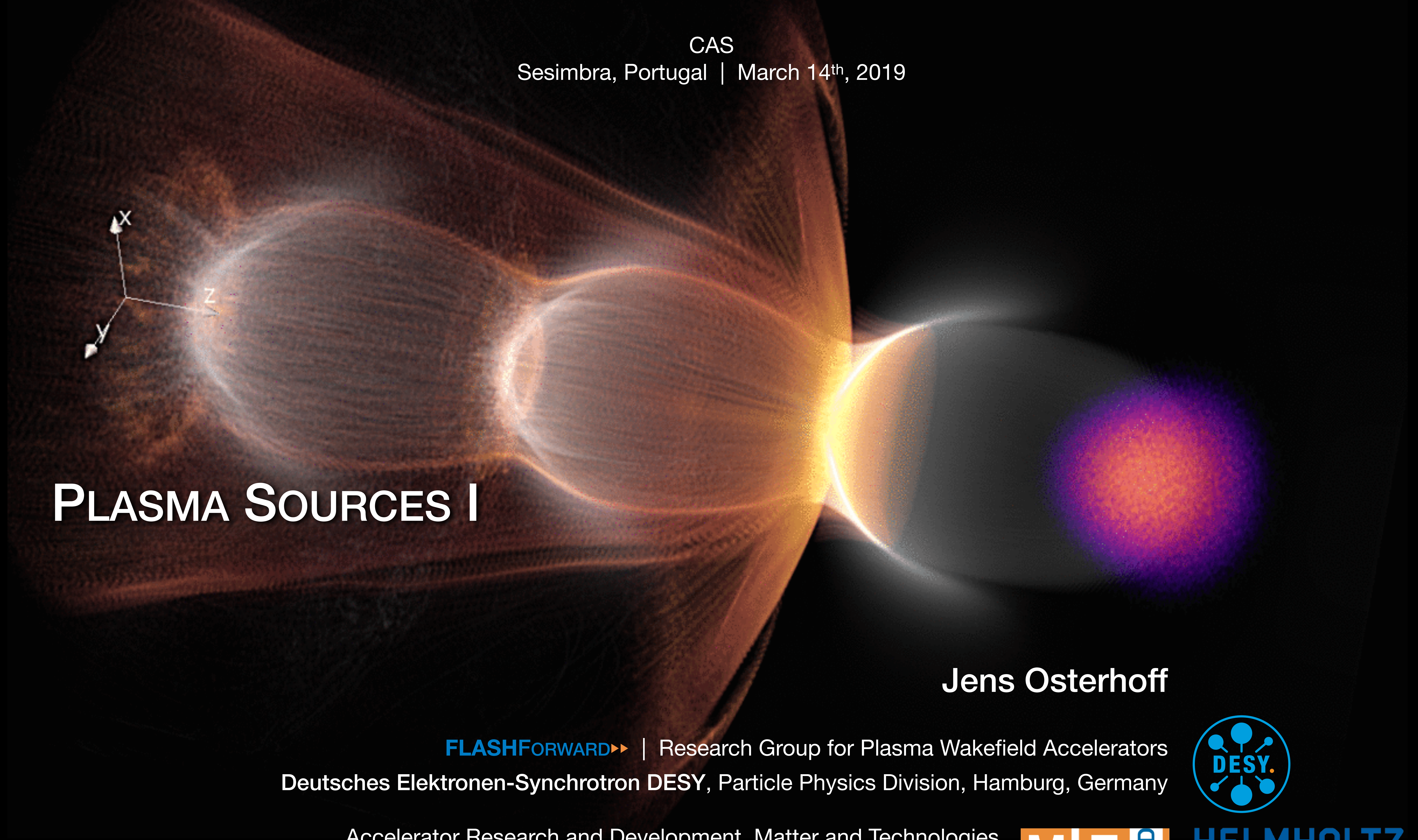
CAS
Sesimbra, Portugal | March 14th, 2019



# PLASMA SOURCES I

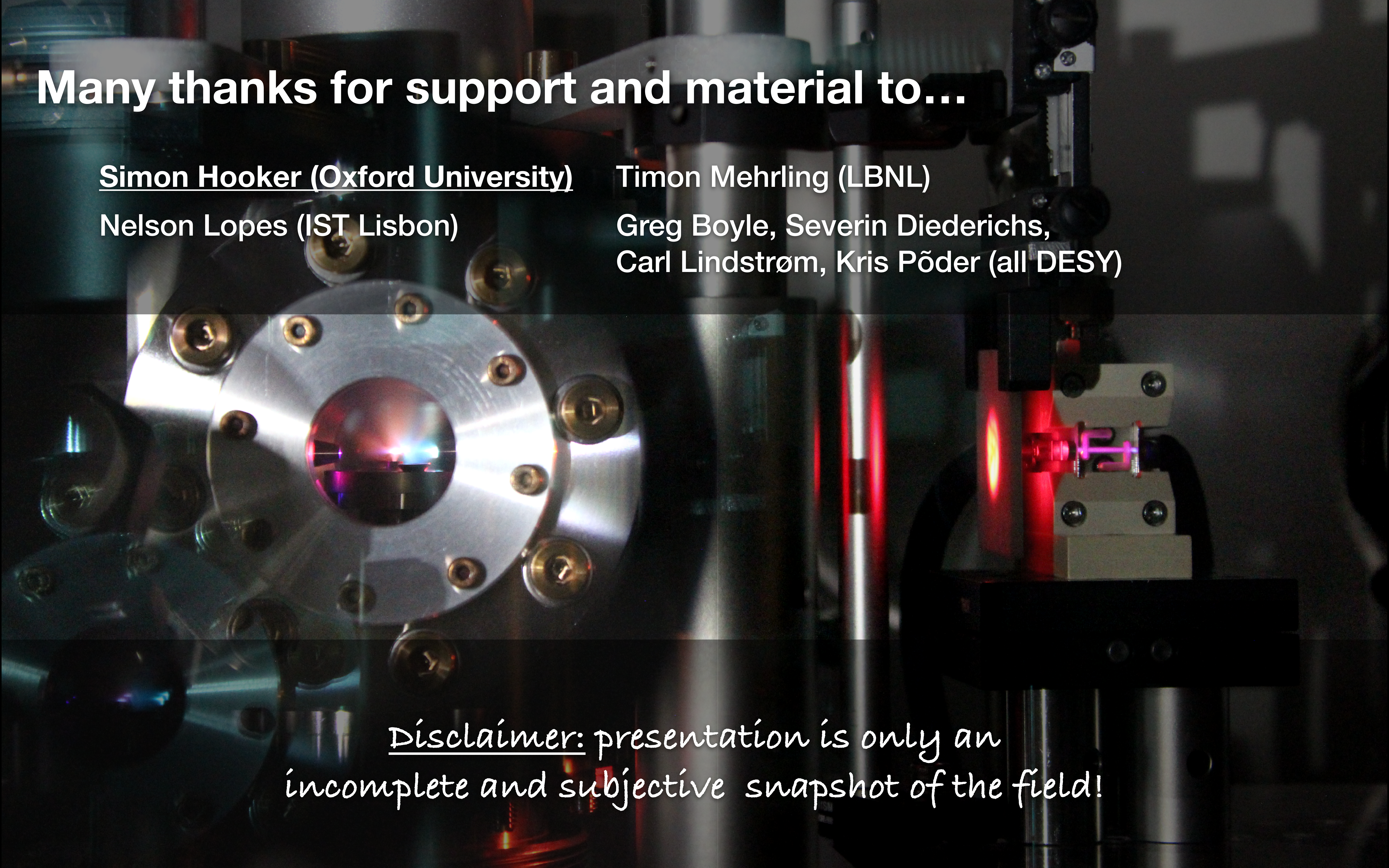
**Jens Osterhoff**

FLASHFORWARD▸▸ | Research Group for Plasma Wakefield Accelerators
**Deutsches Elektronen-Synchrotron DESY**, Particle Physics Division, Hamburg, Germany

Accelerator Research and Development, Matter and Technologies
**Helmholtz Association of German Research Centres**, Berlin, Germany

*simulation by Alberto Martinez de la Ossa*

# Many thanks for support and material to…



Simon Hooker (Oxford University)

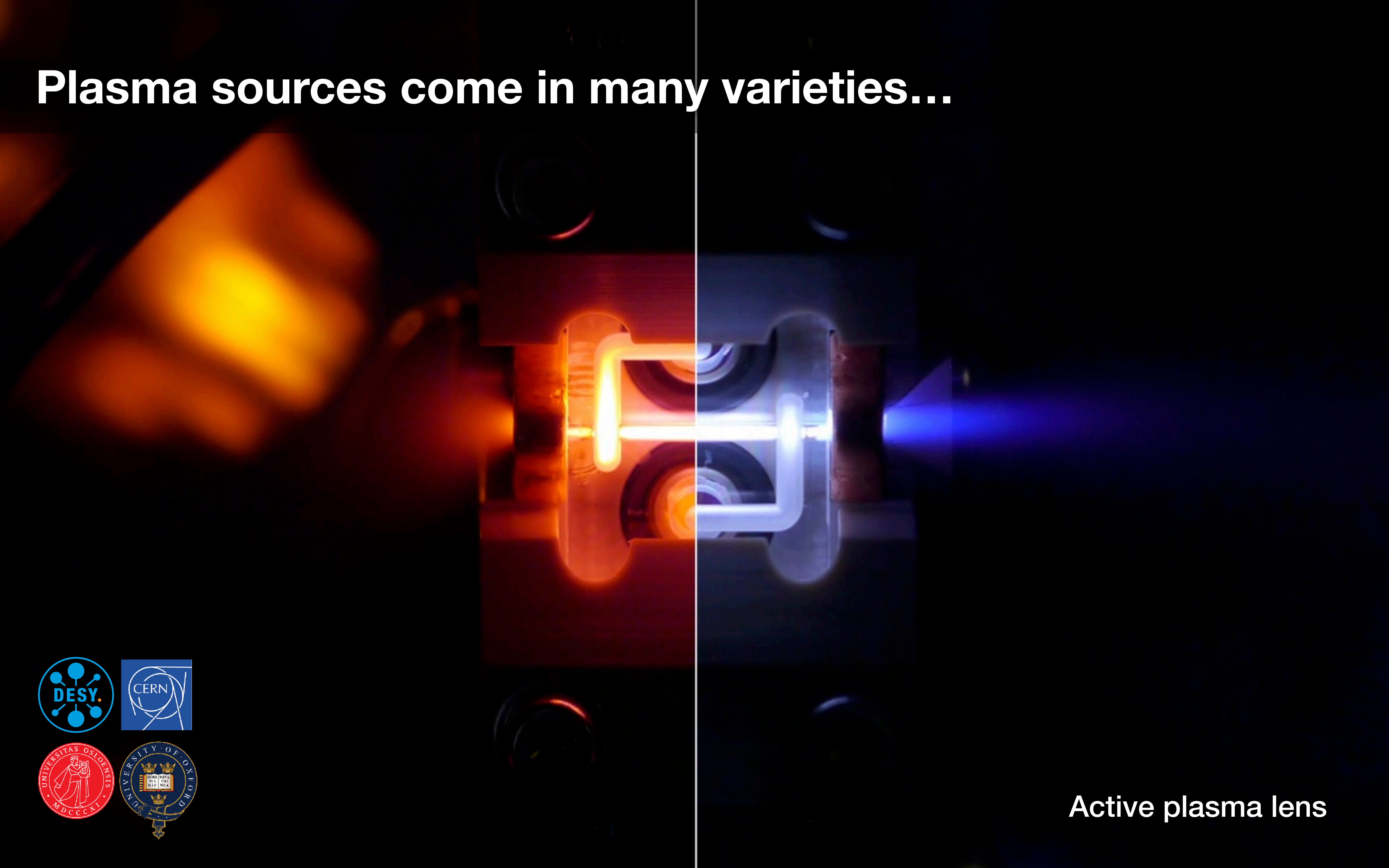
Nelson Lopes (IST Lisbon)

Timon Mehrling (LBNL)

Greg Boyle, Severin Diederichs,
Carl Lindstrøm, Kris Põder (all DESY)

*Disclaimer: presentation is only an incomplete and subjective snapshot of the field!*

# Plasma sources come in many varieties…

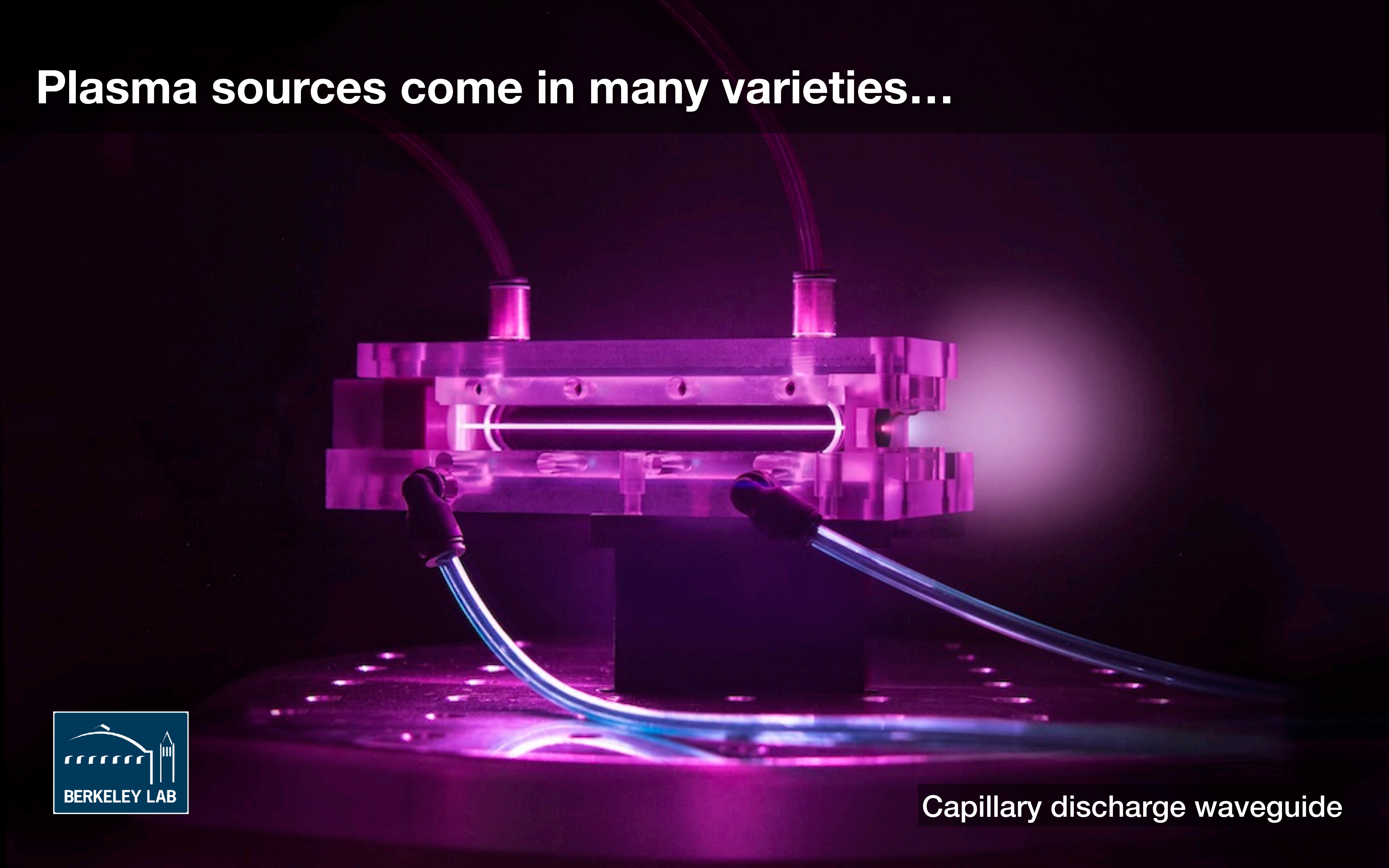


Active plasma lens

# Plasma sources come in many varieties…

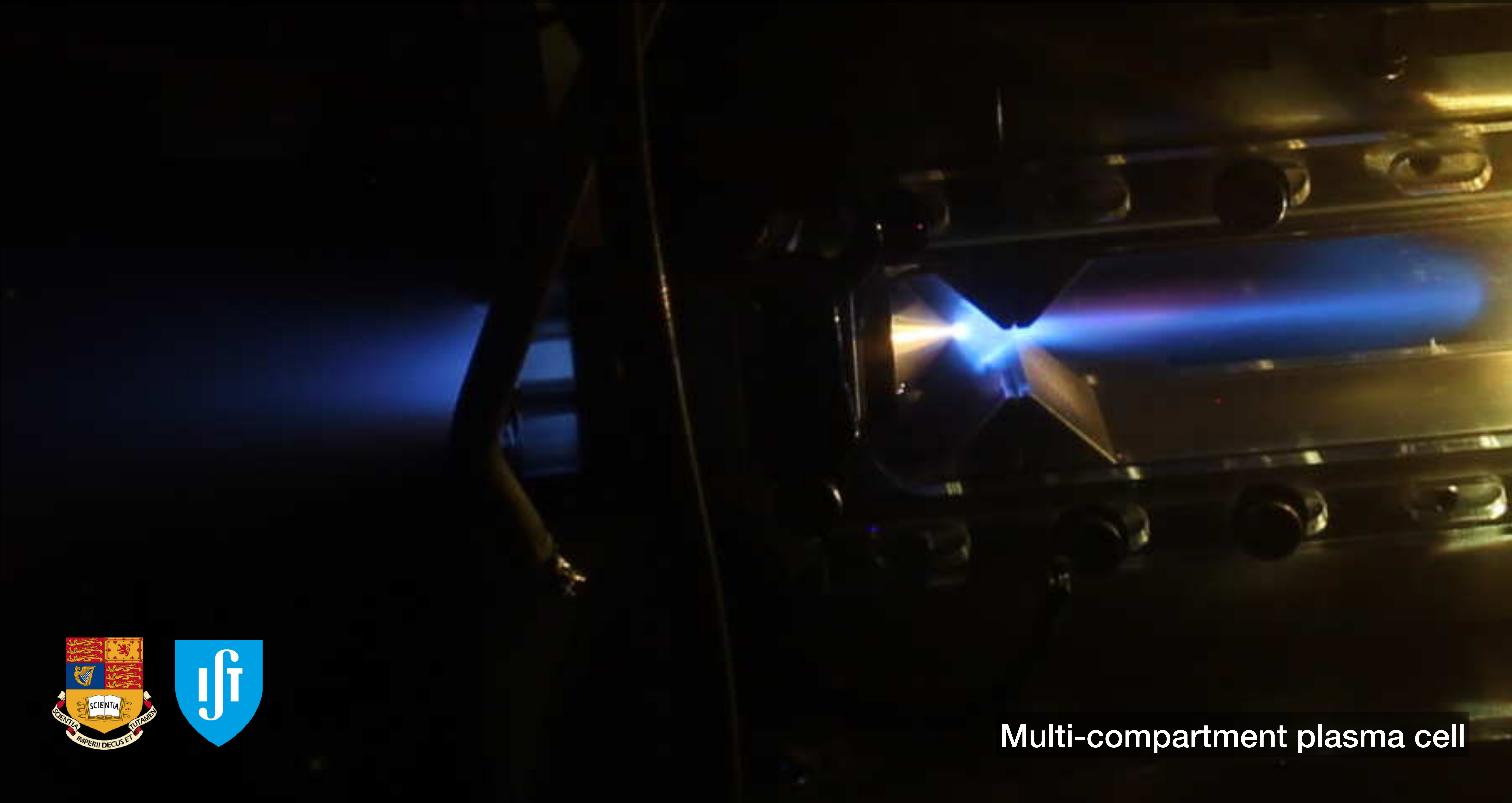
AWAKE alkali vapor oven

# Plasma sources come in many varieties…



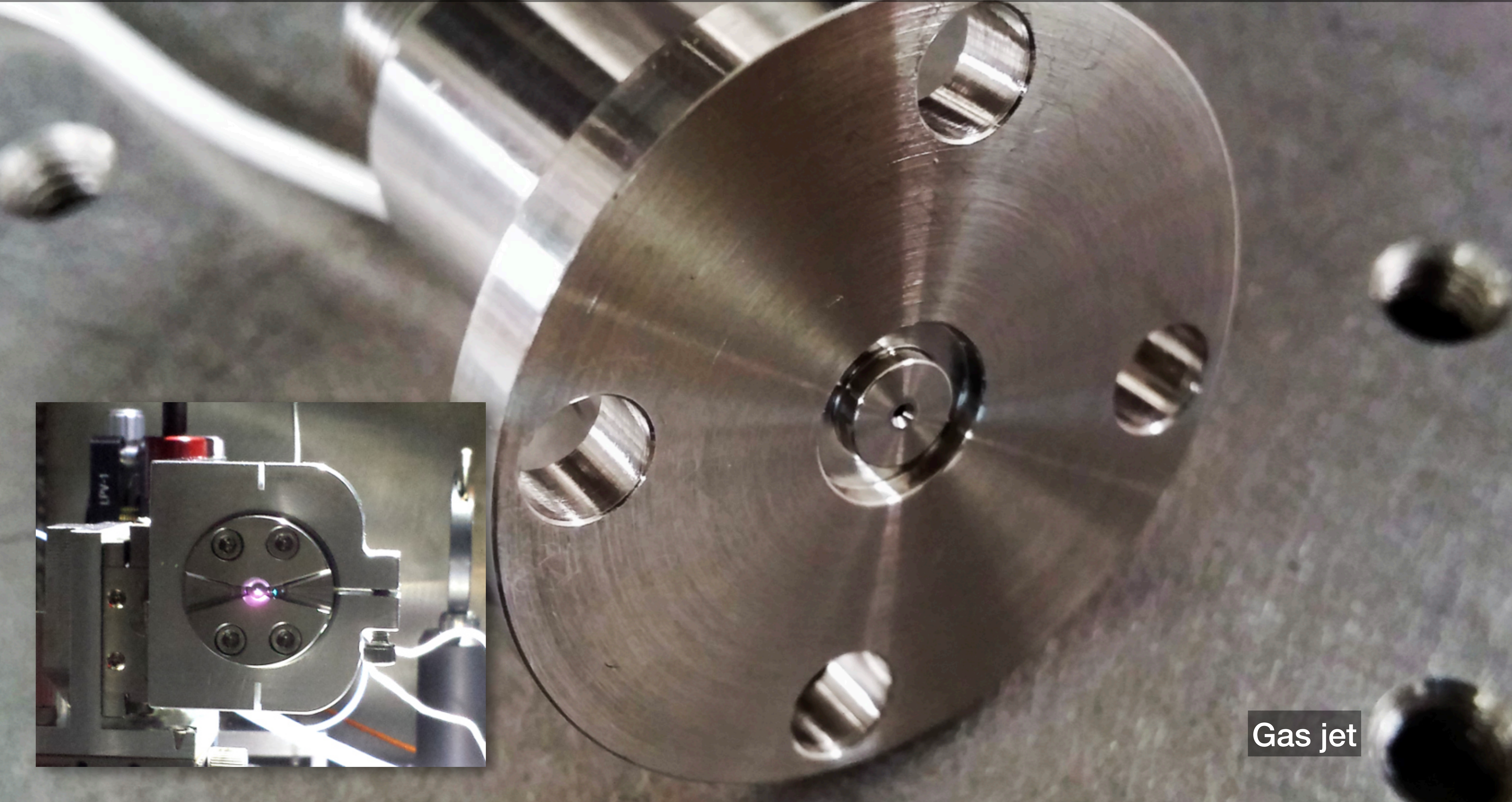
Capillary discharge waveguide

# Plasma sources come in many varieties…



Multi-compartment plasma cell

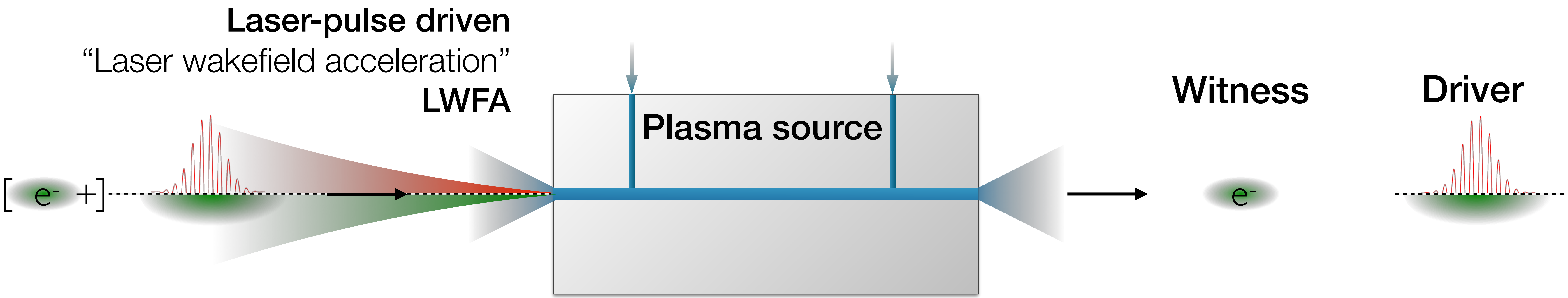
# Plasma sources come in many varieties…



# Lecture Series on Plasma Sources and Diagnostics

- **Plasma Sources I**
  - Thursday, March 14, 9:00 - 10:00
  - **Conceptual aspects**
- **Plasma Sources II**
  - Friday, March 15, 9:00 - 10:00
  - **Technical aspects**
- **Plasma Diagnostics**
  - Tuesday, March 19, 10:00 - 11:00
  - **Diagnostics:** how to measure plasmas

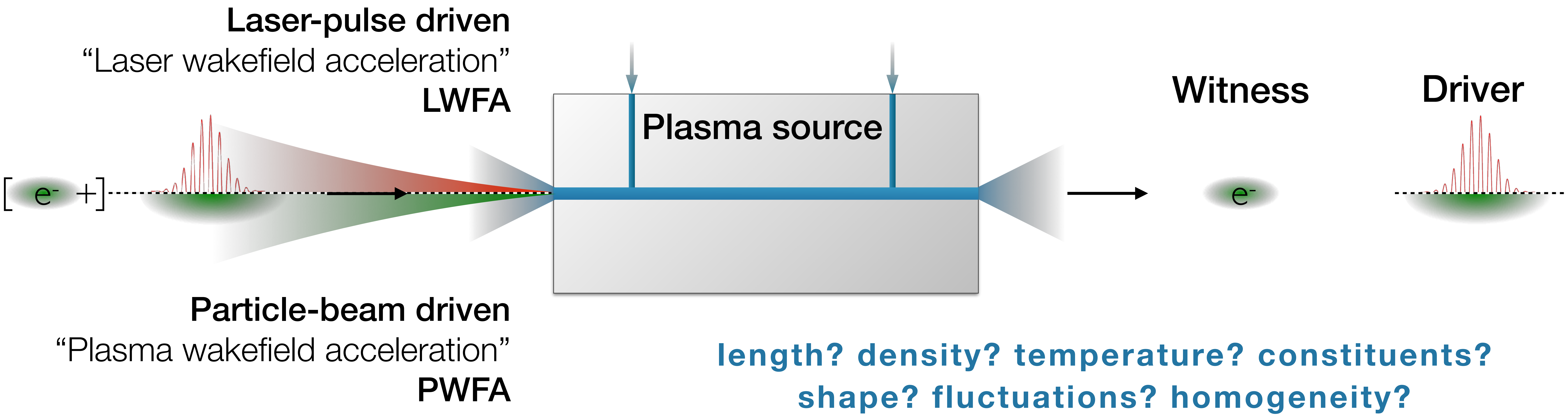
# Outline - Plasma Sources I - Concepts



**Particle-beam driven**
"Plasma wakefield acceleration"
**PWFA**

**length? density? temperature? constituents?**
**shape? fluctuations? homogeneity?**
**technical compatibility?**

# Outline - Plasma Sources I - Concepts



length? density? temperature? constituents?
shape? fluctuations? homogeneity?
technical compatibility?

- > **Design aspects for a plasma source**
- > **Plasma generation mechanisms**
- > **Tailoring plasma properties to control wakefield and plasma processes**

# Design aspects

- Adjustable plasma density $n_e$
- Tailored density profile $n_e(x,t)$
- Defined (and adjustable) length $L$
- Controlled species composition
- Controlled plasma temperature profile $T_e(x,t)$

- Spatial uniformity
- Temporal stability

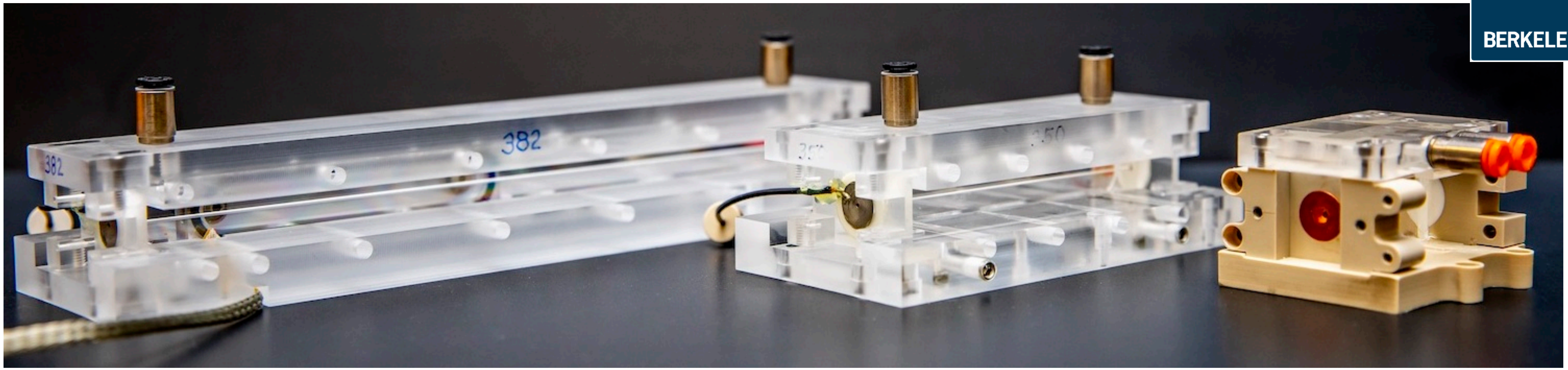
- Durability (# of events)

- Support traversing of driver and witness

- Accessible to diagnostics

- Materials and gas flow compatible with vacuum requirements

- Cost

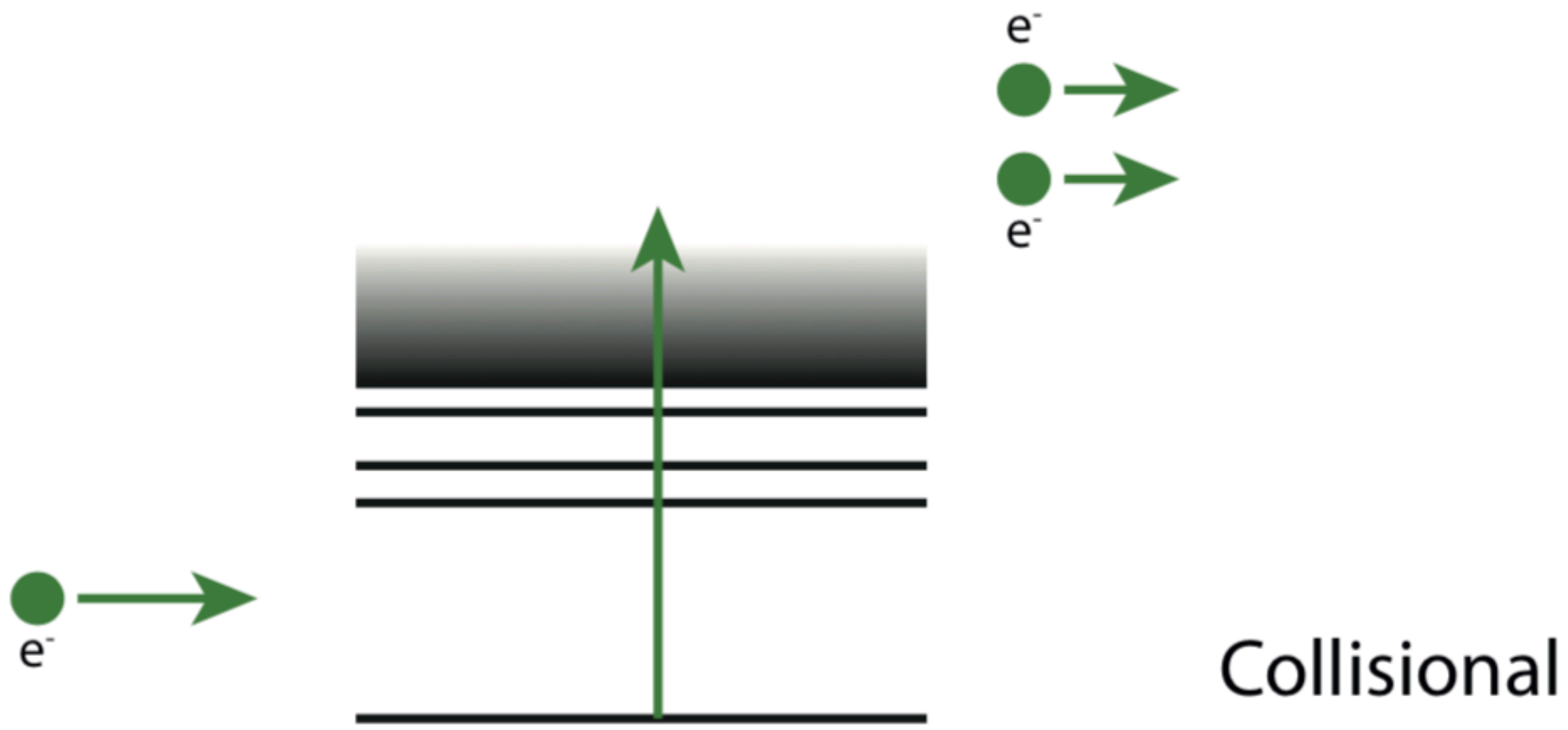


# Plasma generation: ionization

# How to create a plasma

Plasma can be formed by different mechanisms

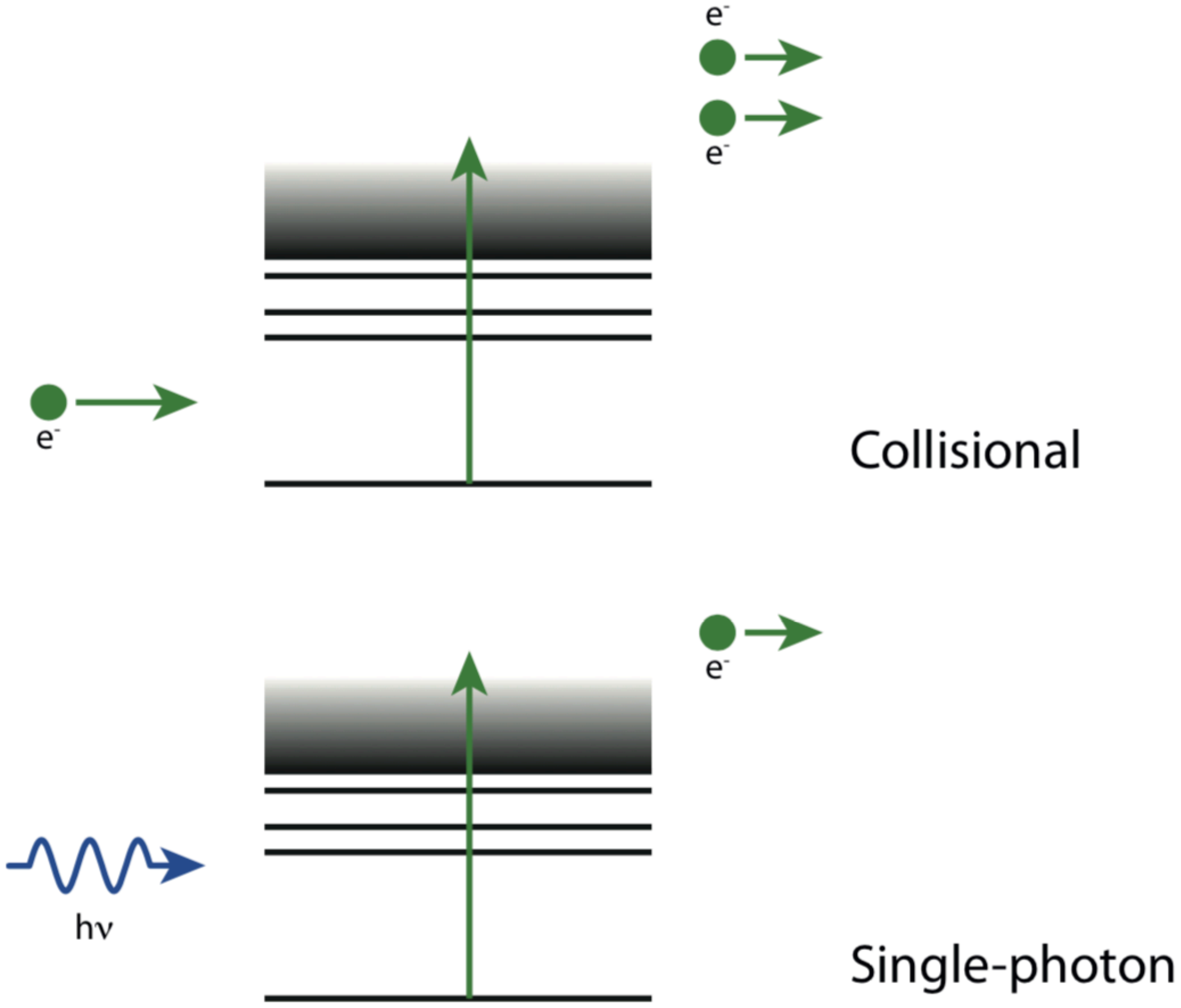
- Collisional ionization
  - discharges, laser-heated electrons, particle beams



