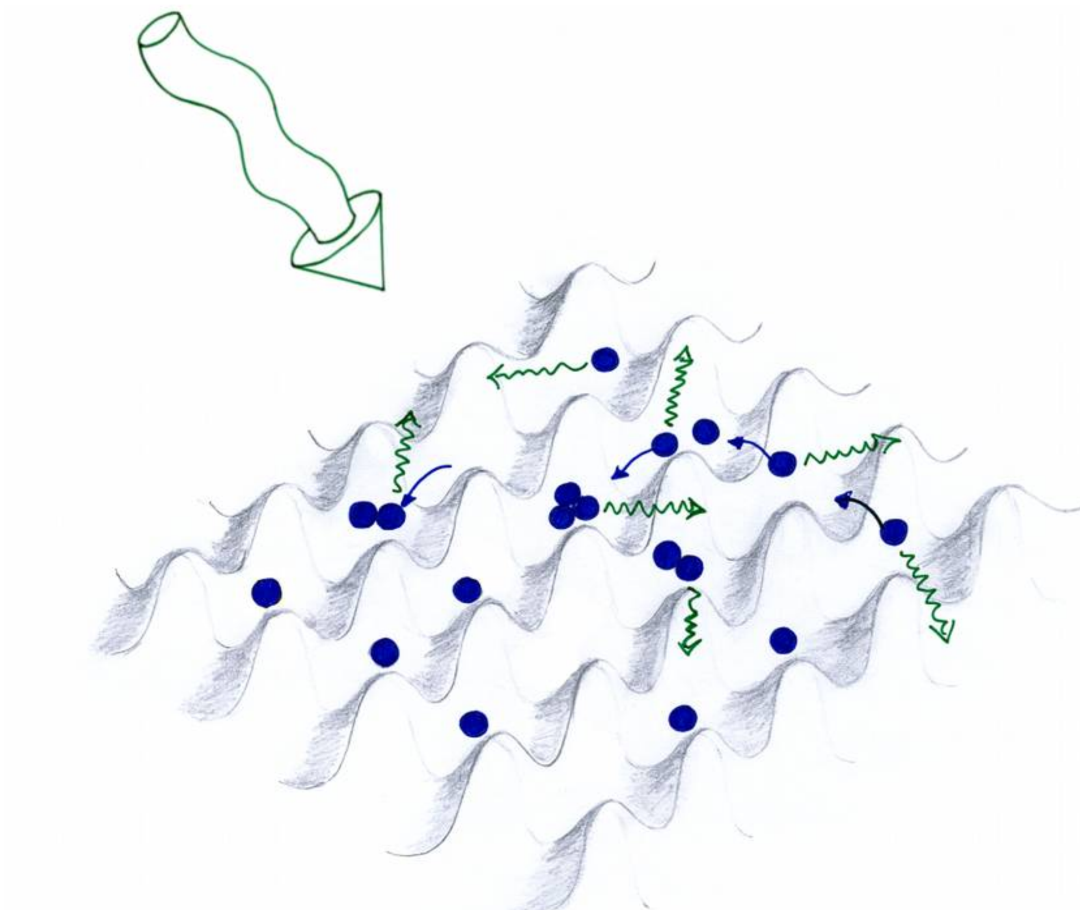
Anomalous momentum diffusion in a dissipative many-body system



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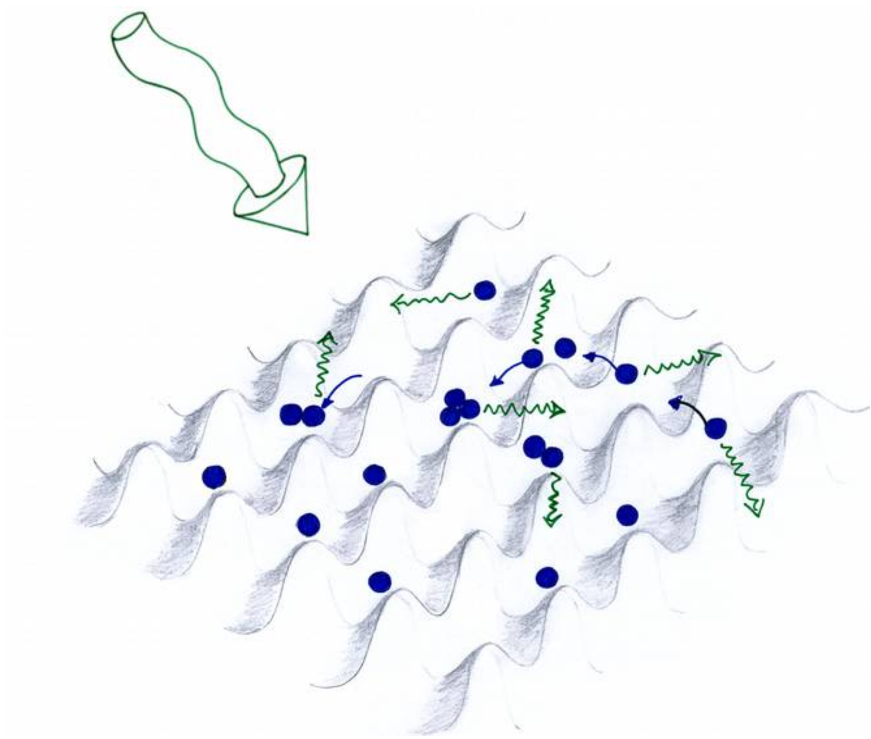

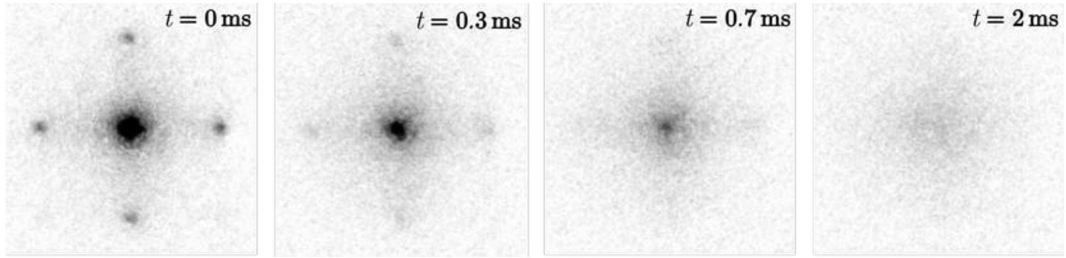

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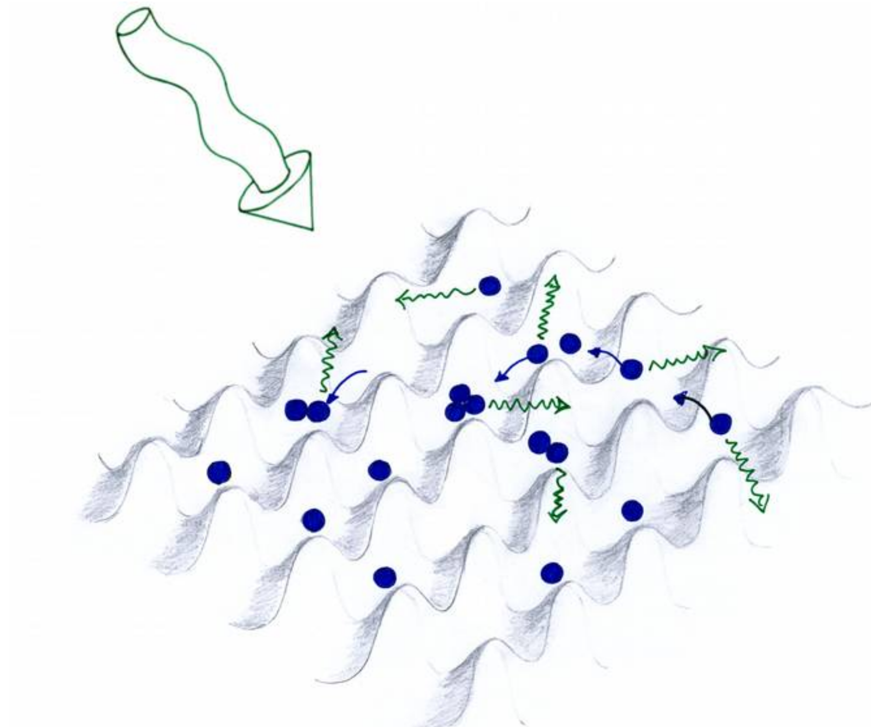
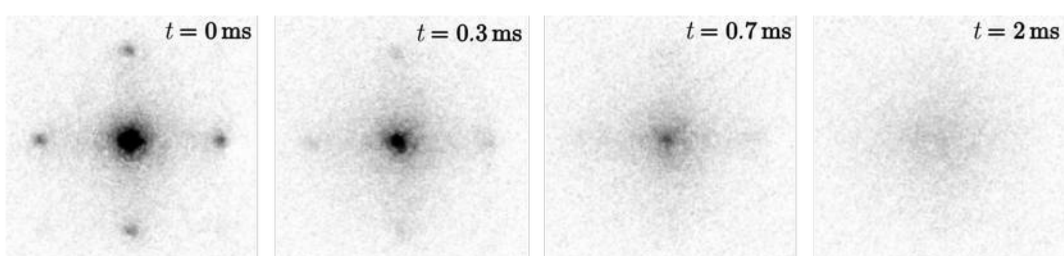


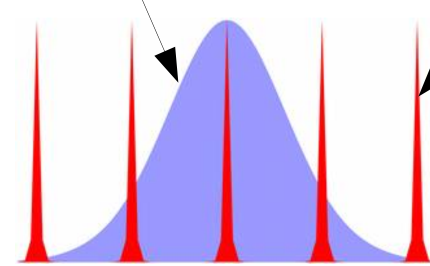
$$\rho^{(1)}(\boldsymbol{r}, \boldsymbol{r'}) = \langle \Psi(\boldsymbol{r}) \Psi^{\dagger}(\boldsymbol{r'}) \rangle$$

$$n(\boldsymbol{k}) \approx \widetilde{w}(\boldsymbol{k}) \times \mathcal{S}(\boldsymbol{k})$$

Form factor

Structure factor





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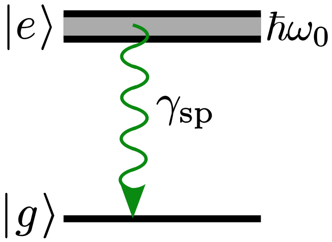
⟨ Spontaneous emission ⟩

SE: coupling to the vacuum electro-magnetic field
random emission directions



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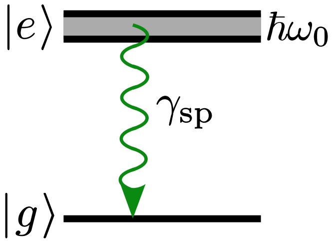

In free space:

→ exponential decay of spatial coherences: $\partial_t \rho(\boldsymbol{r}, \boldsymbol{r}') \propto -|\boldsymbol{r} - \boldsymbol{r}'|^2 \rho(\boldsymbol{r}, \boldsymbol{r}')$

→ Brownian diffusion: $\Delta p \propto \sqrt{t}$

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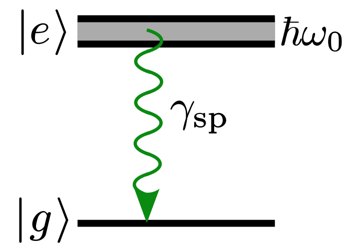

