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Ion channel formation for advanced betatron emission

Andrea R. Rossi

INFN - Milan Section

On behalf of the EuPRAXIA@SPARC_LAB and SL_BETATEST collaboration

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Introduction

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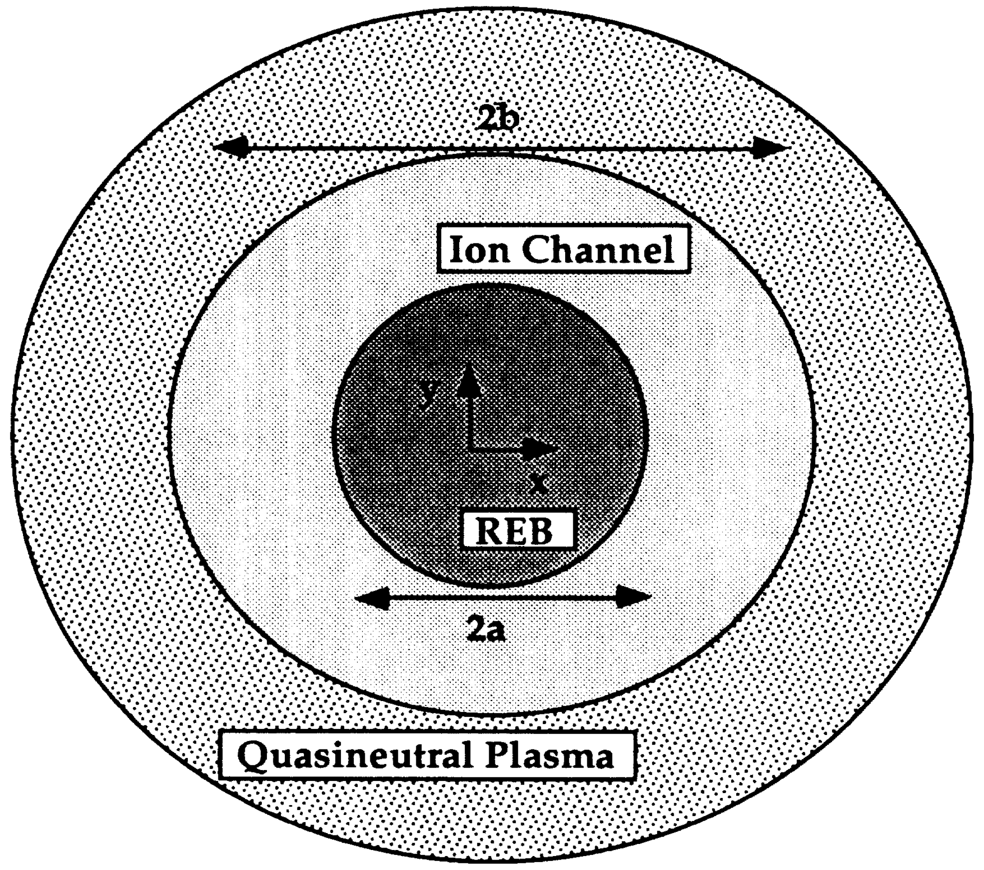
Ion-Channel Laser

David H. Whittum and Andrew M. Sessler
Lawrence Berkeley Laboratory, Berkeley, California 94720

John M. Dawson
Department of Physics, University of California at Los Angeles, Los Angeles, California 90024
(Received 5 February 1990)



- Relativistic electron beams (REBs) void a preformed plasma by electrons. The plasma has linear radial forces: focuses the beam and electrons perform betatron oscillations. In some situations, the longitudinal electric field may be negligible (wakeless regime).
- Betatron oscillations at $\omega_\beta \propto \omega_p/\sqrt{\gamma}$ provide a source of e.m. radiation with a fundamental frequency $\omega_0 \propto \gamma^{3/2}\omega_p$.
- If oscillations amplitude is small (i.e negligible harmonic emission), collective effects in e.m. radiation emission may set in, realizing a plasma based FEL or ion-channel laser.
- Compared to standard magnetic undulators, the ICL has larger acceptance in bunch energy spread, due to large Pearson parameter.

Motivation

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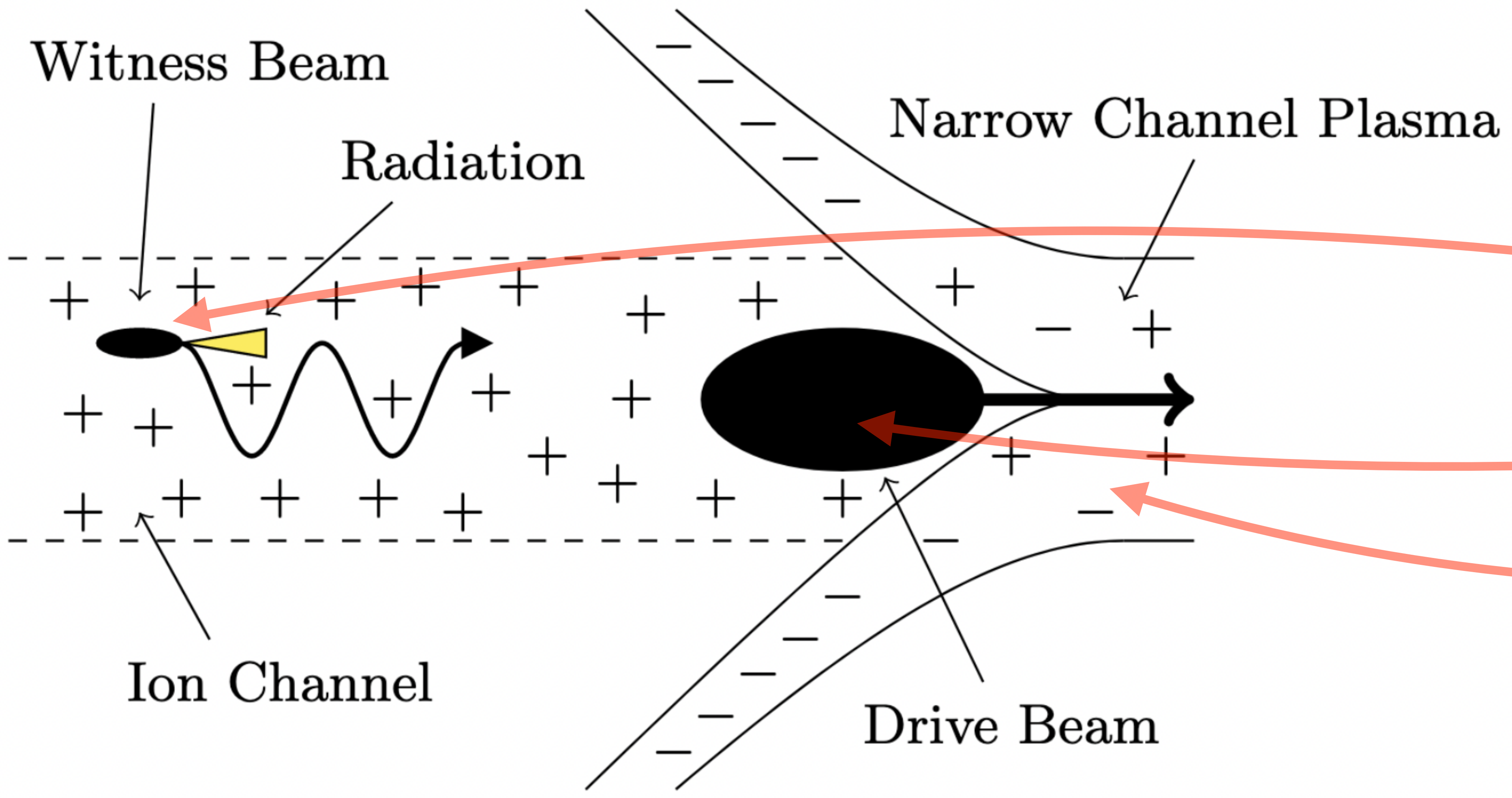
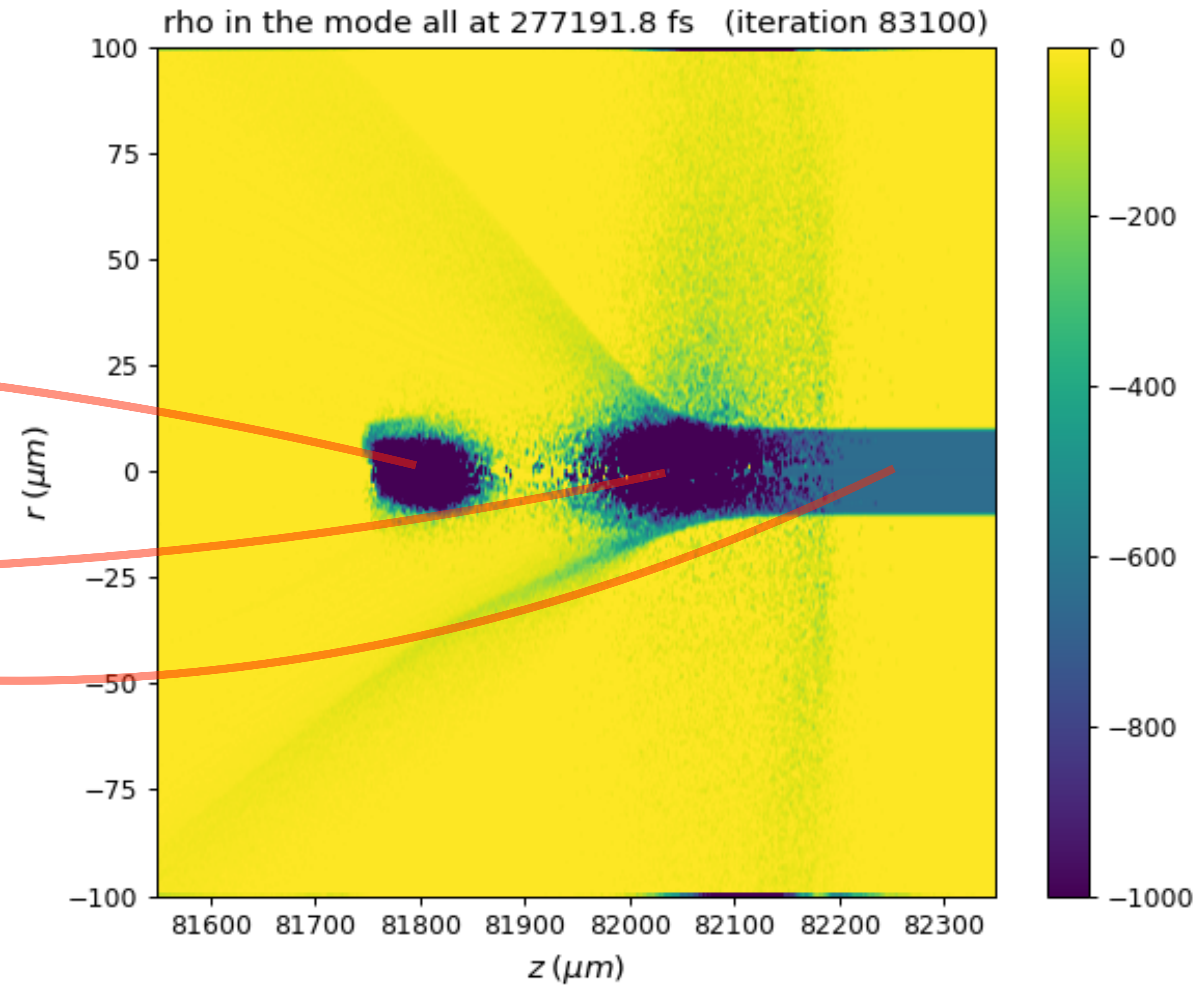
- The wakeless regime can be realized when plasma is preformed in a cylindrical volume with limited radius R_{ch} and a drive bunch manages to expel all electrons from it, realizing a plasma based compact undulator.
- Even without emission collective effects, the resulting betatron source can have a much reduced emission band compared to emission with acceleration.
- Drive bunch creates the wakeless channel; a properly tailored and injected witness emits radiation.



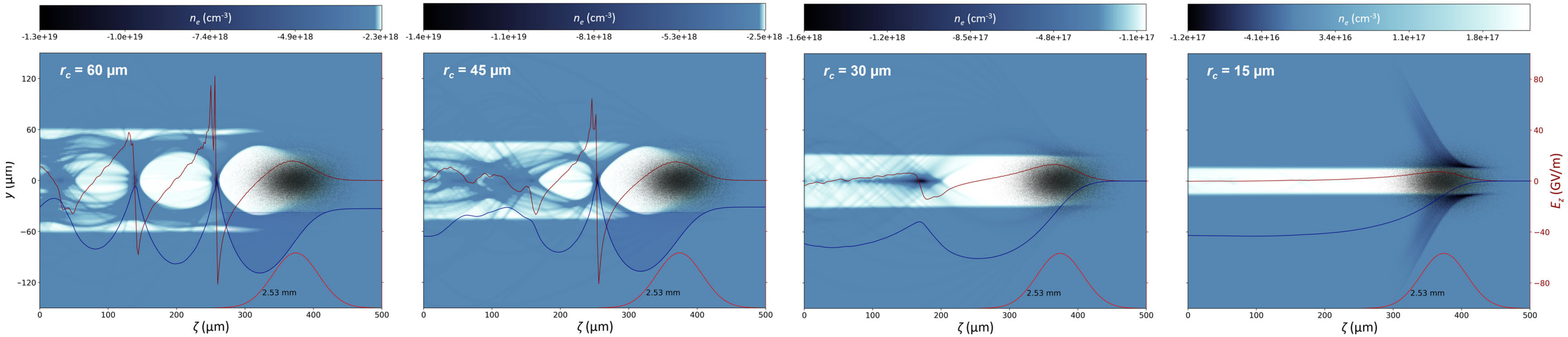


Test experiment @ SPARC_LAB

State of the art

The idea dates back to 1990 but…

- All published papers (not many!!) deal with radiation emission conditions and properties.
- Only one gives some hints about channel formation but just as a limitation in PWFA!