# How to create a plasma

Plasma can be formed by different mechanisms

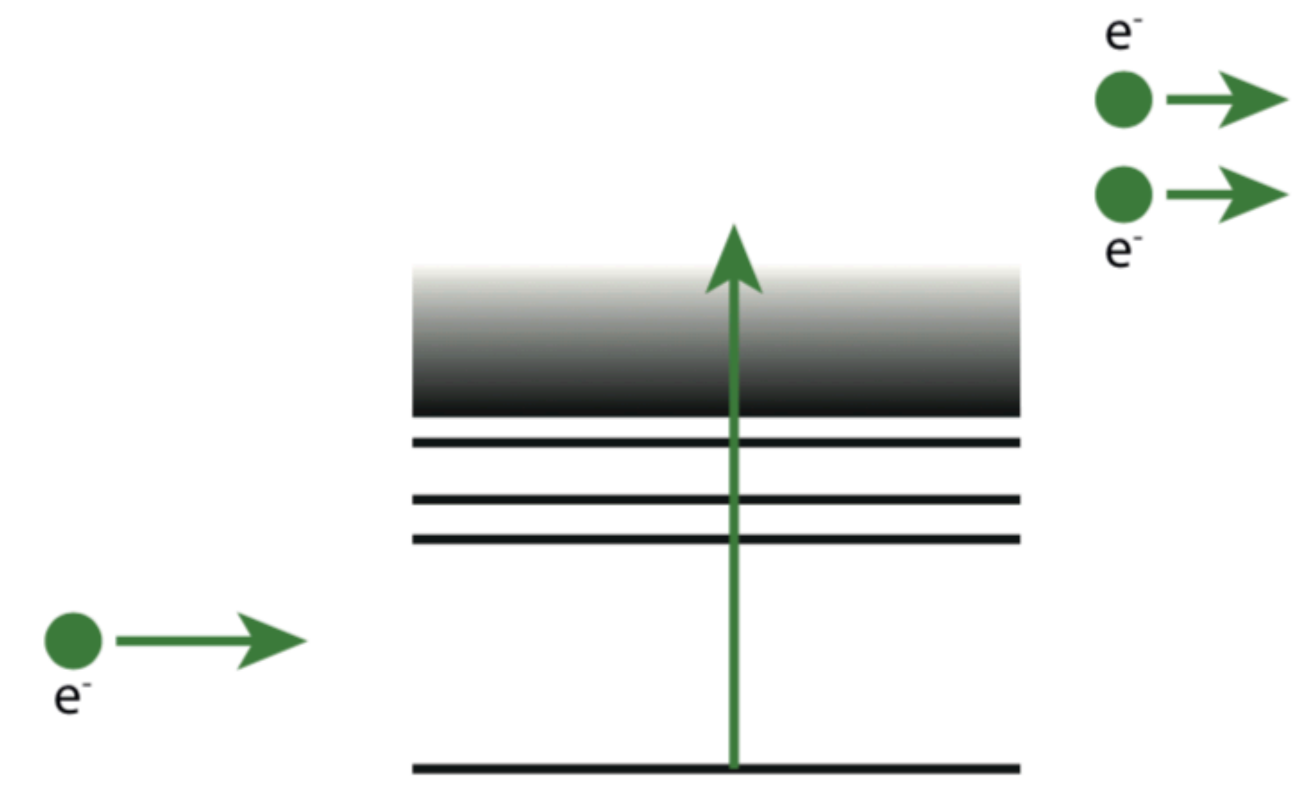
- Collisional ionization
  - discharges, laser-heated electrons, particle beams
- Single-photon ionization
  - high-energy photons: $h\nu > I_p$



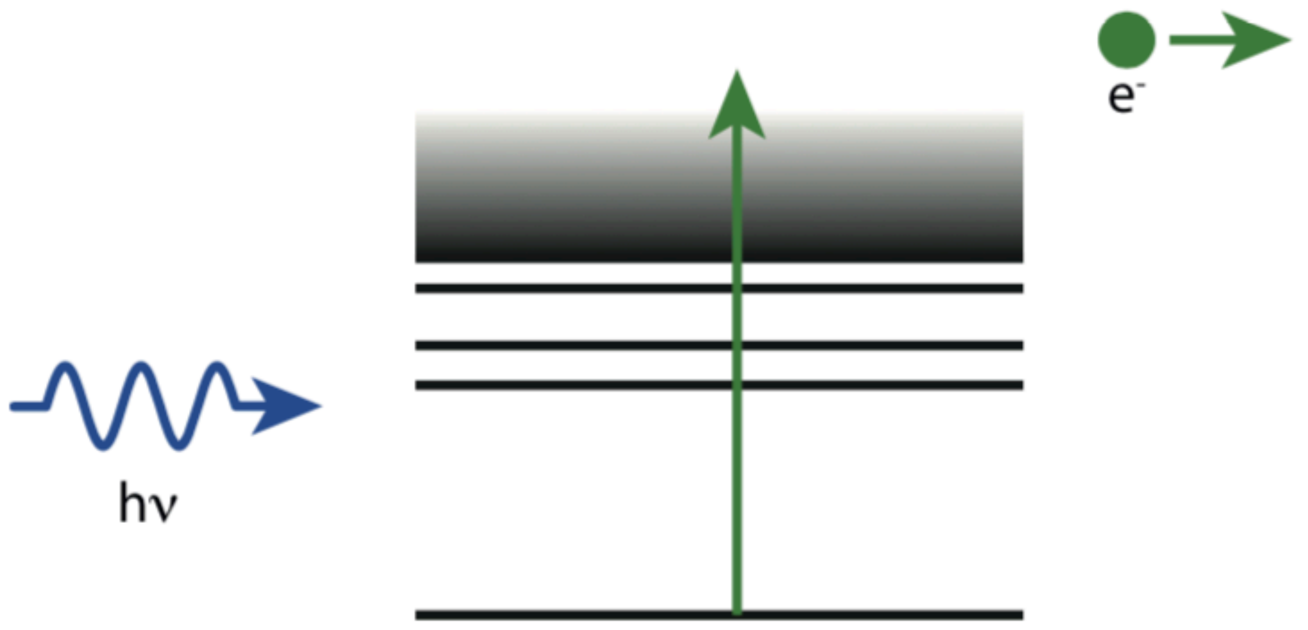
# How to create a plasma

Plasma can be formed by different mechanisms

- Collisional ionization
  - discharges, laser-heated electrons, particle beams
- Single-photon ionization
  - high-energy photons: $h\nu > I_p$



Collisional



Single-photon

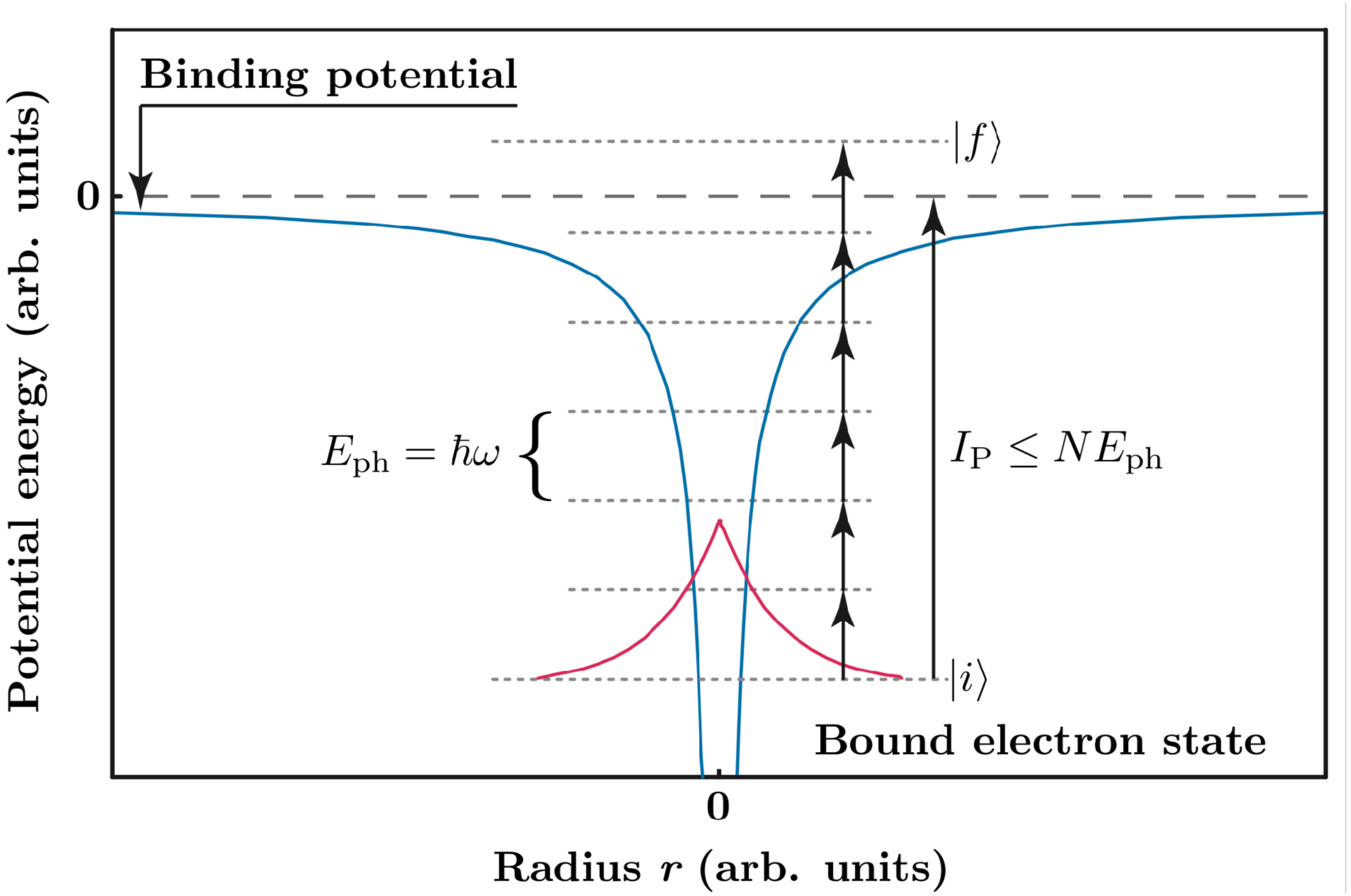
**Keldysh parameter:** $$\gamma_K = \sqrt{\frac{I_P}{2U_P}}$$

- $\gamma_K > 1$ → Multi-photon ionization
- $\gamma_K \ll 1$ → Field ionization (tunneling or barrier suppression)

# Multi-photon ionization (MPI)

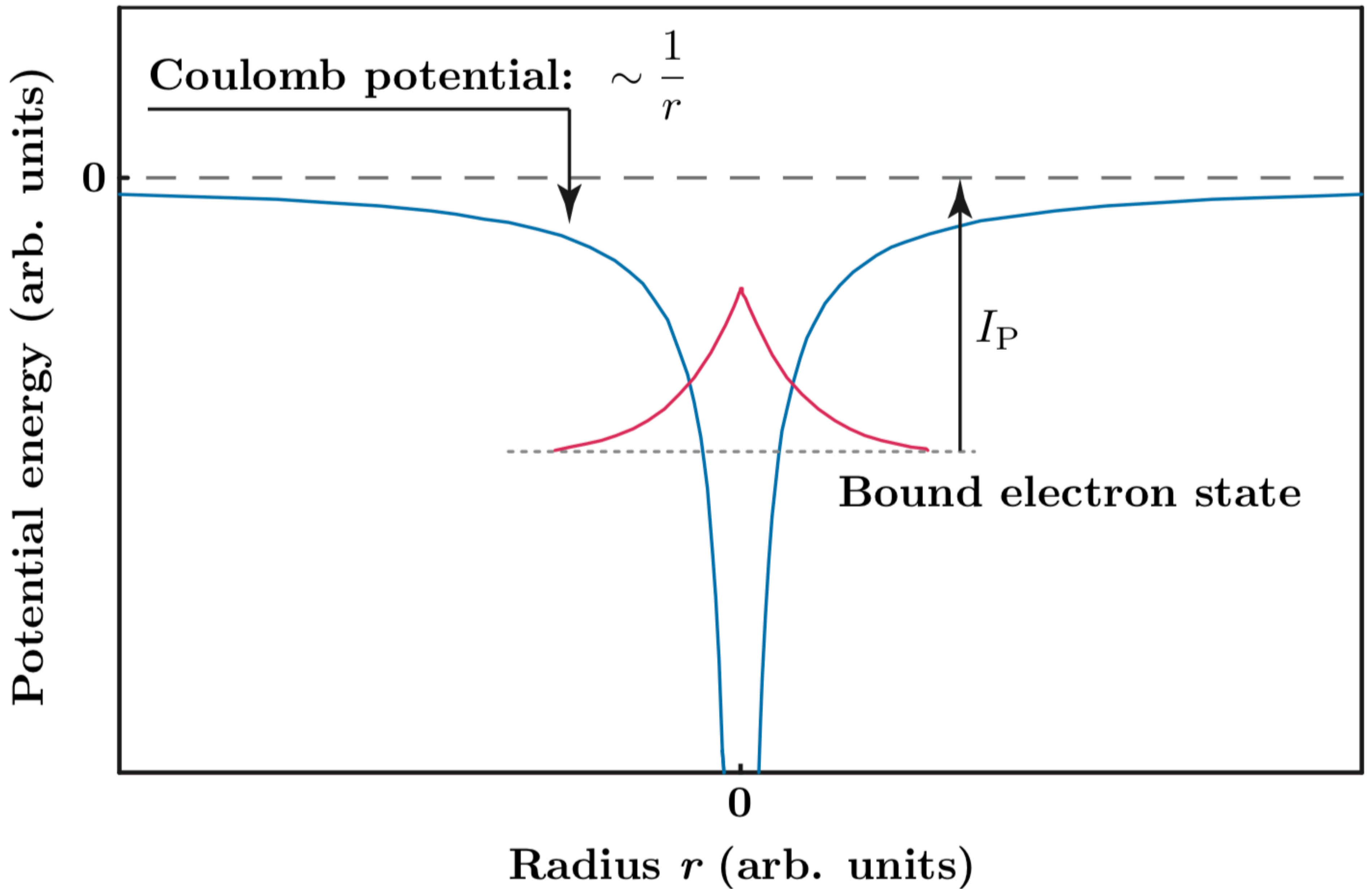
- MPI typically relevant only for moderate laser intensities (or in temporal and spatial wings)
  - *Example:* $\gamma_K > 1$ for $I < 1.1\times10^{14}$ W cm$^{-2}$ and $\lambda = 800$ nm

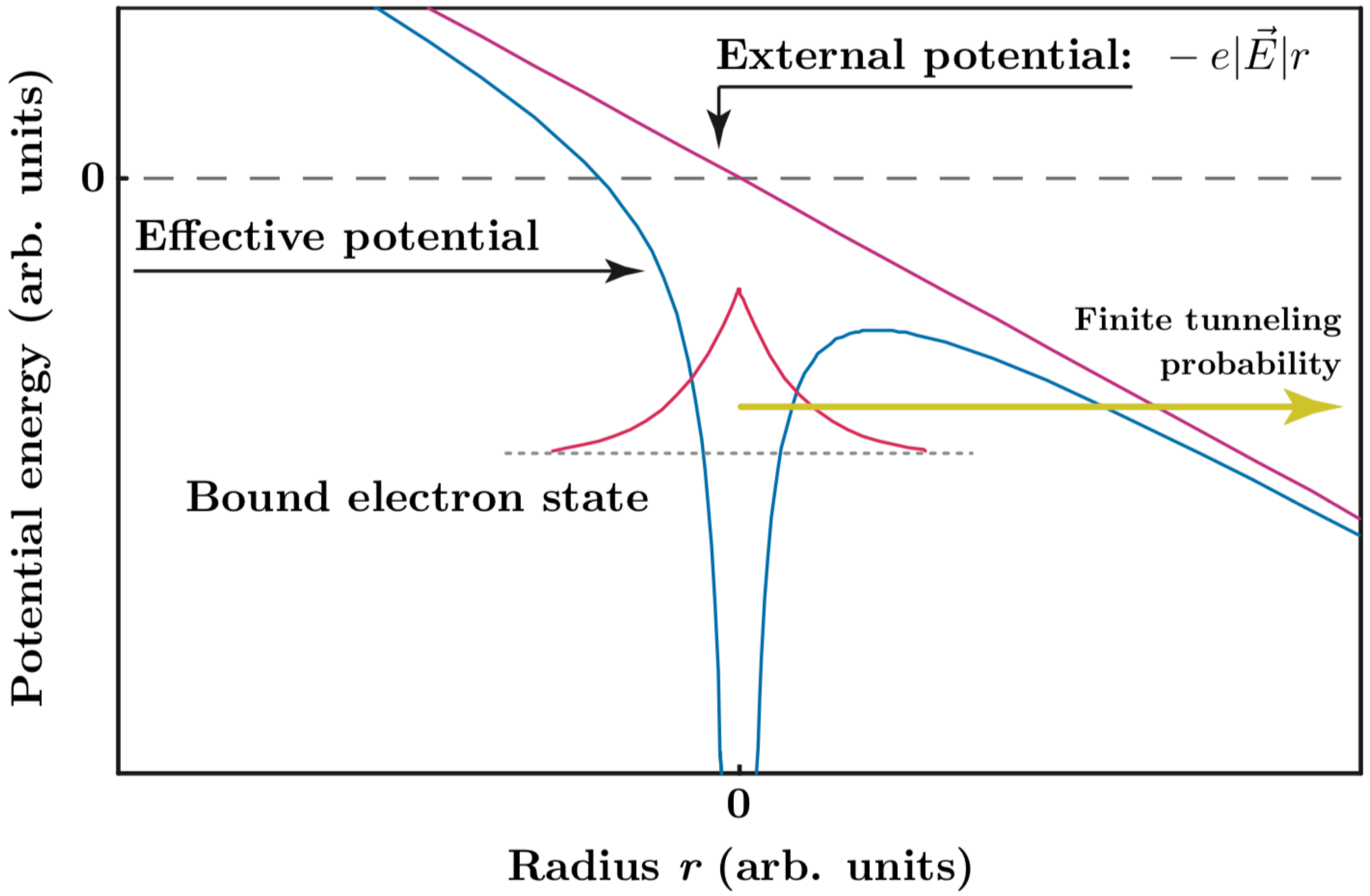
- Ionization rate $\Gamma_{\mathrm{i}\to\mathrm{f}} = \sigma^{(N)}_{\mathrm{i}\to\mathrm{f}} I^N$
- Cross-section from Fermi's Golden Rule



# Tunneling ionization

M. V. Ammosov *et al.* *Sov. Phys. JETP* **64** 1191 (1986)
P. B. Corkum *Phys. Rev. Lett.* **71** 1994 (1993)





- External E-field comparable to binding field
- External field distorts atomic potential
- Valence electron can tunnel through barrier
- Accurate solution can be found by solving the Schrödinger equation → complex
- Described by simplified models, popular: ADK (Ammosov, Delone, and Krainov)

- ADK ionization rate

$$W[\mathrm{fs}^{-1}] = 1.52 \times \frac{4^{n*}}{n*\Gamma(2n*)}\left(20.5\frac{E_I}{E}\right)\exp\left(-6.83\frac{E_I^{3/2}}{E}\right)$$

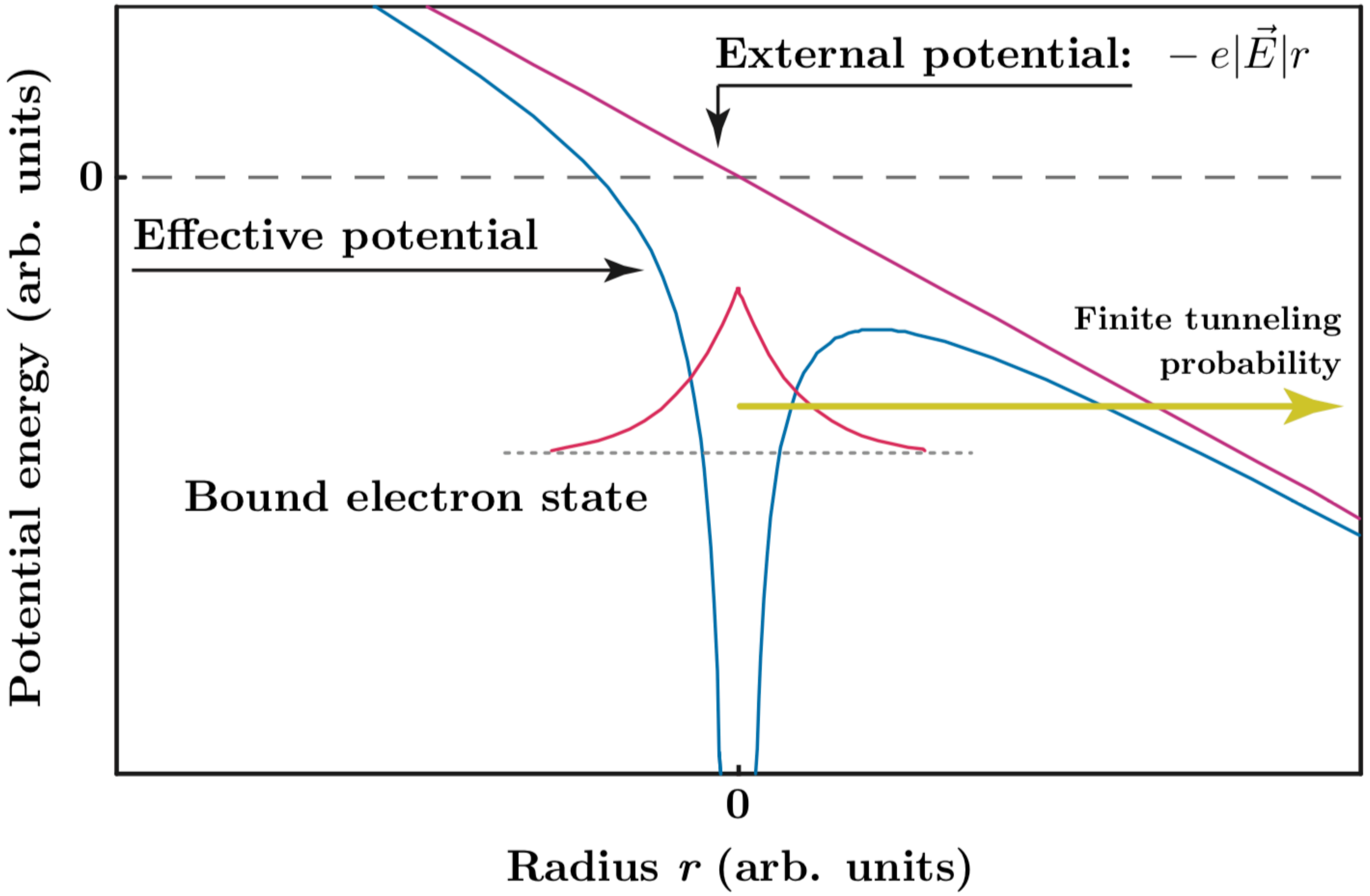
$E_I$ = Ionization potential (eV)

$E$ = Electric field (GV / m)

$n* = 3.68Z/\sqrt{E_I}$ Effective quantum number

# Tunneling ionization

M. V. Ammosov *et al.* *Sov. Phys. JETP* **64** 1191 (1986)
P. B. Corkum *Phys. Rev. Lett.* **71** 1994 (1993)



- ADK ionization model only valid below

$$E_{crit} = \frac{1}{16Z}\left(\frac{U_{ion}}{U_H}\right)^2 E_\alpha$$

$$E_\alpha = m_e c \alpha^4 / r_e e \approx 5.14\,\mathrm{GV/cm}$$

- ADK ionization rate

$$W[\mathrm{fs}^{-1}] = 1.52 \times \frac{4^{n*}}{n*\Gamma(2n*)}\left(20.5\frac{E_I}{E}\right)\exp\left(-6.83\frac{E_I^{3/2}}{E}\right)$$

$E_I =$ Ionization potential (eV)

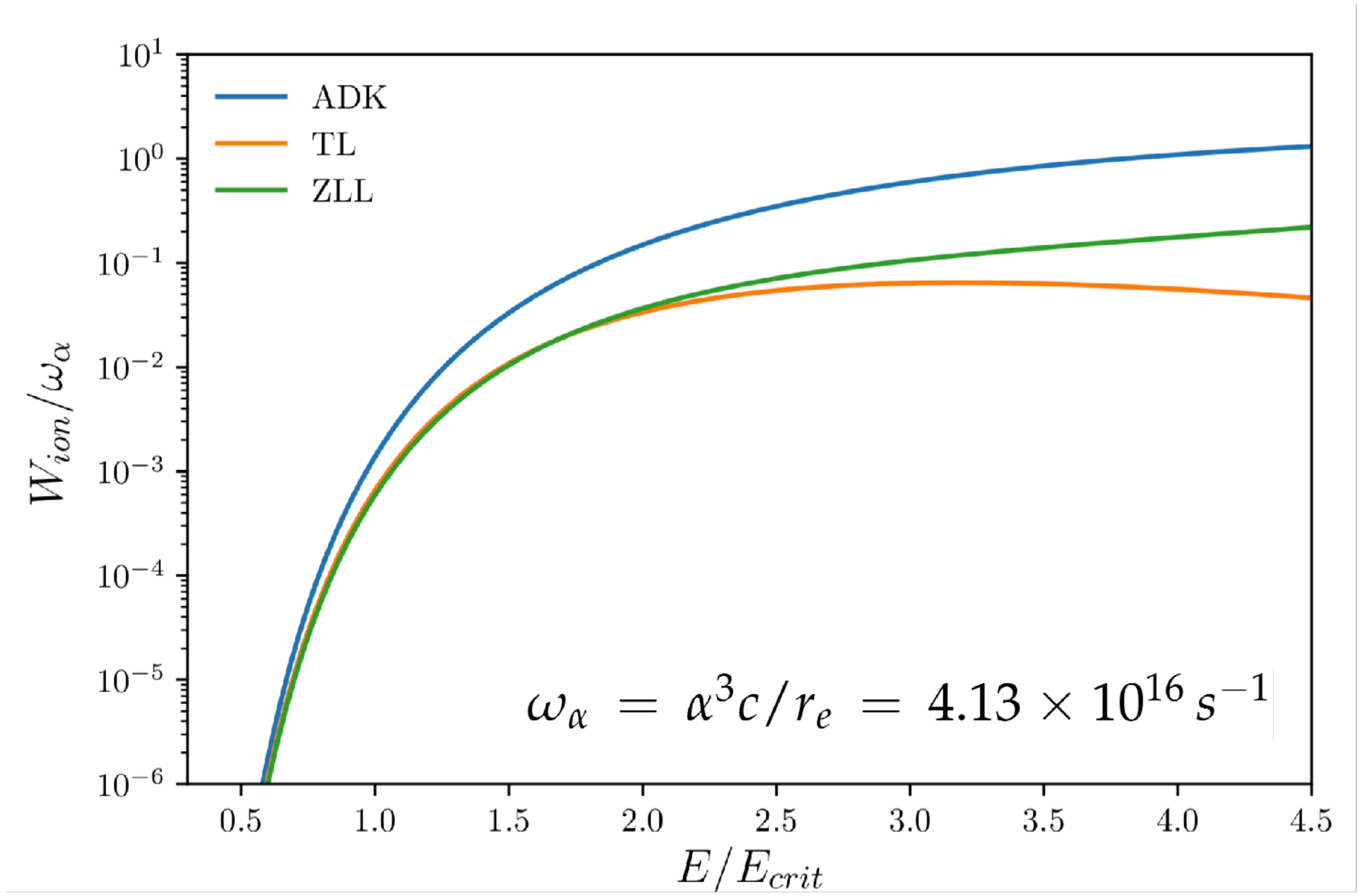
$E =$ Electric field (GV / m)

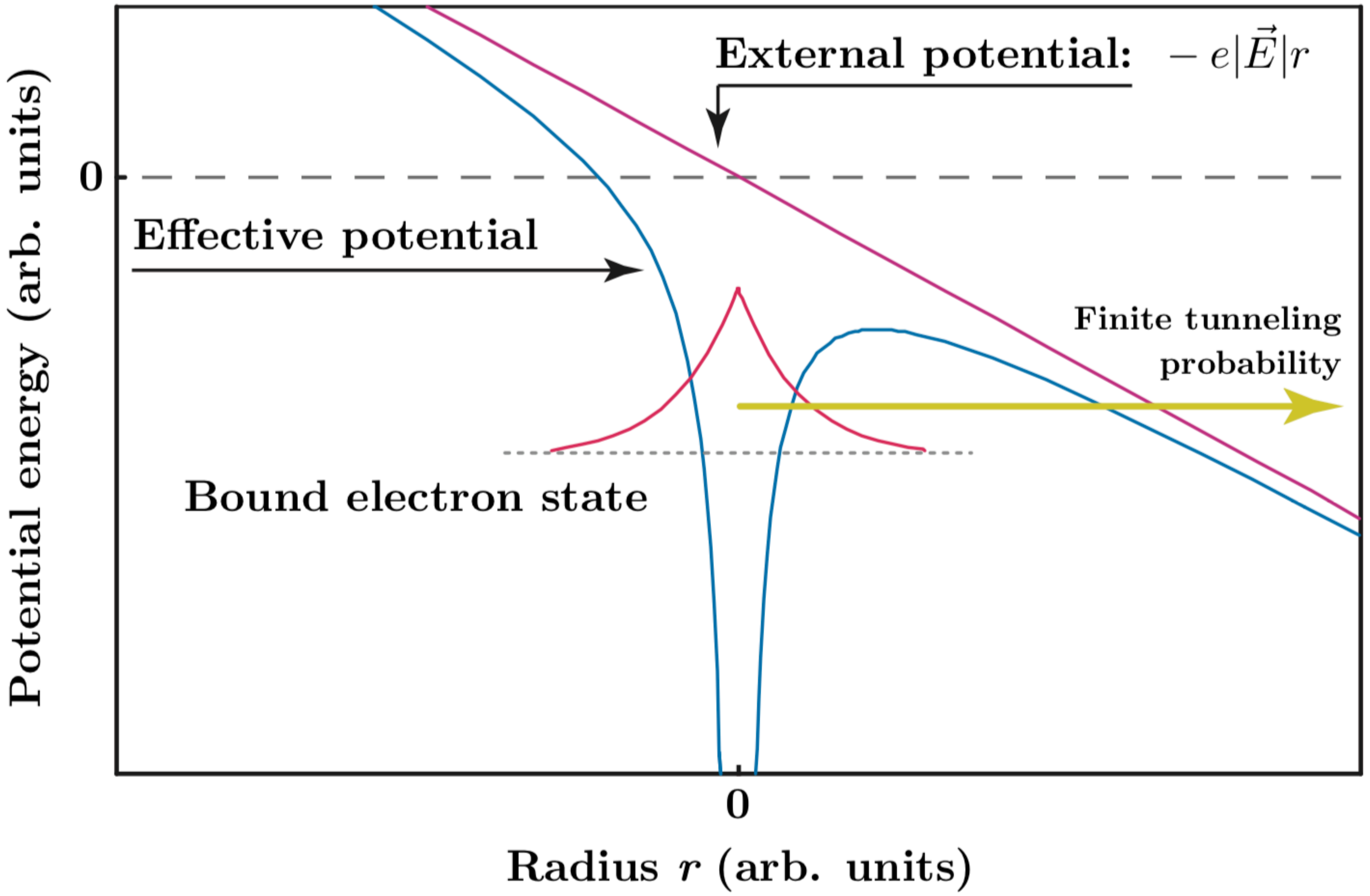
$n* = 3.68Z/\sqrt{E_I}$ Effective quantum number

- (Special case) model extensions exist. Care needed!

# Tunneling ionization

M. V. Ammosov *et al.* *Sov. Phys. JETP* **64** 1191 (1986)
P. B. Corkum *Phys. Rev. Lett.* **71** 1994 (1993)





- ADK ionization model only valid below

$$E_{crit} = \frac{1}{16Z}\left(\frac{U_{ion}}{U_H}\right)^2 E_\alpha$$

$$E_\alpha = m_e c \alpha^4 / r_e e \approx 5.14\,\mathrm{GV/cm}$$

- ADK ionization rate

$$W[\mathrm{fs}^{-1}] = 1.52 \times \frac{4^{n*}}{n*\Gamma(2n*)}\left(20.5\frac{E_I}{E}\right)\exp\left(-6.83\frac{E_I^{3/2}}{E}\right)$$

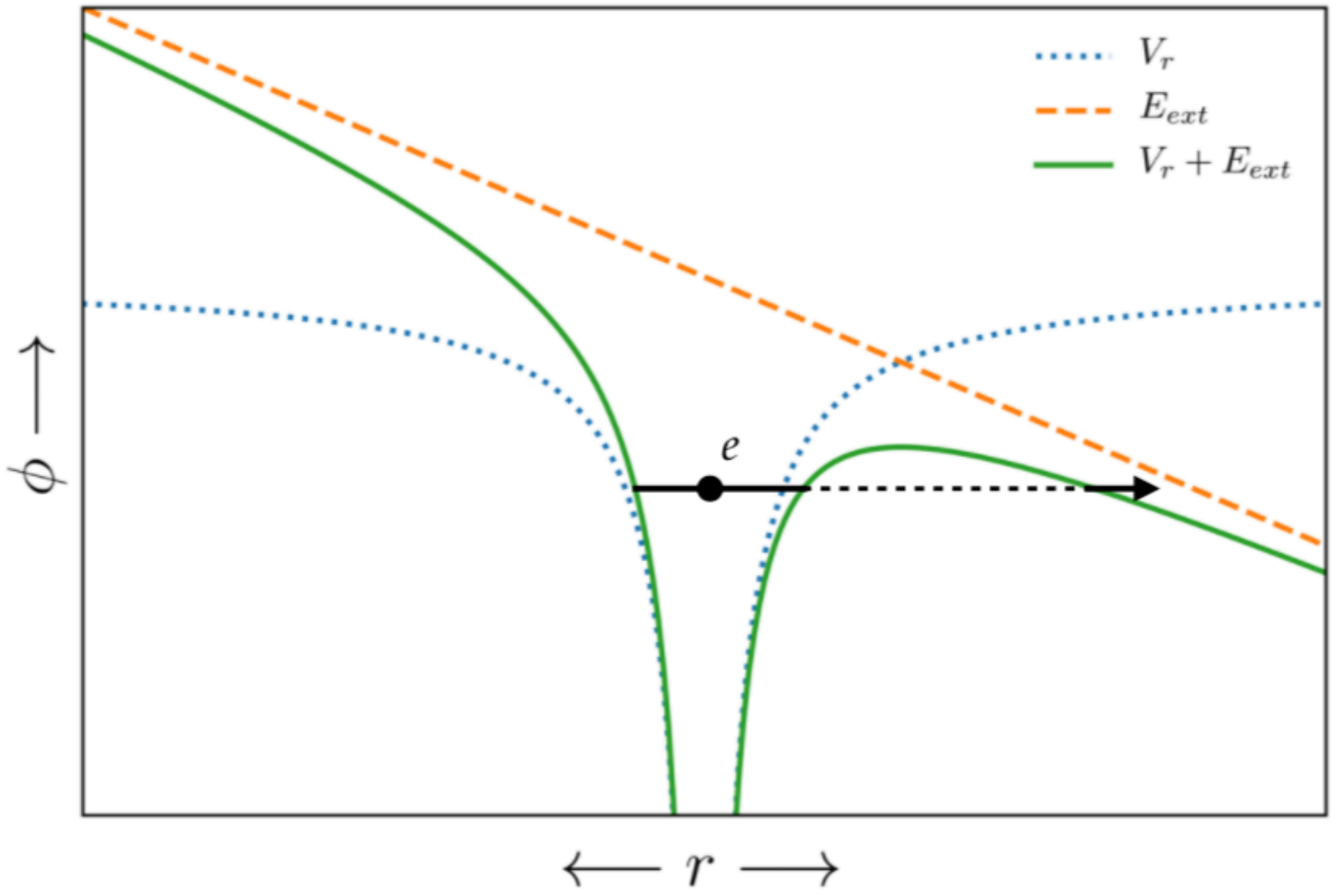
$E_I =$ Ionization potential (eV)

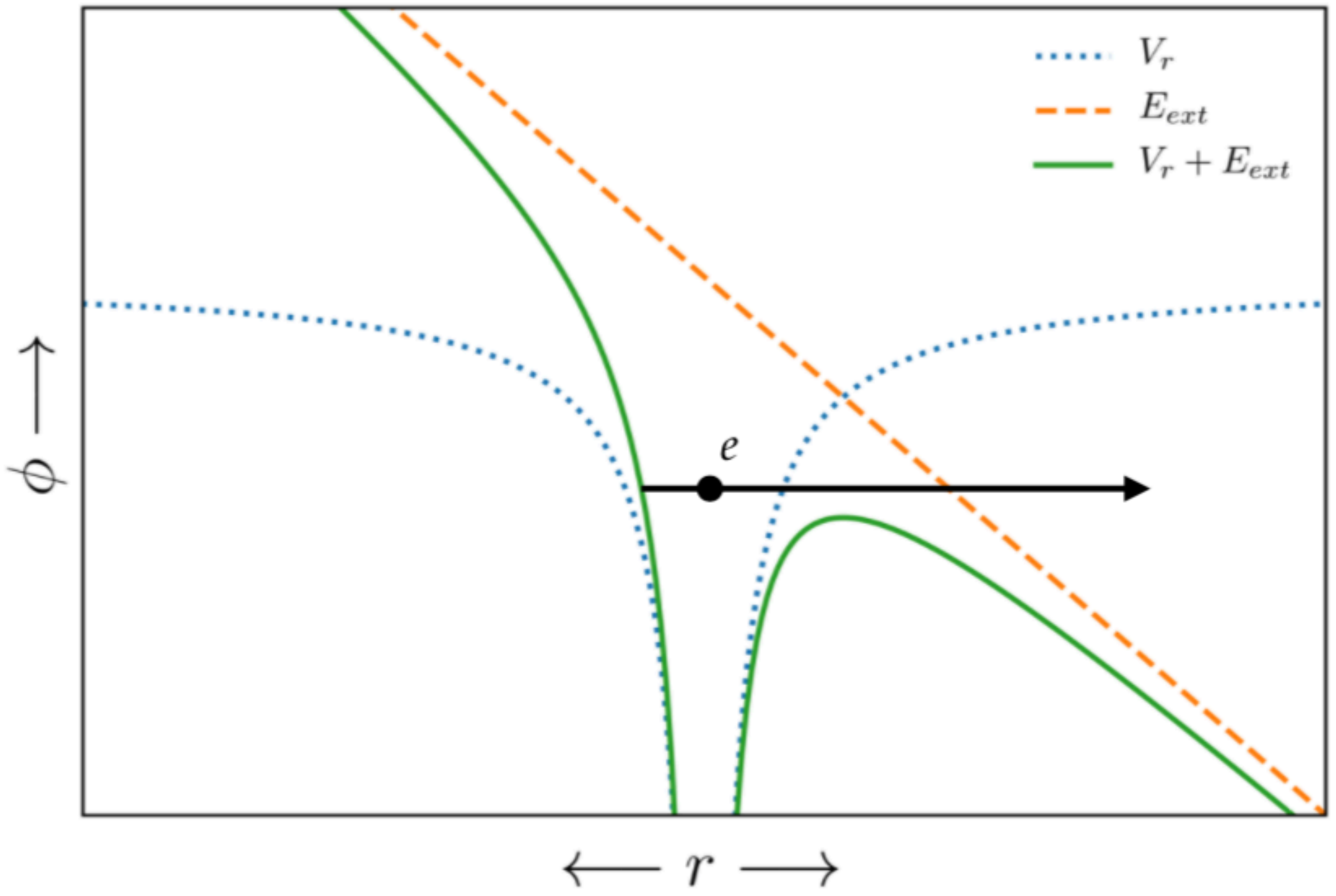
$E =$ Electric field (GV / m)

$n* = 3.68Z/\sqrt{E_I}$ Effective quantum number

- (Special case) model extensions exist. Care needed!

