An overview of evidence for a quantum critical point underlying the high-temperature superconducting dome

Important new Probes for high magnetic field research

A. Using **Focused Ion Beam Sample-Shaping** …pioneered by Philip Moll… to acquire High-Precision Magnetotransport in a Cuprate Superconductor

B. Using **Specific Heat** to measure Total Electronic Density of States that participates in superconductivity in a Pnictide Superconductor

Phenomena near optimum doping….

1. Evidence for **Peak in the "Hall Number":** non-monotonic evolution of Hall effect
2. Evidence for **Linear-in-T resistivity in the low temperature limit**
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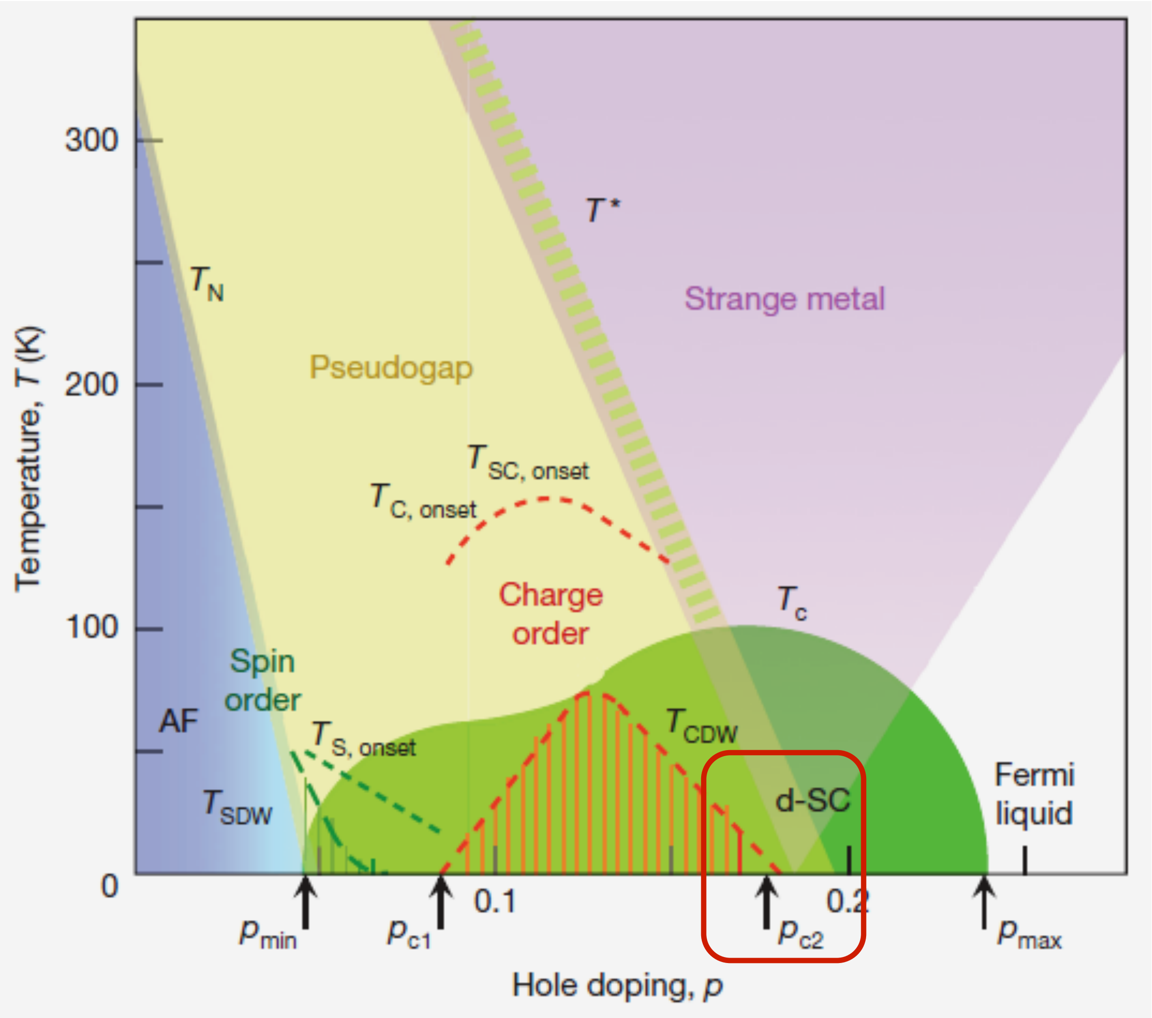
4. Evidence for **Quasiparticle Mass Divergence** …from YBCO quantum oscillations
5. Evidence for **Quasiparticle Mass Divergence**…from specific heat in a pnictide

Greg Boebinger

NATIONAL HIGH MAGNETIC FIELD LABORATORY

The Phase Diagram in 2015:



B. Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, J. Zaanen
Nature 518, 179 (2015).
"From quantum matter to high-temperature superconductivity in copper oxides."

Thank You

Linear magnetoresistance in LSCO thin films grown by MBE

Paula Gallo, J.A. Galvis, Z. Stegen, K.A. Modic, F.F. Balakirev, J.B. Betts, X. Lian, C. Moir, S.C. Riggs, B.J. Ramshaw, R.D. McDonald, GSB, A. Shekhter

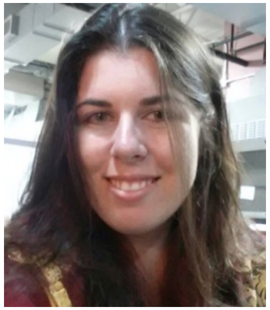
J. Wu, A.T. Bollinger, X. He, I. Božović

Linear magnetoresistance in LSCO single crystals

Xiujun Lian, R.D. McDonald, B.J. Ramshaw, F. Weickert, J.B. Betts, GSB, A. Shekhter

S. Ono

Mass divergence approaching critical doping in BaFe2(As,P)2



Camilla Moir, J.A. Galvis, P. P. Giraldo-Gallo, X. Lian, A. Shekhter, GSB

P. Walmsley, J-H Chu, I.R. Fisher

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Los Alamos NATIONAL LABORATORY EST. 1943

BROOKHAVEN NATIONAL LABORATORY

FLORIDA STATE UNIVERSITY 1851

CRIEPI Central Research Institute of Electric Power Industry

NSF

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Direct Evidence of a Quantum Phase Transition near Optimum Tc:

Peak in "Hall Number" in LSCO and Bi2201

Peak in "Hall Number" as a General Phenomenon?

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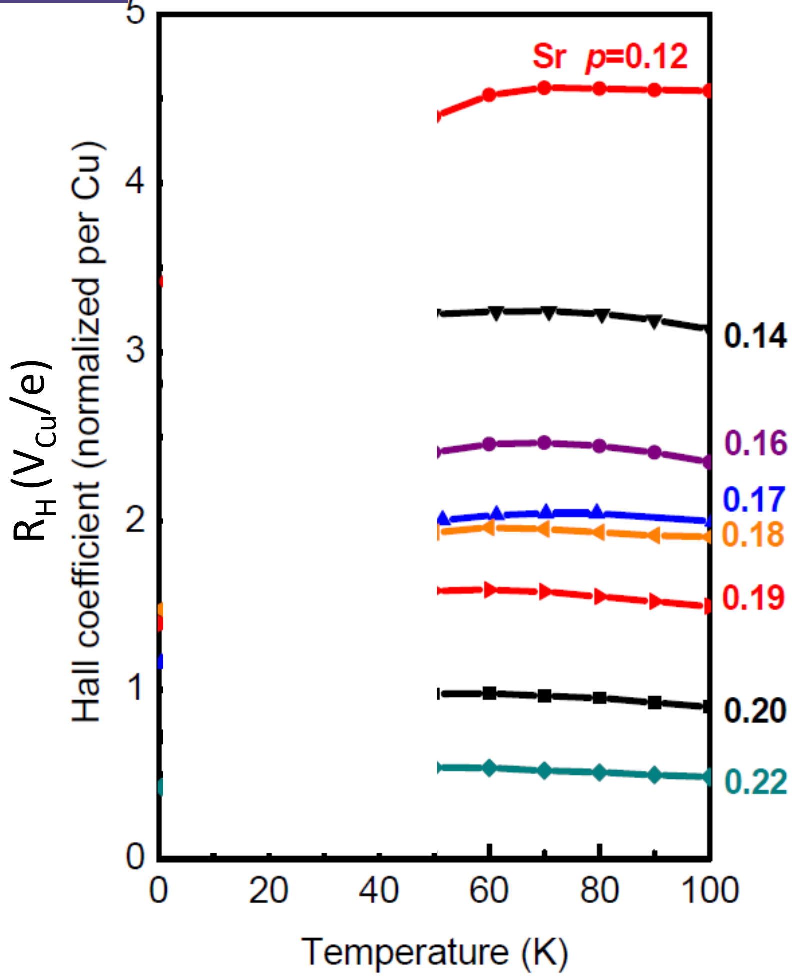
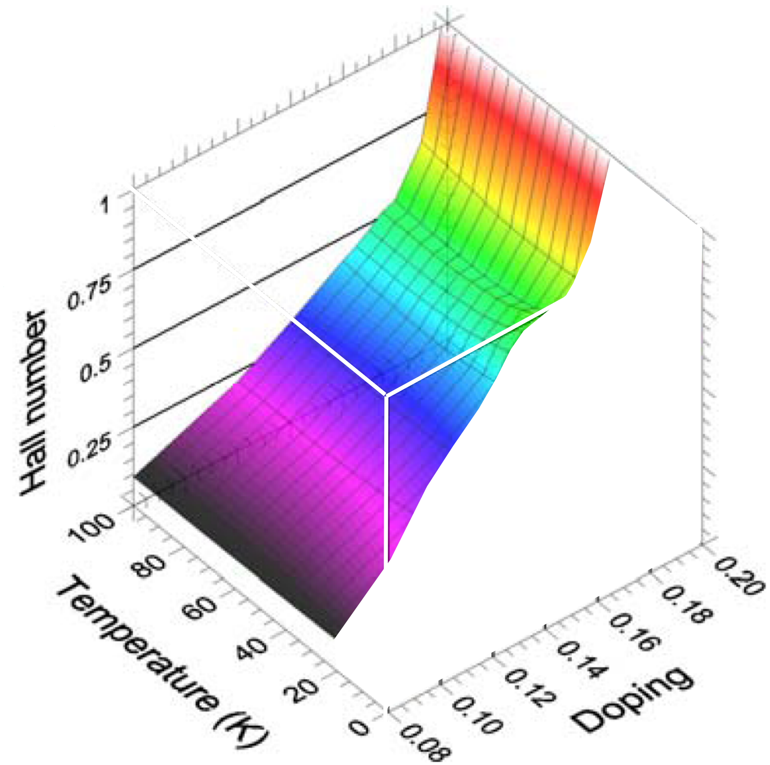
The Hall Coefficient, R_H, of the Normal State of LSCO in the Zero-Temperature Limit





F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando, G. S. Boebinger, Phys.Rev.Lett. 102, 017004 (2009).
"Quantum Phase Transition in the Normal State of High-Tc Cuprates at Optimum Doping."

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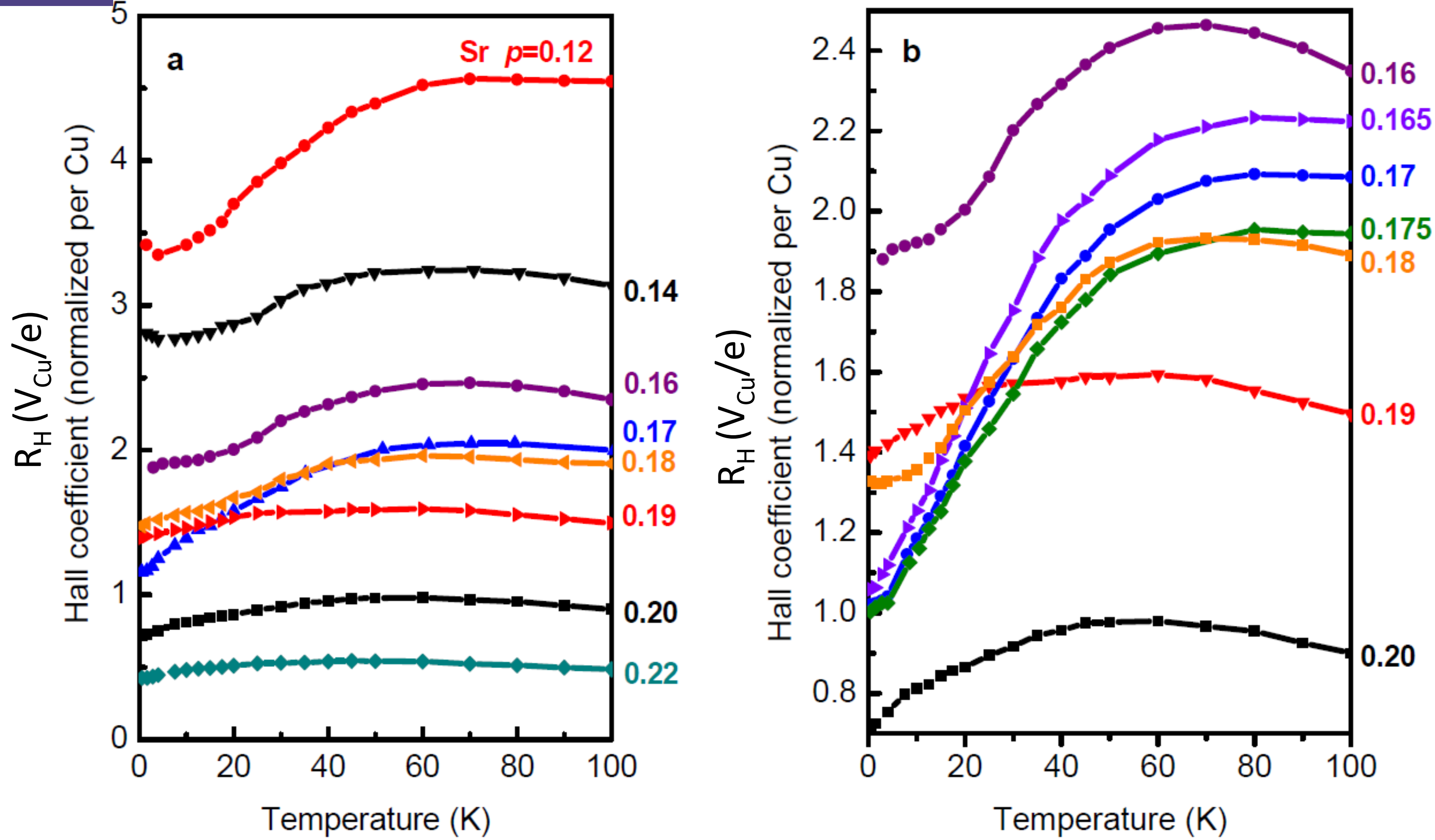

