Proposals for laser experiments on vacuum fluctuations

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- Introduction into short laser pulses and pump-probe experiments
- Dimensions of vacuum fluctuations
- Proposals for experiments on vacuum fluctuations

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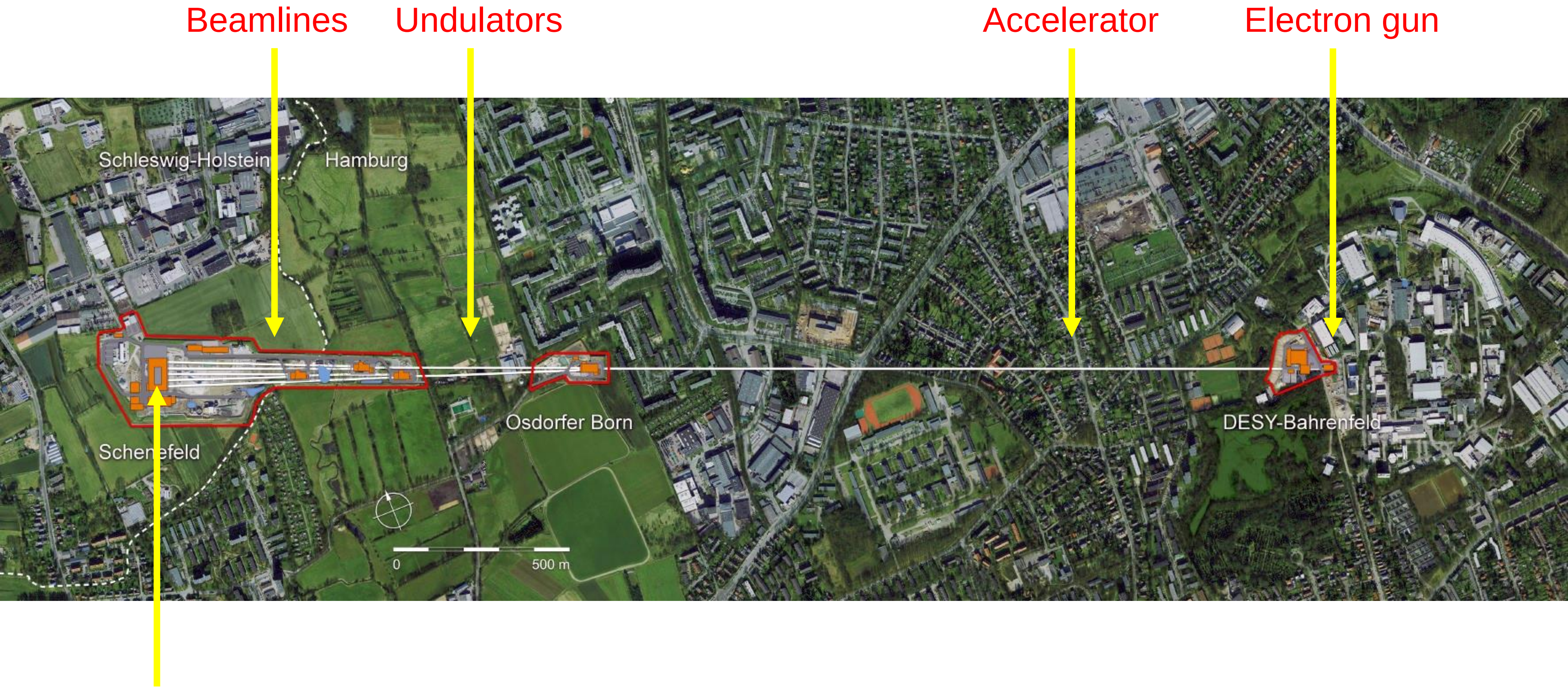
The 14th Biennial Conference on Classical and Quantum Relativistic Dynamics of Particles and Fields

3 - 6 June 2024 ♦ Aalto University

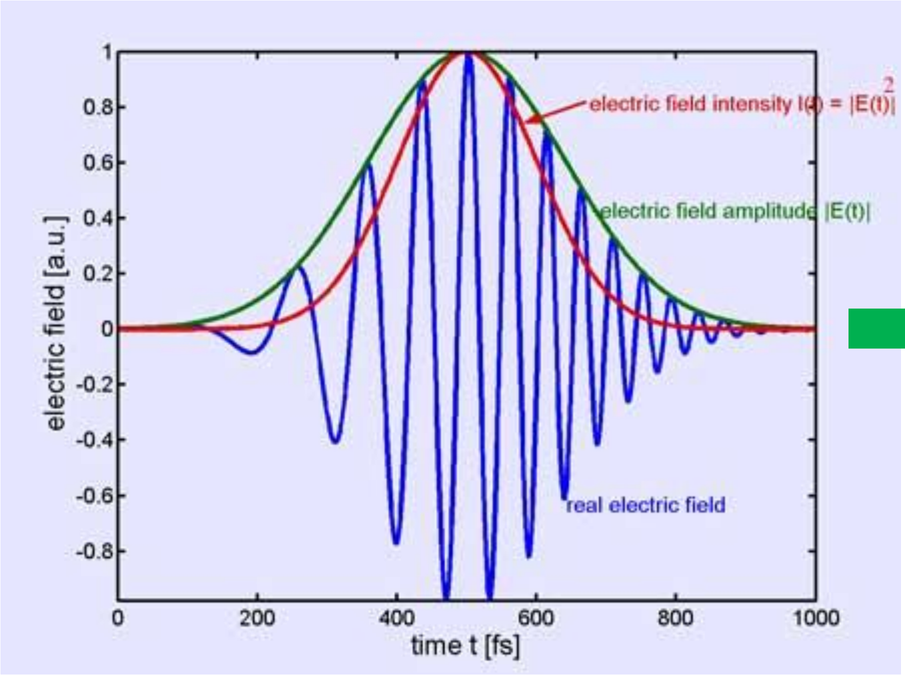
European X-ray Free Electron Laser (EuXFEL)



