Aalto University
School of Science

Quantum geometry effects on superconductivity, light-matter interactions, and Bose-Einstein condensation

Päivi Törmä

Aalto University

Hamburg Theoretical Physics Symposium 2021

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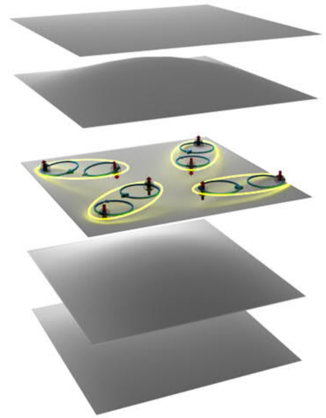
<u>Quantum geometry and superconductivity</u>

- **Can we reach room temperature superconductivity?**
- **What does quantum geometry have to do with this?**

<u>Quantum geometry and BEC</u>

<u>Quantum geometry and light-matter interactions</u>

<u>Briefly: Bose-Einstein condensation and magnetic switching in a plasmonic lattice (experiment)</u>



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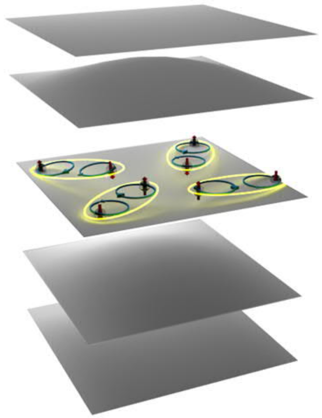
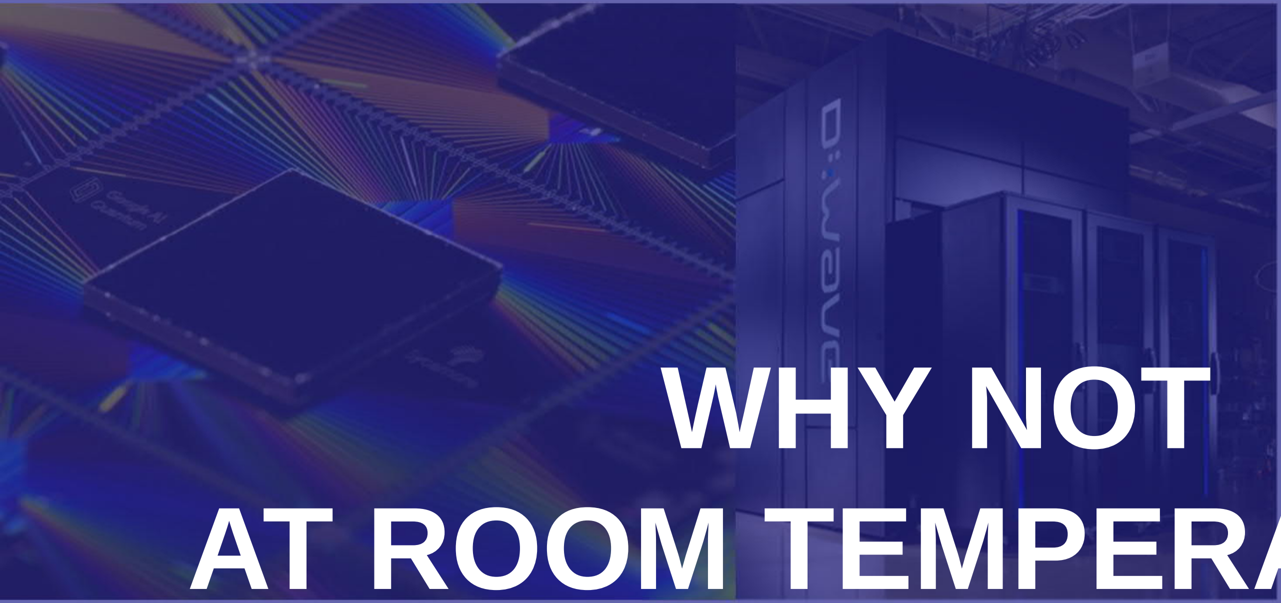
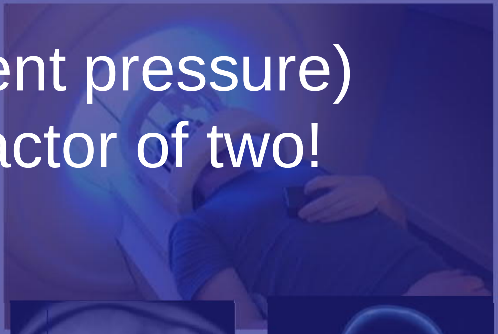


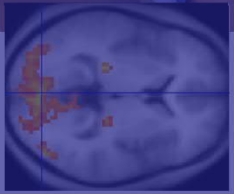
SUPERCONDUCTIVITY



WHY NOT AT ROOM TEMPERATURE?

Highest T_c (ambient pressure) ~150 K – just a factor of two!





Superconductivity: BEC of Cooper pairs

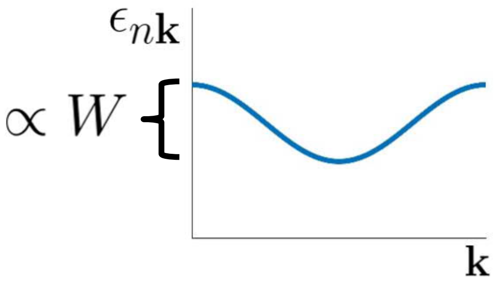
Weak interaction U
Large kinetic energy (Fermi level)
Low critical temperature

$$T_c \propto e^{-1/(U n_0(E_f))}$$

Remove the kinetic energy to maximize the effect of interactions!

Flat bands: interactions dominate

Dispersive band U<<W:



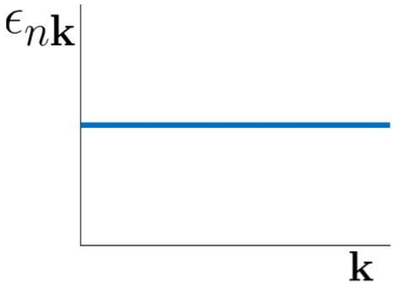
$$\psi_n(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u_{n\mathbf{k}}(\mathbf{r})$$

(periodic part of) the Bloch function

T_c for Cooper pairing

$$T_c \propto e^{-1/(U n_0(E_f))}$$

Flat band U>>W:



$\epsilon_{n\mathbf{k}} =$ constant

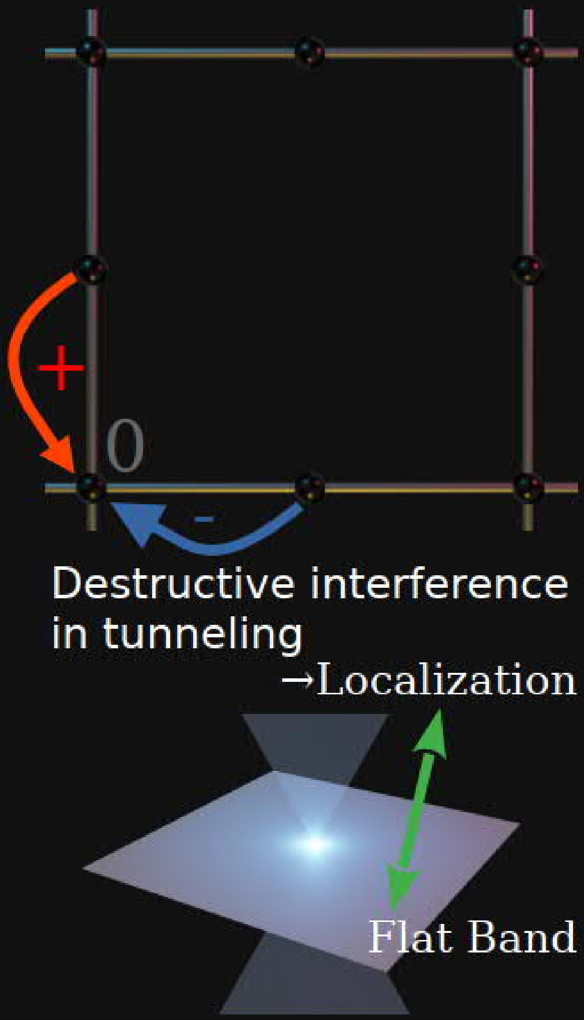
Group velocity: $\frac{\partial \epsilon_{n\mathbf{k}}}{\partial k} = 0$

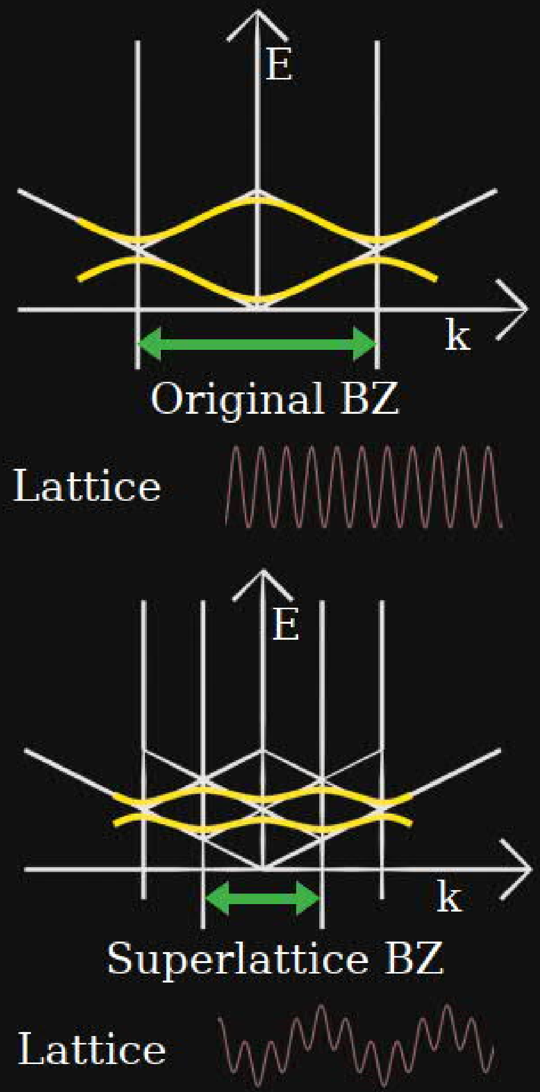
No interactions: insulator at any filling

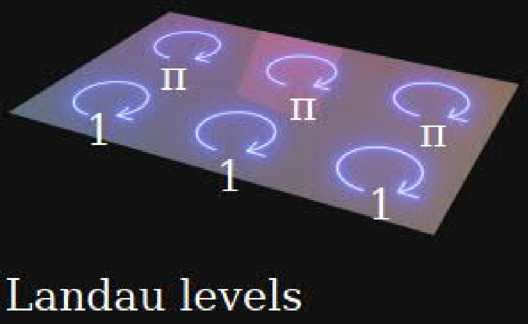
$$T_c \propto U V_{\text{flat band}}$$

High T_c for pairing
(Khodel, Shaginyan, Volovik, Kopnin, Heikkilä)

Formation of flat bands







But is supercurrent stable at a flat band?

