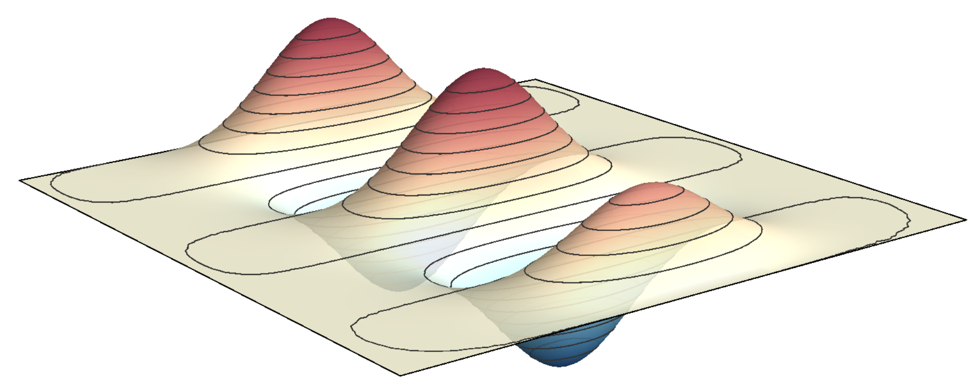
PLASMA BEAM DUMPS

Preliminary studies for EuPRAXIA



Alexandre Bonatto* (UFCSPA)
Roger P. Nunes (UFRGS)
Denis Perret-Gallix (LAPP-IN2P3/KEK)†

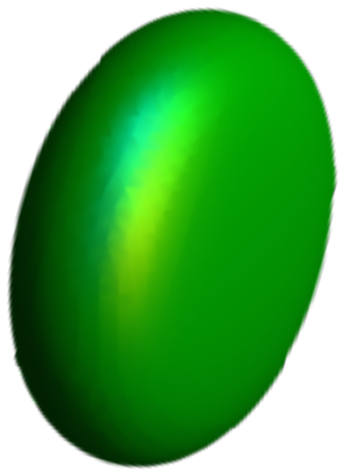
Federal University of Health Sciences of Porto Alegre - UFCSPA - RS, Brazil
Beam Physics Group - Medical Physics - DECESA
***abonatto@ufcspa.edu.br**, **www.ufcspa.edu.br**
† Deceased.

Introduction

- In this work we present some preliminary studies for the plasma-based deceleration of 5 GeV;
- We show analytical estimates for the beam total energy loss obtained for a half-sine longitudinal and parabolic transverse (HSP) (Bonatto et al. 2015);
- We also show analytical estimates from a model developed for a beam with longitudinal Gaussian profile and compare both models (to be published).
- We focus our attention in the passive case, providing some analytical estimates and 1D PIC simulations for the mentioned case.

The Model - beam energy loss (passive beam dump)

- Half-sine longitudinal and parabolic transverse (HSP):



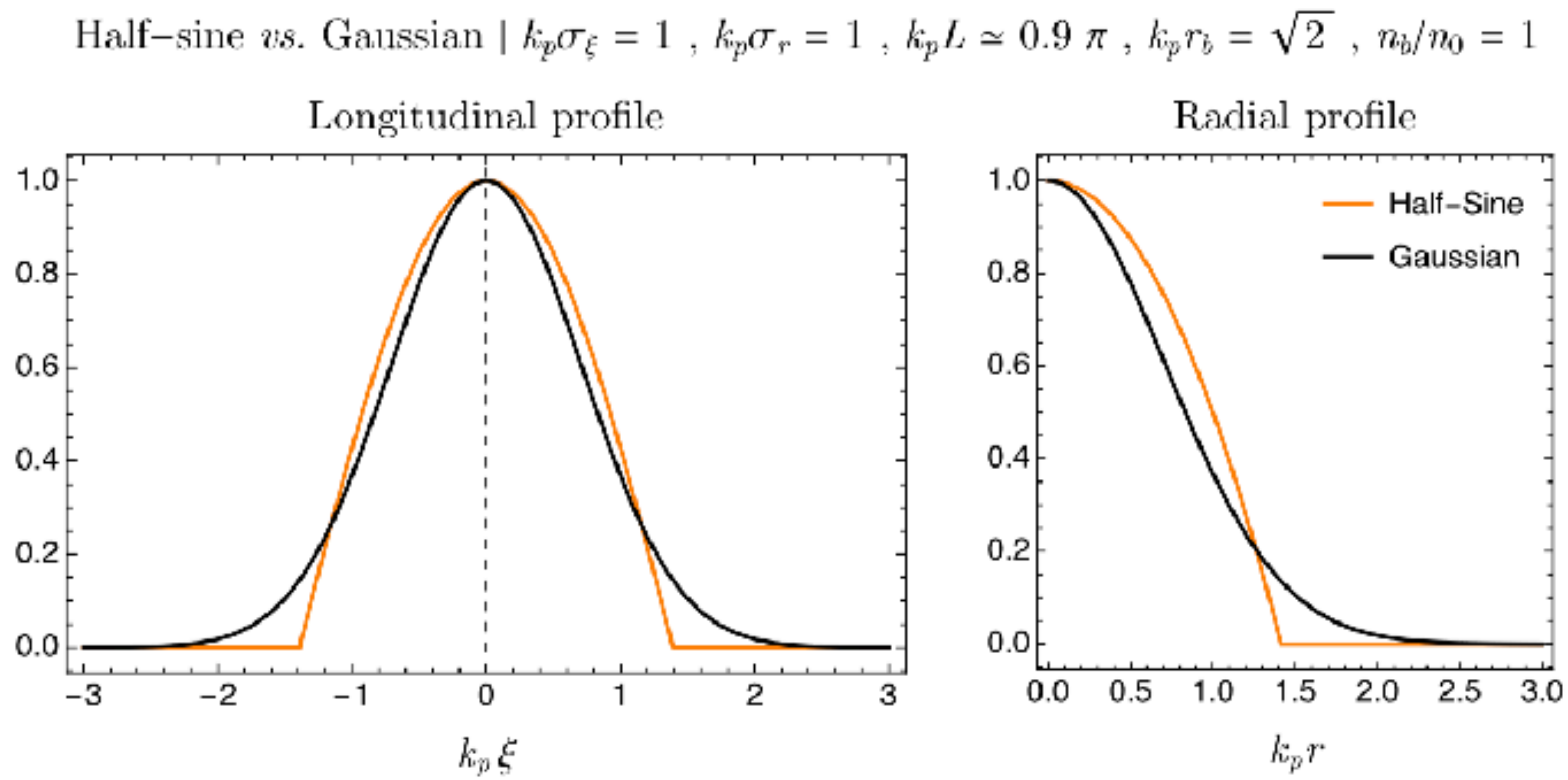
$$n_b(\xi, r) = \frac{n_b}{n_o} \sin\left(\frac{\pi\xi}{L}\right)\left(1 - \frac{r^2}{r_b^2}\right) \ , \ \left[\begin{array}{l} 0 \leq \xi \leq L \\ 0 \leq r \leq r_b \end{array}\right.$$

- Beam total energy loss as a function of the propagated distance s (Bonatto et al, 2015):

$$\frac{U(s)}{U_0} = 1 - k_p s \ \frac{\pi^3 k_p L \, (n_b/n_0) \cos^2(k_p L/2)}{\gamma_0(\pi^2 - k_p^2 L^2)^2} \, \frac{2}{3} \left[\frac{k_p^2 r_b^2 - 6 + 24 \, I_2(k_p r_b) K_2(k_p r_b)}{k_p^2 r_b^2}\right]$$

Half-sine / Parabolic (HSP) vs. bi-Gaussian beam

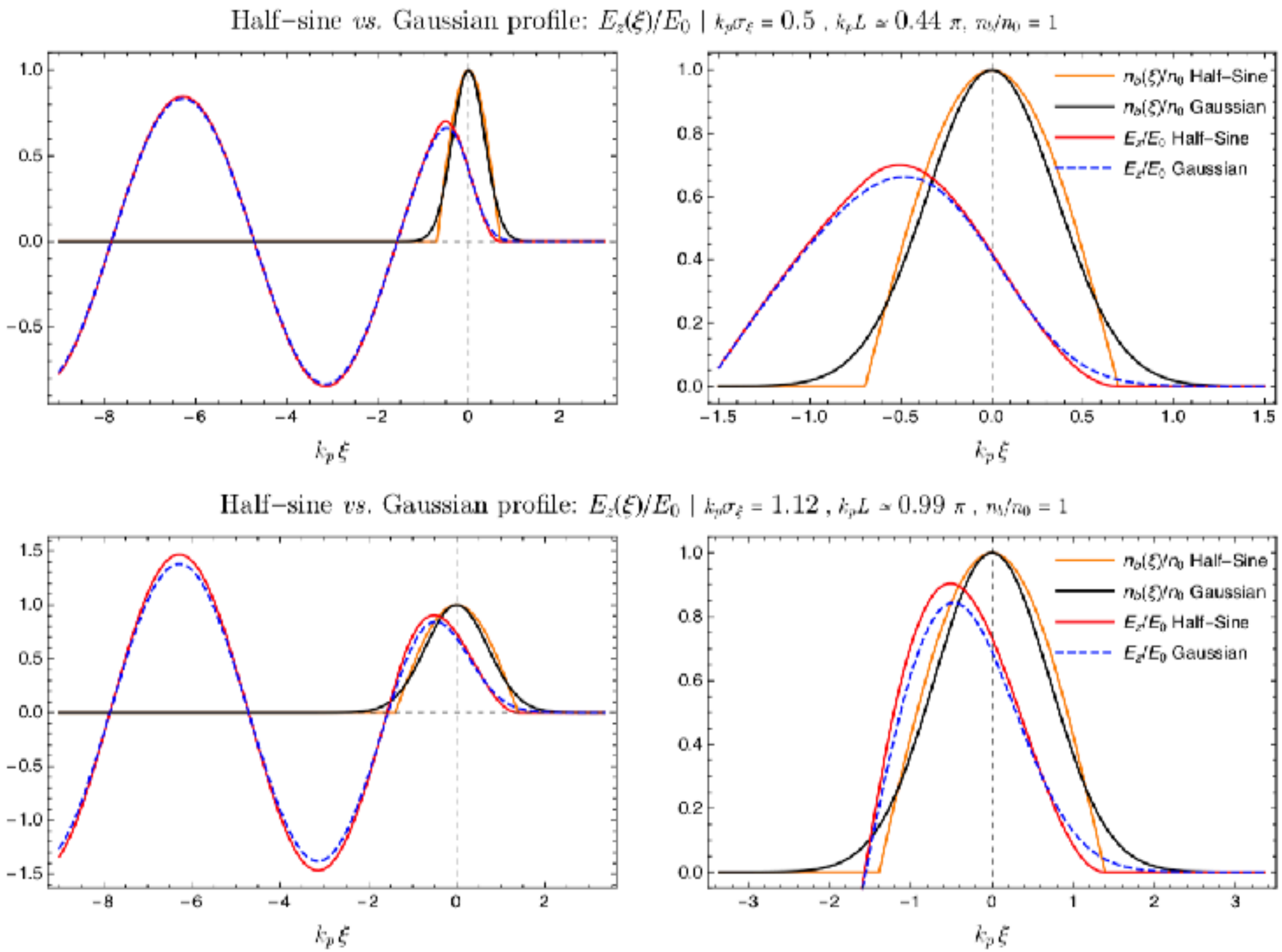
- Gaussian beam length $L_b = 5.15\sigma_\xi$.
- HSP model can be used to describe a Gaussian beam if they are matched to have the same n_b/n_0 $(E_z/E_0 \propto n_b/n_0)$;



- Matching condition: $L_{HSP} = (1/2)\pi^{3/2}\sigma_\xi$, and $r_{b,HSP} = \sqrt{2}\sigma_r$.

