Signatures of a Pair Density Wave at High Magnetic Fields in Stripe-Ordered Cuprates

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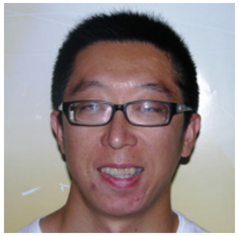
Collaborators



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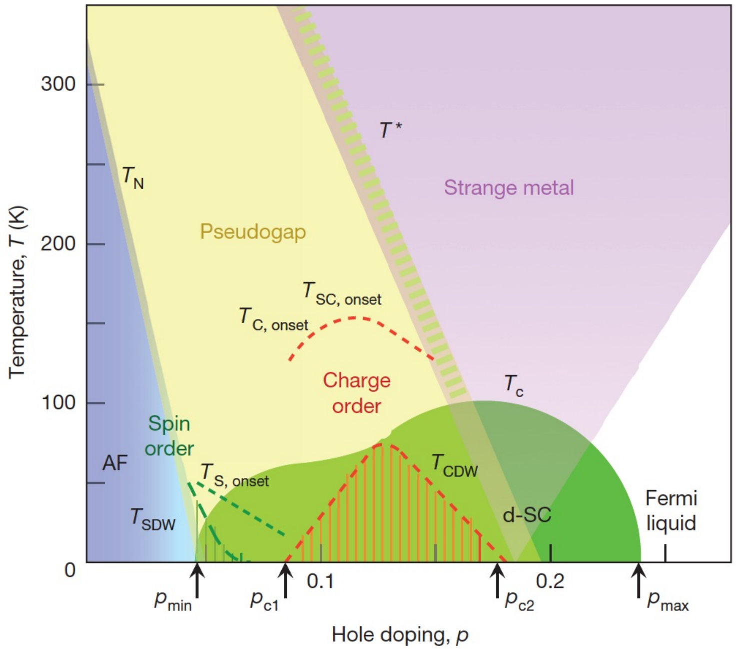
LSCO, LESCO, LNSCO crystals

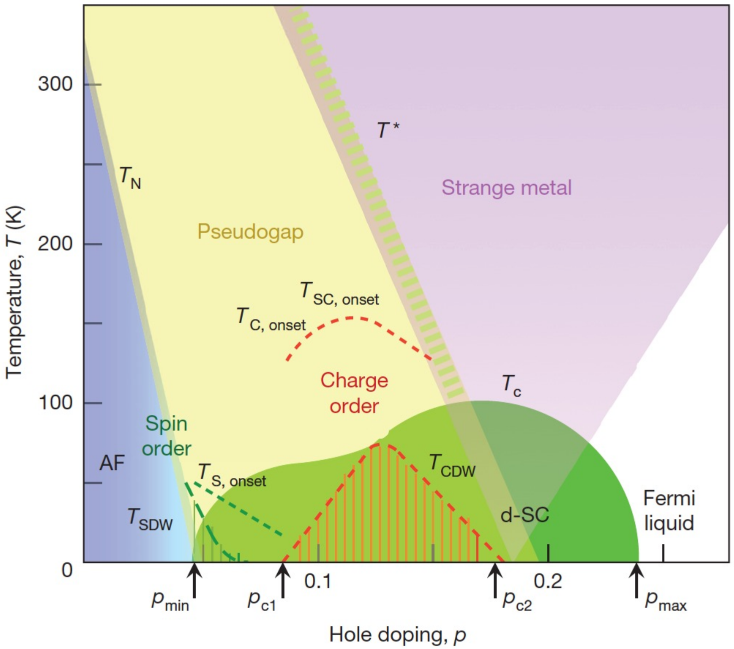
Copper-oxide high-temperature superconductors: Questions that we address



[Keimer *et al*., Nature 518, 179 (2015)]

- Nature of the ground state (if superconductivity is removed)?
- Interplay of charge and spin orders with cuprate superconductivity?
- Origin of the pseudogap regime?
- Role of the **pair-density wave (PDW) superconductivity** in cuprate physics?

Copper-oxide high-temperature superconductors



[Keimer *et al*., Nature 518, 179 (2015)]

- Pseudogap, charge and spin orders, superconductivity…
  ⇒ **Pair density wave (PDW):** superconducting (SC) order parameter is oscillatory in space; spatial average = zero

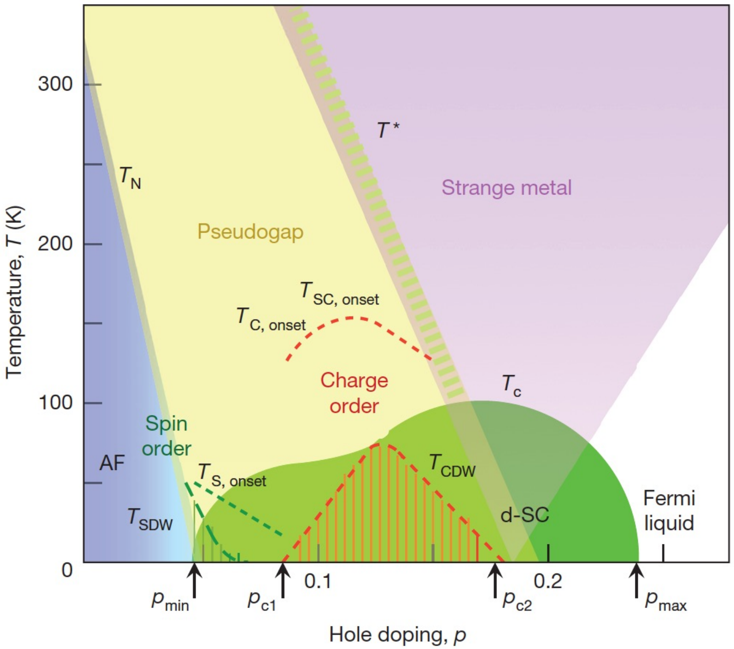
  Review on PDW in cuprates and beyond:

  D. Agterberg *et al., Annu. Rev. Condens. Matter Phys.* **11**, 231 (2020)

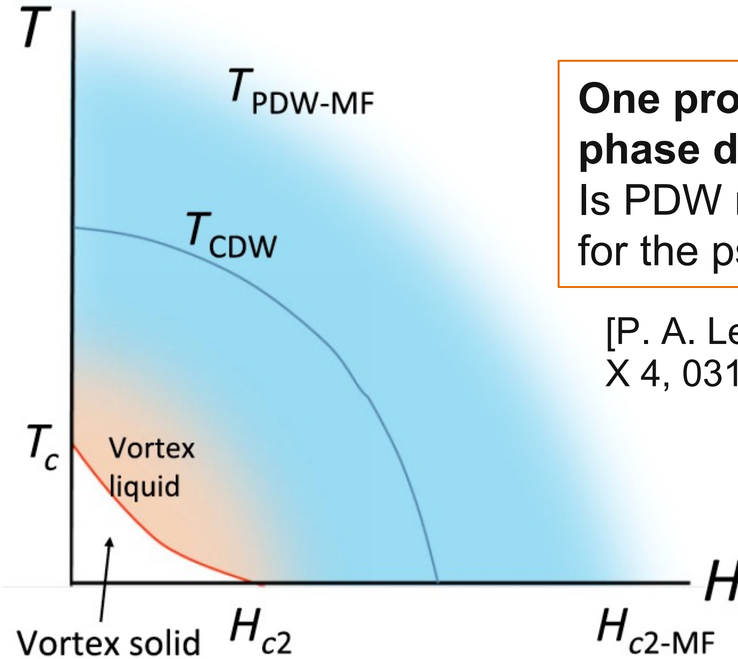
- **Evidence** for PDW has been largely **indirect**

- **Broader relevance** of a PDW state to cuprate physics is an open question

Role of PDW in the physics of copper-oxide high-temperature superconductors?



[Keimer *et al*., Nature 518, 179 (2015)]



One proposed phase diagram:
Is PDW responsible for the pseudogap?

[P. A. Lee, Phys. Rev. X 4, 031017 (2014)]

- **Needed:** transport signatures of the PDW in the regime where superconductivity is destroyed by quantum phase fluctuations ($T \rightarrow 0$, high H)
- Study La-214 family: charge orders with strongest correlations, in the form of charge and spin stripes

Outline

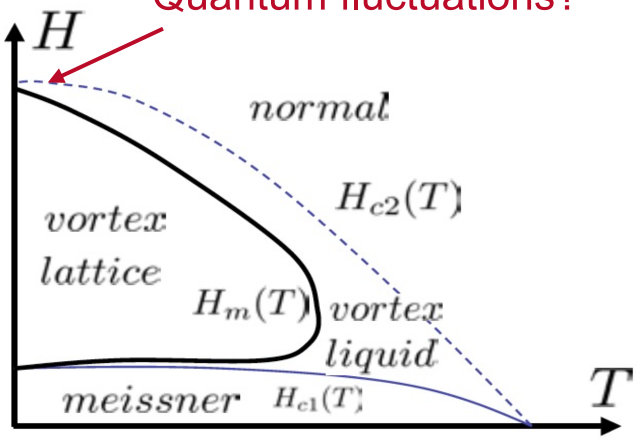
- At what field does the superconductivity vanish?
  What is the value of the upper critical field H_{c2}?
  Vortex phase diagram

- Behavior for $H < H_{c2}$ in stripe-ordered cuprates:
  Evidence of PDW in the regime of SC phase fluctuations
  from $T > T_c^0$ in H=0 to H=H_{c2} as $T \rightarrow 0$

Vortex phase diagram

- At what field does the superconductivity vanish?
  What is the value of the upper critical field H_{c2}?
  Vortex phase diagram

Quantum fluctuations?



