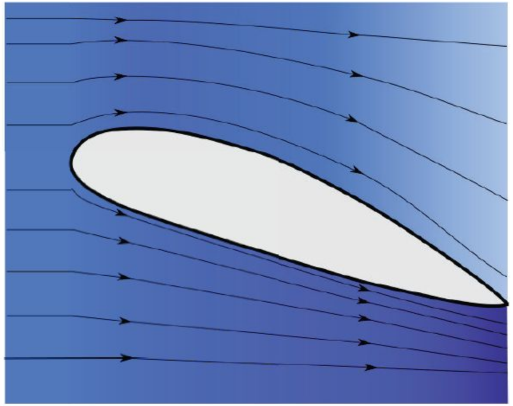
Electron fluids

Leonid Levitov (MIT)

Boulder Summer School 2025

Fluids: chaotic on microscales, orderly on macroscales (conservation laws!)



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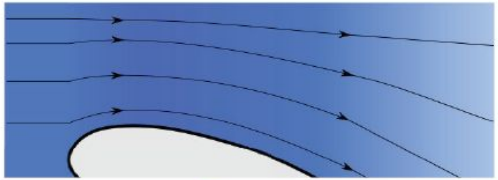

Hydrodynamics: theory of everything

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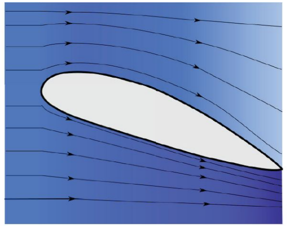
Hydrodynamic description (big picture)

- Space and time symmetries: Eulidean P, T, O(3), spin SU(2)
- Continuous (global) symmetries result in (local) conservation laws
- Local transport equations
- Example: Fermi liquids $\partial_t n+\nabla j=0$, $\partial_t p+\nabla \Pi+\gamma=enE$, where n and p – particle and momentum density – conserved quantities, j and Π – current and stress tensor (aka Fermi pressure) – functions of conserved quantities, γ – momentum dissipation rate (disorder or phonons)
- Separation of time scales–nonconserved quantities quickly erased from system memory (Boltzmann). Ordered behavior from chaotic behavior



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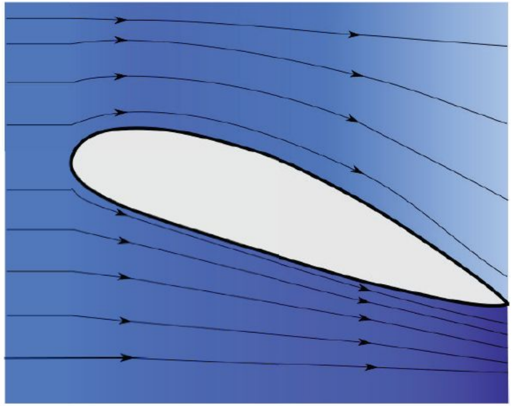
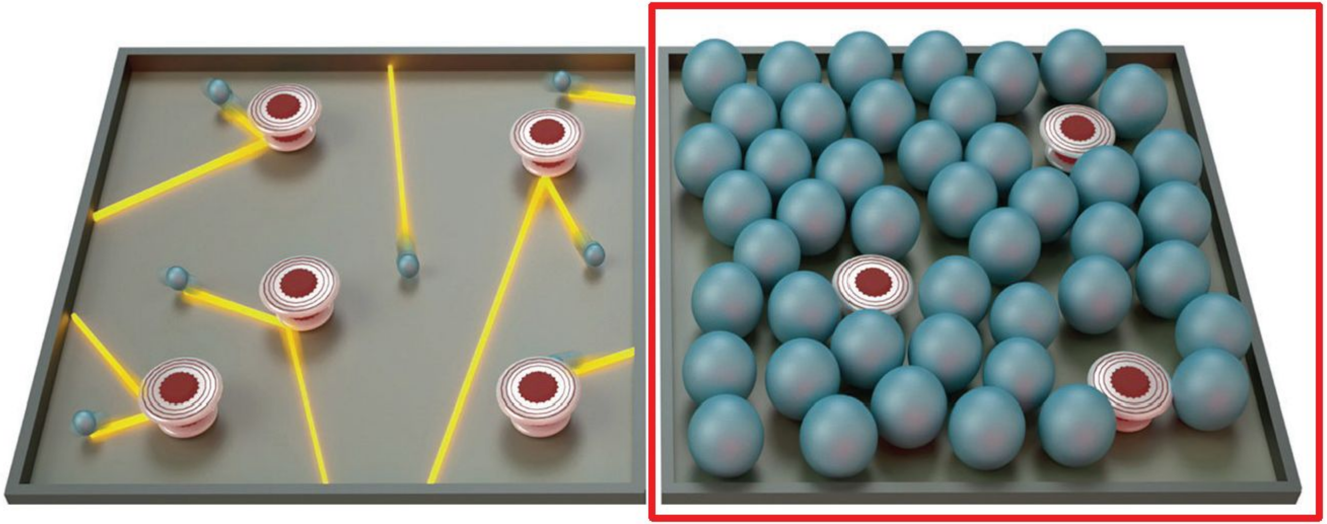


Ergodicity and separation of scales

- Short-time memory for nonconserved quantities, long-time memory for conserved quantities
- Markovian picture (hydrodynamics justification and validity)
- Interesting non-Markovian effects:
  - in classical gases (Dorfman and Cohen),
  - in quantum systems with disorder: quenching of diffusion, Anderson localization and weak localization (Gorkov, Larkin, Khmelnitskii),
  - many-body localization,
  - many others
- Manifestations:
  - nonlocal transport equations,
  - kinetic coeffieints with long-time memory,
  - infinite or diverging thermalization rates

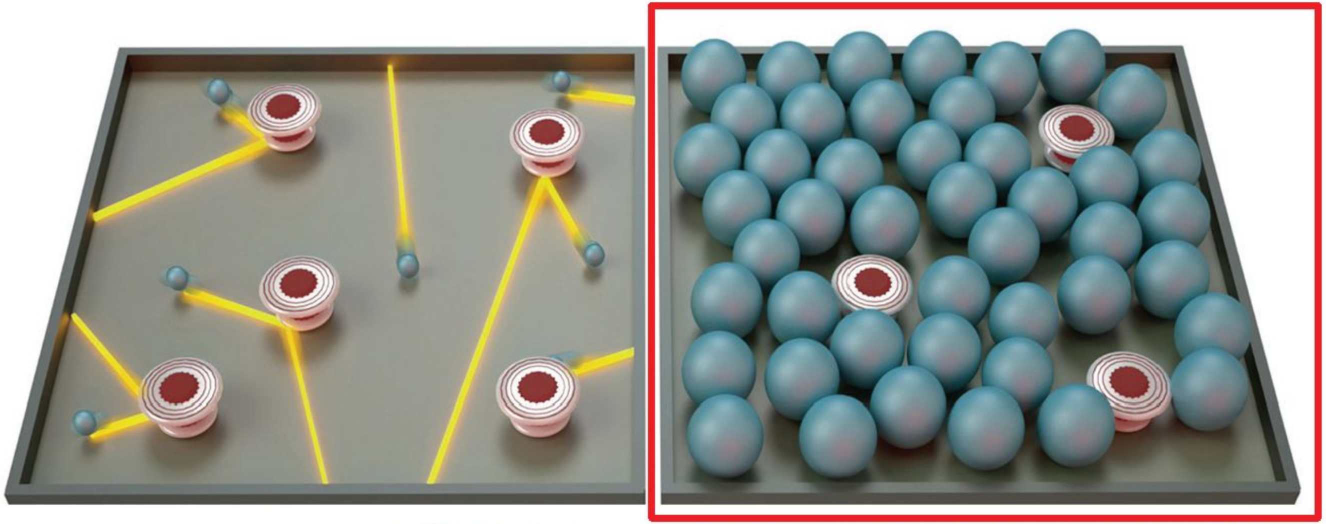
Is hydrodynamics ever relevant in metals?



credit: Andy Lucas; from: Jan Zaanen, Science 2016

- High-mobility electron systems (graphene, GaAs 2DES, $PdCoO_2$, etc):
- Non-Fermi liquids, high-Tc superconductors, strange metals

Is hydrodynamics ever relevant in metals?



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- High-mobility electron systems (graphene, GaAs 2DES, $PdCoO_2$, etc):
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Literature

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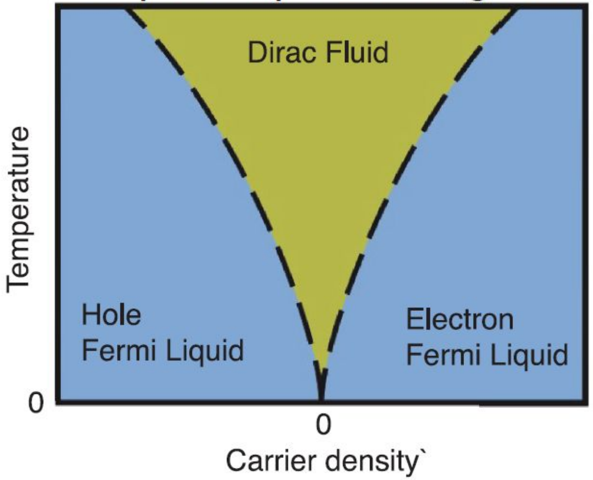
Gooth *et al.* Electrical and Thermal Transport at the Planckian Bound of Dissipation in WP2 (2017)

...

Viscous electron fluids in 2D systems

- Strong interactions (enhanced in 2D, graphene)
- Graphene: weak electron-phonon scattering, no Umklapp ee scattering
- Fast p-conserving ee collisions, shear viscosity

Graphene phase diagram



Sheehy and Schmalian, PRL 99, 226803 (2007)

Guo et al. 1607.07269 1612.09239 Bandurin et al. 1703.06672, Ledwith et al. 1708.01915, 1708.02376

Viscous electron fluids in 2D systems

- Strong interactions (enhanced in 2D, graphene)
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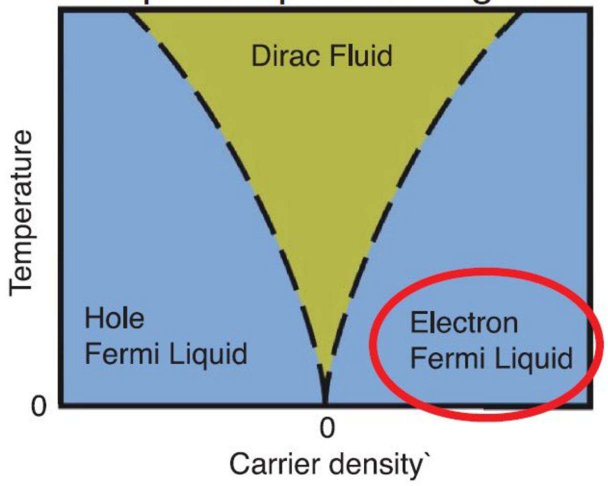
- **Signatures of viscous effects?**
- **New collective phenomena?**

Graphene phase diagram



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Why to be interested in electron hydrodynamics?

- Viscous transport: A new regime showing a counterintuitive behavior: **carrier collisions assist conduction**. Compare to motional narrowing in spin resonance (Van Fleck and Anderson) or collision-narrowing in optics (the Dicke effect)
- **Conductance grows with T**: R(T=0)>R(T≠0). Other instances: Kondo impurity scattering or localization (dG/dT>0 reflects spin correlations or suppression of quantum coherence)
- This lecture: **a non-Fermi-liquid temperature dependence** in electron hydrodynamics. Surprisingly, the measured T dependence is **linear** rather than T^2. Explanation?

