Development of mid-infrared lasers for soft X-ray high harmonic generation

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Annual Program Review

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JILA

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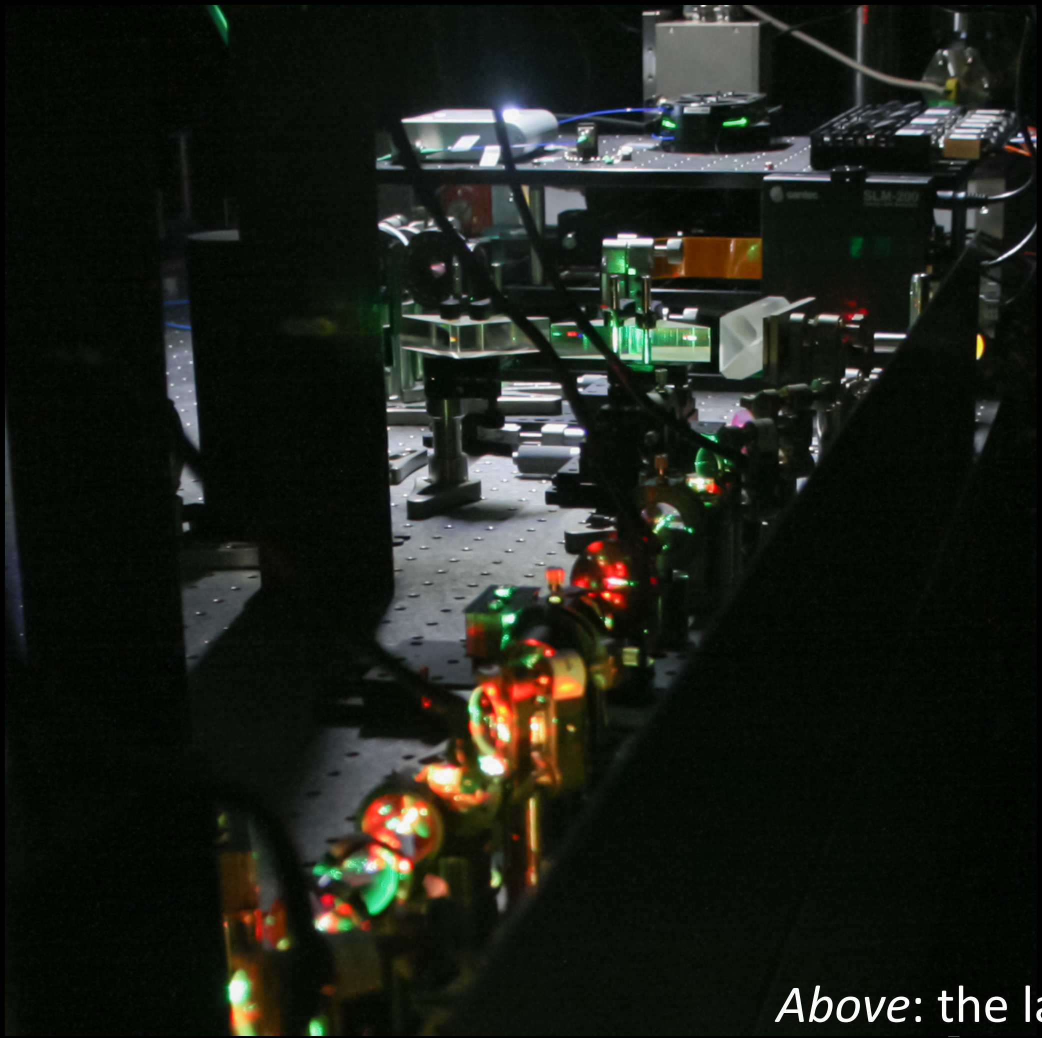


Above: the lab

Outline

Part one

What motivates the project:

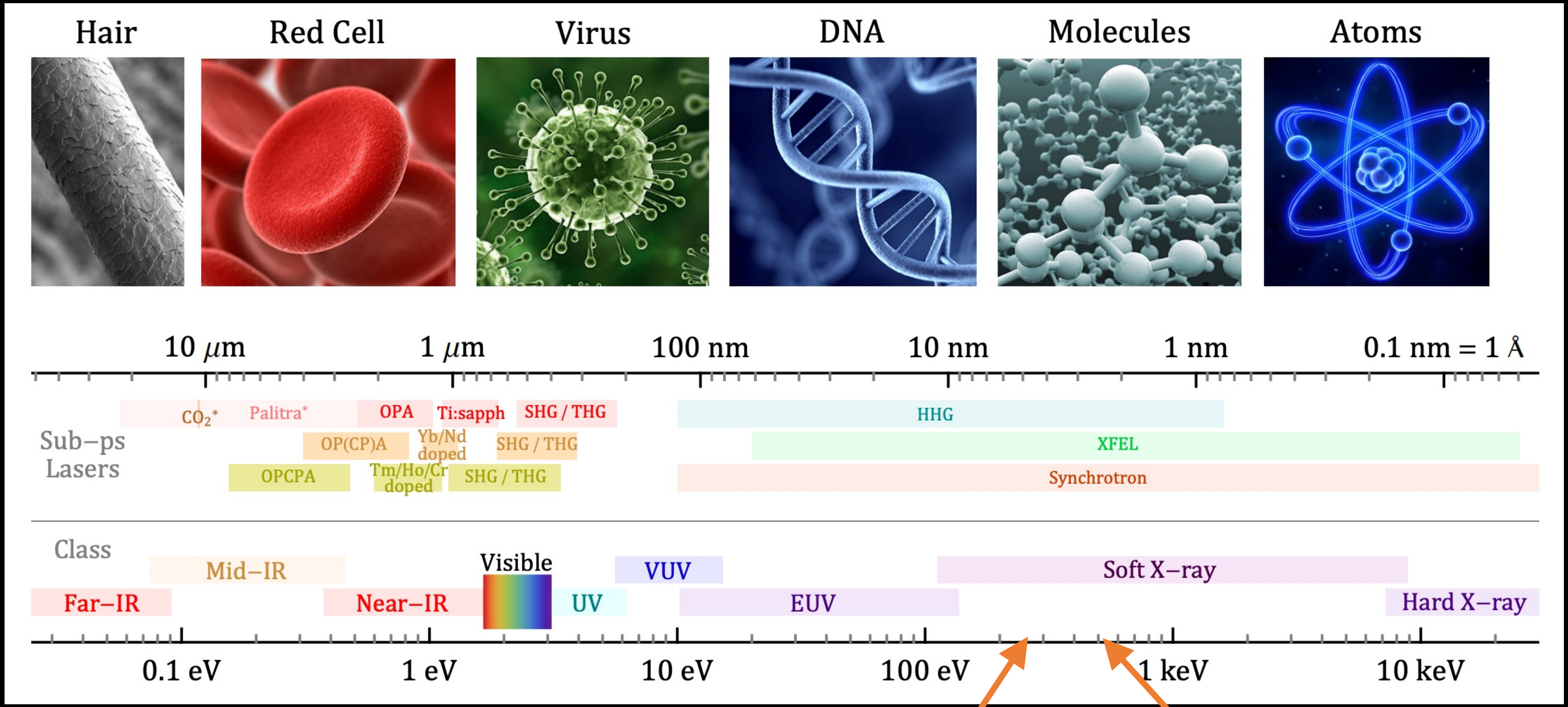
Why is a tabletop source of laser-like soft X-ray light needed, and how do you do it?

Part two

Building a 3.1 micron wavelength ultrafast laser

- Optical parametric chirped pulse amplification
- Stretching, shaping and compressing laser pulses
- Fiber front end laser

Soft X-ray light



Carbon k-edge @ 282 eV

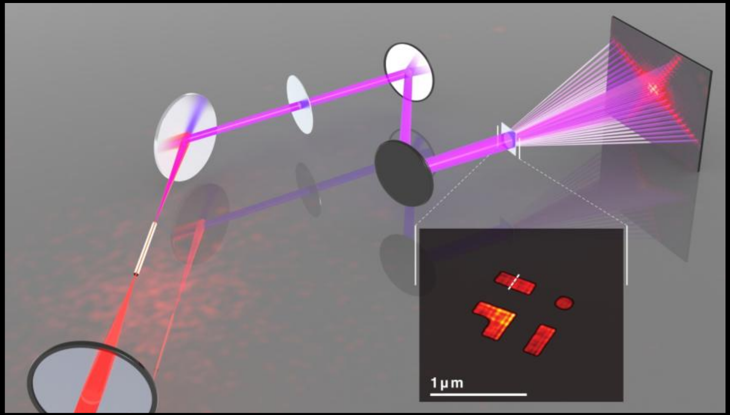
Oxygen k-edge @ 533 eV

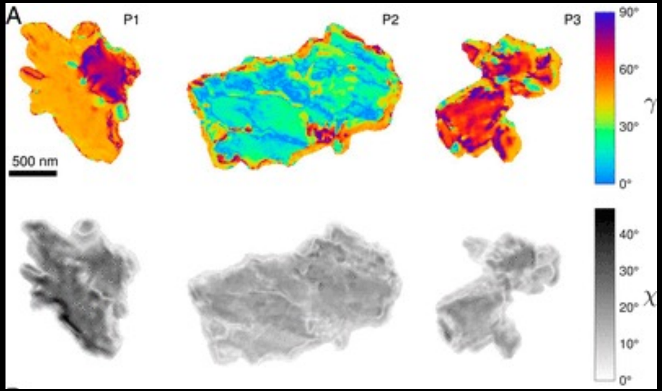
Water window

The usefulness of coherent soft X-ray light

- nanometer spatial resolution (1 keV → λ=1.2 nm)
- femtosecond temporal resolution (for HHG)

