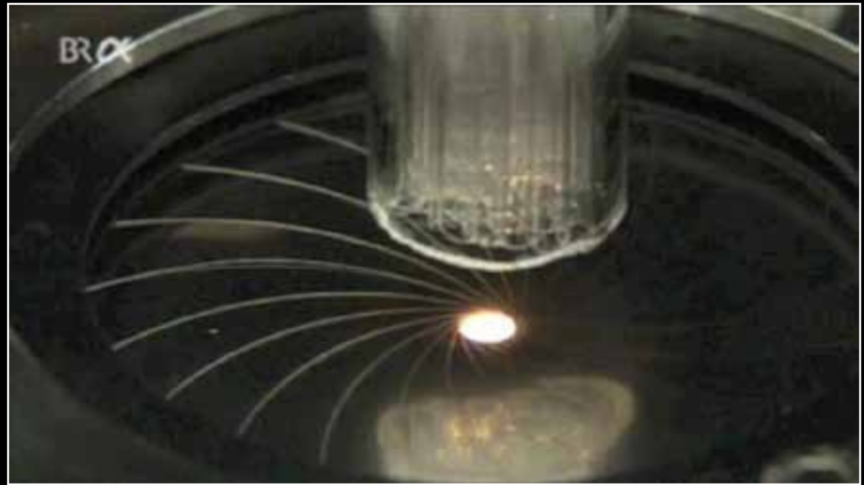
PCF fabrication: Stacking & drawing





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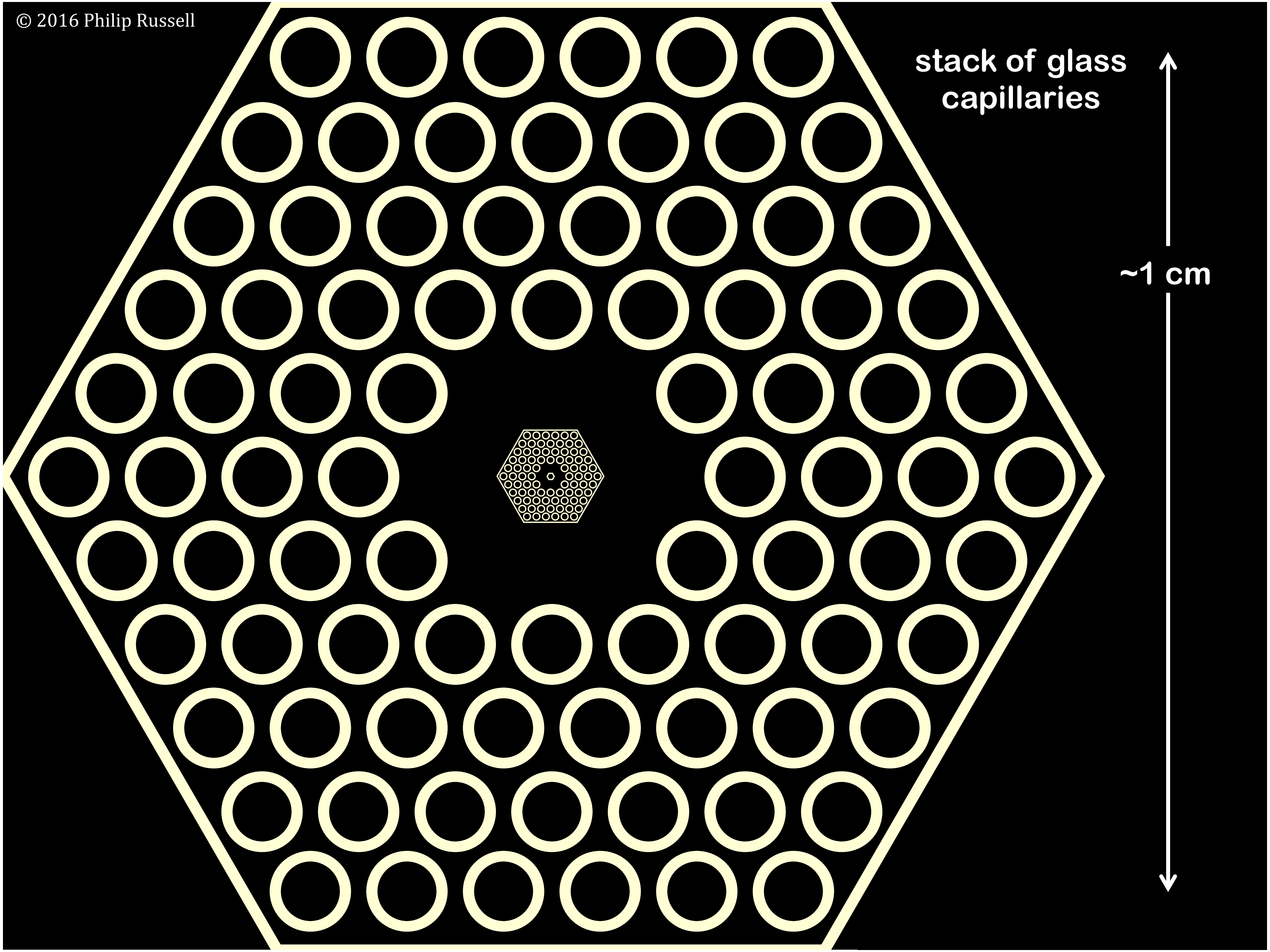
© 2016 Philip Russell
stack of glass
capillaries
~1 cm

University of Bath Group in 2004

University of Bath
12th October 2004

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THE FIRST PCF

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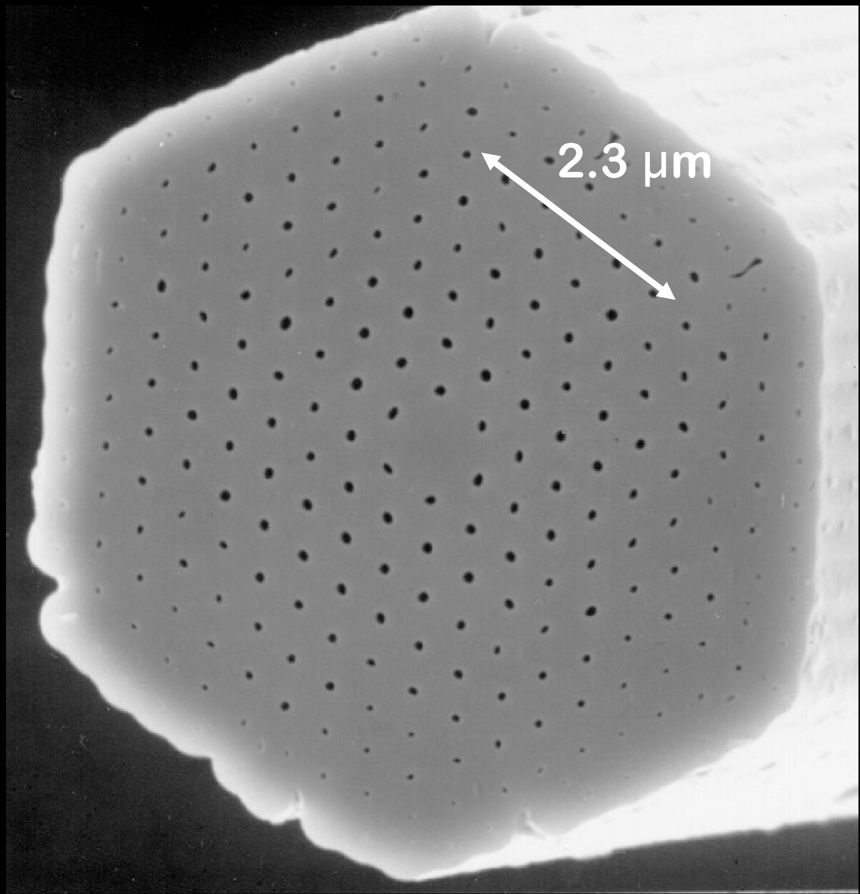
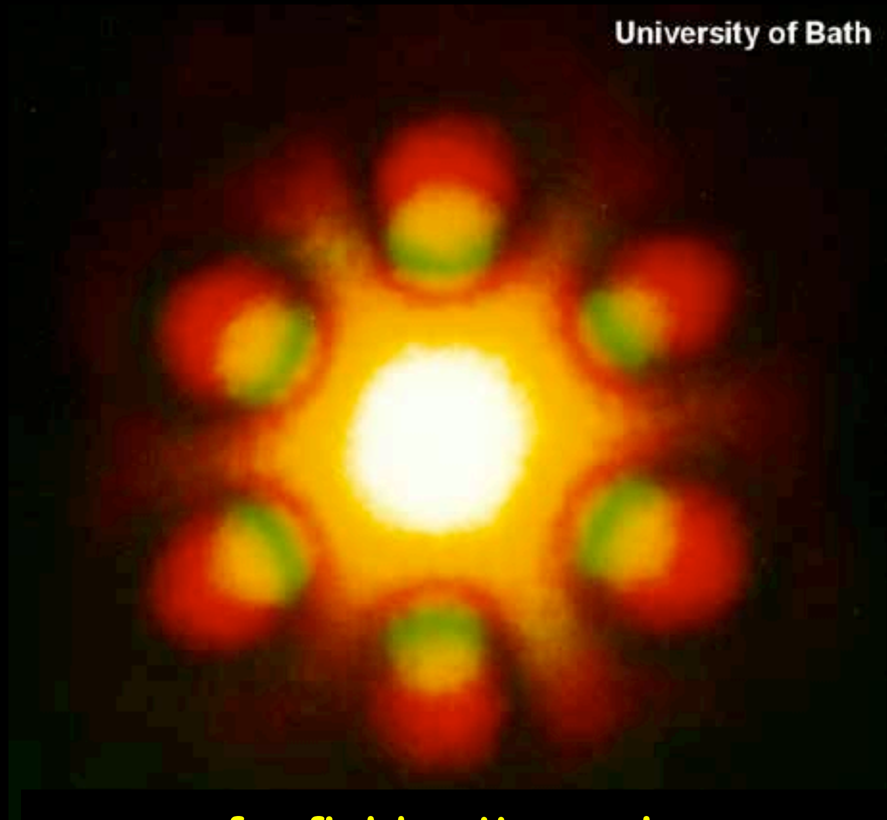
The first guiding photonic crystal fibre…

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





far-field pattern when carrying green & red light

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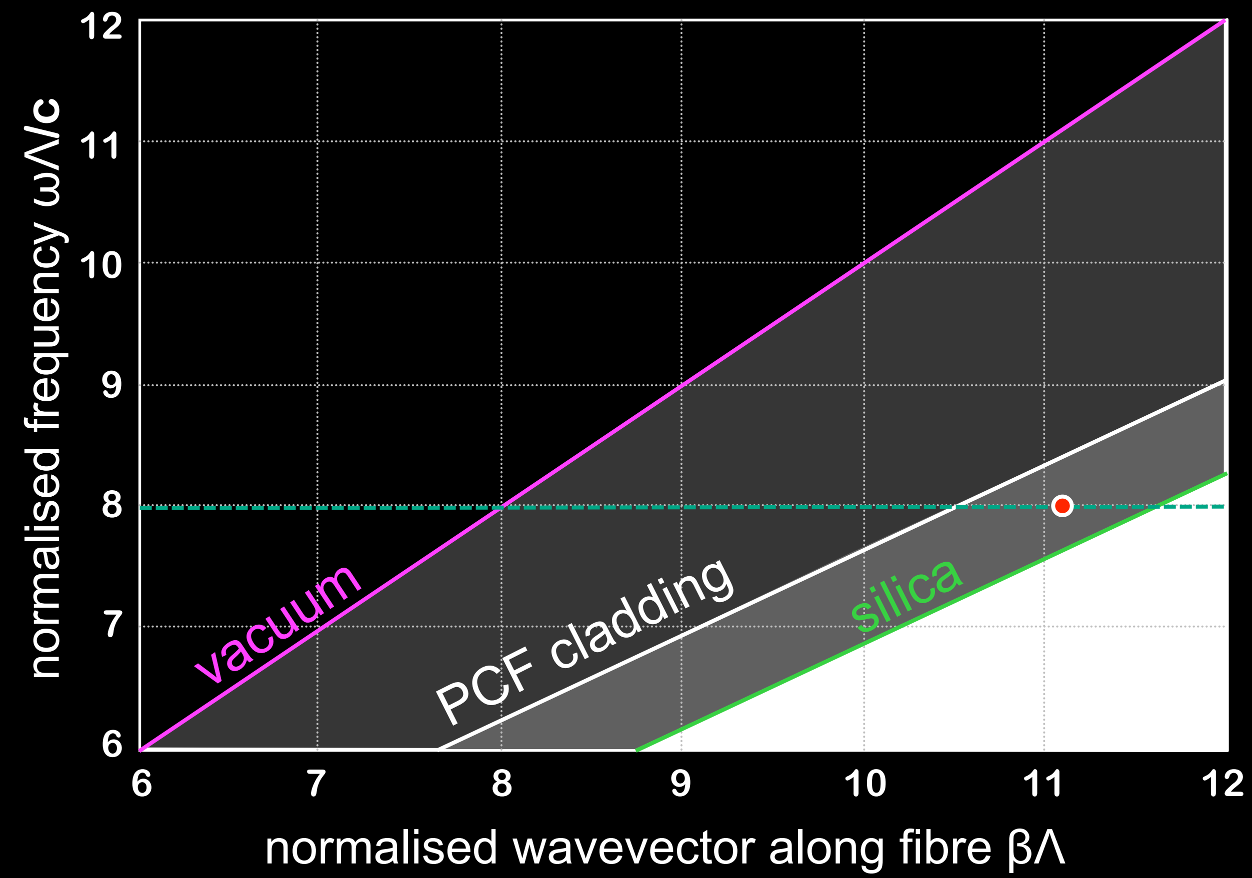
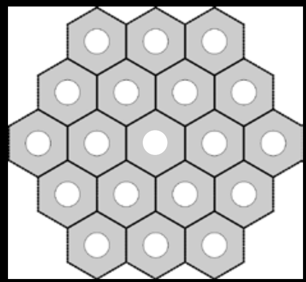
Modified total internal reflection

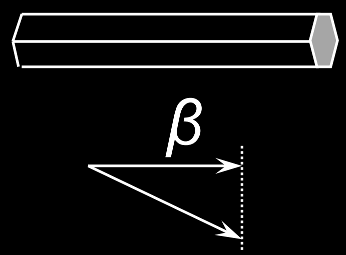
Knight et al, Electron.Lett. **31**, 1941 (1995)

45% air filling fraction
index contrast 1:1.46



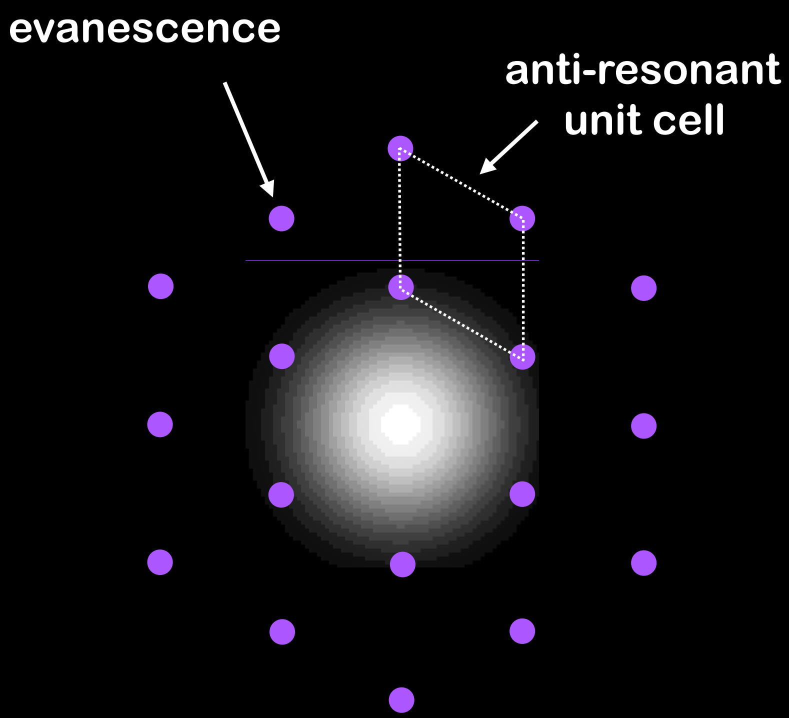


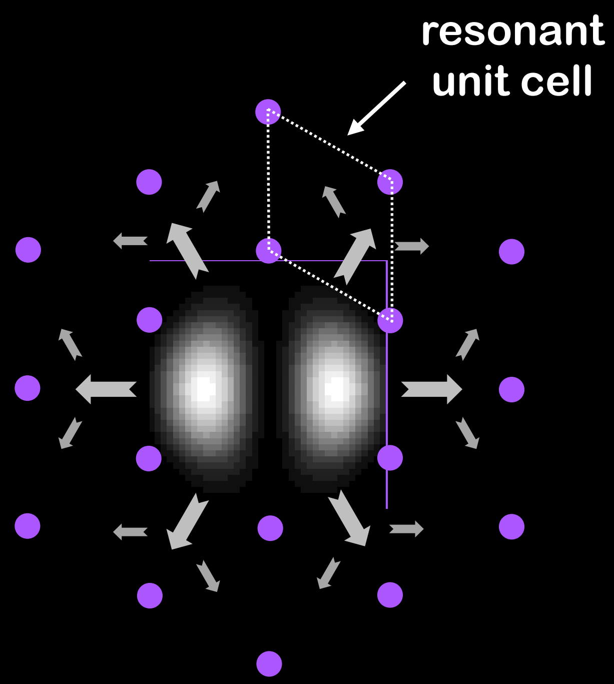
dispersion of PCF cladding depends on photonic crystal design



