Longitudinal phase space diagnostics for ultrashort bunches with a plasma deflector

I. Dornmair[1*]

with C. B. Schroeder[2], K. Floettmann[3], B. Marchetti[3], and A. R. Maier[1]

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CFEL SCIENCE

LAOLA. is a collaboration of

LUX Junior Research Group

Junior Research group at CFEL and Hamburg University

commission & operate 200 TW ANGUS laser system

build and operate the LUX beamline for laser-plasma driven undulator radiation

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Andi


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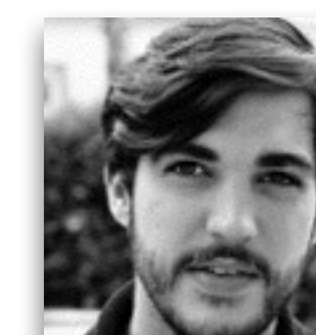
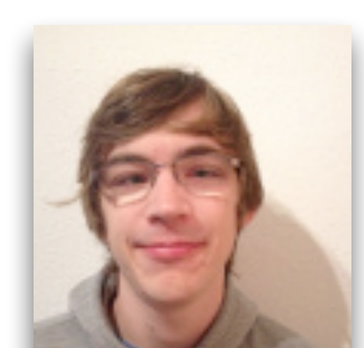

Manuel


Max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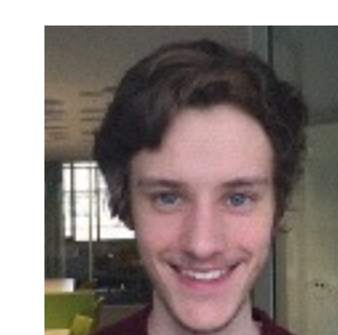
Henning


Kevin

Laser Plasma Acceleration (LPA)

- focus high power laser pulse into plasma target
  - typical laser parameters:
    1 -10 J pulse energy,
    30 fs pulse length,
    20 µm spot size

target chamber @ LUX

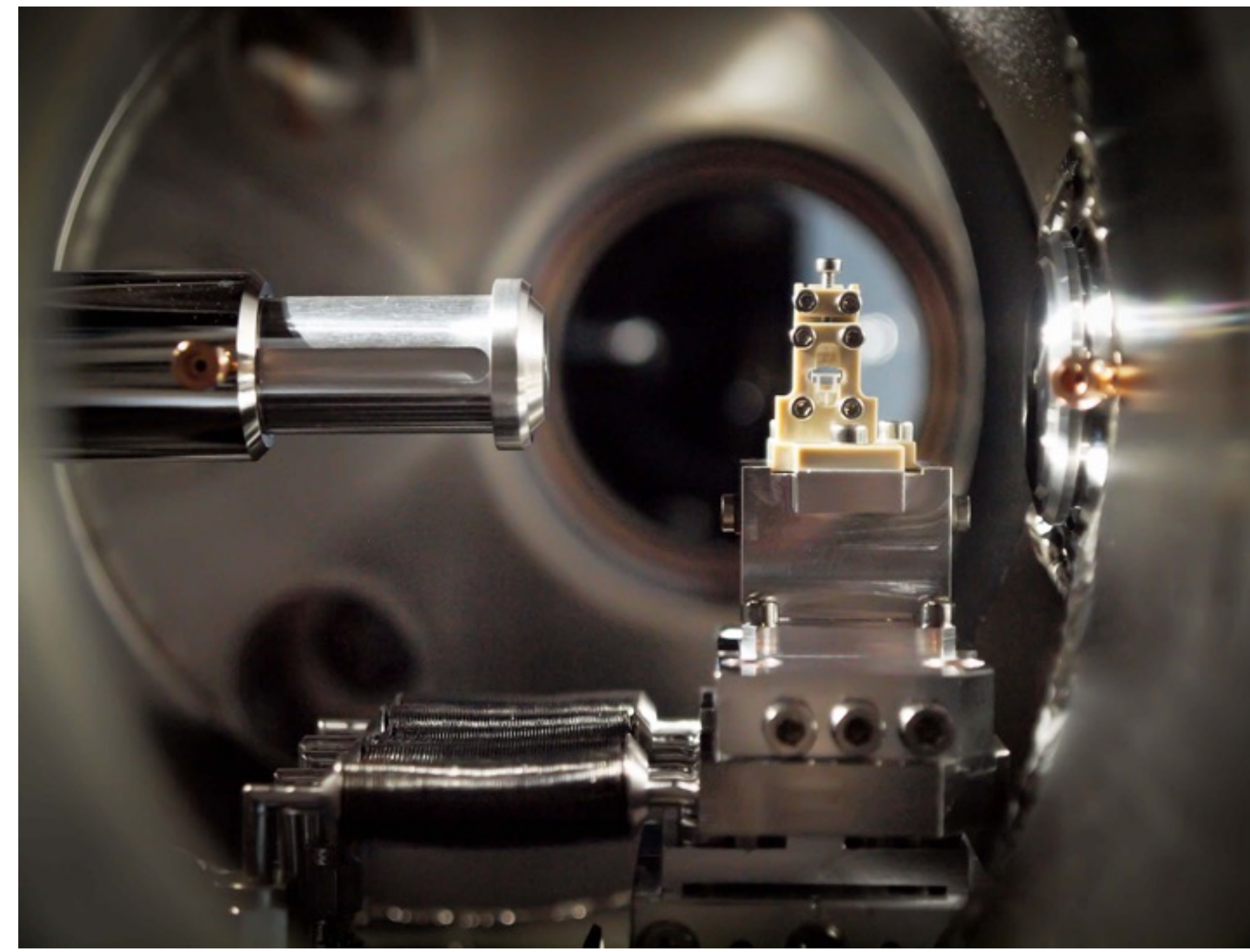
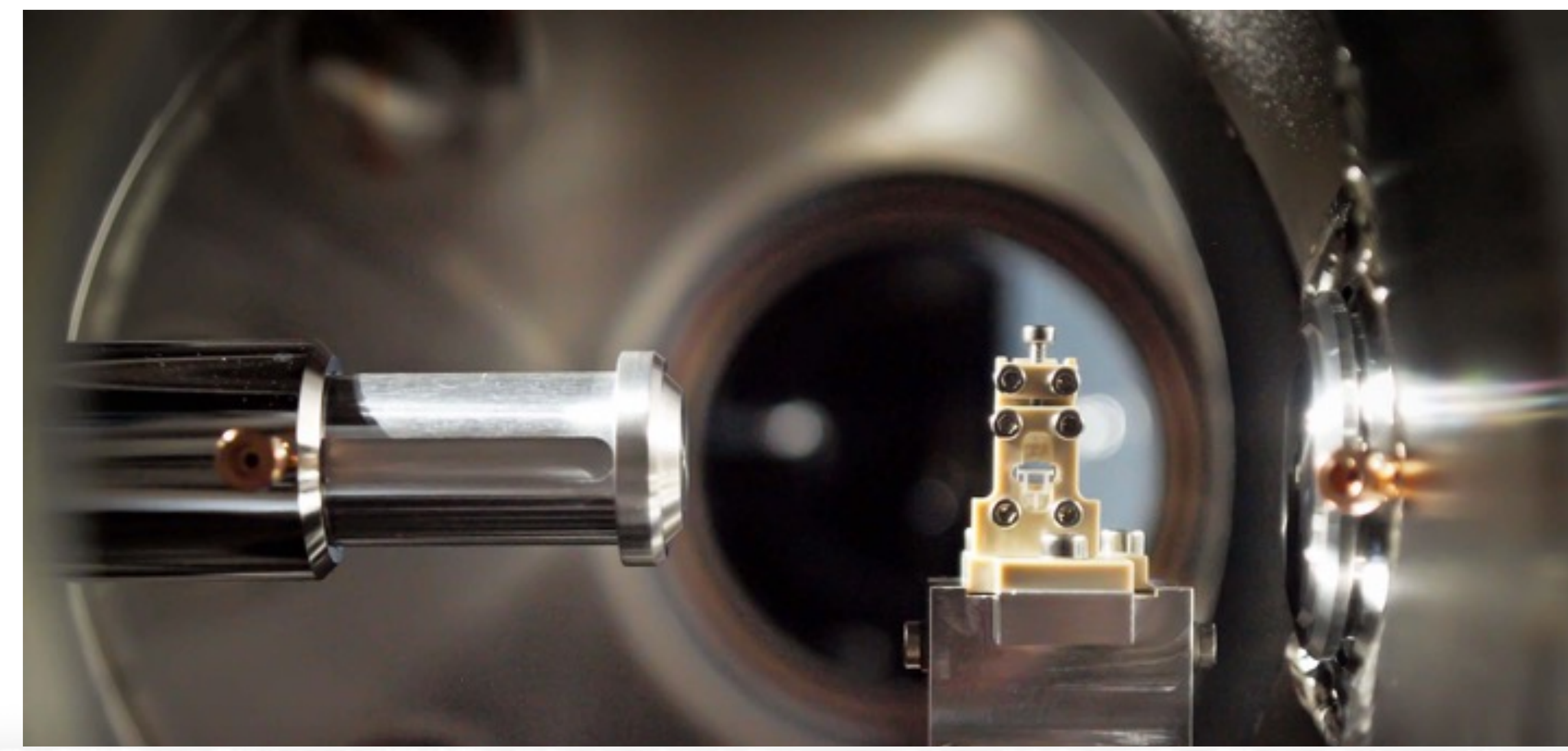


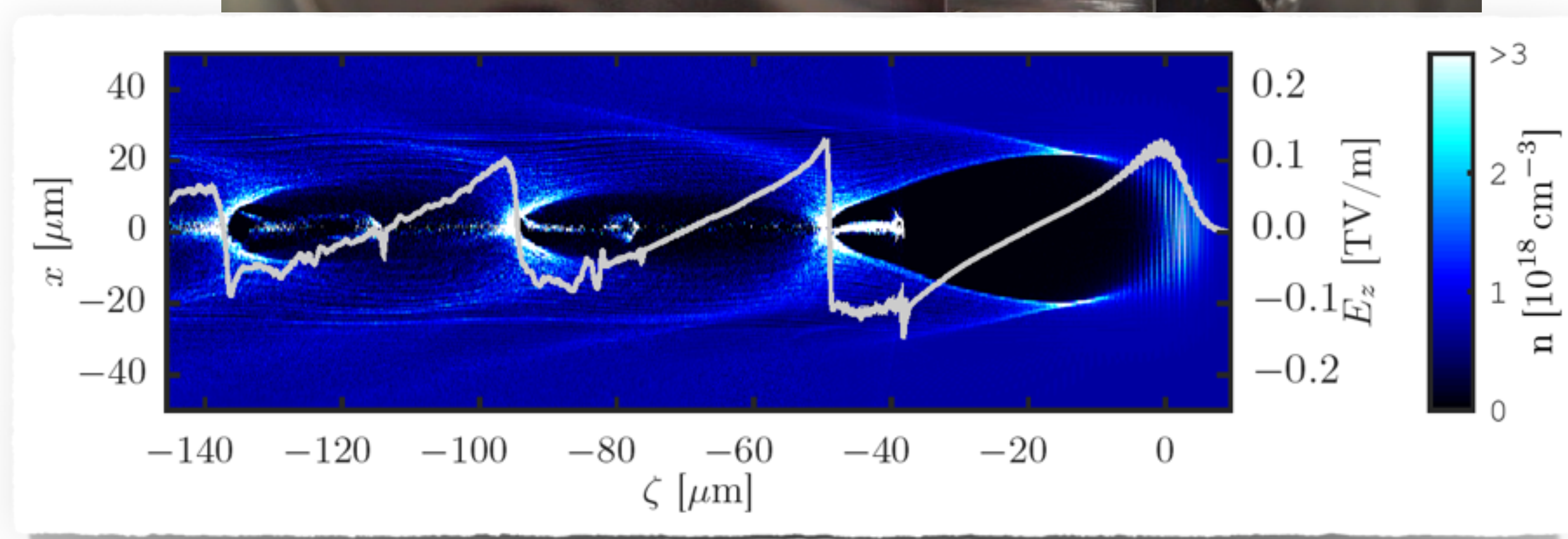
photo: N. Delbos

Laser Plasma Acceleration (LPA)

- focus high power laser pulse into plasma target
  - typical laser parameters:
    1 -10 J pulse energy,
    30 fs pulse length,
    20 µm spot size
- laser excites wakefield
  - charge separation
  - typical scale: plasma wavelength 10 - 100 µm

