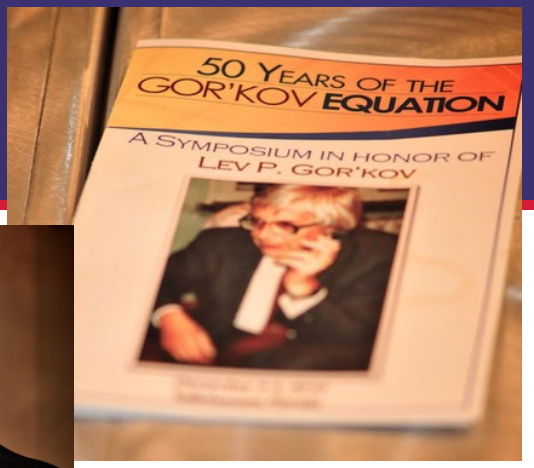
The 2010 LevFest in Tallahassee

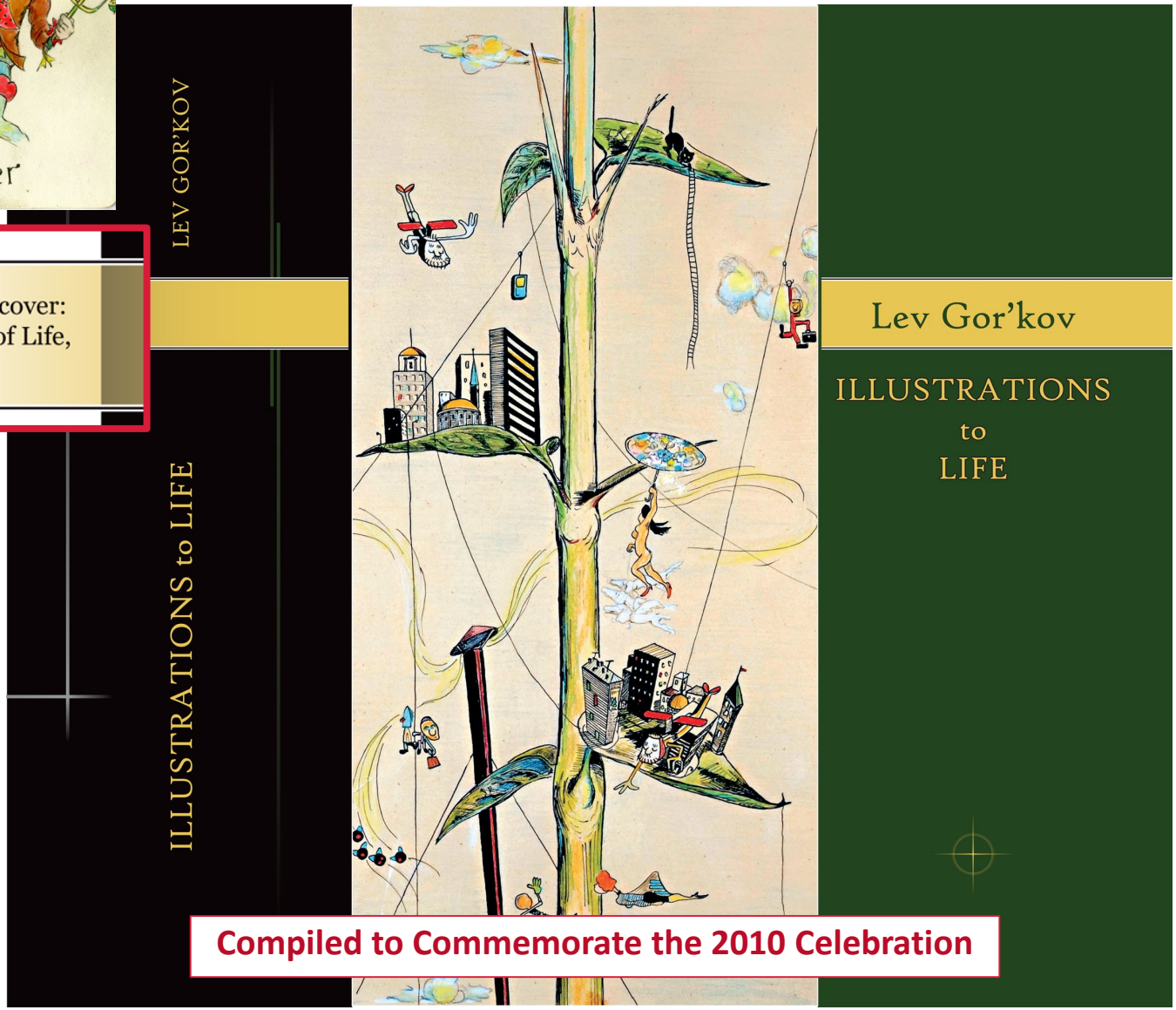


Celebrating Lev's 80th Birthday (when he was 81) and Celebrating 50 Years of the Gor'kov Equation

The 2010 LevFest in Tallahassee

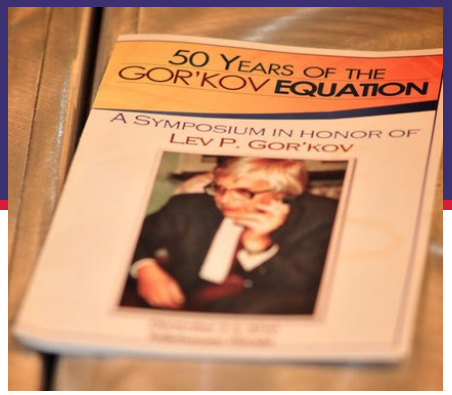
Front cover:
Stem of Life,
1964.

The Untitled Drawing on the Back Cover



Compiled to Commemorate the 2010 Celebration

The 2010 LevFest in Tallahassee



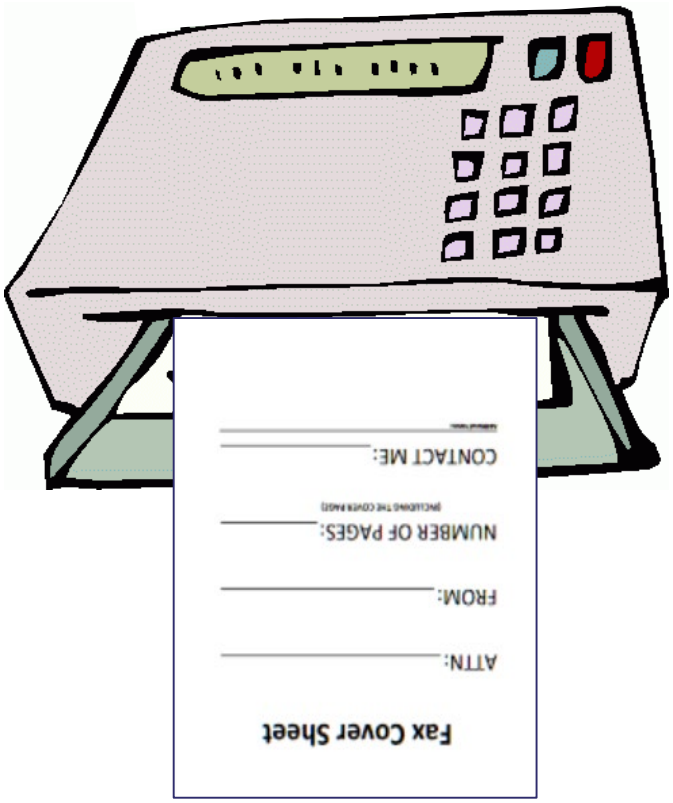
What was it like to be Lev's "boss"? (His word. Not mine!)

1. The university bureaucracy insisted that I evaluate Lev's work:
Lev: *"Here, boss, this is a list of what I have tried to accomplish this year."*
Greg: "This is exceeds Florida State University's high performance standards."

2. Virtually every interaction
(a) began with a smile and
(b) ended with laughter.

3. When Lev laughed, I almost always understood what he was laughing about.
When Lev smiled broadly, I thought I understood only 50% of the time…
…but when Lev was only smiling a little…

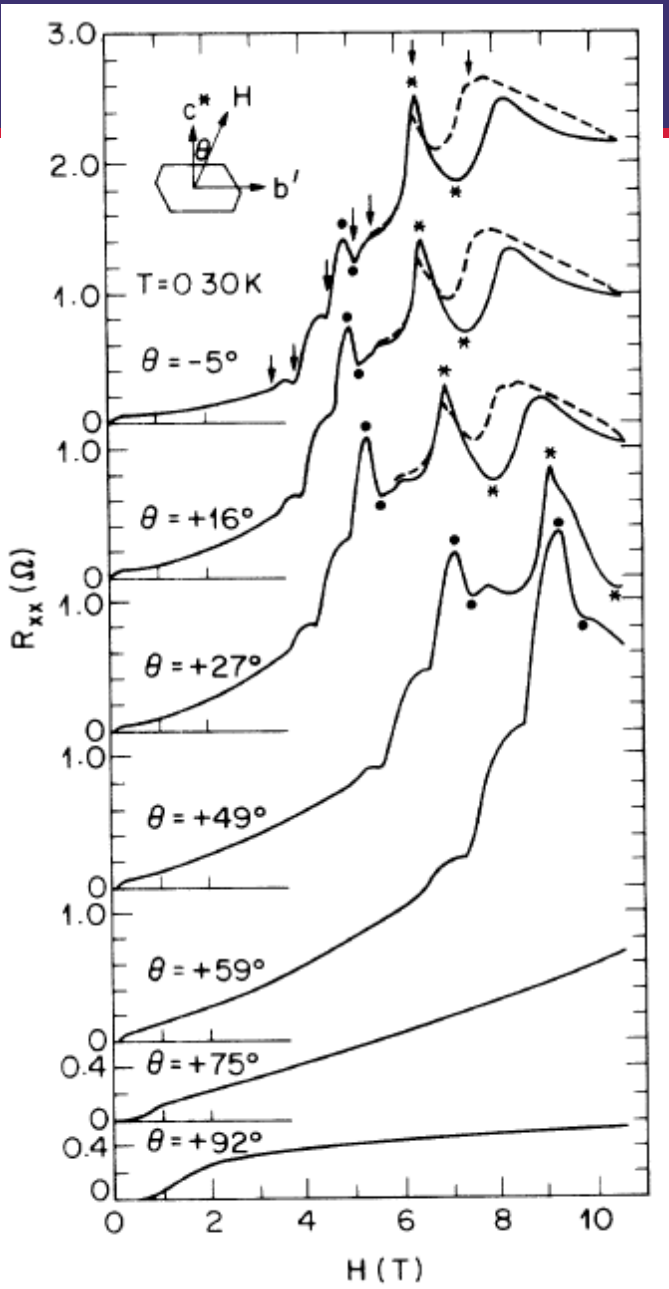
The First Time I Encountered Lev Gor'kov (1990)



Greg's Story: Fuzzy Dot-Matrix Paper Emerging from Fax Machine

Leonid's Story: Inspirational Lights in the Sky

We had interesting data in a Quasi-1D Metal



Magnetic Field Induced
Spin Density Wave
Transitions in (TMTSF)2ClO4
[later appeared in PRL 64, 591 (1990)]

L.P. Gor'kov and A.G. Lebed (1984)
Motion in Real Space for Quasi-1D Electrons

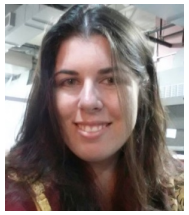
Anisotropy of an instability for a spin density wave induced by a magnetic field in a *Q1D* conductor

A. G. Lebed'
L. D. Landau Institute of Theoretical Physics, Academy of Sciences of the USSR

(Submitted 24 December 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 3, 137–139 (10 February 1986)

The threshold field for the formation of a spin density wave in $(TMTSF)_2X$ compounds is shown to have an oscillatory anisotropy in the plane perpendicular to the chains, **H**⊥**a**. This field is at a minimum for the direction making an angle $\varphi \approx 30°$ with the c^* axis.

