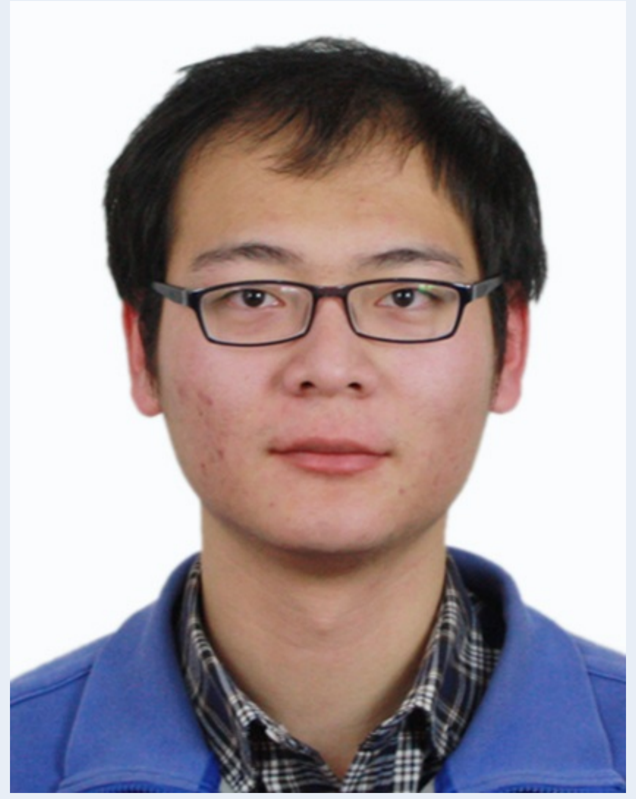
Analog simulation of effective field theories with 1D Bose gases

Amin - Schmiedmayer Lab - VCQ, TU Wien

KRb Experiment

Jörg Schmiedmayer



Si-Cong Ji

Federica Cataldini

Nataliia Bezhan

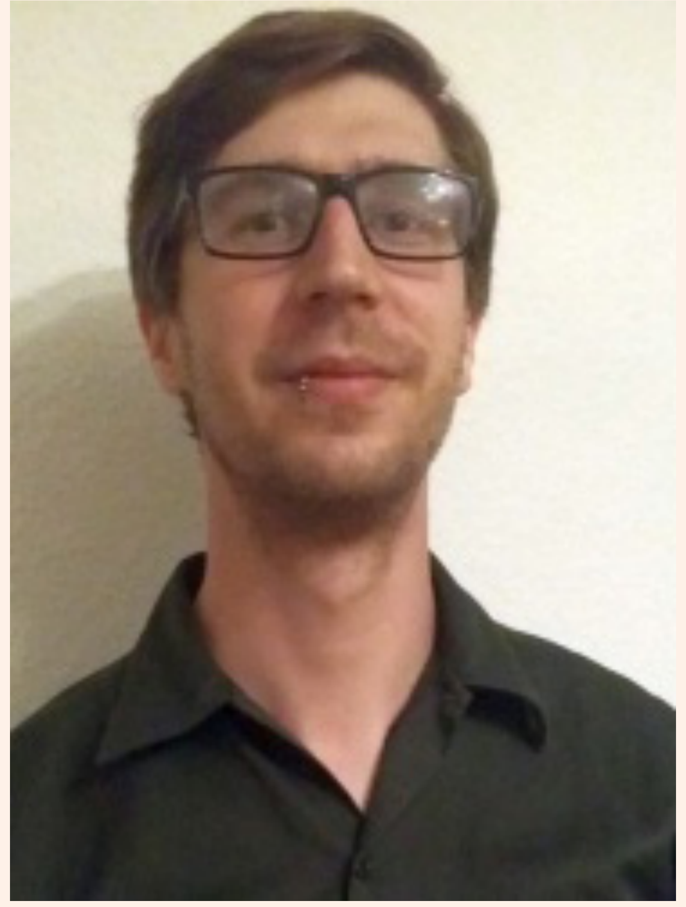
João Sabino

Frederik Møller

Philipp Schüttelkopf

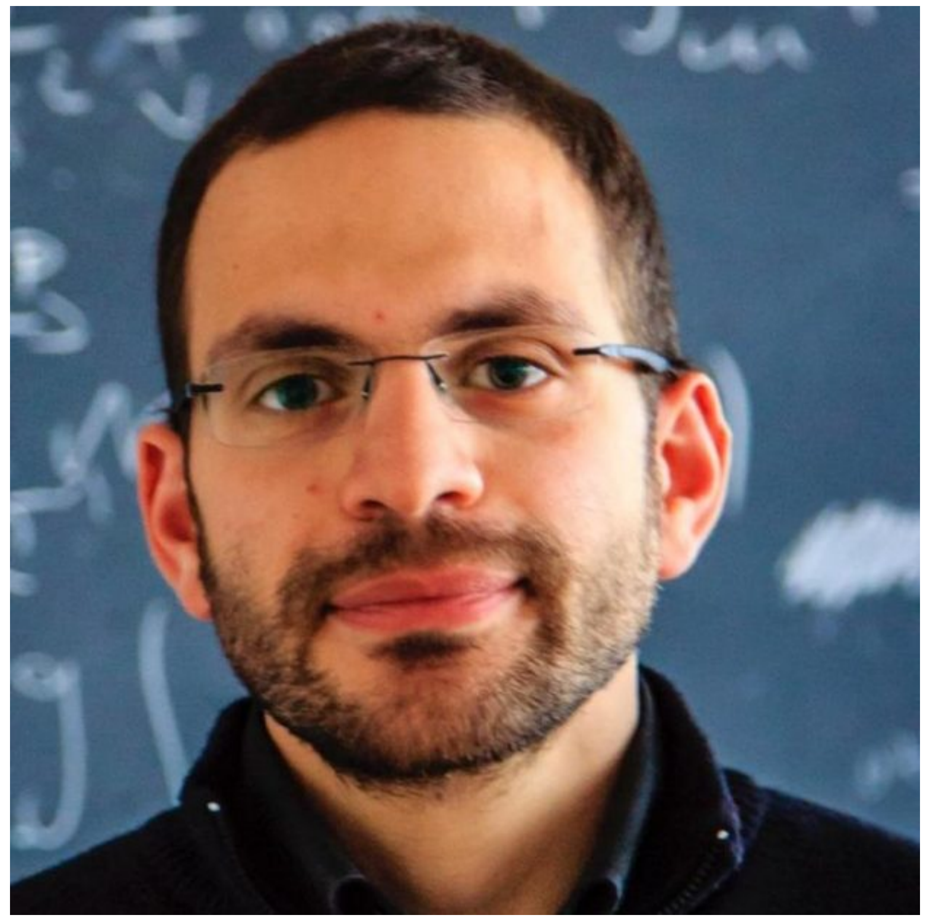
Theory support

Igor Mazets



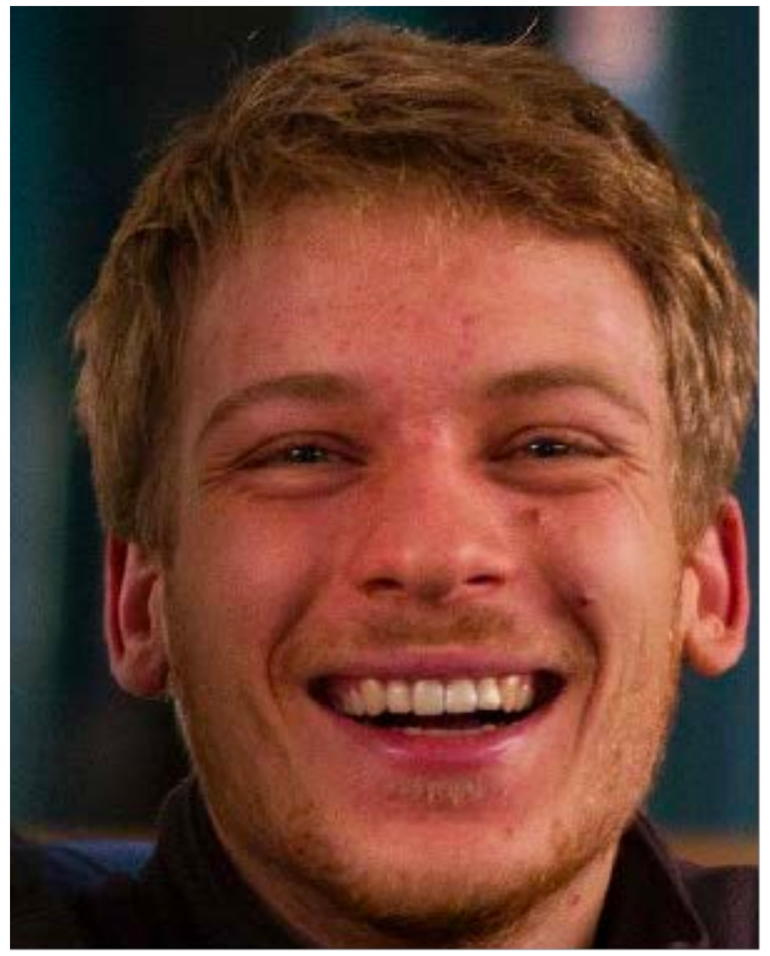
Sebastian Erne

Theory Collaborators



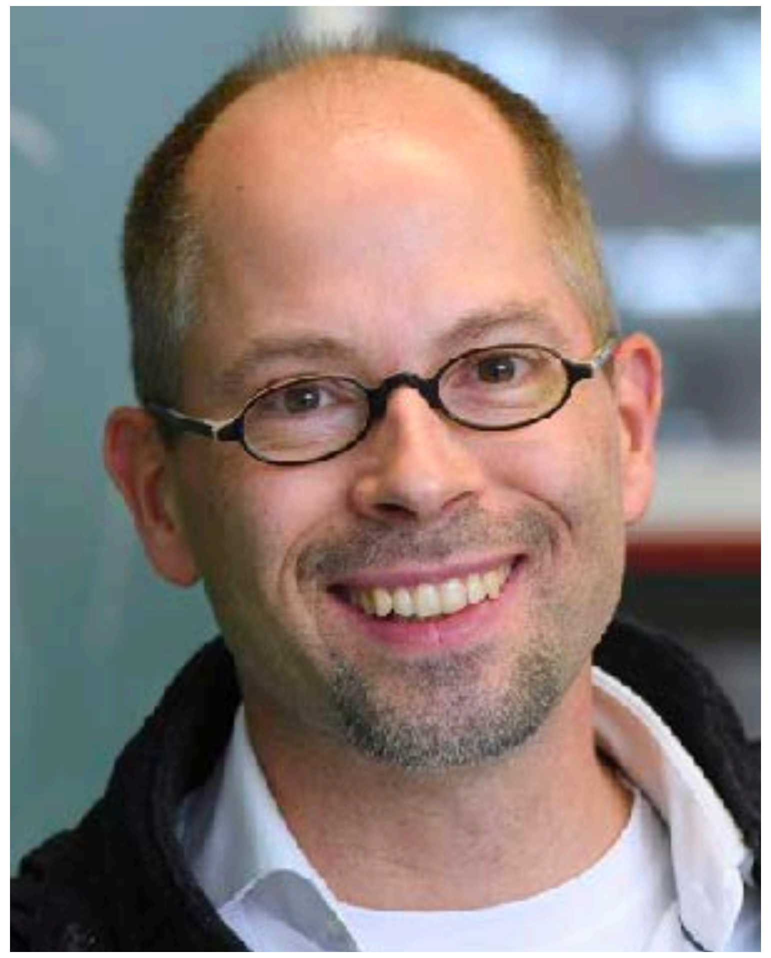
Spyros Sotiriadis
University of Crete

Nicolas Sebe
EP Paris

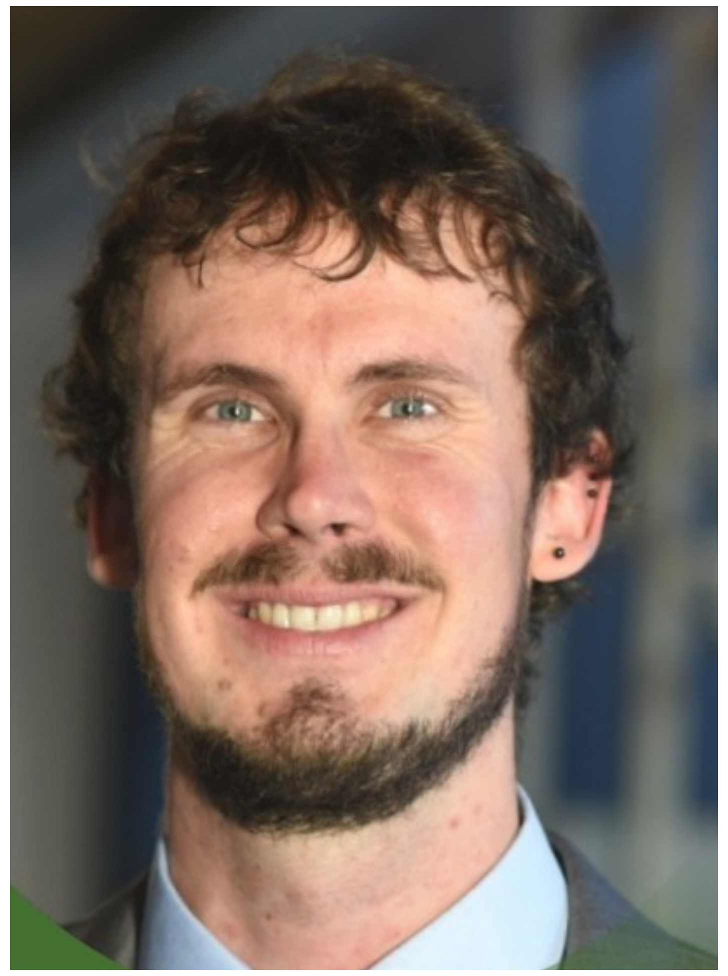


Marek Gluza
NTU Singapore

Giacomo Guarnieri
FU Berlin



Jens Eisert
FU Berlin



Ivan Kukuljan
MPI

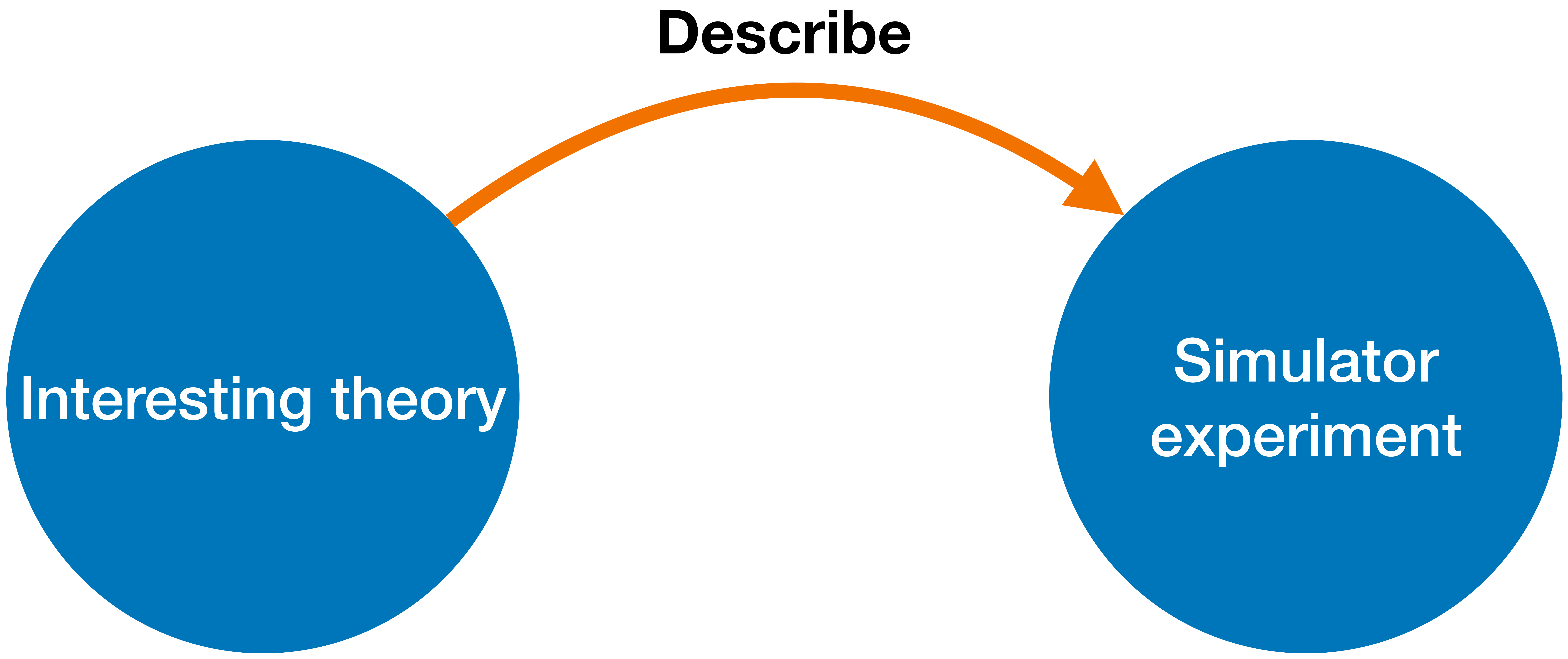
Dries Sels
NYU

Eugene Demler
ETH

Interesting theory

Interesting theory

Simulator experiment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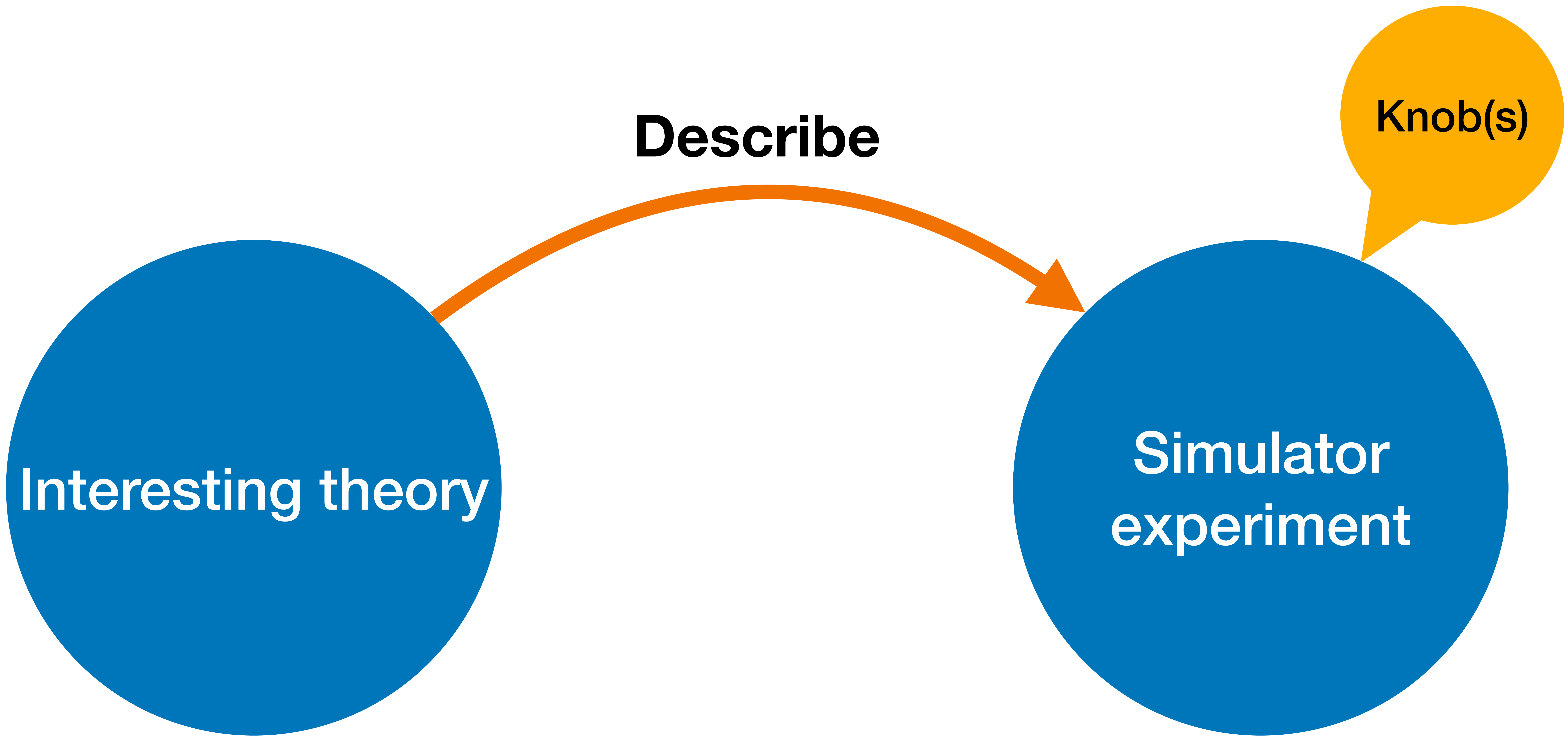
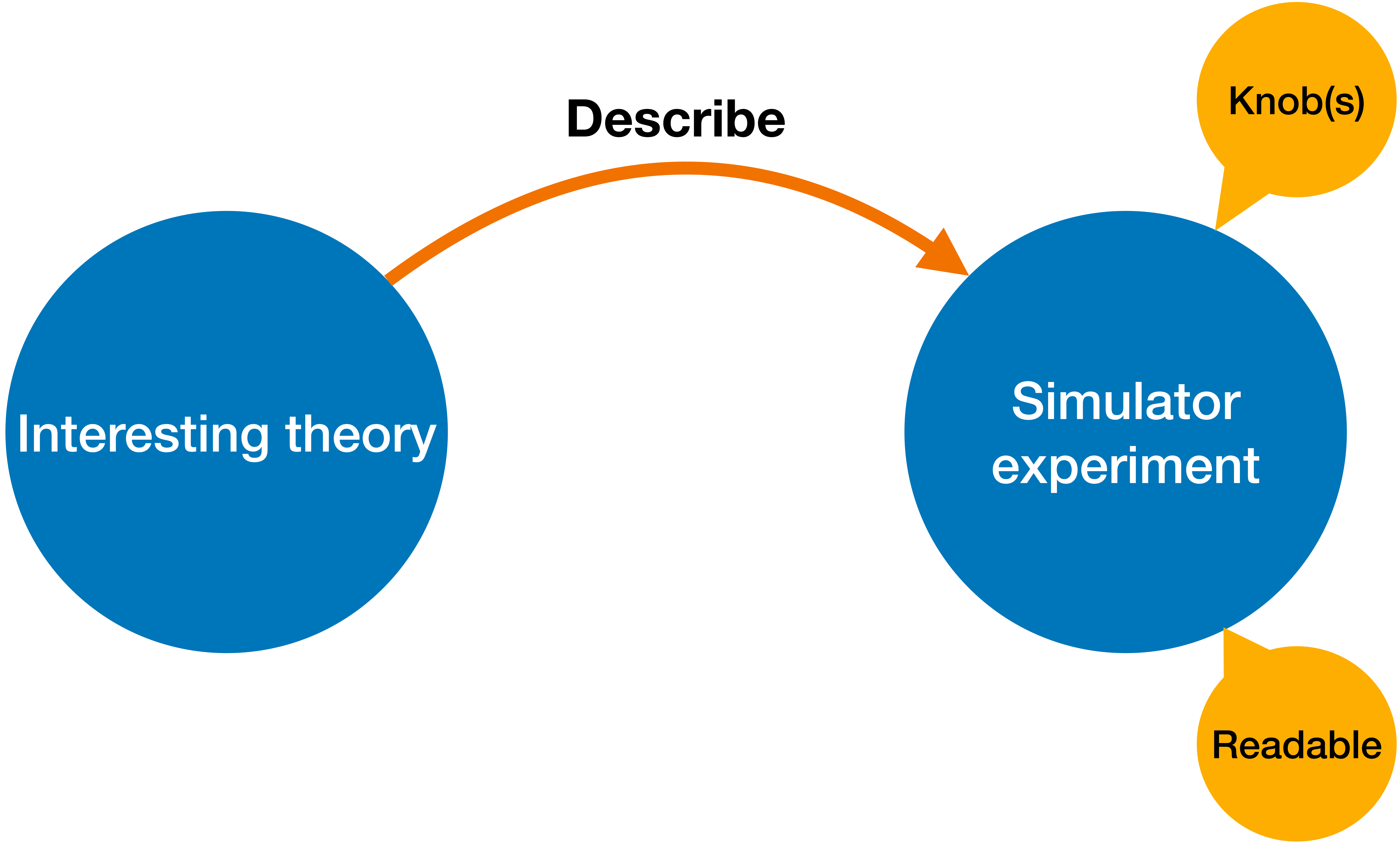
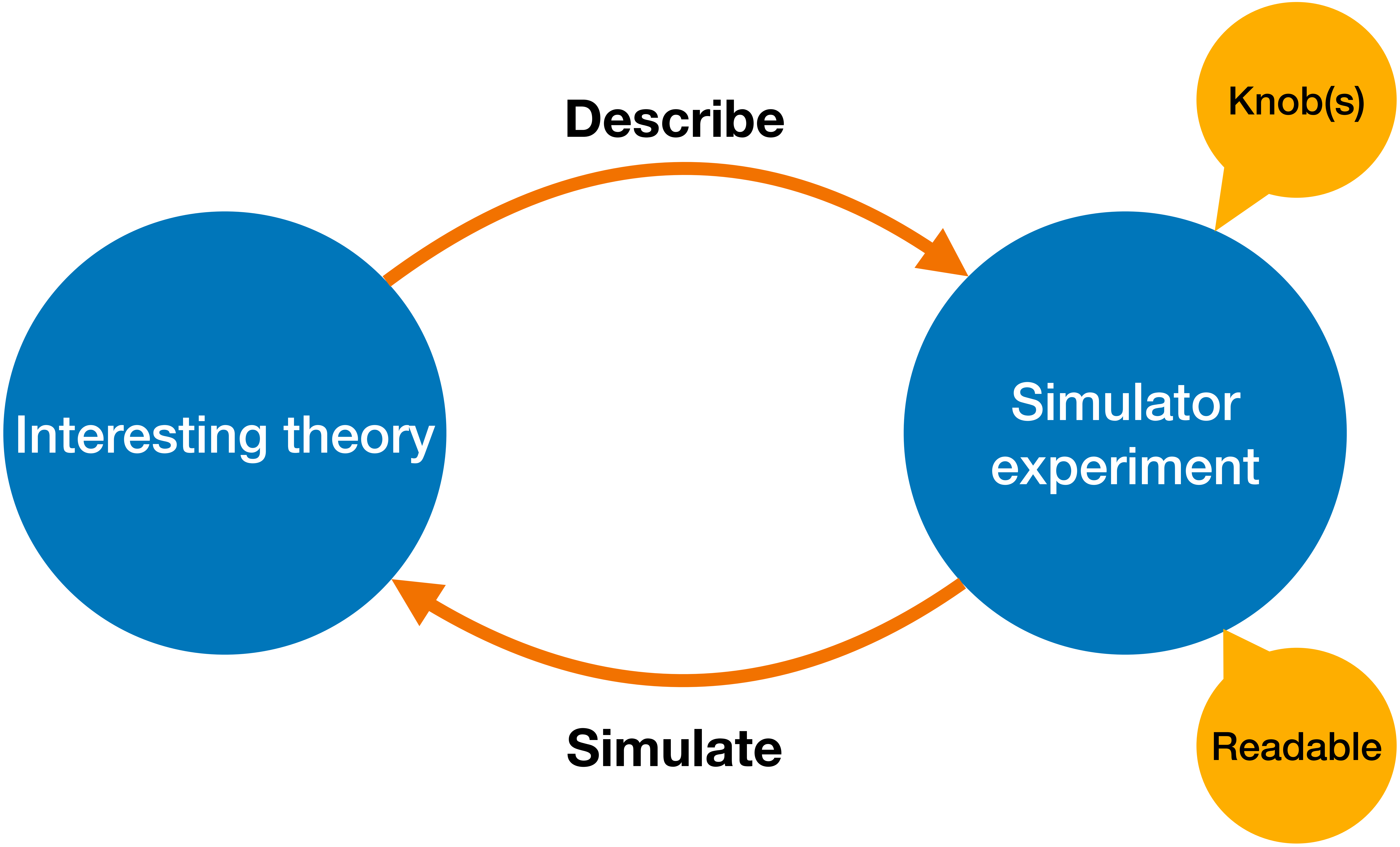
Interesting theory
Simulator
experiment



Describe
Knob(s)
Interesting theory
Simulator
experiment


Describe
Knob(s)
Interesting theory
Simulator experiment
Readable


Describe
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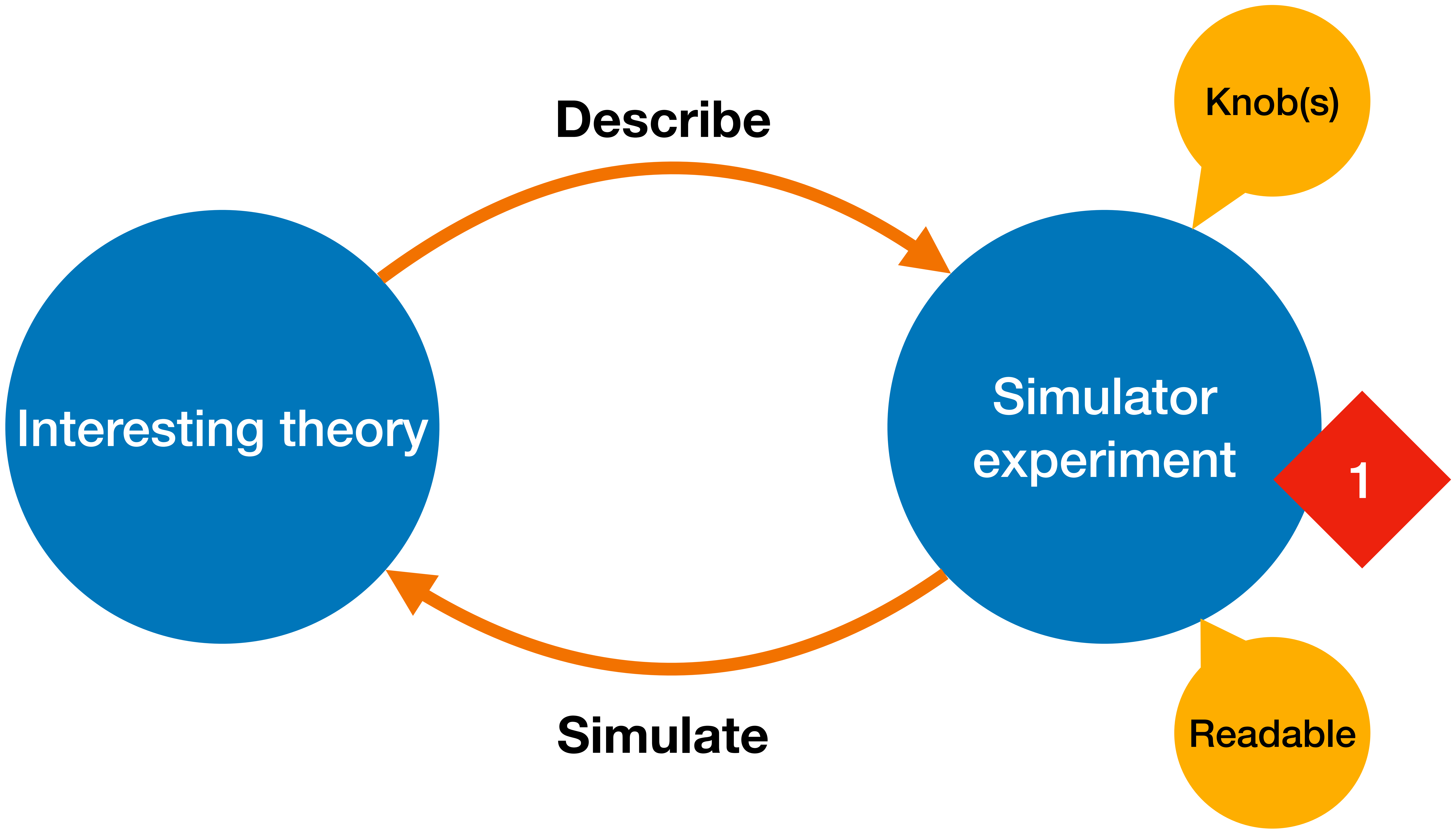
Describe
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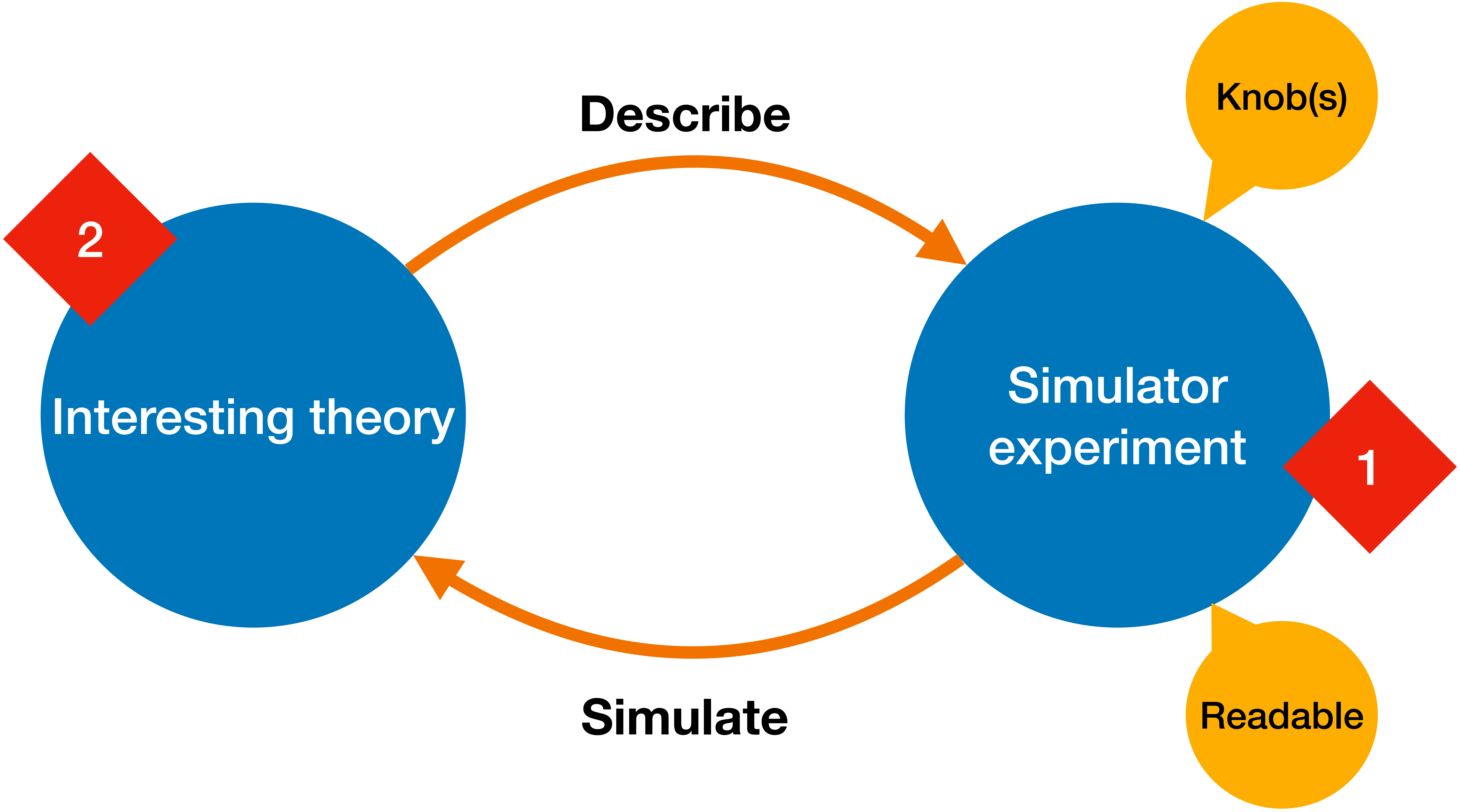
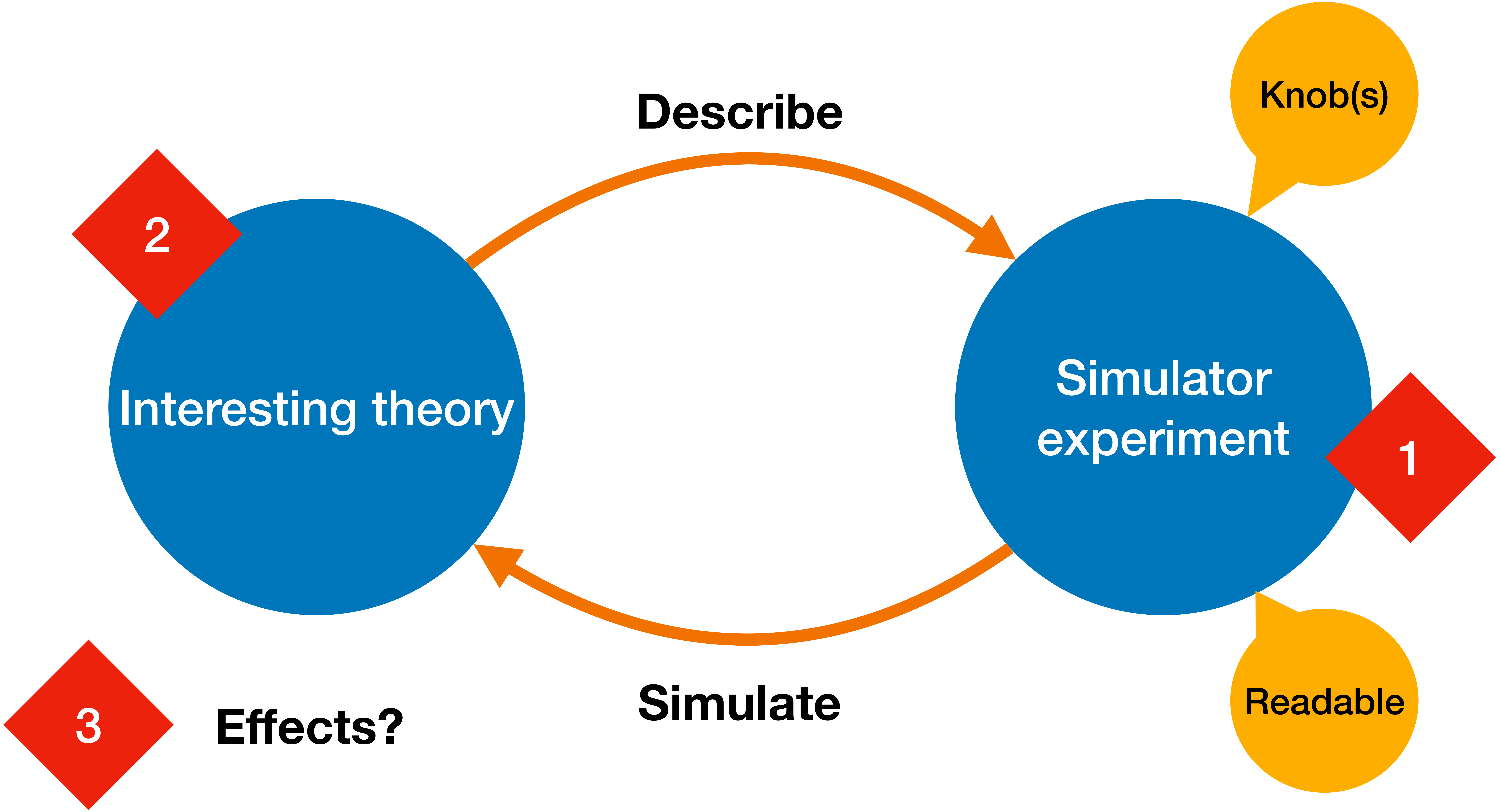
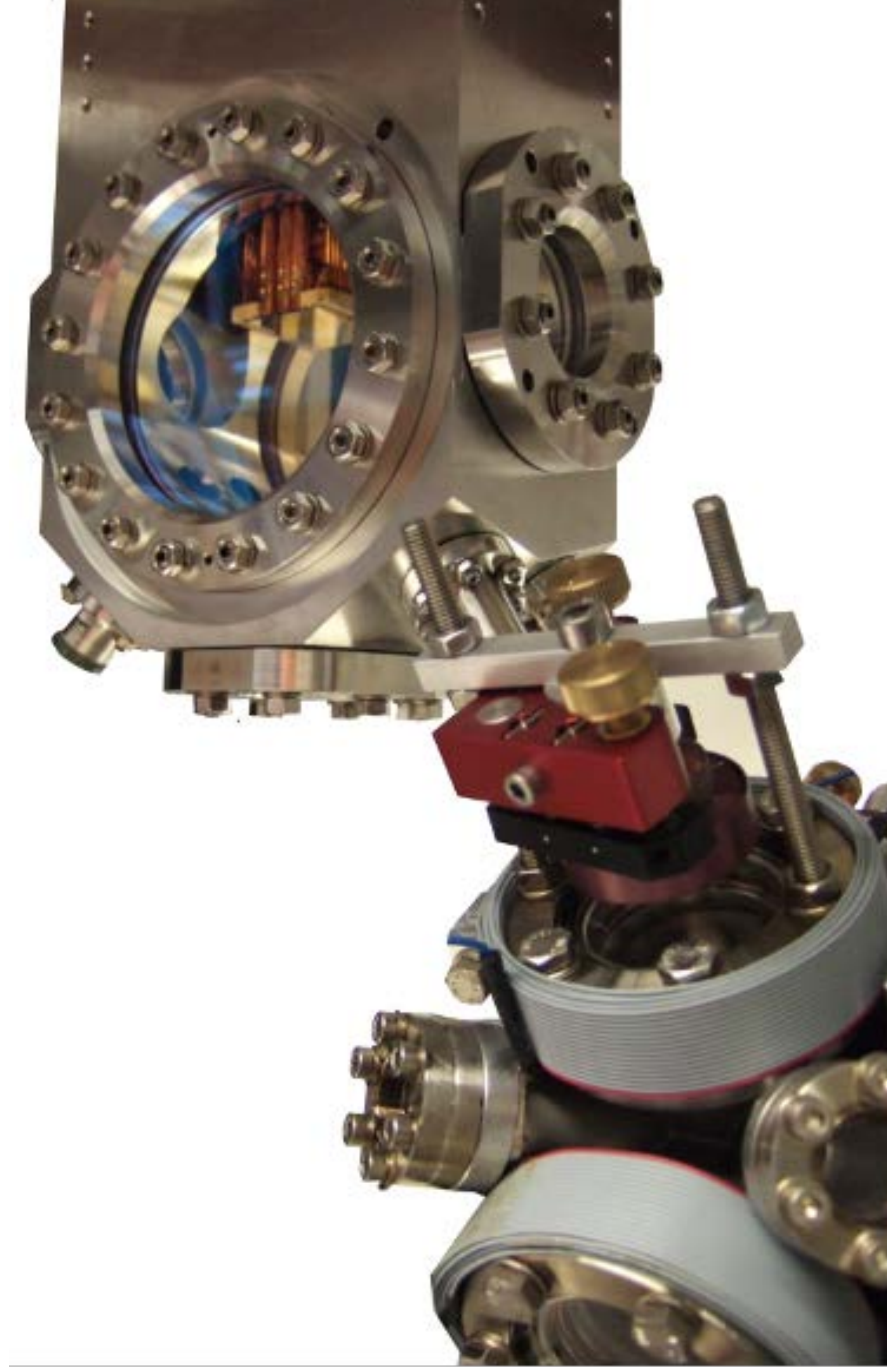
1
Simulate
Readable