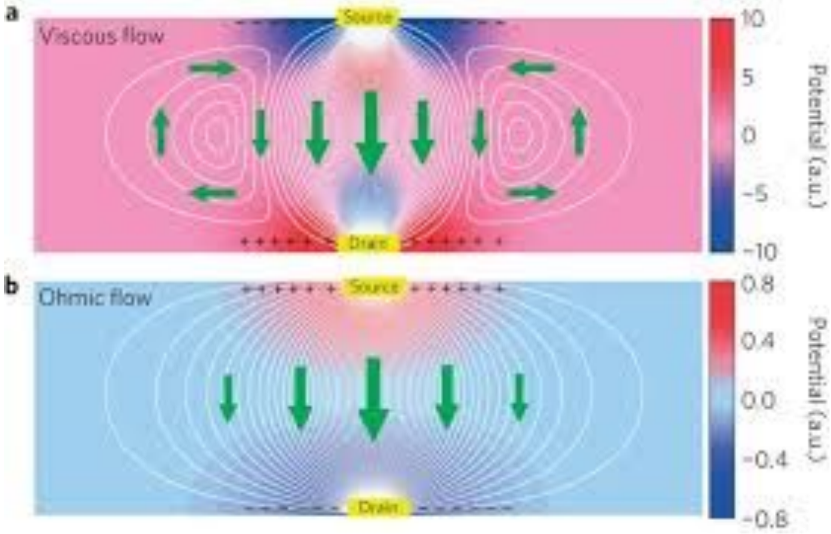
Serhii Kryhin ‘22

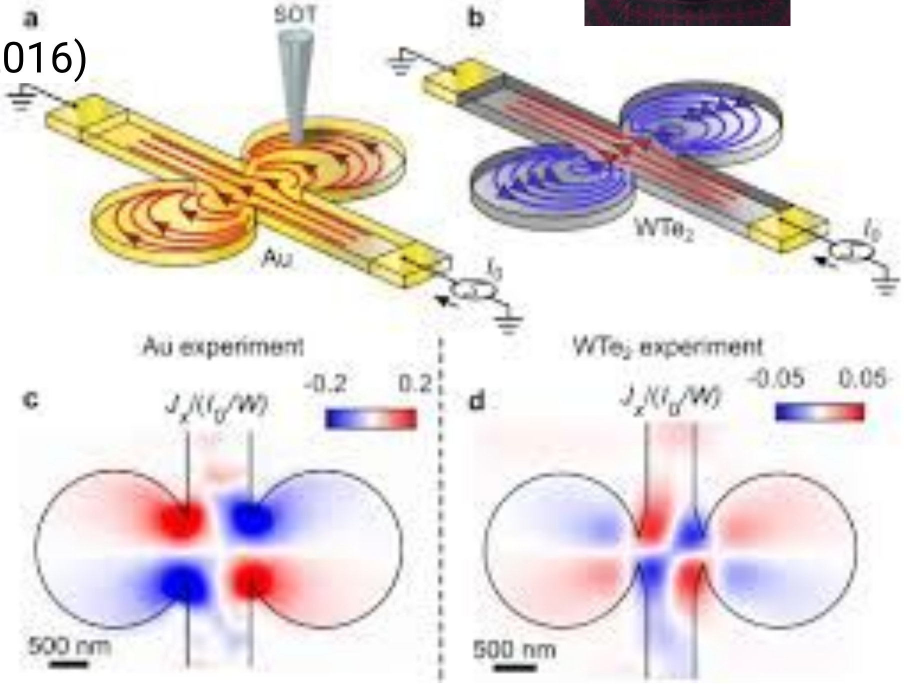
Why to be interested in electron hydrodynamics?

Vortices in electron fluids studied by scanning probe (Zeldov goup, Weizmann Institute).

Current flow opposite to E field

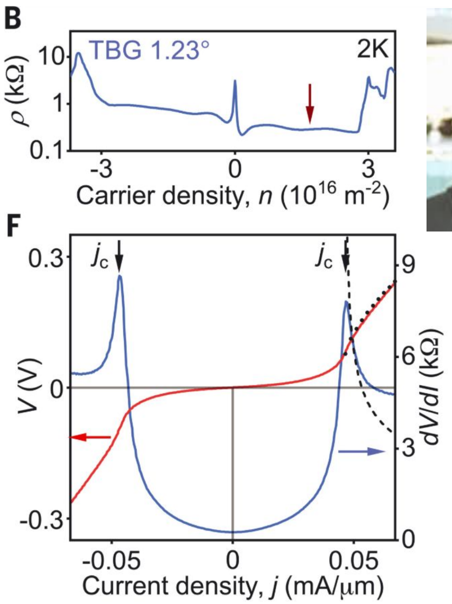
LL & Falkovich, Nature Phys 12, 672–676 (2016)

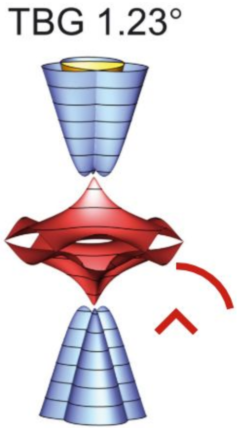




Why to be interested in electron hydrodynamics?

Hydrodynamic instabilities under small, experimentally accessible fields. Current-induced inversion of band occupation (experiments in graphene multilayers and monolayers, moire and non-moire. Current-driven ordering?





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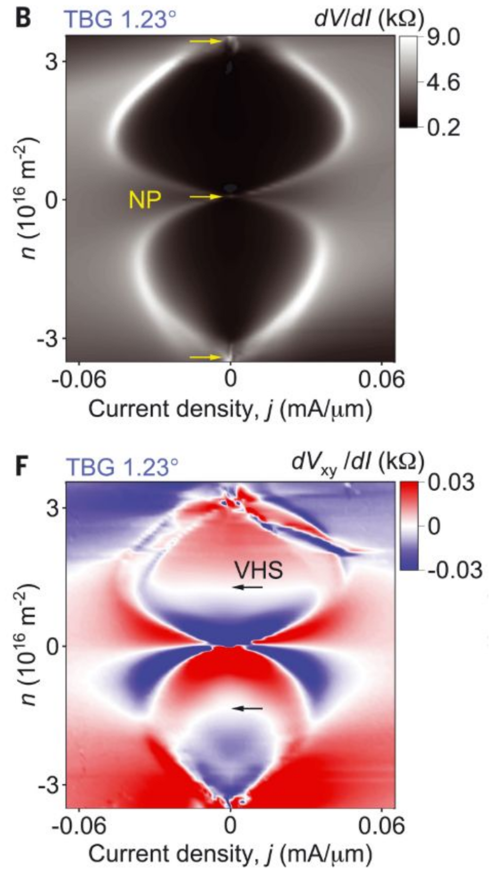
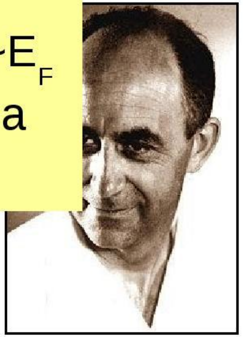


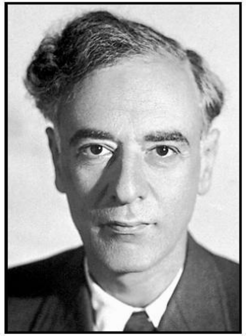
Tomographic electron fluids

- Quasiparticle lifetimes
- Kinetic coefficients
- Nonlocal conductivity
- Tomographic transport
- New phenomena

Quasiparticle lifetimes in Landau Fermi-liquids:

- Fermi sea (filled states with $E<E_F$)
- All the action at the Fermi surface, $E \sim E_F$
- Quasiparticles: quasi-free particles in a strongly interacting system





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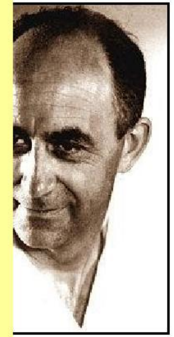
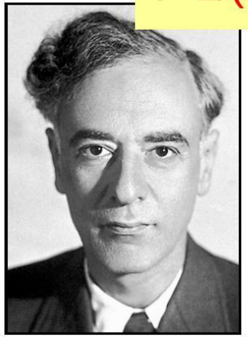
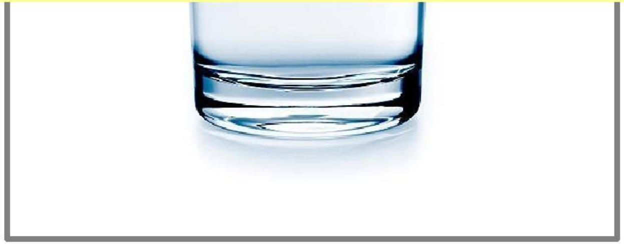
- Relatively long lifetimes in 3D systems: $\tau \sim 1/(E-E_F)^2$, $\tau \sim 1/(k_B T)^2$
- Even longer lifetimes in 2D systems: $\tau \sim 1/(k_B T)^4$ for odd-parity excitations







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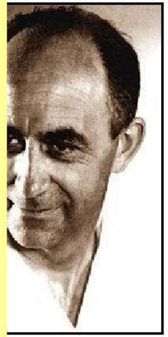

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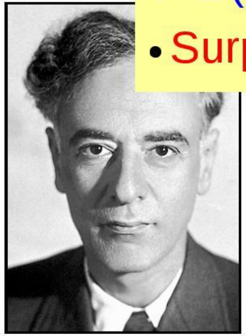
- Surprising collective behaviors in e-fluids



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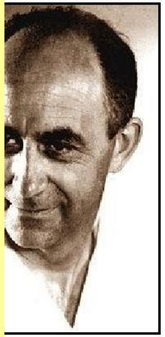
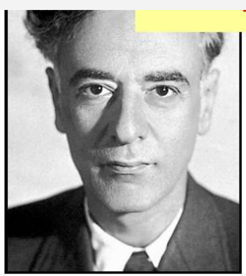
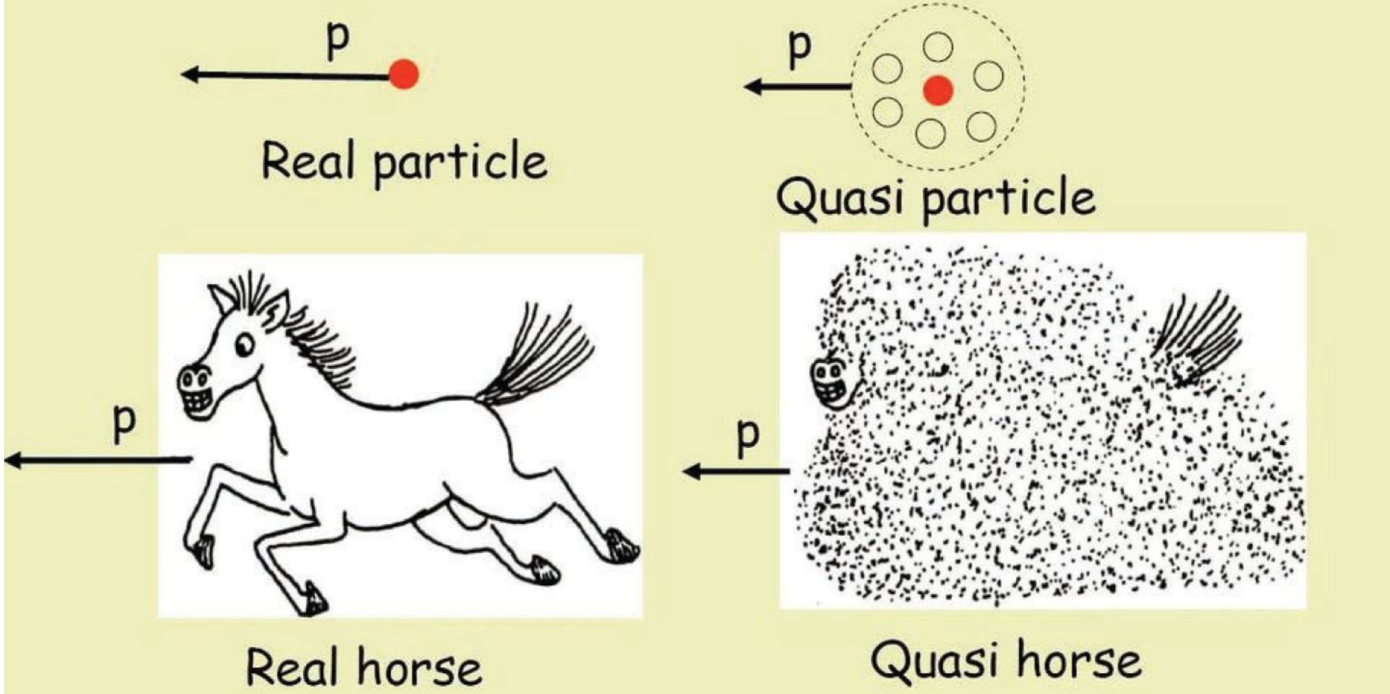


