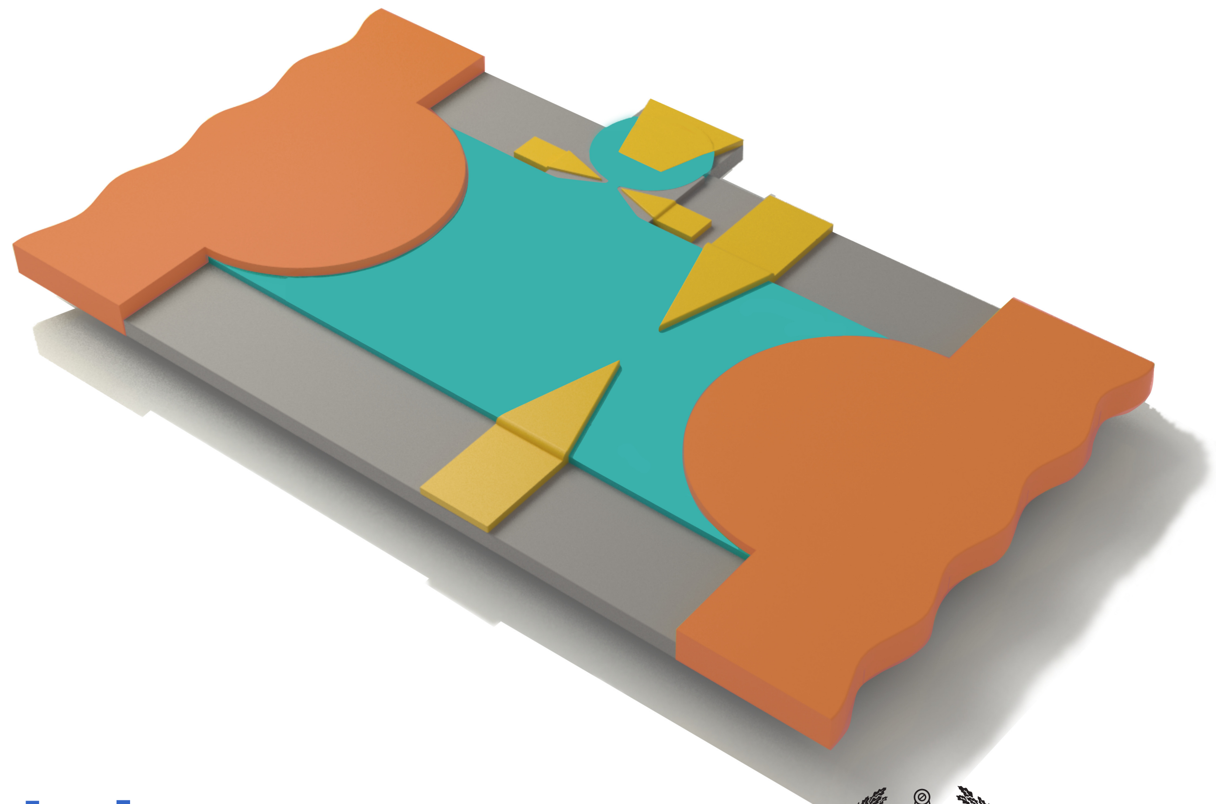
Heat current and fluctuations of single-electron excitations: Fundamental properties and detection



Nastaran Dashti,

Janine Splettstoesser, Maciej Misiorny,

Peter Samuelsson

Outline

Introducing single-electron sources (SES)

Relevant Observables as a tool to characterize SES

How to detect observables?

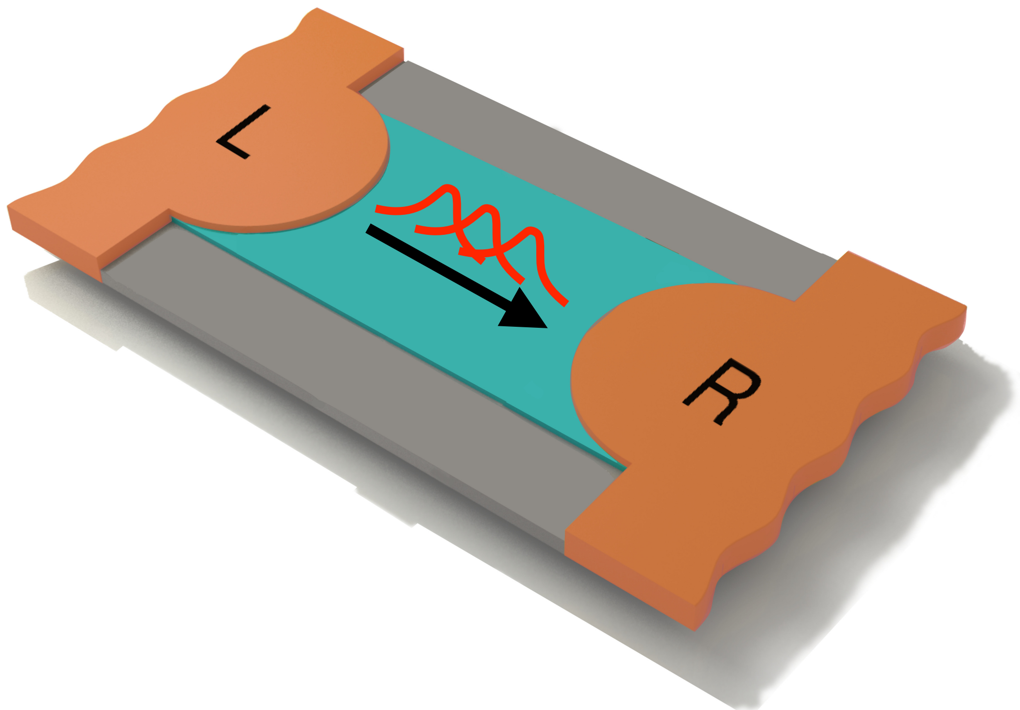
Detection scheme

Reading out Observables

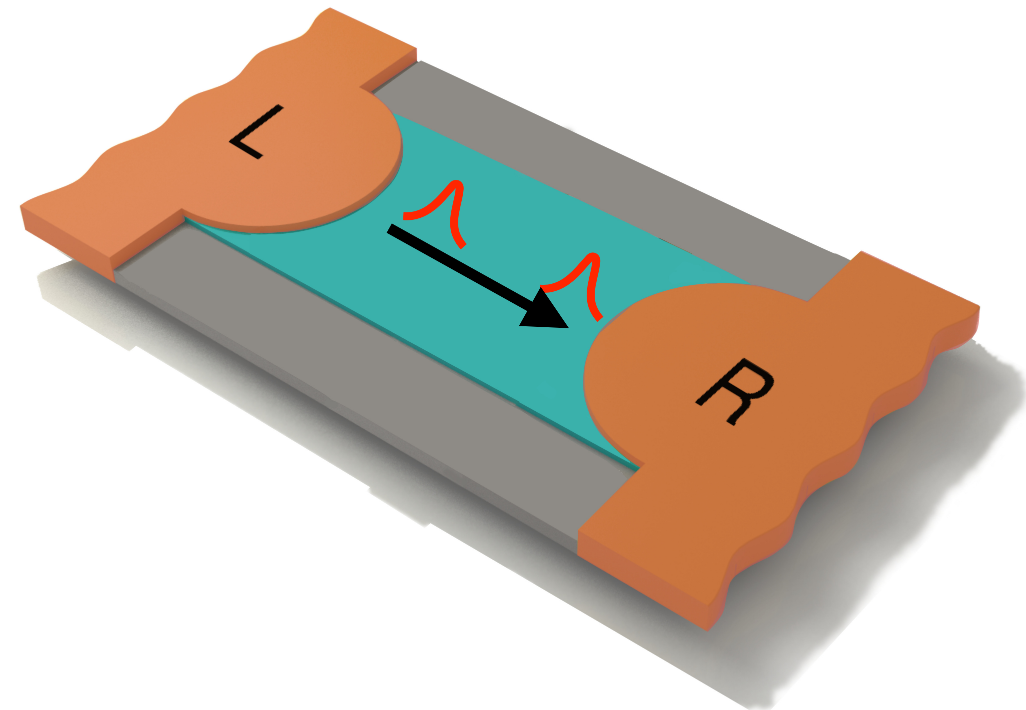
Outlook: Energy-resolved detection

Why single electron sources?

Many electrons sources



Single electron sources (SES)



control over emitted electrons

What are the properties of emitted electrons?

On-demand single-electron source

Superconducting turnstiles:

Pekola, Jukka P. et al., Nat. Phys. **4**, 120 (2007)

Surface acoustic wave :

K. Flensberg et al., Int. J. Mod. Phys. B **13**, 2651 (1999); R. P. G. McNeil et al., Nature **477**, 439 (2011); S. Hermelin et al., Nature **477**, 435 (2011)

Dynamical quantum dots:

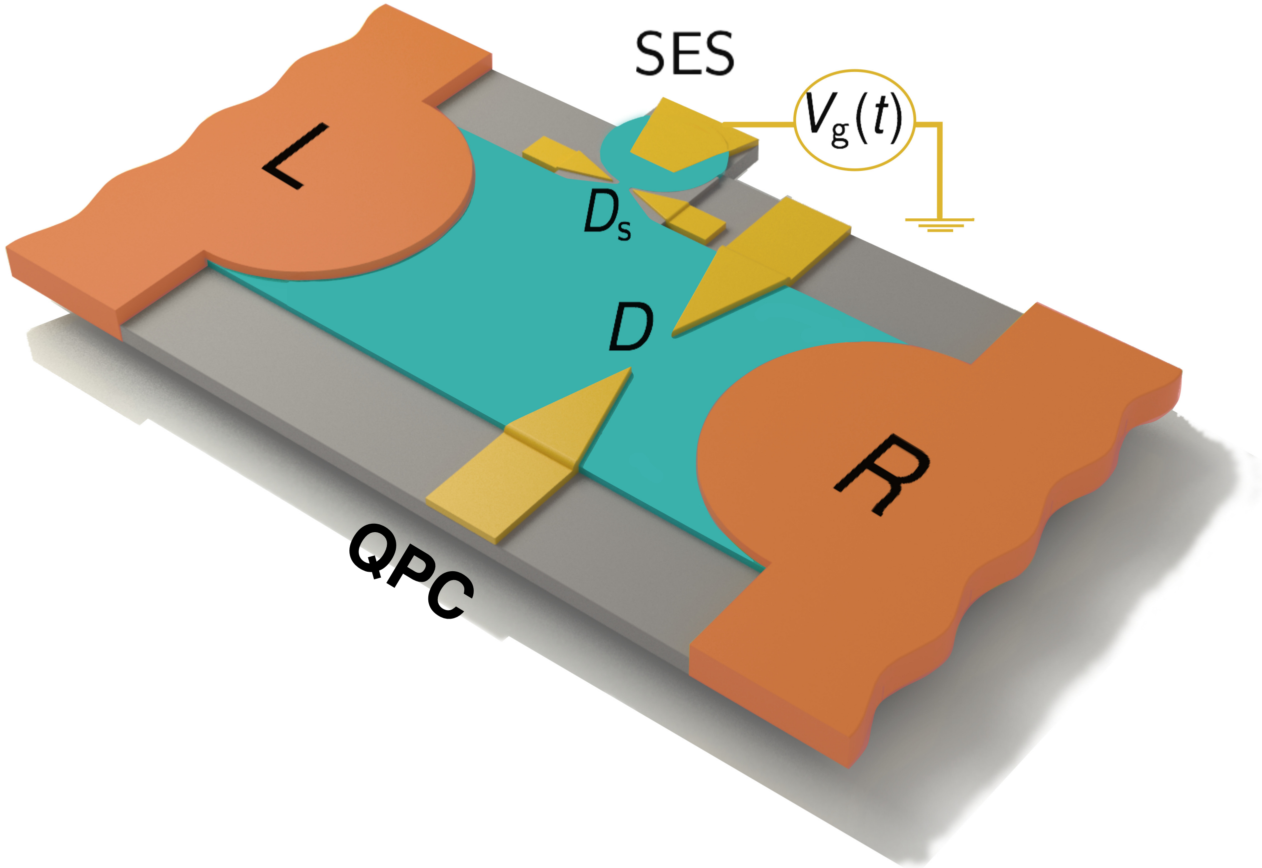
C. Leicht et al., Semicond. Sci. Technol. **26**, 055010 (2011); M. D. Blumenthal et al., Nat. Phys. **3**, 343 (2007)

