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MAX-PLANCK-GESELLSCHAFT

Complex oxides: a new playground for physics and technology

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EPSRC

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A major challenge for 21st century science:

Complex systems, notably the emergence of simplicity from complexity.

Classical: biology, soft condensed matter, telephone networks, financial systems etc.

Quantum: e.g. particle physics, atomic physics and 'hard' condensed matter, notably **strongly correlated electron systems.**

.. and also for 21st century technology:

Semiconductors – materials with similar lattice parameters display:

Externally tunable conductivity

Metal-insulator transitions, ferromagnetism

Oxides – materials with similar lattice parameters display:

Externally tunable conductivity

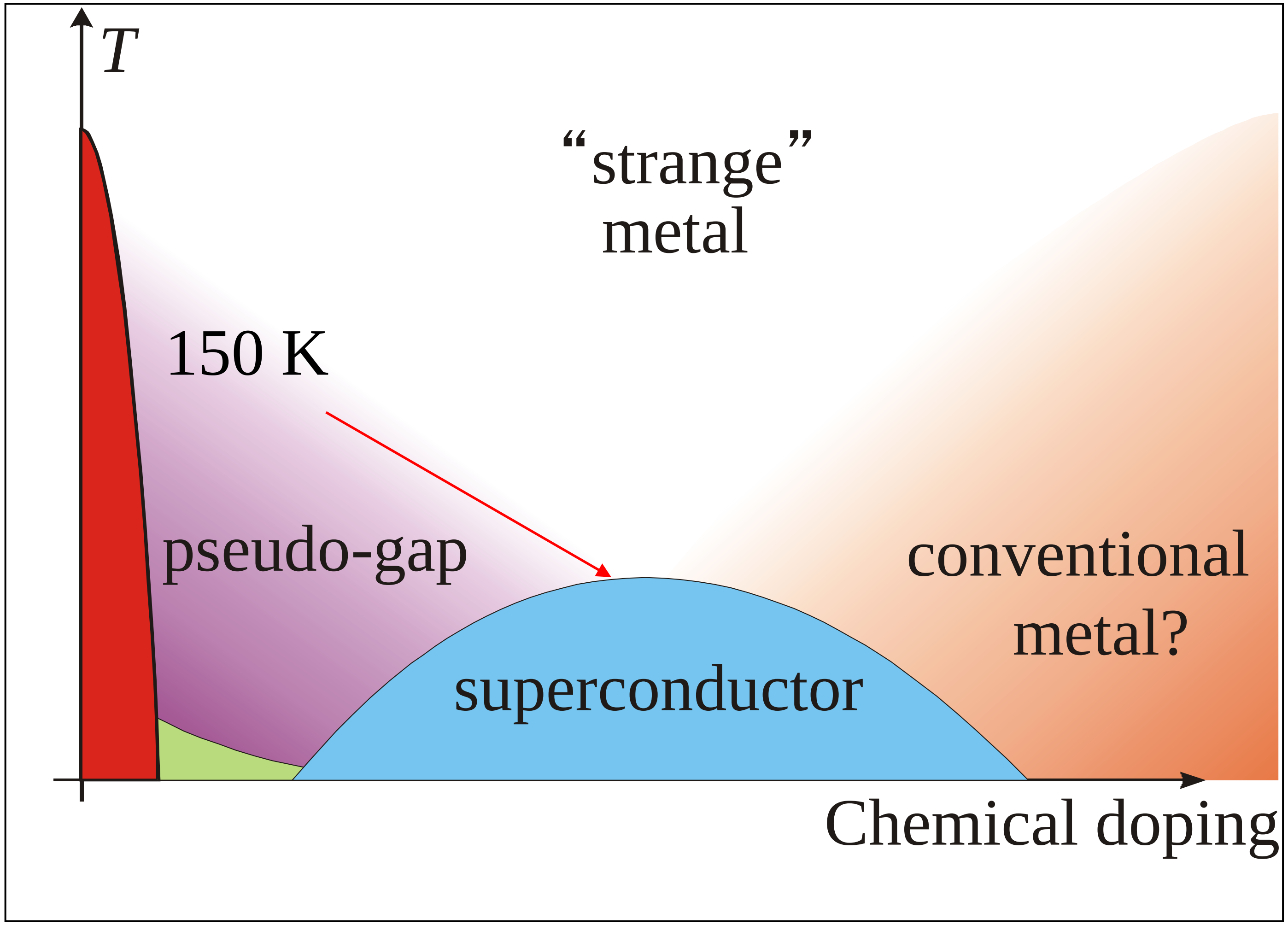
Metal-insulator transitions, ferromagnetism, antiferromagnetism

