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Fibre-based Supercontinuum Sources Format and Performance

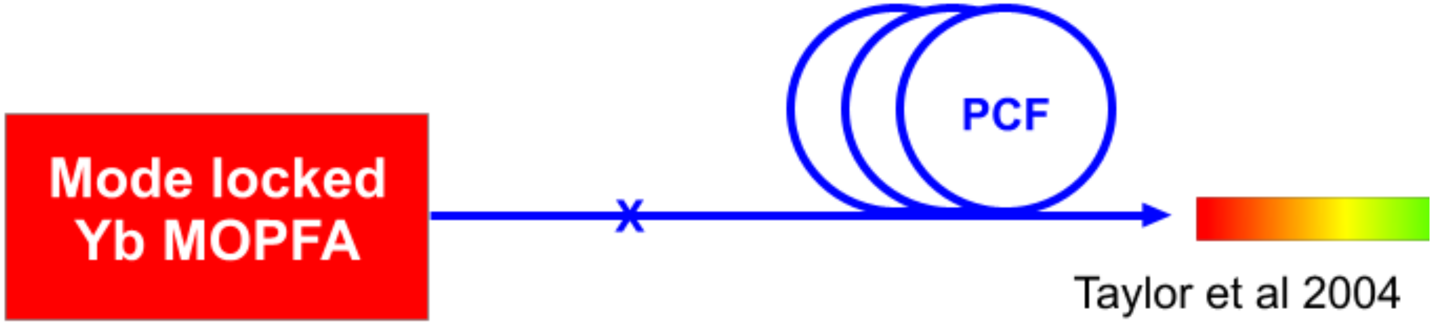
Did much change in 40 years?

SYSTEM	PULSE	EXTENT (nm)	AV POWER	FIBRE LENGTH	REFERENCE
CPM DYE + AMPS	~100fs	550-700 nm	< 1mW	< 1 cm	Shank et al. App.Phys.Lett. 46,1120 (1985)
Ti:S	100fs	400-1600 nm	10's mW	75cm	Ranka et al. Opt.Lett. 25, 25 (2000)
CAV DUMP Kr ION	60 ps	500-900 nm	10's mW	10m	Coen et al. Opt.Lett. 26, 1336 (2001)
FREQ DBLE PML MICROCHIP	~1 ns	500-800 nm	~mW	1.8m	Provino et al. Elect. Lett. 39,558 (2001)
PML Nd:GLASS + FIBRE AMP + COMP BULK	11 ps	500-1800 nm	5W	1.8m	Schreiber et al. Opt.Commun. 228, 71 (2003)

Supercontinuum generation

Lin and Stolen, App. Phys. Lett. 28, 216 (1976)

Contributing effects SPM, FWM, Raman, solitons, soliton self interaction



Taylor et al 2004

Average power ~ 10s W

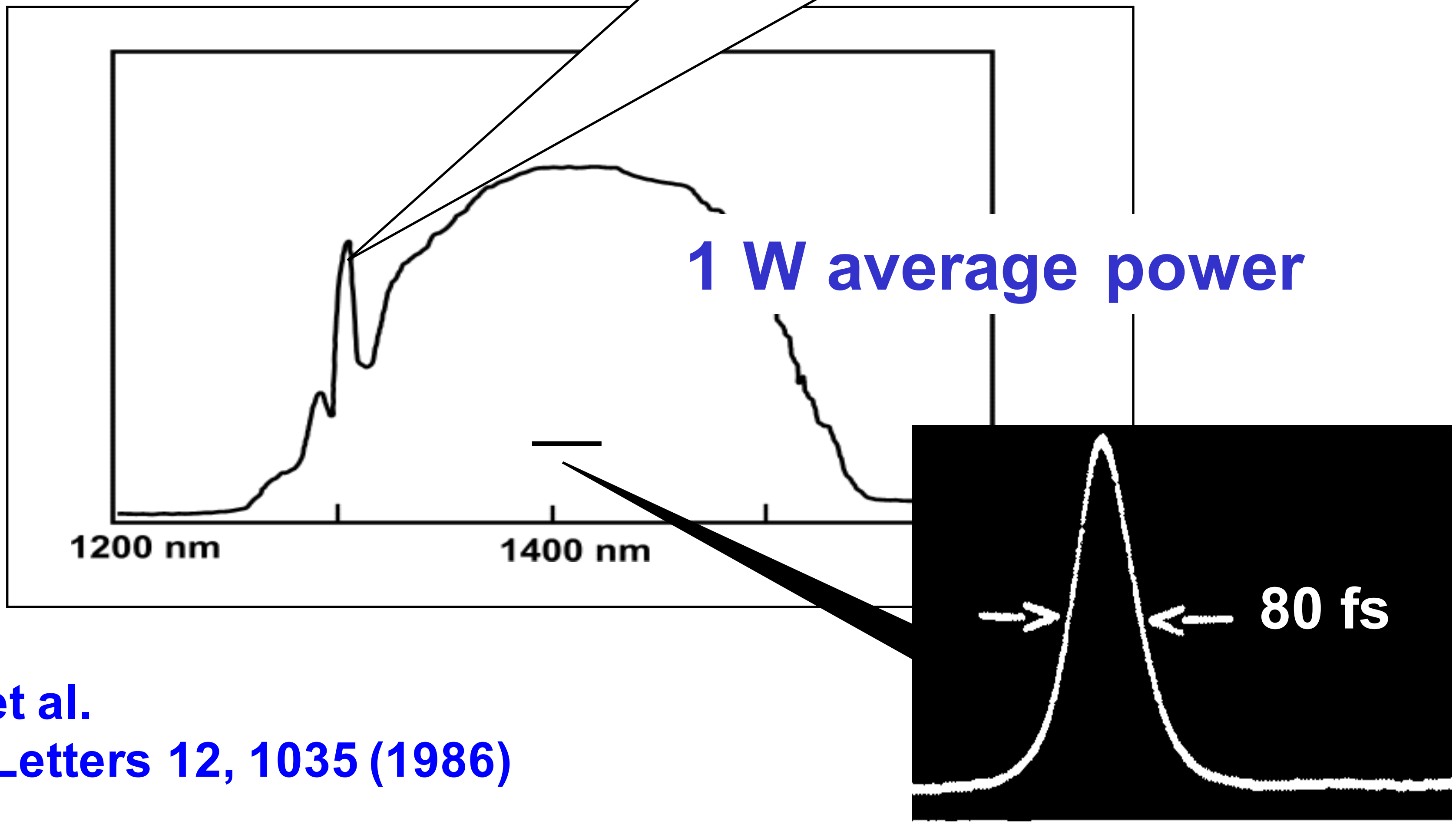
Advantages:-

- Fully fibre integrated
- Power scaling – spectral power densities 10s-100 mW/nm
- Control of pump wavelength – Yb, Er, Tm or Raman fibre lasers
- Precise control of fibre parameters
  - ✓ manipulate dispersion and group velocity matching
  - ✓ manipulate nonlinearity

High average power continuua

Bulk Nd:YAG laser pump

Conventional s.m. fibre

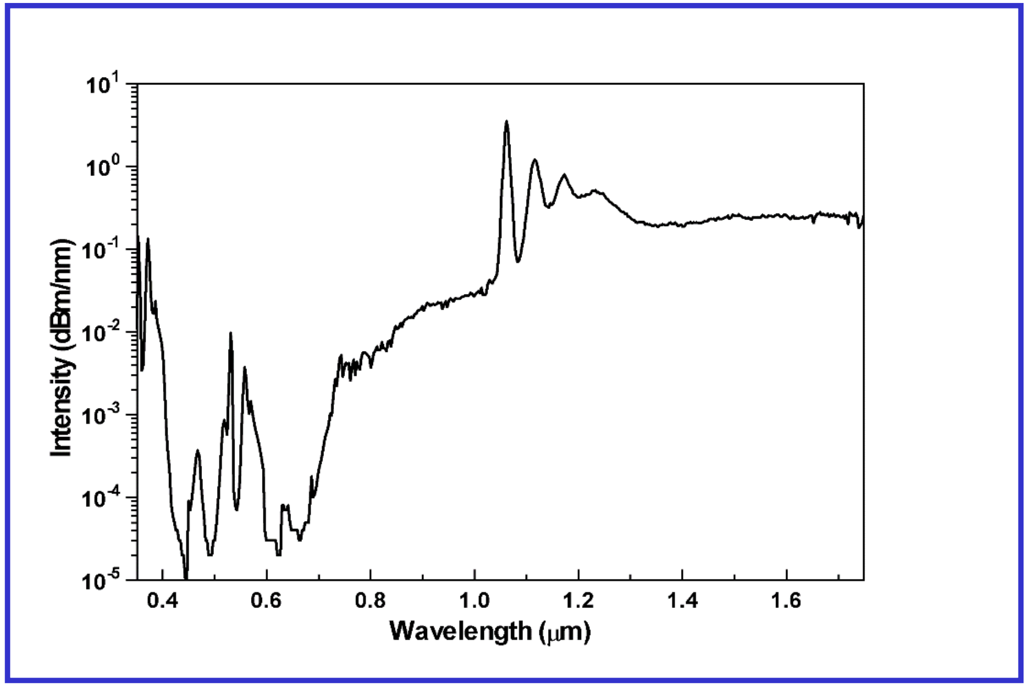


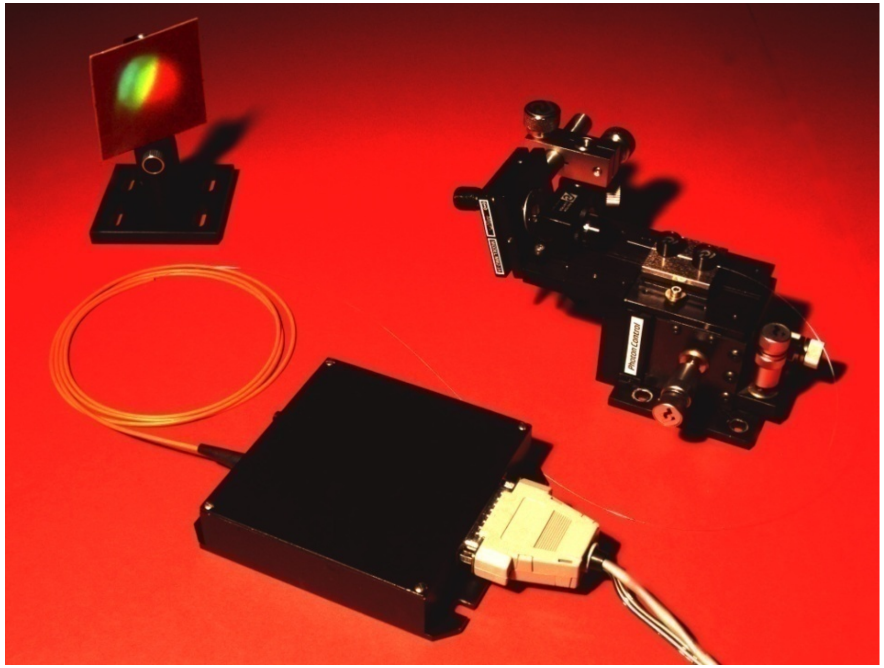
Taylor et al.
Optics Letters 12, 1035 (1986)

Compact continuum source?

Average power 1W, pulse duration 2ns
Repetition rate kHz (selectable)
Peak power in continuum~ 10-100W/nm

Taylor et al   Opt Lett 22, 298 1997





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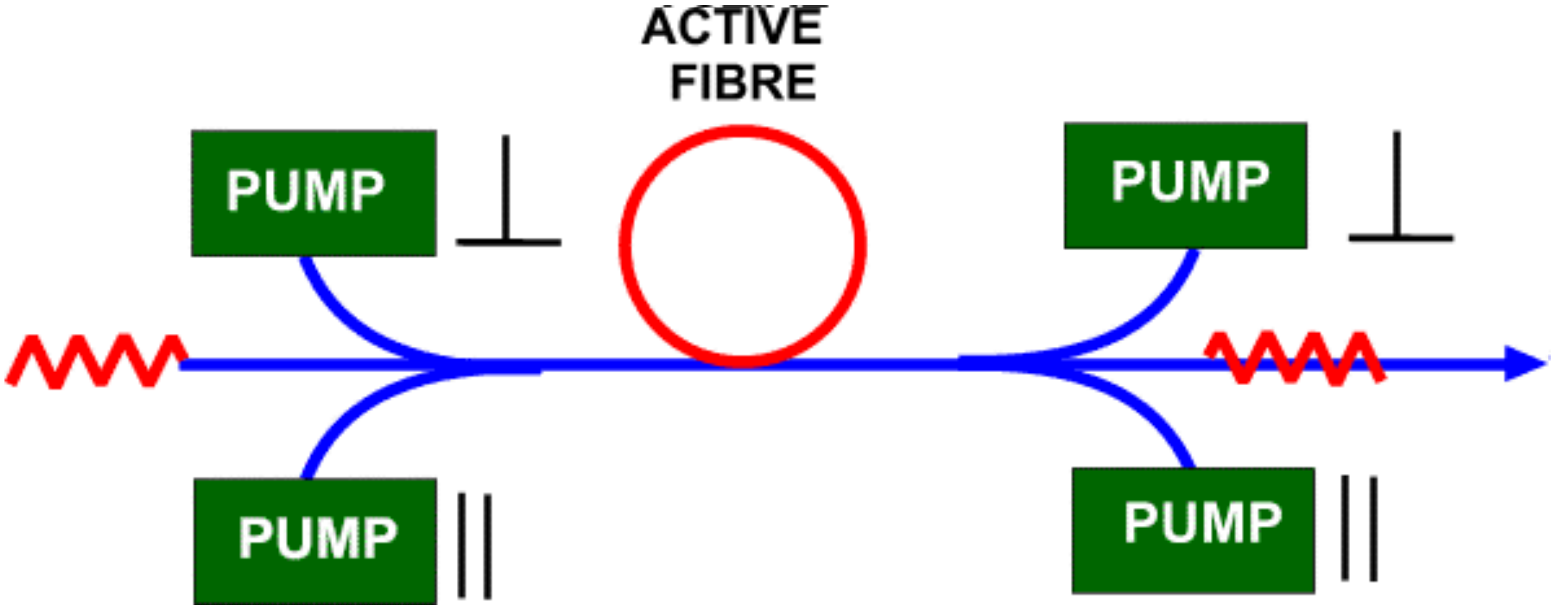
Single mode fiber lasers



With end pumping need diffraction limited sources

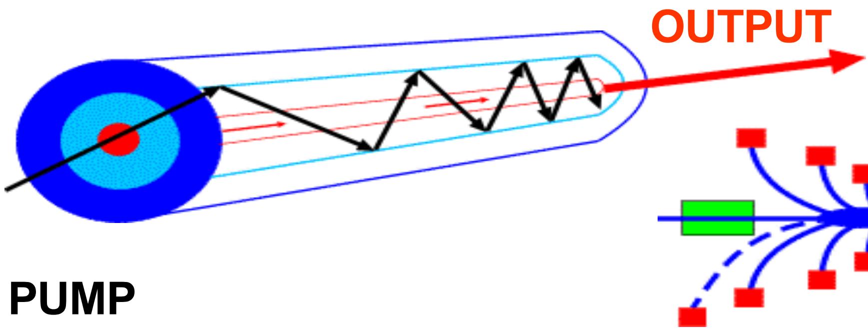
Limited power scaling through polarization combining

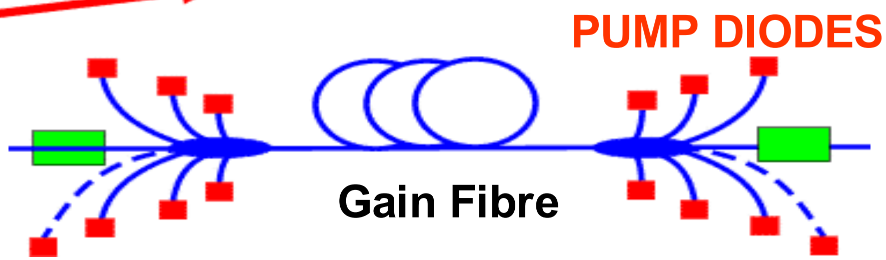
Double Clad Fibres

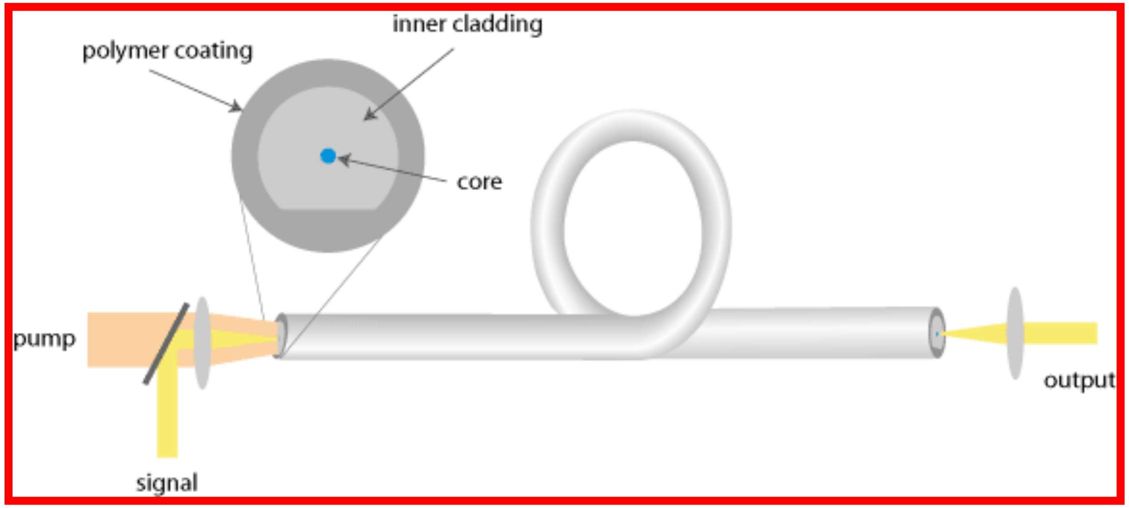
Problem of diffraction limited pump sources negated by using cladding pumping

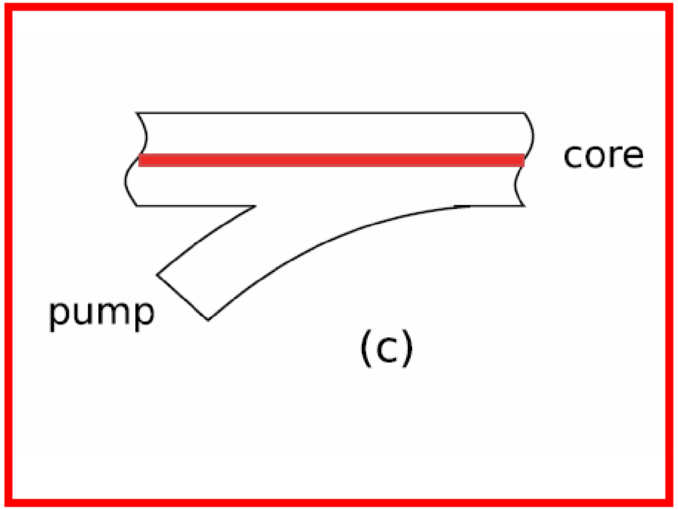
Broad stripe diodes enable high power pumping

power scaling – up to 10kW single mode









Fibre fuse in high average power systems

Macroscopic

Microscopic

For powers of ~ $1 MWcm^{-2}$
Backward propagation ~ $1 ms^{-1}$
Temperature increase 700-1000 C, softens glass, catastrophic damage
Formation of oxygen bubbles

