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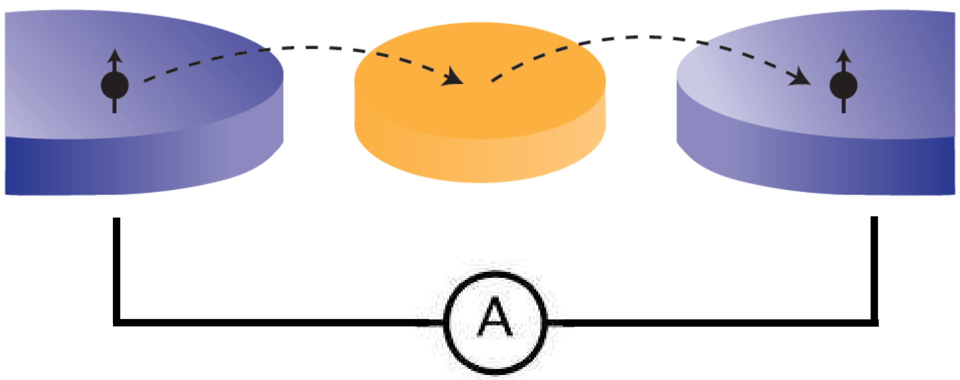
Measuring and controlling quantum transport of heat in trapped-ion crystals

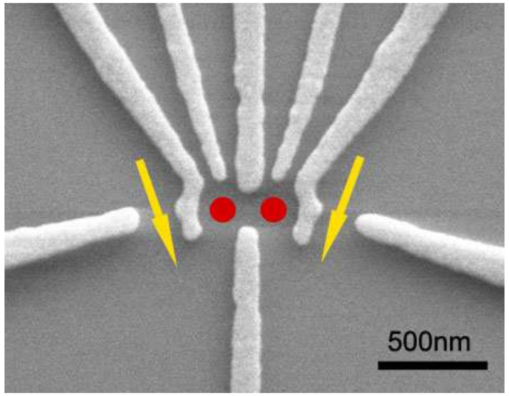
August 14th 2013

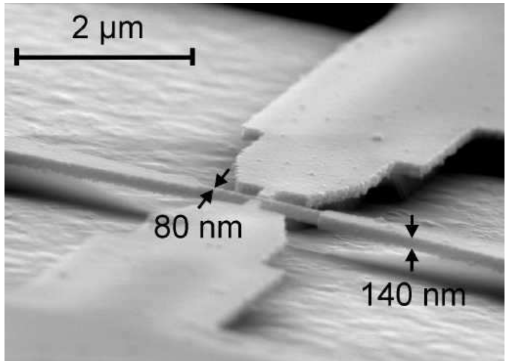
Alejandro Bermudez
Martin Bruderer
Martin B. Plenio

Alexander von Humboldt
Stiftung / Foundation

Nanoscale Electronic Transport

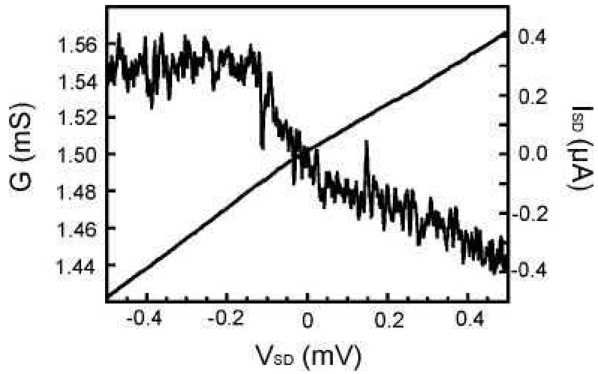






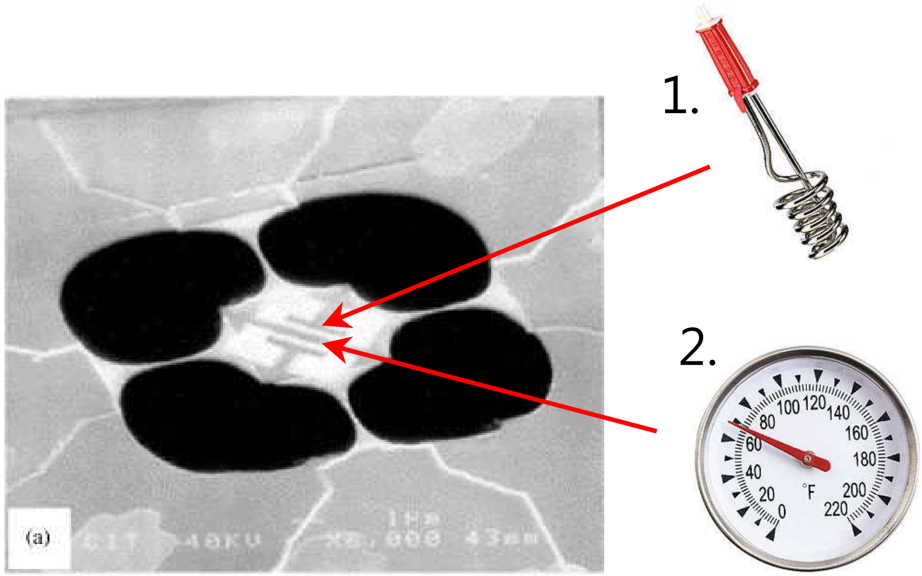
State-of-the-art in electronic transport

- Control current via bias & gate voltage
- Measure electronic currents & fluctuations using amperemeter (pA)
- Charge gives a handle on electrons