One cannot live in society and be free from society (V I Lenin)



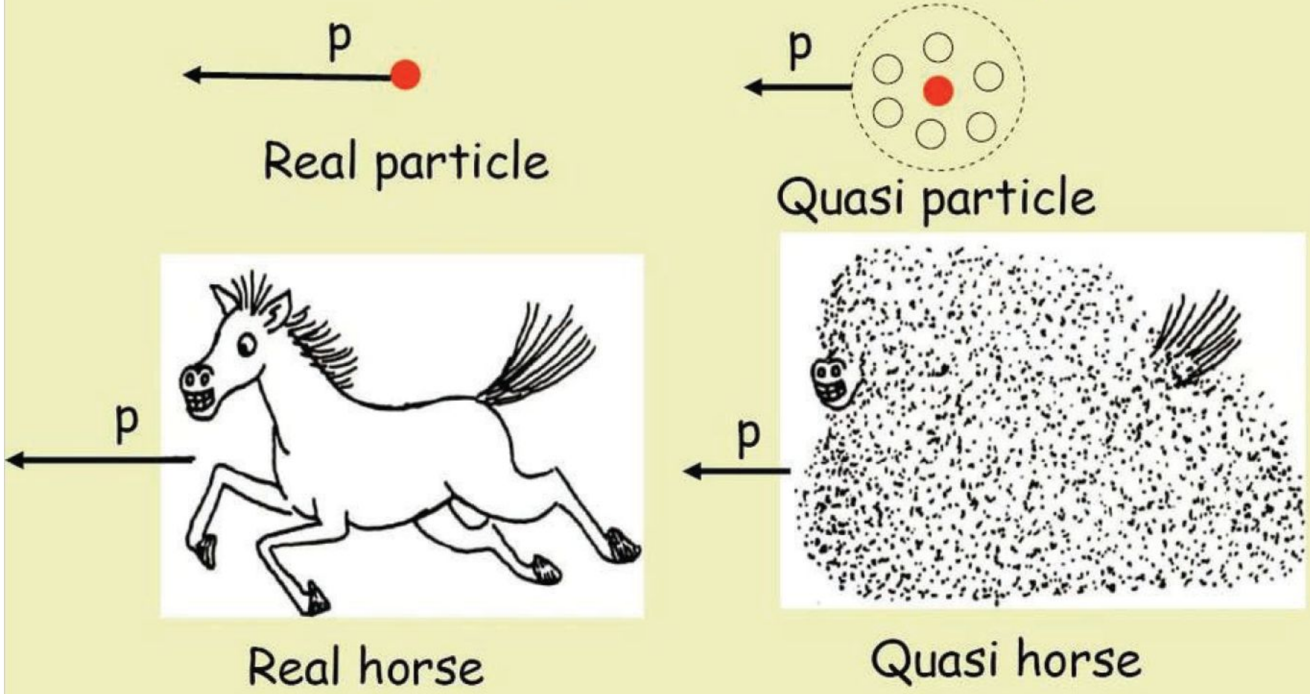
Quasiparticle concept



R. D. Mattuck, a guide to Feynman Diagrams in the MB problem, Dover, 1976

A quasiparticle has an effective mass, selfenergy (energy and lifetime).

Quasiparticle concept



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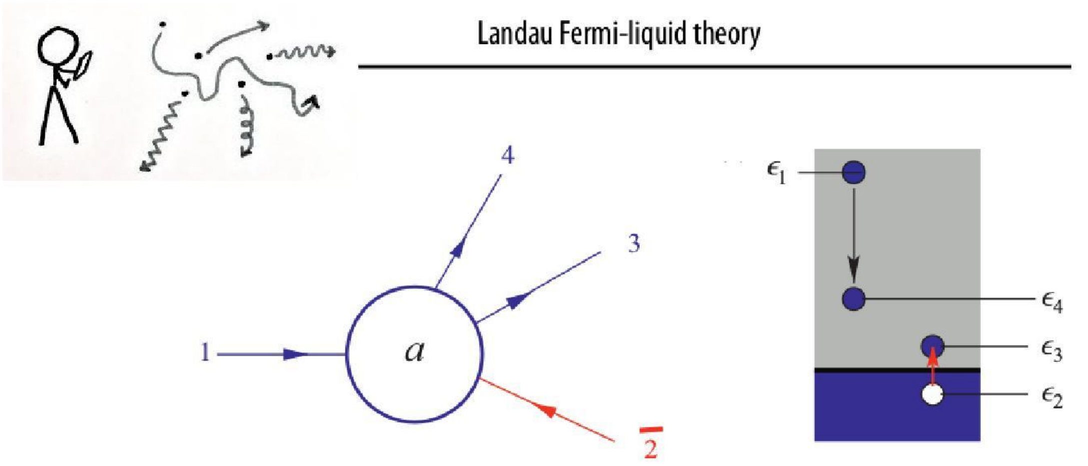
The phase space argument



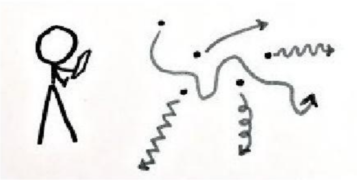
$$\gamma \sim \int\int \delta(\epsilon_1 + \epsilon_2 - \epsilon_3 - \epsilon_4) f(\epsilon_2)(1 - f(\epsilon_3))(1 - f(\epsilon_4)) \sim max[\epsilon_1^2, T^2]$$

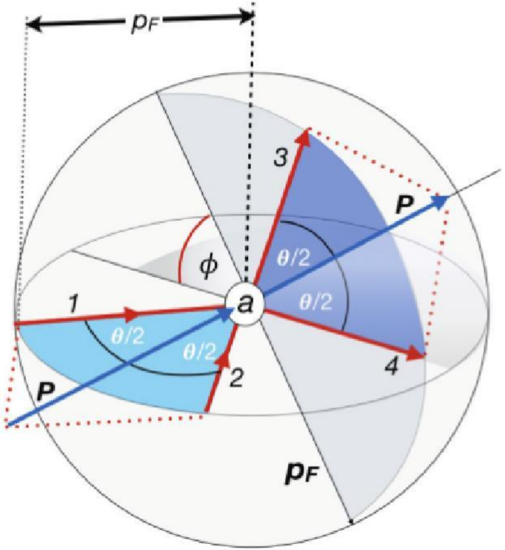
credit: Coleman, Introduction to many-body physics

Kinematics of ee scattering:

In 3D angular relaxation not a bottleneck (and thus does not matter)

Landau argument works





credit: Coleman, Introduction to many-body physics

Kinematics of ee scattering:

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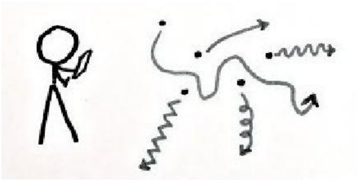
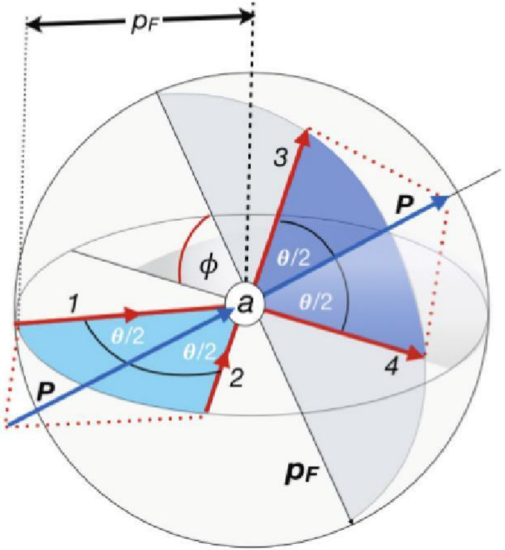
Landau argument works

However, in 2D it does matter!

angular relaxation IS a bottleneck

revision of Fermi-liquid theory required





credit: Coleman, Introduction to many-body physics

Tomographic electron fluids

- Quasiparticle lifetimes
- Kinetic coefficients
- Nonlocal conductivity
- Tomographic transport
- New phenomena

Team

Patrick Ledwith '19

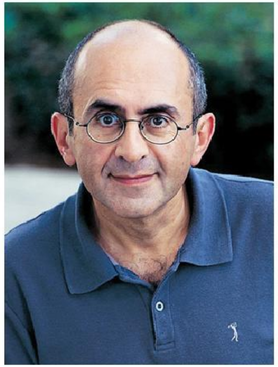
Lev Kendrick '19

Haoyu Guo '18

Andrey Shytov
(Exeter, UK)

