Coherent optical manipulation of plasma waves

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Frontiers in Quantum Materials' Control

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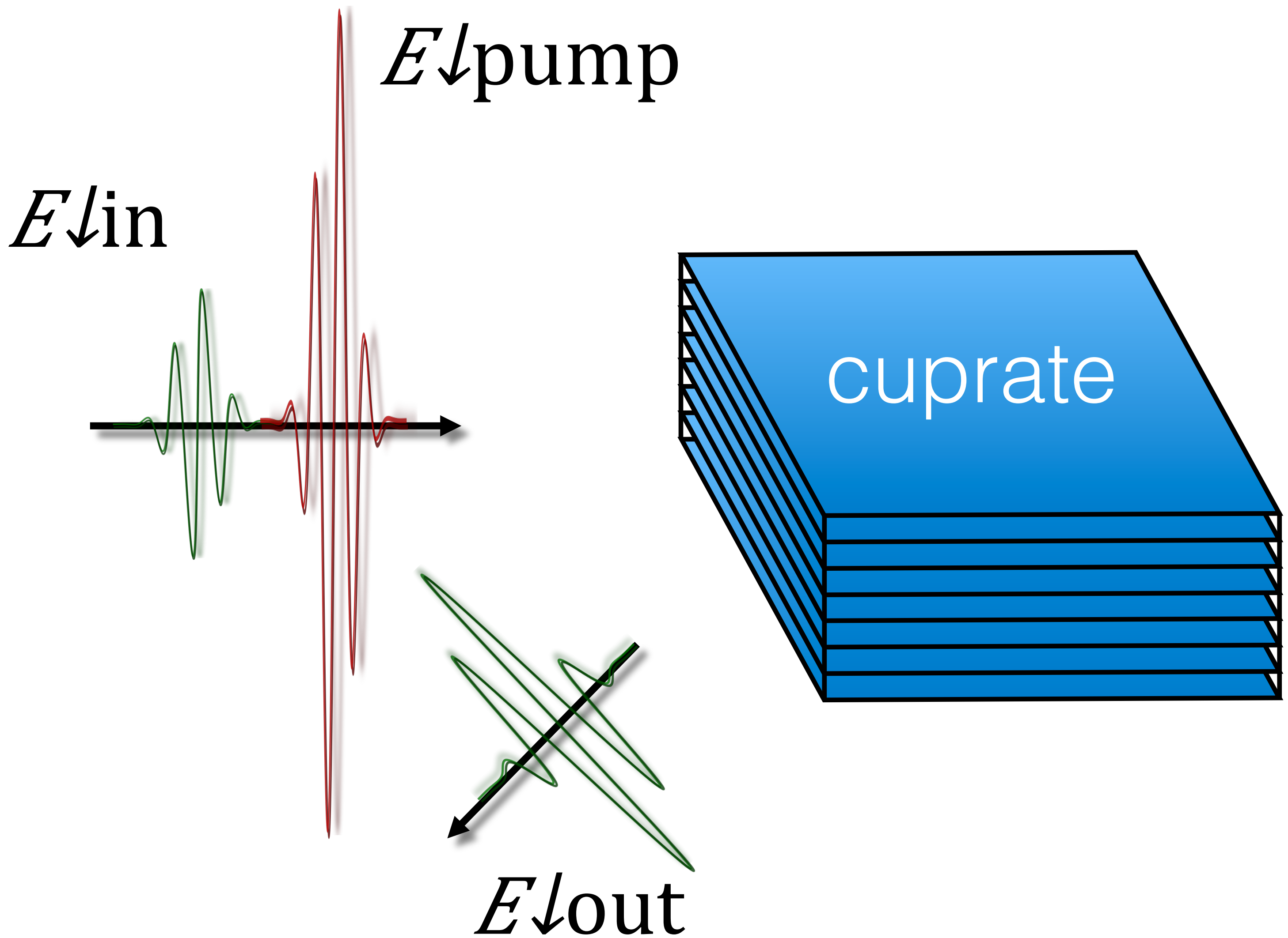
Motivation

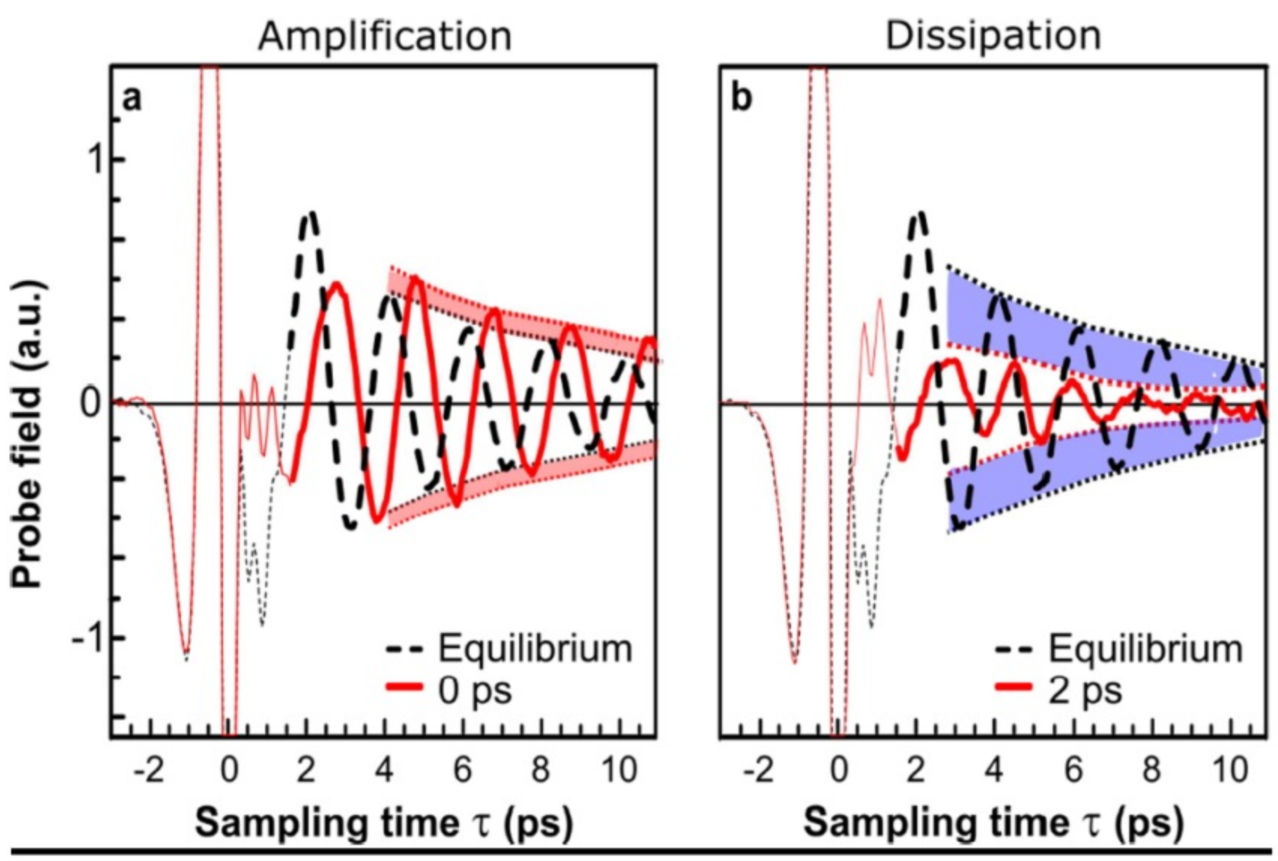


Large nonlinearity:

- manipulate probe optical field
- drive macroscopic state of cuprate

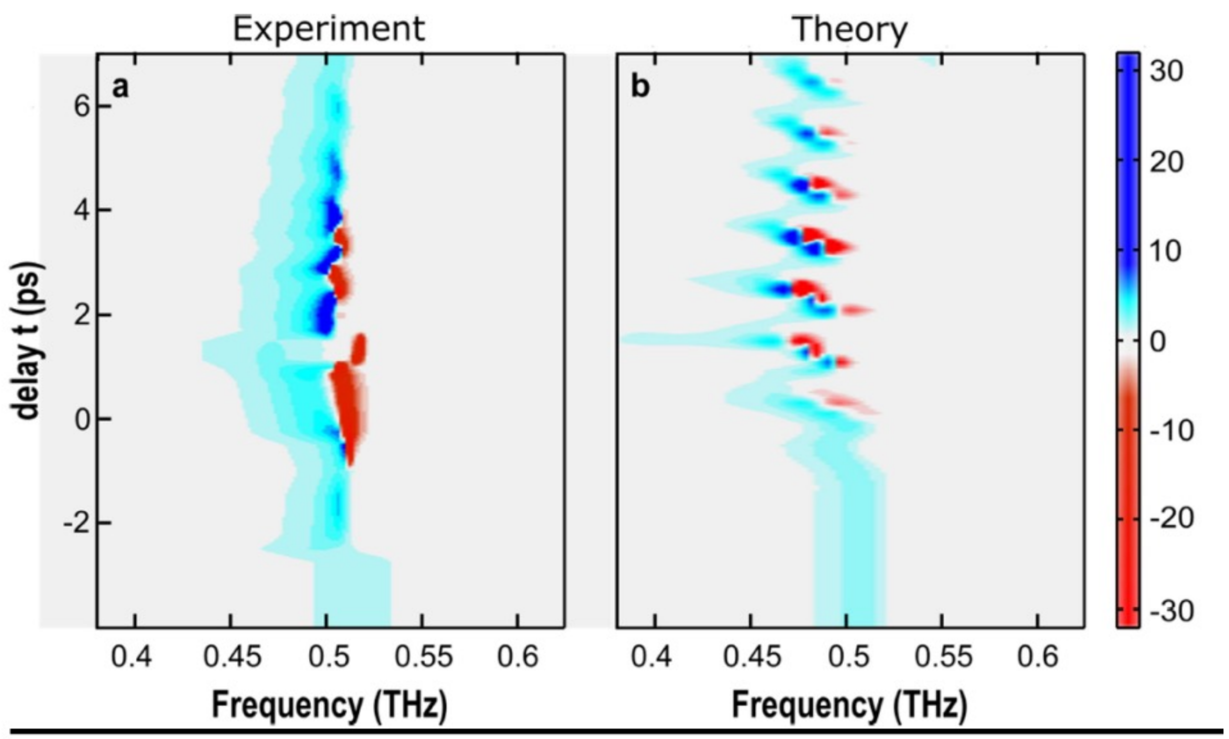
Parametric Amplification of a Terahertz Quantum Plasma Wave, Srivats Rajasekaran, Eliza Casandruc, Yannis Laplace, Daniele Nicoletti, Genda D. Gu, Stephen R. Clark, Dieter Jaksch, Andrea Cavalleri, arXiv:1511.08378 (to appear in Nature Physics 2016).

Experimental results



Probe field amplification (a) and suppression (b) due to strong driving field

Parameter regions of suppression (red) and amplification (blue)



Josephson physics

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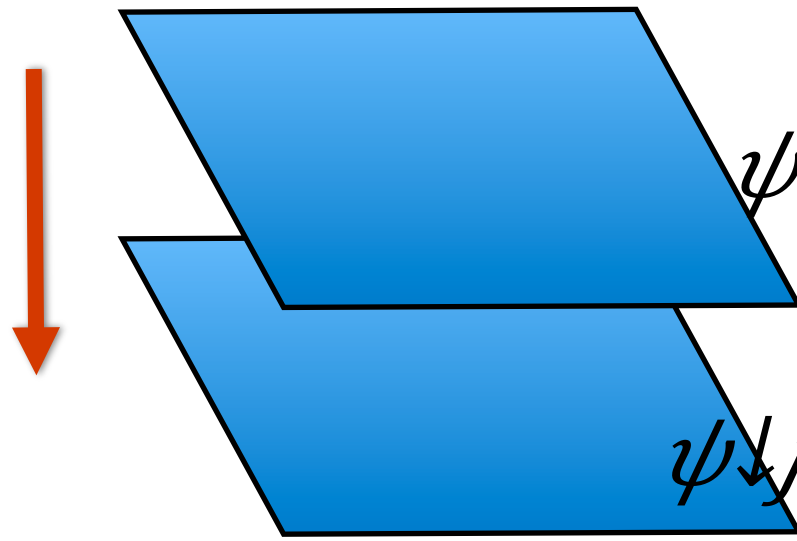
$$I = I_0 \sin(\theta_{j+1,j})$$



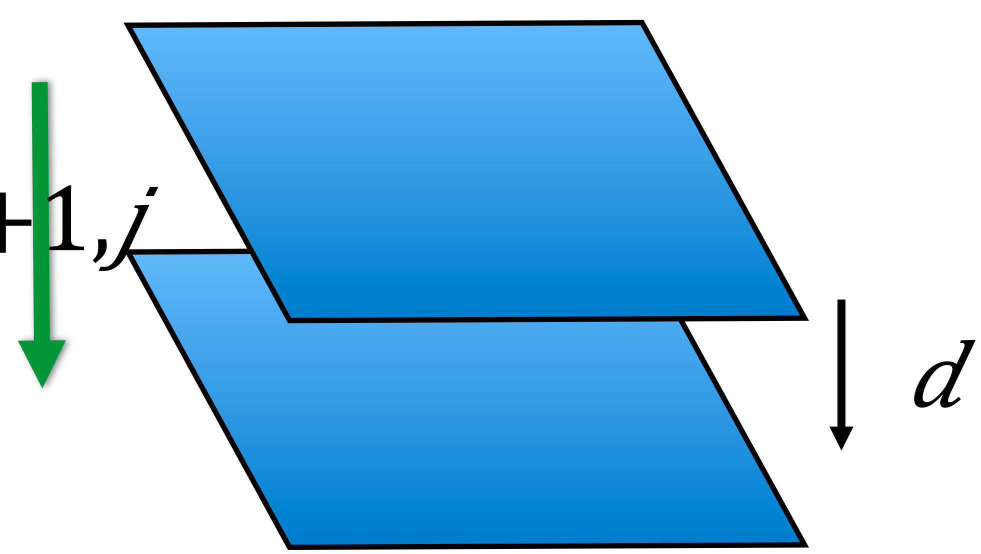
$$\psi_j = |\psi_j| e^{i\theta_j}$$

$$\psi_{j+1} = |\psi_{j+1}| e^{i\theta_{j+1}}$$

$$\theta_{j+1,j} = \theta_{j+1} - \theta_i$$

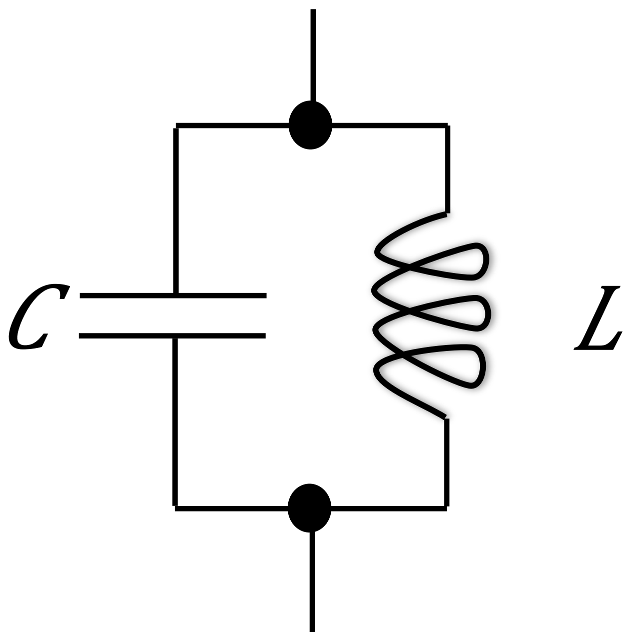
External optical field $E = E_0 \cos(\omega_{JP} t)$ induces a phase differenc

$$V = Ed = \hbar/2e \, \theta_{j+1,j}$$



Josephson physics

Assume no excitations above the superconducting gap $|\psi_j| \approx$ const



$$\omega_{JP}^2 = 1/LC$$

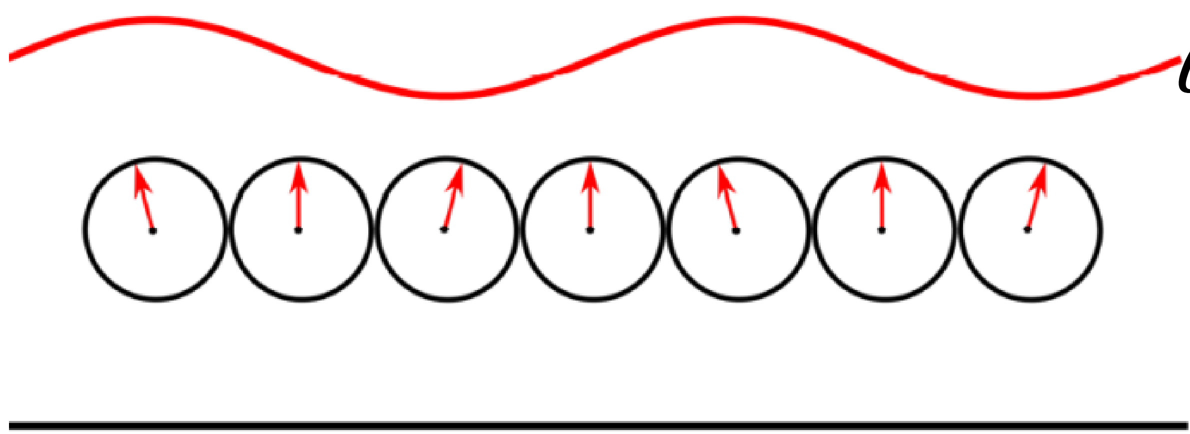
$$L = \hbar/2eI_0 \cos\theta_{j+1,j}$$

$$\theta_{j+1,j} = \theta_{j+1} - \theta_j$$

A strong driving field will change the oscillator strength

$$f_{j+1,j} = f_0 \cos(\theta_0 \cos(\omega_{JP} t)) \quad \theta_0 = 2ed/\hbar\omega_{JP} E_0$$