Kashyap et al 1988, Elect. Lett. 24, 47

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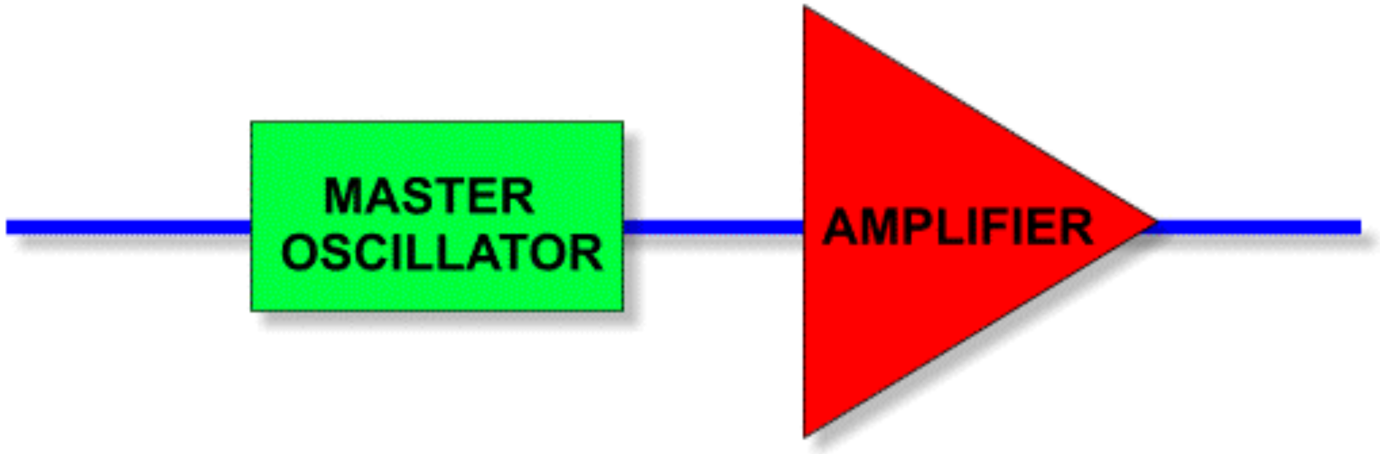
MOPFA Technology



Master Oscillator

- Diode/fibre laser seeding
- Versatile parameter control
- Direct modulation
- Fibre integrated

High Power Fibre Amplifier

- High single pass gains
- Wavelength diversity
- High energy storage
- Fibre integrated

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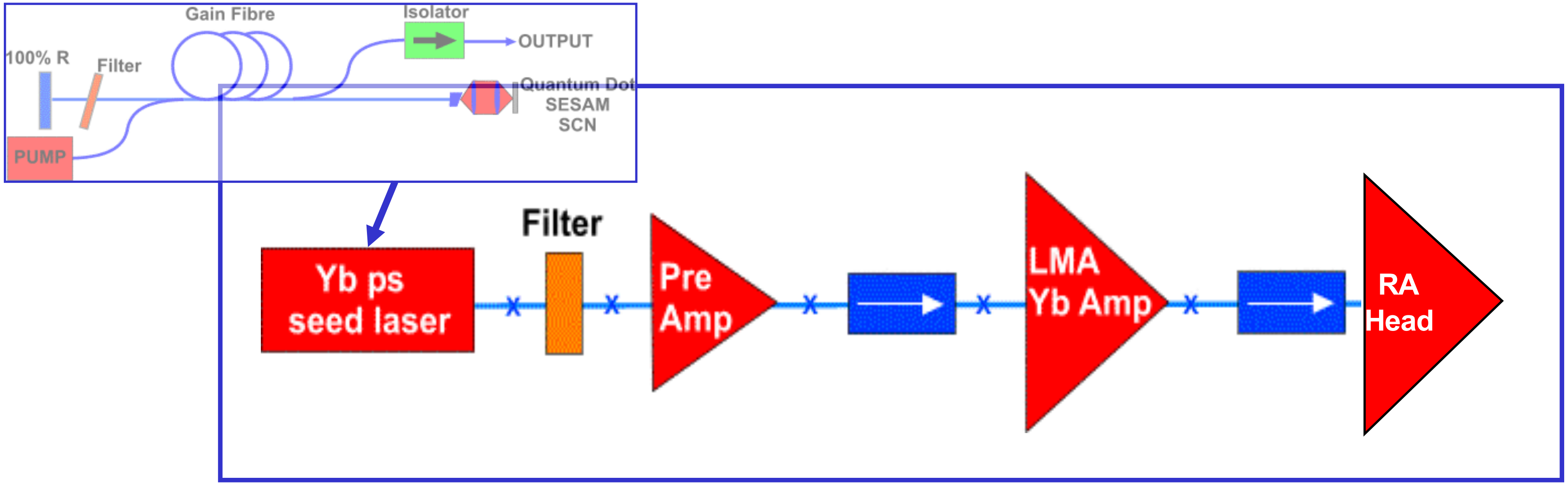
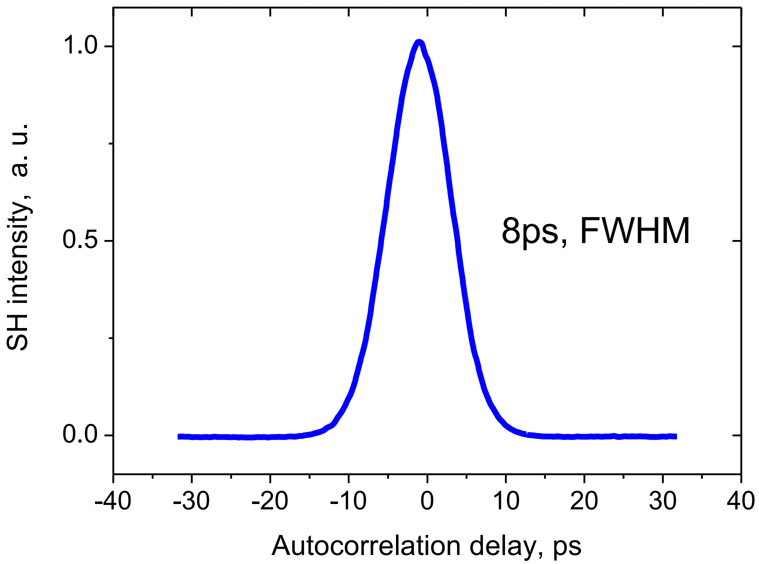
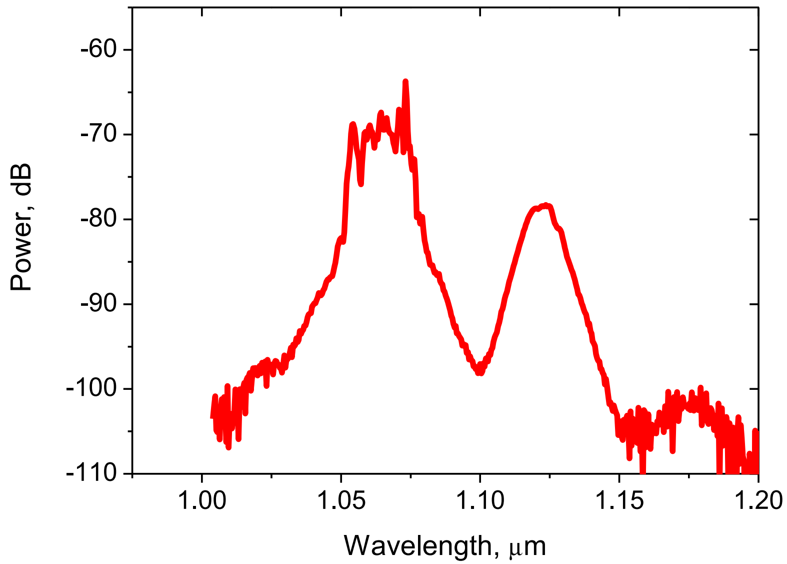
Passively mode locked laser seeded amplifiers







8ps, 10W average, 41kW peak power (Raman nonlinearity limited)

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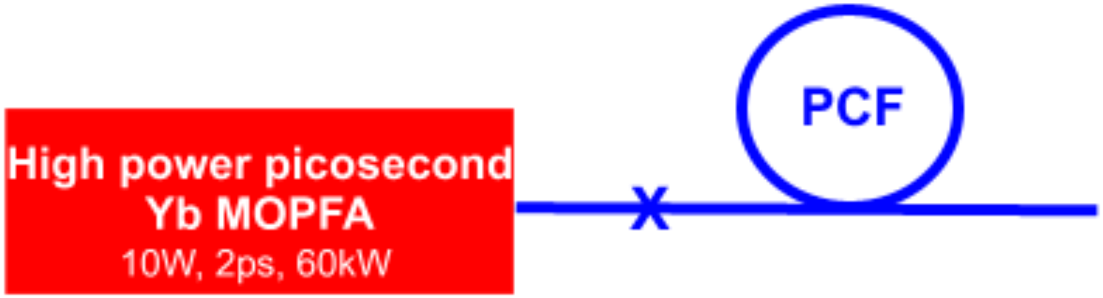
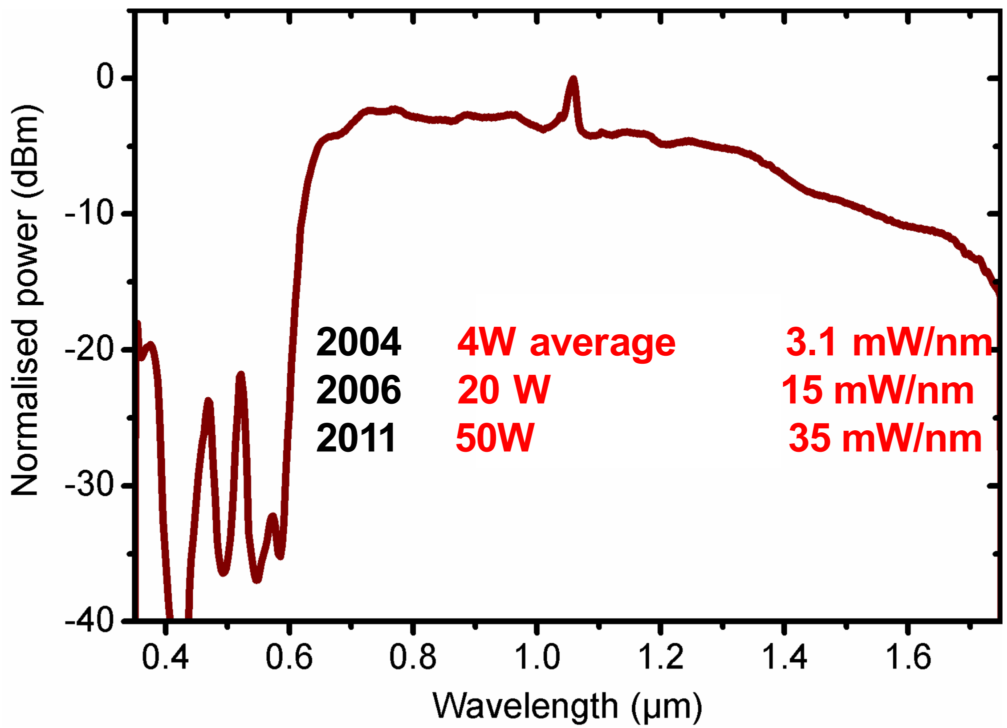
High Average Power Picosecond Pumping

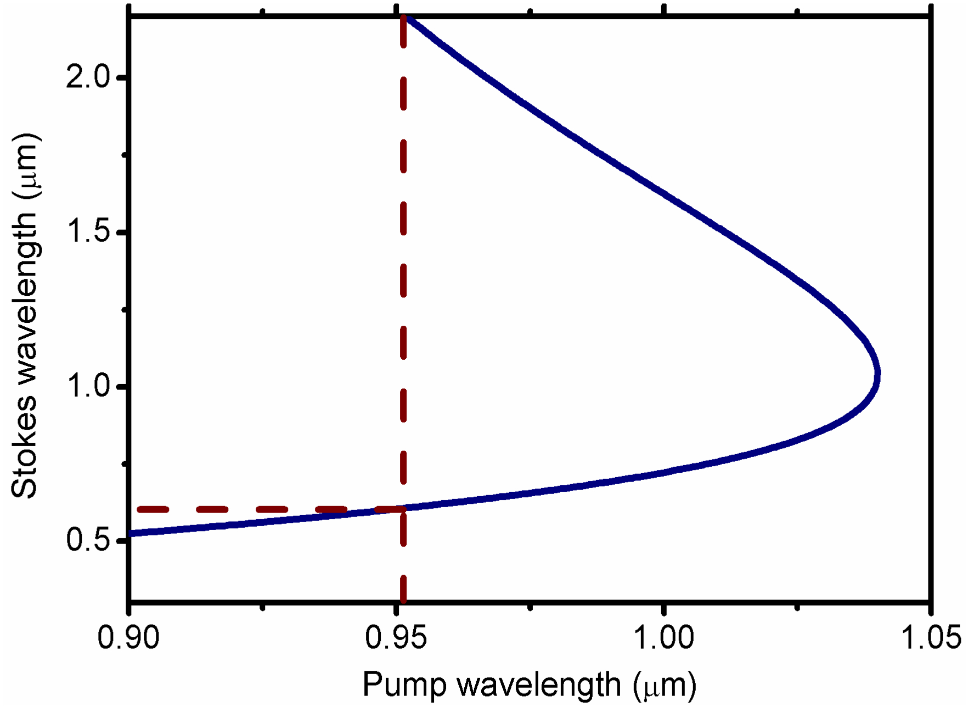
Rulkov et al, Paper CDPC7 CLEO San Francisco (2004)



Single uniform PCF

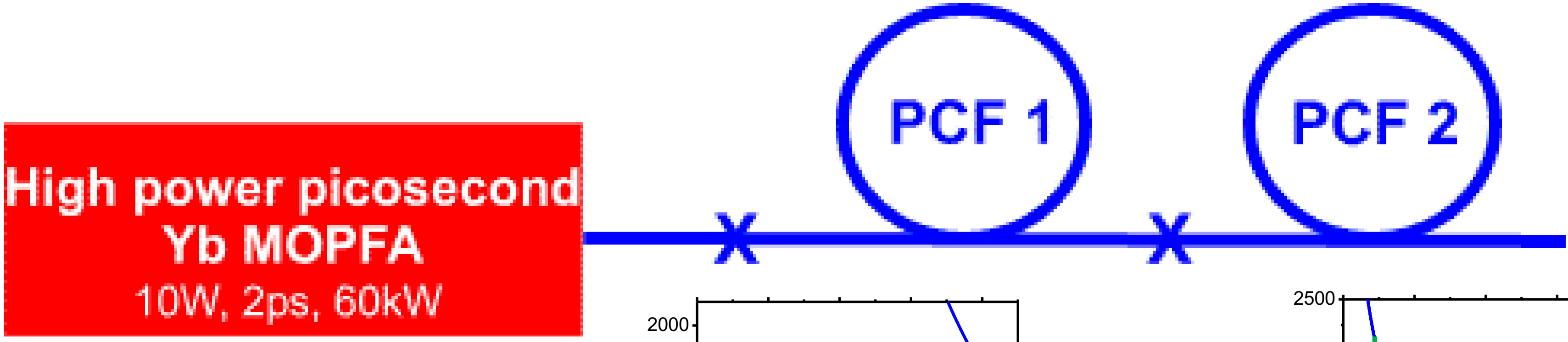
Operation down to 600nm !

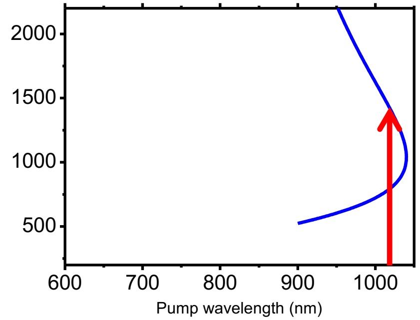


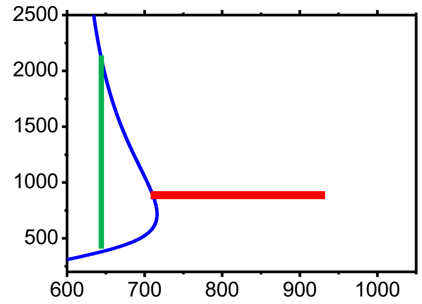


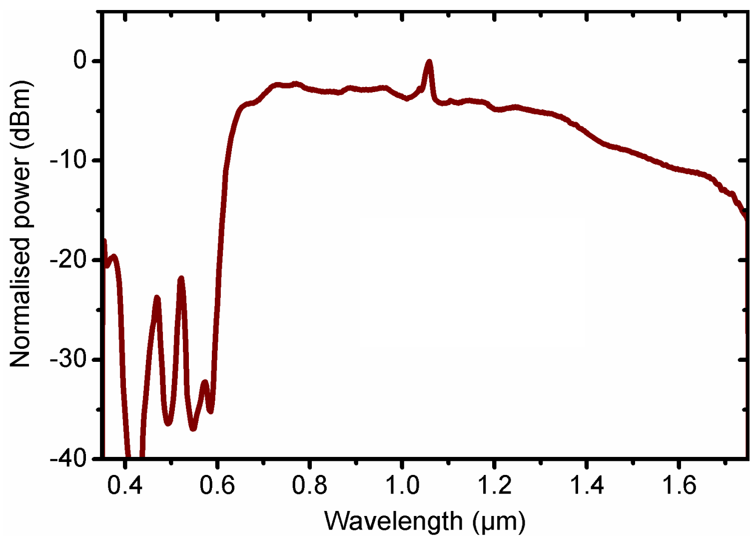
Spectral extension - Cascaded Fibres

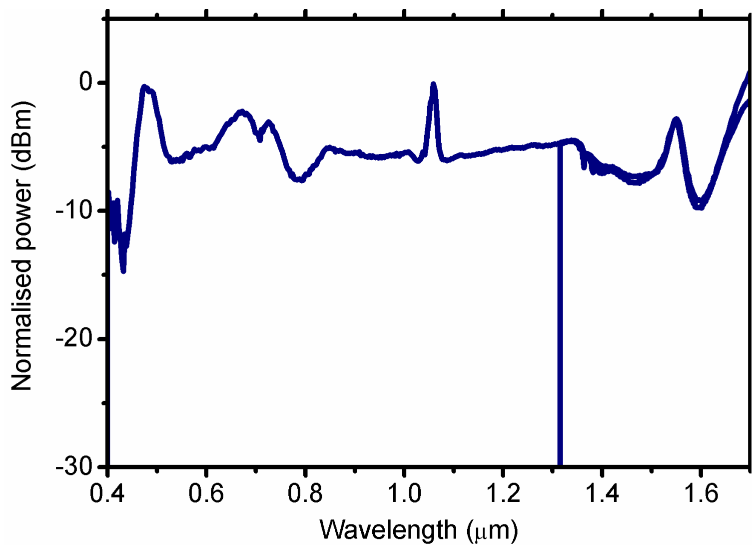
Travers et al, Opt Lett 30, 3132 (2006)