Lorentzian-shaped time-dependent bias voltage (Leviton)

Dubois, J. et al., Nature **502**, 659 (2013);T. Jullien et al., Nature **514**, 603 (2014)

On-demand single-electron source

Slowly time-dependently driven mesoscopic capacitor



Experiment: Gabelli, J. et al., *Science* **313**, 499 (2006); Fève, G. et al. Science **316,**1169 (2007)

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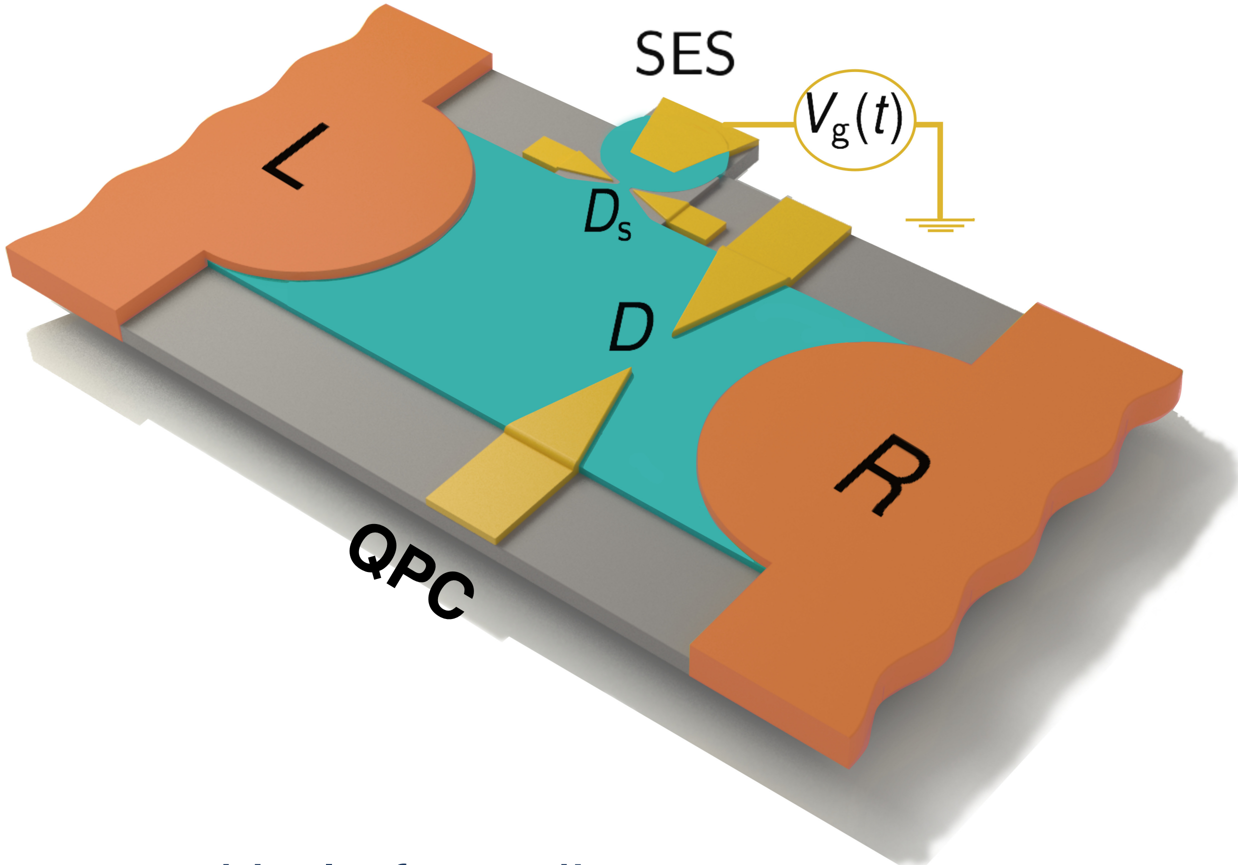
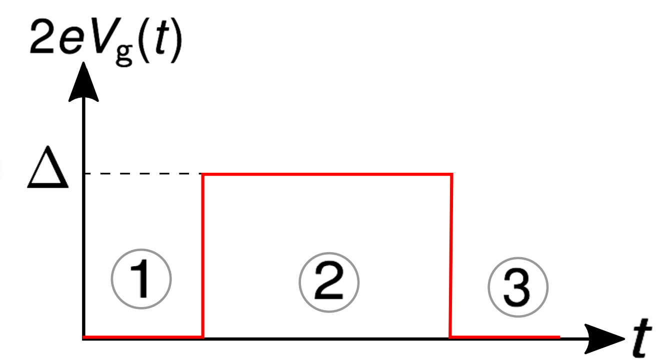
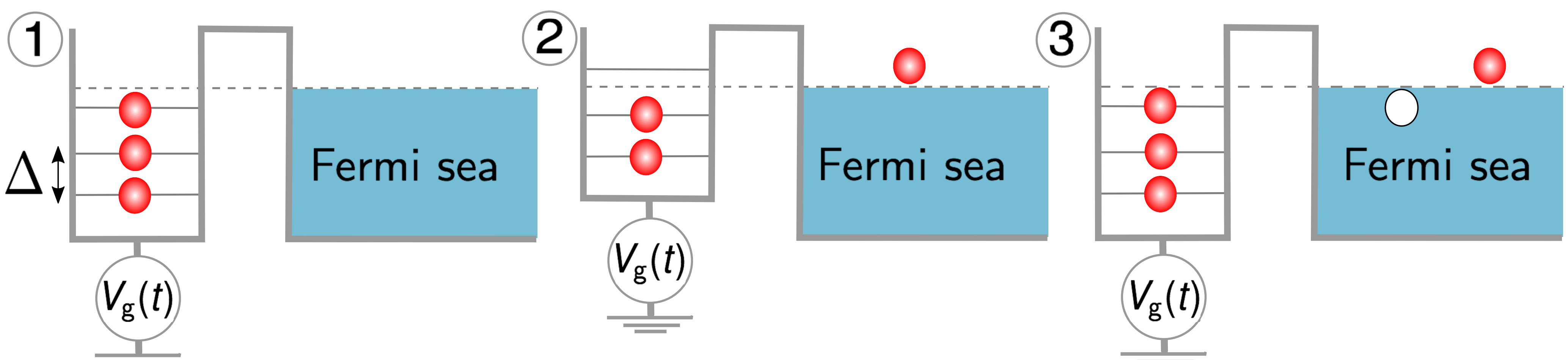




Emitted electron and hole from discrete spectrum



Experiment: Gabelli, J. et al., *Science* **313**, 499 (2006); Fève, G. et al. Science **316,**1169 (2007)

Aim

How to charactrized SES by observables ?

Heat/charge current

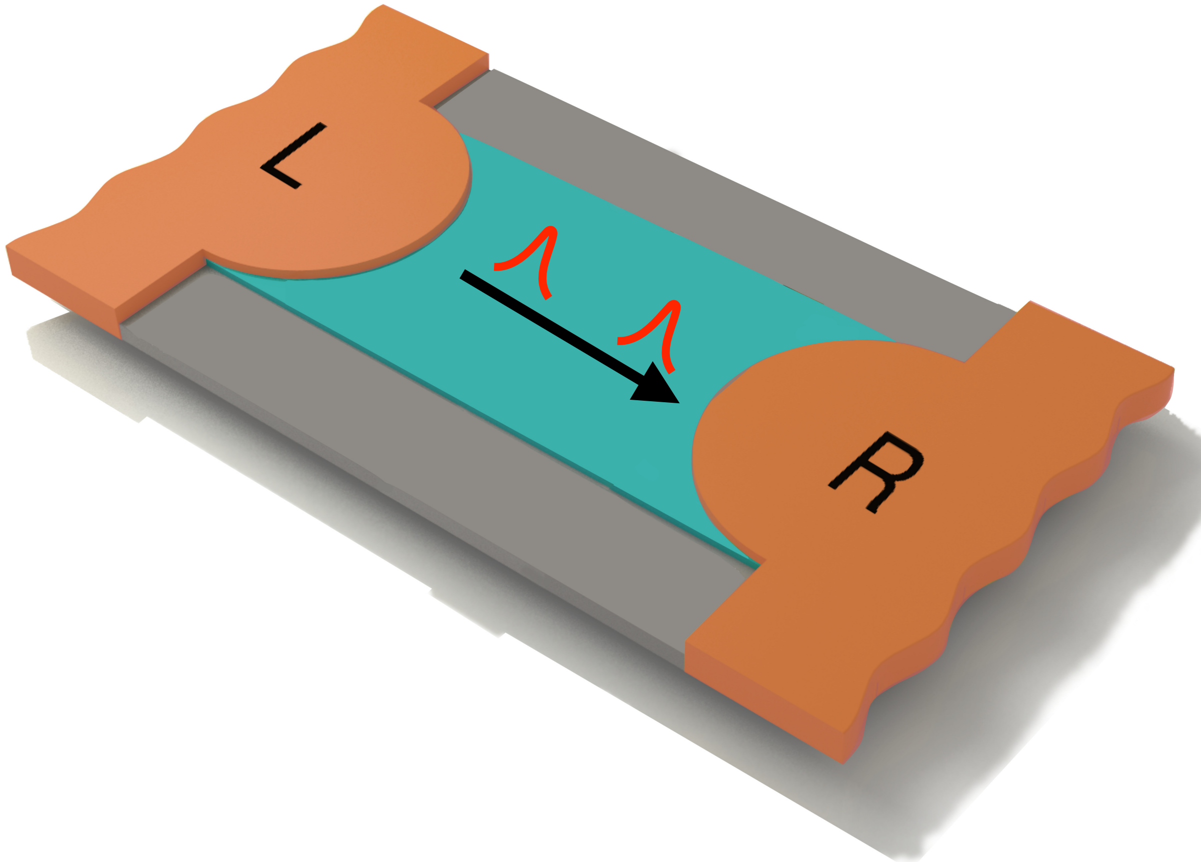
Heat/charge-current noise

How to read out these observables?