(Using High Magnetic Fields to Reveal…) Evidence of Critical Behavior near Optimum Doping in High-Temperature Superconductors



Camilla M. Moir, Scott Riggs, Jose Galvis, Paula Giraldo-Gallo, Xiujun Lian, Philip Walmsley, Jiun-Haw Chu, Ian R. Fisher, Arkady Shekhter, GSB

"Multi-band mass enhancement towards a critical doping in a pnictide superconductor." $BaFe_2(As_{1-x}P_x)_2$

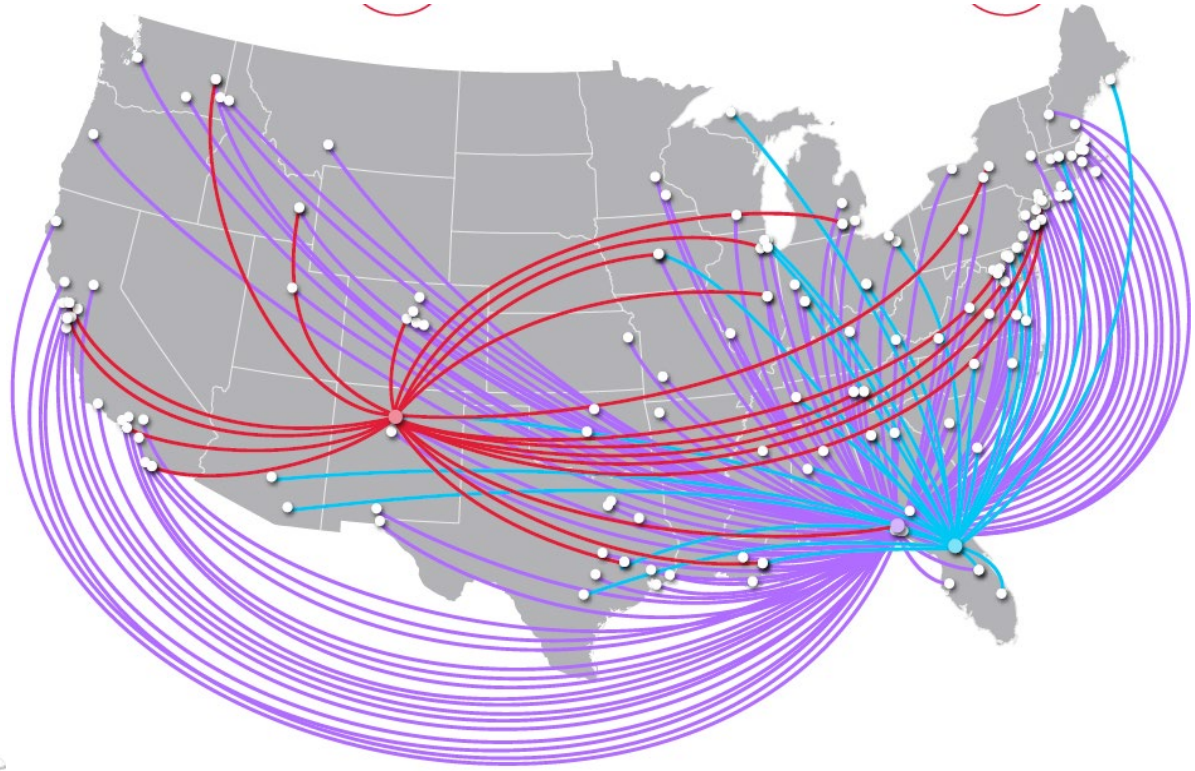
Nature Quantum Materials **4** (2019) DOI: 10.1038/s41535-018-0144-x.

NATIONAL HIGH MAGNETIC FIELD LABORATORY

FLORIDA STATE UNIVERSITY 1851 VIRES ARTES MORES

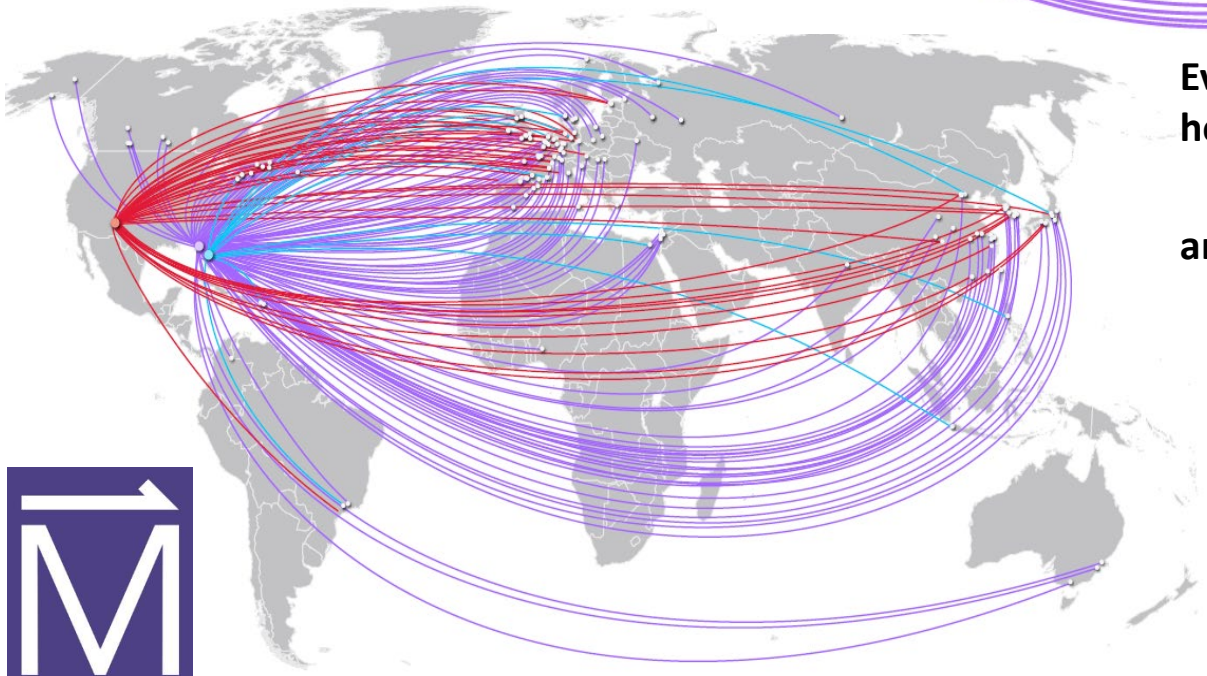
NSF

The MagLab attracts Researchers from Around The World



In 2018 alone, the MagLab hosted experiments by more than 2050 users from 162 institutions across the United States…

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



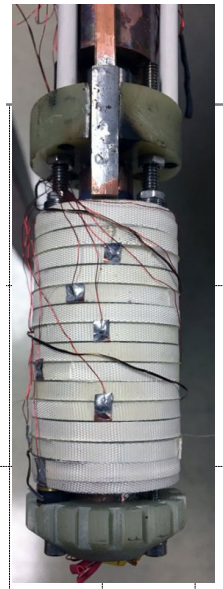
Every year…the MagLab User Program:
helps to train ~225 postdocs
and ~560 graduate students

and publishes ~450 refereed papers:

6	*Proc. Nat'l Acad. Sciences*
24	*Nature Journals*
20	*Physical Review Letters*
62	*Physical Review B*
9	*J American Chemical Society*

~ 25% of Principal Investigators are first-time-ever PI's at the MagLab

Peak Fields for Superconducting, Magnets



nature
International journal of science

Letter | Published: 12 June 2019

45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet

Seungyong Hahn, Kwanglok Kim, Kwangmin Kim, Xinbo Hu, Thomas Painter, Iain Dixon, Seokho Kim, Kabindra R. Bhattarai, So Noguchi, Jan Jaroszynski & David C. Larbalestier

The Phase Diagram in 2001:

Compilation of Evidence of a Quantum Phase Transition near Optimum Doping from High-Temperature Behaviors

J.L. Tallon, J.W. Loram, Physica C 349, 53 (2001)

"The doping dependence of T* - what is the real high-Tc phase diagram?"

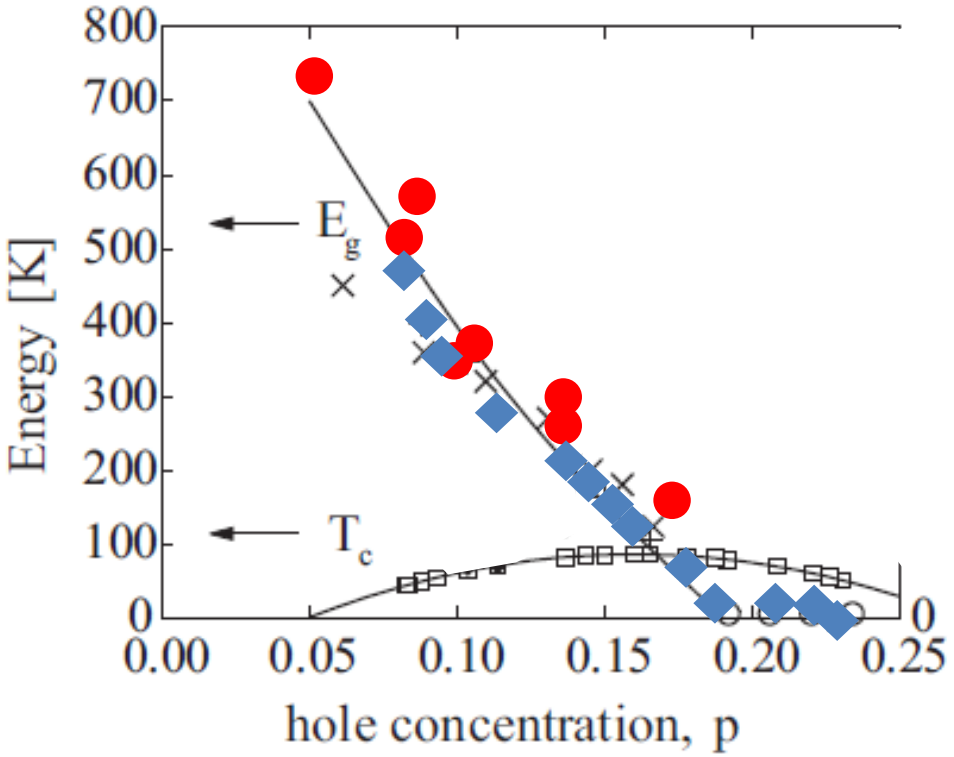
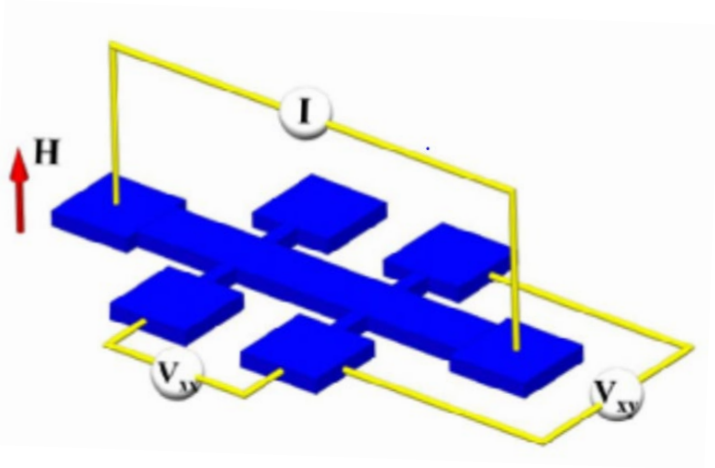


Fig. 4. The doping dependence of E_g for $Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{7-\delta}$ from $^{89}K_s$ (●), from heat capacity (◆) jump at *Tc* , from the scaling of the resistivity (x), and the superconducting *Tc* □).