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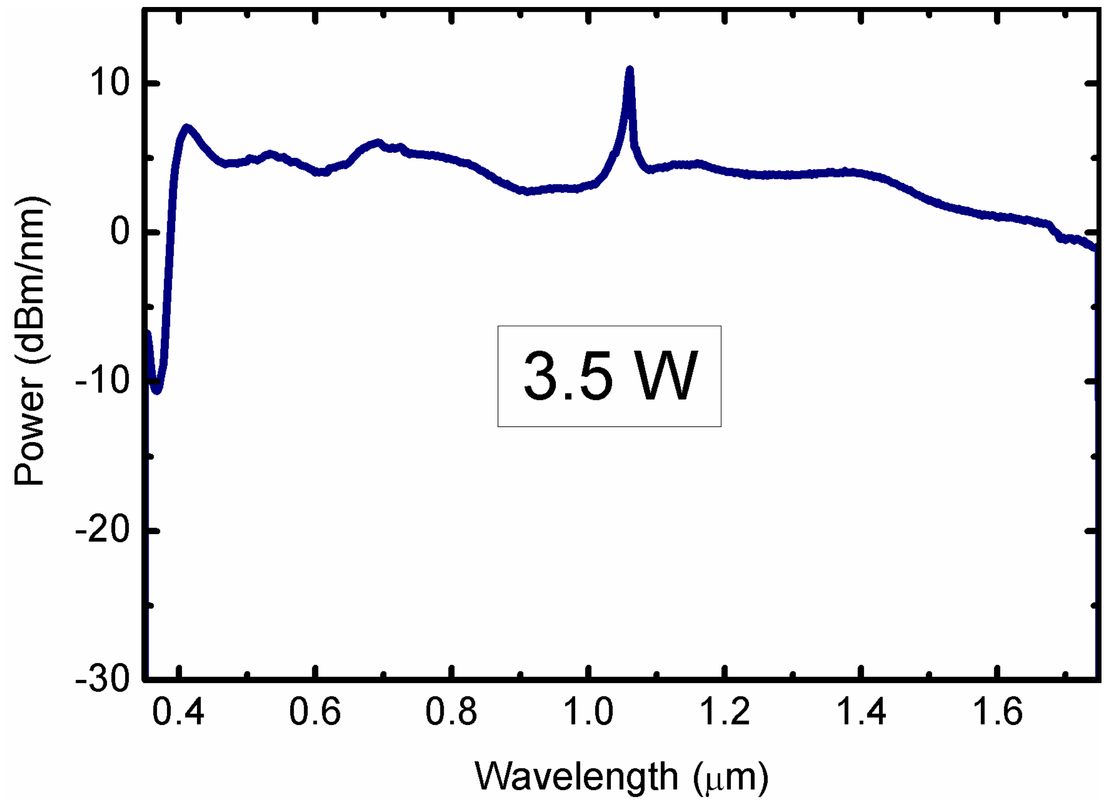
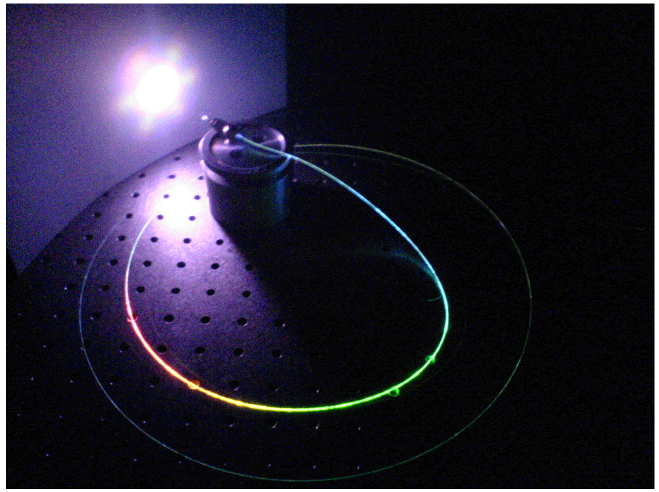
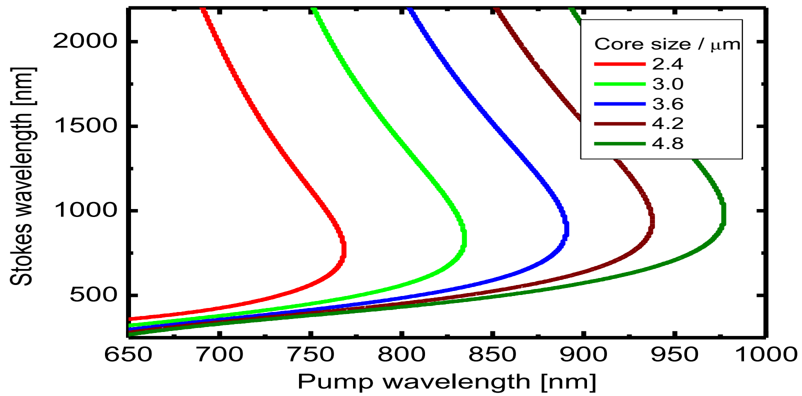
Spectral extension - Tapered PCF

Kudlinski et al. Opt Express 14, 5715 (2006)

Operation down to 320 nm







- **Over 3.5 W**
- **Continuum from 320 – 2300 nm**
- **Over 2 mW/nm 400 – 800 nm**

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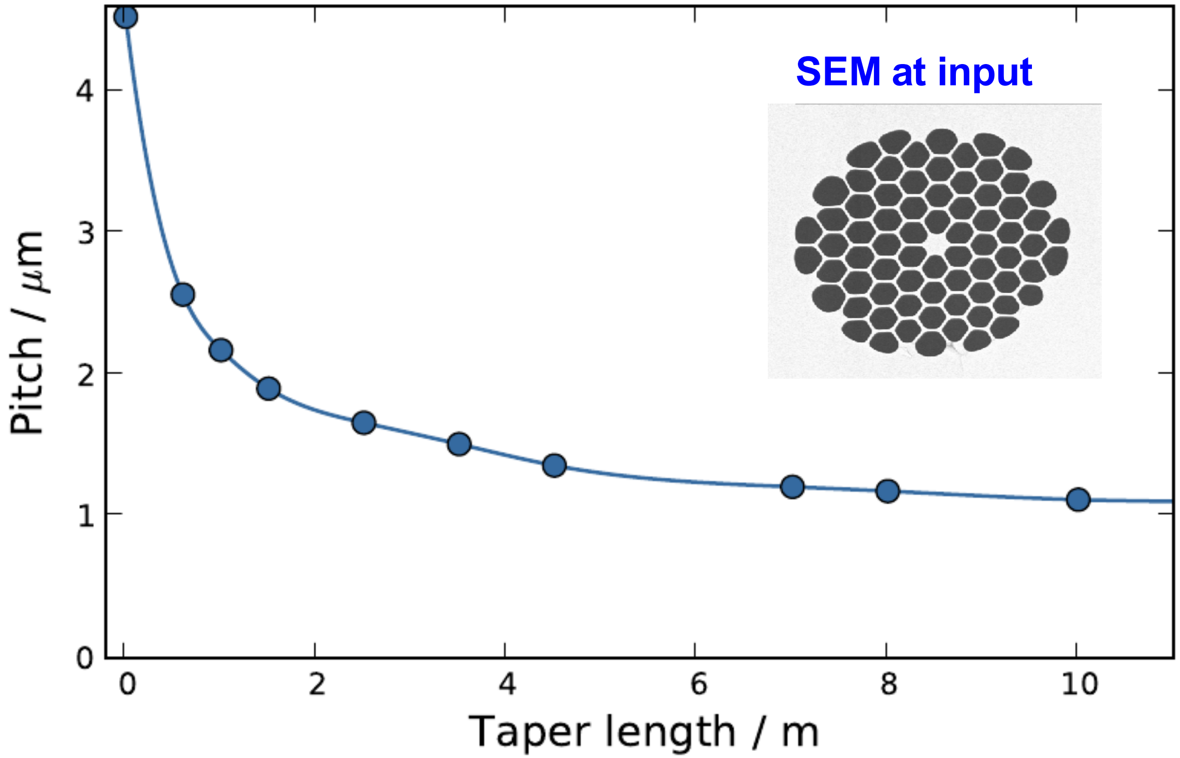
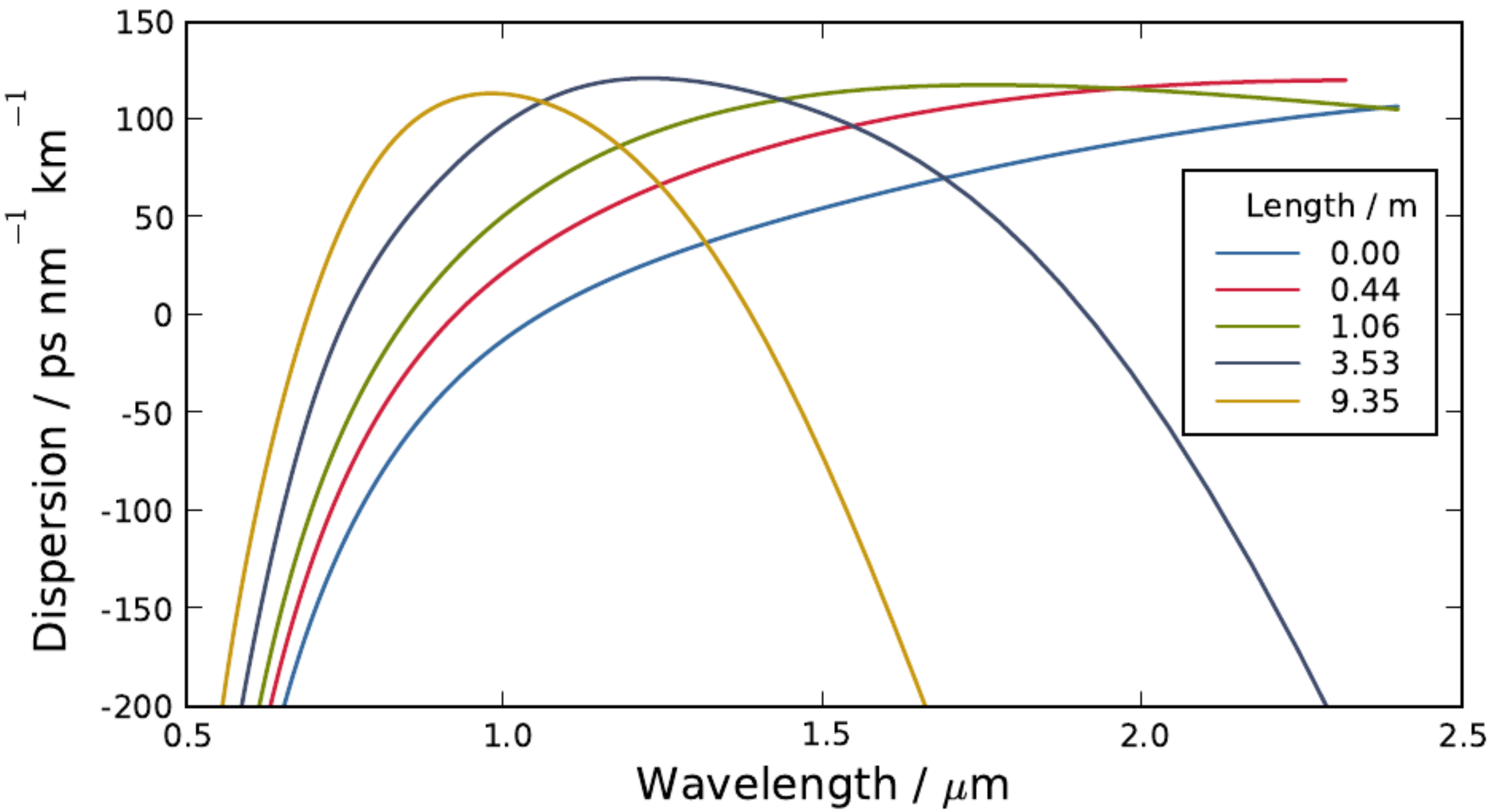
PCF Tapers - Design



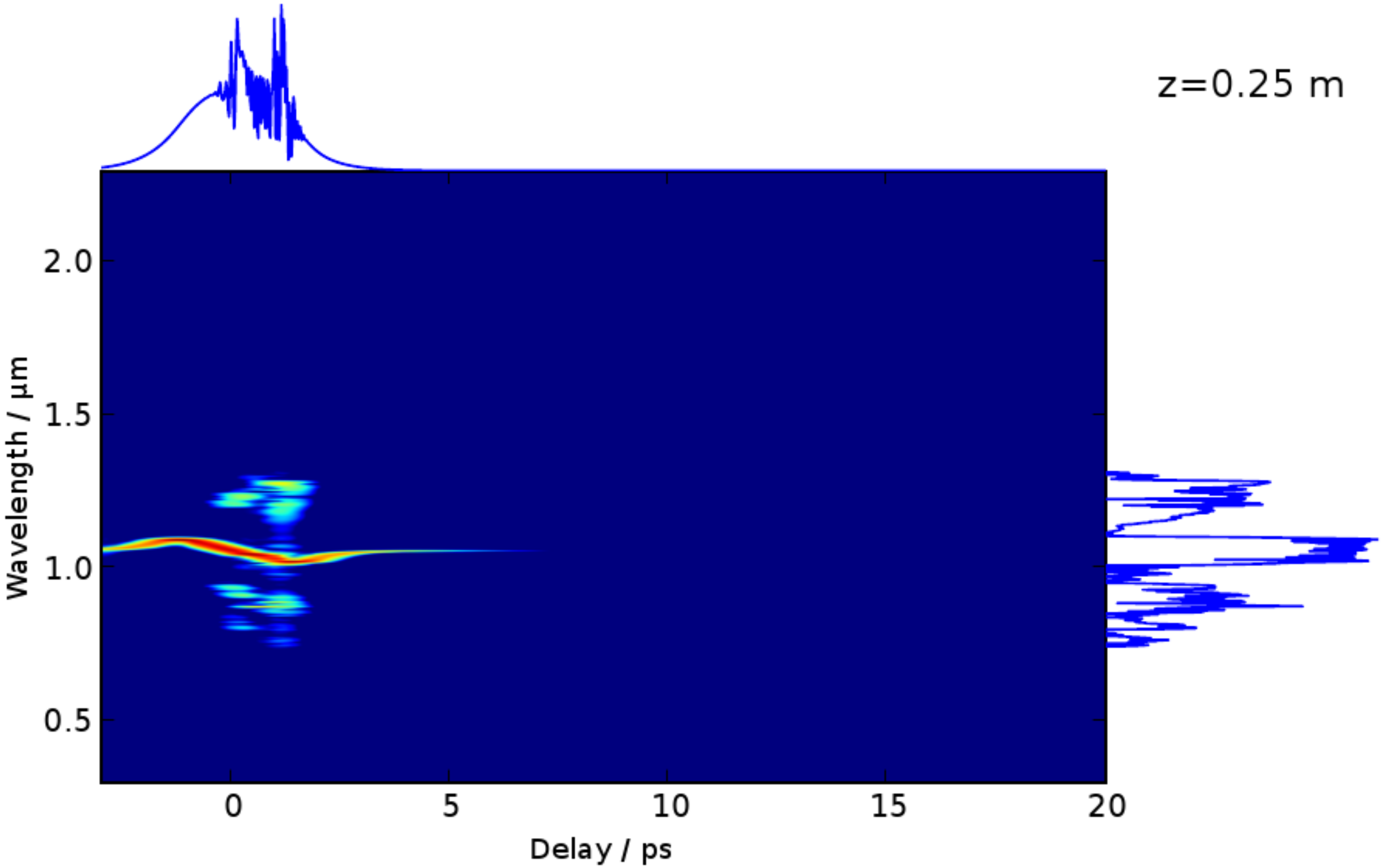
- Manufactured by Bath University group at the drawing tower
- d/Λ = 0.7 (constant)
- Long lengths possible
- Dispersion controls supercontinuum spectrum

PCF Tapers - Dispersion

- **Dispersion profiles evolve along the fibre length**
- **This *changes the phase and group velocity matching* conditions**

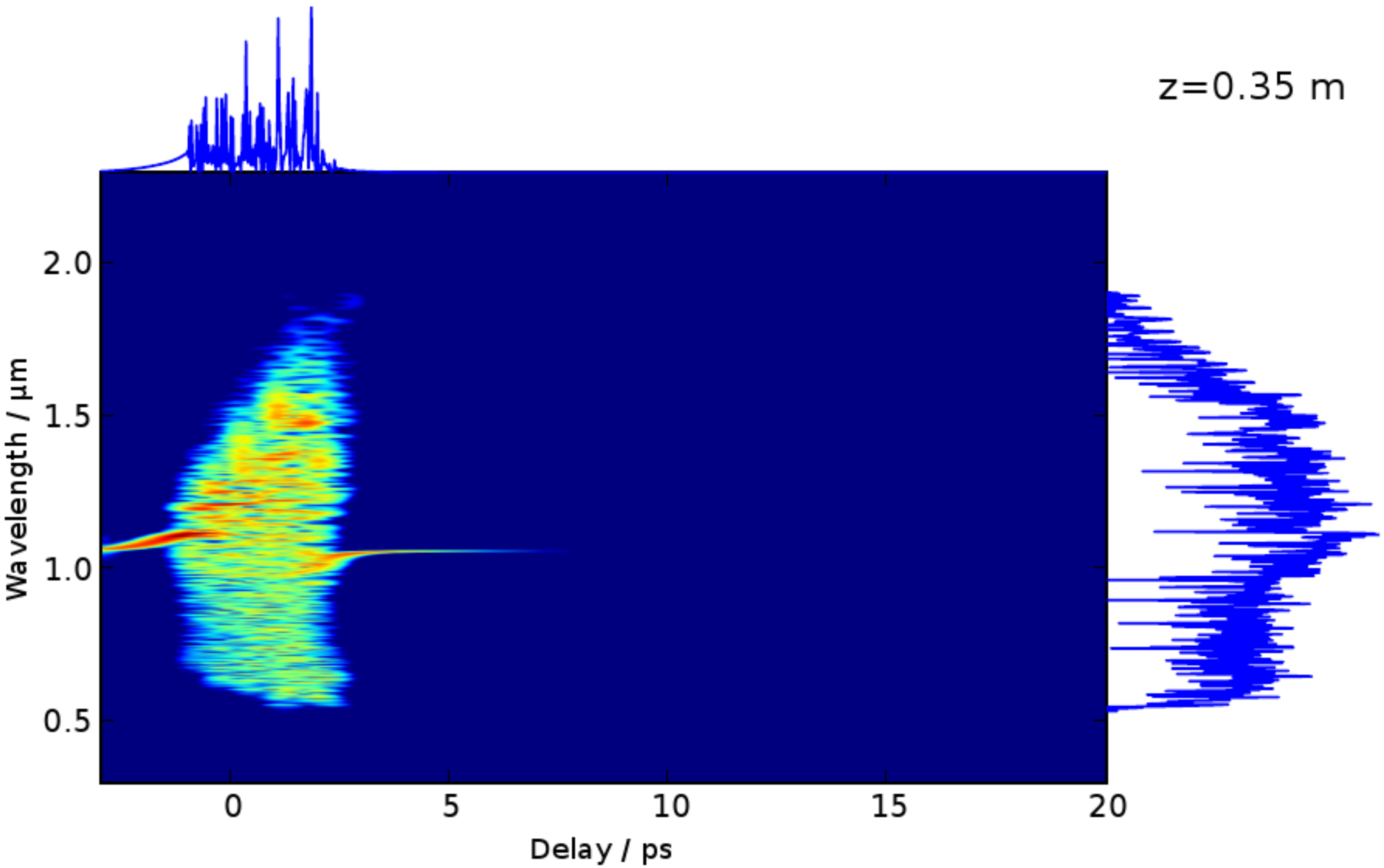


Picosecond Continuum Dynamics 1



- **Supercontinuum initiated by modulation instability**
- **Generates > 100 kW power *fundamental* solitons from ~10 kW pump**

