# RPMBT22: Quantum Avalanche as Nonequilibrium Instability

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We are trying find a foothold for theoretical models of DC nonequilibrium many-body phenomena that permit an accessible solution.

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**Correlated insulator collapse due to quantum avalanche via in-gap ladder states**

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**Avalanche instability as nonequilibrium quantum criticality**

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# Talk Outline

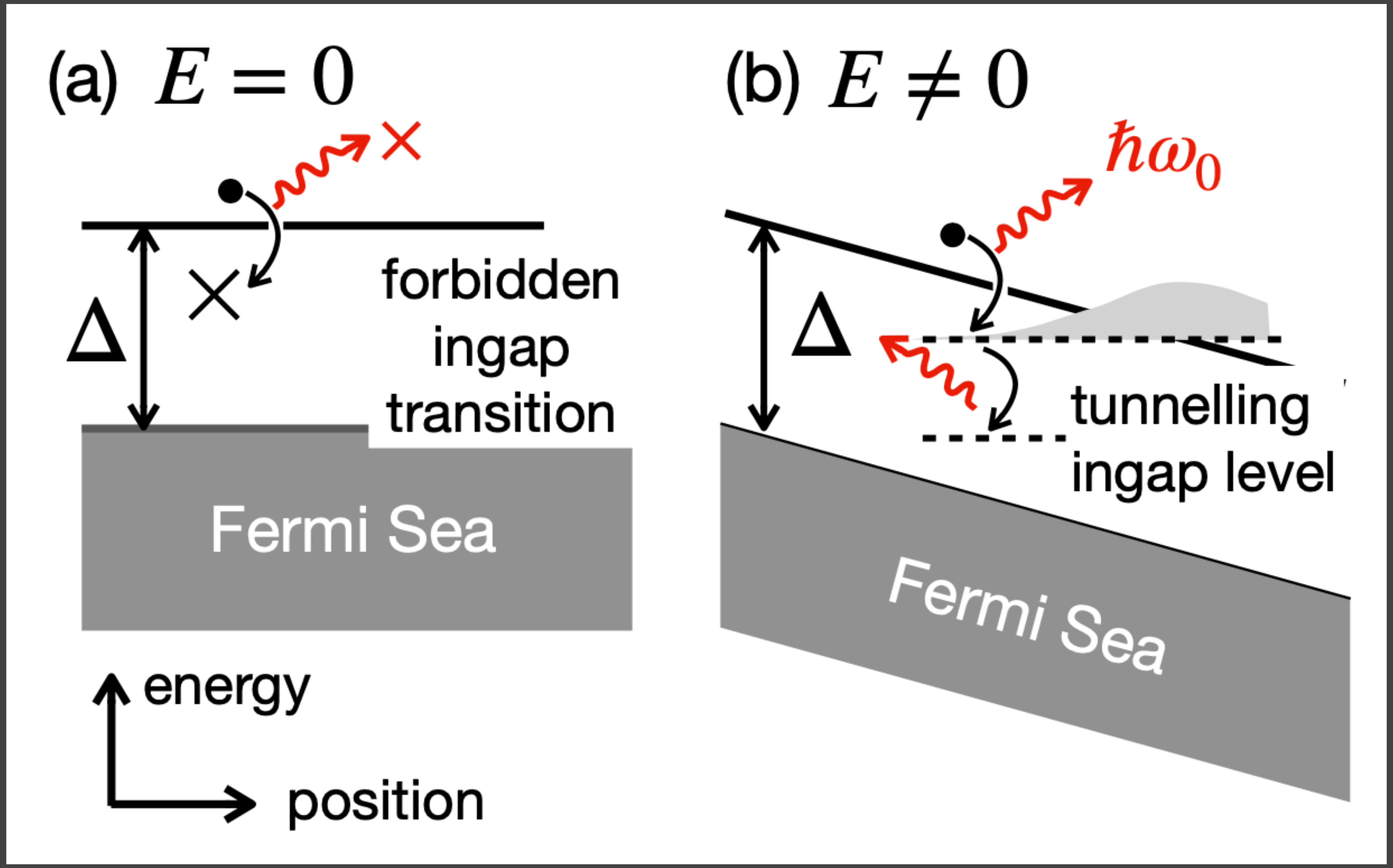
## a minimal model

- Intro: Is an electronic band stable under a DC electric-field?
- Set up fermion- and boson-baths for steady-state noneq. limit
- Phase transition controlled by the coupling to environment

## application: insulator-to-metal transition by an electric field

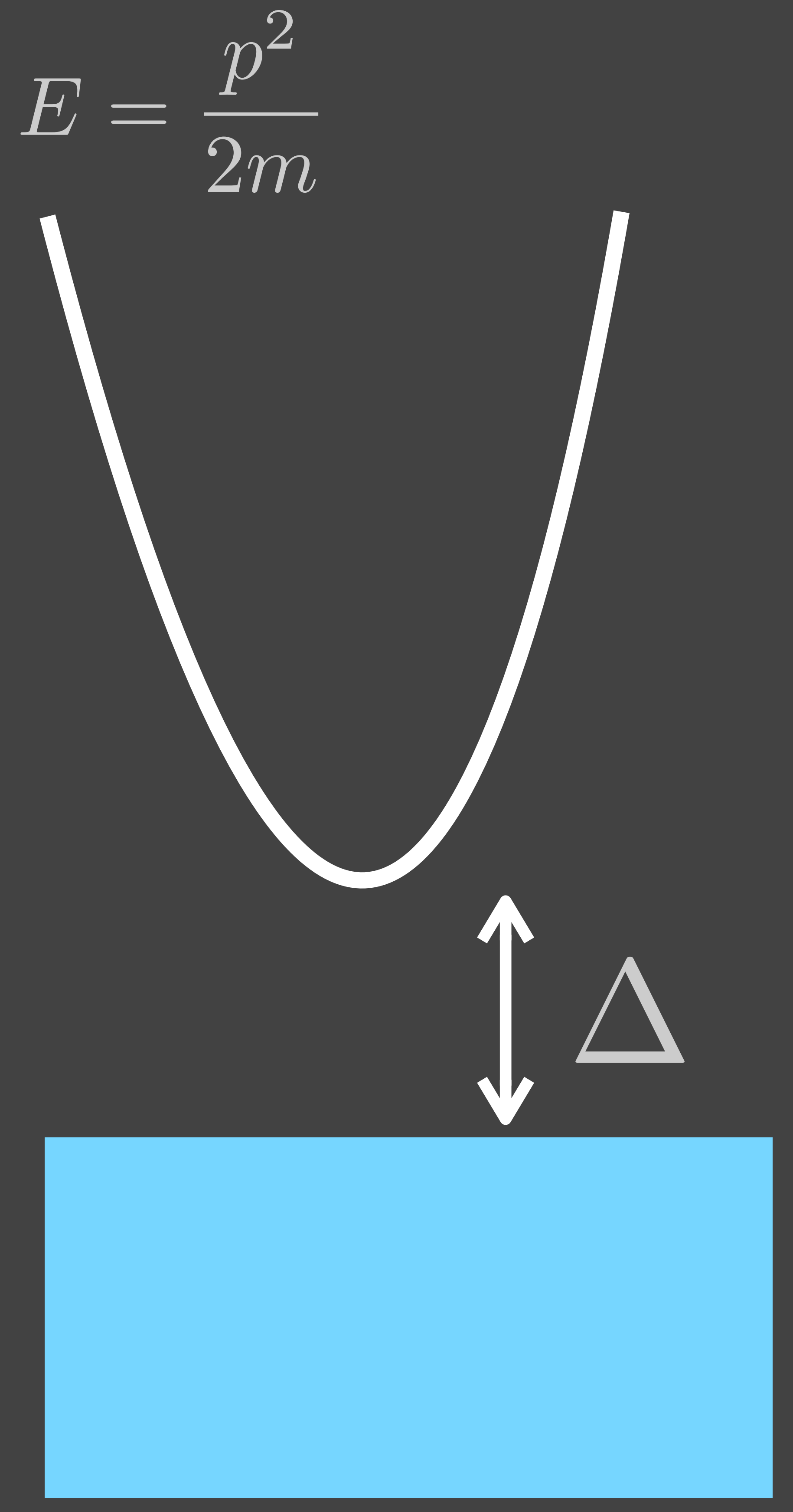
- Two-band model for symmetry-broken Insulators
- Relevance to experiments: why we didn’t see it earlier?

