

# Beating Carnot efficiency with periodic driven chiral conductors

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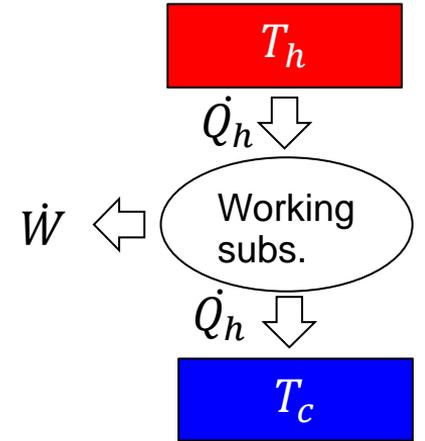
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What is the **bound for efficiency** of heat engines limited by the 2<sup>nd</sup> law?

In macro-engines: Clausius relation  $\dot{S} = \frac{\dot{Q}_h}{T_h} + \frac{\dot{Q}_c}{T_c}$

➤ *Carnot efficiency*  $\eta_c = 1 - \frac{T_c}{T_h}$



In micro-engines: nonequilibrium control (e.g., Maxwell demon [J. V. Koski, et al., PNAS (2014)])

- Efficiency beyond Carnot limit
- Entropy = ?

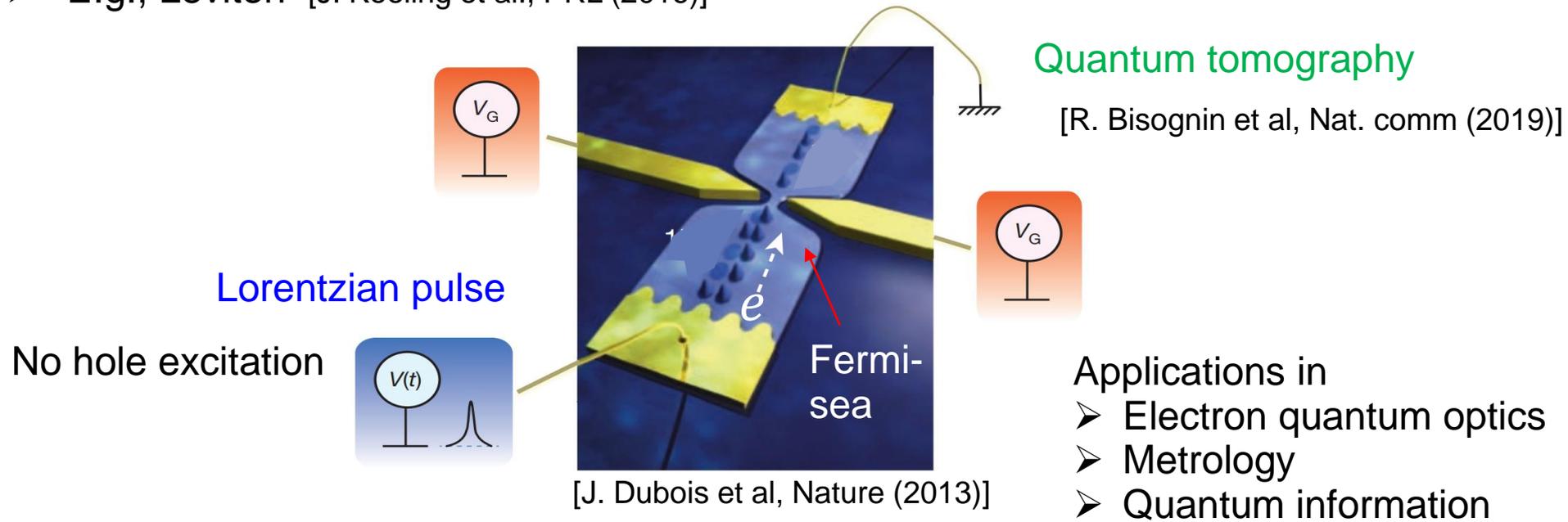
Merit of nonequilibrium bath:

- Nonequilibrium demon [R. Sánchez, et al., PRL (2019)]
- Coherence as resource [M.O. Scully, et al., Science (2003)]

What is the effect of **nonequilibrium bath** driven by **AC voltage**?

Such study is desirable and timely !

