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Thermoelectric (TE) detections in cuprate superconductors

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Outlines

- **Background**

  - Introduction to thermoelectric (TE) effect and its application in superconductors

- **On-chip TE detections in superconductors**

  - Extension of on-chip thermometry towards sub-10 K regime via Kondo effect

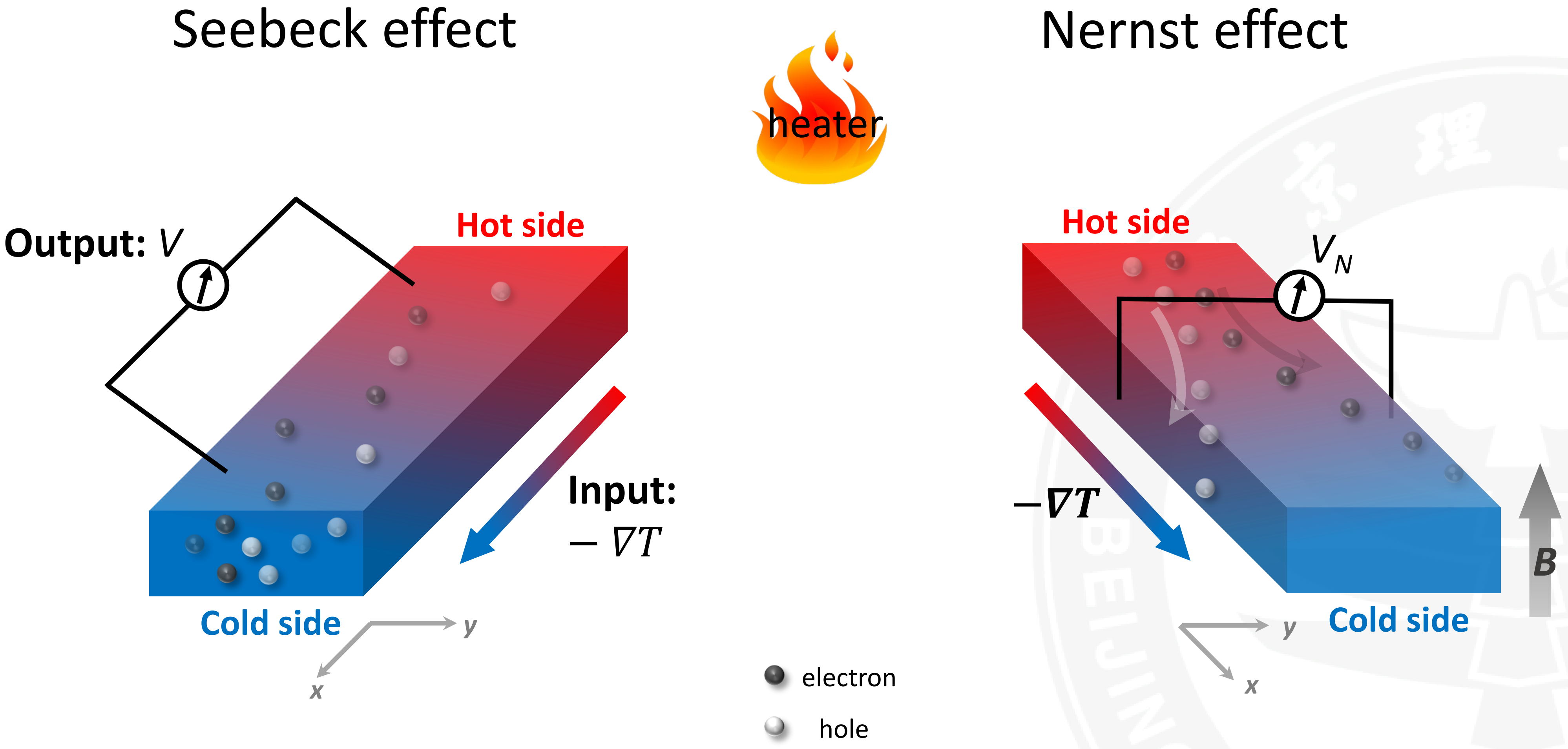
  - Enhanced Seebeck effect in ultrathin $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212)

  - Reduction of vortex entropy in ultrathin Bi-2212 from Nernst measurements in the underdoped regime

