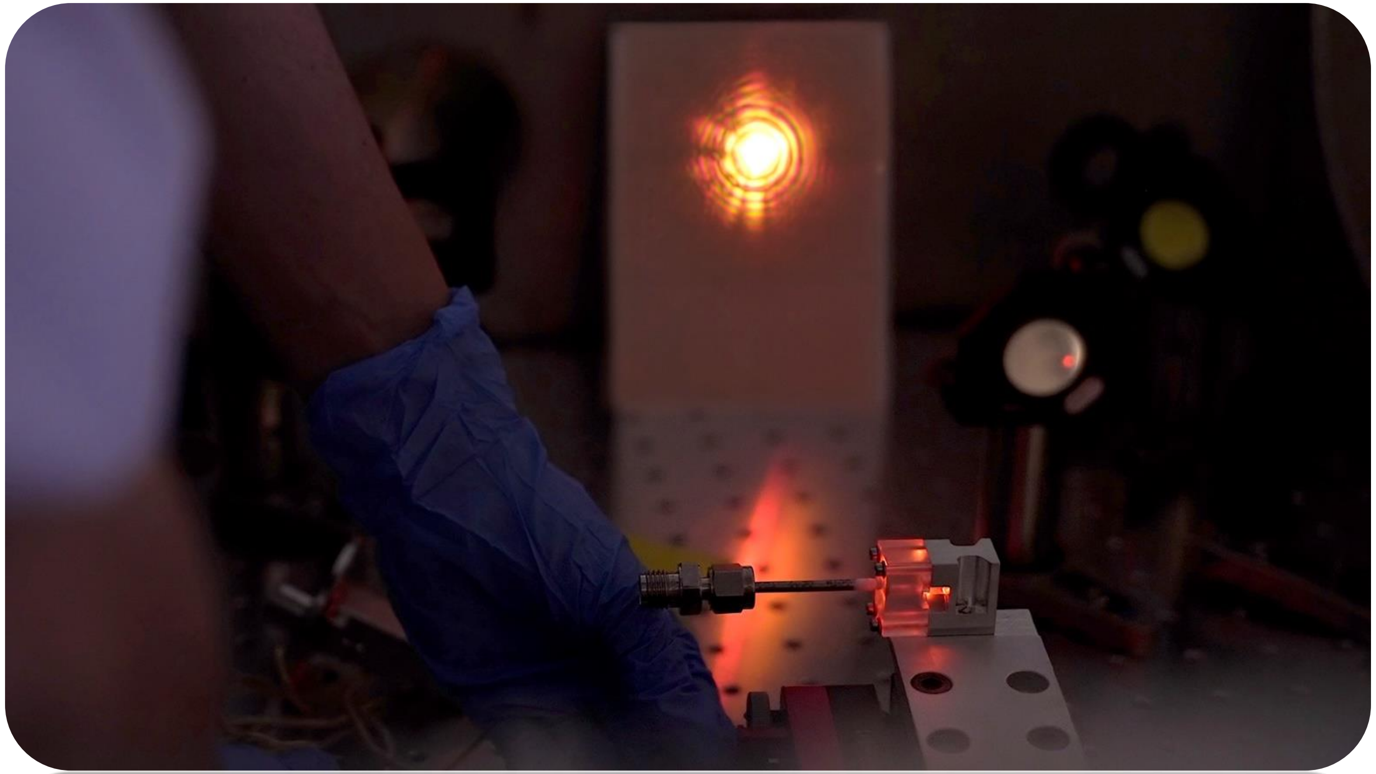
Development of table-top XUV and soft-X sources based on microfluidic devices

Anna Gabriella Ciriolo

CNR IFN Istituto di Fotonica e Nanotecnologie



The Ultrafast DYNamics In matter team

ultrafast spectroscopy from THz to X-rays

CNR IFN
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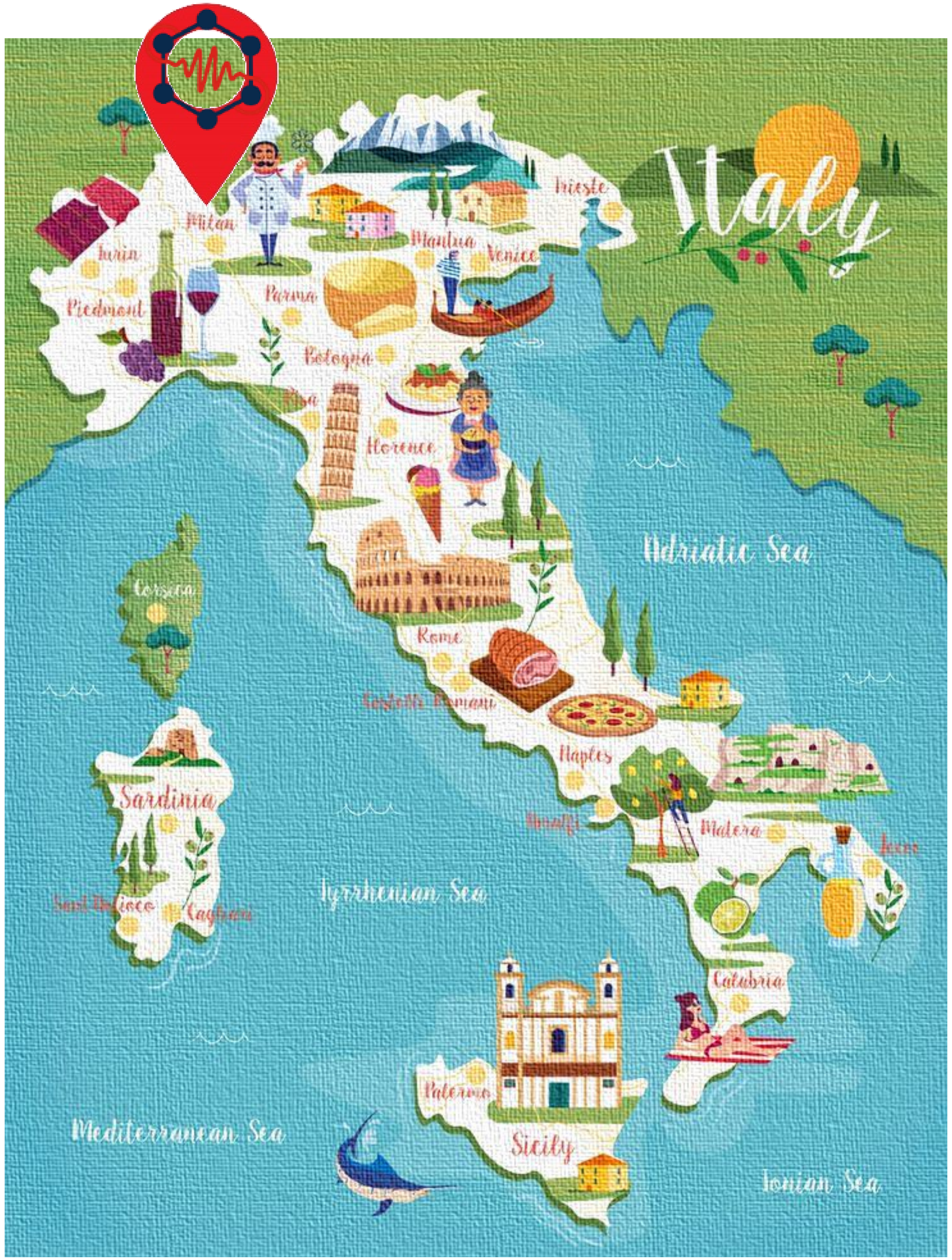
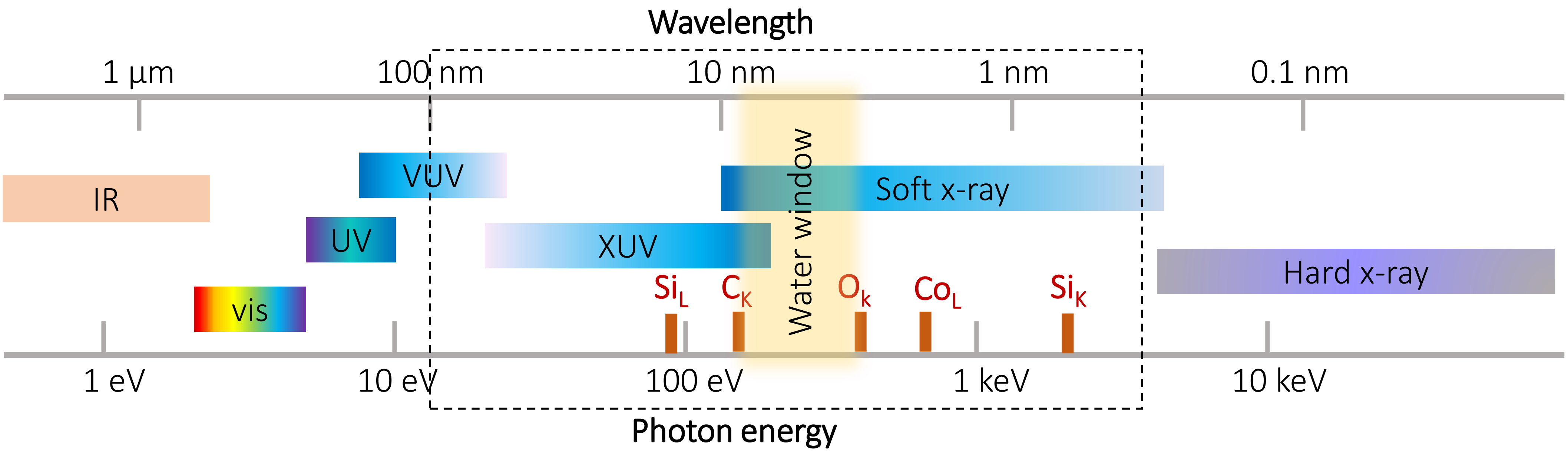


UDynI team IN A NUTSHELL

Milan,
Politechnic University

eXtreme UltraViolet (XUV) and Soft X-ray sources



K edges	**L edges**	**M edges**	**N edges**
B @ 188 eV	Al @ 72 eV	Ga @ 19 eV	I @ 70 eV
C @ 284 eV	Si @ 99 eV	Ge @ 30 eV	Pb @ 150 eV
O @ 543 eV	P @ 135 eV	As @ 42 eV	
	S @ 163 eV	Ti @ 33 eV	
		Br @50 eV	
		Fe @ 52 eV	
		Co @ 59 eV	
		Ni @ 67 eV	

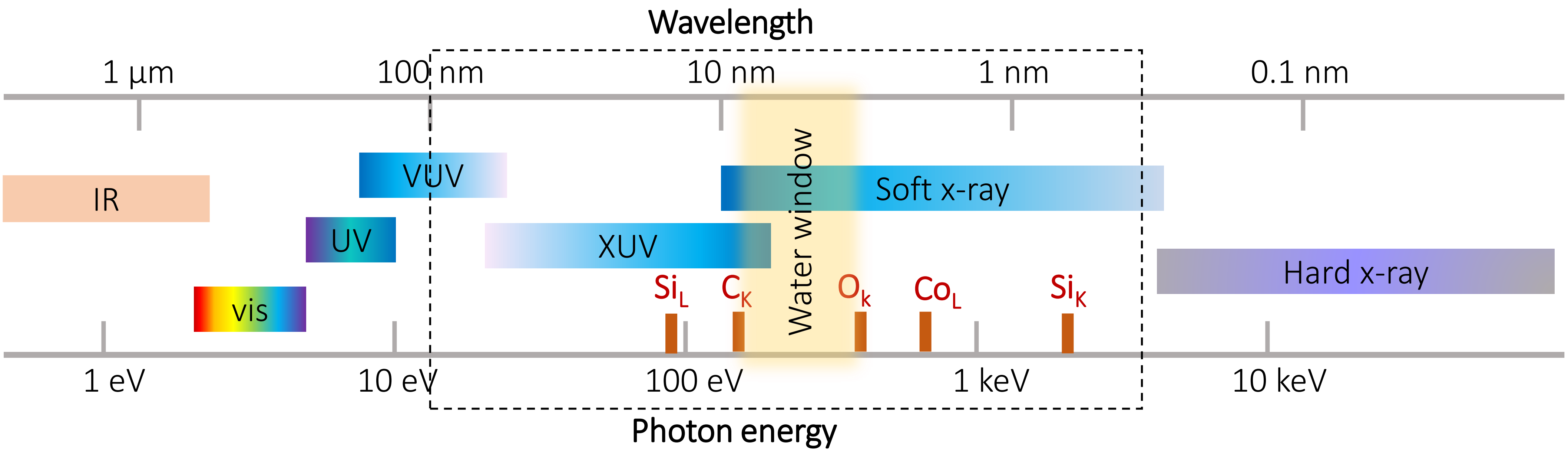
Semiconductors
Metals
Halogen
Bio-relevant

