

A simple model of many-particle entanglement: how it describes black holes and superconductors

J62: Physical Review Invited Session:
Forefront Research Across Disciplines

APS March Meeting

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Subir Sachdev

Talk online: sachdev.physics.harvard.edu



HARVARD

A remarkable connections has emerged
in modern physics between

(A) the quantum theory of many strongly
interacting particles (e.g. electrons in a crystal)
and

(B) the quantum theory of black holes.

**A remarkable connections has emerged
in modern physics between**

**(A) the quantum theory of many strongly
interacting particles (e.g. electrons in a crystal)
and**

(B) the quantum theory of black holes.

**Among the many remarkable features:
gravity is completely negligible in (A),
while gravitational forces are
extremely strong in (B).**

I will illustrate this connection using
a simple example: the Sachdev-Ye-Kitaev (SYK)
model which describes
certain quantum many particle systems
and
certain black holes

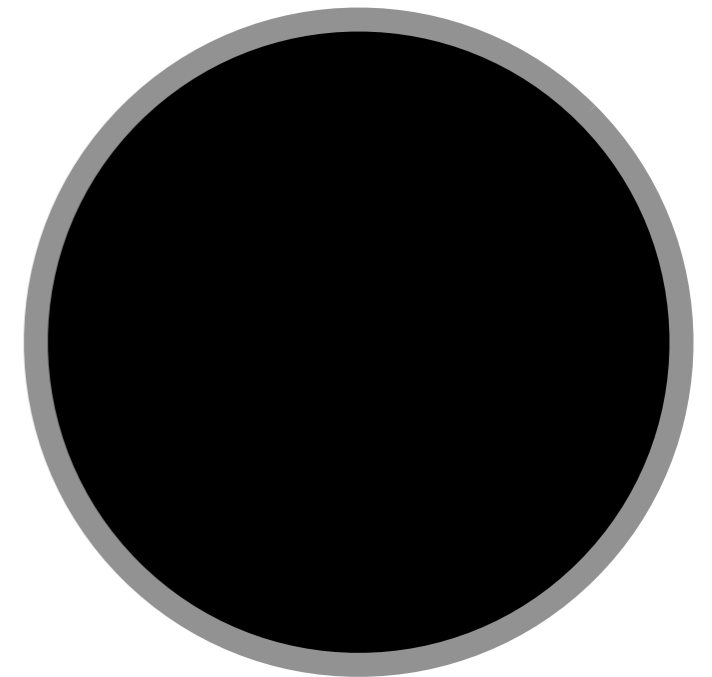
**Quantum
entanglement**

**Black
holes**

Black Holes

Objects so dense that light is gravitationally bound to them.

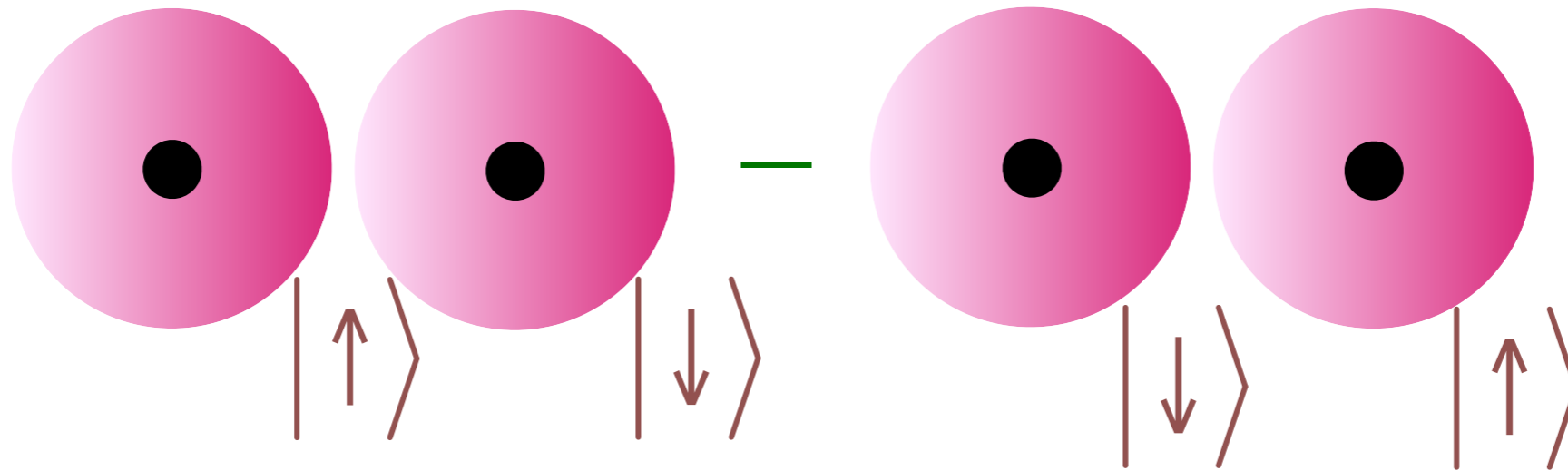
In Einstein's theory, the region inside the black hole **horizon** is disconnected from the rest of the universe.



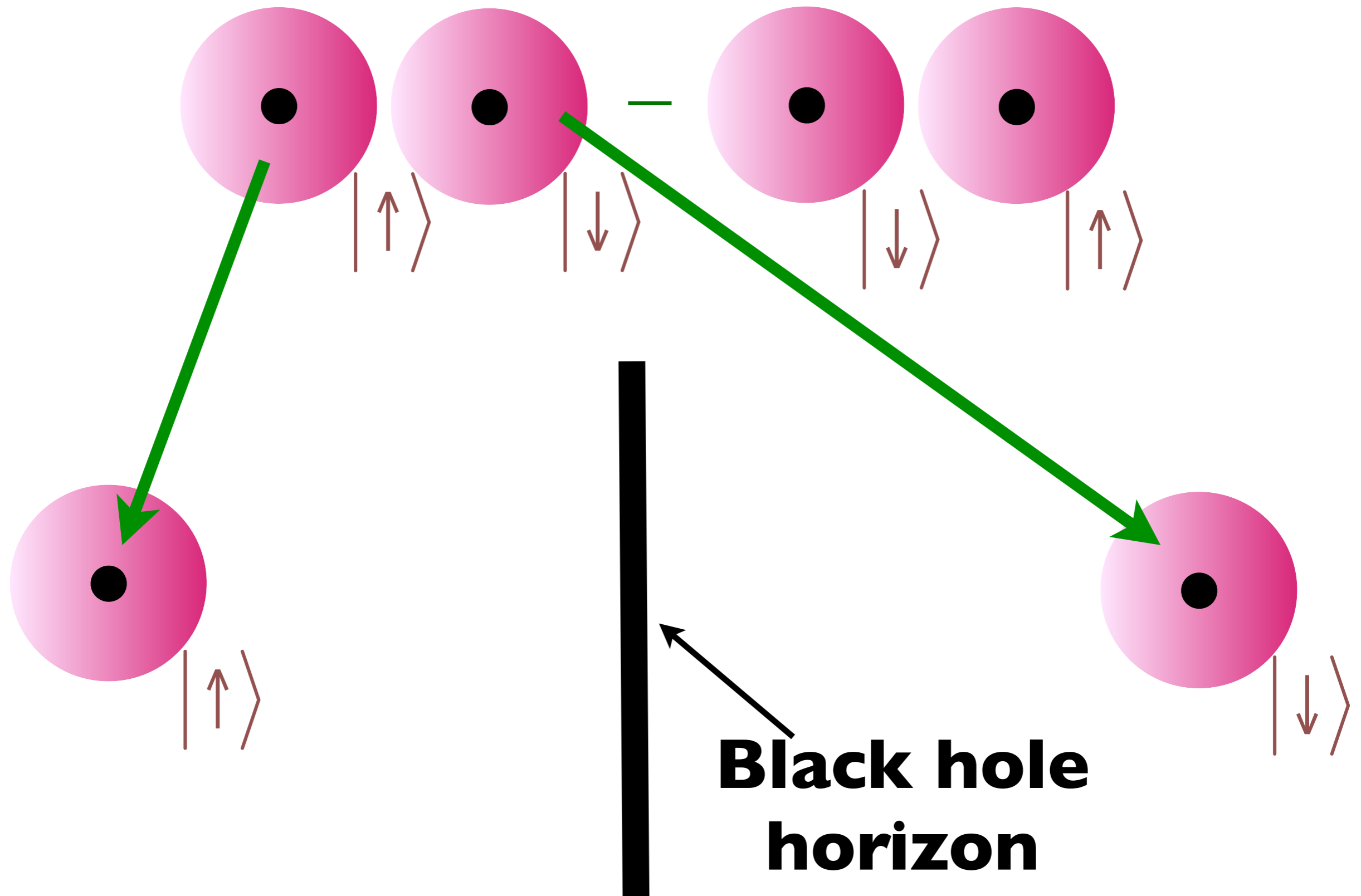
$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

G Newton's constant, c velocity of light, M mass of black hole
For $M = \text{earth's mass}$, $R \approx 9 \text{ mm!}$

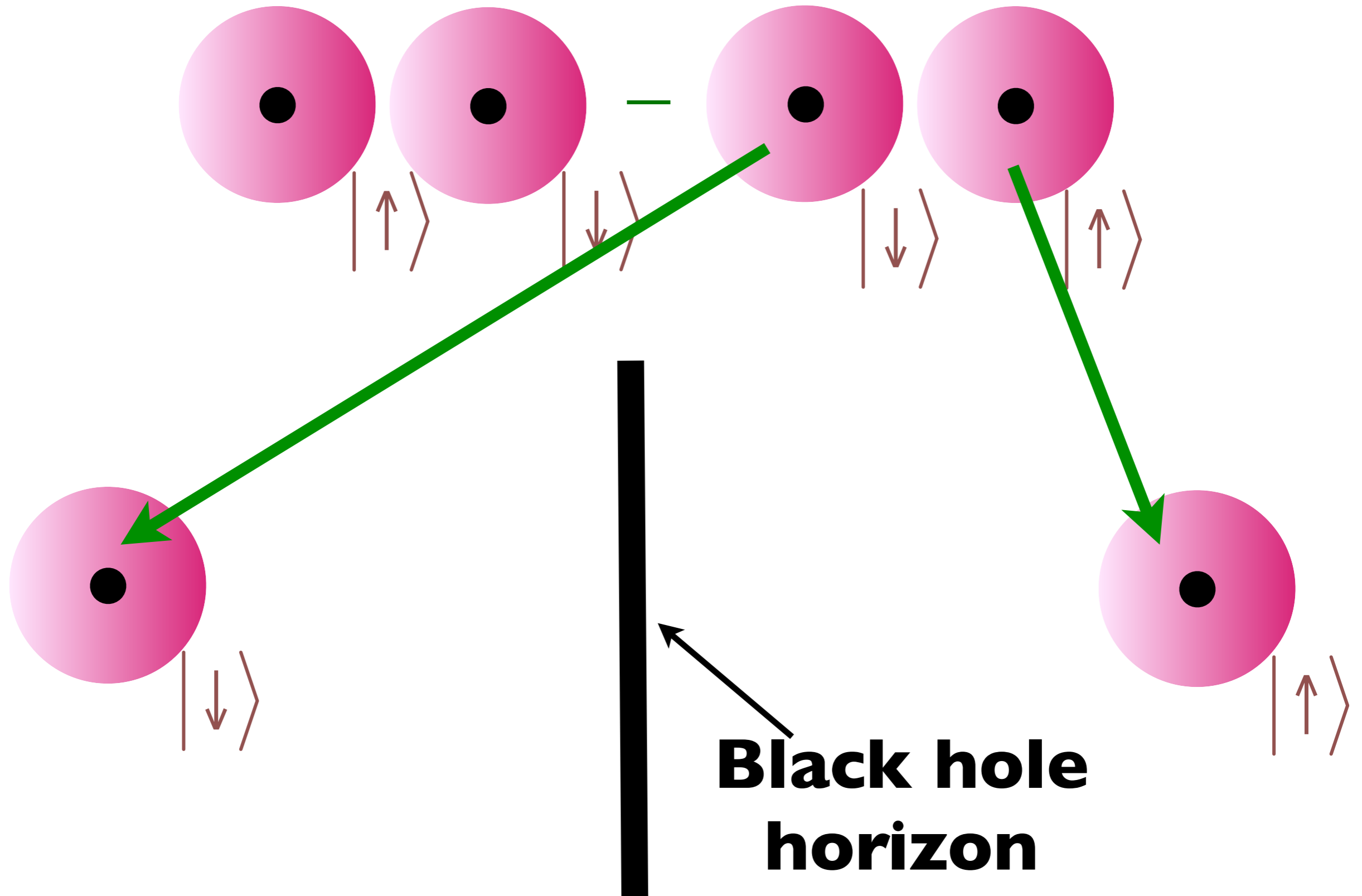
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

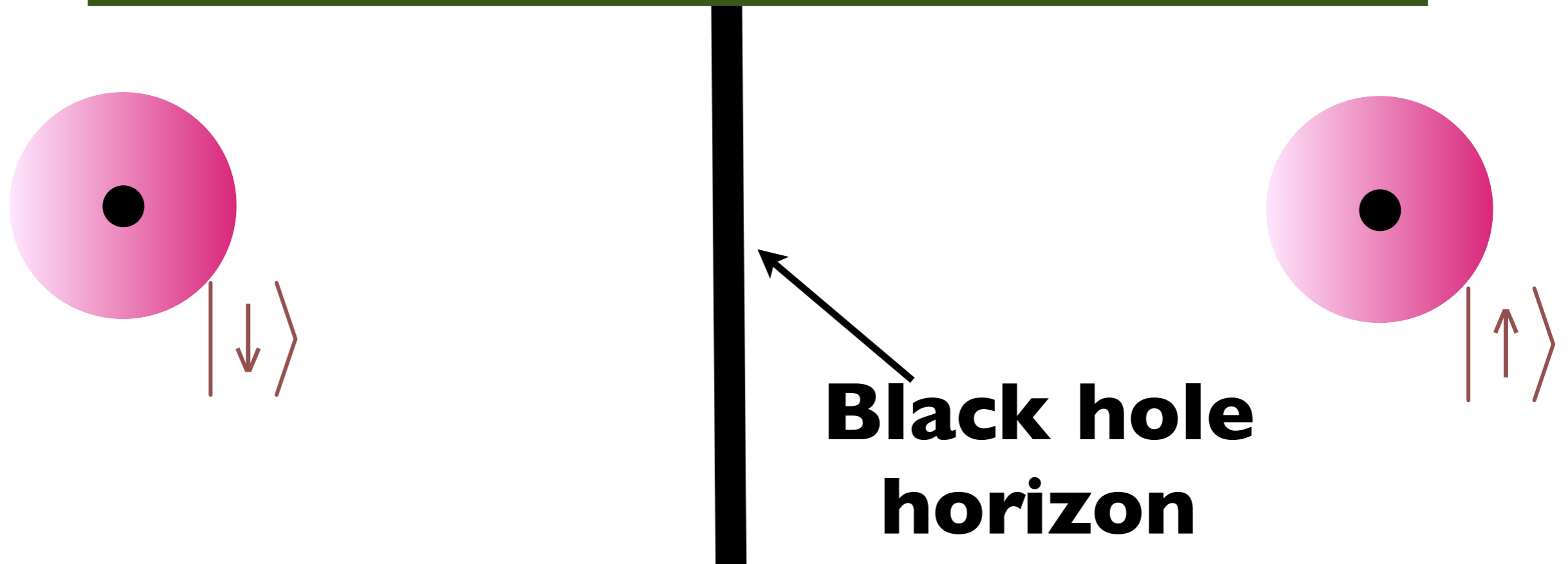


Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

Hawking used this to show that black hole horizons have an entropy and a temperature (because to an outside observer, the state of the electron inside the black hole is an unknown)



Quantum Black holes

- Black holes have an entropy and a temperature, T_H .
- The entropy, S_{BH} is proportional to their surface area.

Bekenstein (1973)
Hawking (1974)

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Bekenstein (1973)
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All many-body quantum systems
(without quantum gravity)
have an entropy
proportional to their volume !?!?

Thermodynamics of quantum black holes:

$$\int \mathcal{D}g_{\mu\nu} \exp \left(-\frac{1}{\hbar} \mathcal{S}_{\text{Einstein gravity}}^{(d+1)} [g_{\mu\nu}] \right)$$

Metric of
spacetime




Quantum gravity: a summation over all possible configurations of spacetime, each weighted by a factor which is the exponential of (the ‘action’ of Einstein gravity)/(Planck’s constant)

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Gibbons, Hawking (1977)

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Metric of spacetime

Gibbons, Hawking (1977)

In general, this summation is not well defined, because to the uncontrollably large number of spacetime configurations.

But in recent years, we have learnt how to evaluate the summation for Einstein gravity in some cases, and obtain the exact value of $\dots????\dots$

thanks to connections to the *Sachdev-Ye-Kitaev* model.

Holography and duality

Thermodynamics of quantum black holes:

$$\int \mathcal{D}g_{\mu\nu} \exp\left(-\frac{1}{\hbar} \mathcal{S}_{\text{Einstein gravity}}^{(d+1)}[g_{\mu\nu}]\right)$$

$$= \exp(S_{BH}) \times \left(\text{Many body quantum theory} \right)$$

in $d - 1$ spatial dimensions *without* gravity

Metric of spacetime

Black holes are represented as a 'hologram' by a quantum many-body system in one lower dimension.

Duality: a 'change of variables' between the many-particle configurations and the metric of spacetime

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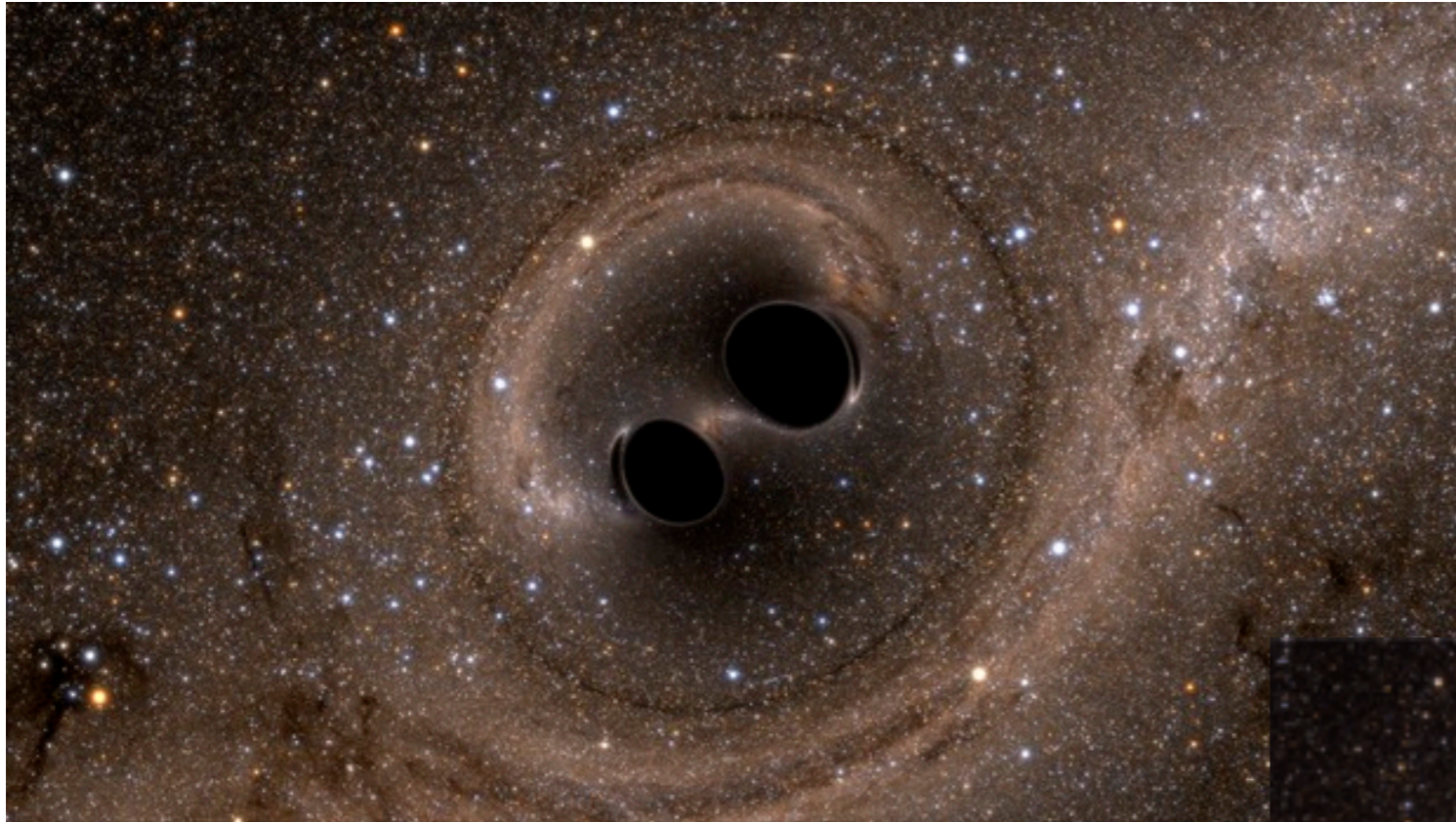
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Black holes are represented as a '*hologram*' by a quantum many-body system in one lower dimension.

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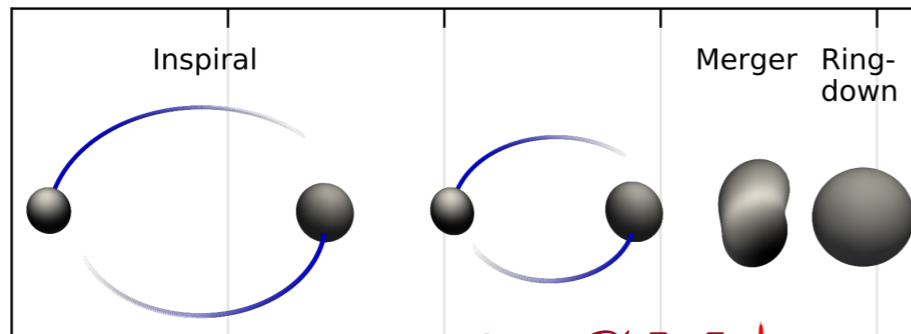
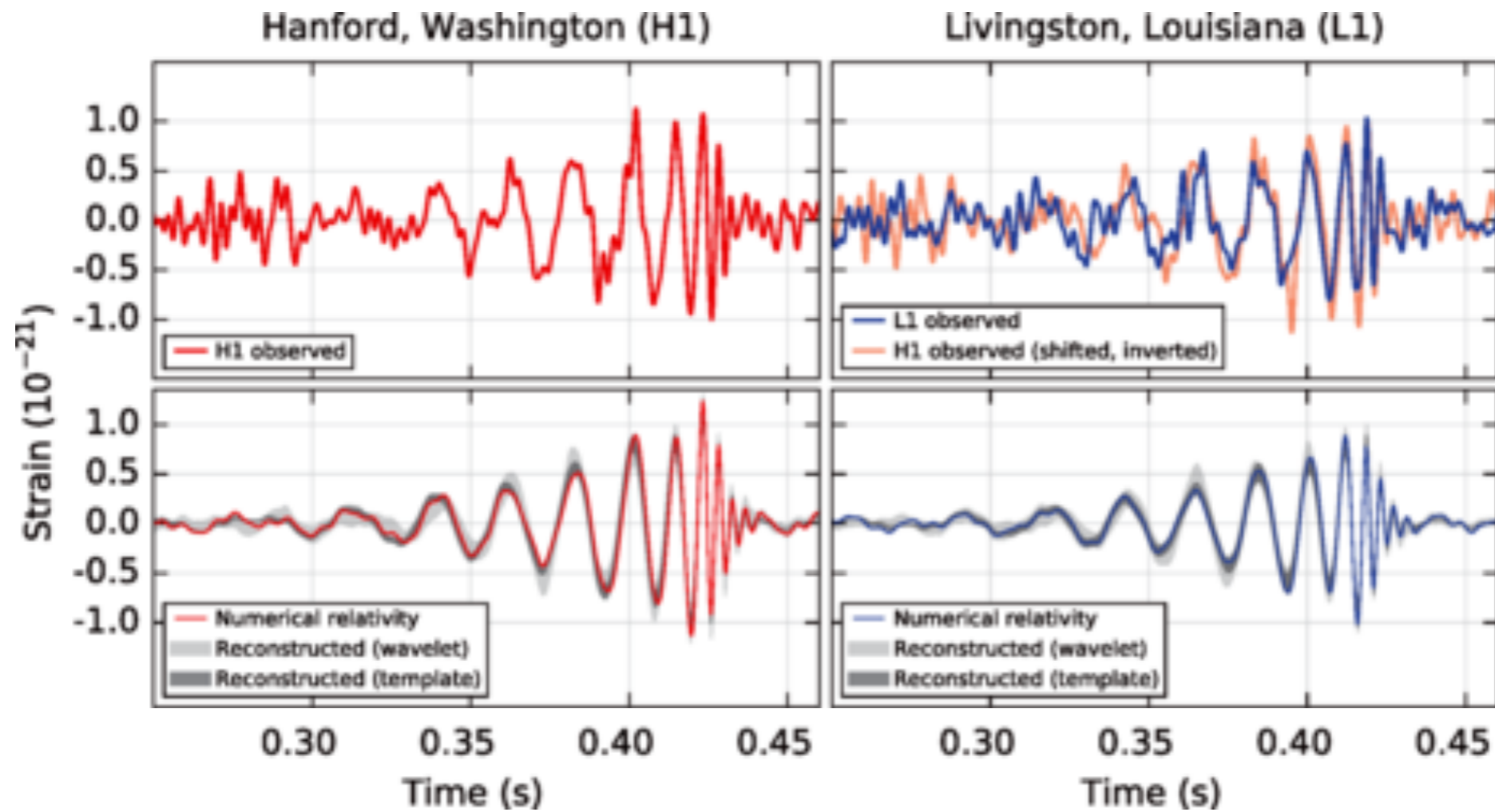
Susskind, Maldacena.....

On September 14, 2015, LIGO detected the merger of two black holes, each weighing about 30 solar masses, with radii of about 100 km, 1.3 billion light years away



0.1 seconds later !

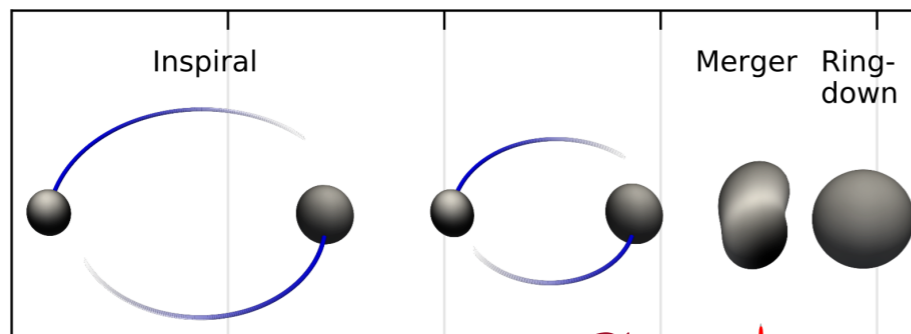
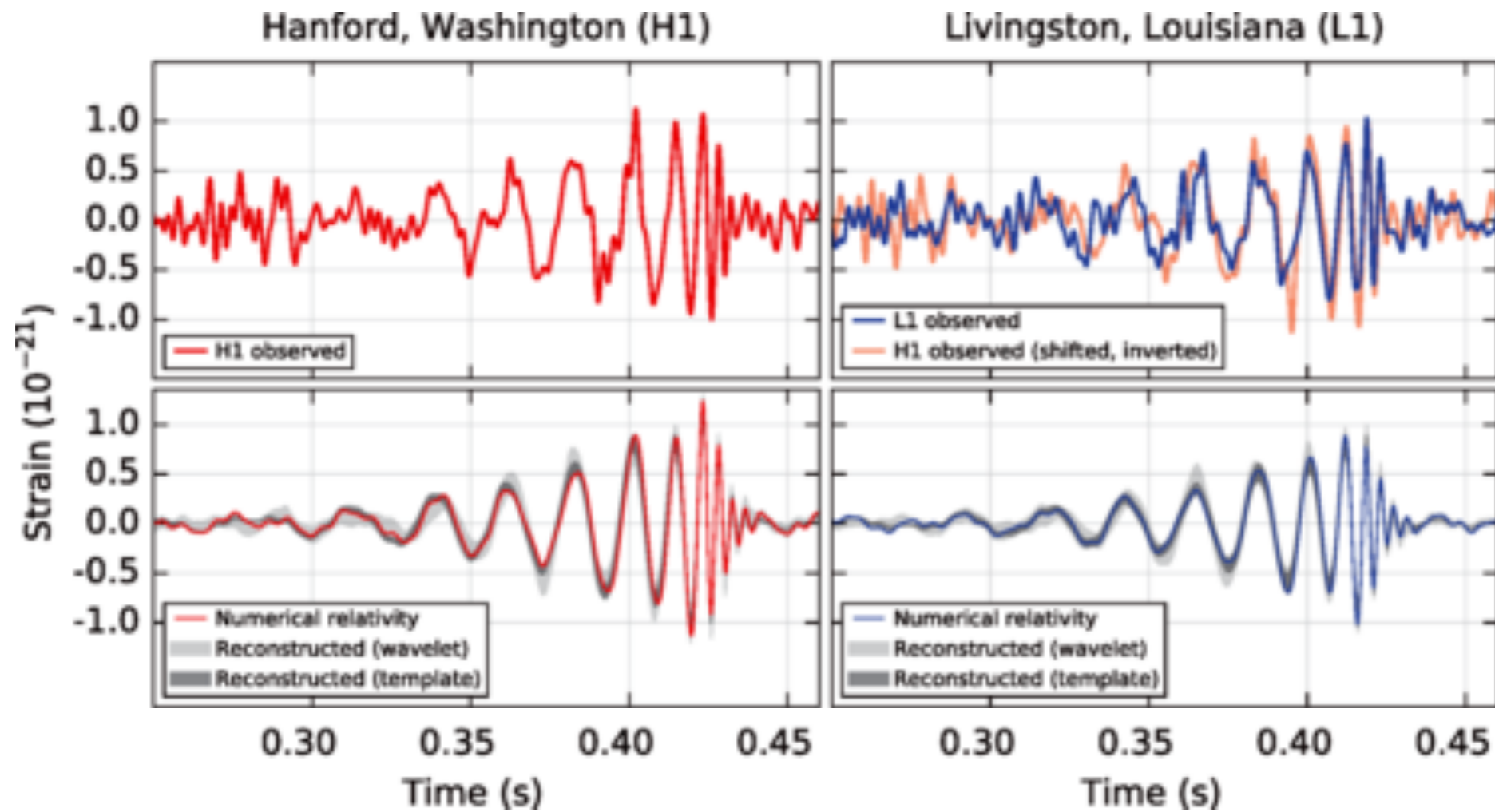




LIGO
September 14, 2015

- The ring-down time $\frac{8\pi GM}{c^3} \sim 8$ milliseconds. Curiously, for essentially all types of black holes, the ring-down time equals

$$\frac{\hbar}{k_B T_H}, \quad \hbar \text{ Planck's constant, } k_B \text{ Boltzmann's constant}$$