# A Simpler Question: Is a Band Stable in Noneq.?




Field-induced tunneling (Franz-Keldysh effect) enables multiple spontaneous emission of bosons

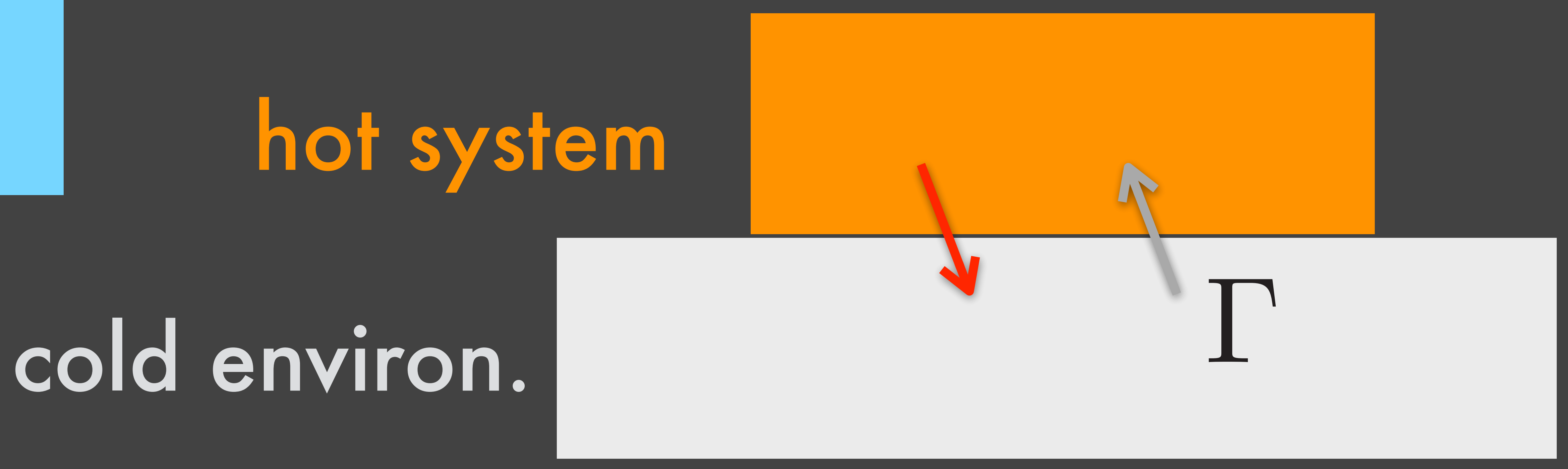
# Single Band above Fermi-Energy



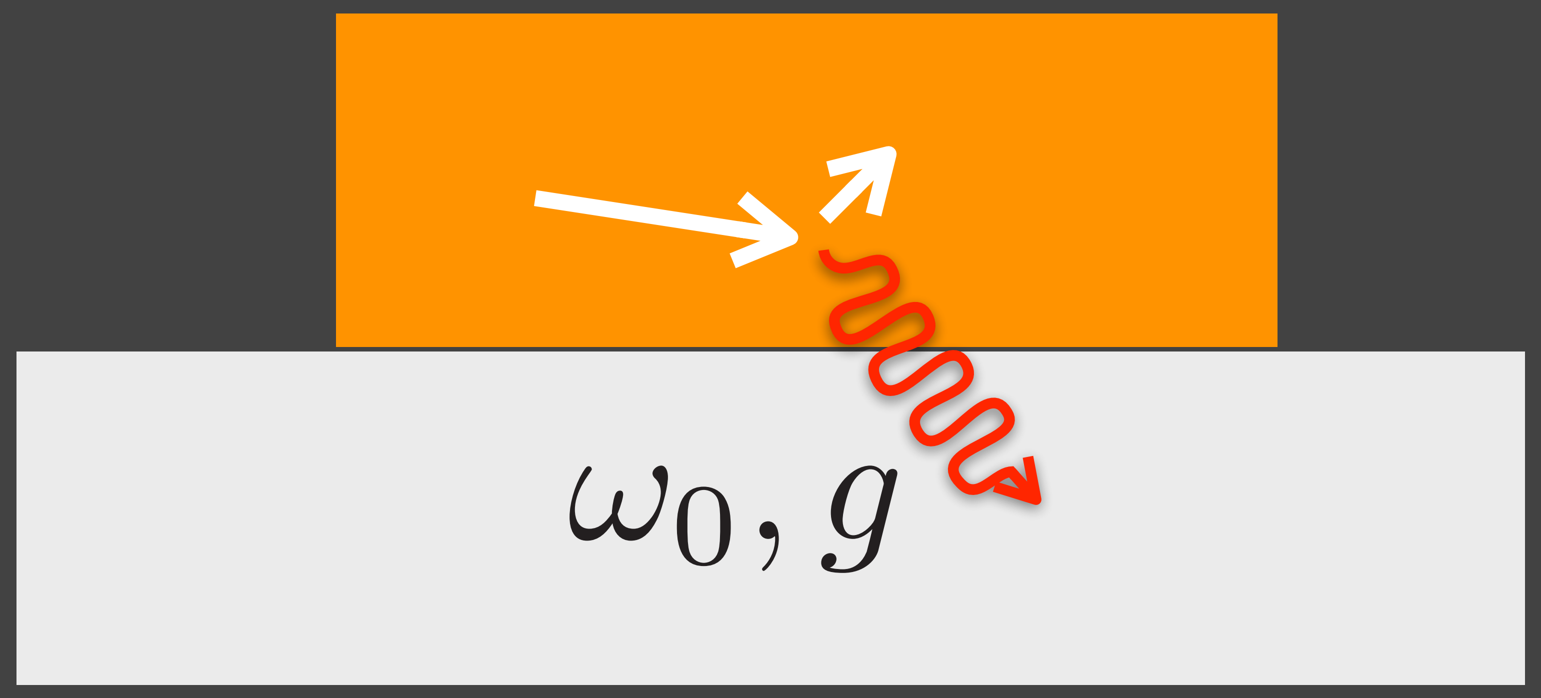

Electric-field ↓   gap from Fermi-energy ↓

$$H(t) = \int \left[ \psi^\dagger(x) \left( \frac{1}{2m} (-i\partial_x + Et)^2 + \Delta \right) \psi(x) + \frac{1}{2}[p_\varphi(x)^2 + \omega_0^2 \varphi(x)^2] + g_{\text{ep}} \varphi(x) \psi^\dagger(x) \psi(x) \right] dx$$