Half-sine vs. Gaussian beam

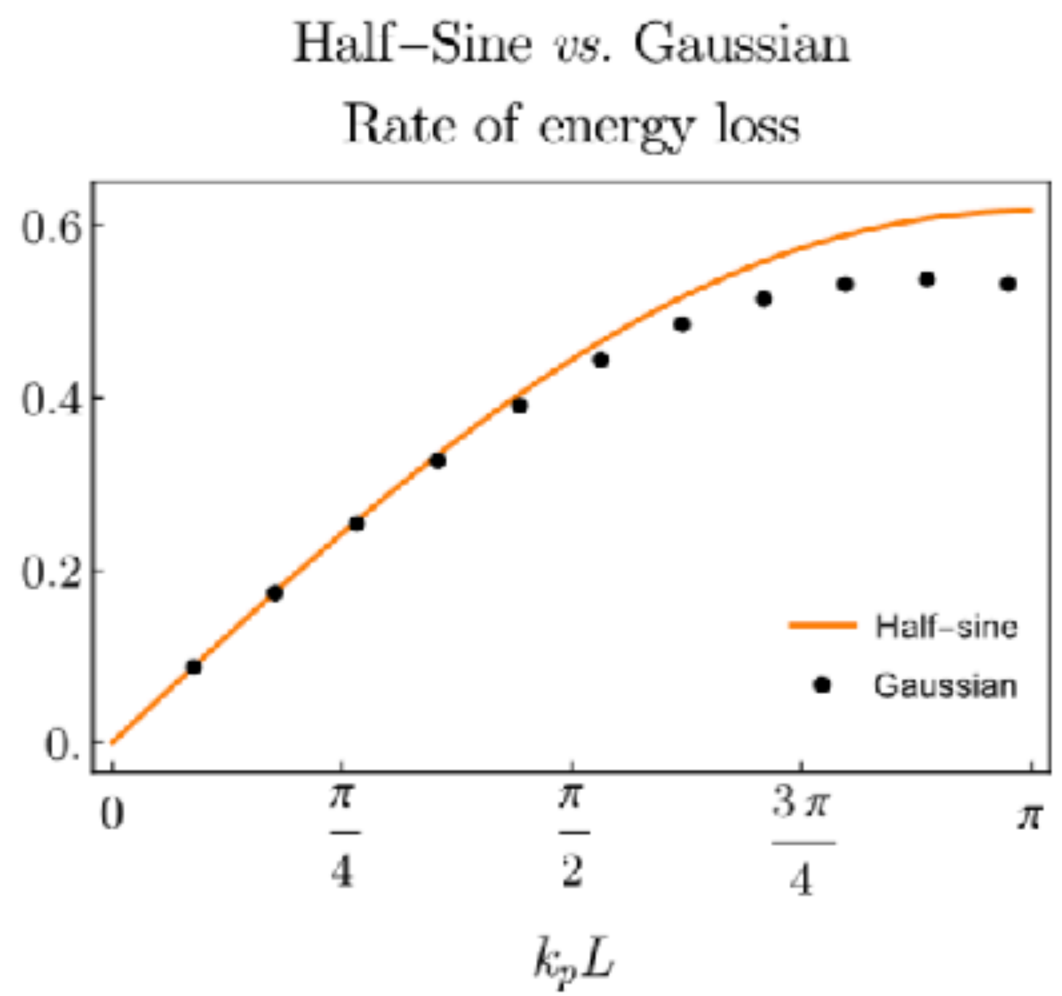
→ The lower the $k_p L_b$, the better is the matching.



Half-sine vs. Gaussian beam

- → Matched HSP has $L \simeq 2.8\,\sigma_\xi$ ($\sim 84\%$ of the Gaussian area).
- → Gaussian tails: $\sim 8\%$ of the particles on each.
- → As $k_p \sigma_\xi \to \pi$, the fraction of the later tail reaching an E_z/E_0 accelerating phase increases.
- → This slightly attenuates the beam energy extraction.

- → Comparison (1D):



EuPRAXIA

- Table from “Design of a 5 GeV laser-plasma accelerating module in the quasi-linear regime” (Xiangkun L. et al., 2018)

Typical parameters for the EuPRAXIA Laser–plasma acceleration stage.

Variable	Value	Unit
Laser		
Strength a_0	$\sqrt{2}$	
Spot size $k_p w_0$	3.3	
Duration $k_p \sigma_L$	$\sqrt{2}$	
Peak power P_L	~150	TW
Energy E_L	~15	J
Plasma		
Density n_p	1.5	10^{17} cm^{-3}
acc. length L_{acc}	~30	cm
Channel depth $\Delta n/\Delta n_c$	<1[a]	
Electron		
Charge Q	30	pC
Energy E_k	150	MeV
Energy spread $\Delta E/E$	0.5	%
Beam size σ_x	~1[a]	µm
Emittance $\varepsilon_{n,x}$	1.0	π mm mrad
Bunch length σ_z	1–3[a]	µm

- We consider a beam with the same parameters, but with higher energy (5 GeV).

EuPRAXIA

- Better agreement with the model if $n_b/n_0 \lesssim 10$ (linear, quasi-linear regime);

<u>Electron beam</u>:

- Bi-Gaussian profile:

$$\frac{n_b(\xi,r)}{n_0} = \frac{n_b}{n_0}\exp\left[-\left(\frac{\xi^2}{\sigma_\xi^2}+\frac{r^2}{\sigma_r^2}\right)\right] \ , \ \begin{cases}\sigma_\xi & = 1 \sim 3\,\mu\mathrm{m} \\ \sigma_r & \simeq 1\,\mu\mathrm{m}\end{cases}$$

- bunch length (99% of the beam particles);
- charge = -30 pC;
- energy = 5 GeV (*monoenergetic*)

Plasma:

- Density chosen according to the desired normalized bunch length k_pL_b;
    - $k_pL_b \rightarrow \pi \quad \Rightarrow \quad$ faster / less uniform energy extraction;
    - $k_pL_b \ll \pi \quad \Rightarrow \quad$ slower / more uniform energy extraction;

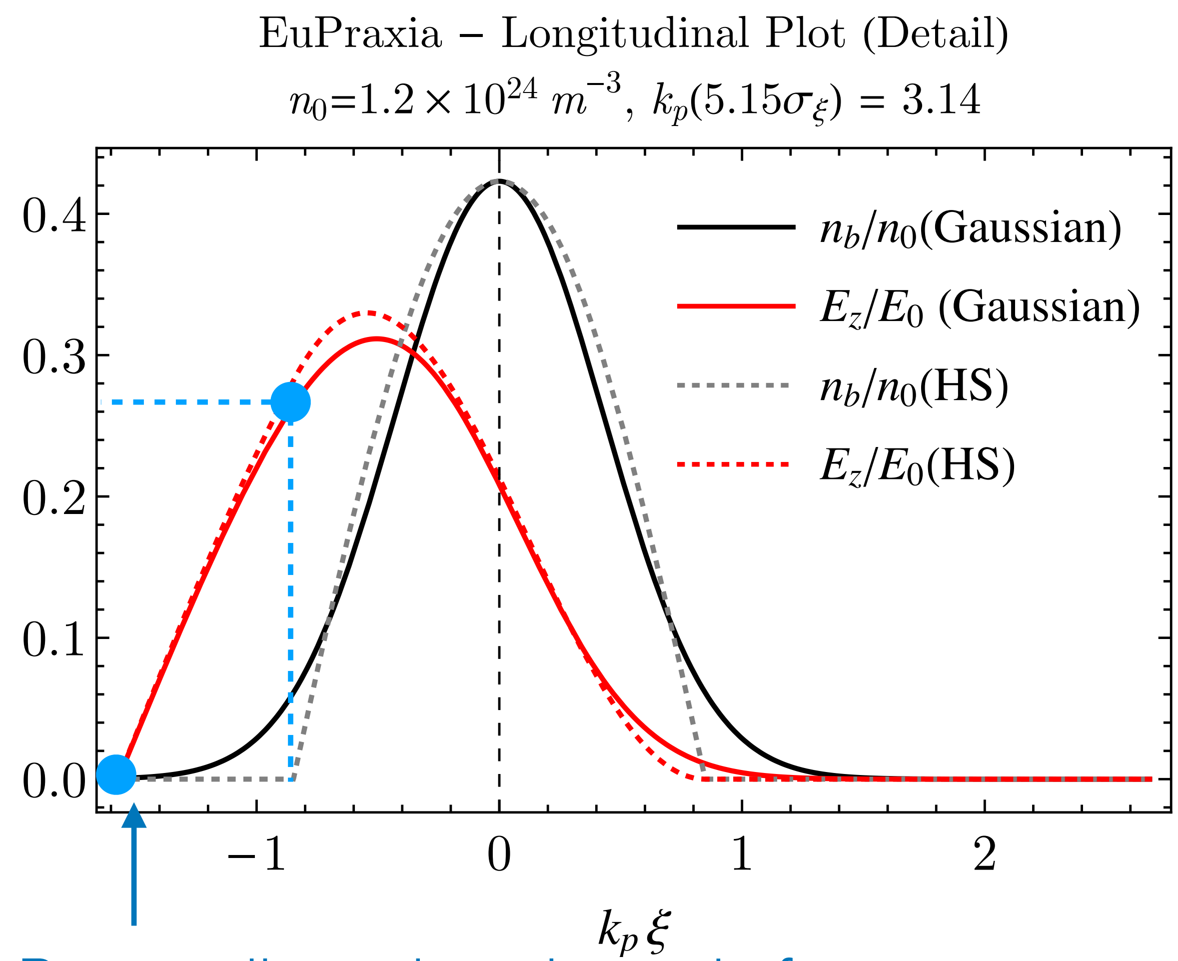
- Better agreement with the model if $n_b/n_0 \lesssim 10$ (linear, quasi-linear regime);

EuPRAXIA, sim. 1: $\sigma_\xi = 3\,\mu\text{m}$, $\sigma_r = 1\,\mu\text{m}$, $k_b L_b = \pi$

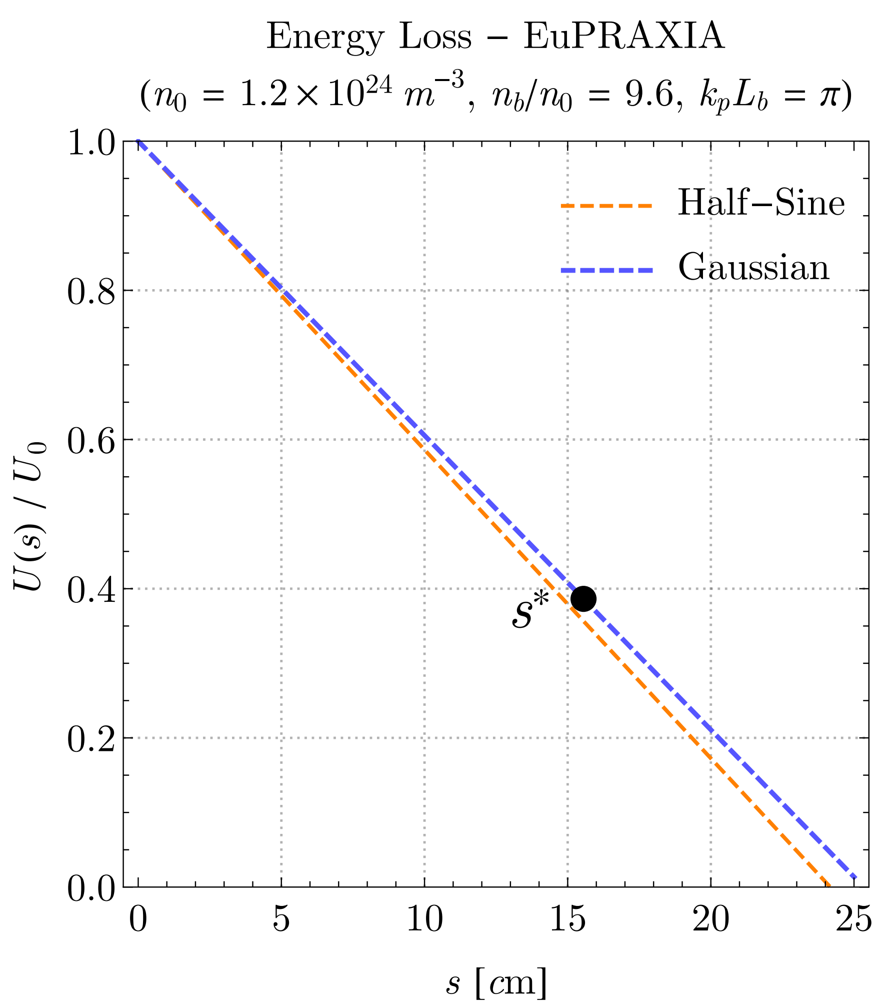
<u>Shorter normalized length</u>:

- $L_b = 5.15\sigma_\xi$;
- $k_p L_b = \pi$;

Faster overall energy extraction, but lower E_z/E_0 over beam tail (higher energy chirp)



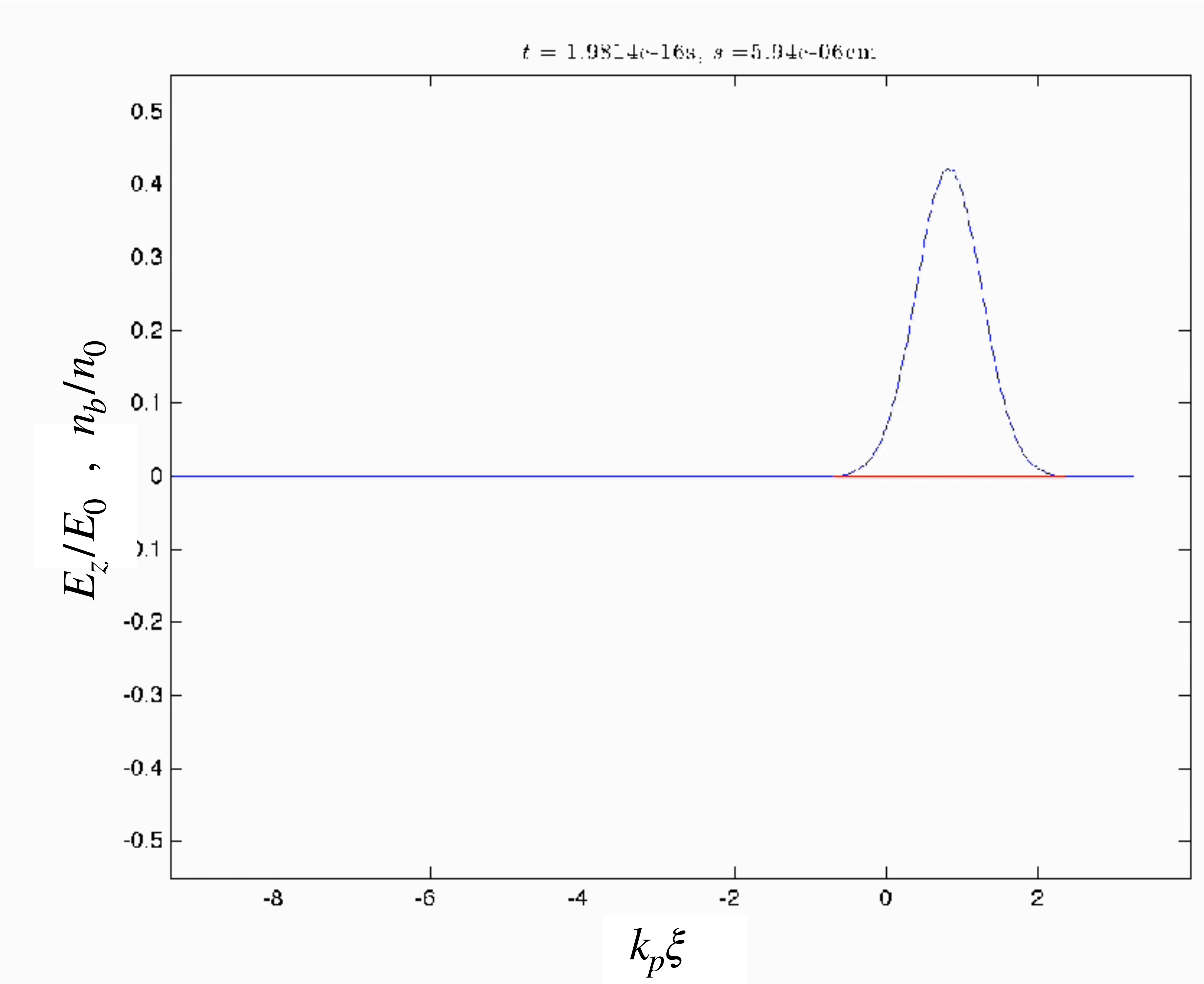
Beam tail touches the end of E_z/E_0 decelerating phase



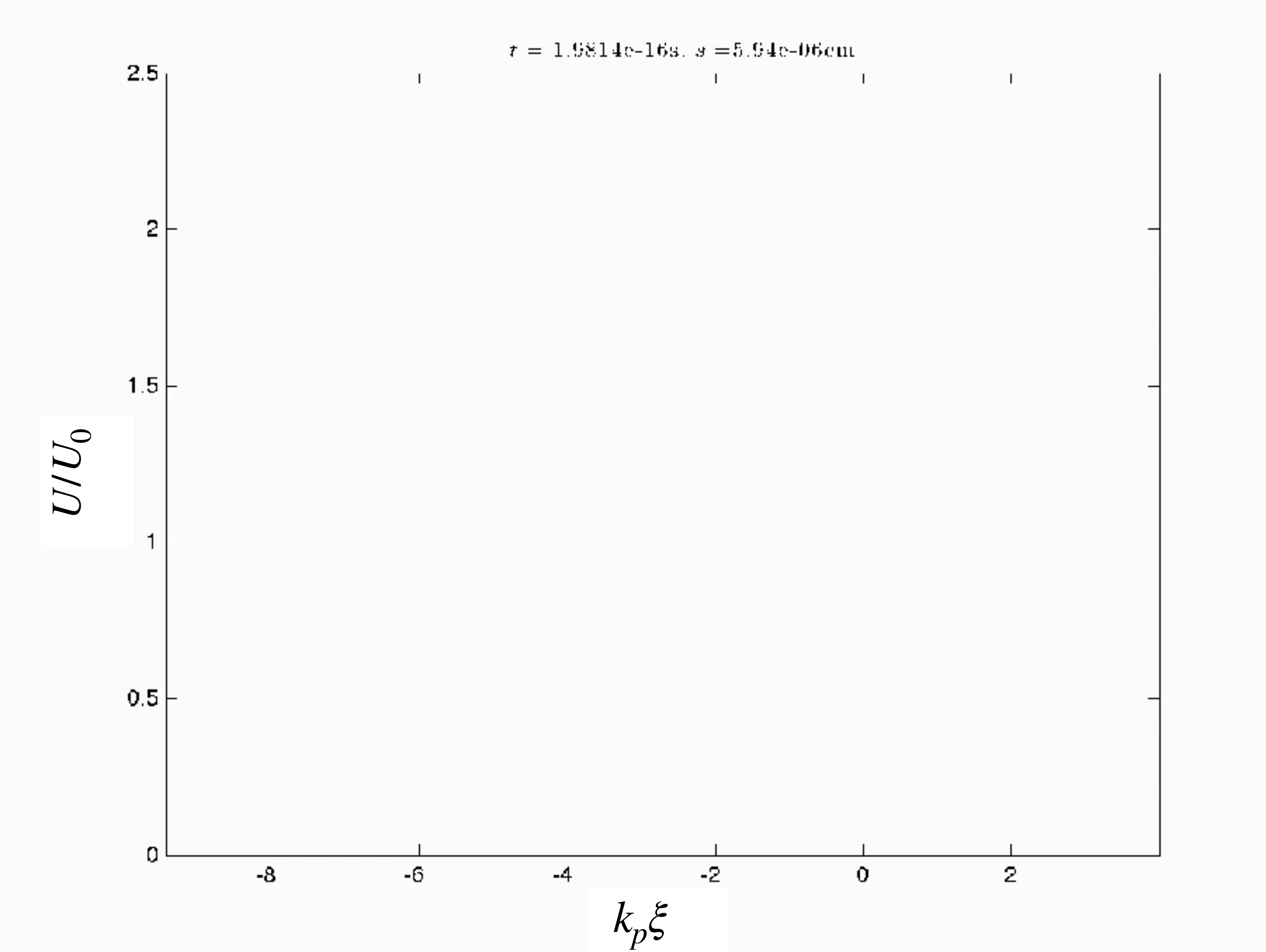
<u>Analytical estimate</u>:

- $s^* \sim 0.15$ cm (saturation point);
- $U(s^*)/U_0 \sim 0.40$ (normalized energy)

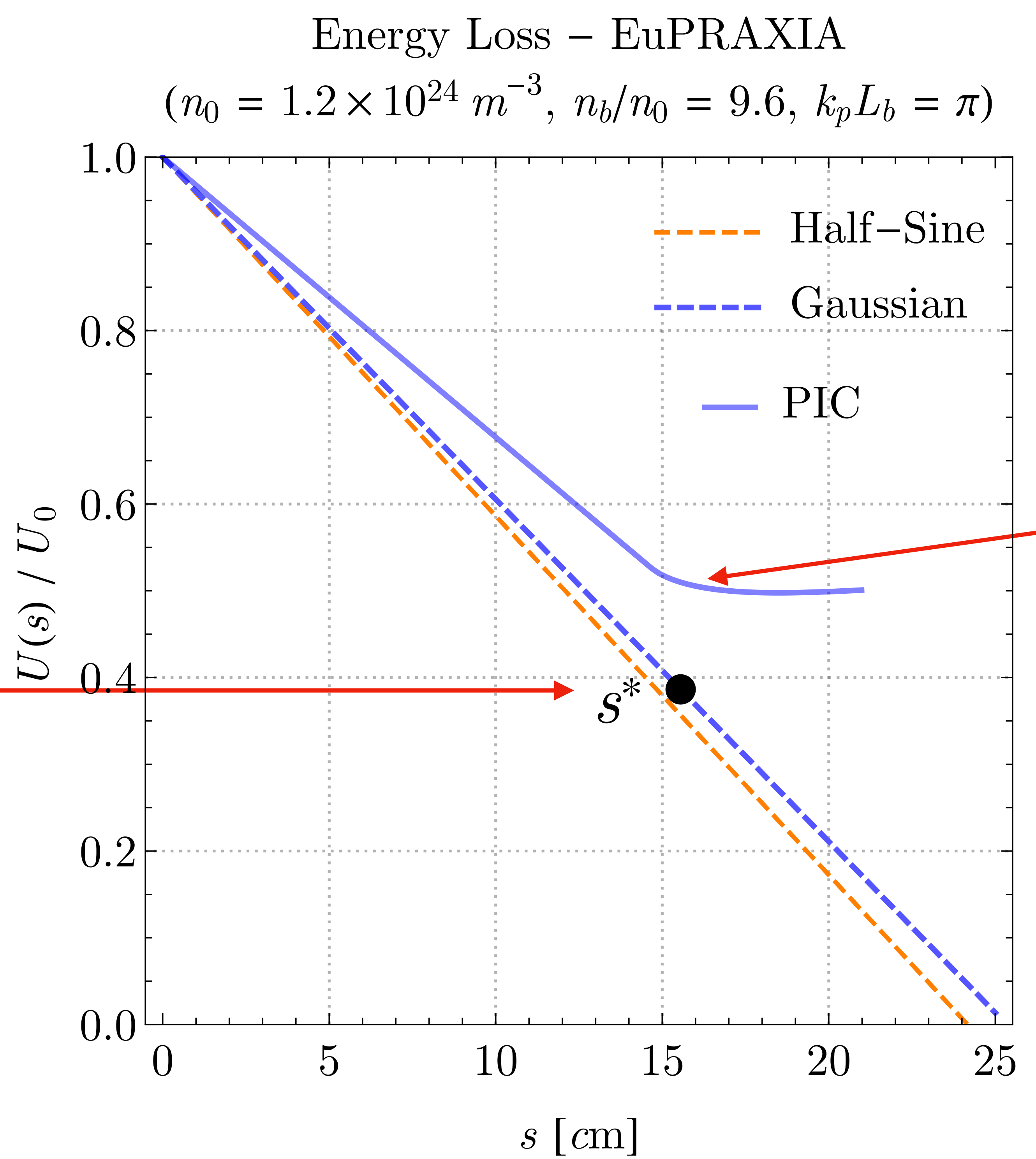
EuPRAXIA, sim. 1: $\sigma_\xi = 3\,\mu$m , $\sigma_r = 1\,\mu$m , $k_b L_b = \pi$