Picosecond Continuum Dynamics 2



- A cascade of four wave mixing processes extends the continuum to visible

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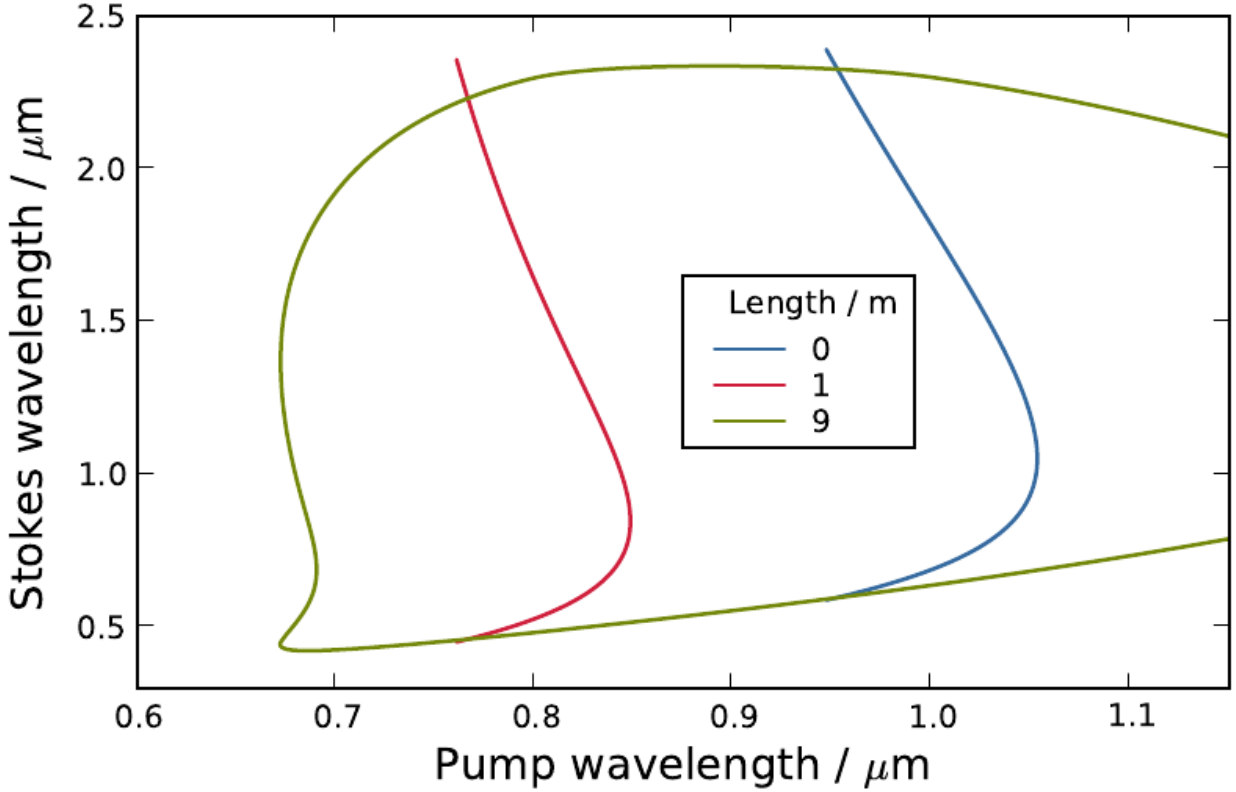
Four wave mixing

Phase-matching limits

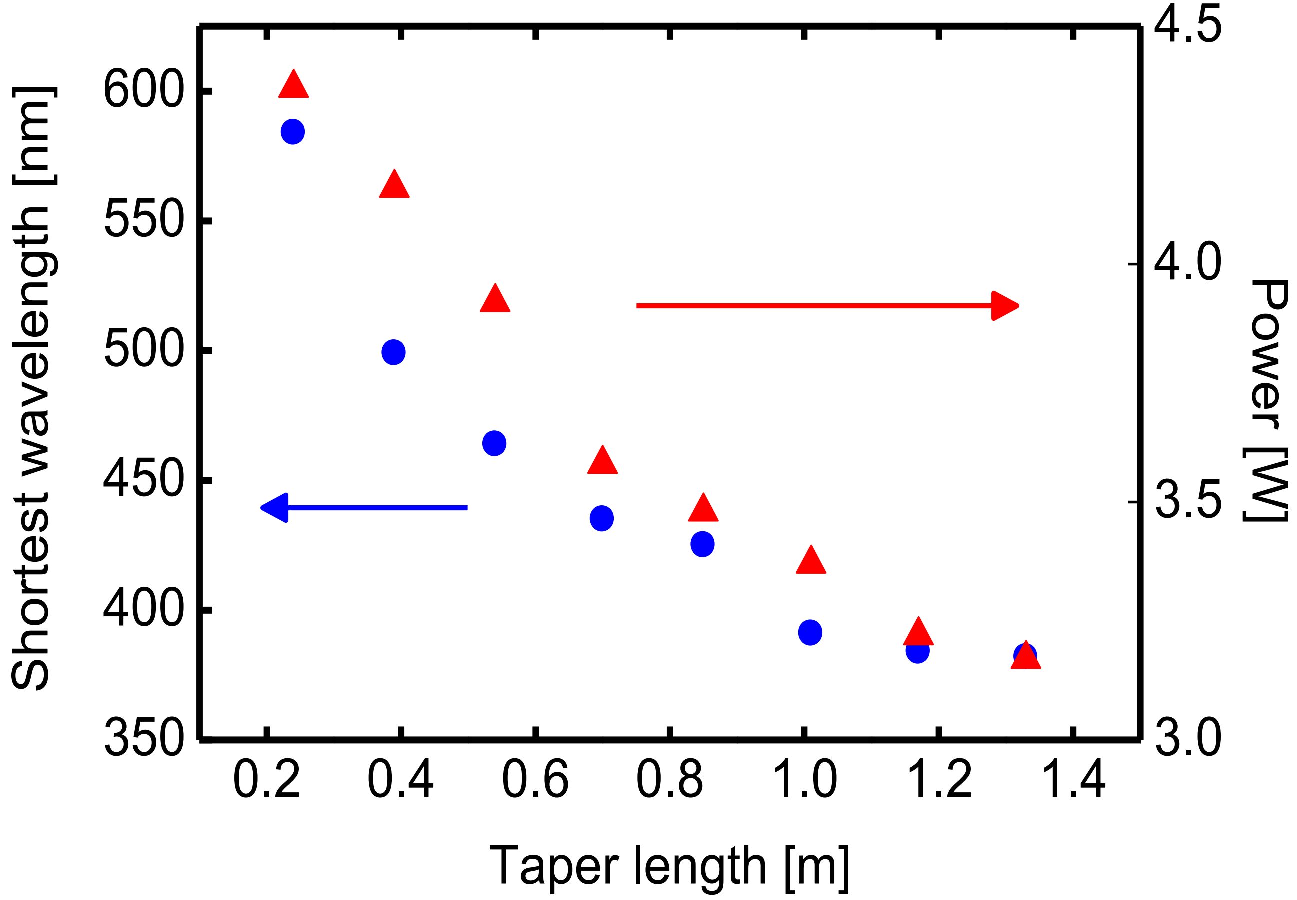


From the FWM phase-matching diagrams we find the short-wavelength limit:

> 500 nm in length used

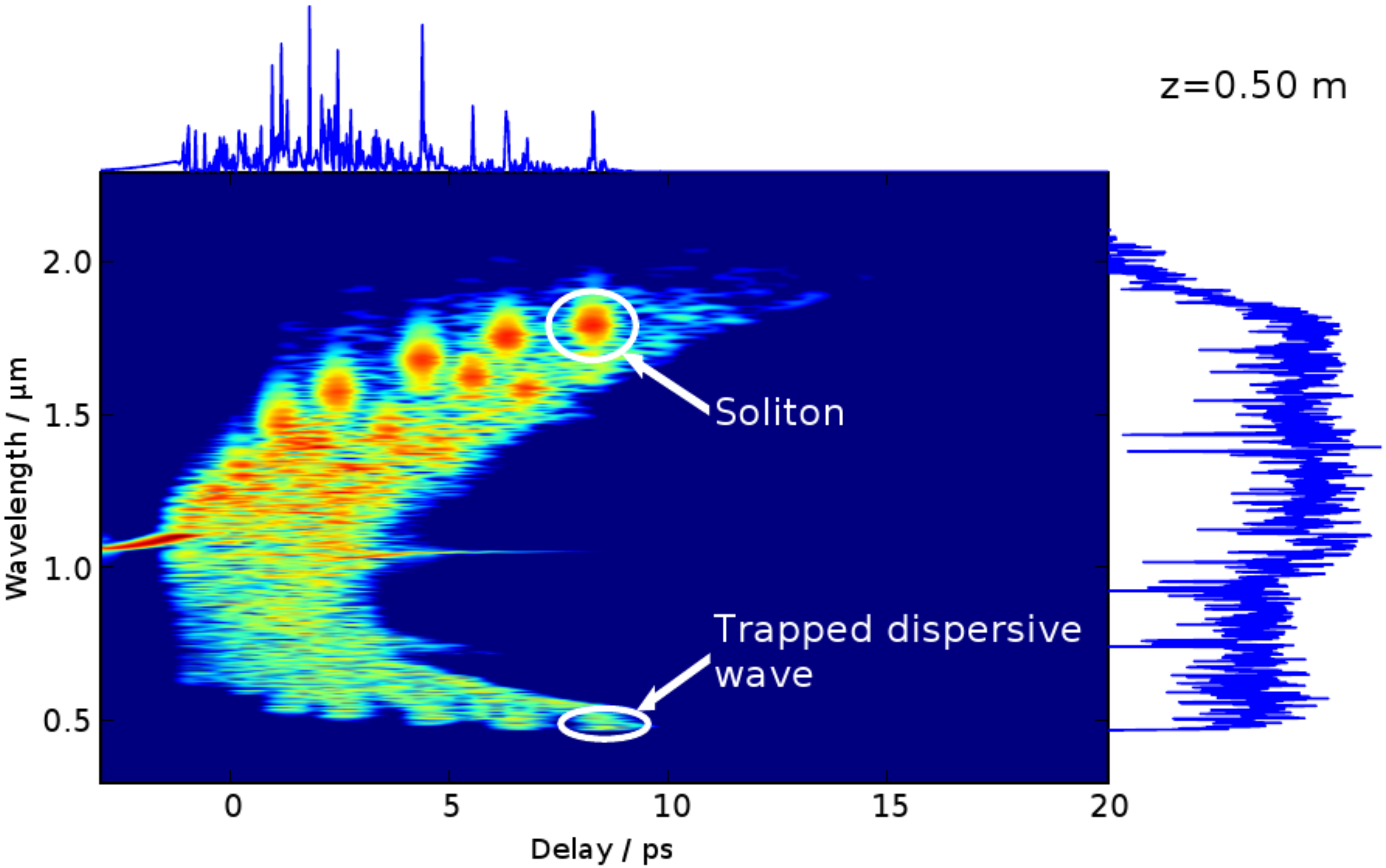
Supercontinuum generation in taper

Experimental measurement of development with length



Picosecond Continuum Dynamics 3

Further extension due to soliton-dispersive wave interactions



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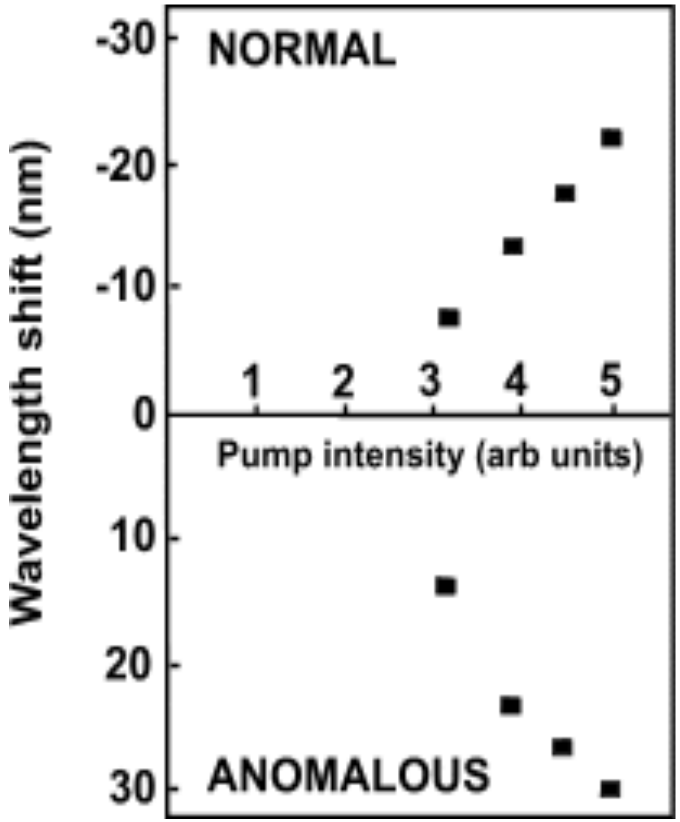
Trapping of dispersive waves

High power solitons trap dispersive waves

Beaud, Hodel, Zysset and Weber, IEEE J QE 23, 1938 (1987)

Gouveia-Neto, Faldon and Taylor, Opt. Commun 69, 173 (1988)



Gorbach and Skyrabin, Phys Rev A 76, 053803 (2007)

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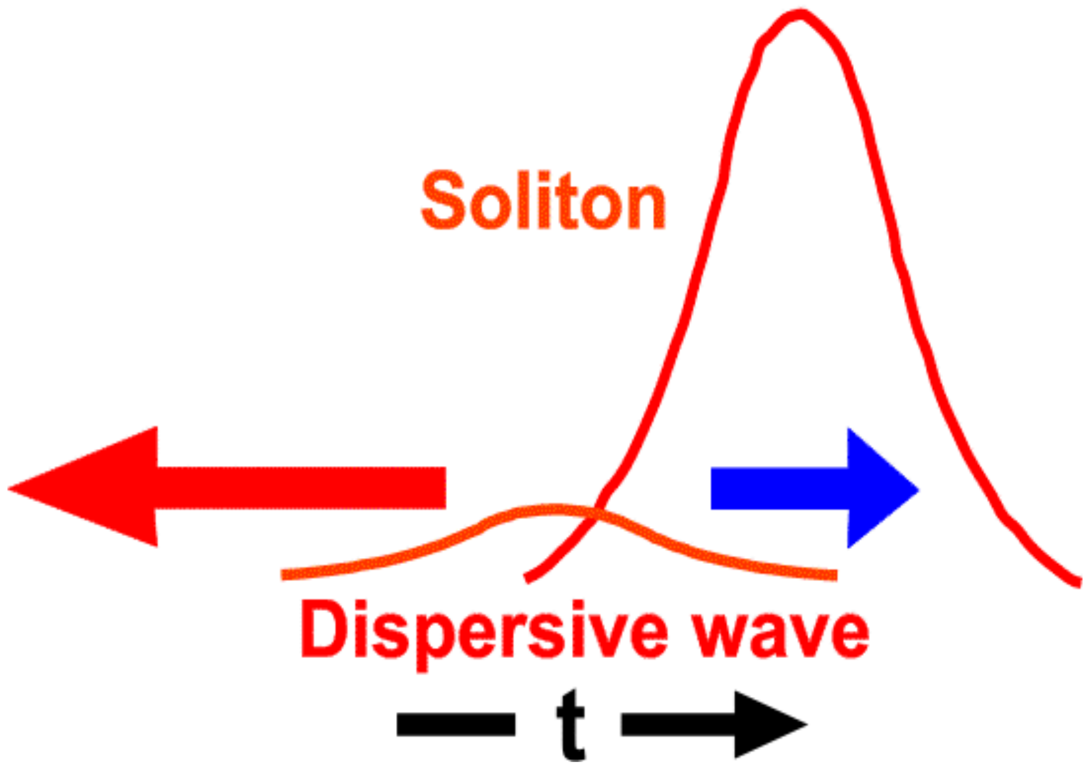
Soliton trapping of dispersive waves

Originating in region of minimum dispersion

Cross phase modulation – soliton and dispersive wave



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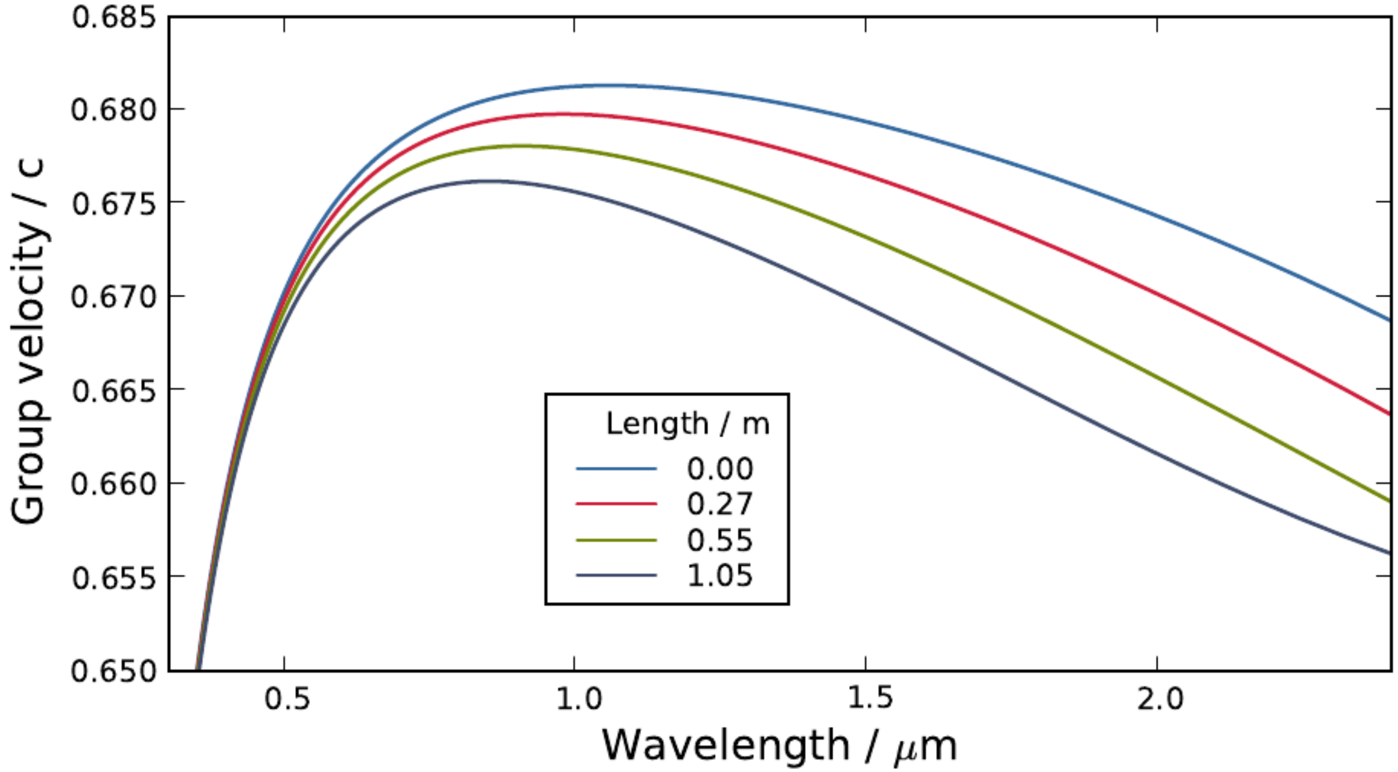
Group velocity matching 1

- **The trapping process requires group velocity matching**
  In constant core PCF this is very limited

✓ **In tapered PCF the matching conditions can be continuously changing**



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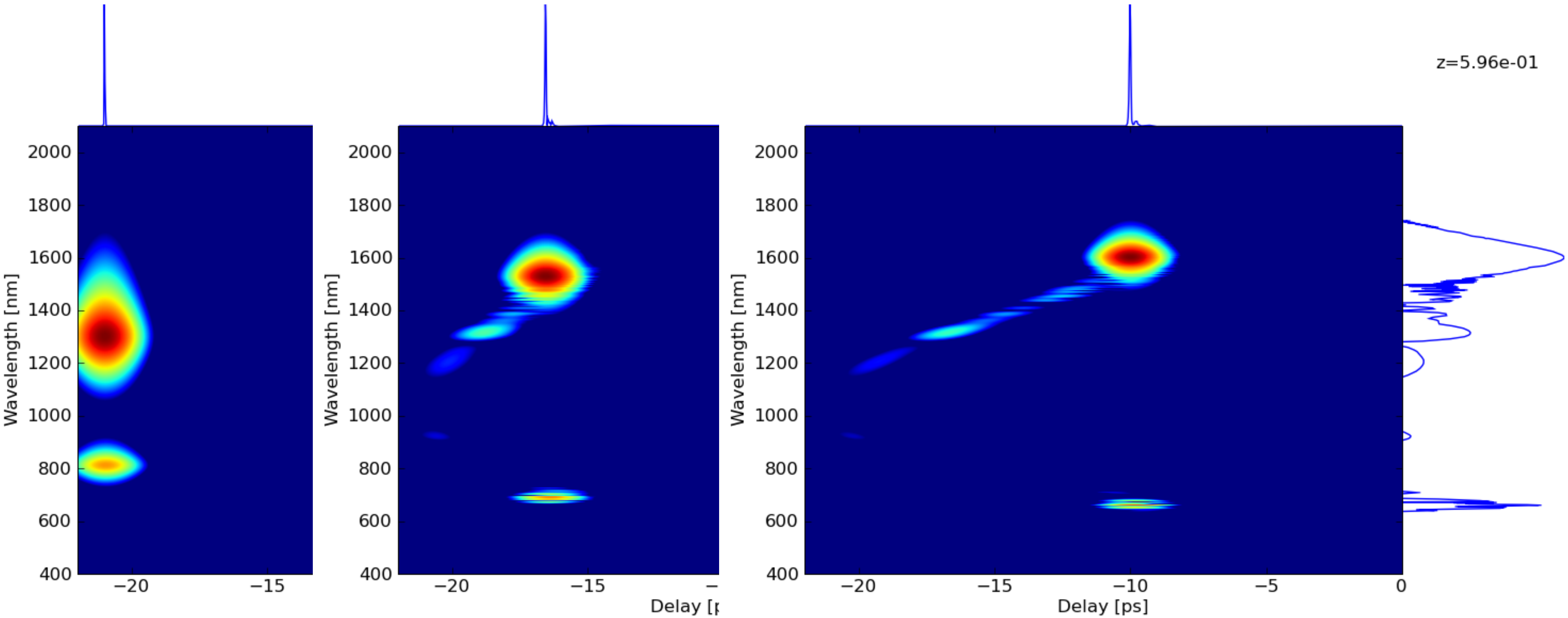
Trapping in standard PCF

