Excitonic superfluidity/supersolidity in electron-hole bilayer systems

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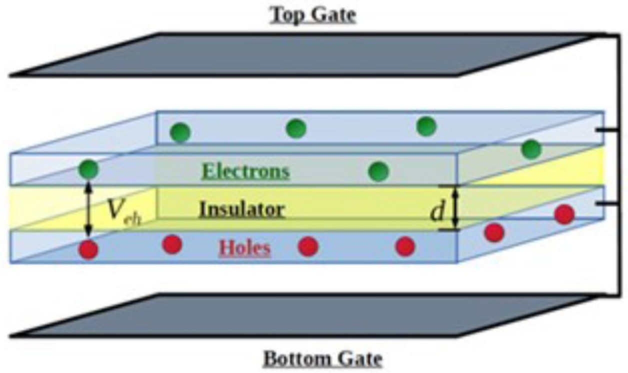
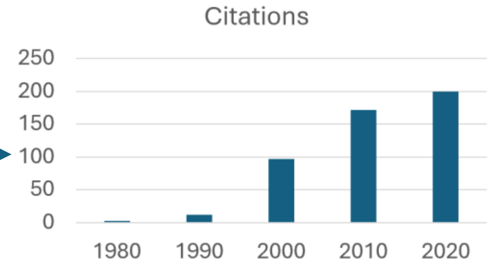
Luis Peña Ardila (Trieste)
Andrea Perali (Camerino)
Giordano Scappucci (Delft)

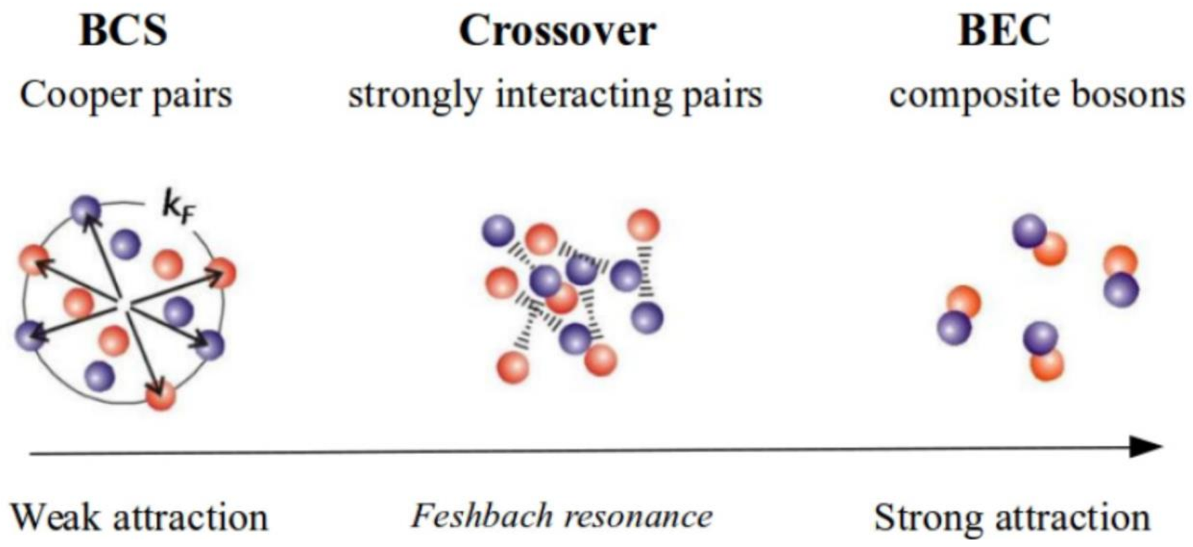
fwo Research Foundation Flanders Opening new horizons

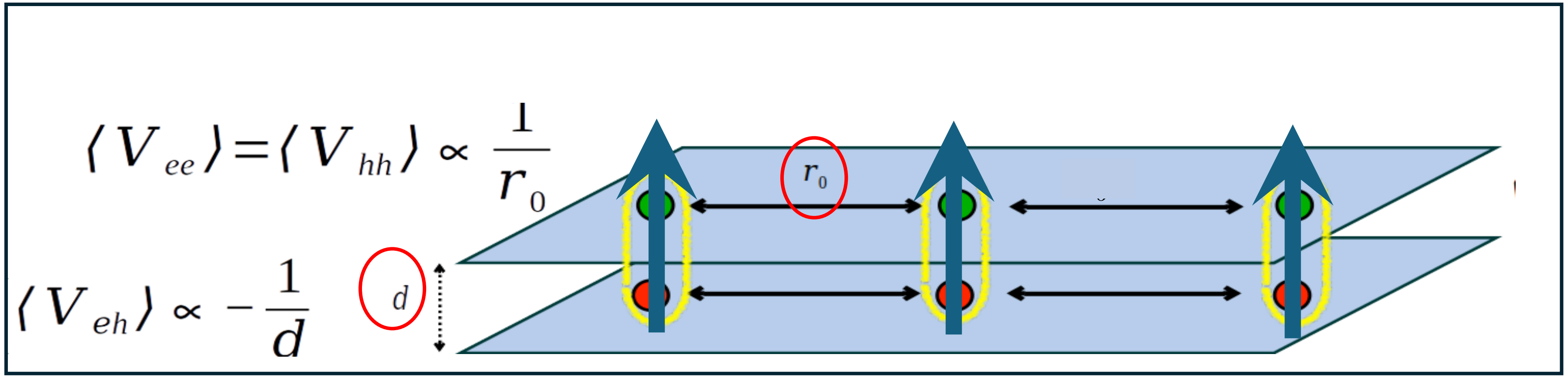


Strong Coulomb long-range electron-hole attraction → Electron-hole pairs → Quantum condensation and superfluidity → High Temperatures ?

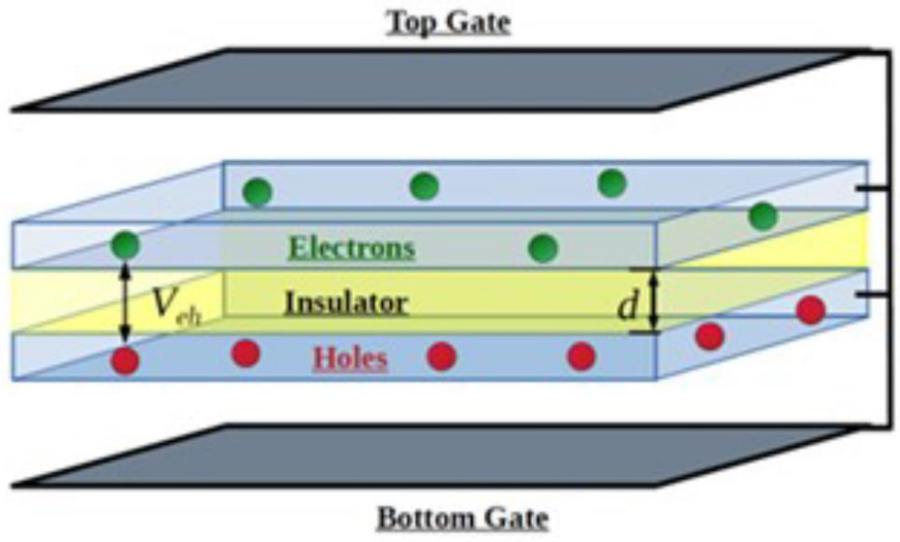
L. V. Keldysh and Y. V. Kopaev *Possible instability of semimetallic state toward Coulomb interaction*
Sov. Phys. - Solid State **6** 2219 (1965) (Fizika Tverdogo Tela, **6**, 2791 (1964))
Y. E. Lozovik and V. Yudson *Feasibility of superfluidity of paired spatially separated electrons and holes*
JETP Lett. **22** 274 (1975) (Pis'ma Zh. Eksp. Teor. Fiz. **22**, 556 (1975))
S. I. Shevchenko *Theory of superconductivity of systems with pairing of spatially separated electrons and holes*
Sov. J. Low Temp. Physics **2** 251(1976) (Fiz. Nizk. Temp. **2**, 505 (1976))