EuPRAXIA, sim. 1: $\sigma_\xi = 3\mu$m , $\sigma_r = 1\mu$m , $k_b L_b = \pi$



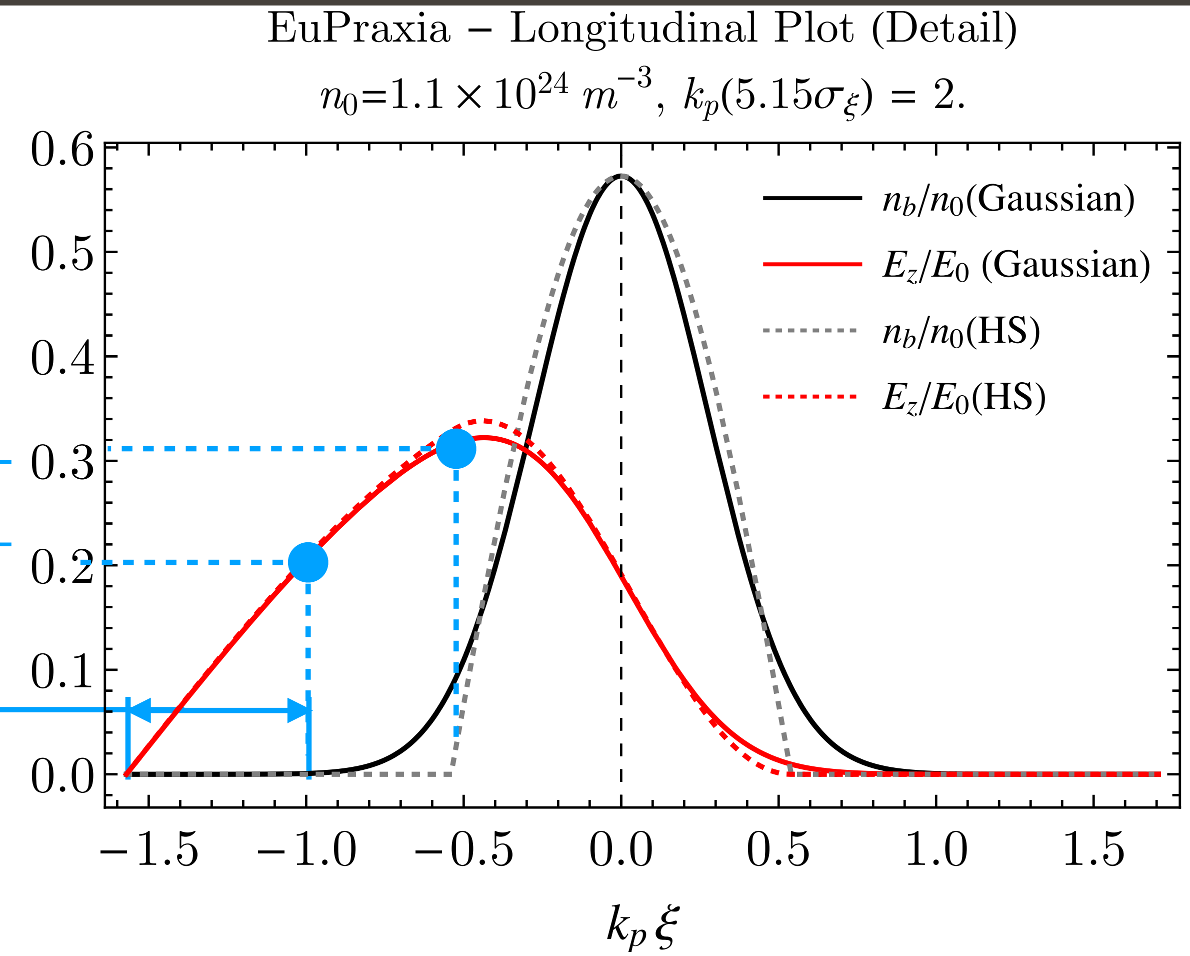
EuPRAXIA, sim. 1: $\sigma_\xi = 3\,\mu\mathrm{m}$, $\sigma_r = 1\,\mu\mathrm{m}$, $k_b L_b = \pi$



PIC Simulation

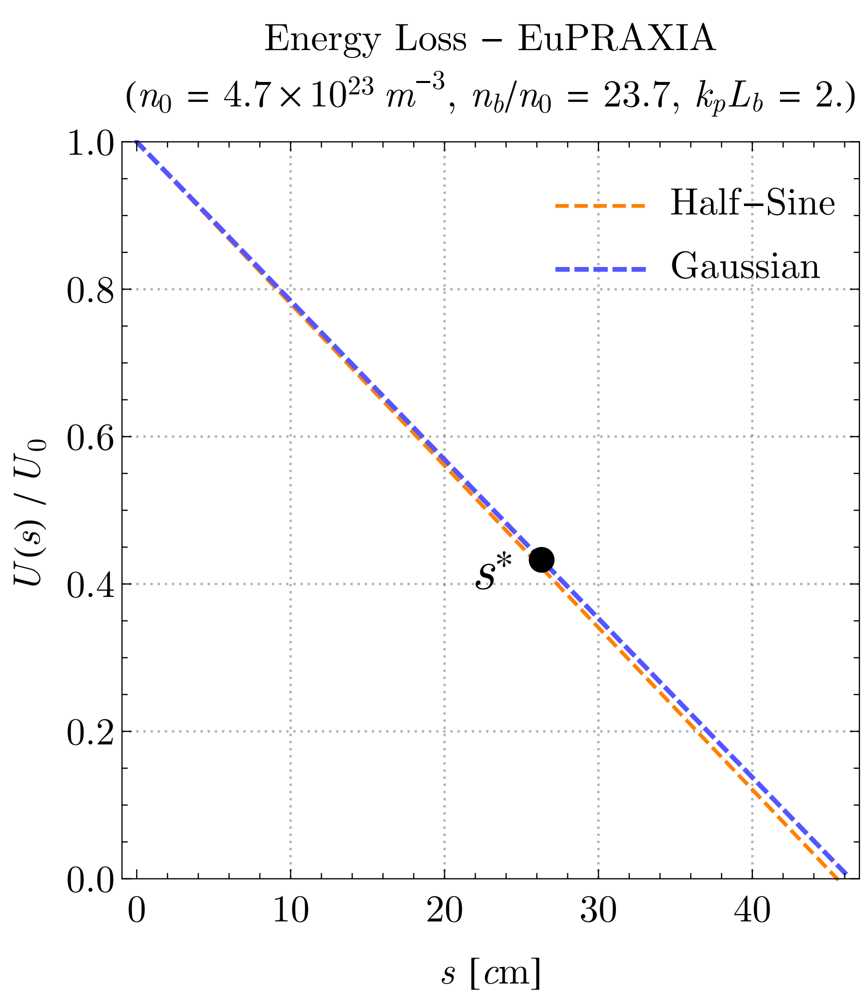
Analytical estimate

EuPRAXIA, sim. 2: $\sigma_\xi = 3\,\mu m$, $\sigma_r = 1\,\mu m$, $k_b L_b = 2$



Shorter normalized length:

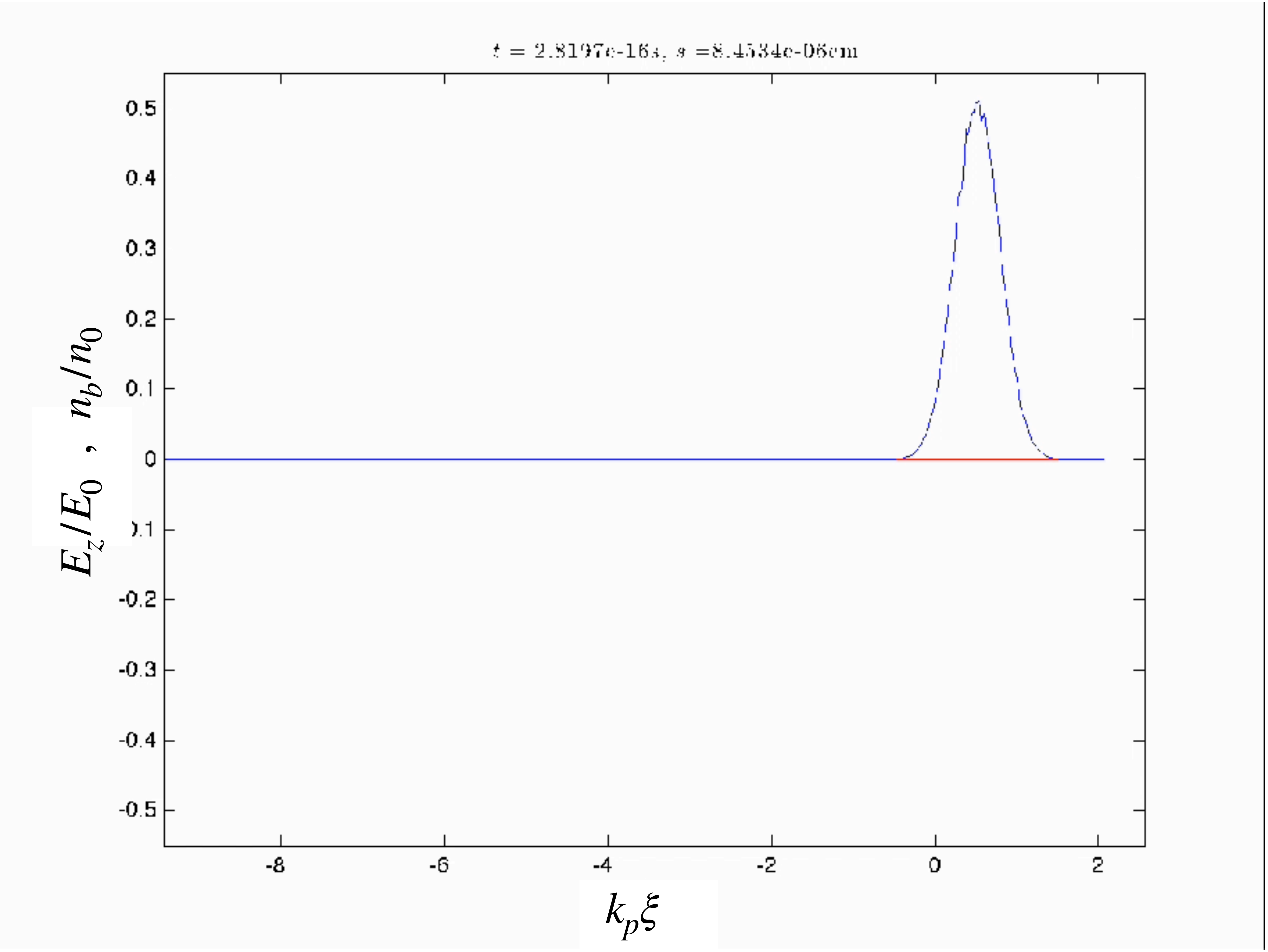
- $L_b = 5.15\sigma_\xi$;
- $k_p L_b = 2$;



