# Reducing phase fluctuations in a layered superconductor via driving

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# Reducing phase fluctuations via driving

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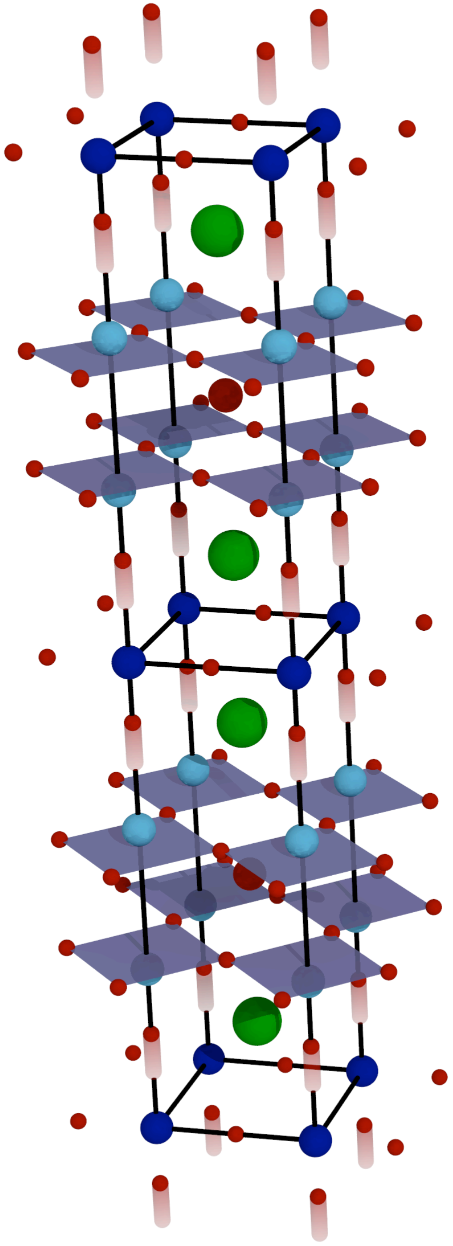
Pump-probe experiments in YBCO

Dynamic enhancement of superconductivity

Modeled via coupled Josephson junctions

Reduction of inter-layer phase fluctuations

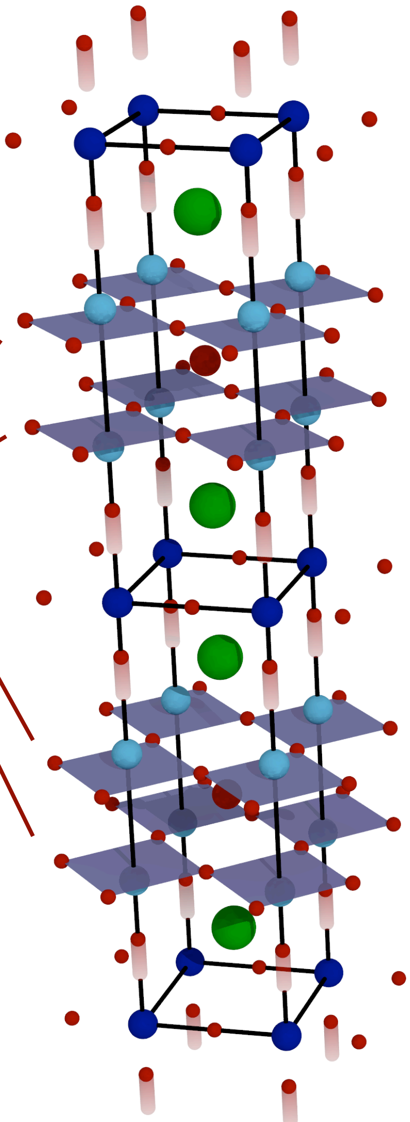
c-m/1406.3609



# Overview

- Motivation and setup of the model
  - YBCO, plasmons, pump-probe experiments, Josephson junctions, fluctuations...
- Toy models: two coupled junctions, single driven junctions
  - Dynamical suppression of fluctuations, power spectrum...
- Full model of the bulk system
  - Comparison to toy models, in-plane dynamics...
- Conclusions

# Layered superconductors




YBCO

Pairing field

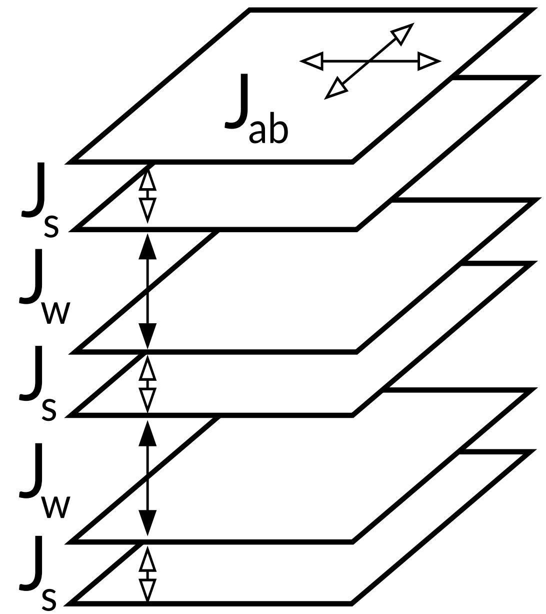
$$\psi_i \approx \sqrt{n_0 + \delta n_i}\,\exp\left(i\theta_i\right)$$

