Spin-valley modes of the electron liquid in graphene

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ETH-ITS

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Under Review w/ PRL
arXiv:2107.02819

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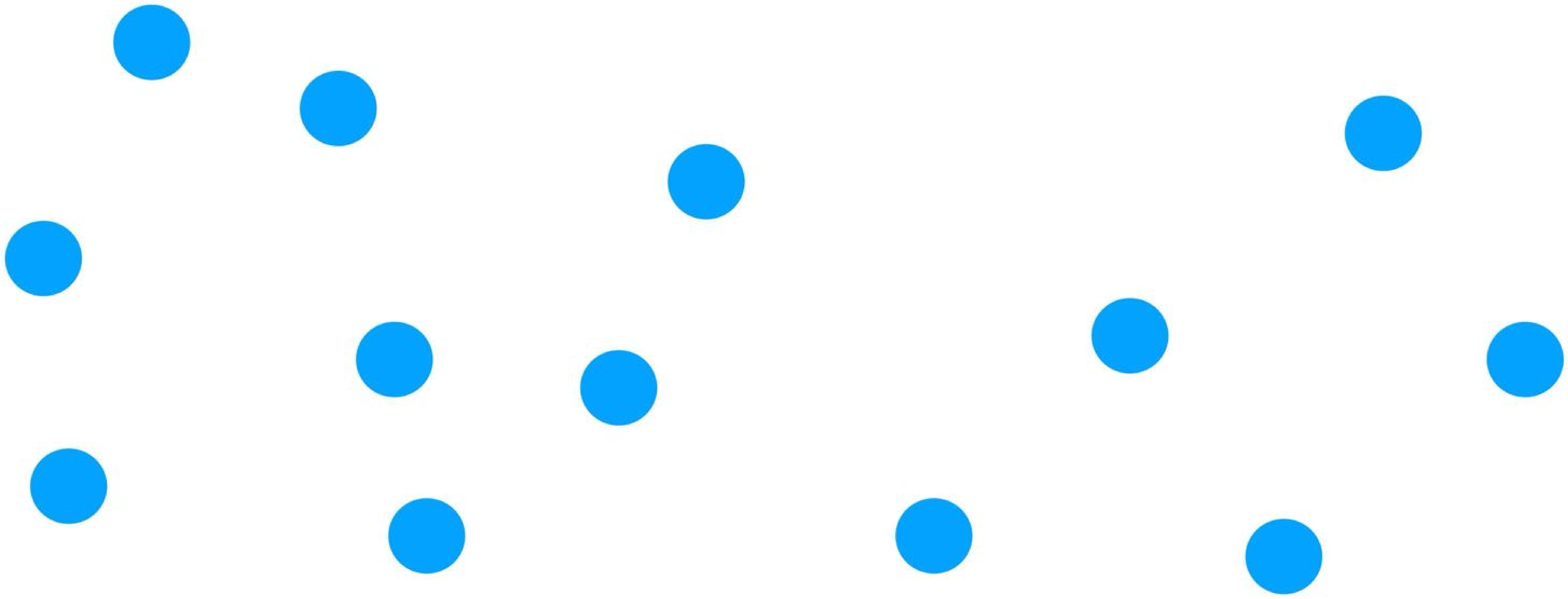
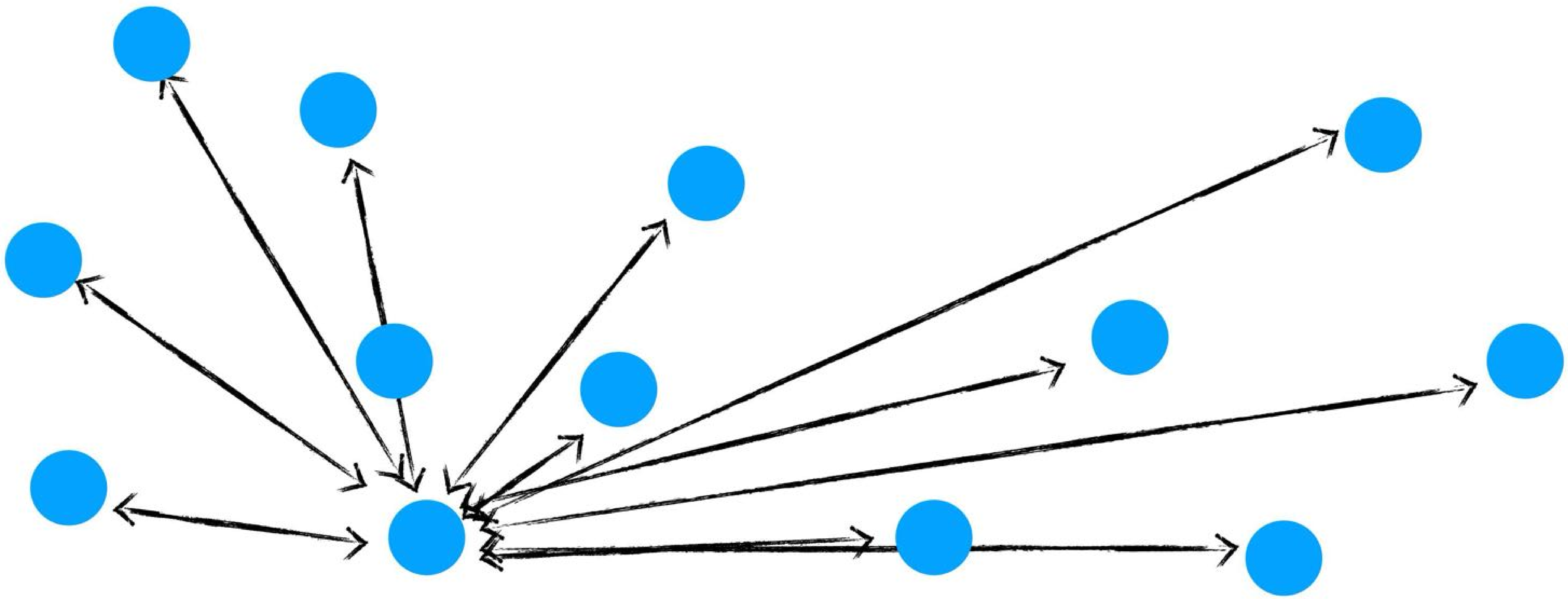


$$\cdots \times 10^{23}$$



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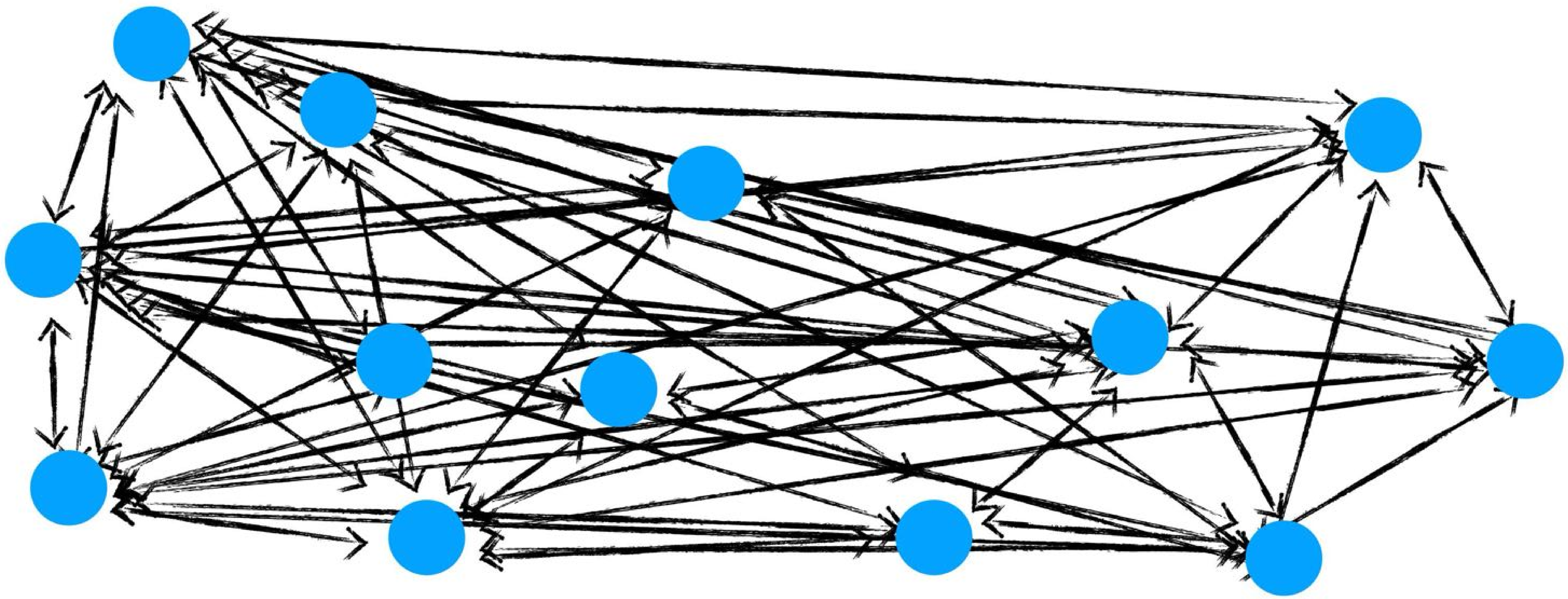
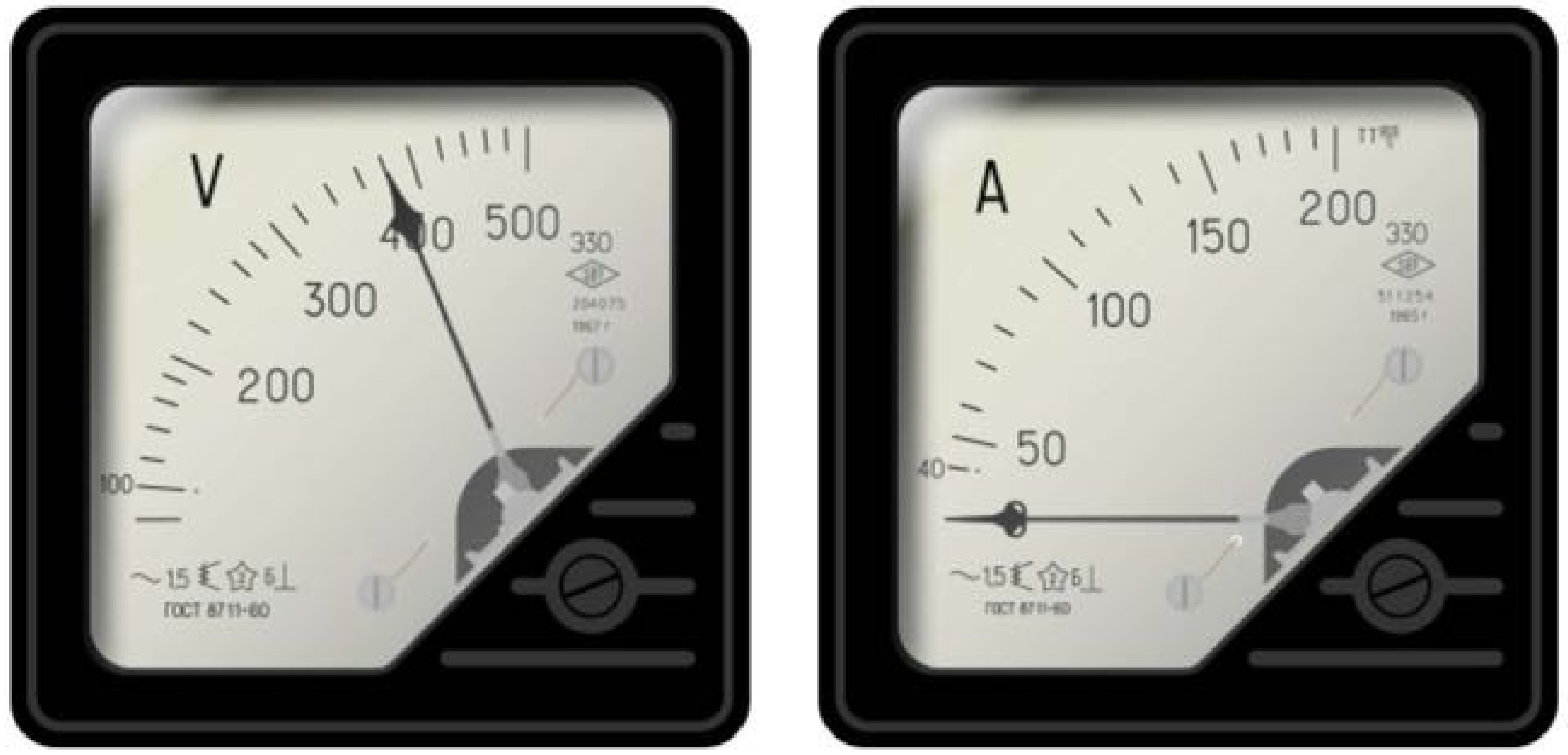


$\cdots \times 10^{23}$

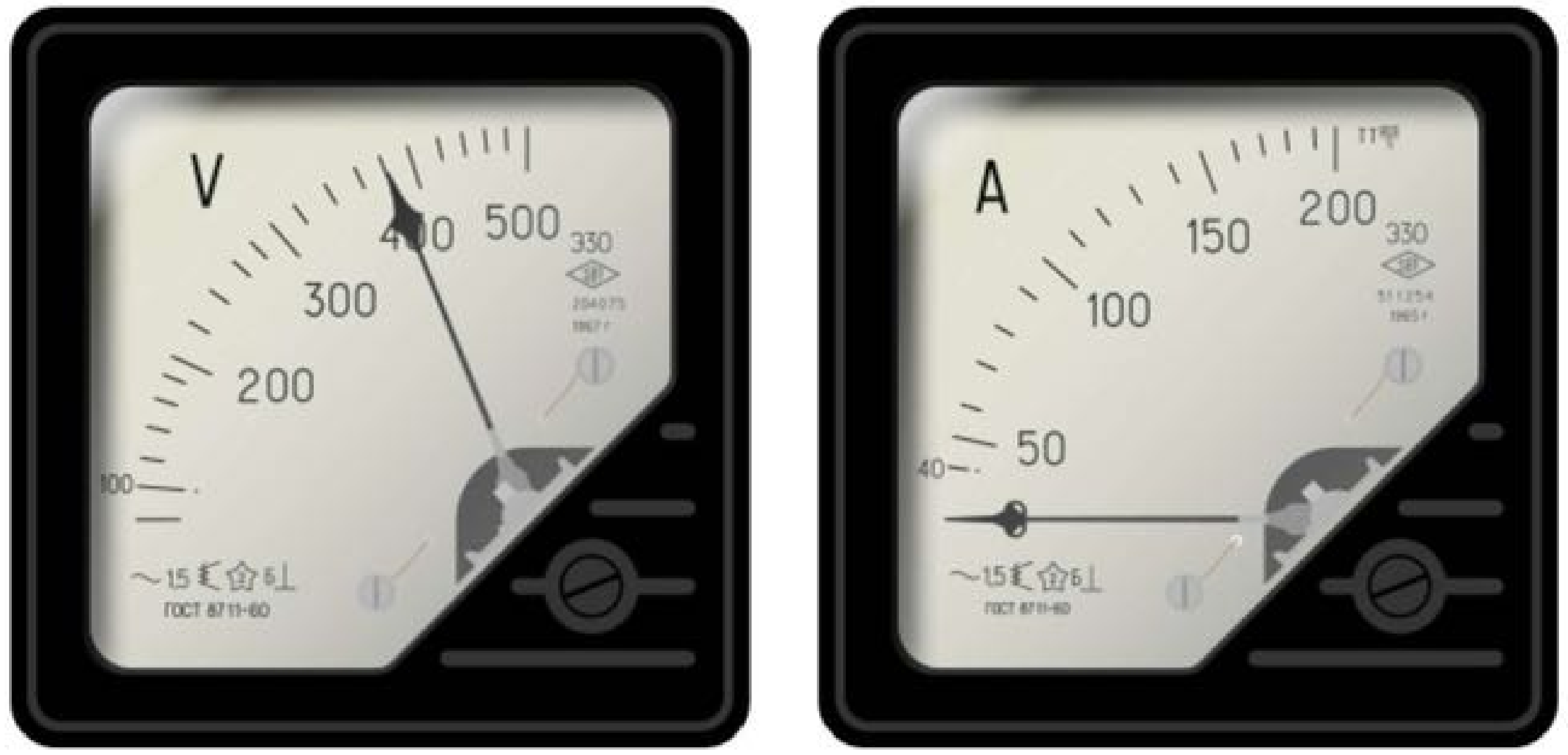
What is it that we're interested in?

- Generally we want to calculate some set observable properties accessible on macroscopic length and time scales
    - Electrical and thermal conductivities
    - Compressibility
    - Sound velocities



What is it that we’re interested in?

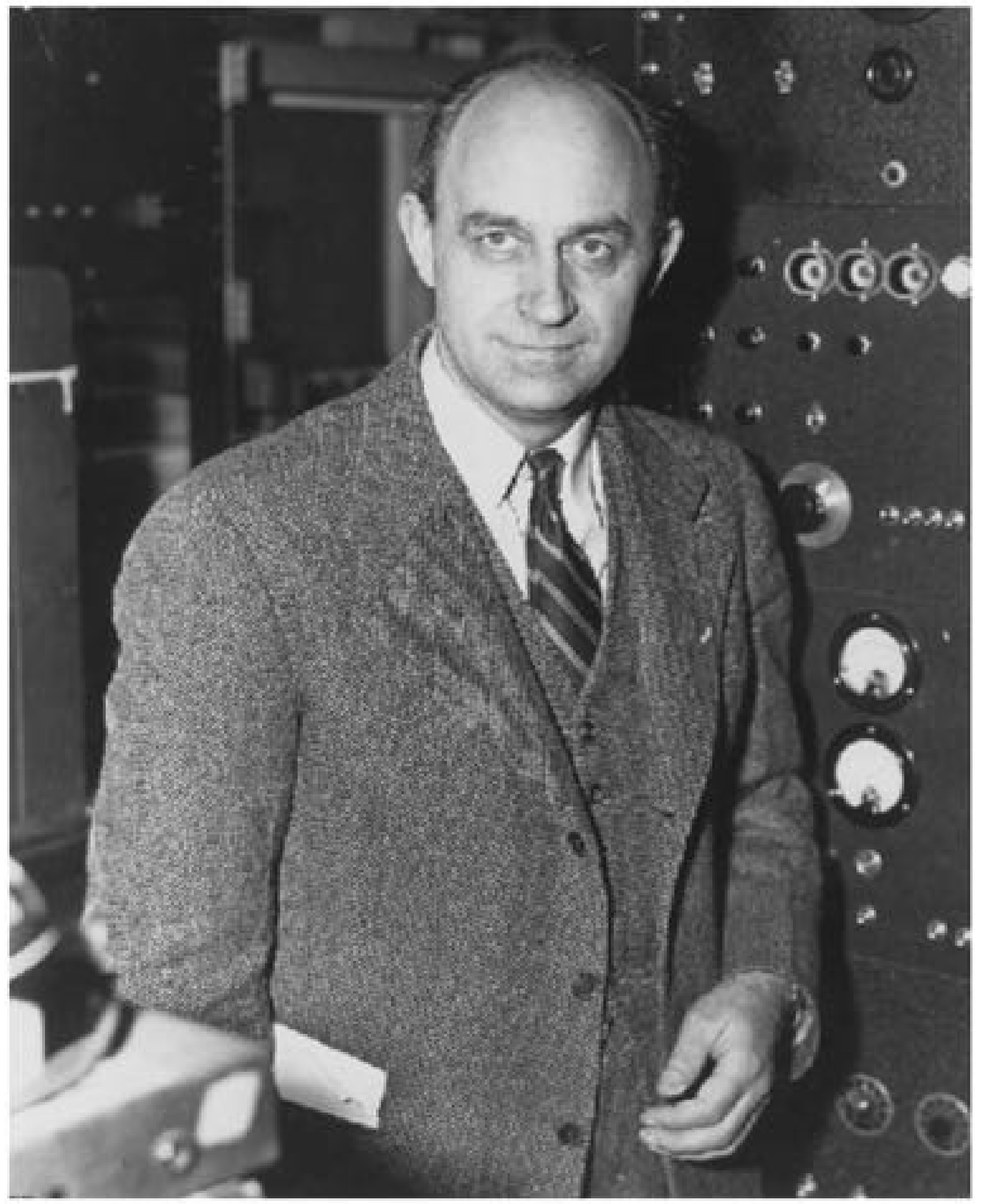
- The systems is described by a probability distribution for the configuration of all particles
- Generally we want to calculate observable properties that depend on the low energy behavior of the system
- Out of an infinite number of moments of the distribution we care about some small subset
- Can we express the state space in terms of intuitive objects which approximately reproduce these moments?

