Impurity particle driven through a quantum fluid by a constant force

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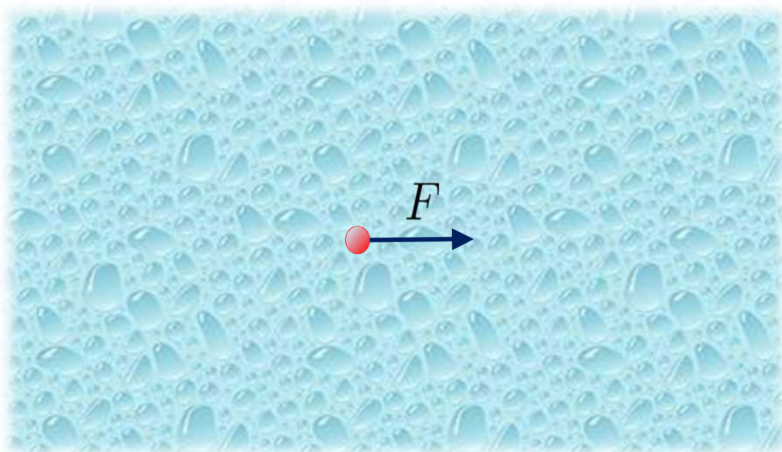
Plan

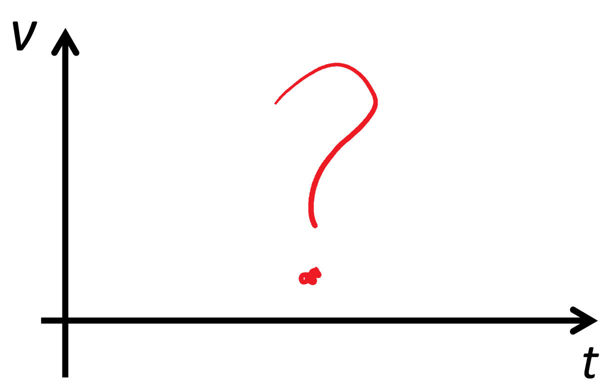
- Setup
- Depleton model
- Kinetic theory
- Comparison
- Cusp controversy
- Outlook

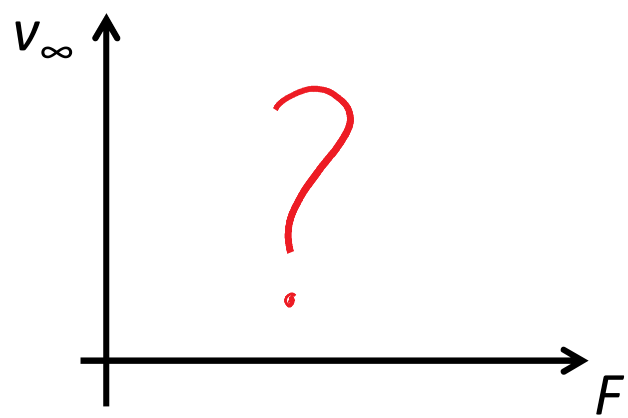
Impurity particle drugged by a constant force through quantum fluid



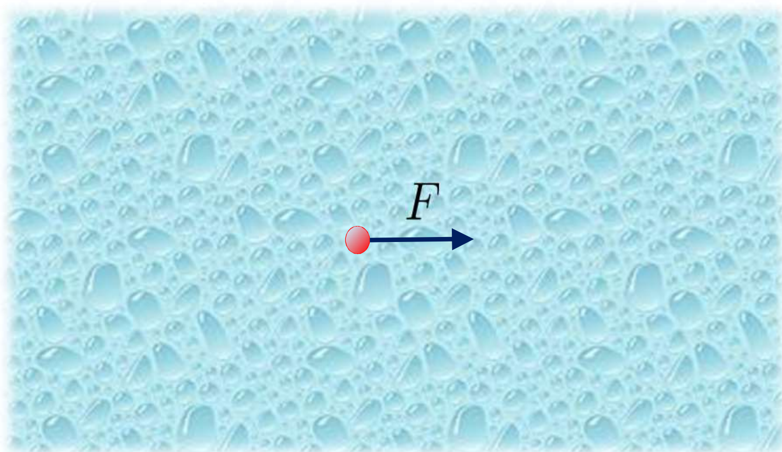
impurity particle of a finite mass *m*

$$H = H_{\rm f} + \frac{(P_{\rm imp} + Ft)^2}{2m} + H_{\rm imp-f}$$



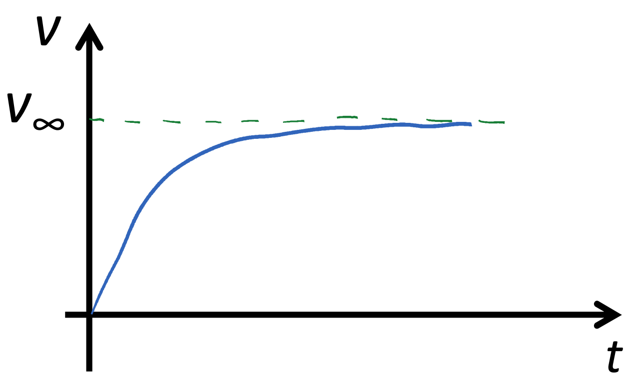


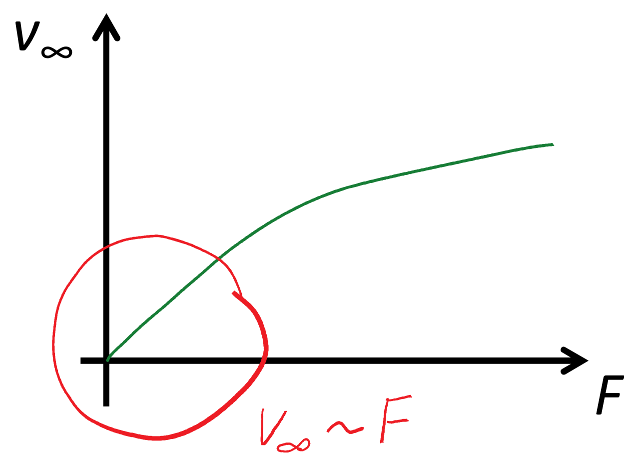
Impurity particle drugged by a constant force through quantum fluid



impurity particle of a finite mass *m*

classical liquid/gas, Fermi liquid:



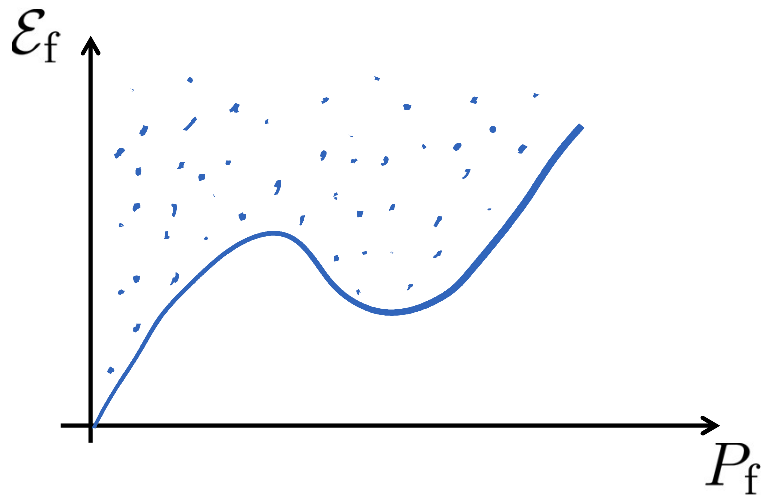


Fluids with nontrivial spectral edge

$\mathcal{E}_{\rm f}$ - eigenenergy of $H_{\rm f}$

$$\mathcal{E}_{\rm f} \geq \varepsilon(P_{\rm f})$$

spectral edge of the fluid (*aka* fluid dispersion)



nontrivial spectral edge:

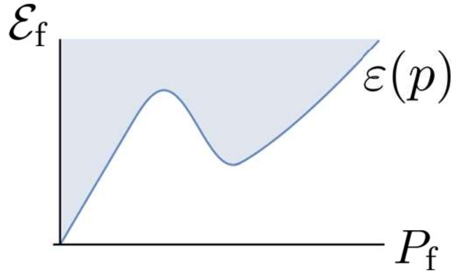
$$\varepsilon(p) \neq \text{const}$$

trivial spectral edge:

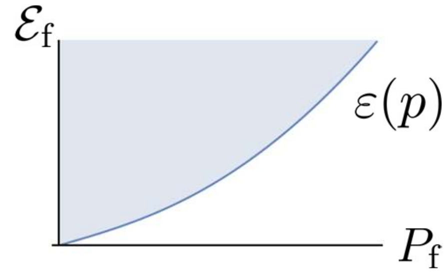
$$\varepsilon(p) = \text{const}$$

(classical gas and liquid, Fermi liquid, ...)

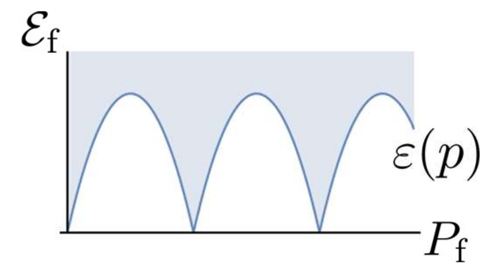
Fluids with nontrivial spectral edge



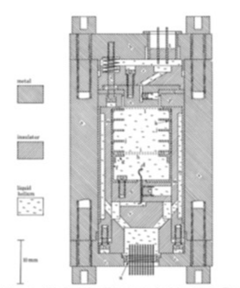
superfluid He



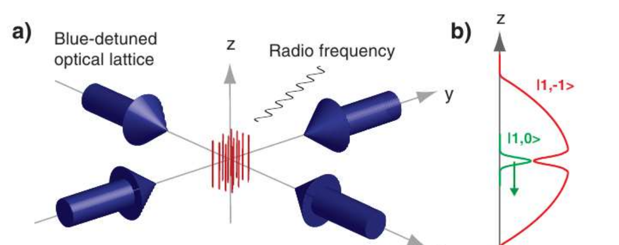
Bose-Einstein condensate



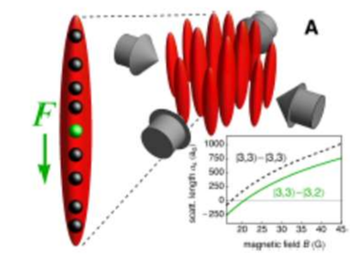
1D fluid



Allum, McClintock, Phillips
Phil. Trans. R. Soc. Lond. A 1977

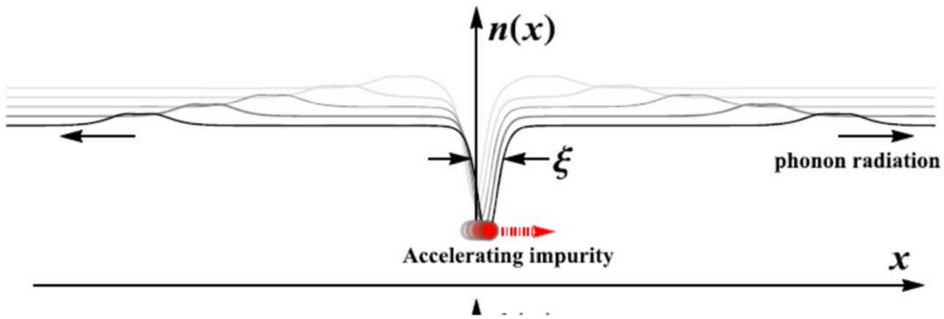


Pazler et al Phys. Rev. Lett. 2009



Meinert et al Science 2017

Depleton model



D. M. Gangardt and A. Kamenev, Phys. Rev. Lett. **102**, 070402 (2009)

M. Schecter, D. Gangardt, and A. Kamenev, Ann. Phys. **327**, 639 (2012)

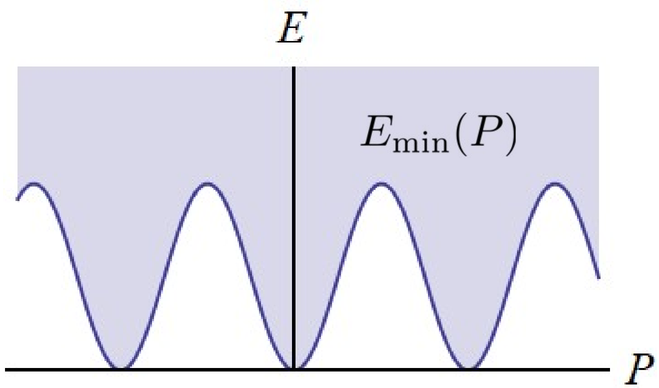
M. Schecter, A. Kamenev, D. M. Gangardt, and A. Lamacraft, Phys. Rev. Lett. **108**, 207001 (2012)

