Vortex mediated Josephson plasmon bound states

Marios H. Michael
Max Planck Institute for the Structure and Dynamics of Matter

Mathematical aspects of condensed matter physics, ETH 2023

Vortex mediated Josephson plasmon bound states

Marios H. Michael

Max Planck Institute for the Structure and Dynamics of Matter

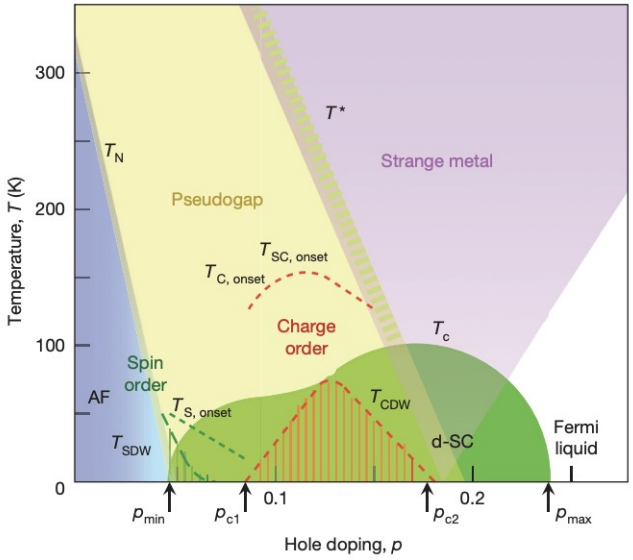
Mathematical aspects of condensed matter physics, ETH 2023

Dissipationless currents in pseudogap YBCO

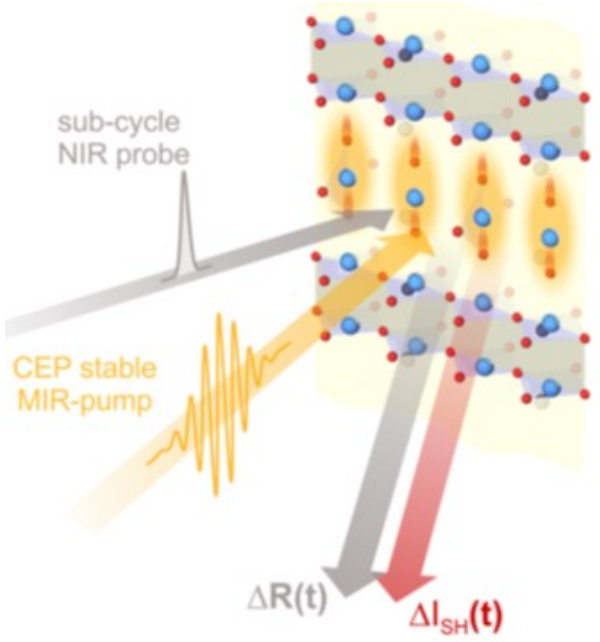
Marios H. Michael
Max Planck Institute for the Structure and Dynamics of Matter

Mathematical aspects of condensed matter physics, ETH 2023

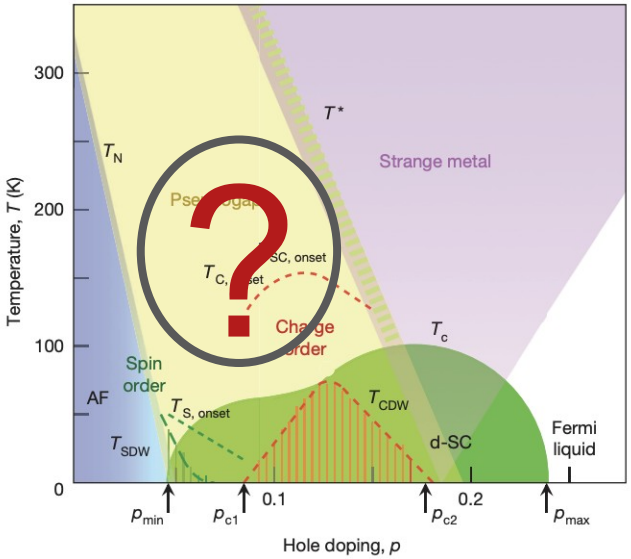
High Tc cuprates - the pseudogap phase



B. Keimer, A. Kivelson et al., Nature (2015)

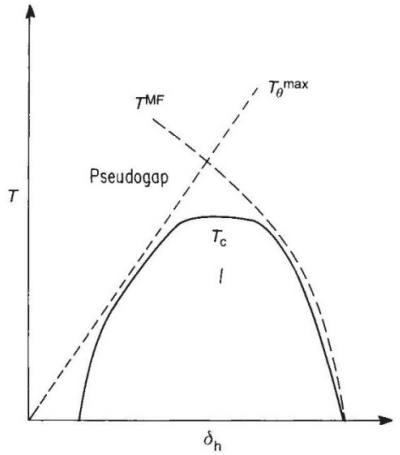


High Tc cuprates - the pseudogap phase



B. Keimer, A. Kivelson et al., Nature (2015)

Competition between mean field and phase fluctuation transition:



V. J. Emery & S. A. Kivelson, Nature (1995)

This talk :