…was endlessly single-mode

Birks et al: Opt. Lett. **22**, 961 (1997)



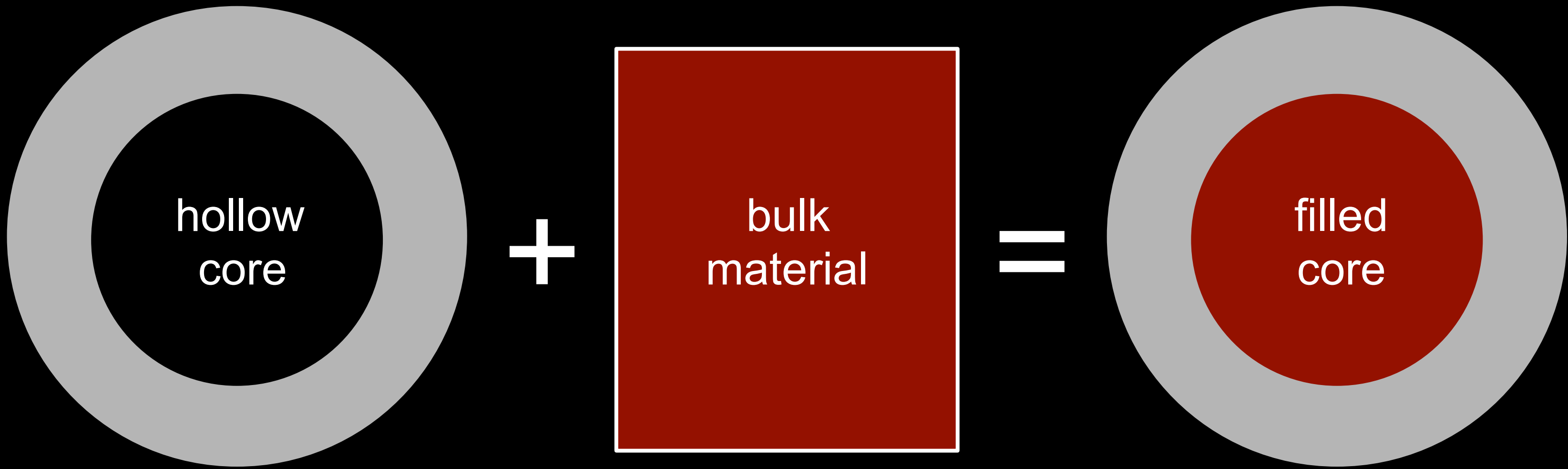


- fundamental mode cannot squeeze between air-holes
- higher-order modes can escape into cladding

10,000 TIMES BRIGHTER THAN THE SUN

Chromatic dispersion in waveguides

bluer faster | bluer slower | depends



optical modes of hollow waveguides always have anomalous dispersion (geometrical effect)

bulk glass or gas typically has normal dispersion (material response)

dispersion of filled core combination is the balance of the two

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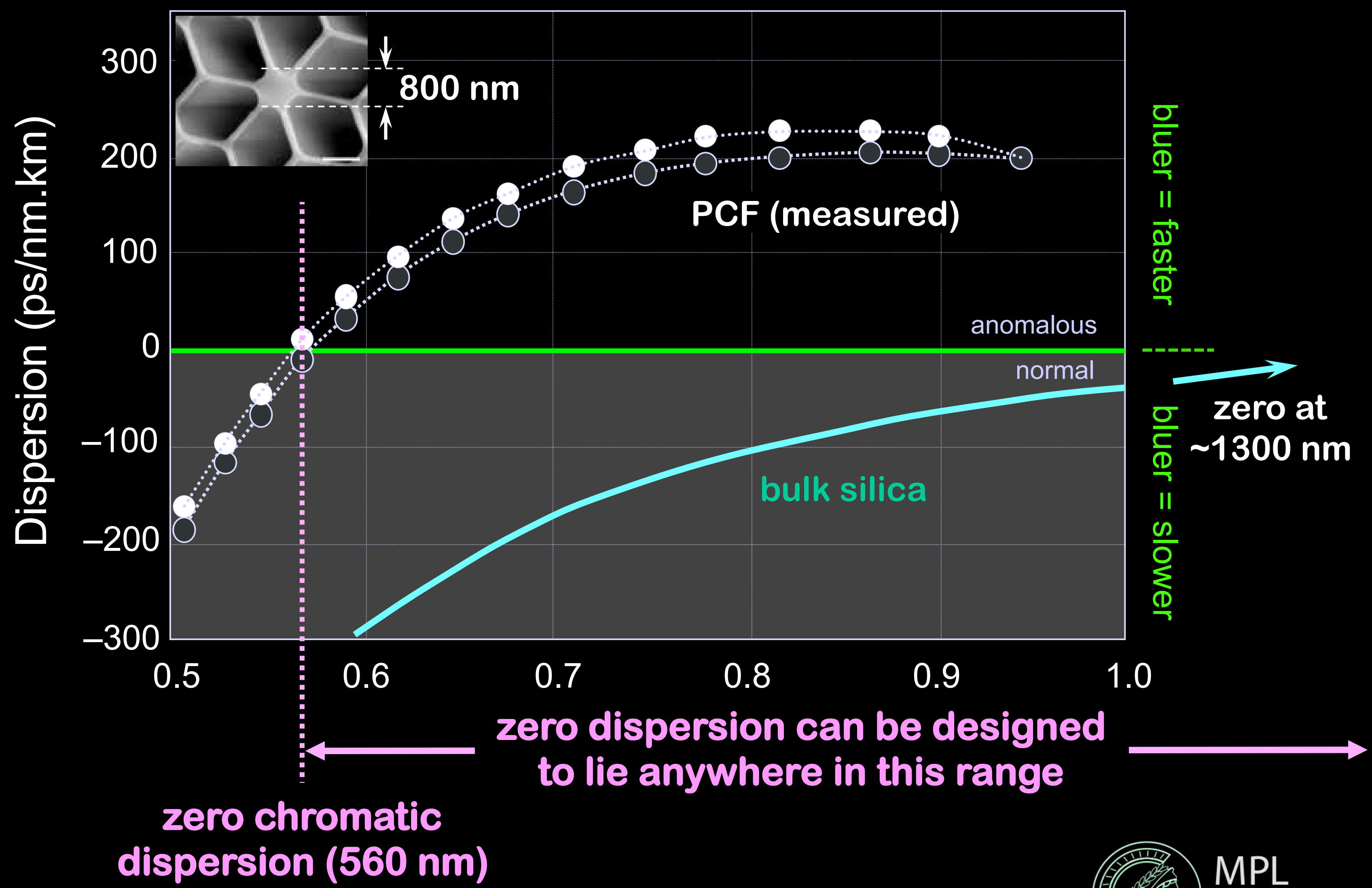
Chromatic dispersion of pure silica PCF

Knight et al, Phot Tech Lett, **12**, 807 (2000)



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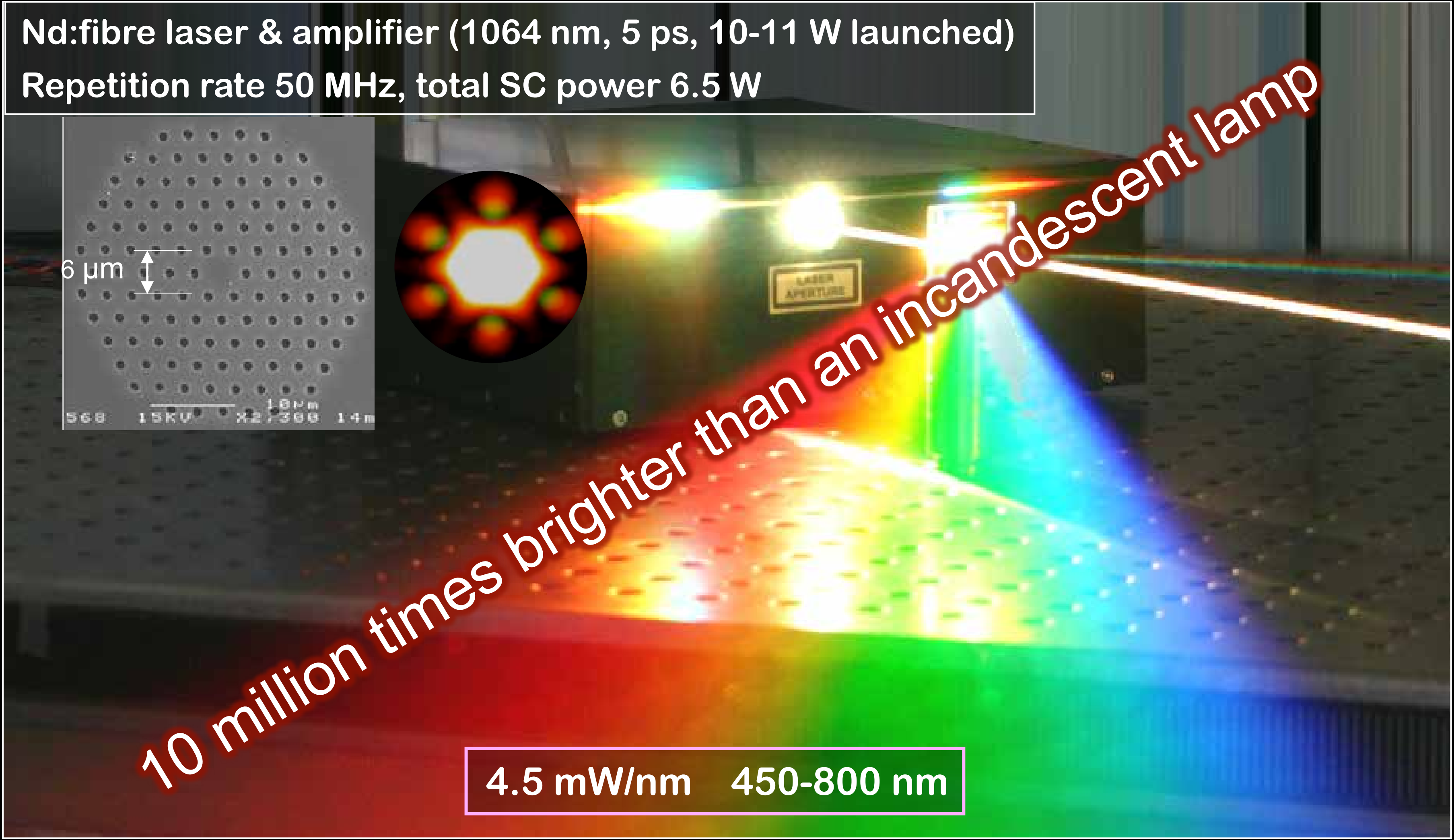
White-light generation in solid-core PCF

extreme nonlinear optics

Fianium Ltd



Ranka et al: Opt. Lett. **25**, 25 (2000)
Dudley et al: Rev. Mod. Phys. **78**, 1135 (2006)

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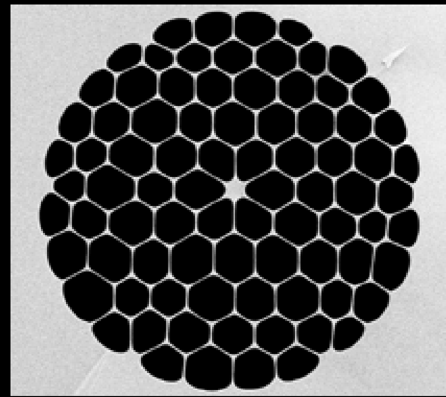
Deep-UV supercontinuum in ZBLAN PCF

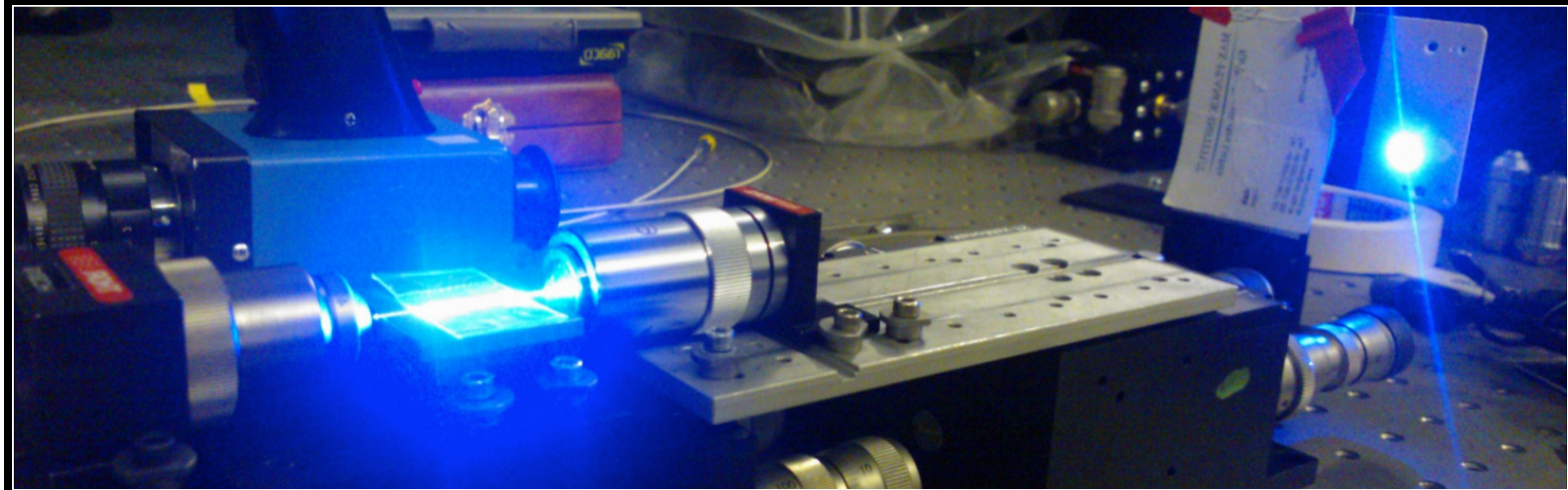
Jiang et al: Nat. Phot. **9**, 133 (2015)