Supercurrent density: given by superfluid weight and Cooper pair momentum

$$\mathbf{J} = \frac{1}{4} D_s \hbar \mathbf{q}$$

Conventional BCS: $D_s = \frac{n_{\rm p}}{m_{\rm eff}} \left(1 - \left(\frac{2\pi\Delta}{k_{\rm B}T} \right)^{1/2} e^{-\Delta/(k_{\rm B}T)} \right)$

$n_{\rm p}$ Particle density

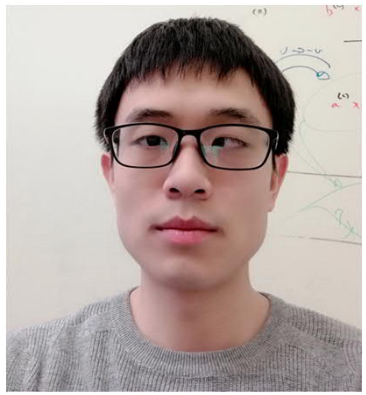
$$\frac{1}{m_{\rm eff}} \propto J \propto \partial_{k_i} \partial_{k_j} \epsilon_{\mathbf{k}}$$

Bandwidth $i, j = x, y, z$

Zero at a flat band!!!

Superfluidity and quantum geometry

Sebastiano Peotta



Long Liang

Sebastian Huber

Murad Tovmasyan

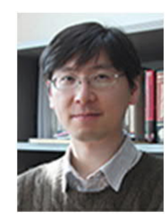
Aleksi Julku

Tuomas Vanhala

Peotta, PT, Nat Comm 2015
Julku, Peotta, Vanhala, Kim, PT, PRL 2016
Tovmasyan, Peotta, PT, Huber, PRB 2016
Liang, Vanhala, Peotta, Siro, Harju, PT, PRB 2017
Liang, Peotta, Harju, PT, PRB 2017
Tovmasyan, Peotta, Liang, PT, Huber, PRB 2018
PT, Liang, Peotta, PRB(R) 2018

Ari Harju

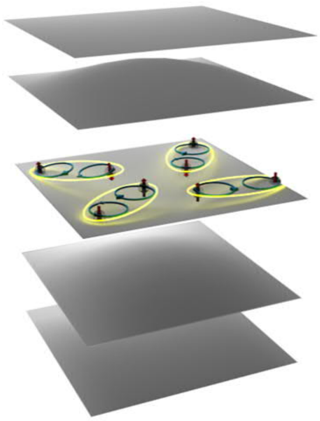
Topi Siro



Dong-Hee Kim

Our multiband approach

MULTIBAND BCS MEAN-FIELD THEORY
multiband two-component attractive
Fermi-Hubbard model –U < 0



$$H = -\sum_{ij\alpha\beta\sigma} t^{\sigma}_{i\alpha j\beta} c^{\dagger}_{i\alpha\sigma} c_{j\beta\sigma} - U \sum_{i\alpha} n_{i\alpha\uparrow} n_{i\alpha\downarrow} - \mu \sum_{i\alpha\sigma} n_{i\alpha\sigma}$$

Introduce a modulation of the order parameter phase to generate supercurrent

$$\Delta(\mathbf{r}) \to \Delta(\mathbf{r}) e^{2i\mathbf{q}\cdot\mathbf{r}}$$

$2\mathbf{q}$: Cooper pair momentum

$$[D_s]_{ij} \propto \left. \frac{\partial^2 \Omega}{\partial q_i \partial q_j} \right|_{\mathbf{q}=0}$$

$i, j = x, y, z$

$$\mathbf{j}(\mathbf{q}, \omega) = K(\mathbf{q}, \omega) \mathbf{A}(\mathbf{q}, \omega)$$

$$D_s = \lim_{\mathbf{q}\to 0} K(\mathbf{q}, \omega = 0)$$

Superfluid weight in a multiband system

$$D_s = D_{s,\text{conventional}} + D_{s,\text{geometric}}$$

$$i, j = x, y, z$$

$$\propto \partial_{k_i} \partial_{k_j} \epsilon_{\mathbf{k}}$$

Can be nonzero also in a flat band
Present only in a multiband case
Proportional to the quantum metric

$$[D_{s,\text{geometric}}]_{ij} \propto U g_{ij}$$

Quantum geometric tensor

Metric for the distance between quantum states

$$d\ell^2 = ||u(\mathbf{k}+d\mathbf{k}) - u(\mathbf{k})||^2 = \langle u(\mathbf{k}+d\mathbf{k}) - u(\mathbf{k})|u(\mathbf{k}+d\mathbf{k}) - u(\mathbf{k})\rangle$$

$$\approx \sum_{i,j} \underbrace{\langle \partial_{k_i} u | \partial_{k_j} u \rangle}\, dk_i dk_j$$

Introduce gauge invariant version $\left(u(\mathbf{k}) \leftrightarrow u(\mathbf{k}) e^{i\phi(\mathbf{k})}\right)$

➡ Quantum geometric tensor

$$\mathcal{B}_{ij}(\mathbf{k}) = 2\langle \partial_{k_i} u | (1 - |u\rangle\langle u|) | \partial_{k_j} u \rangle$$

$\mathrm{Re}\,\mathcal{B}_{ij} = g_{ij}$ quantum metric $d\ell^2 = \sum_{ij} g_{ij} dk_i dk_j$

$\mathrm{Im}\,\mathcal{B}_{ij} = [\mathbf{\Omega}_{\mathrm{Berry}}]_{ij}$ Berry curvature

Provost, Vallee, Comm. Math. Phys. **76**, 289 (1980)

Quantum metric is the same as Fubini-Study metric,
and related to Fisher information

Lower bound for flat band superfluidity

The quantum geometric tensor $\mathcal{B}_{ij}$
is complex positive semidefinite

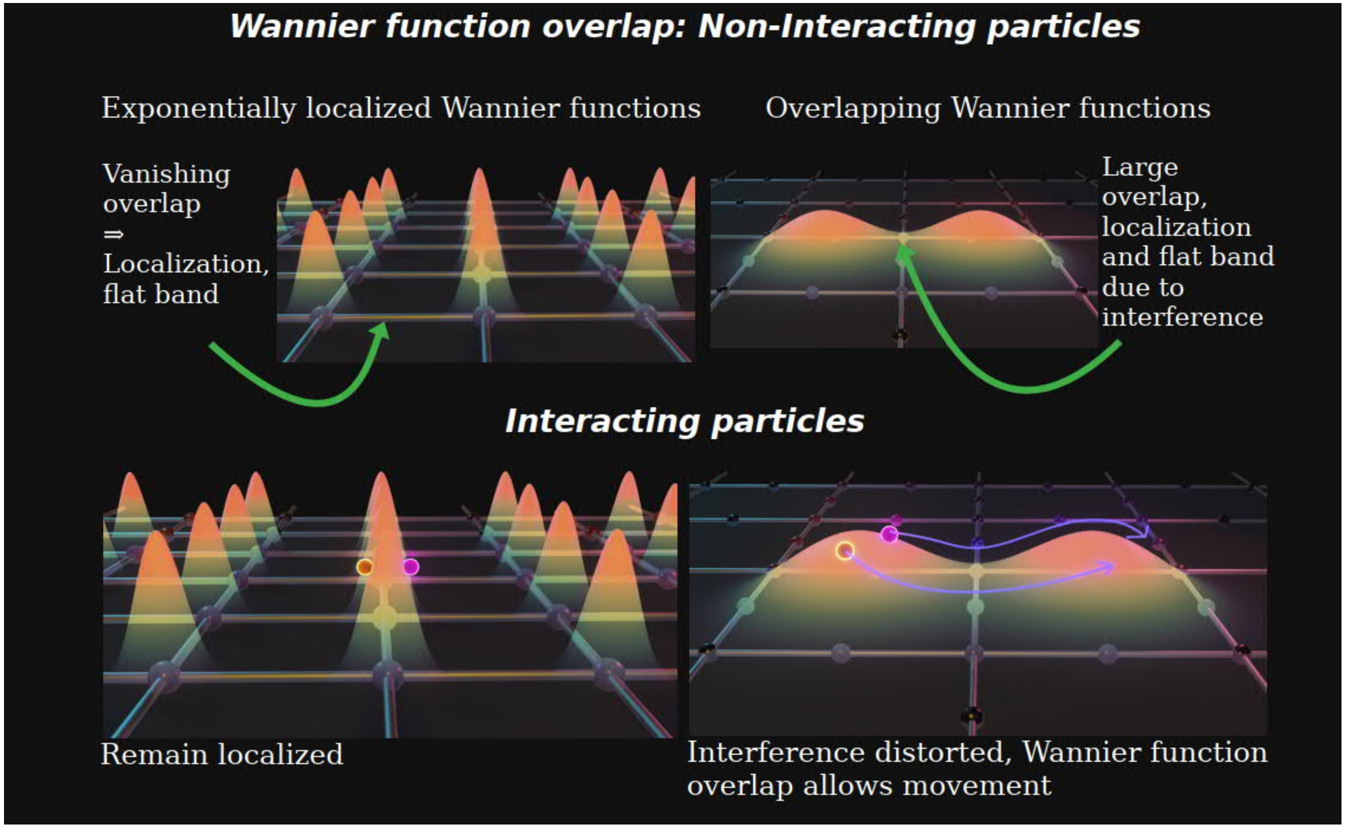
$$\Rightarrow \quad \boxed{D_s \geqslant \int_{B.Z.} d^d\mathbf{k} |\mathbf{\Omega}_{\text{Berry}}(\mathbf{k})| \geqslant C}$$

Berry curvature: $\Omega(\mathbf{k}) = i\hat{z} \cdot \nabla \times \langle u_{n\mathbf{k}} | \partial_{\mathbf{k}} u_{n\mathbf{k}} \rangle$

Chern number: $C = \frac{1}{2\pi} \int_{B.Z.} d^2\mathbf{k}\ \Omega(\mathbf{k})$

Mean-field results confirmed by:
exact diagonalization, DMFT, DMRG, perturbation theory

Why can there be transport in a flat band?



$$C \neq 0 \Leftrightarrow \text{non-localized } w(\mathbf{r}) = \mathcal{F}[u(\mathbf{k})]$$

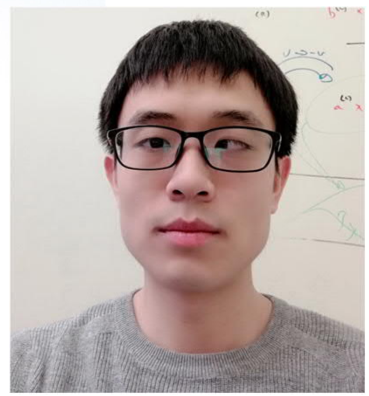
Brouder, Panati, Calandra, Marzari, PRL 2007