Through **macroscopic fluctuations** of a small contact

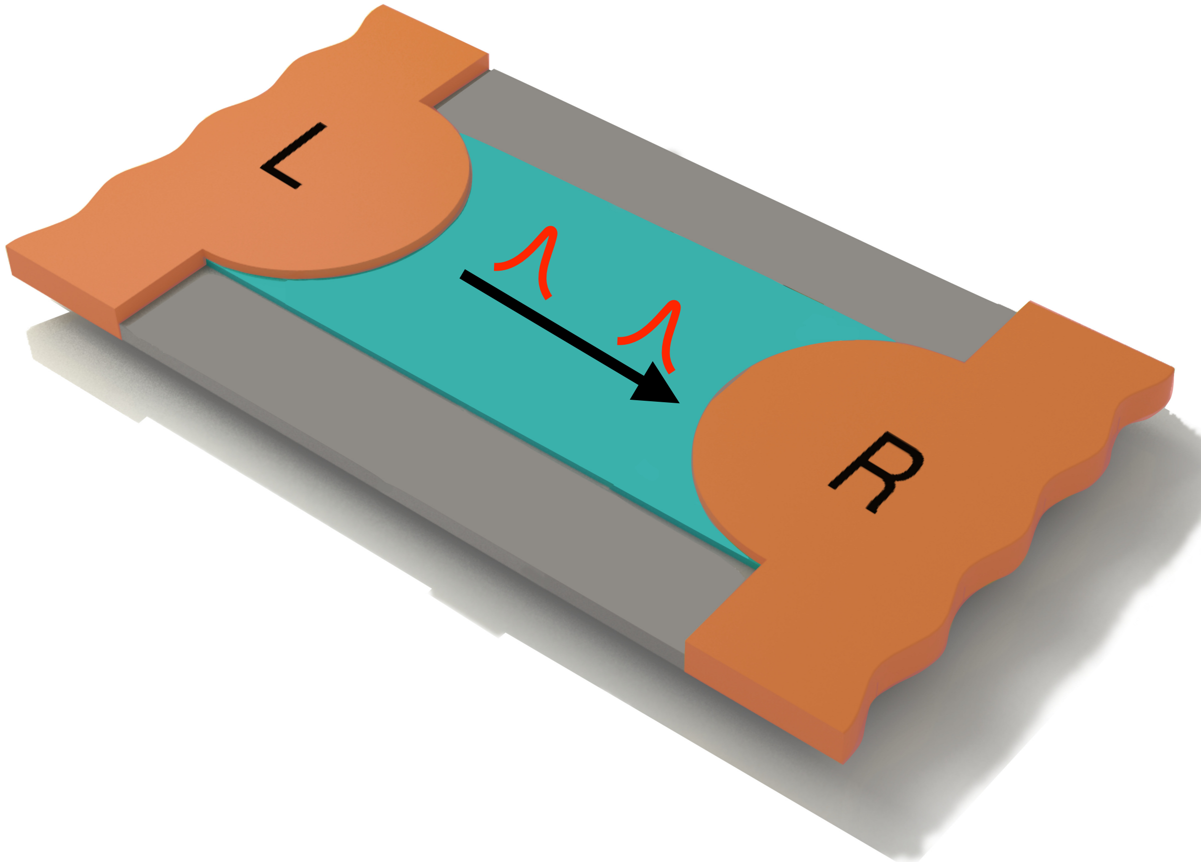
Increasing selectivity by energy-resolved readout

Observables



Time-resolved charge current: $I_\alpha(t)$

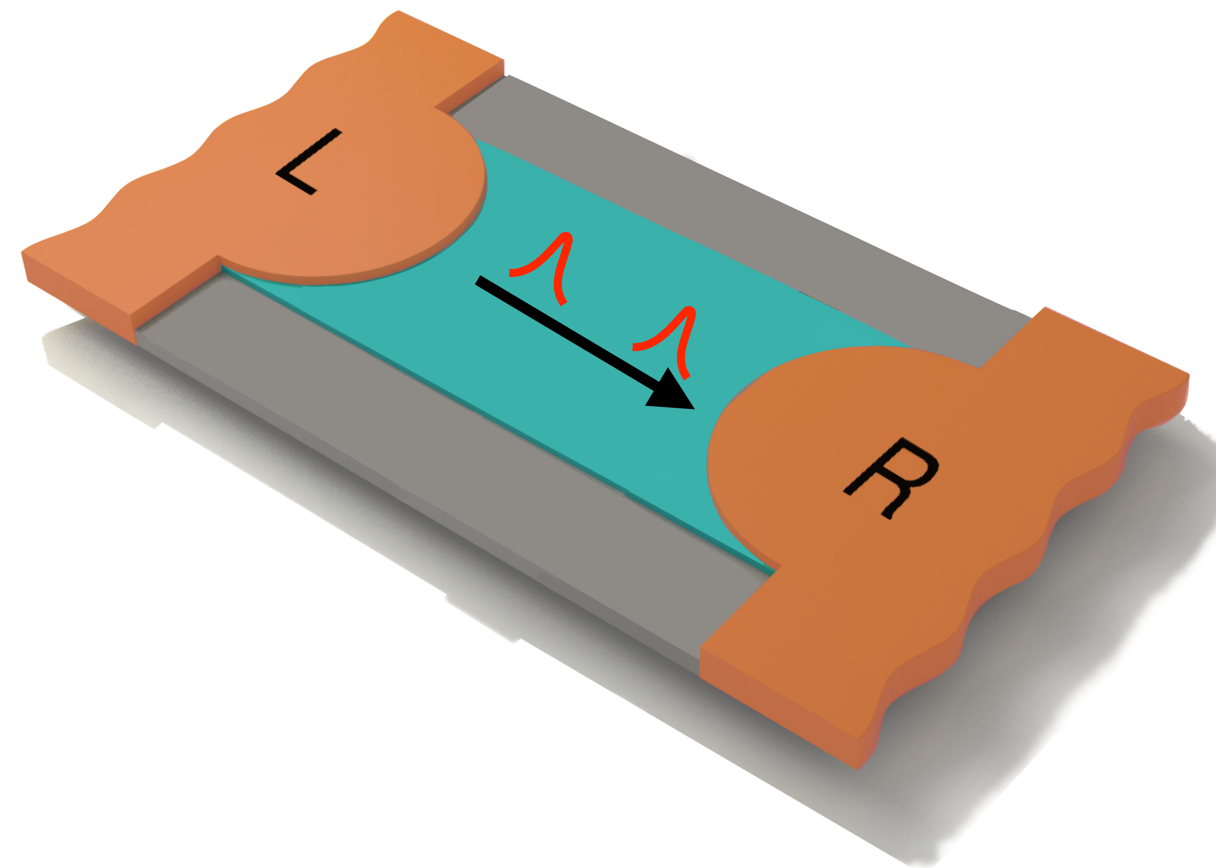
Observables



Time-resolved charge current: $I_\alpha(t)$

Spectral current: $i_\alpha(E)$

Observables

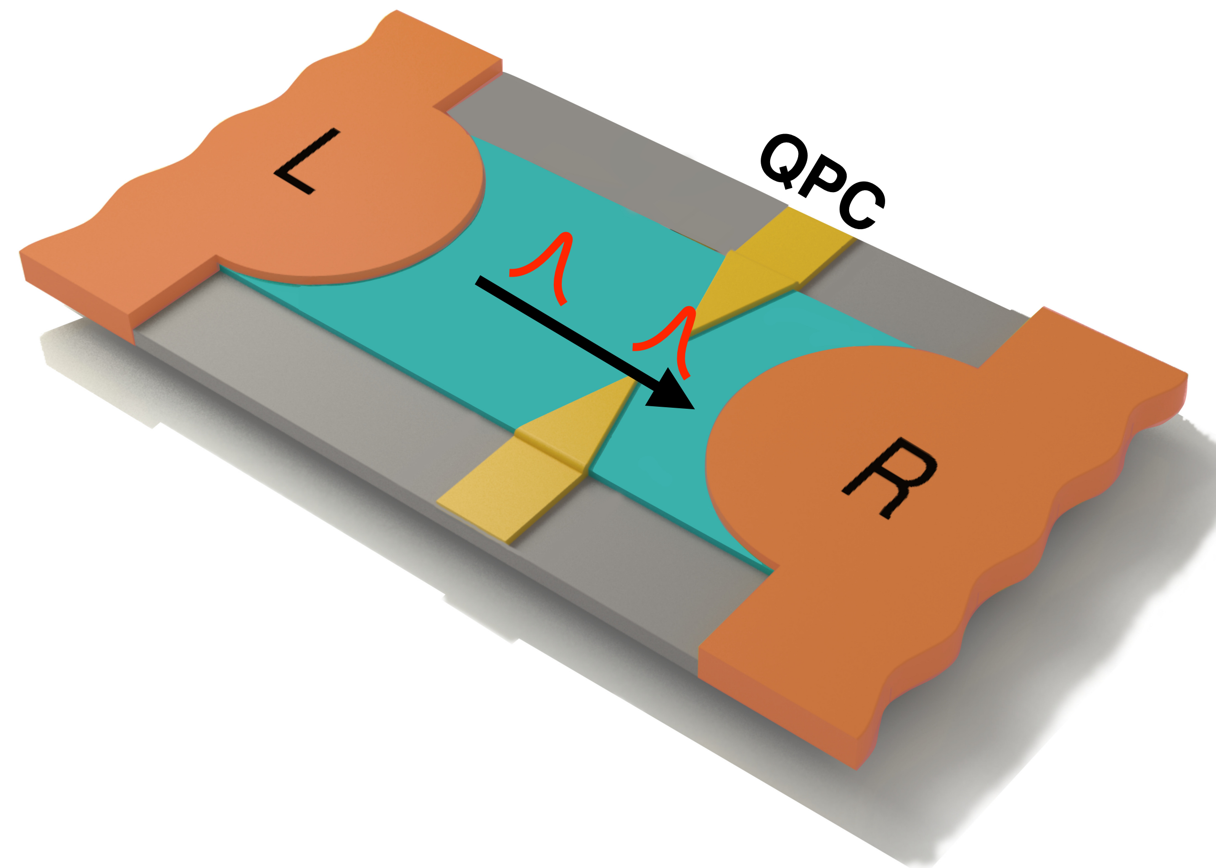


Time-resolved charge current: $I_\alpha(t)$

Spectral current: $i_\alpha(E)$

Time-resolved heat current: $J_\alpha(t)$

Observables



Time-resolved charge current: $I_\alpha(t)$

Spectral current: $i_\alpha(E)$

Time-resolved heat current: $J_\alpha(t)$

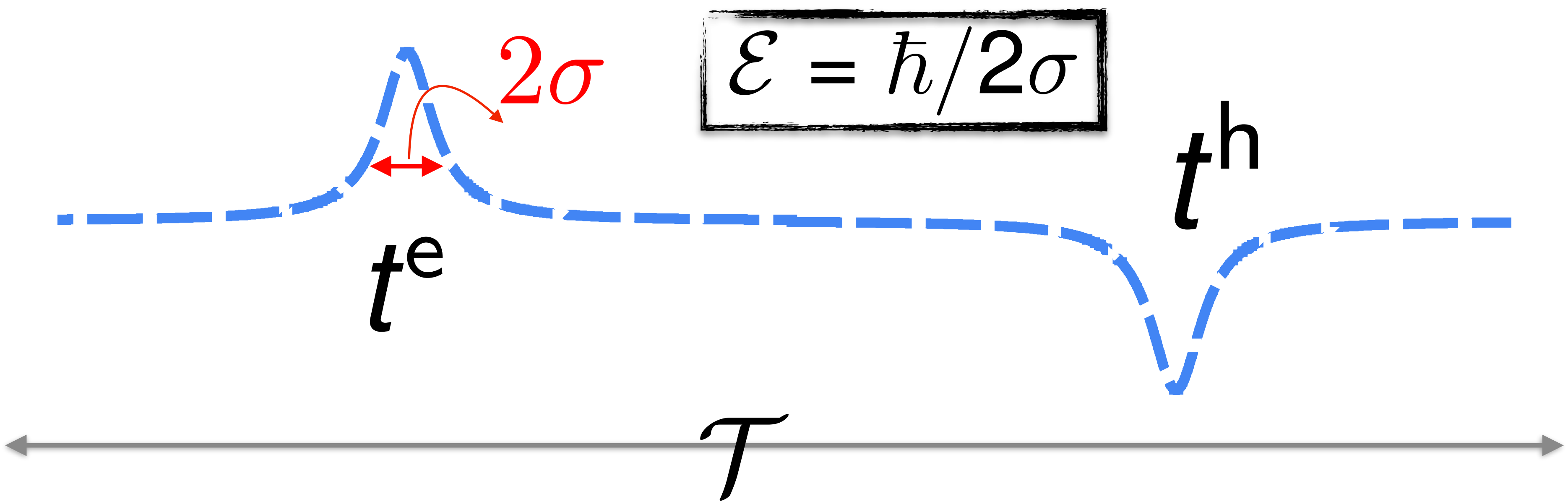
Fluctuations $\Delta\hat{I}_\alpha(t) = \hat{I}_\alpha(t) - \langle \hat{I}_\alpha(t) \rangle$