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Using High Magnetic Fields to Evidence a Quantum Phase Transition near Optimum Doping in High Temperature Superconductors (LSCO and Bi-2201)

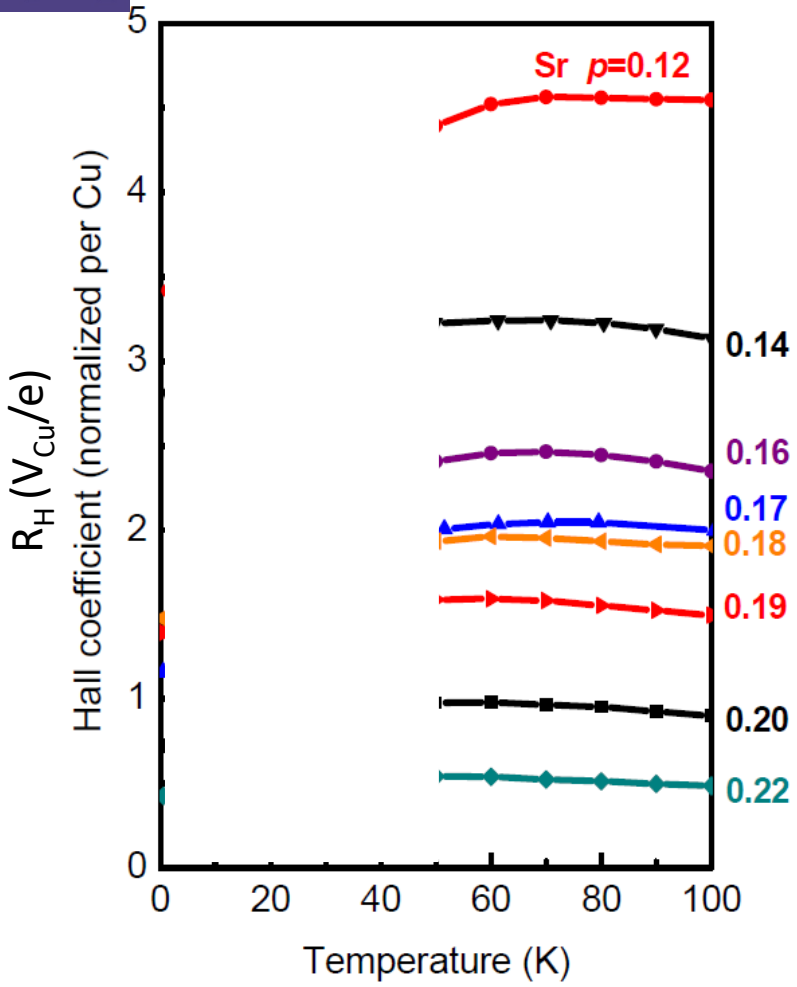


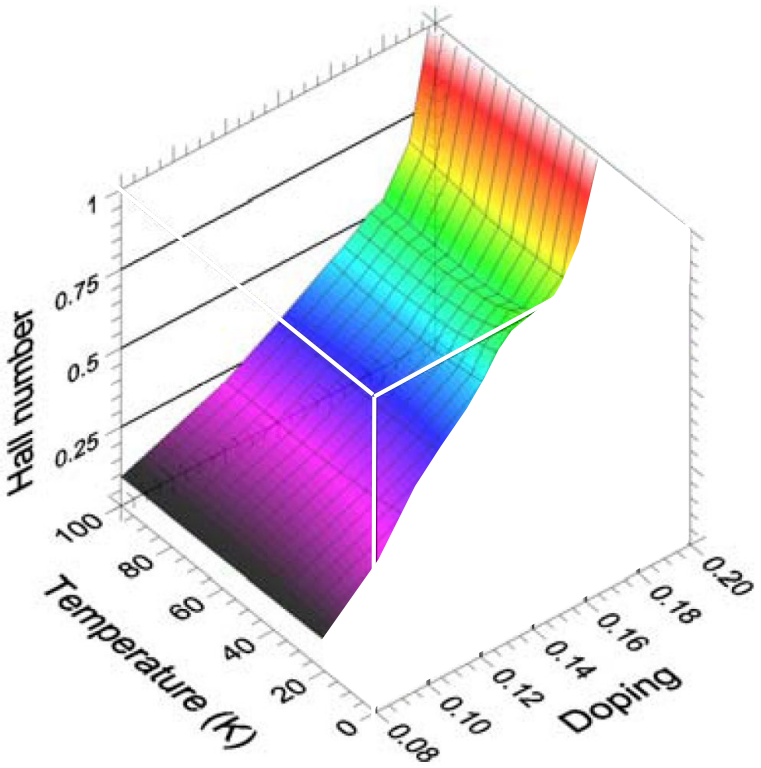
In a single band metal,

$V_{xy} / I = H/ne \equiv R_{hall} H$

"Hall number"

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

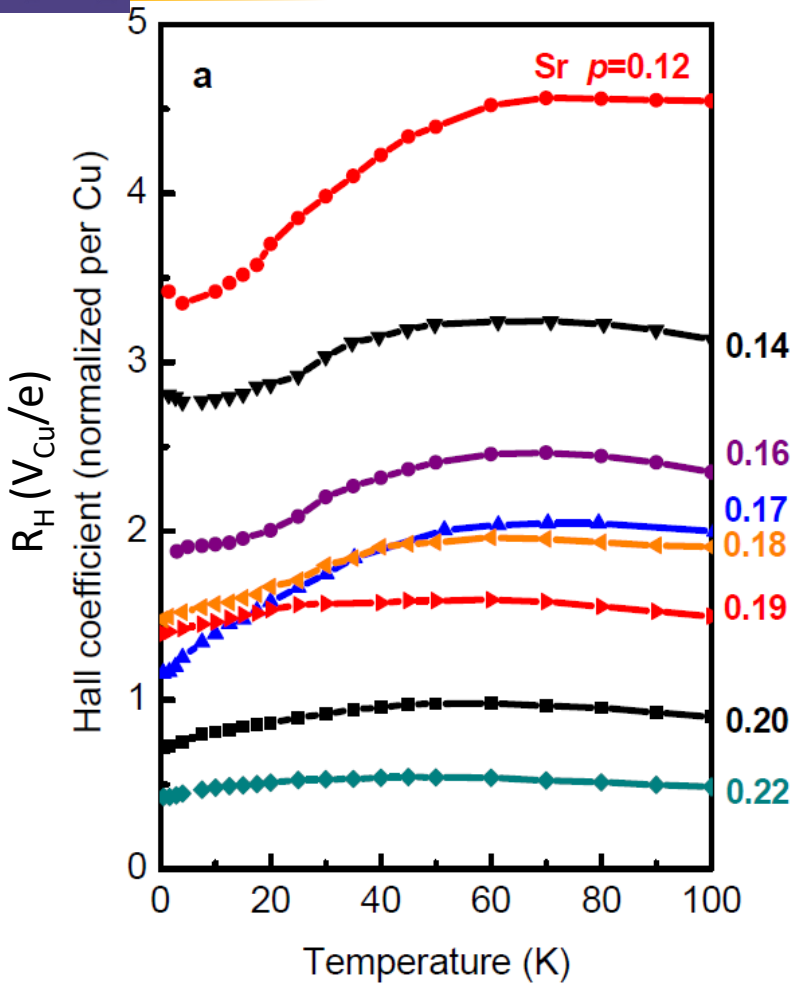


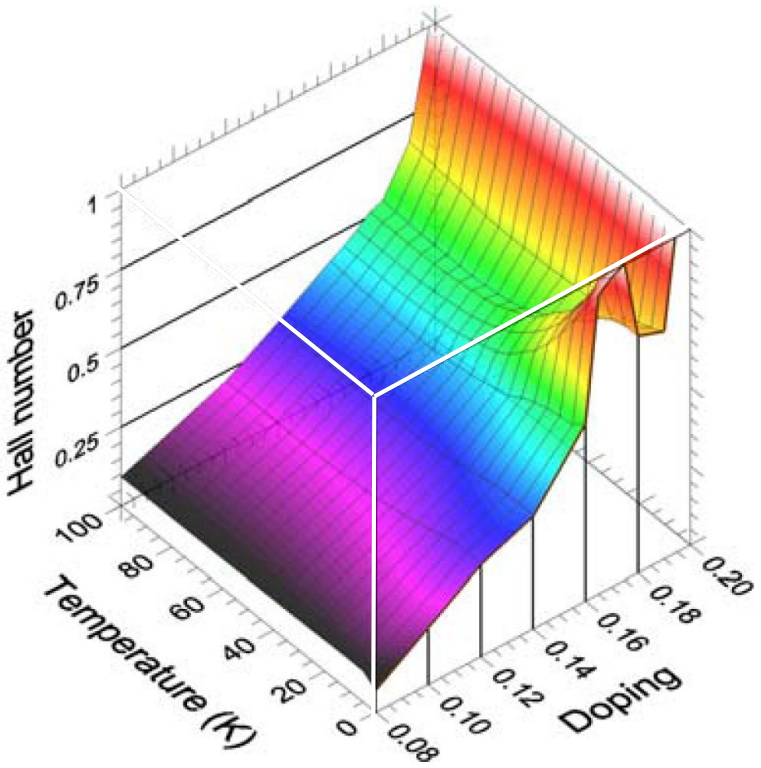


F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando, G. S. Boebinger, Phys.Rev.Lett. 102, 017004 (2009).

"Quantum Phase Transition in the Normal State of High-Tc Cuprates at Optimum Doping."

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).

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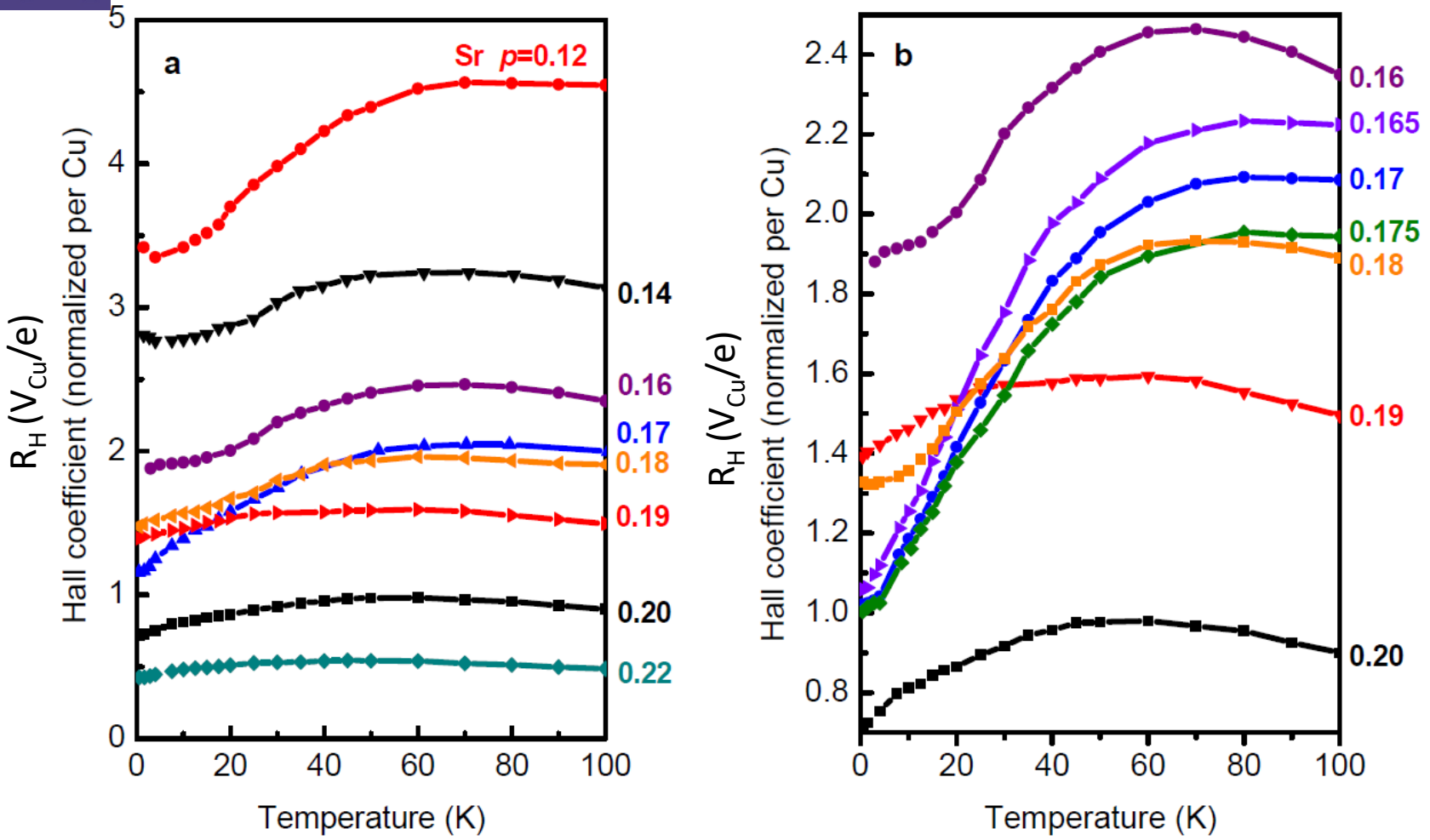