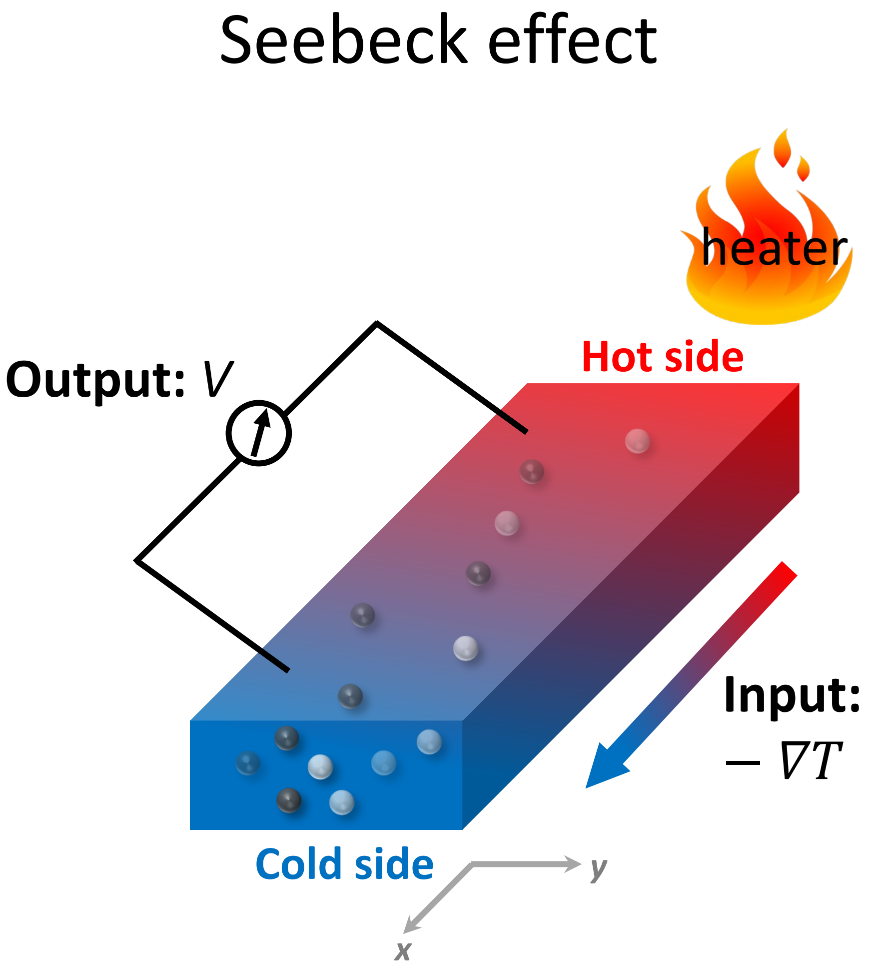
- **Summary & Outlook**

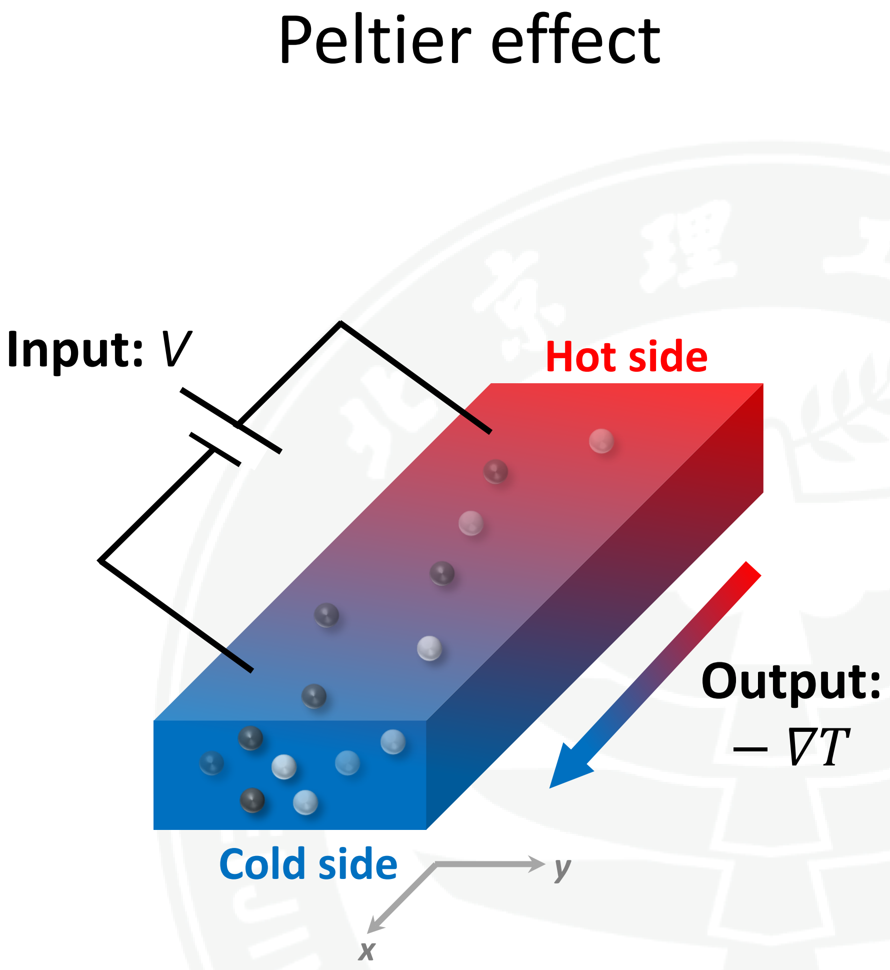
Thermoelectric effects

TE effects: direct conversion between thermal and electrical energies



Seebeck effect and its converse effect



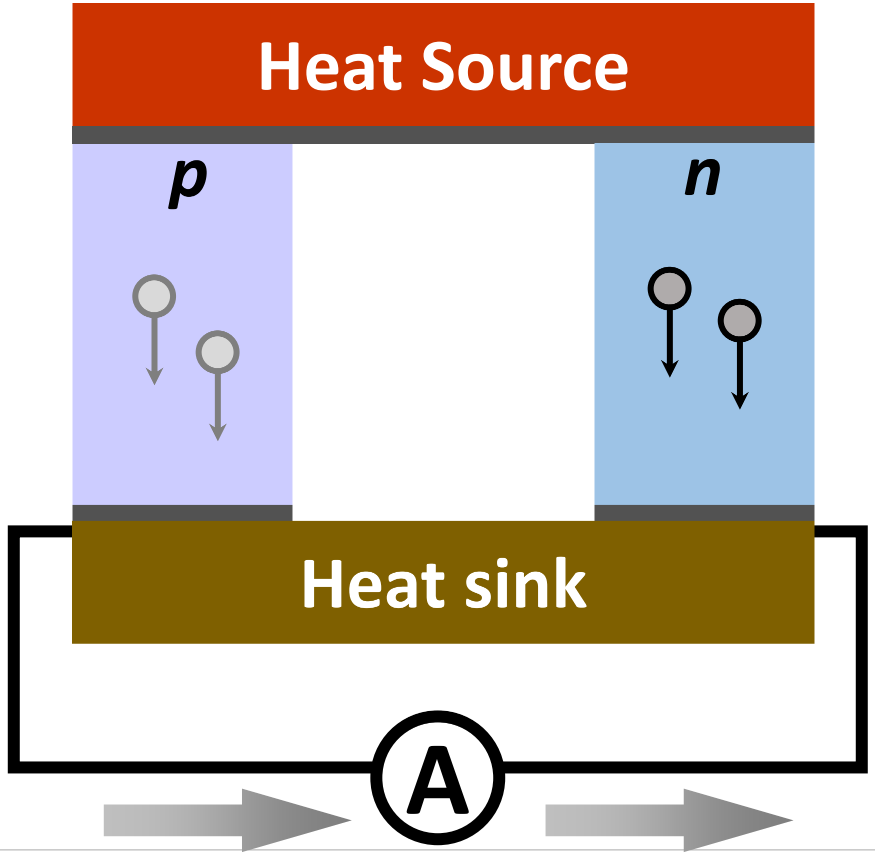


electron

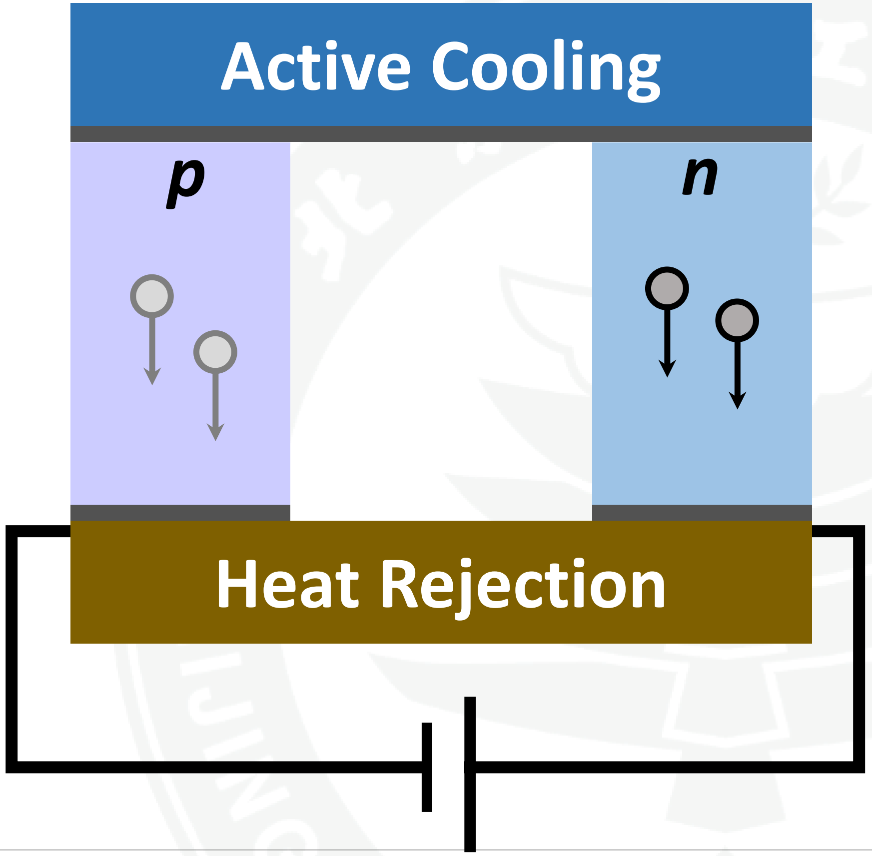
hole

Thermoelectrics in applications

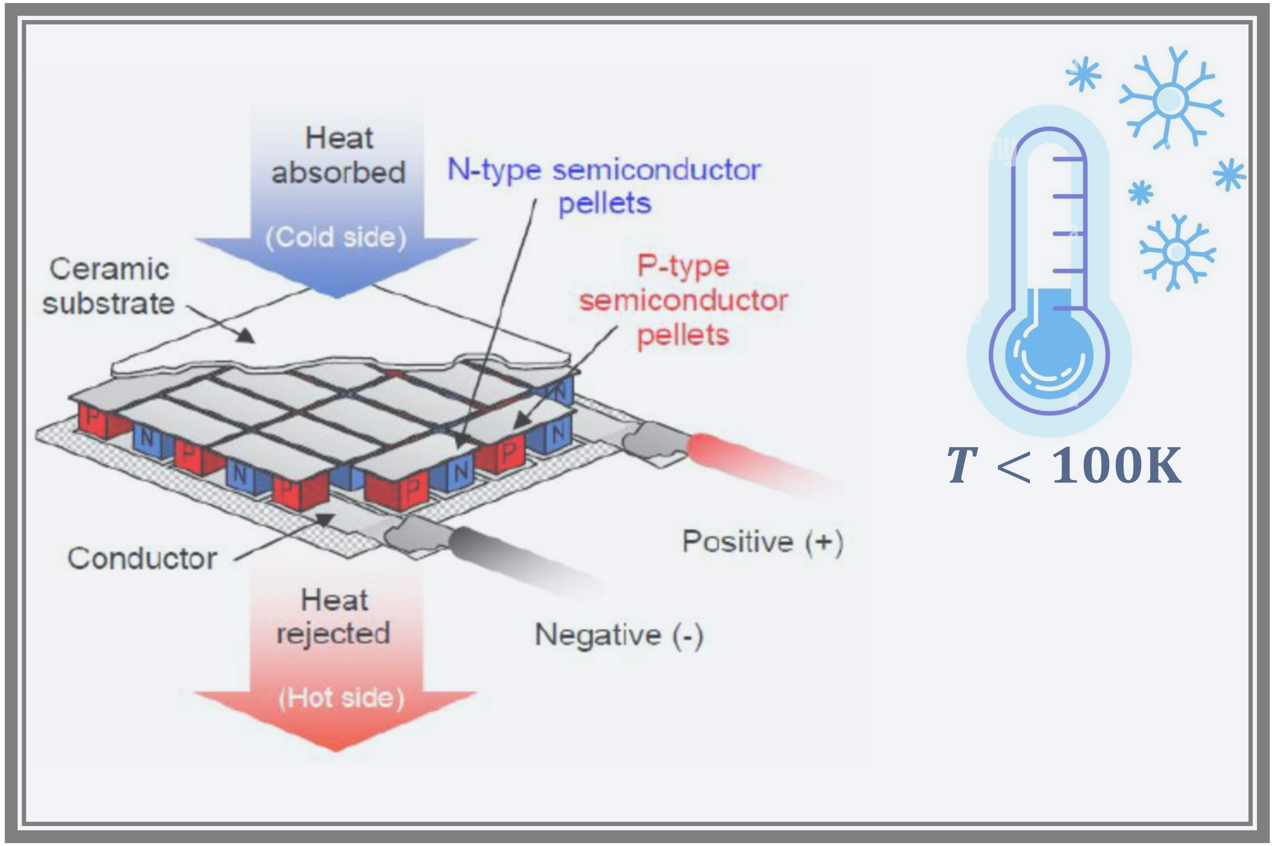
Power Generation Mode



Refrigeration Mode

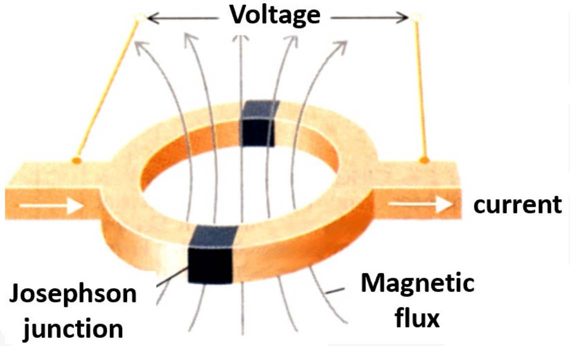


Cryogenic TE cooling



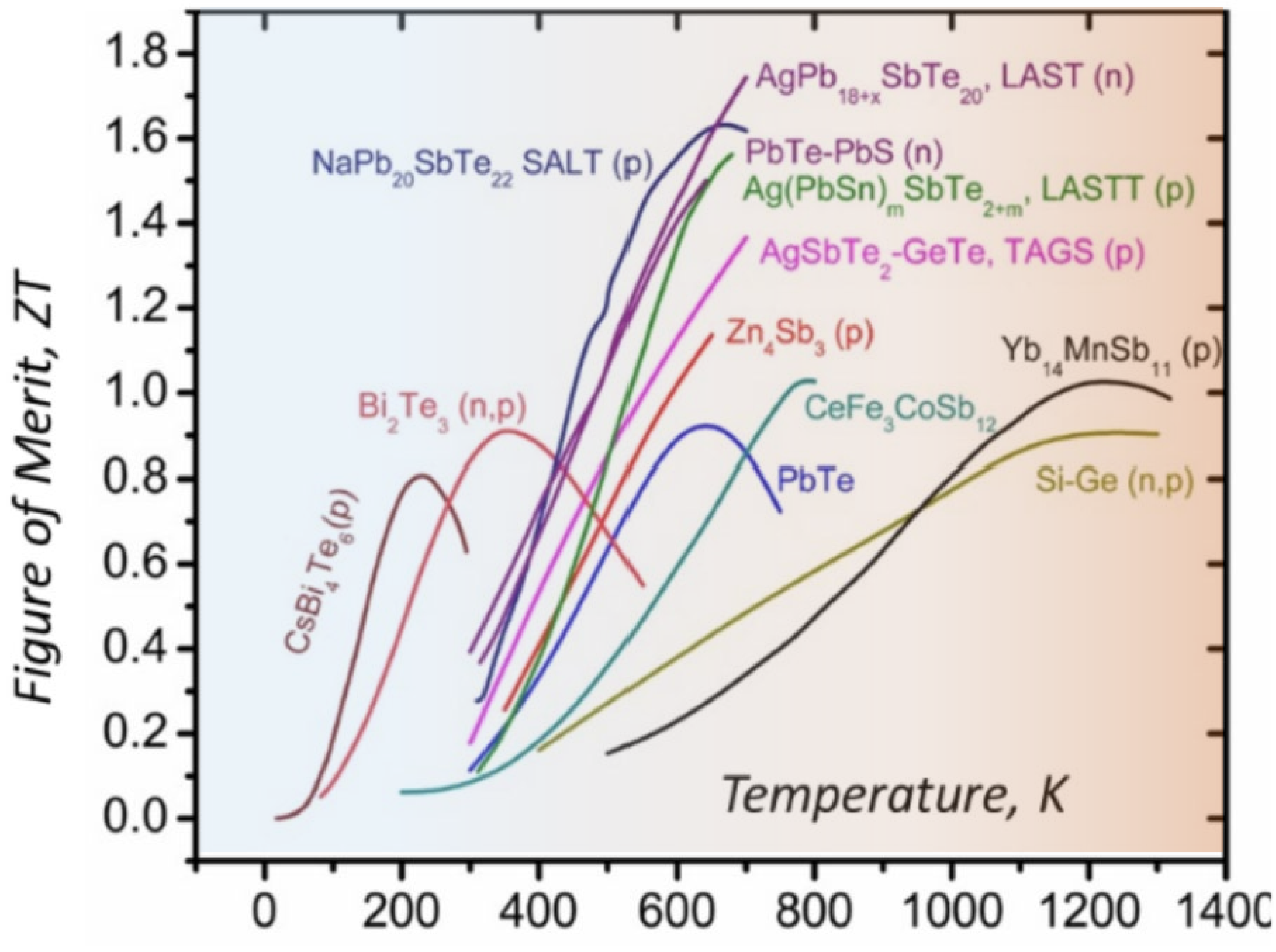
far-infrared radiation detectors in space

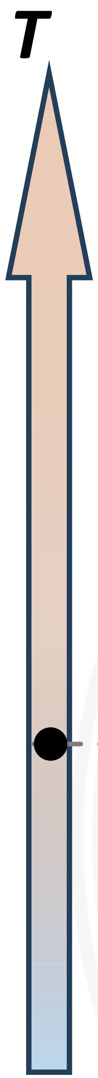
Superconducting sensors (e.g., SQUID)



Pictures from Internet

TE materials





Above 950 K:
SiGe alloys

550-950 K:
PbSe, PbTe, SnTe, GeTe, LAST, etc.

300-500 K:
Bi_2Te_3-based alloys

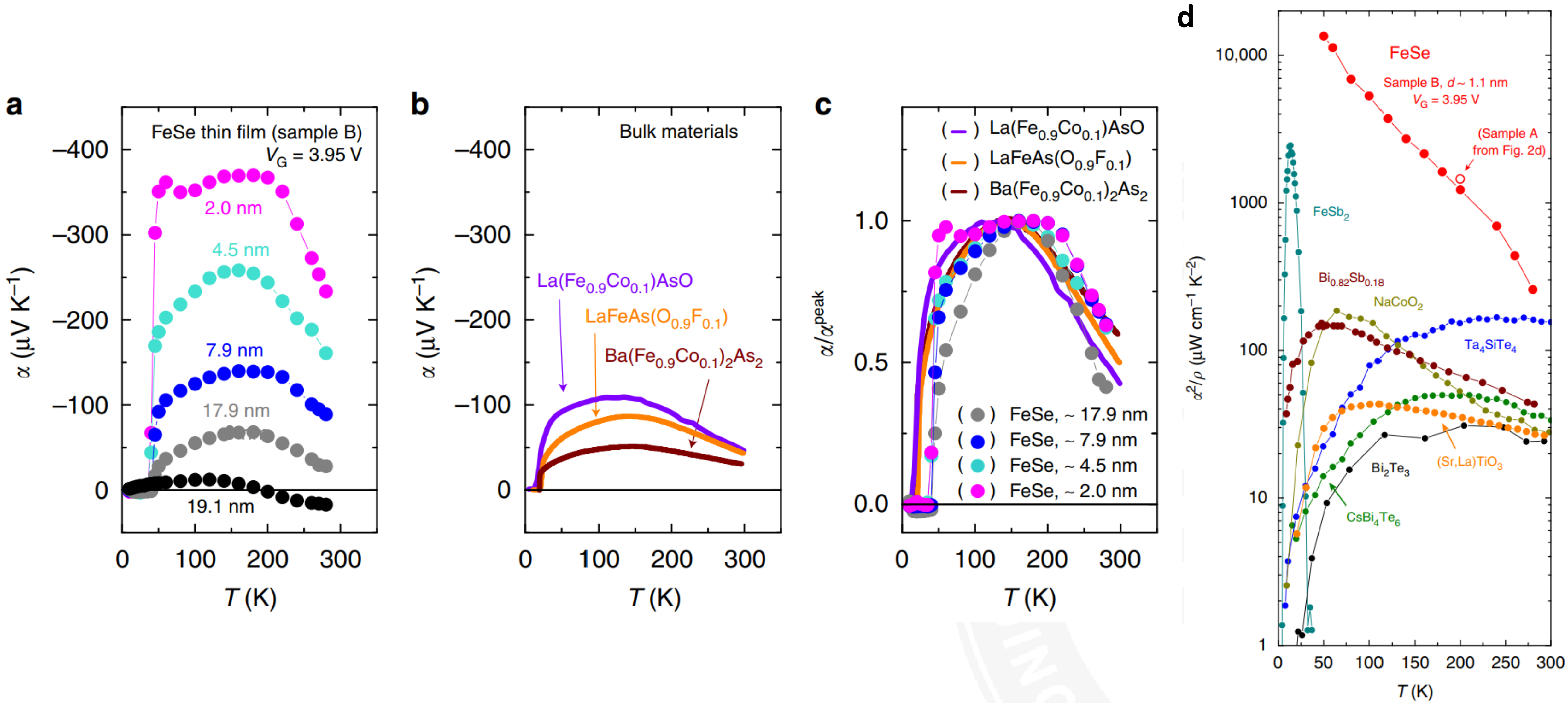
Linear thermoelectricity:

T ↓ , S ↓

$$\boldsymbol{S\ (1\ \mathrm{K})\ = 1\mu V \cdot K^{-1}}$$

P. MohanKumar *et al.*, Sci **1**, 37 (2019)

Giant Seebeck effect in iron-based superconductors



Shimizu *et al*. Nat. Commun. **10**, 825 (2019)

Thickness dependence of TE power factor in FeSe

Ultrathin FeSe (1 nm thick)

$PF = S^2/\rho =$

$13000\ \mu WK^{-2}cm^{-1}\ (50\ K)$

$260\ \mu WK^{-2}cm^{-1} (280\ K)$

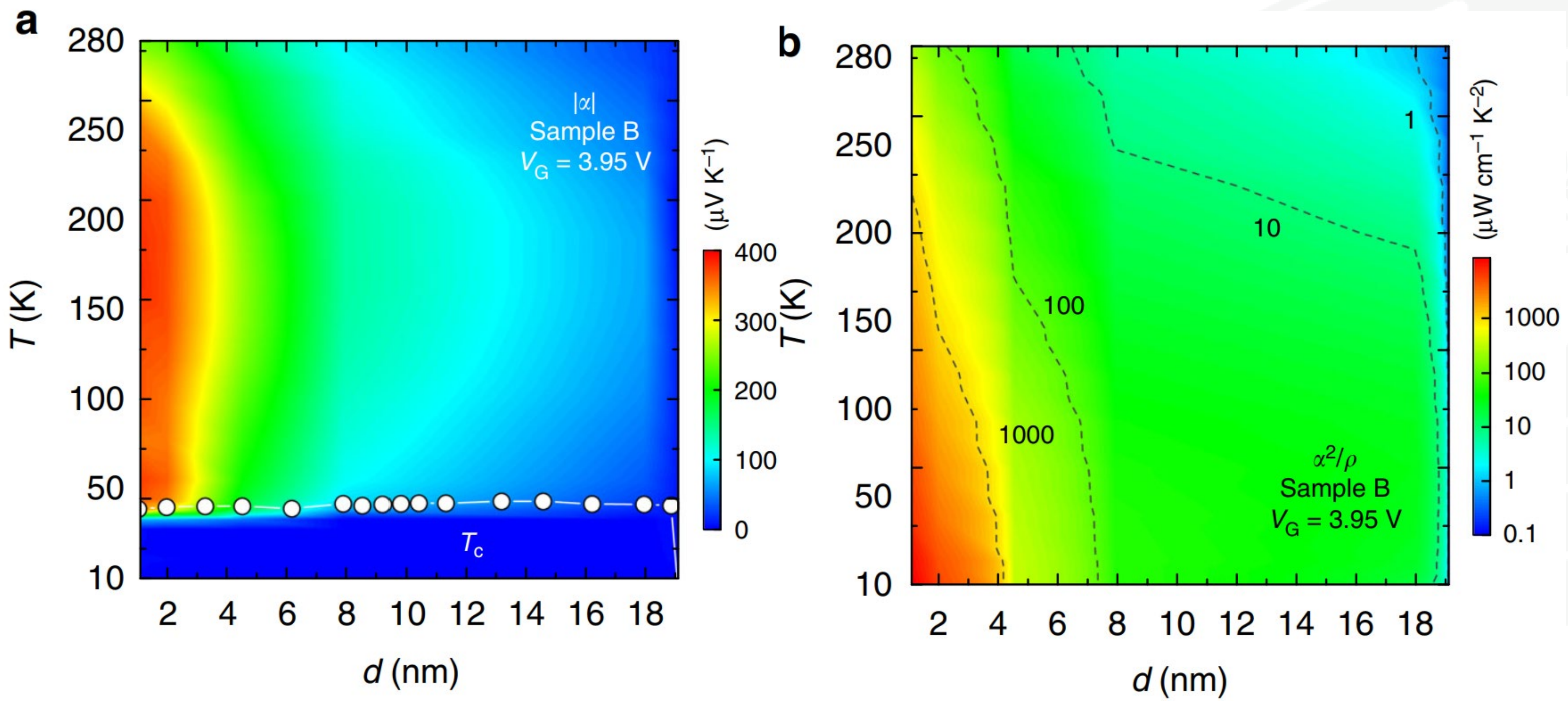
V.S.