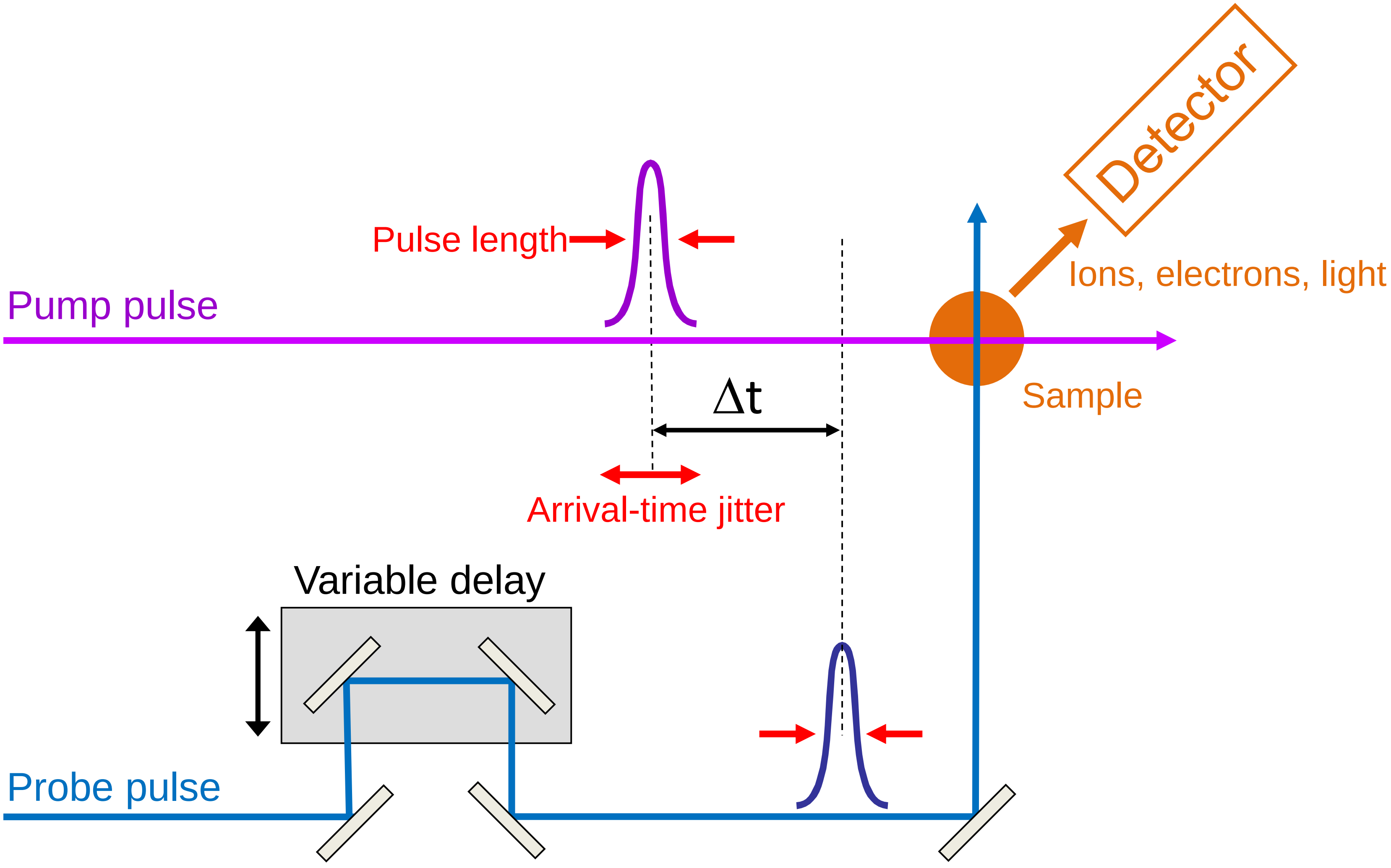
W. Decking et al., Nature Photonics **14** 391 (2020)