phase

Charge fluctuations

(extended) Lawrence-Doniach model

$$H_\theta = -\sum_{<ij>} J_{ij}\cos\left(\theta_i - \theta_j\right)$$



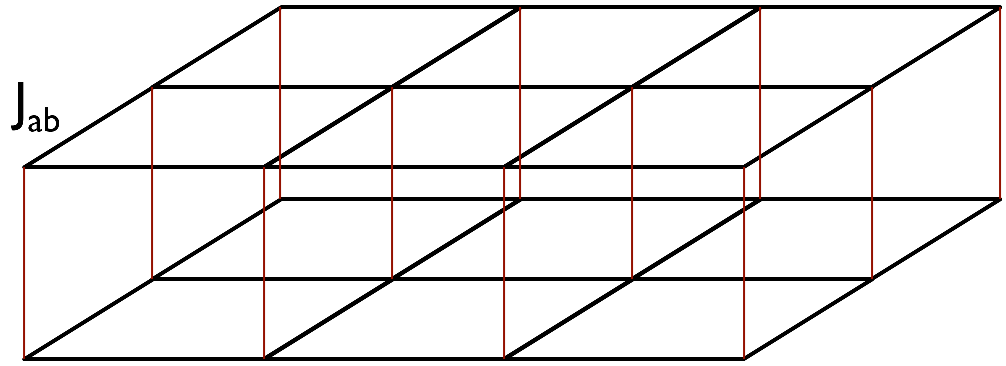

Layered system of coupled Josephson junctions

Lawrence + Doniach, '71

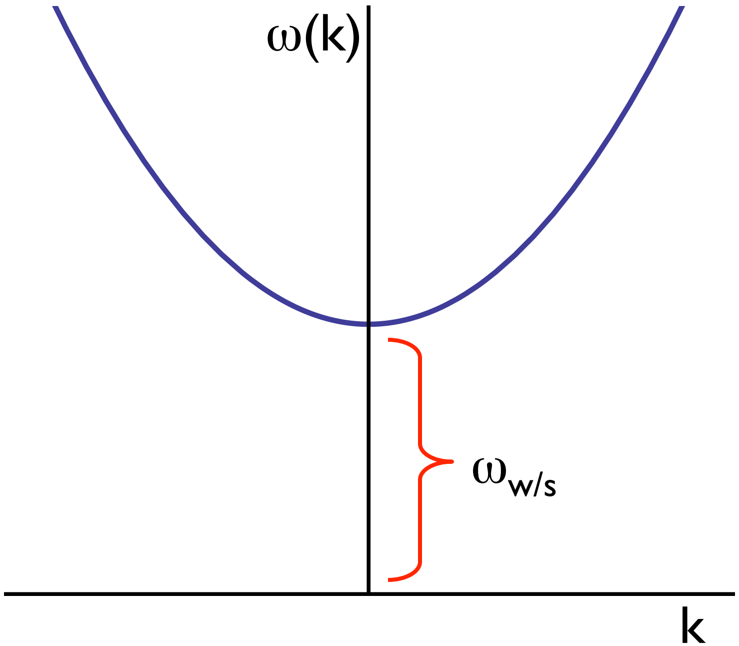
# Plasmon modes

Charging energy

$$H_n = \frac{E_c}{2}\sum_i \delta n_i^2$$



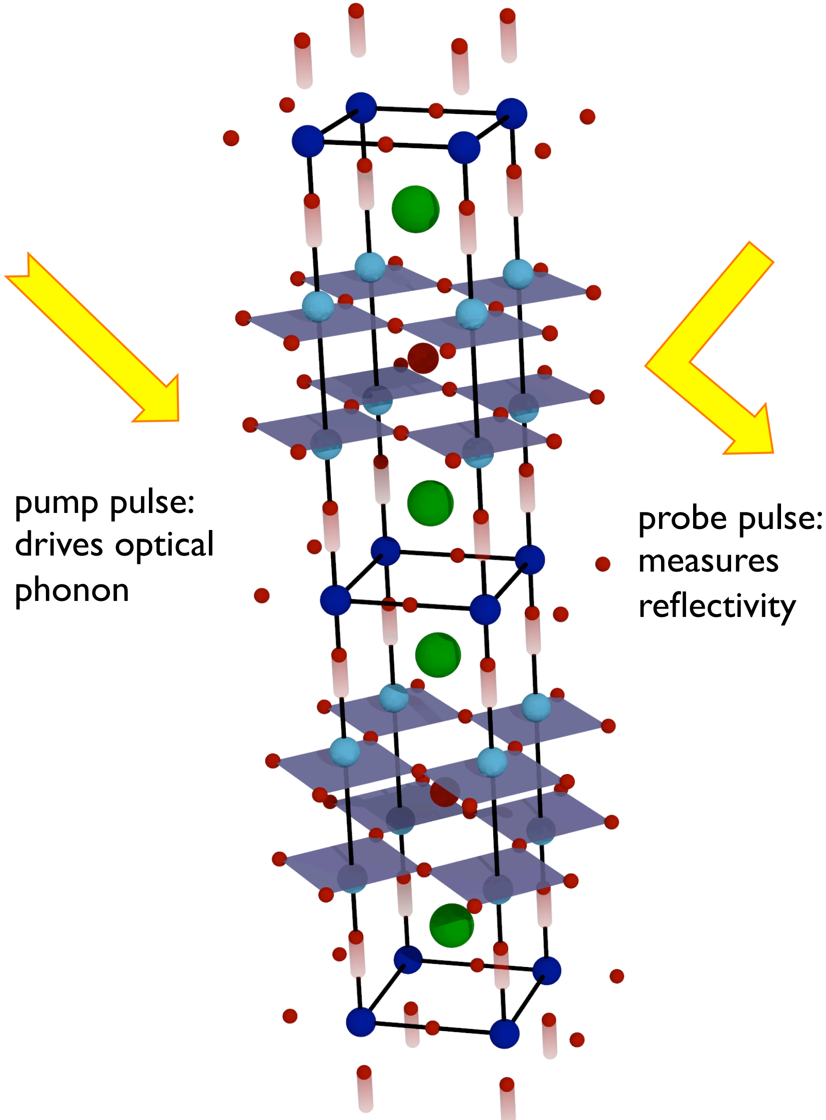

i=w,s




Plasmon frequencies

$$\omega_{w/s} = \sqrt{2J_{w/s}E_c}$$

# Pump-probe experiments



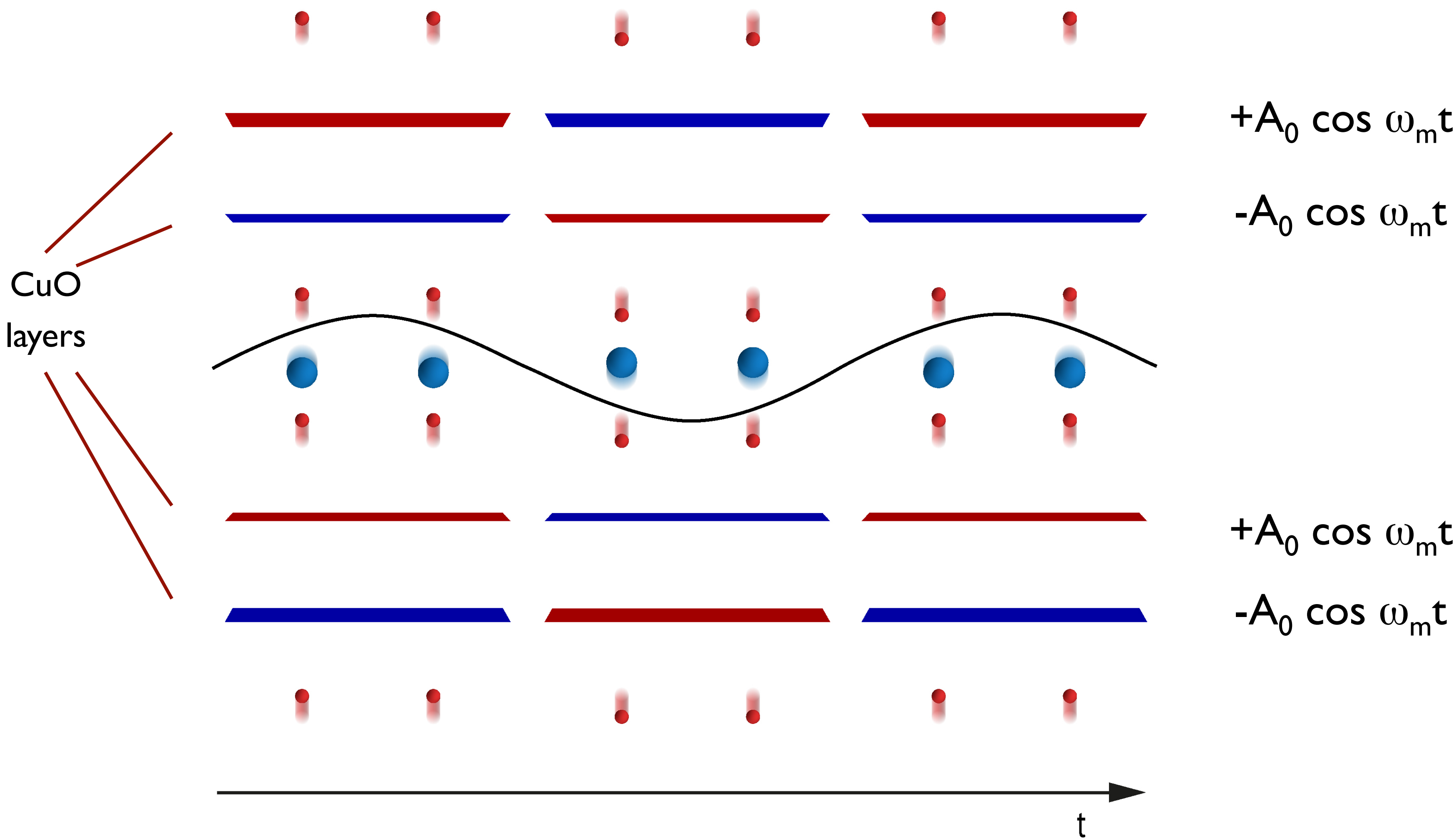

Observation:

Pump pulse boosts the optical conductivity at low frequencies

Superfluid density $\omega\ \sigma_2(\omega, t)$ is enhanced.

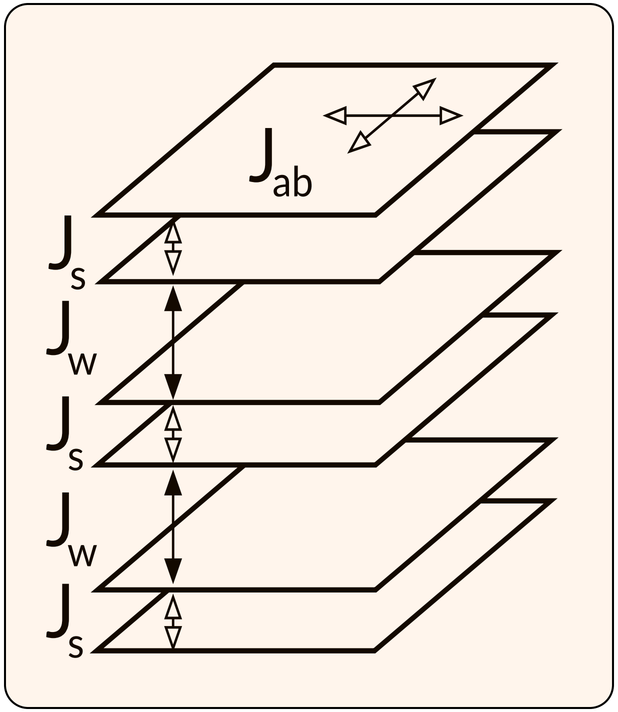
Cavalleri group: Hu, et al., c-m/1308.3204, Kaiser, et al., c-m/1205.4661

# Effect of driven phonons




$$H_{dr} = \sum_i A_i(t)\delta n_i$$

# Coupled Josephson junctions, with a thermal bath




T, γ

Example: single Josephson junction coupled to a thermal bath

$$\ddot{\theta} = -\omega_w^2 \sin\theta + F_0 \sin(\omega_m t) - \gamma\dot{\theta} + \xi$$