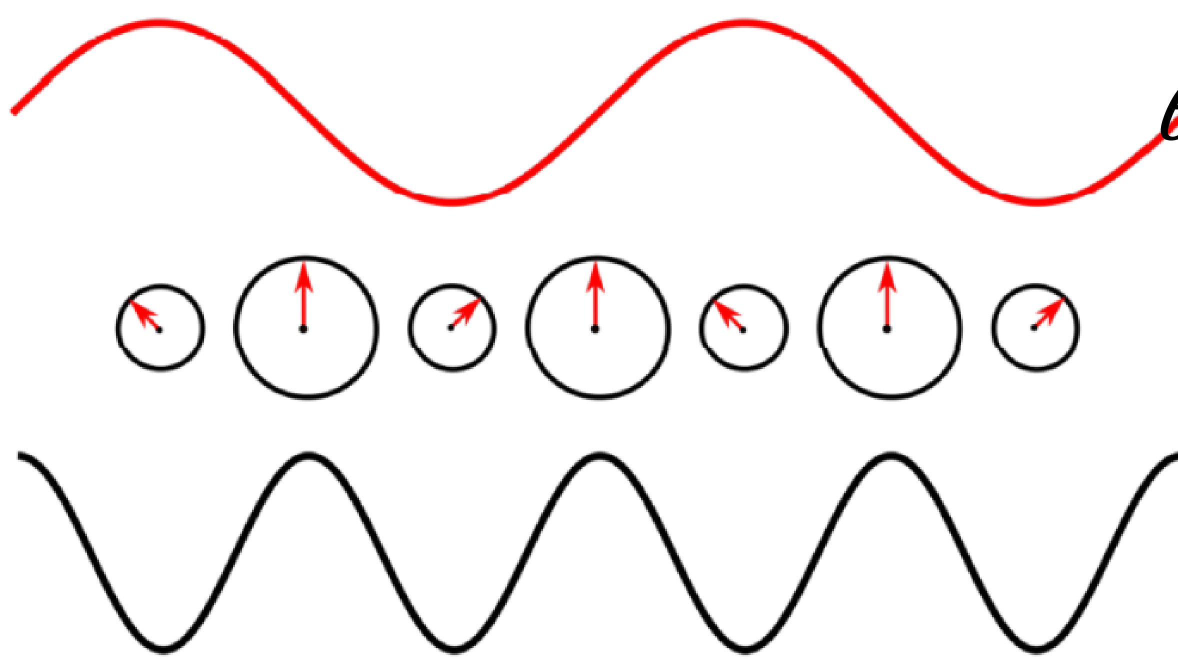
Linear vs non-linear regime



$\theta_{j+1,j}$ modulated at ω_{JP}

f is approximately constant

Weak driving



$\theta_{j+1,j}$ modulated at ω_{JP}

f modulated at $2\omega_{JP}$

Strong driving

Pump and probe field

From the Josephson equations we get

$$-\frac{1}{\gamma}\frac{\partial \theta_{j+1,j}}{\partial t} - \frac{\epsilon_r}{c^2}\frac{\partial^2 \theta_{j+1,j}}{\partial t^2} = \omega_p^2 \frac{\epsilon_r}{c^2}\theta_{j+1,j}$$

The oscillator strength is modified by the driving field

$$f(t) = \omega_{JP}^2\left(1 - \theta_0^2\,\frac{(1+\cos(2\omega_{JP}t))}{4}\right)$$

The probe field is described by

$$\frac{1}{\gamma}\frac{\partial \theta_{\mathrm{probe}}}{\partial t} + \frac{\epsilon_r}{c^2}\frac{\partial^2 \theta_{\mathrm{probe}}}{\partial t^2} + \omega_p^2 \frac{\epsilon_r}{c^2}\left(1 - \theta_0^2\,\frac{(1+\cos(2\omega_{JP}t))}{4}\right)\theta_{\mathrm{probe}} = 0$$

This is a damped Matthieu equation

Including spatial variations and BCs.

Junction described by a Sine-Gordon equation

$$\frac{\partial^2 \theta_{j+1,j}}{\partial x^2} - \frac{1}{\gamma}\frac{\partial \theta_{j+1,j}}{\partial t} - \frac{\epsilon_r}{c^2}\frac{\partial^2 \theta_{j+1,j}}{\partial t^2} = \omega_p^2 \frac{\epsilon_r}{c^2} \theta_{j+1,j}$$

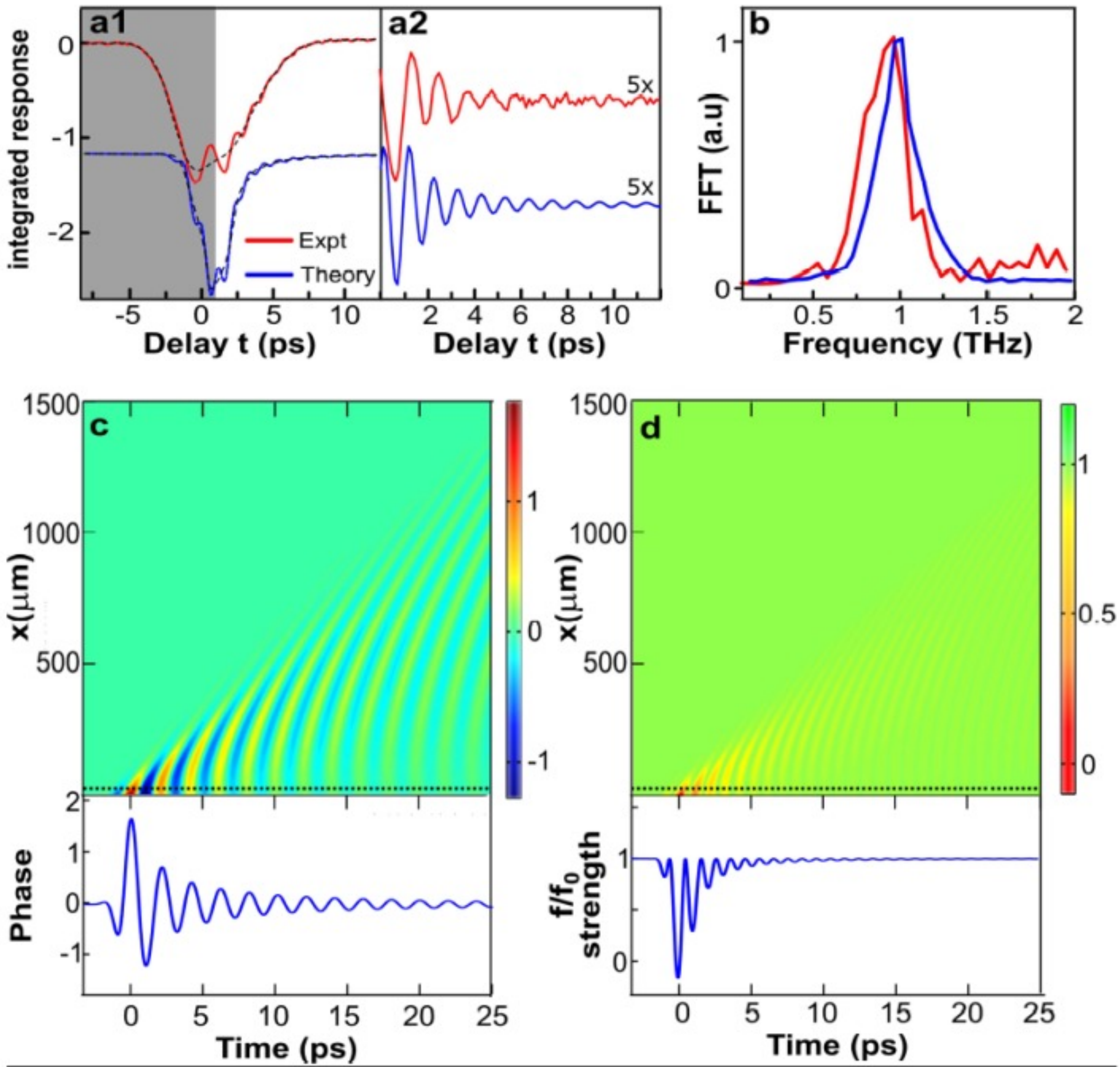
and boundary conditions for the electric E and magnetic field H determined by the Maxwell equations

$$[E_i(t)+E_r(t)]_{x=-0} = E_c(t)_{x=+0} = \frac{H_0}{\omega_{JP}\sqrt{\epsilon_r}}\left(\frac{\partial \theta_{j+1,j}}{\partial t}\right)_{x=+0}$$

$$[H_i(t)+H_r(t)]_{x=-0} = H_c(t)_{x=+0} = -H_0 \lambda_j \left(\frac{\partial \theta_{j+1,j}}{\partial x}\right)_{x=+0}$$

with $H_0 = \phi_0 / 2\pi d \lambda_j$ and $\phi_0 = \mathrm{hc}/2\mathrm{e}$ the flux quantum.