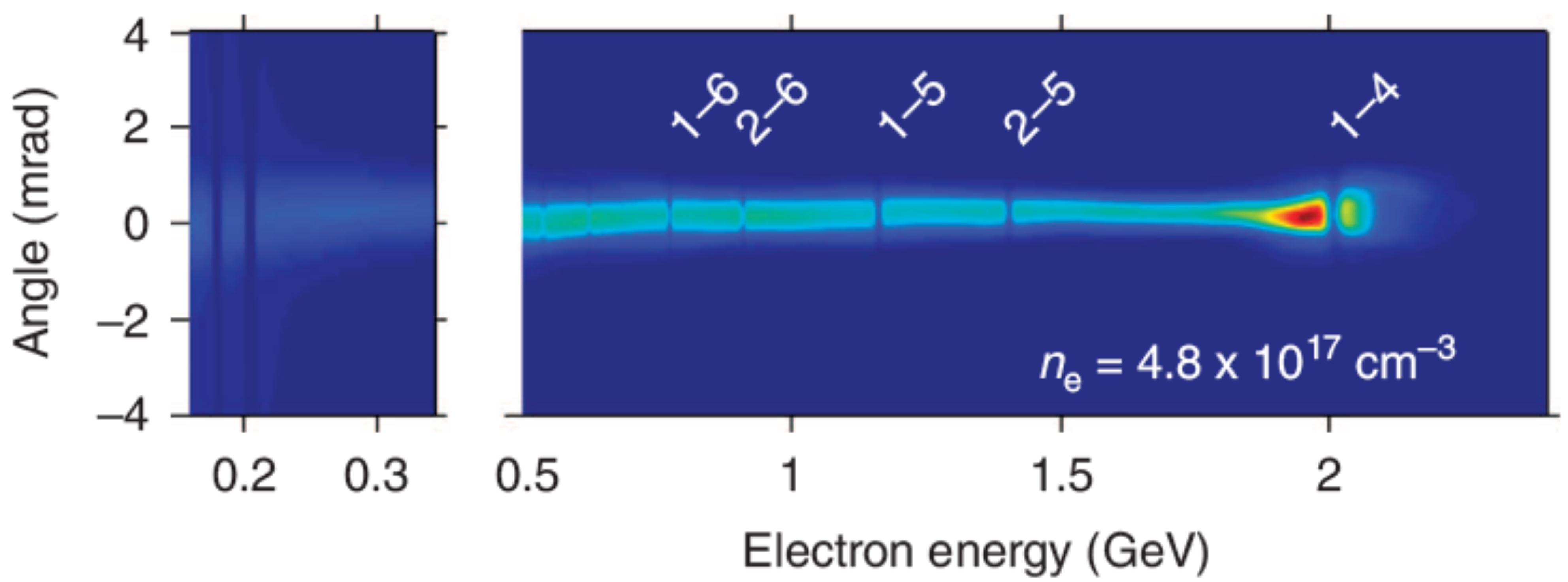
target chamber @ LUX



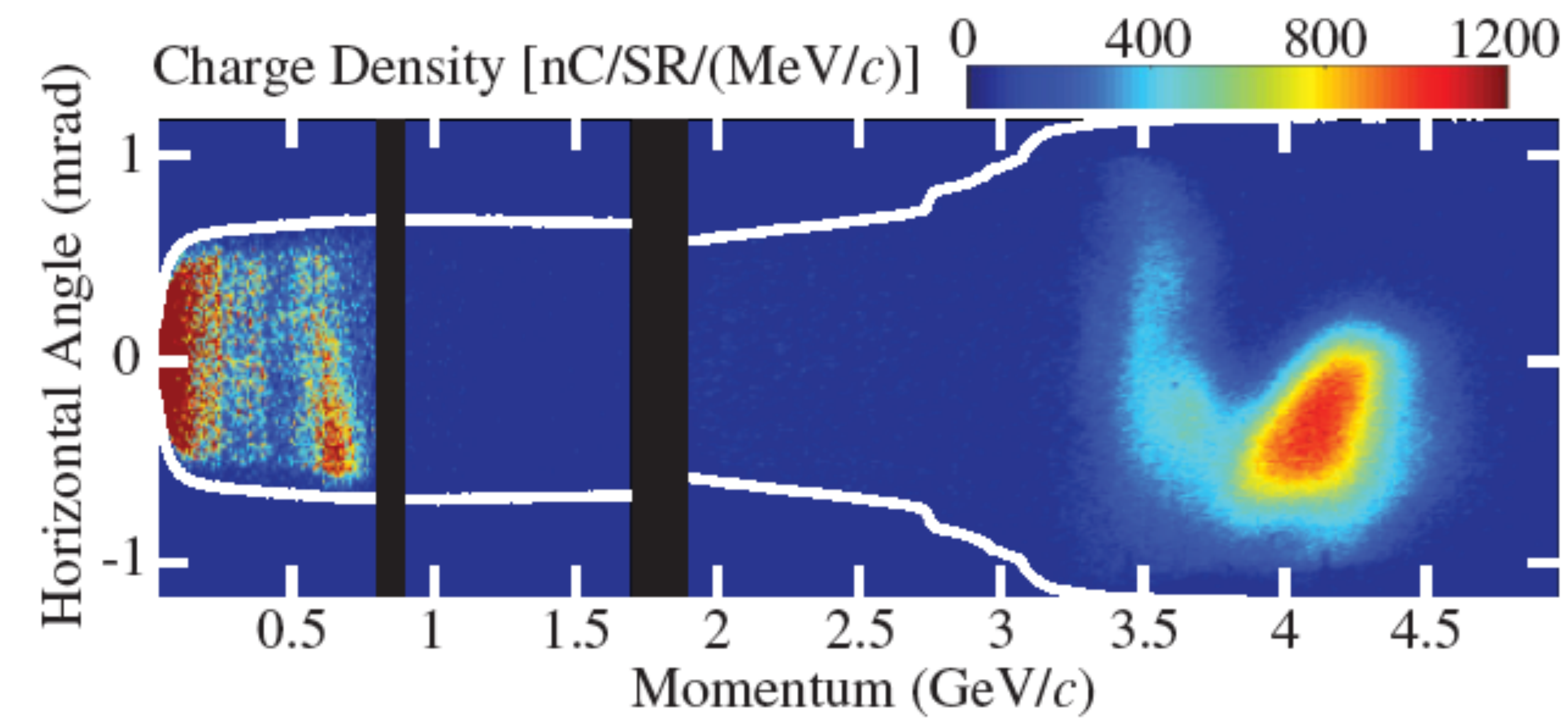


Laser Plasma Acceleration (LPA)

- high gradients



X. Wang et al., Nat. Commun. 4, 1988 (2013)

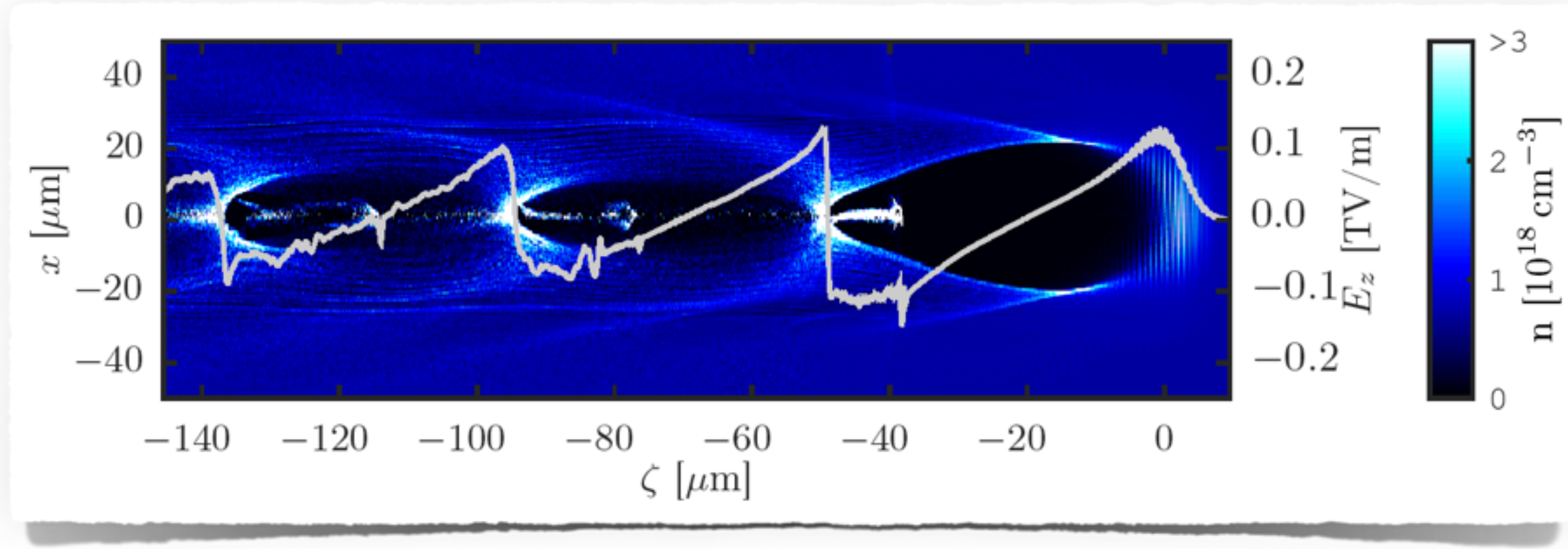


W. Leemans et al., PRL 113, 245002 (2014)

- University of Texas: 2 GeV over 7 cm
- LBNL: 4 GeV over 9 cm

Laser Plasma Acceleration (LPA) - Beam Quality

- challenges
  - stability
  - reproducibilty
  - beam quality
- originate from
  - laser and plasma stability
  - injection mechanism



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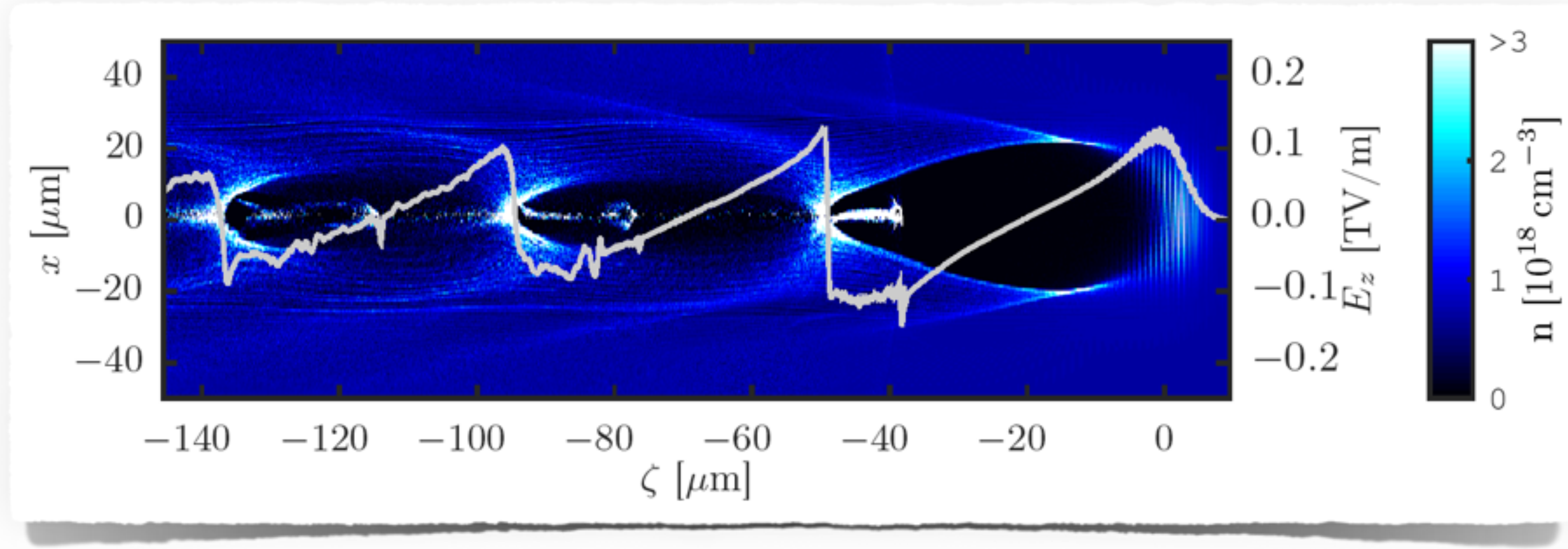

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diagnose bunch for feedback

external injection

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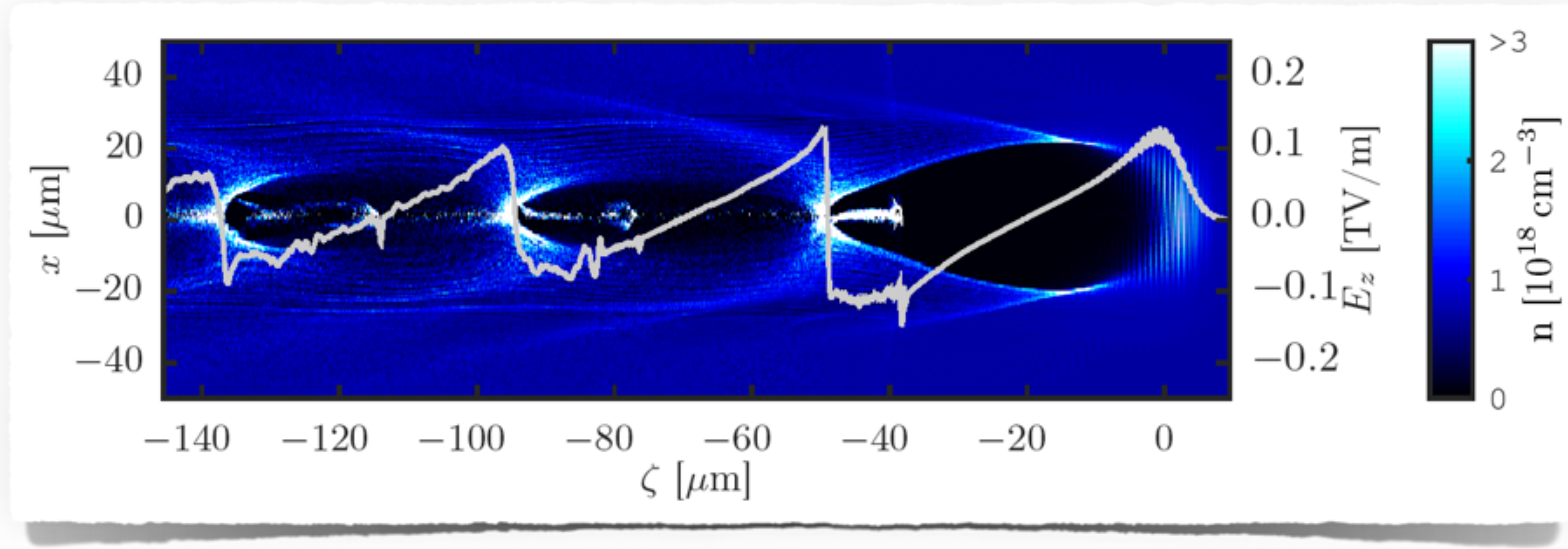


- originate from
  - laser and plasma stability
  - injection mechanism

→ diagnose bunch for feedback

→ external injection

typical bunch length ≈ 2 fs rms [1,2]