deterministic damping noise

# Parameters

Plasmon frequencies

$$\omega_w = \sqrt{2J_w E_c} \qquad \sim 1 \text{ Thz}$$

$$\omega_s = \sqrt{2J_s E_c} \qquad \sim 10 \text{ Thz}$$

Kosterlitz-Thouless scale

$$J_{ab} \quad \sim 10^2 \text{ K}$$

Ratios

$$J_{ab} : J_s : J_w \sim 1000 : 100 : 1$$

Driving energy

$$A_0 \quad \sim 50 \text{ K} \sim 1 \text{ THz}$$

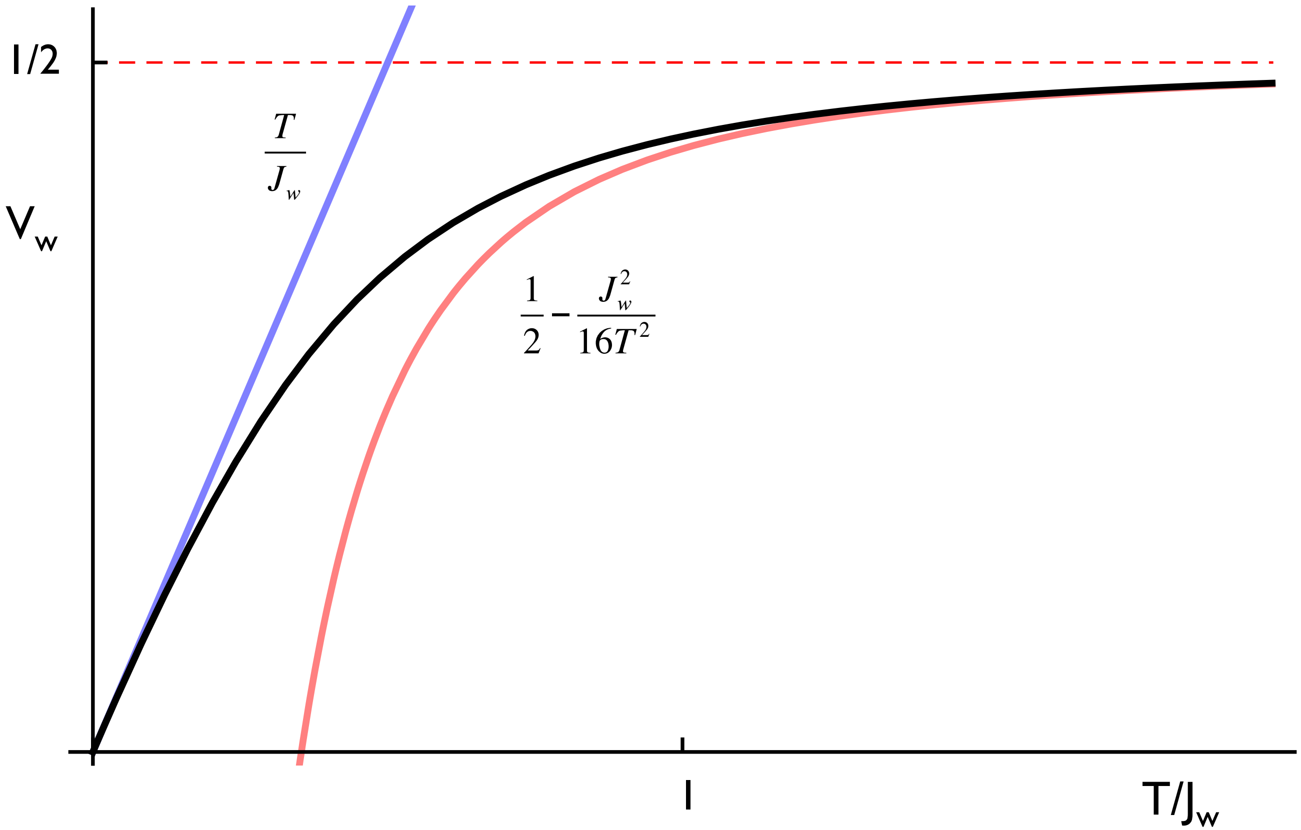
Damping

$$\omega_s > \gamma > \omega_w \qquad \gamma \ \sim 10^1 - 10^2 \text{ K}$$

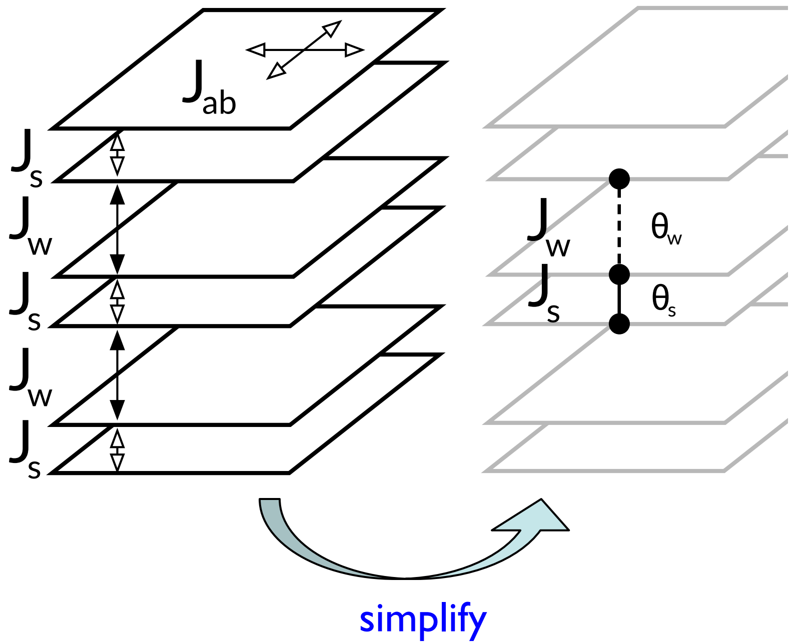
# Phase and current fluctuations

$$V_w = \langle \sin^2\theta_w \rangle - \langle \sin\theta_w \rangle^2 \sim \langle j_w^2 \rangle - \langle j_w \rangle^2 \qquad j_w = 2J_w \sin\theta_w$$

Example: single junction, H = J cos θ



# Toy model



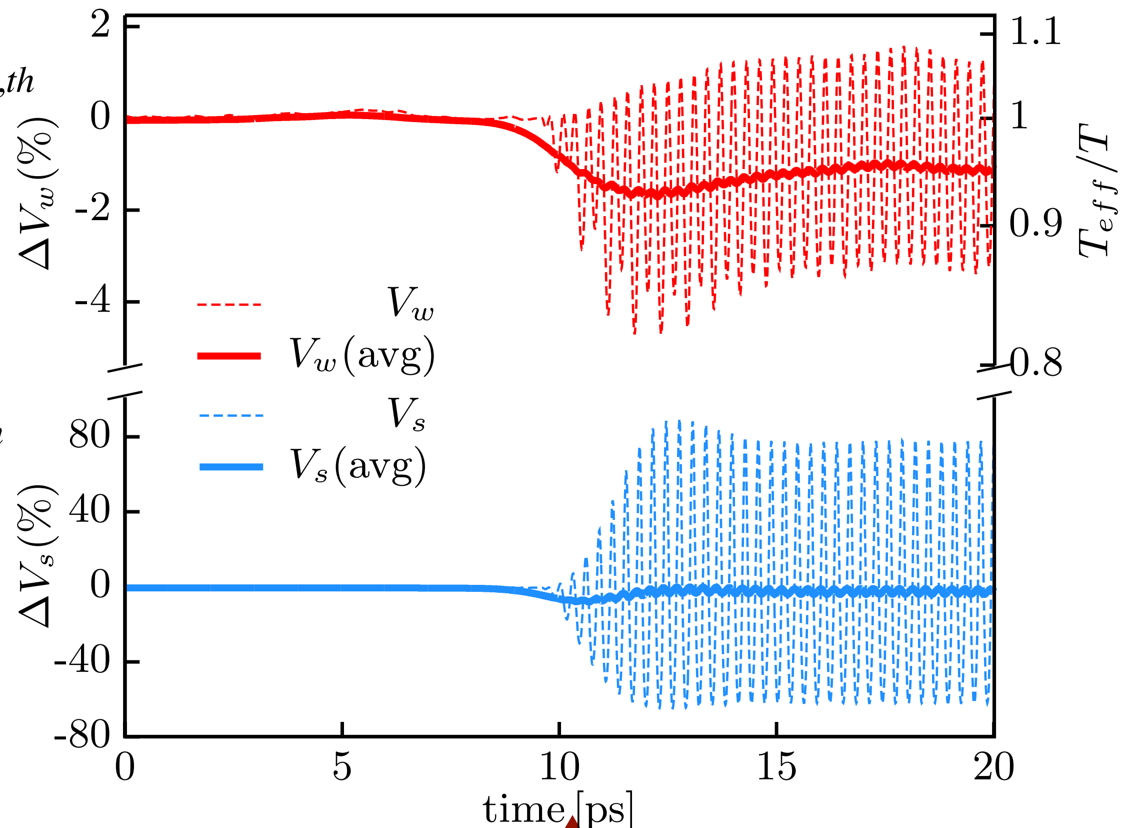

Langevin and Fokker-Planck approach

# Time evolution

$$V_{w,dr} = V_{w,th}(T_{eff})$$

$$\Delta V_w = V_w - V_{w,th}$$

$$\Delta V_s = V_s - V_{s,th}$$

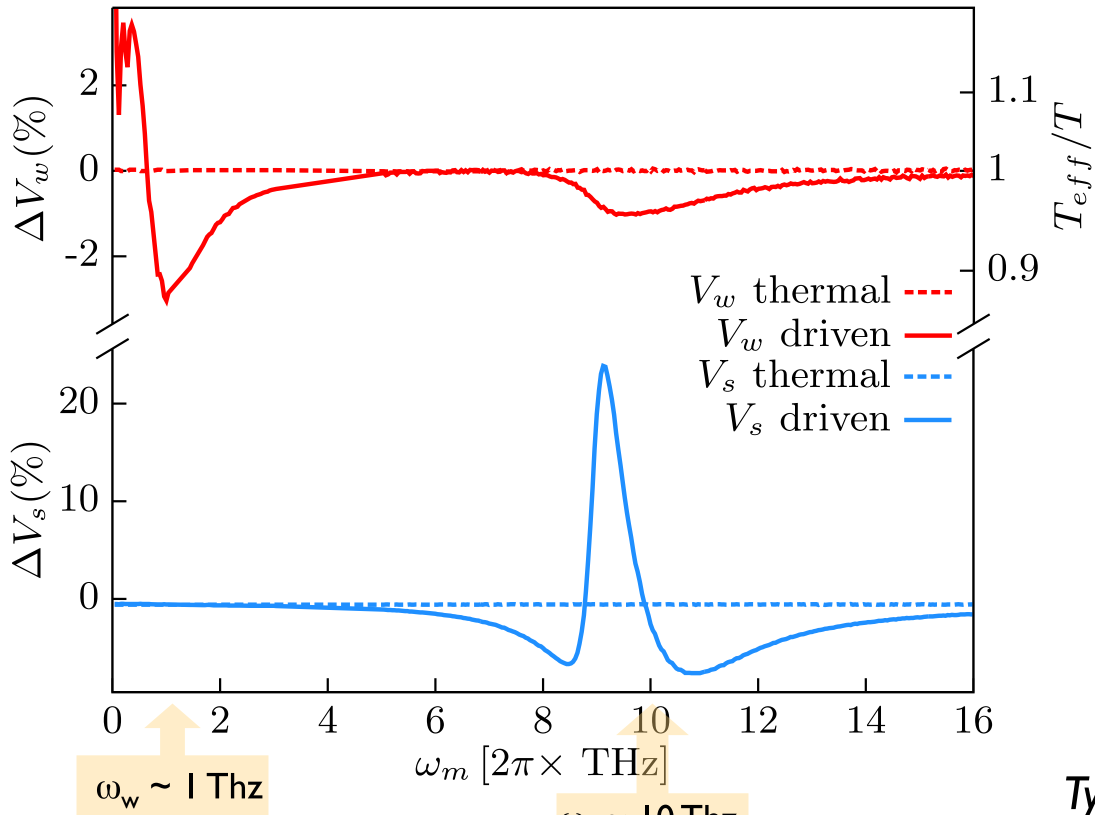



turn on driving

Reduction of fluctuations!