Edges identify the Binding Energy (BE) of a core shell

K edge → BE of n=1 shell
L edge → BE of n=2 shell
M edge → BE of n=3 shell
N edge → BE of n=4 shell

The energies of absorption edges in X-ray absorption spectra reveal the identity of the corresponding absorbing elements.

eXtreme UltraViolet (XUV) and Soft X-ray sources



Free electron lasers

high intensity (10^{20} W/cm^2)

spectral purity

polarization control

Table-top sources

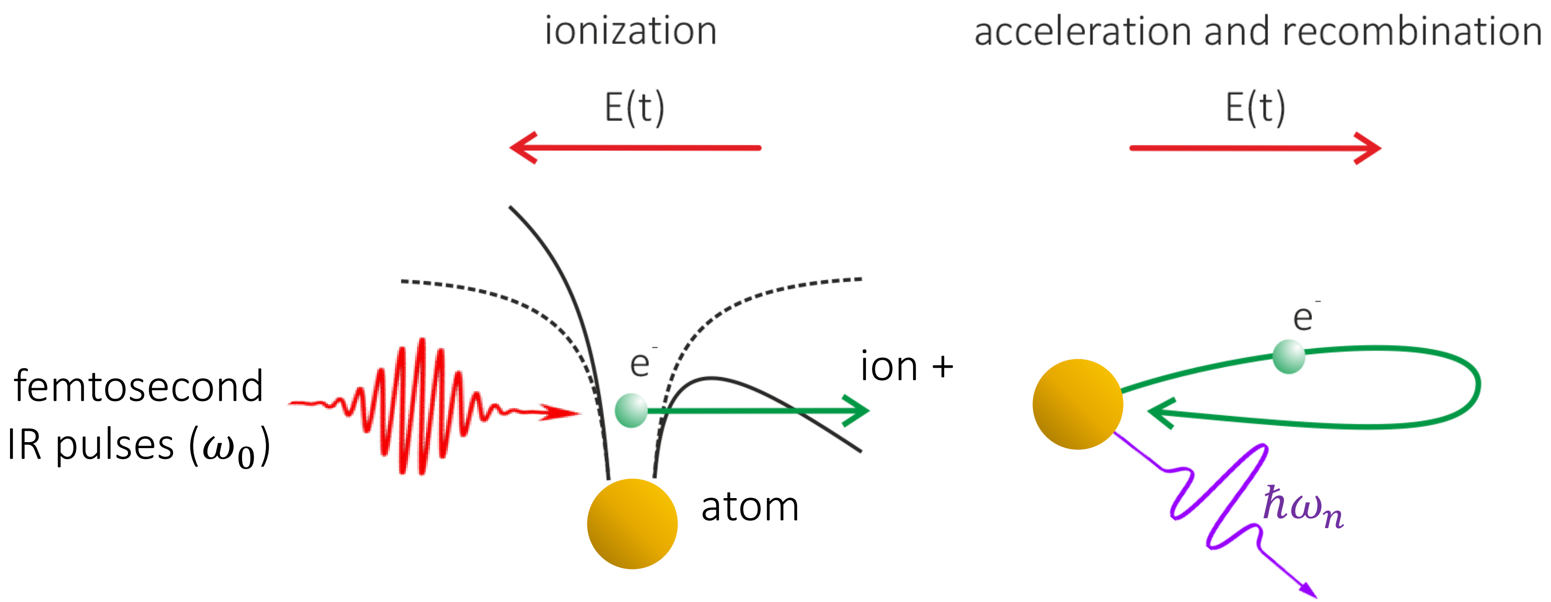
(high-order harmonic generation)

Price & Accessibility

Temporal resolution (50 as)

Flexibility

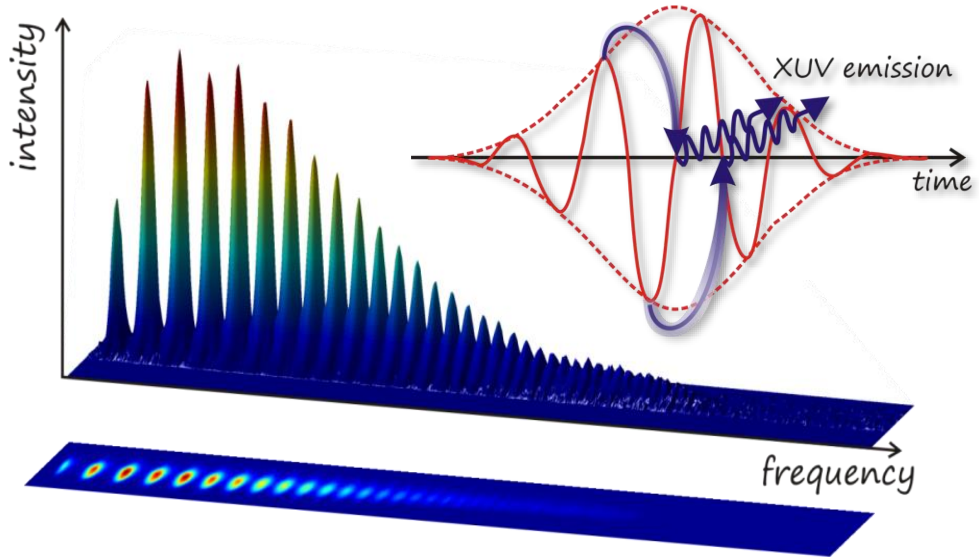
Table-top sources: High-order Harmonic Generation (HHG)



I. **Ionization** by tunnel ionization

II. **Propagation:** the free electron is accelerated by the laser field

III. **Recombination**: emission of a high-energy photon



Broadband spectrum, $\hbar\omega_{max} = I_p + 3.17\ U_p$ $(U_p \sim E^2\lambda_0^2)$

Generation of **attosecond pulses** (*as*, 1 *as* = *10*$^{-18}$*s*)

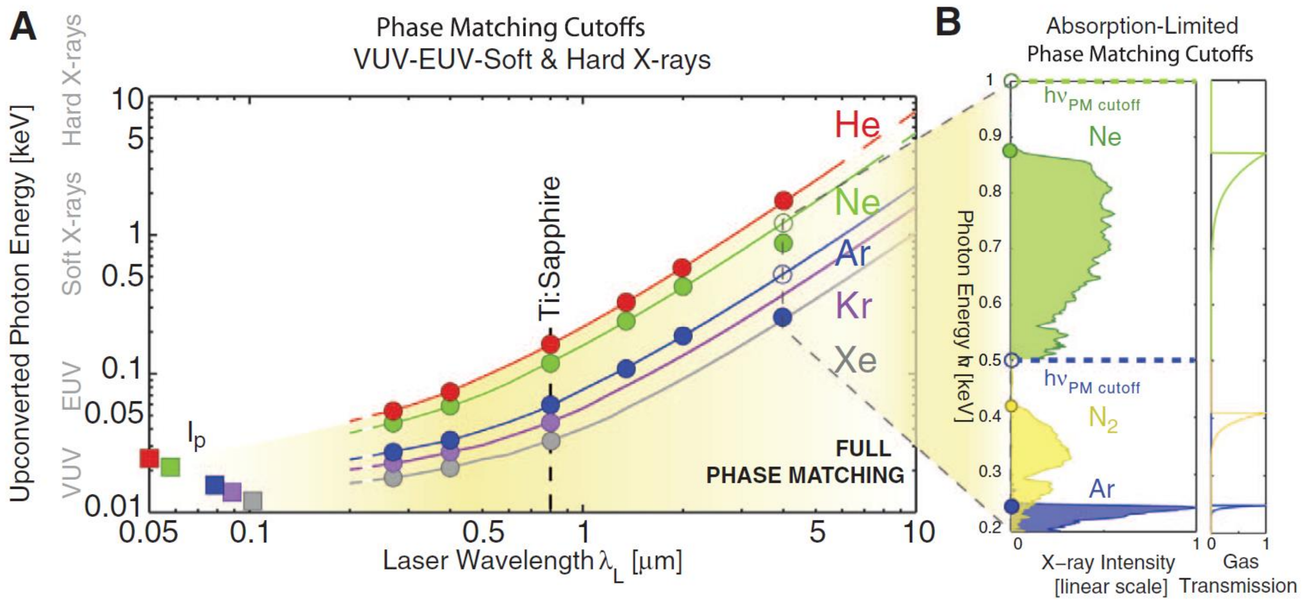
low conversion efficiency (≈ $10^{-6} \div 10^{-9}$ with 800-nm driver)

How to increase the HHG cutoff

- Increase I_p
- Increase the driving intensity
- Increase the driving wavelength

$$\hbar\omega_{max} = I_p + 3.17\ U_p$$

$$U_p \propto E^2\lambda_0^2$$



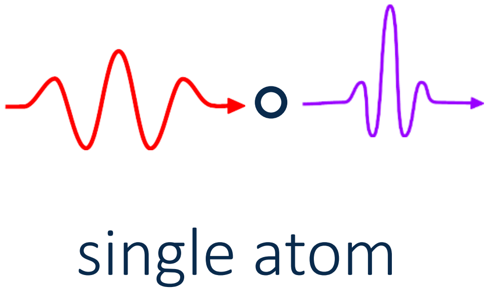
T. Popmintchev et al. *Science* 336.6086 (2012): 1287-1291.

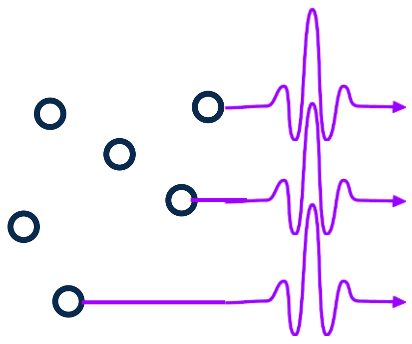
Physical constraints

- Conversion efficiency (CE) scales as $\sim\lambda^{-6}$

  (CE @ 1.6 µm is 2^{-6} lower than @ 800nm)
- Collective effects: phase matching and absorption

Phase matching in HHG





In HHG $\varphi_{driving\ pol} - \varphi_{harmonic} = 0$

- gas medium
- driving laser wavelength/intensity
- geometry of the interaction

q-th harmonic order $$k_{driving} - q \cdot k_q = \Delta k_q(x) = \Delta k_q^{disp} + \Delta k_q^{dipole} + \Delta k_q^{geom}$$

$\Delta k_{\text{Dispersion}}$—due to the optical dispersion of the generating medium (neutral atoms and free electrons),

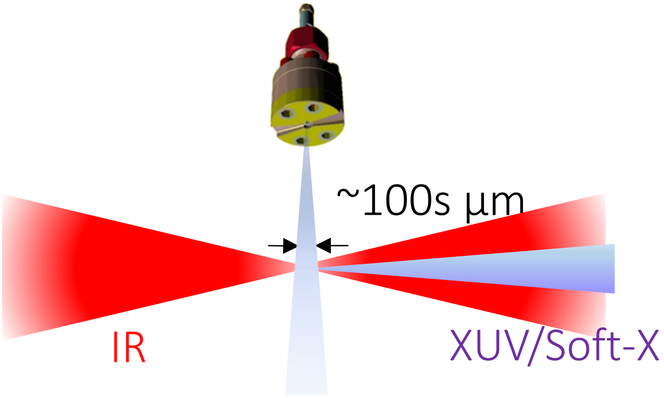
Δk_{Dipole}—due to the intensity dependent dipole phase,

Δk_{geom}—the geometrical wave vector mismatch caused by focusing/waveguide

$$\frac{dE_q}{dx} = \underbrace{b(x)}_{\text{source}} \underbrace{e^{i\int_{-x_0}^{x} \Delta k_q(x')dx'}}_{\text{phase-mismatch}} - \underbrace{\alpha_q(x)E_q}_{\text{absorption}}$$

Generation strategies

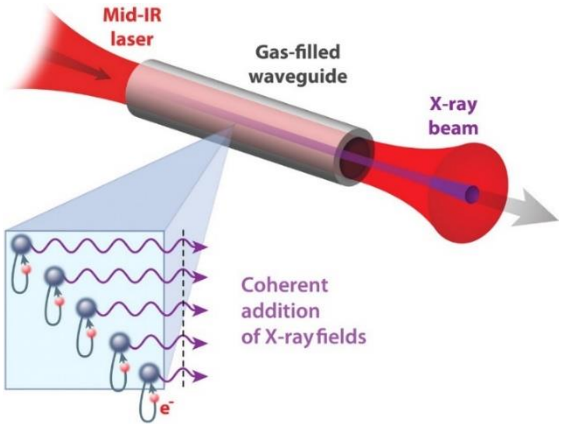
Free gas expansion



- ✗ Short interaction volume (~100s μm)
- ✓ Low absorption

P. Salieres et al., Phys. Rev. Lett. **74**, 3776 (1995)

Confined gas media
(capillary, gas cell)