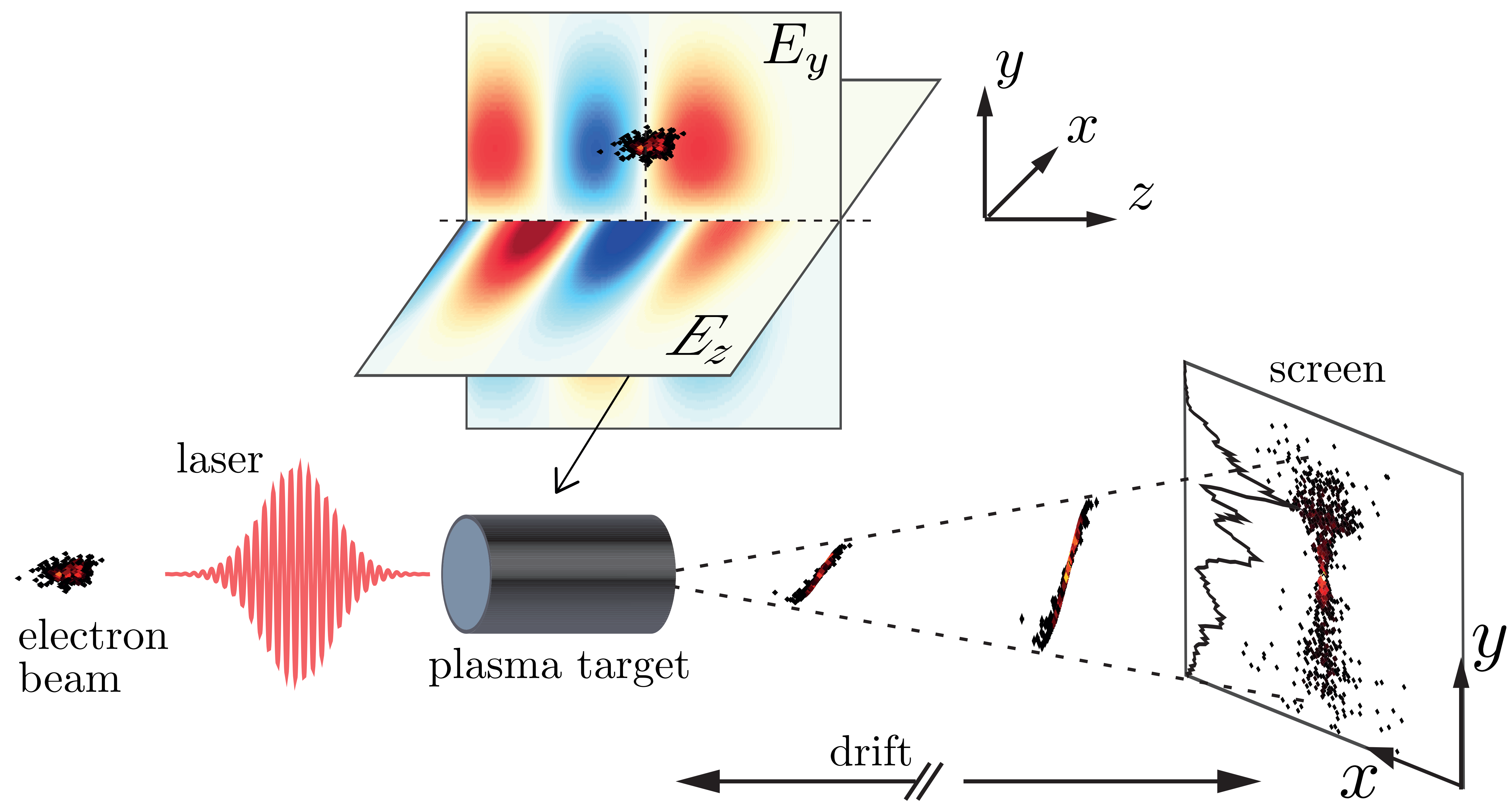
[1] A. Buck et al., Nat. Phys. 7, 543 (2011)

[2] O. Lundh et al., Nat. Phys. 7, 219 (2011)

Plasma based current profile diagnostic

- laser drives linear wakefield
- inject electron bunch off-axis in y
- experiences streaking field

- advantages:
  - strong fields
  - short (plasma) wavelength
  - short target



I. Dornmair et al., PRAB 19, 062801 (2016)

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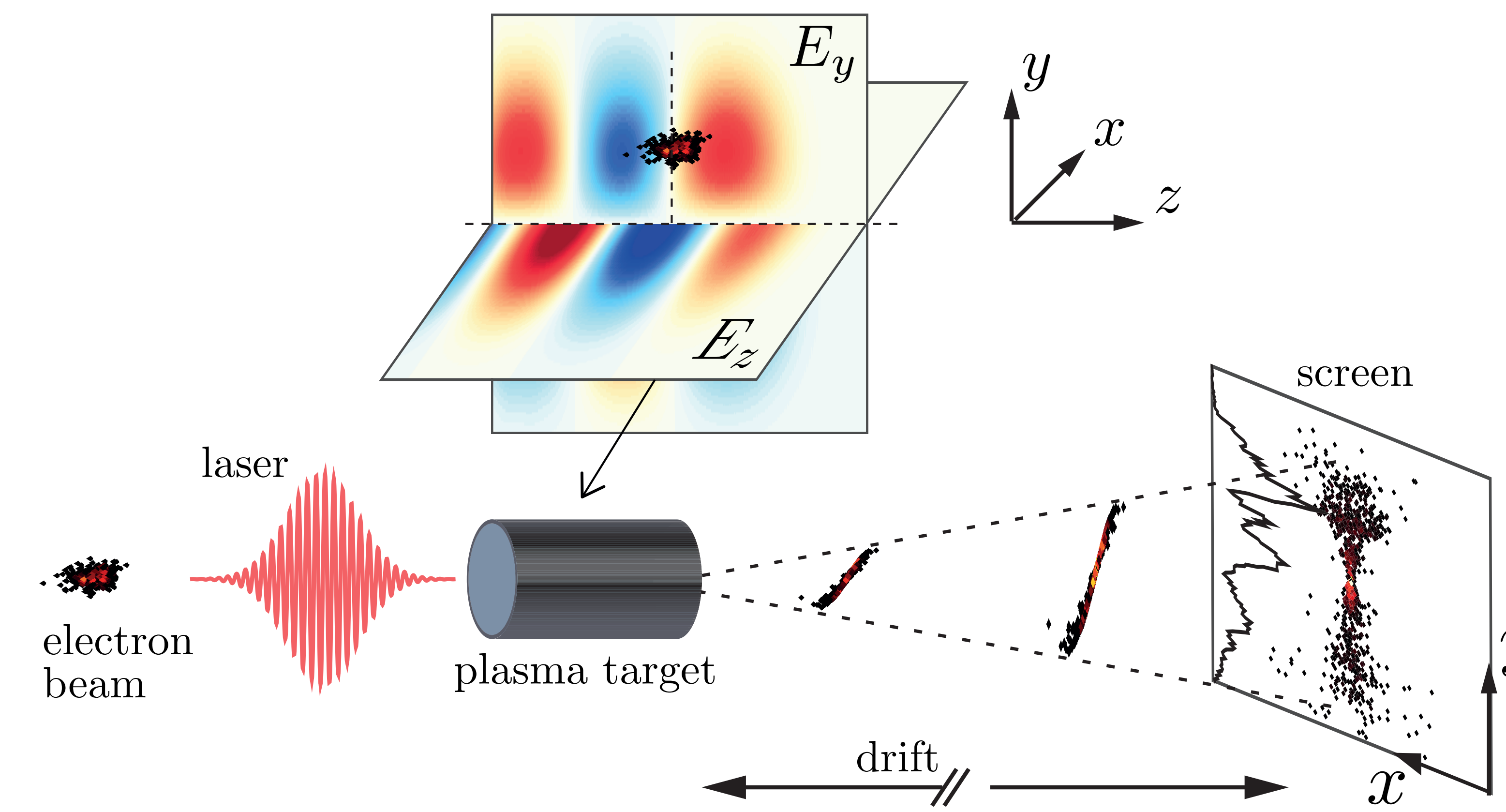
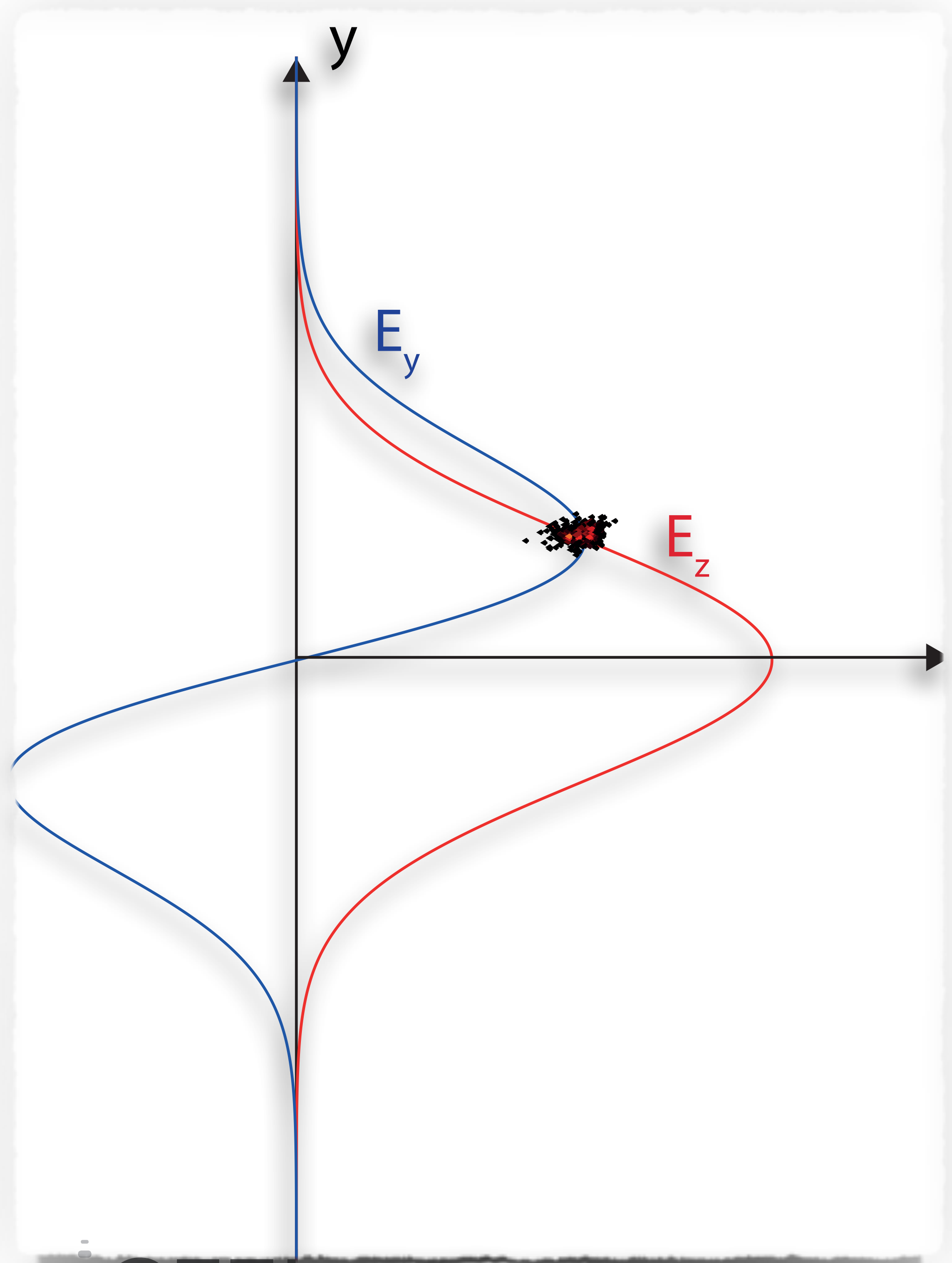
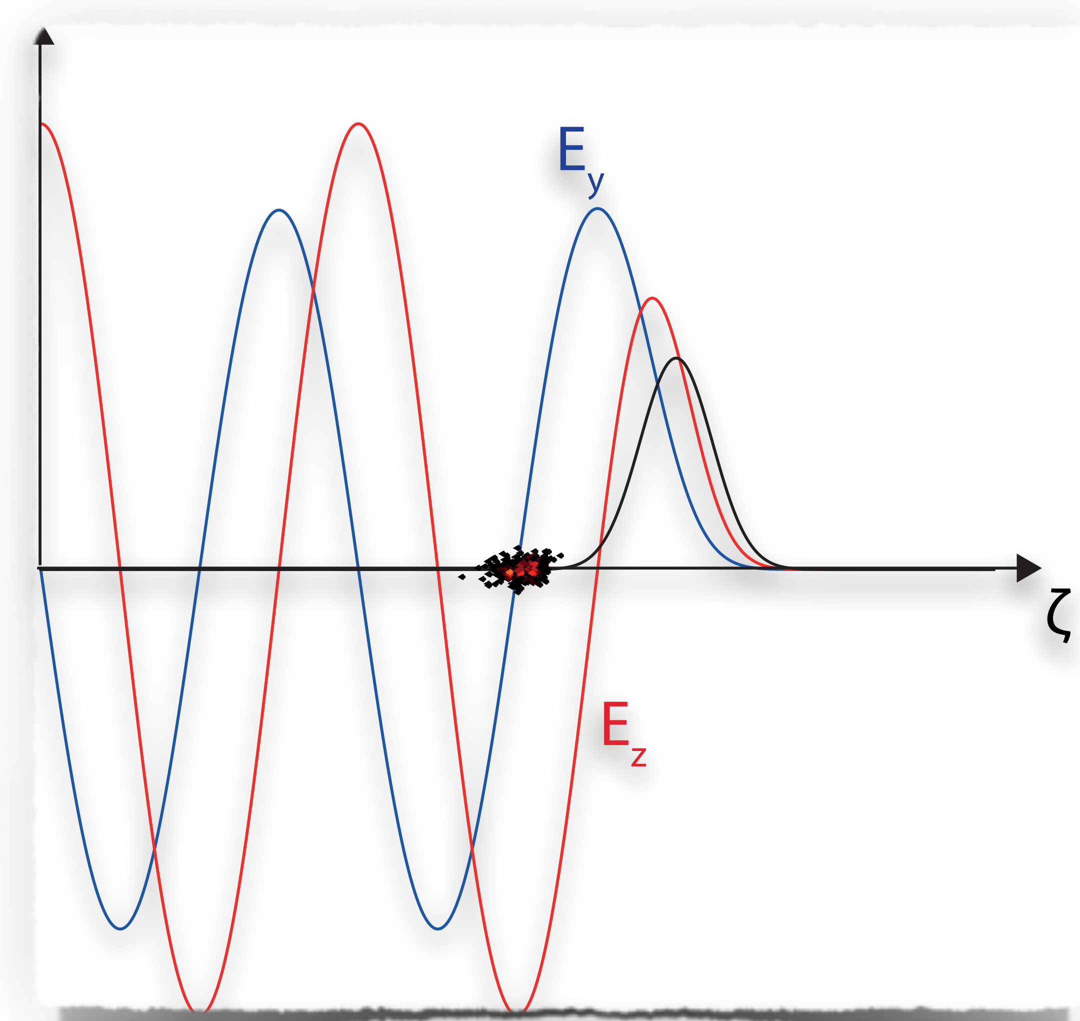