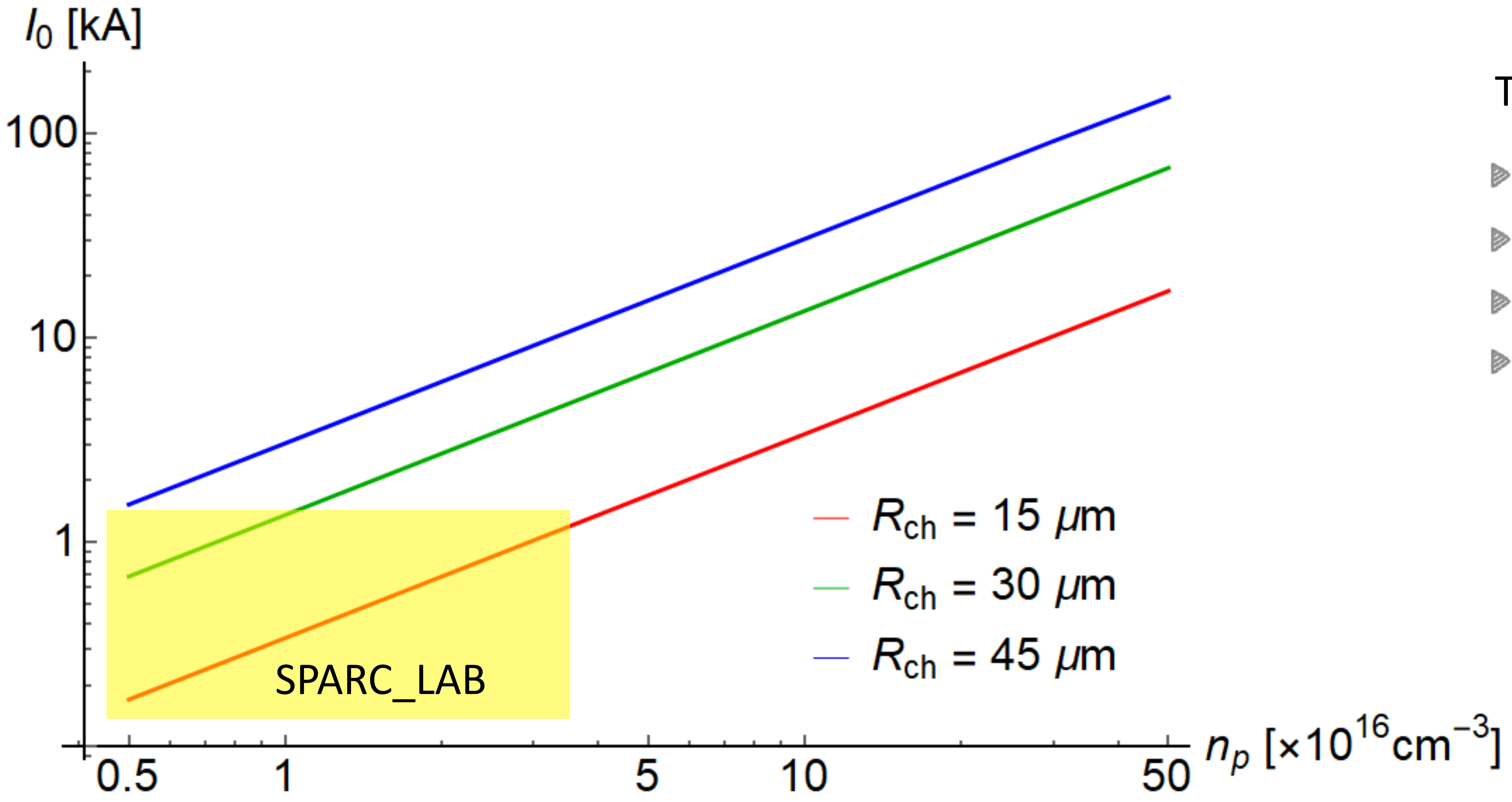


A.F. Habib et al., Plasma Photocathodes, Ann. Phys. 535, 2200655 (2023). A.F. Habib et al., arXiv:2111.01502v1 (2021).

- As the preformed channel radius gets thinner and thinner, the ICL formation improves…

A bit of theory

- Whittum et al. provide an estimate for the blowout radius $R_{bl} \sim \sigma_x \sqrt{n_b/n_p}$, assuming $n_b > n_p$.
- Assuming a bi-Gaussian bunch, and requiring $R_{bl} > R_{ch}$, leads to $I_b/I_0 > 1$ with $I_0 = \pi e c R_{ch}^2 n_p$ (**beware: the condition is only necessary!!!**)



Take away informations from scaling:

- Small R_{ch} favors formation.
- High current required $\gtrsim 1$ kA.
- No clues about channel quality, if formed.
- Assuming $E_b \sim 100$ MeV, achievable photon energies in the fundamental are around $\sim 10s - 100s$ meV (IR to visible), depending on emitting bunch transverse size.

How to “measure” channel formation?

Total charge density

$$\chi = \frac{\langle \rho \rangle}{\rho_N^{(0)}}$$

Ions unperturbed charge density

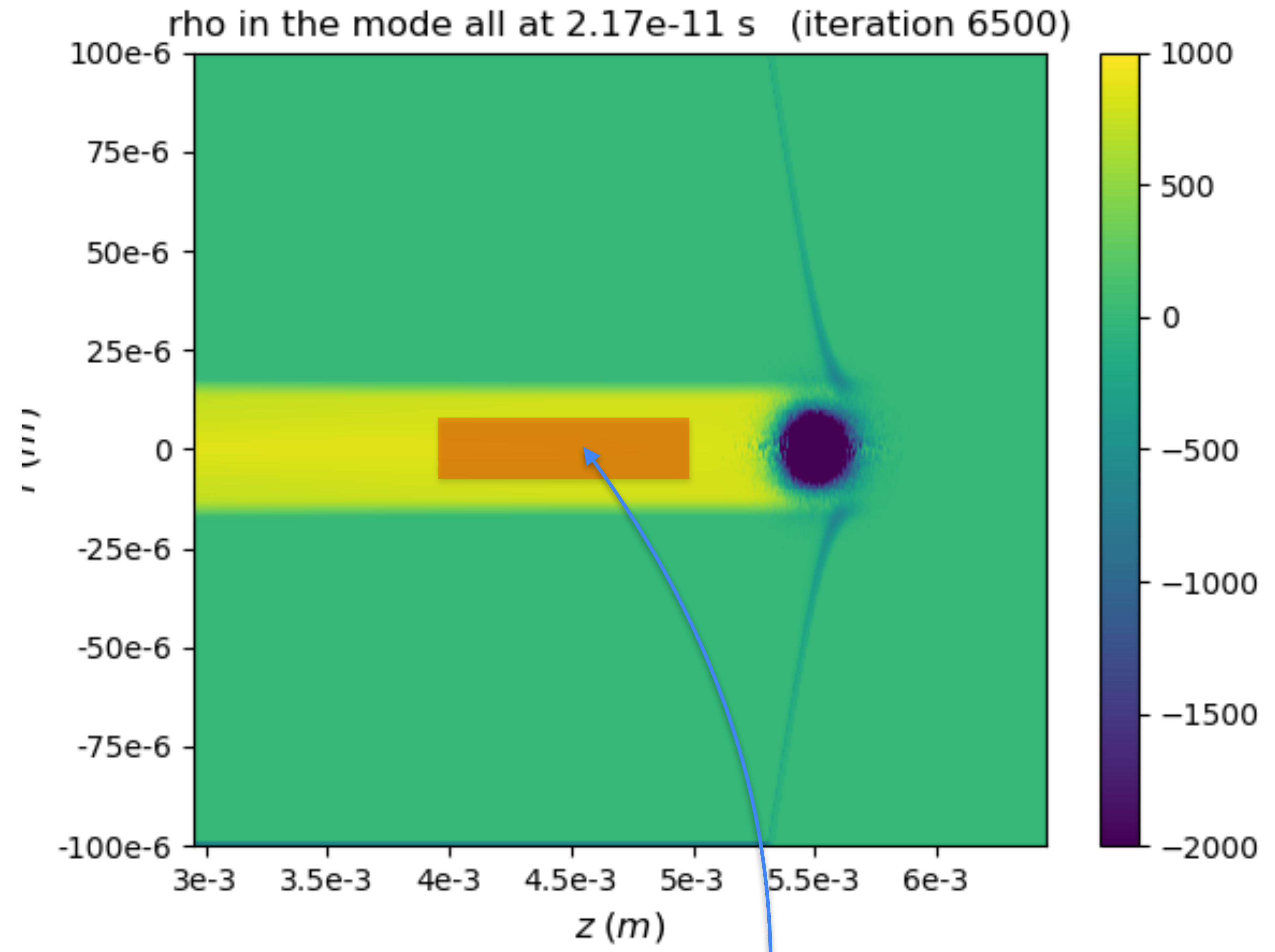
χ → > 1 “Over-formed” channel

χ → ~ 1 Good channel

χ → < 1 Poor channel

σ_χ → ~ 0 Uniform channel

σ_χ → > 0 Non-uniform channel



The average is calculated on a cylindrical volume V with radius $r_V = \frac{2}{3} R_{ch}$ and length equal to about 25% of the window length (1 mm)

Does it work?

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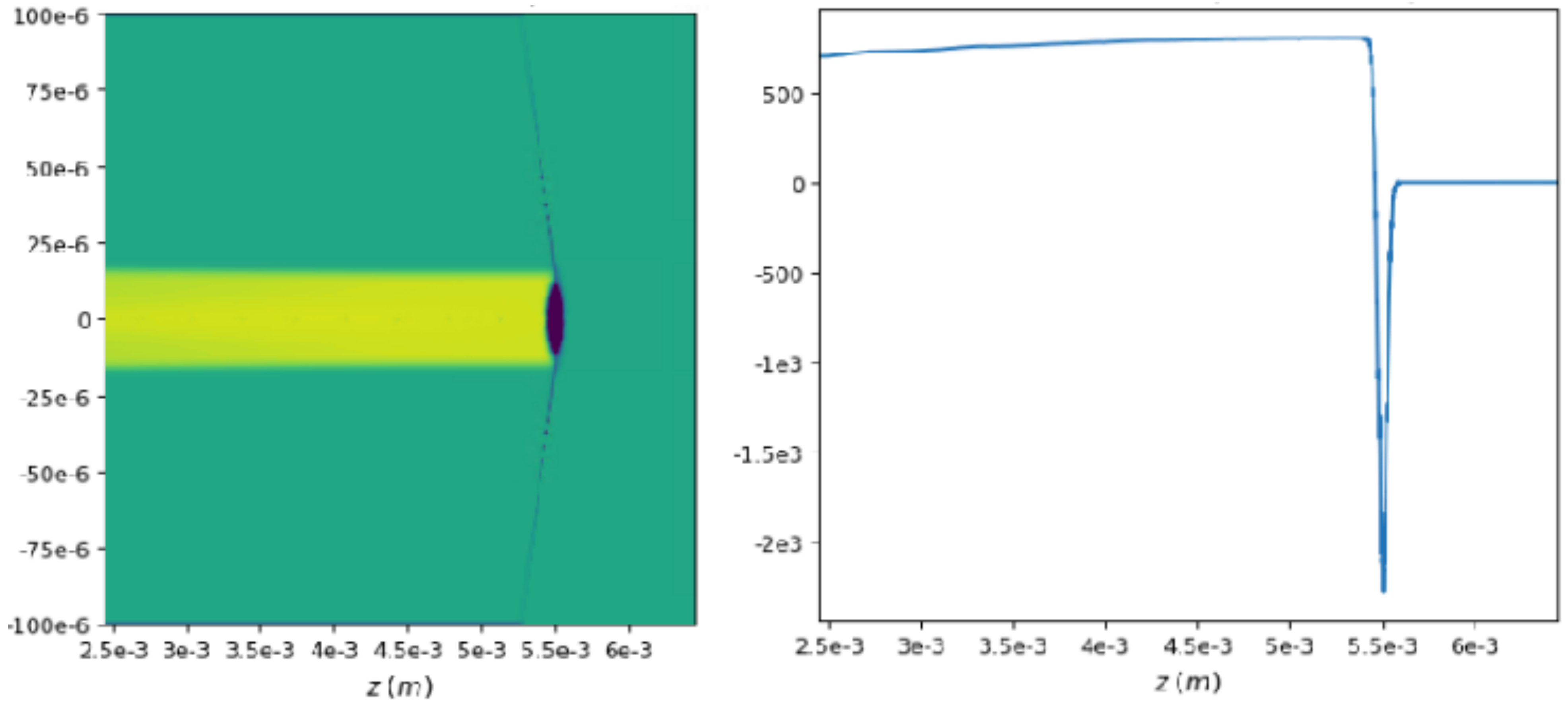
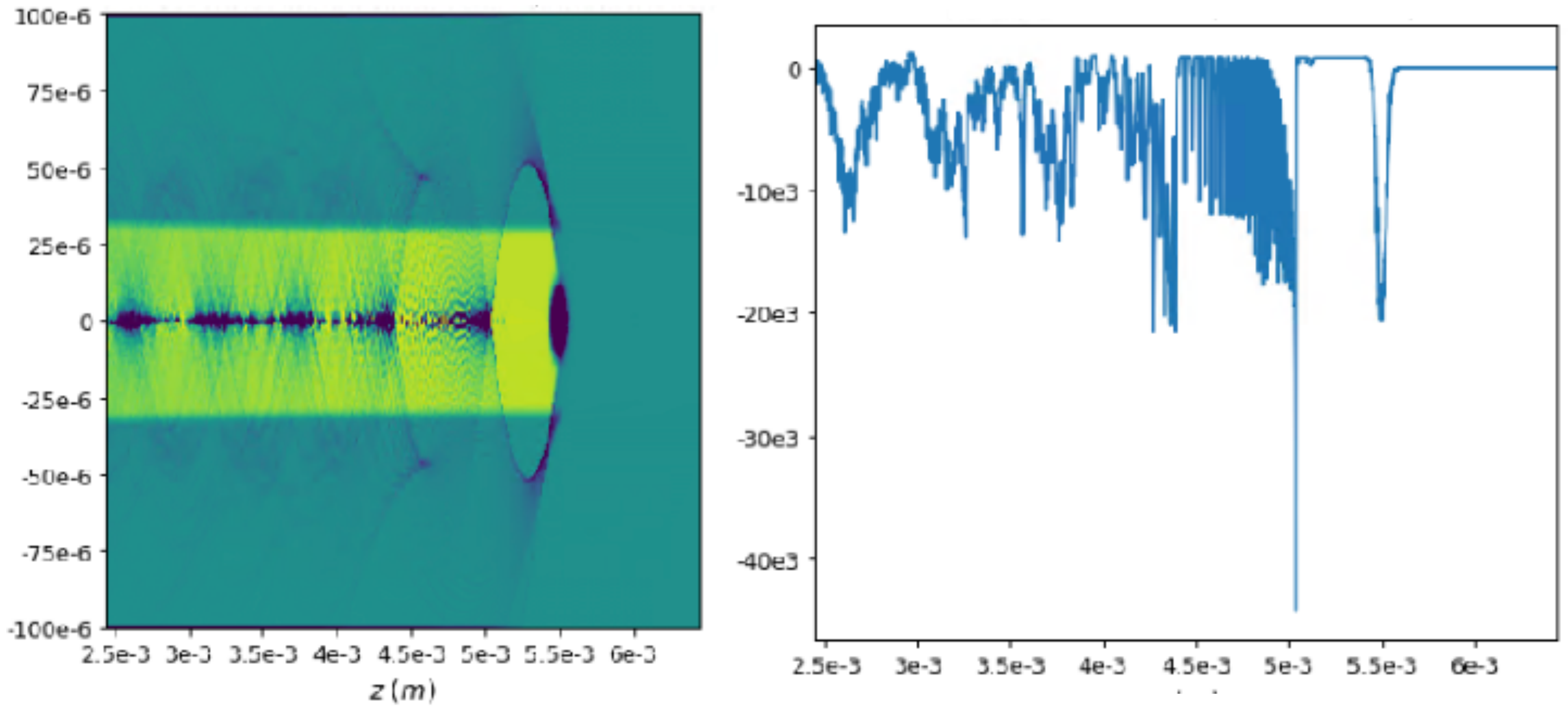
$R_{\text{ch}} = 15\ \mu\text{m},\ n_0 = 5 \times 10^{15}\ \text{cm}^{-3}$ $\chi = 0.99$