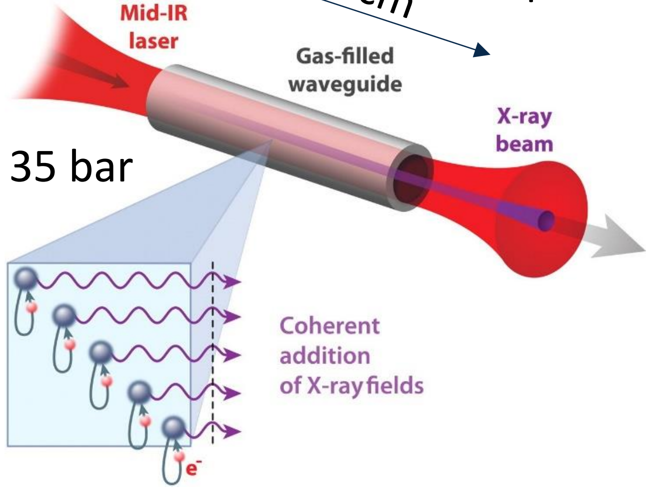
- ✓ Long interaction volume (~10s cm)
- ✓ High-density gas media (up to 100s bar)
- ✗ Absorption

C. G. Durfee III et al., PRL **83**, 2187 (1999)
T. Popmintchev et al., PNAS **106**, 10516 (2009)

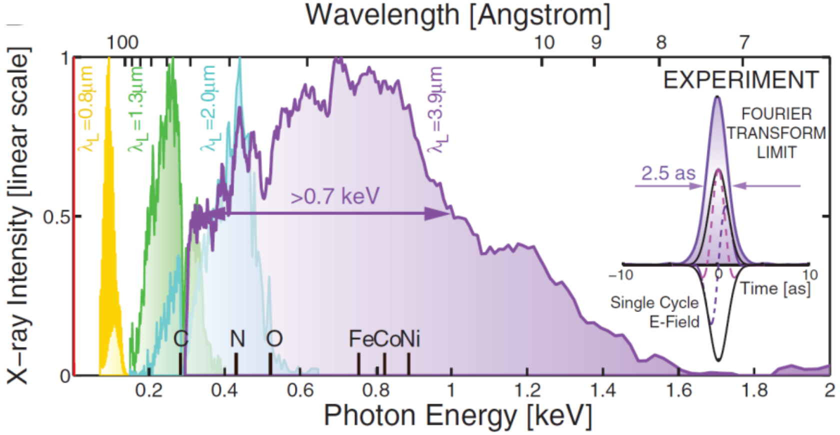
State of the art in table-top HHG

5 cm capillary

He p = 35 bar



HHG up to 1 keV driven by mid-IR pulses at 3.9 µm



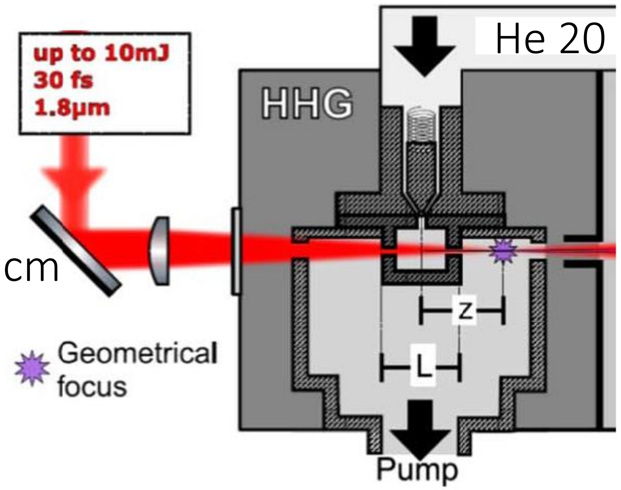
T. Popmintchev et al. *Science* 336.6086 (2012): 1287-1291.

gas cell

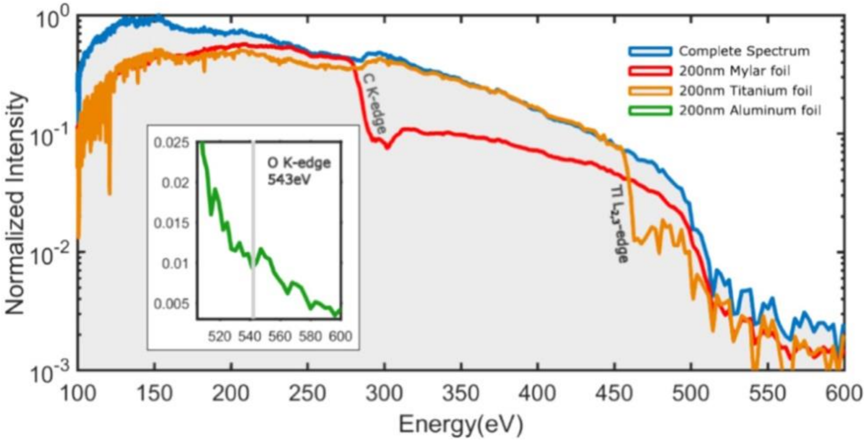
He 20 bar backing pressure

F=60 cm

L=8 mm



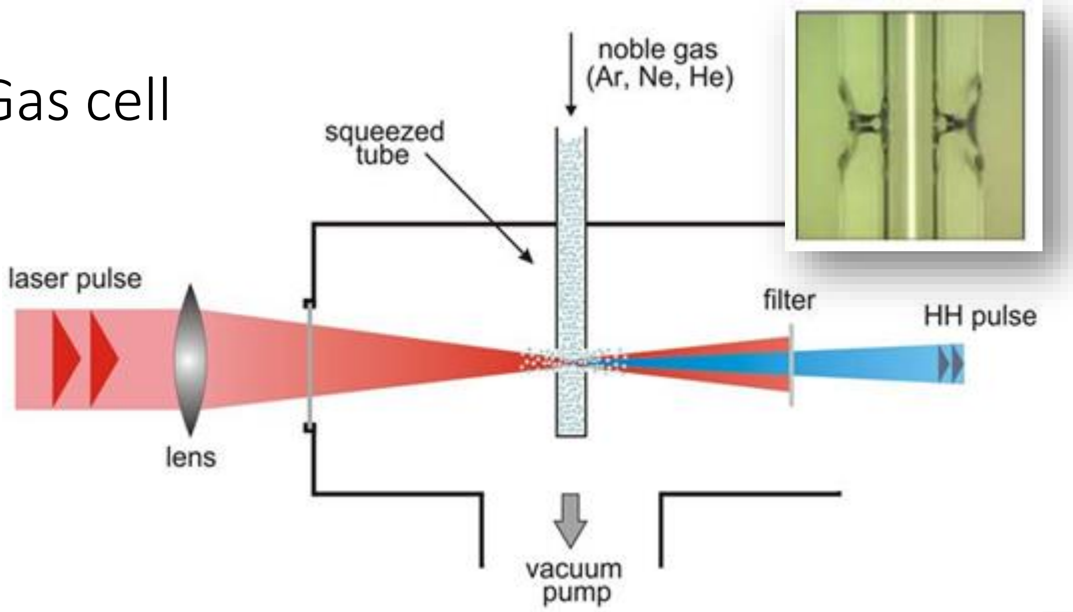
Water-window HHG sources driven by near-IR pulses



V. Cardin et al., J. Phys. B: At. Mol. Opt. Phys. 51 (2018) 174004

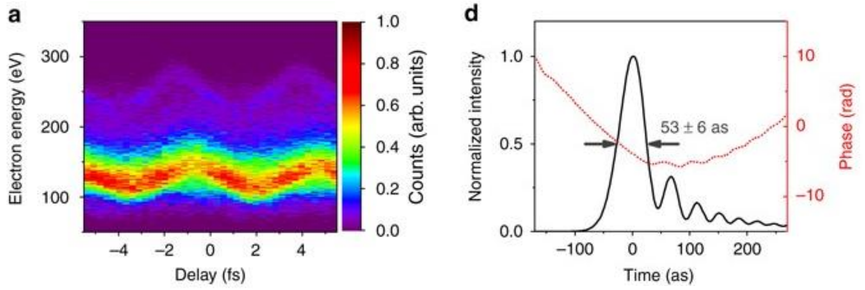
State of the art in table-top HHG and attosecond sources

Gas cell



53 as X-ray pulses up to the C_k by 1.8 µm driver

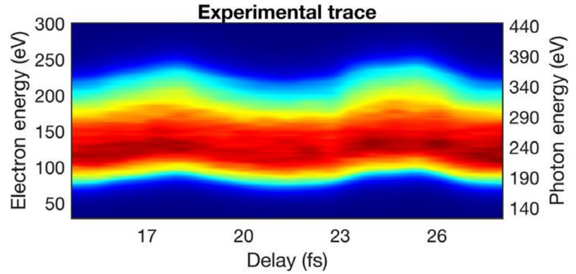
1.5 mm-long cell, 1 bar neon gas



J. Li et al. *Nature communications* 8.1 (2017): 186.

322 as pulses in the water window by 1.8 µm driver

500 um-long cell, 3 bar neon gas

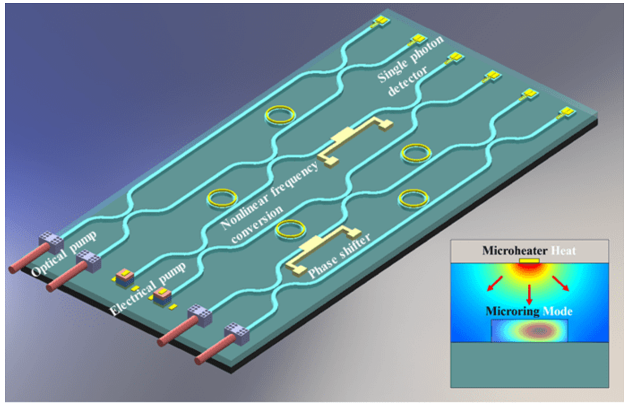


S. L. Cousin et al., Phys. Rev. X 7, 041030 (2017)

A novel approach: microfluidic devices for HHG and attosecond science

Inspired to integrated photonics

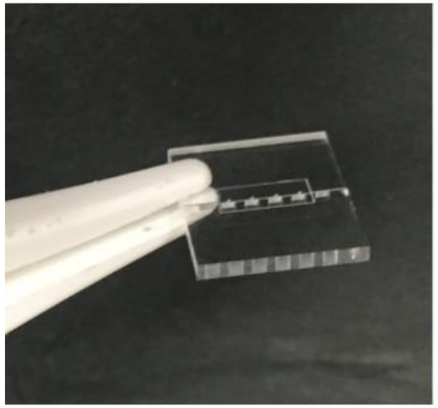
Vis-IR:Dielectric waveguides



Absorption hinders bulk Photonics in the XUV-SXR

Replacing dielectric with **hollow waveguides**

XUV-X: hollow waveguides



The potentials of microfluidics applied to XUV – soft X:

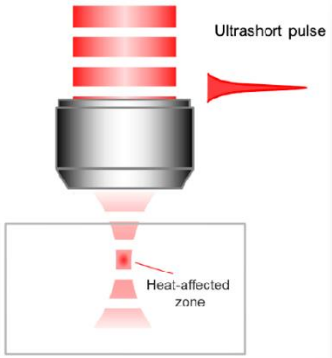
- Efficiency of HHG in capillaries/waveguides
- Propagation the fundamental and XUV/X-rays beams in a waveguide regime
- Micro-manipulation of gas (or liquid samples)
- Miniaturization

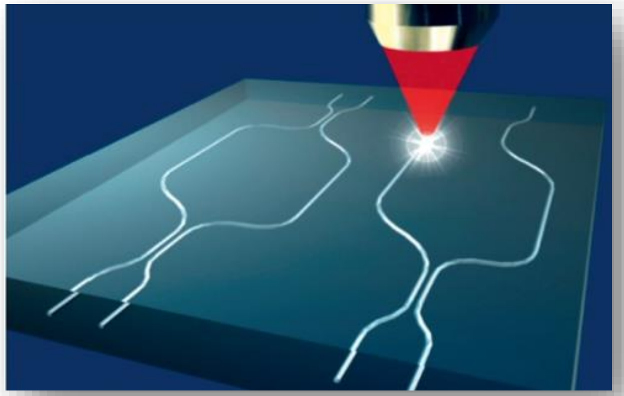
The technology

In collaboration with
The Femtosecond Laser Micromachining group
Dr. R. Martínez-Vázquez

Femtosecond Laser Irradiation followed by Chemical Etching (FLICE)