The trapping effect enhances four-wave mixing interaction



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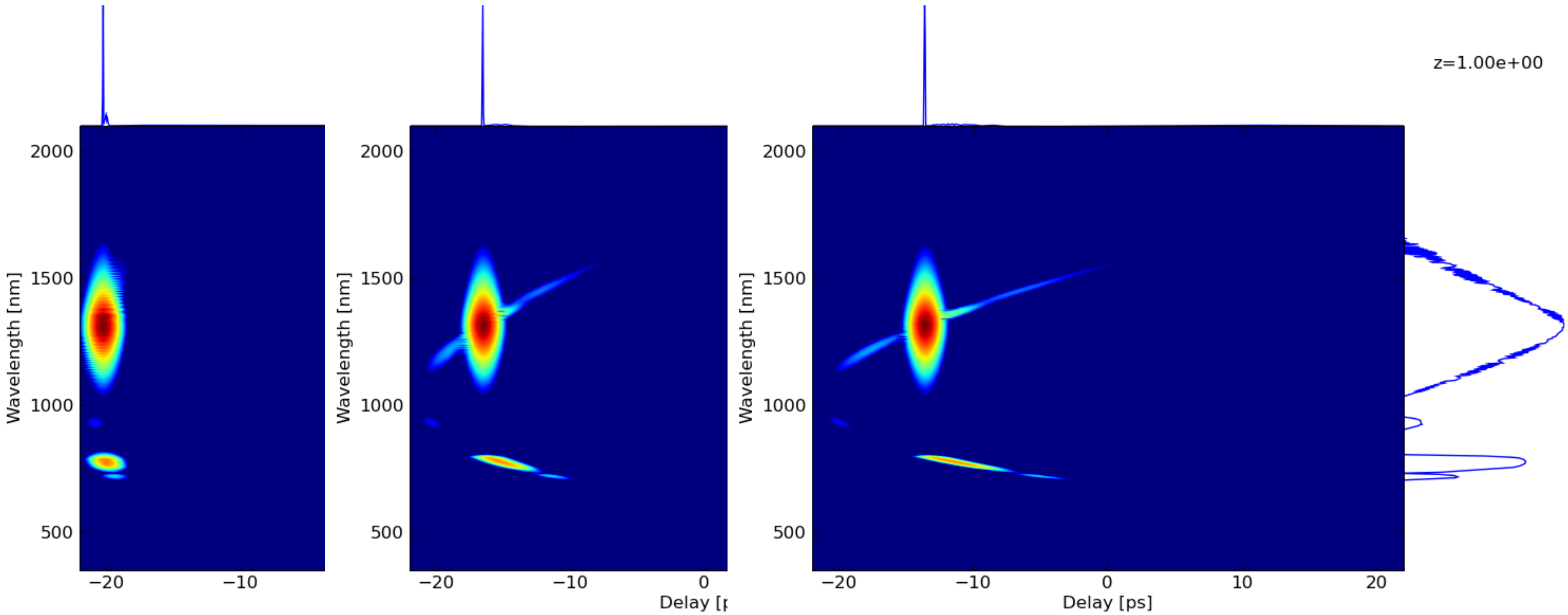
Trapping in standard PCF

The trapping effect requires Raman to decelerate solitons

NO RAMAN PRESENT



What do tapers do ?

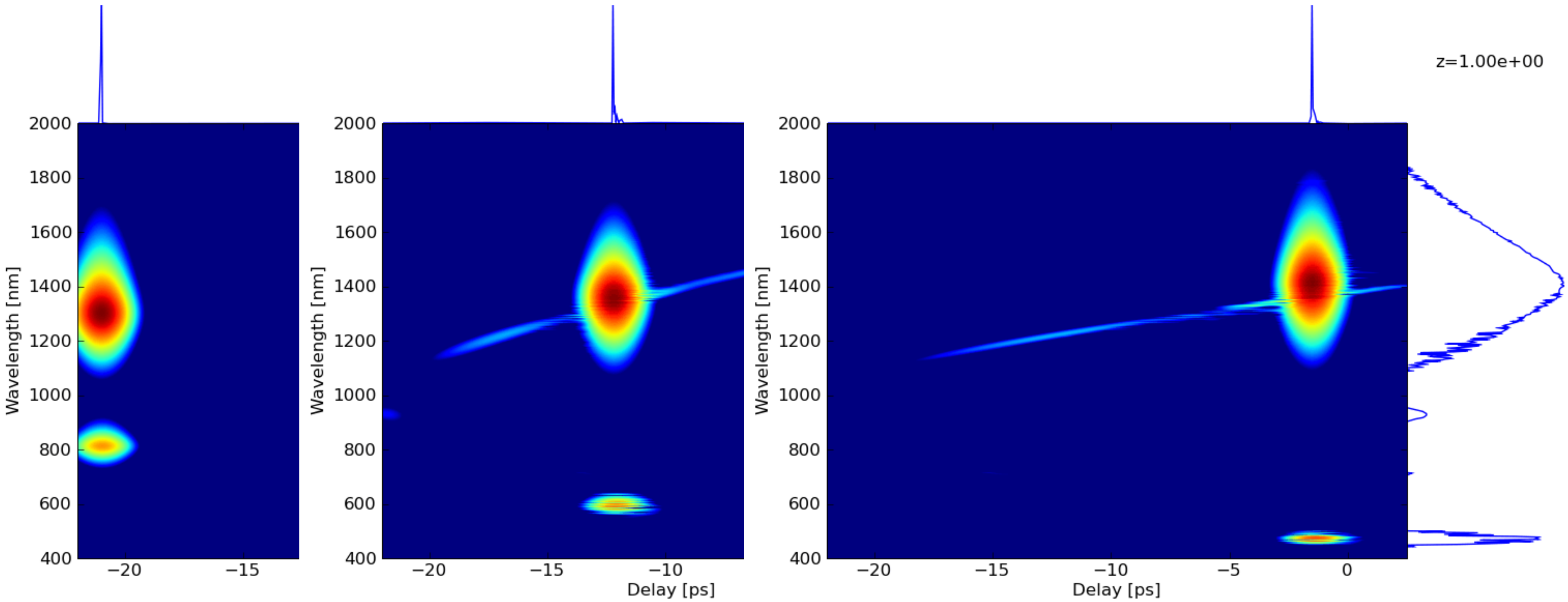
Tapers contribute in two ways:

- Group velocity matching conditions
- Soliton enhancement

Trapping in tapered PCF

The taper decelerates solitons *without Raman*, due to the *changing group velocity*

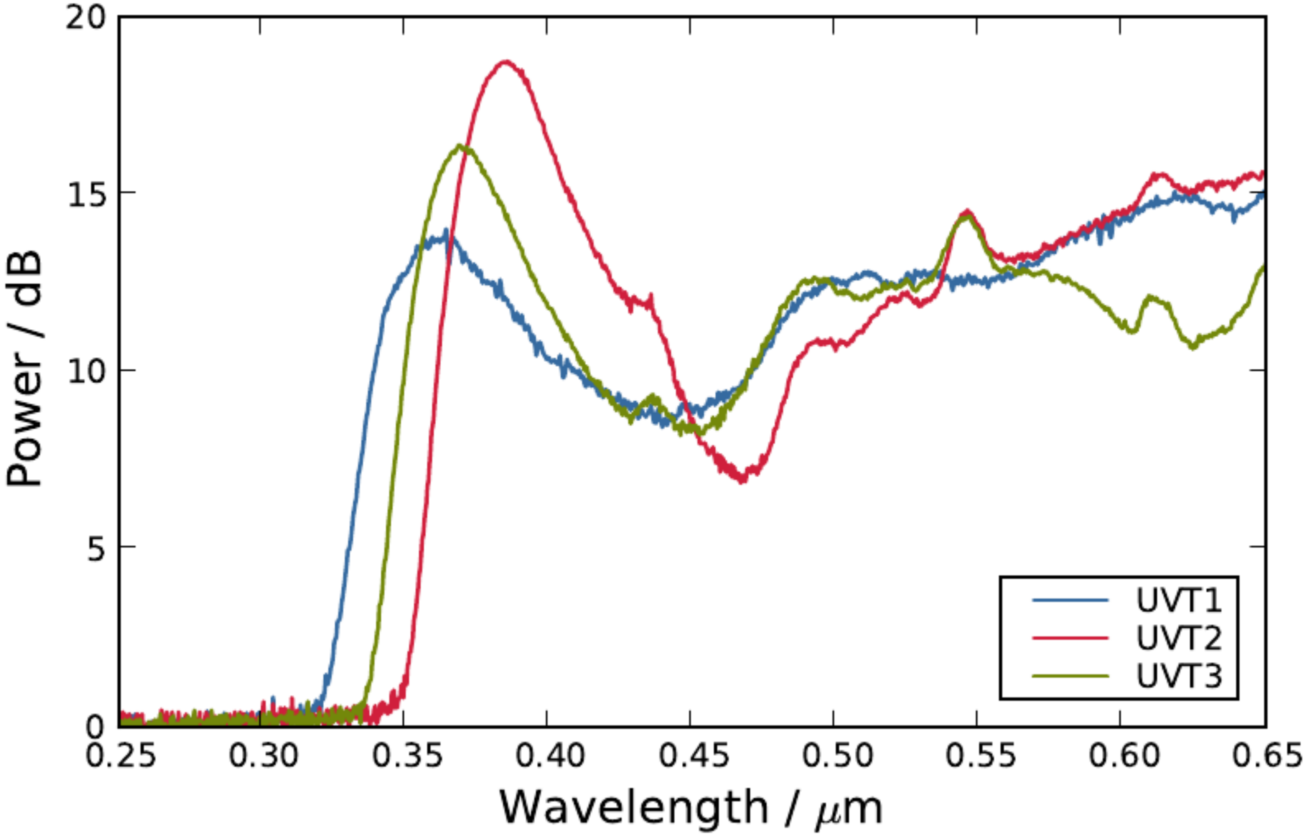
NO RAMAN PRESENT



Explains uv enhancement

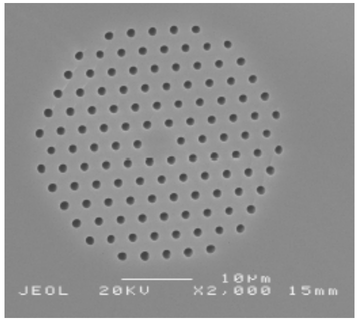
Near UV generation from 1.06 µm pump source

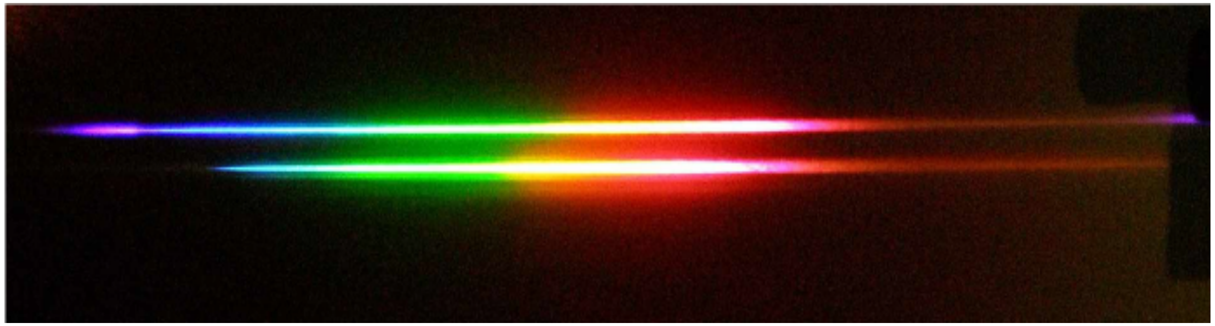
Taper gives 300 nm extra bandwidth compared to constant core fibre

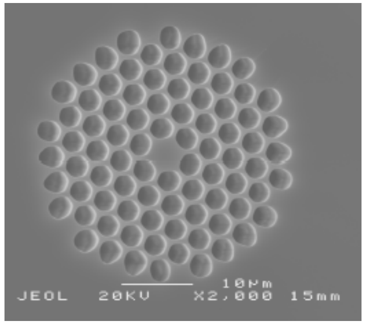


Spectral extension – IR group index

Stone and Knight, Opt Express 16, 2670 (2008)

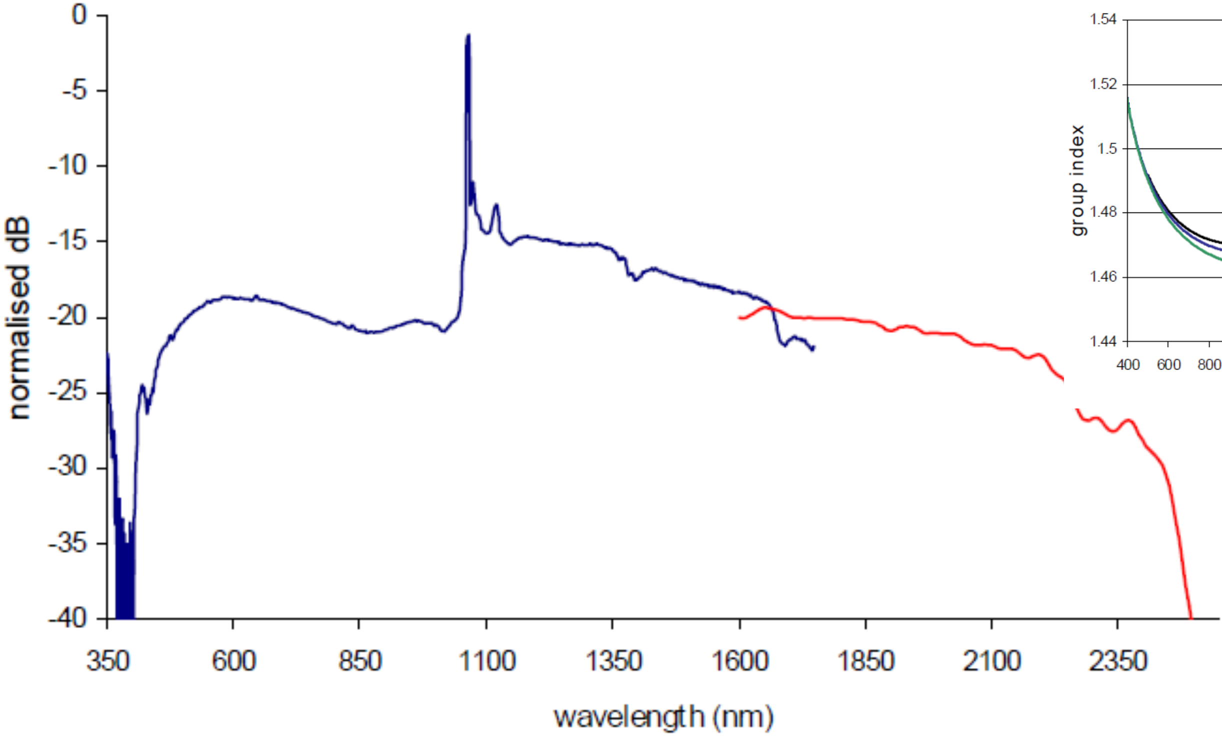


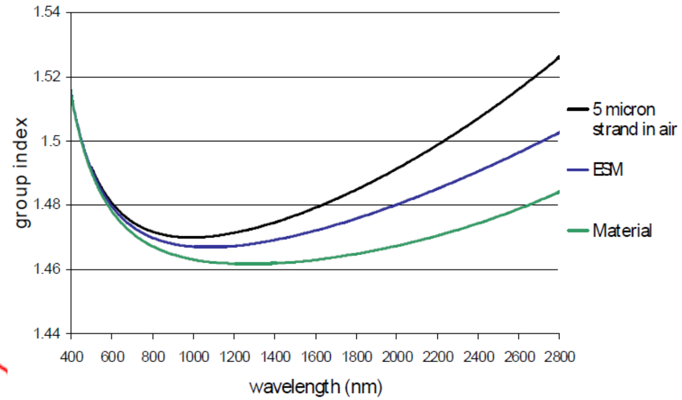




Conventional ESM PCF

Large core high delta





C W Pumped Supercontinua

Increasing the average power

Femtosecond systems – damage limited

Long pulse / cw pumped systems provide solution

Are cw systems capable of generating supercontinua ?

Nonlinearity - It's only Power X Length

Femtoseconds ~ 10kW in 1 cm ~ 100W.m

CW laser pumped a few 10's W in 10s m

Are the formation mechanisms the same ?

