# Influence of proton bunch parameters on a proton-driven plasma wakefield acceleration experiment

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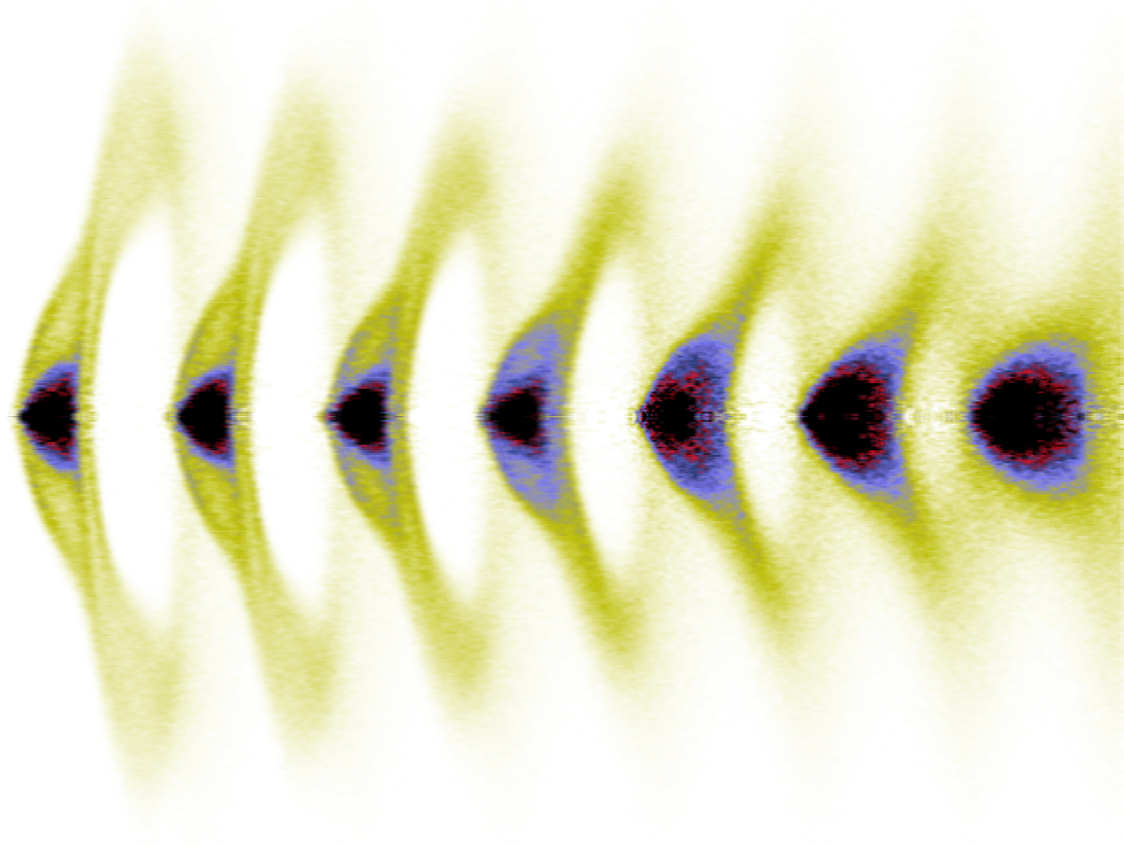

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# AWAKE: a proton-driven PWFA

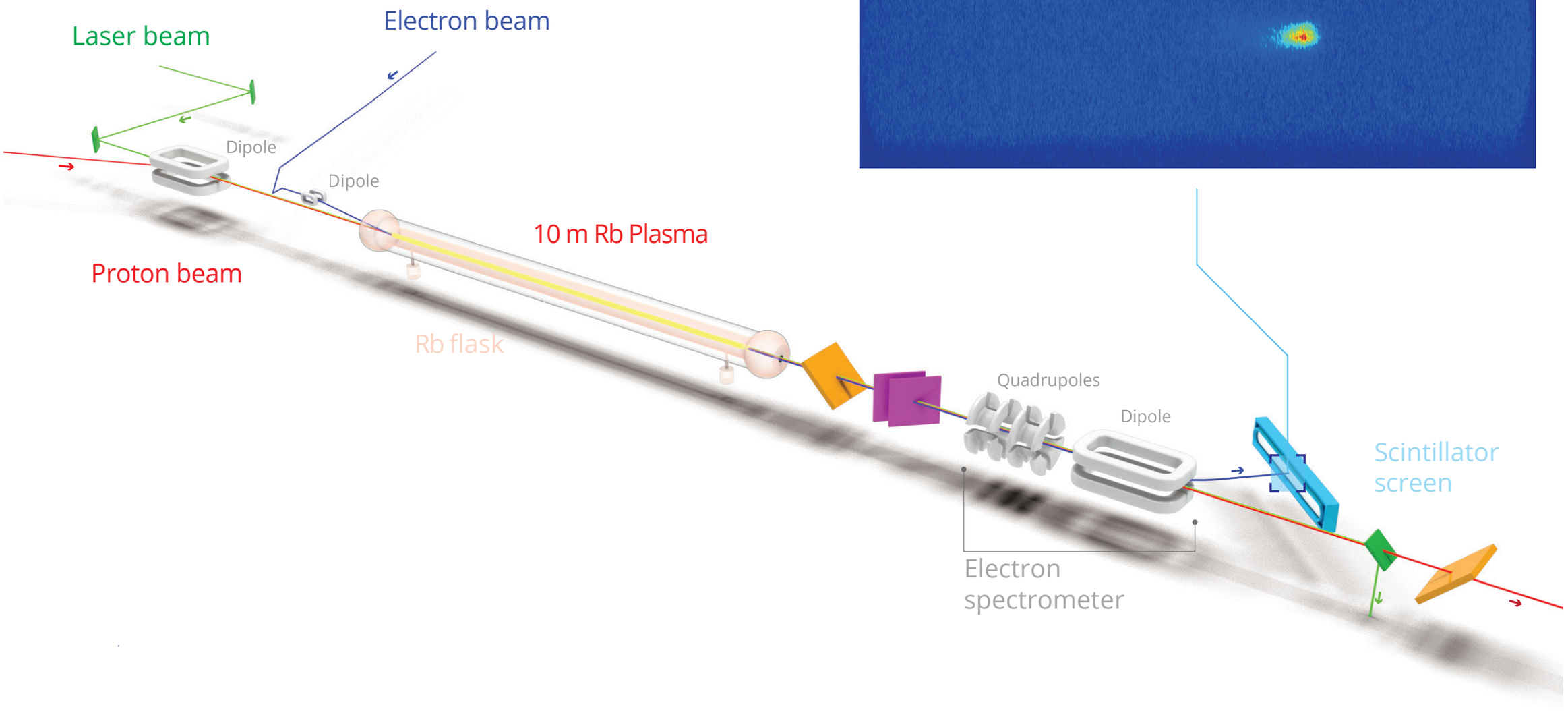
**Proof-of-concept experiment**

400 GeV proton bunch

10 m plasma

# Successful Run 1

## Demonstrated acceleration of electrons



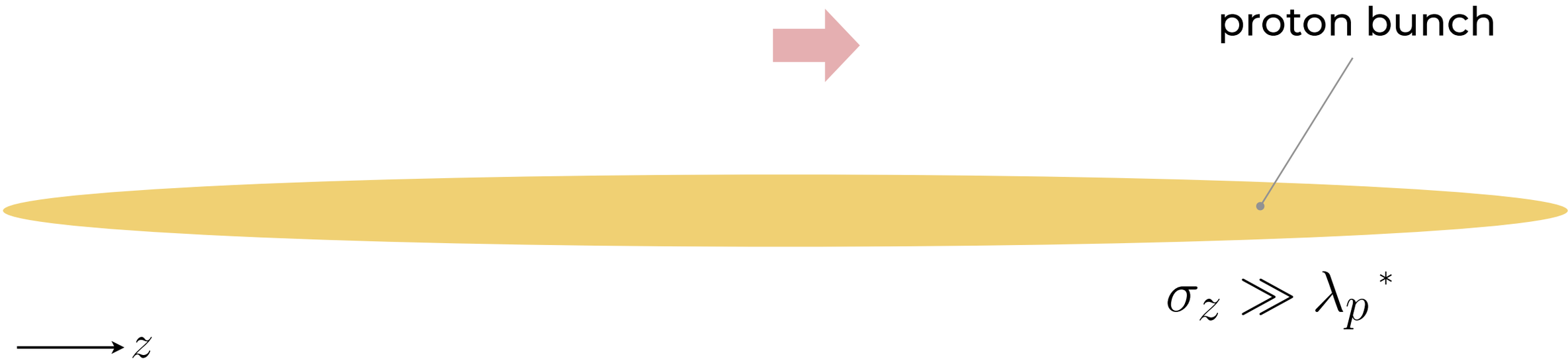




* The AWAKE Collaboration, Nature 561, 363-367 (2018)