Charge-current noise: $\mathcal{P}^{II}_{\alpha\beta} = \int_0^{\mathcal{T}} \frac{dt}{\mathcal{T}} \int_{-\infty}^{\infty} dt' \langle \Delta I_\alpha(t') \, \Delta I_\beta(t+t') \rangle$

Heat: $\mathcal{P}^{JJ}_{\alpha\beta}$ **Mixed:** $\mathcal{P}^{IJ}_{\alpha\beta}$

Observables

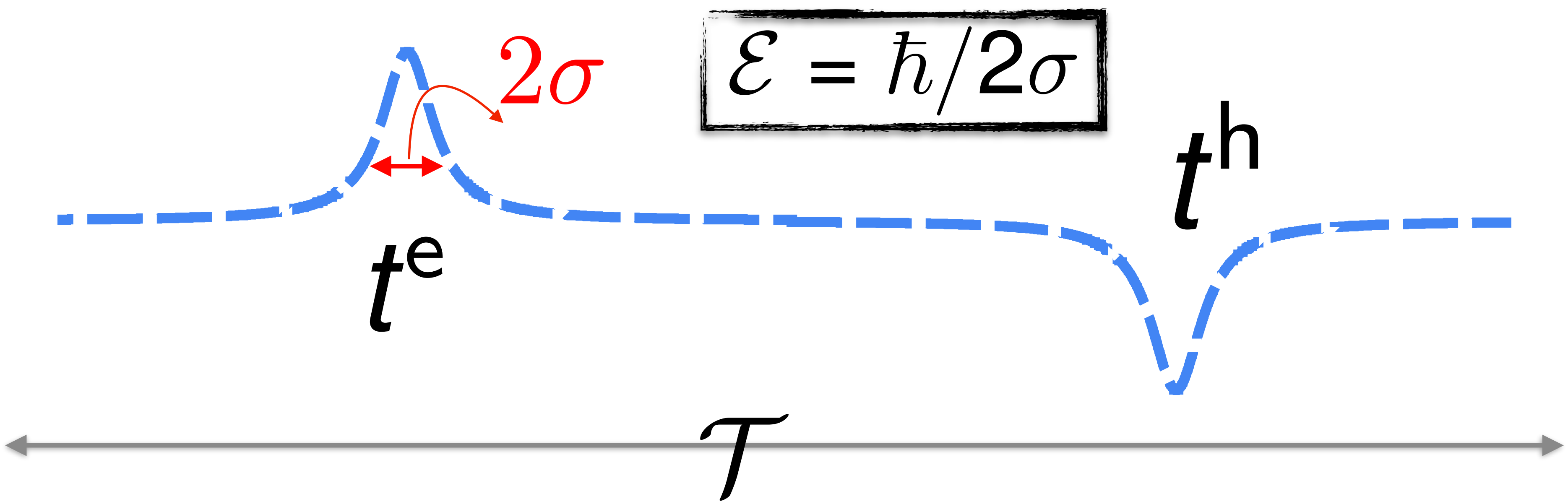
Time-resolved charge current of emitted particles



Dashti, N., Misiorny, M., Kheradsoud, S., Samuelsson, P., and Splettstoesser, J. **arXiv,1902.01209 (2019), Accepted for publication in PRB**

Observables

Time-resolved charge current of emitted particles



$$\bar{I} \propto N_{\mathrm{e}} - N_{\mathrm{h}}$$

$$\bar{J} \propto (N_{\mathrm{e}} + N_{\mathrm{h}})\varepsilon$$

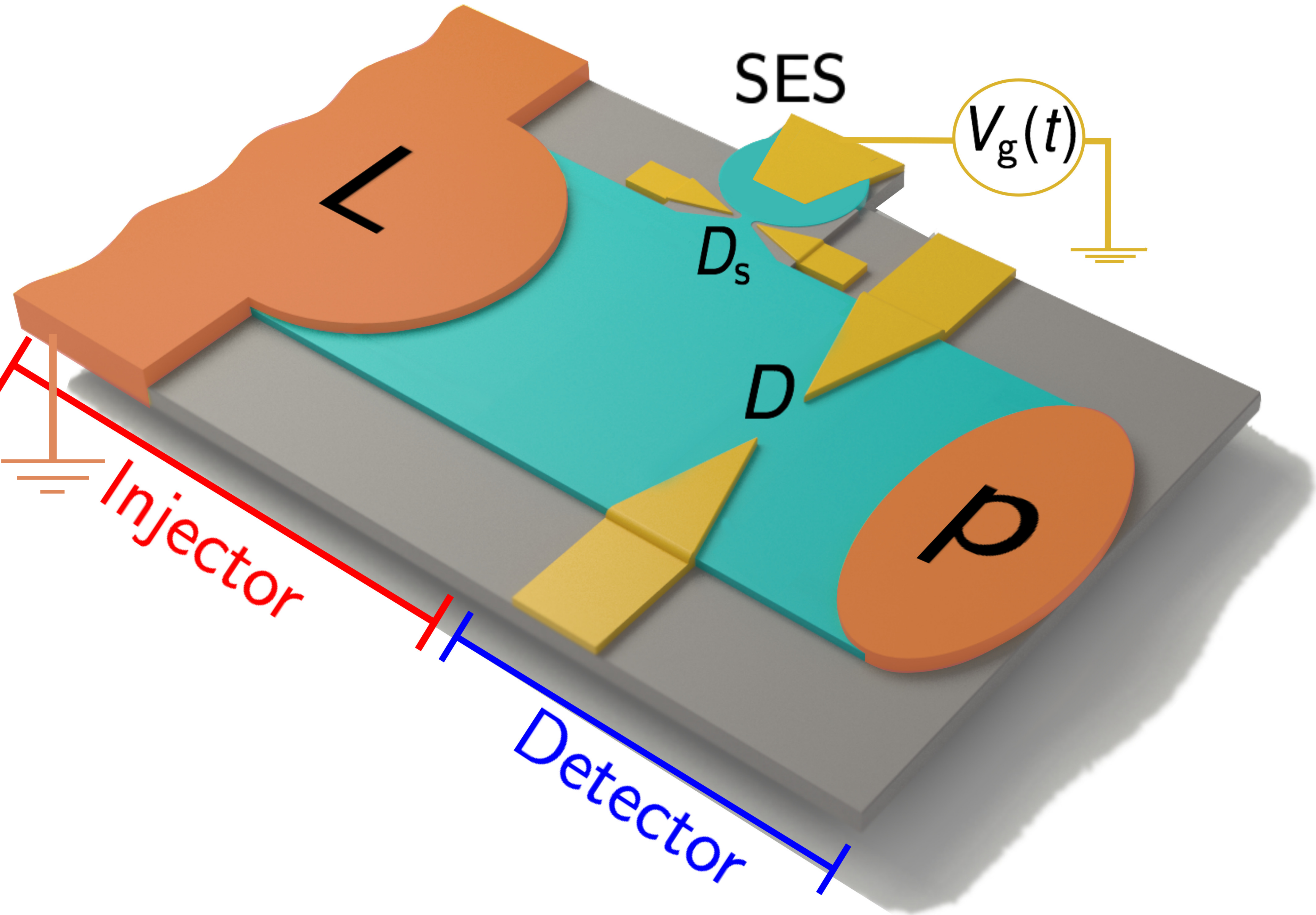
$$\mathcal{P}^{II} \propto N_{\mathrm{e}} + N_{\mathrm{h}}$$

$$\mathcal{P}^{JJ} \propto (N_{\mathrm{e}} + N_{\mathrm{h}})\varepsilon^2$$

Dashti, N., Misiorny, M., Kheradsoud, S., Samuelsson, P., and Splettstoesser, J. **arXiv,1902.01209 (2019), Accepted for publication in PRB**

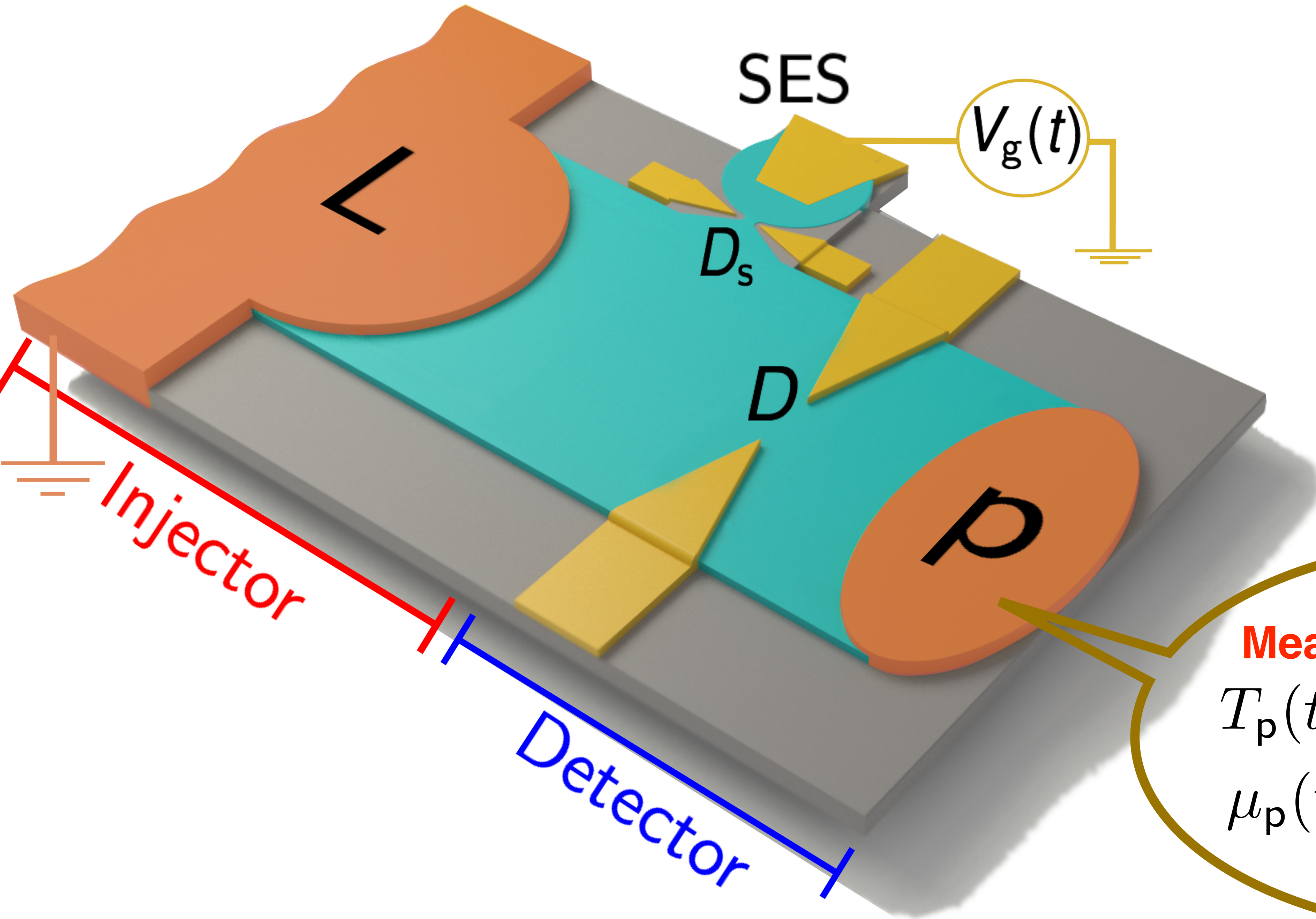
How to detect heat-current noises?

