Hawking Radiation and Non-Equilibrium Quantum Critical Current Noise

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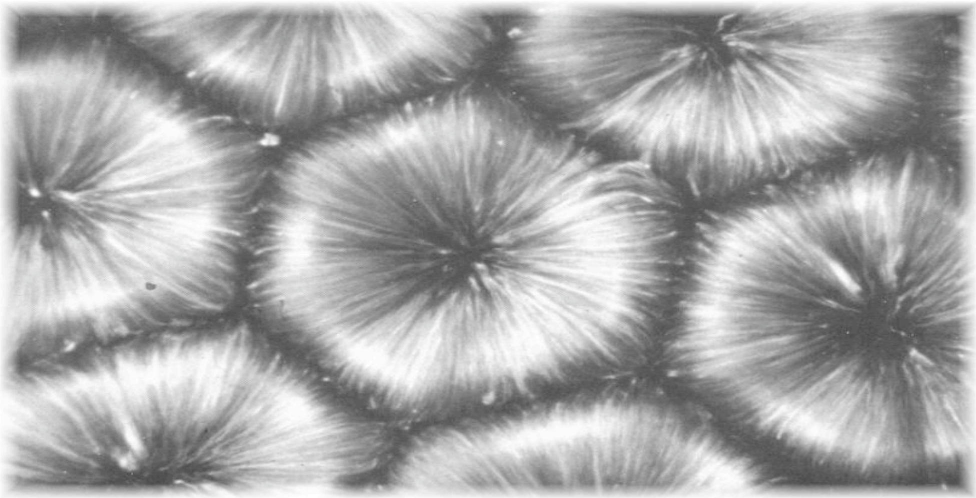
Strongly Correlated Systems Out of Equilibrium



New Scientific and Technological Frontier

Fewer over-riding principles than Equilibrium

Quantum Critical systems – Out-of-Equilibrium Universality

Outline:

Quantum Critical Current Noise: AGG

- Central Idea
- Bose-Hubbard Model Out of Equilibrium
  - -Boltzmann Eq – steady state current
  - -Boltzmann Langevin – current noise

Holographic Current Noise: JS

- General Setting
- Details
- Discussion and Outlook

QC Current Noise

Central Idea:

Quantum Critical systems show additional universality out of equilibrium

Dynamical scaling in equilibrium is inherited by out-of-equilibrium steady state.

Early results have bourne out this expectation…

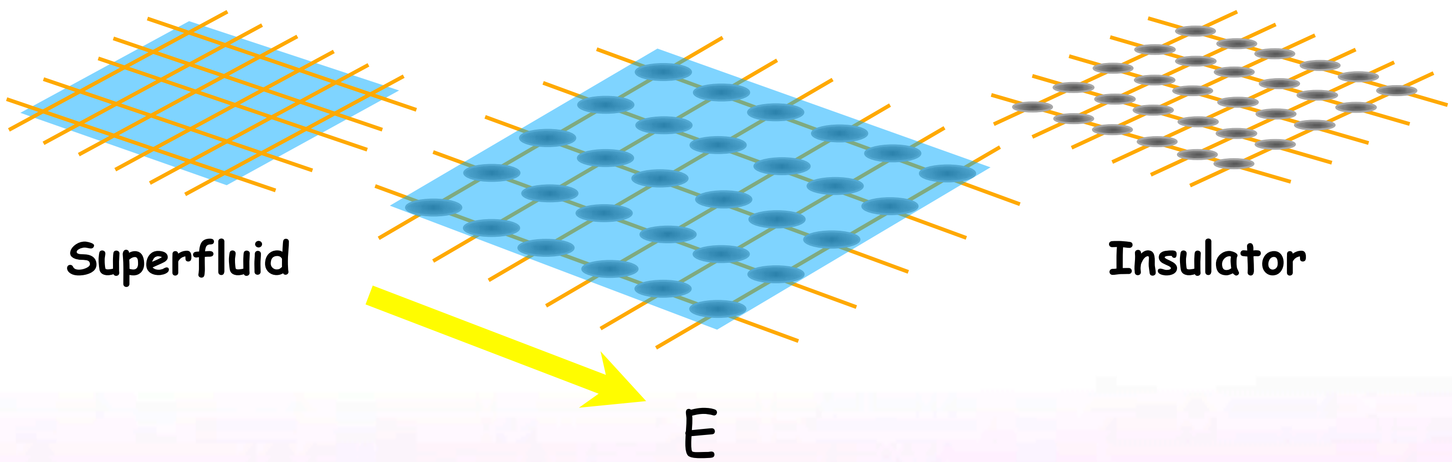
[Dalidovich+Phillips PRL2004]
[Green+Sondhi PRL2005]
[Green, Moore, Sondhi+Vishwanath PRL2006]
[Mitra, Takei, Kim+Millis PRL2006]
[Karch+Sondhi JHEP2011]