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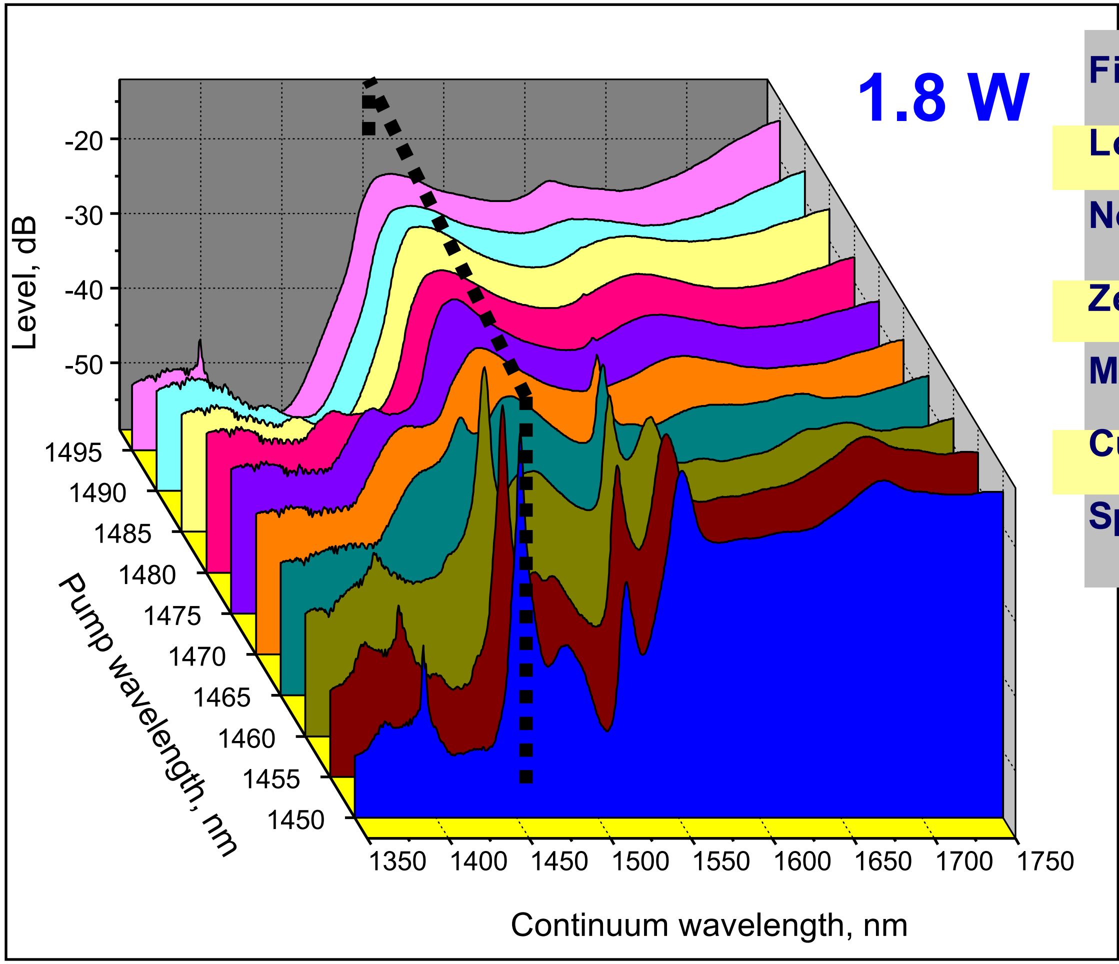
C W Pumped Supercontinua

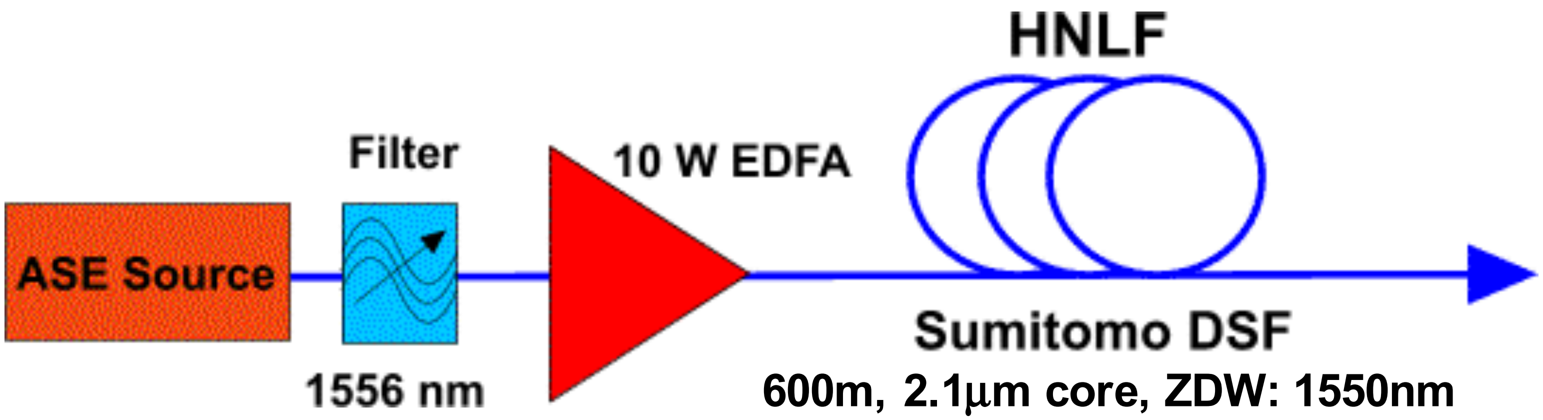
Rulkov, Popov & Taylor 2003

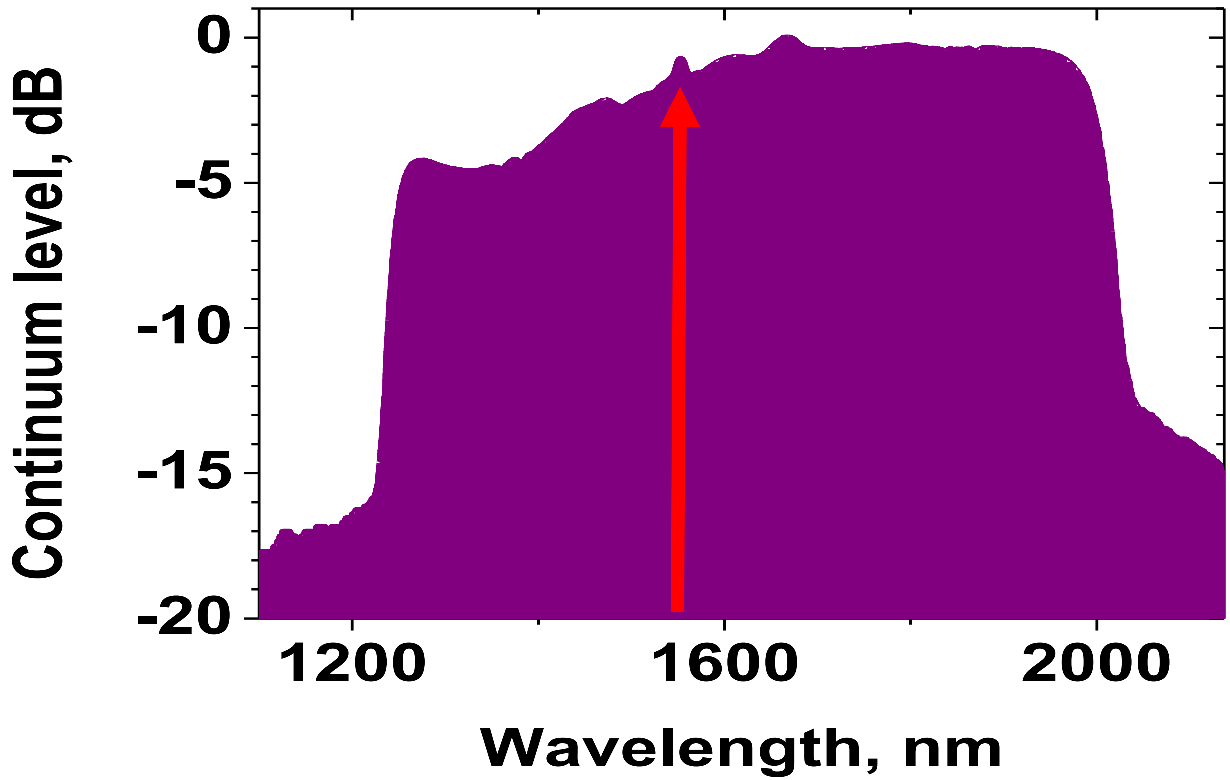
HNLF, pumping with a CW, tunable, Raman fiber laser:



Fibre Parameter	Value
Losses, λ=1.55 μm, dB/km	0.99
Nonlinearity, (W km)$^{-1}$	19
Zero dispersion wavelength, nm	1457
Mode field diameter , μm^2	11
Cutoff wavelength, nm	1270
Splice losses with STF, dB	<0.9

C W Pumped Supercontinua





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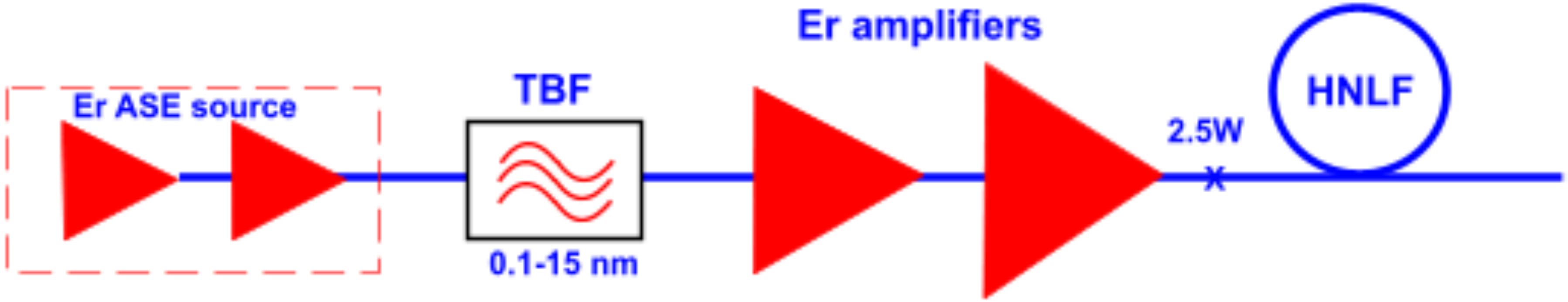
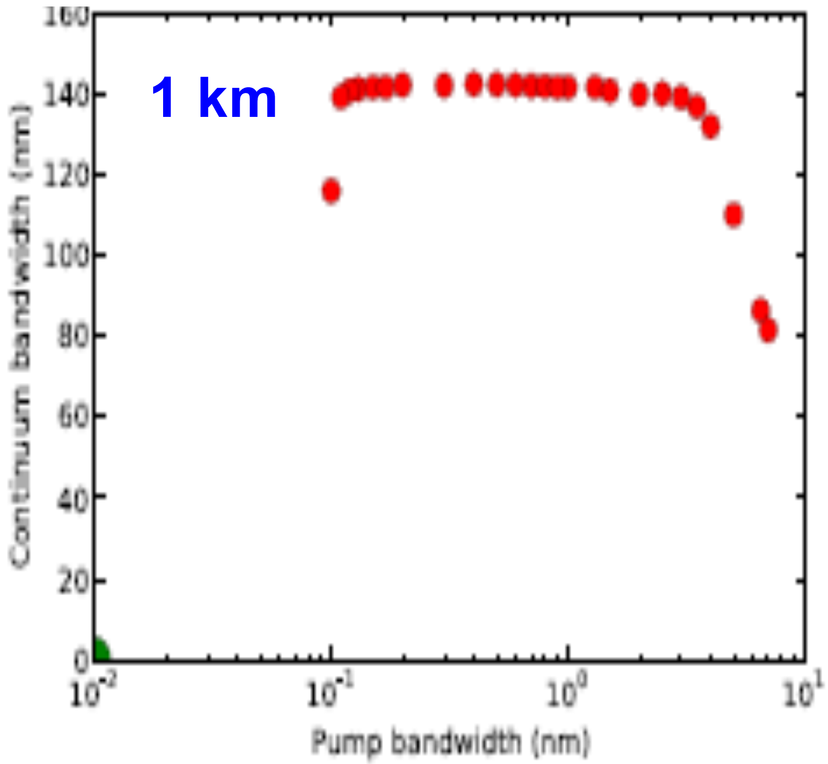
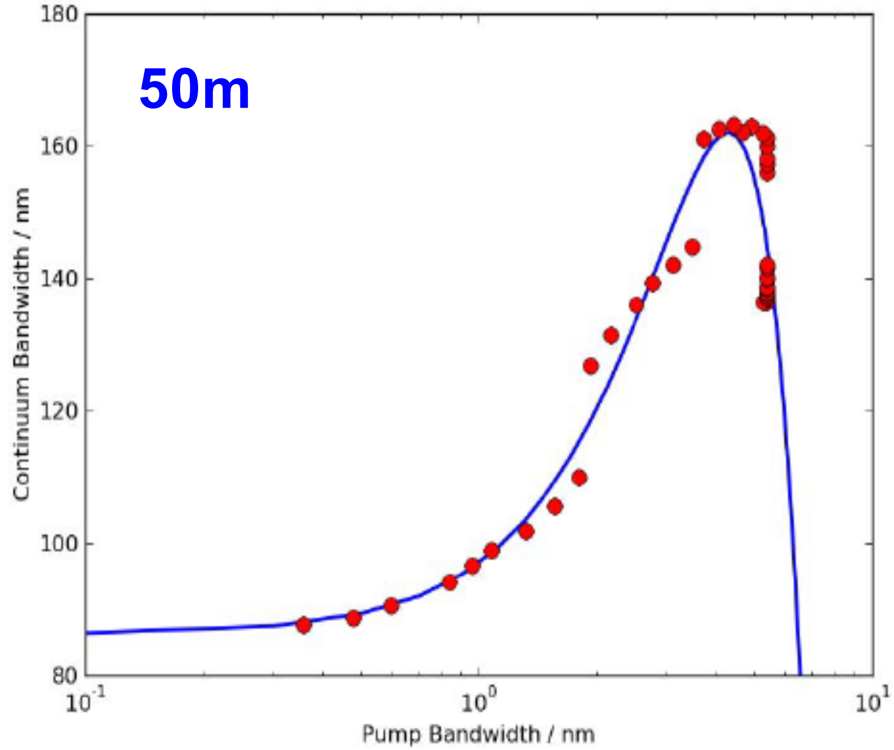
Coherent control of supercontinuum bandwidth



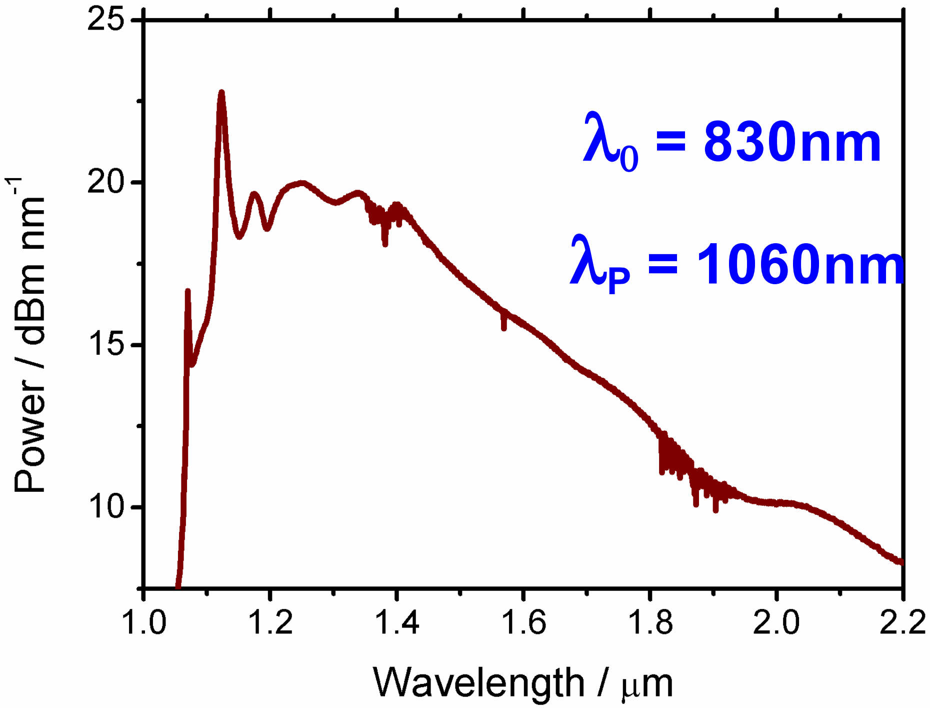


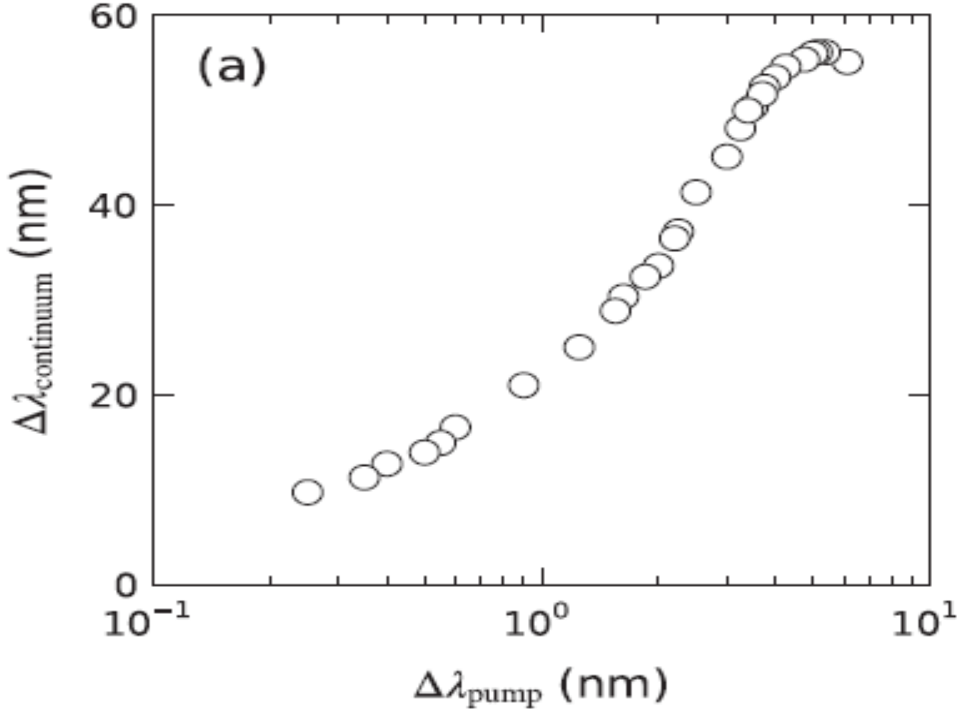


High Power CW Pumping of PCF

Cumberland et al, Opt Express 16 5954 (2008)

Pump wavelength and pump linewidth dependent





- Output power 50 W
- Spectral powers ~ 100 mW/nm
- No short wavelength generation

- Narrow pump spectrum

  Noise structures too long temporally

- Broad pump spectrum

  Noise structures too short temporally

  High power needed

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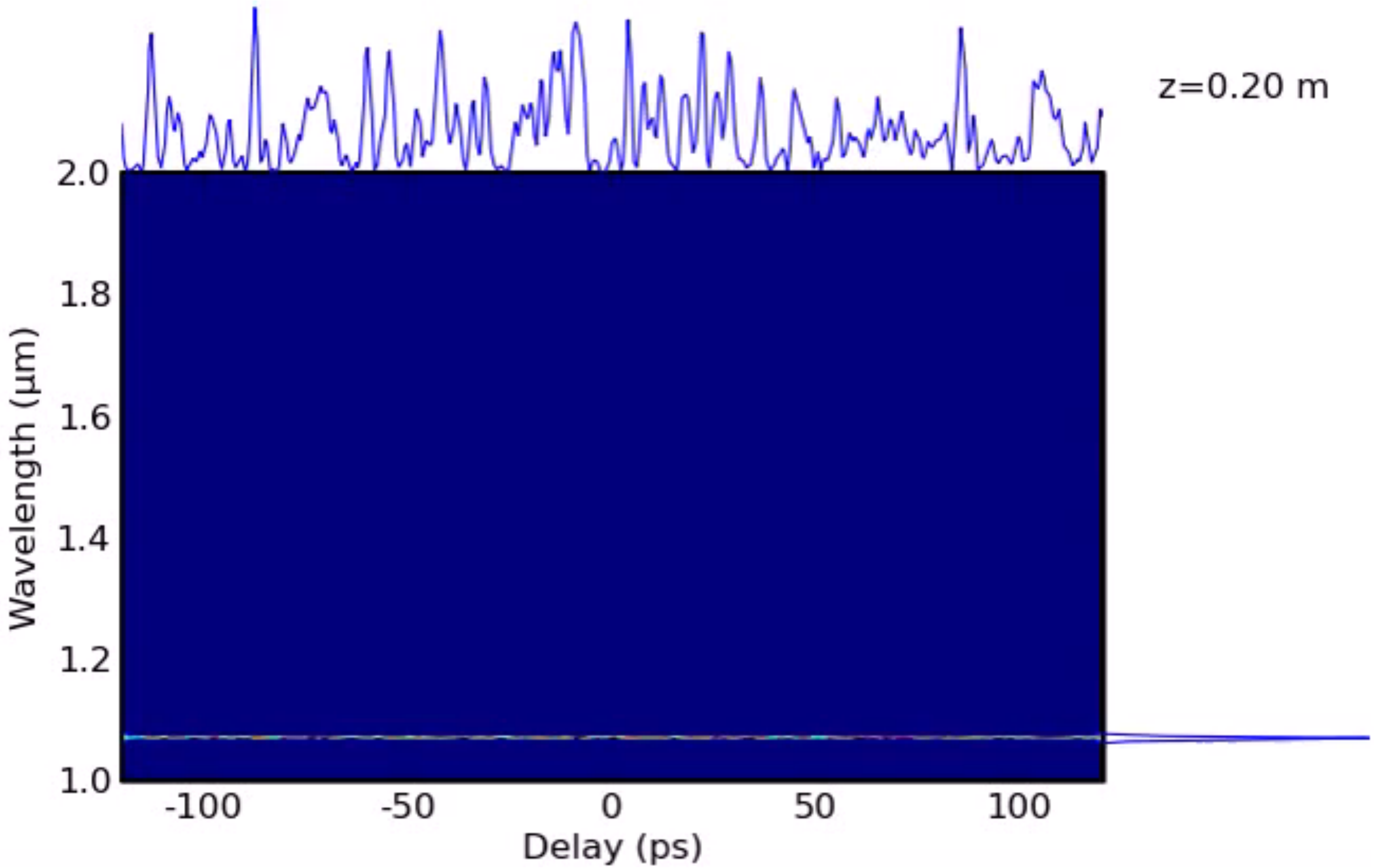
Simulation Spectrogram



