Ultraviolet Light Generated
in gas-filled photonic crystal fibre

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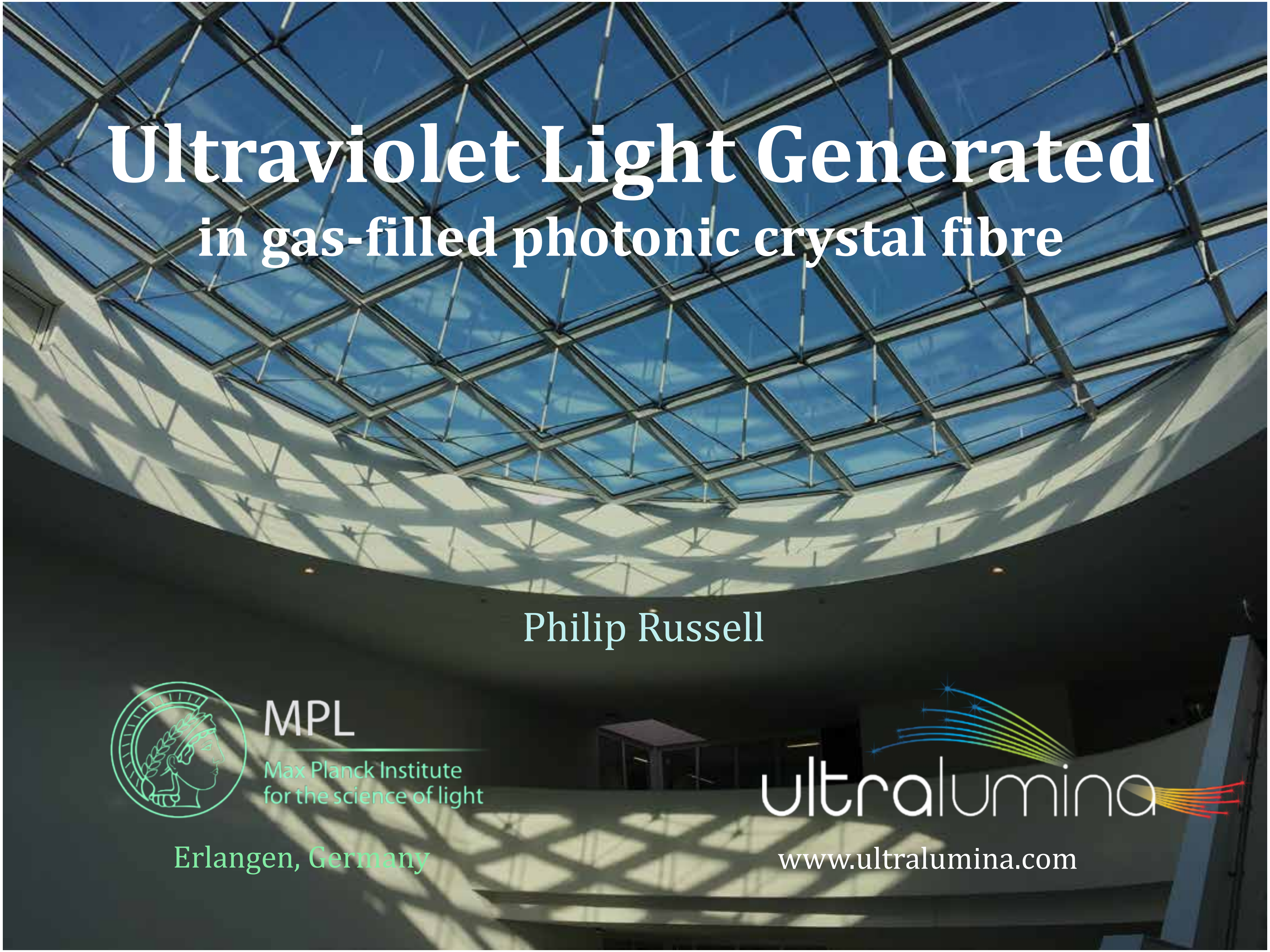

Topics

- Hollow-core anti-resonant-reflecting photonic crystal fibre (ARR-PCF)
- Extreme pulse compression & generation of deep UV light in noble-gas-filled ARR-PCFs
- Soliton self-frequency blue-shift & high harmonic generation

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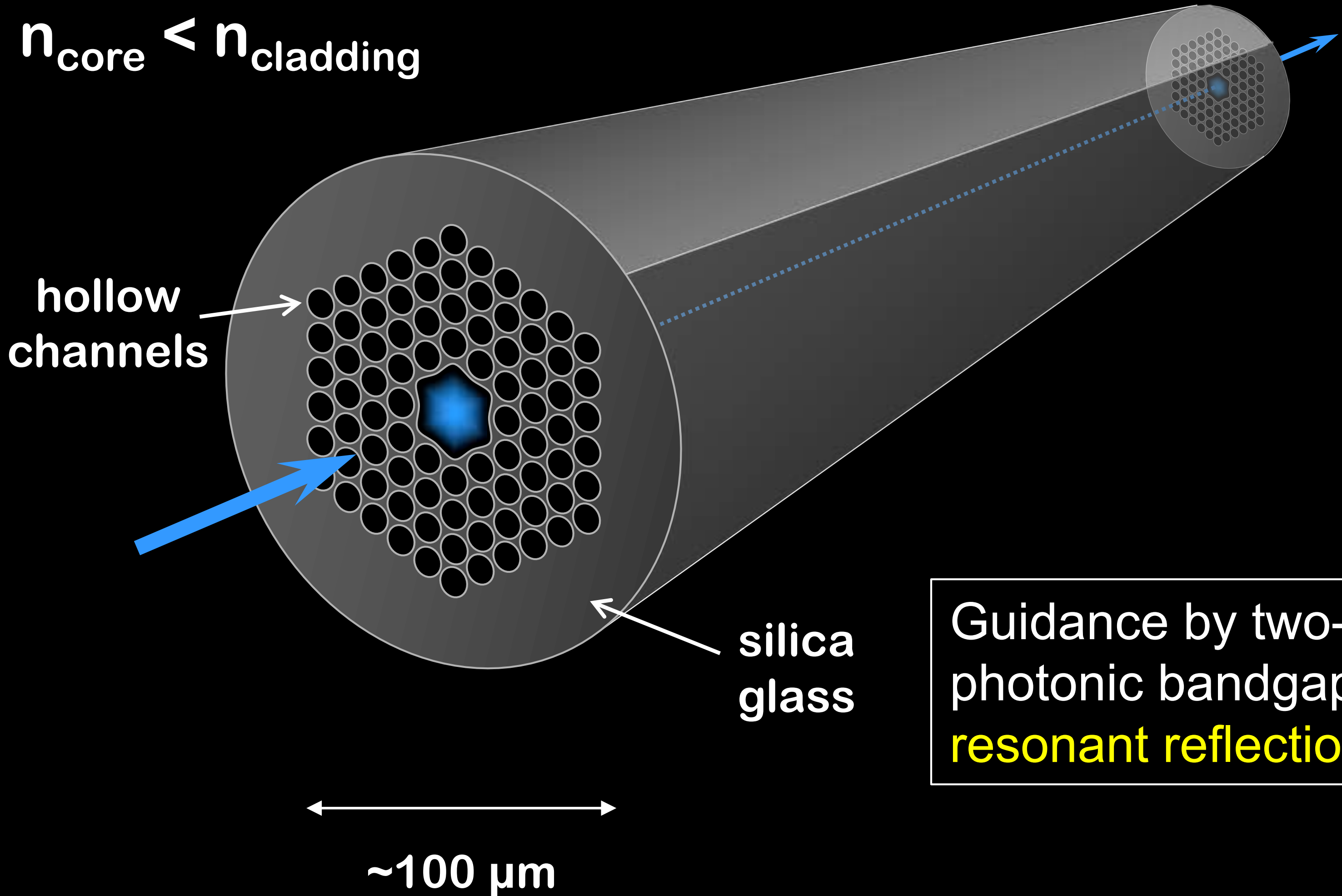
Hollow core PCF (1999)

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

$n_{core} < n_{cladding}$



Guidance by two-dimensional photonic bandgap or anti-resonant reflection (e.g., kagomé)

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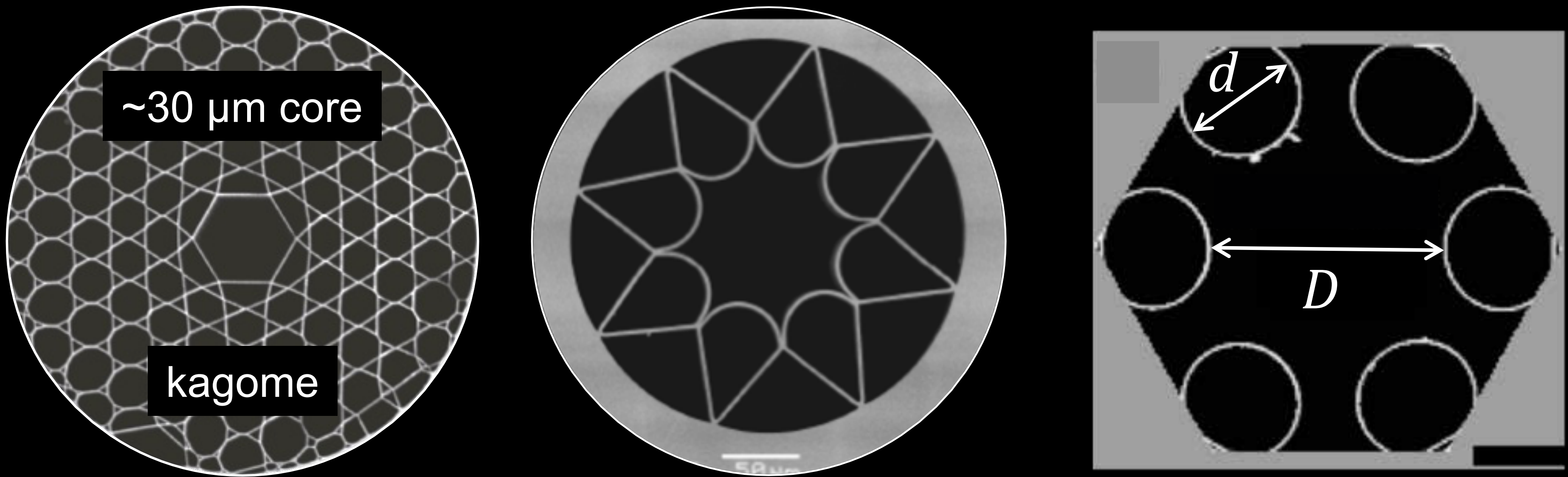
Anti-resonant reflecting (ARR) hollow-core PCFs