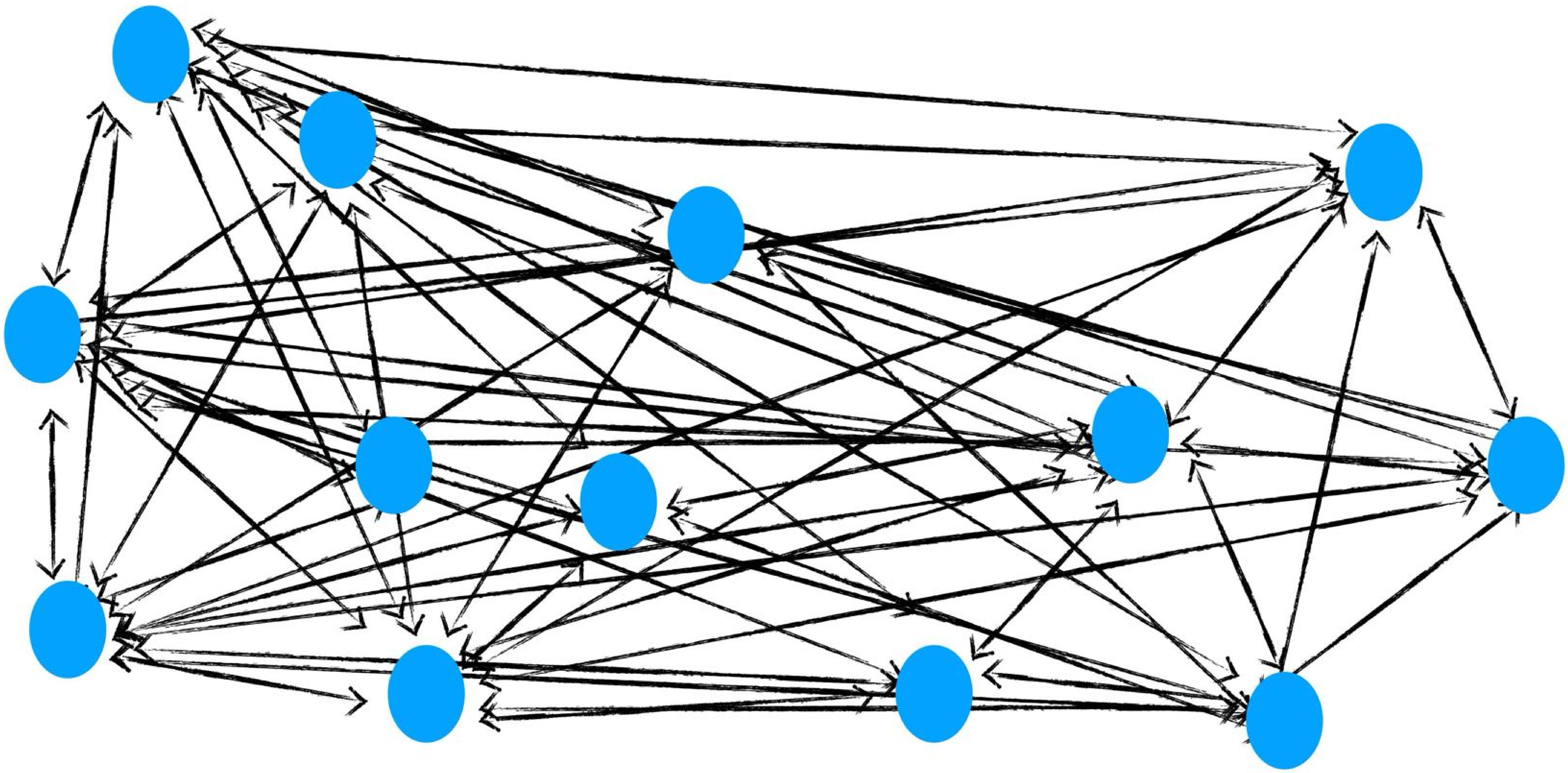


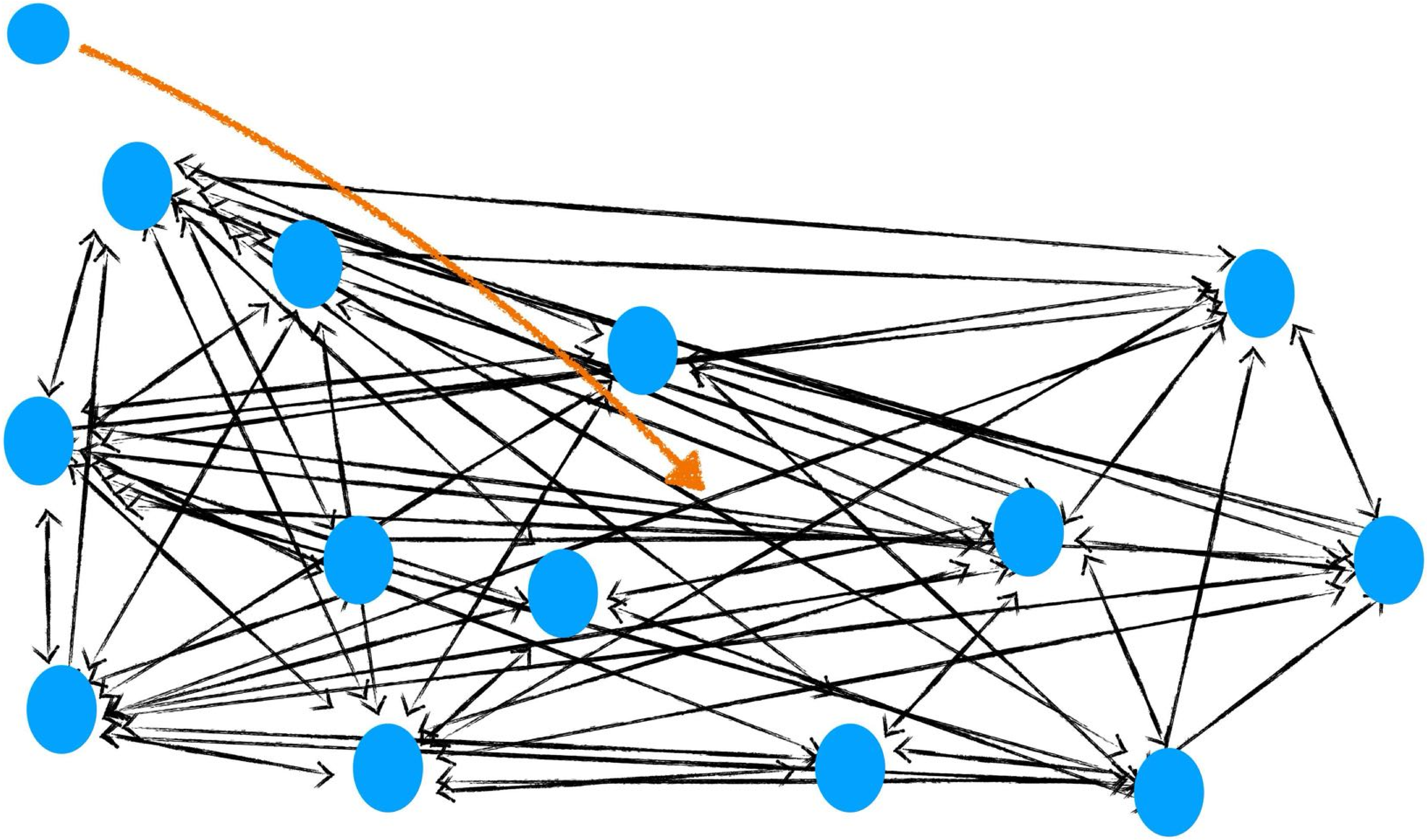
The Fermi Gas

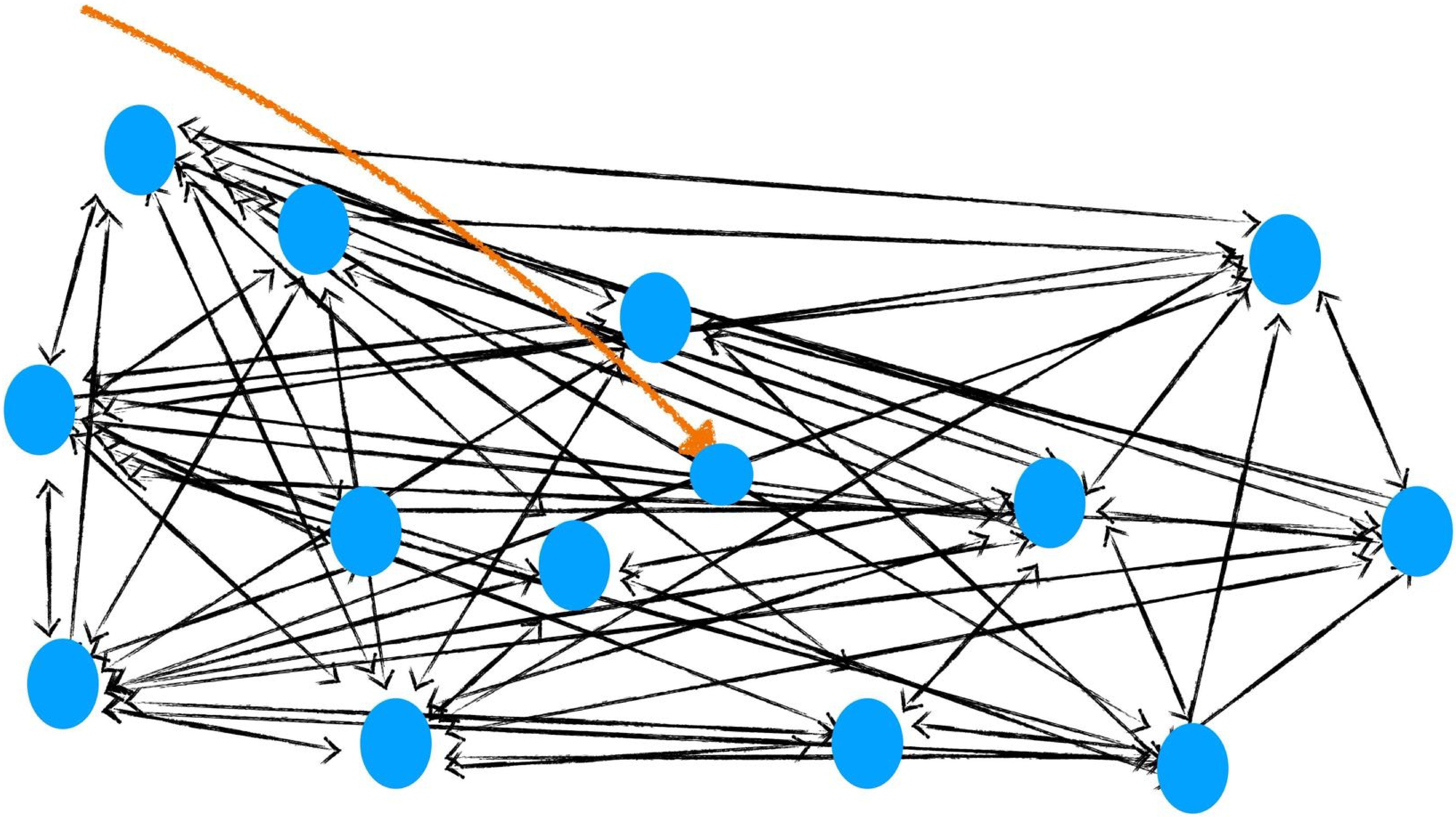
- We know how to treat a collection of noninteracting electrons

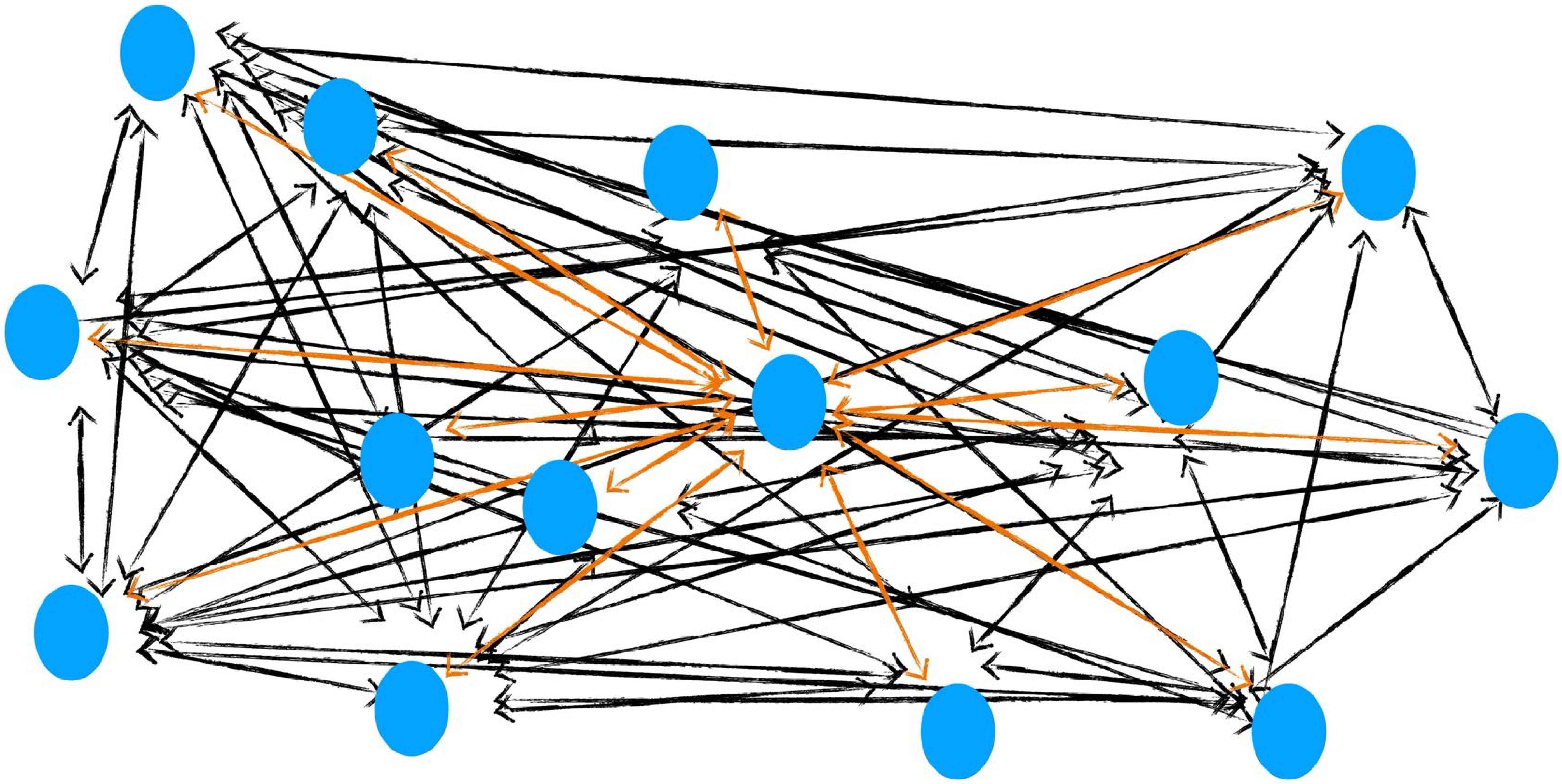
- For such a theory we can obtain thermodynamic and transport properties