- Exciton quasi-dipoles align perpendicular to the layers
- Small $d \Rightarrow$ strong binding but weak interactions between dipolar excitons
- Large $d \Rightarrow$ strong interactions between excitons
- Exciton-exciton interaction is **always repulsive** (unlike for cold atoms)



Exciton Superfluidity AT EQUILIBRIUM (NOT OPTICALLY PUMPED)

GaAs	Double bilayer graphene	Double TMD monolayers	Strained Si/Ge
Theory: **Neilson** (Antwerp), **Perali** (Camerino). Experiment: **Das Gupta**, **Croxall** (Cambridge), **Lilly** (Sandia), **Hamilton** (Sydney)	Theory: **Conti**, **Neilson**, **Perali** (Camerino) Exp: **Tutuc** (Texas), **Dean** (Columbia)	Theory: **Fogler** (San Diego), **Conti**, **Neilson** (Antwerp), **Perali** (Camerino). Experiment: **Mak** (Cornell), **Kim** (Harvard), **Schaibley** (Arizona)	Theory: **Conti**, **Neilson** Exp: **Scappucci** (Delft)

PRL **101,** 246801 (2008) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2008

Anomalous Coulomb Drag in Electron-Hole Bilayers

A. F. Croxall, K. Das Gupta,* C. A. Nicoll, M. Thangaraj, H. E. Beere, I. Farrer, D. A. Ritchie, and M. Pepper
Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, United Kingdom

Selected for a Viewpoint in *Physics*
PRL **117,** 046802 (2016) PHYSICAL REVIEW LETTERS week ending 22 JULY 2016

Negative Coulomb Drag in Double Bilayer Graphene

J. I. A. Li,[1] T. Taniguchi,[2] K. Watanabe,[2] J. Hone,[3] A. Levchenko,[4] and C. R. Dean[1]

Strong Coulomb drag and broken symmetry in double-layer graphene

R. V. Gorbachev, A. K. Geim, M. I. Katsnelson, K. S. Novoselov, T. Tudorovskiy, I. V. Grigorieva, A. H. MacDonald, S. V. Morozov, K. Watanabe, T. Taniguchi & L. A. Ponomarenko

Nature Physics **8**, 896–901 (2012) | Cite this article

PRL **102,** 026804 (2009) PHYSICAL REVIEW LETTERS week ending 16 JANUARY 2009

Coulomb Drag in the Exciton Regime in Electron-Hole Bilayers

J. A. Seamons, C. P. Morath, J. L. Reno, and M. P. Lilly*
Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
(Received 8 August 2008; published 14 January 2009)

PHYSICAL REVIEW LETTERS **120,** 177702 (2018)

Editors' Suggestion Featured in Physics

Strongly Enhanced Tunneling at Total Charge Neutrality in Double-Bilayer Graphene-WSe_2 Heterostructures

am Burg,[1] Nitin Prasad,[1] Kyounghwan Kim,[1] Takashi Taniguchi,[2] Kenji Watanabe,[2] Allan H. MacDonald,[3] Leonard F. Register,[1] and Emanuel Tutuc[1,*]

Evidence of high-temperature exciton condensation in two-dimensional atomic double layers

Zefang Wang, Daniel A. Rhodes, Kenji Watanabe, Takashi Taniguchi, James C. Hone, Jie Shan & Kin Fai Mak

Nature **574**, 76–80 (2019) | Cite this article

PRL 101, 246801 (2008) PHYSICAL REVIEW LETTERS week ending 12 DECEMBER 2008

Anomalous Coulomb Drag in

A. F. Croxall, K. Das Gupta,* C. A. Nicoll, M. Thangaraj, I

Cavendish Laboratory, University of Cambridge, J.J. Thoms

[Submitted on 26 Sep 2023]

Perfect Coulomb drag in a dipolar excitonic insulator

Phuong X. Nguyen, Liguo Ma, Raghav Chaturvedi, Kenji Watanabe, Takashi Taniguchi, Jie Shan, Kin Fai Mak

Ultraviolet interlayer excitons in bilayer WSe_2

Kai-Qiang Lin, Paulo E. Faria Junior, Ruven Hübner, Jonas D. Ziegler, Jonas M. Bauer, Fa

Matthias Florian, Felix Hofmann, Kenji Watanabe, Takashi Taniguchi, Jaroslav Fabian, Alexa

Alexey Chernikov, Sebastian Bange & John M. Lupton

Nature Nanotechnology **19**, 196–201 (2024) | Cite this article

6028 Accesses | 1 Citations | 13 Altmetric | Metrics

SCIENCE ADVANCES | RESEARCH ARTICLE

Sci. Adv. **11**, eadr1772 (2025) 3 January 2025

Imaging interlayer exciton superfluidity in a 2D semiconductor heterostructure

Jacob Cutshall[1]†, Fateme Mahdikhany[1,2]†, Anna Roche[1], Daniel N. Shanks[1], Michael R. Koehler[3], David G. Mandrus[4,5,6], Takashi Taniguchi[7], Kenji Watanabe[8], Qizhong Zhu[9,10], Brian J. LeRoy[1], John R. Schaibley[1]*

gly Enhanced Tunneling at Total Charge Neutrality in Double-Bilayer Graphene-WSe_2 Heterostructures

William Burg,[1] Nitin Prasad,[1] Kyounghwan Kim,[1] Takashi Taniguchi,[2] Kenji Watanabe,[2] Allan H. MacDonald,[3] Leonard F. Register,[1] and Emanuel Tutuc[1,*]

J. A. Seamons, C. P. Morath, J. L. Reno, and M. P. Lilly*

Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

Evidence of high-temperature exciton c two-dimensional atomic double layers

Zefang Wang, Daniel A. Rhodes, Kenji Watanabe, Takashi Taniguchi, James C. Mak

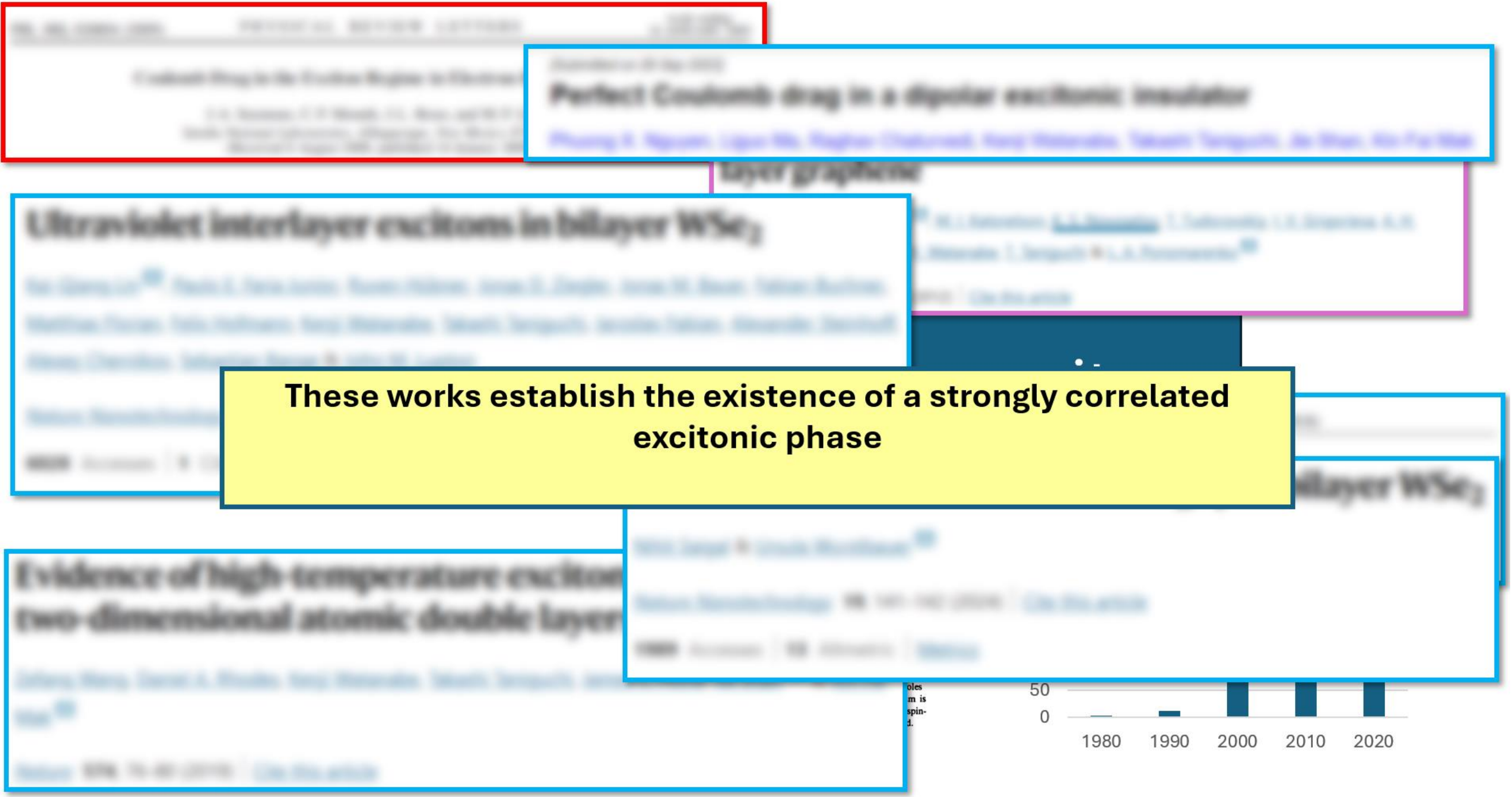
Nature **574**, 76–80 (2019) | Cite this article