Bulk FeSe

$PF =$

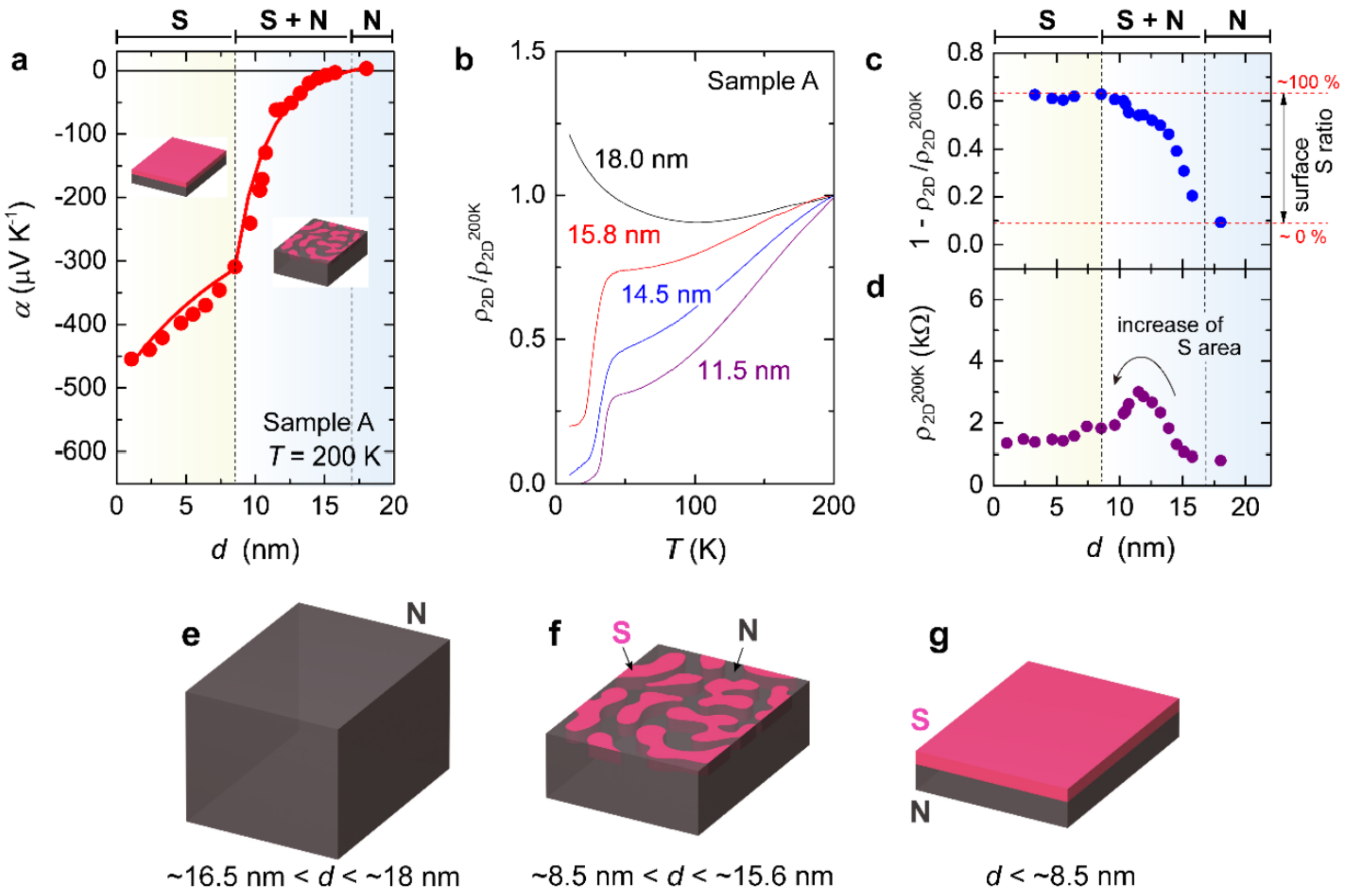
$< 10\ \mu WK^{-2}cm^{-1}\ (50\ K)$

$< 1\ \mu WK^{-2}cm^{-1} (280\ K)$



Shimizu *et al*. Nat. Commun. **10**, 825 (2019)

Origin of thickness dependence: band structure modulation



Electric field carrier doping

Thick film → Thin film

Semi-metallic | N-type semiconductor-like

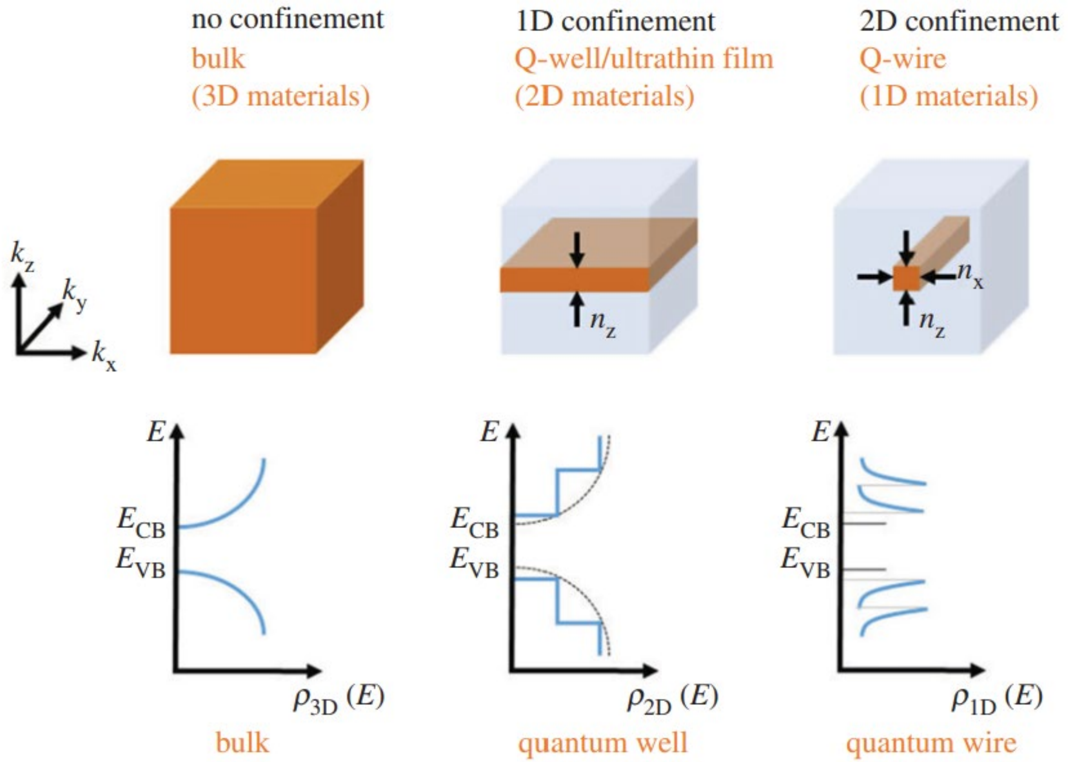
$\alpha_N = +3.8\ \mu V/K$ $\quad$ $\alpha_S = -454\ \mu V/K$

Shimizu *et al*. Nat. Commun. **10**, 825 (2019)

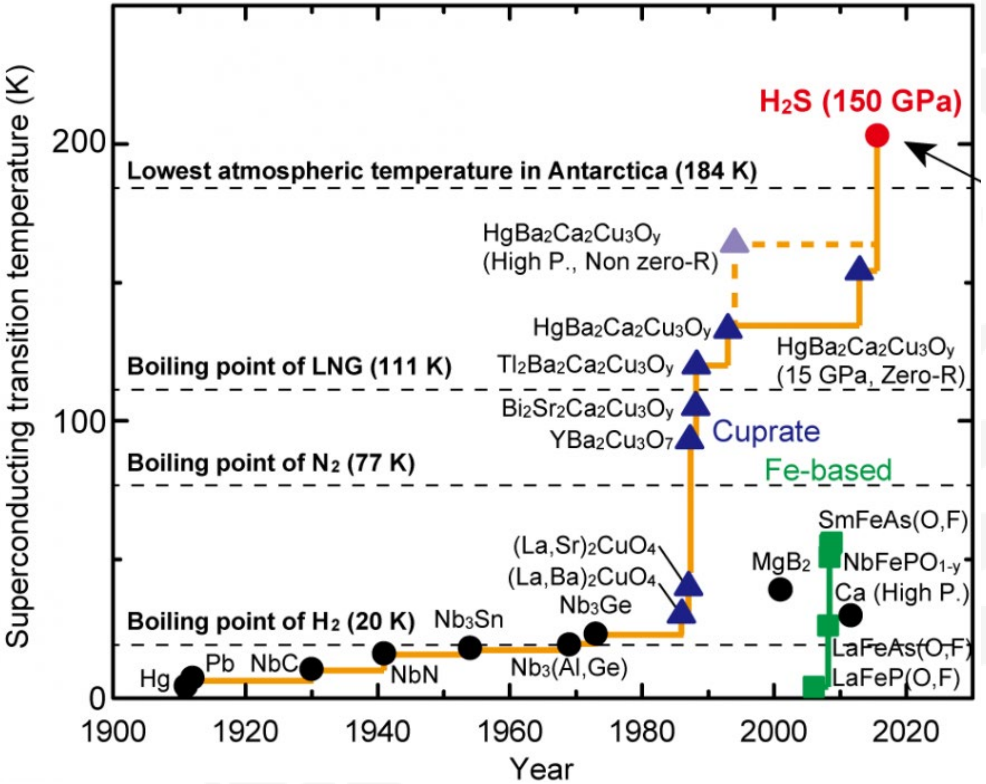
TE detection in low-dimensional superconductors

Low-*T* TE cooling material candidates

Dimensionality reduction

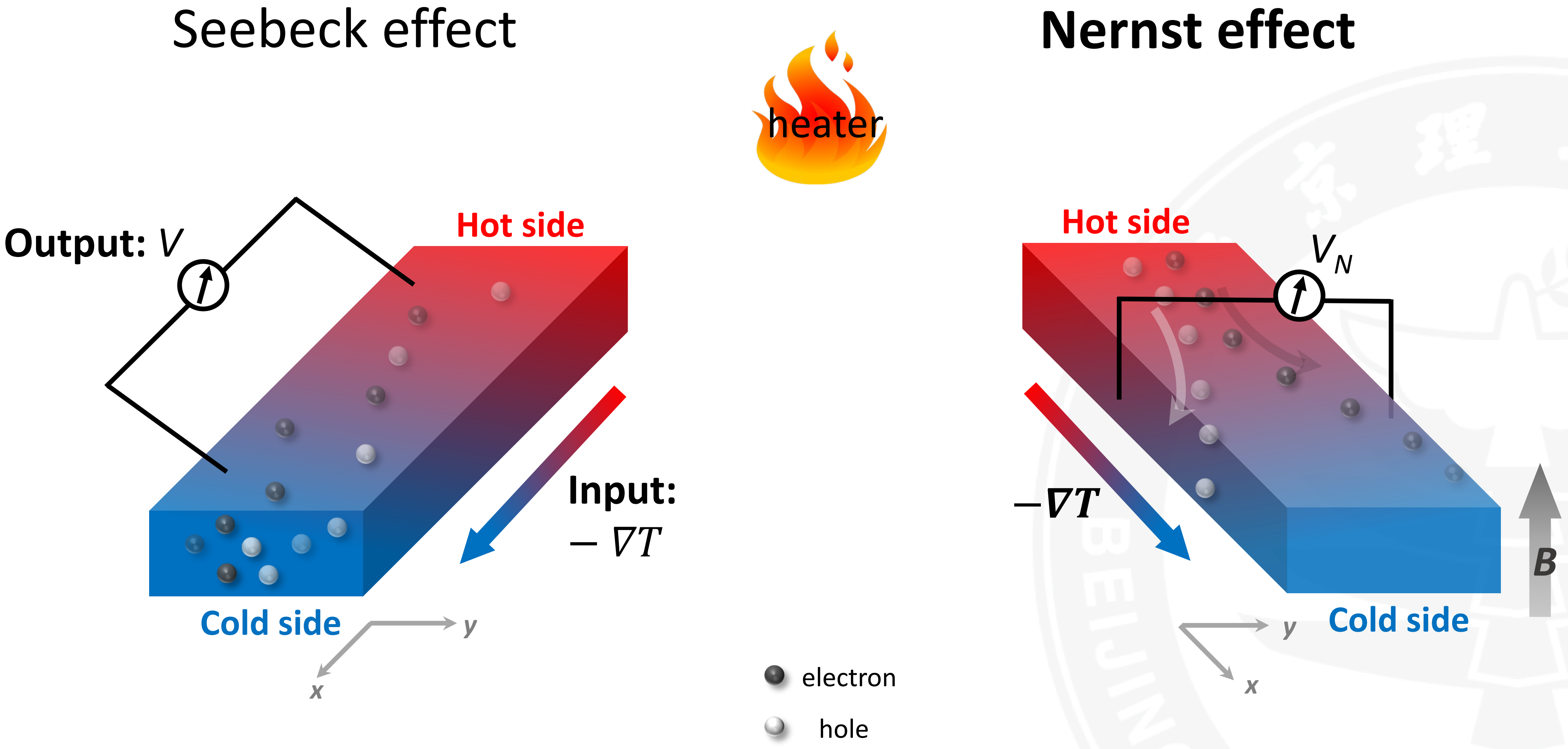


Superconductors



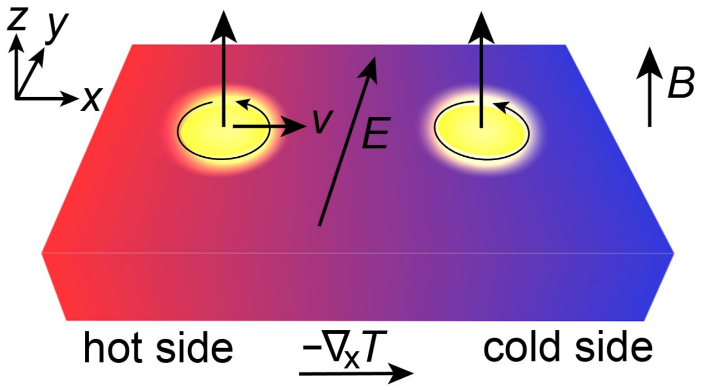
T. Edvinsson, R. Soc. Open sci. **5**, 180387 (2018)   Hicks & Dresselhaus, Phys. Rev. B **47**, 12727(1993)