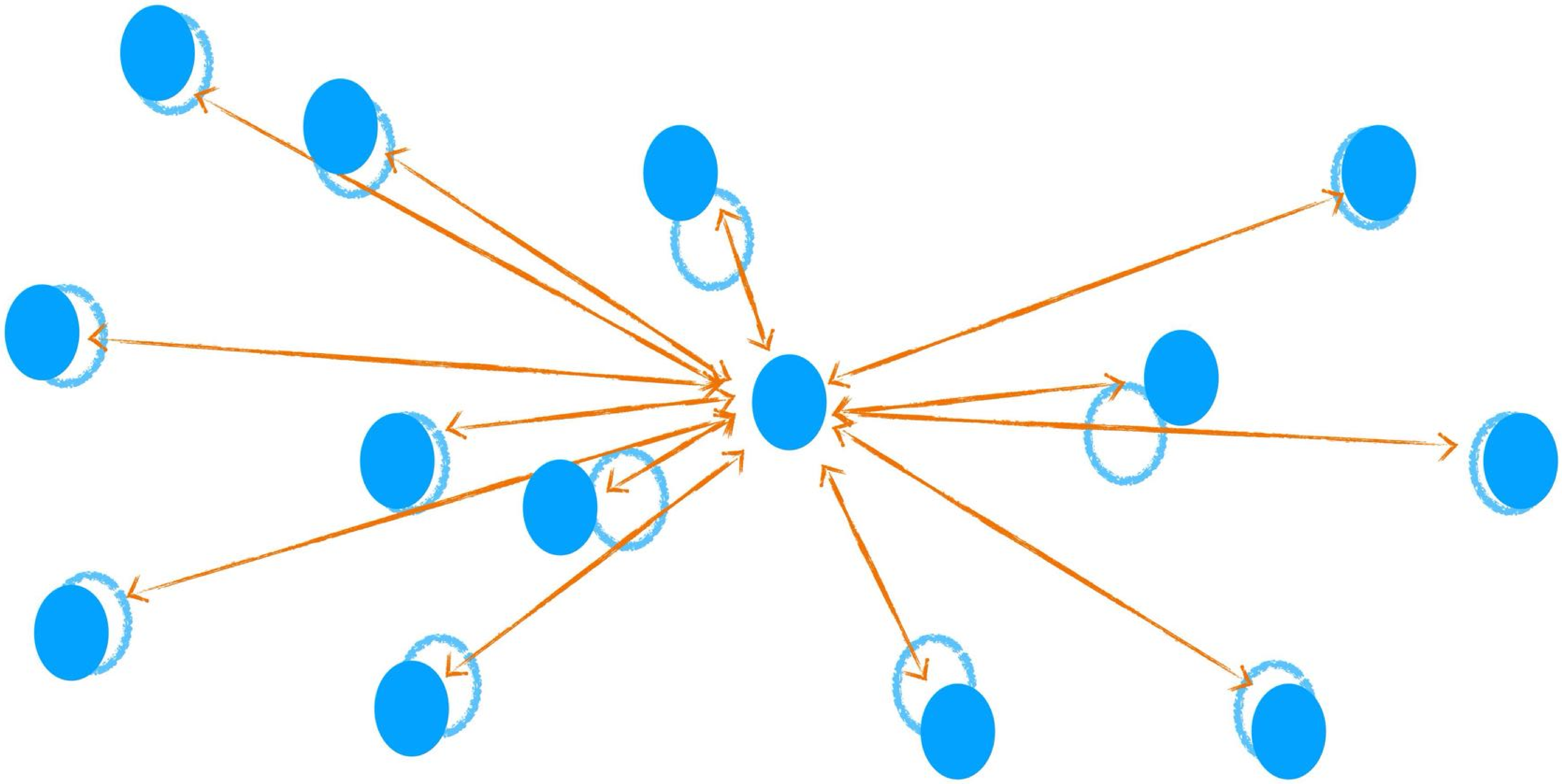


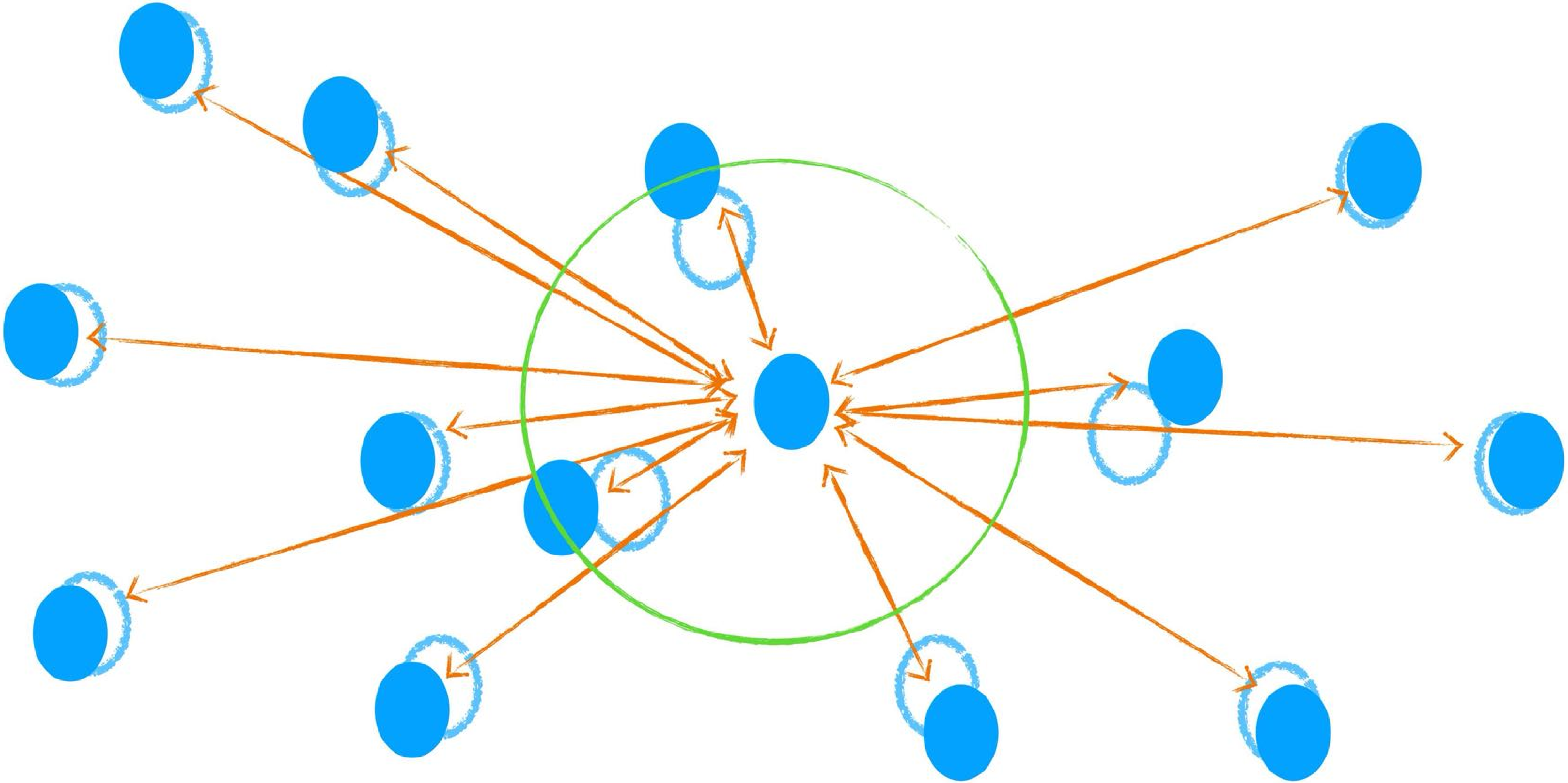


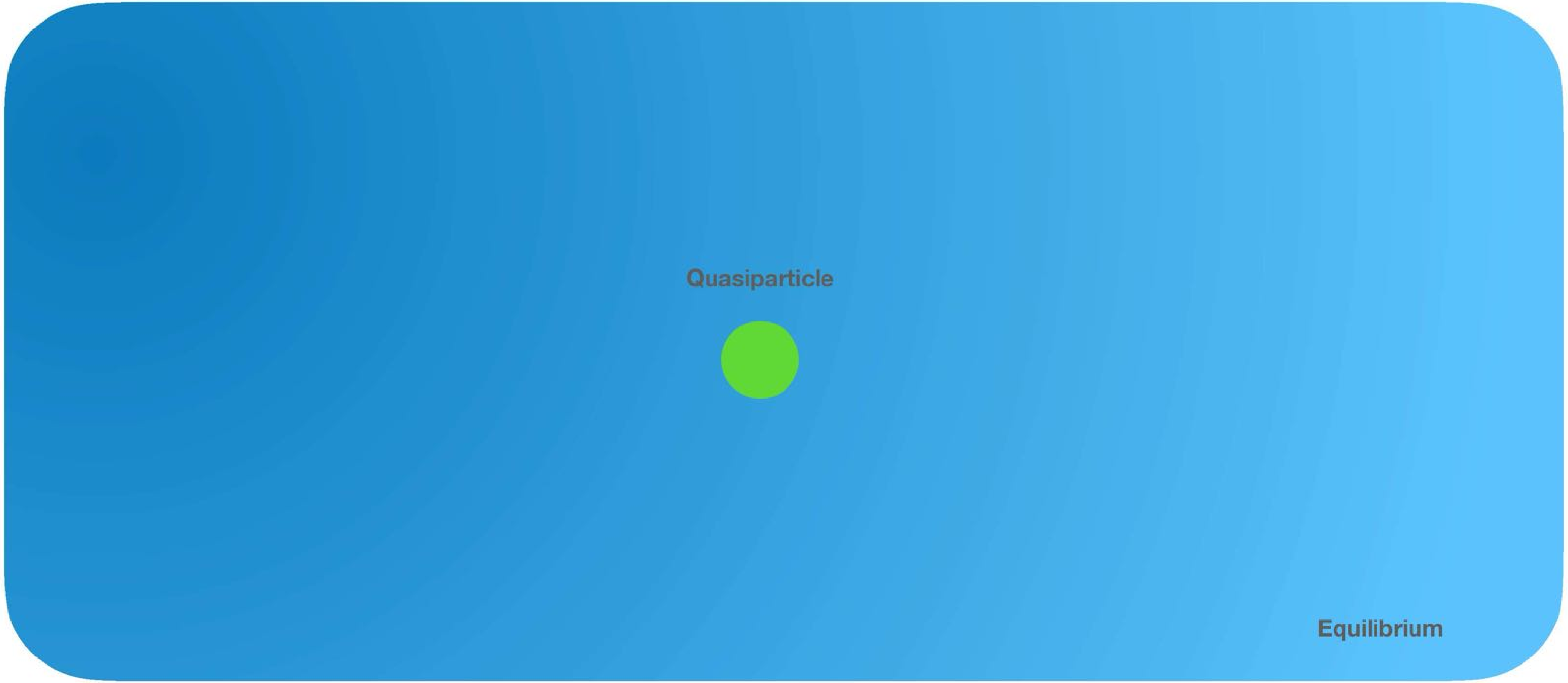






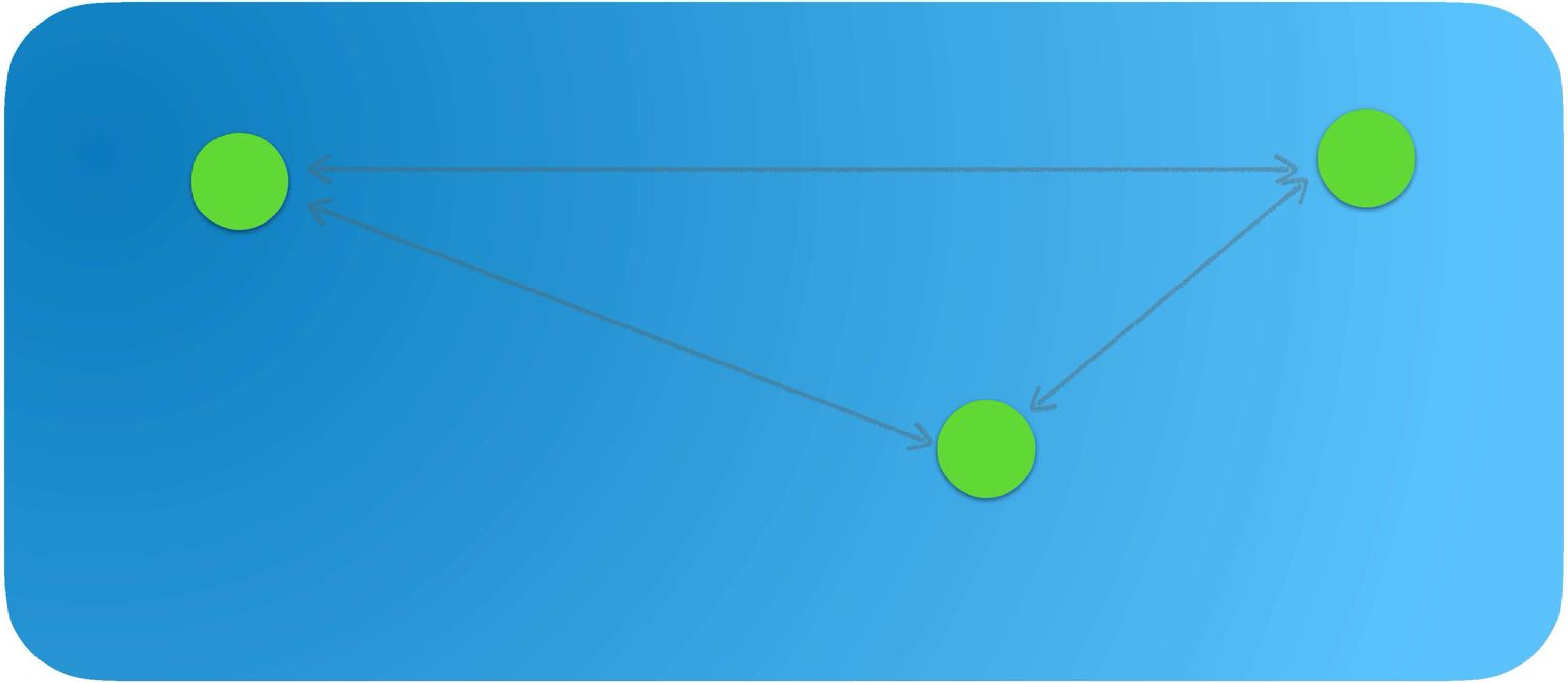






“Quasi-electron” - Electron dressed by the nearby polarization of the electronic sea

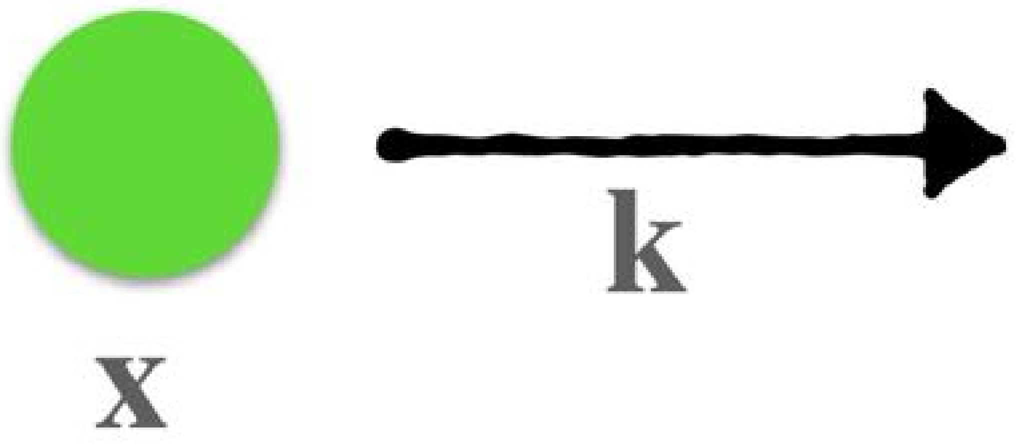
Let's try to express our system in terms of some diffuse collection of "quasi-particles"

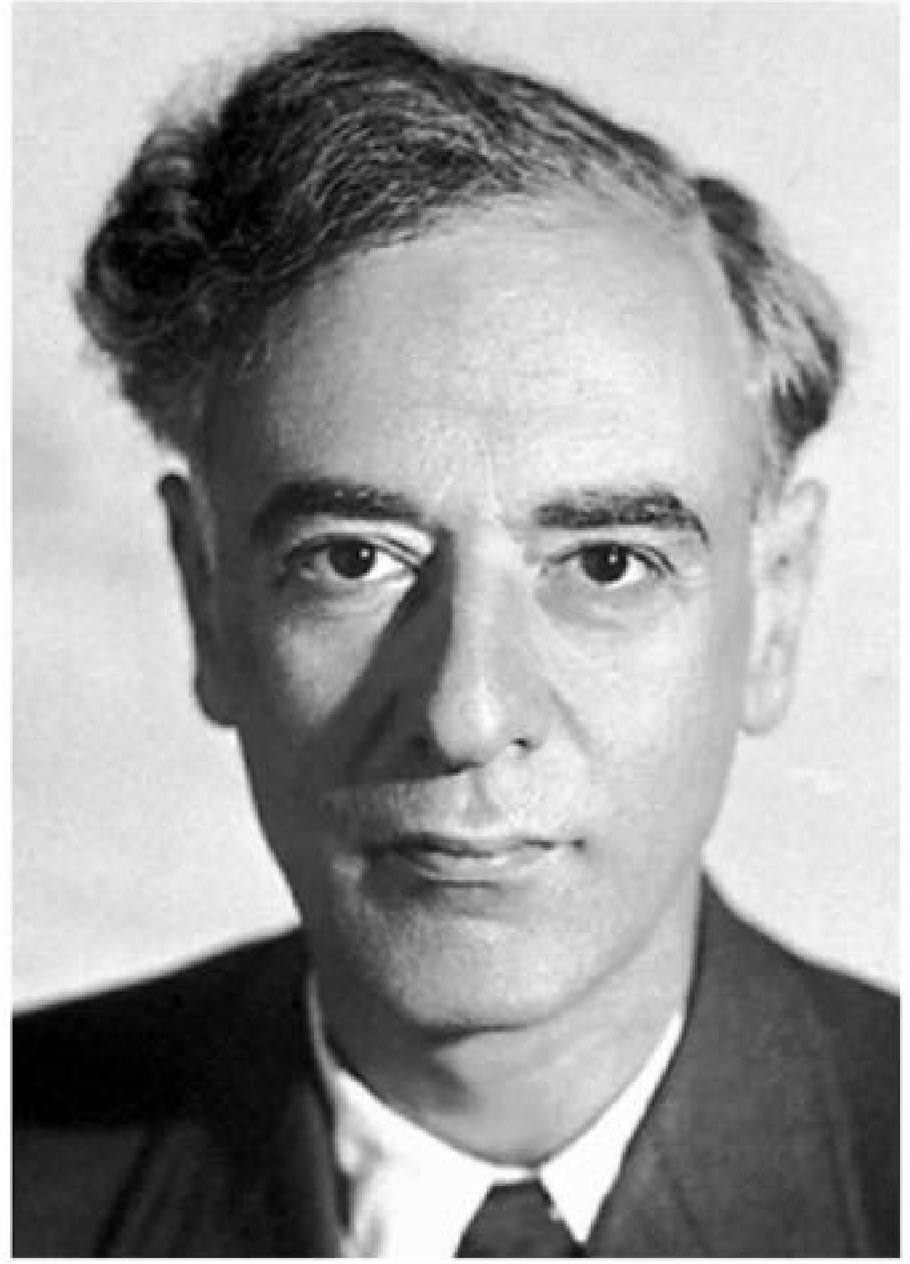


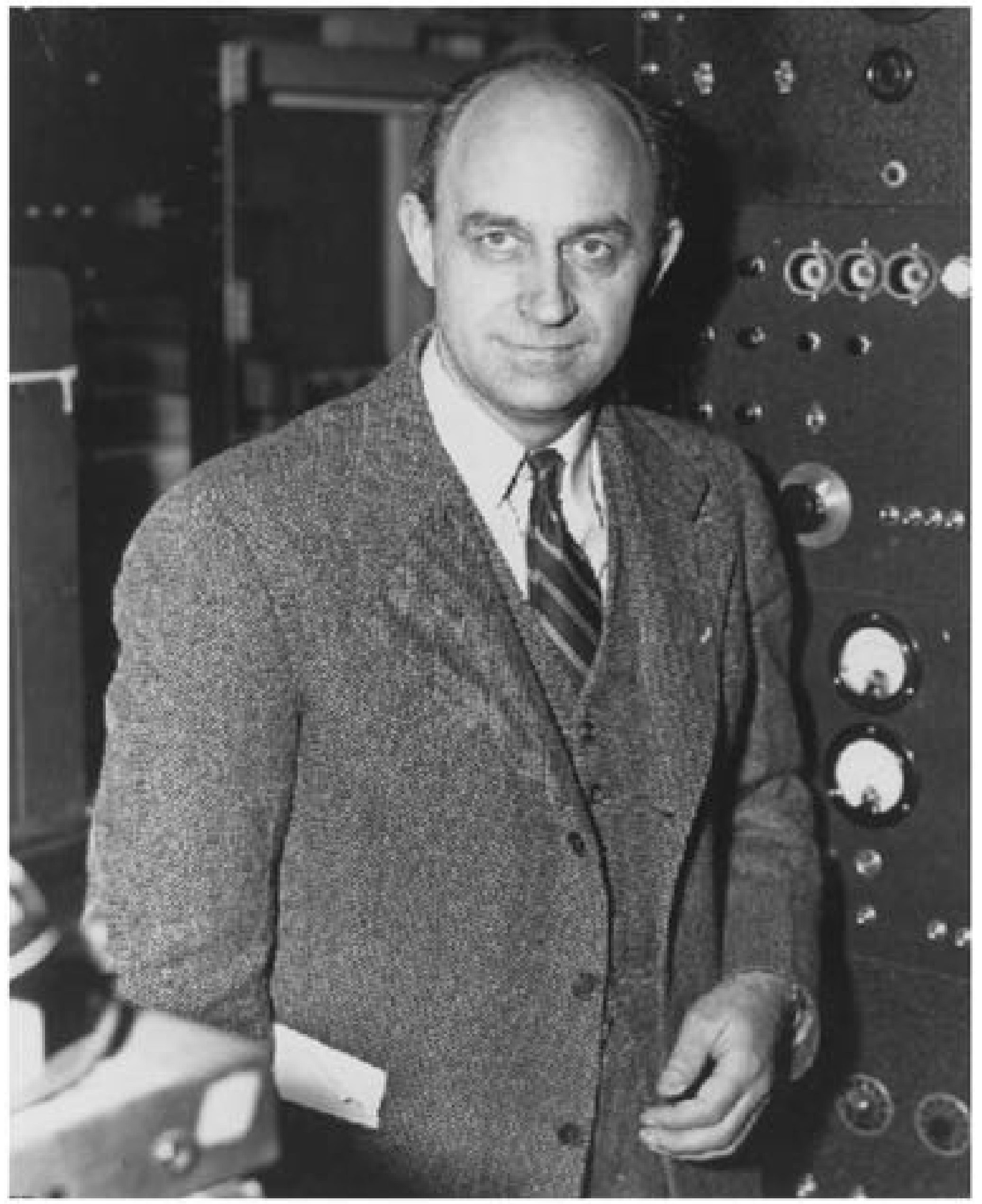
$$n \ll N \sim 10^{23}$$

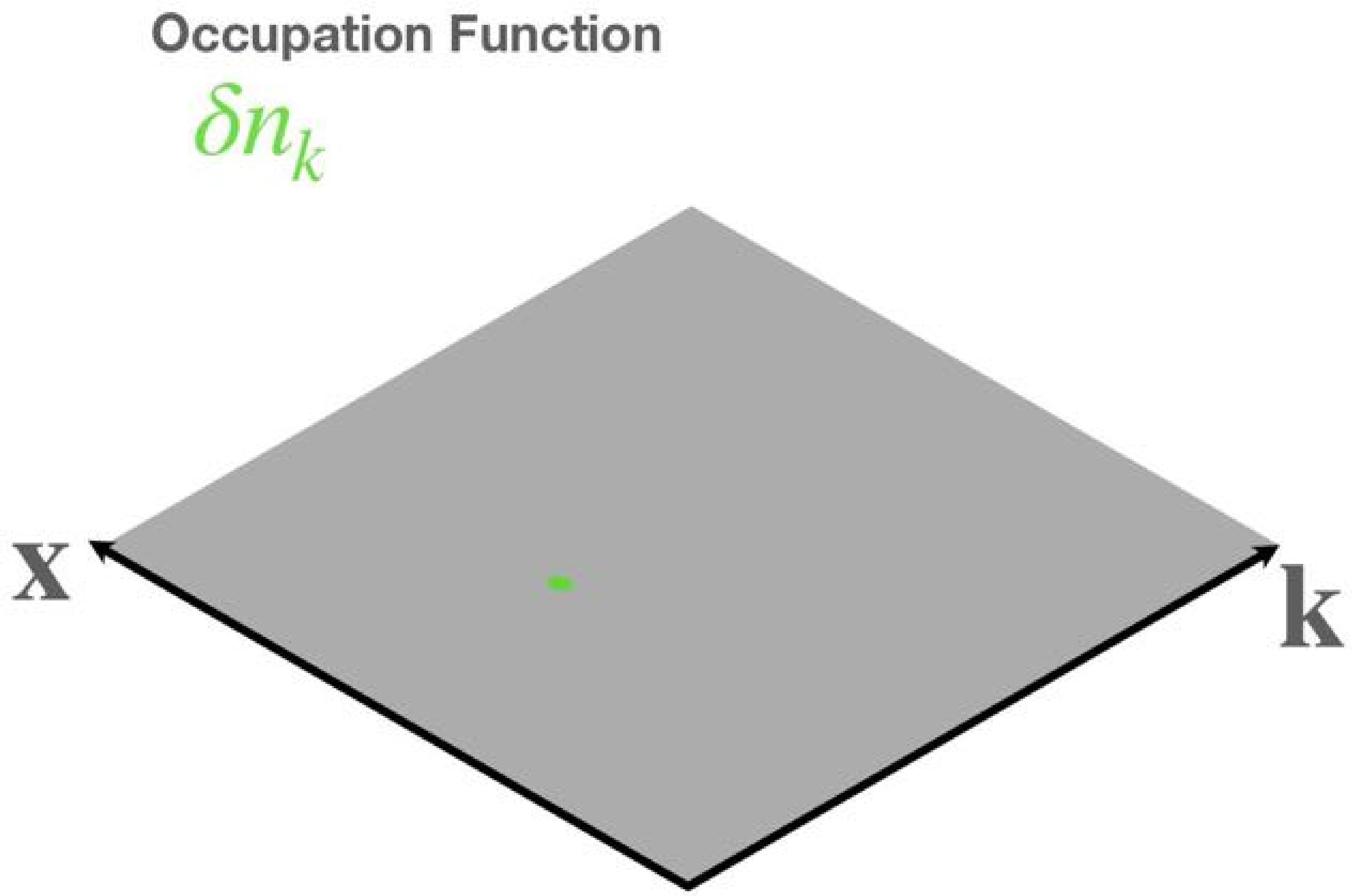
Landau Fermi Liquid Theory

A weakly interacting "gas" of quasiparticles





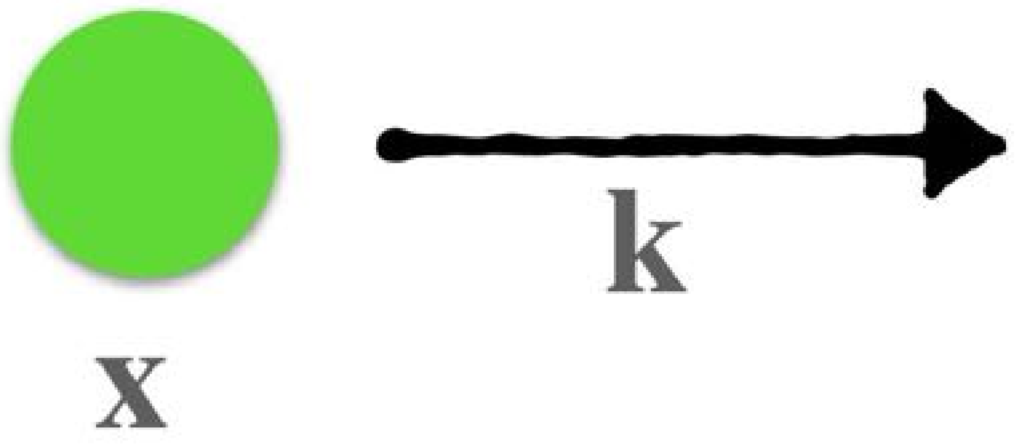




We can think of quasiparticles via a density on a semiclassical "phase-space" $(\mathbf{k}, \mathbf{x})$

Landau Fermi Liquid Theory

Quasiparticles



- Expand the free energy in powers of the small parameter $\sum_k \delta n_k / N \ll 1$
- Quasiparticles are considered to be particle excitations “dressed” by polarization of the background
- Semiclassically $\mathscr{F}$ determines evolution equation by providing and effective Hamiltonian for quasiparticles

Free Energy

$$\mathscr{F} = \mathscr{F}_0 + \sum_k \xi_k \delta n_k + \sum_{k,k'} F_{kk'} \delta n_k \delta n_{k'} + \cdots$$

Bare Quasiparticle Energy

ξ_k

Landau Interaction Function

$F_{kk'}$

Occupation Function

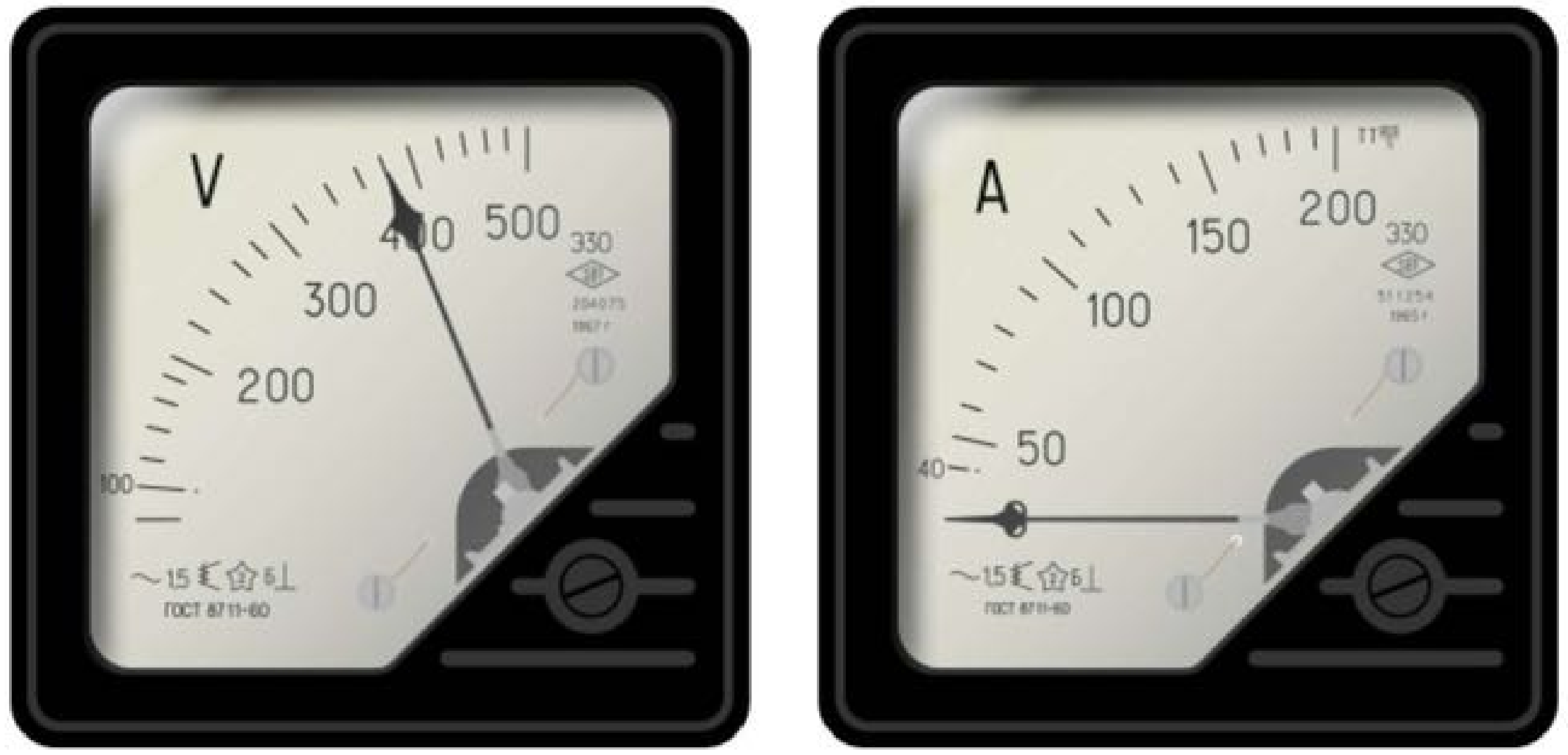
δn_k

+ Evolution equation

$$\frac{\partial \delta n_k}{\partial t} = \cdots$$

Observable Consequences

- Fermi liquid theory allows us to obtain
    - Electrical and thermal conductivities
    - Compressibility
    - Sound velocities