Describe
Knob(s)
2
Interesting theory
Simulator experiment
1
Readable
Simulate

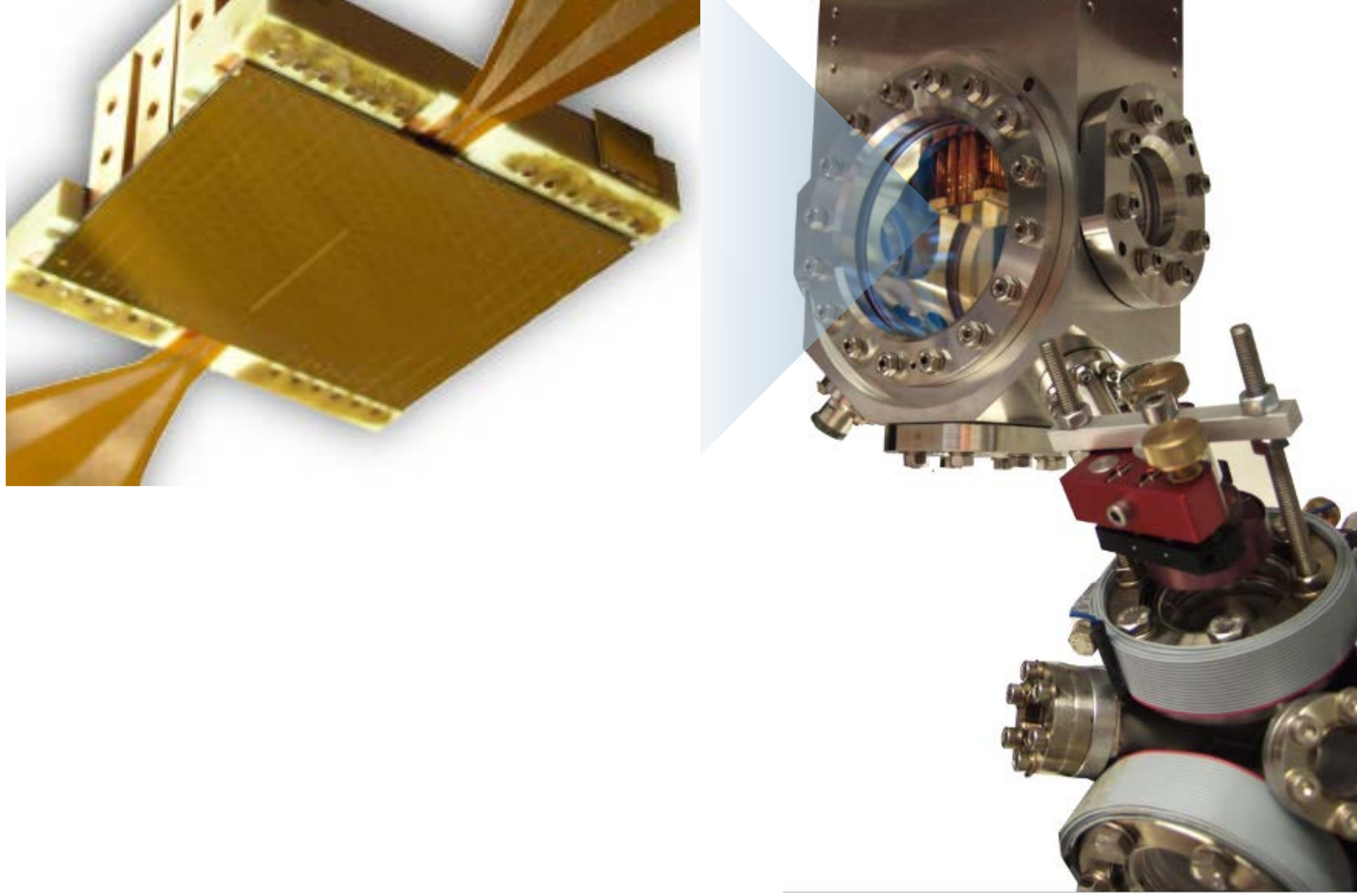

Describe
Knob(s)
2
Interesting theory
Simulator
experiment
1
Readable
3
Effects?
Simulate

1



For more information on experiment, read T. Schweigler or B. Rauer thesis

1



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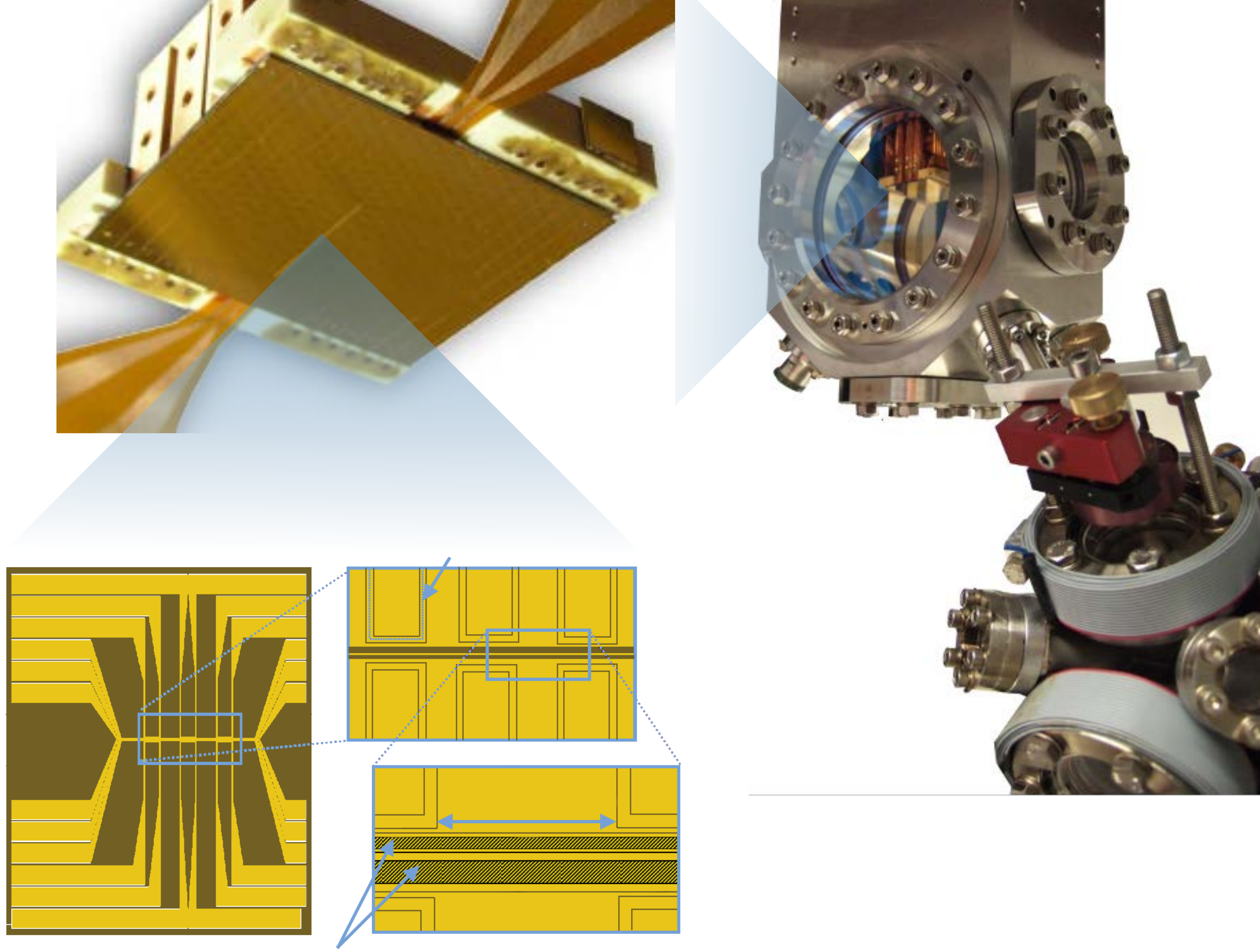

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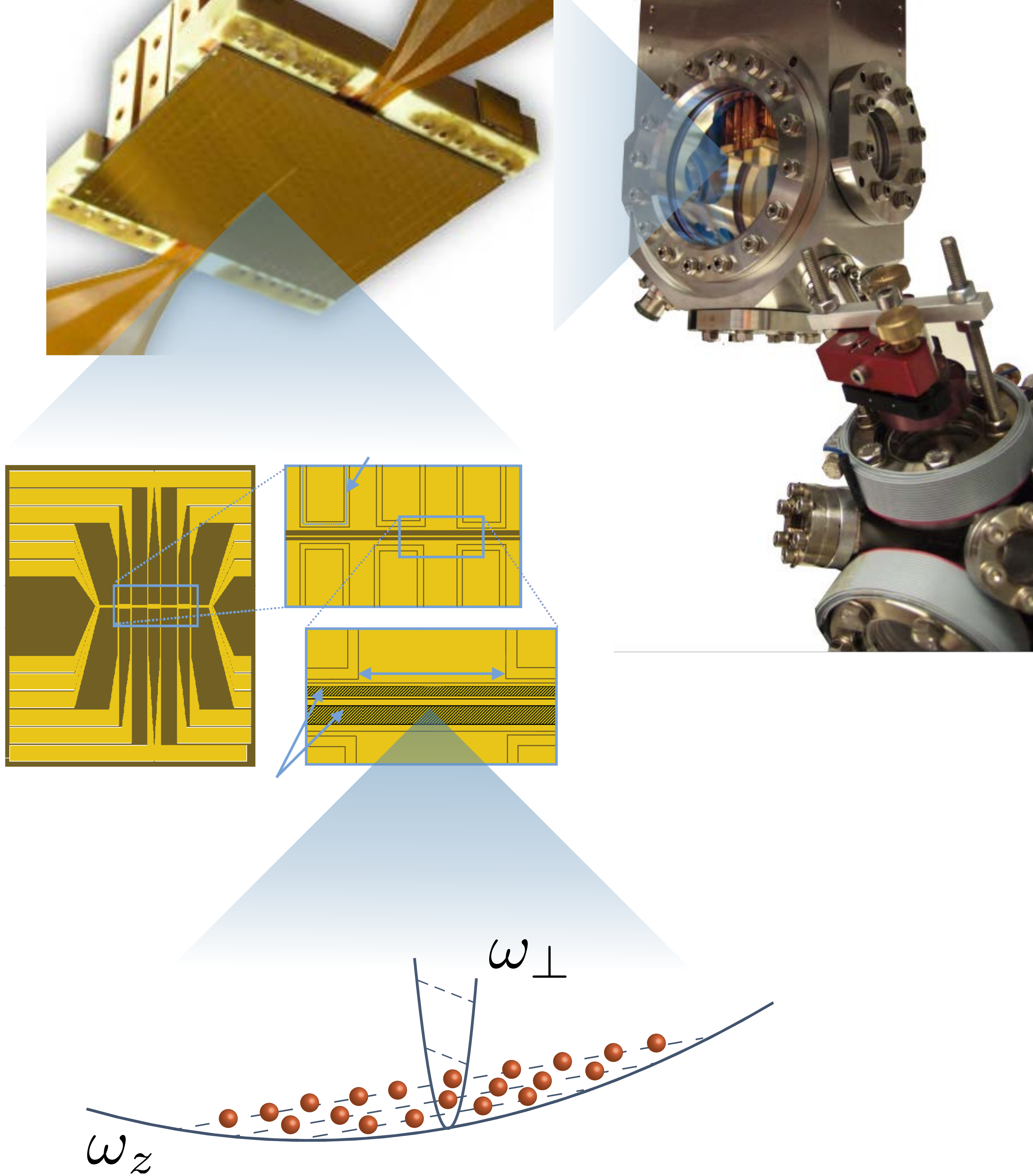

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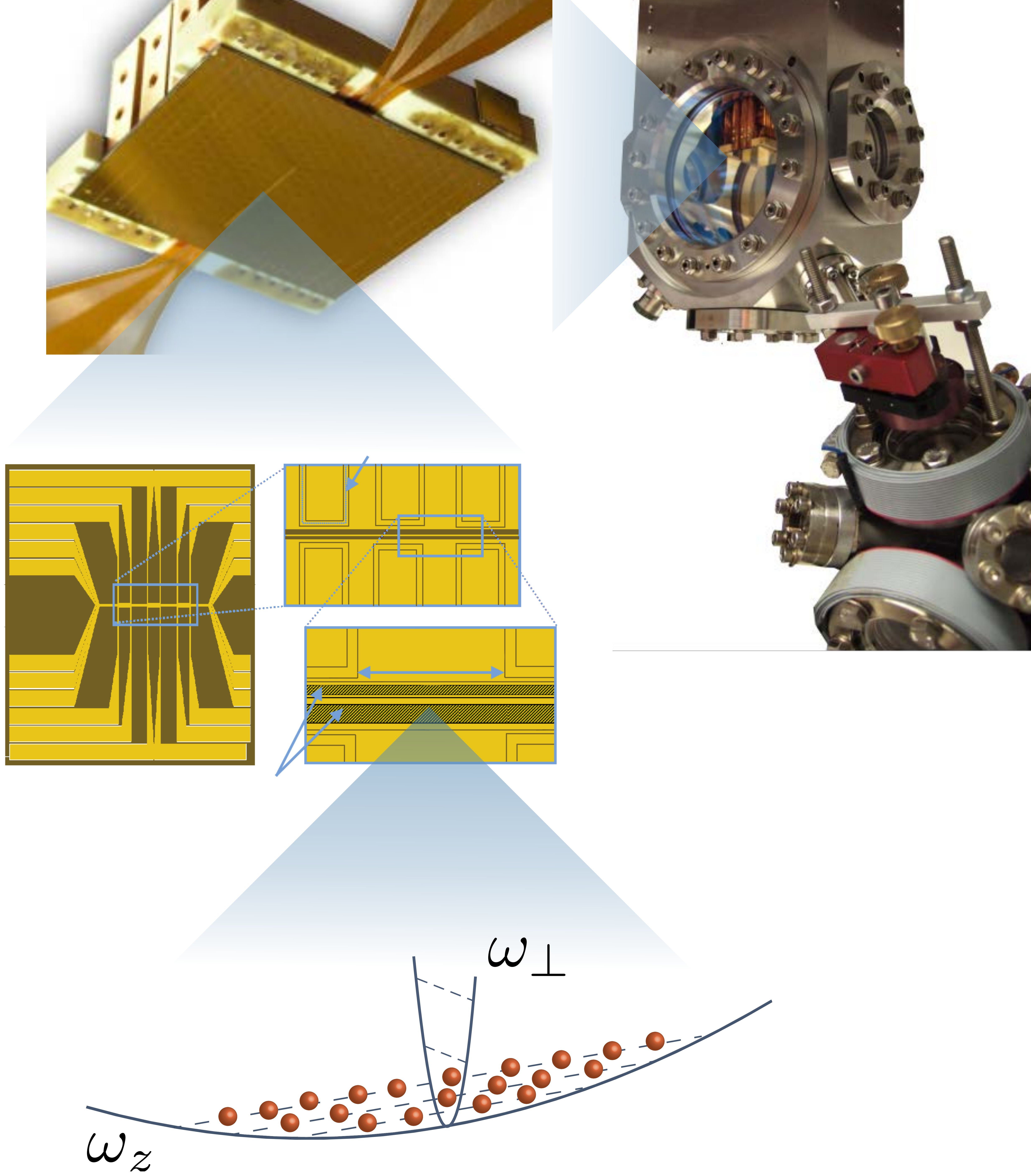


1D condition:

$$\mu,\ k_{\mathrm{B}}T < \hbar\omega_\perp$$

For more information on experiment, read T. Schweigler or B. Rauer thesis

1

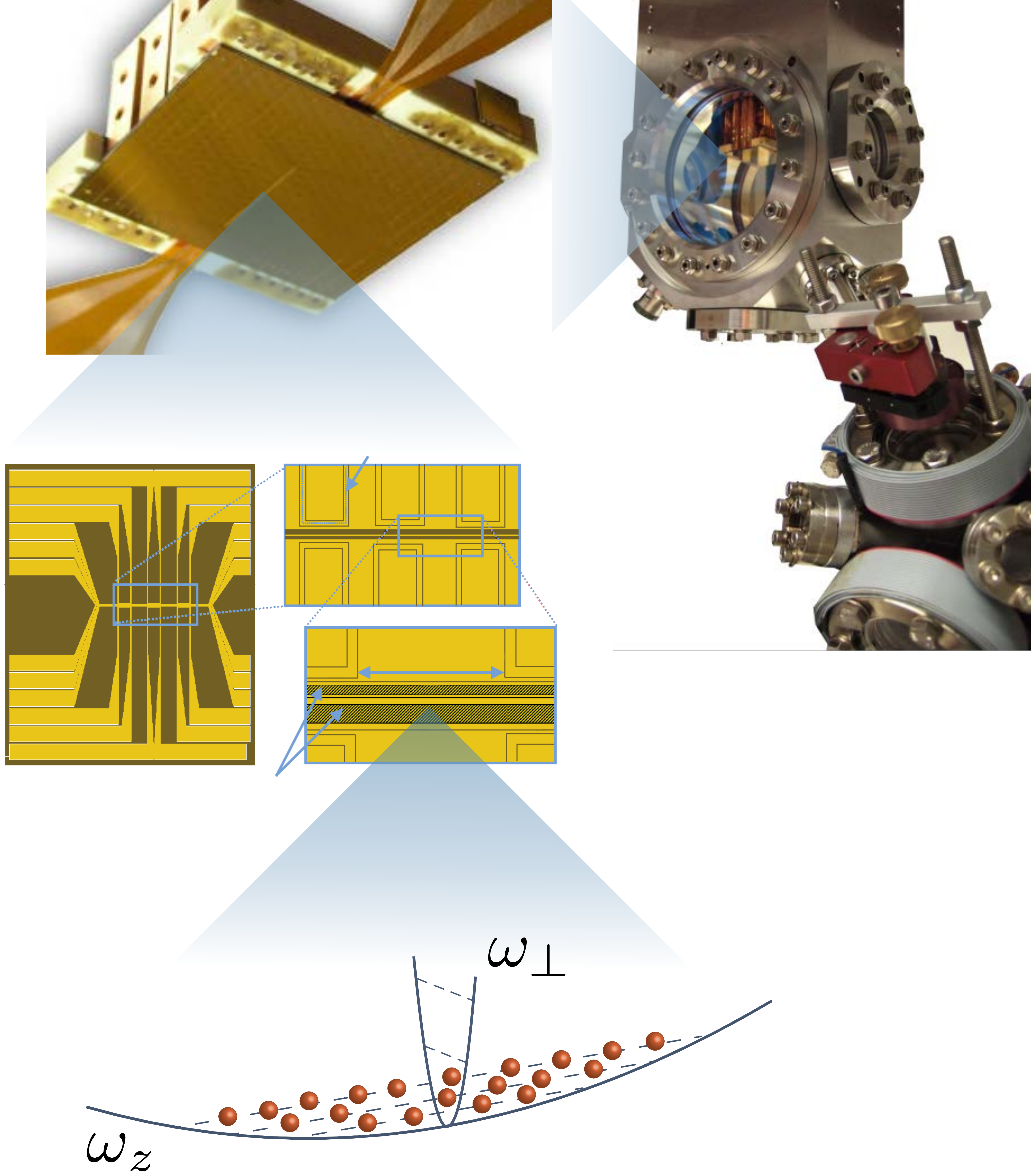
Experimental parameters:

$$N_{\text{atoms}} = 2000 - 20000$$

$$T = 20 - 150\,\text{nK}$$

$$\omega_\perp \approx 2\pi \times 2\,\text{kHz}$$

$$\omega_z \approx 2\pi \times 10\,\text{Hz}$$



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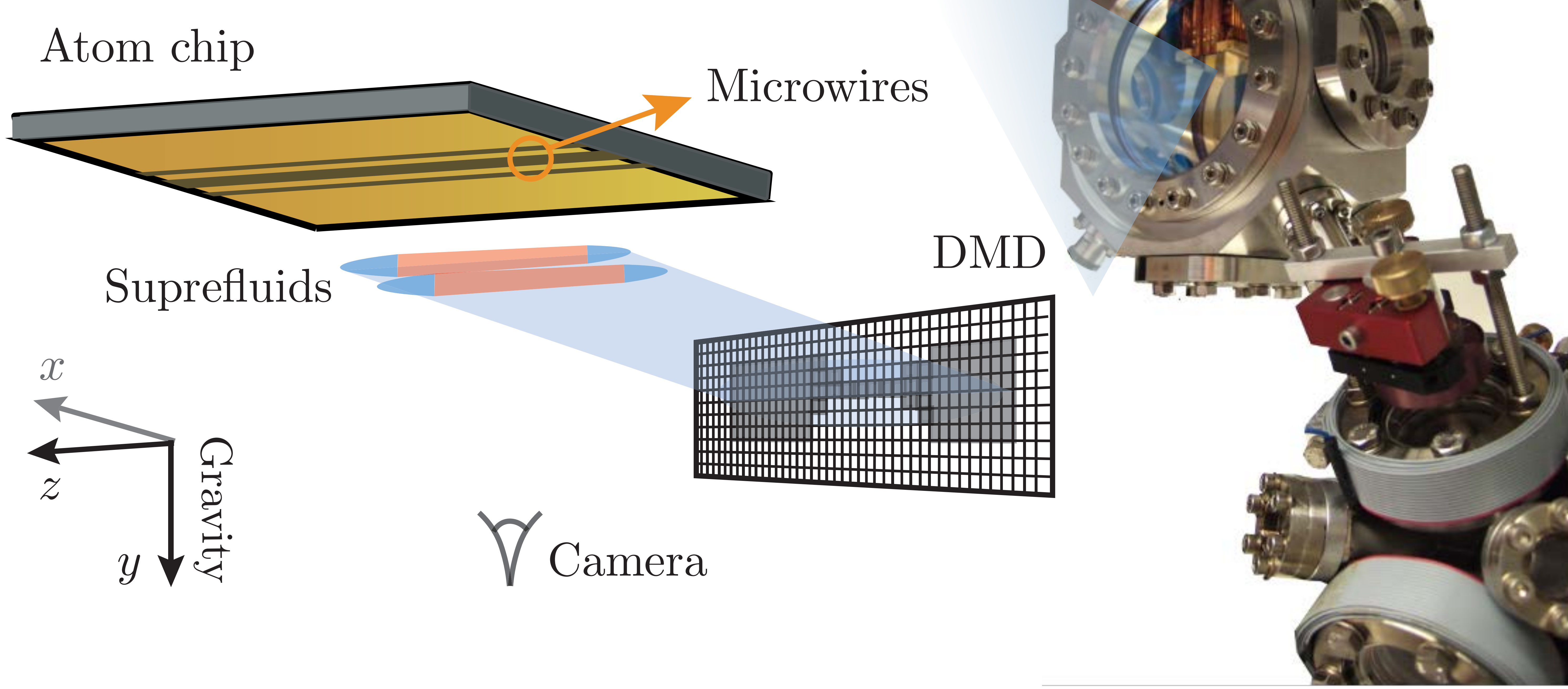
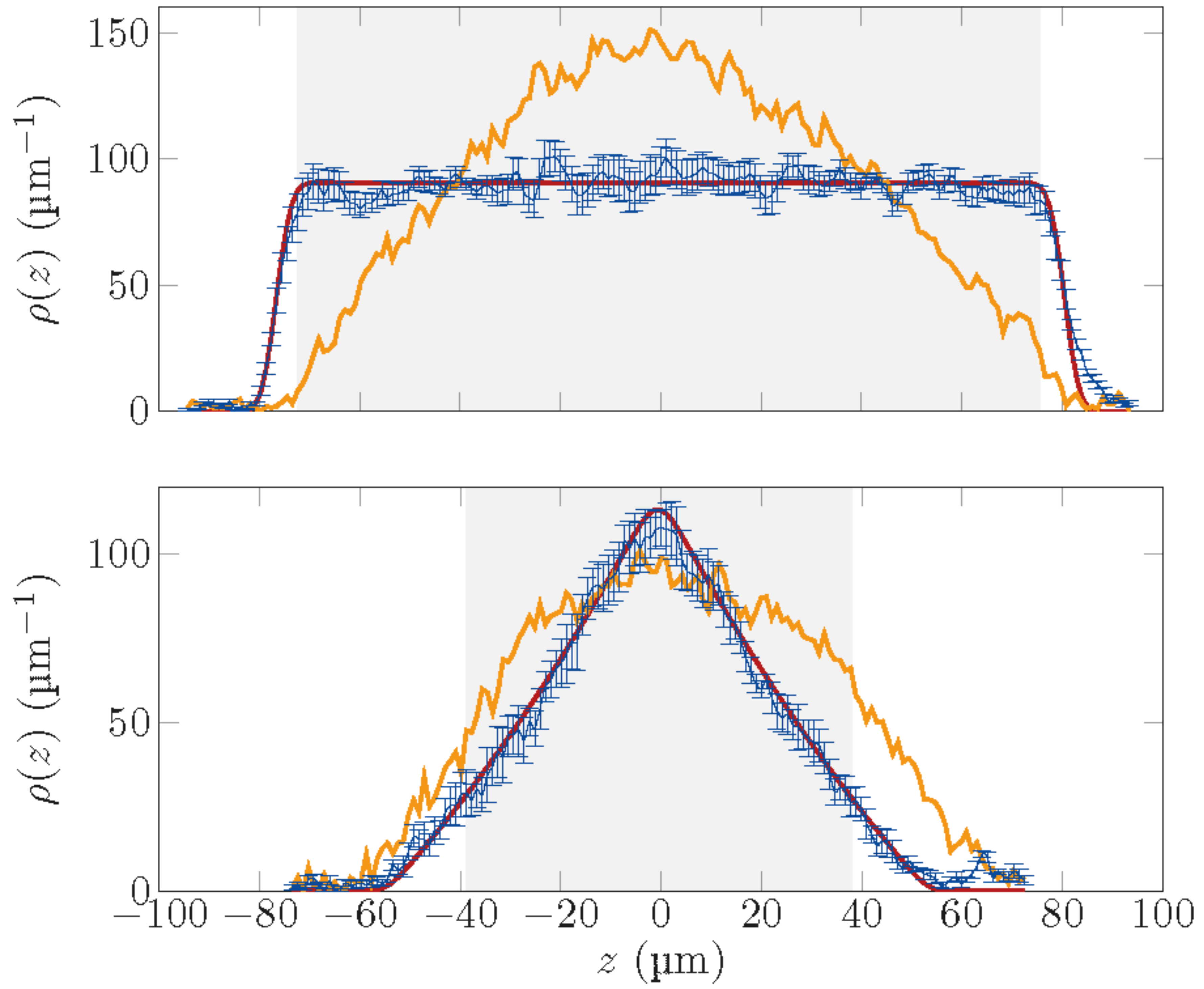
Tajik et al. Optics Express (2019)





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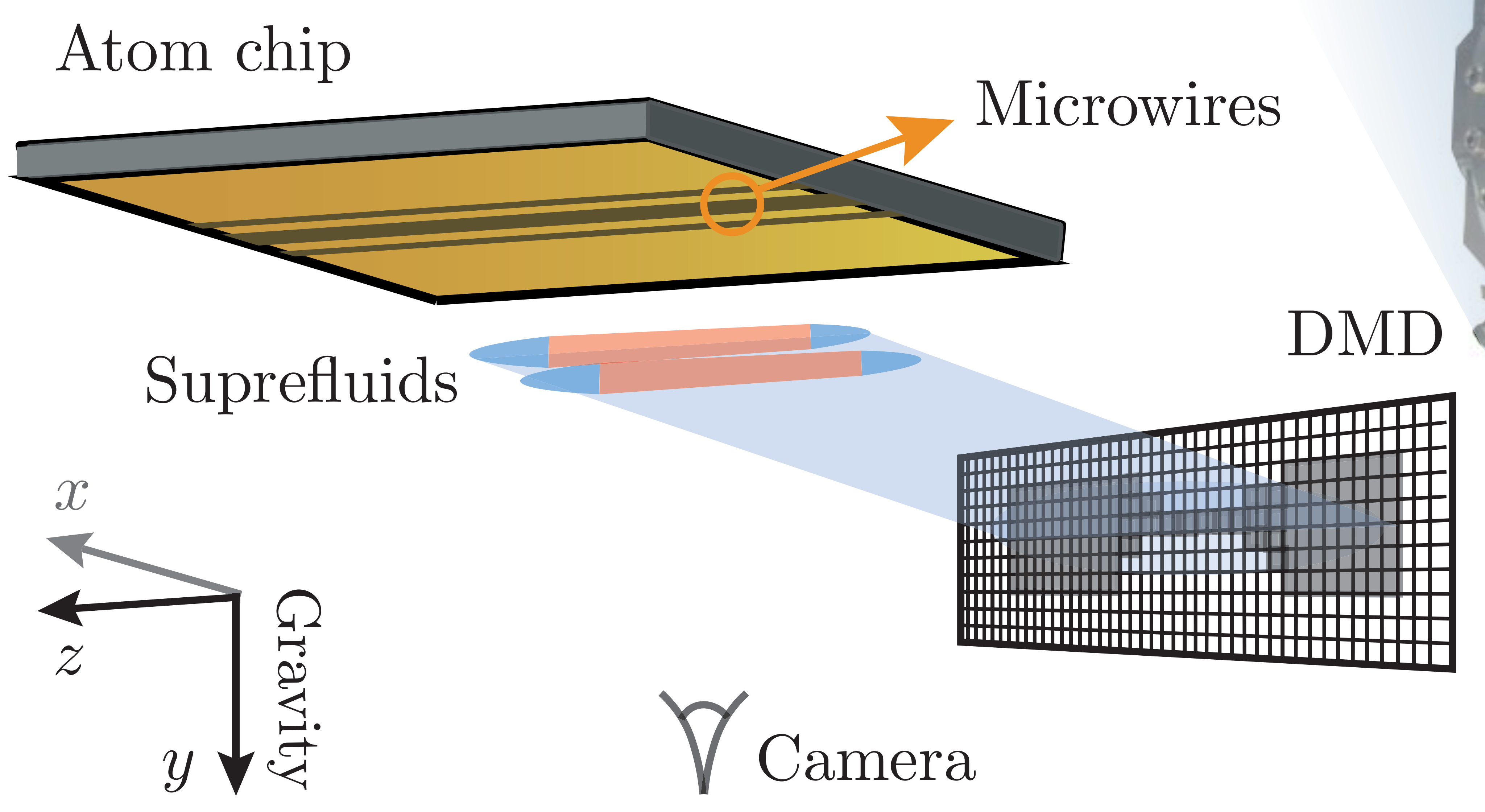