Results

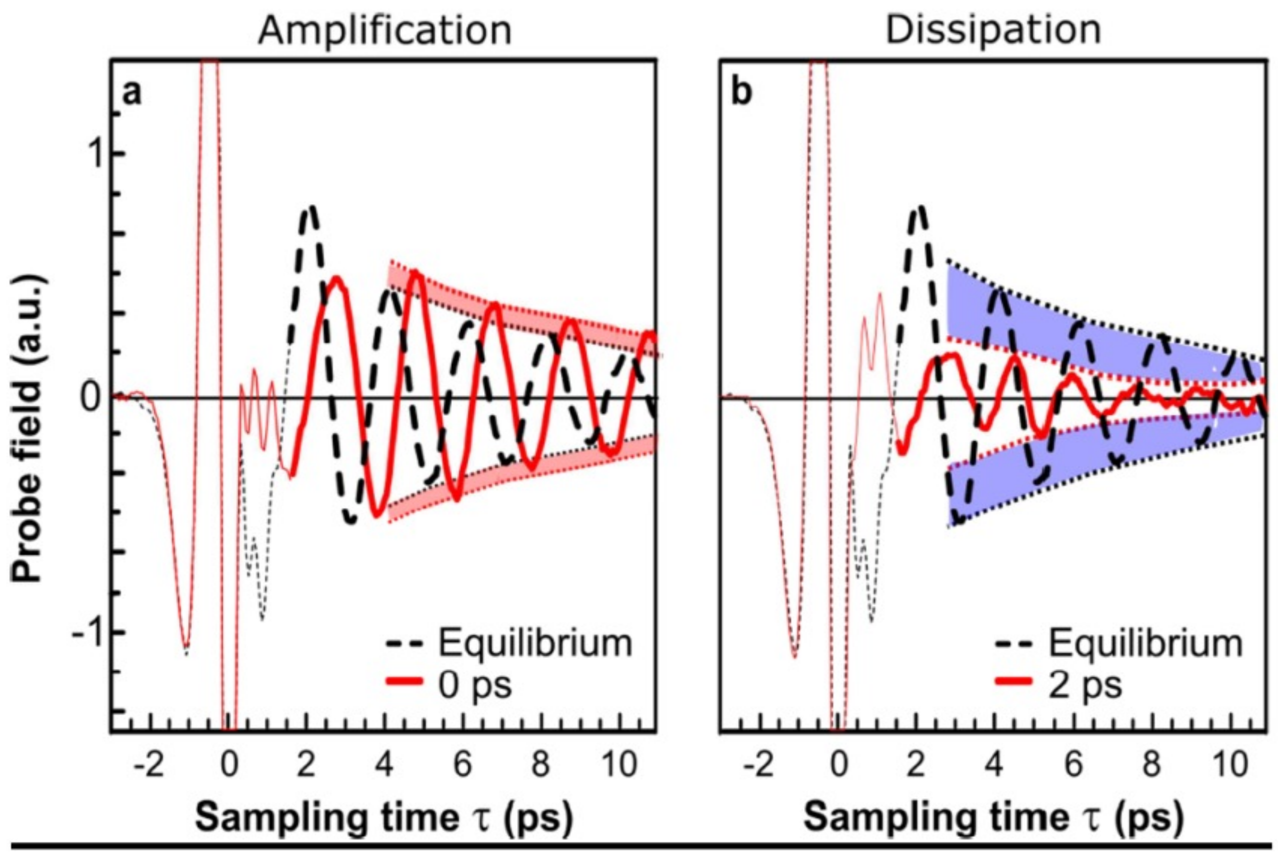


Strong response at $2\omega_{JP}$

Plasma waves moving into the SC

Negative oscillator strength

Amplification of the probe field



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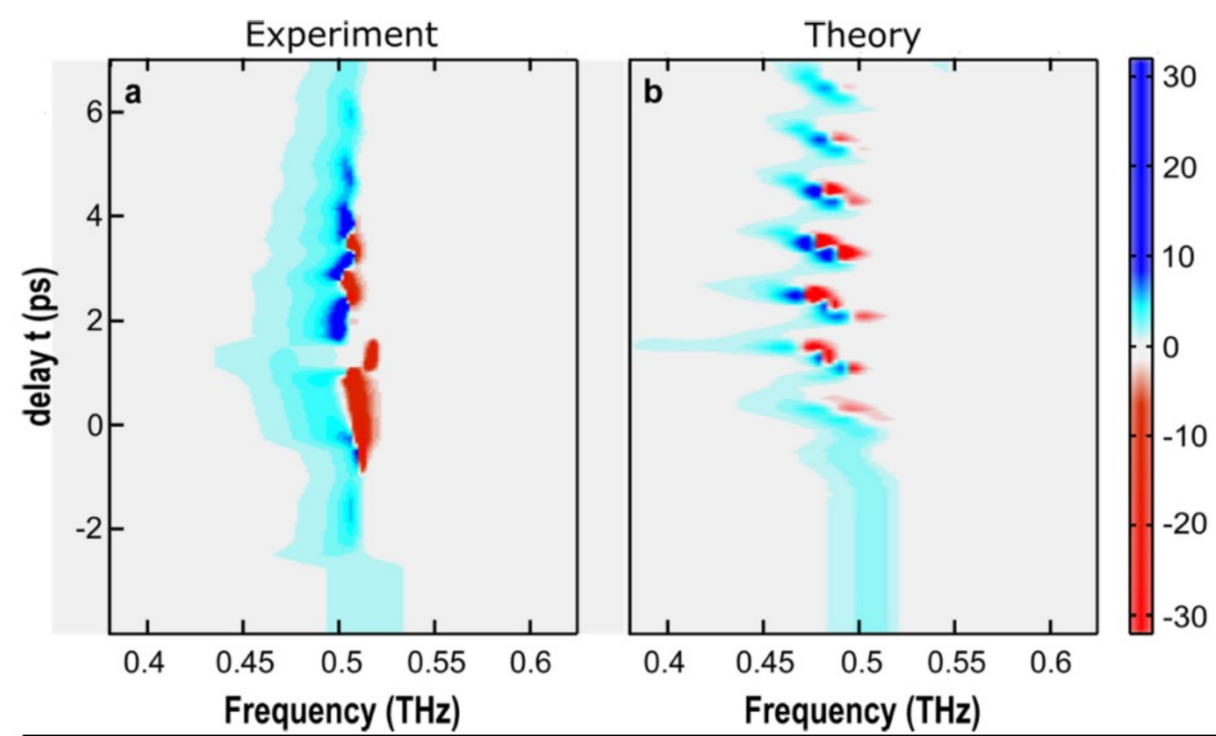
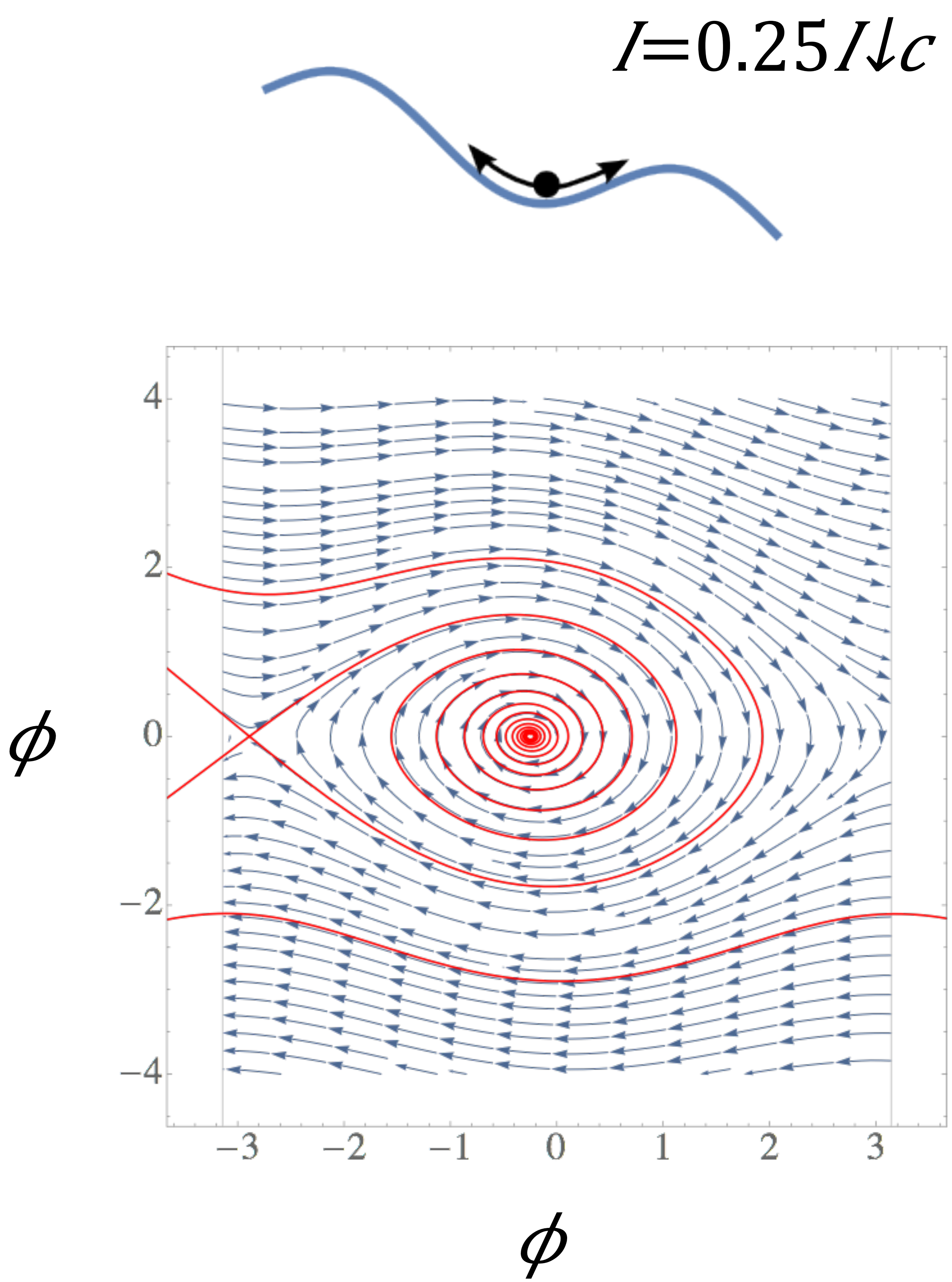
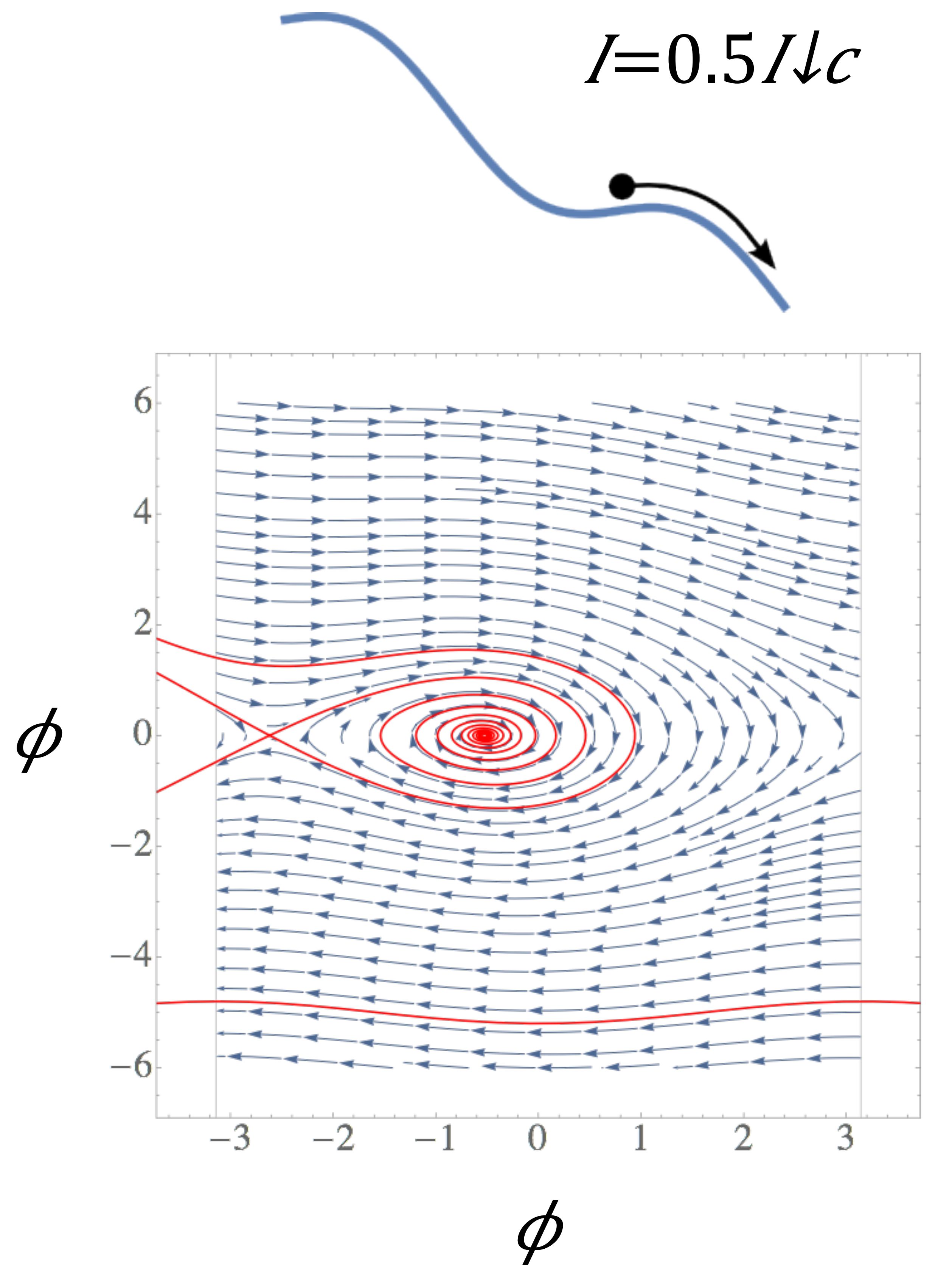
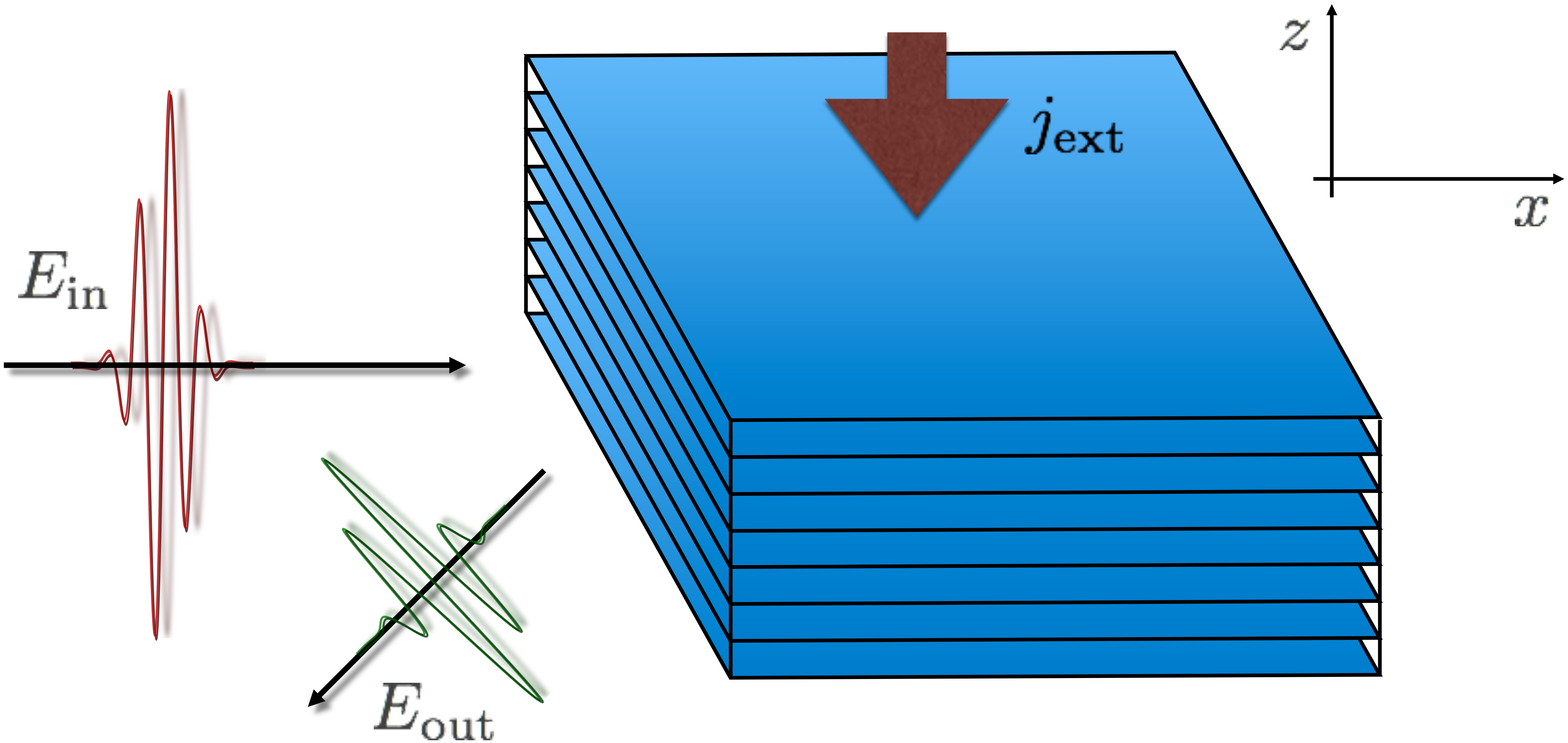


External currents and phase space





External Currents: Optical Nonlinearity



External current: $\sin(\phi_0) = j_{\mathrm{ext}}$

vanishes without current

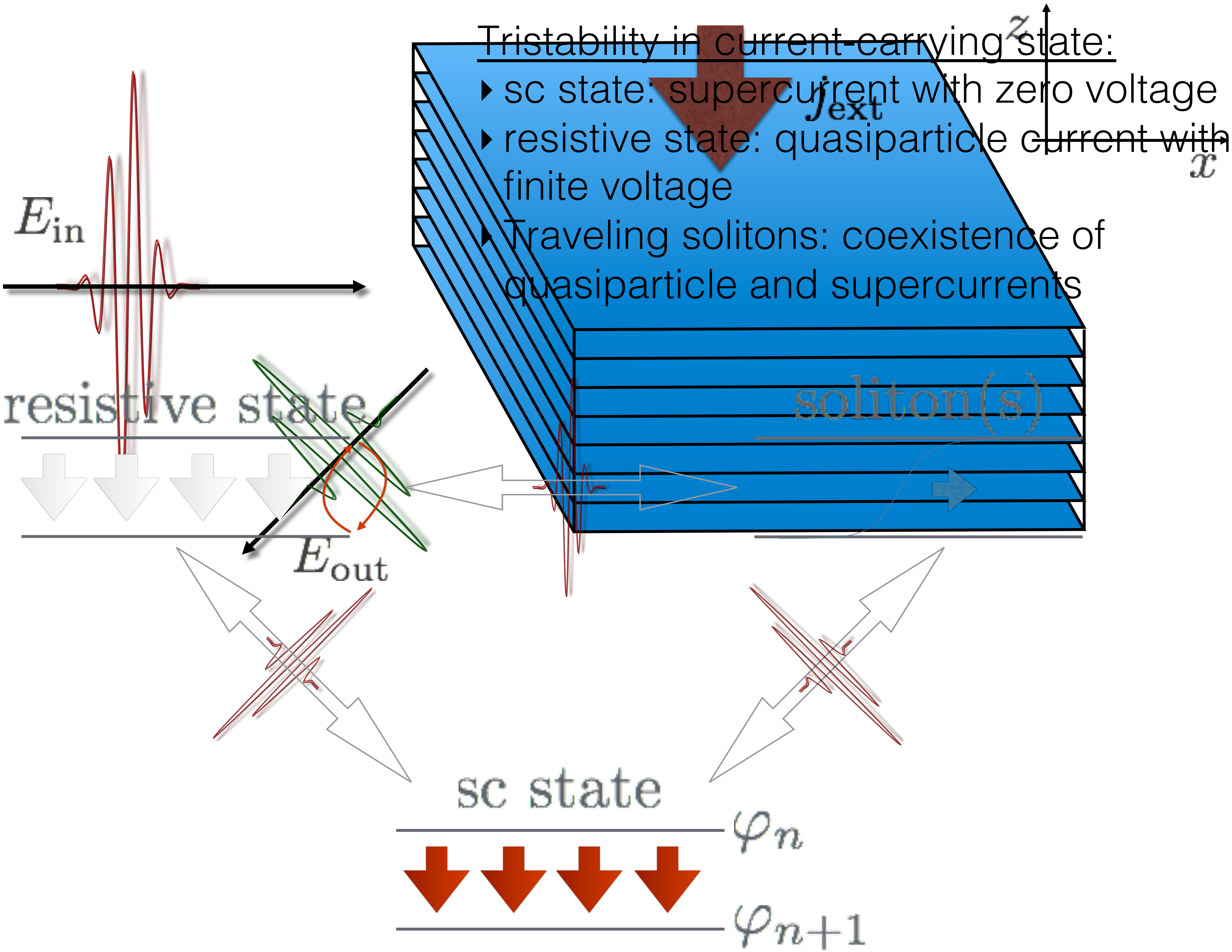
Fluctuations: $\sin(\phi_0 + \phi_\epsilon) = \sin(\phi_0) + \cos(\phi_0)\phi_\epsilon - \frac{1}{2}\sin(\phi_0)\phi_\epsilon^2 + \cdots$

External currents change (enhance) nonlinear response

Currents: Steady states

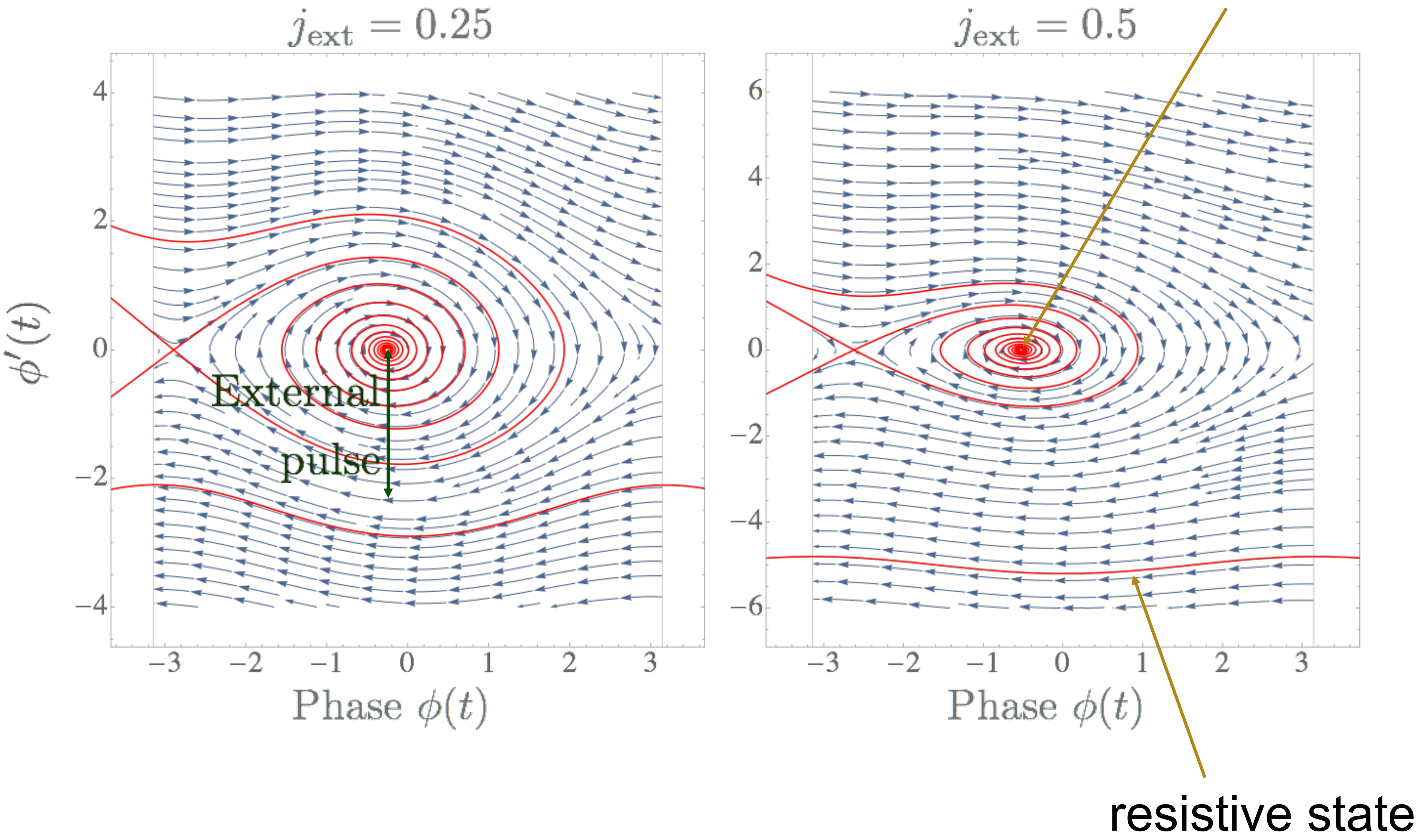
Tristability in current-carrying state:

- sc state: supercurrent with zero voltage
- resistive state: quasiparticle current with finite voltage
- Traveling solitons: coexistence of quasiparticle and supercurrents