$Q_b = 200\ \text{pC},\ \sigma_z = 24\ \mu\text{m}$ $\sigma_\chi = 0.02$



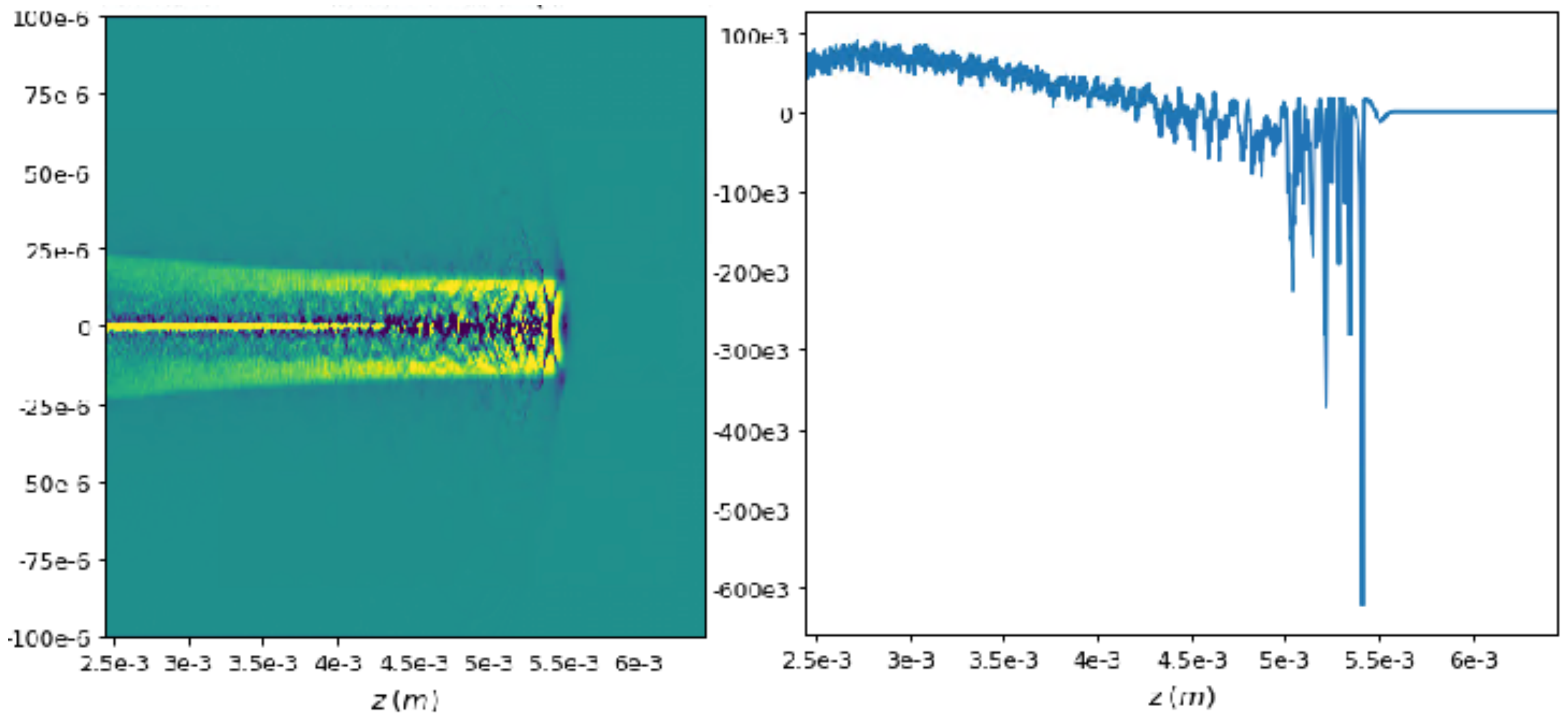
$R_{\text{ch}} = 30\ \mu\text{m},\ n_0 = 5 \times 10^{15}\ \text{cm}^{-3}$ $\chi = 0.67$

$Q_b = 200\ \text{pC},\ \sigma_z = 24\ \mu\text{m}$ $\sigma_\chi = 0.34$



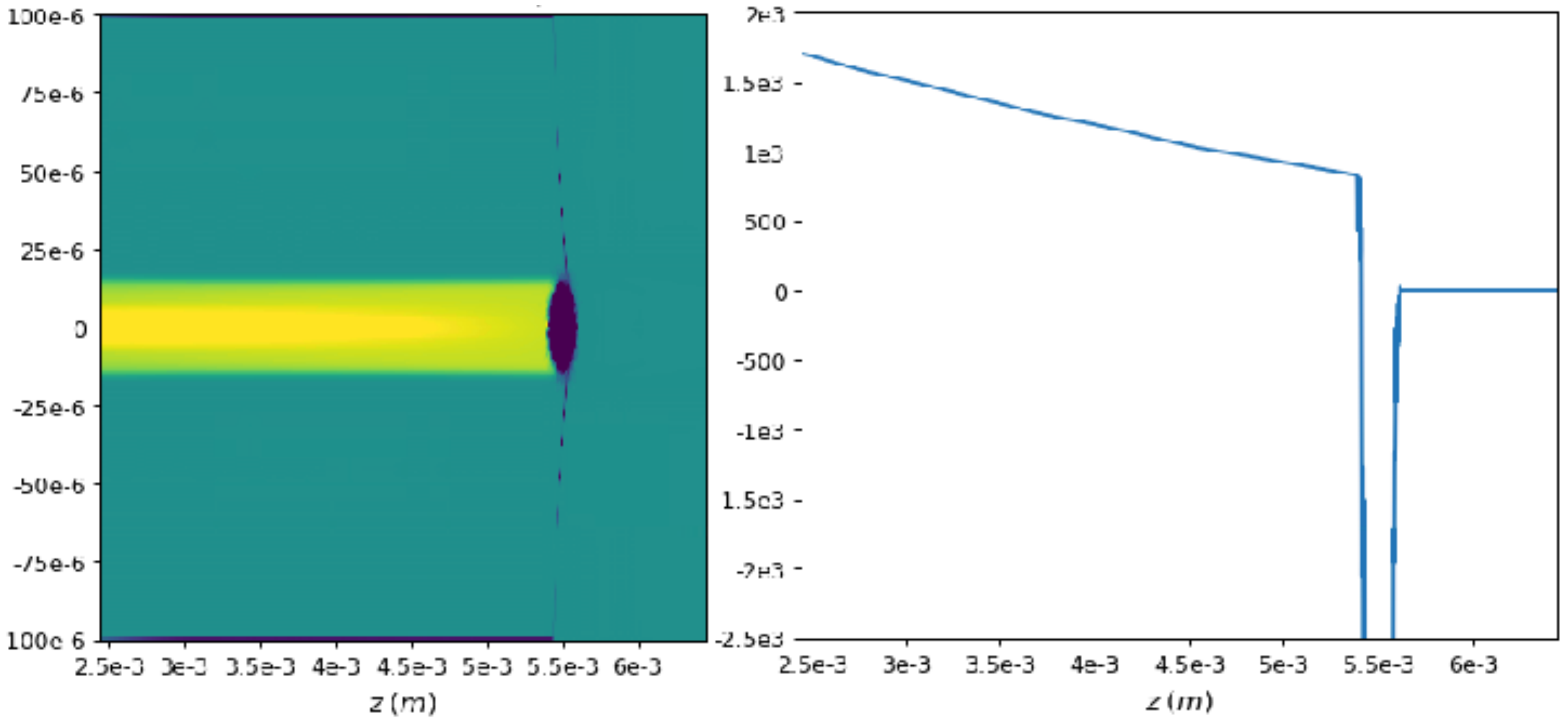
$R_{\text{ch}} = 15\ \mu\text{m},\ n_0 = 10^{17}\ \text{cm}^{-3}$ $\chi = -0.03$

$Q_b = 200\ \text{pC},\ \sigma_z = 24\ \mu\text{m}$ $\sigma_\chi = 0.14$



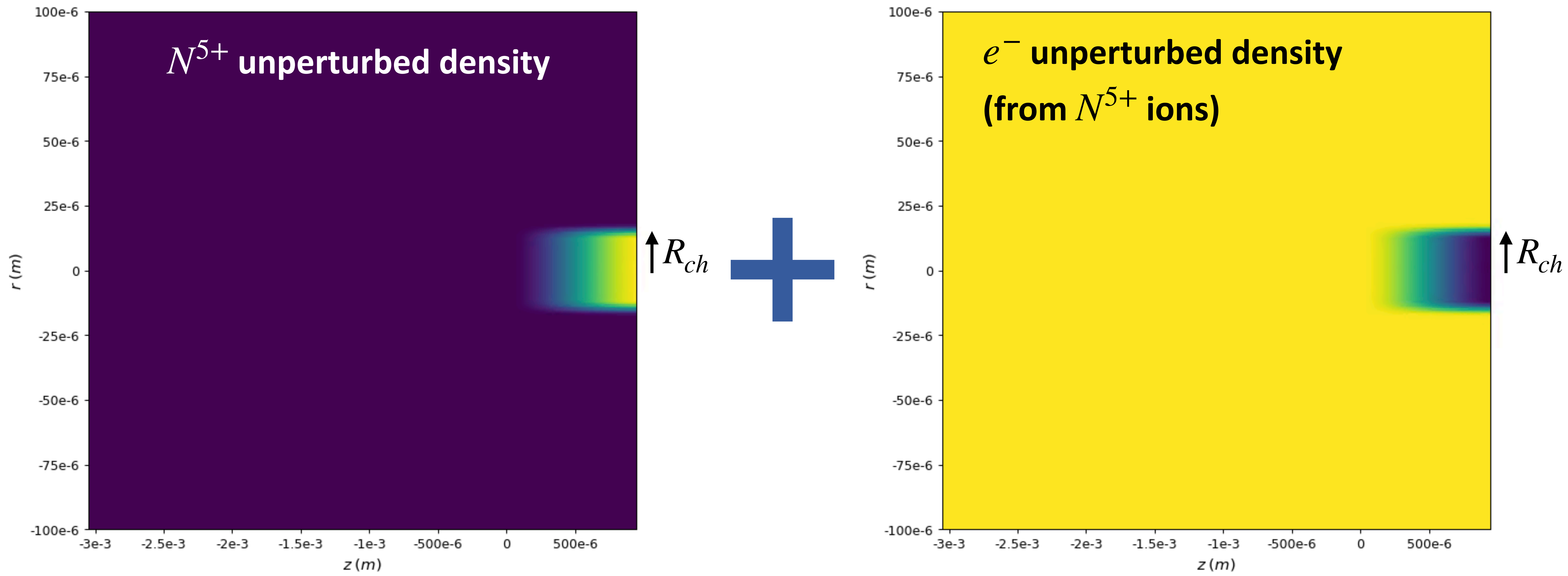
$R_{\text{ch}} = 15\ \mu\text{m},\ n_0 = 5 \times 10^{15}\ \text{cm}^{-3}$ $\chi = 1.17$