1. Present numerical simulations of the pseudogap phase.

2. Intuition behind the existence of dissipationless counterflow currents in YBCO.

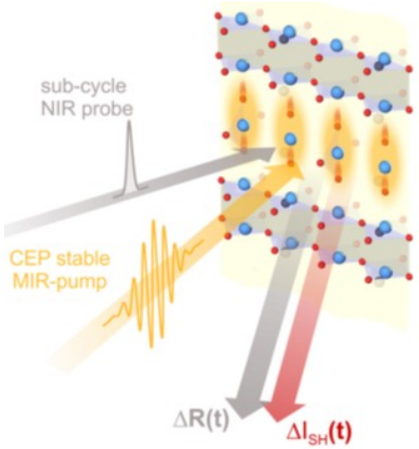
3. Connection with experimental observations in light-driven YBCO. **(references)**

Phys. Rev. B **102**, 174505 **M. H. M.** et al. (2020)

Phys. Rev. X 12, 031008 (2022) (2022) Alex von Hoegen

Physical Review B, 89, 184516 (2014), S. Kaiser et al.

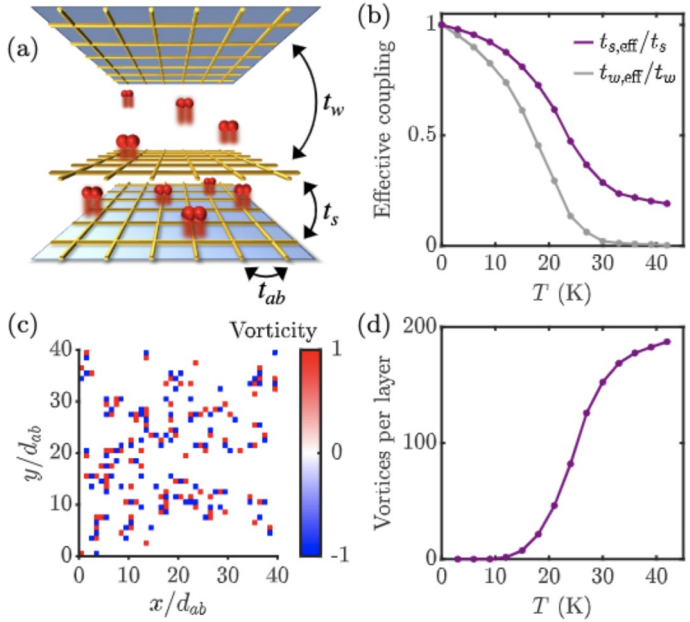
Nature Materials, 13, 705–711 (2014), W. Hu et al.



Dissipationless counterflow currents above T_c in bilayer superconductors

Guido Homann,[1] Marios H. Michael,[2] Jayson G. Cosme,[3] and Ludwig Mathey[1,4]

[1] *Zentrum für Optische Quantentechnologien and Institut für Quantenphysik, Universität Hamburg, 22761 Hamburg, Germany*
[2] *Max Planck Institute for the Structure and Dynamics of Matter, Luruper Chausse 149, 22761 Hamburg, Germany*
[3] *National Institute of Physics, University of the Philippines, Diliman, Quezon City 1101, Philippines*
[4] *The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany*

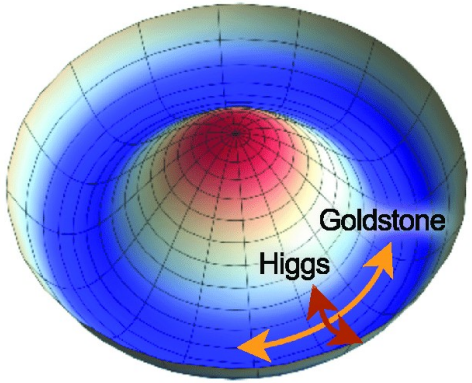


Guido Homann

to appear on arXiv soon...

Theory of pseudogap YBCO:

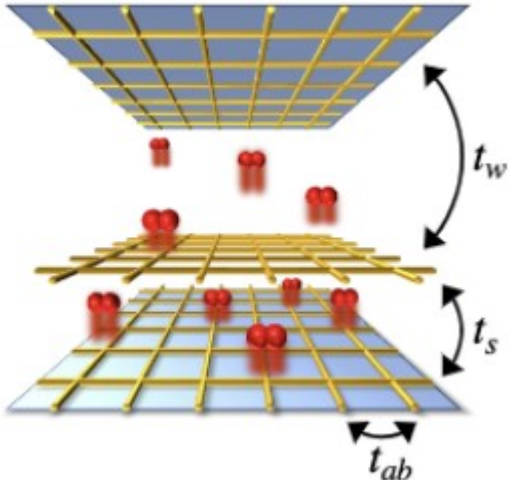
U(1) gauge invariant bilayer model



Mexican hat potential

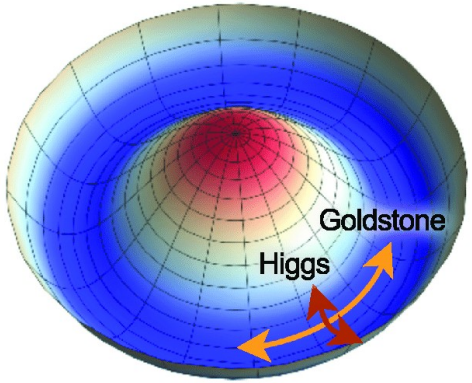
Superconducting potential:

$$\mathcal{L}_{\rm sc} = \sum_{\mathbf{r}} K\hbar^2 |\partial_t \psi_{\mathbf{r}}|^2 + \mu|\psi_{\mathbf{r}}|^2 - \frac{g}{2}|\psi_{\mathbf{r}}|^4 ;$$