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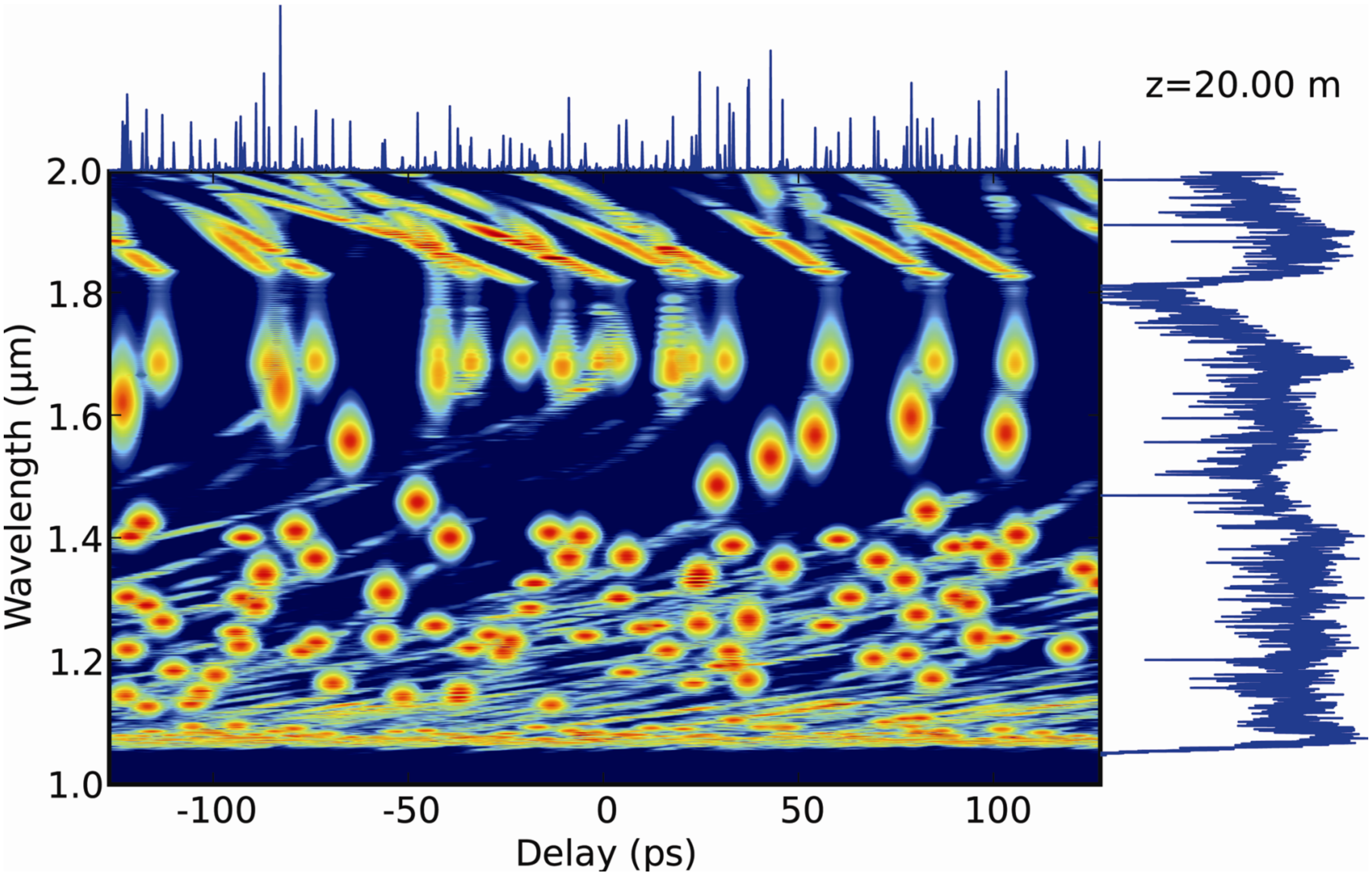
Simulation Spectrogram



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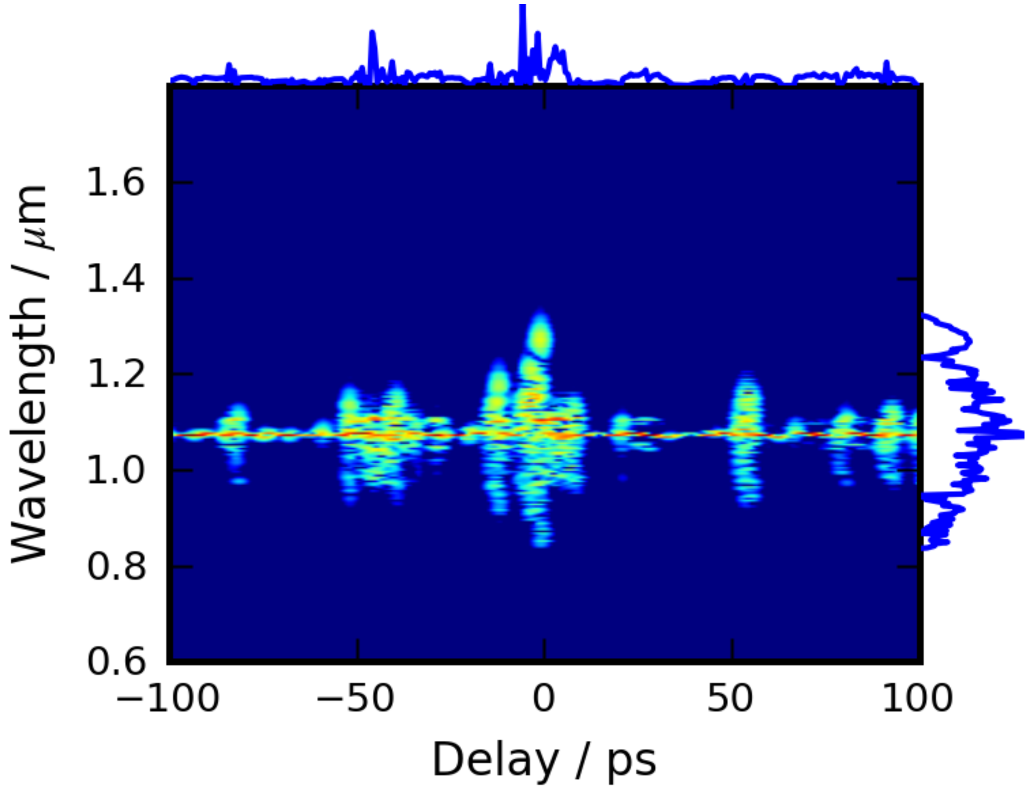
CW pumped supercontinuum Visible generation

Zero dispersion wavelengths at 1050 nm, pump 1060 nm



- Get dispersive waves at short wavelengths
- MI side-lobes or MI induced fundamental solitons, overlap with normal dispersion => dispersive waves

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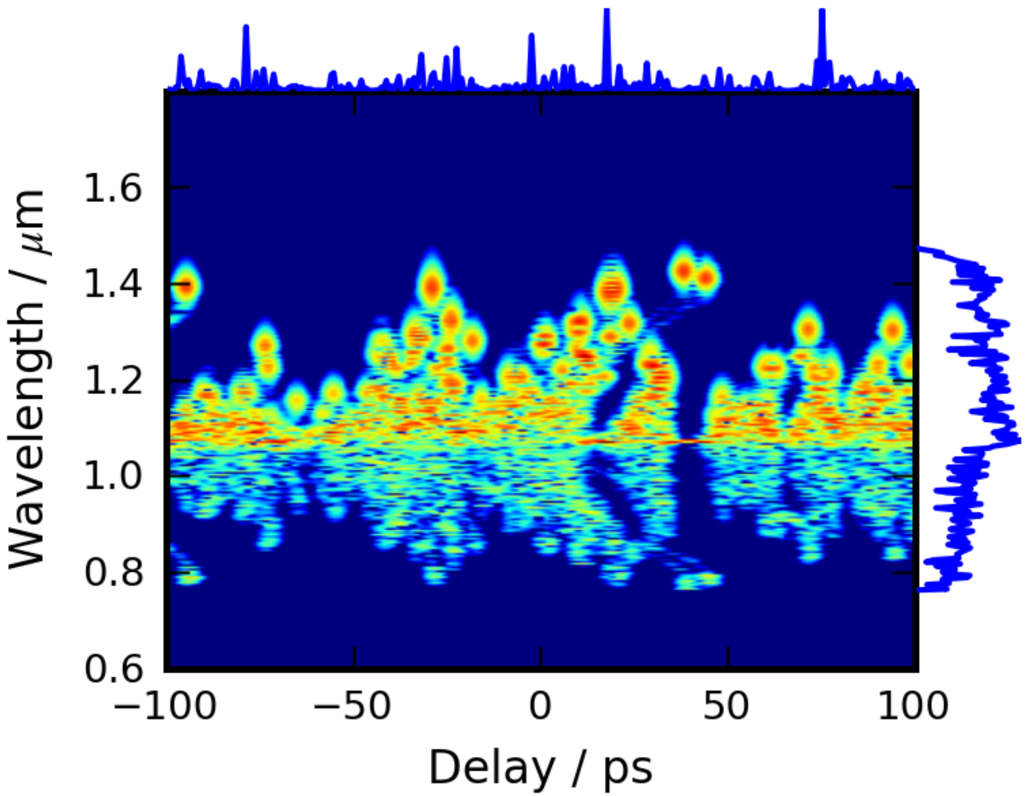
CW pumped supercontinuum Visible generation

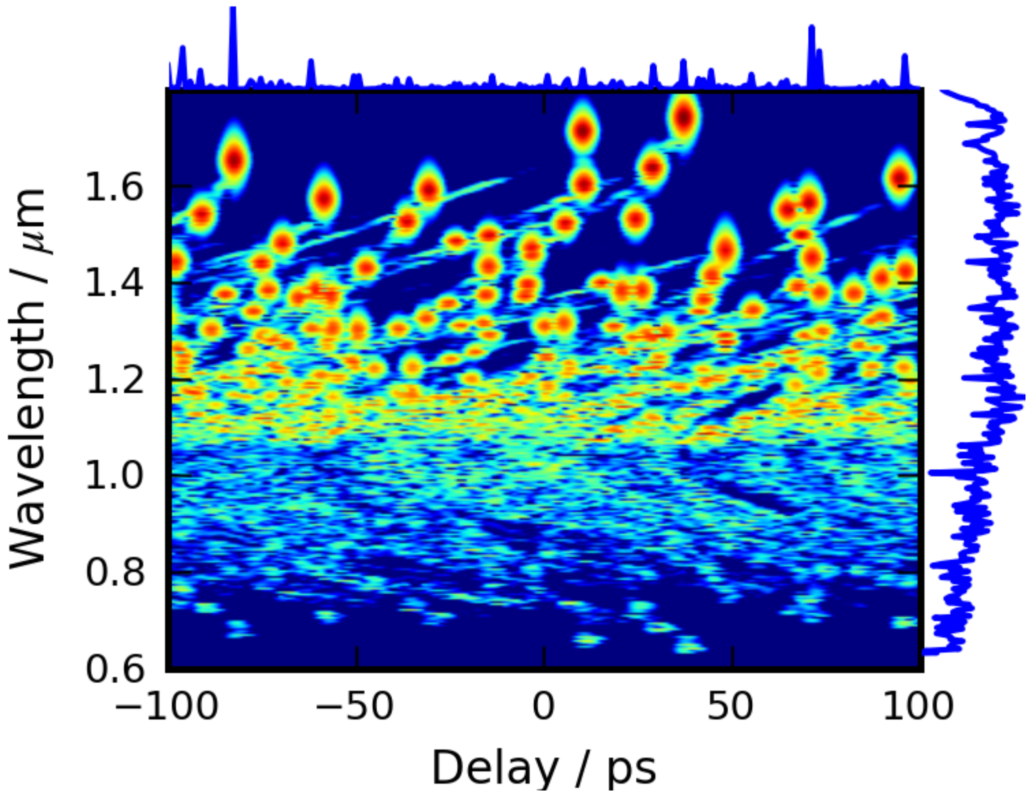
Zero dispersion wavelengths at 1050 nm, pump 1060 nm



- Trapped dispersive waves pushed to shorter wavelengths

CW pumped supercontinuum Visible generation

Zero dispersion wavelengths at 1050 nm, pump 1060 nm



- Supercontinuum spans visible to mid-IR

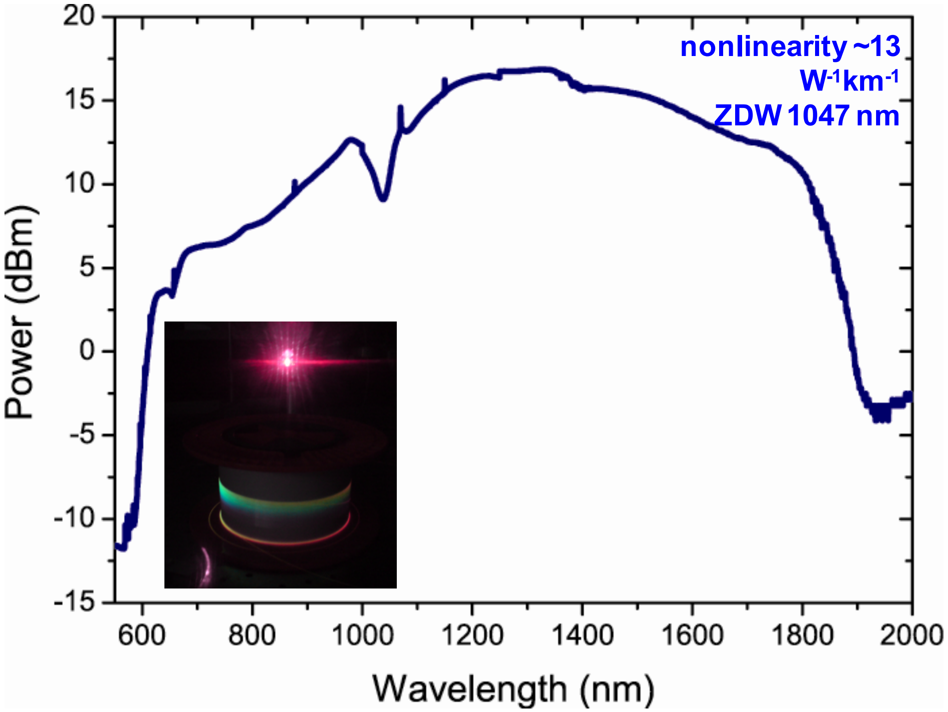
Visible Wavelength Generation CW Pump

Travers et al, Opt Express 16 14435 (2008)

High power pumping – up to 300W CW

Kudlinski and Mussot, Opt Lett 38 2407 (2008)