[Blatter *et al.*, Rev. Mod. Phys. 66, 1125 (1994)]

- Thermal fluctuations: Melting of the vortex lattice into a vortex liquid
- Vortex lattice suppressed to below the crossover line $H_{c2}(T)$
- **Does the vortex liquid survive as $T \rightarrow 0$?**

T-H phase diagram in underdoped cuprates

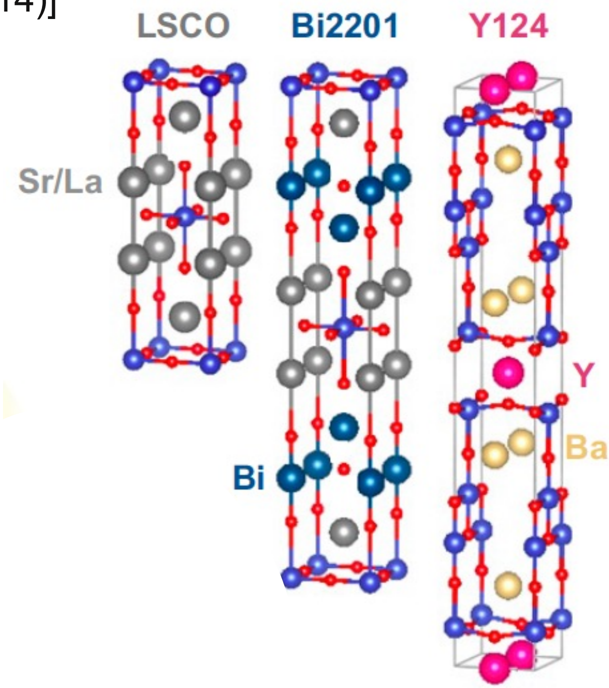
- At what field does the superconductivity vanish? What is the value of H_{c2}?

Vortex phase diagram

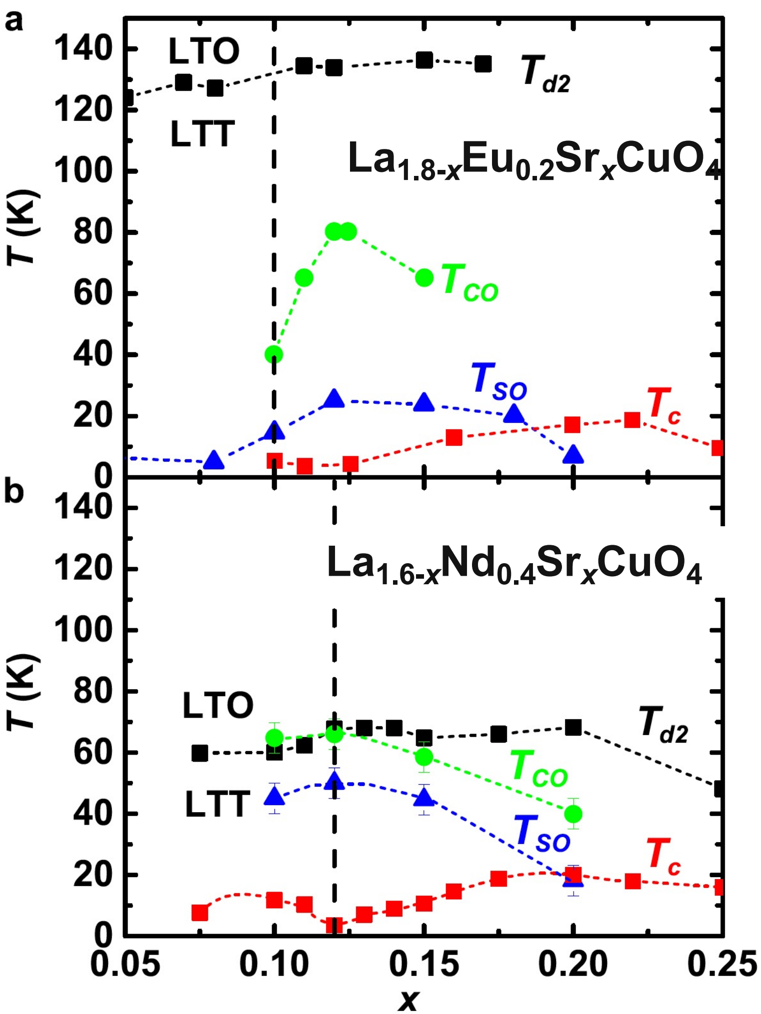
Qualitatively the same regardless of the presence of charge or spin orders

Linear and nonlinear transport:

- **LSCO** (spin order; LTO) [X. Shi *et al.*, Nature Phys. 10, 437 (2014)]
- spin- and charge-striped **Nd-LSCO** (LTT), **Eu-LSCO** (LTT) [Z. Shi *et al.*, Sci. Adv. 6, eaay8946 (2020)] and **$La_{2-x}Ba_xCuO_4$** (LBCO) [Y. Li *et al.*, Sci. Adv. 5, eaav7686 (2019)]
- spin- and charge-striped **Fe-LSCO** (LTO) [B. K. Pokharel *et al.*, unpublished]
- **Bi-2201** (charge order; tetragonal) [J. Terzic *et al.*, unpublished]
- **YBCO** (no spin order, static charge order at high *H*) [Y.-T. Hsu *et al.*, PNAS 118, e2021216118 (2021); Y.-T. Hsu *et al.*, PNAS 118, e2016275118 (2021)]



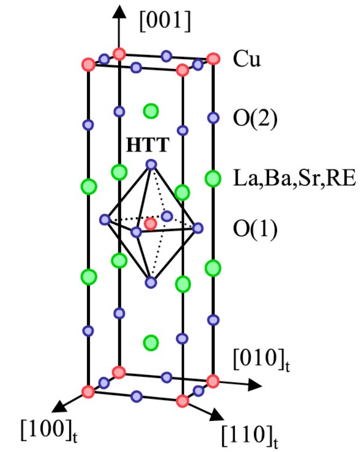
Stripe-ordered Eu-LSCO and Nd-LSCO



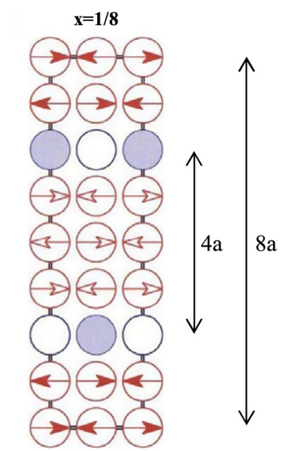
(Data pts from the literature)

- Similar to LBCO

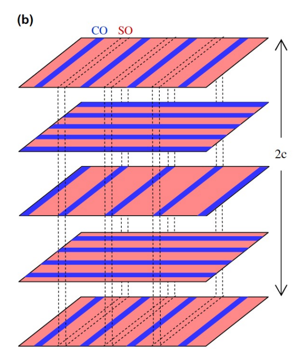
[M. Hücker, Physica C 481, 3 (2012)]



- **Short-range** charge and spin stripes present in H=0; both enhanced when T_c is suppressed by H



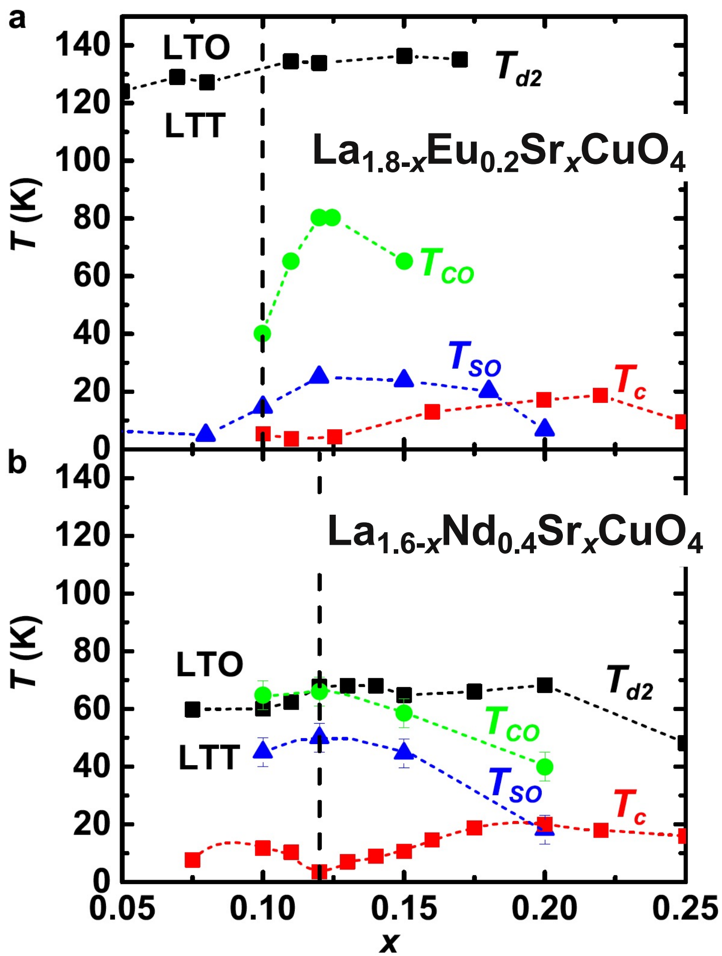
[Tranquada *et al.*, Nature 375, 561 (1995)]



x=1/8

[M. Hücker, Physica C 481, 3 (2012)]

Stripe-ordered Eu-LSCO and Nd-LSCO



(Data pts from the literature)

- $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ and $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$

$La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ (LESCO): x=0.10

T_c^0= (5.7± 0.3) K (where in-plane resistivity ρ_{ab} goes to zero)