$Q_b = 1000\ \text{pC},\ \sigma_z = 30\ \mu\text{m}$ $\sigma_\chi = 0.13$



Simulations setup

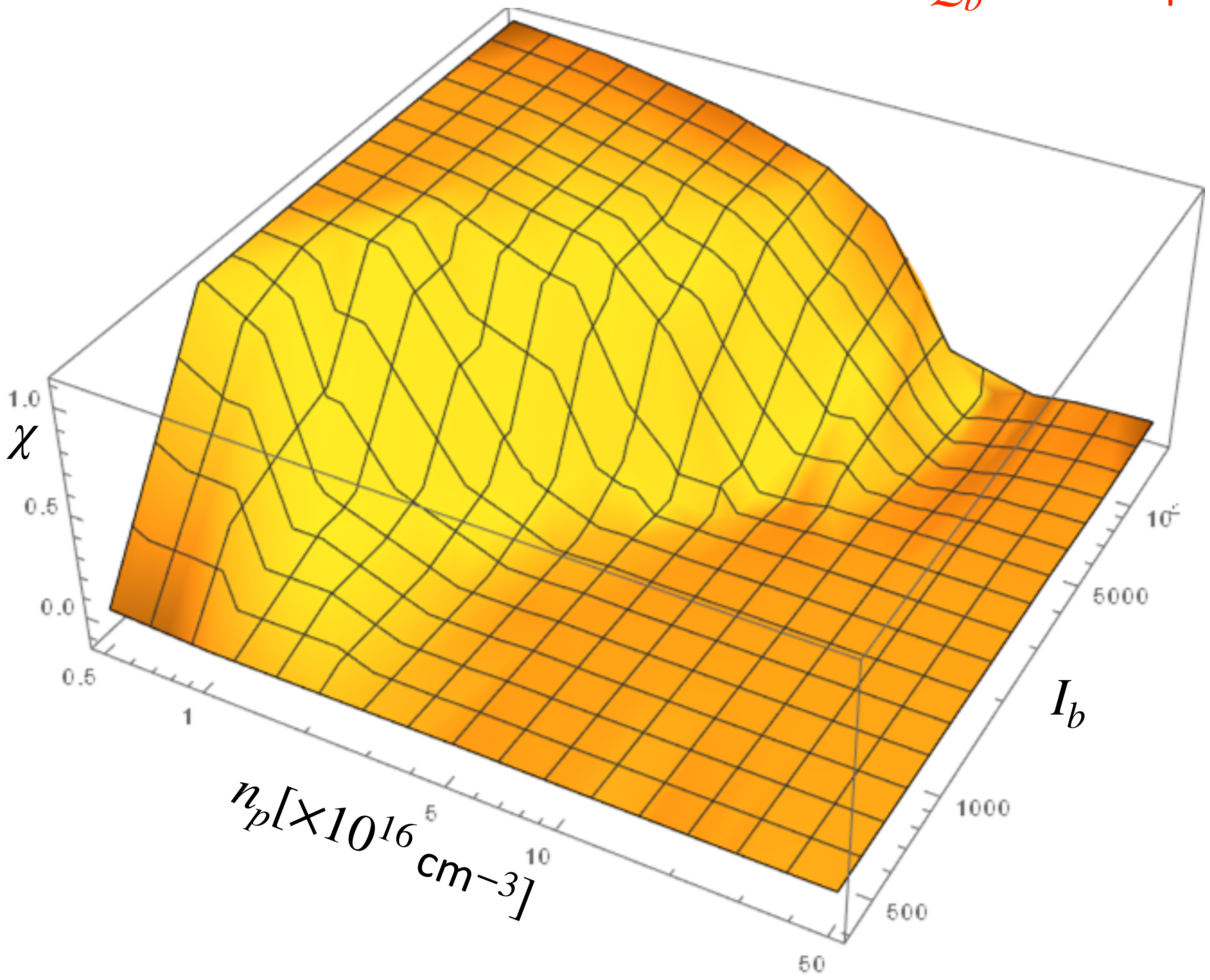
- Pre-ionized channel: N^{5+} within R_{ch} and neutral N outside
- Constant parameters: $\sigma_x = 5$ µm, $E_b \to \infty$
- Scanned parameter: I_b/I_0 which is a function of R_{ch}, n_p, Q_b and σ_z.

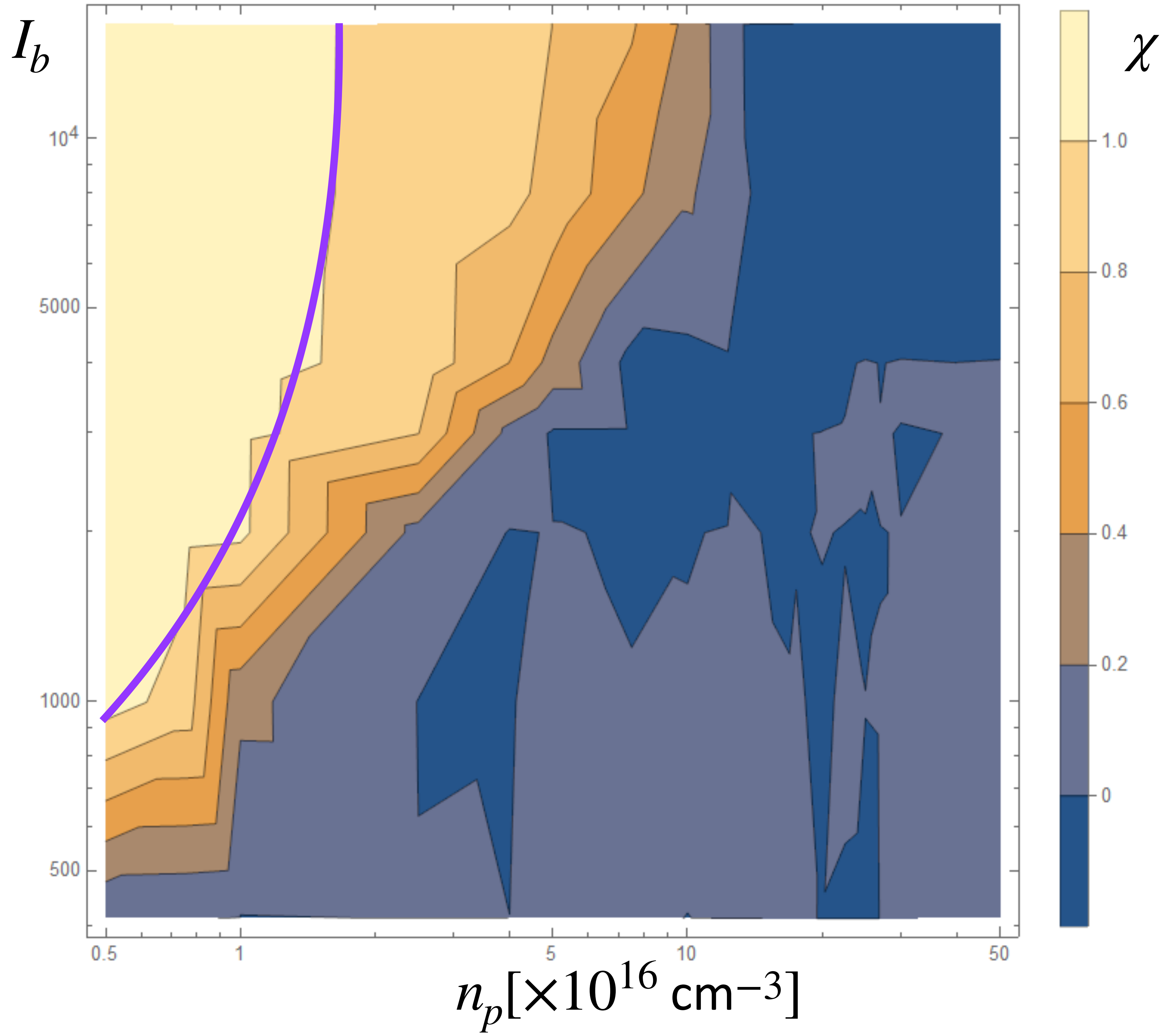


Simulation results: channel formation

Constant parameters: $\sigma_x = 5$ µm, $E_b \to \infty$ Scanned parameter: I_b/I_0 which is a function of R_{ch}, n_p, Q_b and σ_z.

$Q_b = 1500$ pC, $R_{ch} = 30$ µm

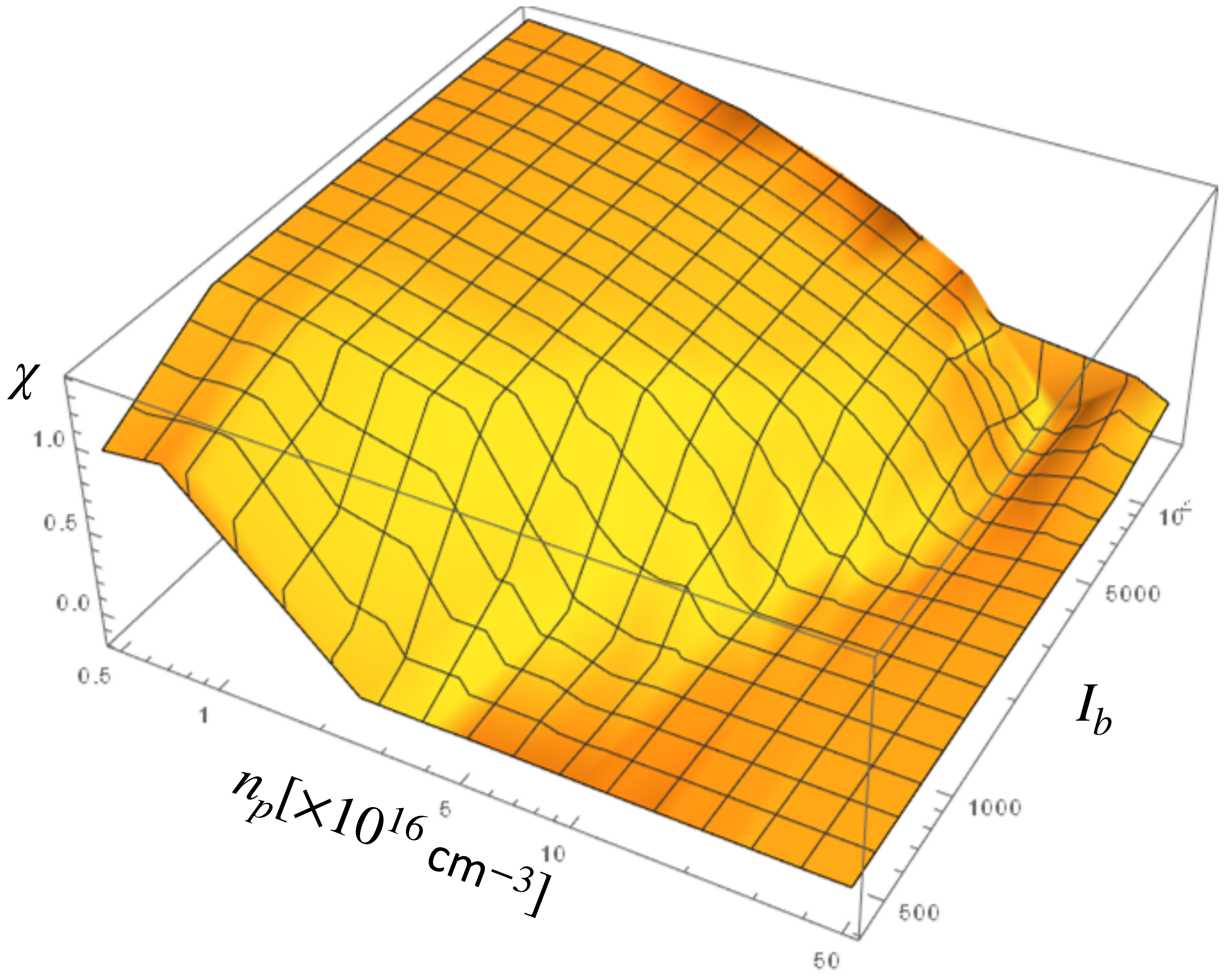


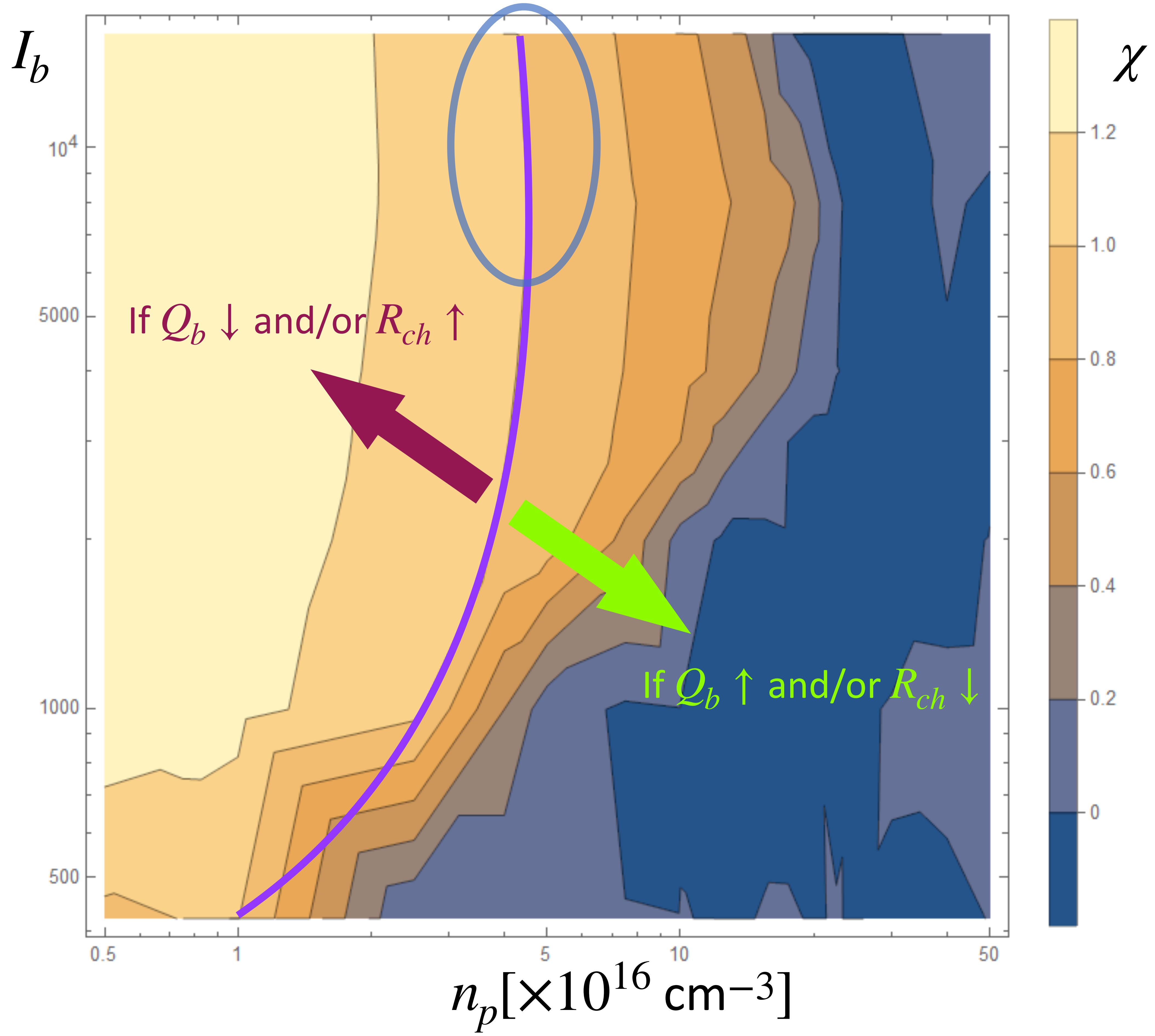


Simulation results: channel formation

Constant parameters: $\sigma_x = 5$ μm, $E_b \to \infty$ Scanned parameter: I_b/I_0 which is a function of R_{ch}, n_p, Q_b and σ_z.