+ “Dissipation”

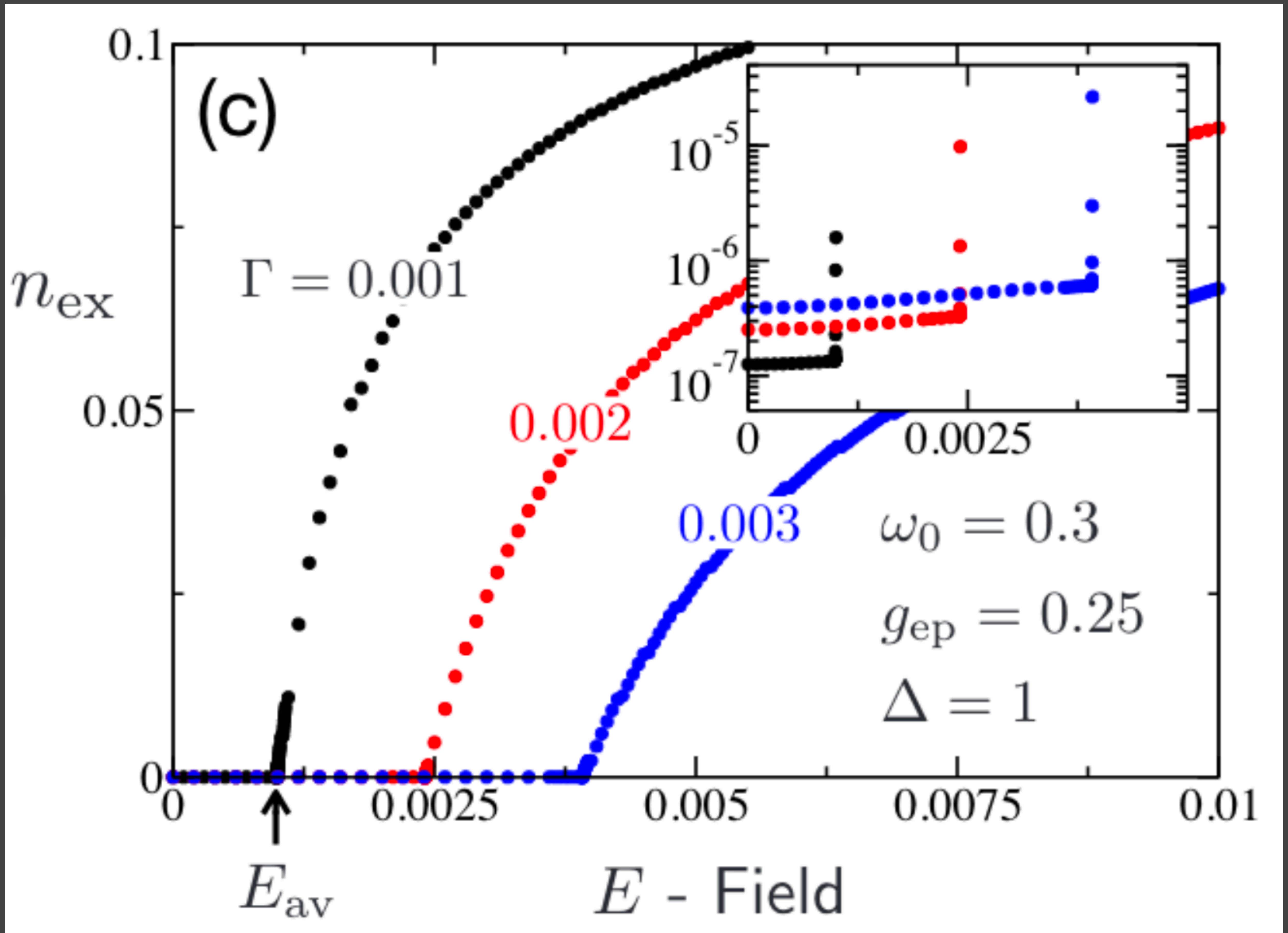



dissipate by exchange



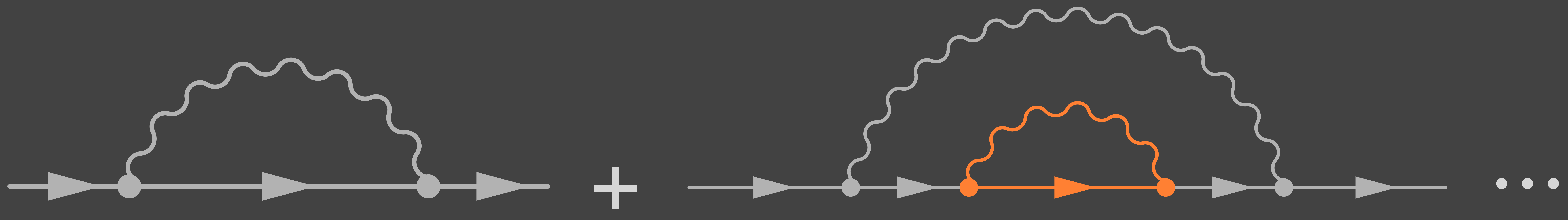

dissipate by emission

# Coupling to Environment Controls Avalanche




- The avalanche field $E_{av}$ is proportional to the coupling $\Gamma$ to the environment ( $\Gamma = 0$ is a singular limit in steady-state nonequilibrium).
- Continuous nonequilibrium transition
- Avalanche easier for less thermally excited conditions! – quantum nature

# Multiple Emission by (Keldysh) Diagrammatics



"Eliashberg" diagrams

- Multiplicative factor $\lambda \approx 1$ signals an avalanche
- Simplifying limits make an analytic calculation possible: occupation number $n_{\rm ex} \ll 1$, dephasing rate $\Gamma \ll E, \omega_0, \Delta$

# Criterion for Transition

$$\lambda = \frac{\Sigma_p^{(4),<}(0)}{\Sigma_p^{(2),<}(0)} \approx \frac{img_{\rm ep}^2}{2\omega_0} \int \frac{dq}{2\pi} \int ds \frac{e^{i(q^2/2m+\omega_0)s}}{qEs + 2im\Gamma}$$

$$= \frac{mg_{\rm ep}^2}{4\omega_0 E} \int_{-\infty}^{\infty} \frac{dq}{|q|} \exp\left(-\frac{2m\Gamma}{E}\frac{q^2/2m+\omega_0}{|q|}\right)$$

$$= \boxed{\frac{mg_{\rm ep}^2}{\omega_o E} K_0\left(\frac{2\Gamma\sqrt{2m\omega_0}}{E}\right) = 1}$$