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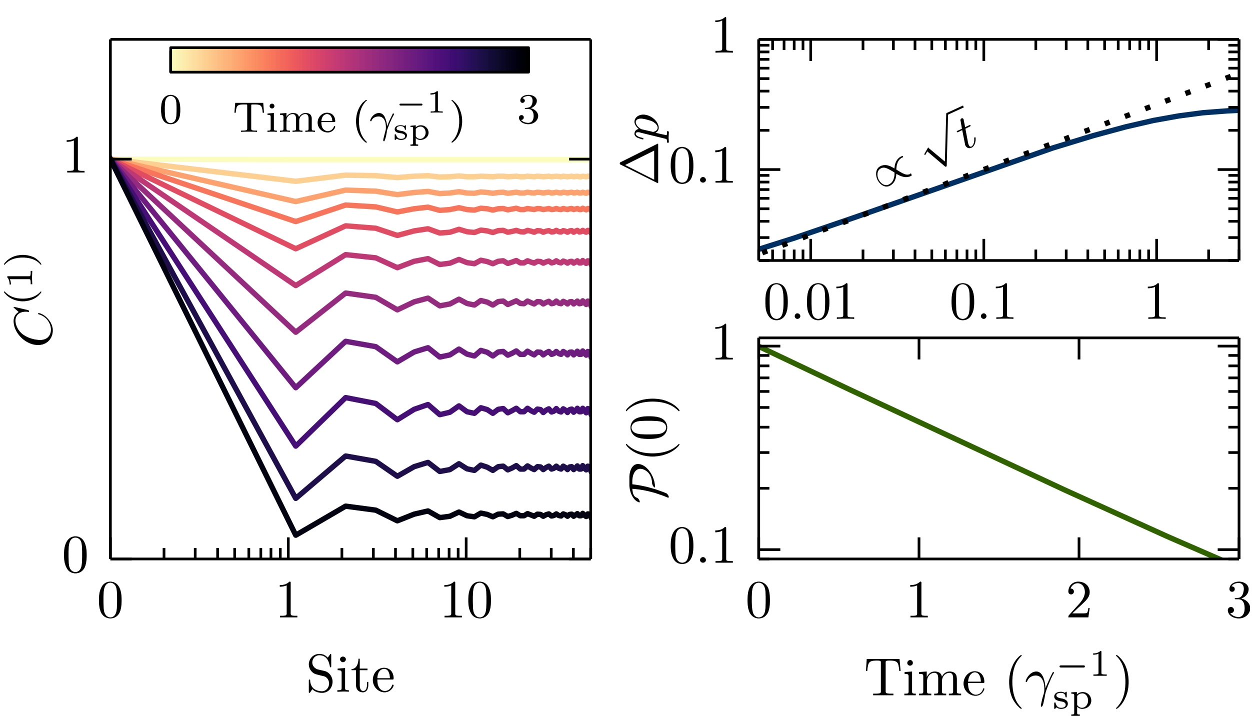
In an optical lattice:

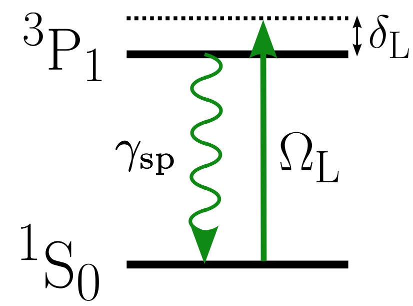
Initial delocalized state k=0

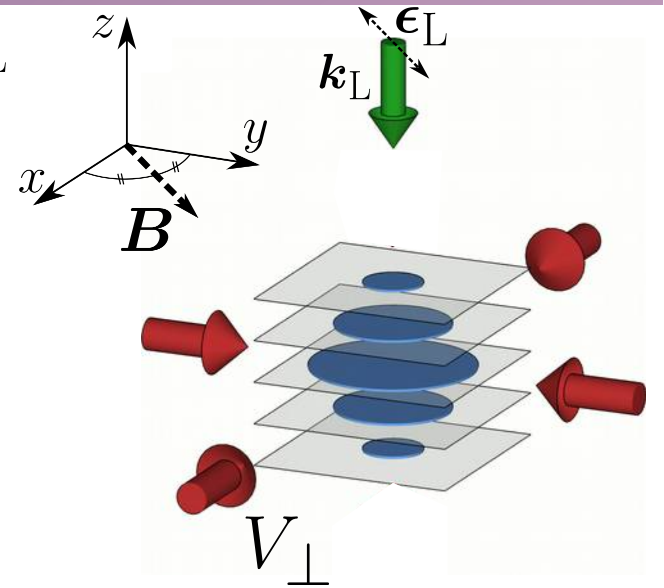


⟨ Dissipation in optical lattices ⟩

→ Control of spontaneous emission on the intercombination transition

Waist: 1 mm
Tunable power
→ spontaneous emission rate
→ saturation parameter s≪1





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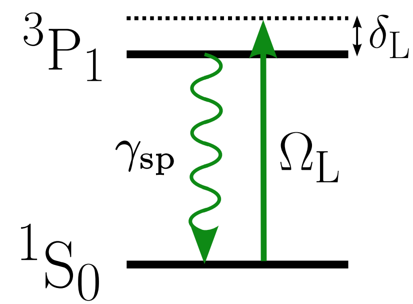
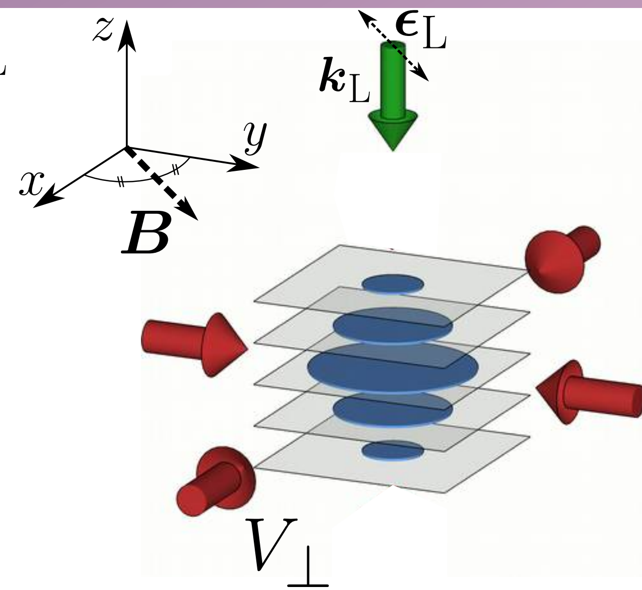




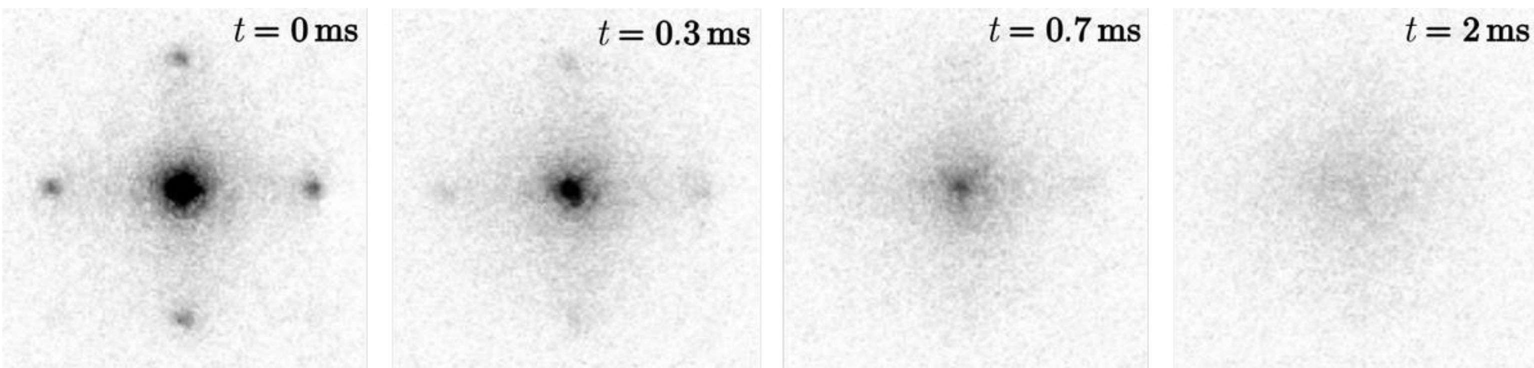
Waist: 1 mm

Tunable power

→ spontaneous emission rate

→ saturation parameter s≪1

→ Time-of-flight reveals momentum distribution



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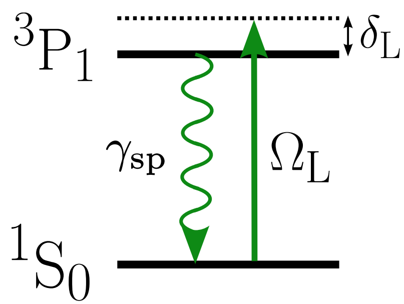