200m PCF (100m tapered), high efficiency, low power pump 20W



- **50 W output power from continuum**
- **Pump is heavily depleted**

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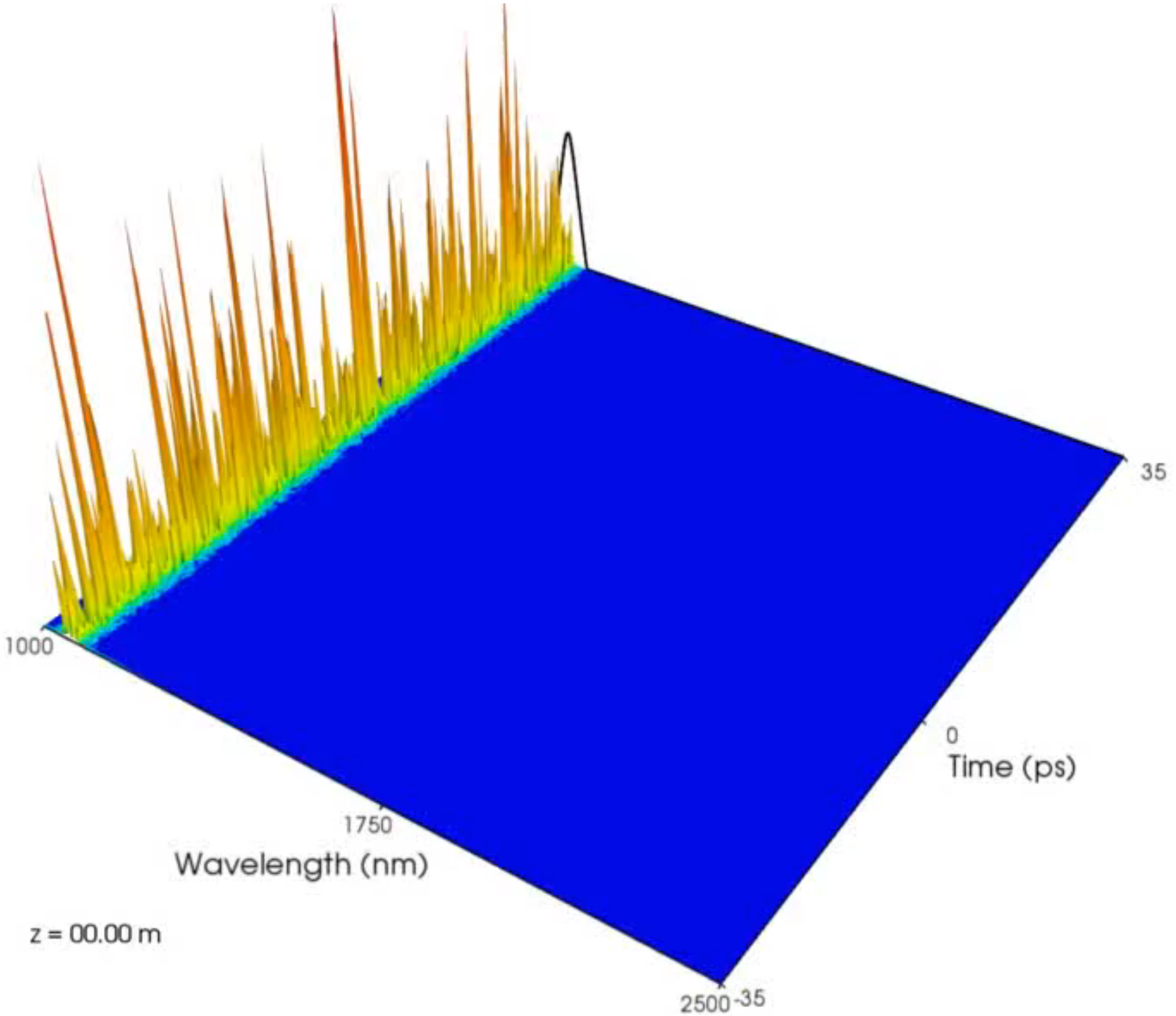
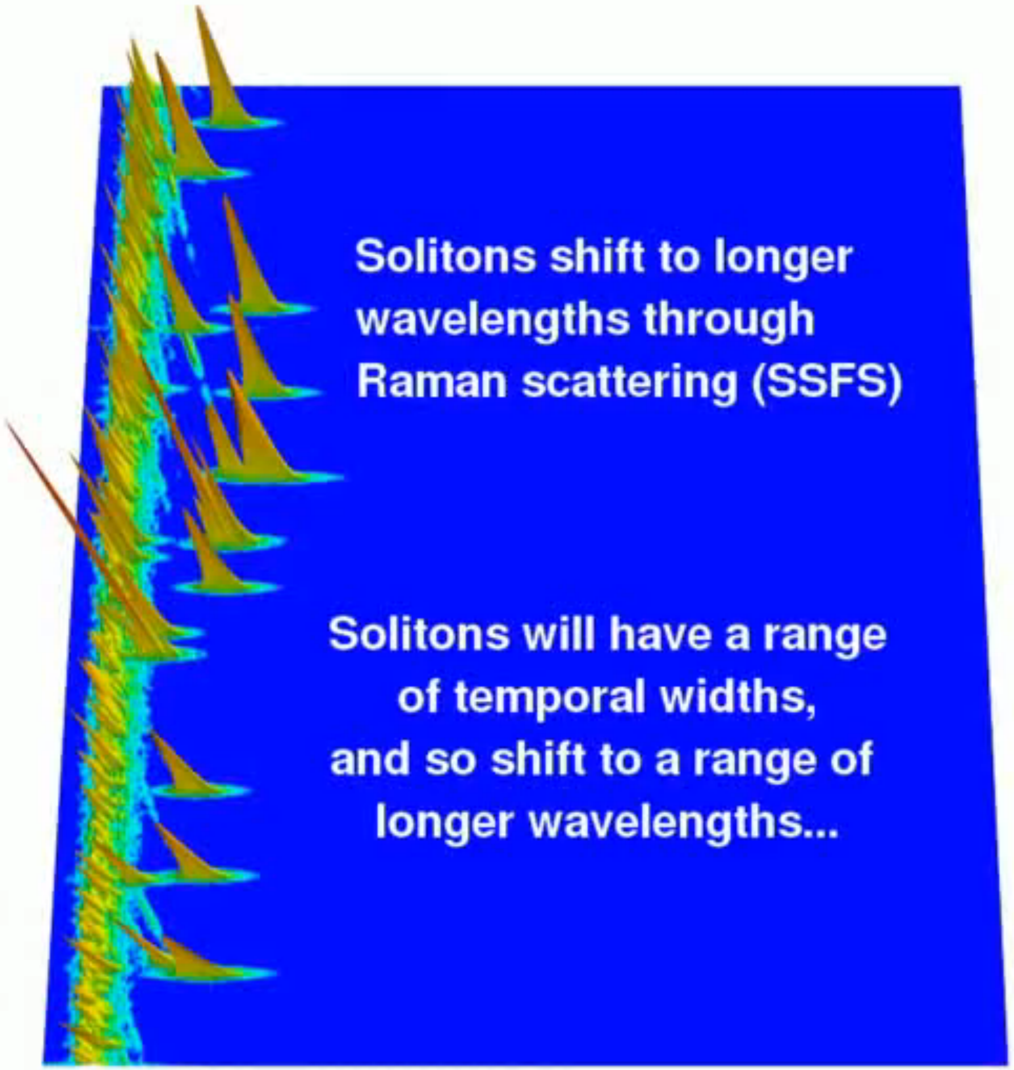
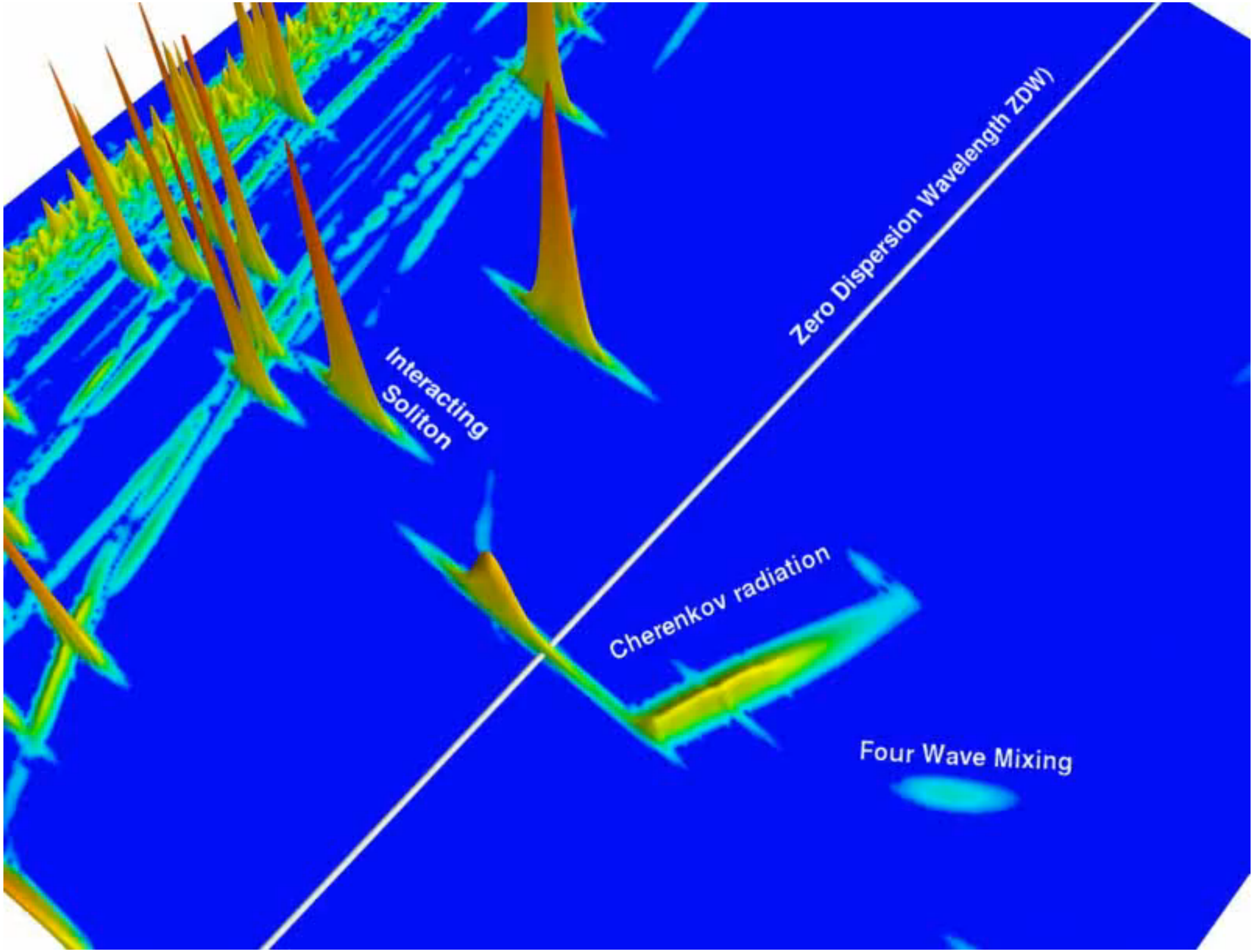
Supercontinuum evolution



Supercontinuum evolution

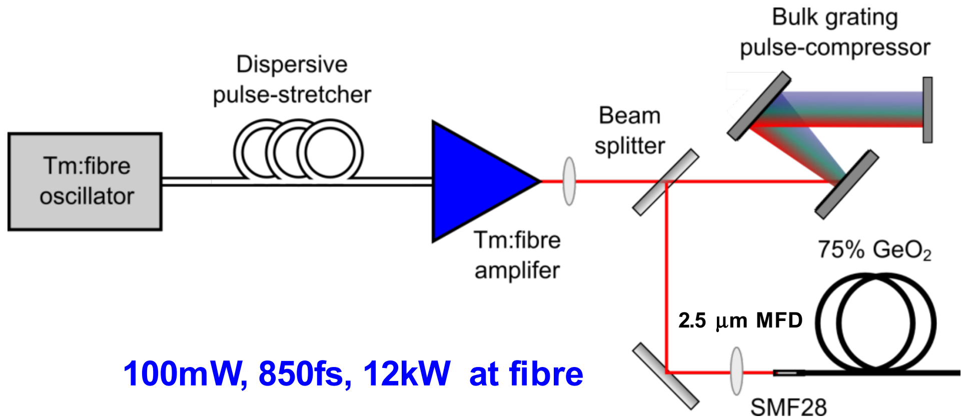


Supercontinuum evolution

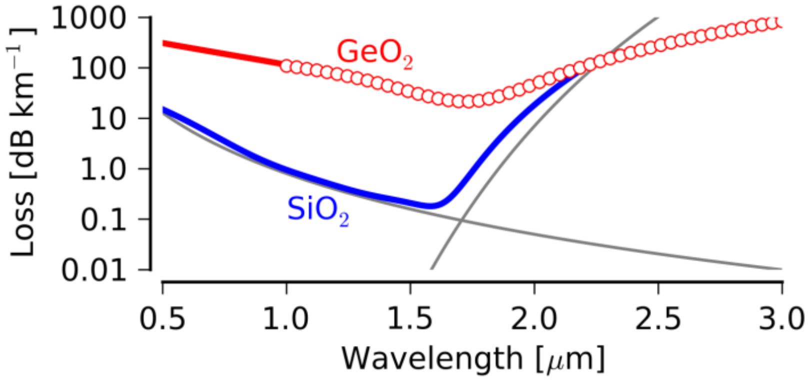


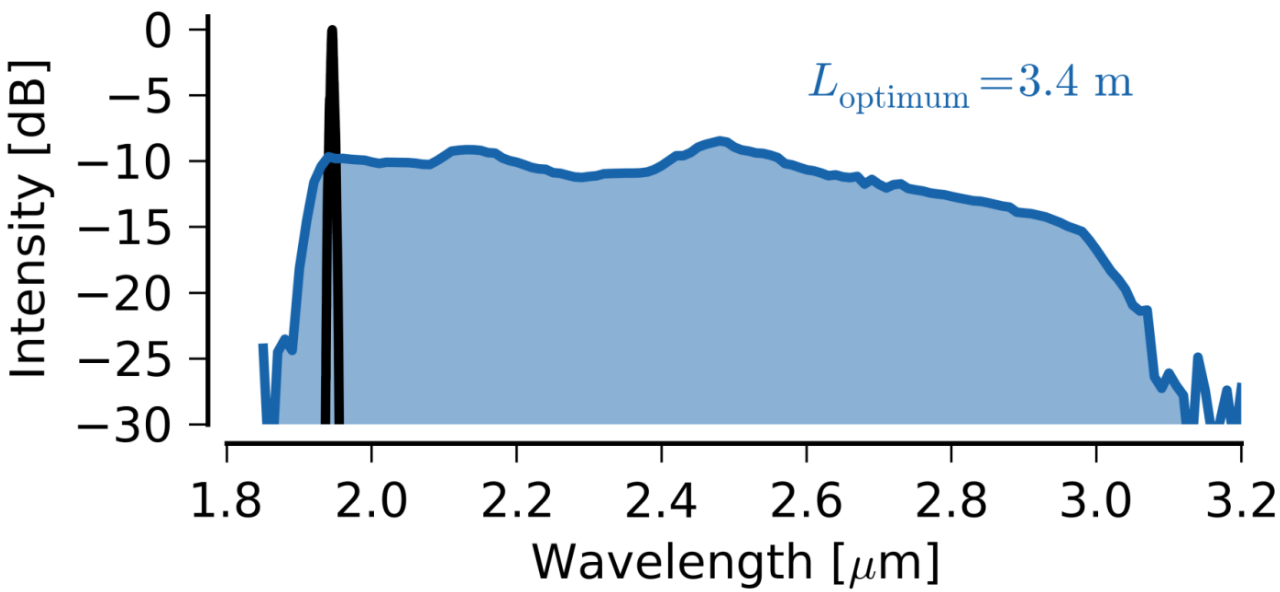
Long wavelength extension

Low power Tm-doped fibre CPA



100mW, 850fs, 12kW at fibre





With increased power scaling – hence shorter (~cm) fibre length

- **spectral extension to 4.5 μm should be possible**

Supercontinuum Generation - Summary

Femtosecond

Normal

SPM dominates continuum may evolve to anomalous

Anomalous

Soliton dynamic dominate $L_D=\tau^2/\beta_2$ $L_{NL}=(\gamma P)^{-1}$

High order solitons $N= [L_D / L_{NL}]^{1/2}$ - fission

Initial phase, rapid compression $L=L_D /N$

Highest stability – instabilities follow

Long Pulse and CW

Normal

Raman dominates plus SPM

Anomalous

As τ increases fission becomes less important

MI and FWM dominate initial propagation

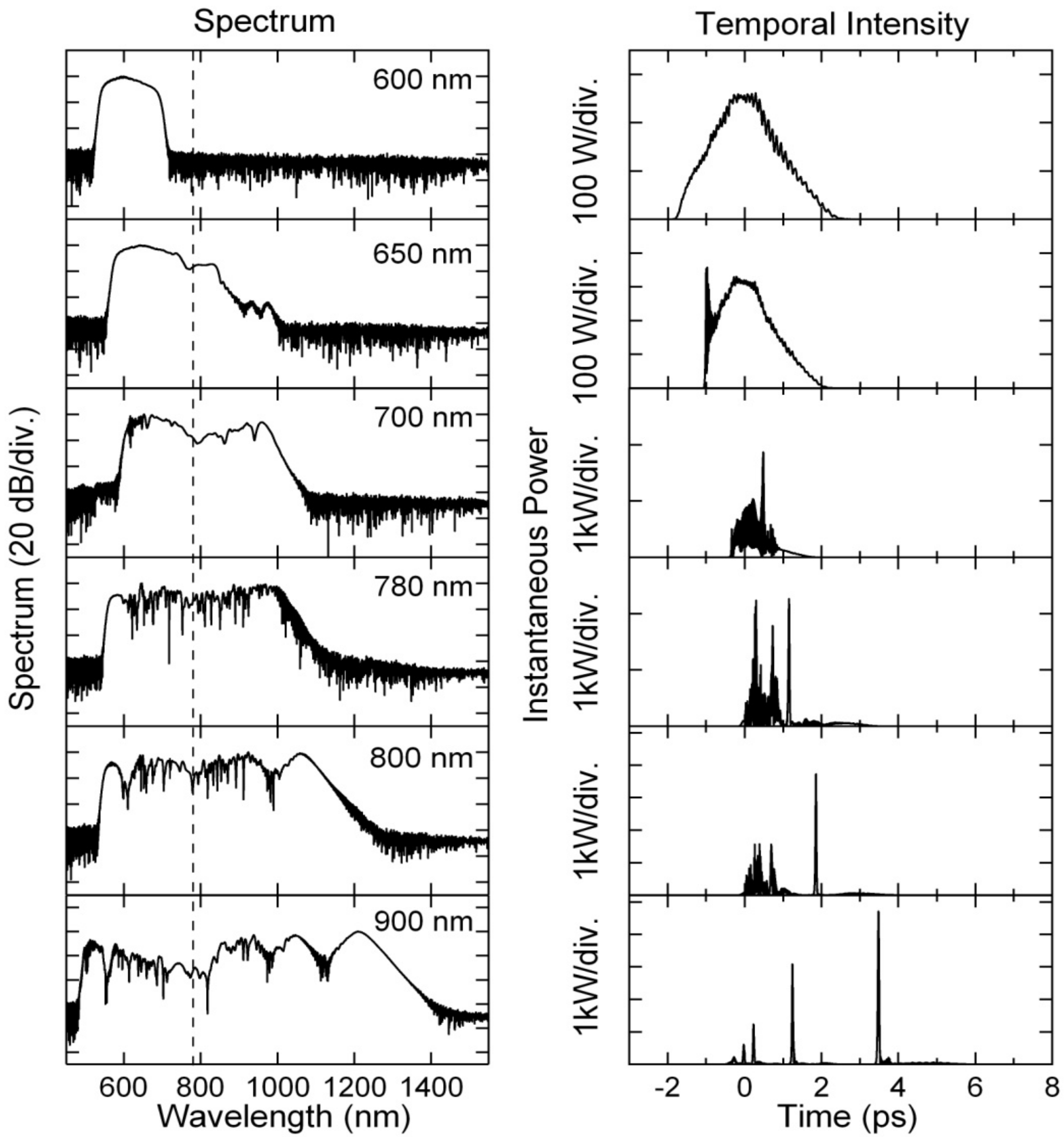
Soliton and dispersive wave effects follow

Generally less stable, more noise

Pump wavelength dependence

SPM

Soliton

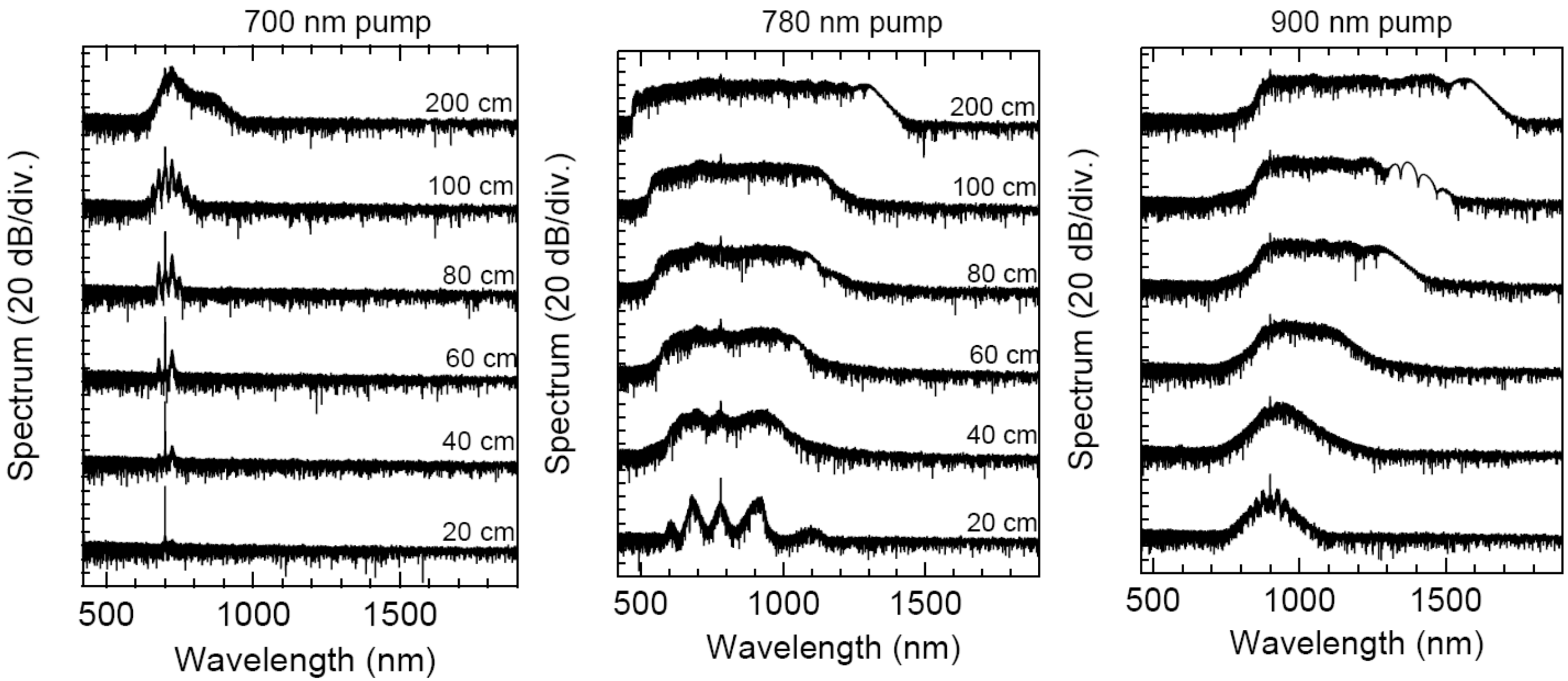


Long pulse pumped supercontinua

50 psec, 500W, 2m PCF, λ_0=780nm **Dudley**

Initial spectral broadening dominated by Raman and or parametric processes

Soliton and dispersive wave dynamics can develop with propagation



Normal
Raman

Zero
FWM-MI / solitons

Anomalous
MI/Raman/solitons