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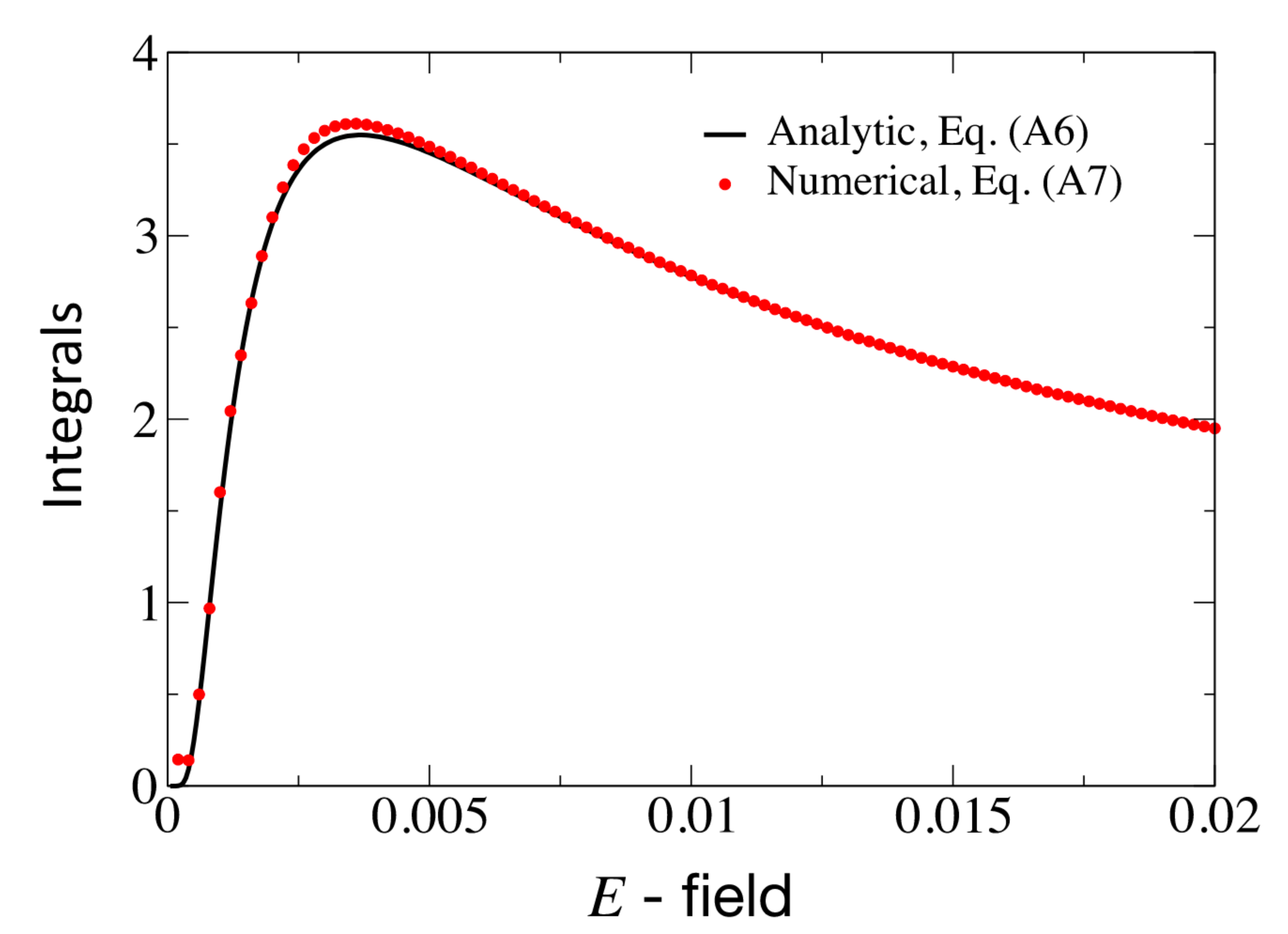
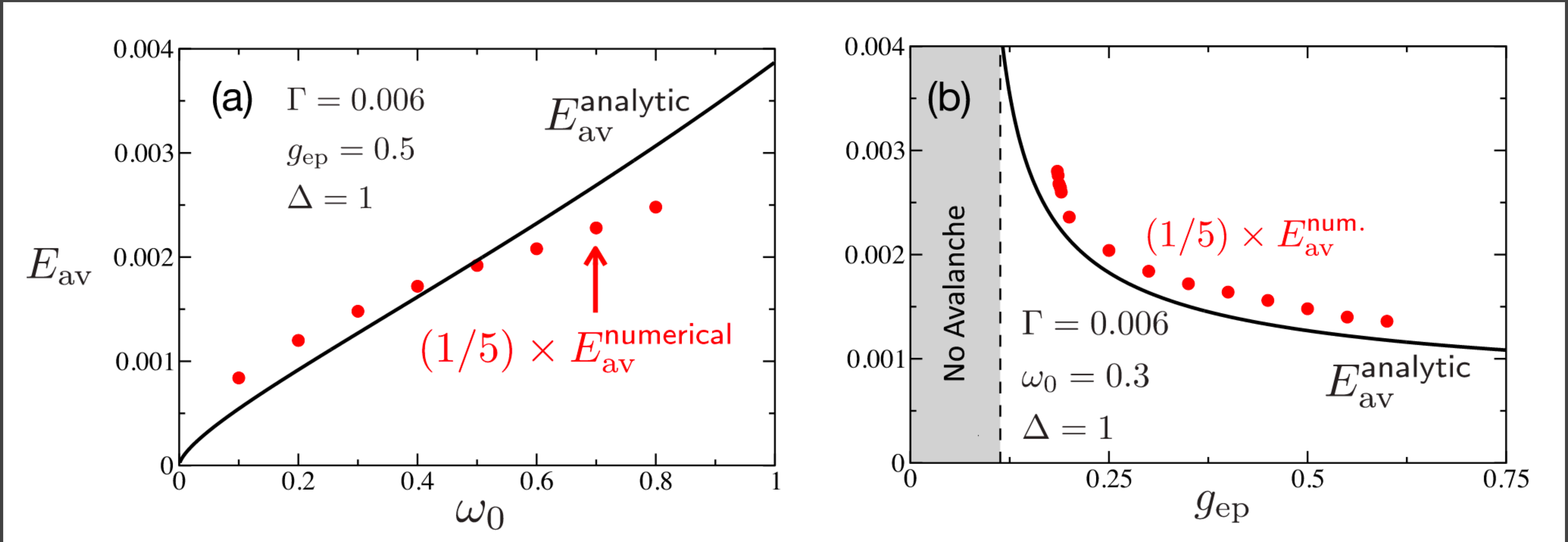
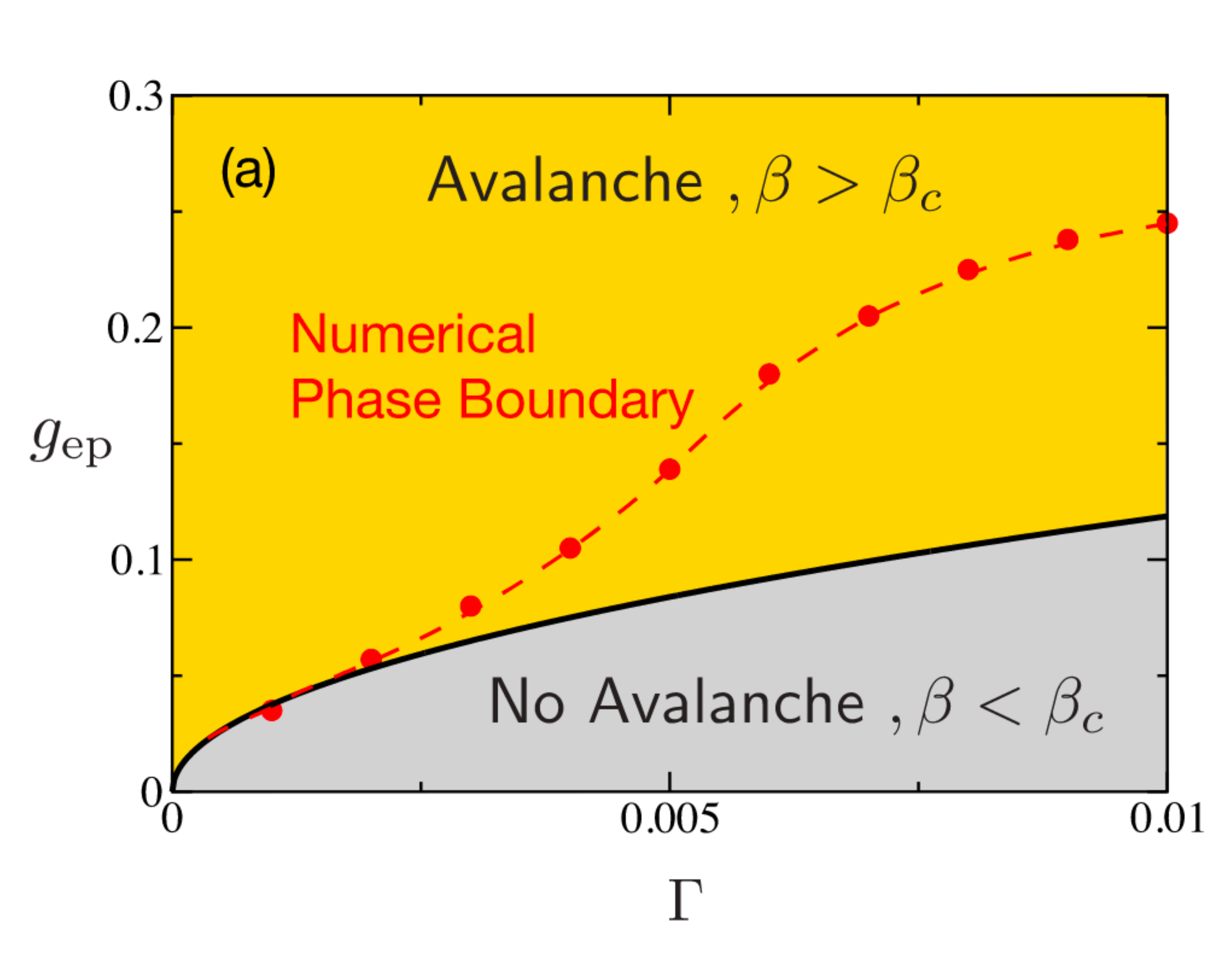