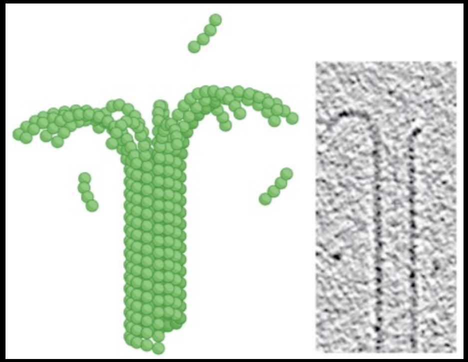
Example: coherent diffractive imaging



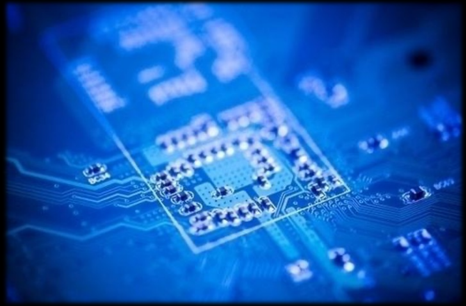


Mapping coral crystal orientation using O edge (536.5 eV) at COSMIC, ALS

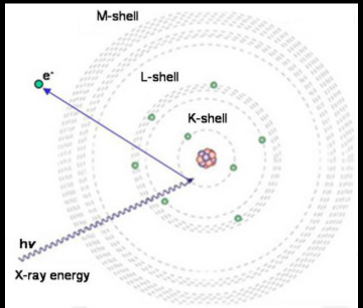
Biological imaging



Semiconductor chip metrology



Core-level spectroscopies



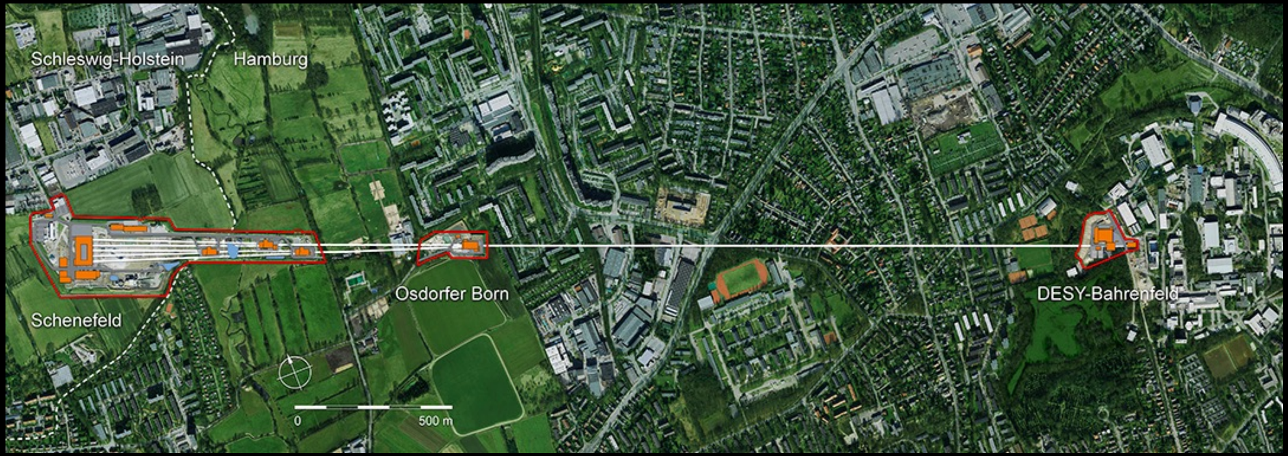
Optics Express 19, 22470 (2011); *PNAS **118** (3) e2019068118 (2021)*

"If you can't measure it, you cannot understand or optimize…"

Current sources of coherent soft X-rays

Synchrotrons & free electron lasers

als.lbl.gov



xfel.eu

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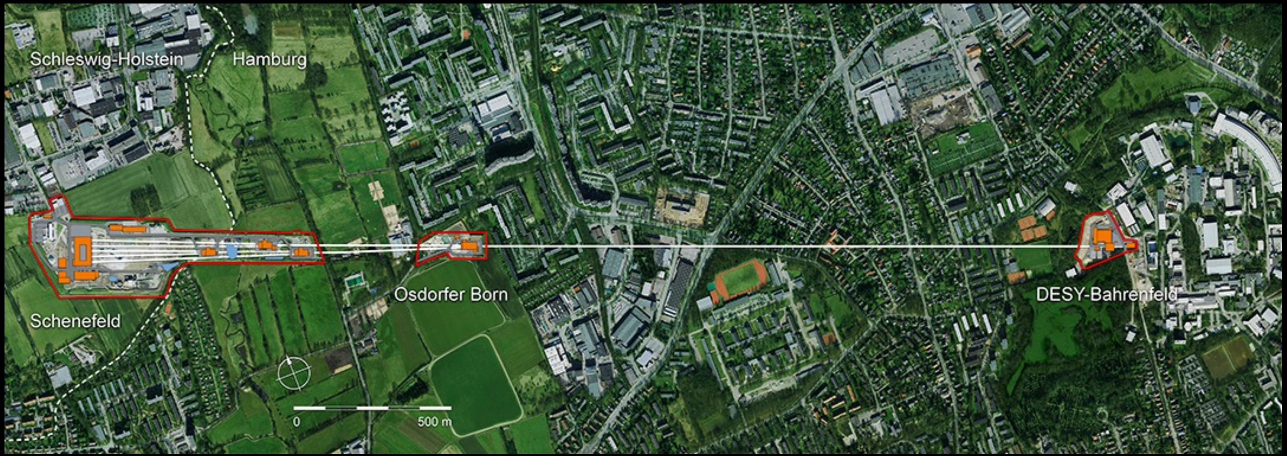
als.lbl.gov



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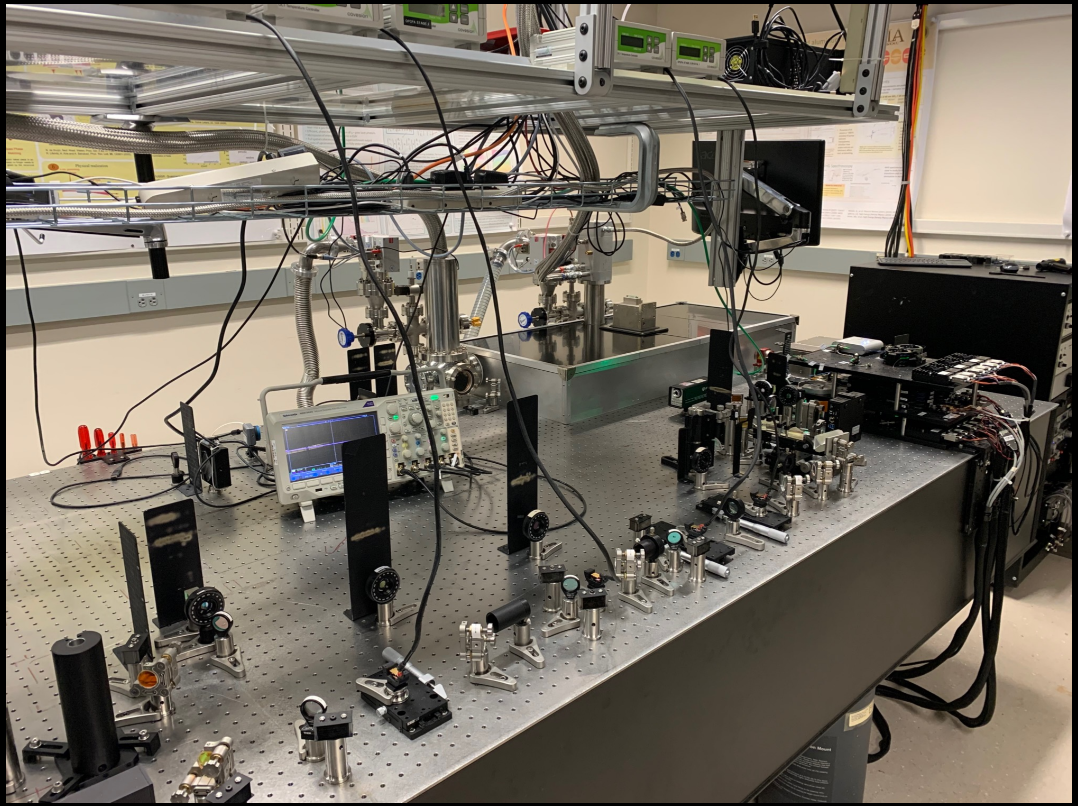
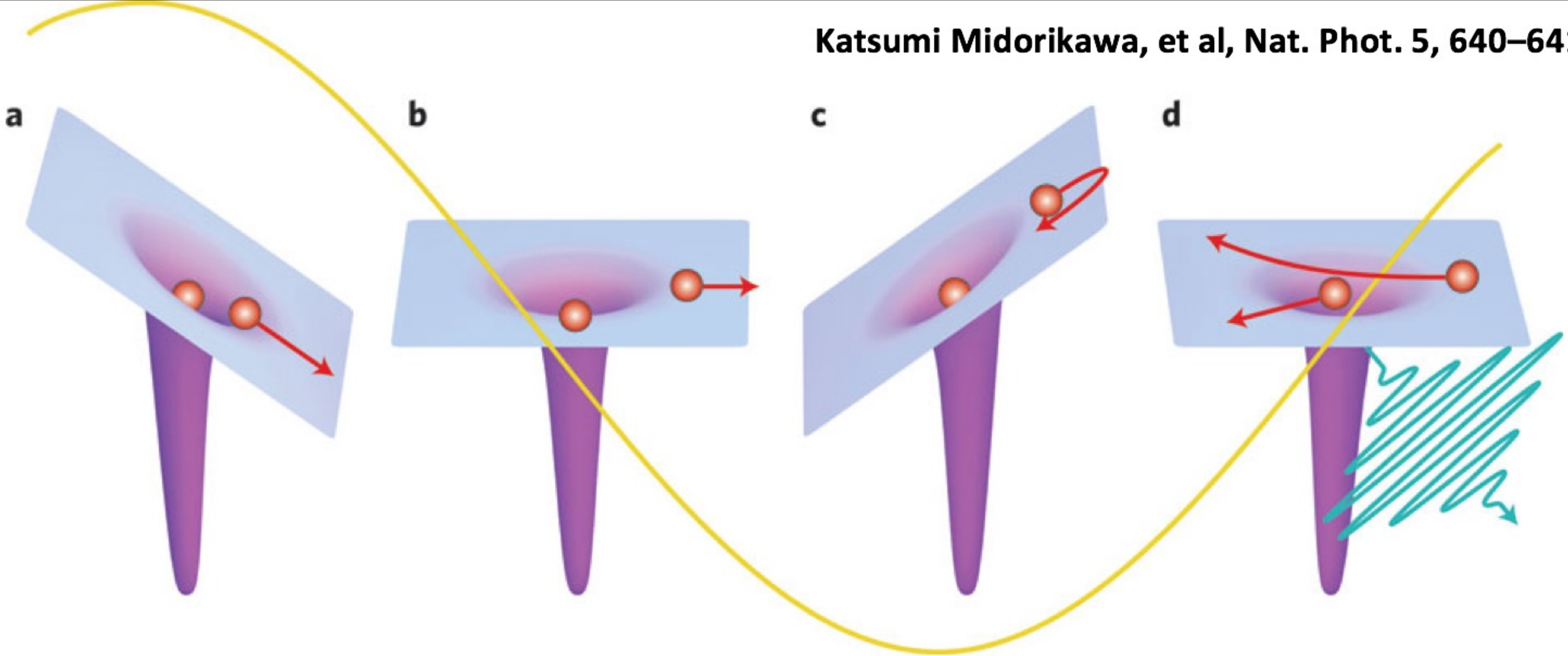
Tabletop sources complimentary

