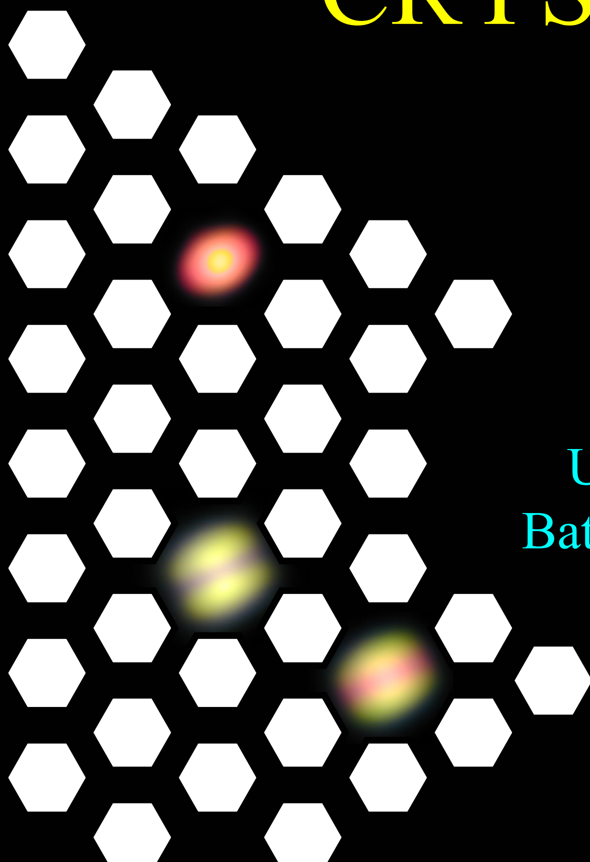
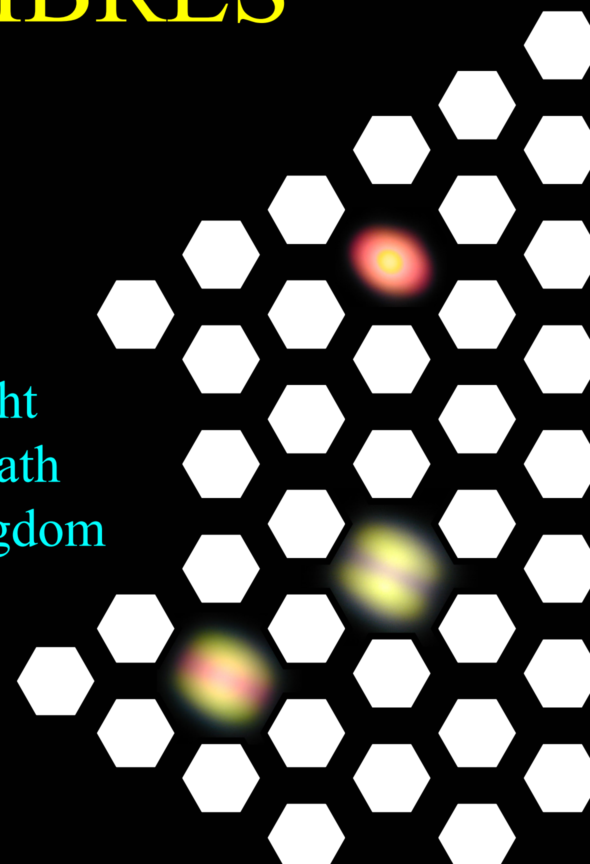
DISPERSION AND NONLINEARITY IN PHOTONIC CRYSTAL FIBRES



Jonathan Knight
University of Bath
Bath, United Kingdom



The filling in the photonic crystal fibre sandwich…

Philip Russell
(yesterday)

John Dudley
(Friday morning)

The filling in the photonic crystal fibre sandwich…

Yourselves

Lunch

The photonic crystal fibre sandwich…

Philip Russell
(yesterday)

John Dudley
(Friday morning)

Other bits…

- Contributed talks: Skryabin and Yulin
  Petroloulos and Monro
  Kobtsev and Smirnov

- Posters: Luan, Bolognini, Wang, Rahman, Hundertmark, Skryabin, Antonopoulos, Cordeiro, Parmentier, Kobtsev, Fuochi, Joly, Biancalana, Leon-Saval, Humbert, Kerrinckx, Kosolapov, Minkovich

This talk…

1. Introductory + dispersion
2. Selected features of NLO in solid-core and hollow-core fibres

Bath Photonic Crystals team

David Bird, Tim Birks, Jonathan Knight, Fetah Benabid, William Wadsworth, Feng Luan, Aimin Wang, Greg Antonopoulos, Greg Pierce, Philip Russell, Georges Humbert, Nicolas Joly, Ravi Kumar, Alan George, Fabio Biancalana, Dmitry Skryabin, Wei Ding, Cristiano Cordeiro blazephotonics

Brian Mangan, John Roberts, Dave Williams, Lance Farr, Hendrik Sabert, Alan Langford, Francois Couny…

Fibres with holes in…
why use them for nonlinear optics?

1. **Control of nonlinearity over 5 orders of magnitude or more…**

Nonlinear coefficient in fibre optics…

$$\gamma = n_2\omega_0/cA_{eff}$$

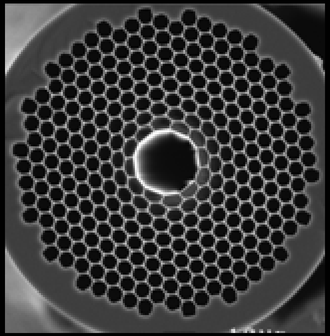
…units are $W^{-1}\ m^{-1}$

Standard fibres have $\gamma \sim 5 \times 10^{-3}\ W^{-1}m^{-1}$

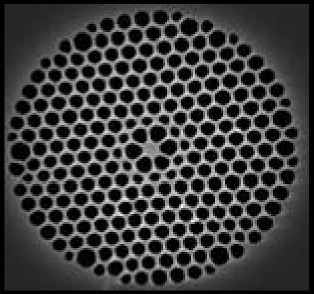
Nonlinear coefficient in PCF…

Standard fibres have $\gamma \sim 5 \times 10^{-3}\ W^{-1}m^{-1}$

- Hollow core… A_{eff} =27 μm^2 (800 nm wavelength)
  $n_2 \approx 2.9\times10^{-23}$ m^2/W (air)
  $\rightarrow$ $\gamma = 8 \times 10^{-6}\ W^{-1}m^{-1}$



- Nonlinear solid core… A_{eff} = 1.2μm^2 (800nm wavelength)
  $n_2 = 2.5 \times10^{-20}$ m^2/W (silica)
  $\rightarrow$ $\gamma = 0.164\ W^{-1}m^{-1}$



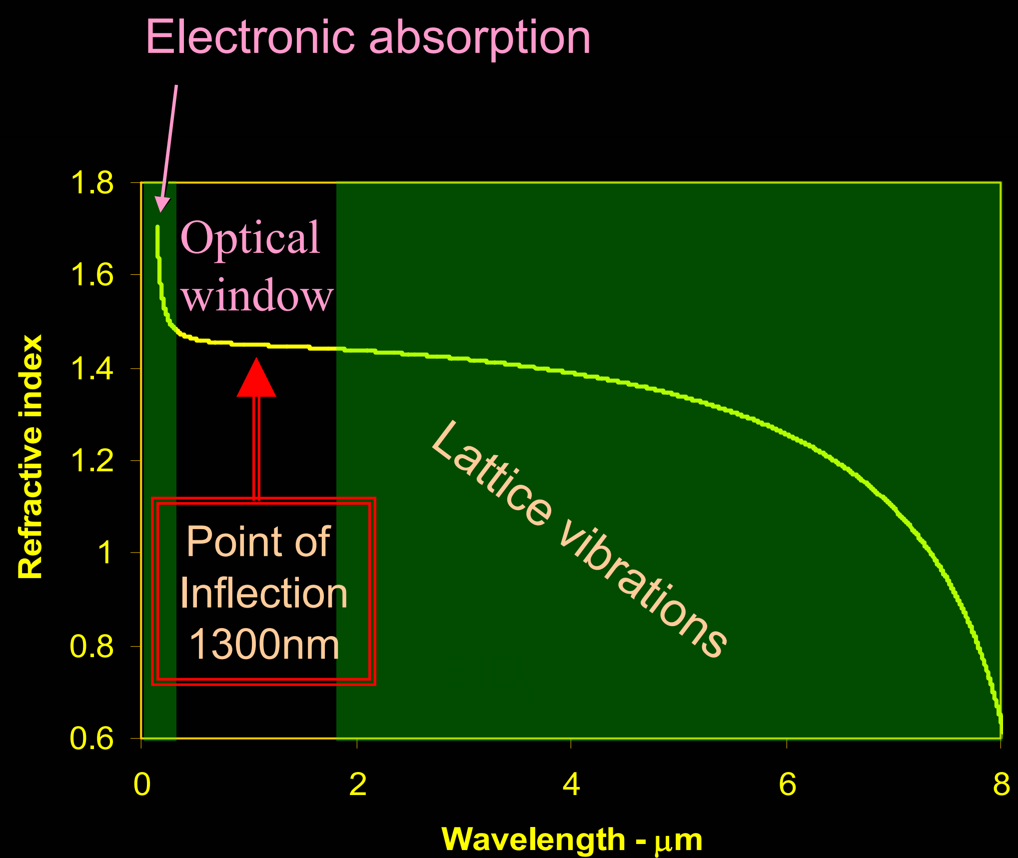
…and other materials have a much higher n_2

Fibres with holes in…
why use them for nonlinear optics?

1. Control of nonlinearity over 5 orders of magnitude…
2. **Strong control over the dispersion**

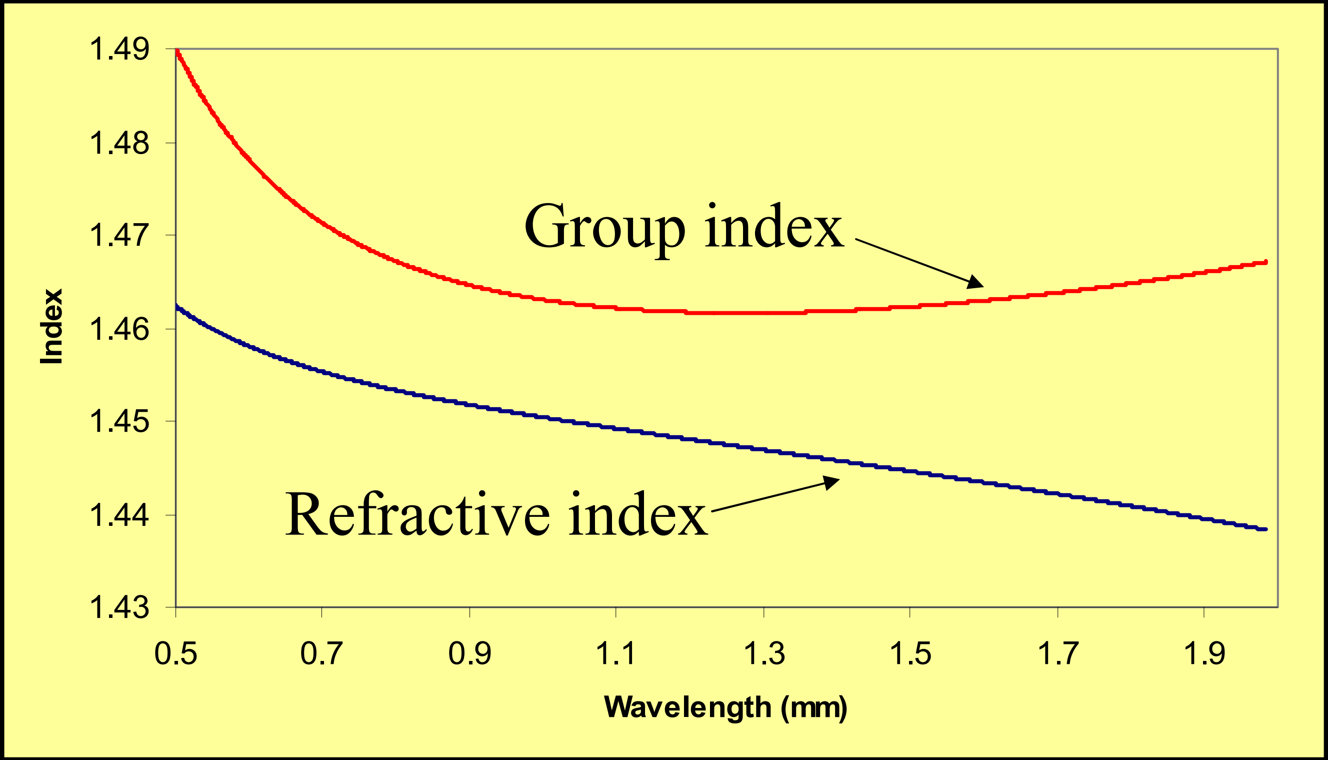
Material dispersion – SiO_2

- Can be computed from the refractive index, for simple materials
- Remember, GVD is related to the **second derivative** of the index

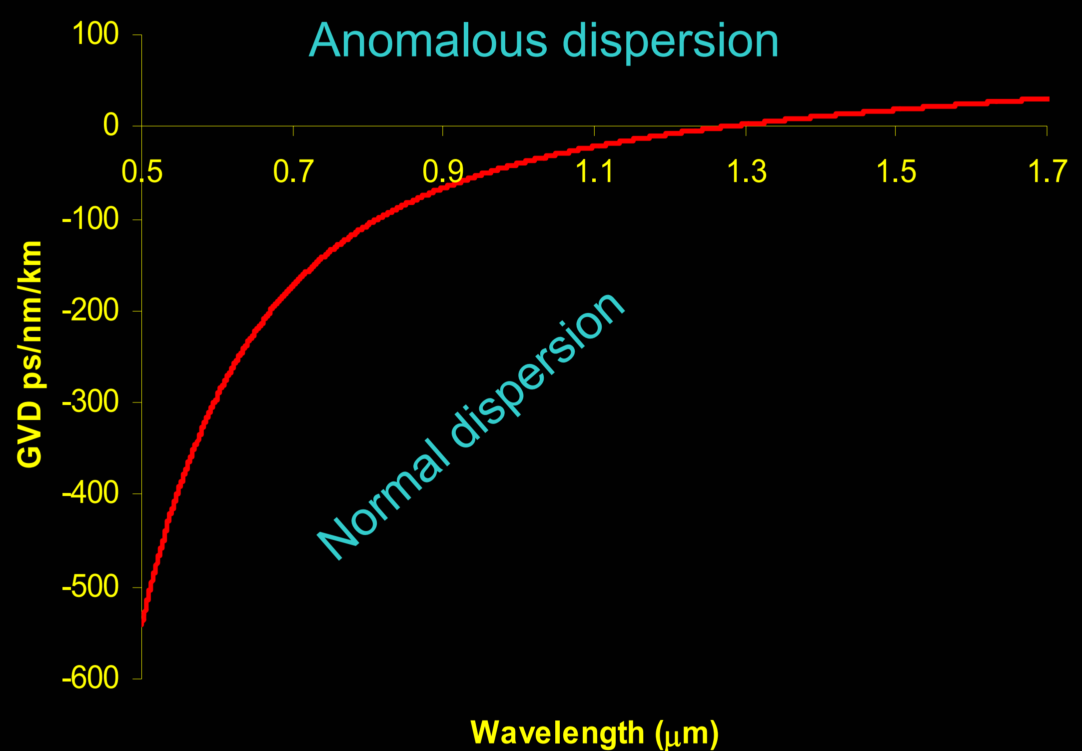


Group index of bulk silica

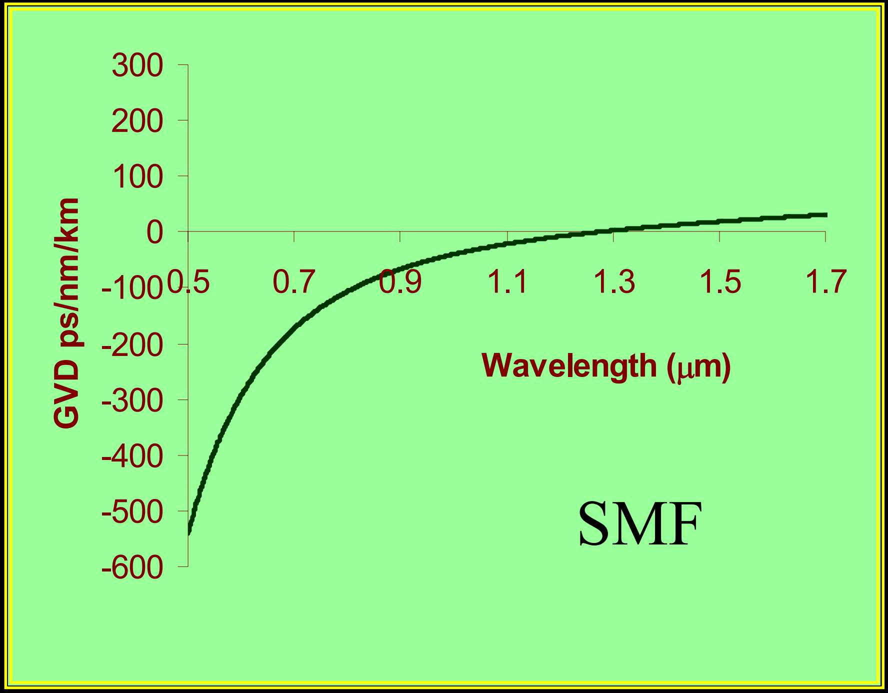
$$n_g = n + \omega \frac{dn}{d\omega}$$

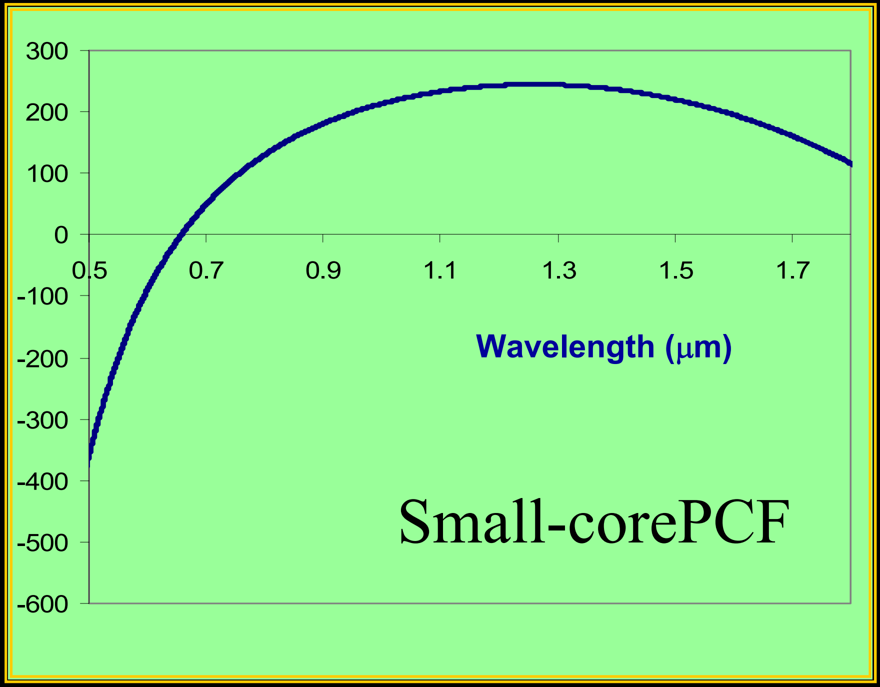


Group velocity dispersion (GVD) of silica



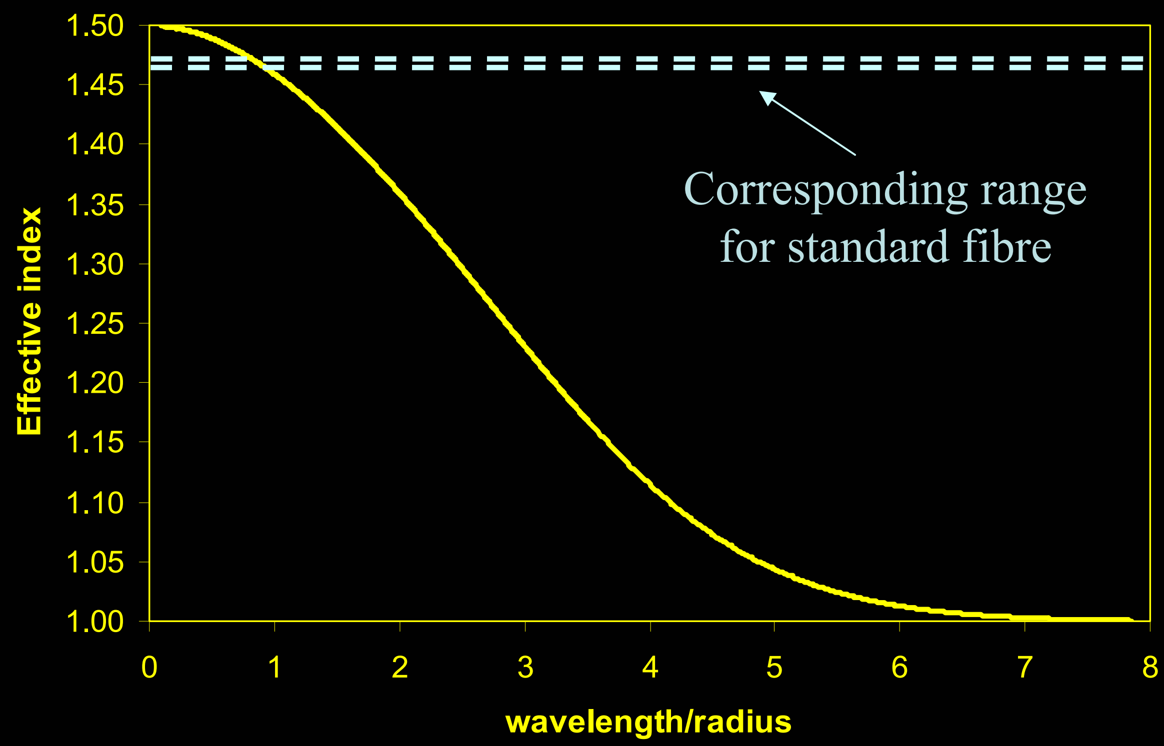
Group velocity dispersion in solid core PCF