Excitons stabilize above the band gap in bilayer WSe_2

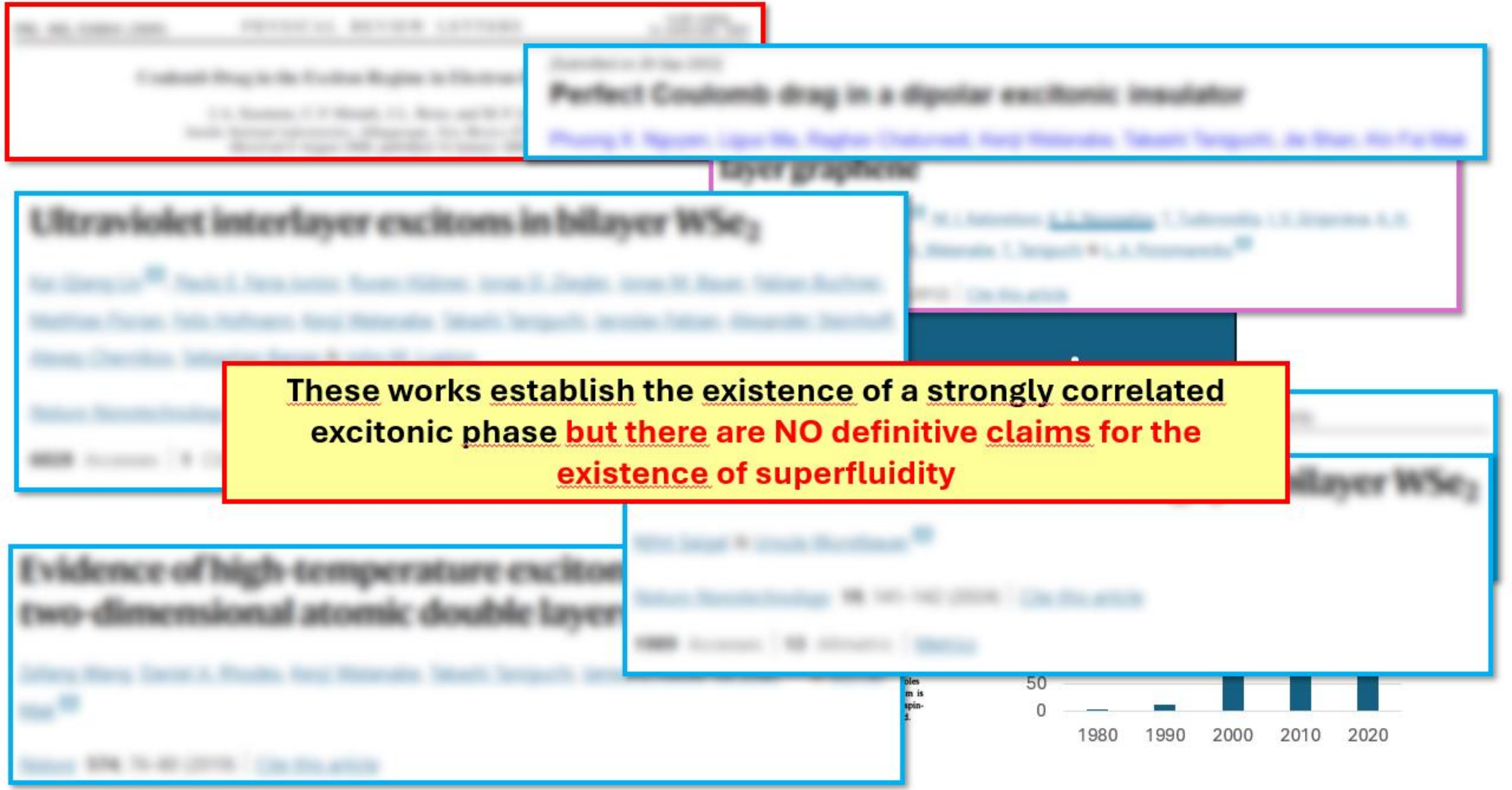
Nihit Saigal & Ursula Wurstbauer

Nature Nanotechnology **19**, 141–142 (2024) | Cite this article

1989 Accesses | 13 Altmetric | Metrics



These works establish the existence of a strongly correlated excitonic phase



These works establish the existence of a strongly correlated excitonic phase **but there are NO definitive claims for the existence of superfluidity**

Superfluid equations

$$V_{\mathbf{q}}^{S} = V_{\mathbf{q}}^{ee} = V_{\mathbf{q}}^{hh} = \frac{2\pi e^2}{4\pi\epsilon\epsilon_0|\mathbf{q}|} \text{ and } V_{\mathbf{q}}^{D} = V_{\mathbf{q}}^{eh} = V_{\mathbf{q}}^{he} = -V_{\mathbf{q}}^{S}\mathrm{e}^{-|\mathbf{q}|d}$$

$$\boxed{\begin{aligned} \Delta_{\mathbf{k}} &= -\frac{1}{A}\sum_{\mathbf{k}'} V_{\mathbf{k}-\mathbf{k}'}^{D}\frac{\Delta_{\mathbf{k}'}}{2E_{\mathbf{k}'}} \\ n &= \frac{g}{A}\sum_{\mathbf{k}} v_{\mathbf{k}}^{2}. \end{aligned}}$$

BCS mean-field is a good approximation at *T=0* for strong- and weak-coupling superfluidity

P. Nozières & F. Pistolesi, *From semiconductors to superconductors*, Euro. Phys. B **10** 649 (1999)

energies $E_{\mathrm{k}} = \sqrt{\xi_{\mathrm{k}}^2 + \Delta_{\mathrm{k}'}^2}, \xi_{\mathrm{k}} = \varepsilon_k - \mu,$

Bogoliubov factors, $v_k = \sqrt{\frac{1}{2}(1 - \xi_k/E_k)}$ $\qquad u_k = \sqrt{\frac{1}{2}(1 + \xi_k/E_k)}$