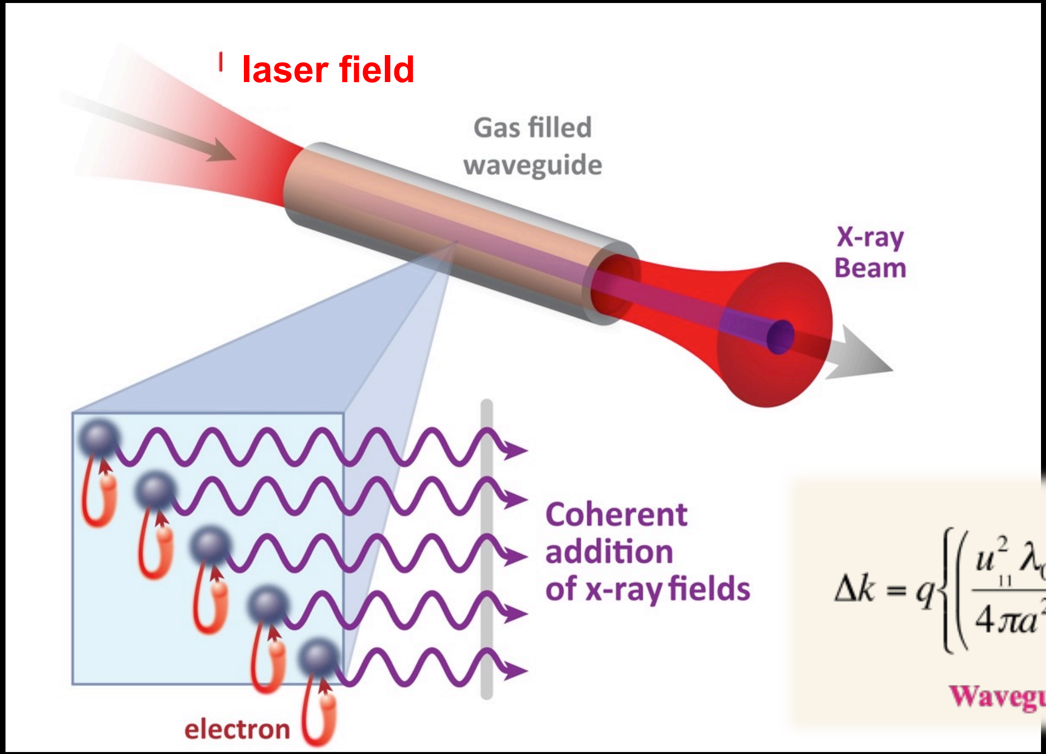


High harmonic generation (HHG)

Katsumi Midorikawa, et al, Nat. Phot. 5, 640–641 (2011)



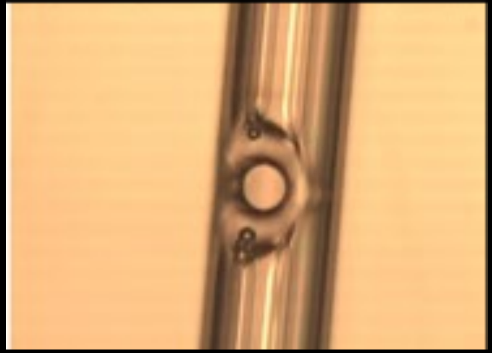
High harmonic generation (HHG) in a waveguide



$$\Delta k = q\left\{\left(\frac{u_{11}^2 \lambda_0}{4\pi a^2}\right) - P\left((1-\eta)\frac{2\pi}{\lambda_0}\Delta\delta - \eta\left[N_{atm} r_e \lambda_0\right]\right)\right\}$$

Waveguide — Neutrals — Plasma

An early high pressure HHG source

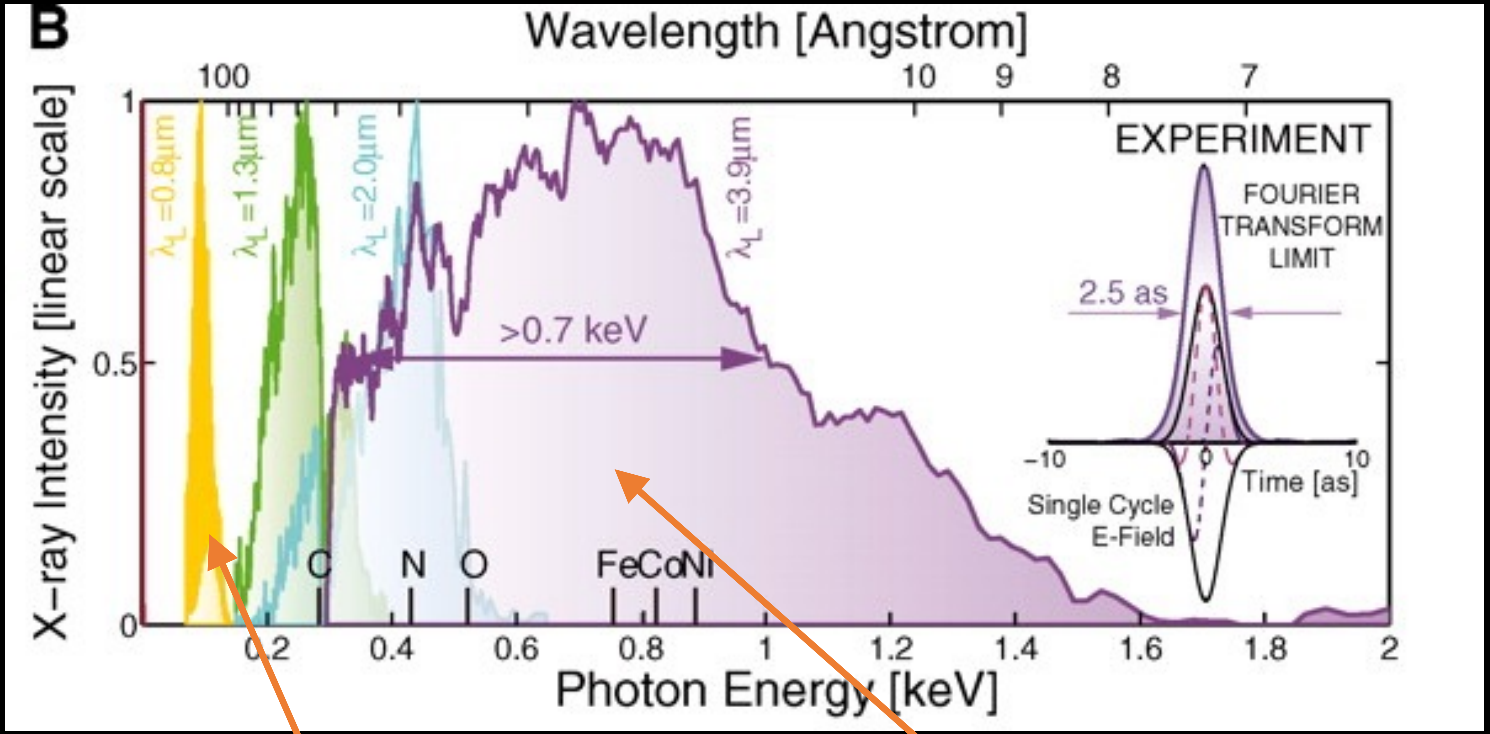


Laser machined gas inlets

- Phase matching requirement limits peak laser intensity
- Using a gas filled waveguide increases interaction volume

Science 280, 1412 (1998); Physical Review Letters 83, 2187 (1999)

Higher HHG photon energies require longer wavelength driving lasers



$h\nu_{max} \propto I_{laser}\lambda^2$

Conventional Ti:sapphire 800nm laser

Mid-IR OPCPA

Set to 700 C and feel 3 µm micron wavelength light

Popmintchev, Science 336, 1287-1291 (2012)

