

Visualizing Plasma Waves and Long-Living Soliton-Like Structures in a Laser-Wakefield Accelerator

Yu Zhao^{1,2}, Alexander Sävert¹, Xinhe Huang¹, Matt Zepf, Daniel Seipt¹, and Malte C. Kaluza^{1,2}

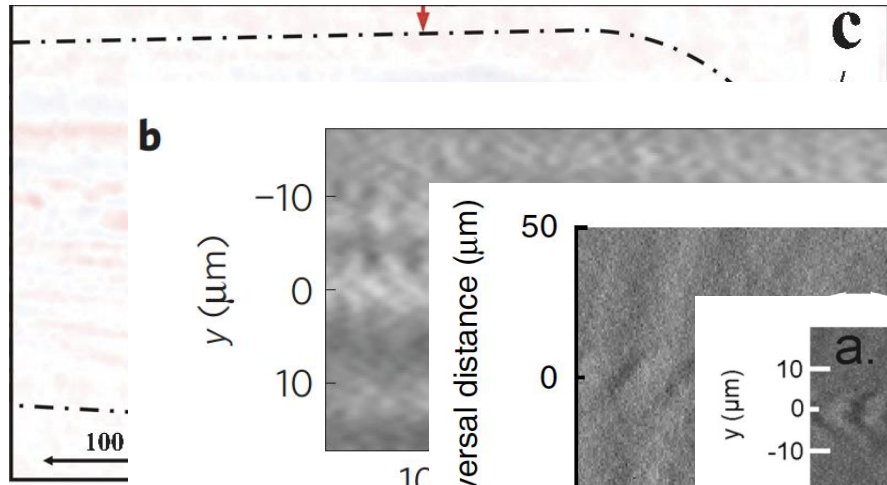
¹Helmholtz Institute Jena, Germany.

²Institute of Optics and Quantum Electronics, Jena, Germany.

Motivation

- Why (and when) is (few-cycle) probing of plasma accelerators useful?
- Which acceleration scenarios can be investigated with a pump-probe configuration?
- Which parameters of the interaction can be diagnosed?
 - plasma parameters (density, temperature,...)
 - acceleration fields (E- and B-fields),
 - laser field?
 - ...?
- What are the next steps on our agenda?

Optical Probing of Laser-Matter Interactions



M. Kaluza *et al.*, PRL **3**, 109 (2010)

A. Buck *et al.*, Nat. Physics **7**, 543 (2011)

M. Schnell *et al.*, Nat. Comm. **4**, 2421 (2013)

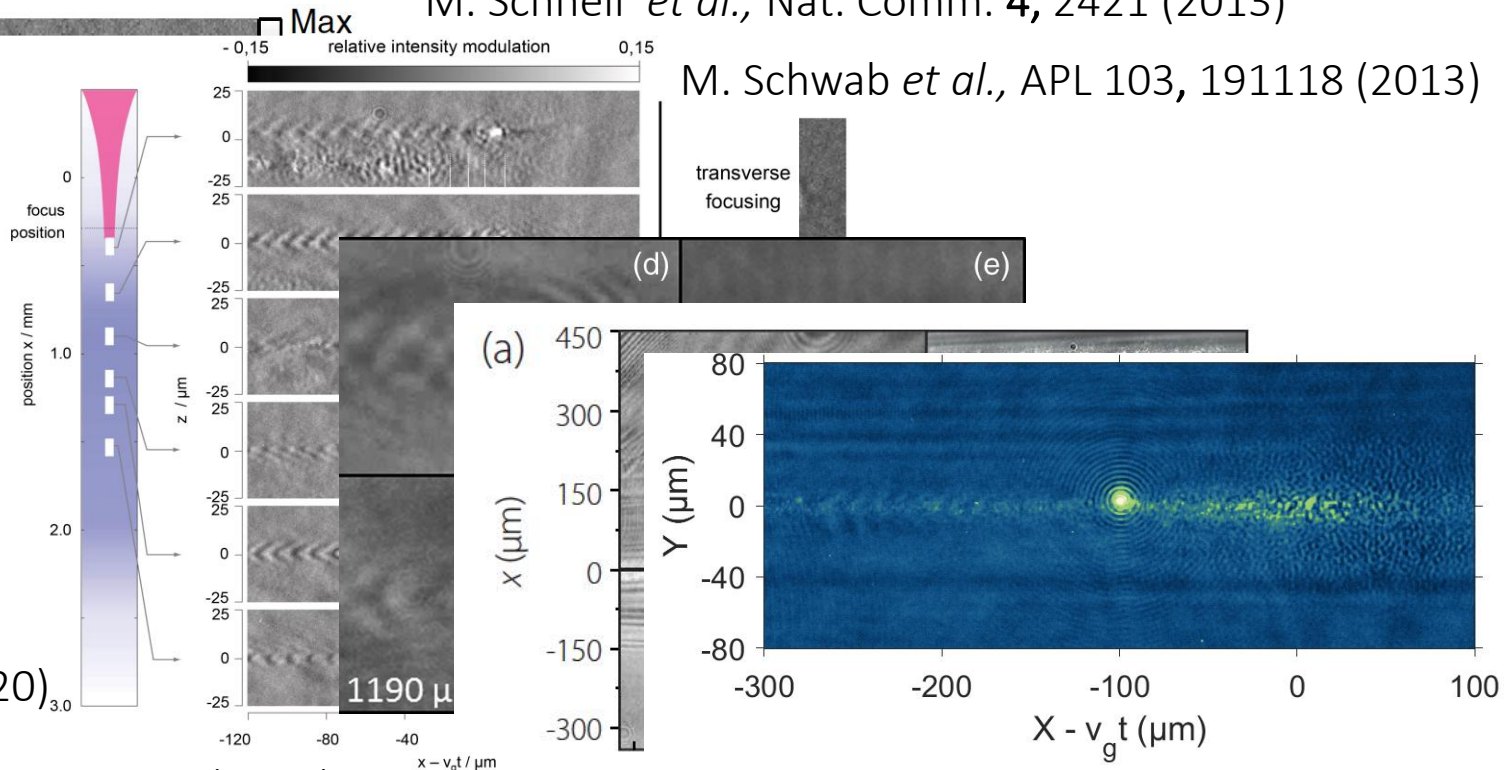
M. Schwab *et al.*, APL 103, 191118 (2013)

A. Sävert *et al.*, PRL **115**, 055002 (2015)

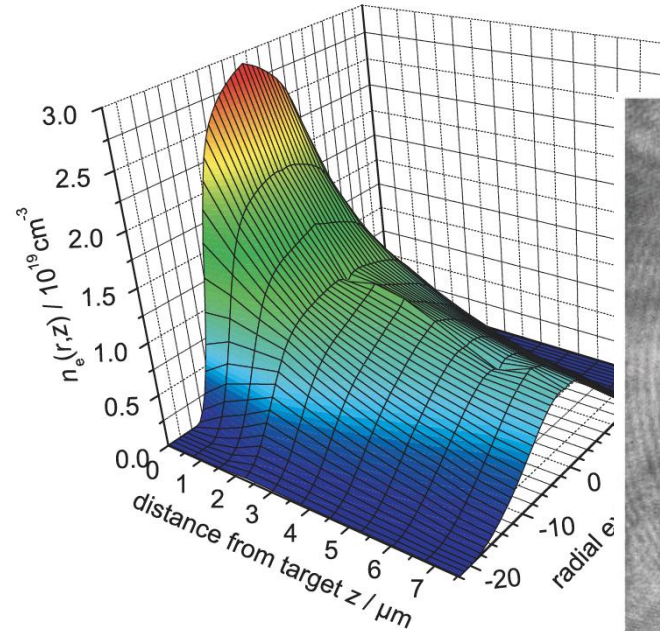
M. Schwab *et al.*, PRAB 23, 032801 (2020)