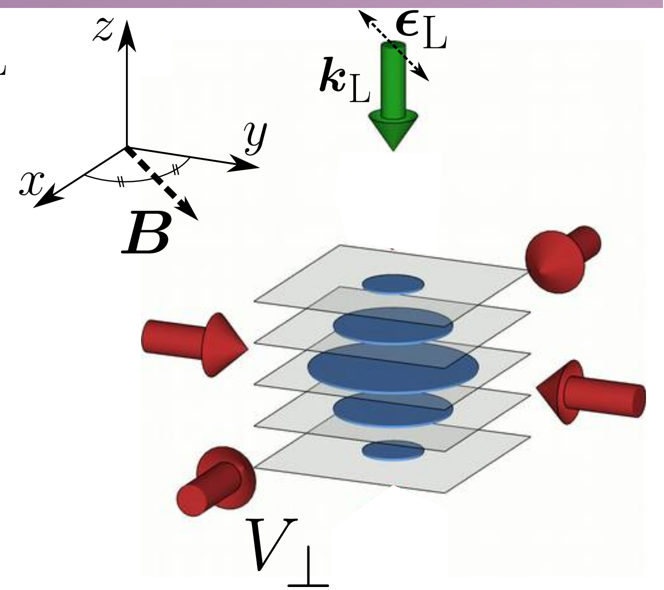

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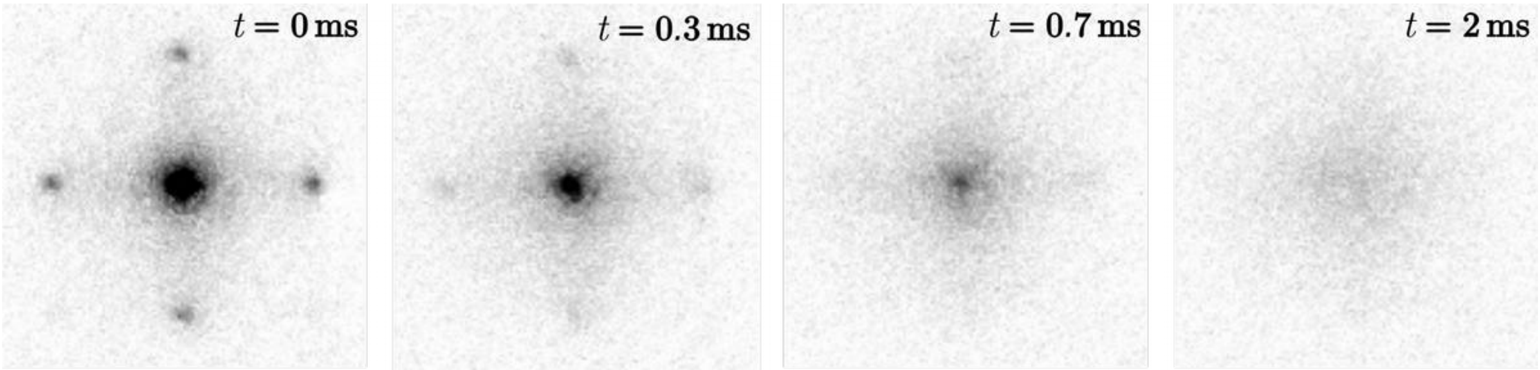
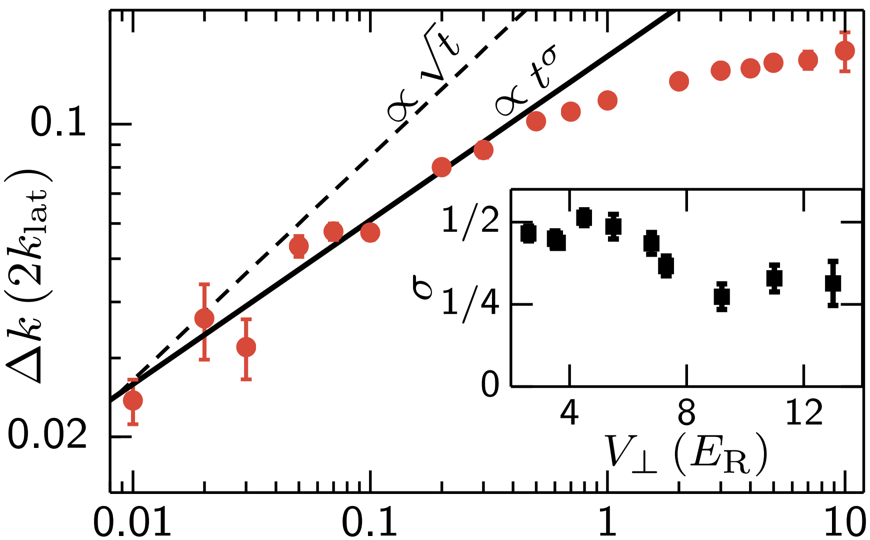


- momentum width
- condensate fraction

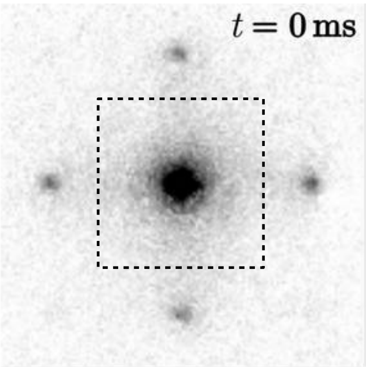
⟨ Bare observables ⟩

→ Momentum distribution:



$V_\perp = 7.3\,E_{\rm R}$

$$\gamma_{\rm sp} \approx 500\,{\rm s}^{-1}$$
$$\gamma_{\rm sp} \lesssim U/\hbar$$



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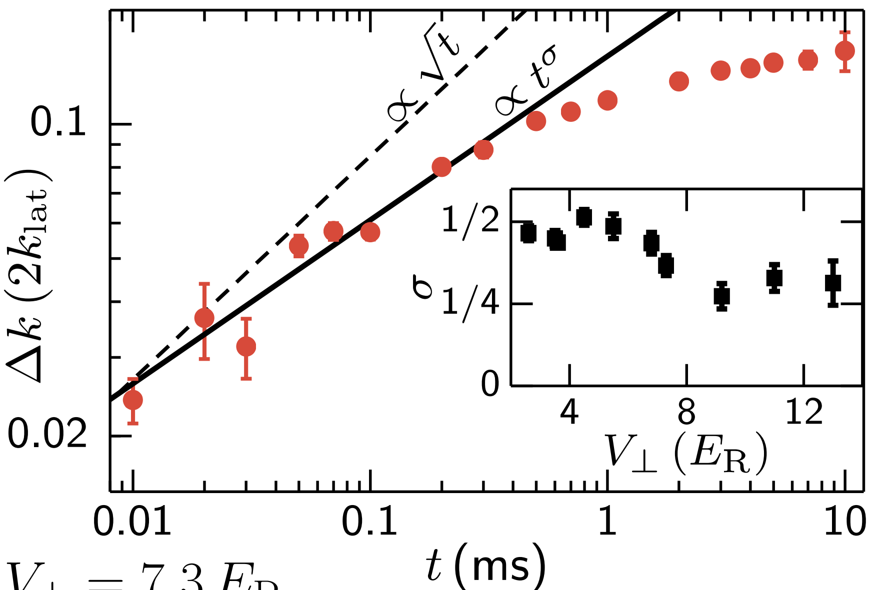
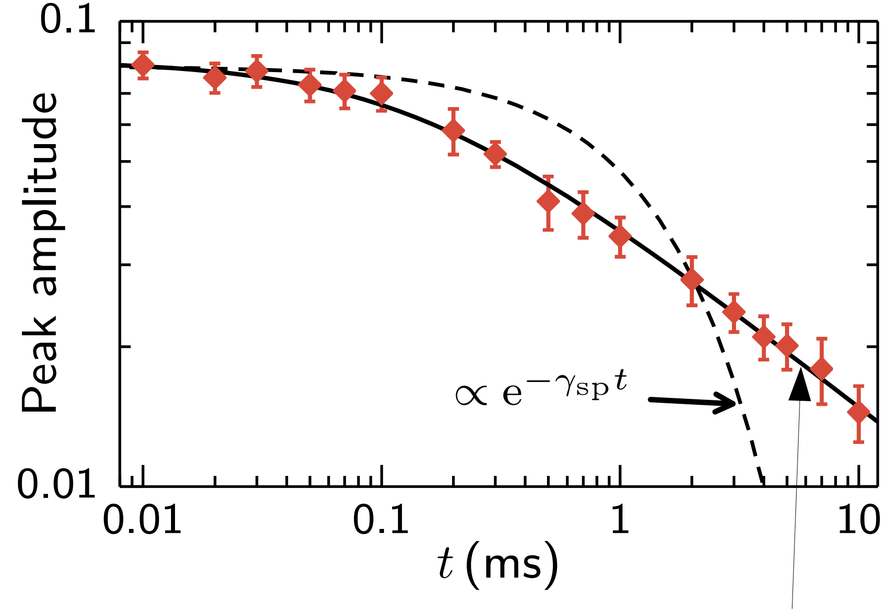


$V_\perp = 7.3\,E_{\mathrm{R}}$

→ Condensed fraction:



$$\propto \frac{1}{(1+x)^{\alpha}}$$

$$\gamma_{\mathrm{sp}} \approx 500\,\mathrm{s}^{-1}$$

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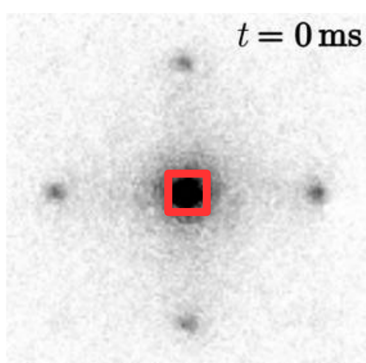

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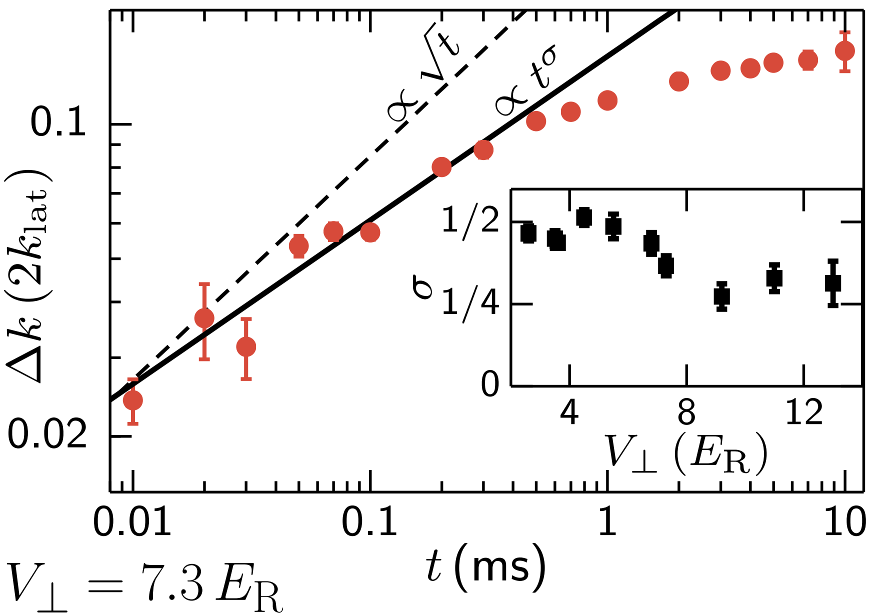

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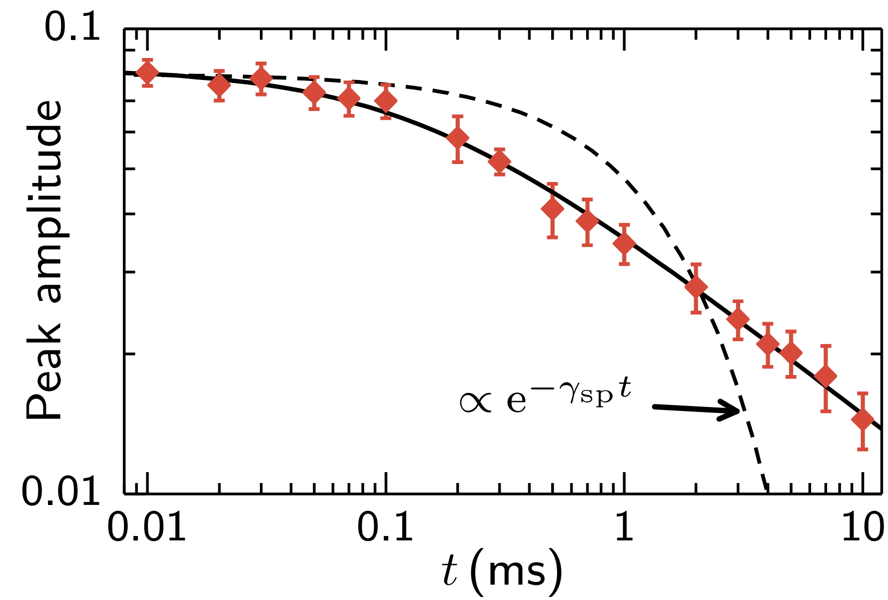