$$D_s \propto g_{ij} \geqslant C$$

Twisted bilayer graphene (TBG) superconductivity and quantum metric

Aleksi Julku

Teemu Peltonen



Long Liang

Tero Heikkilä

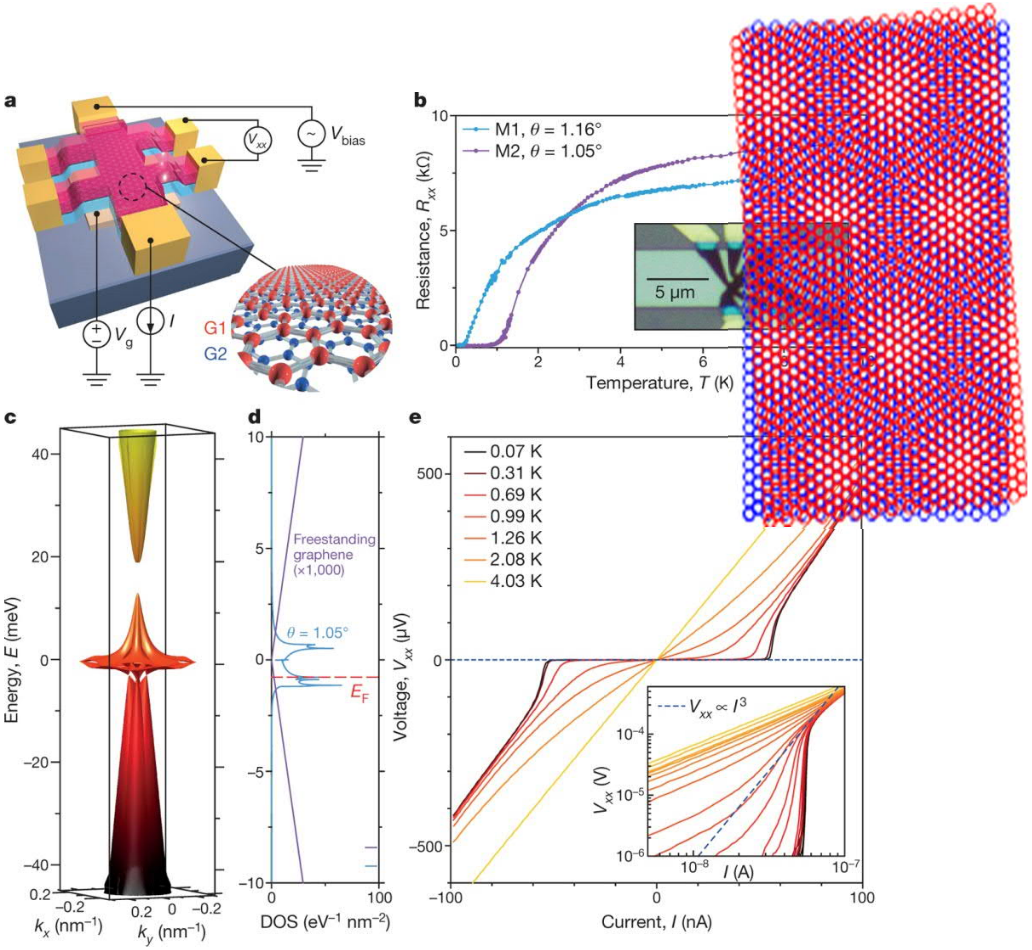
Julku, Peltonen, Liang, Heikkilä, PT, PRB(R) (2020); Editors' Suggestion

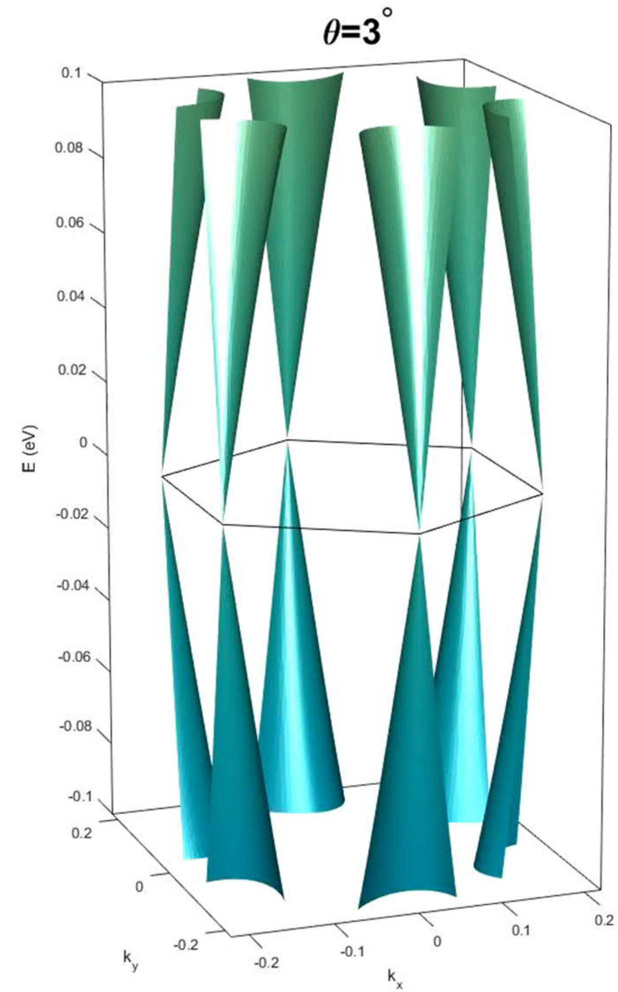
For APS Physics news, google Geometry resques superconductivity

MA-TBG: Magic **A**ngle**-T**wisted **B**ilayer **G**raphene

Twisting graphene layers produces flat bands

(unconventional) superconductivity





Y Cao *et al. Nature* **556**, 43–50 (2018)

Also

Nature 556, 80 (2018)

Science 363, 1059 (2019)

Nature 574, 653-657 (2019)

VIEWPOINT

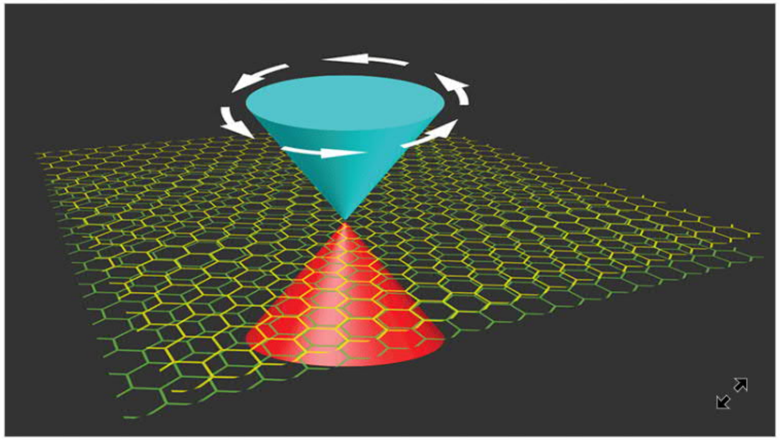
PDF Version

Geometry Rescues Superconductivity in Twisted Graphene

Laura Classen
School of Physics and Astronomy, University of Minnesota, Minneapolis, MN, USA

February 24, 2020 • *Physics* 13, 23

Three papers connect the superconducting transition temperature of a graphene-based material to the geometry of its electronic wave functions.



APS/Alan Stonebraker

Figure 1: Electrons moving through the sheets of twisted bilayer graphene (TBG) have special points in their band structure where two cone-shaped bands meet. The inherent "curvature" of the states in these bands turns out to contribute to the magnitude of TBG'... Show more

On its own, a sheet of graphene is a semimetal—its electrons interact only weakly with each other. But as experimentalists discovered in 2018 [1, 2], the situation changes when two sheets of graphene are stacked together, with a slight ($\sim 1°$) rotation between them (Fig. 1). At this so-called magic twist angle [3] and at low temperatures [1], the electrons become correlated, forming insulating or superconducting phases depending on the carrier density [2–7]. These phases appear to come from a twist-induced flattening of the electronic energy bands, which

Geometric and Conventional Contribution to the Superfluid Weight in Twisted Bilayer Graphene
Xiang Hu, Timo Hyart, Dmitry I. Pikulin, and Enrico Rossi
Phys. Rev. Lett. 123, 237002 (2019)
Published December 5, 2019
Read PDF

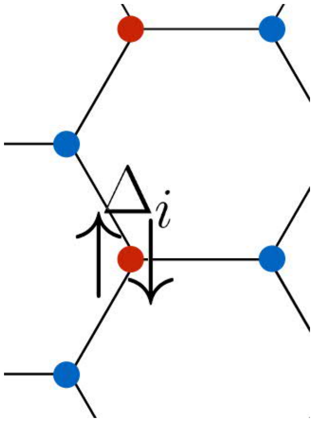
Superfluid weight and Berezinskii-Kosterlitz-Thouless transition temperature of twisted bilayer graphene
A. Julku, T. J. Peltonen, L. Liang, T. T. Heikkilä, and P. Törmä
Phys. Rev. B 101, 060505 (2020)
Published February 24, 2020
Read PDF

Topology-Bounded Superfluid Weight in Twisted Bilayer Graphene
Fang Xie, Zhida Song, Biao Lian, and B. Andrei Bernevig
Phys. Rev. Lett. 124, 167002 (2020)
Published April 24, 2020
Read PDF

Fermi-Hubbard lattice model with TBG geometry:

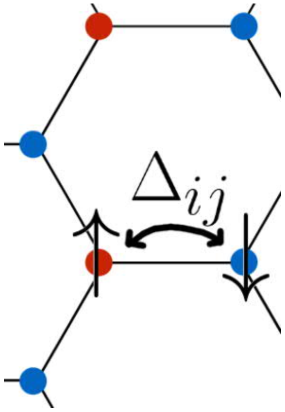
$$H = \sum_{ij\sigma} t_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} + H_{\text{int}}$$

Two distinct pairing schemes:



$$H_{\text{int}} = J \sum_{i} c^{\dagger}_{i\uparrow} c_{i\uparrow} c^{\dagger}_{i\downarrow} c_{i\downarrow}$$

J< 0 is attractive interaction strength



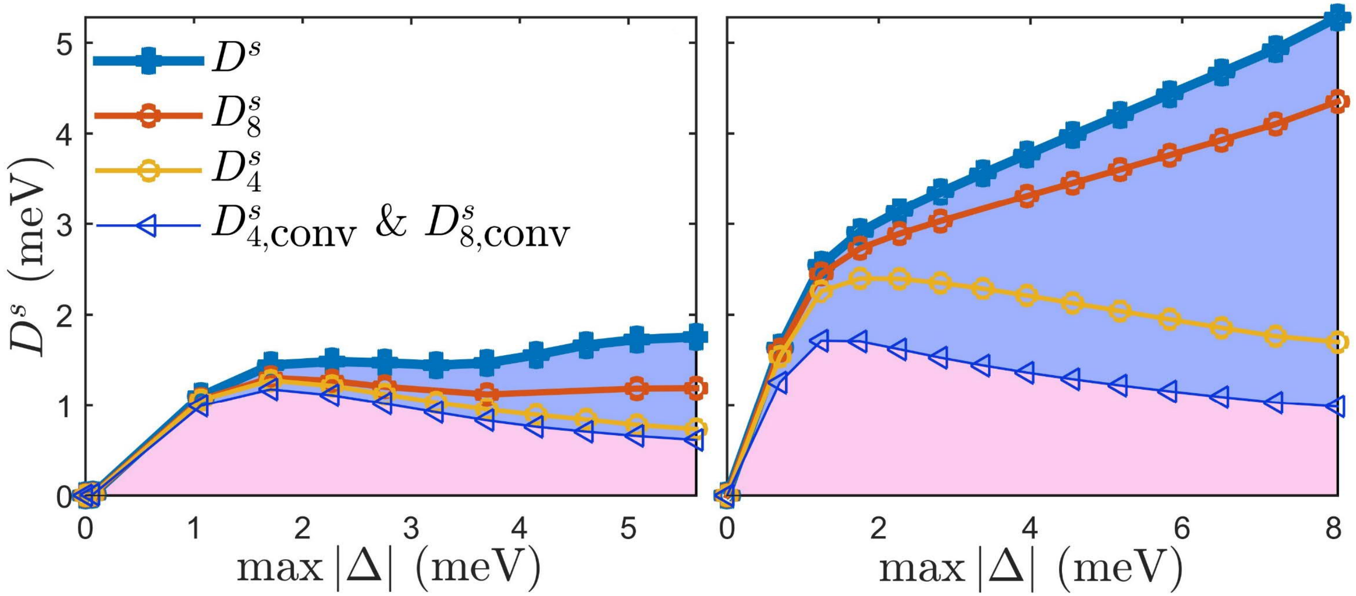
$$H_{\text{int}} = \frac{J}{2} \sum_{\langle ij \rangle} h^{\dagger}_{ij} h_{ij}$$

$$h_{ij} = c_{i\downarrow} c_{j\uparrow} - c_{i\uparrow} c_{j\downarrow}$$

Geometric contribution in TBG

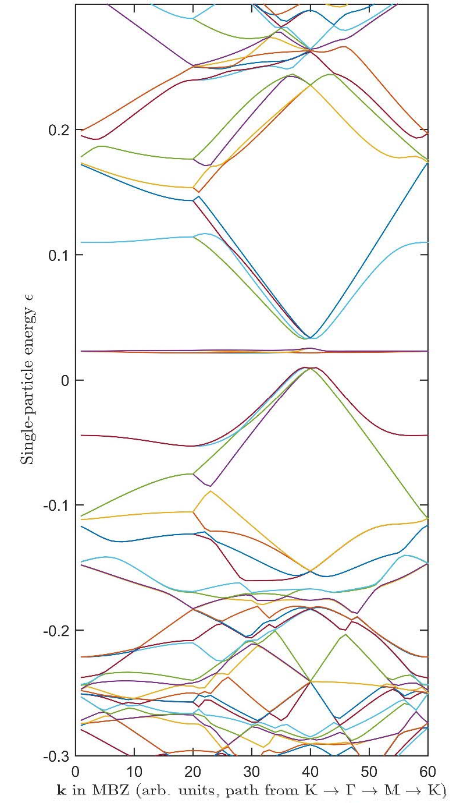
$$D^s = D^s_{\text{conv}} + D^s_{\text{geom}}$$