# Frequency scan

Time-average, in steady state $\bar{V}_w = \langle V_w(t) \rangle_t$



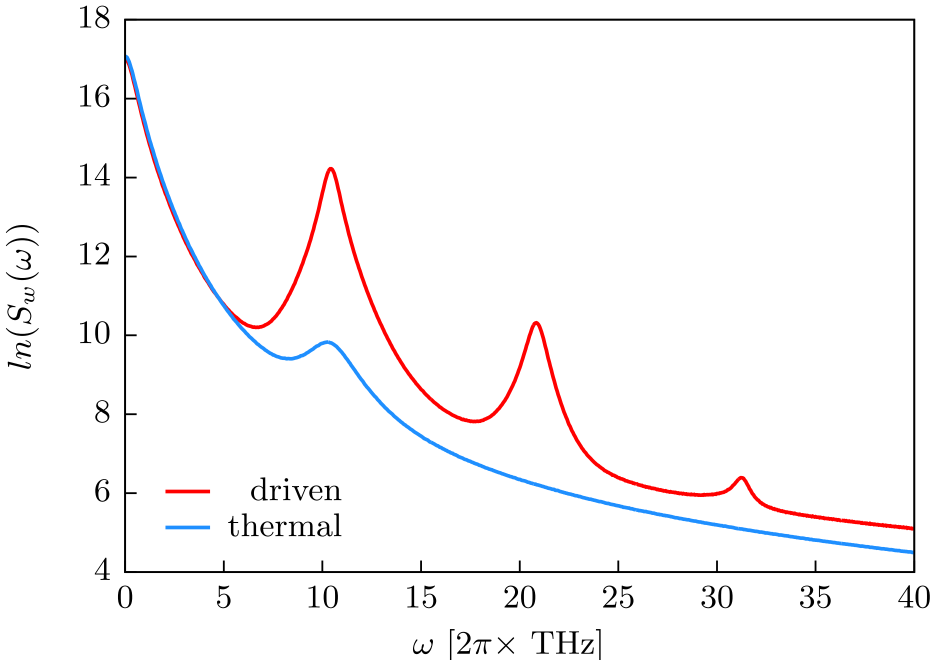

*Typical exp. driving frequency ~ 15 THz*

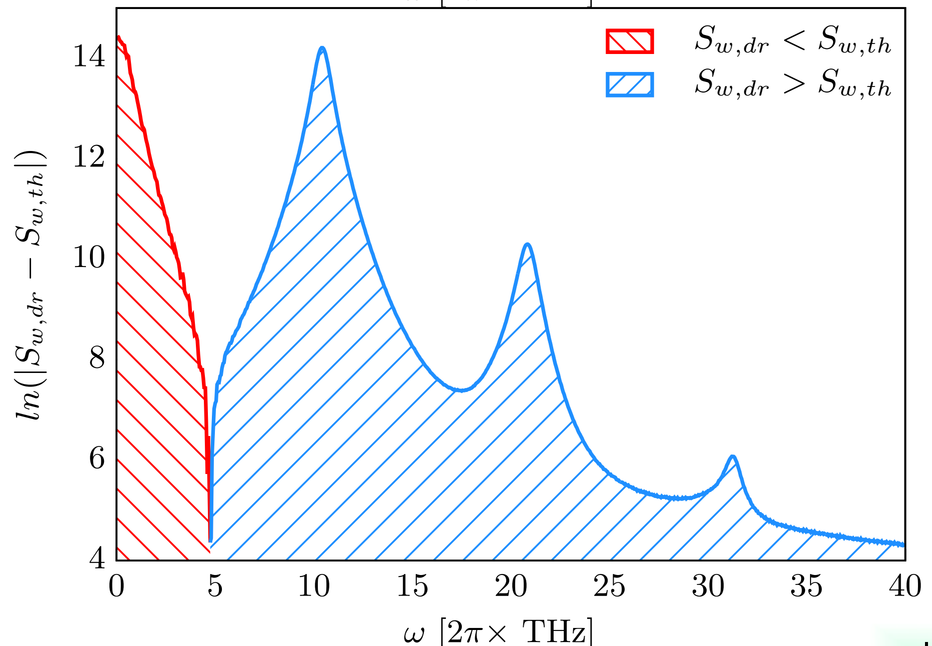
Strong junction amplifies external driving

# Power spectrum of the weak junction

$$S_w(\omega) = \langle j_w(-\omega) j_w(\omega) \rangle$$

with $\quad j_w = 2J_w \sin\theta_w$



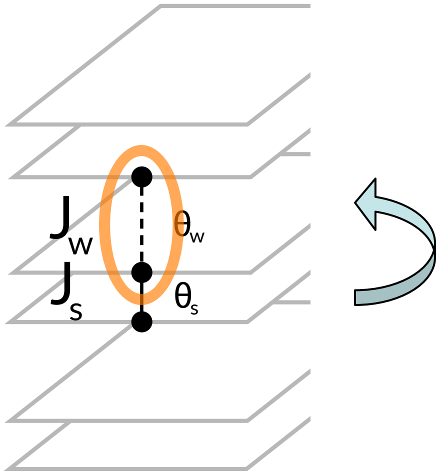




- ✓ Suppression of low-frequency fluctuations
- ✓ Enhancement high-frequency fluctuations

Redistribution of spectral weight!

# Single junction approximation

Focus on weak junction




Treat strong junction as external drive

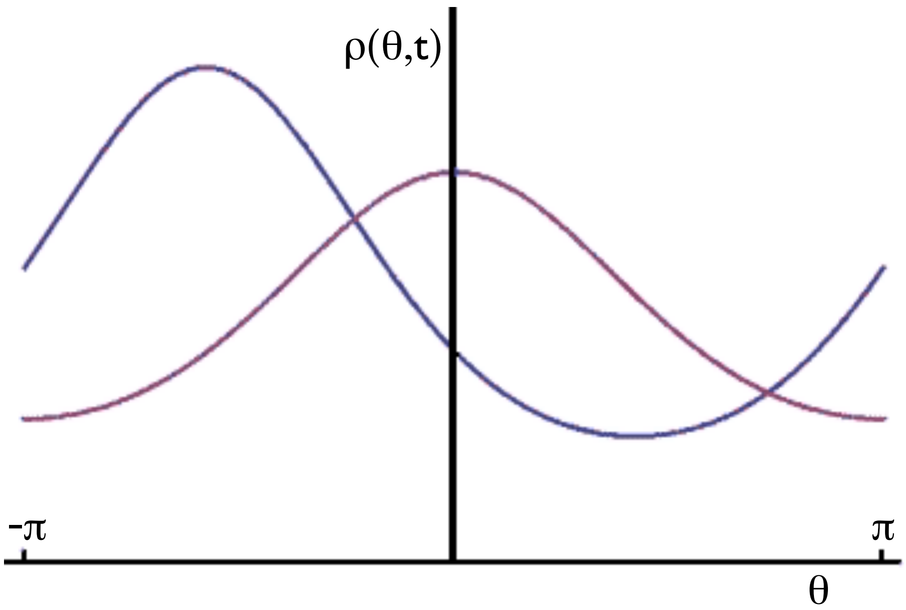
Driven, damped Josephson junction in themal bath

$$\ddot{\theta} = -\omega_w^2 \sin\theta + F_0 \sin(\omega_m t) - \gamma\dot{\theta} + \xi$$

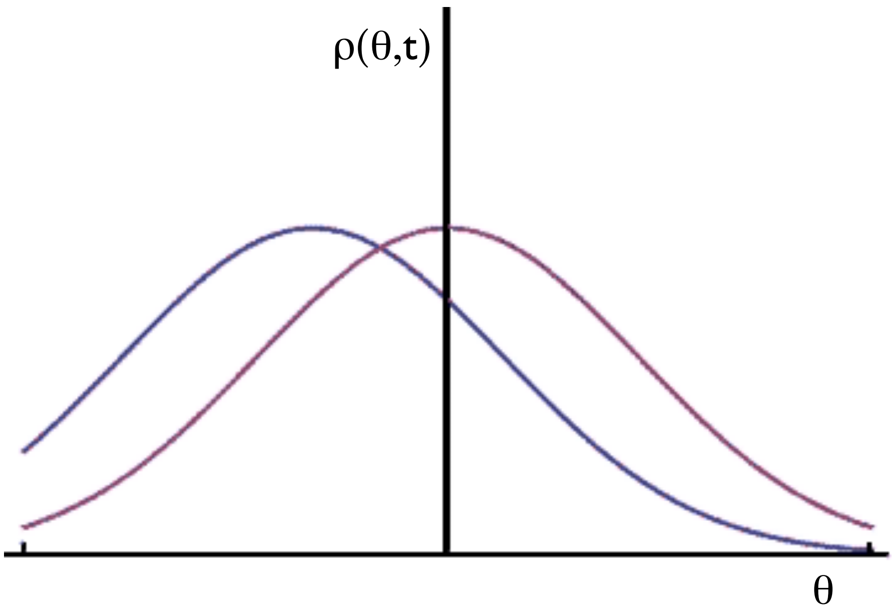
# Overdamped, driven Josephson junction

$$\cancel{\ddot{\theta}} = -\omega_w^2 \sin\theta + F_0 \sin(\omega_m t) - \gamma\dot{\theta} + \xi \quad \Rightarrow \quad \dot{\theta} = -\frac{\omega_w^2}{\gamma}\sin\theta + \frac{F_0 \sin(\omega_m t)}{\gamma} + \frac{\xi}{\gamma}$$