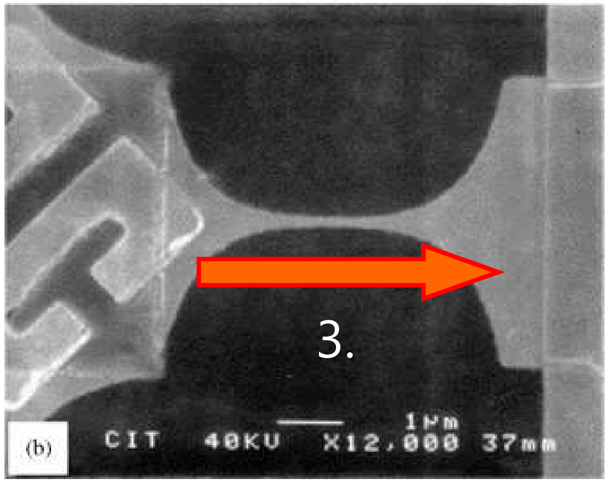
Pictures: Nanophysics Group, LMU München

Nanoscale Heat Transport



Measureing heat currents in nanoscale systems

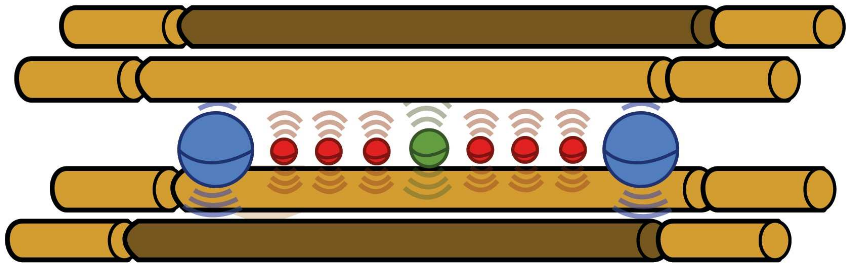
1. Controlled heating
2. Temperature measuremnt
3. Infer heat current from 1. & 2.

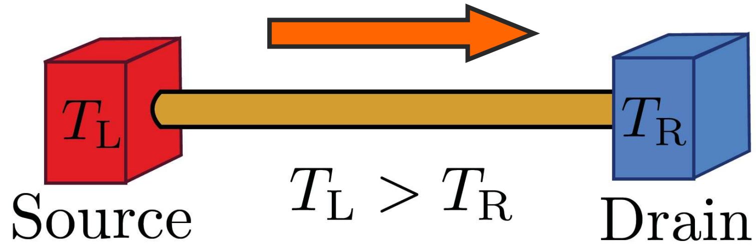


- No ‘ampere meter’ for heat currents
- No charge for heat
- Difficult to control heat currents

K. Schwab, E. A. Henriksen, J. M. Worlock and M. L. Roukes, Nature **404**, 974 (2000)

Trapped-Ion Crystal Toolbox





Ion crystal is made of

- Bulk ions

  Transverse vibrations (vibrons)

  ▹ coupled harmonic oscillators

- Reservoir ions (source & drain)

  Cooled to different temperatures

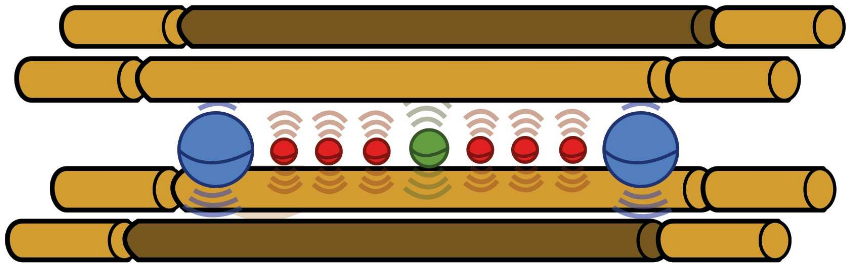
  ▹ induce thermal currents

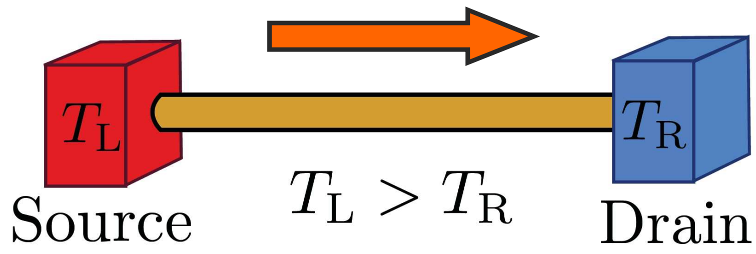
- Probe ions

  Vibrons coupled to internal states

  ▹ 'ampere meter' for heat current

Trapped-Ion Crystal Toolbox





Ion crystal is made of

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- **Reservoir ions (source & drain)**
  Cooled to different temperatures
  ▻ induce thermal currents
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  Vibrons coupled to internal states
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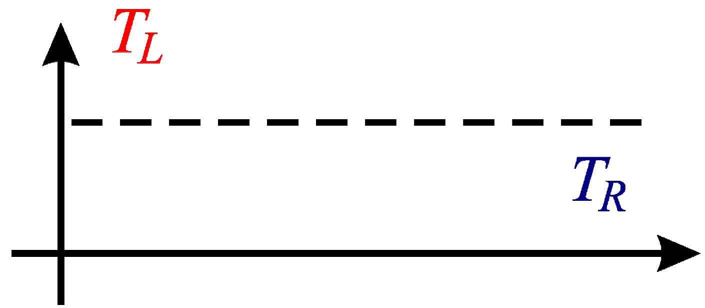
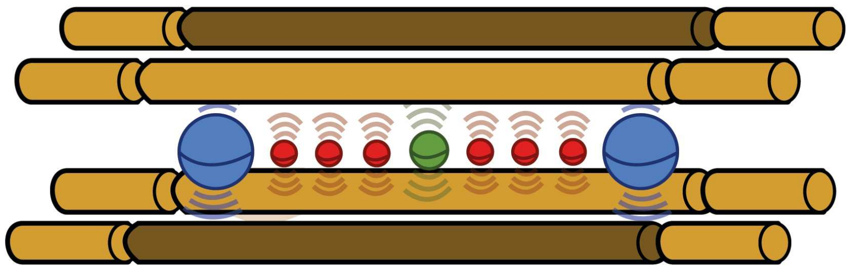
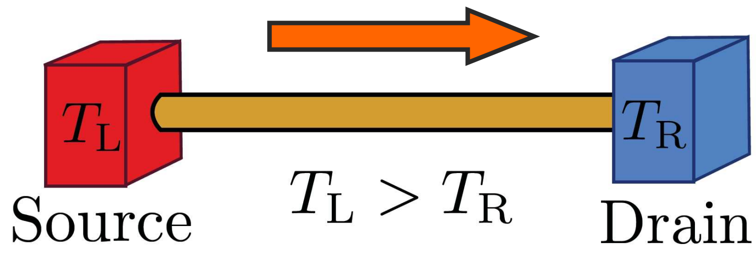