- 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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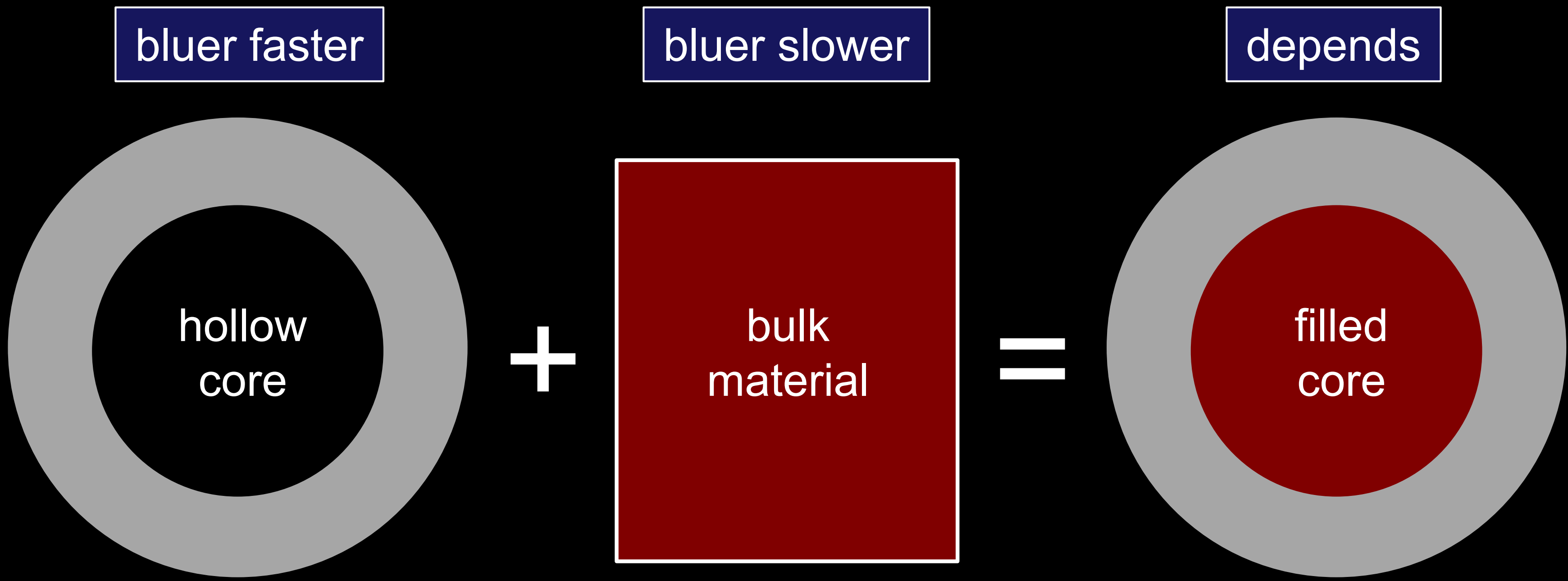
Chromatic dispersion in waveguides



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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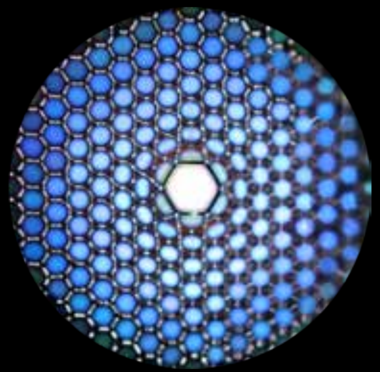
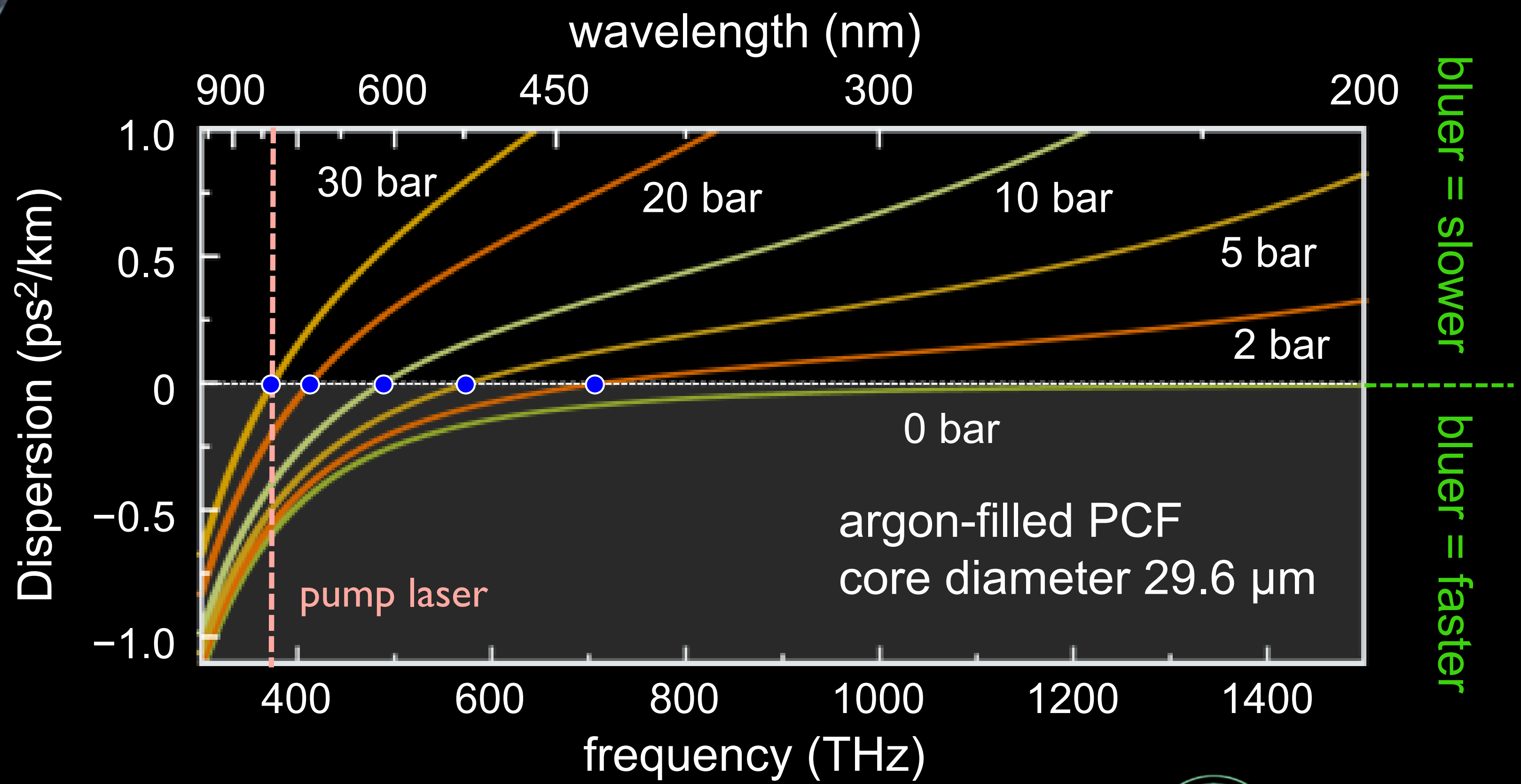
Pressure-tunable dispersion: ARR-PCF

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

kagome



- broadband guidance (for few-cycle pulses)
- low light-glass overlap (high damage threshold)
- low & anomalous dispersion (for solitons)



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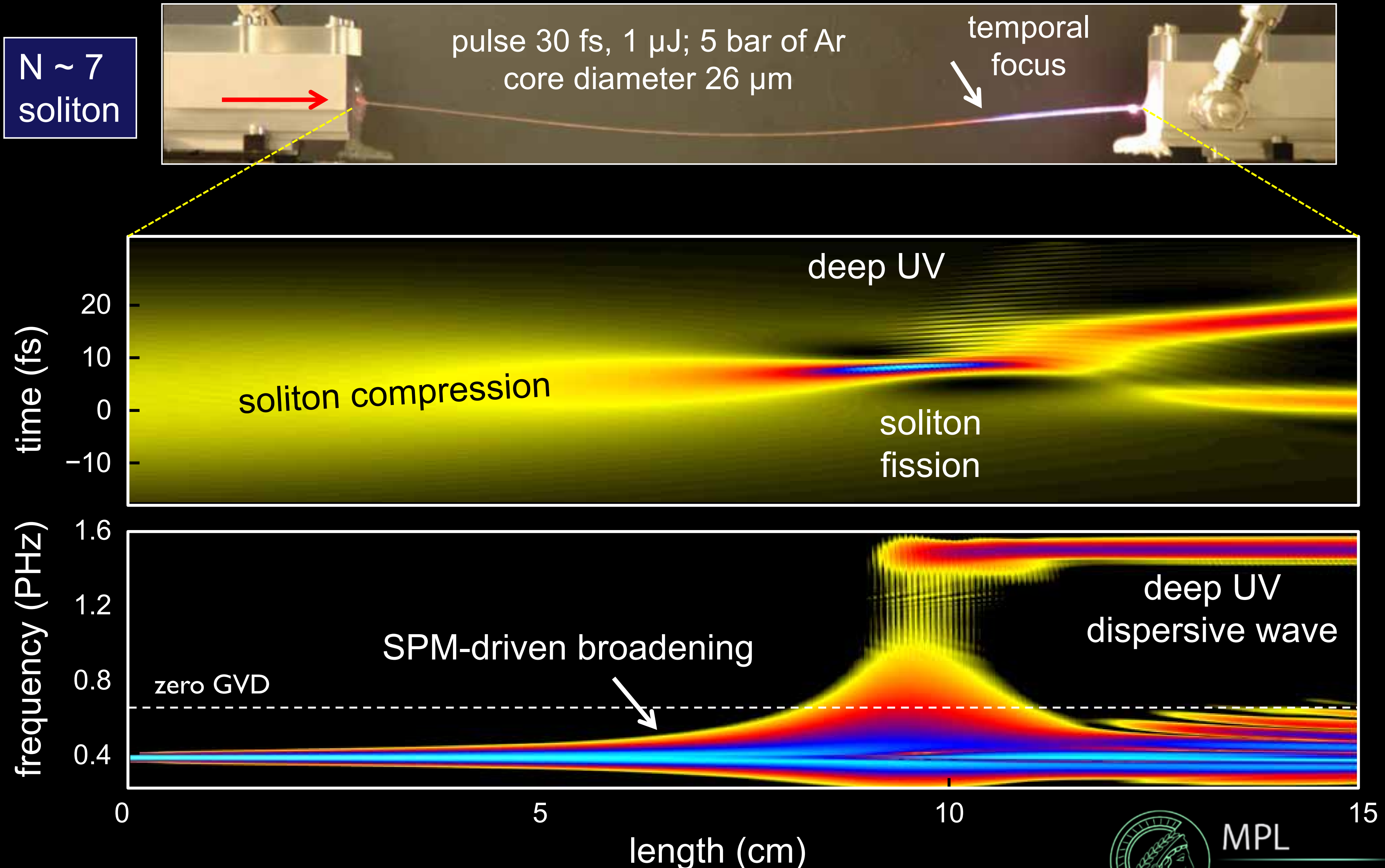
Soliton break-up & UV dispersive wave