Fokker-Planck solution gives ρ(θ,t)




Josephson junction



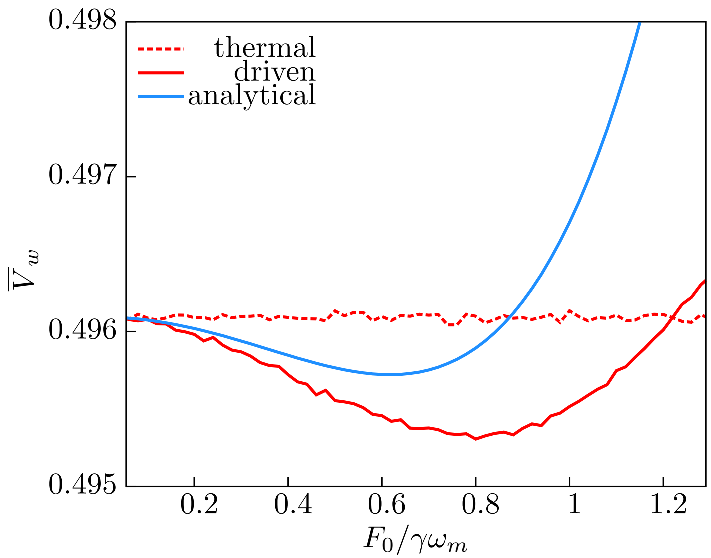

Harmonic oscillator

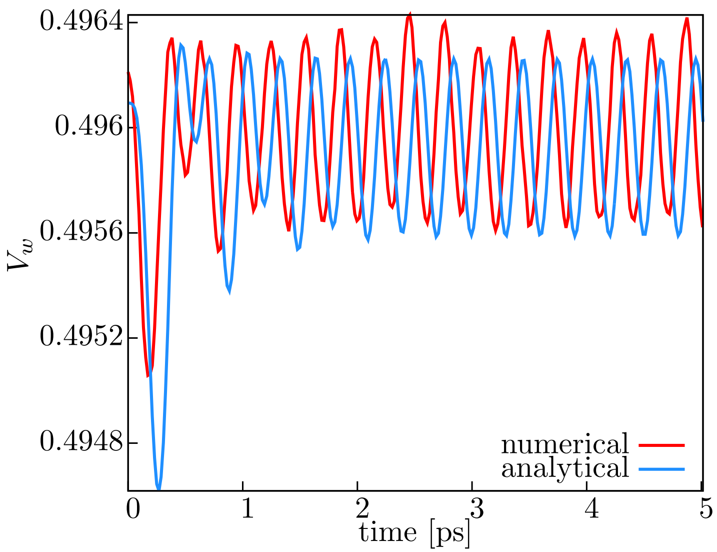
# Reduction in steady state, transient behavior

High temperature expansion

$$V_w \approx \frac{1}{2} - \frac{J_w^2}{16T^2} - \frac{1}{32}\frac{J_w^2}{T^2}\frac{F_0^2}{\gamma^2\omega_m^2} + \frac{21}{512}\frac{J_w^2}{T^2}\frac{F_0^4}{\gamma^4\omega_m^4}$$

Reduction of $T_{eff}$: 5 – 10%

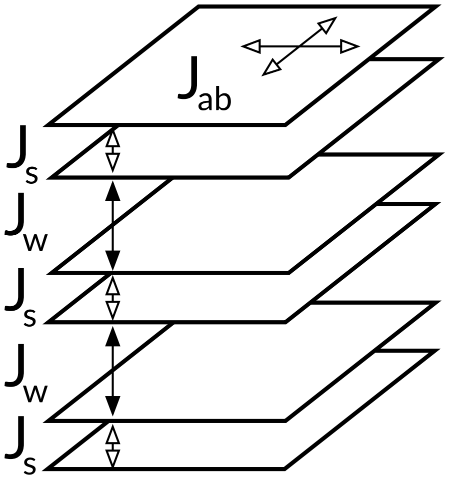



Transient behavior

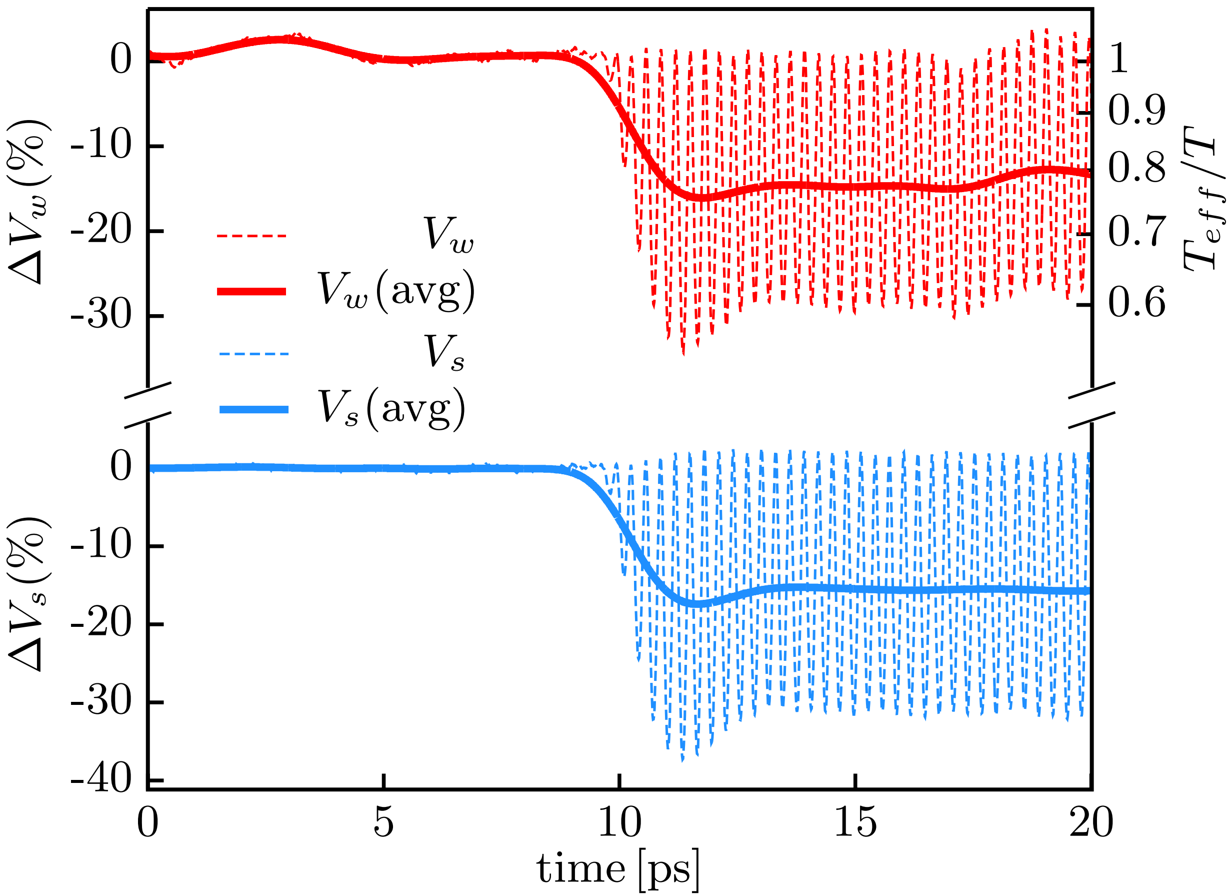
$$t_{tr} = \frac{\gamma}{2TE_c}$$

# Bulk system



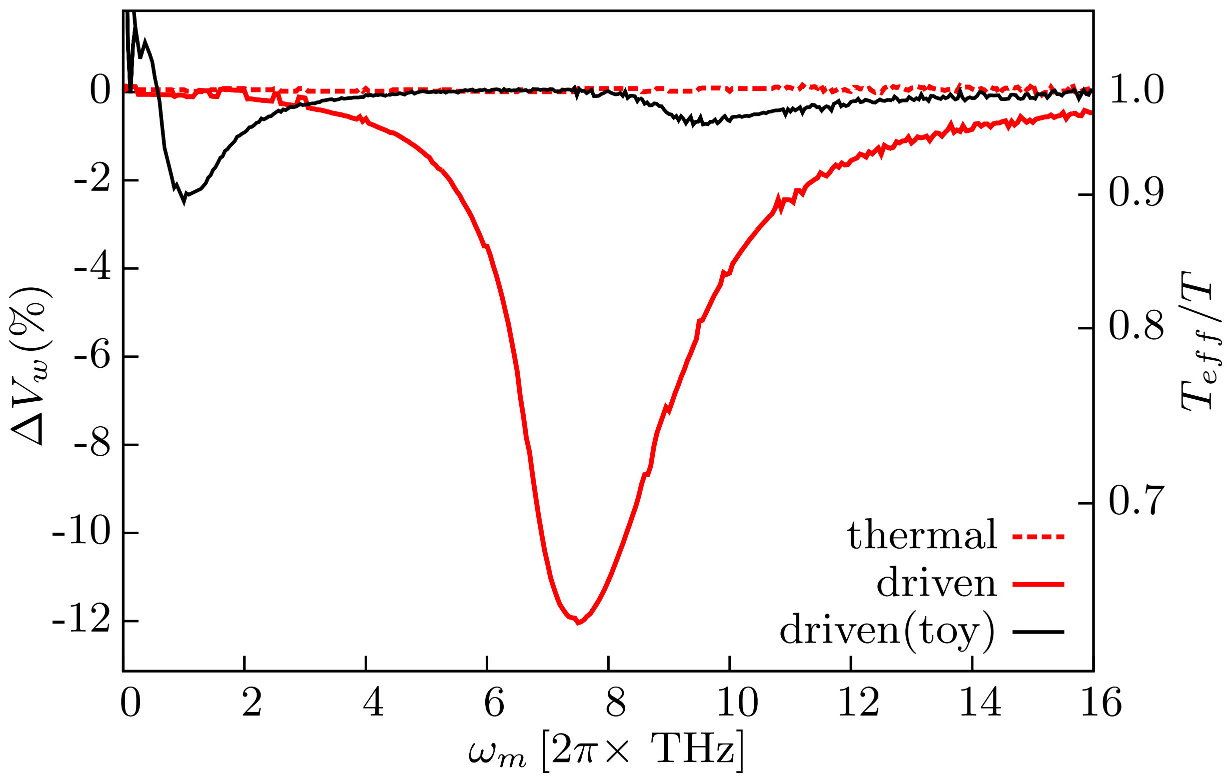

Lattice: 128 * 128 * 4

# Time evolution of the bulk system




- ✓ Qualitatively similar to the toy model
- ✓ Larger reduction of phase fluctuations