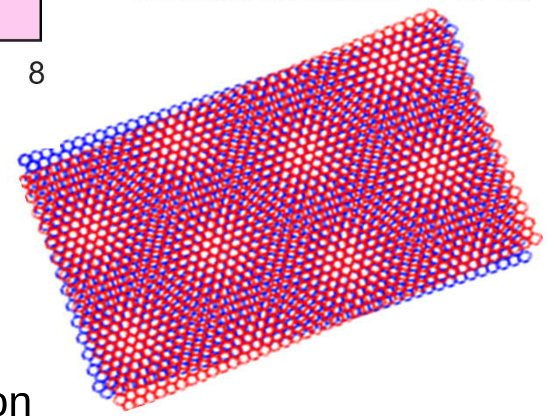
$$T_{\text{BKT}} = \frac{\pi}{8}\sqrt{\det D^s(T_{\text{BKT}})}$$



Non-local (RVB) interaction

Local (s-wave) interaction





Julku, Peltonen, Liang, Heikkilä, PT, PRB(R) (2020); Editors' Suggestion
Confirmed by (only s-wave): Hu, Hyart, Pikulin, Rossi, PRL (2019)
For APS Physics news, google Geometry resques superconductivity

Review

arXiv.org > cond-mat > arXiv:2111.00807

Search...

Help | Advanc

Condensed Matter > Superconductivity

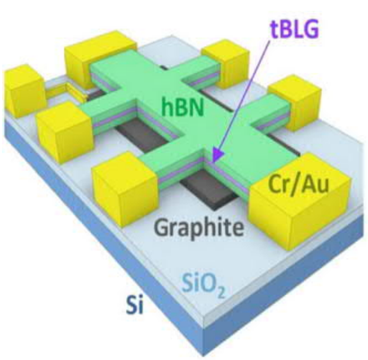
[Submitted on 1 Nov 2021]

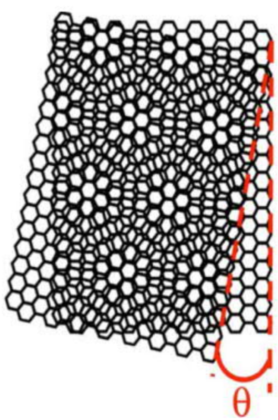
Superfluidity and Quantum Geometry in Twisted Multilayer Systems

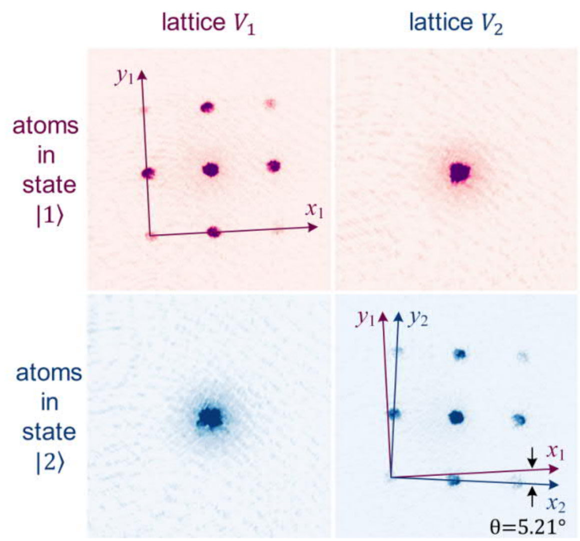
P. Törmä, S. Peotta, B.A. Bernevig

$$\det \mathcal{M}^{\mathrm{R}} \geq \mathcal{C}^2\,, \text{ with } \mathcal{M}^{\mathrm{R}}_{ij} = \frac{1}{2\pi}\int d^2\mathbf{k}\, g_{ij}(\mathbf{k})$$

$$\frac{1}{4\pi}\int_{\mathrm{BZ}} d^2k\, \mathrm{tr}\, g(\mathbf{k}) \geq \frac{1}{2\pi}\int_{\mathrm{BZ}'} d^2k\, |f_{xy}| \geq \left|\frac{1}{2\pi}\int_{\mathrm{BZ}'} d^2k\, f_{xy}\right| = |e_2|\,.$$







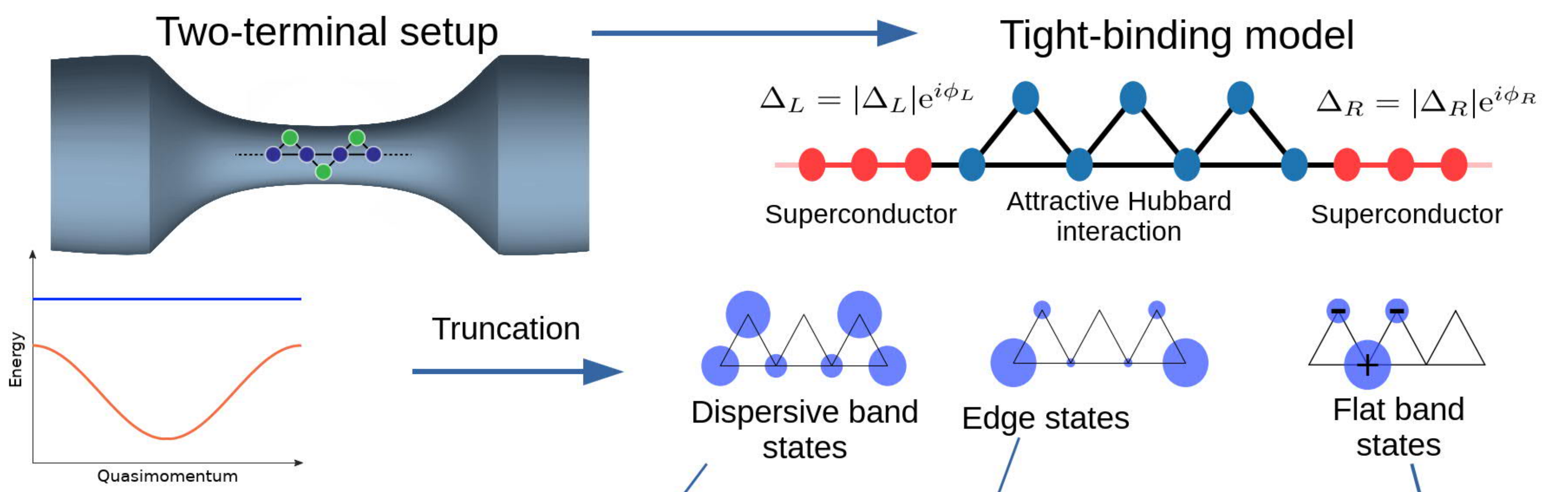
J. Zhang group

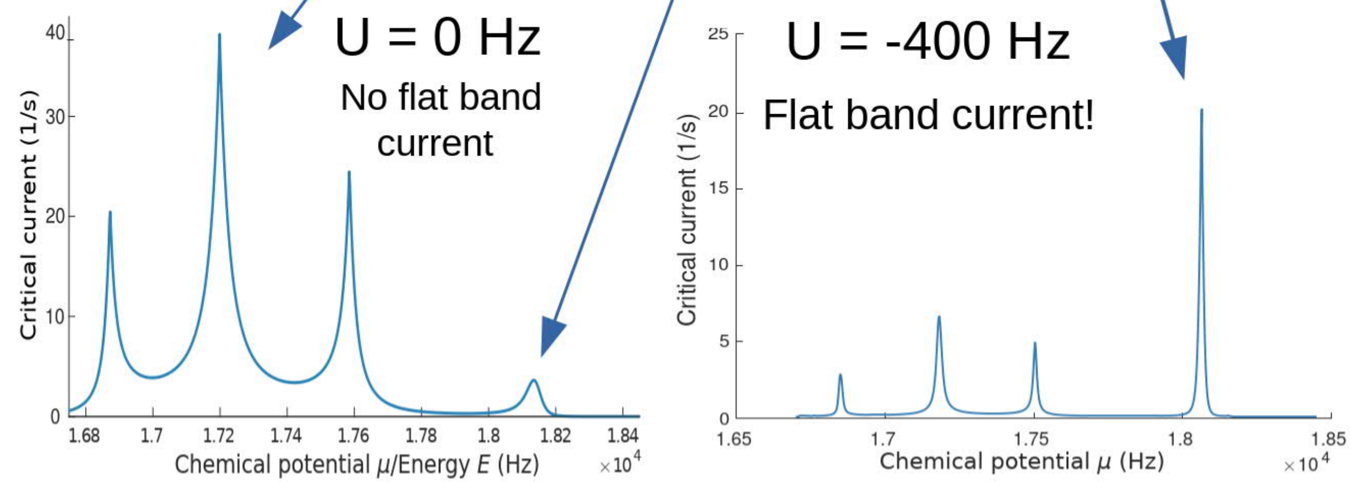
Flat band transport and Josephson effect through a saw-tooth lattice

Ville Pyykkönen Sebastiano Peotta Philipp Fabritius Jeffrey Mohan Tilman Esslinger

Pyykkönen, Peotta, Fabritius, Mohan, Esslinger, PT, PRB (2021)

Ultracold sawtooth lattice transport setup





Interaction → finite Josephson current through flat band states!