$Q_b = 1500$ pC, $R_{ch} = 15$ μm





Simulation results: channel uniformity

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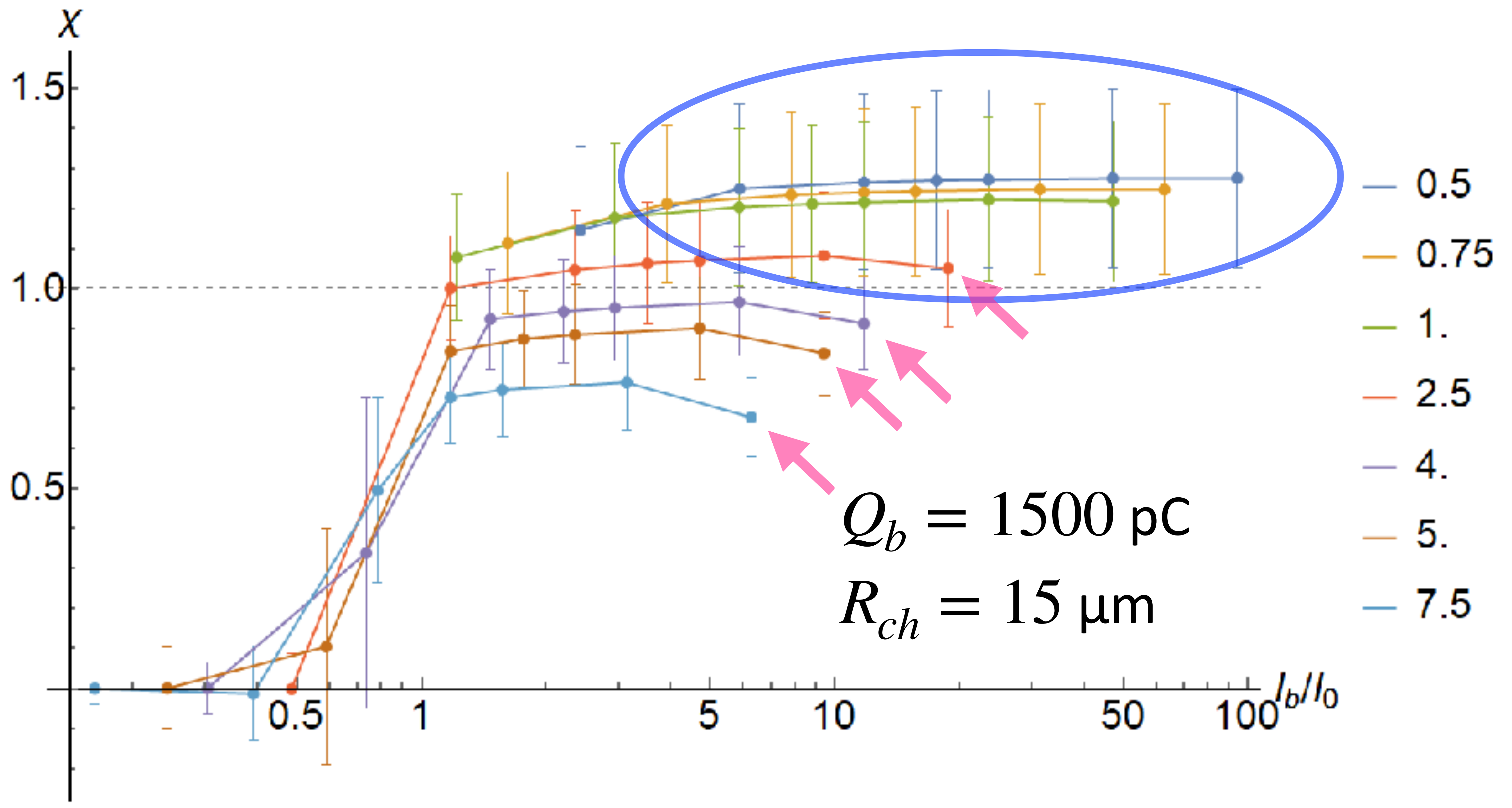
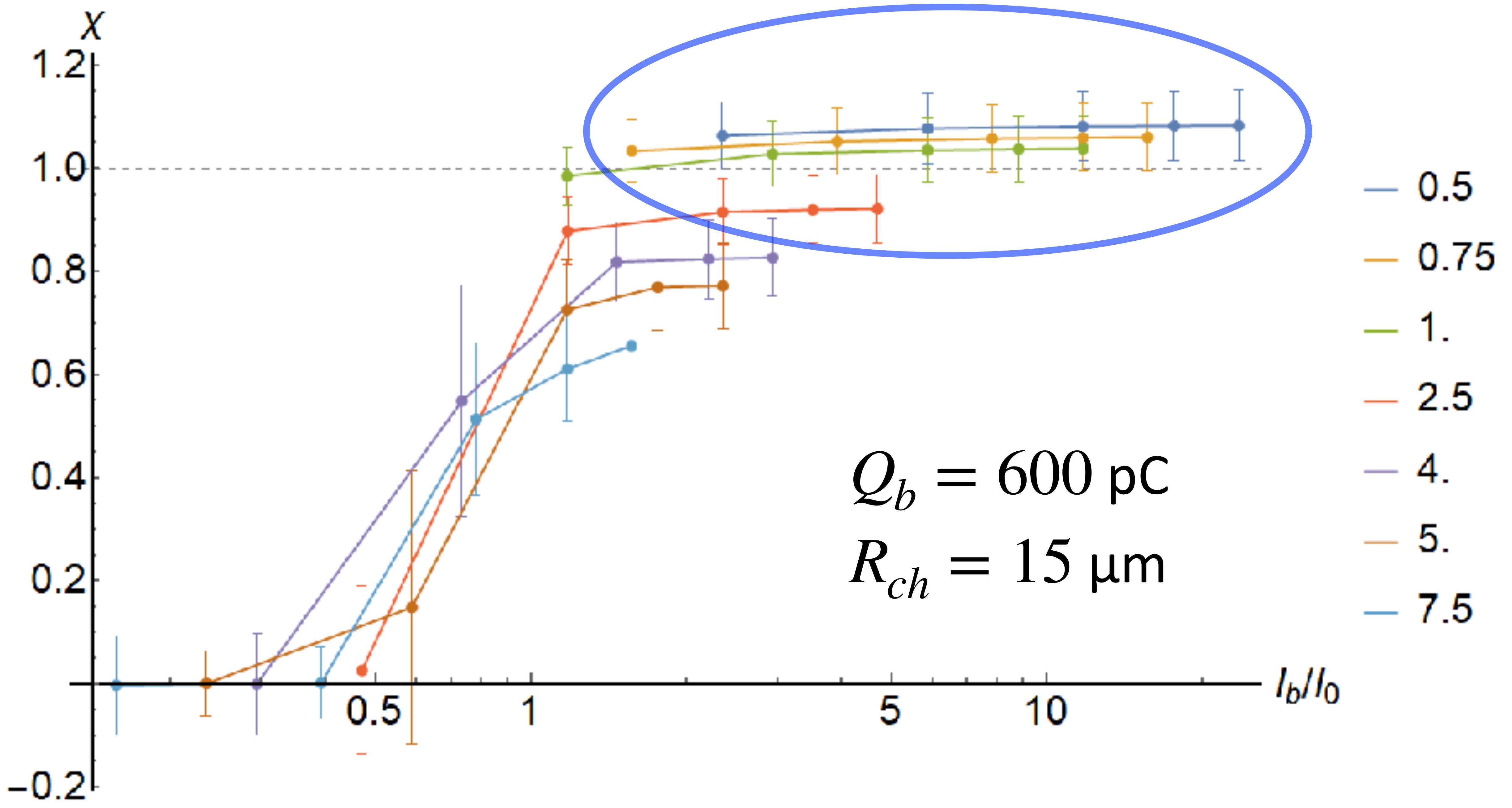
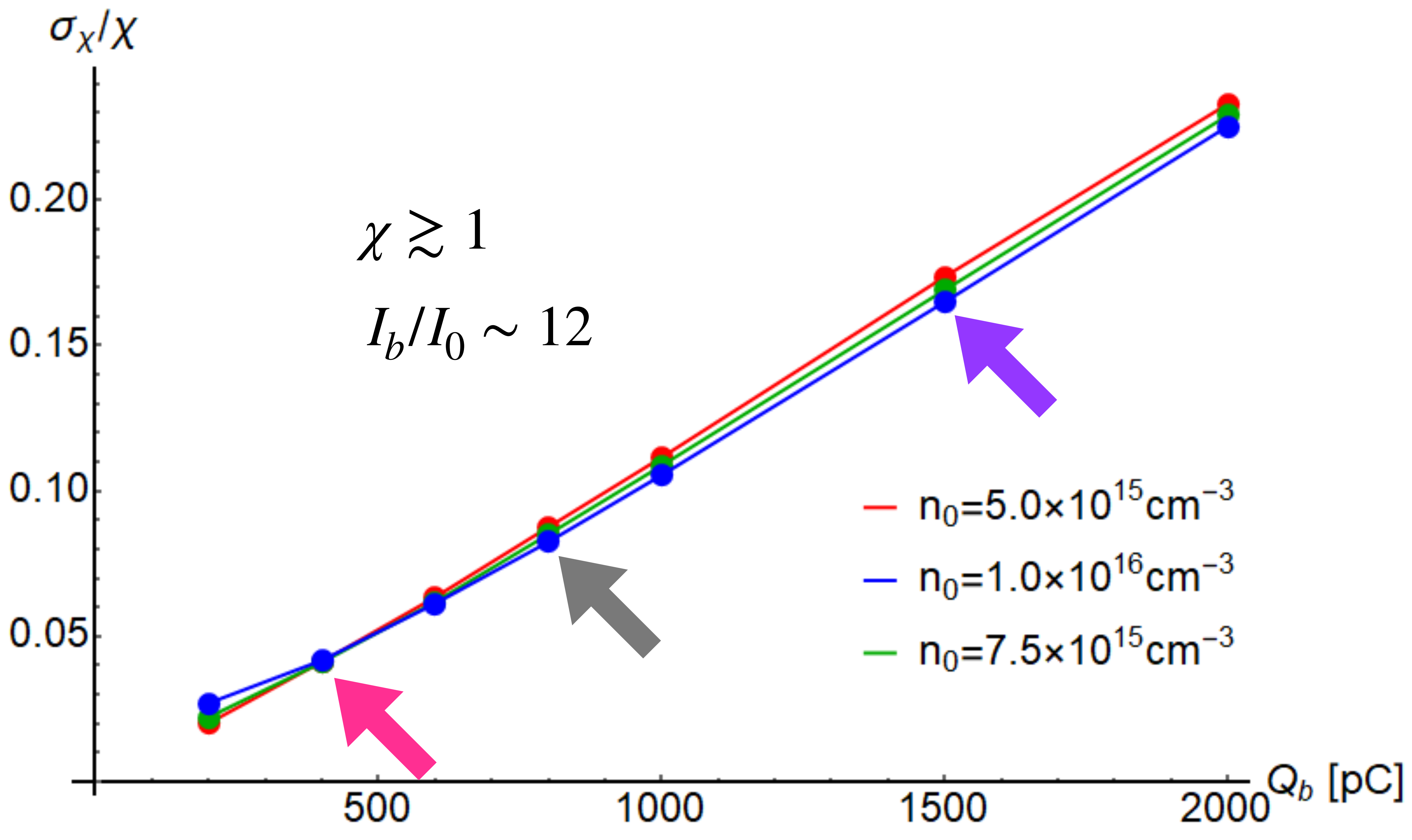
Constant parameters: $\sigma_x = 5$ µm, $E_b \to \infty$ Scanned parameter: I_b/I_0 which is a function of R_{ch}, n_p, Q_b and σ_z.