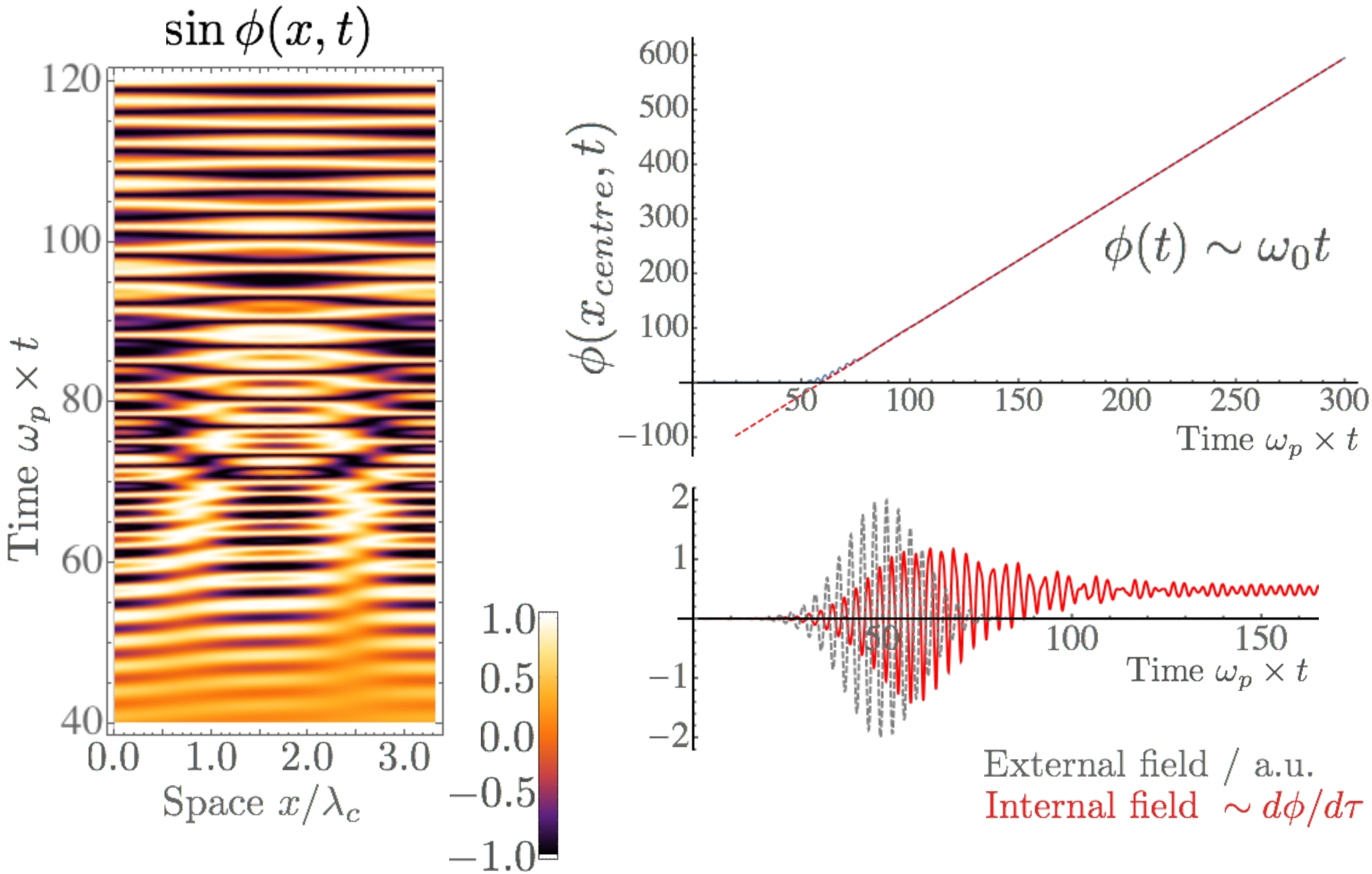
Phase space diagrams

Uniform plasma oscillations: $\phi(x,t) = \phi(t)$

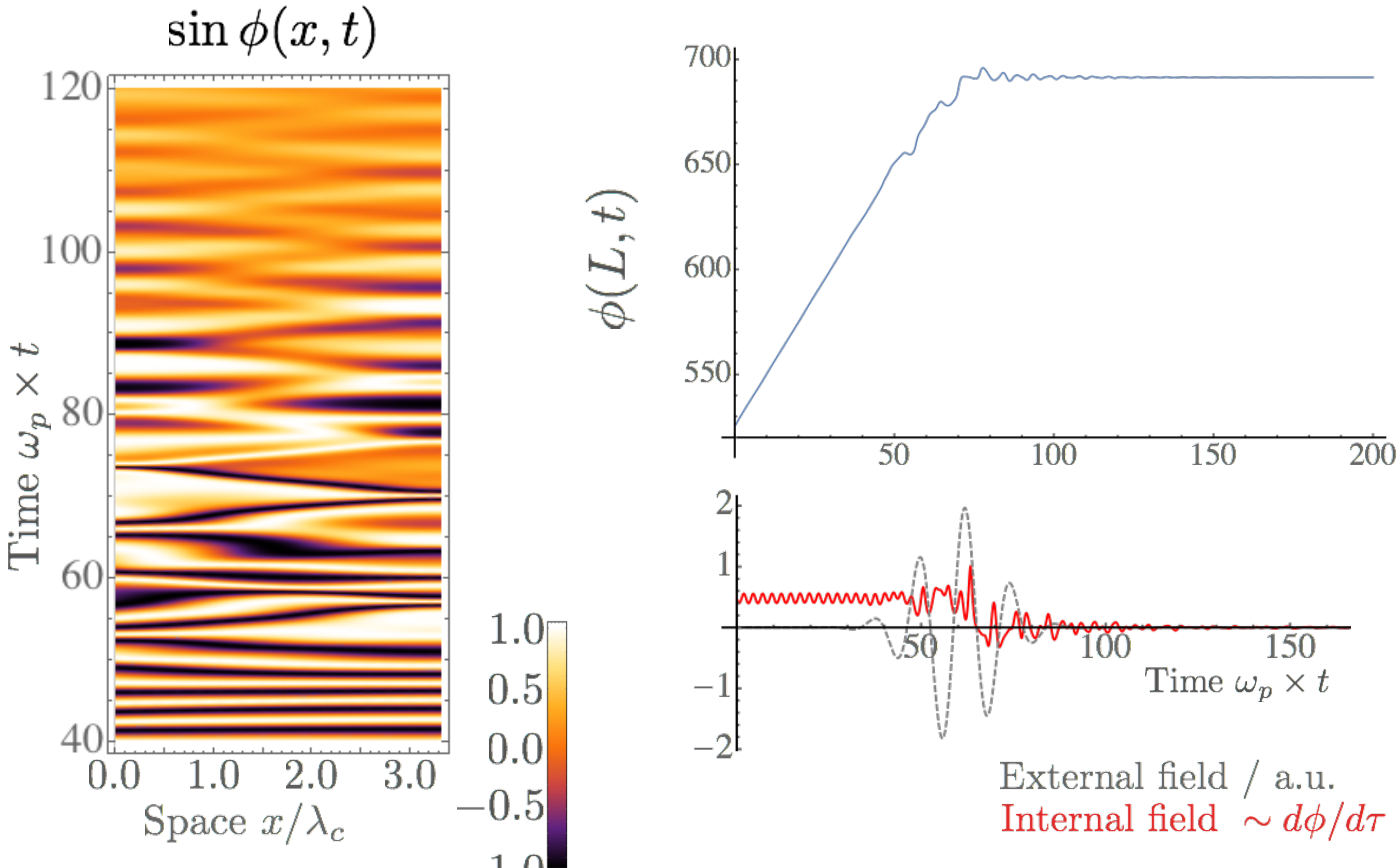


Electric field $\propto \phi'(t)$

Switching I: SC → resistive state

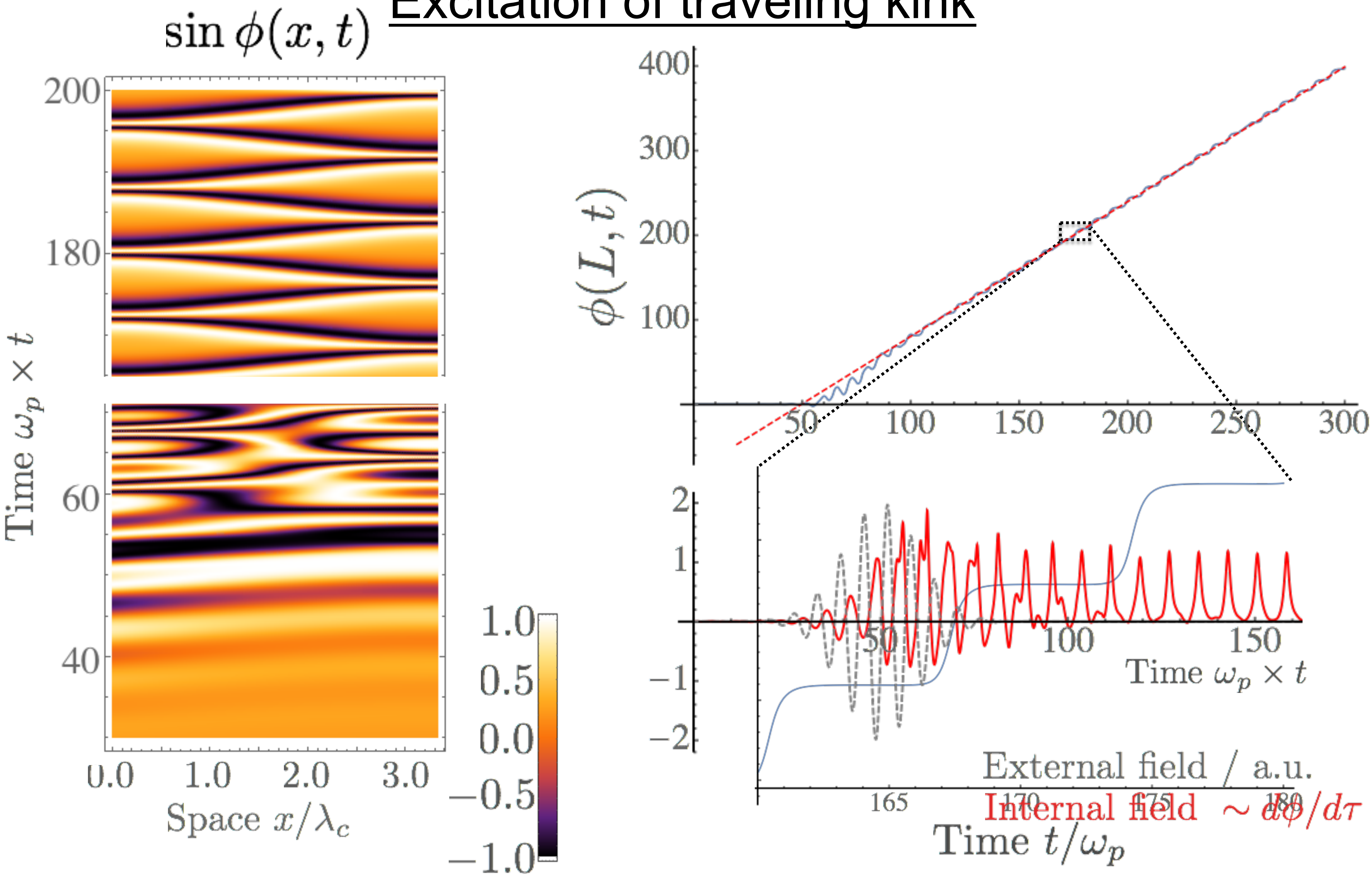


Switching I: resistive state → SC



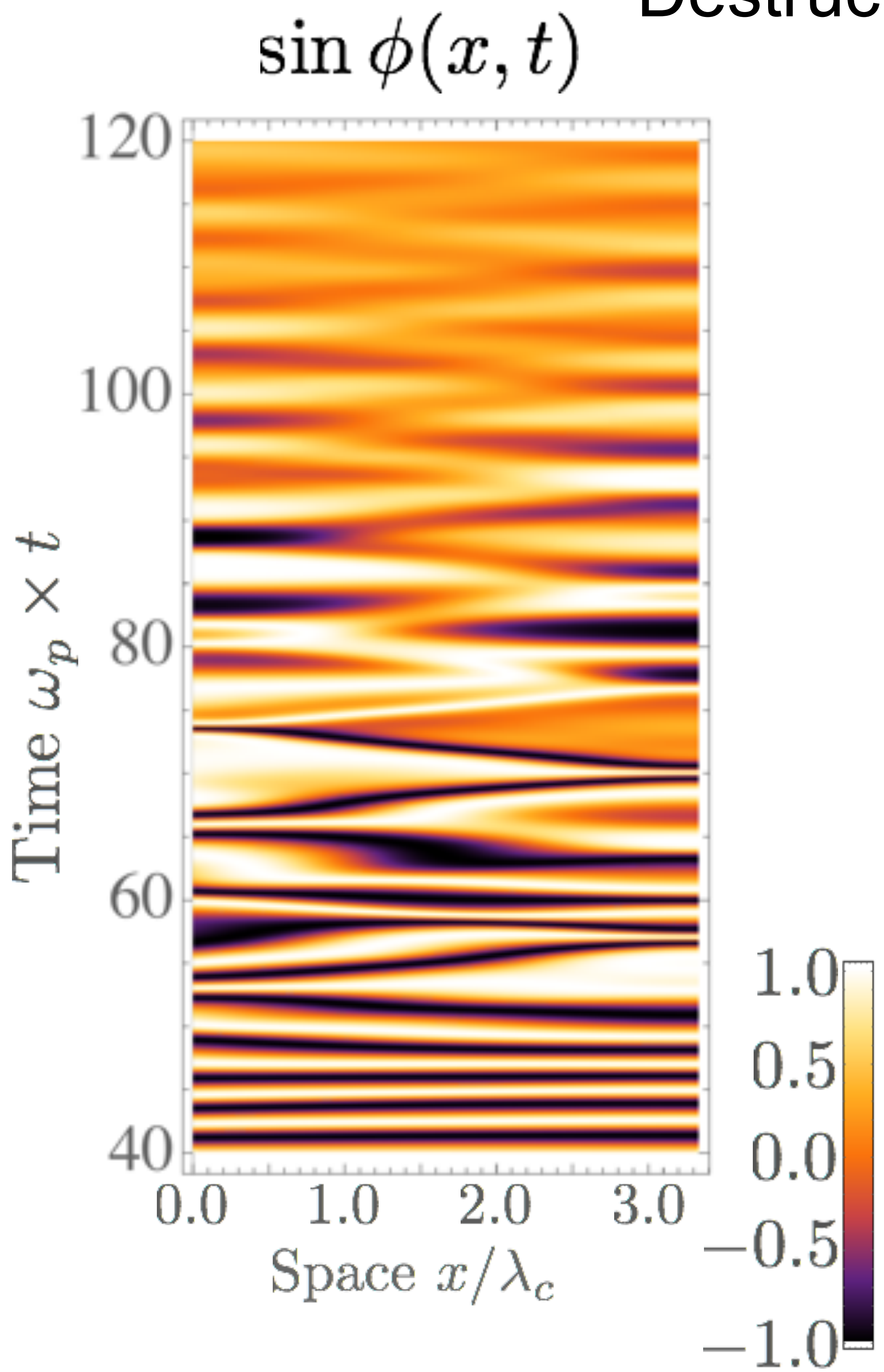
Switching II: SC → kink

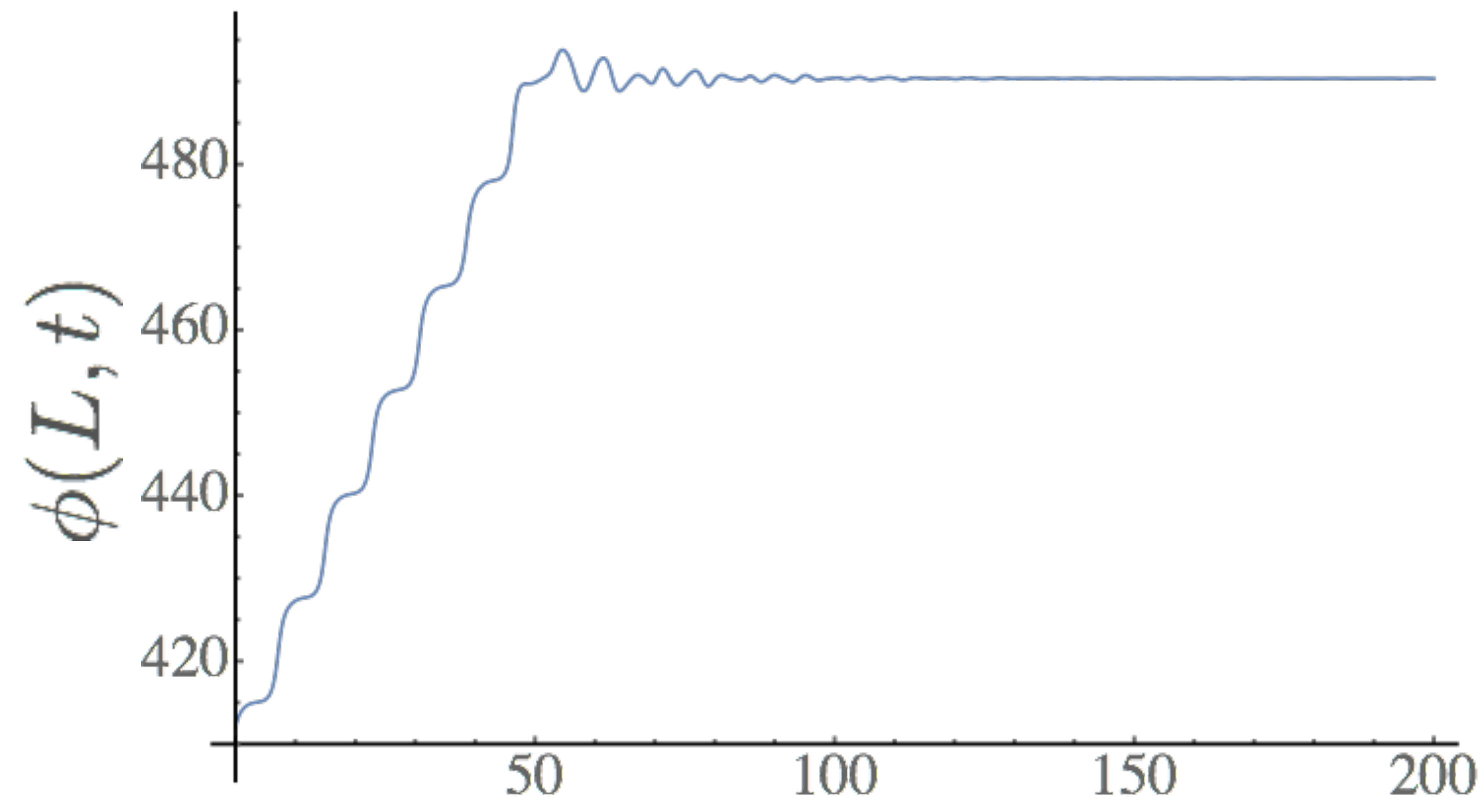
<u>Excitation of traveling kink</u>

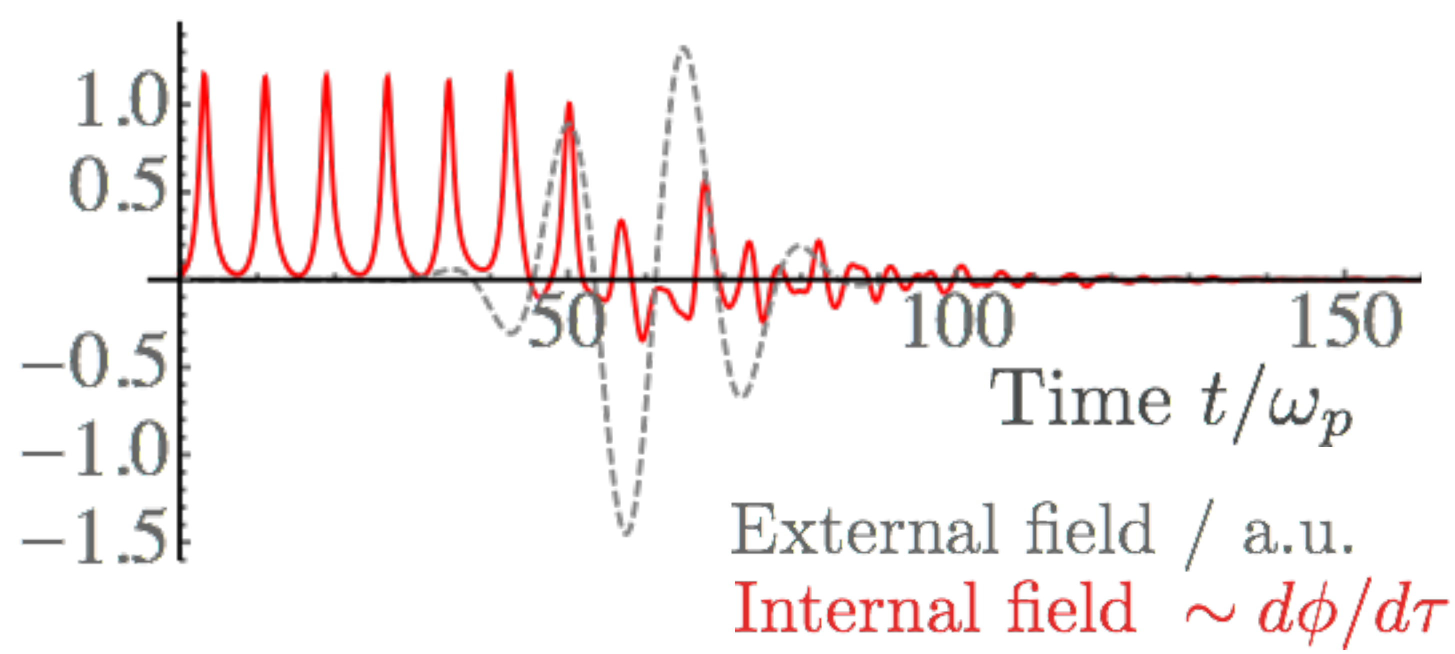