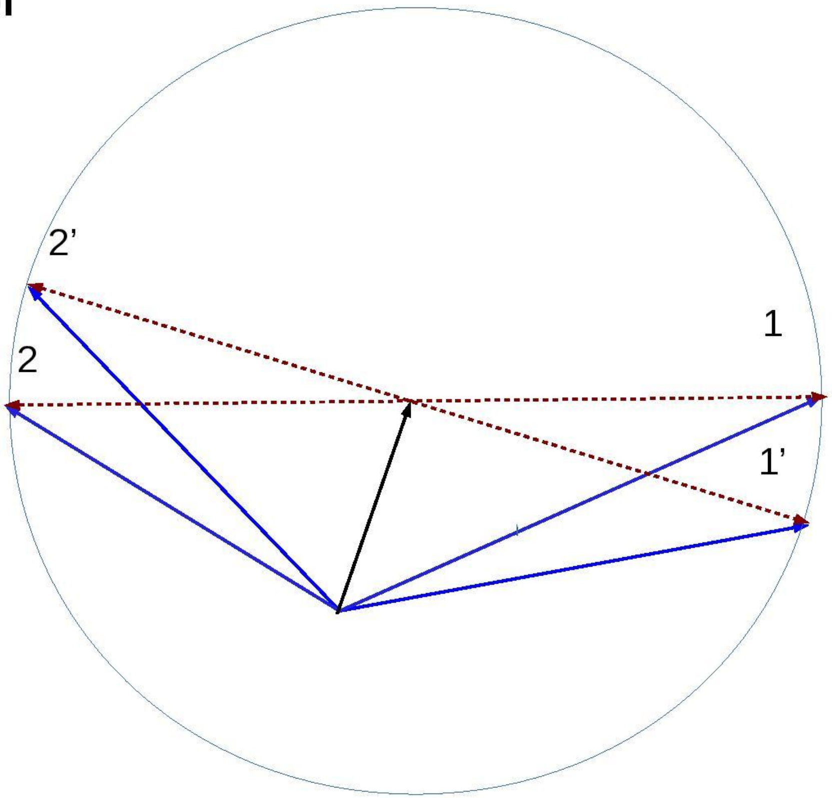
Qiantan Hong '21

Serhii Kryhin '22



Gregory Falkovich
Weizmann Institute

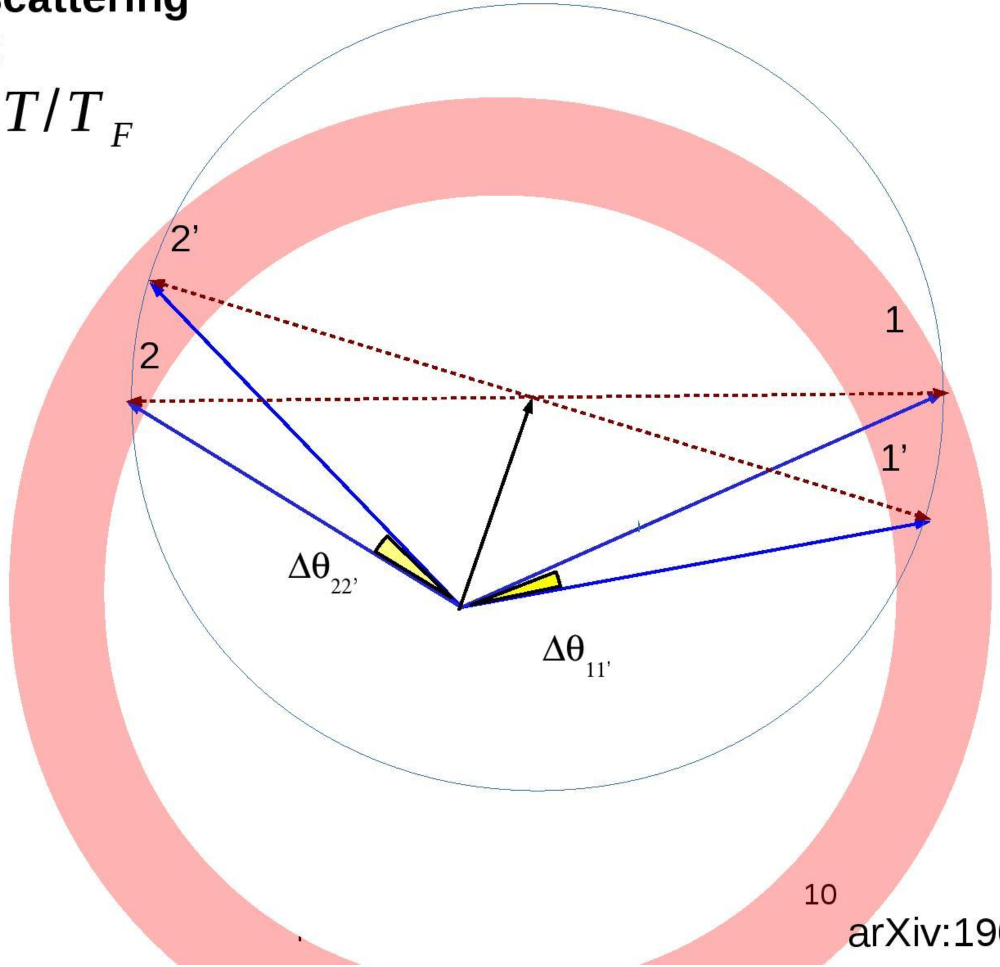
Kinematics of two-body collisions:



arXiv:1905.03751

Small scattering angles:

$$\Delta\theta \sim T/T_F$$



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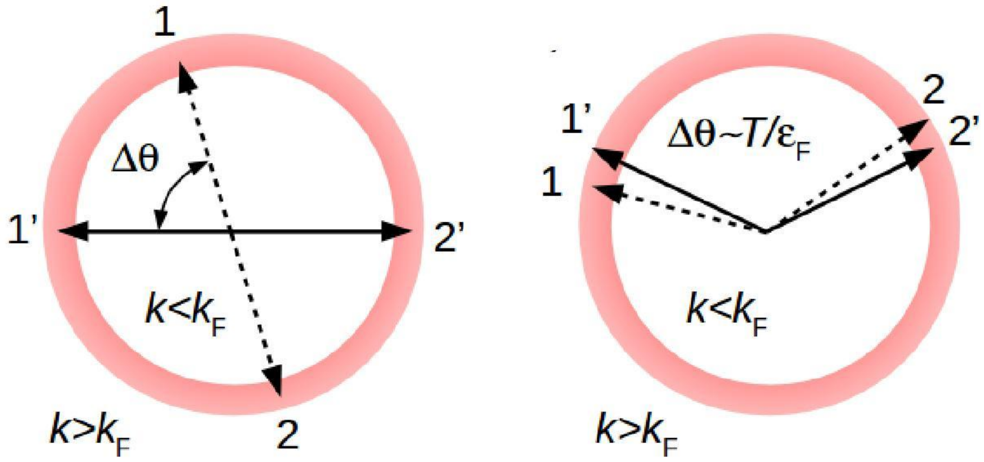
New behavior in 2D

- Momentum conservation and fermion exclusion single out two types of collisions: a) head-on, and b) small-angle
- Angular relaxation dominated by (near) head-on collisions.
- The **even-parity** and **odd-parity** parts of momentum distribution, $\delta f(p)=\delta f(-p)$ & $\delta f(p)=-\delta f(-p)$ relax at different rates



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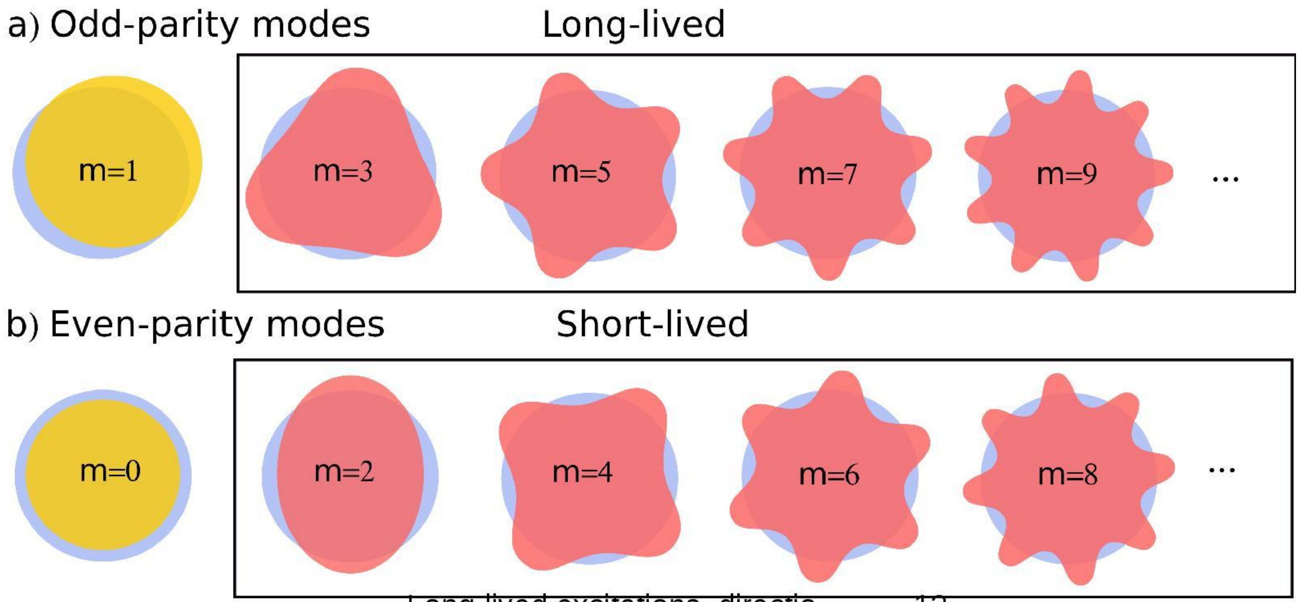
Even and odd harmonics

- The **even-parity** and **odd-parity** parts of momentum distribution, $\delta f(p)=\delta f(-p)$ & $\delta f(p)=-\delta f(-p)$ relax at different rates.
- Relaxation rates for the $\delta f(p)$ harmonics of the **odd** and **even** parity can differ by orders of magnitude: $\gamma'/\gamma\sim(T/T_F)^2$, $\gamma\sim T^2/T_F$



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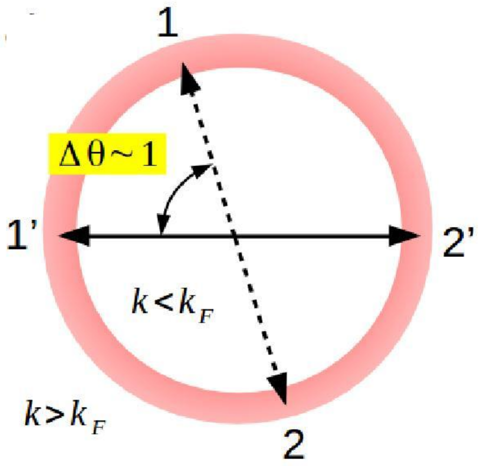
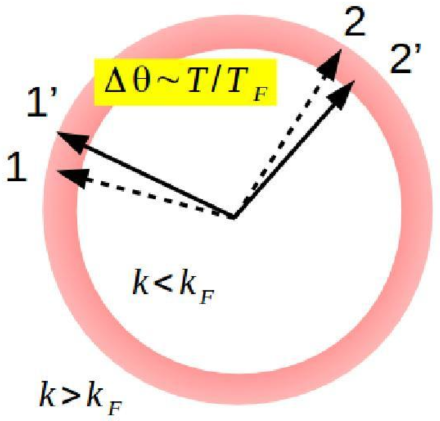
The rates γ_m

Estimating the rates

Angular diffusion

$$\gamma_{m\,even} \sim R_* \frac{T^2}{T_F^2} \qquad \gamma_{m\,odd} \sim R_* \frac{T^2}{T_F^2} \Delta\theta^2 m^2 \sim R_* \frac{T^4}{T_F^4} m^2$$





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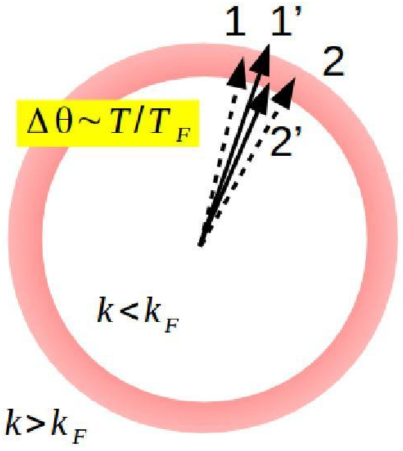
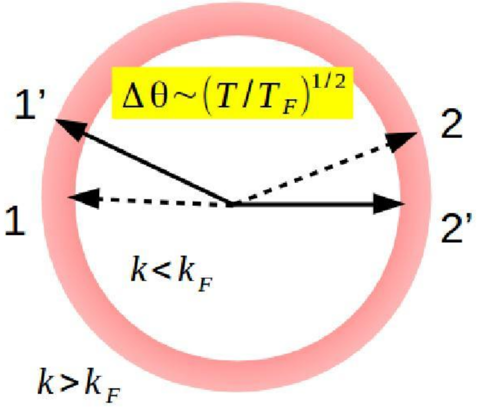
The odd-*m* rates:

$$\gamma_m \sim R_* \frac{T^2}{T_F^2} \Delta\theta^2 m^2 \sim R_* \frac{T^4}{T_F^4} m^2$$



Naively:

$$\gamma_m \sim R_* \frac{T^2}{T_F^2} \Delta\theta^2 m^2 = R_* \frac{T^3}{T_F^3} m^2$$



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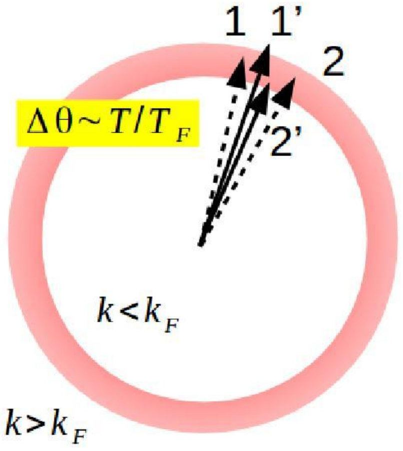