# The self-modulation instability

## The SMI For Dummies




* ~10 cm versus 1-3 mm

# The self-modulation instability

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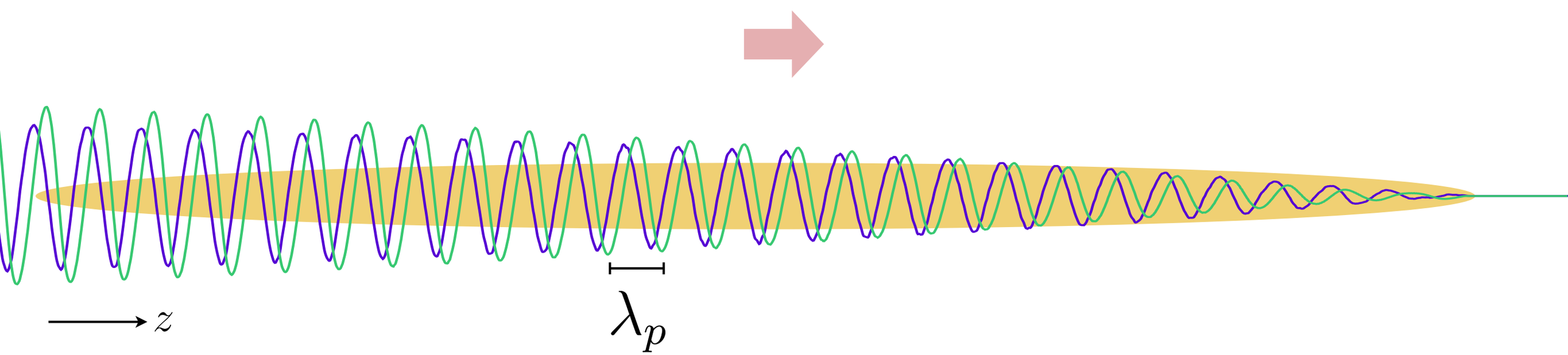
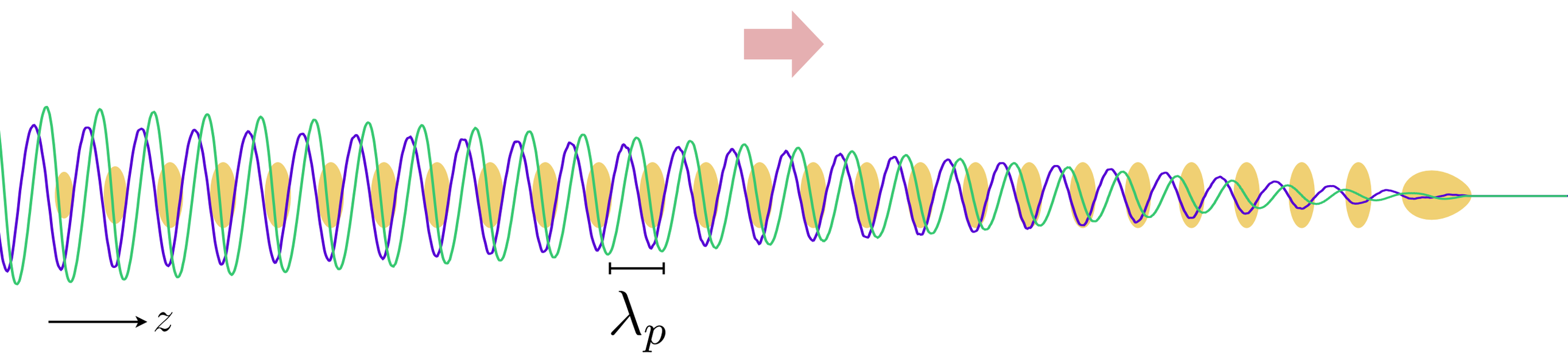



$$\Delta\phi = \pi/2 \quad \subset \quad \boxed{\begin{array}{ll} & E_z \\ & E_r \end{array}}$$