Detection scheme



Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Detection scheme



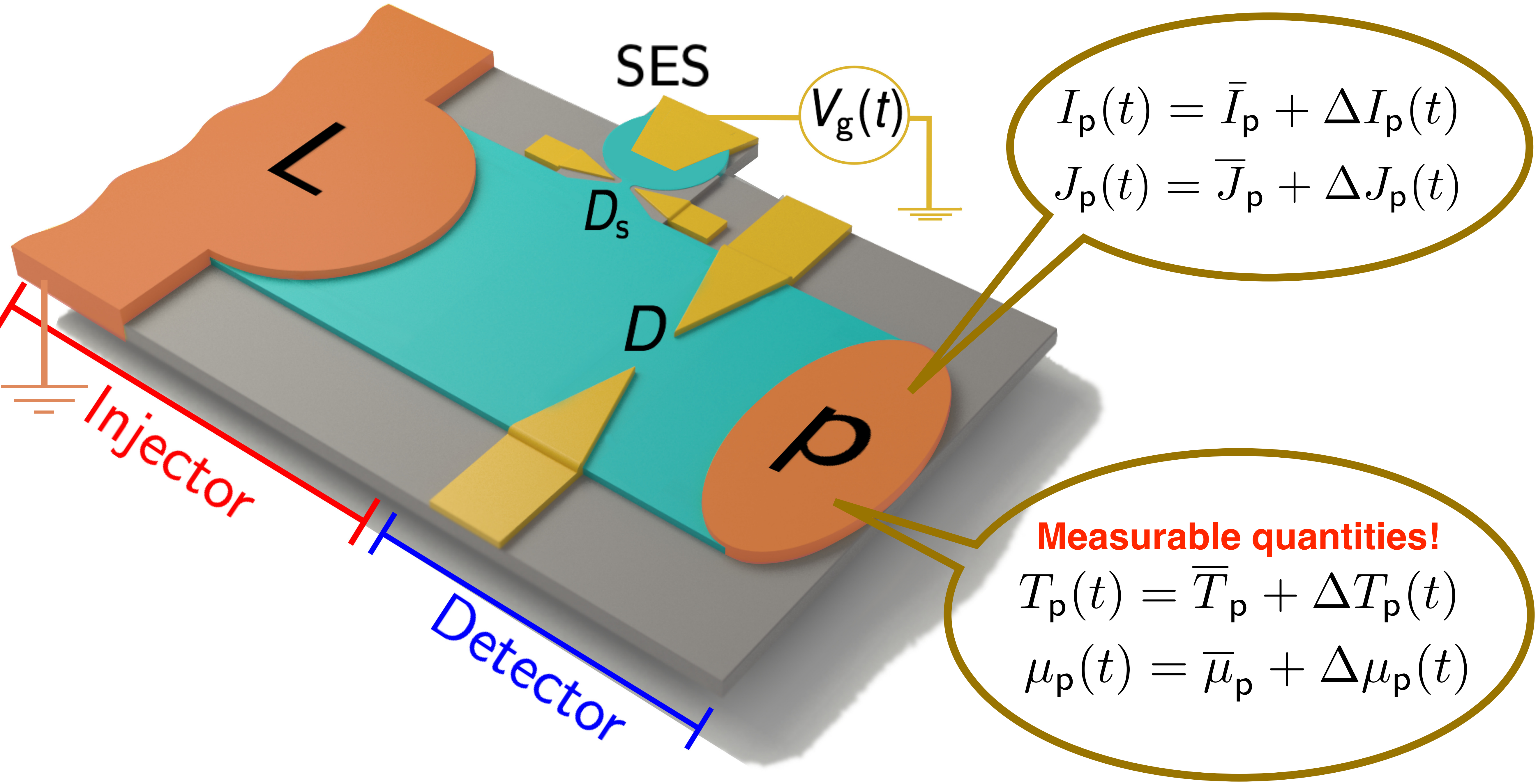
Measurable quantities!

$$T_p(t) = \overline{T}_p + \Delta T_p(t)$$

$$\mu_p(t) = \overline{\mu}_p + \Delta \mu_p(t)$$

Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Detection scheme



Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Average potential and temperature

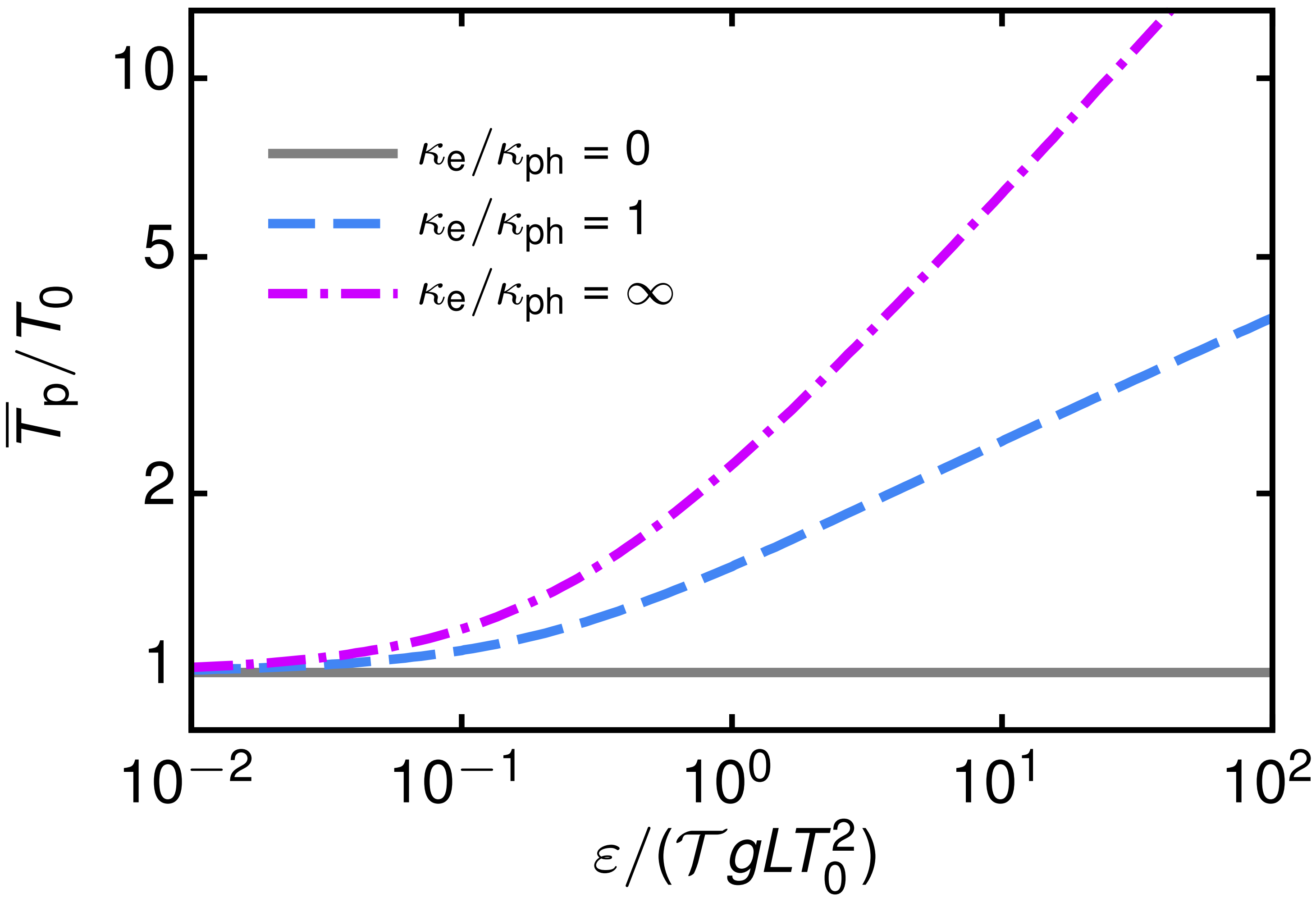
$$\overline{\mu}_{\mathrm{p}} = -\frac{h}{e}\bar{I}_{\mathrm{s}} = 0$$

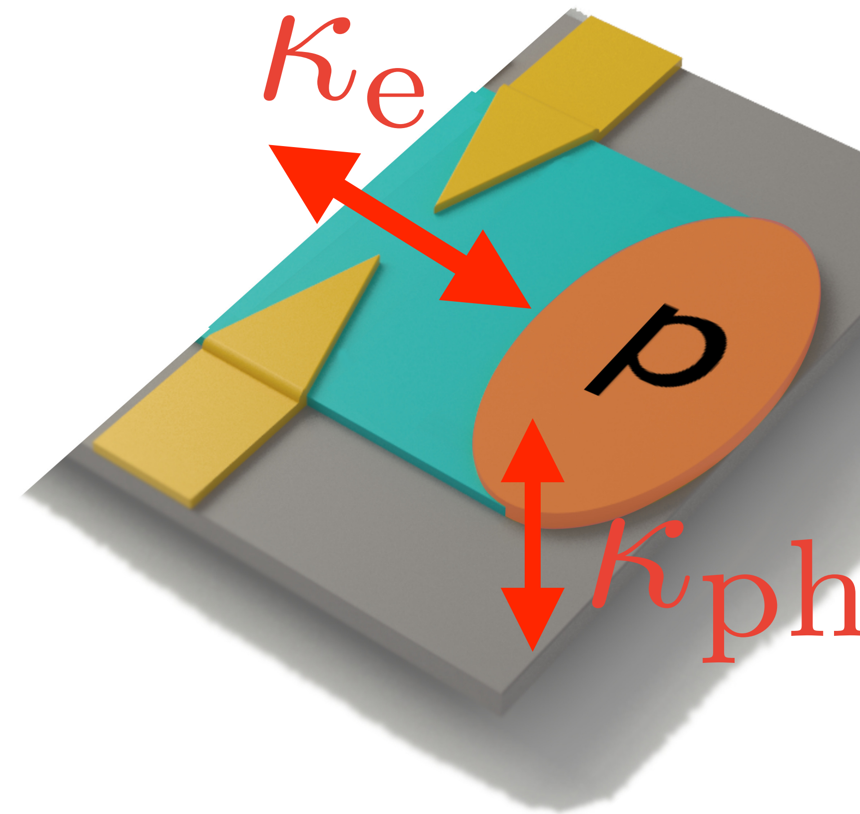
Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Average potential and temperature

$$\overline{\mu}_{\rm p} = -\frac{h}{e}\bar{I}_{\rm s} = 0$$

$$(\frac{\overline{T}_{\rm p}}{T_0})^5 - 1 = \frac{2}{5}\frac{\kappa_{\rm e}}{\kappa_{\rm ph}}\left[1 - (\frac{\overline{T}_{\rm p}}{T_0})^2 + \varepsilon\,\frac{4}{\mathcal{T}gLT_0^2}\right]$$