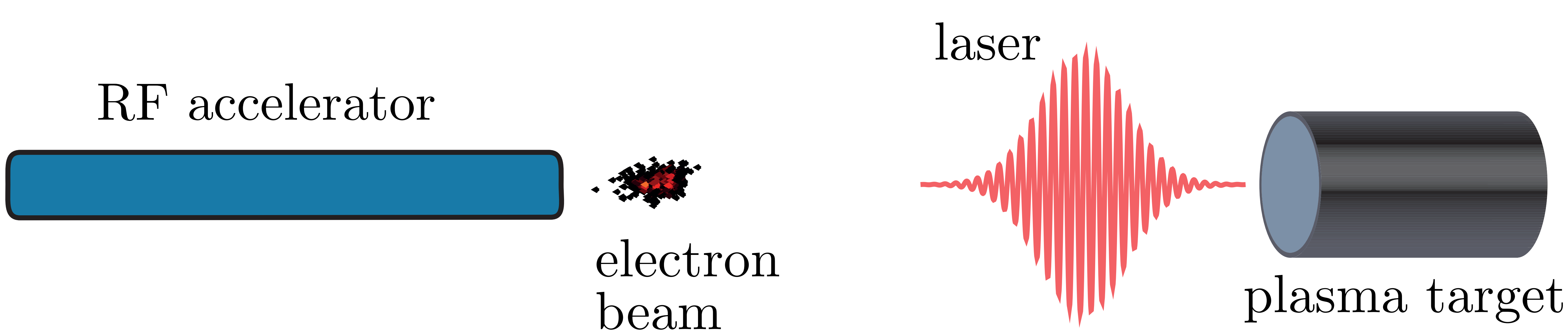


I. Dornmair et al., PRAB 19, 062801 (2016)

Example: PIC simulations

- Electron beam from SINBAD LINAC [1]
  - E_{kin} = 110 MeV
  - ε_{nx} = 0.09 mm mrad
  - σ_x = 17 µm
  - detuned phase ⇒ spiky current profile

- external injection setup
  - diagnose bunch at injection position



[1] SINBAD: R. Assmann et al., Proc. IPAC2014, Dresden, TUPME047

SINBAD LINAC: B. Marchetti et al., Proc. IPAC2015, Richmond, TUPWA030

I. Dornmair et al., PRAB 19, 062801 (2016)

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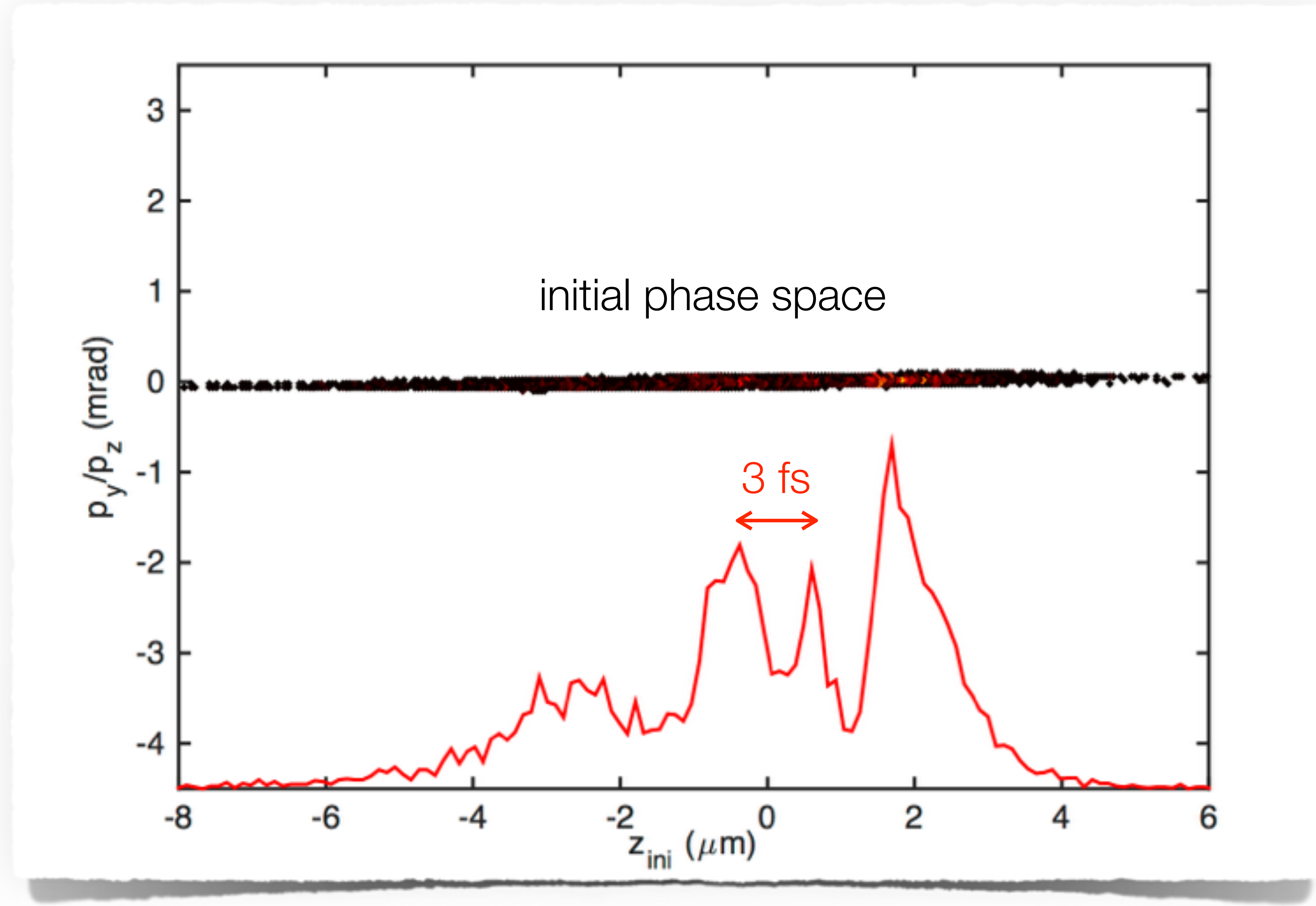
- Laser (3 J pulse energy)
  - a_0 = 0.3
  - τ = 41 fs (FWHM)
  - w_0 = 150 μm
- Plasma:
  - $1{\cdot}10^{18}$ cm^{-3}
  - l = 3.5 mm
- distance laser - beam: 34 μm



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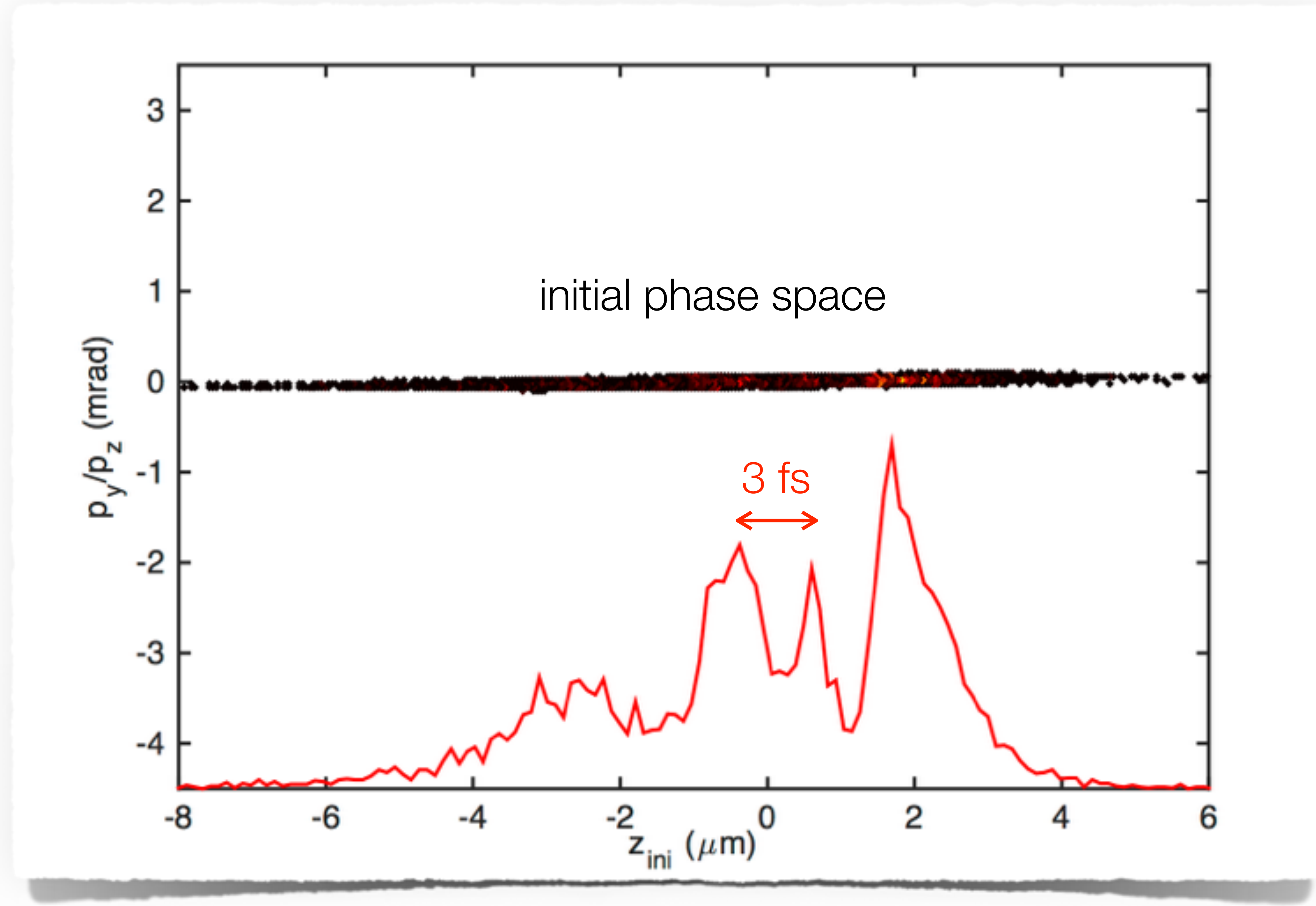

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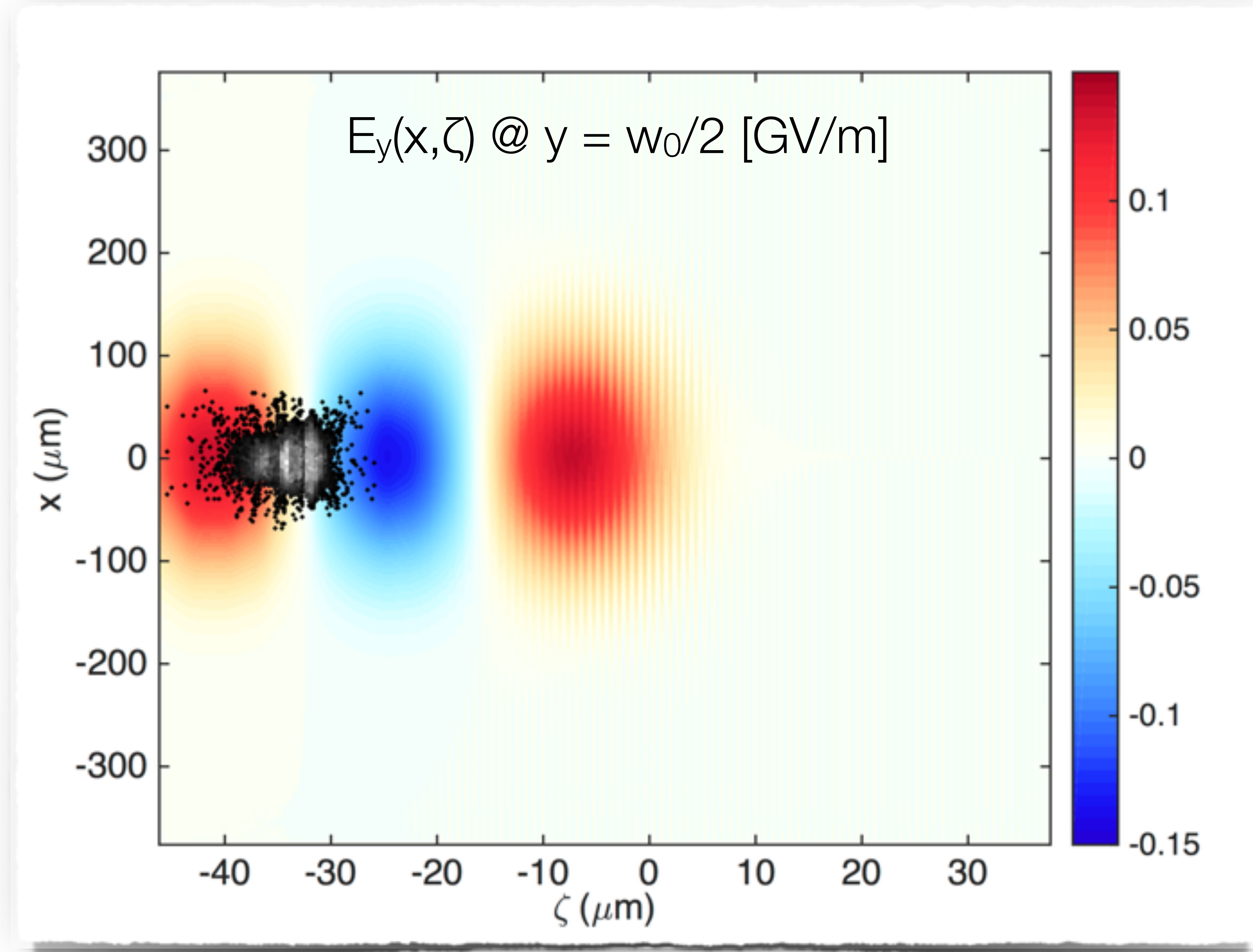
- using WARP* in the boosted frame (γ_{boost} = 10)