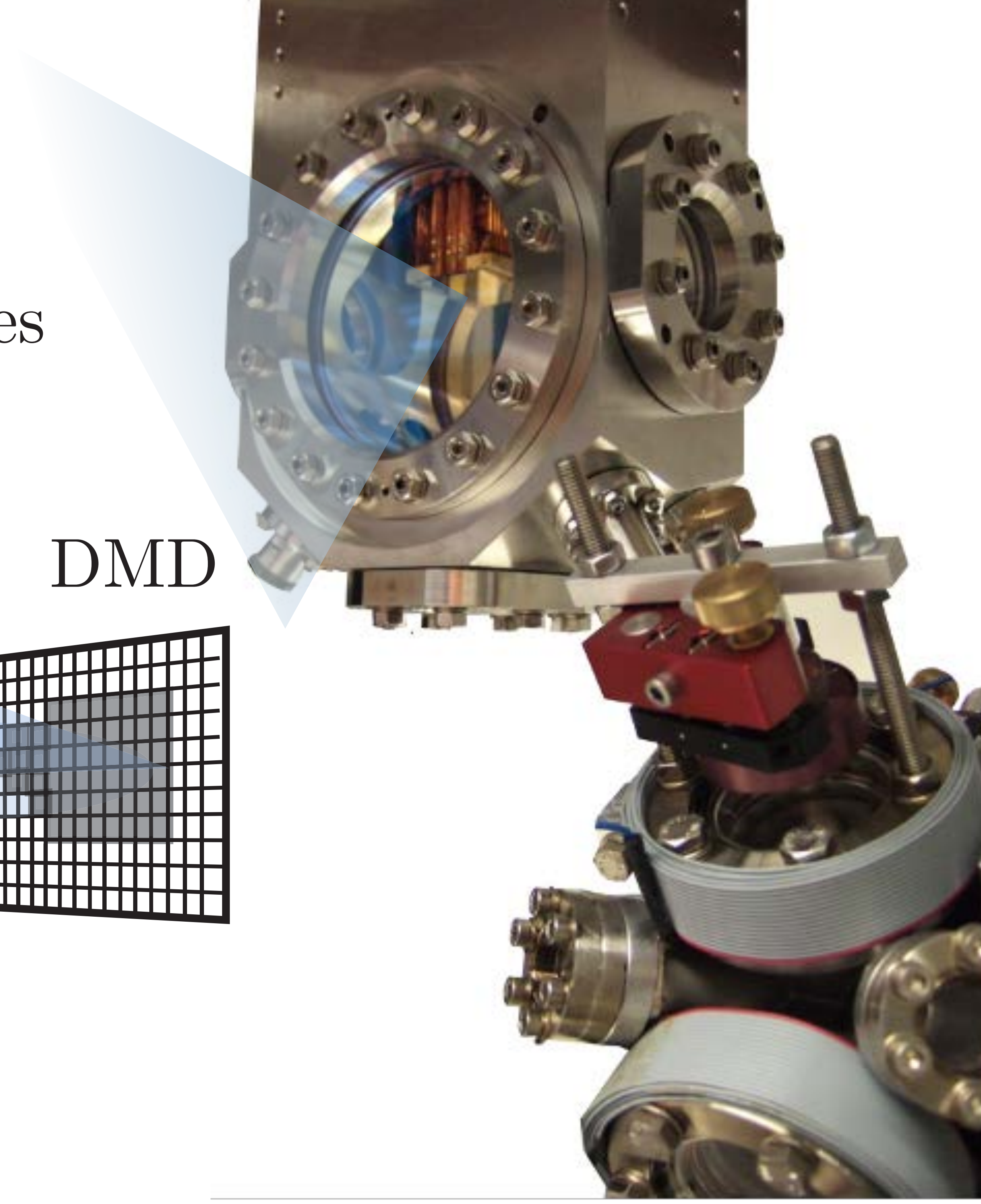

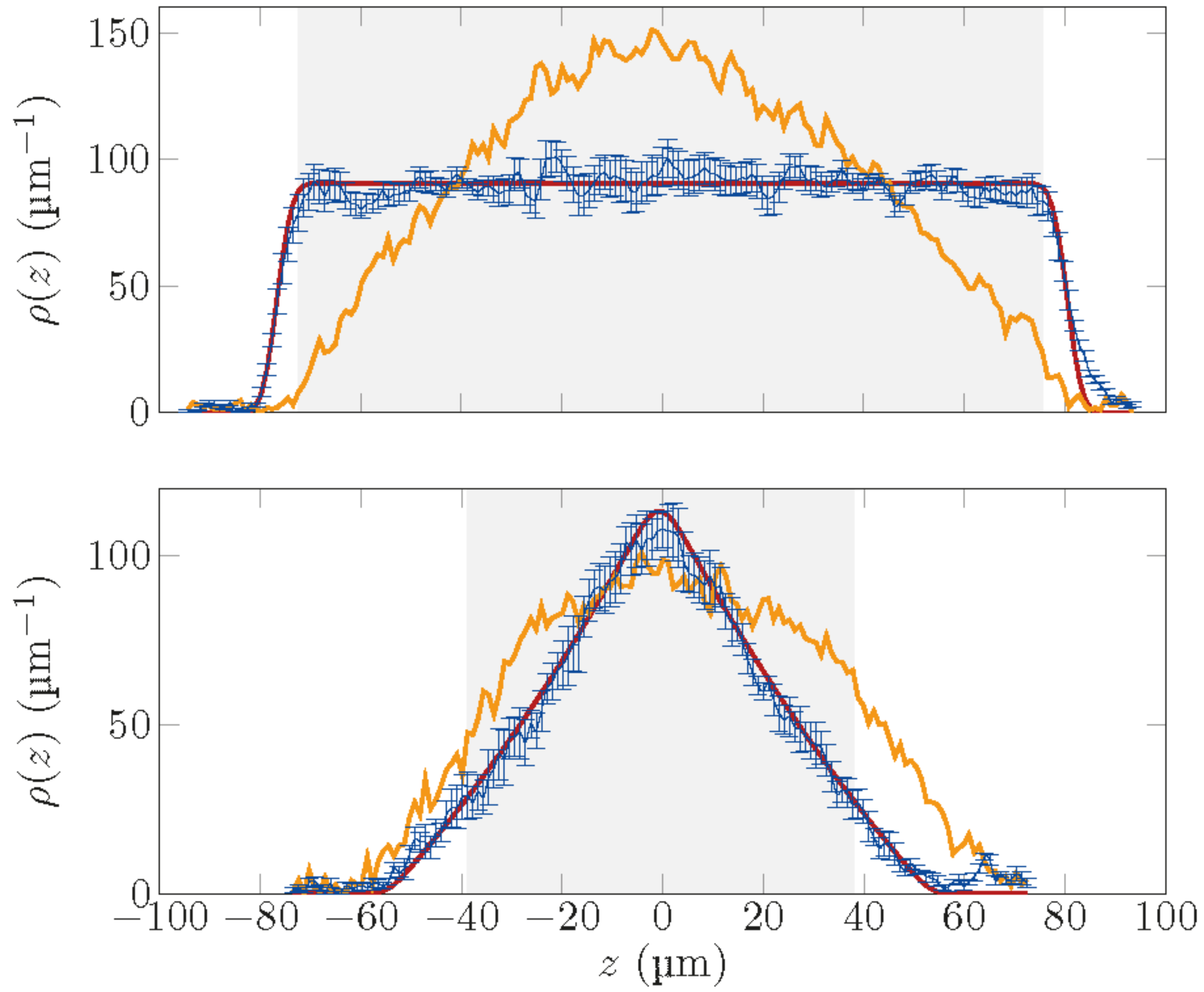

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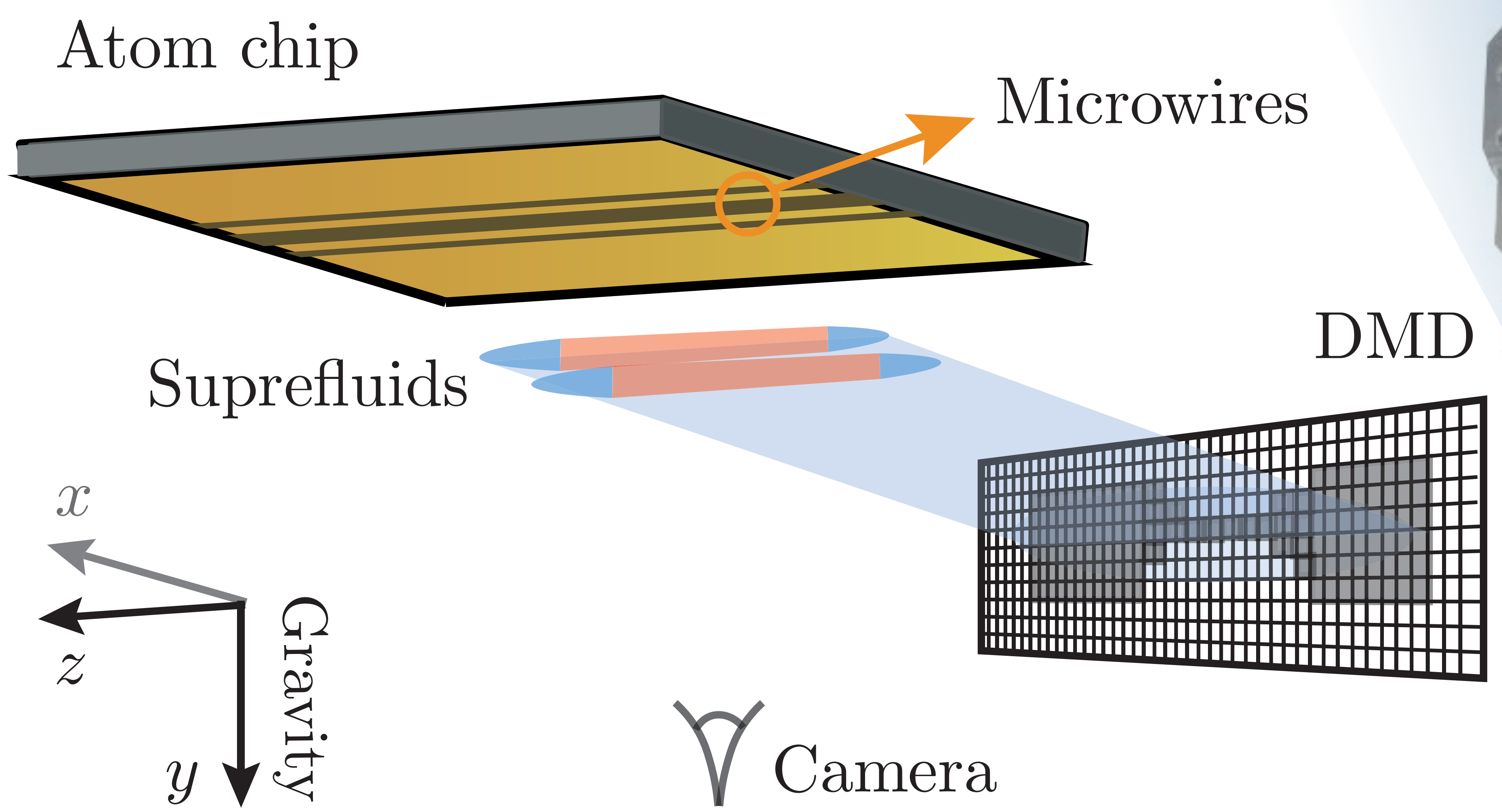
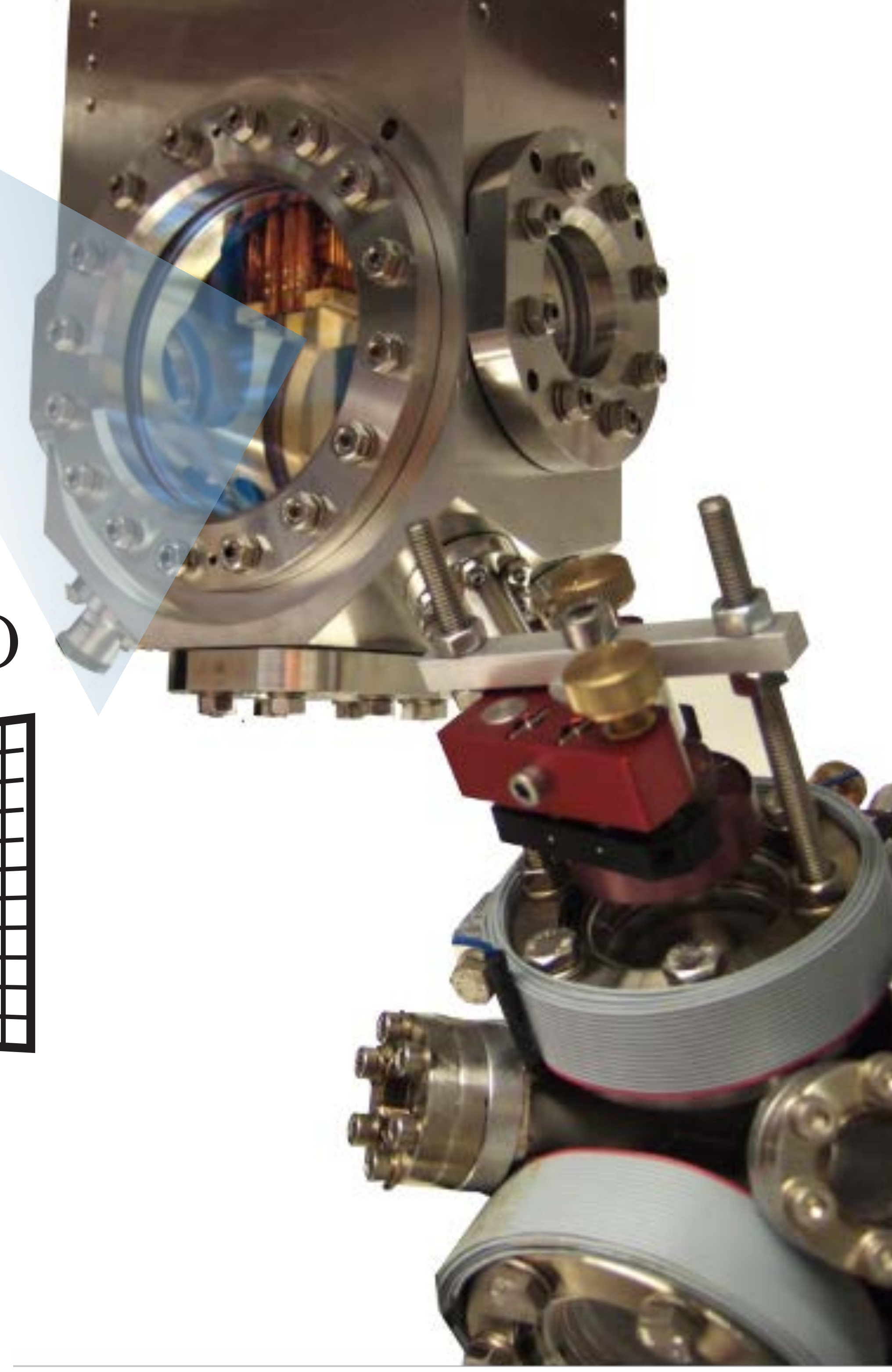
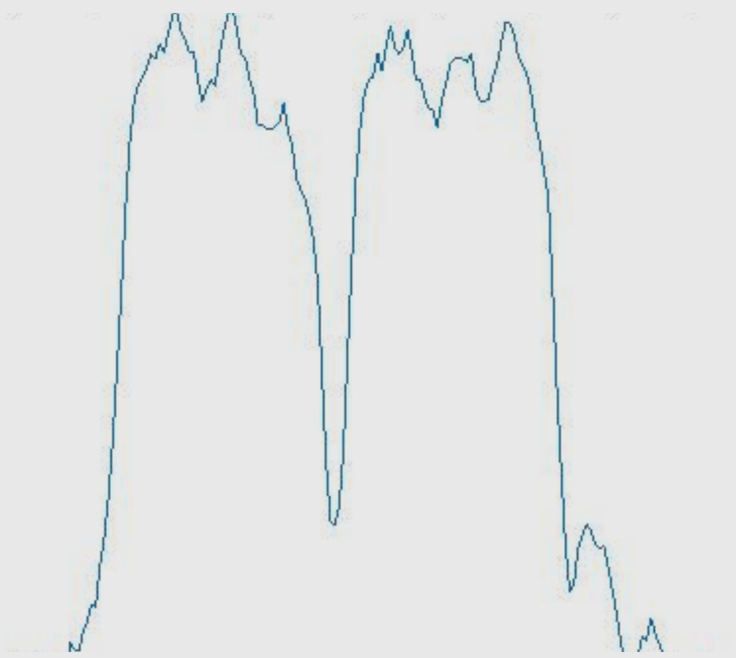
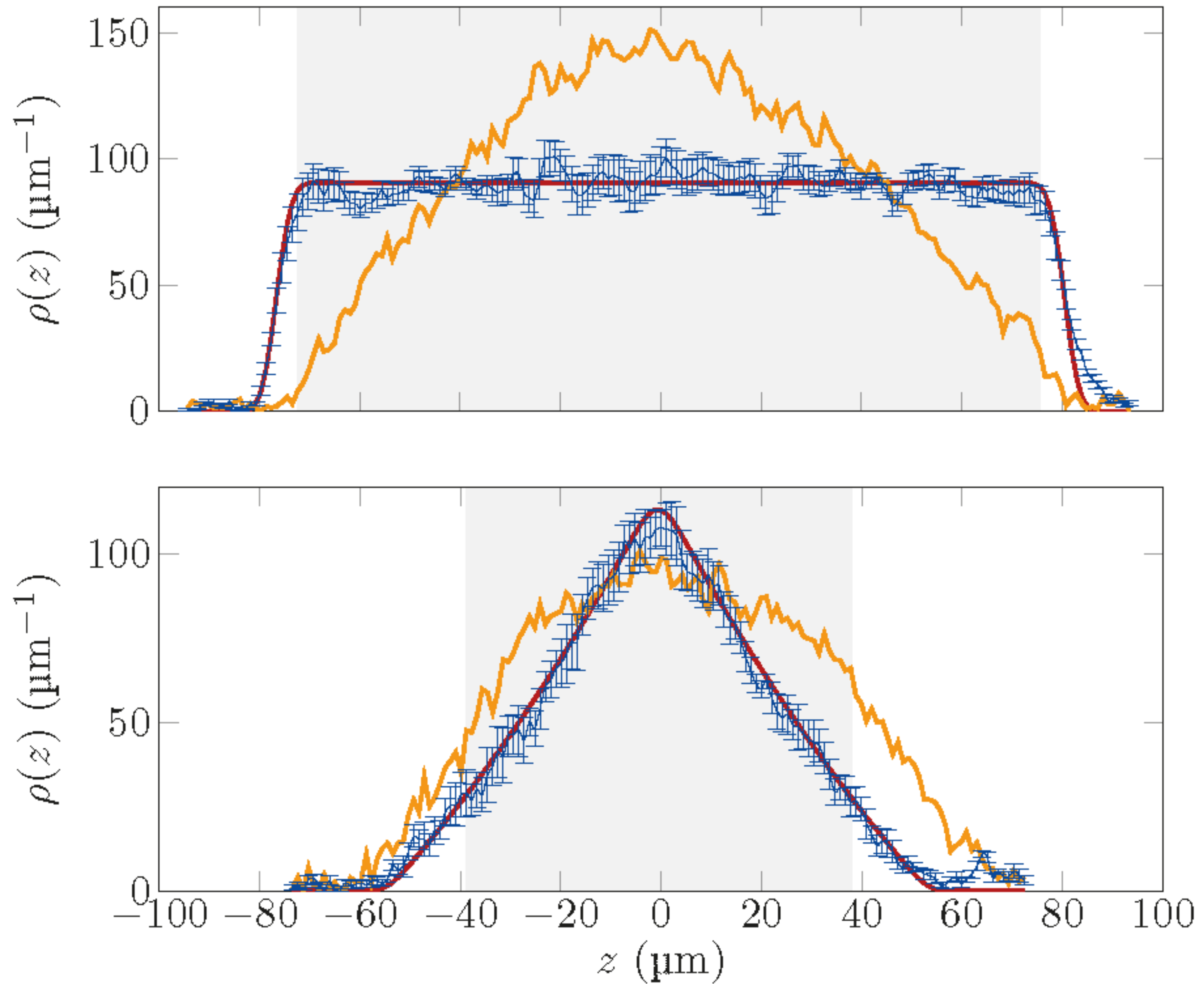




Quantum field machines
João S. & Philipp S.





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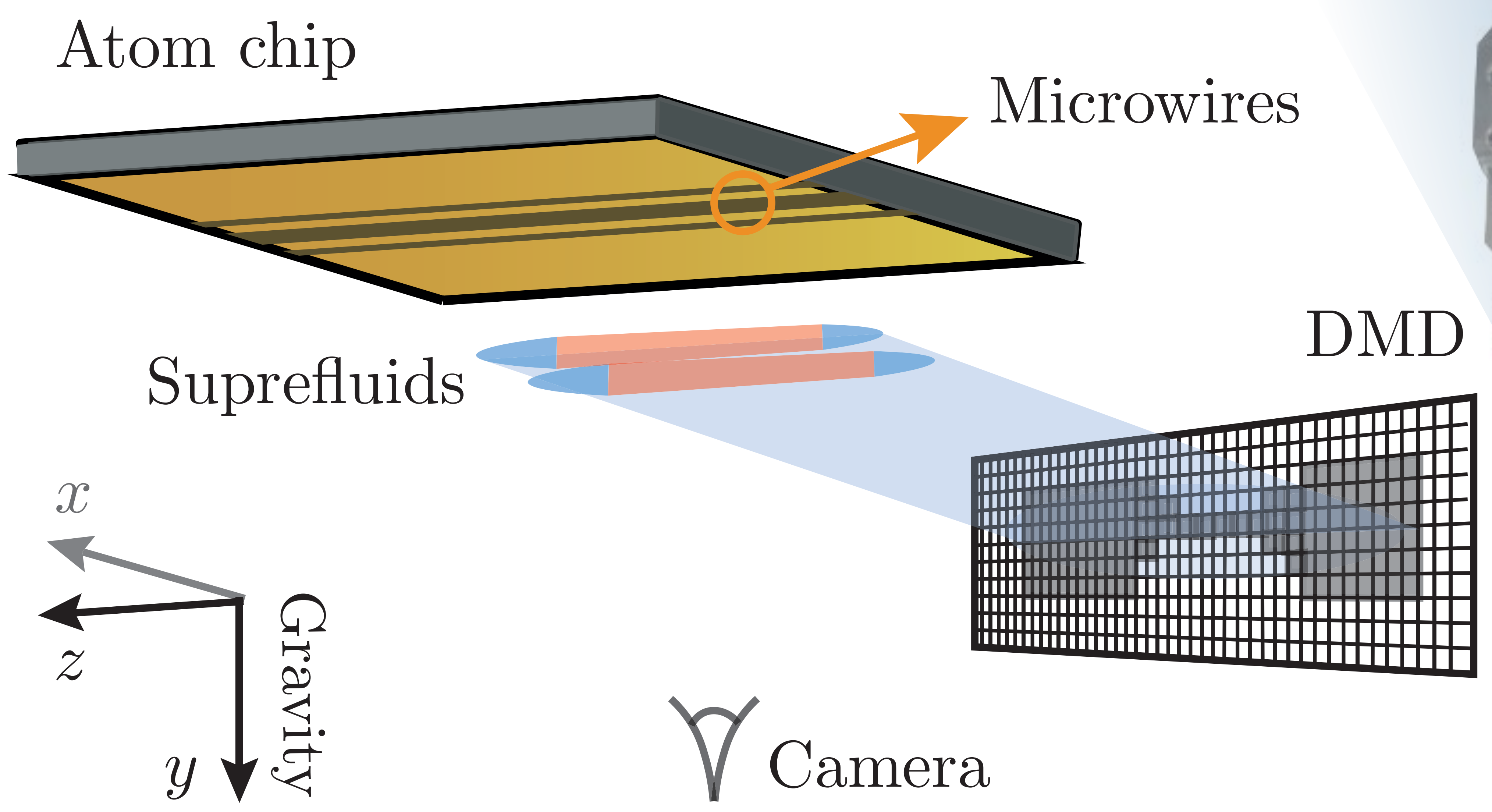

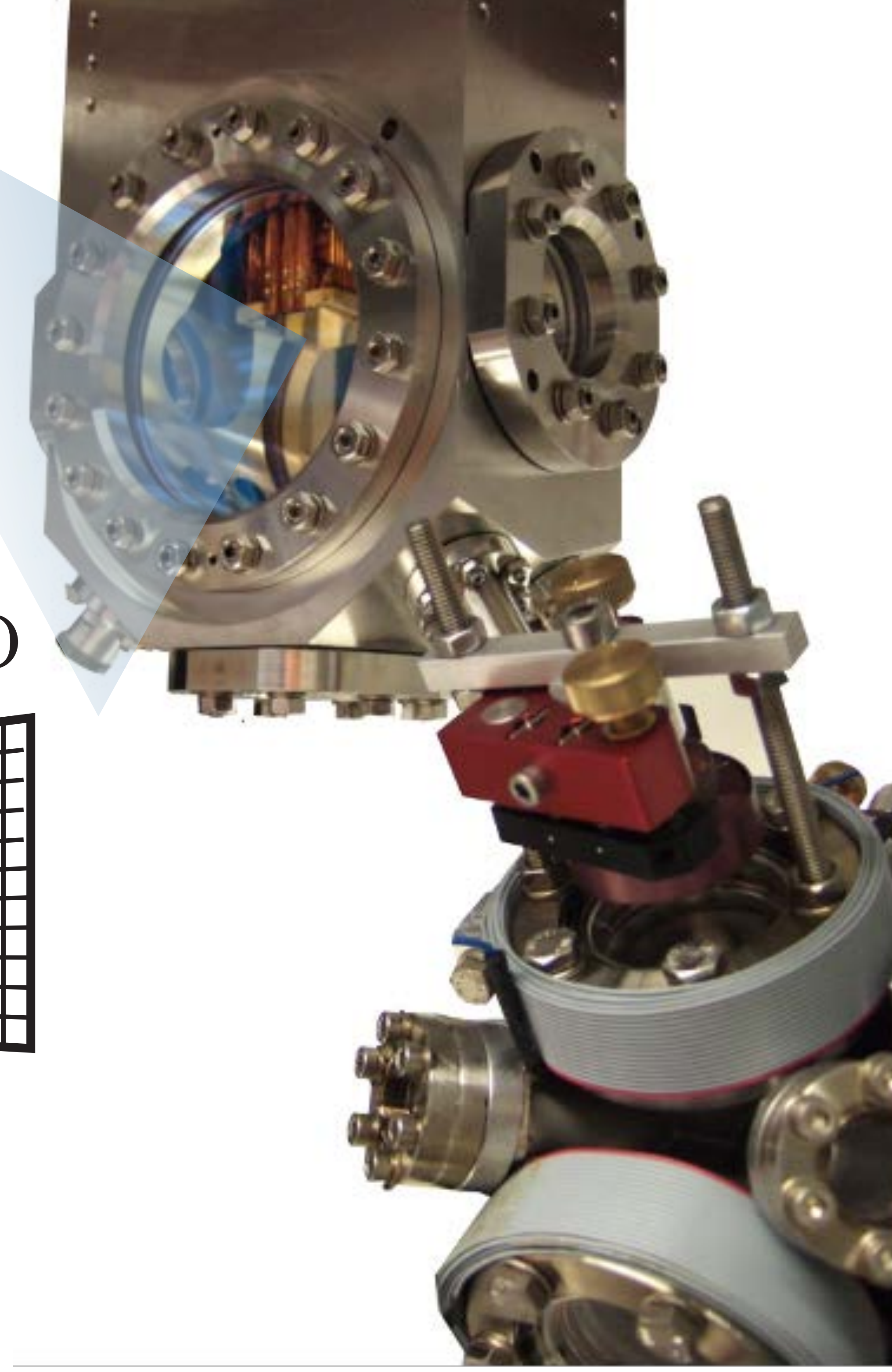

Quantum field machines
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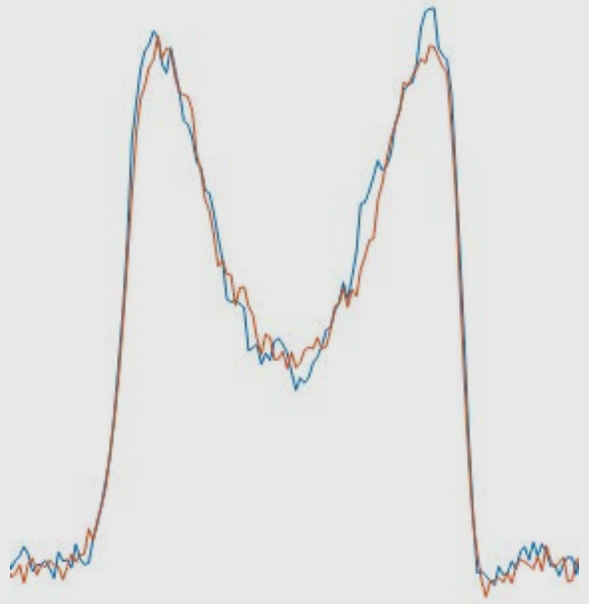
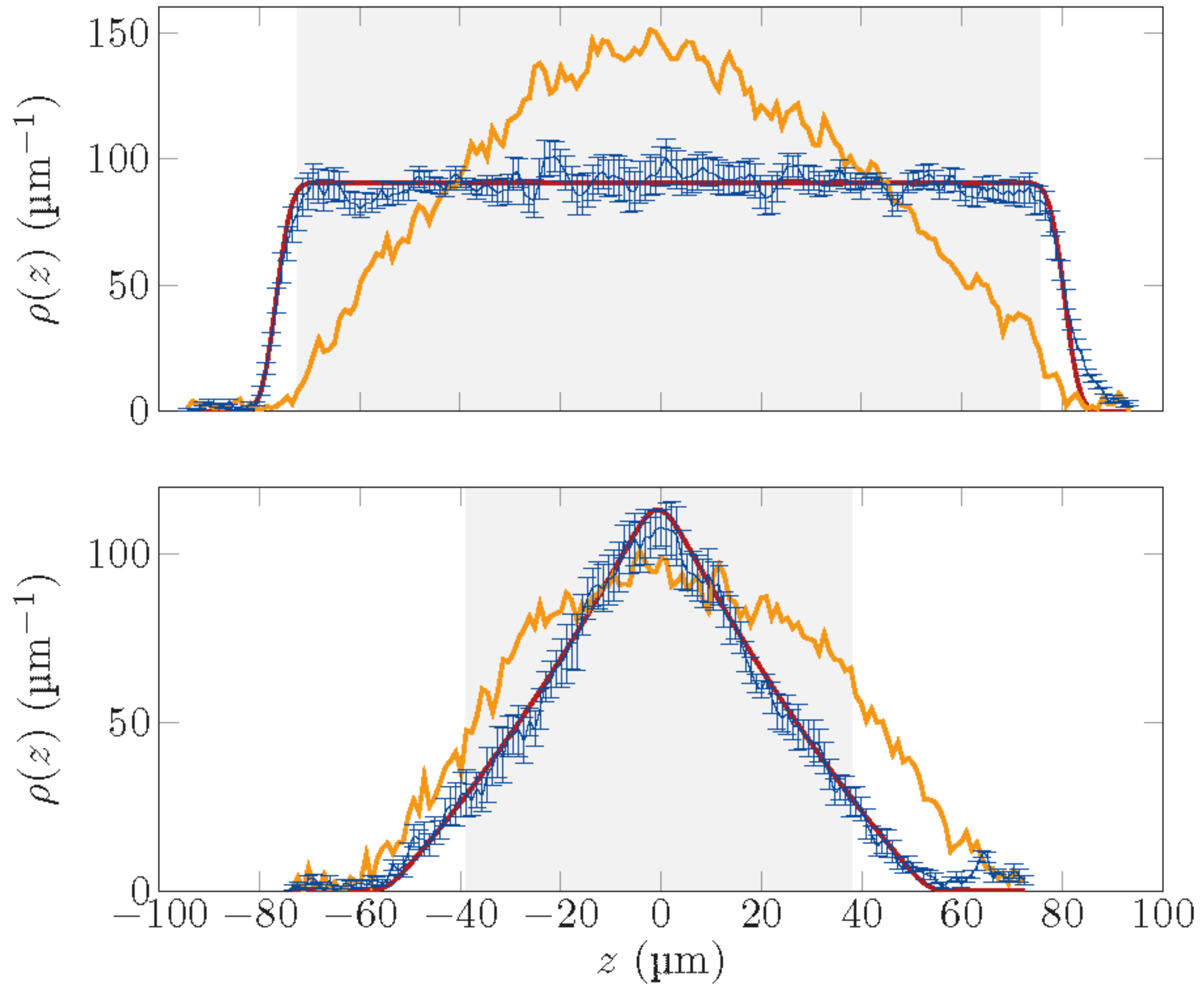
Excitation propagation & decay + GHD
Federica C. & Frederik M.