Switching II: kink → SC

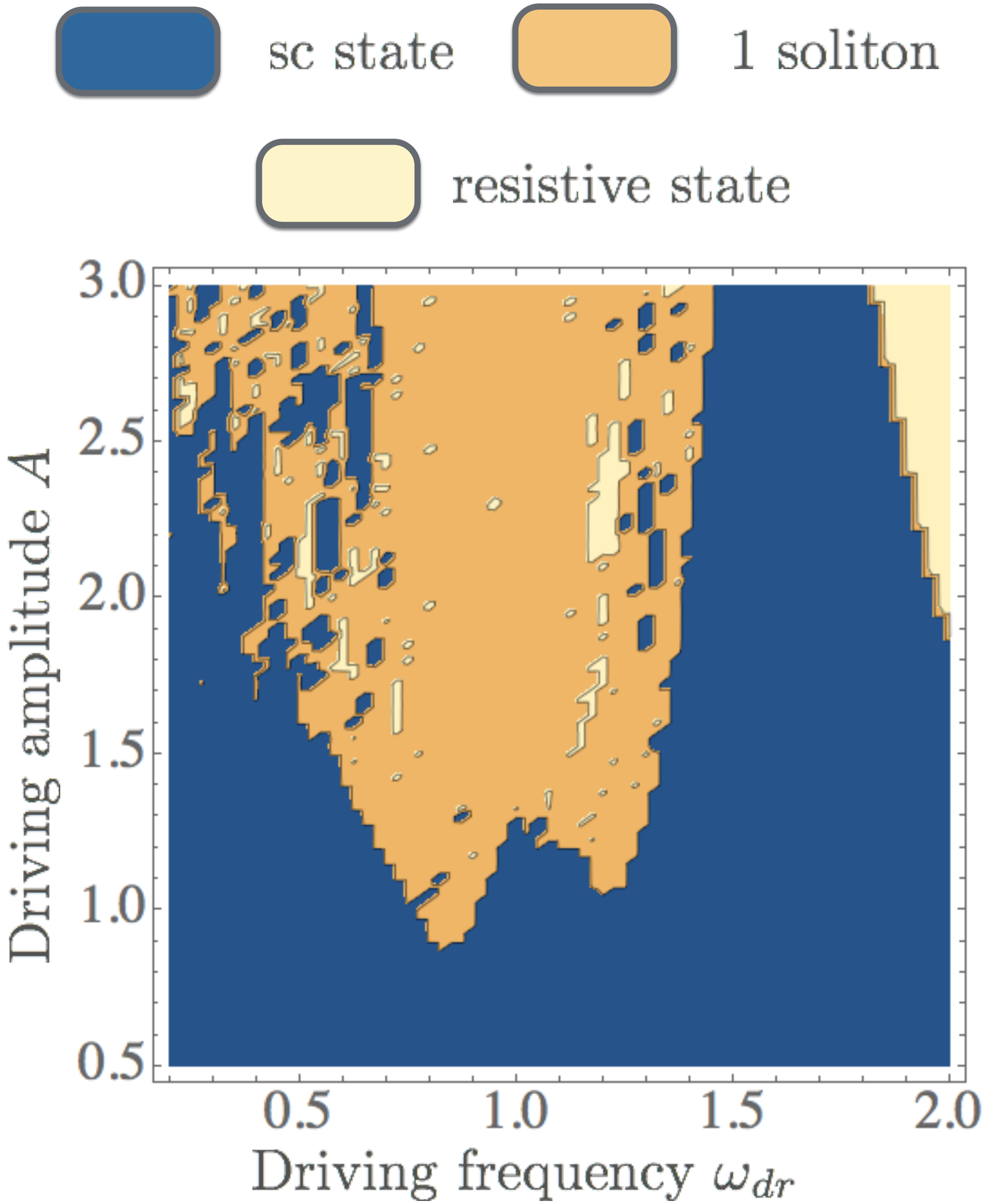
Destruction of traveling kink



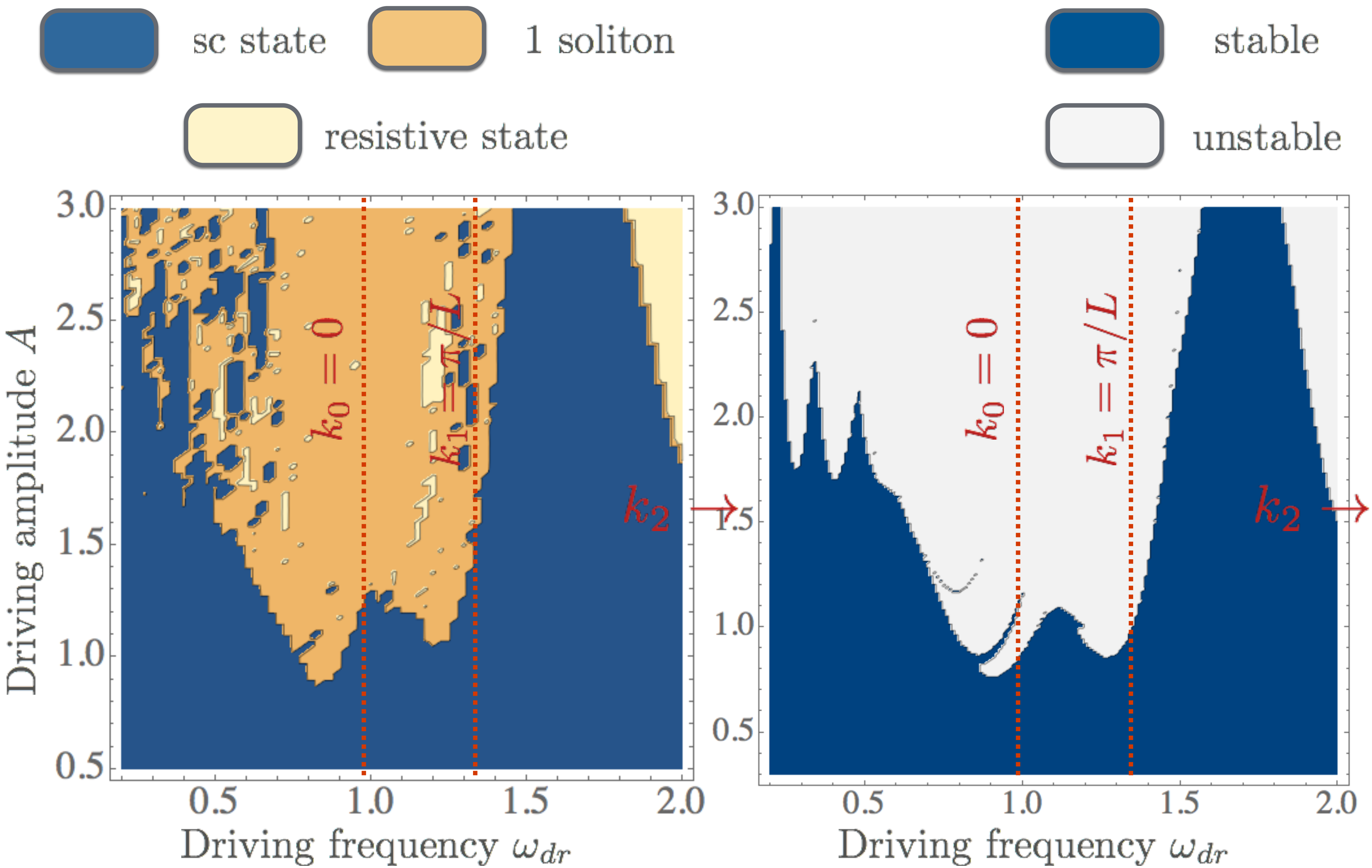




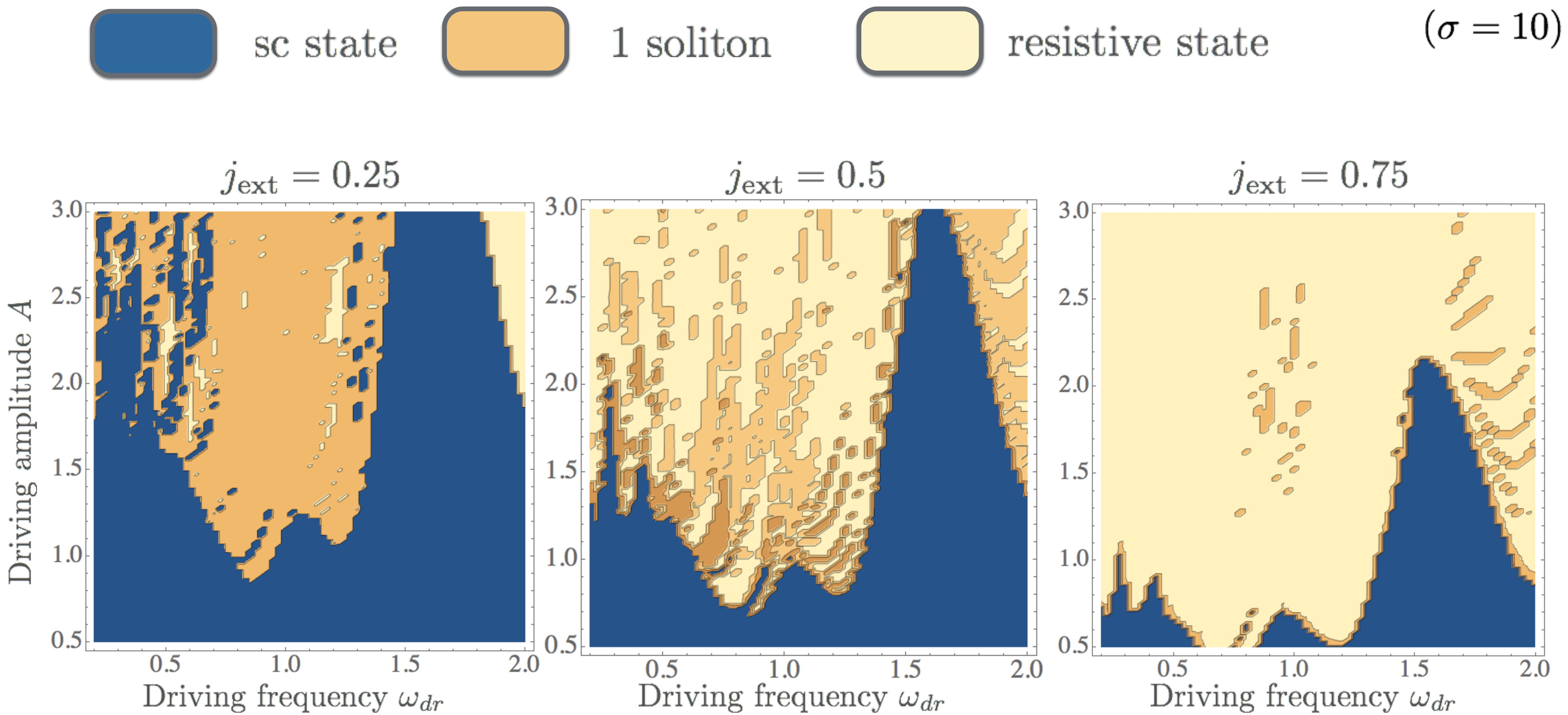
Parameter space I



Parameter space I: SC → ?



Parameter space II

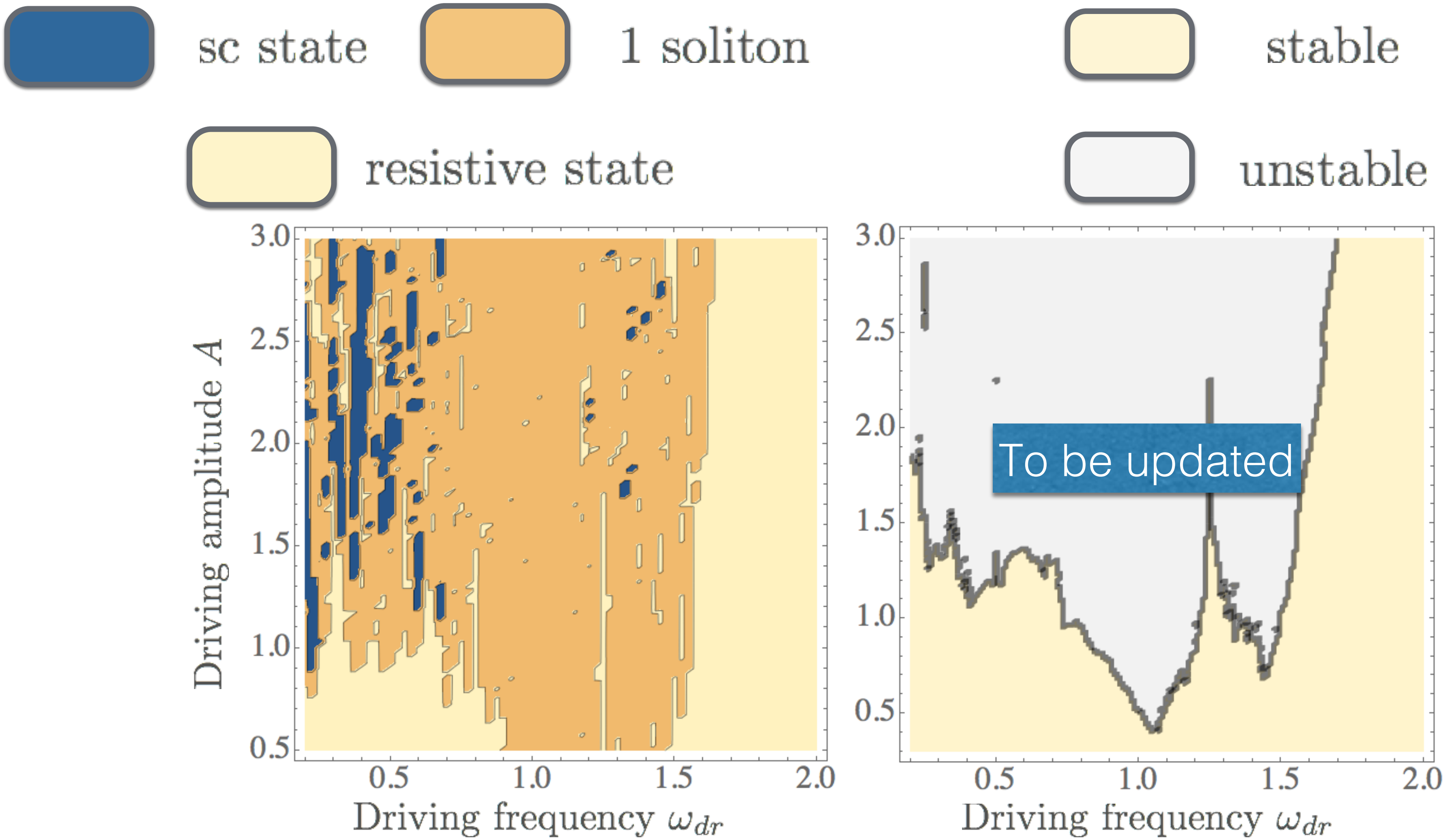


Initial SC state: $\phi_0 = \arcsin j_{\text{ext}}$

External driving: $h_{ext}(t) = A\sin(\omega_{dr}t + \gamma)e^{-(t-t_0)^2/(2\sigma^2)}$

Parameter space: resistive → ?