Short laser pulse

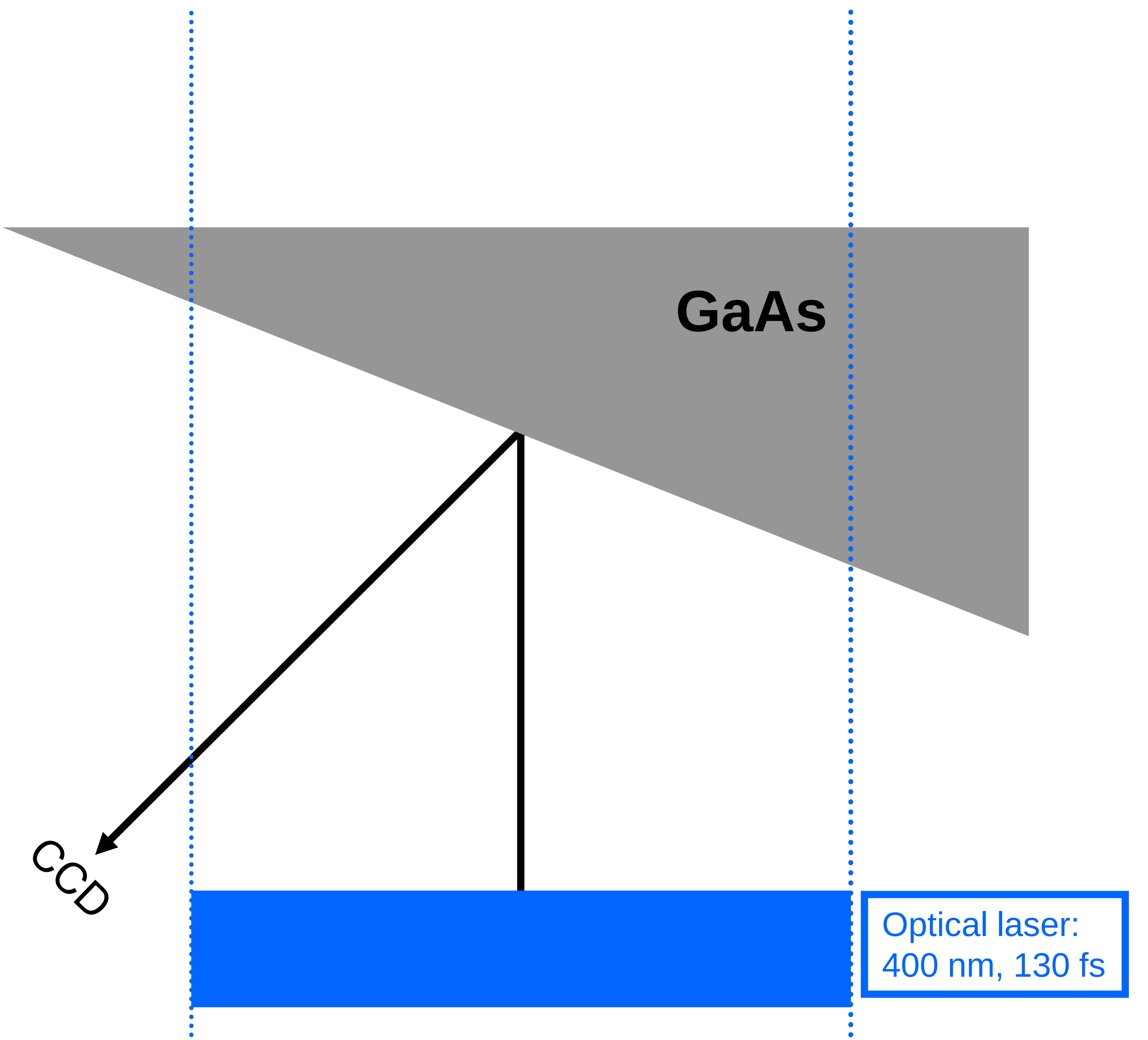
1 ps → 300 μm
1 fs → 300 nm



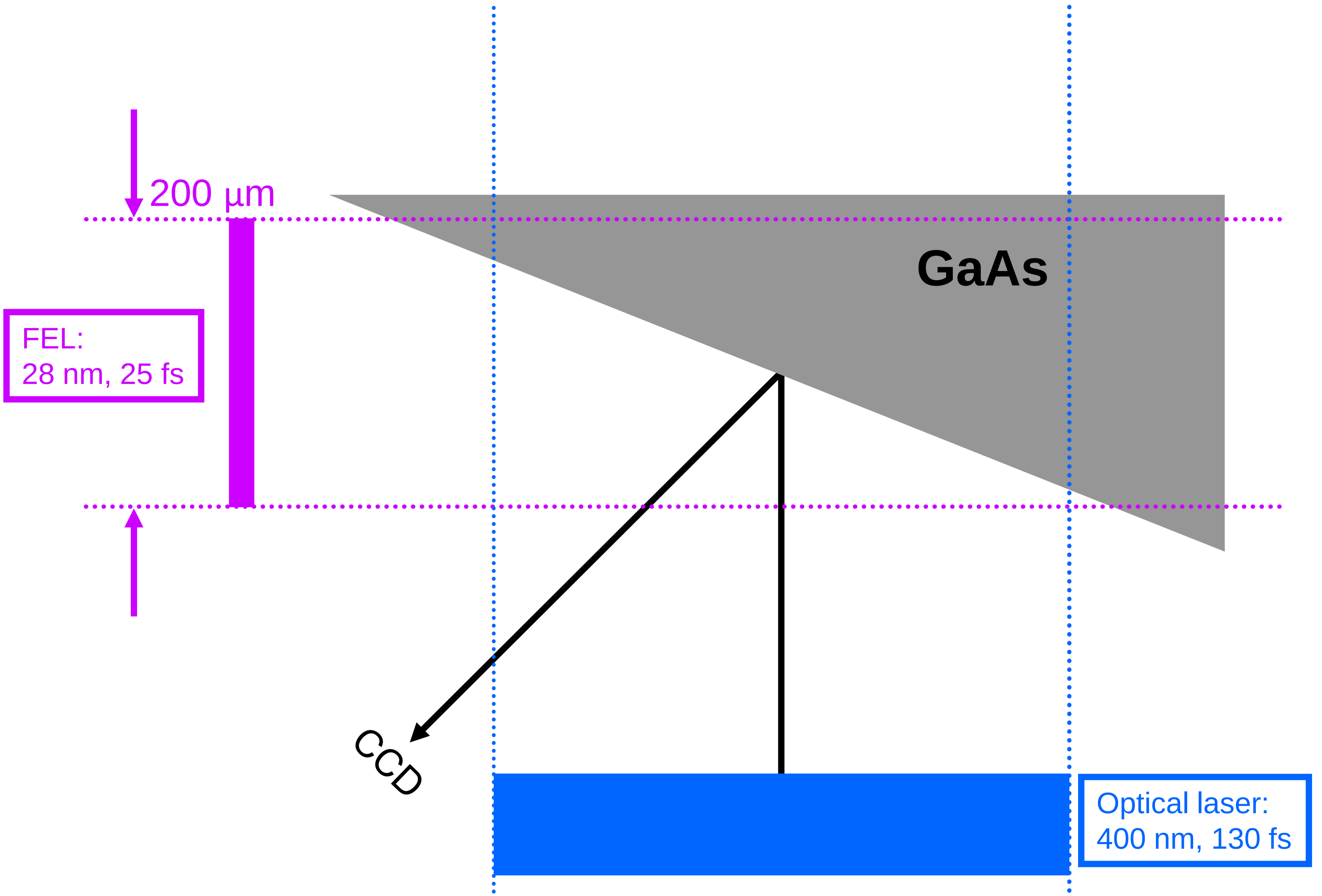
Pump-probe experiments



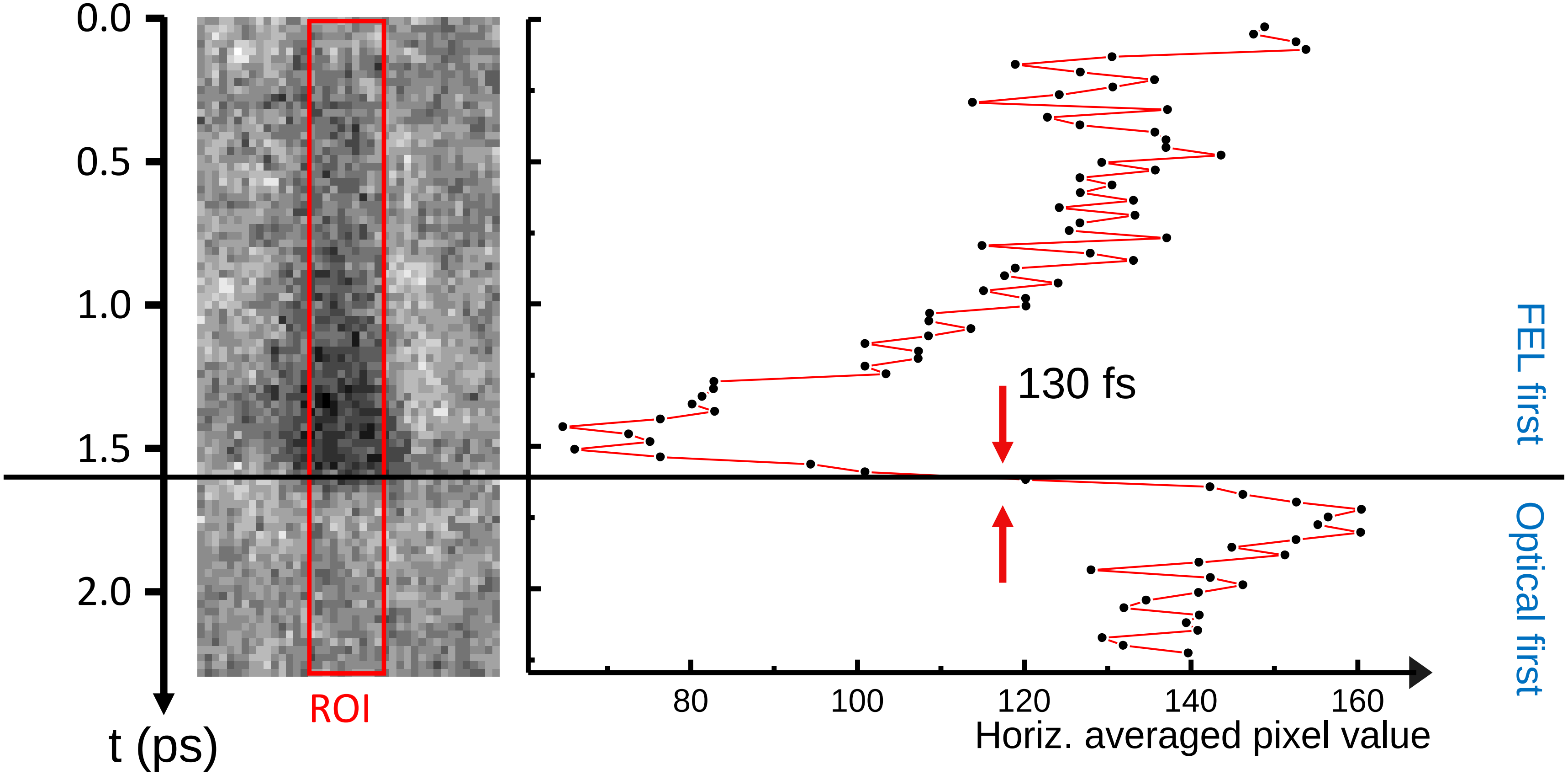
Photon in / photon out method



Time to space mapping



Single-shot arrival-time measurement



1 pix ≡ 26.5 fs

Th. Maltezopoulos et al., NJP **10** 033026 (2008)

Standard vacuum technology

Ambient air

1 bar at 300 K

2.4×10^{25} part. / m^3

Scroll pump

10^{-4} mbar at 300 K

2.4×10^{18} part. / m^3

Turbo pump

10^{-10} mbar at 300 K

2.4×10^{12} part. / m^3

+ ion-getter pumps + baking at > 100 °C + cold traps:

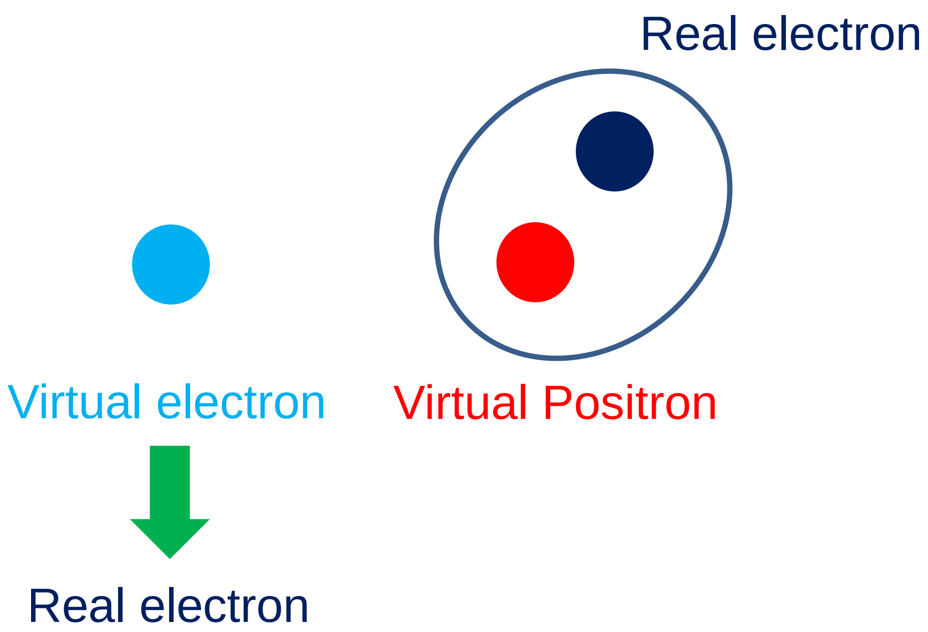
10^{-12} mbar at 300 K

2.4×10^{10} part. / m^3

Vacuum fluctuations

G. B. Mainland and B. Mulligan

J. Phys. Conf. Ser. **1239** 012016 (2019)
J. Phys. Conf. Ser. **1956** 012016 (2021)



In 1934 Furry and Oppenheimer wrote:
Vacuum fluctuations of charged particle–antiparticle pairs would affect the value of the dielectric constant of the vacuum, because of the polarizability of the nascent pairs, the dielectric constant of space into which no matter has been introduced differs from that of truly empty space

In 1957 Dicke wrote:
Vacuum could be considered as a dielectric medium

Frank Wilczek:
Virtual particles are transients, which appear in our equations but not in our detectors.”

For parapositronium that is a VF, the Heisenberg uncertainty principle is

$$\Delta E_{\text{p-Ps}}\,\Delta t_{\text{p-Ps}} \geq \frac{\hbar}{2}. \tag{9}$$

Density of VF

G. B. Mainland and B. Mulligan

J. Phys. Conf. Ser. **1239** 012016 (2019)
J. Phys. Conf. Ser. **1956** 012016 (2021)

Denoting the mass of an electron (or positron) by m_e, $\Delta E_{\text{p-Ps}}$ is the energy $2m_e c^2$ for the production of parapositronium that is a VF.[5] The minimum time Δt is the average lifetime $\Delta t_{\text{p-Ps}}$ for the existence of parapositronium that is a VF. Thus (9) yields

$$\Delta t_{\text{p-Ps}} = \frac{\hbar}{4m_e c^2}. \quad = 3.2\times10^{-22}\ \text{sec} \tag{10}$$

During the time $\Delta t_{\text{p-Ps}}$, a beam of light travels a distance $L_{\text{p-Ps}}$ given by

$$L_{\text{p-Ps}} = c\,\Delta t_{\text{p-Ps}} = \frac{\hbar}{4m_e c}. \quad = 9.7\times10^{-14}\ \text{m} \tag{11}$$

Since a parapositronium VF appears from the vacuum at essentially a single location and since nothing can travel faster than the speed of light, while they exist the maximum distance between the electron and positron in parapositronium is $L_{\text{p-Ps}}$. Having already borrowed energy $2m_e c^2$ from a volume $\mathbb{V}_{\text{p-Ps}} \equiv (L_{\text{p-Ps}})^3$ of the vacuum, a second parapositronium VF is unlikely to form in the same volume while the first still exists. This suggests the Ansatz,

$$\text{Number density of parapositronium VFs} = \frac{1}{(L_{\text{p-Ps}})^3} \equiv \frac{1}{\mathbb{V}_{\text{p-Ps}}}, \tag{12}$$

$= 1.1\times10^{39}$ VF / m^3

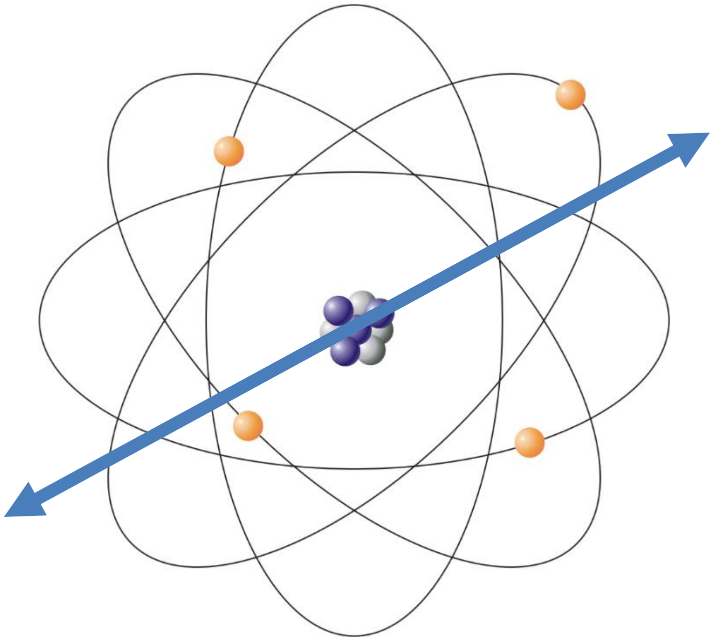
a result that can immediately be generalized to other charged lepton–antilepton VFs and quark–antiquark VFs.

The center of mass of a VF will remain fixed, accompanied by an internal zitterbewegung of the VF, giving the VF its size [41, 42]. The zitterbewegung internal to the VF has an amplitude [43][6]

$$\frac{\hbar}{4m_e c} \equiv L^{Z}_{\text{p}-Ps} = L_{\text{p}-Ps}\,, \tag{13}$$

where the final equality follows from (11). Eq. (13) allows a length $L^{Z}_{\text{p}-Ps}$ to be associated with the zitterbewegung. The volume $(L^{Z}_{\text{p-Ps}})^3 = (L_{\text{p-Ps}})^3 \equiv \mathbb{V}_{\text{p-Ps}}$ results from zitterbewegung and represents the volume of a VF. Requiring that there be only one VF in the volume of a VF as calculated from zitterbewegung yields the same for-