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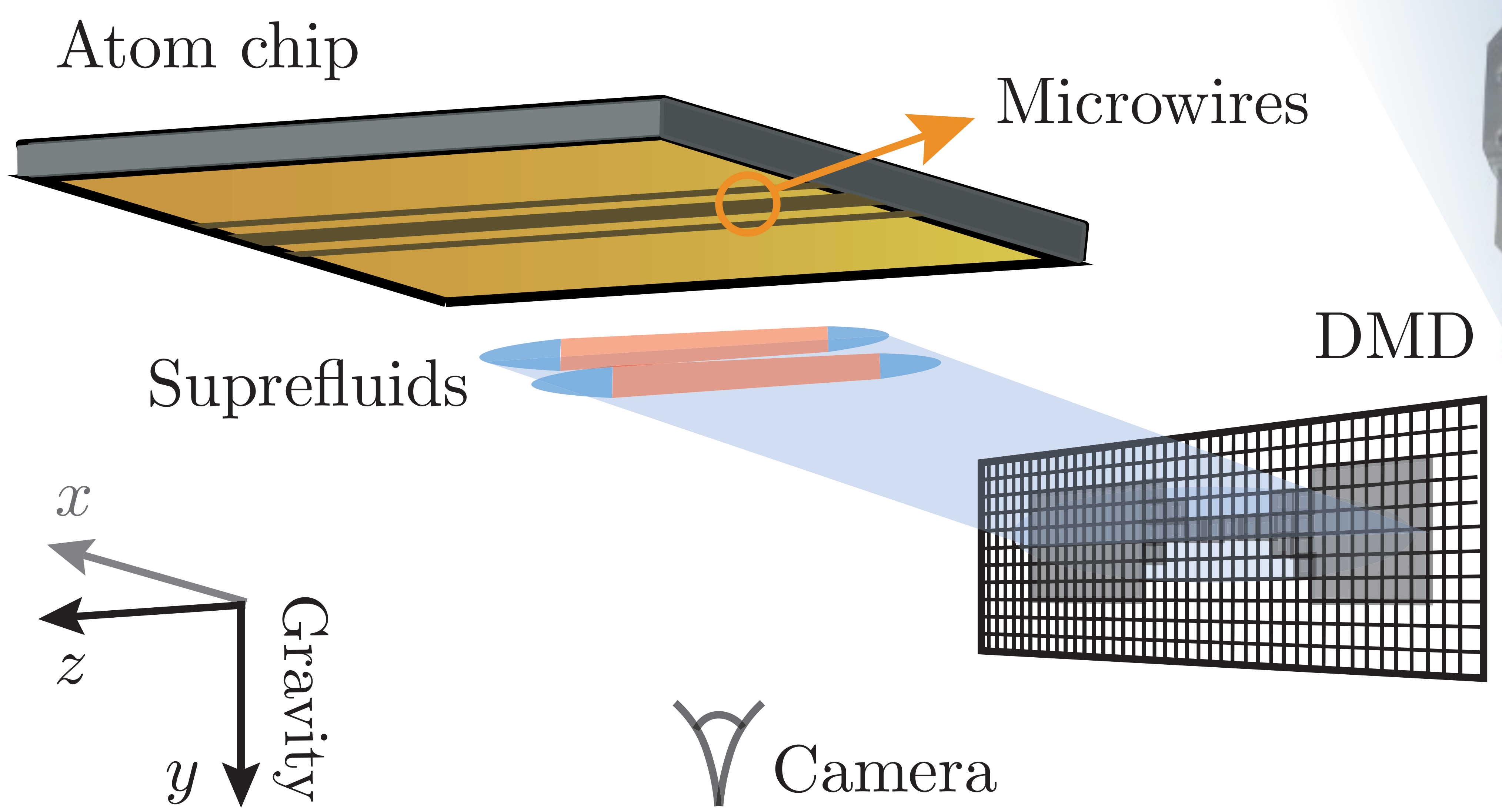

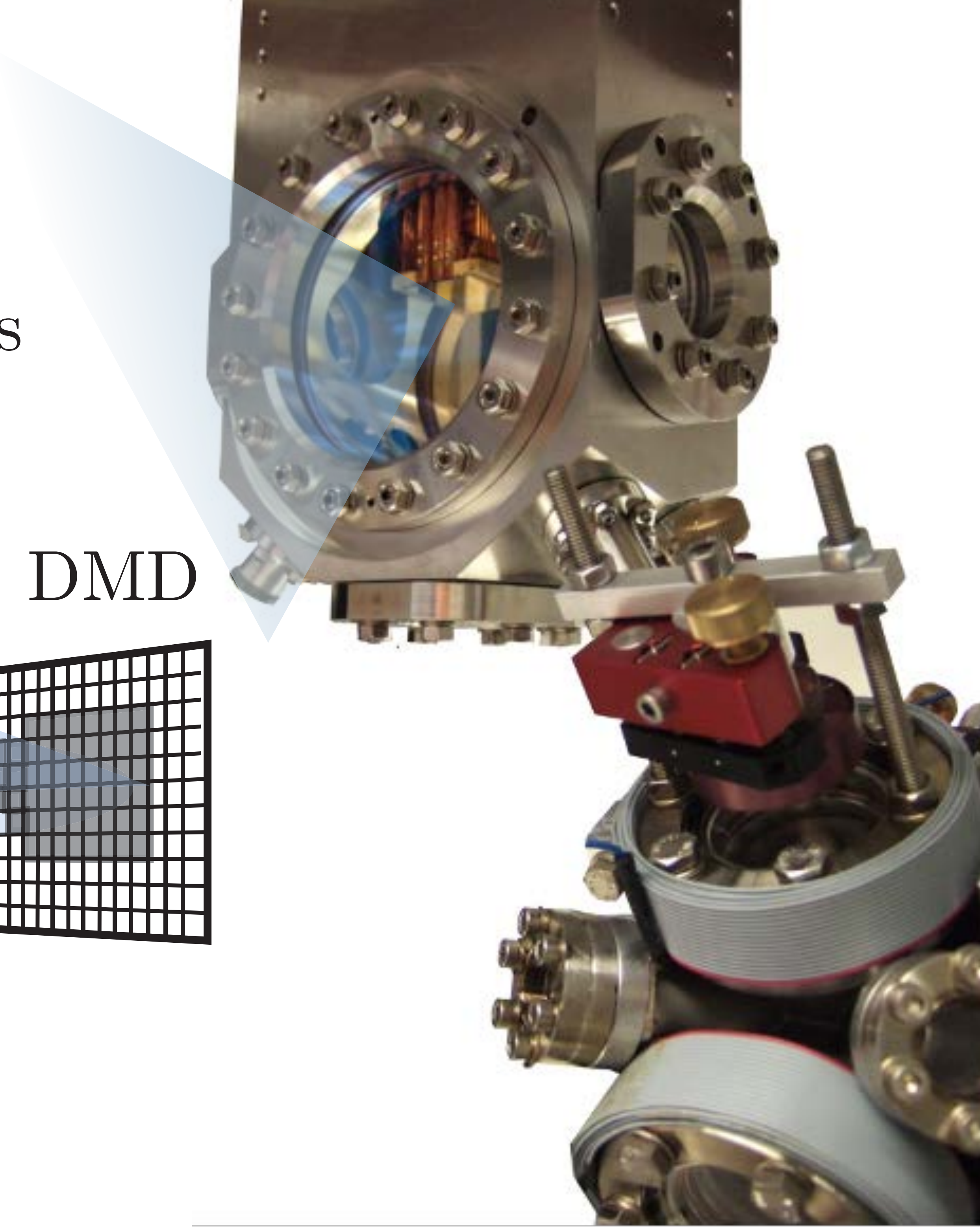

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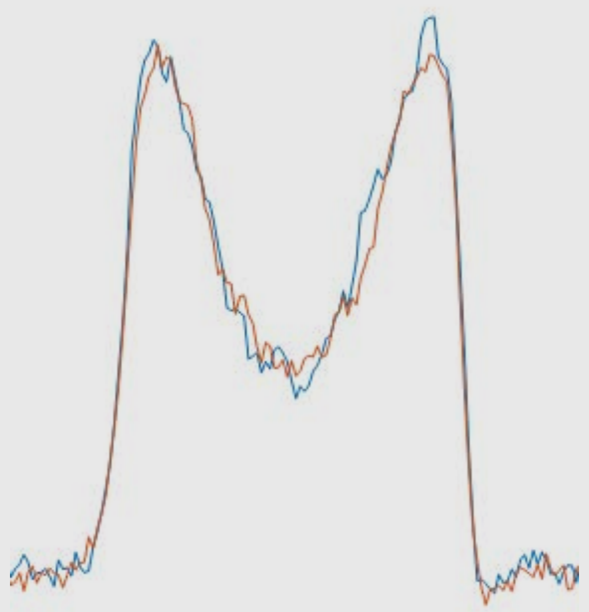
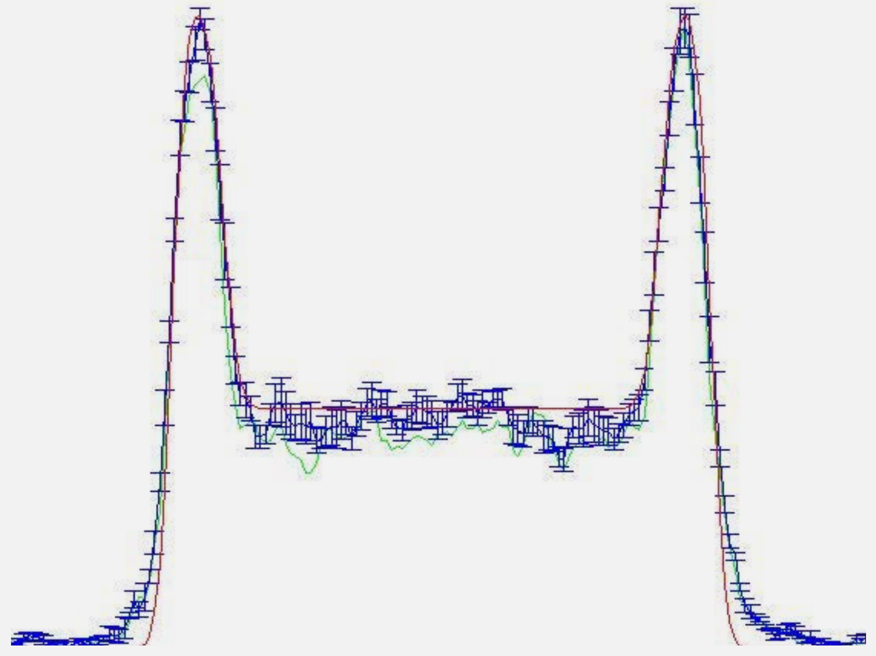
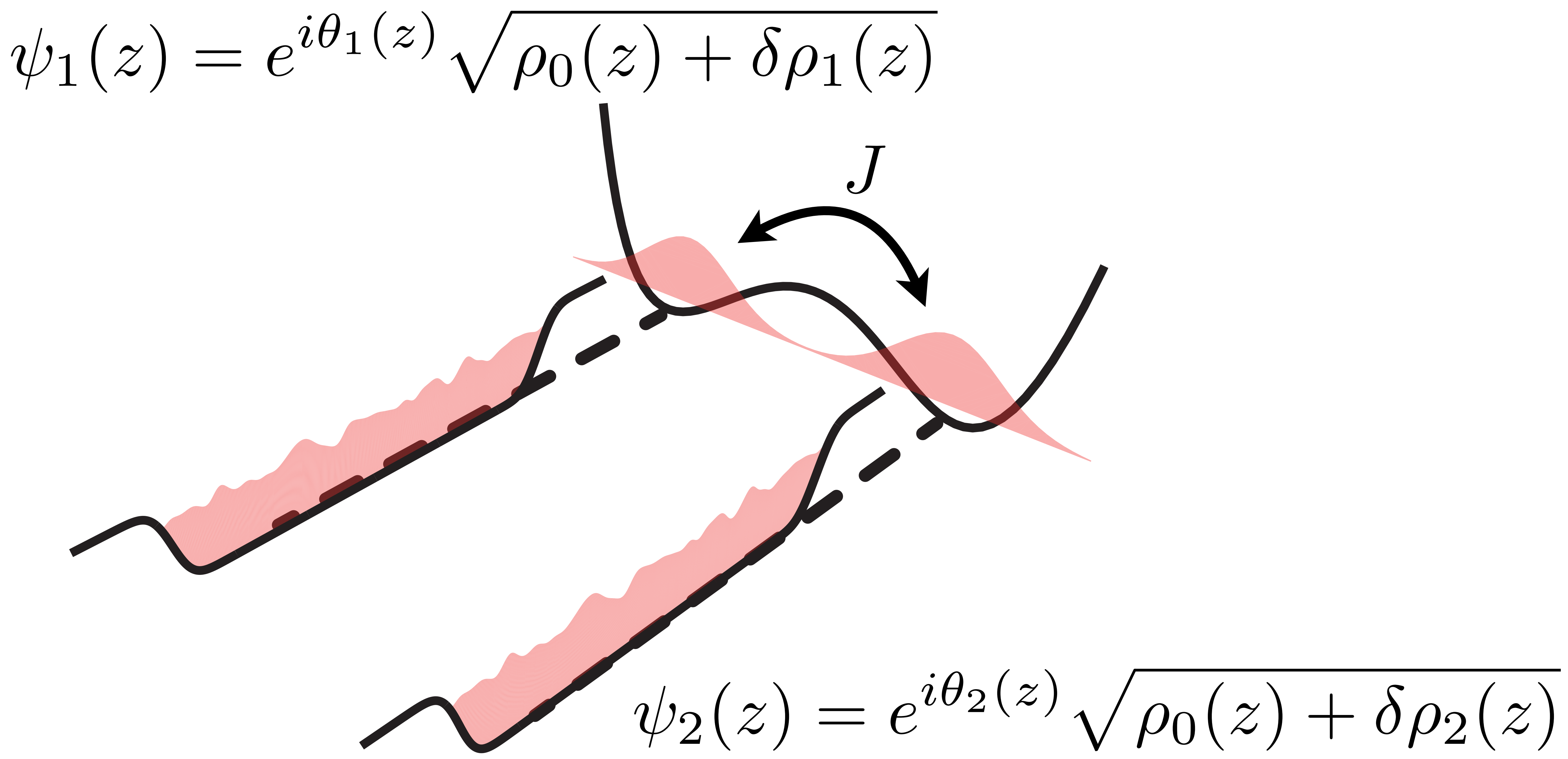
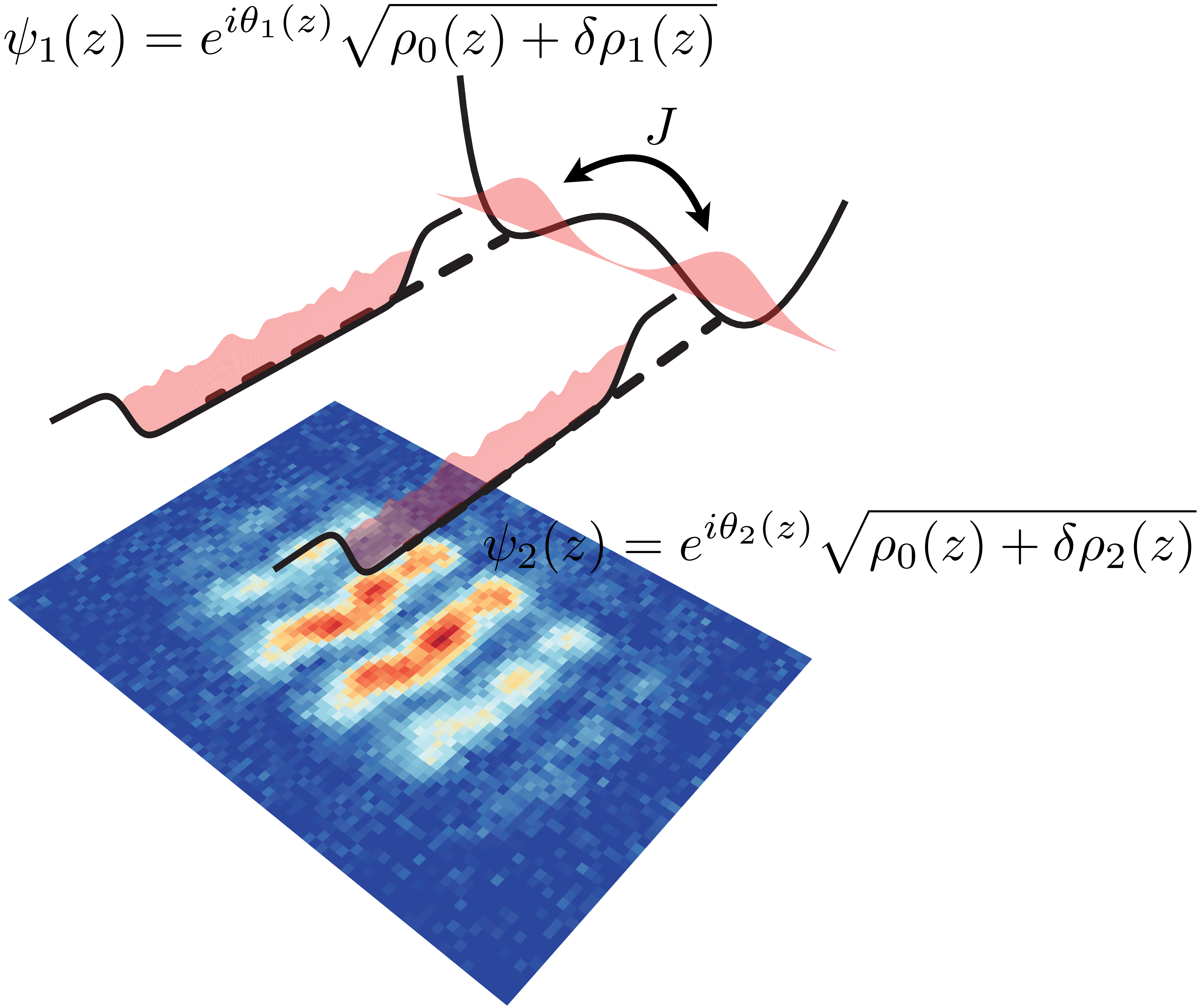


Boundary Sine-Gordon
Amin T. , Sebastian E.
& Nataliia B.




$\psi_1(z) = e^{i\theta_1(z)}\sqrt{\rho_0(z) + \delta\rho_1(z)}$
J
$\psi_2(z) = e^{i\theta_2(z)}\sqrt{\rho_0(z) + \delta\rho_2(z)}$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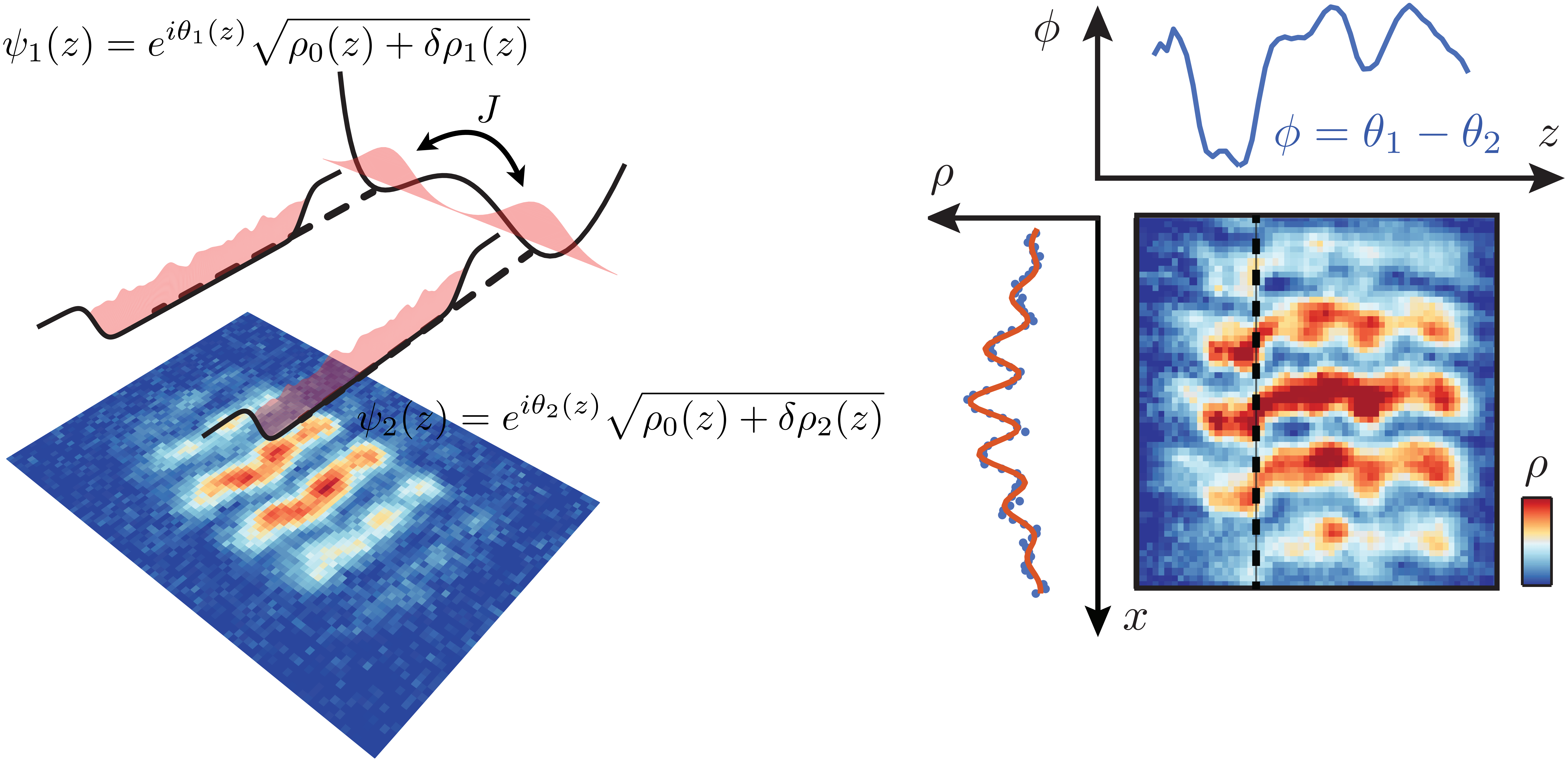

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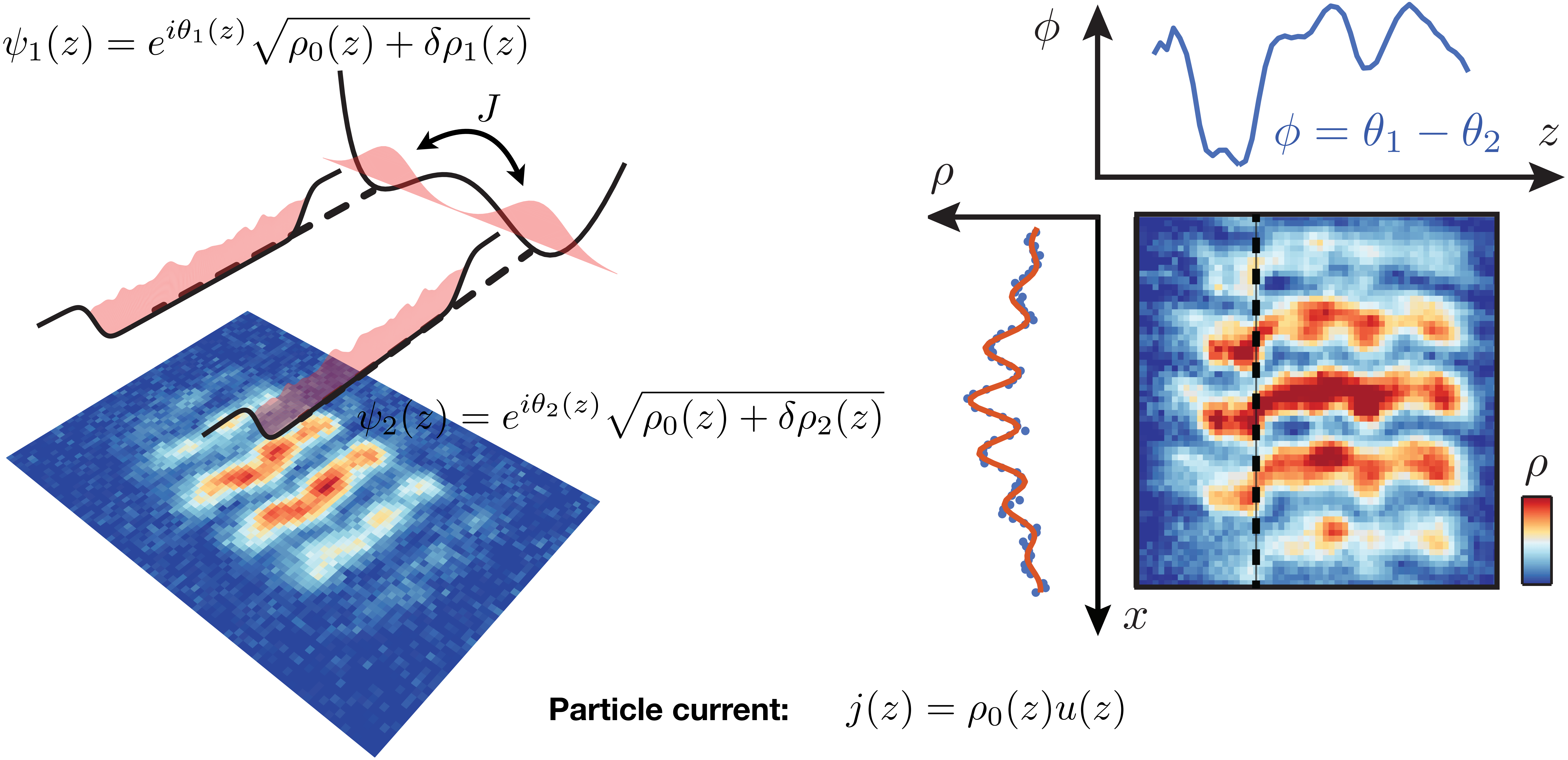
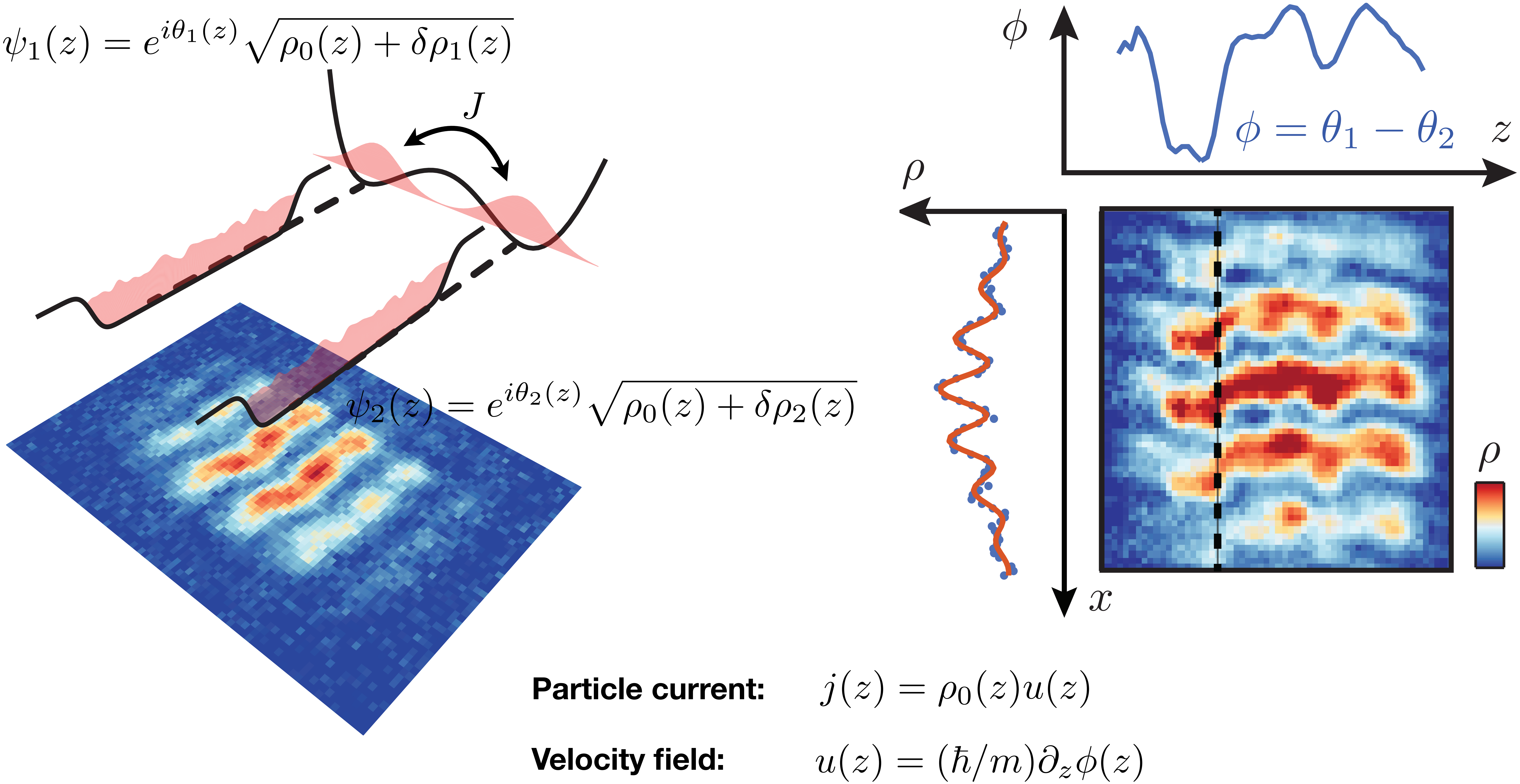
ϕ
$\phi = \theta_1 - \theta_2$
z
ρ
x
ρ



Particle current: $j(z) = \rho_0(z)u(z)$



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ϕ
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z
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Particle current: $j(z) = \rho_0(z)u(z)$
Velocity field: $u(z) = (\hbar/m)\partial_z\phi(z)$

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Particle current: $j(z) = \rho_0(z)u(z)$
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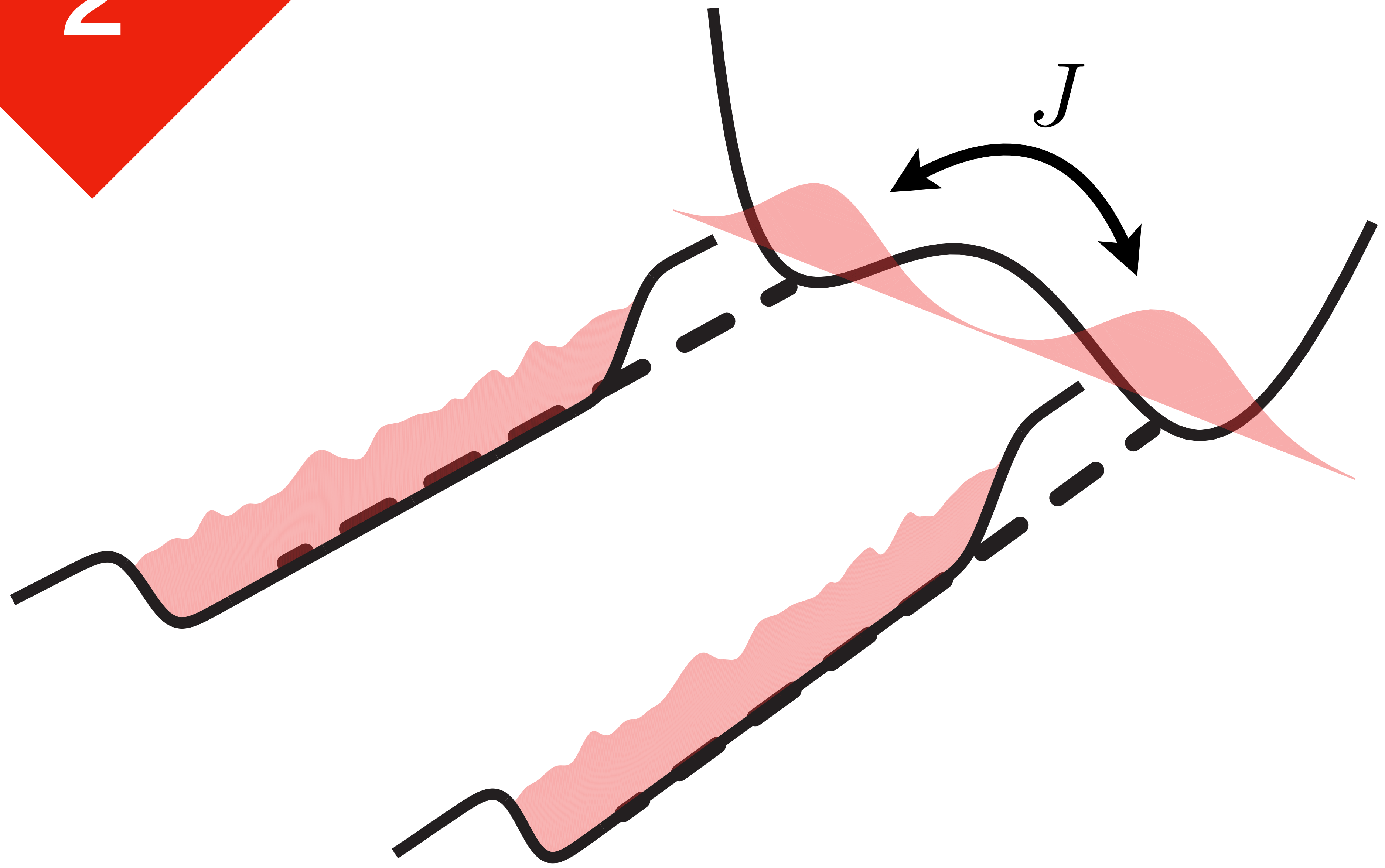
From sine-Gordon to Klein-Gordon - Dynamics of relative DOF

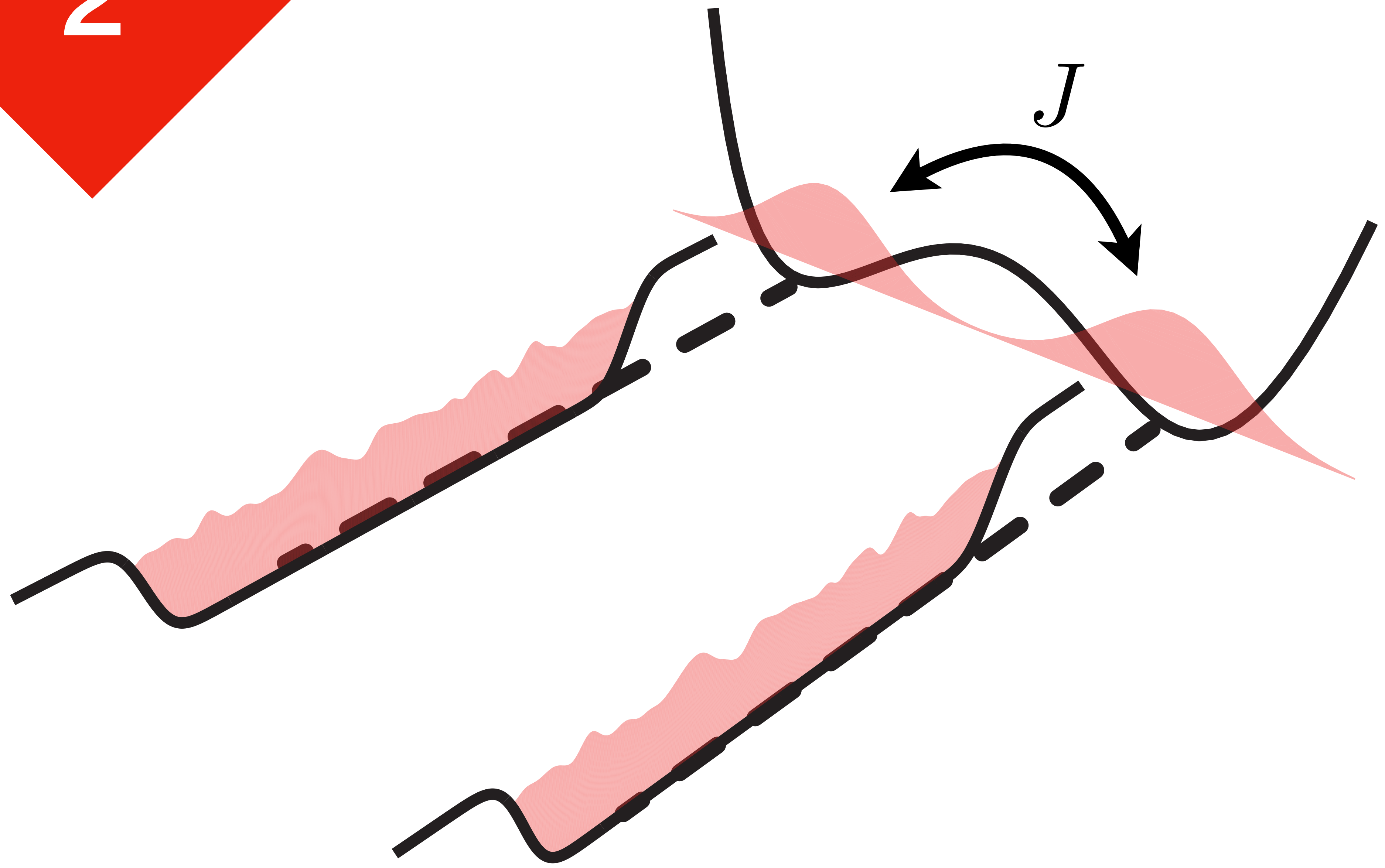


$$H_{\mathrm{sG}} = \int \mathrm{d}z \left[\frac{\hbar^2 \rho_0(z)}{4m} (\partial_z \phi)^2 + \gamma \delta\rho^2 - 2\hbar J \rho_0(z) \cos(\phi) \right]$$

Schweigler et al., Nature (2017)
Schweigler et al., Nat. Phys. (2021)

Rauer et al., Science (2018)

2



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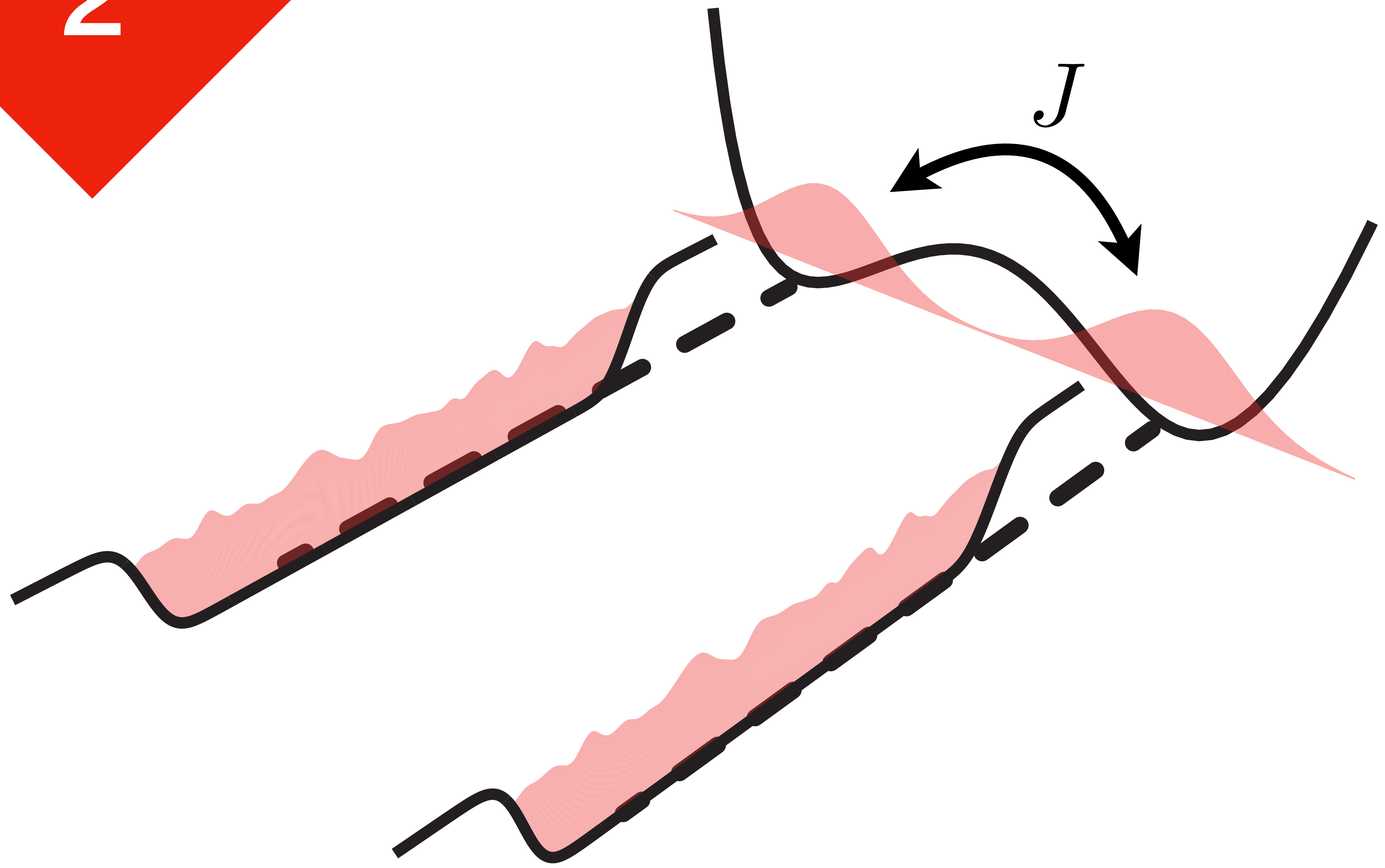
For strong tunnelling

$$H_{\mathrm{KG}} = \int \mathrm{d}z \left[\frac{\hbar^2 \rho_0(z)}{4m} (\partial_z \phi)^2 + \gamma \delta\rho^2 + \hbar J \rho_0(z) \phi^2 \right]$$