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



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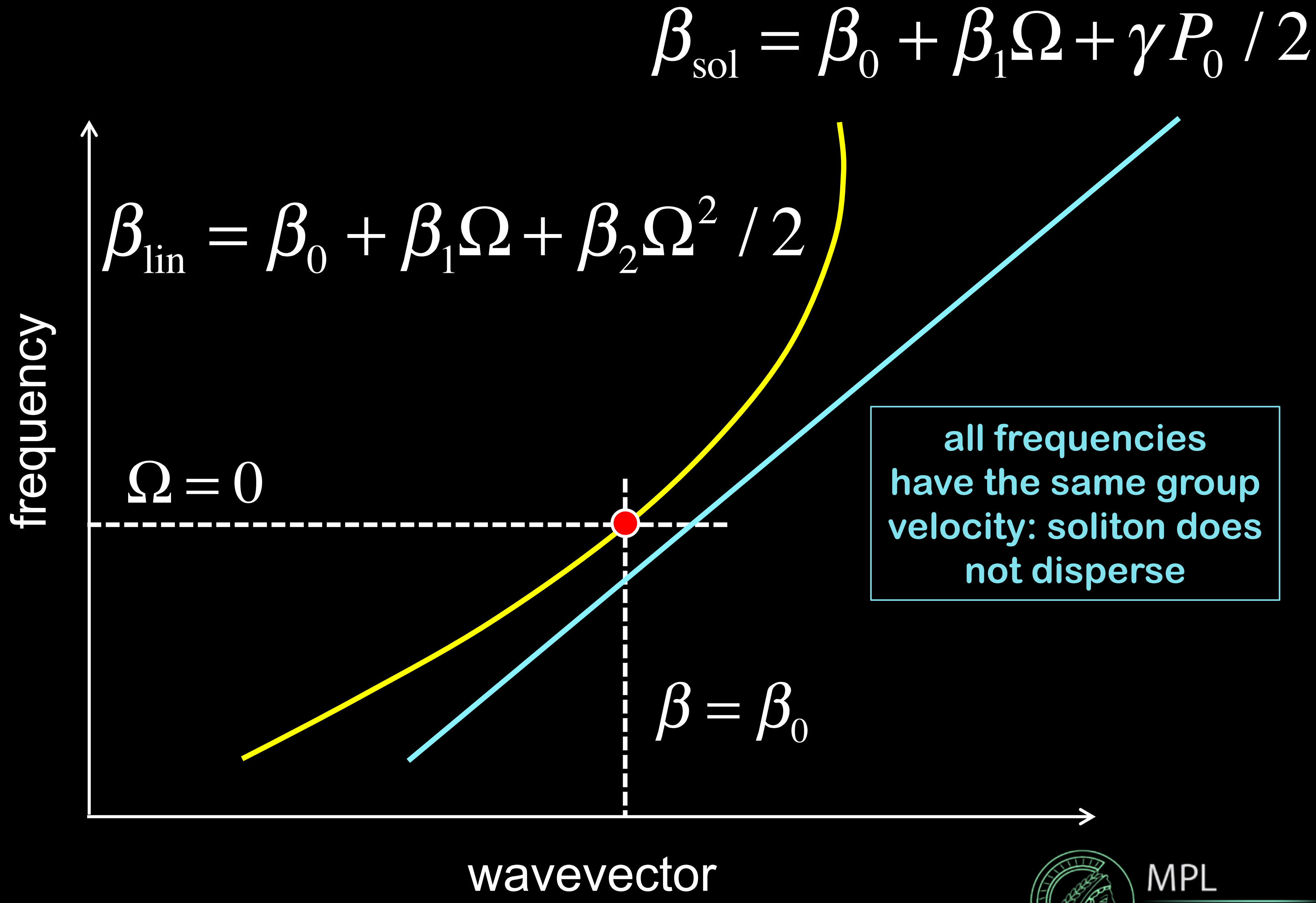
How does UV dispersive wave form?

Perfect Schrödinger solitons



all frequencies have the same group velocity: soliton does not disperse

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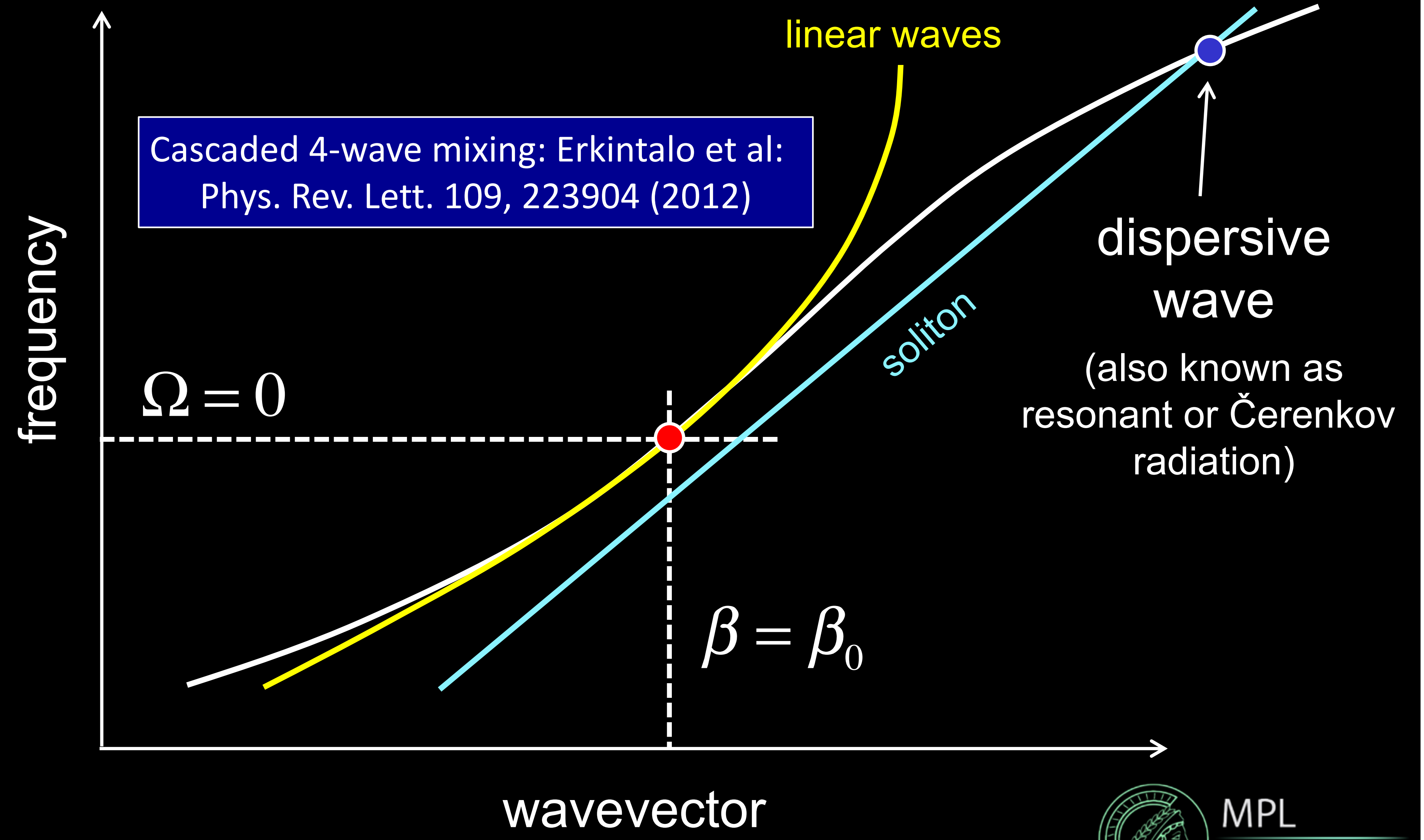
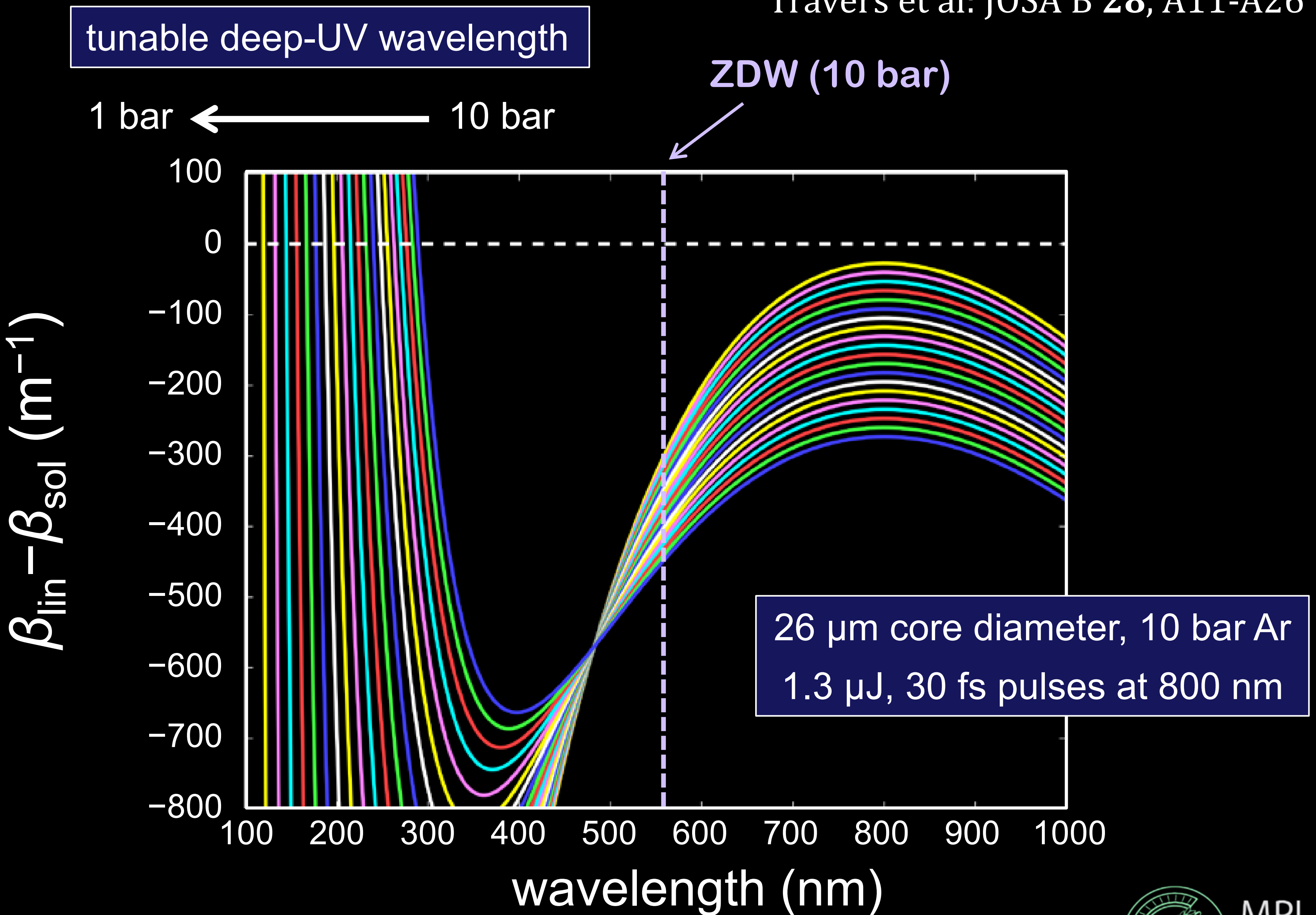
Dispersive waves radiate from solitons