Observable Consequences

- Fermi liquid theory allows us to obtain
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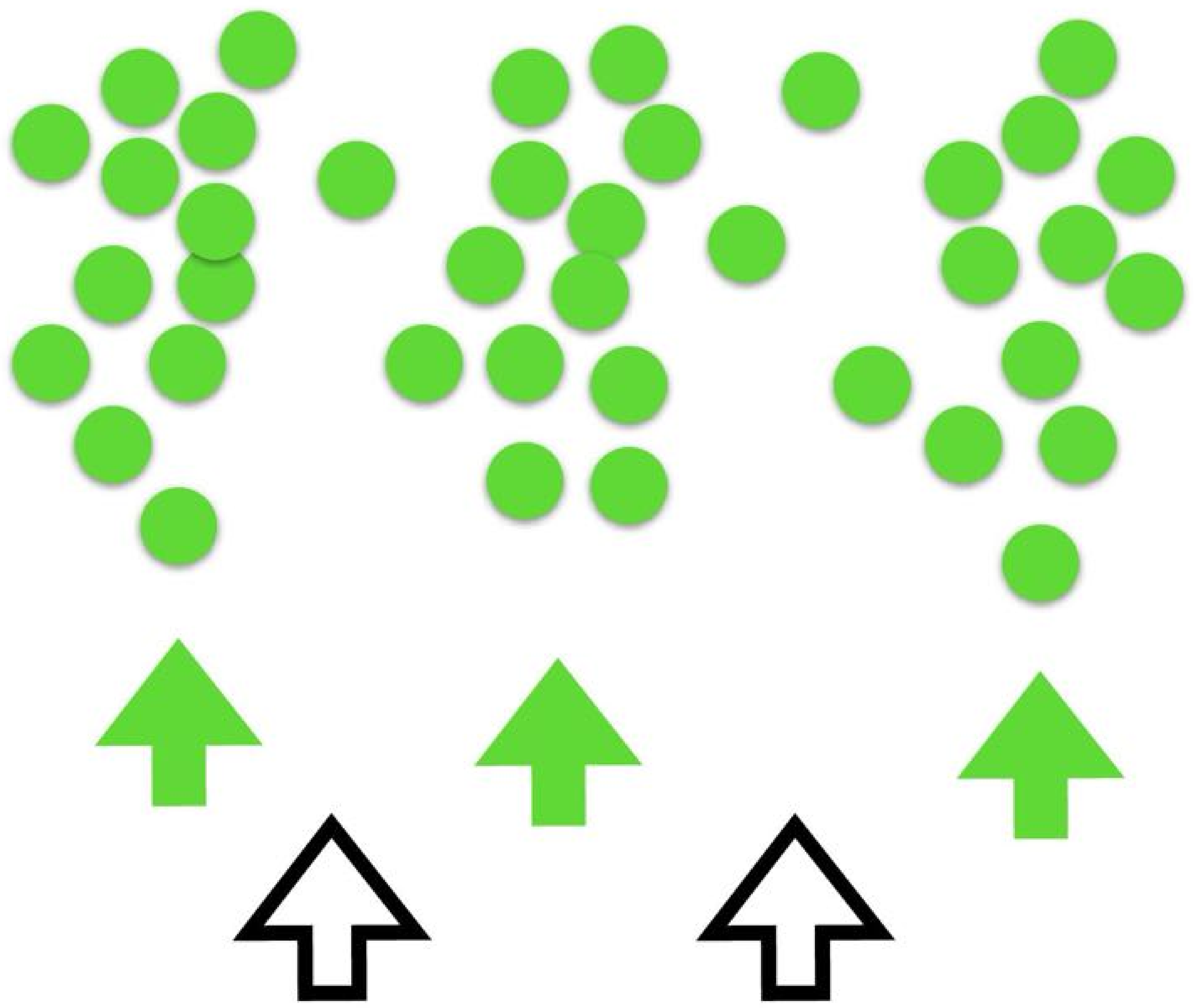
Observable Consequences

Collective modes

- Fermi liquid theory allows us to obtain
  - Electrical and thermal conductivities
  - Compressibility
  - **Sound** velocities
    - **Sound** is a coordinated motion of many quasiparticles



Graphene

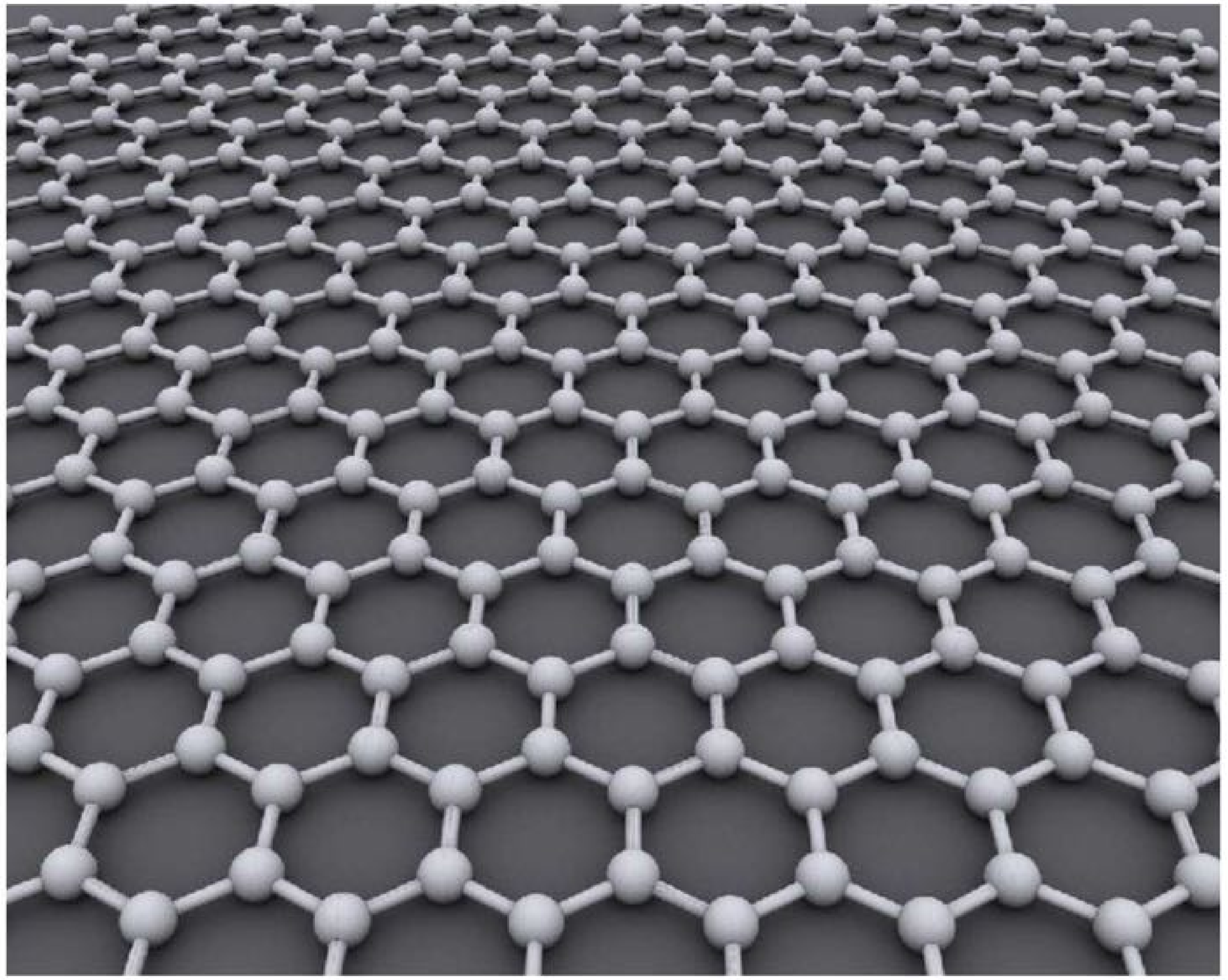
Published: 10 November 2005

Two-dimensional gas of massless Dirac fermions in graphene

K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, M. I. Katsnelson, I. V. Grigorieva, S. V. Dubonos & A. A. Firsov

Nature **438**, 197–200 (2005) | Cite this article

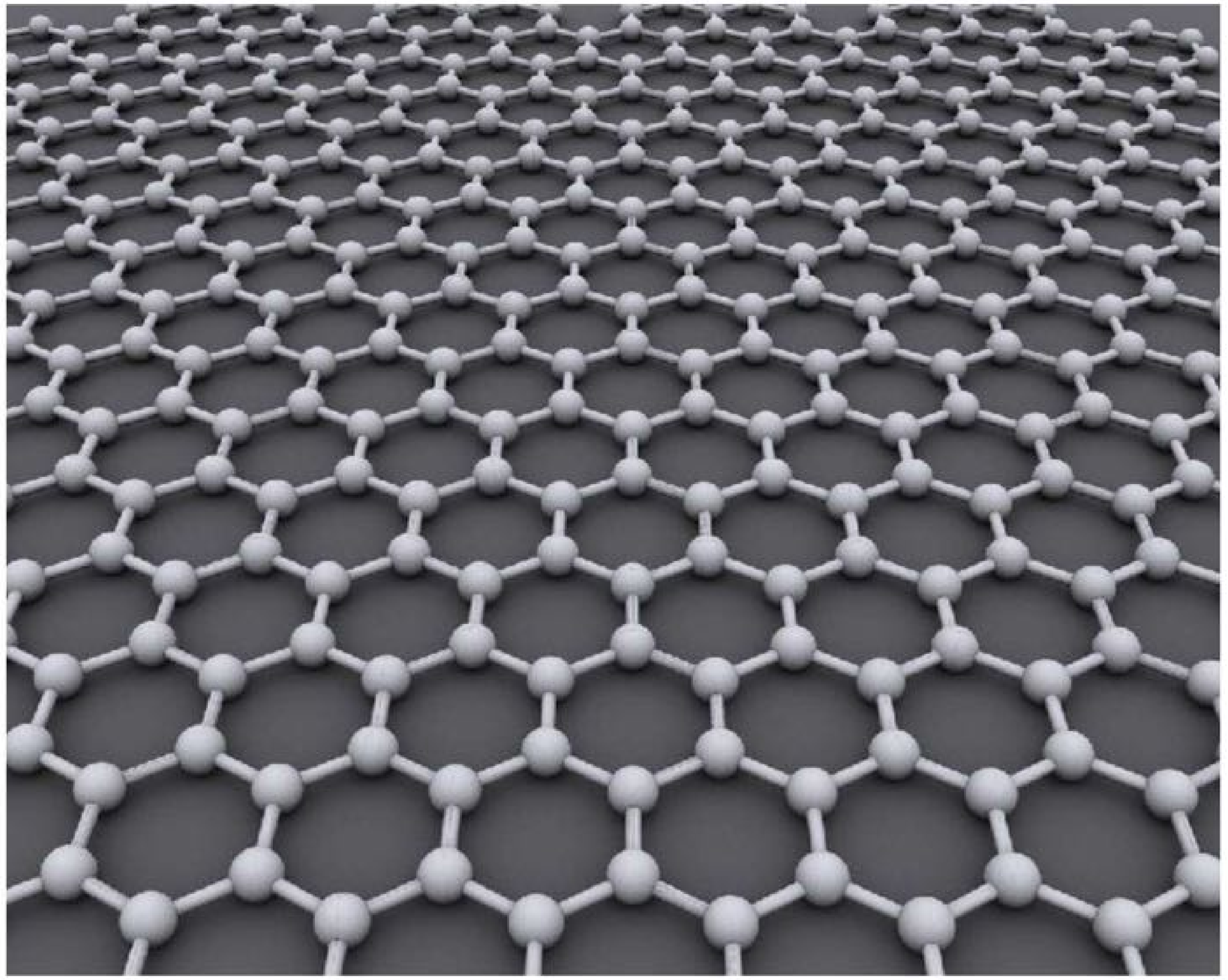
116k Accesses | **15944** Citations | **119** Altmetric | Metrics



A single layer lattice of carbon atoms

Graphene

- A material of intense interest over the past 15 years for e.g.
  - Device applications
  - Analogies with quantum electrodynamics
  - Material properties
- But has additional complexity over the usual metal



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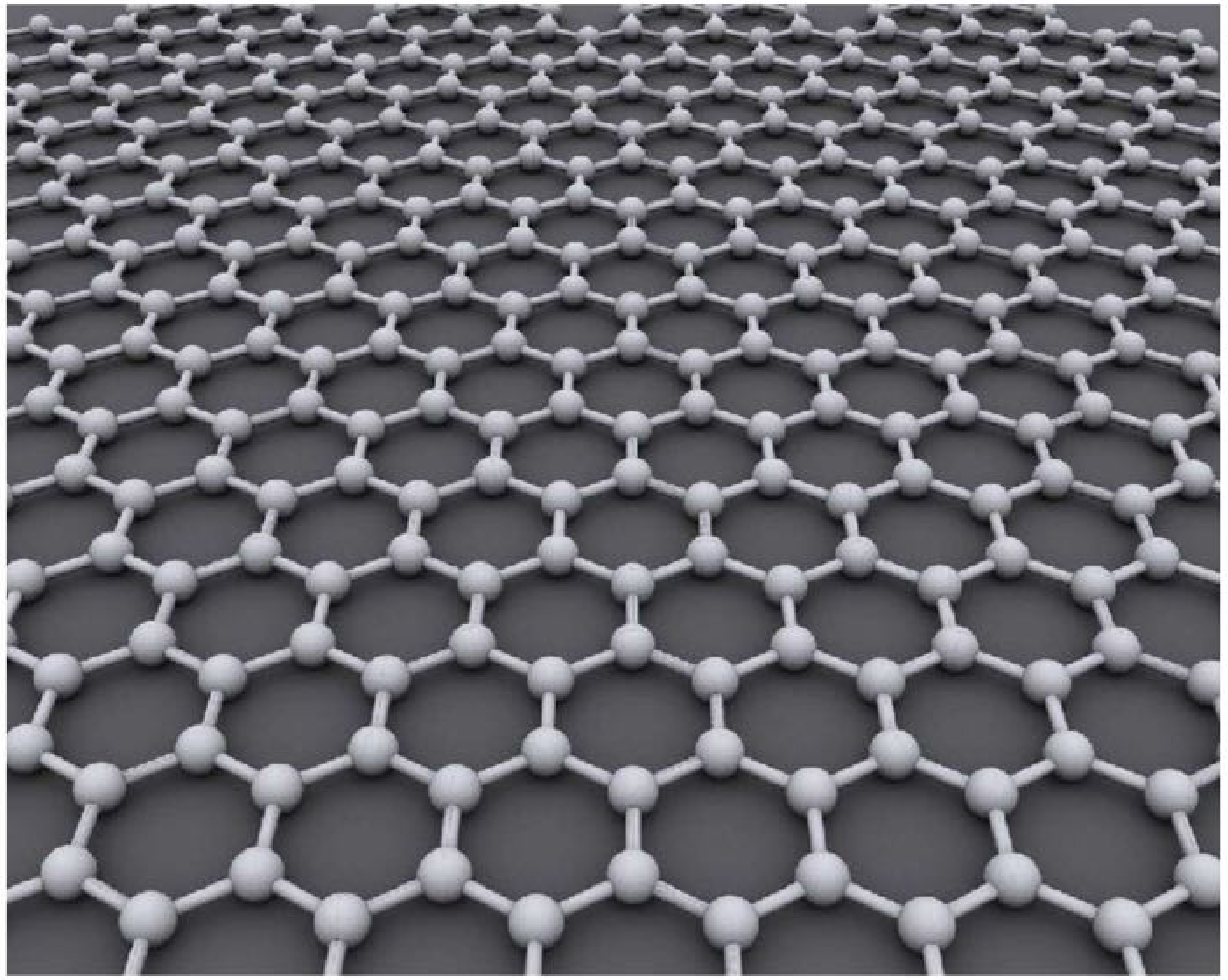
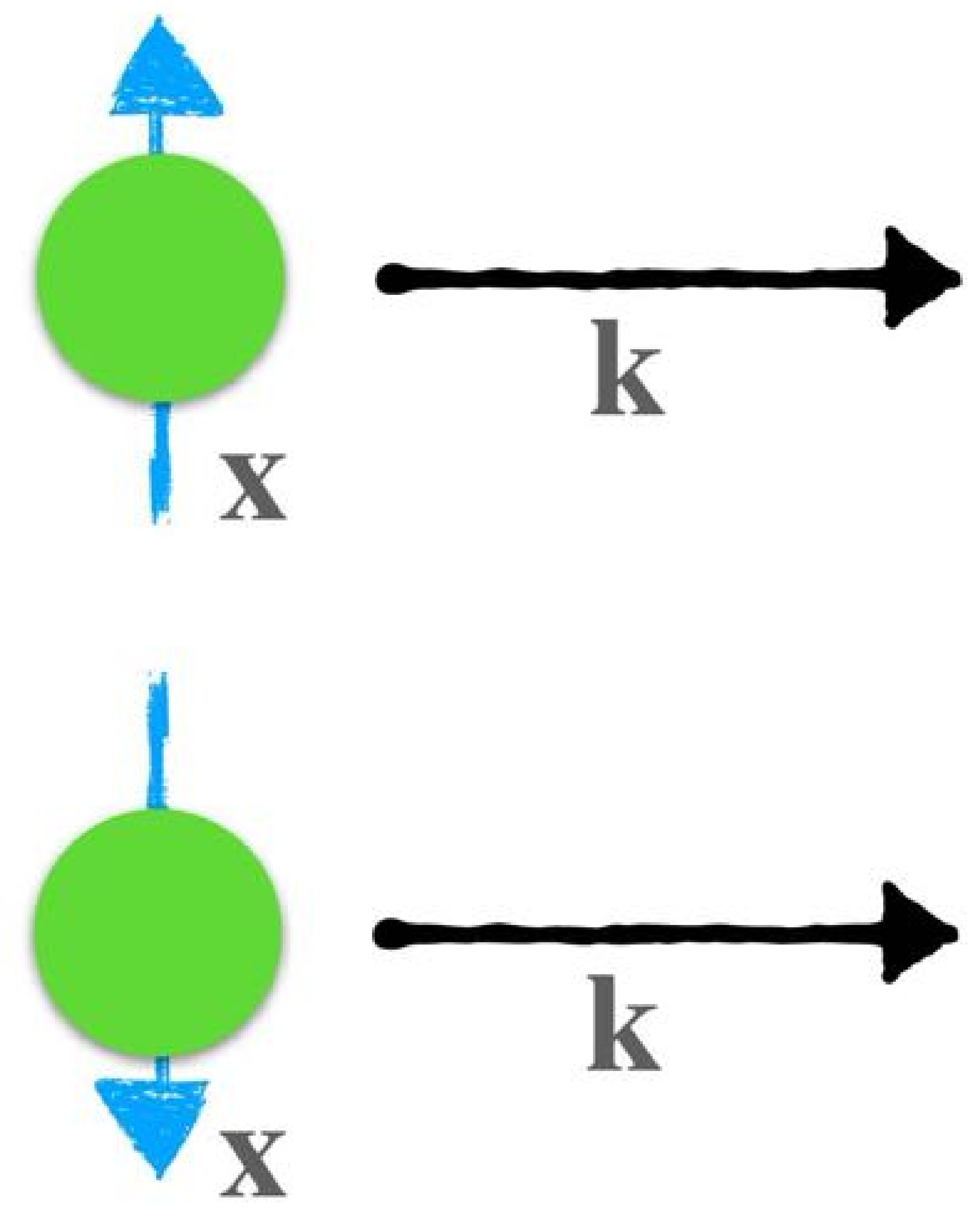


A single layer lattice of carbon atoms

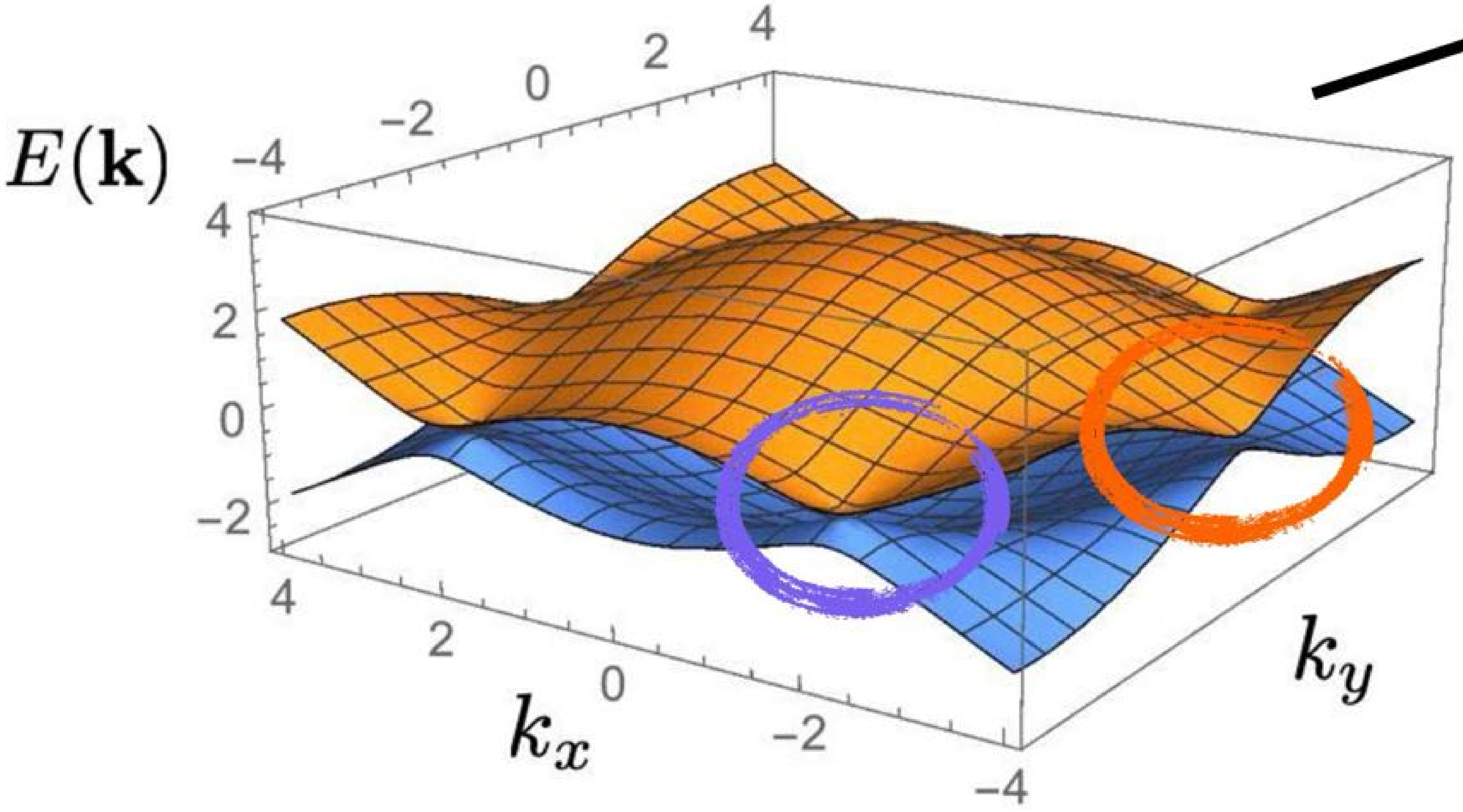
Extra Structure

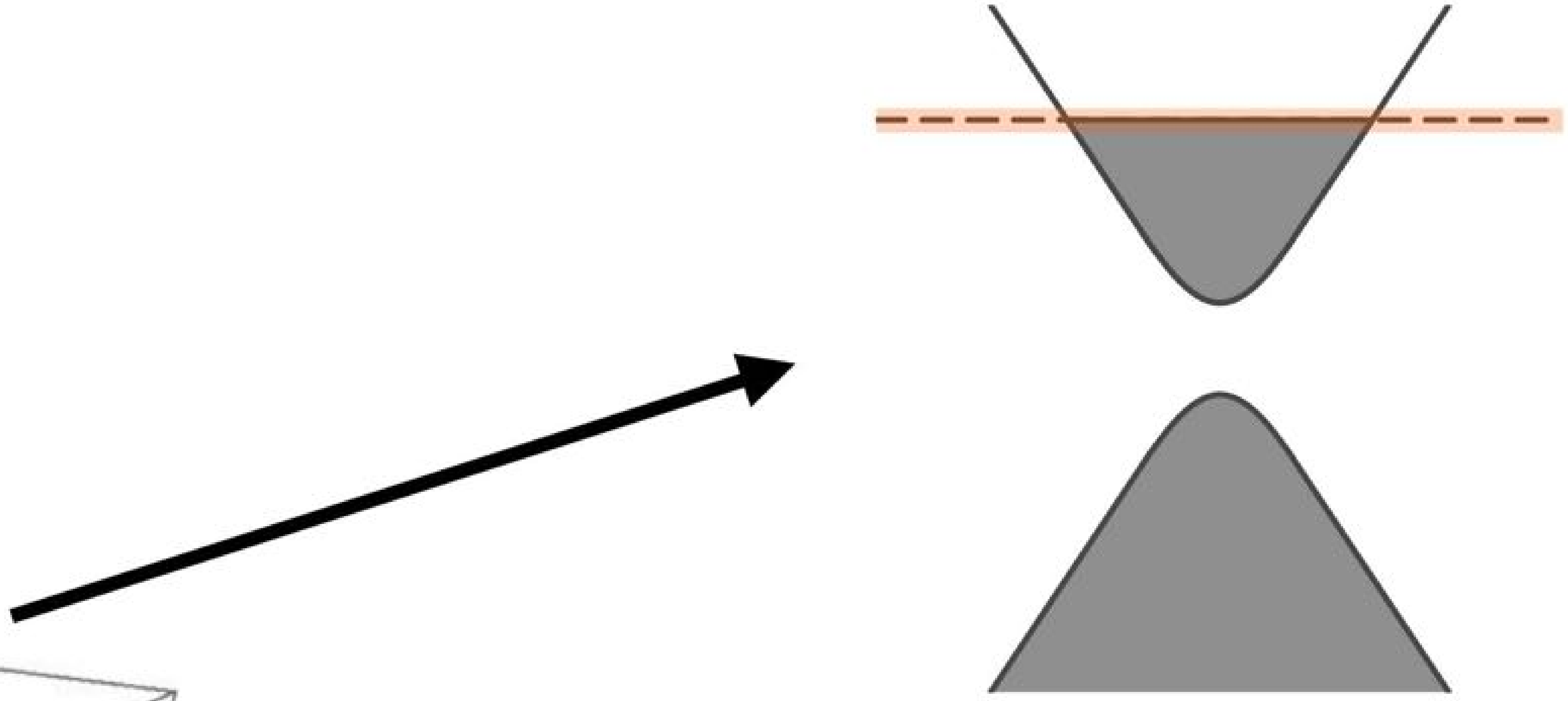
Substrate induced spin effects

- Quasi-2D materials, such as graphene, are often grown on top of some other material or placed atop another material (a substrate)
- This setup can induce a relation between the quasiparticle's motion and its internal state (spin)
  - This requires the internal spin degree of freedom to be taken into account in more detail