Rauer et al., Science (2018)

2



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Rauer et al., Science (2018)

1+1 D action

$$\mathcal{S}[\phi] \sim \int \mathrm{d}z \mathrm{d}t \sqrt{-g} K(z) \left[g^{\mu\nu} (\partial_\mu \phi)(\partial_\nu \phi) + \tfrac{1}{2} M^2 \phi^2 \right]$$

$$\mathrm{d}s^2 = g_{\mu\nu} \mathrm{d}x^\mu \mathrm{d}x^\nu = -v(z)^2 \mathrm{d}t^2 + \mathrm{d}z^2$$

$$v(z) = \sqrt{\gamma \rho_0(z)/m}$$

$$K(z) = \frac{\hbar \pi}{2} \sqrt{\frac{\rho_0(z)}{m\gamma}} \qquad M = \sqrt{2\hbar m J/\gamma}$$

3

1+1 D action

$$\mathcal{S}[\phi] \sim \int \mathrm{d}z\mathrm{d}t\sqrt{-g}K(z)\left[g^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi) + \frac{1}{2}M^2\phi^2\right]$$

Tajik et al., PNAS (2023)

3

1+1 D action

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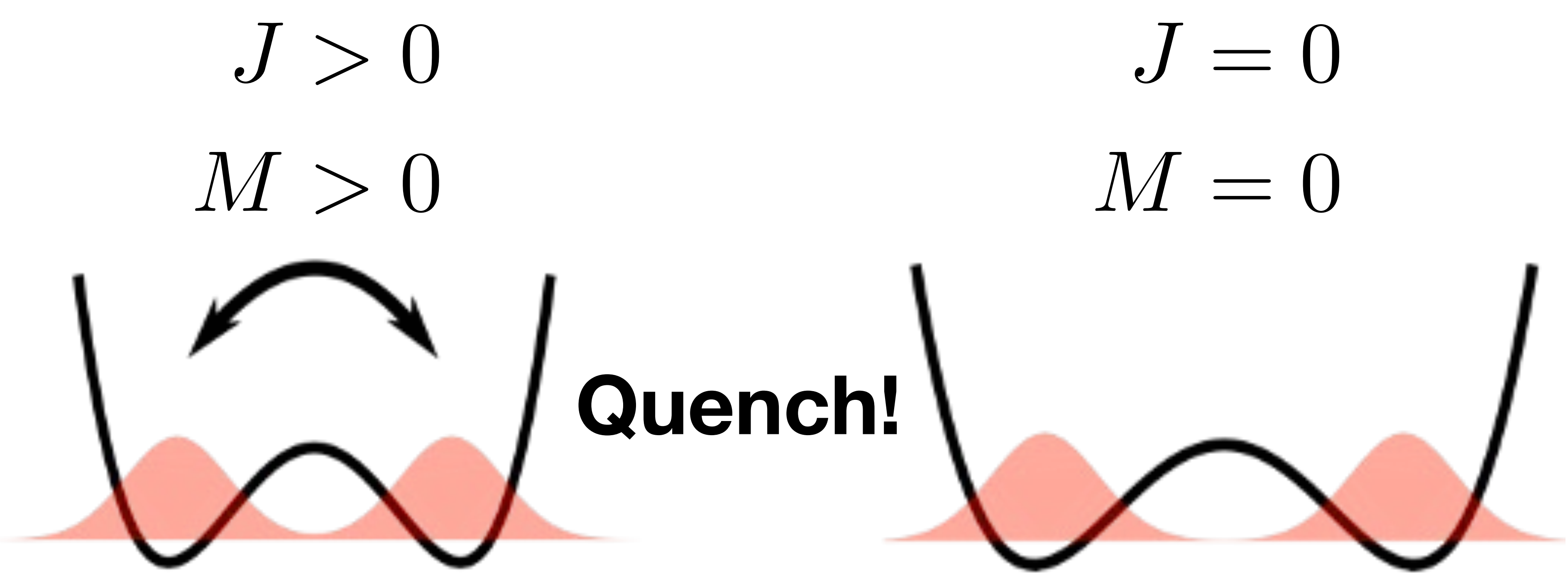

Tajik et al., PNAS (2023)

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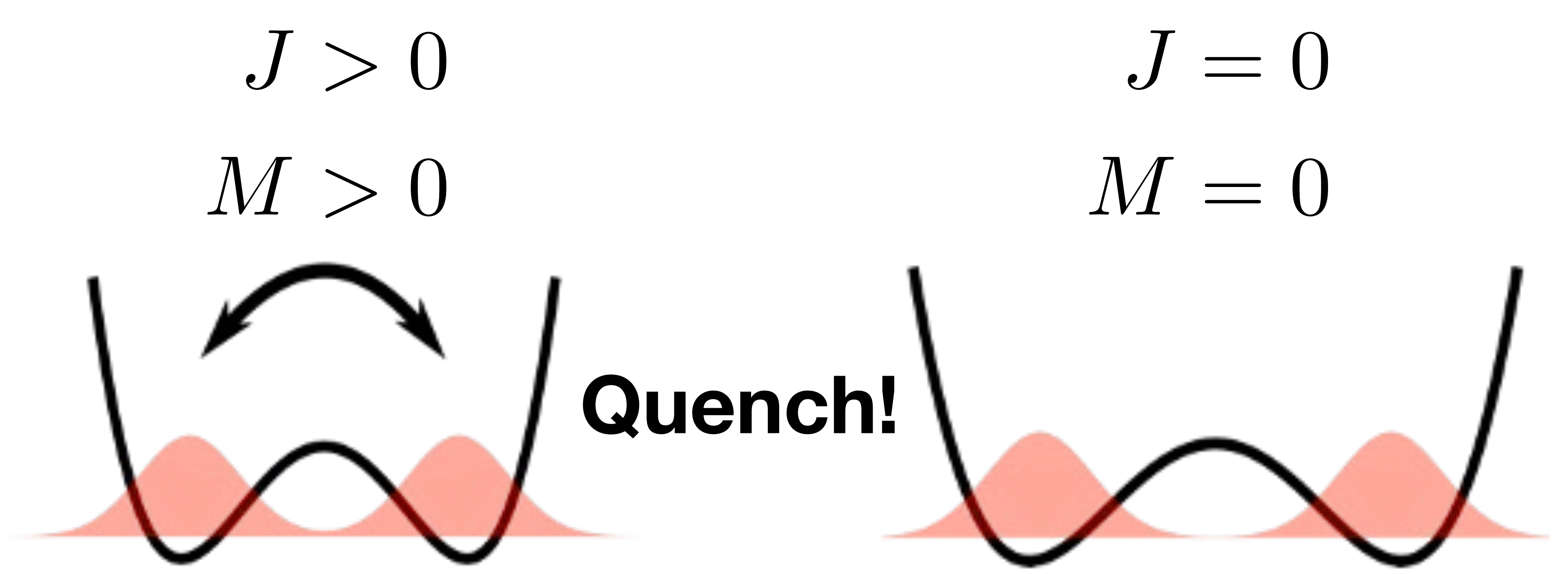

Tajik et al., PNAS (2023)

Velocity field: $u(z) = (\hbar/m)\partial_z\phi(z)$

3

1+1 D action

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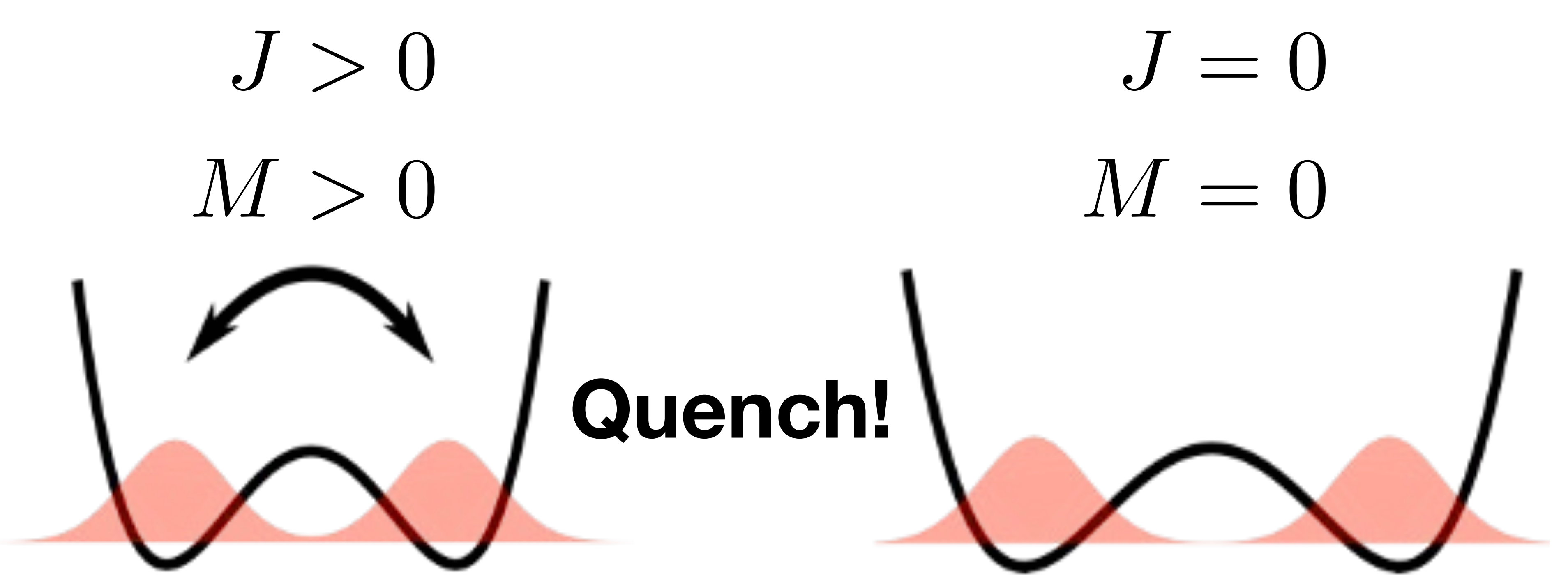

Tajik et al., PNAS (2023)

Velocity field:

$$u(z) = (\hbar/m)\partial_z\phi(z)$$

$$C_u(z,z') = \langle u(z)u(z')\rangle$$

3

1+1 D action

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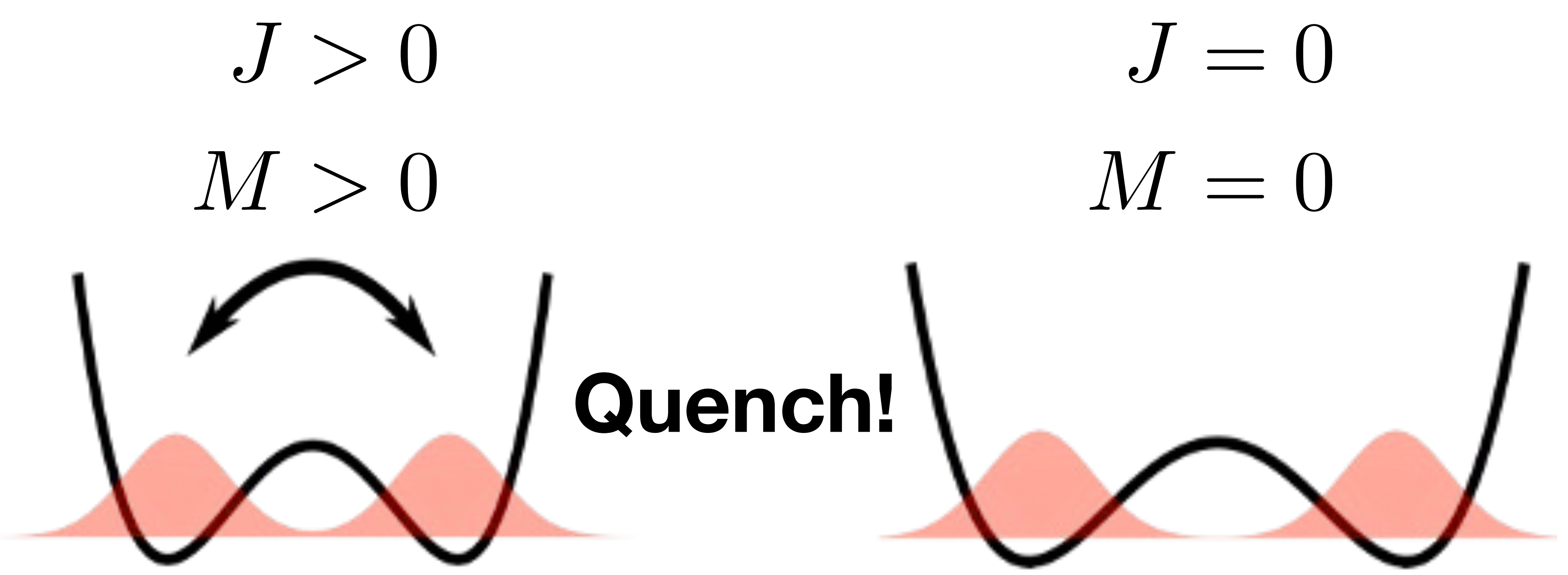

Tajik et al., PNAS (2023)

Velocity field:

$$u(z) = (\hbar/m)\partial_z \phi(z)$$

$$C_u(z, z') = \langle u(z) u(z') \rangle$$

$$\langle u(z) \rangle = 0$$

3

1+1 D action

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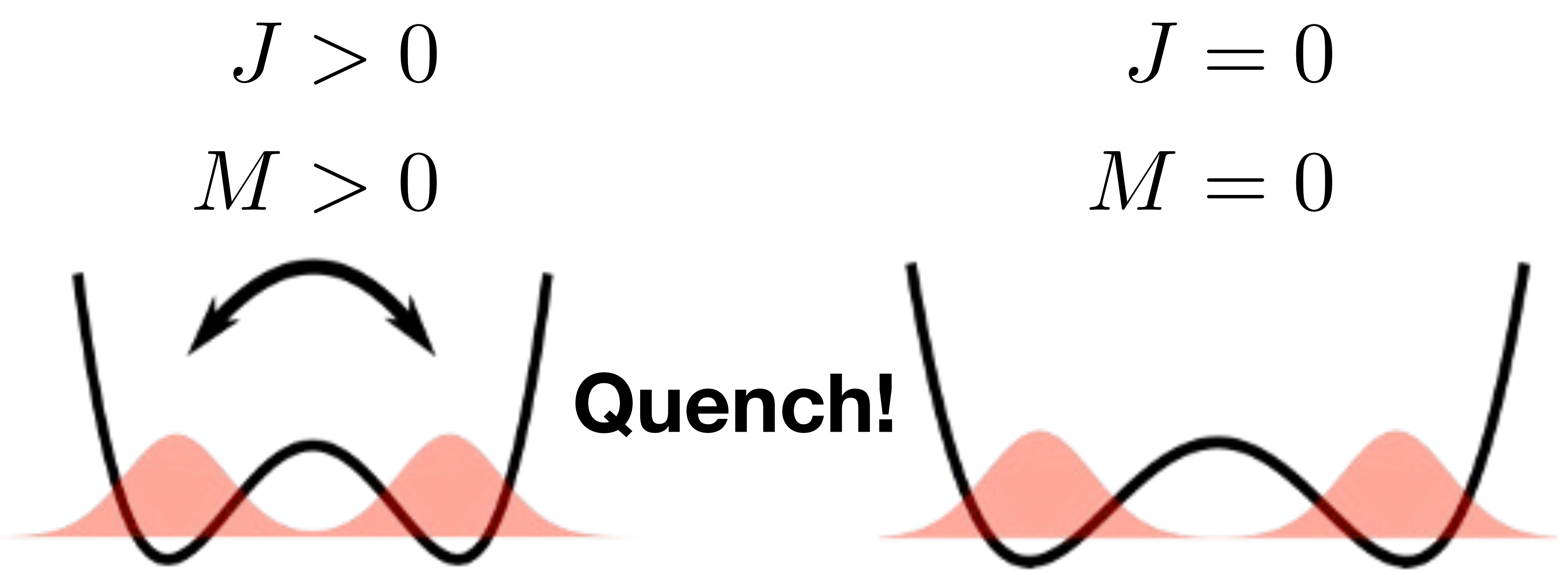


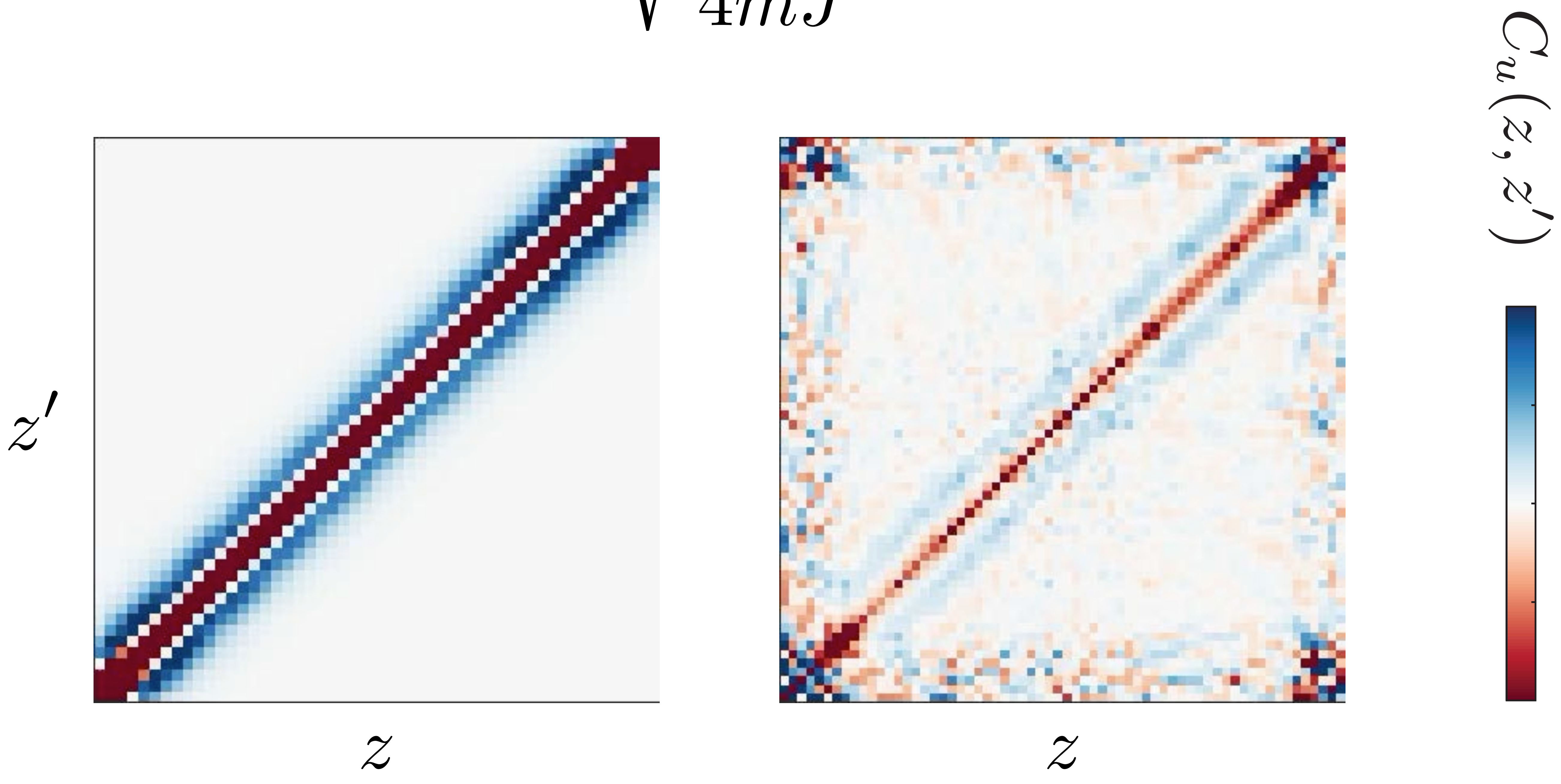
Tajik et al., PNAS (2023)

Correlation length $\ell_J = \sqrt{\dfrac{\hbar}{4mJ}}$

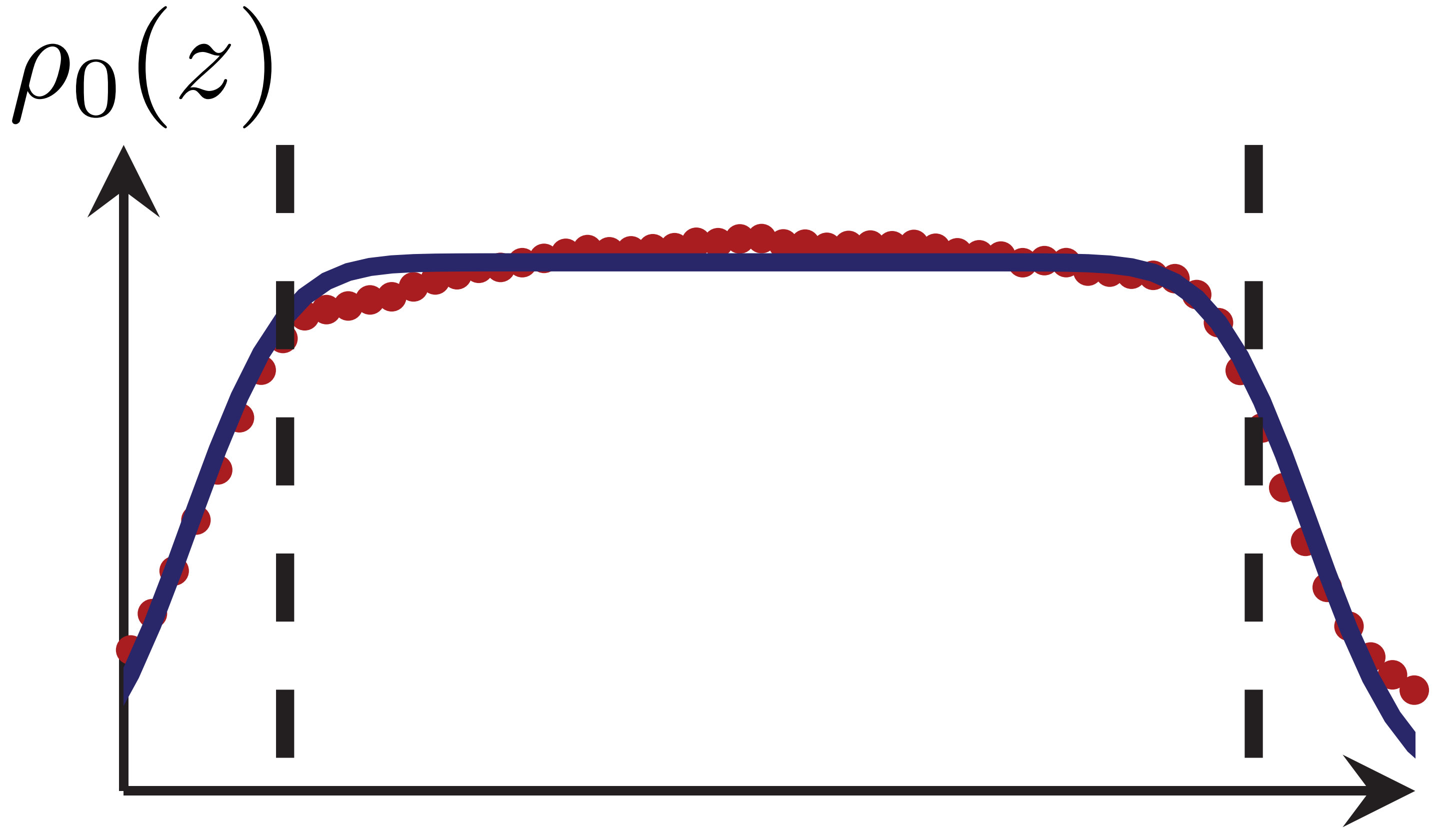
Velocity field: $u(z) = (\hbar/m)\partial_z\phi(z)$

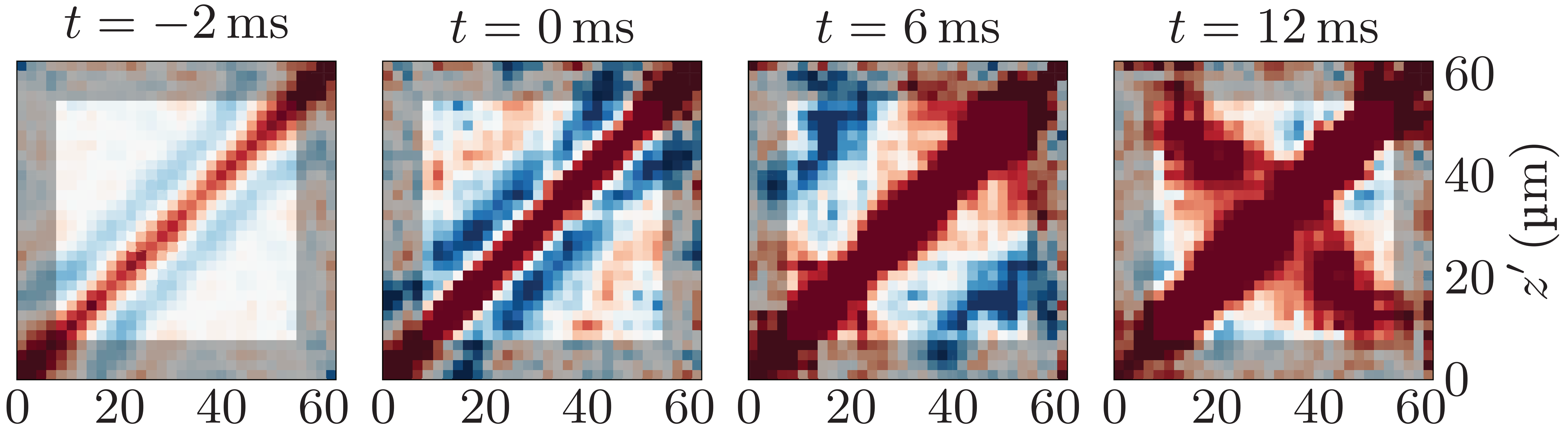
$$C_u(z,z') = \langle u(z)u(z')\rangle$$

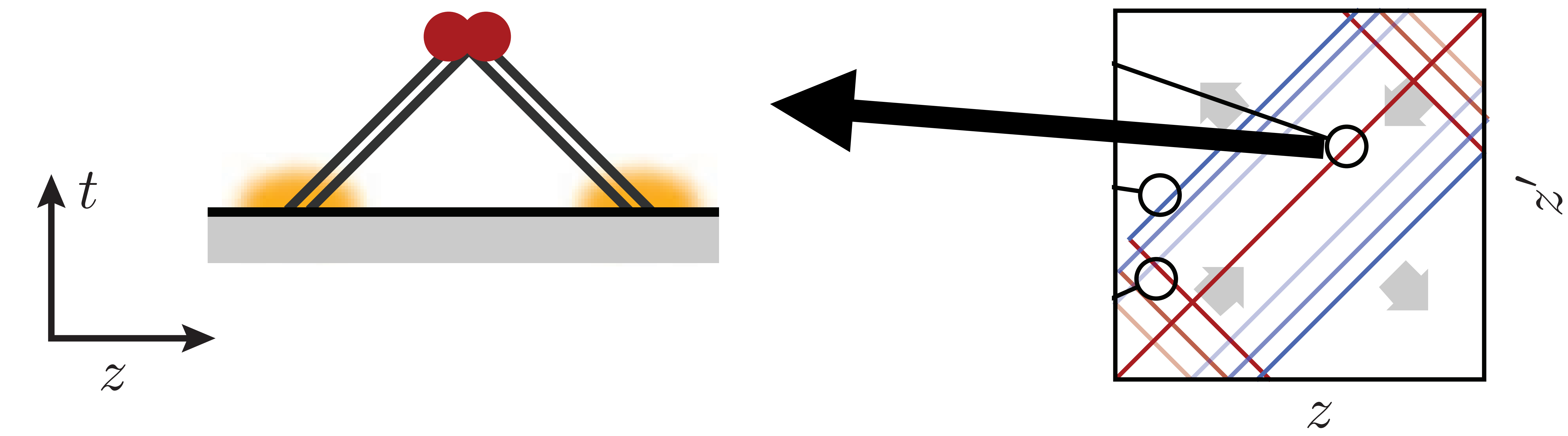
$$\langle u(z)\rangle = 0$$



Homogeneous background density







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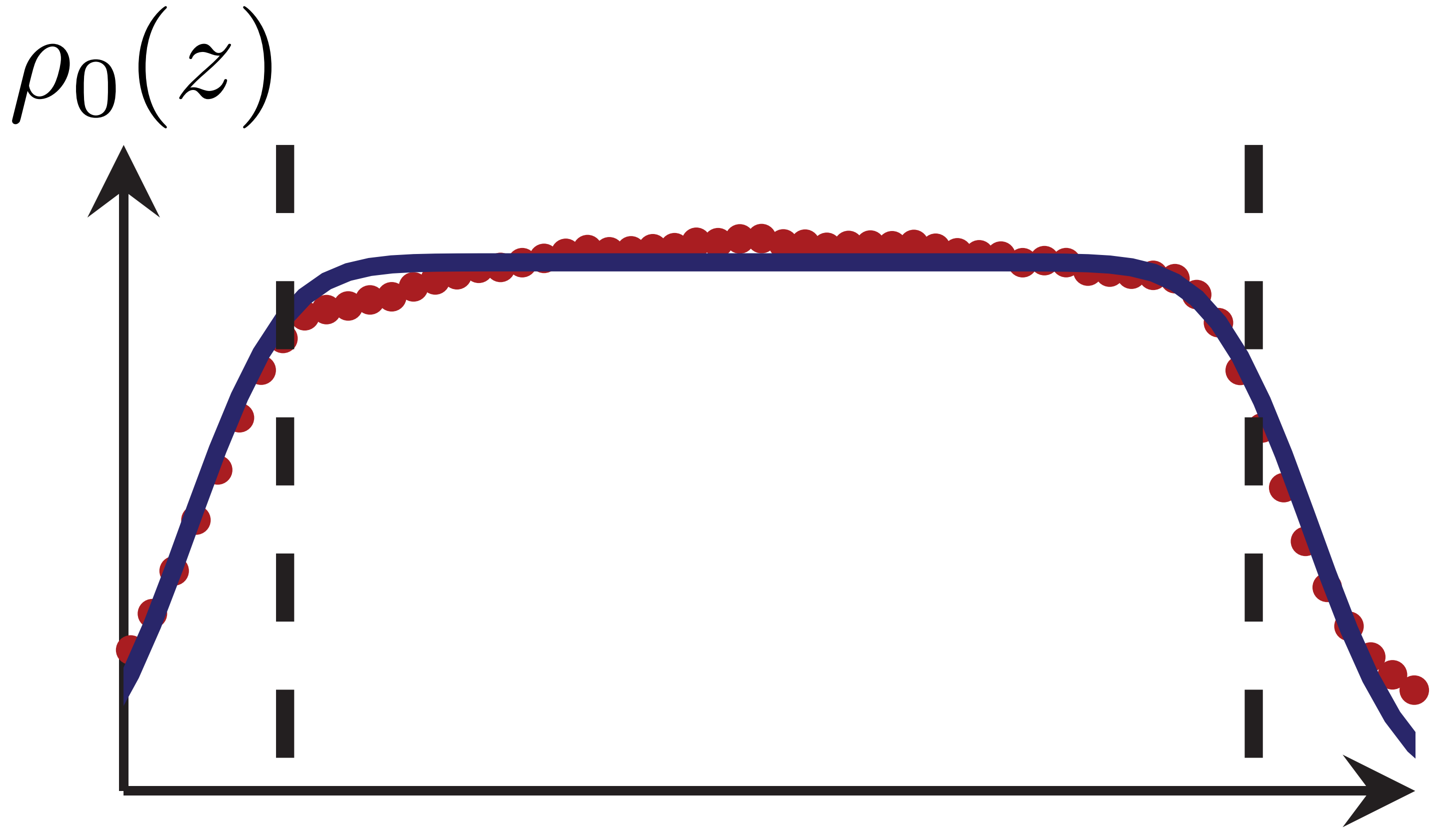
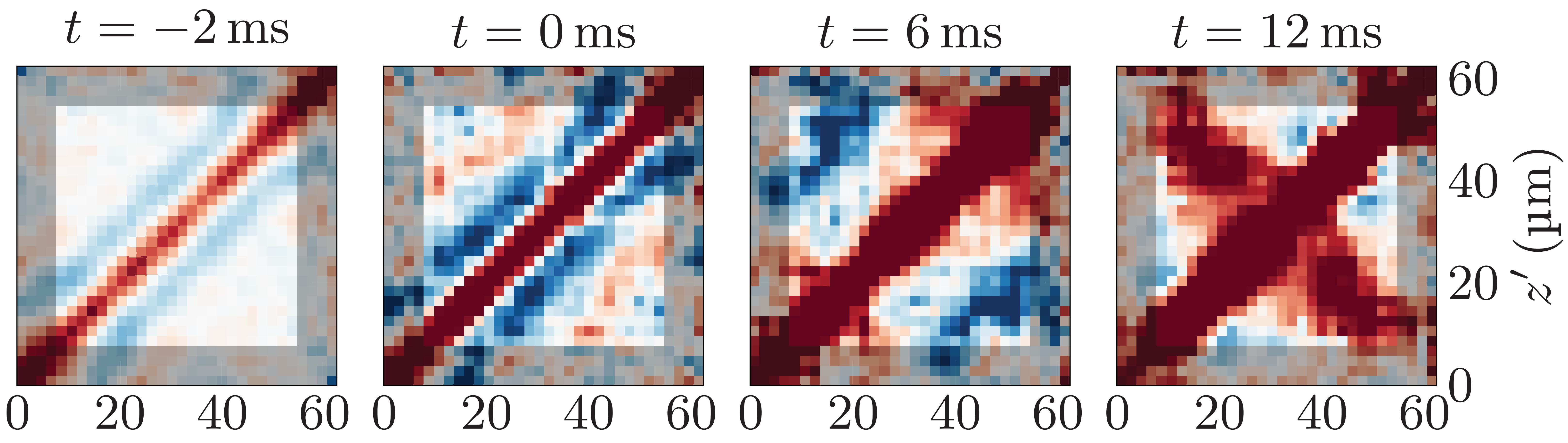
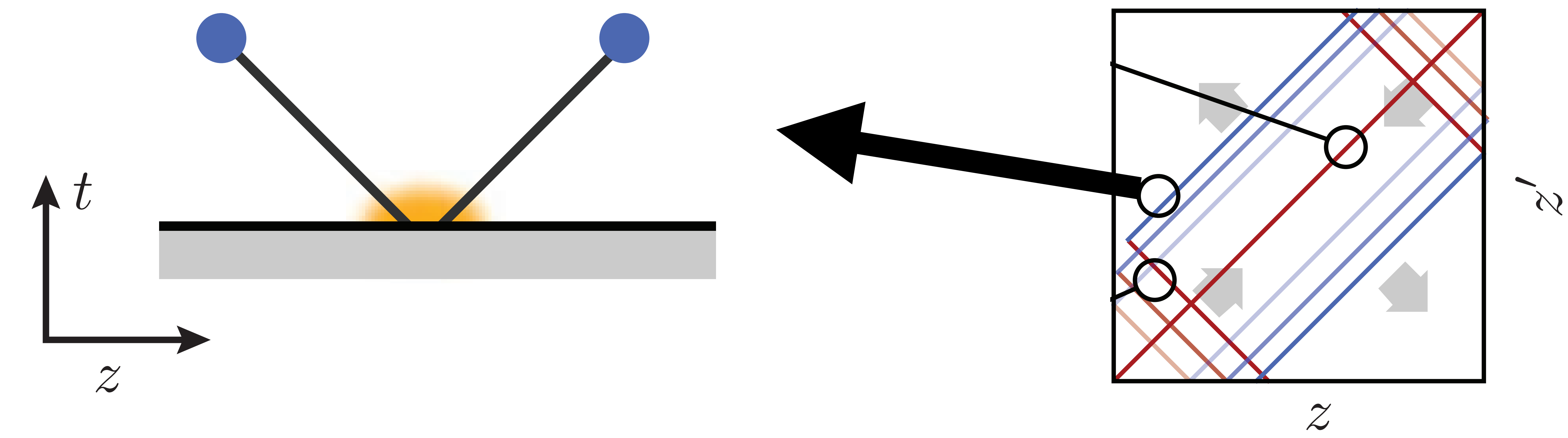
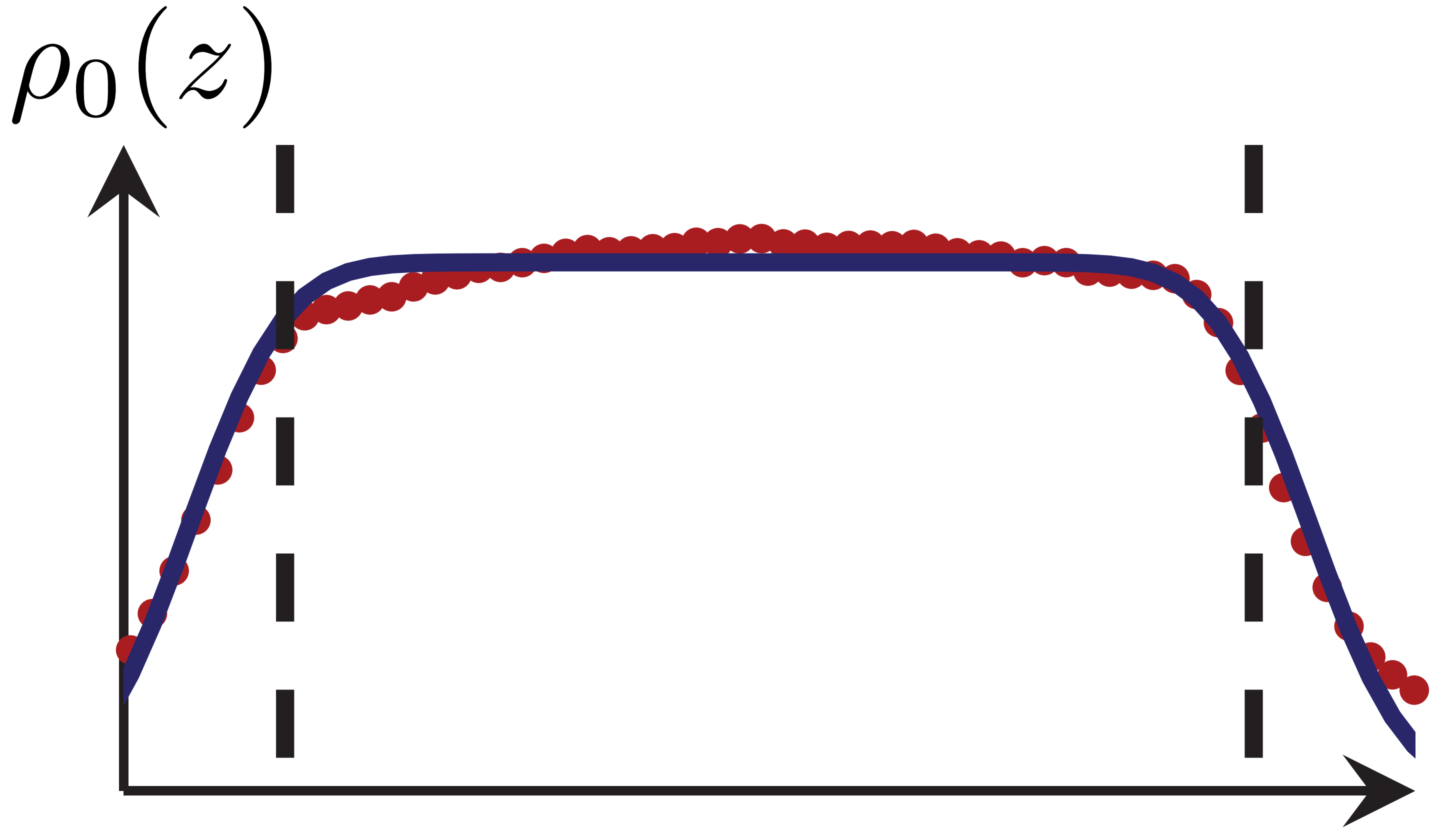
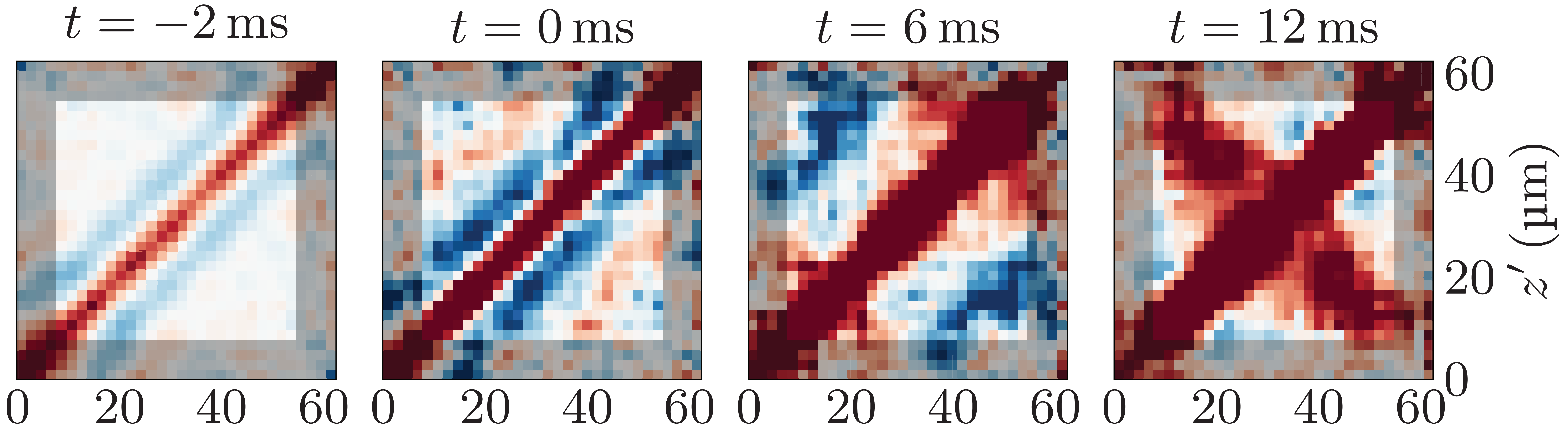