Outline

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Part two

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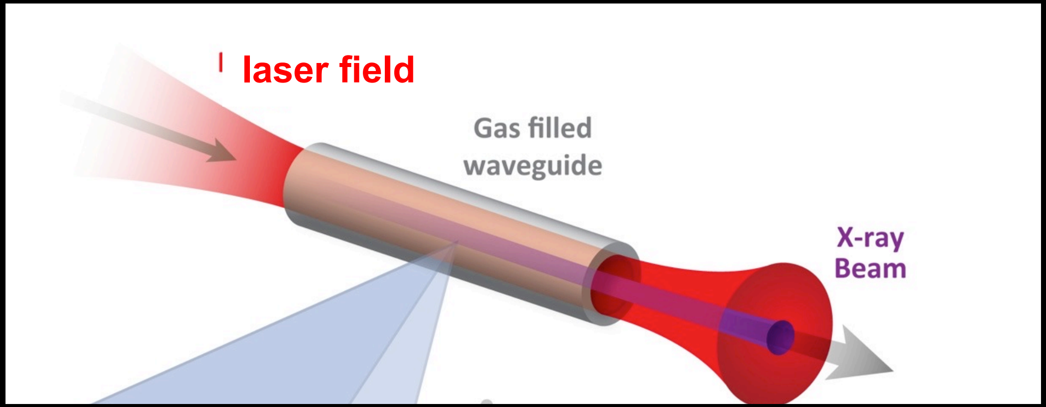
- A fiber-based front end
- Stretching, shaping and compressing laser pulses
- Optical parametric amplification

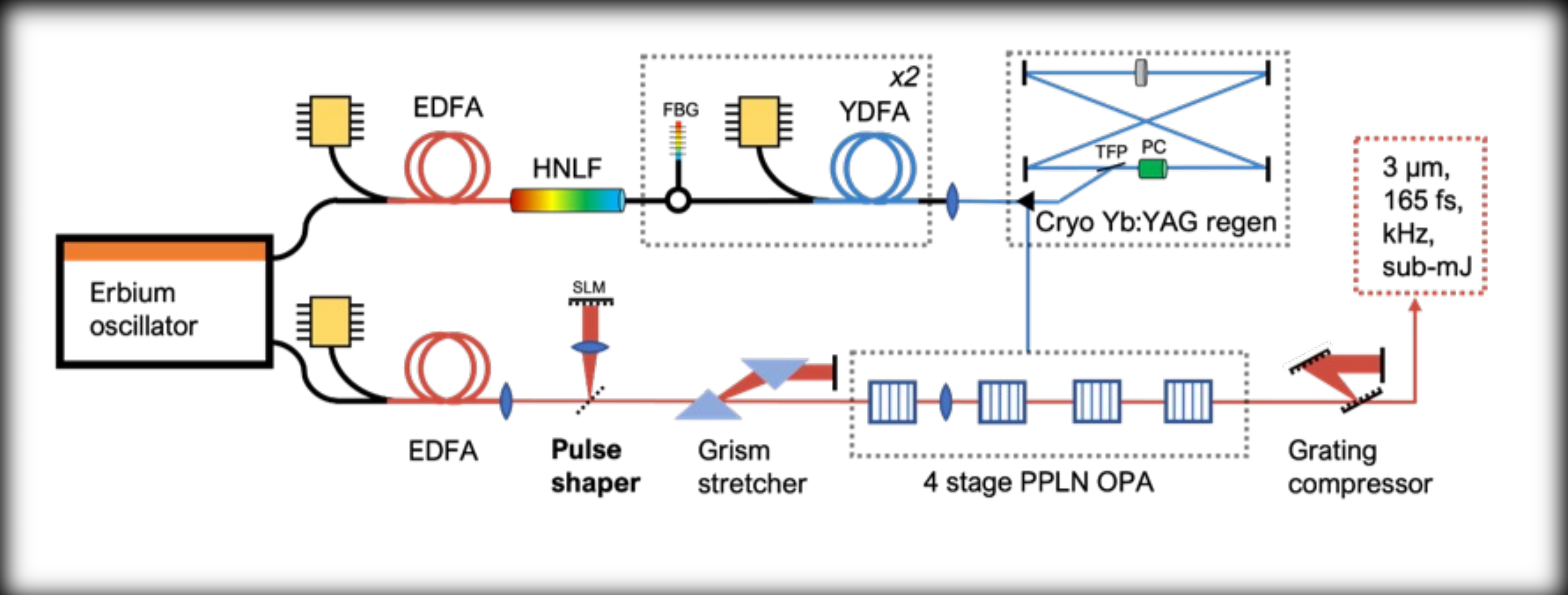
A laser source to drive soft X-ray HHG

- 2-4 μm wavelength ← mid-infrared
- Pulse duration ~ 8 cycles (80 fs)
- Repetition rate ≥ 1 kHz
- Pulse energy 1-3 mJ ← Depends on spot size

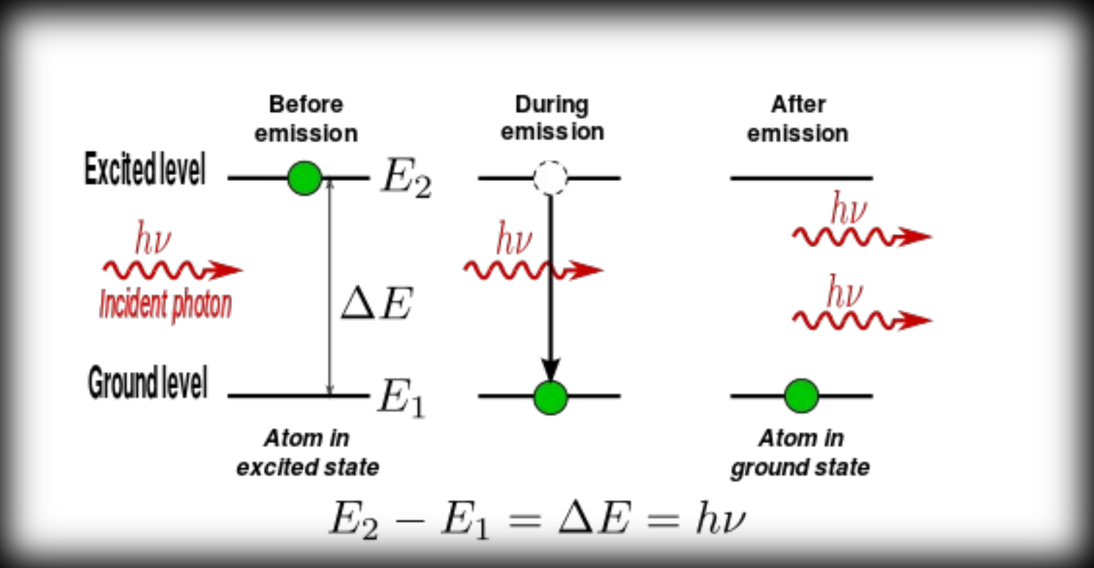


CliffsNotes version for experts: *overview of the OPCPA*

In 8 minutes, you will understand this, or your money back!



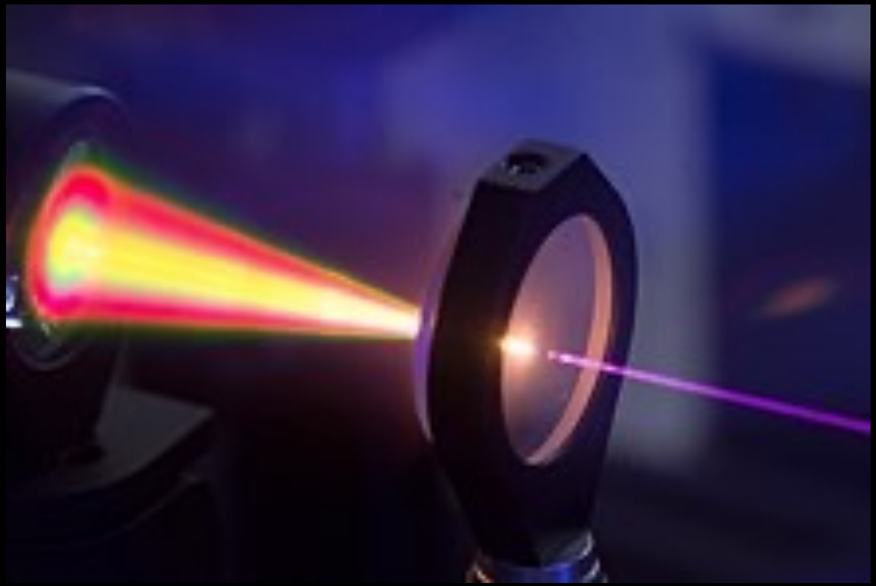
Mid-infrared laser sources



Direct laser emission in the mid-infrared is possible (ie, Cr- and Fe-doped chalcognides), but technology is still immature.