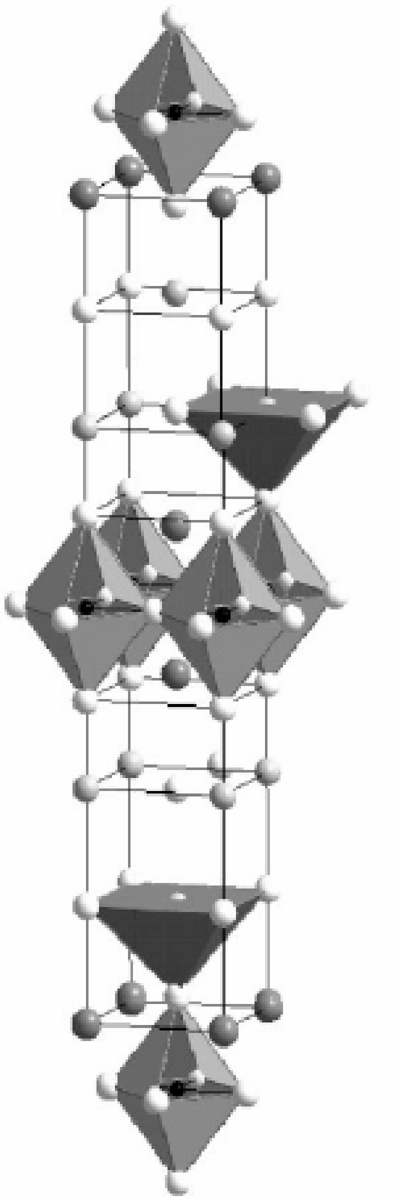
ferrimagnetism, superconductivity, superconductor-insulator