M. Schecter, D. Gangardt, and A. Kamenev, New J. Phys. 18, 065002 (2016)

A. Campbell, D. Gangardt, SciPost Phys. 3, 015 (2017)

Bloch oscillations without a lattice

E(P) – eigenenergy of *H* at a fixed *P*



J. B. McGuire, J. Math. Phys. **6**, 432 (1965)
A. Lamacraft, Phys. Rev. B **79**, 241105(R) (2009)

- driving: $P = Ft$
- (approximate) adiabatic following :

$$E\big(P(t)\big) \simeq E_{\min}\big(P(t)\big)$$

- Hellmann-Feynman Theorem:

$$v(P) = \partial E/\partial P$$

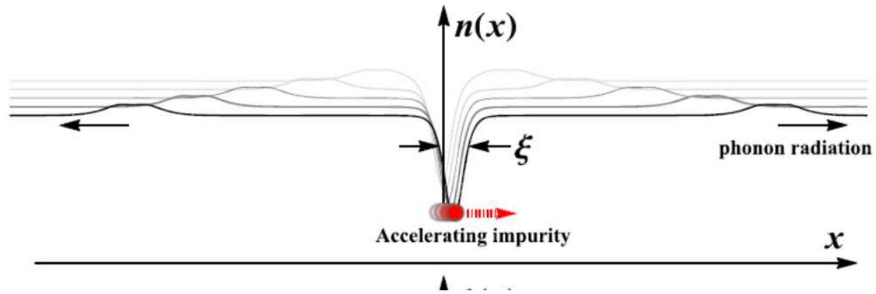
Bloch oscillations:

$$v(t) \simeq \partial E_{\min}/\partial P\Big|_{P=Ft}$$

D. M. Gangardt and A. Kamenev, Phys. Rev. Lett. **102**, 070402 (2009)

Depleton model

$E_{\min}(P)$ - dispersion relation of a ***depleton***



D. M. Gangardt and A. Kamenev, Phys. Rev. Lett. **102**, 070402 (2009)

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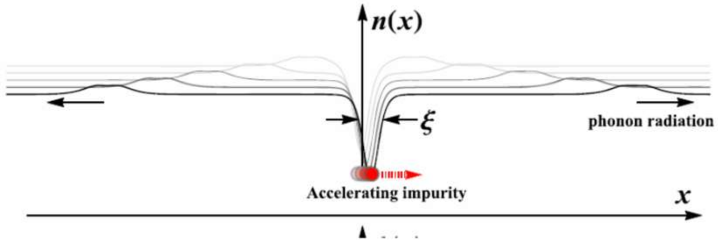
M. Schecter, A. Kamenev, D. M. Gangardt, and A. Lamacraft, Phys. Rev. Lett. **108**, 207001 (2012)

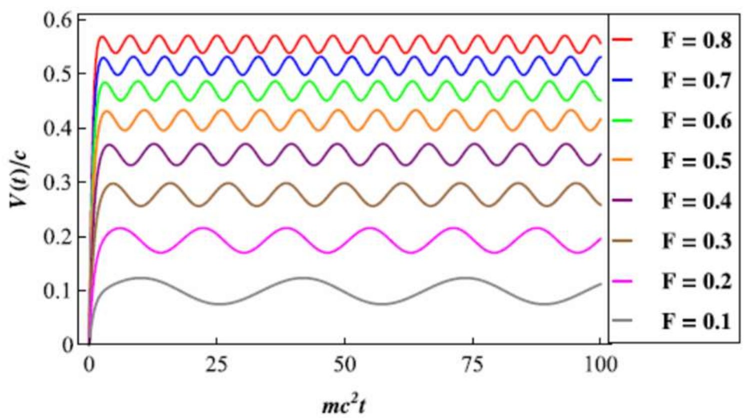
M. Schecter, D. Gangardt, and A. Kamenev, New J. Phys. 18, 065002 (2016)

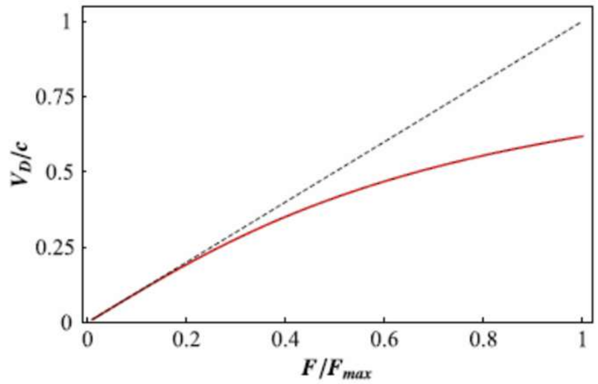
A. Campbell, D. Gangardt, SciPost Phys. 3, 015 (2017)

Bloch oscillations in depletion model at zero temperature



- Bloch oscillations are ***universal*** (any 1D fluid, any impurity mass and coupling), provided $E_{\min}(P)$ is ***smooth***
- Bloch oscillations are superimposed on drift velocity V_∞ linear in *F* (for small *F*)





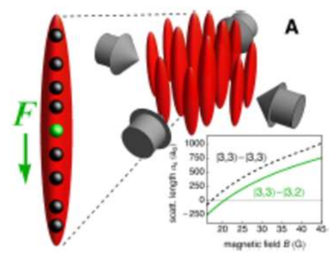
M. Schecter, D. Gangardt, and A. Kamenev, Ann. Phys. **327**, 639 (2012)

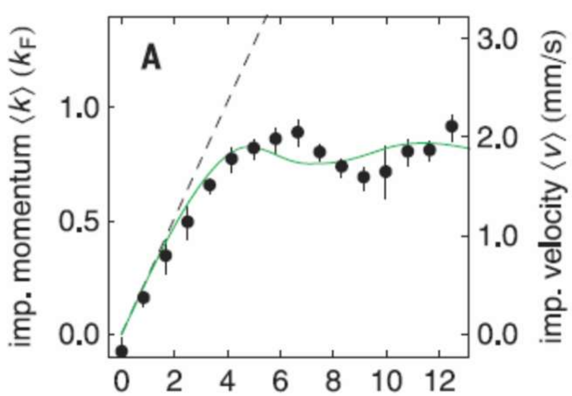
Bloch oscillations without a lattice - observation

Meinert et al., Science 356, 945–948 (2017)

strongly interacting Bose gas

$m_{imp} = m_{gas}$





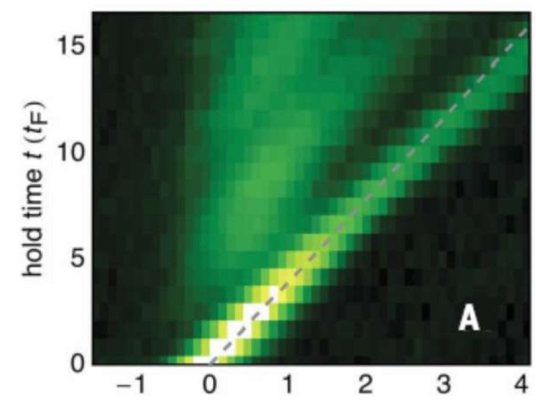
REPORT

QUANTUM GASES

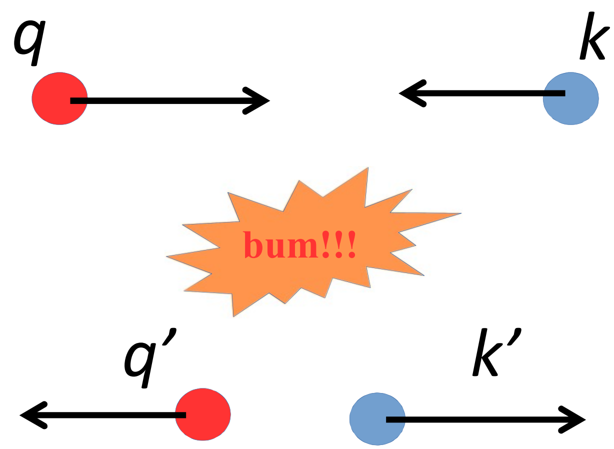
Bloch oscillations in the absence of a lattice

Florian Meinert,[1] Michael Knap,[2] Emil Kirilov,[1] Katharina Jag-Lauber,[1] Mikhail B. Zvonarev,[3] Eugene Demler,[4] Hanns-Christoph Nägerl[1*]

The interplay of strong quantum correlations and far-from-equilibrium conditions can give rise to striking dynamical phenomena. We experimentally investigated the quantum motion of an impurity atom immersed in a strongly interacting one-dimensional Bose liquid and subject to an external force. We found that the momentum distribution of the impurity exhibits characteristic Bragg reflections at the edge of an emergent Brillouin zone. Although Bragg reflections are typically associated with lattice structures, in our strongly correlated quantum liquid they result from the interplay of short-range crystalline order and kinematic constraints on the many-body scattering processes in the one-dimensional system. As a consequence, the impurity exhibits periodic dynamics, reminiscent of Bloch oscillations, although the quantum liquid is translationally invariant. Our observations are supported by large-scale numerical simulations.



Kinetic theory of mobile impurity in a quantum fluid



GW Rayfield, Phys. Rev. Lett. **16**, 934 (1966)

R. Bowley and F. Sheard, in *Proceedings of the International Conference on Low Temperature Physics*, 1, 165 (1975)

R. Bowley and F. Sheard, Phys. Rev. B 16, 244 (1977)

D. Allum, P. V. McClintock, and A. Phillips, Philos. Trans. R. Soc. London. Ser. A 284, 179 (1977)

E. Burovski, V. Cheianov, O. Gamayun, and O. Lychkovskiy, Phys. Rev. A 89, 041601 (R) (2014)

O. Gamayun, O. Lychkovskiy, and V. Cheianov, Phys. Rev. E 90, 032132 (2014)

O. Gamayun, Phys. Rev. A 89, 063627 (2014)

O. Lychkovskiy, Phys. Rev. A 89, 033619 (2014)

O. Lychkovskiy, Phys. Rev. A 91, 040101 (R) (2015)

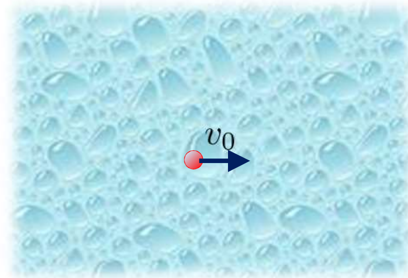
Y. Castin, I. Ferrier-Barbut, and C. Salomon, C. R. Phys. 16, 241 (2015)

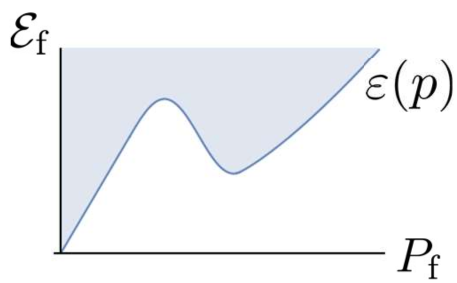
...