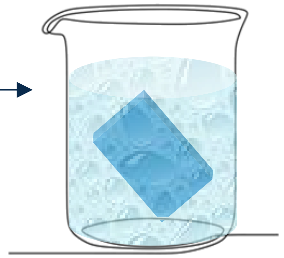
Irradiation



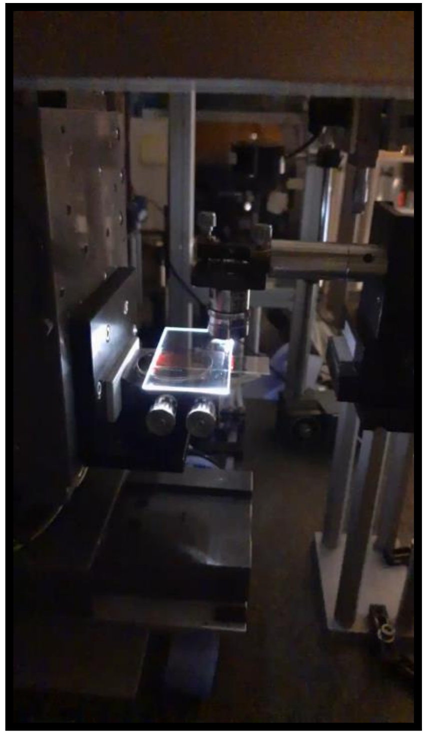


Etching

HF solution

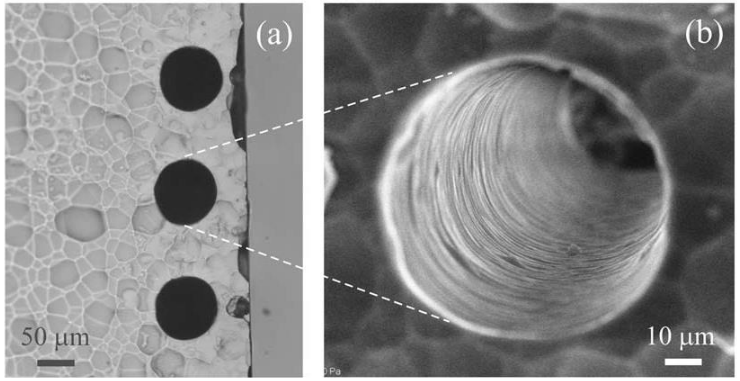


Etching rate ~20 times faster in the irradiated regions



FLICE capability

Maselli et al., Appl. Phys. Lett, 2006

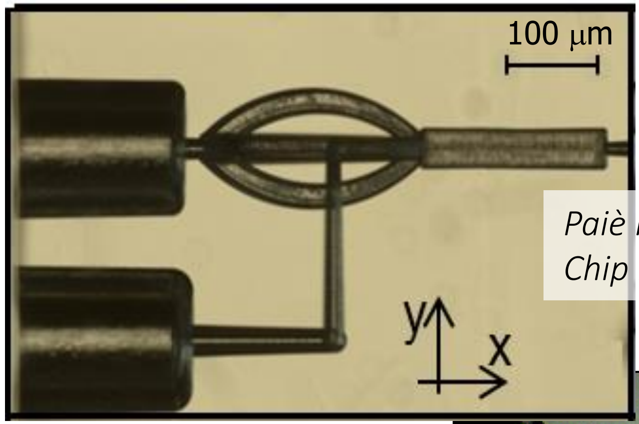


✓ 3D hollow structures

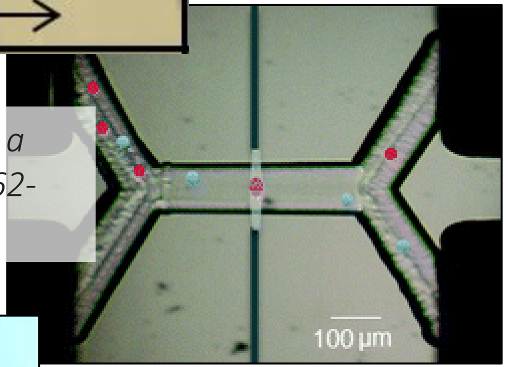
✓ high accuracy (<1 μm)

Lab-On-a Chip (LOC)

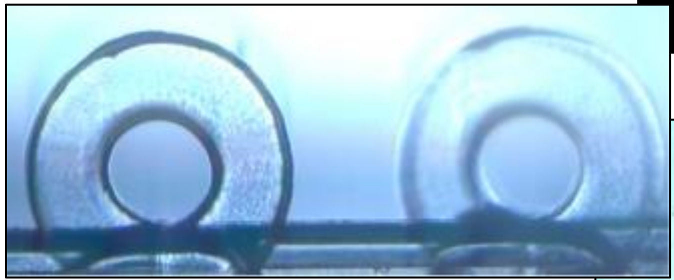
integrates multiple laboratory functions on a single, handheld chip.

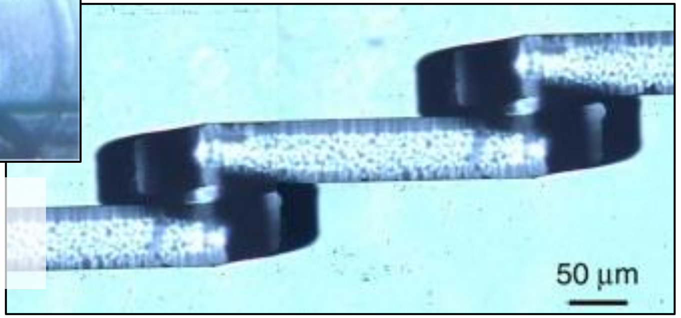


*Paiè Petra, et al., Lab on a Chip **14** 1826-1833 (2014).*



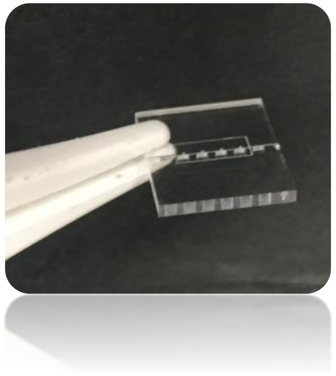
Yang, T., et al, Lab on a Chip 15.5 (2015): 1262-1266.

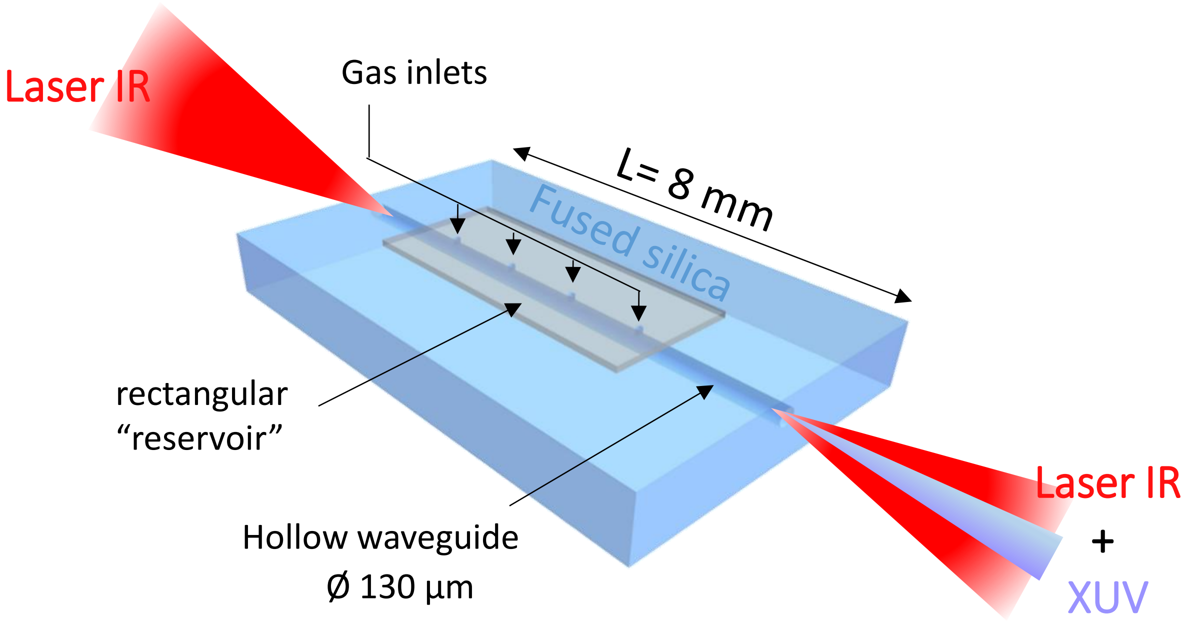




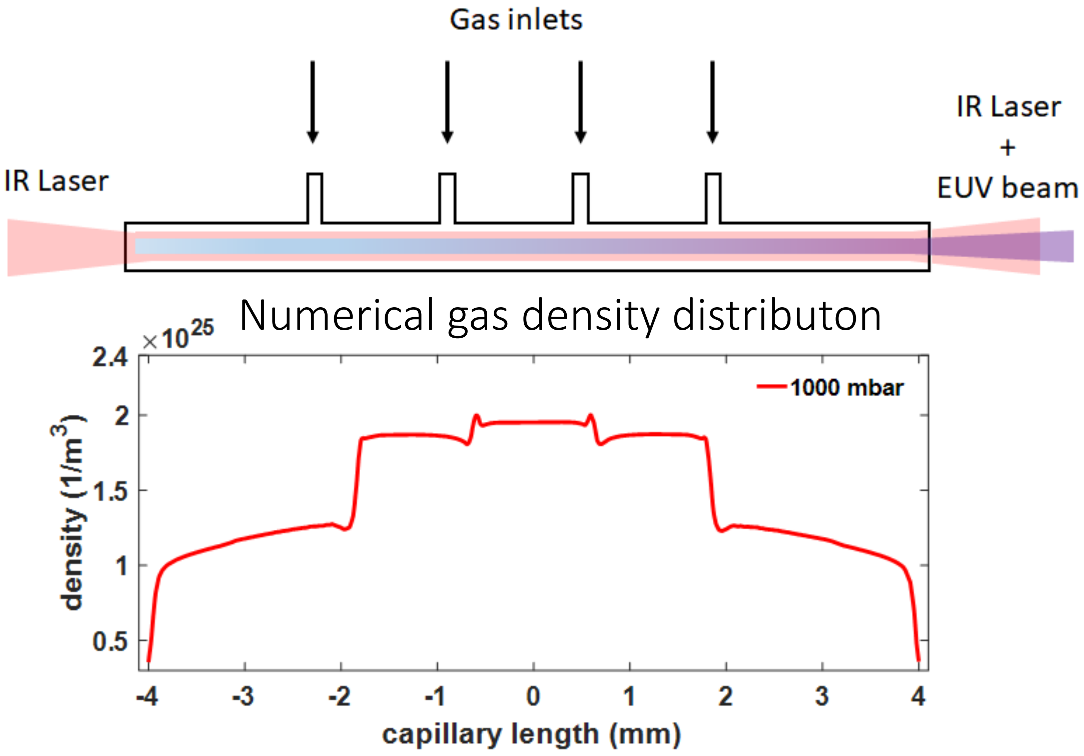
Paiè, Petra, et al. Microsystems & nanoengineering 3.1 (2017): 1-8.