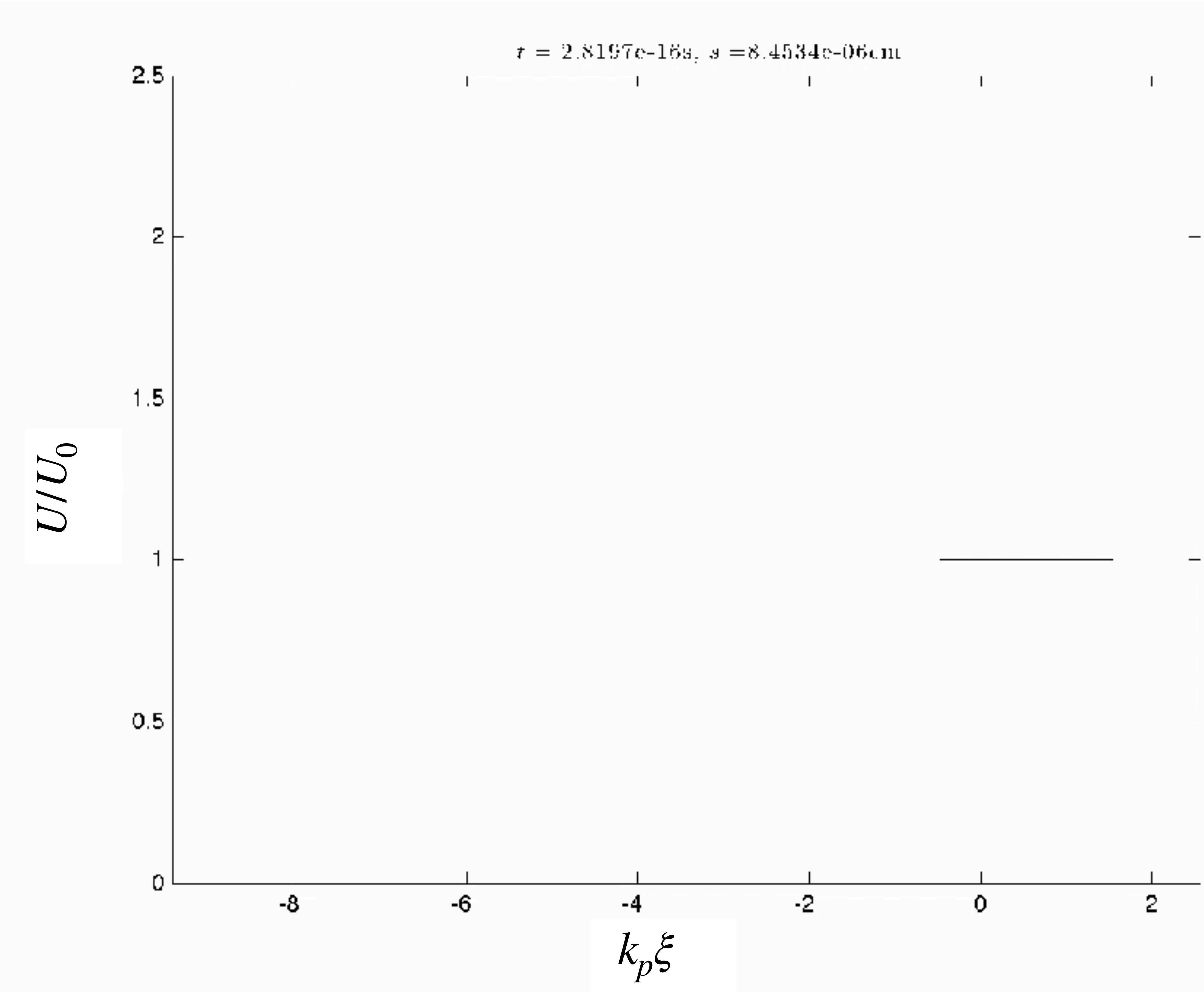
Analytical estimate:

- $s^* \sim 0.26$ cm (saturation point);
- $U(s^*)/U_0 \sim 0.43$ (normalized energy)

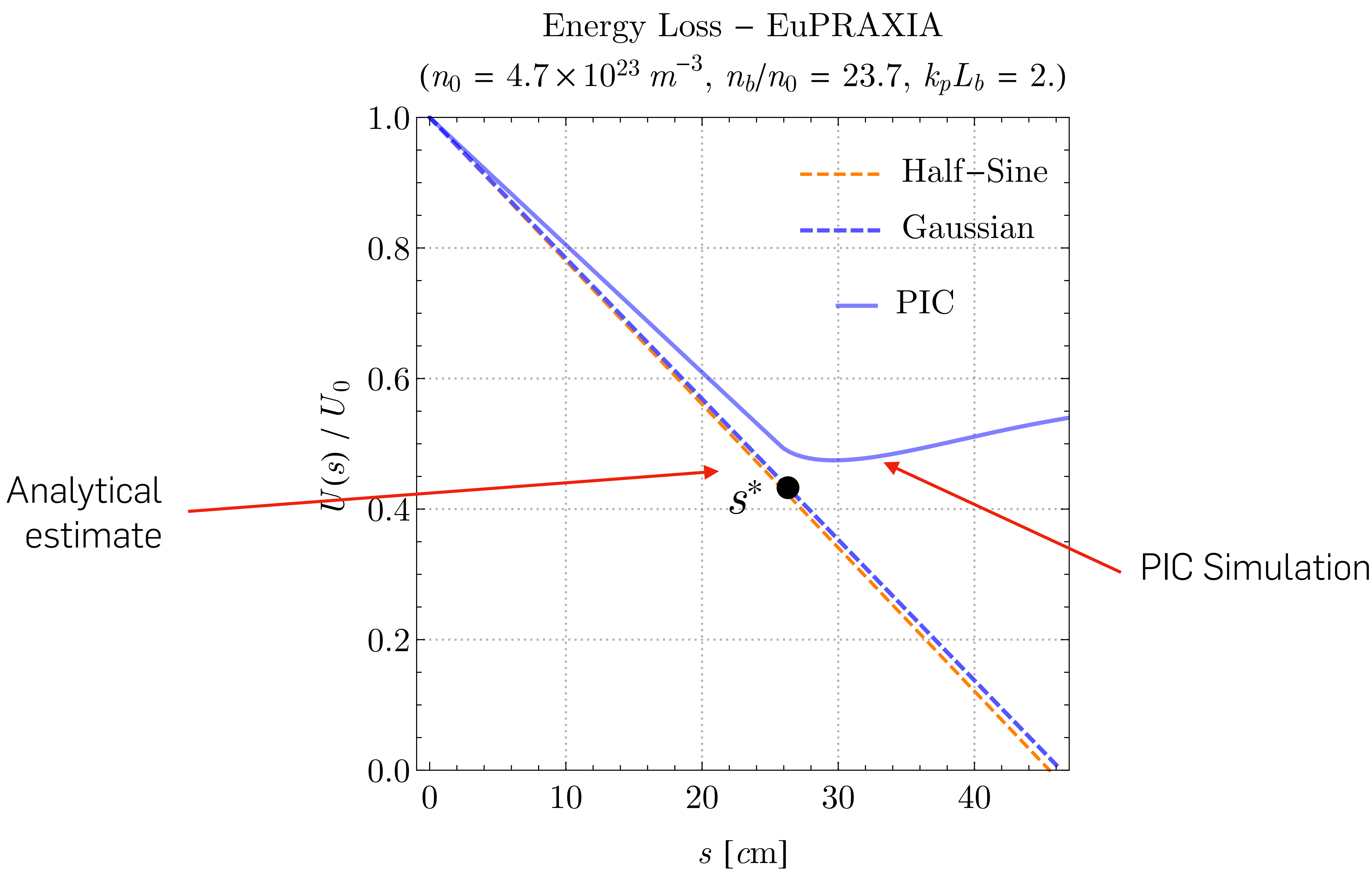
EuPRAXIA, sim. 2: $\sigma_\xi = 3\mu\mathrm{m}$, $\sigma_r = 1\mu\mathrm{m}$, $k_b L_b = 2$



EuPRAXIA, sim. 2: $\sigma_\xi = 3\,\mu\mathrm{m}$, $\sigma_r = 1\,\mu\mathrm{m}$, $k_b L_b = 2$



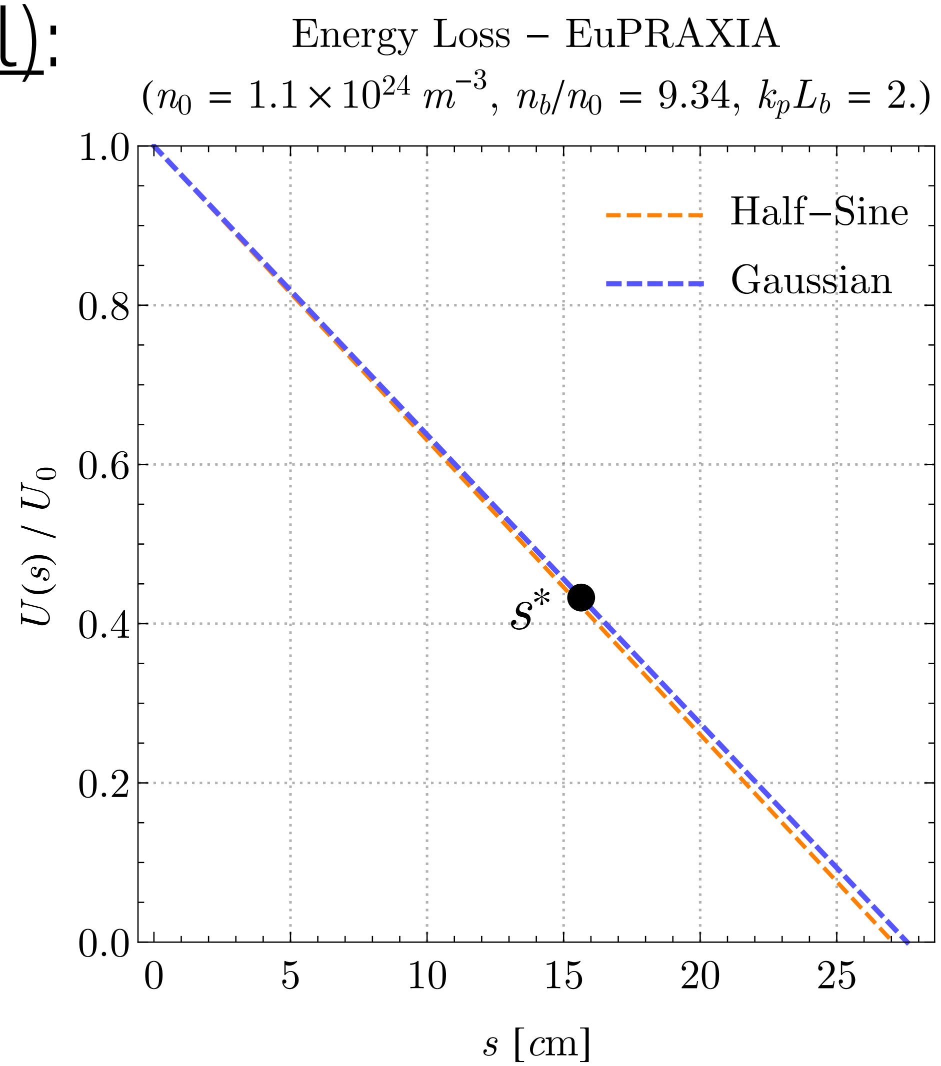
EuPRAXIA, sim. 2: $\sigma_\xi = 3\mu\mathrm{m}$, $\sigma_r = 1\mu\mathrm{m}$, $k_b L_b = 2$