$$\beta_{\text{lin}} = \beta_0 + \beta_1\Omega + \beta_2\Omega^2/2 + \beta_3\Omega^3/6$$



Pressure-tunable UV from 120-300 nm

Travers et al: JOSA B **28**, A11-A26 (2011)



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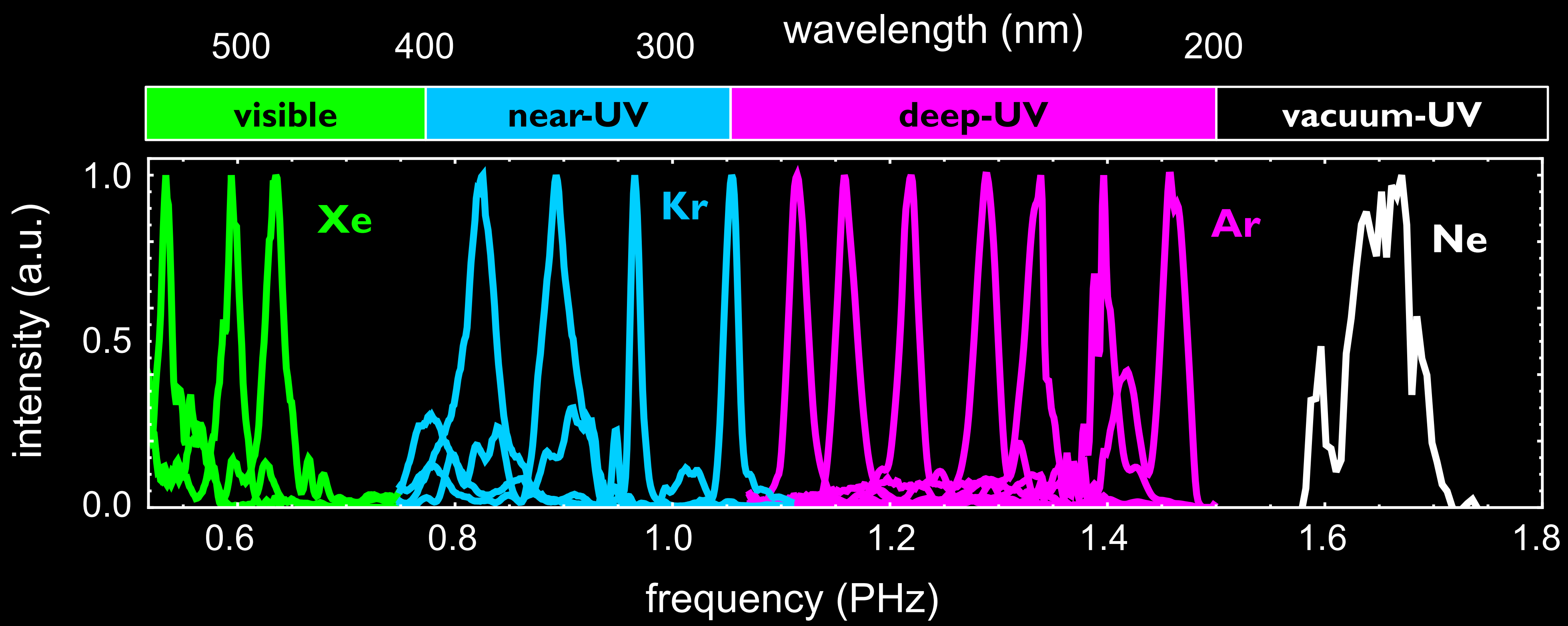
Tunability by varying pulse, fibre & gas parameters

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



4% to 10% conversion from near-IR to vacuum-UV

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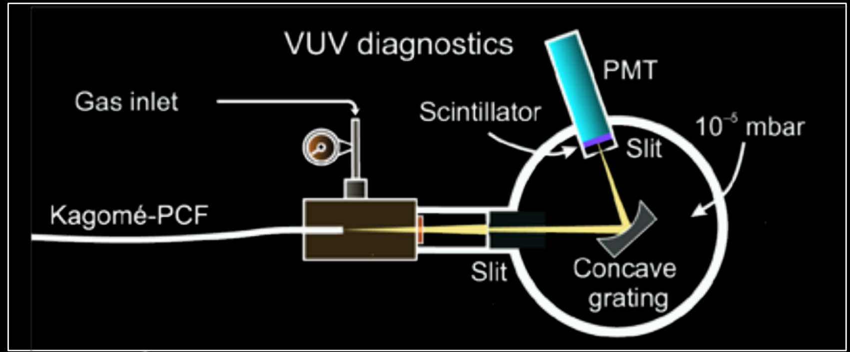
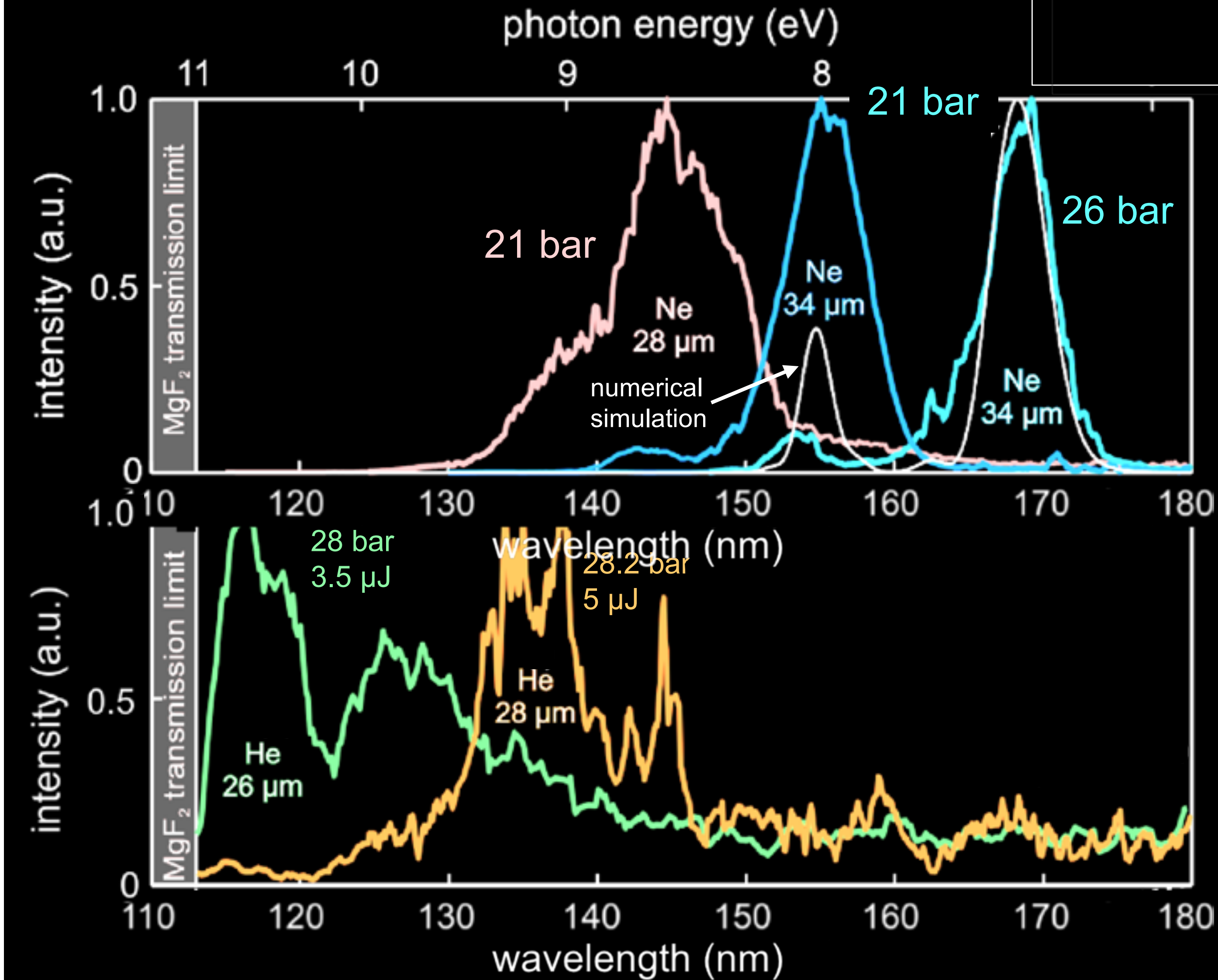
Tunable VUV dispersive wave emission