Kinetic theory of mobile impurity in a quantum fluid

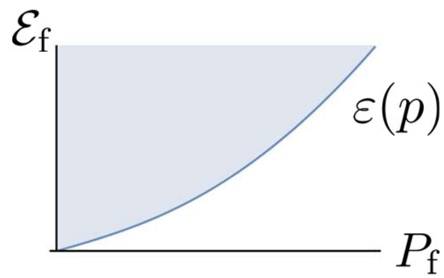
$$\begin{cases} m\mathbf{v}_0 = m\mathbf{v} + \mathbf{P}_\mathrm{f} \\ \dfrac{m\mathbf{v}_0^2}{2} = \dfrac{m\mathbf{v}^2}{2} + \mathcal{E}_\mathrm{f} \end{cases}$$

$$\mathcal{E}_\mathrm{f} \geq \varepsilon(\mathbf{P}_\mathrm{f})$$

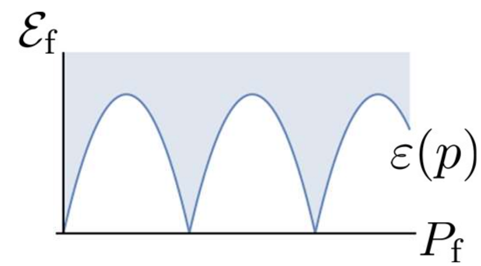




superfluid He



Bose-Einstein condensate



1D fluid

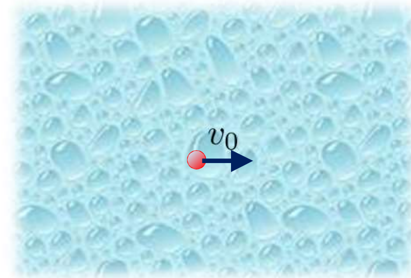
Perpetual motion of impurity in a quantum fluid

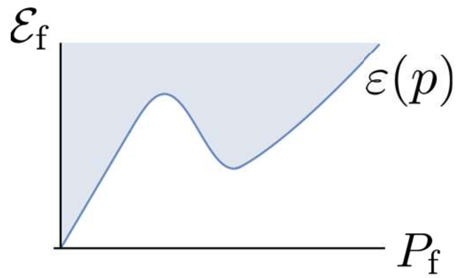
$$\begin{cases} m\mathbf{v}_0 = m\mathbf{v} + \mathbf{P}_\mathrm{f} \\ \dfrac{m\mathbf{v}_0^2}{2} = \dfrac{m\mathbf{v}^2}{2} + \mathcal{E}_\mathrm{f} \end{cases}$$

$$\mathcal{E}_\mathrm{f} \geq \varepsilon(\mathbf{P}_\mathrm{f})$$

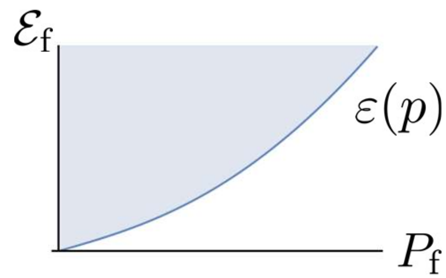
no solutions for $v_0 = |\mathbf{v}_0| < v_c$

v_c - generalized critical velocity

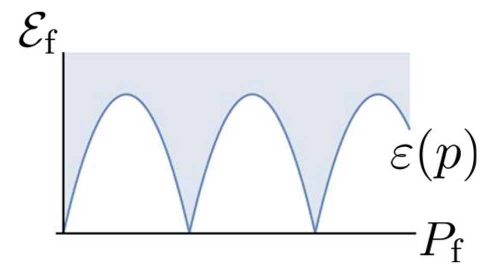




superfluid He



Bose-Einstein condensate

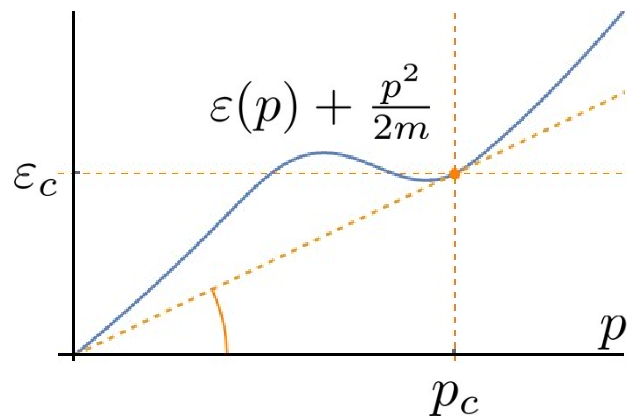


1D fluid

Generalized critical velocity

$$v_c = \inf_p \frac{\varepsilon(p) + \frac{p^2}{2m}}{p}$$

GW Rayfield, Phys. Rev. Lett. **16**, 934 (1966)



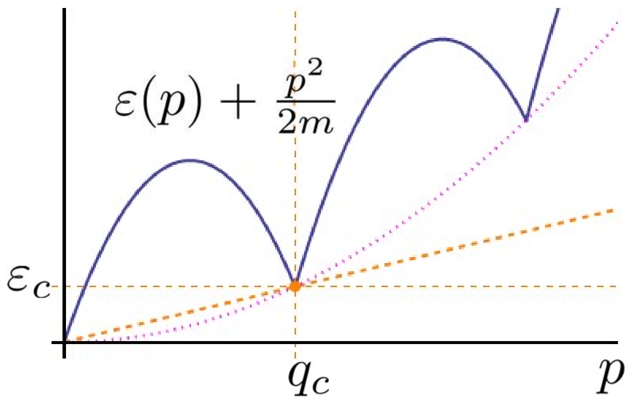
$$v_c = \varepsilon_c / p_c$$

Landau critical velocity (Landau, 1941): m=∞ $v_c > v_L$

Critical velocity in one dimension

Generalized critical velocity:

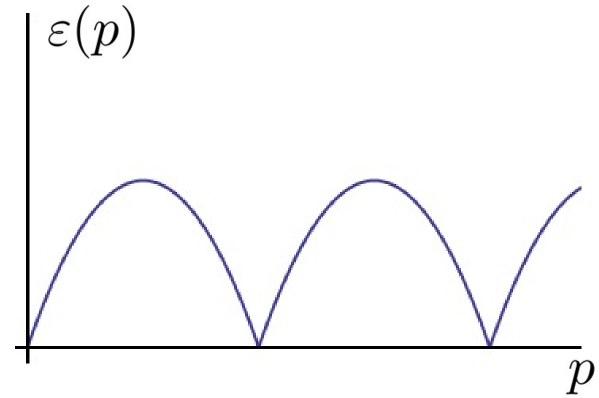
$$v_c = \inf_p \frac{\varepsilon(p) + \frac{p^2}{2m}}{p}$$



$v_c \neq 0$

Landau critical velocity:

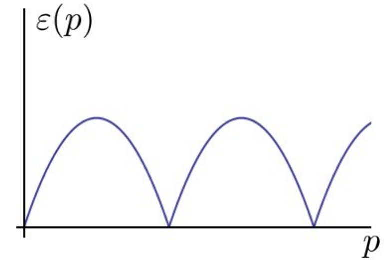
$$v_L = \inf_p \frac{\varepsilon(p)}{p}$$



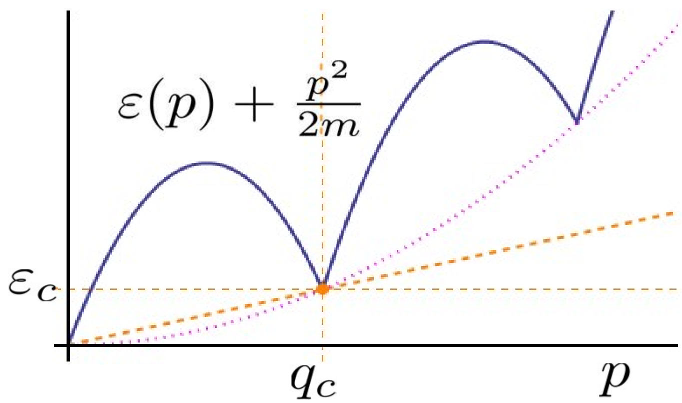
$v_L = 0$

Critical mass

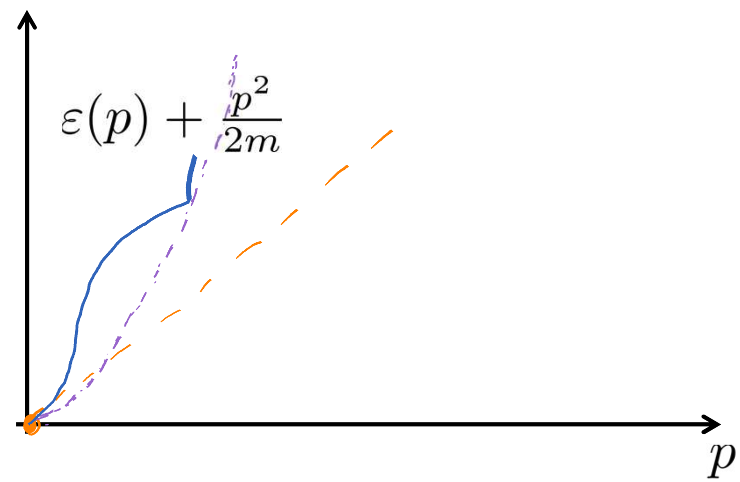
$$v_c = \inf_p \frac{\varepsilon(p) + \frac{p^2}{2m}}{p}$$