Optimal when edge and flat band states degenerate

Aalto University
School of Science

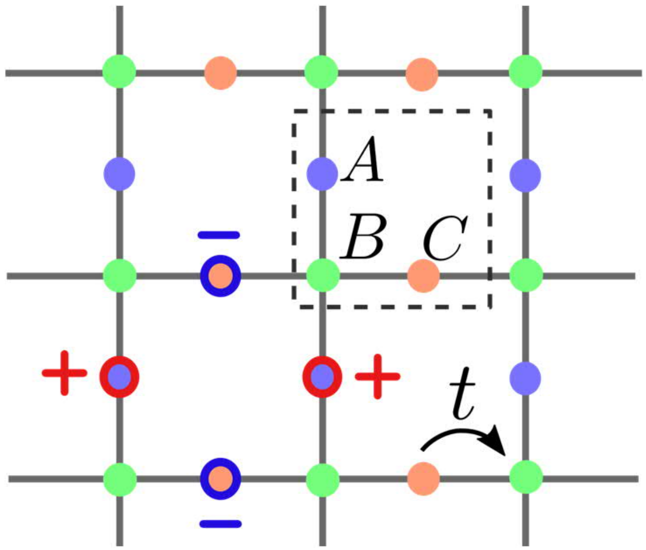
Pyykkönen, Peotta, Fabritius, Mohan, Esslinger and Törmä: Flat band transport and Josephson effect through a finite-size sawtooth lattice, PRB 103, 144519, 2021

Insulator – pseudogap crossover in the Lieb lattice normal state

Kukka-Emilia Huhtinen

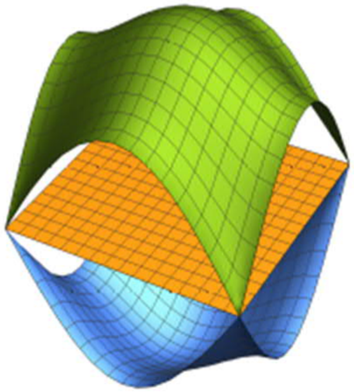
KE Huhtinen, PT, PRB(L) (2021)

Hubbard model on the Lieb lattice



Attractive Hubbard model

$$H = \sum_{\sigma} \sum_{i\alpha, j\beta} t_{ij} c^{\dagger}_{\sigma,i\alpha} c_{\sigma,j\beta} - \sum_{\sigma} \sum_{\mathrm{i}\alpha} \mu_{\sigma} n_{\sigma,i\alpha}$$
$$+U \sum_{i\alpha} (n_{\uparrow,i\alpha} - 1/2)(n_{\downarrow,i\alpha} - 1/2)$$

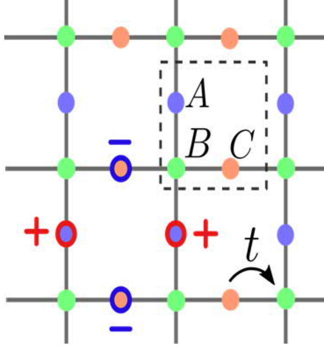


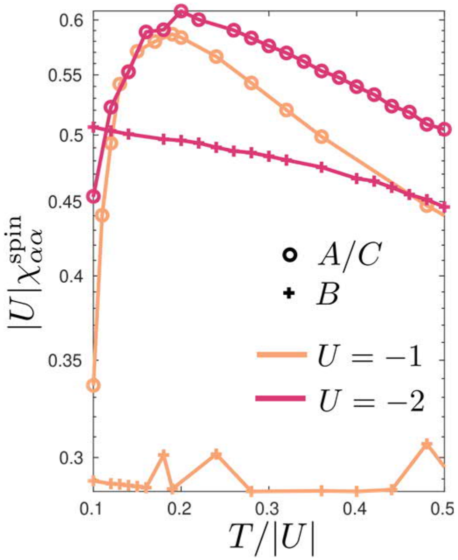
Flat band states reside at A and C sites

DMFT cluster: A, B and C

FOCUS ON THE NORMAL STATE ABOVE SUPERCONDUCTIVITY

Large (U>t) interactions: pseudogap





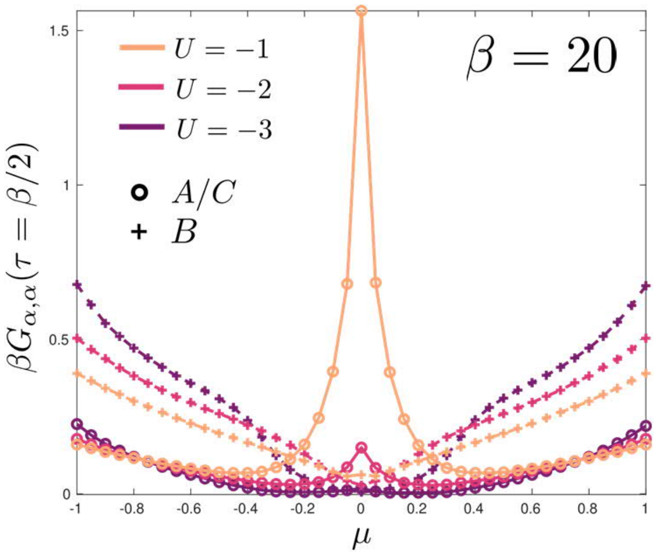
Generalized spin susceptibility:

$$\chi^{\rm spin}_{\alpha\alpha} = \frac{2}{\beta^2}\sum_{\omega,\omega'}\left(\chi^{{\rm ph},\omega,\omega',\nu=0}_{\uparrow\alpha,\uparrow\alpha,\uparrow\alpha,\uparrow\alpha} - \chi^{{\rm ph},\omega,\omega',\nu=0}_{\uparrow\alpha,\uparrow\alpha,\downarrow\alpha,\downarrow\alpha}\right)$$

$$\chi_{ijkl}(\tau_1,\tau_2,\tau_3) = G^{(4)}_{ijkl}(\tau_1,\tau_2,\tau_3) - G_{ij}(\tau_1,\tau_2)G_{kl}(\tau_3,0)$$

$$G^{(4)}_{ijkl}(\tau_1,\tau_2,\tau_3) = \langle T_\tau[c^\dagger_i(\tau_1)c_j(\tau_2)c^\dagger_k(\tau_3)c_l(0)]\rangle$$

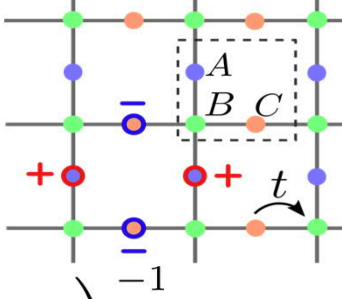
$$G_{ij}(\tau_1,\tau_2) = \langle T_\tau[c^\dagger_i(\tau_1)c_j(\tau_2)]\rangle$$



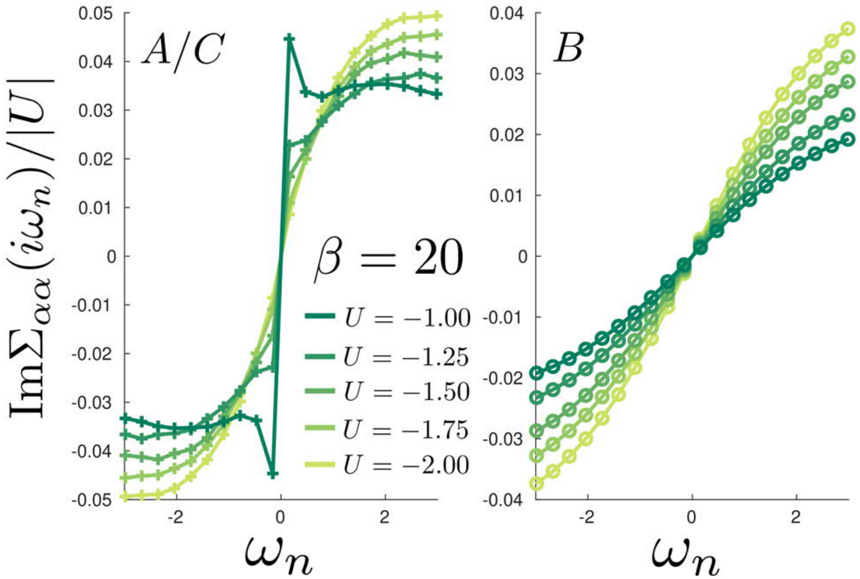
Local contribution to spin susceptibility decreases sharply with temperature at A/C sites.

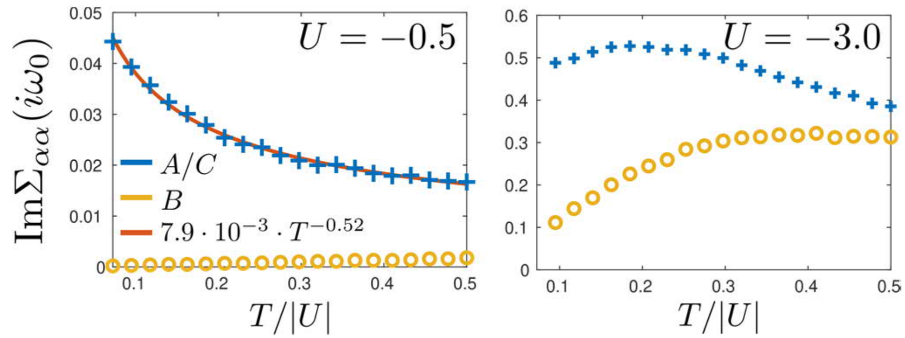
At low temperatures, $\beta G_{\alpha\alpha}(\beta/2) \approx \mathcal{A}_\alpha(\omega=0)$, where $\mathcal{A}_\alpha$ is the orbital-resolved spectral function.

As interaction is increased, the spectral function becomes depleted around half-filling.



Low interaction (U<t): insulator





$$Z = \left(1 - \frac{\mathrm{Im}\Sigma(i\omega_n)}{\omega_n}\bigg|_{\omega_n \to 0}\right)^{-1}$$

In DMFT, $Z = m/m^*$, where m is the bare mass and m^* is the effective mass.

The self-energy diverges at low frequencies when the interaction strength is decreased.

The temperature dependence is $T^{-1/2}$ rather than T^{-1} found for Mott insulator.

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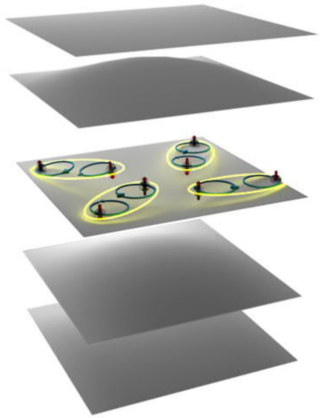
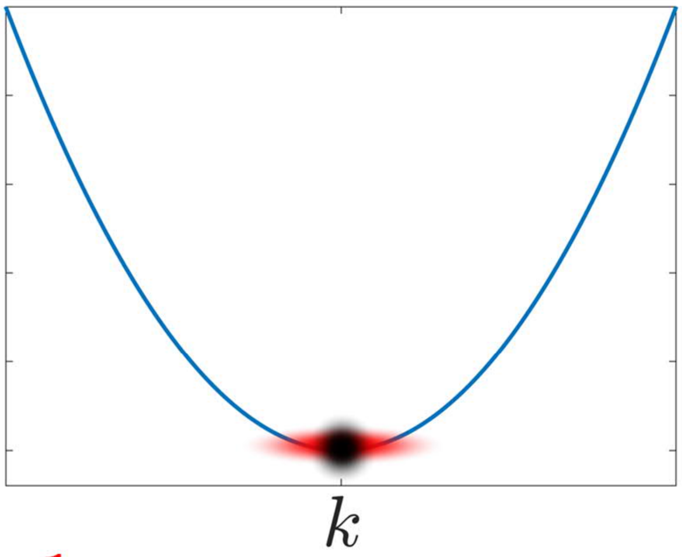
Briefly: Bose-Einstein condensation and magnetic switching in a plasmonic lattice (experiment)



BEC in continuum

$$\epsilon(\mathbf{k}) = \frac{k^2}{2m_{eff}}$$



$$n_{\mathrm{ex}}(\mathbf{k}) = \frac{\epsilon(\mathbf{k}) + Un_0}{\sqrt{\epsilon(\mathbf{k})[\epsilon(\mathbf{k}) + 2Un_0]}} - 1$$

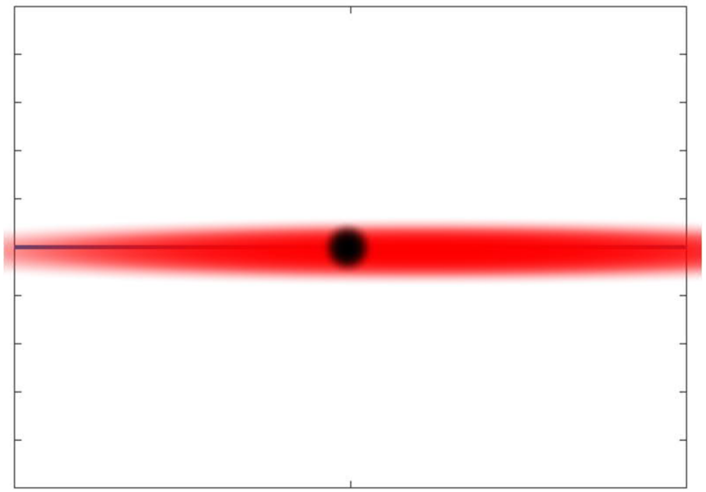
n_0 condensate density U repulsive contact interaction strength

n_{ex} = density of non-condensed bosons (quantum depletion)

BEC in continuum

$$m_{eff} \to \infty$$

$$\epsilon(\mathbf{k}) = \frac{k^2}{2m_{eff}} \to 0$$



For any finite interaction:

$$n_{\rm ex} \to \frac{Un_0}{\sqrt{\epsilon(\mathbf{k})2Un_0}} - 1 \to \infty$$

Obviously, flat band BEC in a single band model not possible.