Transition from ballistic to diffusive transport

- Onset of Fourier's law

Trapped-Ion Crystal Toolbox





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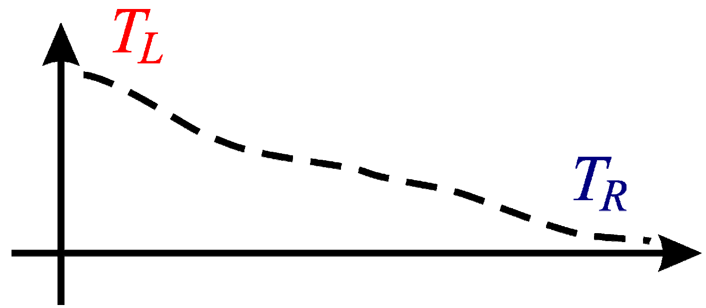
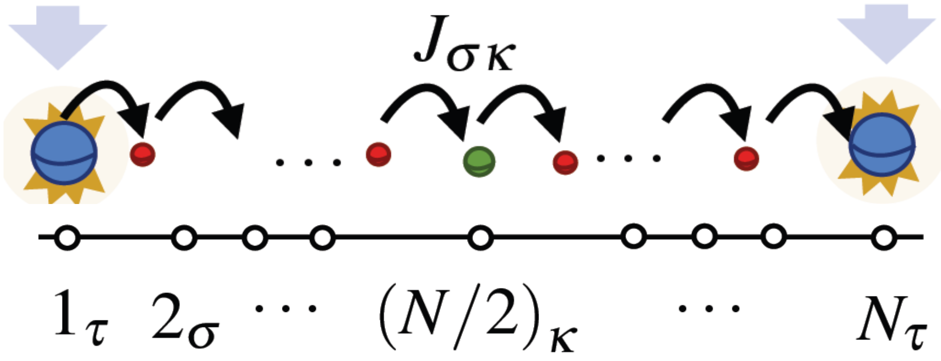


Transition from ballistic to diffusive transport

- Onset of Fourier's law

Vibron Hopping Model



Additional functionality by using internal states

- slow dynamics
- fully controllable

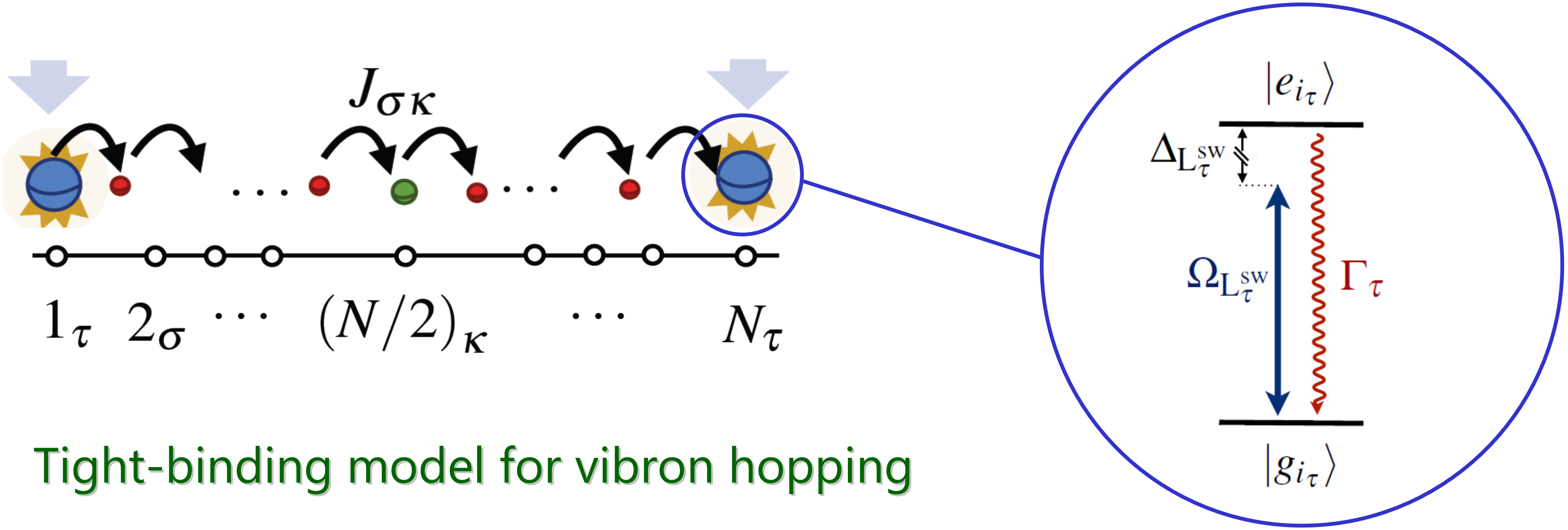
Tight-binding model for vibron hopping

$$H_{\text{tb}} = \sum_{\alpha, i_\alpha} \omega_{i_\alpha} a^\dagger_{i_\alpha} a_{i_\alpha} + \sum_{\alpha,\beta} \sum_{i_\alpha \neq j_\beta} \left(J_{i_\alpha j_\beta} a^\dagger_{i_\alpha} a_{j_\beta} + \text{H.c.} \right)$$

- ▹ small oscillations above ground state
- ▹ coupling via dipole-dipole interaction $J \sim 1/d^3$
- ▹ energy (heat) transport by vibron hopping