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Relate current fluctuations to macroscopic fluctuations

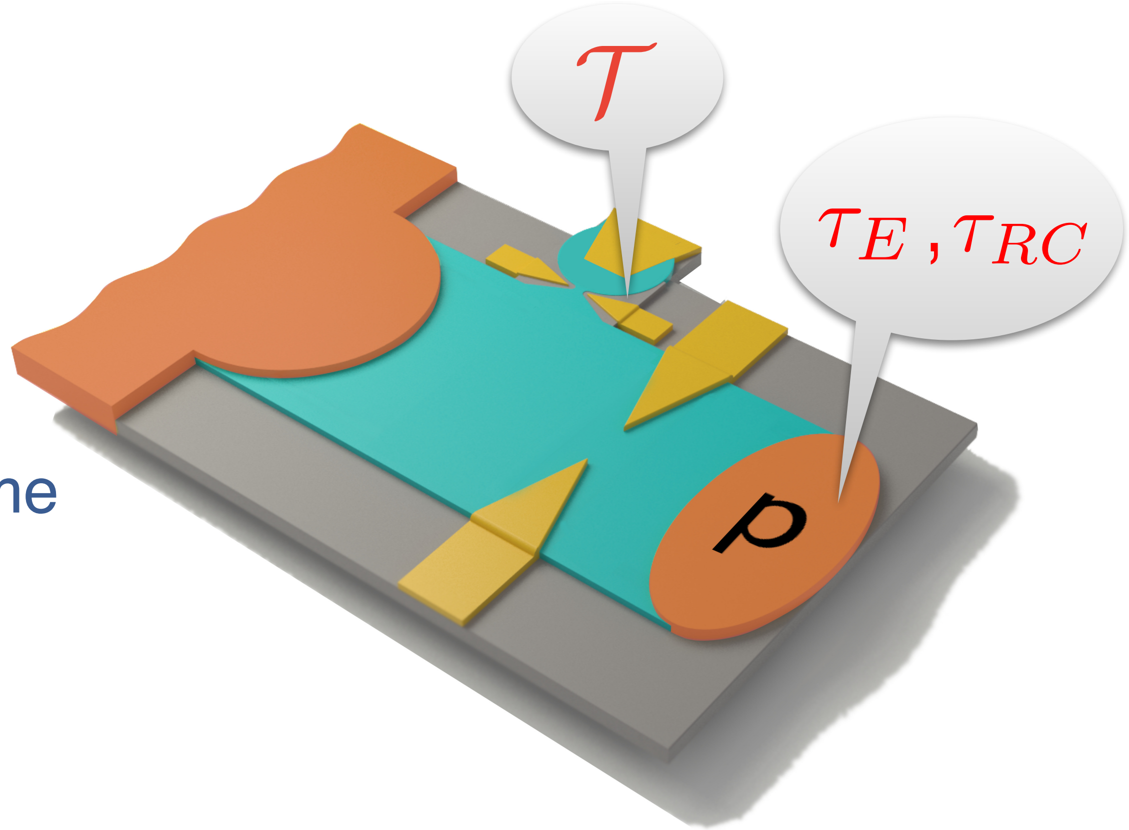
$$\boxed{\mathcal{T} \ll \tau_{RC}, \tau_E}$$

Charge relaxation time

$$\tau_{RC} = C/(Dg)$$

Energy relaxation time

$$\tau_E = C_E/\kappa$$



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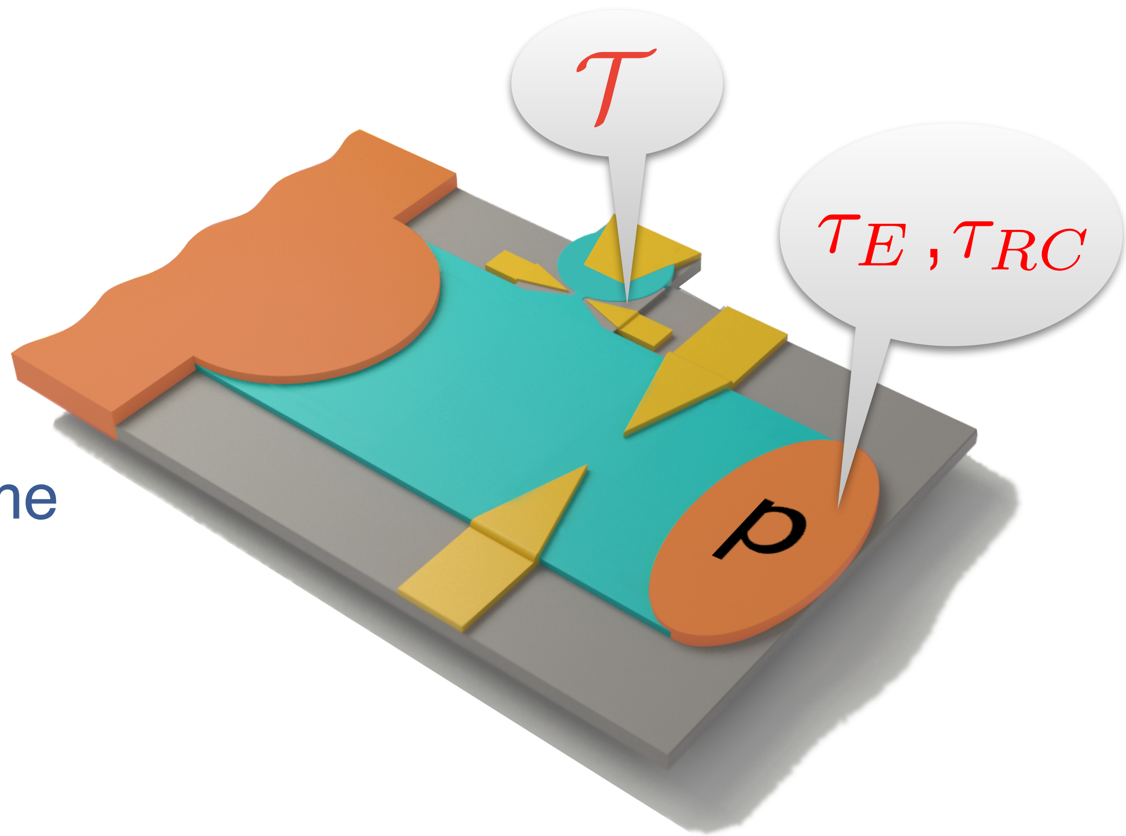


$$\Delta I_{\mathrm{p}}(t) = \delta I_{\mathrm{p}}\,(t) - Dg\ \ \Delta\mu_{\mathrm{p}}(t)/e$$

$$\Delta J_{\mathrm{p}}(t) = \delta J_{\mathrm{p}}\,(t) - \kappa\,\Delta T_{\mathrm{p}}(t)$$

Bare/fast fluctuations **Slow fluctuations**

Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Noise

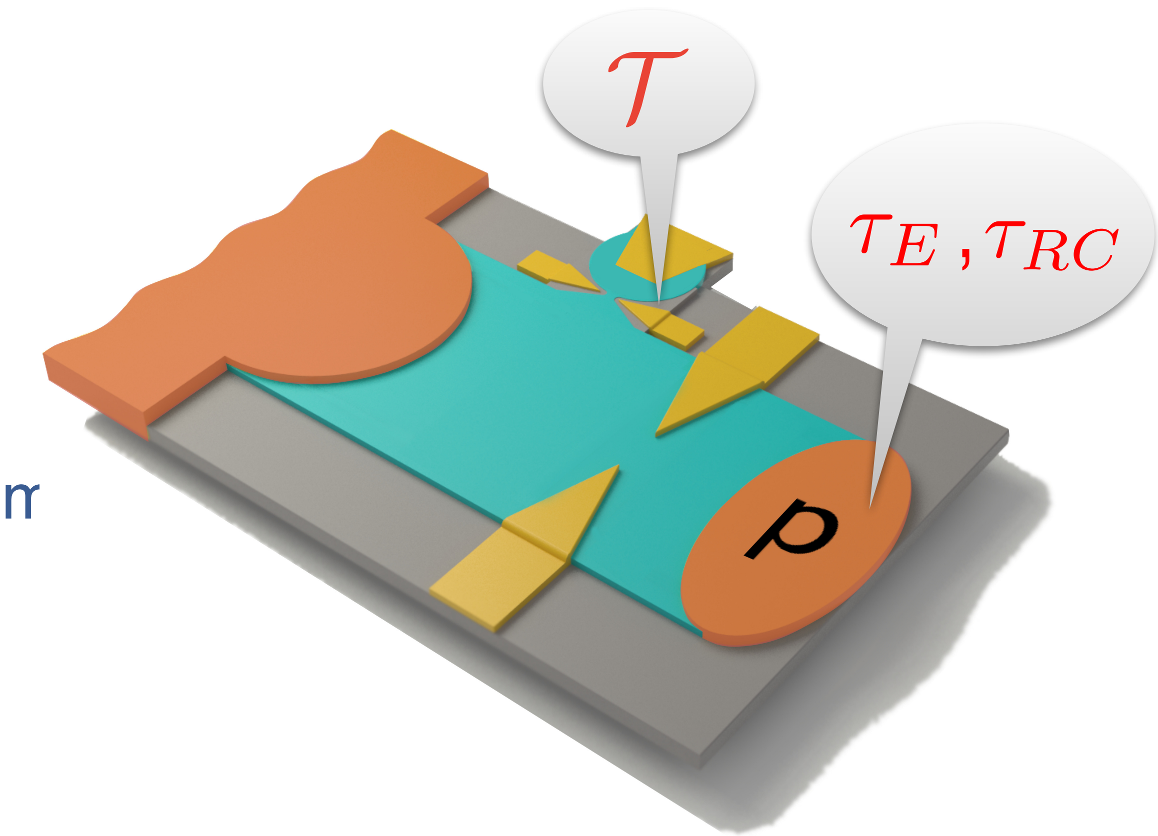
$$\boxed{\mathcal{T} \ll \tau_{RC}, \tau_E}$$

Charge relaxation time

$$\tau_{RC} = C/(Dg)$$

Energy relaxation tim

$$\tau_E = C_E/\kappa$$



$$\mathcal{P}_{\mathsf{p}}^{\mu\mu}(\omega) = \frac{e^2}{(Dg)^2}\frac{1}{1+(\omega\tau_{RC})^2}\mathcal{P}_{\mathsf{p}}^{II}$$

$$\mathcal{P}_{\mathsf{p}}^{TT}(\omega) = \frac{1}{\kappa^2}\frac{1}{1+(\omega\tau_{E})^2}\mathcal{P}_{\mathsf{p}}^{JJ}$$

Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Optimizing parameters

$$\mathcal{P}_{\mathrm{p}} = \mathcal{P}_0 + \mathcal{P}_{\mathrm{dir}} + \mathcal{P}_{\mathrm{ind}}$$