# The self-modulation instability

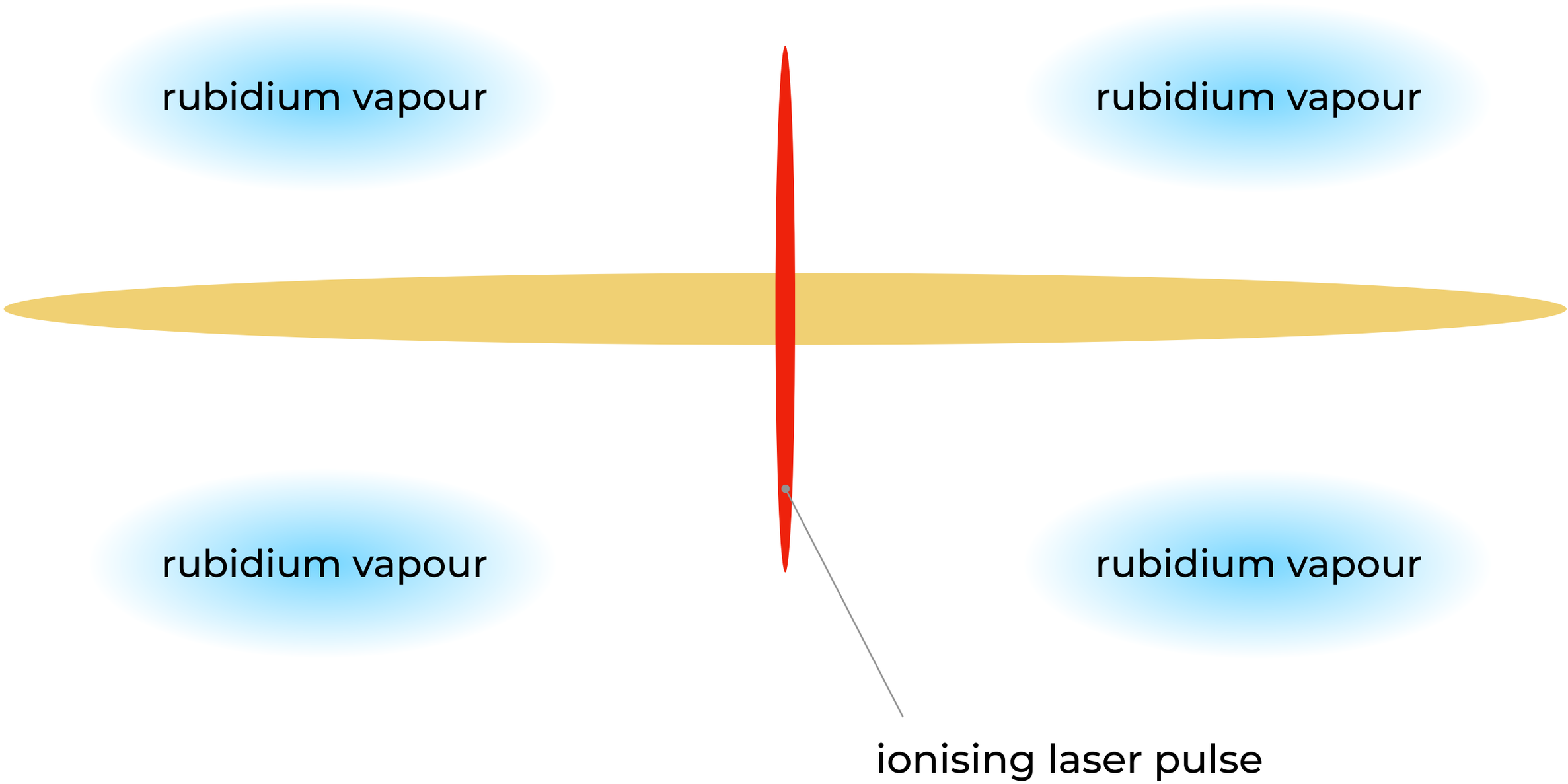
## The SMI For Dummies




$$\Delta\phi = \pi/2 \text{ (}$$ $E_z$, $E_r$

# Seeded self-modulation (SSM)

## A sharp ionisation front fixes the phase



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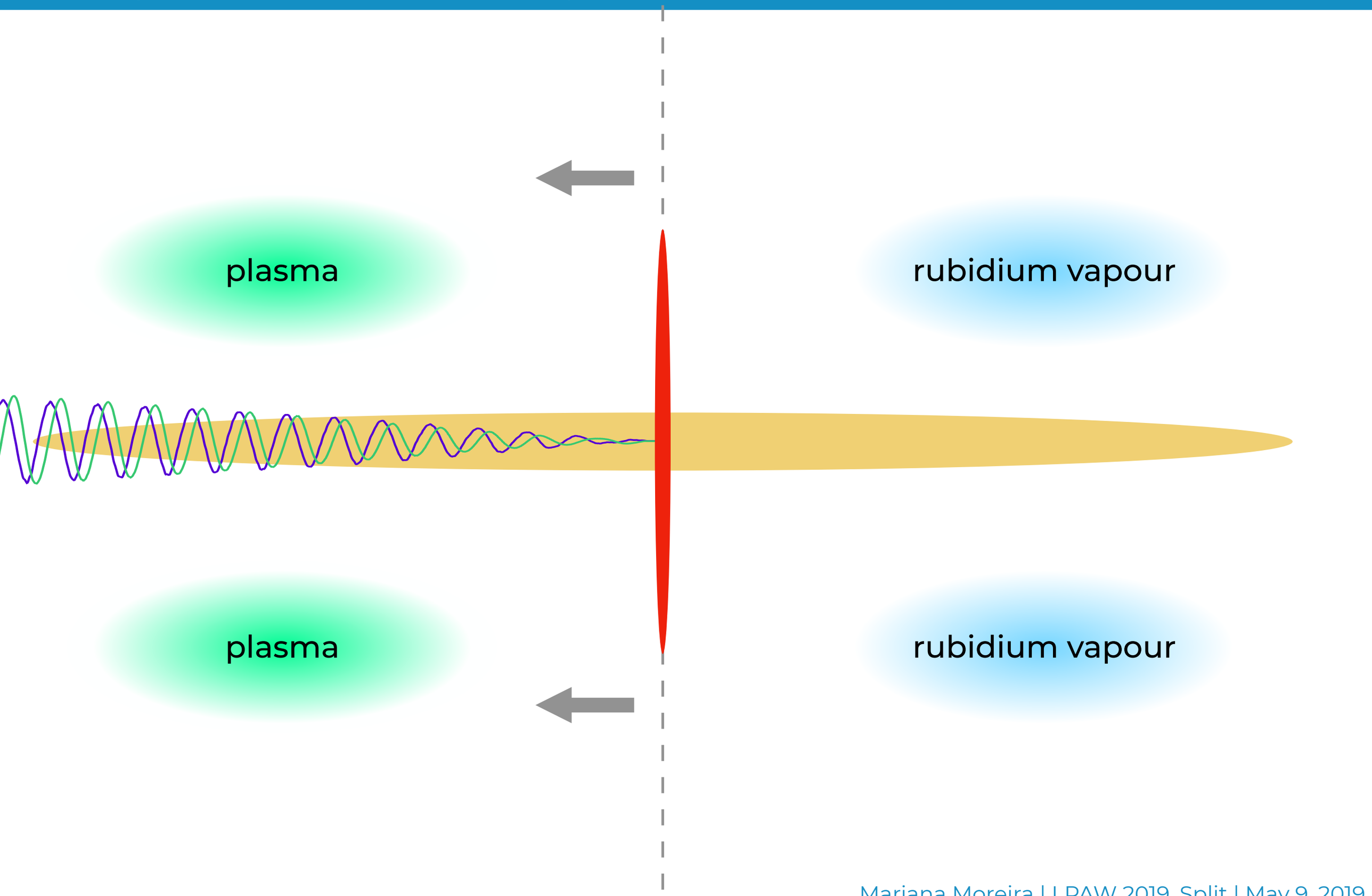


# Questions we addressed

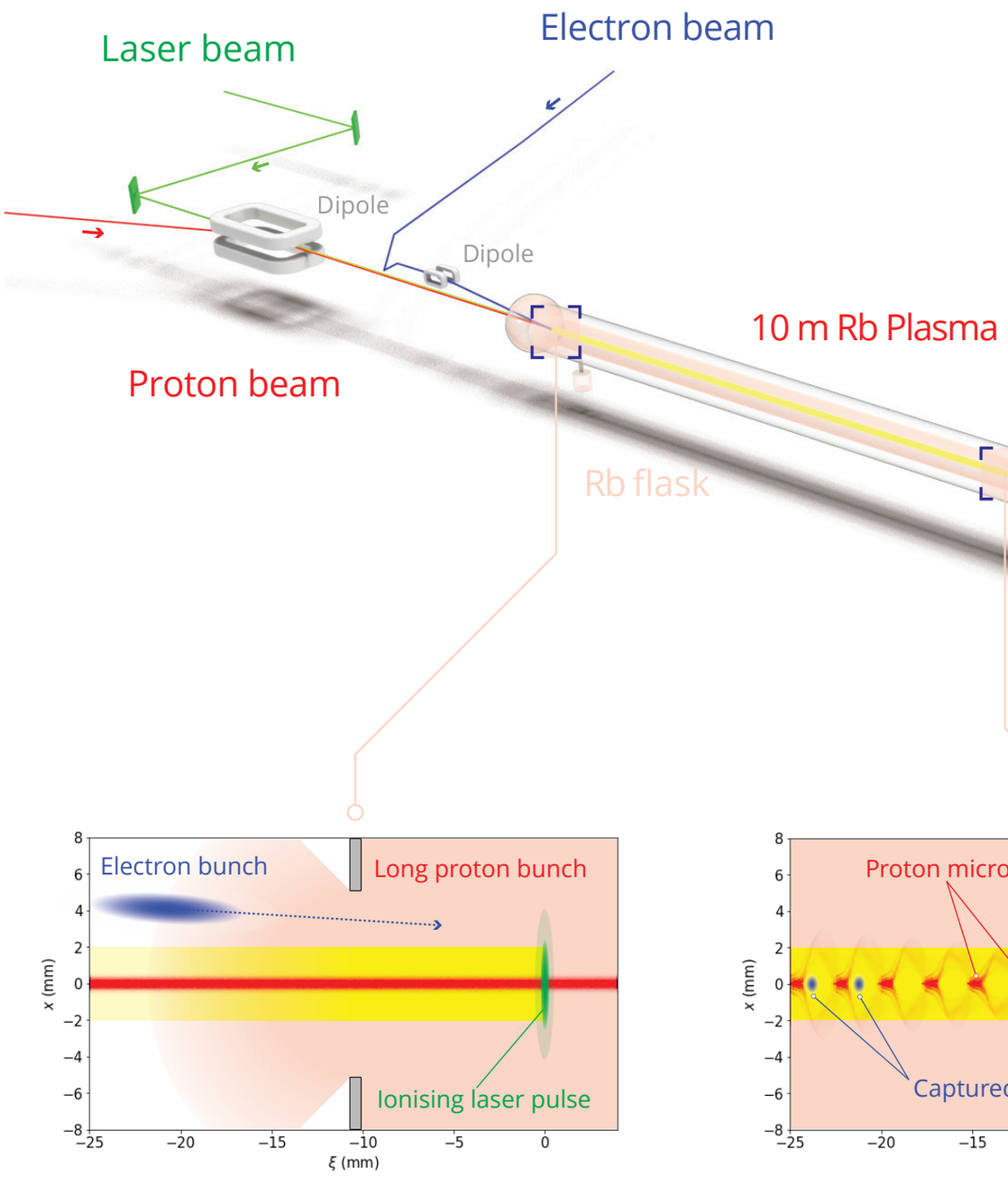
1 Are the wakefields robust against natural fluctuations of the initial bunch parameters?

2 How is it possible to optimize the acceleration of injected electrons?

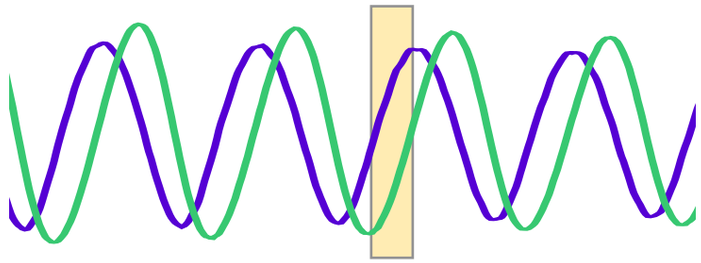
Why?