D. Porras and J. I. Cirac, PRL **93**, 263602 (2004)

Heat Reservoirs



Tight-binding model for vibron hopping

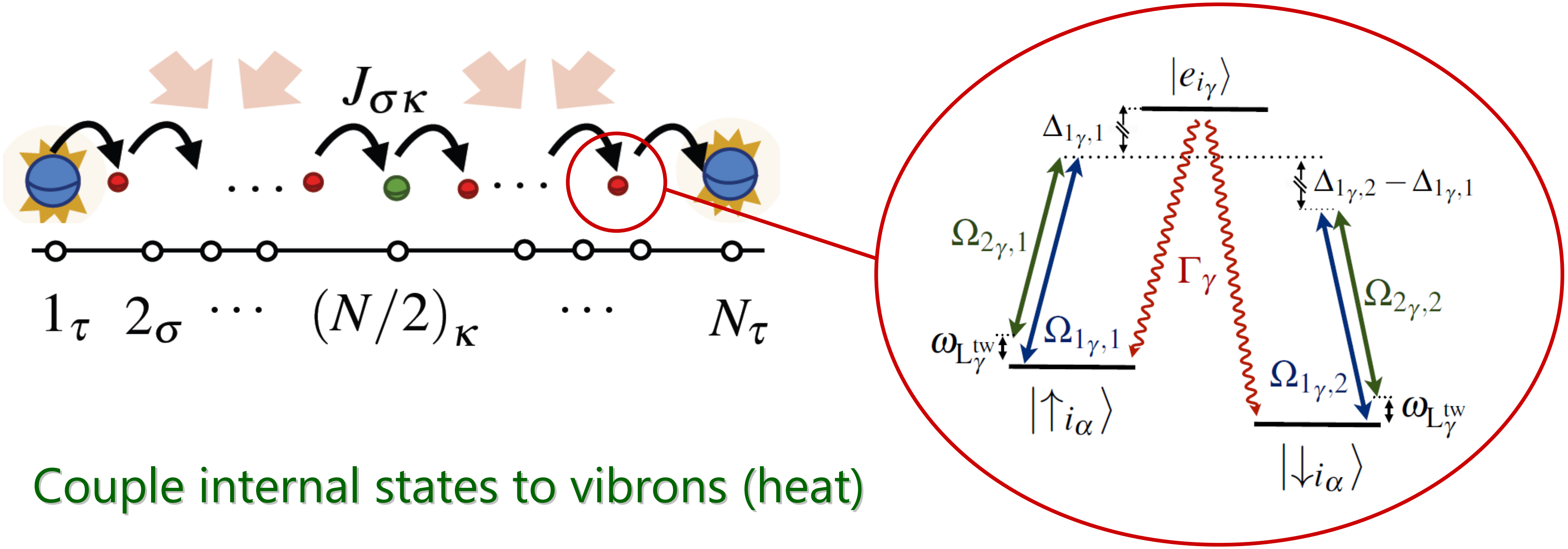
$$H_{\text{tb}} = \sum_{\alpha, i_\alpha} \omega_{i_\alpha} a_{i_\alpha}^\dagger a_{i_\alpha} + \sum_{\alpha,\beta} \sum_{i_\alpha \neq j_\beta} (J_{i_\alpha j_\beta} a_{i_\alpha}^\dagger a_{j_\beta} + \text{H.c.})$$

Doppler cooling of edge ions at rate

$$\mathscr{D}^{i_\alpha}(\mu) = \mathscr{D}[\Lambda_{i_\alpha}^+, a_{i_\alpha}^\dagger, a_{i_\alpha}](\mu) + \mathscr{D}[\Lambda_{i_\alpha}^-, a_{i_\alpha}, a_{i_\alpha}^\dagger](\mu)$$

- Effective cooling rate $\gamma_{i_\alpha} = \text{Re}\{(\Lambda_{i_\alpha}^-)^* - \Lambda_{i_\alpha}^+\}$
- Doppler cooling much faster than hopping $\gamma_{i_\alpha} \gg J_{i_\alpha, j_\beta}$

Spin-Vibron Coupling



Couple internal states to vibrons (heat)

$$H_{\rm SV}^{i_\alpha}(t) = \tfrac{1}{2}(\Delta\omega_\alpha^+ + \Delta\omega_\alpha^- \sigma_{i_\alpha}^z)\cos(\nu_\alpha t - \varphi_\alpha) a_{i_\alpha}^\dagger a_{i_\alpha}$$

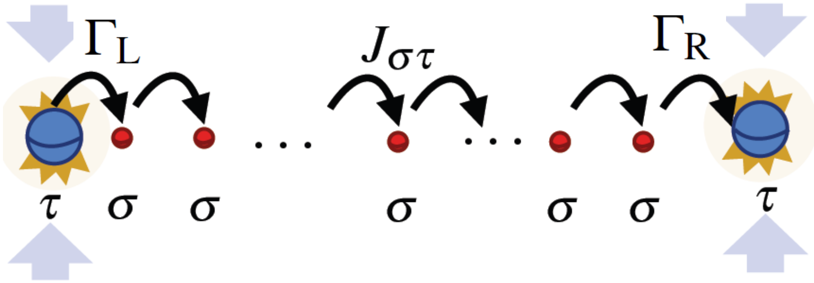
- internal states (spins) $|\uparrow\rangle$, $|\downarrow\rangle$
- two-photon transition

(1) $H_{\rm SV}^{i_\alpha}(t) = \tfrac{1}{2}\Delta\omega_\alpha^+ \cos(\nu_\alpha t)\, a_{i_\alpha}^\dagger a_{i_\alpha}$ ▹ Photon-assisted tunneling

(2) $H_{\rm SV}^{i_\alpha} = \tfrac{1}{2}\Delta\omega_\alpha^- \sigma_{i_\alpha}^z\, a_{i_\alpha}^\dagger a_{i_\alpha}$ ▹ Probing & Disorder

What physics can we do?