heavy impurity, *m>m*$_c$



light impurity, *m>m*$_c$

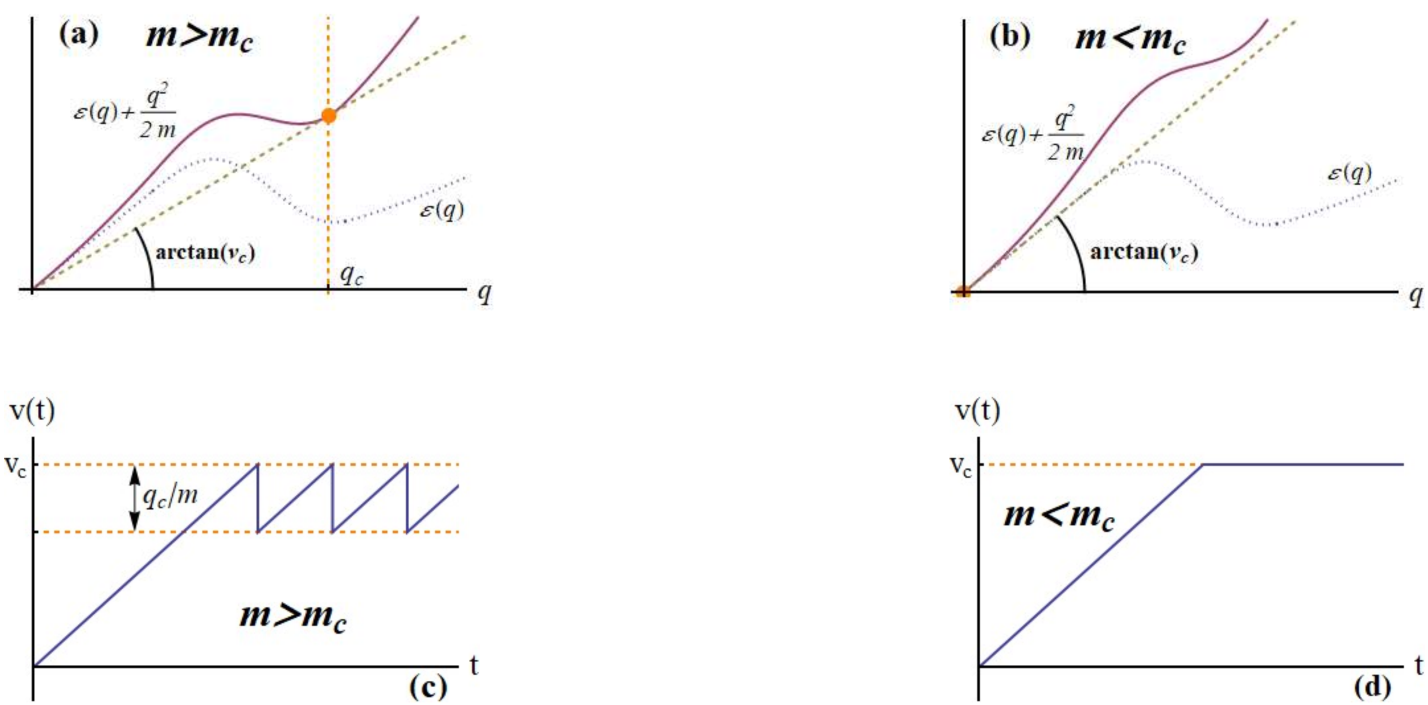


$\varepsilon_c = 0$ $\quad$ $q_c = 0$

Impurity dragged by a constant force: two regimes

heavy impurity

light impurity

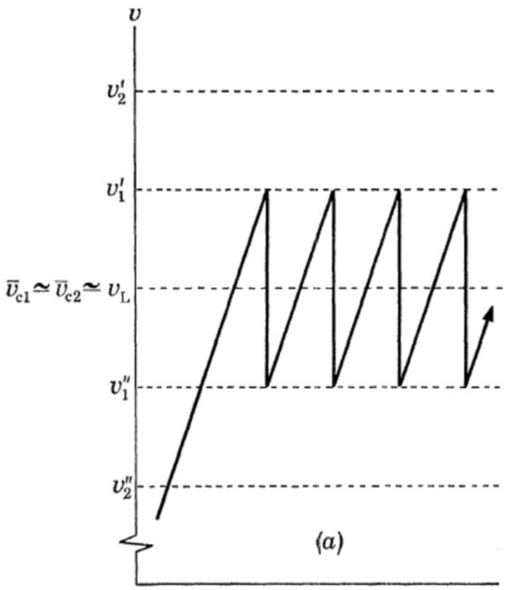


oscillations

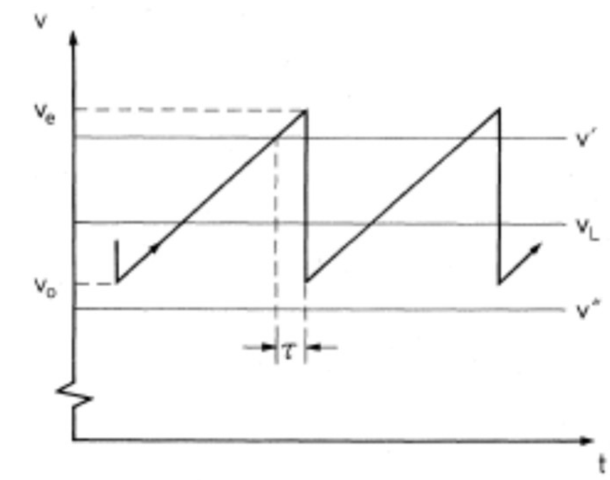
saturation without oscillations

O. Lychkovskiy, Phys. Rev. A 91, 040101 (R) (2015)

Ions accelerated by electric field in in superfluid He



D. Allum, P. V. McClintock, and A. Phillips, Philos. Trans. R. Soc. London. Ser. A **284**, 179 (1977).



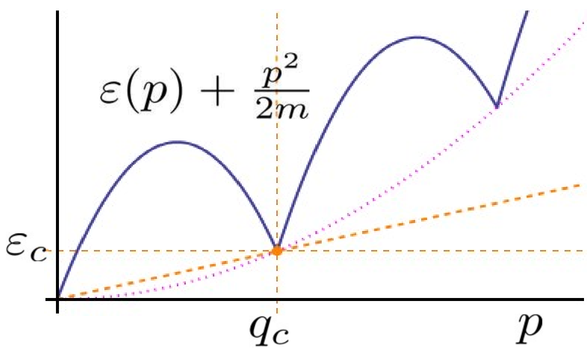
R. Bowley and F. Sheard, Phys. Rev. B **16**, 244 (1977).

Impurity dragged through 1D gas of noninteracting fermions

$$H = \sum_{j=1}^{N} \frac{P_j^2}{2m_{\rm h}} + \frac{P_{\rm imp}^2}{2m} + \frac{\gamma\rho}{m}\sum_{j=1}^{N}\delta(x_j - x_{\rm imp})$$

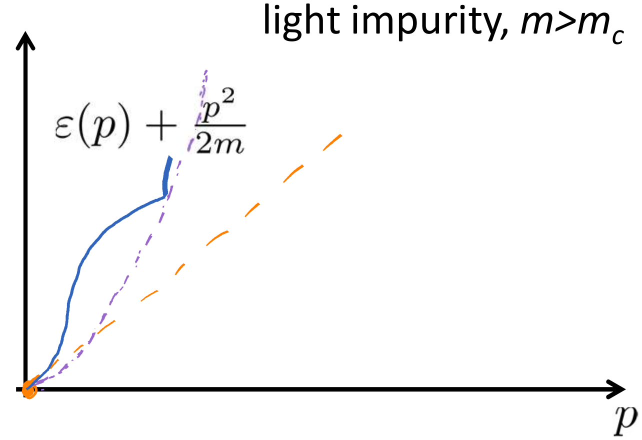
$$m_c = m_{\rm h}$$

heavy impurity, $m>m_c$



$$q_c = k_{\rm F}$$

light impurity, $m>m_c$



$$q_c = 0$$

Impurity dragged through 1D gas of noninteracting fermions

$$H = \sum_{j=1}^{N} \frac{P_j^2}{2m_{\mathrm{h}}} + \frac{P_{\mathrm{imp}}^2}{2m} + \frac{\gamma\rho}{m} \sum_{j=1}^{N} \delta(x_j - x_{\mathrm{imp}})$$

Boltzmann equation:

total scattering rate

partial scattering rate

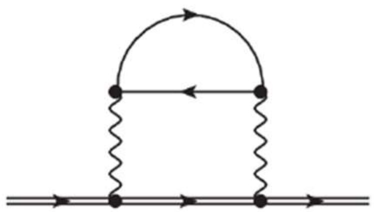
$$\frac{\partial w_k(t)}{\partial t} + F \frac{\partial w_k(t)}{\partial k} = -\Gamma_k w_k(t) + \sum_q \Gamma_{q\to k} w_q(t).$$

momentum distribution of impurity

Quantum Boltzmann Equation (QBE)

Quantum kinetic equations $[\mathbb{G}]^{-1} = [\mathbb{G}^{(0)}]^{-1} - \hat{\Sigma}$

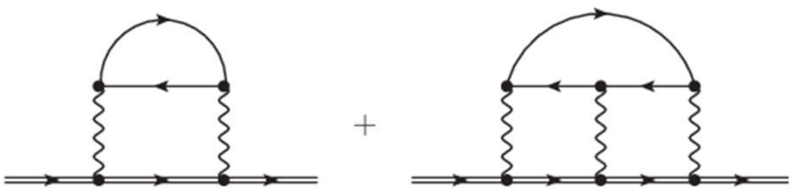
Pure Boltzmann

$\hat{\Sigma}^B =$ 

$$n_p^\infty = Z_{p_0} \frac{\theta(k_F - |p|)}{p_0 - p}, \quad p_0 > k_F.$$

$$p_\infty^B = p_0 - \theta\left(|p_0| - k_F\right) \frac{2k_F}{\ln \frac{p_0+k_F}{p_0-k_F}}$$

Multiple Scattering Events

$\hat{\Sigma}^L =$  $+ \dots$

$$\gamma \to \frac{\gamma}{|\eta - 1|} \quad \overset{\eta\to1\,\gamma\to0}{\Longrightarrow} \quad n_p^\infty = \tilde{Z}_{p_0} \frac{\theta(k_F - |p|)}{(p_0 - p)^2}, \quad p_0 > k_F.$$

$$p_\infty = p_0 - \theta\left(p_0^2 - k_F^2\right) \frac{p_0^2 - k_F^2}{2k_F} \ln \frac{p_0 + k_F}{p_0 - k_F}$$

O. Gamayun, Phys. Rev. A 89, 033619 (2014)

Boltzmann equation – validity conditions

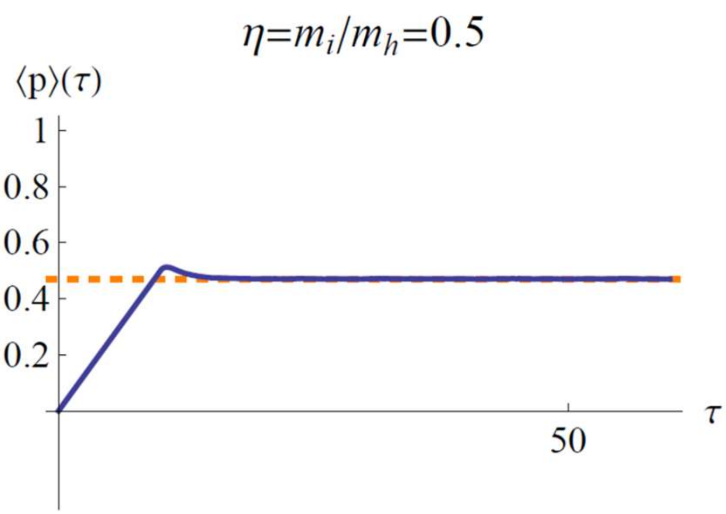
$\gamma \ll 1$ weak coupling

$$F \gg \left(\frac{\gamma^2 k_{\mathrm{F}}^3}{2\pi^3 m_c}\right) e^{-\frac{\pi^4}{\gamma^2}\frac{m^2 - m_c^2}{m^2}}, \qquad m > m_c$$

$$F \gg \left(\frac{\gamma^2 k_{\mathrm{F}}^3}{2\pi^3 m_c}\right) \gamma^2 (m/m_c), \qquad m < m_c$$