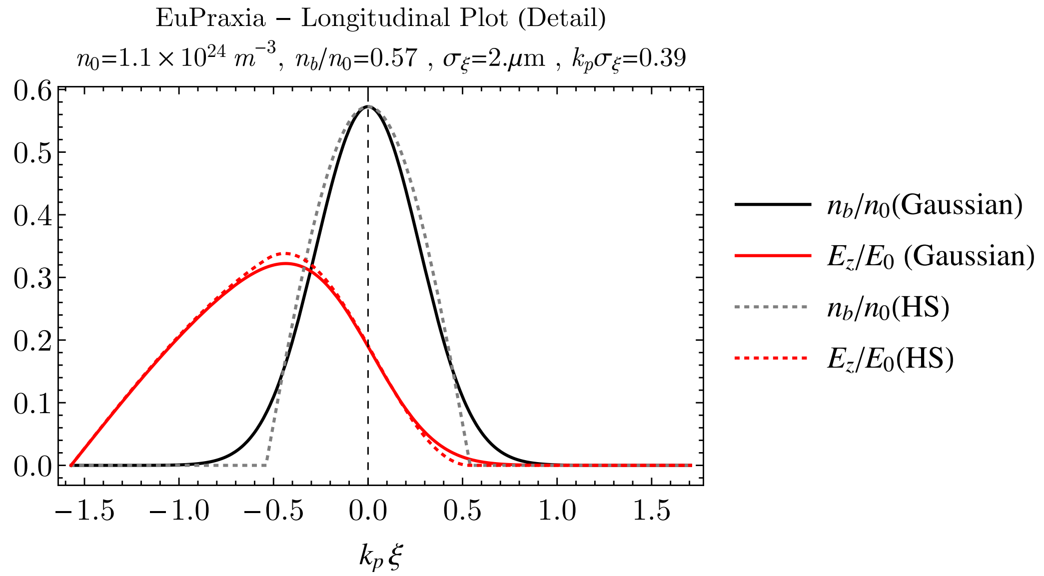


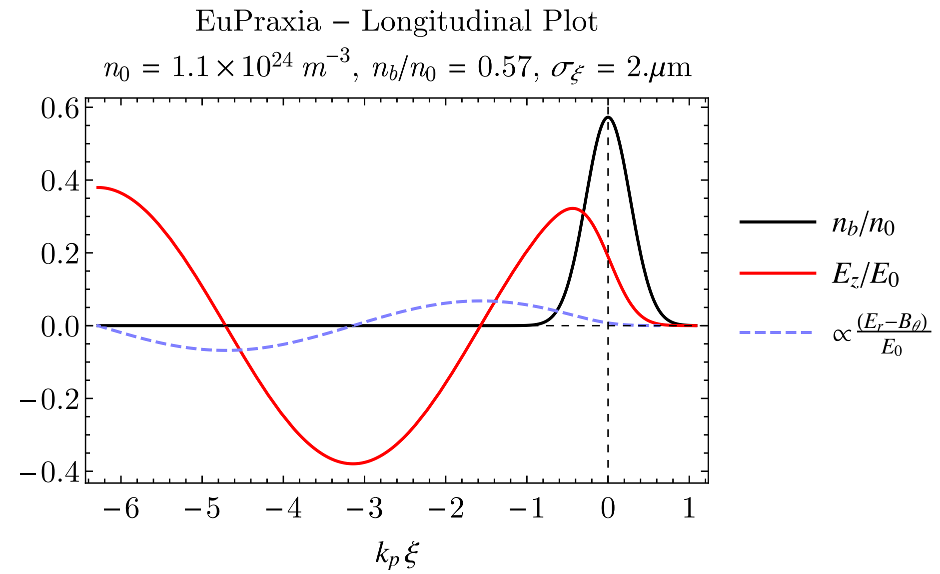
EuPRAXIA, sim. 3: $\sigma_\xi = 2\mu m$, $\sigma_r = 1.3\mu m$, $\sigma_b L_b = 2$

Parameter Set 3 (optimal):

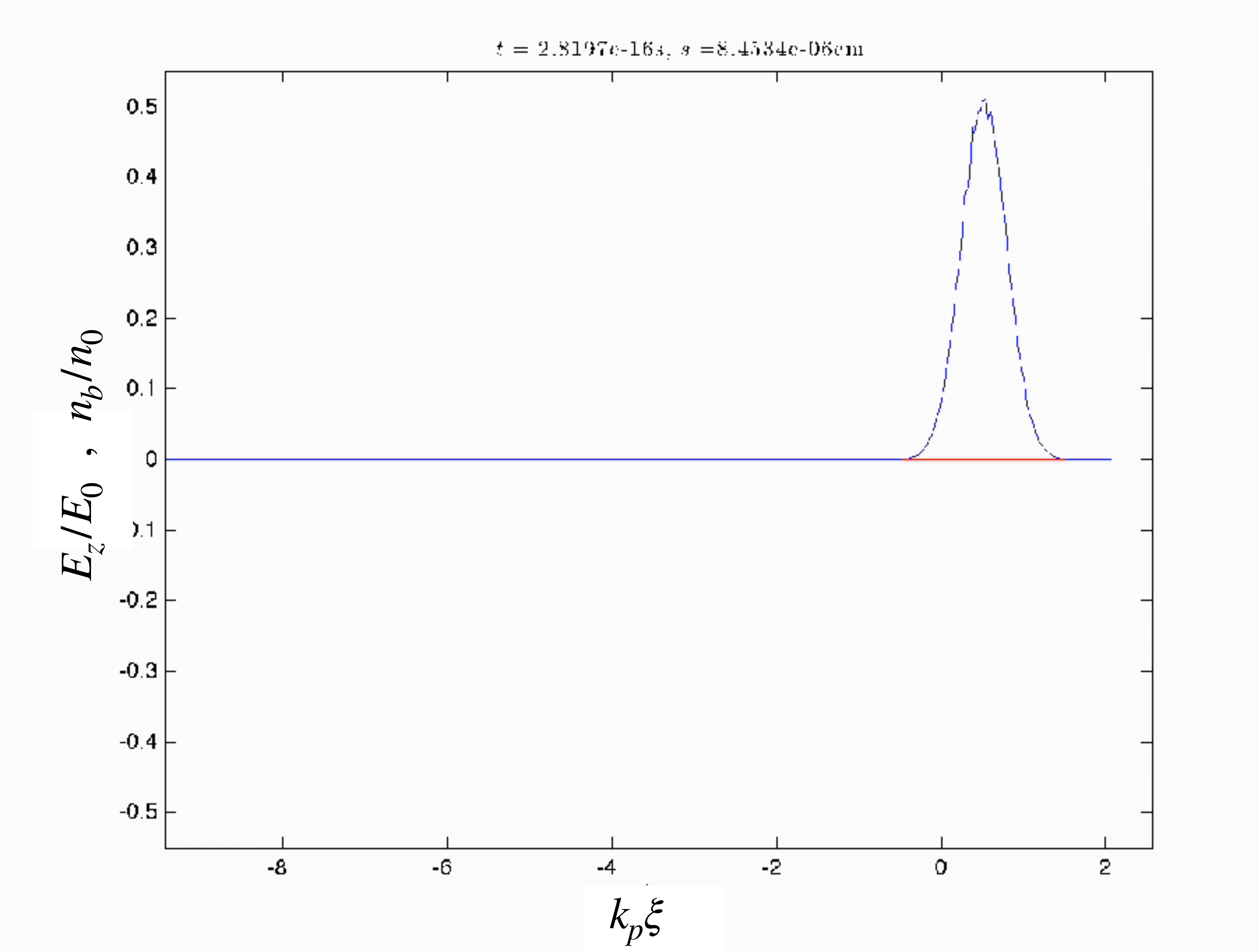
- $L_b = 5.15\sigma_\xi$;
- $k_p L_b = 2$;
- $s^* \sim 0.26$;
- $U(s^*)/U_0 \sim 0.43$.