core diameter ~3 µm

Bright stable spectrum down to 200 nm wavelength

1042 nm, 140 fs, 75 MHz, 13 nJ



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FIBRES WITH NO CORE

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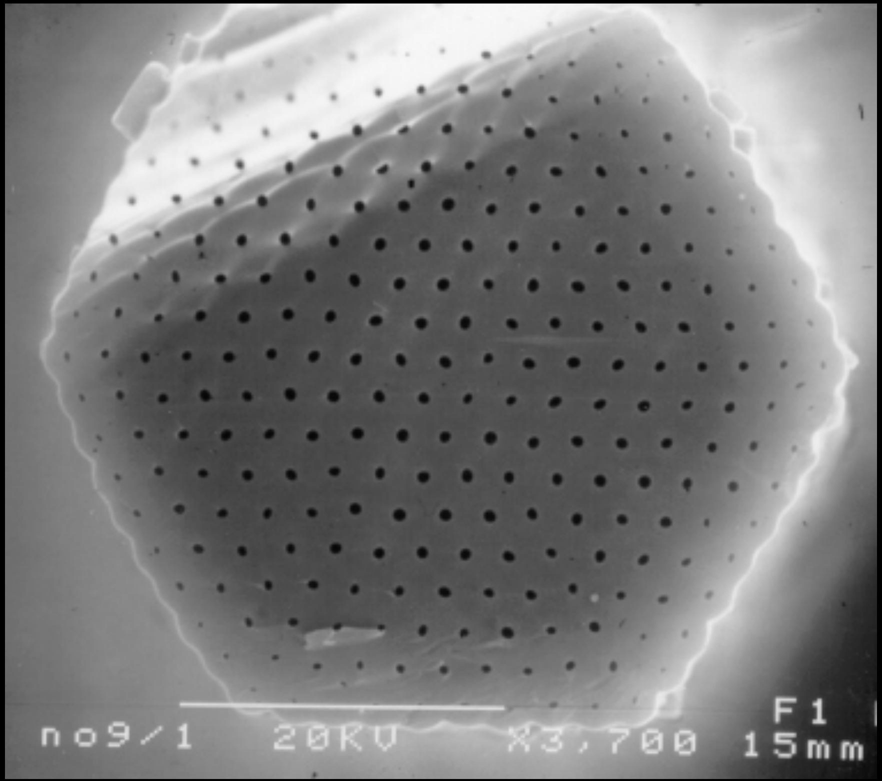
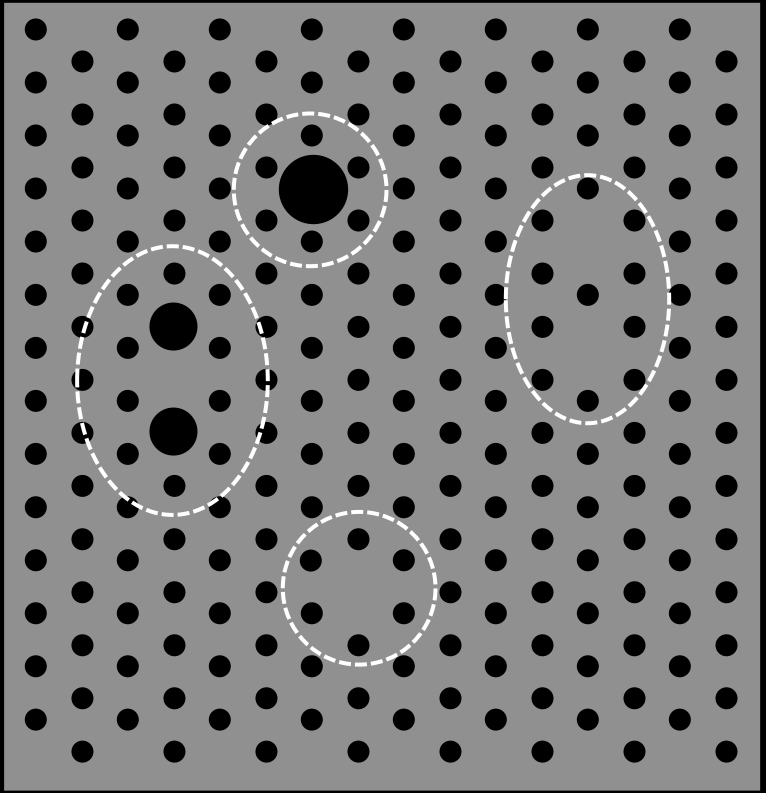
Excerpt from a talk (by me) in late 1990s

"The first photonic crystal fibre was useless…
…because it needed defects"

November 1995

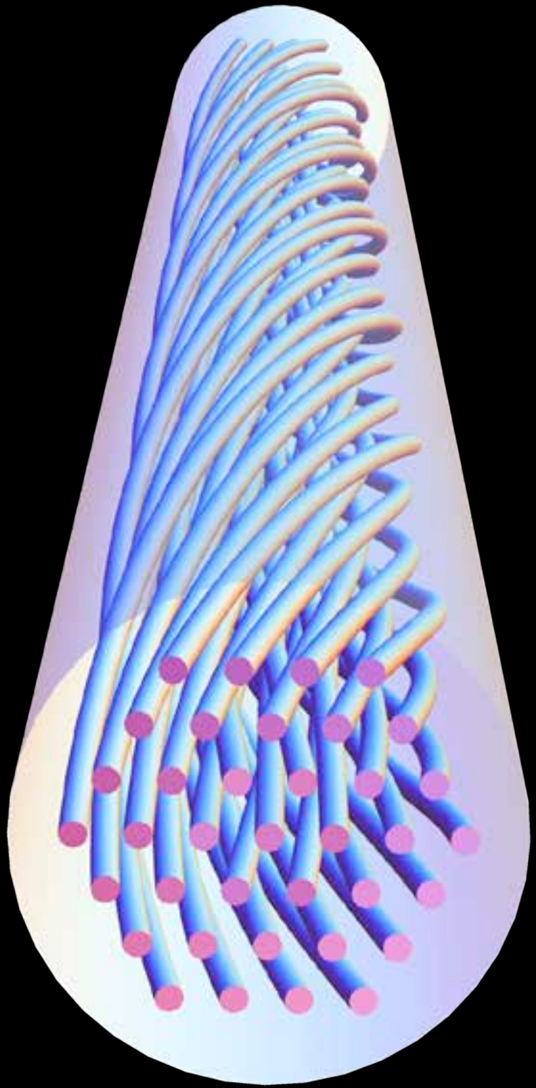


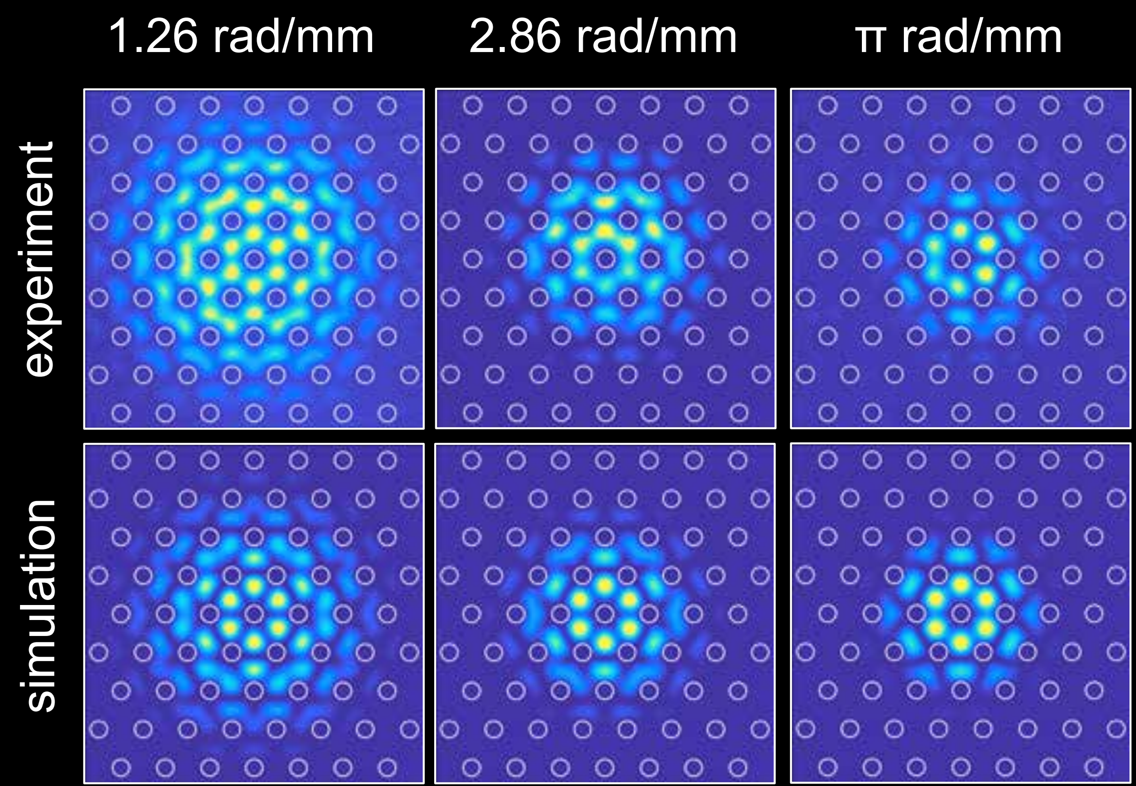
2 µm pitch



Coreless PCF guides light when helically twisted

Beravat et al: Science Adv. **2**, e1601421 (2016)





hole diameter 2.2 μm
spacing 5.7 μm
wavelength 818 nm

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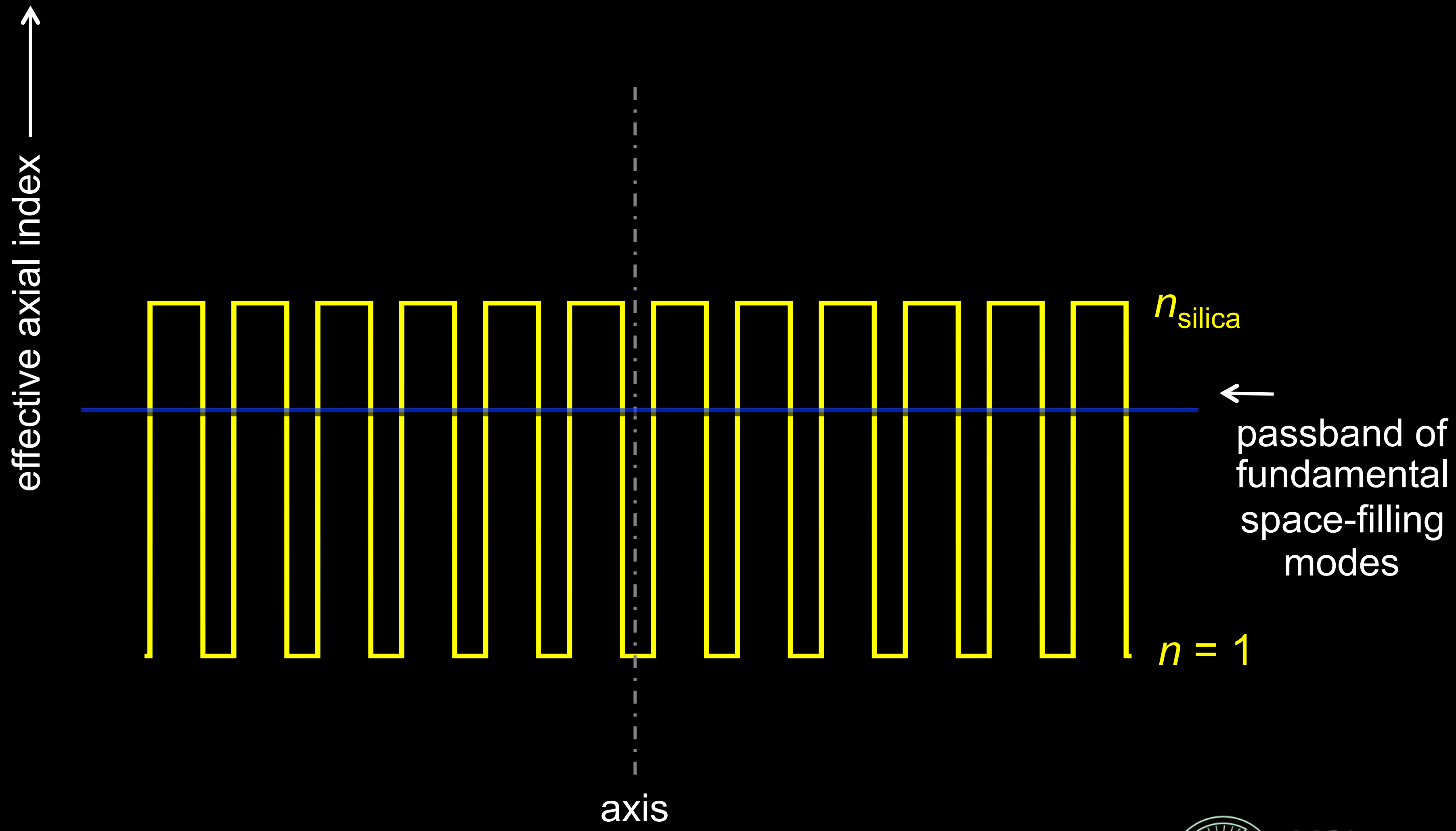
Untwisted coreless PCF

Beravat et al: Science Adv. **2**, e1601421 (2016)



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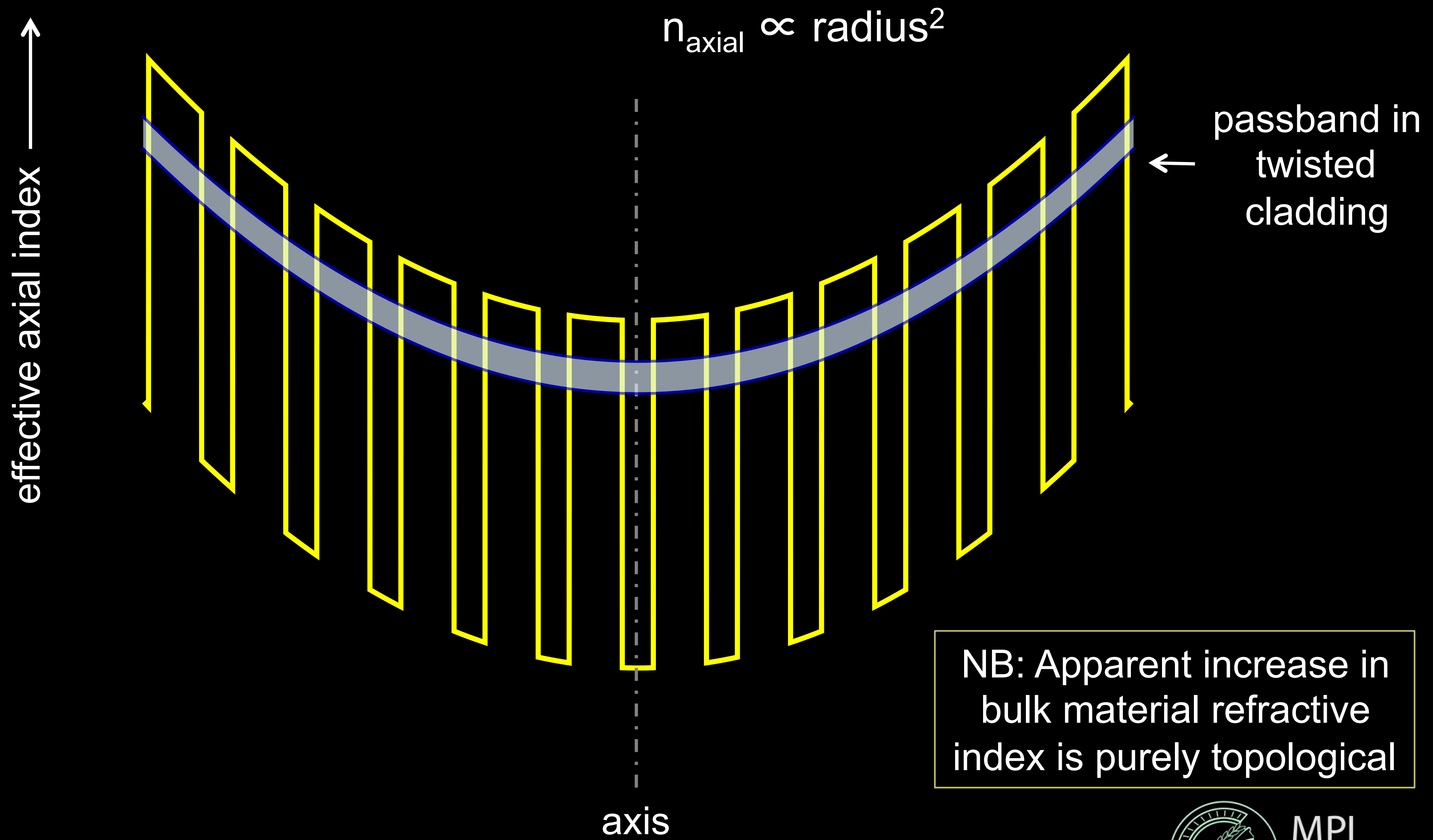
Twisted coreless PCF

Beravat et al: Science Adv. **2**, e1601421 (2016)

Geometrical increase in path-length with radius:



NB: Apparent increase in bulk material refractive index is purely topological

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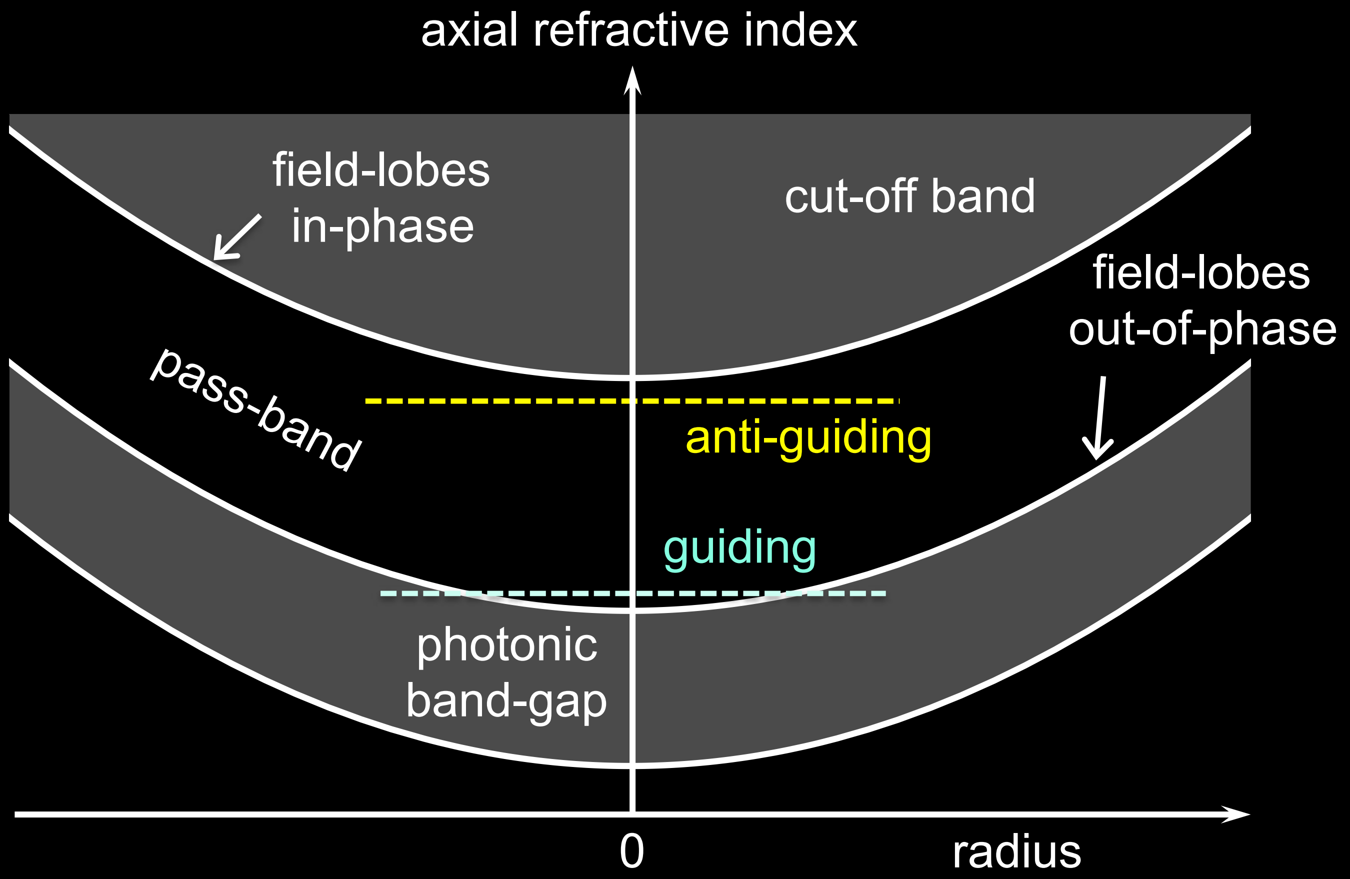
Mode is guided on-axis at bottom of passband

Beravat et al: Science Adv. **2**, e1601421 (2016)



A gravitational "wormhole" for light in helically curved periodic space

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HOLLOW CORE PCF

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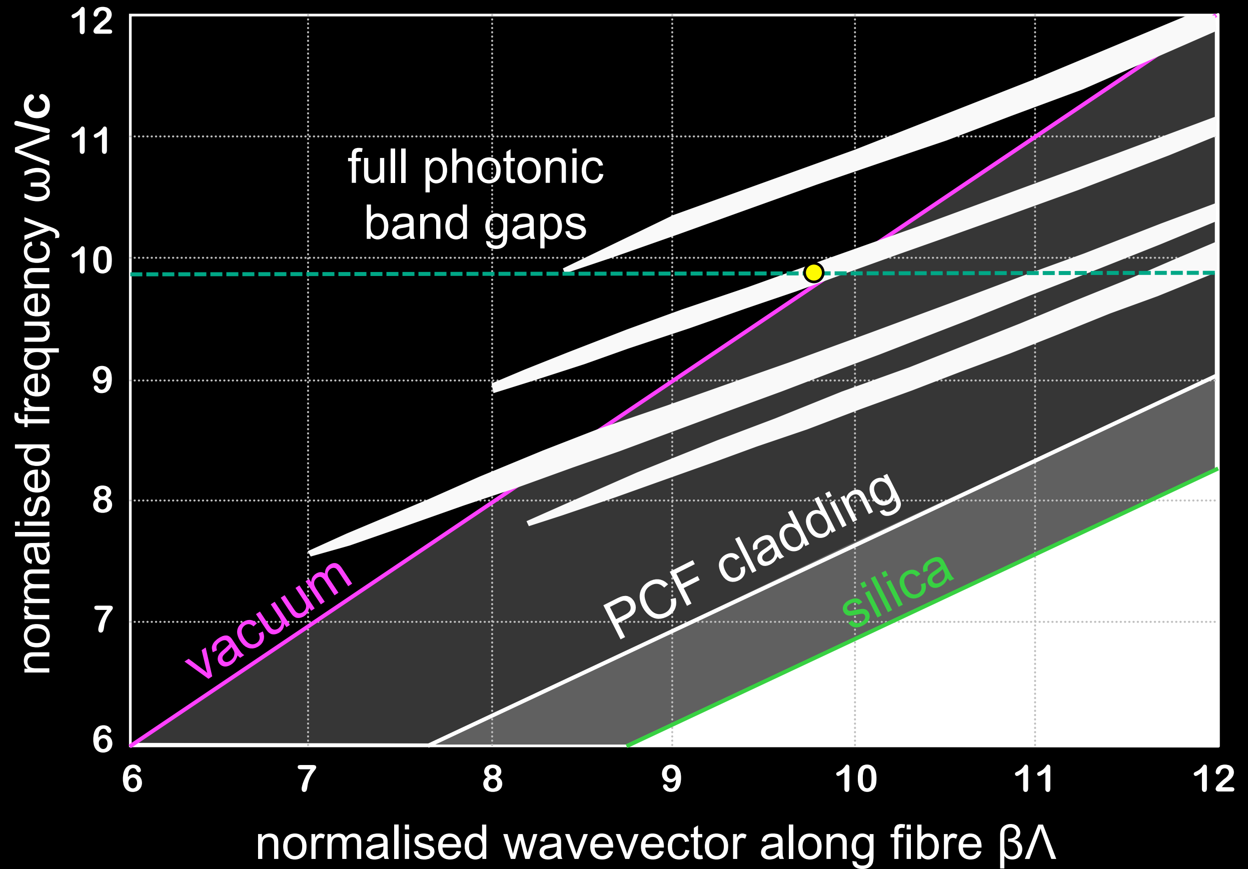
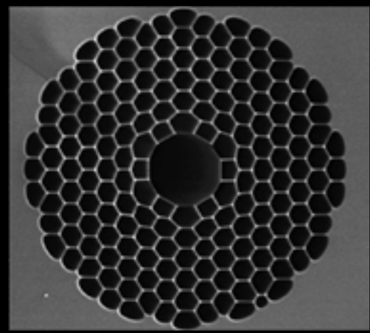
Guidance by 2D bandgap possible in air

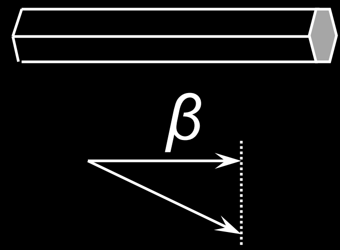
Birks et al, Electron.Lett. **31**, 1941 (1995)
Cregan et al: Science 285, 1537 (1999)

45% air filling fraction
index contrast 1:1.46





dispersion of PCF cladding depends on photonic crystal design



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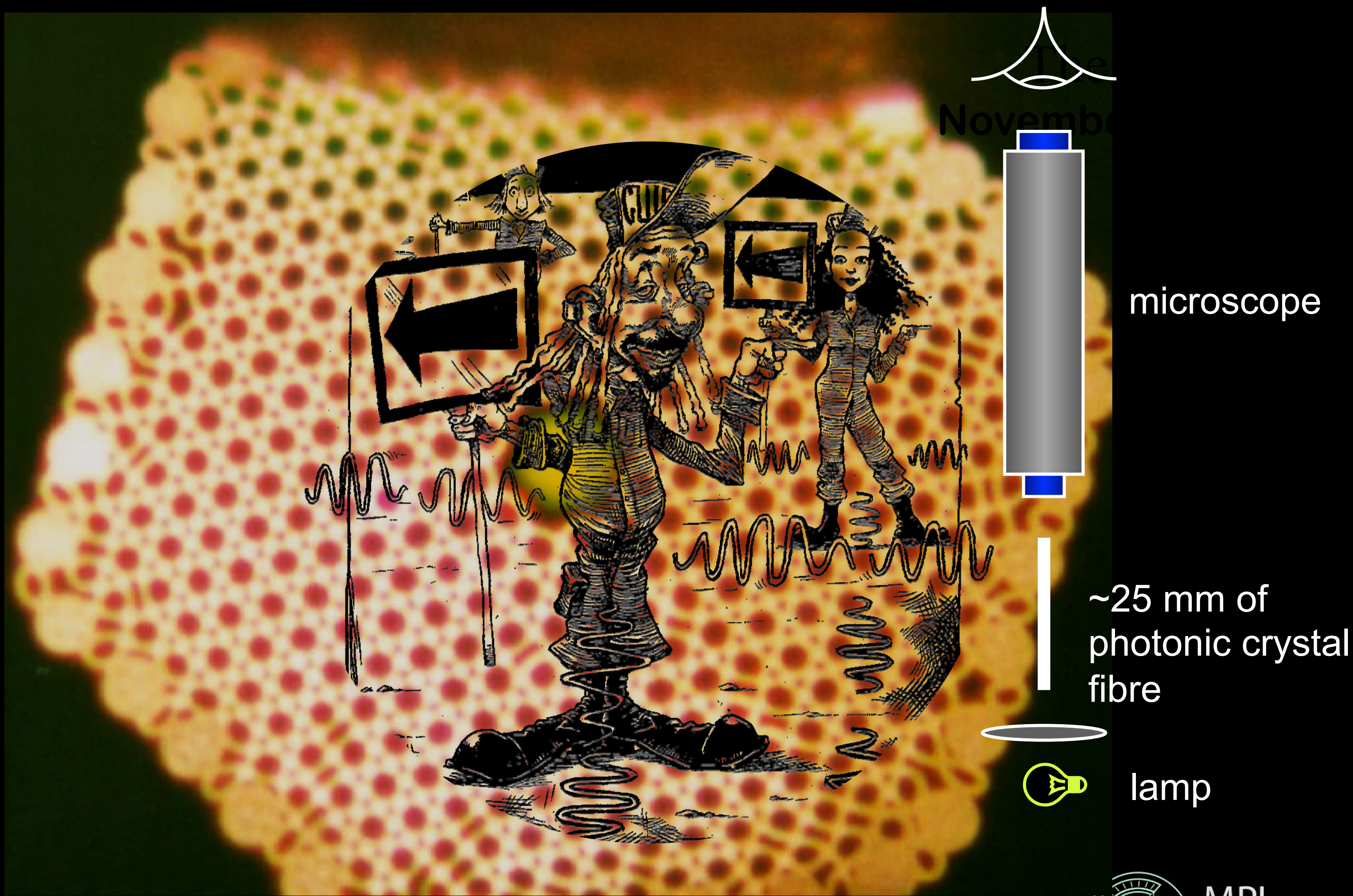

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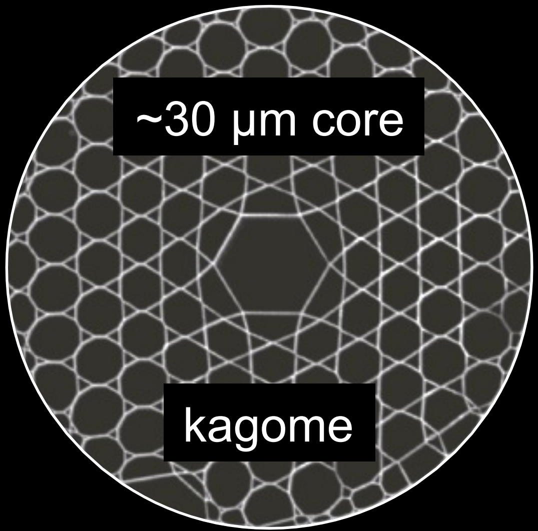
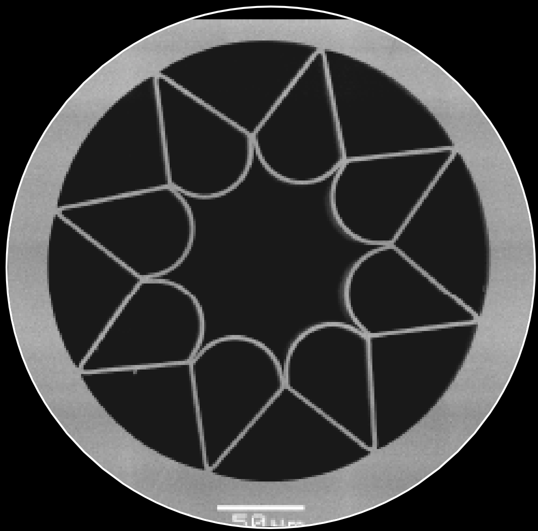
Anti-resonant reflecting (ARR) hollow-core PCFs

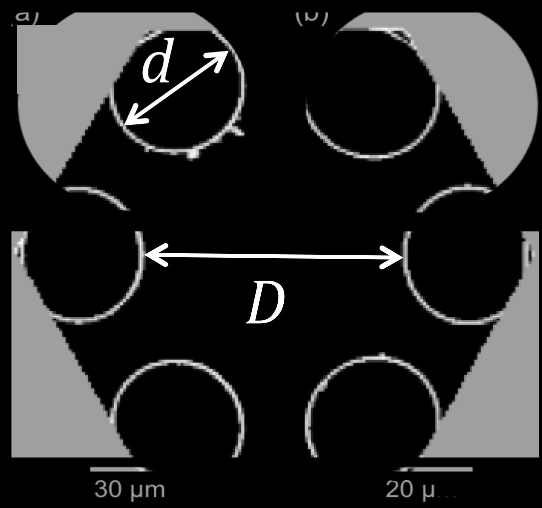
- Benabid et al: Science **298**, 399 (2002)
- Pryamikov et al: Opt. Exp. **19**, 1441 (2011)
- Yu et al: Opt. Exp. **20**, 11153 (2012)
- Debord et al: Opt. Lett. **39**, 6245 (2014)
- Uebel et al: Opt. Lett. **41**, 1961 (2016)
- Frosz et al: Phot. Res. **5**, 88 (2017)



2002



2012



2016

- higher loss (~1 dB/m)
- ultra-broadband (1000s of nm)
- design of first layer critical

- nonlinear gas-light interactions enhanced >10,000 times c.f. focused Gaussian beam