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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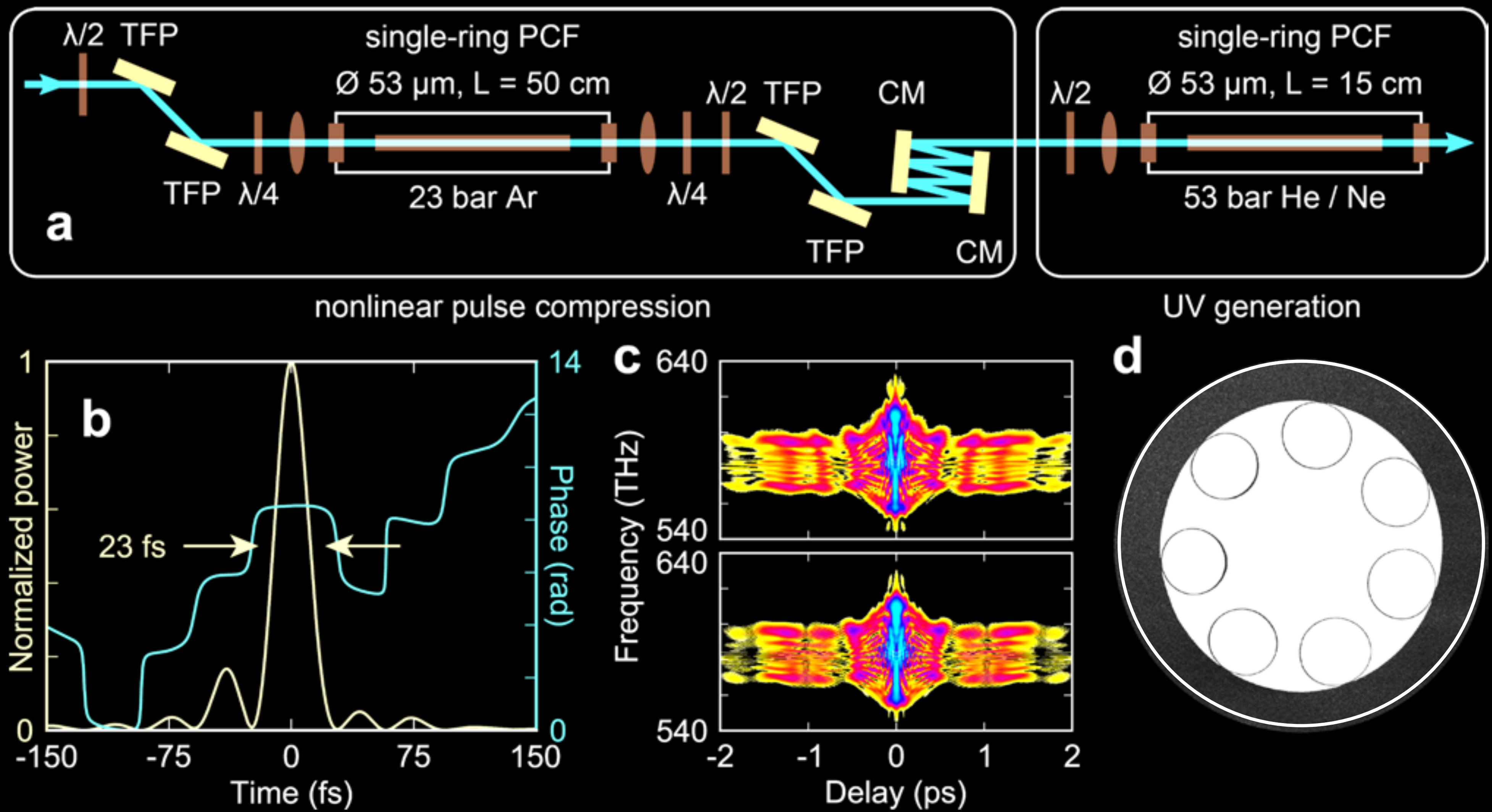
High repetition rate in single-ring PCF

Köttig et al: Optica **4**, 1272 (2017)

Pump: 300 fs fibre laser at 1 μm wavelength

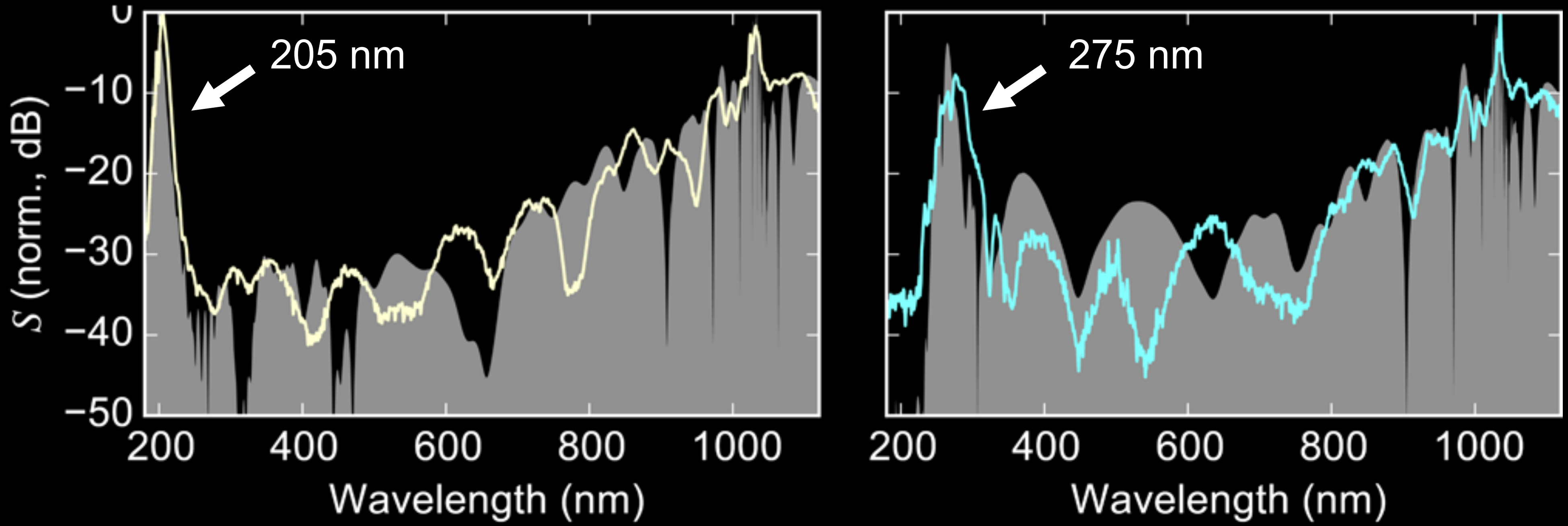


High repetition rate UV dispersive waves

Köttig et al: Optica **4**, 1272 (2017)

- Helium, 53 bar, 100 kHz
- Pump power 1.7 W (17 µJ)
- Average UV power 74 mW
- 6.2% conversion to UV

- Neon, 53 bar, 1.92 MHz
- Pump power 17.2 W (9 µJ)
- Average UV power 1 Watt
- 6% conversion to UV



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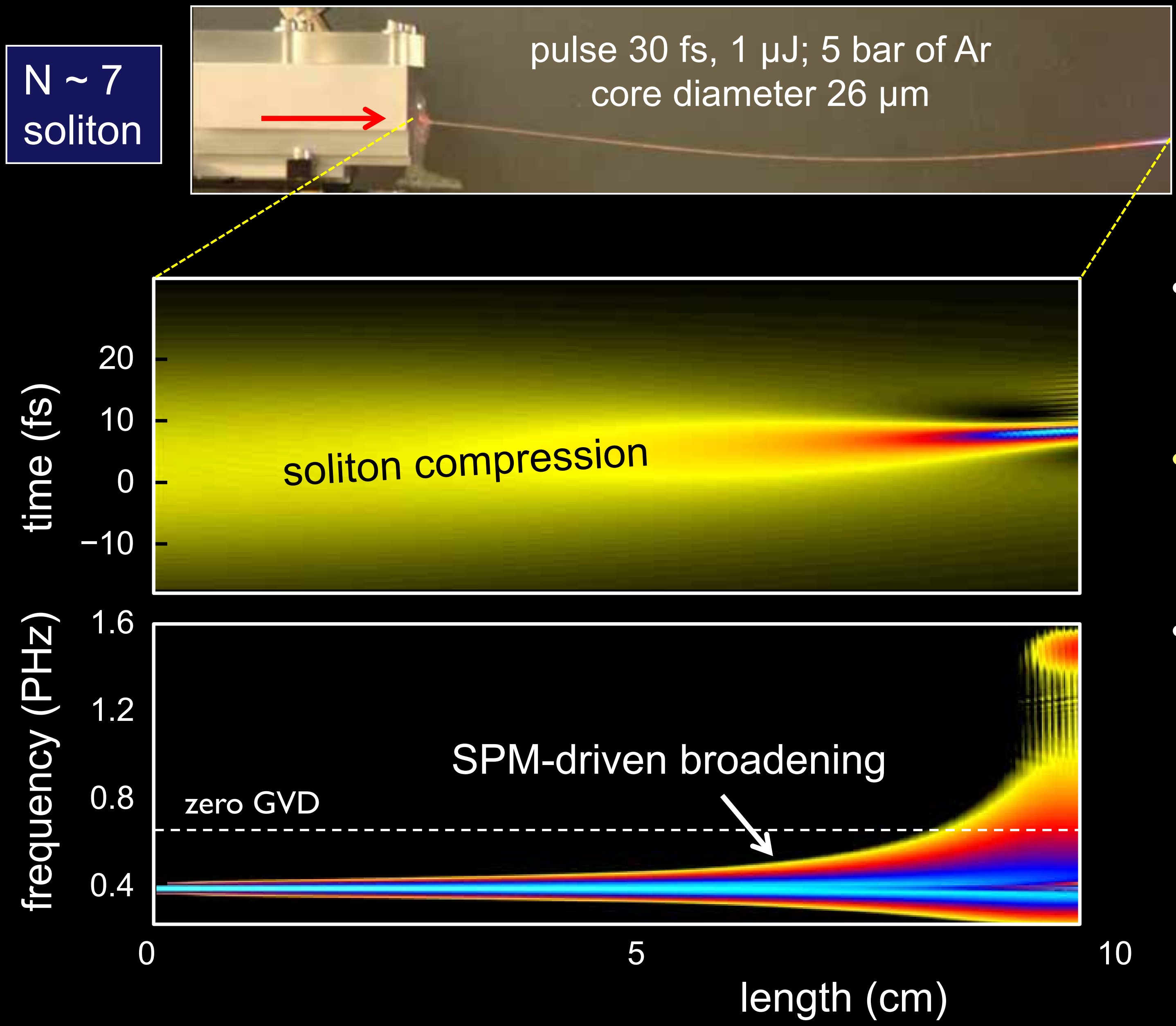
Extreme soliton self-compression