Waveguide dispersion

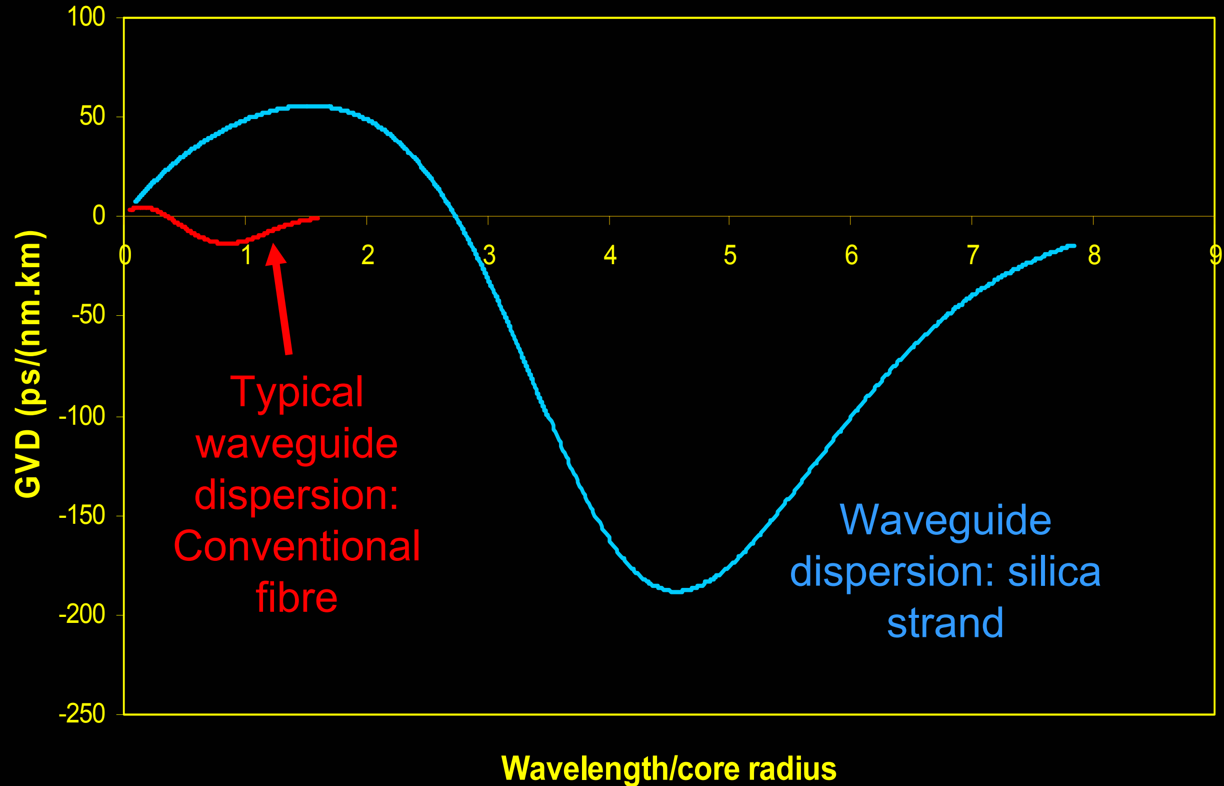
For air-clad PCF, cladding index changes massively over a narrow range: the waveguide dispersion is huge.



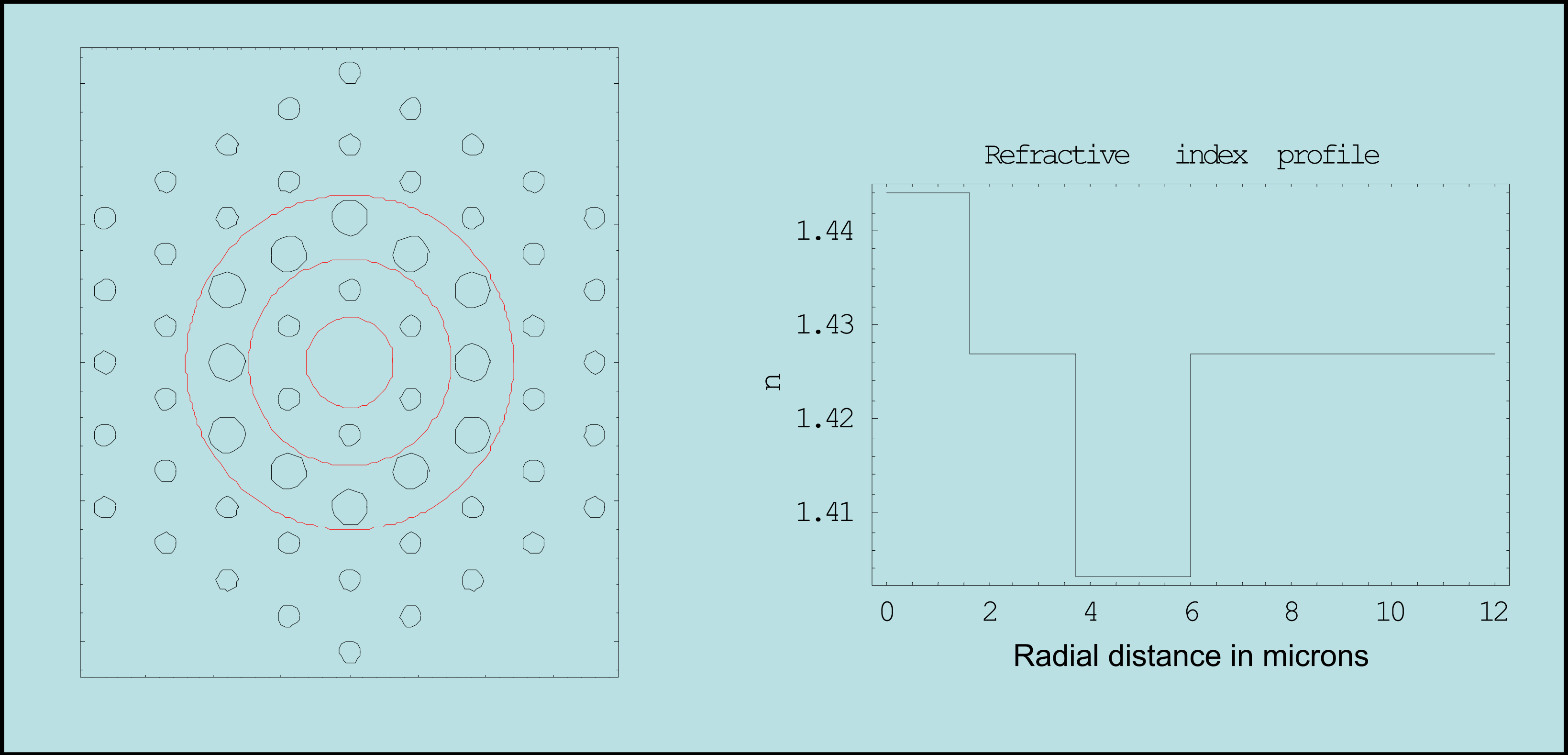
Computations for the fundamental mode in a circular strand of glass index 1.5 surrounded by air

Waveguide dispersion in solid-core PCF: effect on group-velocity dispersion

Large value of Δ enables high waveguide dispersion



Effective index models



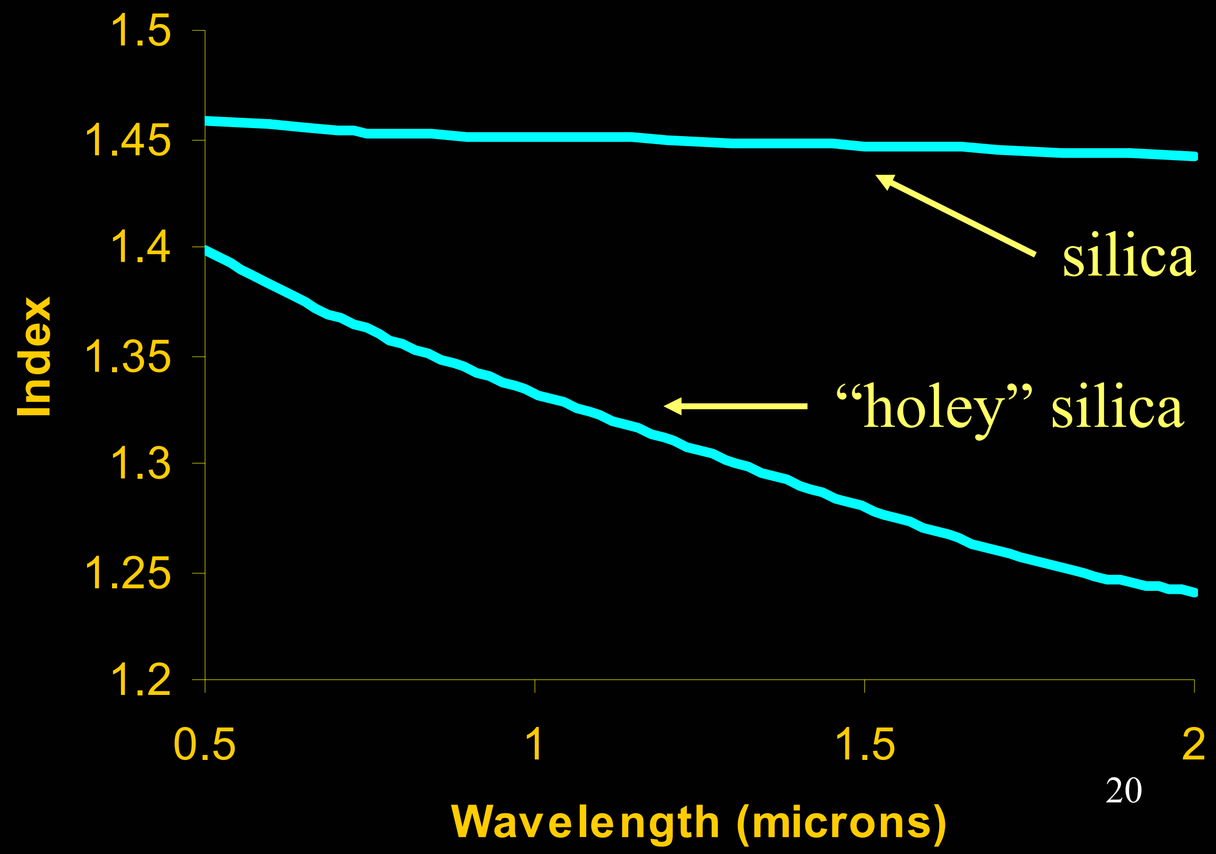
Then: use standard fibre optics to determine field patterns, dispersion etc.

Cladding dispersion

- Material dispersion of silica
- Waveguide dispersion
- Dispersion of the "holey" material

Index of the "fundamental space-filling mode"

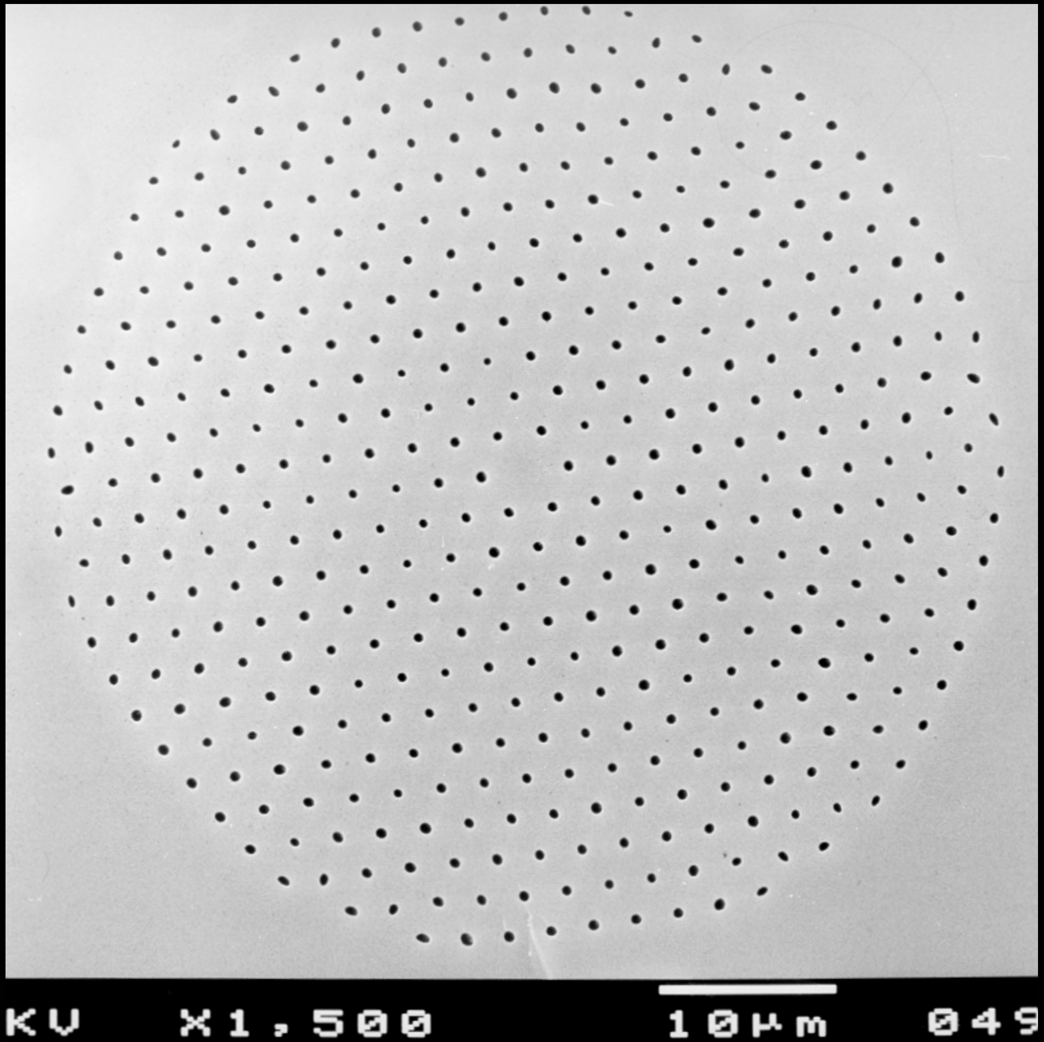
$\Lambda = 2\mu m$, $d/\Lambda = 0.8$



Dispersion-flattened PCF

- Structure has around 2.5μm pitch, air hole diameter 570nm
- Fiber is single-mode at all wavelengths

Total dispersion is due to SiO_2, photonic crystal cladding, waveguide dispersion



Will Reeves

Dispersion-flattened PCF

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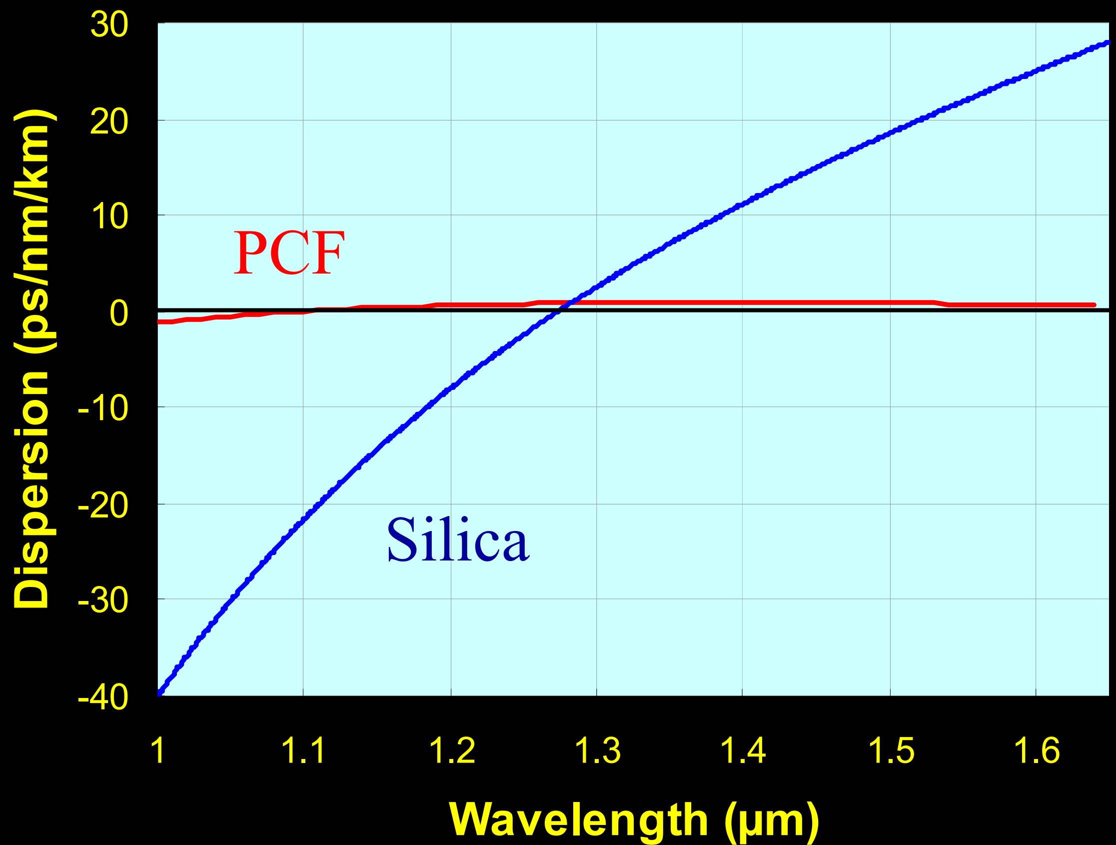