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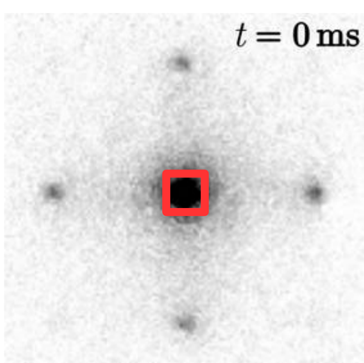
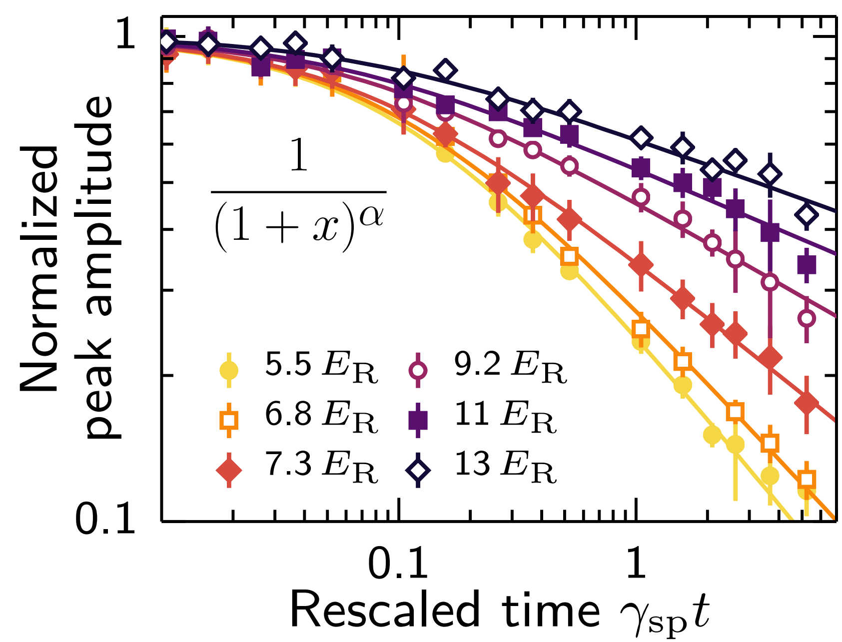
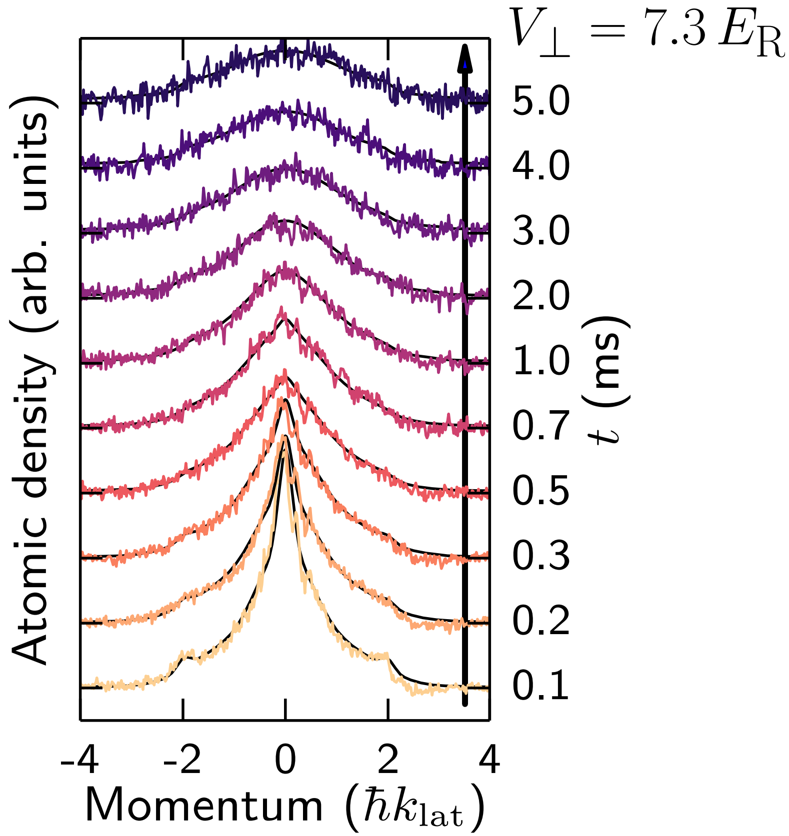




⟨ Fitted coherences ⟩



$$\mathcal{S}(\boldsymbol{k}) = \sum_{i,j} \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{r}_i - \boldsymbol{r}_j)} \langle \hat{a}_i^\dagger \hat{a}_j \rangle$$
$$\approx N_\mathrm{at} + \sum_i C_\mathrm{nn} \left[2\cos(k_x d) + 2\cos(k_y d)\right]$$

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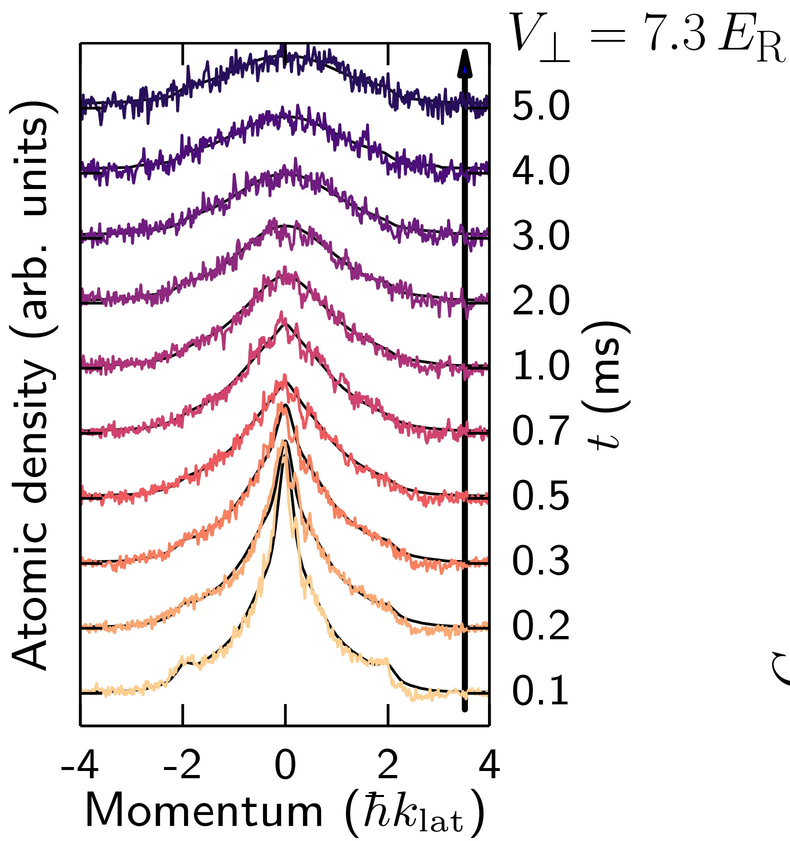

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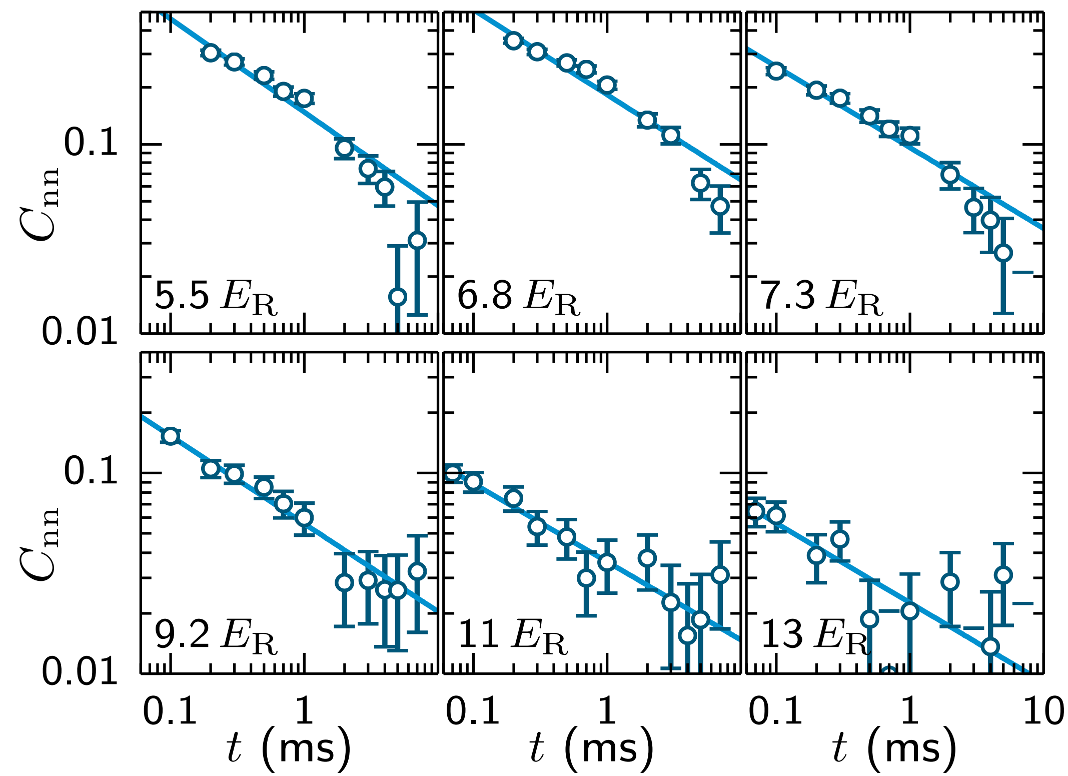

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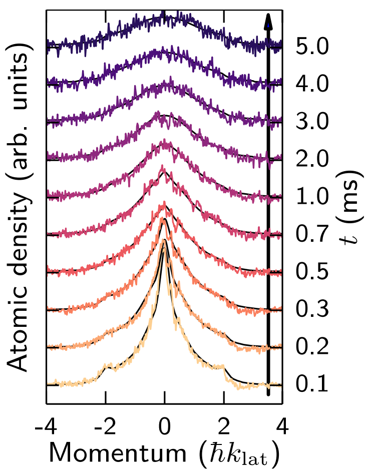

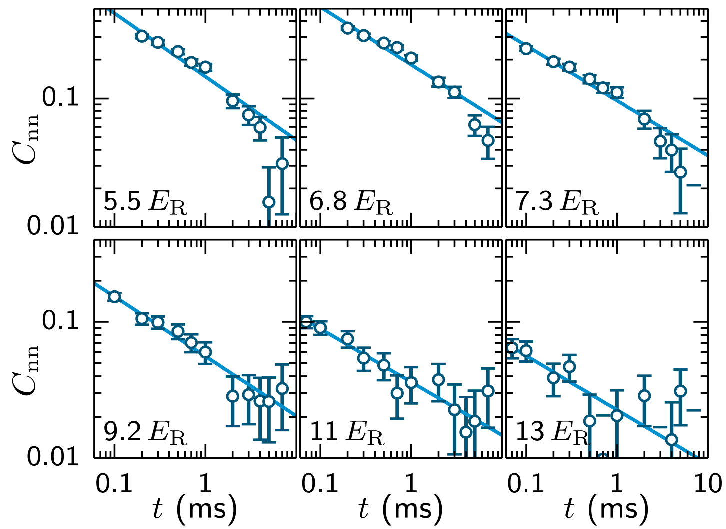

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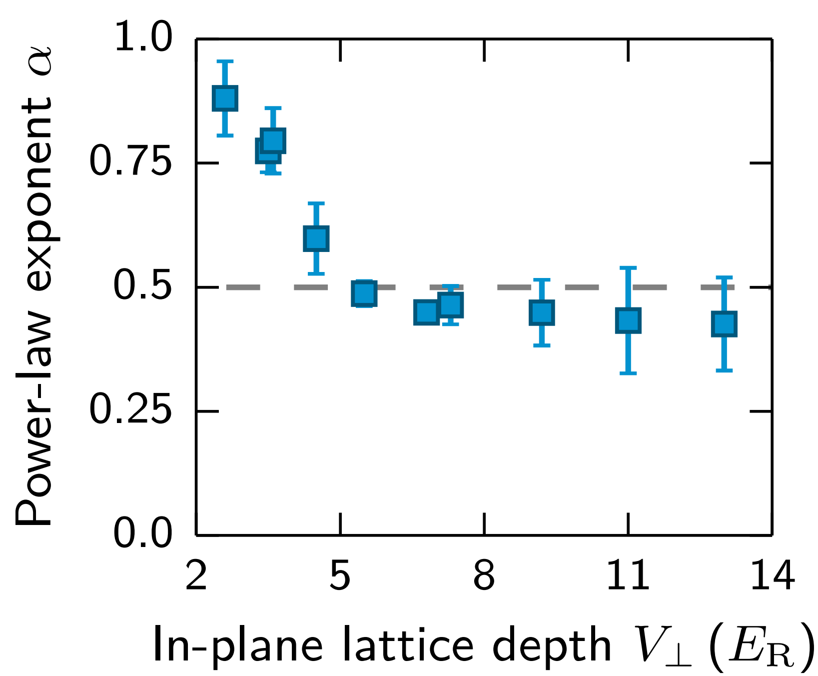