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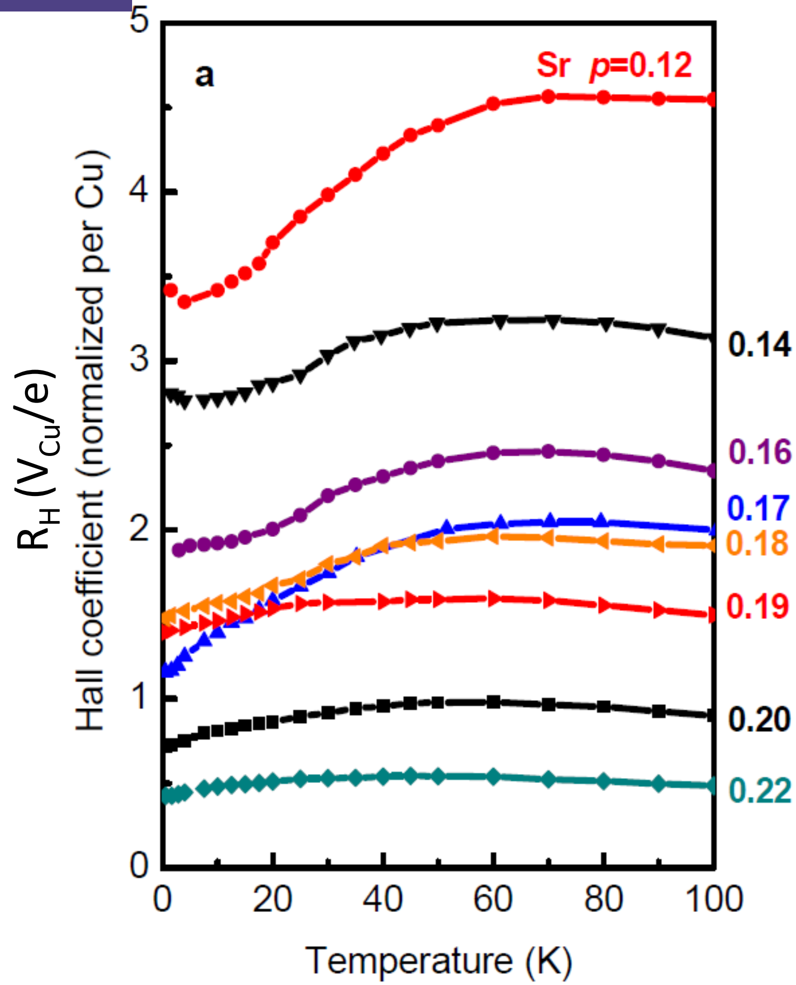

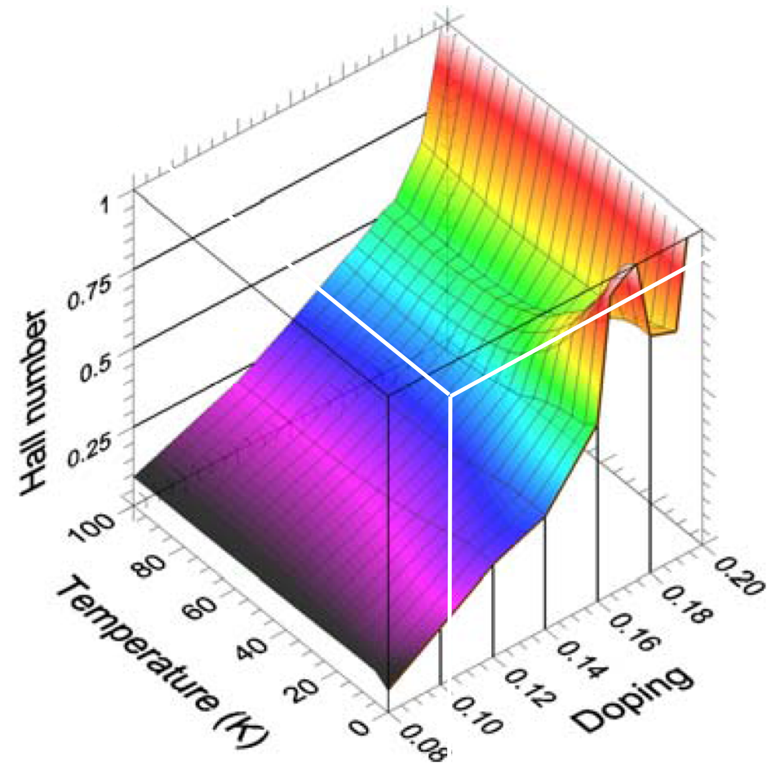

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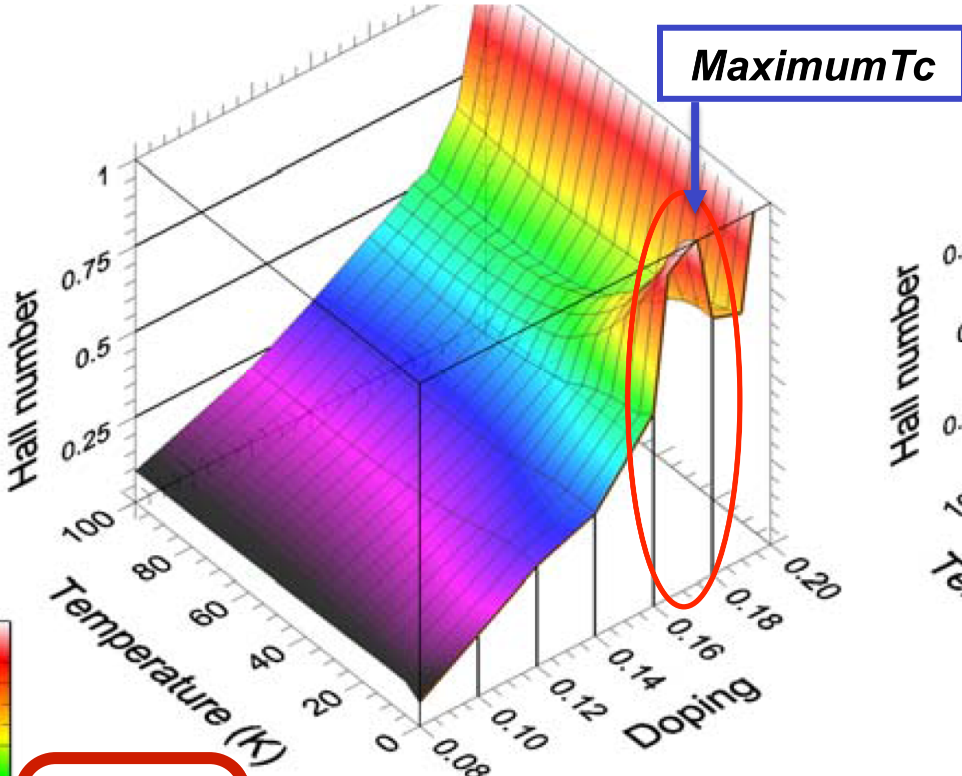
Phys.Rev.Lett. 102, 017004 (2009).
"Quantum Phase Transition in the Normal State of High-Tc Cuprates at Optimum Doping."

Peak in Hall Number near Optimum Tc seen in two systems

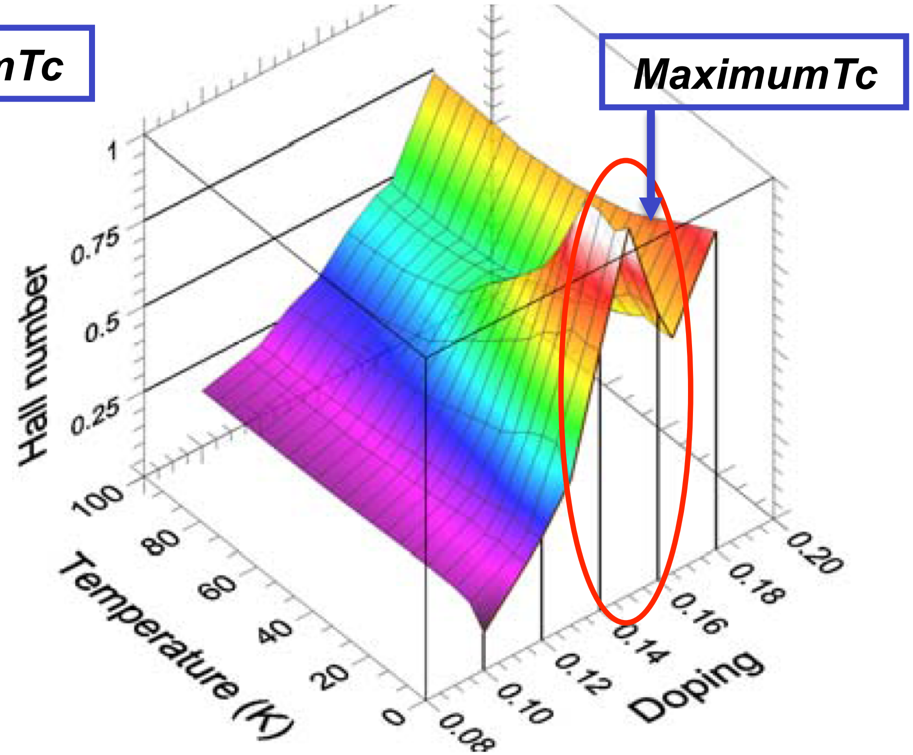
Reported in LSCO thin films in 2009…

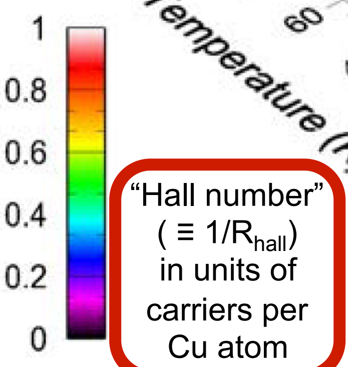
F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando, G. S. Boebinger, Phys.Rev.Lett. 102, 017004 (2009). "*Quantum Phase Transition in the Normal State of High-Tc Cuprates at Optimum Doping.*"



…but first observed in Bi-2201 single crystals in 2003

Fedor F. Balakirev, Jonathan B. Betts, Albert Migliori, S. Ono, Yoichi Ando & Gregory S. Boebinger, Nature 424, 912 (2003). "Signature of optimal doping in Hall-effect measurements on a high-temperature superconductor"





In electron-doped PrCeCuO4, evidence of phase transition (kink and change in sign of Hall coefficient)

W. Yu, J.S. Higgins, P. Vach & R.L. Greene, **PRB (RC) 020503 (2007).**

Number of Carriers versus Doping: Peak or No Peak?

Hall Effect in BSLCO to 60T
F. F. Balakirev, J. B. Betts, A. Migliori, S. Ono, Y. Ando, and G S. Boebinger, Nature **424,** 912 (2003).

Hall Effect in LSCO to 60T
F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando, G.S. Boebinger
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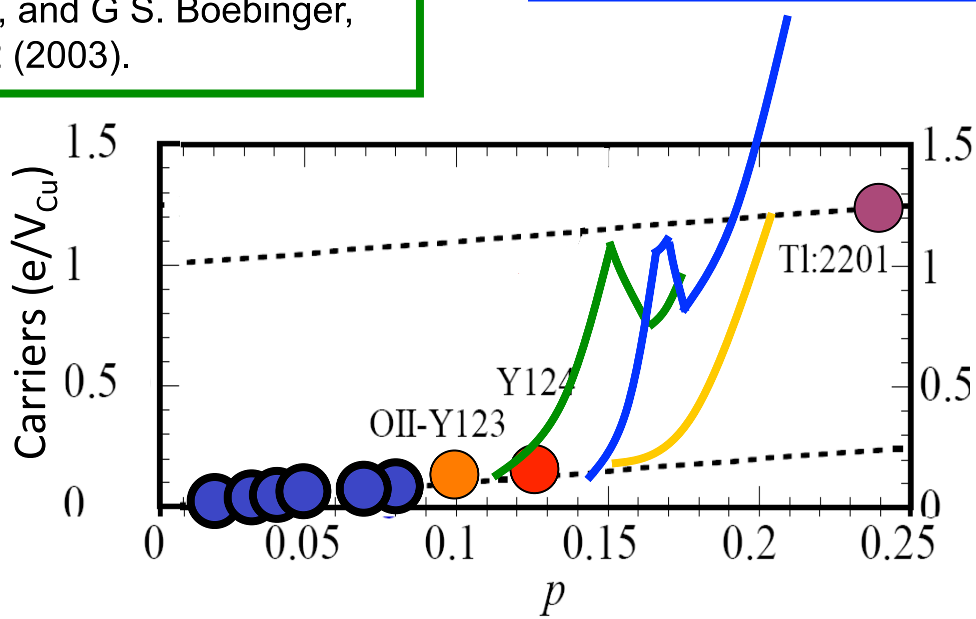

Quantum Oscillations in Tl-2201
Hussey et al, Nature **425,** 814 (2003)

Hall Effect in LSCO
Y. Ando, *et al.,* PRL **92** 197001 (2004)

Quantum Oscillations in Ortho-II YBCO
N. Doiron-Leyraud, *et al.,* Nature **447** 565 (2007)

Quantum Oscillations in YBCO124
Yelland *et al*., PRL **100**, 047003 (2008)

Hall Effect in YBCO to 88T
S. Badoux, W. Tabis, F. Laliberte, G. Grissonnanche, B. Vignolle, D. Vignolles, J Beard, D.A. Bonn, W.N. Hardy, R. Liang, N. Doiron-Leyraud, Louis Taillefer & Cyril Proust, Nature **531**, 210 (2016)