Screening in the superfluid

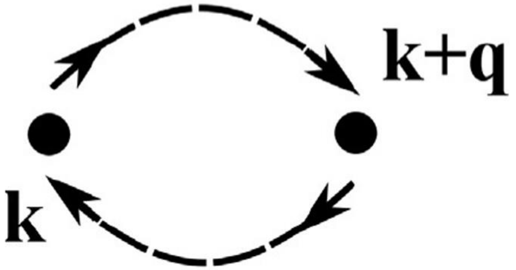
Screening of the long-range Coulomb attraction for the pairs is a major challenge

$$G(\mathbf{k}, \mathrm{i}\varepsilon_n) = \frac{u_k^2}{\mathrm{i}\varepsilon_n - E_k} + \frac{v_k^2}{\mathrm{i}\varepsilon_n + E_k}$$

$$F(\mathbf{k}, \mathrm{i}\varepsilon_n) = \frac{u_k v_k}{\mathrm{i}\varepsilon_n - E_k} - \frac{u_k v_k}{\mathrm{i}\varepsilon_n + E_k}$$

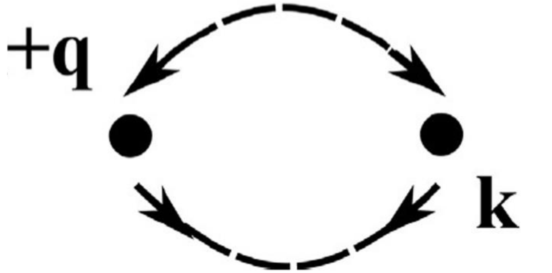
$$\Pi_0^N(\mathbf{q}) = \frac{ig}{\hbar A} \sum_{\mathbf{k}} \lim_{\eta,\omega\to 0} \int d\tau e^{i(\omega\tau + i\eta|\tau|)} iG_{\mathbf{k}+\mathbf{q}}(\tau) iG_{\mathbf{k}}(-\tau)$$

$$= -\frac{g}{A} \sum_{\mathbf{k}} \frac{u_{\mathbf{k}}^2 v_{\mathbf{k}+\mathbf{q}}^2 + v_{\mathbf{k}}^2 u_{\mathbf{k}+\mathbf{q}}^2}{E_{\mathbf{k}} + E_{\mathbf{k}+\mathbf{q}}},$$

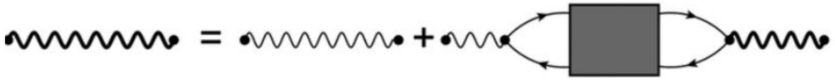


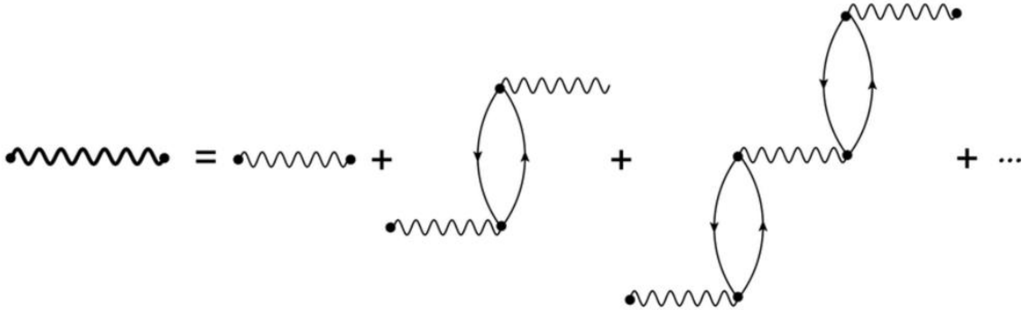
$$\Pi_0^A(\mathbf{q}) = -\frac{ig}{\hbar A} \sum_{\mathbf{k}} \lim_{\eta,\omega\to 0} \int d\tau e^{i(\omega\tau + i\eta|\tau|)} iF_{\mathbf{k}+\mathbf{q}}^*(\tau) iF_{\mathbf{k}}(-\tau)$$

$$= -\frac{2g}{A} \sum_{\mathbf{k}} \frac{u_{\mathbf{k}} v_{\mathbf{k}} v_{\mathbf{k}+\mathbf{q}} u_{\mathbf{k}+\mathbf{q}}}{E_{\mathbf{k}} + E_{\mathbf{k}+\mathbf{q}}}.$$