# Agreement with Numerical Lattice Model

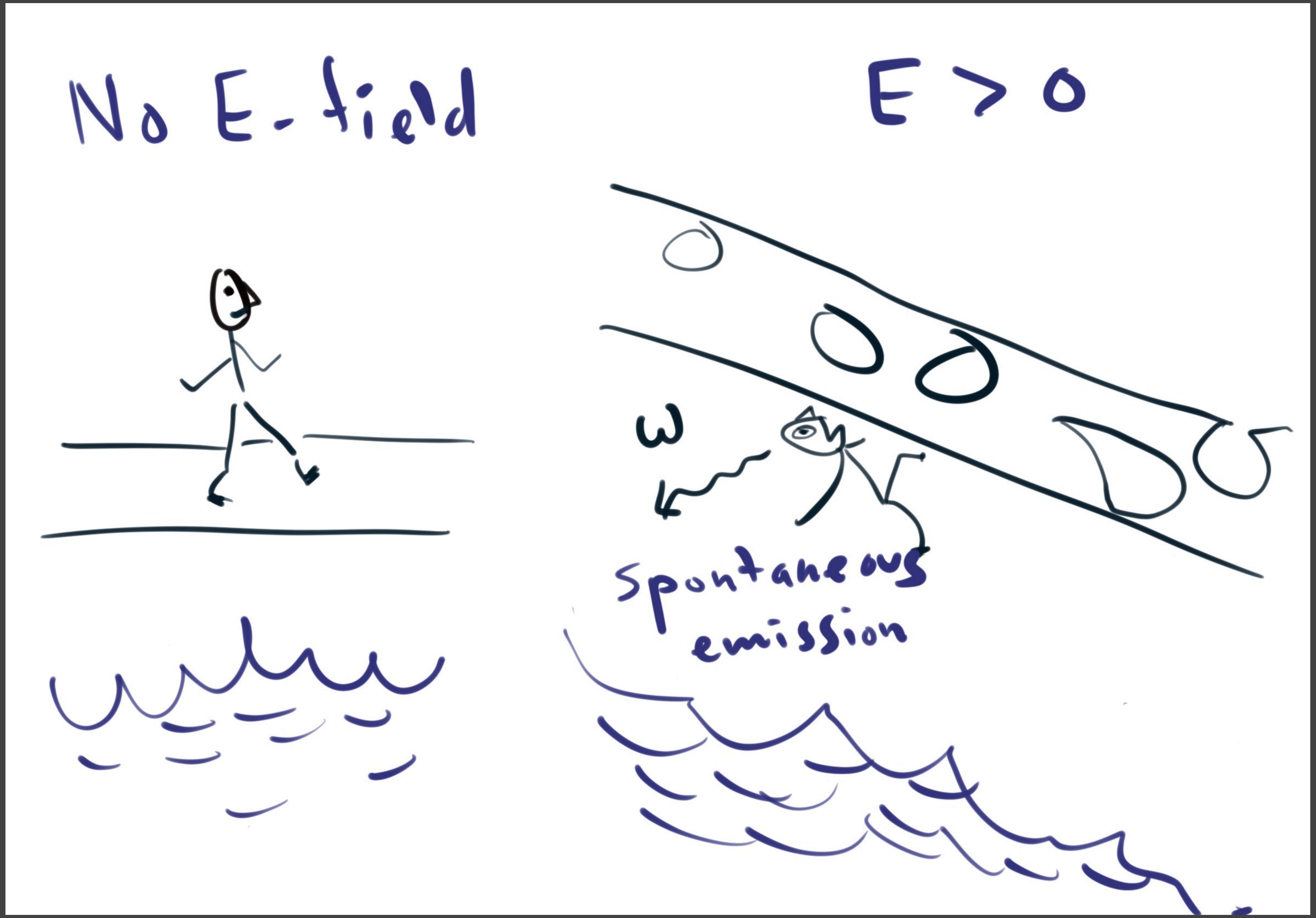



Excellent agreement with numerical lattice calculations, except for an overall factor*

# Competition of Avalanche with Dephasing



# Quantum Avalanche (in Cartoon)




The quantum avalanche occurs not because electrons become energetic, but because the floor becomes unstable due to the spontaneous emission.