# Future goals for AWAKE

## Acceleration of an electron *bunch*

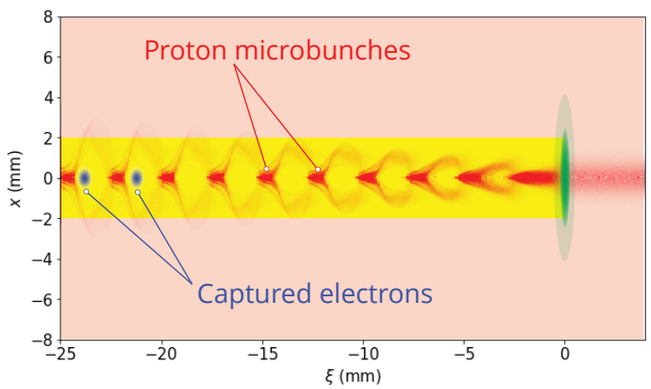



accelerating + focusing



$\lambda_p/4$

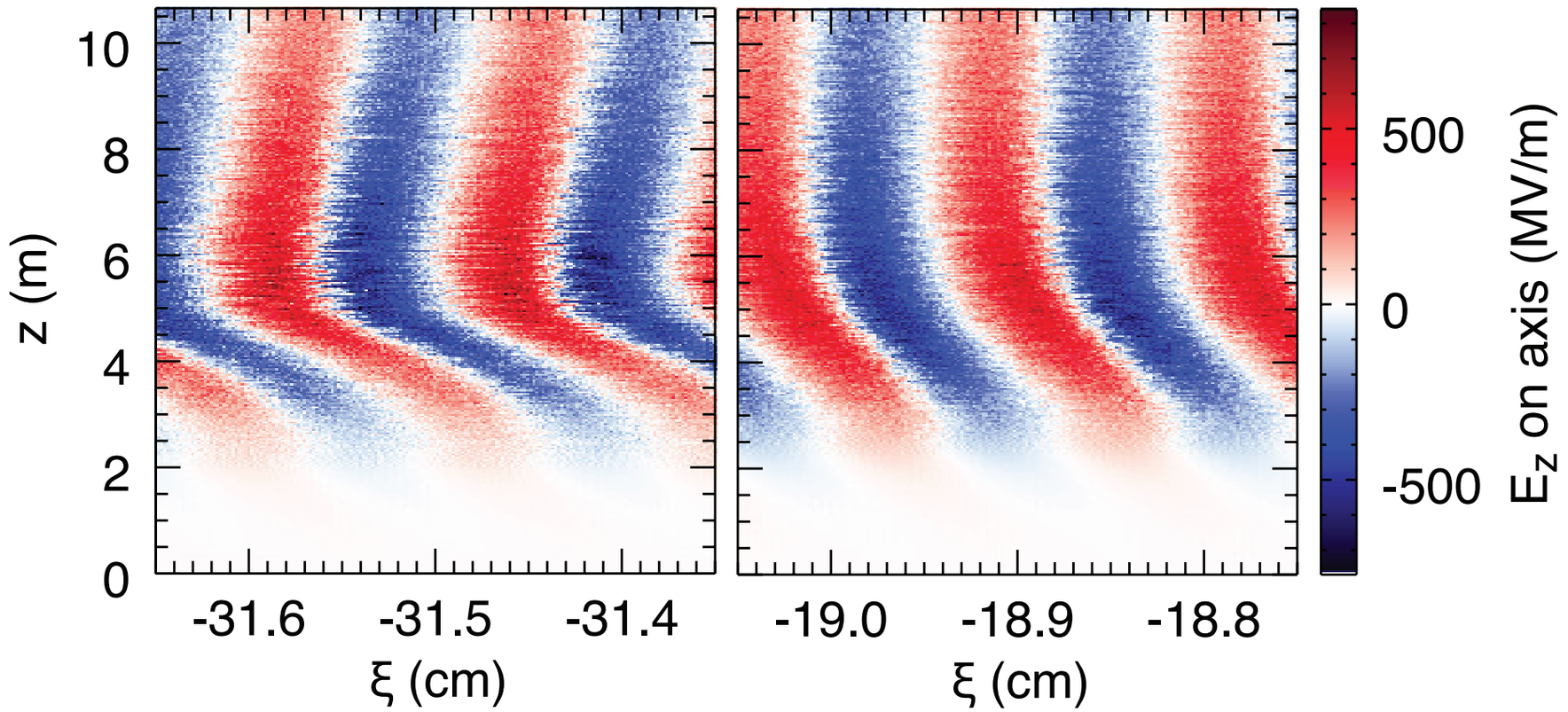


# Wake phase velocity evolution

**The phase velocity varies during the growth of the SMI/SSM**

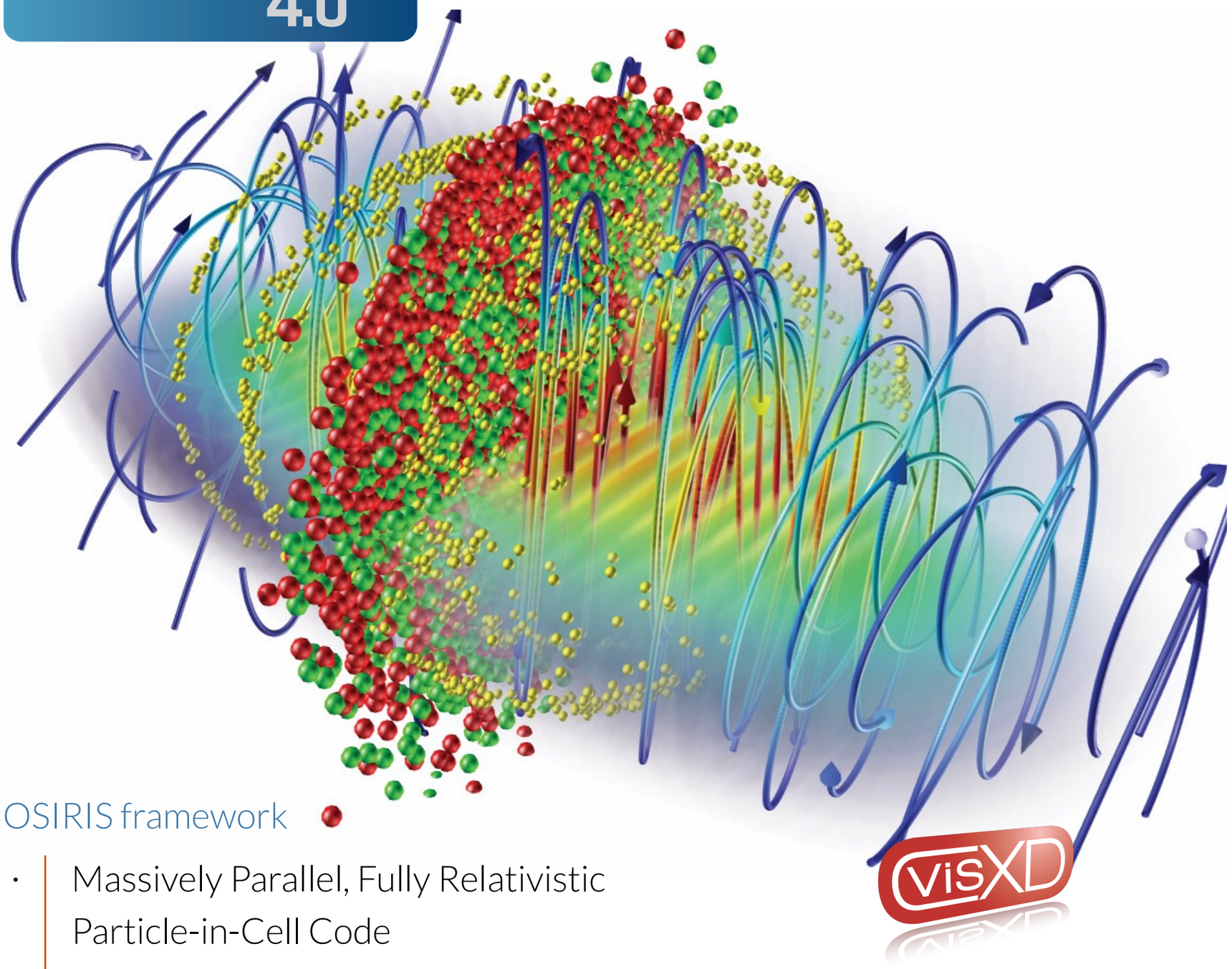
## Waterfall plot of $E_z$ on axis




$$\xi = z - ct$$

# Osiris 4.0

# *Committed to open science*




## OSIRIS framework

- Massively Parallel, Fully Relativistic Particle-in-Cell Code
- Parallel scalability to 2 M cores
- Explicit SSE / AVX / QPX / Xeon Phi / CUDA support
- Extended simulation/physics models

## Open-access model

- 40+ research groups worldwide are using OSIRIS
- 300+ publications in leading scientific journals
- Large developer and user community
- Detailed documentation and sample inputs files available

## Using OSIRIS 4.0

- The code can be used freely by research institutions after signing an MoU
- Find out more at:

**http://epp.tecnico.ulisboa.pt/osiris**

UCLA TÉCNICO LISBOA

**Ricardo Fonseca:** ricardo.fonseca@tecnico.ulisboa.pt

# Simulations used for this work

**2D cylindrical, moving window (Osiris)**

| Parameter | Value | Units |
|---|---|---|
| Plasma density $n_0$ | $7 \times 10^{14}$ | $cm^{-3}$ |
| Proton bunch population $N_b$ | $1.5 \times 10^{11}$ | 1 |
| Proton bunch RMS length $\sigma_{zb}$ | 12.6 | cm |
| Proton bunch RMS width $\sigma_{rb}$ | 0.2 | mm |
| Proton energy | 450 | GeV |
| Plasma radius $r_p$ | 1.5 | mm |
| Seed position | middle | — |

# Compare parameter scans to baseline

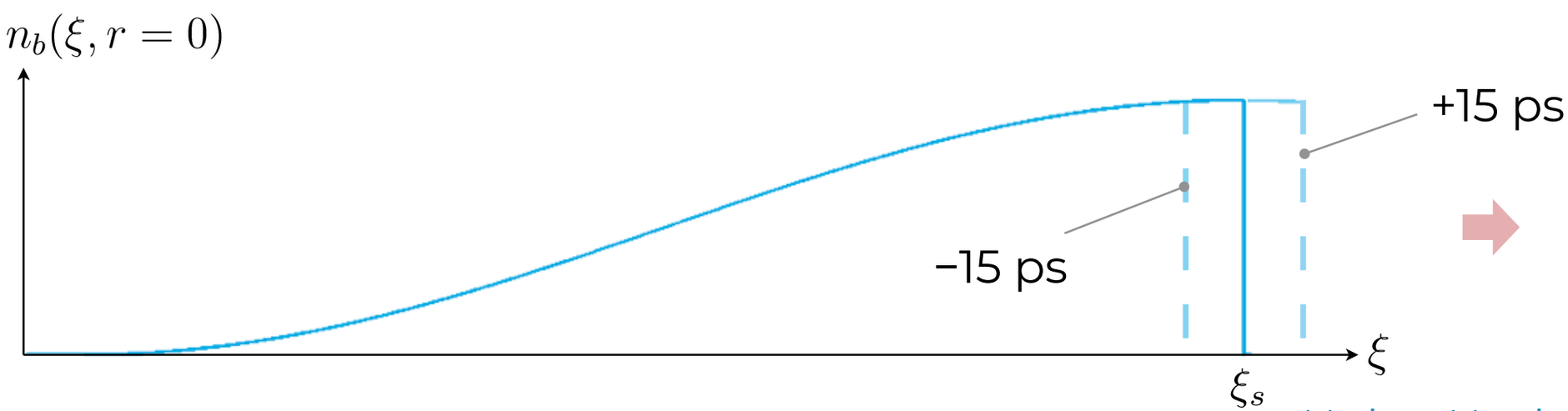
**Parameters varied**

- Bunch population $\mathbf{N_b}$
- Bunch RMS length $\boldsymbol{\sigma_{zb}}$
- Bunch RMS width $\boldsymbol{\sigma_{rb}}$
- Plasma radius $\mathbf{r_p}$