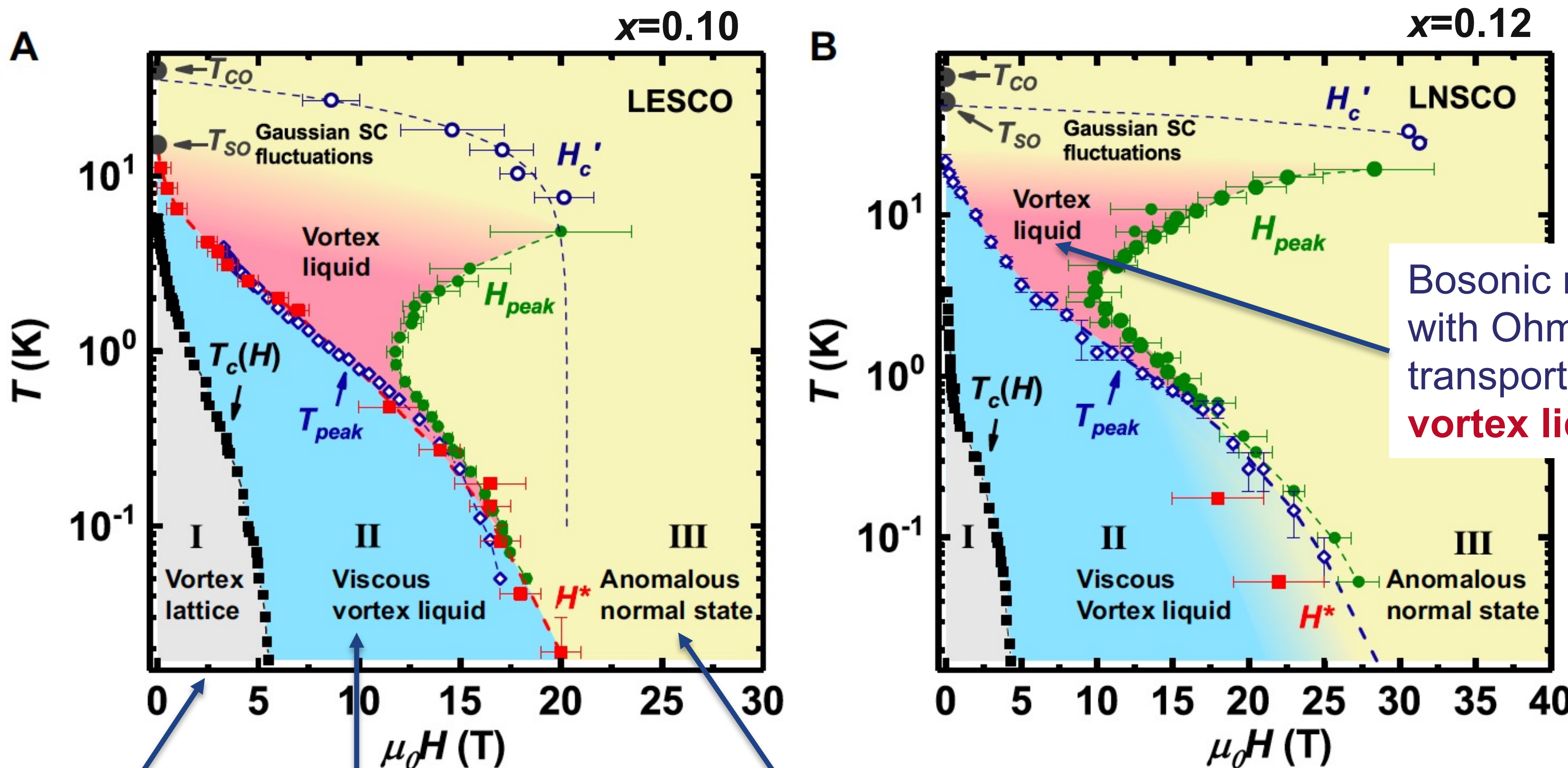
T_{SO} ~ 15 K, T_{CO} ~ 40 K, $T_{pseudogap}$ ~ 175 K

$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ (LNSCO): x=0.12

T_c^0= (3.6± 0.4) K (where in-plane resistivity ρ_{ab} goes to zero)

T_{SO} ~ 50 K, T_{CO} ~ 70 K, $T_{pseudogap}$ ~ 150 K

Vortex phase diagram of stripe-ordered Eu-LSCO and Nd-LSCO



Bosonic regime with Ohmic transport: **vortex liquid**

$T_c(H) > 0$
ρ_{ab} ($T<T_c$) = 0
$I_c \neq 0$

$T_g=T_c=0$
ρ_{ab} ($T>0$) ≠ 0
I_c = 0, non-Ohmic
(for $I_{dc} \neq 0$)

No SC
ρ_{ab} ($T>0$) ≠ 0
Ohmic

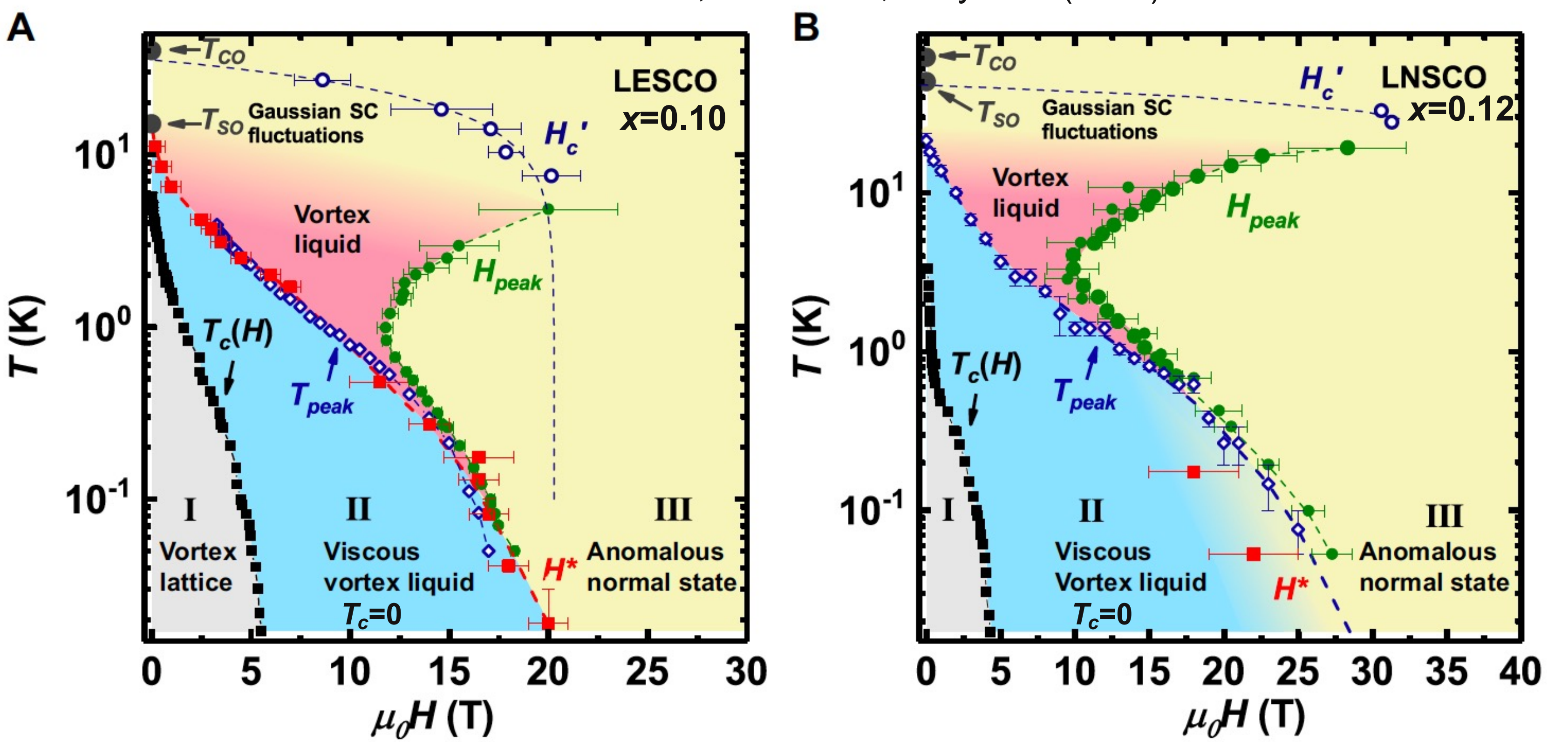
$H_c'(T \rightarrow 0) \approx H^*(T \rightarrow 0)$

Upper critical field

(False color)

Vortex phase diagram of stripe-ordered Eu-LSCO and Nd-LSCO

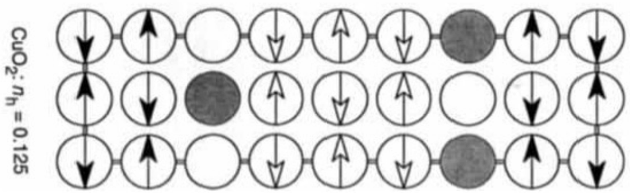
Z. Shi *et al.*, Sci. Adv. 6, eaay8946 (2020)



- **Superconductivity is destroyed by quantum phase fluctuations** ($T \to 0$, high H)
- ***H*=0:** Onset of phase fluctuations at T ~ a few T_c^0

Pair density wave in the presence of stripe order

[J. Tranquada *et al.*, Nature 375, 561 (1995)]

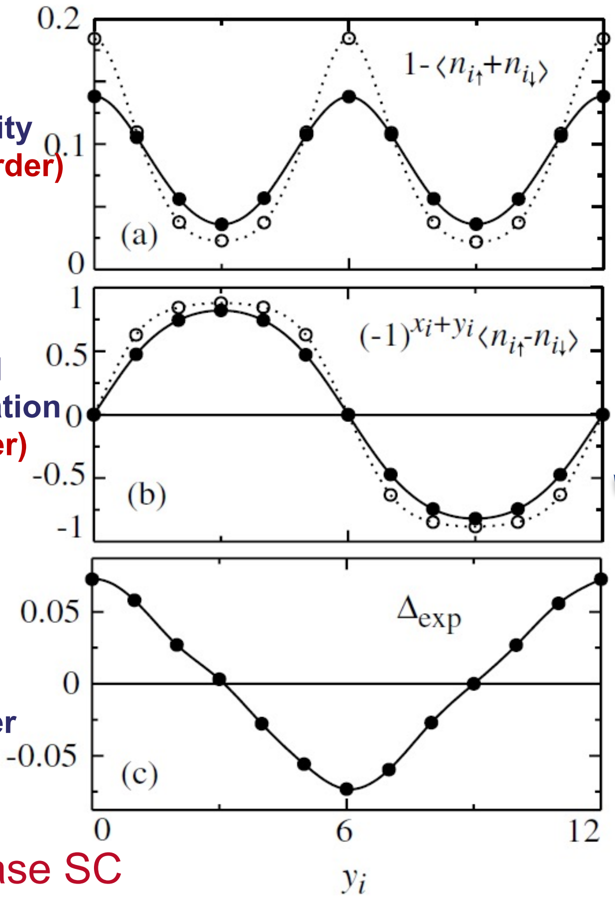


La-214

Hole density
(Charge order)