* thanks to the WARP team: J.-L. Vay, R. Lehe (LBNL), D. P. Grote (LBNL/LLNL)

I. Dornmair et al., PRAB 19, 062801 (2016)

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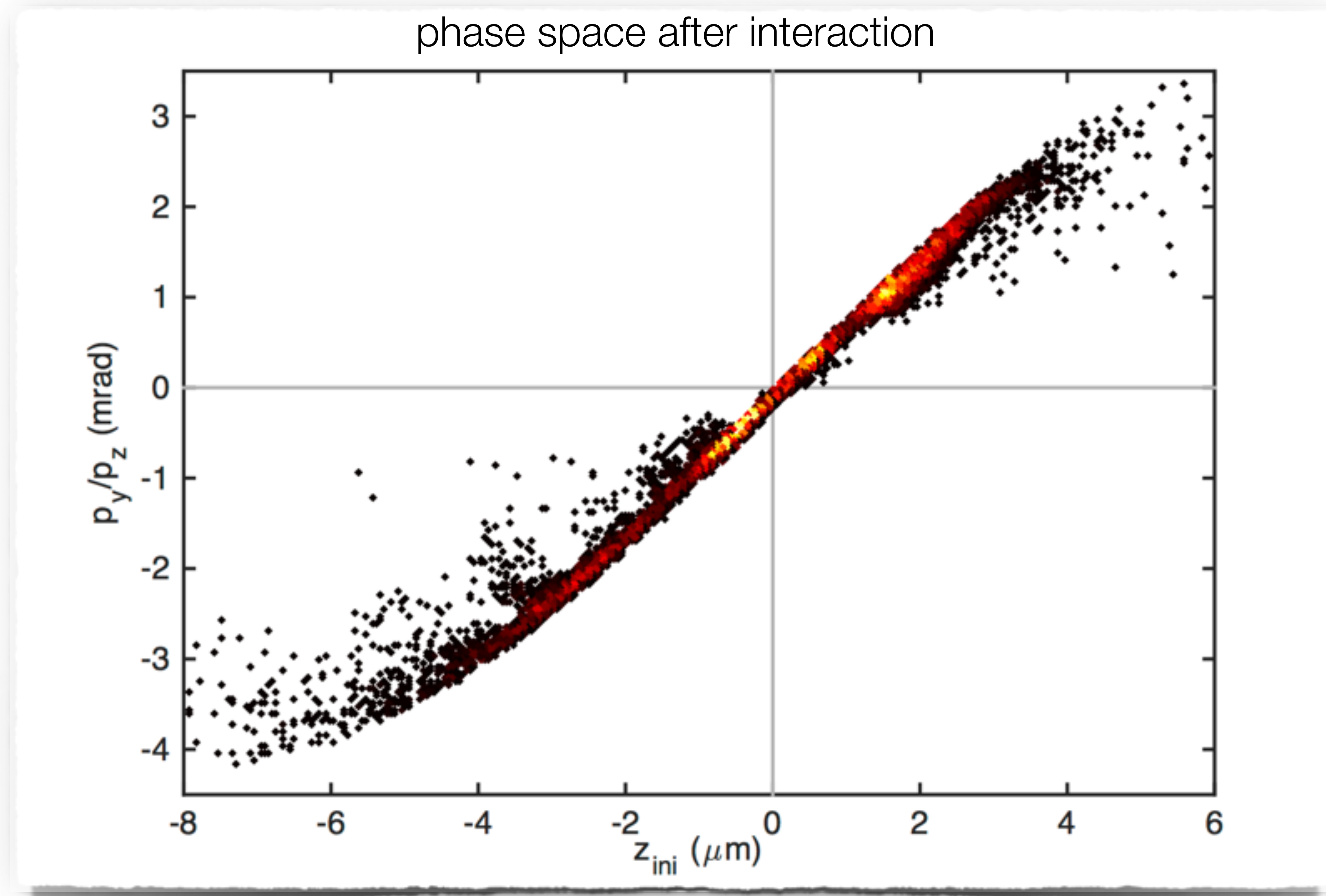
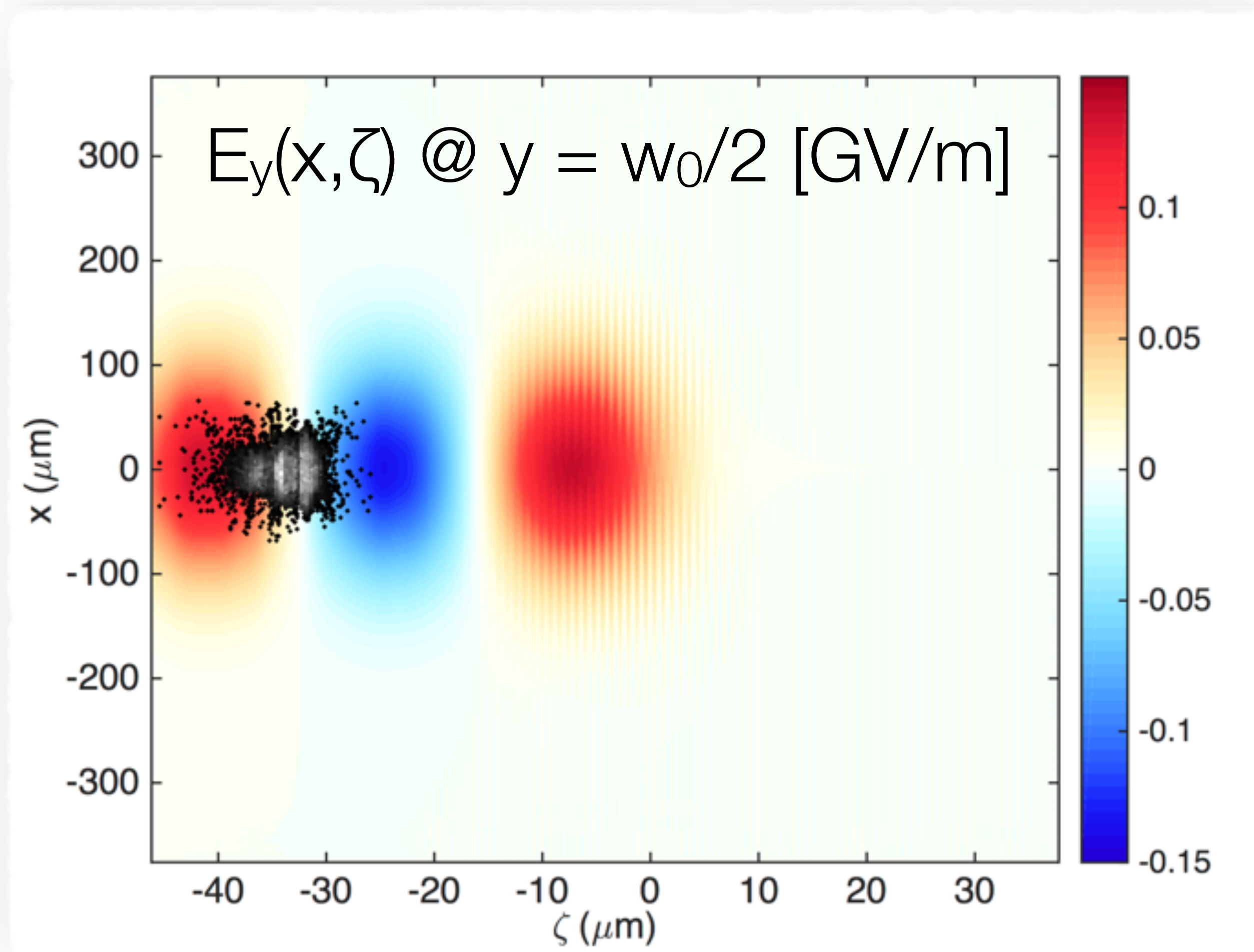


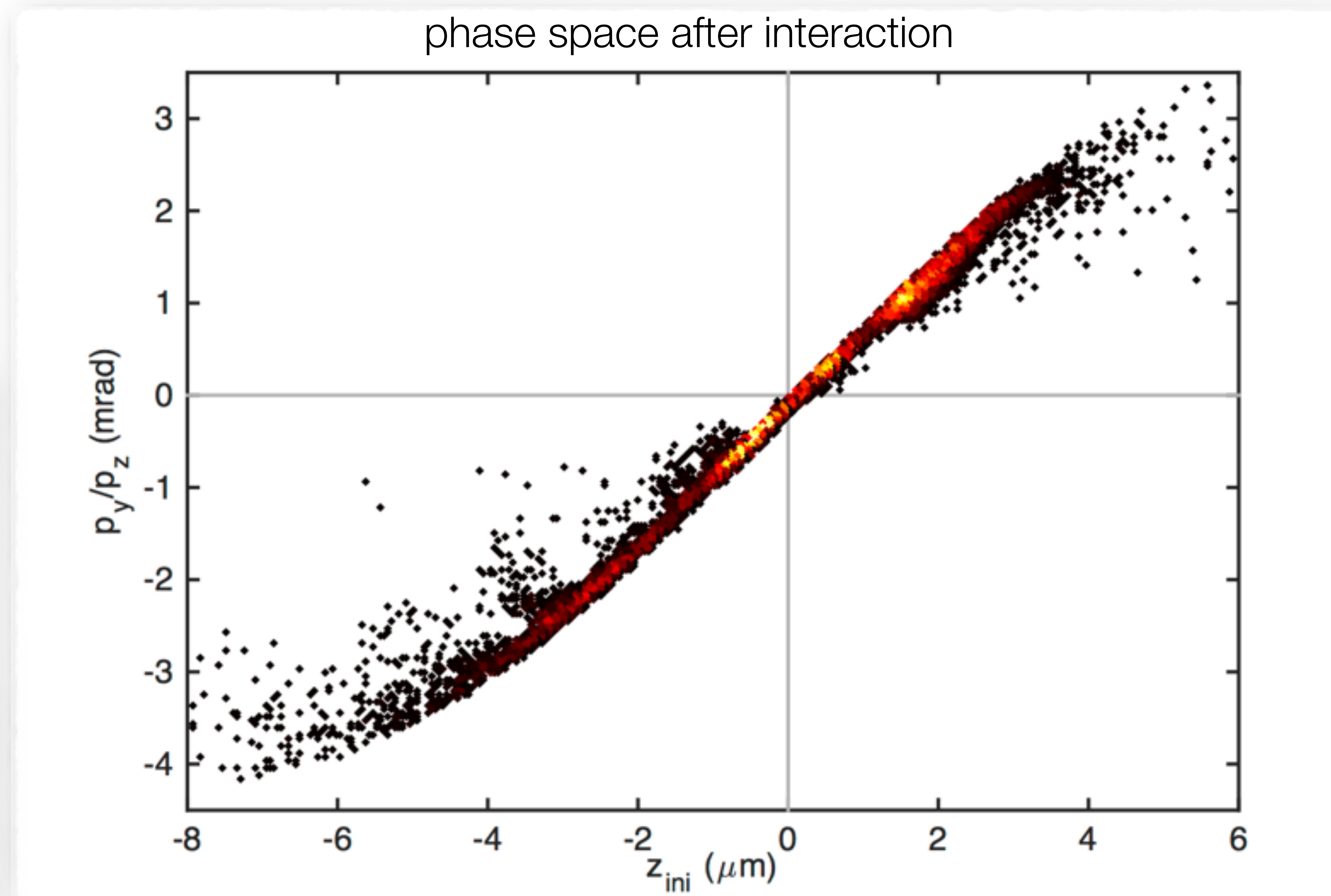
I. Dornmair et al., PRAB 19, 062801 (2016)

Higher order field correlations

- E_y is curved in x and y
- streaking gradient smears over wide bunch
- independent of plasma length

$$\Delta\zeta \geq \frac{\sqrt{10}}{2}\left(\frac{2\sigma_y}{w_0}\right)^2 |\zeta|$$