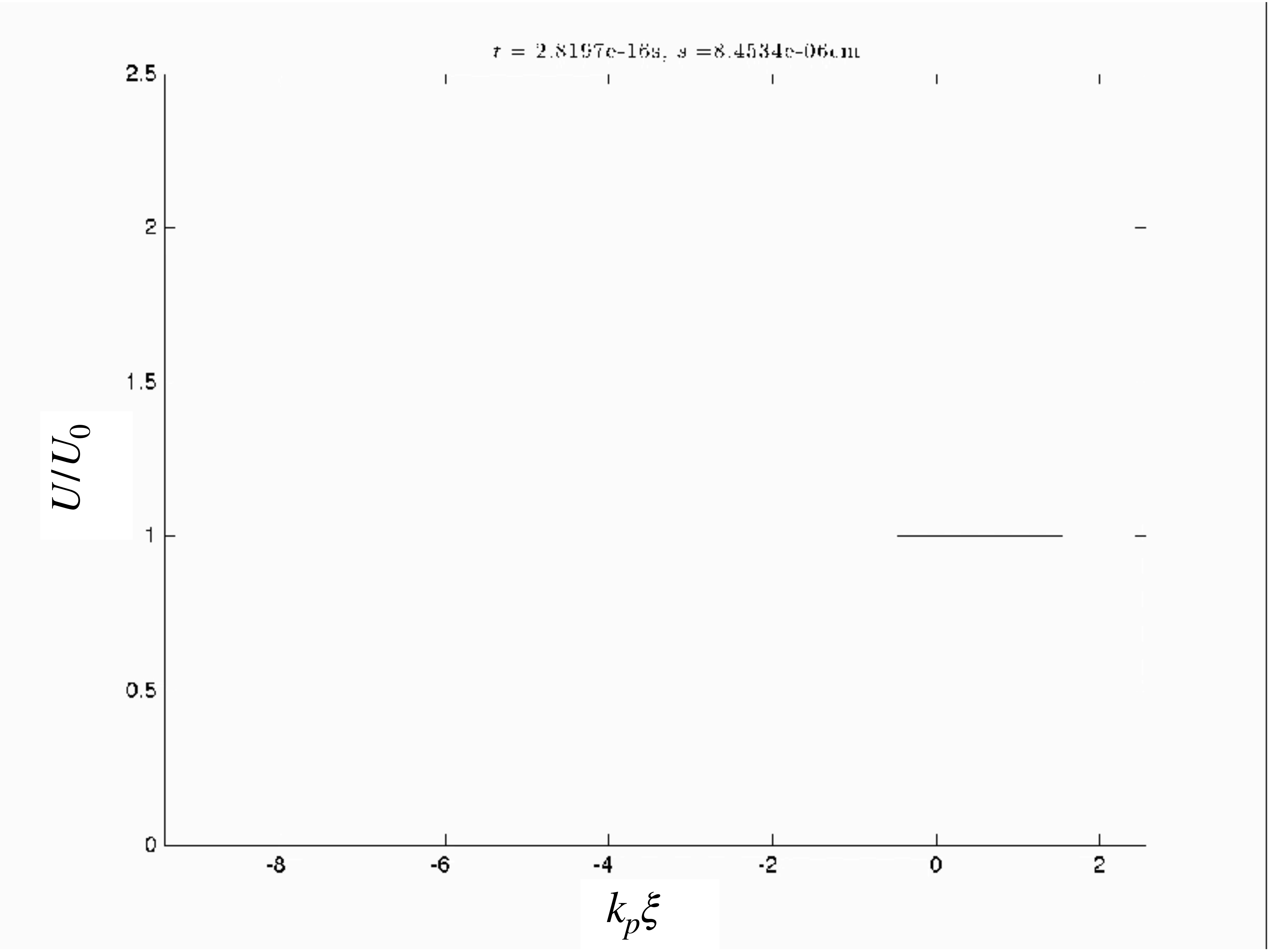




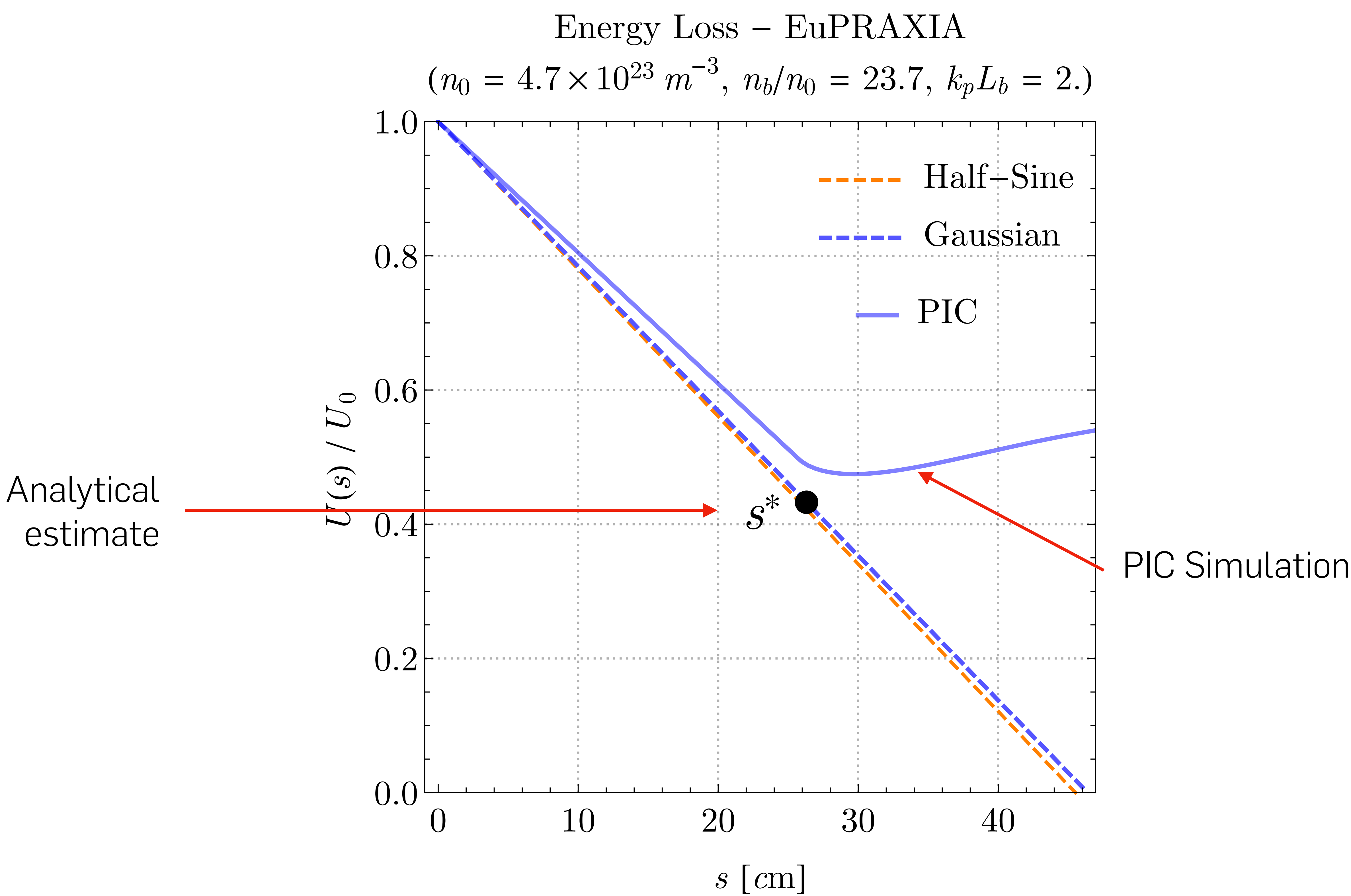
EuPRAXIA, sim. 3: $\sigma_\xi = 2\mu m$, $\sigma_r = 1.3\mu m$, $\sigma_b L_b = 2$



EuPRAXIA, sim. 3: $\sigma_\xi = 2\mu\text{m}$, $\sigma_r = 1.3\mu\text{m}$, $\sigma_b L_b = 2$

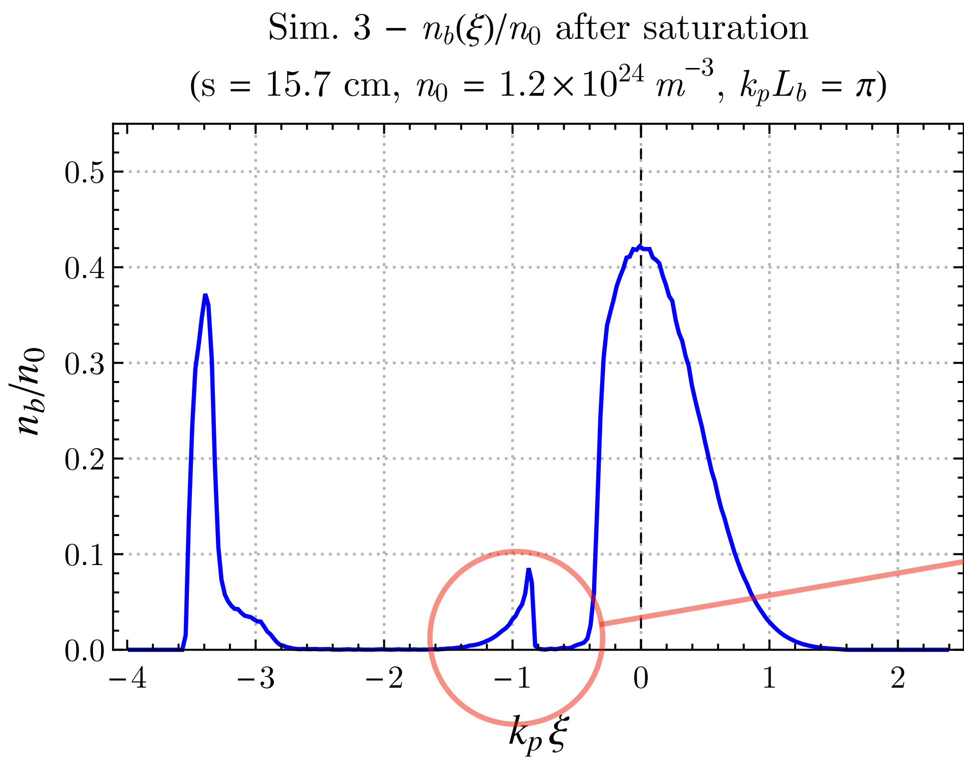


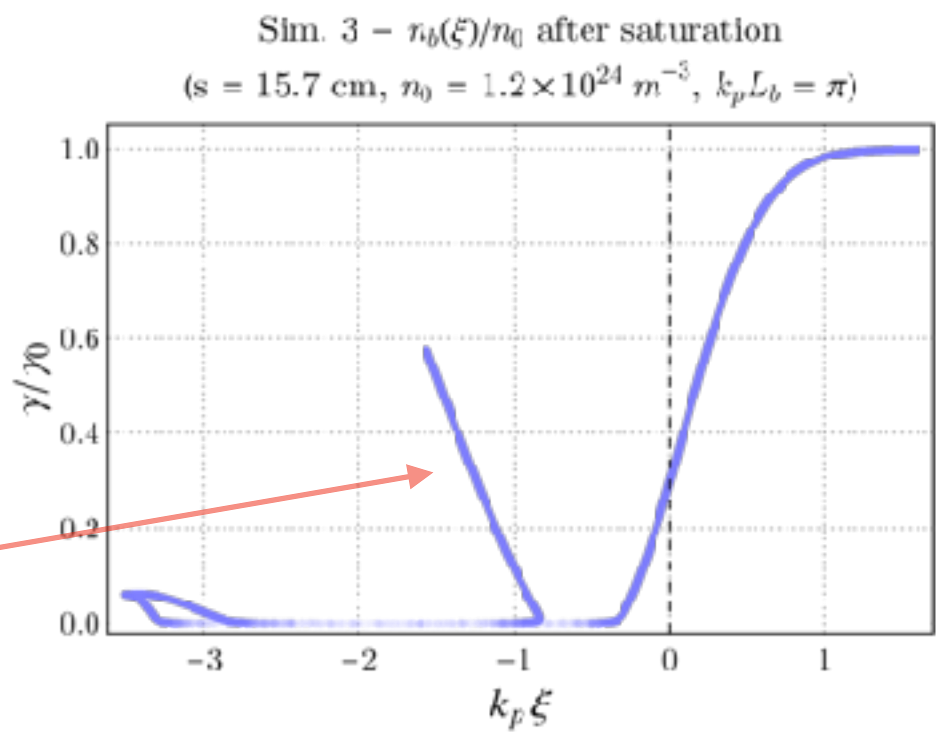
EuPRAXIA, sim. 3: $\sigma_\xi = 2\mu m$, $\sigma_r = 1.3\mu m$, $\sigma_b L_b = 2$

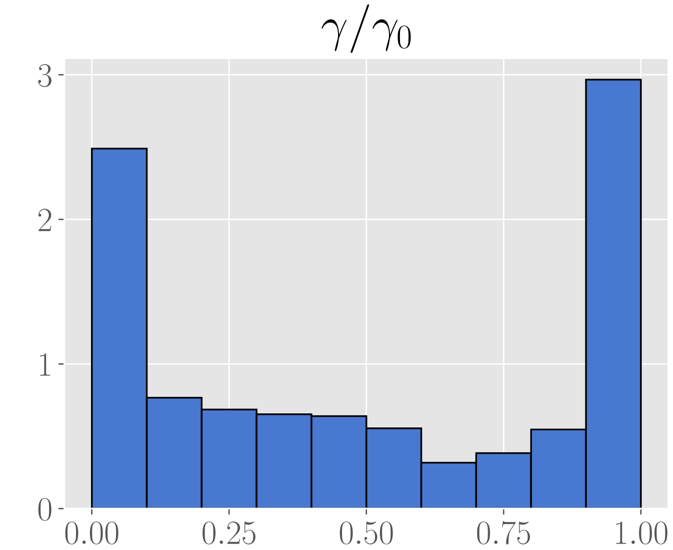


EuPRAXIA - Sim. 1 ($k_pL_b = \pi$) vs. Sim. 2 ($k_pL_b = 2$)

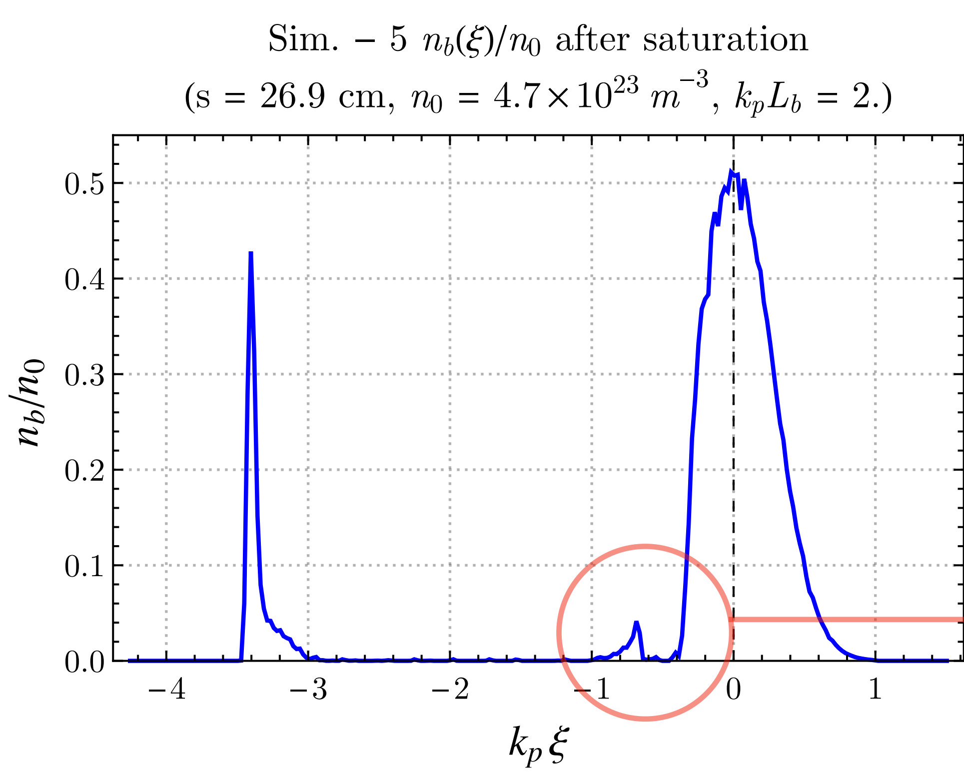
- Sim. 1: $k_pL_b = \pi$, $\sigma_\xi = 3\ \mu$m , $\sigma_r = 1\ \mu$m