Screening in the superfluid

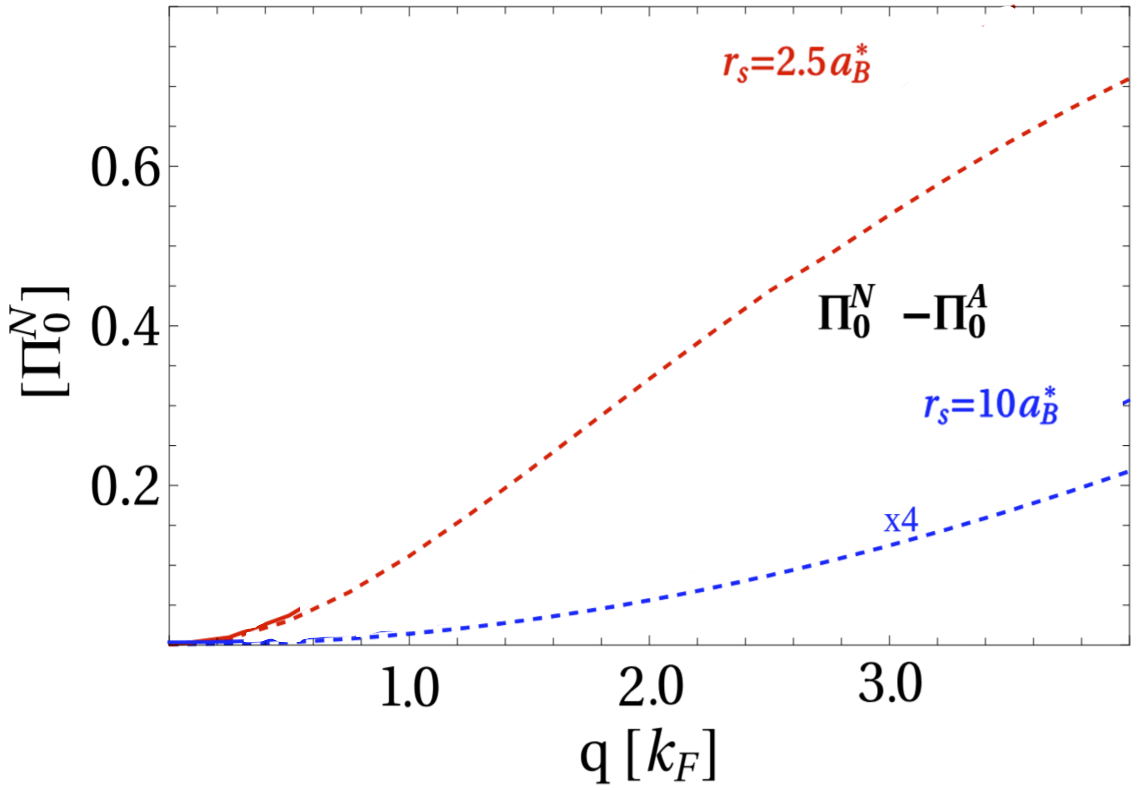


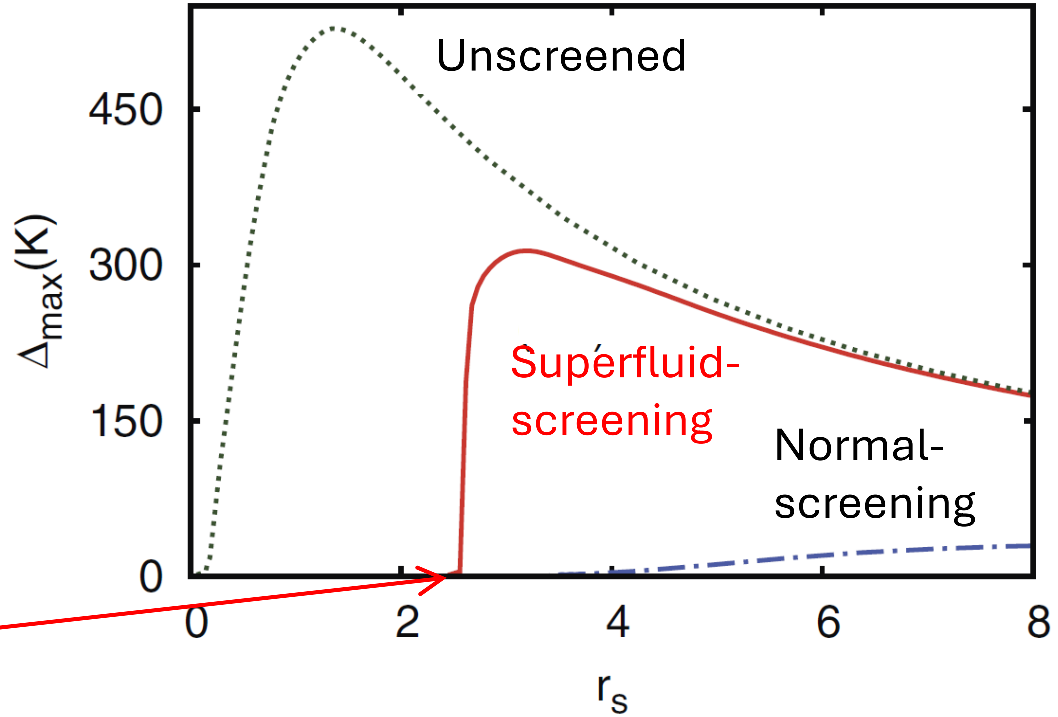


$$V_{\mathbf{q}}^{S,RPA} = \frac{V_{\mathbf{q}}^{S} - \Pi_0^N(\mathbf{q})\mathcal{A}_{\mathbf{q}}}{1 - 2(\Pi_0^N(\mathbf{q})V_{\mathbf{q}}^{S} + \Pi_0^A(\mathbf{q})V_{\mathbf{q}}^{D}) + \mathcal{A}_{\mathbf{q}}((\Pi_0^N(\mathbf{q}))^2 - (\Pi_0^A(\mathbf{q}))^2)}$$

$$V_{\mathbf{q}}^{D,RPA} = \frac{V_{\mathbf{q}}^{D} + \Pi_0^A(\mathbf{q})\mathcal{A}_{\mathbf{q}}}{1 - 2(\Pi_0^N(\mathbf{q})V_{\mathbf{q}}^{S} + \Pi_0^A(\mathbf{q})V_{\mathbf{q}}^{D}) + \mathcal{A}_{\mathbf{q}}((\Pi_0^N(\mathbf{q}))^2 - (\Pi_0^A(\mathbf{q}))^2)}$$

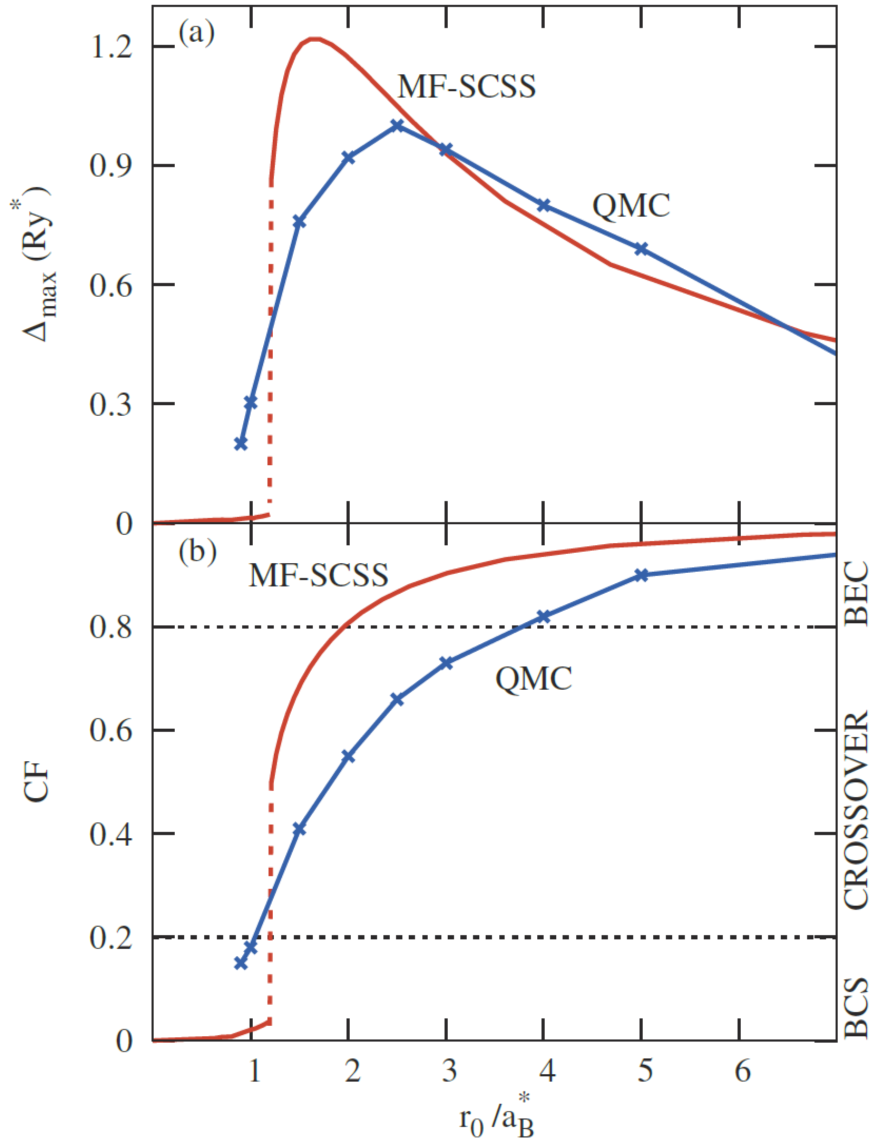
with $\mathcal{A}_{\mathbf{q}} = (V_{\mathbf{q}}^{S})^2 - (V_{\mathbf{q}}^{D})^2$ and $\mathcal{B}_{\mathbf{q}}$ $V_{\mathbf{q}}^{D} = -V_{\mathbf{q}}^{S} \mathrm{e}^{-|\mathbf{q}|d}$





Electron-hole superfluidity is a low-density phenomenon

Gap, onset density, and crossover physics

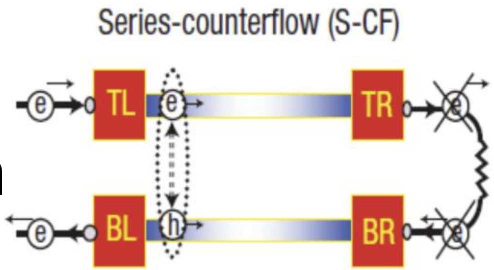


Across superfluid region, the *Condensate Fraction CF ≳ 0.2*
⇒ no BCS regime

There has been no definite experimental claim of superfluidity

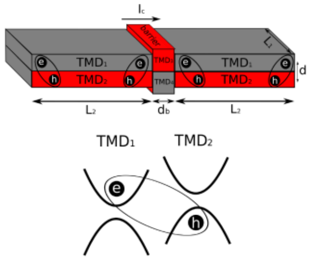
It is timely to find *fingerprints* to unambiguously identify the superfluidity

- ~~Steady-state dissipationless counterflow current cannot be straightforwardly induced because of increasing interlayer tunnelling and e-h recombination~~

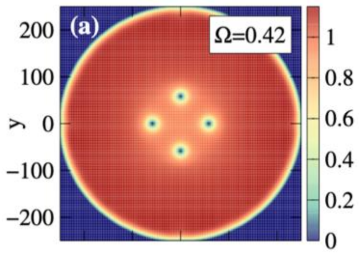


- ~~No Meissner effect in a neutral system~~

Could use:



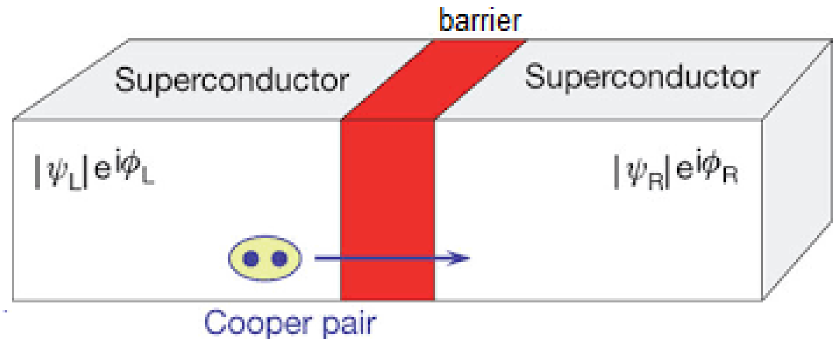
✓ Josephson ✓



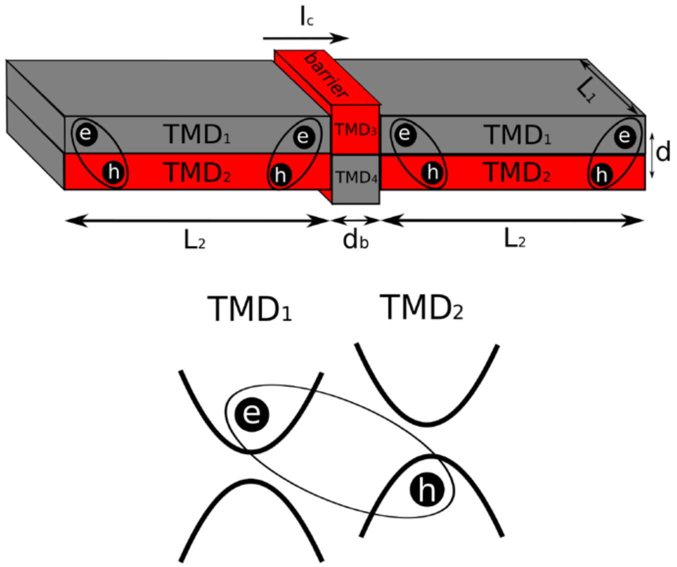
✓ Detection of vortices ✓

✓ Additional collective modes ✓

Josephson effect



Dissipationless macroscopic coherent current of Cooper pairs without a driving potential flowing between two superconductors separated by a barrier.



DC JE: Measurement of a super tunneling current and zero voltage drop across the barrier.

Problems: Difficult to measure very low values of resistance and voltage.

Possible solution: Shapiro steps.

AC JE: Highly oscillating super current in the barrier region related to the time evolution of the phase order parameter.

Collective modes

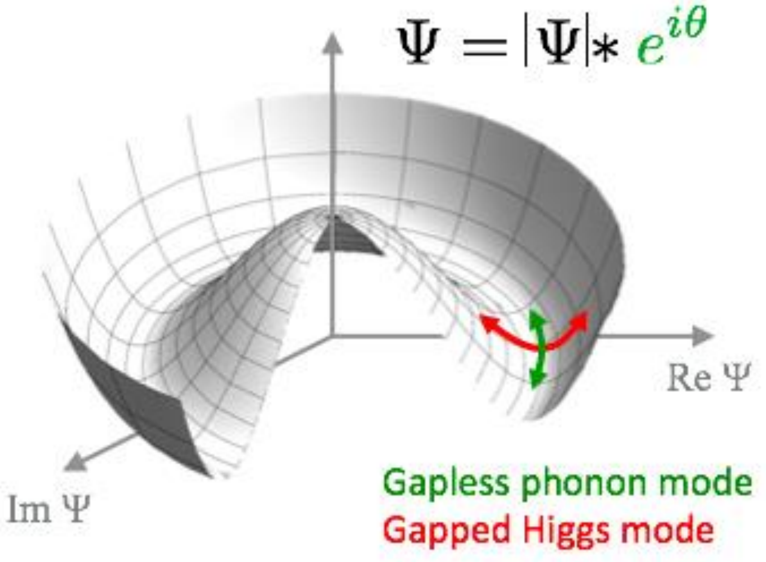
From small perturbations around the ground state - of what?.

Order parameter:

$$\Psi_0 = |\Psi_0|e^{i\theta_0}$$

- Phase fluctuations $\theta = \theta_0 + \delta\theta$:
  Gapless phonon mode.

- Amplitude fluctuations $|\Psi| = |\Psi_0| + |\delta\Psi|$:
  Gapped pair-breaking mode.



Phase and Amplitude collective modes **only** in the superfluid phase.

Density collective modes from normal to superfluid phase.

Vortices

In the BEC regime, exciton-exciton repulsive interaction is unscreened:

$$V_{\mathrm{XX}}(r) = \frac{2e^2}{4\pi\epsilon}\left(\frac{1}{r} - \frac{1}{\sqrt{r^2 + d^2}}\right)$$

Vortex properties and numbers will depend on interaction strength ~ d^2

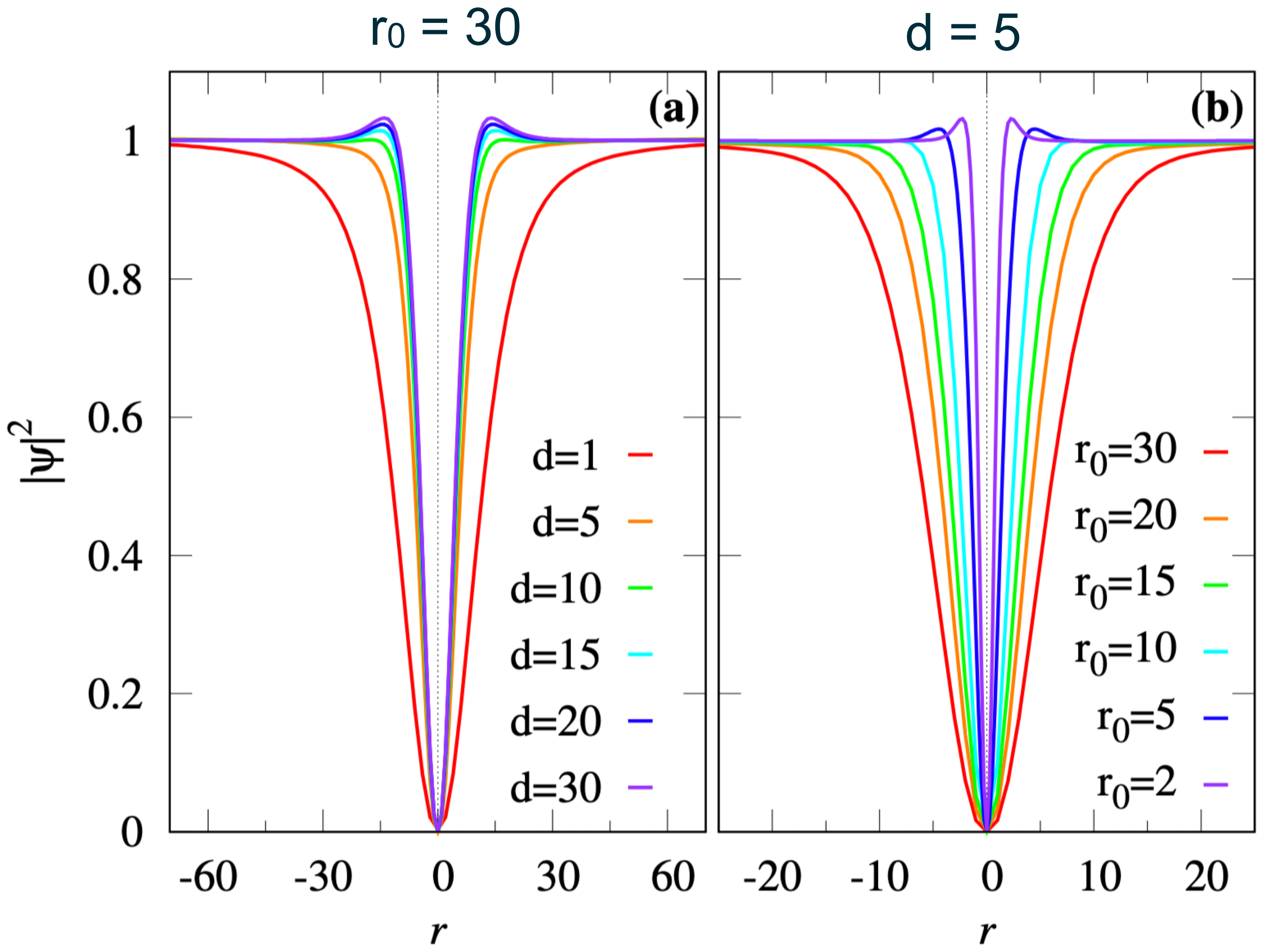
→ Gross-Pitaevskii equation for superfluid in rotating frame