C. Zepter *et al.*, PRR 5, L012023 (2023)

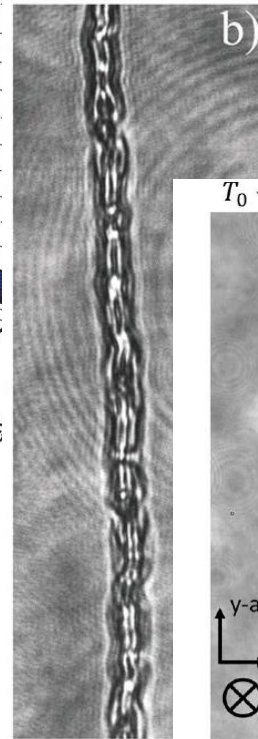
Y. Zhao *et al.*, submitted (2026)



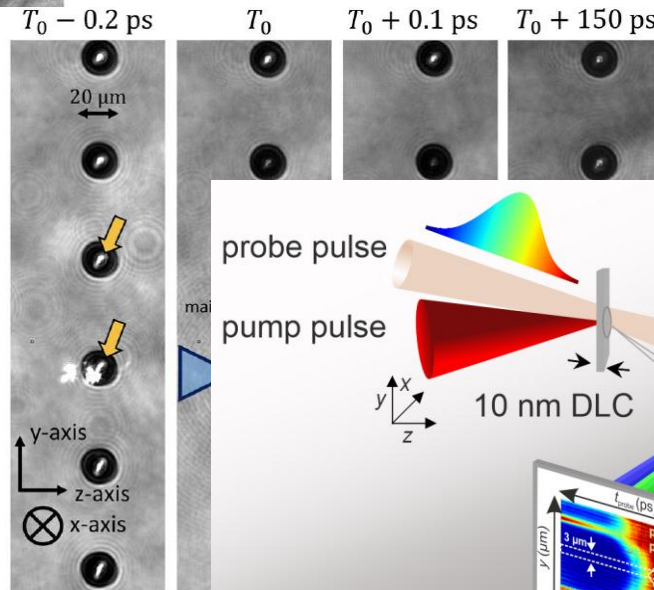
Optical Probing of Laser-Matter Interactions



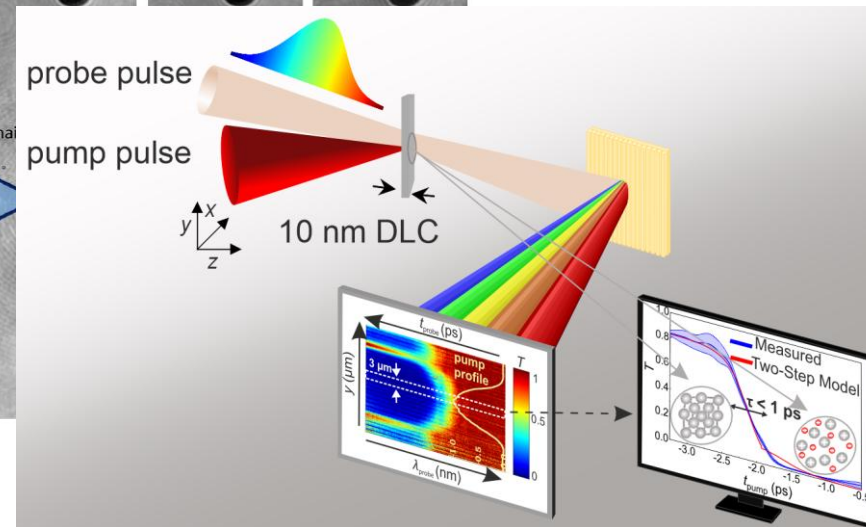
O. Jäckel *et al.*, NJP **12**, 103027 (2010)



J. Polz *et al.*, Sci. Rep. 9, 16534 (2019)



G. Becker *et al.*, Sci. Rep. 9, 17169 (2019)

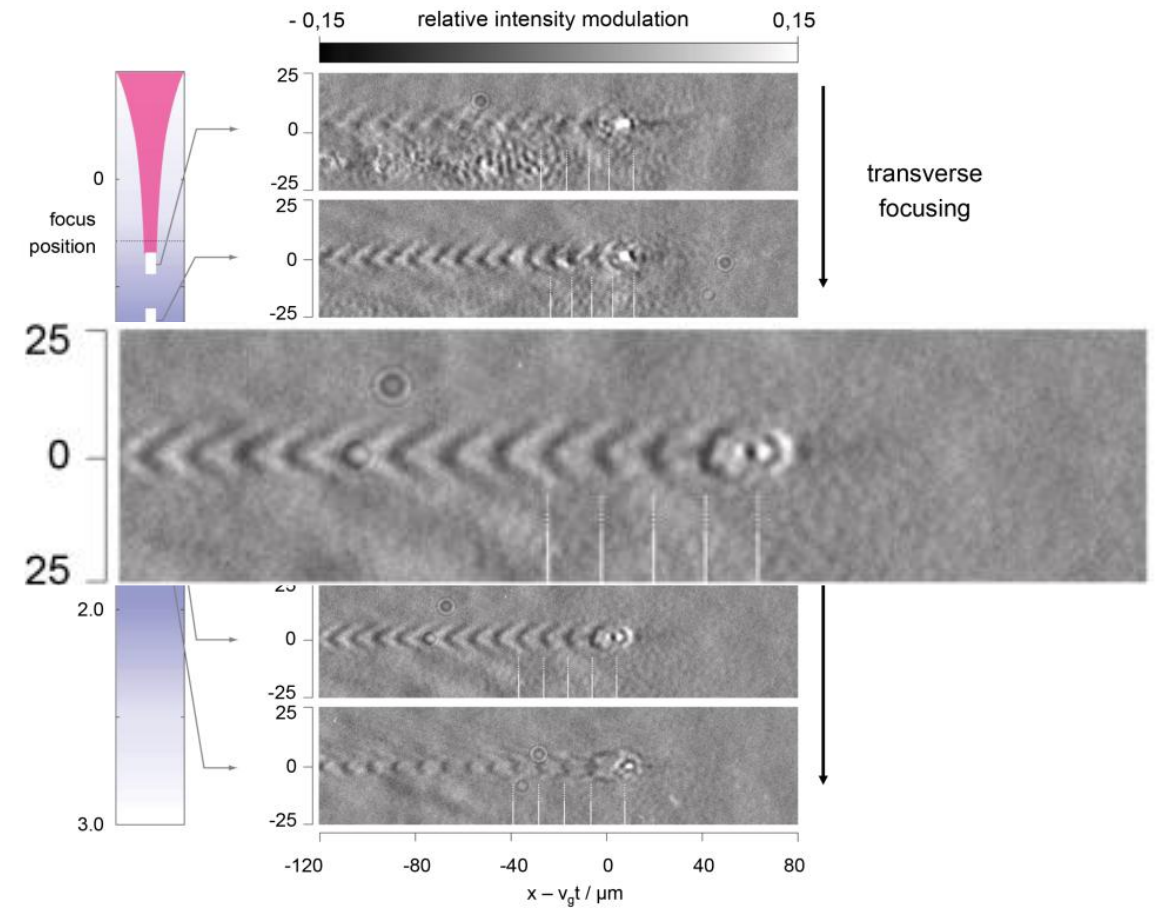
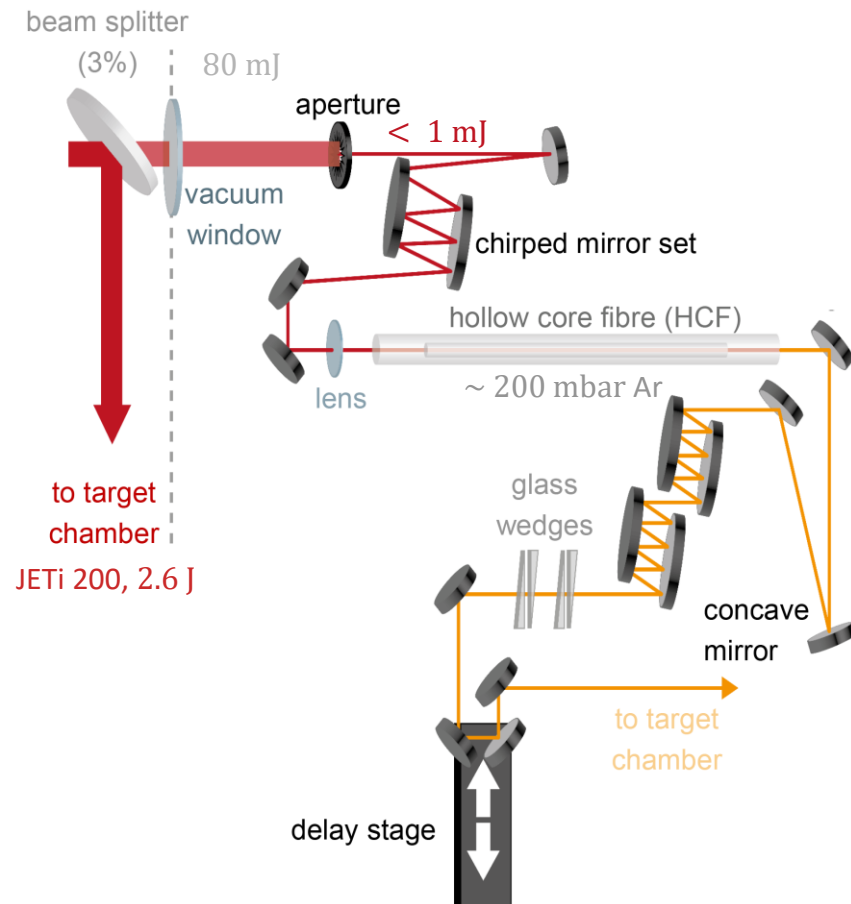