A microfluidic device for HHG

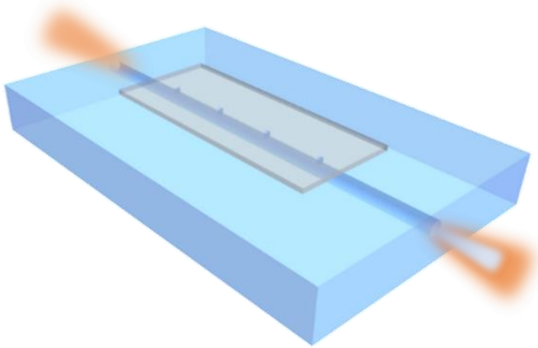




A. G. Ciriolo et al., Journal of Physics: Photonics **2** 024005 (2020)



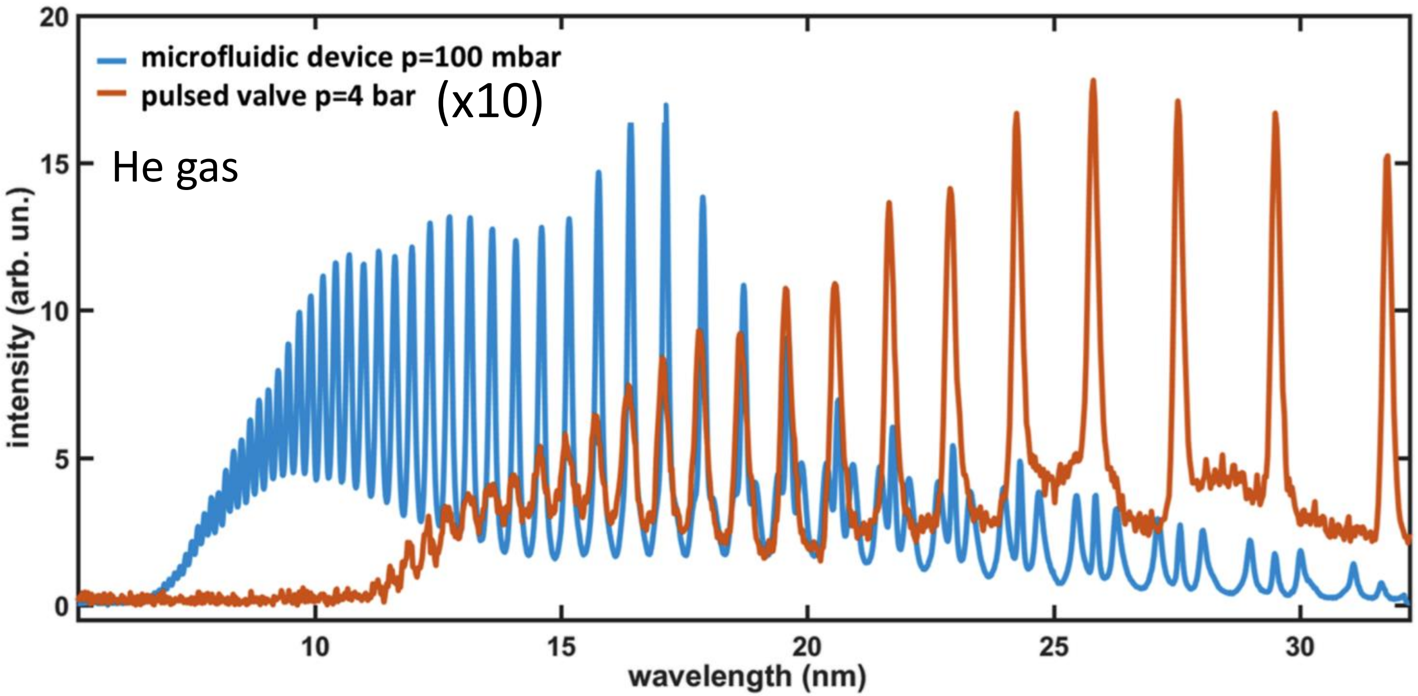
HHG spectra from the microfluidic cell



Amplified Ti:Sa laser system @ 800nm
(Amplitude, Aurora laser system)

- Repetition rate 1 kHz
- Pulse energy 450 µJ
- Pulse duration 30 fs

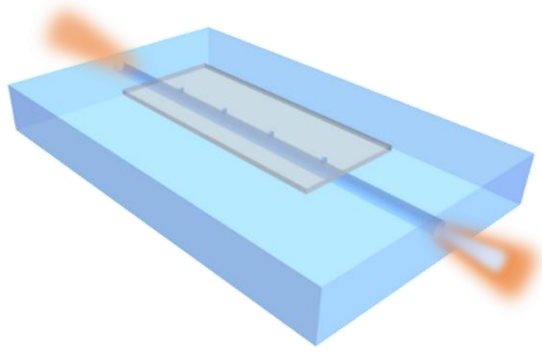
Microfluidic device vs gas valve



A. G. Ciriolo et al., Journal of Physics: Photonics **2** 024005 (2020)

A. G. Ciriolo, et al., *APL Photonics* 7.11 (2022).

HHG spectra from the microfluidic cell



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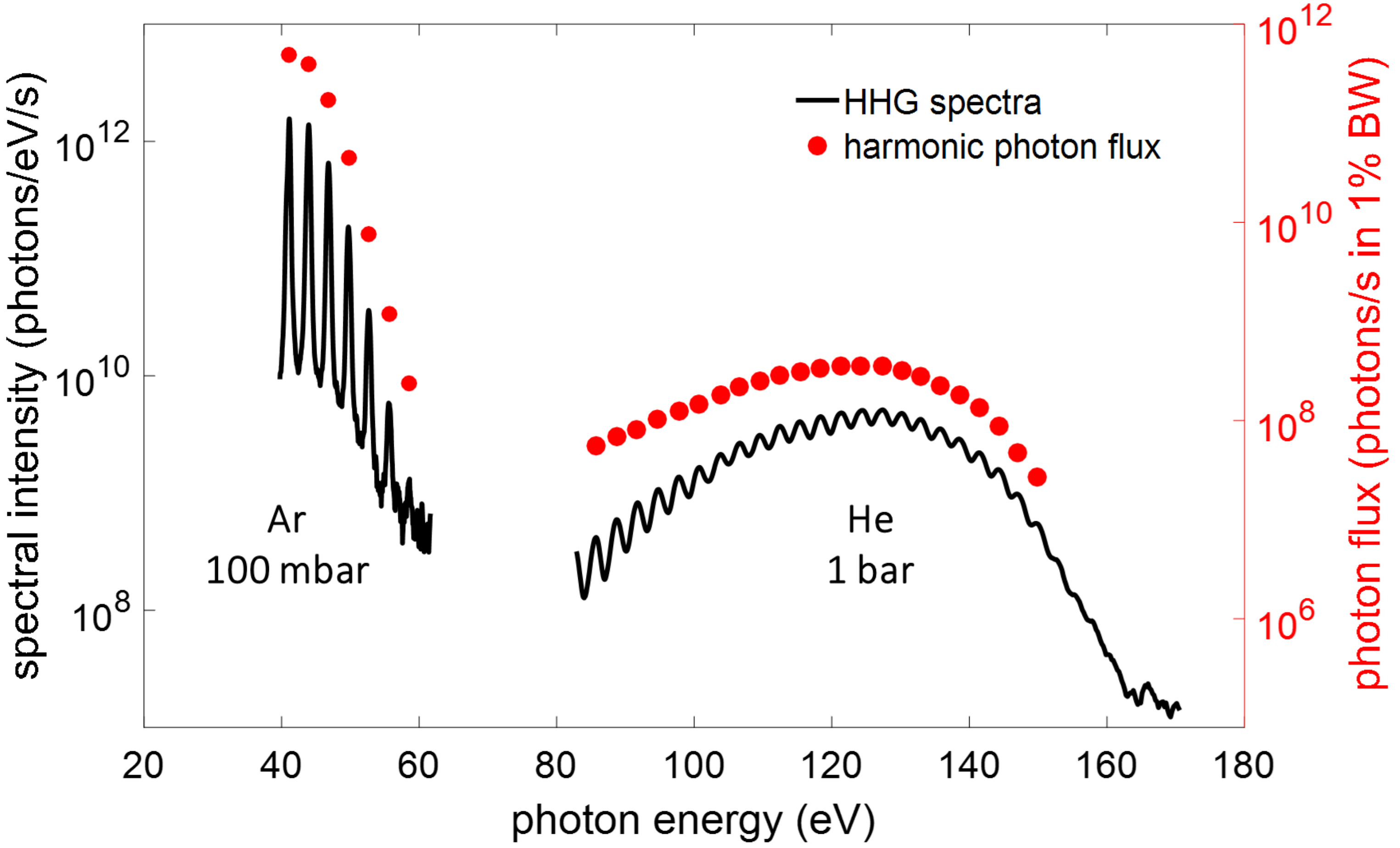
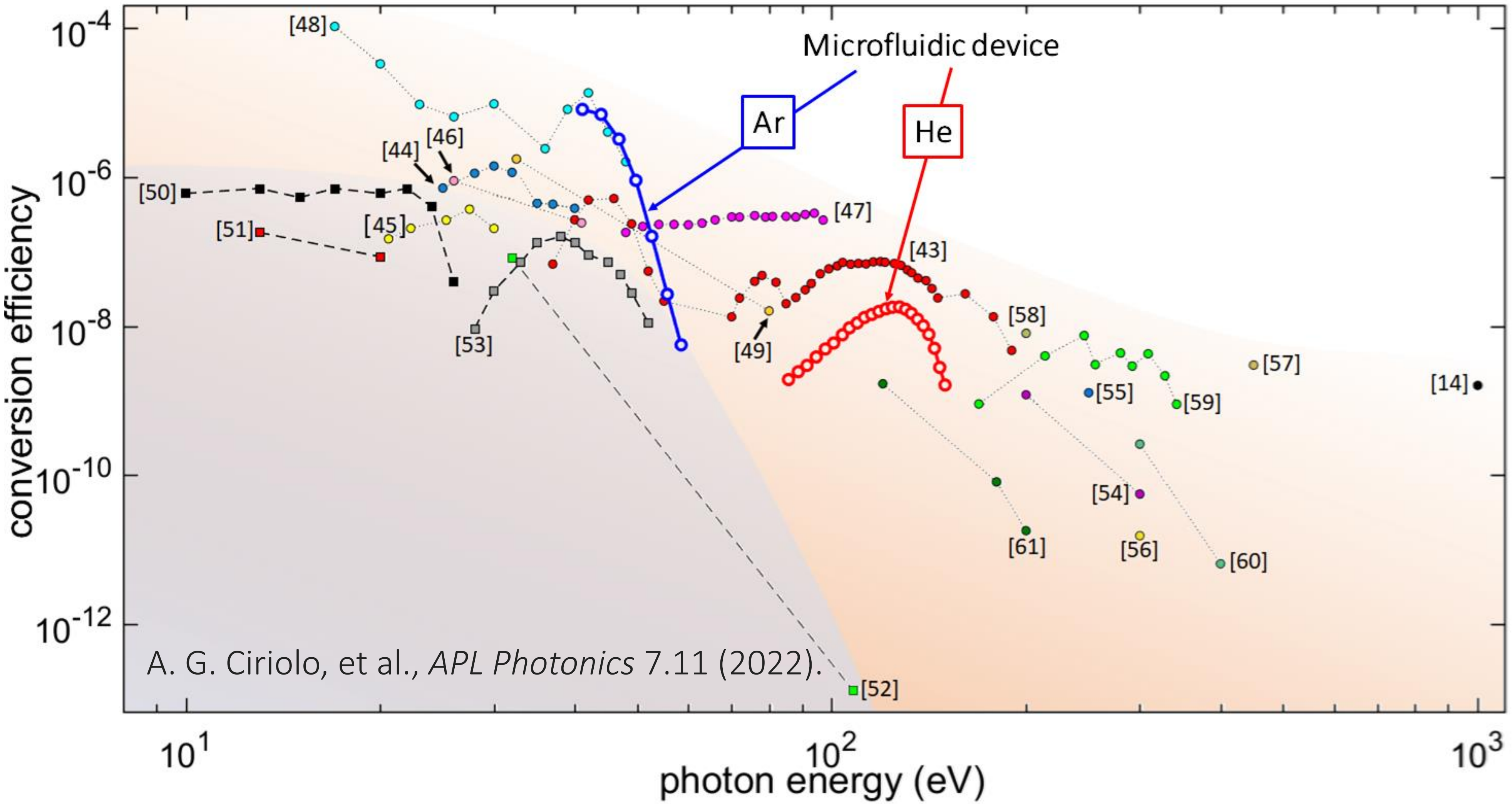


A. G. Ciriolo et al., Journal of Physics: Photonics **2** 024005 (2020)

A. G. Ciriolo, et al., *APL Photonics* 7.11 (2022).

Performances of the microfluidic source



[48] E. J. Takahashi, et al., IEEE JSTQE 10, 1315 (2004) → **gas cell**
[43] C. Ding, Optics express, vol. 22, pp. 6194-6202 (2014) → **capillary**

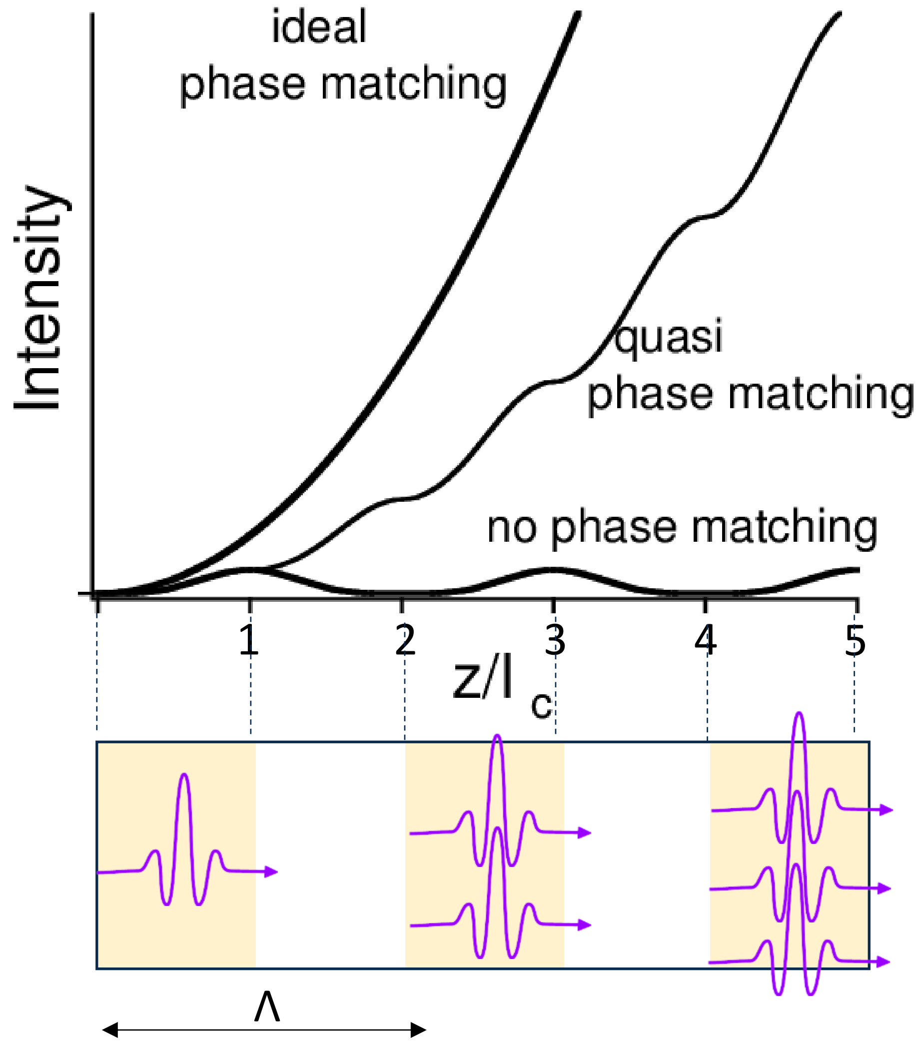
Quasi Phase Matching (QPM)