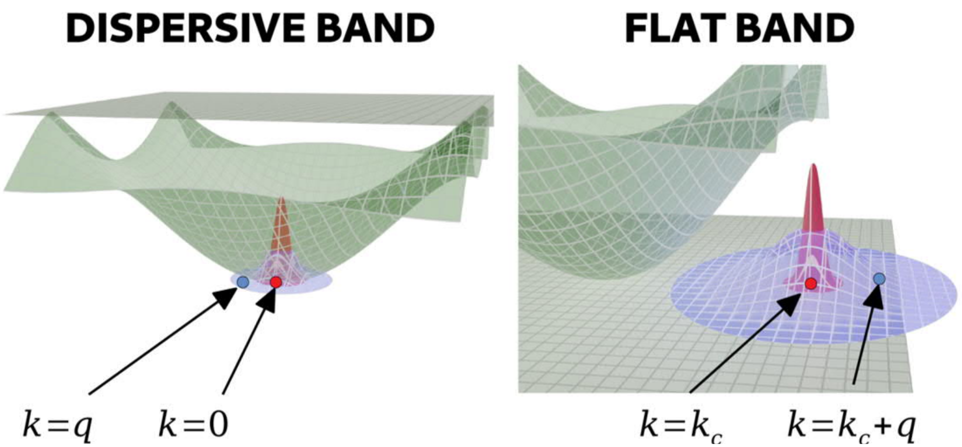
BEC in a flat band?

- Clearly, BEC in a flat band should not be possible ???
- True for a single band system, **not for multiband model** (as shown in earlier works)

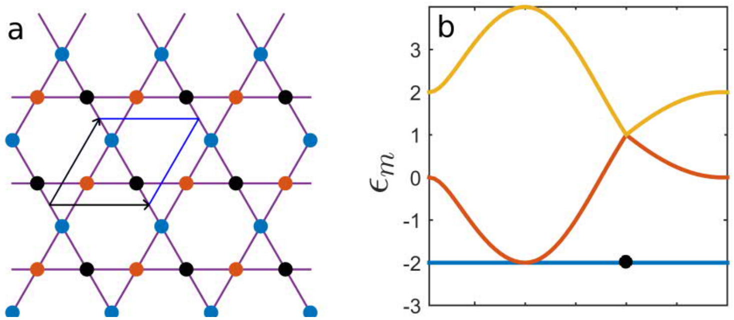
Huber & Altman, PRB 82, 184502 (2010)
You et al., PRL 109, 265302 (2012) (H. Zhai group)

- **What determines the stability?**

Flat band BEC & quantum geometry



Kagome lattice:

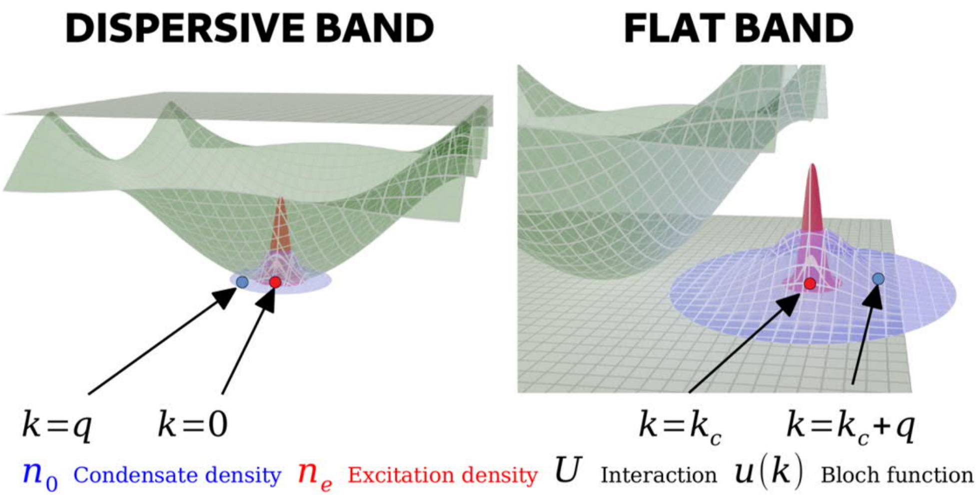


Aleksi Julku

Georg Bruun

Julku, Bruun, PT, PRL 2021

Flat band BEC & quantum geometry



SPEED OF SOUND

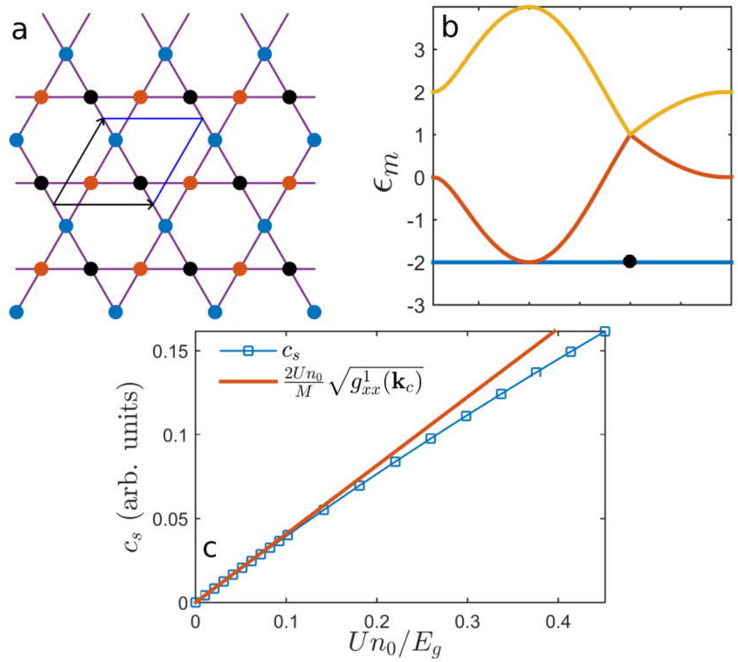
$c_s \propto \sqrt{U n_0}$

$c_s \propto U n_0 \sqrt{g_{\alpha\beta}(k_c)}$

Quantum metric

$$g_{\alpha\beta} = \Re[\langle \partial_\alpha u | \partial_\beta u \rangle - \langle \partial_\alpha u | u \rangle \langle u | \partial_\beta u \rangle]$$

Kagome lattice:



Quantum metric dictates the speed of sound

Aleksi Julku

Georg Bruun

Julku, Bruun, PT, PRL 2021

Flat band BEC & quantum geometry

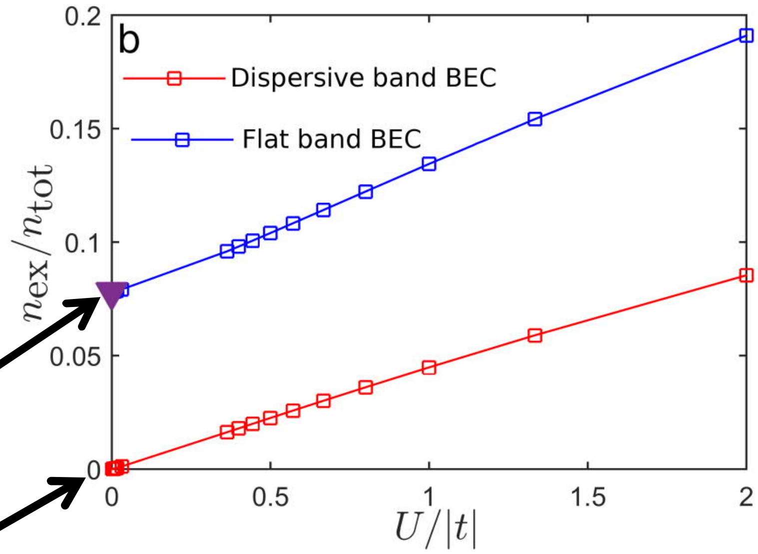
Excitations do not cost energy? Can BEC stable?

Answer: Yes it can, finite **quantum distance** between Bloch states sets the limit for excitation density -> stable BEC

$$n_e(k) \xrightarrow[U\to 0]{} \frac{1-D}{2D}$$

Quantum distance

$$D=\sqrt{1-\left|\langle u(k_c+q)|u(k_c-q)\rangle\right|^2}$$



Excitation density can be finite in the non-interacting limit...

...in contrast to dispersive band BEC

Interaction effects prominent even in the limit of vanishing interactions

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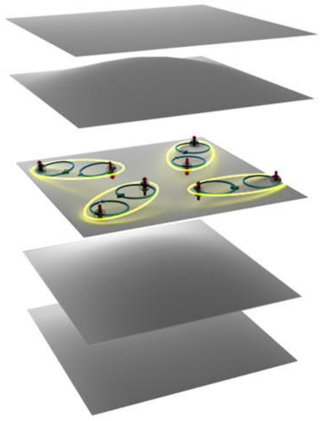
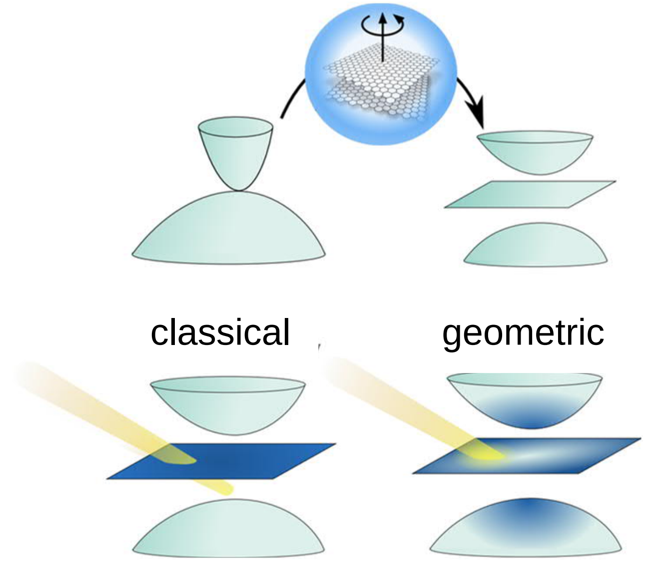