Y. Azamoum *et al.*, Light: Science & Applications **13**, 109 (2024)

Underdense Plasma: Wakefield Generation

- Probing of underdense laser-matter interactions:
 - Laser-driven electron acceleration
- Methods
 - ***Experiment:*** Space & time-resolved “movies” of plasma wave and optical emission
 - ***Numerical Simulations:*** see next talk by Daniel Seipt
- Results
 - Signatures of long-living soliton-like structures

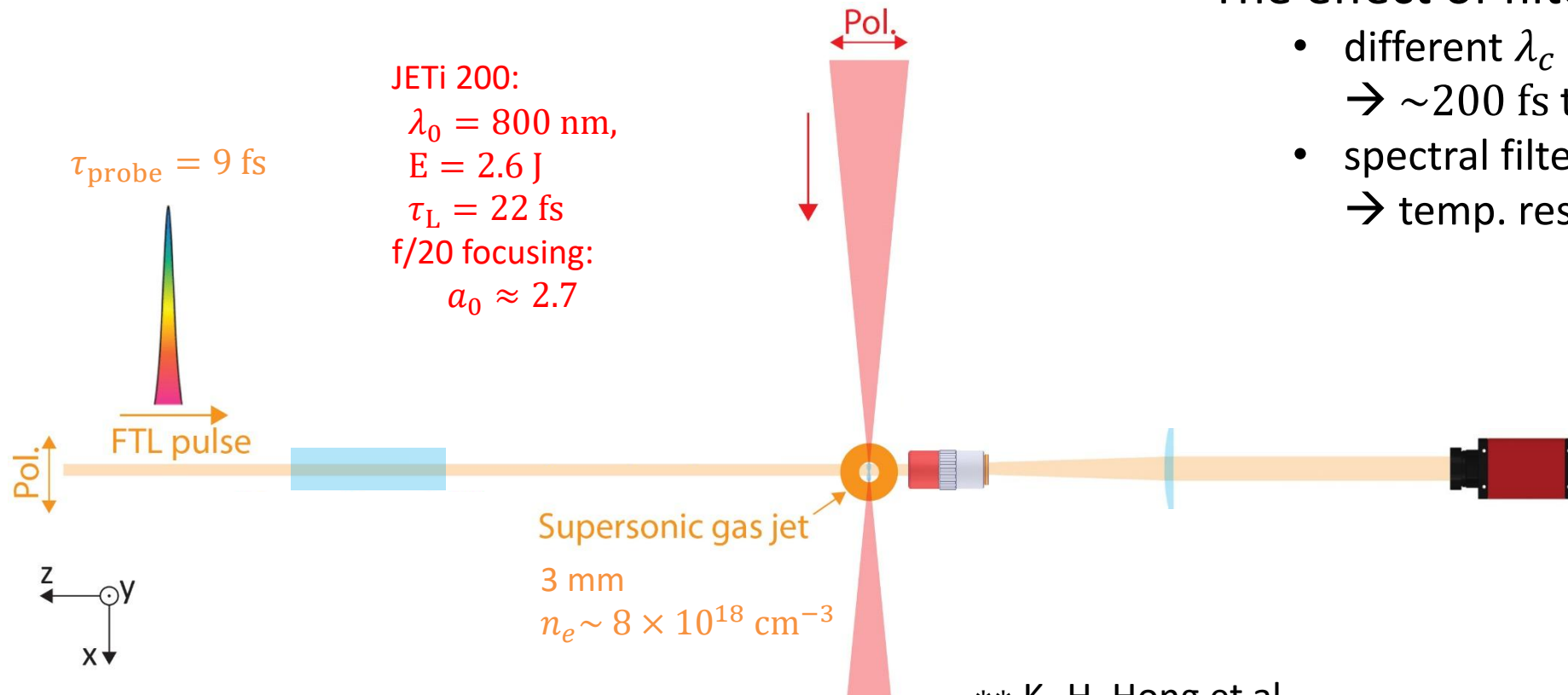
Few-cycle probing of wakefields



Limitation: only ONE snapshot from a single interaction

Few-cycle microscopic burst imaging

Few-cycle microscopy



The effect of filters:

- different $\lambda_c \rightarrow$ different Δt
 $\rightarrow \sim 200$ fs time window
- spectral filtering
 $\rightarrow$ temp. resolution < 16 fs **

** K.-H. Hong et al.,
Appl. Phys. B 74, S231 (2002)

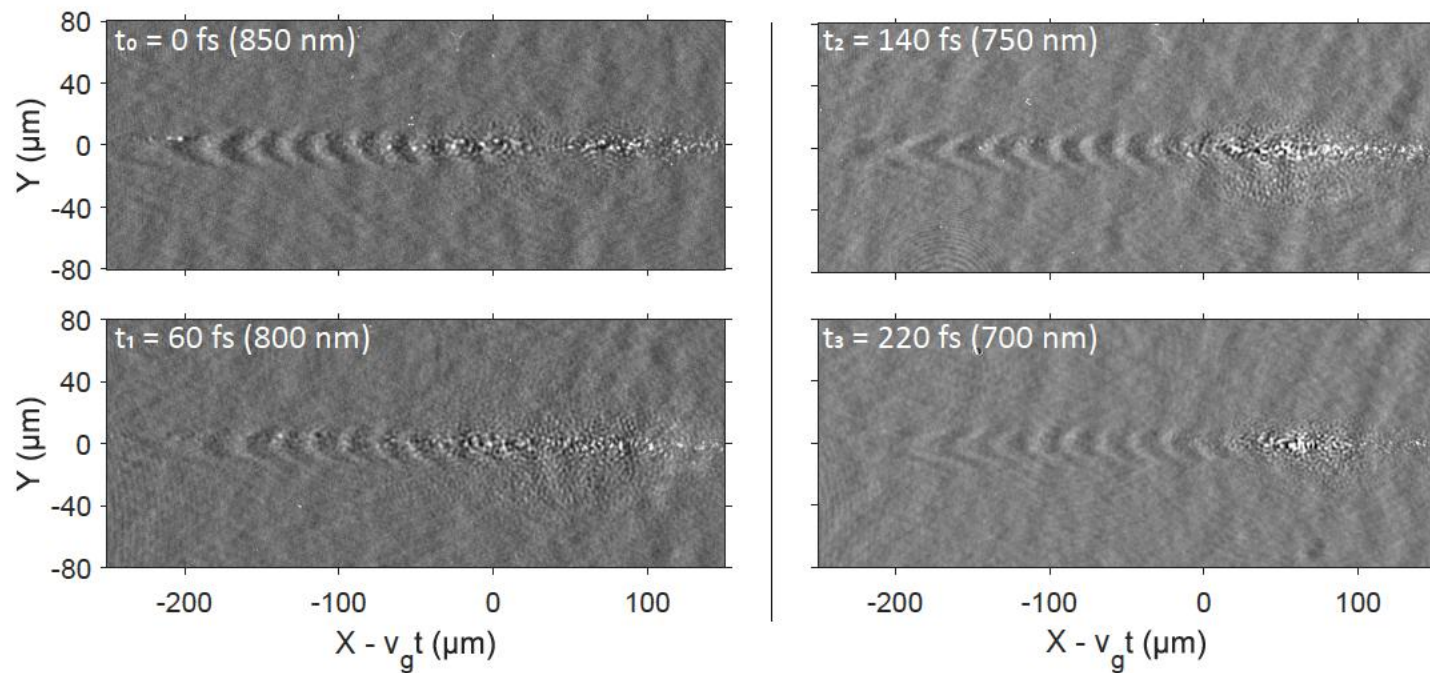
HI JENA
Helmholtz Institute Jena

* K. Nakagawa et al., Nature Photonics 8, 695–700 (2014)