…and Holography may have something to add

QC Current Noise

Central Idea: dynamical scaling in equilibrium is inherited by out-of-equilibrium steady state.

Bose-Hubbard Model: $$\mathcal{H} = -J\sum_{<i,j>}\hat{c}_i^+\hat{c}_j + \frac{1}{2}U\sum_i \hat{n}_i(\hat{n}_i - 1)$$

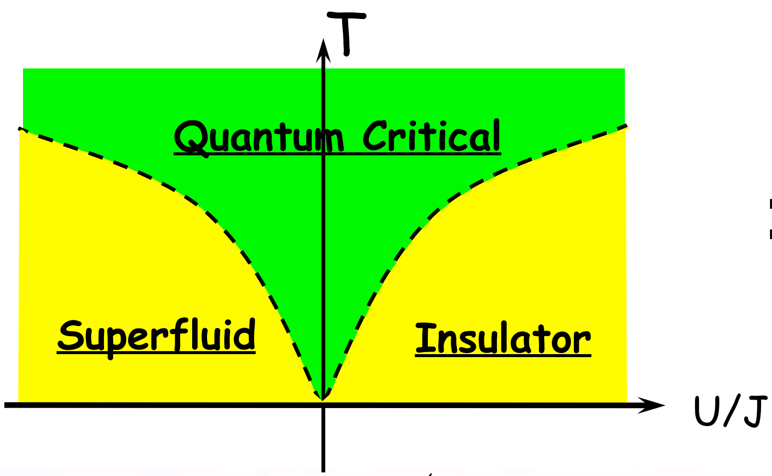


Response to Strong in-plane E-Field

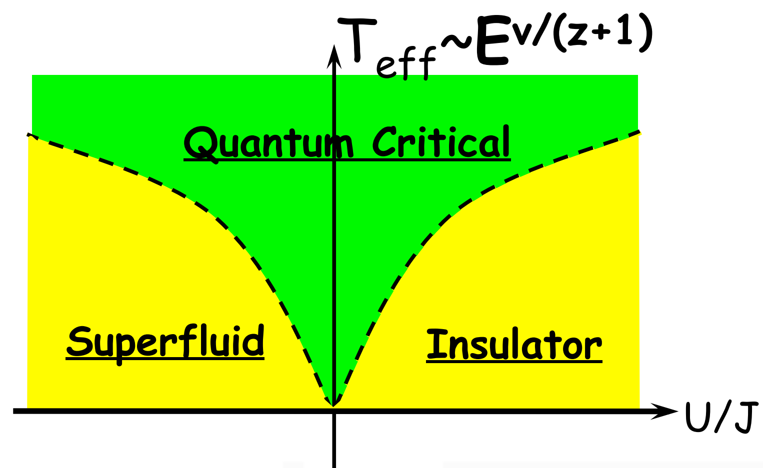
QC Current Noise

Central Idea: dynamical scaling in equilibrium is inherited by out-of-equilibrium steady state.

Scaling Analysis:



?
$\Rightarrow$



$$\sigma(\delta, T) = T^{d-2/\nu}\,\Sigma(\delta/T)$$

$$\sigma(\delta, E) = E^{d-2/z+1}\,\Sigma(\delta/E^{\nu/(z+1)})$$

QC Current Noise

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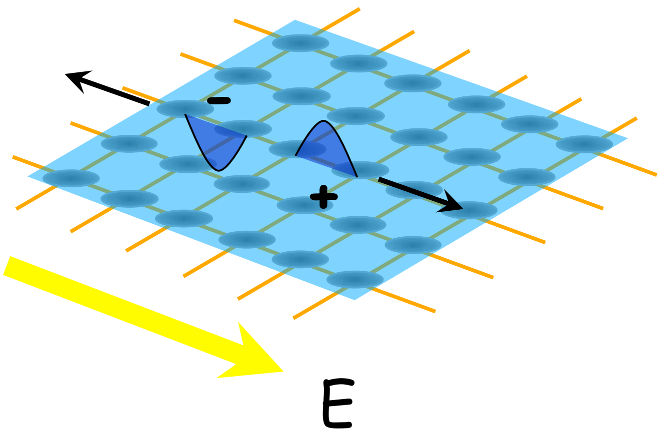