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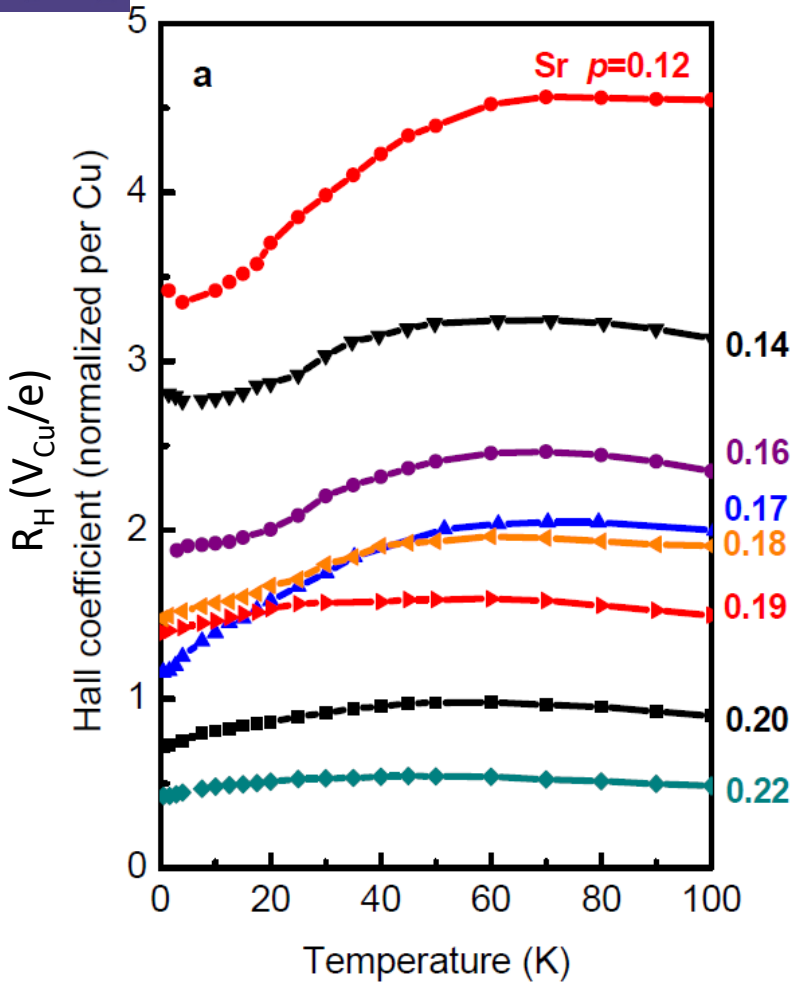
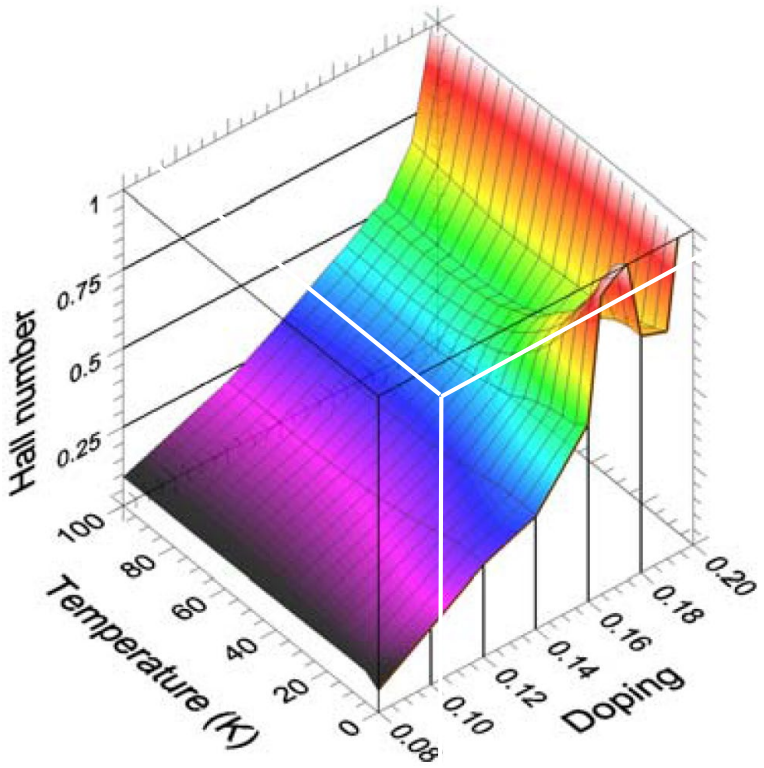




F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando, G. S. Boebinger, Phys.Rev.Lett. 102, 017004 (2009).

"Quantum Phase Transition in the Normal State of High-Tc Cuprates at Optimum Doping."

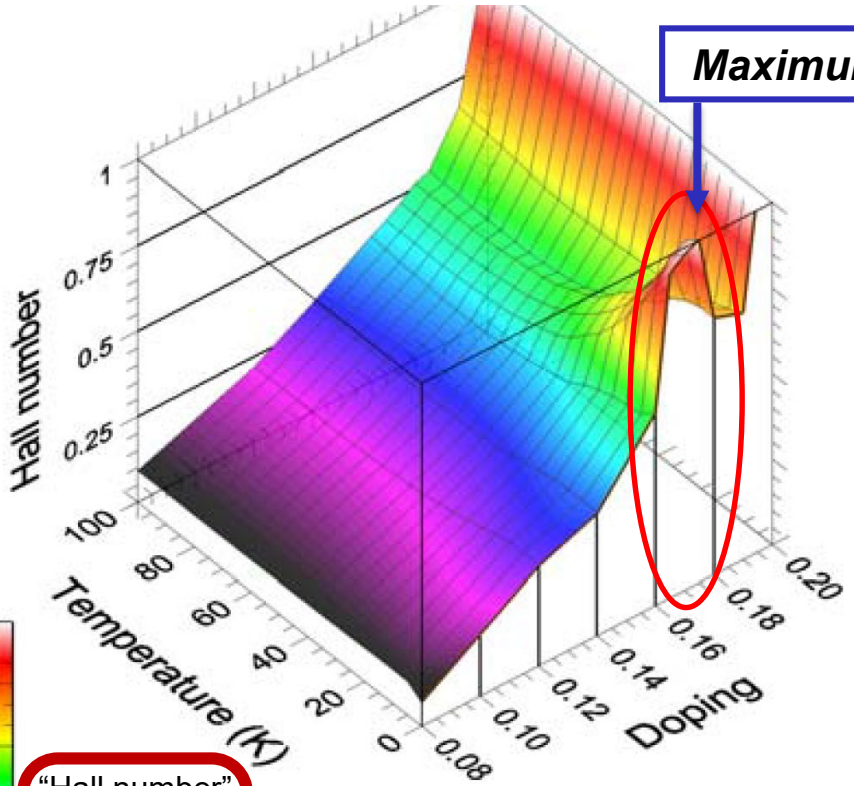
Peak in Hall Number near Optimum Tc seen in two systems

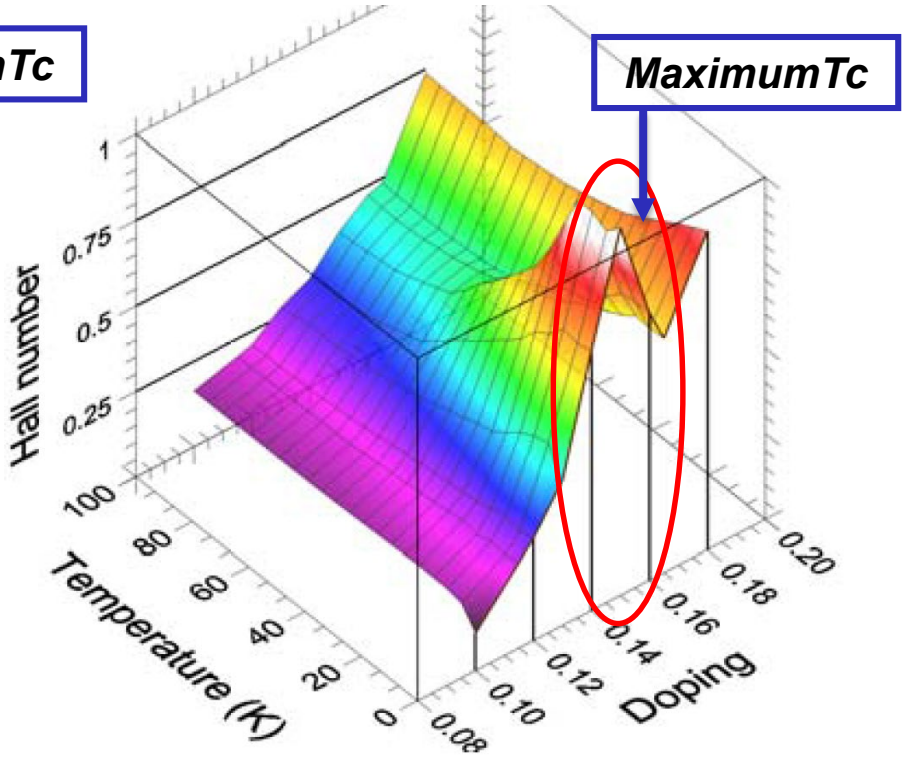
Reported in LSCO thin films in 2009…

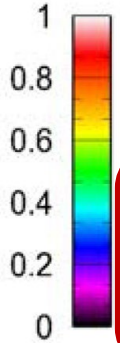
F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando, G. S. Boebinger, Phys.Rev.Lett. 102, 017004 (2009). "*Quantum Phase Transition in the Normal State of High-Tc Cuprates at Optimum Doping.*"

…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"



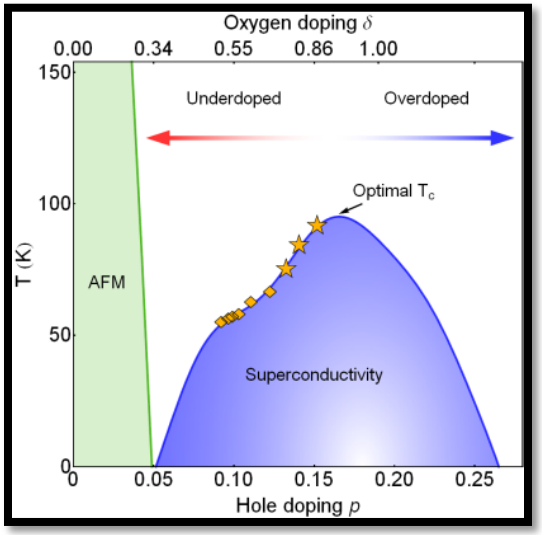




"Hall number" (≡ $1/R_{hall}$) in units of carriers per Cu atom

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Using High Magnetic Fields to Evidence Quantum Criticality near Optimum Doping in a High Temperature Superconductor (Ramshaw, et al. in YBCO)