Coherence length

$$l_c = \frac{\pi}{\Delta k}$$

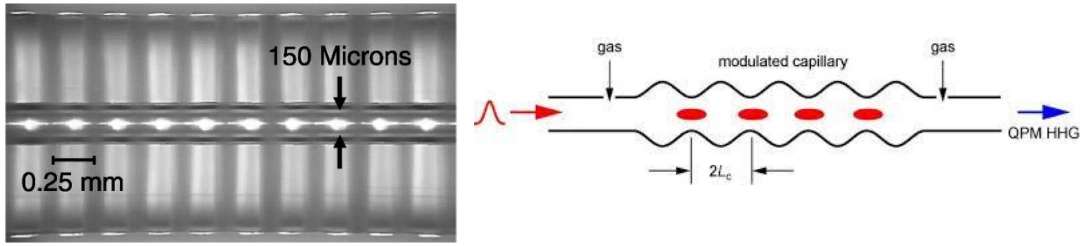
Distance at which the phase difference of two emitters is 180°

spatial modulation of the nonlinear interaction at a regular interval $\Lambda = 2l_c$



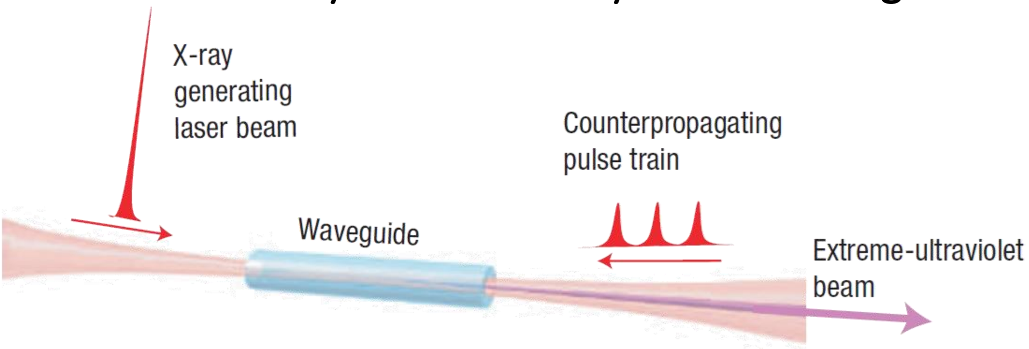
QPM strategies in HHG

Intensity modulation by waveguide diameter modulation



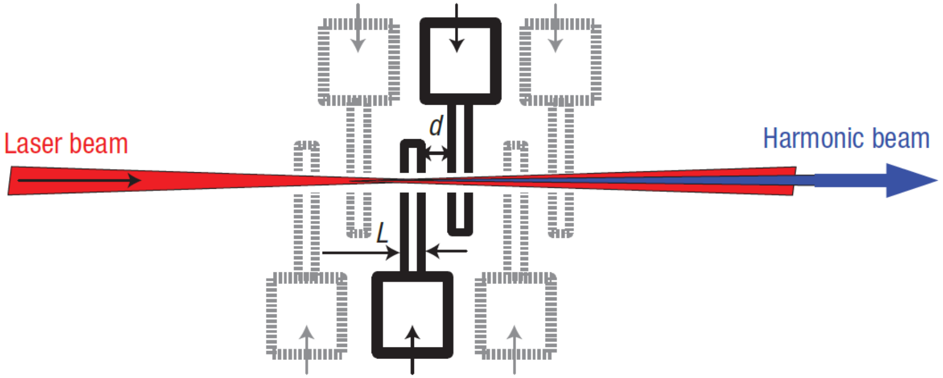
Gibson, Emily A., et al. *Science* 302.5642 (2003): 95-98.

Intensity modulation by mode beating



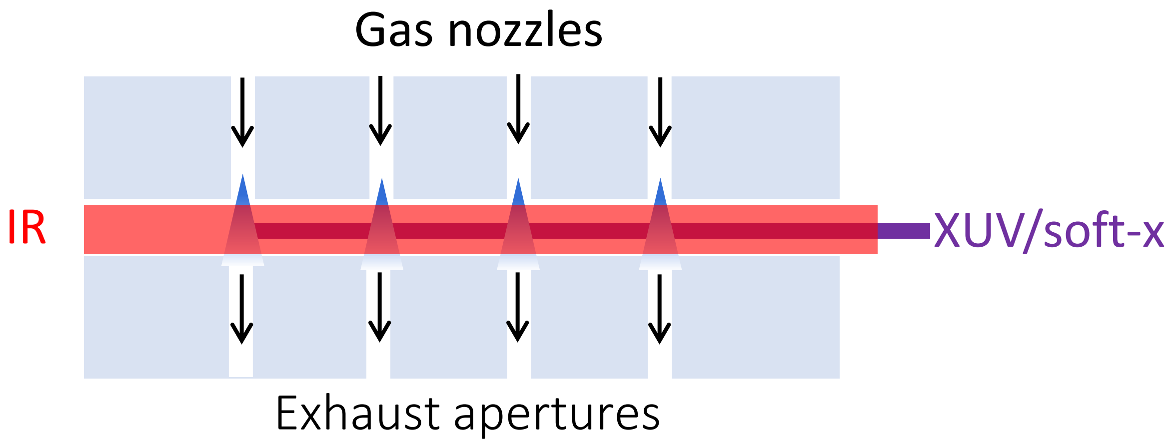
Zhang, Xiaoshi, et al. *Nature Physics* 3.4 (2007): 270-275.
Zepf, Matthew, et al. *PRL* 99.14 (2007): 143901.

Gas density modulation by multiple gas-jets

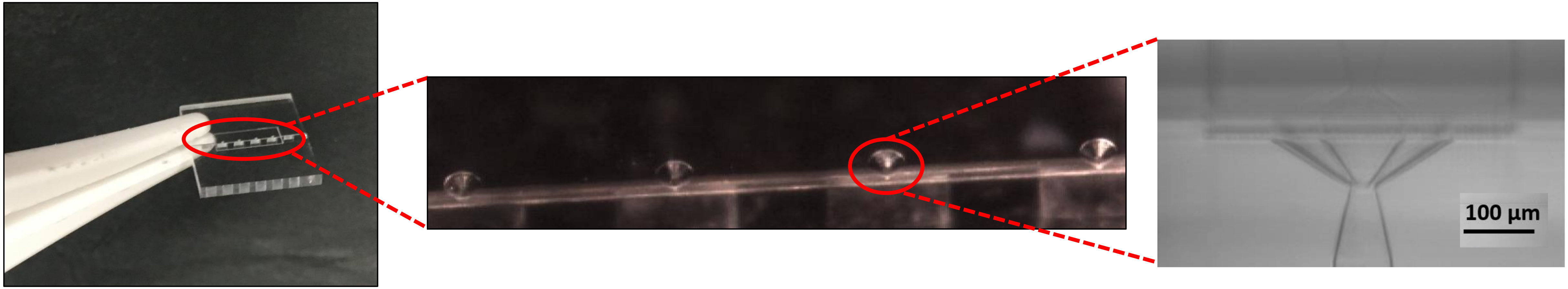


Seres, Jozsef, et al. *Nature Physics* 3.12 (2007): 878-883.

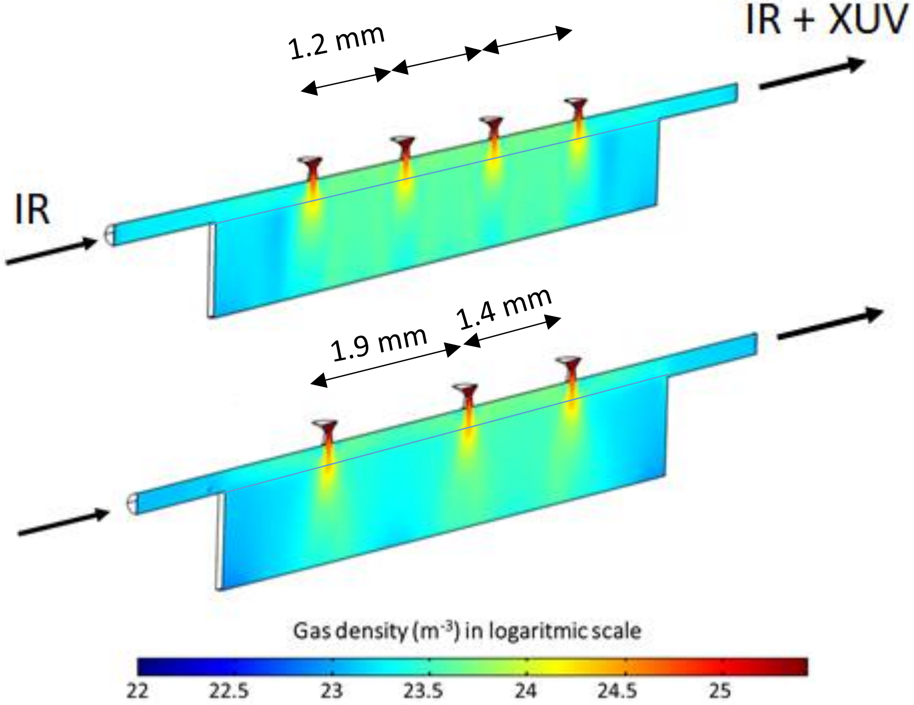
QPM in an integrated array of gas-jets



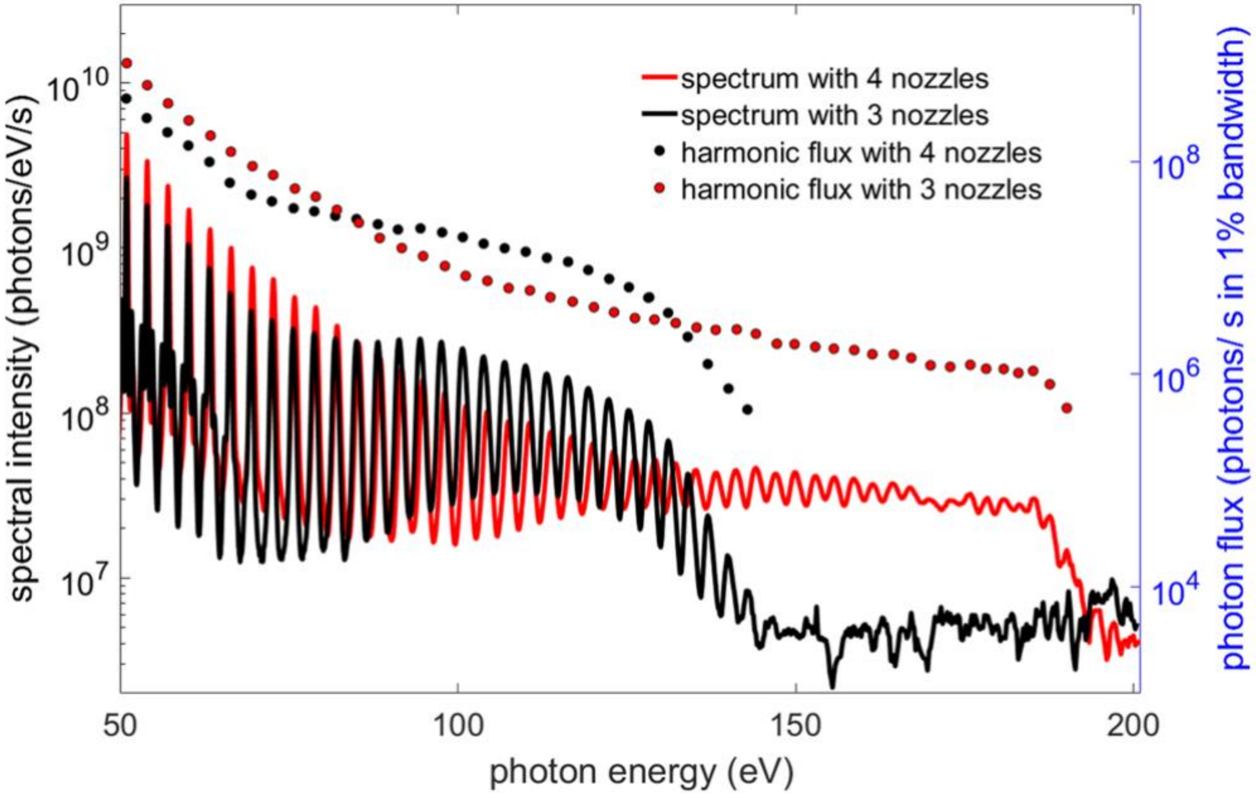
Array of **De Laval micro-nozzles** for confined supersonic gas expansion