$(\sigma = 10)$



Initial resistive state: $\phi_{res}(t) = \omega_0 t + \Im\{e^{i\omega_0 t}/(\omega^2 - i\nu_c\omega)\}$

External driving: $h_{ext}(t) = A\sin(\omega_{dr}t + \gamma)e^{-(t-t_0)^2/(2\sigma^2)}$

Equations of motion

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$$\frac{\partial^2 \phi_n}{\partial \tau^2} + \nu_c \frac{\partial \phi_n}{\partial \tau} + \sin(\phi_n) - \frac{\partial h_n}{\partial x} = j_{\text{ext}} + \eta(x,\tau)$$

$$(\nabla_n^2 - \frac{1}{\ell^2}) h_n + \frac{\partial \phi_n}{\partial x} + \nu_{ab} \frac{\partial}{\partial \tau} (\frac{\partial \phi_n}{\partial x} - \frac{h_n}{\ell^2}) = 0$$

Open Boundaries: $\frac{\ell}{\sqrt{\epsilon_c}} \frac{\partial \phi_n}{\partial \tau} = h_n - 2H_{\text{ext}}(\tau)$

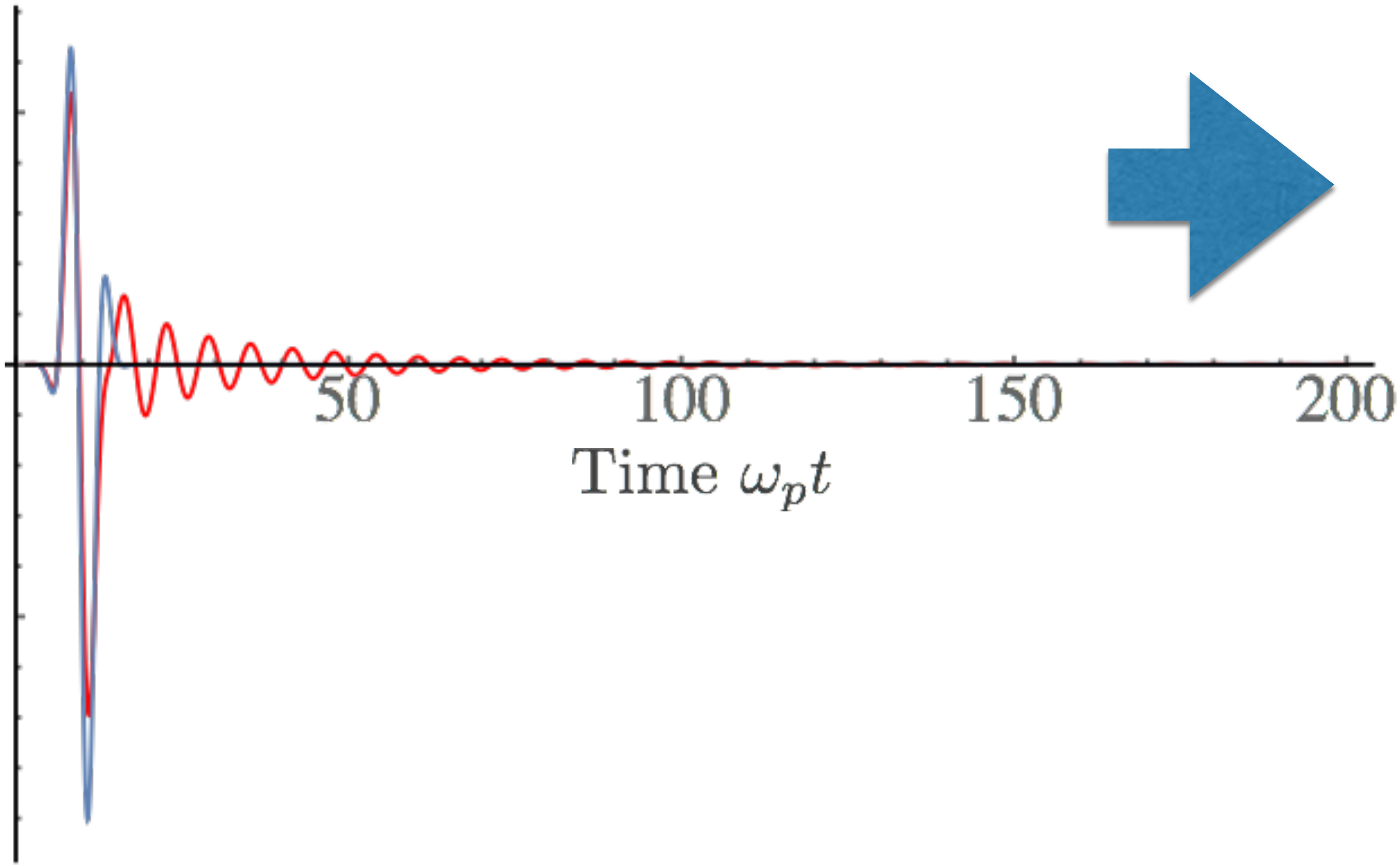
Closed Boundaries: $h_n = 2H_{ext}(\tau)$

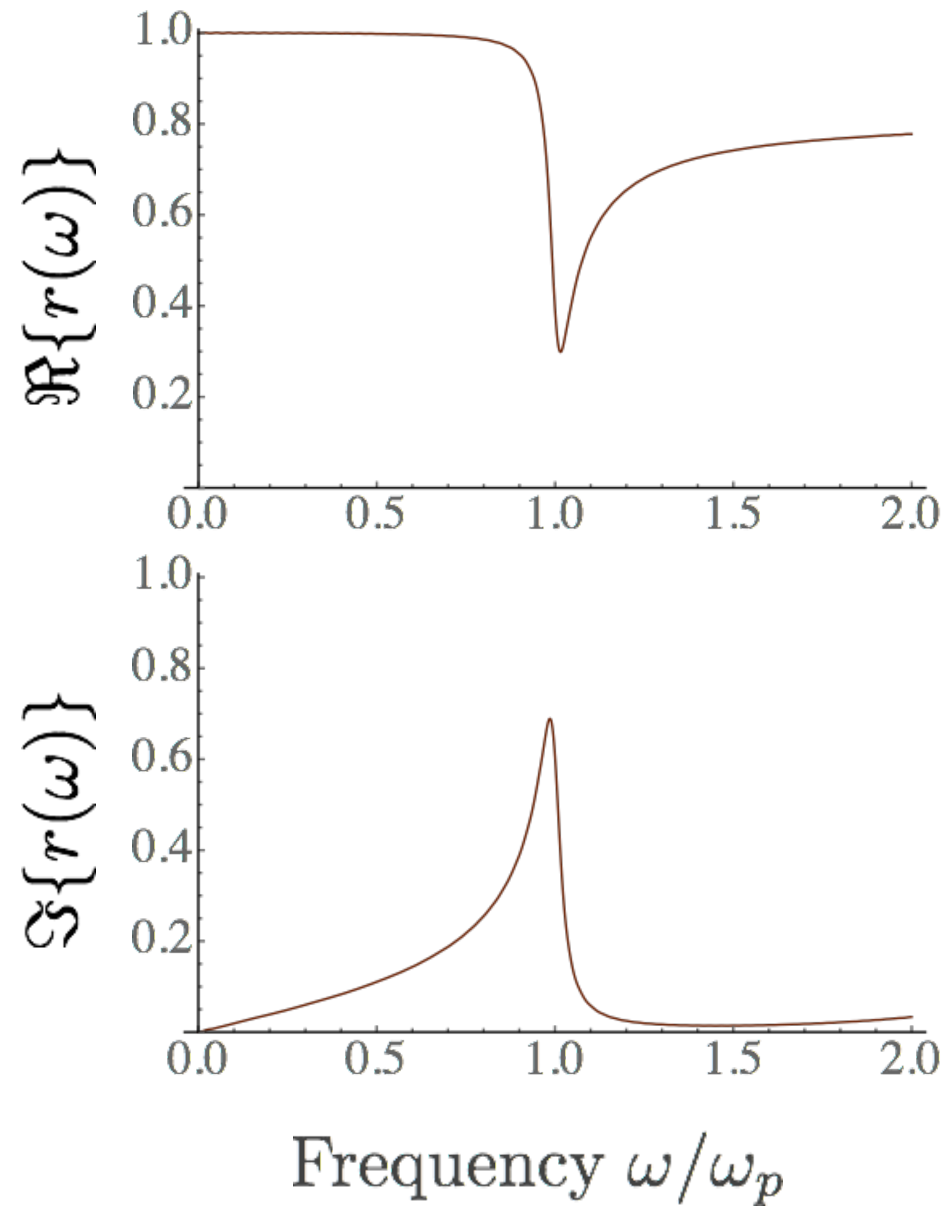
$h \downarrow n$ magnetic field in y-direction in units of critical field

The system is solved by discretising the spatial dimension, and the use of the IDA (Implicit Differential-Algebraic solver) package, developed at the Center for Applied Scientific Computing of Lawrence Livermore National Laboratory.