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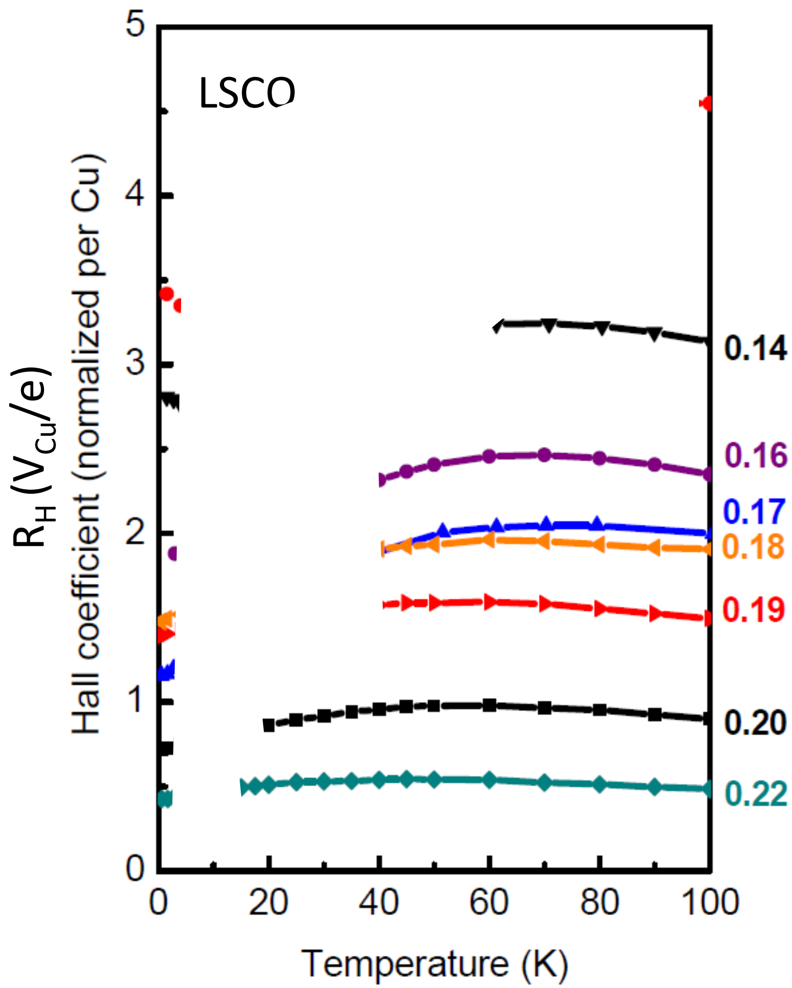

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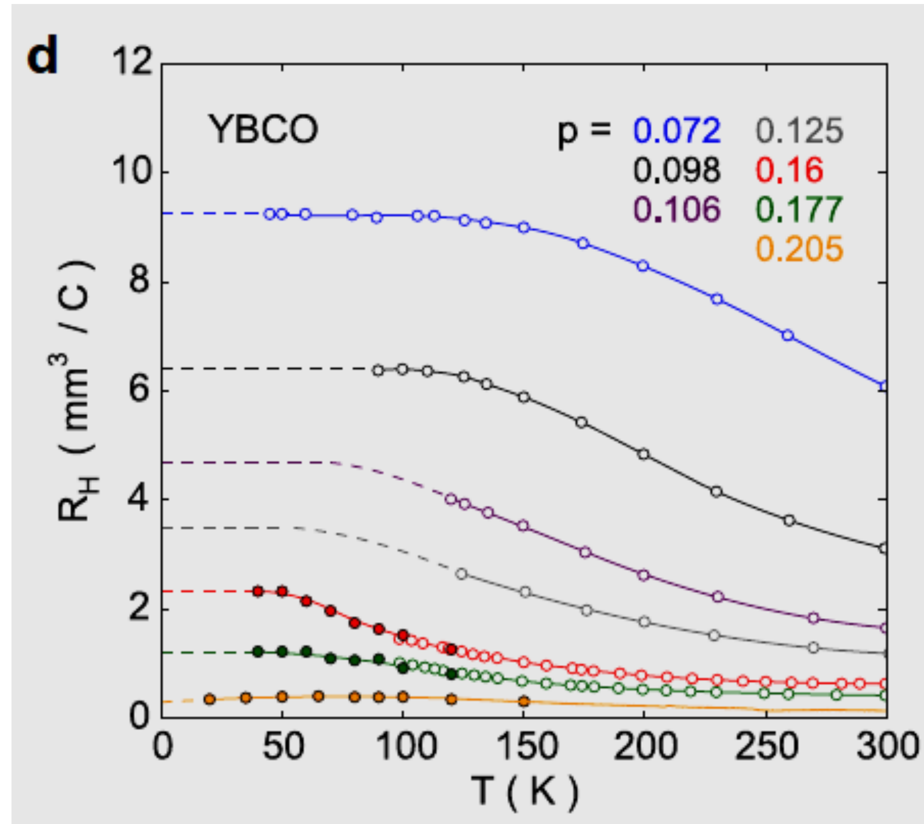

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"Change of carrier density at the pseudogap critical point of a cuprate superconductor."

CLEARLY: We Need Bigger Magnets!

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Linear-in-T Resistivity as T→ 0 in an Electron-Doped Cuprate

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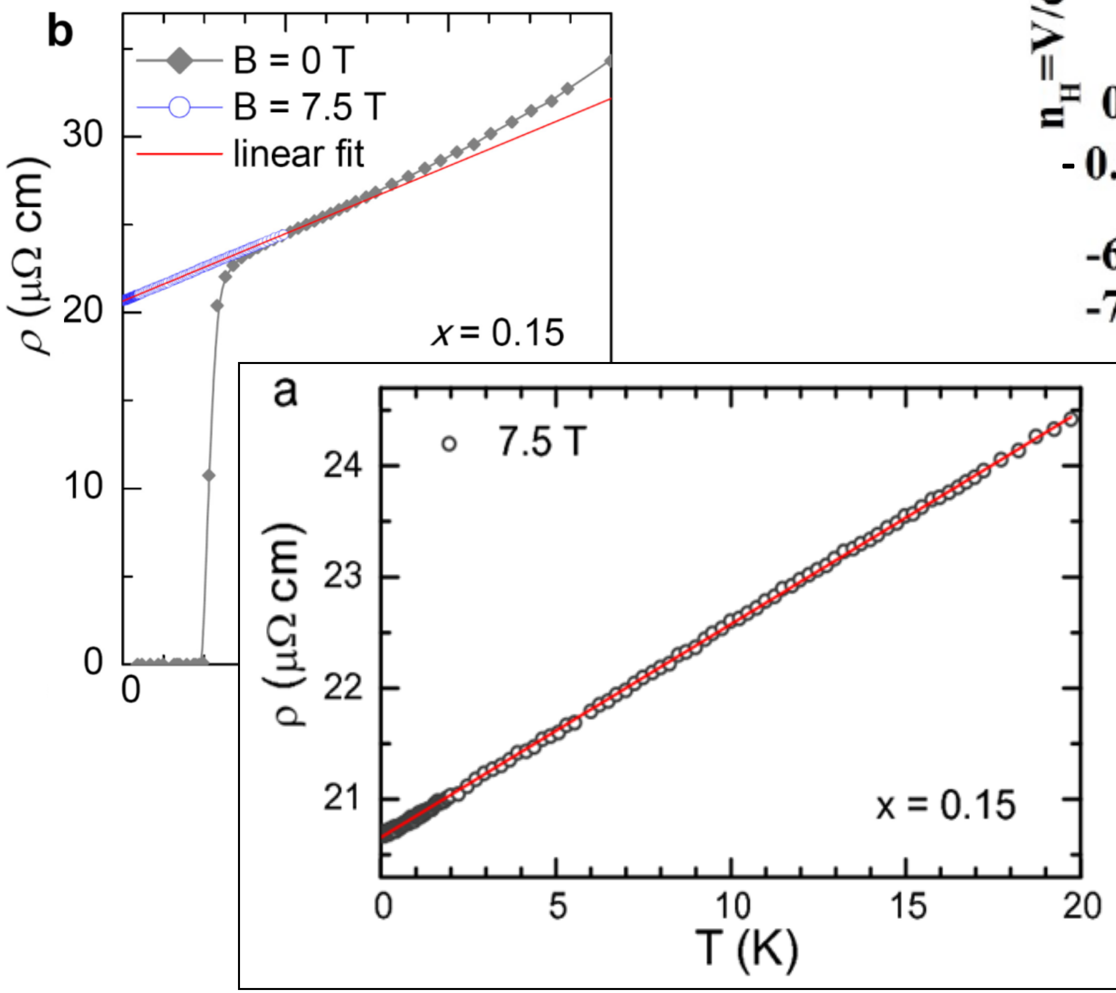
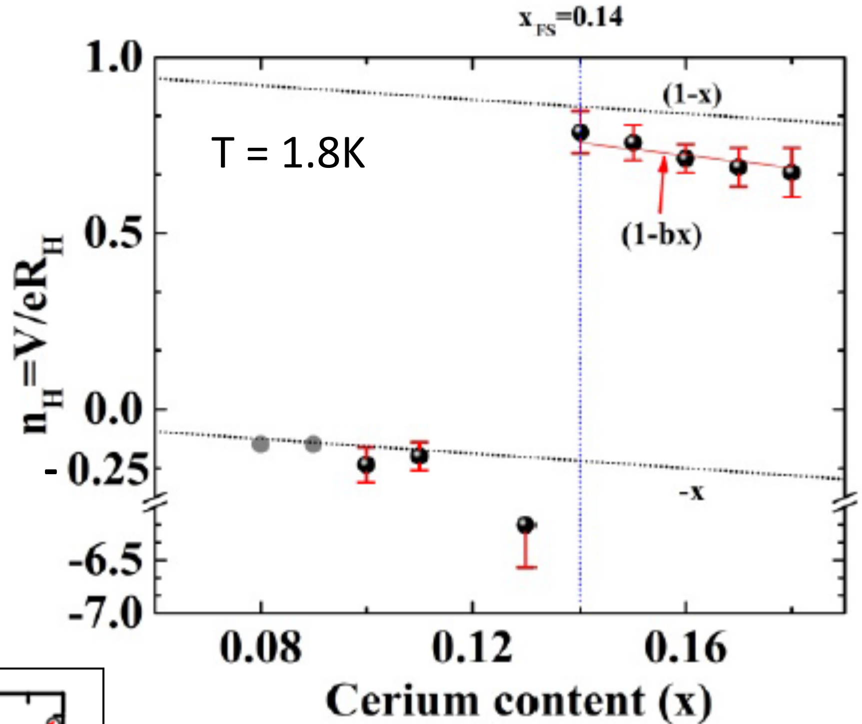
Evidence for Quantum Criticality in (electron-doped) LCCO

Linear-in-T Resistivity for 20mK < T < 20K



From Jin, Greene, et al., Nature 2011



Low-temperature Hall effect changes sign at the quantum phase transition

T. Sarkar, Greene, et al., (UMD)
arXiv:1706.07836

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Linear Magnetoresistance: New Evidence for Quantum Criticality near Optimum Doping in a Cuprate Superconductor.

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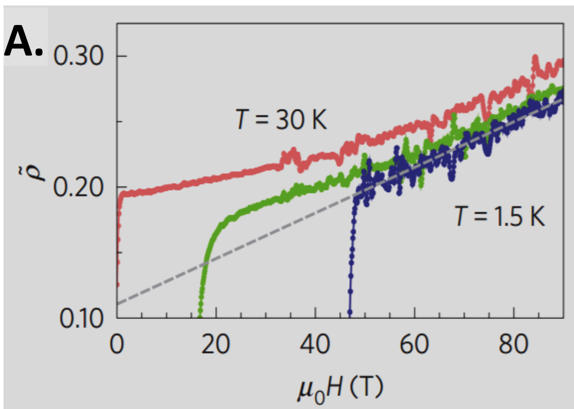
LINEAR MAGNETO-RESISTANCE: A NEW PHENOMENON, COMMON TO BOTH FAMILIES OF HIGH-TEMPERATURE SUPERCONDUCTORS NEAR CRITICAL DOPING

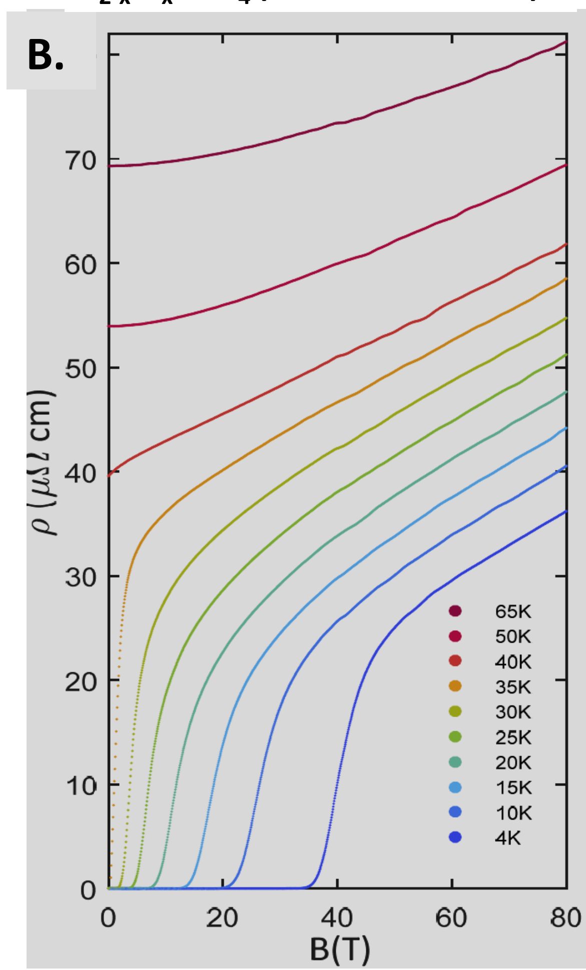
A. Reported to 90T in an iron-pnictide superconductor last year (Analytis Group)
B. Now reported to 80T in LSCO MBE-grown films (MagLab Group)

$BaFe_2(As_{1-x}P_x)_2$ (x=0.31)