- AC experiments are able for **control** and **measurement** of electron excitation
  - E.g., Leviton [J. Keeling et al., PRL (2016)]



However, heat and energy currents are of recent interest

[N. Dashti et al., PRB (2019)]

[Battista et al., PRB (2014)]

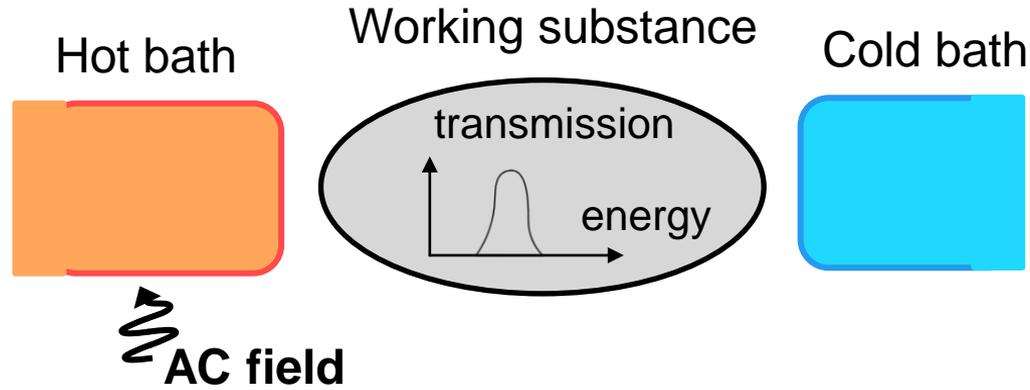
[L. Vannucci et al., PRB (2017)]

- Applications in
- Electron quantum optics
  - Metrology
  - Quantum information

In this talk, we show that

AC driven chiral quantum conductor can have efficiencies beyond the Carnot limit.

## AC driven thermoelectric engine



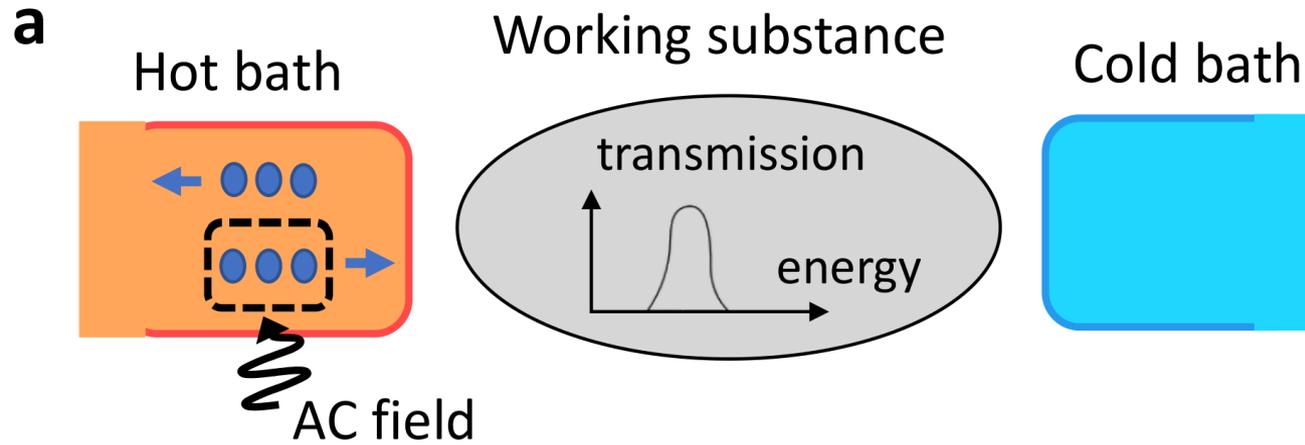
Dynamical e-h asymmetry (Levitons) → enhanced thermoelectric current

But AC field generally injects power  $P_{in}$  to electrons (working substance)