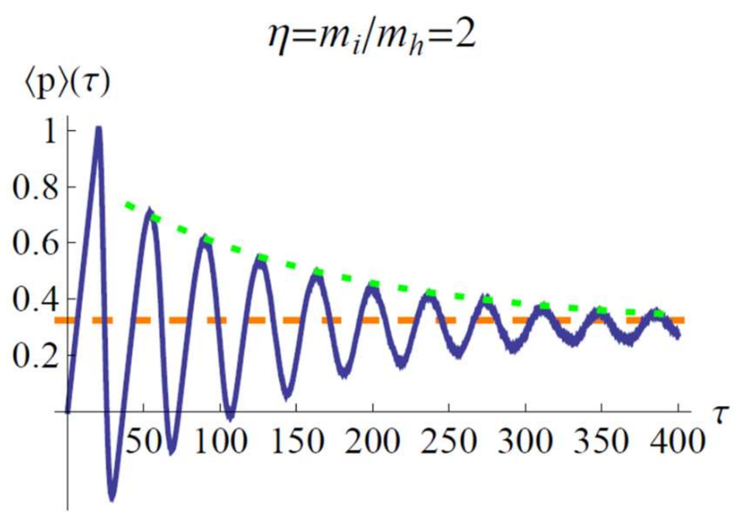
Boltzmann equation: results

light impurity



saturation without oscillations

heavy impurity

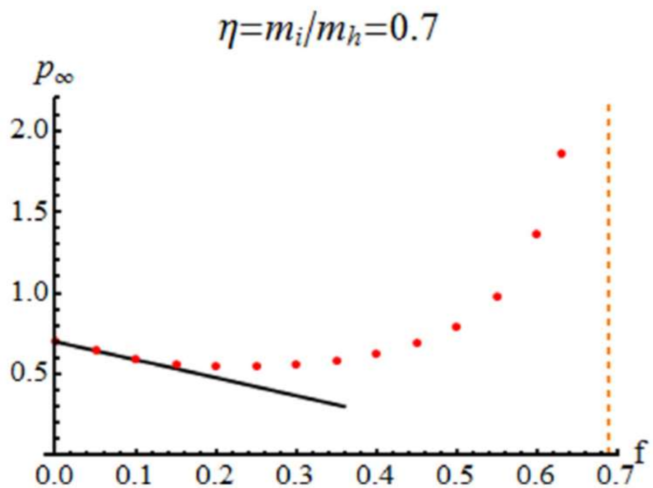


oscillations

O. Gamayun, O. Lychkovskiy, and V. Cheianov, Phys. Rev. E 90, 032132 (2014)

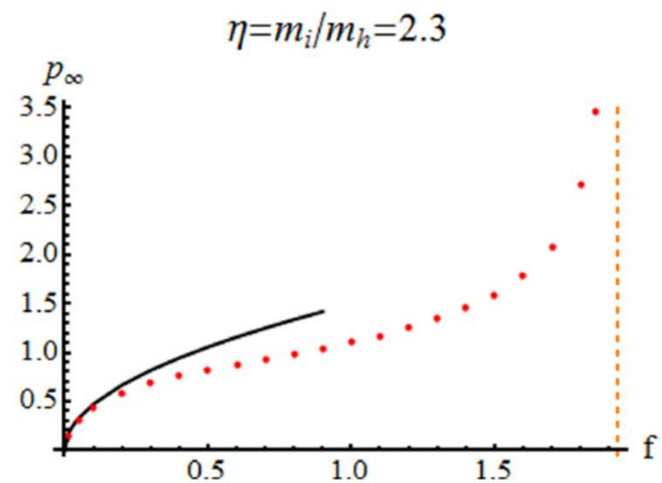
Impurity dragged through 1D gas of noninteracting Fermions

light impurity



$$v_\infty = v_c - \zeta F$$

heavy impurity



$$v_\infty \sim \sqrt{F}$$

O. Gamayun, O. Lychkovskiy, and V. Cheianov, Phys. Rev. E 90, 032132 (2014)

Depleton model *vs* kinetic theory

depleton model

universal oscillations:

any 1D fluid, any impurity mass and coupling

$$v_\infty \sim F$$

nonperturbative effective theory

kinetic theory

$m > m_c$

oscillations

$$v_\infty \sim \sqrt{F}$$

perturbative

$m < m_c$

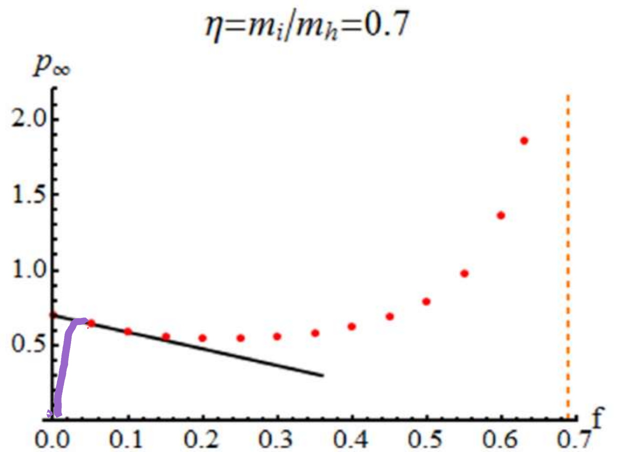
saturation without oscillations for

$$v_\infty = v_c - \zeta F$$

Depleton model *vs* kinetic theory

Formally, two approaches can be reconciled if kinetic theory is grossly inadequate for $F<F_c$

However, such reconciliation could be quite a bizarre, particularly for light impurities:



Depleton model *vs* kinetic theory: nonperturbative effects

PHYSICAL REVIEW E **92**, 016101 (2015)

Comment on "Kinetic theory for a mobile impurity in a degenerate Tonks-Girardeau gas"

Michael Schecter,[1] Dimitri M. Gangardt,[2] and Alex Kamenev[1,3]

perturbative treatment can miss binding between the hole and the impurity

$$\Delta \sim e^{-2\pi^2/\gamma}$$

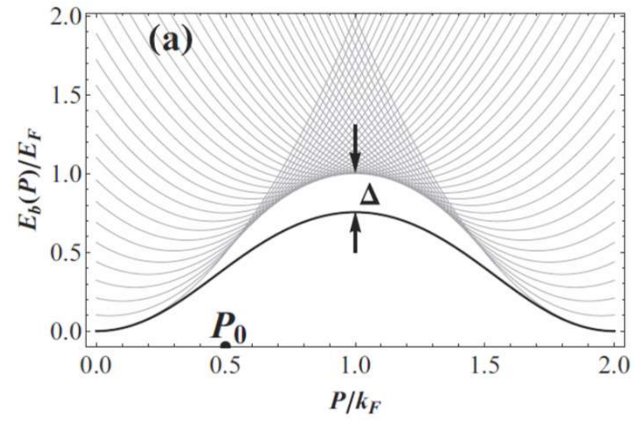
PHYSICAL REVIEW E **92**, 016102 (2015)

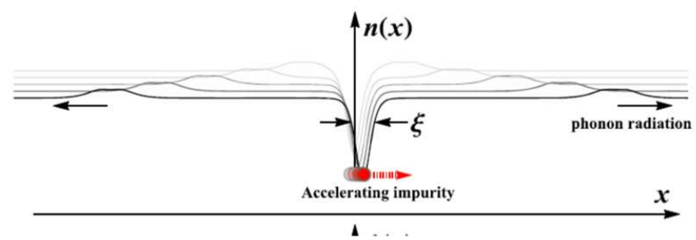
Reply to "Comment on 'Kinetic theory for a mobile impurity in a degenerate Tonks-Girardeau gas'"

O. Gamayun,[1,2,3] O. Lychkovskiy,[4] and V. Cheianov[1,3]

binding and related oscillations can be destroyed by quantum fluctuations

$$\delta E_4 = O(\gamma^4) \gg e^{-2\pi^2/\gamma}$$





Depleton model: finite temperature

At least, ***thermal*** fluctuations do destroy the oscillations in the depletion model:

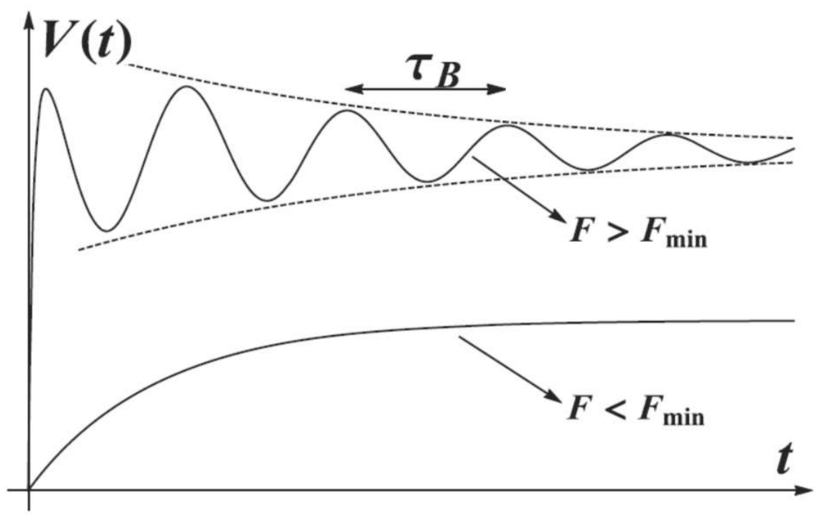


Figure 4. Schematic noise-averaged velocity as a function of time including the effects of fluctuations. For $F < F_{\rm min}$ the impurity velocity saturates below the critical velocity and Bloch oscillations do not occur. For $F_{\rm min} < F < F_{\rm max}$ Bloch oscillations occur, but are attenuated in time due to dephasing, see equation (24).

M. Schecter, D. Gangardt, and A. Kamenev, New J. Phys. 18, 065002 (2016)

Cusps in the impurity-fluid dispersion

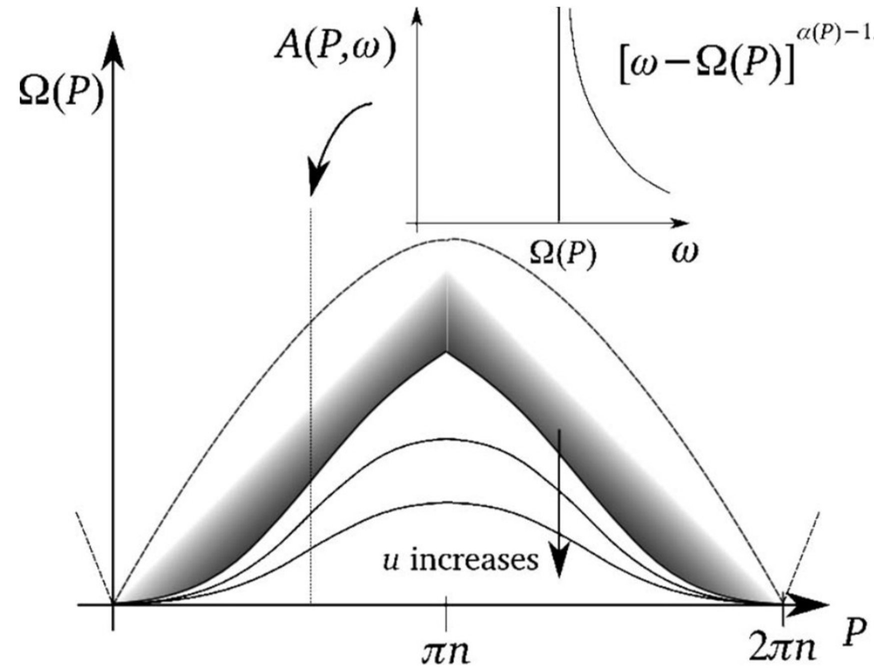
A. Lamacraft, Phys. Rev. B **79**, 241105(R) (2009):