# Barrier suppression ionization





**(a)** Noble gas ions

| Ion | $I_P$ (eV) | $I_{BSI}$ (W cm$^{-2}$) |
|---|---|---|
| $He^{+}$ | 24.59 | $1.4 \cdot 10^{15}$ |
| $He^{2+}$ | 54.42 | $8.8 \cdot 10^{15}$ |
| $Ne^{+}$ | 21.6 | $8.6 \cdot 10^{14}$ |
| $Ne^{2+}$ | 40.96 | $2.8 \cdot 10^{15}$ |
| $Ne^{7+}$ | 207.3 | $1.5 \cdot 10^{17}$ |
| $Ar^{8+}$ | 143.5 | $2.6 \cdot 10^{16}$ |
| $Xe^{+}$ | 12.13 | $8.6 \cdot 10^{13}$ |
| $Xe^{8+}$ | 105.9 | $7.8 \cdot 10^{15}$ |

**(b)** Miscellaneous ions

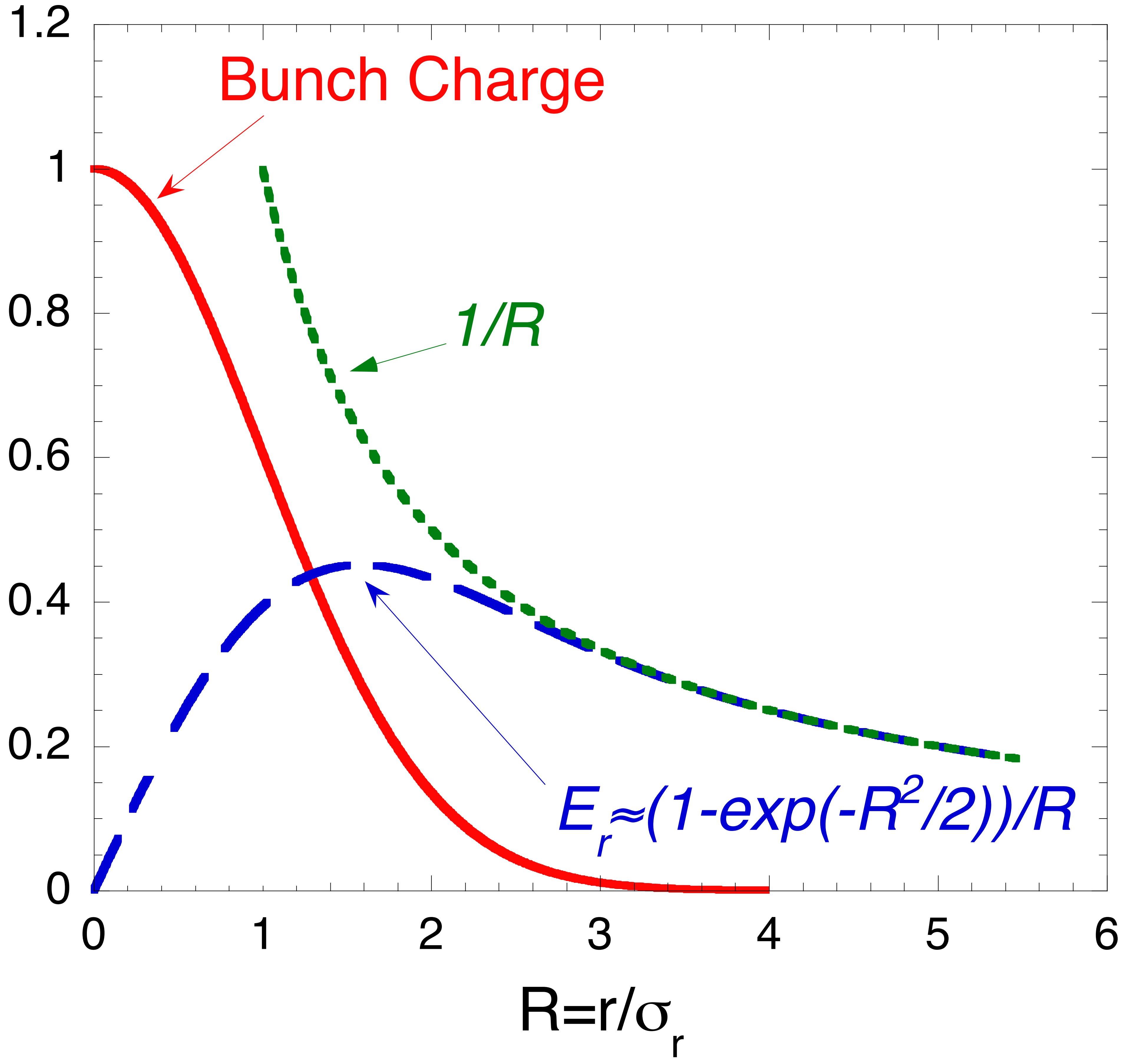
| Ion | $I_P$ (eV) | $I_{BSI}$ (W cm$^{-2}$) |
|---|---|---|
| $H^{+}$ | 13.61 | $1.4 \cdot 10^{14}$ |
| $C^{+}$ | 11.2 | $6.4 \cdot 10^{13}$ |
| $C^{4+}$ | 64.5 | $4.3 \cdot 10^{15}$ |
| $N^{5+}$ | 97.9 | $1.5 \cdot 10^{16}$ |
| $O^{6+}$ | 138.1 | $4.0 \cdot 10^{16}$ |

- At high fields the barrier is completely suppressed (Barrier Suppression Ionization)

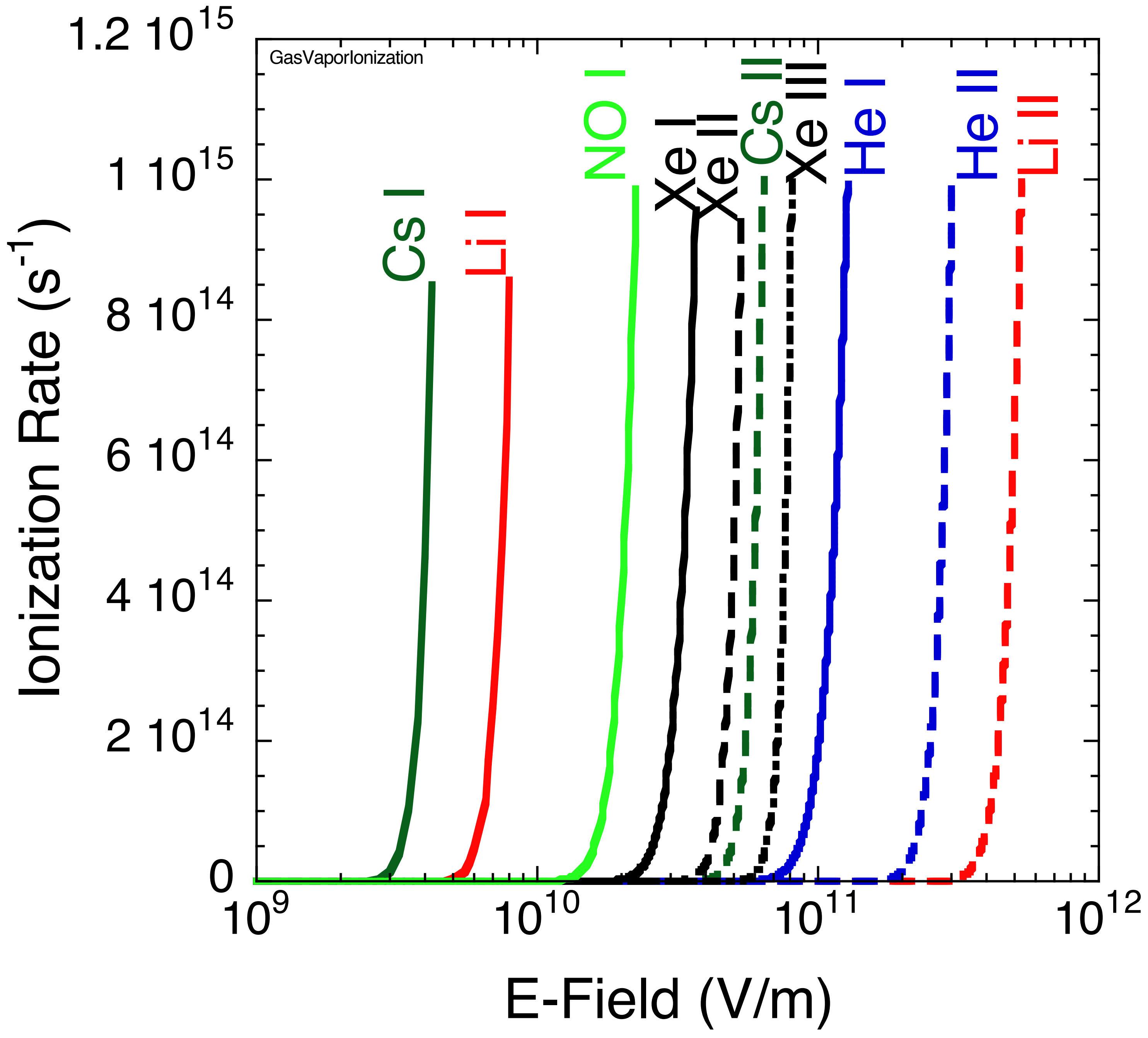
$$I_{\mathrm{BSI}} \geq \frac{I_{\mathrm{P}}^4 \pi^2 c \epsilon_0^3}{2 Z^2 e^6} \gtrsim 4.00 \cdot 10^9 \, \frac{I_{\mathrm{P}}^4}{Z^2} \quad \text{in W cm}^{-2} \text{ with } [I_{\mathrm{P}}] = \text{eV}$$

# Field ionization by particle beams

$$E_{r,\mathrm{peak}}(r \approx 1.6\sigma_r)$$



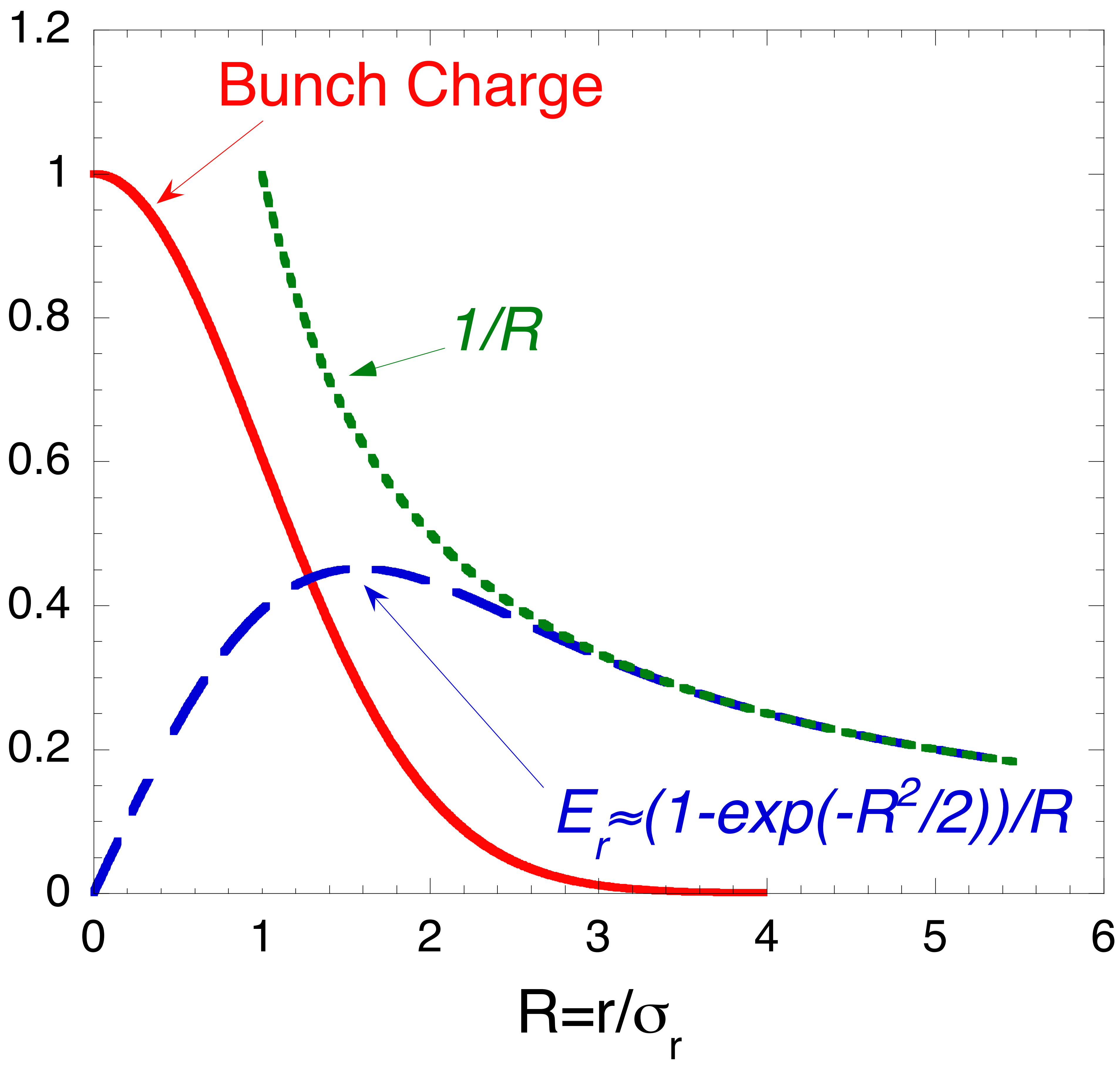
- Coulomb fields of particle beams can trigger ionization
- Field maximum is off-axis for symmetric beams



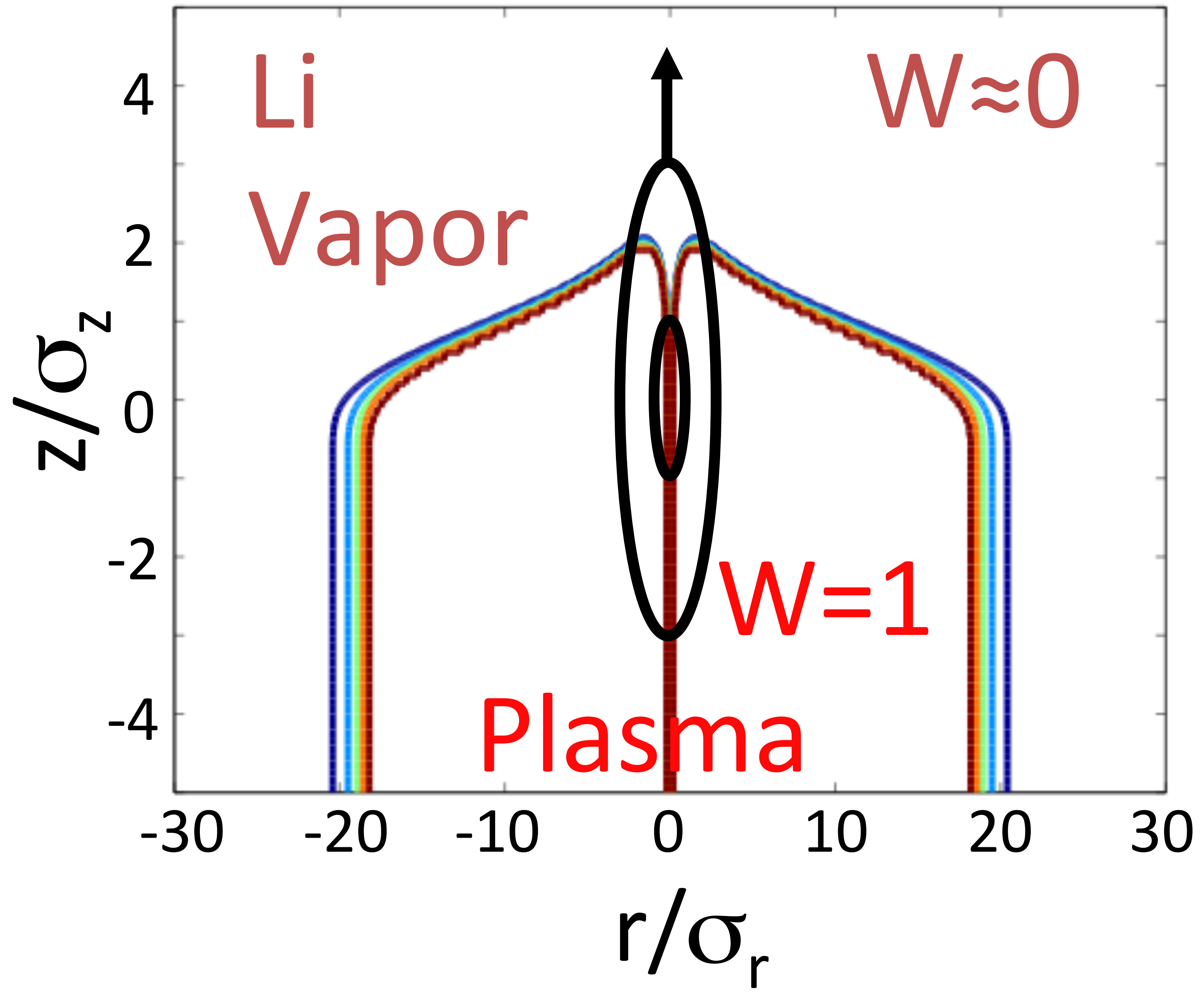
Courtesy Patric Muggli
Max Planck Institute for Physics, Munich

# Field ionization by particle beams

$$E_{r,\mathrm{peak}}(r \approx 1.6\sigma_r)$$



- Coulomb fields of particle beams can trigger ionization
- Field maximum is off-axis for symmetric beams



Courtesy Patric Muggli
Max Planck Institute for Physics, Munich

# Tailoring plasma properties to control wakefield processes

# What do we want to control?

- **Plasma density $n_e(x,t)$, $n_i(x,t)$**
  - injection ($n_e$ density down-ramps)
  - dephasing ($n_e$ density up-ramps)
  - laser guiding (transverse $n_e$ profiles)
  - emittance preservation in beam release (tailored plasma to vacuum transition)
  - emittance preservation in beam capturing/matching (tailored vacuum to plasma transition)
  - hosing seed mitigation (tailored vacuum to plasma transition)
  - head-erosion mitigation (preionized beam-driven)
  - decoupled acceleration and focussing fields (hollow-core channels)
  - positron acceleration (hollow-core channels)
  - chirp mitigation (alternating plasma densities)

- ***Control:*** **set parameters with high precision**
- ***Stability:*** **small event fluctuations**

# What do we want to control?

- **Plasma density $n_e\,(x,t)$, $n_i\,(x,t)$**
  - injection ($n_e$ density down-ramps)
  - dephasing ($n_e$ density up-ramps)
  - laser guiding (transverse $n_e$ profiles)
  - emittance preservation in beam release (tailored plasma to vacuum transition)
  - emittance preservation in beam capturing/matching (tailored vacuum to plasma transition)
  - hosing seed mitigation (tailored vacuum to plasma transition)
  - head-erosion mitigation (preionized beam-driven)
  - decoupled acceleration and focussing fields (hollow-core channels)
  - positron acceleration (hollow-core channels)
  - chirp mitigation (alternating plasma densities)
- **Plasma temperature $T_e\,(x,t)$, $T_i\,(x,t)$**
  - usually of lesser concern: $T_{e/i} \approx I_p \ll U_p$
  - important for non-wakefield applications, e.g. active plasma lenses

- ***Control:* set parameters with high precision**
- ***Stability:* small event fluctuations**

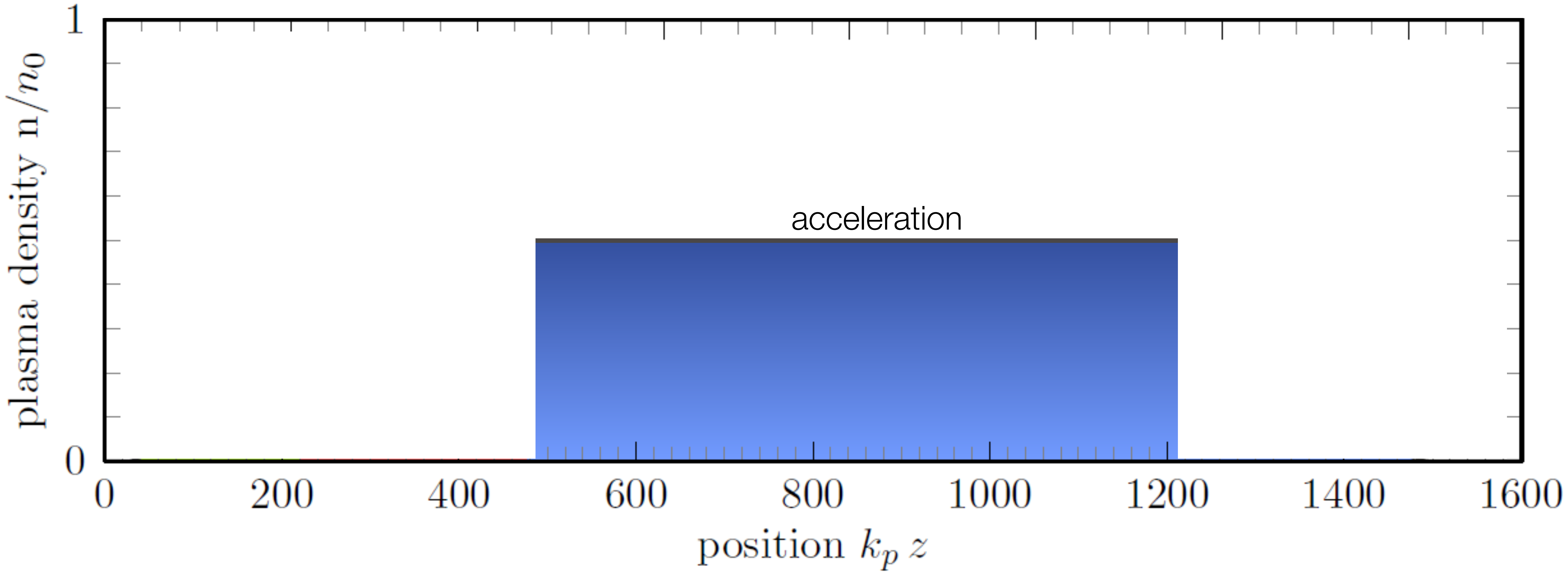
# What do we want to control?

- **Plasma density $n_e(x,t)$, $n_i(x,t)$**
  - injection ($n_e$ density down-ramps)
  - dephasing ($n_e$ density up-ramps)
  - laser guiding (transverse $n_e$ profiles)
  - emittance preservation in beam release (tailored plasma to vacuum transition)
  - emittance preservation in beam capturing/matching (tailored vacuum to plasma transition)
  - hosing seed mitigation (tailored vacuum to plasma transition)
  - head-erosion mitigation (preionized beam-driven)
  - decoupled acceleration and focussing fields (hollow-core channels)
  - positron acceleration (hollow-core channels)
  - chirp mitigation (alternating plasma densities)
- **Plasma temperature $T_e(x,t)$, $T_i(x,t)$**
  - usually of lesser concern: $T_{e/i} \approx I_p \ll U_p$
  - important for non-wakefield applications, e.g. active plasma lenses
- **Plasma constituents (also from gas mixtures)**
  - unionized electronic levels → ionization injection, ionization defocussing
  - ion mass → ion motion effects, thermal conductivity
  - tracer atoms → diagnostics

- ***Control:* set parameters with high precision**
- ***Stability:* small event fluctuations**

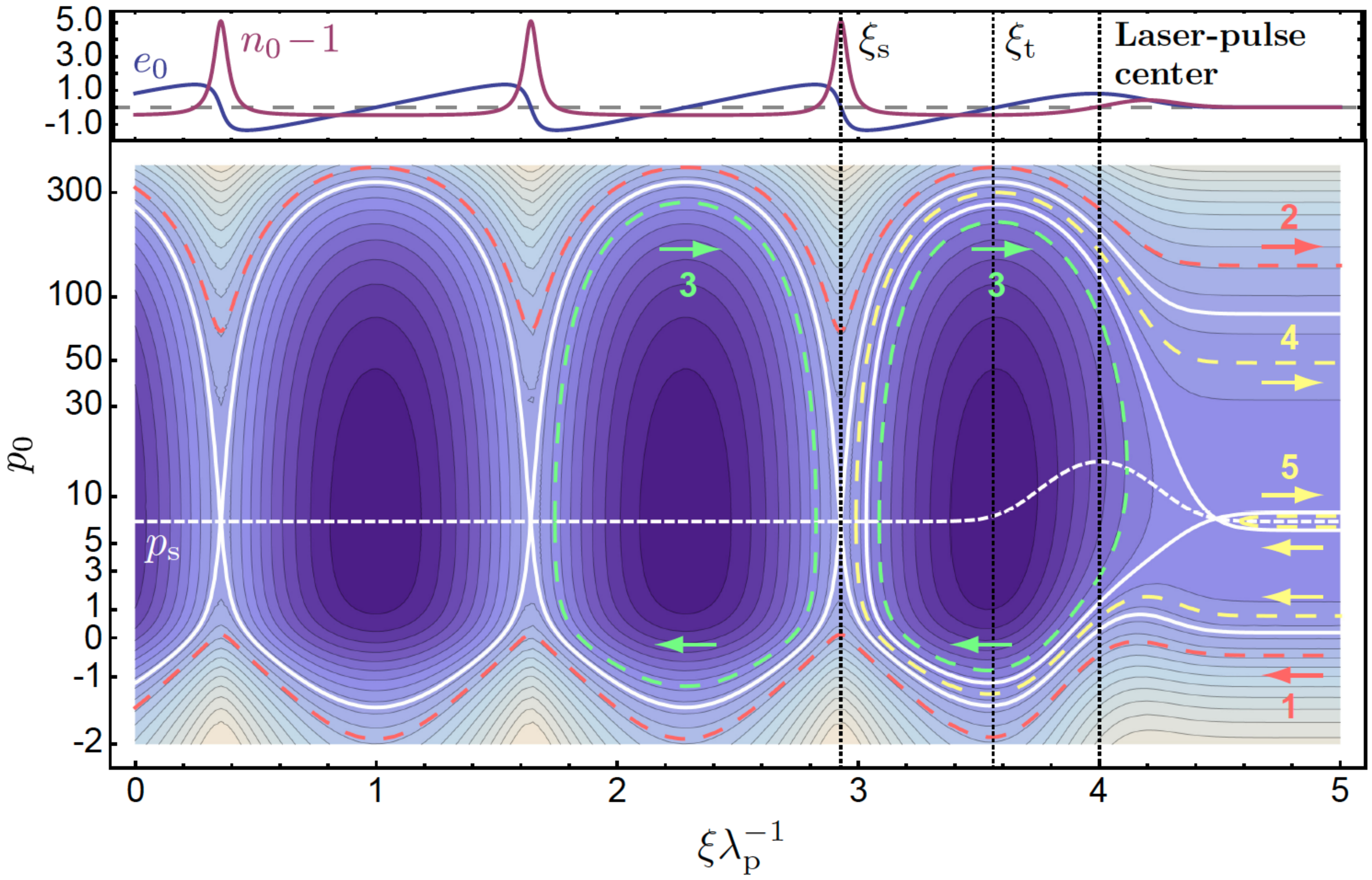
# Plasma density control

- Plasma density $n_e$ (x,t) governs acceleration process
- Usually: flat acceleration section



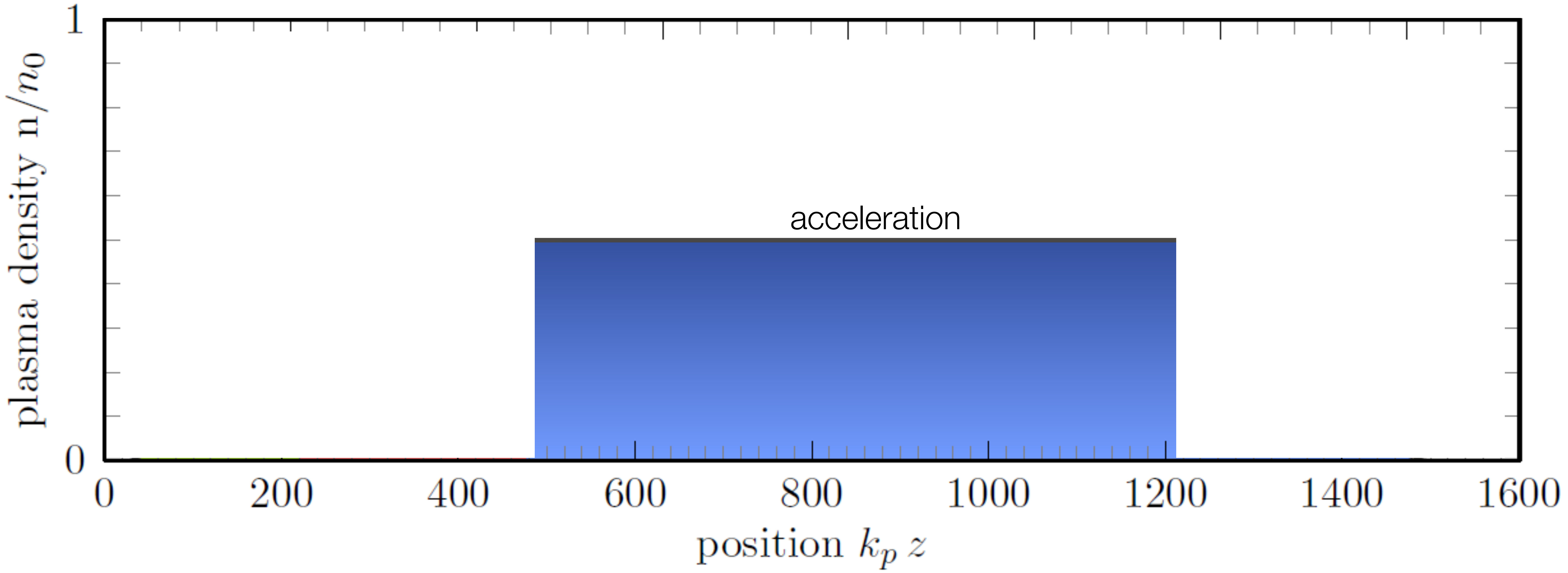
# Plasma density control

- Plasma density $n_e$ (x,t) governs acceleration process
- Usually: flat acceleration section



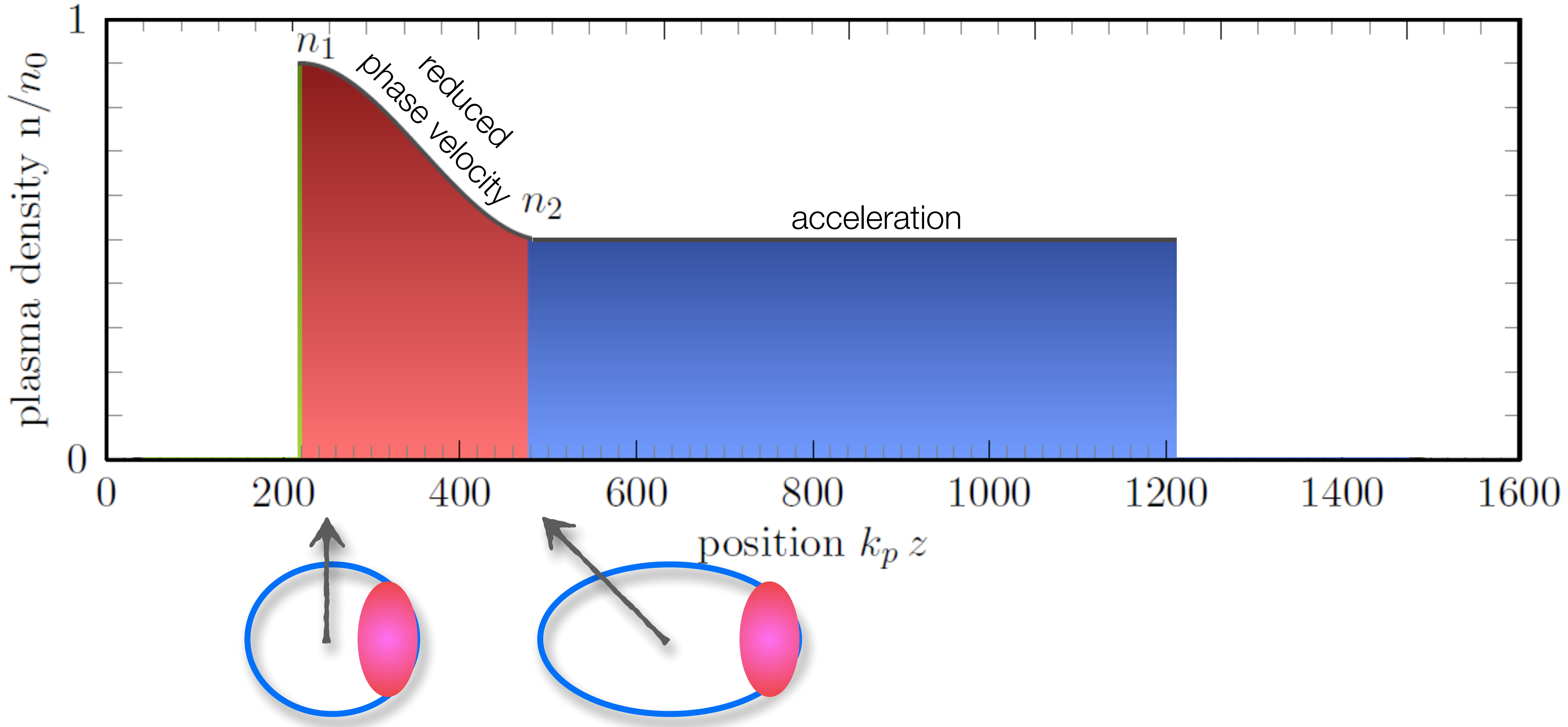
# Plasma density control

- Plasma density $n_e(x,t)$ governs acceleration process
- Usually: flat acceleration section