www.hi-jena.de

Few-cycle microscopic burst imaging

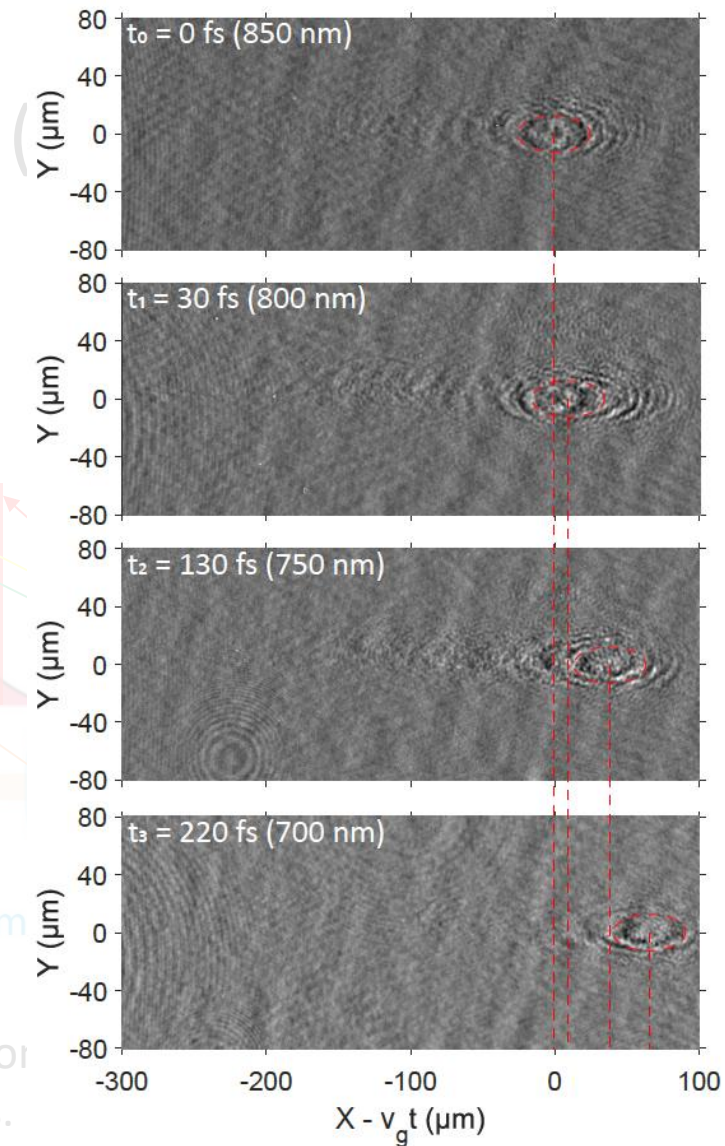
4 image frames of the same laser shot and interaction region:



$x \downarrow$

$$n_e \sim 8 \times 10^{18} \text{ cm}^{-3}$$

** K.-H. Ho
Appl. Phys.



$t \Delta t$
 w
 16 fs^{**}

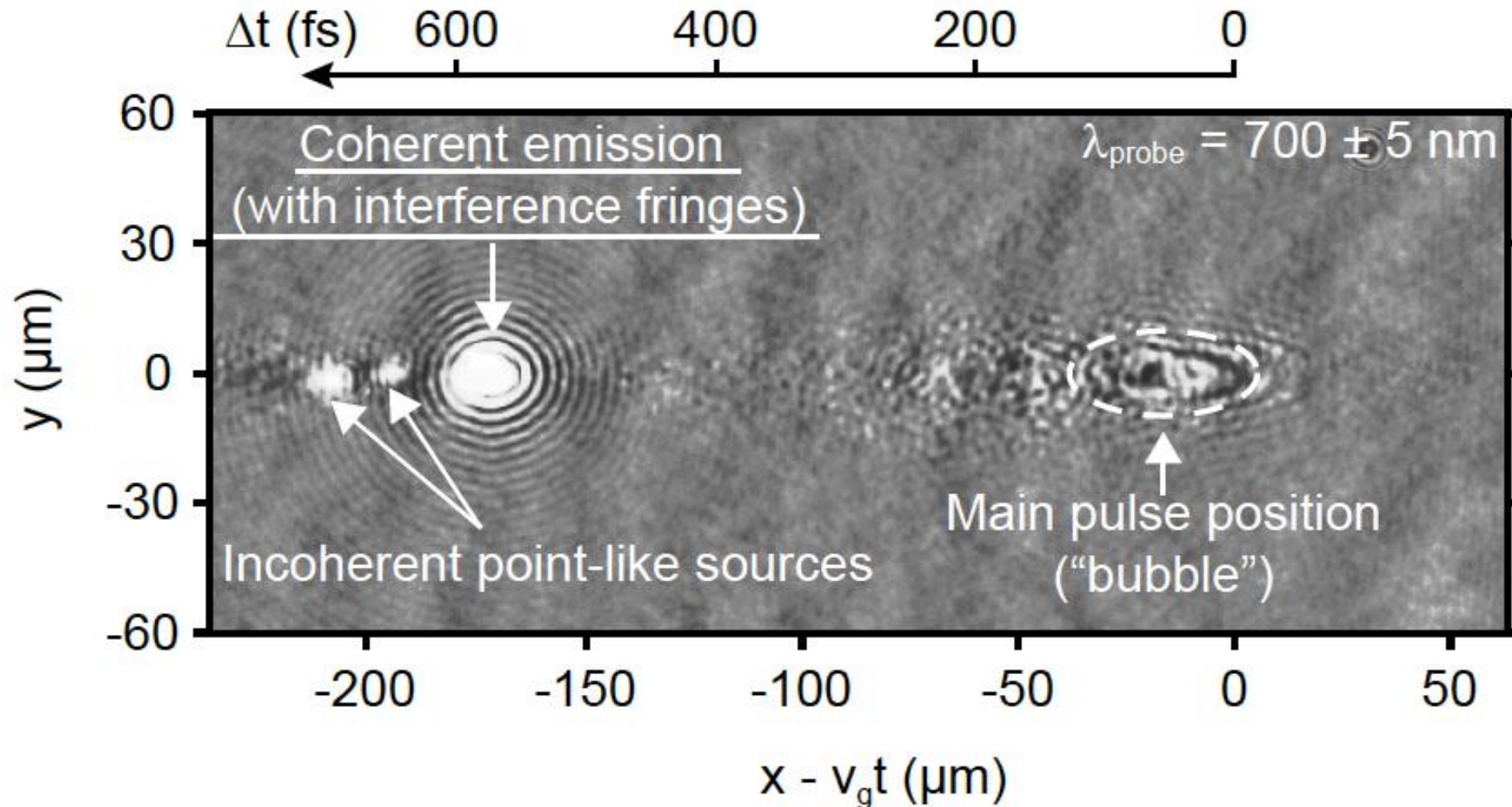
* K. Nakagawa et al., Nature Photonics 8, 695–700 (2014)