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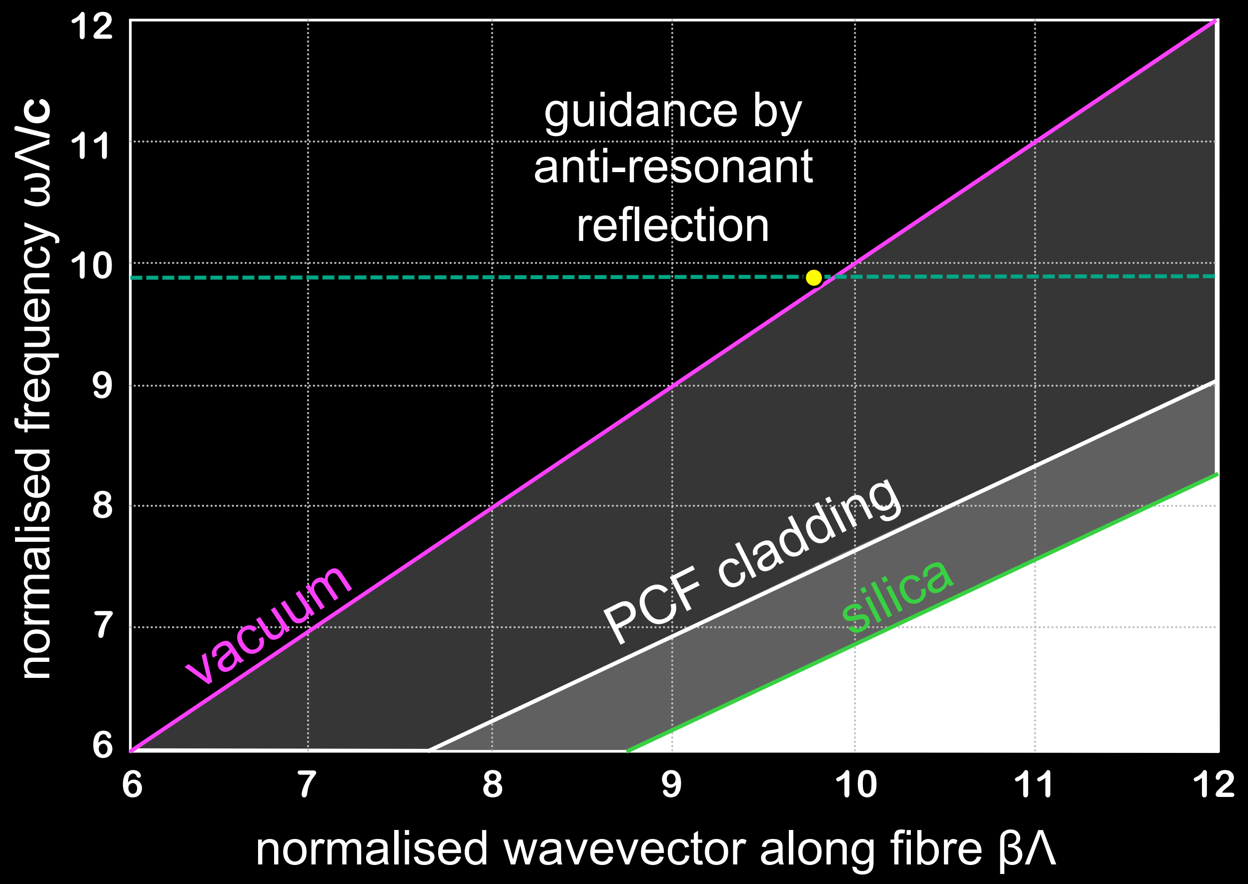
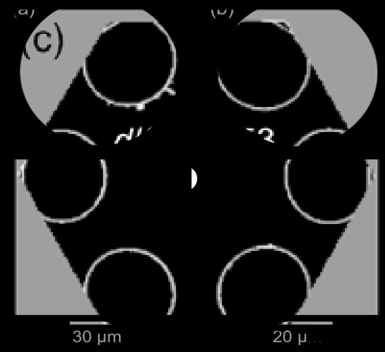
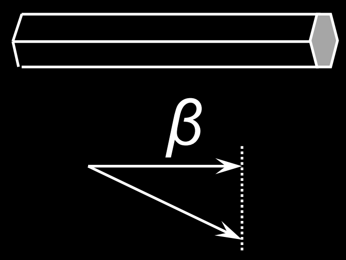
Guidance by antiresonant reflection in air

45% air filling fraction
index contrast 1:1.46



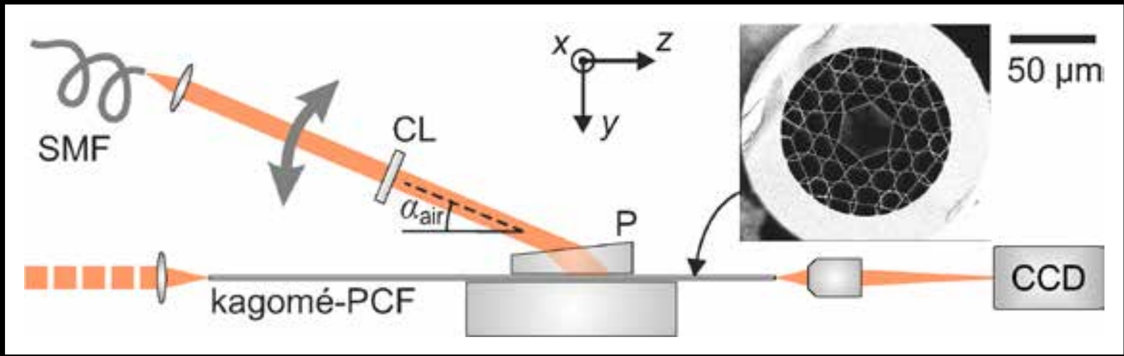


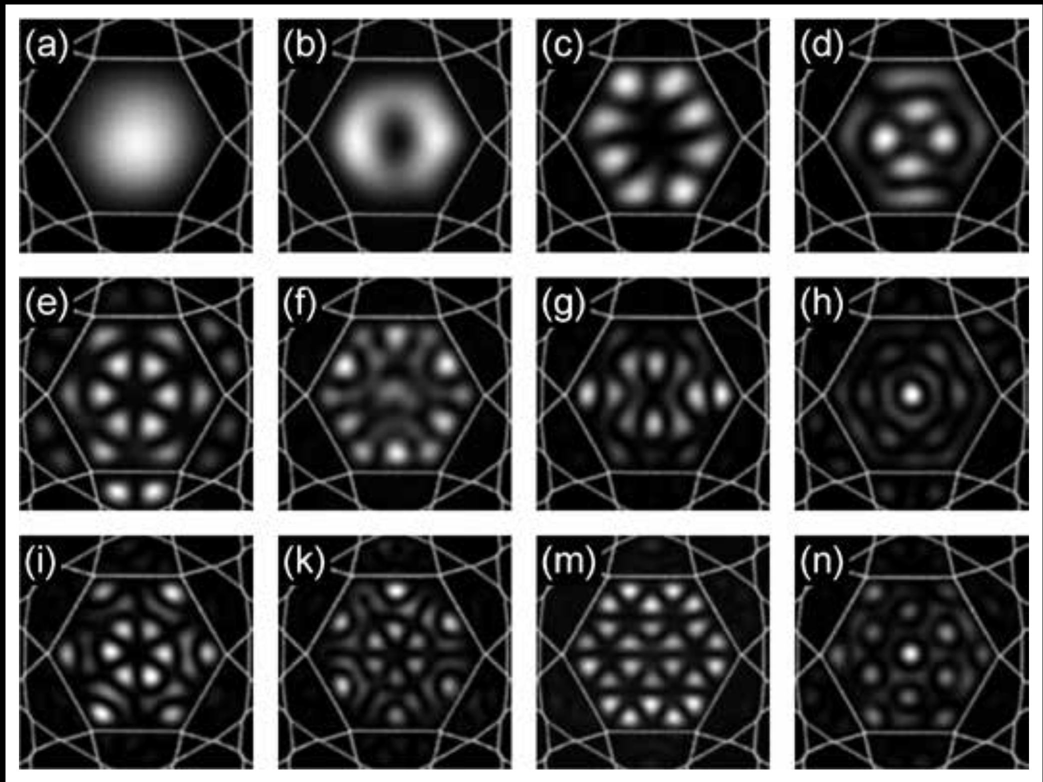
core mode is anti-resonant with modes of capillaries in the ring



ARR HC-PCFs are not usually single-mode

Trabold et al: Opt. Lett. **39**, 3736 (2014)



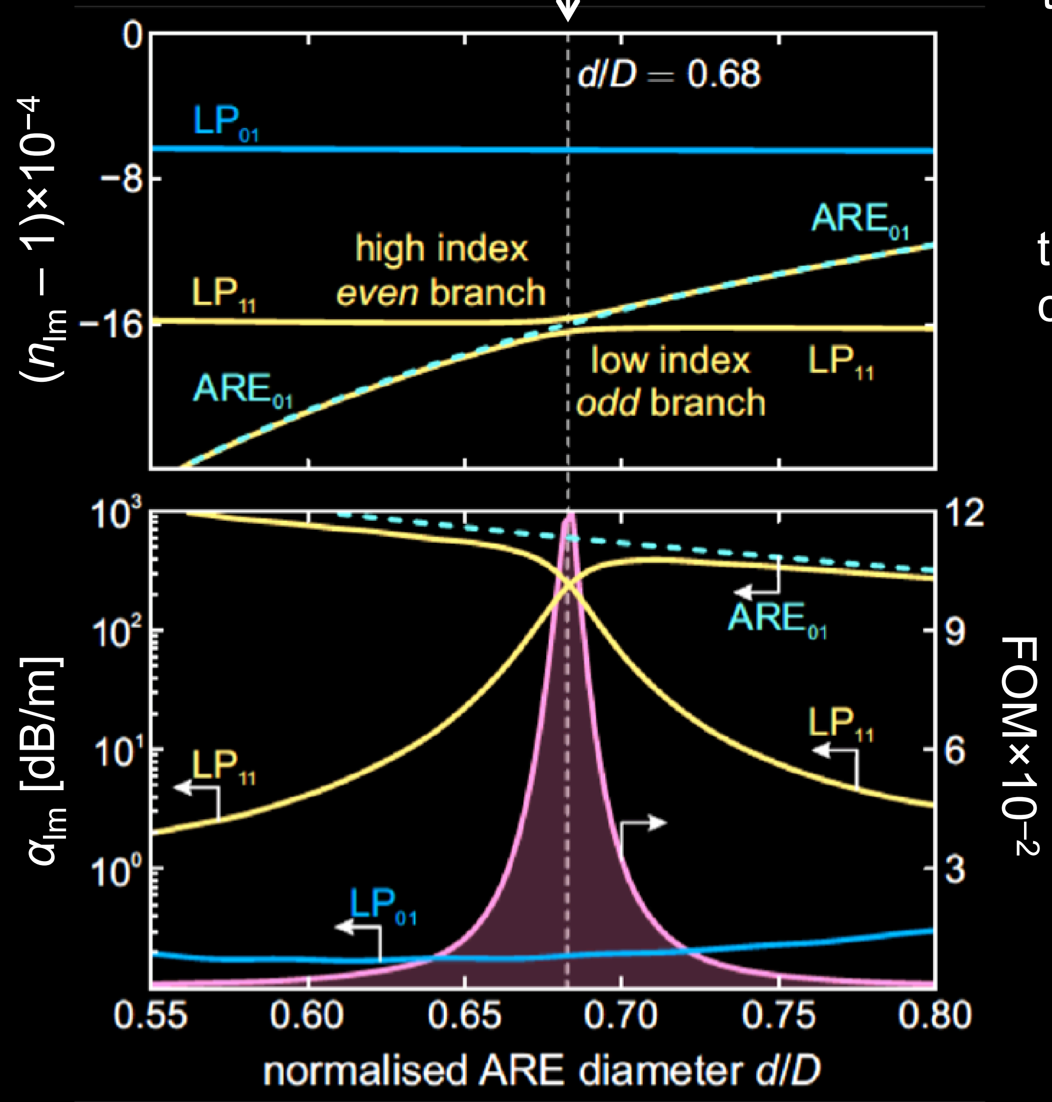


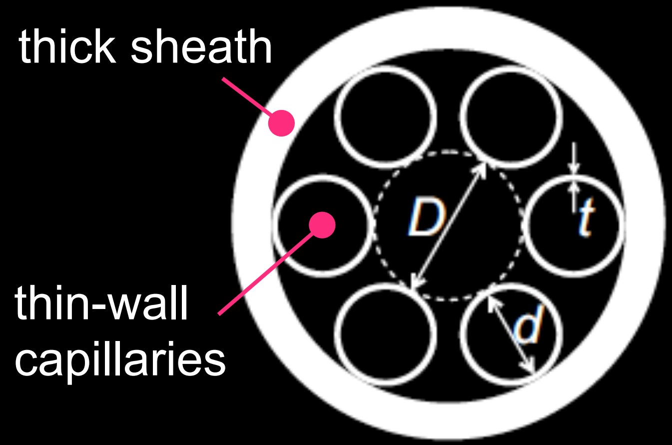
- Prism-coupling through the cladding
- Absence of PBG means that light can pass into core resonance
- Allows accurate measurement of modal phase indices and loss
- Modal field patterns can be imaged
- **How to suppress higher order modes?**

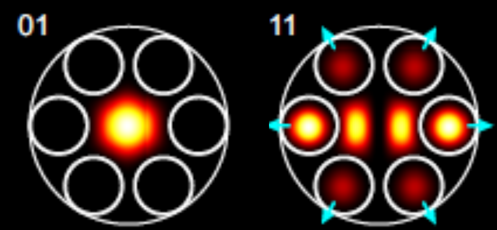
Suppressing HOMs in single-ring ARR-PCF

$$d_{\text{cap}} / D_{\text{core}} \approx z_1(J_0) / z_1(J_1) = 0.68$$

Uebel et al: , Opt. Lett. **41**, 1961 (2016)







$$\mathrm{FOM}_{11} = \frac{\alpha_{11} - \alpha_{01}}{\alpha_{01}}$$

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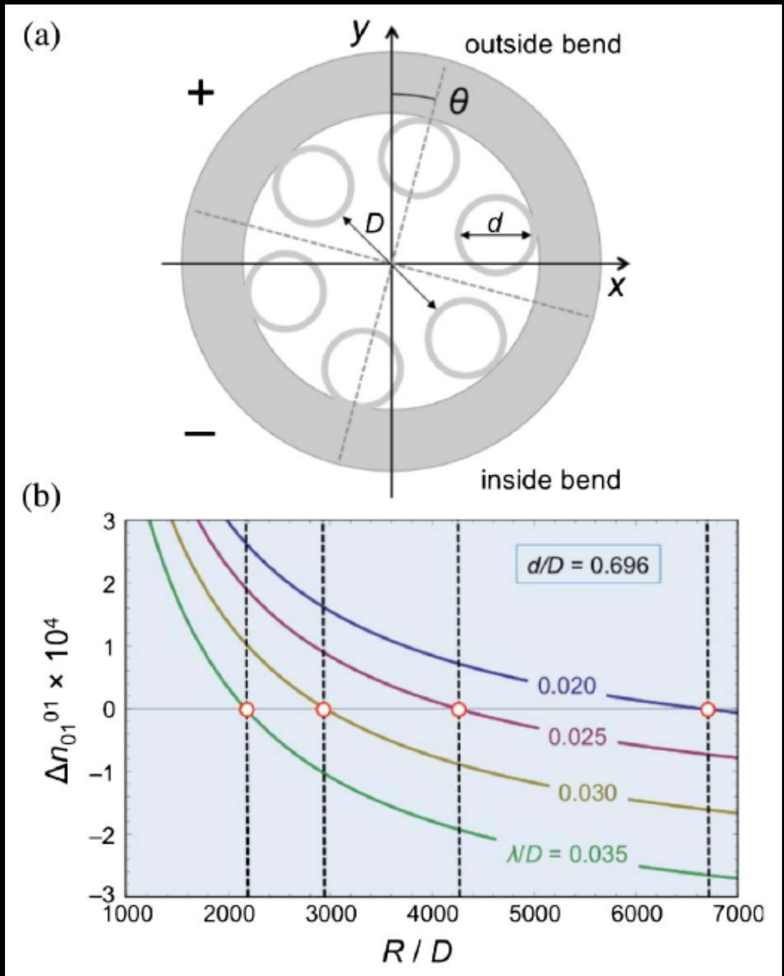
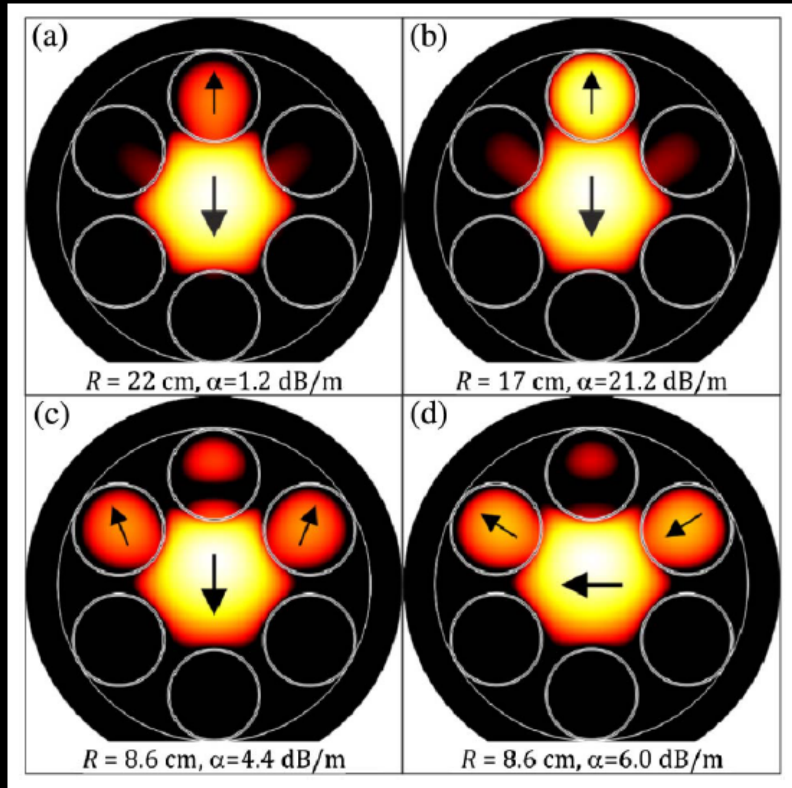
Bend loss in single-ring PCFs