C.f. Joule's law:  $P_{in} \propto \overline{V_{ac}^2} > 0$

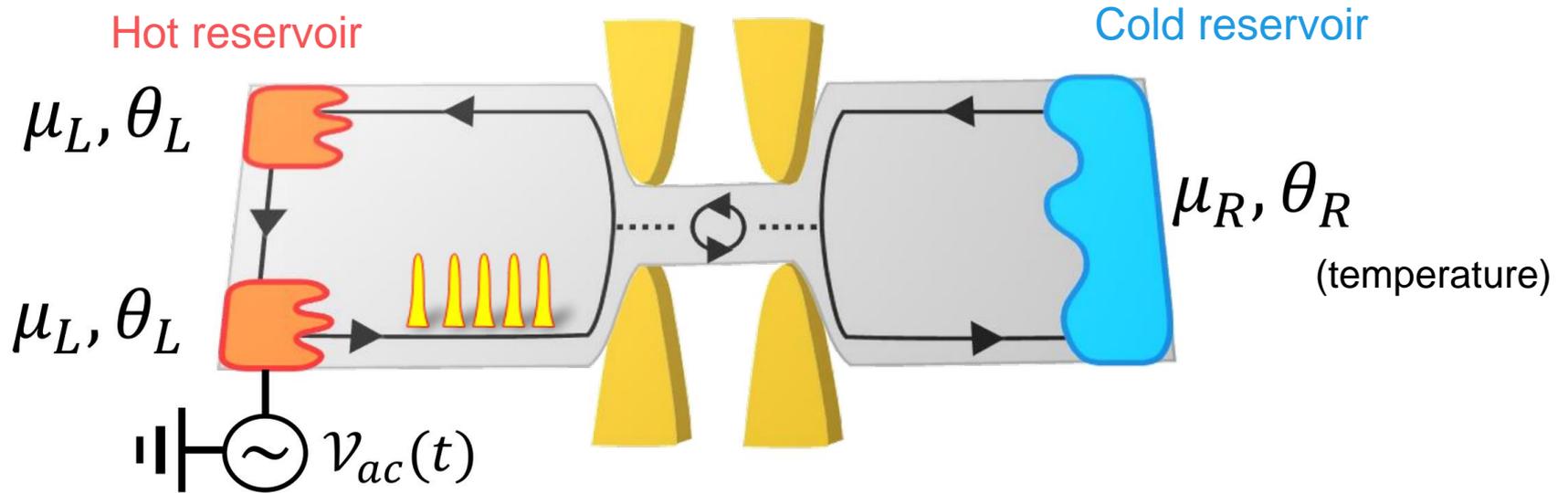
→  $P_{in}$  hinders efficiency enhancement by AC ∴  $\eta = \frac{P_e - P_{in}}{\dot{Q}_H}$

We find that a chiral AC driving completely avoids any power injection by AC driving !



→ key factor for remarkable efficiency enhancement.

## Realization using chiral conductor



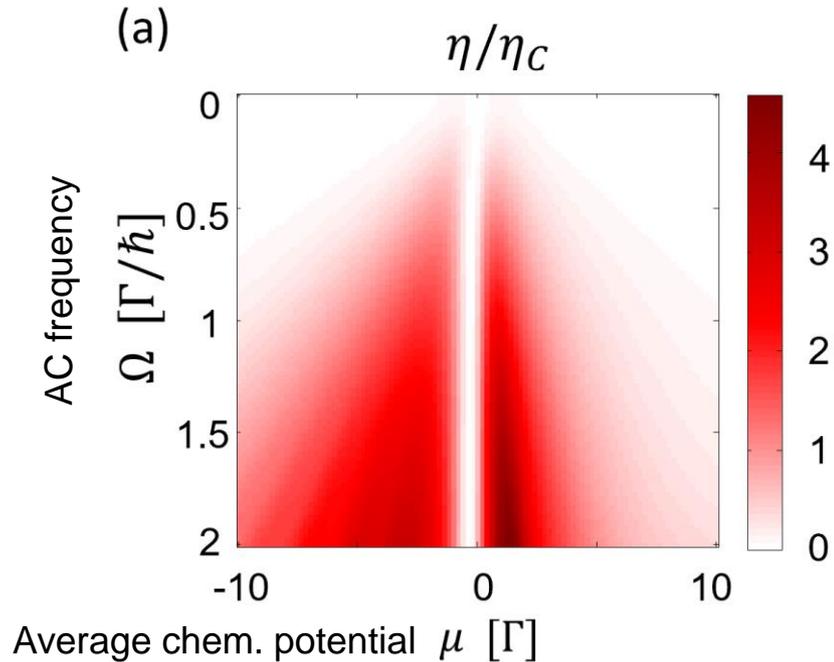
$v_{ac}(t)$ : Lorentzian pulses which excite Levitons

We only consider time-averaged currents of charge/heat/energy.