Problems: Resolution

Calculating optical signals - Reflectivity





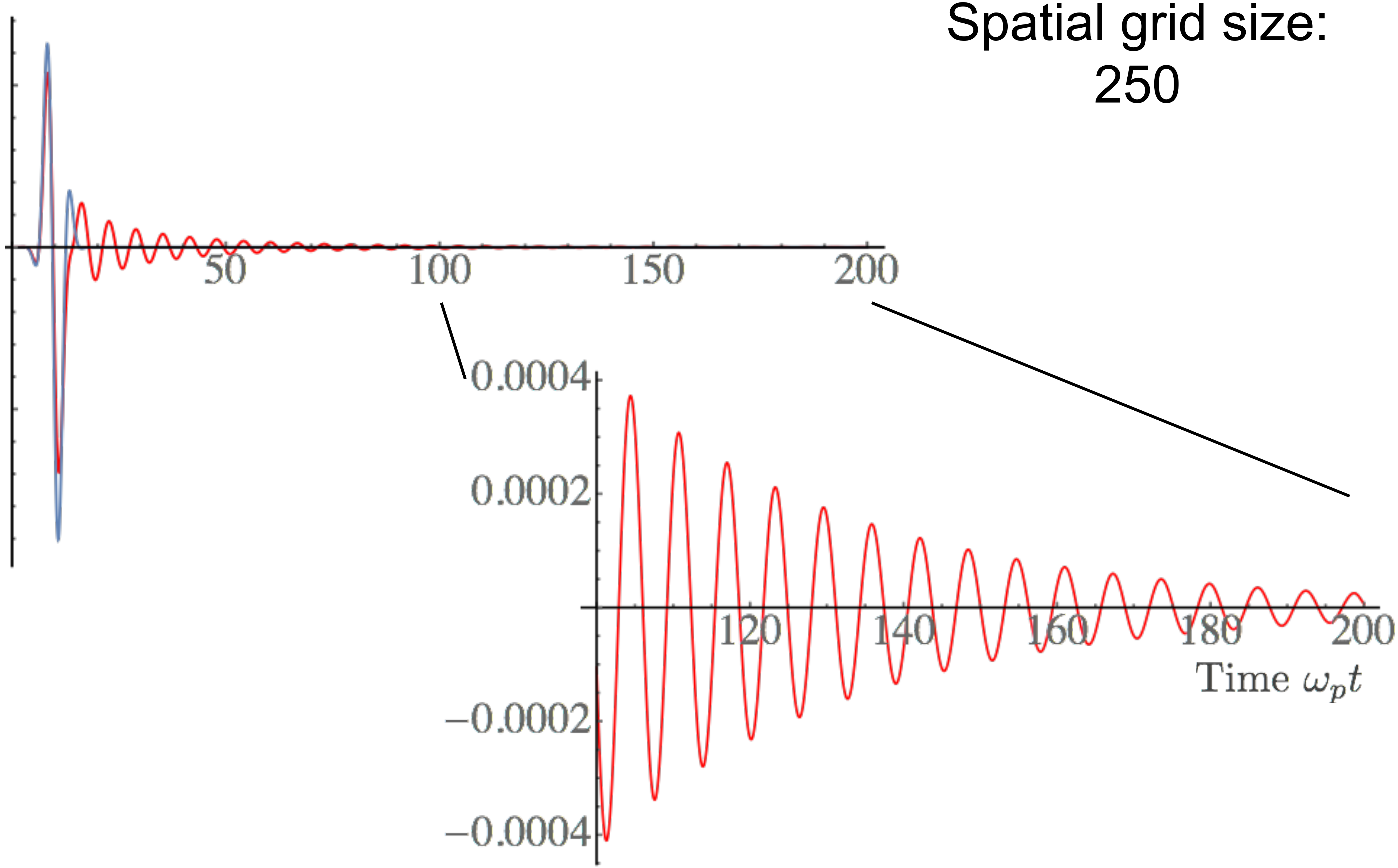
Incident electric field

Reflected electric field $\propto \dfrac{\partial \phi_n}{\partial \tau}$

Problems: Resolution

Close-up to small values

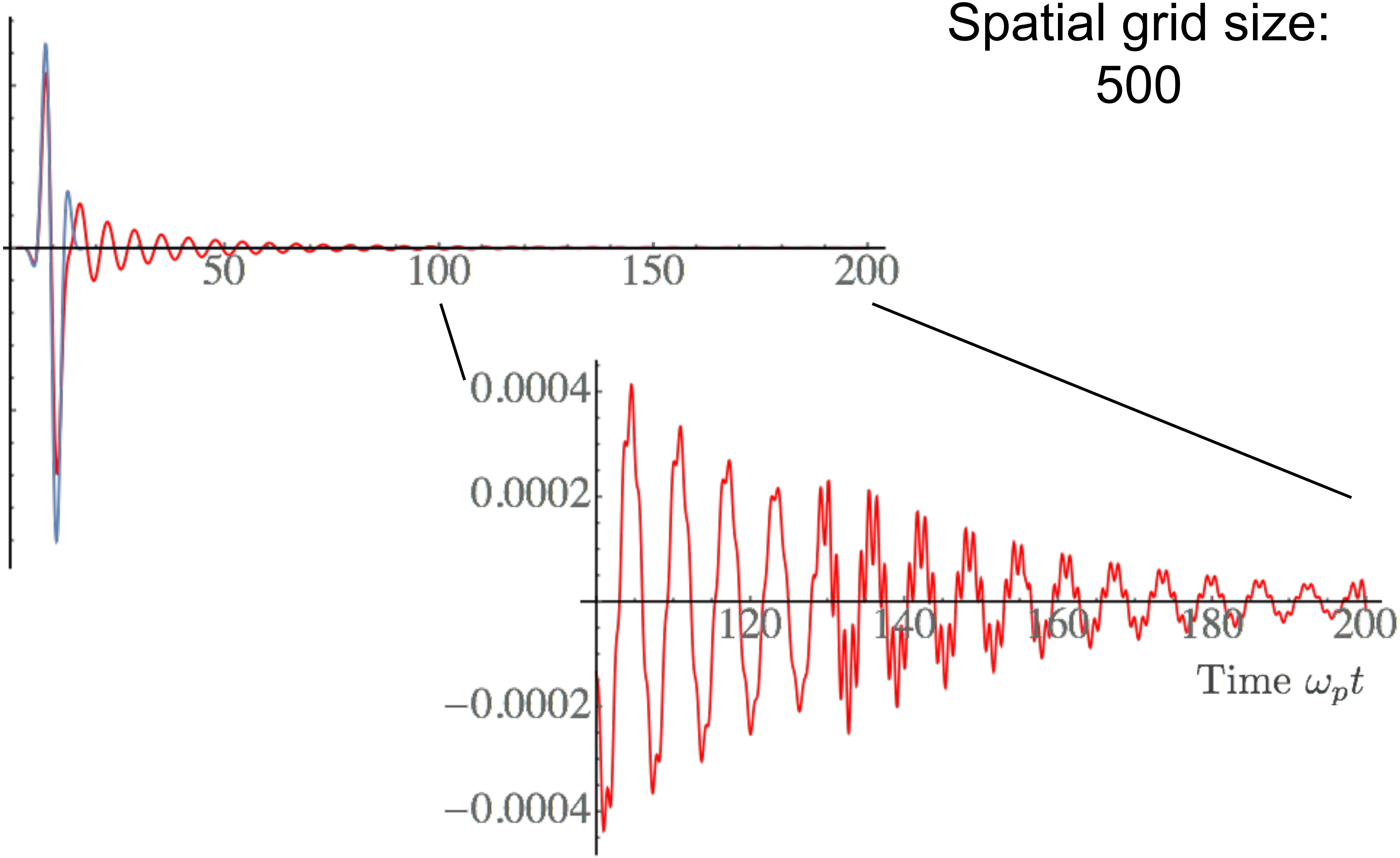
Spatial grid size: 250



Problems: Resolution

Close-up to small values

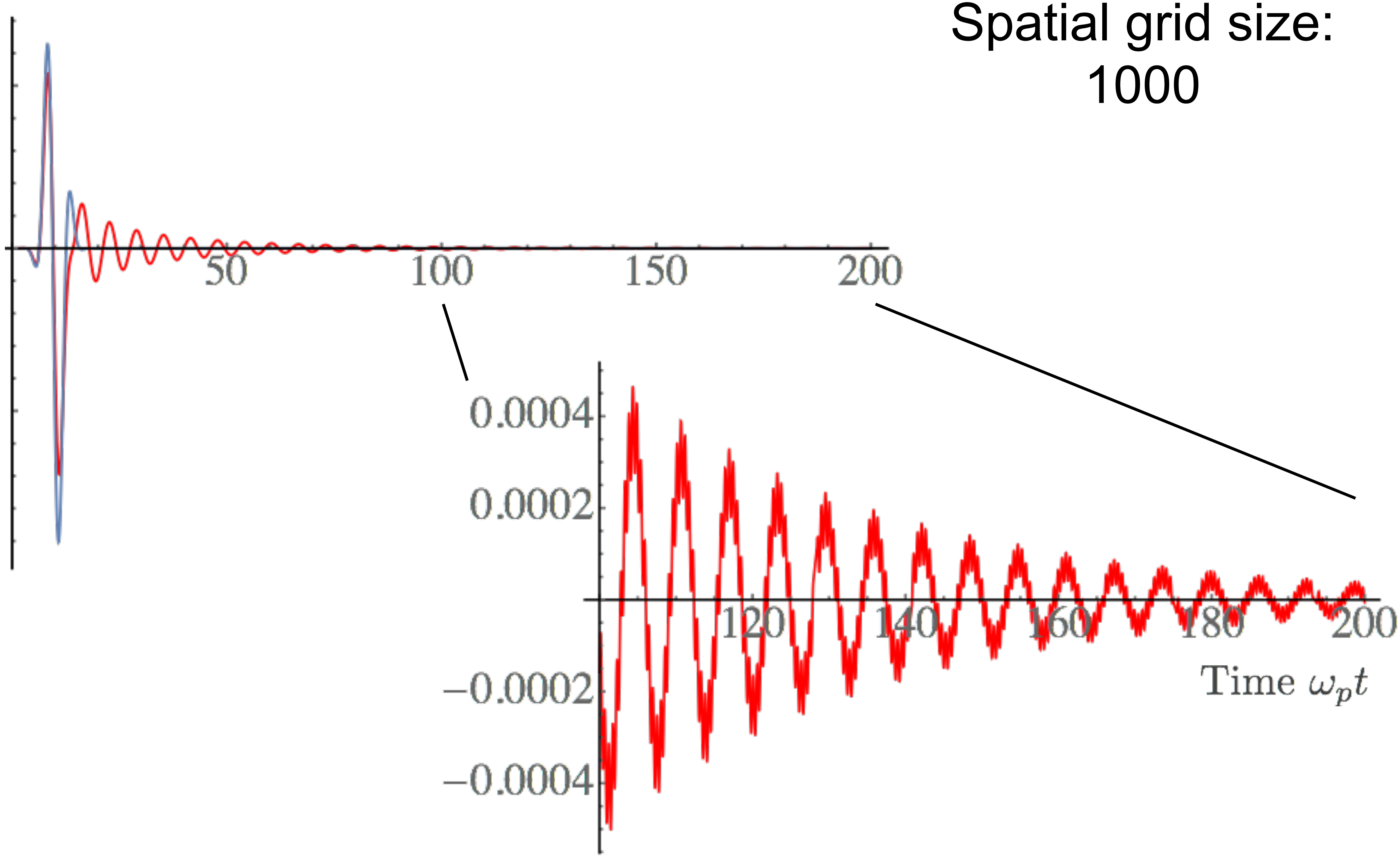
Spatial grid size: 500



Problems: Resolution

Close-up to small values

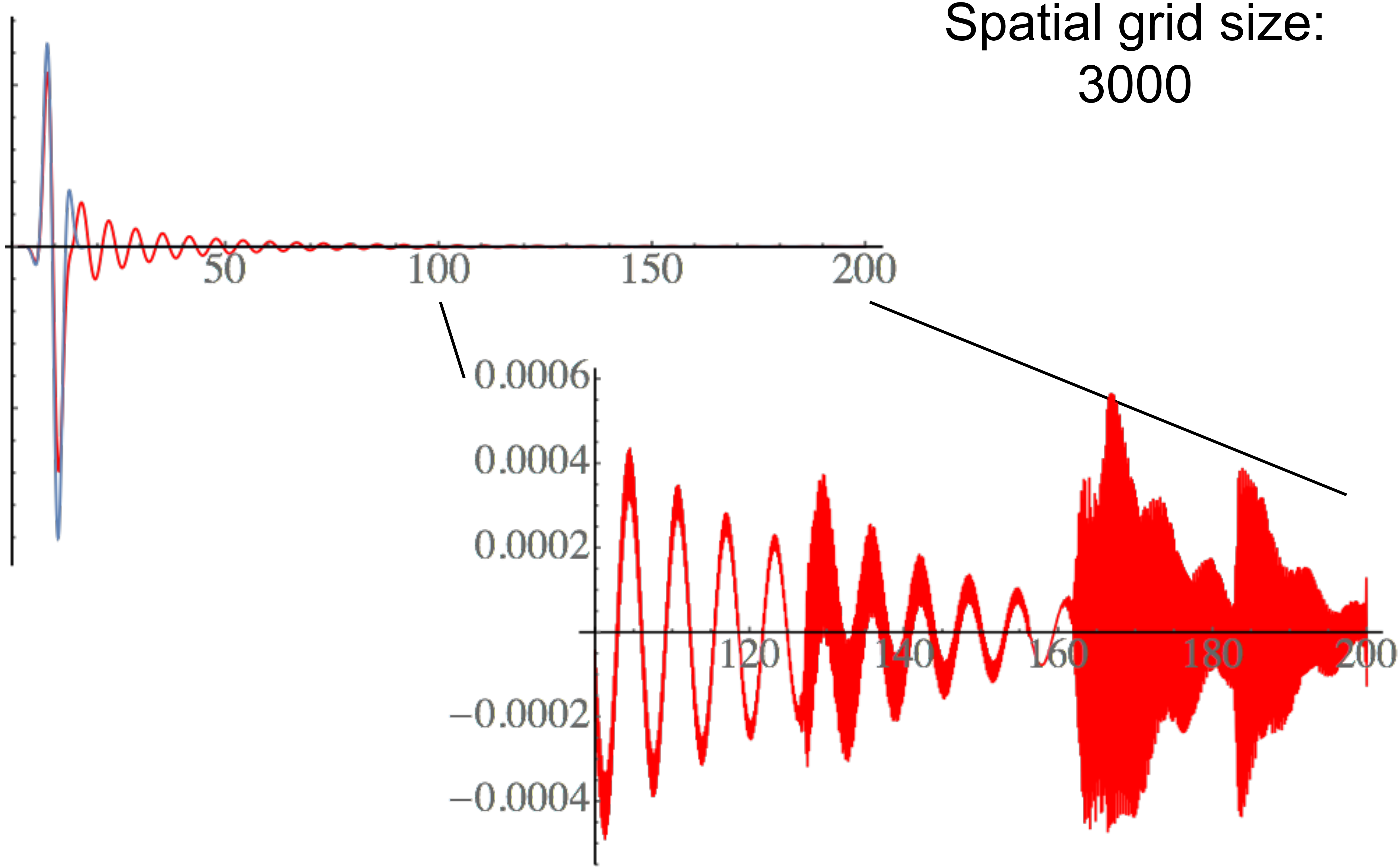
Spatial grid size: 1000



Problems: Resolution

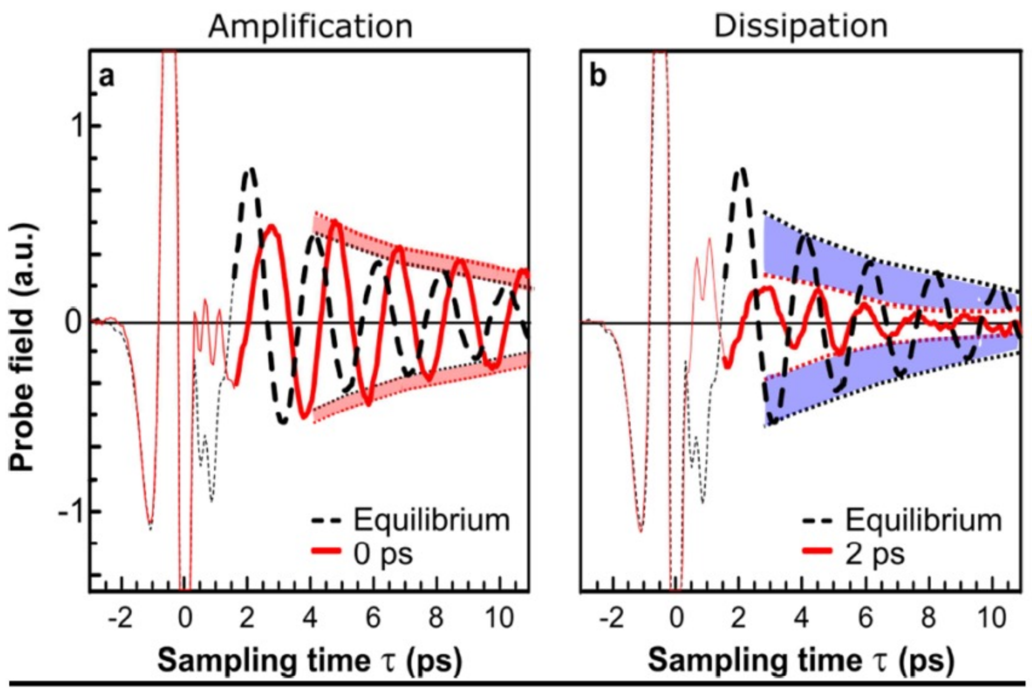
Close-up to small values

Spatial grid size:
3000



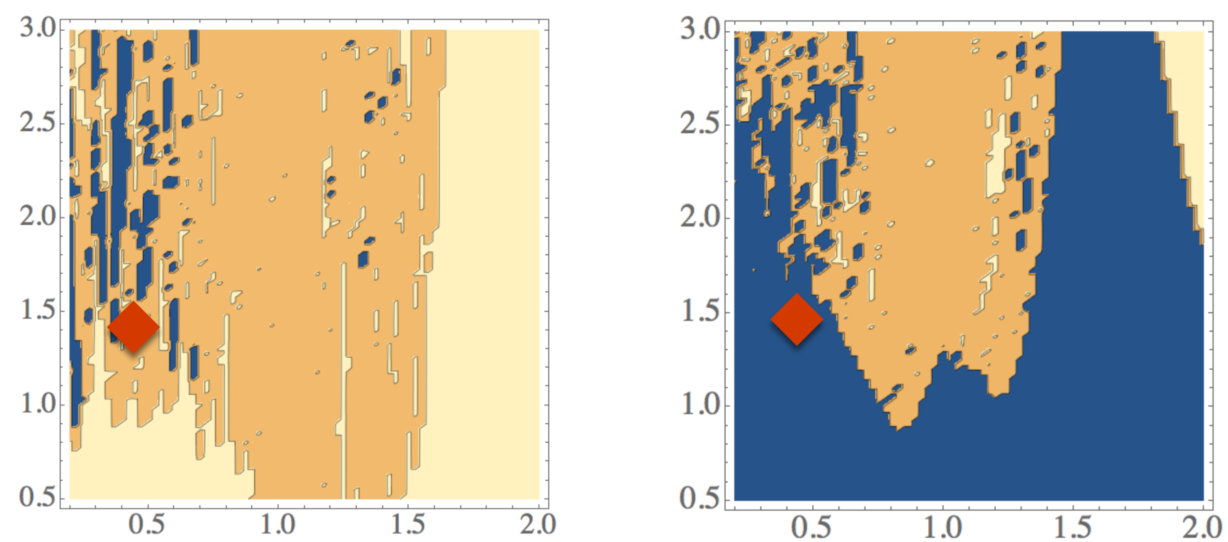
Summary

- Amplification of plasma waves
- Manipulation of currents with THz pulses
- Control of the system's phases



Challenge:

- Get accurate numerical results in the highly non-linear regime



Thanks to the team and collaborators

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  - Andreas Buchleitner
  - Stefan Kuhr
  - Martin Plenio
  - Javier Prior
  - Numerical Algorithms Group

Q-MAC

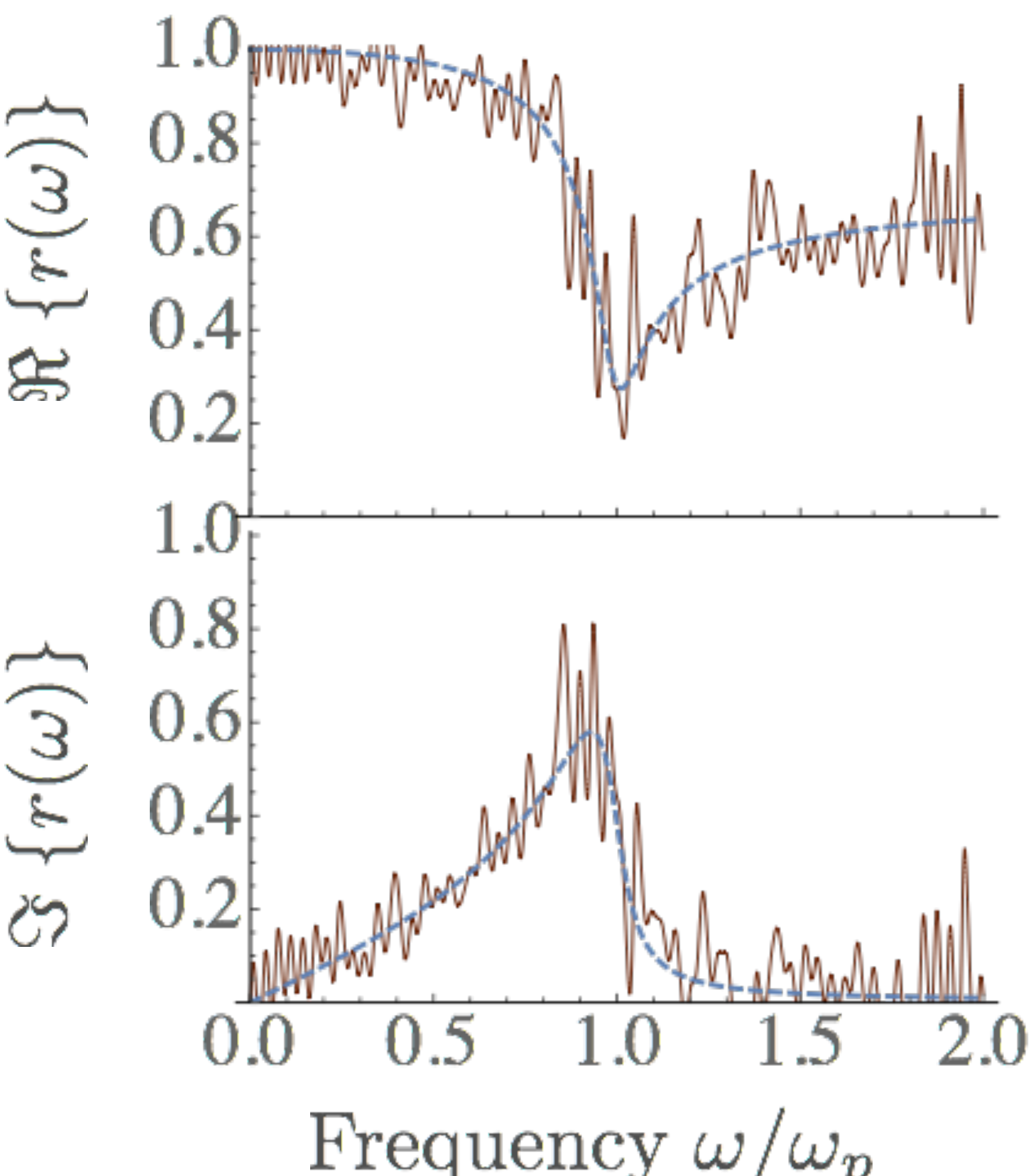
NQIT Networked Quantum Information Technologies

uProCS

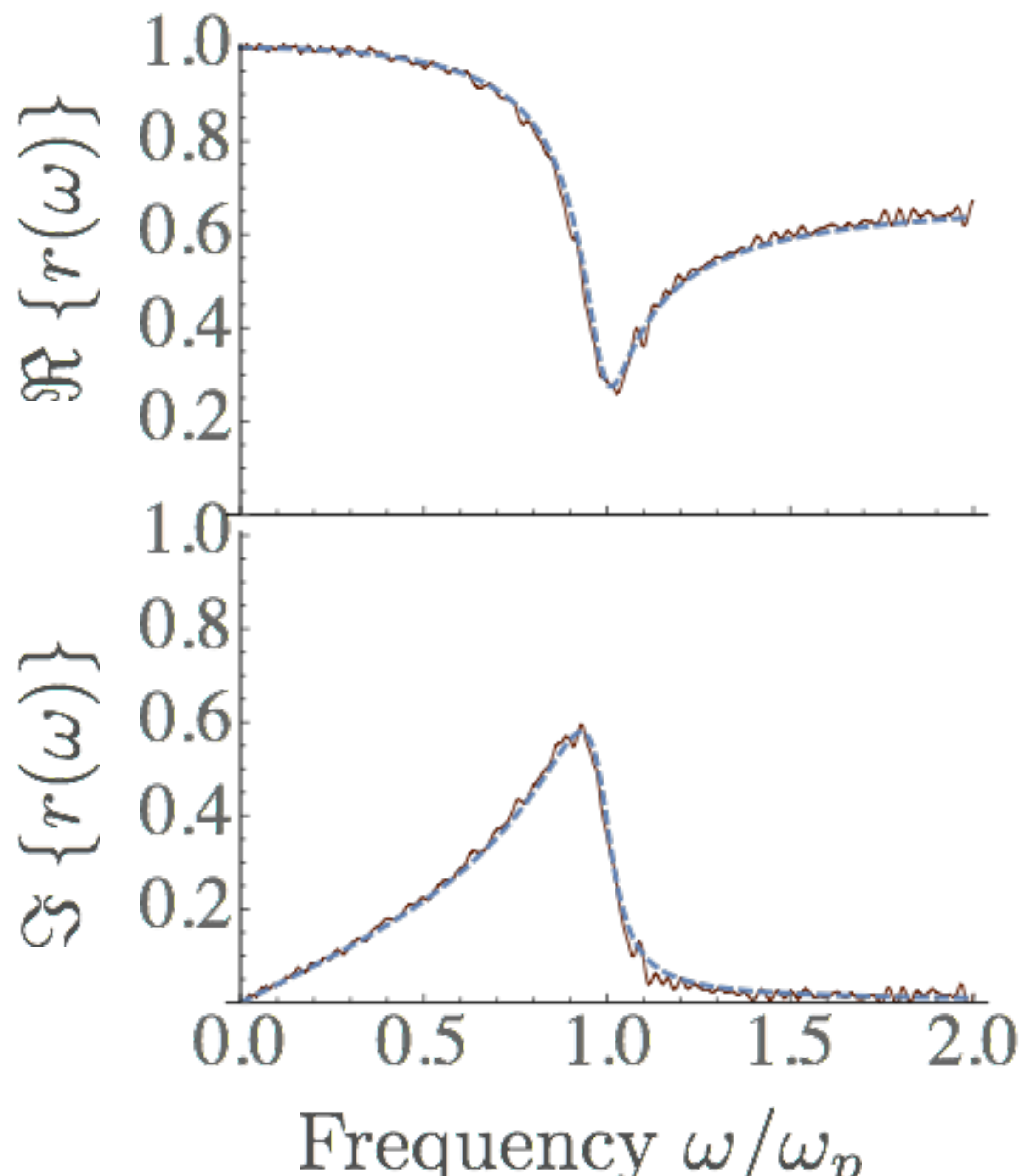
Noise

Dashed line: $\epsilon_0(\omega) = \epsilon_c \left(\sqrt{1 - j_{\text{ext}}^2} - \frac{1}{\omega^2} + i\frac{\nu_c}{\omega} \right)$ $(A = 0.5)$