Thermal noise

Source information

Back-action of the probe

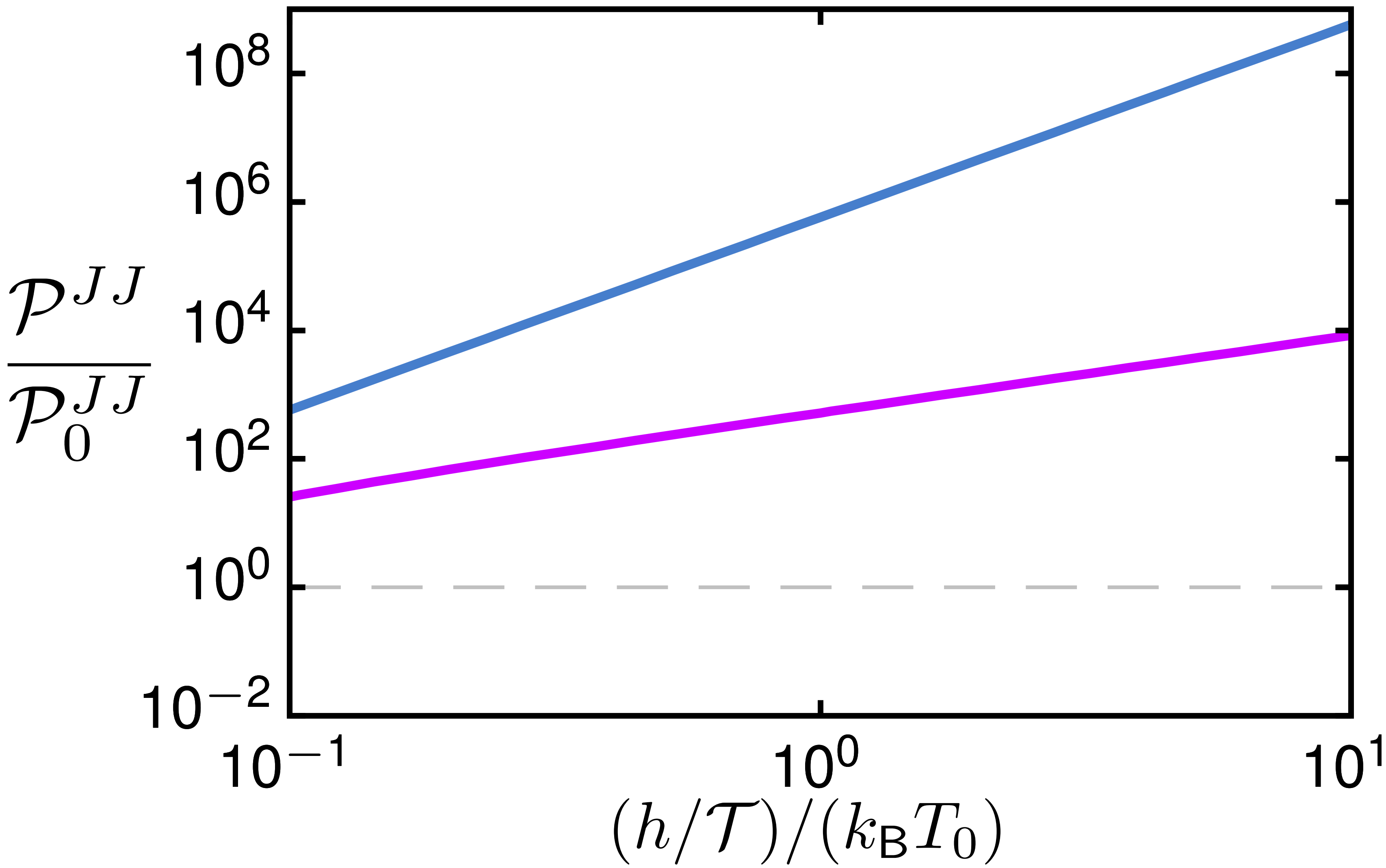
Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Optimizing parameters

$$\frac{\mathcal{P}_{\mathsf{p}}^{TT}(\omega)}{\mathcal{P}_0^{JJ}} = \frac{1}{\kappa^2}\,\frac{1}{1+(\omega\tau_E)^2}\left[1+\frac{\mathcal{P}_{\mathsf{s,dir}}^{JJ}}{\mathcal{P}_0^{JJ}}+\frac{\mathcal{P}_{\mathsf{s,ind}}^{JJ}}{\mathcal{P}_0^{JJ}}\right]$$

Source information

Back-action of the probe



$$D = 0.1$$

$$\sigma/\mathcal{T} = 10^{-3}$$

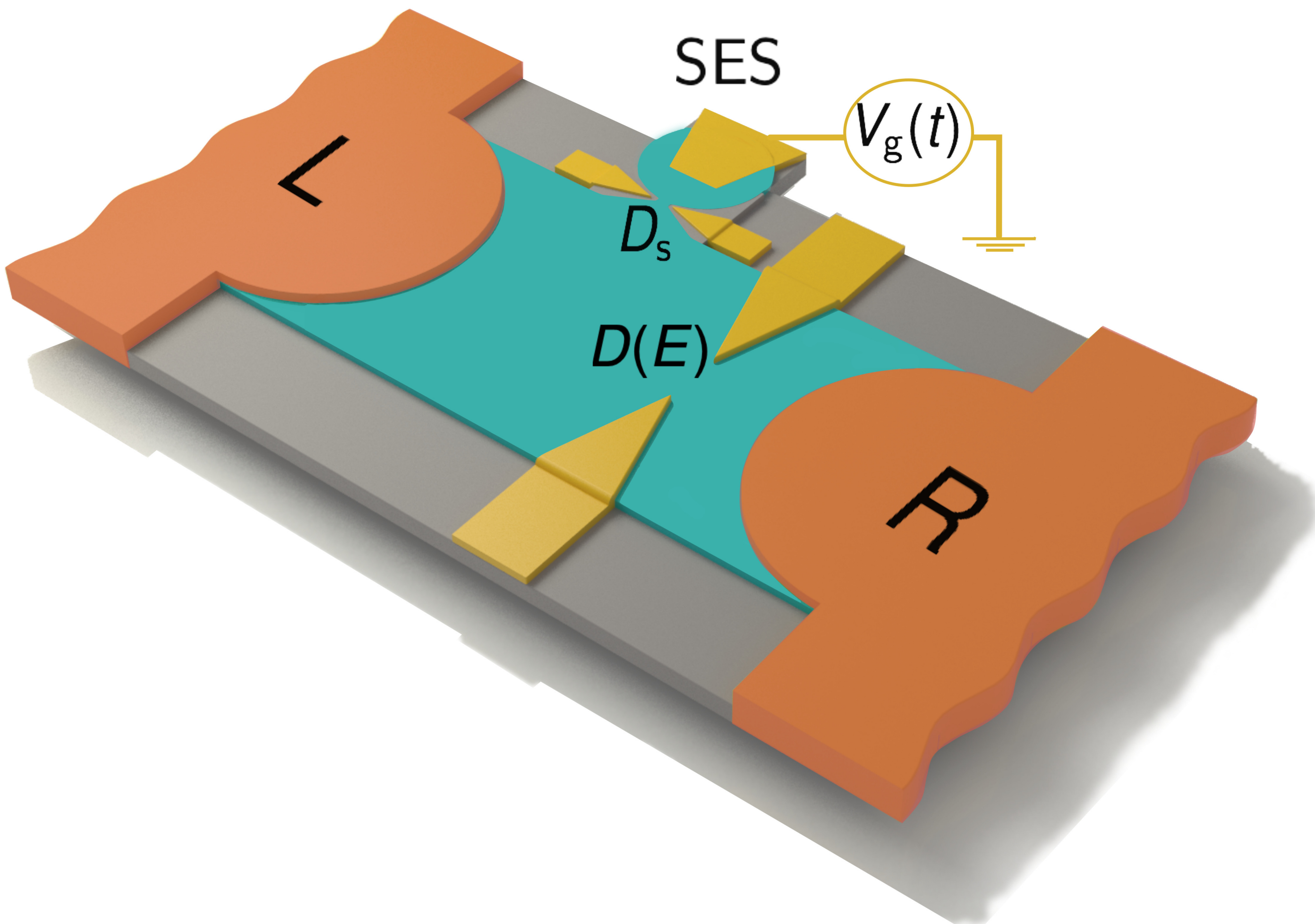
$$\kappa_{\mathsf{ph}}/(\pi k_\mathsf{B} T_0) = 10^2$$

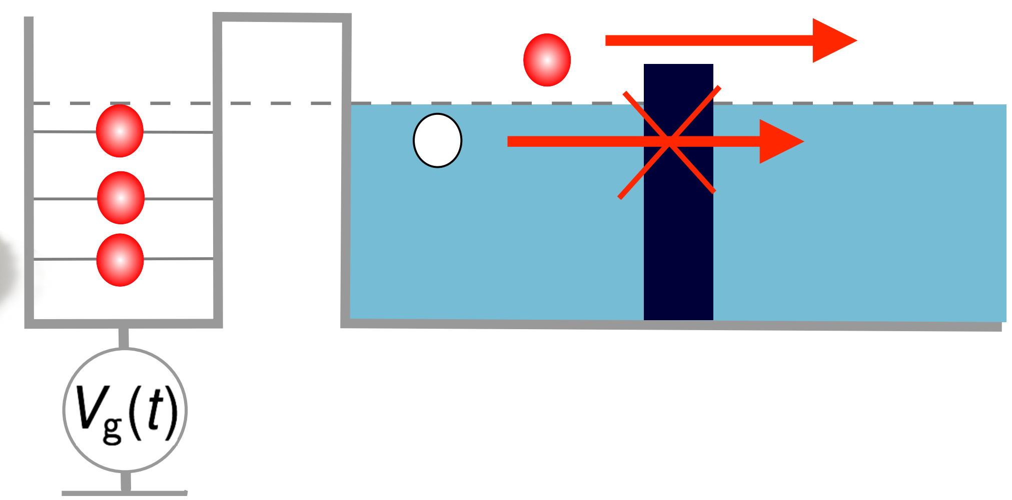
Disentangle desired signal from back-action

Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Outlook

Characterization of single electron sources from transport measurement with energy-selective transmission





Kheradsoud, S., Dashti, N., Misiorny, M., Potts, P. P., Splettstoesser, J., & Samuelsson, P. **arXiv:1904.03912 (2019)**

Dashti, N., Kheradsoud, S., Misiorny, M., Samuelsson, P., and Splettstoesser, J. In preparation.

Outlook

Energy-selective detector (thermoelectric effect)

$$\begin{pmatrix} I_{\mathrm{R}} \\ J_{\mathrm{R}} \end{pmatrix} = \begin{pmatrix} G & L \\ M & K \end{pmatrix} \begin{pmatrix} \Delta\mu/e \\ \Delta T \end{pmatrix}$$

Dashti, N., Kheradsoud, S., Misiorny, M., Samuelsson, P., and Splettstoesser, J. In preparation.

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$$\begin{pmatrix} \bar{I}_{\mathsf{R}} \\ \bar{J}_{\mathsf{R}} \end{pmatrix} = \begin{pmatrix} G + G_{\mathsf{s}} & L + L_{\mathsf{s}} \\ M + M_{\mathsf{s}} & K + K_{\mathsf{s}} \end{pmatrix} \begin{pmatrix} \Delta\mu/e \\ \Delta T \end{pmatrix} + \begin{pmatrix} \bar{I}_{\mathsf{s}}^{\mathsf{dir}} \\ \bar{J}_{\mathsf{s}}^{\mathsf{dir}} \end{pmatrix}$$

Modification of TE coefficient due to the response of the SES current to bias via filtering.

Current from the SES modified by filtering

Dashti, N., Kheradsoud, S., Misiorny, M., Samuelsson, P., and Splettstoesser, J. In preparation.