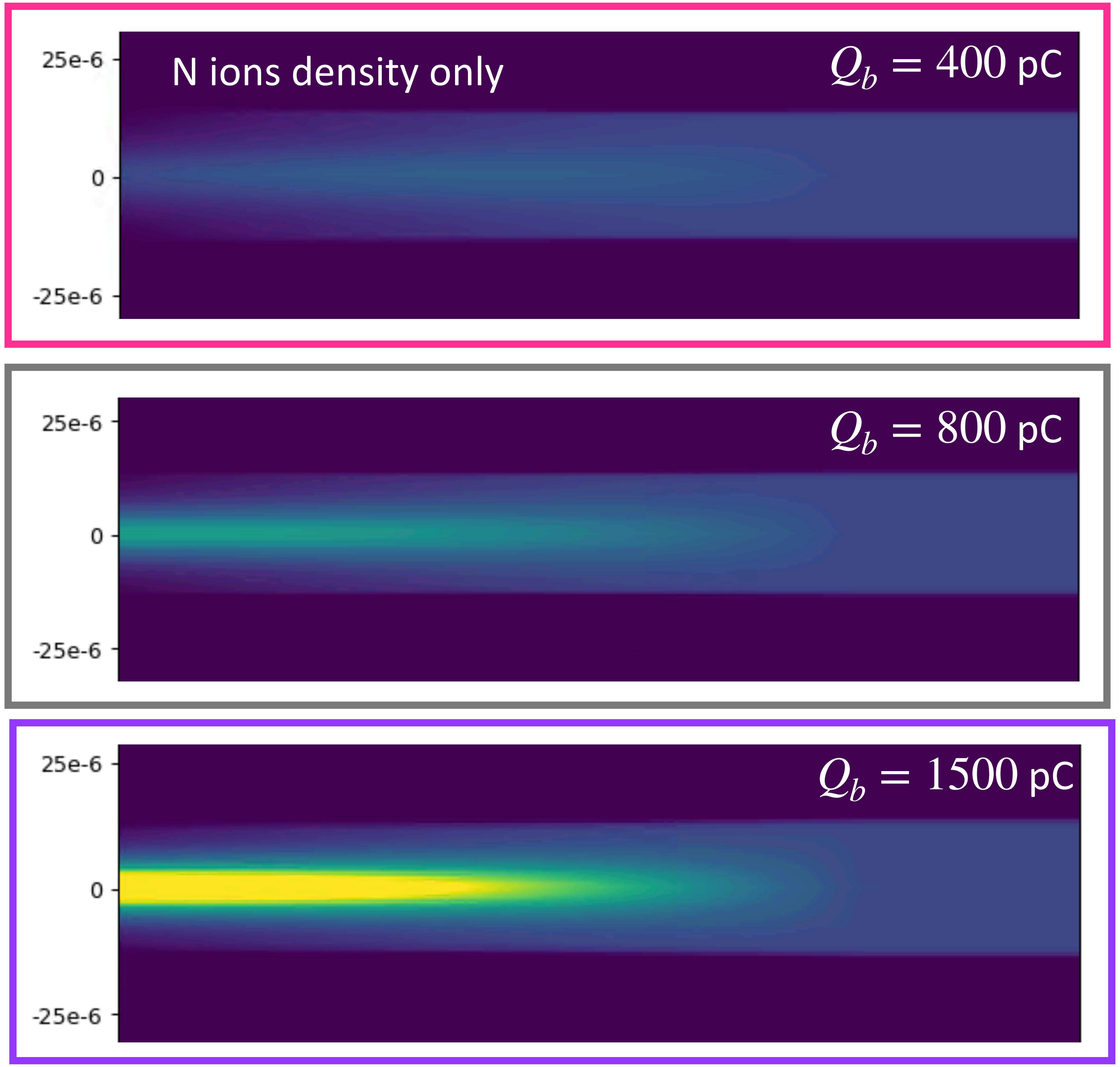




- The condition $I_b/I_0 > 1$ for channel formation seems to be confirmed.
- Once channel is formed, σ_χ seems to strongly increase with Q_b and do not depend on I_b/I_0.
- For $I_b/I_0 \gg 1$ and sufficiently large n_0 values, χ starts to decrease.

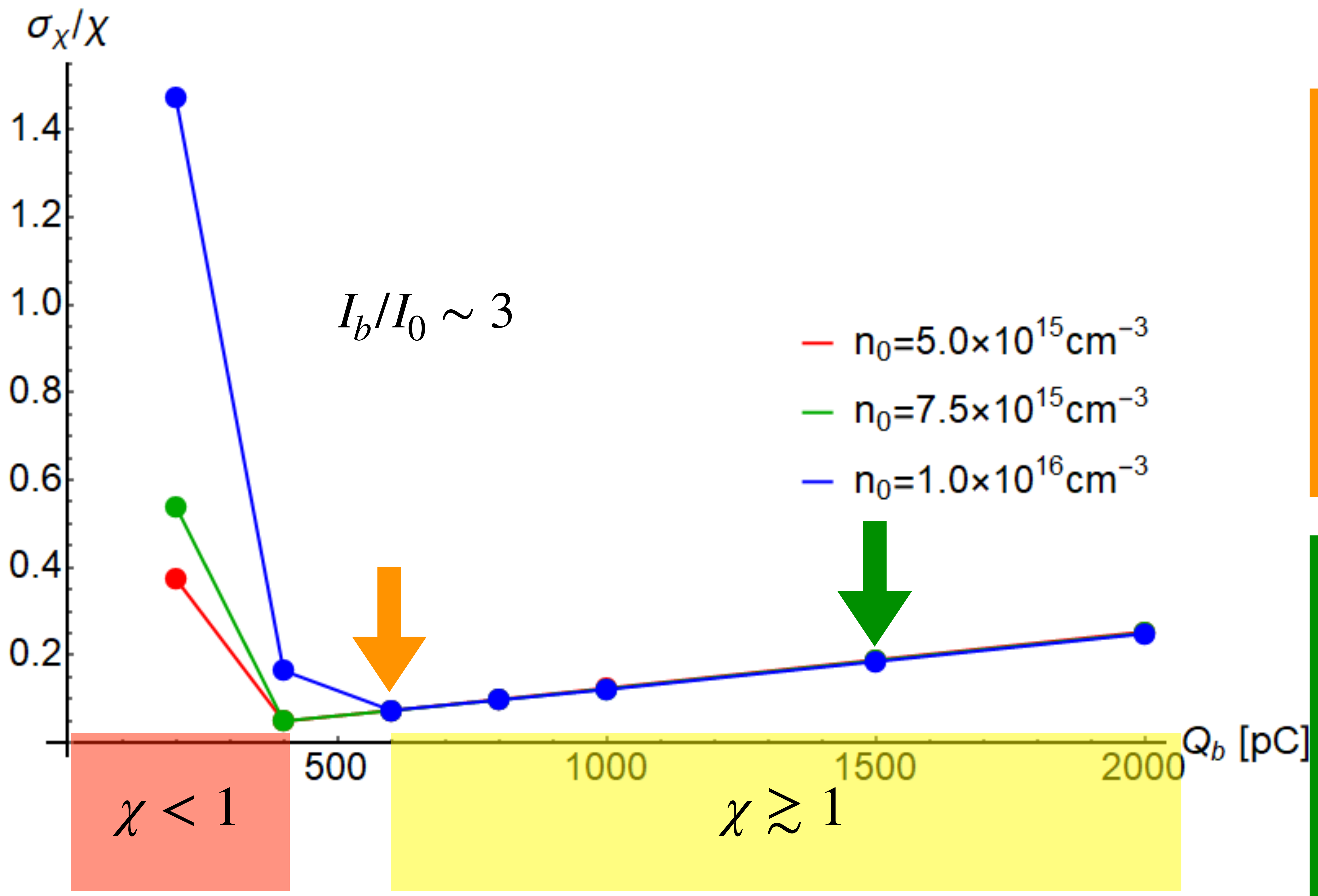
Channel uniformity: charge effects



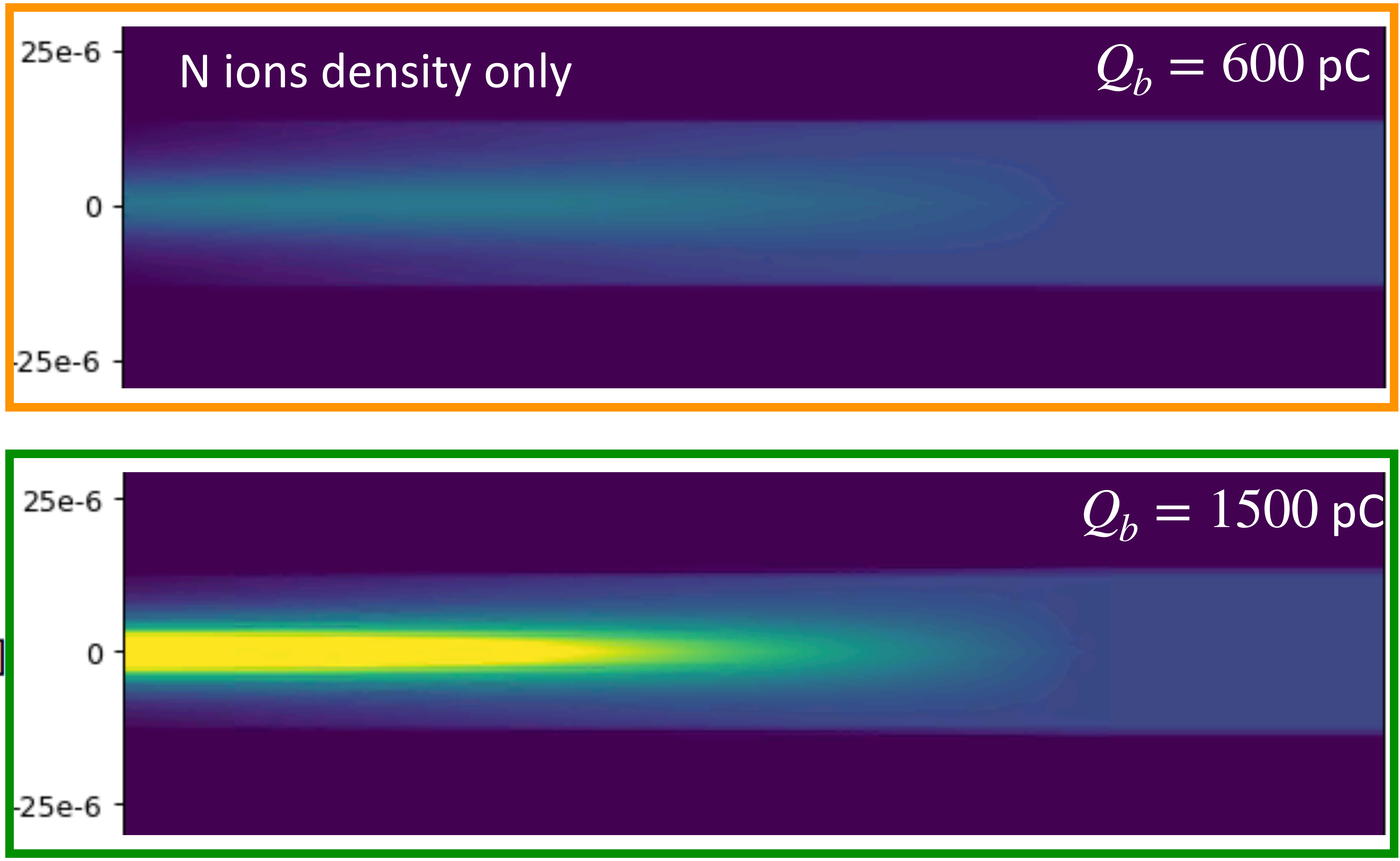


- For fixed $I_b/I_0 \gg 1$, σ_χ/χ grows linearly $\Longrightarrow$ **ION MOTION!**

Channel uniformity: optimization



$n_0 = 10^{16}$ cm^{-3}



- For fixed $I_b/I_0 \gg 1$, σ_χ/χ grows linearly $\Longrightarrow$ **ION MOTION!**
- For fixed $I_b/I_0 \gtrsim 1$, σ_χ/χ reaches a minimum $\Longrightarrow$ **OPTIMIZATION CRITERION!**