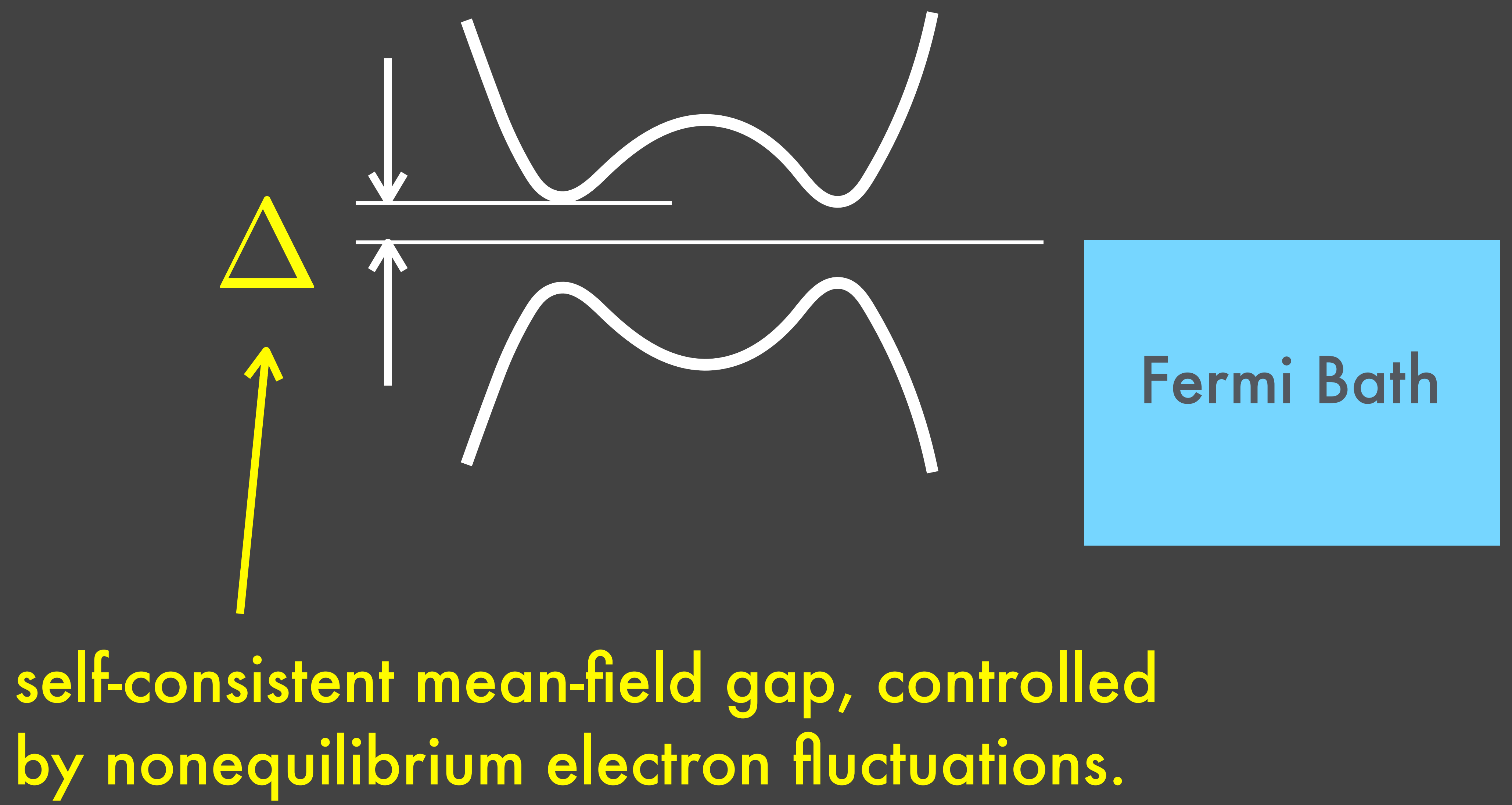
# How it's Relevant? : Resistive Switching (RS)

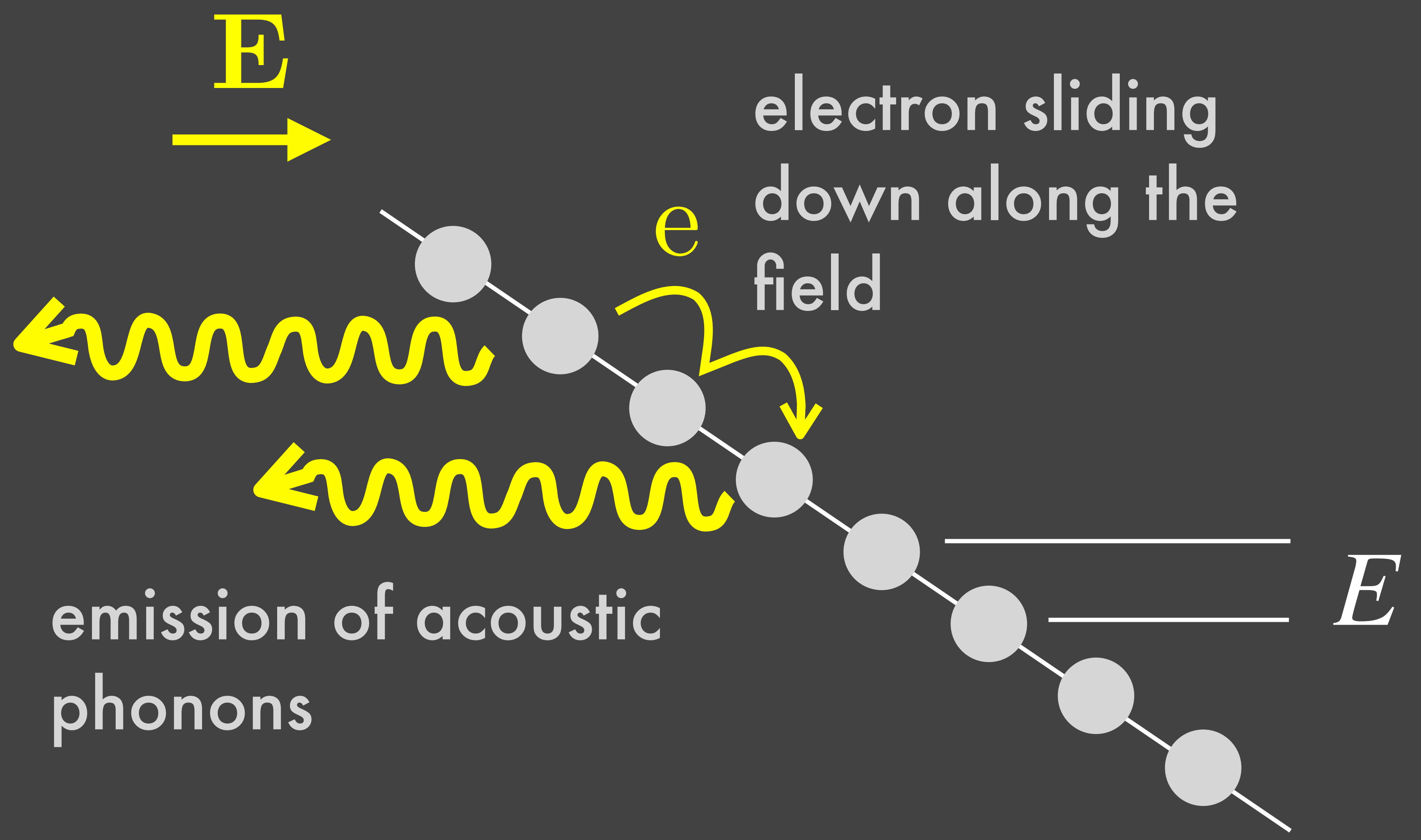
Resistve Switching is a diverse topic and has a long history. It concerns sudden switching of restsivity under a DC electric field. Mechanisms such as impact ionization, electro-migration, lattice transition, and correlation-driven in $V_xO_y$, $NbO_2$ (Mott), $MC_3$ (CDWs) etc.. exist.