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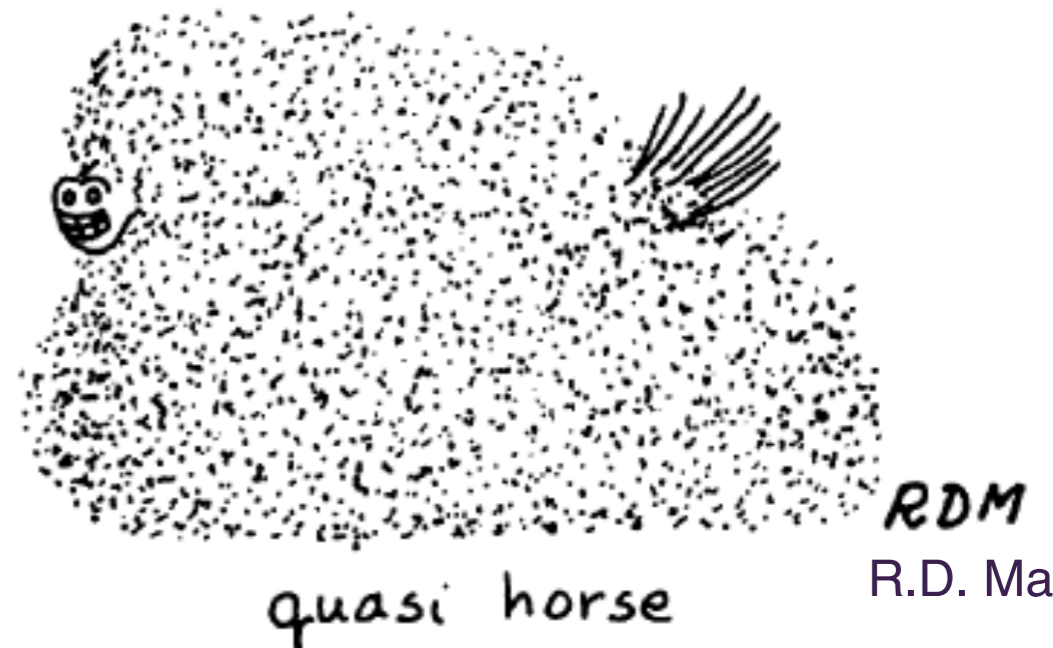
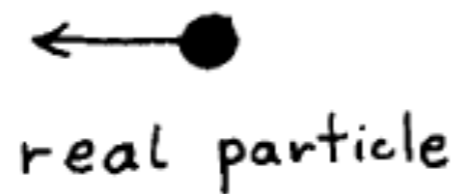
The hologram of a black hole
in d dimensions
is a quantum many-particle system
in $(d - 1)$ dimensions
which relaxes to thermal equilibrium
in a Planckian time $\sim \hbar/(k_B T)$

**Quantum
entanglement**

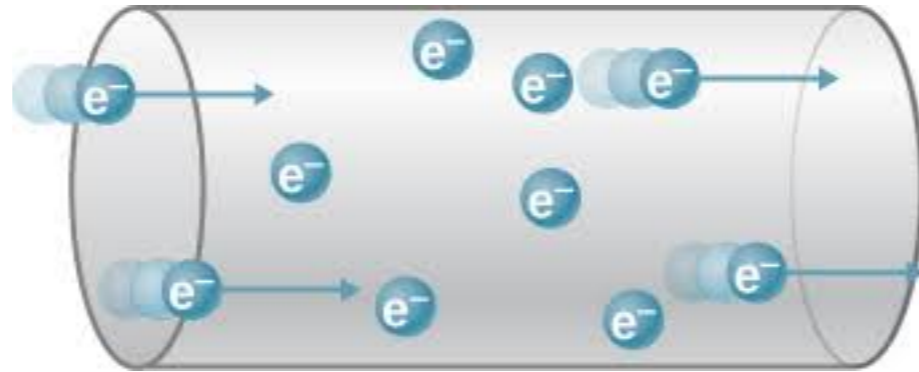
**Black
holes**

**A simple
many-particle
(SYK) model**

Almost all many-electron systems are described by the quasiparticle concept: a quasiparticle is an “excited lump” in the many-electron state which responds just like an ordinary particle. The existence of quasiparticles implies limited many-particle entanglement



Current flow with quasiparticles



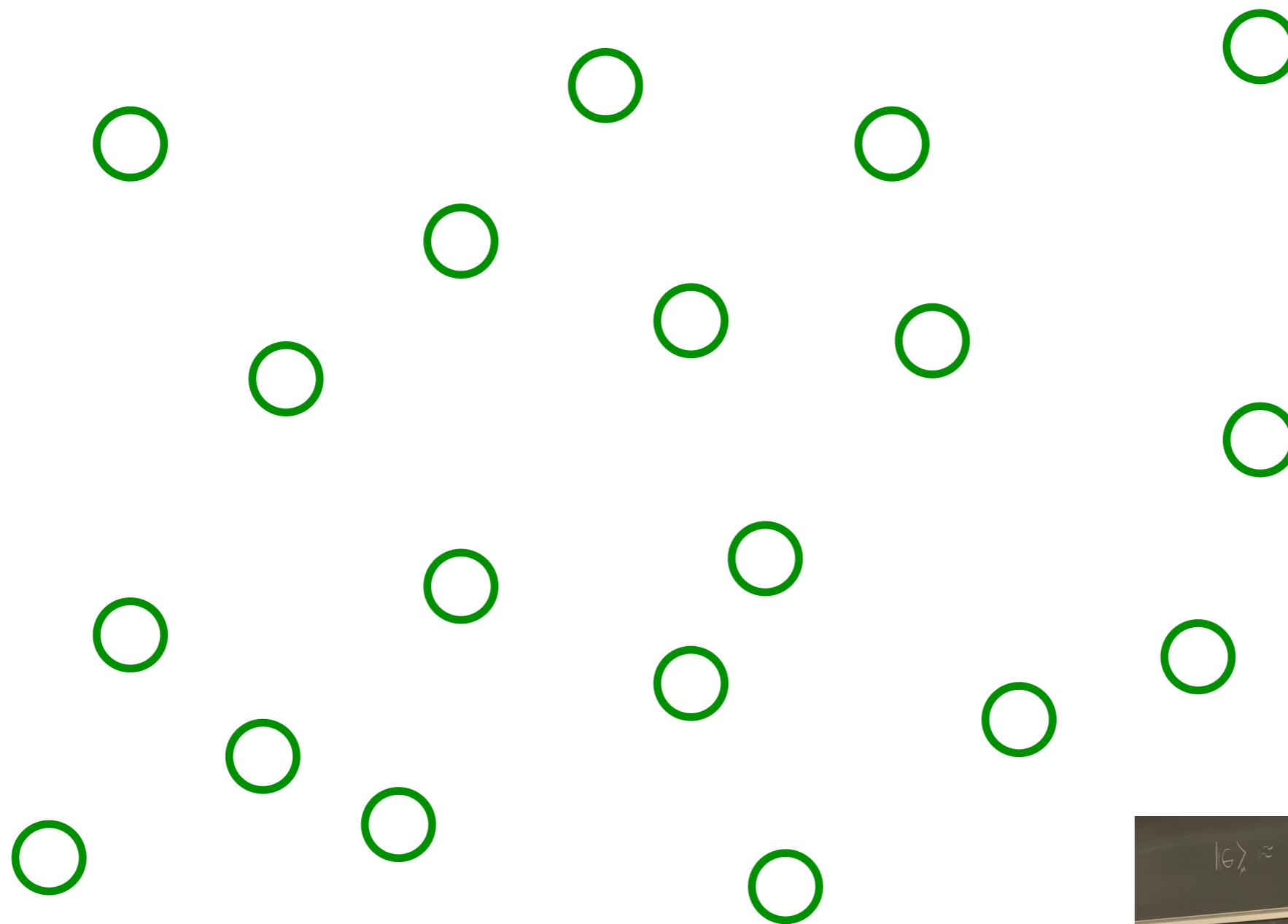
Flowing quasiparticles scatter off each other in a typical scattering time τ

This time is much longer than a limiting
'Planckian time' $\frac{\hbar}{k_B T}$.

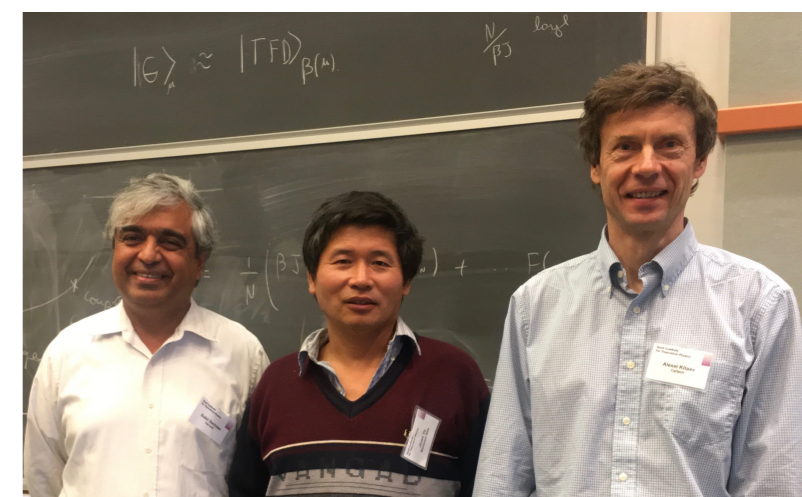
The long scattering time implies that quasiparticles are well-defined.

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

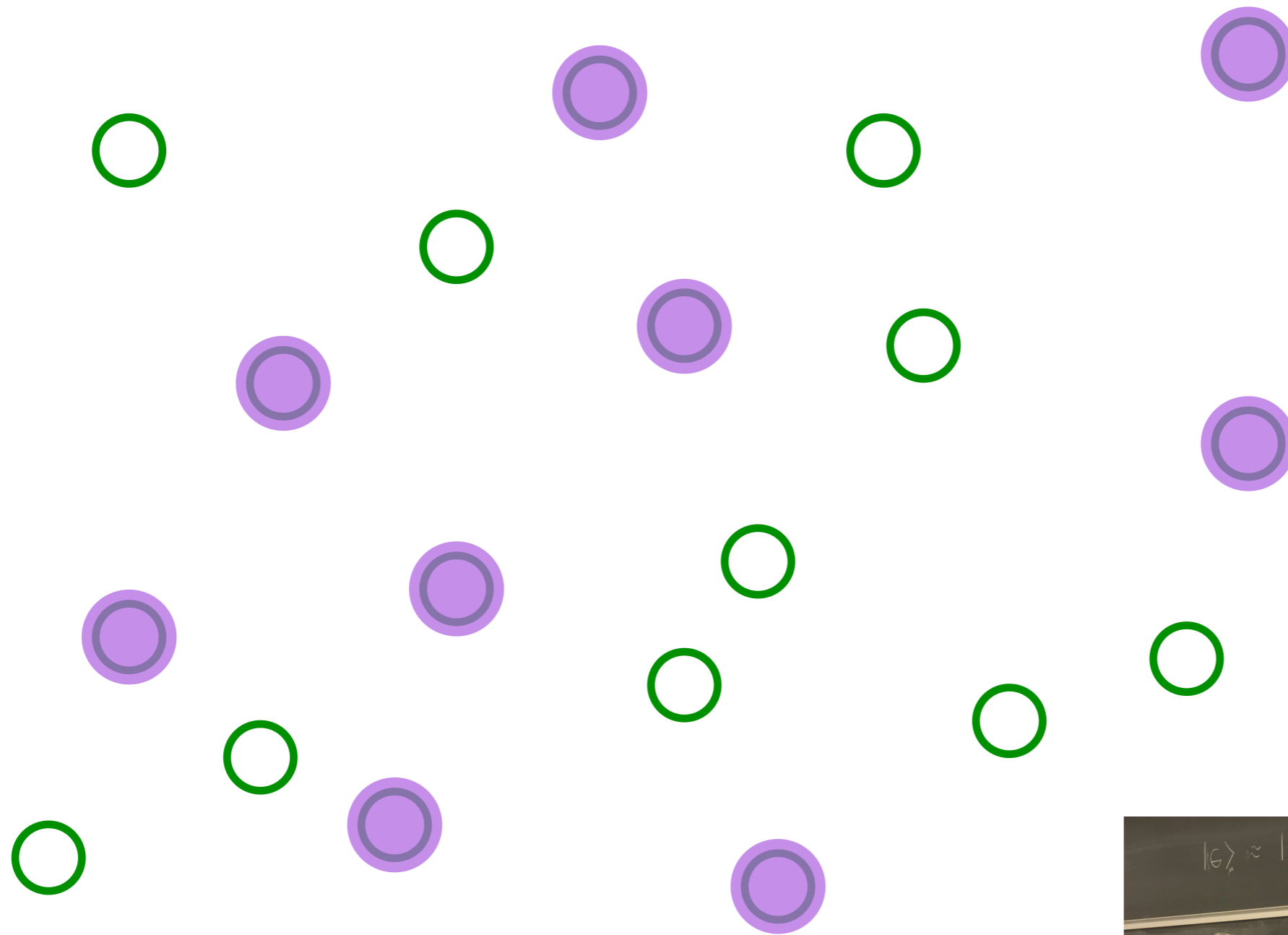


Pick a set of random positions

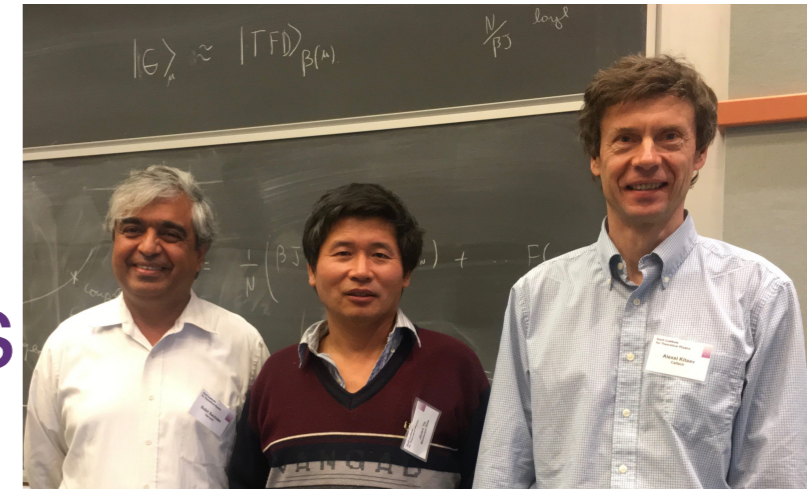


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

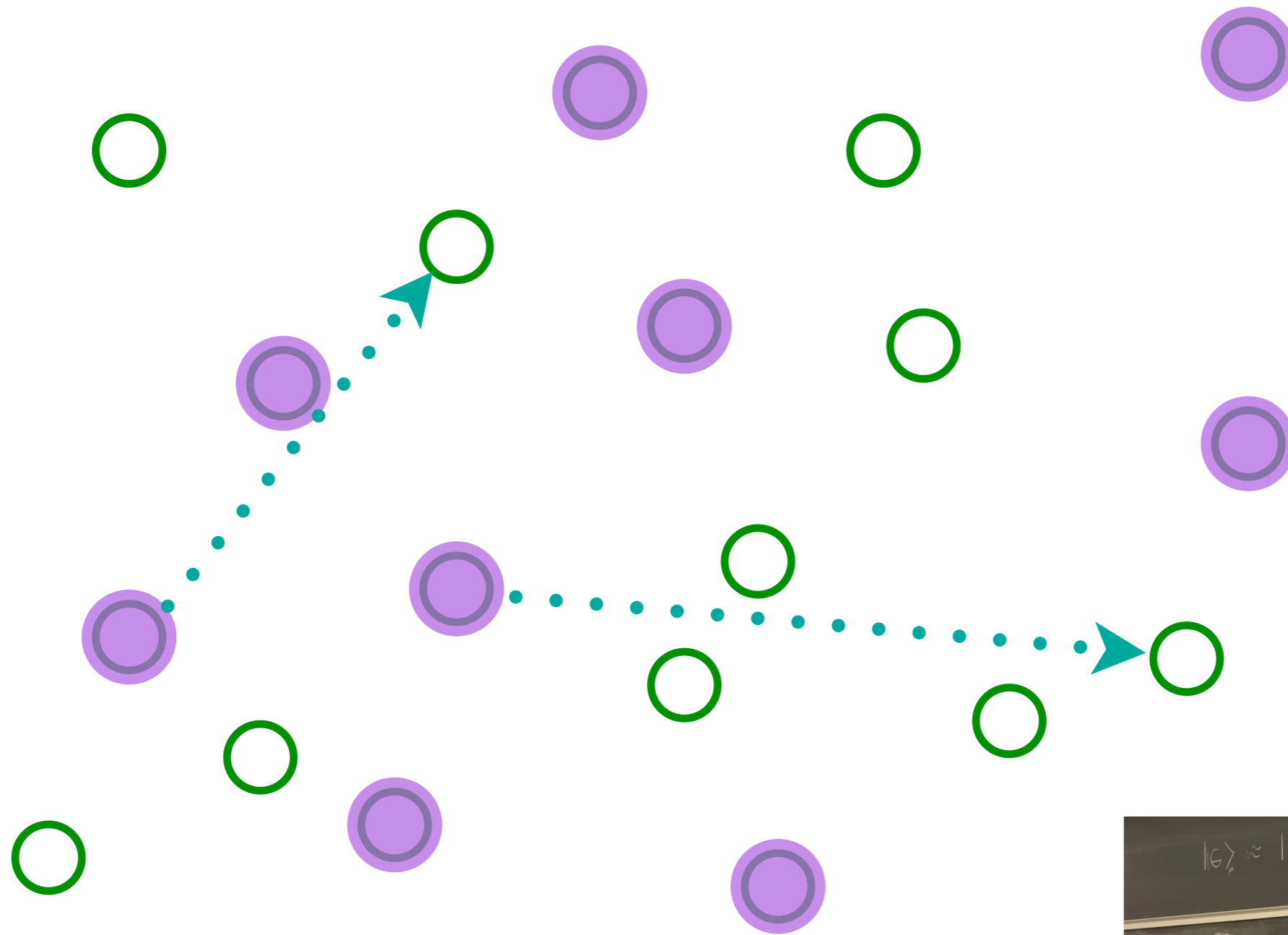


Place electrons randomly on some sites

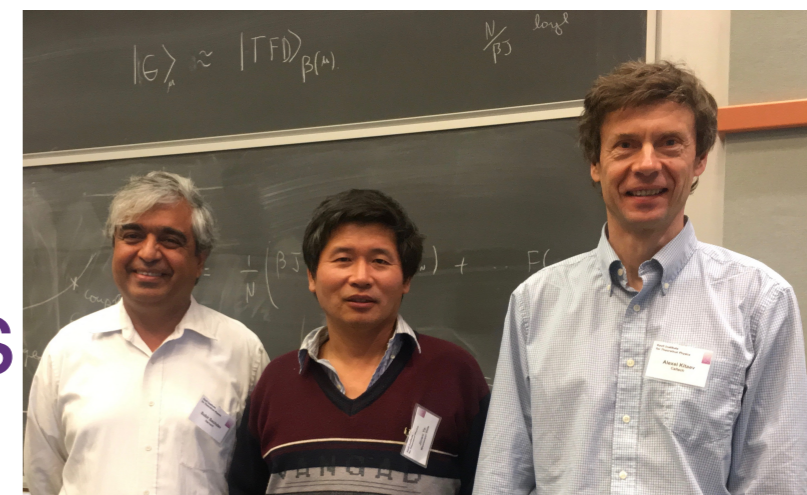


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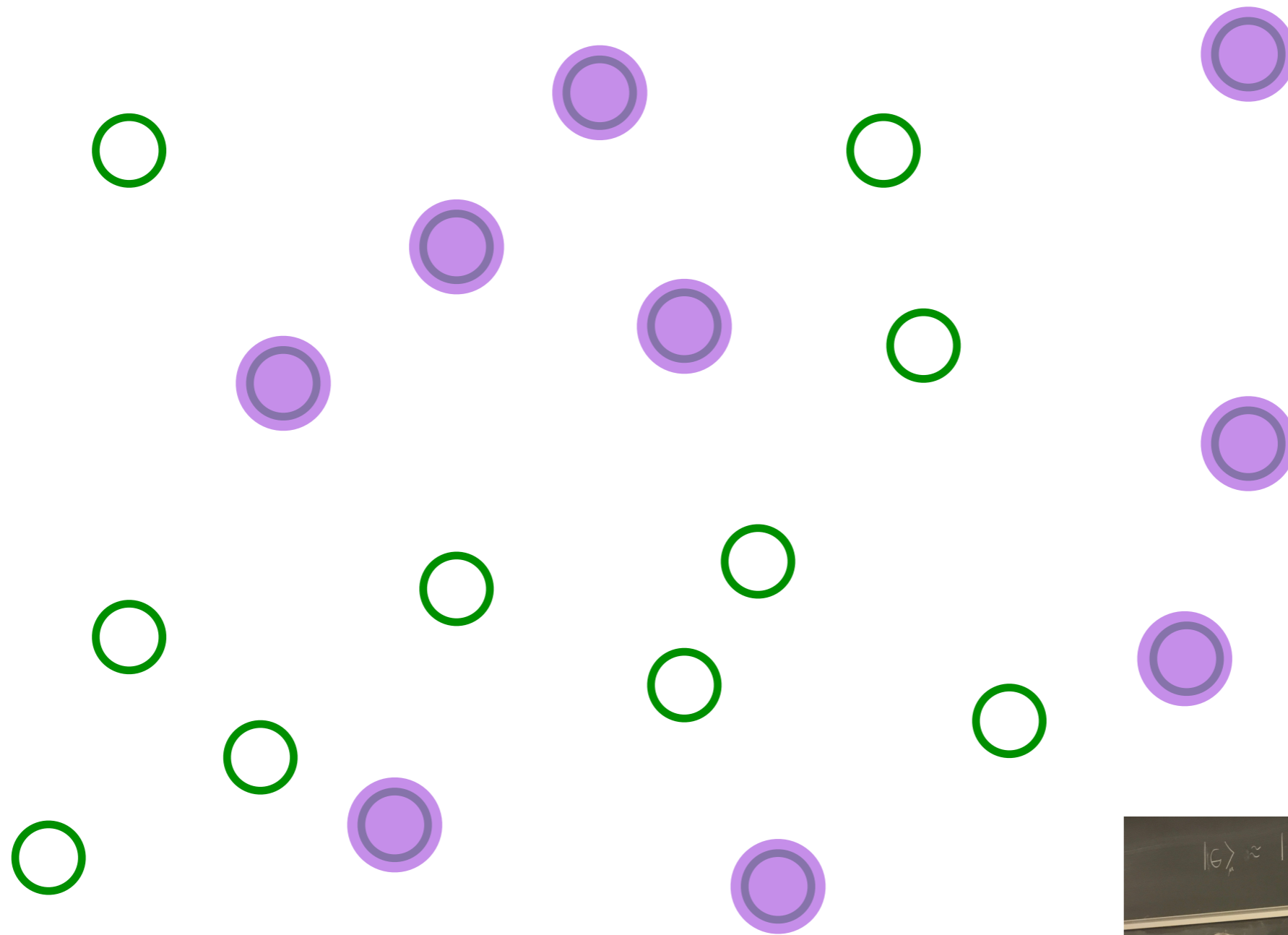


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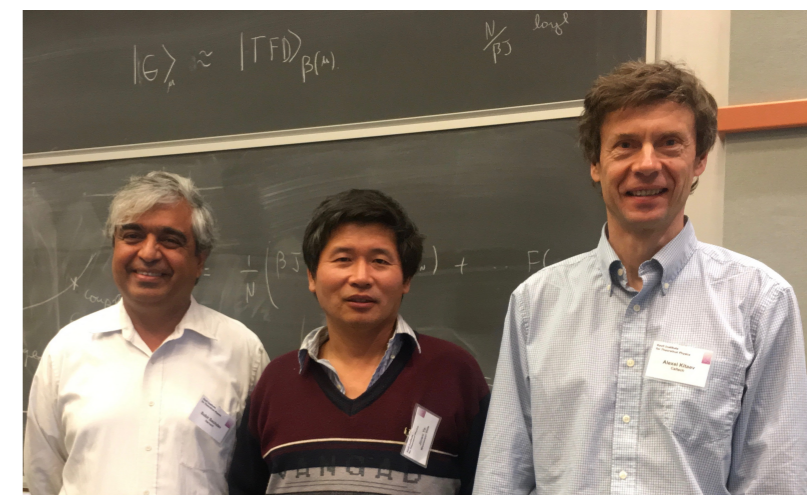


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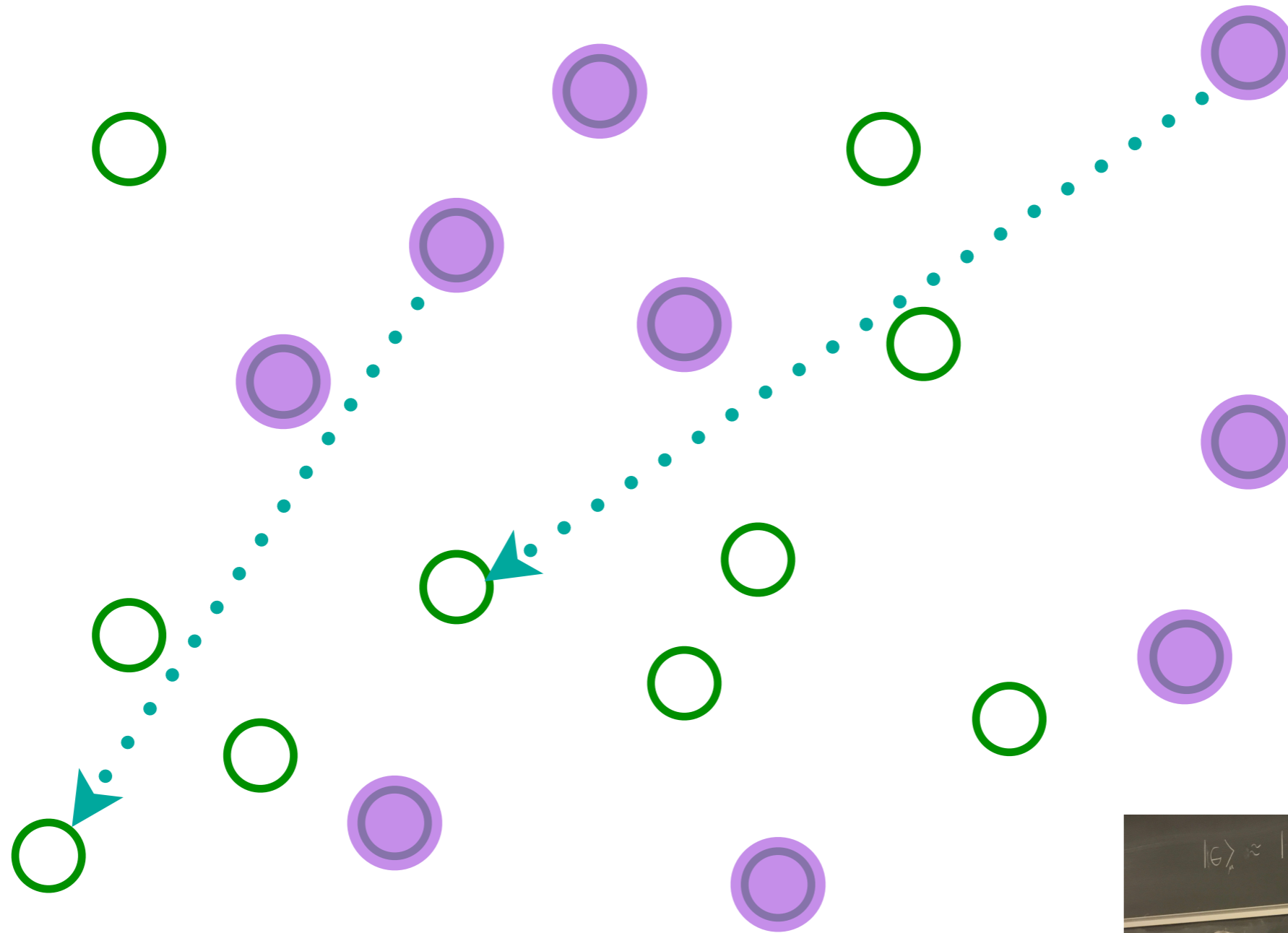


Entangle electrons pairwise randomly

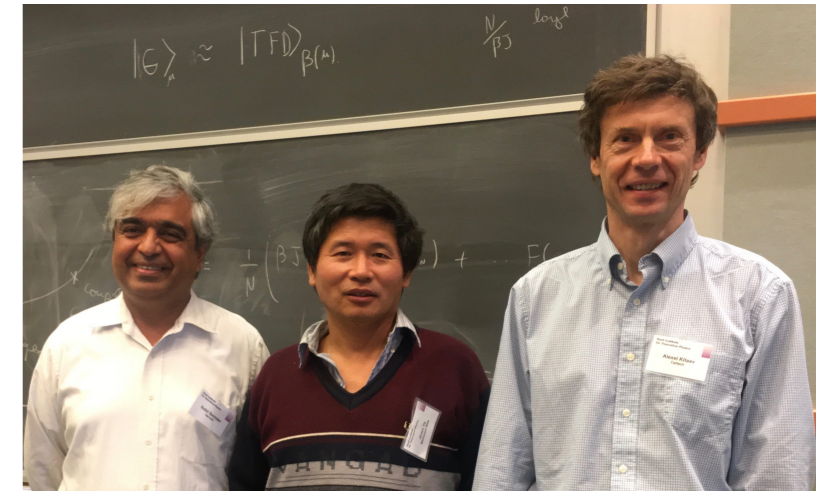


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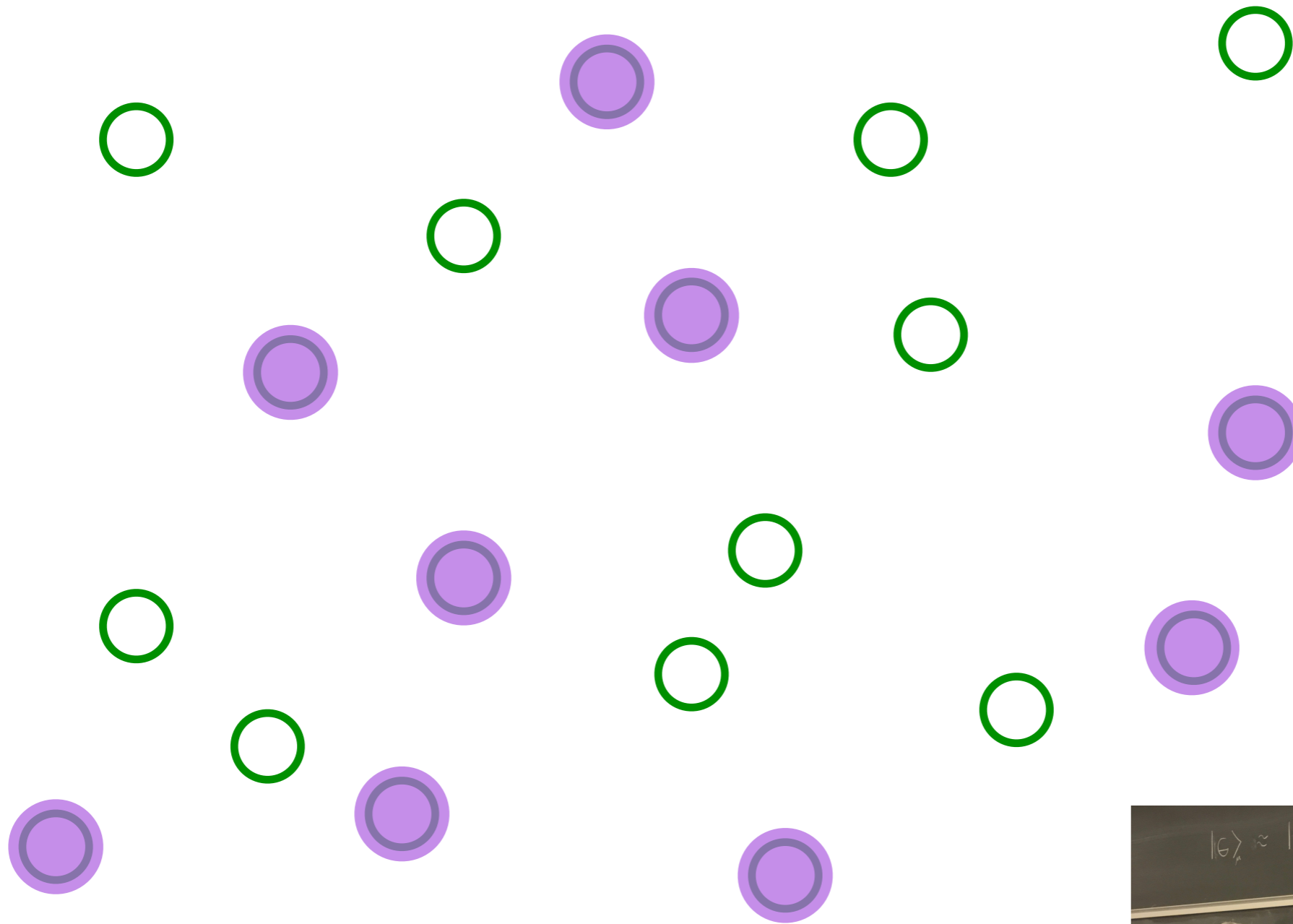