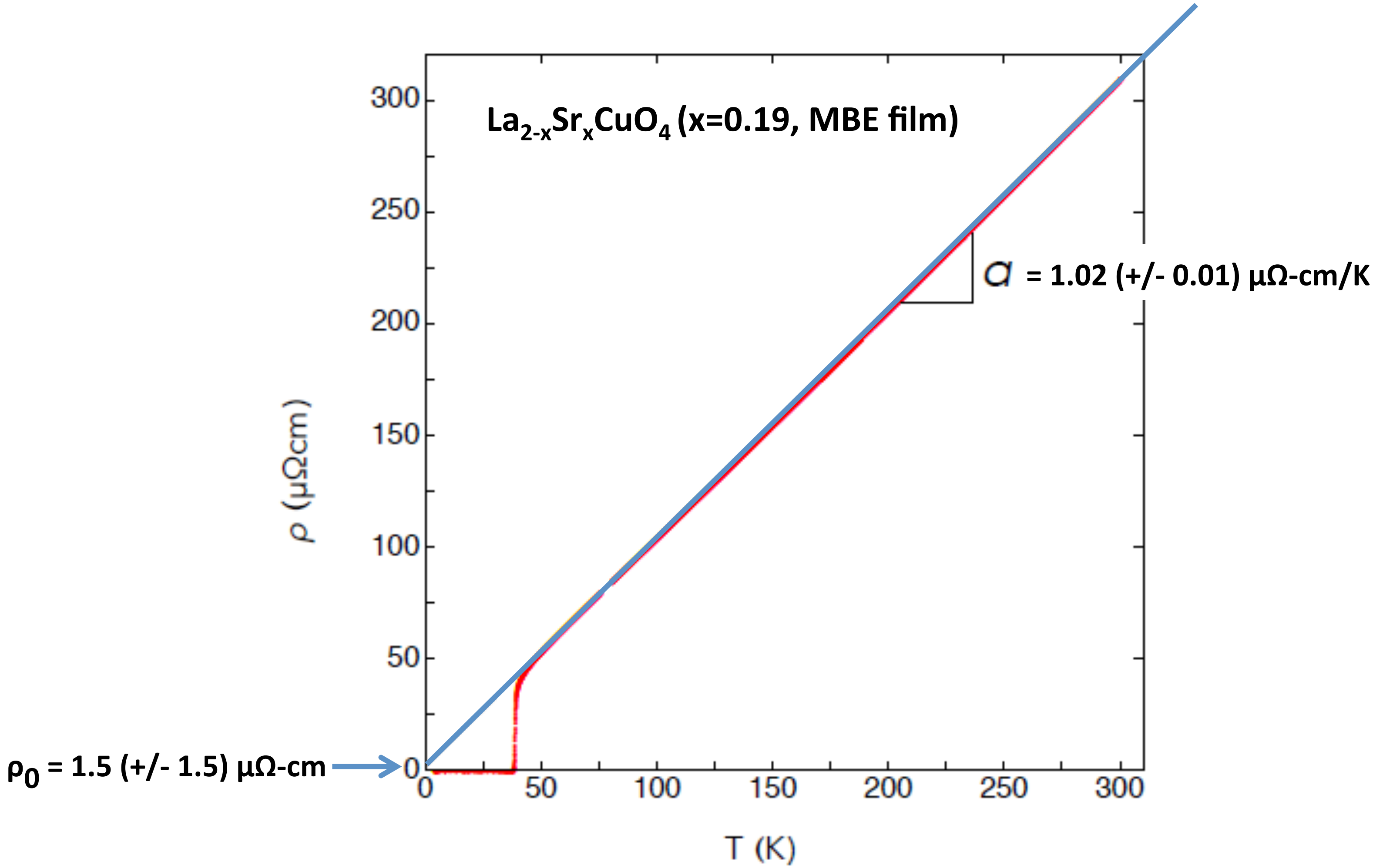
Ian M. Hayes, et. al. (Analytis Group)
Nature Physics **12,** 916 (2016)

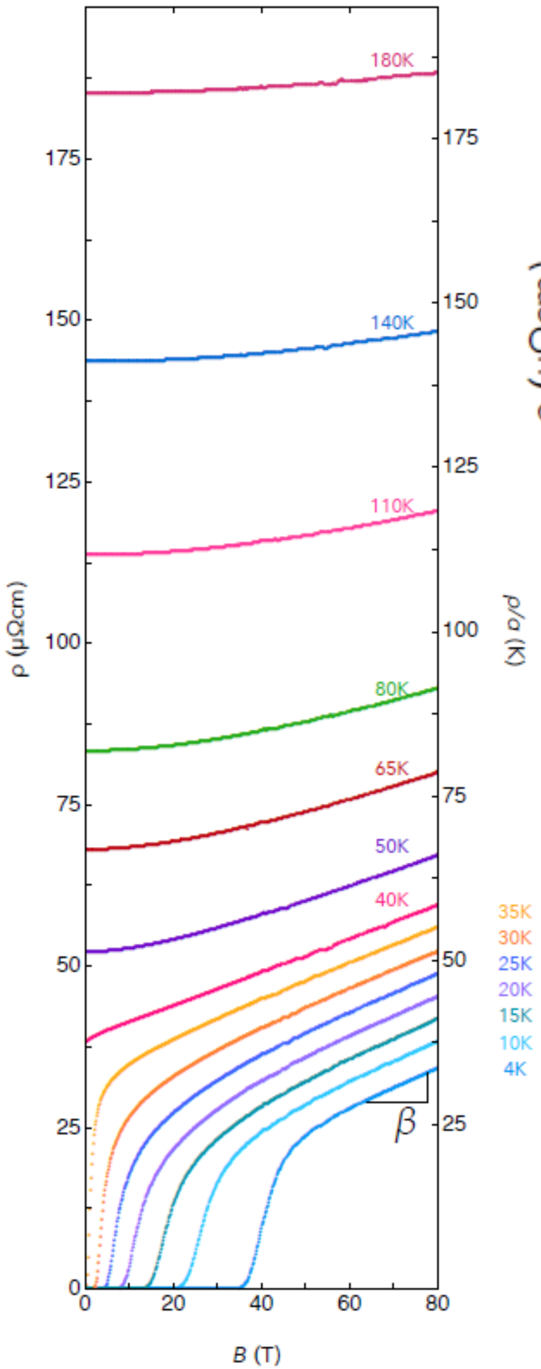
$La_{2-x}Sr_xCuO_4$ (x=0.19, MBE film)

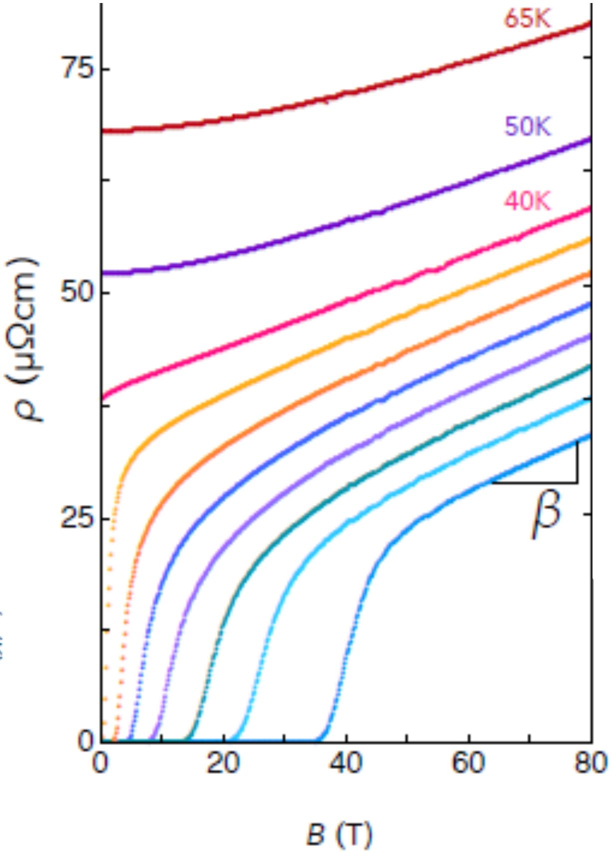


P. Giraldo-Gallo, et.al.
(MagLab Group)
arXiv:1705.05806

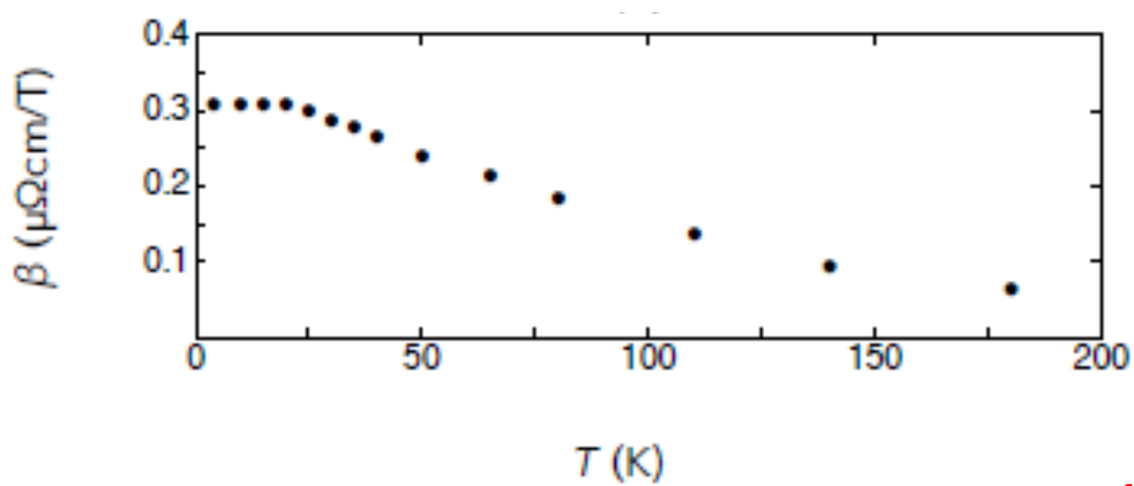
High Quality Cuprate MBE-Grown Films….Who you gonna call? Ivan Bozovic





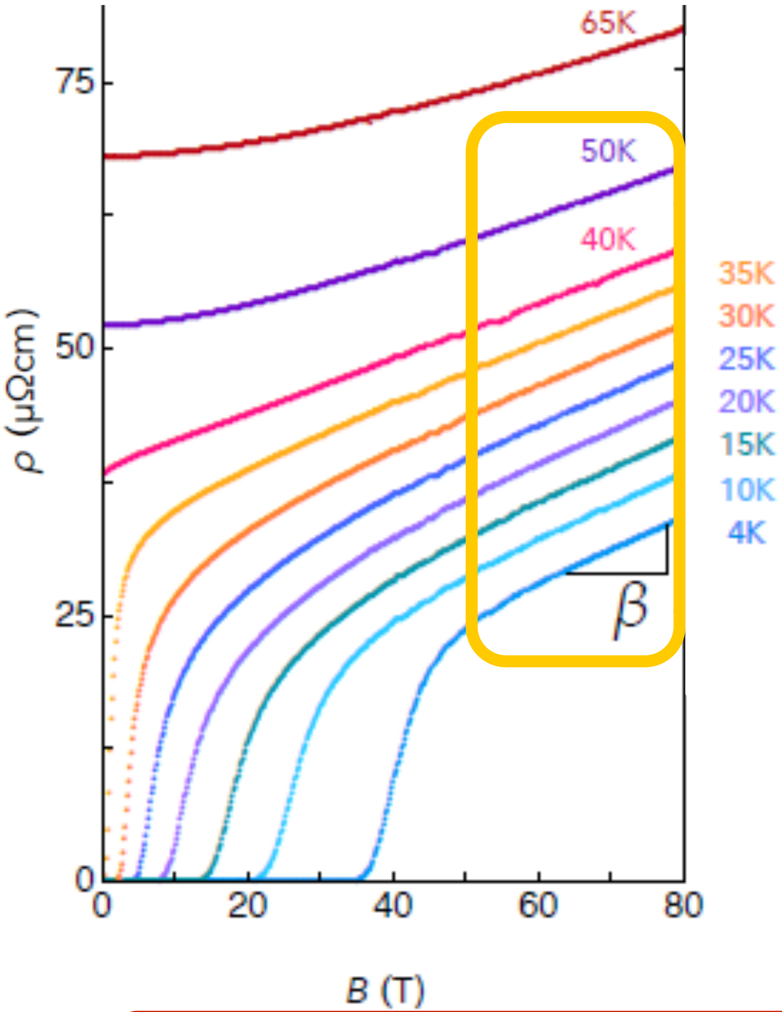


$La_{2-x}Sr_xCuO_4$ (x=0.19, MBE film) shows a remarkably linear magnetoresistance

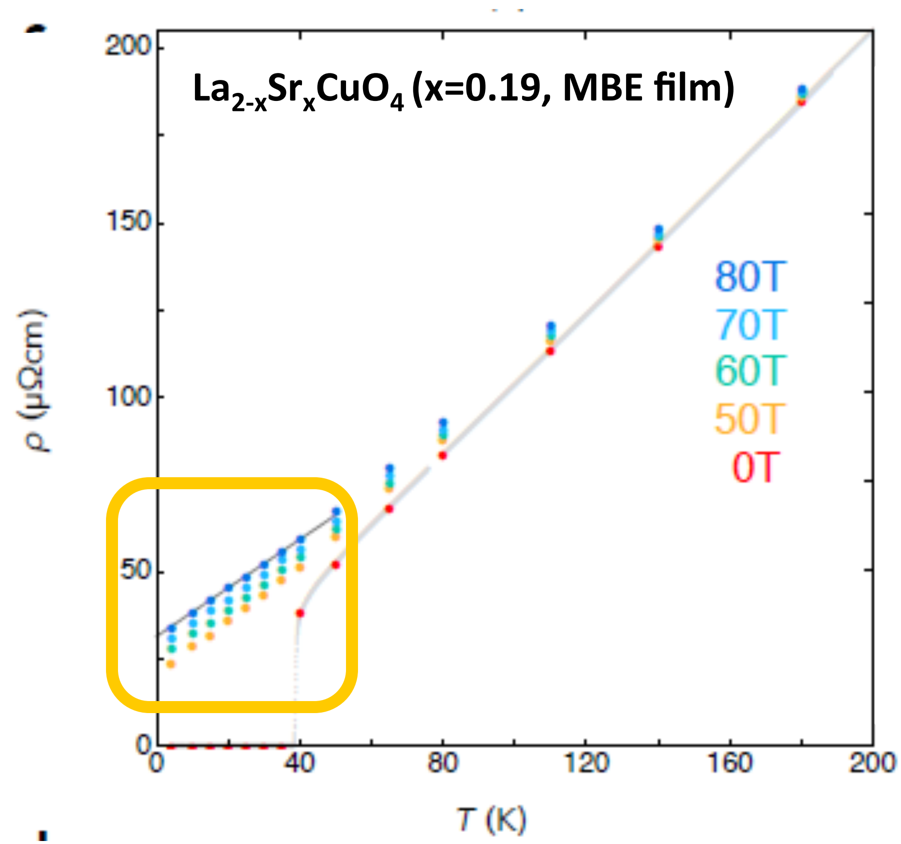


Linear-in-T and Linear-in-B Regimes Coexist !