HHG in multi-nozzle devices



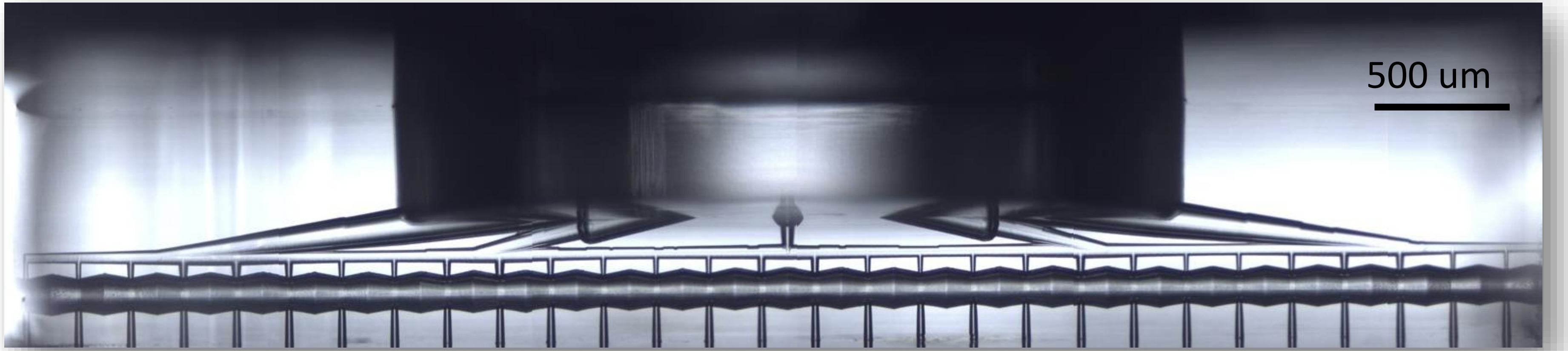
Helium gas



A. G. Ciriolo, et al., *APL Photonics* 7.11 (2022).

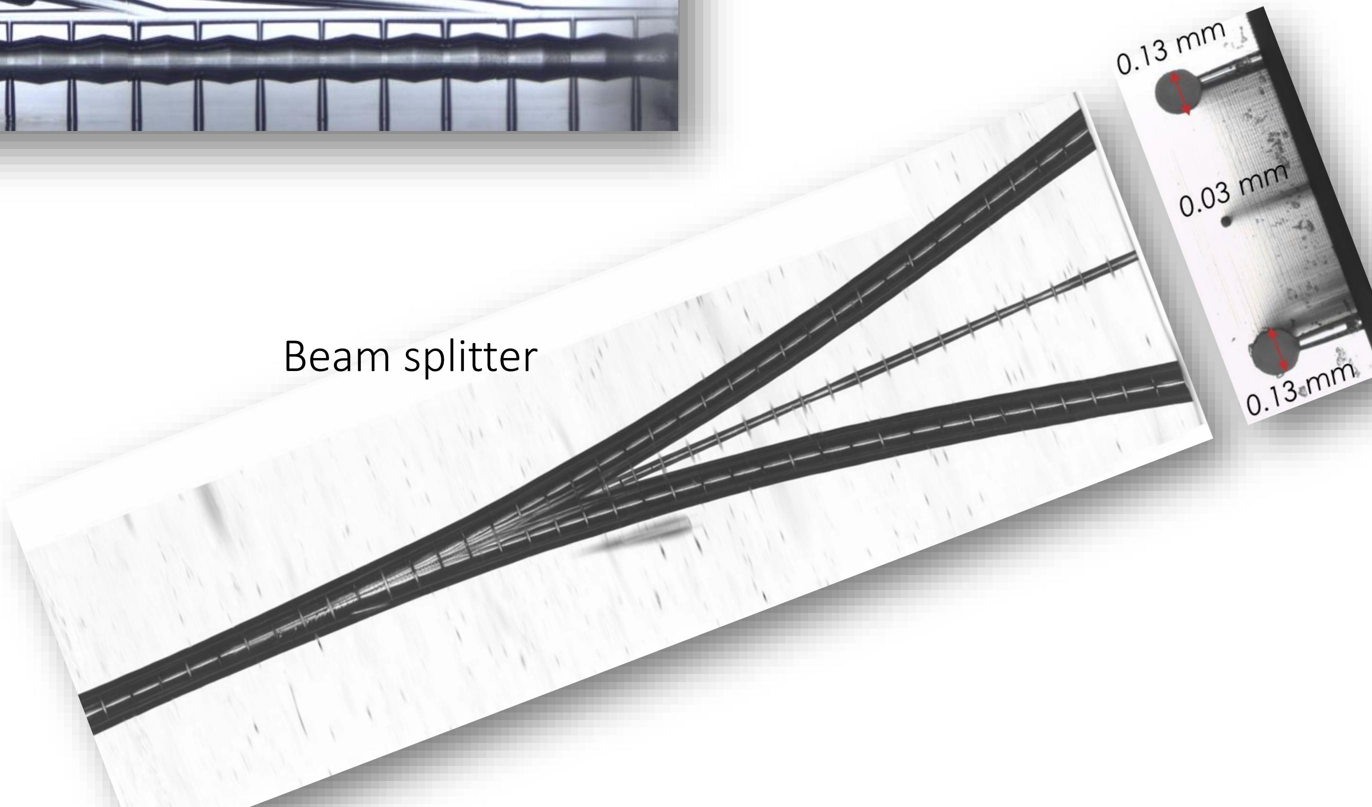
Toward more complex devices

30 nozzles - periodic modulation of the diameter (from 100 to 130 μm)



Ciriolo, A. G., et al. *Micromachines* 11.2 (2020): 165.

Beam splitter



Lab-On-a-Chip
or XUV/Soft-X spectroscopy
and Atto Science

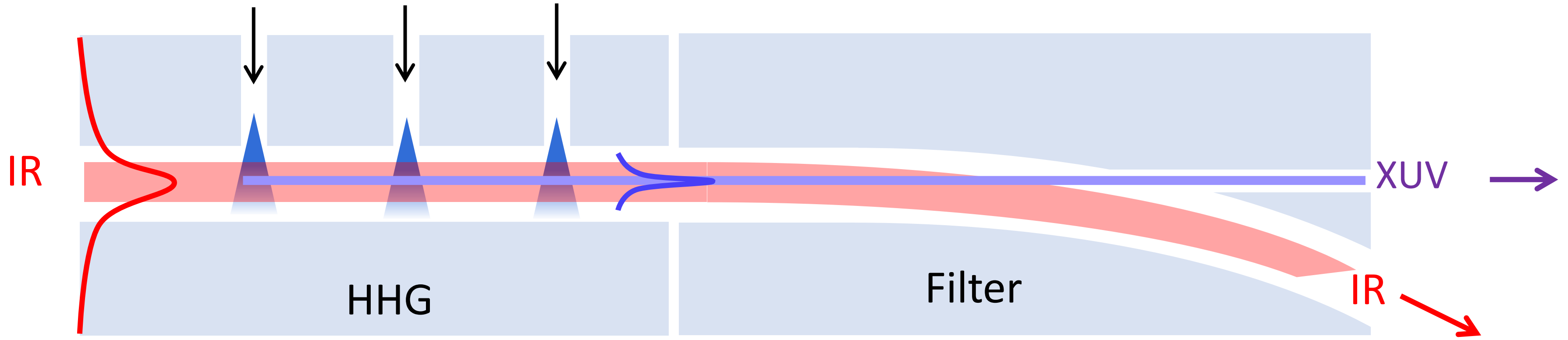
Towards LOC for ultrafast XUV science: IR rejection

Metallic thin filters

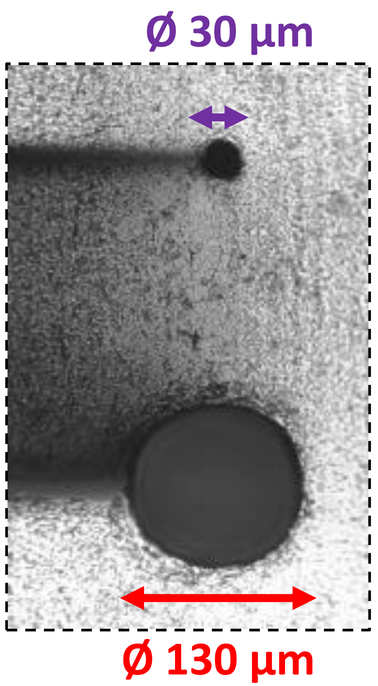
IR attenuation $I/I_0 \approx 10^{-6} \div 10^{-7}$
Expensive and prone to damage

Al filter: 20-70 eV
Zr filter: 60-200 eV

Integrated beam splitter



Output section



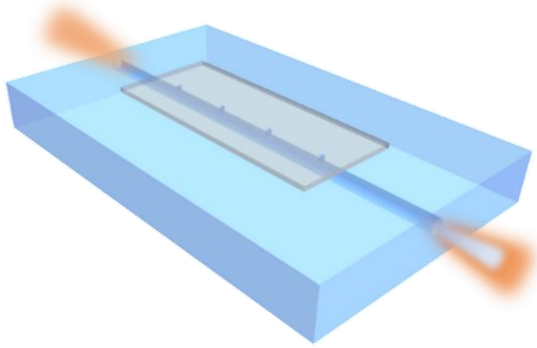
XUV beam spatial property

Confined in the center of the waveguide
$\boldsymbol{r_{xuv}} \ll \boldsymbol{a}$ (with a wavegudie radius)

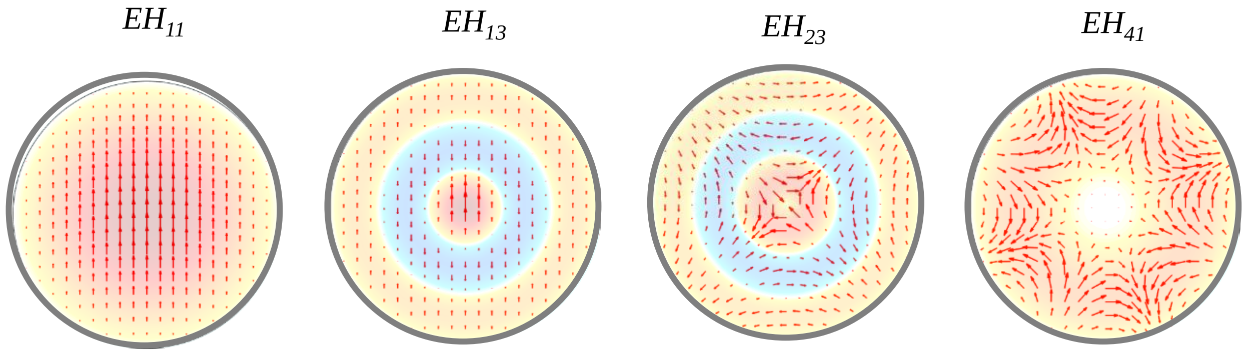
IR attenuation law

$$\alpha_{nm} = \frac{\lambda^2}{a^3} U_{nm}(\nu)$$

Structured light in a hollow waveguide



modes

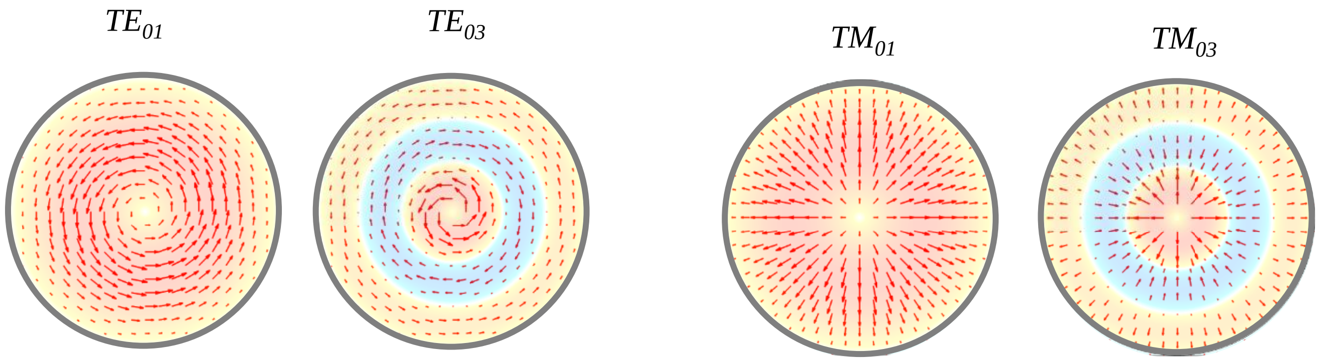


$$E_{n,m}(\theta) = J_{n-1}(u_{n,m}r/a)\cos n\theta$$
$$E_{n,m}(r) = J_{n-1}(u_{n,m}r/a)\sin n\theta$$

Hybrid modes (EH)
Non-zero electric and magnetic fields in the direction of propagation.