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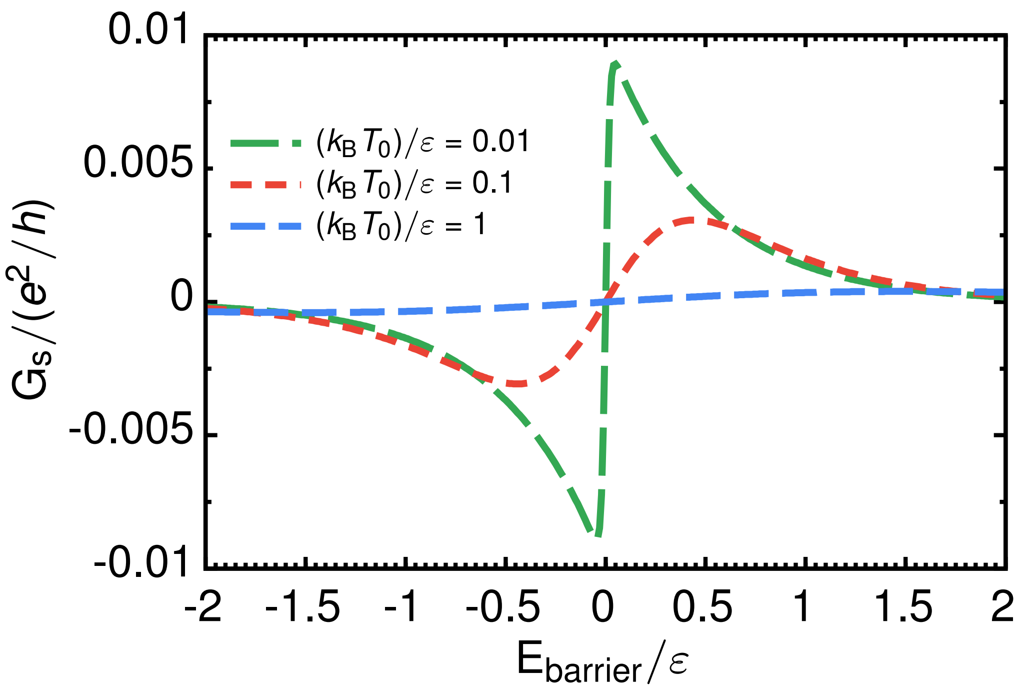
$$G_\mathrm{s}/e = \frac{\partial I}{\partial \Delta\mu}\Big|_\text{source on} - \frac{\partial I}{\partial \Delta\mu}\Big|_\text{source off}$$



J. Waldie et al.: Phys. Rev. B 92, 125305 (2015)
Dashti, N., Kheradsoud, S., Misiorny, M., Samuelsson, P., and Splettstoesser, J. In preparation.

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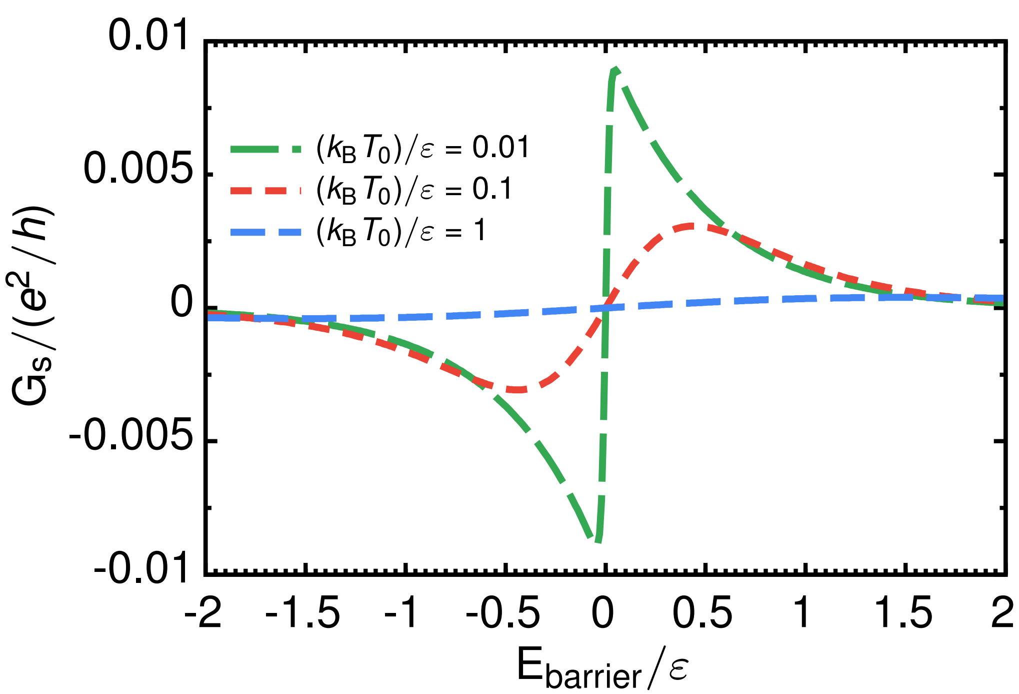

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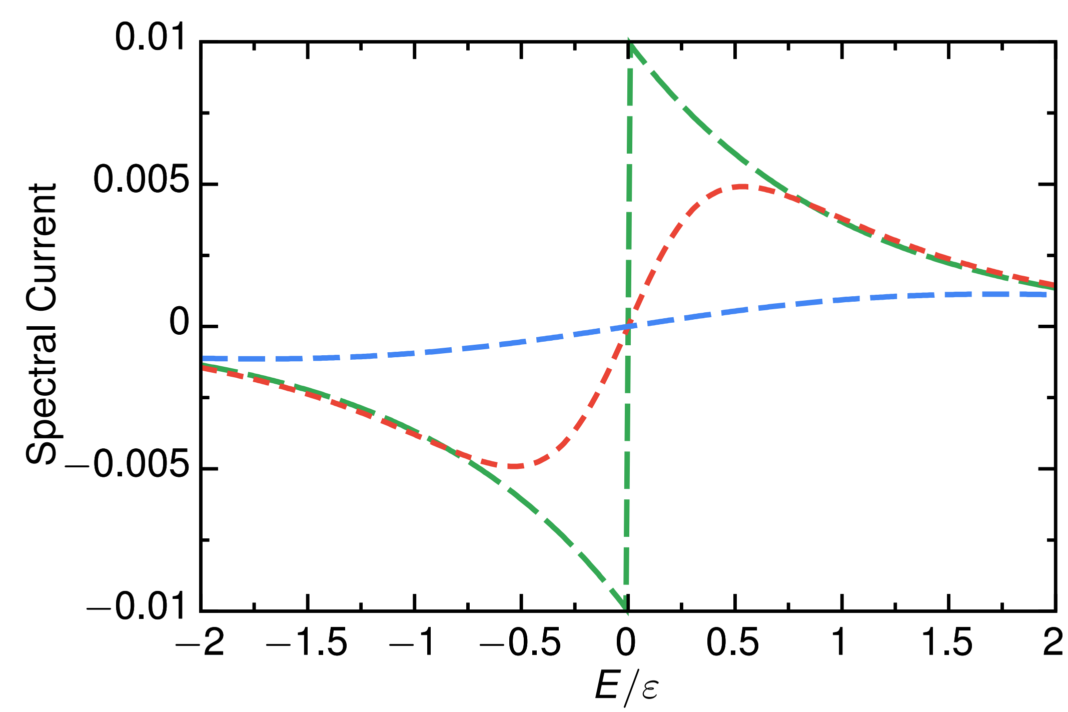

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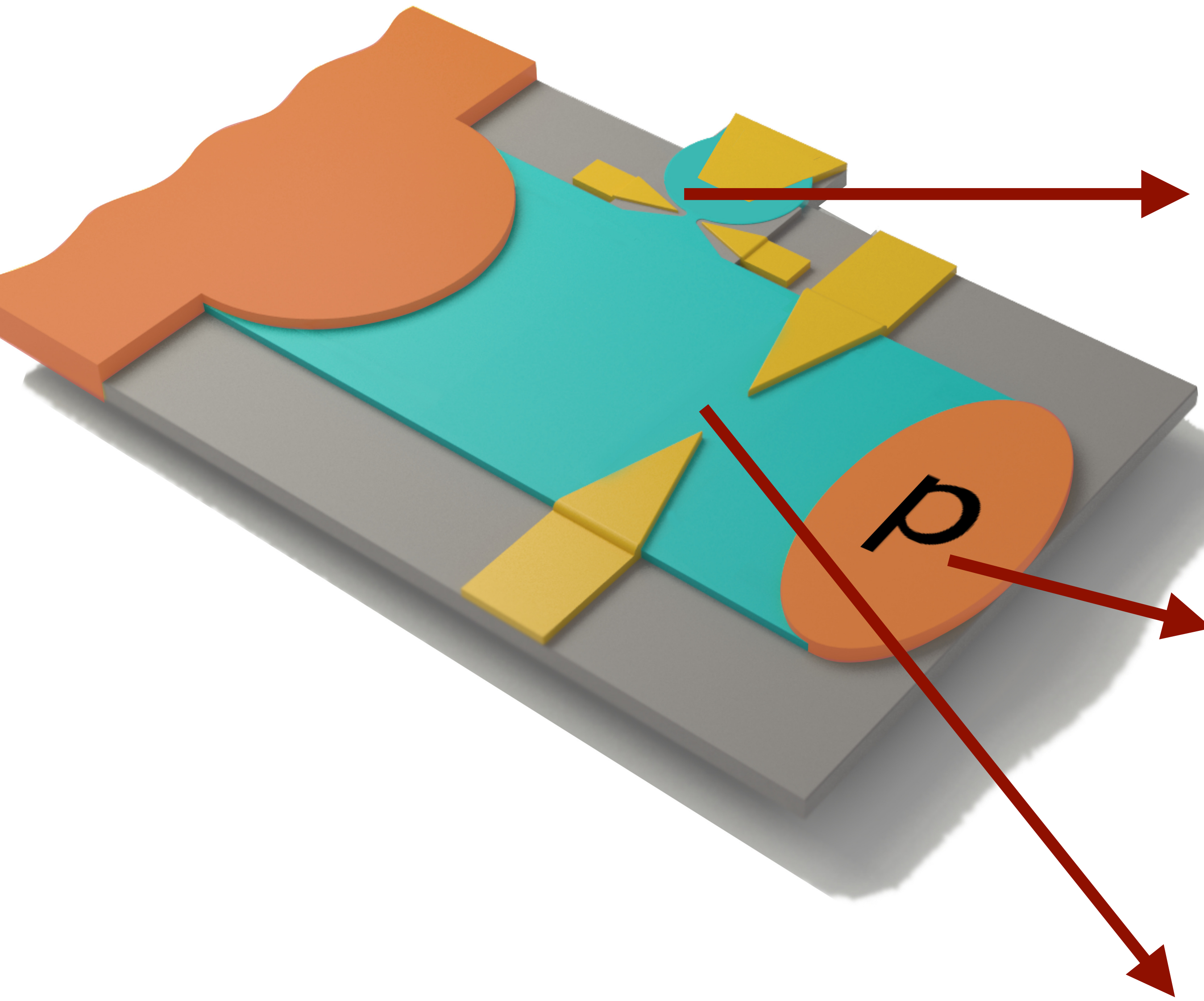
Summary



Characterizing SES by transport properties

Dashti, N., Misiorny, M., Kheradsoud, S., Samuelsson, P., and Splettstoesser, J. **arXiv,1902.01209 (2019). Accepted for publication in PRB**

Detecting charge and energy transport properties

Dashti, N., Misiorny, M., Samuelsson, P., and Splettstoesser, J. **Phys. Rev. Appl. 10(2), 024007 (2018)**

Detecting transport quantities by energy-selective transmission

Dashti, N., Kheradsoud, S., Misiorny, M., Samuelsson, P., and Splettstoesser, J. In preparation.