Staggered magnetization
(Spin order)

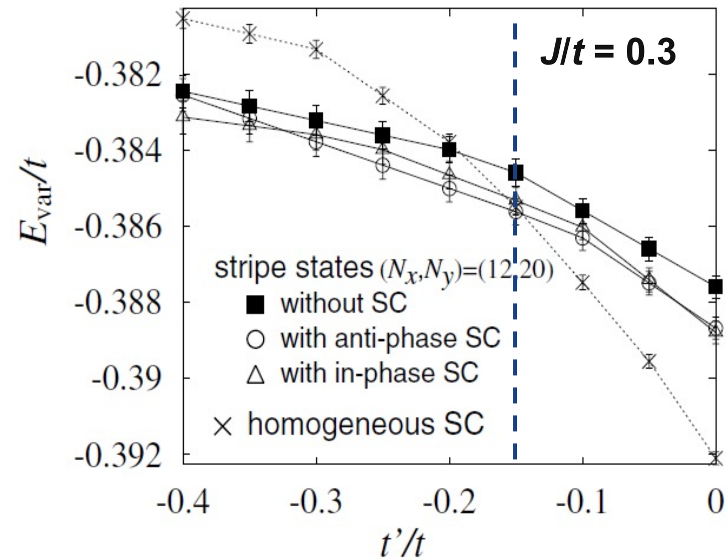
d-wave
SC order
parameter



Antiphase SC

[A. Himeda *et al.*, PRL 88, 117001 (2002)]

Monte Carlo simulation using 2D t-t'-J model

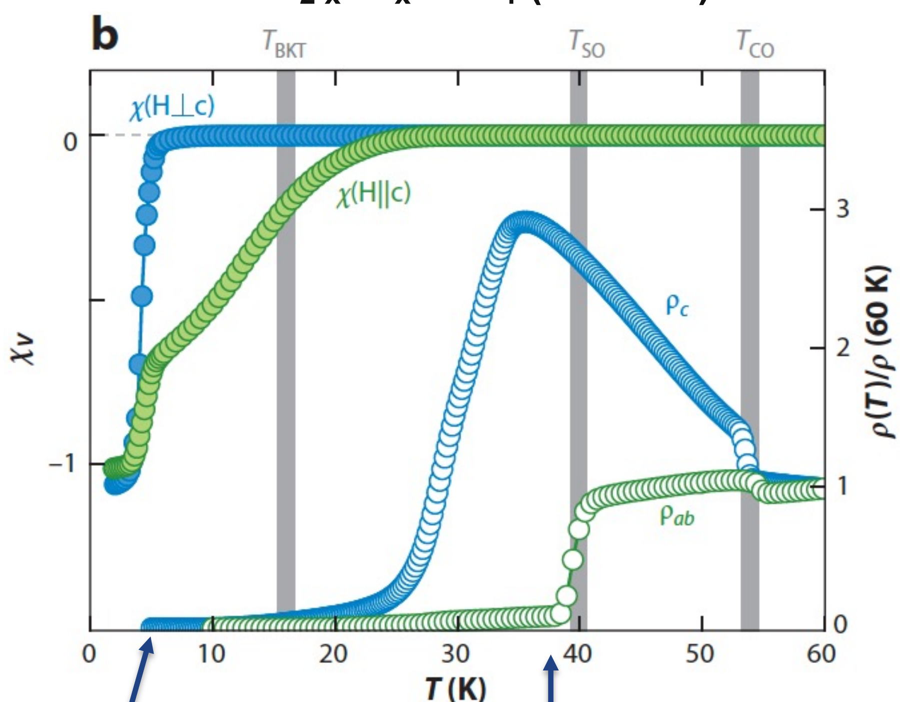


In-phase and antiphase (PDW) SC very close in energy

Effective Josephson coupling between neighboring charge stripes in each plane is **mediated by spin stripes**

Layer decoupling: Pair density wave scenario

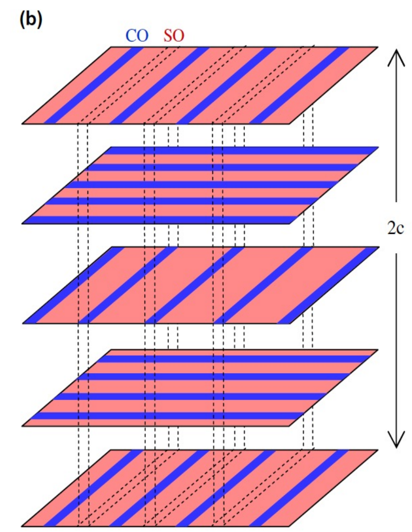
$La_{2-x}Ba_xCuO_4$ (x=0.125)



[Q. Li *et al.*, PRL 99, 067001 (2007); J. M. Tranquada et al., PRB 78, 174529 (2008)]

3D, uniform SC order

Onset of 2D (PDW) SC correlations



x=1/8

[M. Hücker, Physica C 481, 3 (2012)]

Orthogonally-stacked antiphase SC leads to frustration of interlayer Josephson coupling and layer decoupling

[E. Berg *et al.*, PRL 99, 127003 (2007)]

Effect reduced for doping away from *x*=1/8 and with increasing disorder

Experimental evidence consistent with the PDW in cuprates

Dynamical layer **decoupling in *H*=0 for *x*=1/8**:

- **transport in LBCO**:
  Q. Li *et al.*, PRL 99, 067001 (2007)
- **optical measurements in $La_{1.85-y}Nd_ySr_{0.15}CuO_4$**:
  S. Tajima *et al.*, PRL 86, 500 (2001)

Dynamical layer **decoupling by *H*** (stabilizes spin stripes) **for *x* away from 1/8**:

- **transport in underdoped LBCO**:
  Z. Stegen *et al.*, PRB 87, 064509 (2013)
- **optical measurements in underdoped LSCO**:
  A. A. Schafgans *et al.*, PRL 104, 157002 (2010)

- **$Bi_2Sr_2CaCu_2O_8$: STM, *H*=0**

  [Hamidian *et al.*, Nature 532, 343 (2016);
  Du *et al.*, Nature 580, 65 (2020)]

Testing theoretical predictions - consequences of a PDW SC state:

[E. Fradkin *et al.*, Rev. Mod. Phys. 87, 457 (2015)]

- **Charge order modulation** (CDW 1*Q* order) **in vortex halos** in **$Bi_2Sr_2CaCu_2O_8$**; **STM**, $H/T_c^0 \lesssim 0.1$ T/K (vortex solid regime)

  [S. D. Edkins *et al.*, Science 364, 976 (2019)]

Probing interlayer frustration

La-214: reorienting spins in spin stripes in every other plane by an in-plane magnetic field

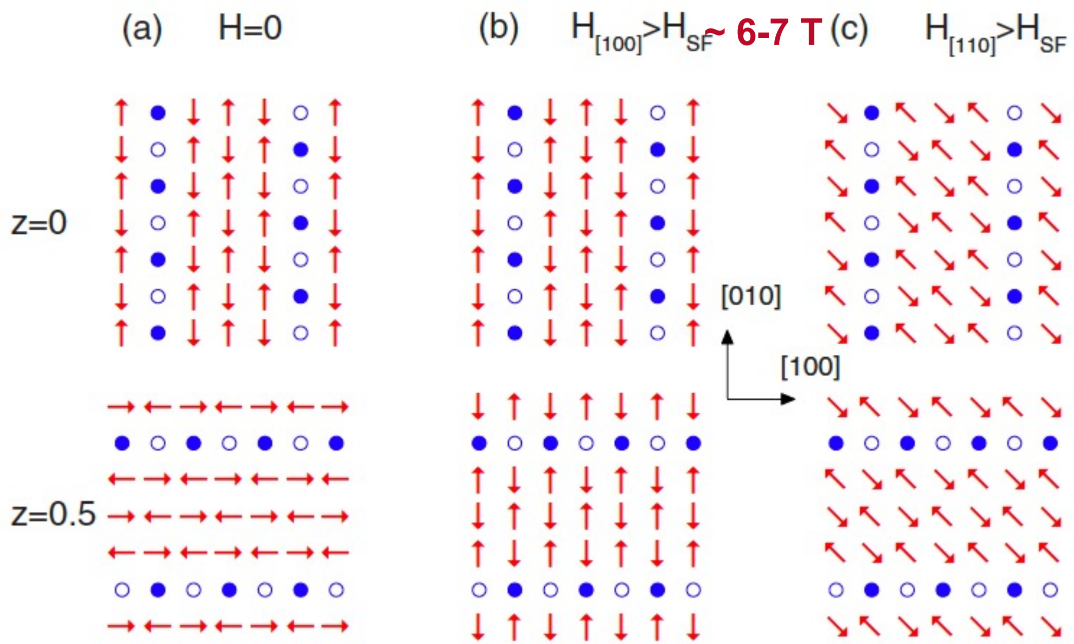


FIG. 5. (Color online) Model for spin structure of site-centered stripes as a function of field. (●,○) Half-filled charge stripes. Stripes in adjacent planes at $z=0$ and 0.5 are perpendicular. (a) Spin structure for $H=0$, (b) $\mathbf{H}\parallel[100]$, and (c) $\mathbf{H}\parallel[110]$.