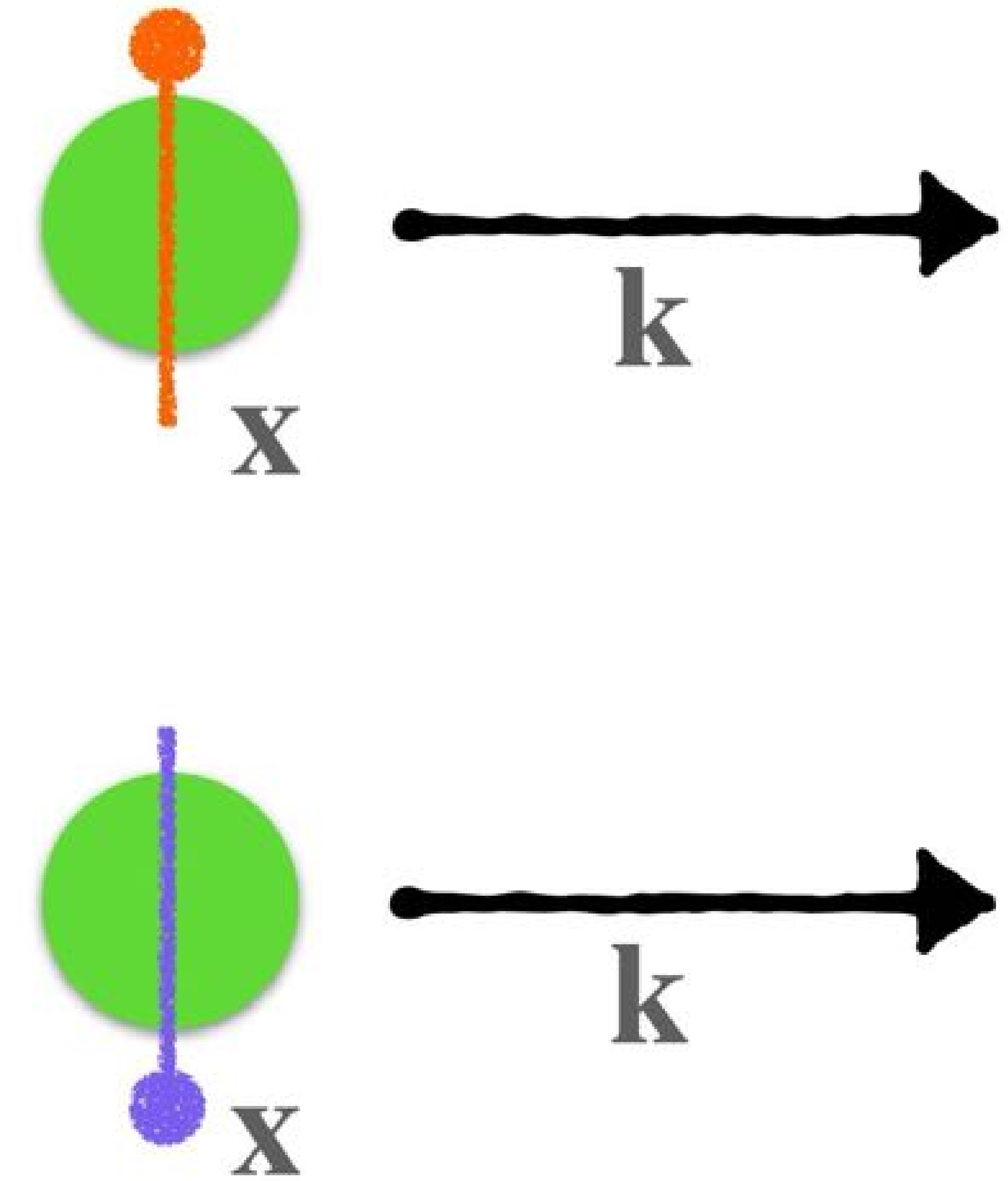


Graphene
Valley structure





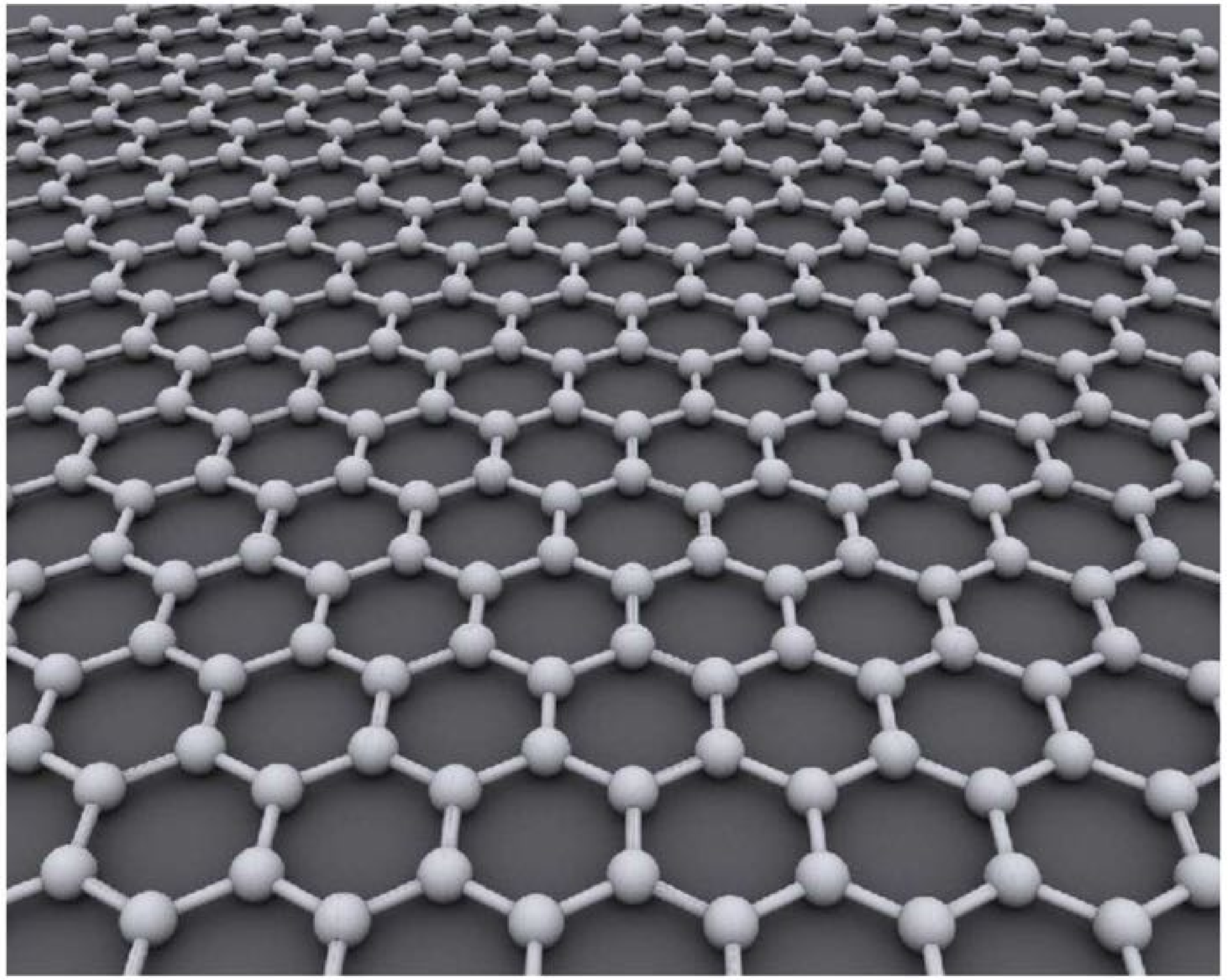
Valley Index



- The response is governed by the low energy behavior
- Valley degrees of freedom emerge when we restrict our attention to low energy

Graphene

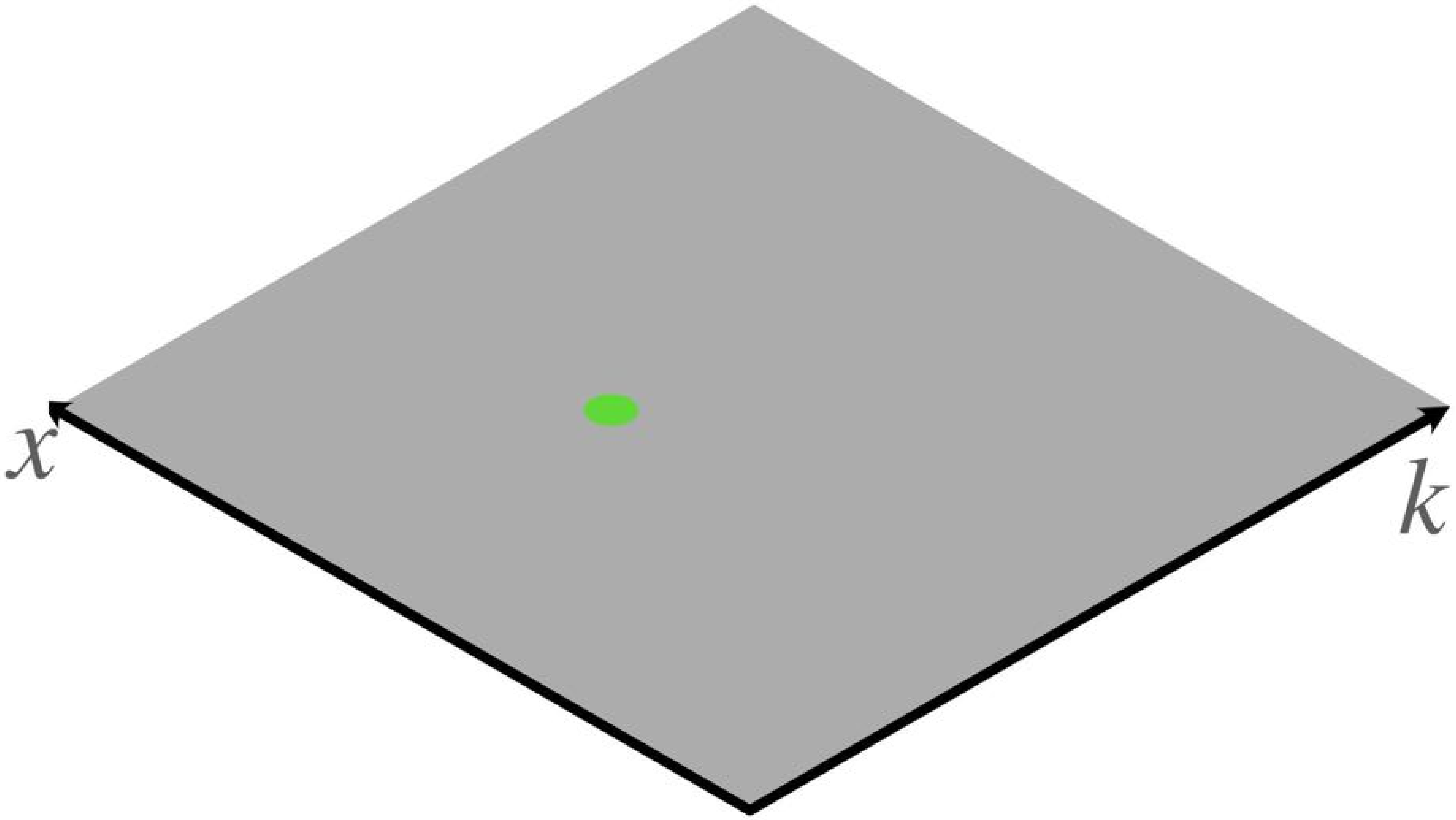
- Valley and spin degrees of freedom are both of interest for device applications
    - Both must be accounted for in a theory of graphene quasiparticles
- Extra degrees of freedom require us to go beyond the conventional single component Fermi liquid description



Internal structure/degrees of freedom

In the metallic phase

- Previously our quasiparticles were associated with points in phase space
  - Quasiparticles are conventionally featureless
- To accommodate the spin and valley structure we must consider additional data at each point in phase space



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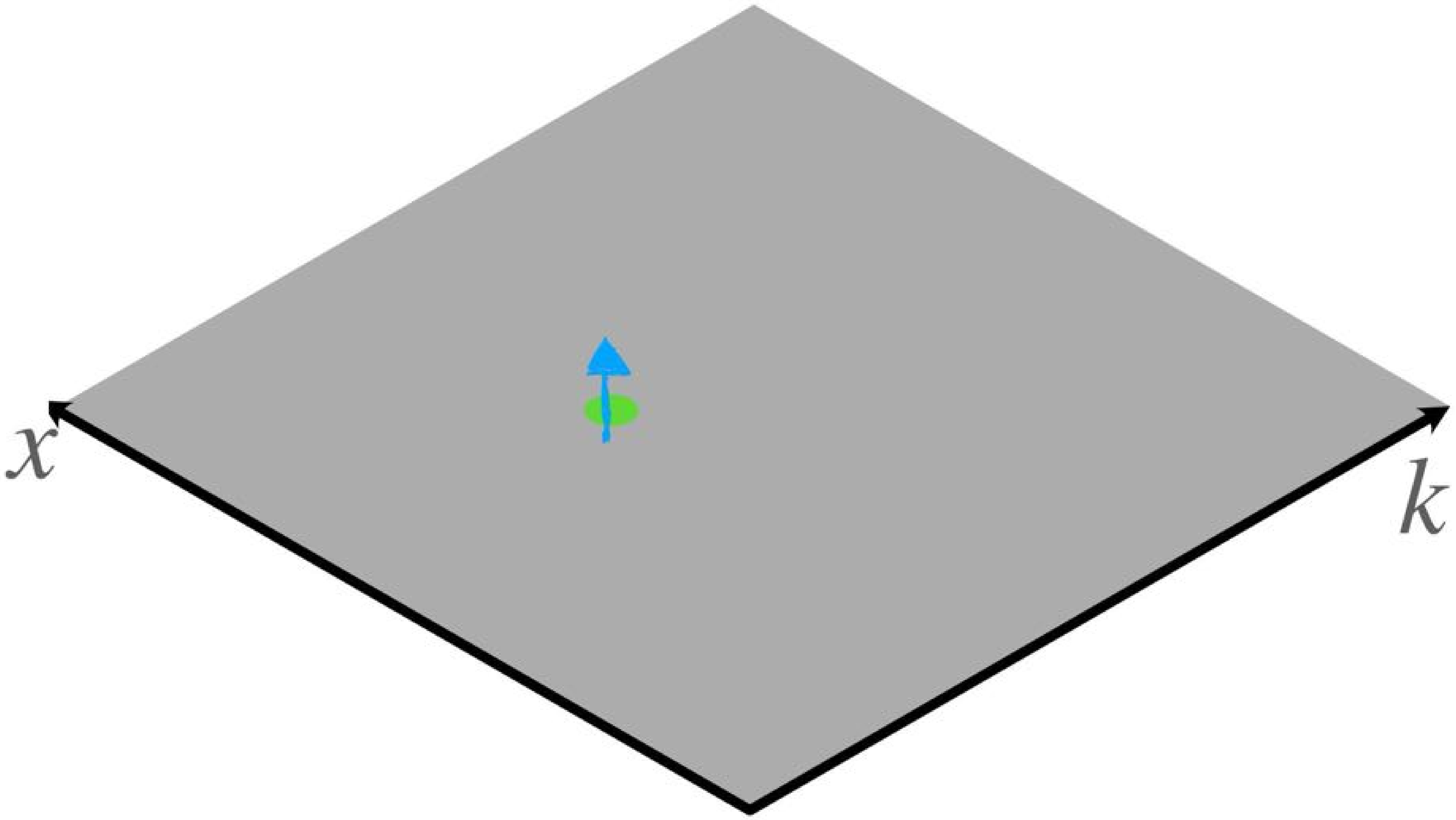

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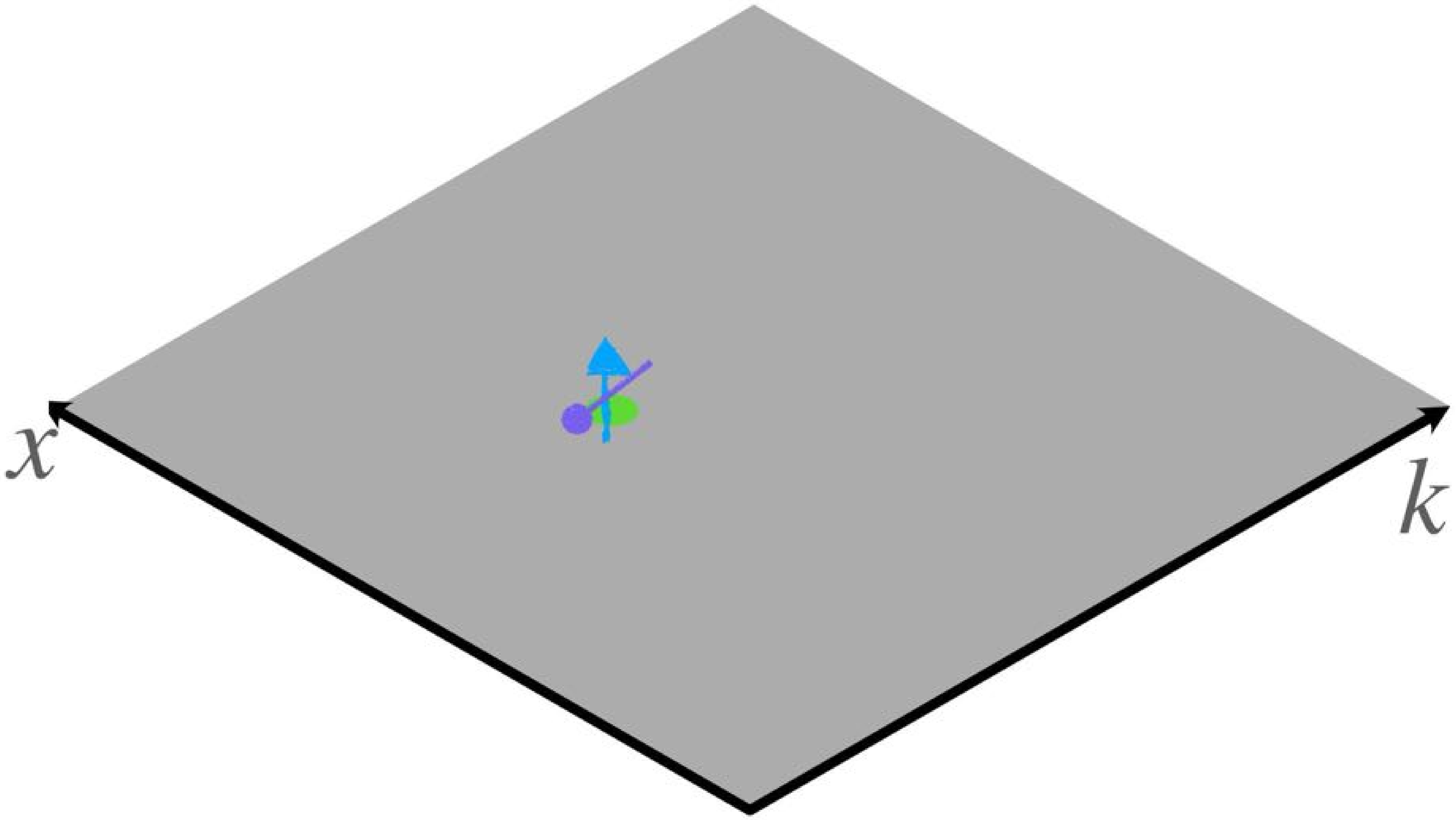