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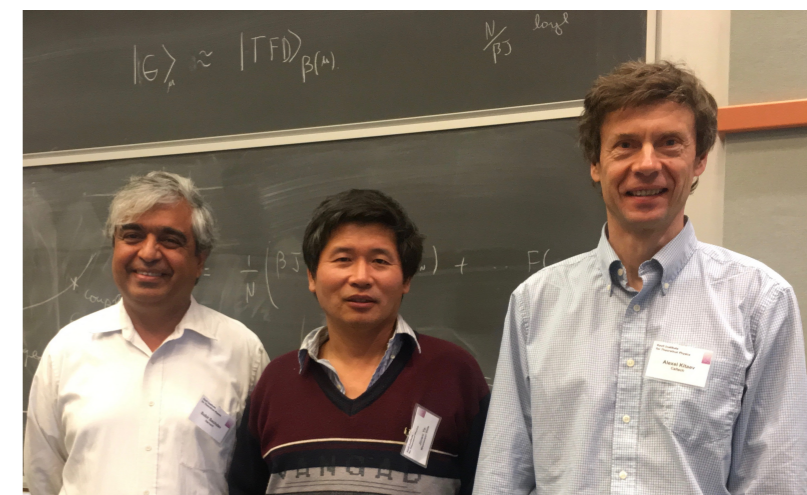


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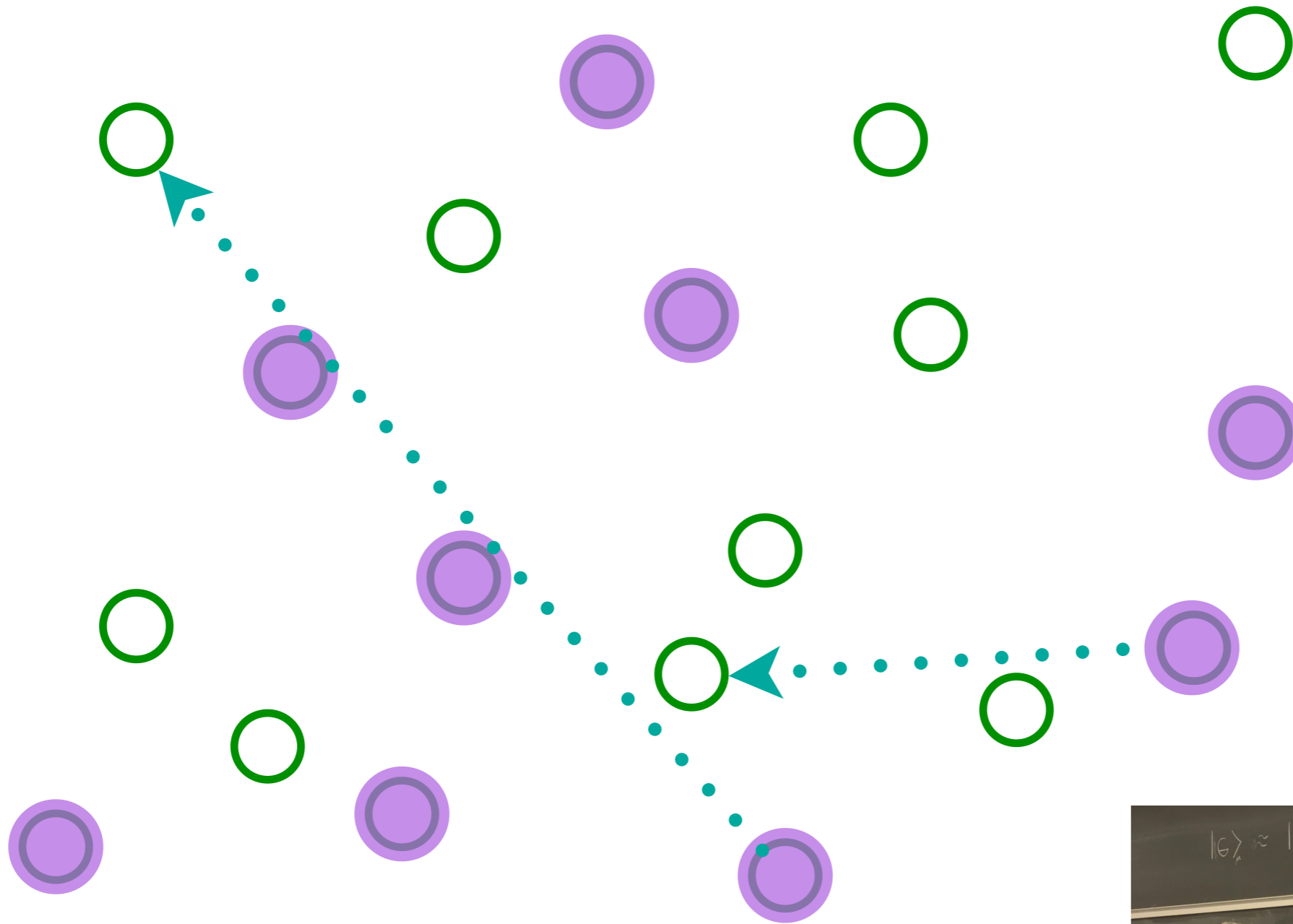


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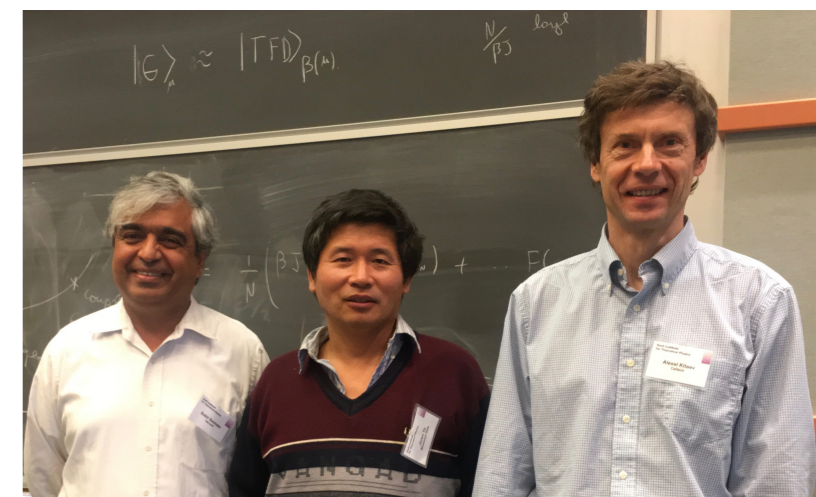


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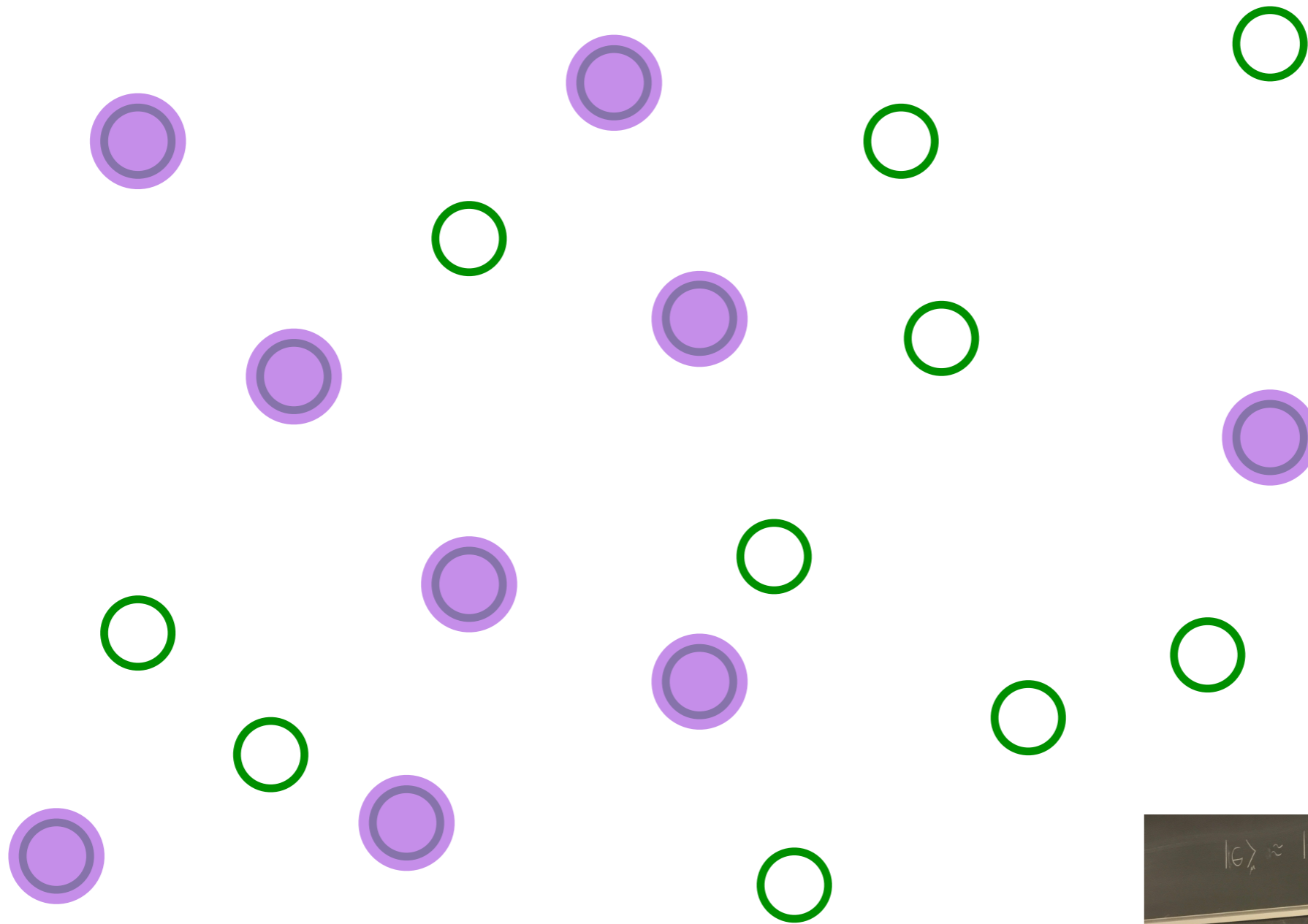


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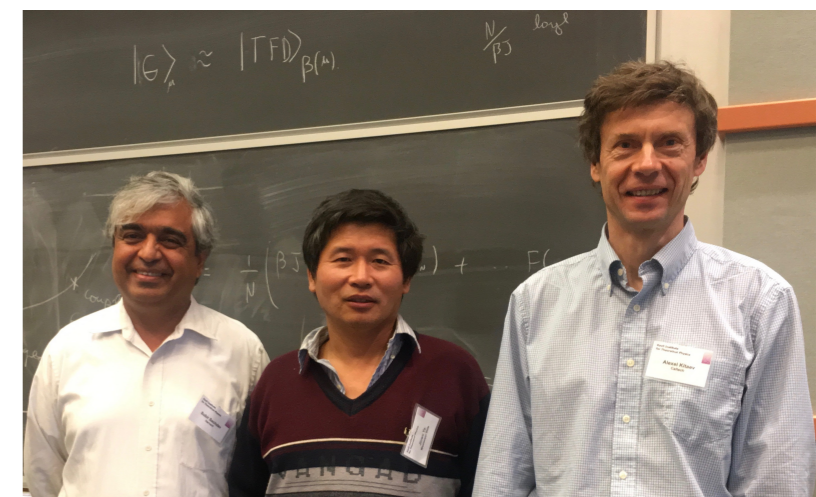


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Entangle electrons pairwise randomly



The complex SYK model

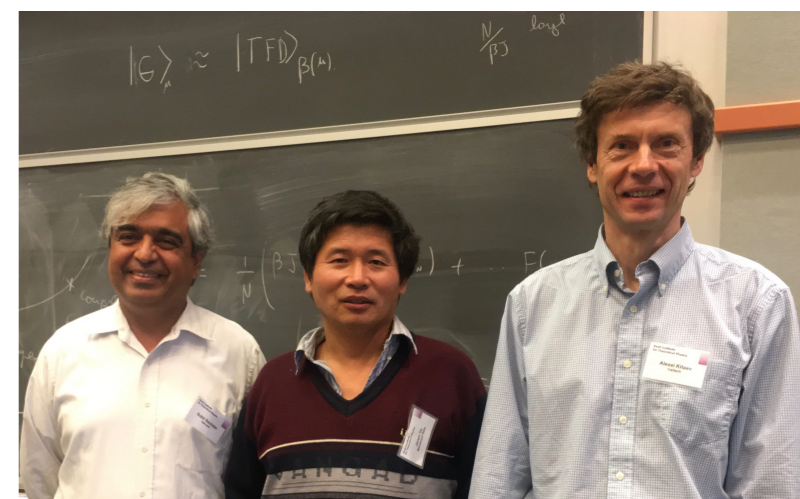
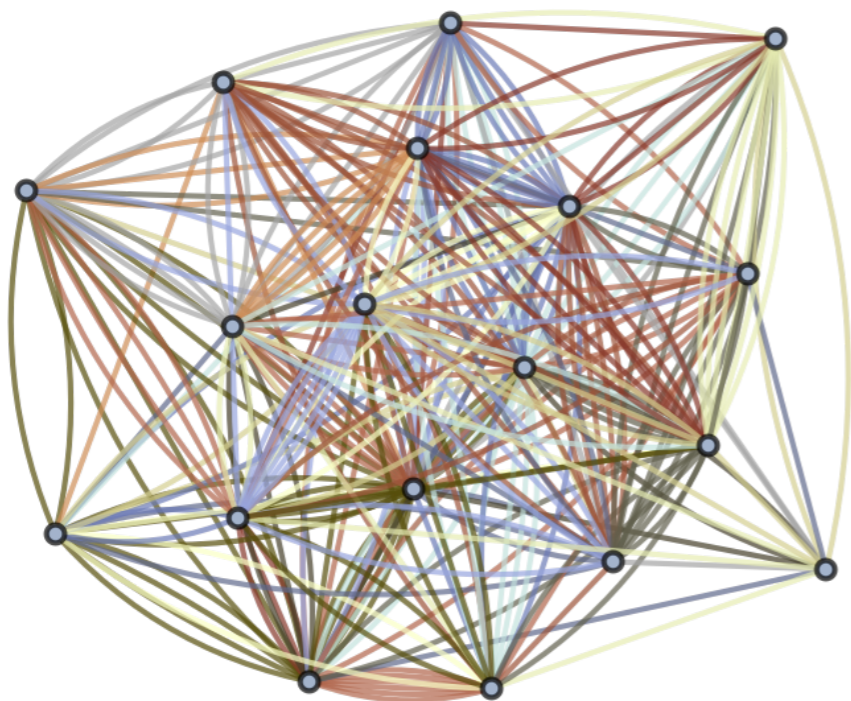
(See also: the “2-Body Random Ensemble” in nuclear physics; did not obtain the large N limit; T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

$$H = \frac{1}{(2N)^{3/2}} \sum_{\alpha, \beta, \gamma, \delta=1}^N U_{\alpha\beta; \gamma\delta} c_{\alpha}^{\dagger} c_{\beta}^{\dagger} c_{\gamma} c_{\delta} + \epsilon \sum_{\alpha} c_{\alpha}^{\dagger} c_{\alpha}$$

$$c_{\alpha} c_{\beta} + c_{\beta} c_{\alpha} = 0 \quad , \quad c_{\alpha} c_{\beta}^{\dagger} + c_{\beta}^{\dagger} c_{\alpha} = \delta_{\alpha\beta}$$

$$Q = \frac{1}{N} \sum_{\alpha} c_{\alpha}^{\dagger} c_{\alpha}$$

$U_{\alpha\beta; \gamma\delta}$ are independent random variables with $\overline{U_{\alpha\beta; \gamma\delta}} = 0$ and $\overline{|U_{\alpha\beta; \gamma\delta}|^2} = U^2$
 $N \rightarrow \infty$ yields critical strange metal.



Sachdev, Ye (1993)

Kitaev (2015), Sachdev (2015)

Complex multi-particle entanglement in the SYK model leads to a state without ‘quasiparticle’ excitations; *i.e.*

multiple excitations cannot be built by composing an elementary set of ‘quasiparticle’ excitations.

Complex multi-particle entanglement in the SYK model leads to a state without ‘quasiparticle’ excitations; *i.e.*

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Many-body chaos and thermal equilibration in the shortest possible Planckian time $\sim \frac{\hbar}{k_B T}$.

The complex SYK model

Feynman graph expansion in $U_{\alpha\beta;\gamma\delta}$, and graph-by-graph average, yields exact equations in the large N limit:

$$G(i\omega) = \frac{1}{i\omega - \epsilon - \Sigma(i\omega)} \quad , \quad \Sigma(\tau) = -U^2 G^2(\tau) G(-\tau)$$
$$G(\tau = 0^-) = Q.$$

Low energy solution with q -fermion Hamiltonian ($\Delta = 1/q$):

- $$G(\tau) = -Ae^{-2\pi\mathcal{E}T\tau} \left(\frac{T}{\sin(\pi T\tau)} \right)^{2\Delta} \quad , \quad 0 < \tau < 1/T,$$

where the ‘particle-hole asymmetry’ is determined by \mathcal{E} .

- There is a ‘Luttinger relation’ between $-\infty < \mathcal{E} < \infty$ and $0 < Q < 1$:

$$e^{2\pi\mathcal{E}} = \frac{\sin(\pi\Delta + \theta)}{\sin(\pi\Delta - \theta)}, \quad Q = \frac{1}{2} - \frac{\theta}{\pi} + \left(\Delta - \frac{1}{2} \right) \frac{\sin(2\theta)}{\sin(2\pi\Delta)}$$

- The entropy is also determined by \mathcal{E} : $dS/dQ = 2\pi\mathcal{E}$.

Sachdev, Ye (1993),
Georges, Parcollet (1999),
Georges, Parcollet, Sachdev (2001),
Davison, Wenbo Fu, Georges,
Yingfei Gu, Jensen, Sachdev (2017)

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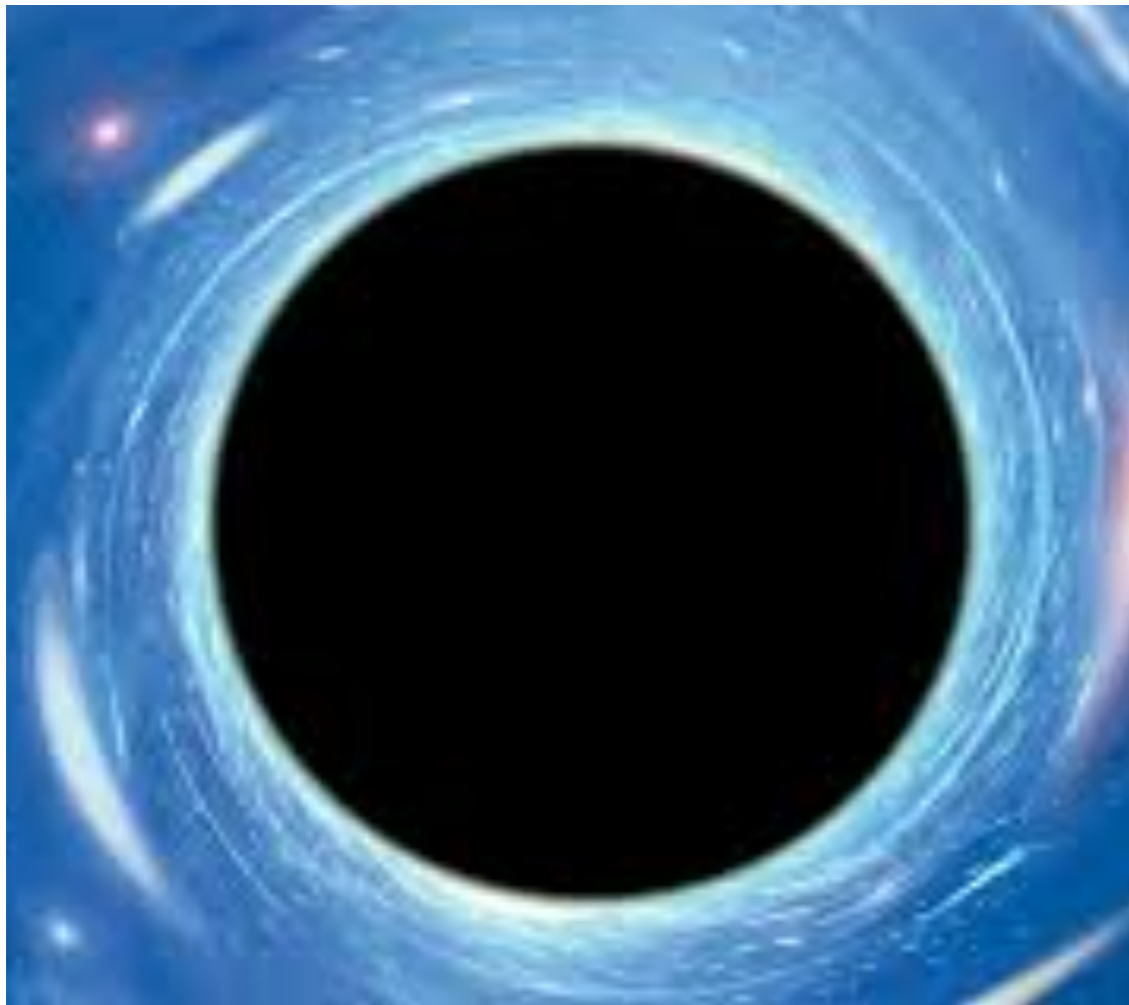
Black
holes

Hologram ?

A simple
many-particle
(SYK) model

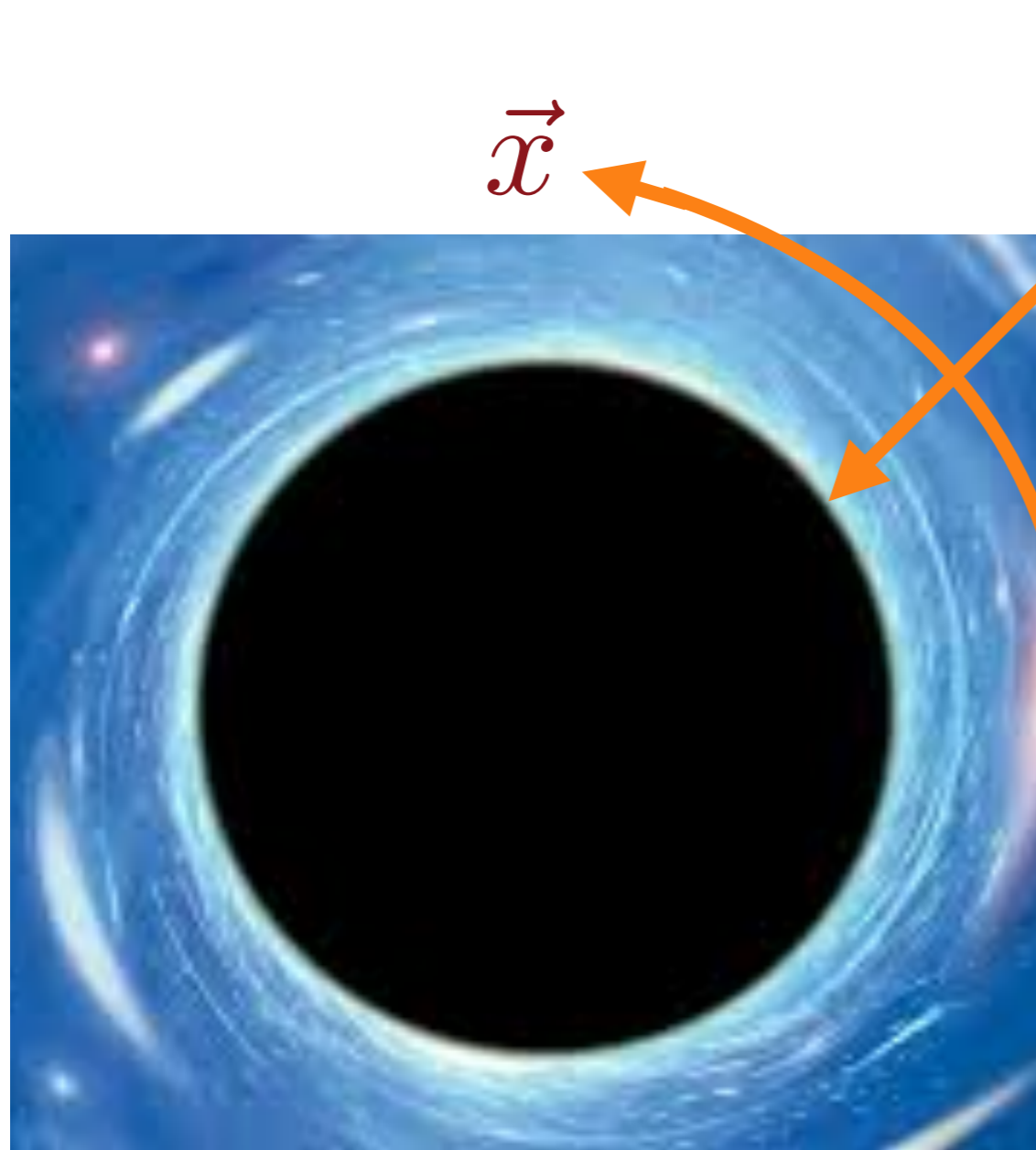


Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge





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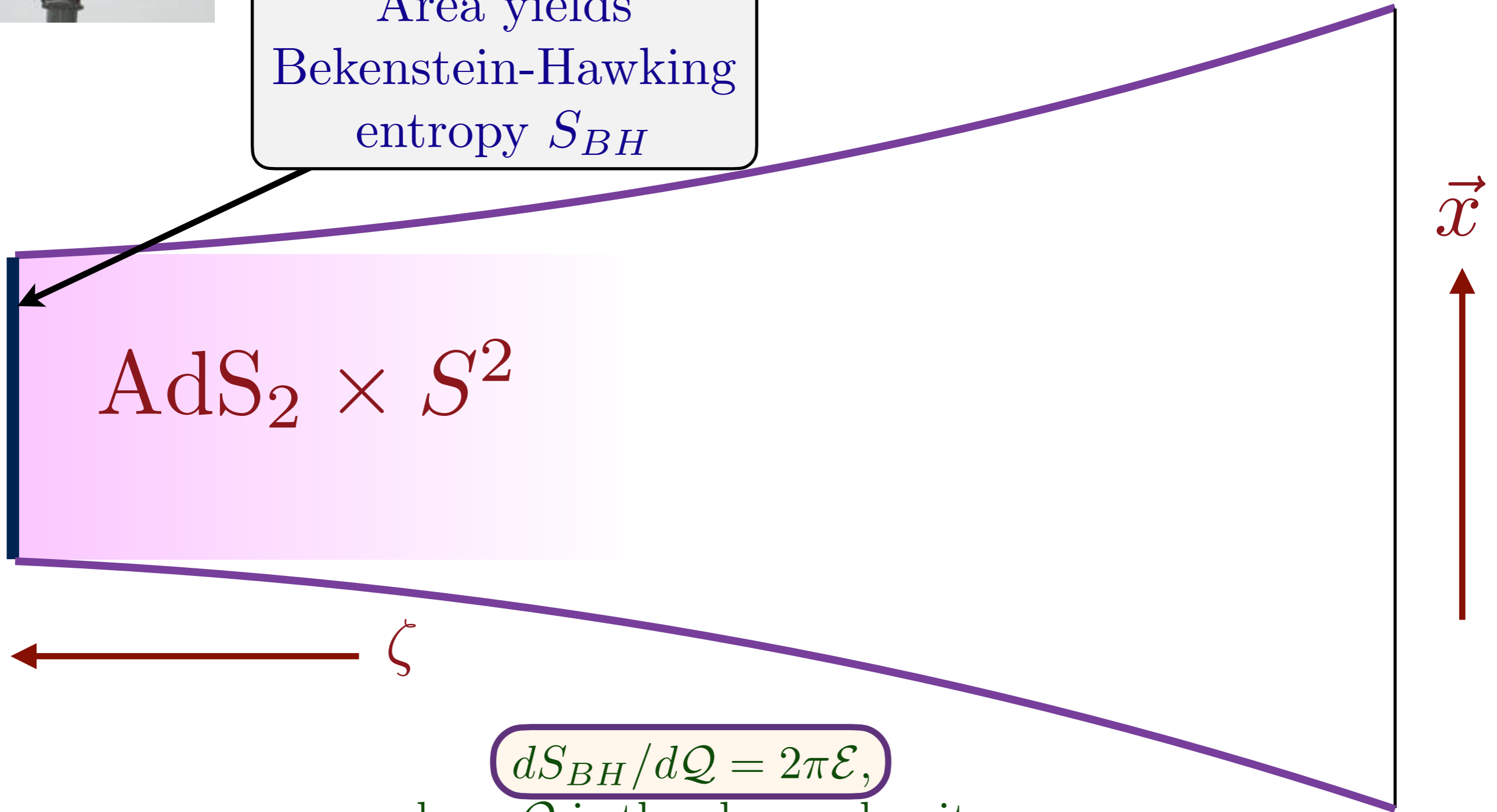


Zooming into the near-horizon region of a charged black hole at low temperature, yields a gravitational theory in one space (ζ) and one time dimension

SYK model and charged black holes



Horizon
Area yields
Bekenstein-Hawking
entropy S_{BH}



$$dS_{BH}/dQ = 2\pi\mathcal{E},$$

where Q is the charge density,
and \mathcal{E} is the electric field on the horizon.