} **±5%**

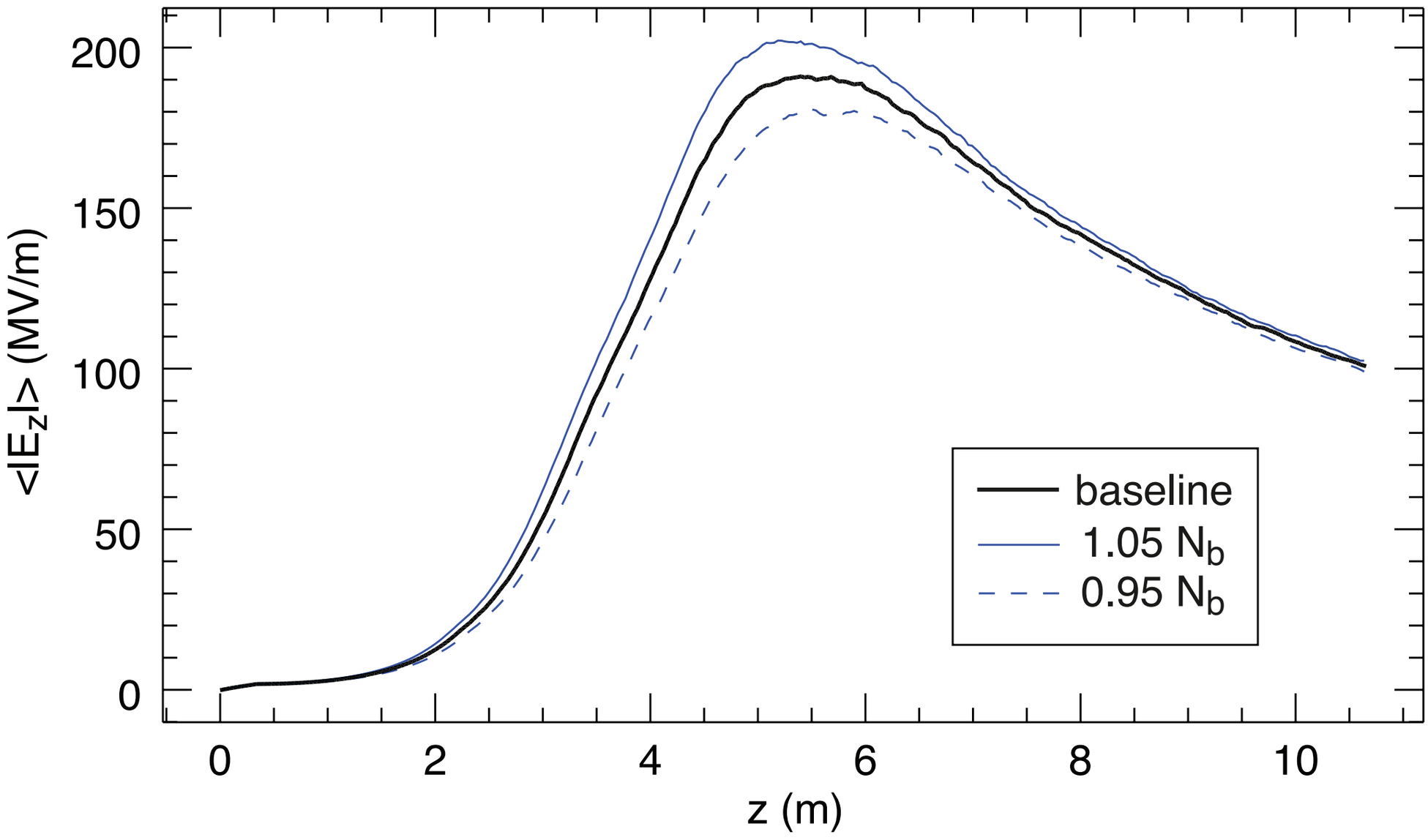
- Timing jitter between proton bunch and laser pulse **Δt**

} **±15 ps**



# Effects on the wakefield amplitude

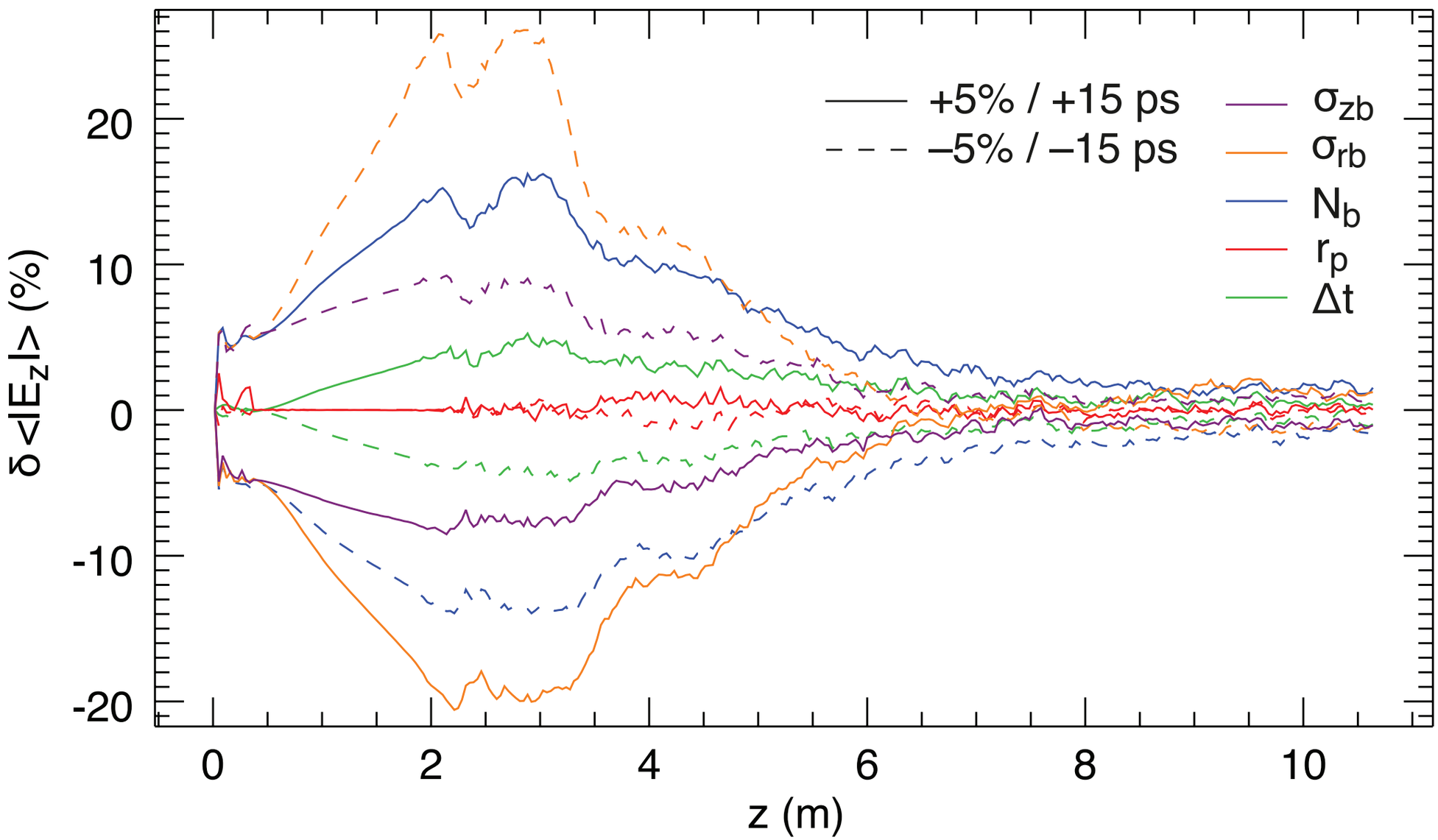
## Average* absolute value of $E_z$




* Spatial average horizontally along the entire simulation window and vertically up to $r = k_p^{-1}$.