Dimensions - VF versus atom



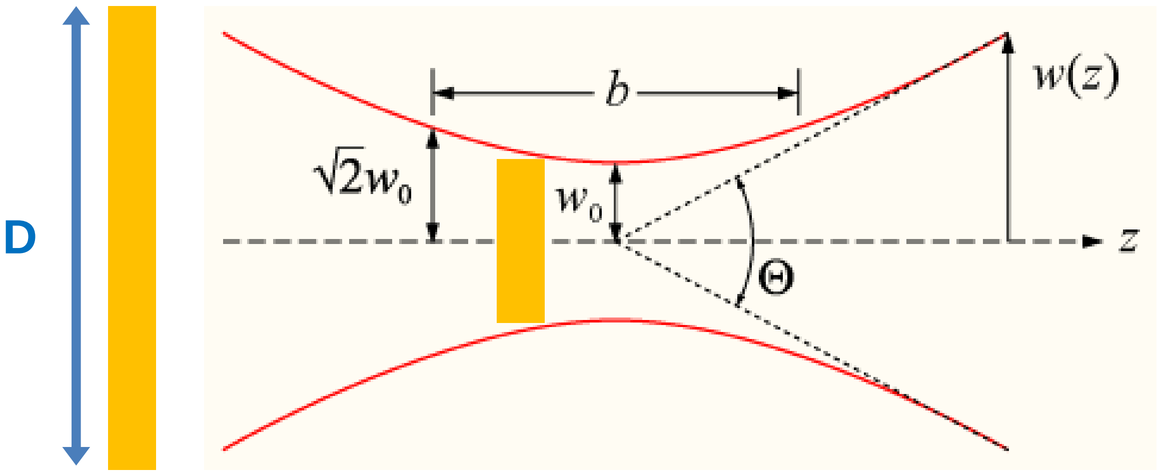
Bohr diameter: $1.06{\times}10^{-10}$ m
VF length: $9.7{\times}10^{-14}$ m
Bohr diameter = 1093 VF length

Bohr volume = $6.9{\times}10^{8}$ VF volume

$E = hf$, $f = E/h = 2mc^2 / h$
$f_{electron} = 2.48{\times}10^{20}$ Hz and $T_{electron} = 4.04{\times}10^{-21}$ sec
Zitterbewegung gives a particle its “size”

Bohr “orbit time” 150 as = $1.5{\times}10^{-16}$ seconds
Electron interacts with VFs 37122 times during one orbit !!!

Focus of high-power laser pulse



Depth of field: b
Rayleigh length: z_R

$$b = 2 \cdot z_R = 2 \cdot \frac{n \cdot \pi \cdot w_0^2}{\lambda}$$

$$w_0 = \frac{2 \cdot \lambda \cdot f}{\pi \cdot D}$$

D = 7 cm, λ = 800 nm, f = 41 cm → w_0 = 3 μm,

w_0 = 3 μm → b = 71 μm (with n = 1)

c* = c / 137 with refractive index n = c/c* = 137 (diamond has 2.4)

Light through 3 μm "normal" VF: 10 fs
Light through 71 μm "normal" VF: 237 fs
Light through 71 μm doubly photo-excited VF: 237 fs x 137 = 32.5 ps

Approaching VF density …

Specifications	Pulsar 60	Pulsar 140	Pulsar 250
Repetition Rate (Hz)[1,2]		Up to 5	
Peak Power (TW)[3]	> 60	> 140	> 250
Energy Per Pulse (J)	> 1.5	> 3.5	> 6.25
Central Wavelength (nm)		800 ± 10	
Pulse Width (fs FWHM)[4]		< 25	
Pulse To Pulse Energy Stability (% RMS)	< 1.5	< 1.2	< 1.0
Nanosecond Contrast		$> 10^8 : 1$	
Picosecond Contrast		$> 10^3$:1 beyond 1 ps	
		$> 10^6$:1 beyond 5 ps	
		$> 10^8$:1 beyond 10 ps	
ASE Contrast		$> 10^{10}$:1 beyond 100 ps	
Strehl Ratio[5]	> 0.9	> 0.85	
Pointing Stability (μrad RMS)[6]		< 10	

20 fs correspond to 6×10^{-6} m = 6 μm

Focus area: $\pi * (3\ \mu m)^2 = 2.83\times10^{-11}\ m^2$

Focus volume = $1.7\times10^{-16}\ m^3$

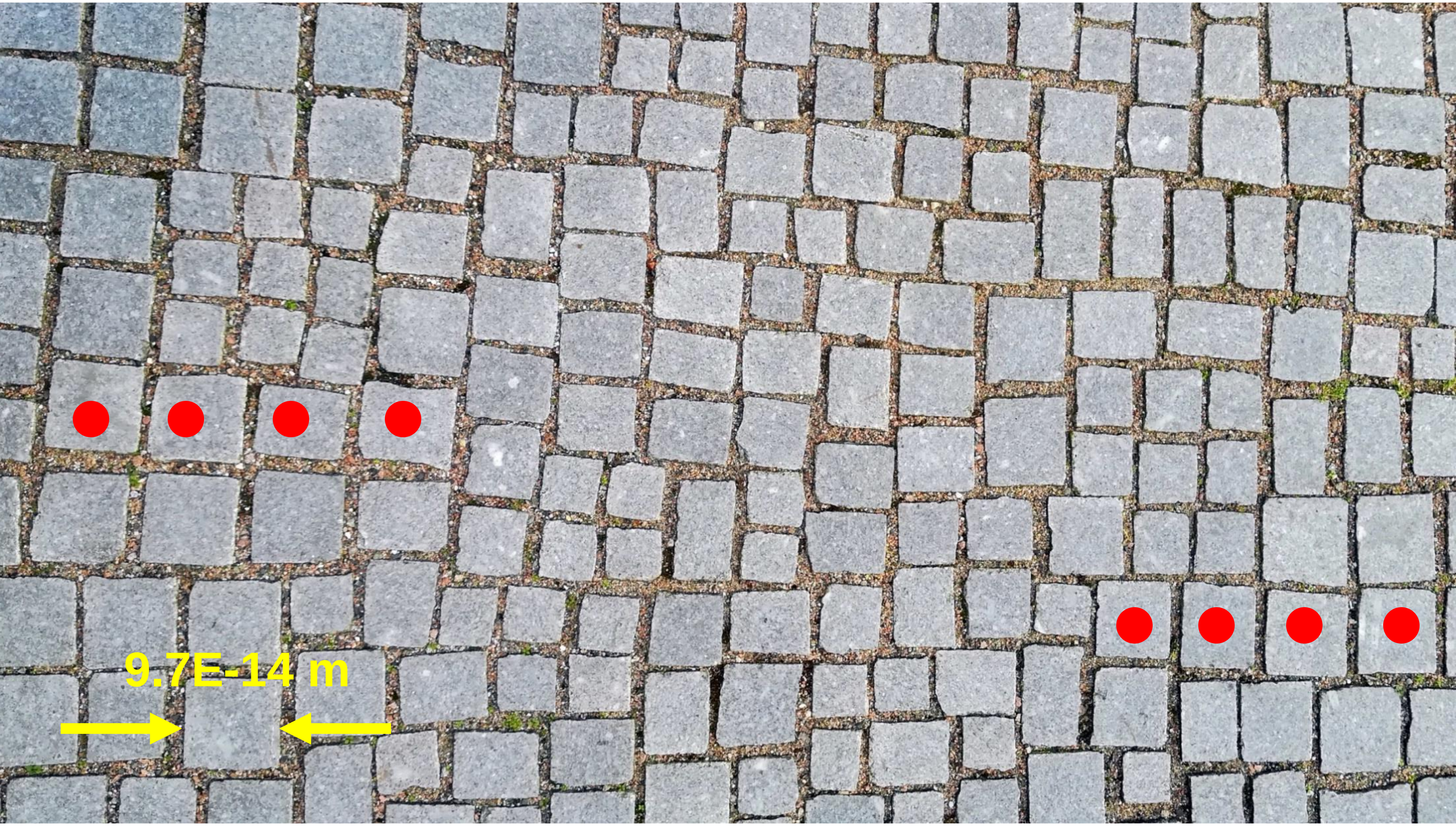
6 J / 1.5 eV leads to 2.5×10^{19} photons per pulse