Frosz et al: Phot. Res. **5**, 88 (2017)

$$\frac{R_{\text{cr}}^{01}}{D} = \frac{D^2}{\lambda^2}\frac{\pi^2}{u_{01}^2}\frac{\pi^2 (d/D)^2}{1-d/D}\cos\theta$$





BRIGHT ULTRAVIOLET LIGHT

ultralumina

www.ultralumina.com

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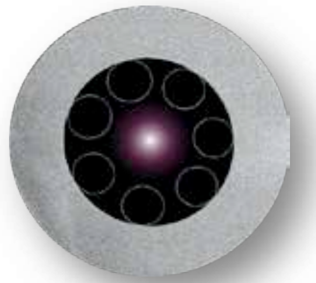
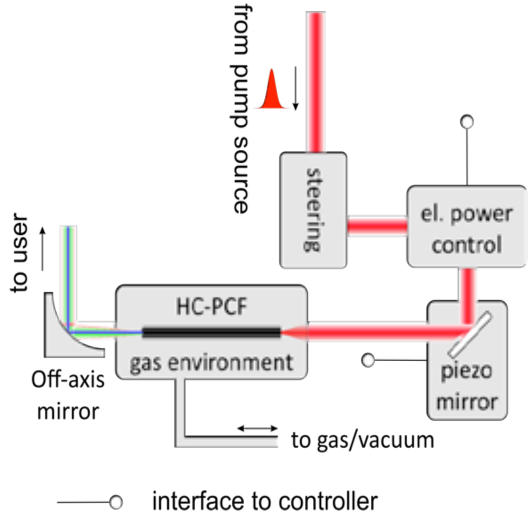
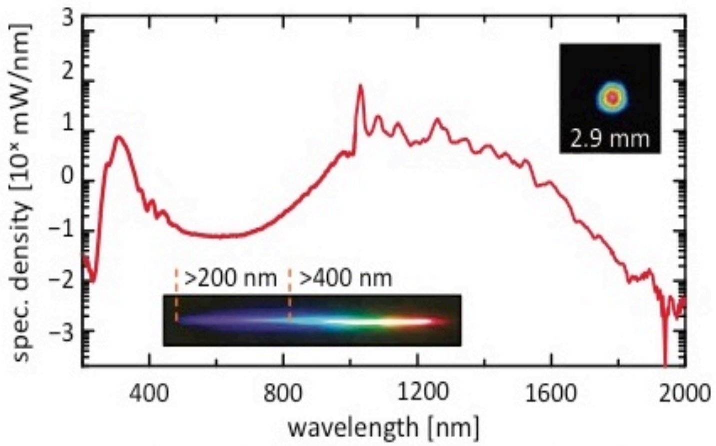
Portfolio of ultralumina's products & services

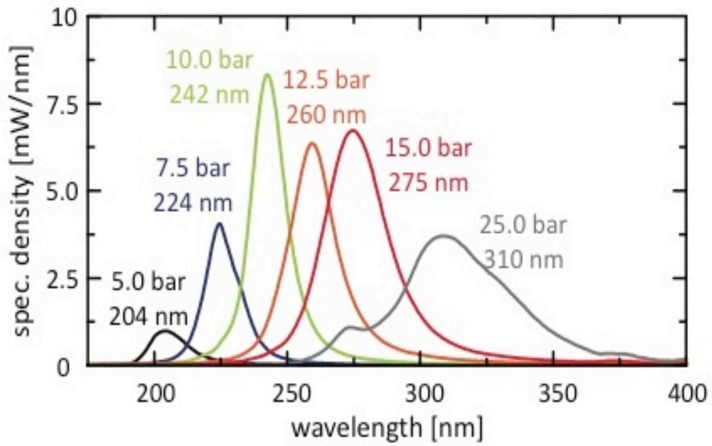
	What we do	Applications	
Optical Fibres	▪ Design ▪ Fabrication ▪ Characterization ▪ Hollow-core Photonic crystal fibres	▪ High-power beam delivery ▪ fs beam delivery ▪ Low latency ▪ Gas-filled fibre-based light sources	
Light Sources	▪ Deep UV supercontinuum ▪ Tunable deep UV ▪ MHz repetition rate, µJ energy, sub-50 fs lasers	▪ Semiconductor metrology ▪ Time-resolved native fluorescence detection ▪ Advanced material processing	
Services	▪ Consulting ▪ Development projects	▪ Deep-level market & application understanding ▪ Evaluation of HC-PCF related business cases ▪ Fibre development & system integration	

A supercontinuum light source for the deep UV

Key specifications	▪ 180 – 1600 nm spectral range ▪ Beam quality $M^2 < 1.3$ ▪ mW/nm power spectral density ▪ W level average power
Technology	▪ Spectral pulse broadening in gas-filled hollow-core PCF
Applications	▪ Semiconductor metrology ▪ Adv. material characterization ▪ Time-resolved fluorescence detection



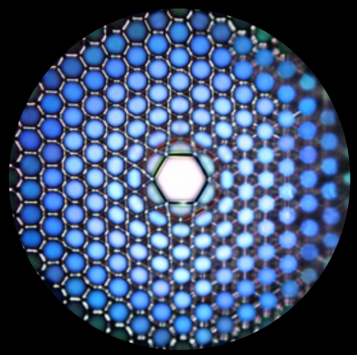




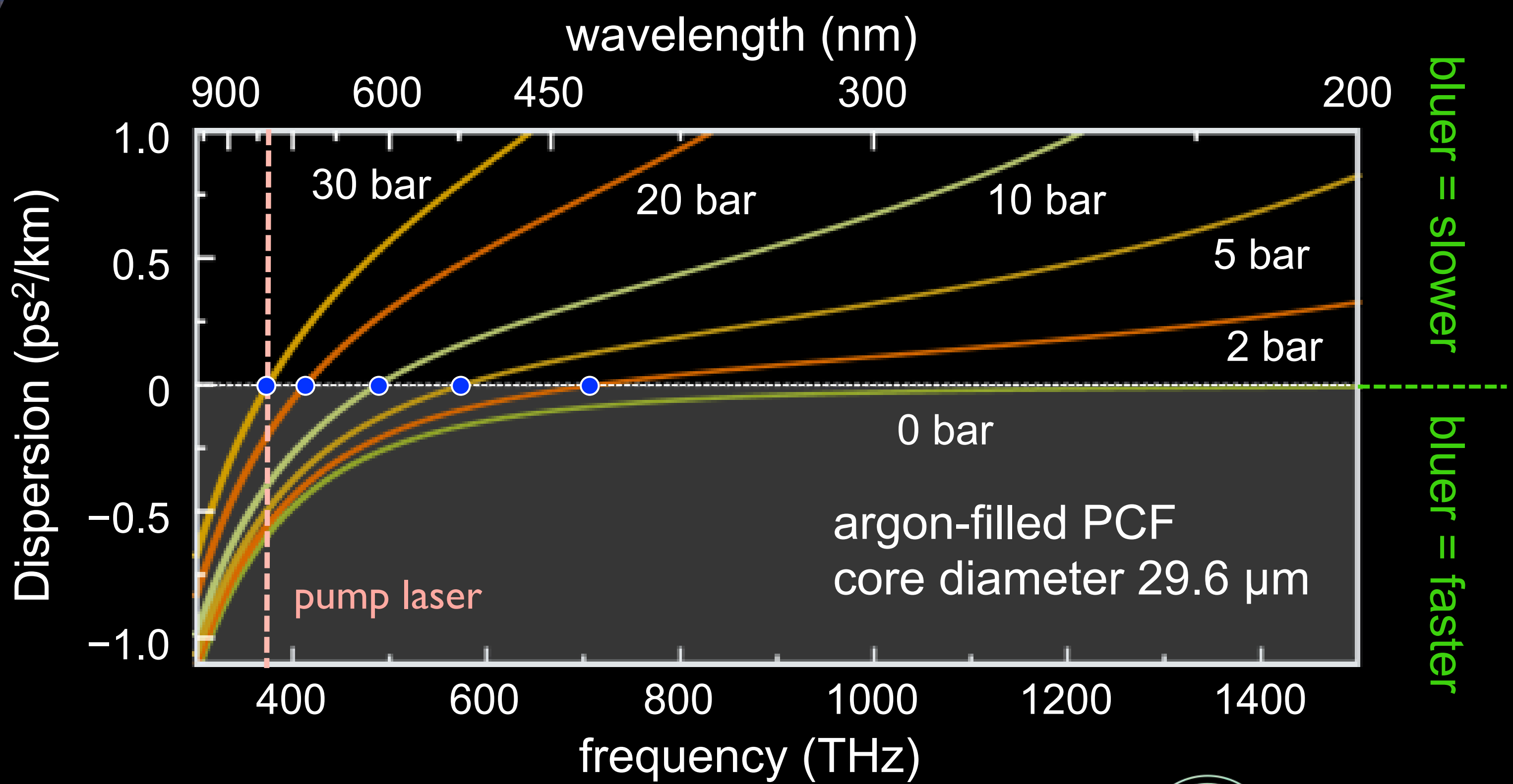
Pressure-tunable dispersion in ARR-PCF

Reviews: PR et al: Nat. Phot. **8**, 278 (2014)
Travers et al: JOSA B **28**, A11-A26 (2011)

kagome



- long well-controlled path-lengths
- broadband guidance (for few-cycle pulses)
- low light-glass overlap (high damage threshold)
- tunable low anomalous/normal dispersion



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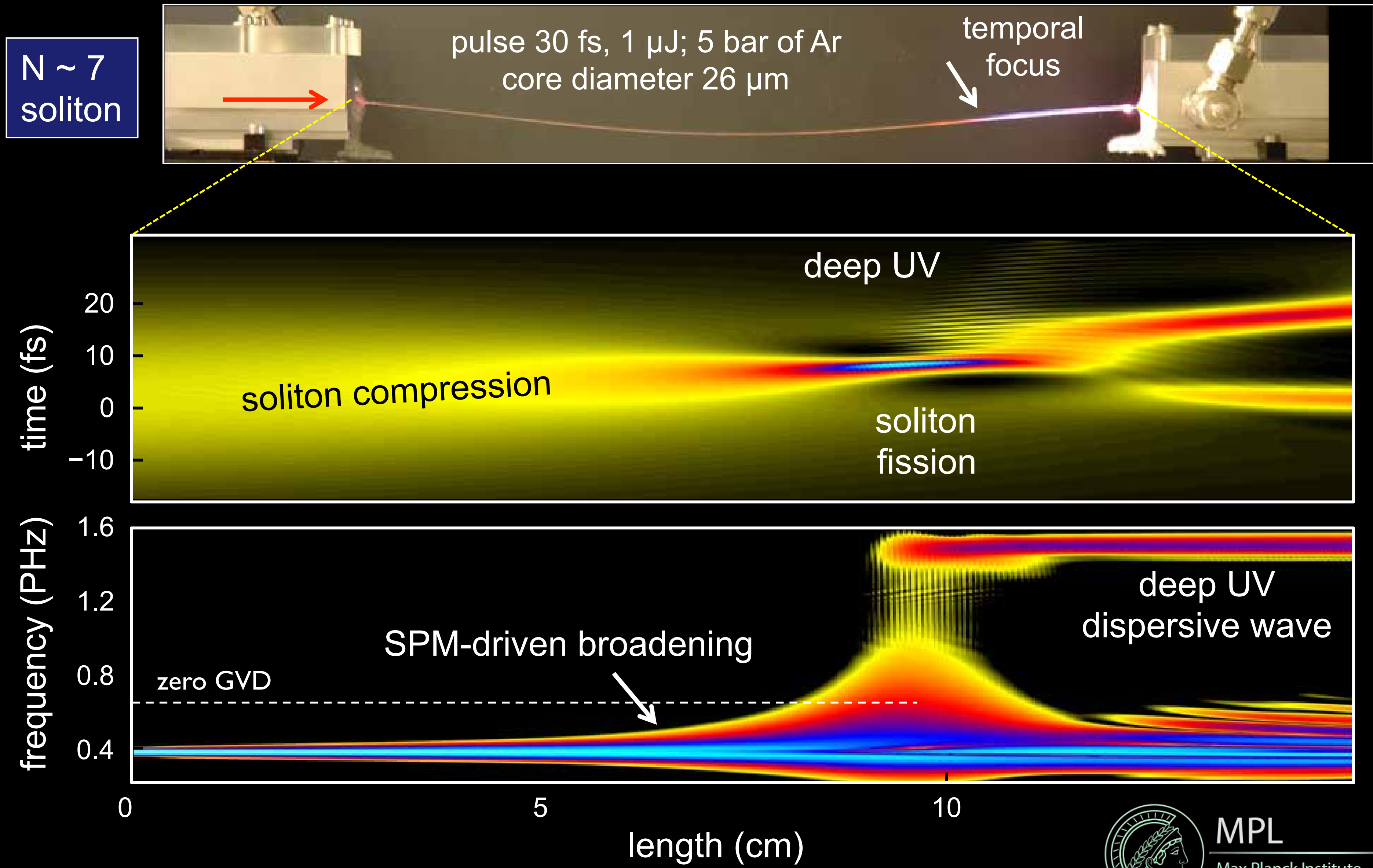
Ultrashort pulses of DUV/VUV light

Joly et al: Phys. Rev. Lett. **106**, 203901 (2011)