transitions, charge and spin texturing, quantum critical points

and associated giant response functions, multiferroicity and more

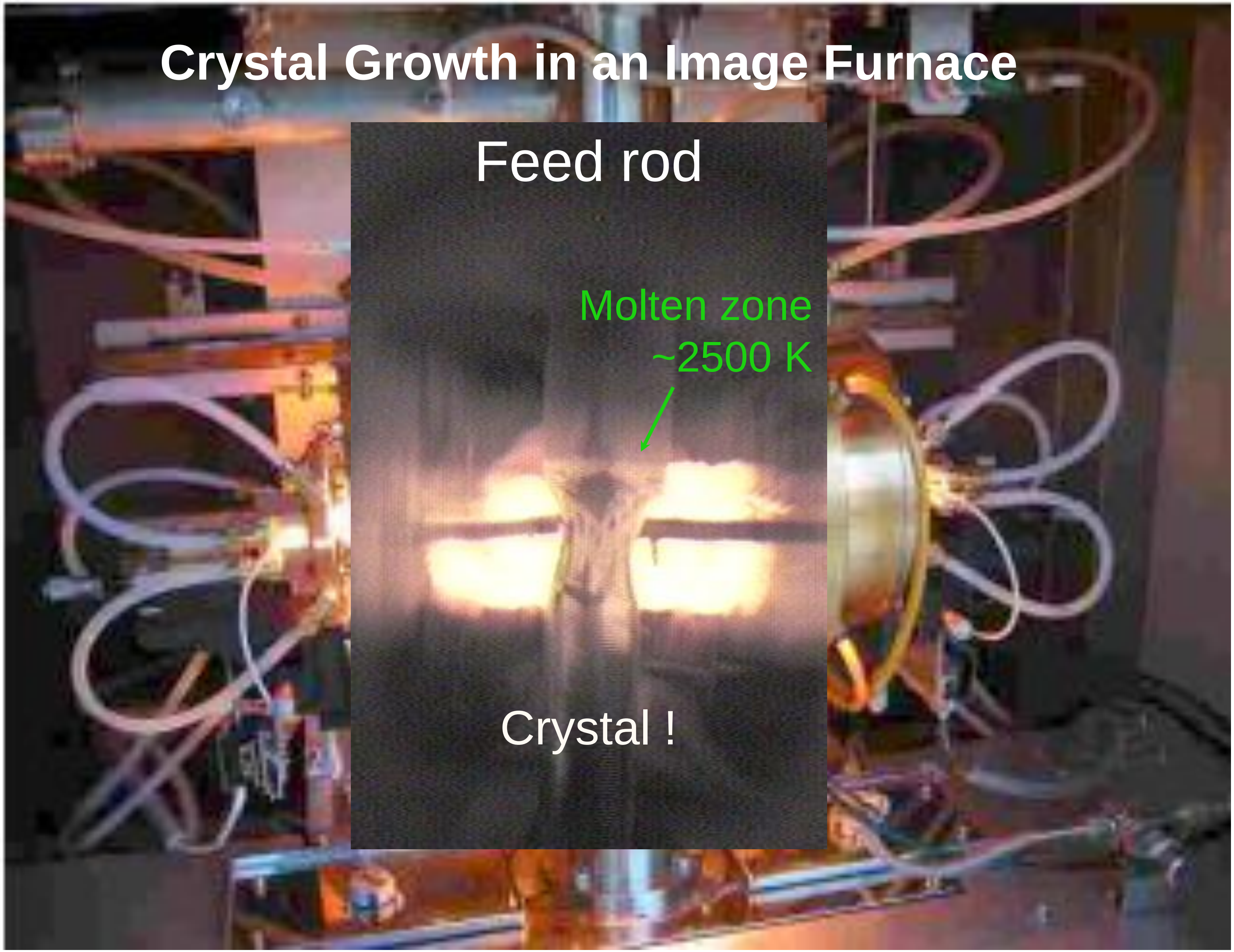
Why oxides? High temperature superconductivity



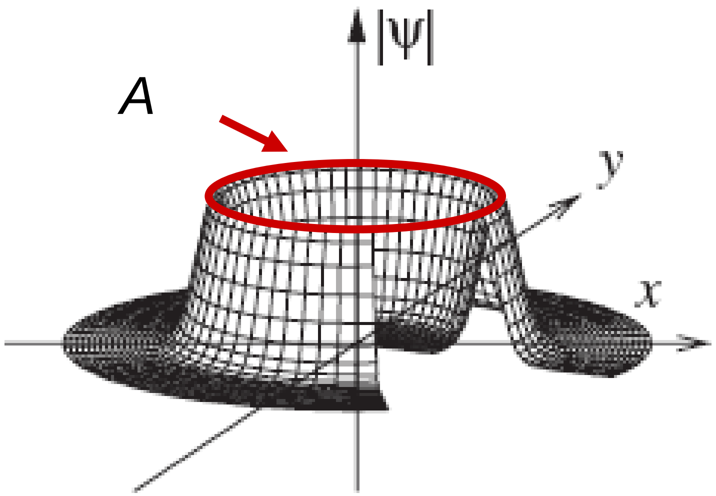


J G Bednorz and K A Müller, Z Phys B **64**,189 (1986)

Key goal: improve the quality of the materials



'Acid test' of metallic purity: Quantum Oscillations



Landau quantised orbital motion of electrons perpendicular to an applied magnetic field

Orbit area in real space is quantised such that flux $\Phi = AH_z = n\,\Phi_o$

'whereby we recognize a fundamental unit equal to the flux from one of Dirac's hypothetical magnetic poles'

L. Onsager, Phil Mag 1952; also I.M. Lifshitz

In any system of fermions (bare electrons *or* many-body quasiparticles) with a Fermi surface, the density of states will oscillate as the field is changed and Landau levels cross the Fermi surface.