# Plasma density control - down-ramp injection

- Plasma density $n_e$ (x,t) governs acceleration process



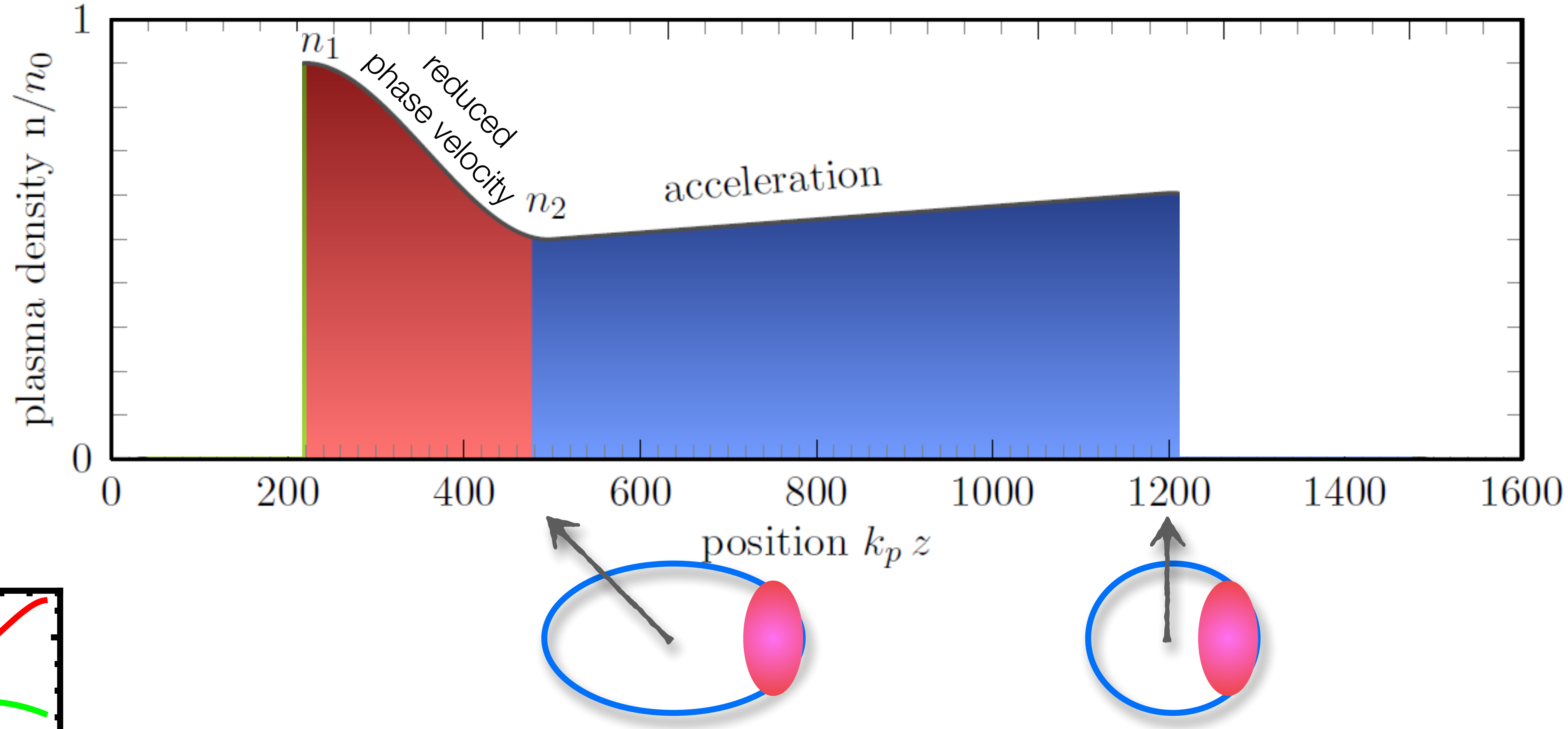
- Phase velocity of plasma wake reduced on density down-slope
- Velocity of plasma electrons may exceed $v_\Phi$, leads to trapping
- Trapping possible in multiple buckets

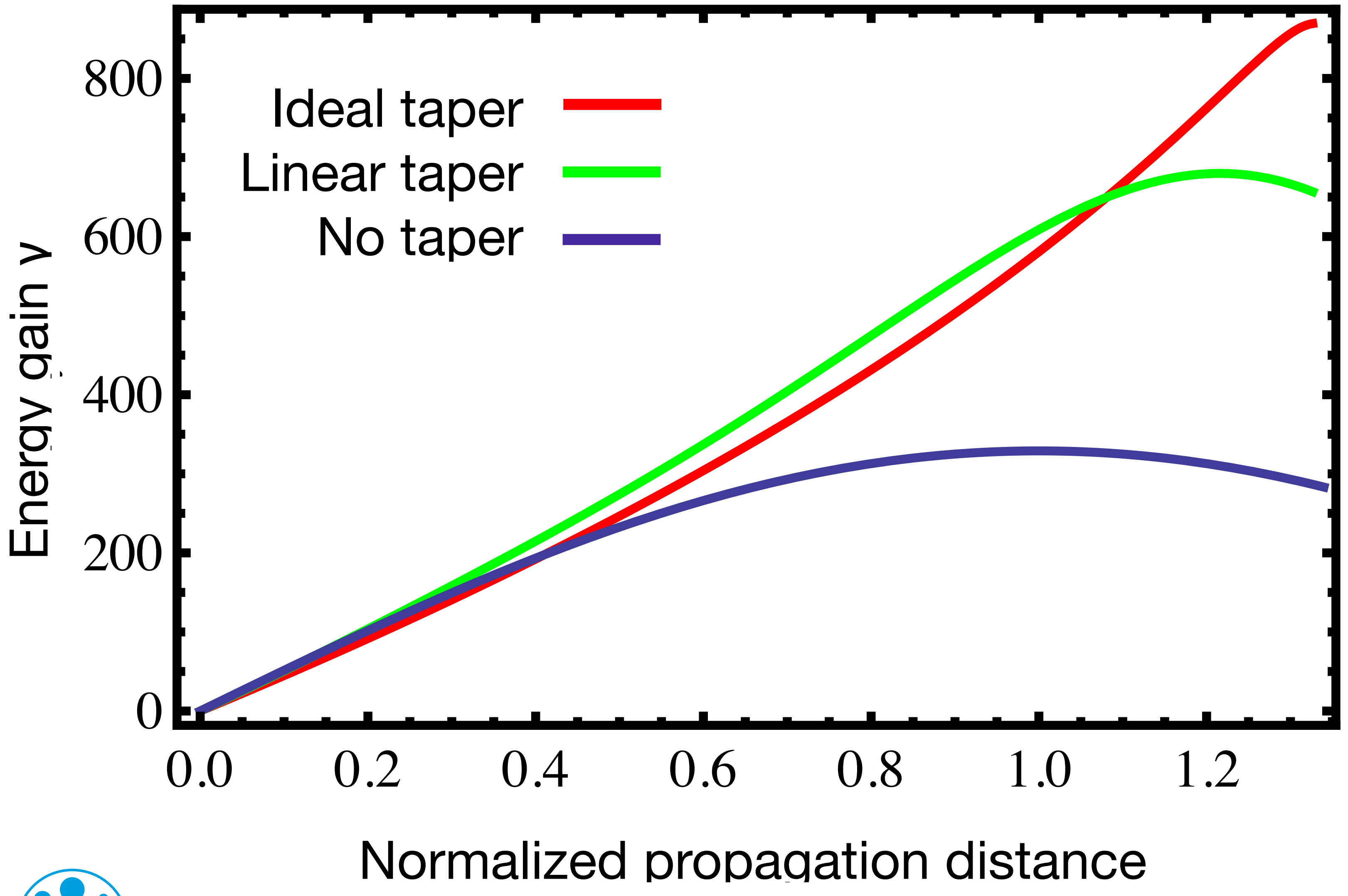
$$\frac{v_\phi}{c} - 1 \approx -\frac{\xi}{2n_e}\frac{dn_e}{dz}$$

*idea:* S.Bulanov *et al.*, Phys. Rev. E **58**, R5257 (1998)
*experiment:* C.G.R.Geddes *et al.*, Phys. Rev. Lett. **100**, 215004 (2008)

# Plasma density control - phase locking

- Plasma density $n_e$ (x,t) governs acceleration process



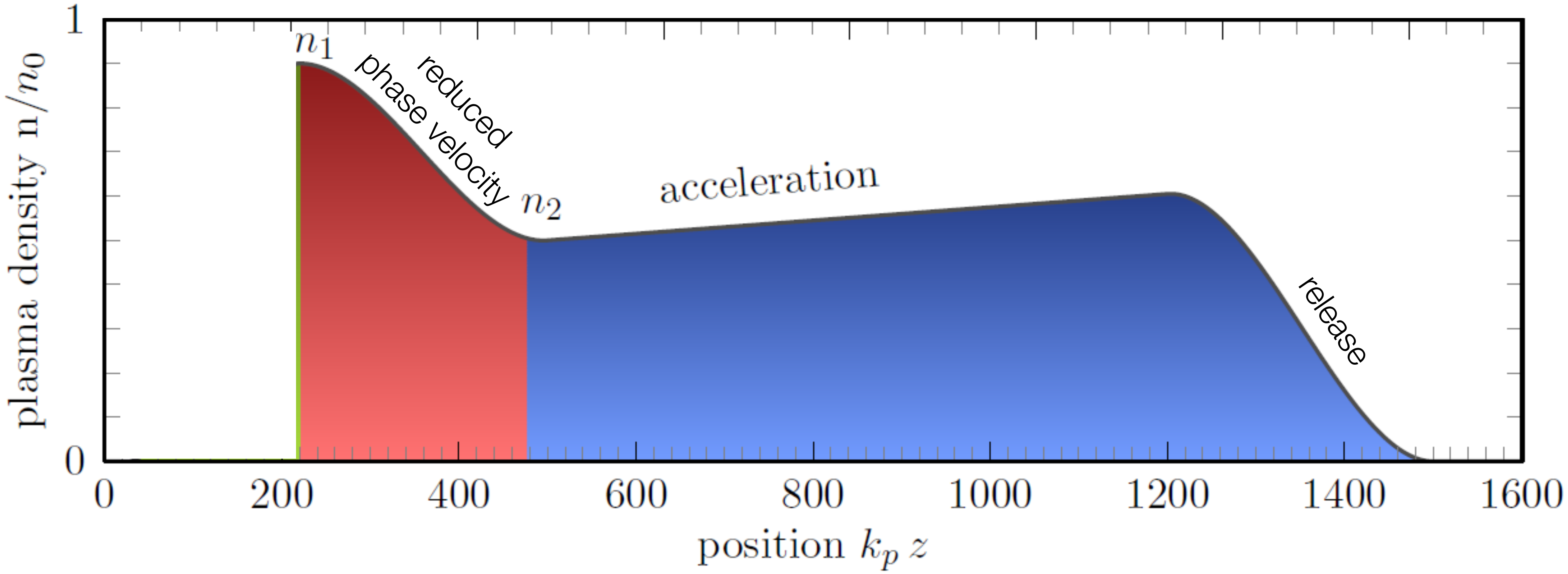


- Phase velocity of plasma wake increased on density up-slope
- Plasma wave phase velocity $v_\Phi$ may be locked to velocity of injected beam
- Electrons can be locked in acceleration phase

Rittershofer *et al.*, Phys. Plasmas 17, 063104 (2010)

# Plasma density control - beam release

- Plasma density $n_e$ (x,t) governs acceleration process

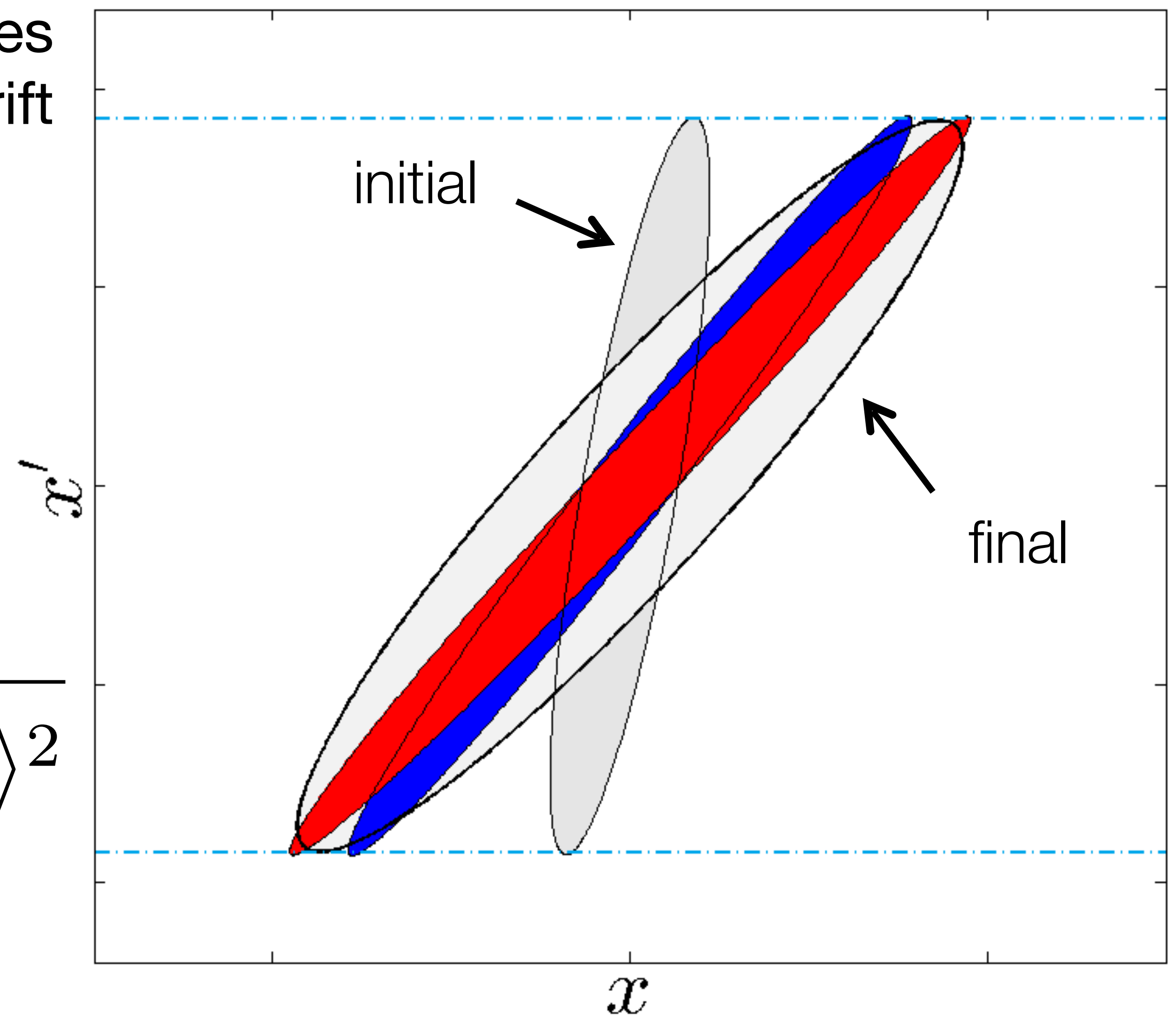


- Beams at plasma exit
  - ~% level energy spread
  - ≲ mm beta function, ~mrad divergence
- Leads to transverse emittance growth in free drift

$$\varepsilon_n{}^2 \cong \langle \gamma \rangle^2 \cdot (\sigma_E{}^2 \sigma_{x'}{}^4 s^2 + \varepsilon^2)$$

→ K. Floettmann, Phys. Rev. STAB 6, 034202 (2003)

Phase space ellipses during drift

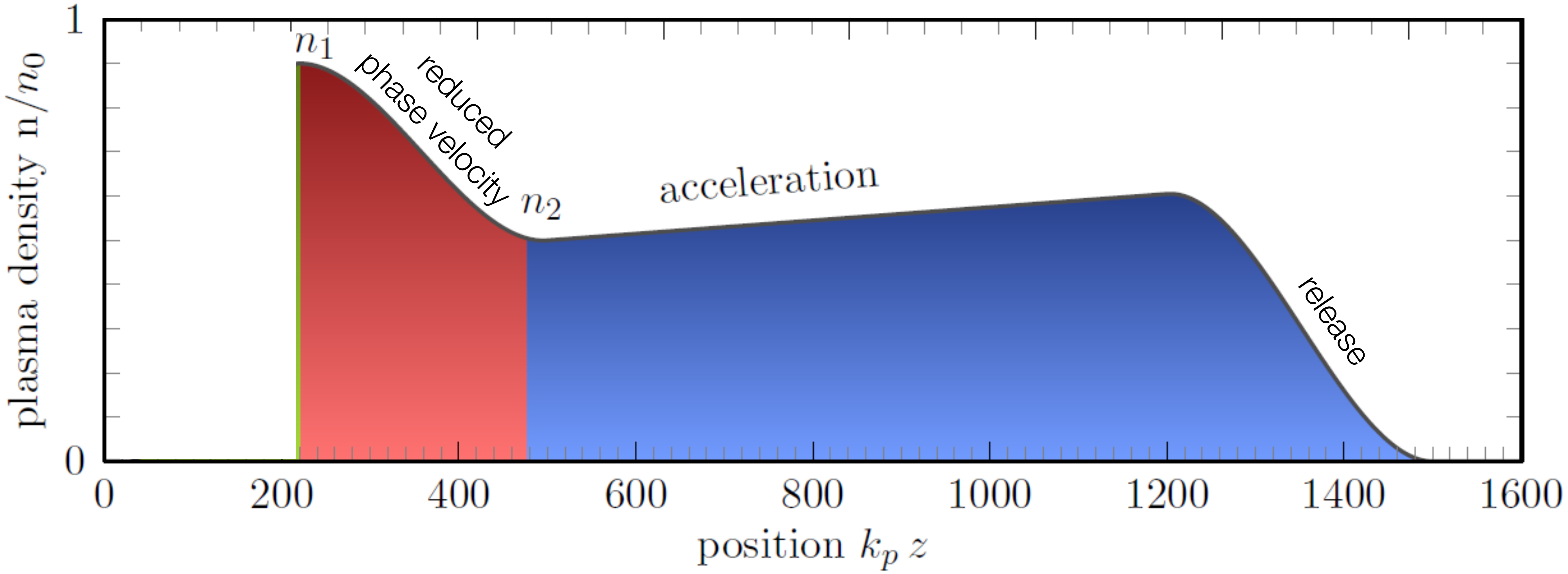


$$\epsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

with $x' = p_x / p_z$

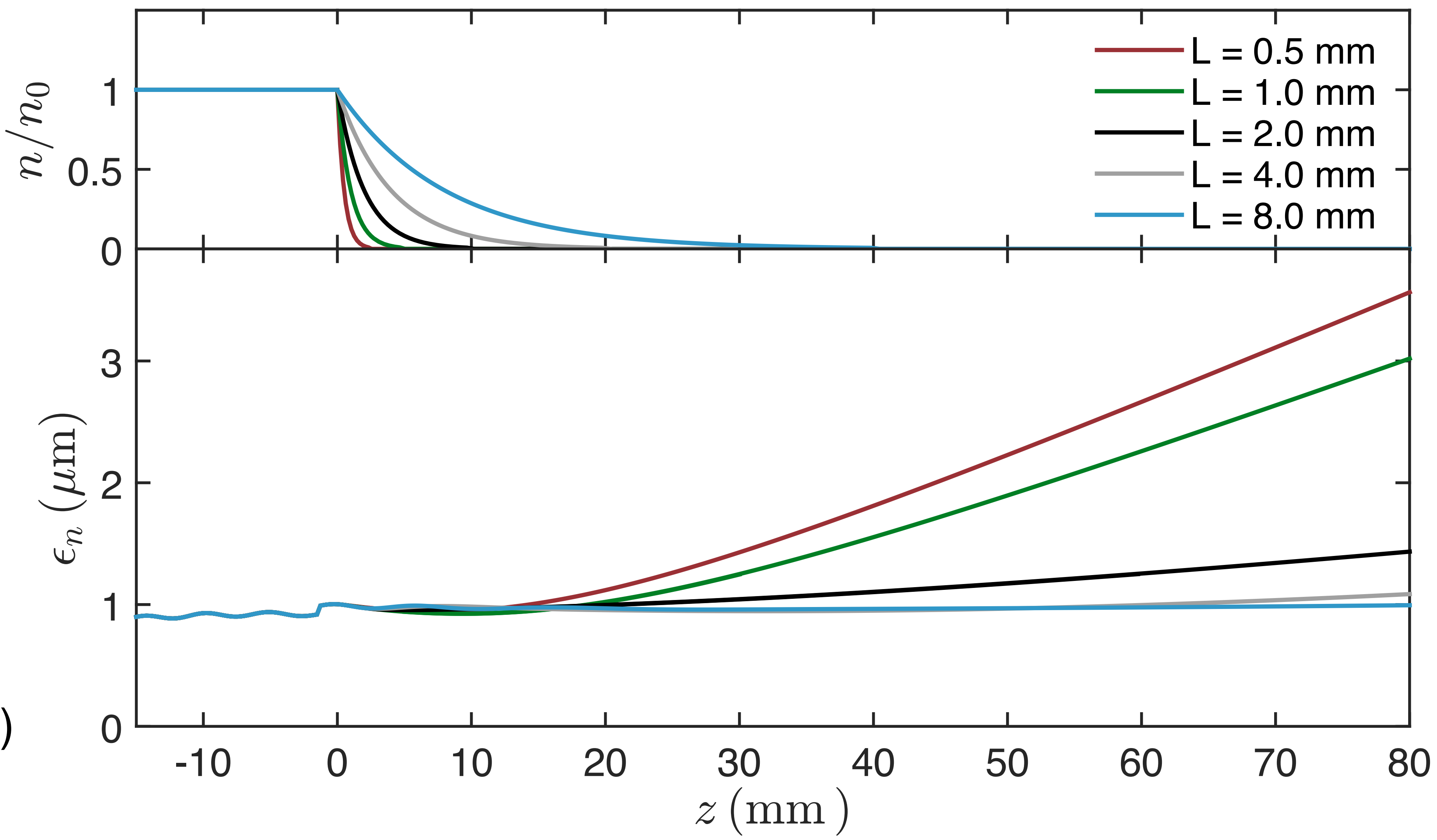
# Plasma density control - beam release

- Plasma density $n_e\,(x,t)$ governs acceleration process



- Beams at plasma exit
  - ~% level energy spread
  - ≲ mm beta function, ~mrad divergence
- Leads to transverse emittance growth in free drift
- Plasma-to-vacuum transition length » β for adiabatic mitigation of emittance growth
- Strong focussing elements for beam capturing required

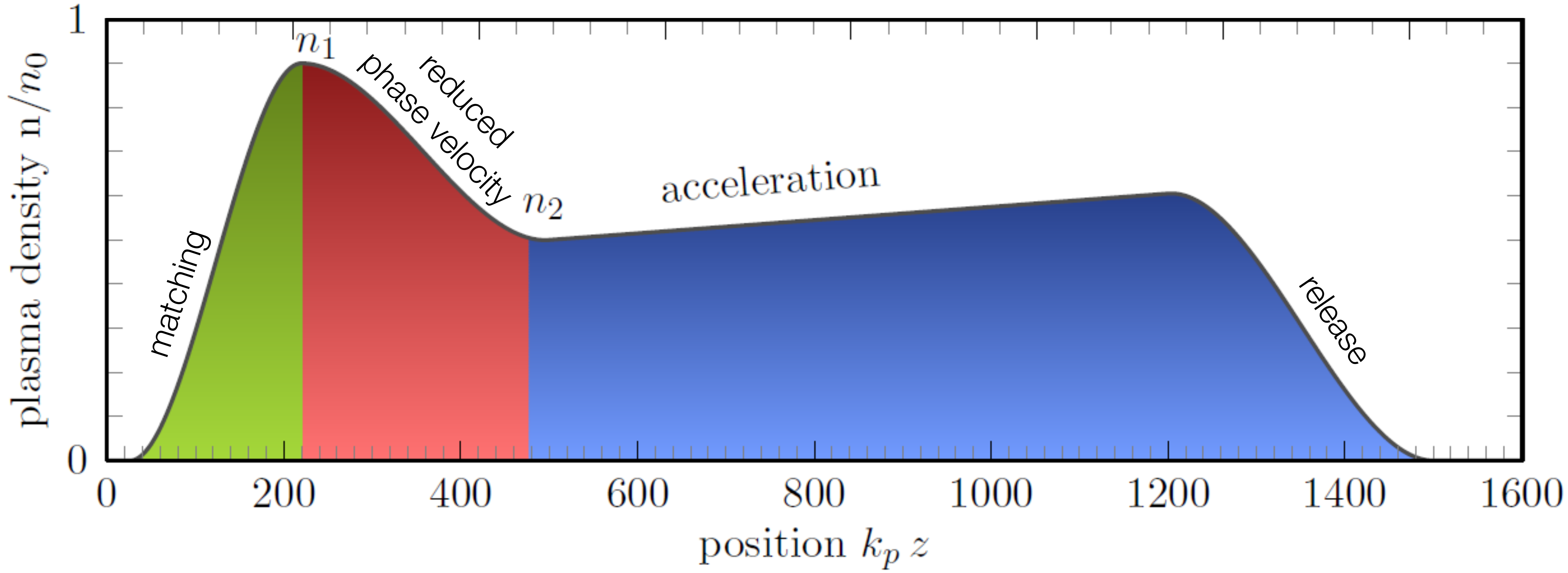
Emittance growth depends on transition length



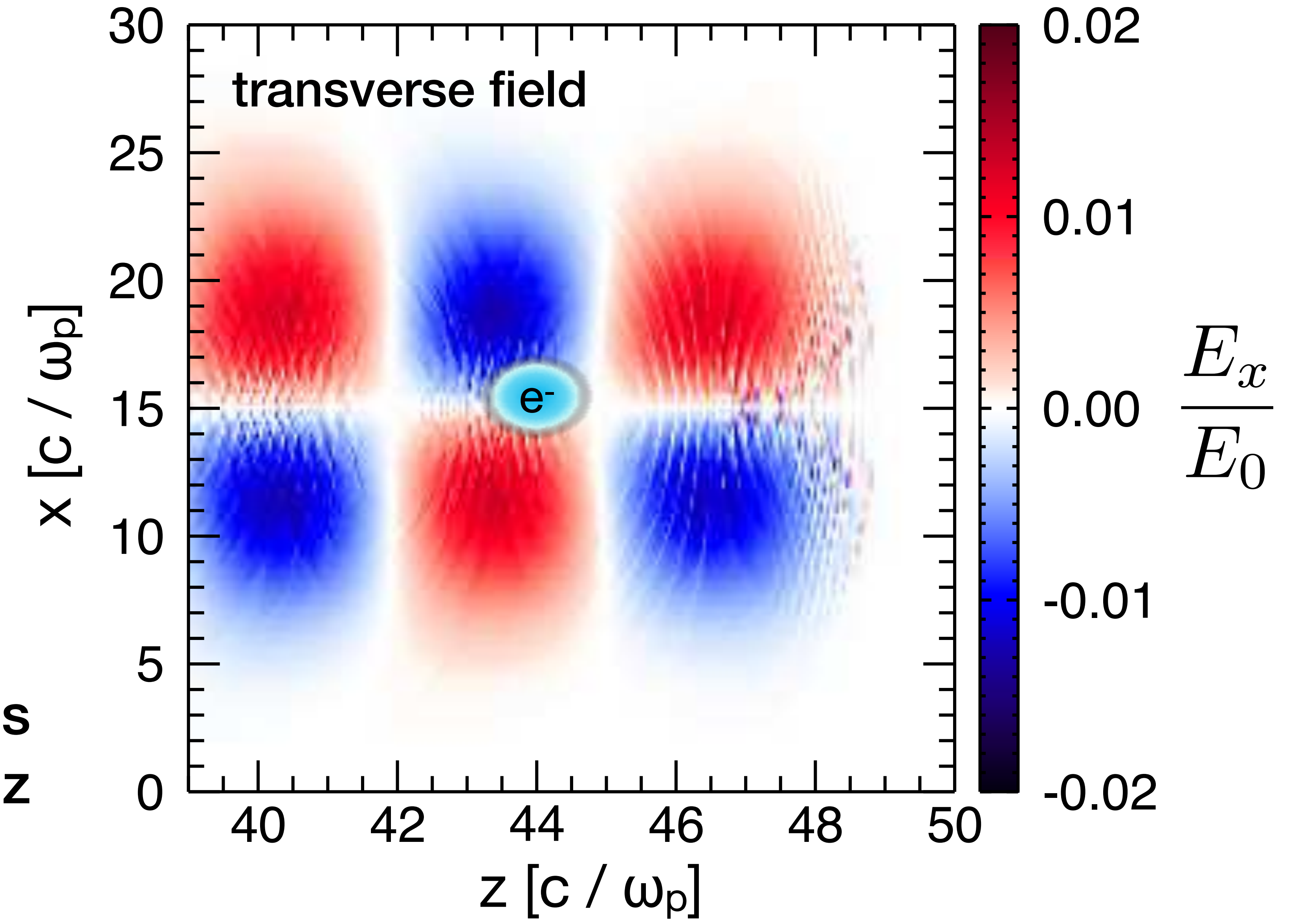
→ T. Mehrling *et al.*, NIM A **829**, 367 (2016)

# Plasma density control - beam capturing/matching

- Plasma density $n_e$ (x,t) governs acceleration process



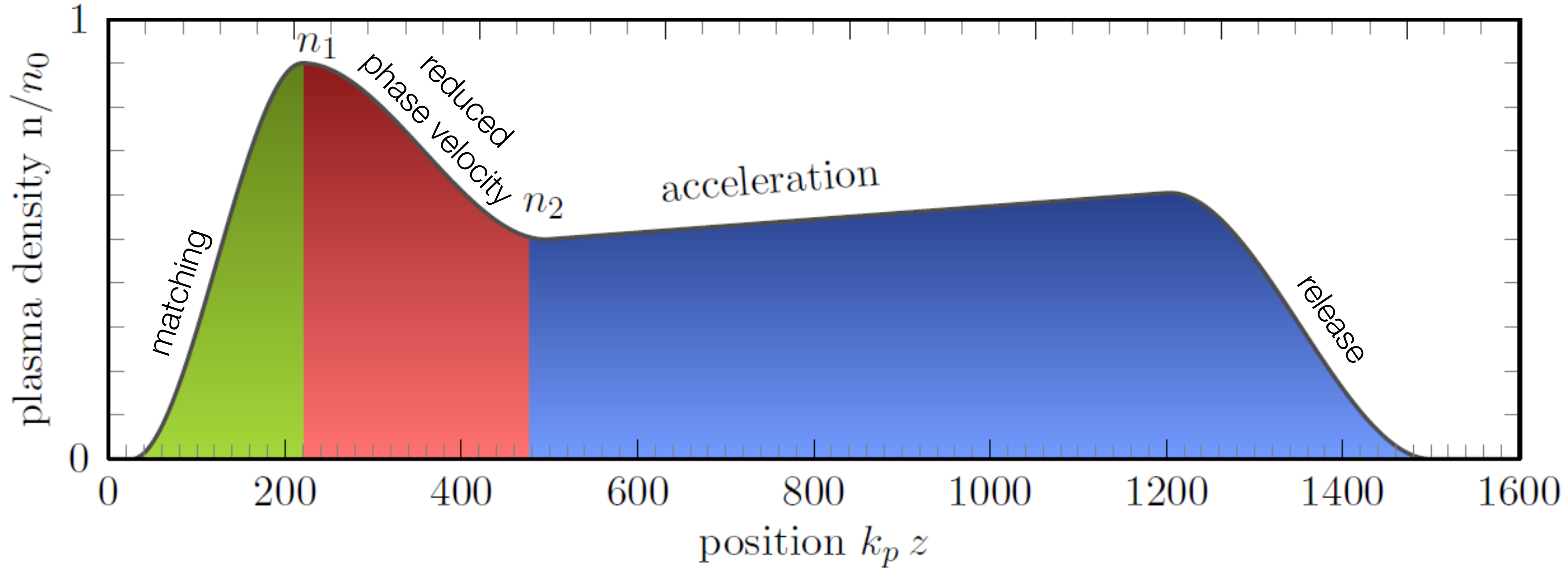
- External beams need to be matched to wakefield to preserve normalized emittance



Beam slice energy & focusing forces may vary in plasmas in z

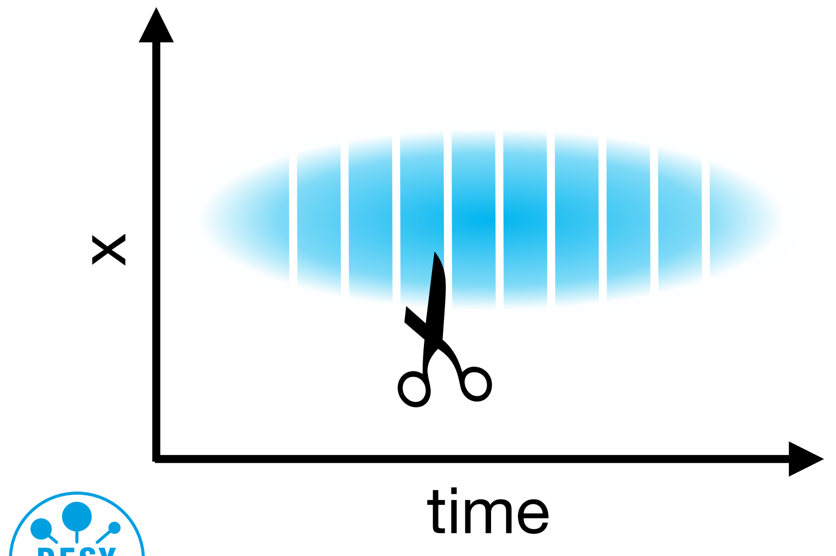
# Plasma density control - beam capturing/matching

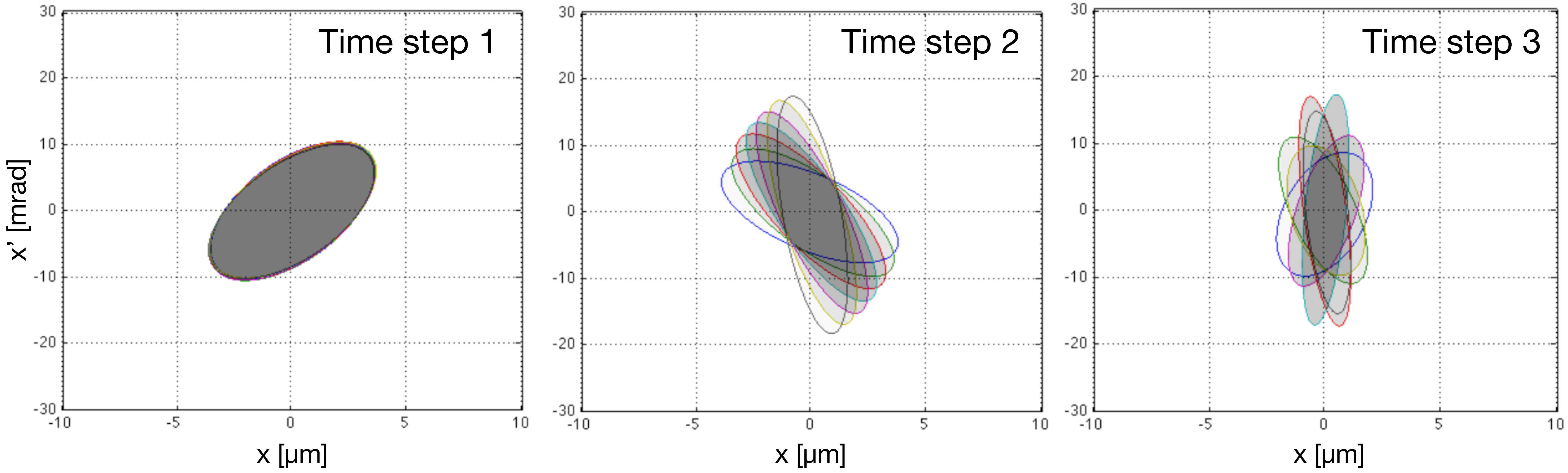
- Plasma density $n_e$ (x,t) governs acceleration process