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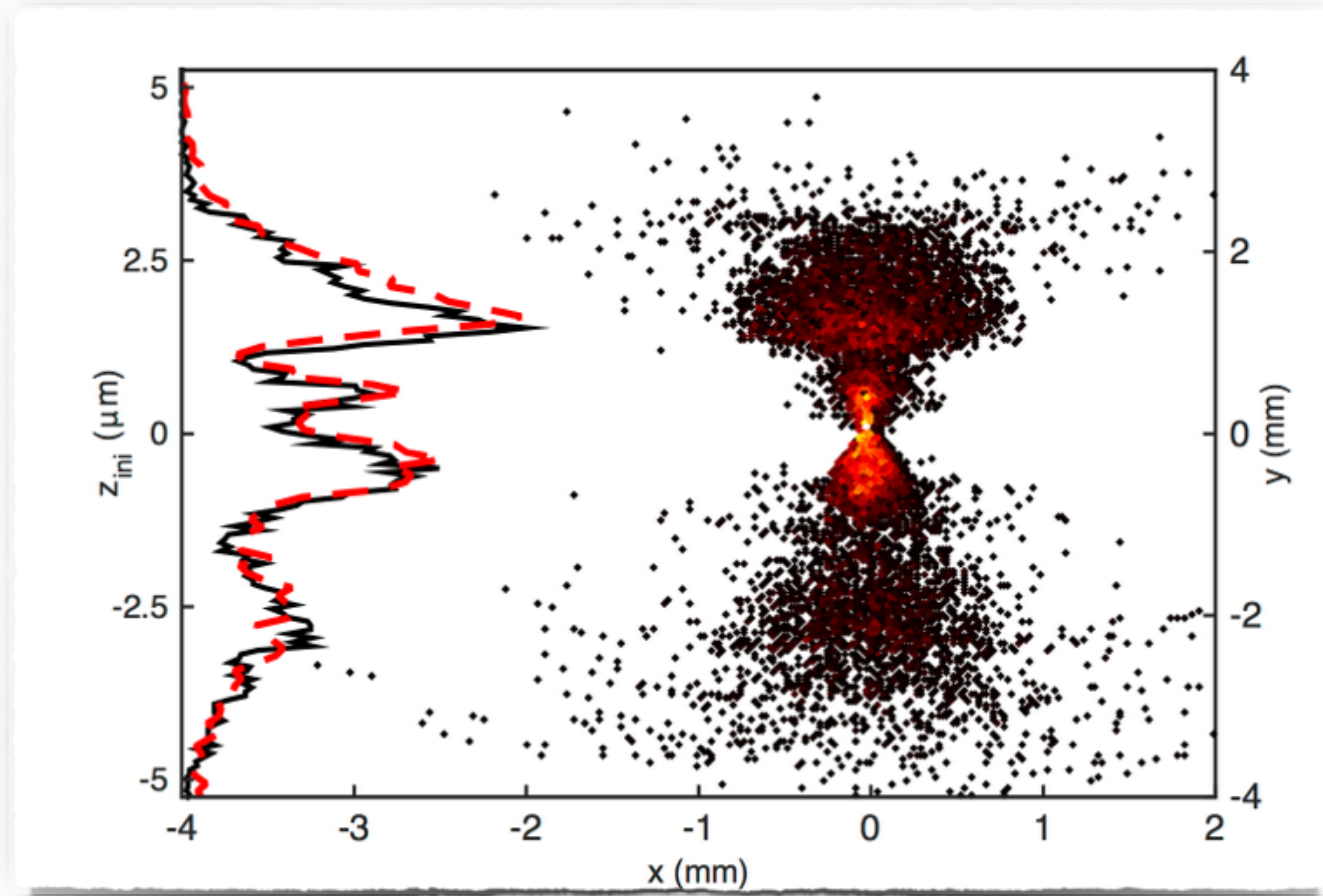

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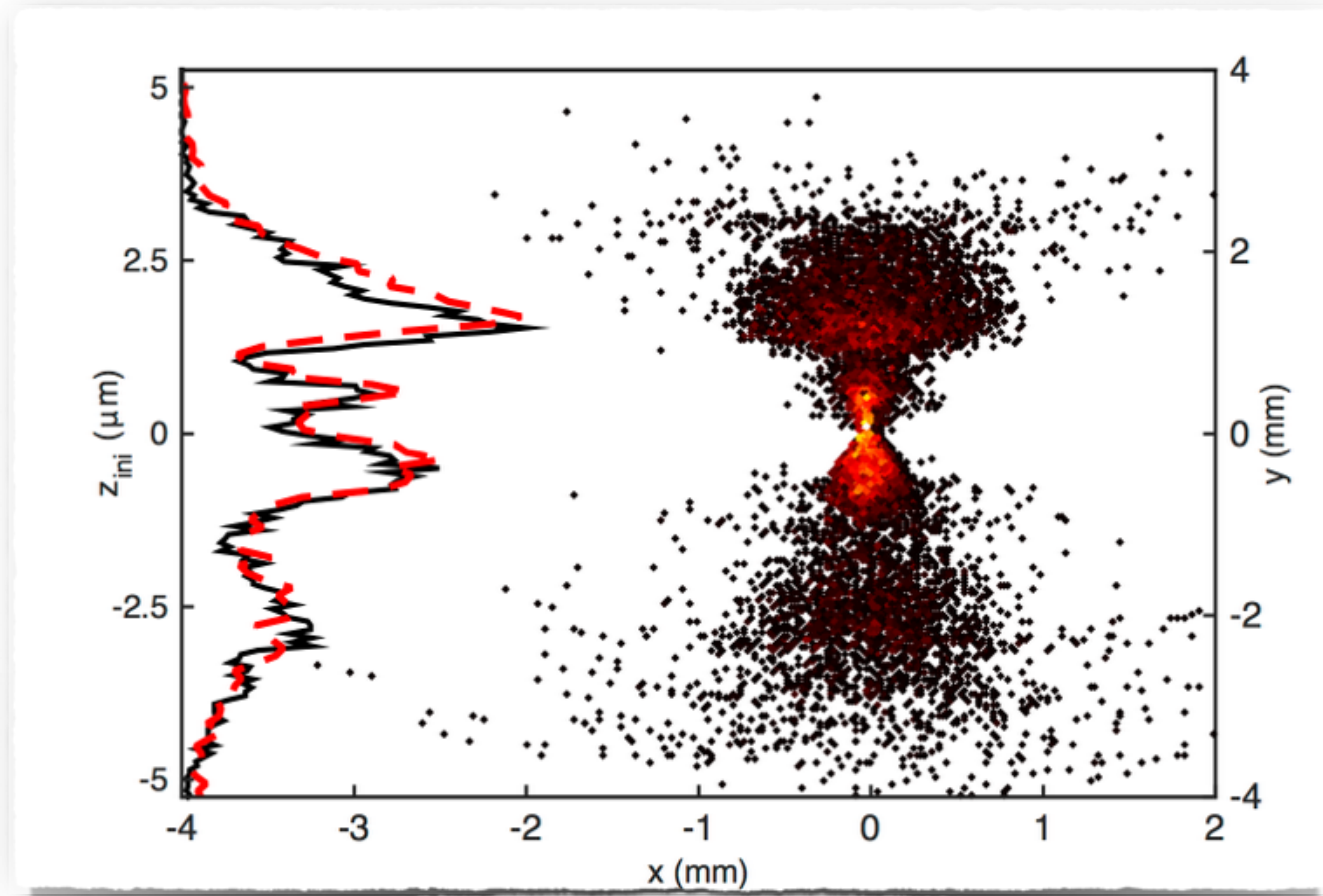
- theoretical resolution: 96 attoseconds

$$\Delta\zeta \geq \frac{\epsilon_{ny} m_e c^2}{\sigma_y e k V}$$



Temporal resolution - higher order correlations

- resolution degradation from curvature:

$$\Delta\zeta \geq \frac{\sqrt{10}}{2}\left(\frac{2\sigma_y}{w_0}\right)^2 |\zeta|$$

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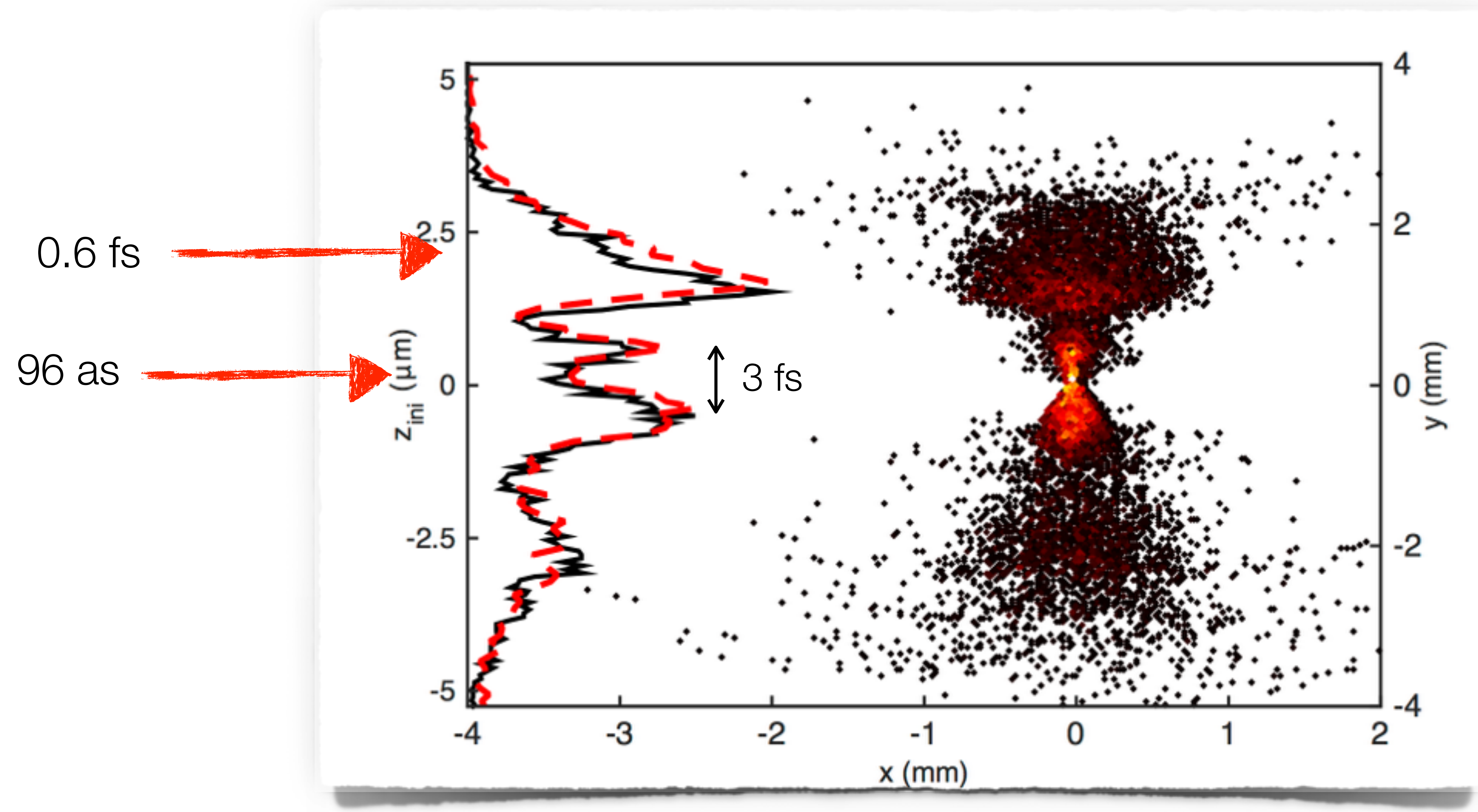


- voltage $V = 0.5\,\mathrm{MV}$
- wavenumber $k = 1.9 \times 10^5\,\mathrm{m}^{-1}$

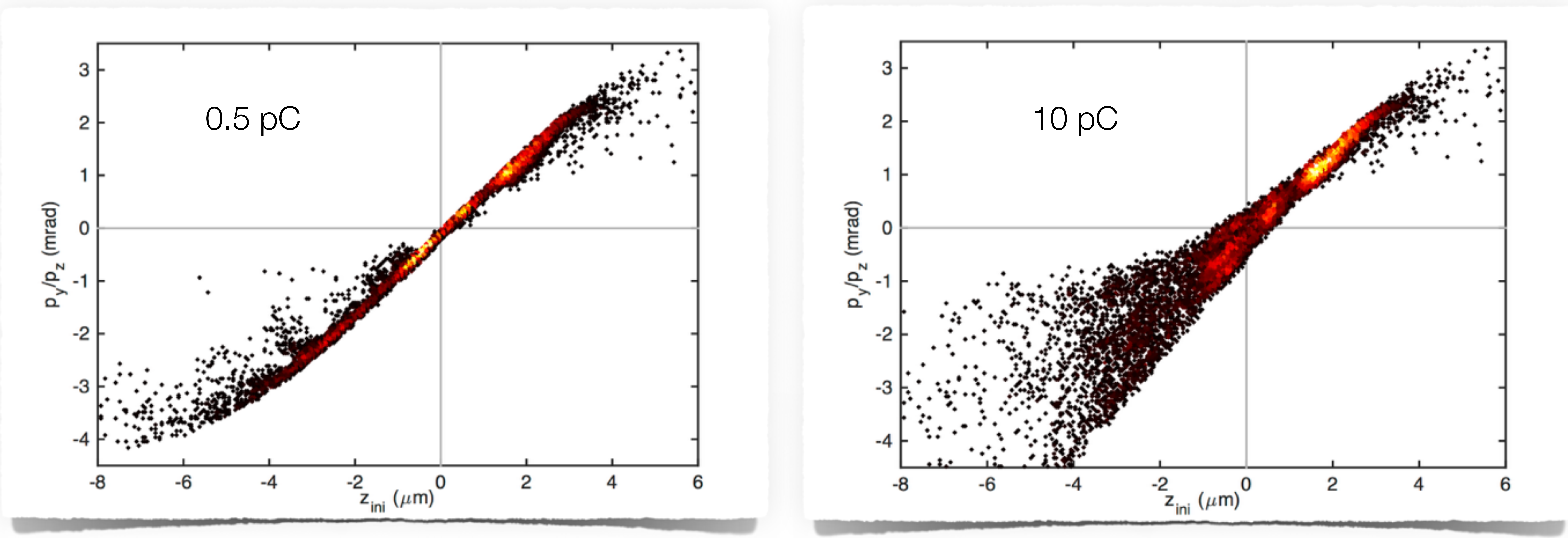
Limitations - Beam Loading

- beam drives own wake
- modifies streaking field

- resolution degradation
  - for Q = 0.5 pC: $\Delta\zeta > 66\,\mathrm{as}$
  - for Q = 10 pC: $\Delta\zeta > 1.3\,\mathrm{fs}$