Nernst effect



Nernst effect: a powerful probe for vortex dynamics

Vortex motion driven by $-\nabla_x T$



y-axis electric field:

$$\vec{E} = \vec{B} \times \vec{v}$$

Nernst signals:

$$N = \frac{E}{-\nabla_x T} = \frac{Bv}{-\nabla_x T}$$

Thermal force on a vortex per *z*-axis length :

$$f_{th} = -\frac{\partial e_{th}}{\partial x} = -\frac{\partial (TS_d)}{\partial x} = -S_d \nabla_x T$$

f_{th} is balanced by the viscosity:

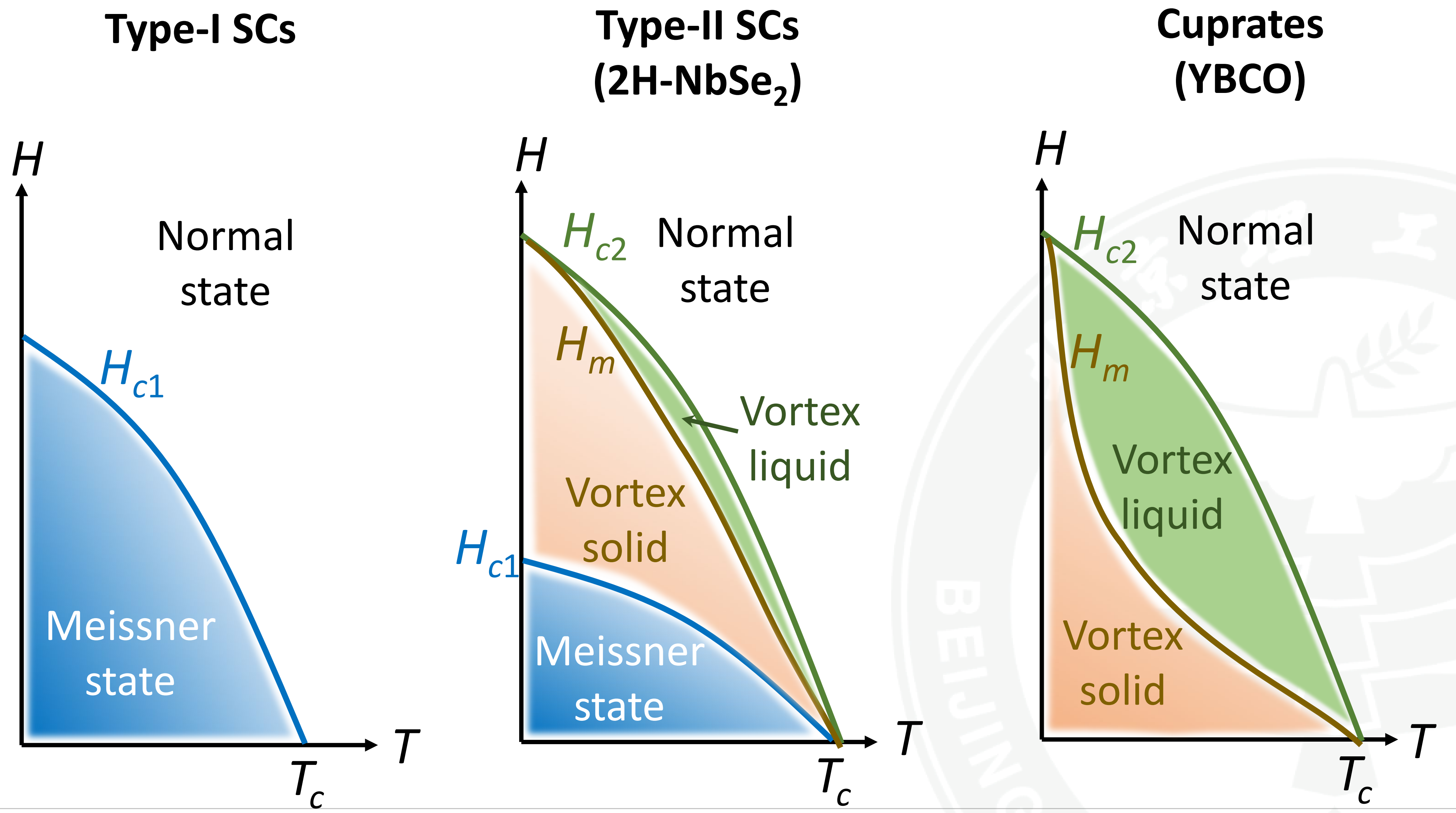
$$-S_d \nabla_x T = \eta v$$

Transport entropy per vortex per length:

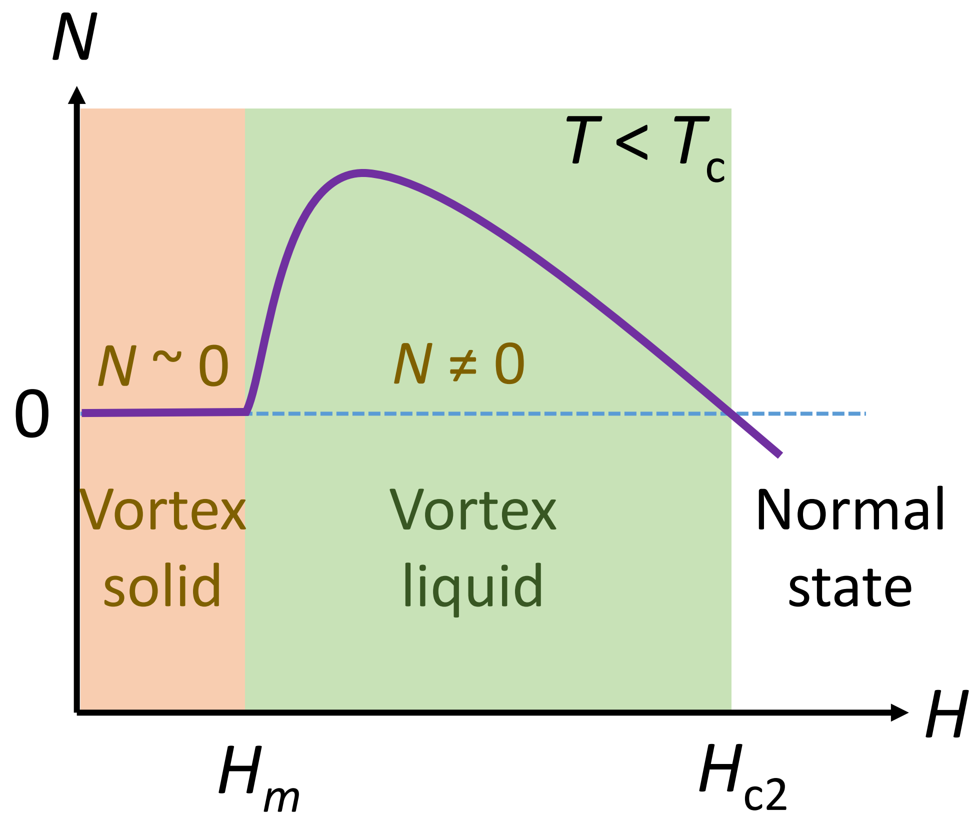
$$S_d = \frac{\Phi_0 N}{\rho_f}$$

Wang, Y. *et al.*, Phys. Rev. B **73**, 024510 (2006)

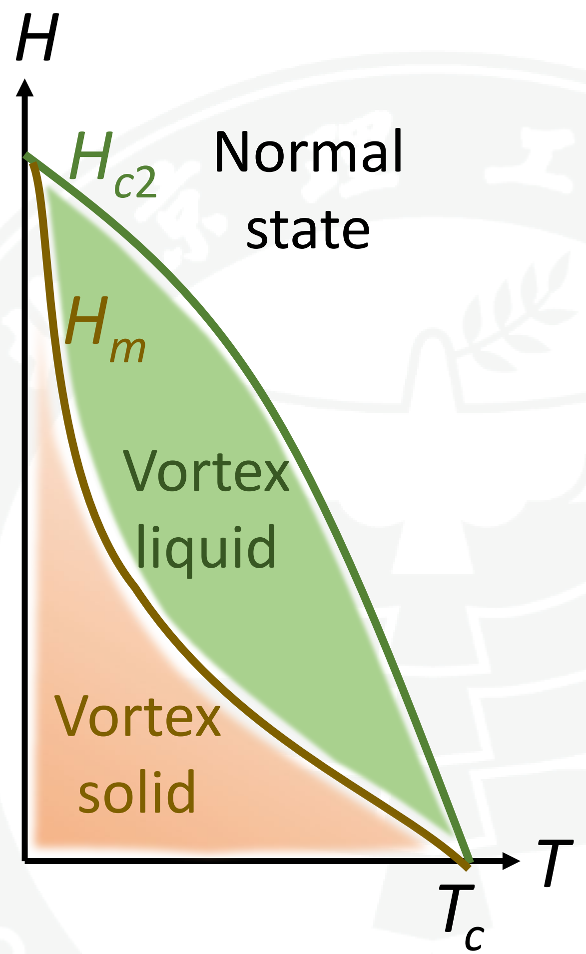
Nernst effect: a tool to determine H_{c2}



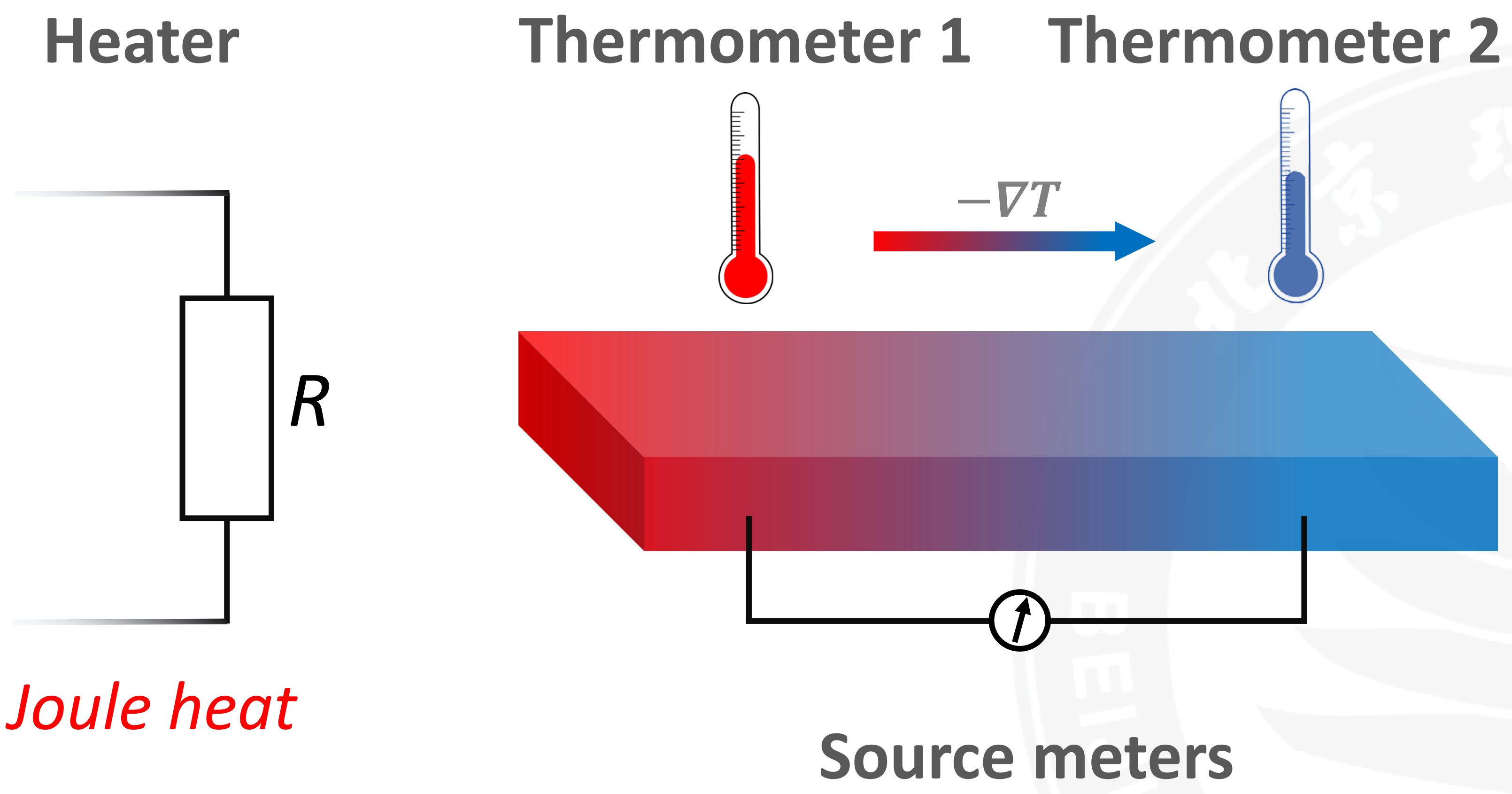
Nernst effect: a tool to determine H_{c2}