⟨ Model of weak localized density measurement ⟩

→ Bose-Hubbard model $\hat{H}_{\mathrm{BH}} = -J \sum_{\langle \boldsymbol{i},\boldsymbol{j} \rangle} \left(\hat{a}^{\dagger}_{\boldsymbol{i}} \hat{a}_{\boldsymbol{j}} + \hat{a}^{\dagger}_{\boldsymbol{j}} \hat{a}_{\boldsymbol{i}} \right) + \frac{U}{2} \sum_{\boldsymbol{i}} \hat{n}_{\boldsymbol{i}} \left(\hat{n}_{\boldsymbol{i}} - 1 \right)$

[1] D. Poletti et al., Phys. Rev. Lett. 109 045302 (2012)
[2] D. Poletti et al., Phys. Rev. Lett. 111 195301 (2013)

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→ Dissipation,
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→ 2 timescales: $\gamma_{\mathrm{sp}}^{-1}$

$t^* \propto \gamma_{\mathrm{sp}}^{-1} \left(\frac{\bar{n} U}{J} \right)^2$

(1) $t \lesssim \gamma_{\mathrm{sp}}^{-1}$ Fast relaxation of long-range coherences

(2) $\gamma_{\mathrm{sp}}^{-1} \lesssim t \lesssim t^*$ Algebraic regime of decay

(3) $t^* \lesssim t$ Final thermalization stage

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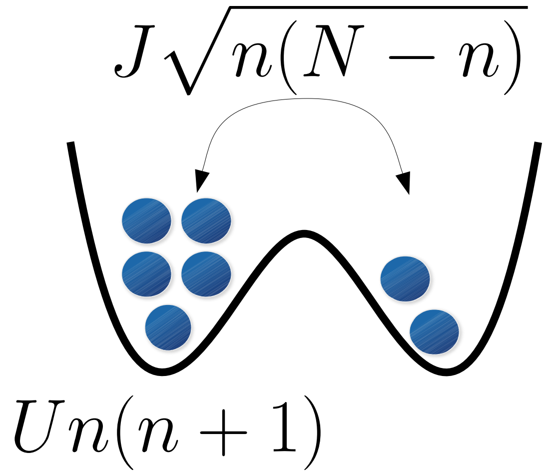
⟨ Double-well case ⟩



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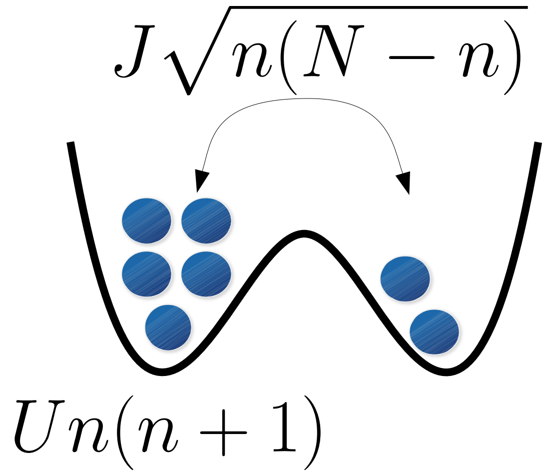

$$\frac{\partial \rho(n)}{\partial t} = \frac{1}{t^*}\nabla\left\{D_{n\to n+1}\nabla\rho(n)\right\}$$

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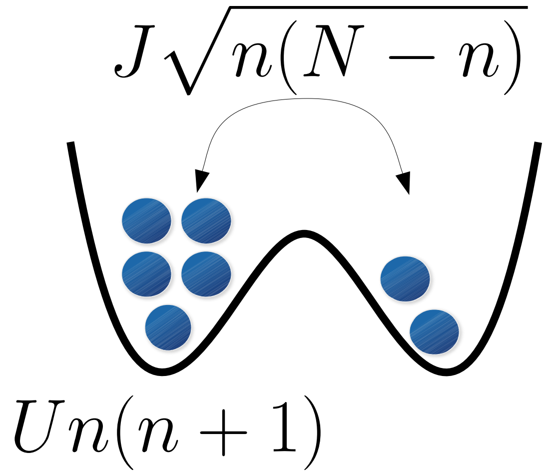

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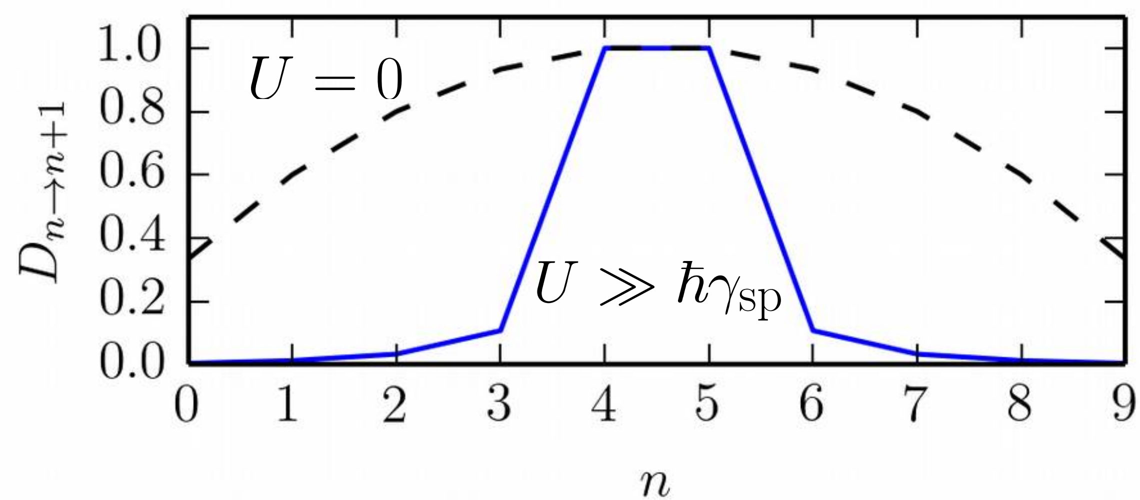

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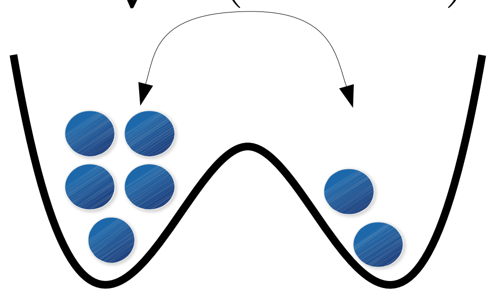
⟨ Double-well case ⟩

$$J\sqrt{n(N-n)}$$



$$Un(n+1)$$

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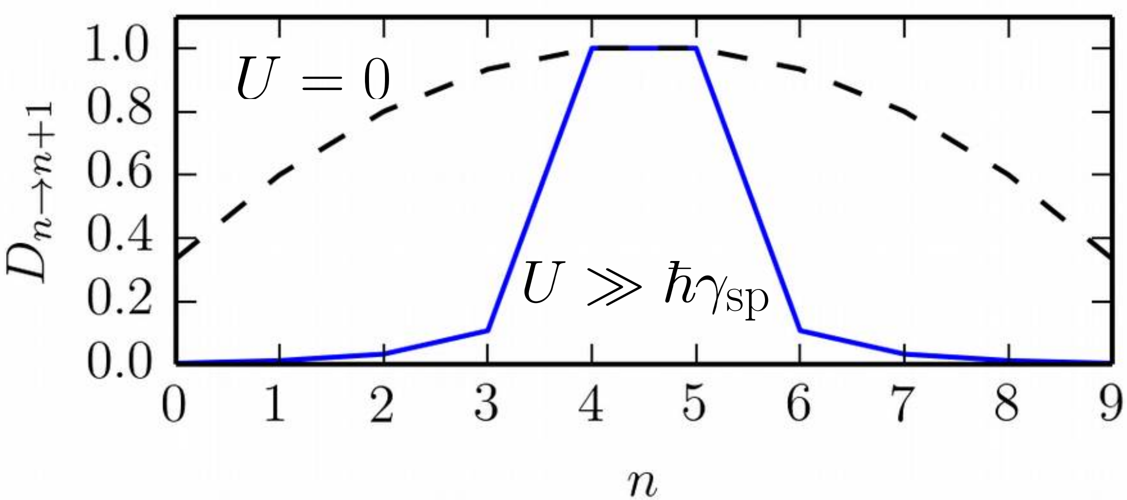

$$\Delta n \propto t^{1/4}$$

$$C \propto \frac{1}{t^{1/2}}$$

[1] D. Poletti et al., Phys. Rev. Lett. 109 045302 (2012)
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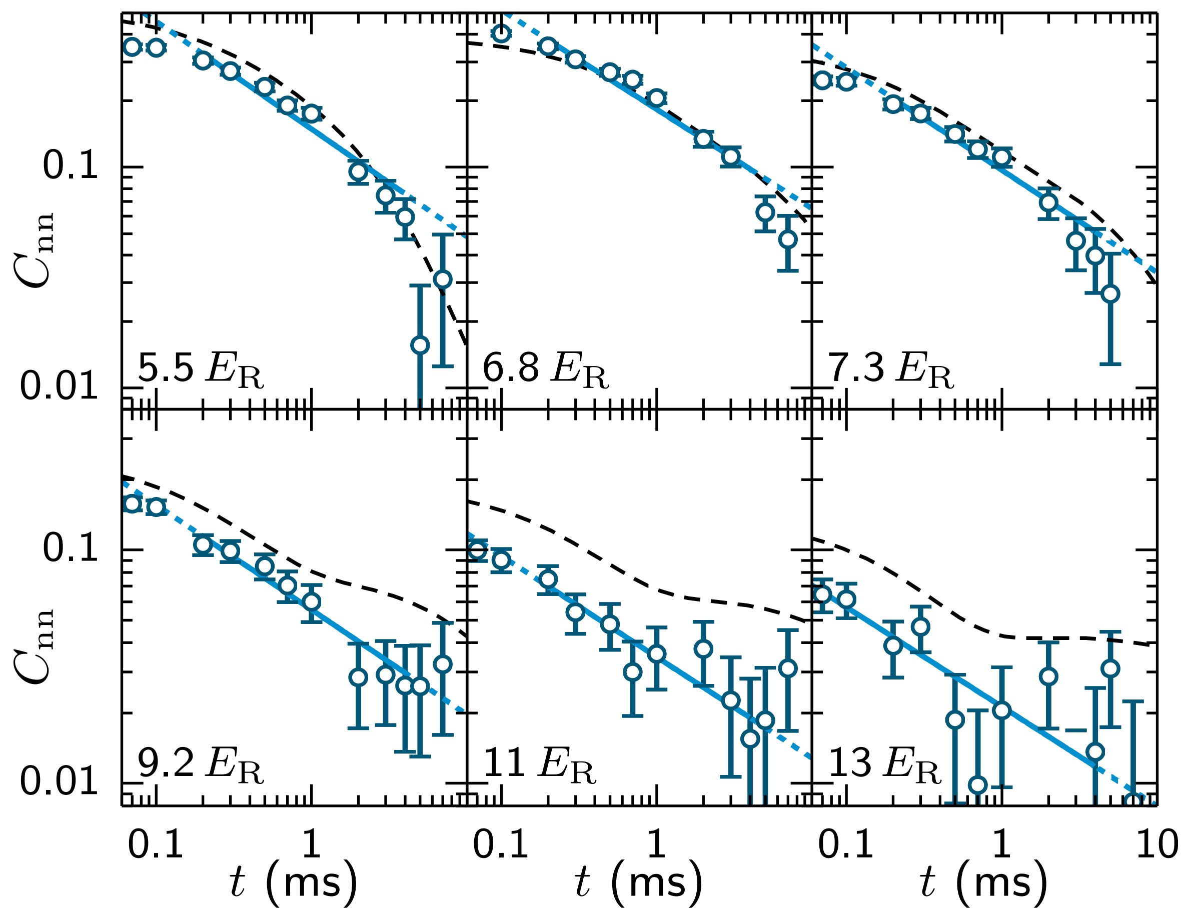
⟨ Extended model ⟩