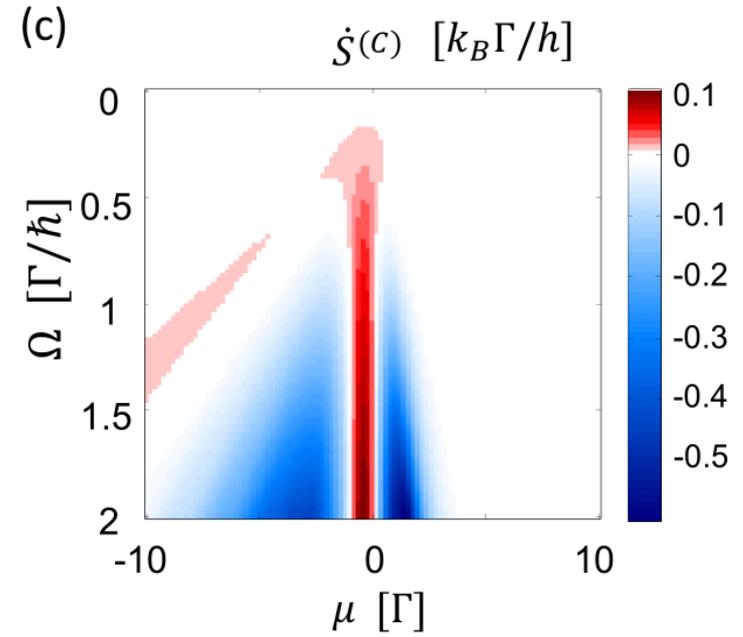
AC driving enhances the efficiency.

Even beyond Carnot limit!

→ Here  $\dot{S}^{(C)} = \frac{\dot{Q}_L}{\theta_L} + \frac{\dot{Q}_R}{\theta_R}$  is *negative*



$\Gamma$  = resonance level broadening



The seeming violation of the second law of thermodynamics is resolved  
 when adopting the Shannon entropy flow as the entropy production,

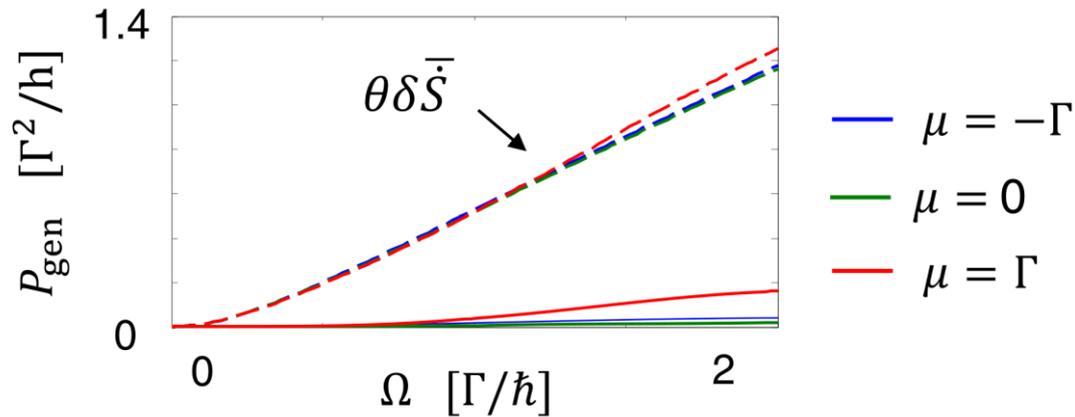
[A. Bruch, et al., PRL (2018)]

[B. Bhandari, et al., PRB 102, 155407 (2020)]

*binary Shannon entropy function*

$$\dot{S} = \frac{k_B}{h} \sum_{\alpha=L,R} \int d\varepsilon \left( \underbrace{-\sigma[f_\alpha(\varepsilon)]}_{\text{Ingoing distribution}} + \underbrace{\sigma[f_\alpha^{(\text{out})}(\varepsilon)]}_{\text{Outgoing distribution}} \right) \geq 0$$

Power generation is possible from isothermal baths,  $\theta_L = \theta_R \equiv \theta$ .



$$\delta\dot{S} = \dot{S} - \dot{S}^{(C)}$$

AC voltage induces

- ➔ more uncertain energy distribution (without injecting any net work)
- ➔ generate pump current
- ➔ power generation violating Kelvin-Planck statement

This does not depend on detailed forms of AC voltage !

- AC driven chiral conductor can exhibit efficiency beyond the Carnot limit due to the negative entropy production when the Clausius relation is assumed.
- The seeming violation of 2<sup>nd</sup> law is resolved when employing entropy production based on Shannon entropy flow.
- Chiral transport is crucial for efficiency enhancement; Nonchiral conductors do not exhibit efficiencies beyond Carnot's as AC injects power which diminishes the generated power.
- We expect experimental realizations as the regime is approachable.



**THANK YOU**  
for your attention