SYK model and charged black holes



1+1
spacetime
dimensions

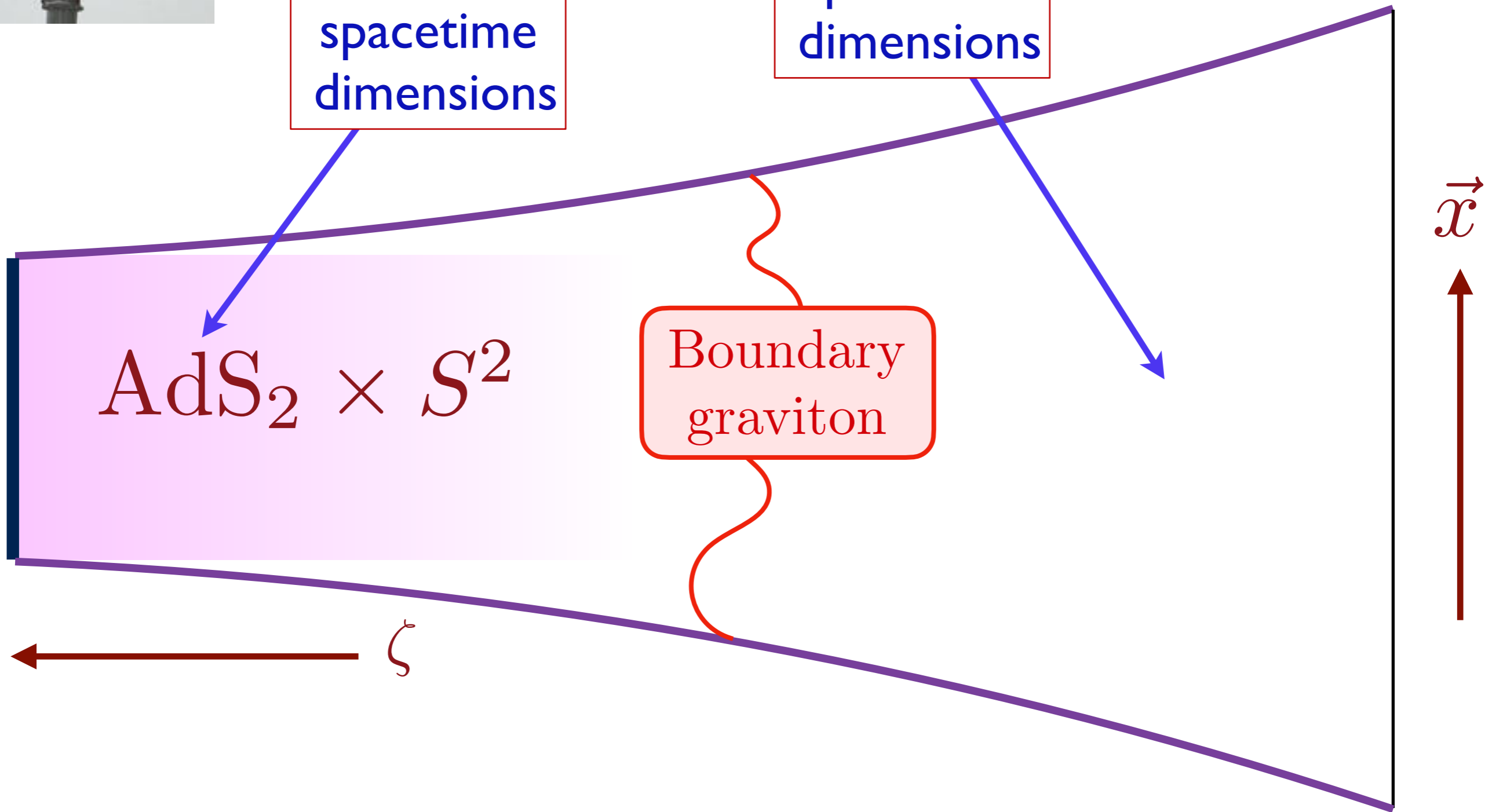
3+1
spacetime
dimensions

$\text{AdS}_2 \times S^2$

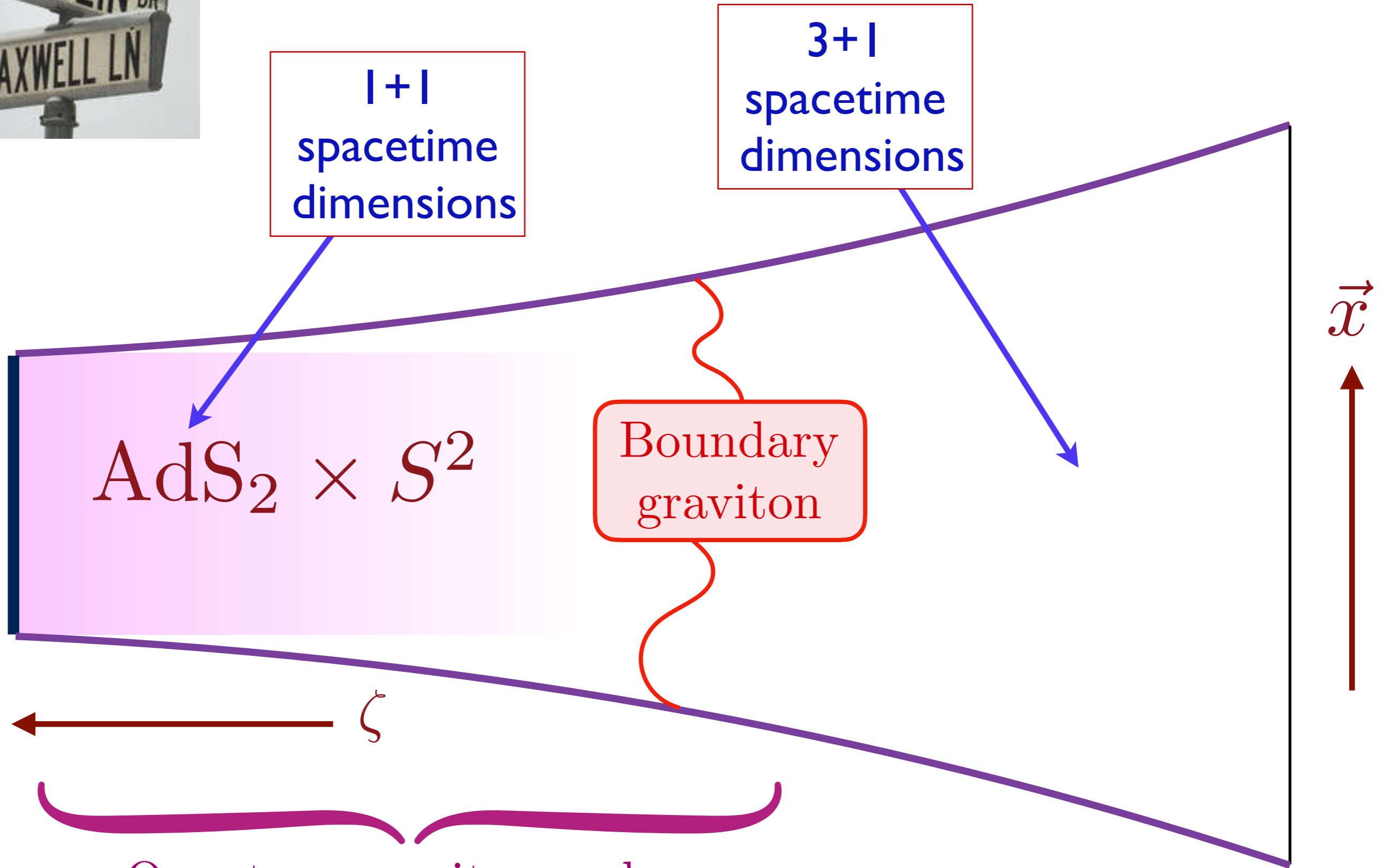
Boundary
graviton

\vec{x}

ζ



SYK model and charged black holes



Quantum gravity can be exactly solved in this region!

SYK model and charged black holes

Thermodynamics of charged quantum black holes

$$\int \mathcal{D}g_{\mu\nu} \exp \left(-\frac{1}{\hbar} \mathcal{S}_{\text{Einstein-Maxwell theory}}^{(3+1)}[g_{\mu\nu}] \right) T \rightarrow 0,$$
$$\approx \int \mathcal{D}g_{\mu\nu} \exp \left(-\frac{1}{\hbar} \mathcal{S}_{\text{Gravity of AdS}_2 \text{ and boundary}}^{(1+1)}[g_{\mu\nu}] \right)$$

SYK model and charged black holes

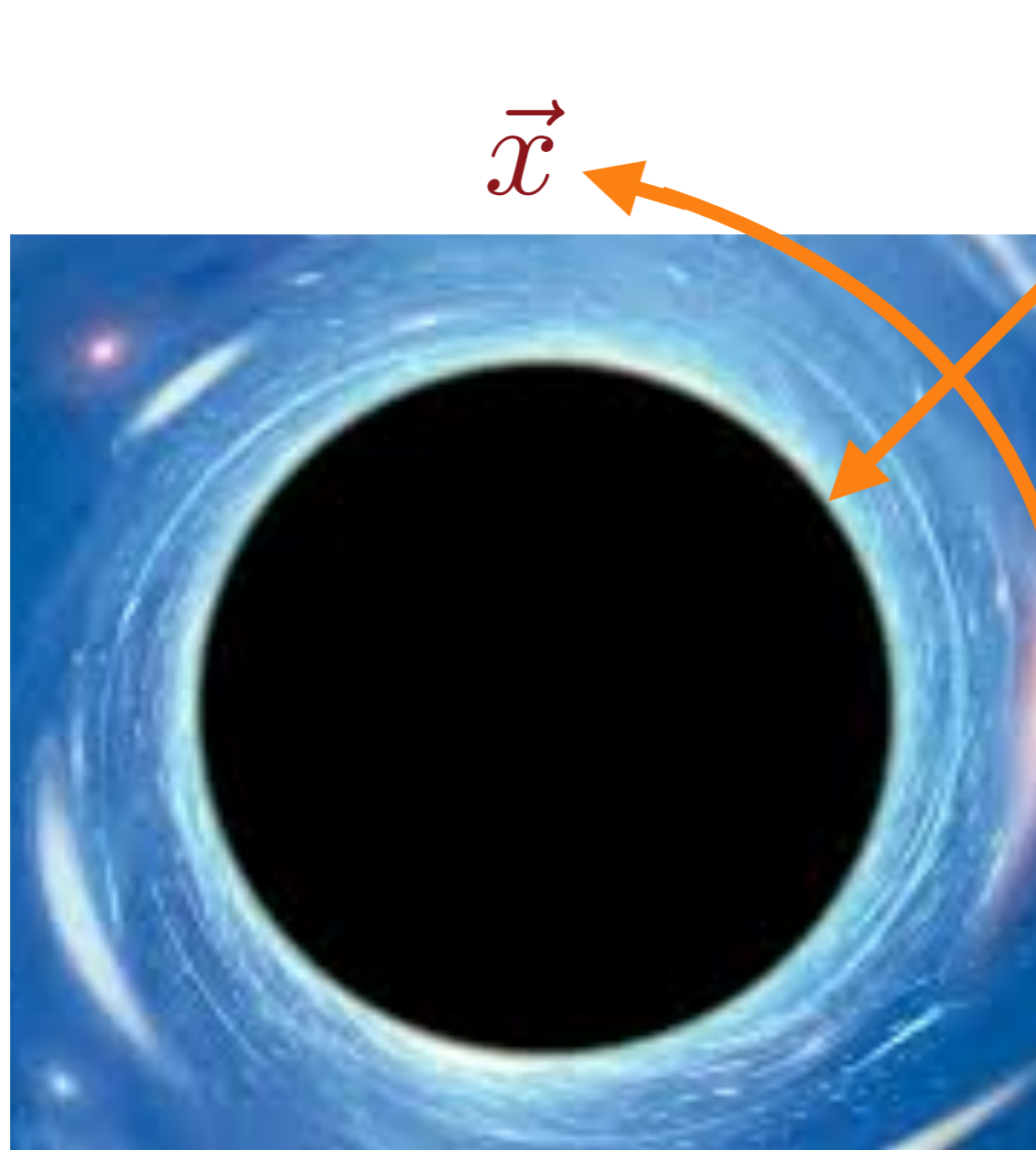
Thermodynamics of charged quantum black holes

$$\begin{aligned} & \int \mathcal{D}g_{\mu\nu} \exp \left(-\frac{1}{\hbar} \mathcal{S}_{\text{Einstein-Maxwell theory}}^{(3+1)}[g_{\mu\nu}] \right) \quad T \rightarrow 0, \\ & \approx \int \mathcal{D}g_{\mu\nu} \exp \left(-\frac{1}{\hbar} \mathcal{S}_{\text{Gravity of AdS}_2 \text{ and boundary}}^{(1+1)}[g_{\mu\nu}] \right) \\ & = \exp(S_{BH}) \times \exp \left(-\frac{1}{T} \times \text{Free energy of SYK model} \right) \end{aligned}$$

The hologram of the 1+1 dimensional gravity near the horizon of a charged black hole is the 0+1 dimensional SYK model



Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



The near-horizon
1+1D-gravity theory is
precisely that of the
low T limit of the
SYK models

Quantum entanglement

A simple many-particle (SYK) model

Charged black holes

Low temperatures

Quantum gravity in 1+1 dimensions

**Quantum
entanglement**

**Charged
black holes**

**A simple
many-particle
(SYK) model**

**Copper-based
superconductors**



Antoine Georges: V2I.00001. Bad Metals and Planckian Metals: DMFT, SYK and physical realisations, 3 PM, Thu Mar 18



Aavishkar Patel: B50.00002. Theories of Planckian dissipation in strange metals, 12:06 PM, Mon Mar 15

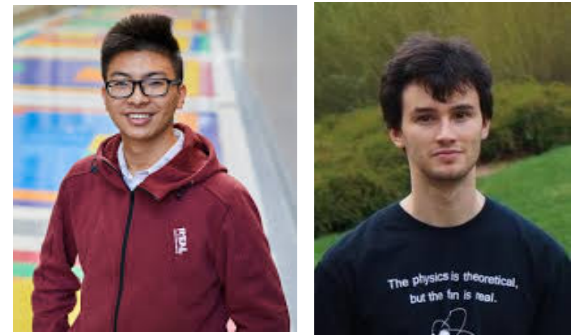


Darshan Joshi: C43.00008. Anomalous density fluctuations in a random t-J model, 4:24 PM, Mon Mar 15



Chenyuan Li: E44.00014. Critical Anomalous Metal Near Superconductivity in a Random Hubbard Model, 10:36 AM, Tue Mar 16

Session R44, Thu 8 AM:



Haoyu Guo, Grigory Tarnopolsky: R44.00001. Excitation spectra of quantum matter without quasiparticles I: Sachdev-Ye-Kitaev models, 8:00 AM, Thu Mar 18



Philipp Dumitrescu, Nils Wentzell, Olivier Parcollet: R44.00002. Deconfined metallic criticality and Sachdev-Ye-Kitaev physics of spin-1/2 electrons at finite doping, 8:12 AM, Thu Mar 18

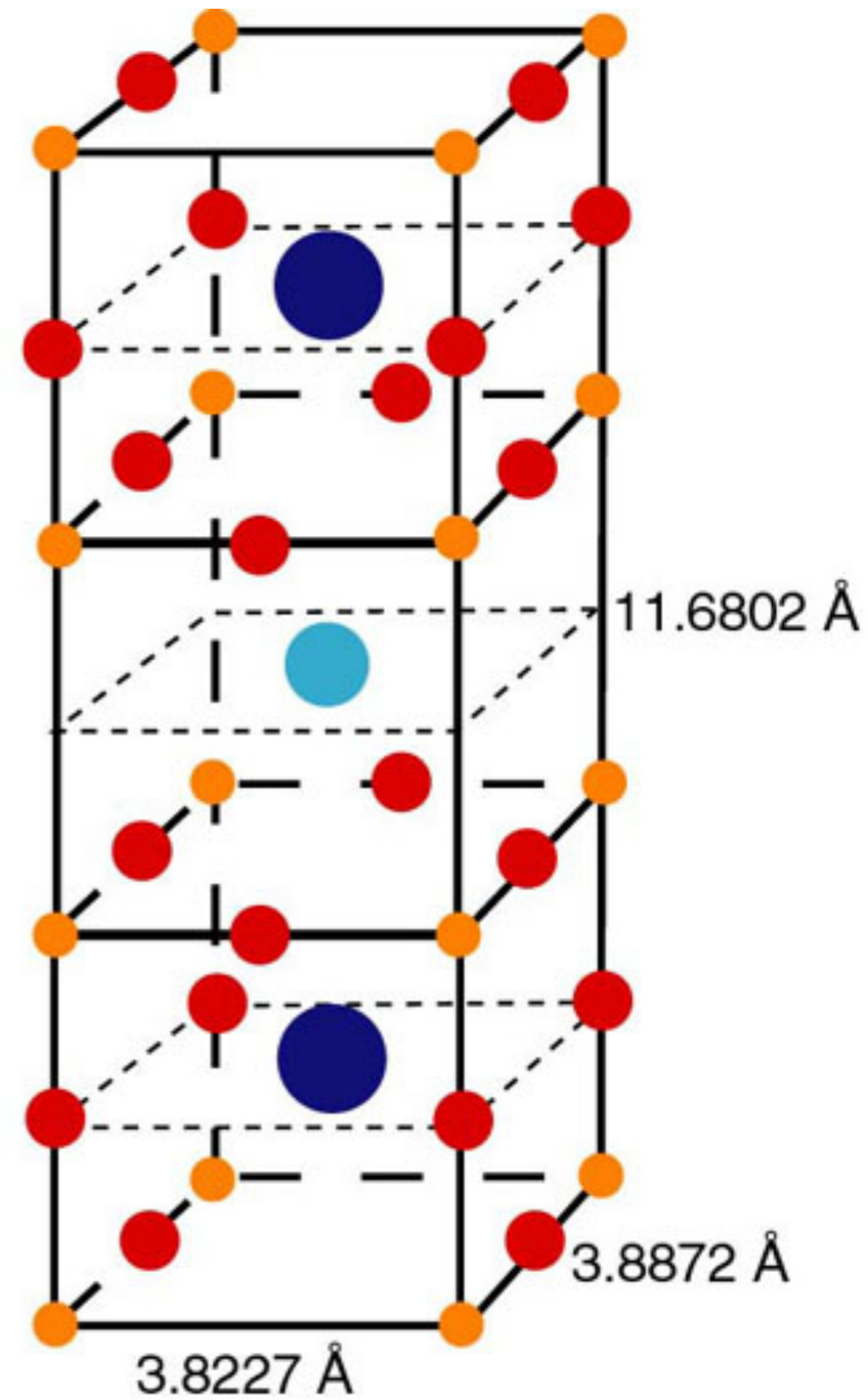
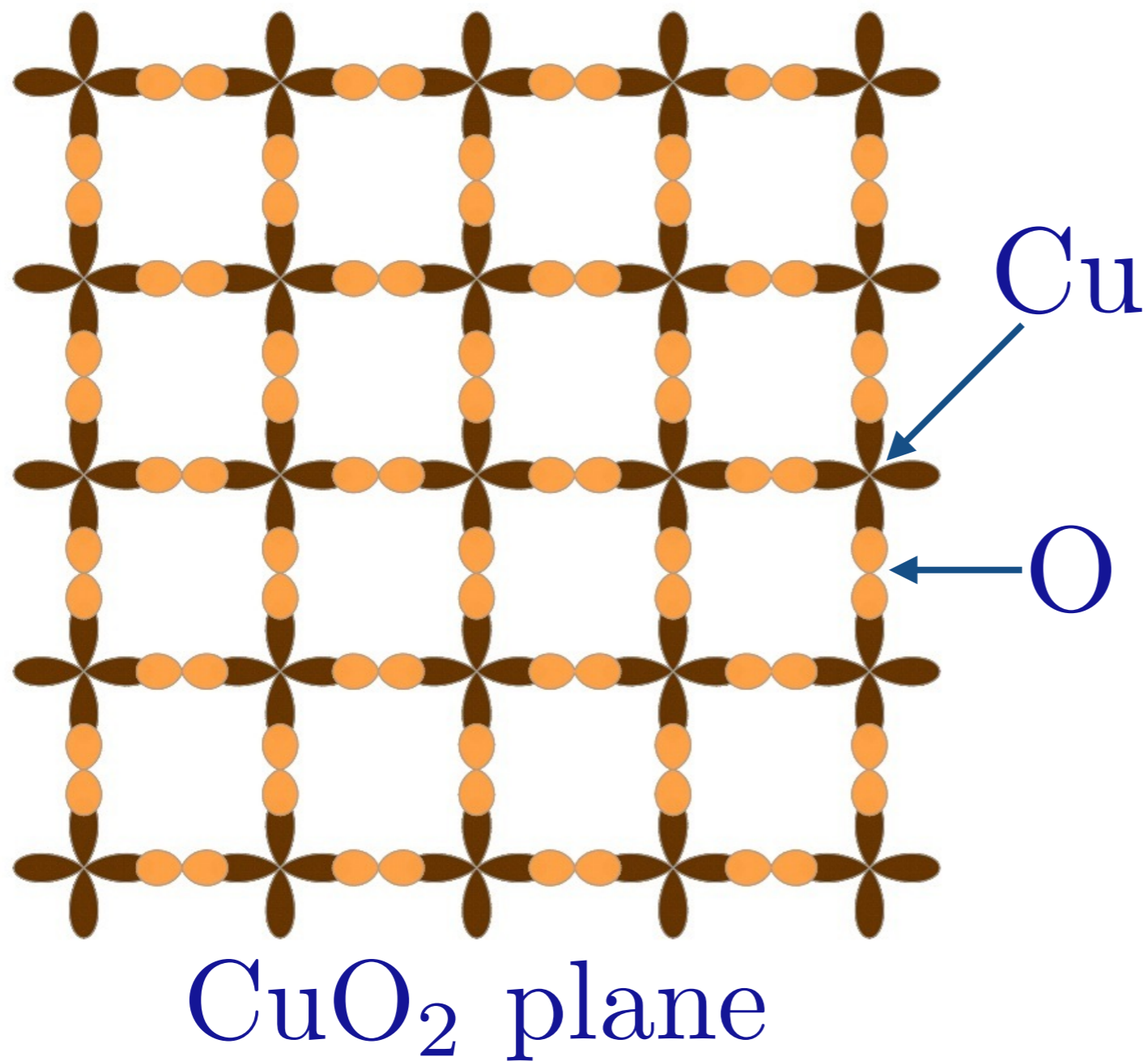


Alexander Wietek, Henry Shackleton: R44.00005. SYK criticality and spin glass order in the random doped Heisenberg model, 8:48 AM, Thu Mar 18

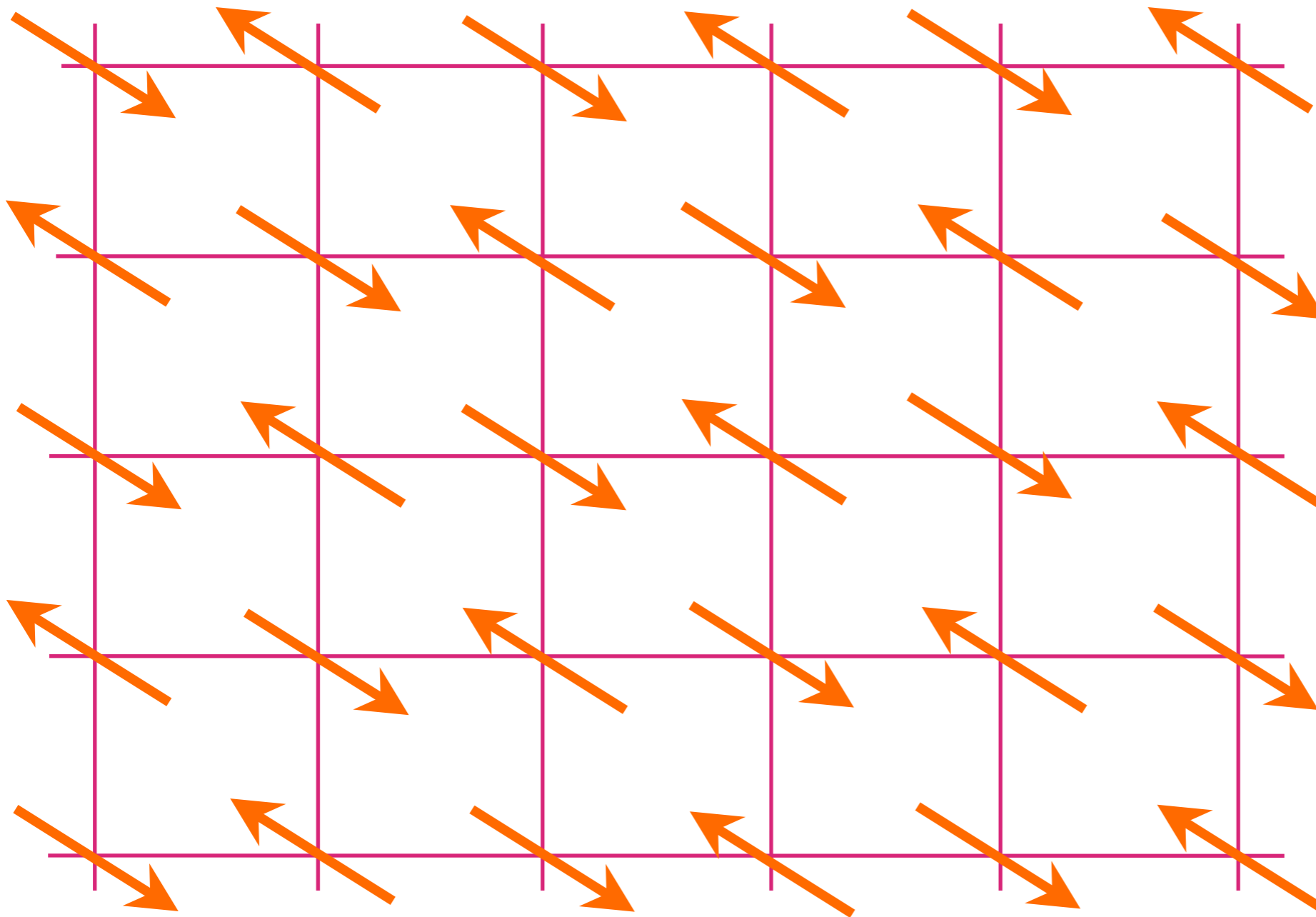


Maria Tikhanovskaya: R44.00011. Excitation spectra of quantum matter without quasiparticles II: random t-J model, 10:00 AM, Thu Mar 18

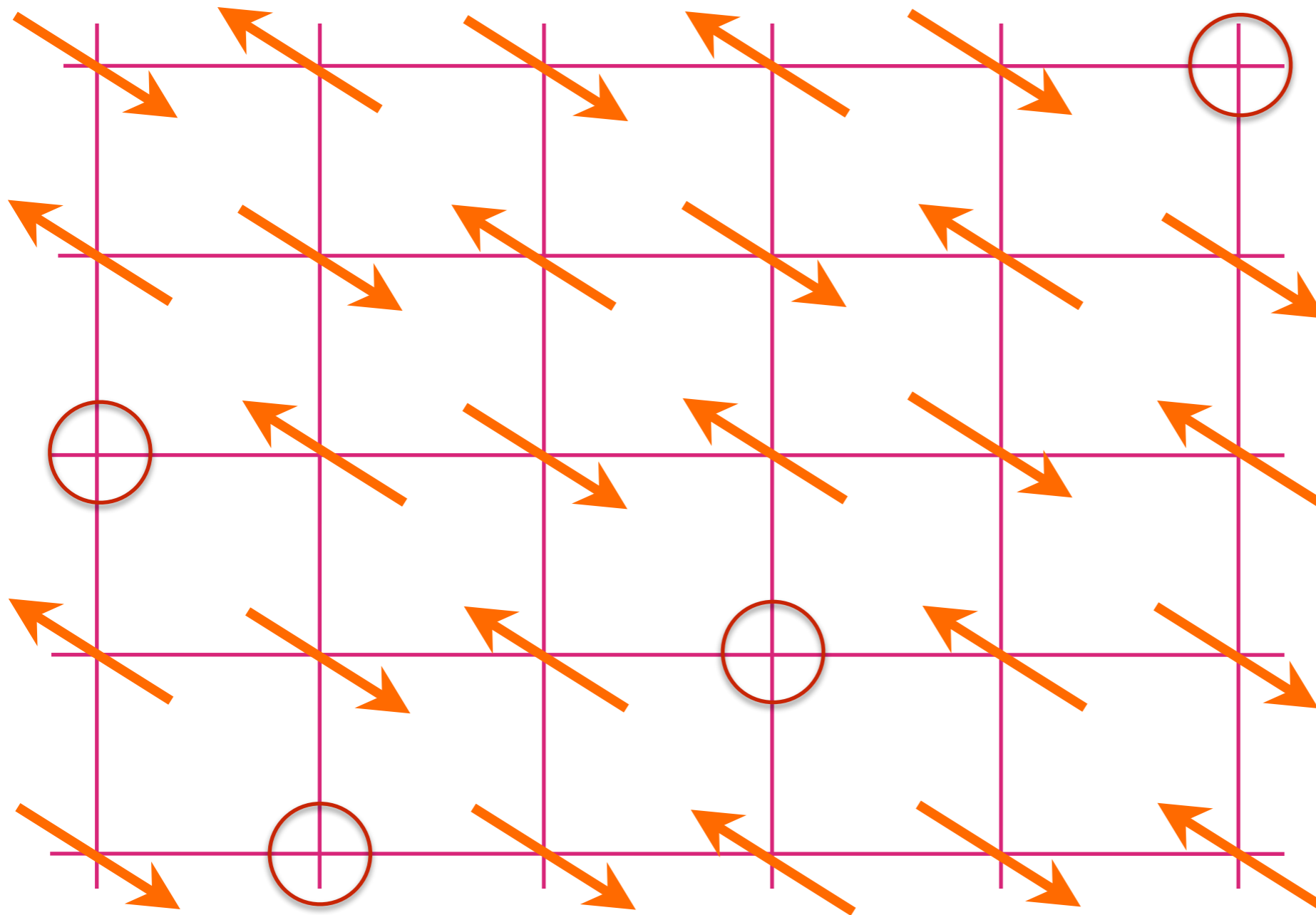
High temperature superconductors



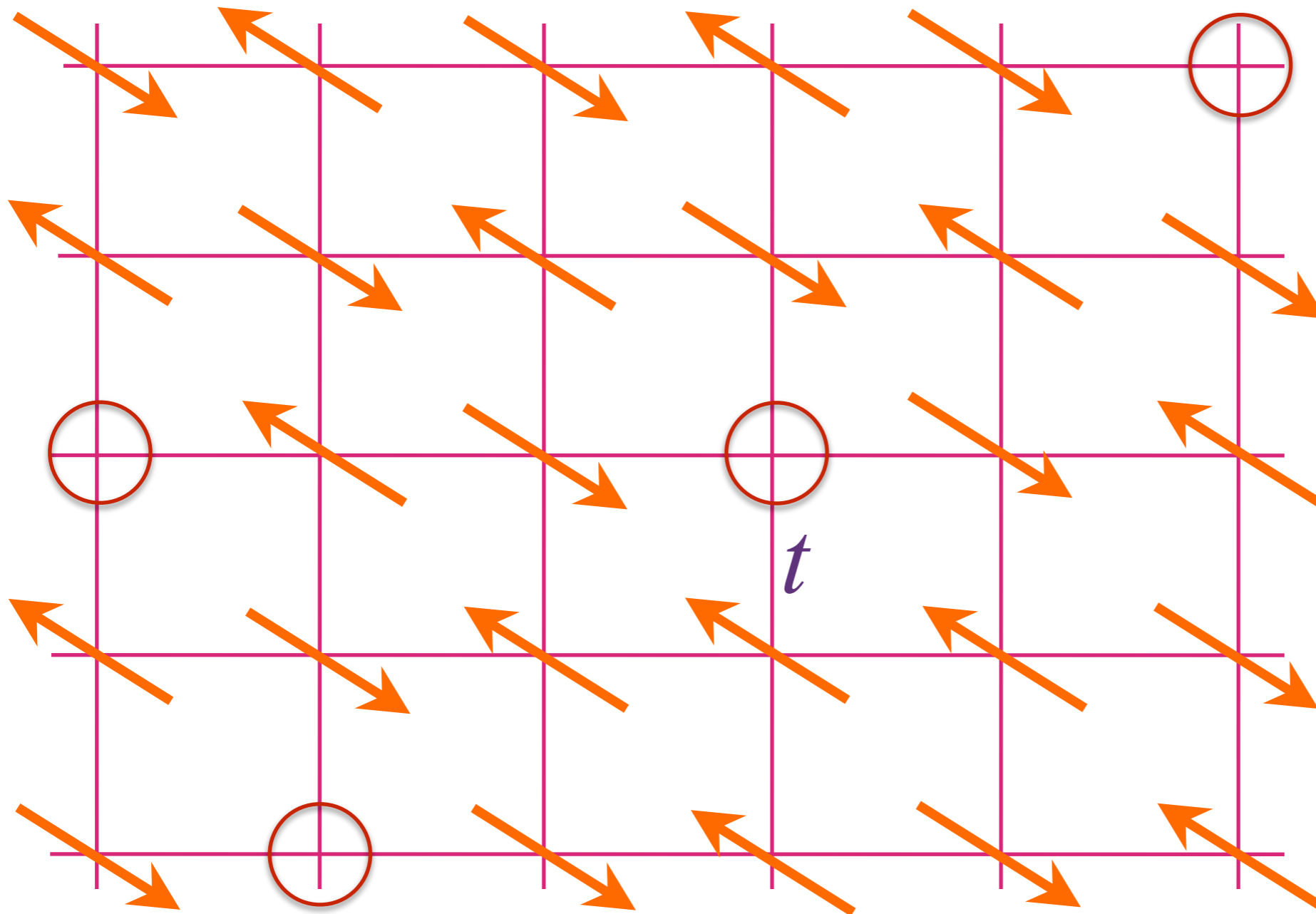
Insulating antiferromagnet



Antiferromagnet doped with hole density p



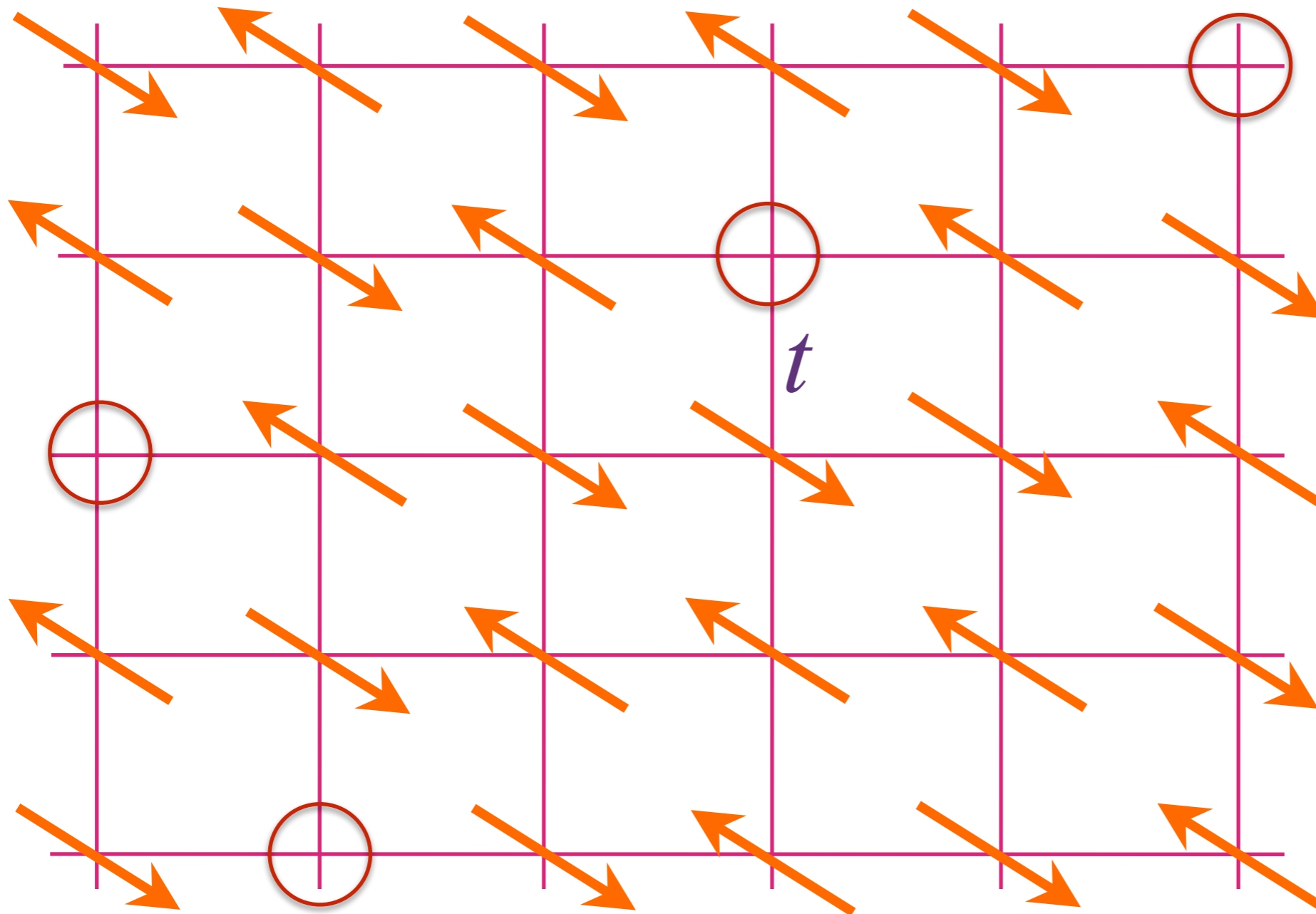
Real-space view



Baskaran,
Anderson (1988)