$E_{\min}(P)$ has a cusp at $P=\pi n$

for fluids with K<1 (bosons)

and for $\gamma < \gamma_c$

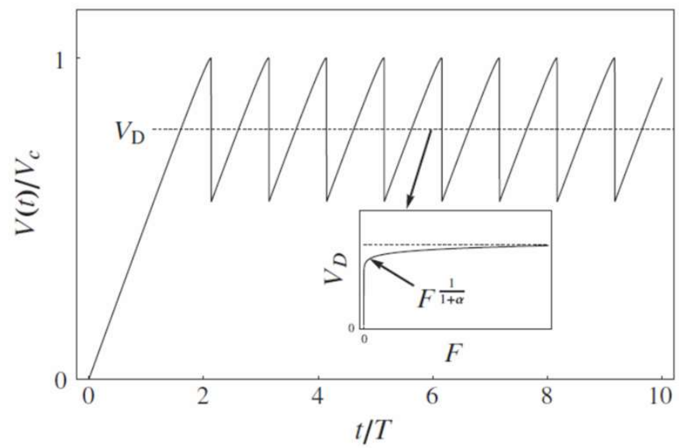
impurity-fluid coupling

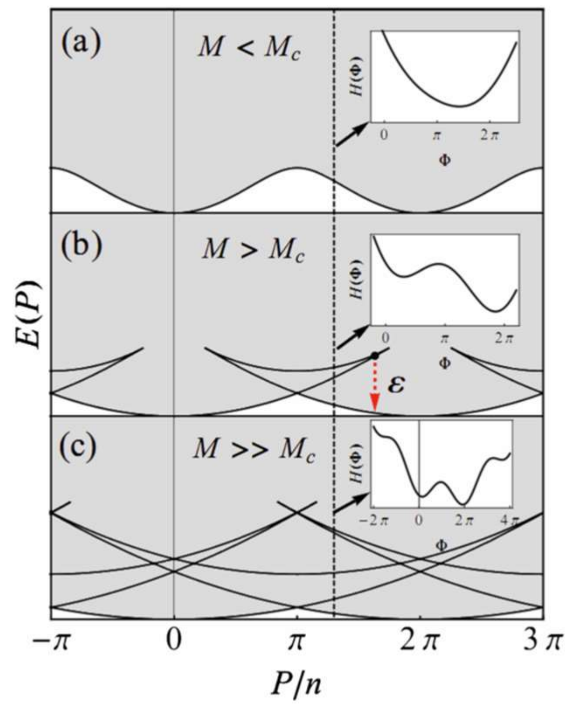


Cusps in the impurity-fluid dispersion

impurity fails to follow $E_{\min}(P)$ adiabatically

V_∞ nonlinear in *F*





M. Schecter, A. Kamenev, D. M. Gangardt, and A. Lamacraft, Phys. Rev. Lett. **108**, 207001 (2012)

Cusps in the impurity-fluid dispersion: integrable model test

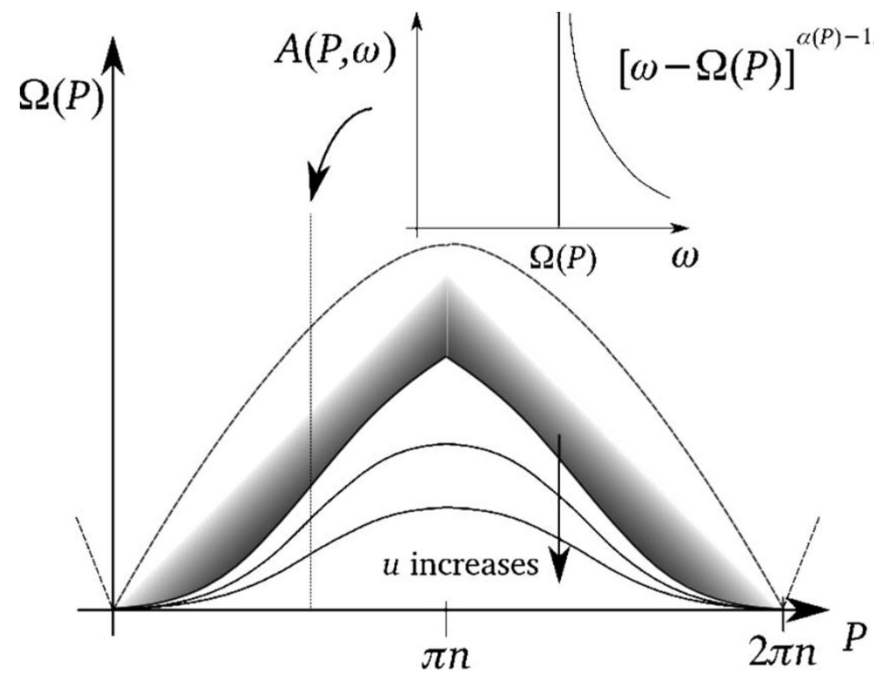
A. Lamacraft, Phys. Rev. B **79**, 241105(R) (2009):

$E_{\min}(P)$ has a cusp at *P=π n*

for fluids with K<1 (bosons)

and for $\gamma < \gamma_c$

Integrable bosonic Yang-Gaudin model:
no cusp for any γ



Cusp in the McGuire model with attraction

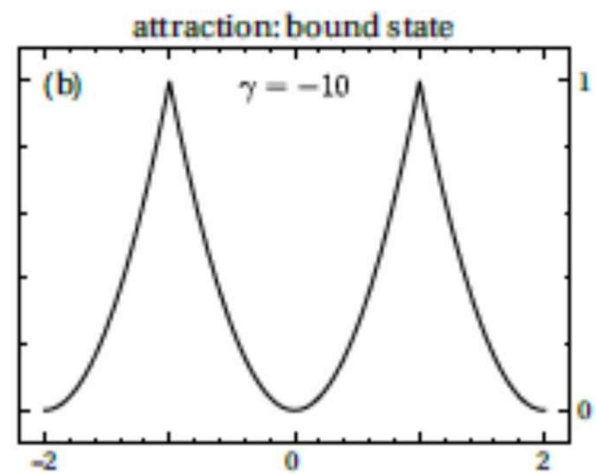
$$H = \sum_{j=1}^{N} \frac{P_j^2}{2m} + \frac{P_{\text{imp}}^2}{2m} + \frac{\gamma\rho}{m} \sum_{j=1}^{N} \delta(x_j - x_{\text{imp}})$$

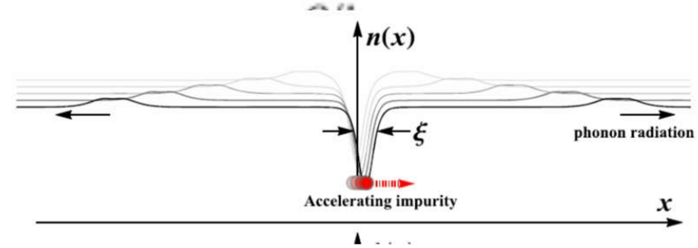
$$\gamma < 0$$

Is this cusp there beyond integrability?

kinetic theory: not sensitive to the sign of γ

depleton model: no impurity-hole binding any more





Summary and outlook

- reconciling kinetic theory and depletion model is nontrivial
- more studies are welcome (numerics, adiabatic perturbation theory, ..., experiments?)
- non-linear-response theory is, in general, lacking
- attractive impurity-fluid interaction: little studied, potentially very interesting

Thank you for your attention!

Funding

2016 -2017:

Quantum dynamics of a mobile impurity in a medium

Russian Foundation for Basic Research grant № 16-32-00669

2018-2020

Far-from-equilibrium dynamics in quantum impurity models

Russian Foundation for Basic Research grant № 18-32-20218

Footnote: no many-body adiabaticity at finite F

necessary adiabatic condition: $F \sim \log L$

O. Lychkovskiy, O. Gamayun, V. Cheianov
PRL119, 200401 (2017);
AIP Conf. Proc. 1936, 020024 (2018)

sufficient adiabatic condition: $F \sim L$ (scaling of energy gap)

necessary and sufficient adiabatic condition: $F \sim L$

O. Lychkovskiy, O. Gamayun, V. Cheianov
Phys. Rev. B 98, 024307 (2018)

Thank you for your attention!

Miscellaneous slides

Impurity dynamics for $v_0 > v_c$: semiclassical picture

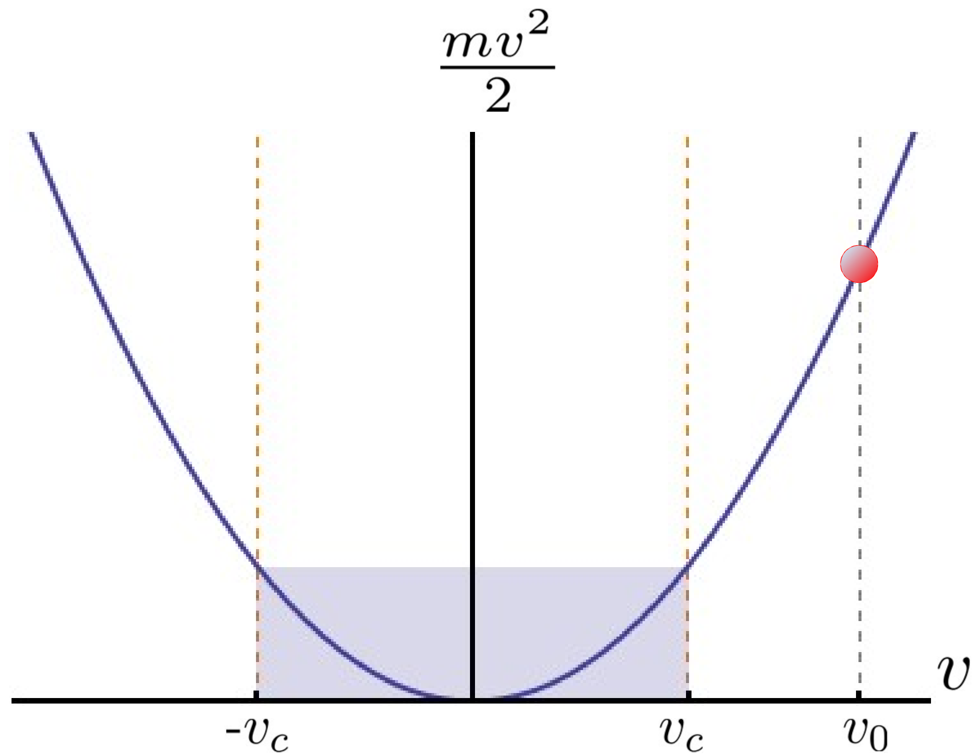
weak impurity-fluid coupling

$$\begin{cases} m\mathbf{v}_0 = m\mathbf{v} + \mathbf{P}_\mathrm{f} \\ \dfrac{m\mathbf{v}_0^2}{2} = \dfrac{m\mathbf{v}^2}{2} + \mathcal{E}_\mathrm{f} \end{cases}$$

$$\mathcal{E}_\mathrm{f} \leq \varepsilon(\mathbf{P}_\mathrm{f})$$

$v_0 < v_c$: scattering forbidden, $v_\infty \simeq v_0$

$v_0 > v_c$: scattering allowed



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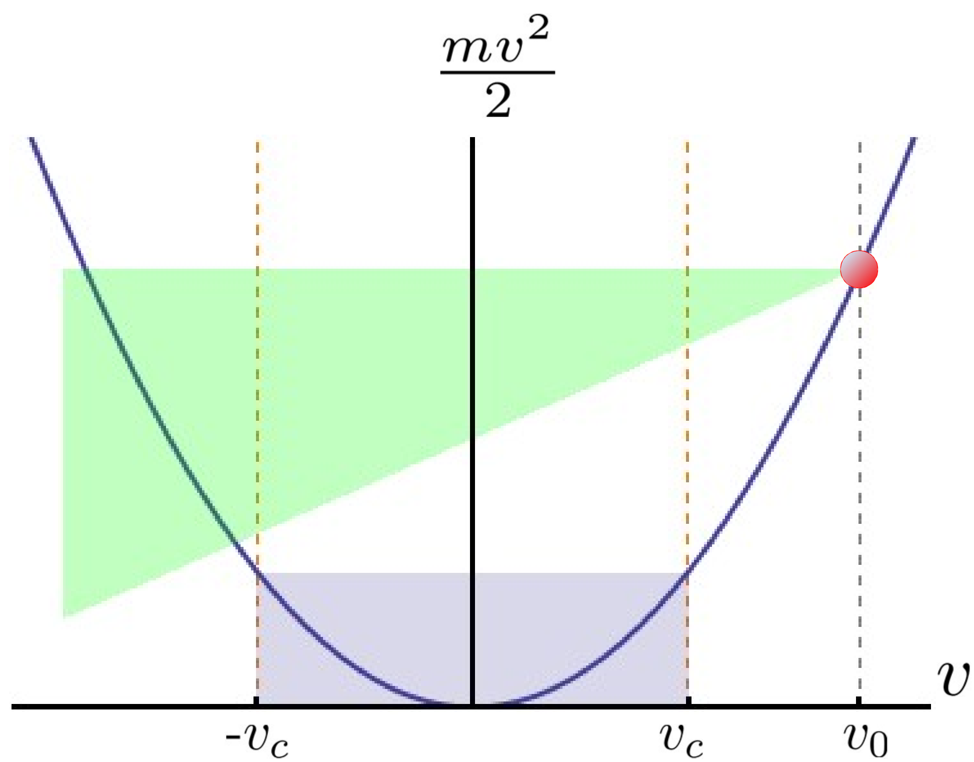