Light-matter coupling (LMC) in multi-band systems

G. E. Topp, C. J. Eckhardt, D. M. Kennes, M. A. Sentef, and PT, PRB 2021



Reminder: Single-band LMC

$$H_{\mathrm{LMC}}^{\mathrm{single}} = \sum_{\mu} \partial_{k\mu}\epsilon(k)\cdot A_\mu + \frac{1}{2}\sum_{\mu\nu}\partial_{k\mu}\partial_{k\nu}\epsilon(k)\cdot A_\mu A_\nu$$

paramagnetic — diamagnetic

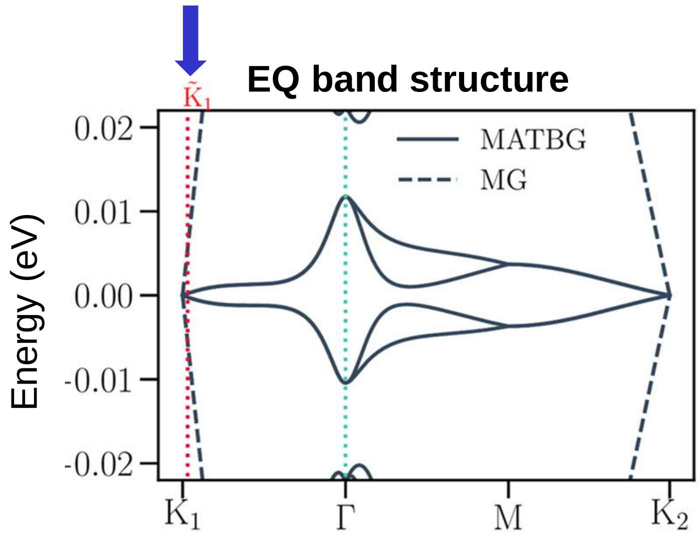
	Linear (A_μ)	**Quadratic** $(A_\mu A_\nu)$
Intra-band (n)	$\partial_\mu \varepsilon_n$	$\partial_\mu\partial_\nu\varepsilon_n - \sum_{n\neq n'}(\varepsilon_n - \varepsilon_{n'})\left(\langle\partial_\mu n\,\vert n'\rangle\langle n'\,\vert\partial_\nu n\rangle + \mathrm{h.c.}\right)$
Inter-band $(n,\, m)$	$(\varepsilon_n - \varepsilon_m)\langle m\,\vert\partial_\mu n\rangle$	$\Big[(\partial_\mu\varepsilon_n - \partial_\mu\varepsilon_m)\langle m\,\vert\partial_\nu n\rangle + \frac{1}{2}\varepsilon_m\langle\partial_\mu\partial_\nu m\,\vert n\rangle + \frac{1}{2}\varepsilon_n\langle m\,\vert\partial_\mu\partial_\nu n\rangle + \sum_{n'}\varepsilon_{n'}\left(\langle\partial_\mu m\,\vert n'\rangle\langle n'\,\vert\partial_\nu n\rangle\right)\Big] + (\mu\leftrightarrow\nu)$

- ‘classical’ = determined by band dispersion (green boxes)
- ‘geometric’ = determined by Bloch states (orange boxes)

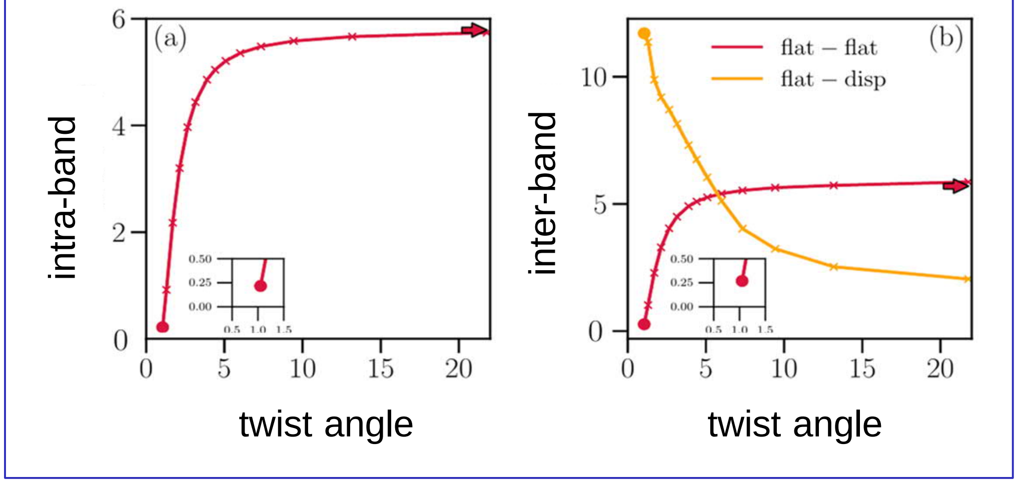
Application: Light-induced Dirac gap in TBG

G. E. Topp, C. J. Eckhardt, D. M. Kennes, M. A. Sentef, and PT, PRB 2021

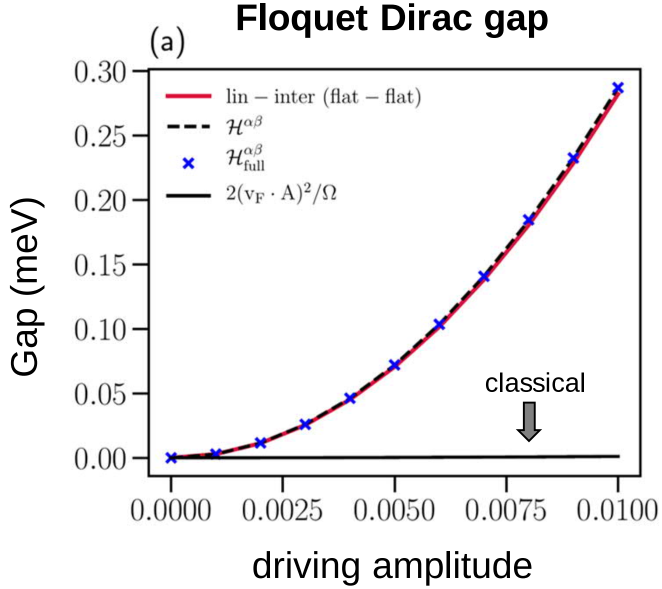
EQ band structure

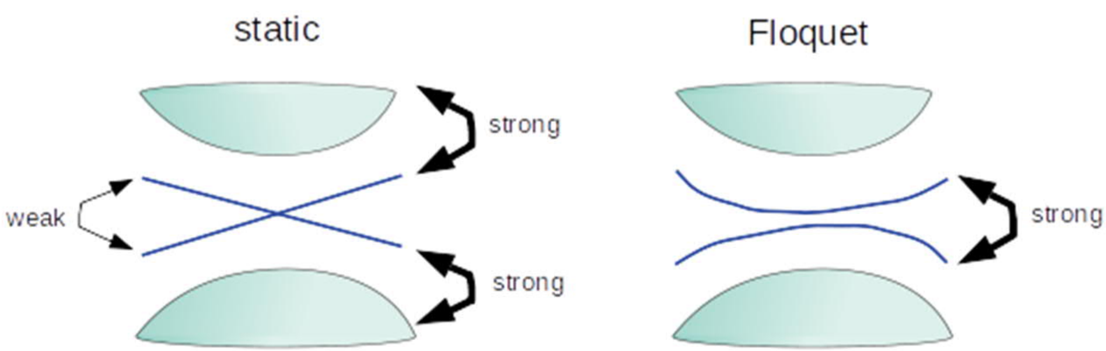


Linear LMC



Floquet Dirac gap





$$\langle m|\, H^A_{\text{FLOQ}}\, |n\rangle = \frac{iA_0^2}{2\Omega}\left[\sum_l \langle m|\frac{\partial H_0}{\partial k_x}|l\rangle\langle l|\frac{\partial H_0}{\partial k_y}|n\rangle - \langle m|\frac{\partial H_0}{\partial k_y}|l\rangle\langle l|\frac{\partial H_0}{\partial k_x}|n\rangle\right]$$

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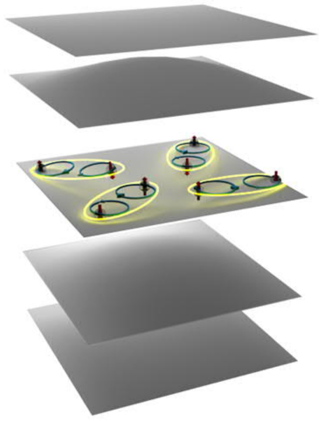
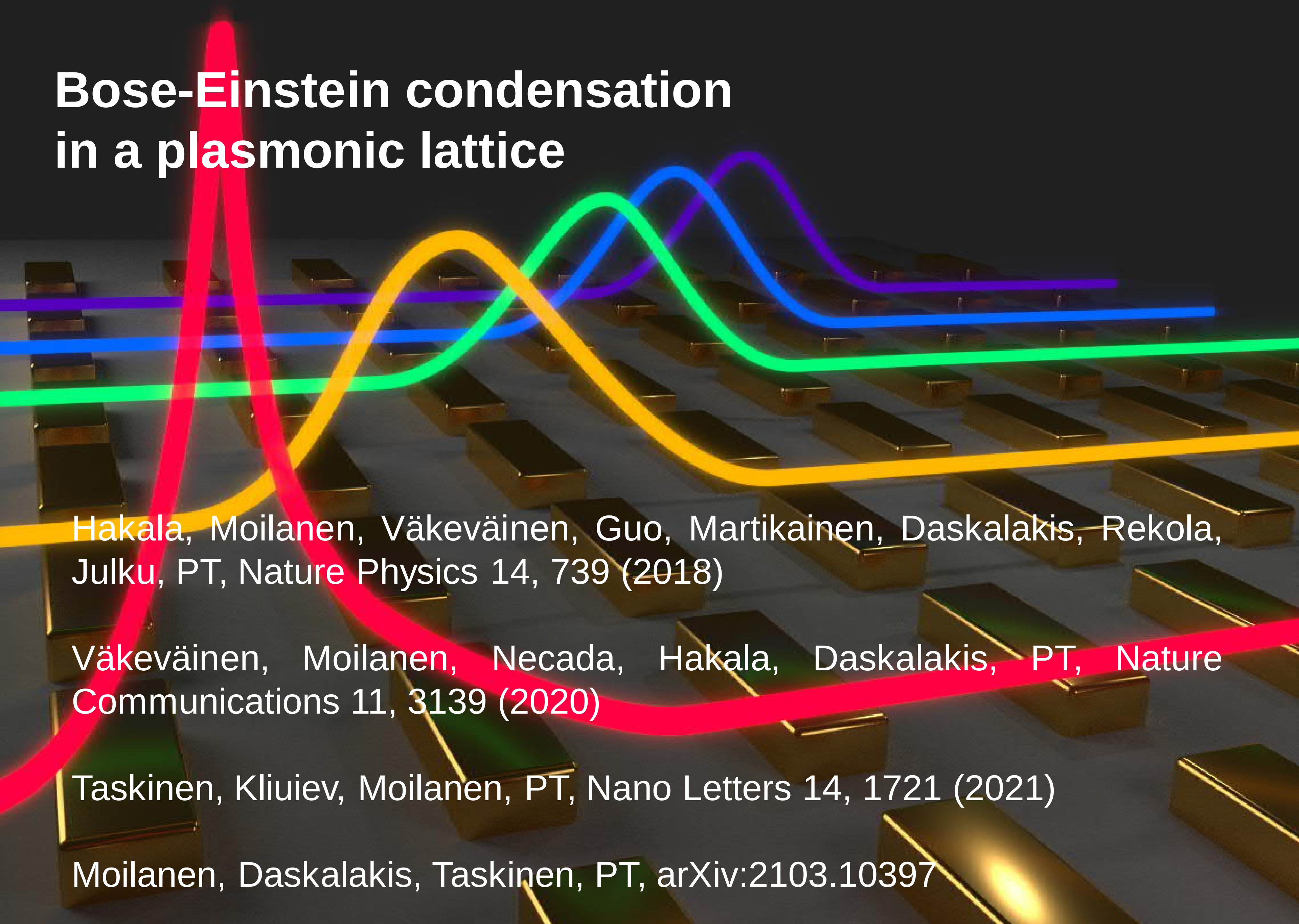