Ballistic Transport



Assume $\gamma_{\ell_\tau} \gg J_{i_\alpha j_\beta}$ and project dynamics onto state $\mu_{1_\tau}^{\text{th}} \otimes \mu_{\text{bulk}} \otimes \mu_{N_\tau}^{\text{th}}$

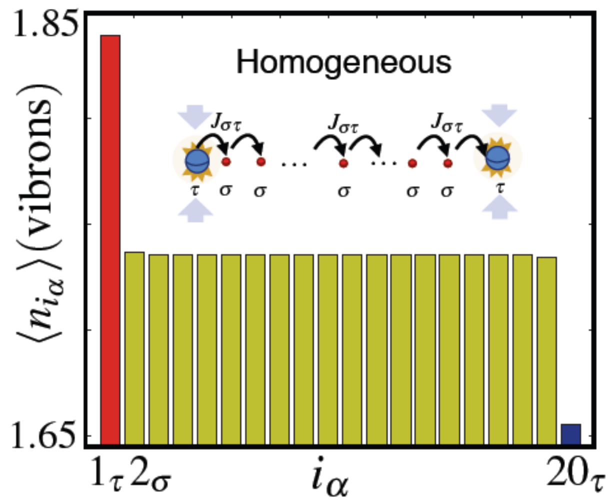
$$\langle n_{i_\alpha} \rangle_{\text{ss}} = \frac{\Gamma_L \bar{n}_L + \Gamma_R \bar{n}_R}{\Gamma_L + \Gamma_R}$$

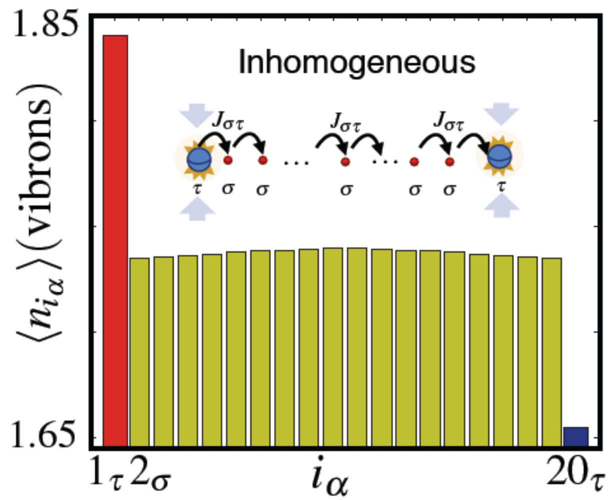
$$\langle I^{\text{vib}}_{\rightarrow i_\alpha} \rangle_{\text{ss}} = \frac{\Gamma_L \Gamma_R}{\Gamma_L + \Gamma_R} (\bar{n}_L - \bar{n}_R)$$

$$\Gamma^{\ell_\tau}_{i_\alpha, j_\beta} = 2\pi J_{i_\alpha,\ell_\tau} \rho_{\ell_\tau}(\omega_{i_\alpha}) J_{\ell_\tau, j_\beta}$$

Ballistic tranport of vibrons across TQW

Vibron occupations in TQW





Spin-Induced Binary Disorder

Strong spin-vibron coupling

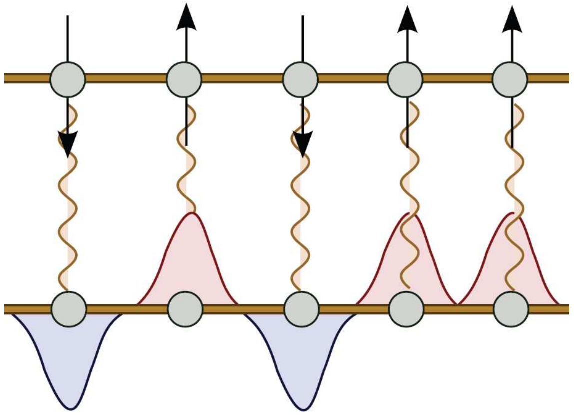
$$H_{\rm SV}^{i_\alpha}(t) = \tfrac{1}{2}\Delta\omega_\alpha^- \sigma_{i_\alpha}^z a_{i_\alpha}^\dagger a_{i_\alpha}$$

Spins in superposition

$$|+_{i_\alpha}\rangle = (|\uparrow_{i_\alpha}\rangle + |\downarrow_{i_\alpha}\rangle)/\sqrt{2}$$

Tight-binding model with disorder

$$H_{\rm stb} = \sum_{\alpha, i_\alpha} \varepsilon_{i_\alpha} a_{i_\alpha}^\dagger a_{i_\alpha} + \sum_{\alpha,\beta} \sum_{i_\alpha \neq j_\beta} (J_{i_\alpha j_\beta} a_{i_\alpha}^\dagger a_{j_\beta} + \text{H.c.})$$



Binary diagonal disorder

$$\varepsilon_{i_\alpha} \in \{\omega_\alpha - \tfrac{1}{2}\Delta\omega_\alpha^-, \omega_\alpha + \tfrac{1}{2}\Delta\omega_\alpha^-\}$$

Exploit "quantum parallelism"

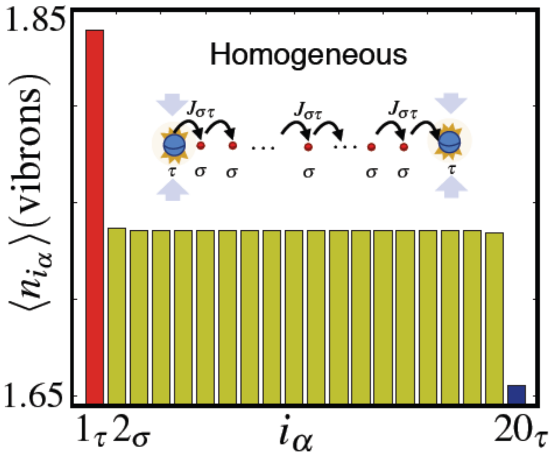
B. Paredes, F. Verstraete & J. I. Cirac, PRL **95**, 140501 (2005)