Bose-Hubbard Model:

$$\mathcal{H} = -J \sum_{<i,j>} \hat{c}_i^{+} \hat{c}_j + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

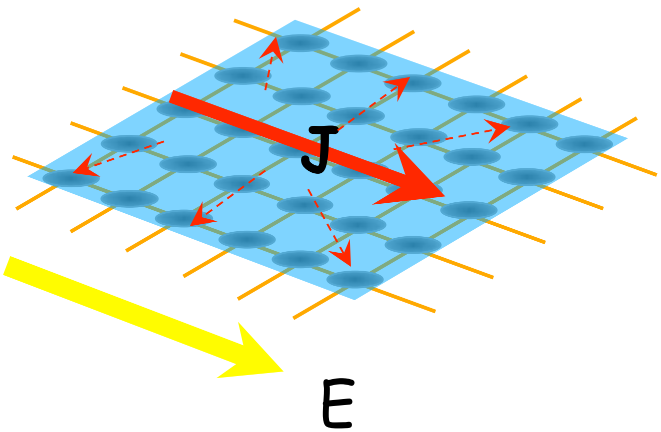
- Field Theory:

  Klein Gordon + nteractions

- Schwinger pair production
- Critical Scattering

QC Current Noise

Heat Flow and the 1/N Trick:



Joule heating => heat sink required for steady state

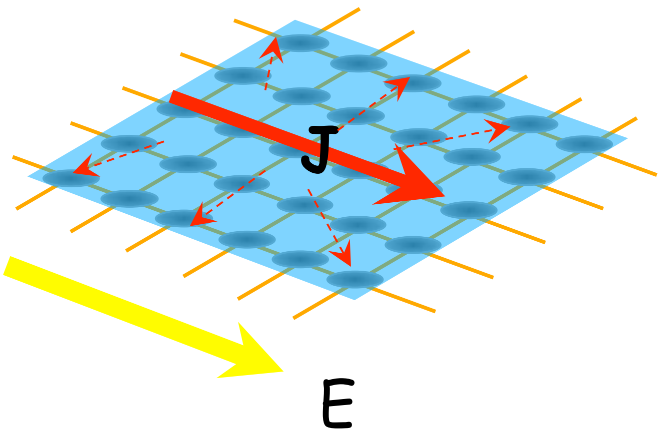
Rate limiting step

- Heat transport => Non-Universal
- Scattering into heat transport modes => Universal

Here $\kappa \longrightarrow \infty$ => Univeral

QC Current Noise

Heat Flow and the 1/N Trick:



Control Theory in 1/N:

Couple one mode to E

N-1 uncoupled modes

- -provide T=0 bath
- -no need to treat heat transport explicitly

[Green+Sondhi PRL2005]

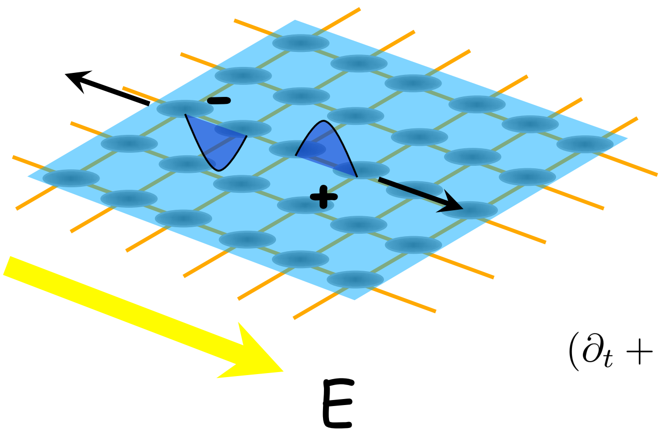
Control Theory in ε:

Must treat transport explicitly

[Berridge, Bhaseen and Green in preparation]

QC Current Noise

Microscopic Analysis:



Normal Modes: +/-ve charge

Boltzmann

scattering

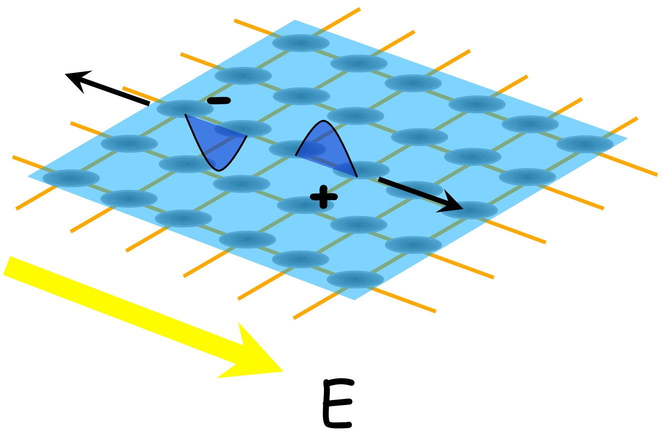
Schwinger pair production

$$
\begin{aligned}
\left(\partial_t + \mathbf{E}.\partial_{\mathbf{k}}\right) f(\mathbf{k},t) &= -\gamma_{\mathbf{k}}(t) f(\mathbf{k},t) + \frac{e^{-\pi(\mathbf{k}^2+m^2)/E}}{16}\delta(\mathbf{k}.\mathbf{E}/E^2) \\
\gamma_{\mathbf{k}}(t) &= \frac{32}{N}\frac{\sqrt{|\mathbf{k}|+k_{\parallel}}}{\epsilon_{\mathbf{k}}}\int \frac{d\mathbf{q}}{(2\pi)^2}\frac{\sqrt{|\mathbf{q}|+q_{\parallel}}}{\epsilon_{\mathbf{q}}} f(\mathbf{q},t) \\
m(E)^2 &= \frac{1}{\pi(N+8)}\int \frac{d\mathbf{q}}{(2\pi)^2}\frac{f(\mathbf{q},t)}{\epsilon_{\mathbf{q}}}
\end{aligned}
$$

[Green+Sondhi PRL2005]

QC Current Noise

Microscopic Analysis:



Normal Modes: +/-ve charge

Boltzmann:
$$\frac{dj}{dt} = \underbrace{aE^{\frac{d+1}{2}}}_{\text{Schwinger pair production}} - \underbrace{b\sqrt{E}j}_{\text{scattering}}$$

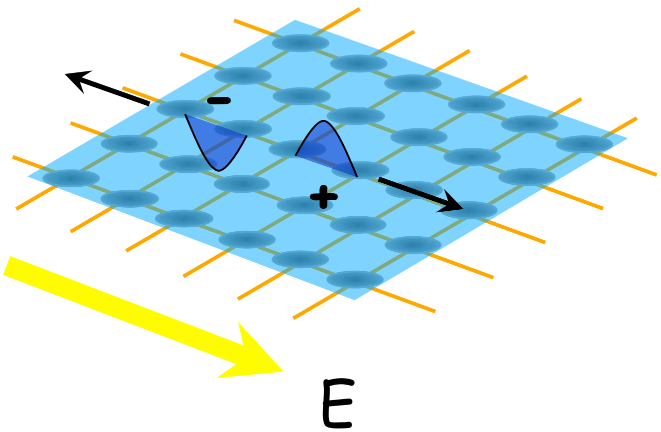
$$\Rightarrow j = \frac{a}{b}E^{\frac{d}{2}}$$

$$\Rightarrow \sigma = \frac{a}{b} \quad \text{const in } d = 2$$

[Green+Sondhi PRL2005]

Conductivity not revealing, but noise is...

Microscopic Analysis:



Normal Modes: +/-ve charge

Boltzmann: $$\frac{dj}{dt} = aE^{\frac{d+1}{2}} - b\sqrt{E}j$$

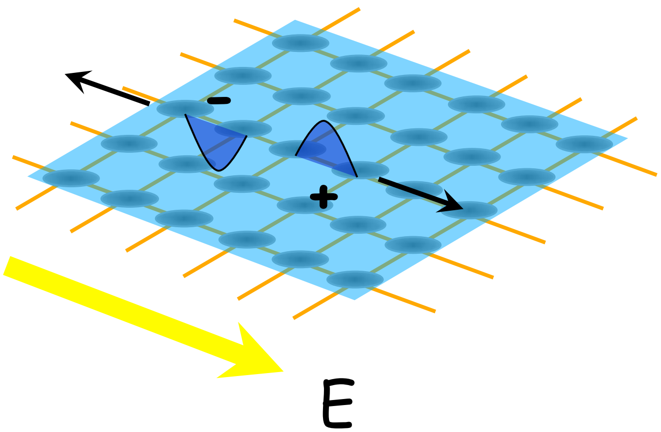
Boltzmann-Langevin:

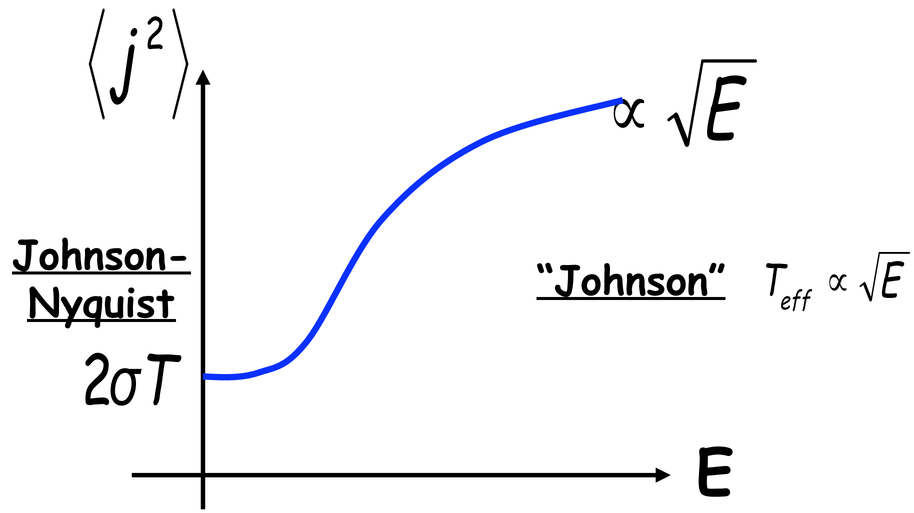
$$\begin{aligned}\frac{d\delta j}{dt} &= -b\sqrt{E}\delta j + \eta \\ \langle \eta(t)\eta(t')\rangle &= 4aE^{\frac{d+1}{2}}\delta(t-t') \\ \Rightarrow \langle j \;\; j_{-} \;\; \rangle &= 4\sigma\sqrt{E} \;\; \text{in } d=2\end{aligned}$$

[Green, Moore, Sondhi+Vishwanath PRL2006]

QC Current Noise

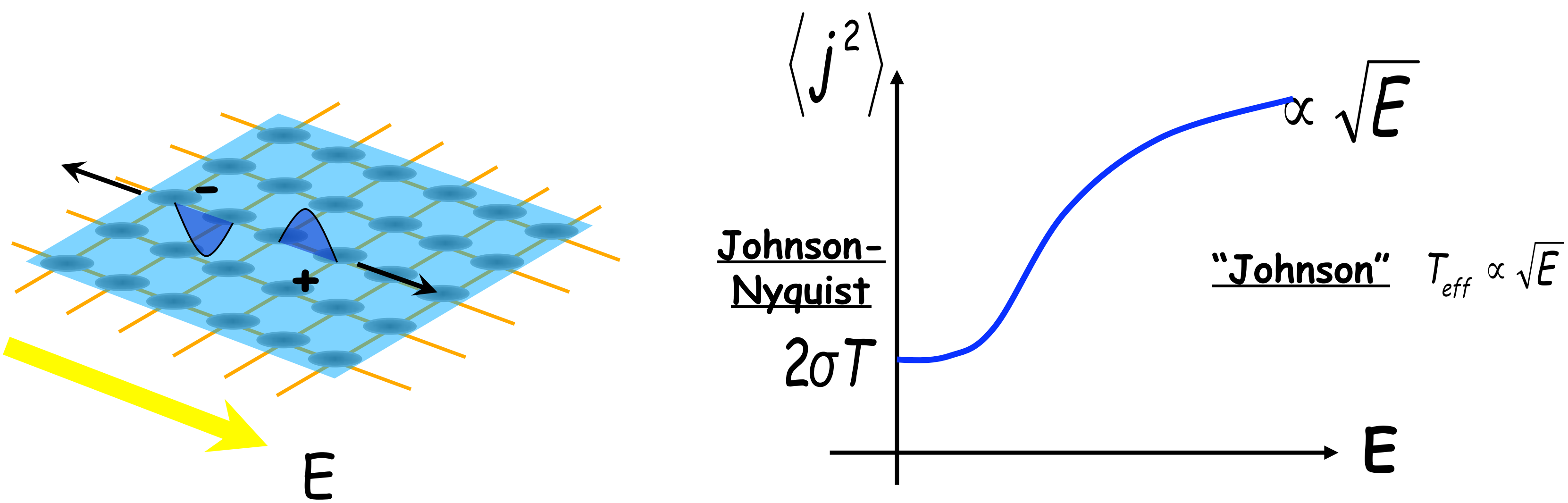
Microscopic Analysis:





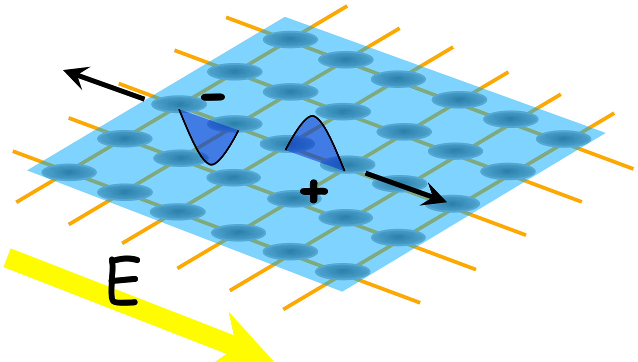
QC Current Noise

Microscopic Analysis:

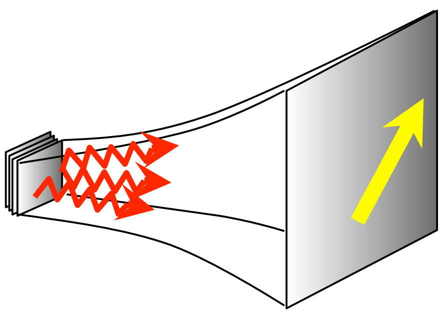


Central Idea: dynamical scaling in equilibrium is inherited by out-of-equilibrium steady state.

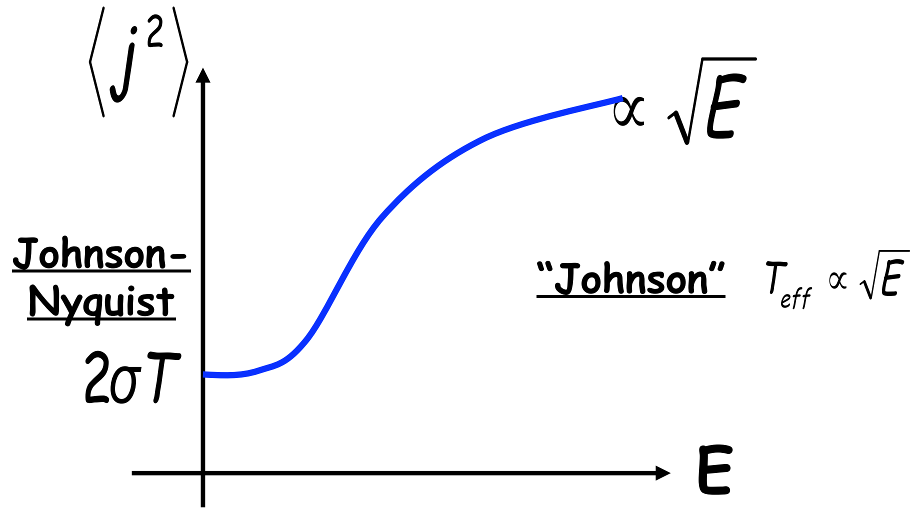
QC vs Holographic Current Noise



Bose-Hubbard



D3/D5 intersection



$$\mathcal{S}_j = 4\sigma(T^*)T^*$$

$$(\pi T^*)^4 = (\pi T)^4 + E^2$$

- Full interpolation low-> high E

Hawking Radiation <-> Current Noise

Summary:

- QC Universal Out-of-Equilibrium
- Particularly apparent in current noise
- Holography:

    Current Noise <-> Hawking Radiation

    Interpolates equilibrium -> out-of-equilibrium