Bose-Einstein condensation in a plasmonic lattice



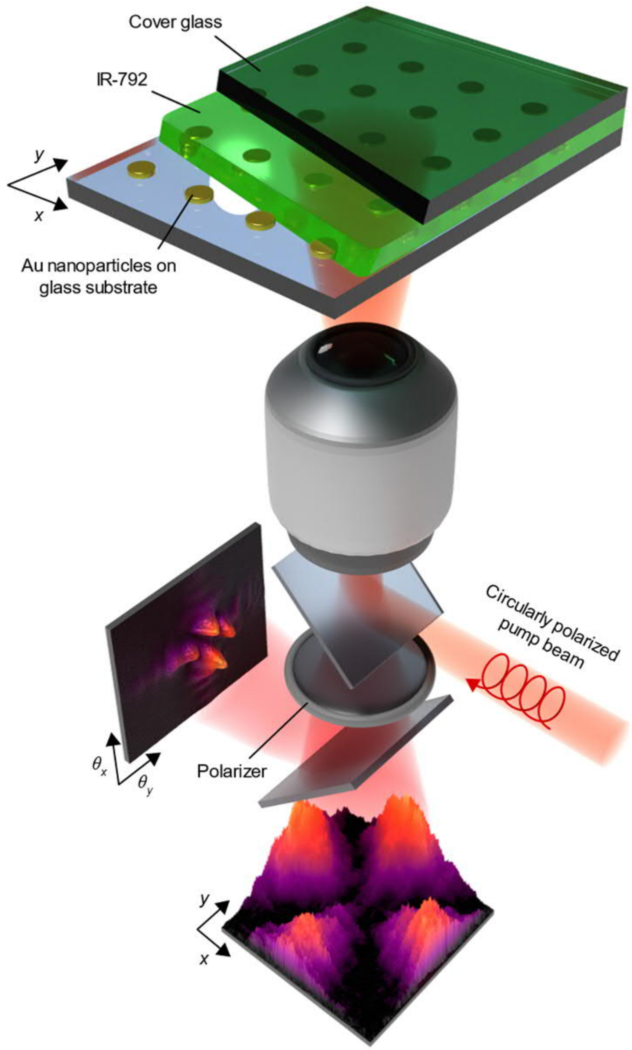
Hakala, Moilanen, Väkeväinen, Guo, Martikainen, Daskalakis, Rekola, Julku, PT, Nature Physics 14, 739 (2018)

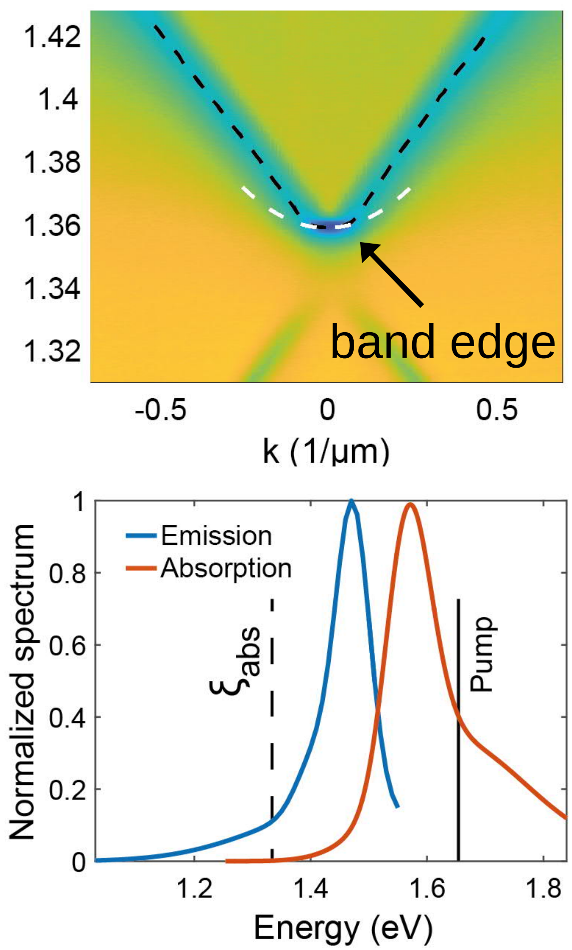
Väkeväinen, Moilanen, Necada, Hakala, Daskalakis, PT, Nature Communications 11, 3139 (2020)

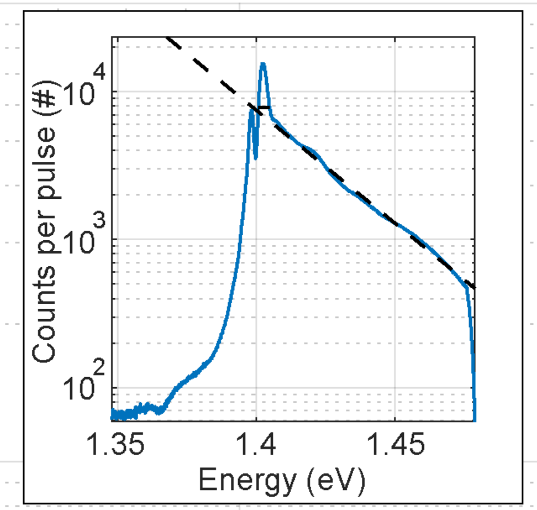
Taskinen, Kliuiev, Moilanen, PT, Nano Letters 14, 1721 (2021)

Moilanen, Daskalakis, Taskinen, PT, arXiv:2103.10397

Nanoparticle array + molecules

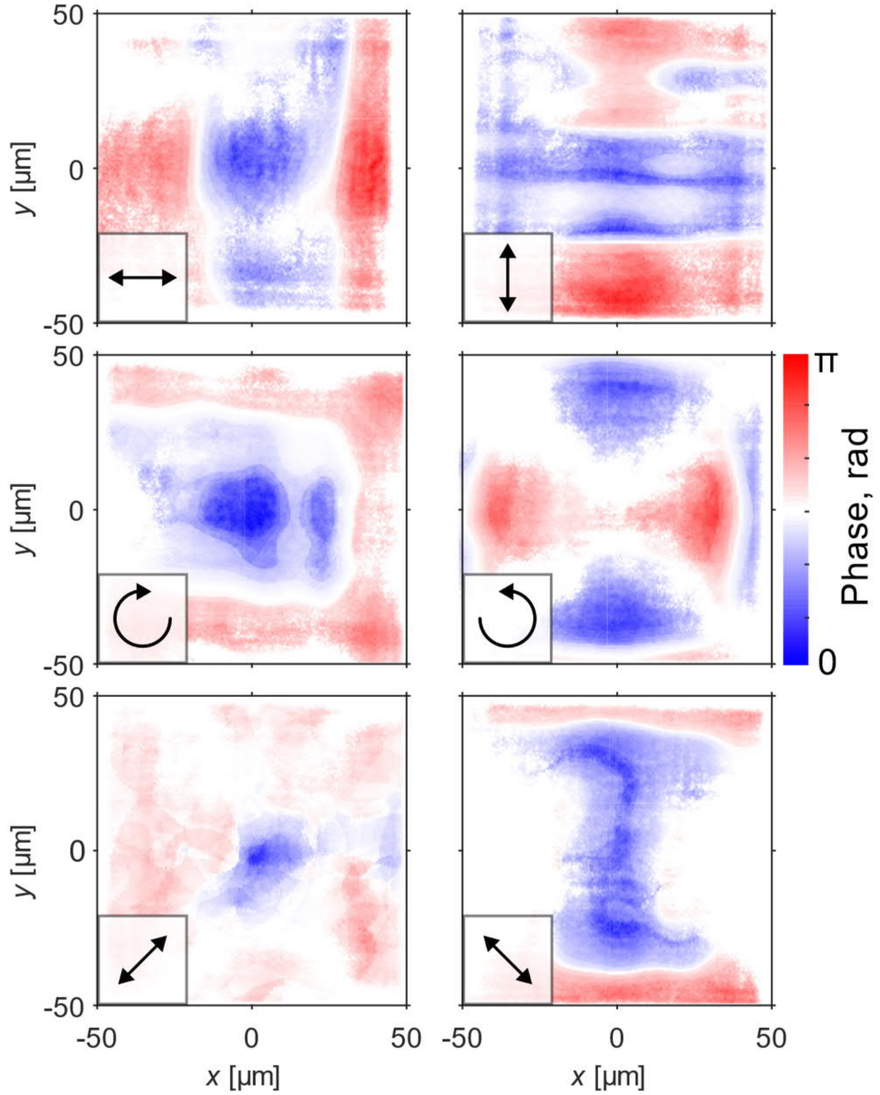






Nature Physics 2018, Nature Communications 2020, arXiv2021

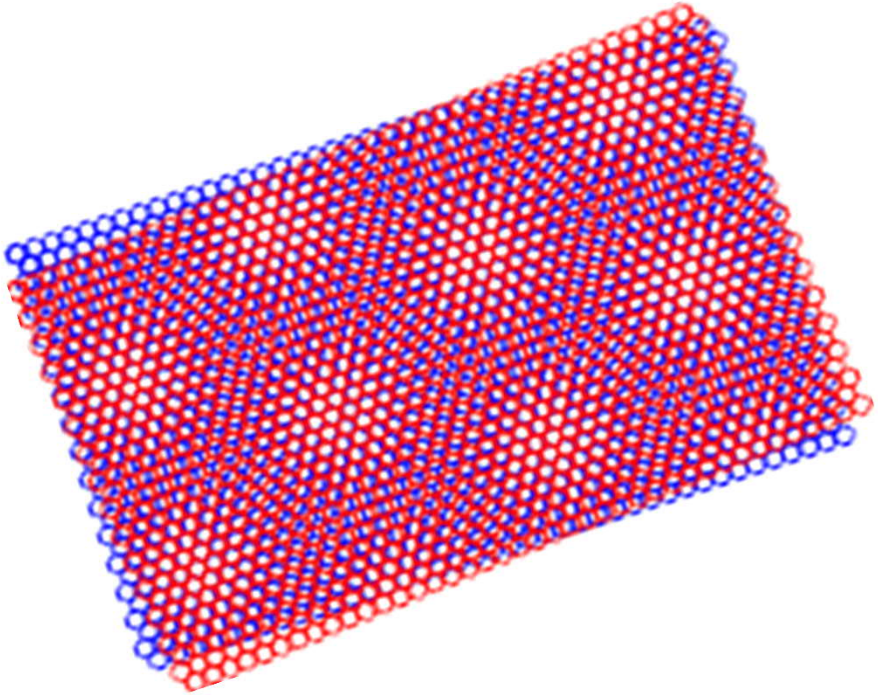
Condensate phase determined for the first time by phase retrieval (Nano Letters 2021)



Magnetic switching of plasmonic lasing

Freire-Fernandez, Cuerda, Daskalakis, Perumbilavil, Martikainen, Arjas, PT, van Dijken, Nature Photonics in press (2021), arXiv:2104.14321

Summary



Quantum geometry governs
- flat band superfluidity
- BEC excitations
- light-matter interactions

Outlook

Towards room temperature superconductivity

Role of quantum geometry and interactions
in photonic systems

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School of Science

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HORIZON2020
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OF FINLAND