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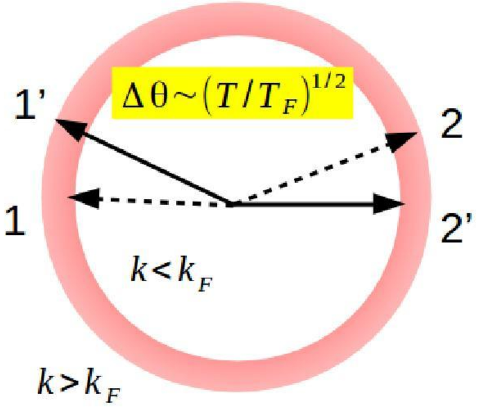
Is this true? Not quite



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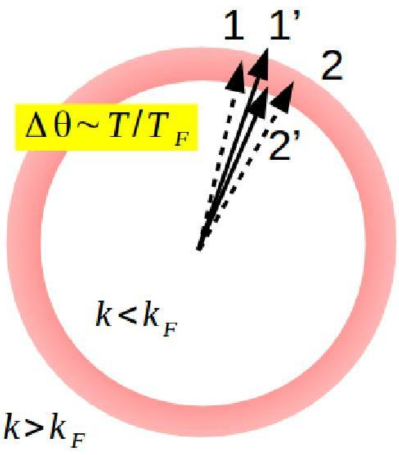
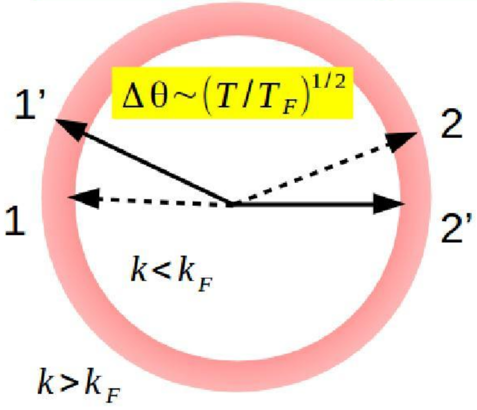


Actually:

Angular superdiffusion

$$\gamma_m \sim R_* \frac{T^2}{T_F^2} (\Delta\theta^2 m^2)^2 = R_* \frac{T^4}{T_F^4} m^4$$

Origin: correlated angular shifts in ee scattering



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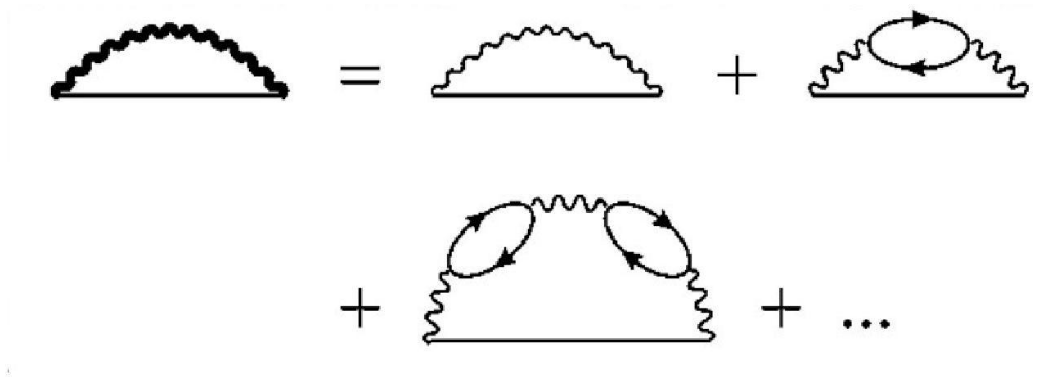
cf. lifetimes from selfenergy in 2D

$$\gamma = -2\Sigma''(\epsilon, p) \sim T^2 \ln(1/T)$$

Chaplik 1971
Hodges, Smith, Wilkins 1971
Bloom 1975
Giuliani, Quinn 1982
Menashe, Laikhtman 1996
Zheng, DasSarma 1996
Chubukov, Maslov 2003



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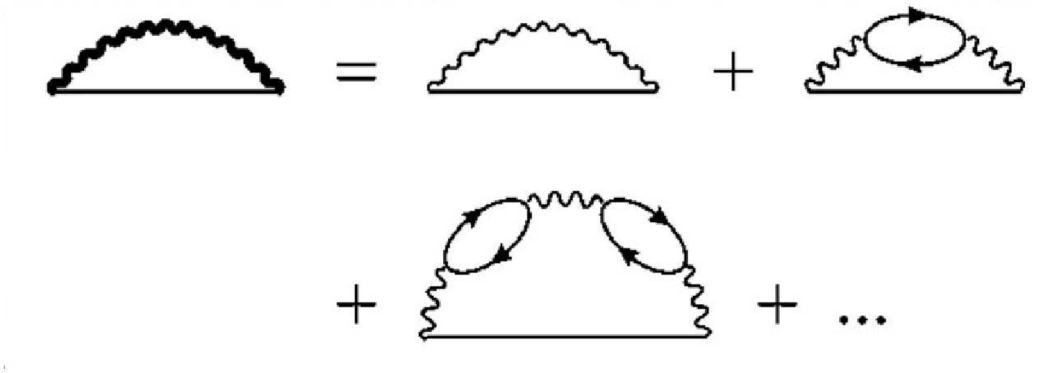
Dominated by the fast pathways (rapid decays)
and by (near) head-on collisions,
Insensitive to slowly decaying modes



Lifetime of two-dimensional electrons measured by tunneling spectroscopy

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(Received 24 October 1994; revised manuscript received 7 June 1995)

For electrons tunneling between parallel two-dimensional electron systems, conservation of in-plane momentum produces sharply resonant current-voltage characteristics and provides a uniquely sensitive probe of the underlying electronic spectral functions. We report here the application of this technique to accurate measurements of the temperature dependence of the electron-electron scattering rate in clean two-dimensional systems. Our results are in qualitative agreement with existing calculations.

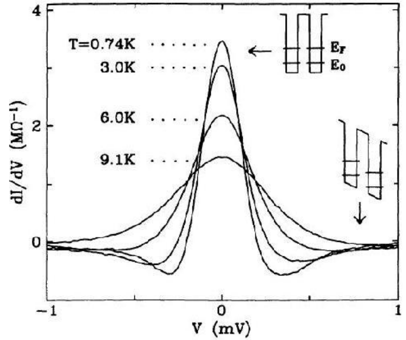

FIG. 1. Typical 2D-2D tunneling resonances observed at various temperatures in a sample with equal densities ($N_s = 1.6 \times 10^{11}$ cm^{-2}) in the two 2DES's. Insets show simplified band diagrams on and off resonance.

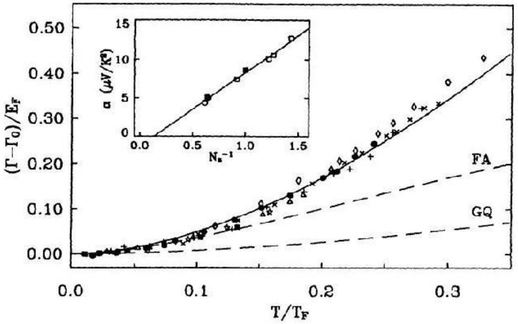

FIG. 3. Tunnel resonance width vs temperature for all samples (having eight different densities). On dividing T by T_F and the resonance width (minus the zero-temperature limit Γ_0) by E_F all the data collapse onto a single curve. The dashed lines are the calculations of GQ (Ref. 18) and FA (Ref. 20). The solid line is 6.3× GQ. Inset: Coefficient of T^2 term in Γ vs inverse density N_s^{-1} (in units of 10^{-11} cm^2).

Lifetimes of individual modes with even and odd *m*, a direct calculation

Kinetic equation, how expansion in T/T_F<<1 fails

Linearize near equilibrium $f(\boldsymbol{p}) = f_0(\boldsymbol{p}) - \frac{\partial f_0}{\partial \epsilon}\eta(\boldsymbol{p})$, $\quad f_0(1-f_0)\frac{d\eta_1}{dt} = I_{\rm ee}\eta$

$$I_{\rm ee}\eta = \sum_{21'2'} \frac{2\pi}{\hbar}|V|^2 F_{121'2'}\delta_{\epsilon_1+\epsilon_2-\epsilon_{1'}-\epsilon_{2'}}\delta^{(2)}_{\boldsymbol{p}_1+\boldsymbol{p}_2-\boldsymbol{p}_{1'}-\boldsymbol{p}_{2'}}\left(\eta_{1'}+\eta_{2'}-\eta_1-\eta_2\right) \qquad F_{121'2'} = f_1^0 f_2^0(1-f_{1'}^0)(1-f_{2'}^0)$$

S Kryhin & LL arXiv:2112.05076

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Focus on individual angular harmonics

$$\eta(\boldsymbol{p},t) = e^{-\gamma_m t}e^{im\theta}\chi_m(x) \qquad -\gamma_m f_0(1-f_0)\chi_m(x) = I_{\rm ee}\chi_m(x)$$

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Integrating over angles yields

$$f_0(1-f_0)\frac{d\chi(x_1)}{dt} = gT^2\int dx_2 dx_{1'}dx_{2'}F\delta(x_1+x_2-x_{1'}-x_{2'})[\chi(x_1)-\chi(x_2)]$$

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Introduce Fourier transform in the energy variable

$$\chi(x) \;=\; 2\cosh\tfrac{x}{2}\,\zeta(x) \qquad \zeta(x) = \int dk e^{ikx} \psi(k)$$

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Obtain a 1D Schrodinger equation with a secanth potential (Poschl-Teller problem)

$$\partial_t \psi(k) = gT^2 \left[\left(\frac{\pi^2}{2} - \frac{\pi^2}{\cosh^2 \pi k} \right) \psi(k) - \frac{1}{2}\psi''(k) \right]$$

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Zero modes, one per each odd *m*

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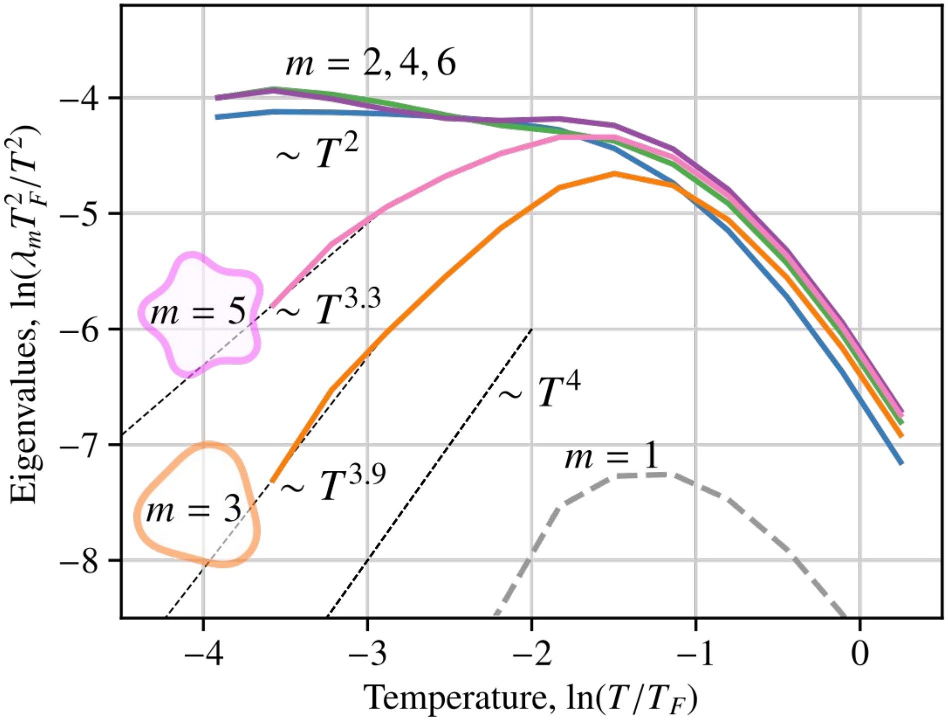
Infinite lifetimes at order T^2