p mobile holes in a background of
fluctuating spins

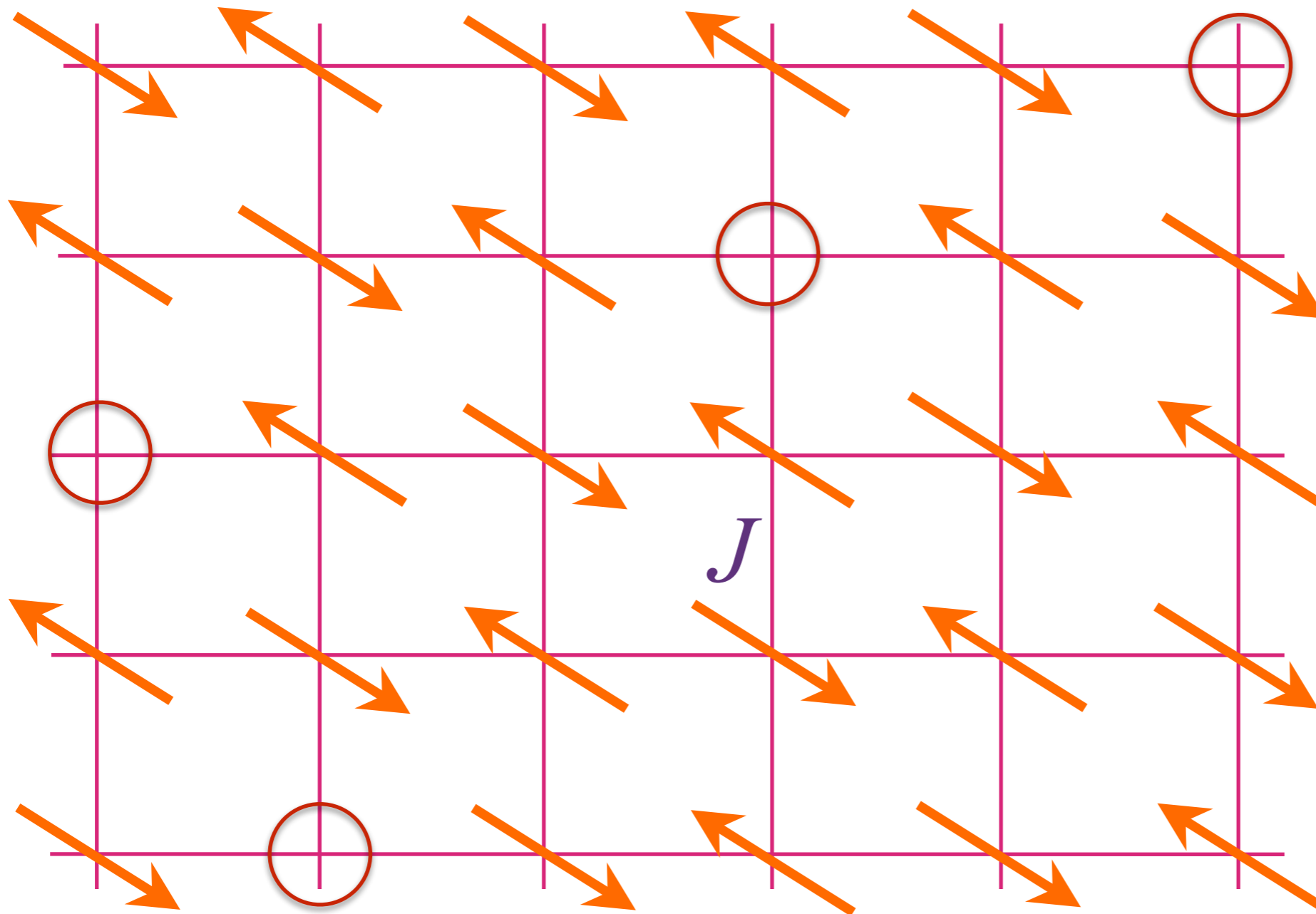
Real-space view



Baskaran,
Anderson (1988)

p mobile holes in a background of
fluctuating spins

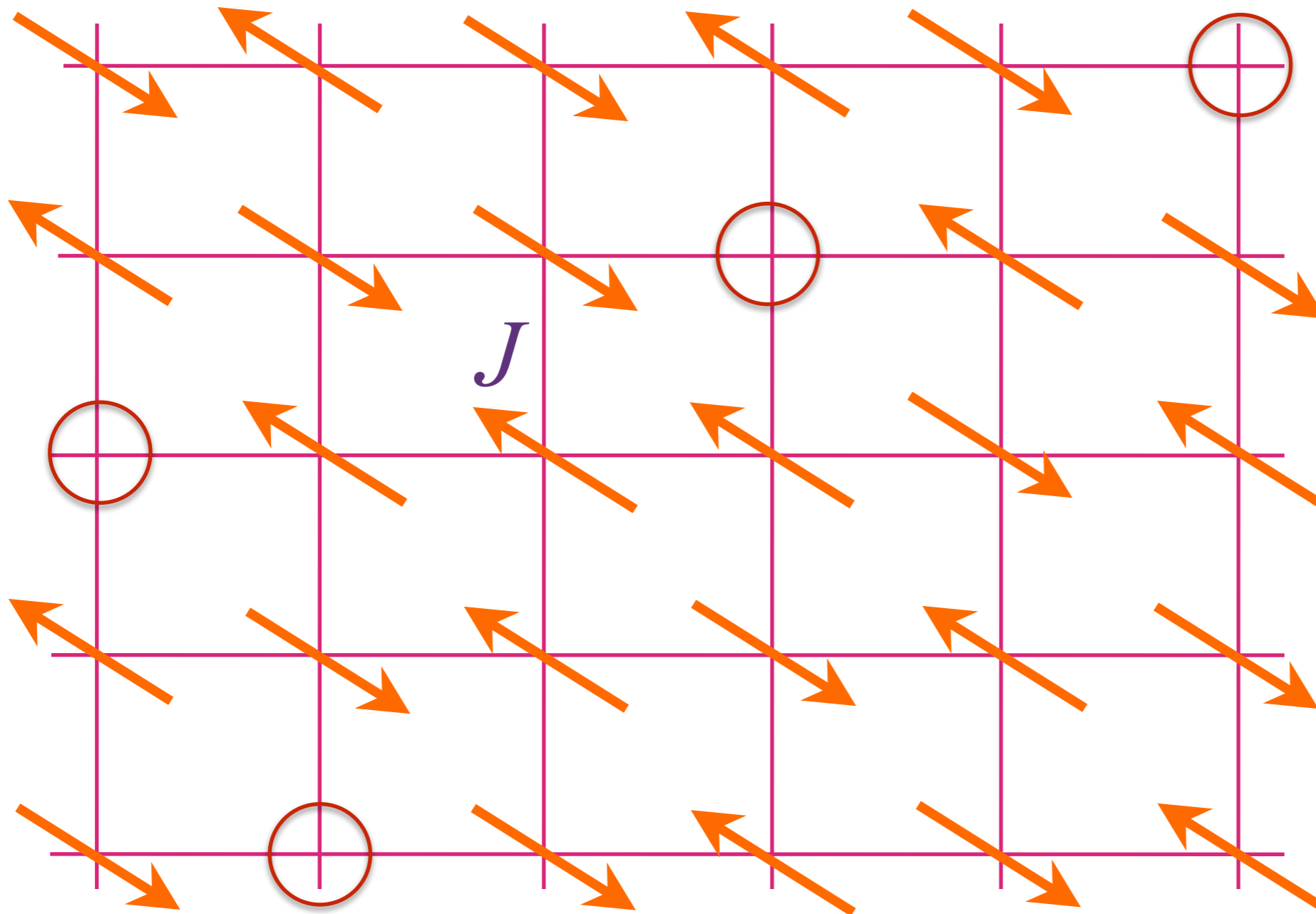
Real-space view



Baskaran,
Anderson (1988)

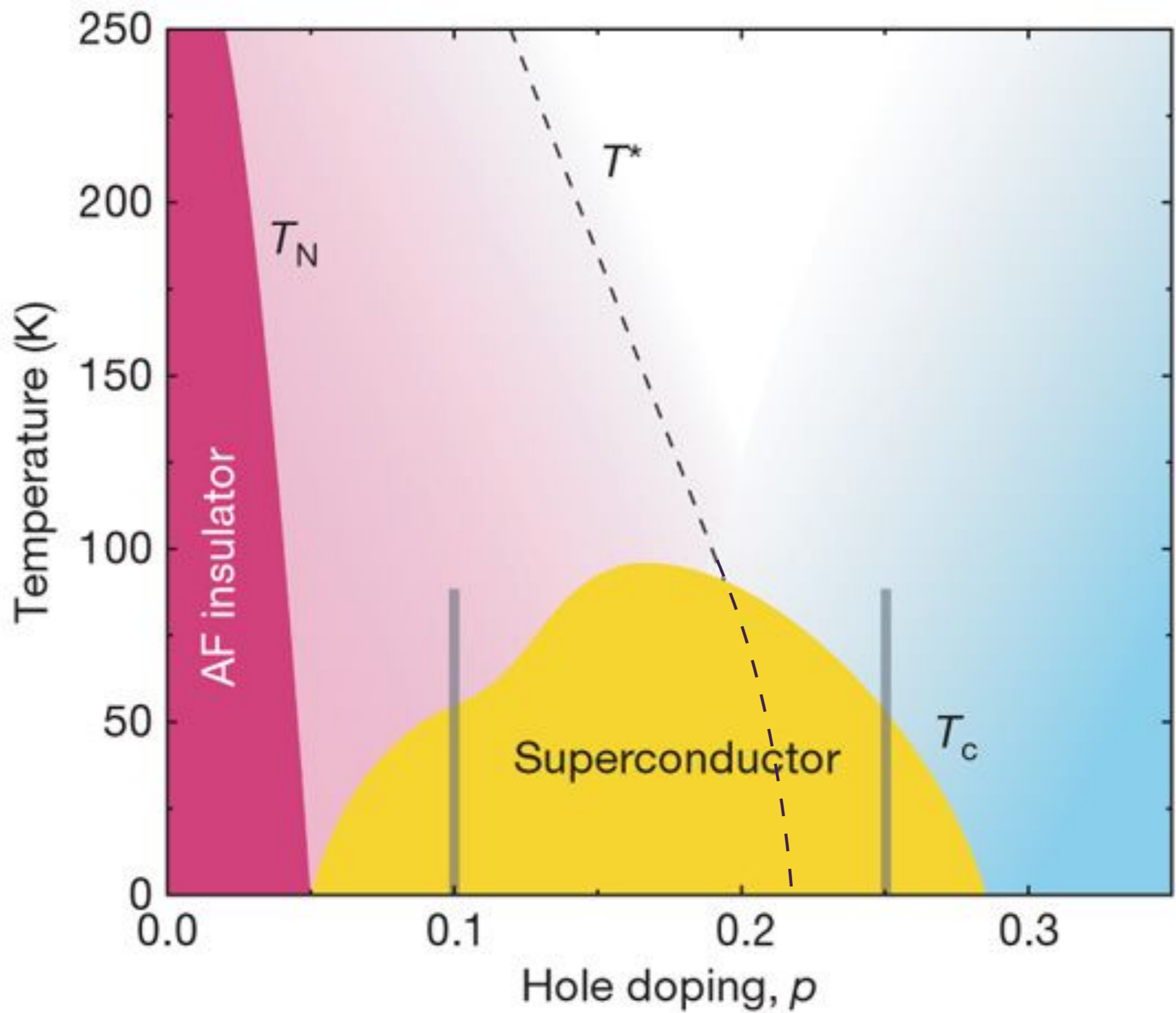
p mobile holes in a background of
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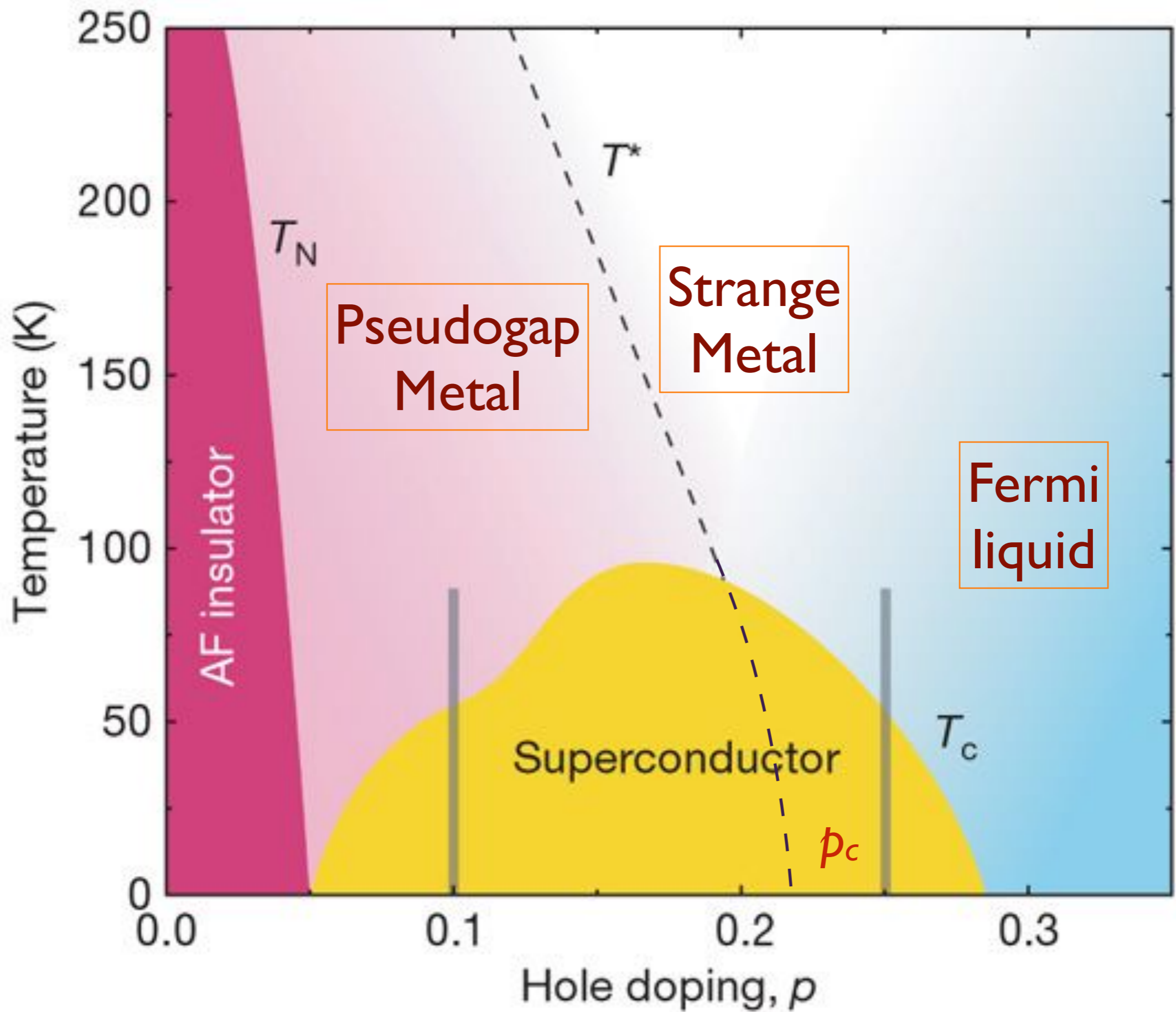
Real-space view

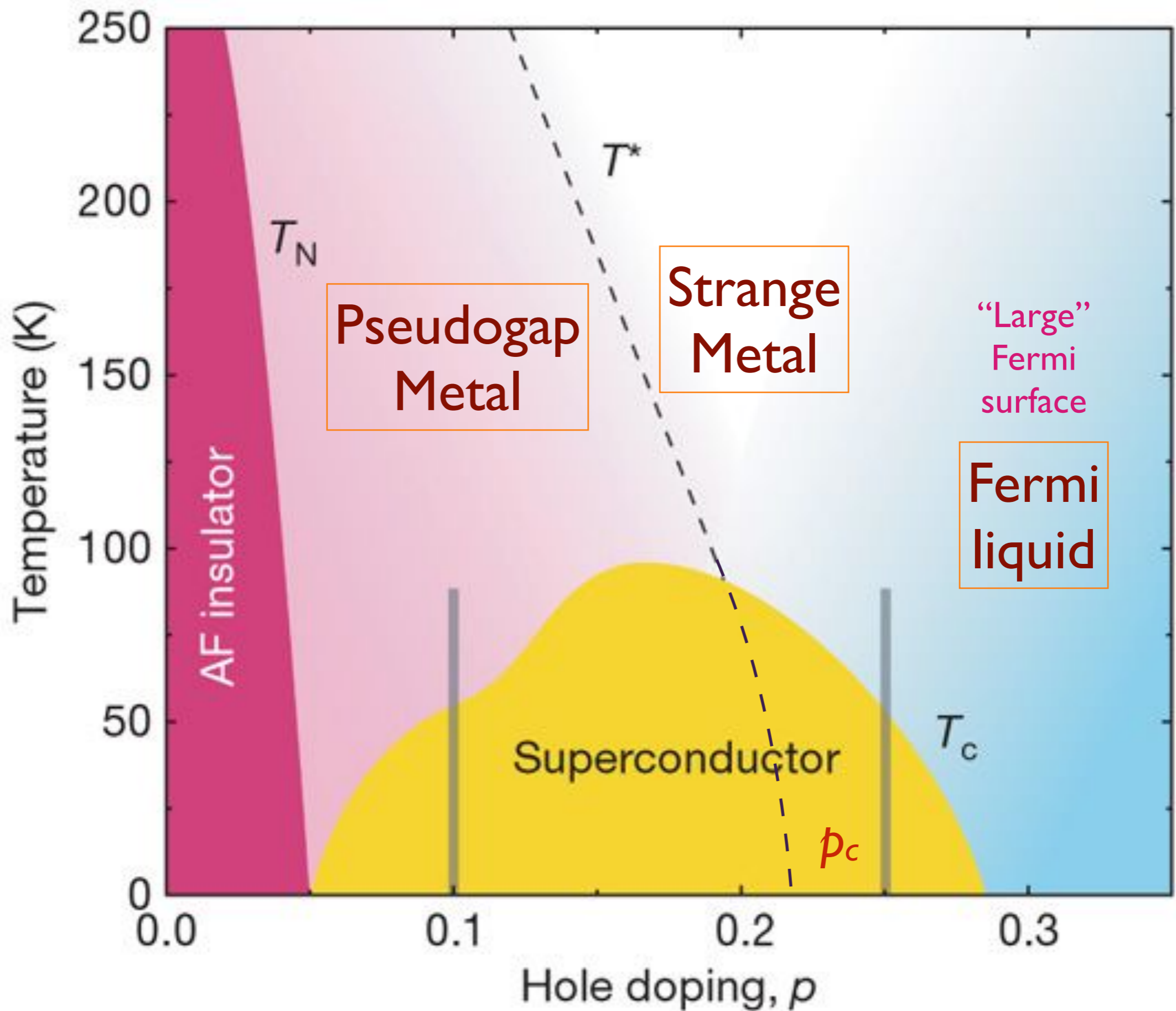


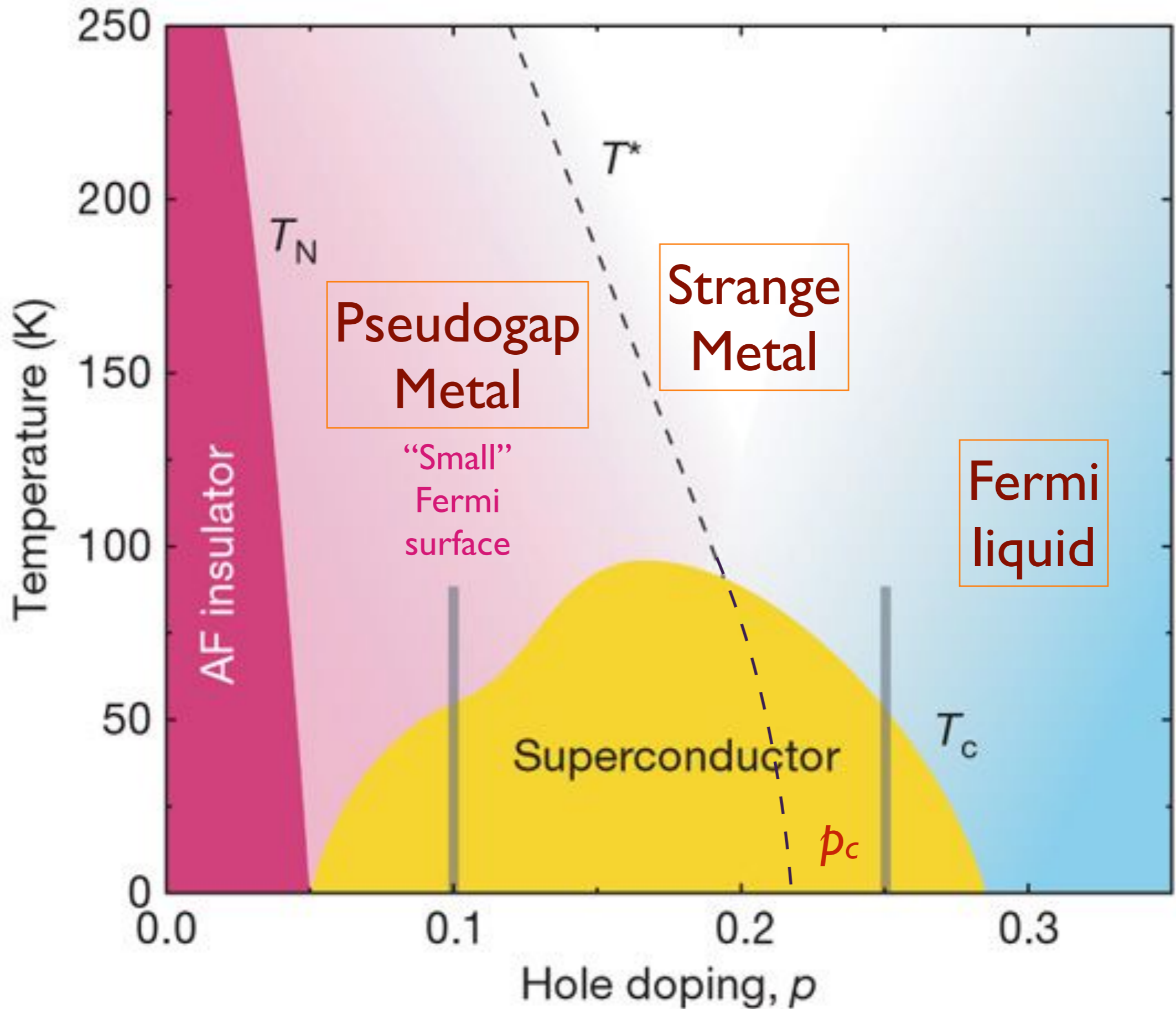
Baskaran,
Anderson (1988)

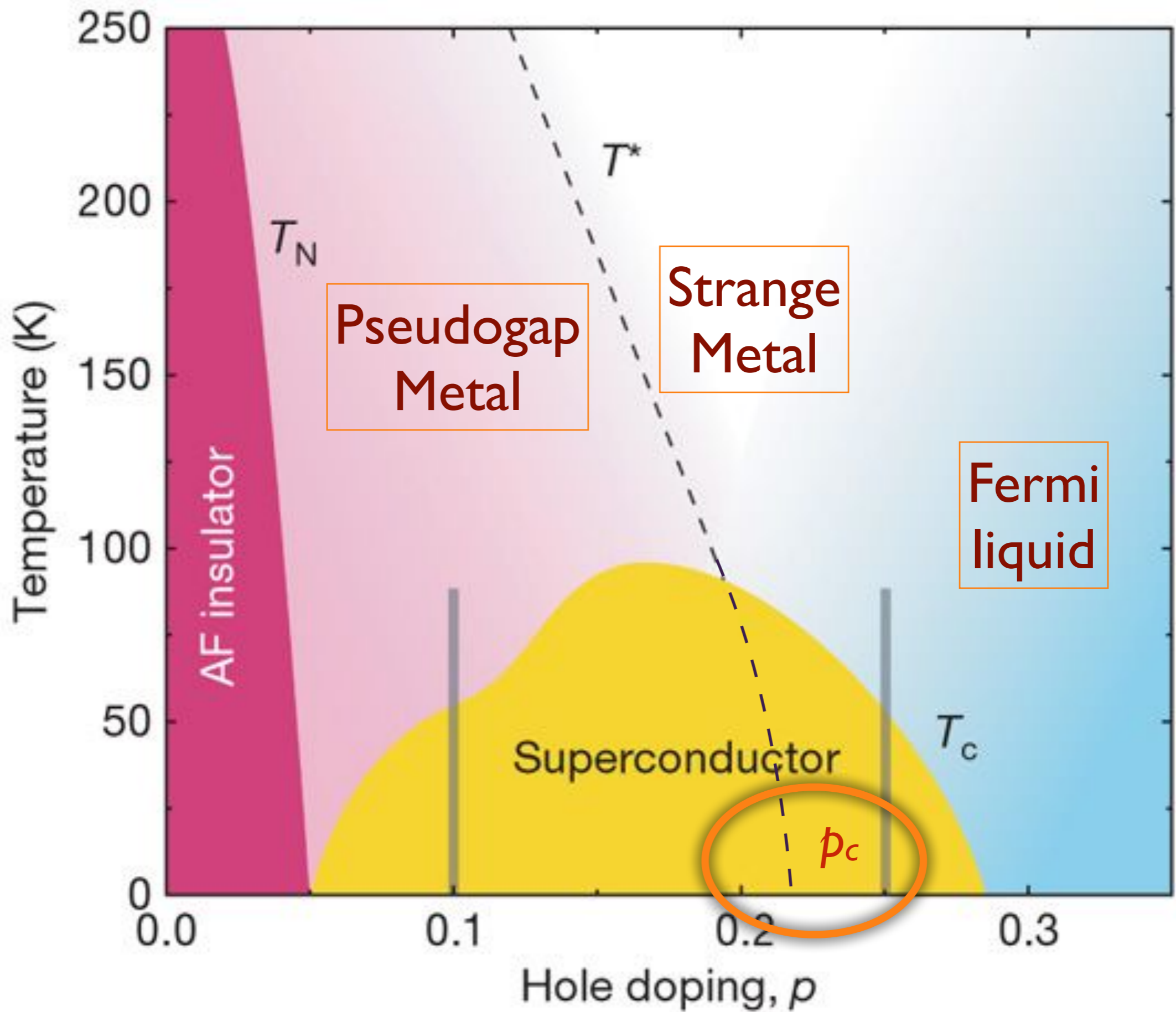
p mobile holes in a background of
fluctuating spins







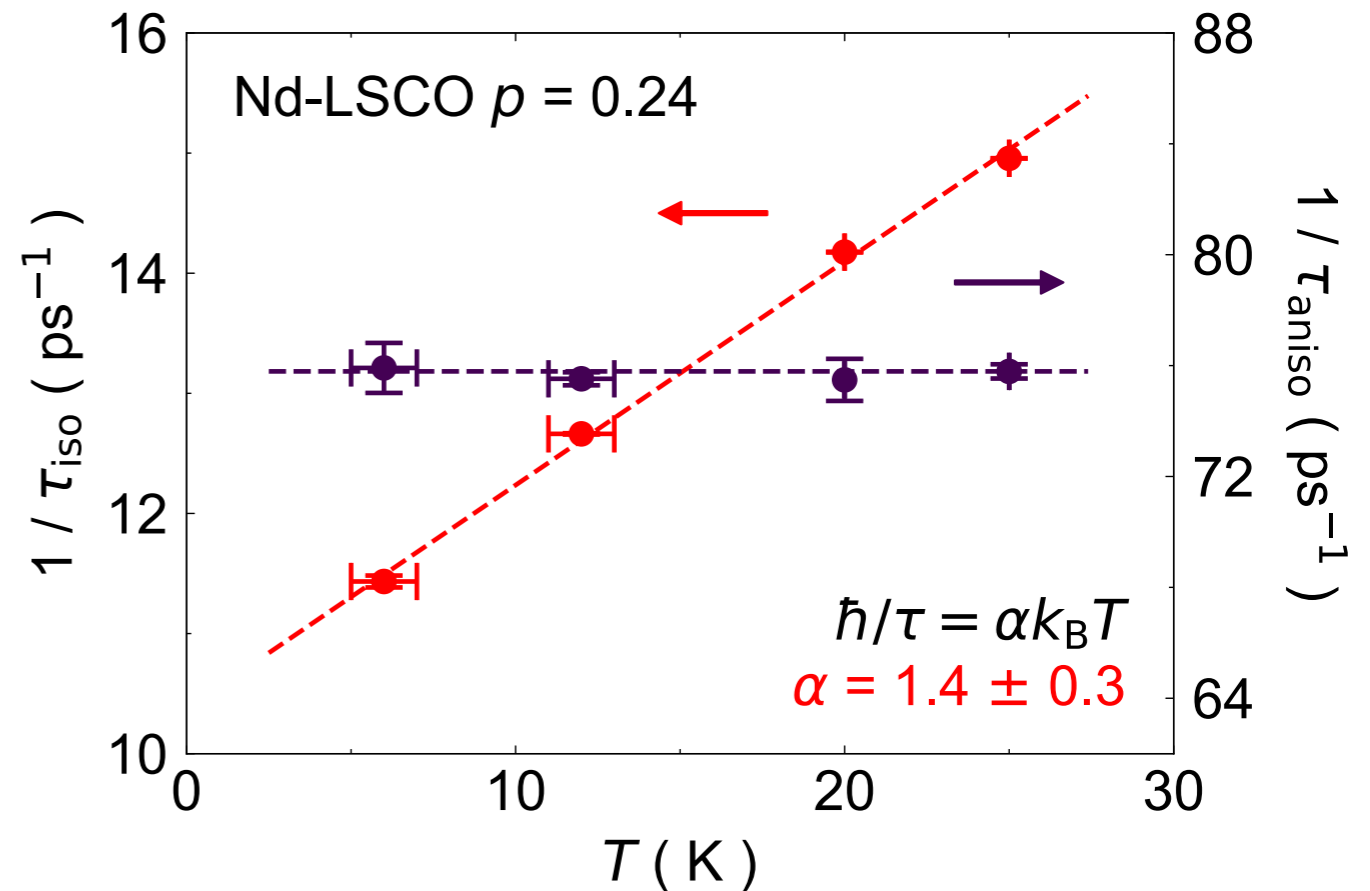
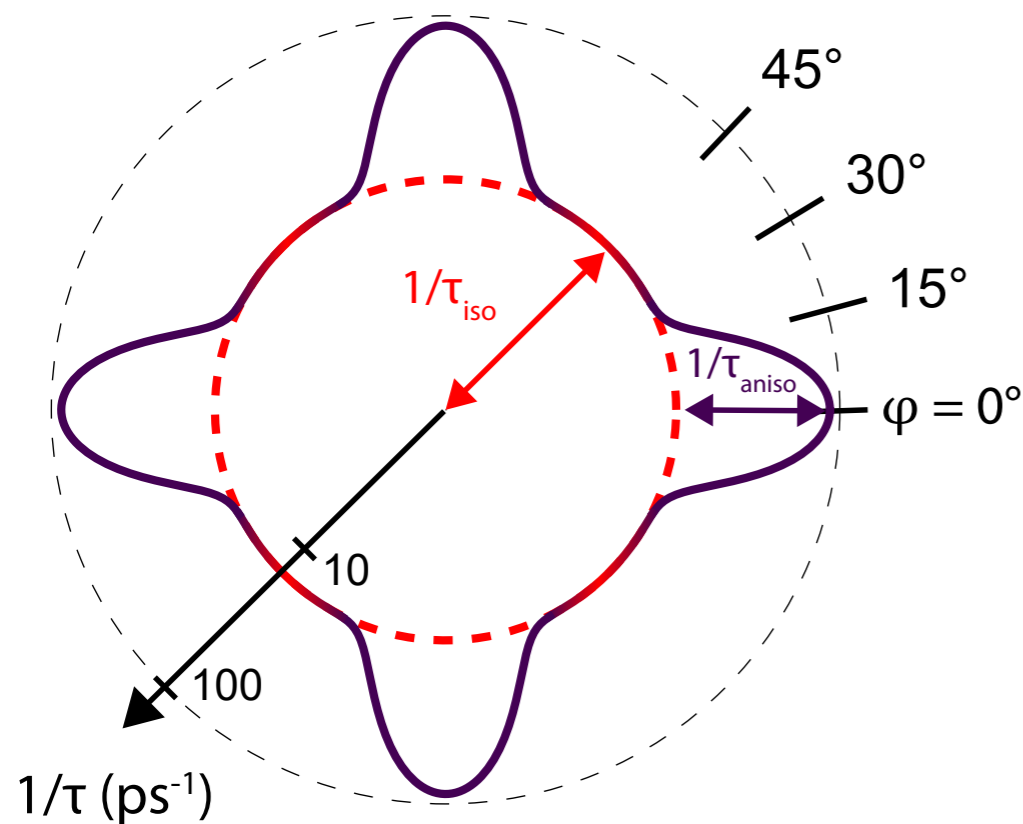




Measurement of the Planckian Scattering Rate

G. Grissonnanche, Y. Fang, A. Legros, S. Verret, F. Laliberté, C. Collignon, J. Zhou, D. Graf, P. Goddard, L. Taillefer, B. J. Ramshaw, arXiv:2011.13054

Angle-dependent magnetoresistance in Nd-LSCO near $p = p_c \approx 0.23$.