Theory of pseudogap YBCO:

U(1) gauge invariant bilayer model

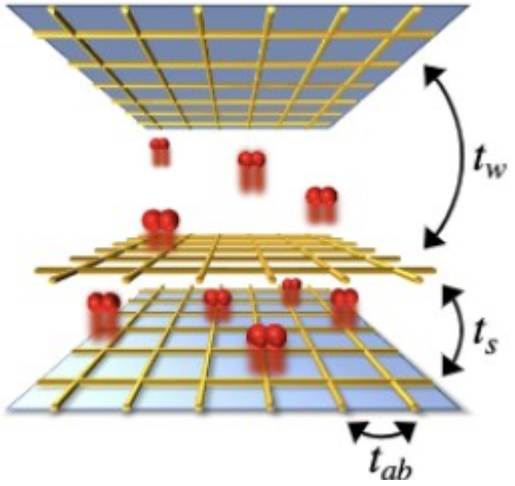


Superconducting potential:

$$\mathcal{L}_{\rm sc} = \sum_{\mathbf{r}} K\hbar^2 |\partial_t \psi_{\mathbf{r}}|^2 + \mu |\psi_{\mathbf{r}}|^2 - \frac{g}{2}|\psi_{\mathbf{r}}|^4$$

Tunneling of cooper pairs:

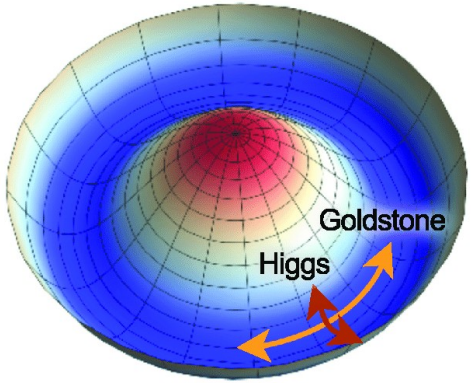
$$\mathcal{L}_{\rm kin} = -\sum_{j,\mathbf{r}} t_{j,\mathbf{r}} |\psi_{\mathbf{r}+\mathbf{u}_j} - \psi_{\mathbf{r}} e^{ia_{j,\mathbf{r}}}|^2$$



Bilayer anisotropic 3D XY-model

Theory of pseudogap YBCO:

U(1) gauge invariant bilayer model

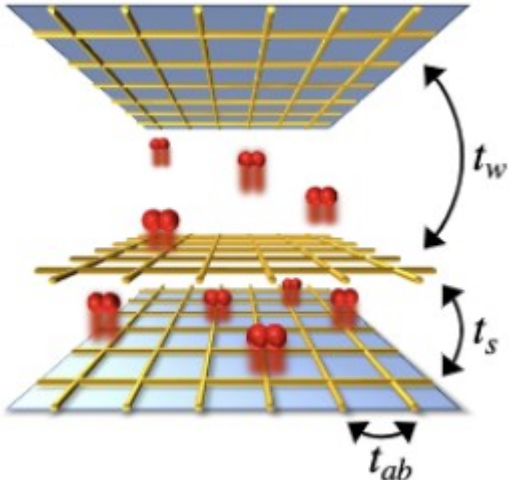


Superconducting potential:

$$\mathcal{L}_{\rm sc} = \sum_{\mathbf{r}} K\hbar^2 |\partial_t \psi_{\mathbf{r}}|^2 + \mu |\psi_{\mathbf{r}}|^2 - \frac{g}{2}|\psi_{\mathbf{r}}|^4$$

Tunneling of cooper pairs:

$$\mathcal{L}_{\rm kin} = -\sum_{j,\mathbf{r}} t_{j,\mathbf{r}} |\psi_{\mathbf{r}+\mathbf{u}_j} - \psi_{\mathbf{r}} e^{i a_{j,\mathbf{r}}}|^2$$



Maxwell Hamiltonian:

$$\mathcal{L}_{\rm em} = \sum_{j,\mathbf{r}} \frac{\kappa_{j,\mathbf{r}} \epsilon_\infty \epsilon_0}{2} E_{j,\mathbf{r}}^2 - \frac{\kappa_{z,\mathbf{r}}}{\kappa_{j,\mathbf{r}} \beta_{j,\mathbf{r}}^2 \mu_0} \left[1 - \cos\left(\beta_{j,\mathbf{r}} B_{j,\mathbf{r}}\right)\right]$$

→ Coupling to light

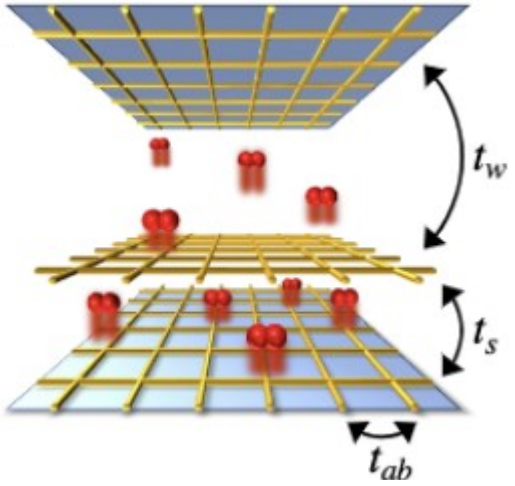
Theory of pseudogap YBCO:

U(1) gauge invariant bilayer model

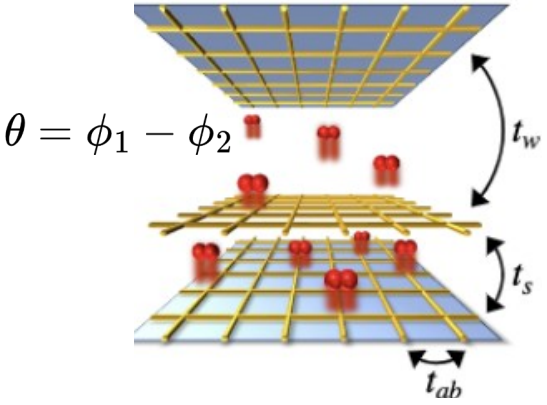
Semi-classical Langevin dynamics:

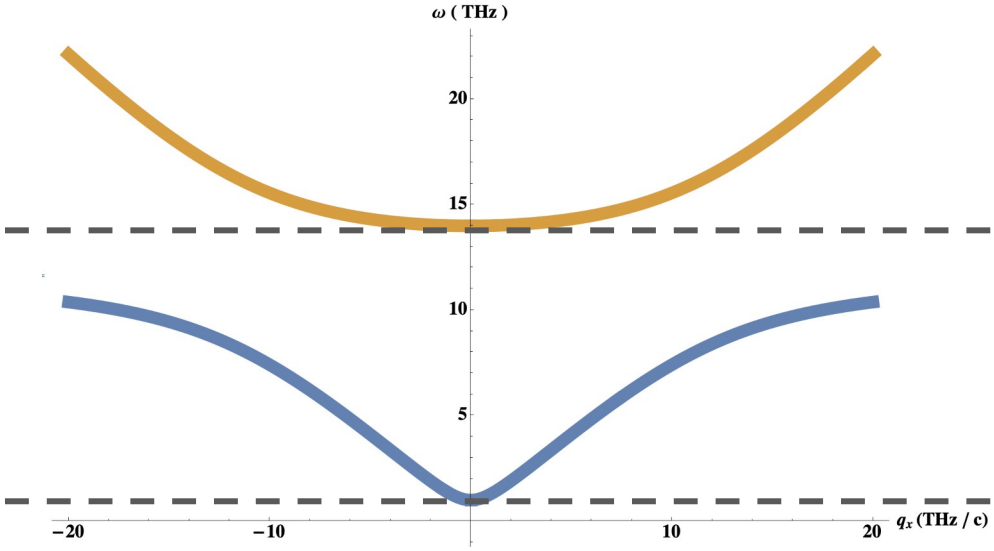
$$\partial_t^2 \psi_{\mathbf{r}} = \frac{1}{K\hbar^2} \frac{\partial \mathcal{L}}{\partial \psi_{\mathbf{r}}^*} - \gamma_{\rm sc} \partial_t \psi_{\mathbf{r}} + \xi_{\mathbf{r}},$$

$$\partial_t^2 A_{j,\mathbf{r}} = \frac{1}{\epsilon_\infty \epsilon_0} \frac{\partial \mathcal{L}}{\partial A_{j,\mathbf{r}}} - \gamma_{j,\mathbf{r}} \partial_t A_{j,\mathbf{r}} + \eta_{j,\mathbf{r}}$$



Collective modes of phase dynamics:

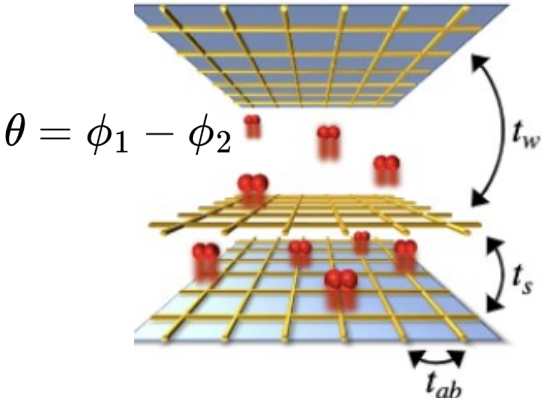


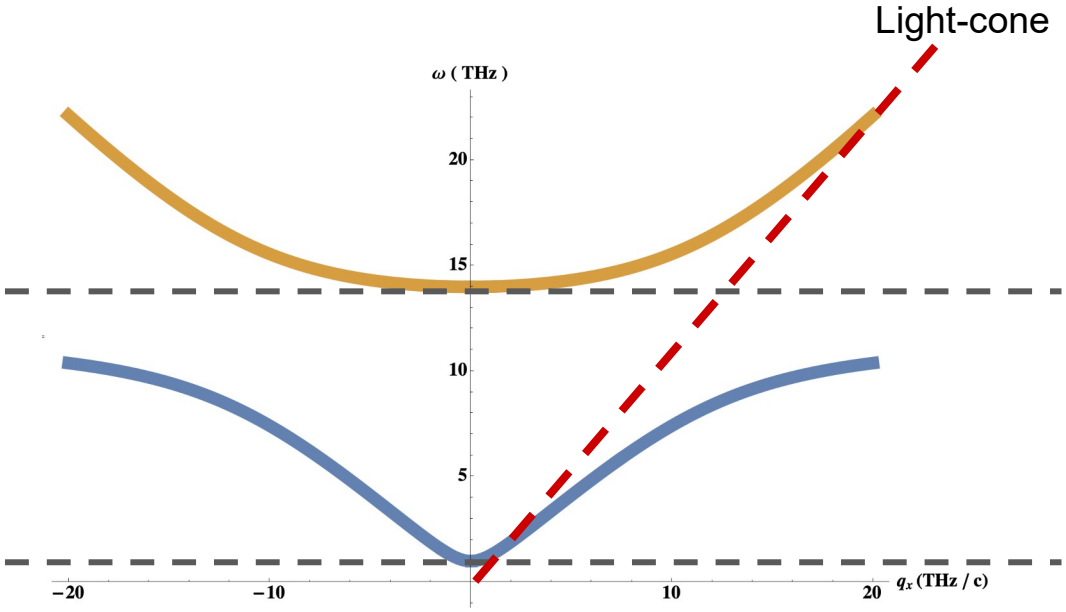


$$\omega_s^2 \approx t_s |\psi_i|^2 \langle \cos(\theta) \rangle$$

$$\omega_w^2 \approx t_w |\psi_i|^2 \langle \cos(\theta) \rangle$$

Collective modes of phase dynamics:





$$\omega_s^2 \approx t_s |\psi_i|^2 \langle \cos(\theta) \rangle$$

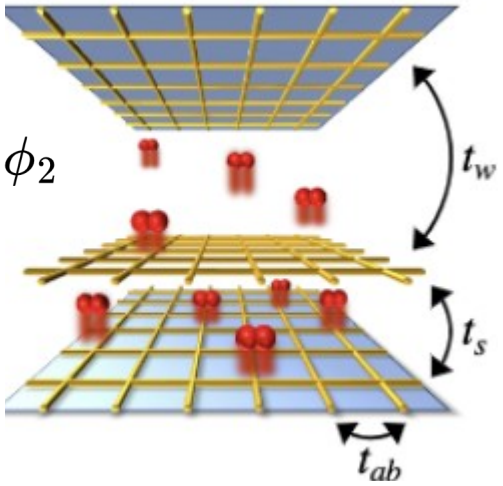
$$\omega_w^2 \approx t_w |\psi_i|^2 \langle \cos(\theta) \rangle$$

Josephson plasmons:

Josephson current:

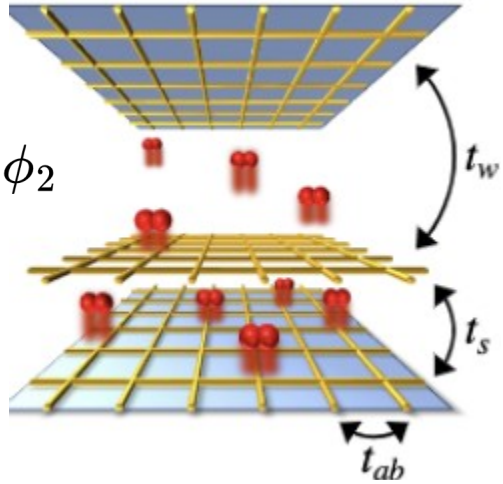
$$j_z = J_c \sin(\theta)$$

$$\theta = \phi_1 - \phi_2$$



Josephson plasmons:

$$\theta = \phi_1 - \phi_2$$



Josephson current:

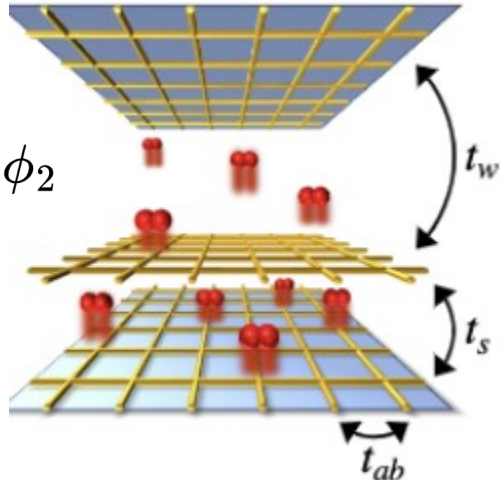
$$j_z = J_c \sin(\theta)$$

Sine-gordon model of a single Josephson layer:

$$\partial_t^2\theta + \gamma\partial_t\theta + c^2\partial_x^2\theta + J_c \sin(\theta) = \lambda E(t)$$

Josephson plasmons:

$$\theta = \phi_1 - \phi_2$$



Josephson current:

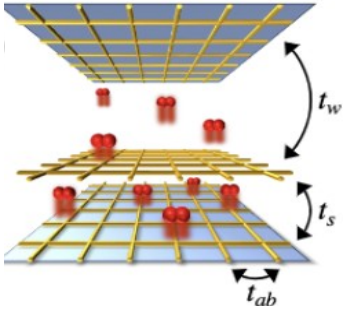
$$j_z = J_c \sin(\theta)$$

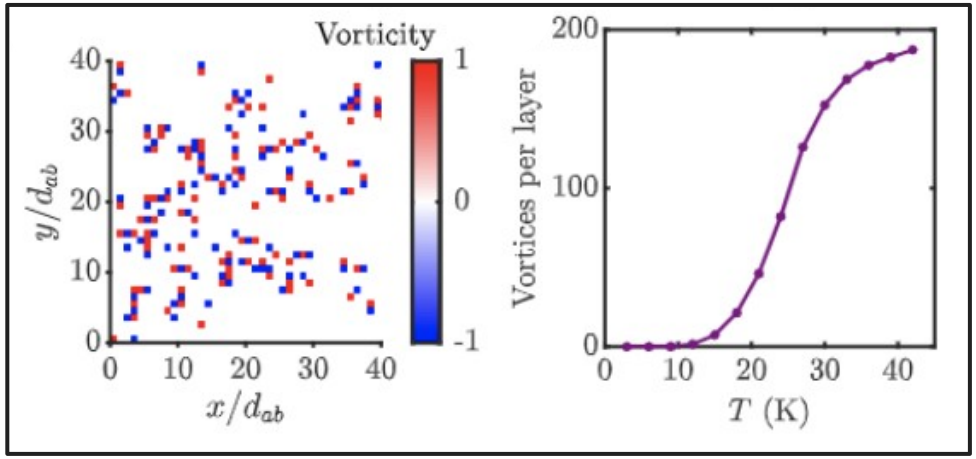
Source of strong non-linearity

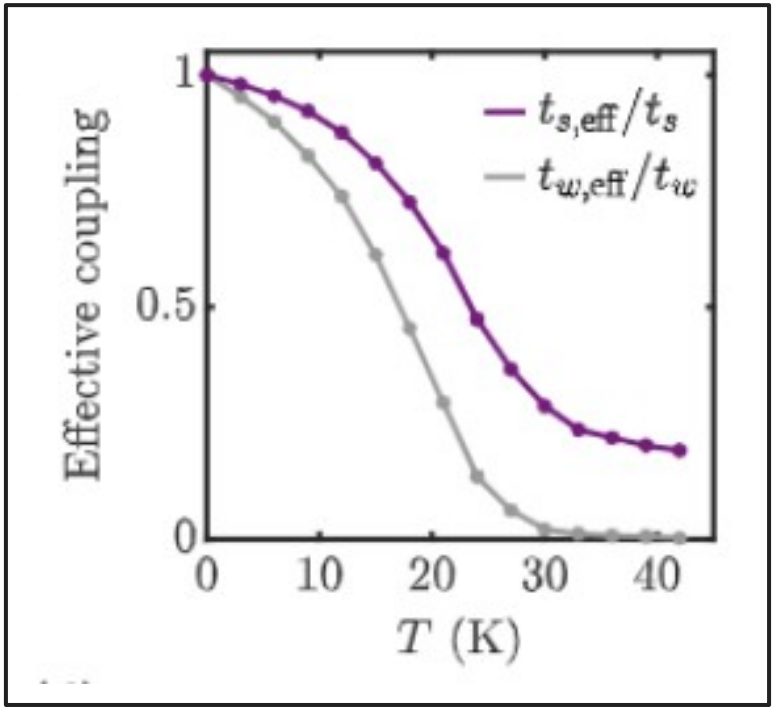
Sine-gordon model of a single Josephson layer:

$$\partial_t^2\theta + \gamma\partial_t\theta + c^2\partial_x^2\theta + J_c \sin(\theta) = \lambda E(t)$$

Results:







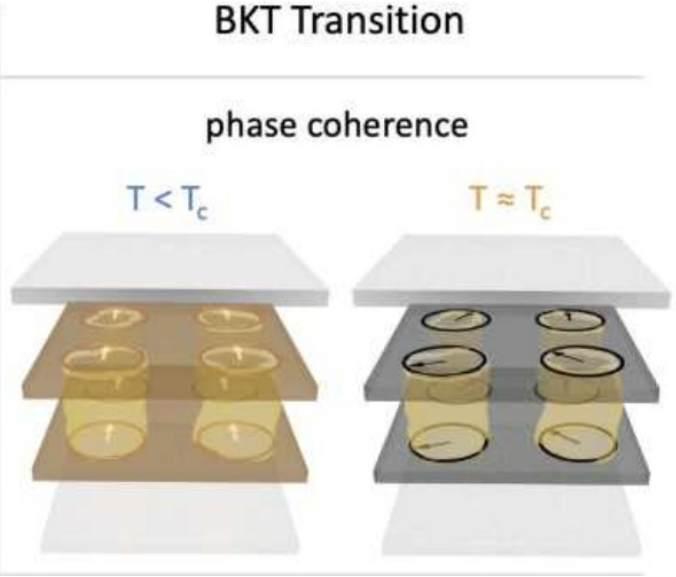
$$t_{w,eff} = t_w \langle cos(\theta) \rangle$$

$$t_{s,eff} = t_s \langle cos(\theta) \rangle$$

Pancake vortices proliferate around 25 K.

Intrabilayer superconducting correlations:

Claim: Short range coherence in 3D anisotropic XY model **sufficient** to explain the plethora of nonlinear responses.