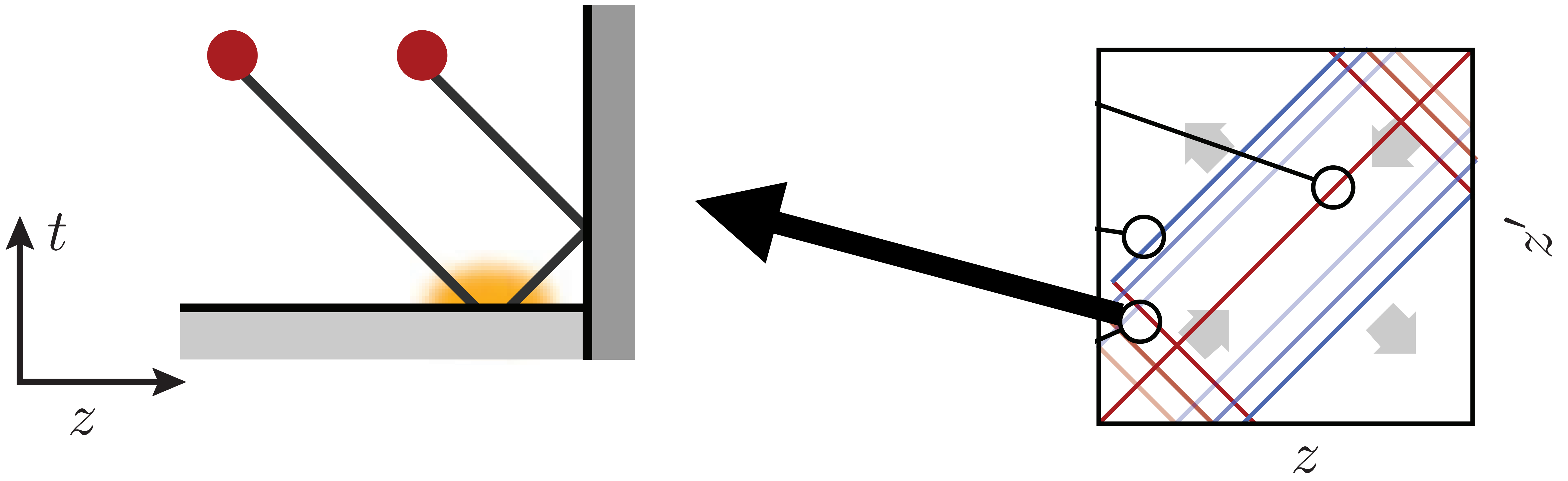




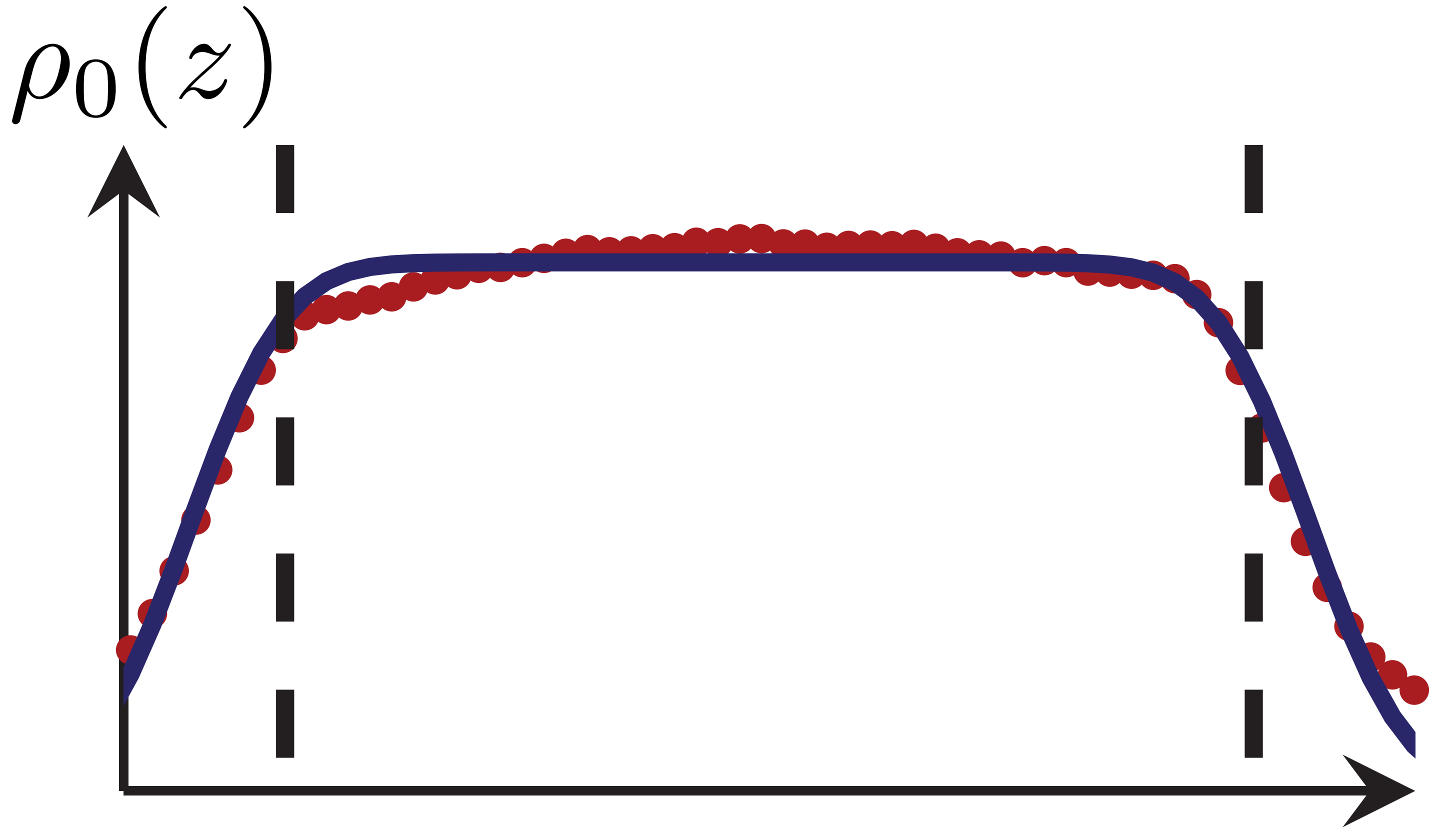
Homogeneous background density

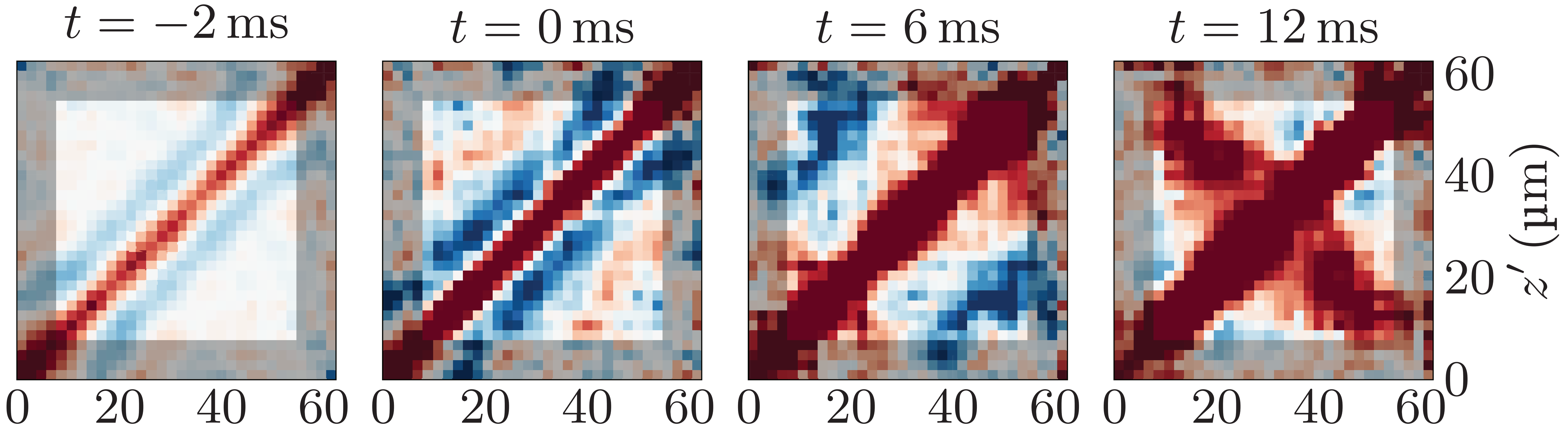


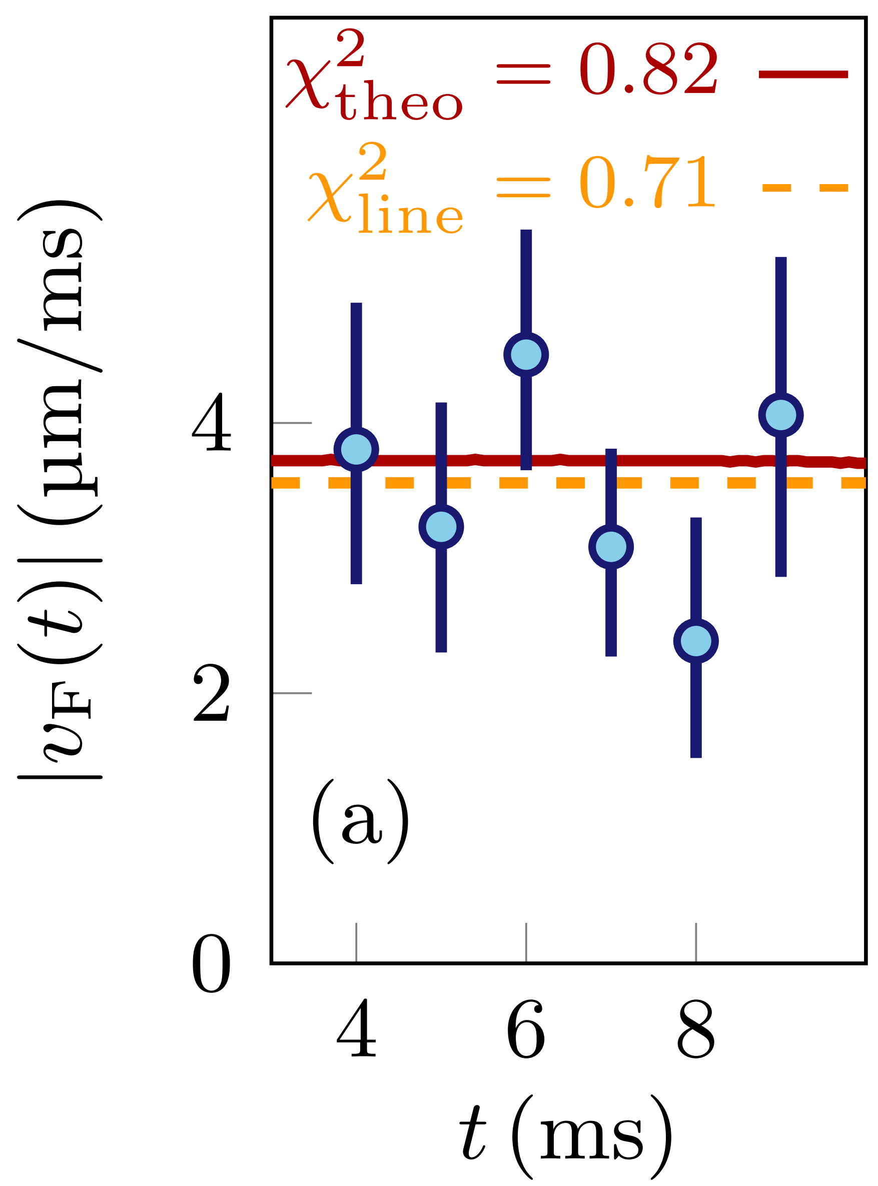


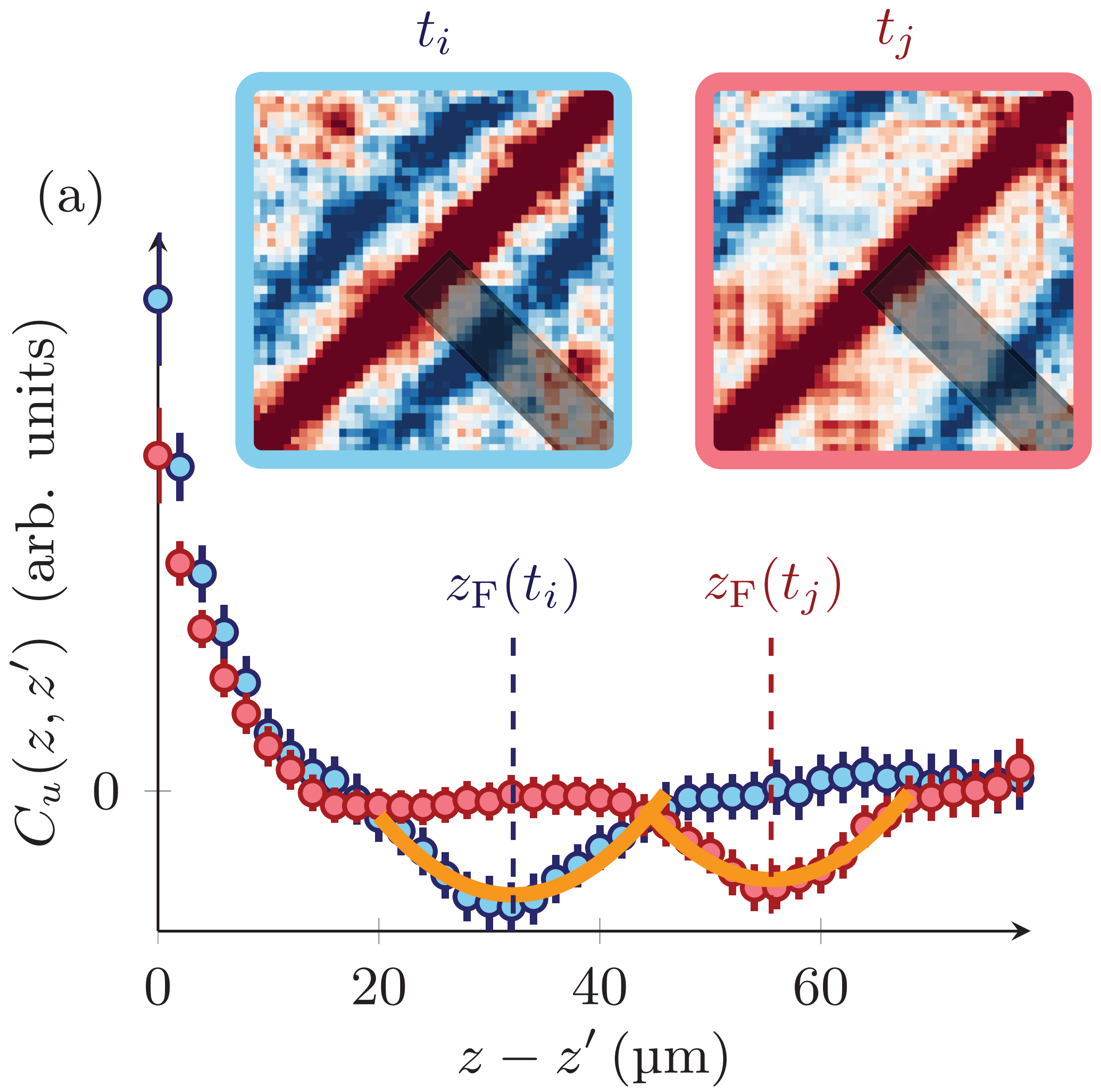


Homogeneous background density





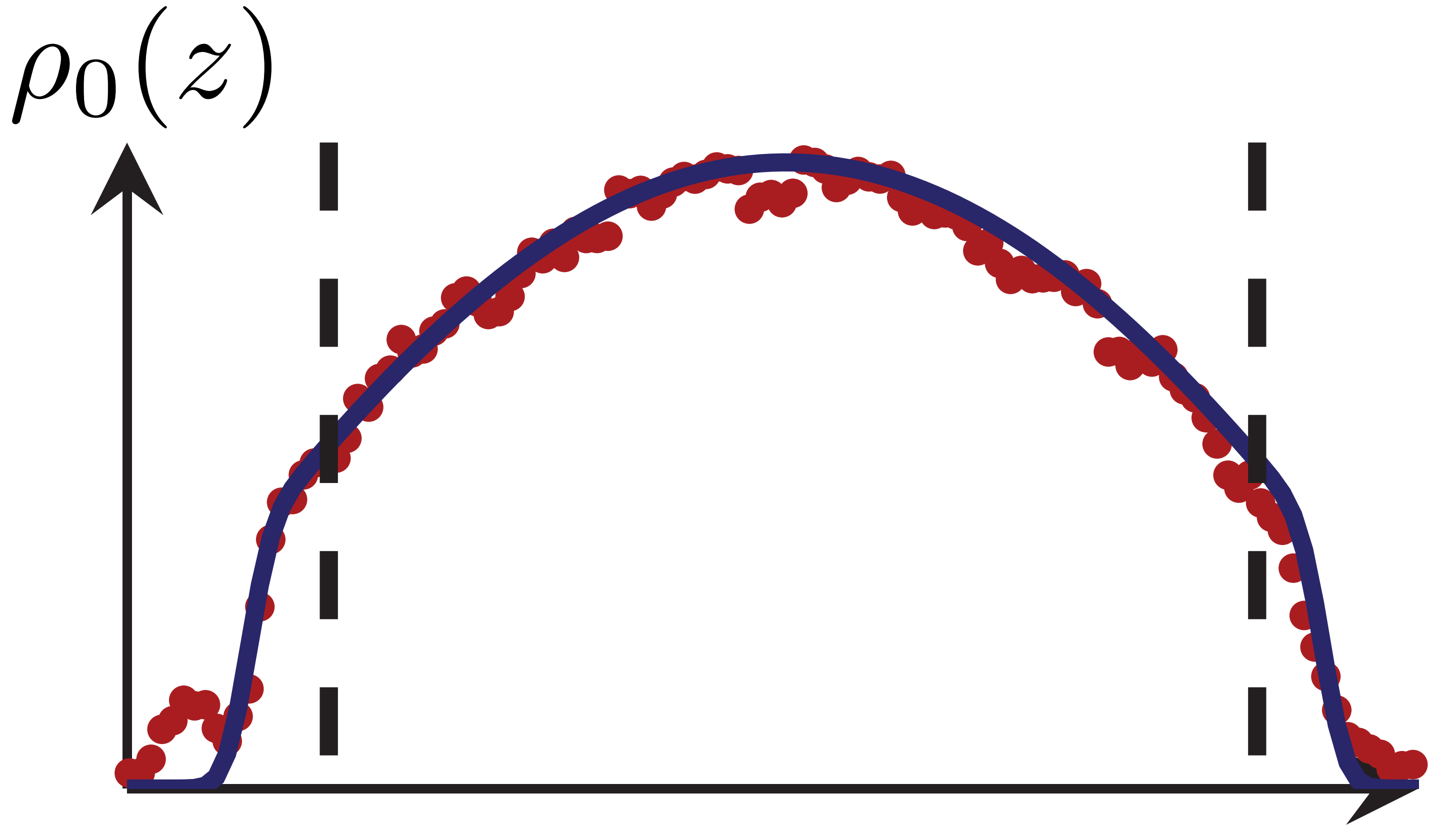


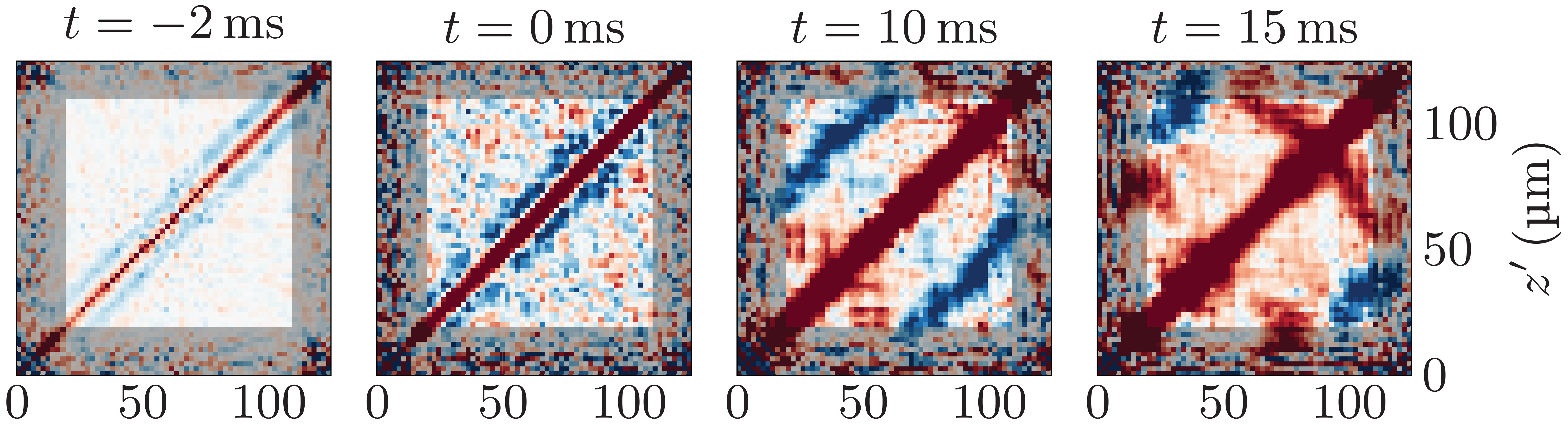


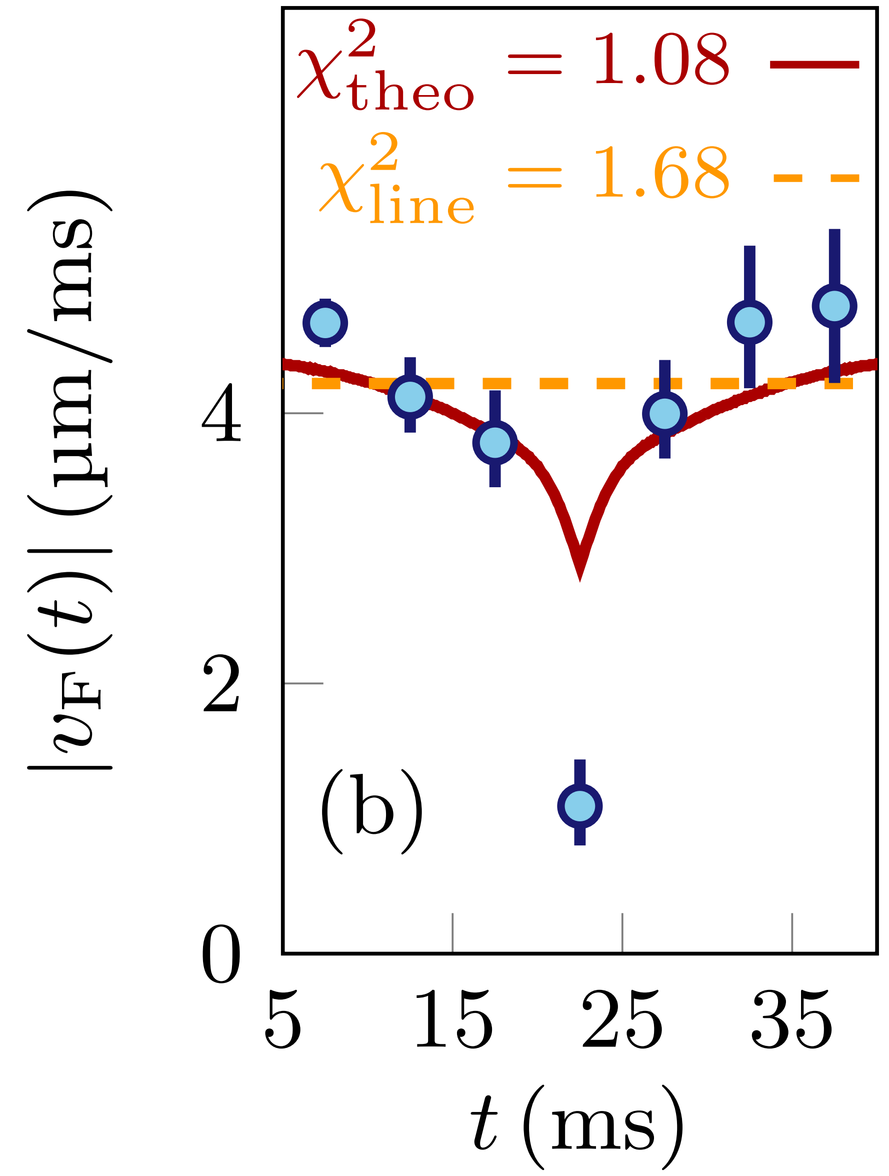
$$v_{\mathrm{F}}(t) = \frac{z_{\mathrm{F}}(t_i) - z_{\mathrm{F}}(t_j)}{t_i - t_j}\,, \quad t = \frac{t_i + t_j}{2}$$

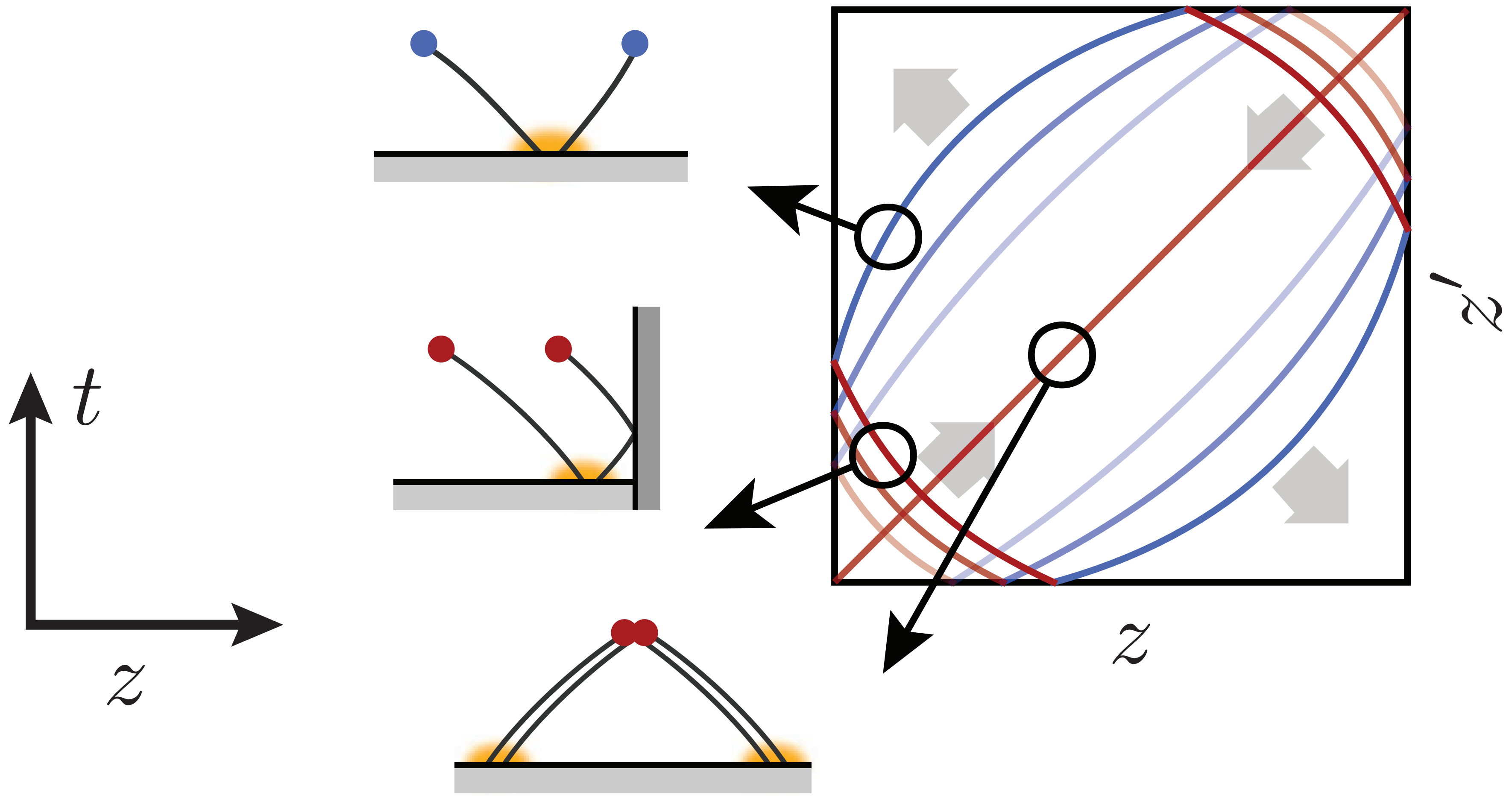
$$\chi^2_{\mathrm{red}} = \frac{1}{N-1}\sum_{i=1}^{N} \frac{(v_{\mathrm{F}}(t_i) - v_{\mathrm{F}}^{\mathrm{theo}}(t_i))^2}{\sigma_i^2}$$