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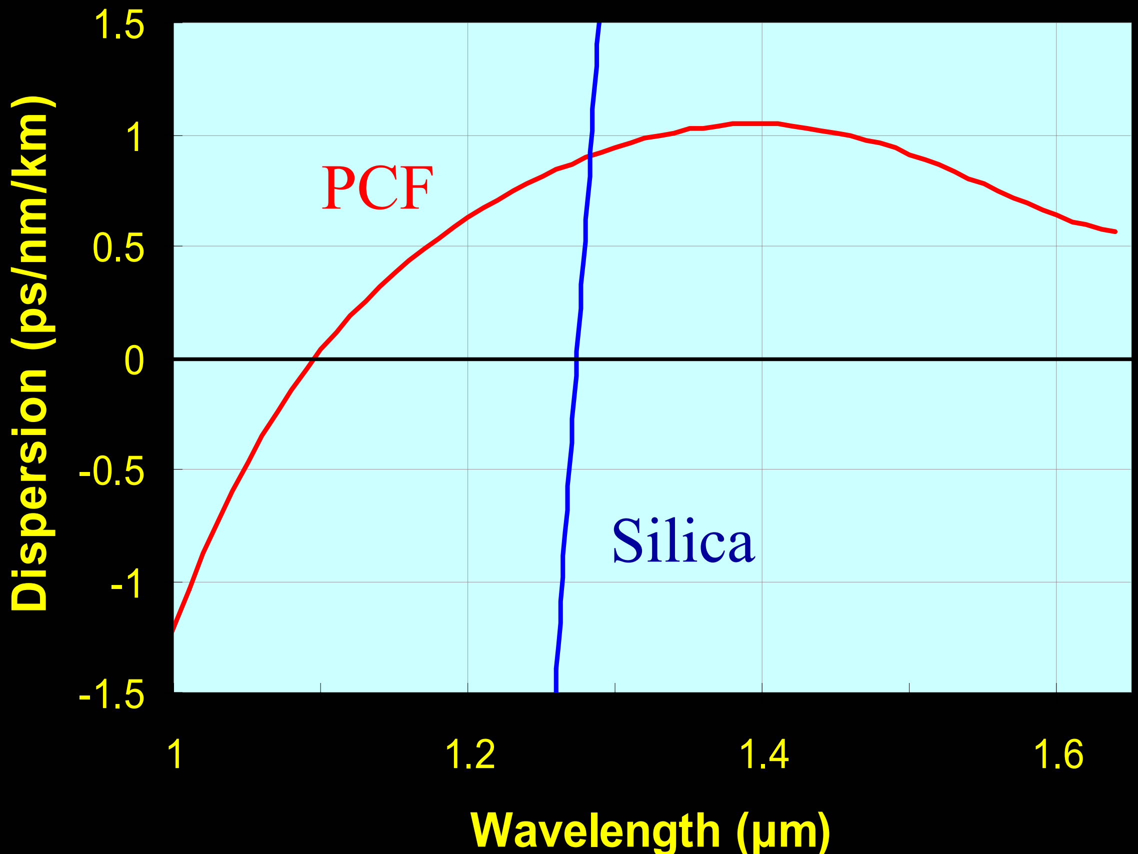
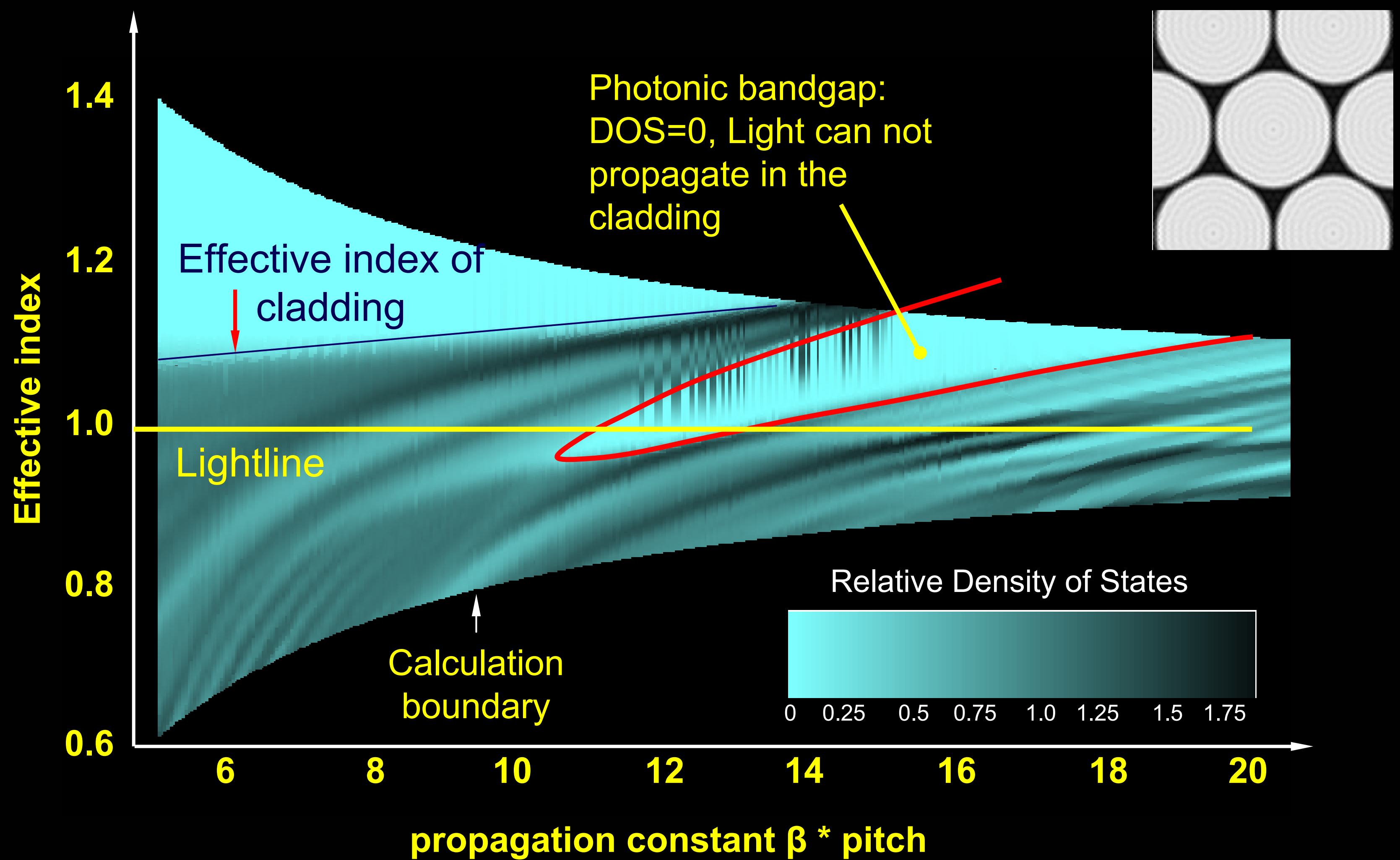
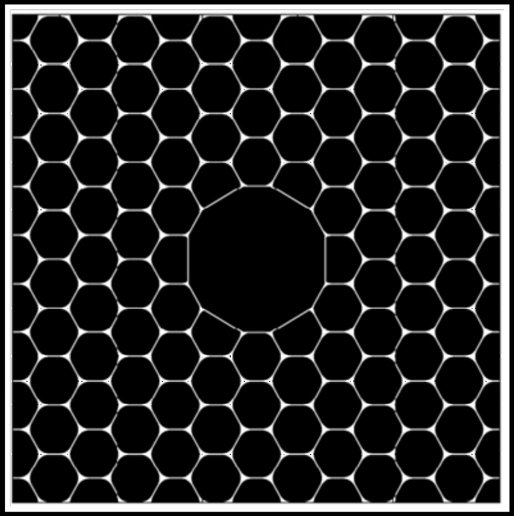