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

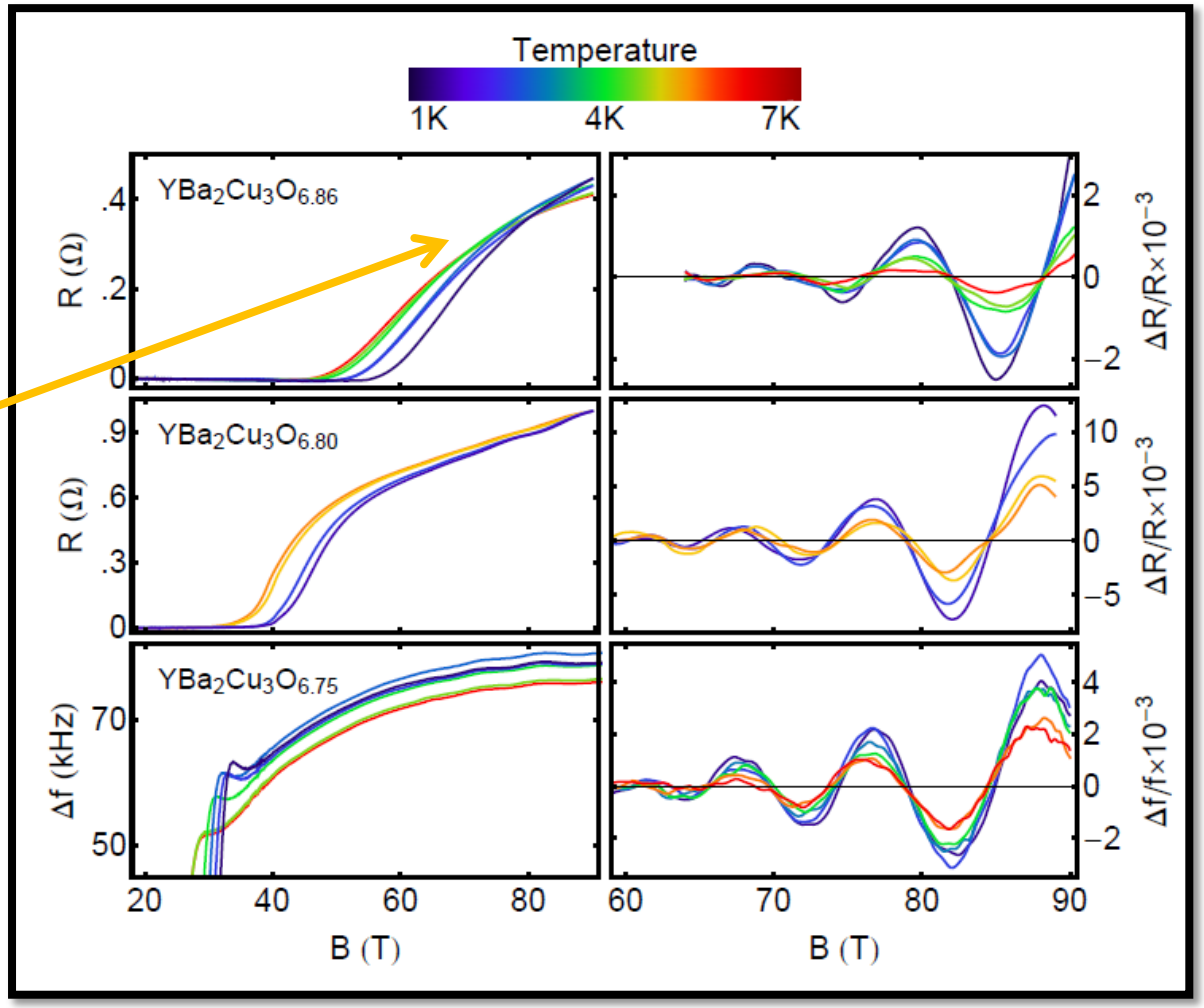
Science (2015) DOI: 10.1126/science.aaa4990

Tc ~ 91K

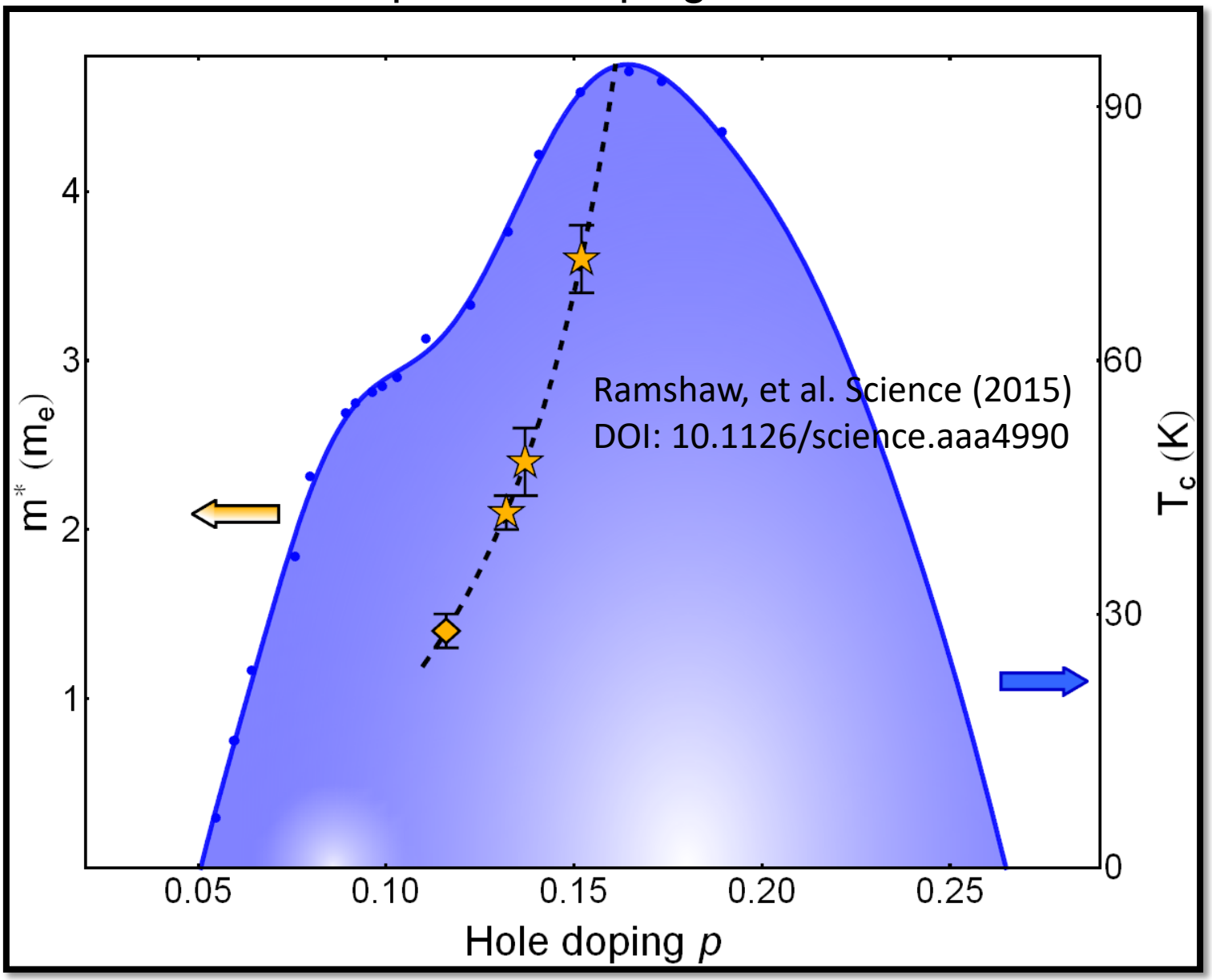
CLEARLY: We Need Bigger Magnets!

Tc ~ 81K

Tc ~ 75K



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



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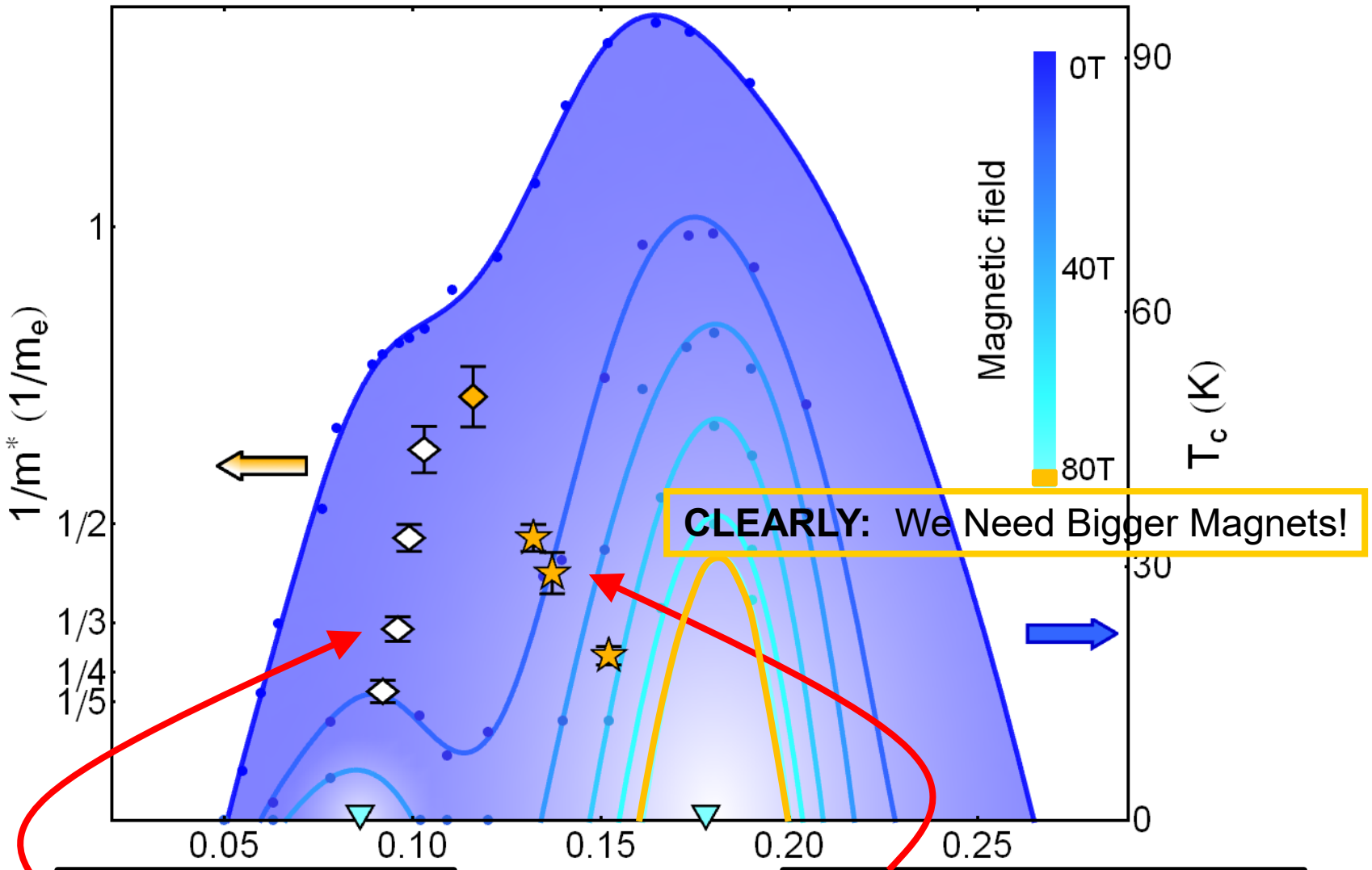


S.E. Sebastian *et al.*
PNAS **107**, 6175 (2010)

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

NATIONAL HIGH MAGNETIC FIELD LABORATORY

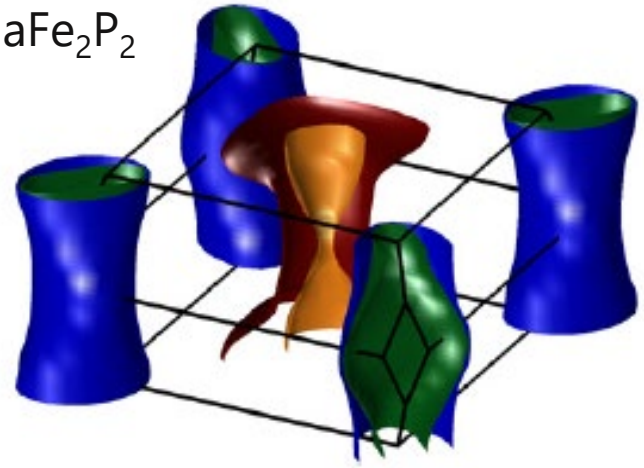
Turn to the Ba122 Iron Pnictide Superconductor
(which has a lower Upper Critical Magnetic Field)