For T < 50K and B > 50T, ρ(B) is linear in B



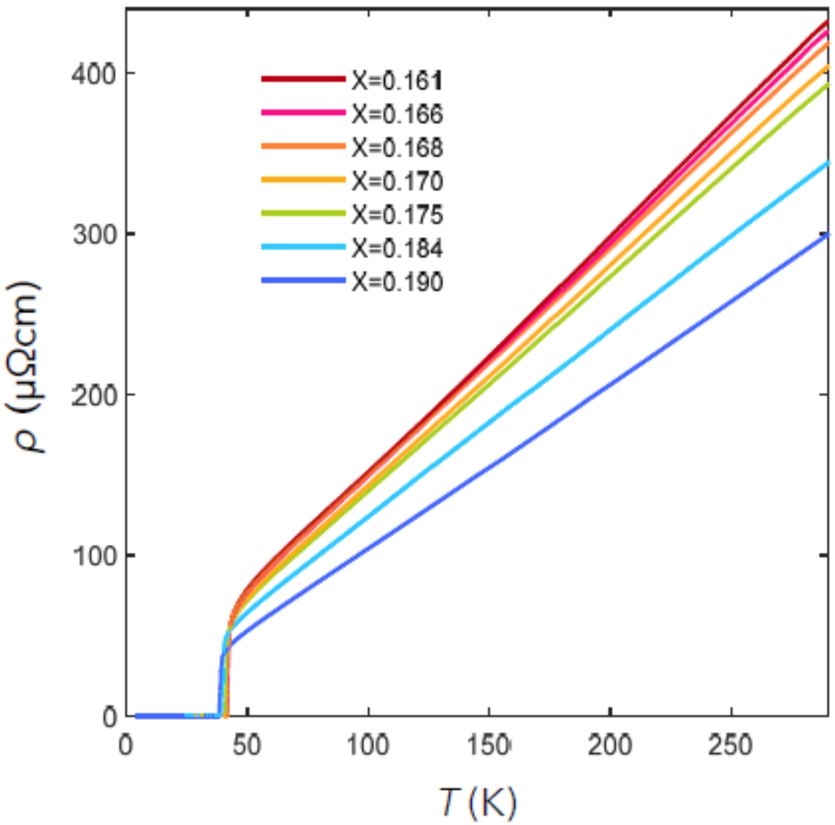
For T < 50K and B > 50T, ρ(T) is linear in T



This is inconsistent with the 'quadrature' behavior seen in Ba-122: $\rho(H,T) - \rho(0,0) \propto \sqrt{(\alpha k_B T)^2 + (\gamma \mu_B \mu_0 H)^2}$

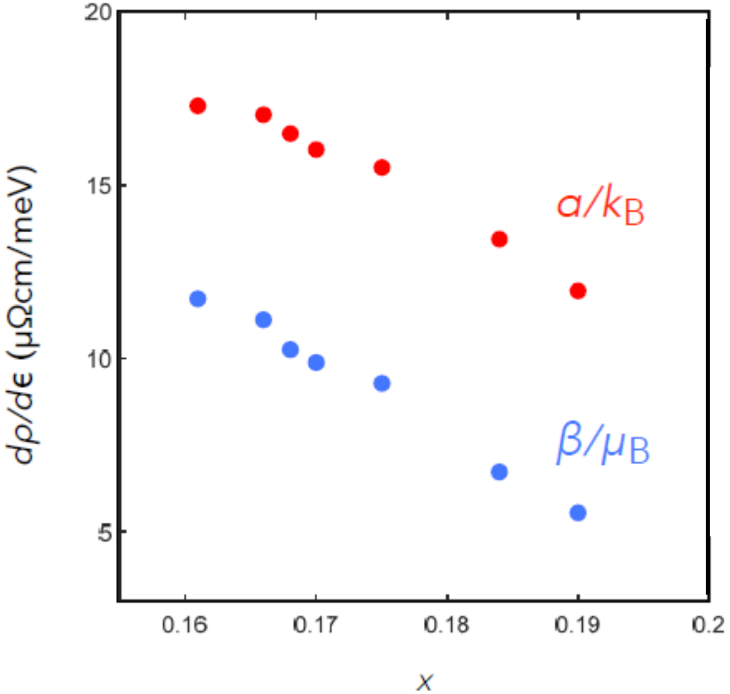
Doping Dependence of Linear-in-T and Linear-in-B Slopes

α and β track each other with doping



Ratio is O(1), but is not a constant:

~1.5 ~2.2



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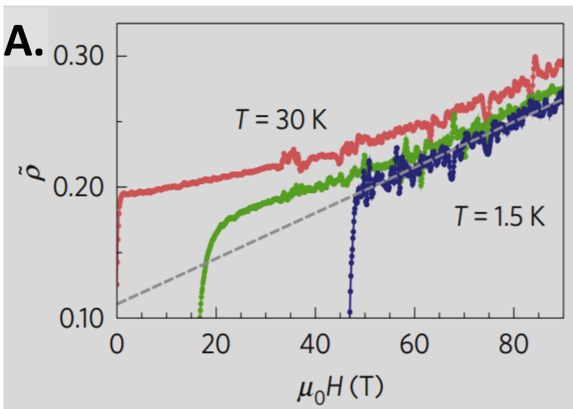

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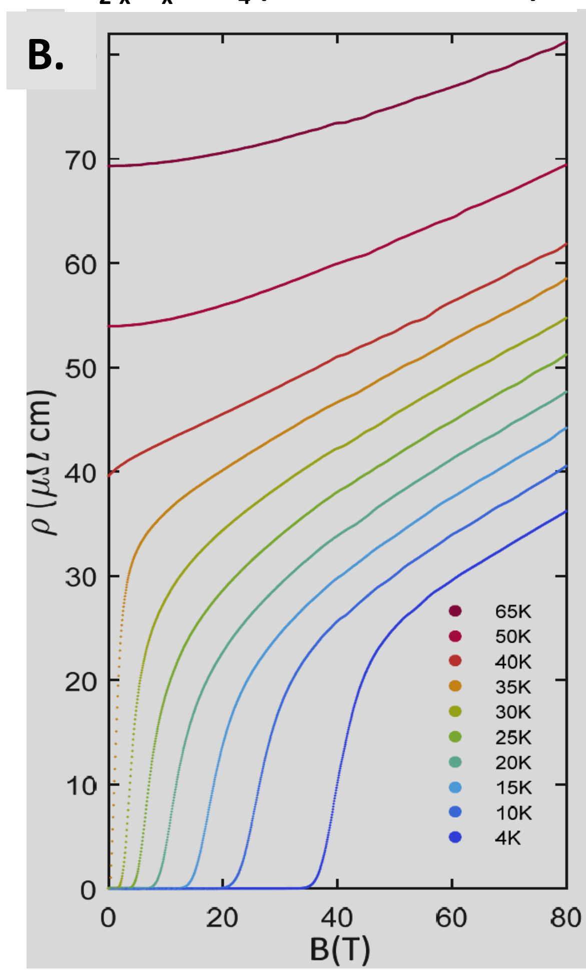

P. Giraldo-Gallo, et.al.
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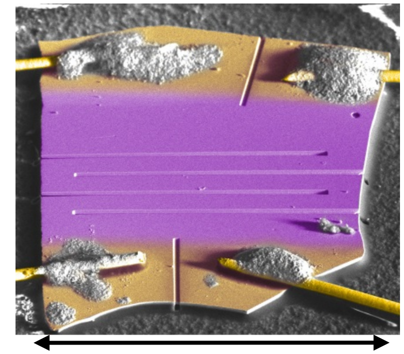
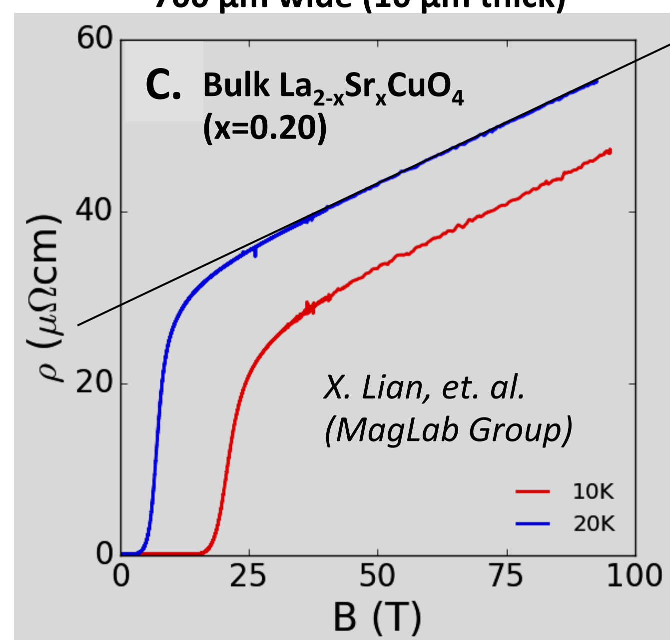
arXiv:1705.05806



700 μm wide (10 μm thick)



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Evidence for Enhanced Electron Mass near Optimum Doping in YBCO.

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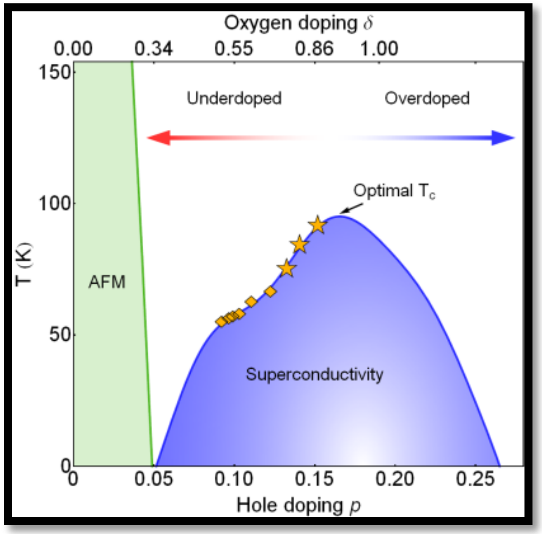
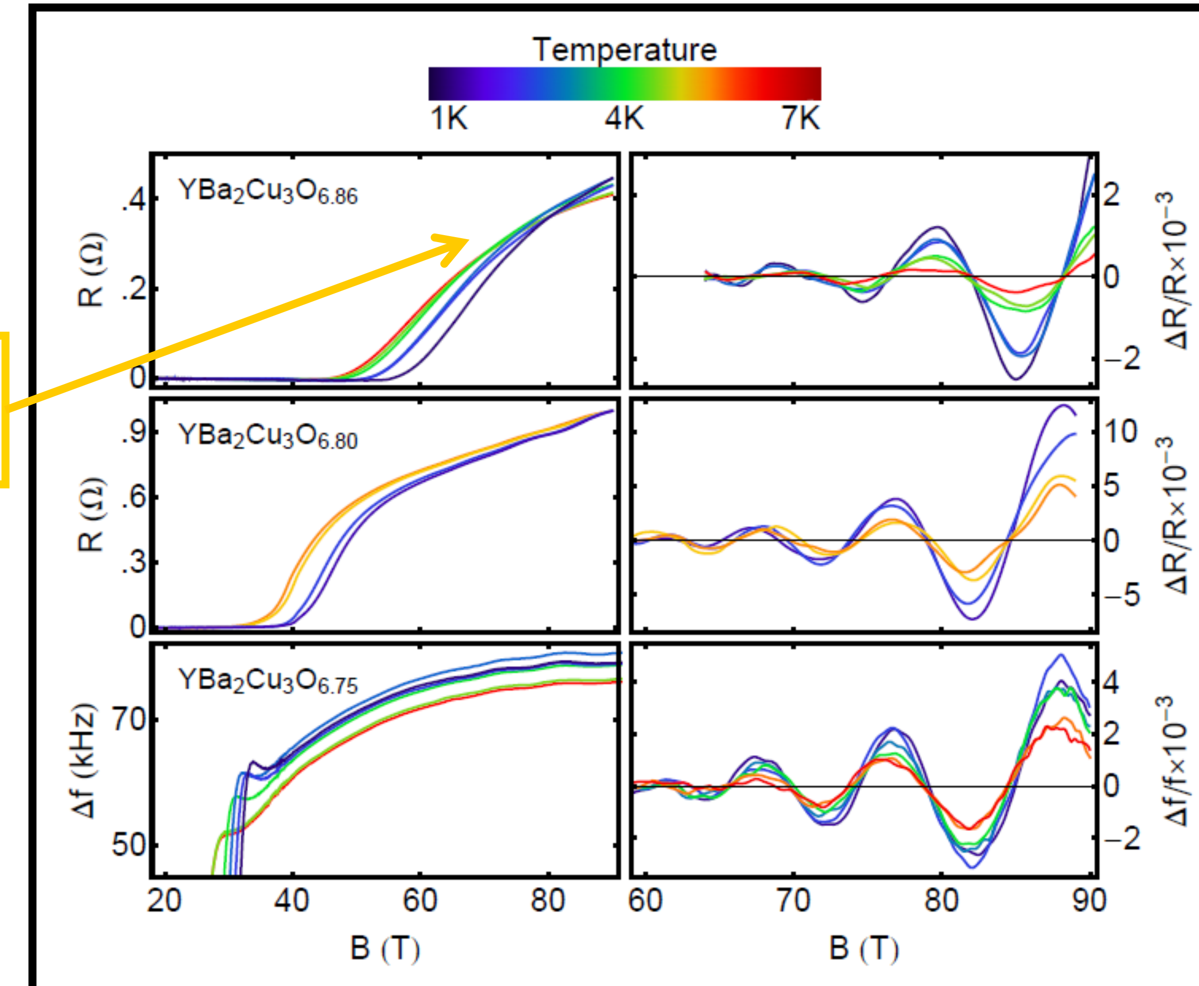


A Quantum Critical Point at the Heart of High-Temperature Superconductivity in YBCO

B. Ramshaw, S.E. Sebastian, R.D. McDonald, James Day, B. Tan, Z. Zhu, J.B. Betts, Ruixing Liang, D.A. Bonn, W.N. Hardy, N. Harrison

Science (2015) DOI: 10.1126/science.aaa4990



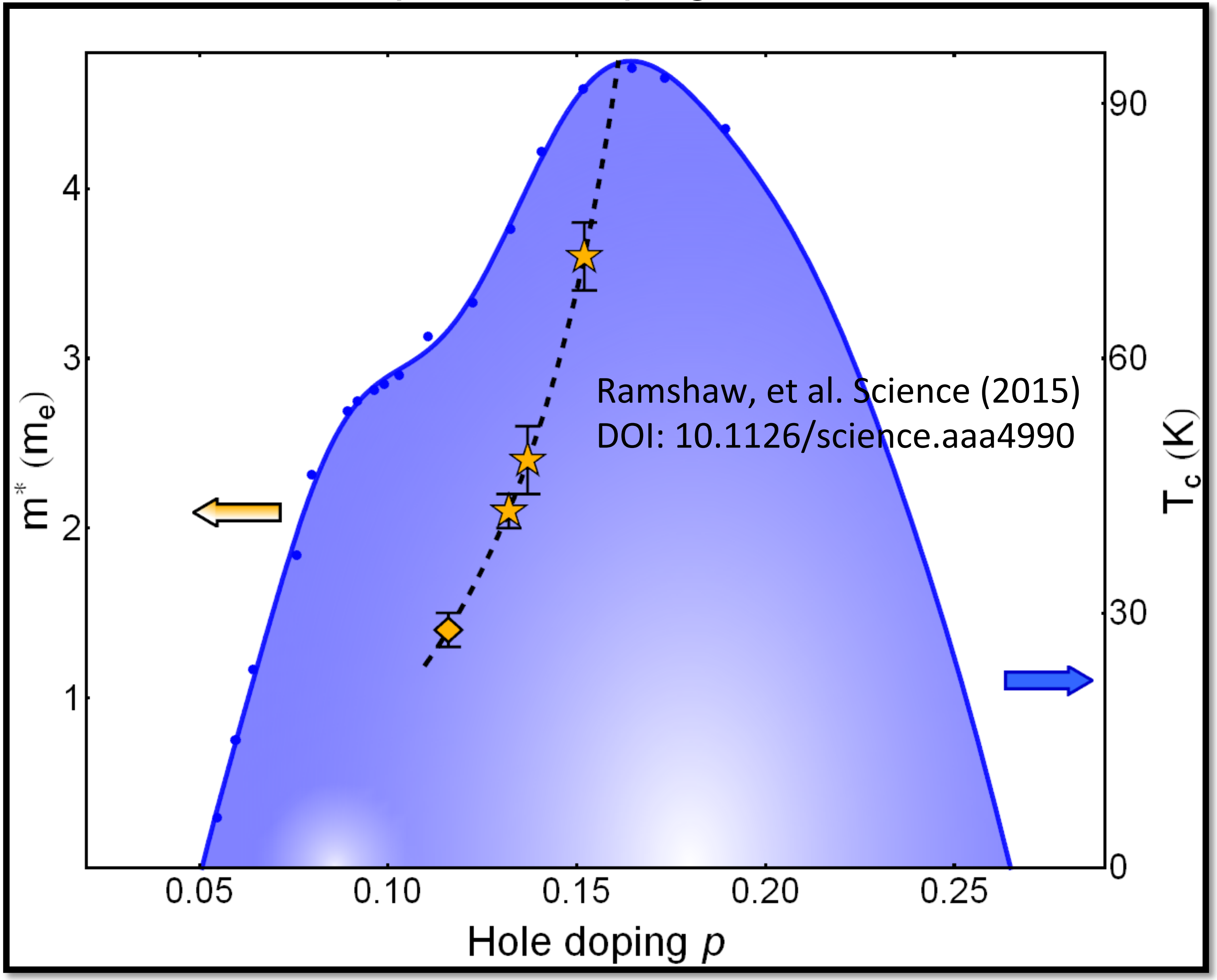
Tc ~ 91K

Tc ~ 81K

Tc ~ 75K

CLEARLY: We Need Bigger Magnets!