# Frequency dependence




- ✓ Strong reduction near high frequency plasmon
- ✓ Feature due to direct driving washed out

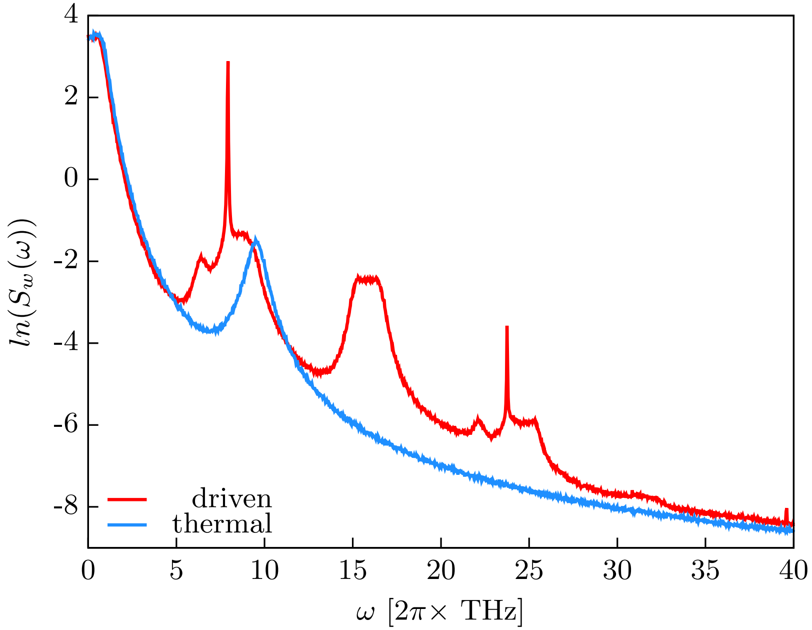
# Power spectrum

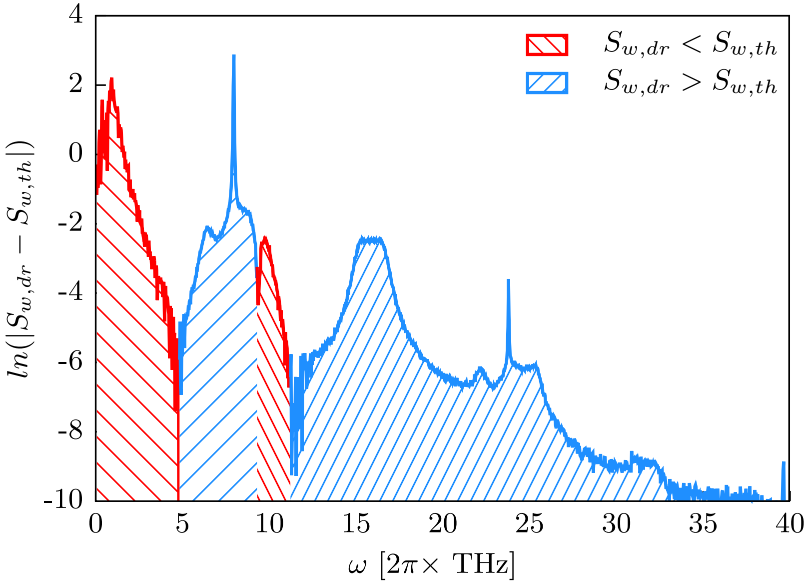
$$S(\omega) = \left\langle j_{w,tot}(-\omega)\, j_{w,tot}(\omega) \right\rangle$$

Sum over a layer

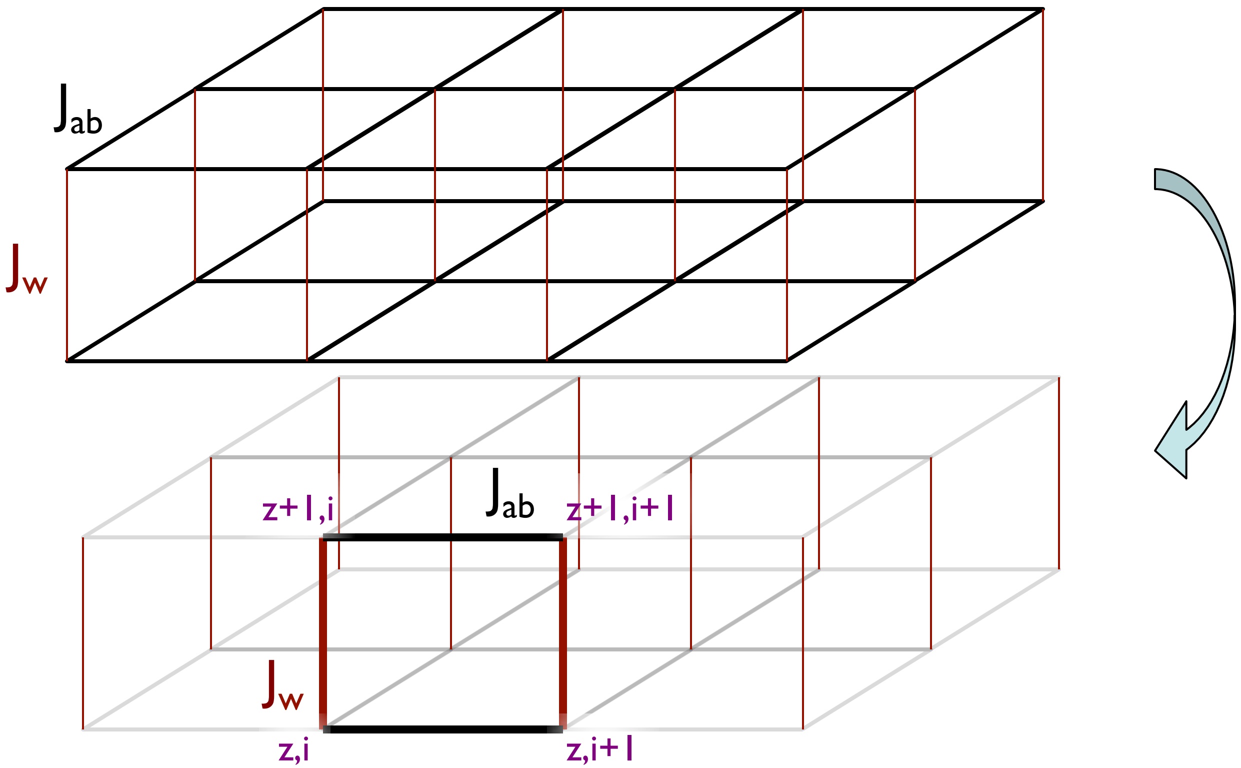
$$j_{w,tot} = \sum_{<ij>} 2J_w \sin(\theta_{ij})$$

- ✓ Suppression of low-frequency modes
- ✓ Enhancement of high frequencies



# Effective single junction model




$$
\begin{aligned}
H &\approx -J_{ab}\left(\cos(\theta_{z+1,i+1}-\theta_{z+1,i})+\cos(\theta_{z,i+1}-\theta_{z,i})\right)\\
&\approx -J_{eff}(T)\cos\left((\theta_{w,i+1}-\theta_{w,i})/2\right)\\
&\approx -J_{eff}(T)\left(\cos(\theta_{w,i}/2)\left\langle\cos(\theta_{w,i+1}/2)\right\rangle+\sin(\theta_{w,i}/2)\left\langle\sin(\theta_{w,i+1}/2)\right\rangle\right)
\end{aligned}
$$