[M. Hücker *et al.,* Phys. Rev. B 78, 214507 (2008); M. Hücker *et al.,* Phys. Rev. B 70, 214515 (2004)]

A consequence of the PDW SC state:

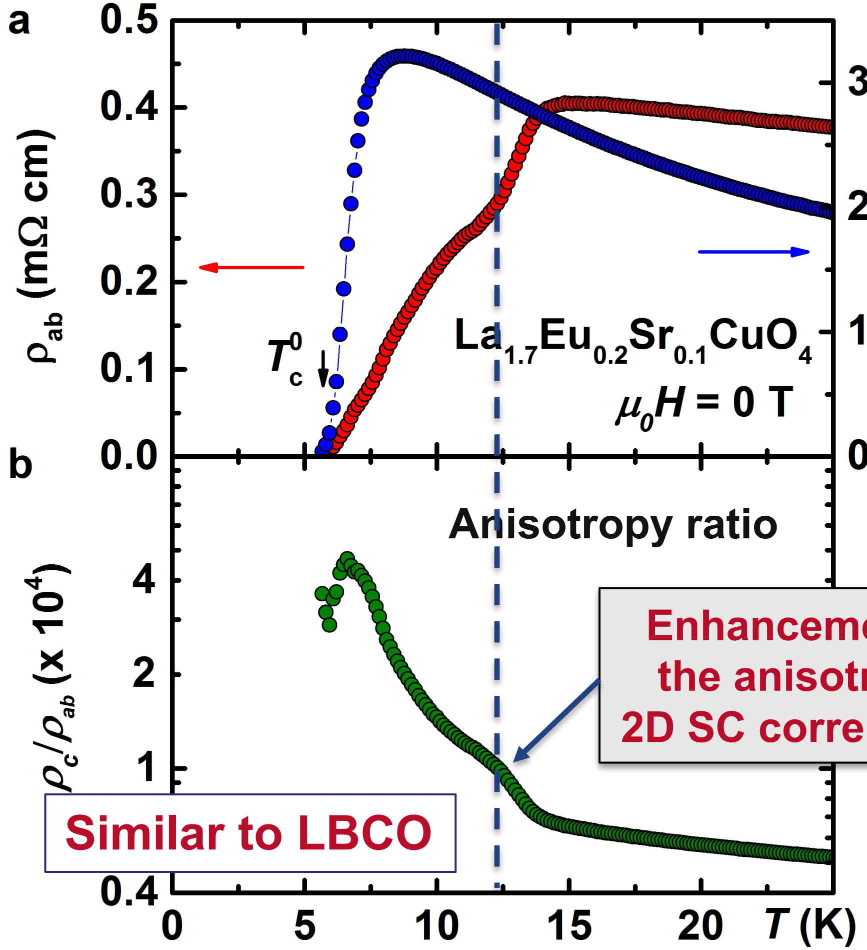
⇒ In-plane *H* relieves the interlayer frustration, i.e. reduces the anisotropy

[E. Berg *et al.,* PRL 99, 127003 (2007); E. Fradkin *et al.*, Rev. Mod. Phys. 87, 457 (2015)]

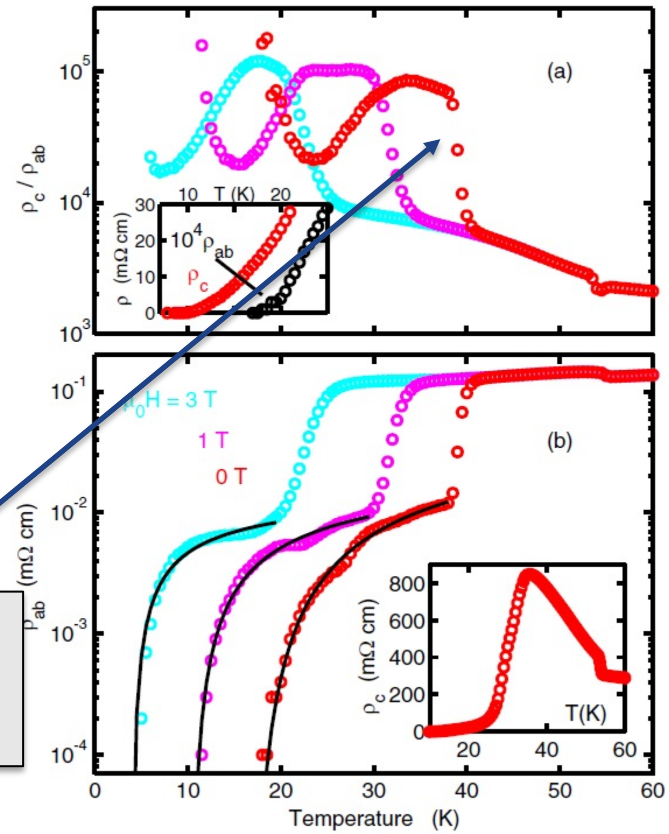
This is what we observed in Eu-LSCO and Nd-LSCO

Eu-LSCO: Anisotropy ratio ρ_c/ρ_{ab} in H=0

In-plane and out-of-plane transport



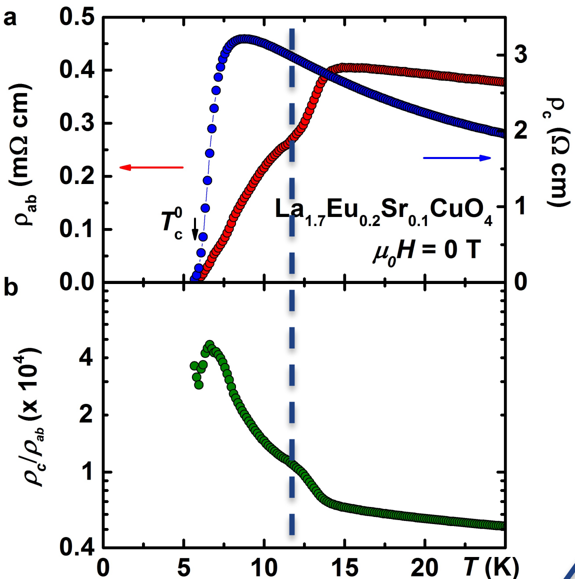
$La_{2-x}Ba_xCuO_4$ (x=0.125)



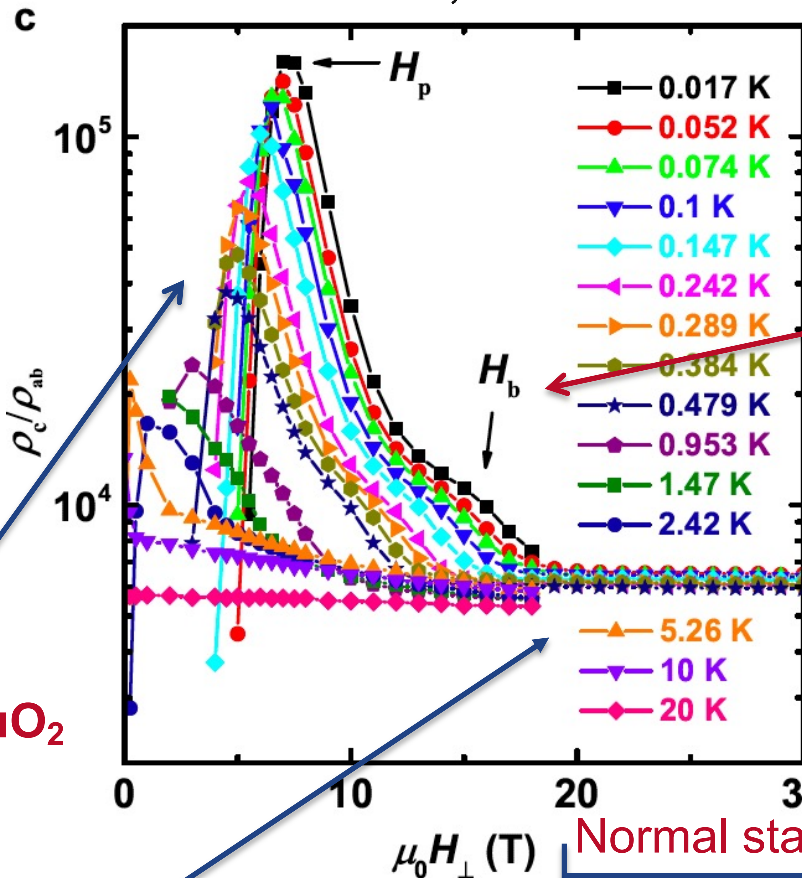
[Q. Li *et al.*, PRL 99, 067001 (2007)]

Same T_c^0 for ρ_{ab} and ρ_c: onset of 3D SC

Evolution of the anisotropy with temperature and perpendicular field



LESCO, x=0.10



T_{SO} ~ 15 K, T_{CO} ~ 40 K

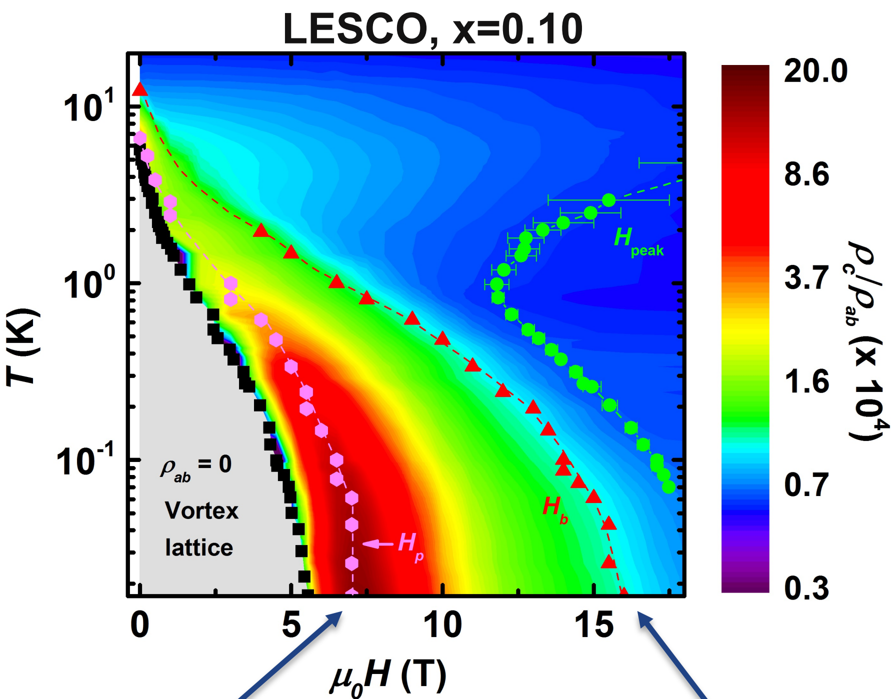
Enhancement of anisotropy!
2D SC correlations