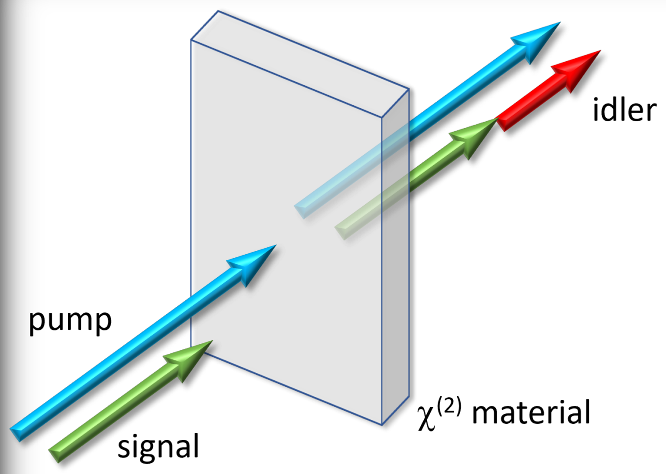
Our approach:

nonlinear frequency conversion

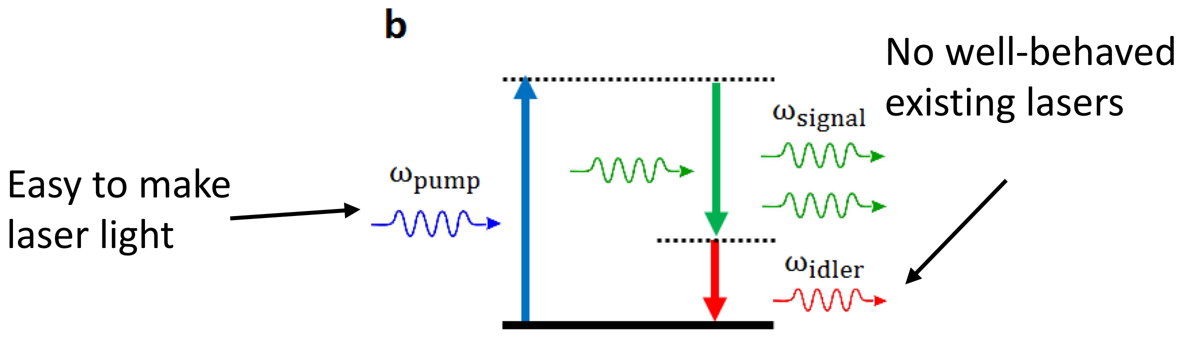


https://en.wikipedia.org/wiki/Laser

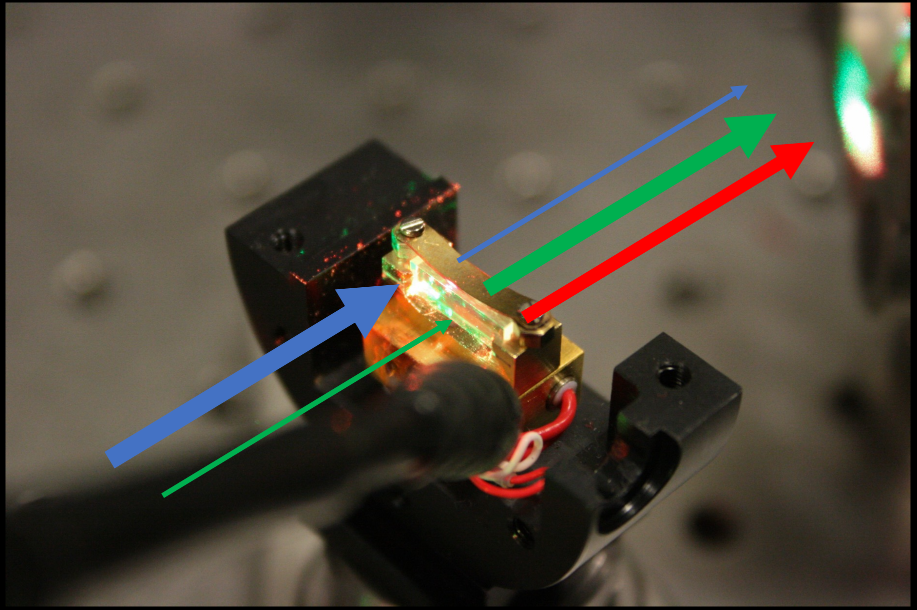
Optical parametric amplification (OPA)



- **1-µm pump light easy to make**
- **No heat load**
- **High gain, tuneable, broad bandwidth**