Inhomogeneous background density with walls

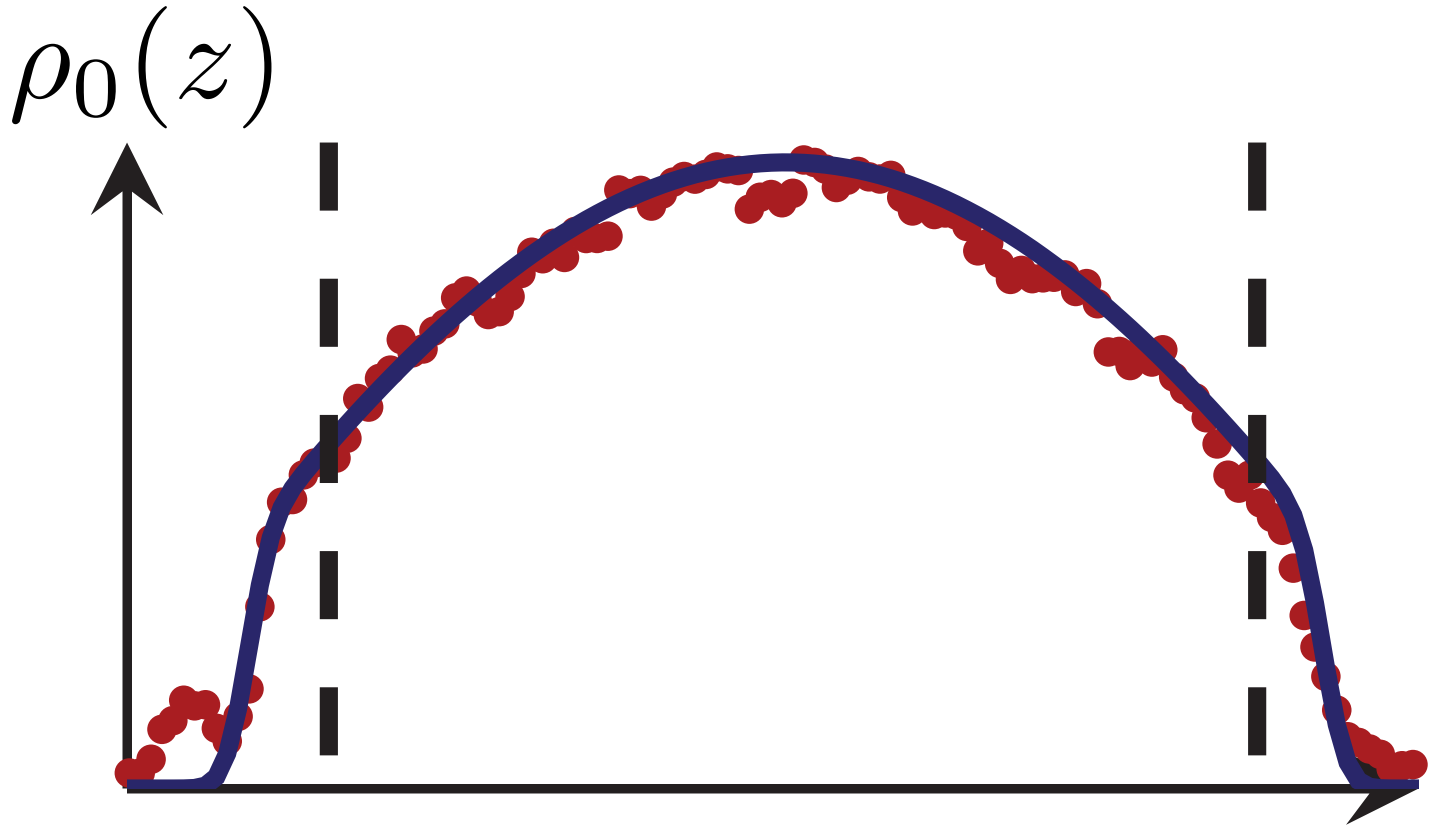


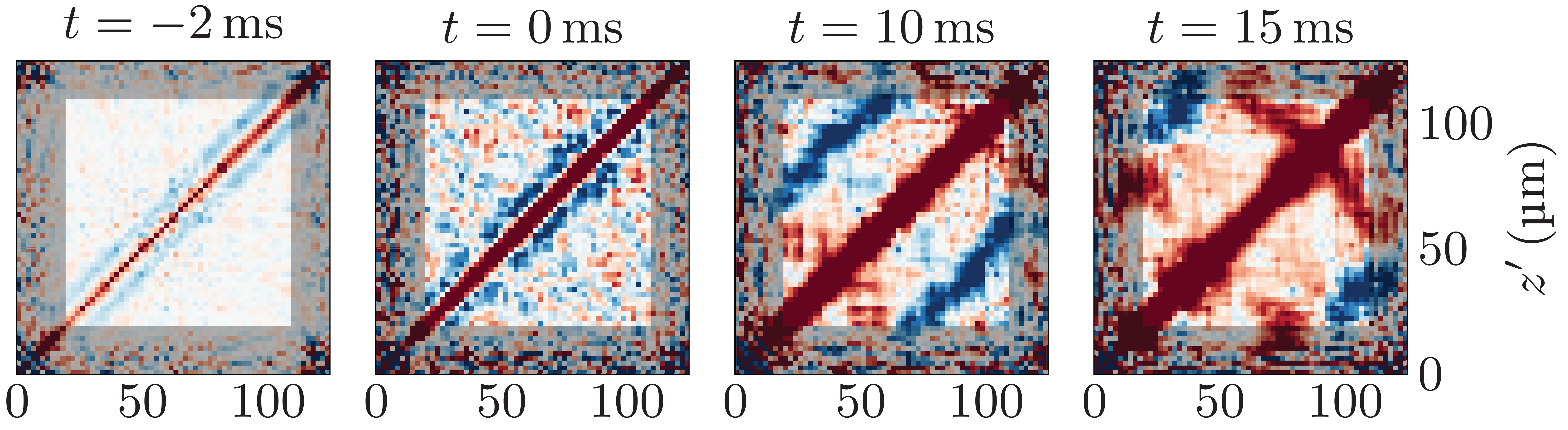


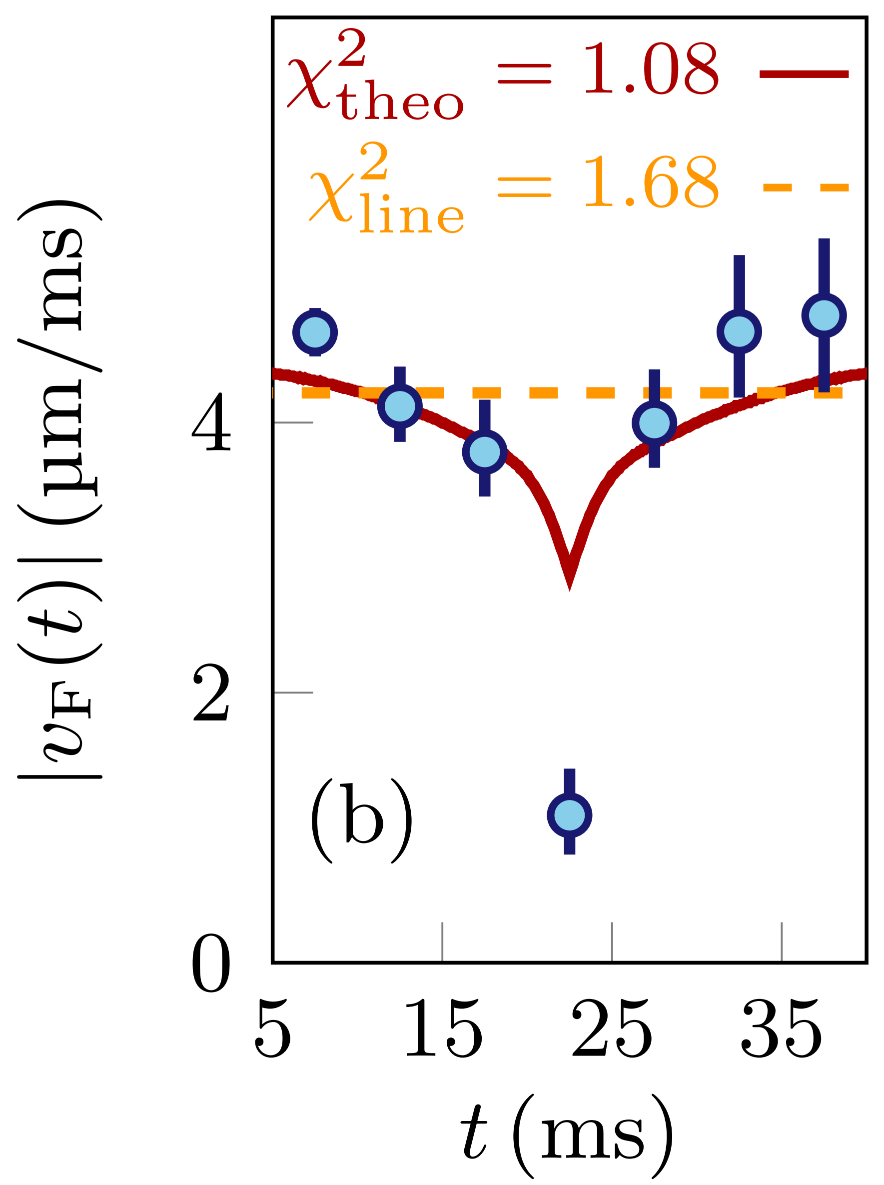


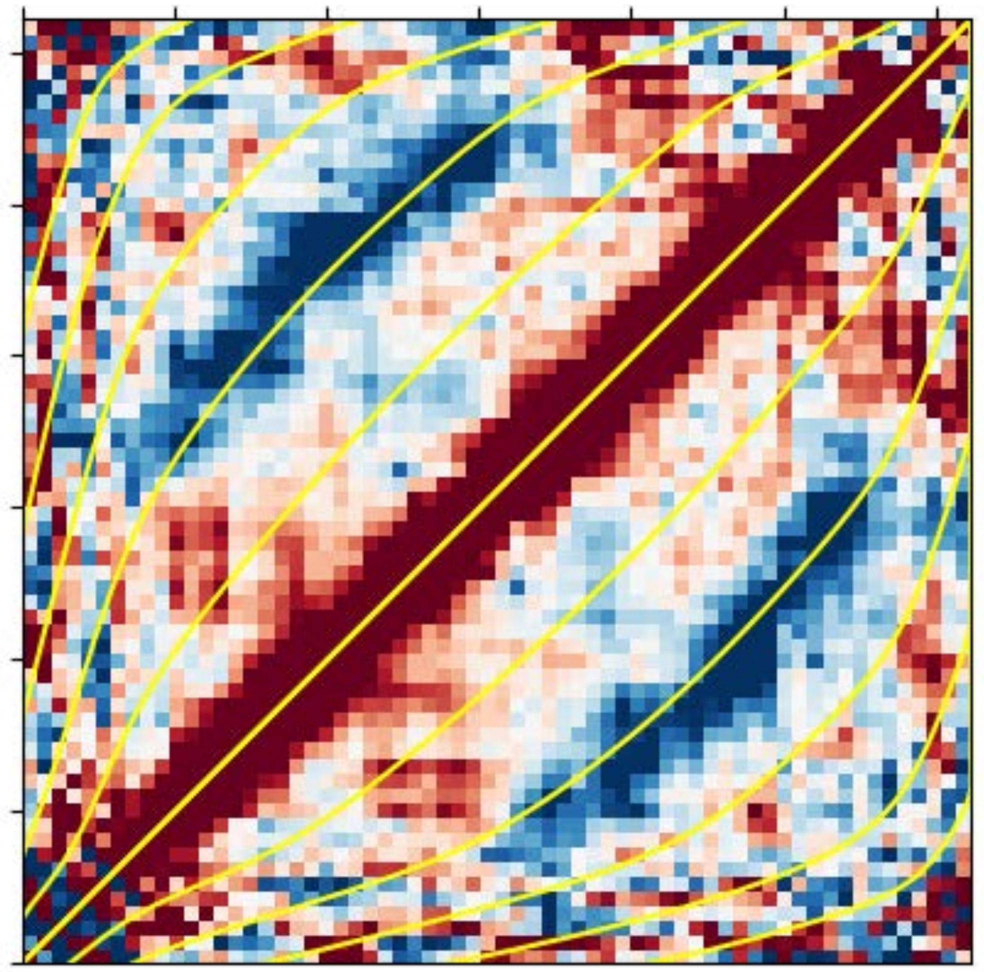


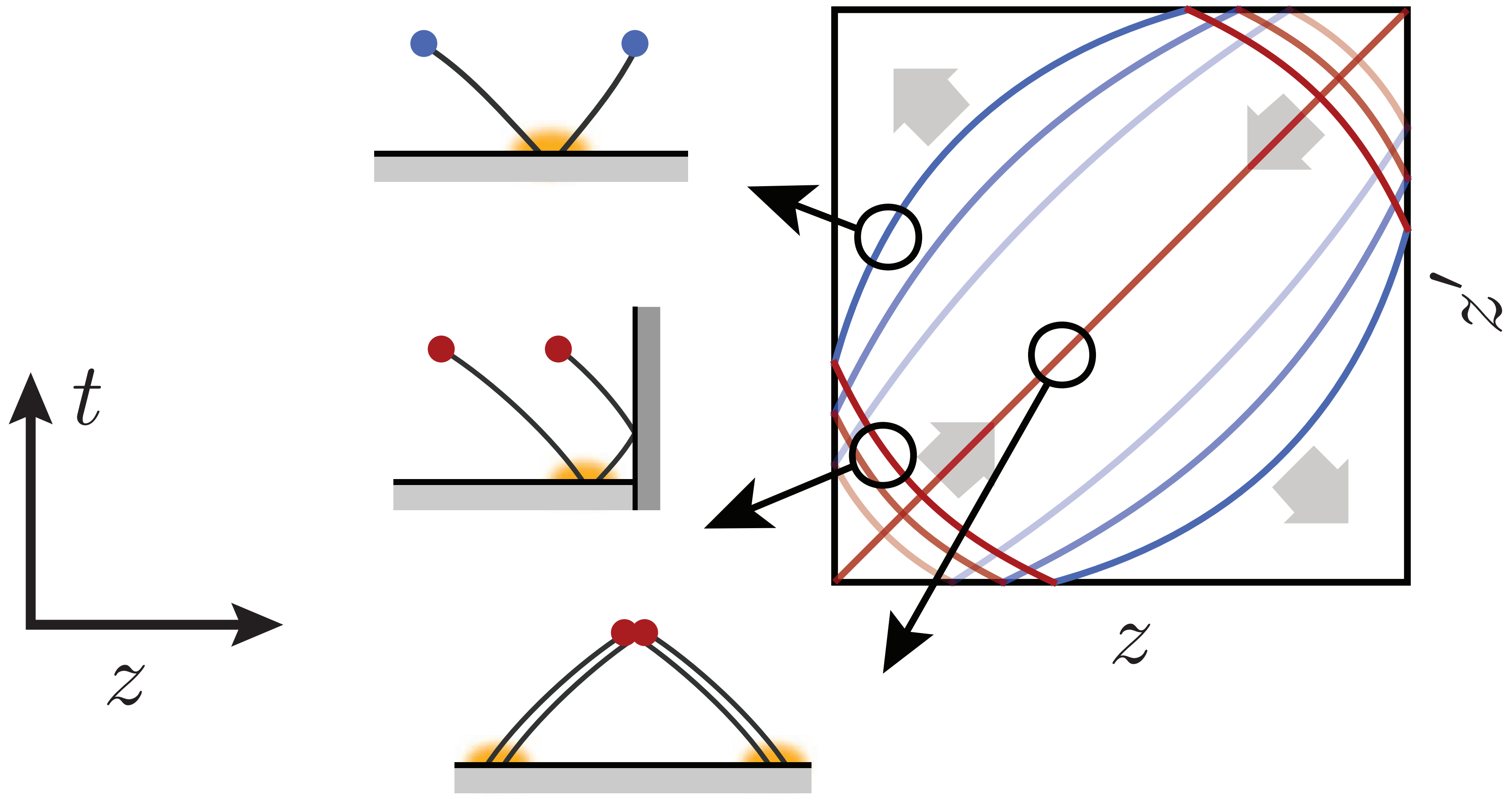
Inhomogeneous background density with walls



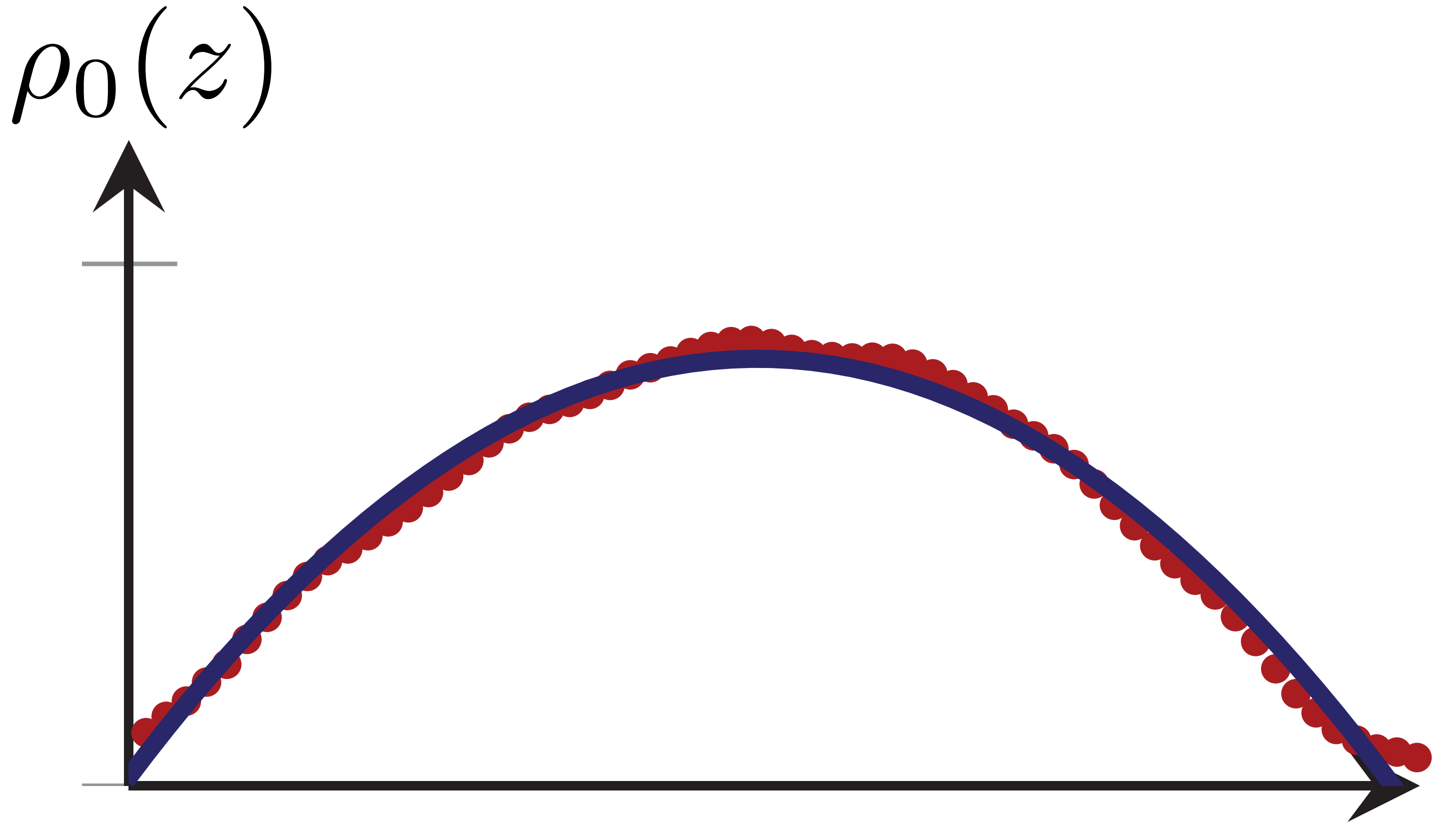


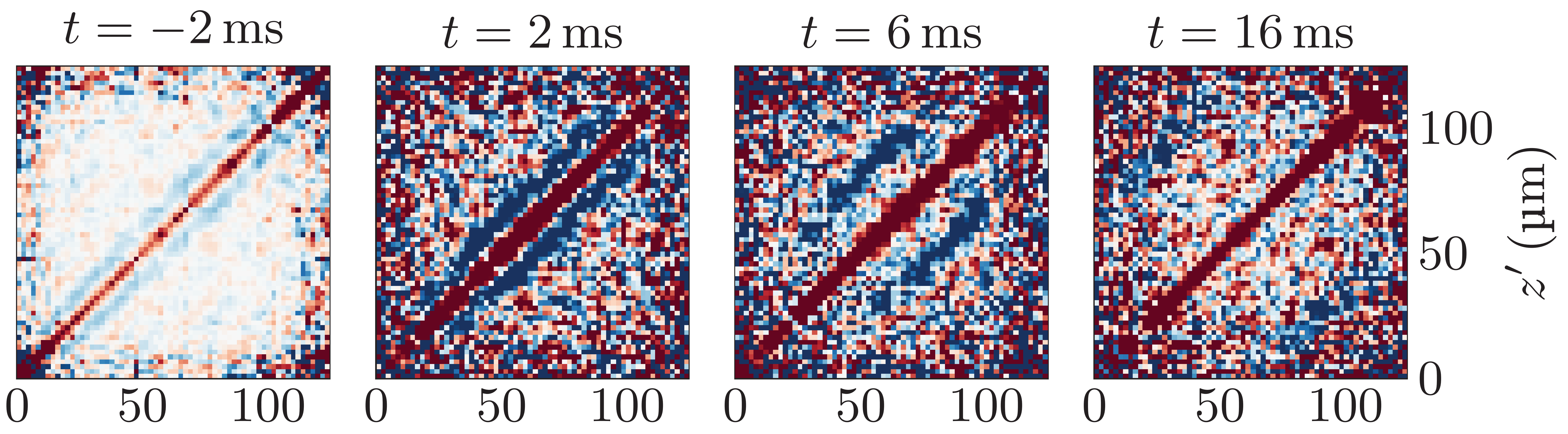


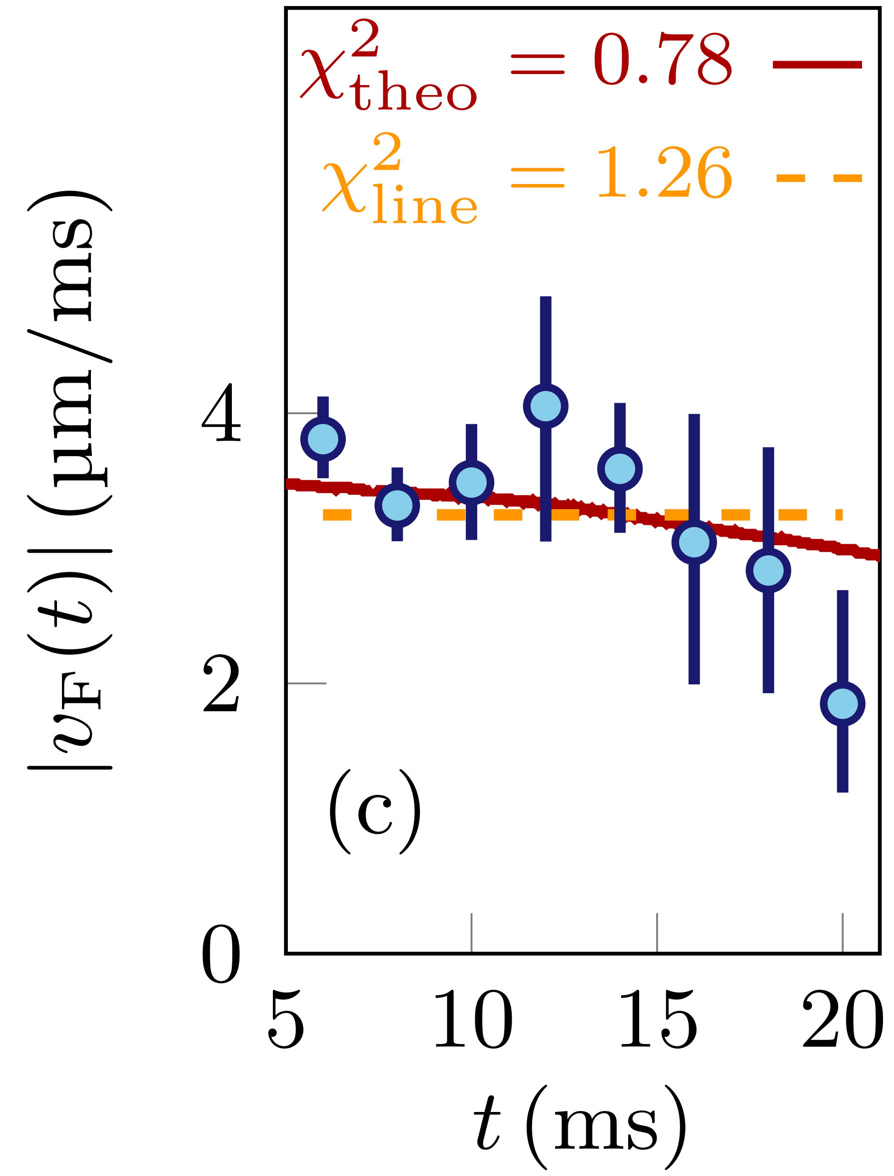


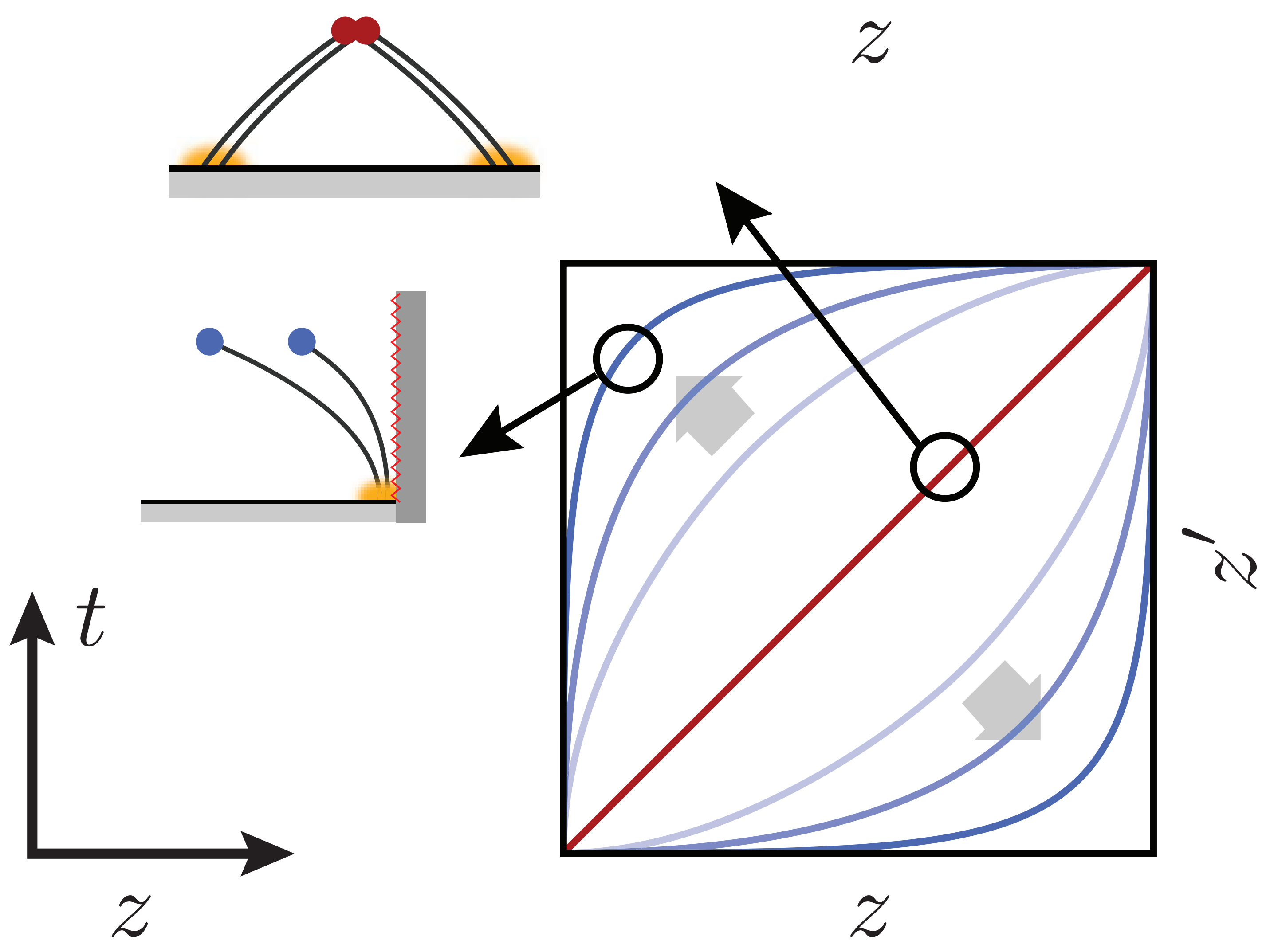


Inhomogeneous background density without walls

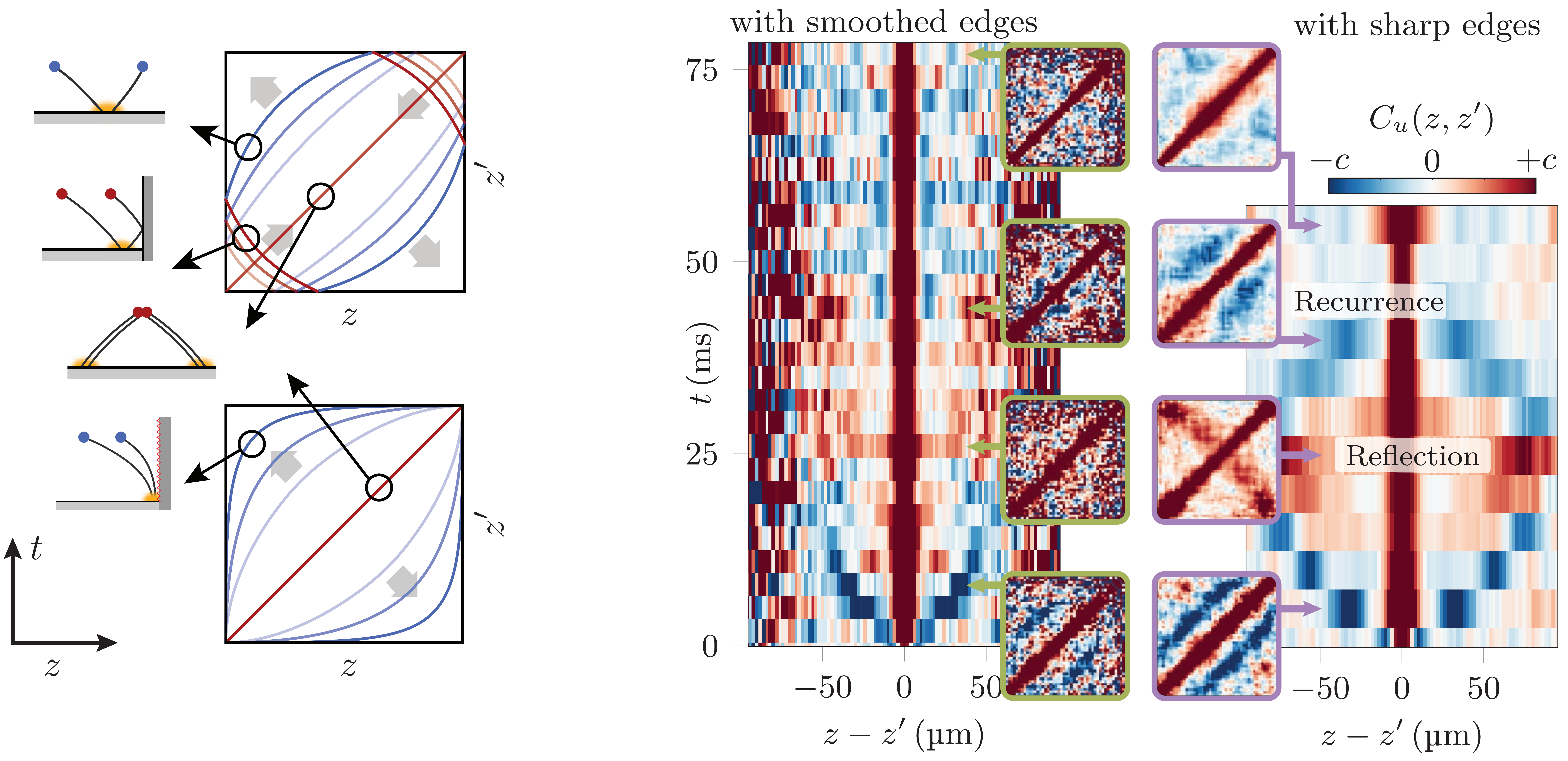




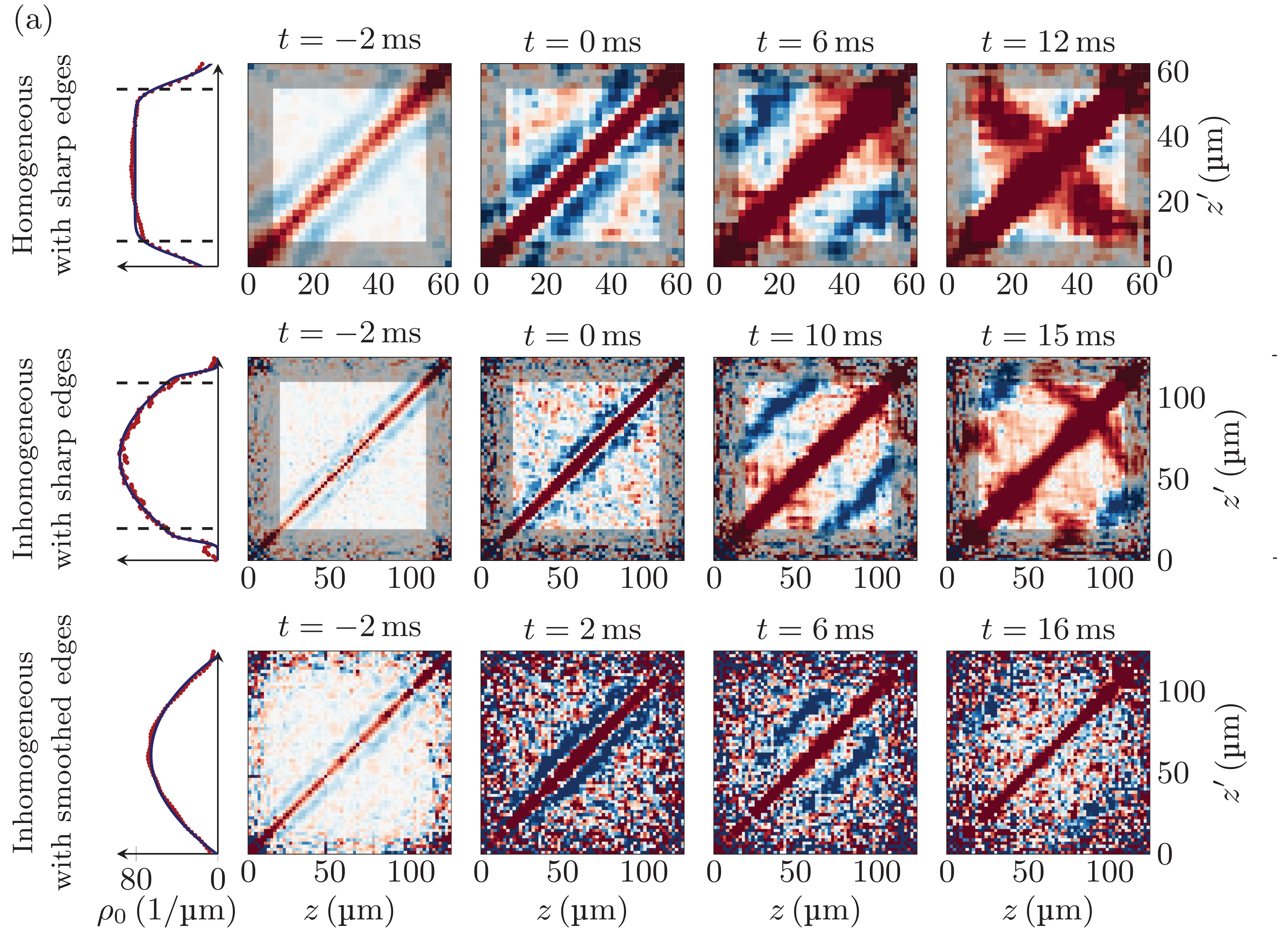




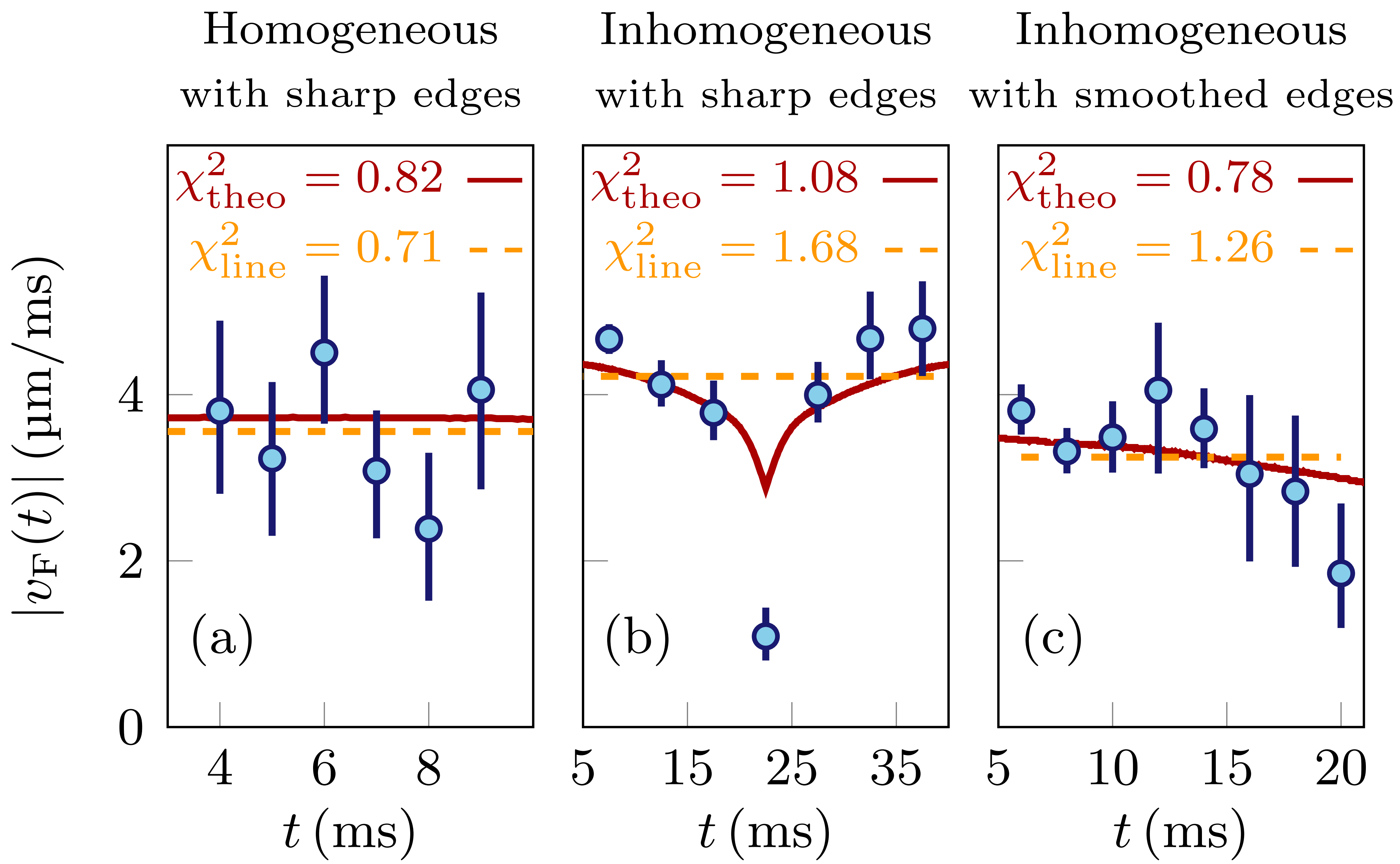
Reflection and recurrence



Summary



(a)
Homogeneous with sharp edges
Inhomogeneous with sharp edges
Inhomogeneous with smoothed edges
t = −2 ms
t = 0 ms
t = 6 ms
t = 12 ms
t = 10 ms
t = 15 ms
t = 2 ms
t = 16 ms
z′ (μm)
ρ0 (1/μm)
z (μm)