- if beam loading dominates:
  - increase laser spotsize
  - increase laser intensity

phase space after interaction



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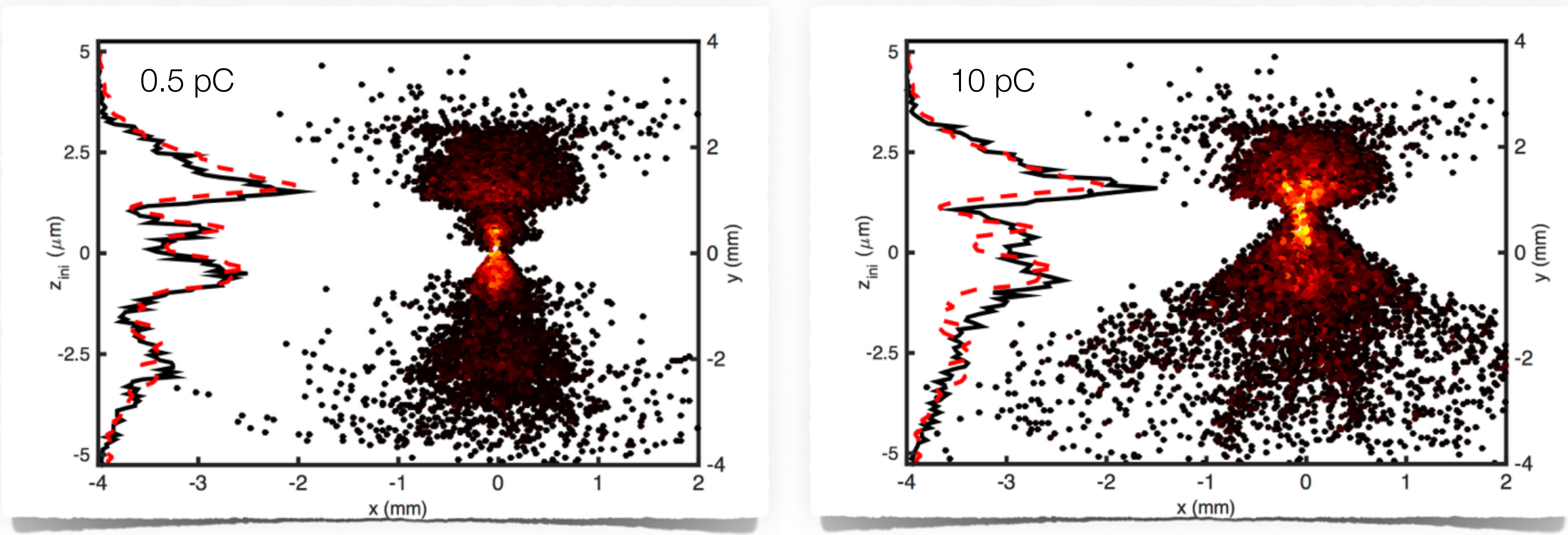
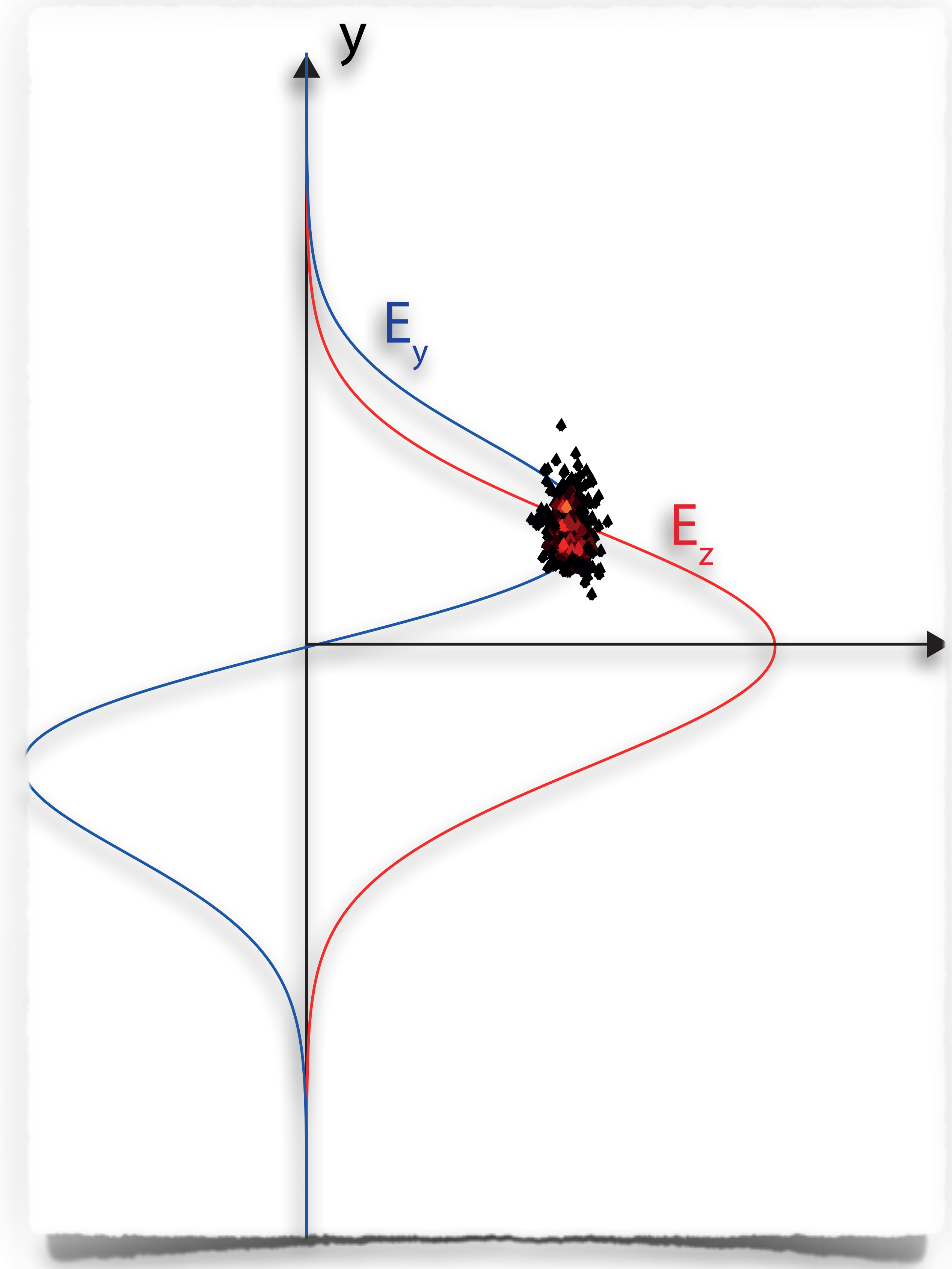
simulated screen image



Limitations - Energy Spread

- slope of E_z
- like in TDS: induced energy spread
  - high temporal resolution ⇔ low energy spread resolution
  - here: accumulated 1.4 % energy spread



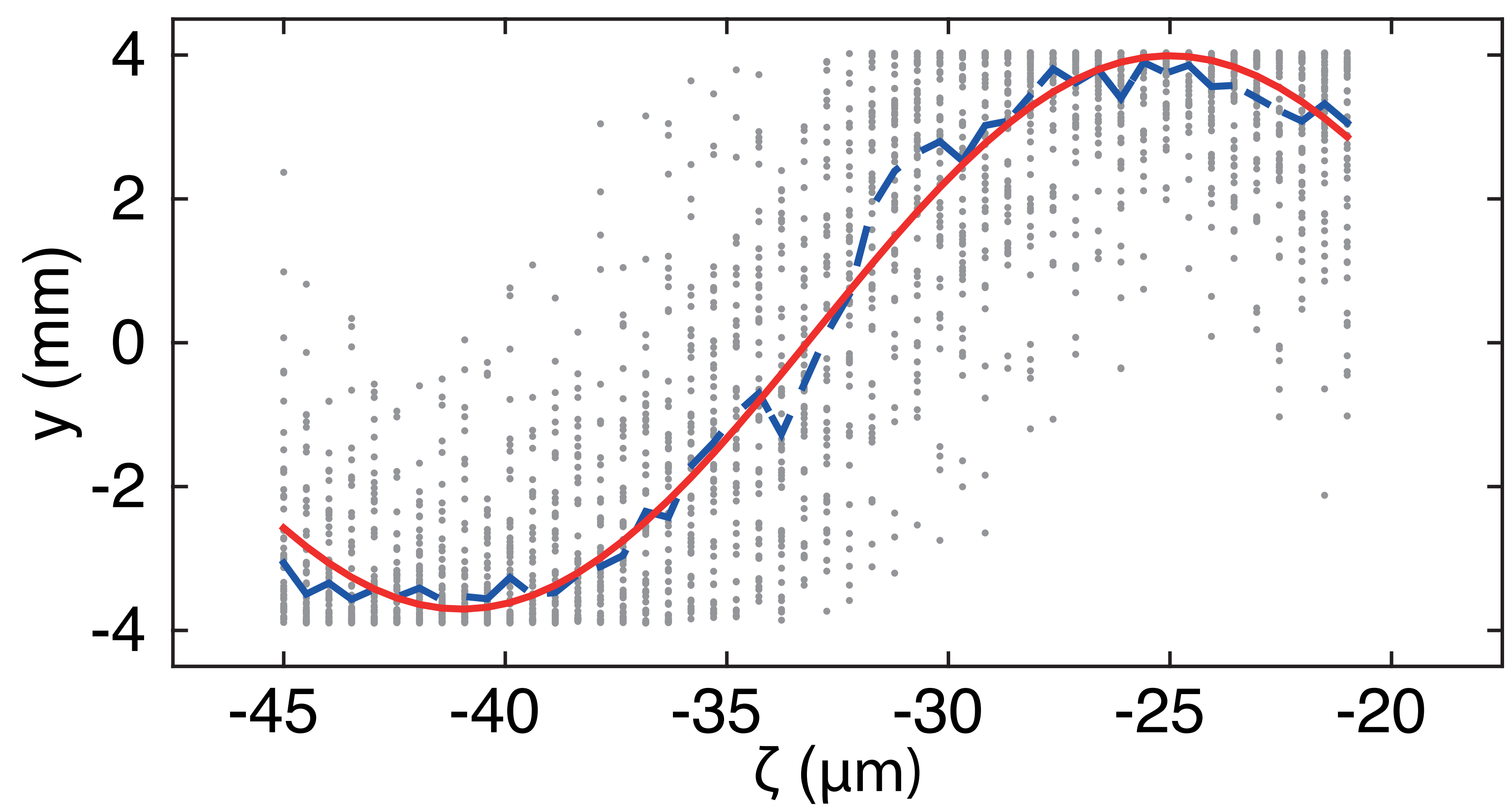
Limitations - Arrival Time Jitter

- timing jitter:
  - shifts beam in phase of wake
  - remain at 10 % of plasma wavelength
    - 10 fs rms

- synchronization: SASE FEL pulse to IR laser @ FLASH
  - 28 fs rms
  - limited by bunch duration
  - S. Schulz et al. Nat. Commun. 6:5938 (2015)

  - also: seeded FEL @ FERMI
  - 6 fs rms
  - M. B. Danailov et al., Opt. Express 22, 12869 (2014)

- ASTRA simulations
- 10 fs rms jitter
- 50 shots at each delay
- rel. calibration error: 6 %



Good	Bad
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Good

- comes for free in external injection experiments
- intrinsically synchronized in LPA
- calibration possible
- direct access to phase space

Bad

- need high power laser system
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tunable frequency	

Good

- comes for free in external injection experiments
- intrinsically synchronized in LPA
- calibration possible
- direct access to phase space
- compact
- tunable frequency
- low charge

Bad

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- need high power laser system
- synchronization to laser in conventional machines
- "active" structure
- limited to low charge
- small beam size required