Effective single junction

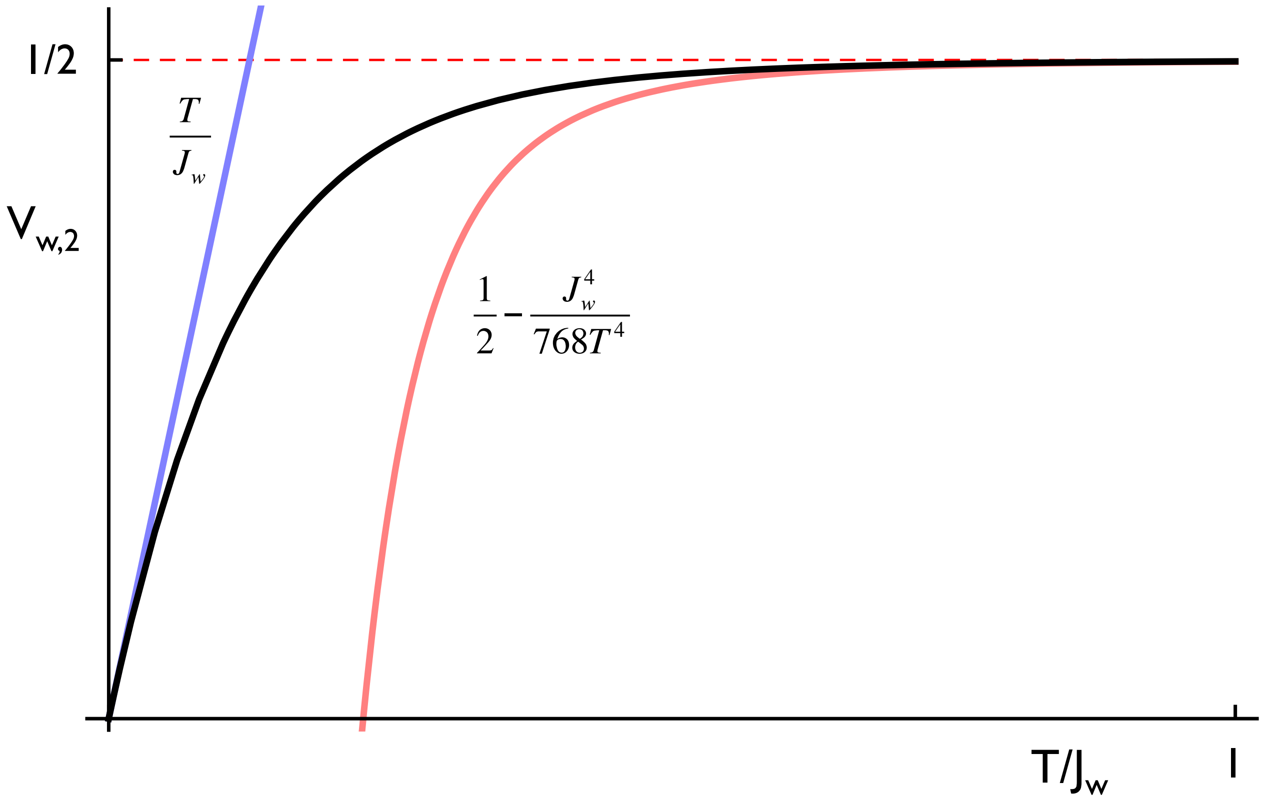
Effective driving

$\cos(\theta/2)$ instead of $\cos(\theta)$

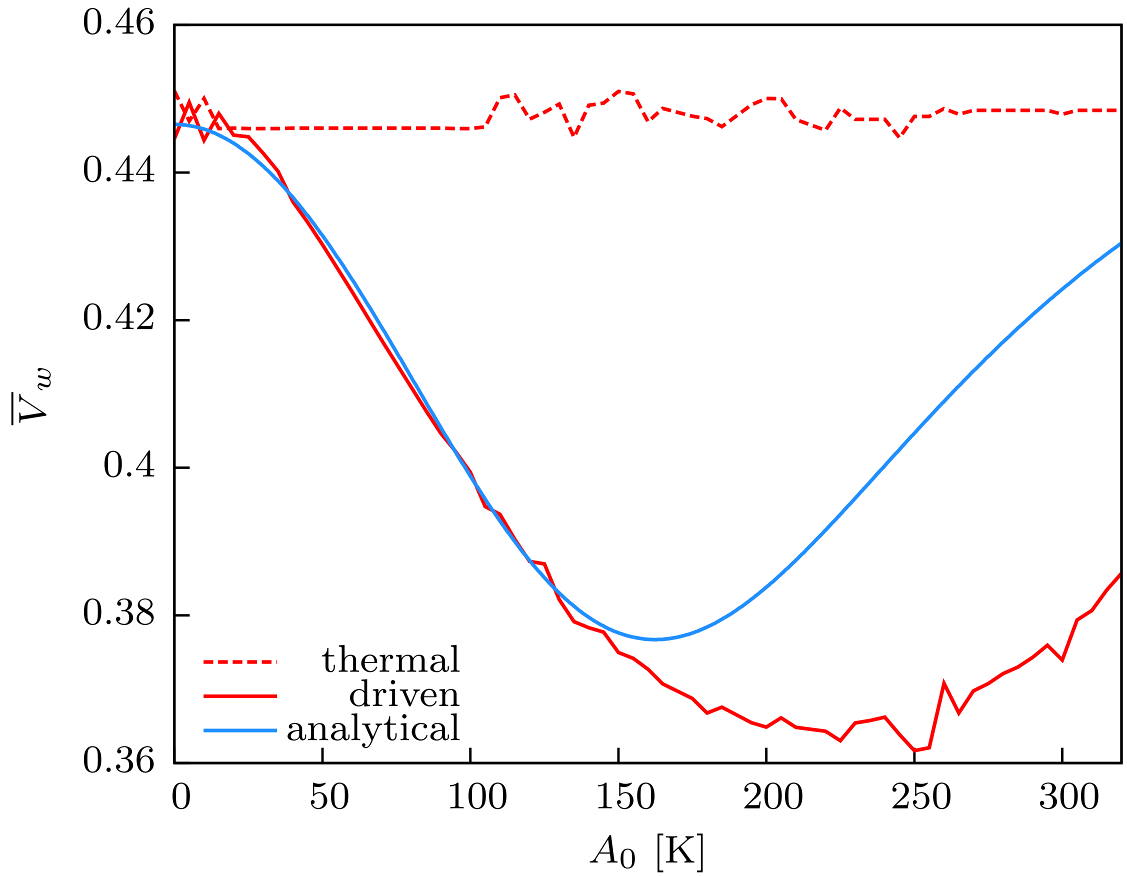
# Effective single junction model for the bulk system

Use $$\dot{\theta} = -\frac{\omega_w^2}{\gamma}\sin\theta + \frac{F_0 \sin(\omega_m t)}{\gamma} + \frac{\xi}{\gamma}$$ with $J_{eff}$ and effective $F_0$

with $$V_{w,2} = \left\langle \sin^2 2\theta_w \right\rangle - \left\langle \sin 2\theta_w \right\rangle^2$$