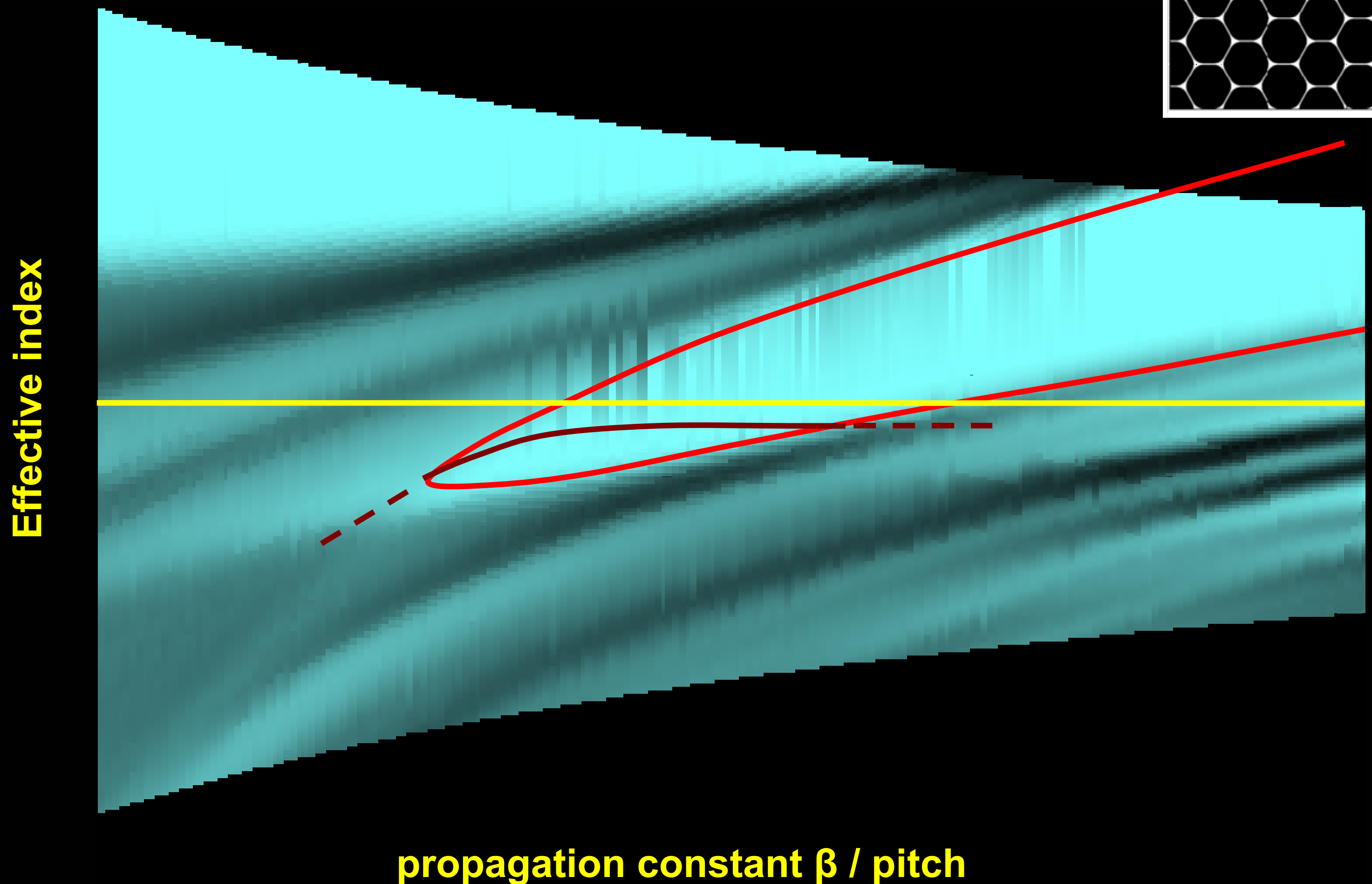
Will Reeves

Band gaps in a silica/air photonic crystal

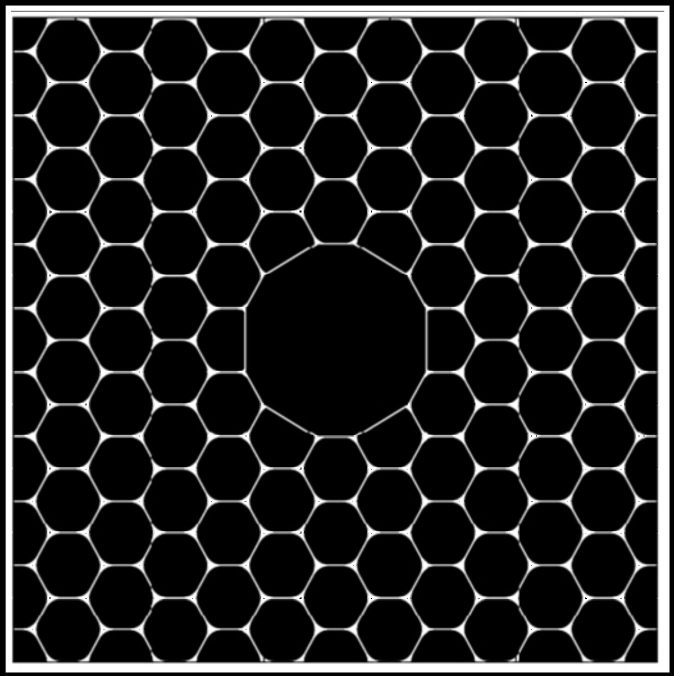


Defect modes in an air-core bandgap fiber

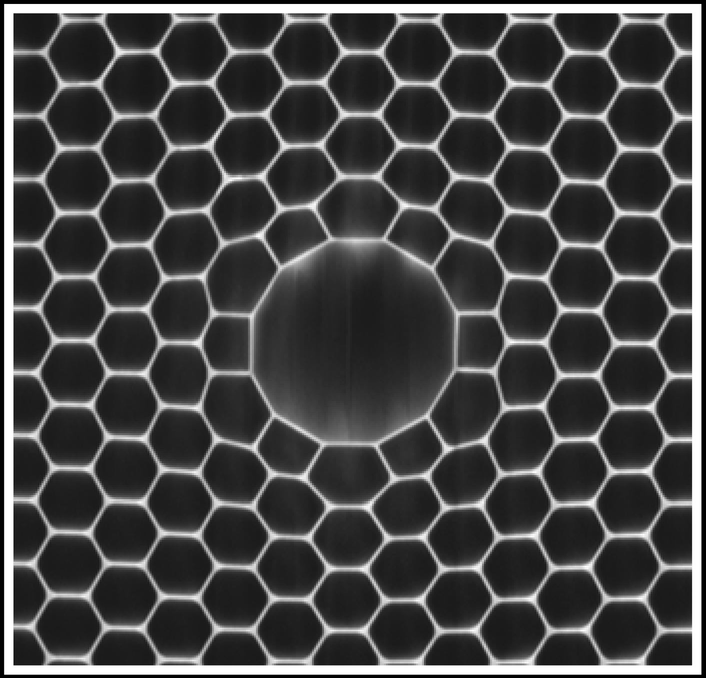




Air-mode guided in the band gap



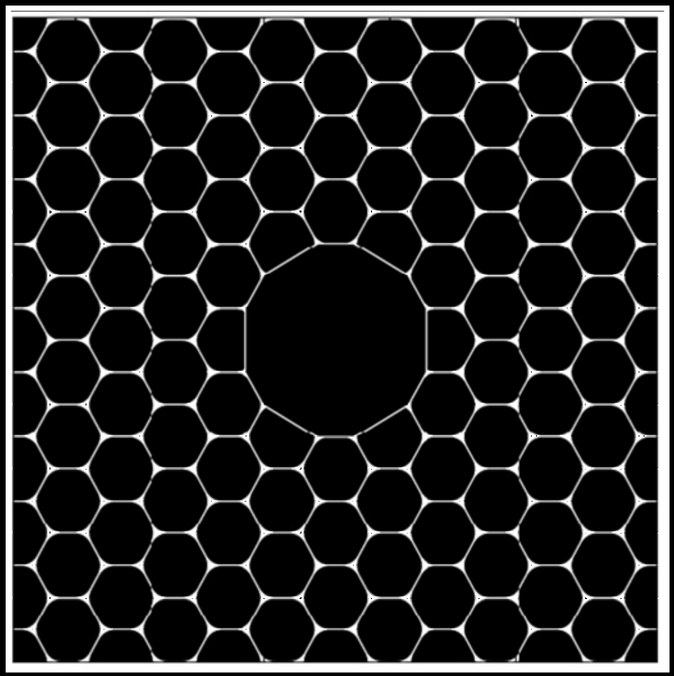
Modelled

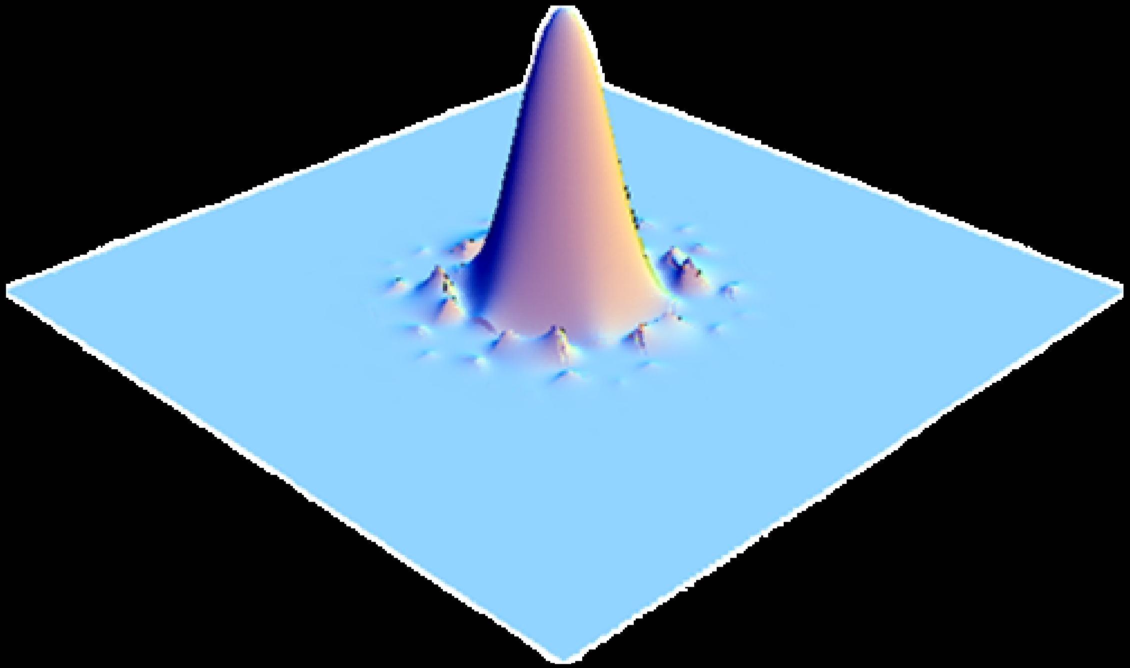


Fabricated

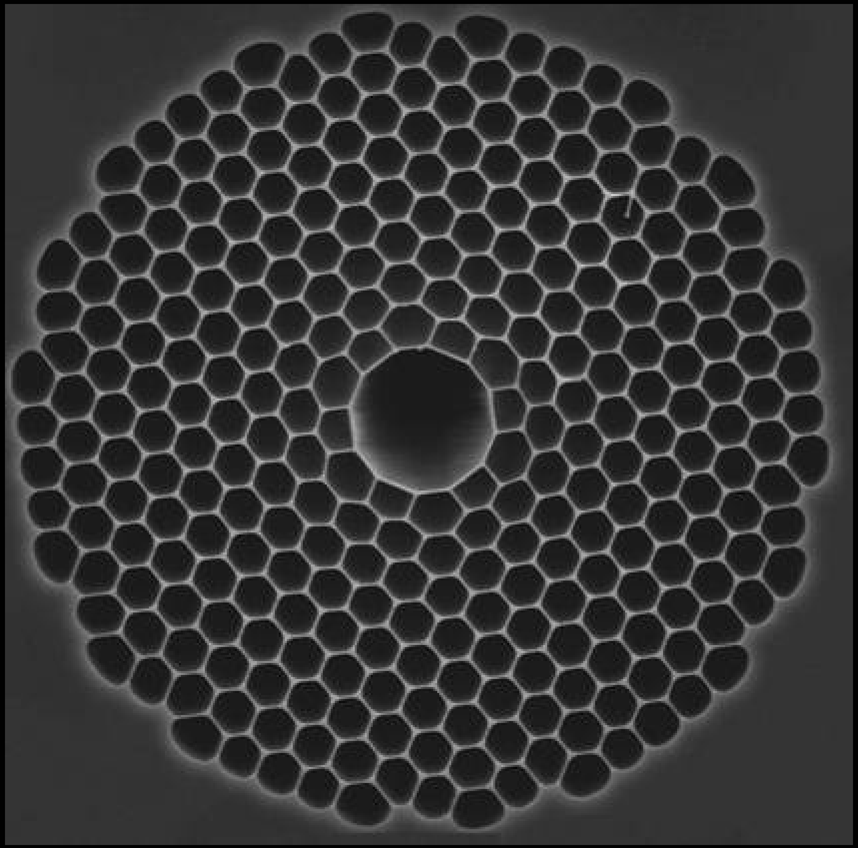
Dave Williams

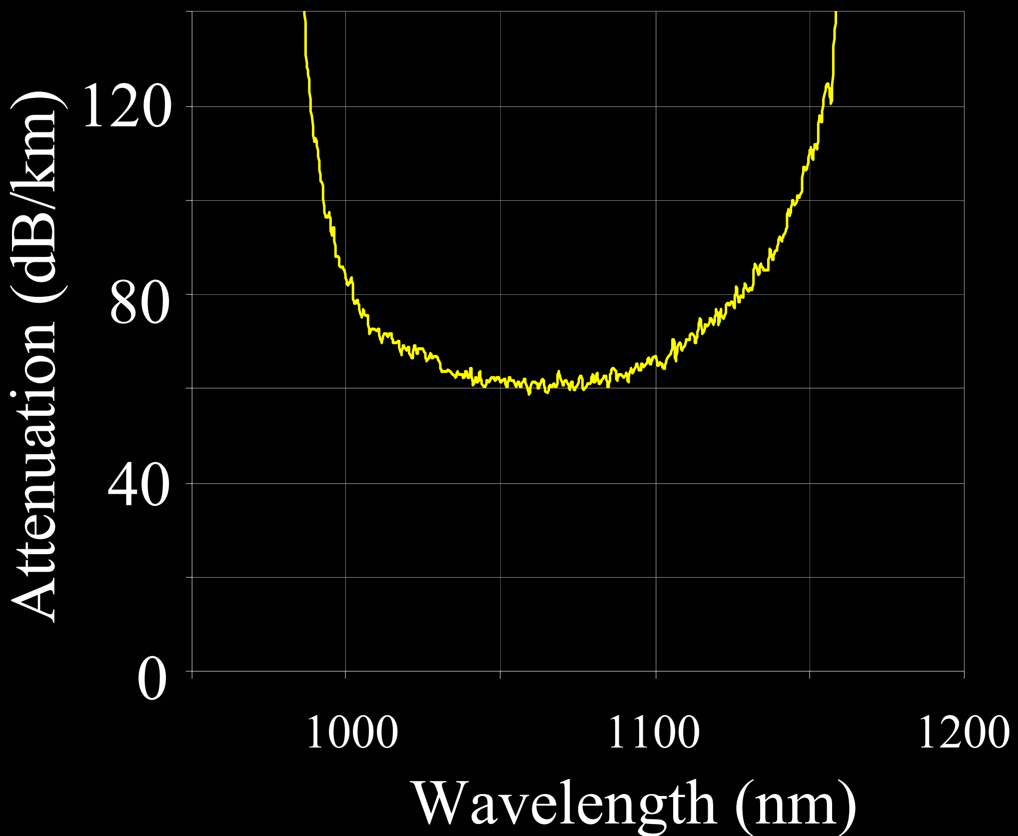
Air-mode guided in the band gap





Hollow-core fiber at 1060nm

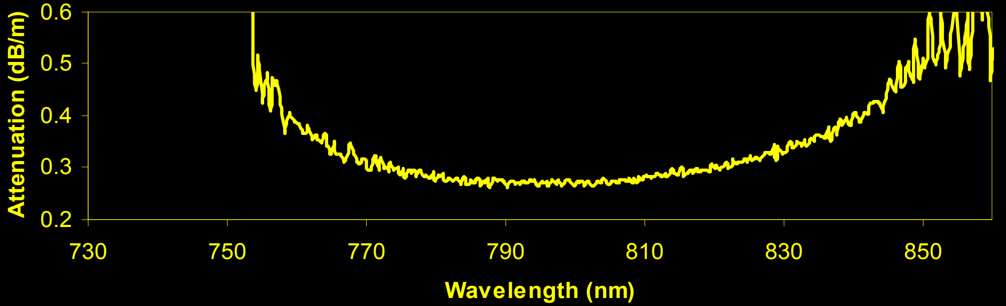


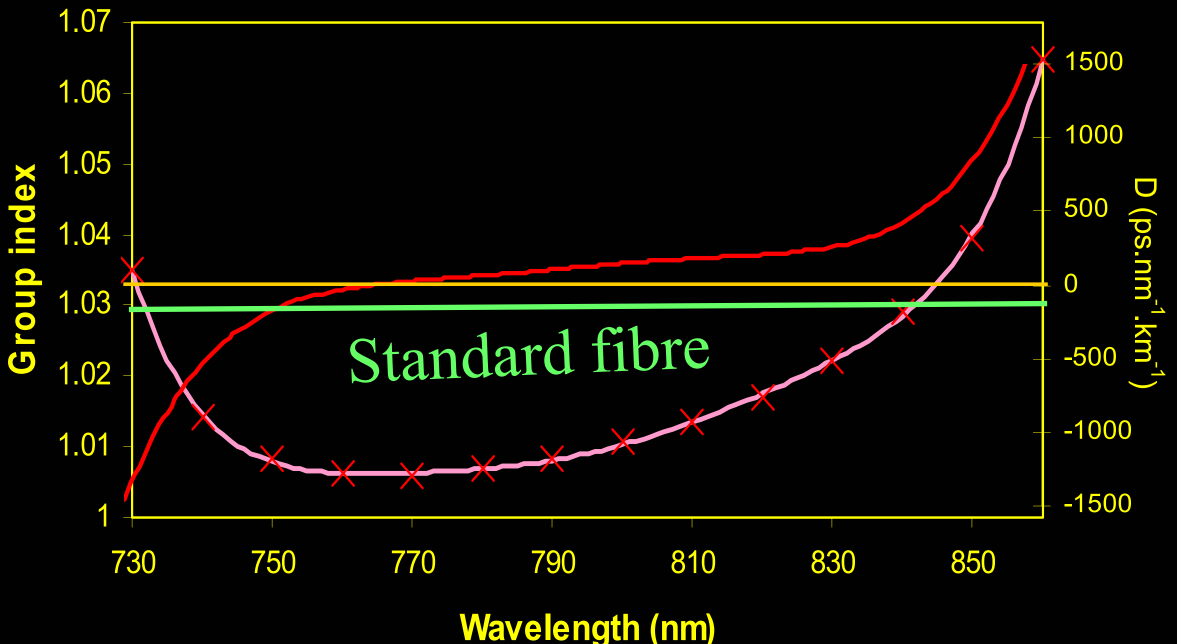


$\Lambda = 3\mu m$
FF > 90%
…with 7-cell defect

Dispersion in hollow-core

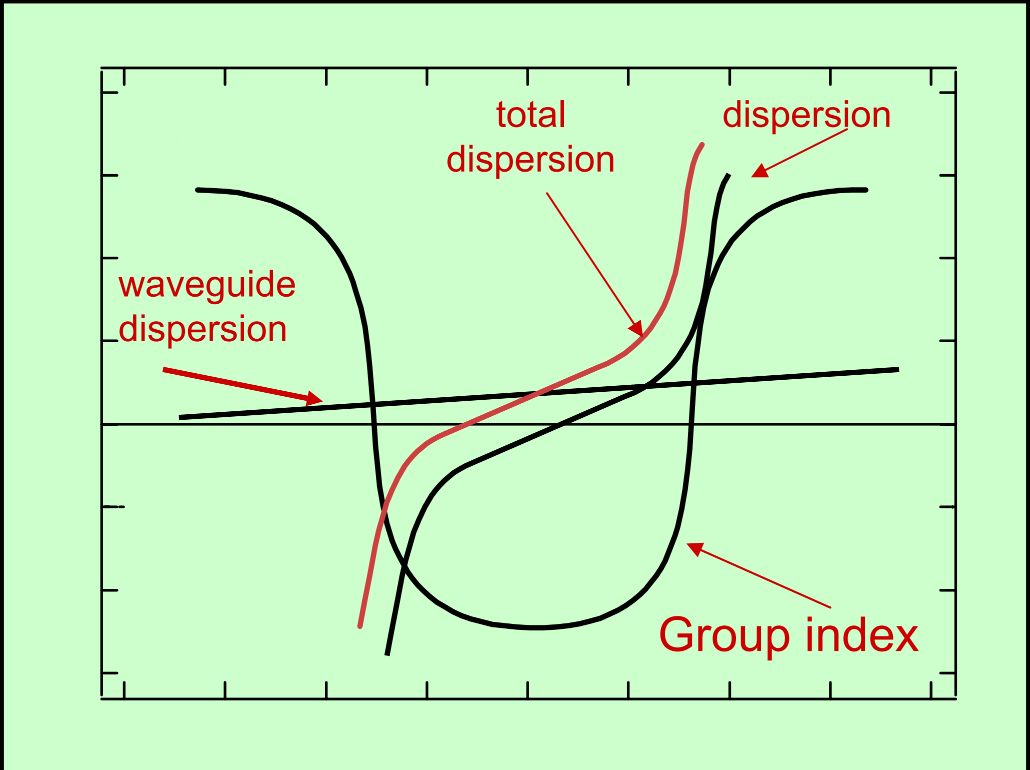
- Group index measured using low-coherence interferometry
- GVD found by differentiating a fit to the group delay points
- Anomalous over most of the band





Luan, Bouwmans

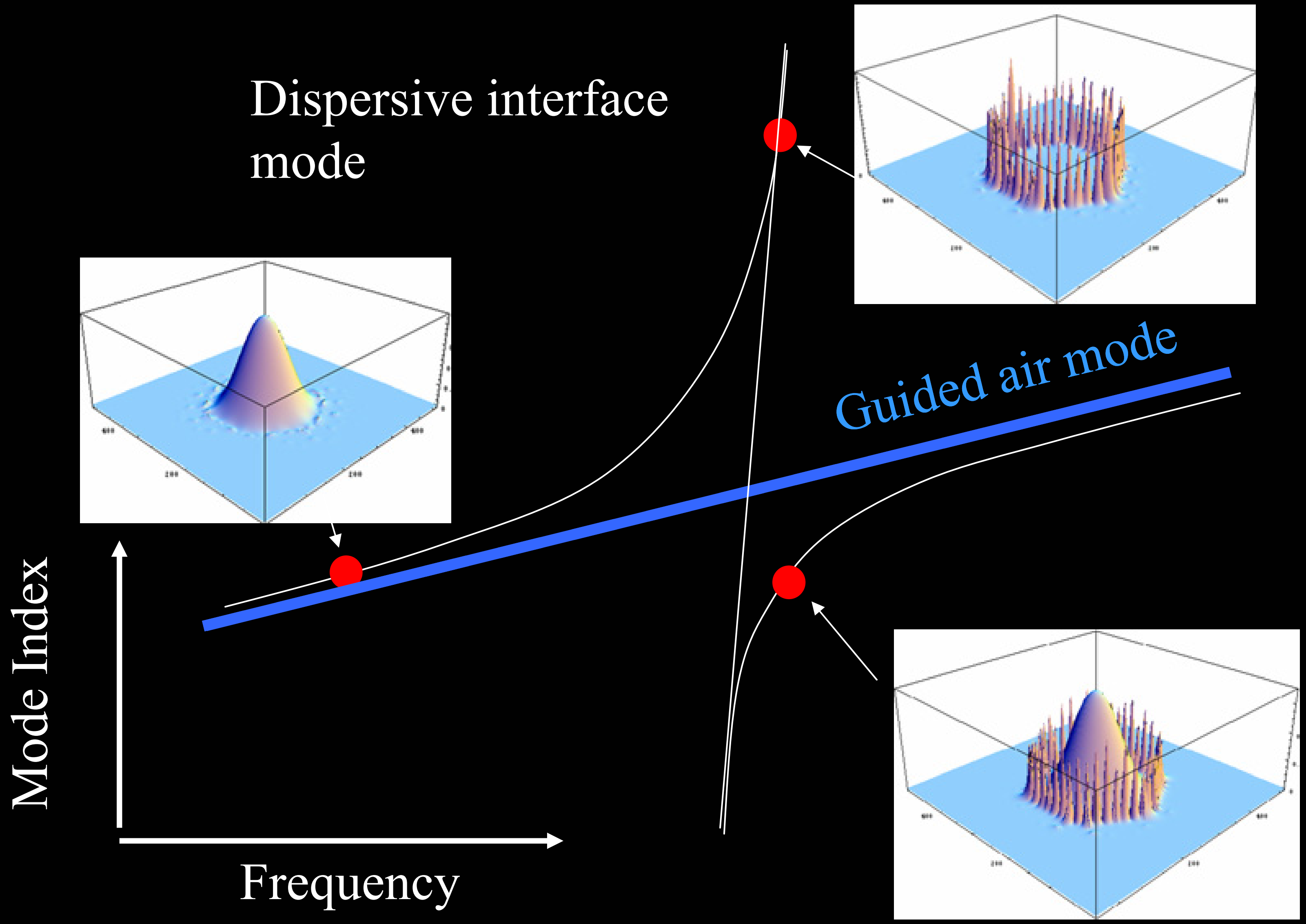
Intuitive Explanation of Dispersion Curve



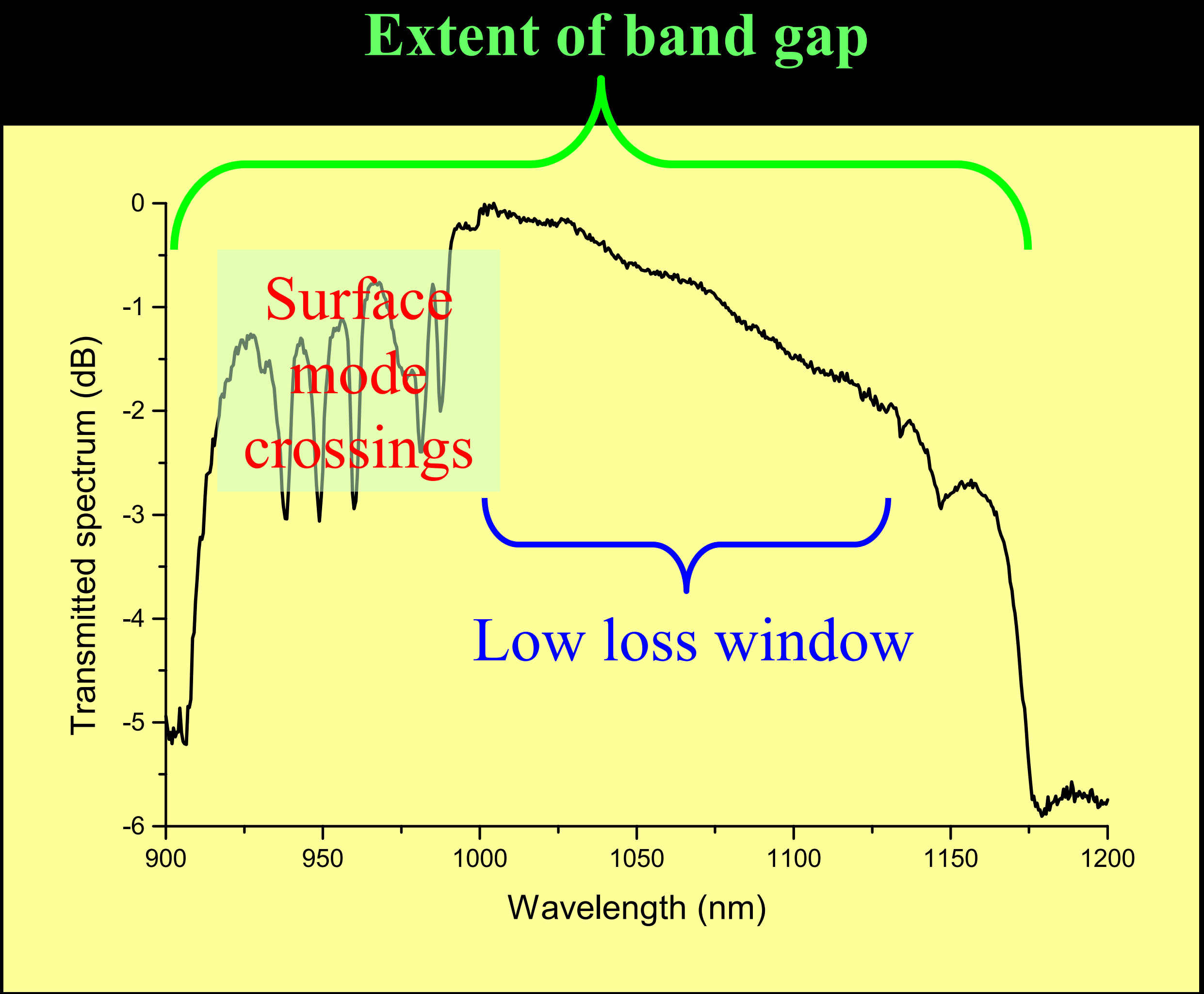
Wavelength (nm)

(Dmitre Ouzounov)

Two classes of core-guided modes

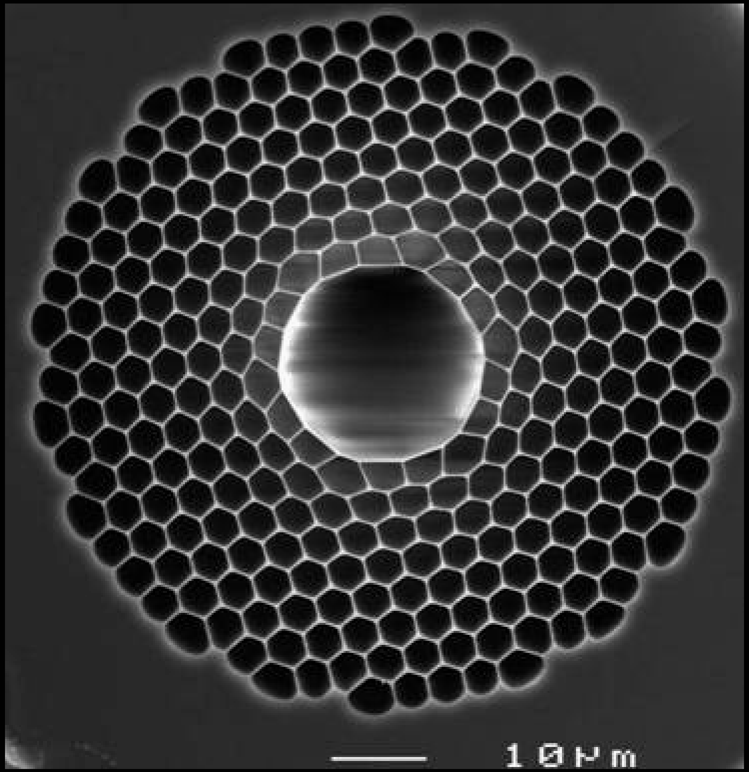


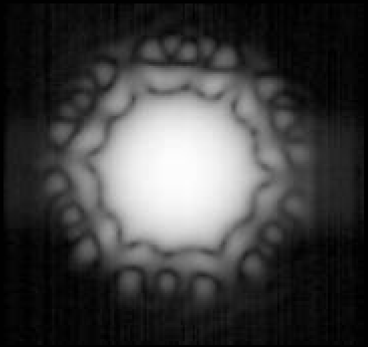
Loss peaks in transmitted spectrum: short fibre