S Kryhin & LL arXiv:2112.05076

Numerically diagonalize the linearized collision operator

A method that does not rely on a small parameter T<<TF



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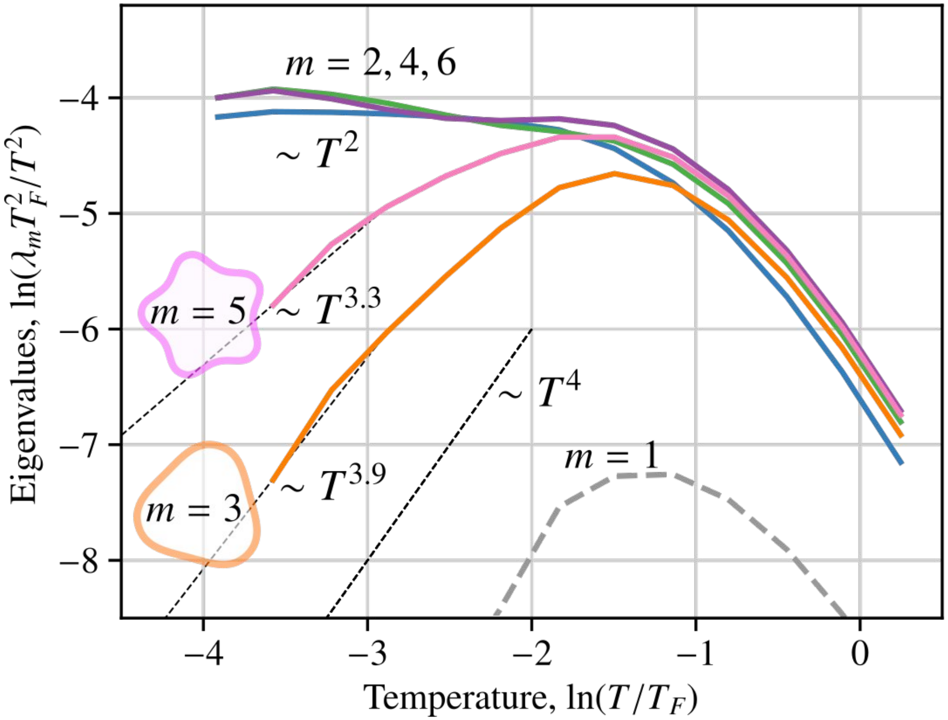
Long-lived excitations: super-Fermi-liquid lifetimes for odd-m harmonics



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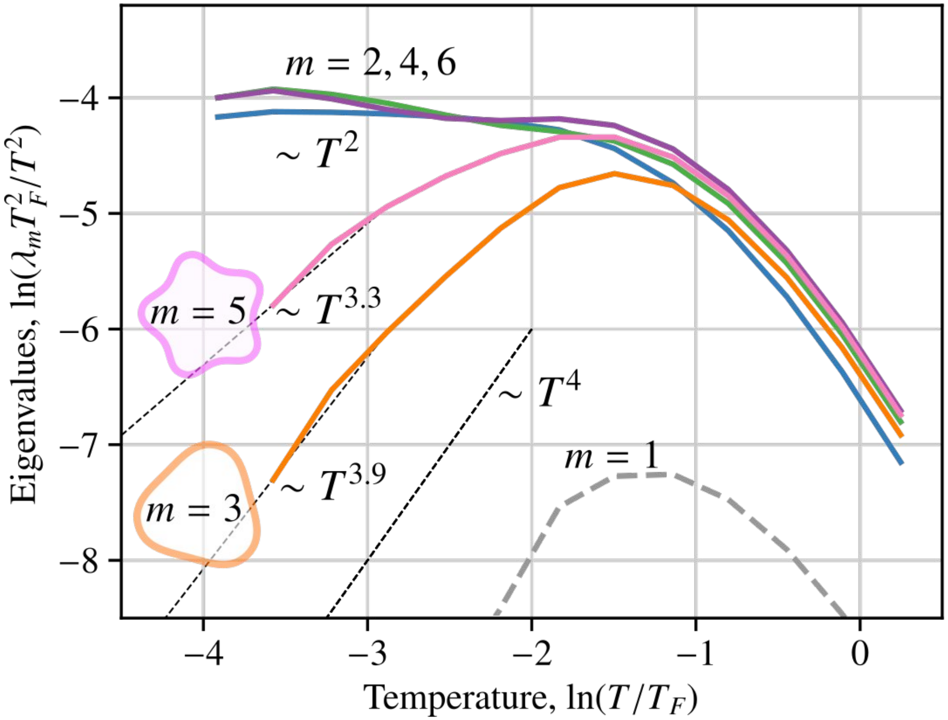
Scaling $\gamma_m \sim T^{\alpha}$, $\alpha \sim 4$



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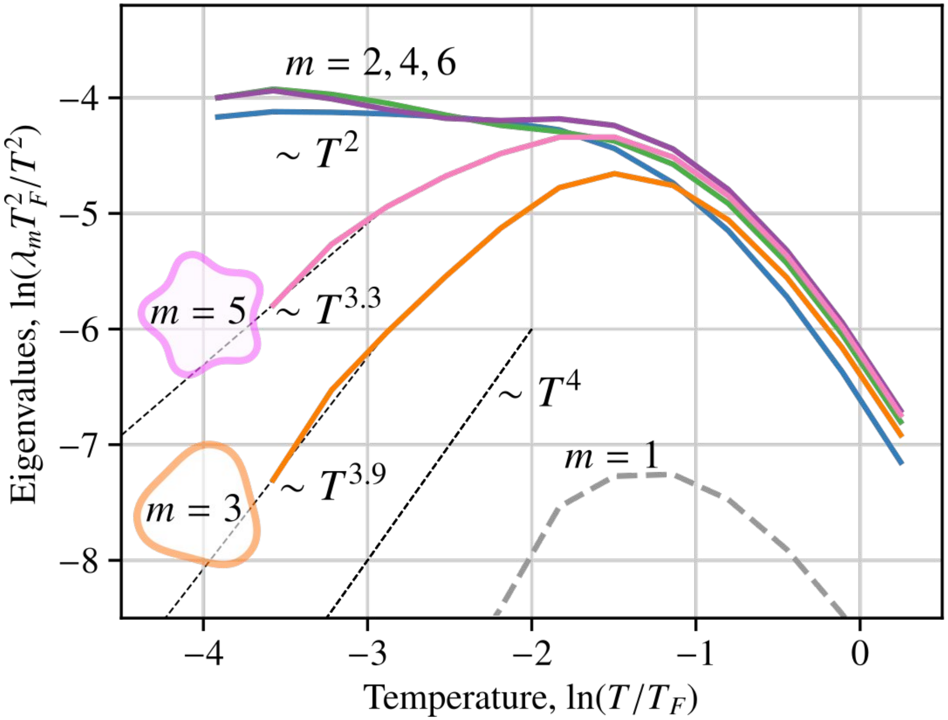
Conventional Fermi-liquid scaling for even-m harmonics



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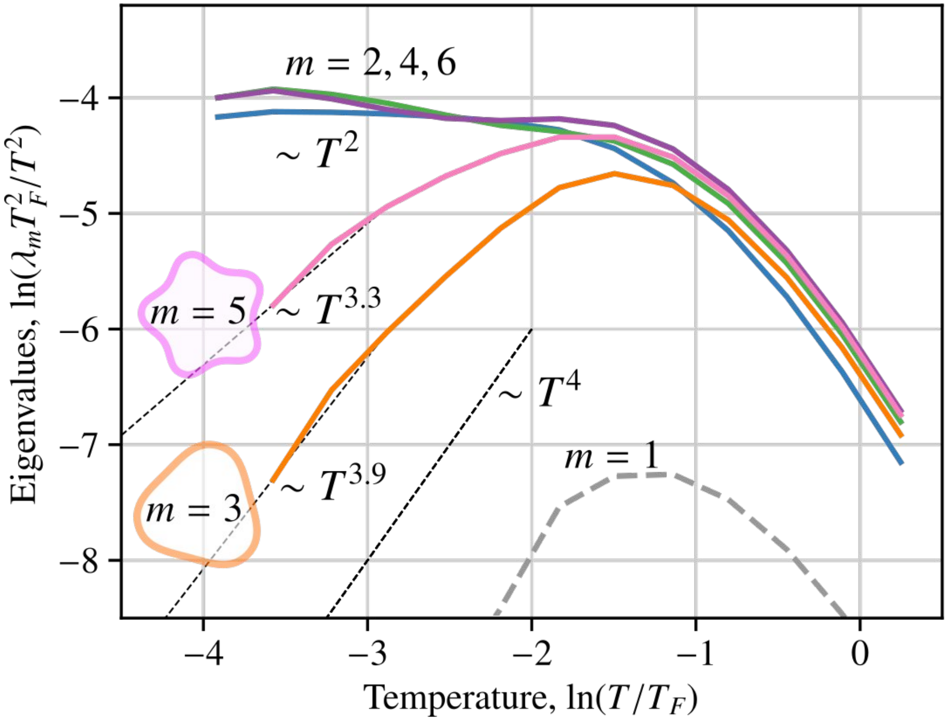
A hierarchy of time scales: $\gamma_{m\ odd} \ll \gamma_{m\ even}$



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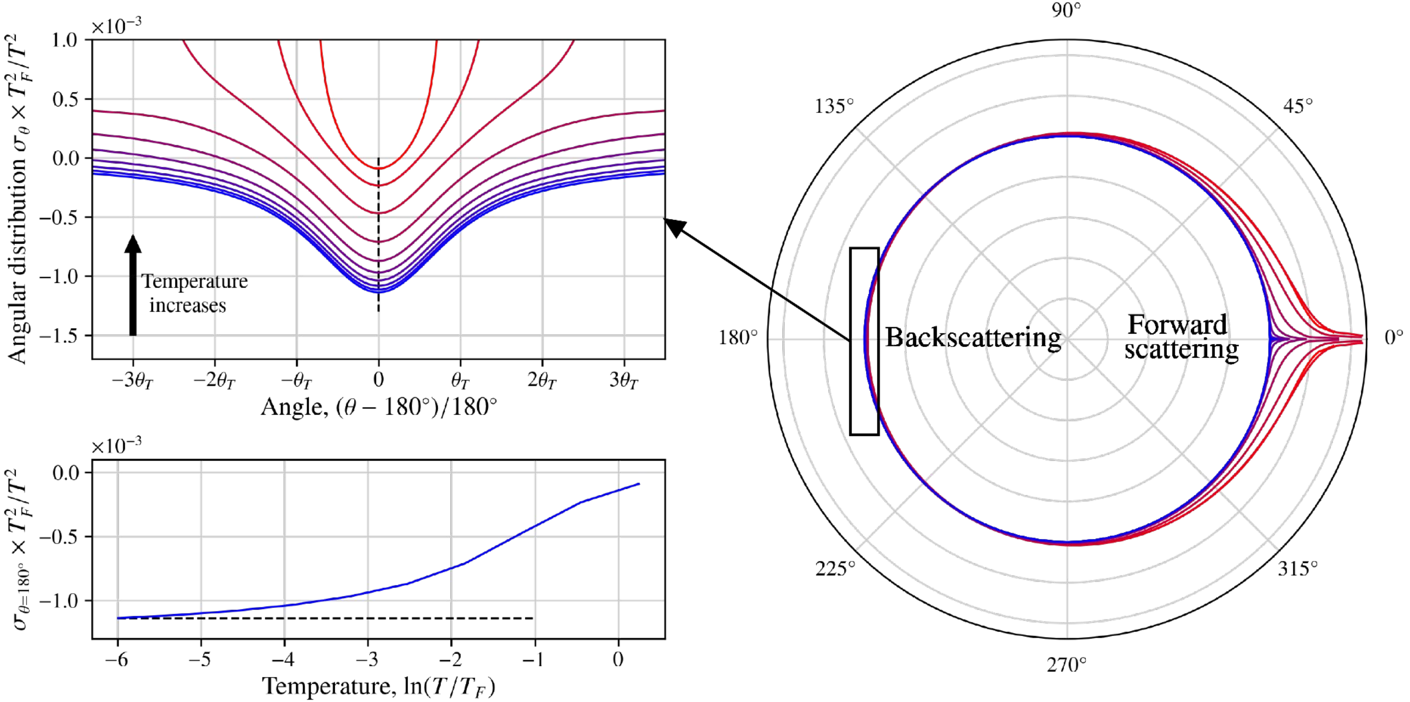
Angular distribution for two-body scattering