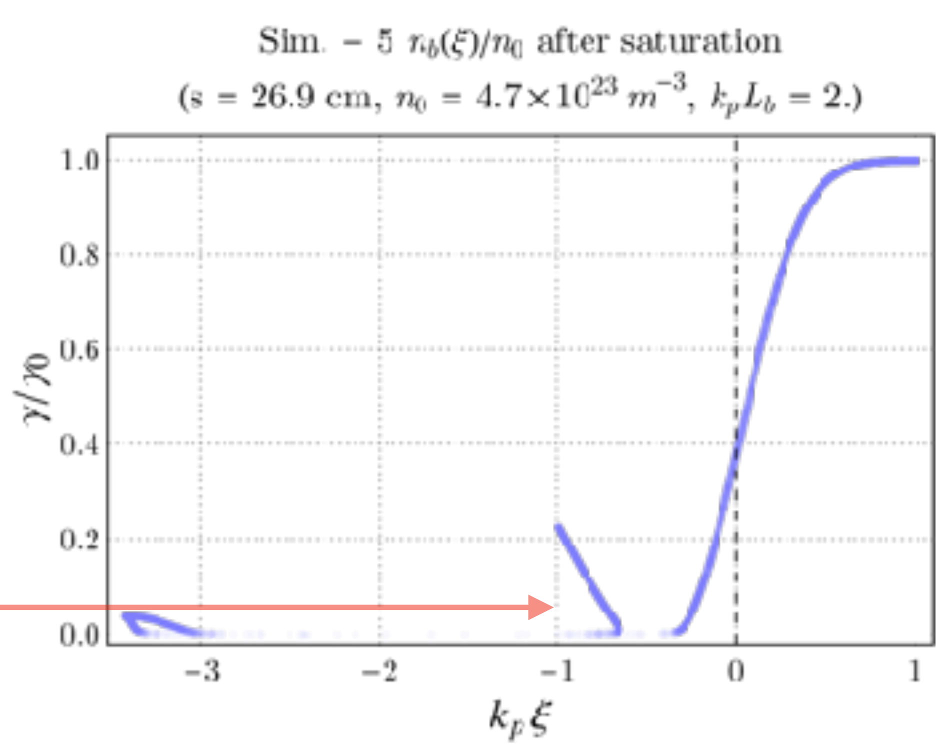


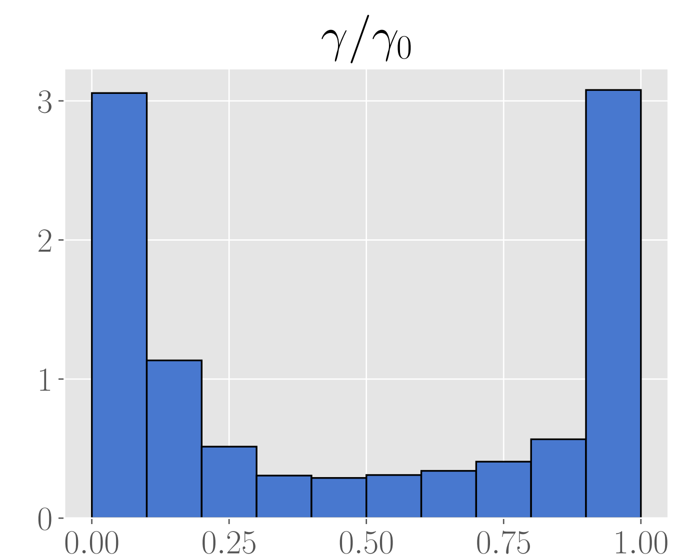




- Sim. 2: $k_pL_b = 2$, $\sigma_\xi = 3\ \mu$m , $\sigma_r = 1\ \mu$m

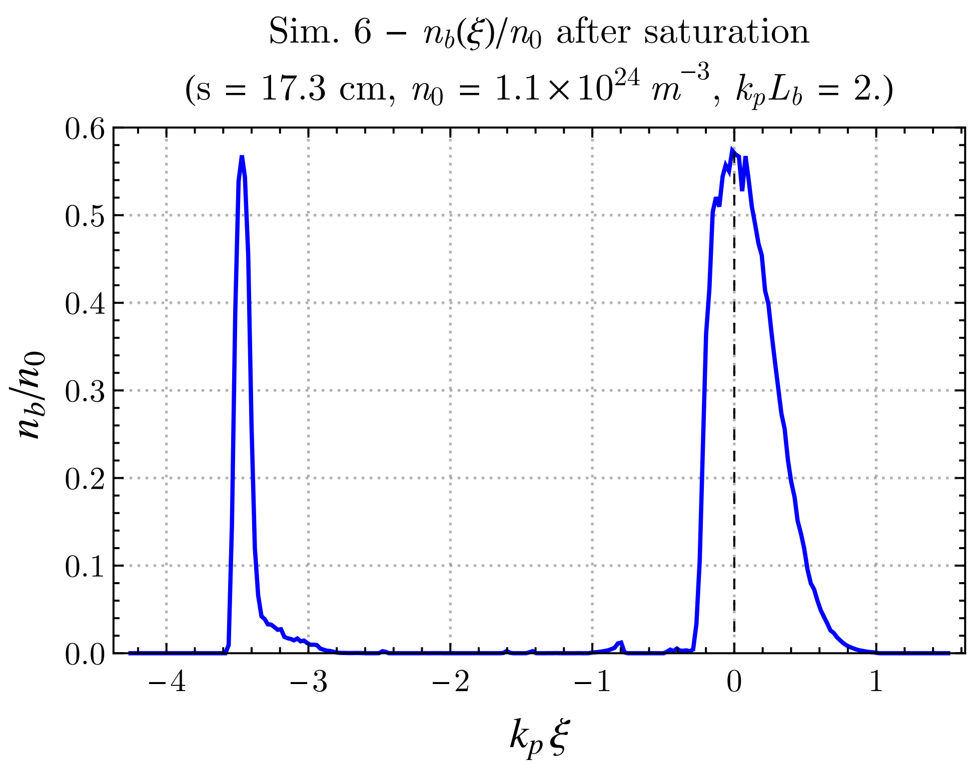


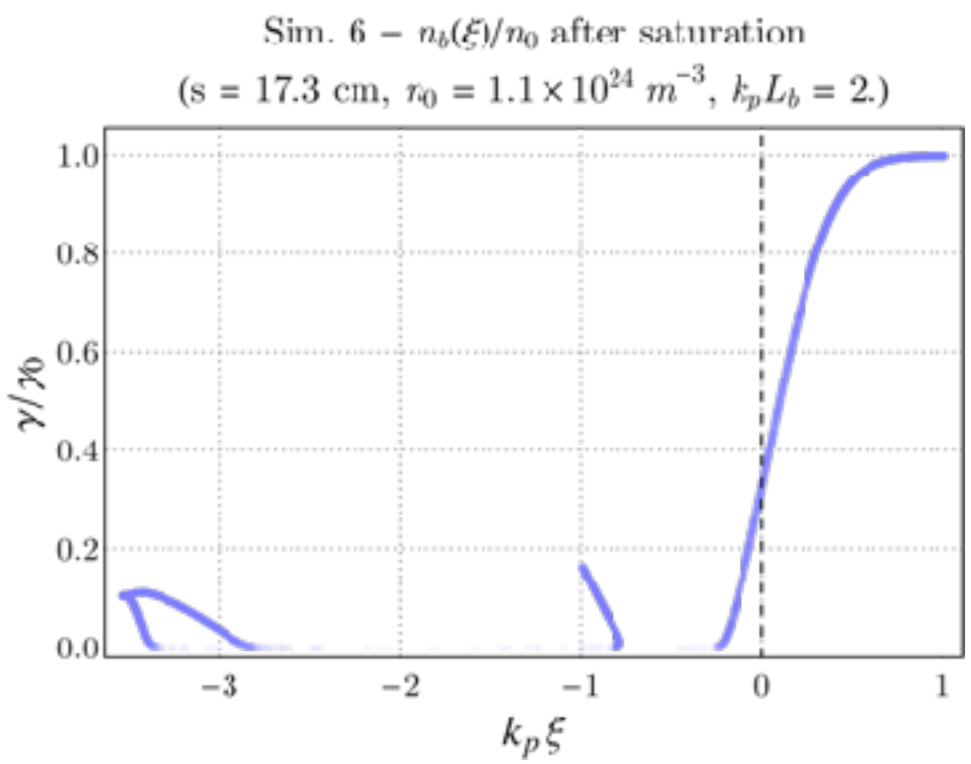


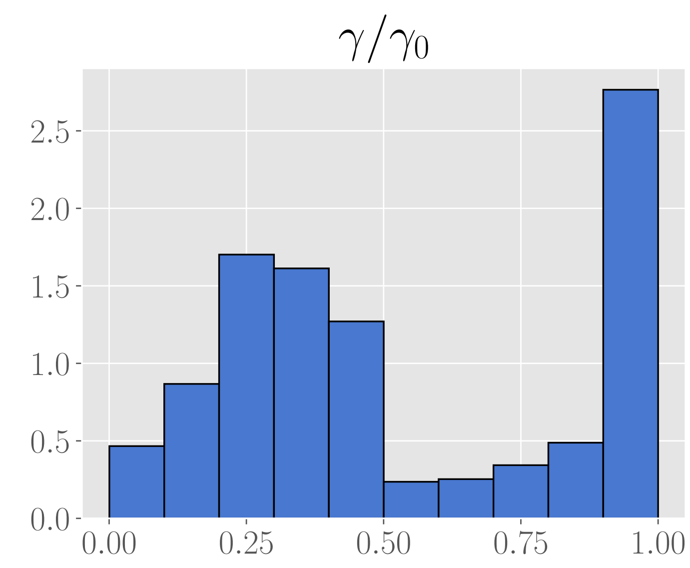


EuPRAXIA - Set 3: $\sigma_\xi = 2\mu\mathrm{m}$, $\sigma_r = 1.3\mu\mathrm{m}$, $\sigma_b L_b = 2$

- Sim. 3: optimal parameters ($\sigma\xi$ = 2 μm , σr = 1.3 μm)







Partial conclusions

- Analytical model shows good agreement with PIC simulations in both linear and quasi-linear regimes.
- HSP model can be used to describe the energy loss of a Gaussian beam (better agreement if $k_pL_b = k_p(5.15\boldsymbol{\sigma}_\xi) \lesssim \boldsymbol{\pi}$.
- In the passive beam dump, phase space behavior is determined by the chosen normalized beam length k_pL_b:
  - $k_pL_b = \boldsymbol{\pi}$: faster extraction, more energy chirp.
  - $k_pL_b < \boldsymbol{\pi}$: slower extraction, less energy chirp.
- For a 5 GeV beam (EuPRAXIA), it should be possible to extract ~ 60% of beam energy in a ~26 cm passive plasma beam dump (but particles at the head of the beam preserve their full initial energy
- An active beam dump could solve this issue (but it is necessary to check the laser cost to do it.