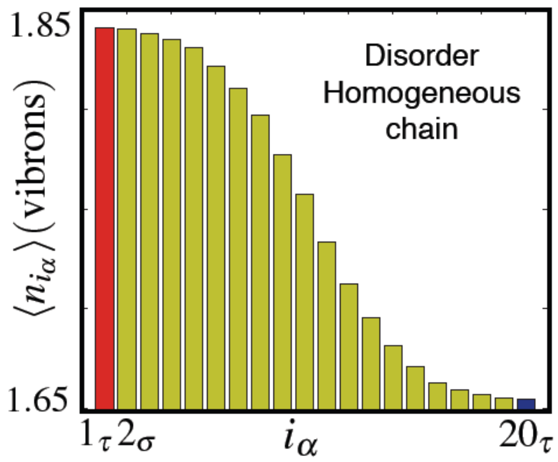
A. Bermudez, M. A. Martin-Delgado & D. Porras, New J. Phys. **12**, 123016 (2010)

Fourier's Law

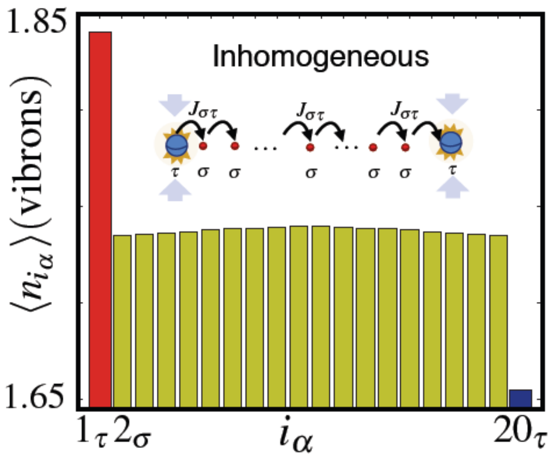
Ballistic | Diffusive

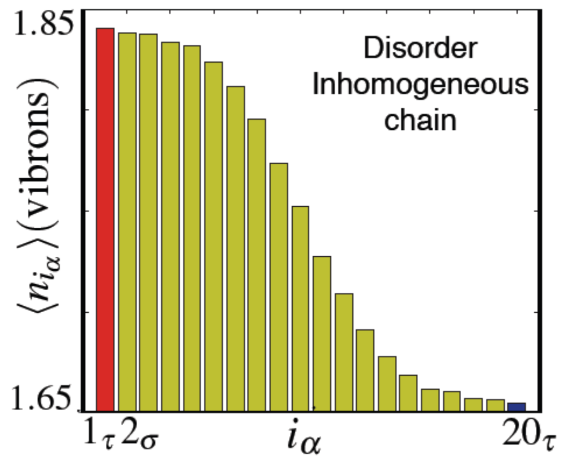
Homogeneous





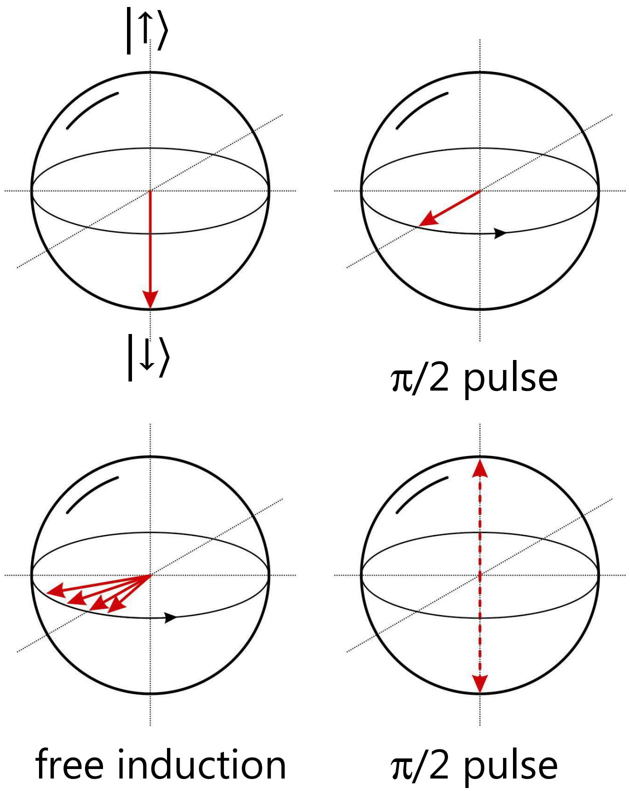
Inhomogeneous

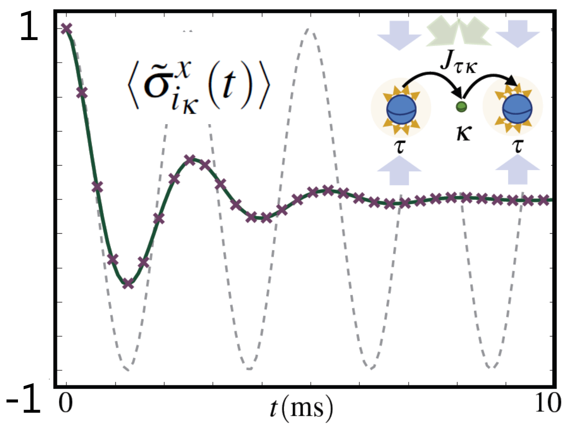




Clear signature for the onset of Fourier's law

Non-Invasive Ramsey Probe





Operator couples weakly to spin

$$H_{\rm SV} = \frac{1}{2}\lambda O_{i_\alpha}\sigma^z_{i_\alpha}$$

Spin evolution

$$\langle\tilde{\sigma}^x_{i_\alpha}(t)\rangle = \cos(\lambda\langle O_{i_\alpha}\rangle_{\rm ss}t)e^{-\lambda^2{\rm Re}\{S_{O_{i_\alpha}O_{i_\alpha}}(0)\}t}$$

$$S_{O_{i_\alpha}O_{i_\alpha}}(\omega) = \int_0^\infty {\rm d}t\,\langle\tilde{O}_{i_\alpha}(t)\tilde{O}_{i_\alpha}(0)\rangle_{\rm ss}e^{-i\omega t}$$

$$\tilde{O}_{i_\alpha} = O_{i_\alpha} - \langle\tilde{O}_{i_\alpha}\rangle_{\rm ss}$$