Diverging Effective Mass: Evidence of a Quantum Critical Point at Optimum Doping in YBCO



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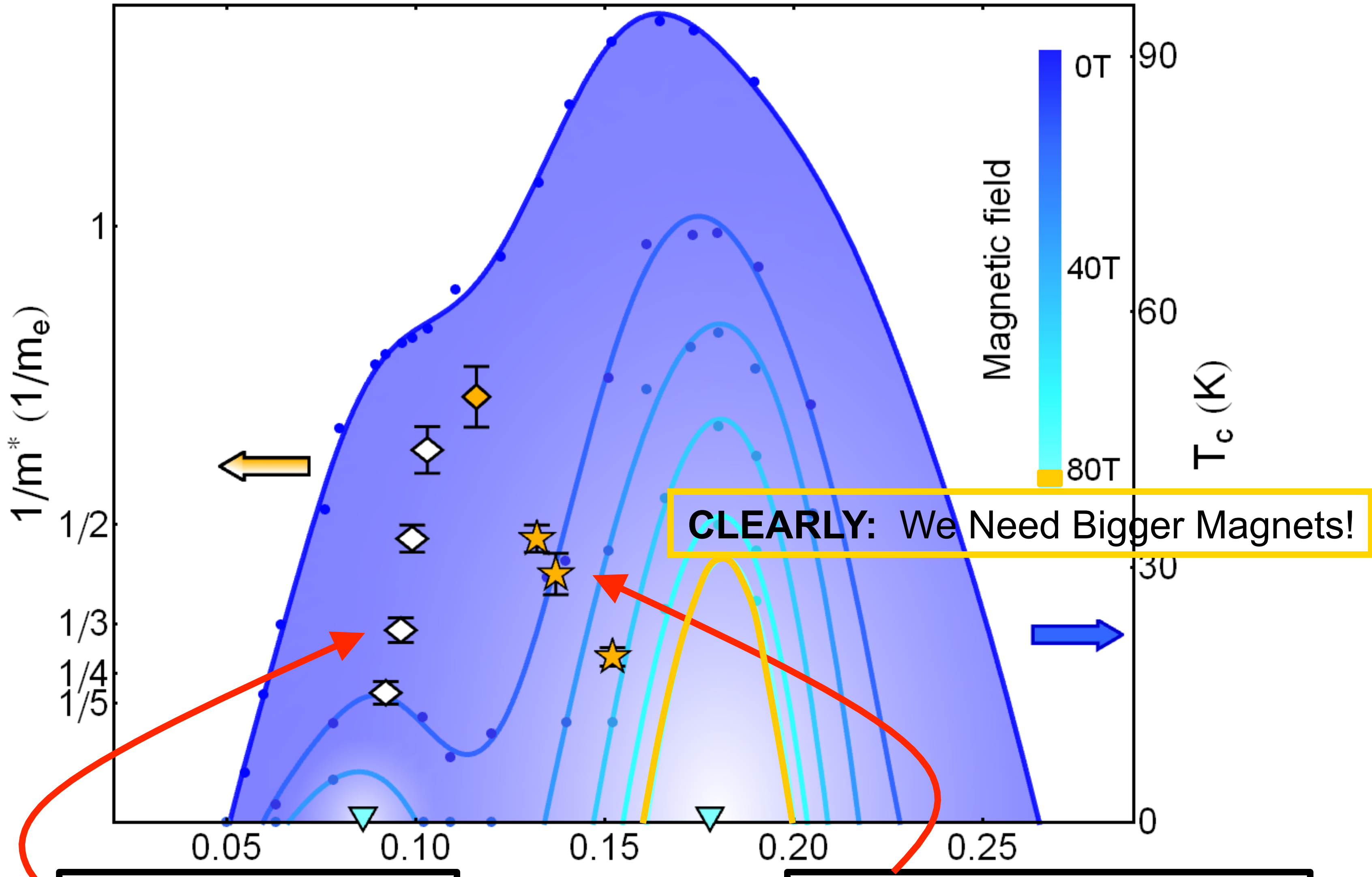

S.E. Sebastian *et al.*
PNAS **107**, 6175 (2010)

Ramshaw, et al. Science (2015)
DOI: 10.1126/science.aaa4990

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Specific Heat to measure Total Electronic Density of States that participates in superconductivity:

Evidence for Enhanced Electron Mass near Optimum Doping in a Pnictide.

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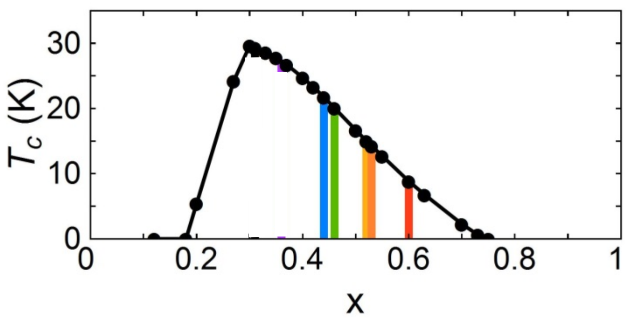
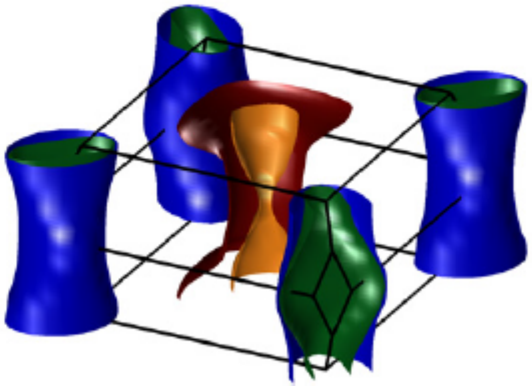
$BaFe_2(As_{1-x}P_x)_2$ Fermi Surface and Phase Diagram

We report on five dopings:

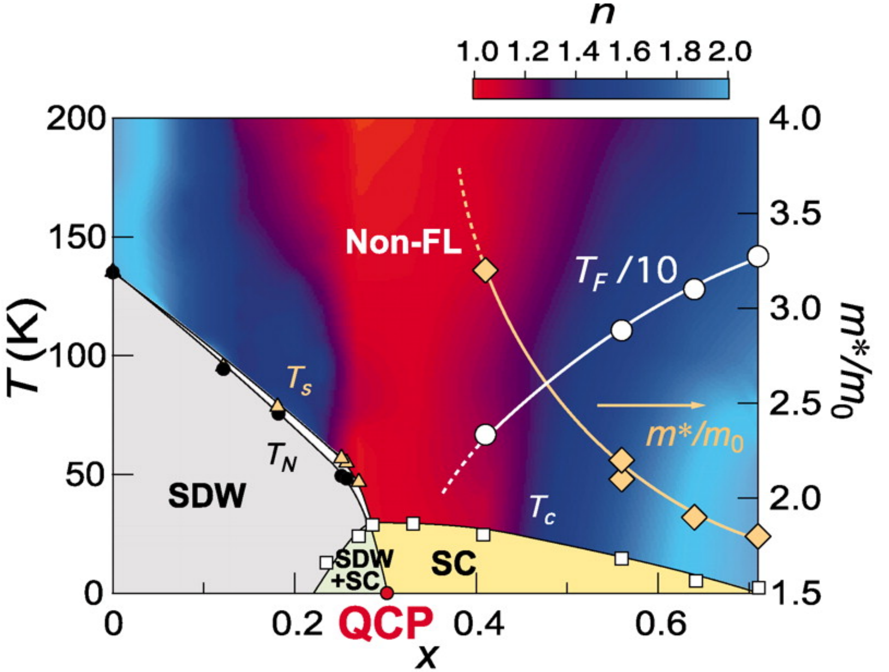




m* enhancement seen in β pocket (blue pocket)

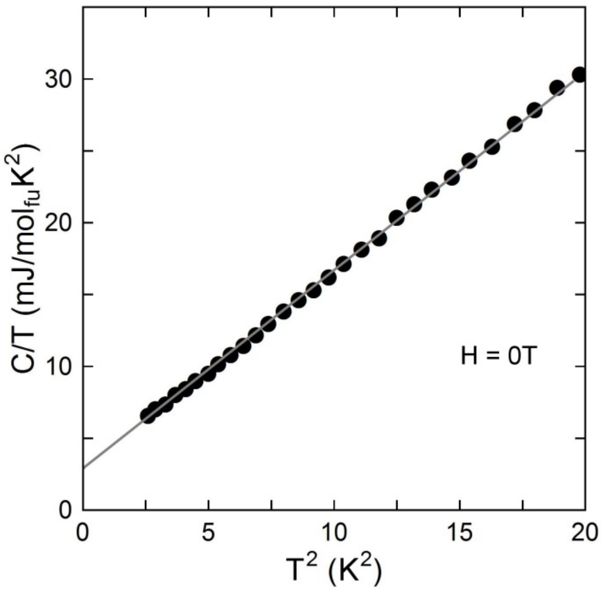
Carrington, A. *Rep. Prog. Phys.* **74**, 124507 (2011)

K. Hashimoto et al. *Science* 2012; **336**:1554-1557

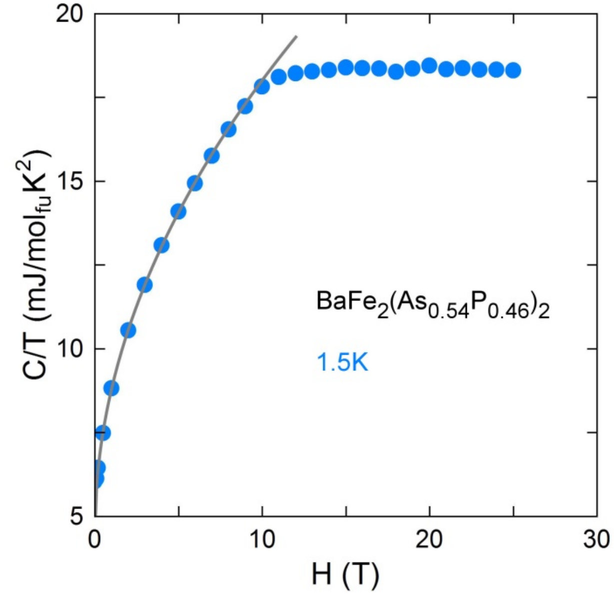


Our Specific Heat Measurements

The change in the specific heat from zero field to the 'normal state' measures the total normal state electronic density of states of all Fermi surface pockets that take part in superconductivity.



Temperature dependence shows standard linear dependence expected for C/T versus T^2 …for H=0… and at all magnetic fields.

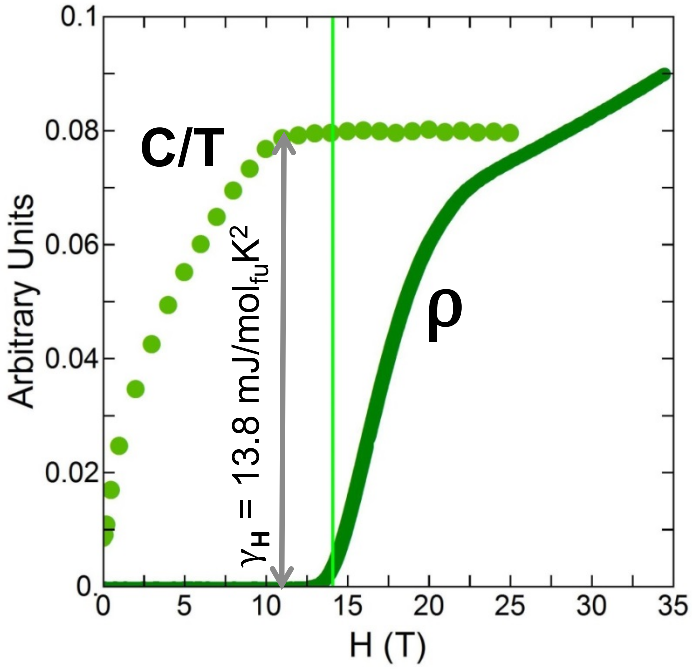


The $\sqrt{H}$ dependence indicates nodes in the superconducting gap. The saturation indicates reaching the normal state.

Moir, C.M. *et. al*. *arXiv:1608.07510* (2016).