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



- **convenient for producing few-cycle pulses**
- **absence of damage - very high intensities**
- **can study effects of ionization & plasma formation**

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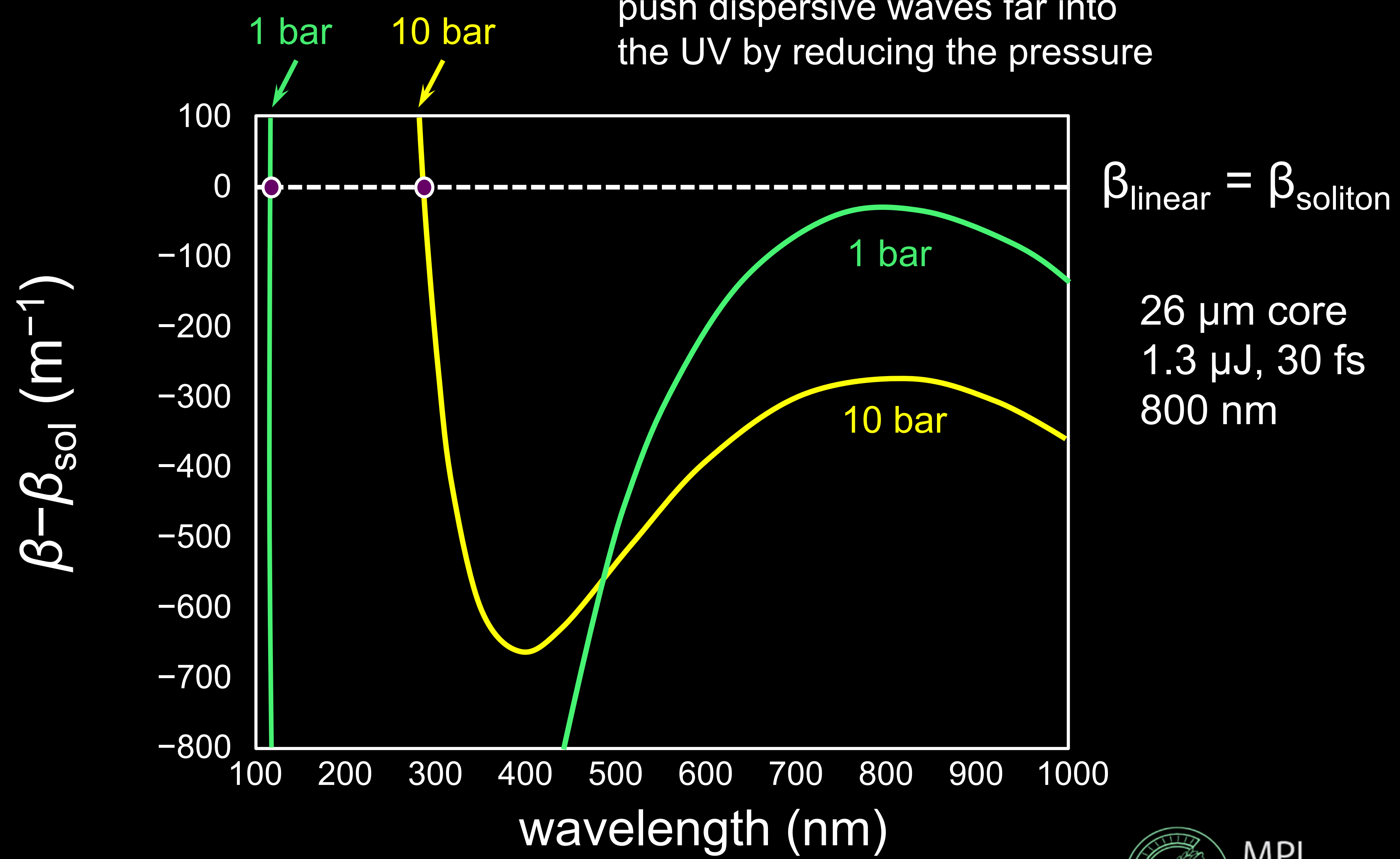
Avoid dispersive wave generation

Hoelzer et al: PRL 107, 203901 (2011)

push dispersive waves far into the UV by reducing the pressure



26 µm core
1.3 µJ, 30 fs
800 nm

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Ionization at temporal focus?

Hoelzer et al: PRL 107, 203901 (2011)

Free electron densities of

$\sim 10^{17}\ cm^{-3}$

are achieved at peak intensities of

$\sim 10^{14}\ W.cm^{-2}$

over length scales of several cm

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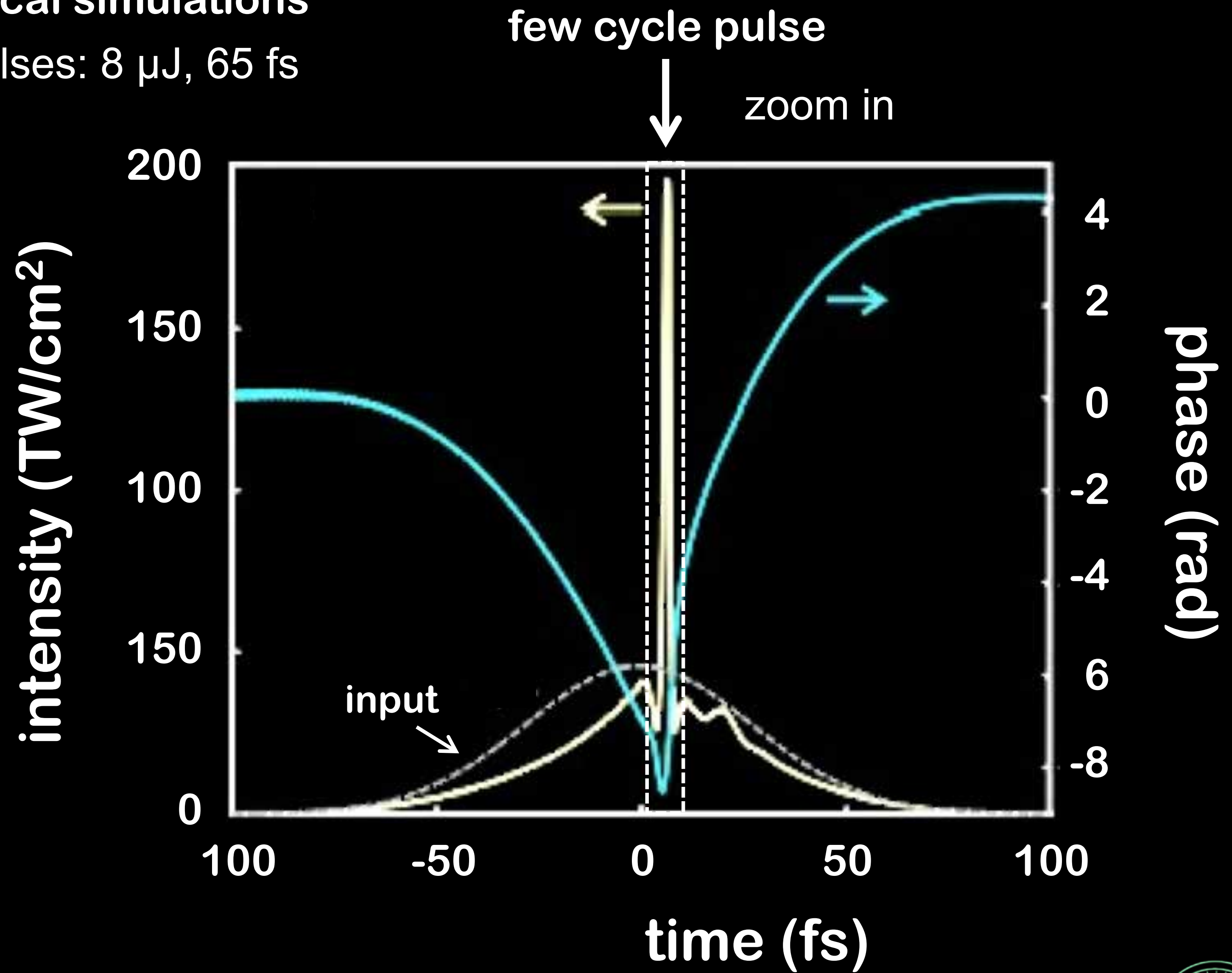
Pulse compression & refractive index