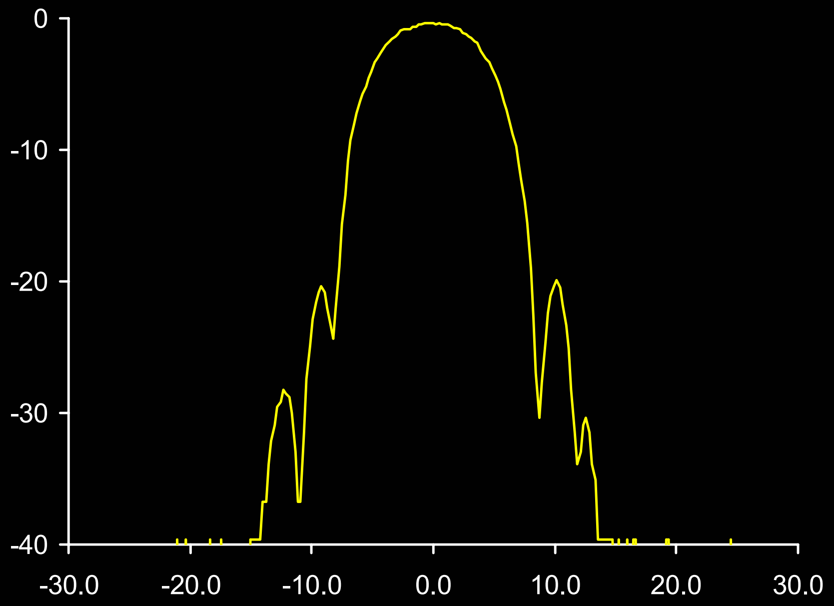


Humbert

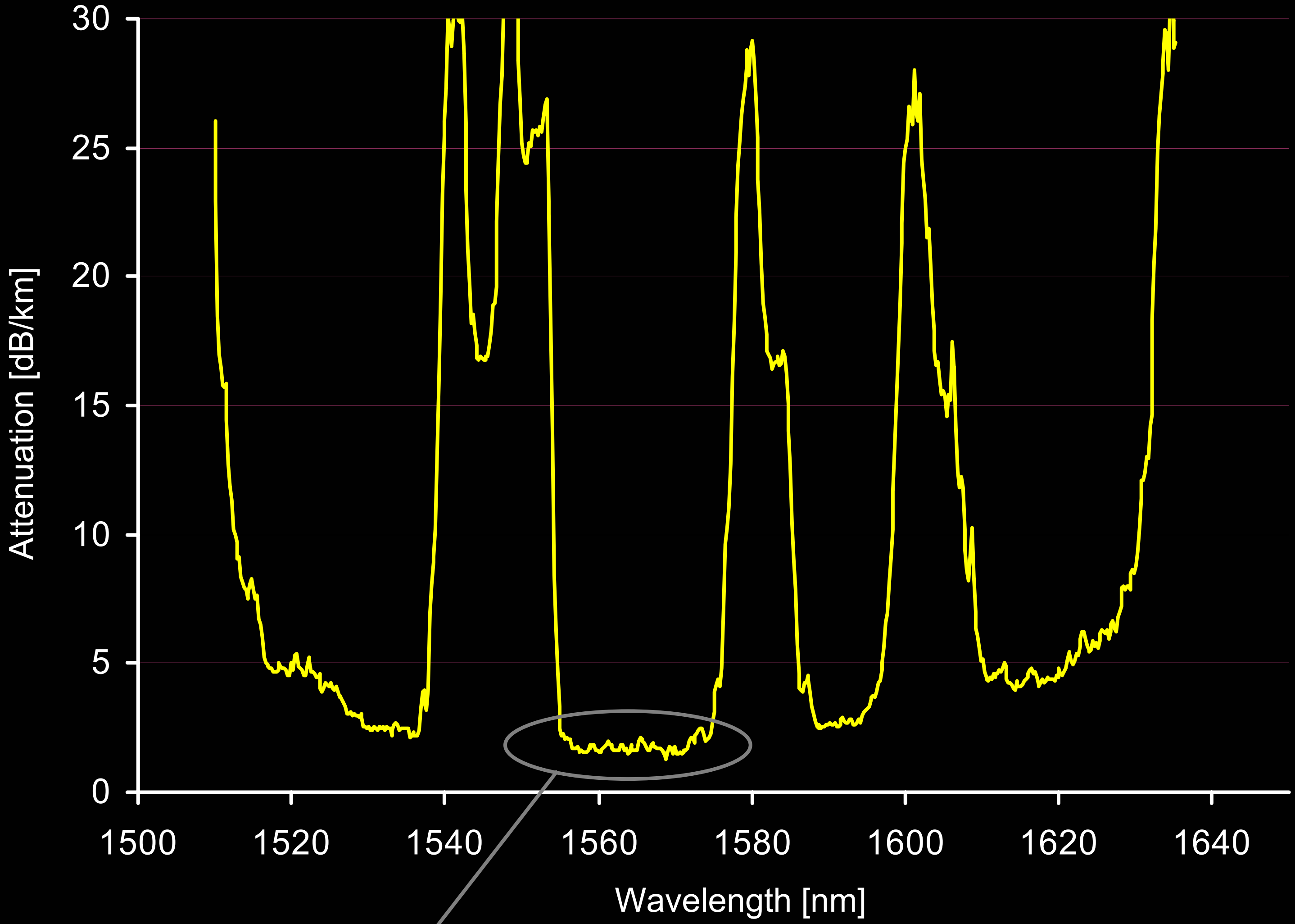
19-cell defect fibre





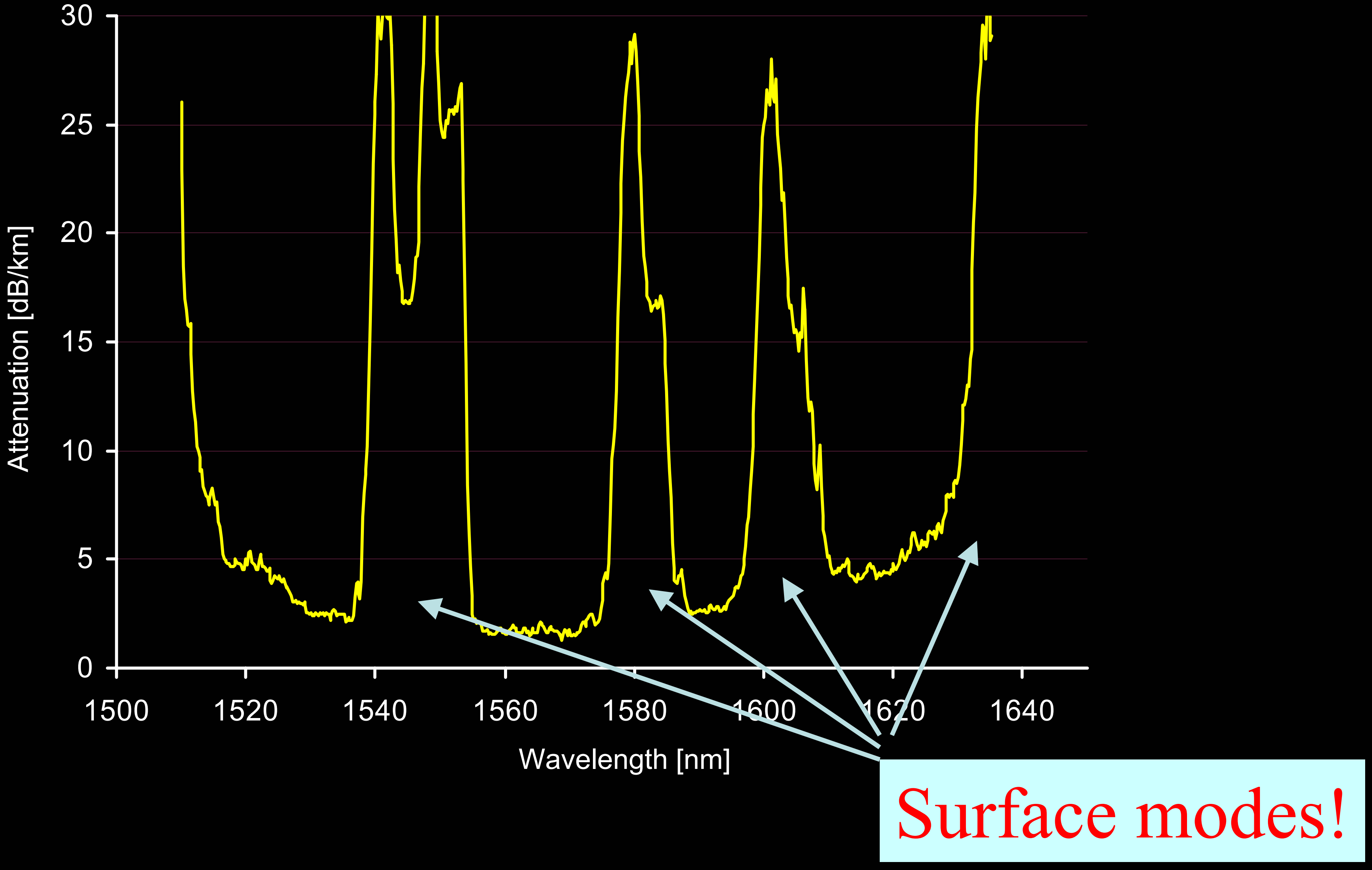


ATTENUATION

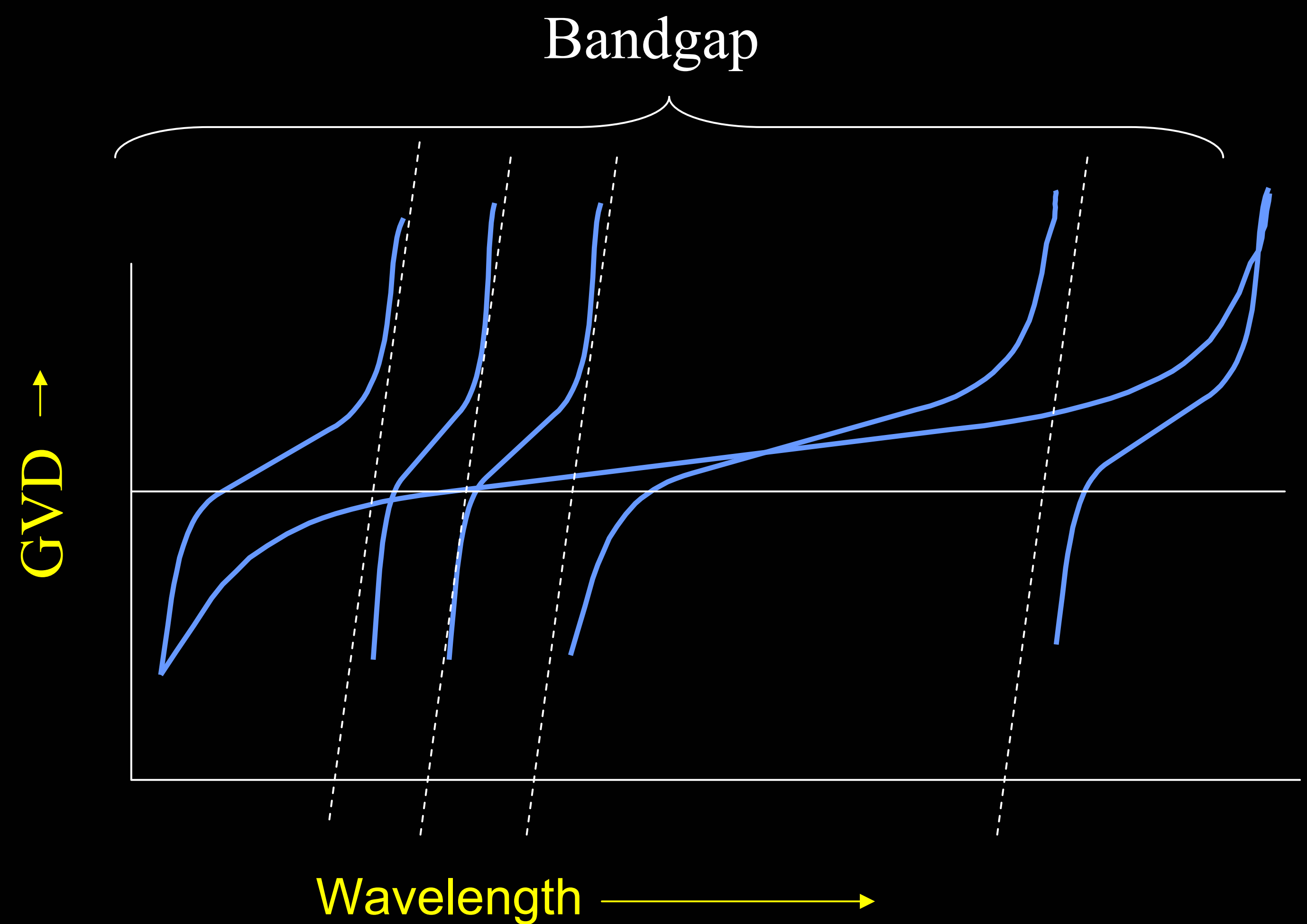


Average 1.72 dB/km
(1560-1570 nm)

ATTENUATION

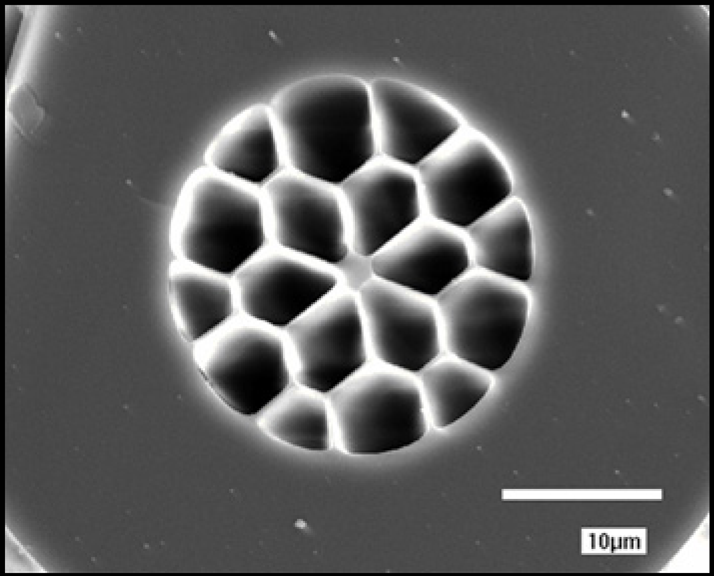


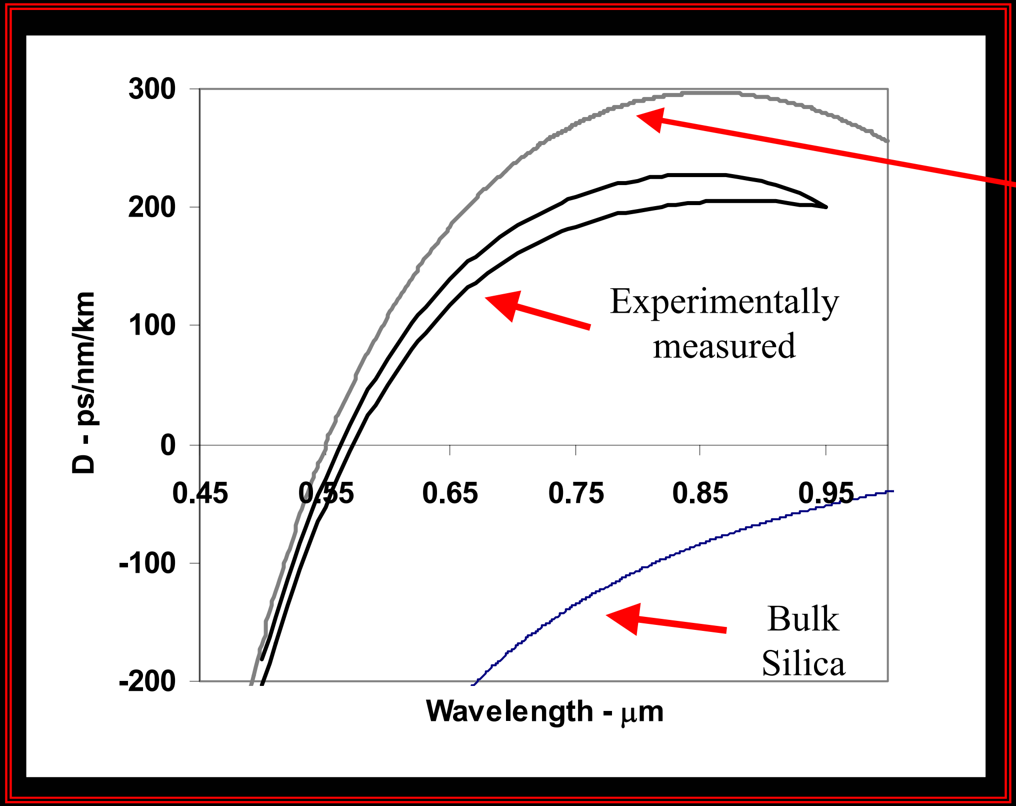
Dispersion around surface mode crossings:



Nonlinear effects in solid cores

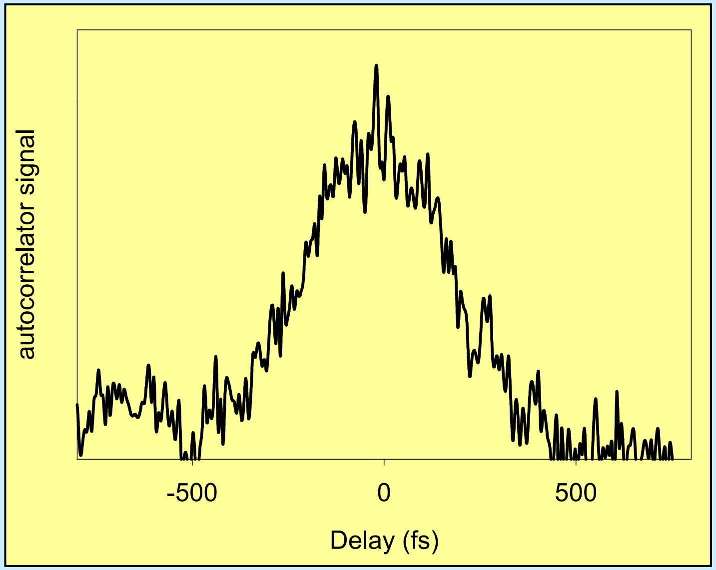
Highly nonlinear fibre is like a strand of silica…





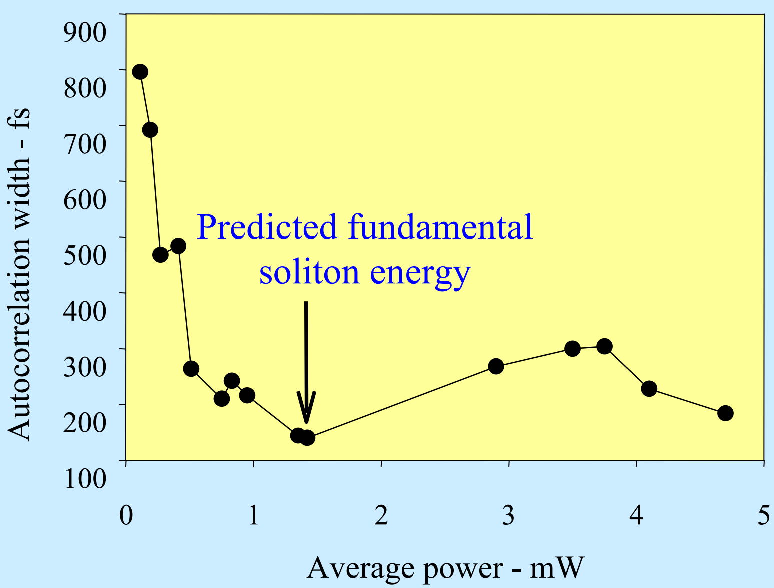
- Demonstrated anomalous GVD as short as 550nm, in good agreement with model

Soliton effects at 850nm



Autocorrelation signals of 100fs pulses transmitted through 3.1m of fiber at 1.35mW average power.

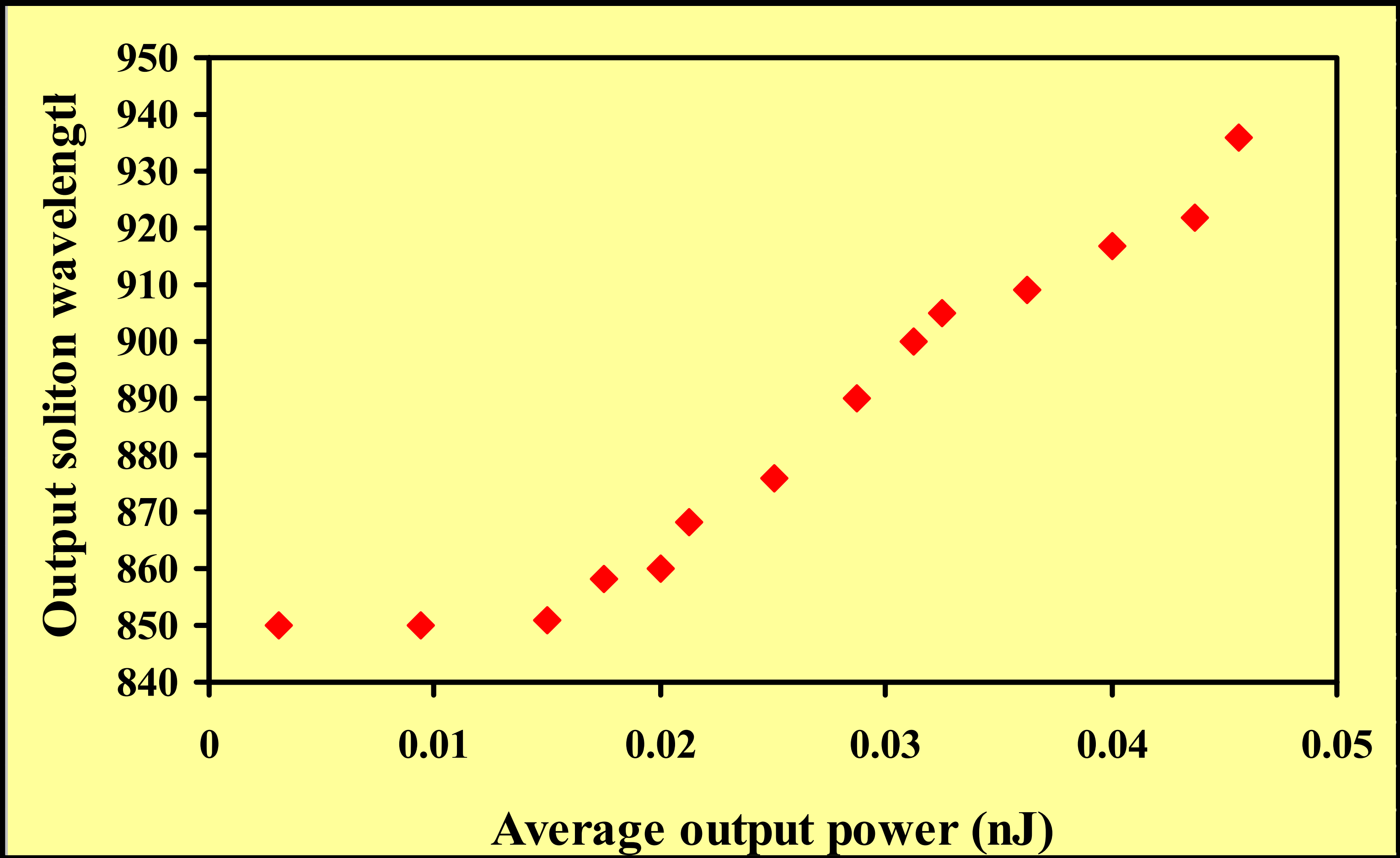
Wavelength - 850nm
Dispersion - 50ps/nm/km
Core diameter - 2.1μm
Fundamental soliton energy ≅ 16pJ
Soliton length ≈ 1m



Autocorrelation width of transmitted pulse as a function of power.