→ 1.5×10^{35} photons / m^3 in the focus

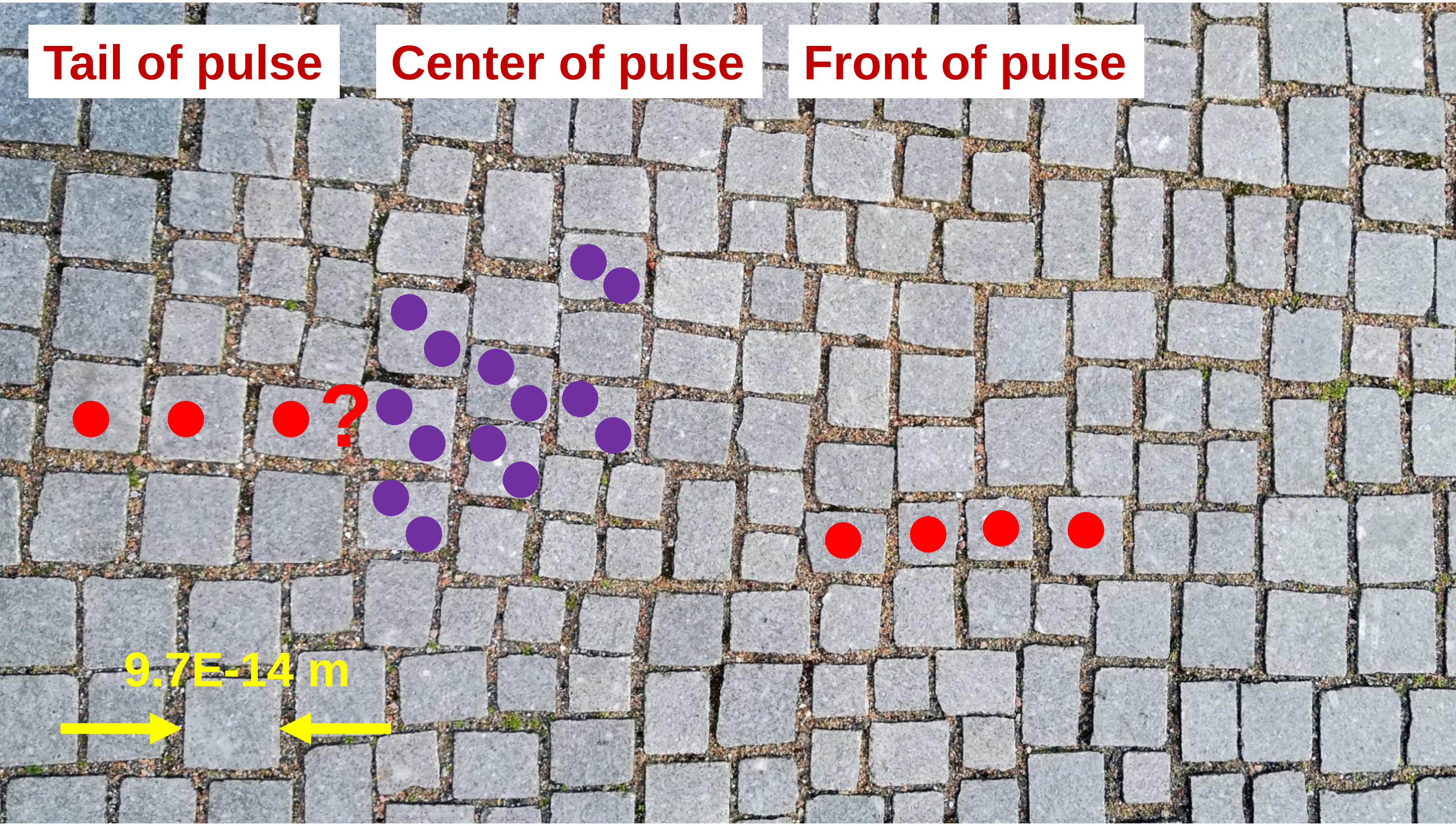
VF density: 1.1×10^{39} VF / m^3

… and ELI is factor of 42 higher (250 J)