… but there is an important catch: the evil exponential

Impurity scattering wipes out the precious oscillations exponentially:

$$\tilde{I}_{\mathrm{meas}} = \tilde{I}_{\mathrm{intrinsic}} \exp\left(-\frac{\pi r_{\mathrm{c}}}{\ell}\right) \qquad r_{\mathrm{c}} = \frac{\hbar k_{\mathrm{F}}}{eB}$$

For a typical metal $k_F \sim 0.5$ Å^{-1}.

A standard ‘large’ laboratory magnetic field ~ 20 T

Very high purity material

$\ell \sim 1000$ Å

$$\frac{\tilde{I}_{\mathrm{meas}}}{\tilde{I}_{\mathrm{intrinsic}}} \approx 0.006$$

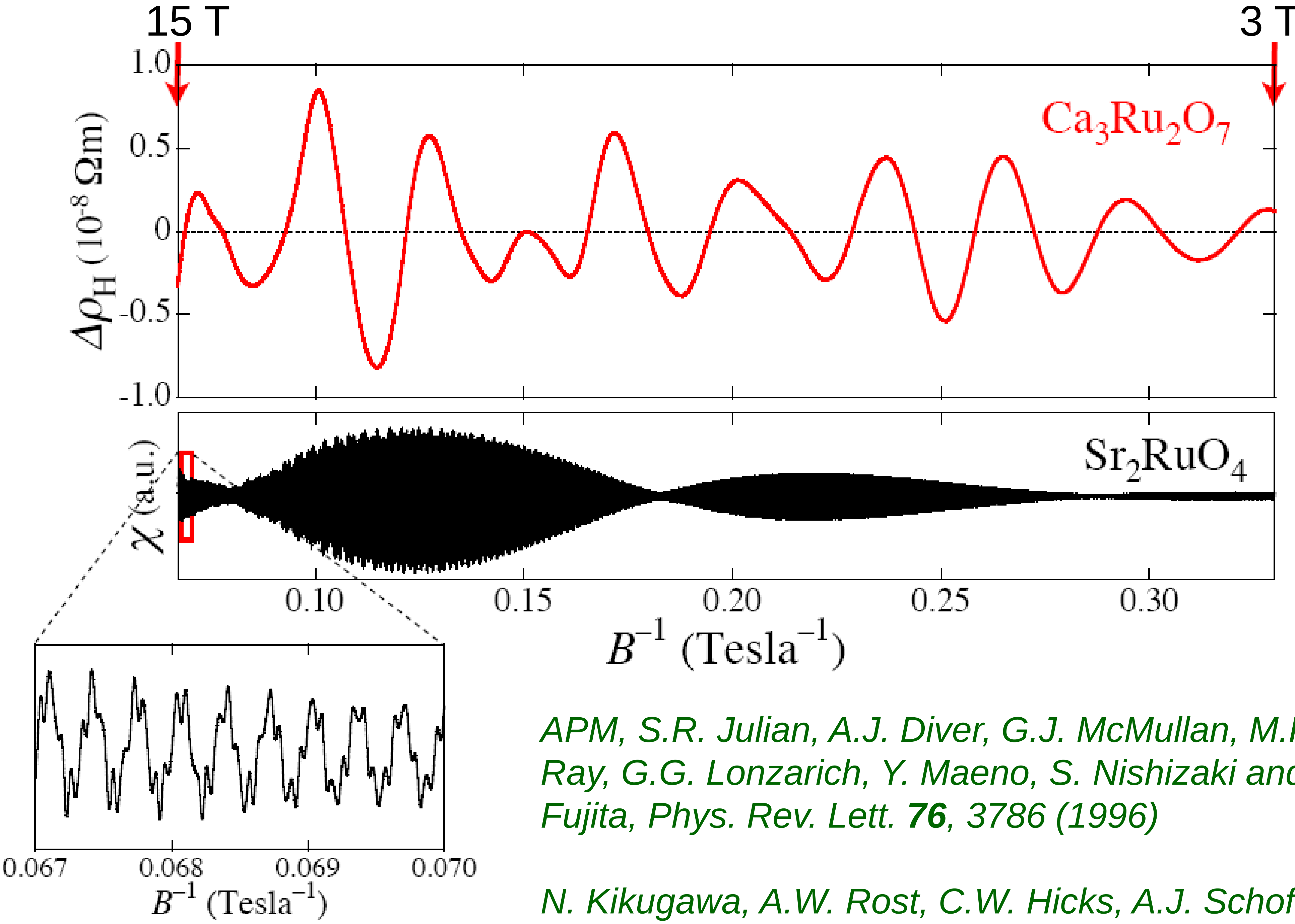
Reasonable purity material

$\ell \sim 100$ Å

$$\frac{\tilde{I}_{\mathrm{meas}}}{\tilde{I}_{\mathrm{intrinsic}}} \approx 4\times10^{-23}$$

Need HUGE magnetic fields or fantastic materials

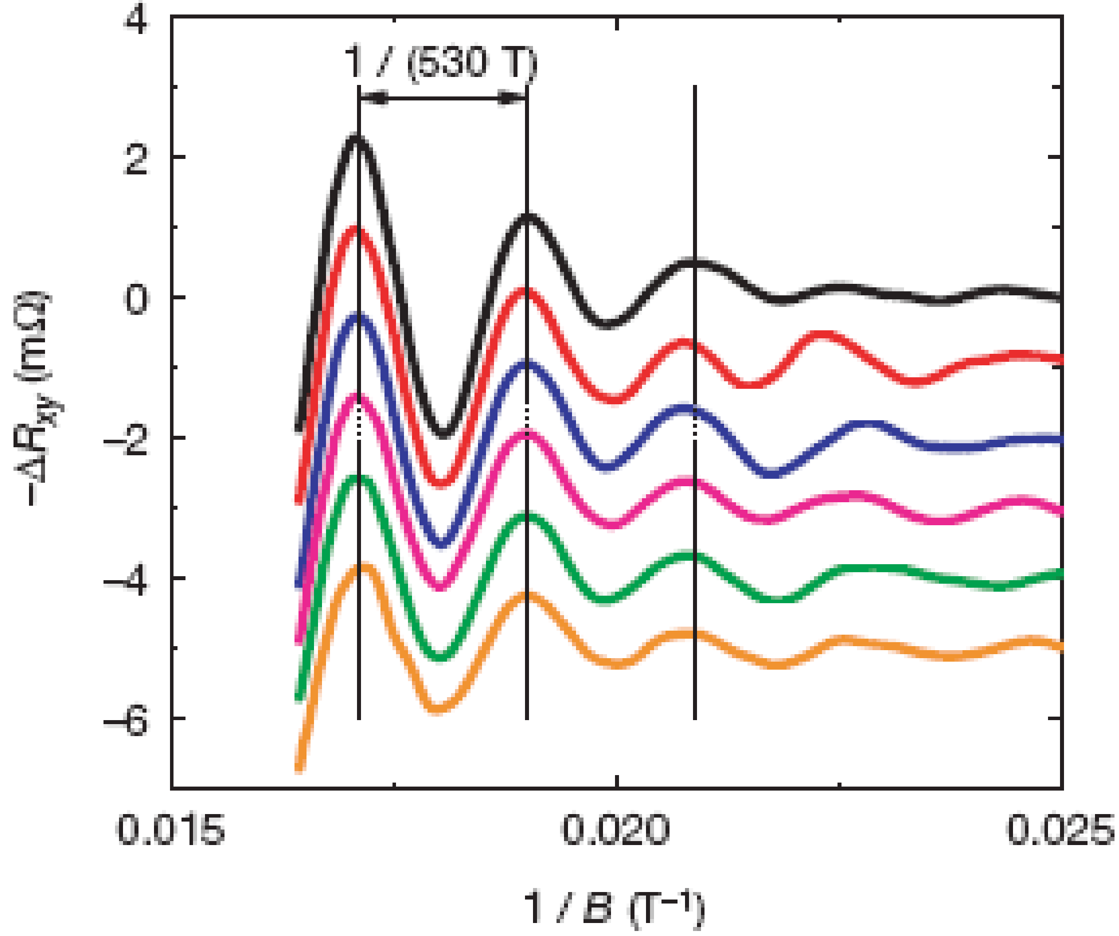
First past the post: ruthenates



APM, S.R. Julian, A.J. Diver, G.J. McMullan, M.P. Ray, G.G. Lonzarich, Y. Maeno, S. Nishizaki and T. Fujita, Phys. Rev. Lett. ***76****, 3786 (1996)*