Transverse electric (TE) modes
No electric field in the direction of propagation.

Transverse magnetic (TM) modes
No magnetic field in the direction of propagation.



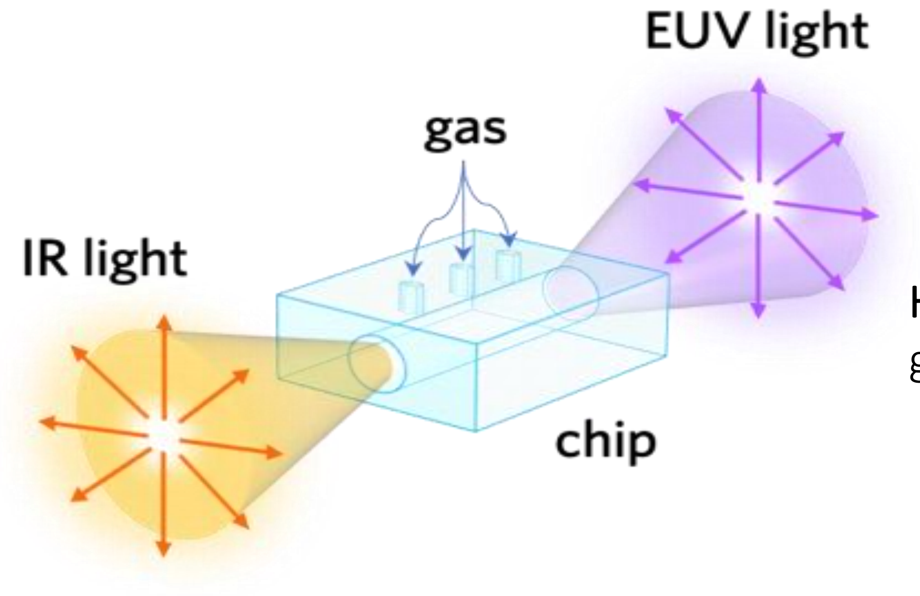
$$E_{0,m}(\theta) = J_1(u_{0,m}r/a)$$

$$E_{0,m}(r) = J_1(u_{0,m}r/a)$$

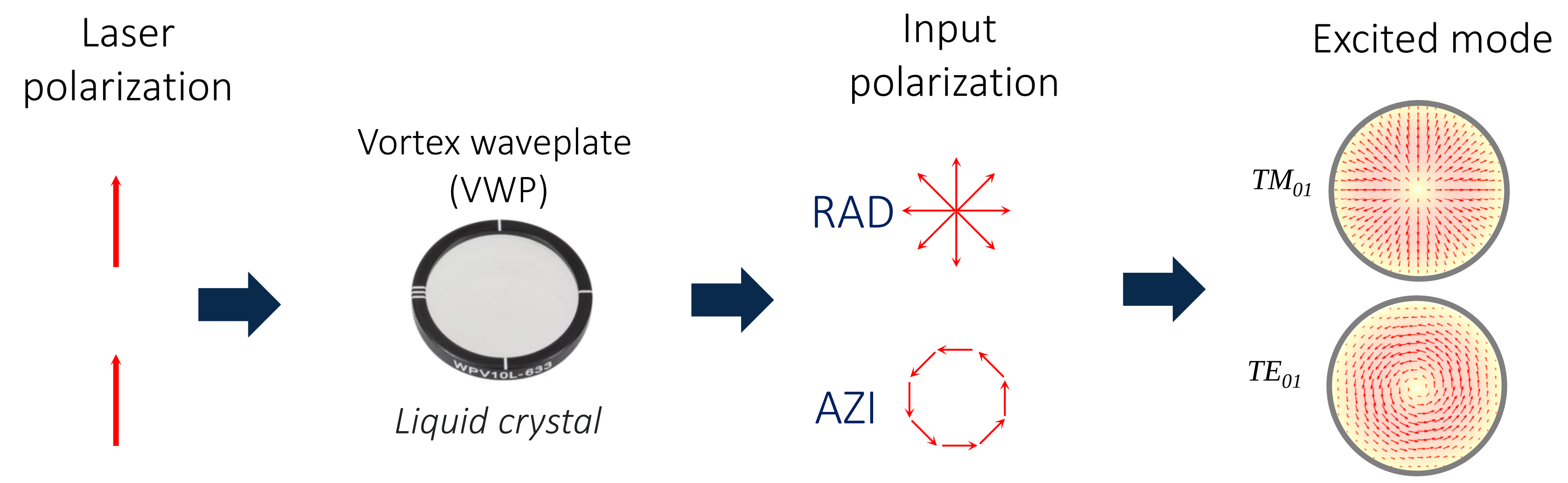
Vector modes/ beams: a beam where the **polarization state varies spatially** across the beam profile

E.A.J. Marcatili and R.A. Schmeltzer, The Bell System technical journal, 1964.

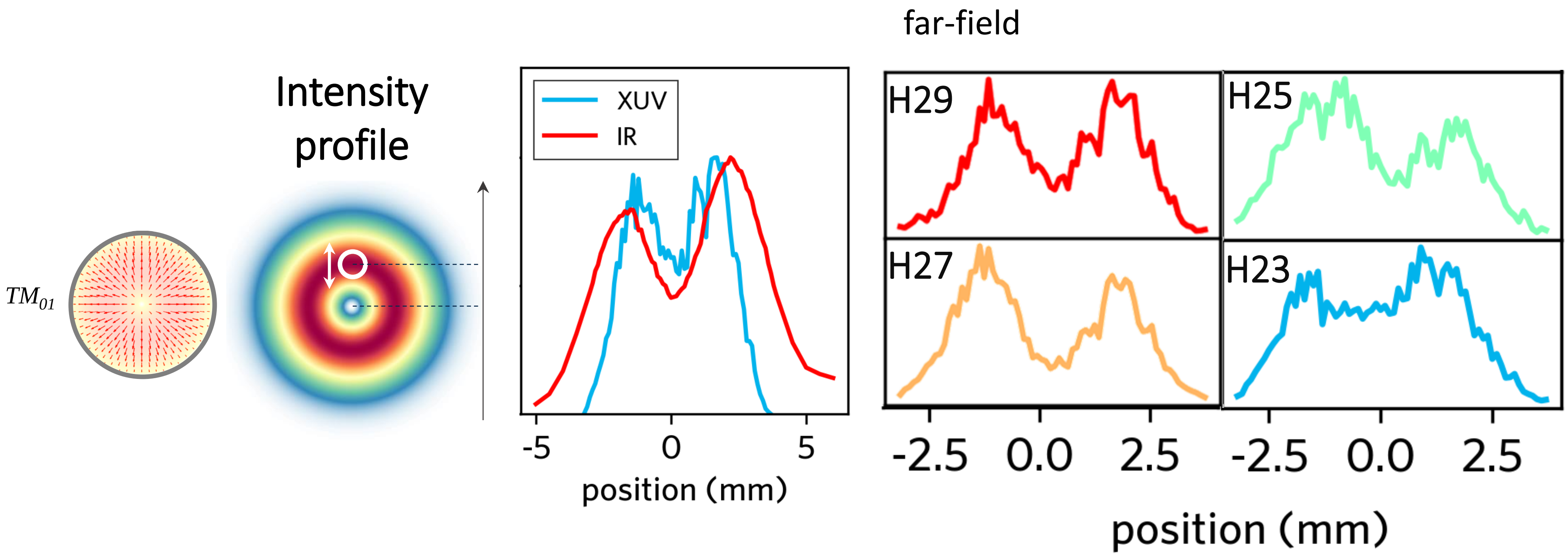
HHG driven by vectorial fields



HHG locally preserves the polarization orientation of the driver: generation of **XUV vector beam** of TM_{01} and TE_{01} symmetry



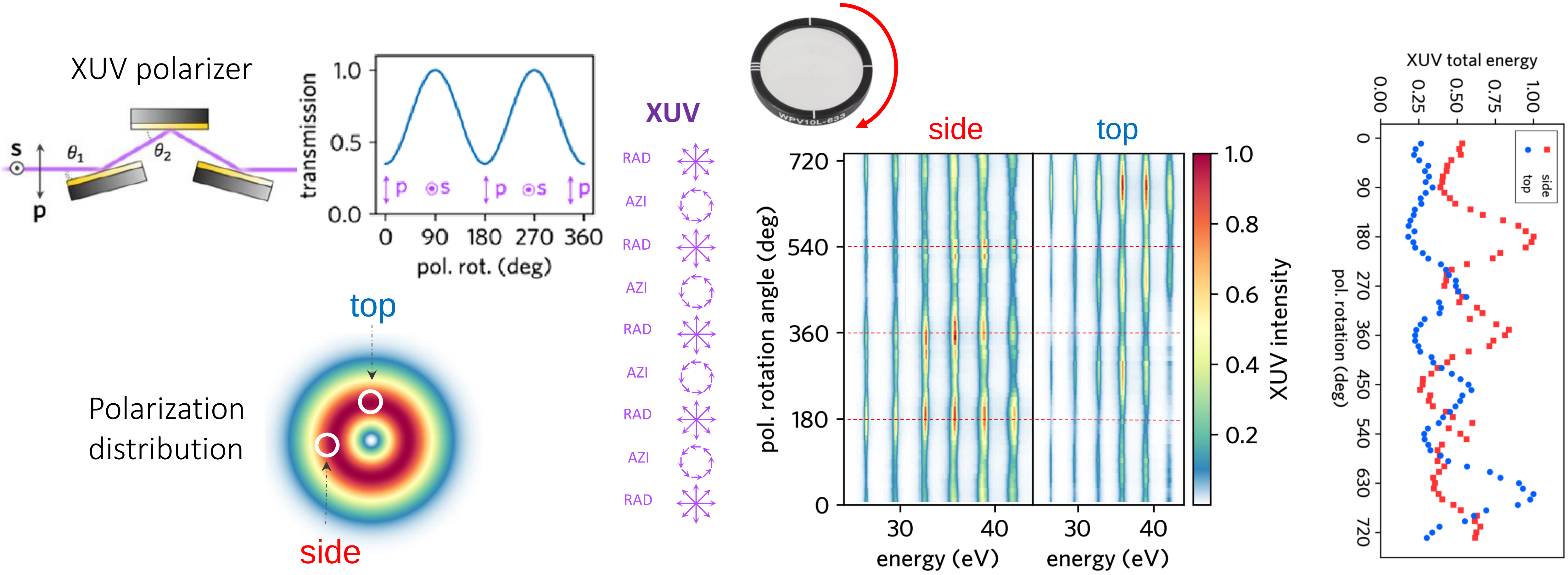
XUV Vector Beam: intensity profile



Singularity in the center of the intensity profile

R. Piccoli et al., http://arxiv.org/abs/2403.11006.

XUV vector beam: polarization

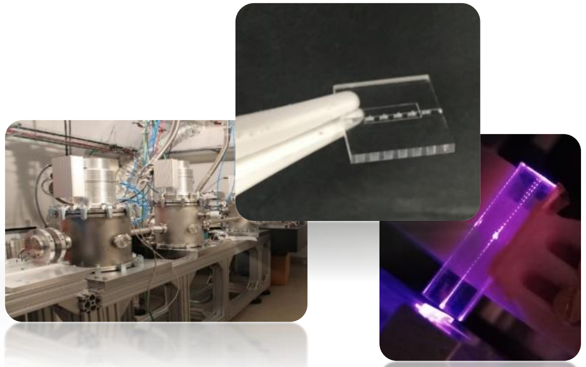


In collaboration with Dr. R. Piccoli
(Università Cà Forscari, Venezia)

R. Piccoli et al., http://arxiv.org/abs/2403.11006.

Conclusion

- Prototyping of **hollow waveguide-based circuits** for efficient HHG
- A compact table-top source of coherent **XUV vector beams**
- Scaling to XUV generation in the **water window** (280-500 eV) by using near/mid-IR drivers
- More complex systems: X-rays LOC



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CONQUEST

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Thank you for your attention!