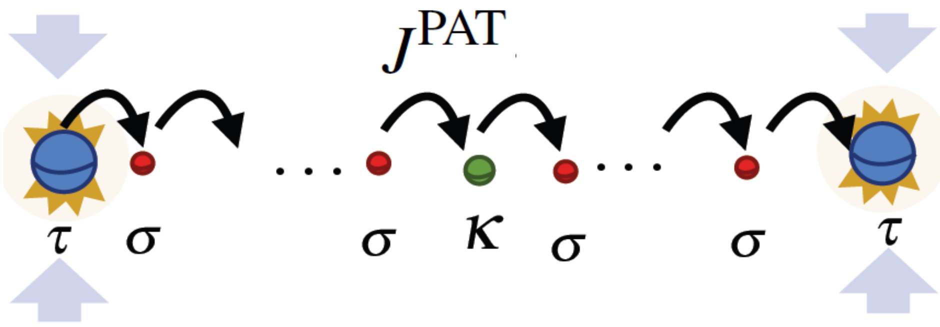
- Oscillations with frequency ~ ⟨O⟩
- Damping by fluctuations ~ $\langle\delta O^2\rangle$

Measure occupations and thermal currents.

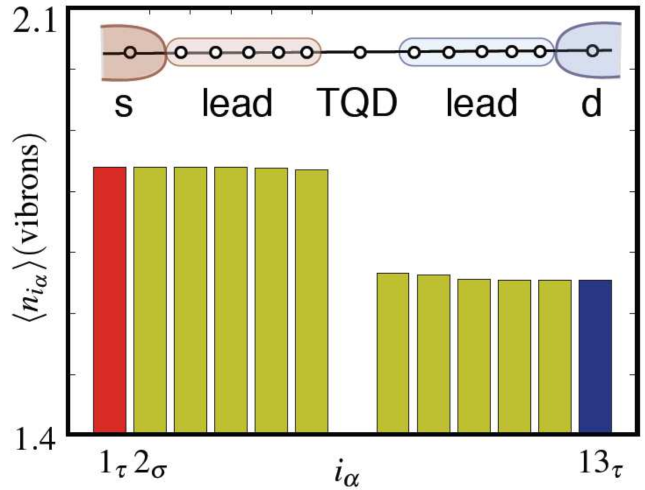
MB and D. Jaksch, New J. Phys. **8**, 87 (2006)

G. B. Lesovik, F. Hassler & G. Blatter, PRL **96**, 106801 (2006)

Single site & thermal leads



$$|{\downarrow_\sigma} \cdots {\downarrow_\sigma}\rangle |\phi_\kappa\rangle |{\uparrow_\sigma} \cdots {\uparrow_\sigma}\rangle$$



Photon-assisted tunneling

$$H_{\text{SV}}^{i_\alpha}(t) = \frac{1}{2}\Delta\omega_\alpha^{+} \cos(\nu_\alpha t)\, a_{i_\alpha}^{\dagger} a_{i_\alpha}$$

$$H_{\text{L}\kappa\text{R}}^{\text{PAT}} = \sum_{i_\sigma} (J_{i_\sigma, p_\kappa}^{\text{PAT}} a_{i_\sigma}^{\dagger} a_{p_\kappa} + \text{H.c.})$$

- Full control of coupling to leads

Energy mismatch left/right

$$H_{\text{SV}}^{i_\alpha}(t) = \frac{1}{2}\Delta\omega_\alpha^{-} \sigma_{i_\alpha}^{z} a_{i_\alpha}^{\dagger} a_{i_\alpha}$$

Bosons versus Fermions

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Same averages for fermions and bosons

$$\langle n_{i\alpha} \rangle_{ss} = \frac{\Gamma_L \bar{n}_L + \Gamma_R \bar{n}_R}{\Gamma_L + \Gamma_R}$$

$$\langle I^{vib}_{\rightarrow i\alpha} \rangle_{ss} = \frac{\Gamma_L \Gamma_R}{\Gamma_L + \Gamma_R} (\bar{n}_L - \bar{n}_R)$$

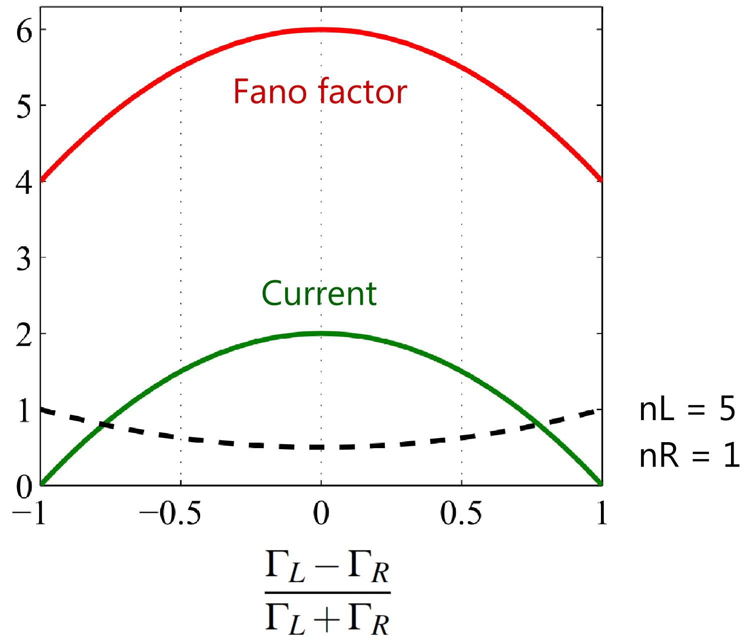
Fluctuations distinguish bosons/fermions

$$F = \frac{\langle O^2 \rangle - \langle O \rangle^2}{\langle O \rangle} \equiv \frac{\langle \delta O^2 \rangle}{\langle O \rangle}$$