To Use Specific Heat in High Magnetic Fields
to reveal Thermodynamic Evidence
of a Quasiparticle Mass Divergence
at Optimum Doping

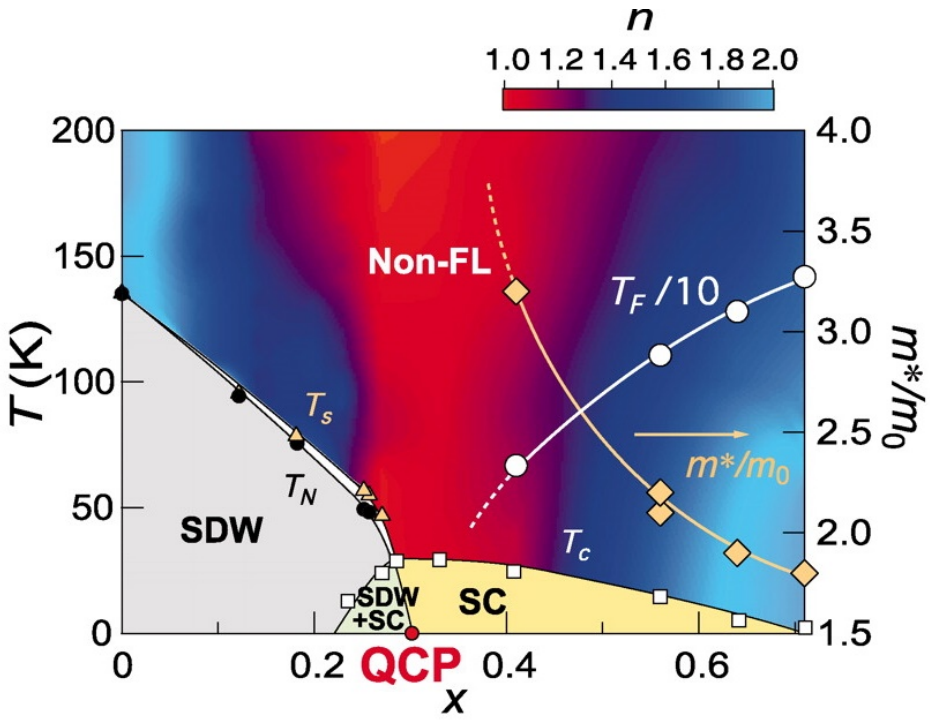
$BaFe_2(As_{1-x}P_x)_2$

- Quasi 2D Fermi surface with multiple pockets
- Isovalent P-substitution maps out a familiar-looking phase diagram
- Non-Fermi-Liquid phase exhibiting linear-in-T resistivity
- Is there a Quantum Critical Point near optimal doping?

$BaFe_2P_2$



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

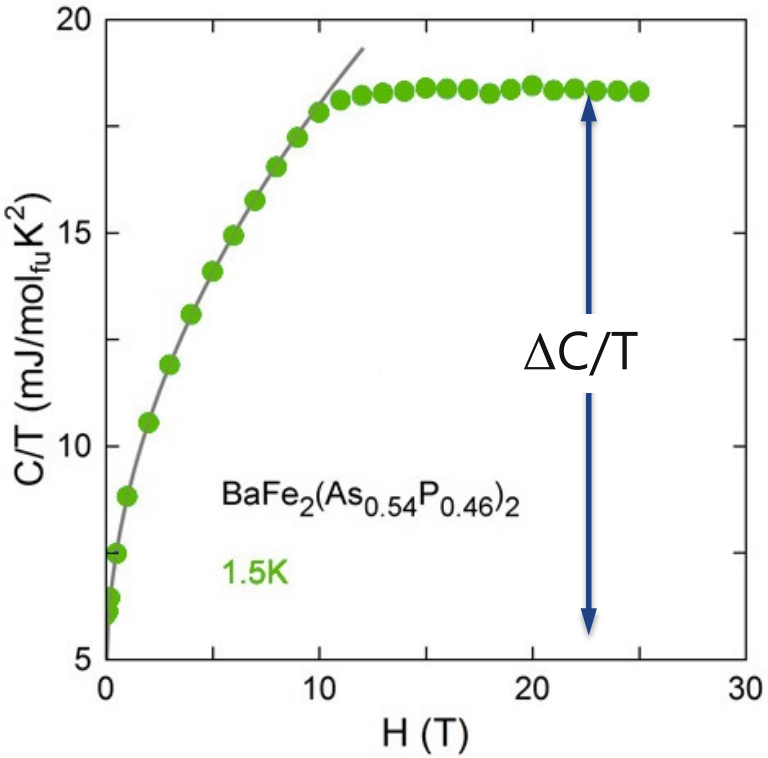


K. Hashimoto et al. *Science* 2012; **336**:1554-1557
[m data from quantum oscillations by H. Shishido et al. Phys. Rev. Lett. 2010; **104**:057008]*

Our Specific Heat Measurements

Heat Capacity as a Function of Magnetic Field

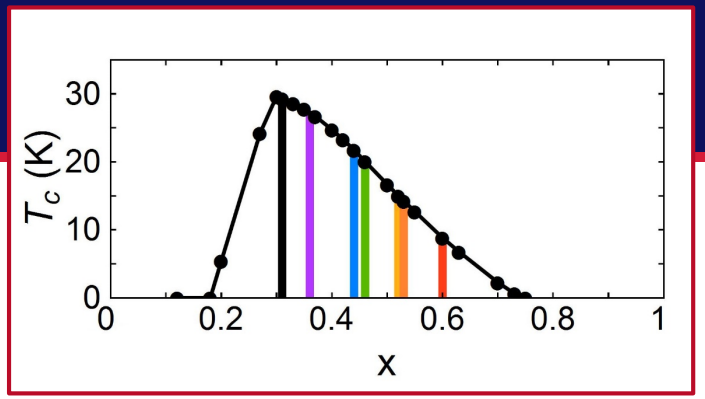
- Sufficiently high magnetic fields (35T) to suppress superconductivity
- For us, $\Delta C/T$ is the specific heat recovered by suppressing superconductivity



35 T resistive magnet at the
National High Magnetic Field Laboratory

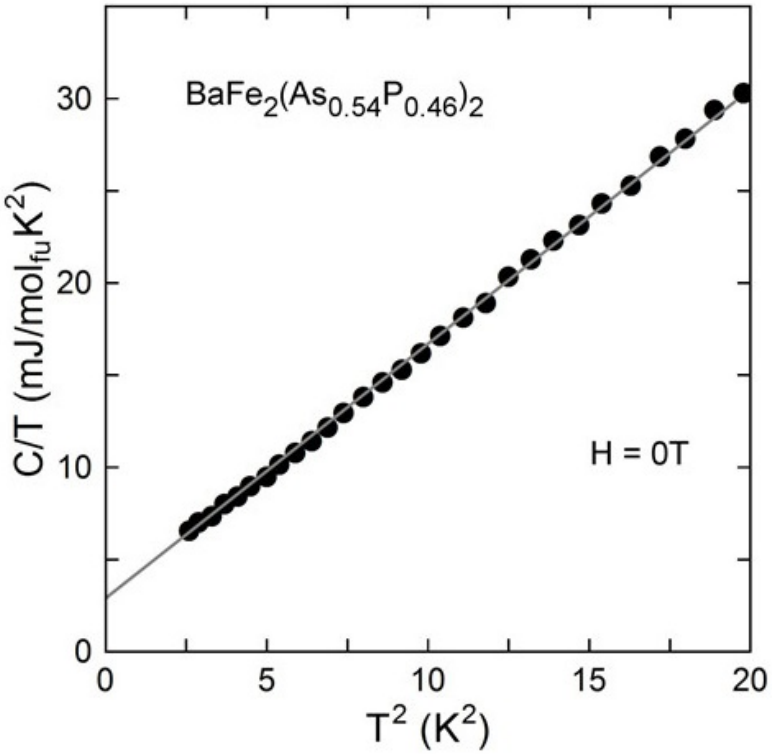
Our Data

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

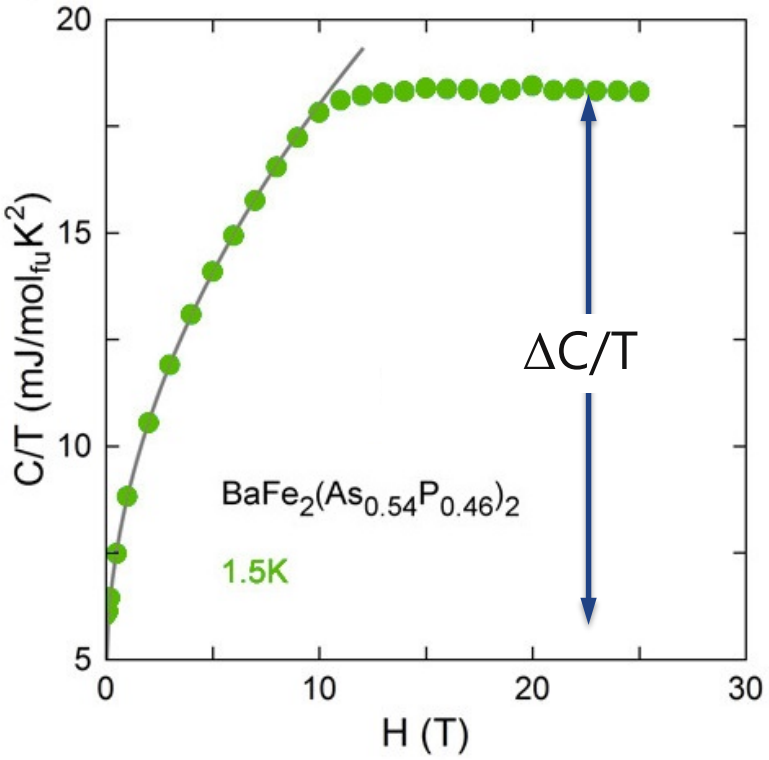


Heat Capacity as a Function of

- Temperature
- Magnetic Field

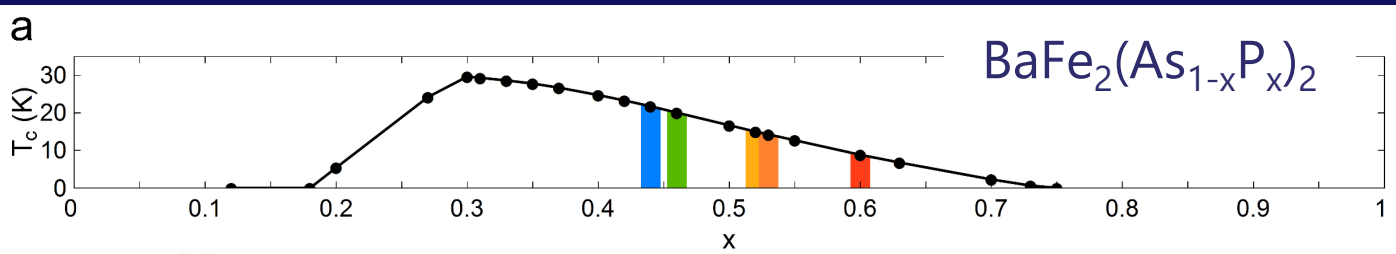


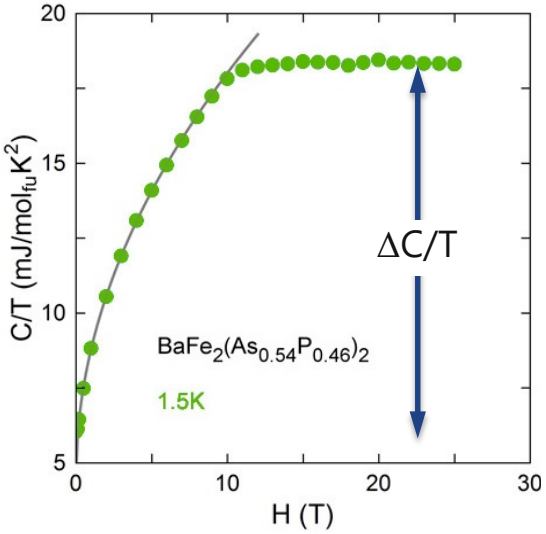
Temperature dependence shows finite C/T at H = 0, T = 0.