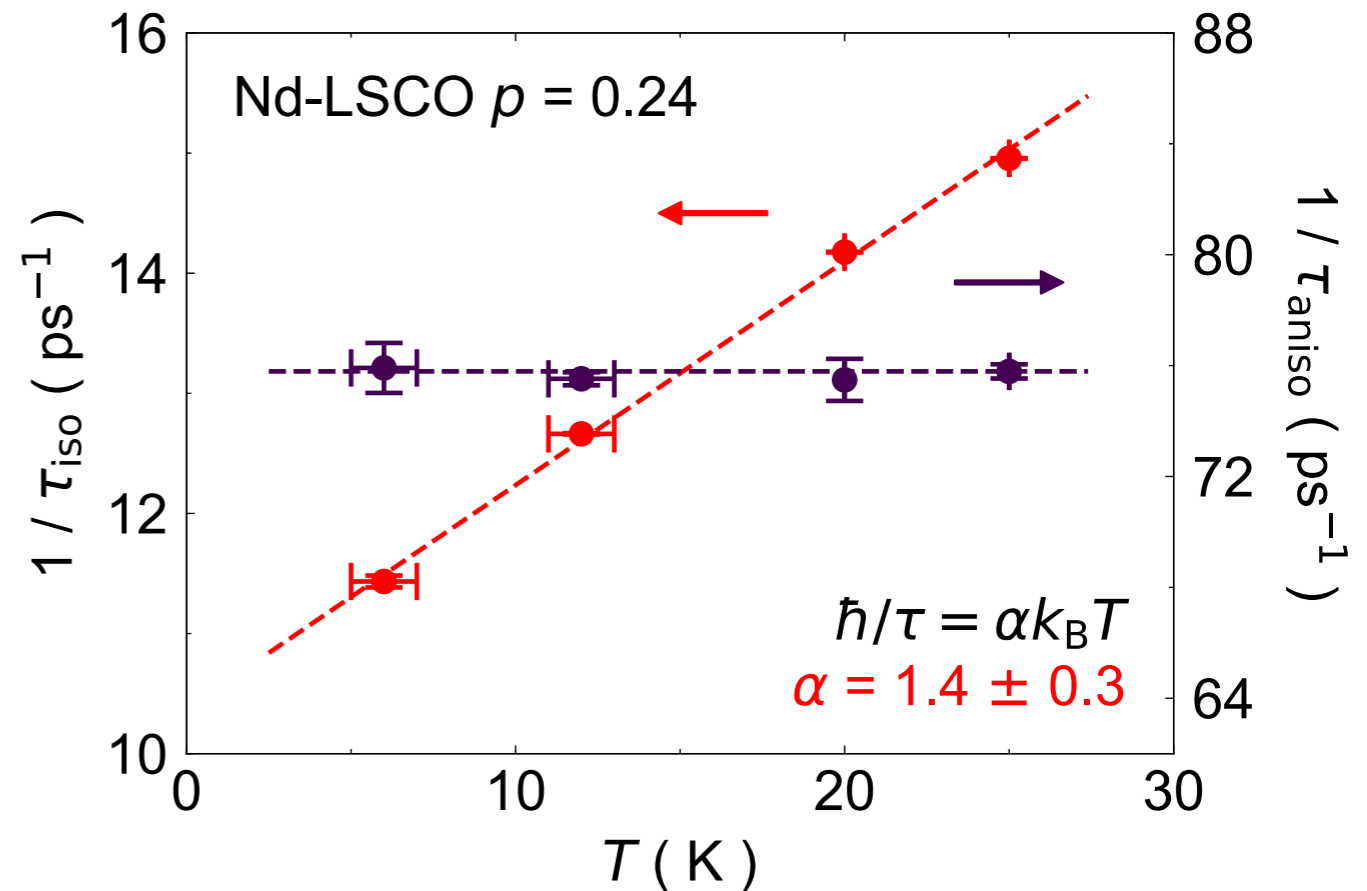
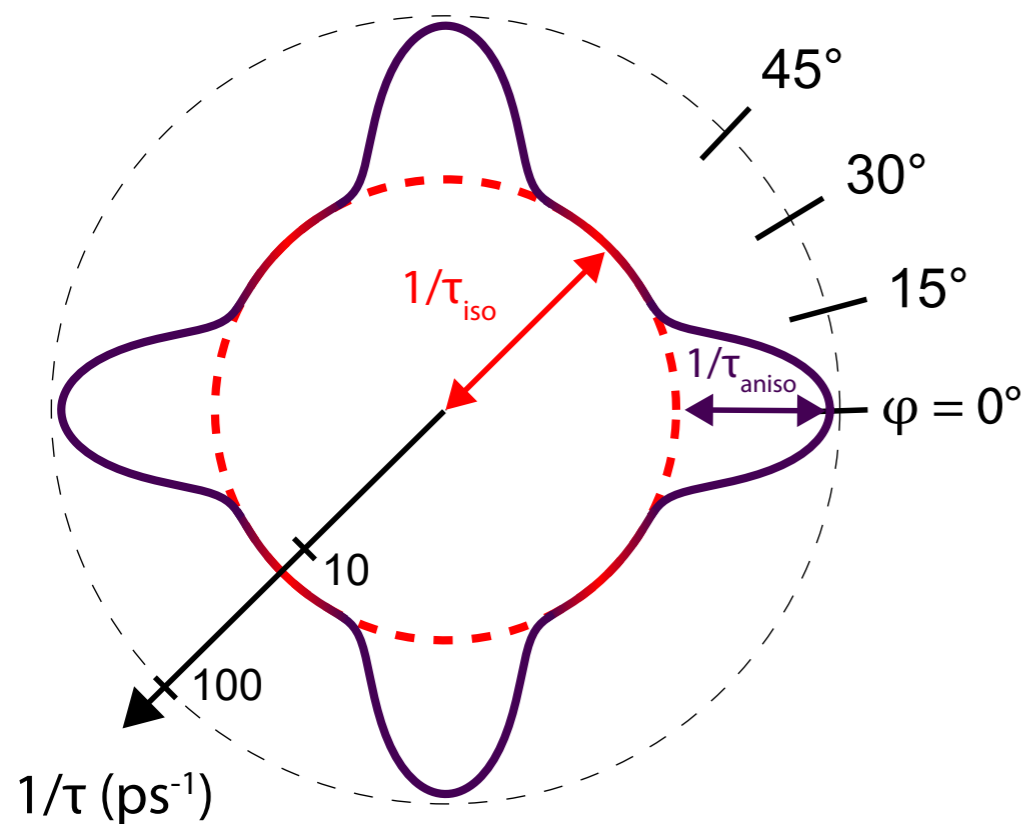


$$\frac{1}{\tau} = \frac{1}{\tau_{\text{aniso}}(\vec{k})} + \frac{\alpha}{\hbar} k_B T$$

Measurement of the Planckian Scattering Rate

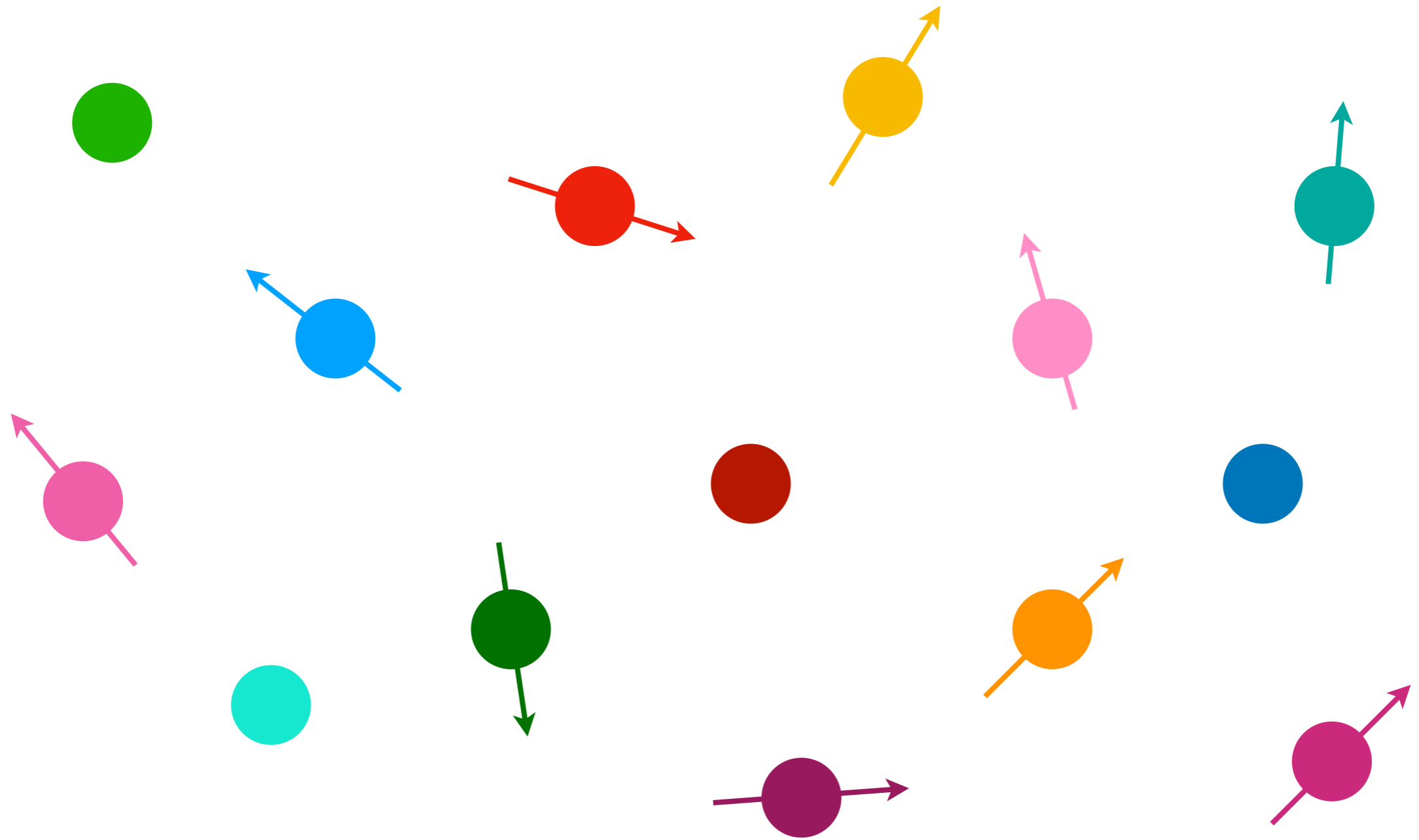
G. Grissonnanche, Y. Fang, A. Legros, S. Verret, F. Laliberté, C. Collignon, J. Zhou, D. Graf, P. Goddard, L. Taillefer, B. J. Ramshaw, arXiv:2011.13054

Angle-dependent magnetoresistance in Nd-LSCO near $p = p_c \approx 0.23$.

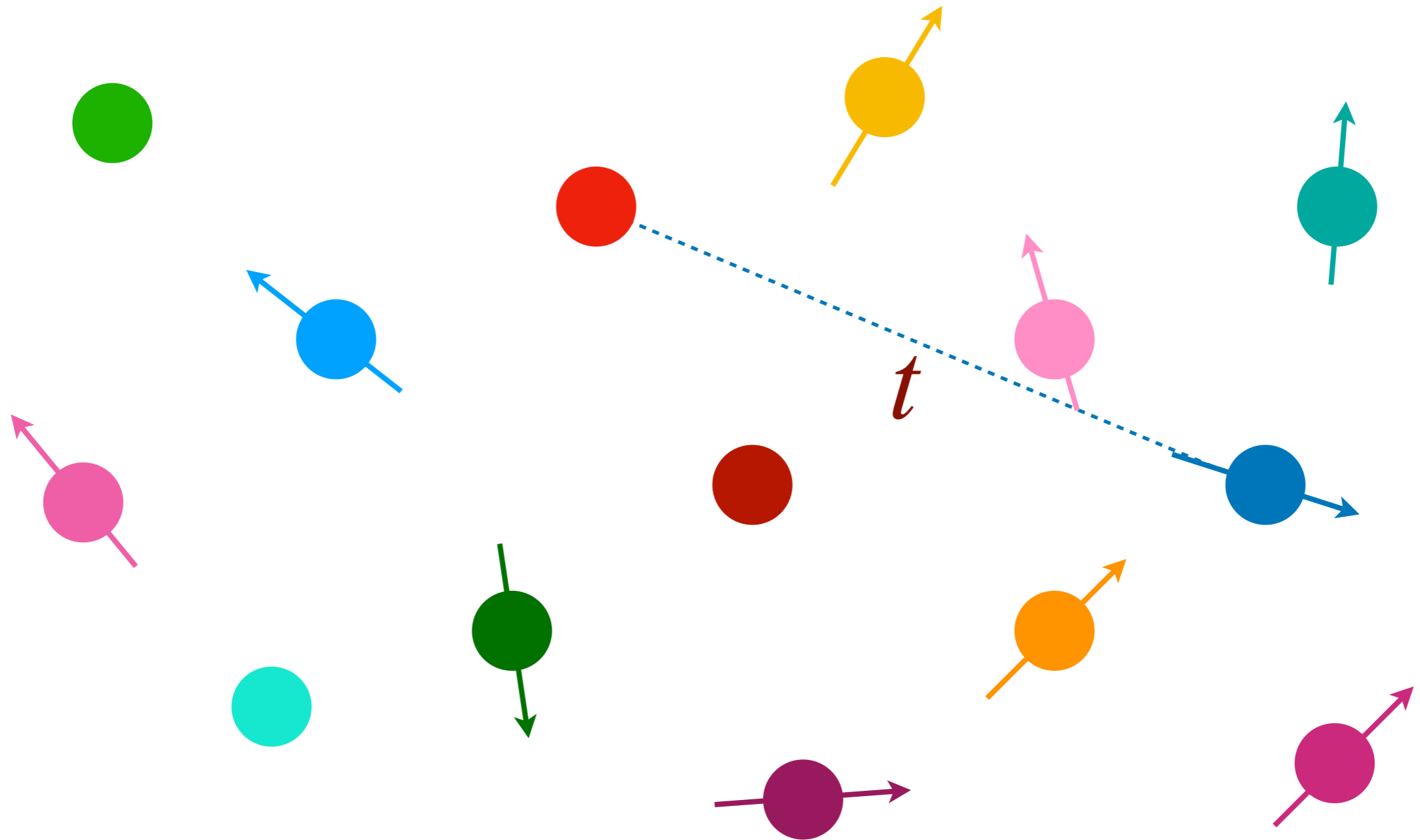


$$\frac{1}{\tau} = \frac{1}{\tau_{\text{aniso}}(\vec{k})} + \frac{\alpha}{\hbar} k_B T$$