$\sim T^2$ for generic angles



$$\sigma(\theta) = \sum_m e^{im(\theta-\theta_i)}(\gamma_m - \gamma_0)$$

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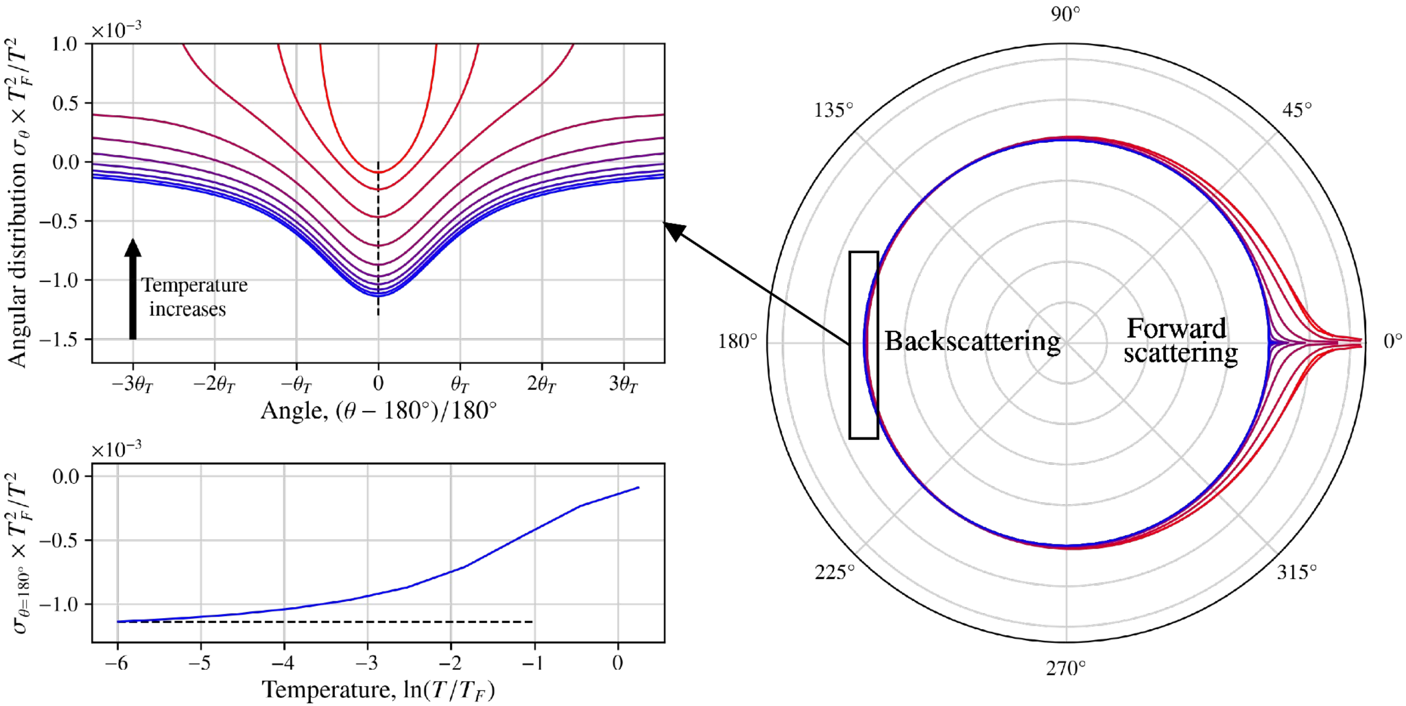
Sharp peaks $\sigma(\theta) \sim T^2/|\theta|$, $\sigma(\theta) \sim T^2/|\theta - \pi|$ for the forward and backscattering directions



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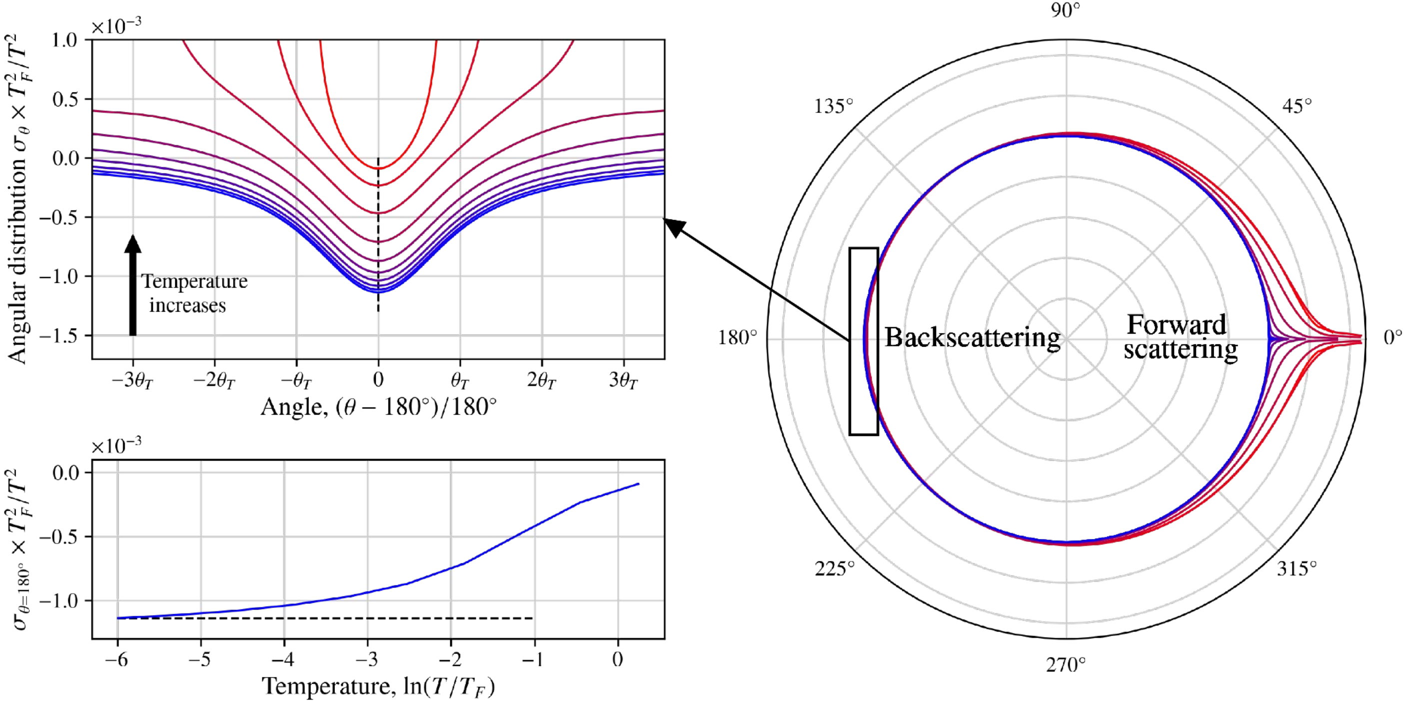
Find γ_m from angular Fourier transform



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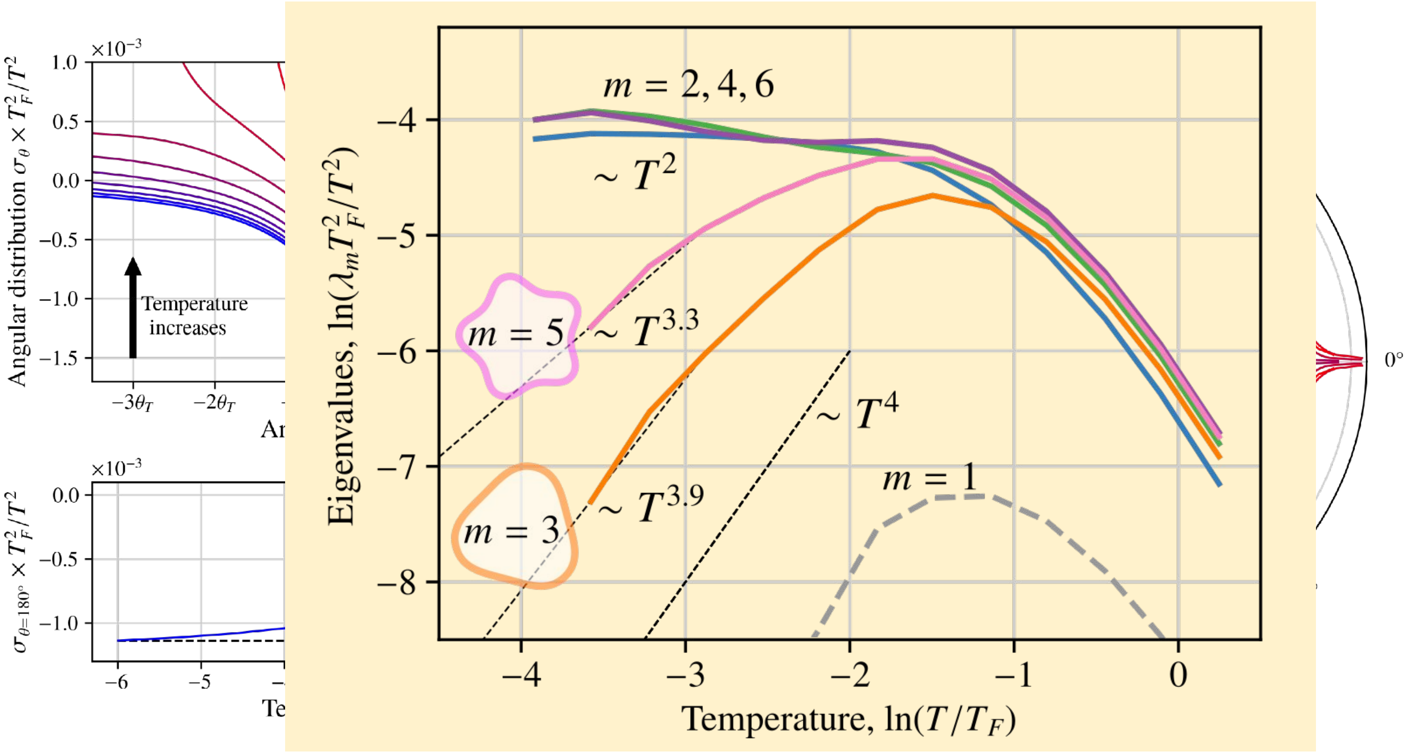