→ Inhomogeneities:
- loading model to determine the initial density distribution
- solve the master equation on each site
- average over the distribution

→ Losses:
- Lindblad operator
- 'adiabatic' extension

$$\mathcal{L}_{2B} = \frac{\gamma_{2B}}{2} \sum_i 2\hat{a}_i^2 \hat{\rho} \hat{a}_i^{\dagger 2} - \hat{a}_i^{\dagger 2} \hat{a}_i^2 \hat{\rho} - \hat{\rho} \hat{a}_i^{\dagger 2} \hat{a}_i^2$$



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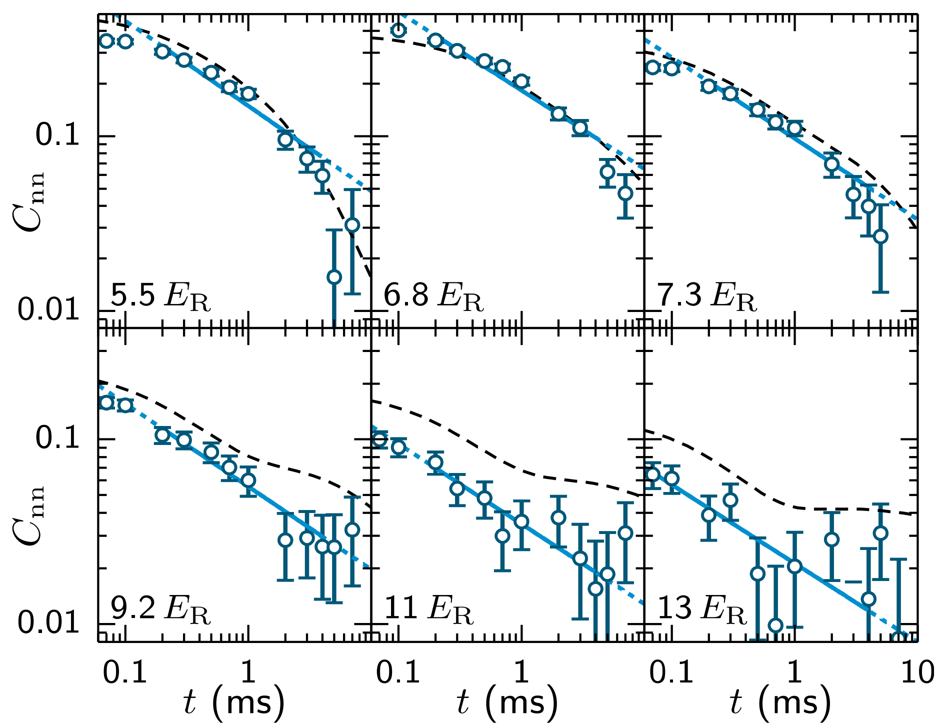
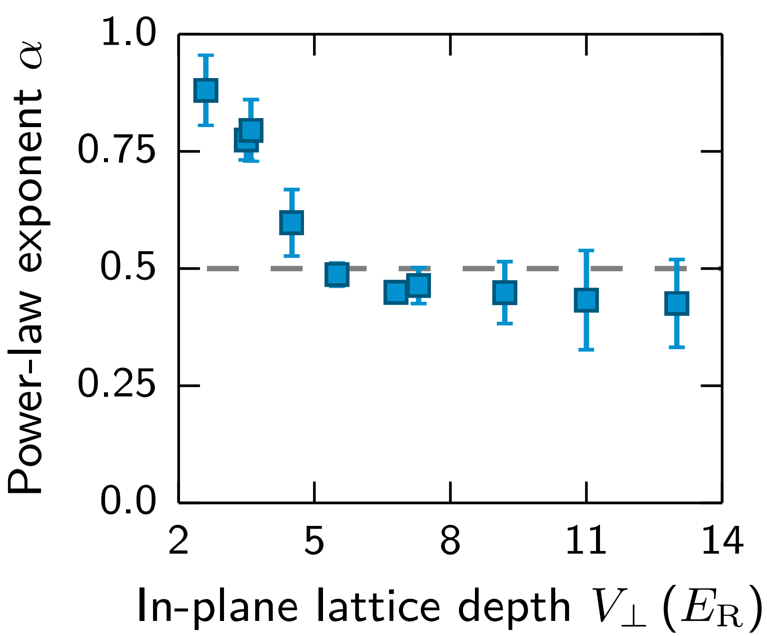




⟨ Conclusion ⟩

✔ Observation of spatial decoherence in a many-body system

✔ For strong interactions: anomalous momentum diffusion

! Decoherence is slowed down

? Inter-band transitions
Collective effects in light-matter interaction

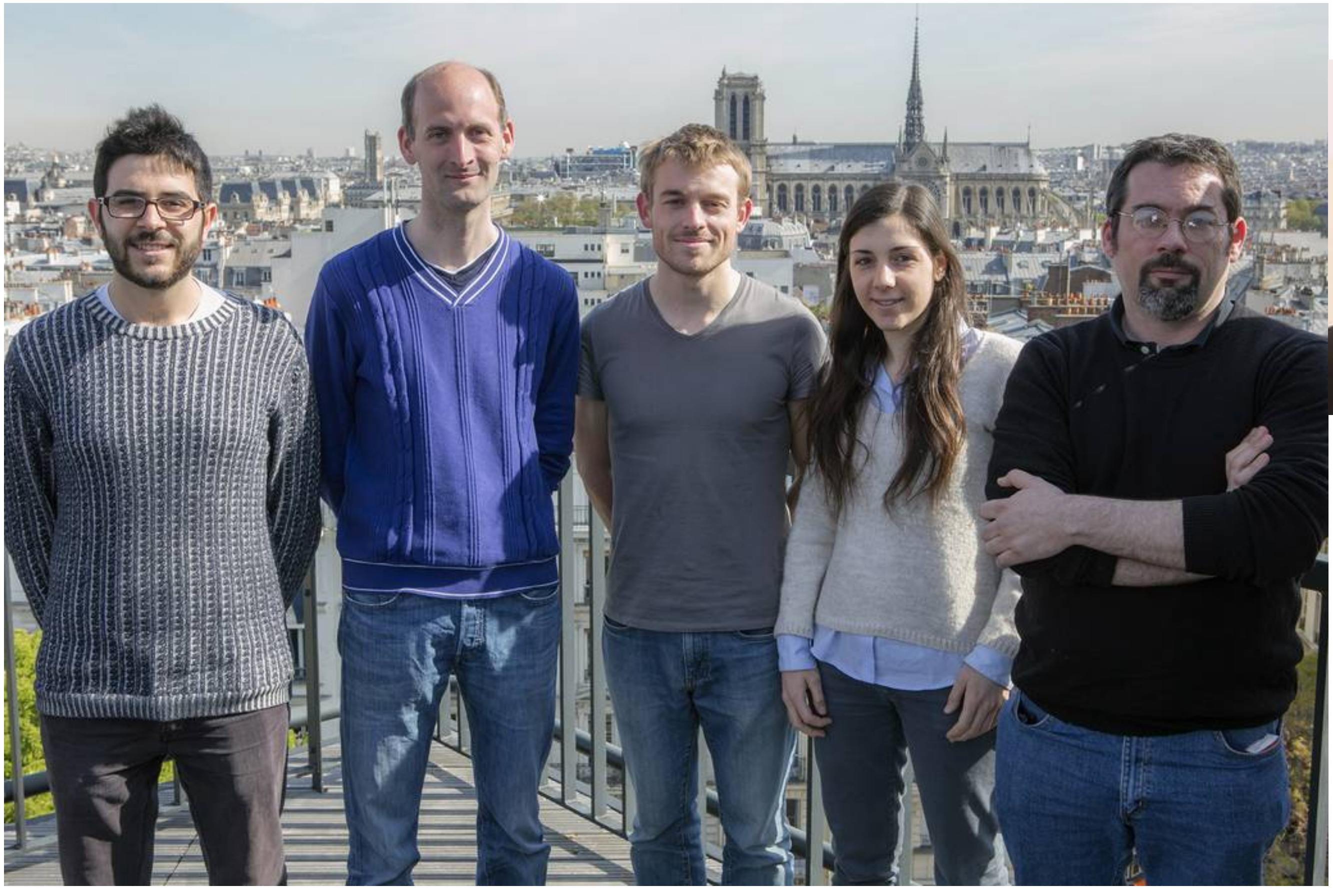
✔ Simple master equation model captures the observed dynamics

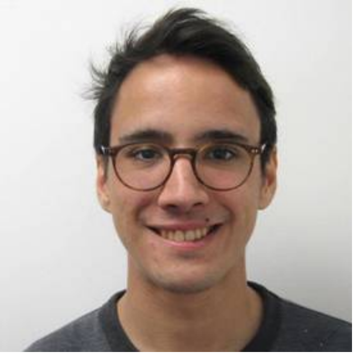
! Losses accelerate the emergence of the anomalous behavior

? Losses give indication on the Fock space dynamics

⟨ The team ⟩

Manel Bosch | Jérôme Beugnon | Raphaël Bouganne | Elisa Soave | Fabrice Gerbier | Alexis Ghermaoui | Rémy Vatré