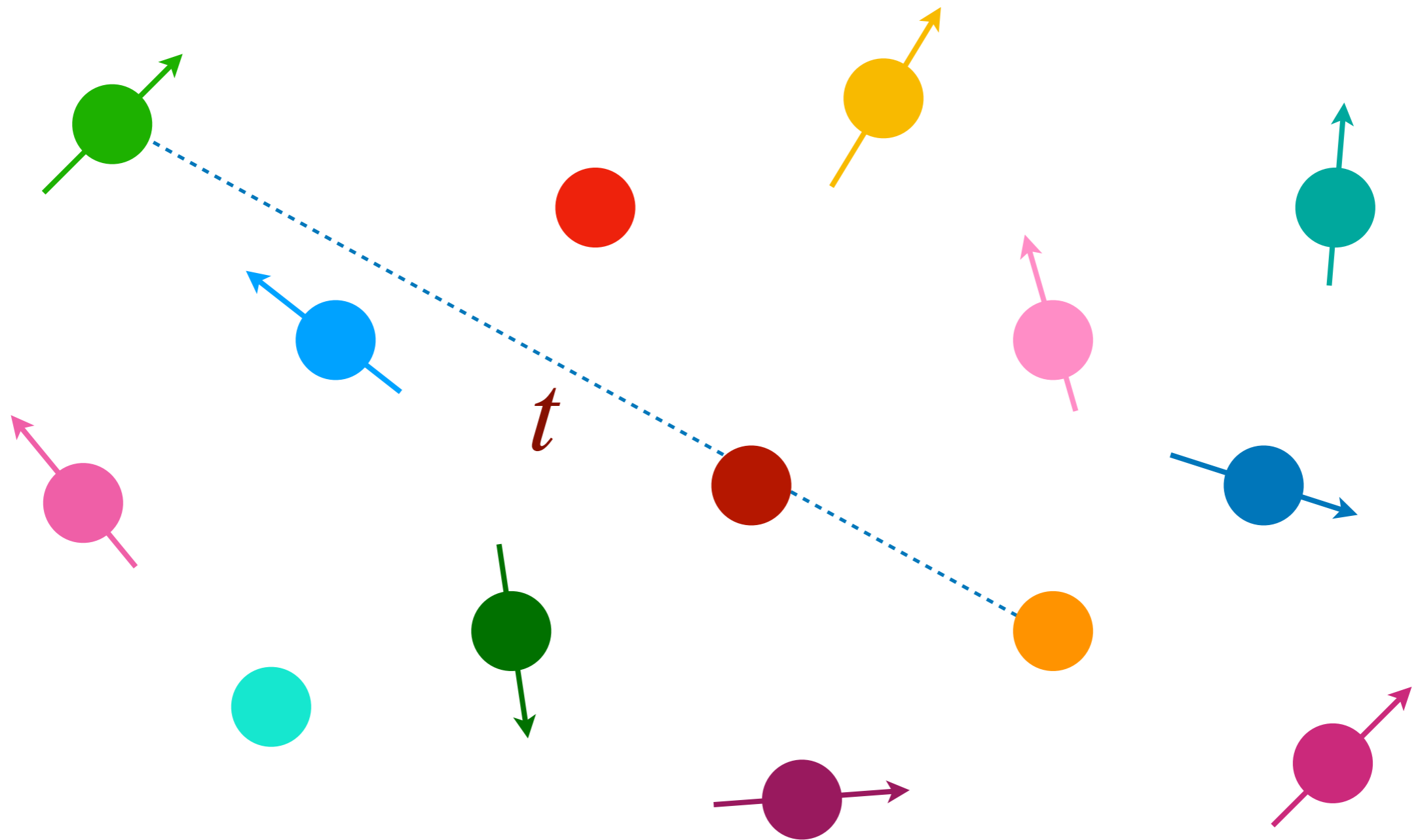
Random t - J model



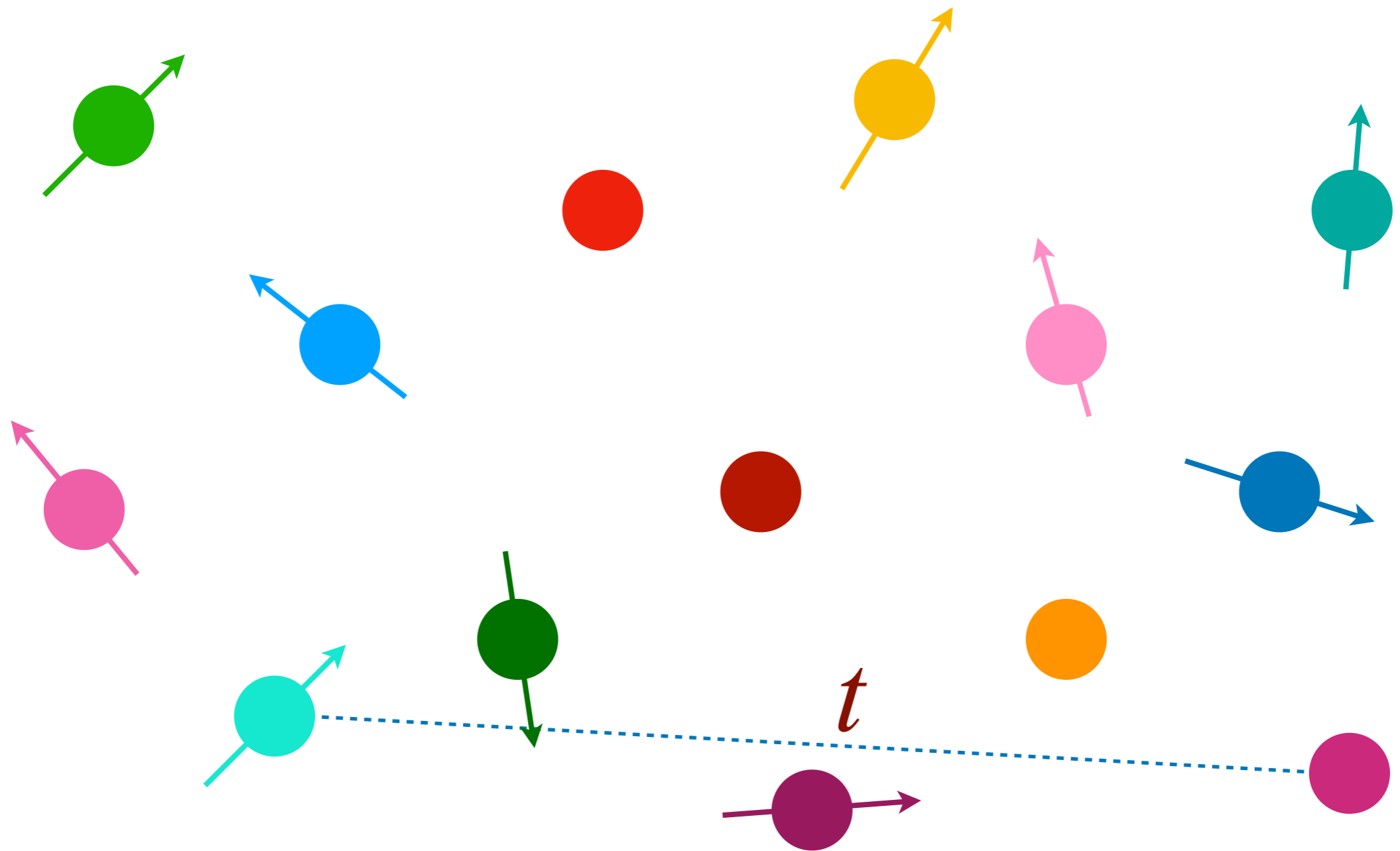
Random t - J model



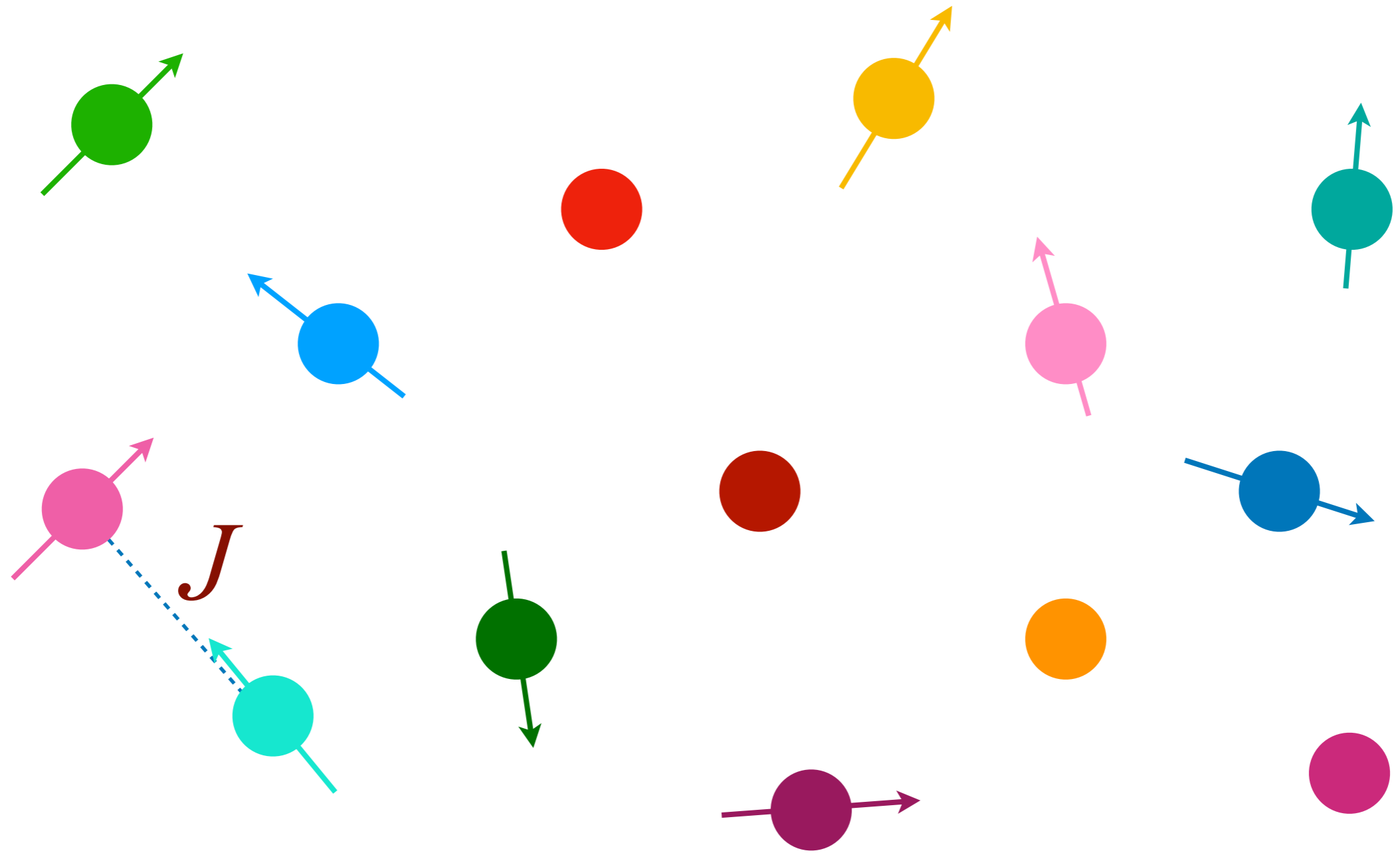
Random t - J model



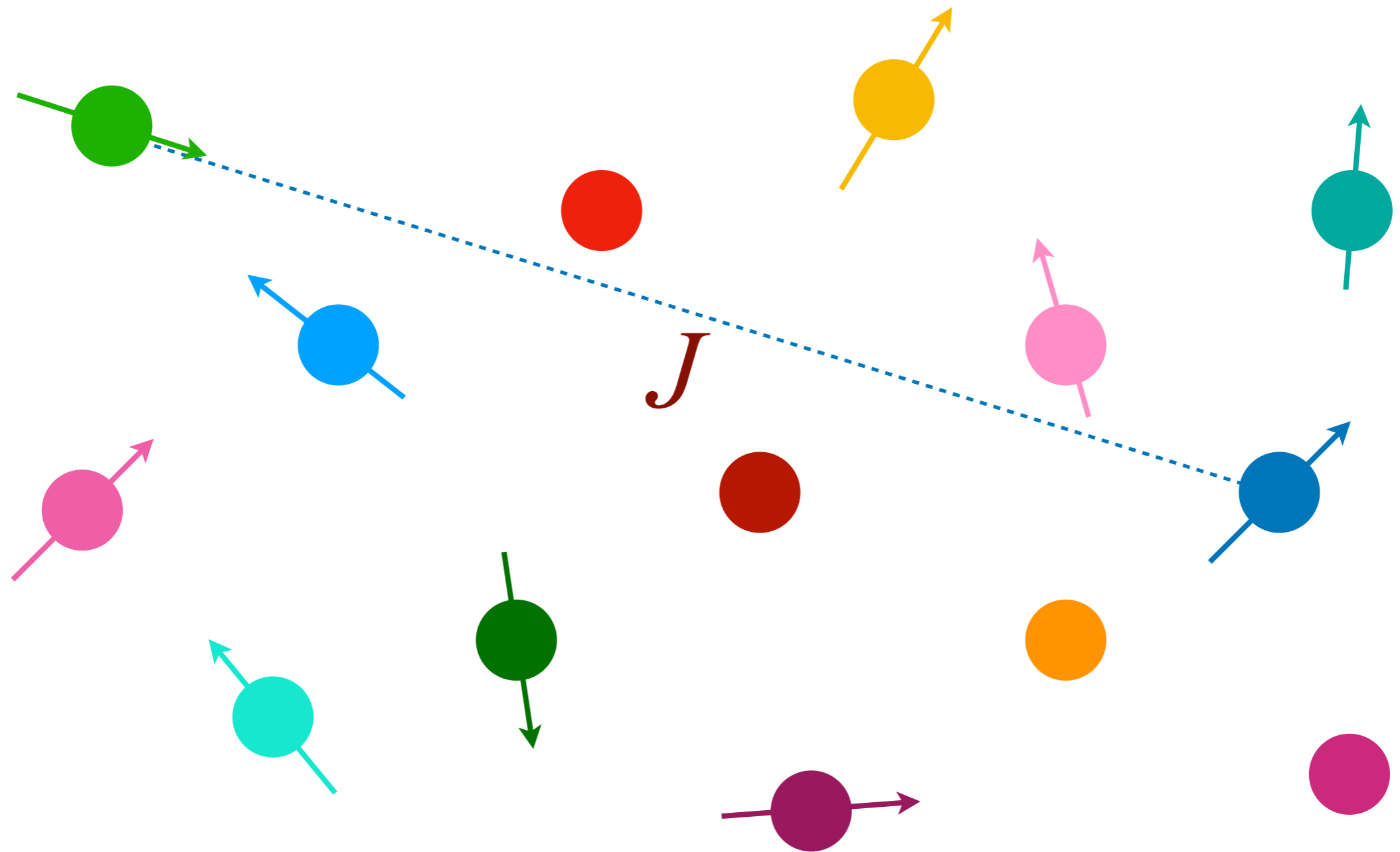
Random t - J model



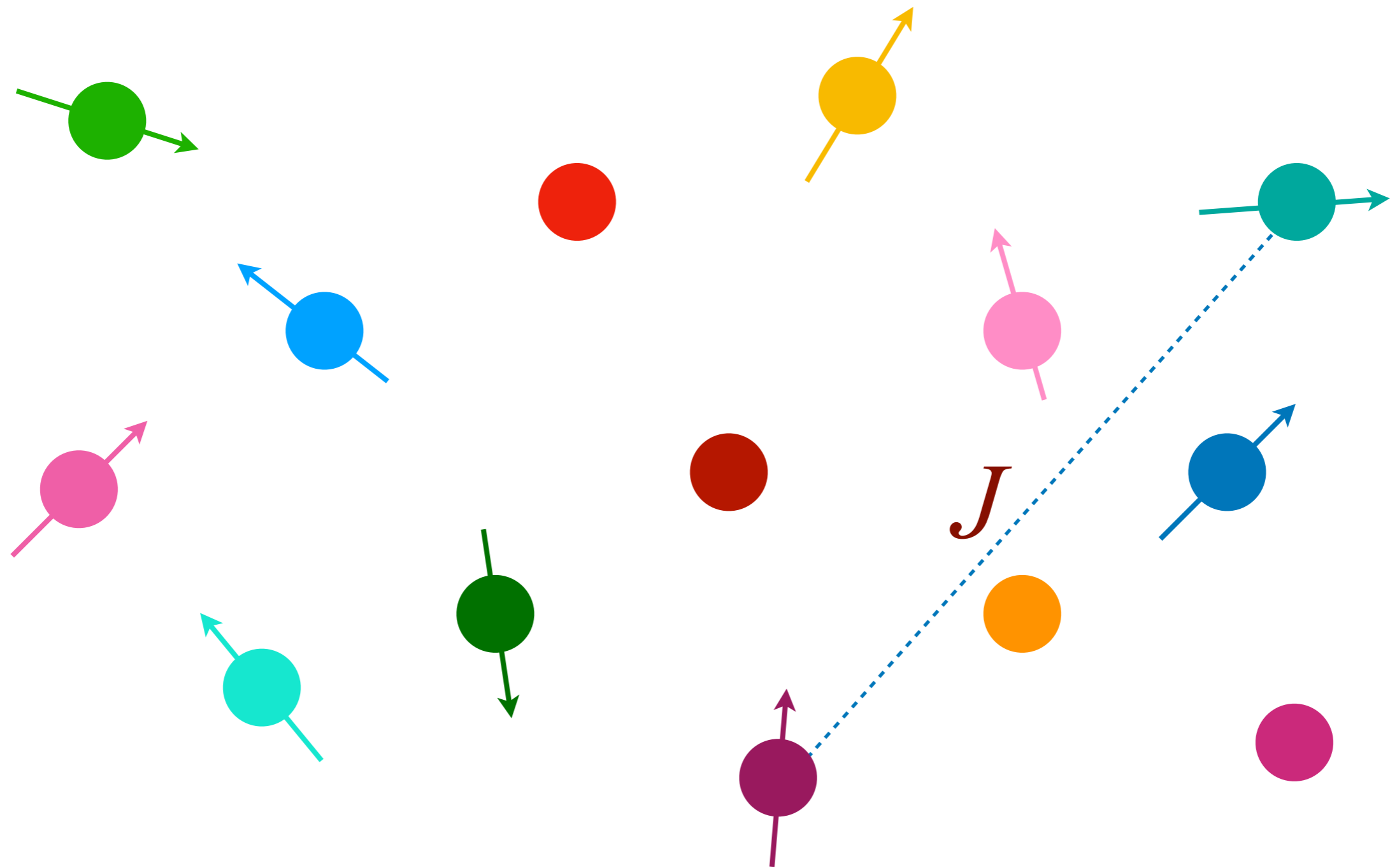
Random t - J model



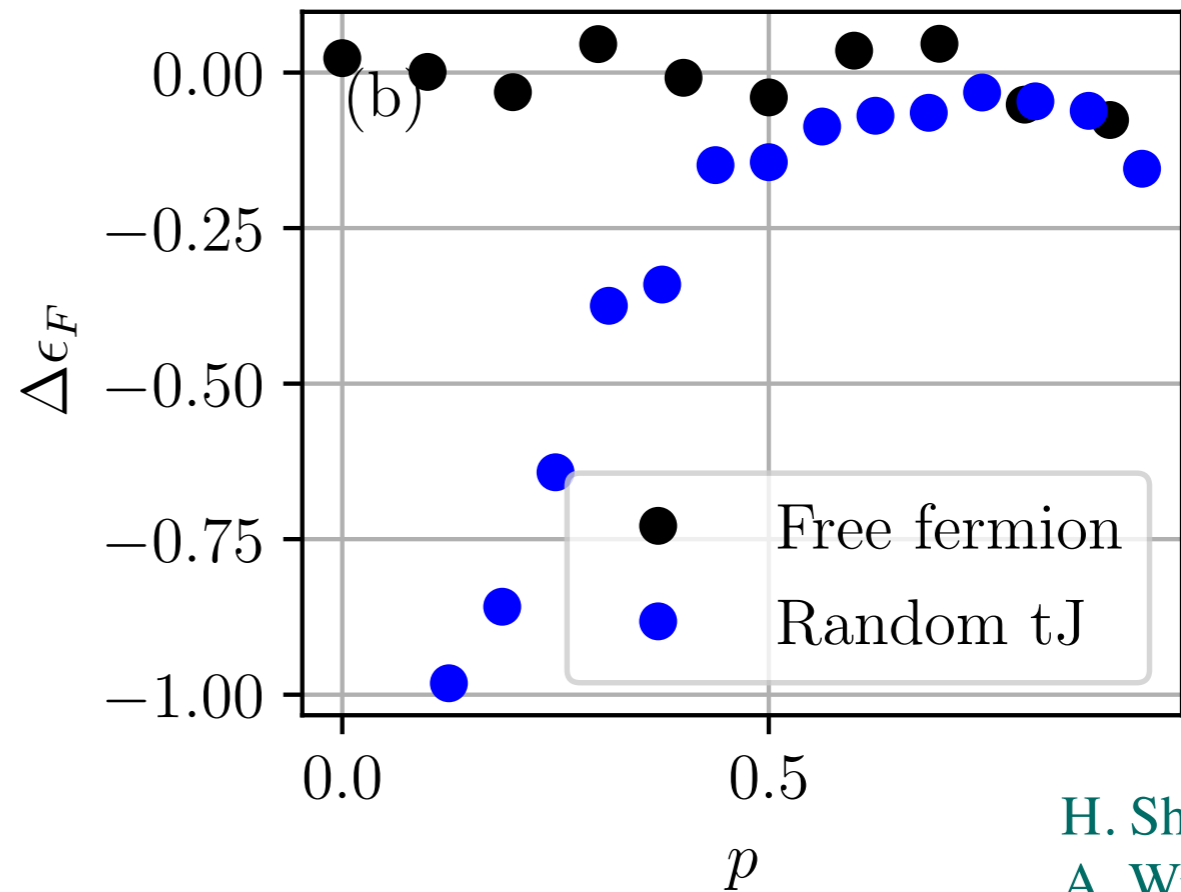
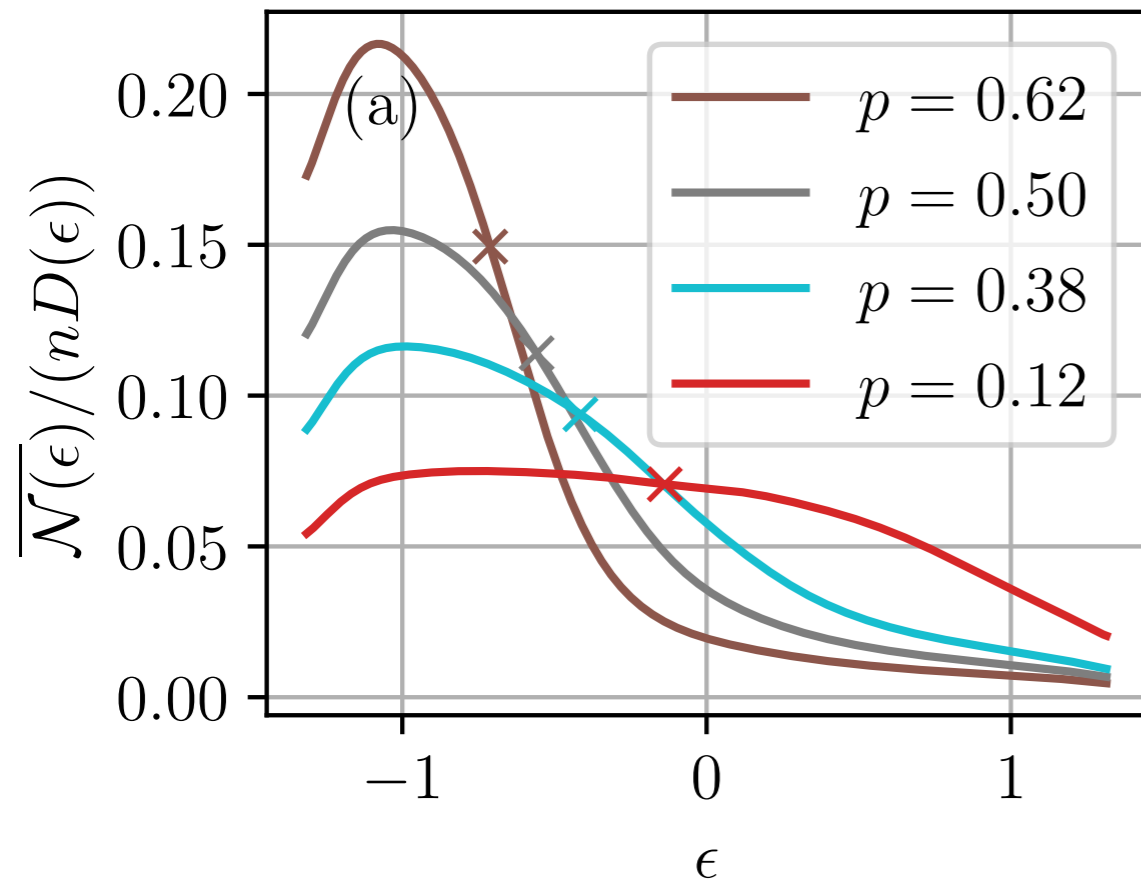
Random t - J model



Random t - J model



One particle energy distribution function

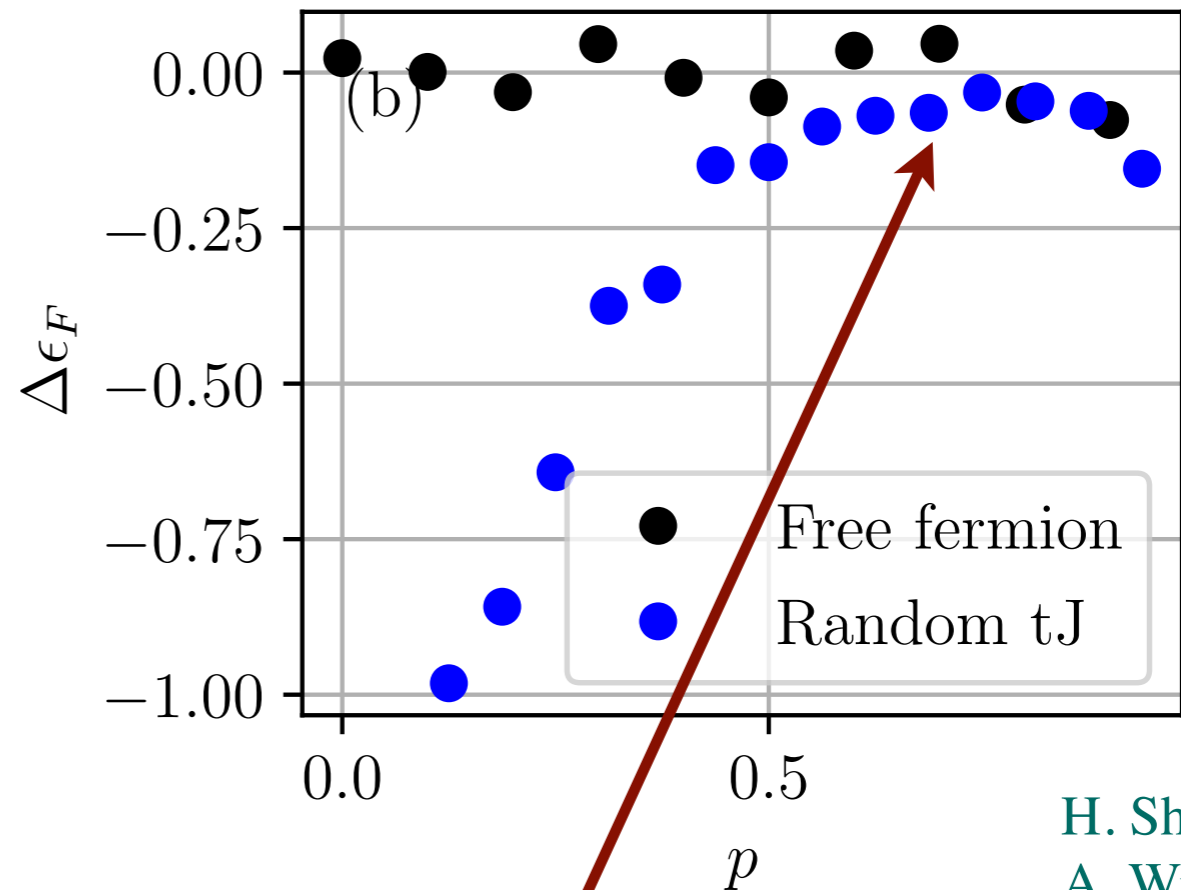
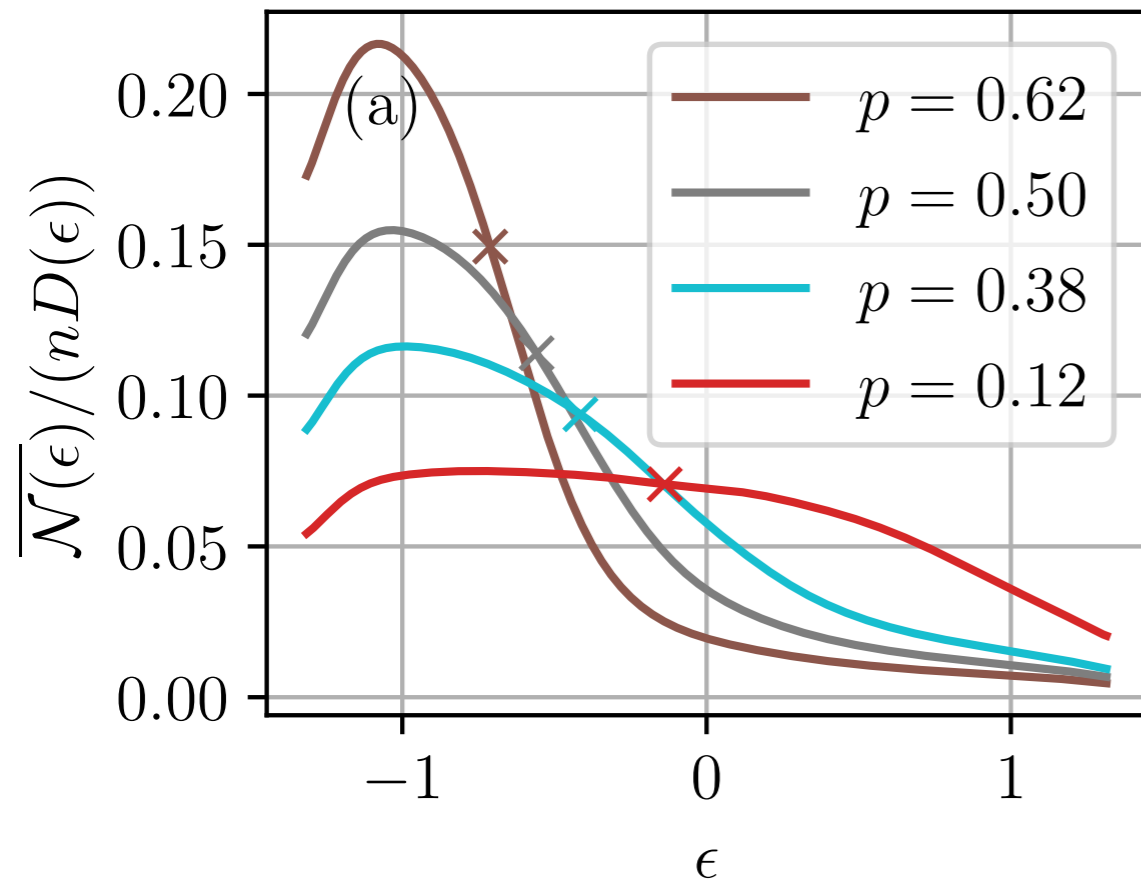


H. Shackleton,
A. Wietek,
A. Georges, and
S. Sachdev, PRL
to appear,
arXiv:2102.06589

$$\mathcal{N}(\epsilon) = \frac{1}{N} \sum_{\lambda} \delta(\epsilon - \epsilon_{\lambda}) \sum_{ij\sigma} \langle \lambda | i \rangle \langle c_{i\sigma}^{\dagger} c_{j\sigma} \rangle \langle j | \lambda \rangle$$

where $|\lambda\rangle$ are one-particle eigenstates of the t_{ij} . In a Fermi liquid, the Luttinger identity implies that $\mathcal{N}(\epsilon)$ has a discontinuity at the free particle Fermi energy ϵ_F . ($D(\epsilon)$ is the Wigner semi-circle density of states.)

One particle energy distribution function



Large Fermi surface

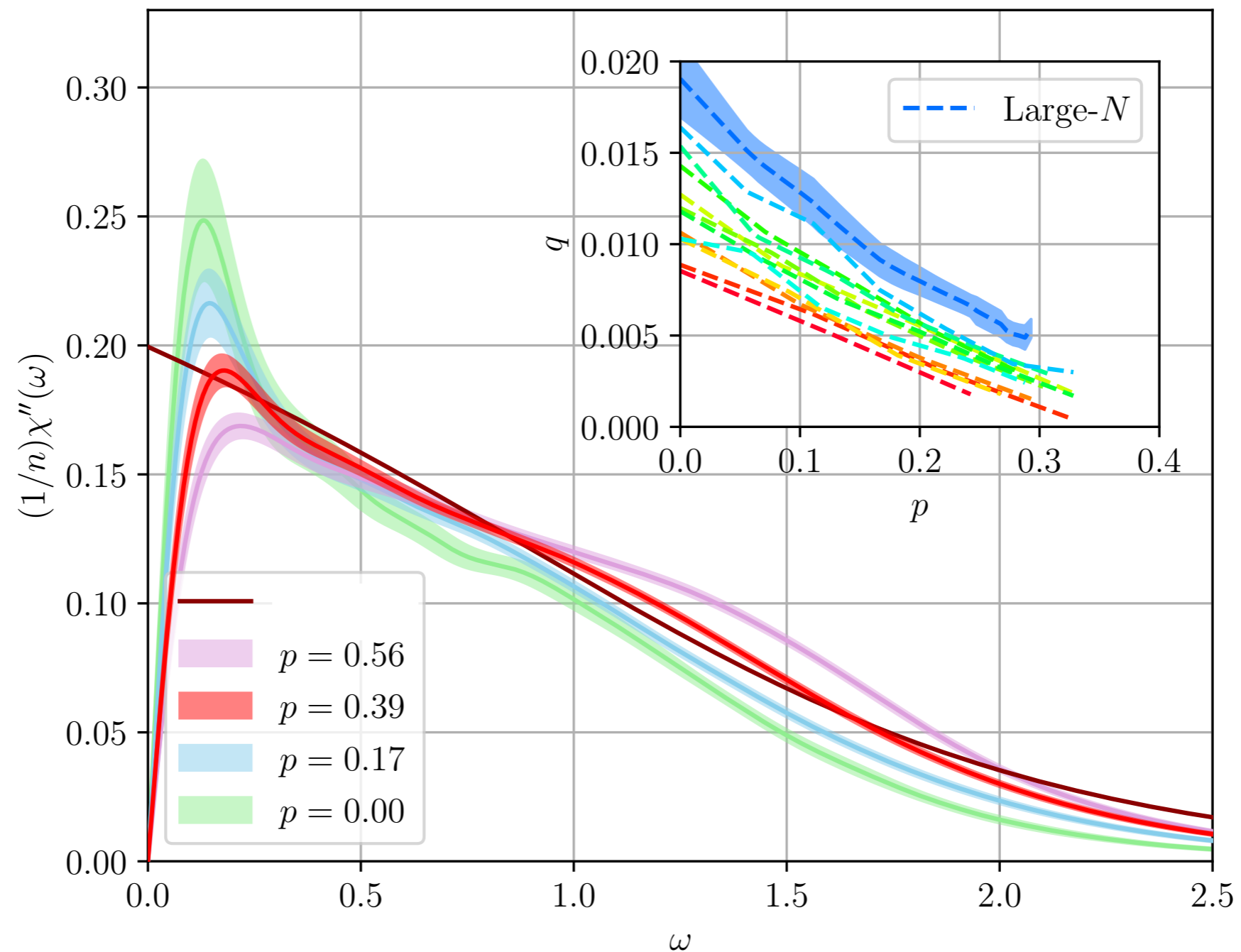
H. Shackleton,
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Dynamic spin susceptibility

Probability to flip an electron spin while absorbing energy $\hbar\omega$

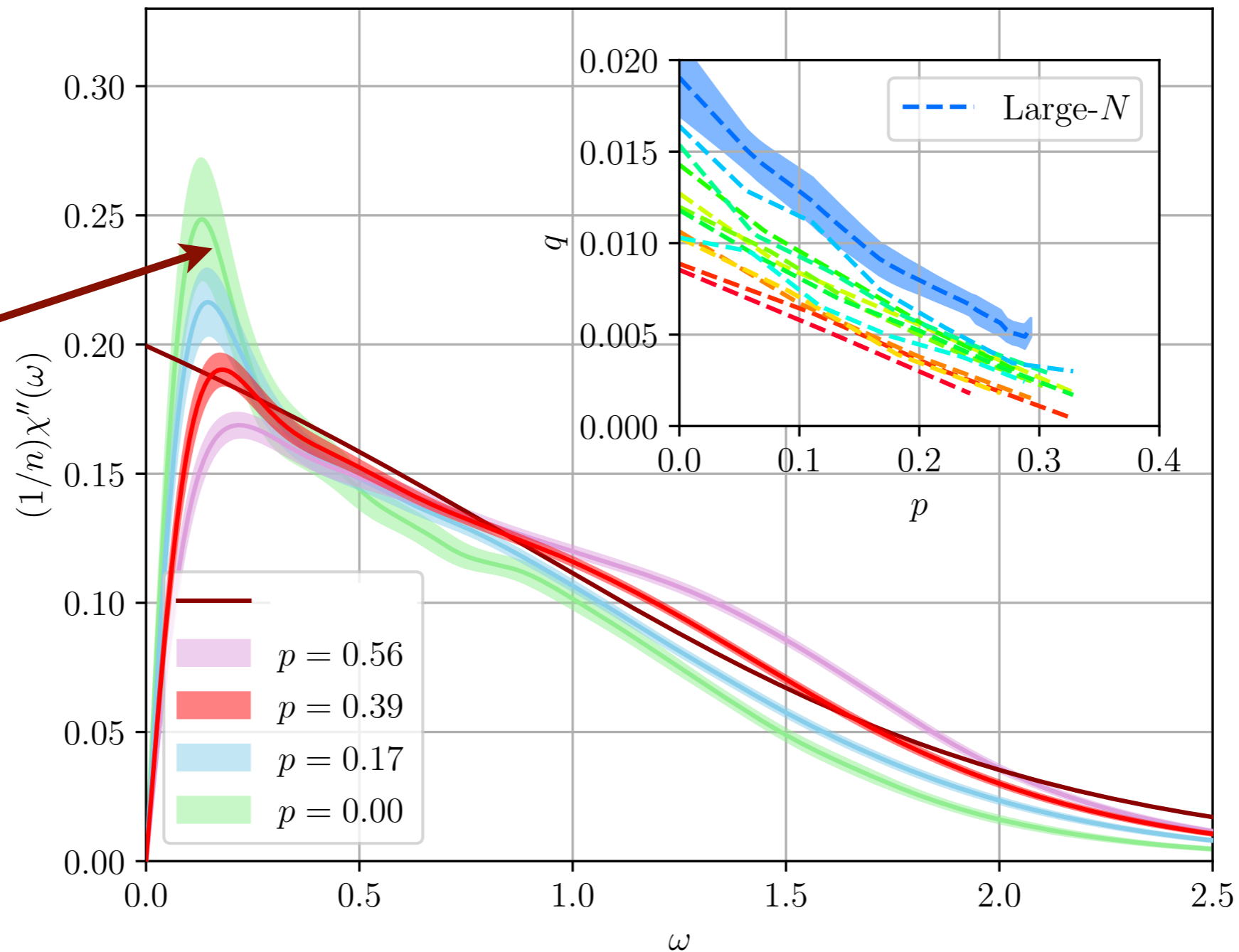


H. Shackleton,
A. Wietek,
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S. Sachdev, PRL
to appear,
arXiv:2102.06589

Dynamic spin susceptibility

Probability to flip an electron spin while absorbing energy $\hbar\omega$

Spin glass order

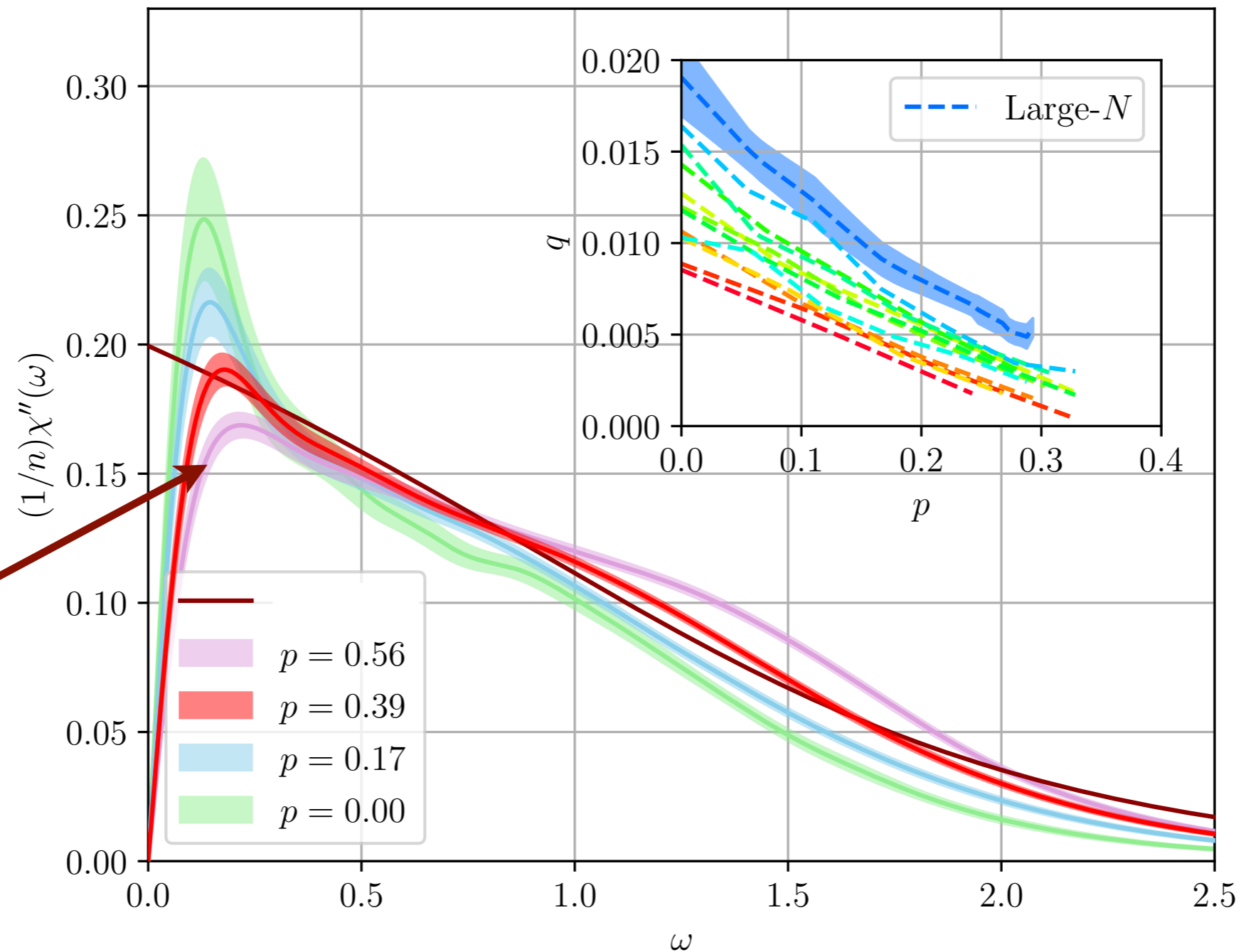


H. Shackleton,
A. Wietek,
A. Georges, and
S. Sachdev, PRL
to appear,
arXiv:2102.06589

Spin glass order q non-zero for $p < p_c \approx 0.4$

Dynamic spin susceptibility

Probability to flip an electron spin while absorbing energy $\hbar\omega$



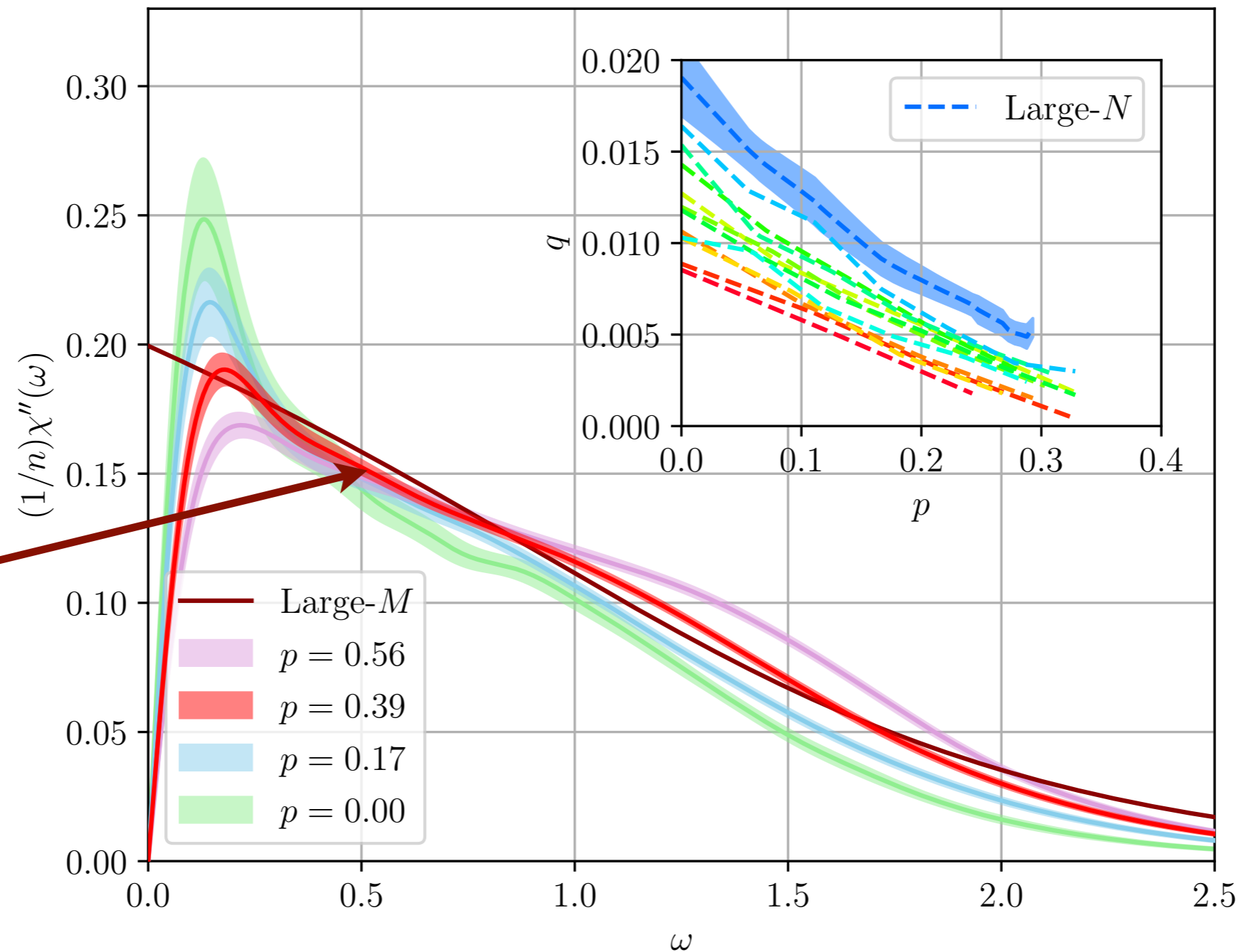
Ordinary
metal

H. Shackleton,
A. Wietek,
A. Georges, and
S. Sachdev, PRL
to appear,
arXiv:2102.06589

Spin susceptibility and other properties
match those of an ordinary metal $p > p_c$