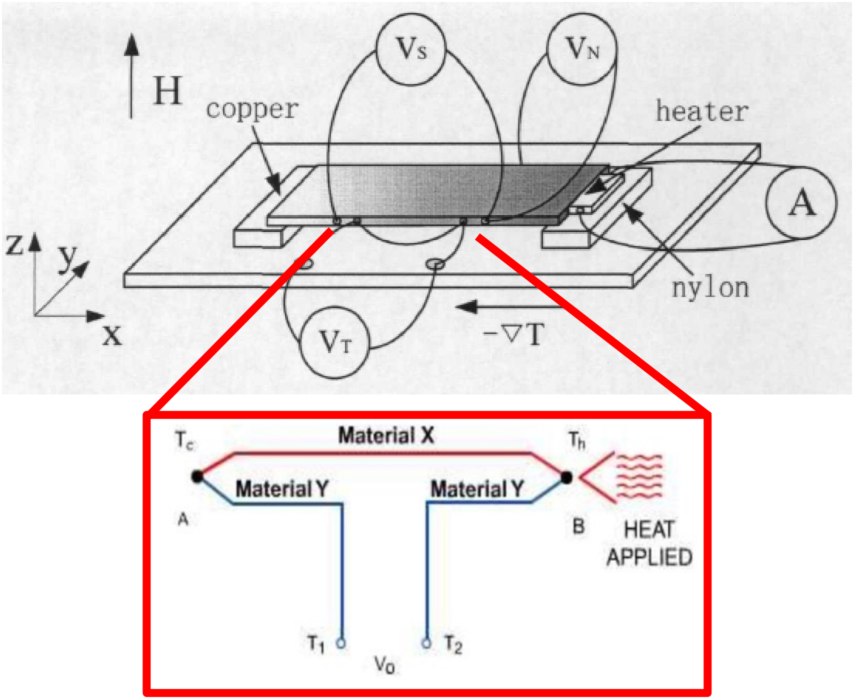
Cuprates (YBCO)



TE device setup configuration

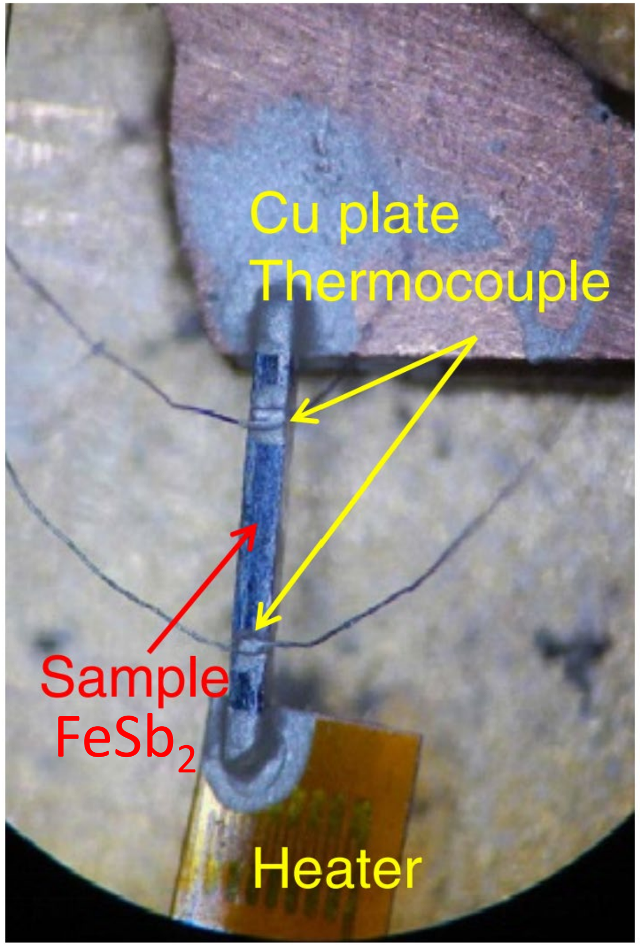


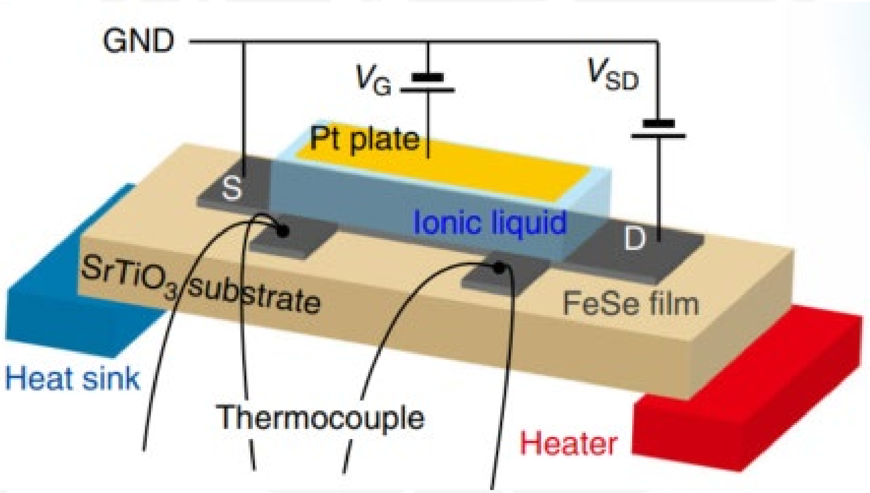
TE device setup for 3D crystal and MBE films



$$S = \frac{E_x}{\nabla_x T} = -\frac{V_S / l_1}{\left(\frac{V_T}{\alpha}\right) / l_2}$$

$$e_y = \frac{E_y}{\nabla_x T} = -\frac{V_N / l_1}{\left(\frac{V_T}{\alpha}\right) / l_2}$$





Where α is exchange coefficient of type-E thermocouple

Takahashi *et al*. Nat. Commun. **7**, 12732 (2016)
Shimizu *et al*. Nat. Commun. **10**, 825 (2019)

TE device setup for low-dimensional materials

Joule heat

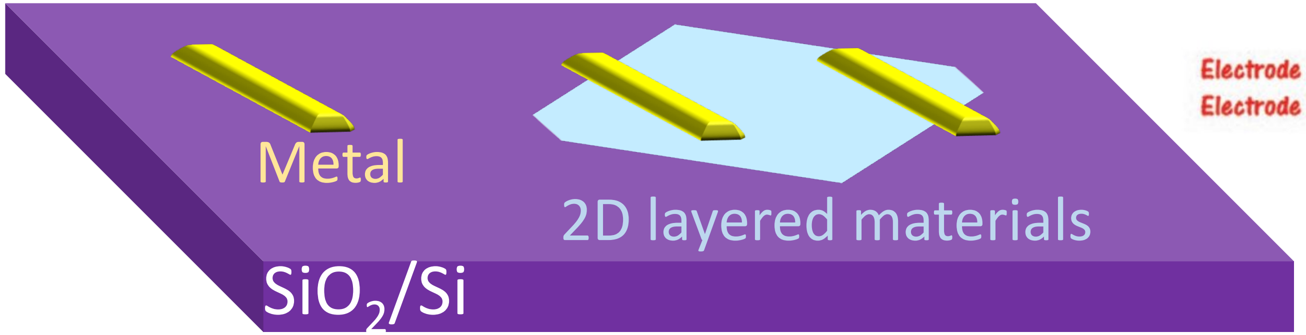
$P = I^2R$

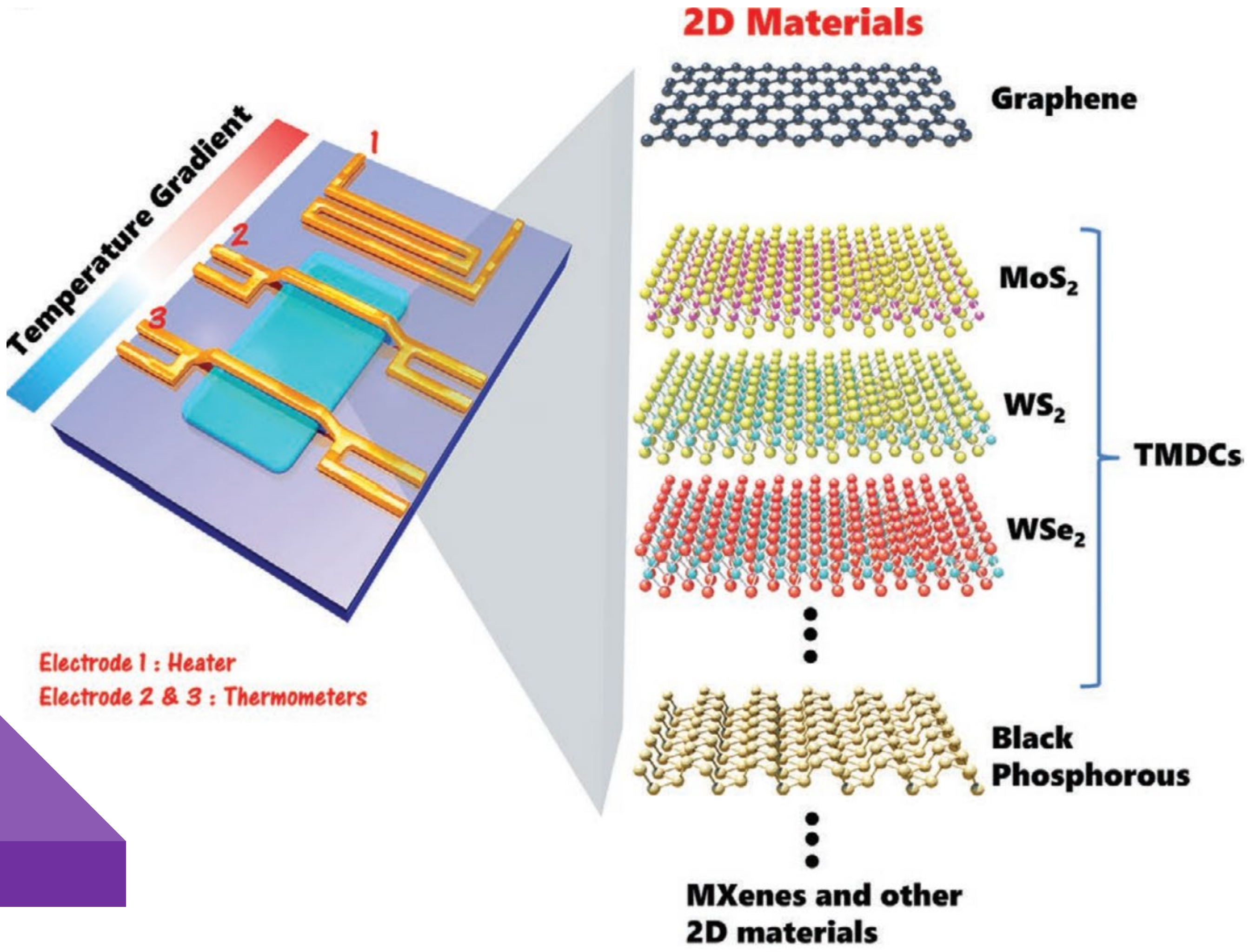
Heater

R as indicator of *T*

based on *R*-*T* curves

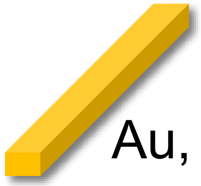
T1 **T2**

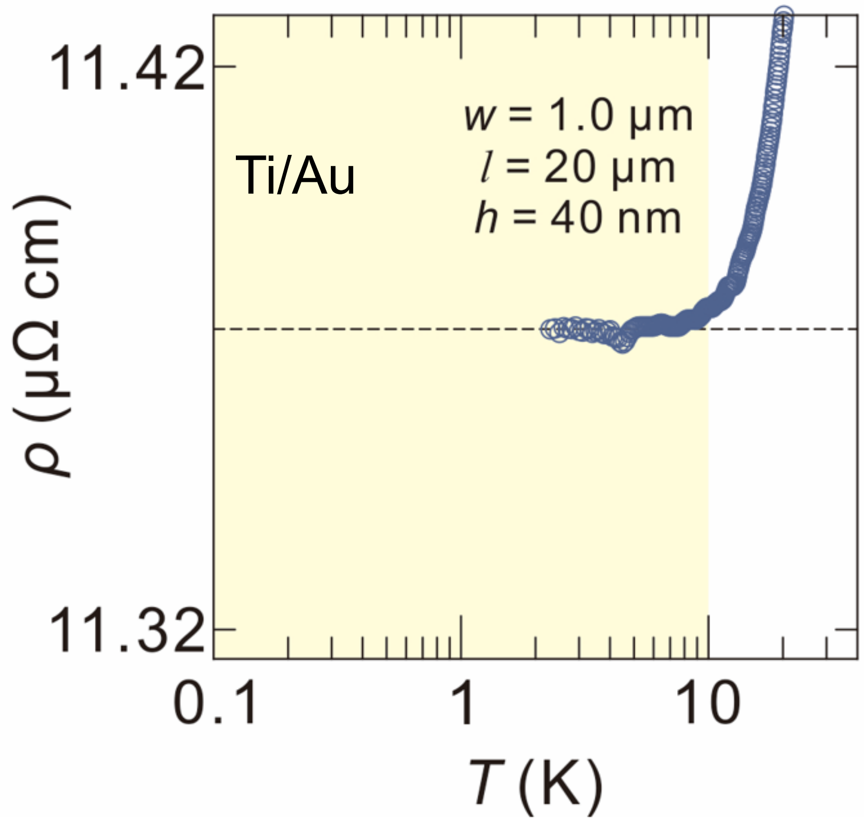




Wu *et al*. Adv. Electron. Mater. **4**, 1800248 (2018)

Limitation of on-chip TE device setup



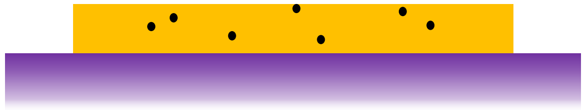


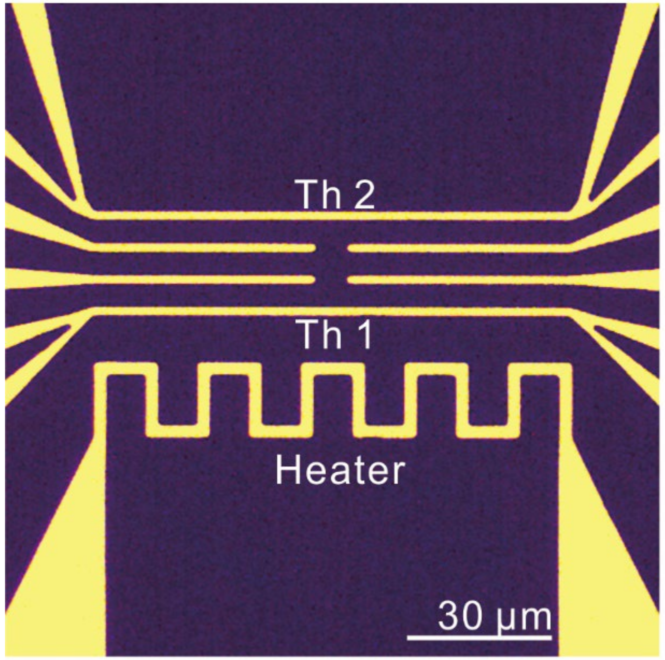
Working range

300 K ~ 10 K	< 10 K
$\frac{\partial R}{\partial T} > 0$	$\frac{\partial R}{\partial T} = 0$
	saturated *R* independent of *T*