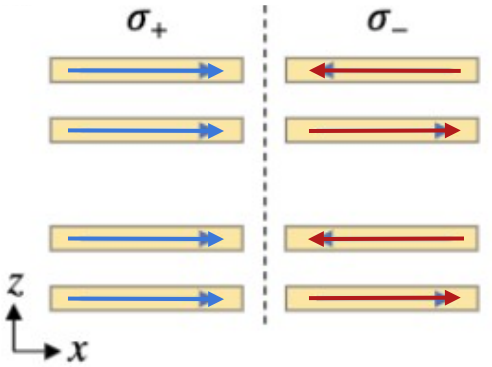
Long range order is lost:

$$\langle \psi^+(x)\psi(x')\rangle \sim |\psi(x)|^2 \langle e^{i\phi(x)-i\phi(x')}\rangle_{XY} = |\psi(x)|^2 e^{-x/\xi}$$

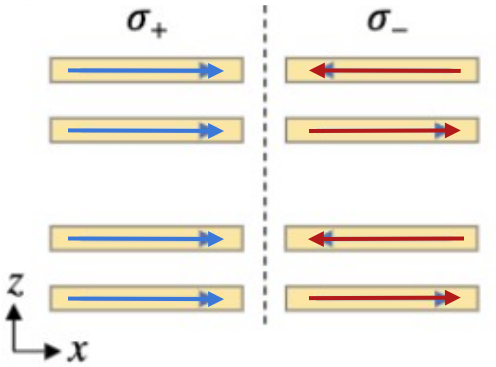
Locally strong Josephson nonlinearity:

$$\langle J_c \cos(\theta(x))\rangle \neq 0$$

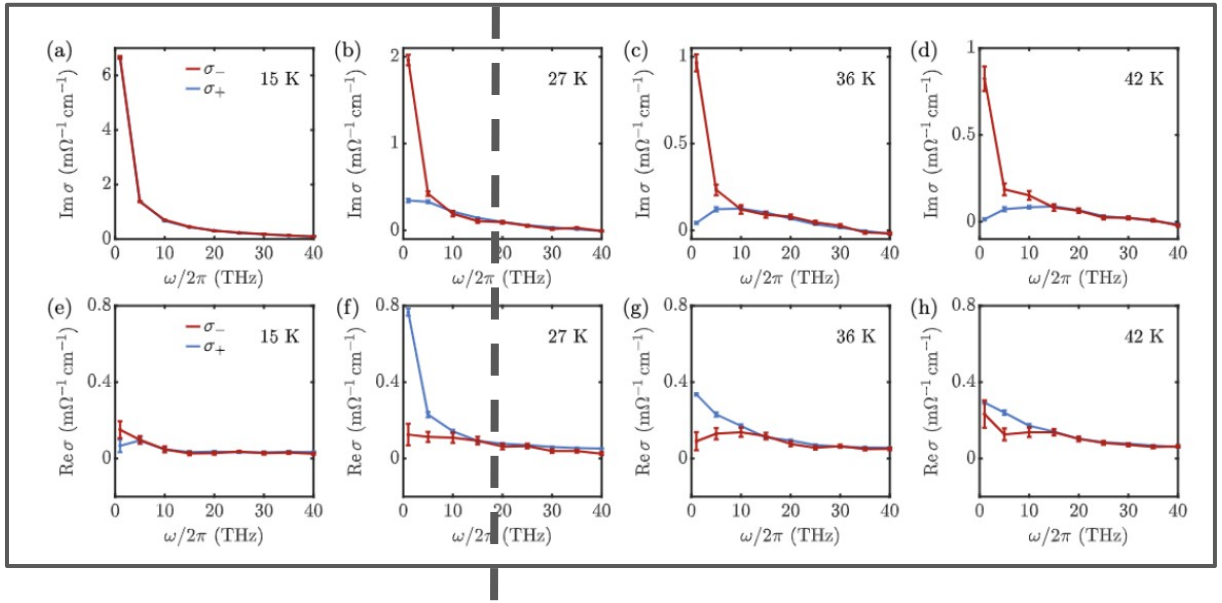
Conductivity in the pseudogap:



Conductivity in the pseudogap:

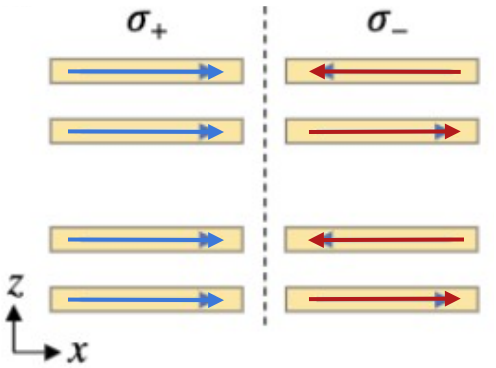


T < Tc T~ Tc T > Tc



Conductivity in the pseudogap:

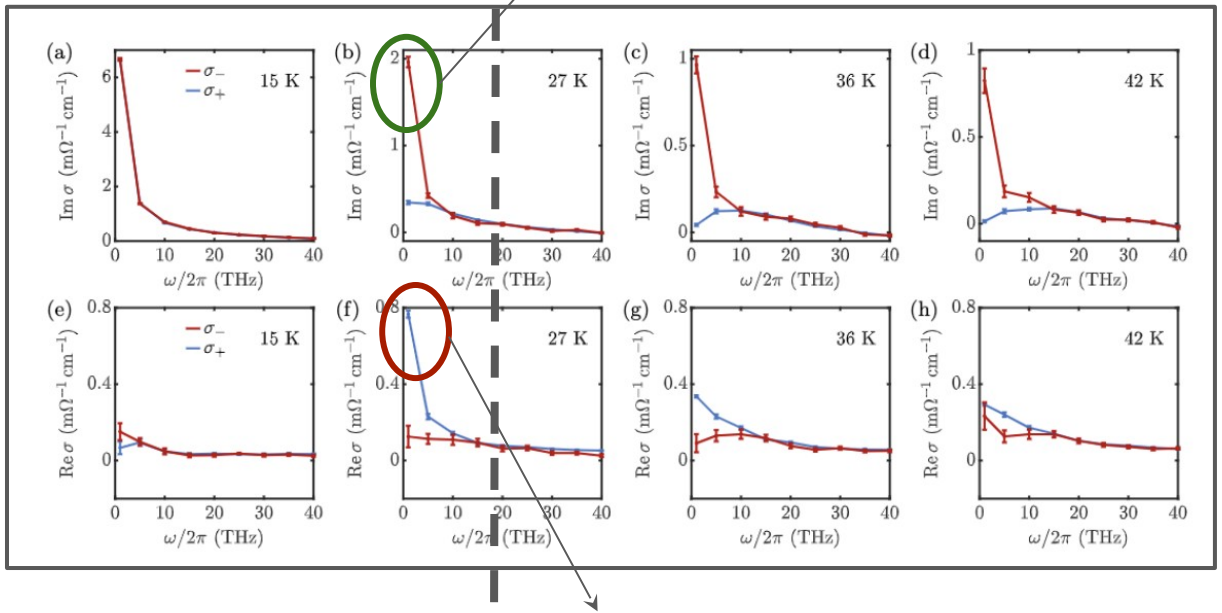
Counterflow supercurrent above Tc!!!



T < Tc

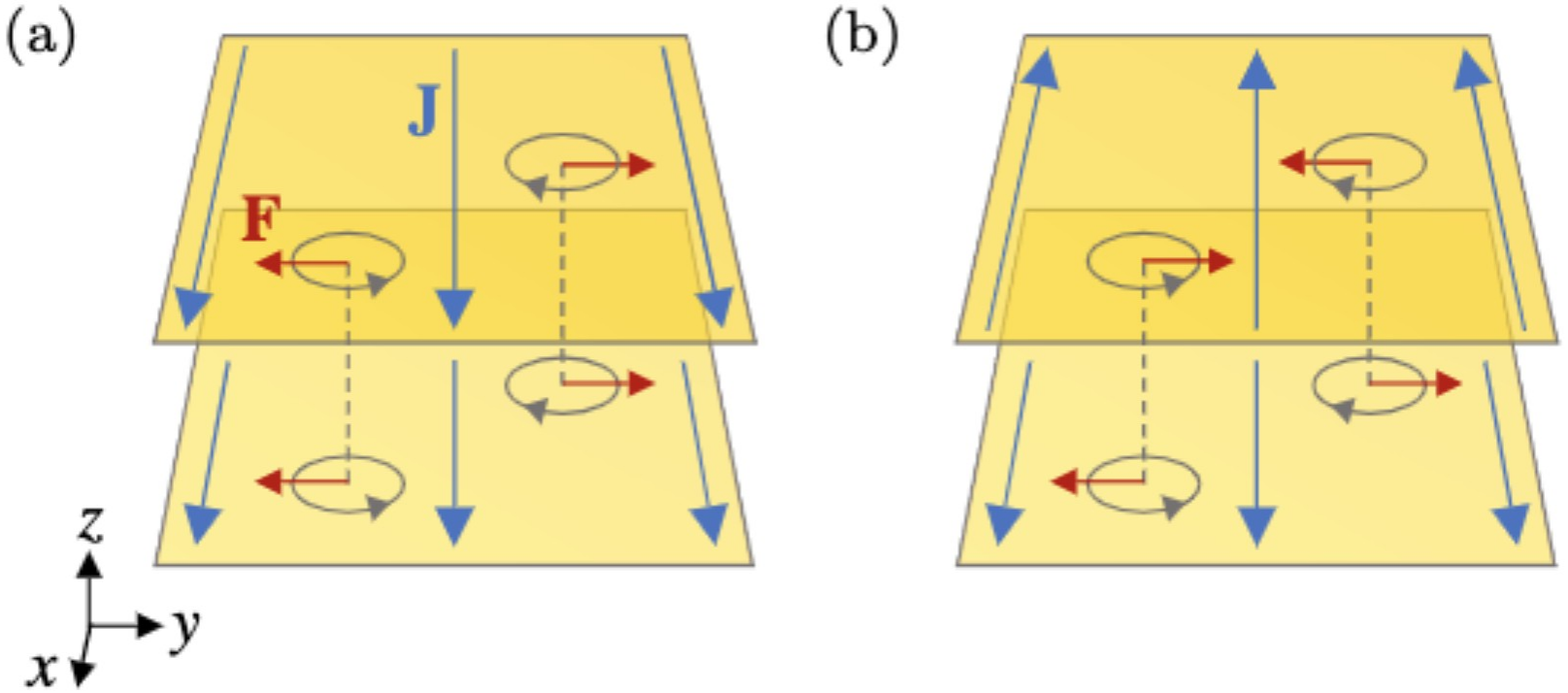
T~ Tc

T > Tc



Resistive transition for total current.

Origin of counterflow superconductivity



Collaborators:

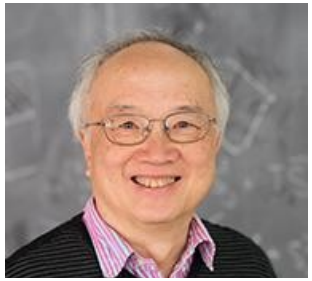
Numerical simulations:

Guido Homann

Ludwig Mathey

Theory:

Eugene Demler



Patrick Lee

Experiments:

Andrea Cavalleri

Thank you !