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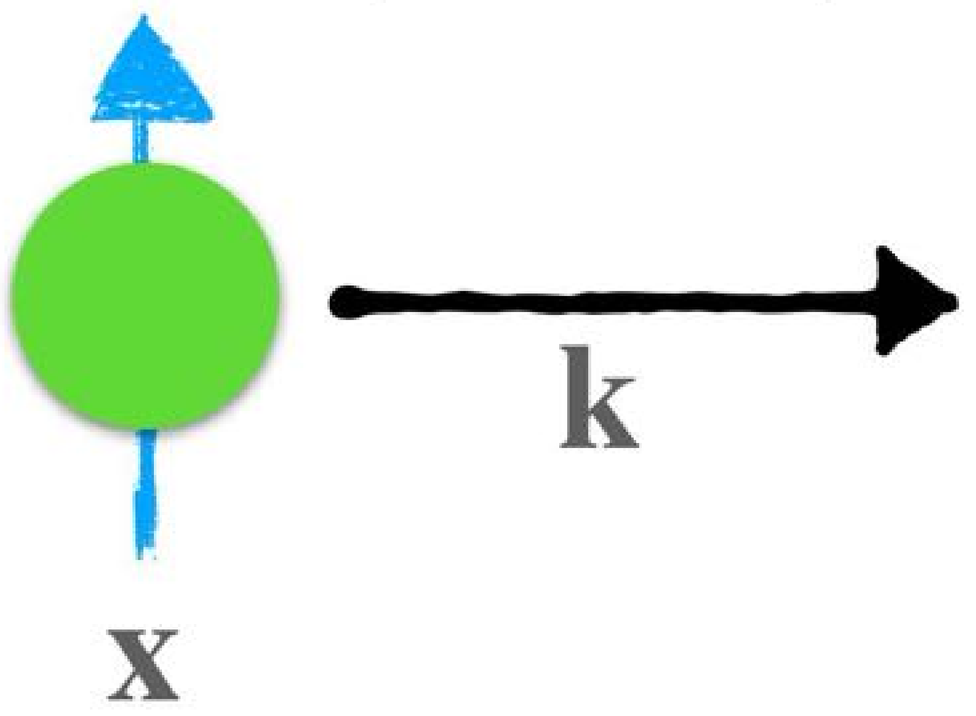
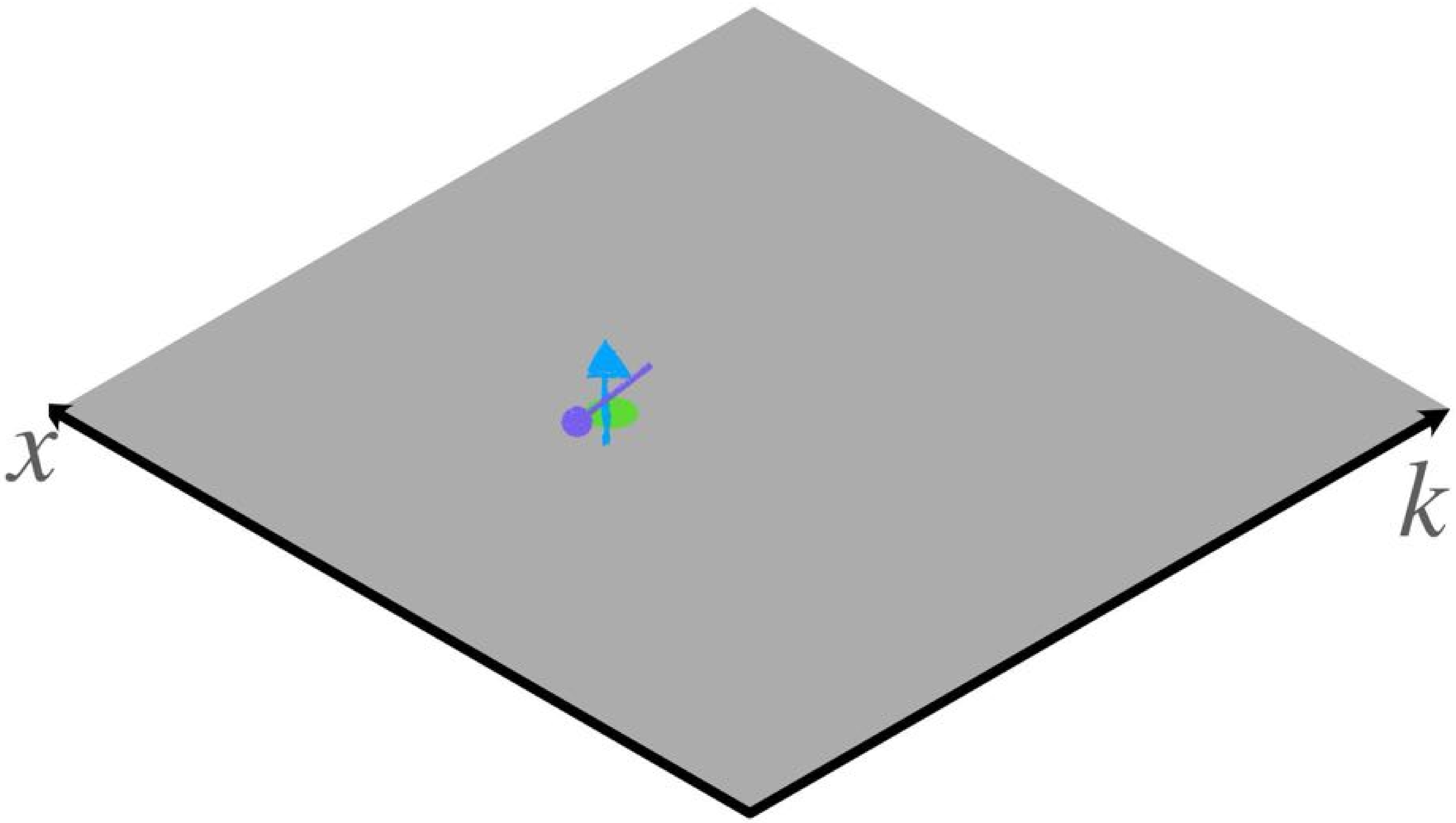
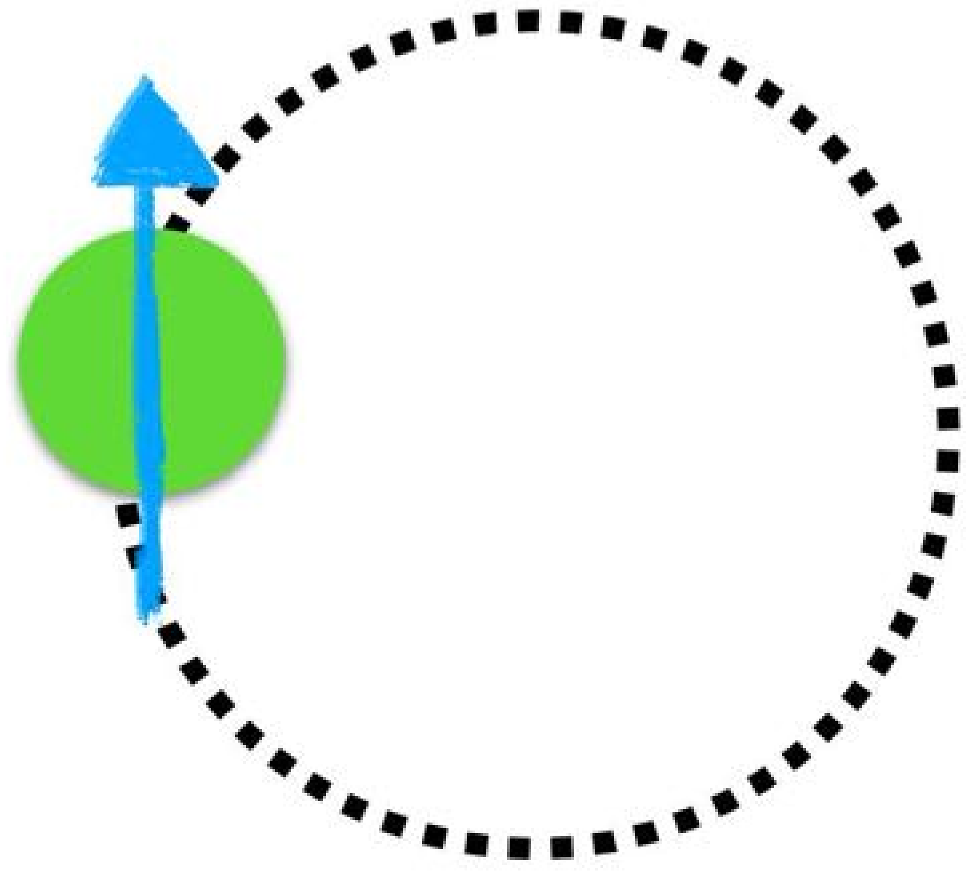




Internal structure/degrees of freedom

Geometry

- Beyond simply keeping track of the data at each point, we must also consider how this data changes as we move through phase space
- The interplay between internal structure and momentum/position must be handles correctly
  - This imbues the problem with additional geometric structure known as the *Berry Connection*



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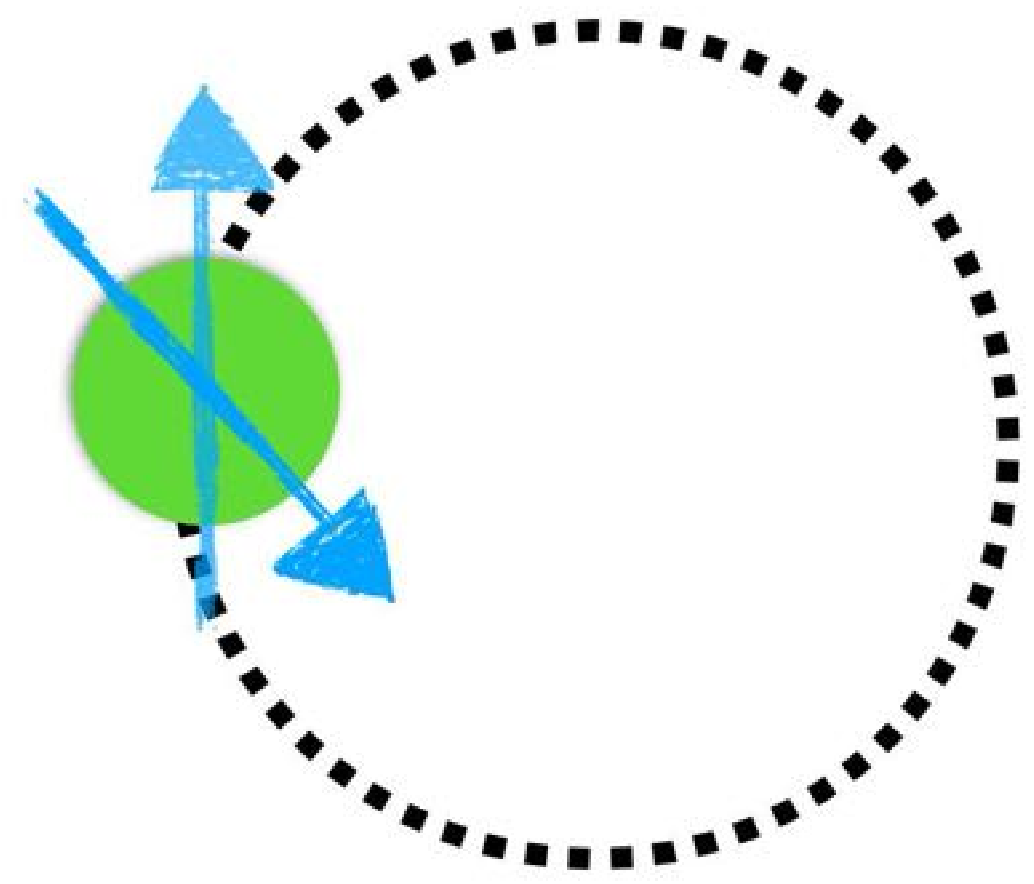
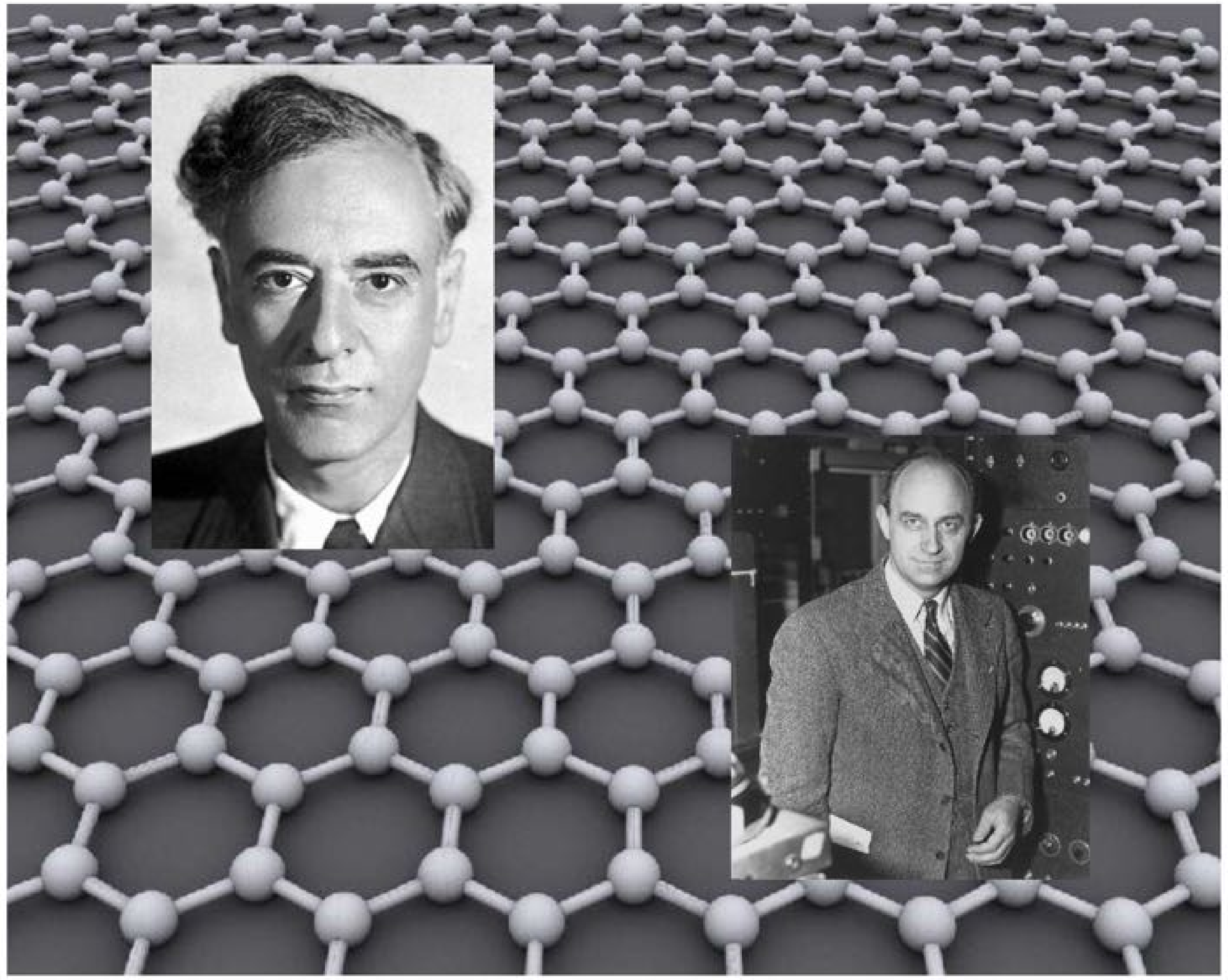


How do these concerns modify Landau’s picture?

Landau Fermi Liquid theory of Graphene

- Consequences of the additional structure can be handled with straightforward generalization of the Fermi liquid theory
  - **Bookkeeping:** Occupation functions become multicomponent $\delta n_{ij}(\mathbf{k}, \mathbf{x})$
  - **Geometry:** The transport equation acquires additional geometric content



Book-keeping

Handling additional components

Free Energy

$$\mathscr{F} = \mathscr{F}_0 + \sum_k \xi_k \delta n_k + \sum_{k,k'} F_{kk'} \delta n_k \delta n_{k'} + \cdots$$

- We must now keep track of not only the number of excitations at each position $\mathbf{x}$ and momentum $\mathbf{k}$, but also how their internal degrees of freedom are arranged
  - We thus have multiple occupation functions
- Particle interactions may depend on the internal state of the two interacting particles

Symmetry distinguished channels

Book-keeping

Handling additional components

Free Energy

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e.g

$$\sum_k \epsilon_{ij} \delta n_{ji}(k)$$

e.g

$$\sum_{k,k'} \delta n_{ij}(k) F^{ij;lm}(k,k') \delta n_{lm}(k')$$

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e.g

$$\sum_k \epsilon_{ij} \delta n_{ji}(k)$$

e.g

$$\sum_{k,k'} \delta n_{ij}(k) F^{ij;lm}(k,k') \delta n_{lm}(k')$$

Bare Quasiparticle Energy

$$\xi_k \to \epsilon_{d;k}, \boldsymbol{\epsilon}_{s;k}, \boldsymbol{\epsilon}_{v;k}, \boldsymbol{\epsilon}_{mi;k}$$

Symmetry distinguished channels

Occupation Functions

$$\delta n_k \to \delta n_k, \delta \mathbf{s}_k, \delta \mathbf{Y}_k, \delta \overleftrightarrow{\mathbf{M}}_k$$

Landau Interaction Functions

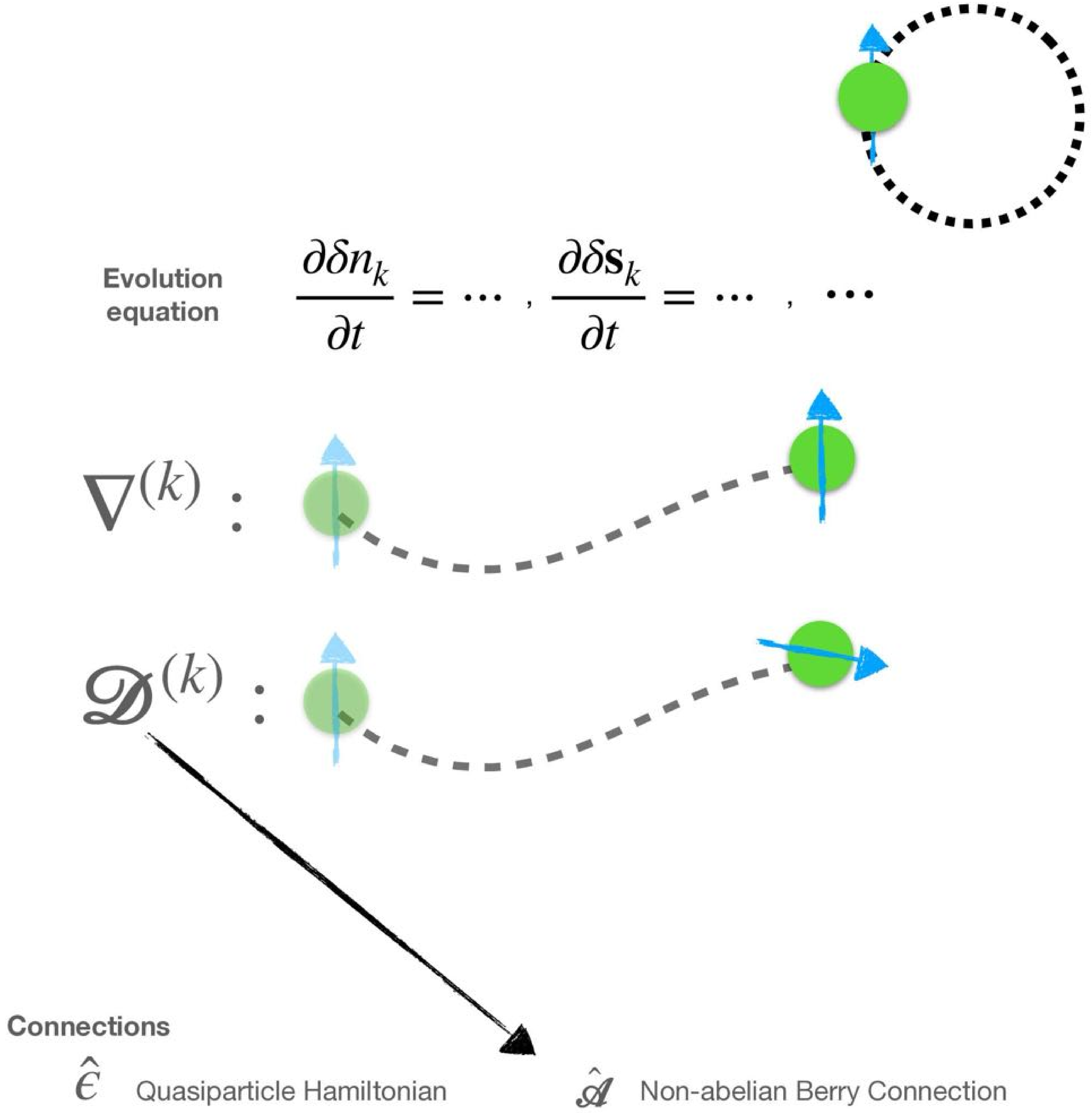
$$F_{kk'} \to F^d_{kk'}, F^s_{kk'}, F^v_{kk';i}, F^m_{kk';i}$$

Symmetry constrained

Geometry

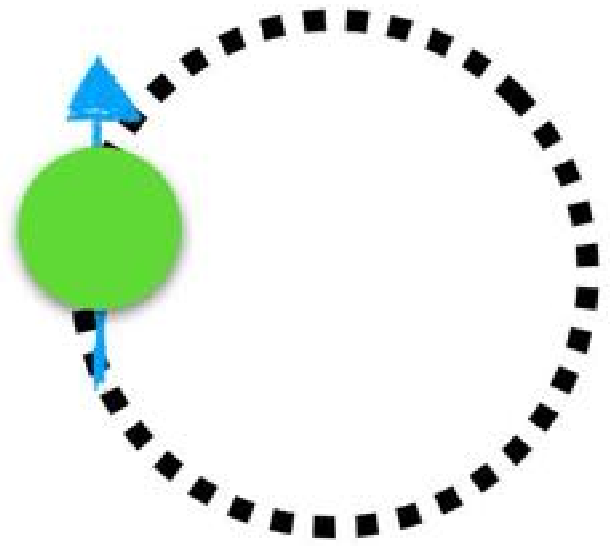
Handling additional geometry

- The additional geometry is encoded in the PDEs governing time evolution of the occupation functions
- The transport equation can be modified to include this geometric structure in a straightforward manner