ENA
stitute Jena

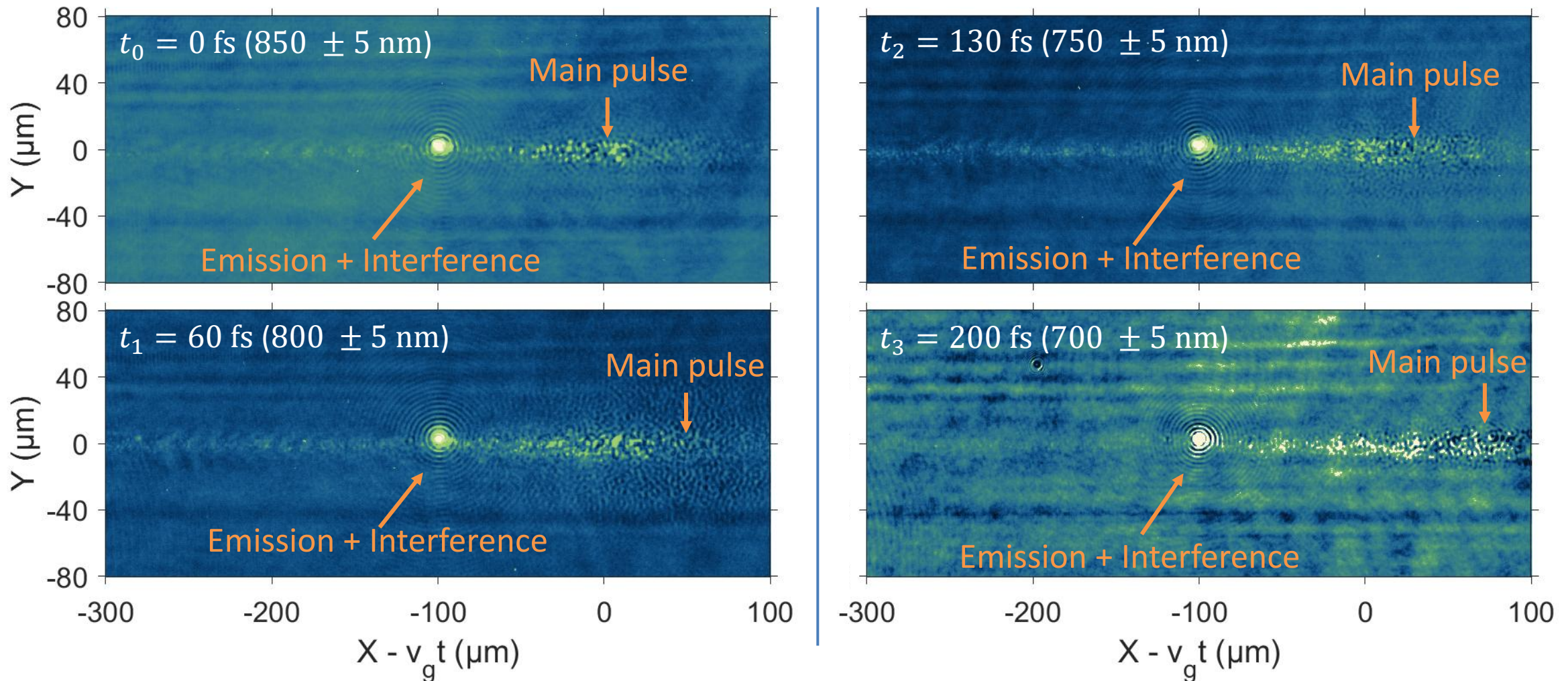
www.hi-jena.de

Localized sources of coherent emission

Only adjusted brightness to optimize visibility

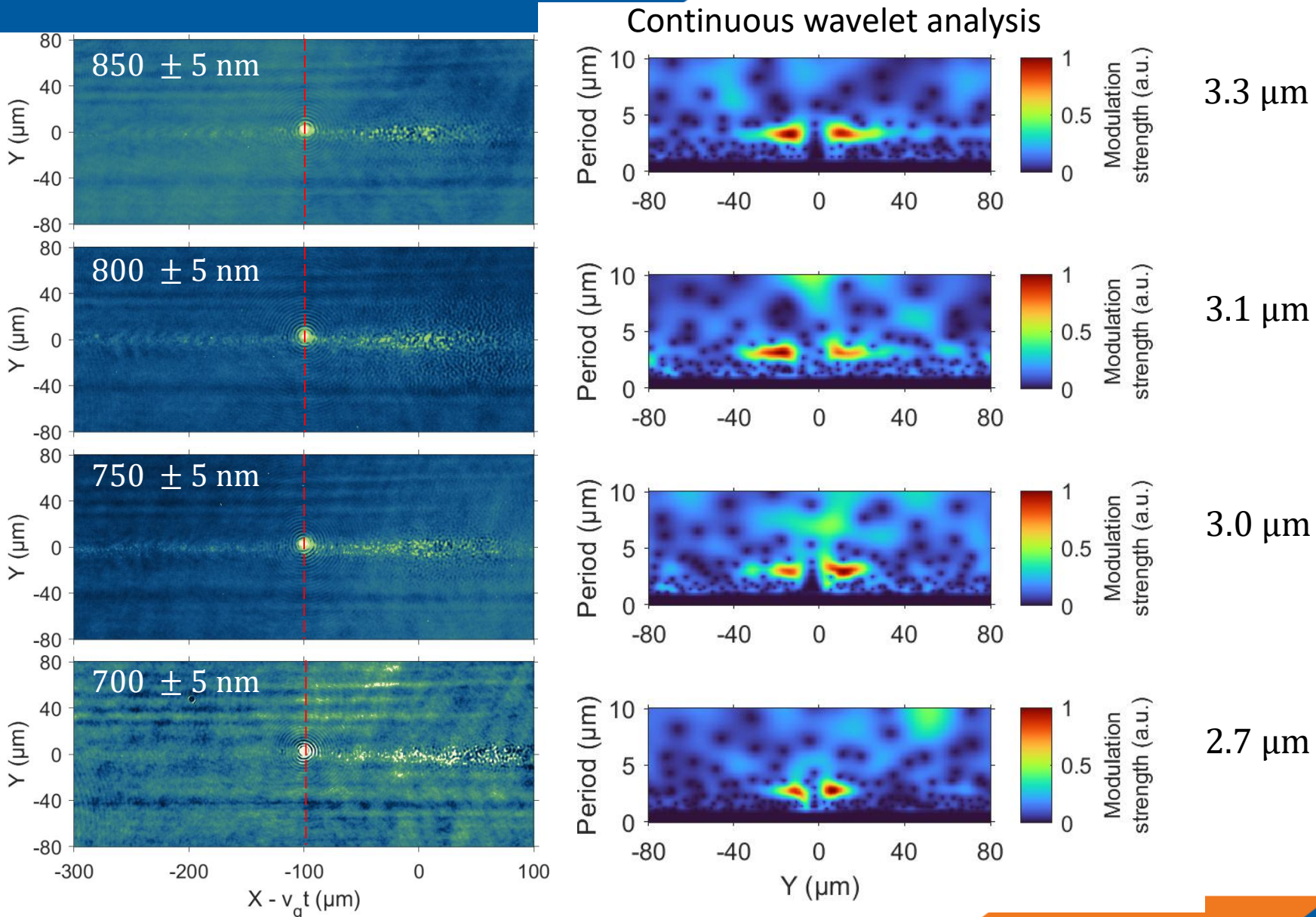


Interference rings around emitters



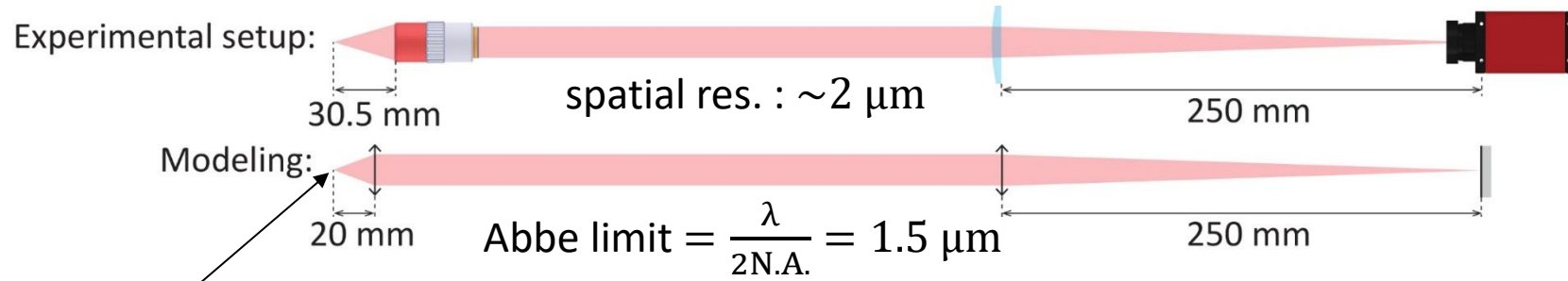
Plasma density: $\sim 7 \times 10^{18} \text{ cm}^{-3}$