W. J. Wadsworth et al, Electron. Lett. **36** 53 (2000)

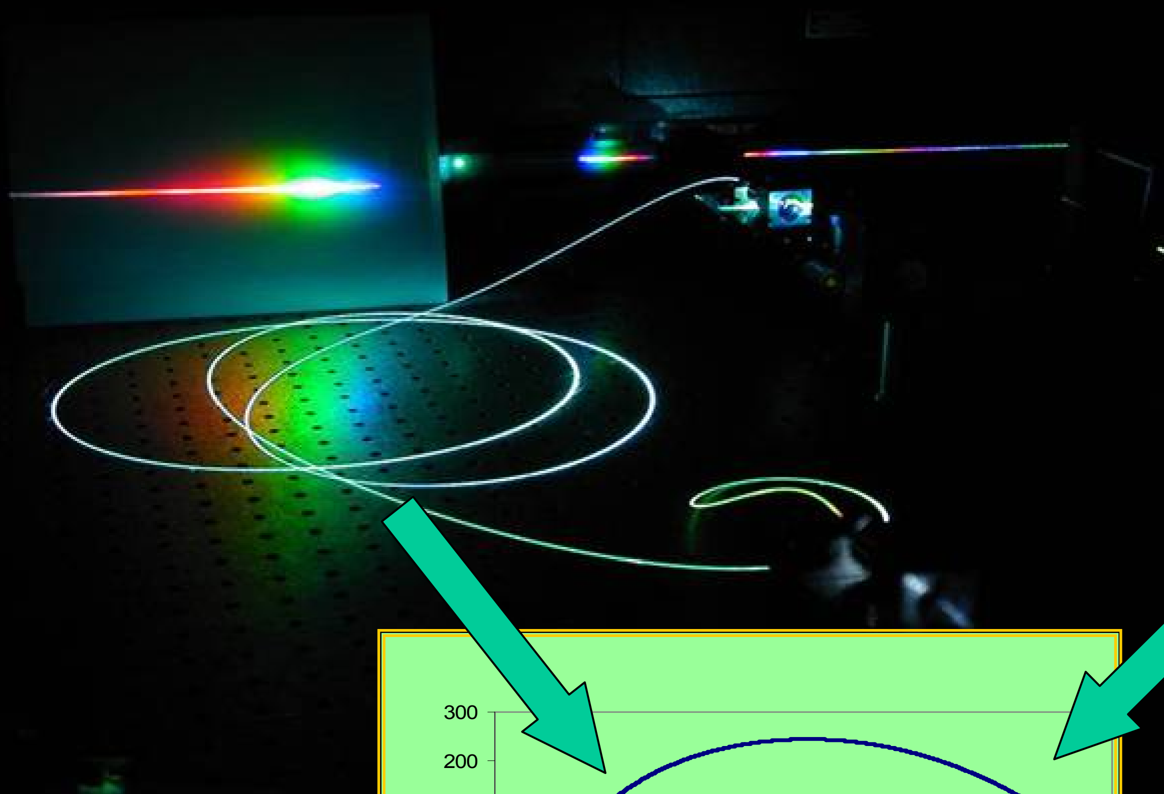
Soliton self-frequency shift from 850nm

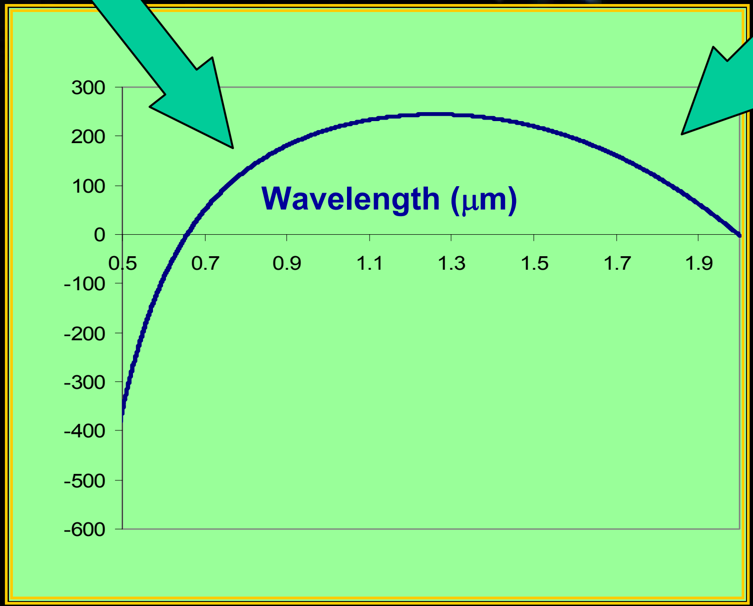


Fiber length 6m, pulse length 200fs, rep rate 76MHz

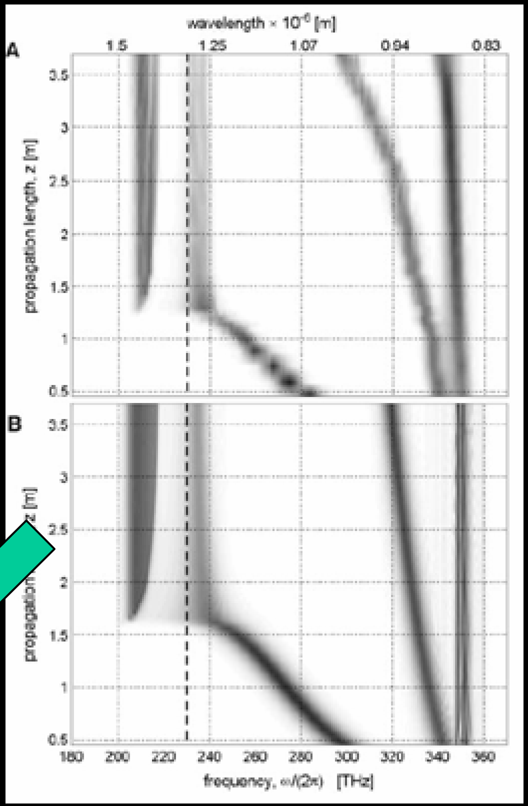
Effect of higher-order dispersion

- Simple soliton picture assumes D is a constant
- In reality, this is never true, and especially it is wrong for PCF, with massive dispersion slope
- Solitons become unstable, shedding radiation most noticeably on the side of decreased dispersion
- Situation further complicated by Raman effects





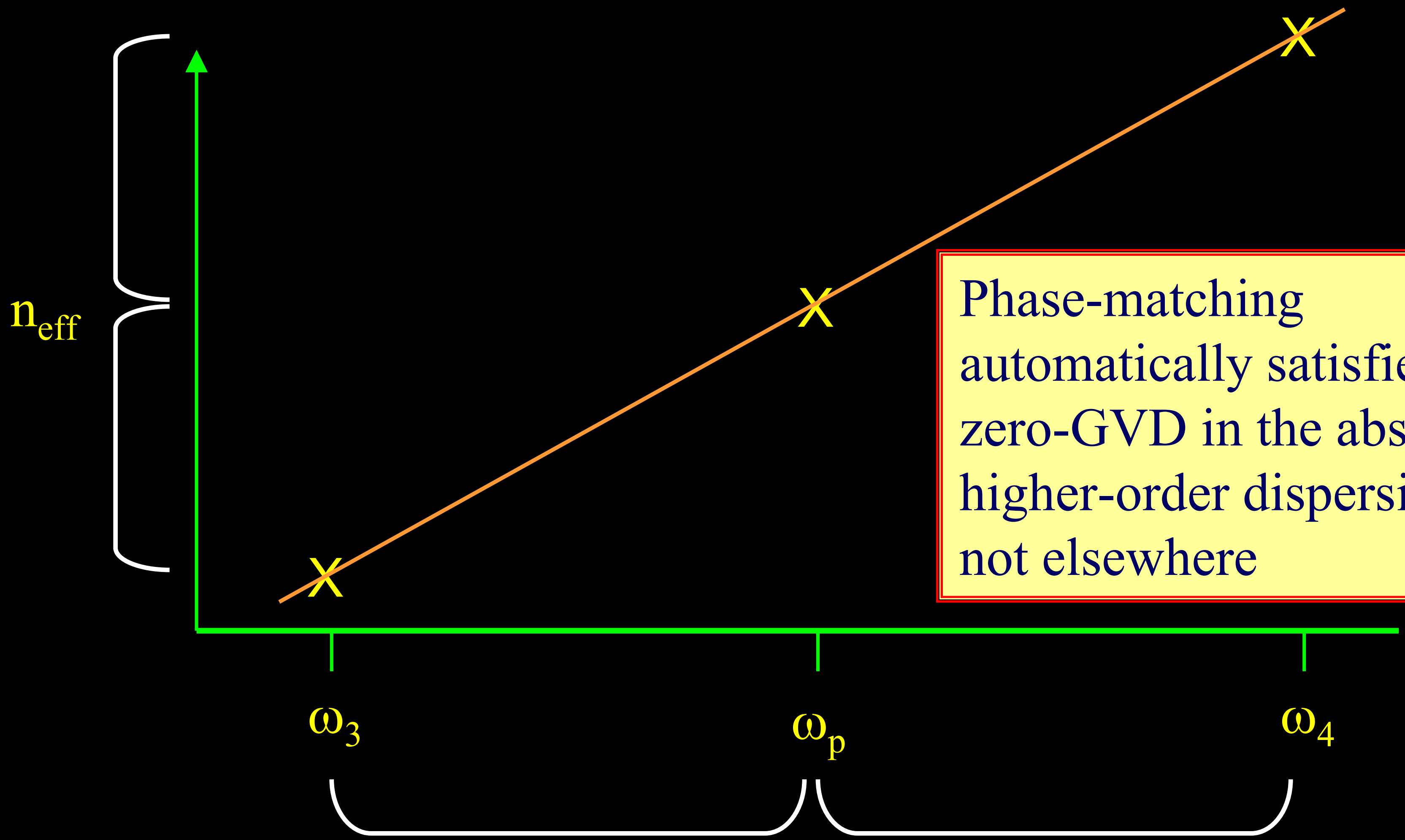
300
200
100
0
-100
-200
-300
-400
-500
-600
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Wavelength (μm)



wavelength × 10^-6 [m]
A
B
1.5
1.25
1.07
0.94
0.83
propagation length, z [m]
0.5
1
1.5
2
2.5
3
3.5
180
200
220
240
260
280
300
320
340
360
frequency, ω/(2π) [THz]

Solid core…

GVD and degenerate FWM in fibres



Phase-matching automatically satisfied at zero-GVD in the absence of higher-order dispersion, but not elsewhere

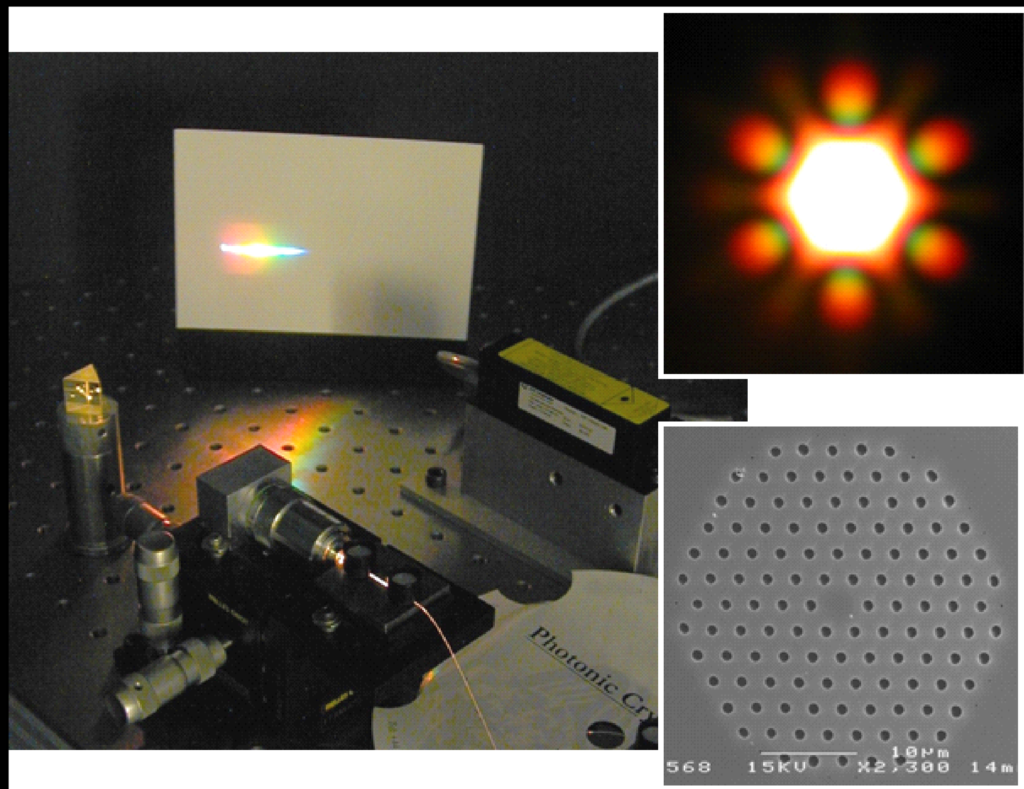
FWM in solid-core PCF

Phase-matching automatically satisfied at zero-GVD (in the absence of higher-order dispersion) but not elsewhere

Not usually valid for solid-core PCF's

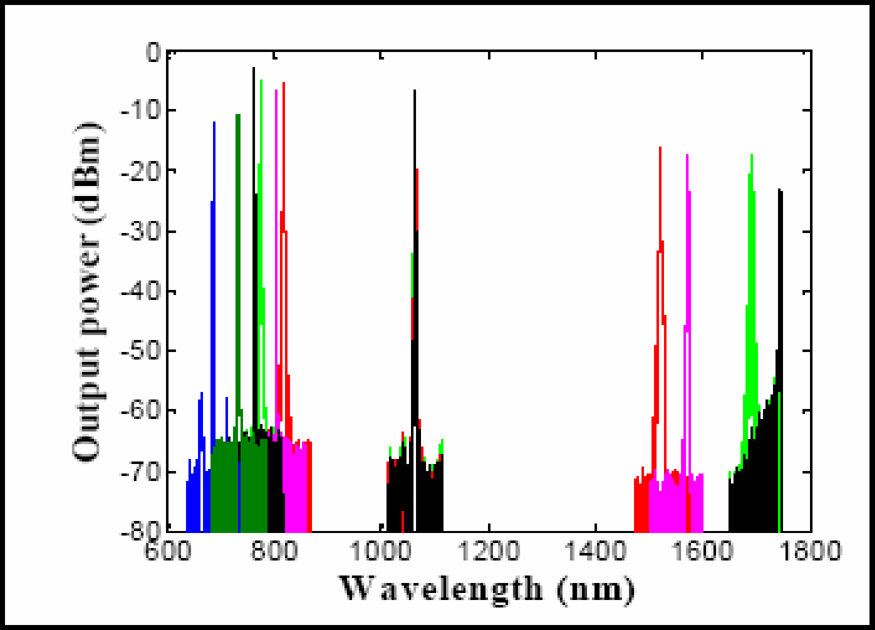
Higher order dispersion (β_4, β_6 etc.) enable phase matching far from the pump wavelength

Nonlinear optics with a little laser

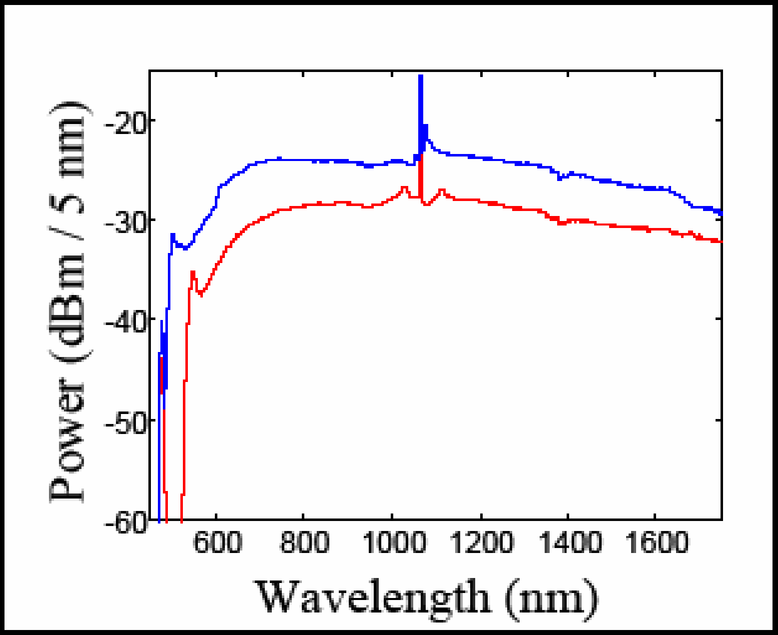


Nd: -based microchip laser, sub-ns pulses, 7kHz rep rate, 30mW average power

Microchip laser and PCF



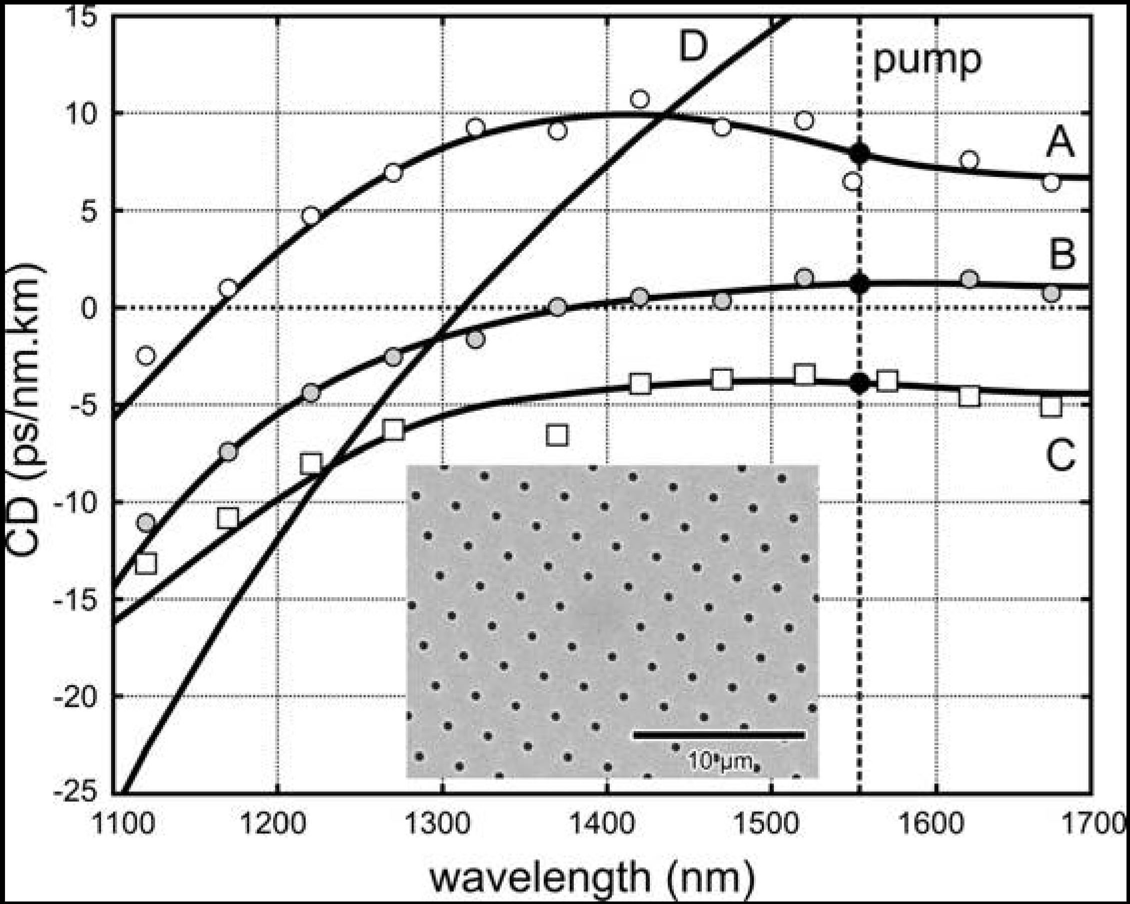
Wavelength conversion (4-wave mixing)