An actual OPA crystal in the lab



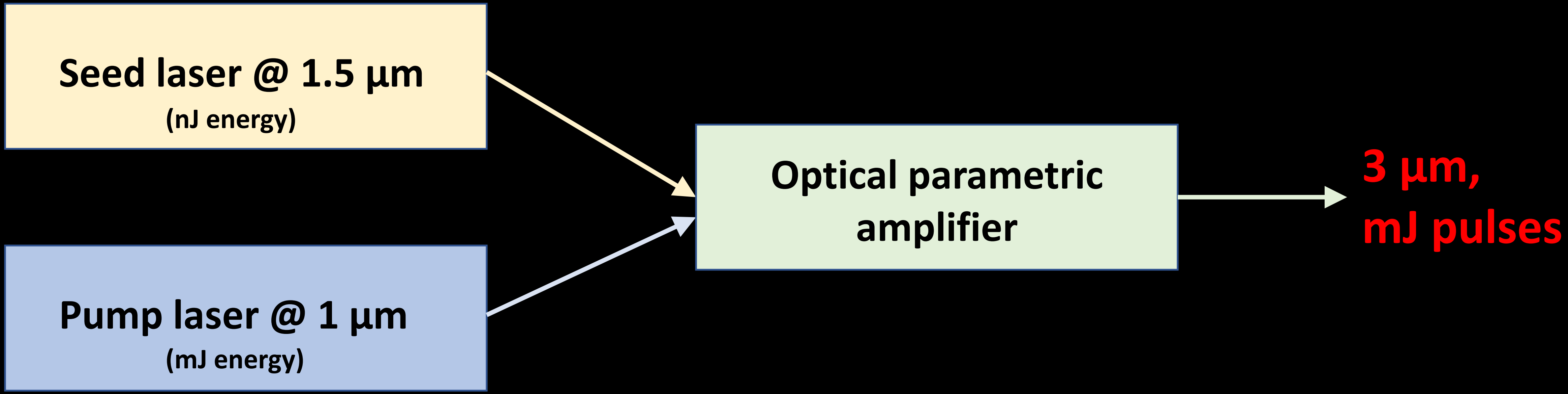
Energy conservation

$$\hbar\omega_{pump} = \hbar\omega_{signal} + \hbar\omega_{idler}$$

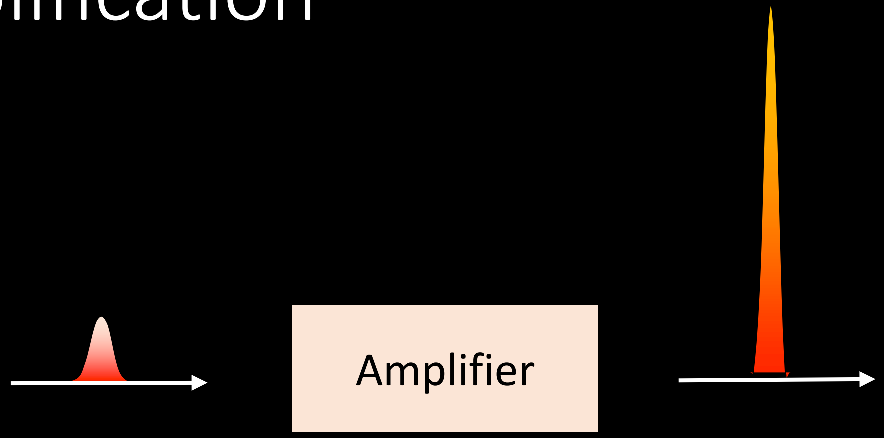
Phase matching

$$\Delta k = k_{pump} - k_{pump} - k_{pump} = 0$$

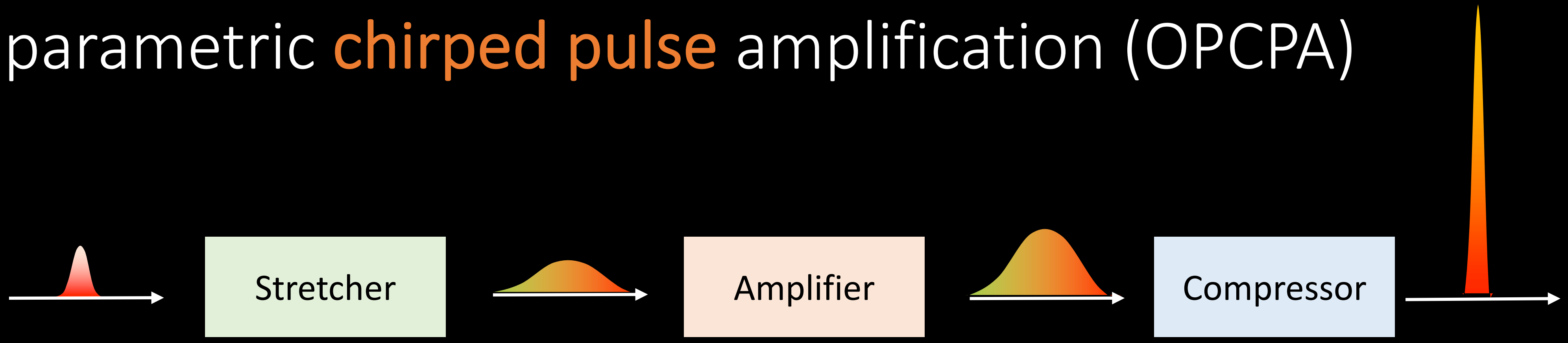
Simplified laser schematic



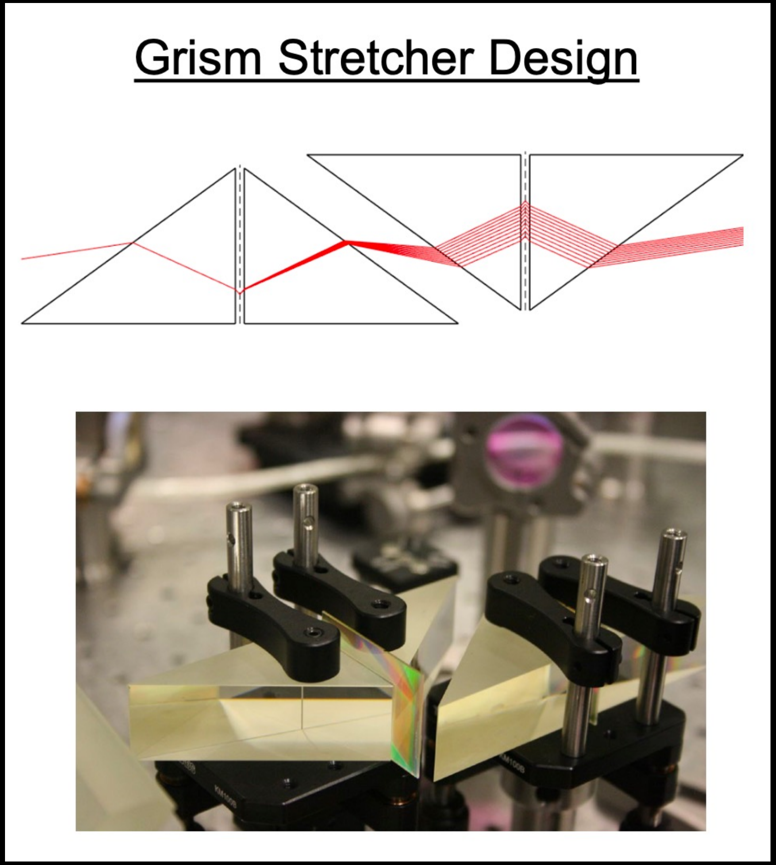
Optical parametric amplification

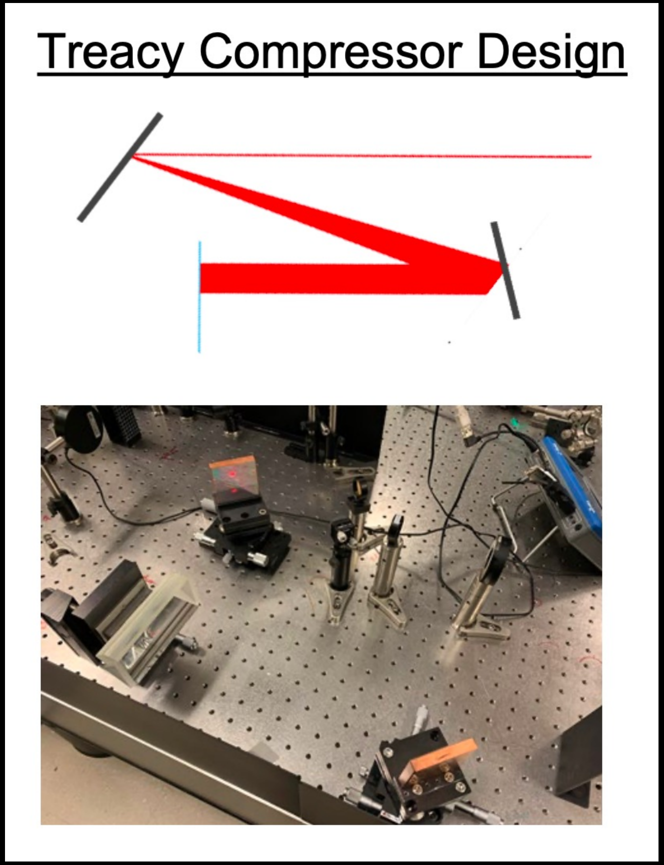


Optical parametric chirped pulse amplification (OPCPA)



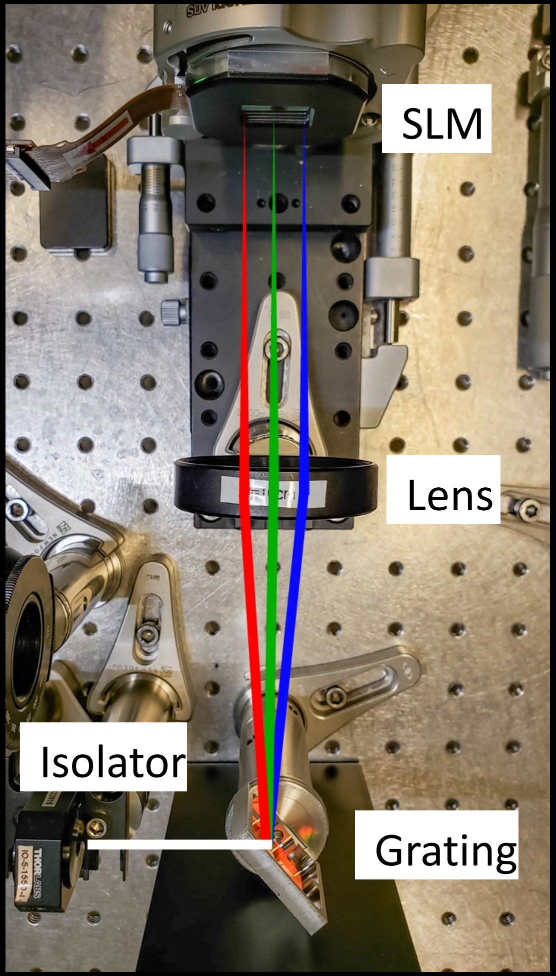
Stretching, compressing and shaping laser pulses