- Insulator-metal transition by electric-field (Mott, CDW systems)
- Unsettled debate over thermal vs quantum origin

In search of an elemental understanding, I will view RS as nonequilibrium (bulk) phase transition.

# Symmetry-Broken 2-Band Model

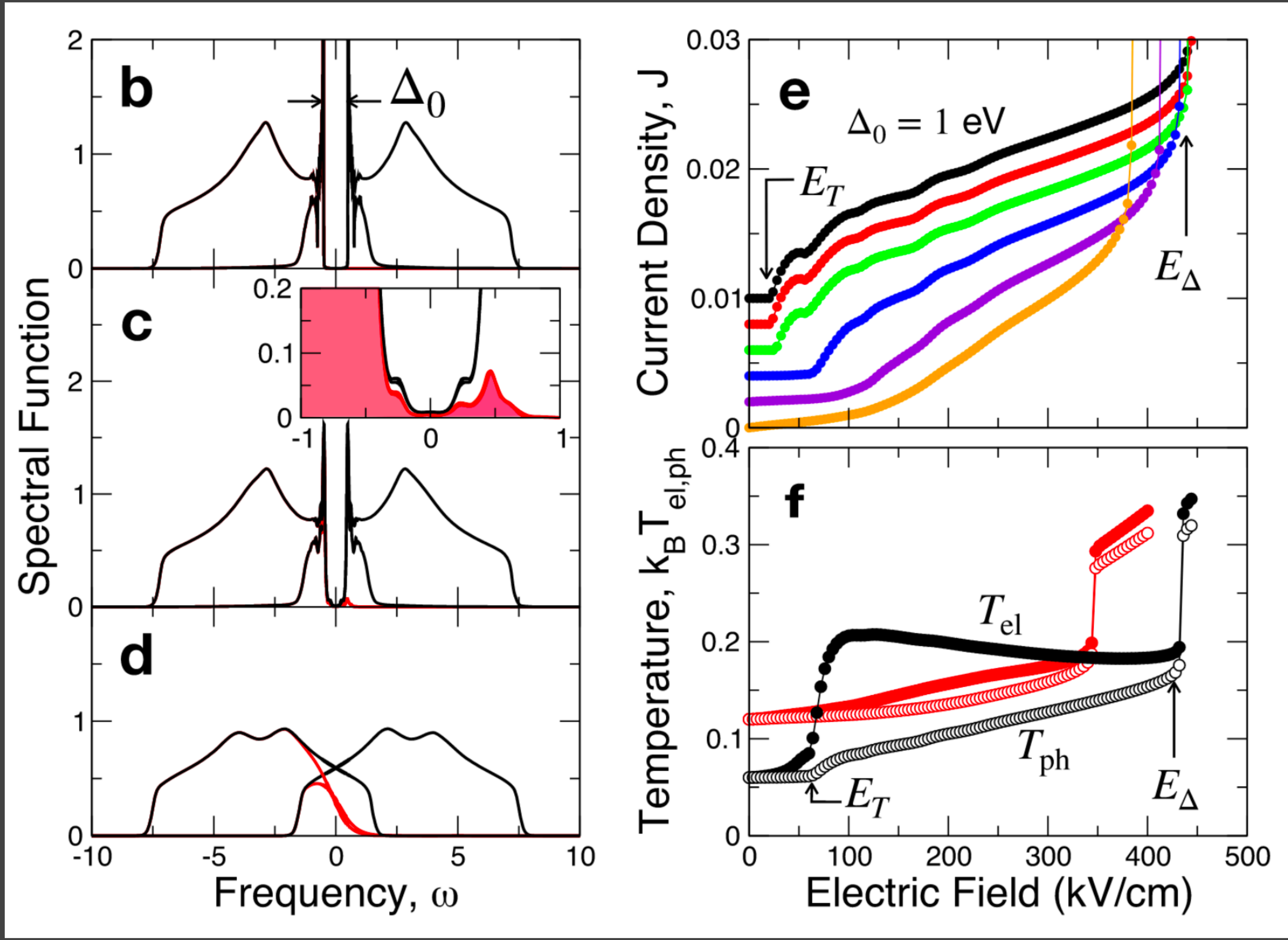


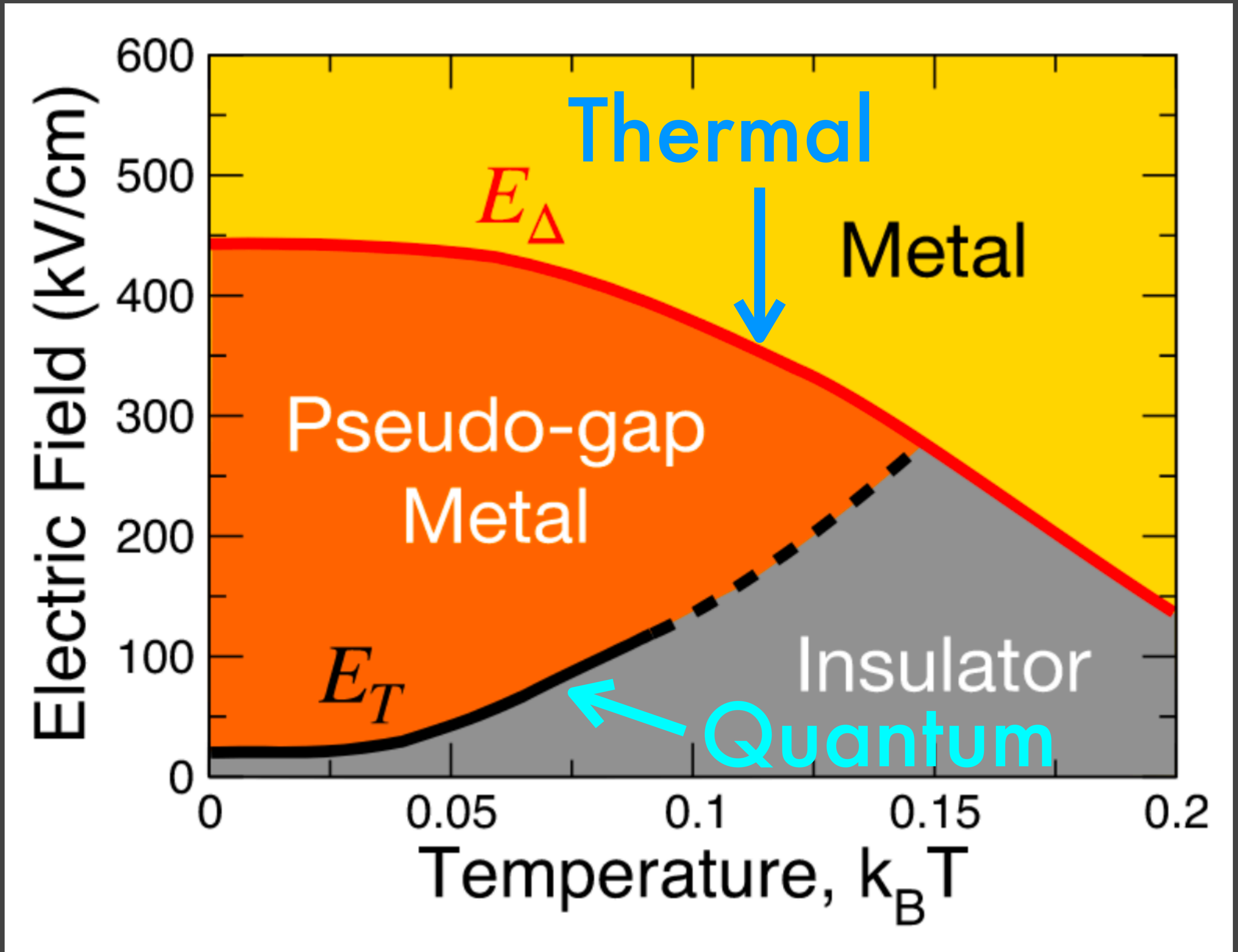

Solve the Keldysh GF with the steady-state bulk condition

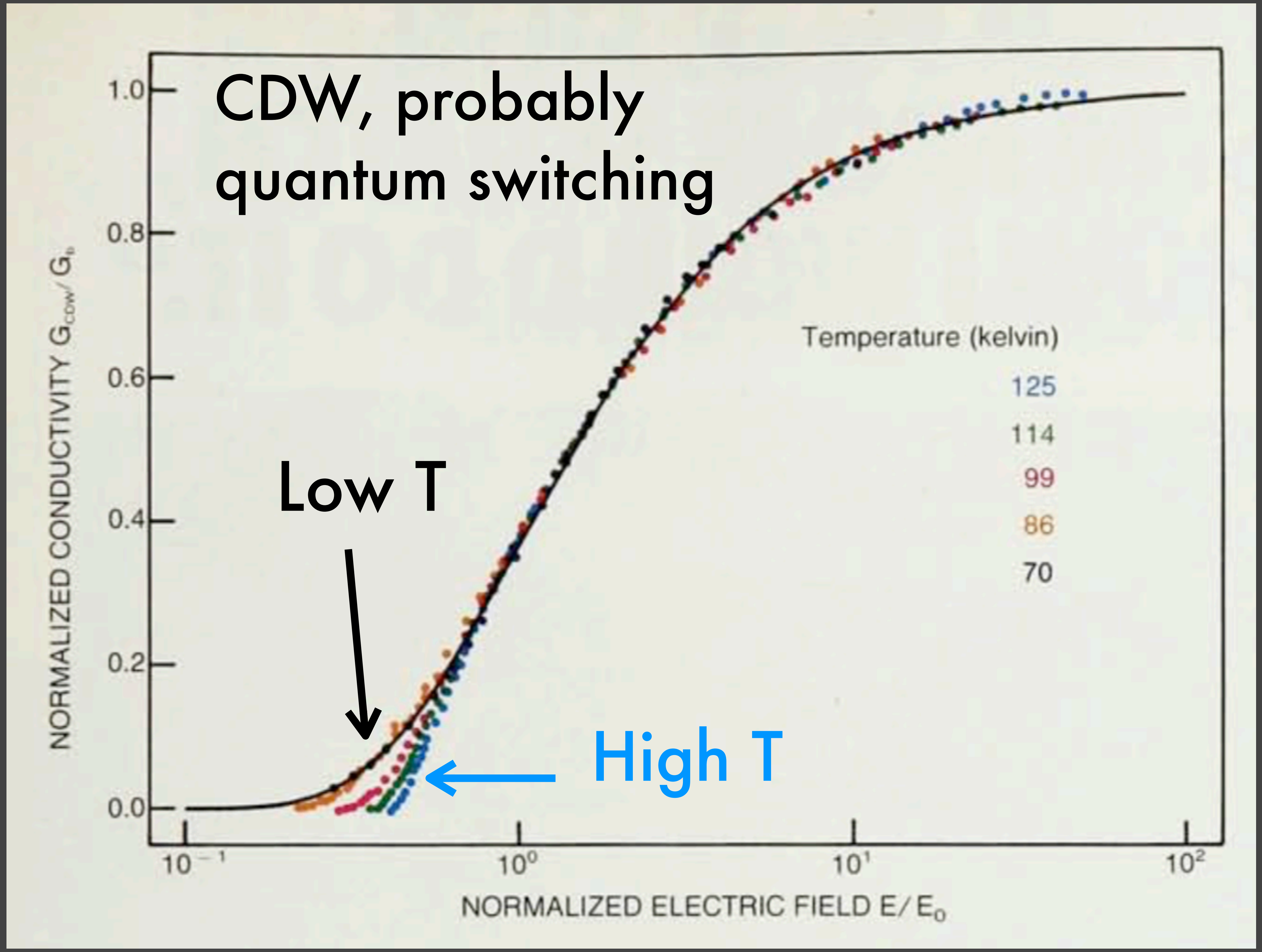
$$G(x,\omega) = G(x+a, \omega + eEa)$$

# Avalanche and Two-Step Transition



# Criterion for Thermal or Quantum?




$NbSe_3$, J. Bardeen, Physics Today (1990)

# Conclusions and Outlook

- We presented a concrete quantum model for nonequilibrium phase transition, with some analytic understanding.
- Need to better understand when the quantum avalnche overcomes the dephasing in interacting models
- Starting to worry about better solvers...