Supplementary Material: Anomalous metallic state driven by magnetic field at the $LaAlO_3/KTaO_3$ (111) interface

Zi-Tao Zhang(张子涛), Yu-Jie Qiao(乔宇杰), Ting-Na Shao(邵婷娜), Qiang Zhao(赵强), Xing-Yu Chen(陈星宇), Mei-Hui Chen(陈美慧), Fang-Hui Zhu(朱芳慧), Rui-Fen Dou(窦瑞芬), Hai-Wen Liu(刘海文), Chang-Min Xiong(熊昌民)†, and Jia-Cai Nie(聂家财)†

Department of Physics, Beijing Normal University, Beijing 100875, People's Republic of China

†To whom correspondence should be addressed. E-mail: cmxiong@bnu.edu.cn; jcnie@bnu.edu.cn.

DEFINITION OF H_A AND H_{c0}

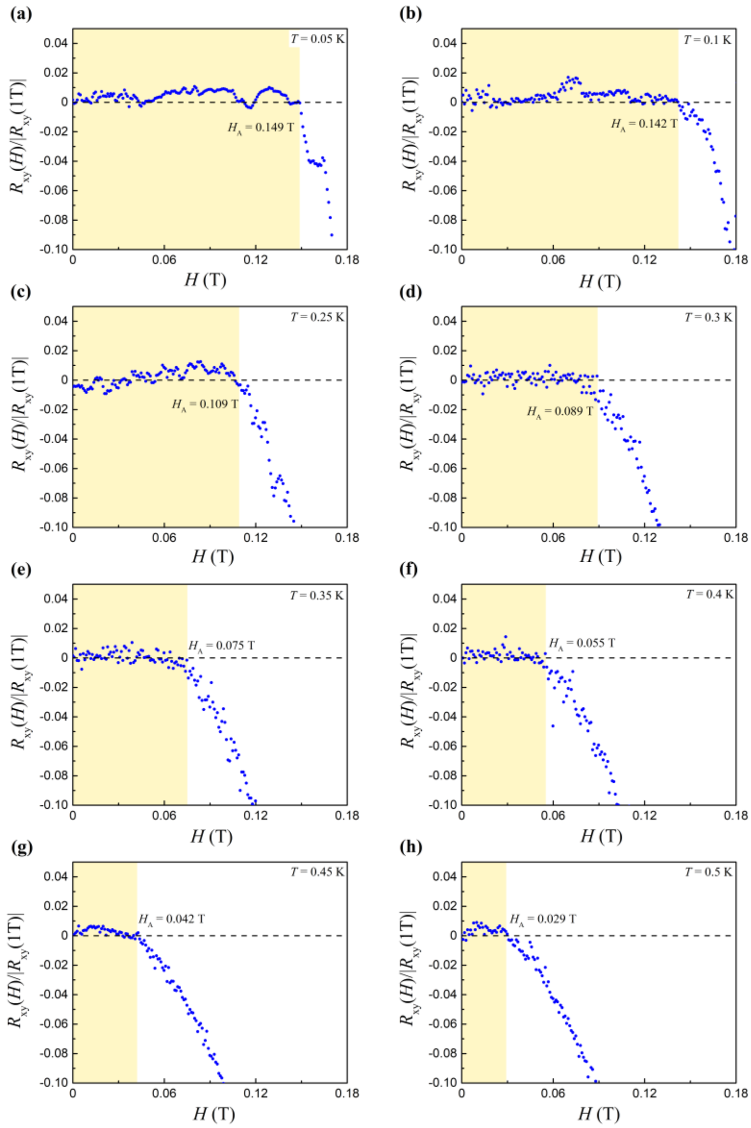

Fig. S1. Normalized transverse resistance as a function of magnetic field at different temperatures from (a) 0.05 K to (h) 0.5 K.