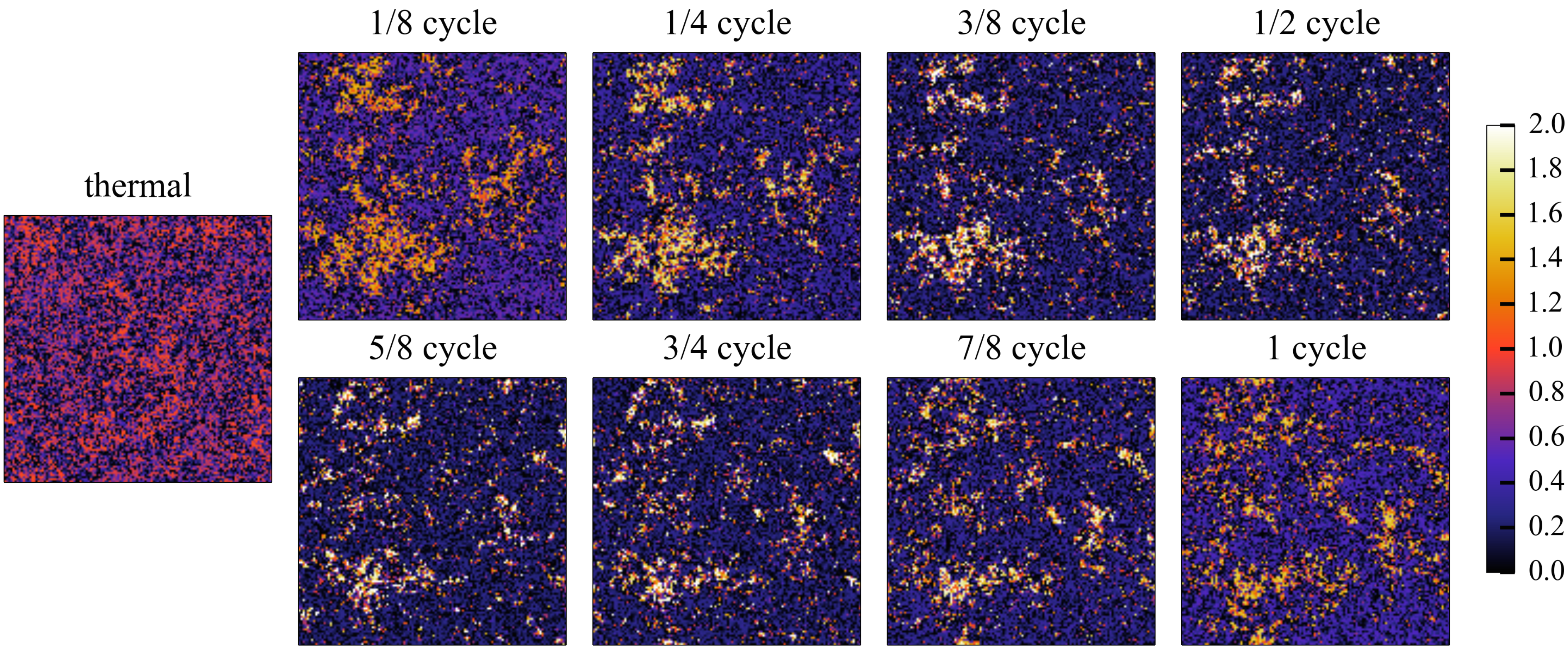
# Amplitude scan




Large reduction captured by effective single junction model

# In-plane dynamics

Current fluctuations $\left(j_w(\vec{r},t)-\bar{j}_w(t)\right)^2$

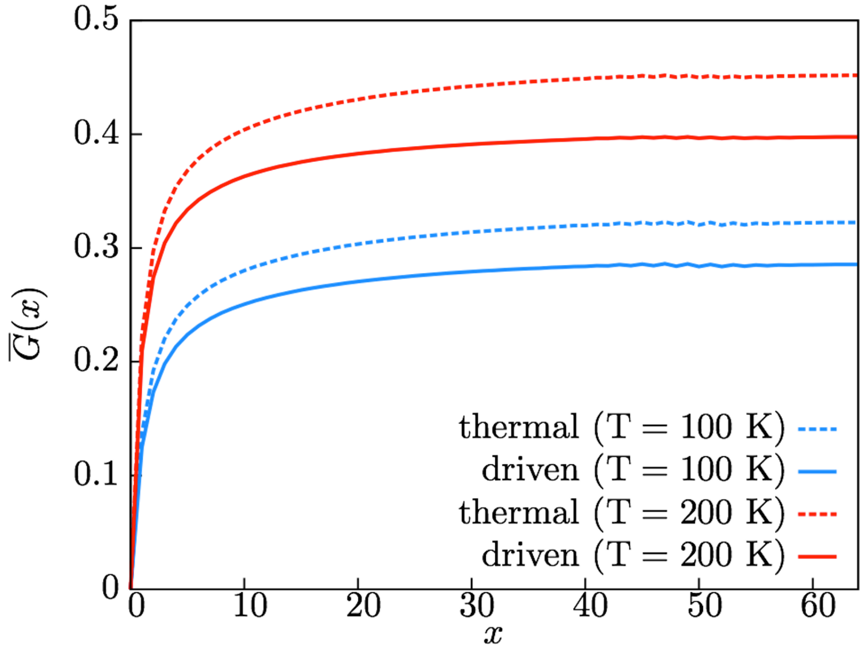



- ✓ Large regions of suppressed fluctuations, ‚hot spots' of enhanced fluctuations
- ✓ Overall periodic breathing

# In-plane current correlations

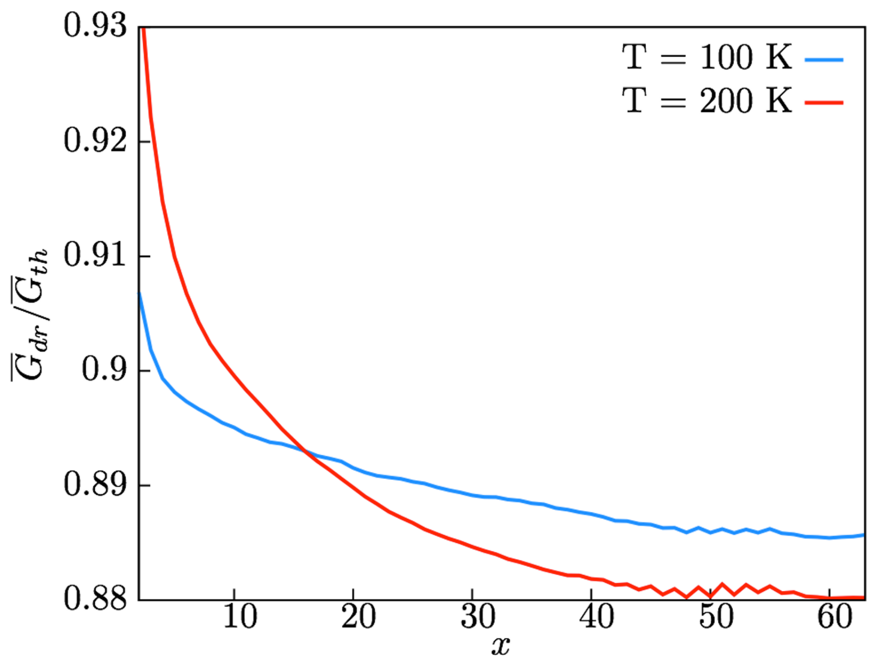
Current fluctuations

$$G(\vec{r},t) \sim \left\langle \left( j_w(0,t) - j_w(\vec{r},t) \right)^2 \right\rangle$$




Overall reduction, esp. at long range

But: correlation length reduced

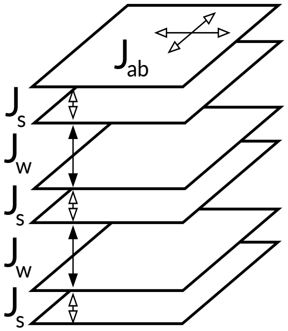



Consistent with:

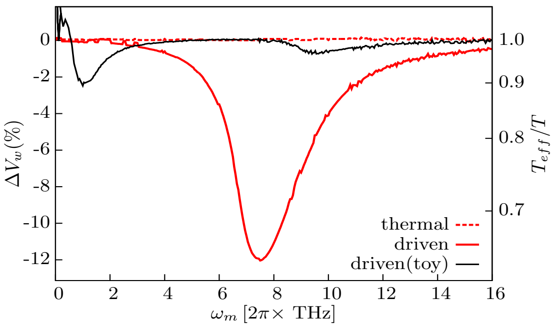
✓ Suppression of low-frequencies

✓ Enhancement of high frequencies

# Conclusions



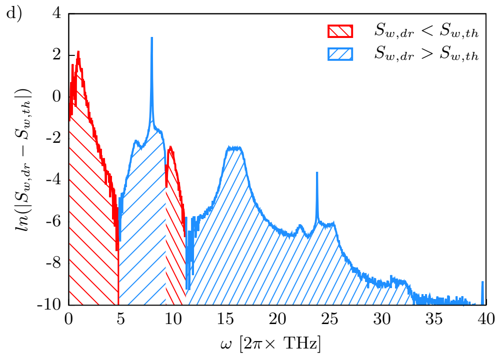

Driven superconductors modelled via layered system of Josephson junctions




Strong reduction of inter-layer phase fluctuations.

In the bulk system: $T_{eff}$ / T ~ 0.6

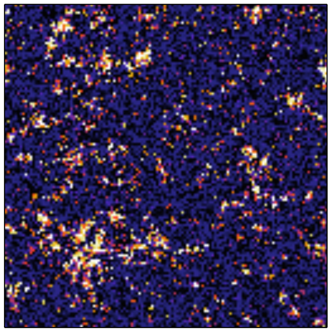
The strong junction serves as an amplifier



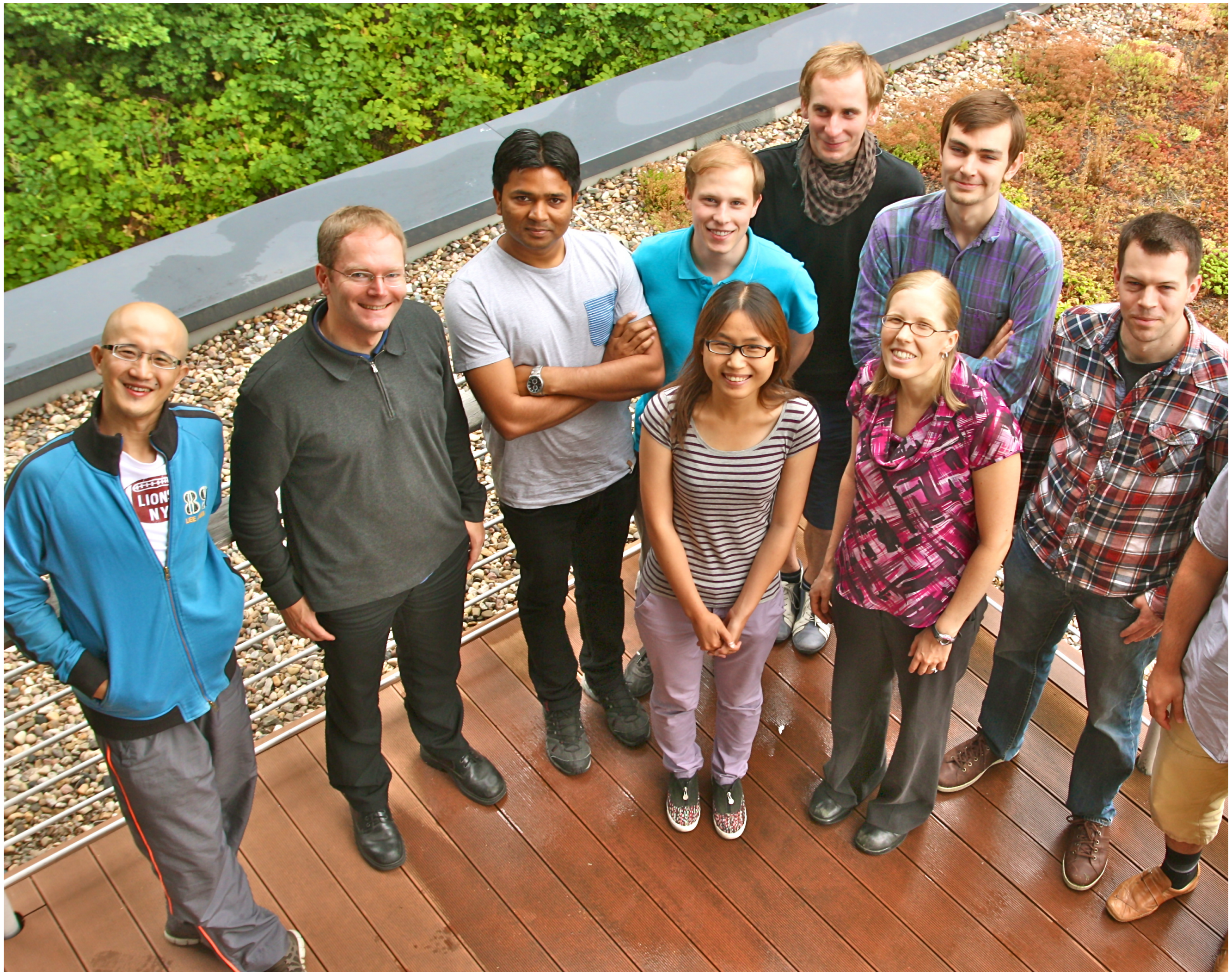

The reduction occurs at low frequencies.

Simultaneous increase of high frequency fluctuations: non-thermal state

In-plane correlations show increased coherence on long-scale



# Team

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