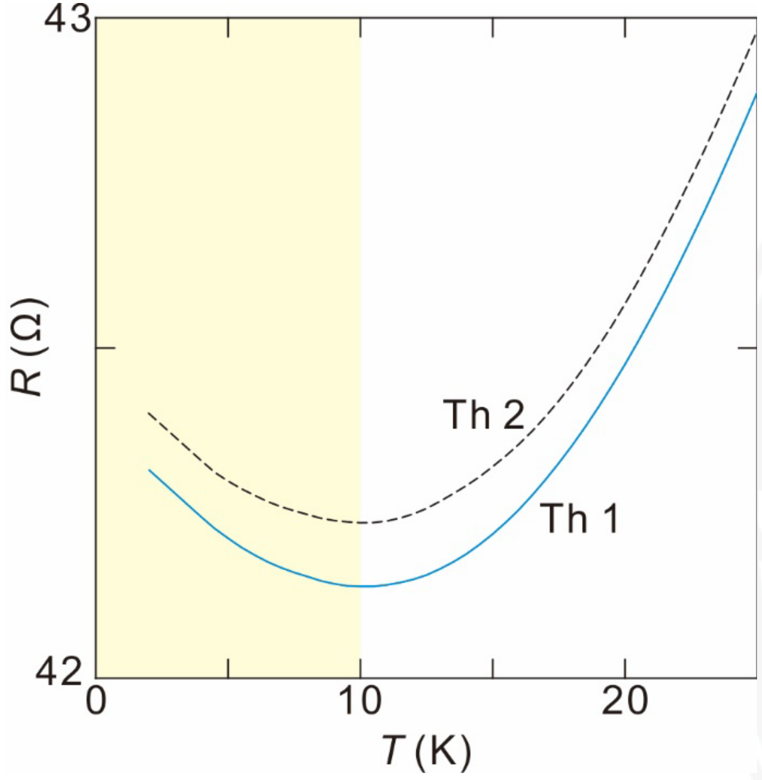
Kondo-effect-assisted TE device setup

Au (Fe) films



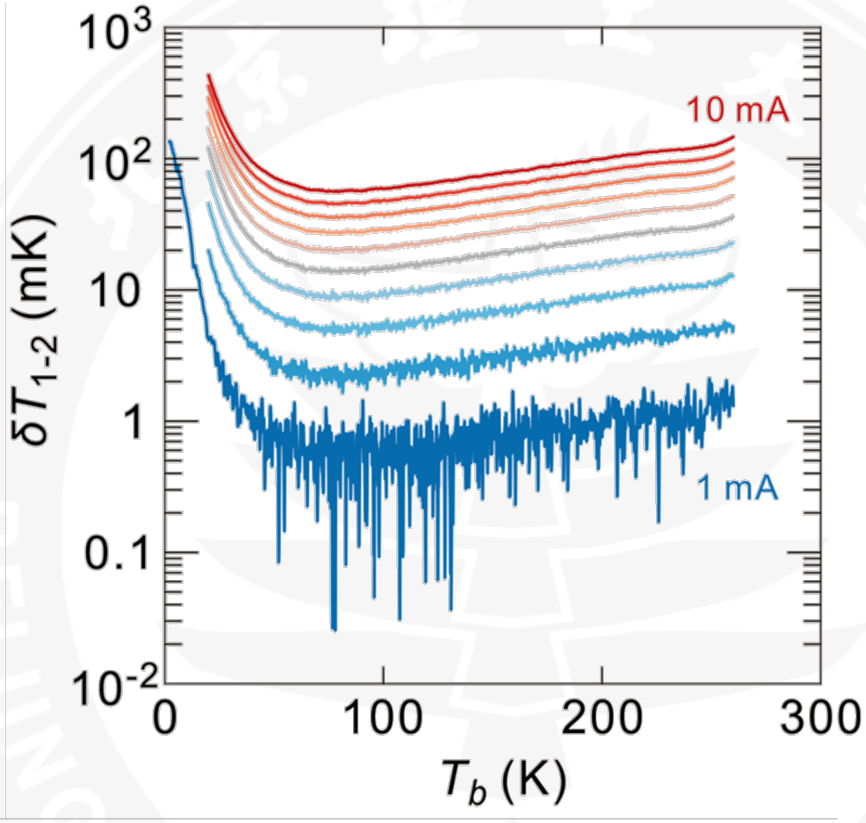


Kondo effect
induced by
magnetic impurities



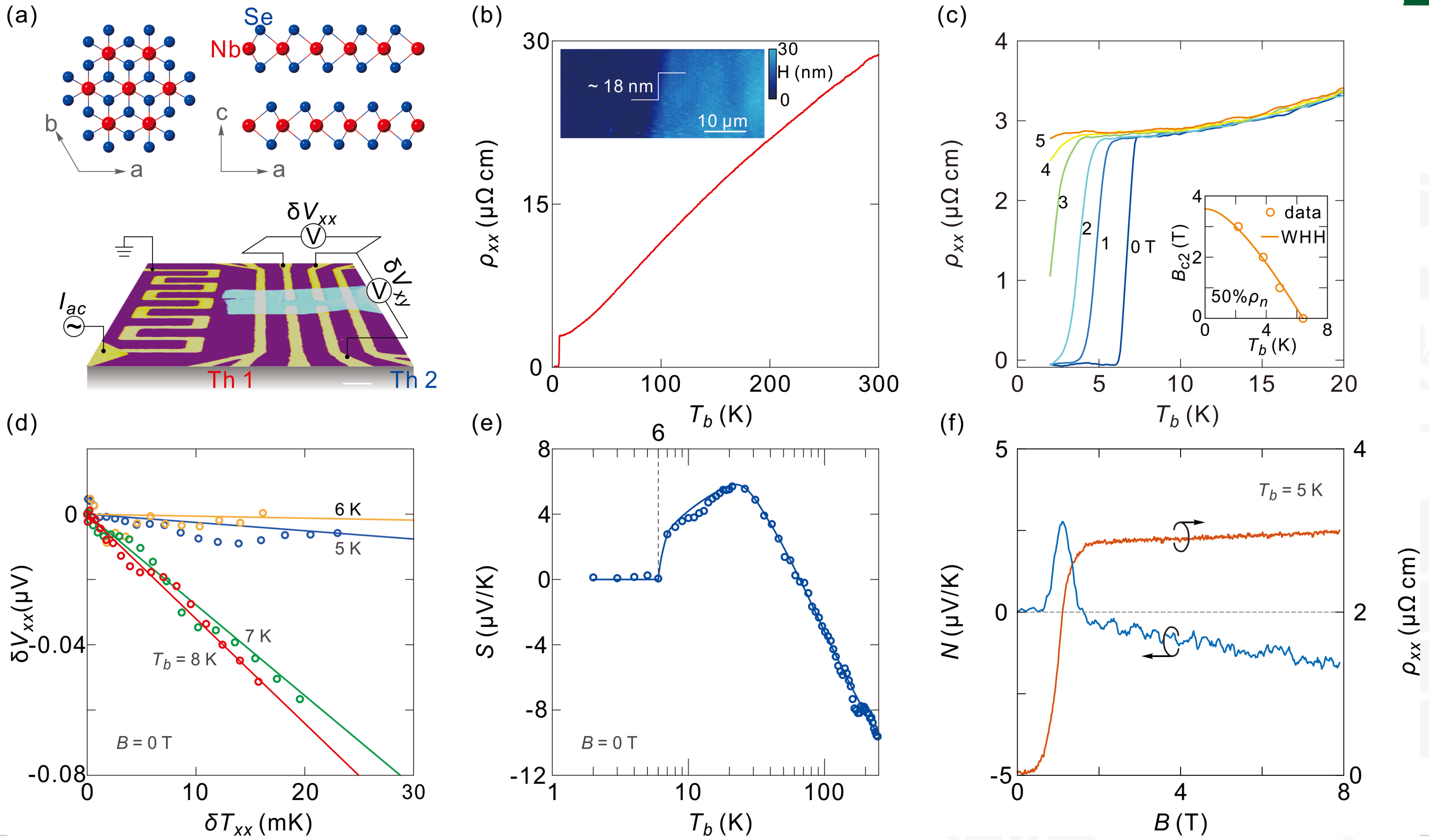
Working range

300 K ~ 1 K



Qiao, Zhang. Appl. Phys. Lett. **120**, 173507 (2022)

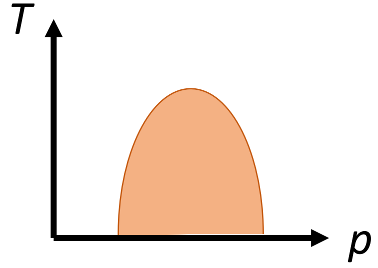
TE detection in $NbSe_2$ thin flakes



Qiao, Zhang. Appl. Phys. Lett. **120**, 173507 (2022)

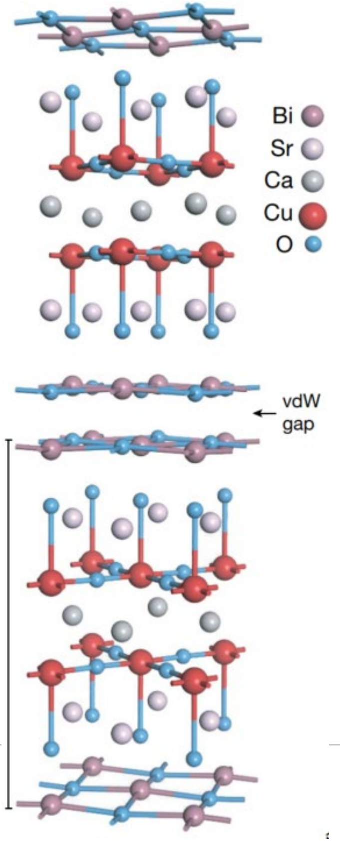
Bi-2212 in the 2D limit

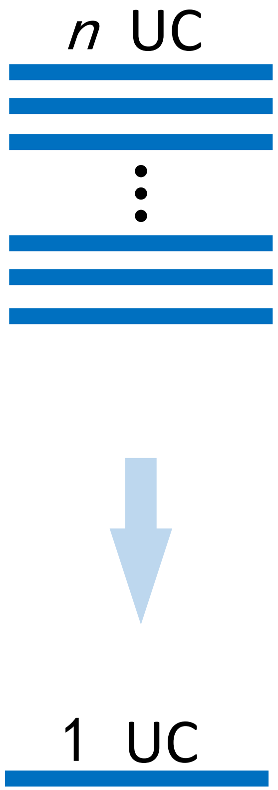
$T_c = 91 \cdot [1 - 82.6(p - 0.16)^2]$



Bilayer
(1 UC)

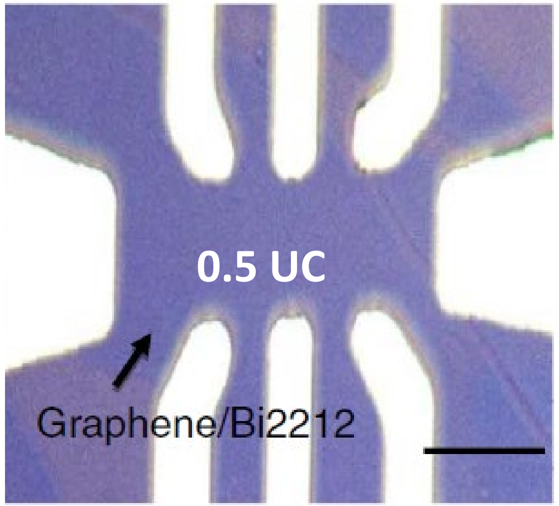
Monolayer
(0.5 UC)



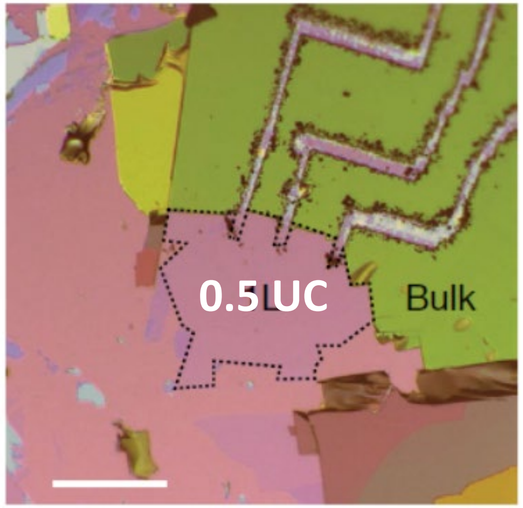


Challenges for fabricating ultrathin Bi-2212:

- Degradation under air exposure
- Oxygen loss at room temperature



Covered by graphene



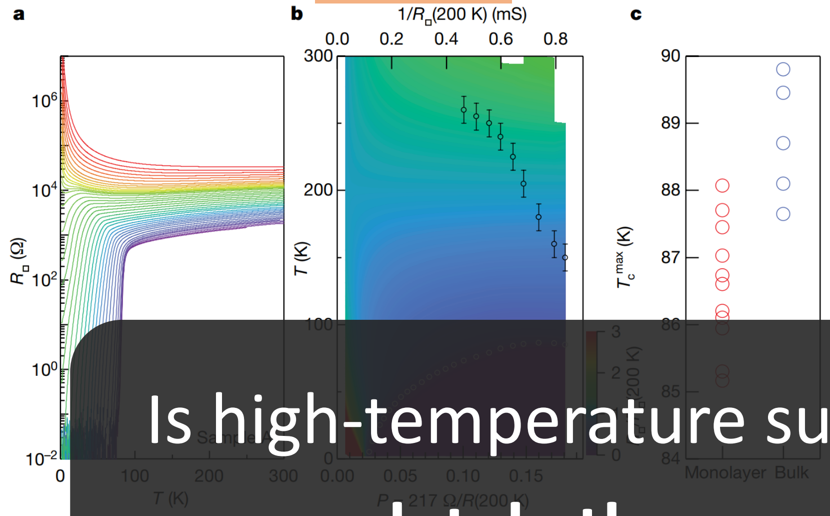
Fabricated at - 40° C

Jiang, D., *et al.*
Nat. Commun. **5**, 5708 (2014)