<u>Single realisation:</u>



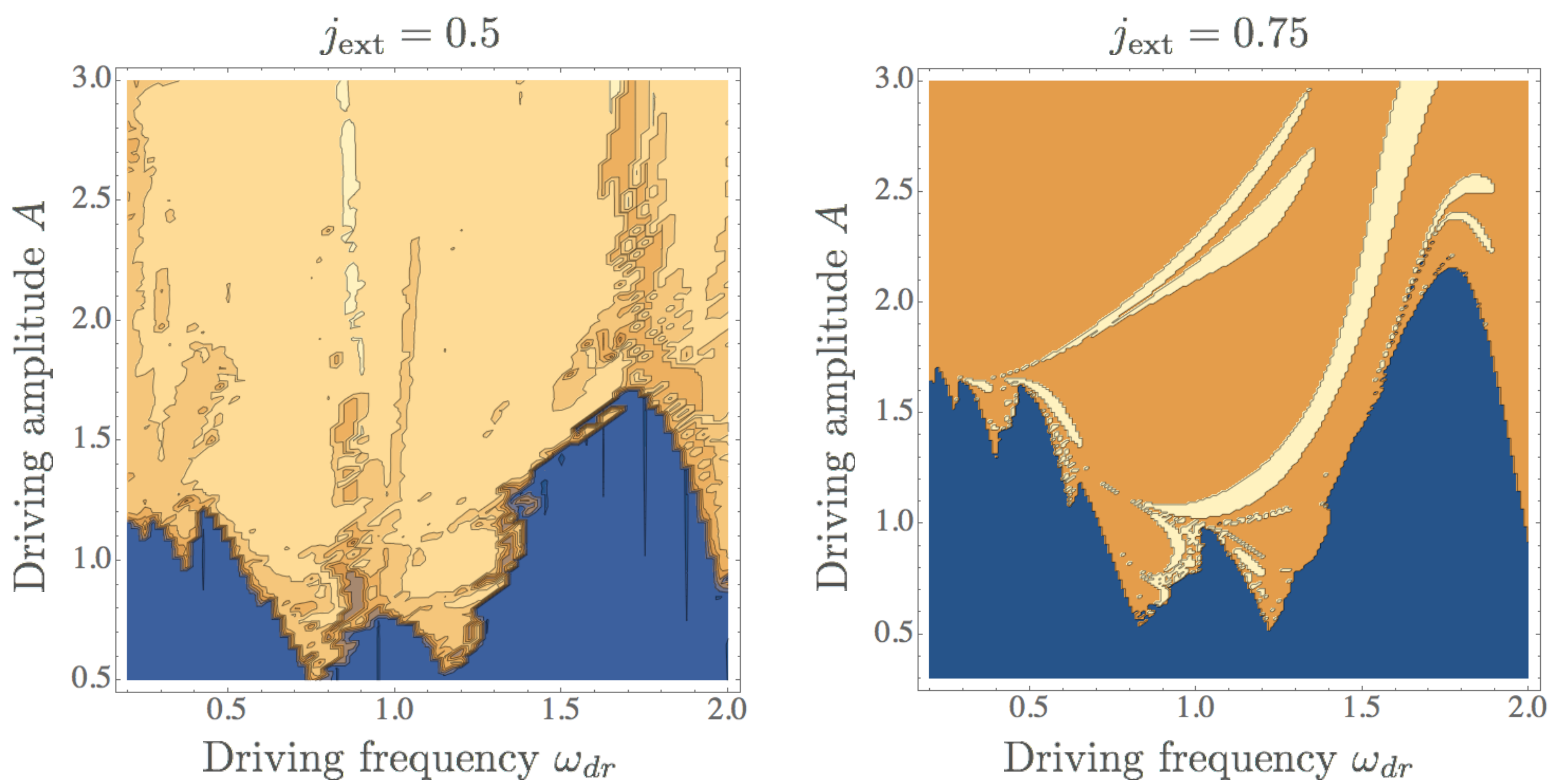
<u>Average:</u>



$\epsilon_c = 27$
$\nu_c = 0.1$
$j_{\text{ext}} = 0.0$

Parameter space II

$(\sigma = \infty)$



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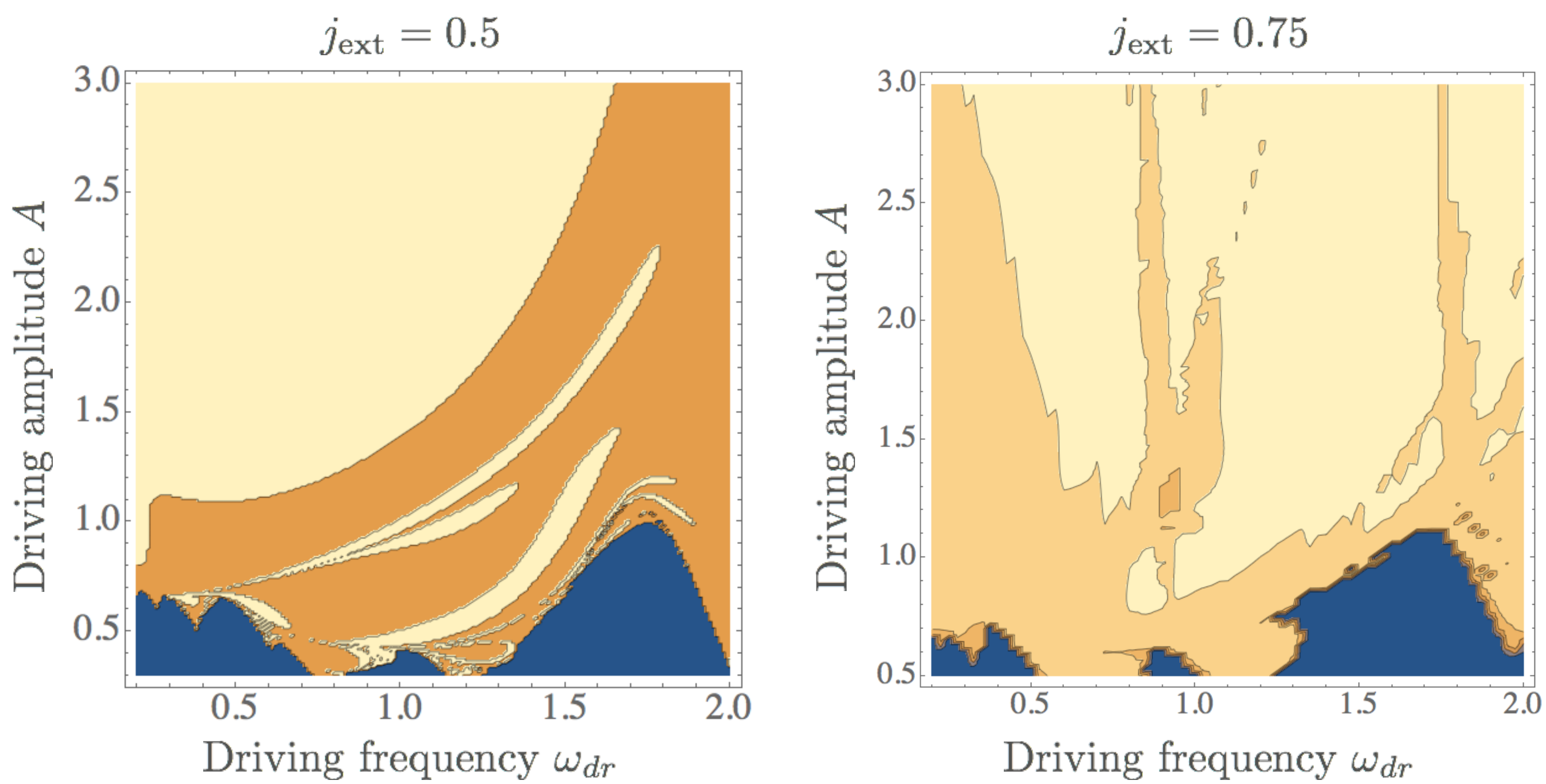


Initial sc state: $\phi_0 = \arcsin j_{\mathrm{ext}}$

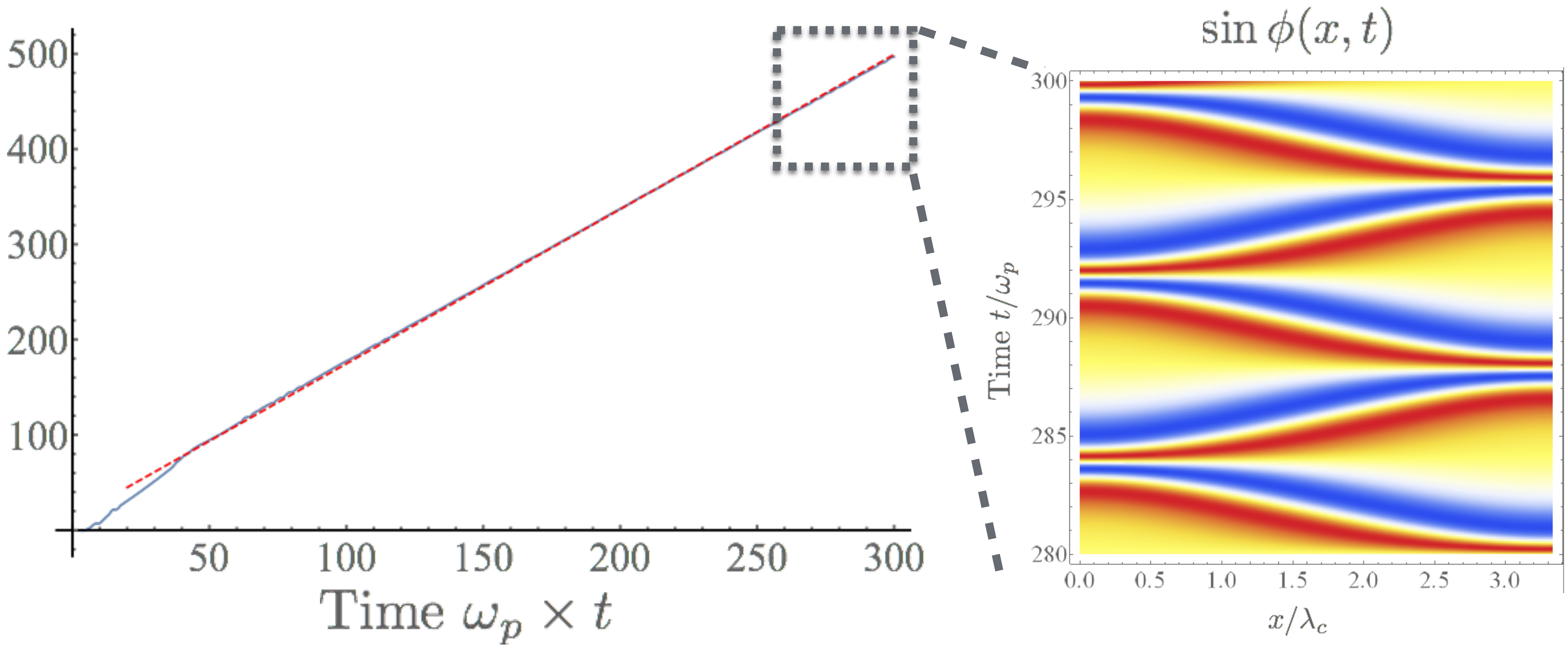
External driving: $h_{ext}(t) = A\sin(\omega_{dr} t)$

Simplified model overestimates excitation amplitude

Long junctions: traveling kinks

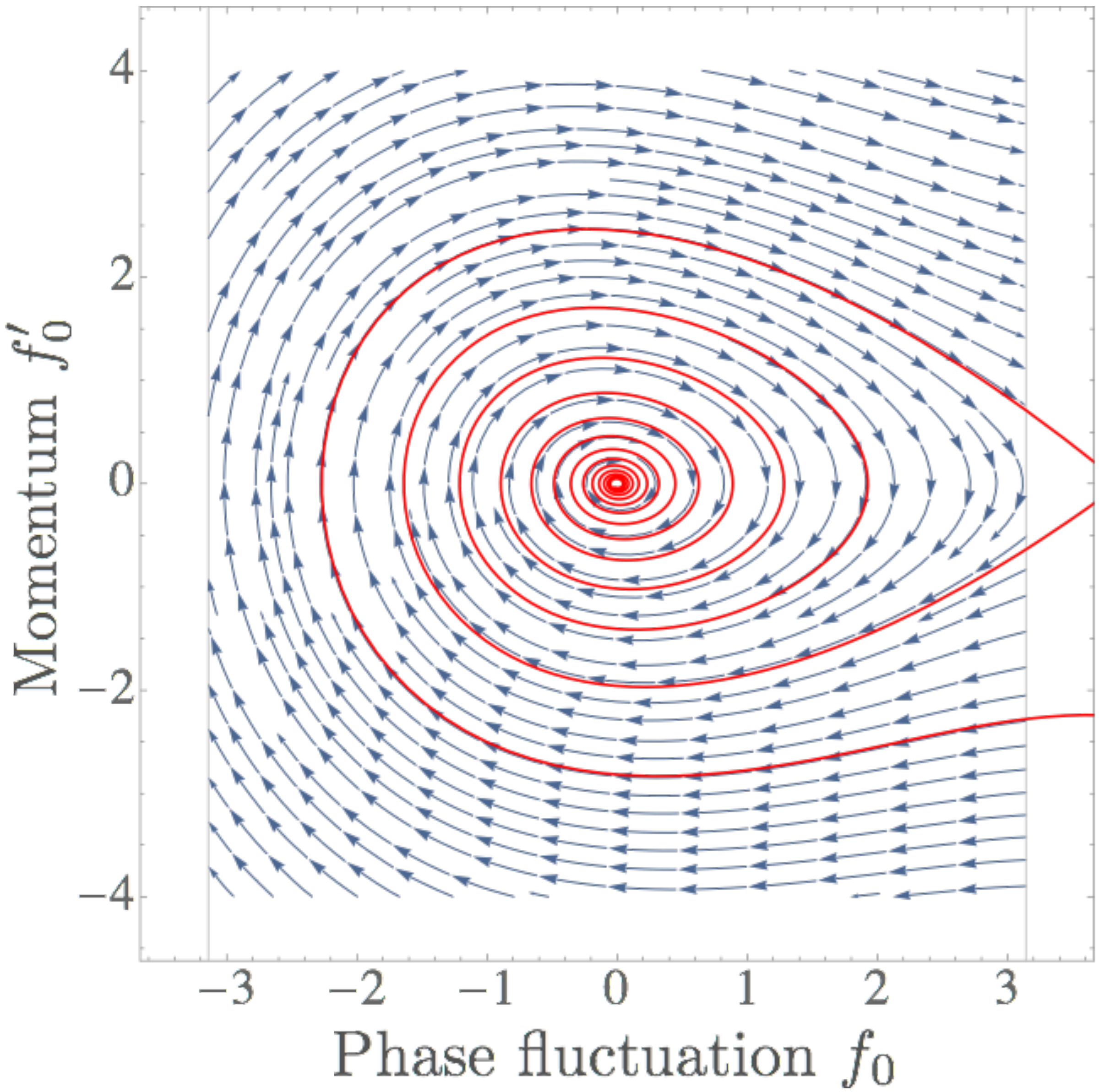
Traveling kink:

$$\phi(x,t) = 4\tan^{-1}\left[\exp\left(\pm\frac{x-ut}{\sqrt{1-u^2}}\right)\right] \qquad 0 \leq |u| \leq 1$$



$(\nu_{ab} \simeq 0)$

Parameter space I



Evolution of uniform oscillations:

$$f_0''(t) + \nu_c f_0'(t) + \sqrt{1 - j_{\text{ext}}^2}\, f_0 - \frac{j_{\text{ext}}}{2} f_0^2 = f_{dr}(t)$$