- External beams need to be matched to wakefield to preserve normalized emittance

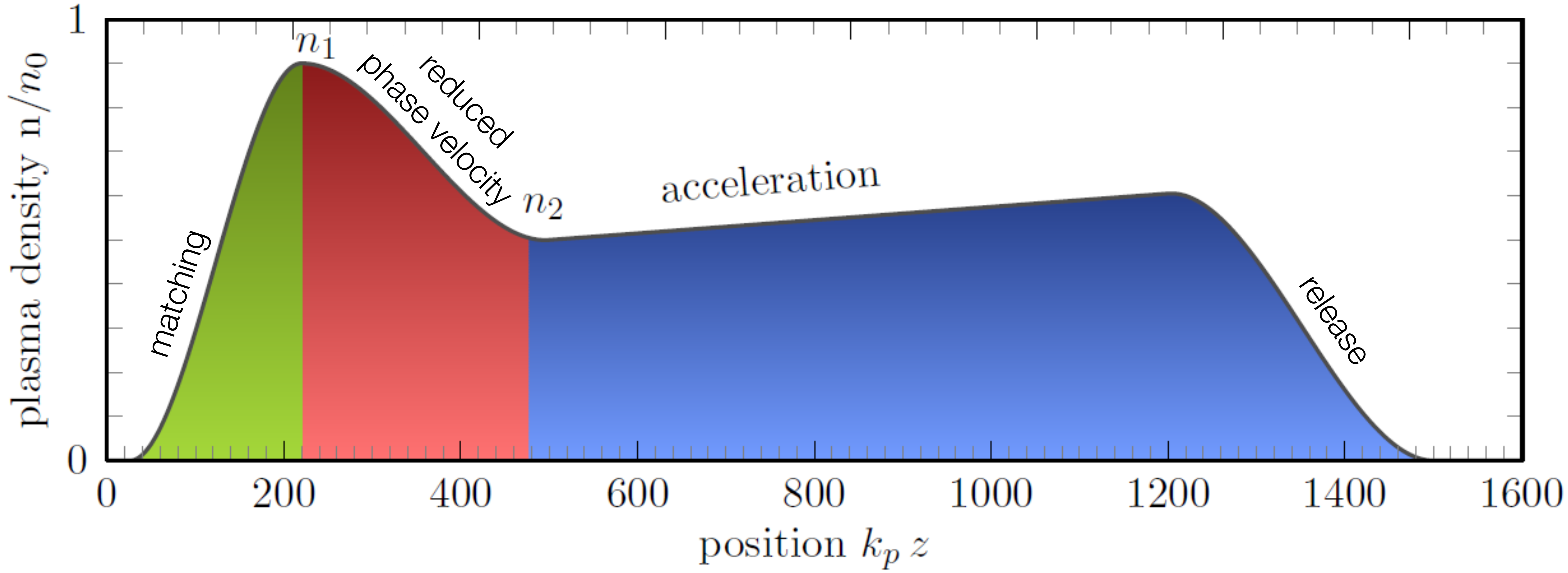
Slice rotation speeds vary along electron bunch





# Plasma density control - beam capturing/matching

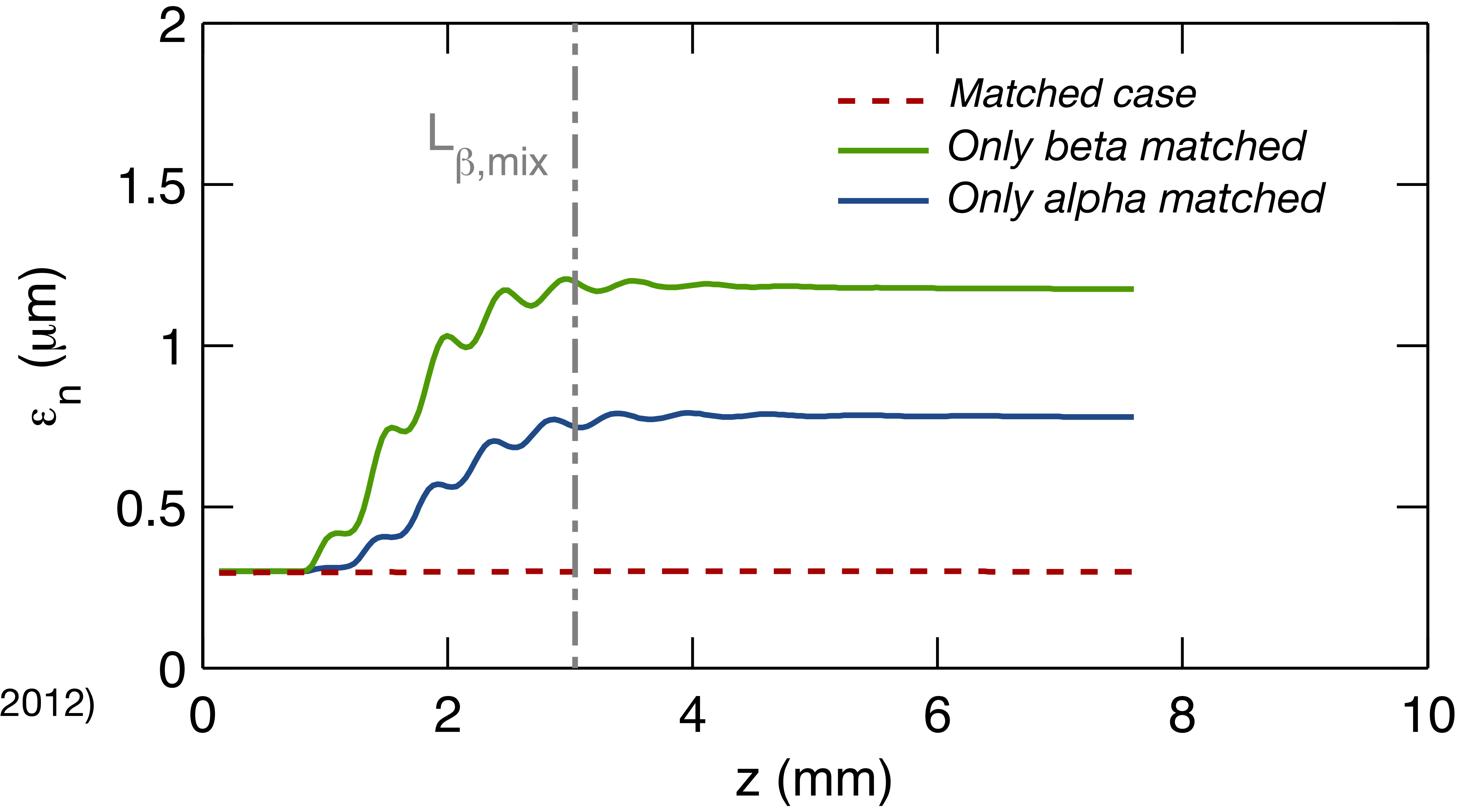
- Plasma density $n_e$ (x,t) governs acceleration process



- External beams need to be matched to wakefield to preserve normalized emittance
- Matching conditions

$$\alpha_{match} = 0 \qquad \beta_{match} \simeq \frac{c}{\omega_\beta}$$

- Matched β (~ mm) can be challenging to achieve
- If matching technically difficult, adiabatic up-ramp may help



→ T. Mehrling *et al.*, Phys. Rev. STAB **15**, 111303 (2012)

# Plasma density control - hosing seed mitigation

**Centroid equations**

Beam centroid equation

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 \left(X_b - X_c\right) = 0$$

**Channel centroid equation** assuming linear plasma sheath response*

$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2}{2} \left(X_c - X_b\right) = 0$$

**Channel centroid equation** including relativistic sheath electrons and varying current and blowout radius along beam**

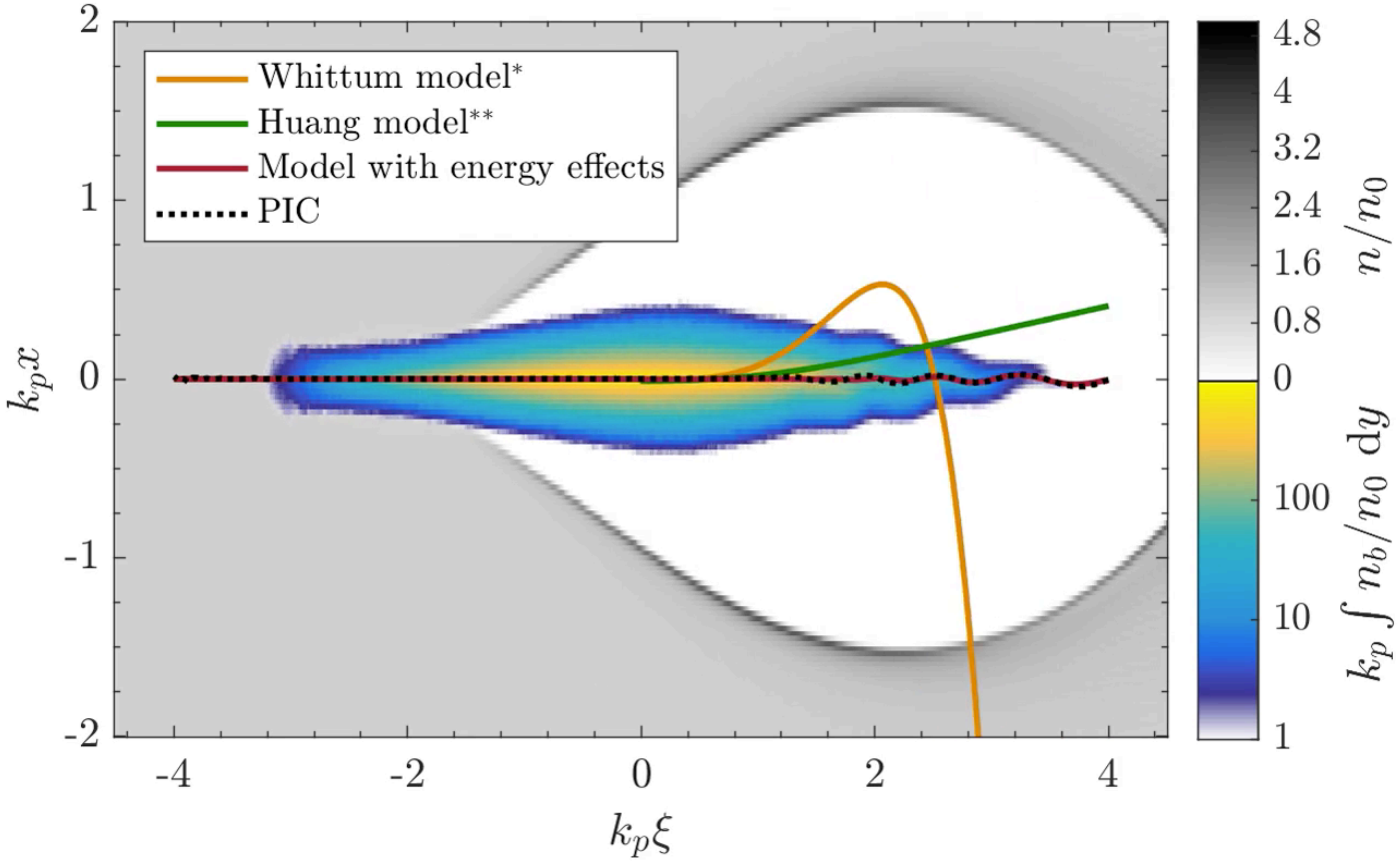
$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2 c_\psi(\xi) c_r(\xi)}{2} \left(X_c - X_b\right) = 0$$

$$\begin{aligned} c_r(\xi) &= 4I_b(\xi)/I_A(k_pR(\xi))^2 \\ c_\psi(\xi) &= 1/(1+\psi(\xi)) \end{aligned}$$

**Dramatic implications for PWFA**

Beam centroid deviations are amplified exponentially in time and along the beam!

*D. H. Whittum, *et al.* Phys. Rev. Lett. **67**, 991 (1991).
**C. Huang, *et al.* Phys. Rev. Lett. **99**, 255001 (2007).



# Plasma density control - hosing seed mitigation

## Centroid equations

Beam centroid equation

$$\frac{\partial^2 X_b}{\partial t^2} + \omega_\beta^2 \left(X_b - X_c\right) = 0$$

**Channel centroid equation** assuming linear plasma sheath response*

$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2}{2} \left(X_c - X_b\right) = 0$$

**Channel centroid equation** including relativistic sheath electrons and varying current and blowout radius along beam**

$$\frac{\partial^2 X_c}{\partial \xi^2} + \frac{k_p^2 c_\psi(\xi) c_r(\xi)}{2} \left(X_c - X_b\right) = 0$$

$$\begin{aligned} c_r(\xi) &= 4I_b(\xi)/I_A(k_p R(\xi))^2 \\ c_\psi(\xi) &= 1/(1+\psi(\xi)) \end{aligned}$$

## Beam centroid equation ***

$$\frac{\partial^2 X_b}{\partial t^2} + \frac{\overline{\omega_\beta}^2}{\overline{\omega_{\beta,0}}} \left(\epsilon + \kappa_1 \Delta\gamma^2\right) \frac{\partial X_b}{\partial t} + \overline{\omega_\beta}^2 (1 + \kappa_2 \Delta\gamma^2)(X_b - X_c) = 0$$

Uncorr. energy spread: $\Delta\gamma = \sigma_\gamma/\overline{\gamma_0}$

Rel. acceleration rate: $\epsilon = -\sqrt{2/\overline{\gamma_0}}\, E_z/E_0$

Coefficients:

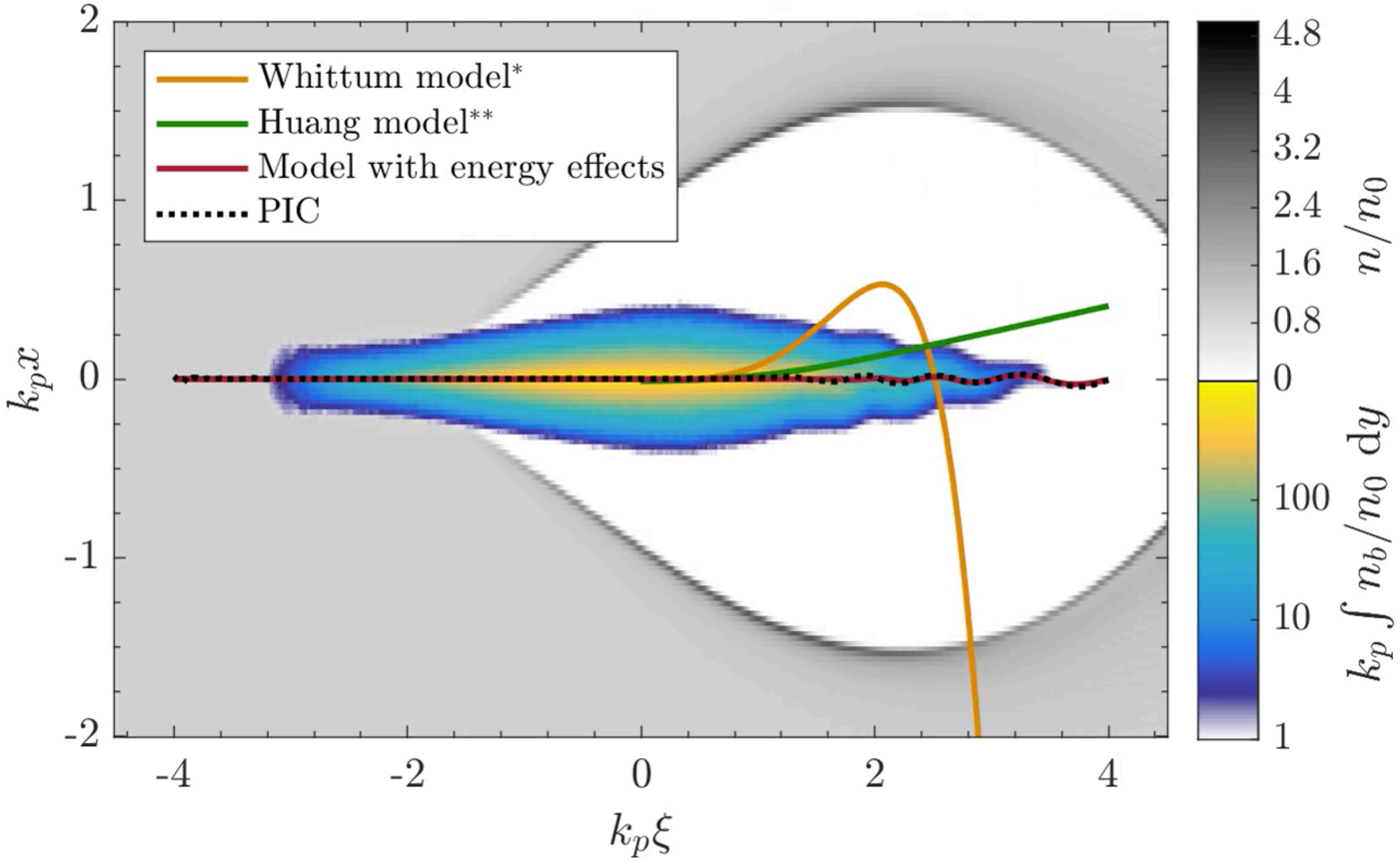
$$\begin{aligned} \kappa_1 &= (\overline{\omega_\beta}/\overline{\omega_{\beta,0}} - (\overline{\omega_\beta}/\overline{\omega_{\beta,0}})^2)/\epsilon \\ \kappa_2 &= (\overline{\omega_\beta}/\overline{\omega_{\beta,0}})^4/2 - (\overline{\omega_\beta}/\overline{\omega_{\beta,0}})^3/4 \end{aligned}$$

Includes the effects of the energy spread and evolution

*** T. J. Mehrling et al., PRL 118, 174801 (2017)

## Dramatic implications for PWFA

Beam centroid deviations are amplified exponentially in time and along the beam!



*D. H. Whittum, *et al.* Phys. Rev. Lett. **67**, 991 (1991).
**C. Huang, *et al.* Phys. Rev. Lett. **99**, 255001 (2007).

# Plasma density control - hosing seed mitigation

**Excellent agreement between analytical estimates, numerical solution and PIC***

Considered beam:

Init. centroid: $k_p X_{b,0}(\xi) = 0.01 \times \Theta(\xi)$

Peak current: $I_b \;=\; I_A/4$

Dimensions: $k_p\sigma_x \;=\; k_p\sigma_y \;=\; 0.1,\ k_p\sigma_z = 1.0$

Considered cases

C1: No energy change

C2: Energy change

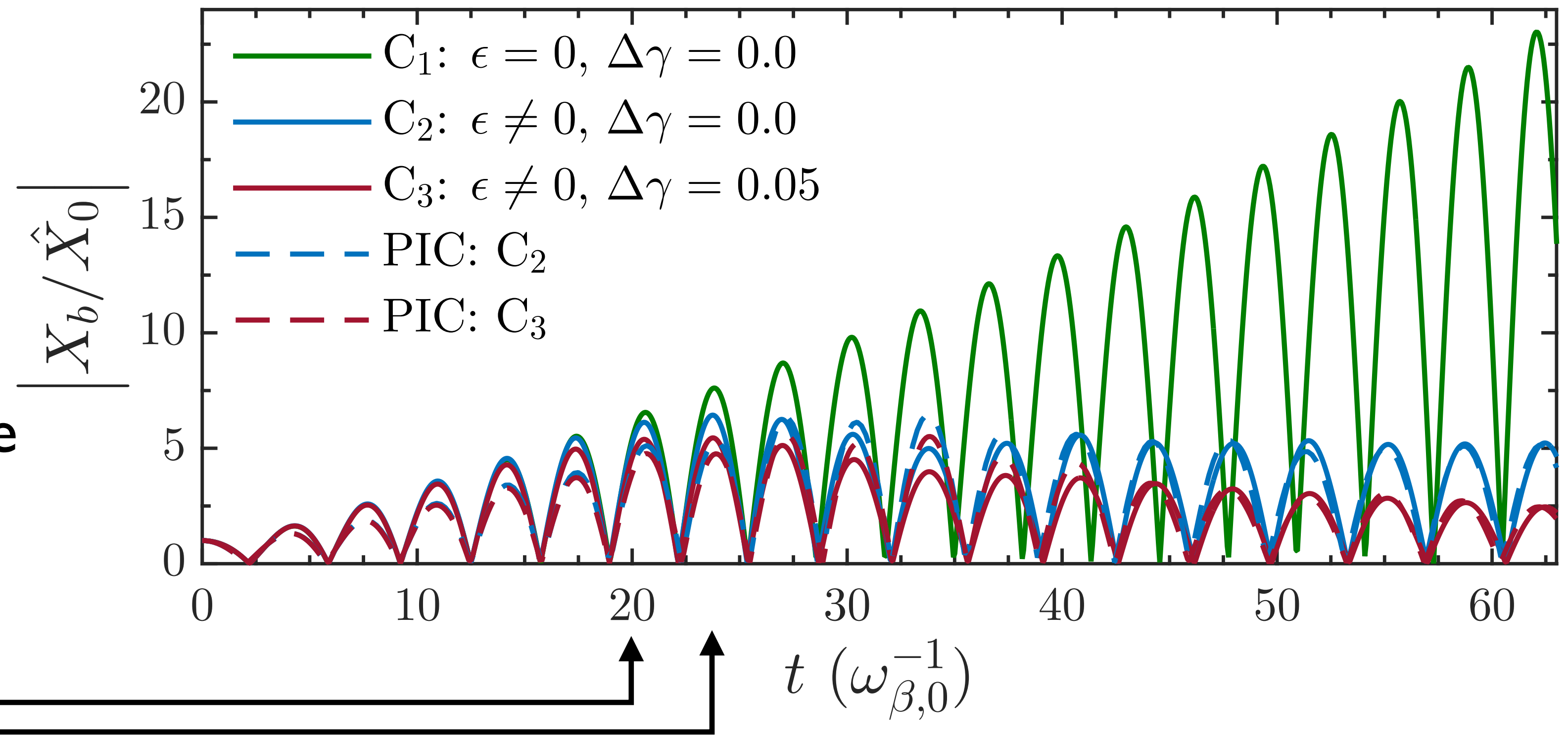
C3: Energy change & spread

decoupling time

$$\overline{\omega_{\beta,0}}^{-1}\sqrt{\frac{3\pi}{\Delta\epsilon}}$$

damping time

$$\frac{\overline{\gamma_0}}{\overline{\omega_{\beta,0}}\,\sigma_\gamma}$$



*** T. J. Mehrling et al., PRL 118, 174801 (2017)**

# Plasma density control - hosing seed mitigation

## Excellent agreement between analytical estimates, numerical solution and PIC*

Considered beam:

Init. centroid: $k_p X_{b,0}(\xi) = 0.01 \times \Theta(\xi)$

Peak current: $I_b = I_A/4$

Dimensions: $k_p\sigma_x = k_p\sigma_y = 0.1,\ k_p\sigma_z = 1.0$

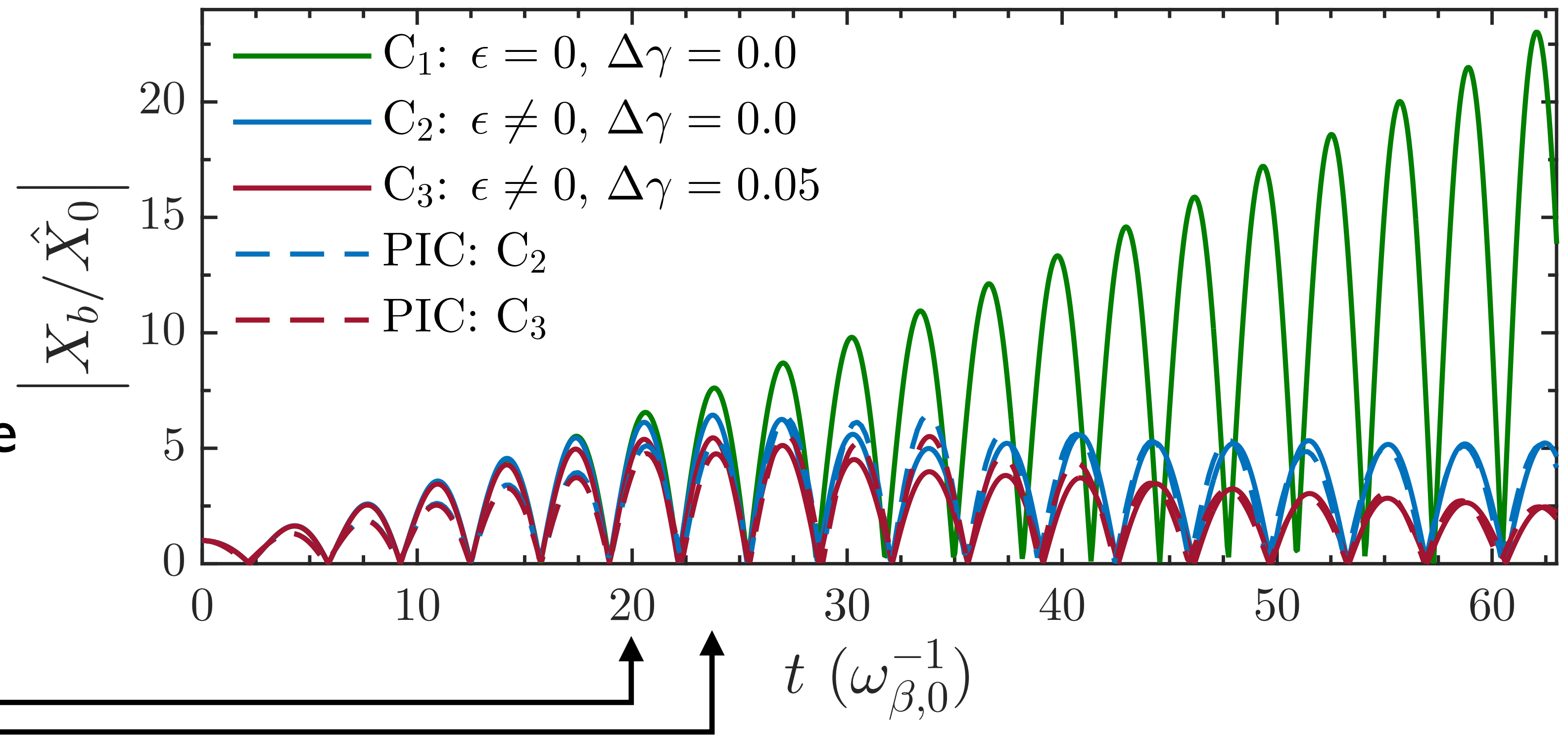
Considered cases
- C1: No energy change
- C2: Energy change
- C3: Energy change & spread

decoupling time

$$\omega_{\beta,0}^{-1}\sqrt{\frac{3\pi}{\Delta\epsilon}}$$

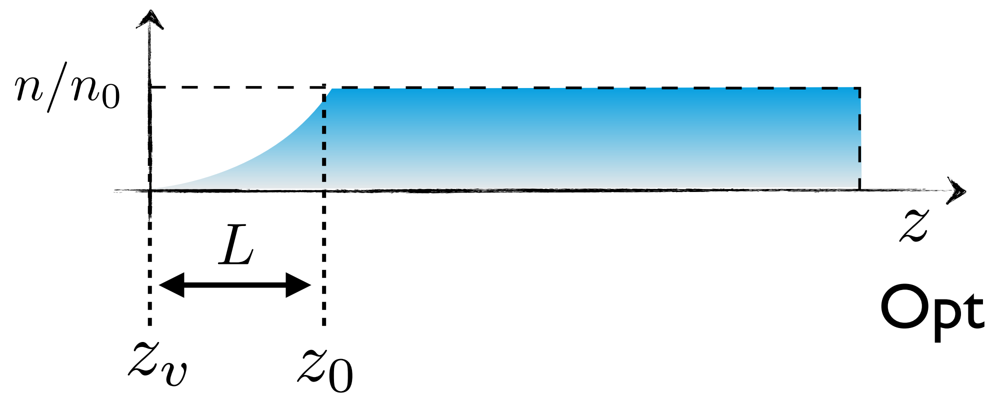
damping time

$$\frac{\gamma_0}{\omega_{\beta,0}\,\sigma_\gamma}$$



* T. J. Mehrling et al., PRL 118, 174801 (2017)

## Tailored density transition for hosing mitigation

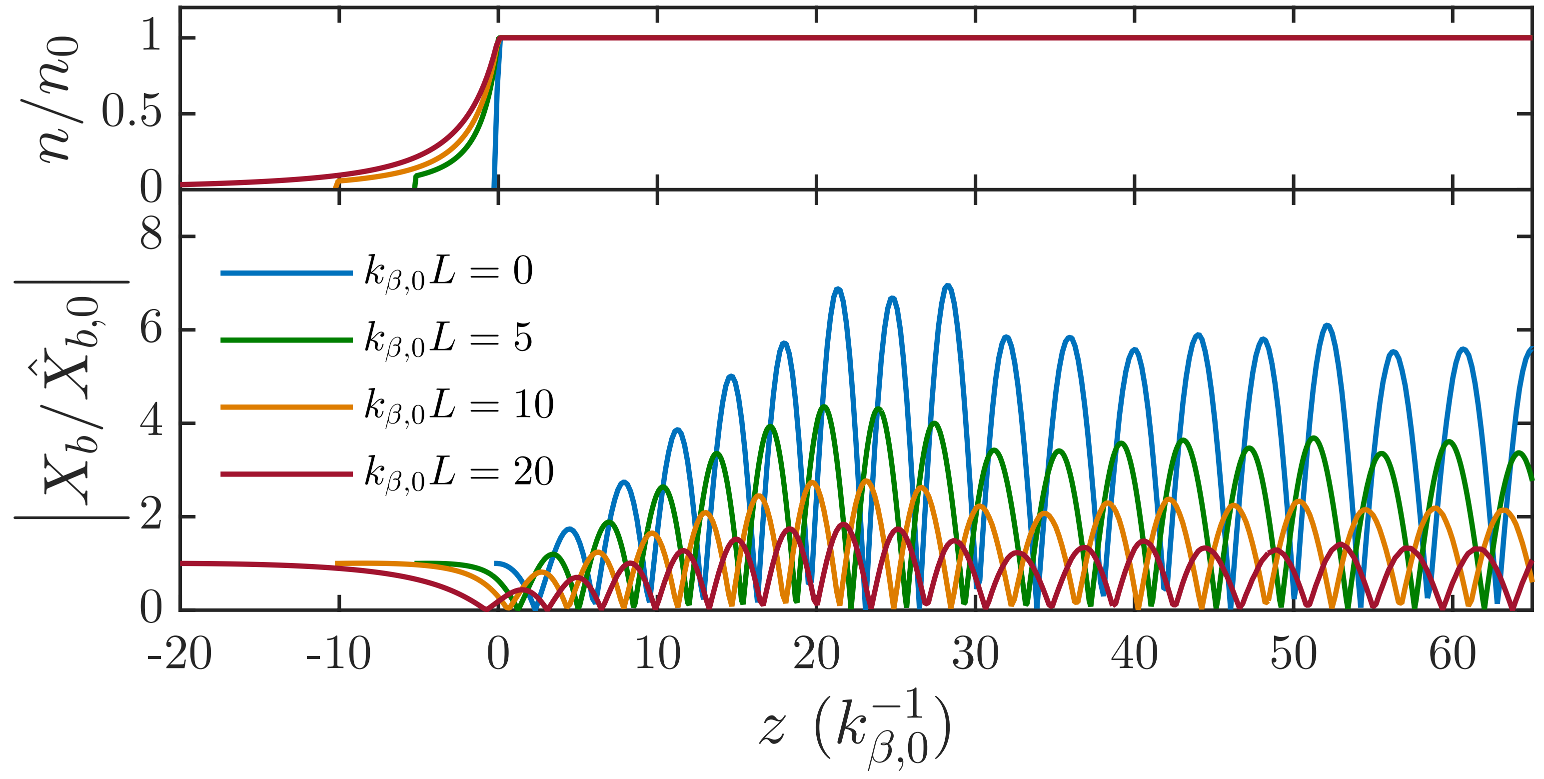


Optimum taper parameter

$$\lambda_{\text{opt}} \simeq L/\sqrt{k_{\beta,0}L}$$

$$n(z) = \begin{cases} 0 & \text{if } z \leq z_v, \\ n_0(1-(z-z0)/\lambda)^{-4} & \text{if } z_v < z \leq z_0, \\ n_0 & \text{if } z > z_0 \end{cases}$$

Betatron wavenumber: $k_\beta = k_{\beta,0}\sqrt{\frac{n}{n_0}}$



Significant mitigation of hose instability!*

# Plasma density control - laser waveguide

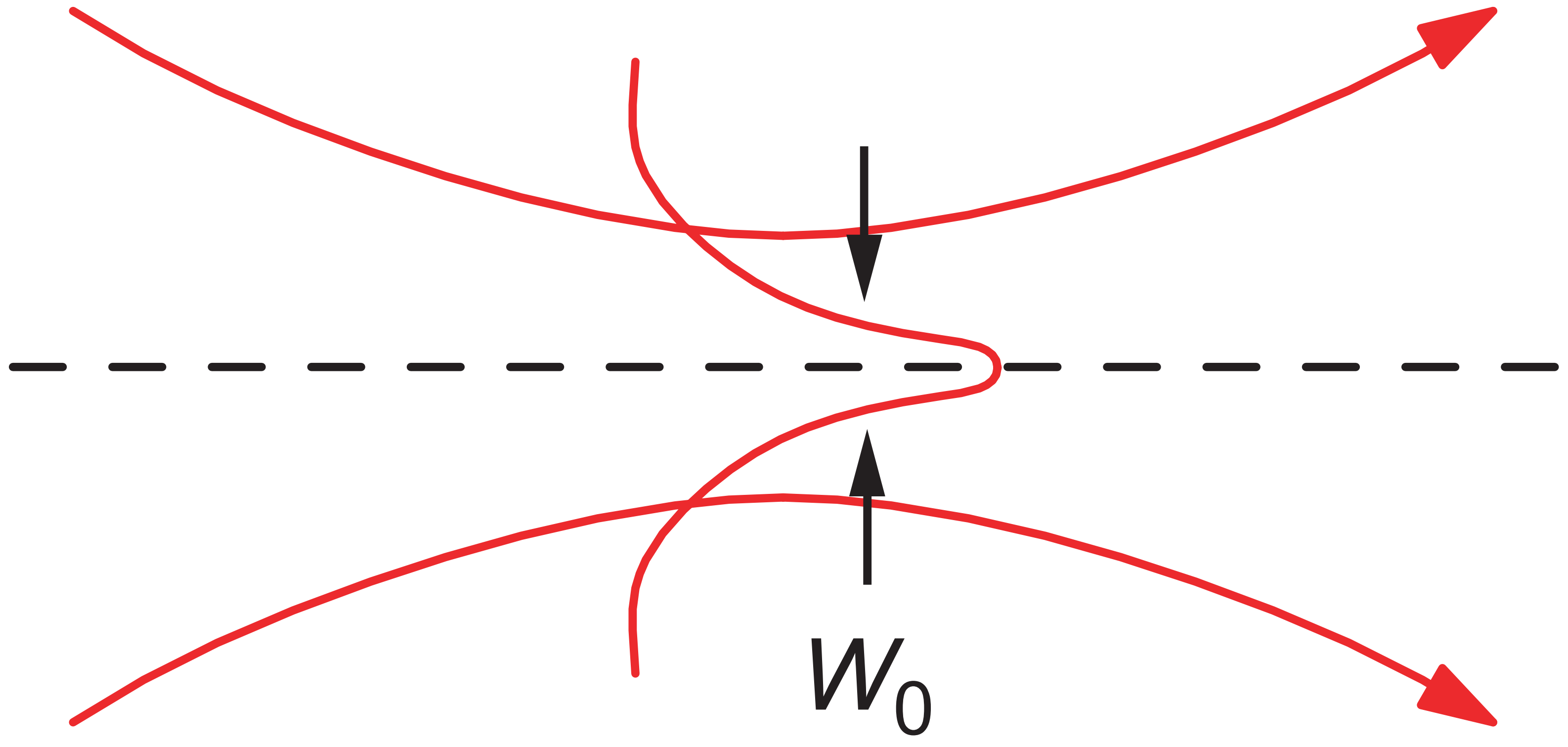
- **Linear scalings for LWFAs**
  - Accelerating field $E_z \propto \omega_p \propto \sqrt{n_e}$
  - Dephasing length $L_d \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$
  - Energy gain $\Delta W = E_z L_d \propto \frac{1}{n_e}$