White light source (long length, pump close to λ_0)

GVD curves for 3 different values of hole size

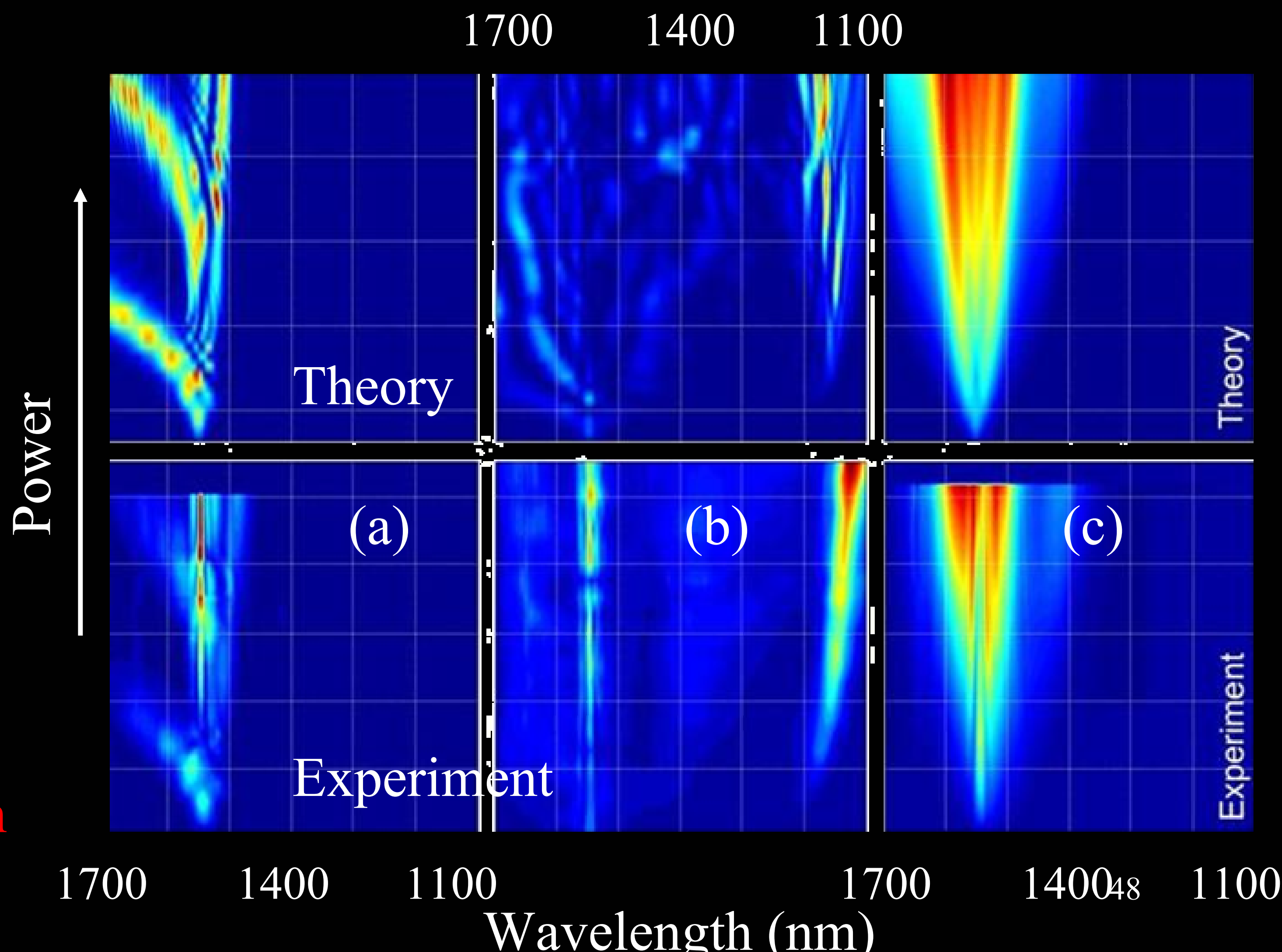
Fibers A, B, C have the same pitch, but differ by around 50nm in average hole size…



Group velocity dispersion determines nonlinear optics

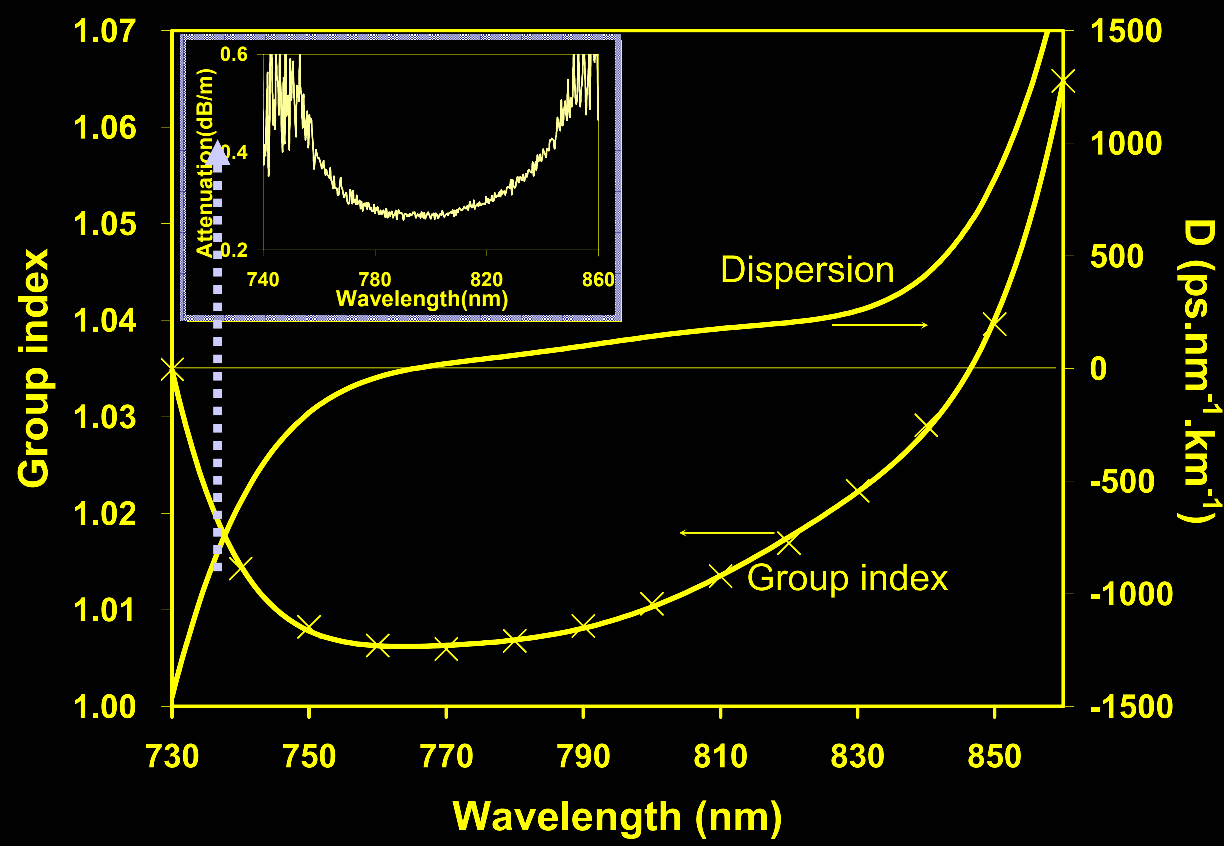
Effects of SSFS, Pulse breakup, phasematched parametric generation, SPM, MI

1550nm pump
100fs pulses
Fiber length 1m

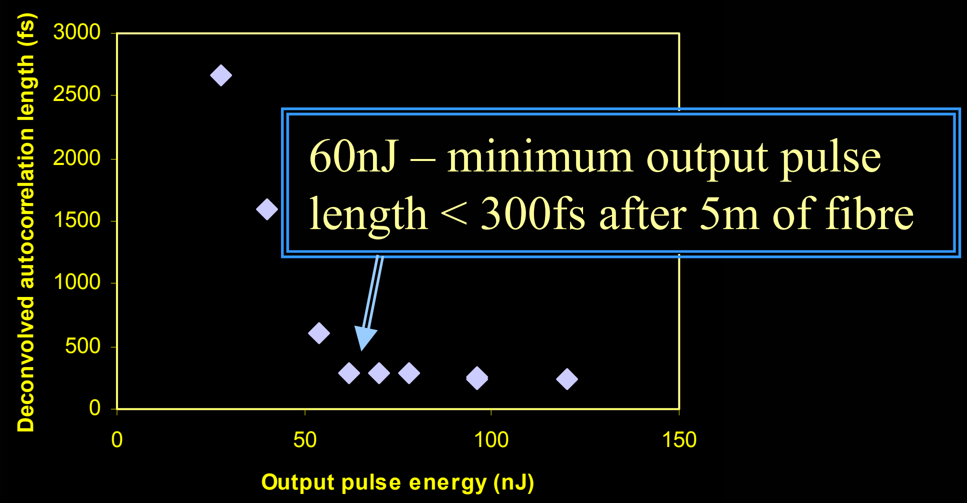


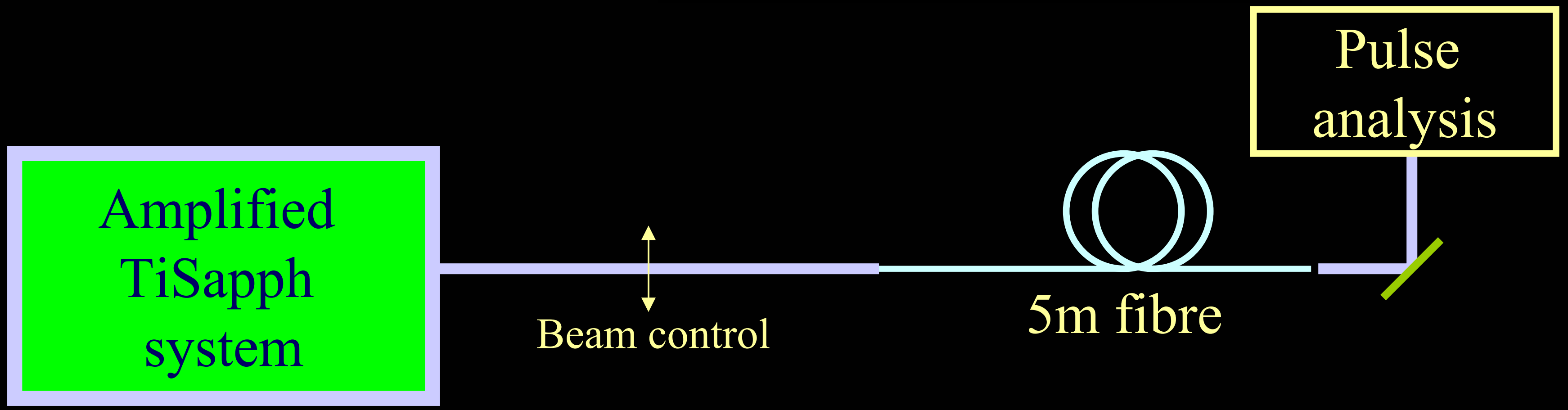
NLO in hollow-core

Group velocity dispersion at 800nm wavelength enables solitons



Delivering short pulses at 800nm wavelength





Nonlinearity in hollow-core fibres

For SiO_2, $n_2 = 2.4 \times 10^{-20} m^2 W^{-1}$

For air, $n_2 = 2.9 \times 10^{-23} m^2 W^{-1}$

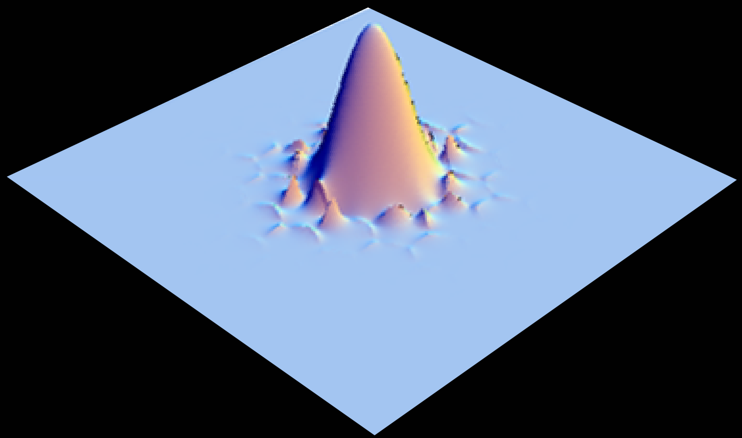
But the light is peaked mainly in the air…let's try the air:

$$P_0 = \frac{3.11 \lambda^3 D A_{eff}}{4\pi^2 c n_2 \tau^2}$$

$\lambda = 800\text{nm}$
$A_{eff} = 27 \mu m^2$
$\tau = 290 fs$

→ 70nJ

HOWEVER…



For this mode,

$$\Delta n_{eff} = P\,(n_2^{air}/A_{eff}^{air} + n_2^{sil}/A_{eff}^{sil})$$

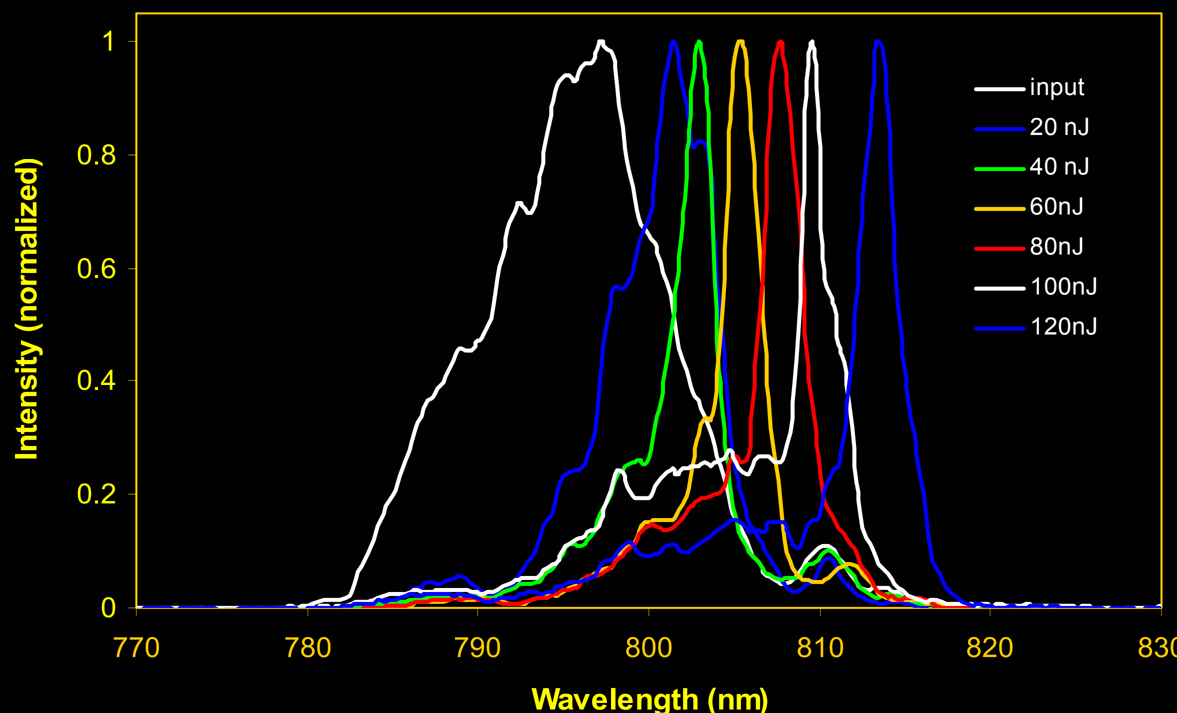
$$= P\,(1.28e\text{-}12 + 1.78e\text{-}12)$$

(units in metres and Watts)

So there are almost equal contributions from the air and from the silica. This should enable engineering the nonlinearity for soliton delivery from a particular laser source.

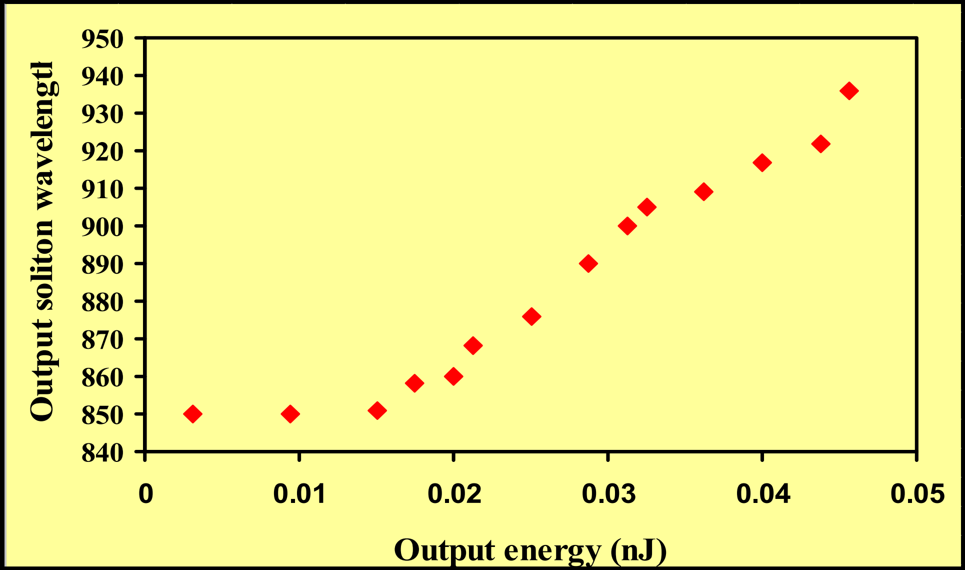
Soliton self-frequency shift in hollow-core

- Most likely, rotational SRS in nitrogen, gain g_R = **0.2 × 10^{-13}m/W** (cf 10^{-13}m/W for SiO_2)
- Shift of 60-90 cm^{-1} (*cf* 440 cm^{-1} in SiO_2) - around 5 nm at 800nm.
- Experiment is firmly in the transient regime