Phenomenology of the Electronic Specific Heat recovered by Suppressing Superconductivity

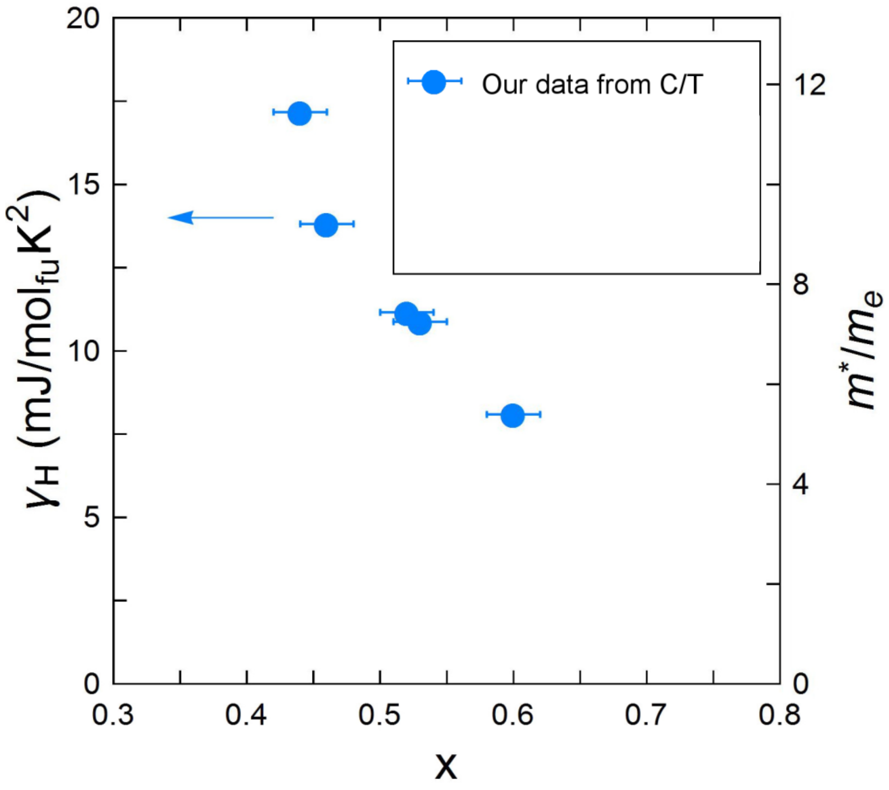
$BaFe_2(As_{0.54}P_{0.46})_2$
T = 1.5 K



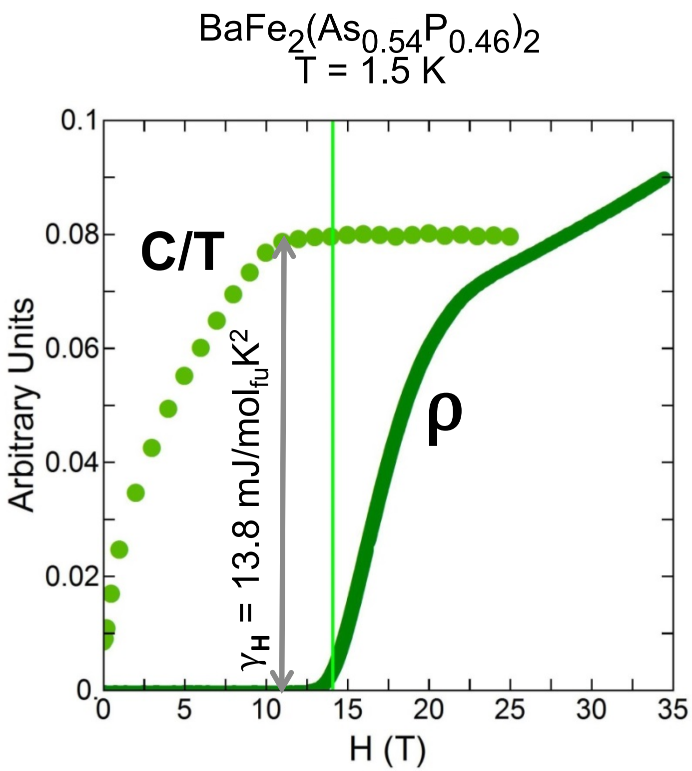
Saturation of specific heat occurs at the onset of finite resistance….implies that the bulk of the sample is non-superconducting at the onset of resistance.

Electronic density of states shows enhancement as x approaches optimum doping, x = 0.3.

$BaFe_2(As_{1-x}P_x)_2$

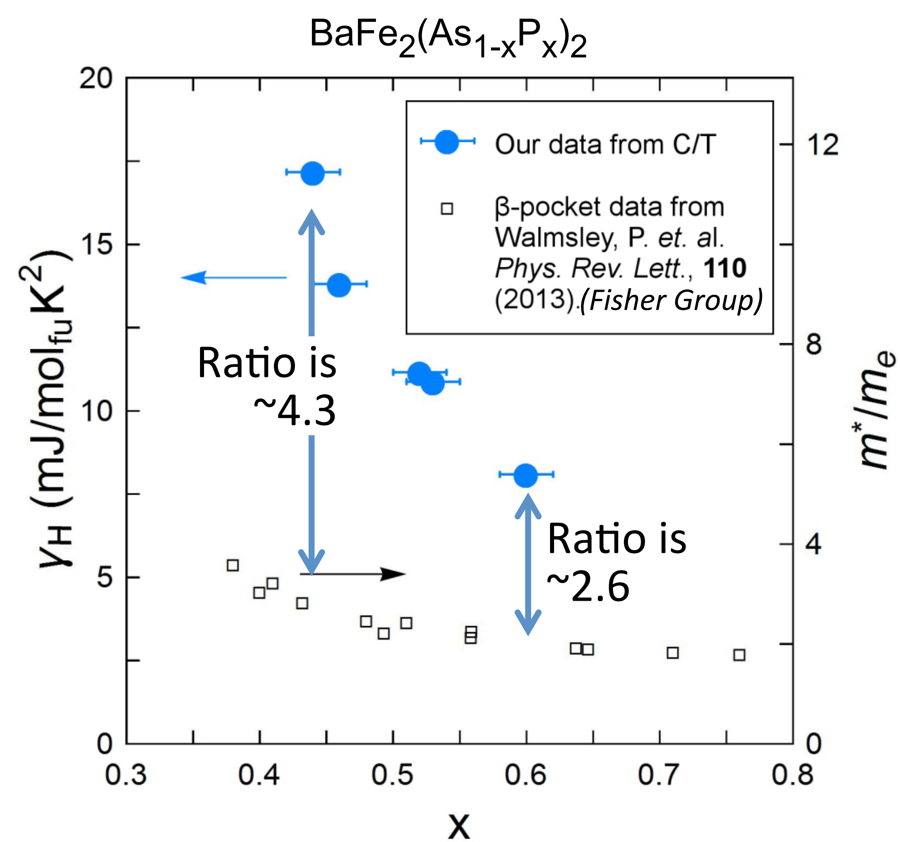


Specific Heat finds a greater enhancement than seen in the β pocket

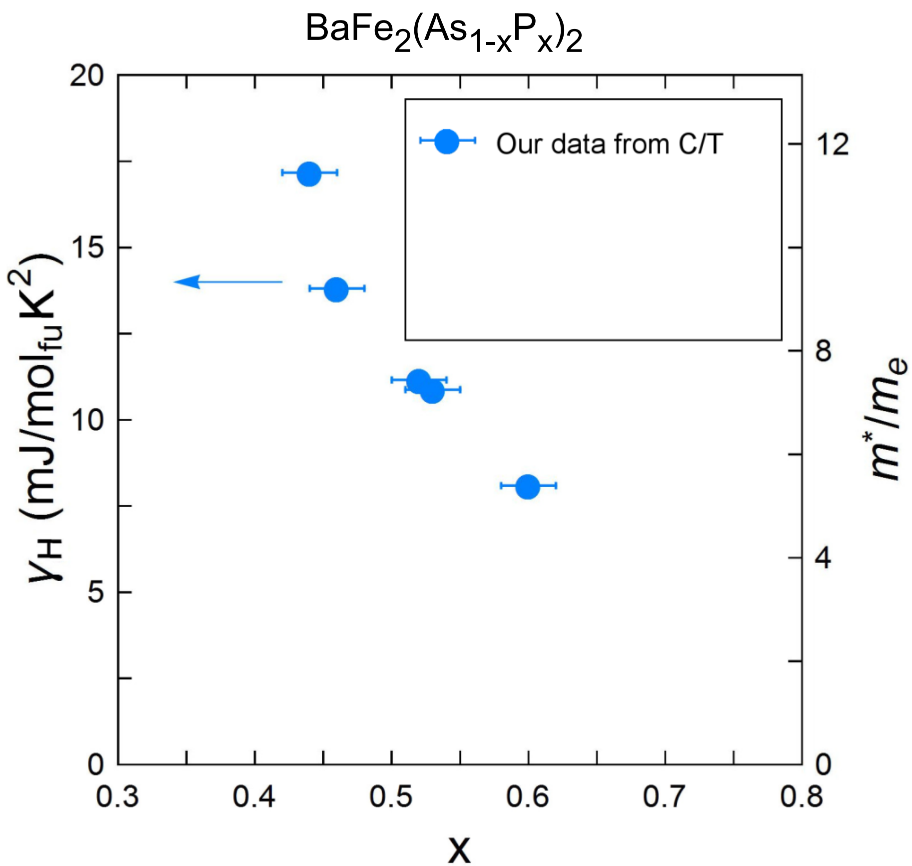


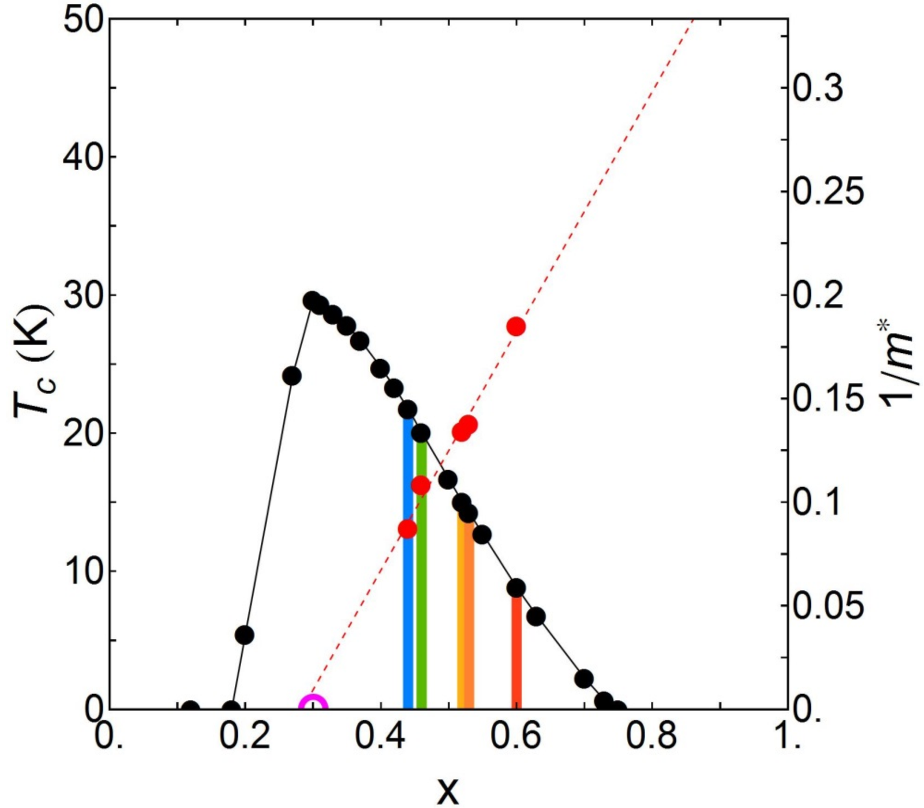
<u>Saturation of specific heat occurs at the onset of finite resistance</u>….implies that the bulk of the sample is non-superconducting at the onset of resistance.

Ratio of the two curves increases as doping approaches x=0.3 optimum doping



Mass Enhancement Appears to Diverge at Optimum Doping





An overview of evidence for a quantum critical point underlying the high-temperature superconducting dome

Phenomena near optimum doping….

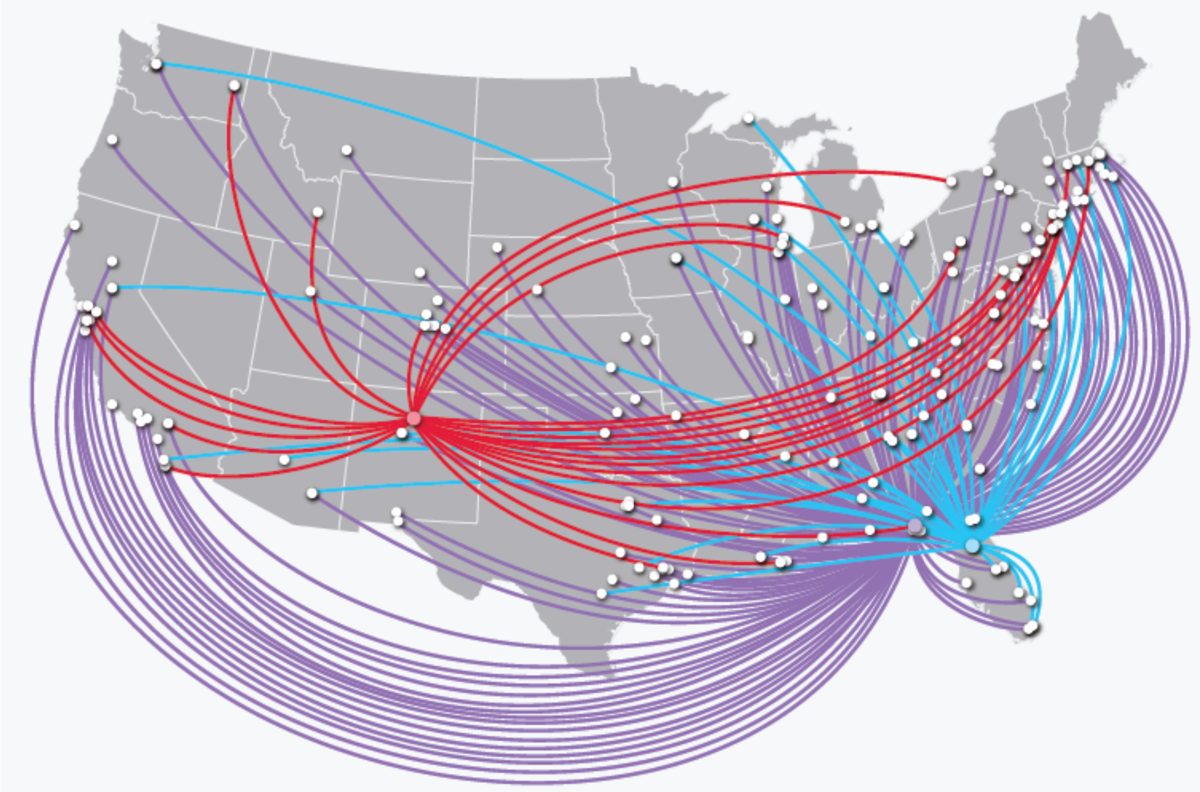
1. **Peak in the "Hall Number":** non-monotonic evolution of Hall effect evidences a quantum phase transition.