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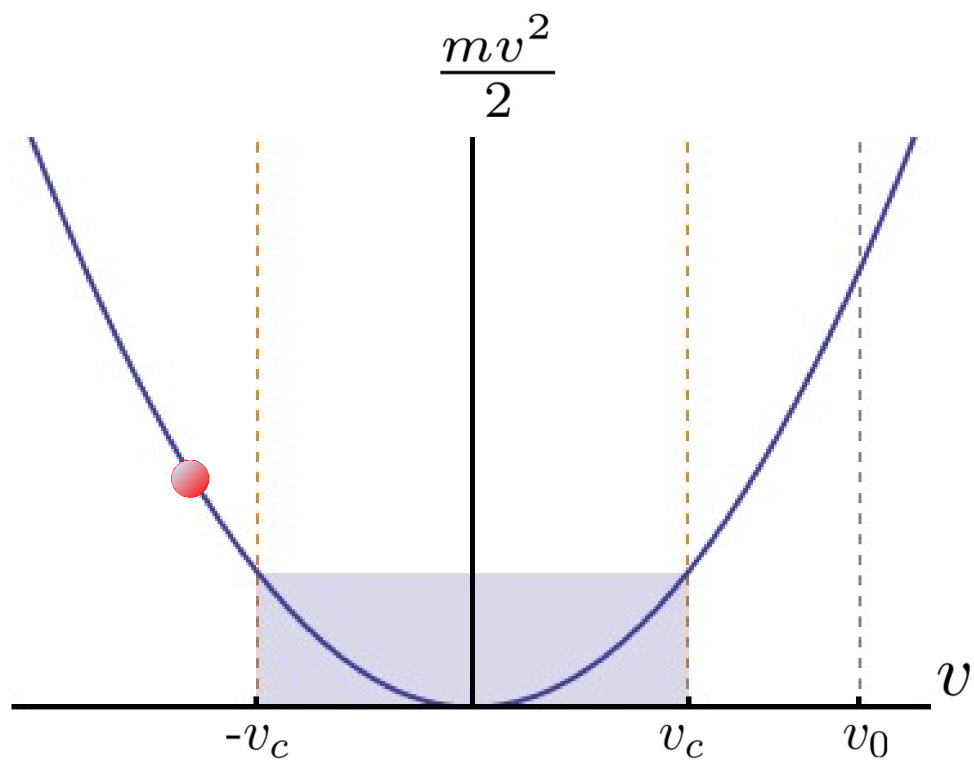

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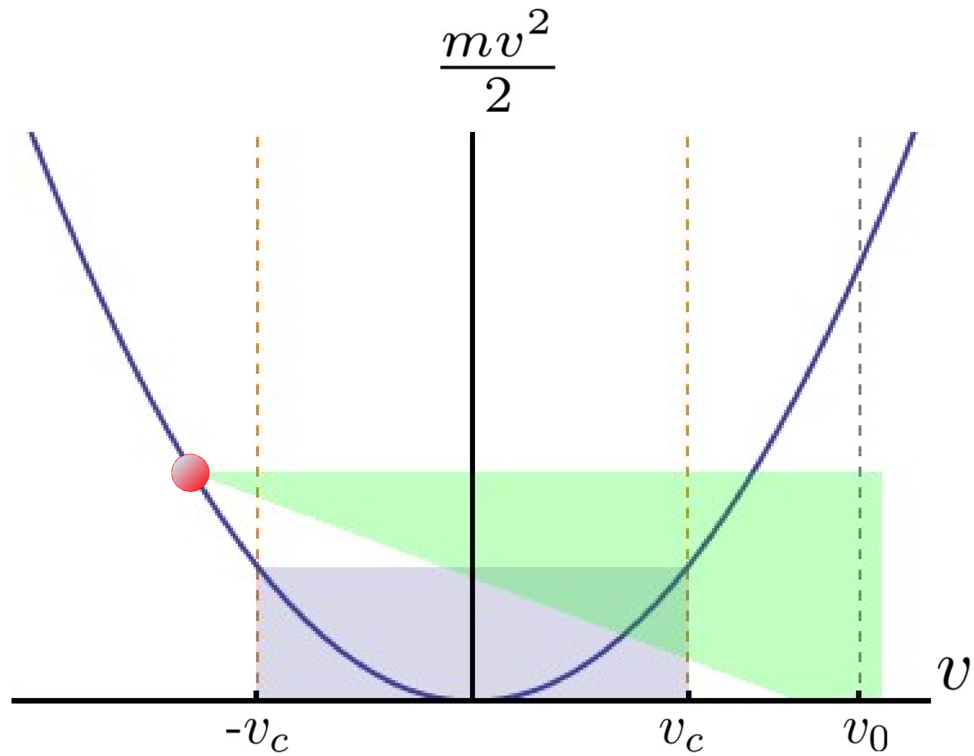

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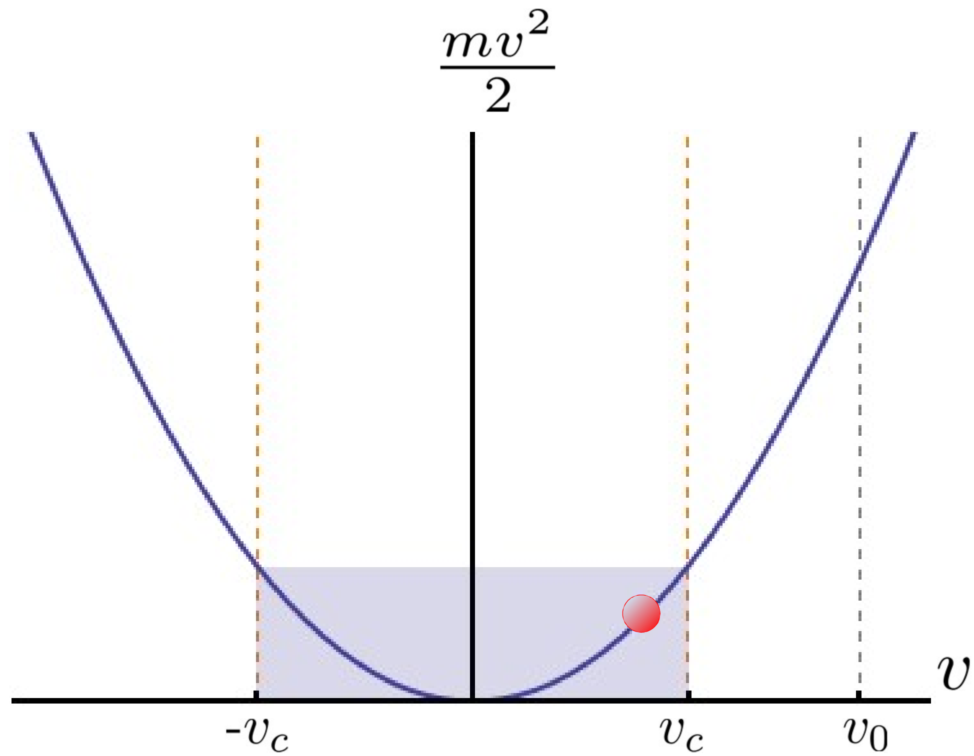

Impurity dynamics for $v_0 > v_c$: semiclassical picture

weak impurity-fluid coupling

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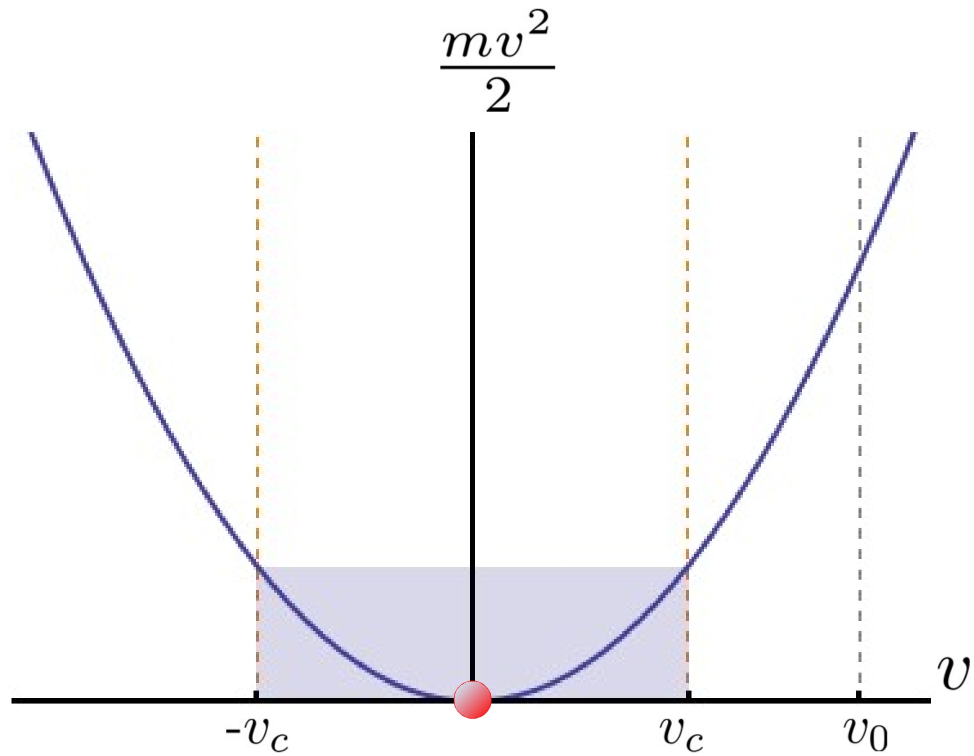


Impurity dynamics: weak coupling

Boltzmann equation:

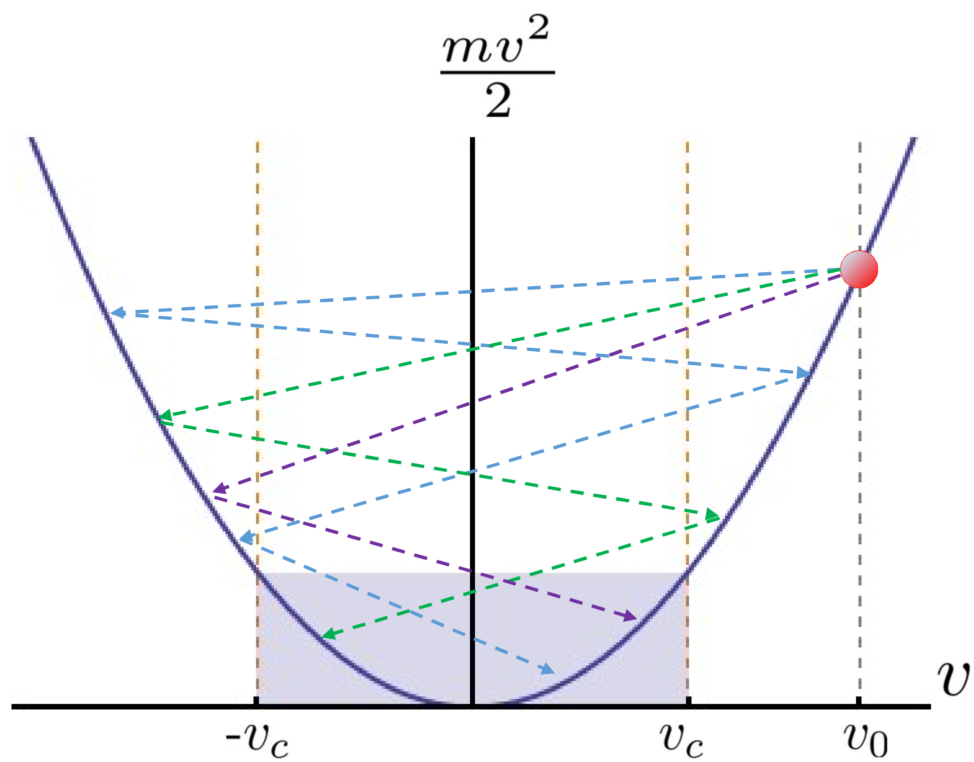
$$\frac{\partial n_k}{\partial t} = -n_k \sum_q \Gamma_{k\to q} + \sum_q n_q \Gamma_{q\to k}$$