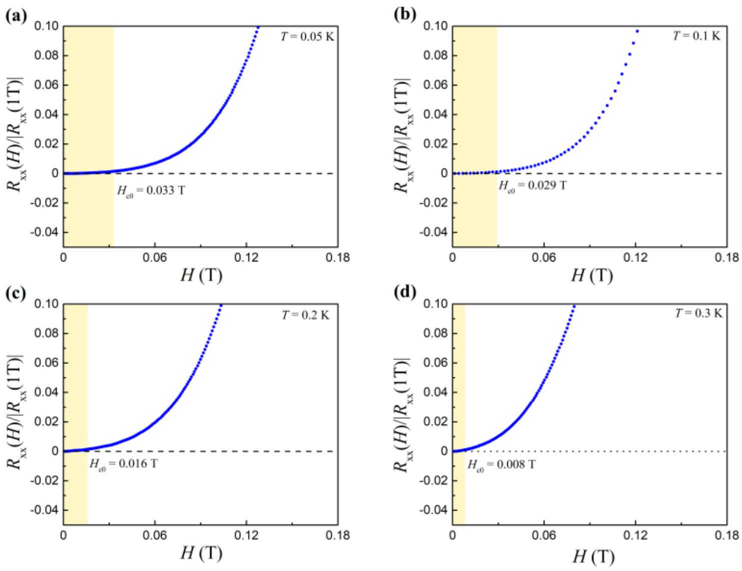

Fig. S2. Normalized longitudinal resistance as a function of magnetic field at different temperatures from (a) 0.05 K to (d) 0.3 K.

ANOMALOUS METALLIC STATE IN SAMPLE #2

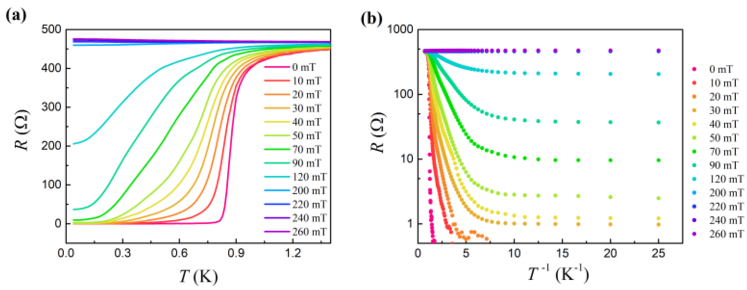

Fig. S3. Temperature dependence of resistance for Sample #2. (a) Resistance versus temperature at different perpendicular magnetic field. (b) Arrhenius plot of resistance for several magnetic fields shows saturation at low temperature, indicating the emergence of an anomalous metallic state. Different samples show the repeatability of the results.

THE MODEL OF QUANTUM TUNNELING OF VORTICES

An alternative explanation of the anomalous metal state is the theoretical model of quantum tunneling of vortices (quantum creep) [1-3]. In this theory, anomalous metallic state is caused by vortex tunneling through narrow superconducting channels. In the framework of this theory, the resistance obeys a general form in the limit of the strong dissipation [1,3,4]:

$$R \sim \frac{h}{4e^2}\frac{\kappa}{1-\kappa} \ ,$$

$$\kappa \sim \exp\left[C\frac{\hbar}{e^2}\frac{1}{R_{\mathrm{N}}}\left(\frac{H-H_{c2}}{H}\right)\right], \tag{S1}$$

where C is a dimensionless constant of order unity, and H_{c2} is the perpendicular upper critical field. As shown in Figure S4, $R(H)$ curves around the magnetic field of 0.1 T at low temperatures (below 200 mK) is well fitted by Eq. S1, indicating that the quantum creep plays a key role in this regime as a possible origin of the anomalous metallic state. The anomalous metallic state in our sample is thus exhibiting a crossover at $H \sim 0.1$ T between the models of Bose metal and quantum creep described by Eq. 3 (in the main text) and Eq. S1. Such crossover has been predicted by Das and Doniach [5].

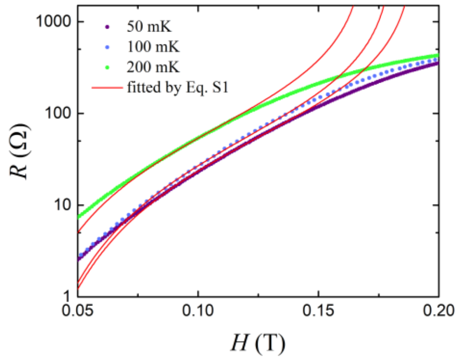

Fig. S4. The R (H) curves of $LaAlO_3/KTaO_3$ (111) at 50, 100, and 200 mK, which can be well fitted (the red solid lines) by Eq. S1 around the magnetic field of 0.1 T.

REFERENCES

[1] Y. Saito, Y. Kasahara, J. Ye, Y. Iwasa, and T. Nojima, Science **350**, 409 (2015).

[2] Y. Li *et al.*, arXiv:2111.15488 (2021).

[3] E. Shimshoni, A. Auerbach, and A. Kapitulnik, Physical Review Letters **80**, 3352 (1998).

[4] Y. Liu *et al.*, Nano Lett **20**, 5728 (2020).

[5] D. Das and S. Doniach, Physical Review B **64**, 134511 (2001).