Hoelzer et al: PRL 107, 203901 (2011)

numerical simulations

pulses: 8 μJ, 65 fs



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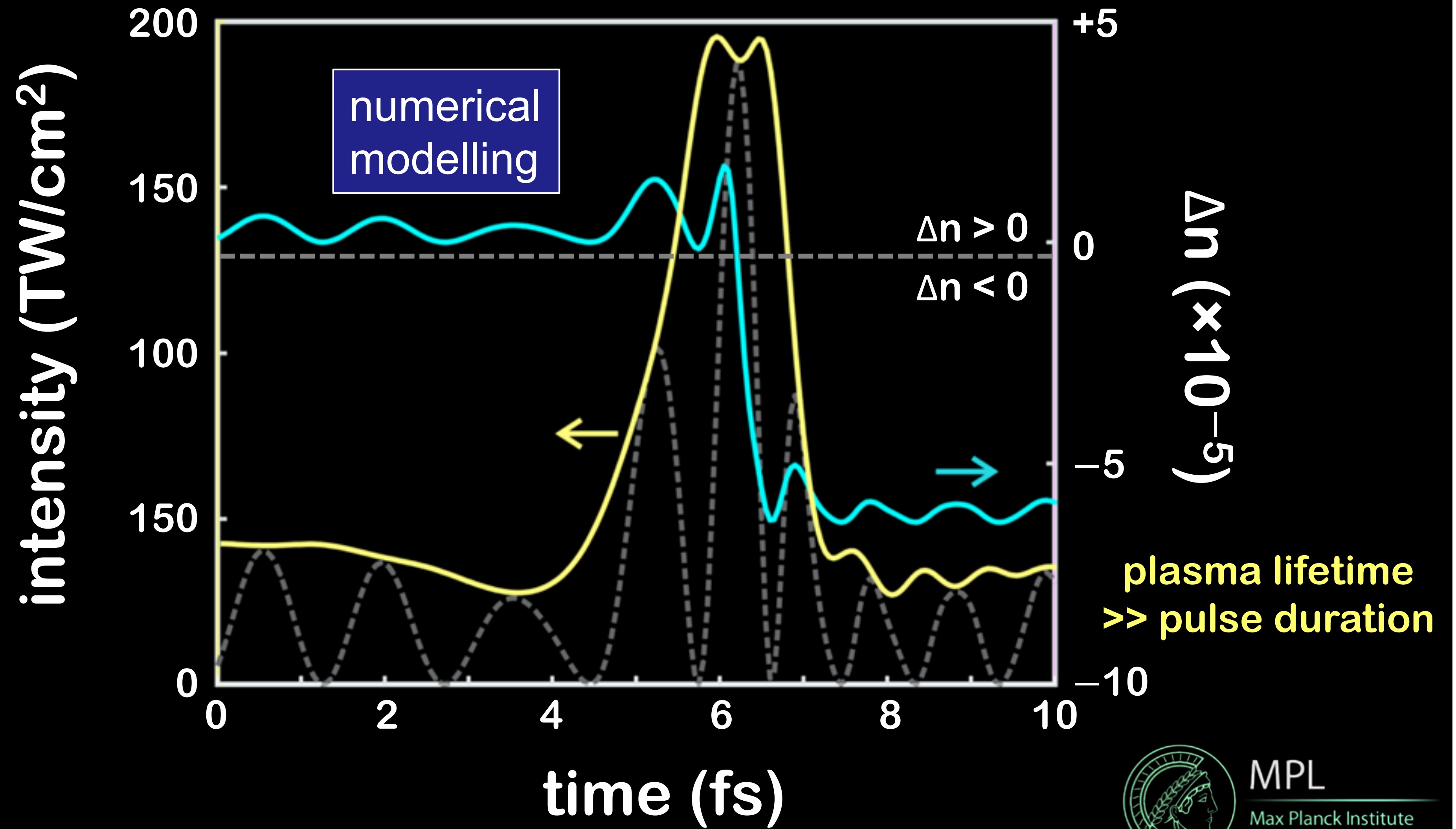
Index change at maximum compression

Hoelzer et al: PRL 107, 203901 (2011)

$$\Delta n = n_2 I - \frac{\omega_p^2}{2n_0\omega_o^2}, \quad \omega_p^2 = \frac{N_e e^2}{m_e \varepsilon_o}$$



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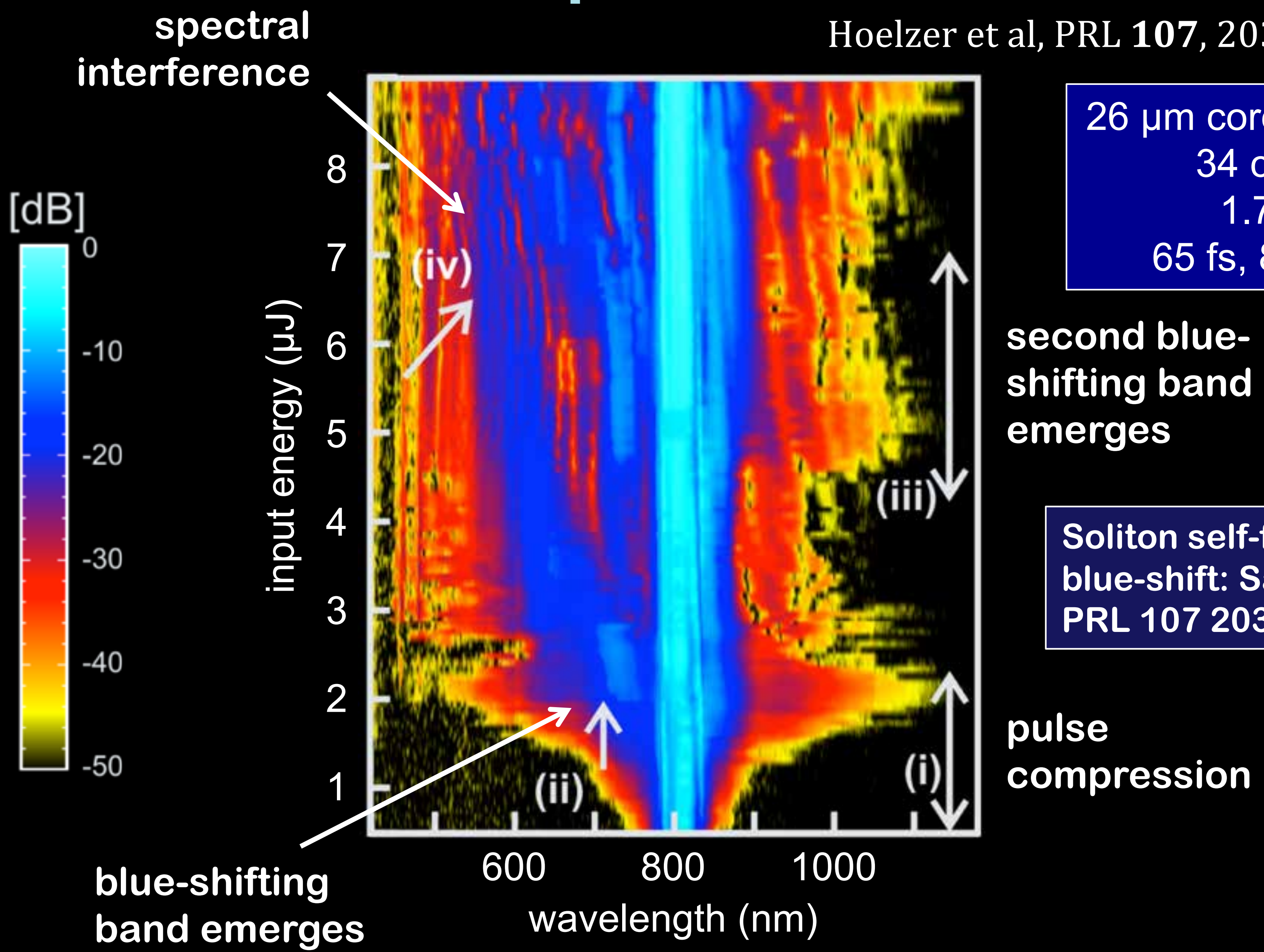
Experimental

Hoelzer et al, PRL **107**, 203901 (2011)



26 μm core diam.
34 cm fibre
1.7 bar Ar
65 fs, 800 nm

Soliton self-frequency blue-shift: Saleh et al, PRL 107 203902 (2011)

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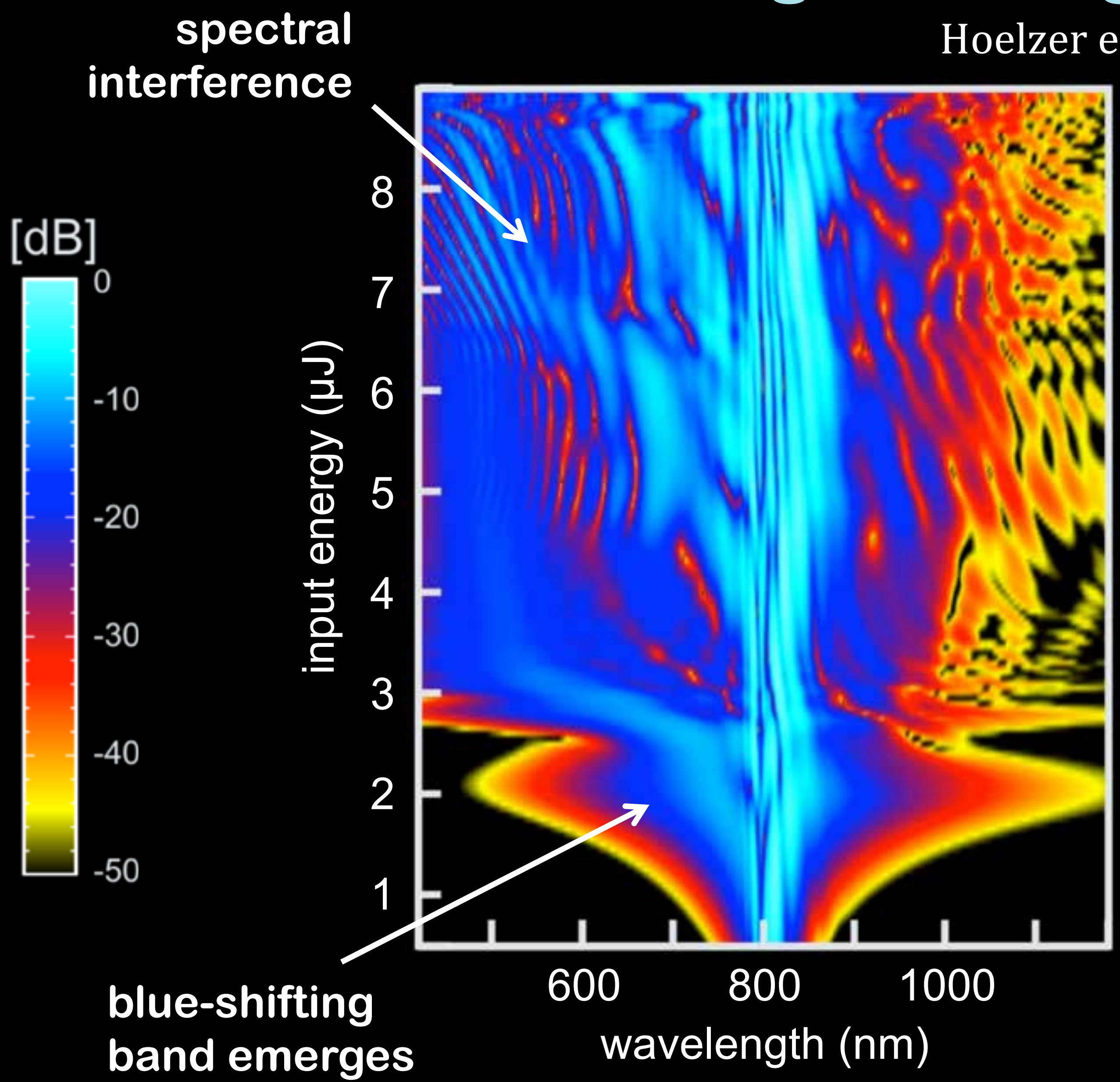
Numerical modelling including ionization