# Effects are small after saturation of the SSM

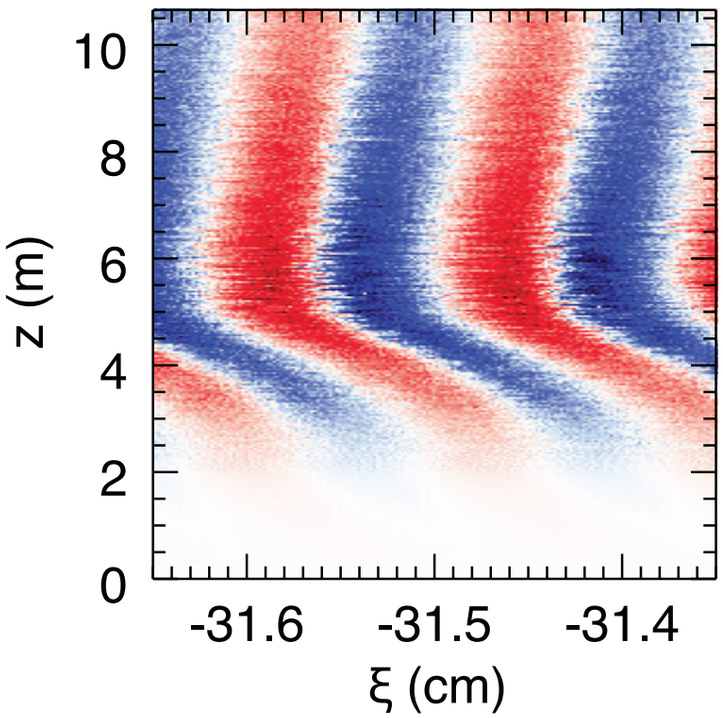
## Relative effects of all variations on $\langle|E_z|\rangle$



# Effects on the wakefield phase

## The phase is important

Waterfall plot of $E_z$ on axis

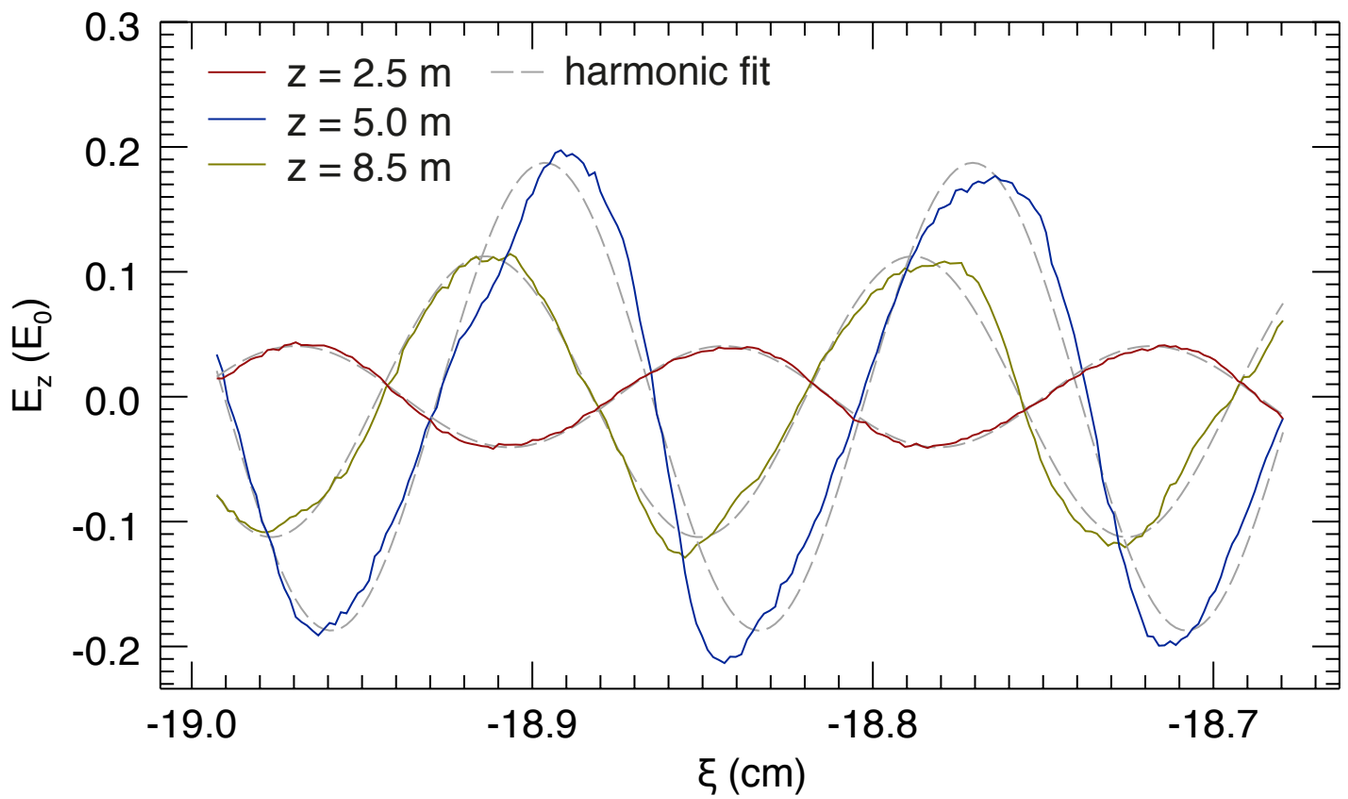



## Procedure for studying the phase

Fit the function

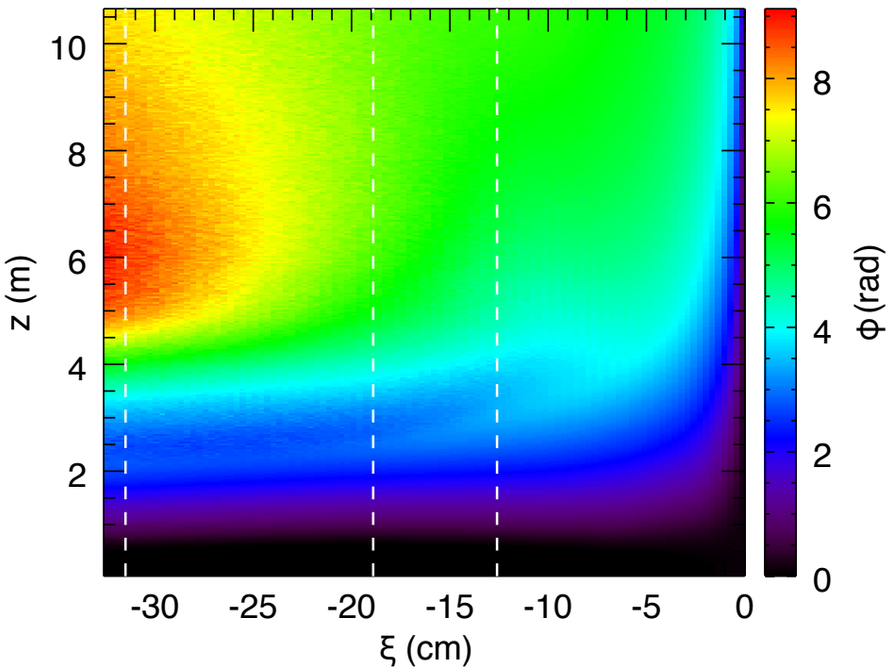
$$f(\xi) = \ A \ \sin\left[k_{pe}\left(\xi - \xi_s\right) + \phi\right]$$

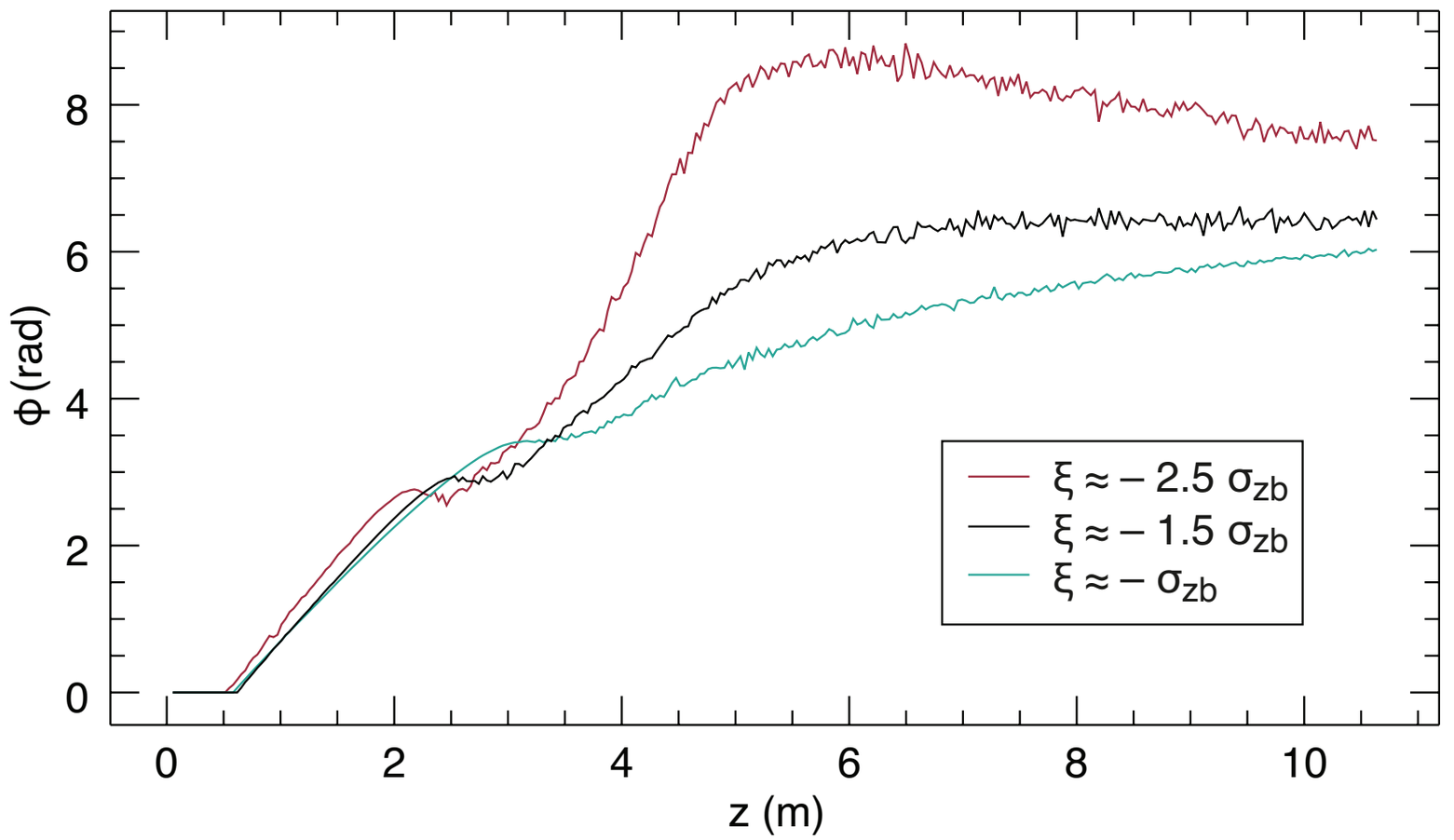
to 2.5-$\lambda_p$-long segments of $E_z$ on axis