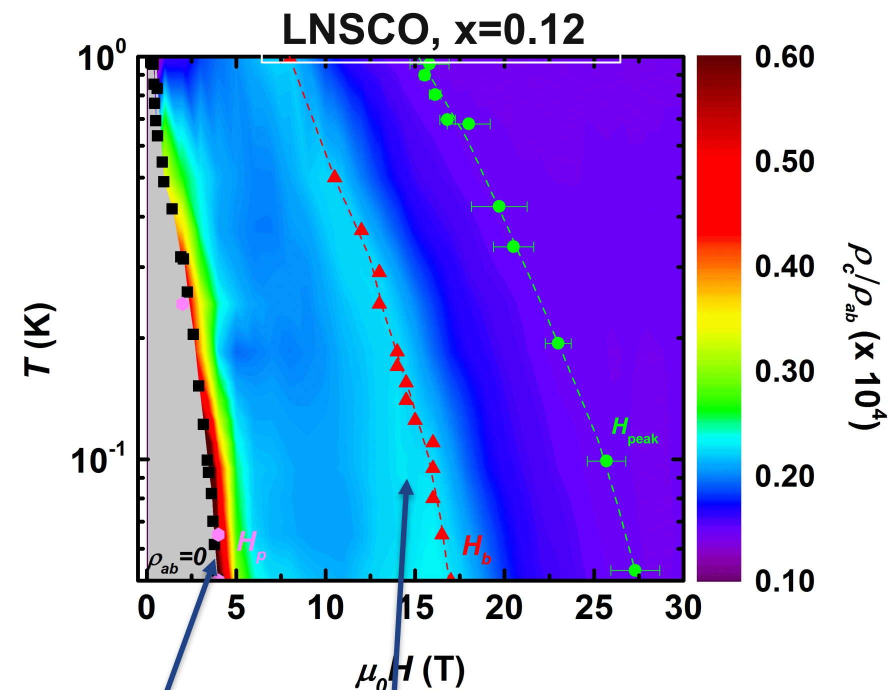
Decoupling of CuO_2 planes by $H_\perp$

Normal state

- **Field-independent anisotropy ratio ρ_c/ρ_{ab} for $H_{peak} \approx H_{c2} < H$**

Evolution of the anisotropy with temperature and perpendicular field





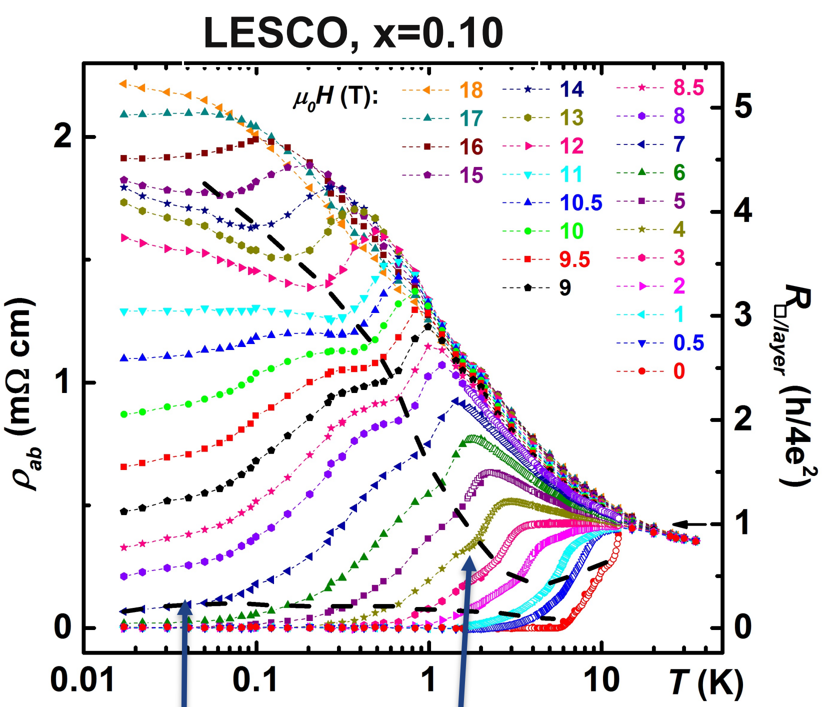
$H_p(T)$: layer decoupling field

$H_p(T) \approx H_c(T)$ [i.e. $T_c(H)$, as expected]

H_b: 2D SC correlations

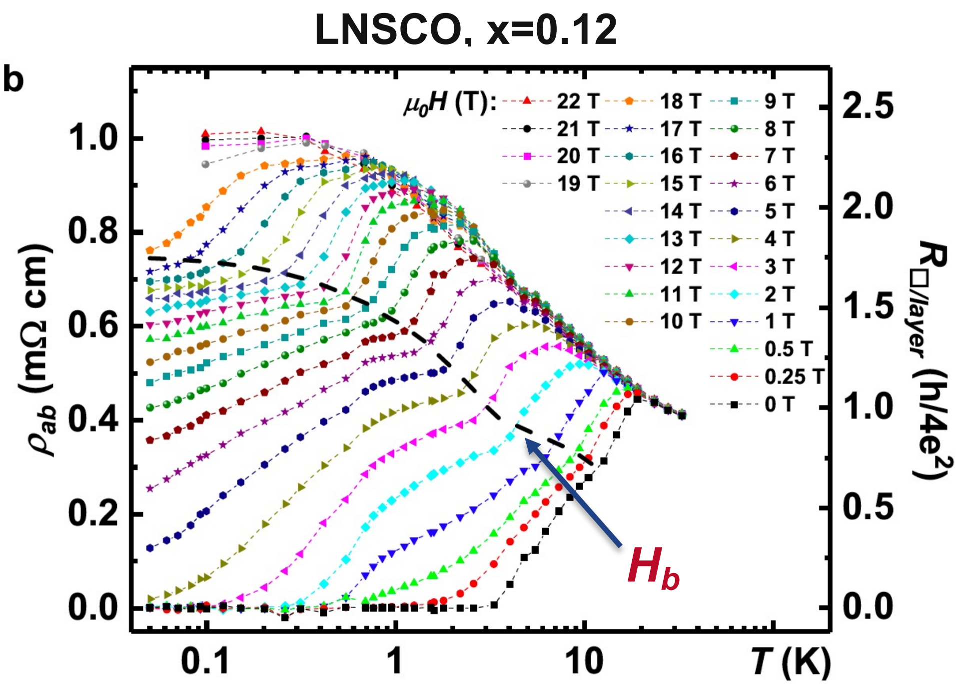
$H_{peak} \sim H_{c2}$

Two-step temperature dependence of the in-plane resistivity ρ_{ab}



H_b Onset at $T>T_c^0$

$H_p(T)$: layer decoupling field



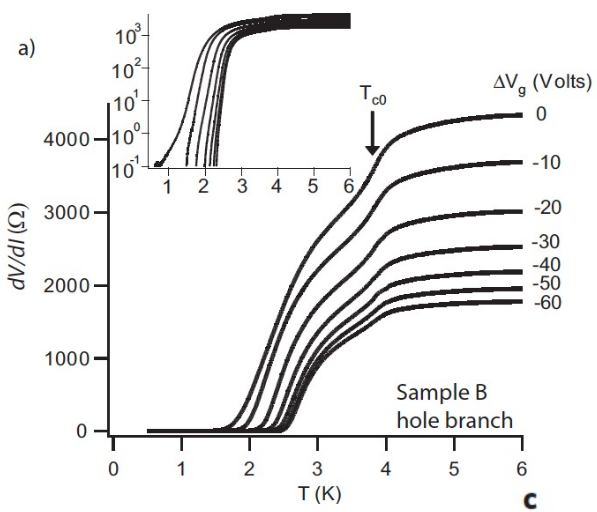
Layer decoupling at ~$T_c(H)$

2D Physics

Two-step temperature dependence of the resistivity: Other 2D superconducting systems

Josephson junction (JJ) arrays

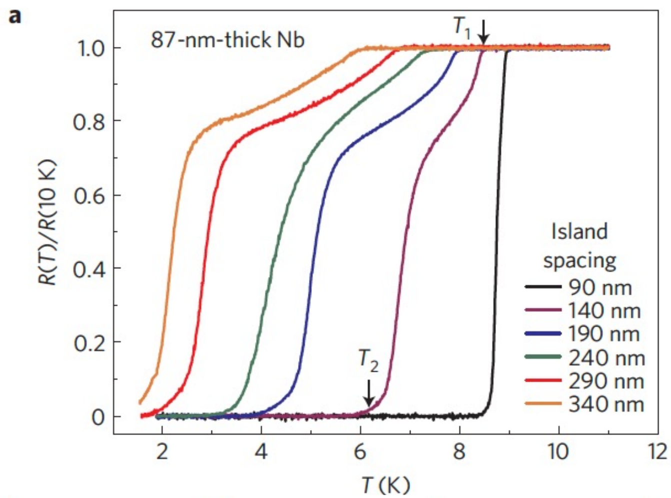
Sn islands on graphene sheet

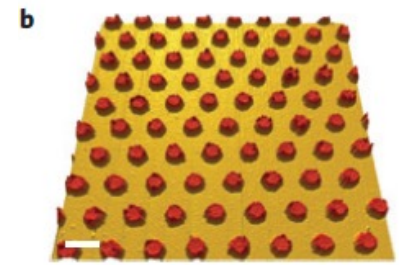


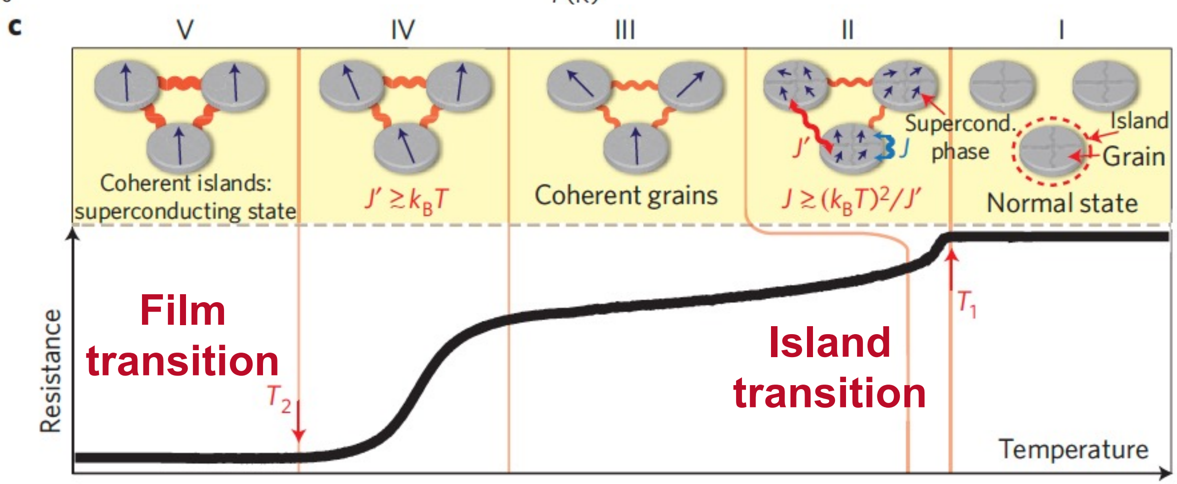
[B. M. Kessler *et al.*, PRL 104, 047001 (2010)]