N. Kikugawa, A.W. Rost, C.W. Hicks, A.J. Schofield & APM, J. Phys. Soc. Jpn. ***79****, 024704 (2010)*

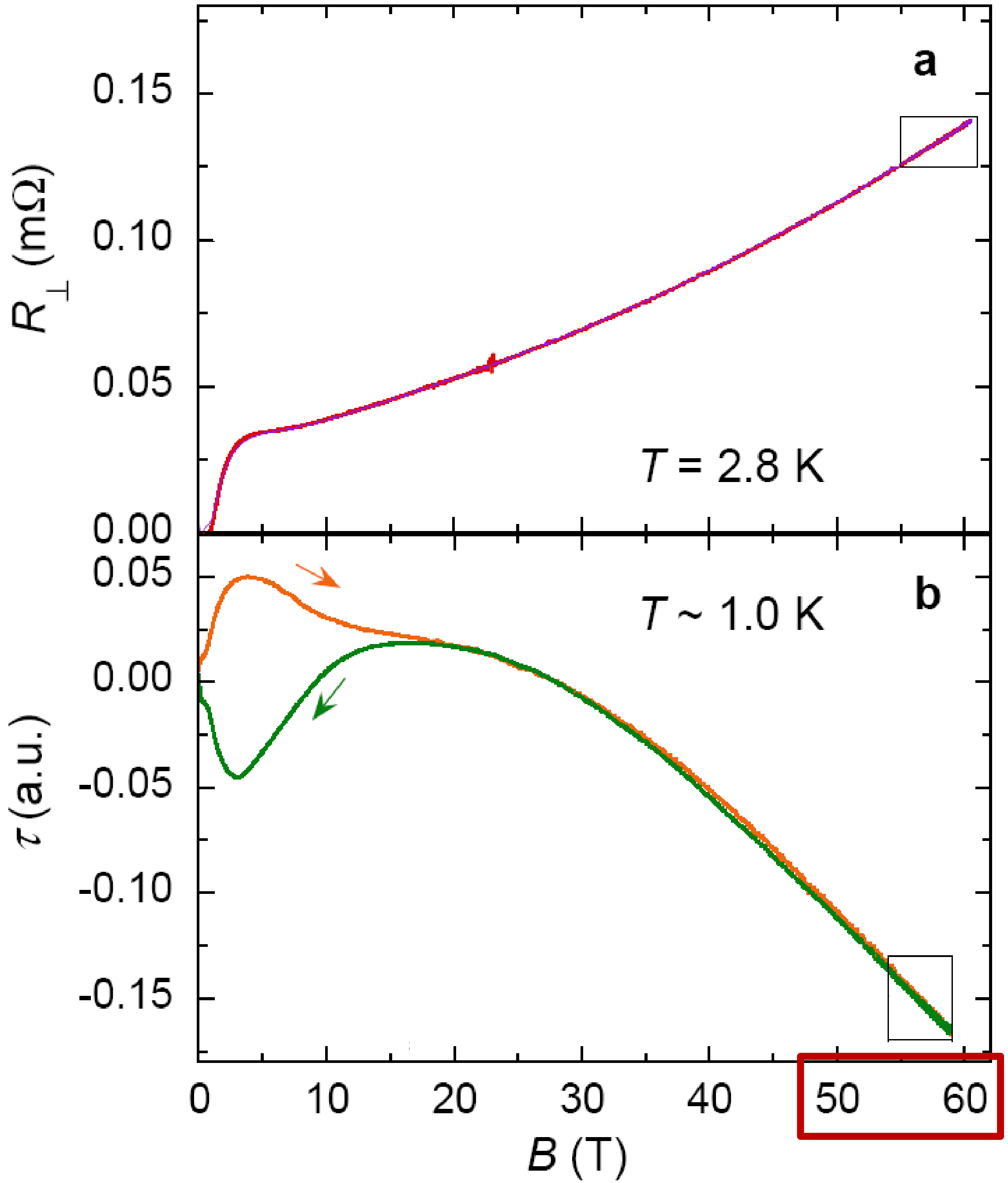
First direct and confirmed observation of quantum oscillations in a high temperature superconductor