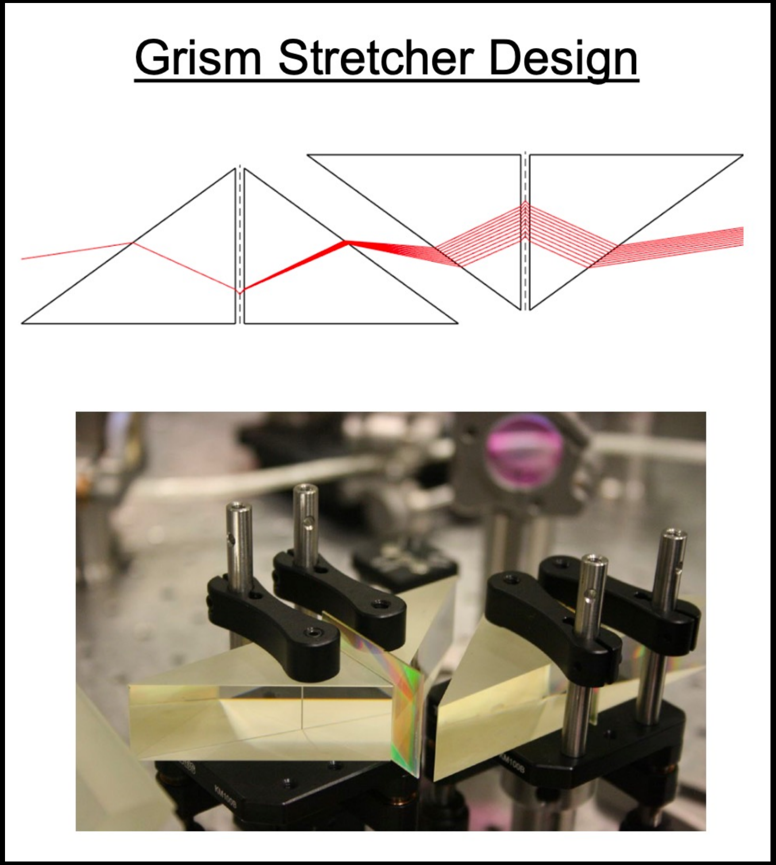


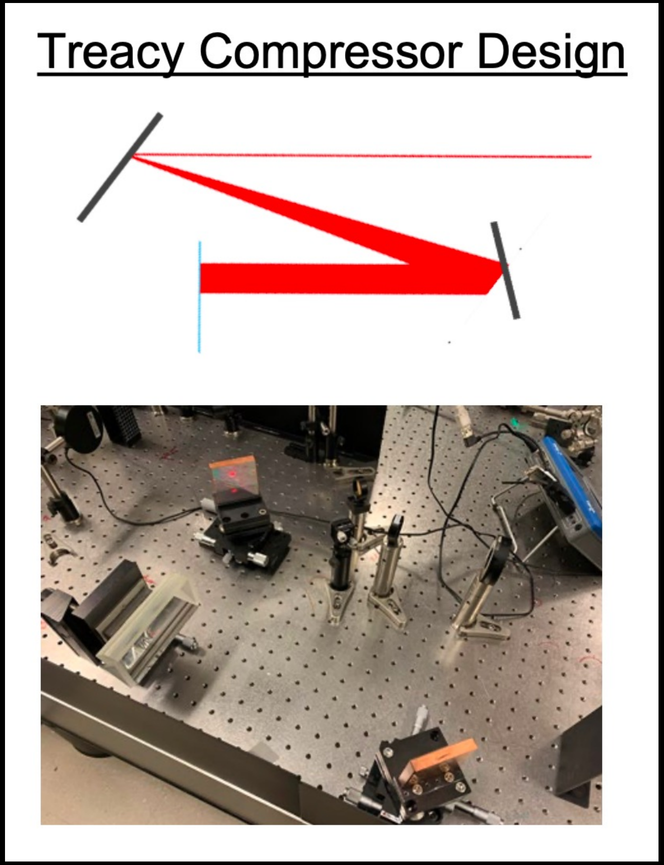


Stretching, compressing and shaping laser pulses

Pulse shaper

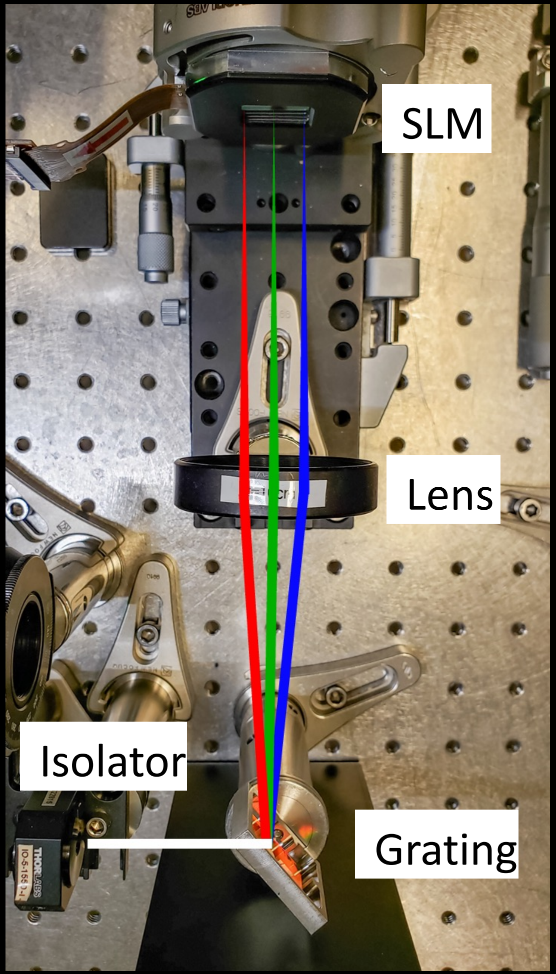




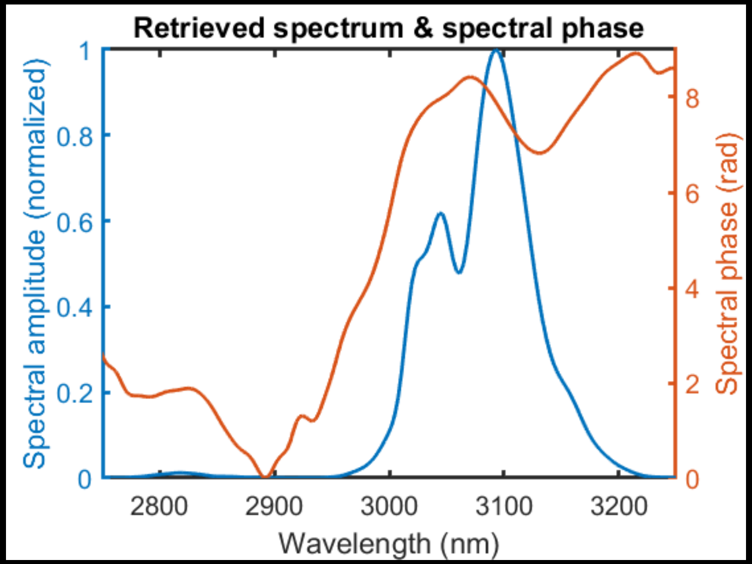


Stretching, compressing and shaping laser pulses

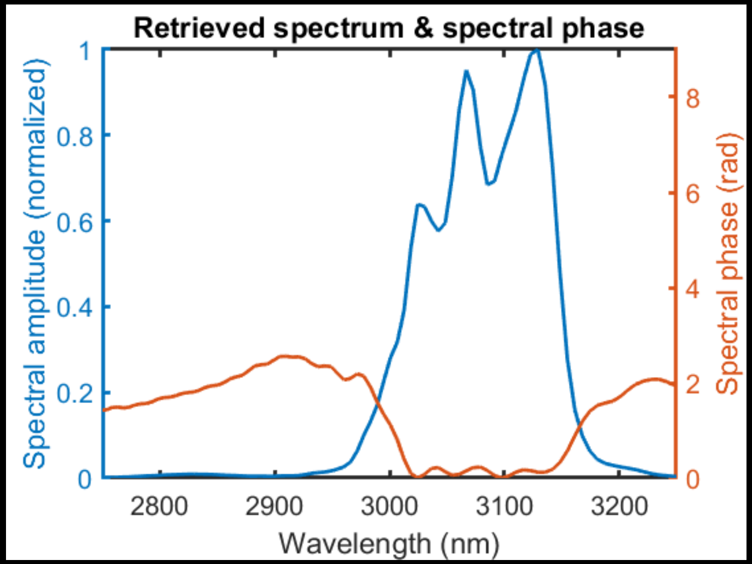
Pulse shaper



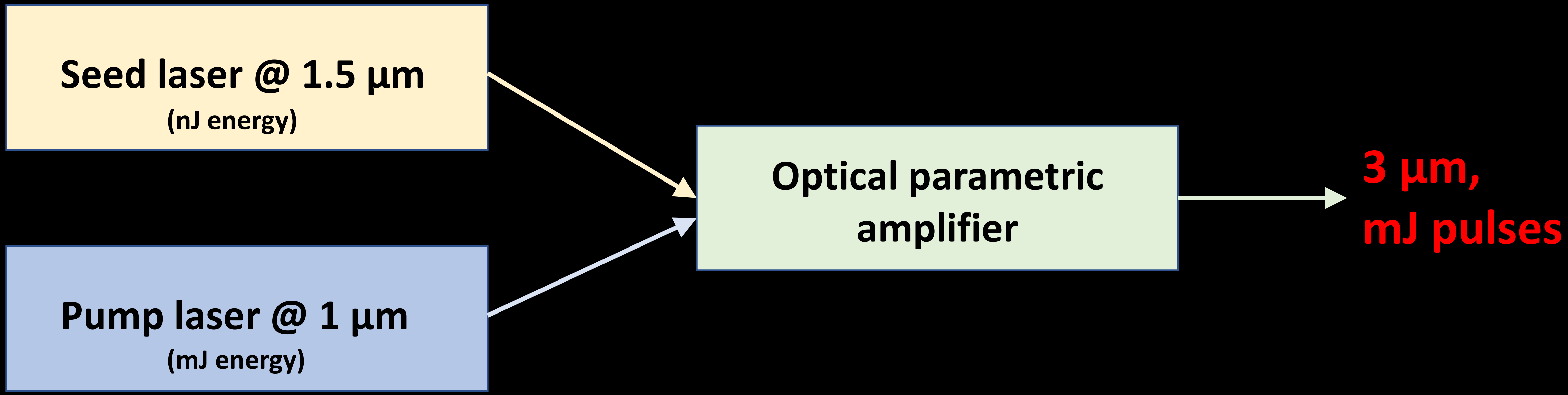
Without pulse shaping



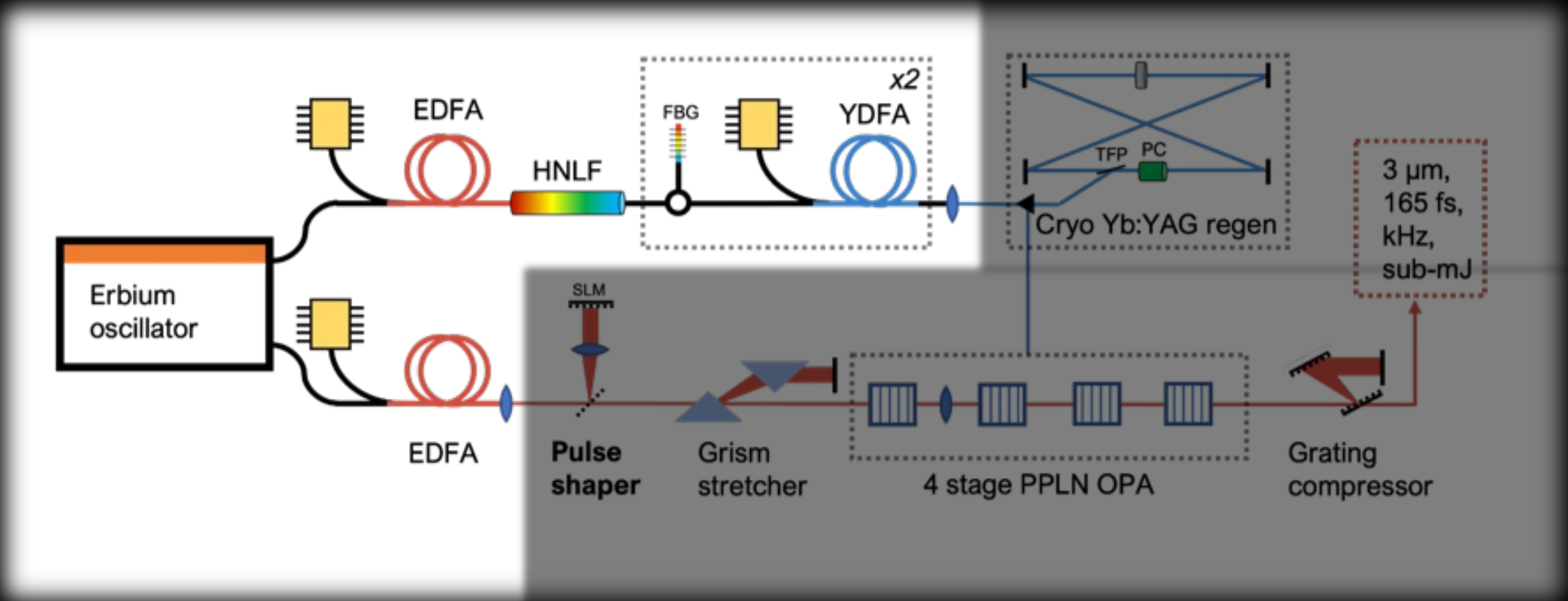
With pulse shaping



Simplified laser schematic

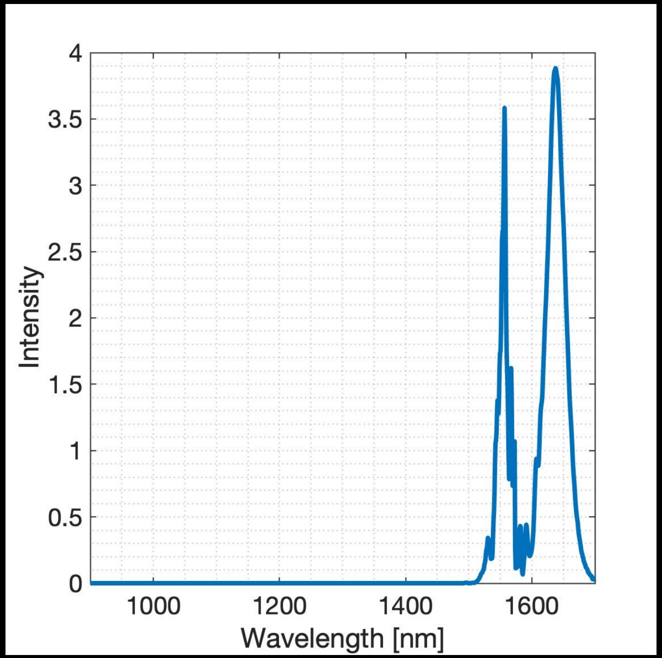


Overview of the OPCPA

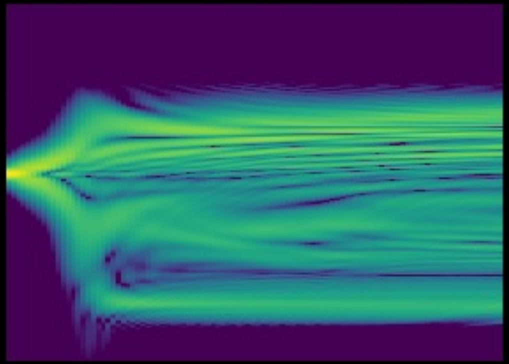


Generation of synchronized 1 μm and 1.5 μm light via highly nonlinear fiber

Measured spectrum before HNLF



40 fs, 4 nJ pulse at 1.55 μm



← Dispersive wave near 1 μm