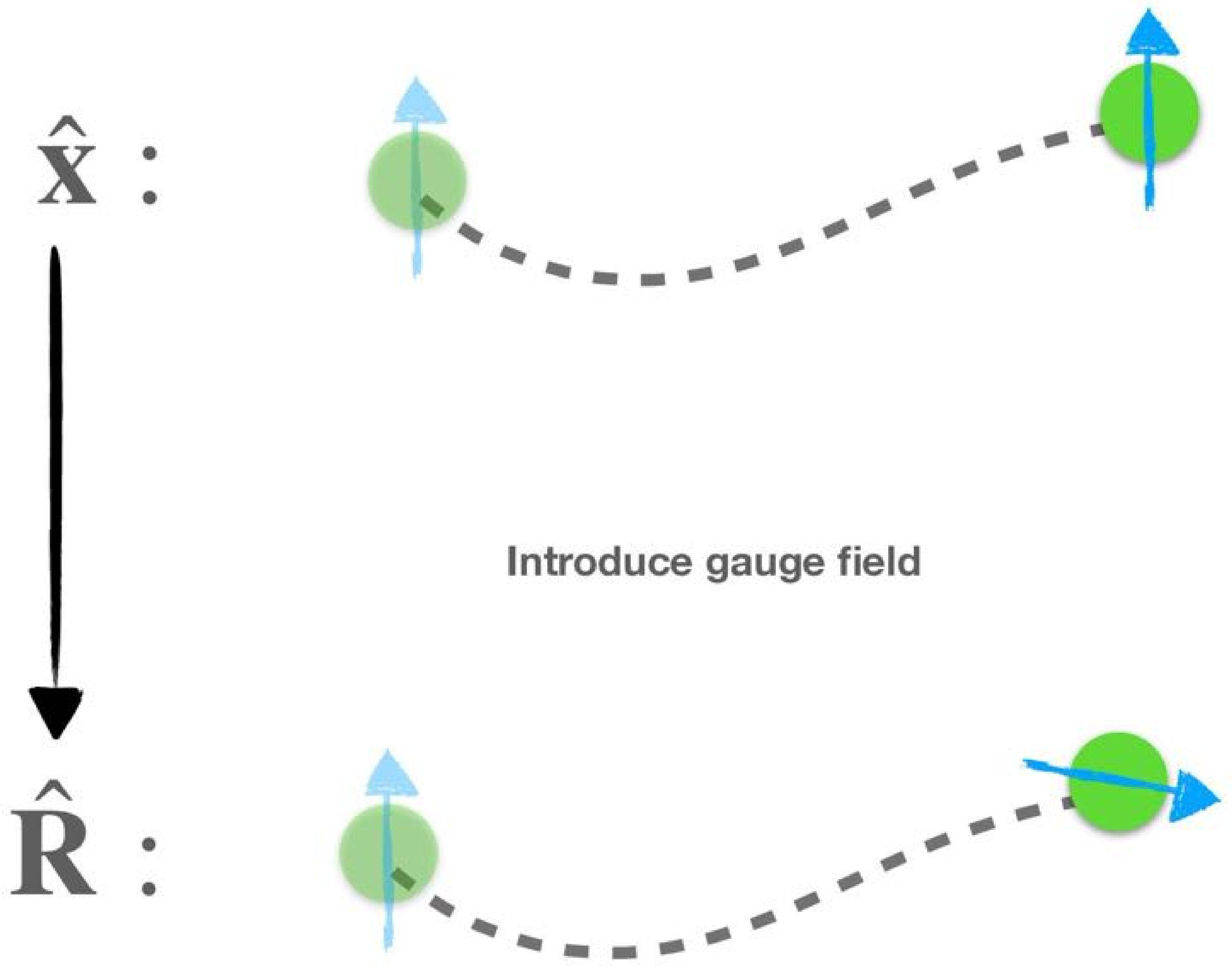


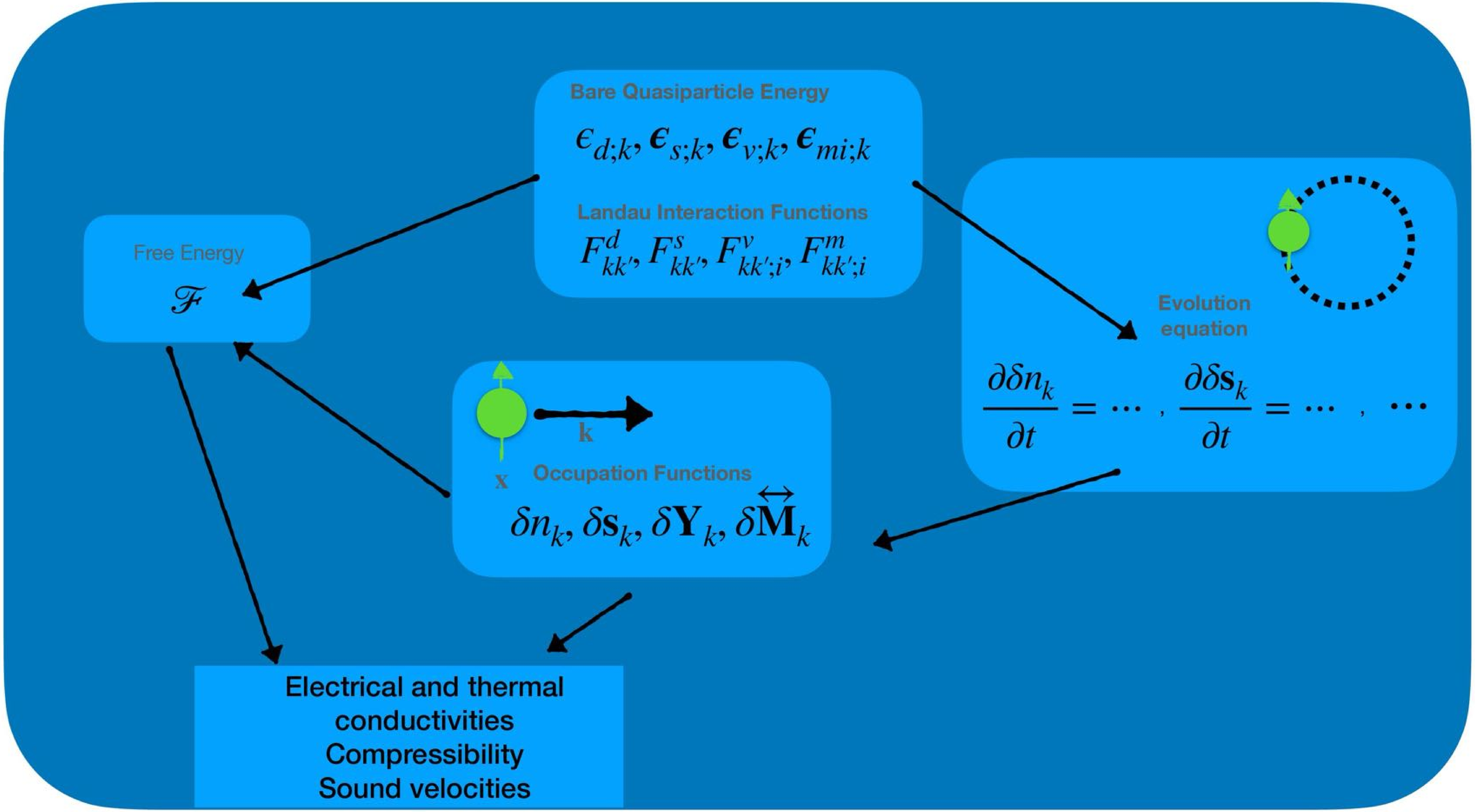
Geometry

Handling additional geometry



- Analogous to gauging of a conventional fluid where we gauge the momentum
  - $\mathbf{p} \to \mathbf{\Pi} = \mathbf{p} - q\mathbf{A}$
- Berry connection here gauges the position
  - $\mathbf{x} \to \mathbf{R} = \mathbf{x} - i[\mathscr{A}, \cdot\,]$



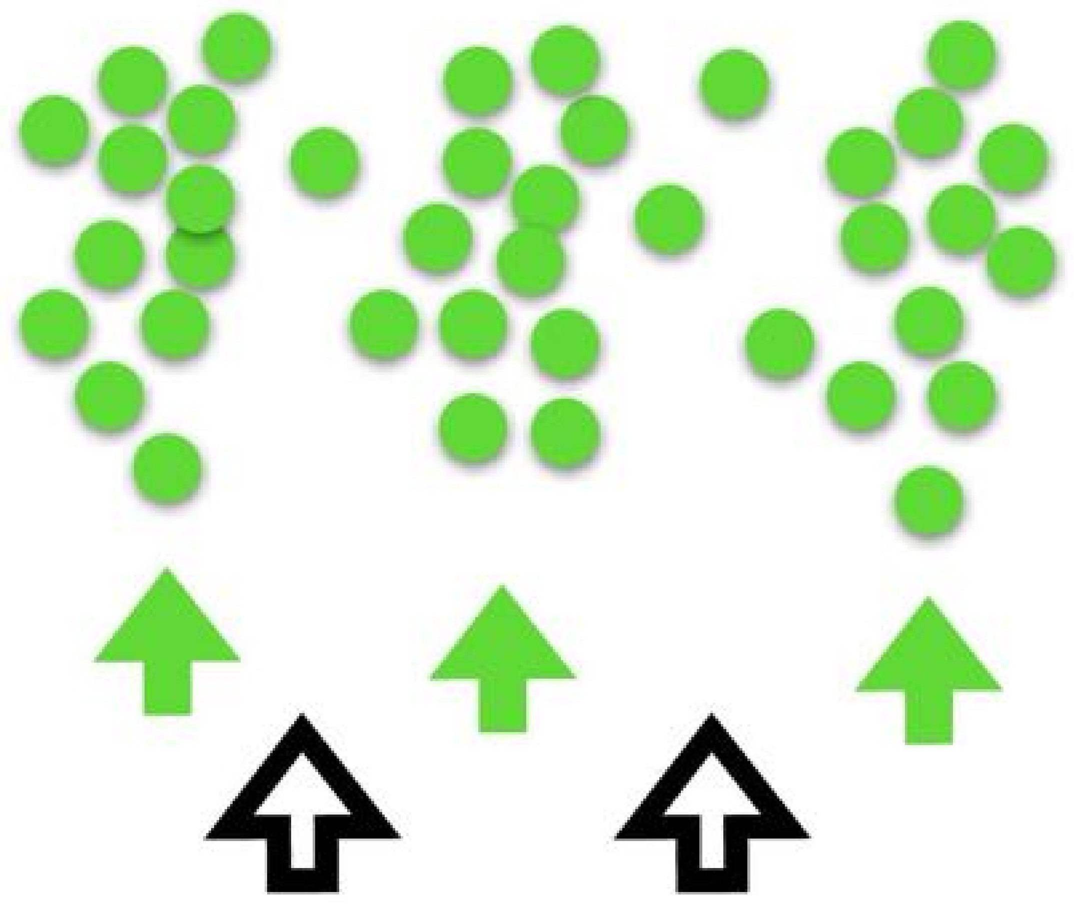


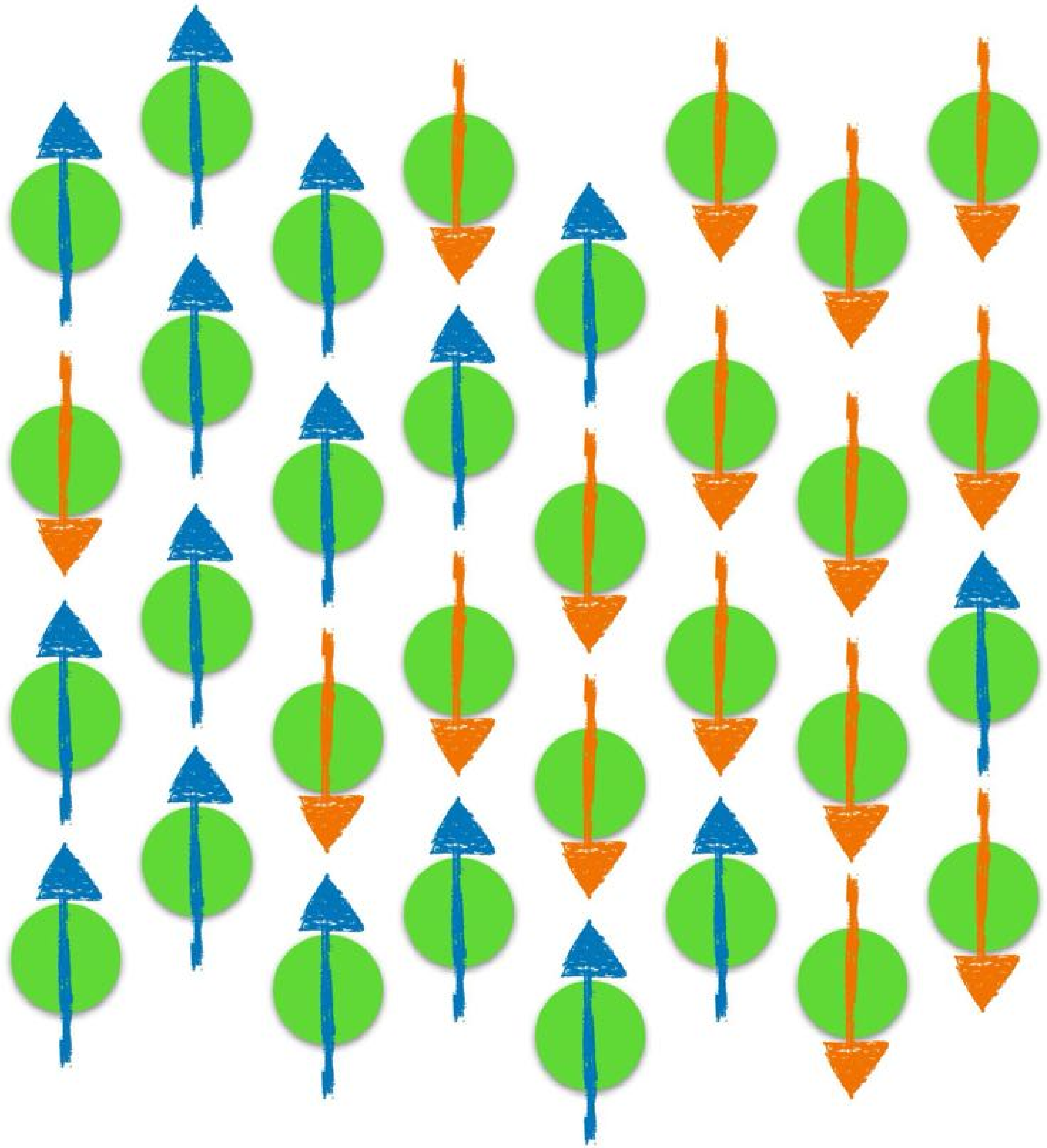
Bare Quasiparticle Energy
$\epsilon_{d;k}, \boldsymbol{\epsilon}_{s;k}, \boldsymbol{\epsilon}_{v;k}, \boldsymbol{\epsilon}_{mi;k}$
Landau Interaction Functions
$F^{d}_{kk'}, F^{s}_{kk'}, F^{v}_{kk';i}, F^{m}_{kk';i}$
Free Energy
$\mathscr{F}$
Evolution equation
$\frac{\partial \delta n_k}{\partial t} = \cdots, \frac{\partial \delta \mathbf{s}_k}{\partial t} = \cdots, \cdots$
k
x
Occupation Functions
$\delta n_k, \delta \mathbf{s}_k, \delta \mathbf{Y}_k, \delta \overleftrightarrow{\mathbf{M}}_k$
Electrical and thermal conductivities
Compressibility
Sound velocities

Observable consequences

Collective mode resonances

- Using these techniques we were able to predict the existence of a type of sound associated with the valley and spin degrees of freedom





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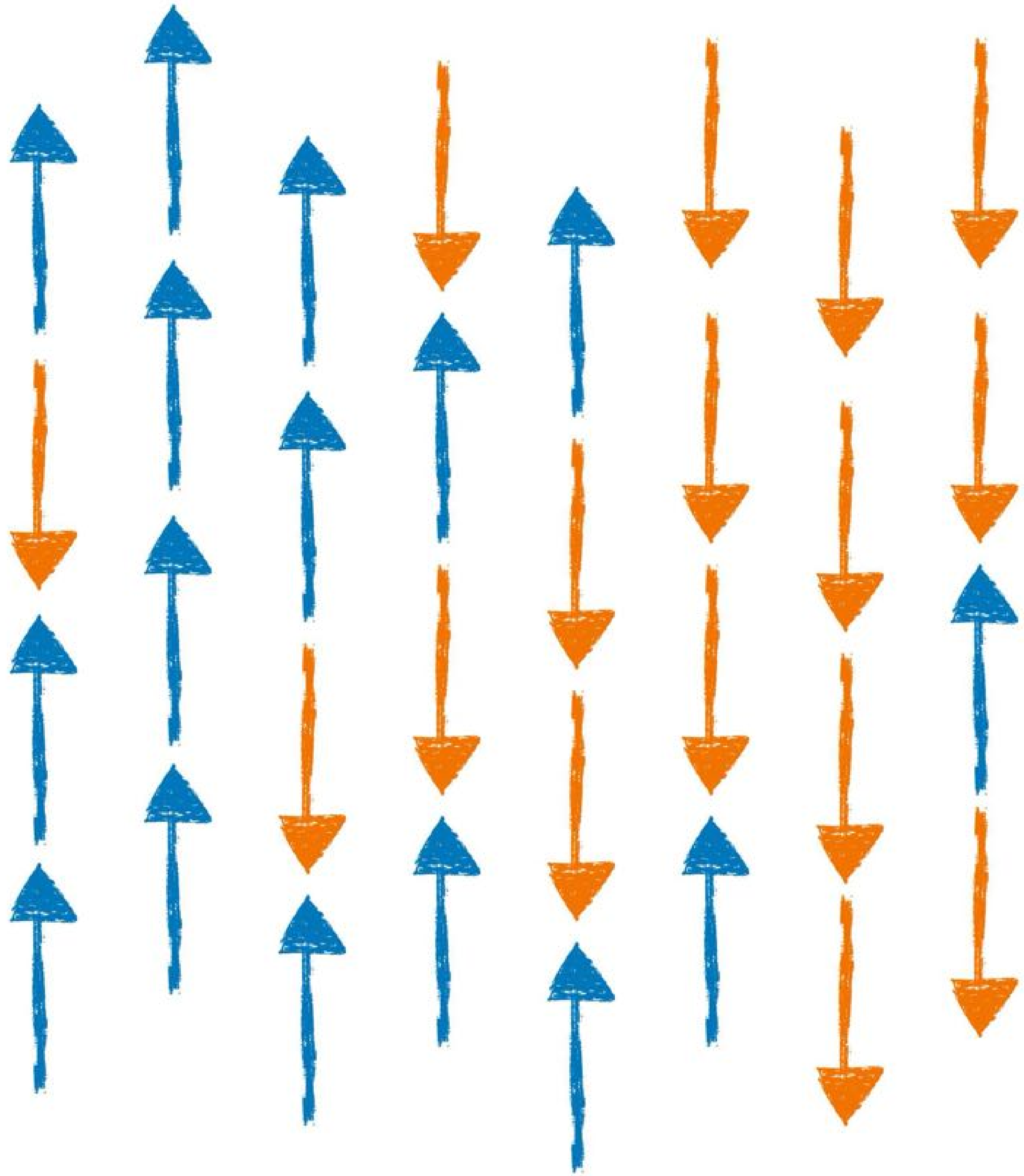
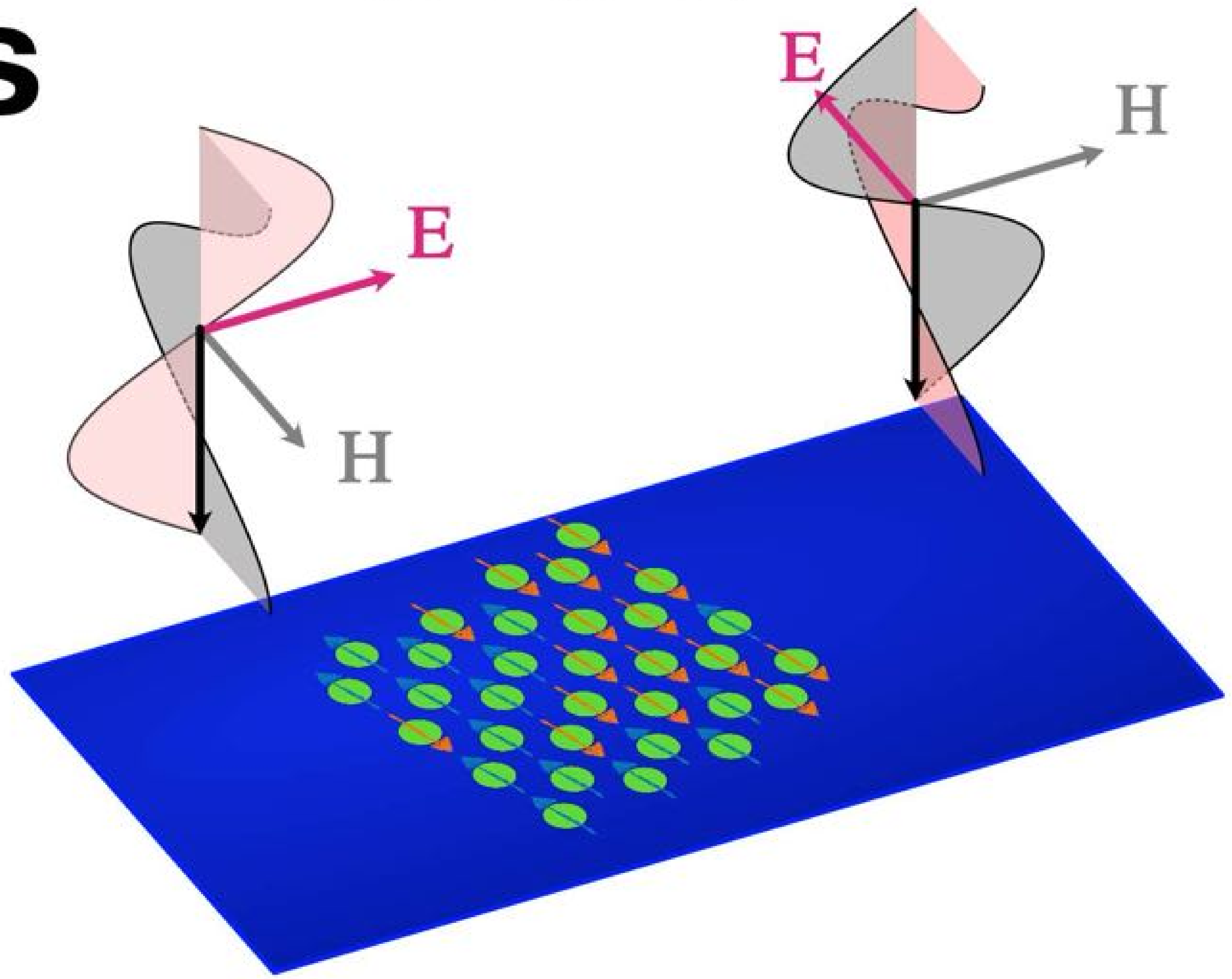


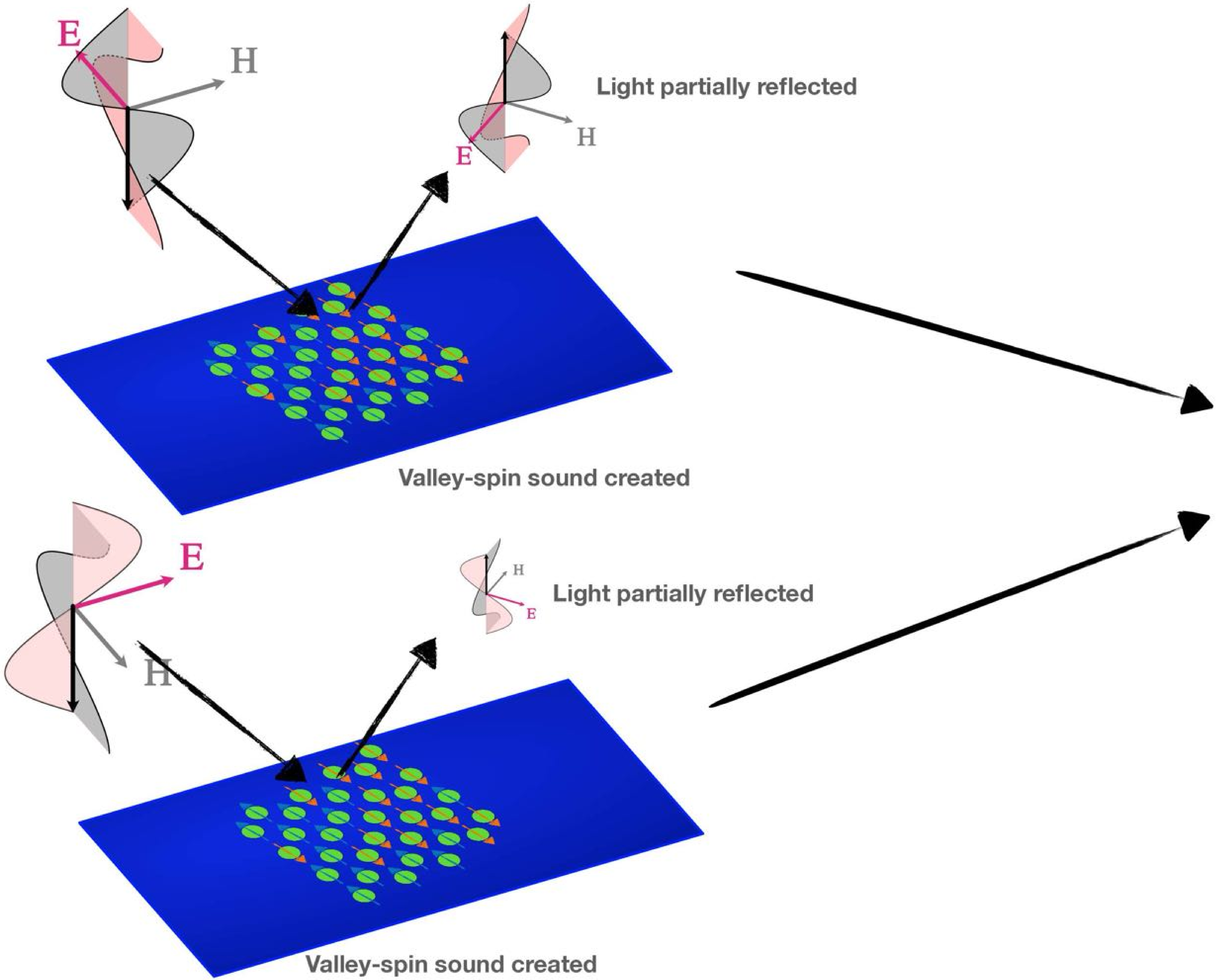
Observable consequences

Collective mode resonances

- Using these techniques we were able to predict the existence of a type of sound associated with the valley and spin degrees of freedom
- These sound modes produce peaks in the absorption of light by graphene
- Measurement of these modes allows to probe the geometric structure on phase space