Emission source: spherical wave

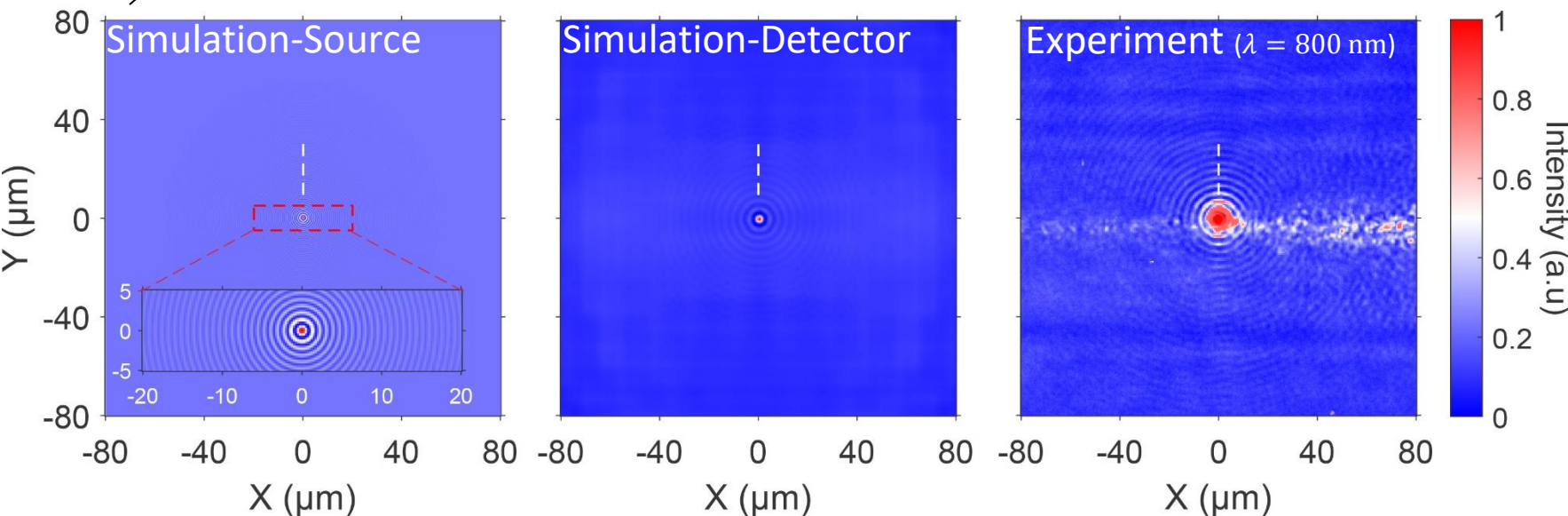


- Interference rings have **constant periods** at each wavelength.
- $\frac{\text{interference period}}{\text{center wavelength}} \approx 4$

Wave optics simulation ($\lambda = 800 \text{ nm}$)

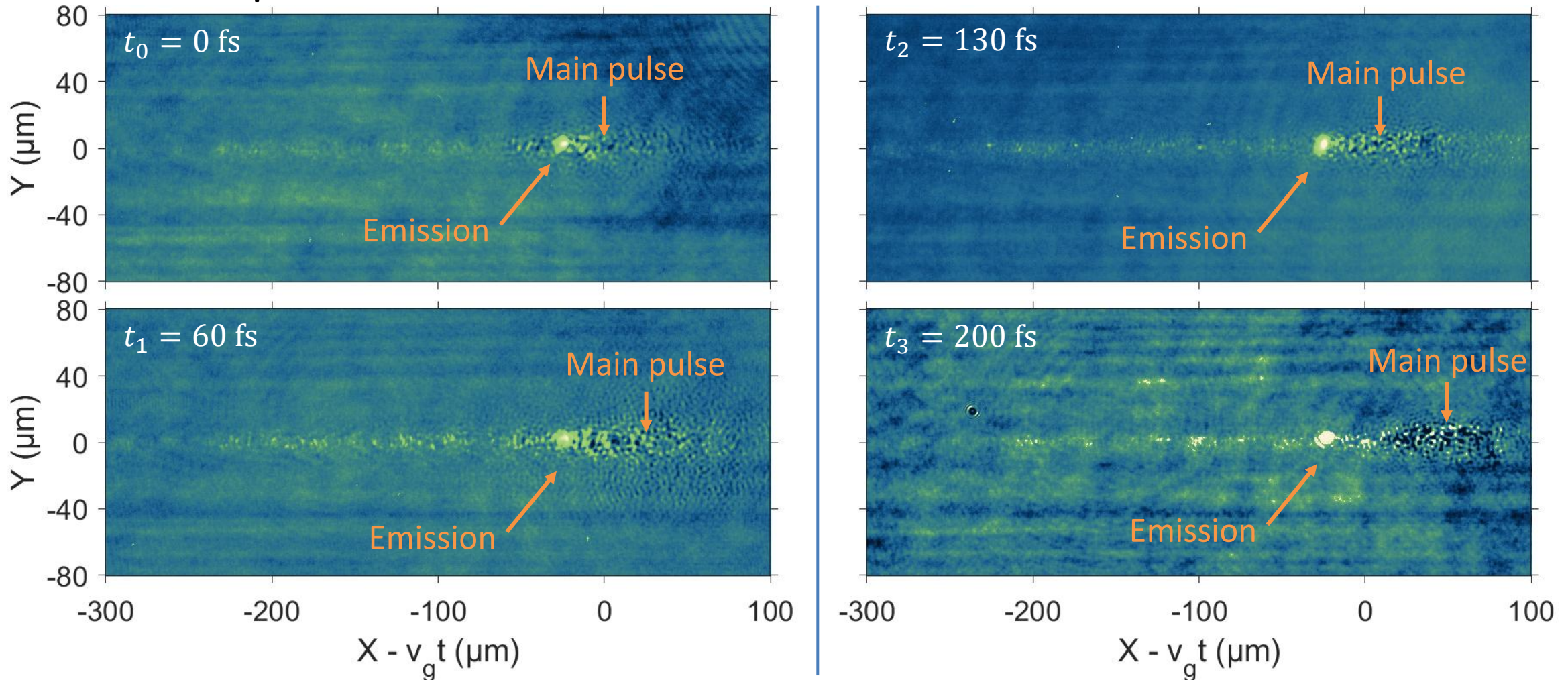


Measured interference =
a plane wave (probe)
+ a spherical wave (emission)
+ imaging system artifact