Homogeneous with sharp edges
Inhomogeneous with sharp edges
Inhomogeneous with smoothed edges
|vF(t)| (μm/ms)
χ²theo = 0.82
χ²line = 0.71
χ²theo = 1.08
χ²line = 1.68
χ²theo = 0.78
χ²line = 1.26
(a)
(b)
(c)
t (ms)

Measuring von Neumann entropy and mutual information

- Definition:

$$I(A:B) = S_A + S_B - S_{A\cup B}$$

von Neumann entropy for subsystem A

$$S_A = -\mathrm{Tr}(\rho_A \ln \rho_A) \quad \text{with} \quad \rho_A = -\mathrm{Tr}_B(\rho_{A\cup B})$$

Gluza et al. Nat Com Phys (2020)

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- Covariance matrix

Gluza et al. Nat Com Phys (2020)

$$\Gamma(z,z') = \begin{pmatrix} \langle \phi(z)\phi(z')\rangle & \langle \phi(z)\delta\rho(z')\rangle \\ \langle \phi(z')\delta\rho(z)\rangle & \langle \delta\rho(z)\delta\rho(z')\rangle \end{pmatrix}$$

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Gluza et al. Nat Com Phys (2020)

Direct measurement

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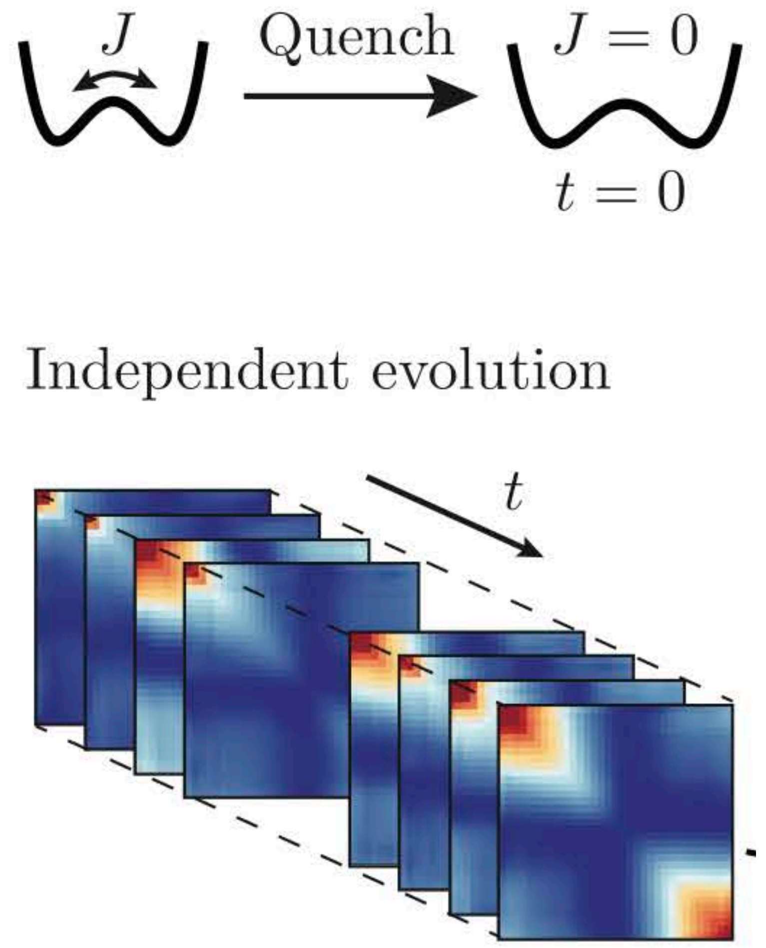
- Covariance matrix

Gluza et al. Nat Com Phys (2020)

Direct measurement: $\langle\phi(z)\phi(z')\rangle$

Tomography: $\langle\phi(z)\delta\rho(z')\rangle$, $\langle\phi(z')\delta\rho(z)\rangle$, $\langle\delta\rho(z)\delta\rho(z')\rangle$

$$\Gamma(z,z') = \begin{pmatrix} \langle\phi(z)\phi(z')\rangle & \langle\phi(z)\delta\rho(z')\rangle \\ \langle\phi(z')\delta\rho(z)\rangle & \langle\delta\rho(z)\delta\rho(z')\rangle \end{pmatrix}$$



von Neumann entropy of Gaussian states

$$S_A = \sum_k (\gamma_k^A + \frac{1}{2}) \ln(\gamma_k^A + \frac{1}{2}) - (\gamma_k^A - \frac{1}{2})(\gamma_k^A - \frac{1}{2})$$

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Eigenvalues of $i \begin{pmatrix} 0 & \mathbb{I} \\ \mathbb{I} & 0 \end{pmatrix} \Gamma^A$

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$$S_A = \sum_k (\gamma_k^A + \frac{1}{2}) \ln(\gamma_k^A + \frac{1}{2}) - (\gamma_k^A - \frac{1}{2})(\gamma_k^A - \frac{1}{2})$$

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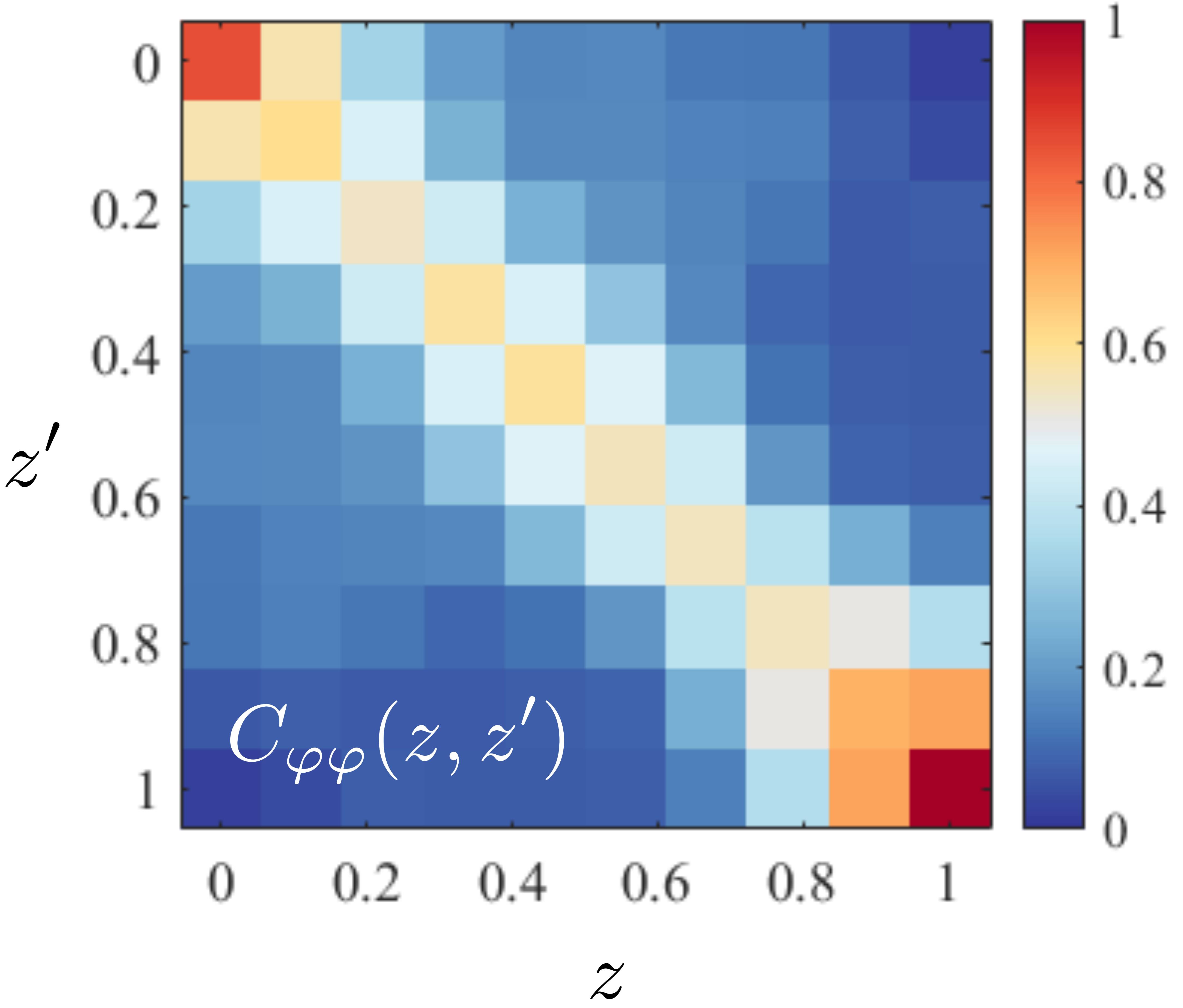

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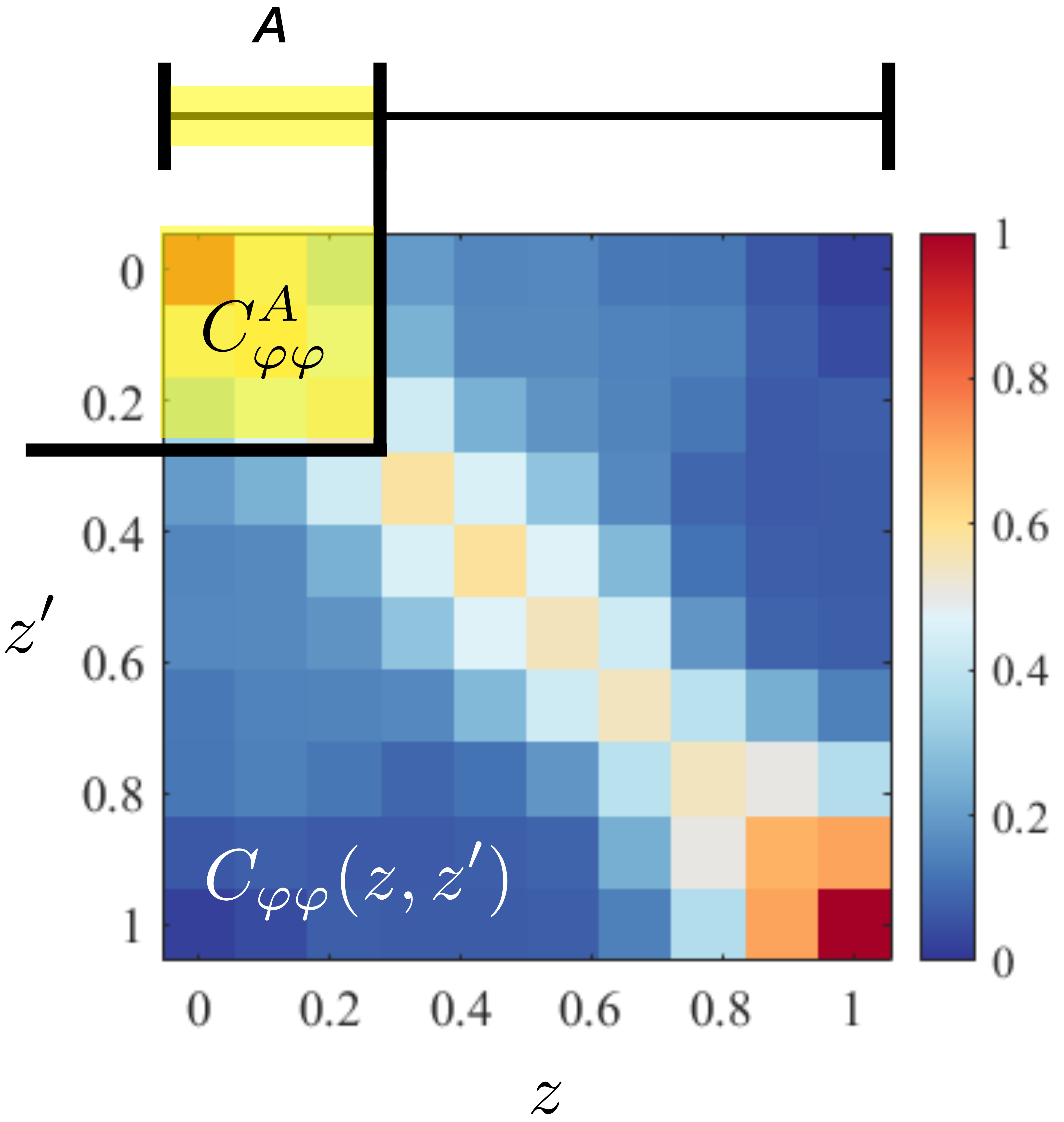
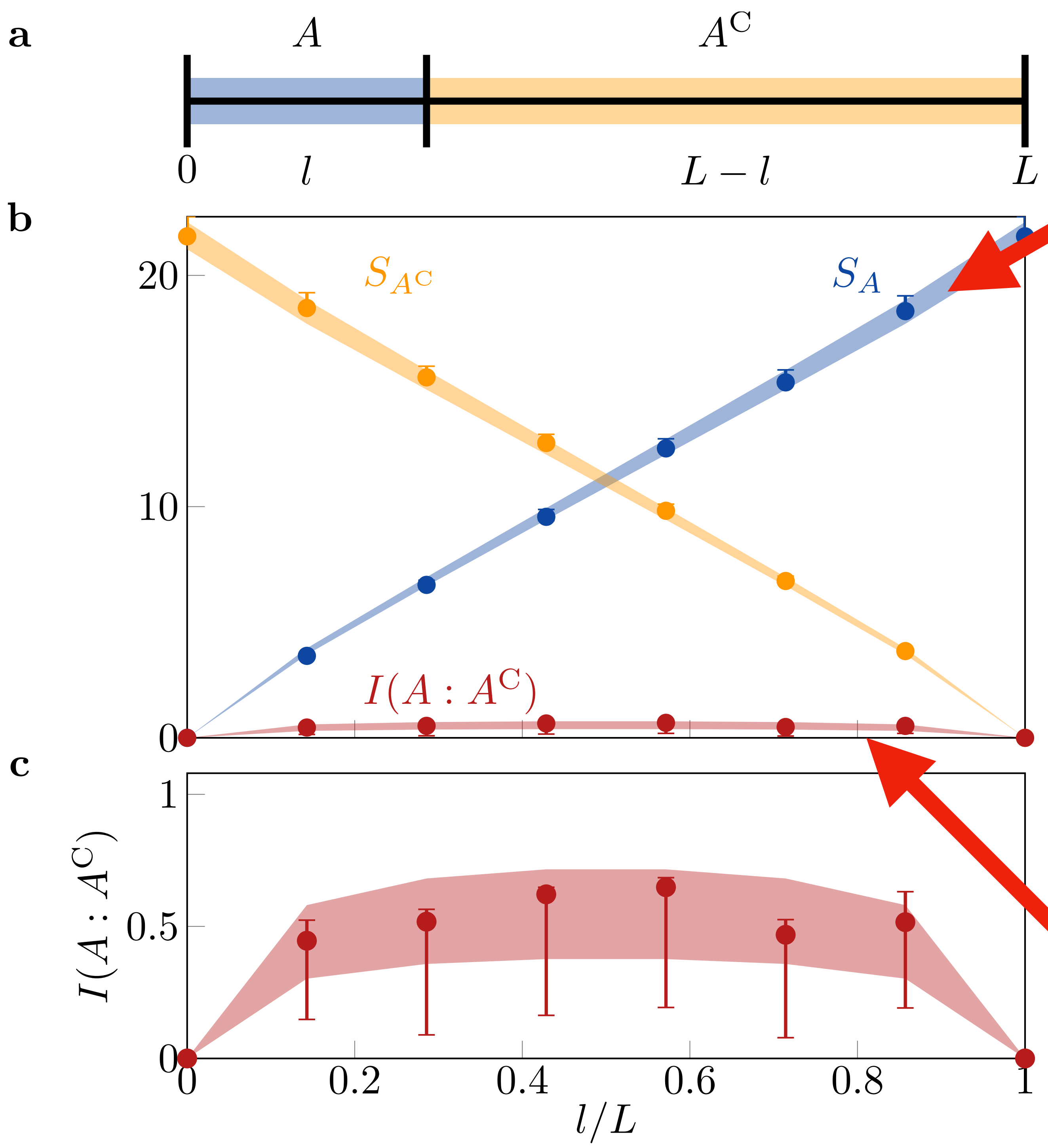


Measuring von Neumann entropy and mutual information

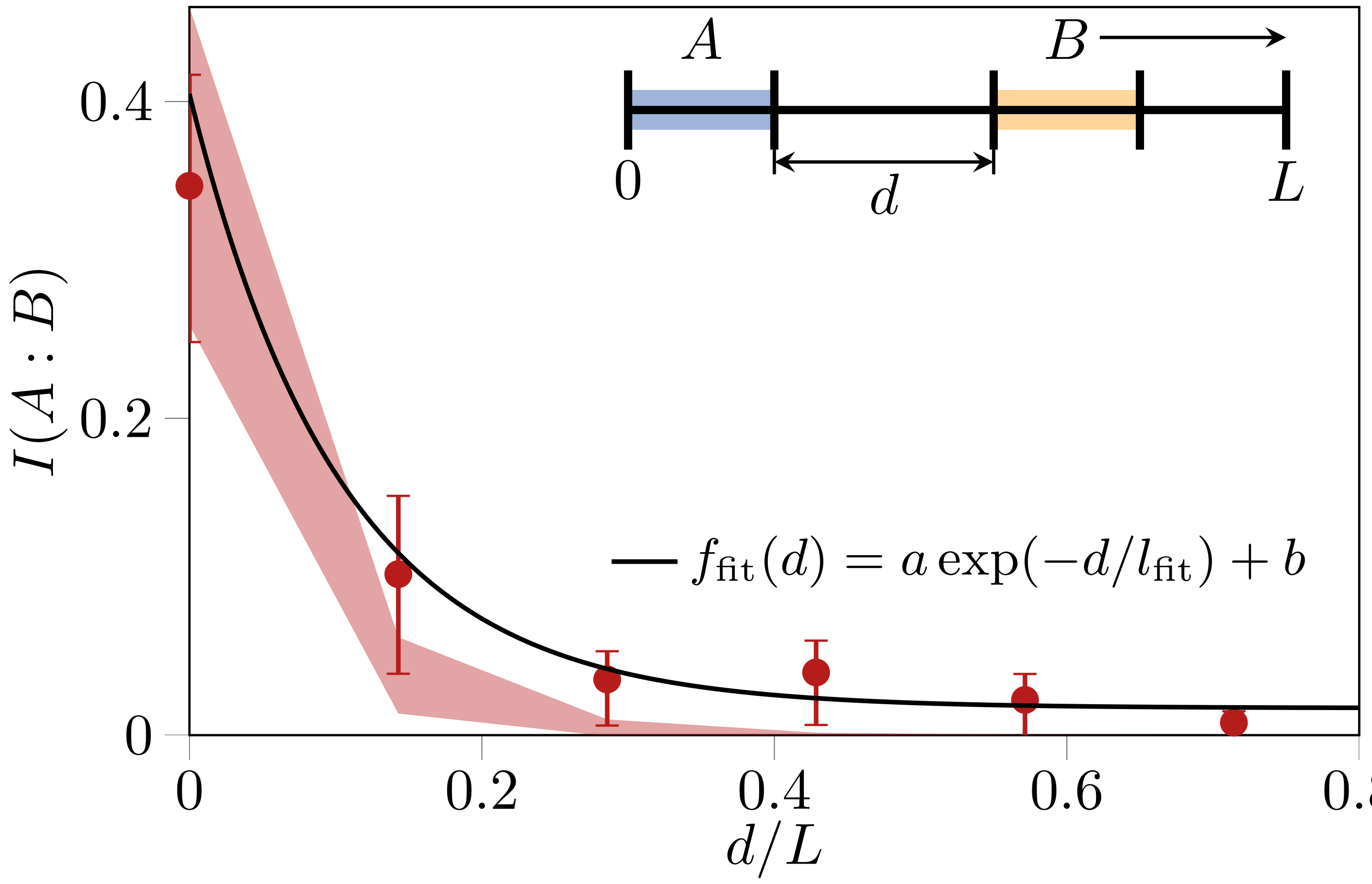
Comparison with theory: Analytical correlations of massive Klein-Gordon model

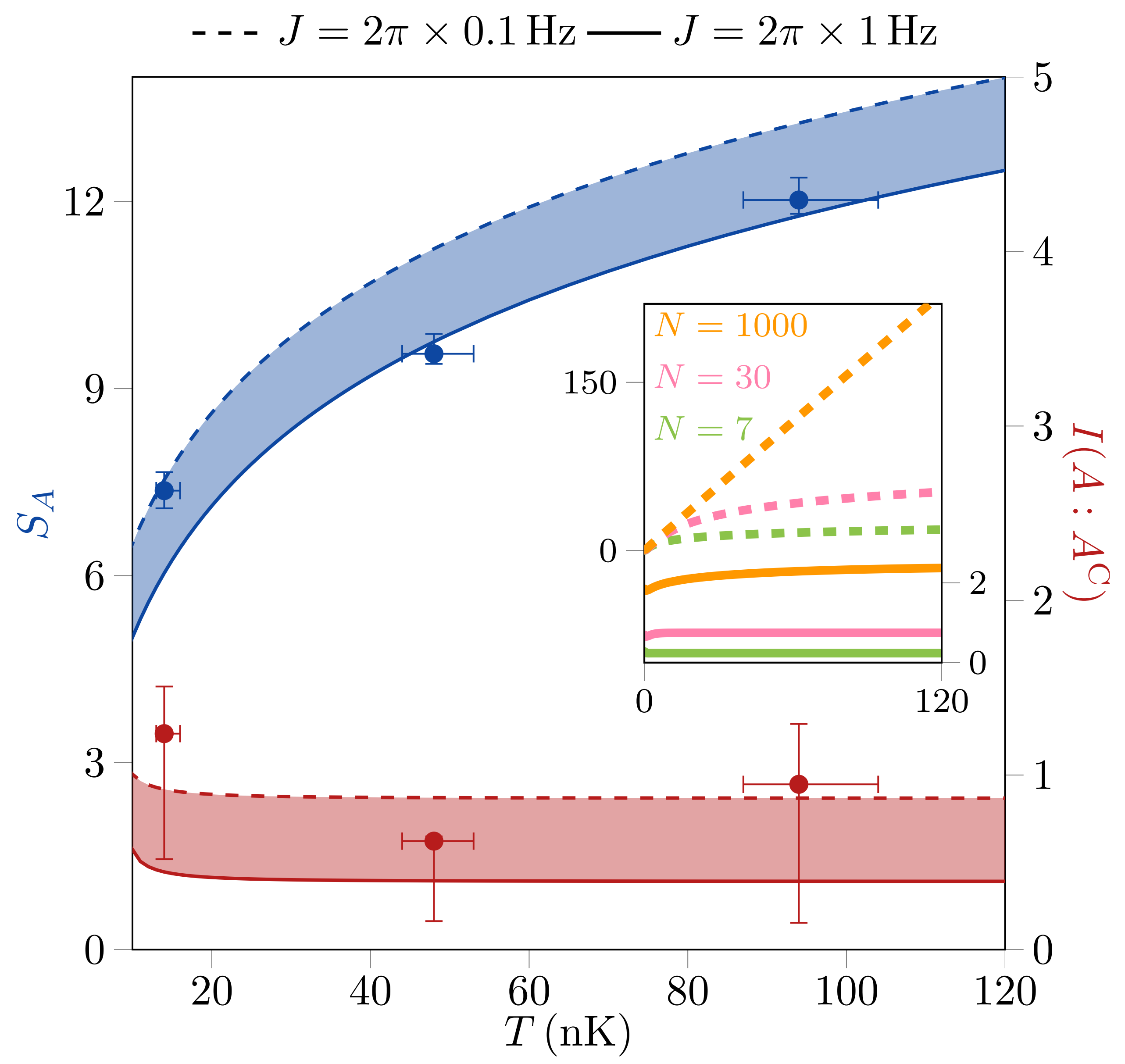
Tajik et al., Nat. Phys.(2023)



Von Neumann entropy: volume law

Mutual information: area law





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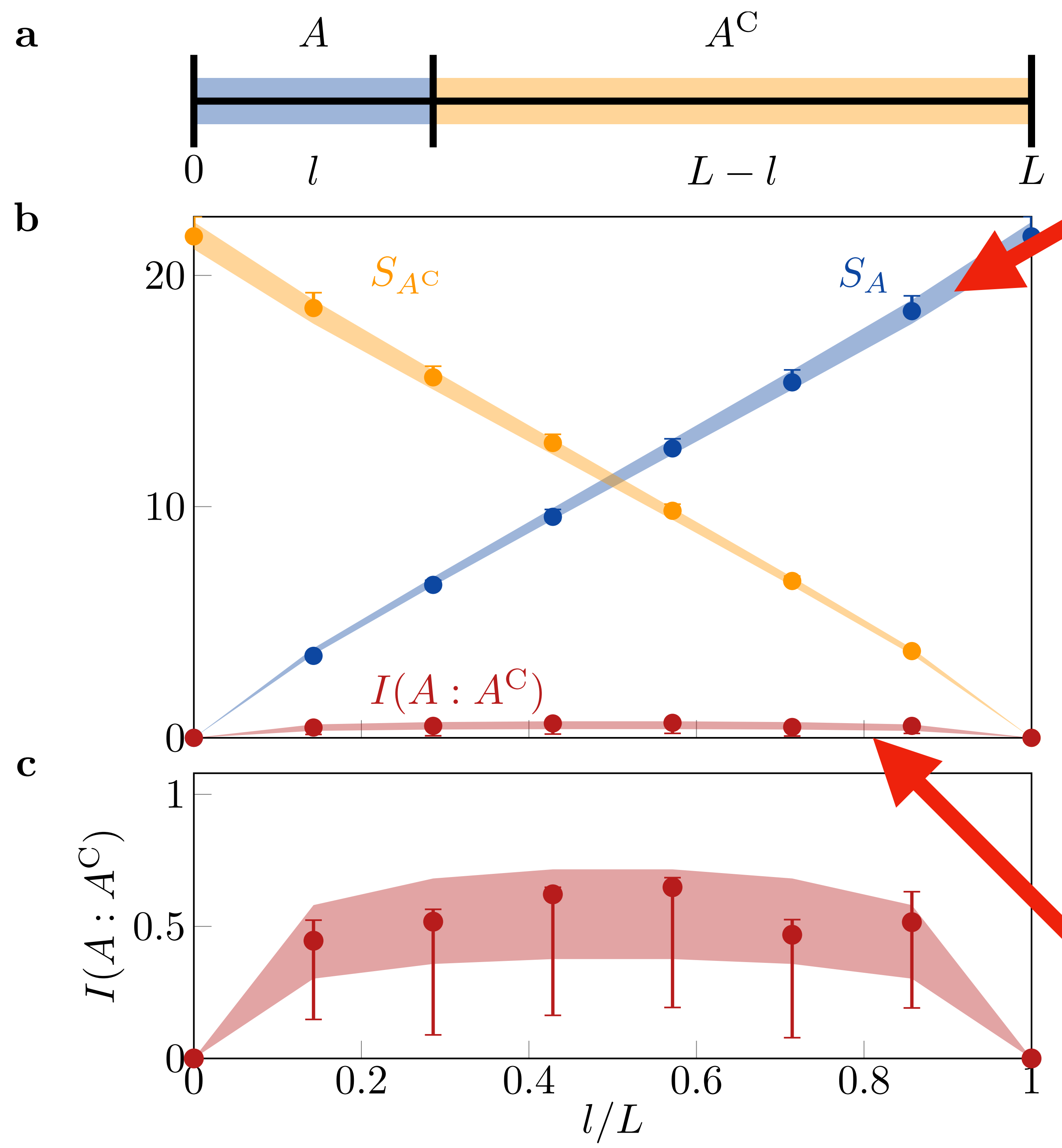
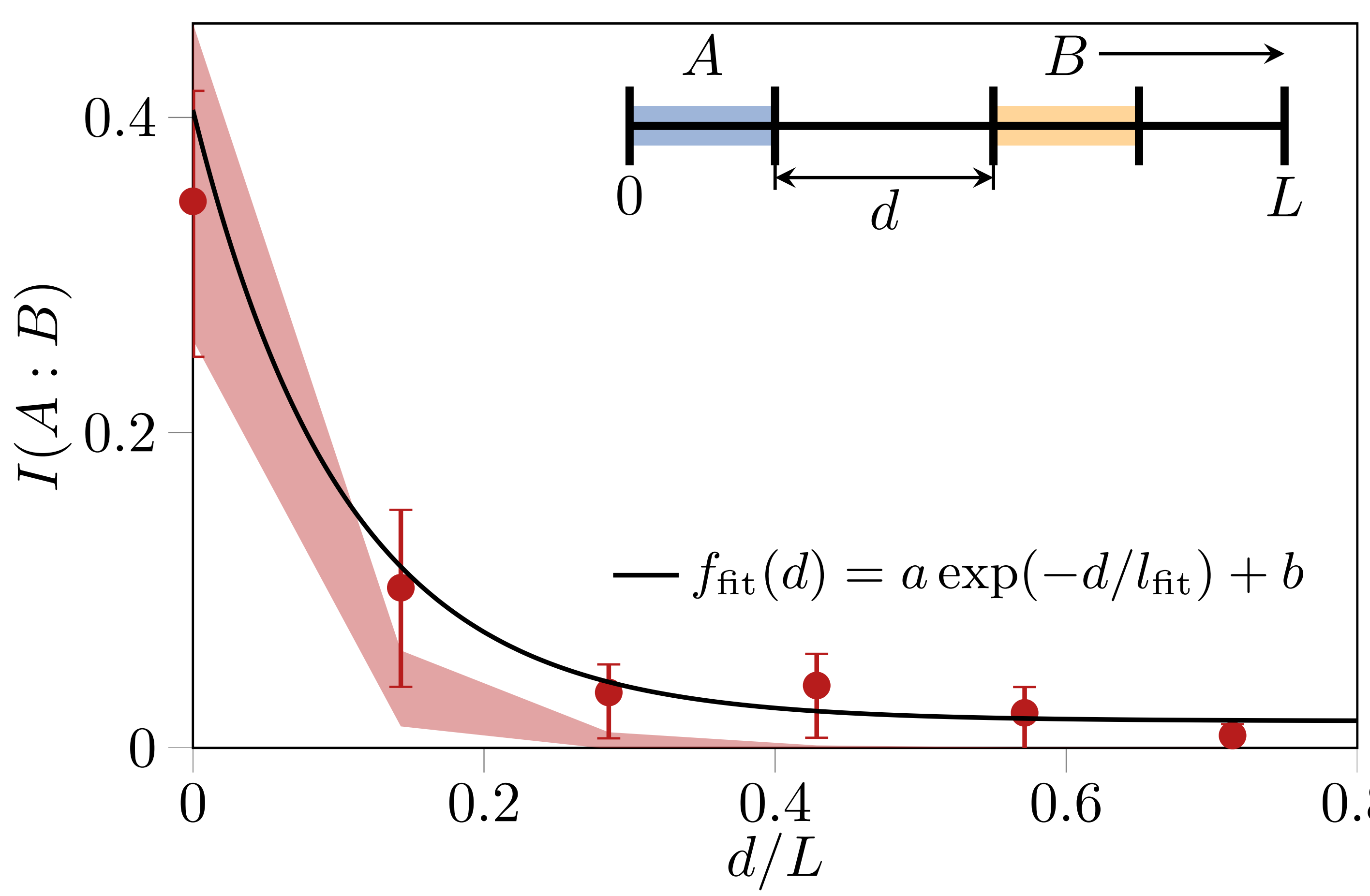


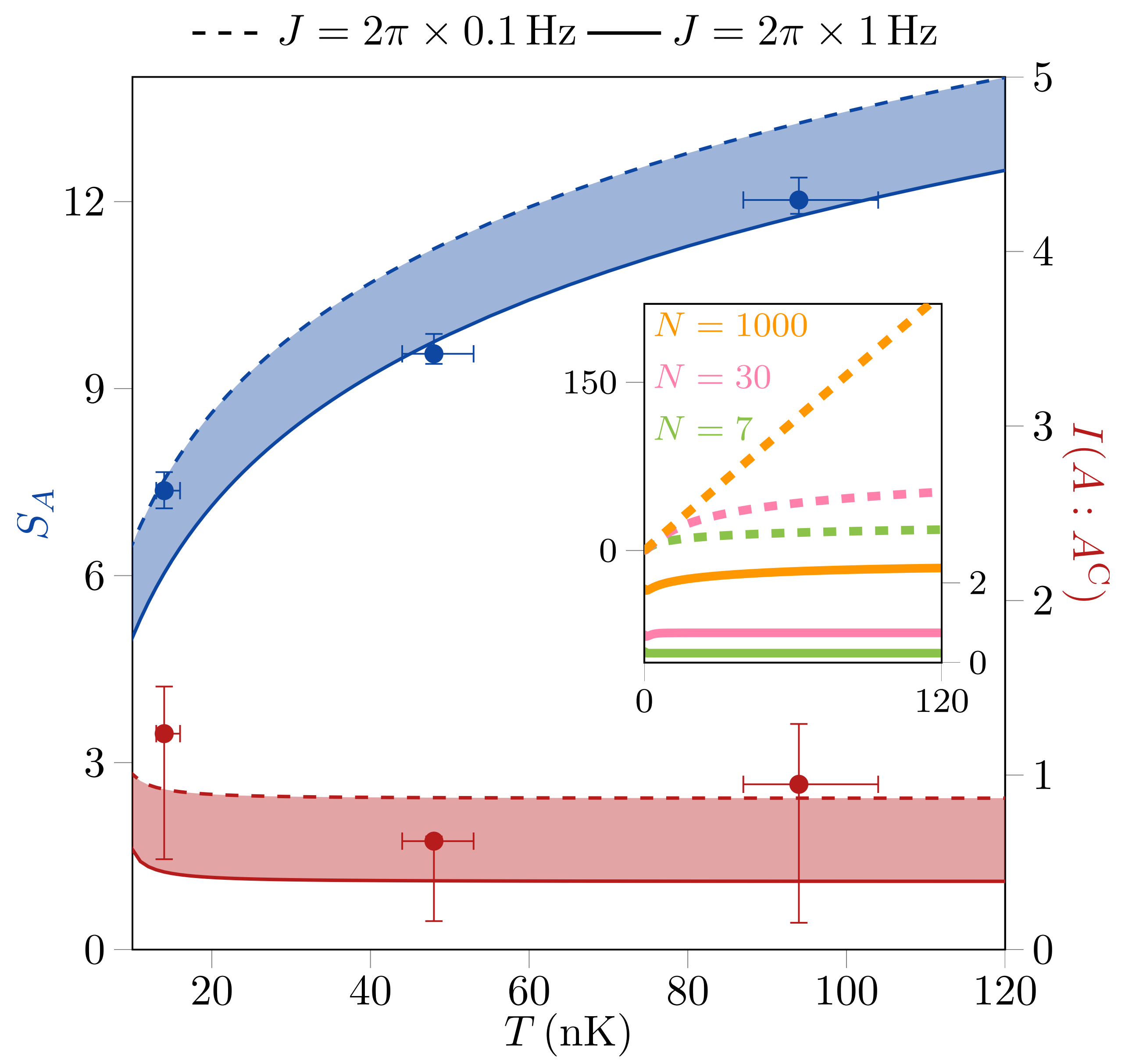
Von Neumann entropy: volume law

Mutual information: area law

Spatial dependence



Decay with separation



Temperature dependence

END