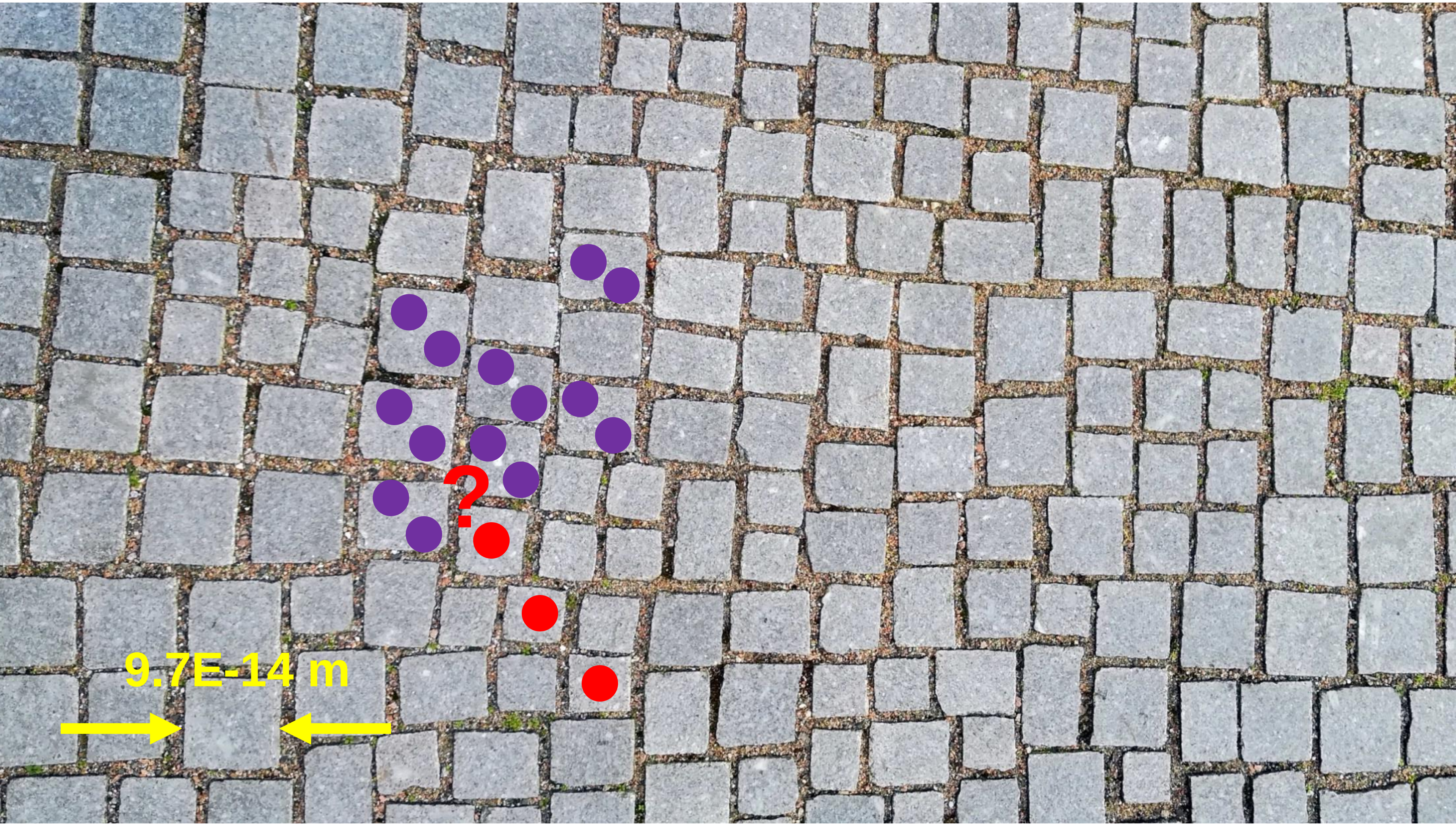
Low photon density



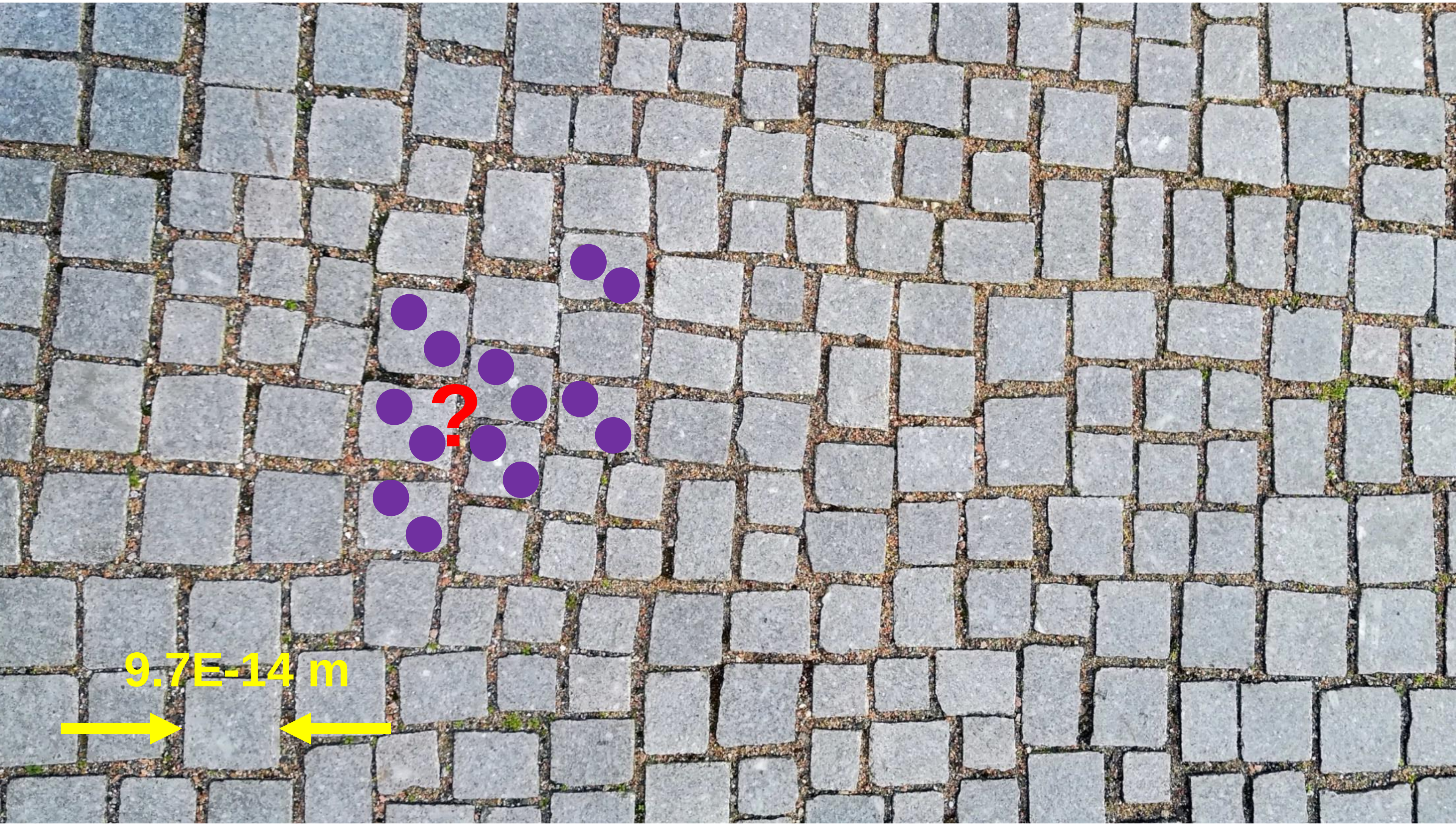
High photon density – Tail of pulse



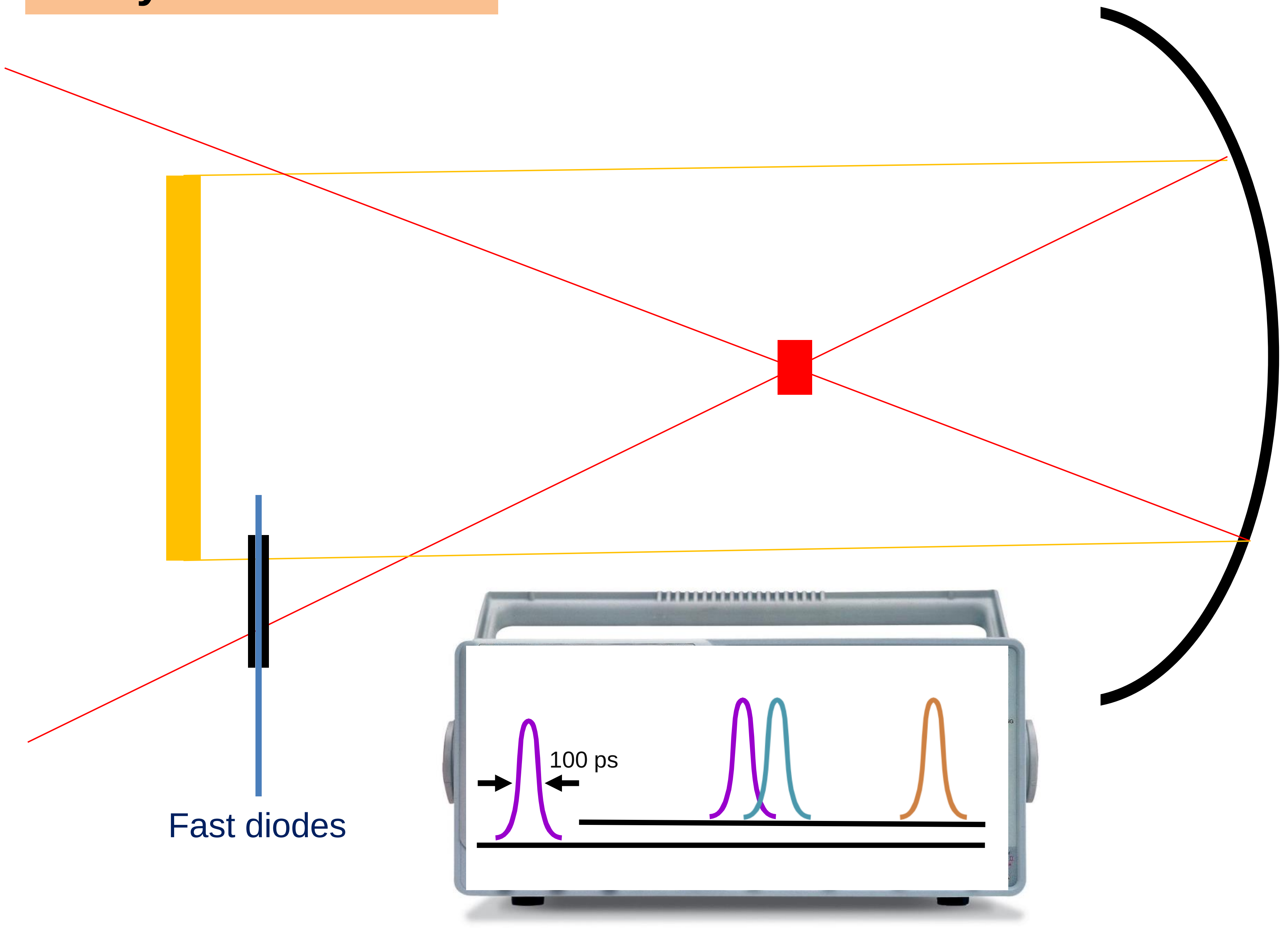
High photon density – Cross-correlation



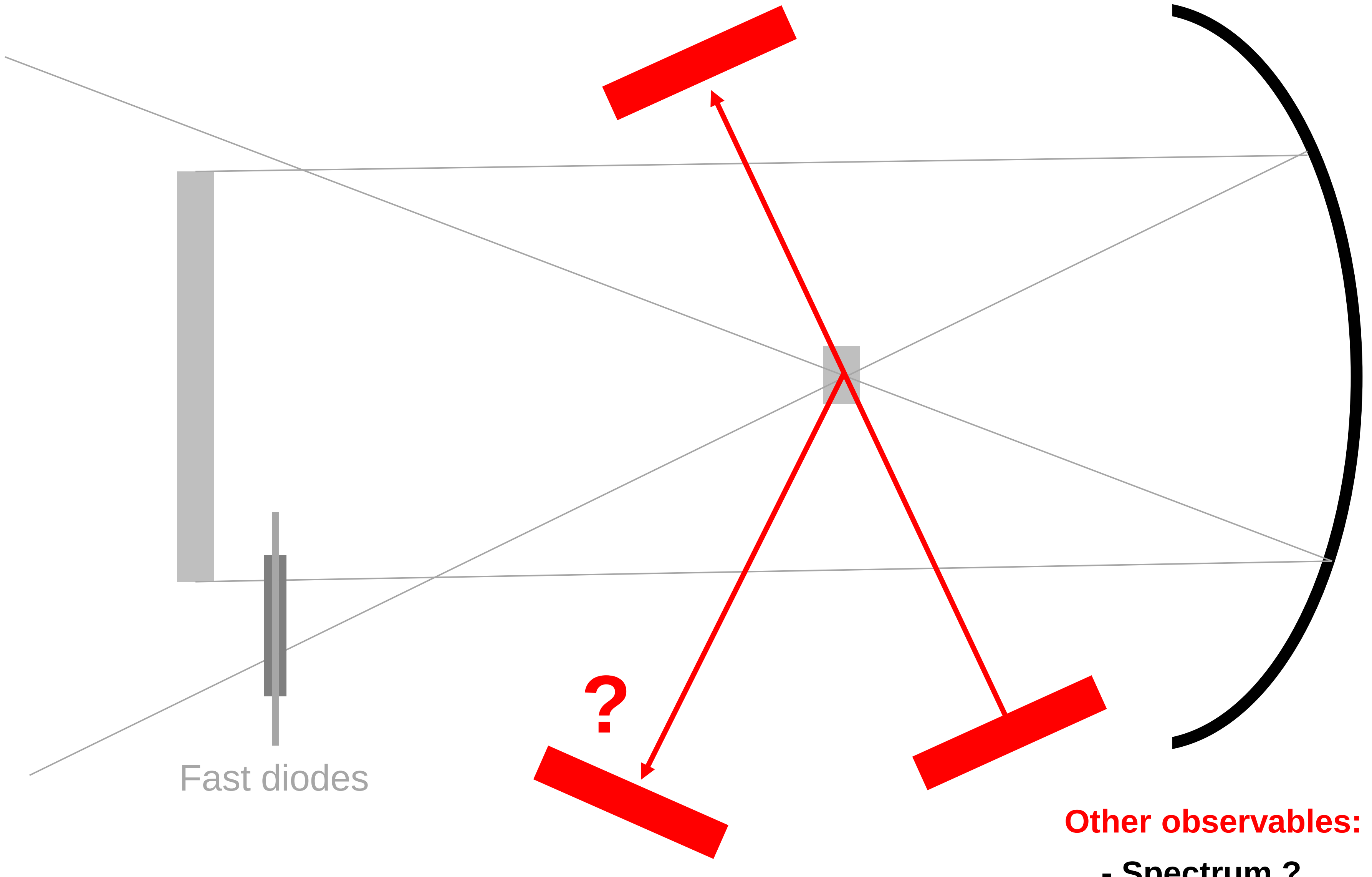
High photon density – Saturation ?



Delay measurement



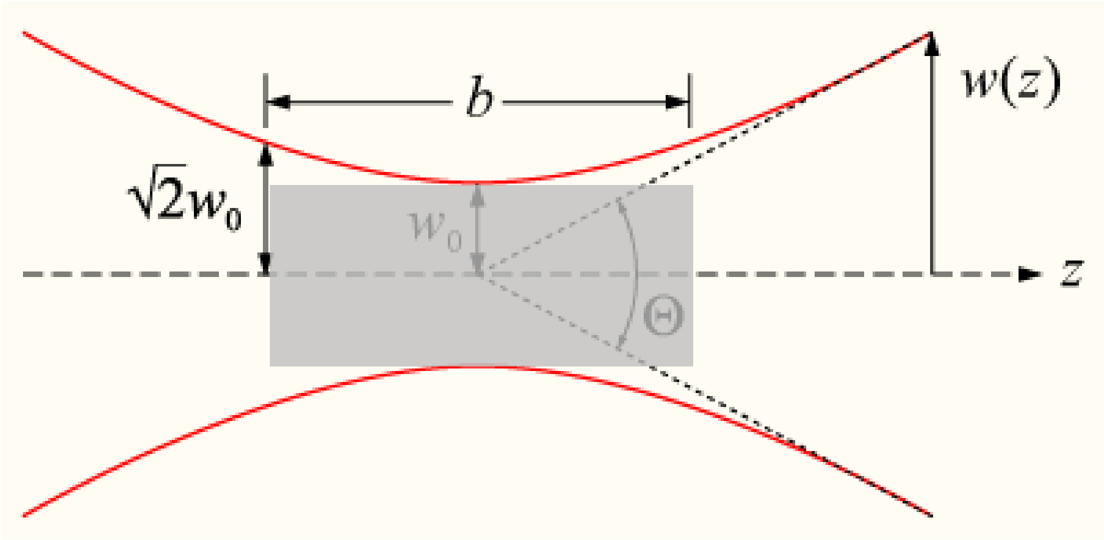
Reflectivity measurement



Other observables:

- **Spectrum ?**
- **Pulse duration ?**
- **Wavefront ?**

Maximal pressure



$V = \pi * w_0^2 * b = \pi * (3\ \mu m)^2 * 71\ \mu m = 2\times10^{-15}\ m^3$

$p * V = N * k_B * T$ ($k_B = 1.38\times10^{-23}$ J/K and $T = 300$ K)

$p_{max} = N/V * k_B * T = 2.1\times10^{-6}$ Pa = 2.1×10^{-8} mbar $\rightarrow$ for N = 1

Summary

- Photon densities in a high power laser focus approach VF densities
- If two photon-excited VF appear, this will increase ε_0 and decrease c
- Ideas for future pump-probe experiments on VF
  like arrival-time, pulse duration, reflectivity change, …

Thank you for your attention !!!