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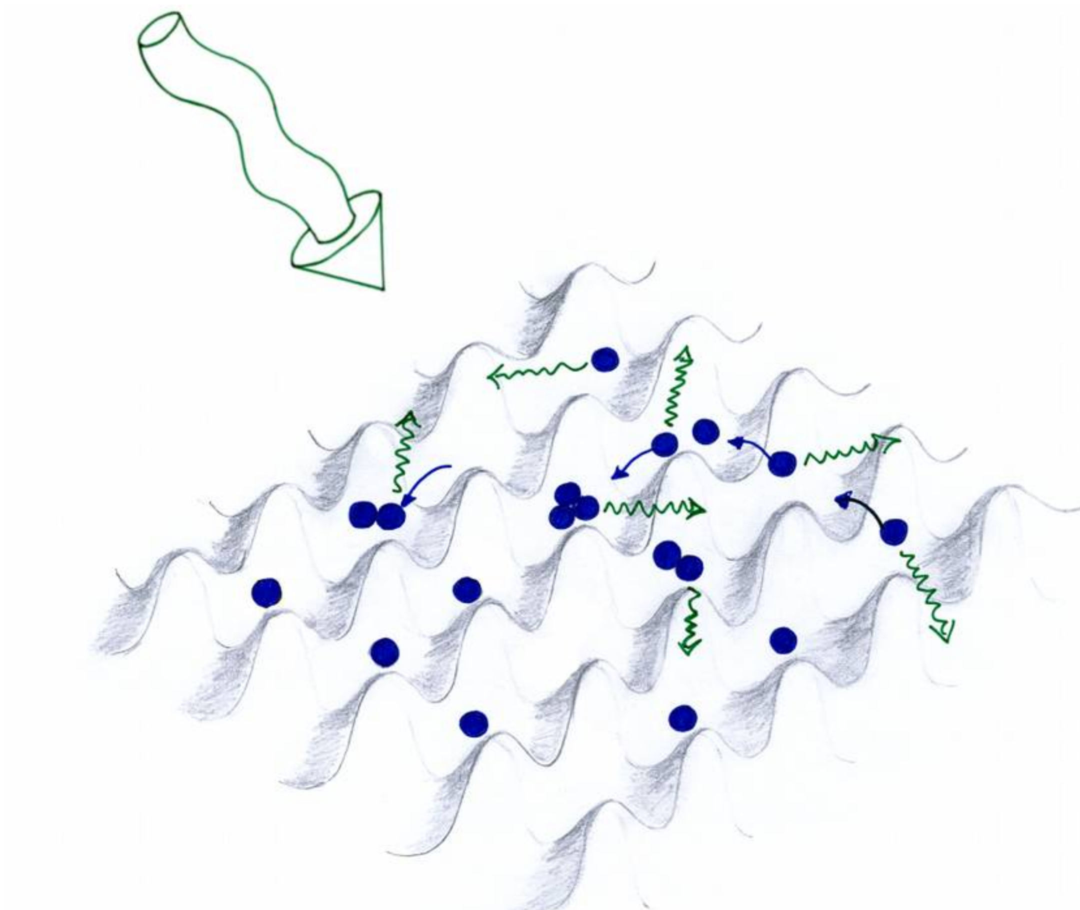

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⟨ In an optical lattice ⟩

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$$\frac{\partial \hat{\rho}}{\partial t} = \frac{1}{\mathrm{i}\hbar}\left[\hat{H}_{\mathrm{BH}}, \hat{\rho}\right] + \gamma_{\mathrm{sp}} \sum_{\boldsymbol{i}} \hat{n}_{\boldsymbol{i}}\hat{\rho}\hat{n}_{\boldsymbol{i}} - \frac{1}{2}\hat{n}_{\boldsymbol{i}}^2\hat{\rho} - \frac{1}{2}\hat{\rho}\hat{n}_{\boldsymbol{i}}^2$$

→ Adiabatic elimination of the coherences + factorization of the density matrix:

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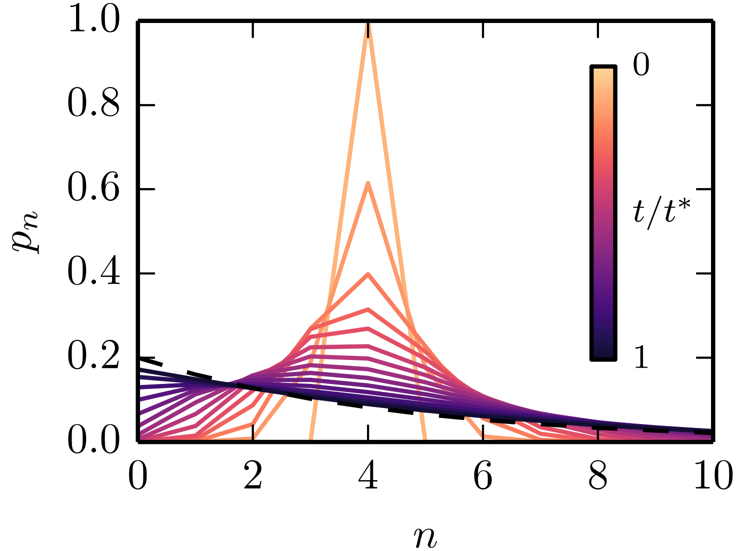

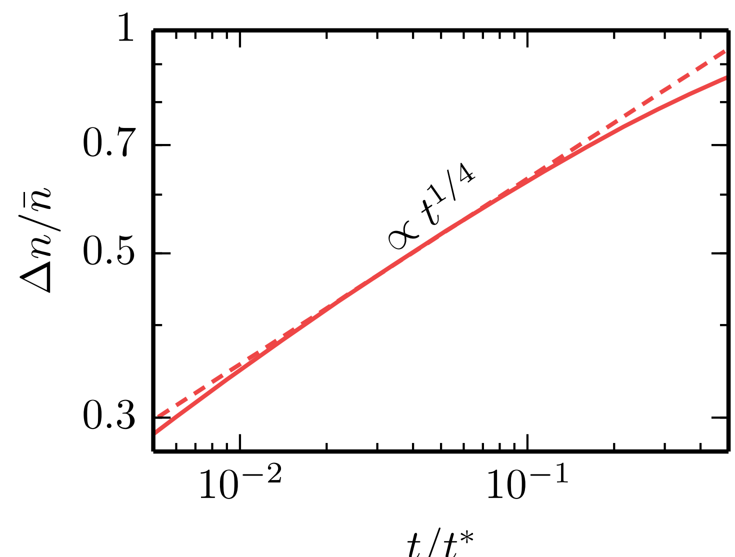

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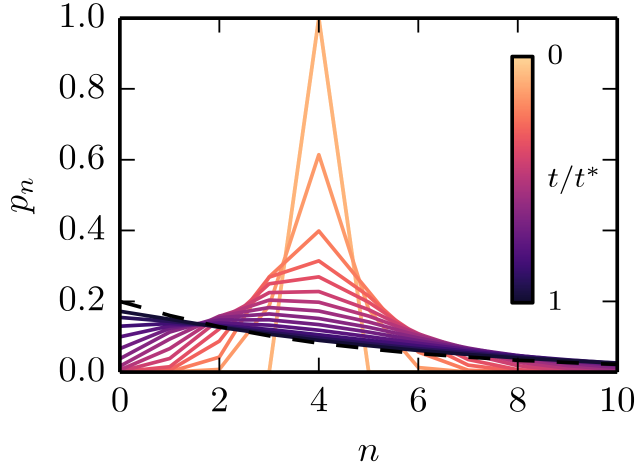
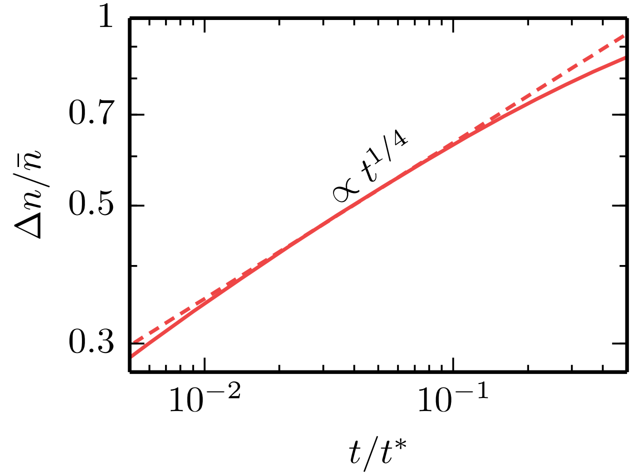
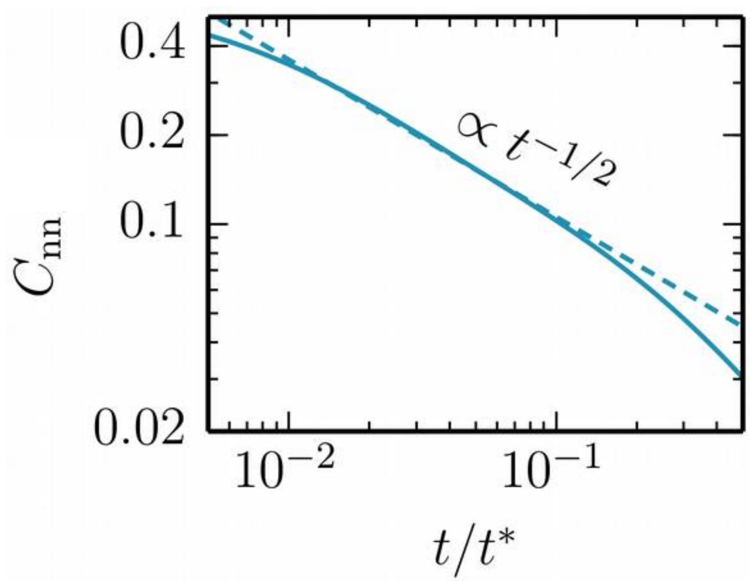




$$\mathcal{S}(\boldsymbol{k}) = \sum_{i,j} \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{r}_i - \boldsymbol{r}_j)} \langle \hat{a}_i^\dagger \hat{a}_j \rangle$$