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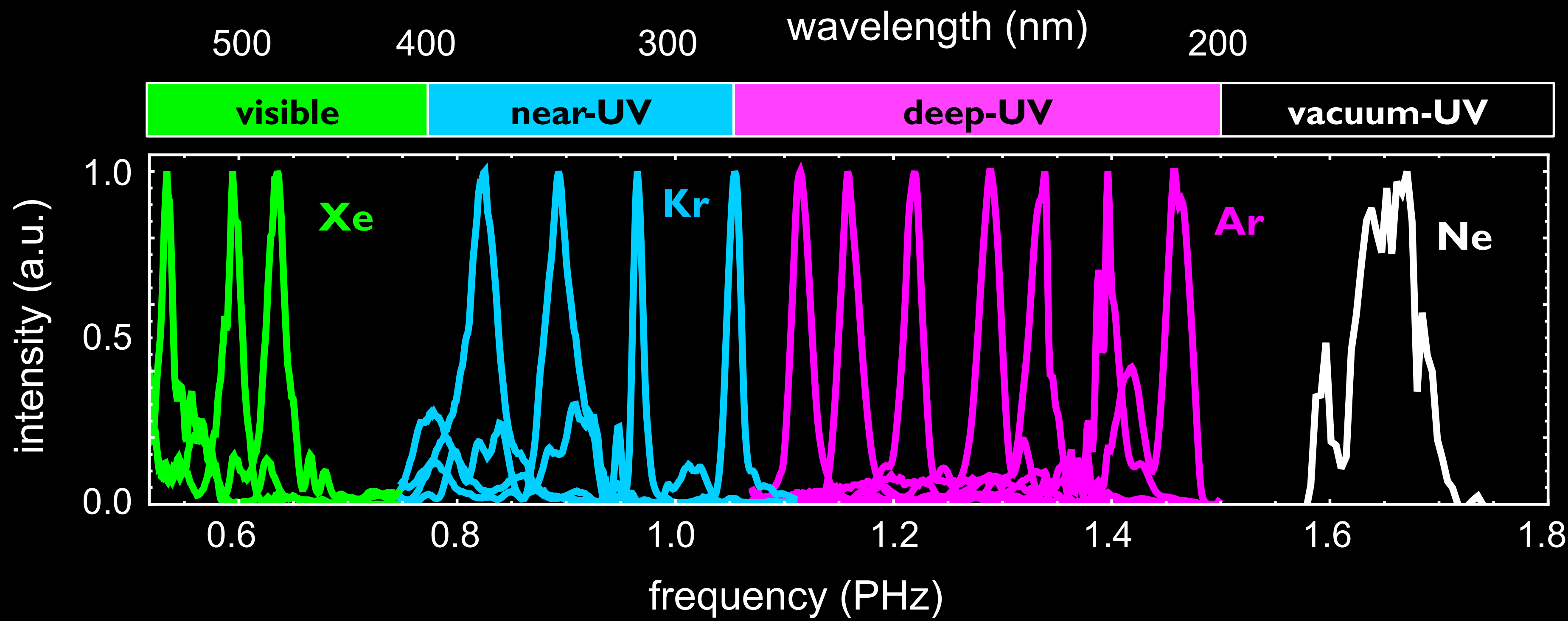
Tunability by varying pulse, fibre & gas

Mak et al: Opt. Exp. **21**, 10942 (2013)



1% to 8% conversion from near-IR to vacuum-UV

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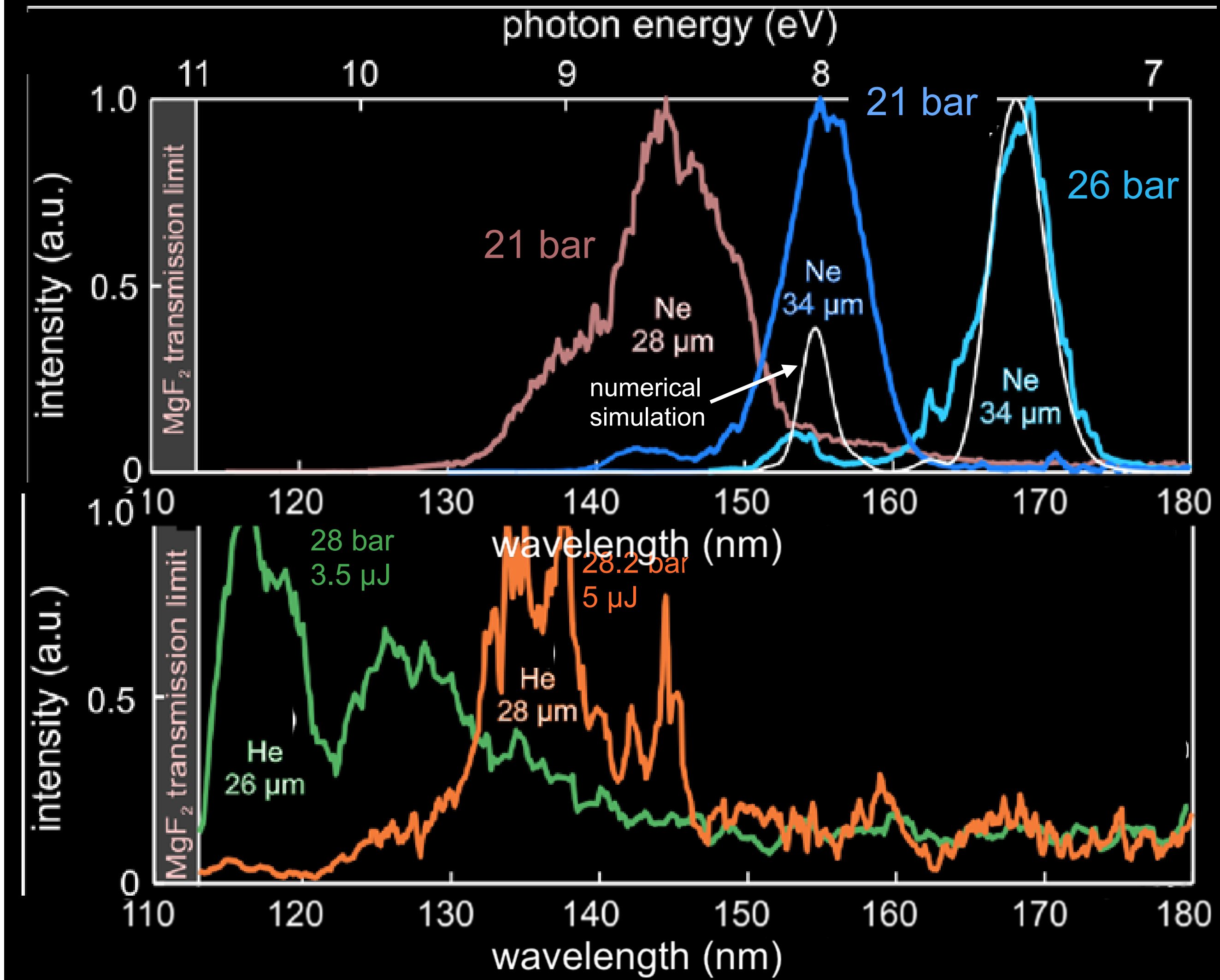
Tunable VUV dispersive wave emission

Ermolov et al: Phys. Rev. A., **92**, 033821 (2015)



Coherent ultrashort DW pulses of VUV light generated in Ne-filled HC-PCF (35 fs, 4 µJ pump at 800 nm)

He-filled HC-PCF: VUV portion of the supercontinuum spectrum (linear scale)

Compressible to 500 attoseconds (theory)

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IMPOSING MOLECULAR ORDER

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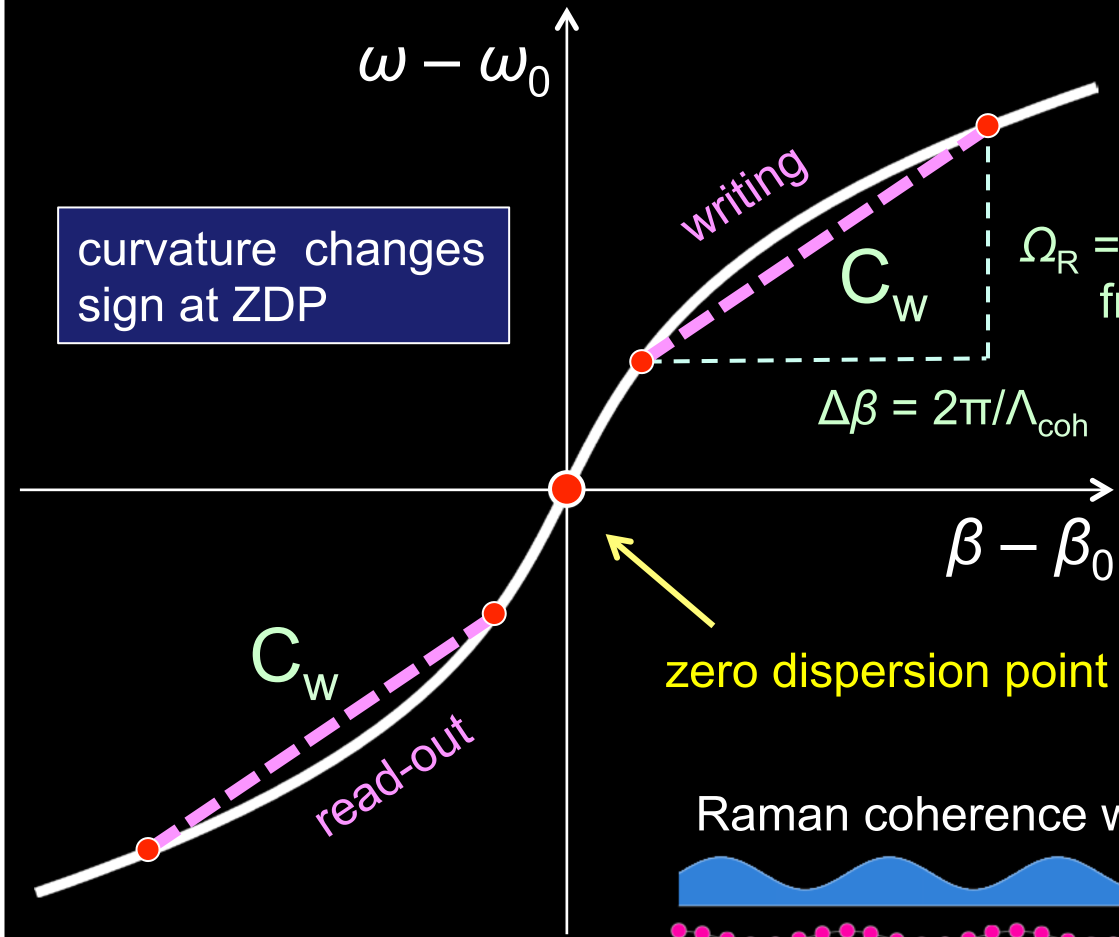
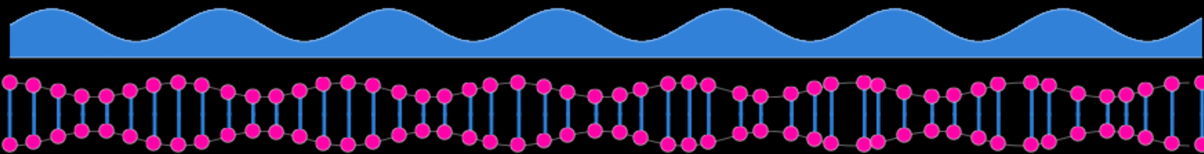
Phase-matching in the vicinity of the ZDP

Bauerschmidt et al: Optica **2**, 536–539 (2015)



Raman coherence wave C_w



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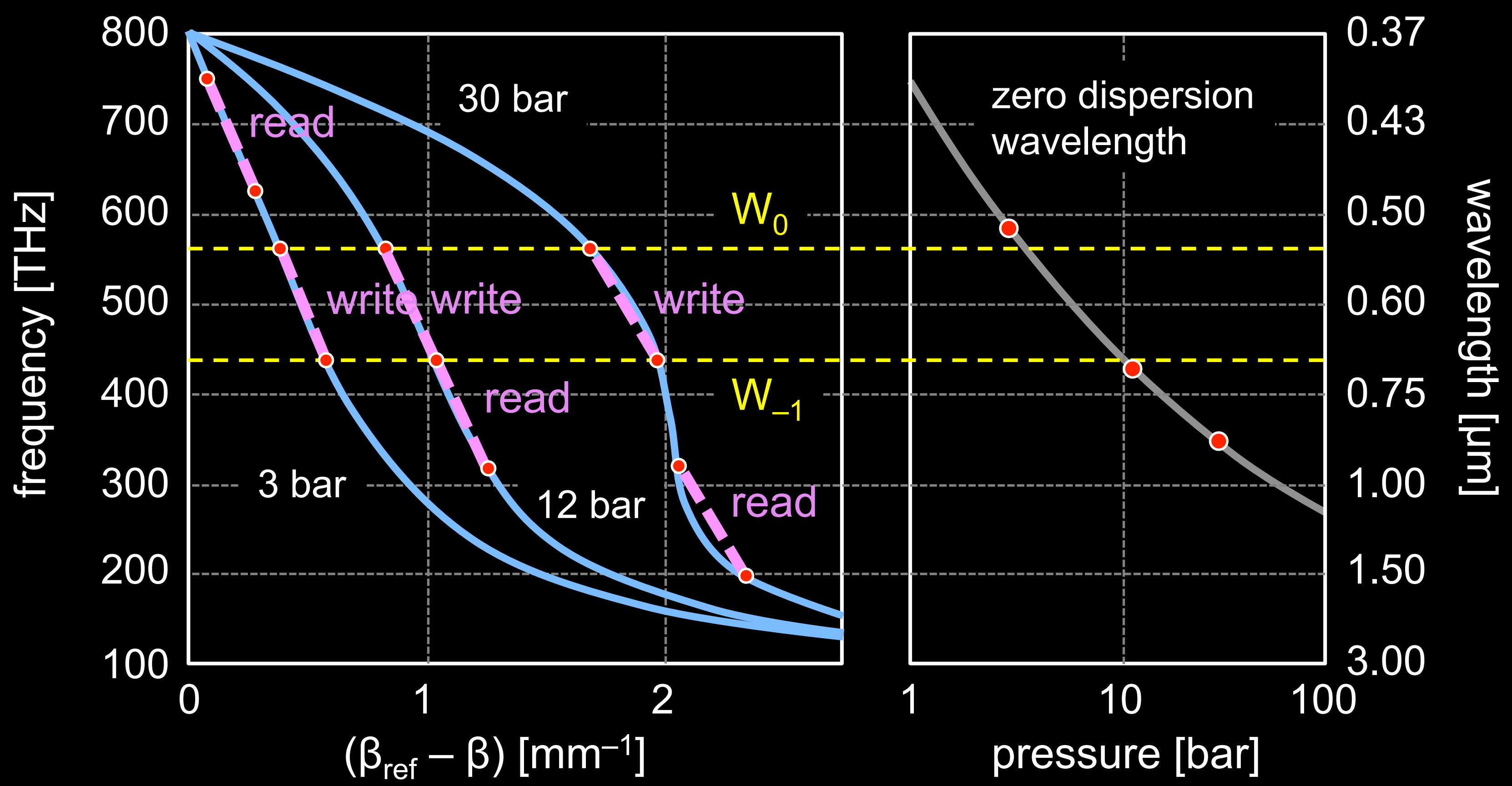
Pressure-tunable from UV to IR

Bauerschmidt et al: Optica **2**, 536–539 (2015)

core diameter ~40 μm



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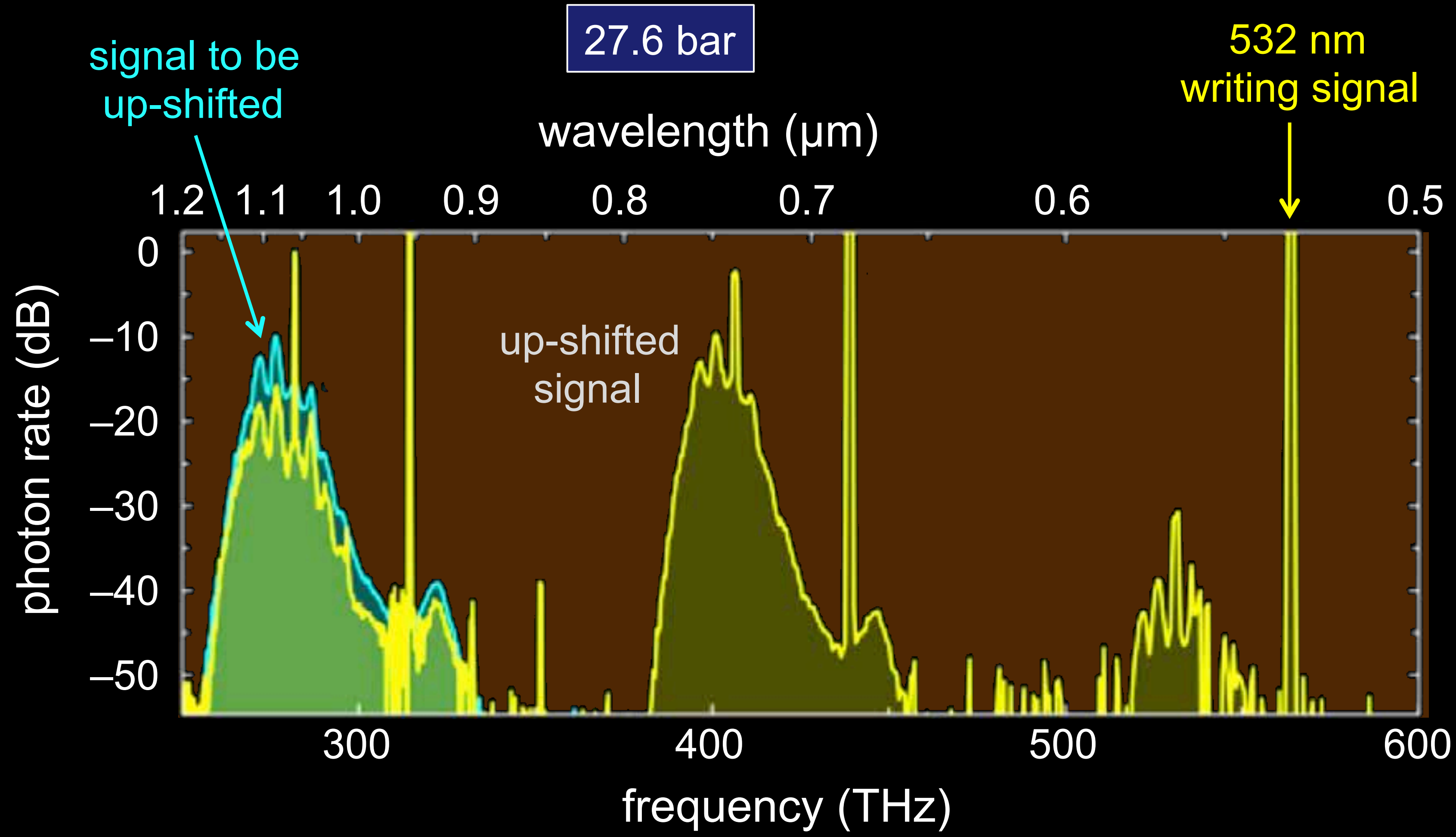
Broad-band spectral up-conversion