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Bad

- need high power laser system
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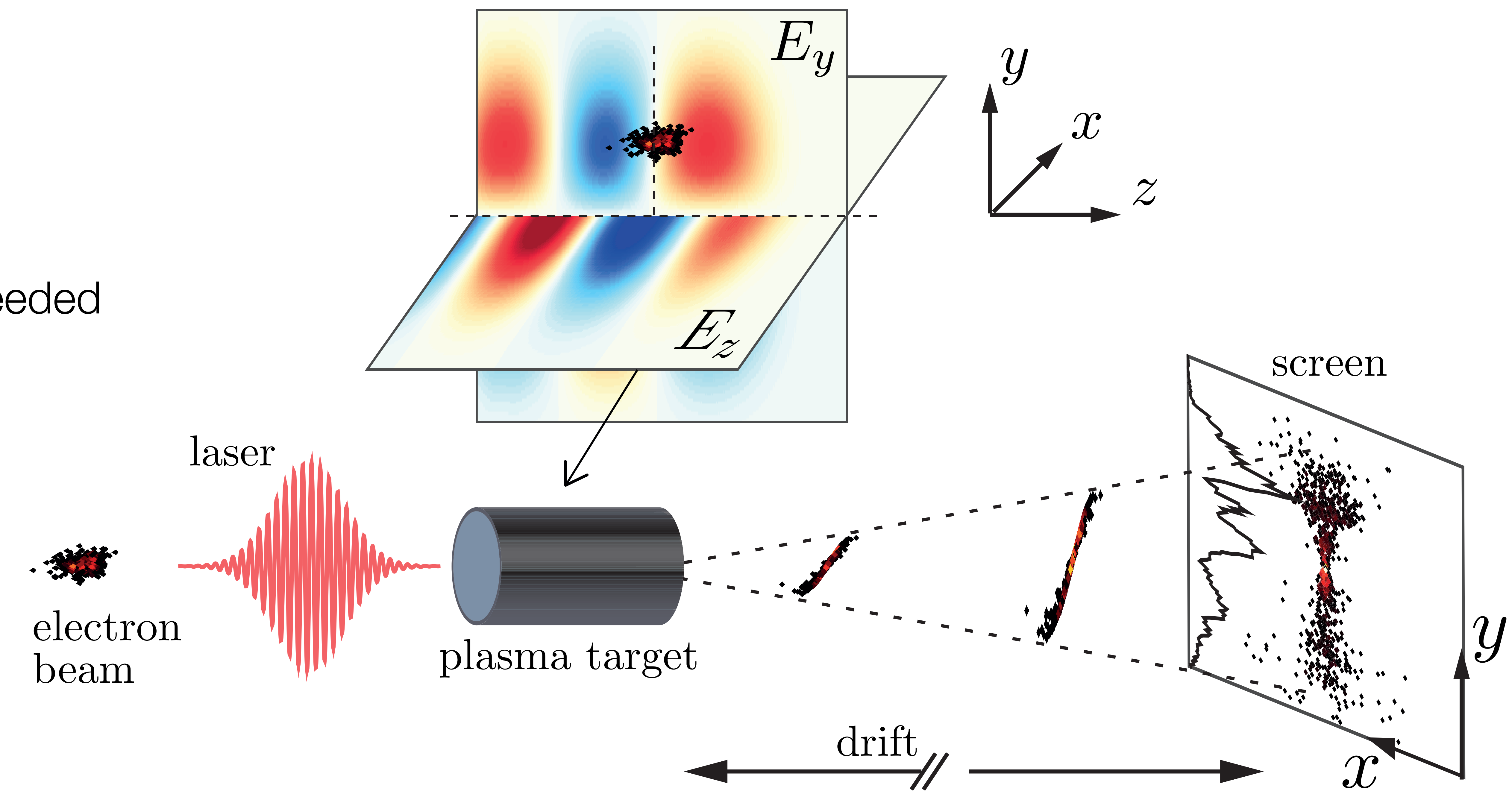
ugly: no demonstration yet

- limited to low charge
- small beam size required

Conclusion

- use plasma wakefield for bunch streaking
- strong fields and short wavelength
- temporal resolution below 1 fs
- high power laser system & synchronization needed
- well suited for laser plasma acceleration



Acknowledgement

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partners

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group
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DESY FS-LA

LBNL
J.-L. Vay
WARP code

group
Brian McNeil

group Georg Korn

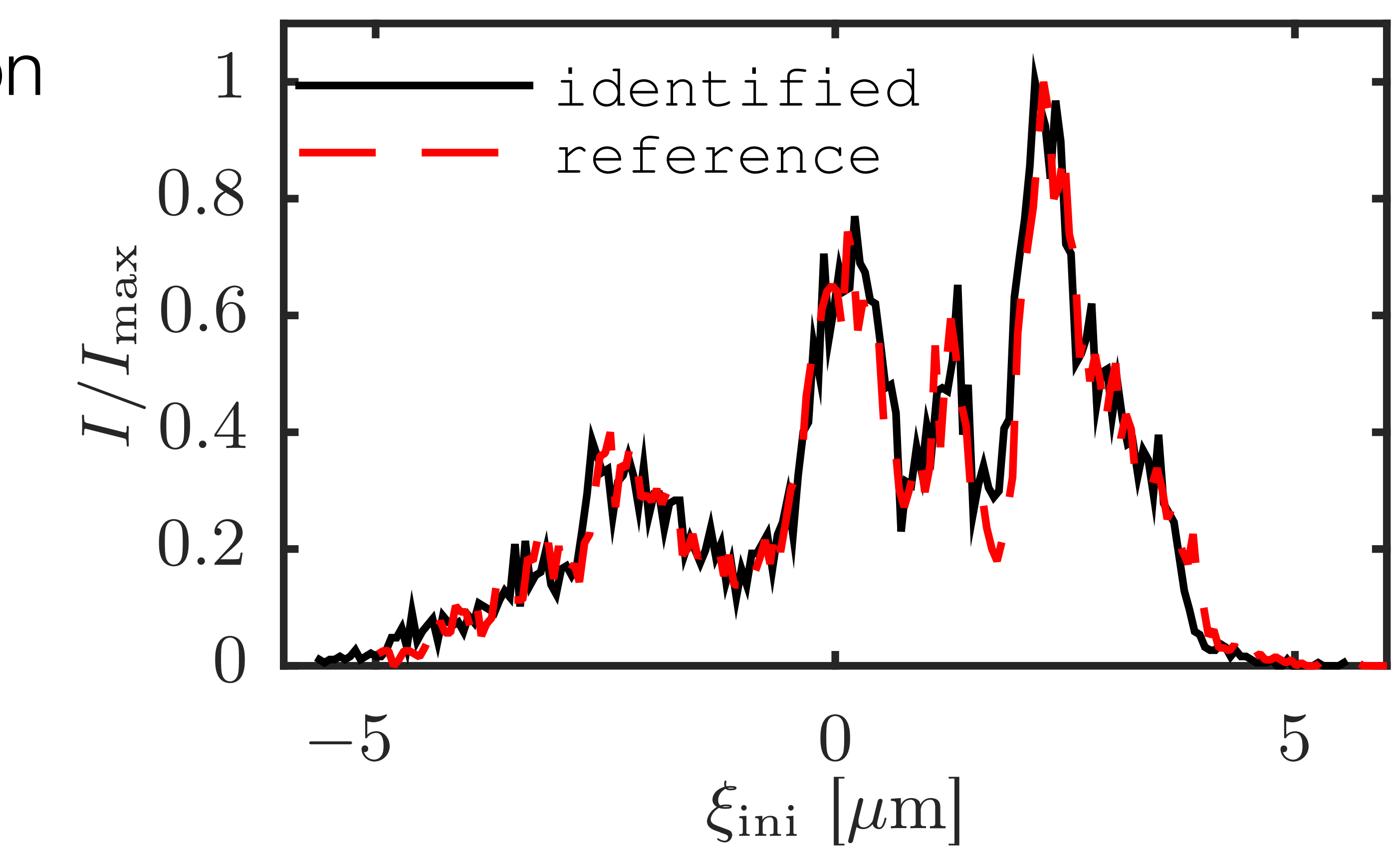
group
Johannes Bahrdt

group
Jens Osterhoff

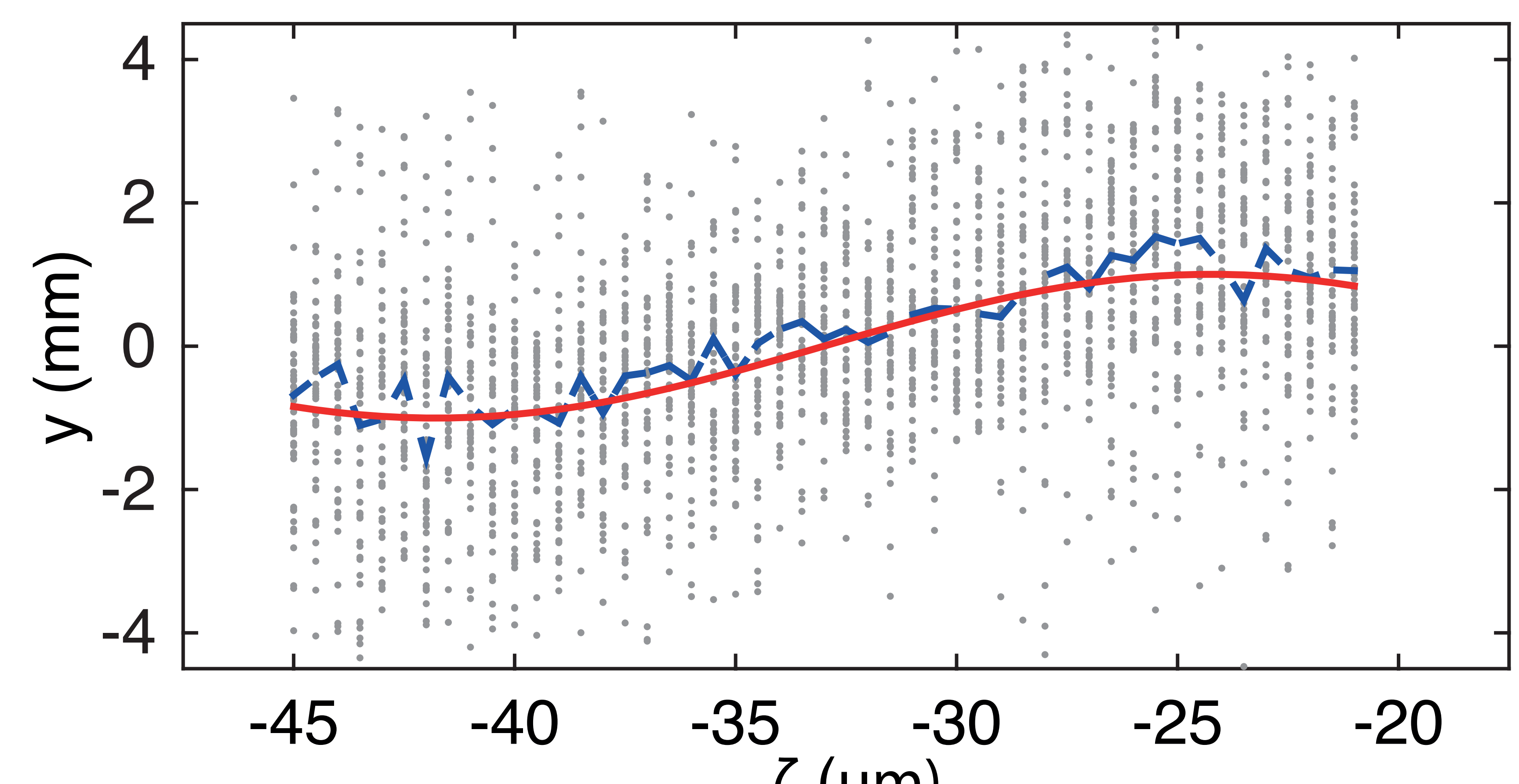
Limitations: Pointing Jitter

- jitter in angle and offset:
  - shifts beam w.r.t. laser
  - streaking voltage drops
- laser stability at LUX
  - before compressor: 2 µrad rms pointing
  - after 40 m beam transport & focused: 40 µrad pointing, 6 µm offset

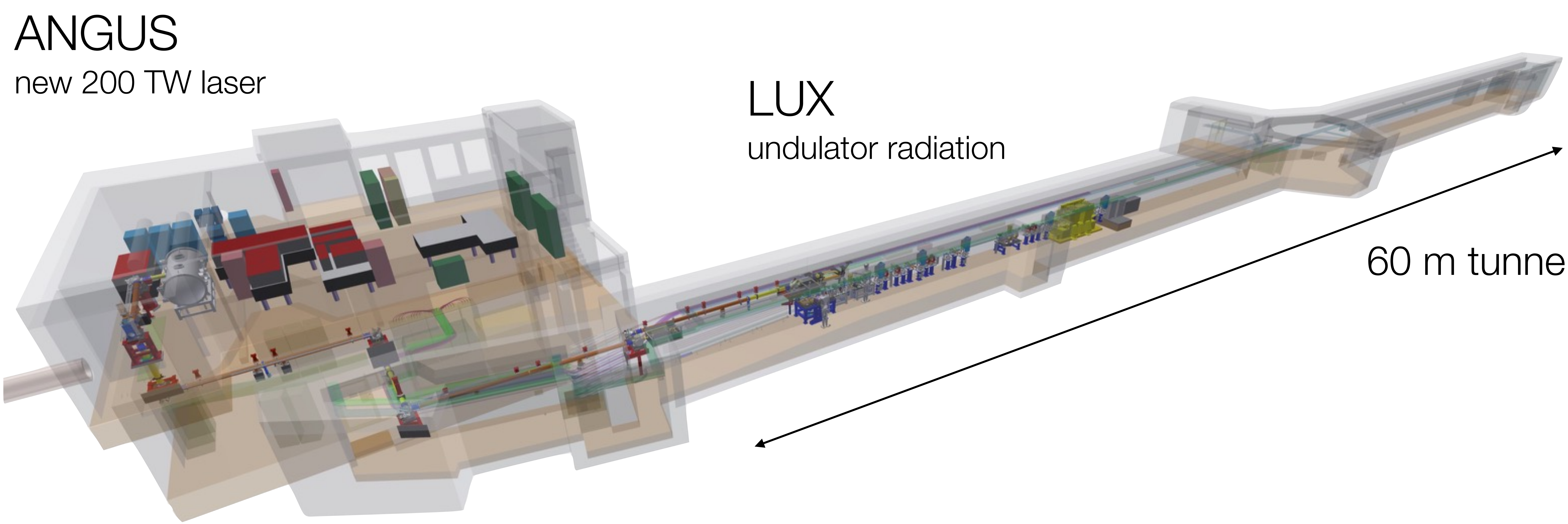
- good shot identification
  - center of screen
  - large extent in y



- ASTRA simulations:
- jitter: 10 fs rms arrival time
  500 µrad pointing
  75 µm offset
- 50 shots at each delay
- rel. calibration error: 3 %



Laser-Driven Plasma Acceleration



see also lux.cfel.de

More longitudinal phase space diagnostics

- TDS cavities
  - down to 1 fs

  C. Behrens et al., Nat. Commun. 5, 3762 (2014)

- electro-optical monitors
  - around 50 fs

  R. Pompili et al., NIM A 740, 216 (2014)
  G. Berden et al., PRL 99, 164801 (2007)

- passive streaker
  - depending on charge, fs range

  S. Bettoni et al., PRAB 19, 021304 (2016)

- coherent transition radiation
  - depending on charge, no hard resolution limit
  - no unique reconstruction

- Faraday rotation
  - few fs
  - need strong magnetic field (high current density)

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