Hoelzer et al, PRL **107**, 203901 (2011)



26 μm core diam.
34 cm fibre
1.7 bar Ar
65 fs, 800 nm

- **modelling using uni-directional full-field wave equation**
- **quasi-static tunnel-ionization model**

Soliton self-frequency blue-shift: Saleh et al, PRL 107 203902 (2011)

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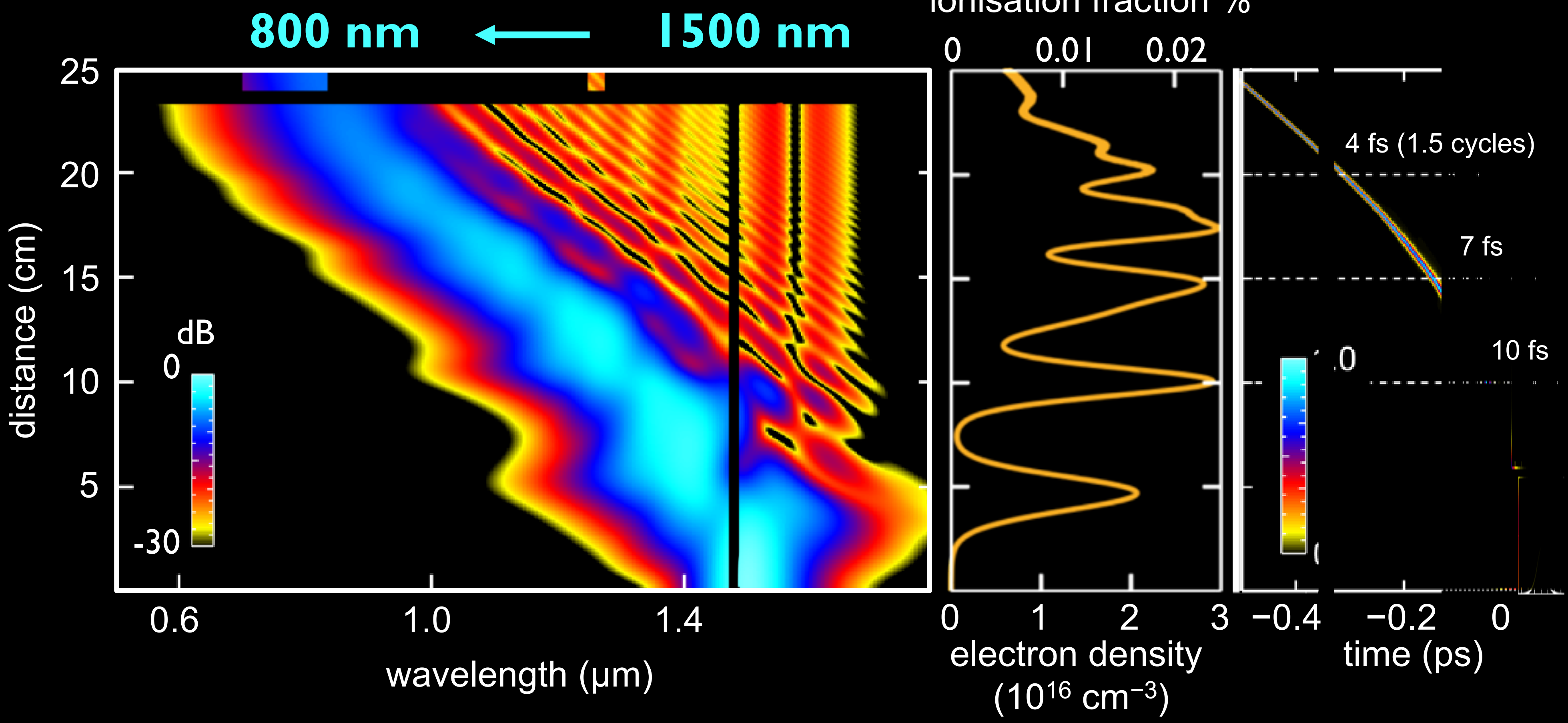
Plasma blue-shifting of a fundamental soliton

Chang et al: Opt. Lett. **38**, 2984 (2013)

conversion efficiency ~30%



soliton number ***N* = 1.4**
30 fs/1.7 μJ pulse, 5 bar of Ar
core diameter 18 μm

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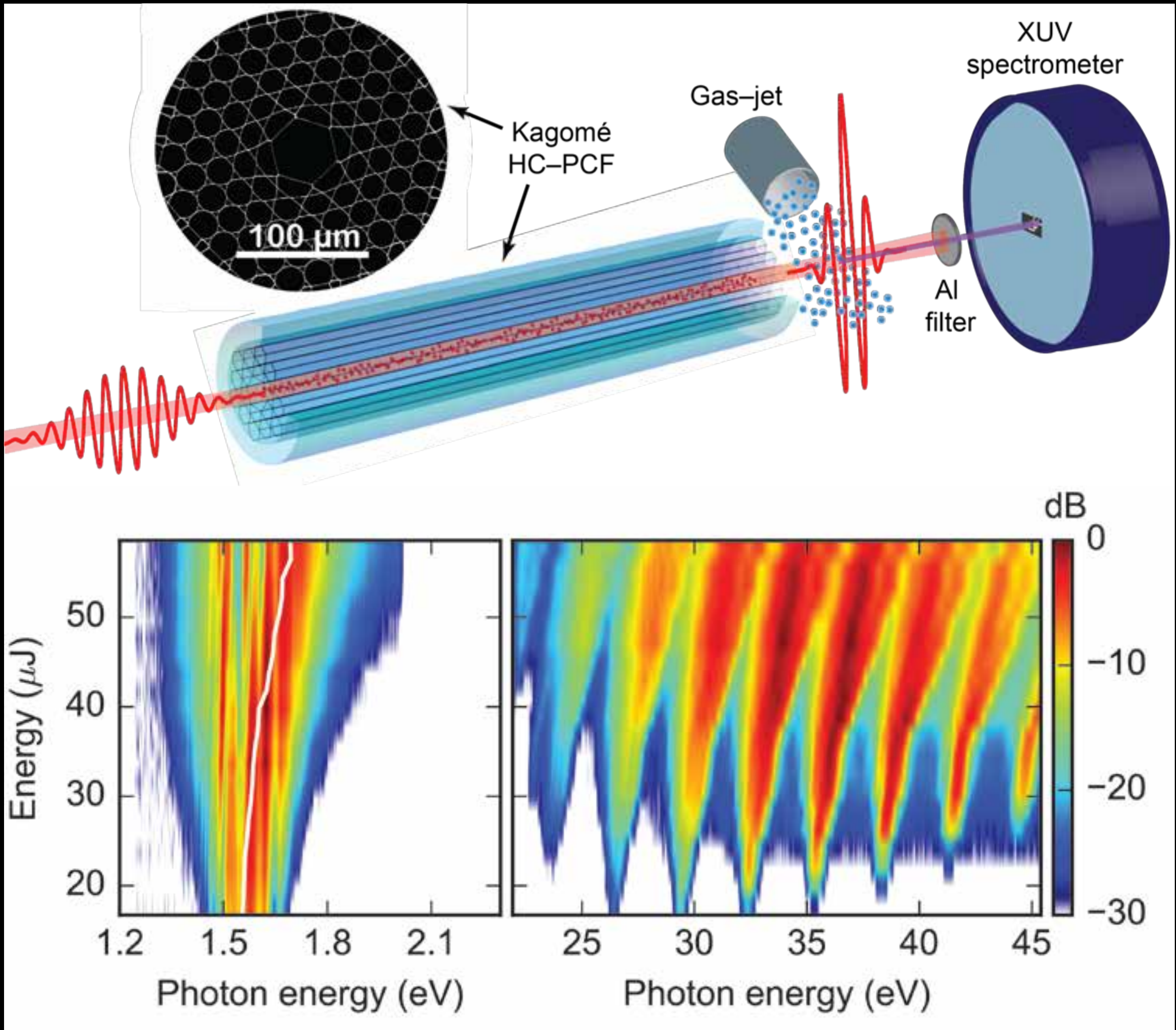
Continuously tunable high harmonics

Tani et al: Opt. Lett. **42**, 1768 (2017)



25 fs, 800 nm, 10-56 μJ, 1 kHz (Femtolasers)

26 cm HC-PCF, 46 μm core diameter

He pressure gradient 5 bar to 10^{-5} mbar

Soliton order 2 to 5

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