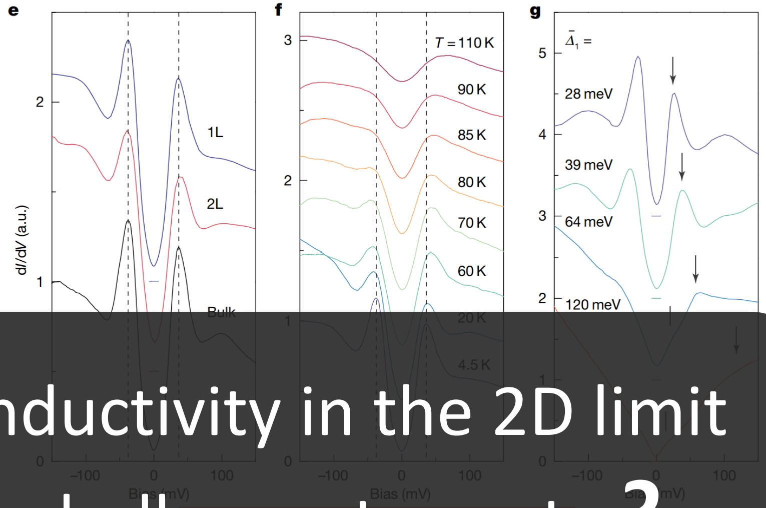
Yu, Y. *et al.*
Nature **575**, 156–163 (2019)

Bi-2212: bulk v.s. monolayer

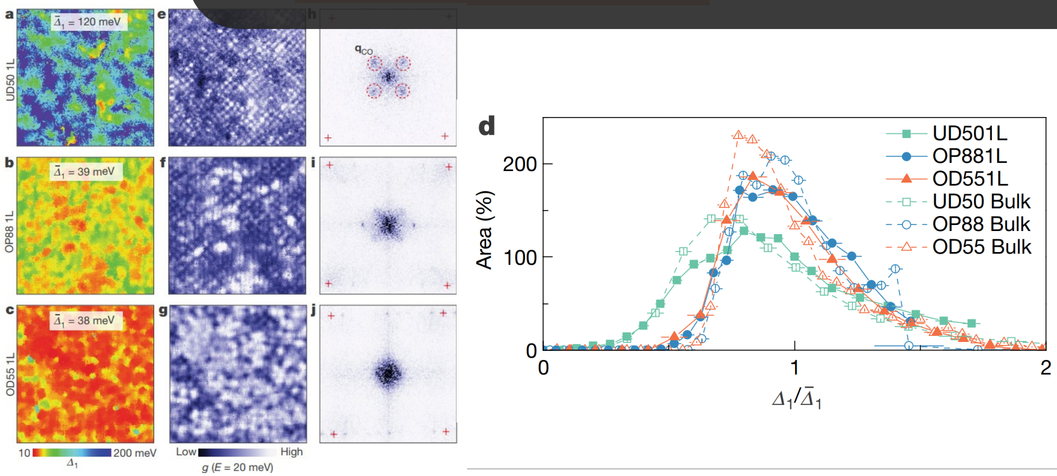
Same T_c



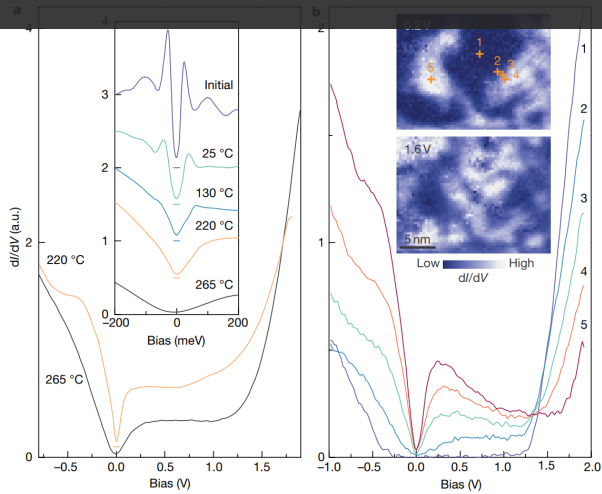
Same pseudogap



Same charge order



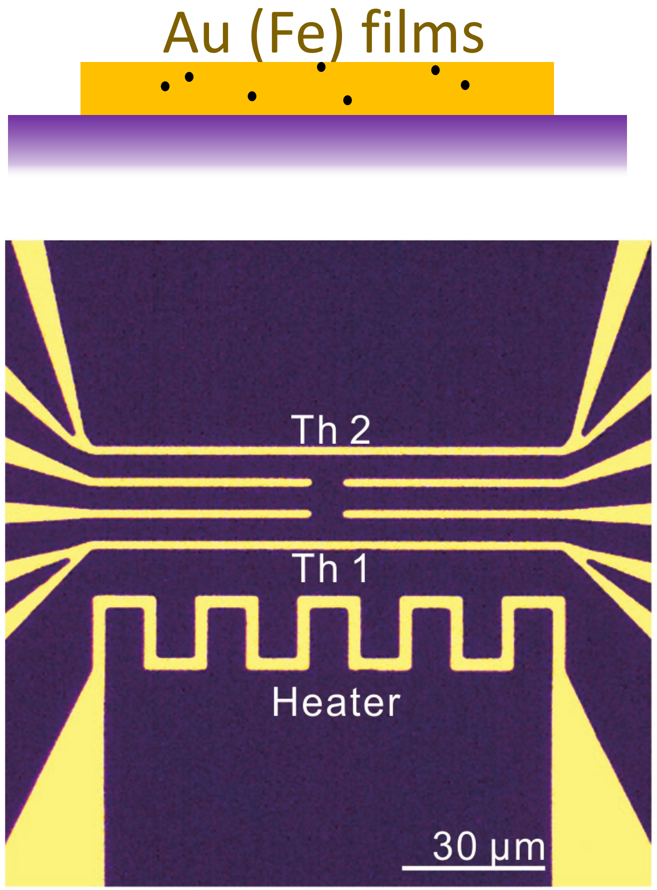
Same Mott phase

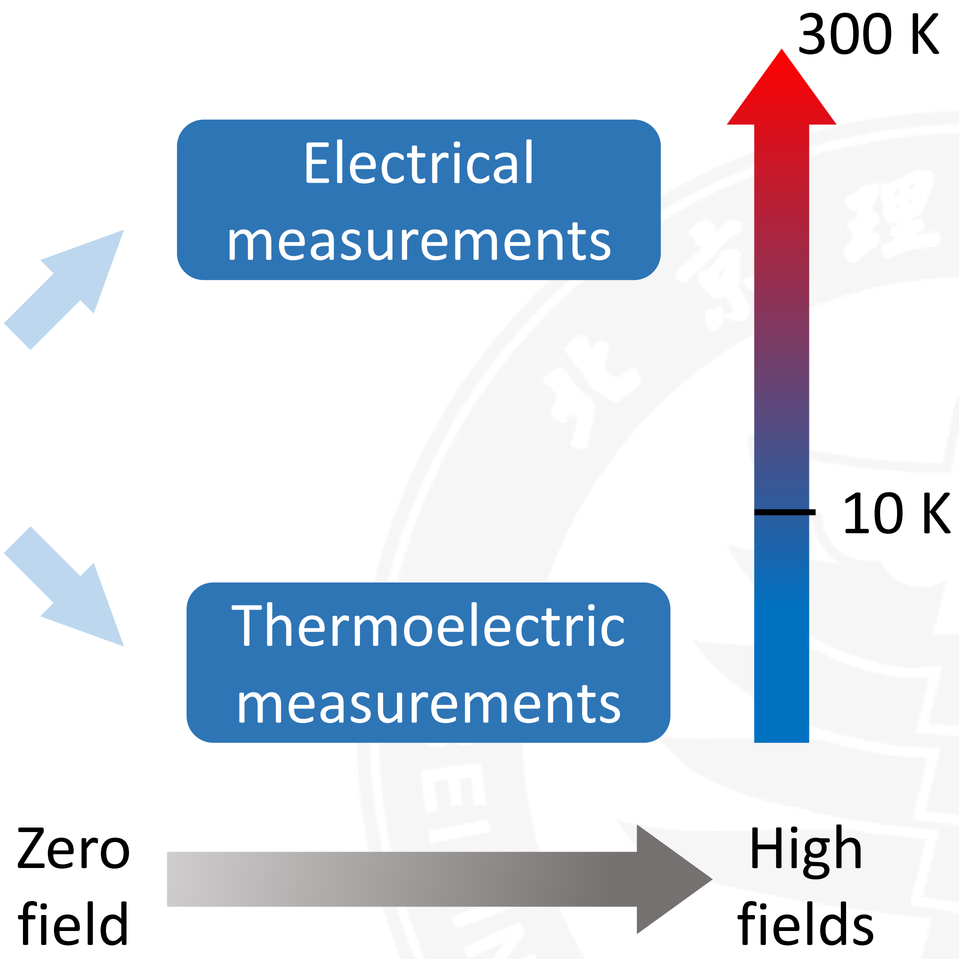


Is high-temperature superconductivity in the 2D limit **completely the same as the bulk counterparts ?**

Yu, Y. *et al*. Nature **575**, 156–163 (2019)

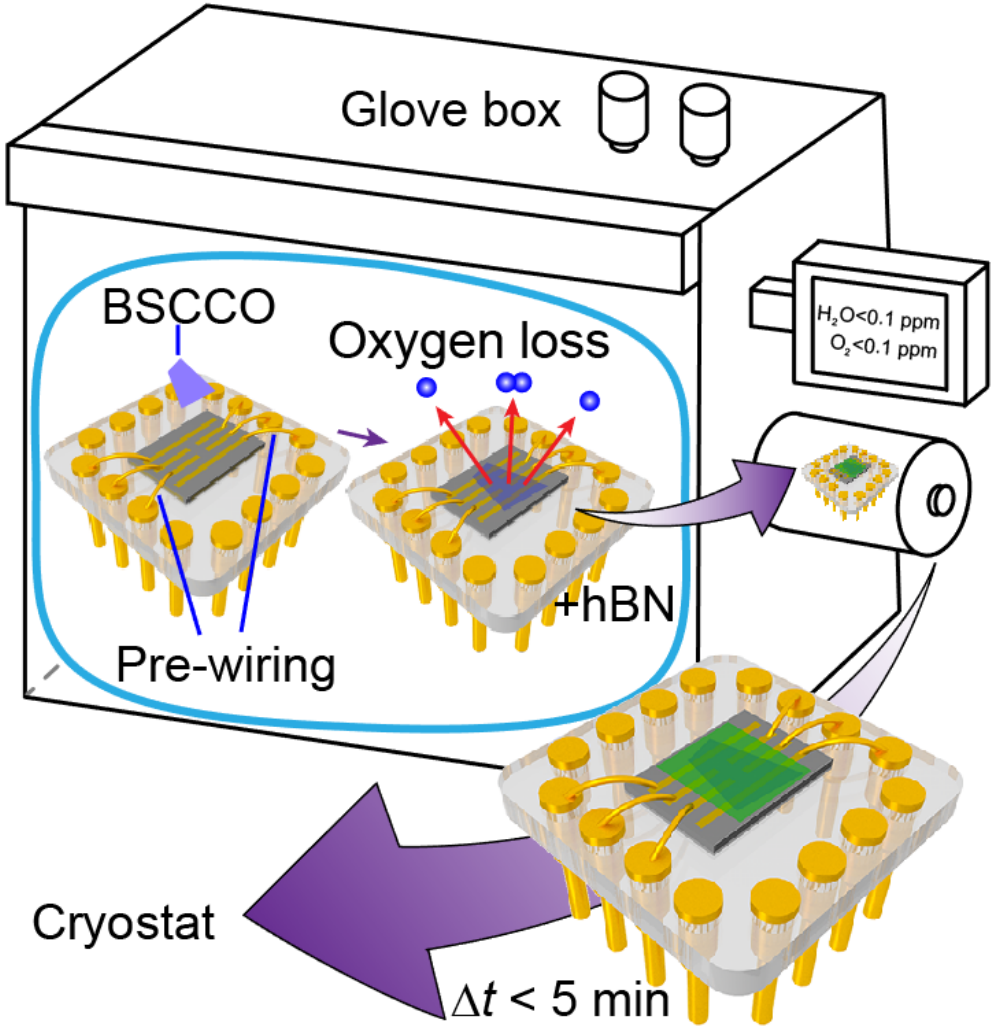
Magneto- and TE transport in ultrathin Bi-2212





Qiao, Zhang. Appl. Phys. Lett. **120**, 173507 (2022)

Preparation of ultrathin Bi-2212 TE device



Exfoliate ultrathin (1.5-2 UC) Bi-2212 onto the PDMS

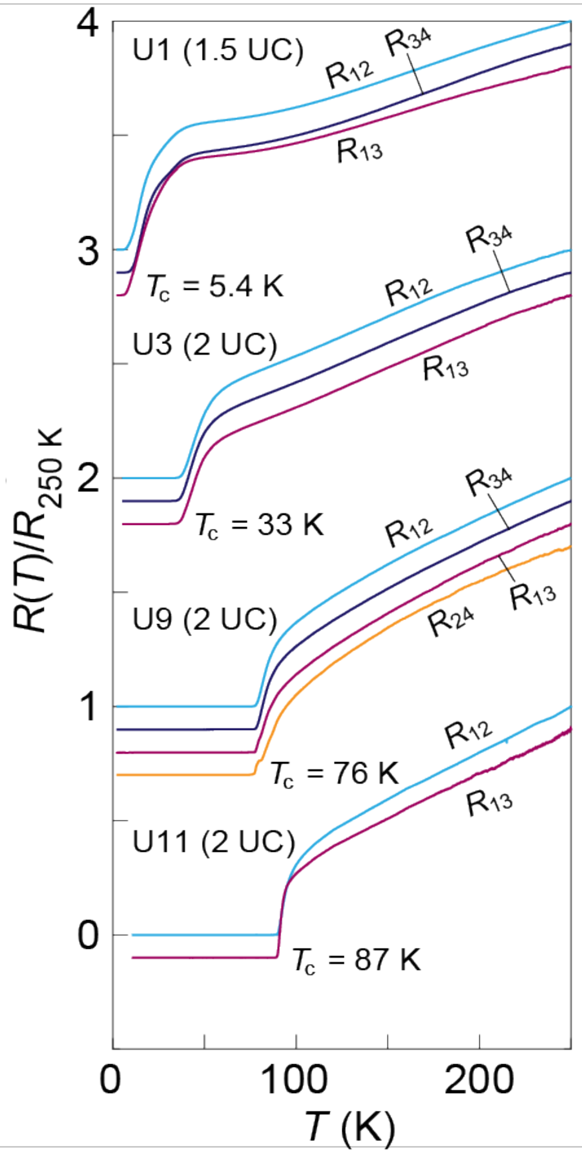
Transfer the ultrathin flake onto the substrate with pre-patterned electrodes