Channel uniformity: current effect

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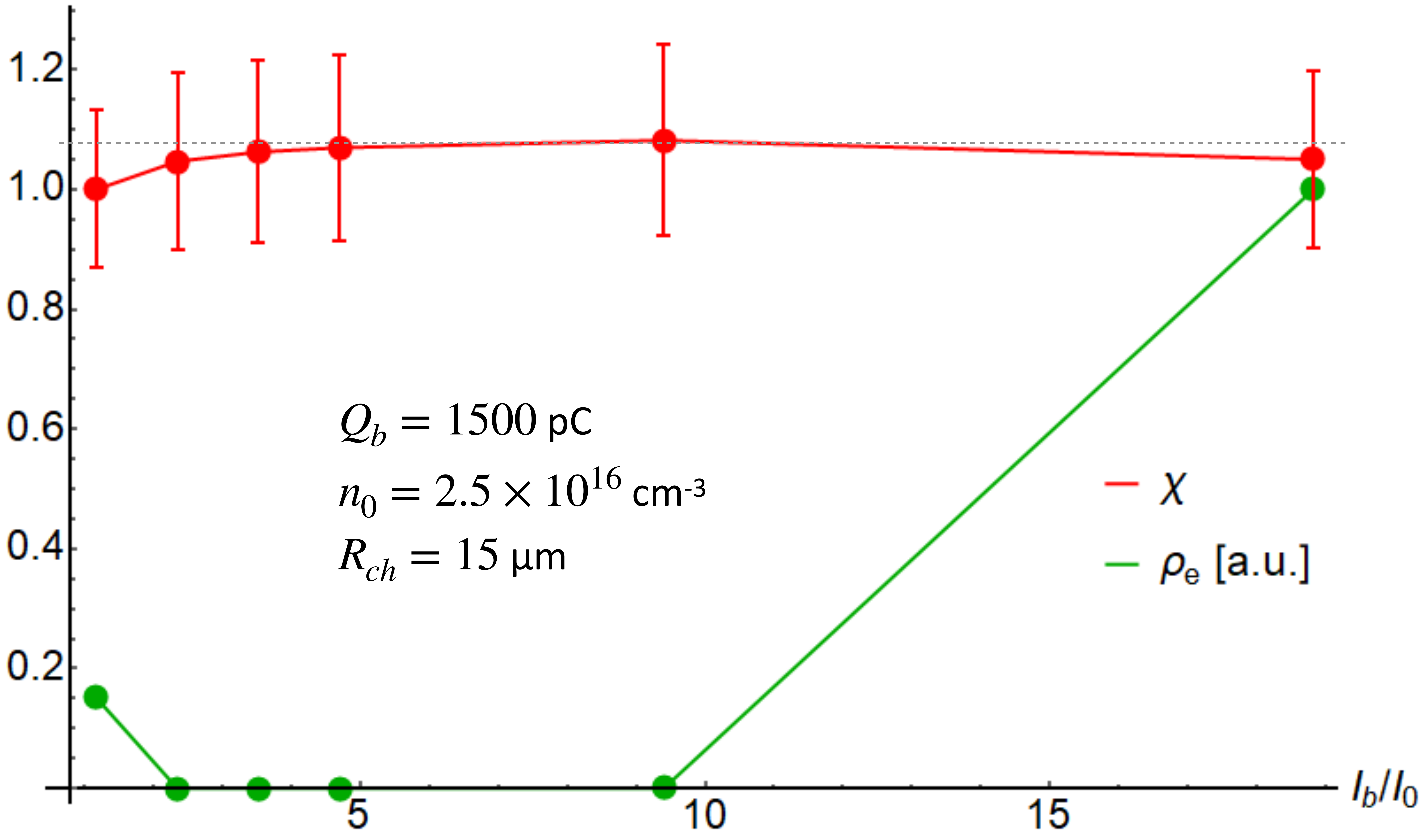
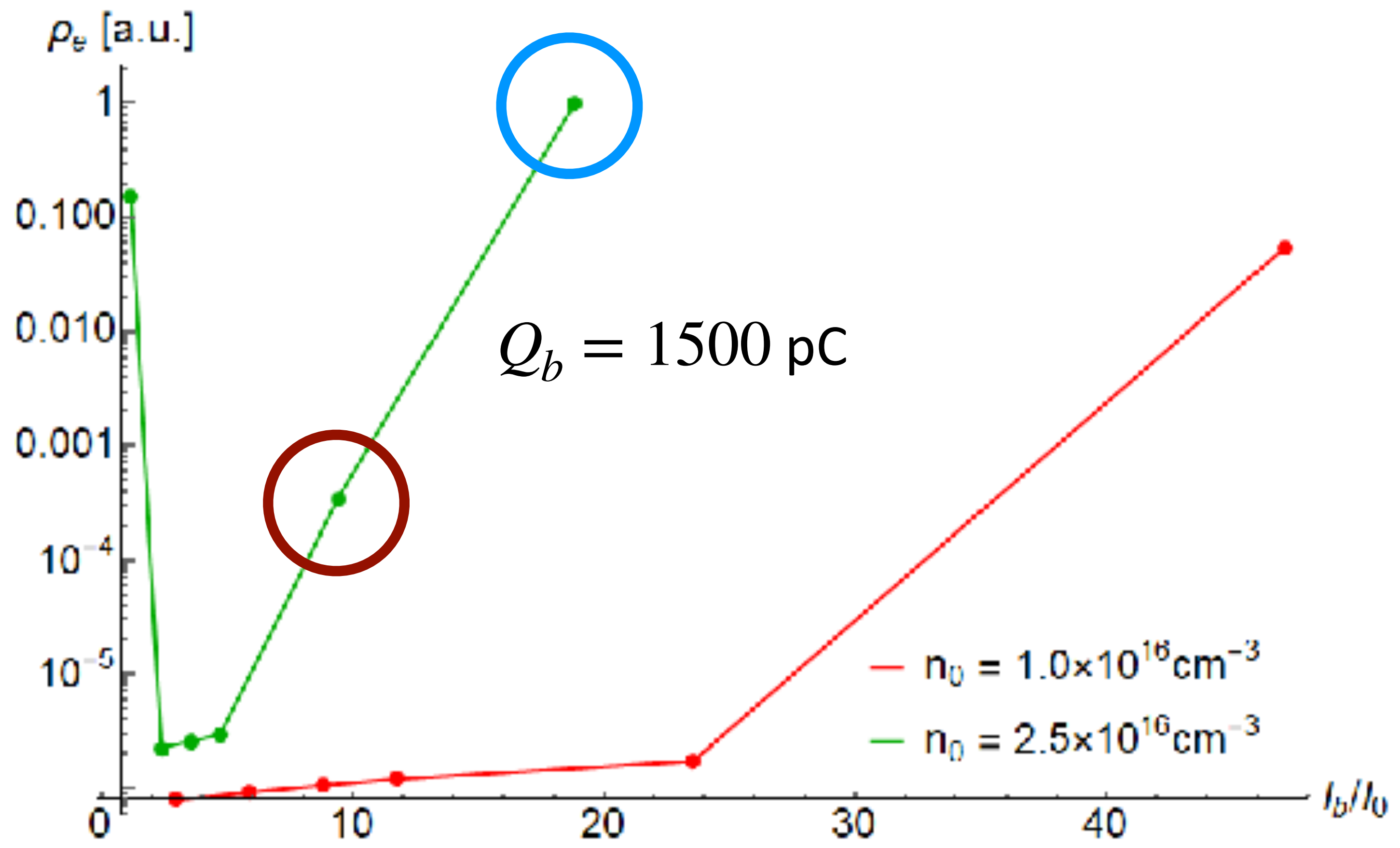
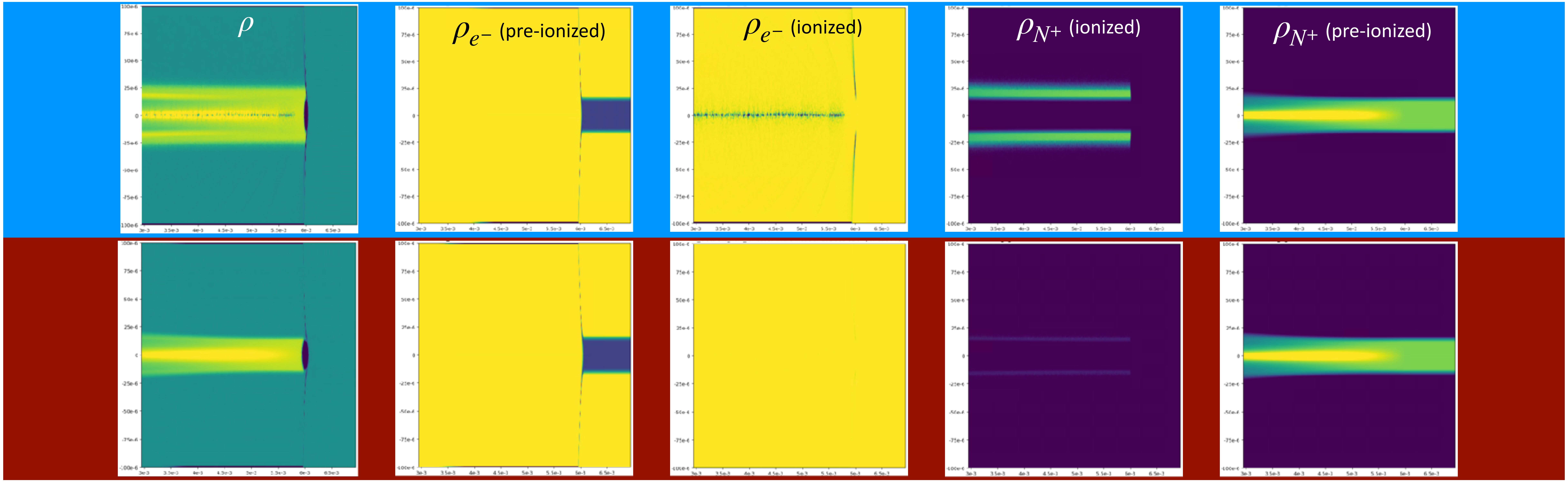
- For $I_b/I_0 \gg 1$, and n_0 *"large enough"*, χ starts to decrease $\Longrightarrow$ **IONIZATION!**



Channel uniformity: current effect



- For $I_b/I_0 \gg 1$, and n_0 "*large enough*", χ starts to decrease $\Longrightarrow$ **IONIZATION!**
- If I_b/I_0 and/or n_0 "*too small*", ionization may be present but **negligible**.
- *Large* and *small* depend on background atoms atomic mass and ionization energies.
- The presence of a minimum represent a possible **optimization** criterion.



Data driven approach to channel formation

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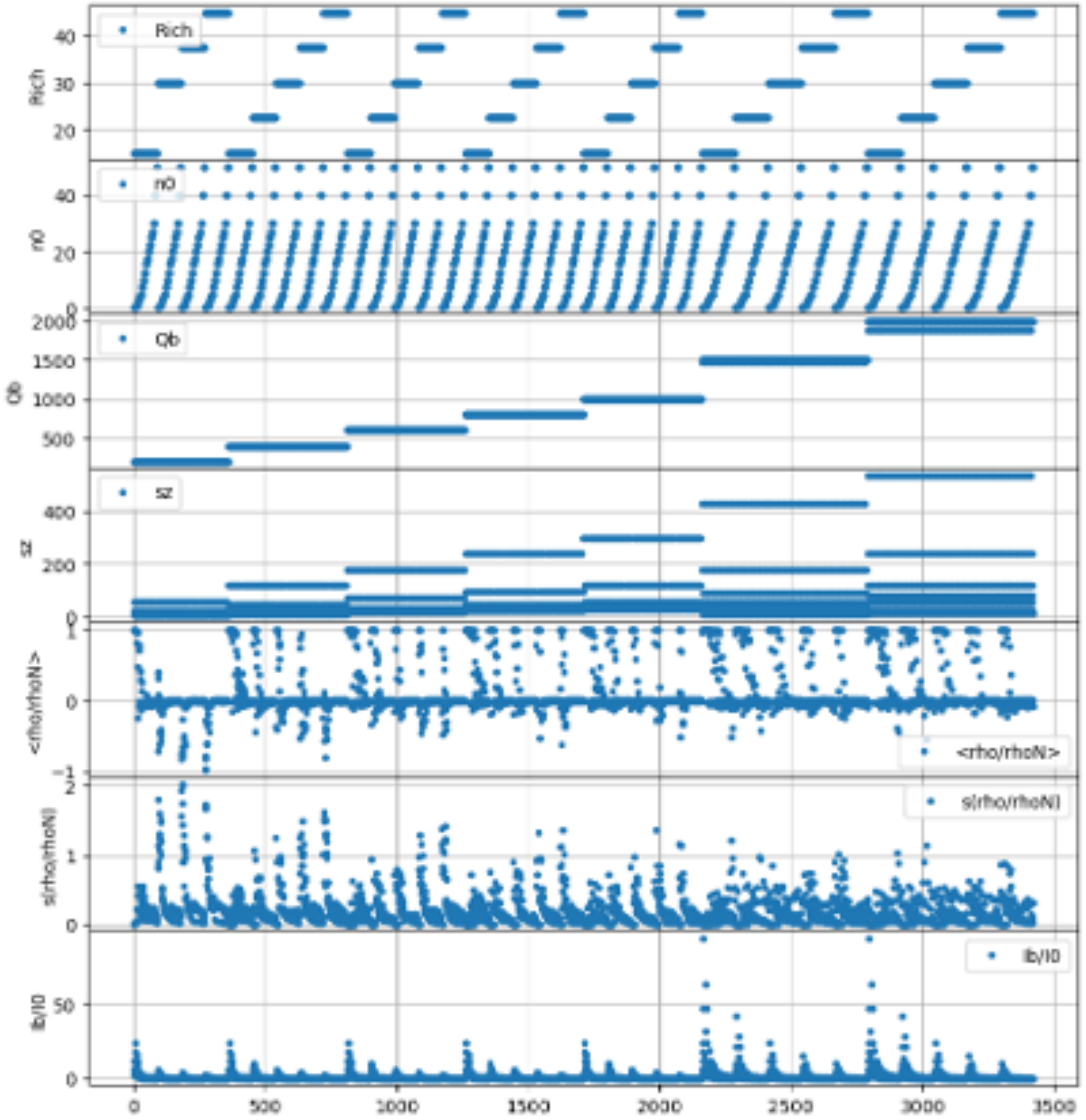
Input-output mapping



Input data structure

- 3420 simulations of plasma channel with varying input parameters
  - Input parameters: $R_{ch}, n_p, Q_b, \sigma_z, I_b/I_0$
  - Output metrics: χ, σ_χ
- The study goal is to find patterns and dependences in incoming parameters to ensure a stable plasma channel formation
- Proposed instrument: **AI Machine Learning**

Courtesy I. Drebot

Study workflow

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Plasma channel simulations (3420)

⇩

Dataset: simulation results

Input parameters:

- R_{ch}
- n_p
- Q_b
- σ_z
- I_b/I_0

Output parameters:

- χ
- σ_χ

⇩

Machine learning model (XGBoost Regression)

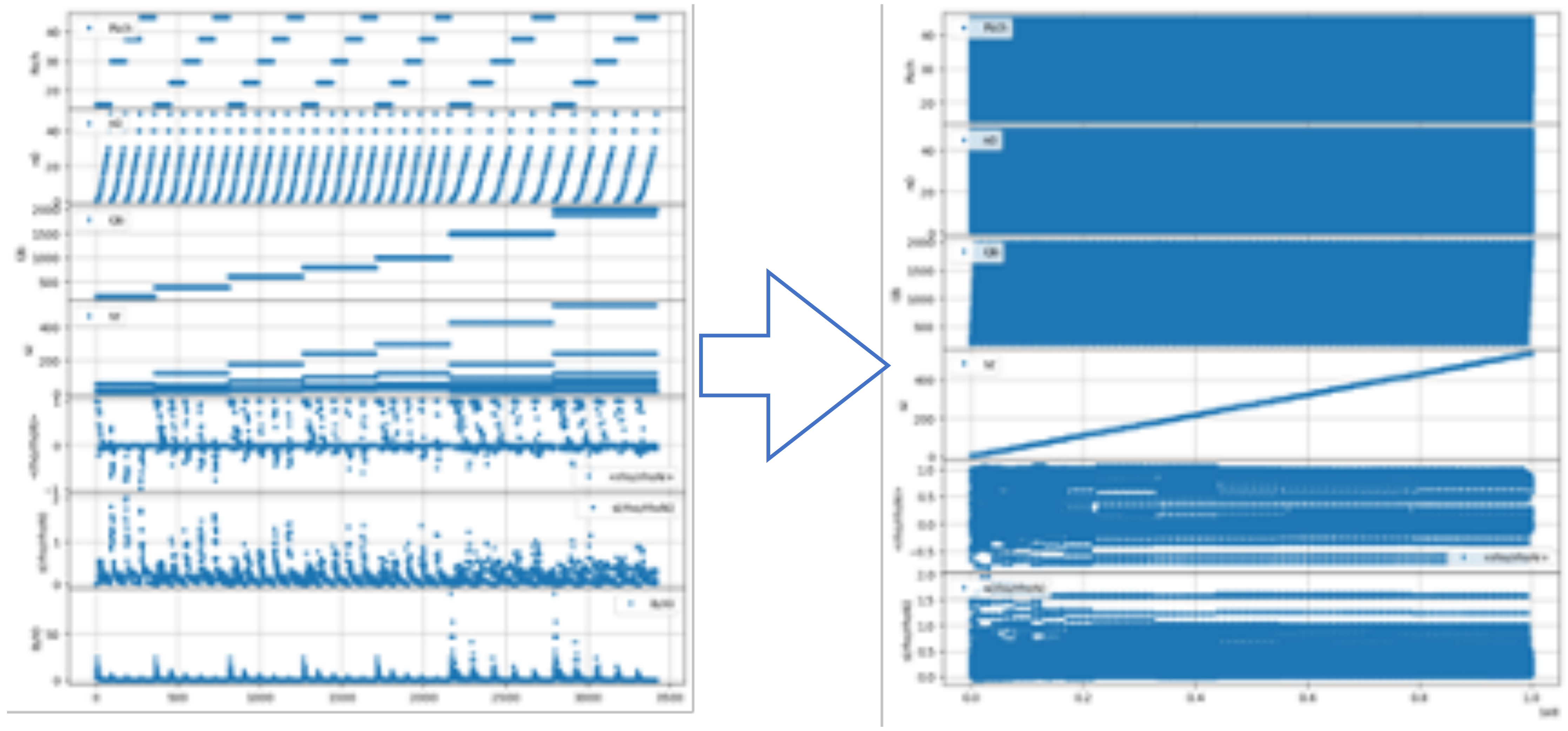
⇩

Prepare input grid & use ML to predict missing data $\Longrightarrow$ virtual simulations