Dynamic spin susceptibility

Probability to flip an electron spin while absorbing energy $\hbar\omega$



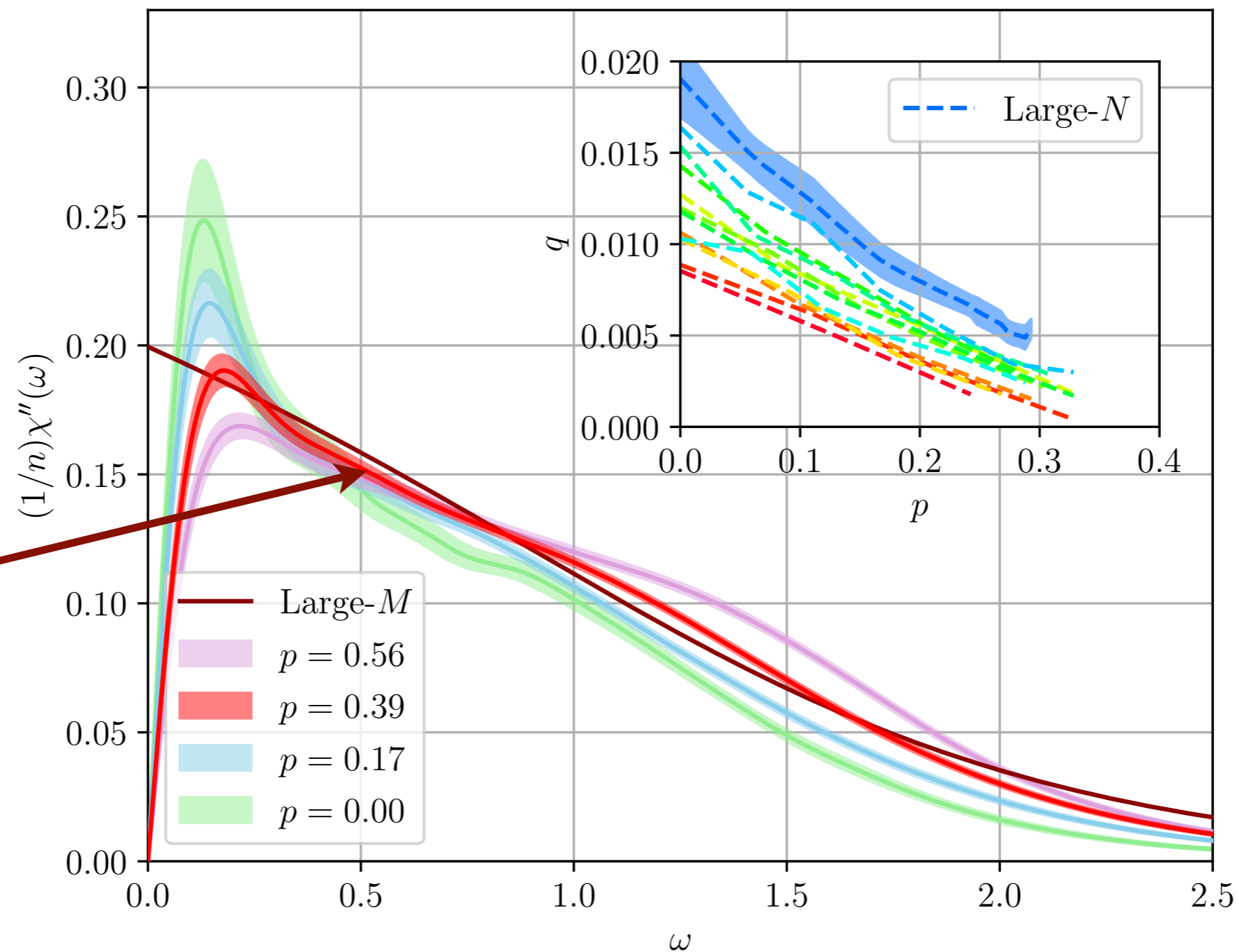
Critical
point

H. Shackleton,
A. Wietek,
A. Georges, and
S. Sachdev, PRL
to appear,
arXiv:2102.06589

Critical spin susceptibility matches the SYK model!
Planckian dissipation in time $\sim \hbar/(k_B T)$,
and frequency dependence $\sim \text{sgn}(\omega) [1 - \mathcal{C}\gamma|\omega| + \dots]$
matches contribution of boundary graviton.

Dynamic spin susceptibility

Probability to flip an electron spin while absorbing energy $\hbar\omega$

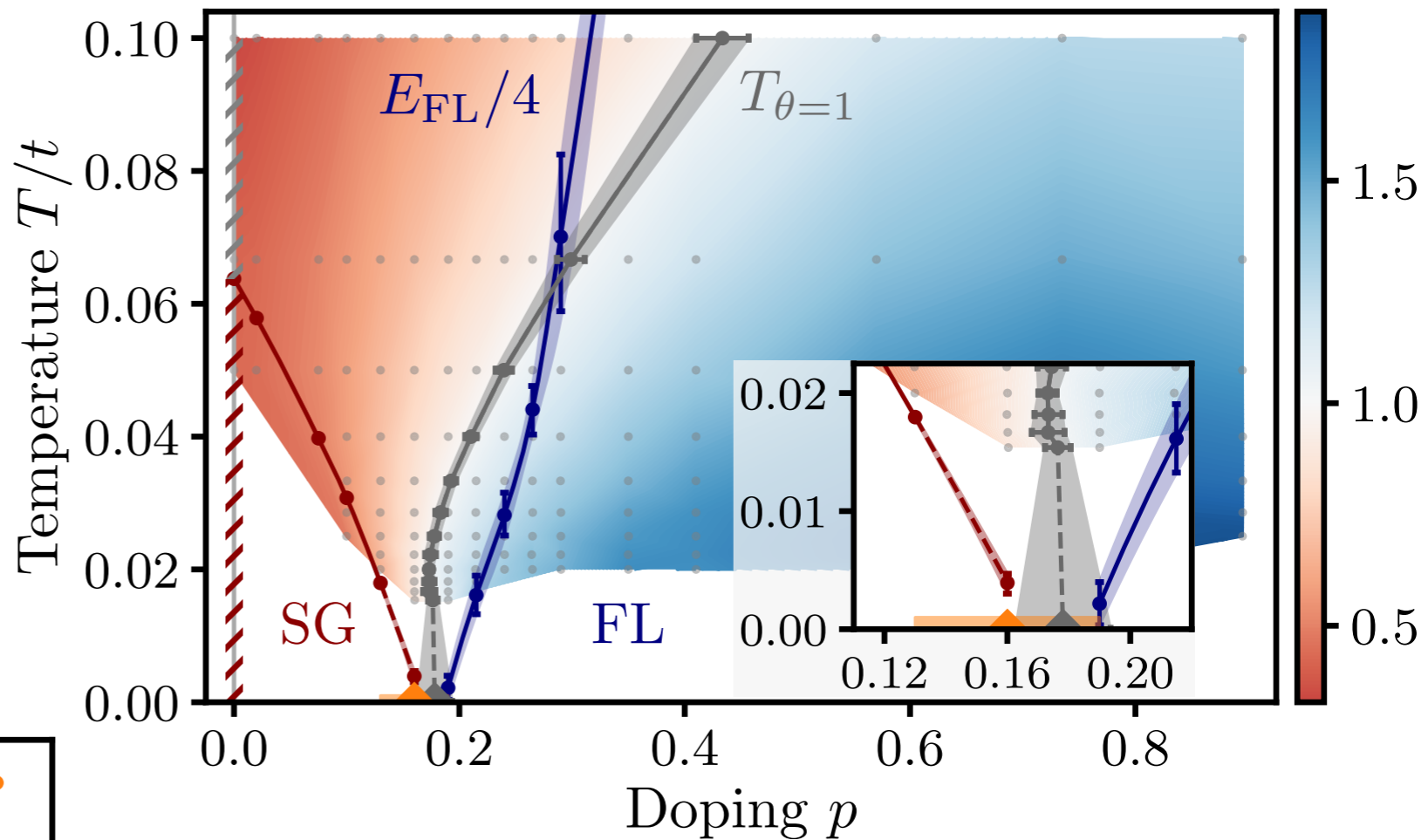
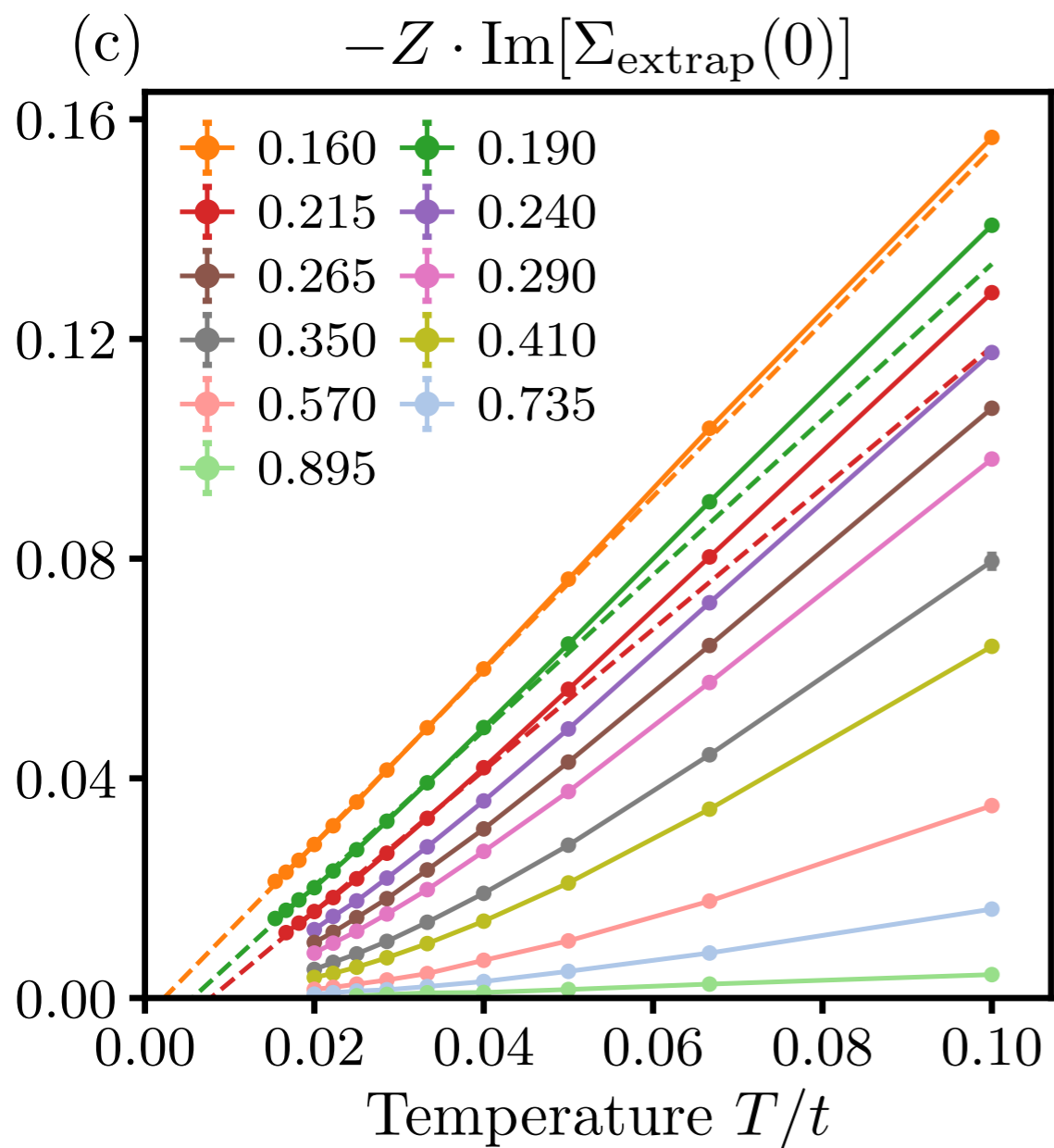


Critical
point

D. G. Joshi,
Chenyuan Li,
G. Tarnopolsky,
A. Georges, and
S. Sachdev,
PRX **10**, 021033
(2020)

SYK criticality can be understood by the fractionalization of the electron into 'partons' carrying its spin and charge.
These partons obey an SYK-like model

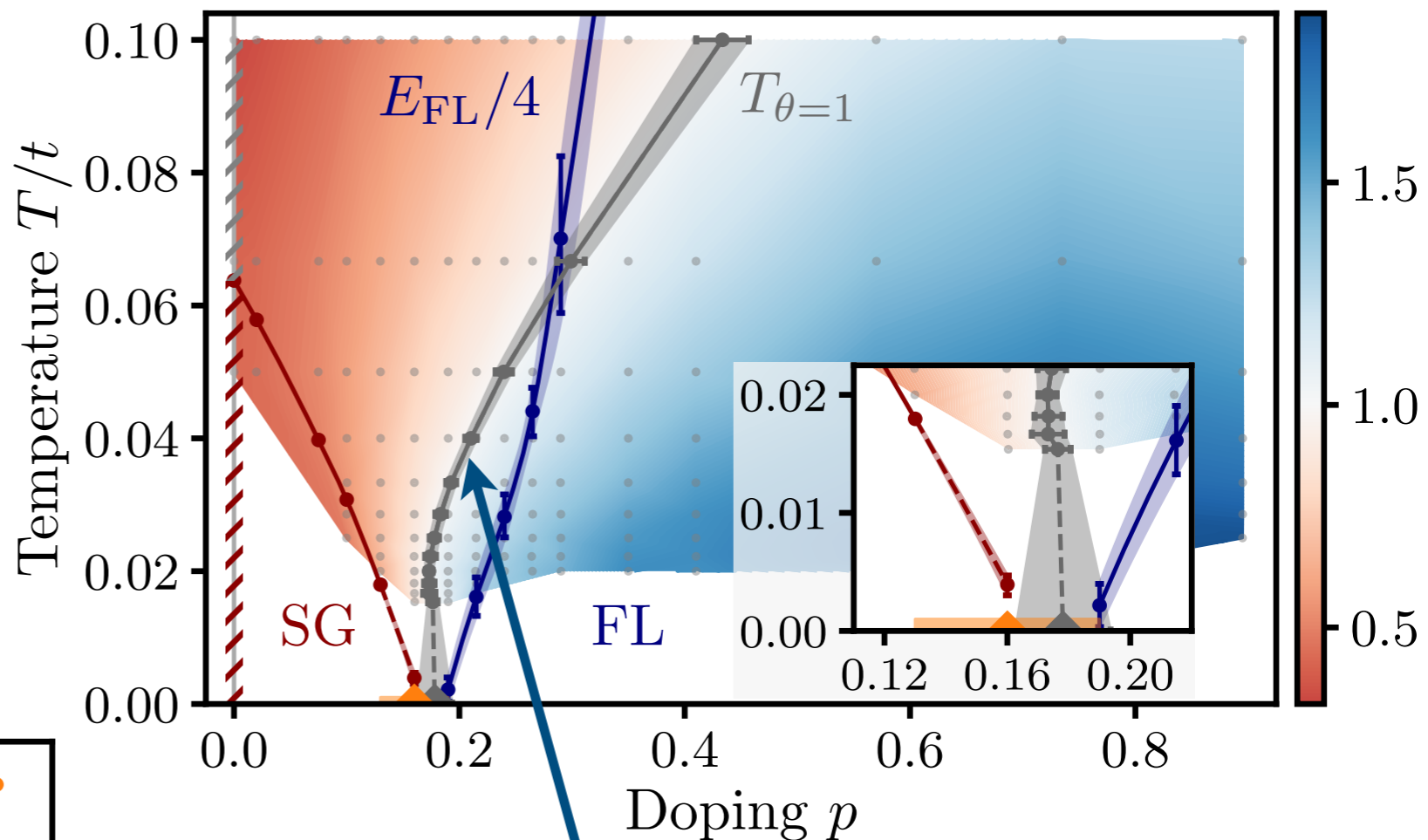
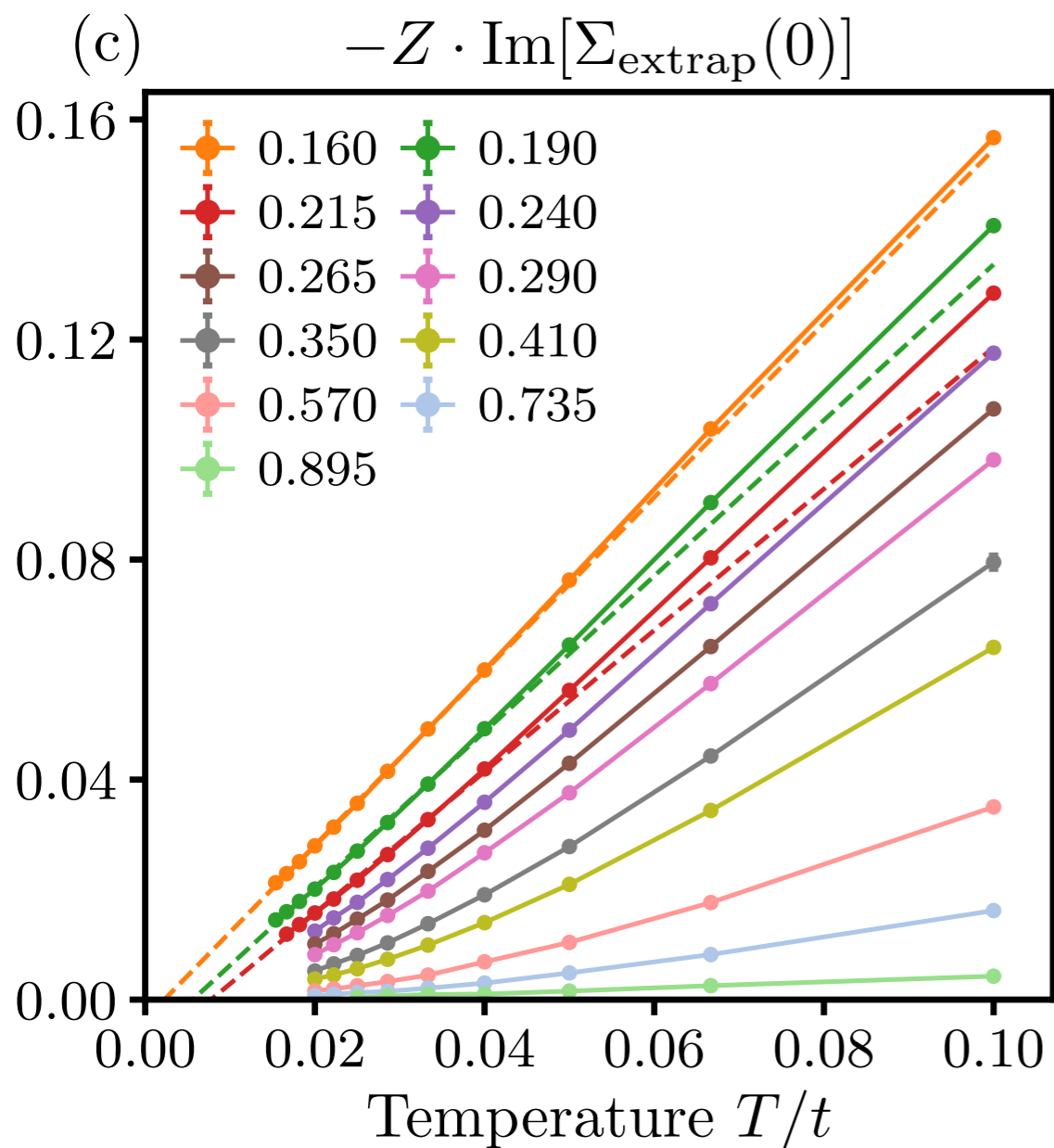
Quantum Monte Carlo of $N = \infty$ model



P. Dumitrescu, N. Wentzell, O. Parcollet, A. Georges,
arXiv:2103.08607; R44.00002, 8:12 AM, Thu Mar 18

Antoine Georges: V21.0000, 3 PM, Thu Mar 18

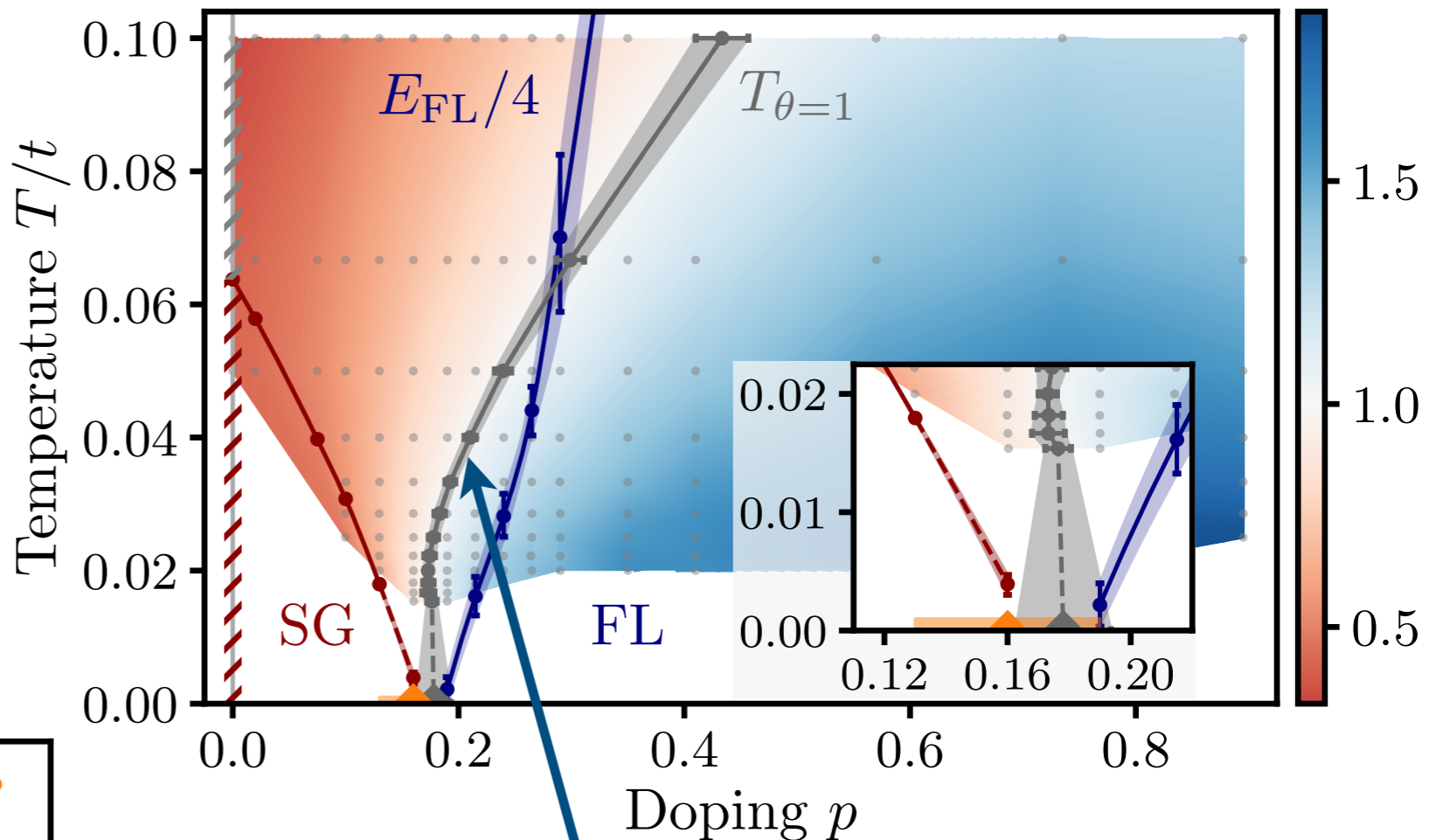
Quantum Monte Carlo of $N = \infty$ model



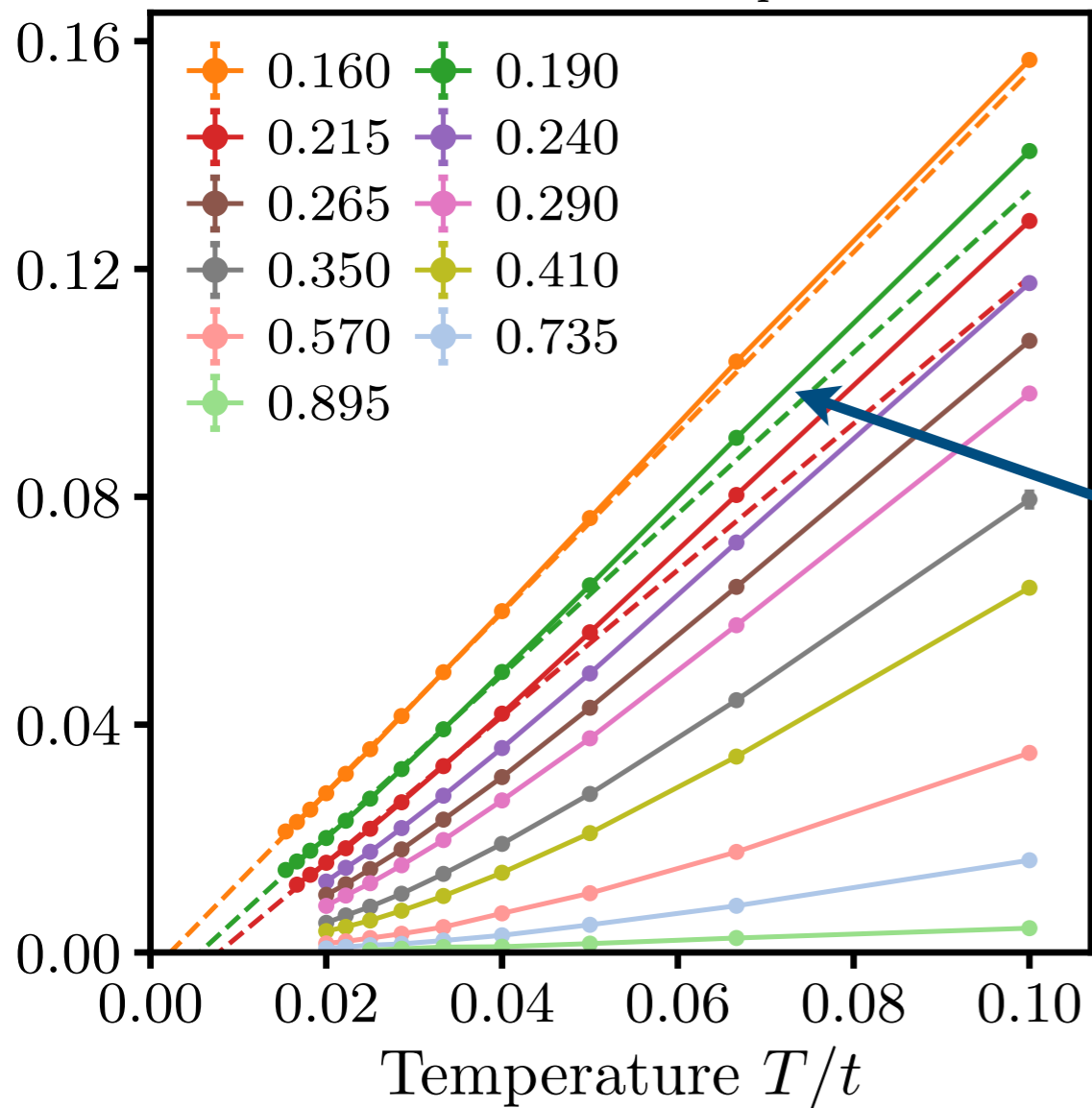
P. Dumitrescu, N. Wentzell, O. Parcollet, A. Georges,
arXiv:2103.08607; R44.00002, 8:12 AM, Thu Mar 18

Antoine Georges: V21.0000, 3 PM, Thu Mar 18

Quantum Monte Carlo of $N = \infty$ model



(c) $-Z \cdot \text{Im}[\Sigma_{\text{extrap}}(0)]$



SYK spin
correlations

$$\frac{1}{\tau^*} = (1.4 \pm 0.1) \frac{k_B T}{\hbar}$$

P. Dumitrescu, N. Wentzell, O. Parcollet, A. Georges,
arXiv:2103.08607; R44.00002, 8:12 AM, Thu Mar 18

Antoine Georges: V21.0000, 3 PM, Thu Mar 18

Random Yukawa model

Fermi surface of ψ fermions coupled to a critical boson ϕ
(representing an order parameter or a gauge field)

$$\begin{aligned} \mathcal{S} = & \int d\tau \int_{\mathbf{k}} \sum_i \left[\psi_i^\dagger(\mathbf{k}, \tau) (\partial_\tau - \varepsilon_{\mathbf{k}} - \mu) \psi_i(\mathbf{k}, \tau) \right] \\ & + \int d\tau \int_{\mathbf{x}} \sum_\ell \phi_\ell (-\partial_\tau^2 - \nabla_{\mathbf{r}}^2 + m^2) \phi_\ell \\ & - \int d\tau \int_{\mathbf{x}} \sum_{i,j,\ell=1}^N \frac{g_{ij\ell}(\mathbf{x})}{N} \psi_i^\dagger(\mathbf{x}, \tau) \psi_j(\mathbf{x}, \tau) \phi_\ell(\mathbf{x}, \tau) \\ & \overline{g_{ij\ell}(\mathbf{x}) g_{i'j'\ell'}^*(\mathbf{x}') = g^2 \delta_{ii'} \delta_{jj'} \delta_{\ell\ell'} \delta^2(\mathbf{x} - \mathbf{x}')} \end{aligned}$$

Yields Planckian transport in $d = 2$

$$\text{with } \frac{1}{\tau^*} = \frac{\pi k_B T}{2 \hbar} \times \frac{\ln \ln T}{\ln T}$$

E. E. Aldape, T. Cookmeyer,
A.A. Patel, and E. Altman,
arXiv:2012.00763;
I. Esterlis, Haoyu Guo,
A.A. Patel, and S. Sachdev,
arXiv:2103.08615;
Aavishkar Patel: B50.00002,
12:06 PM, Mon Mar 15

**Quantum
entanglement**

**Charged
black holes**

**A simple
many-particle
(SYK) model**

**Copper-based
superconductors**

Quantum entanglement

Charged black holes

2D
quantum
gravity

A simple many-particle (SYK) model

Copper-based superconductors

Quantum
entanglement

Charged
black holes

A simple
many-particle
(SYK) model

SYK criticality
of random t - J and
random Yukawa models

Copper-based
superconductors

Complex multi-particle entanglement
leads to quantum systems
without quasiparticle excitations.

Many-body chaos and
thermal equilibration
in the shortest possible
Planckian time $\sim \frac{\hbar}{k_B T}$.