- Simple scaling (in linear regime) shows, factor 10 increase in energy requires:
  - Factor 10 decrease in electron density: $10^{19}$ cm$^{-3}$ → $10^{18}$ cm$^{-3}$ → $10^{17}$ cm$^{-3}$
  - Factor 30 increase in length: 1 - 2 mm → 30 - 60 mm → 900 - 1800 mm

# Plasma density control - laser waveguide

> **Linear scalings for LWFAs**

- Accelerating field $E_z \propto \omega_p \propto \sqrt{n_e}$
- Dephasing length $L_d \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$
- Energy gain $\Delta W = E_z L_d \propto \frac{1}{n_e}$



$$Z_R = \frac{\pi w_0^2}{\lambda}$$

> Simple scaling (in linear regime) shows, factor 10 increase in energy requires:

- Factor 10 decrease in electron density: $10^{19}$ cm$^{-3}$ → $10^{18}$ cm$^{-3}$ → $10^{17}$ cm$^{-3}$
- Factor 30 increase in length: 1 - 2 mm → 30 - 60 mm → 900 - 1800 mm

> The laser intensity must be maintained over the acceleration length

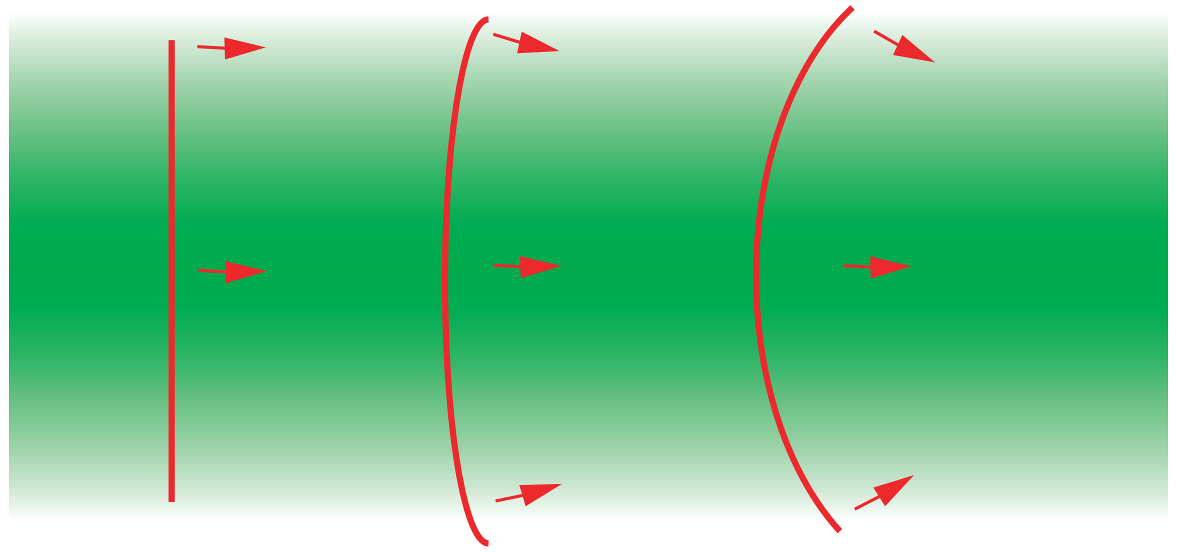
- limited by laser diffraction
- Rayleigh range typically only millimeters

Example :

$$w_0 = 10\,\mu\text{m};\ \lambda = 1\,\mu\text{m}$$
$$\Rightarrow Z_R = 0.3\,\text{mm}$$

# Plasma density control - laser waveguide

- Transverse index of refraction gradient may guide lasers

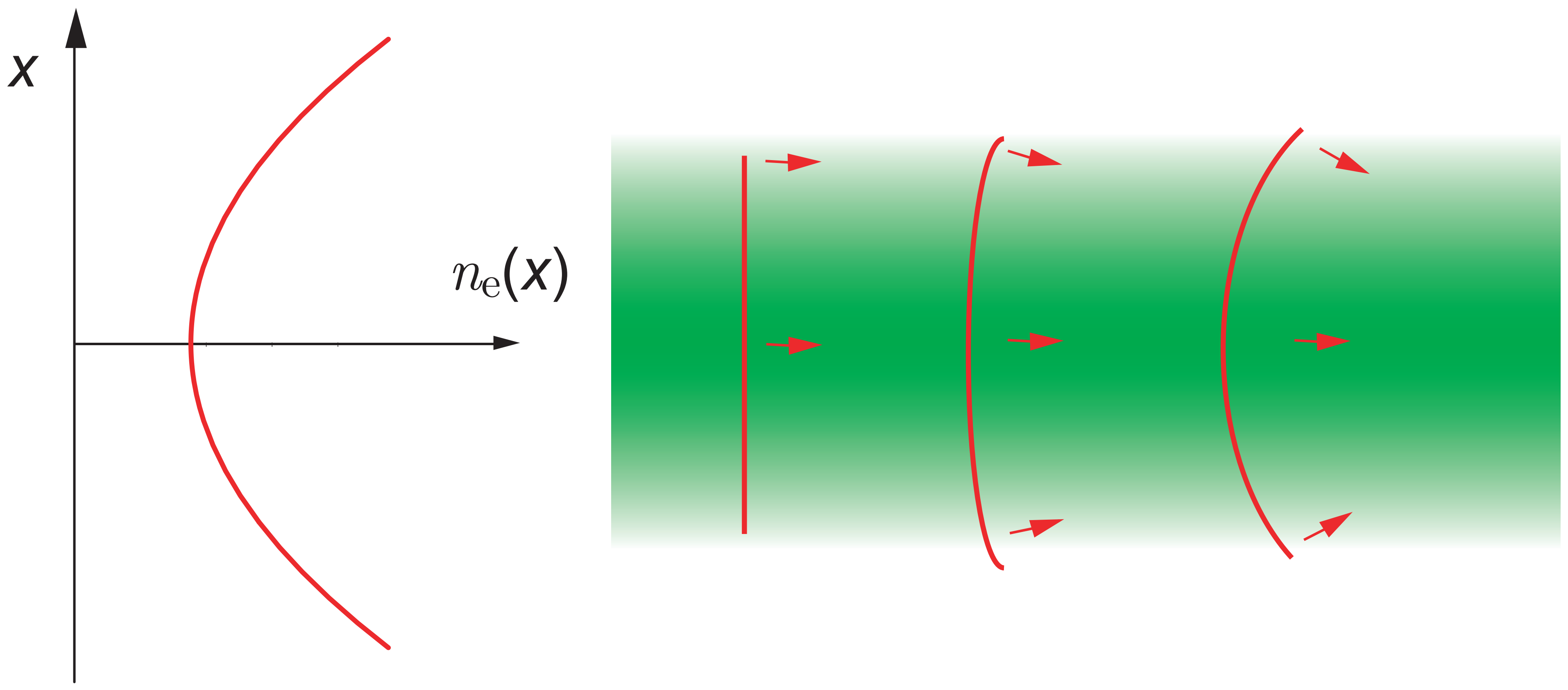


# Plasma density control - laser waveguide

- **Transverse index of refraction gradient may guide lasers**
- **Plasma channel:** transverse variation of electron density gives correct refractive index profile
  - Transverse plasma density gradient gives transverse index of refraction gradient

$$\eta = \sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

  - Changes laser phase velocity $v_\phi = c/\eta$



- Parabolic channel will match Gaussian beam of spot size $W_M = \left(\frac{r_{ch}^2}{\pi r_e \Delta n_e}\right)^{1/4}$

$$n_e(r) = n_e(0) + \Delta n_e\,(r/r_{ch})^2$$

- Shape of channel is not very important: matched spot size mainly determined by channel depth
  - cf. Durfee *et al.*, Opt. Lett. **19,** 1937 (1994)

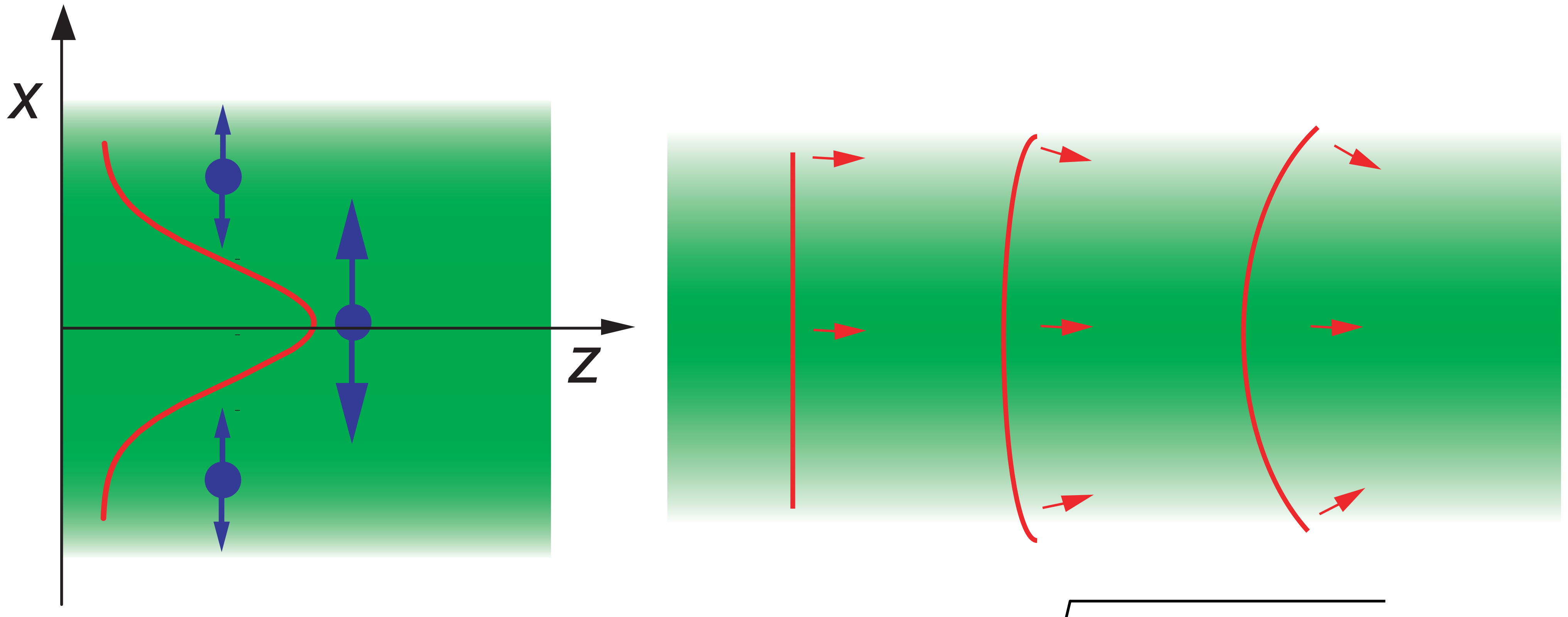
# Plasma density control - laser waveguide

- **Relativistic self-focusing:** transverse variation of intensity gives correct refractive index profile
  - Leads to self-focusing/guiding above a critical power

$$P_c = 17.4 \left(\frac{\omega}{\omega_p}\right)^2 \ \mathrm{GW}$$

Example

$$n_e = 10^{18}\,\mathrm{cm}^{-3}, \lambda = 800\,\mathrm{nm}$$
$$P_c = 8\,\mathrm{TW}$$



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$
$$\approx 1 - \frac{1}{2}\frac{n_e e^2}{\gamma(r) m_e \epsilon_0 \omega^2}$$

# Plasma density control - laser waveguide

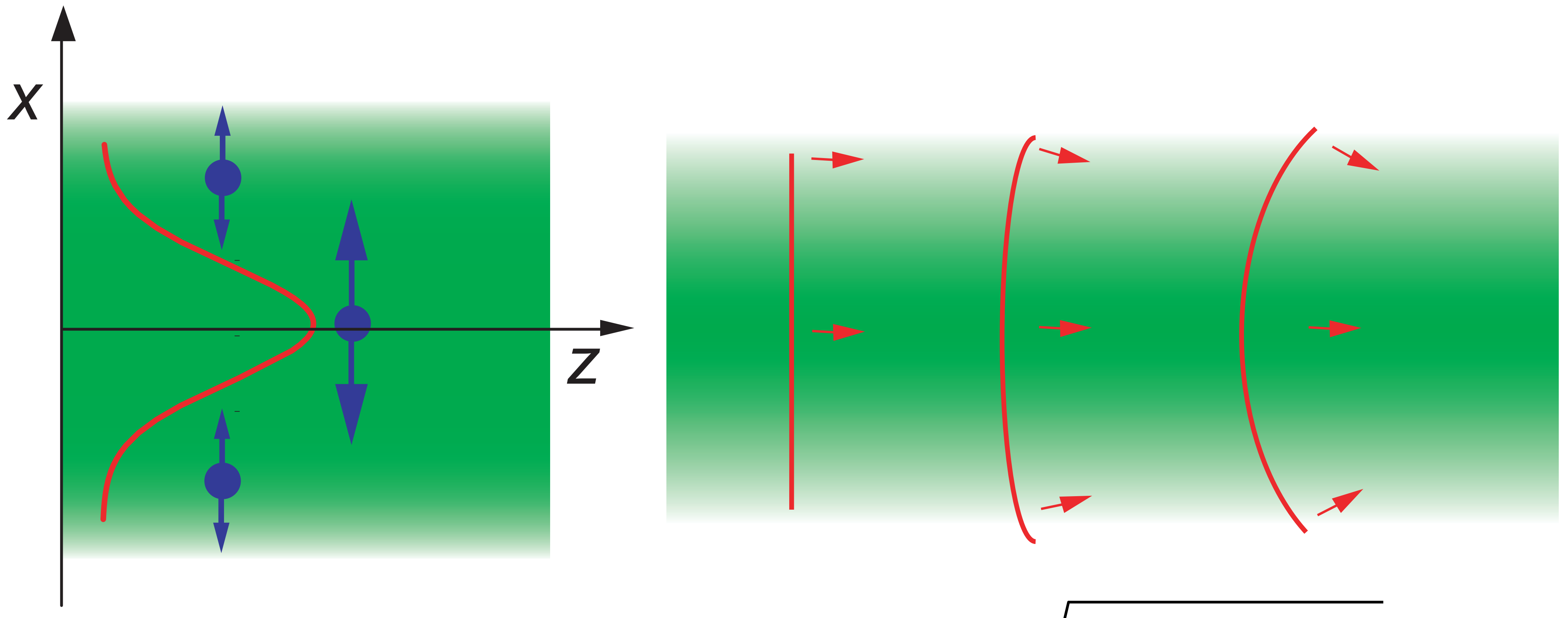
- **Relativistic self-focusing:** transverse variation of intensity gives correct refractive index profile
  - Leads to self-focusing/guiding above a critical power

$$P_c = 17.4 \left(\frac{\omega}{\omega_p}\right)^2 \ \mathrm{GW}$$

Example

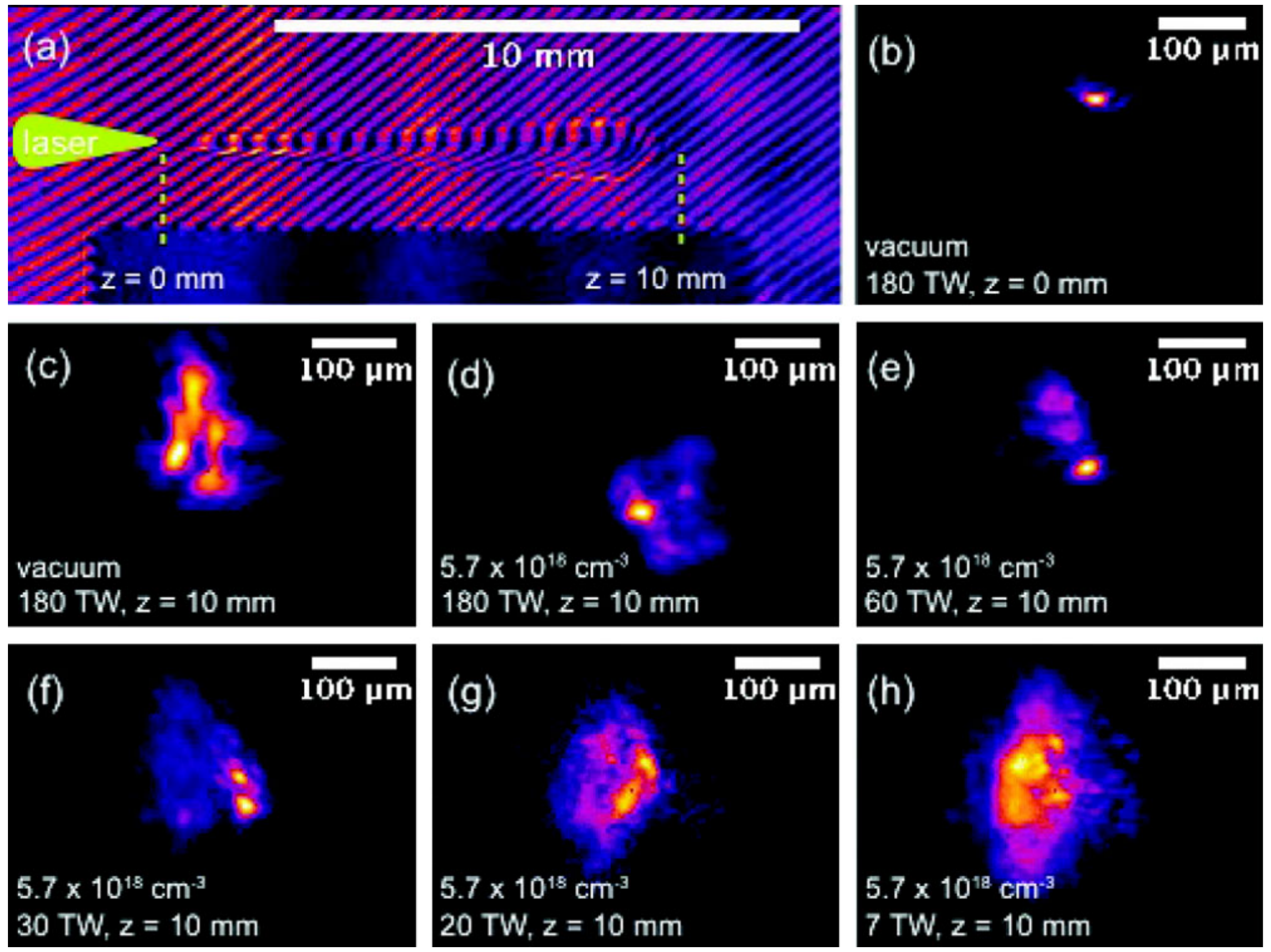
$$n_e = 10^{18}\,\mathrm{cm}^{-3}, \lambda = 800\,\mathrm{nm}$$

$$P_c = 8\,\mathrm{TW}$$



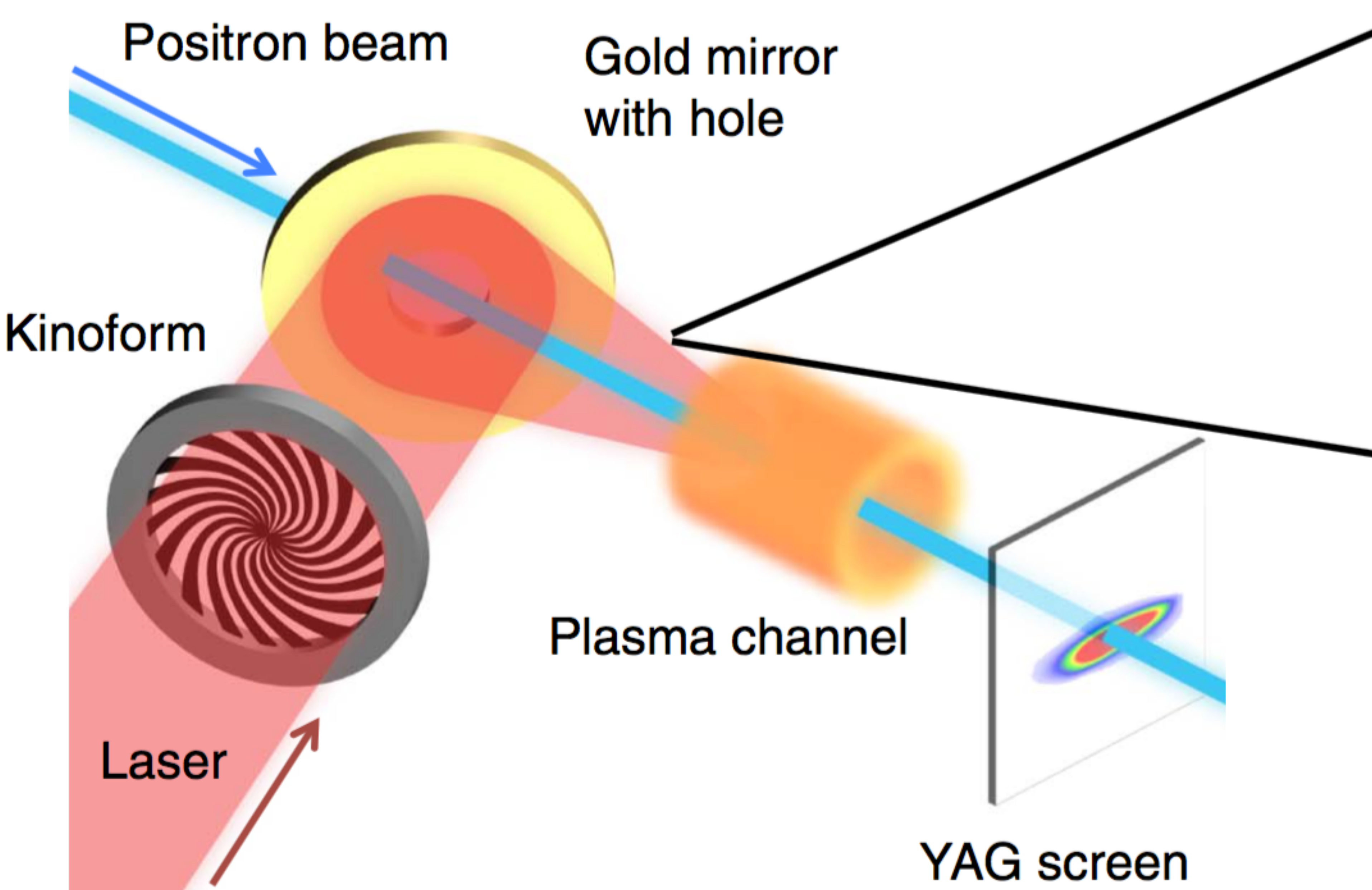
$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$

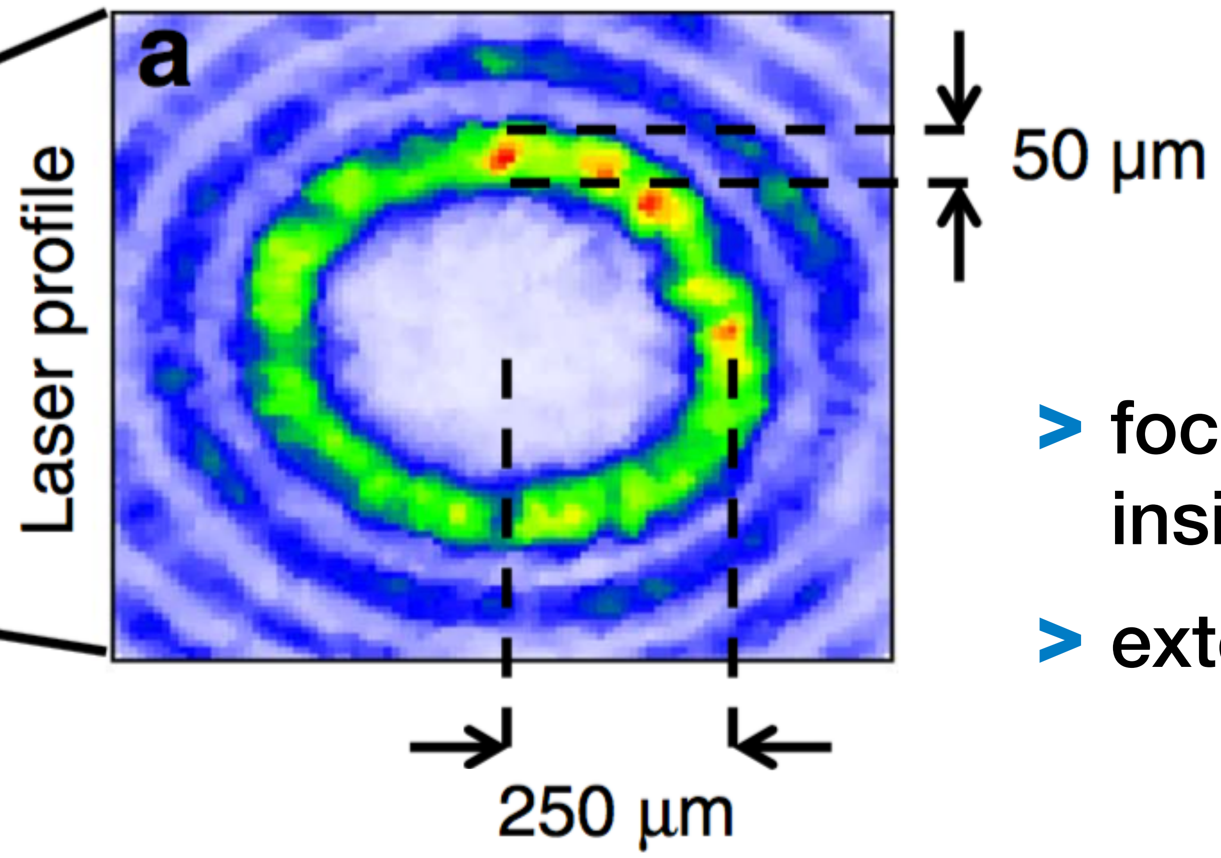
$$\approx 1 - \frac{1}{2}\frac{n_e e^2}{\gamma(r) m_e \epsilon_0 \omega^2}$$



S. Kneip *et al.*,
Phys. Rev. Lett. **103** 035002 (2009)

# Plasma density control - hollow core channels

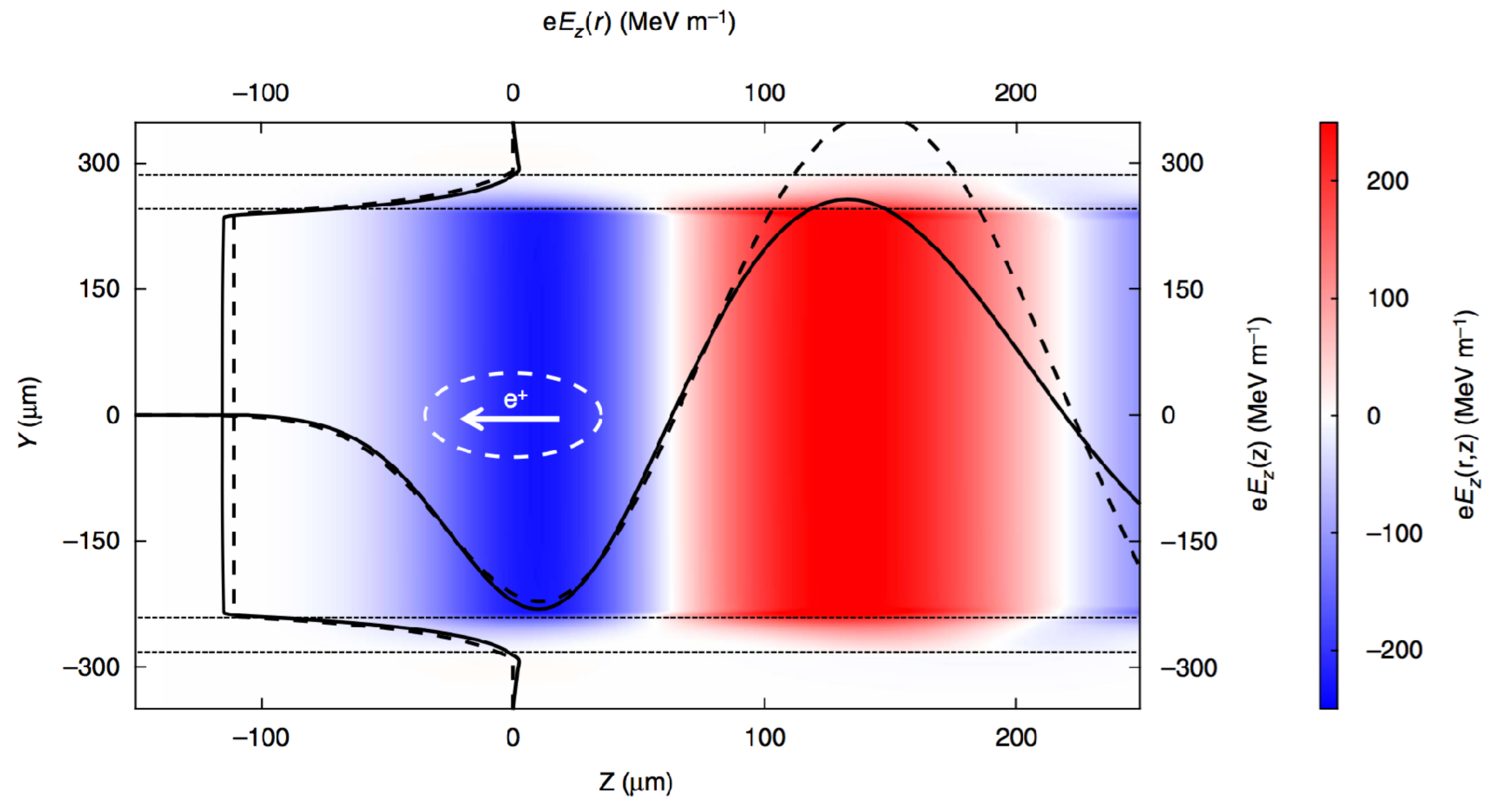




from S. Gessner *et al.*, Nat. Commun. 2016

- focussing fields are zero inside the channel
- external focussing elements required

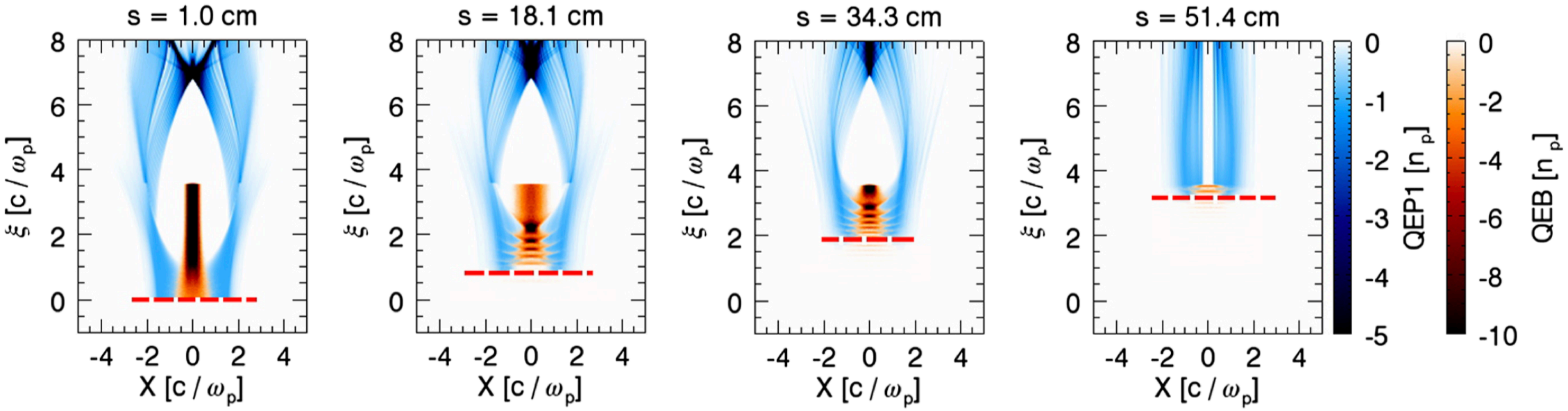
- decoupling of longitudinal and transverse forces
- interesting for positron acceleration



# Plasma density control - head erosion mitigation

- Front of drive beam
  not in focussing channel
  → front is diverging
- Beam erodes from the front
  "head erosion"
- Etching speed scales with

$$\epsilon_N/\gamma N^{1.5}$$



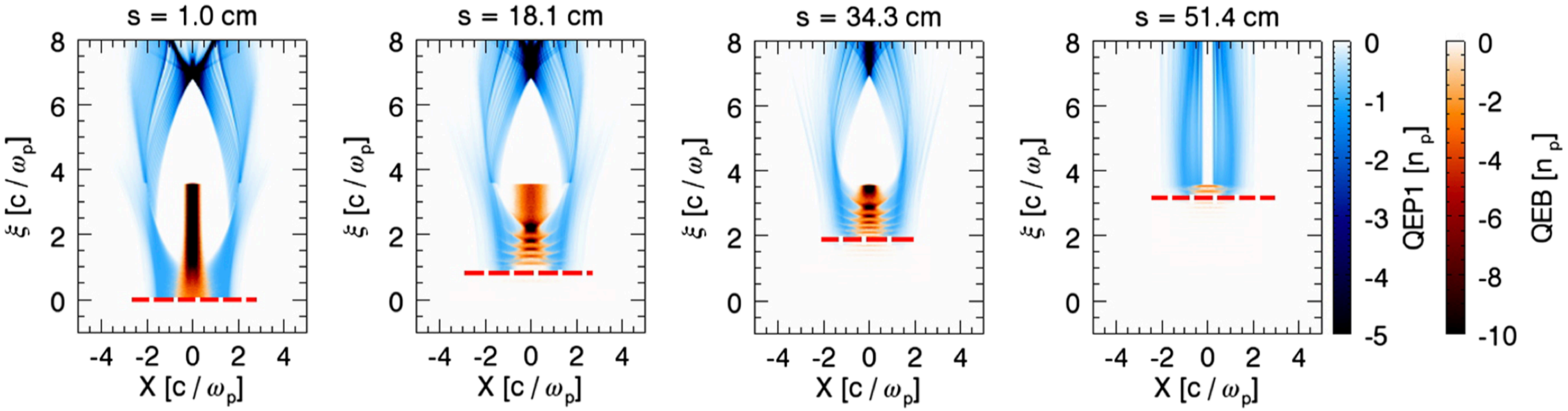
from An *et al.*, Phys. Rev. STAB 16, 101301 (2013)

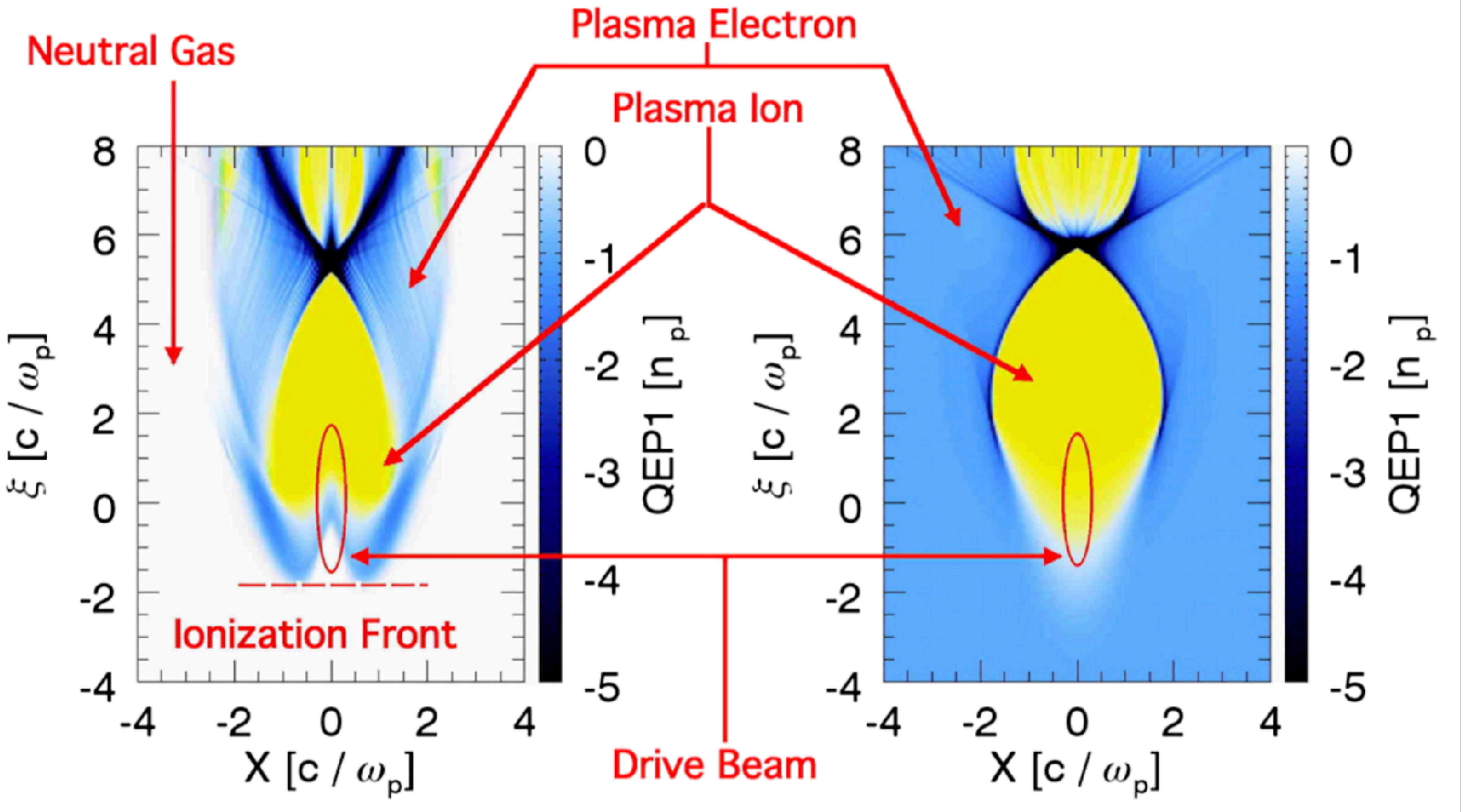
# Plasma density control - head erosion mitigation