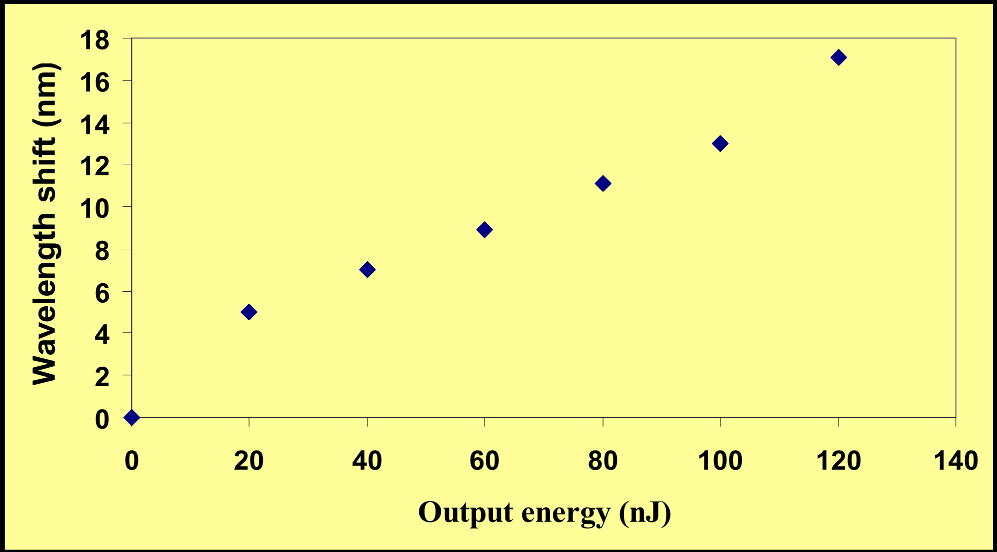
Luan

Compare with solid-core…



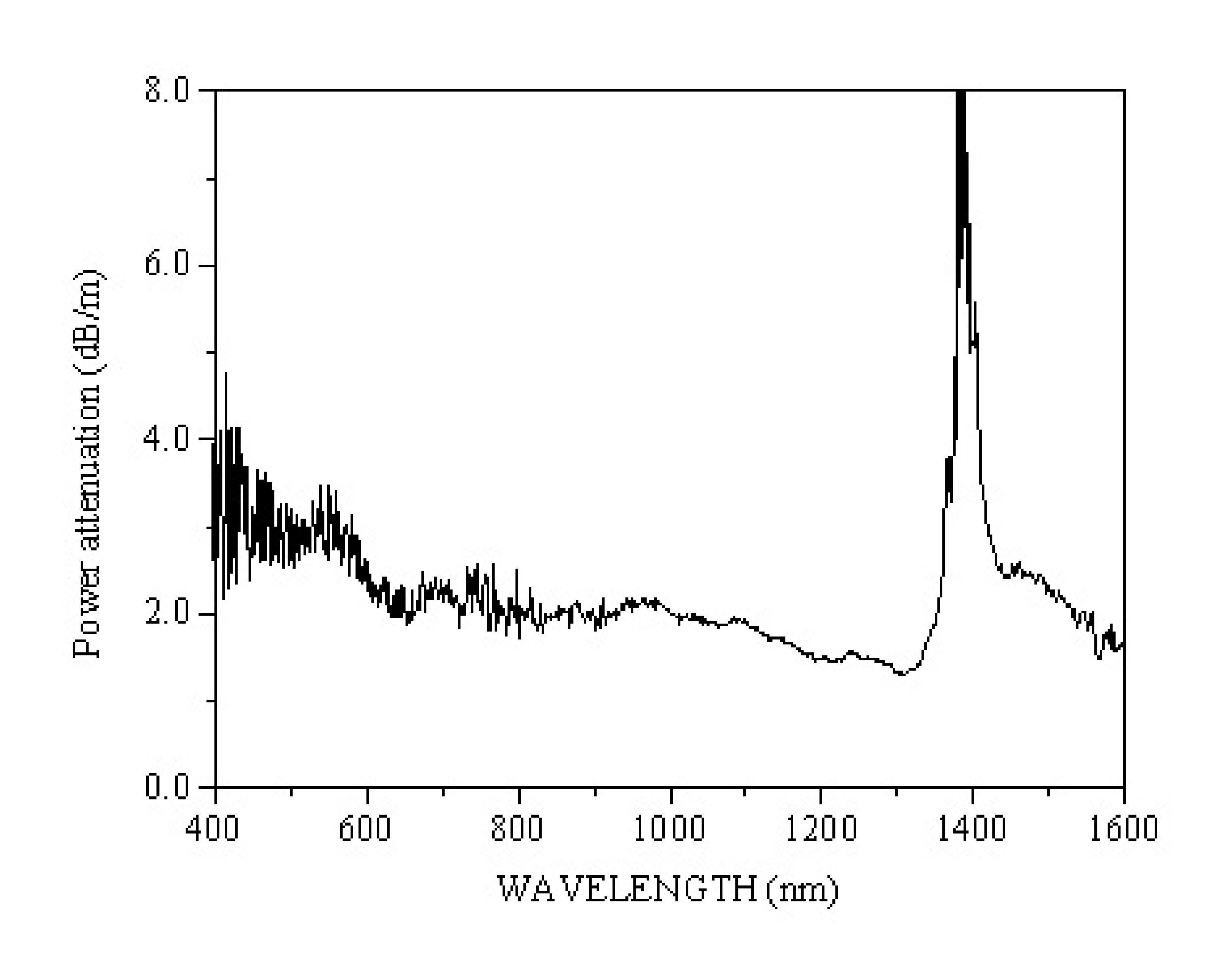
Small solid core

Hollow core

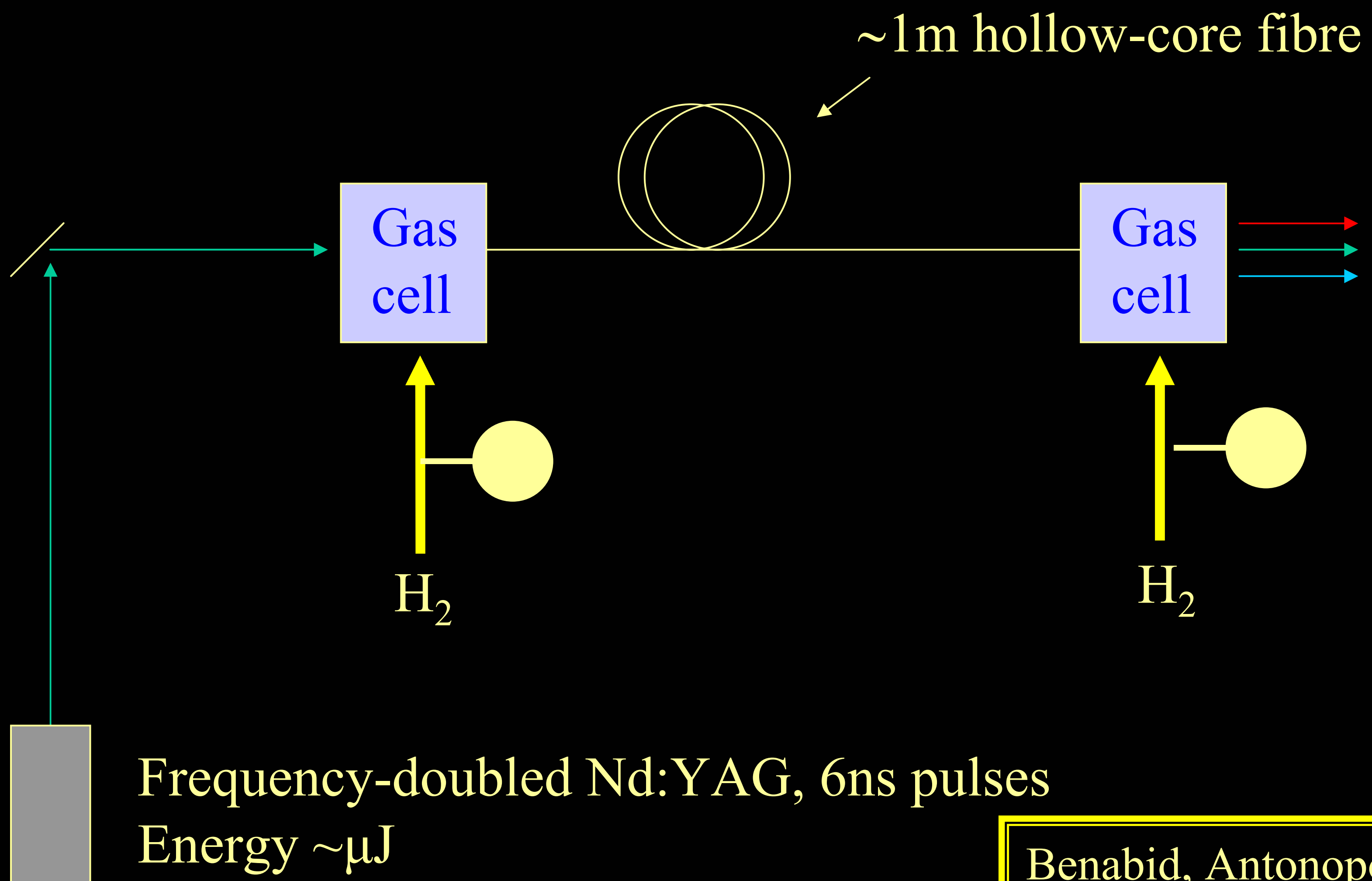


Fibres for gas-based nonlinear optics

Broadband
"Kagome"
fibre



Fibre-based SRS gas cell

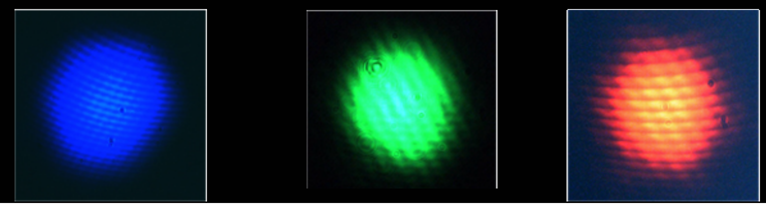


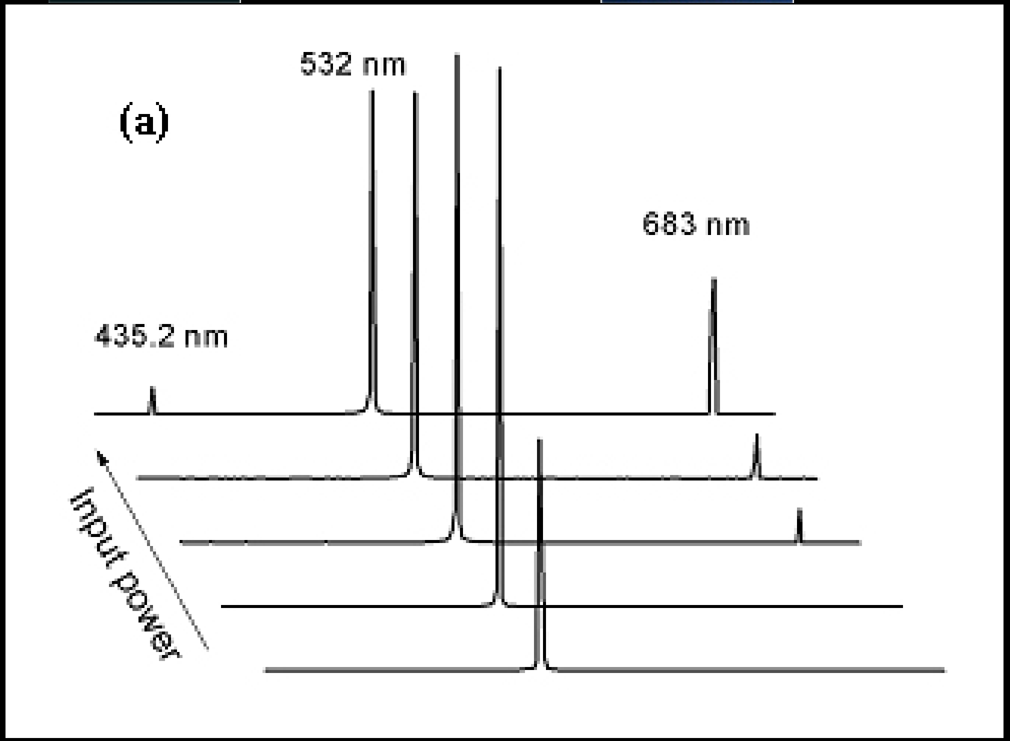
Frequency-doubled Nd:YAG, 6ns pulses
Energy ~μJ

Benabid, Antonopoulos

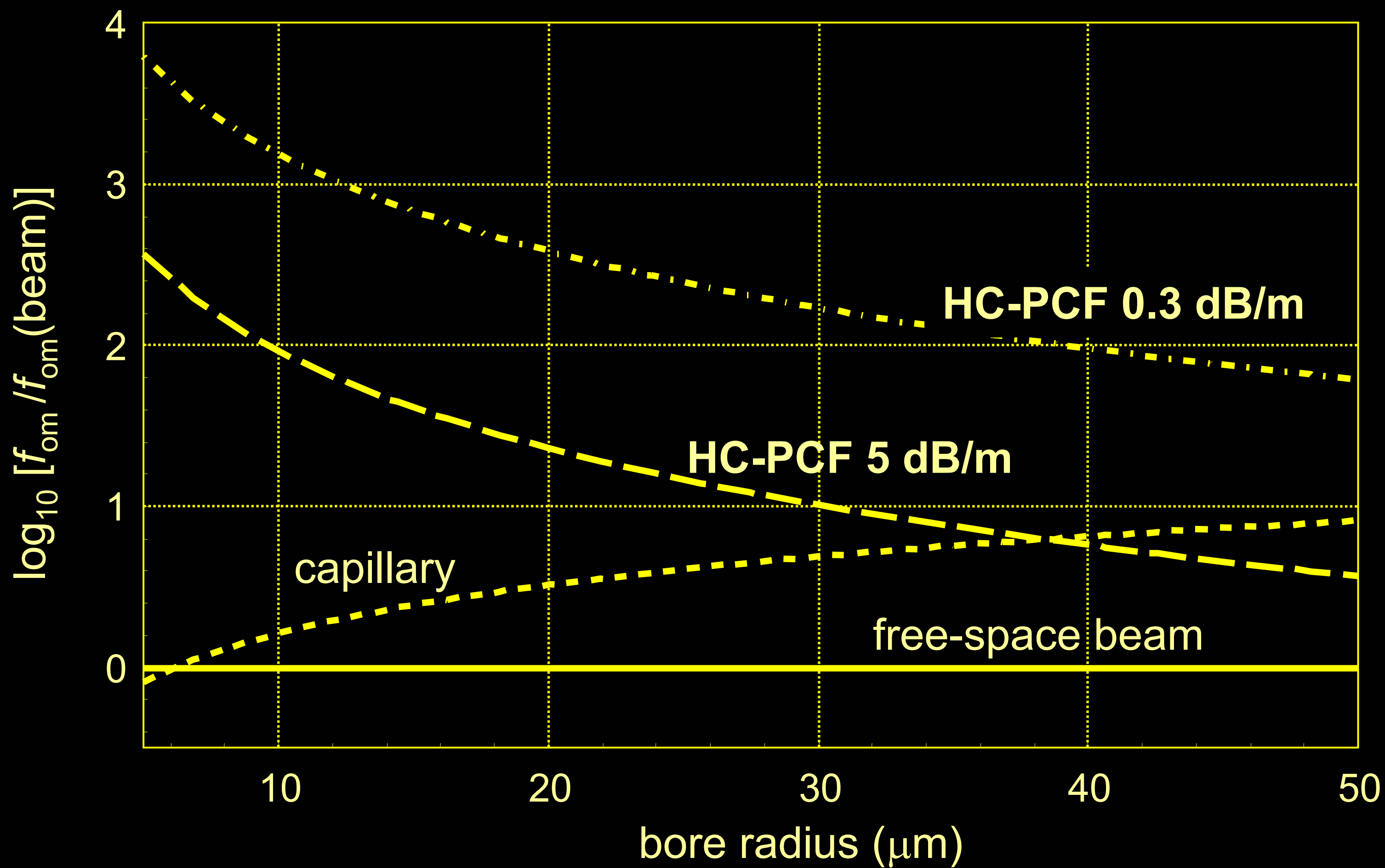
SRS in hydrogen

- Q-switched pulses
- Microjoule pulses from frequency-doubled Nd:YAG
- SRS threshold at 0.8μJ
- simultaneous generation of guided anti-Stokes beam
- saturation effects





Nonlinear figure of merit $f = L_{int}\lambda / Area$

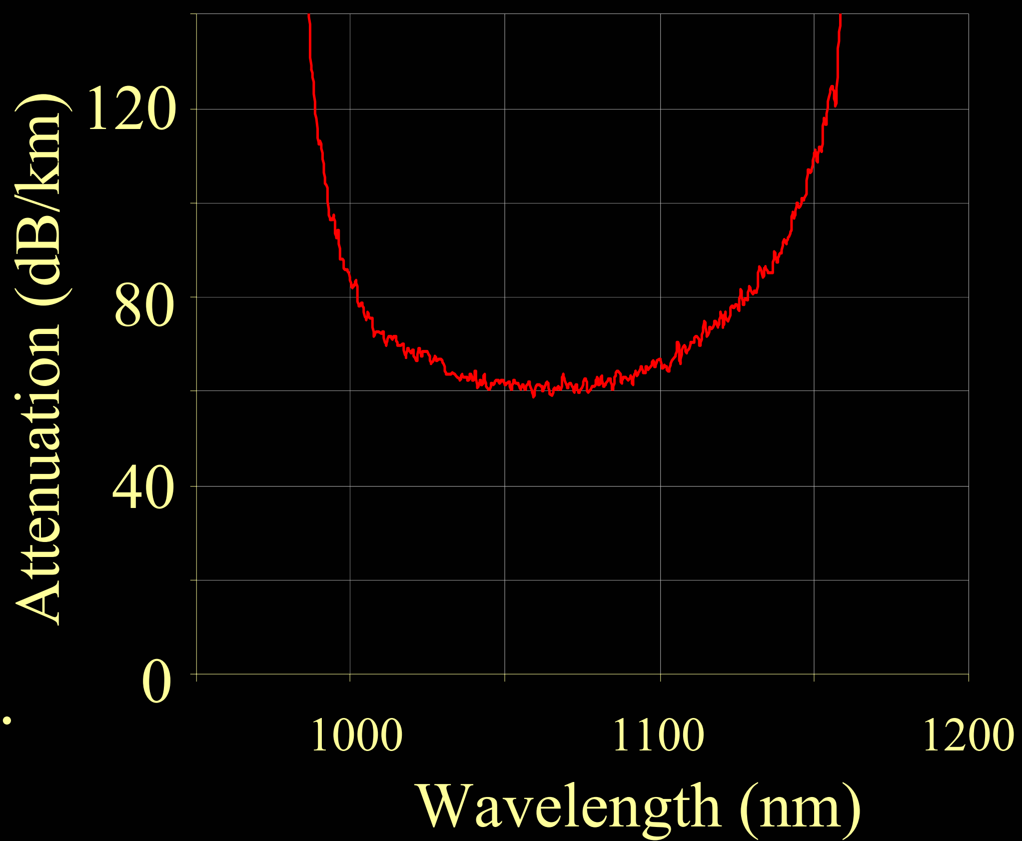


…duty cycle for a mode-locked laser ~ 10^5

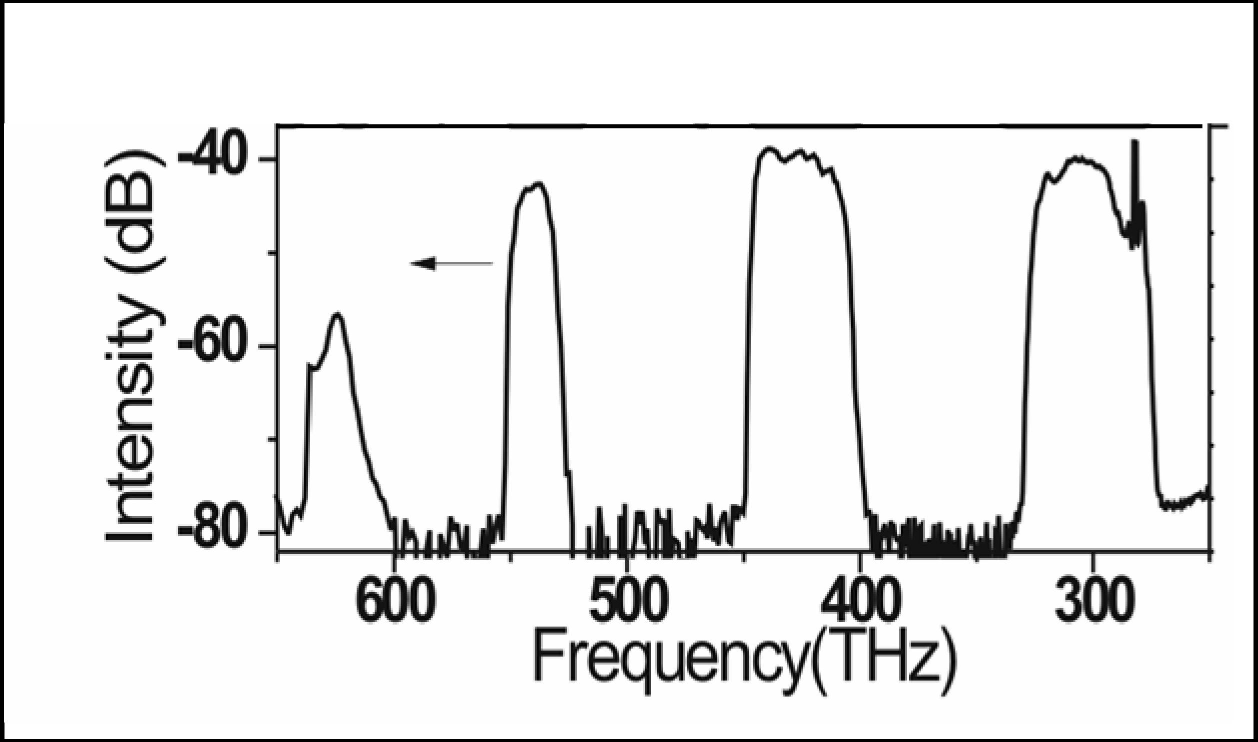
Fibres for gas-based nonlinear optics

Bandgap hollow-core

- gain vs loss
- dispersion
- atomic resonances etc.



Multiple bandgaps in a solid fibre



Transmitted spectrum through 20cm of fibre

F Luan et al, poster outside

And in conclusion:

- PCF has broadened and re-invigorated the field of nonlinear fibre optics
- Plenty of opportunities for both academic and applied research
- NLO in bandgap fibres is a topic of research for the near future

There is still plenty to do…