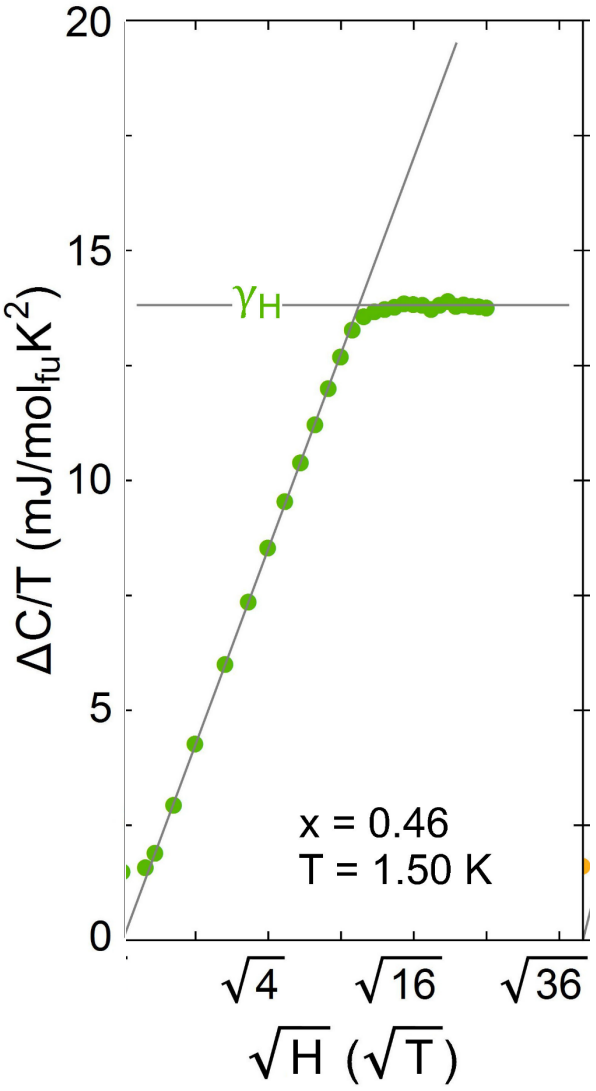
√H dependence indicates line nodes in the superconducting gap.

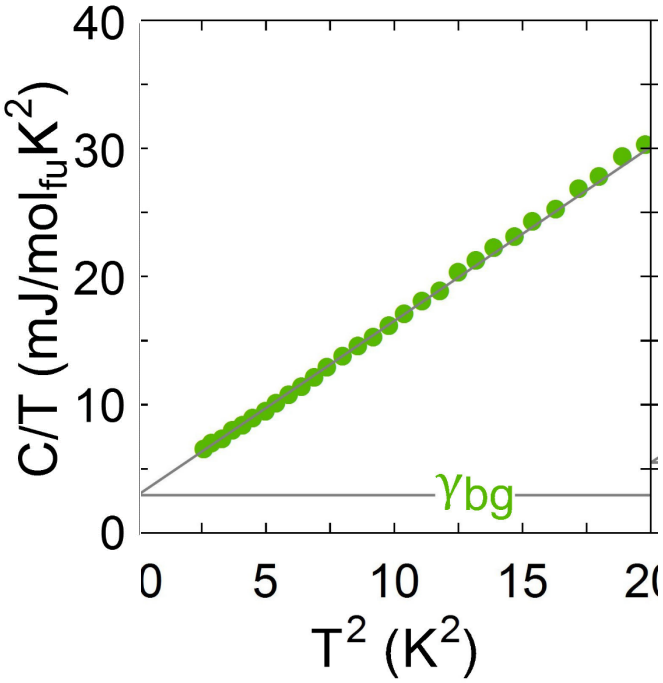
C.M. Moir, *et al.*
Nature Quantum Mat'l (2019)





$\Delta C/T \rightarrow \gamma_H$

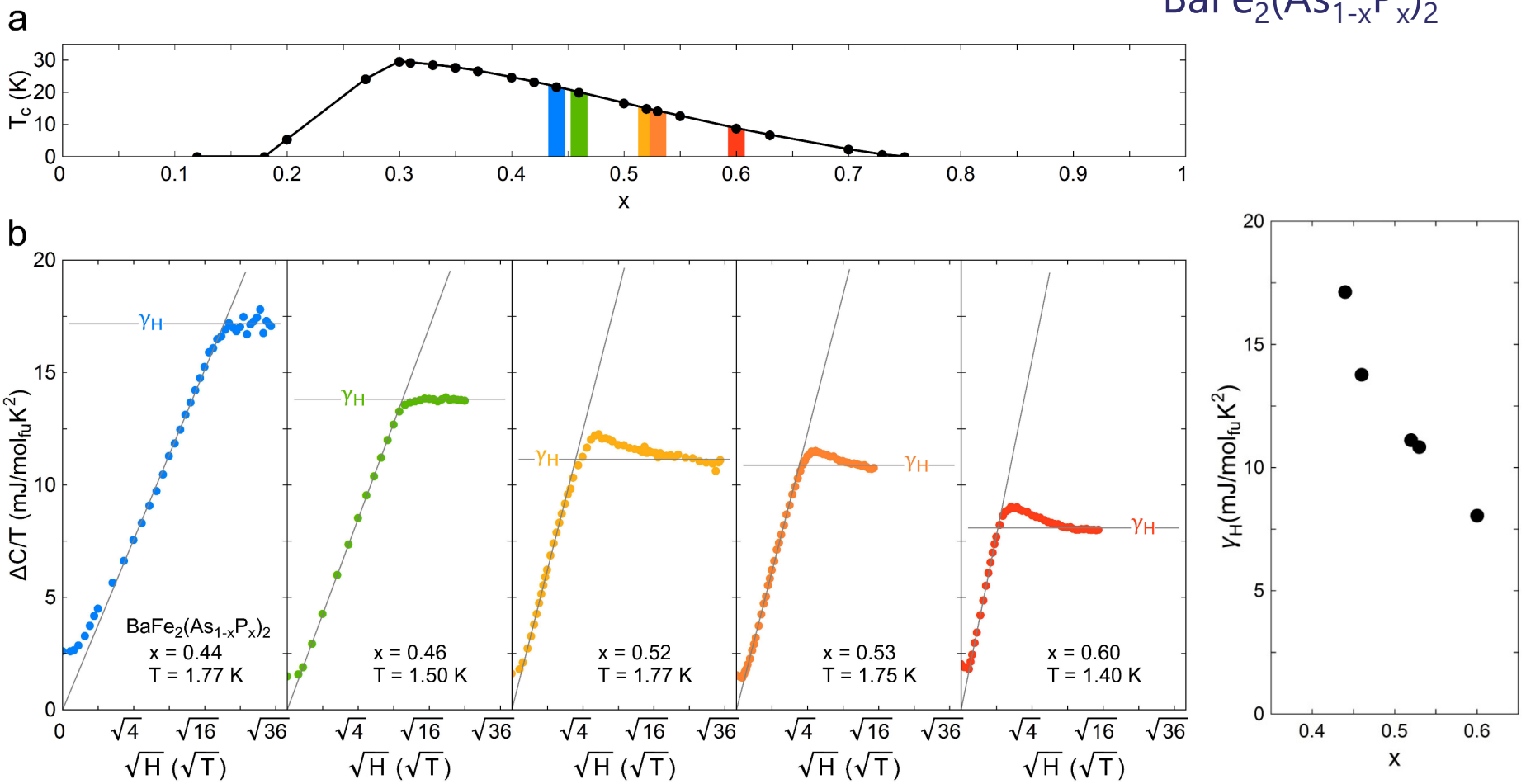




C.M. Moir, *et al.*
Nature Quantum Mat'l (2019)

Doping Dependence of γ_H

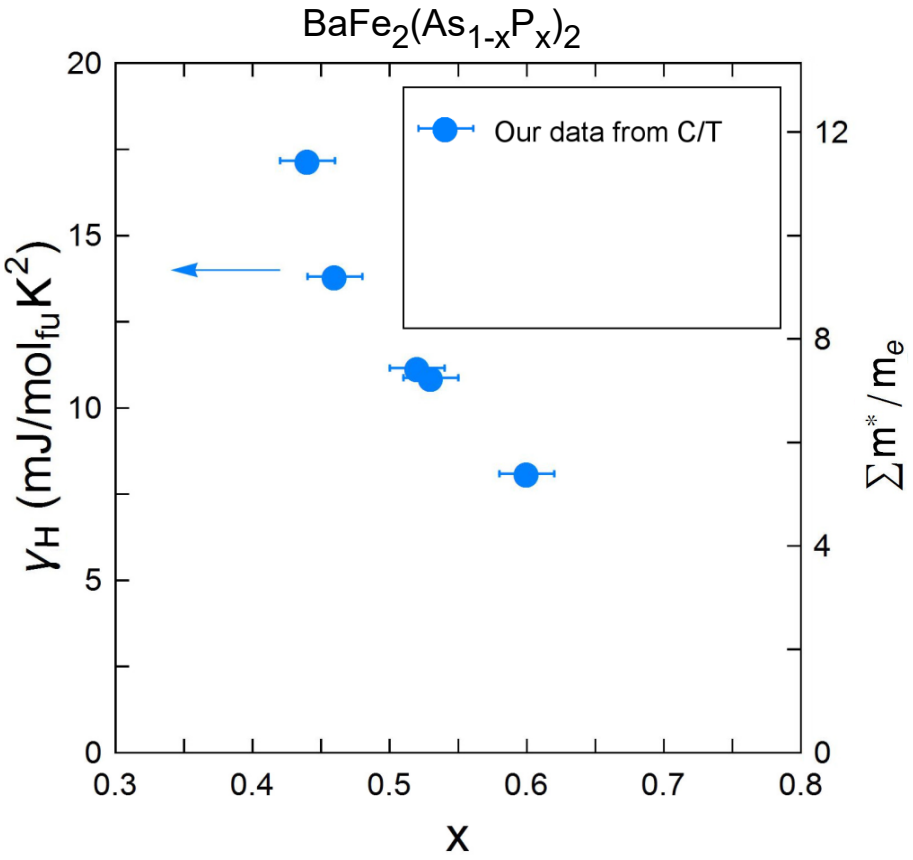
$BaFe_2(As_{1-x}P_x)_2$



C.M. Moir, *et al.*

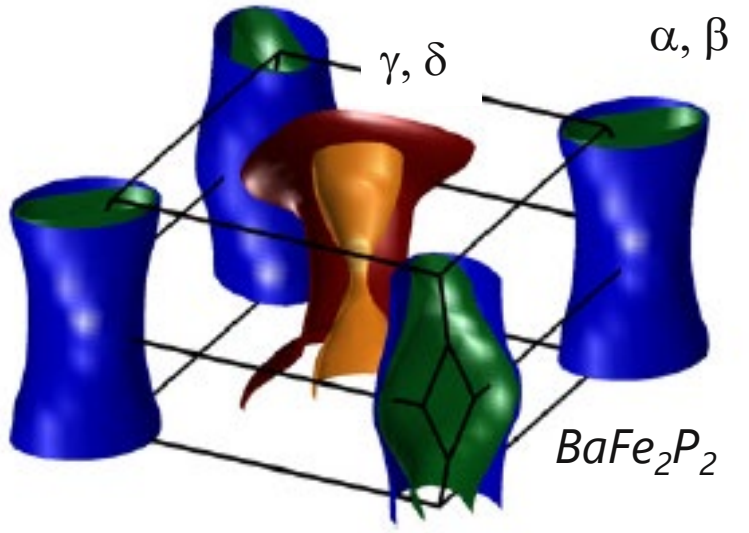
Nature Quantum Mat'l (2019)