Temporal evolution: no interference

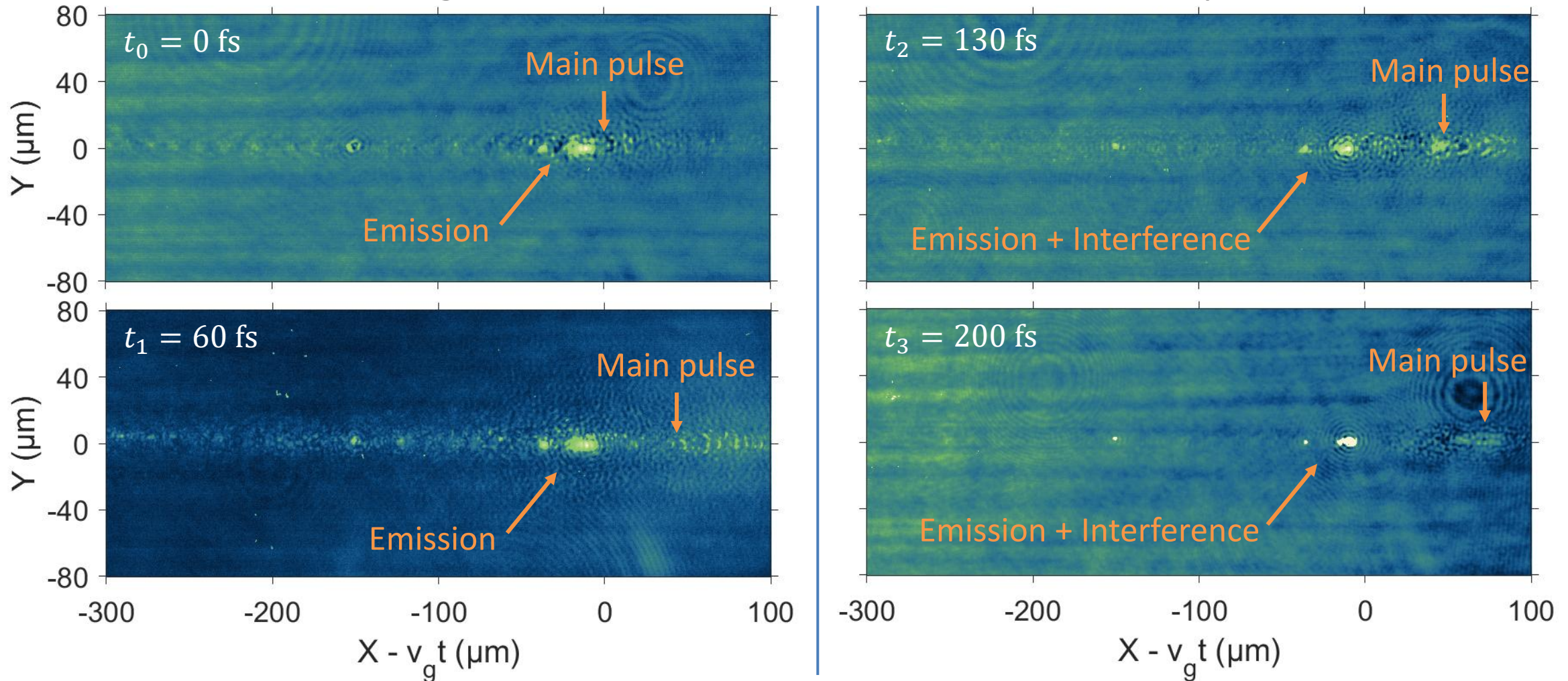
Probe pulse arrived before coherent emission started $\rightarrow$ No interference



Plasma density: $\sim 6 \times 10^{18} \text{ cm}^{-3}$

Temporal evolution: interference appears

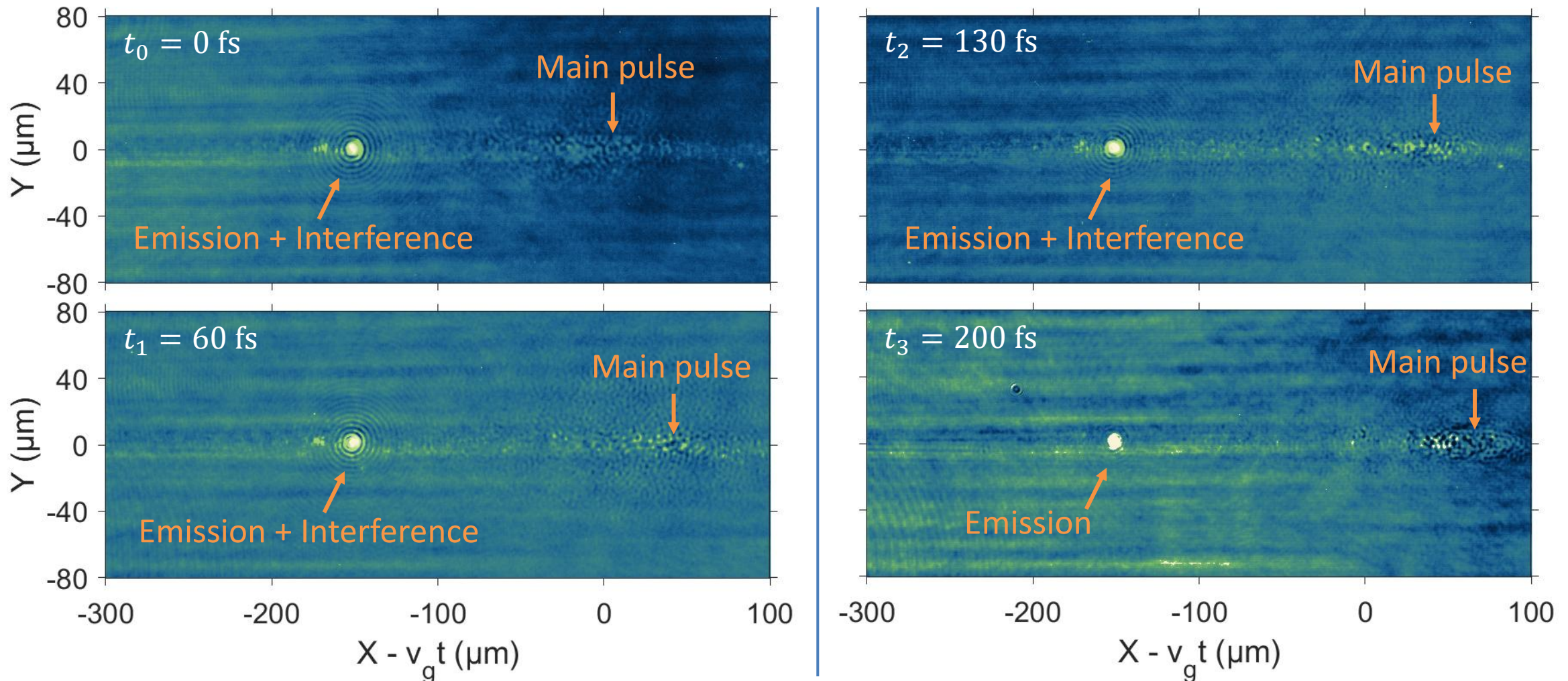
Interference rings observed at 130 fs after the driver pulse



Plasma density: $\sim 8 \times 10^{18} \text{ cm}^{-3}$

Temporal evolution: interference disappears

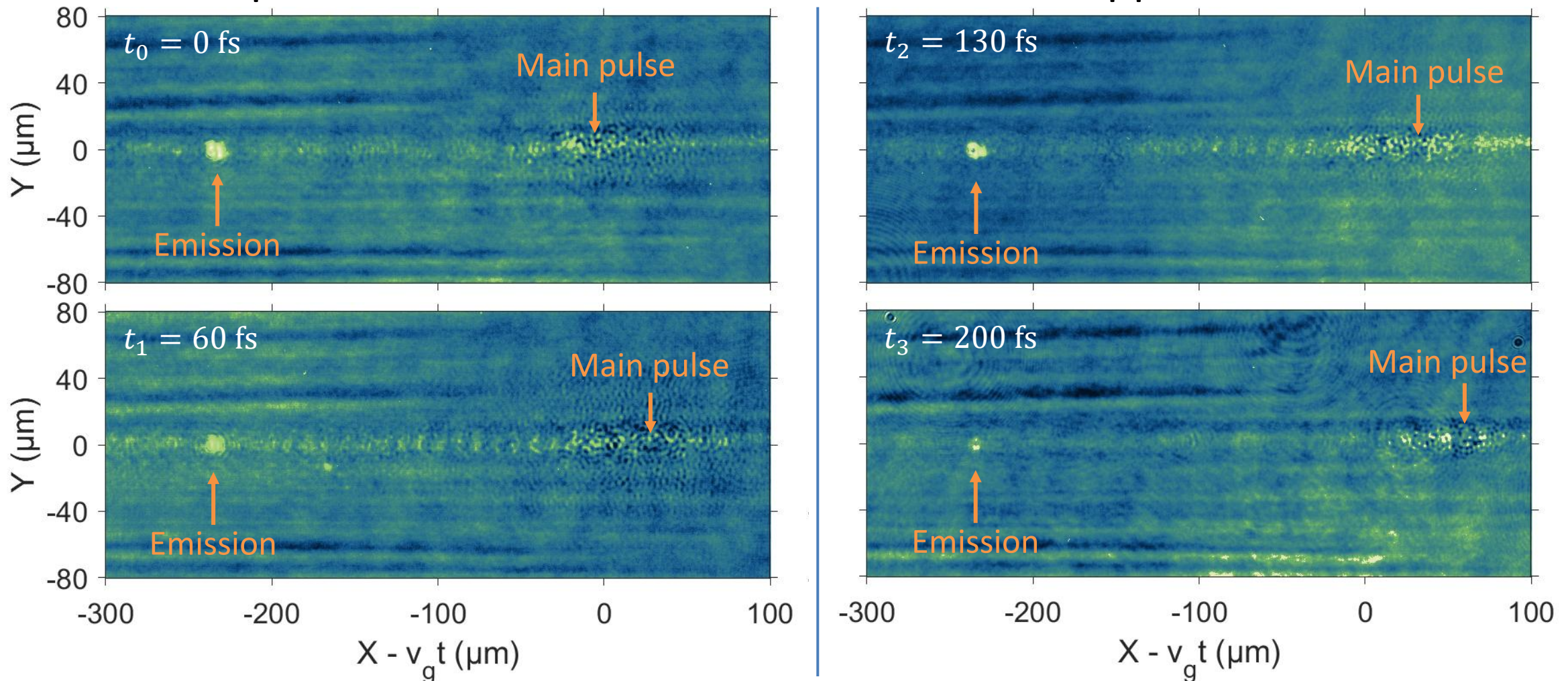
Interference rings vanished at 200 fs after the driver pulse