- Front of drive beam not in focussing channel → front is diverging
- Beam erodes from the front "head erosion"
- Etching speed scales with

$$\epsilon_N/\gamma N^{1.5}$$

- Laser preionization provides focussing plasma for front of beam





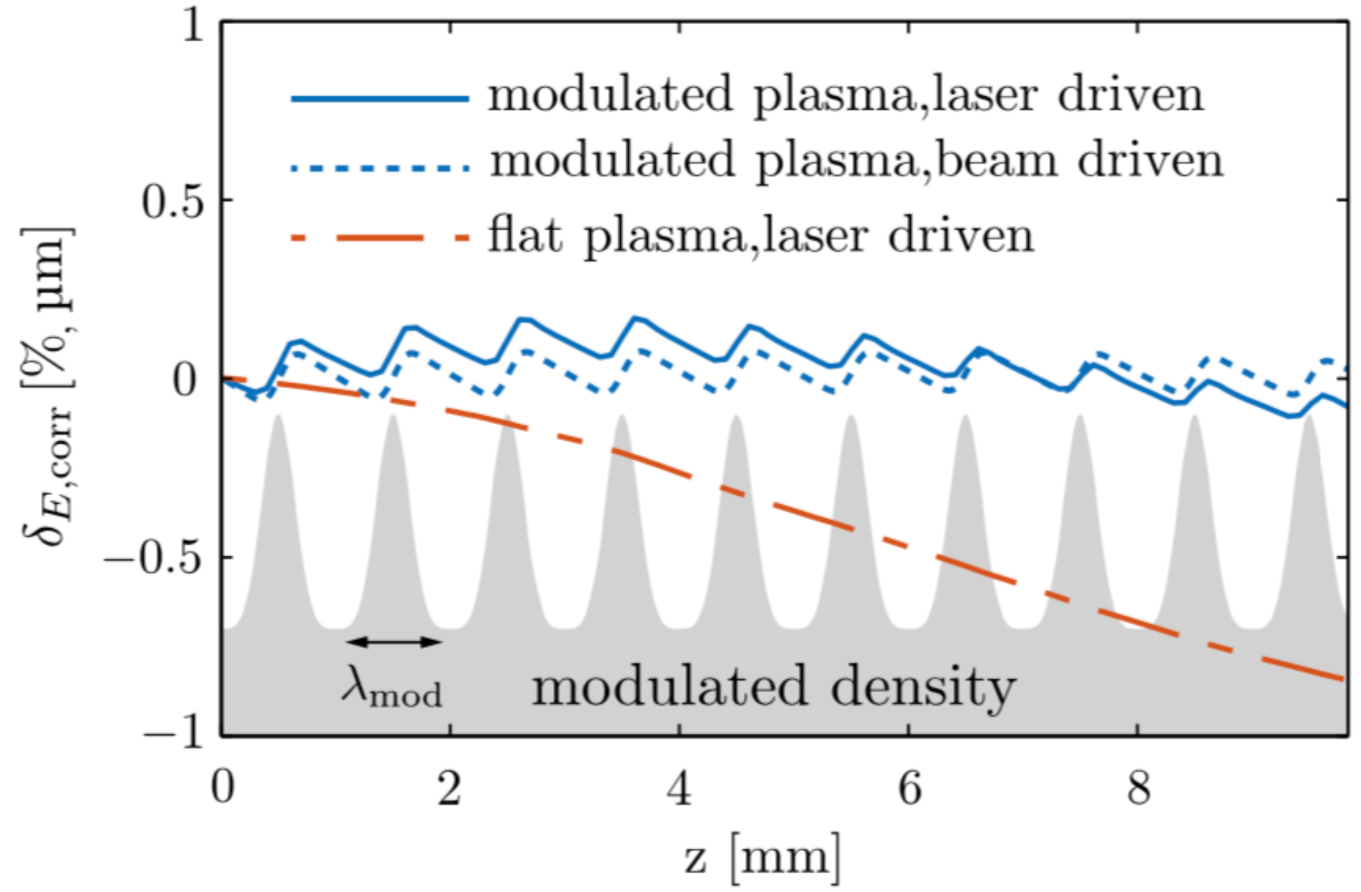
(a) Field-Ionized

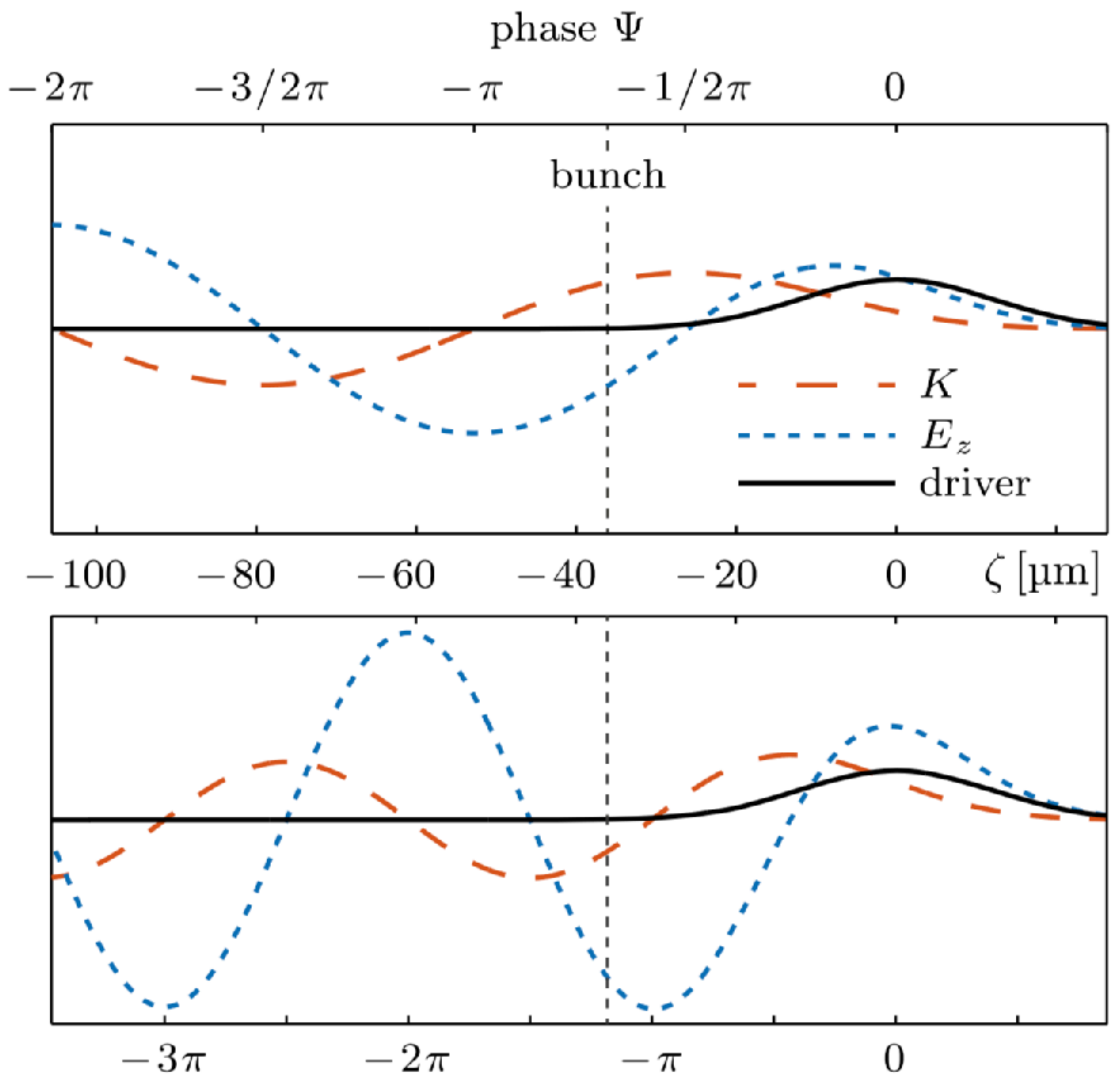
(b) Pre-Ionized

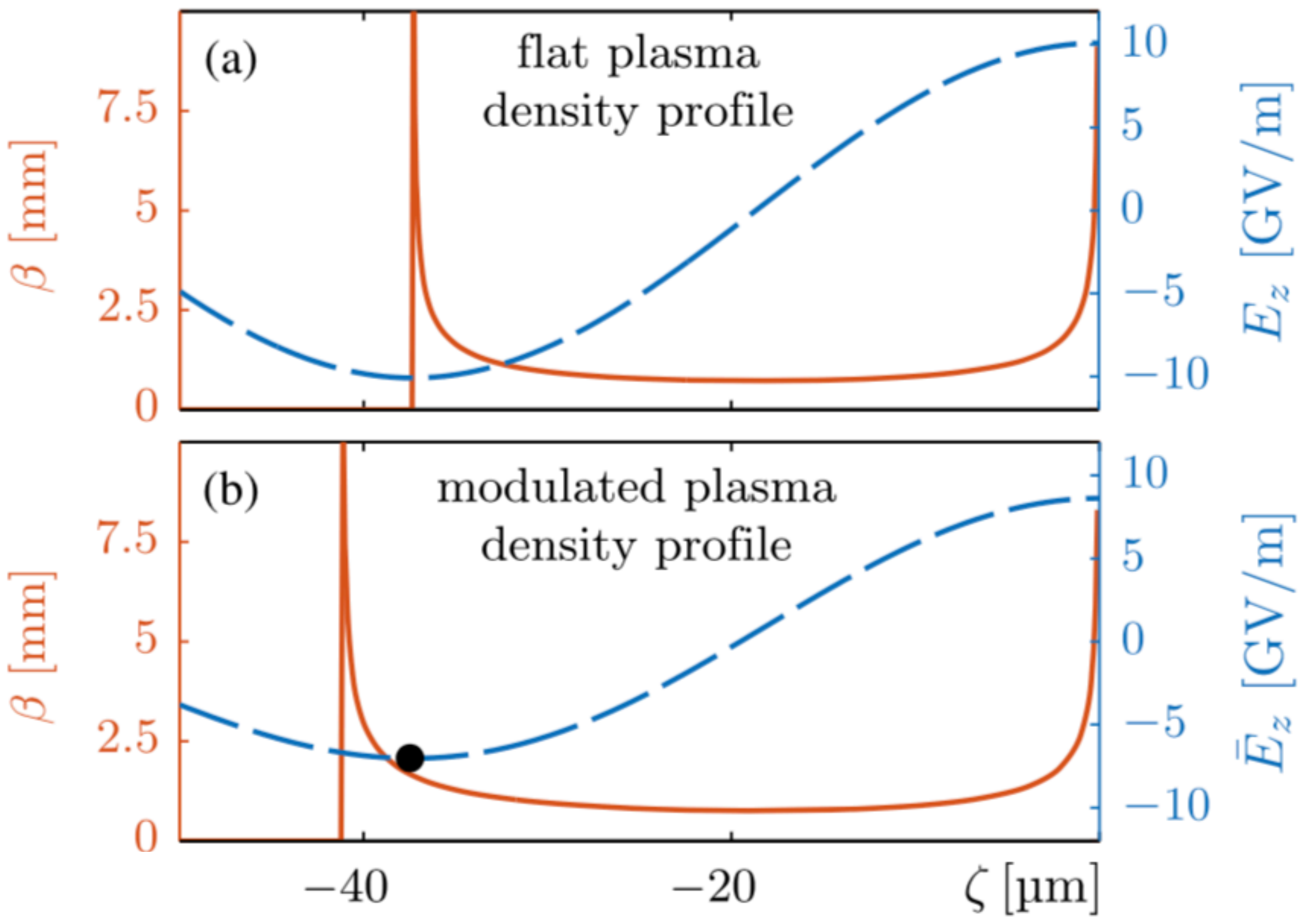
from An *et al.*, Phys. Rev. STAB 16, 101301 (2013)

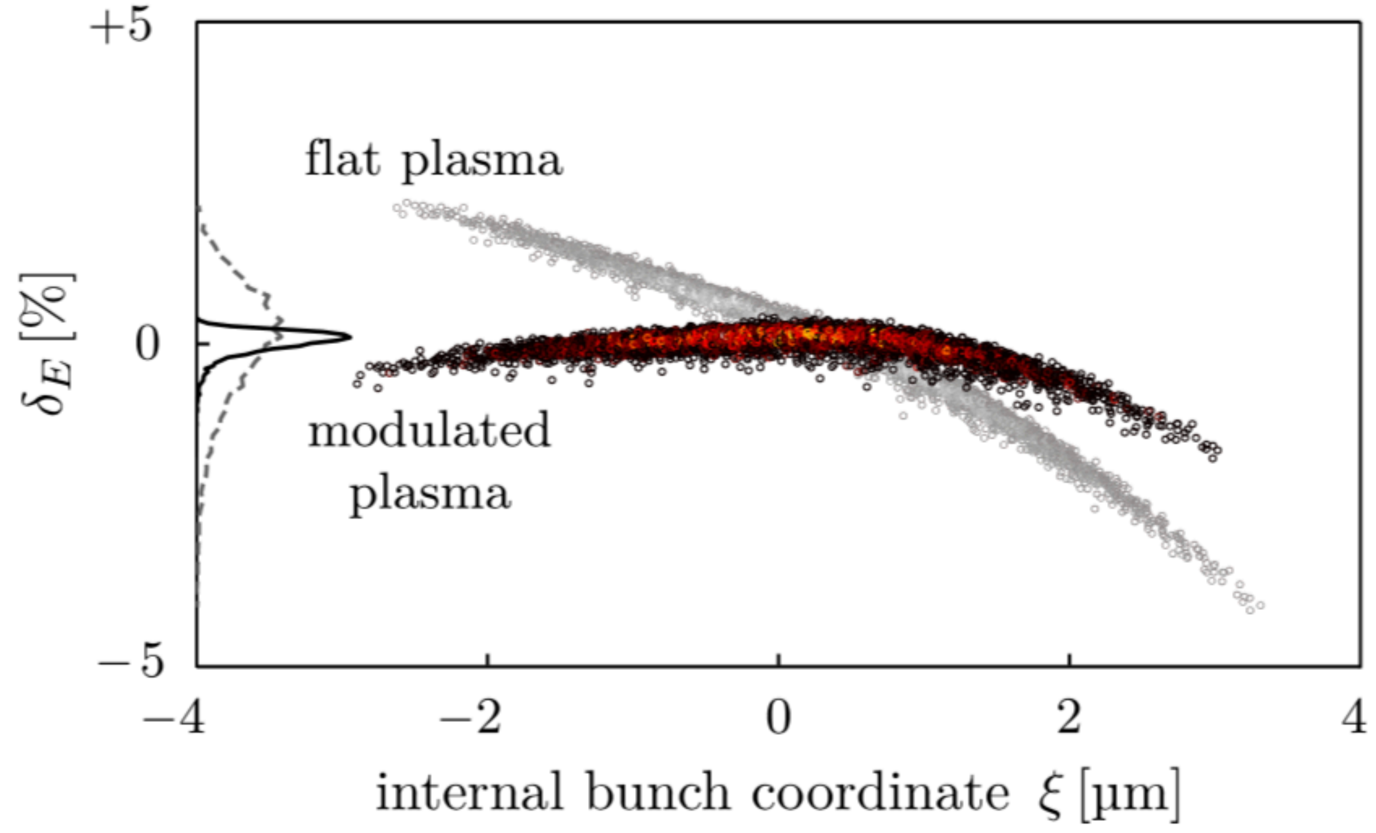
# Plasma density control - chirp mitigation

- Plasma accelerators are operated off-crest (defocussing fields)
- Results in chirped beams (without beamloading)
- *Idea:* alternate plasma densities and generate effective position for stable beam transport and on-crest fields



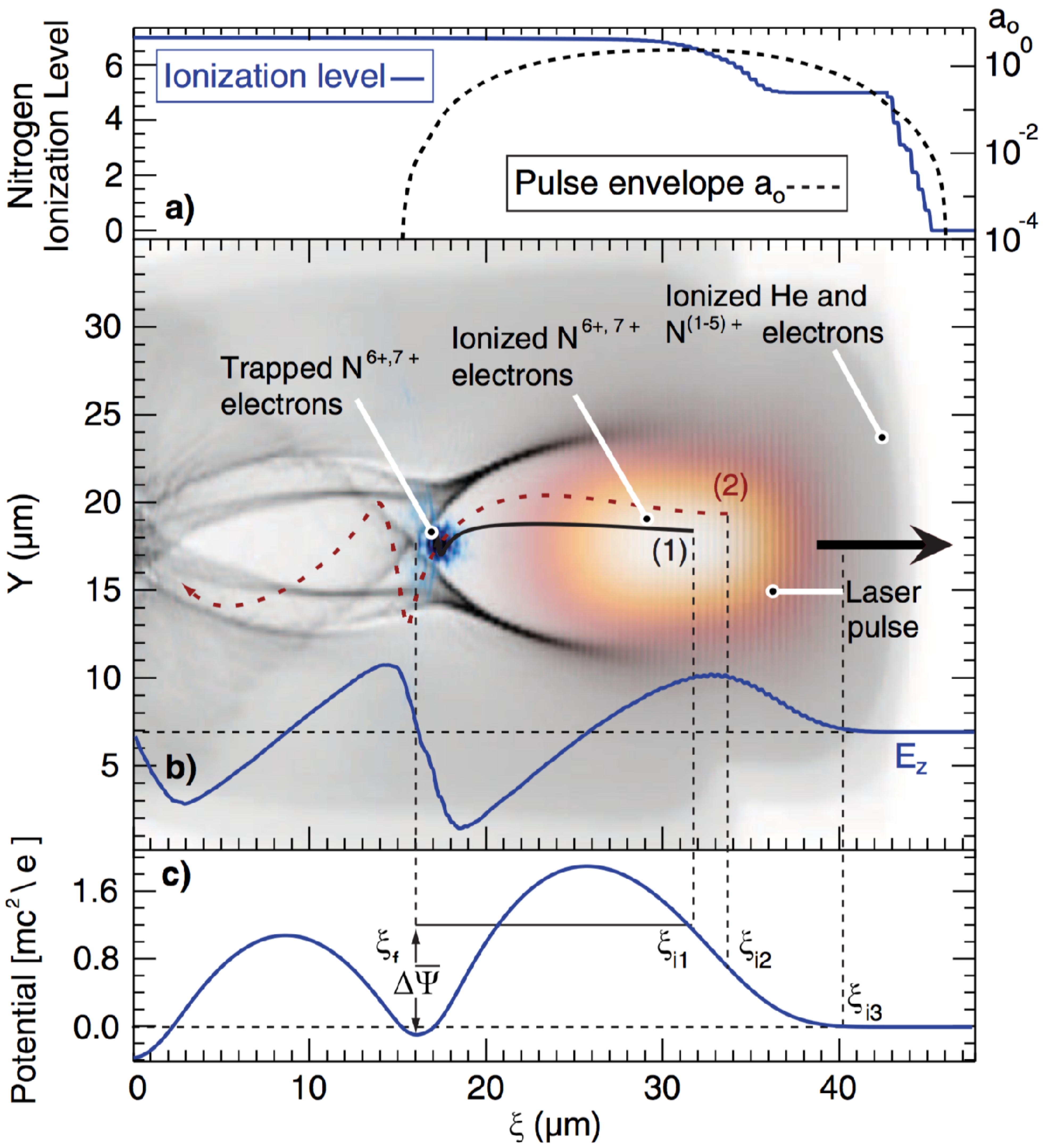






*idea:* Brinkmann *et al.*, Phys. Rev. Lett. 118, 214801 (2017)

# Plasma constituents control - ionization injection



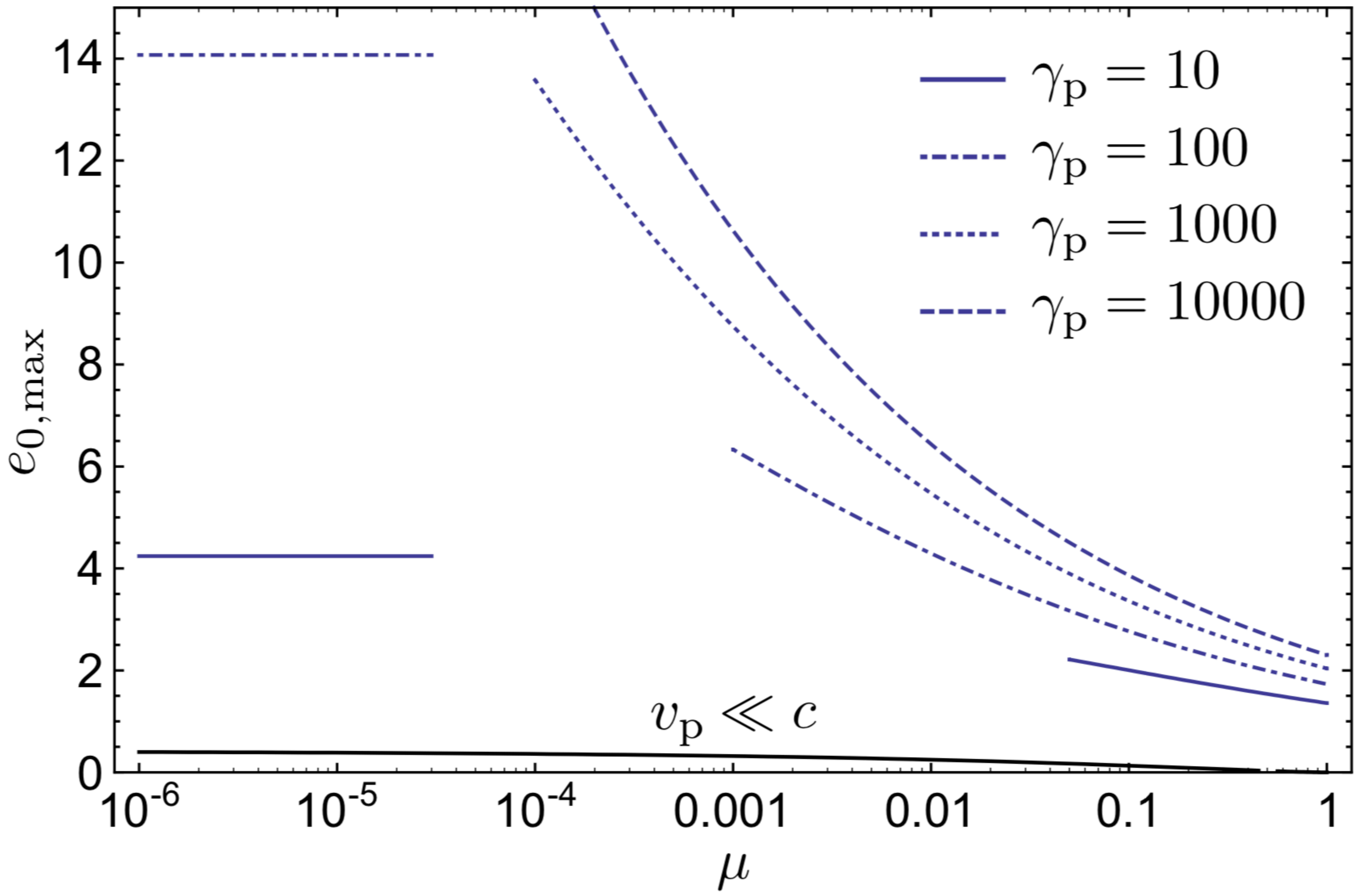
- Ionization of dopant gas near laser-pulse peak intensity
- Dopant concentration to tune injected charge and beam loading

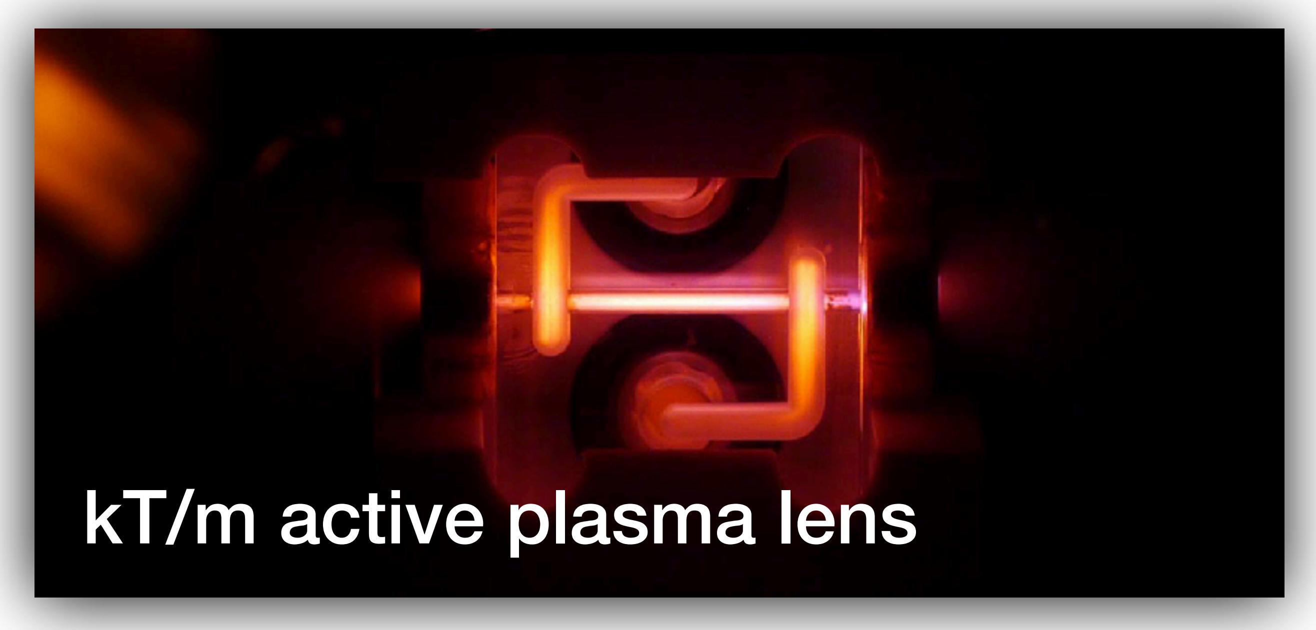
| | |
|---|---|
| *idea:* | D.Umstadter *et al.*, Phys. Rev. Lett. **76**, 2073 (1996) |
| *demonstration:* | A.Pak *et al.*, Phys. Rev. Lett. **104**, 025003 (2010) |
| | C.McGuffey *et al.*, Phys. Rev. Lett. **104**, 025004 (2010) |

# Plasma temperature control

- **Initial plasma temperature *T*$_e$ *(x,t)*, *T*$_i$ *(x,t)* usually small compared to *U*p → effects usually neglected**
- **Influences wave-breaking threshold only at very high plasma temperatures**
- **$\gamma_p$ is relativistic factor associated with phase velocity of wake**

$$\mu = 3k_B T_e (m_e v_p^2)^{-1}$$

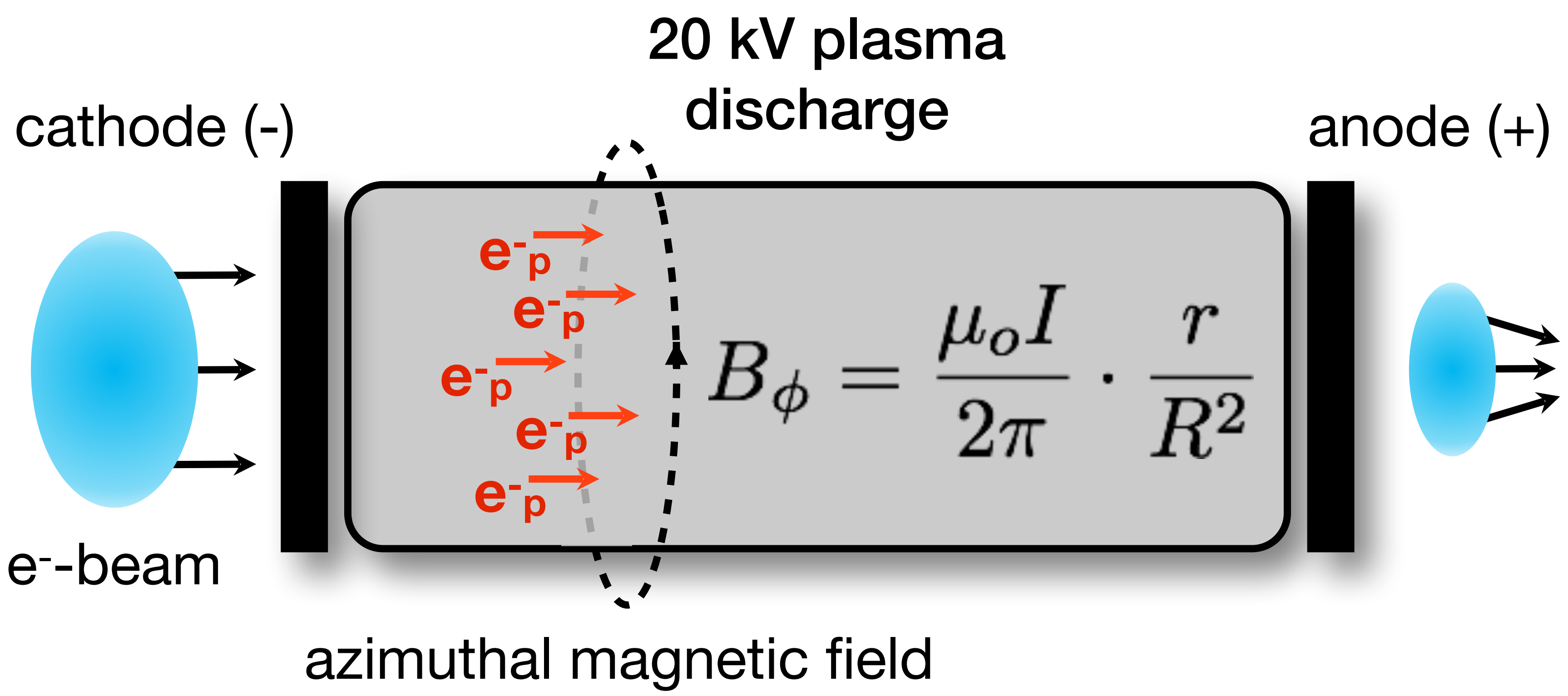




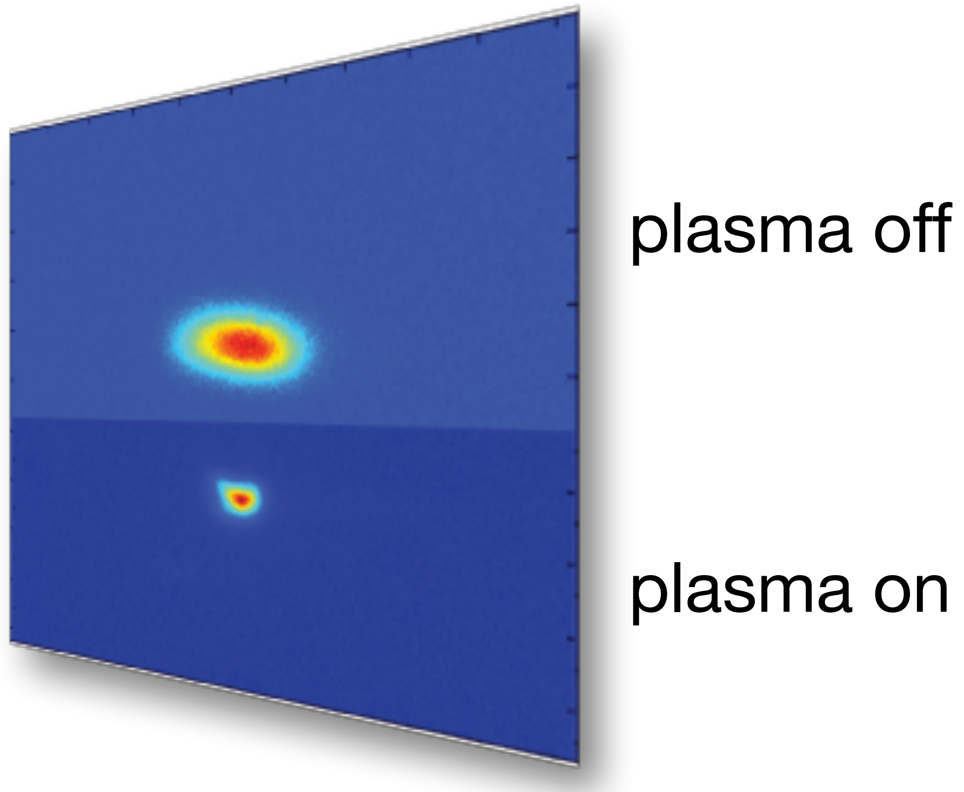
kT/m active plasma lens

# Plasma temperature control - APLs

- Temperature control of crucial importance for active plasma lenses



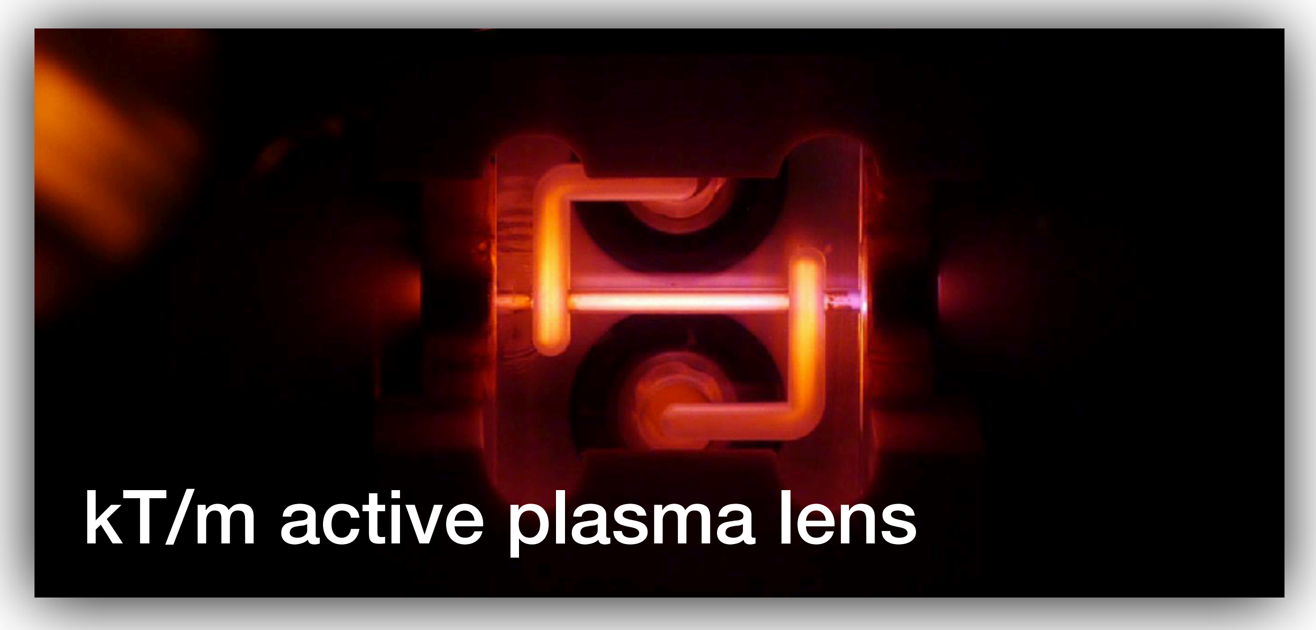
$$B_\phi = \frac{\mu_o I}{2\pi} \cdot \frac{r}{R^2}$$