# 2D distribution of local phase shift

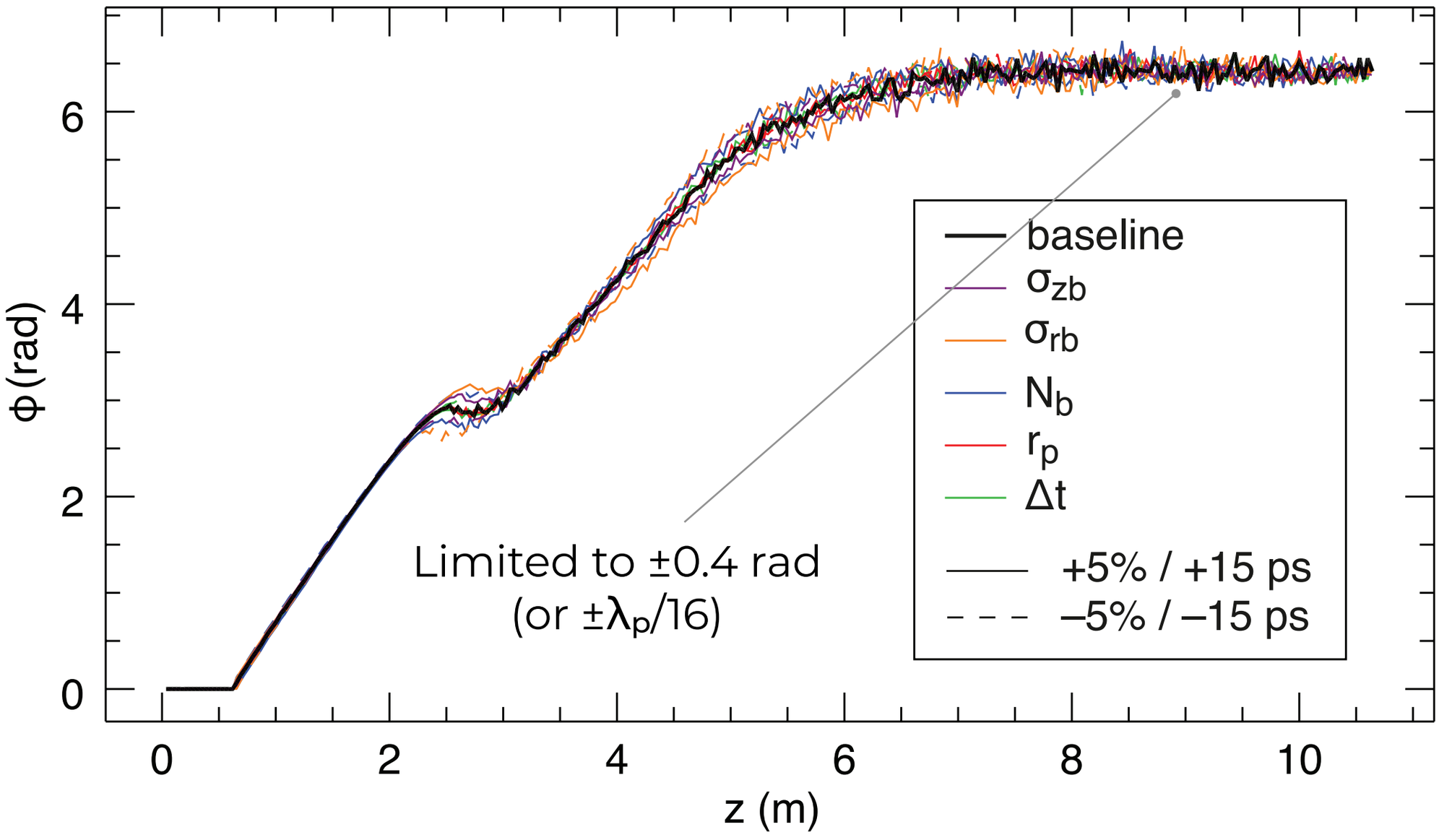
## Local phase shift Φ of the wakefields with respect to the seed



# Again the effects after saturation are small

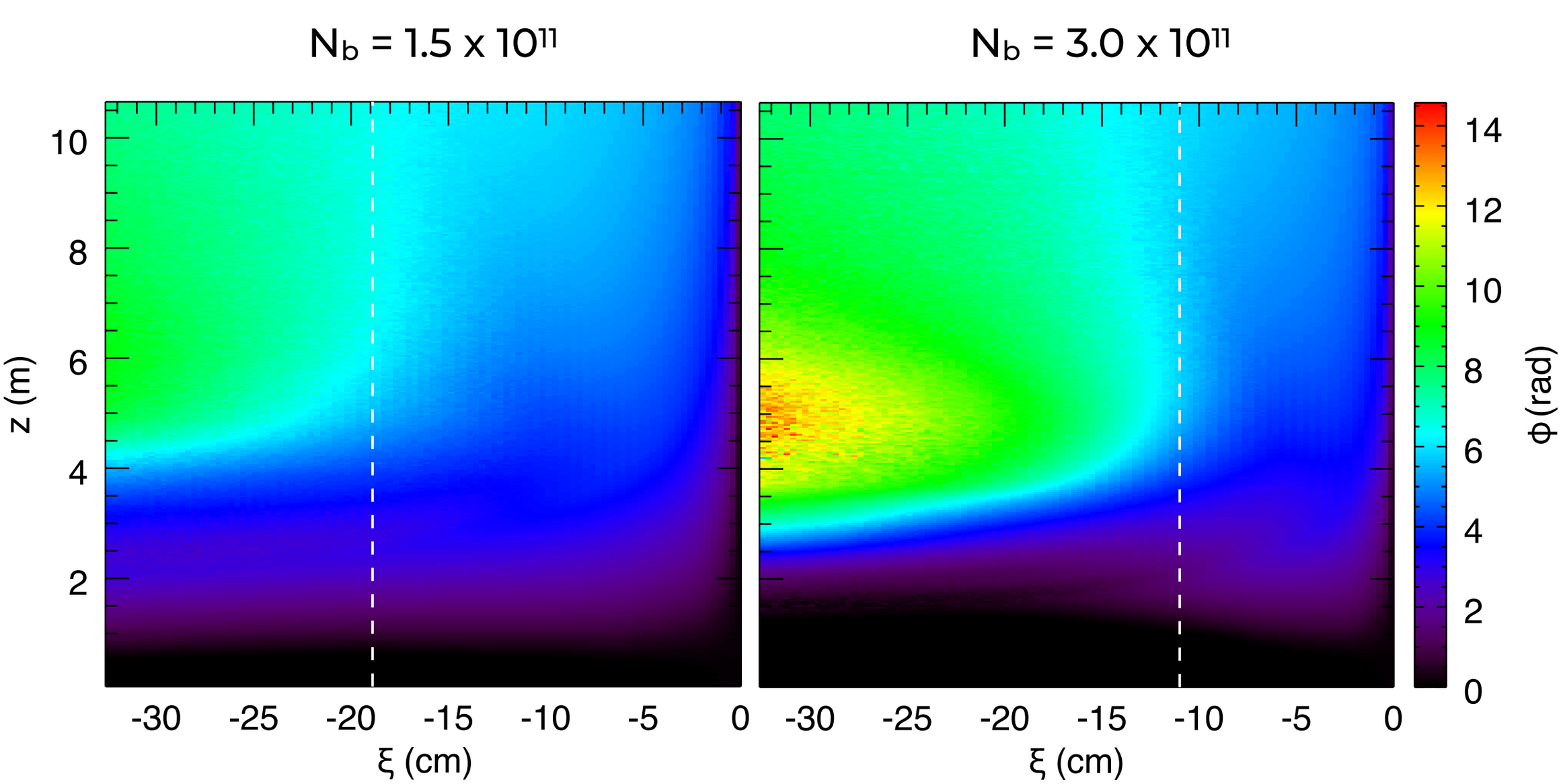
## Local phase shift Φ at ξ = –1.5 $\sigma_{zb}$