Time control for oxygen out-diffusion

Cap hBN

Hu, Qiao*, Zhang* *et al*. submitted

Preparation of ultrathin Bi-2212 TE device



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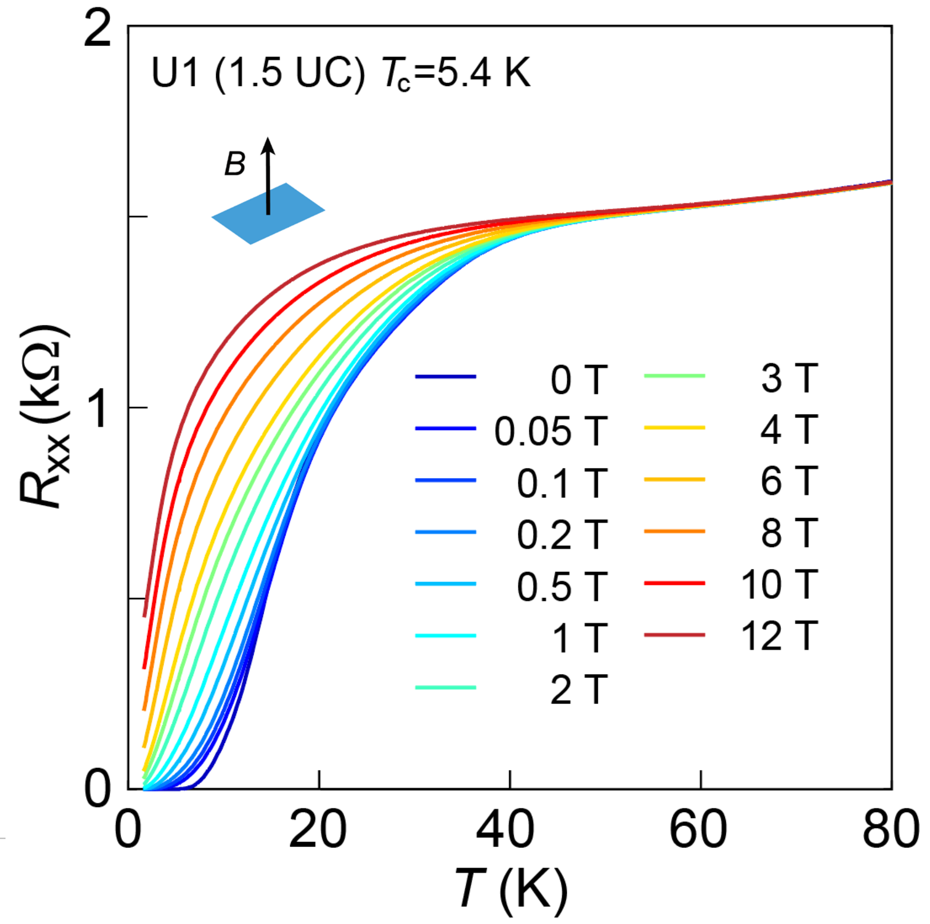
Cap hBN

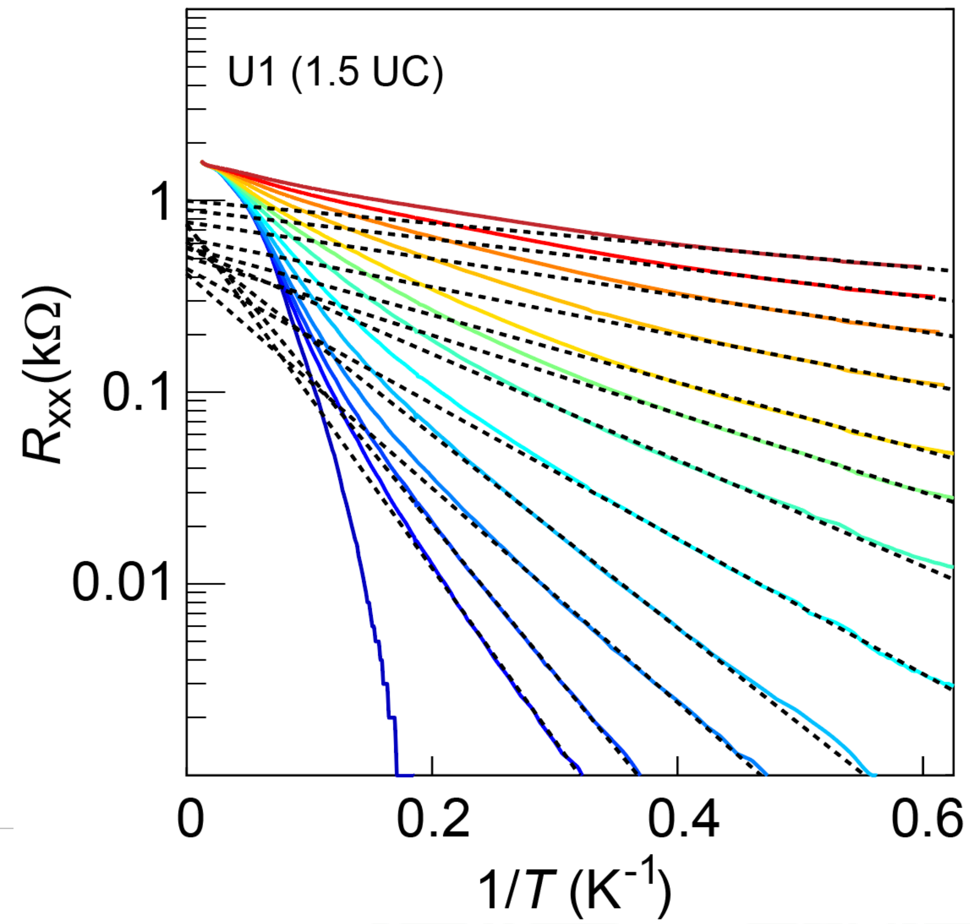
Hu, Qiao*, Zhang* *et al*. submitted

Thermally activated transport in Bi-2212

The resistance at low *T* has a thermally activated behavior:

$$R(B,T) = R_0(B)e^{-\frac{U(B)}{k_B T}}$$

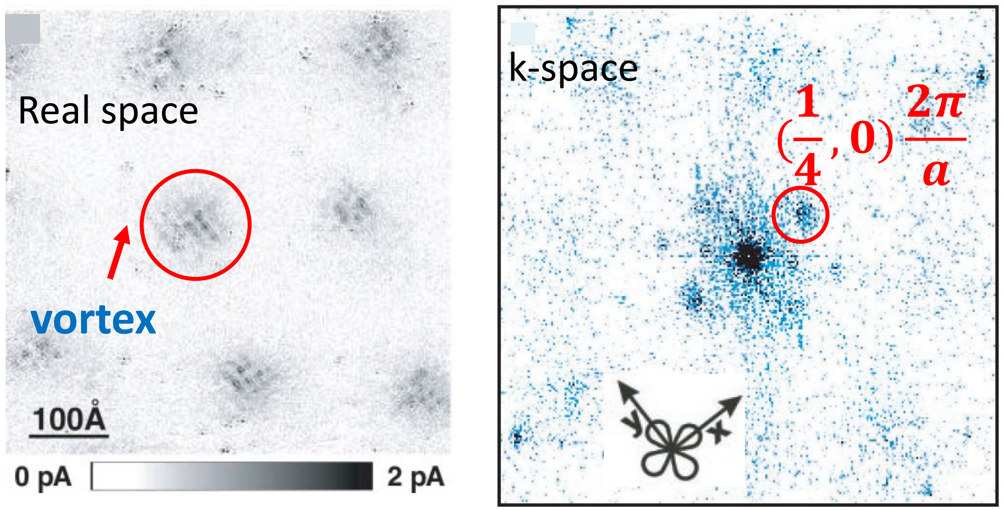




Possible origin: ordering states in the underdoped regime

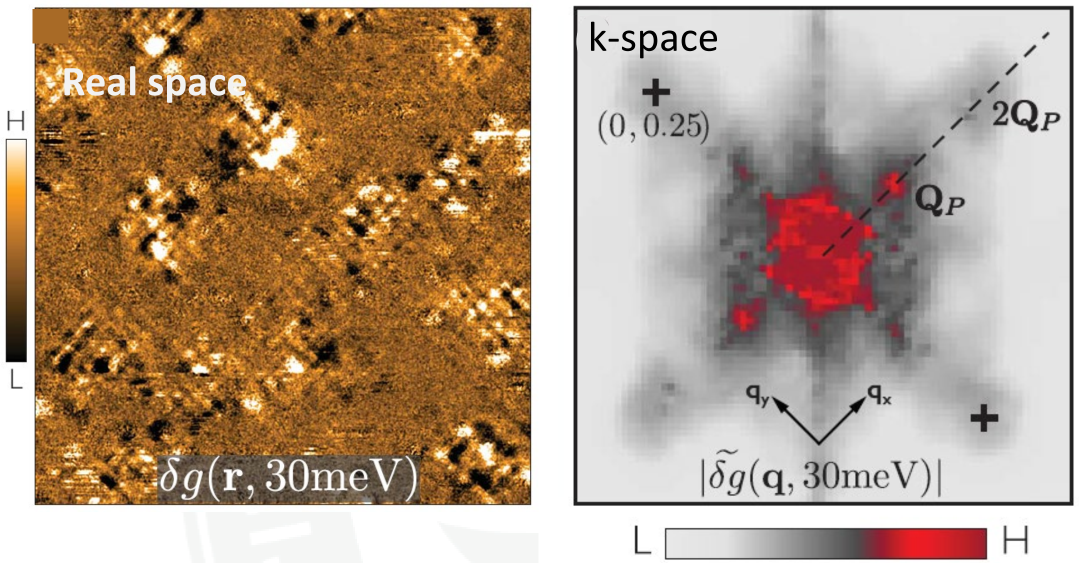
The reduced entropy may be related to ordering states inside the vortices

Checkerboard order around vortex cores



Hoffman, J. E., *et al*. Science **295**, 466-469 (2002)

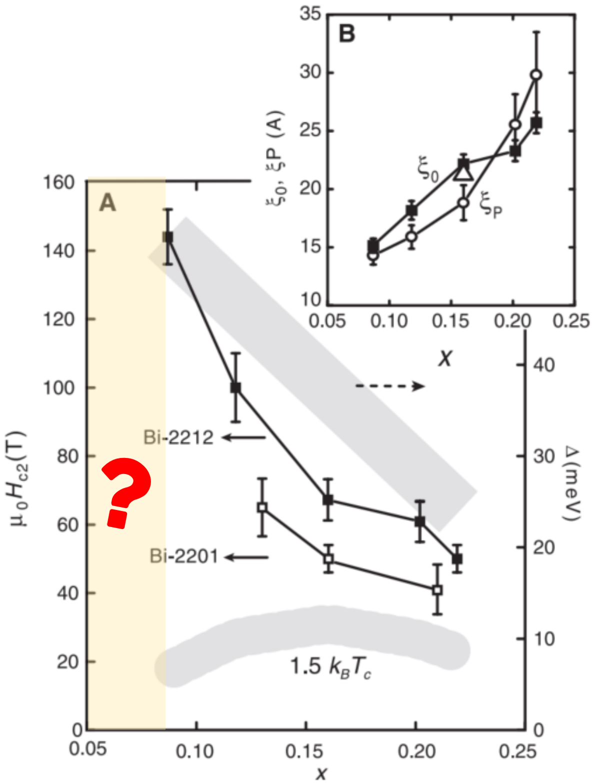
Pair density wave order around vortex cores

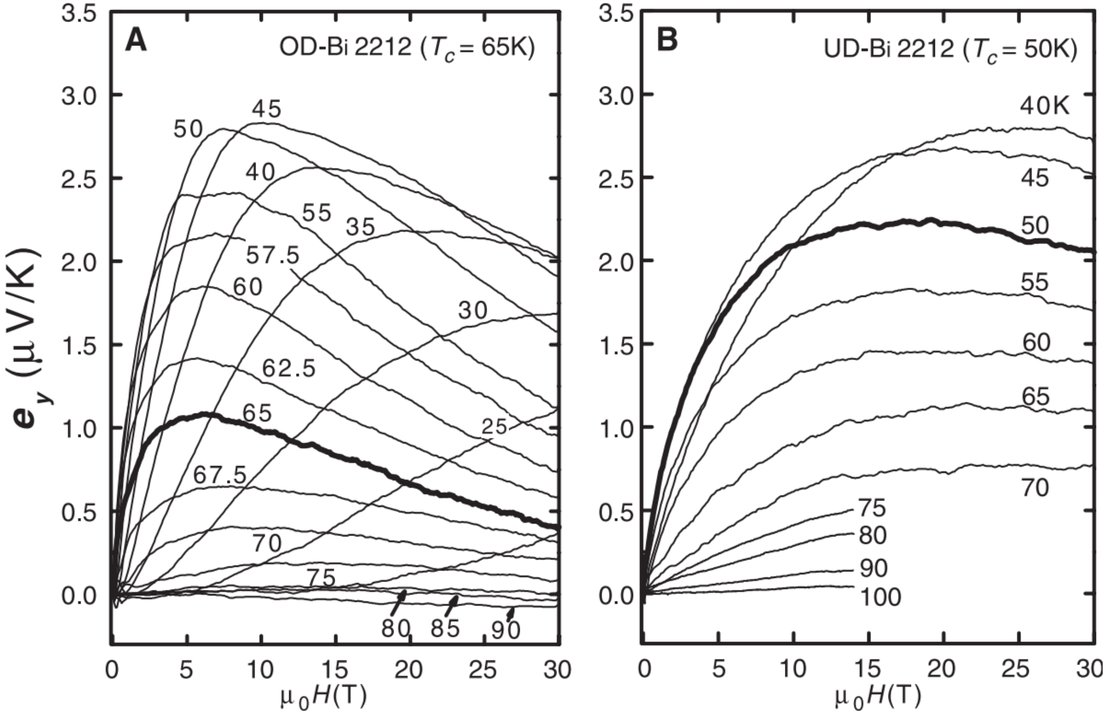


Edkins, S. D., *et al*. Science **364**, 976-980 (2019)

Outlook

- It is unclear how H_{c2} varies with p in Bi-2212
- Determination of $H_{c2}(p)$ in ultrathin Bi-2212 via Nernst measurements
  - $H_{c2}(p)$ in the extremely UD regime (p < 0.1)
  - $H_{c2}(p)$ under a higher magnetic field ($B > 30$ T)





Wang, Y. *et al*. Science **299**, 5603 (2003)

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Thanks for your attention
Any comments are welcome