Response anisotropy encodes quantum geometry





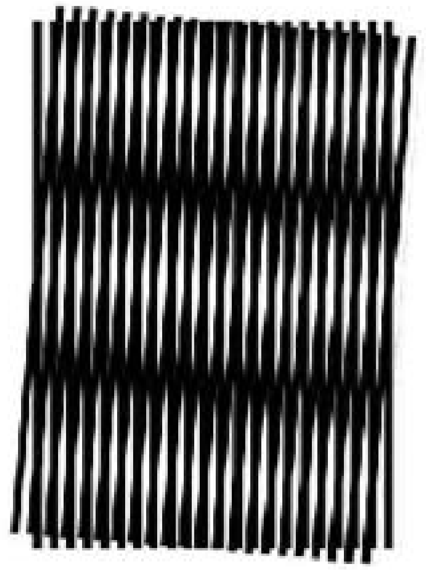
Ratio of absorptions tells us about the quantum geometry

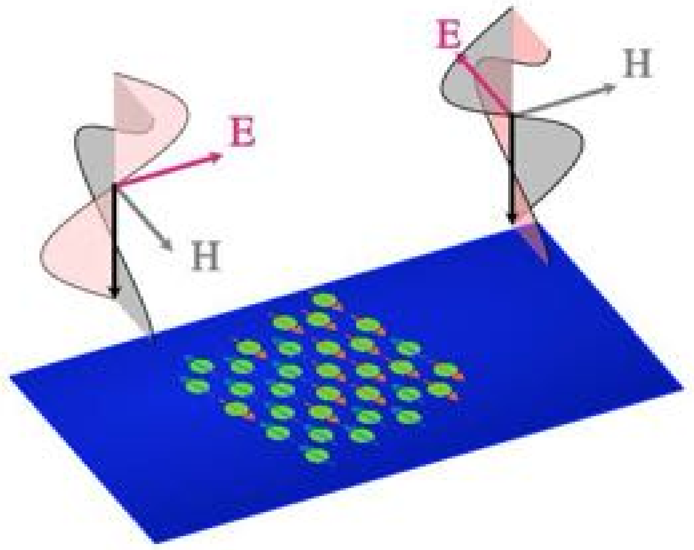
Outlook

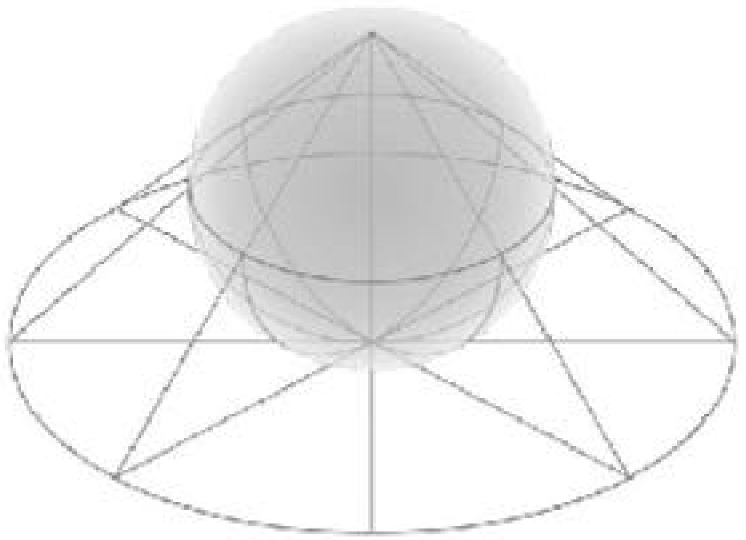
- We generalized the intuitive picture of Landau to a broader class of materials and unified it with results obtainable by other more opaque techniques
  - Previous formulations of the multicomponent Landau picture systematically miss certain classes of effects
- The derived description is valid for general metallic systems with internal structure/geometry
  - This formalism can be applied to study in other systems e.g. transition metal dichalcogenides, twisted multi-layer graphene

Future directions

- Extend these techniques to systems other than metals: superconductors in particular
- Apply these techniques to twisted n-layer (moiré) systems
- Search for other experimental probes of quantum geometry
- Relating geometric formulations of quantum mechanics and semi-classical quasiparticle descriptions

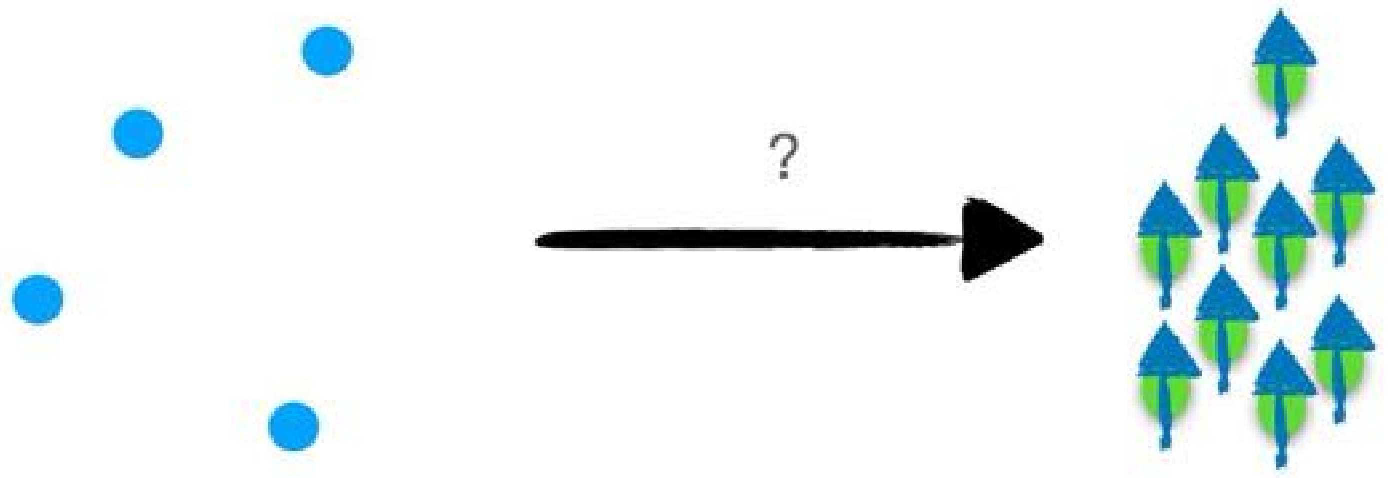






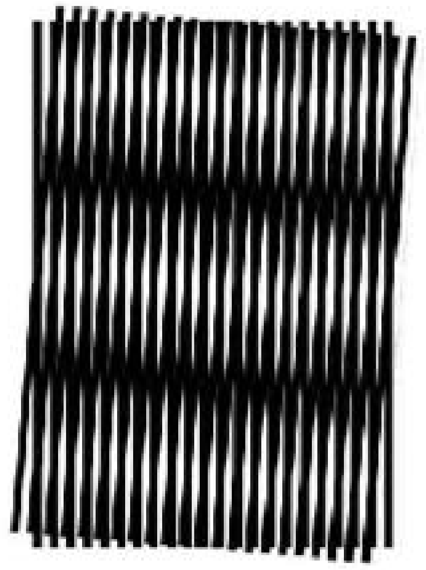
Future directions

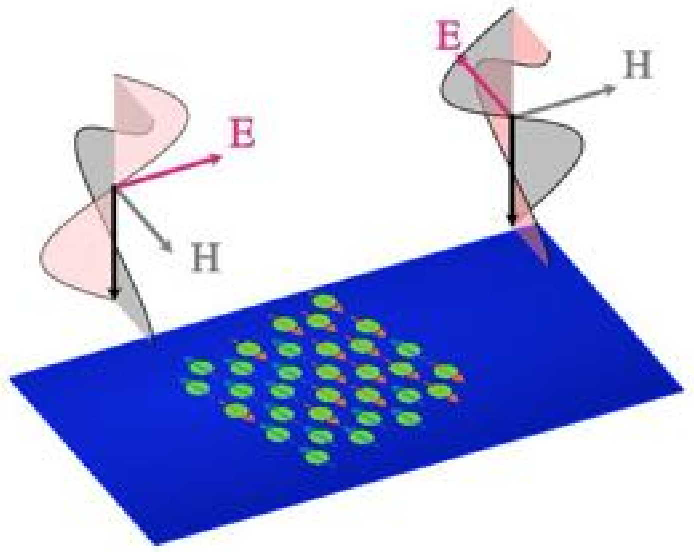
- **Extend these techniques to systems other than metals: superconductors in particular**
  - What if the equilibrium state is not smoothly connected to the Fermi gas?
  - We can have spontaneous symmetry breaking, e.g. magnetism, superconductivity, …
  - A modified Fermi-liquid-like description still applies

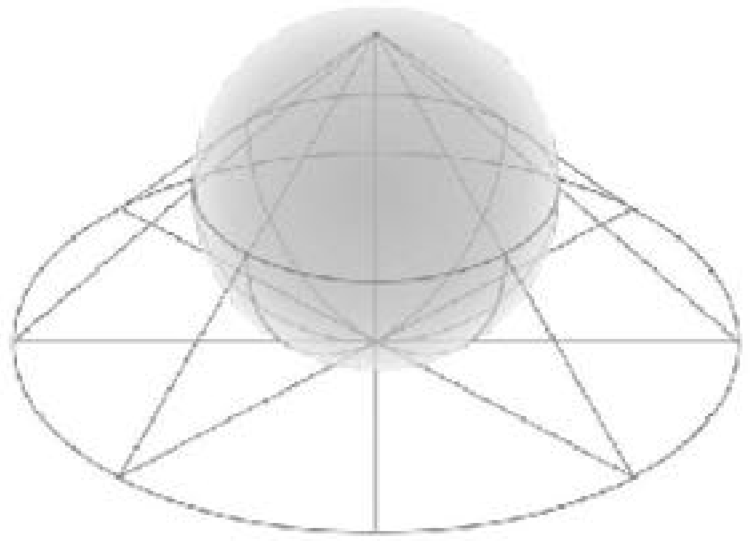


Future directions

- Extend these techniques to systems other than metals: superconductors in particular
- Apply these techniques to twisted n-layer (moiré) systems
- Search for other experimental probes of quantum geometry
- Relating geometric formulations of quantum mechanics and semi-classical quasiparticle descriptions







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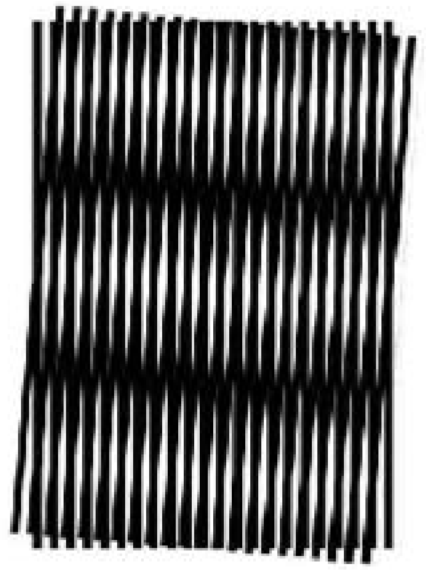

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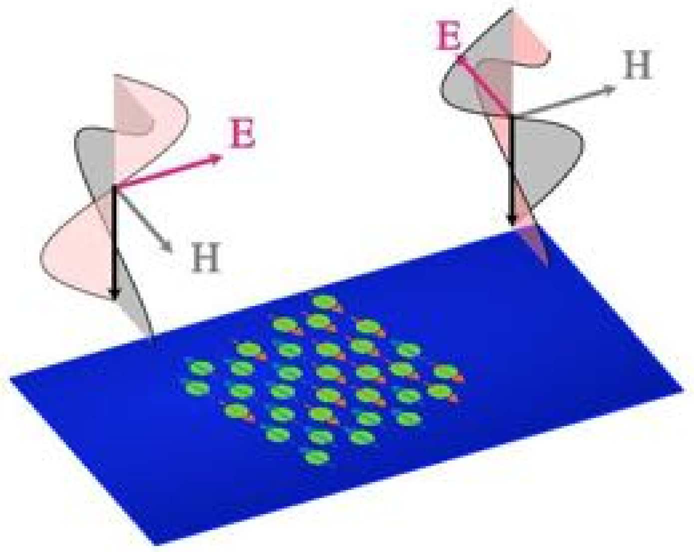

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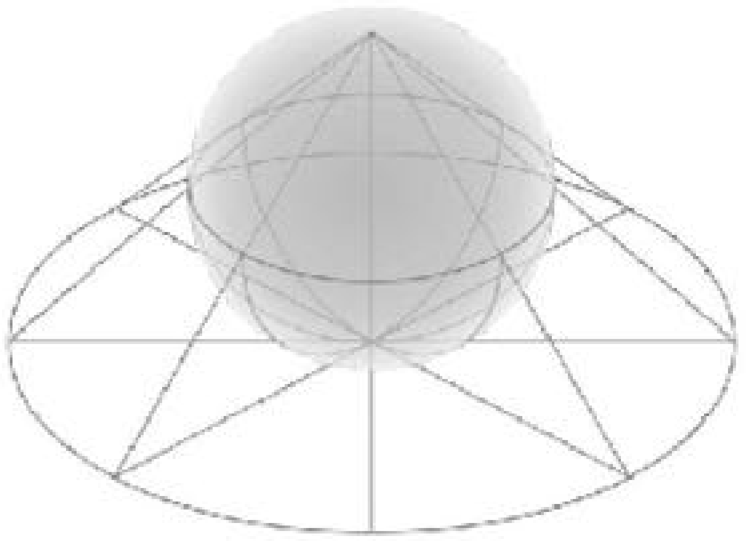
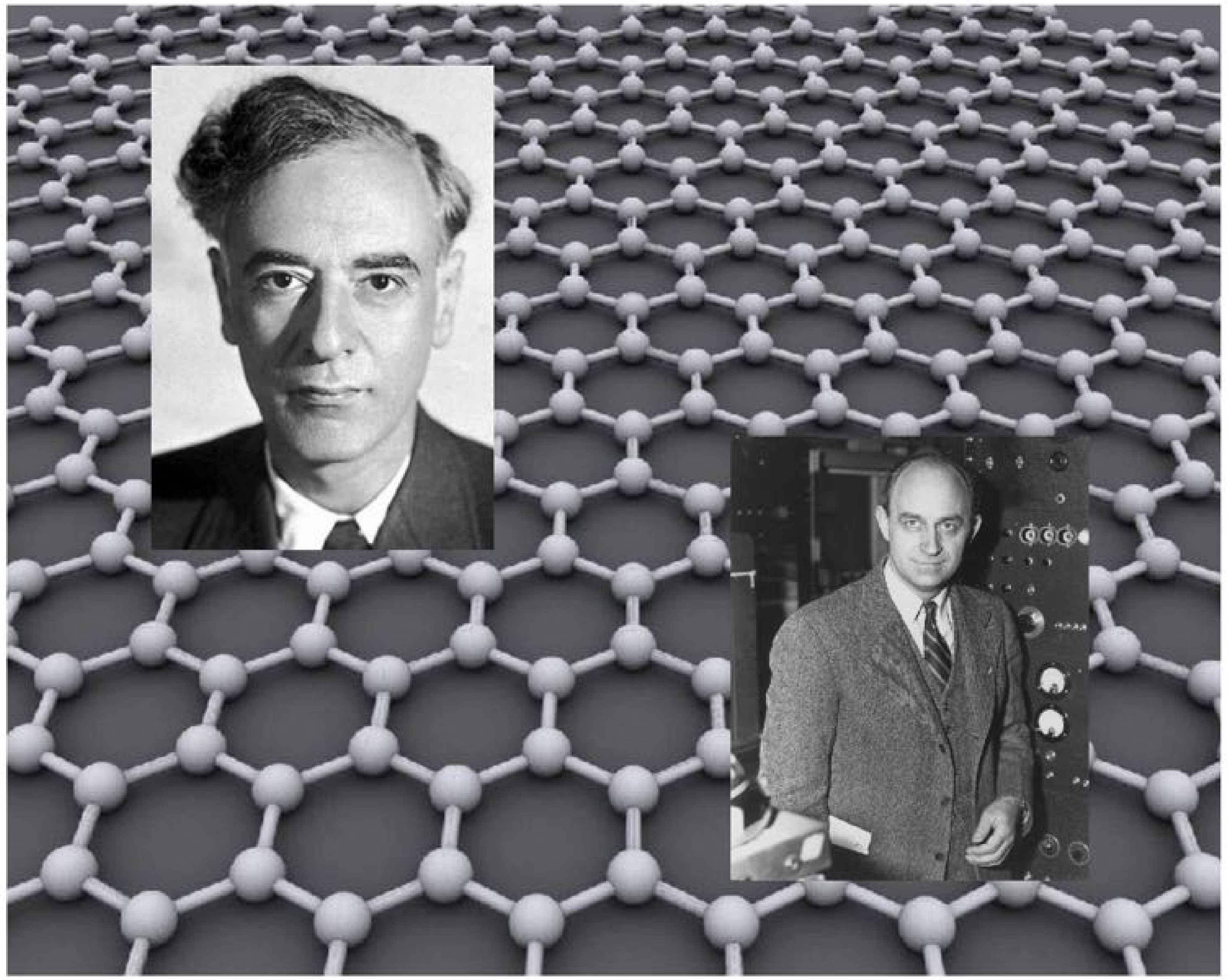


Slides at zmraines.com

Summary

- Landau-Fermi liquid theory formalizes a tractable description of metals in terms of "quasi-particles"
- We have extended this description to systems with more complicated "quasi-particle" structure, e.g. graphene
- The extended theory can be used to derive experimental consequences of the additional structure in these systems



ZMR, **Fal'ko, Glazman**
PRB **103**, 075422 (2021)
10.1103/PhysRevB.103.075422

ZMR, **Maslov, Glazman**
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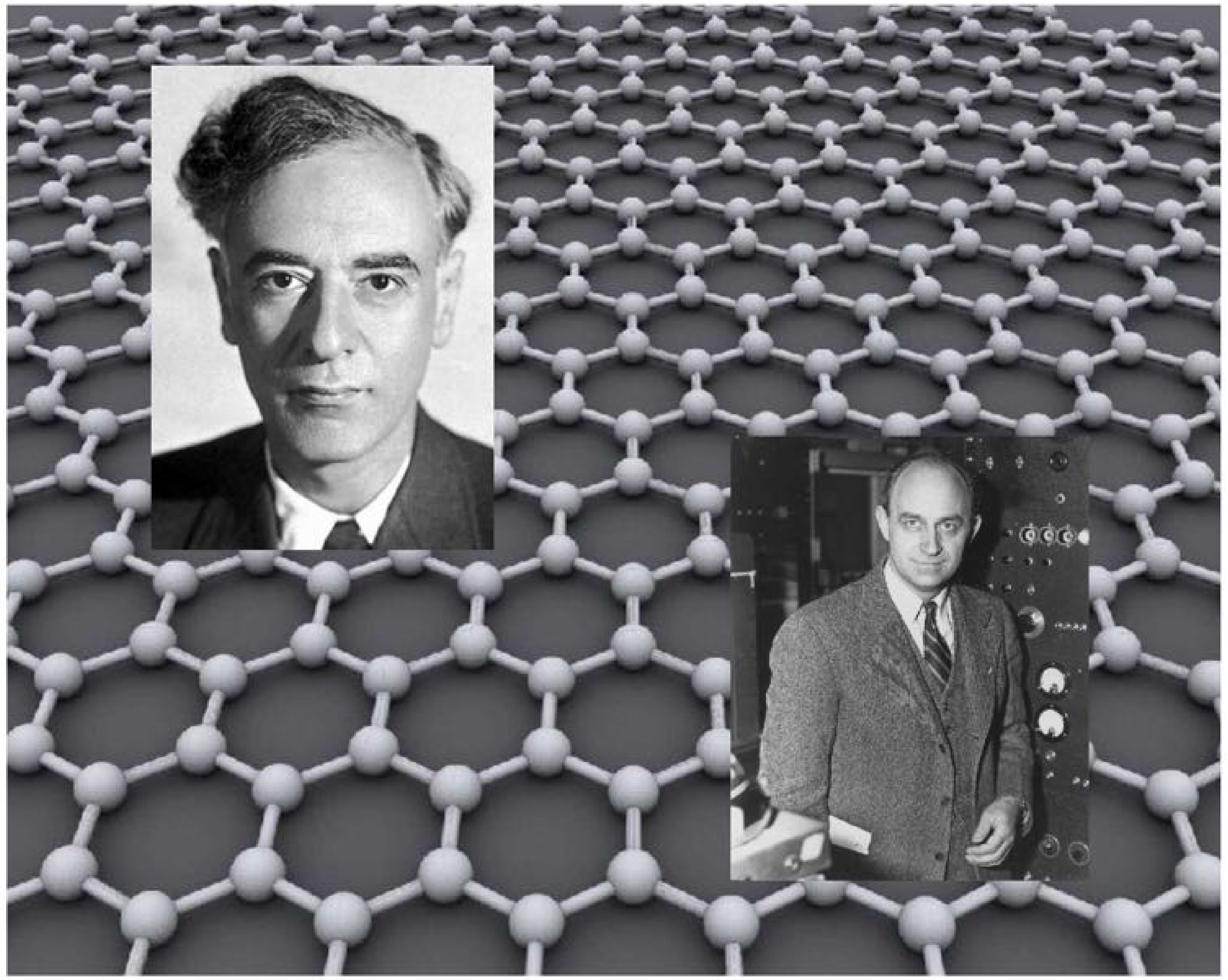

Thank you for your attention!

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