Fano factor

Poissonian F = 1

Mandel Q = F - 1



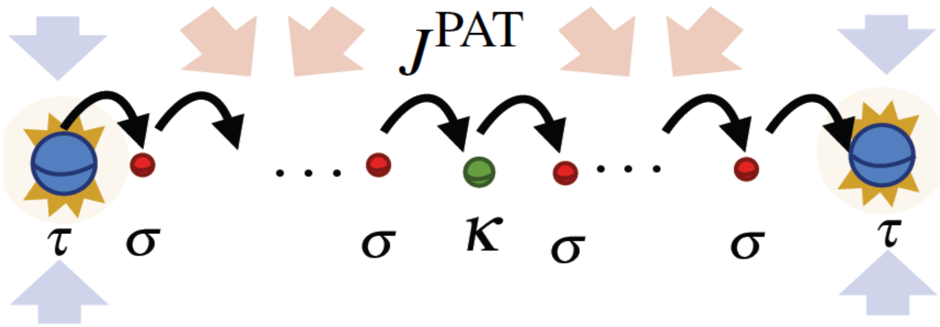
	Fermions	Bosons	Classical
Occupation	1 – ⟨n⟩	1 + ⟨n⟩	⟨n⟩
Current*	1 – ½nL	1 + ½nL	1

* nR = 0 and symmetric coupling

Fluctuations reveal bosonic nature of thermal currents.

M. Esposito, U. Harbola & S. Mukamel, Rev. Mod. Phys. **81**, 1665 (2009)

Nonequilibrium Schrödinger's Cat



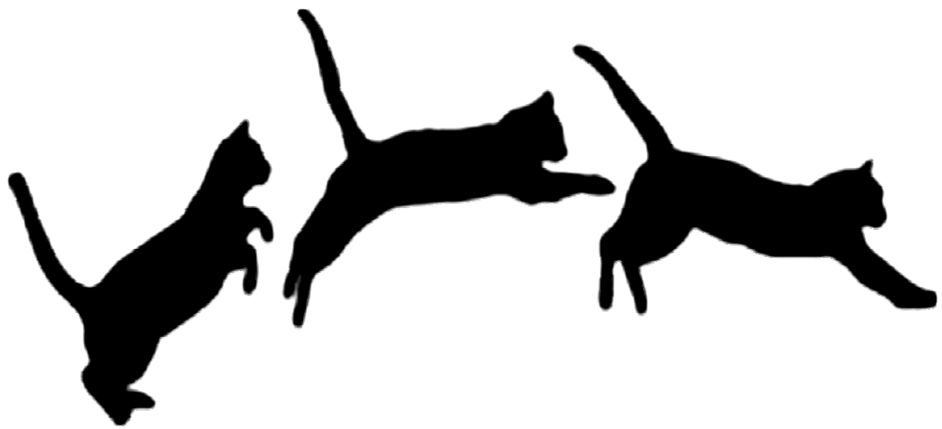
Thermal currents more resilient to decoherence than electronic currents!

Single-spin heat switch

- Spin of TQD controls current

$$J^{\mathrm{PAT}}_{p_\kappa i_\sigma}(\sigma^z_{p_\kappa})|\downarrow_{p_\kappa}\rangle = 0$$

$$J^{\mathrm{PAT}}_{p_\kappa i_\sigma}(\sigma^z_{p_\kappa})|\uparrow_{p_\kappa}\rangle \neq 0$$

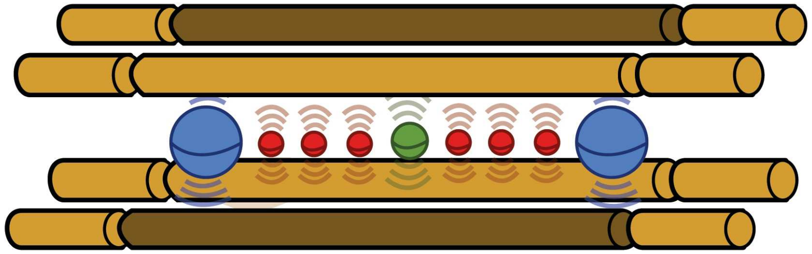


- Superposition of heat current on/off

Conclusions

Thermal reservoirs

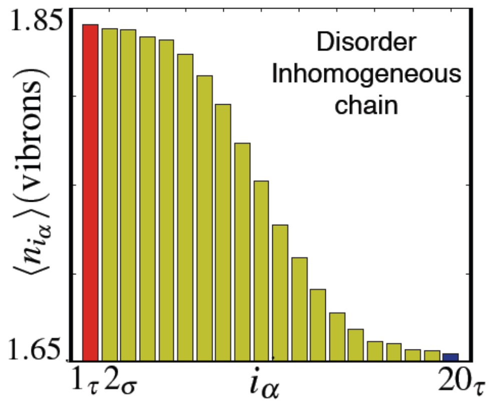
Doppler cooling



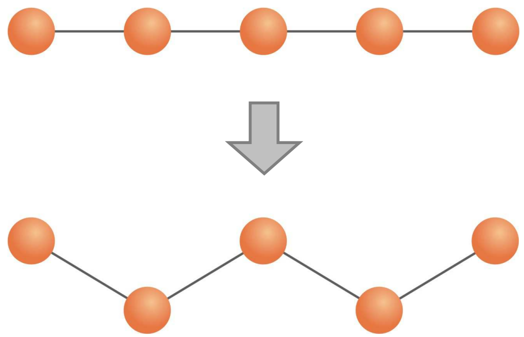
Ampere meter & thermometer

Spin-vibron coupling

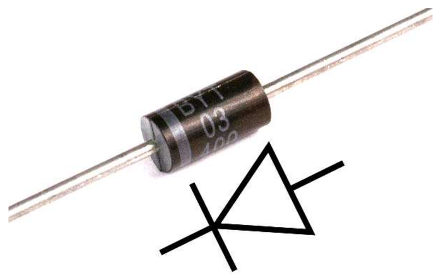
Fourier's law



Zig-zag crossover



Thermal diode & quantum dot



Details in A. Bermudez, MB & M. B. Plenio, PRL **111**, 040601 (2013)