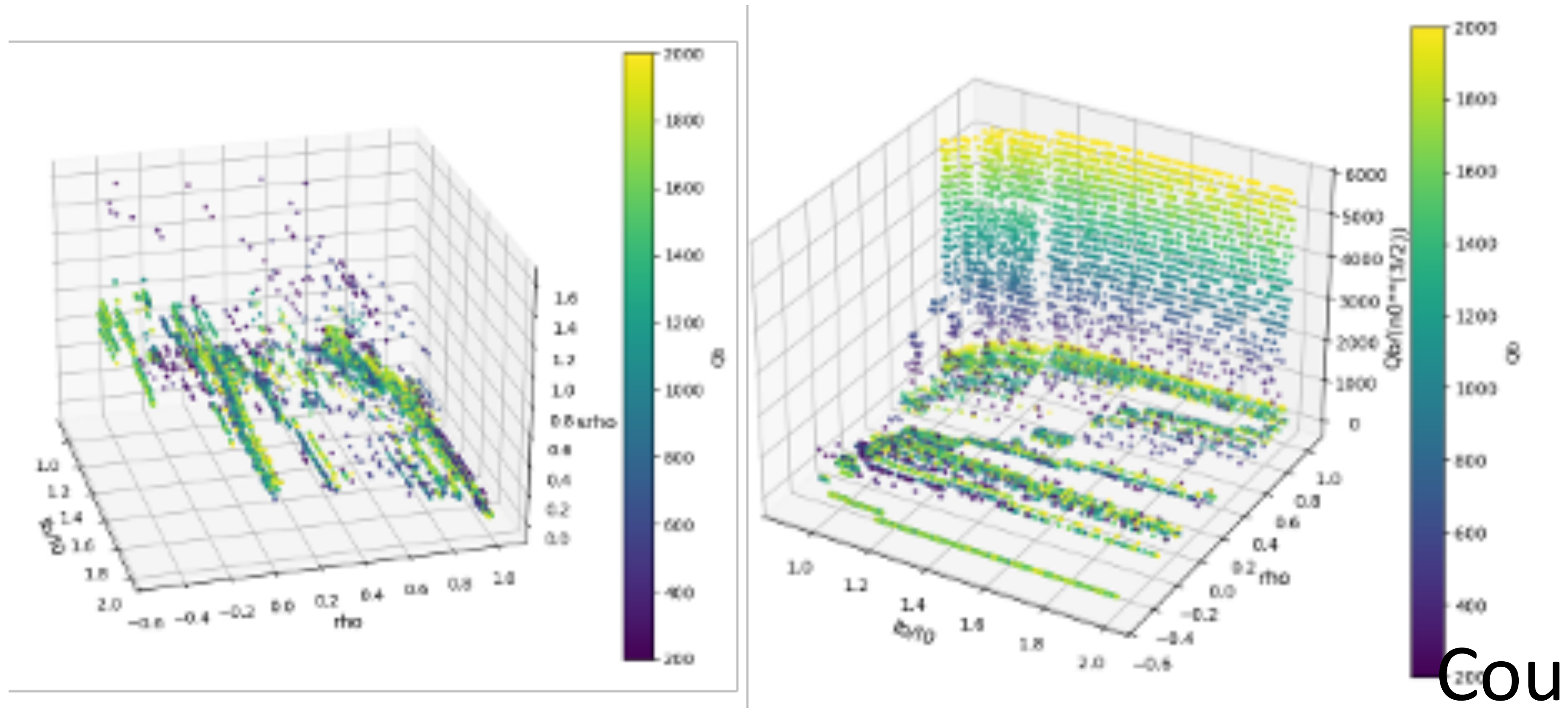
⇩

Analysis of patterns & channel formation conditions in extended dataset

ML “multi-dimensional interpolation” from 3k simulations to a dataset with 10^8 configurations



Extended dataset allows for deeper 6D analysis of trends



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Possible issues

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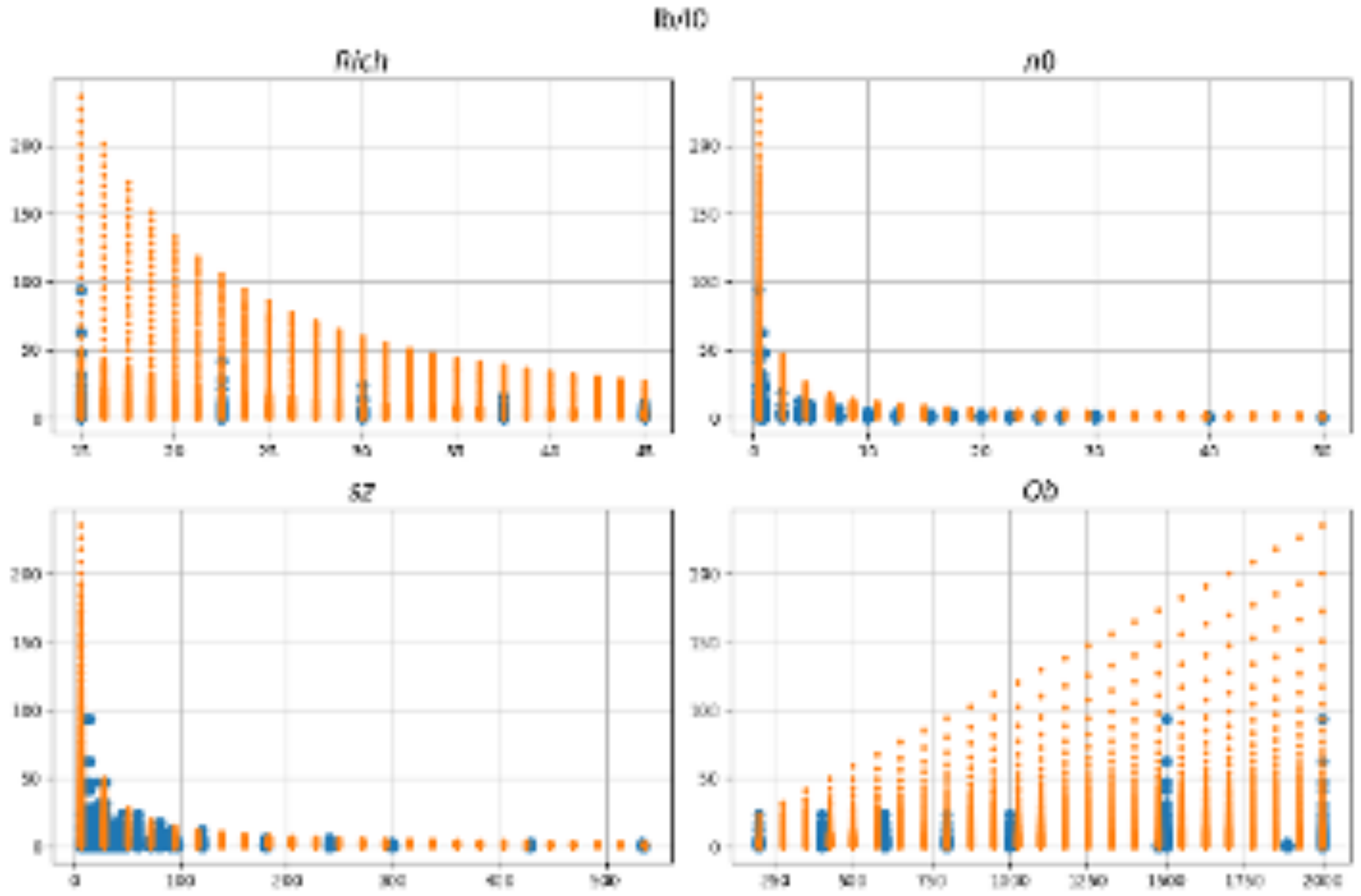
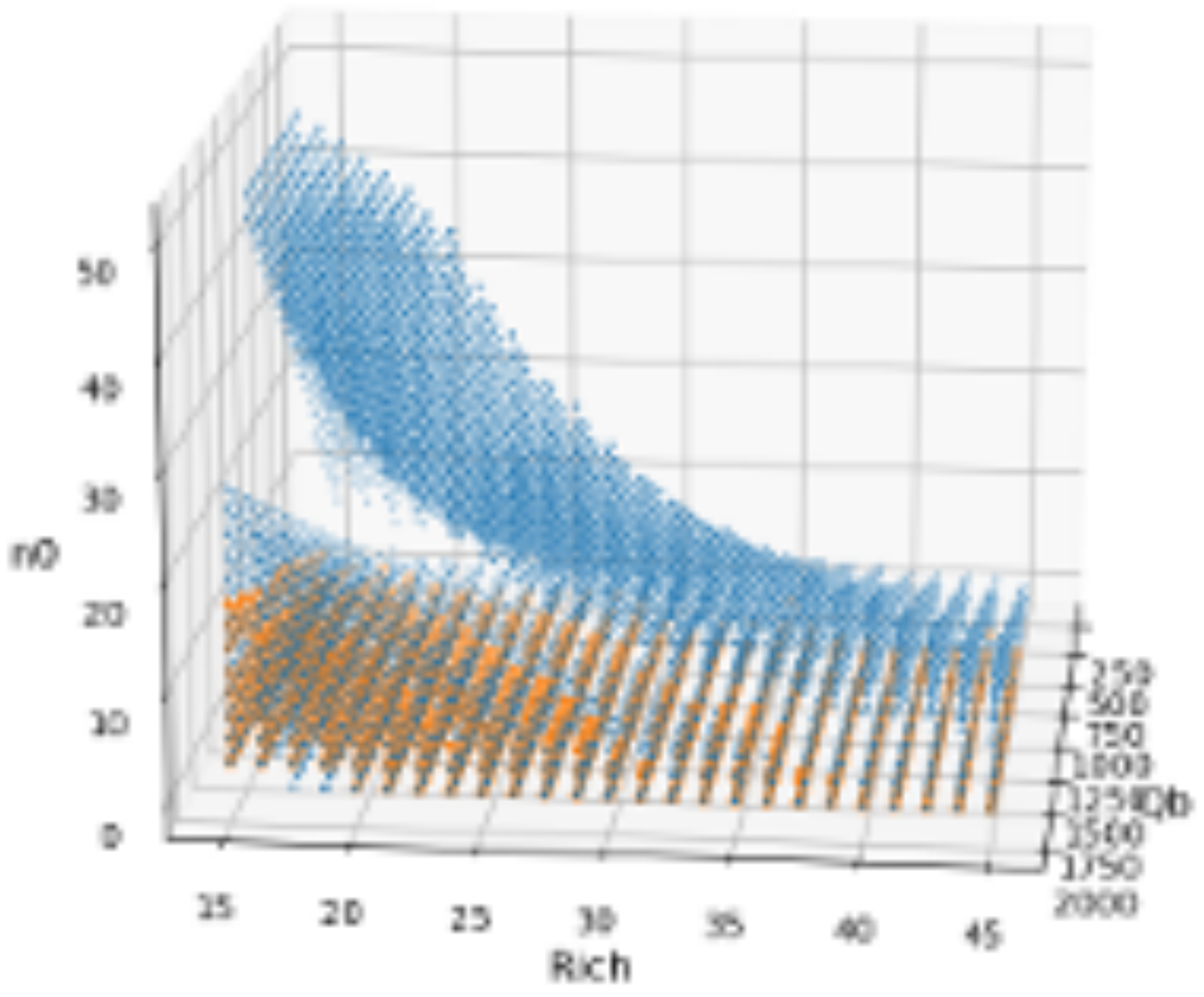
Due to the non-uniform distribution of training data, large parameter regions remain without reference points. As a result, the model extrapolates in these areas, introducing noise into the extended dataset and leading to potentially misleading results.





Example of “missing training” data effect

- Built ML-based model to map plasma channel input parameters → formation indicators
- Generated an extended virtual dataset via ML interpolation
- Identify patterns & stability conditions in multidimensional parameter space
- Highlighted limitations due to non-uniform training data distribution
- Approach provides a data-driven tool for guiding future plasma acceleration studies

Courtesy I. Drebot

Conclusions

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- The IC formation was studied for designing a working point for the betatest experiment @SPARC_LAB
- The validity of a scaling law for channel formation was verified
- Impact of the driving beam parameters on channel uniformity were investigated:
  - A large charge sets in ion motion
  - A large current may cause ionization in neutrals
- Both effects can be minimized (optimization conditions)
- Both effects depend on the chemical nature of neutrals
- We are starting to apply AI to data analysis and interpretation

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