$$C_{\mathrm{nn}} = \langle \hat{a}_i^\dagger \hat{a}_{i+1} \rangle$$



$$C_{\mathrm{nn}} = \frac{\xi}{\sqrt{\gamma_{\mathrm{sp}} t}}$$

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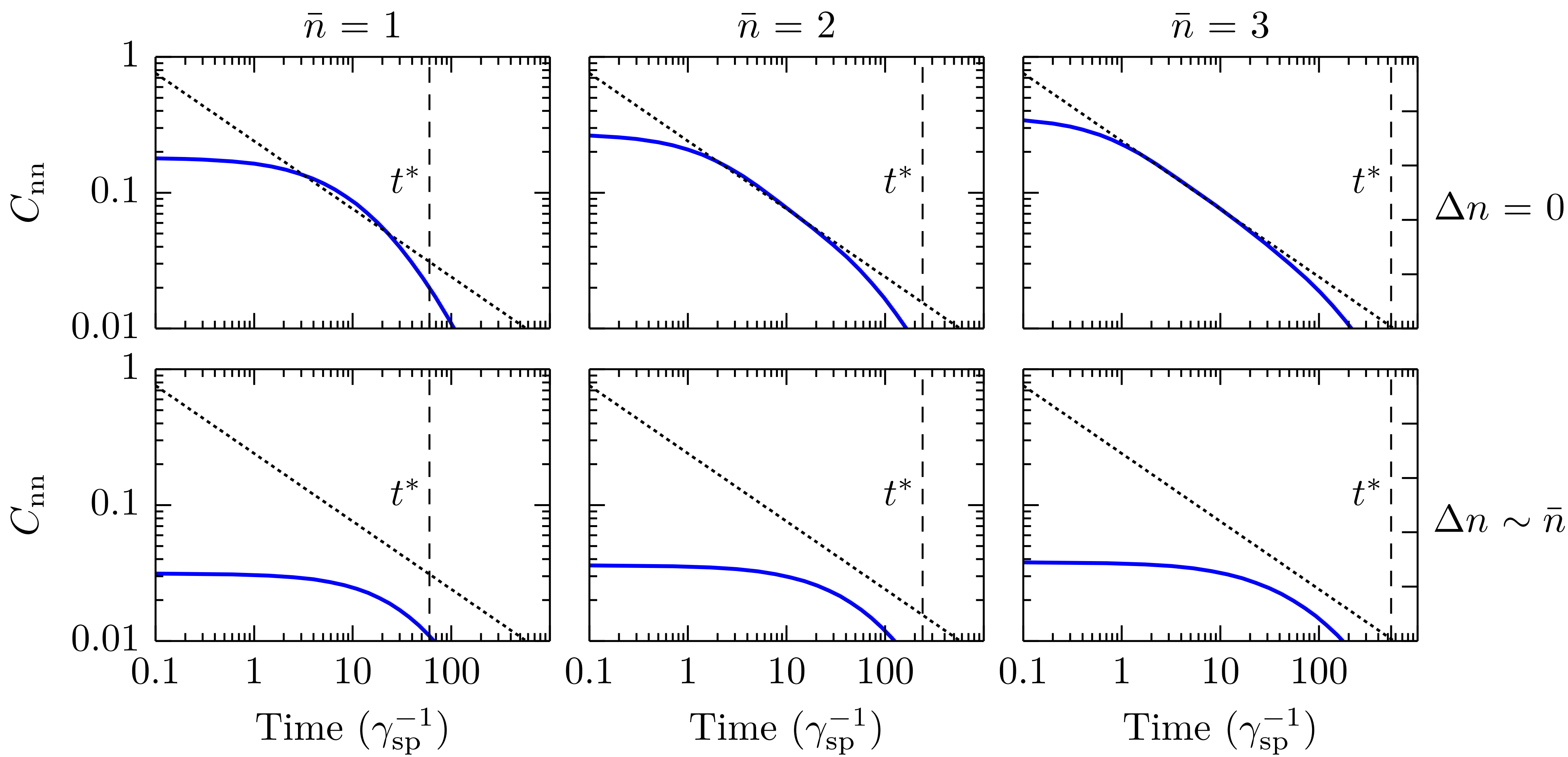
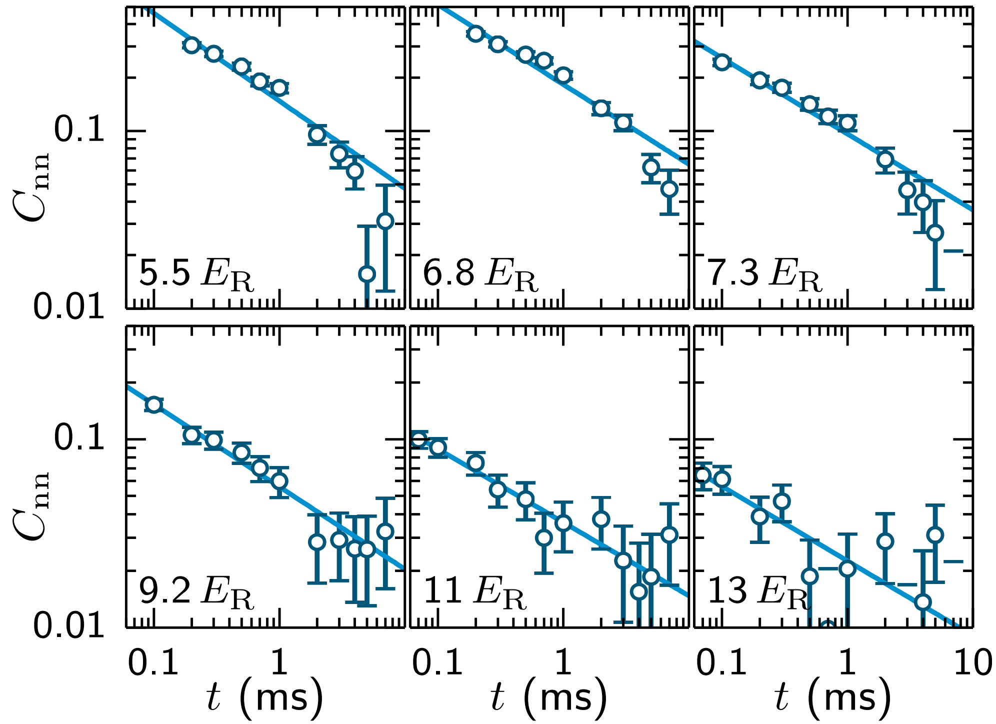
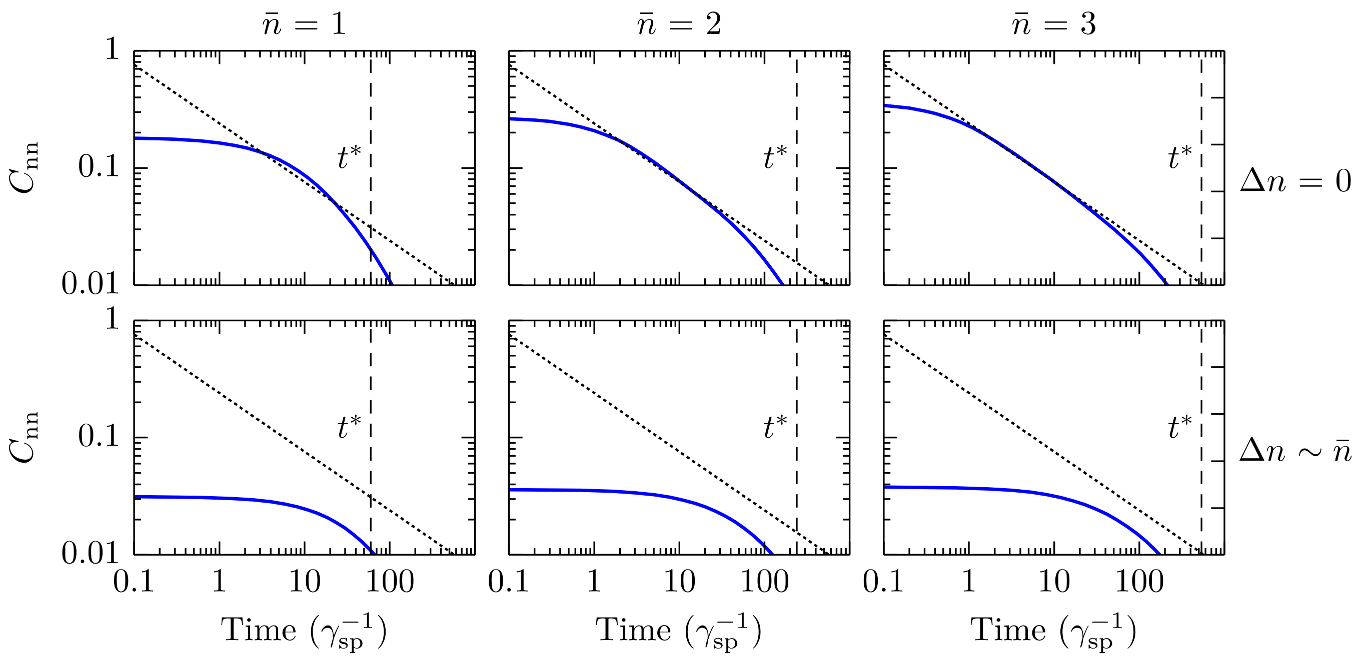


⟨ Time-scales mismatch ⟩





$$t^* \propto \gamma_{\rm sp}^{-1} \left(\frac{\bar{n} U}{J} \right)^2$$

⟨ Extended model ⟩

→ Inhomogeneities:

- loading model to determine the initial density distribution
- solve the master equation on each site
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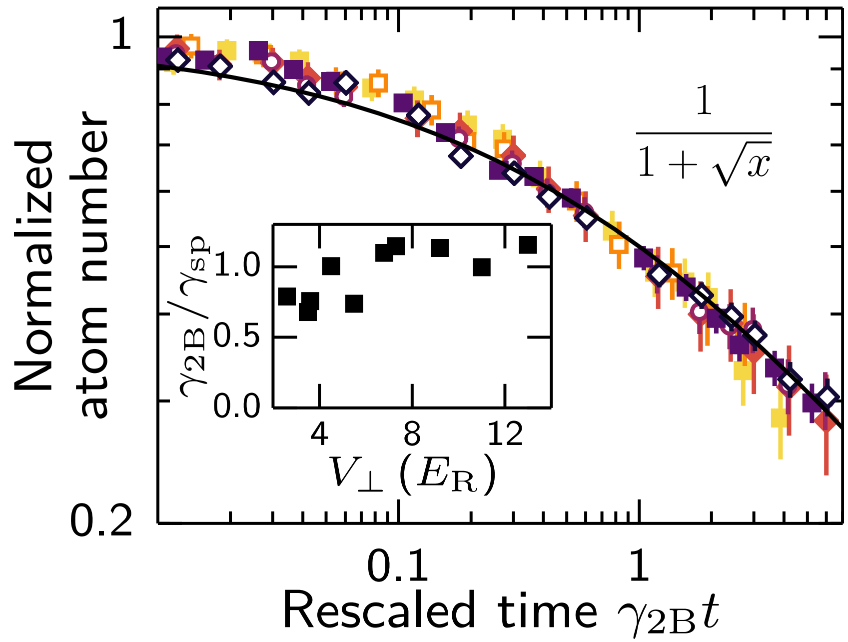

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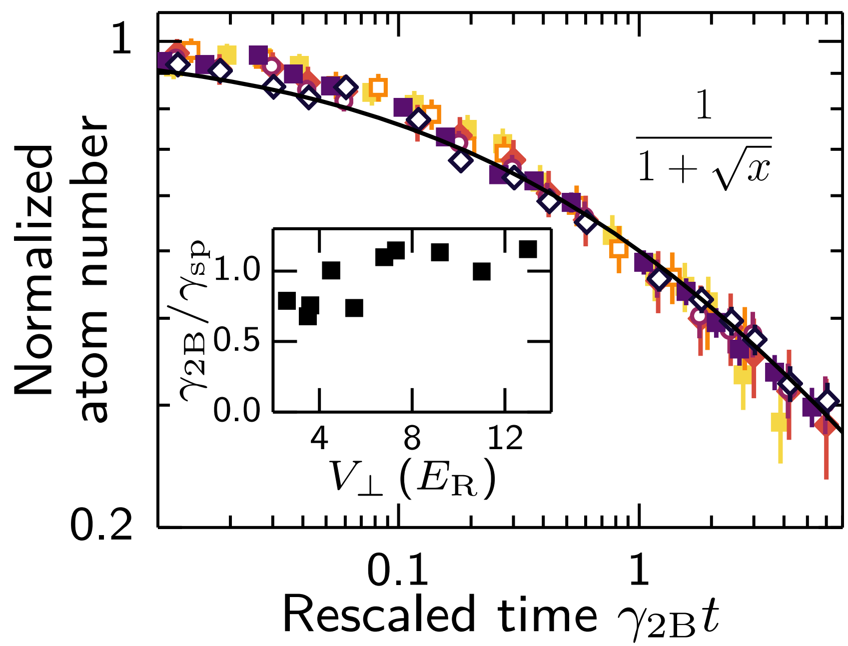

→ Losses:

- Lindblad operator
- 'adiabatic' extension

$$\mathcal{L}_{2B} = \frac{\gamma_{2B}}{2} \sum_i 2\hat{a}_i^2 \hat{\rho} \hat{a}_i^{\dagger 2} - \hat{a}_i^{\dagger 2} \hat{a}_i^2 \hat{\rho} - \hat{\rho} \hat{a}_i^{\dagger 2} \hat{a}_i^2$$