Phenomena evidencing a quantum critical point near optimum doping…

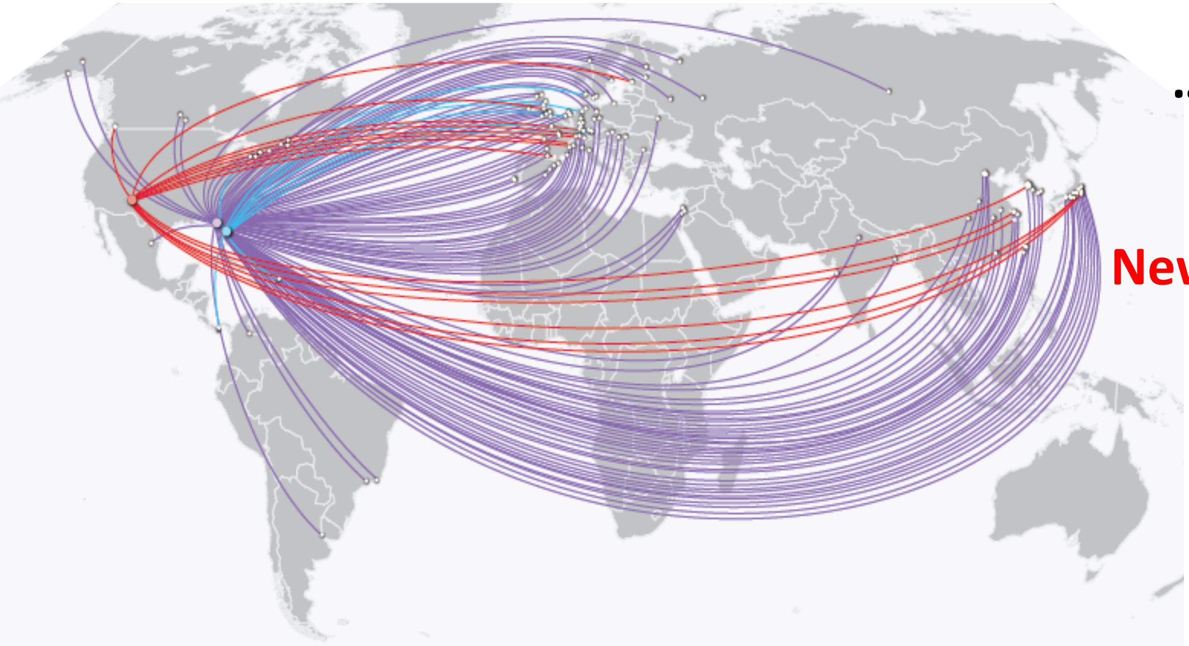
1. **Linear-in-T resistivity in the low temperature limit** in electron-doped cuprates, and hole-doped cuprates.
2. **Linear-in-H resistivity in the low-temperature limit** in both LSCO and Ba122
3. **Quasiparticle Mass Divergence** from YBCO quantum oscillations
4. **Quasiparticle Mass Divergence** from Ba122 quantum oscillations
5. **Quasiparticle Mass Divergence** from Ba122 specific heat

NATIONAL HIGH MAGNETIC FIELD LABORATORY

The MagLab IS Its User Program



In 2016, the MagLab hosted experiments by **1,778 users** from **174 institutions across the United States…**



…and a total of **321 institutions throughout the world.**

Newcomers are welcome: in 2016 24% of Principal Investigators were first-time MagLab PI's

Thank You

CLEARLY: We Need Bigger Magnets!

NATIONAL MAGLAB

Scaling in Ba122 Background Slides

Scaling between magnetic field and temperature in the high-temperature superconductor $BaFe_2(As_{1-x}P_x)_2$

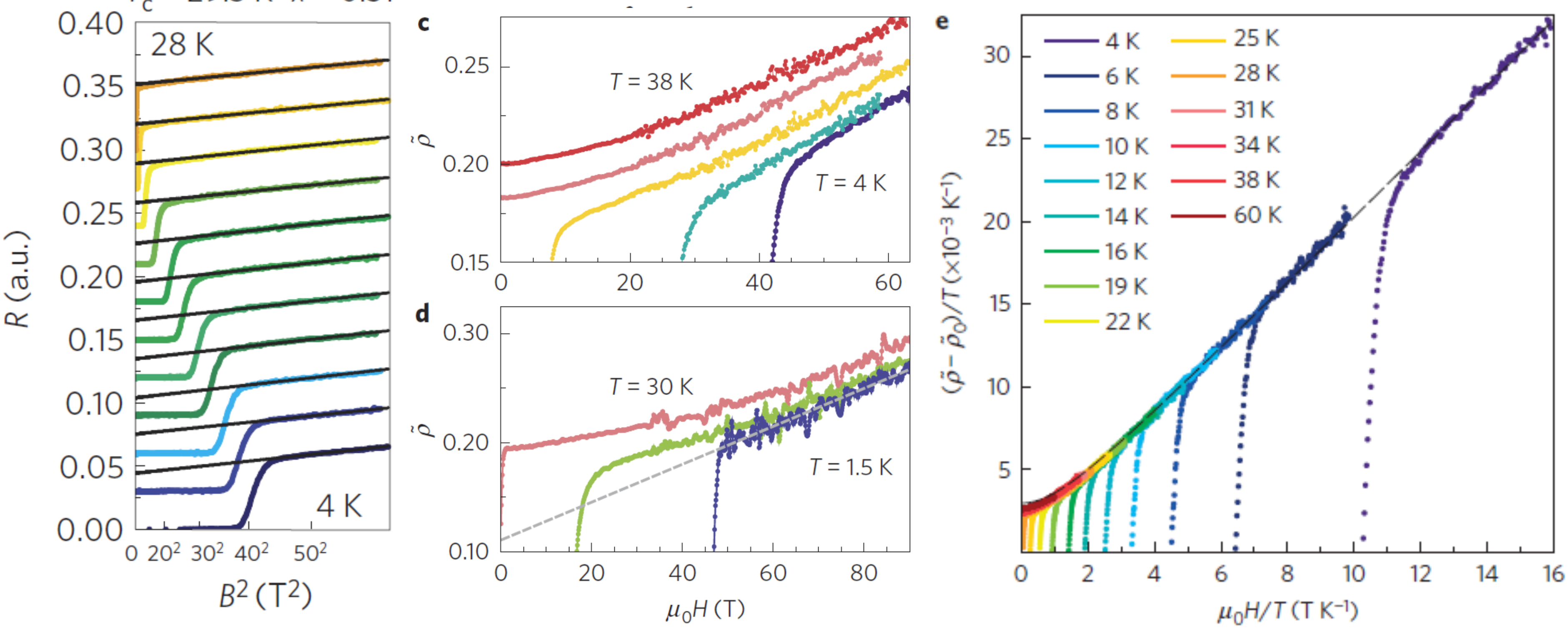
Ian M. Hayes[1,2], Ross D. McDonald[3], Nicholas P. Breznay[1,2], Toni Helm[1,2], Philip J. W. Moll[1], Mark Wartenbe[4], Arkady Shekhter[4] and James G. Analytis[1,2]*

16 MAY 2016 | DOI: 10.1038/NPHYS3773

$$\rho(H,T) - \rho(0,0) \propto \sqrt{(\alpha k_B T)^2 + (\gamma \mu_B \mu_0 H)^2} \equiv \Gamma$$

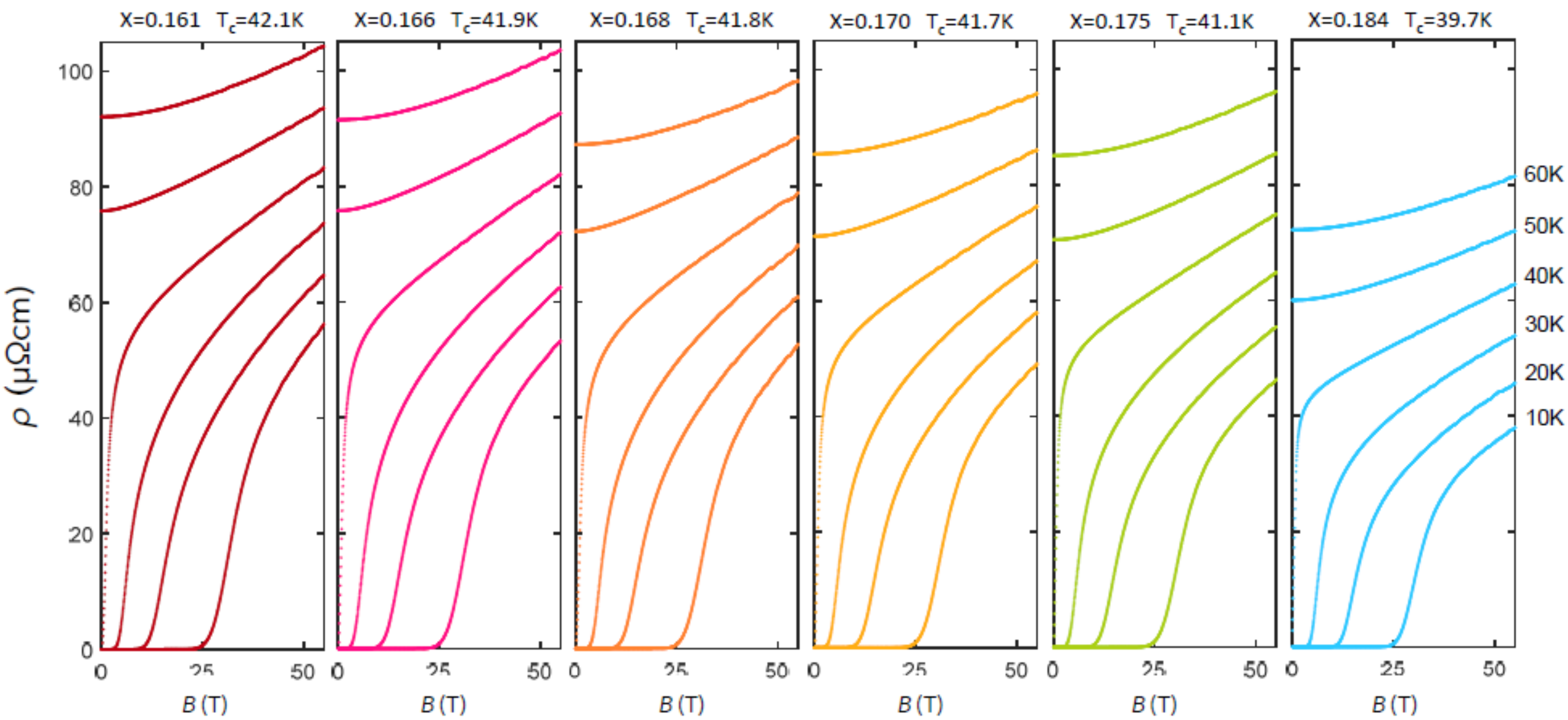
$T_c = 29.5$ K $x = 0.31$

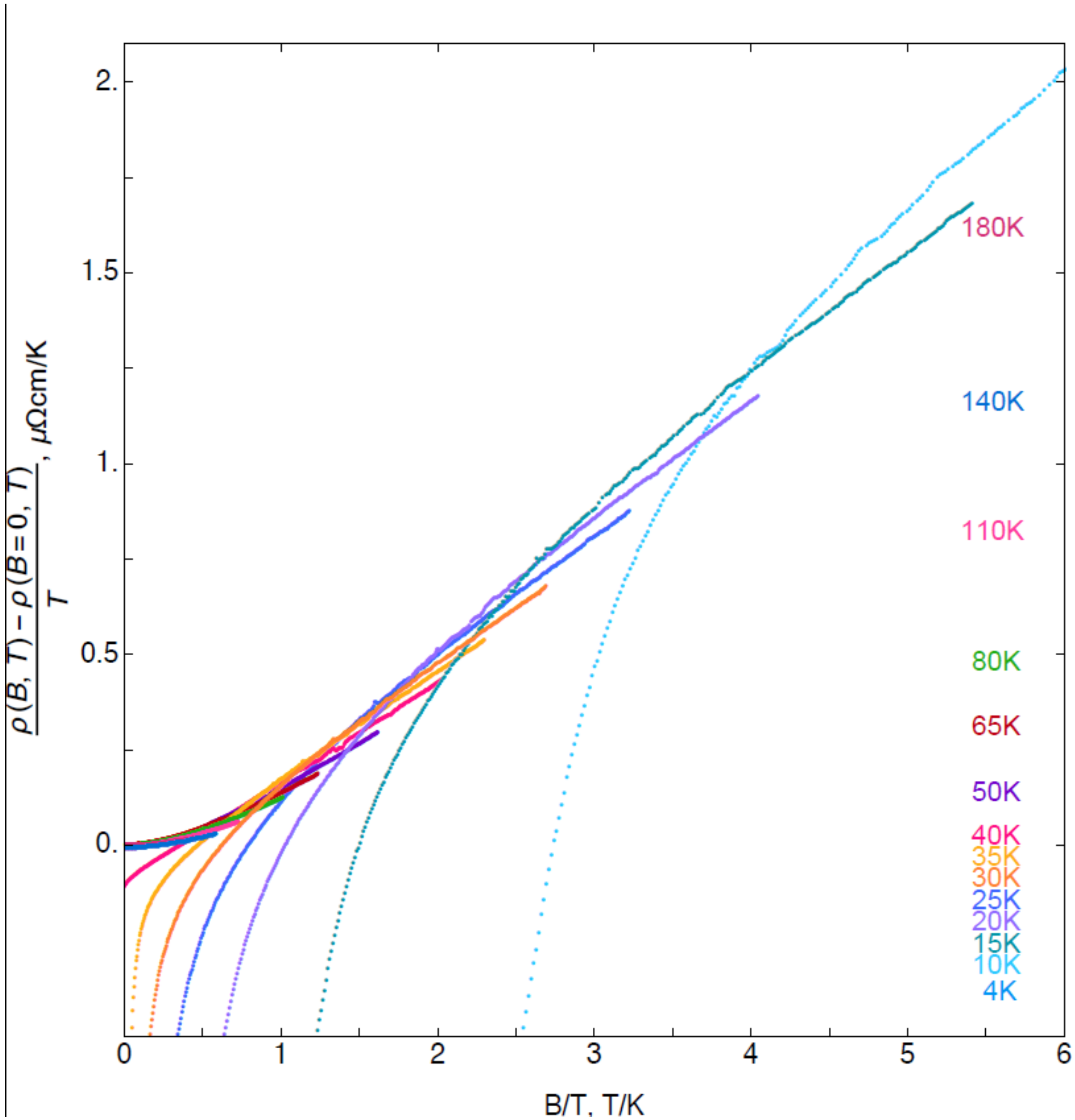
$$\tilde{\rho} = \rho/\rho(300).$$



Linear-in-H in LSCO
and Scaling in LSCO
Background Slides

Doping Dependence of Linear-in-B Slopes





$\frac{\rho(B,T)-\rho(B=0,T)}{T}$, μΩcm/K
B/T, T/K
180K
140K
110K
80K
65K
50K
40K
35K
30K
25K
20K
15K
10K
4K
0.
0.5
1.
1.5
2.
0
1
2
3
4
5
6

Our Specific Heat Measurements Background Slides

Comparison of Specific Heat and Resistive Transitions