Bauerschmidt et al: Optica **2**, 536–539 (2015)



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LIGHT-DRIVEN MECHANICAL MOTION

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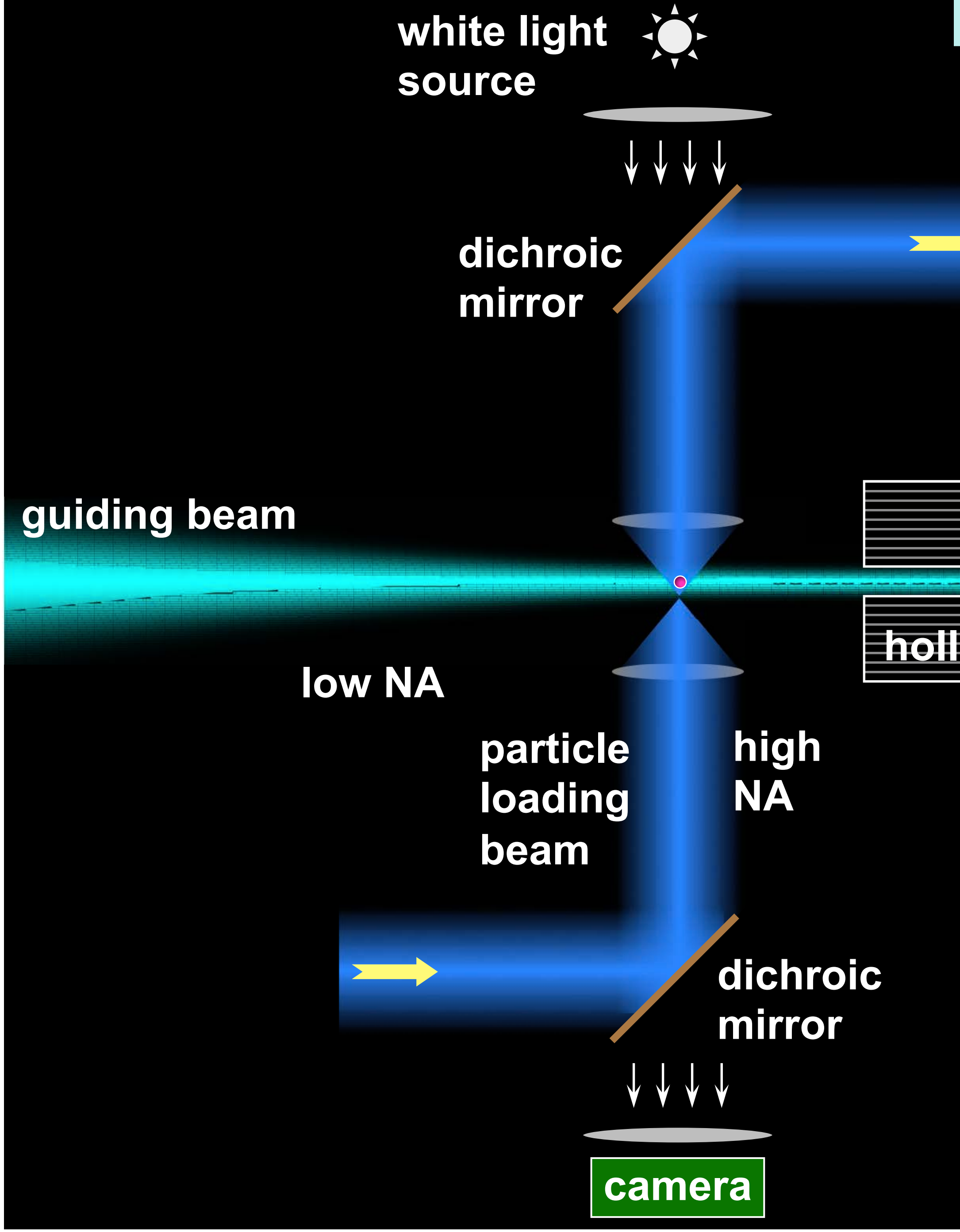
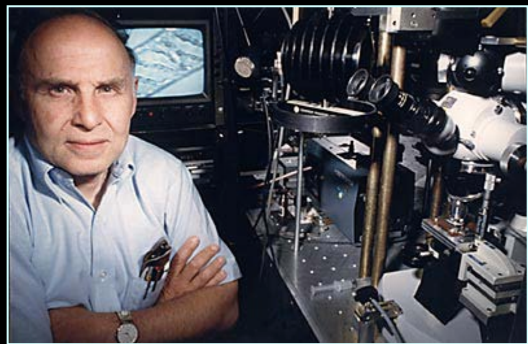
Particle launching in hollow-core PCF

Schmidt et al: Opt. Lett. **37**, 91 (2012)

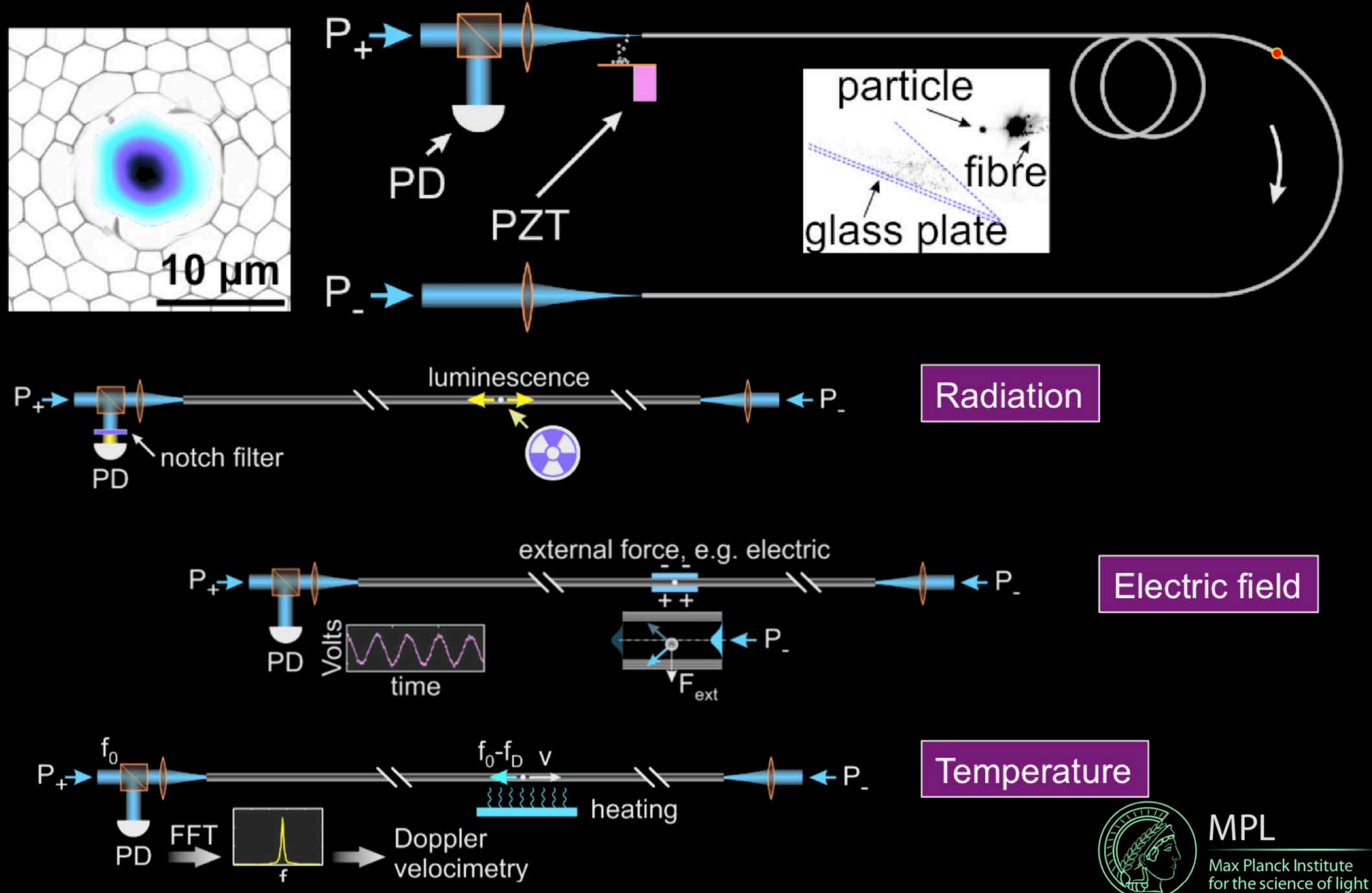




laser tweezers pioneer Arthur Ashkin (1922-)

Flying particle sensors in hollow-core PCF

Bykov et al: Nat. Phot. **9**, 461 (2015)



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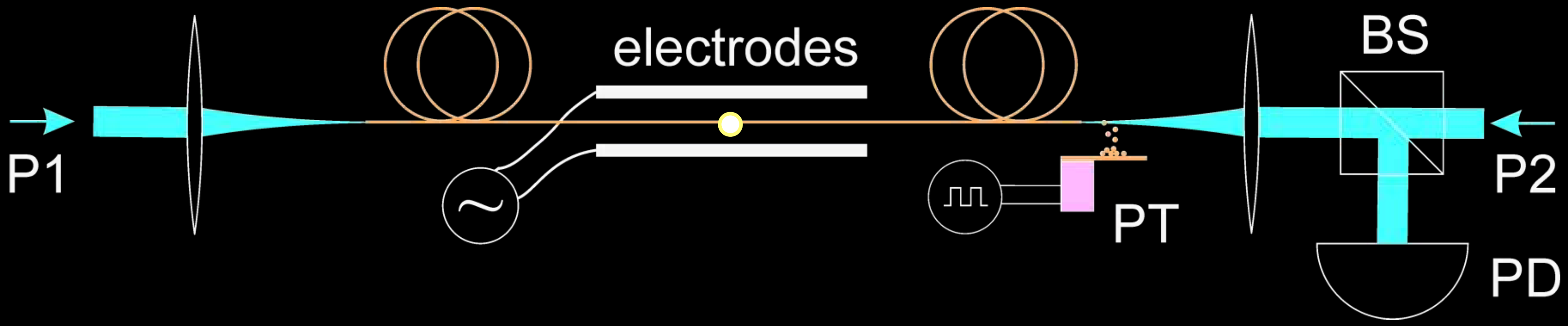
Flying (charged) particle microphone

Bykov et al: Nat. Phot. **9**, 461 (2015)



At the keyboard: Maria Bykova
Recording engineer: Dmitry Bykov

- noise caused by Brownian motion
- quality: not quite as good as a wax cylinder

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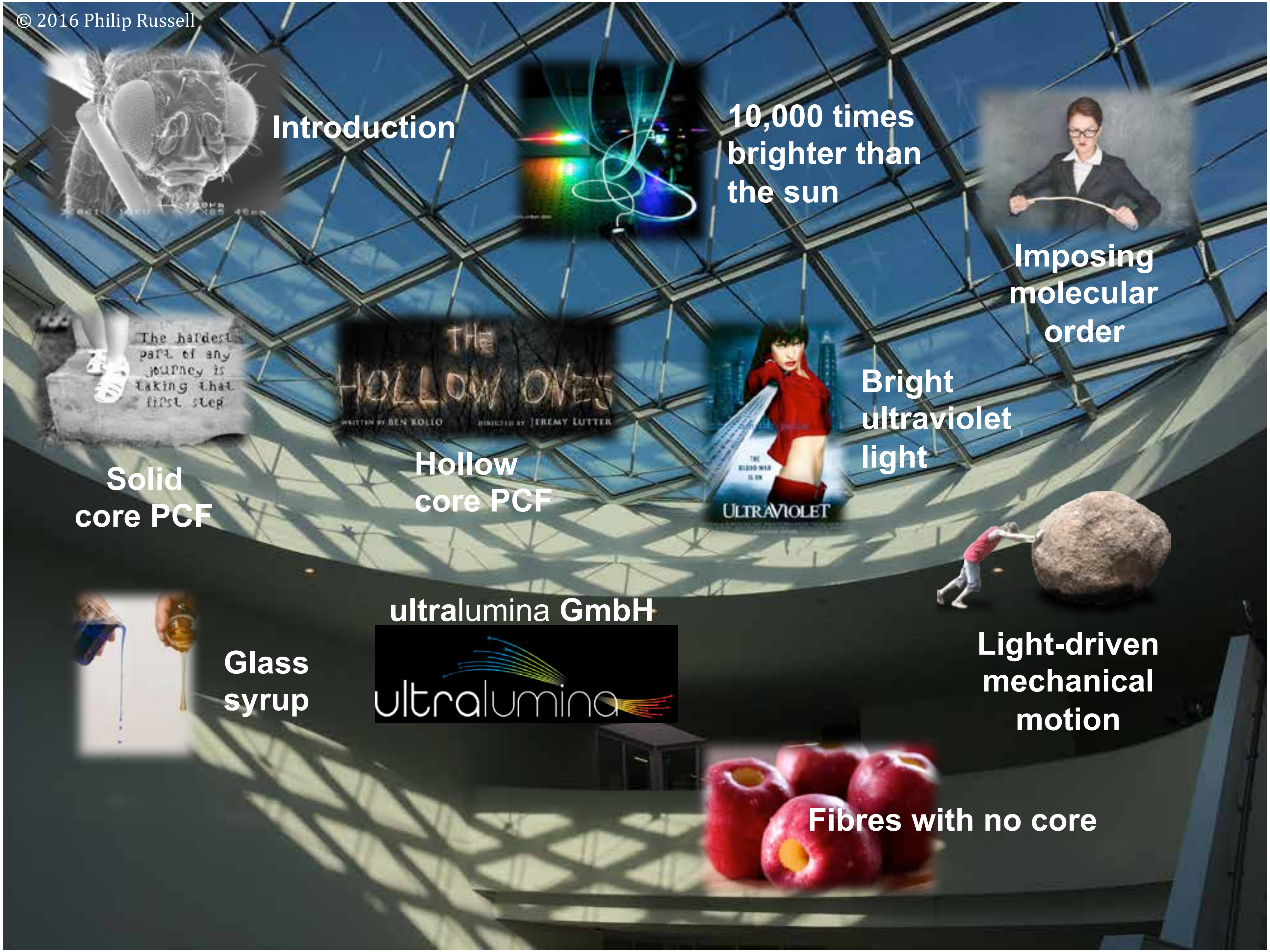
Acknowledgements

Ringberg Castle, June 2017

www.pcfibre.com



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Introduction
10,000 times brighter than the sun
Imposing molecular order
The hardest part of any journey is taking that first step
THE HOLLOW ONES
Solid core PCF
Hollow core PCF
Bright ultraviolet light
ULTRAVIOLET
ultralumina GmbH
ultralumina
Glass syrup
Light-driven mechanical motion
Fibres with no core