$$-\frac{\hbar^2}{2M}\nabla^2\Psi(\mathbf{r}) + \phi_{XX}(\mathbf{r})\Psi(\mathbf{r}) - \boldsymbol{\Omega}\cdot\mathbf{L}\Psi(\mathbf{r}) = \mu\Psi(\mathbf{r})$$

$$\phi_{\mathrm{XX}}(\mathbf{r}) = \int V_{\mathrm{XX}}(|\mathbf{r}-\mathbf{r}'|)\,|\Psi(\mathbf{r}')|^2\,d\mathbf{r}'$$

Ω : angular velocity

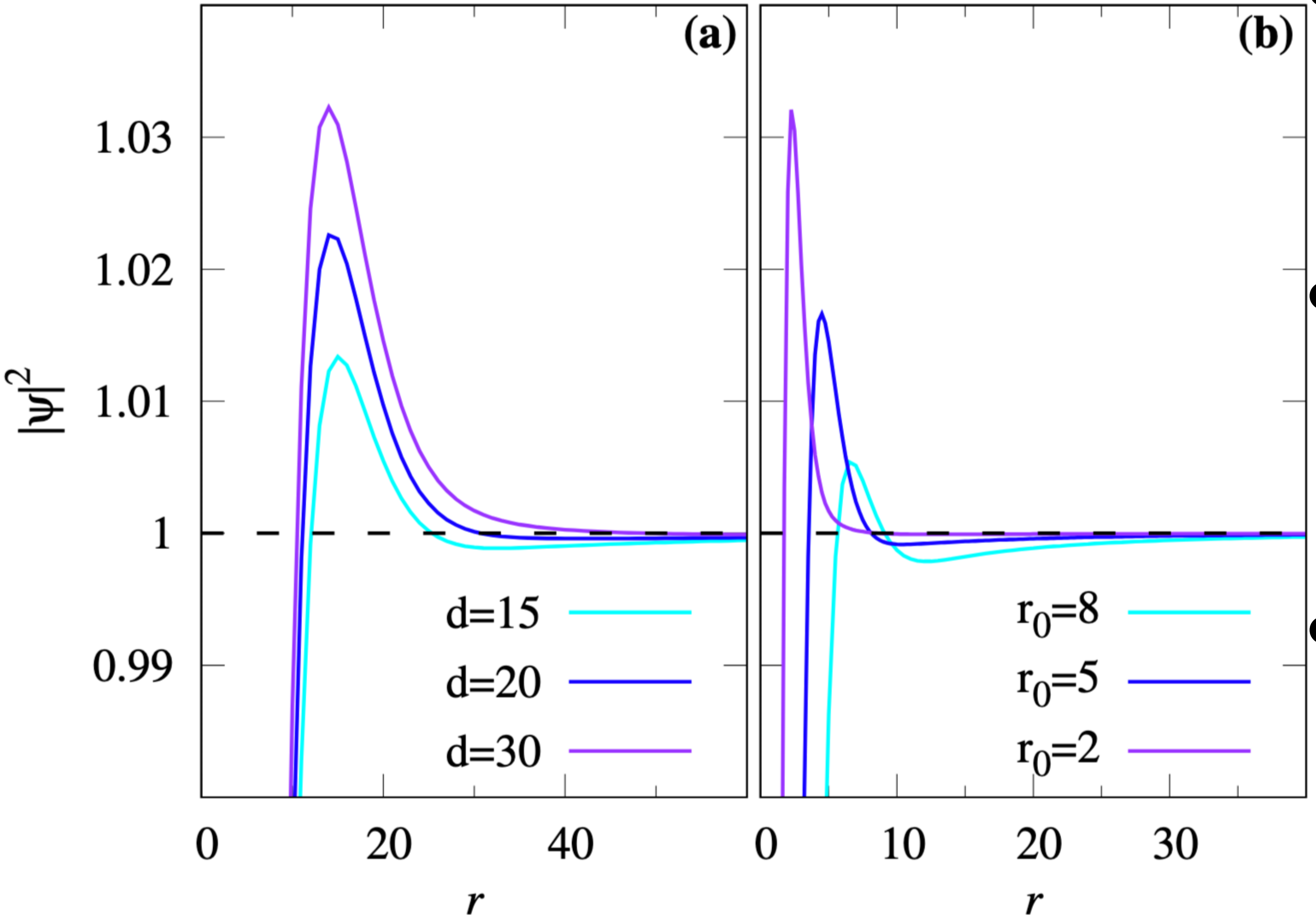
Vortices



With increasing dipole strength *d* or increasing density:

- Vortex radius decreases
- A density pileup peak appears at vortex edge

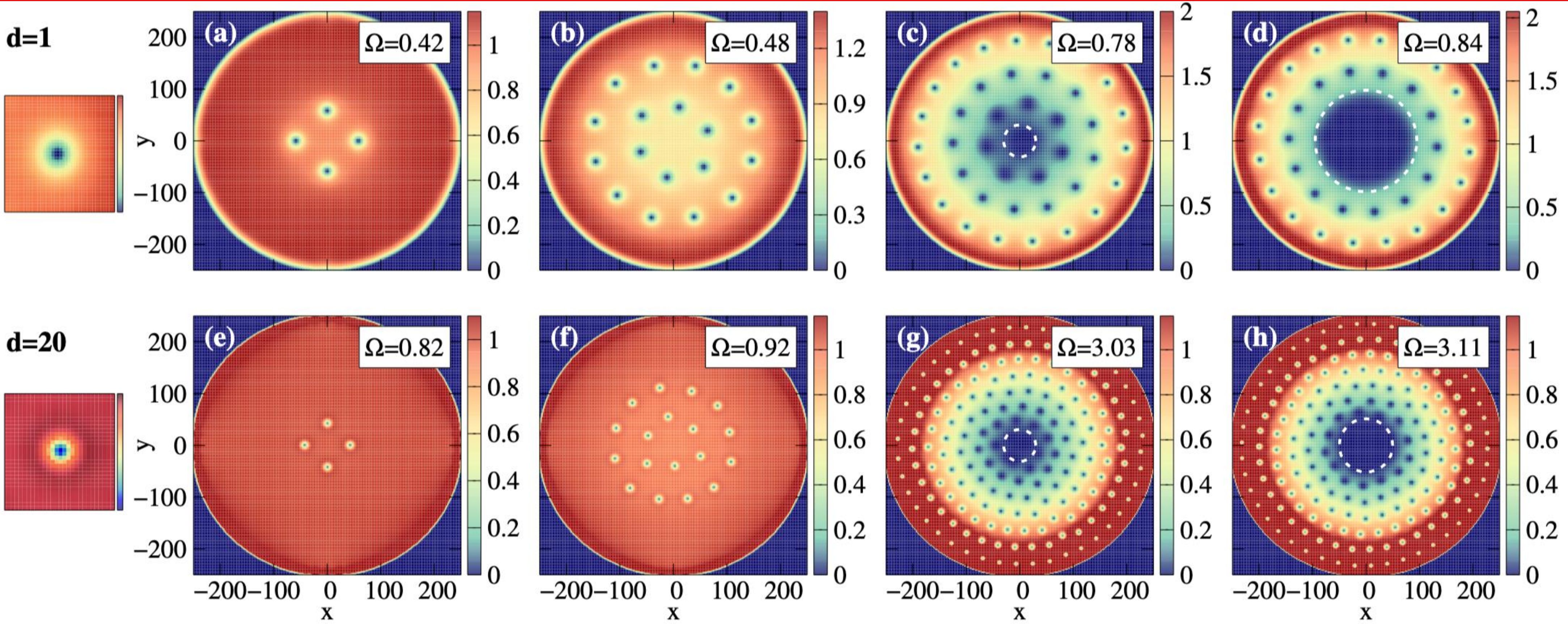
Vortices



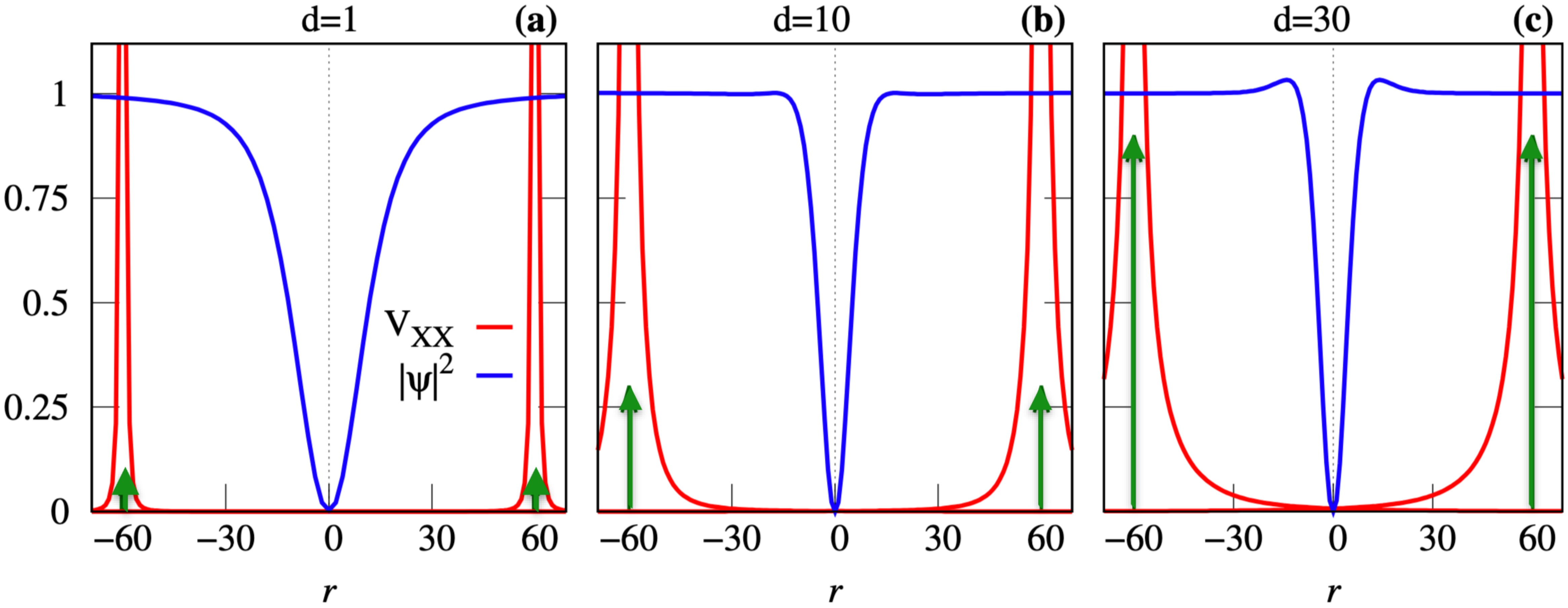
- Cold atoms with dipolar interactions also display a pileup peak when density increases.
- But in cold atoms the peak is accompanied by oscillations further out – associated with a low-lying roton collective excitation.
- **No oscillations** –> suggests: **no roton** for pure repulsion

Vortex Lattices

- The vortices for *d=20* are smaller than for *d = 1*
- The threshold Ω when the vortices overlap is larger for *d=20* than *d = 1*
- The vortices for *d = 20* have wings

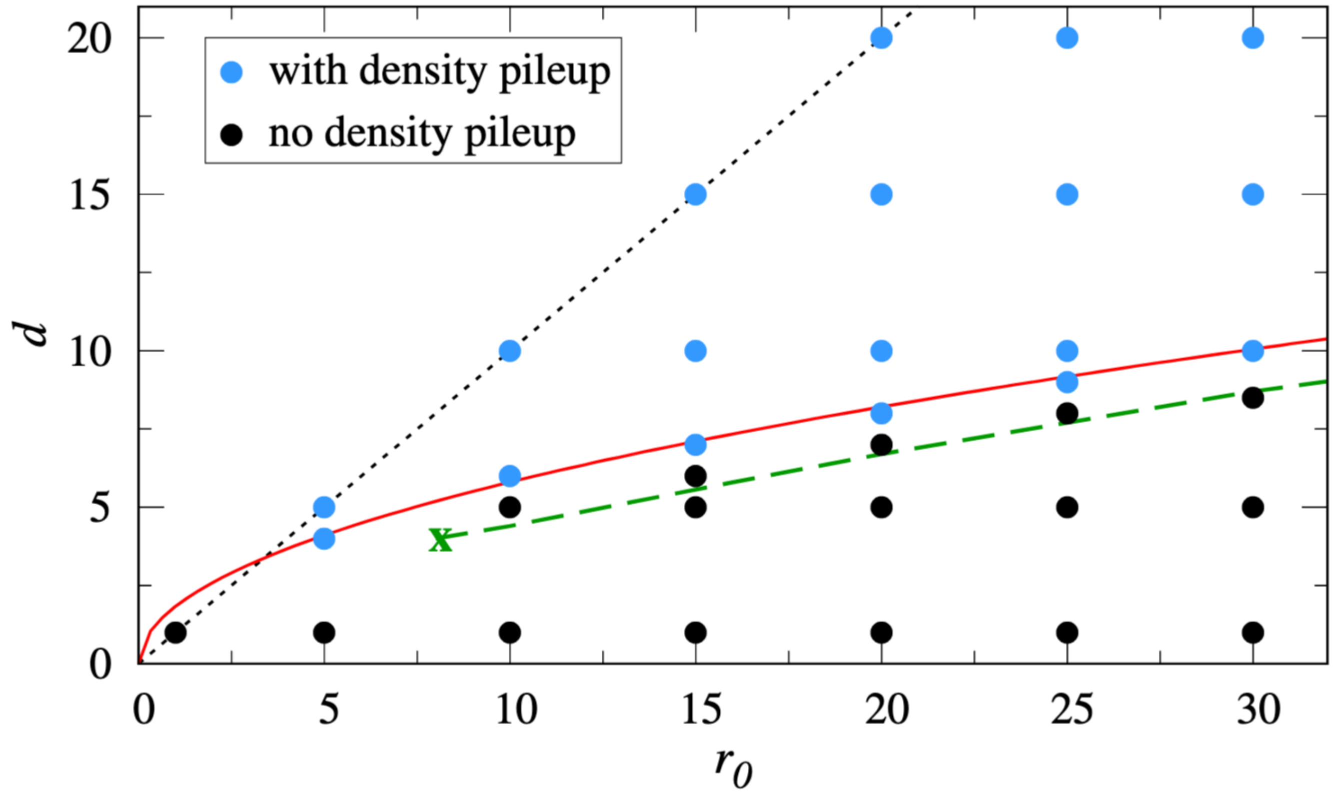


Vortices



The accumulation of density at the vortex edge comes from the competition between the outward **centrifugal force** and the inward **repulsion** from neighbouring dipoles.

Vortices



RED LINE: density pileup appears on vortex.

GREEN LINE: Gross Pitaevskii transition from superfluid to supersolid

Both density pileup and transition occur as the effective range of the interaction becomes of the same order as r_0.