- **Granular films** of conventional superconductors
- …

Nb islands on Au





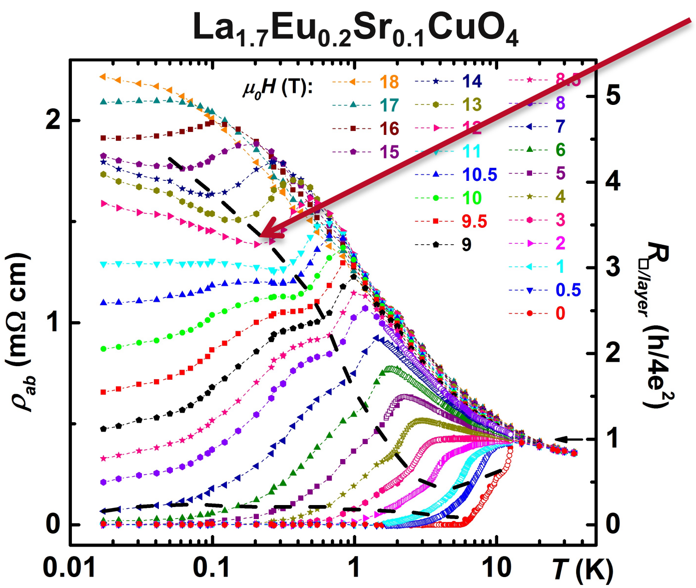


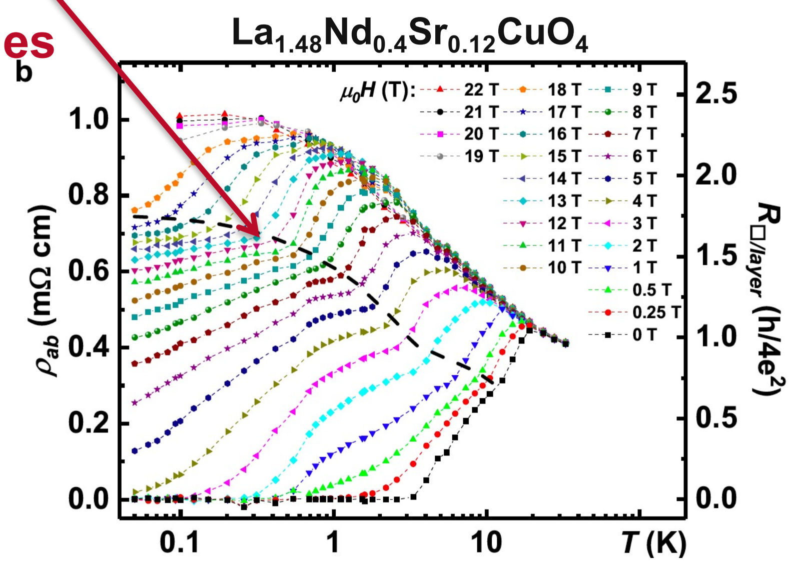
[S. Eley *et al.*, Nature Phys. 8, 59 (2012)]

Two-step temperature dependence of the in-plane resistivity ρ_{ab}: Striped cuprates

- **Onset of SC correlations at $T > T_c^0$**

Superconducting "islands" in the planes





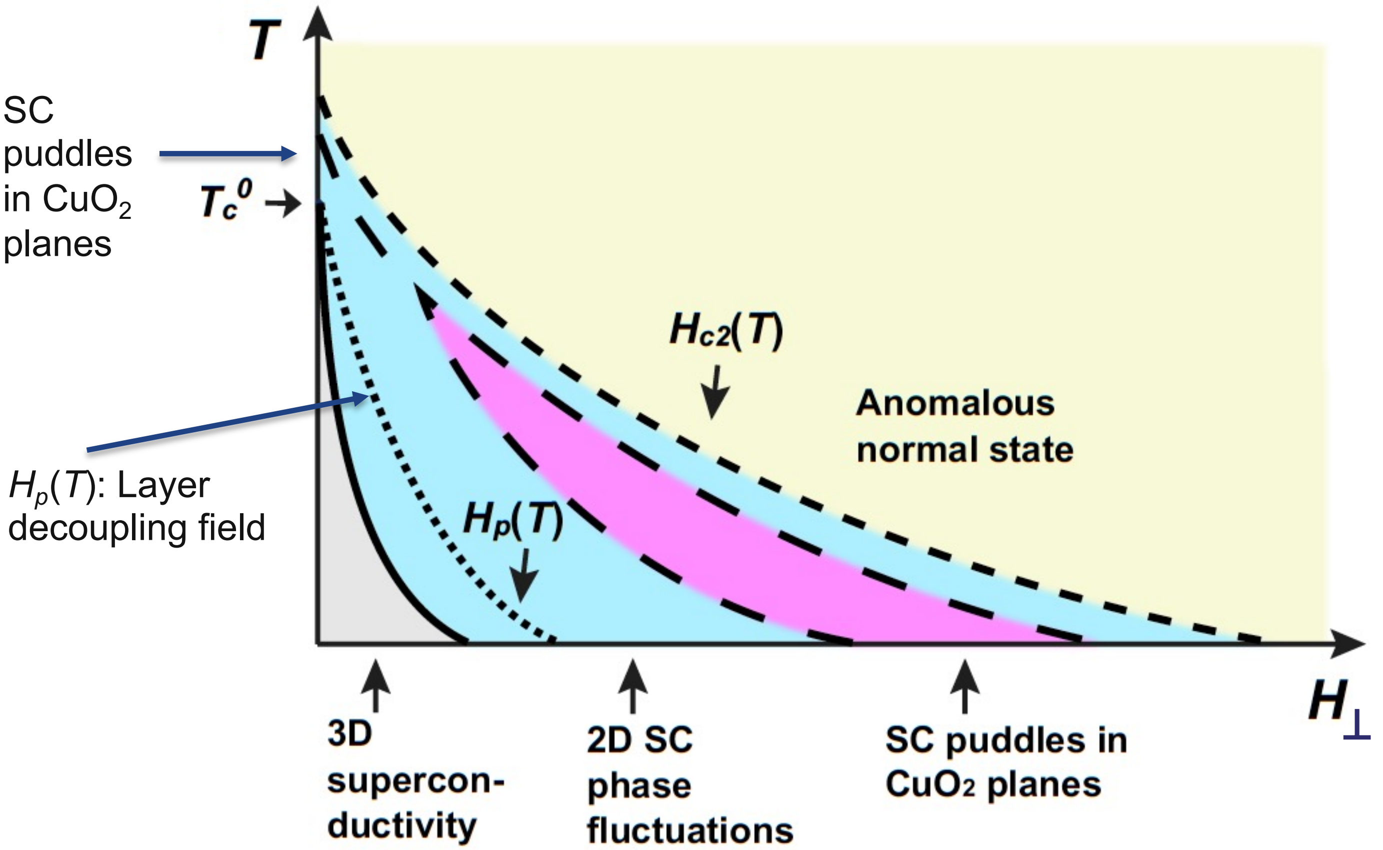
At low T, increasing $H_\perp$ destroys superconductivity in planes by quantum phase fluctuations of Josephson-coupled SC islands

⇒ **Intrinsically granular SC state**

[A. Kapitulnik *et al.,* Rev. Mod. Phys. 91, 011002 (2019)]

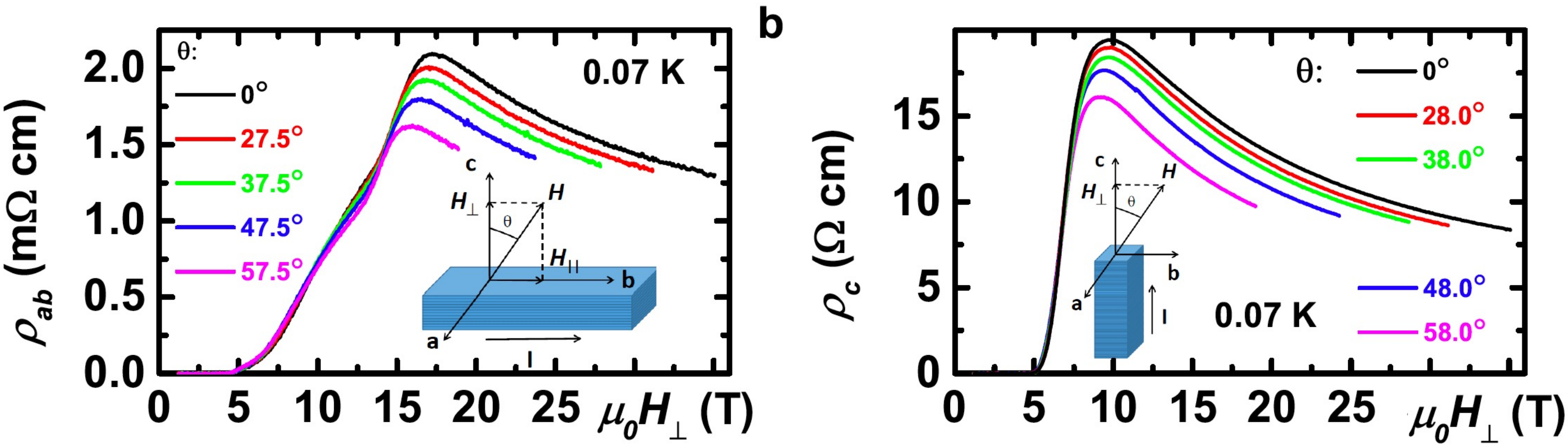
Schematic (T, $H_\perp$) phase diagram of stripe-ordered La-214 cuprates