$\Gamma_{k\to q}$ - scattering probability

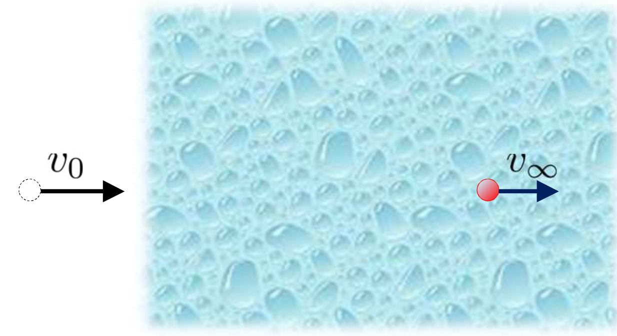
works even in 1D, with reservations

E. Burovski, V. Cheianov, O. Gamayun and OL, Phys. Rev. A 89, 041601 (R) (2014)

O. Gamayun, Phys. Rev. A 89, 063627 (2014)

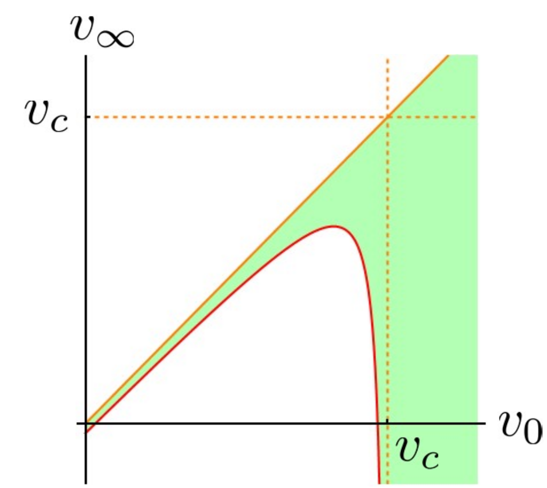


Footnote: generalized critical velocity beyond kinetic theory



$$H = H_{\rm f} + \frac{\mathbf{p}_{\rm imp}^2}{2m} + \sum_{j=1}^{N} U(\mathbf{r}_j - \mathbf{r}_{\rm imp})$$

impurity-fluid interaction



rigorous bound:

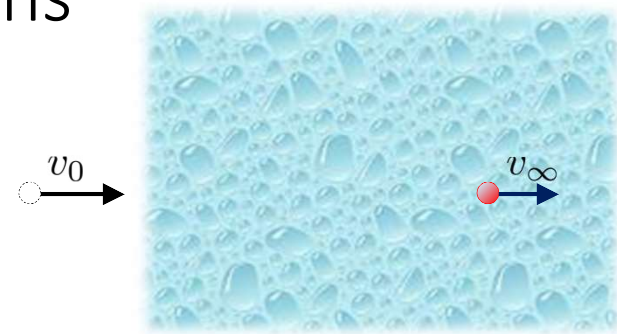
$$|\mathbf{v}_0 - \mathbf{v}_\infty| \leq \frac{\overline{U}}{m(v_c - v_0)}$$

valid for $v_0 < v_c, \quad U(\mathbf{r}) \geq 0$

$\overline{U} = \int d\mathbf{r}\, \rho\, U(\mathbf{r}), \qquad \rho = N/V$ – fluid density

O. Lychkovskiy, Phys. Rev. A 91, 040101 (R) (2015)
O. Lychkovskiy, Phys. Rev. A 89, 033619 (2014)

Accounting for impurity-fluid interactions



$$m\mathbf{v}_0 = m\mathbf{v} + \mathbf{p}$$

$$\frac{m\mathbf{v}_0^2}{2} = \frac{m\mathbf{v}^2}{2} + \varepsilon(\mathbf{p})$$

kinetic energy

$$H = H_\mathrm{f} + \frac{\mathbf{p}_\mathrm{imp}^2}{2m} + \sum_{j=1}^{N} U(\mathbf{r}_j - \mathbf{r}_\mathrm{imp})$$

impurity-fluid interaction

Accounting for impurity-fluid interactions

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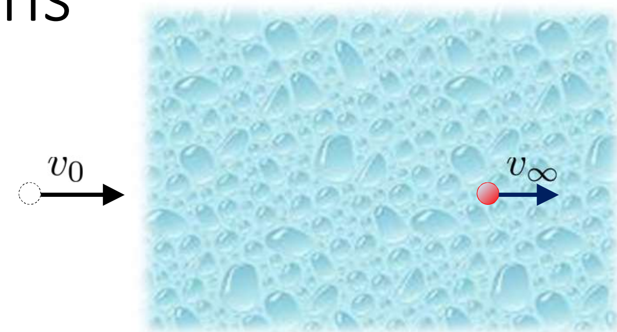

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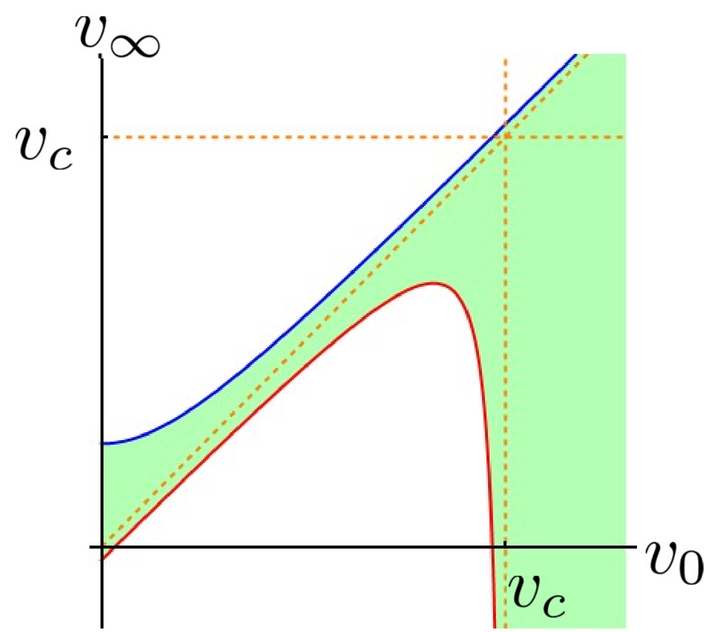

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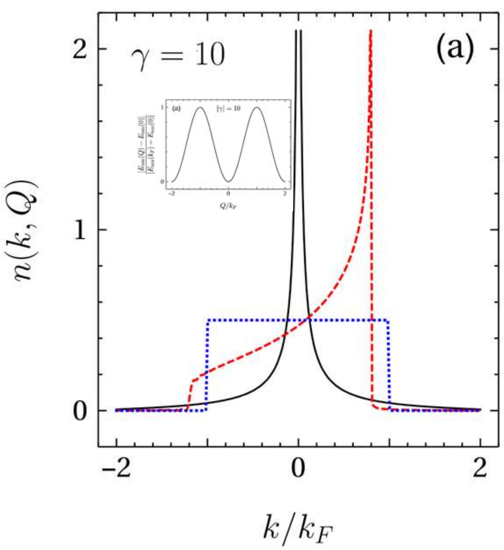
OL, Phys. Rev. A 89, 033619 (2014)
OL, Phys. Rev. A 91, 040101 (R) (2015)

McGuire model: polarons and anyons

$$\varrho(y) = \det(\hat{I} + \hat{K} + \hat{W}) - \det(\hat{I} + \hat{K})$$

$$n(k,Q) = \frac{1}{2\pi}\int_{-\infty}^{\infty} dy\, e^{iky}\varrho(y)$$



Q = 0

Q = 0.8 k_F

Q = k_F

O. Gamayun, O. Lychkovskiy, M. Zvonarev

arXiv 1909.07358

Anyons:

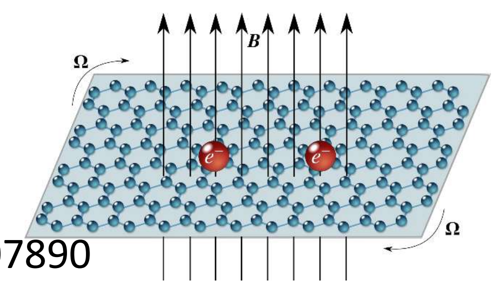
$$\psi(x_1)\psi^\dagger(x_2) = e^{-i\pi\kappa\,\mathrm{sgn}(x_1-x_2)}\psi^\dagger(x_2)\psi(x_1) + \delta(x_1 - x_2)$$

$\kappa = 0:$ bosons $\qquad \kappa = 1:$ fermions

$\gamma \to \infty :\quad n(k,Q) = n_A(k)$ with $\kappa = -Q/k_F$

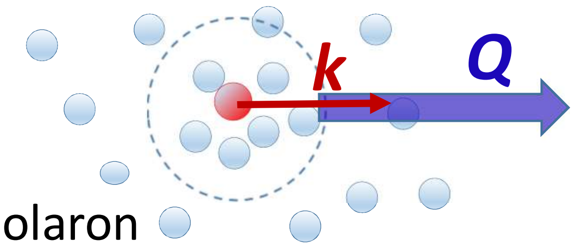
Patu, Korepin, Averin, 2008

similar effect in 2D:

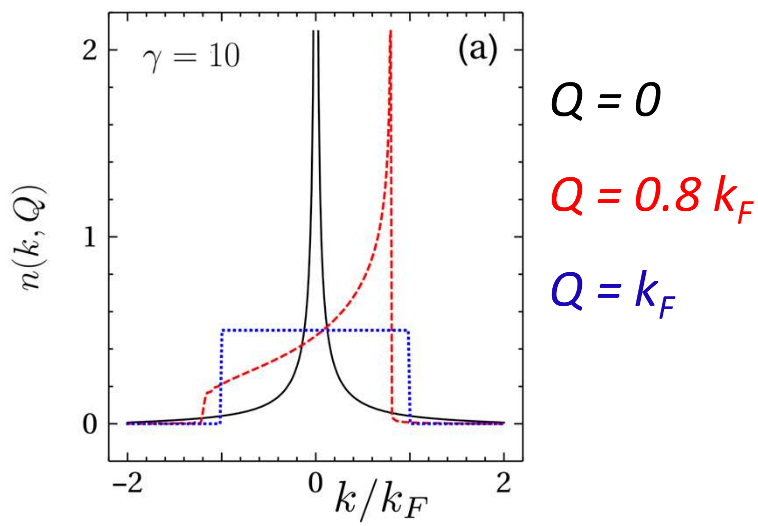


Yakaboylu et al, arXiv1912.07890

McGuire model: polarons and anyons



polaron



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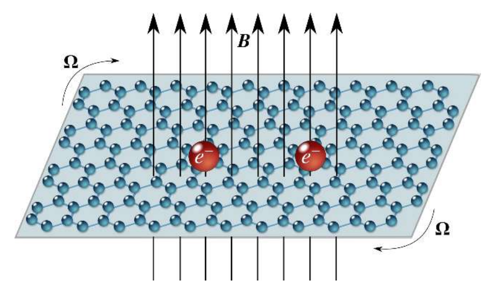

Yakaboylu et al, arXiv1912.07890