# Changing the baseline parameters

**Phase shift evolution is “stretched”**

## Local phase shift Φ for two bunch populations



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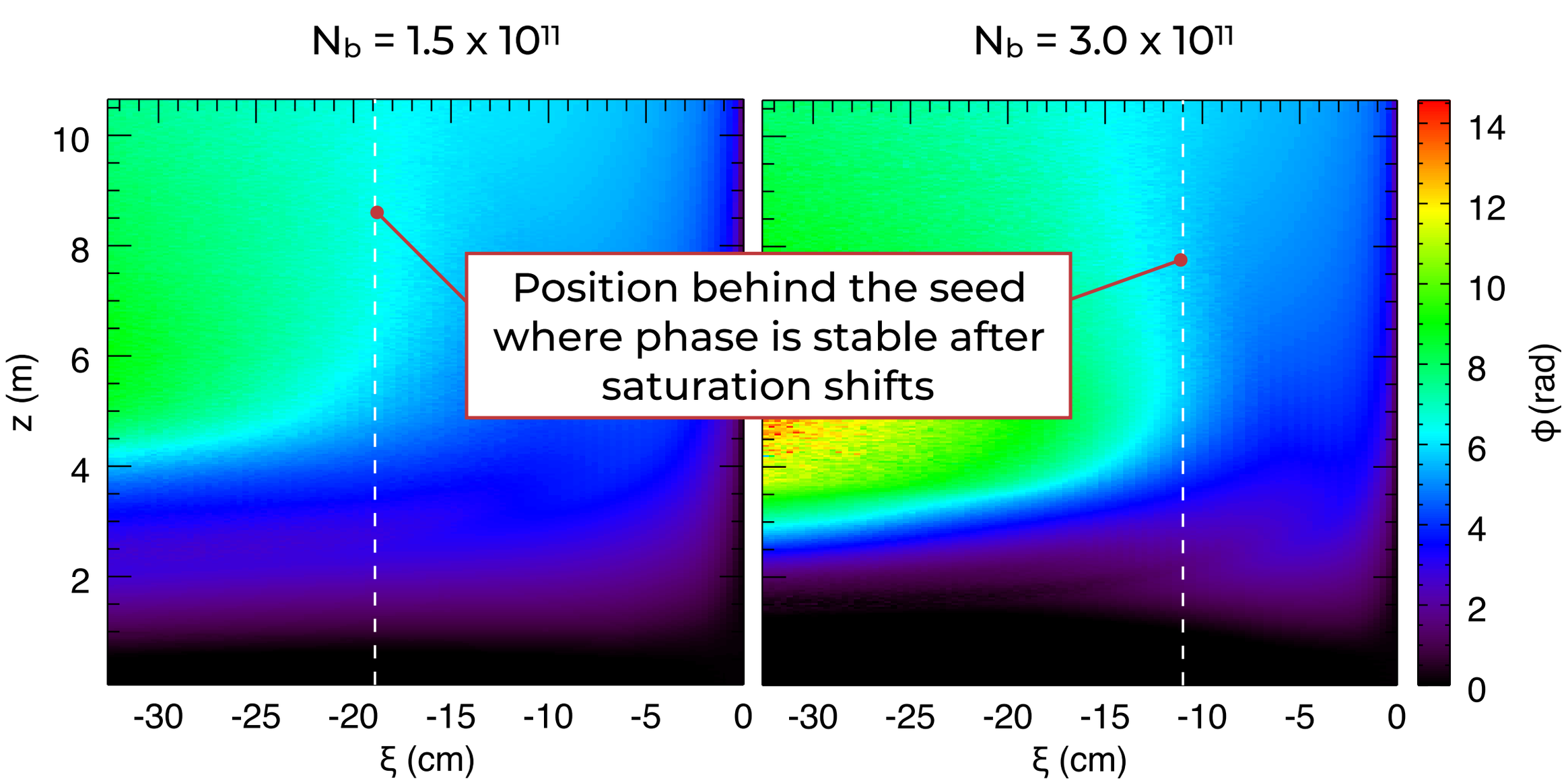

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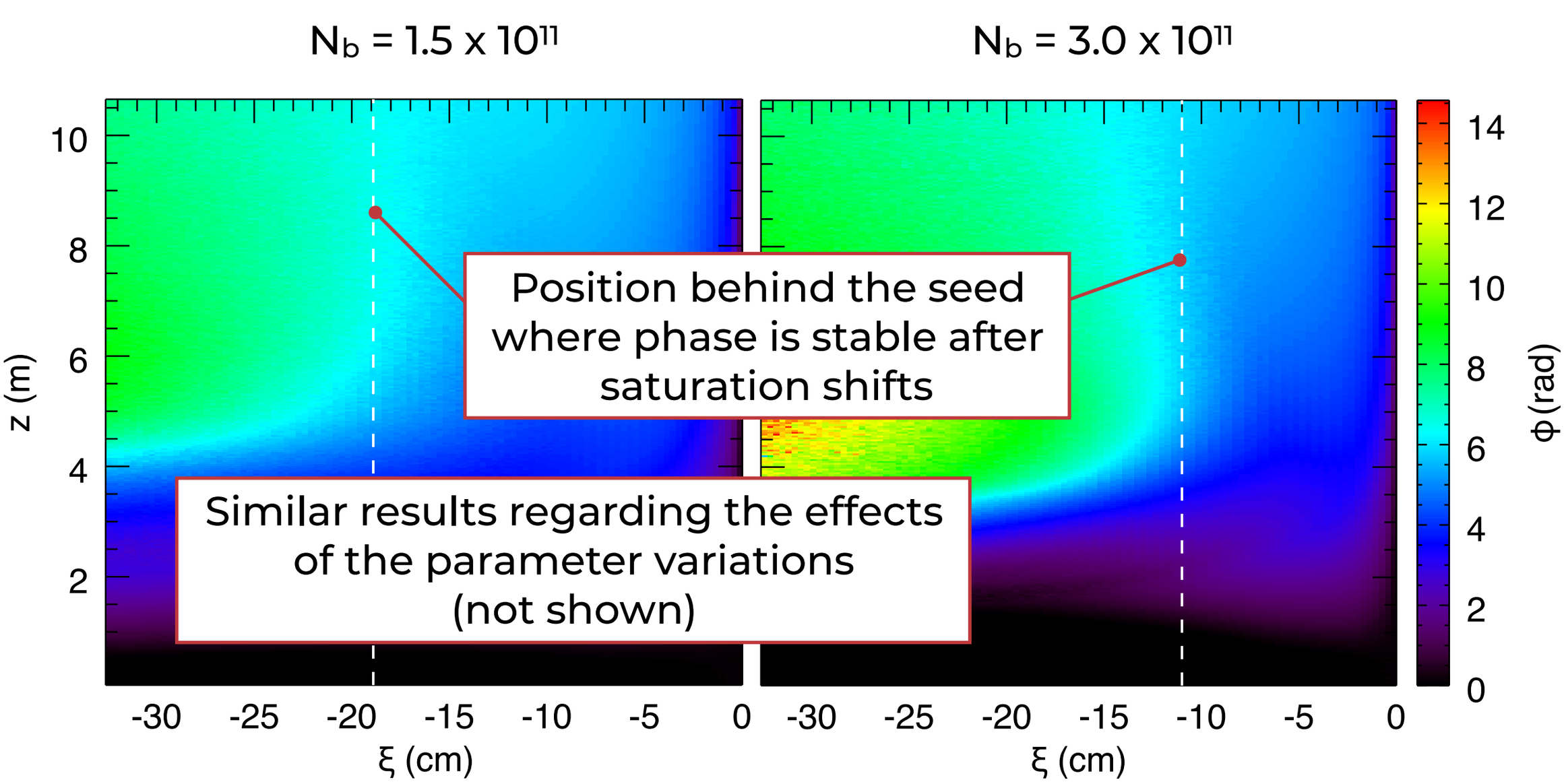

# Takeaways

**1** Effects from initial parameter variations of ±5% converge to a few percent after saturation

**(in particular, to less than $\lambda_p/8$ for the phase)**

**2** There is an optimal position along the bunch for acceleration where the phase is stable after saturation of the SSM

**($n_0 \uparrow$, $N_b \downarrow$ $\Rightarrow$ $\xi_{stable}$ closer to seed)**

* M. Moreira, J. Vieira and P. Muggli, Phys. Rev. Accel. Beams **22**, 031301 (2019)

# Acknowledgments

J. Vieira, P. Muggli

B. Holzer (CERN)

Simulation results obtained with SuperMUC (Garching)

Thank you for your attention!