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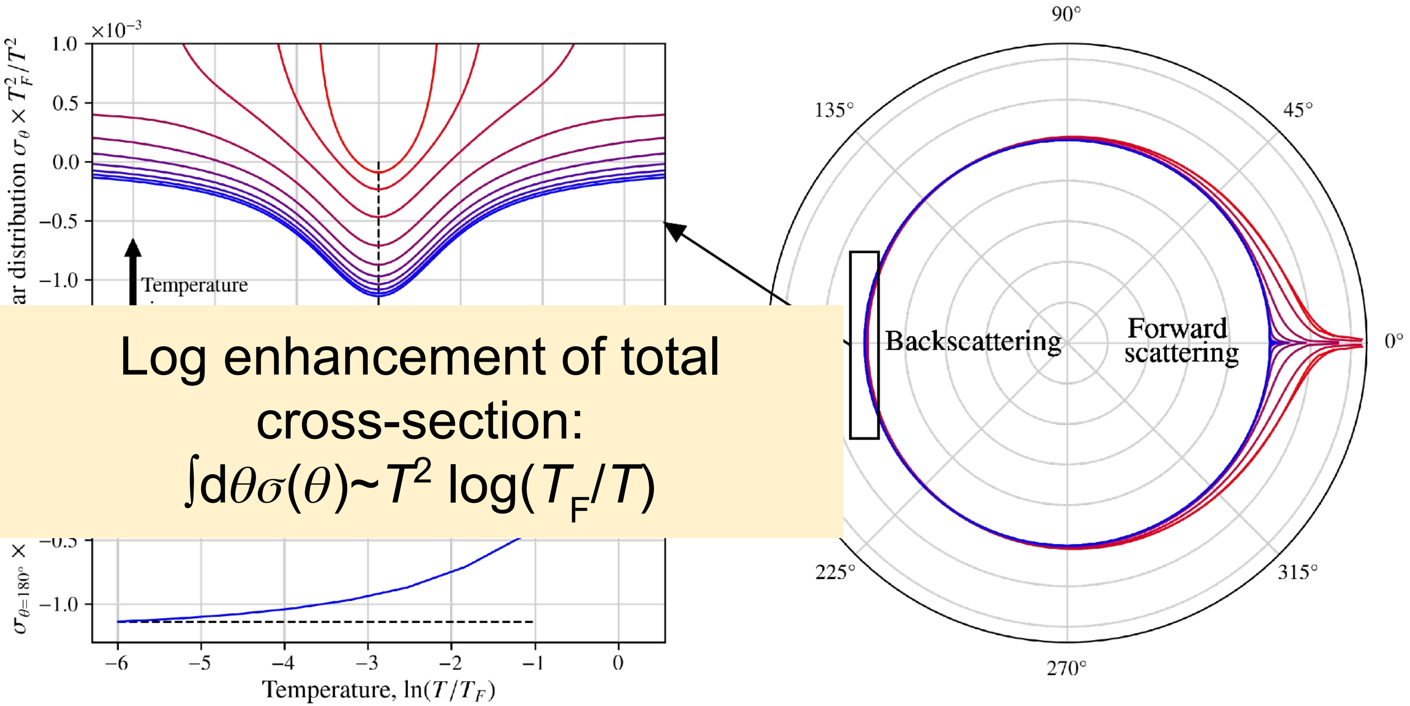

Log enhancement of total cross-section:
$\int d\theta \sigma(\theta) \sim T^2 \log(T_F/T)$

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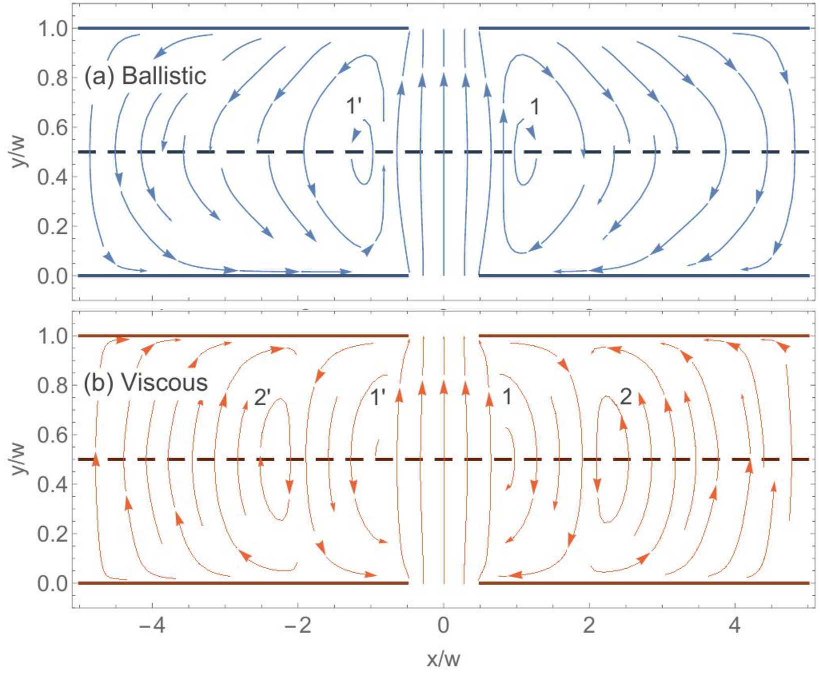
Observables?

$$z = \frac{k^2 v^2}{4}$$

Nonlocal conductivity $j(r)=\int d^2r'\sigma(r-r')E(r')$

$$\sigma(k) = \frac{D}{\gamma_0 + \Gamma(k)} \qquad \Gamma(k) = \frac{z}{\gamma_1 + \frac{z}{\gamma_2 + \frac{z}{\gamma_3 + \cdots}}}$$



K Nazaryan & LL arXiv:2111.09878

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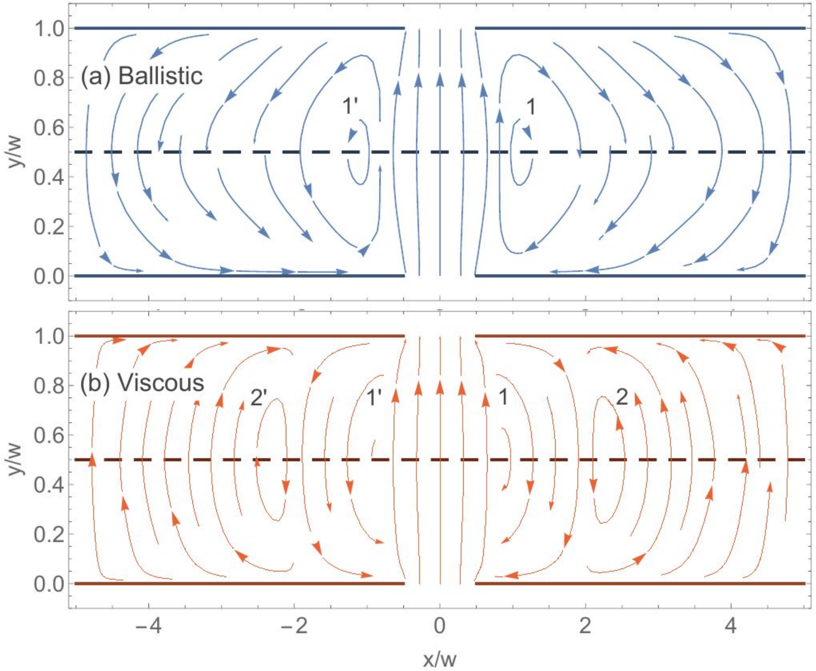
A continued fraction representation of k-dependent response: $j_k=\sigma(k)E_k$



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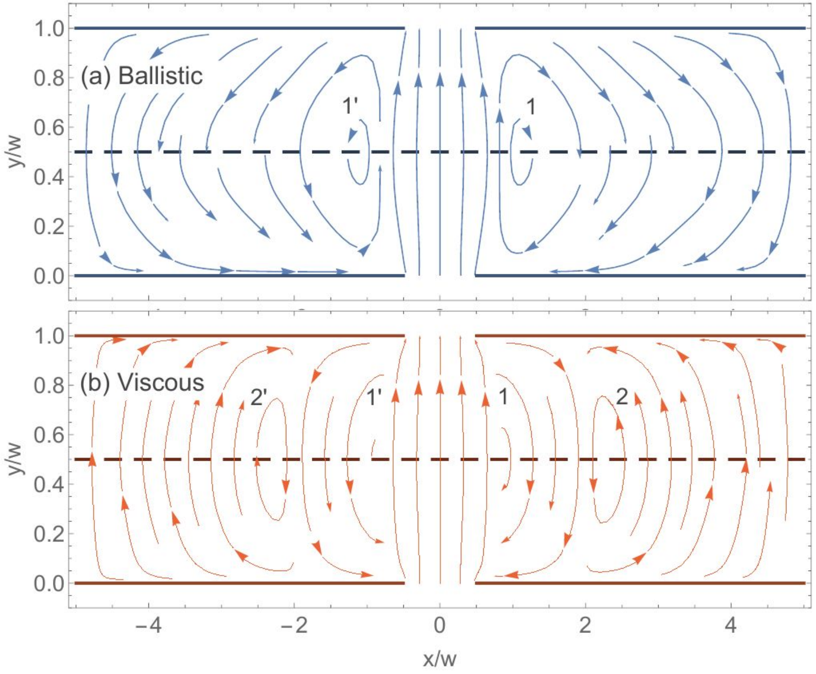
A continued fraction representation of k-dependent response: $j_k=\sigma(k)E_k$

$\sigma(k)$ determines spatial distribution of vorticity and the sensitivity of vortices to momentum relaxing scattering by disorder & phonons



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Vortices in electron fluids, hydro and non-hydro

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A continued fraction representation of the k-dependent response: $j_k=\sigma(k)E_k$

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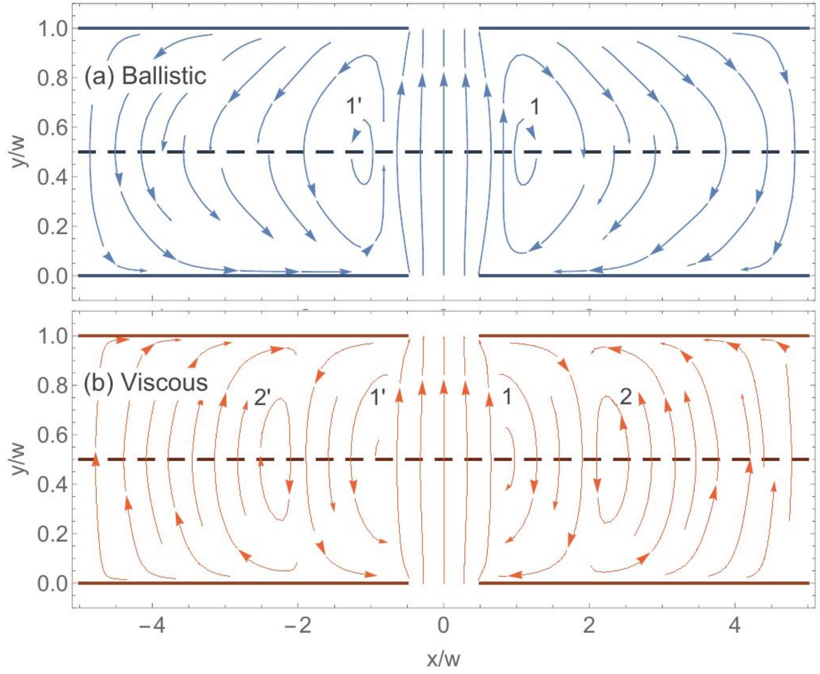
The relaxation rates γ_m are a “genetic code” that governs the dispersion $\sigma(k)$

Robustness of vortices



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Summary/discussion

Abnormally long-lived excitations in a 2D Fermi gas with super-Fermi-liquid lifetimes

Origin: collinear scattering

Implications: sharp angular distributions of scattered particles, hole backscattering, $\log(T_F/T)$ enhanced Fermi-liquid decay rates for other excitations

Robustness: generic 2-body interactions and particle dispersion, OK for weakly non-circular Fermi surfaces

Manifestations: nonlocal transport, current vortices, angular memory of response functions