NLSE simulation, spectral evolution

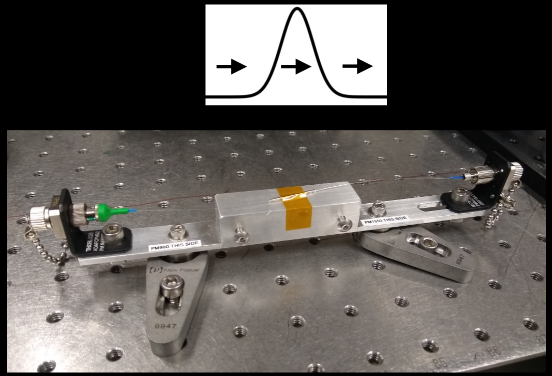
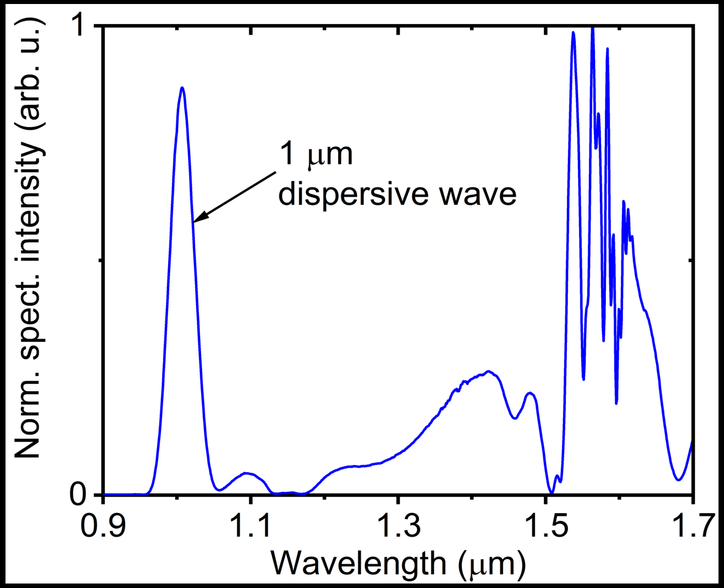


Photo of HNLF

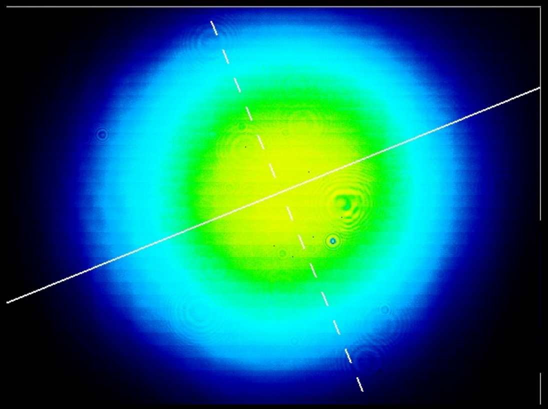
Measured spectrum after HNLF



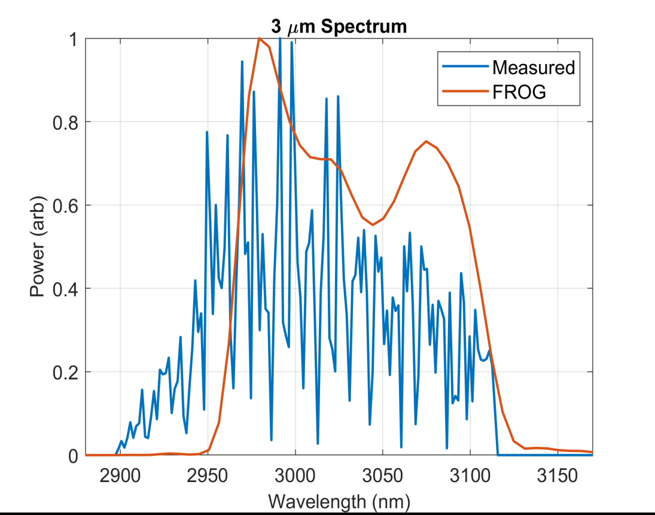
F. Tauser, A. Leitenstorfer, W. Zinth, Opt. Exp. 11 (2003)

OPCPA delivers excellent mode and stability at 3.1 µm

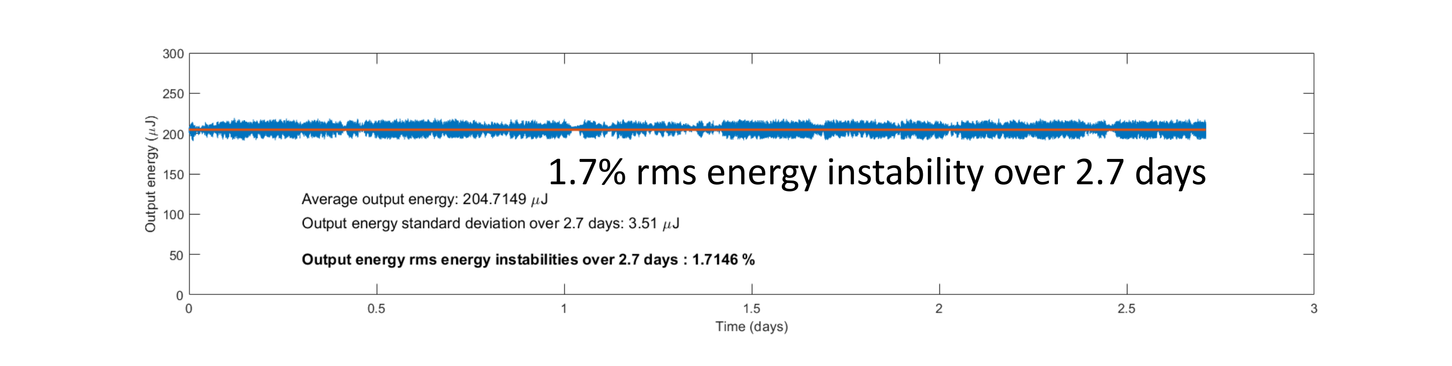
3.1 µm beam profile



3.1 µm spectrum



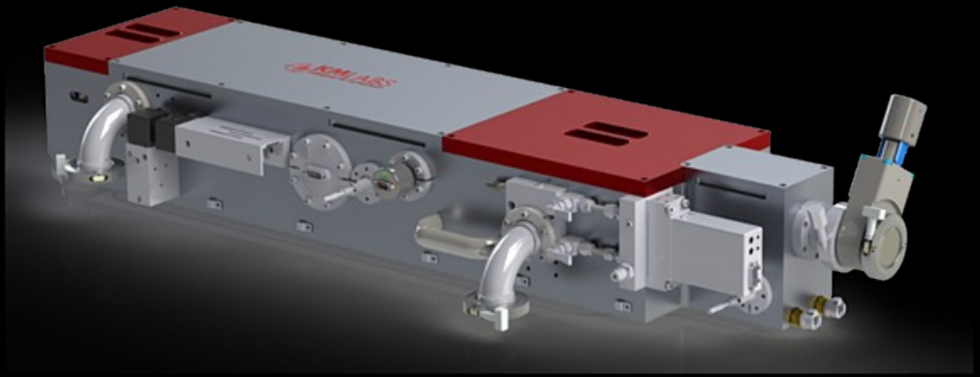
3.1 µm stability (limited by environment)



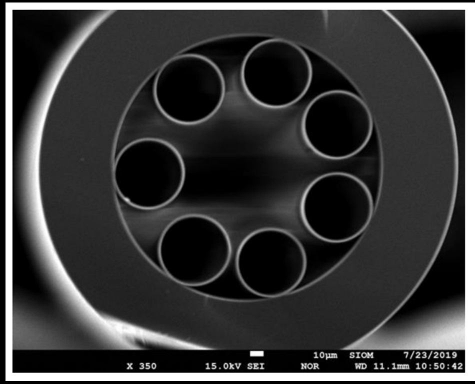
Future work …

Scaling pulse energy by factor of 4

XUUS5 HHG system from KM Labs



Antiresonant hollowcore fiber for HHG



Jaworski et al, *Sensors* 20 (2020)

Acknowledgements

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