Interpreting Enhancement of γ_H as a Quasiparticle Mass Enhancement



In our units, for the warped cylindrical Fermi surfaces of Ba122,

$$\gamma = 1.5 \sum n_i m_i$$

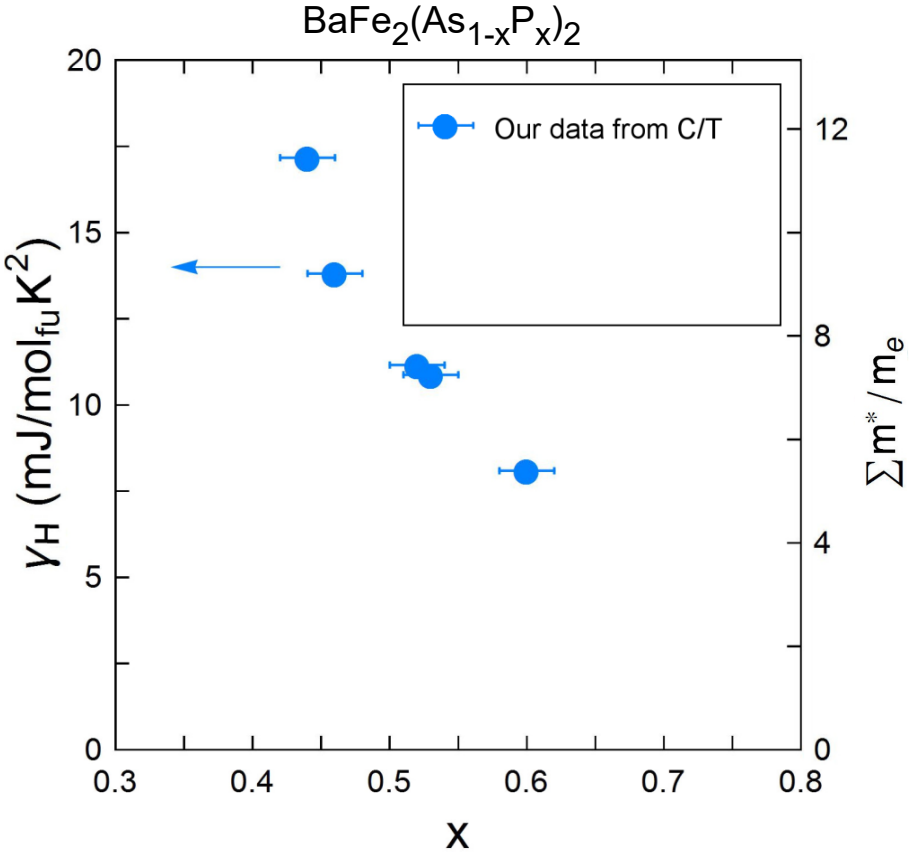


...for all pockets that take part in superconductivity

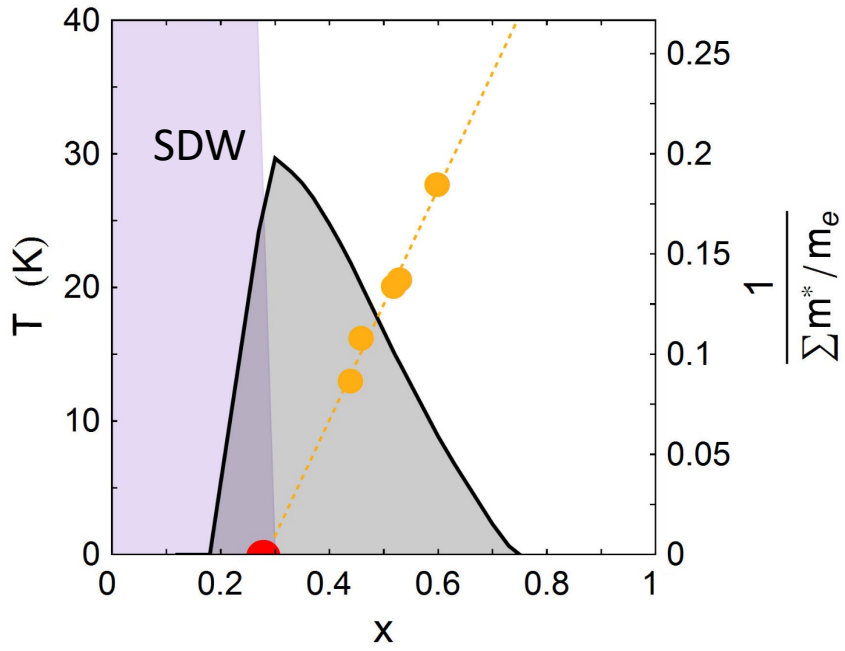
...independent of whether a given pocket shows quantum oscillations.

C.M. Moir, *et al.*
Nature Quantum Mat'l (2019)

Mass Enhancement Appears to Diverge at Optimum Doping



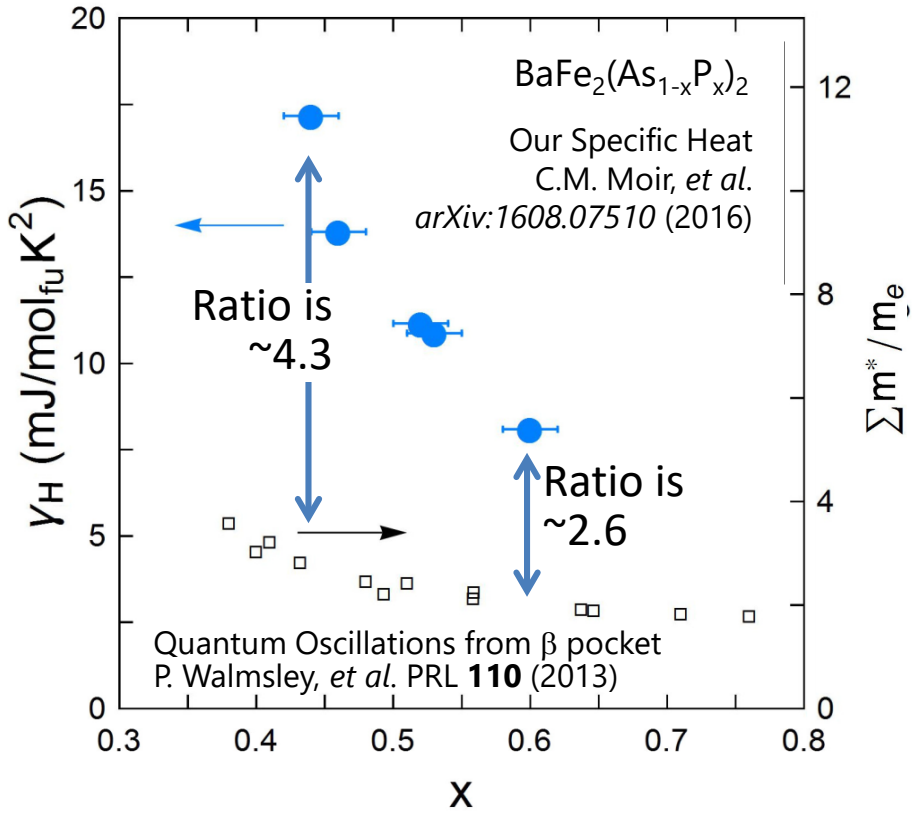
$$\gamma = 1.5 \sum n_i m_i$$

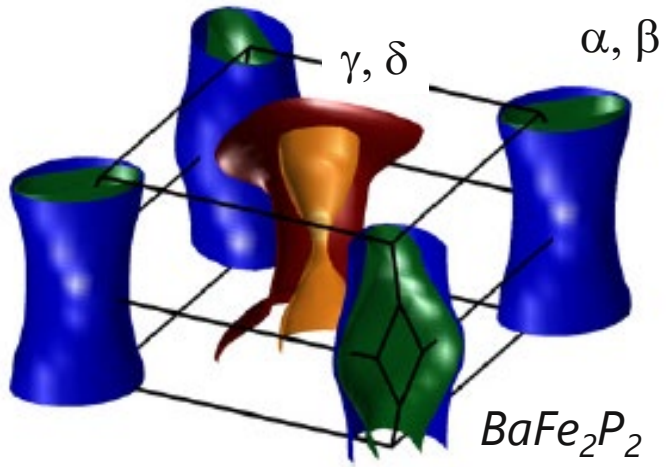


Linear fit to $1/\Sigma m^* m_e$ extrapolates to zero near optimal doping at x=0.31

C.M. Moir, *et al.*
Nature Quantum Mat'l (2019)

Comparison of Mass Enhancement: Specific Heat and Quantum Oscillations





The data suggest that pockets at the center of the Brillouin zone, have stronger mass enhancement and therefore couple stronger to quantum fluctuations in the Ba122 high-temperature superconductor.

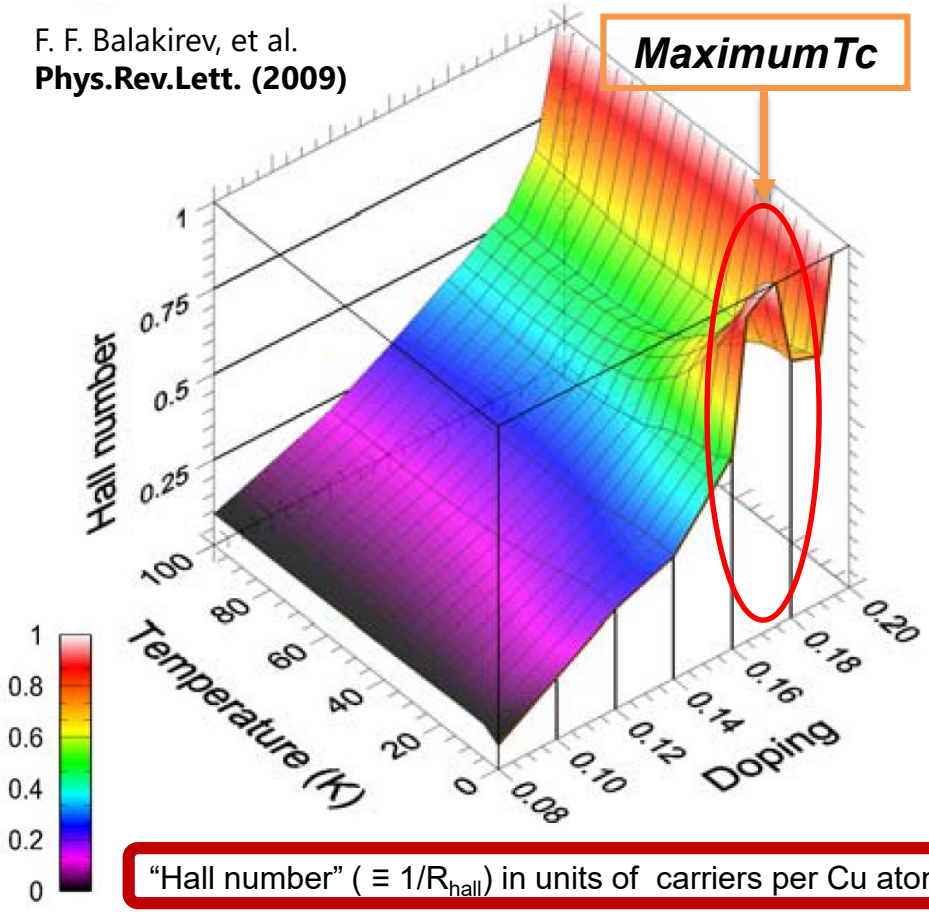
C.M. Moir, *et al.*
Nature Quantum Mat'l (2019)

Conclusions from High-Magnetic-Field Research

After suppressing the HTS phase, what has been discovered near optimum doping?

- Transport in LSCO and Bi-2201 finds evidence of a phase transition (peak in the Hall number)
- Transport in YBCO finds evidence of a quasiparticle mass divergence
  (quantum oscillations by Ramshaw, et al.)
- Specific heat in Ba122 finds evidence of a quasiparticle mass divergence
  (density of states recovered upon HTS suppression)

F. F. Balakirev, et al.
Phys.Rev.Lett. (2009)



"Hall number" (≡ $1/R_{hall}$) in units of carriers per Cu atom

C.M. Moir, *et al.* **Nature Quantum Mat'ls (2019)**