- Consistent with the presence of **local, PDW correlations** (in puddles) that compete with the uniform SC order at $T_c^0 < T < (2\text{-}6)T_c^0$; become **dominant at high enough $H_\perp < H_{c2}$ as $T \to 0$**



Probing interlayer frustration: angle-dependent measurements of ρ_{ab}(H) and ρ_c(H)

LESCO, x=0.10

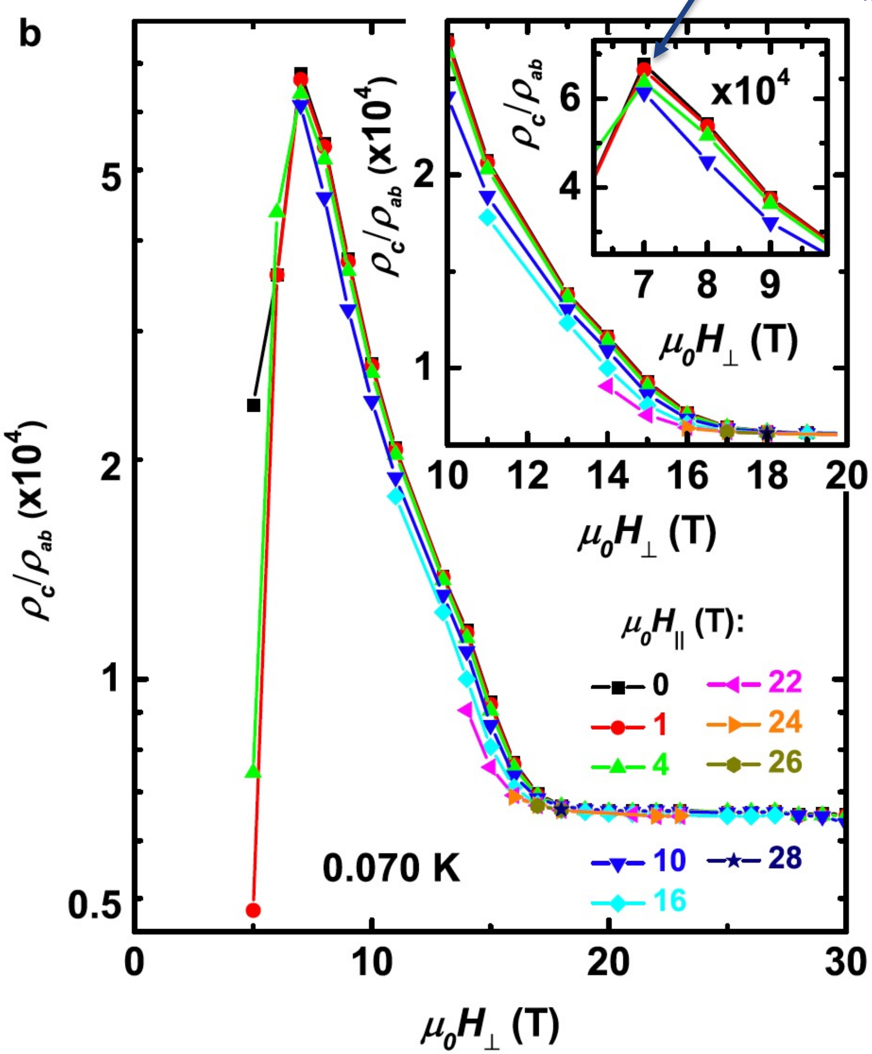


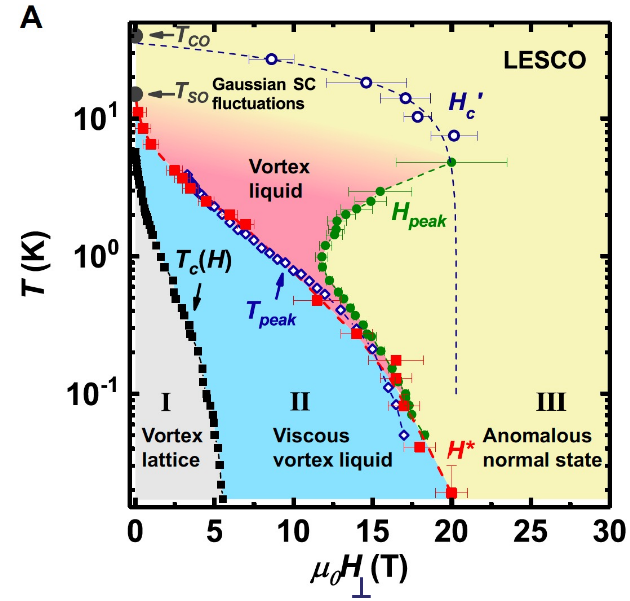
Field perpendicular to the CuO_2 planes: $H_\perp = H \cos\theta$
Field parallel to the CuO_2 planes (i.e. to *a* or *b* axis): **$H_{||} = H \sin\theta$**
$H_{||} = H_\perp \tan\theta$

Probing interlayer frustration: effect of the in-plane (parallel) magnetic field on ρ_c/ρ_{ab}

Reduced by 6000 (~10%) for $H_{||}$=10 T

LESCO, x=0.10





$H_{||}$ reduces the anisotropy for
$H_p \leq H_\perp < H_{c2}$
<u>as predicted in the PDW scenario</u>
(reorientation of spins in stripes)

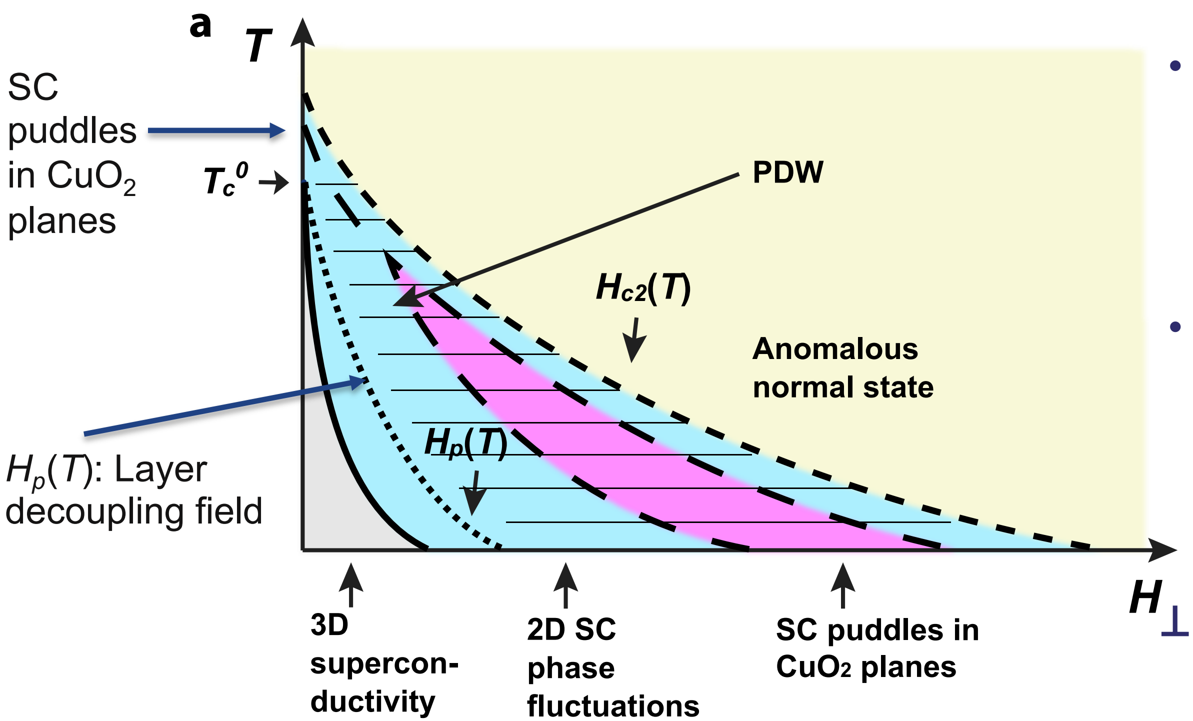
No effect of $H_{||}$ in the normal state:
$H_\perp > H_{c2}$ (T=0.070 K) ≈ 17. 5 T

Signatures of a PDW in stripe-ordered Eu-LSCO and Nd-LSCO

[Zhenzhong Shi *et al.*, Nat. Commun. 11, 3323 (2020)]

- **Probed the previously inaccessible high $H_\perp/T_c^0$ and $T \rightarrow 0$ regime dominated by quantum phase fluctuations and confirmed a theoretical prediction**

⇒ Several signatures of a PDW for $T_c^0 < T < (2\text{-}6)T_c^0 \ll T_{pseudogap}$ and $H_\perp < H_{c2}$



- Results do **not** support a scenario in which the PDW correlations are responsible for the pseudogap
- Observed in the regime with many vortices, **consistent with the STM evidence** for PDW in vortex halos in $Bi_2Sr_2CaCu_2O_8$ vortex solid

[S. D. Edkins *et al.*, Science 364, 976 (2019)]

Conclusions

- **Robust vortex phase diagram for underdoped cuprates**
  - ***T-H* phase diagram, H_{c2}**
  - Key role of quantum phase fluctuations and disorder as $T \rightarrow 0$
  - No qualitative effect of charge and spin orders on the vortex phase diagram

Stripe-ordered cuprates:

- **Signatures of a PDW from $T > T_c^0$ in H=0 to H=H_{c2} as $T \rightarrow 0$**

(in the regime of SC phase fluctuations)

  - Results do **not** support a scenario in which the PDW correlations are responsible for the pseudogap