Plasma density: $\sim 7 \times 10^{18} \text{ cm}^{-3}$

Temporal evolution: no interference

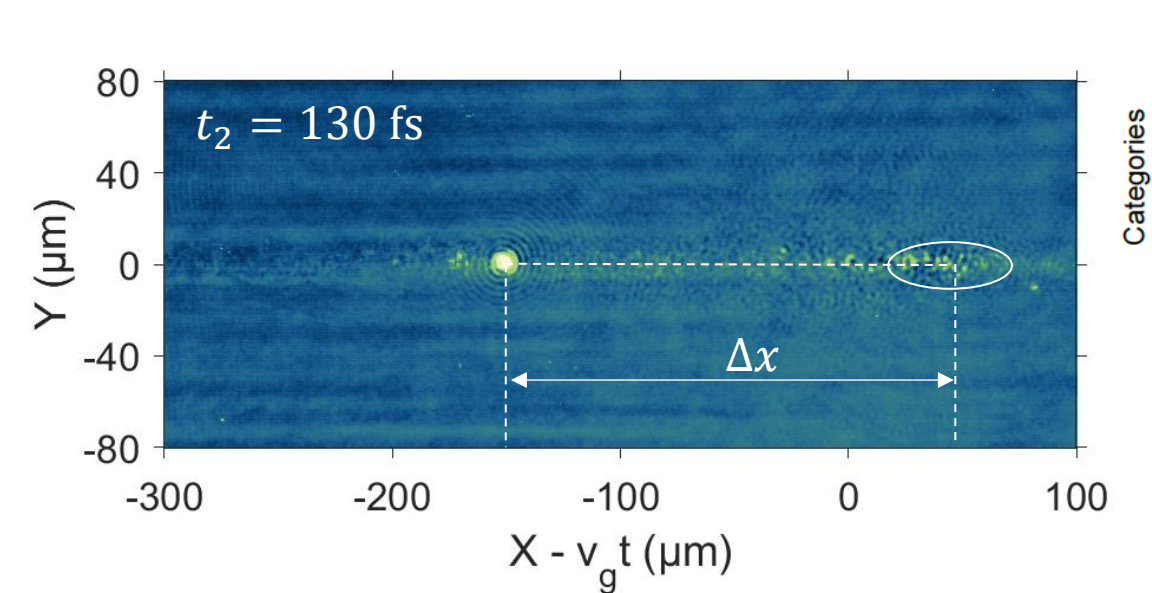
Probe pulsed arrived after coherent emission stopped $\rightarrow$ No interference



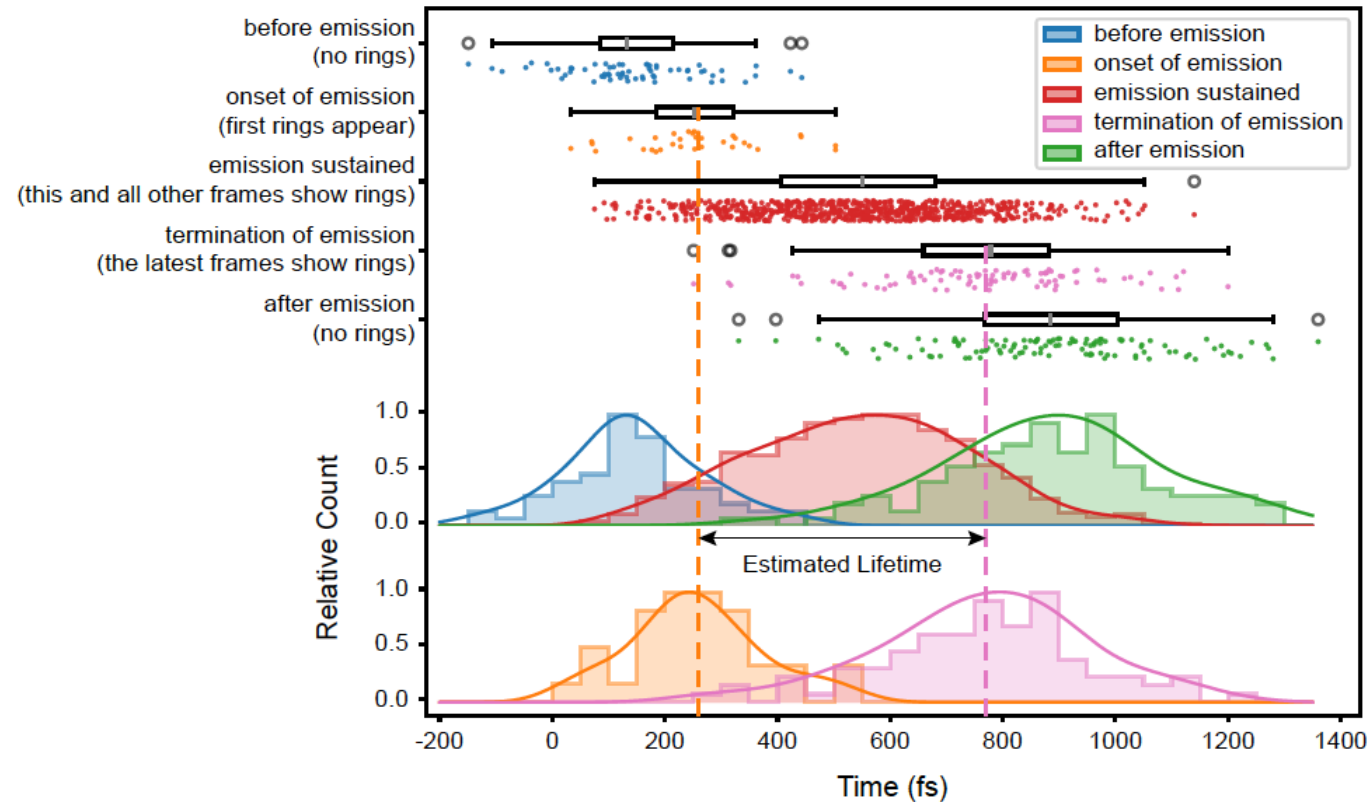
Plasma density: $\sim 8 \times 10^{18} \text{ cm}^{-3}$

Lifetime evaluation

Onset / termination time:



- Onset / termination time relative to the main pulse: $\Delta t = \frac{\Delta x}{c}$
- Average lifetime: 510 ± 30 fs



Conclusion of Experimental Results

We observed features emitting visible radiation in the wake of high-power laser pulses:

1. Micrometer sized
2. Nonpropagating at 200 fs timescale
3. Emitting coherent spherical wave
4. Emitting over broad bandwidth: $> 700 \text{ nm} - 850 \text{ nm}$
5. Long lifetime: $\sim 510 \pm 30 \text{ fs}$

Interpretation possible with numerical simulations: next talk by Dr. Daniel Seipt!

Thank you for your attention!