→ **F = I x B**, tunable and symmetric focussing force for e$^-$-beam

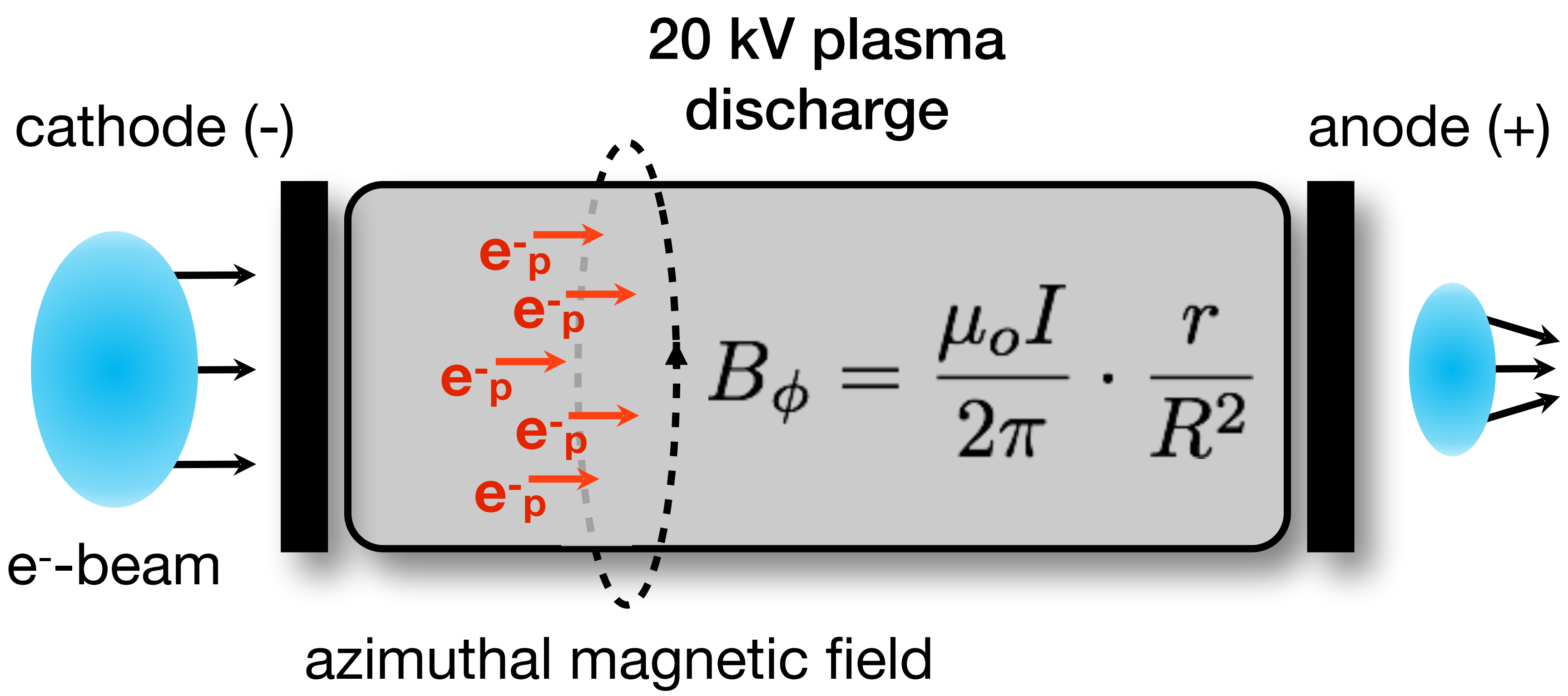
*J. van Tilborg et al., Phys. Rev. Lett.* ***115****, 184802 (2015)*

# Plasma temperature control - APLs



kT/m active plasma lens

- Temperature control of crucial importance for active plasma lenses



20 kV plasma discharge

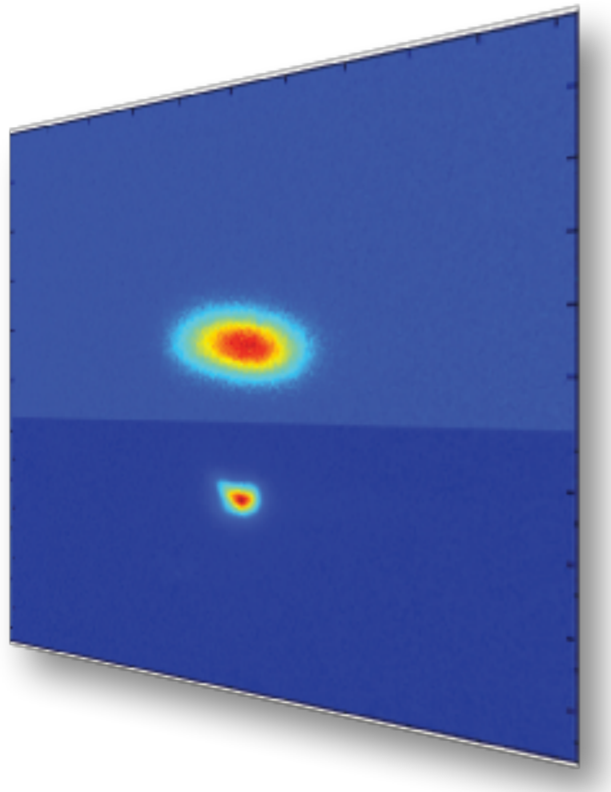
cathode (-)

anode (+)

e--beam

azimuthal magnetic field

$$B_\phi = \frac{\mu_0 I}{2\pi} \cdot \frac{r}{R^2}$$



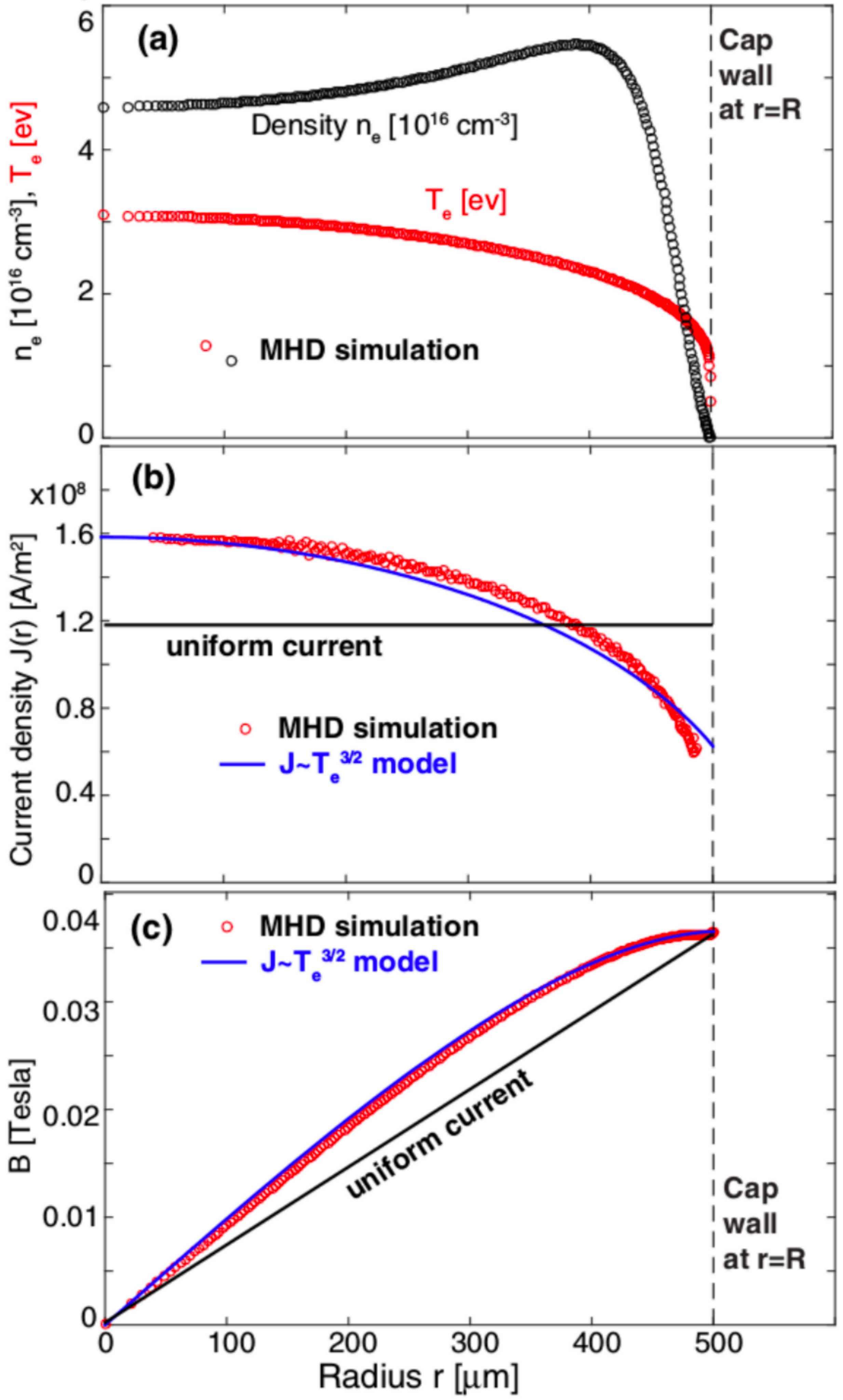
plasma off

plasma on

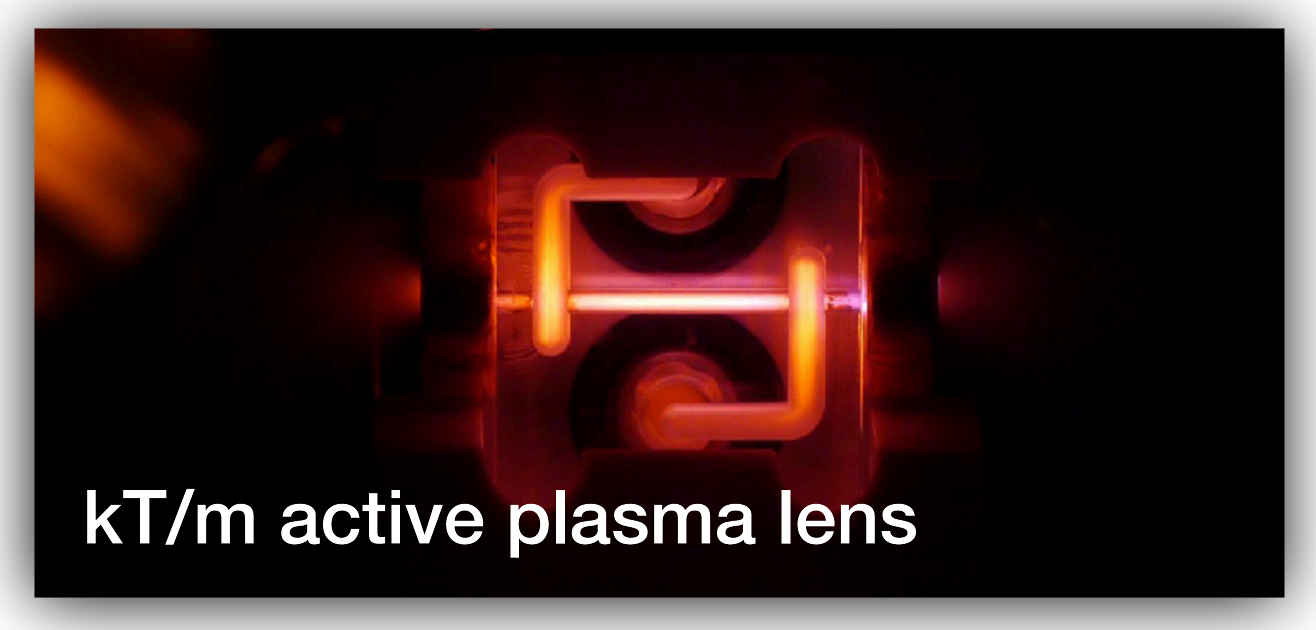
→ **F = I x B**, tunable and symmetric focussing force for e--beam

*J. van Tilborg et al.,*
*Phys. Rev. Lett.* ***115****, 184802 (2015)*

- Plasma heated by current, cooled on walls
  - results in transverse density and temperature gradient
  - ohmic resistance depends on temperature
  - local current density depends on local temperature
  - leads to B-field inhomogeneities
    → nonlinear focussing fields → emittance growth

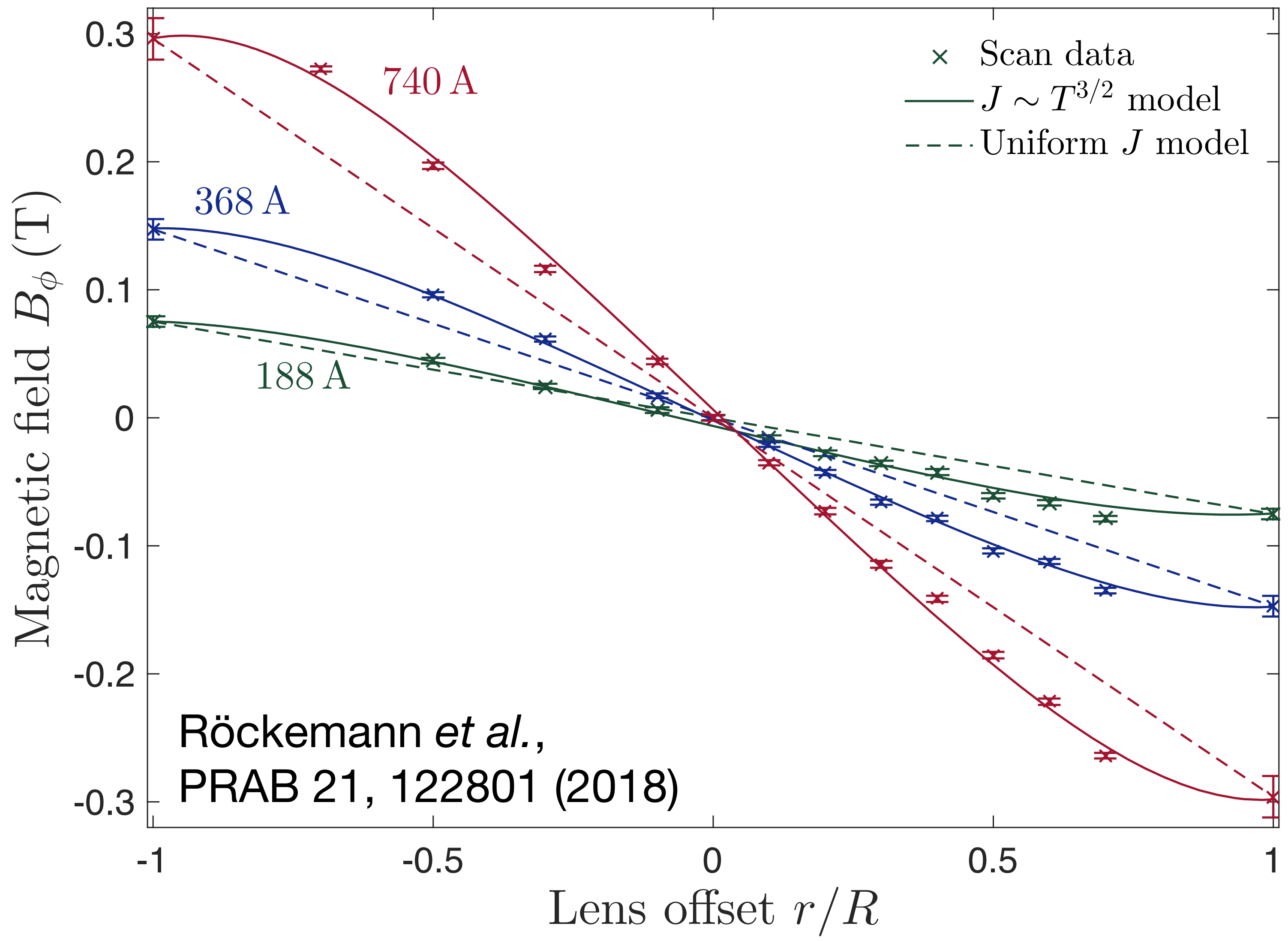


# Plasma temperature control - APLs



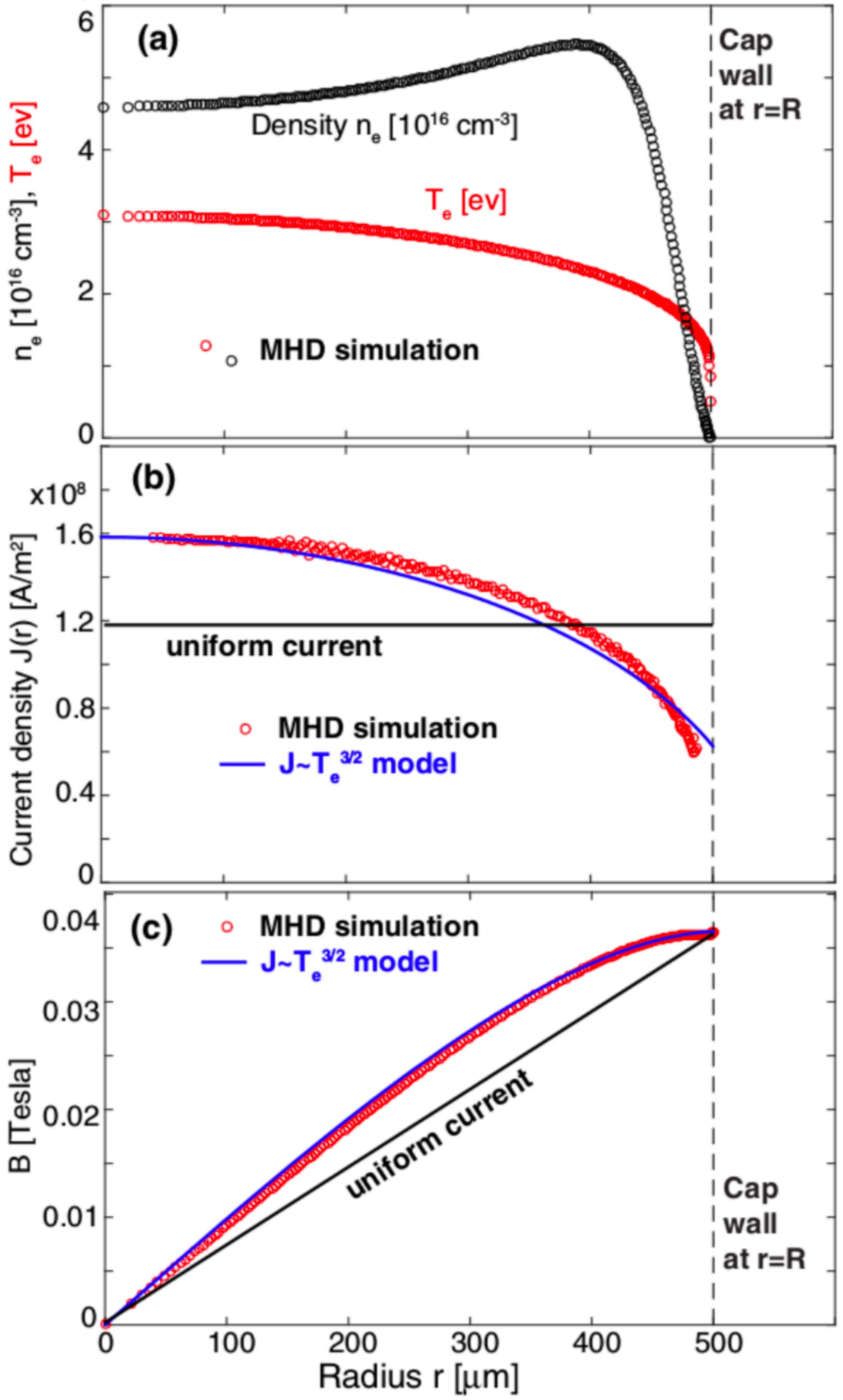
kT/m active plasma lens

- Temperature control of crucial importance for active plasma lenses

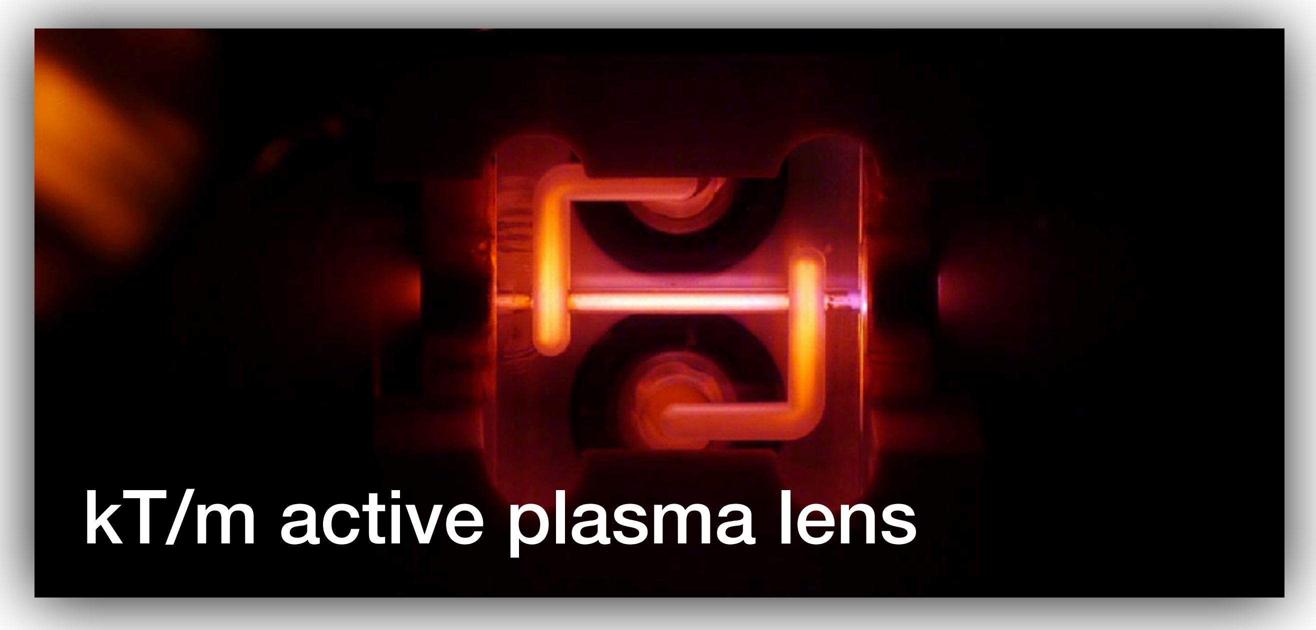


Röckemann *et al.*, PRAB 21, 122801 (2018)

- Plasma heated by current, cooled on walls
  - results in transverse density and temperature gradient
  - ohmic resistance depends on temperature
  - local current density depends on local temperature
  - leads to B-field inhomogeneities → nonlinear focussing fields → emittance growth

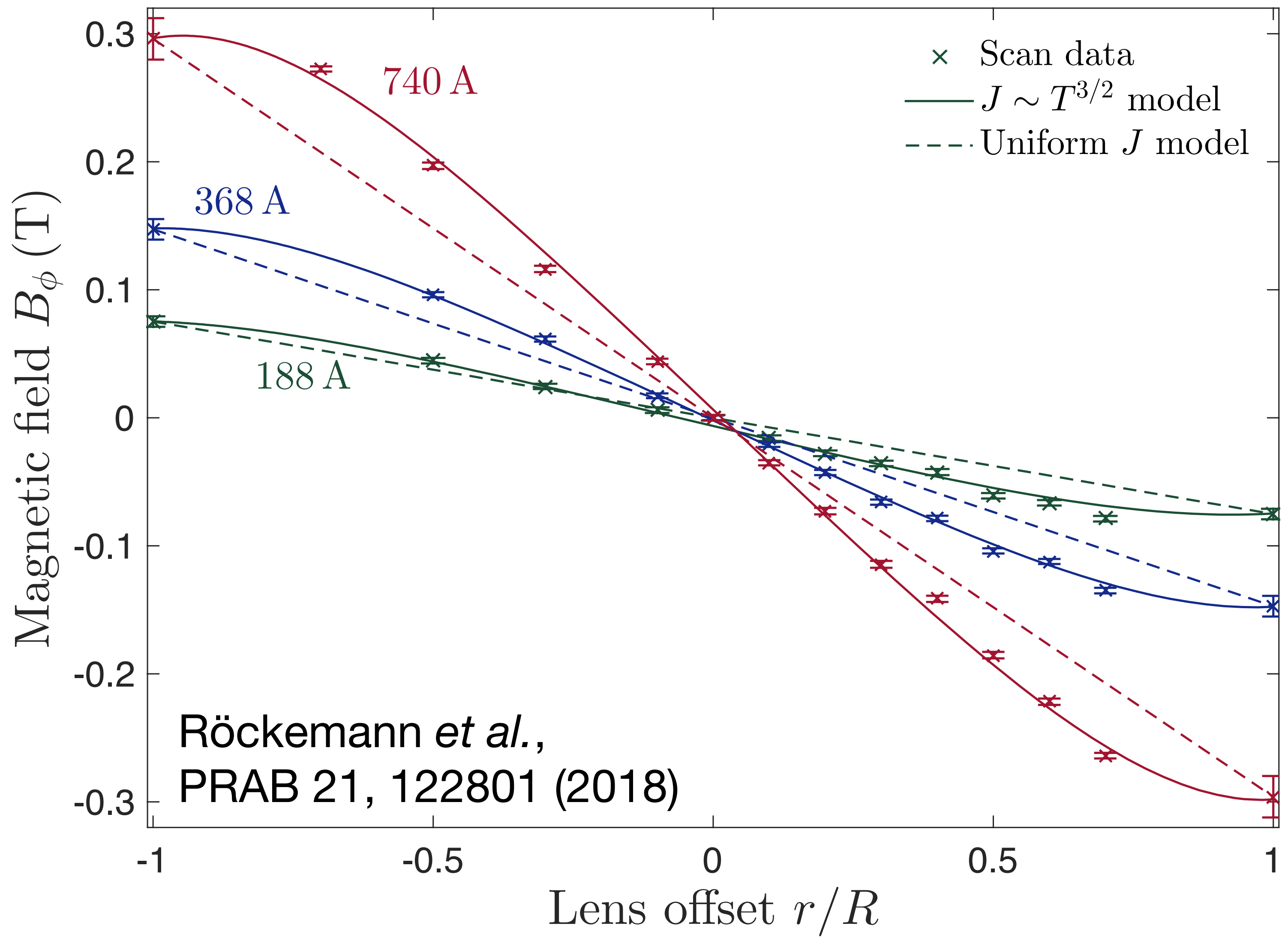


# Plasma temperature control - APLs



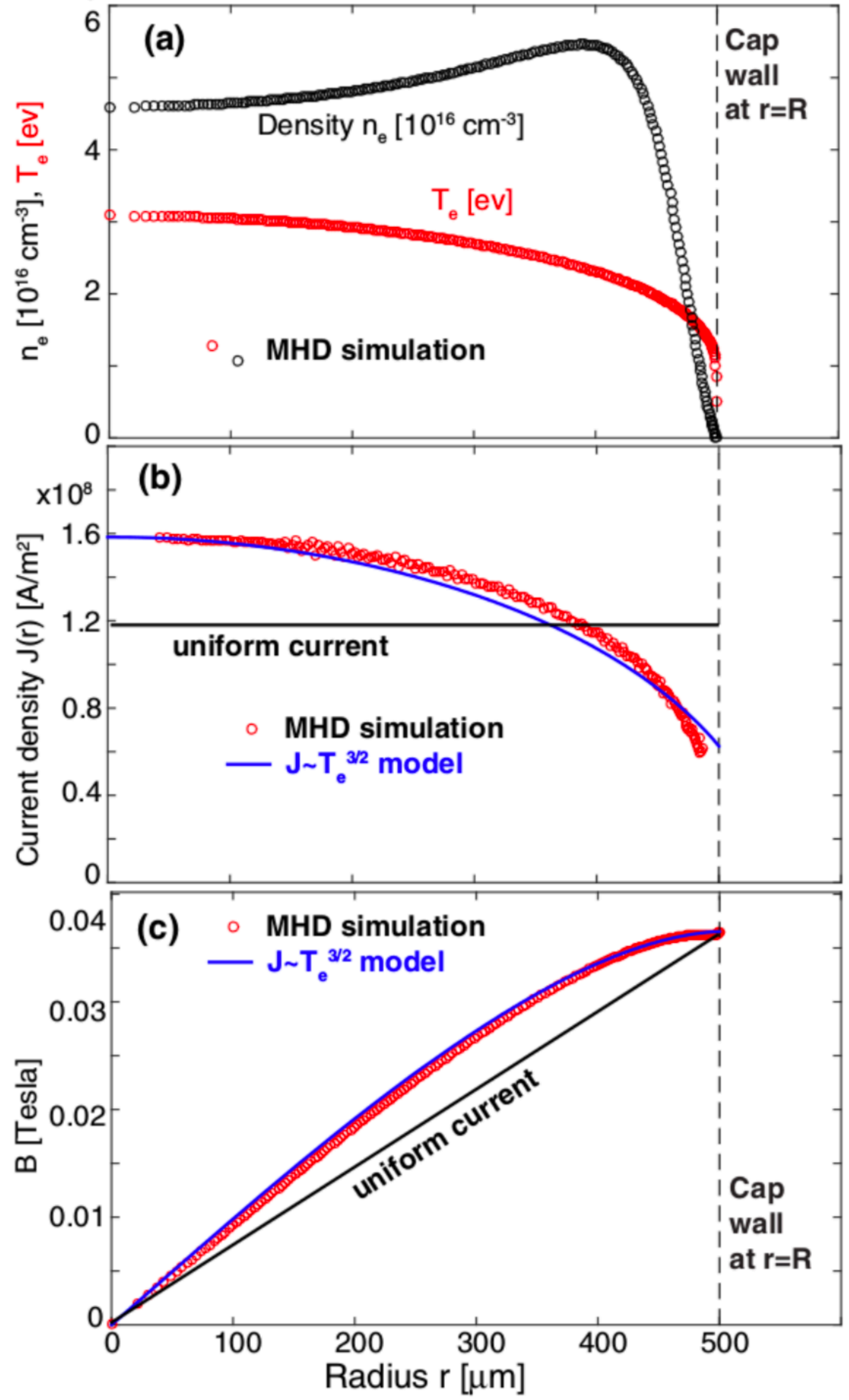
kT/m active plasma lens

- Temperature control of crucial importance for active plasma lenses

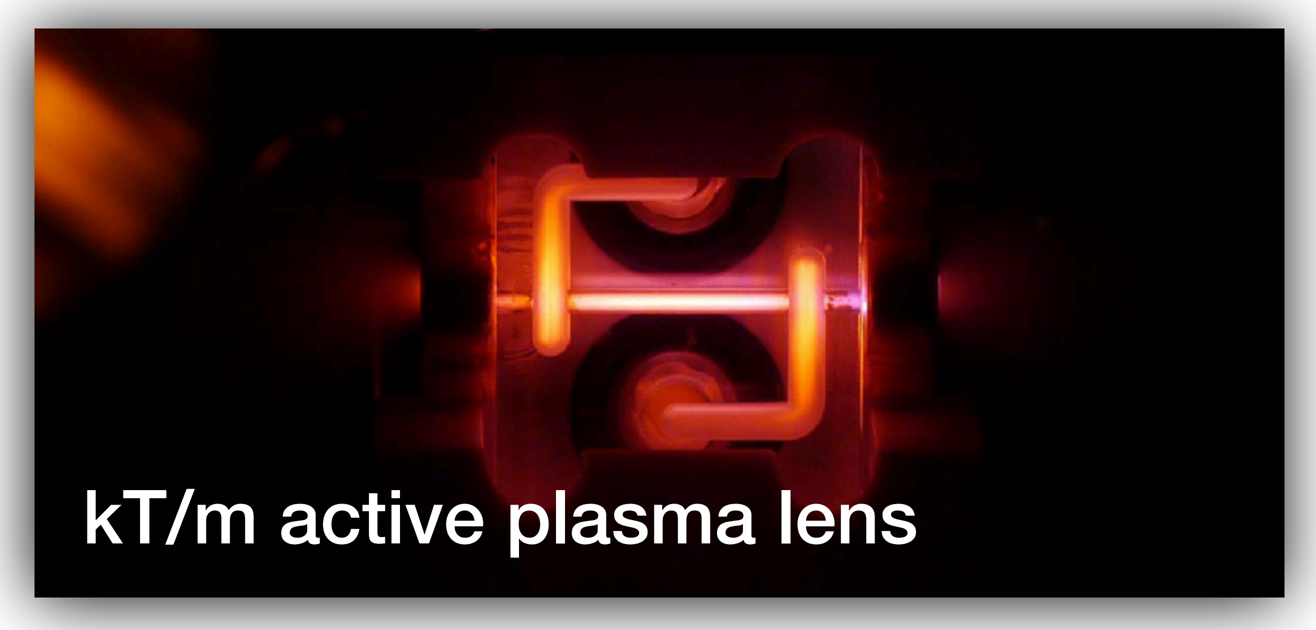


Röckemann *et al.*, PRAB 21, 122801 (2018)

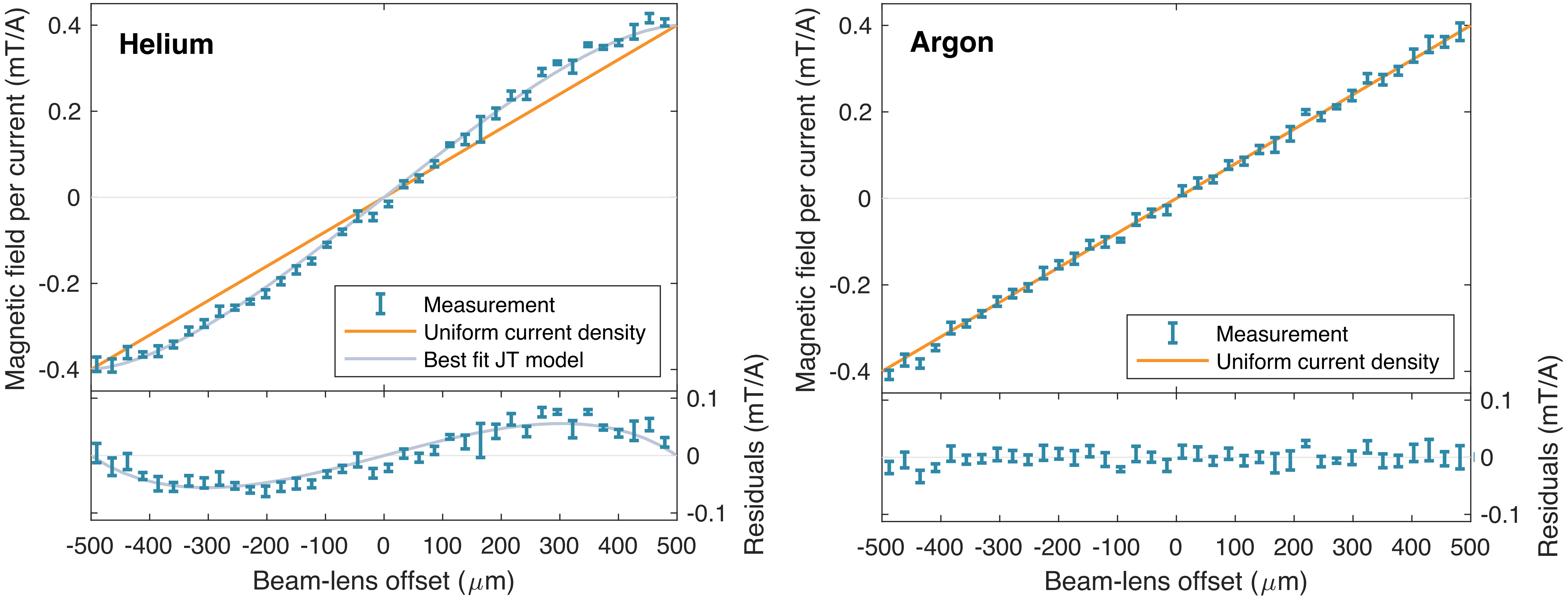
- Plasma heated by current, cooled on walls
  - results in transverse density and temperature gradient
  - ohmic resistance depends on temperature
  - local current density depends on local temperature
  - leads to B-field inhomogeneities → nonlinear focussing fields → emittance growth
- APLs need to be used long before thermal equilibrium is reached, when current density is still uniform



# Plasma temperature control - APLs



- Temperature control of crucial importance for active plasma lenses



C. A. Lindstrom *et al.*,
Phys. Rev. Lett. 121, 194801(2018)

- Substitute Hydrogen/Helium with Argon to extend timescale of temperature equilibration $\propto m_{ion}$
- Experiment at CLEAR, CERN: 216 MeV electrons, 50 µm rms size, 3 µm norm. emittance, 410 A current at 70 ns
- Argon: emittance conservation measured
  Helium: emittance not conserved

# Summary of Plasma Sources I

- *Today*
  - **Design aspects for a plasma source**
  - ***Concepts:* plasma generation mechanisms**
  - ***Concepts:* tailoring plasma properties to control wakefield processes**

- ***Tomorrow:* technical implementation and examples**