N. Doiron-Leyraud, C. Proust, D. LeBoeuf, J. Levallois, J. Bonnemaison, R. Liang, D.A. Bonn, W.N. Hardy & L. Taillefer, Nature ***447***, *565 (2007)*

Other cuprate families join the rush

$Tl_2Ba_2CuO_6$



B. Vignolle, A. Carrington, R.A. Cooper, M.M. J. French, APM, C. Jaudet, D. Vignolles, Cyril Proust & N. E. Hussey, Nature ***455****, 952 (2008)*

LNCMP
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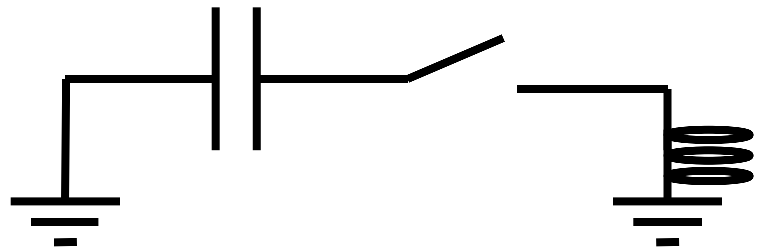
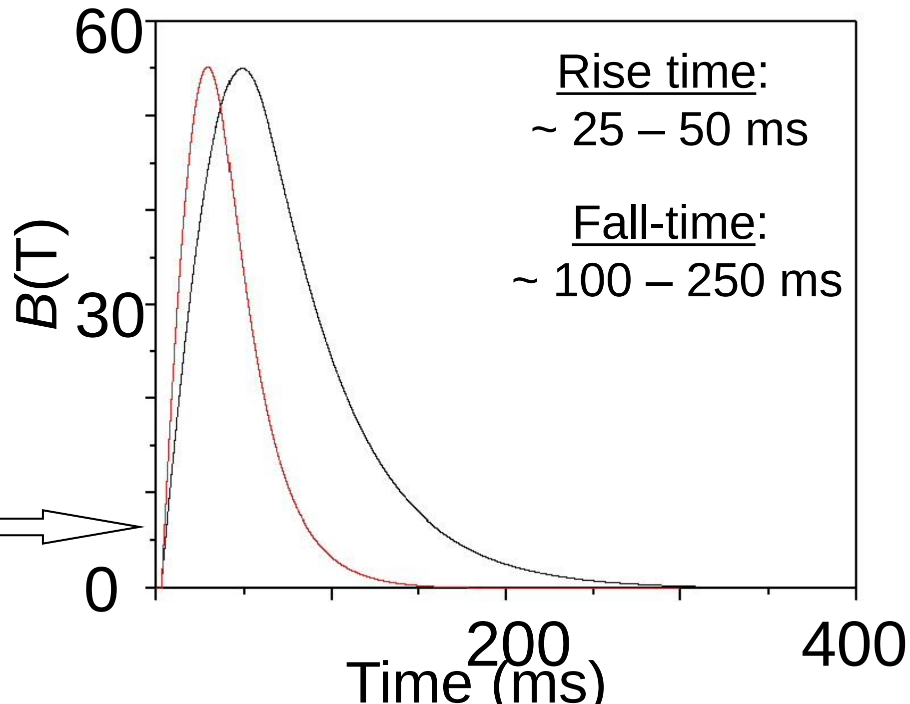
TOULOUSE

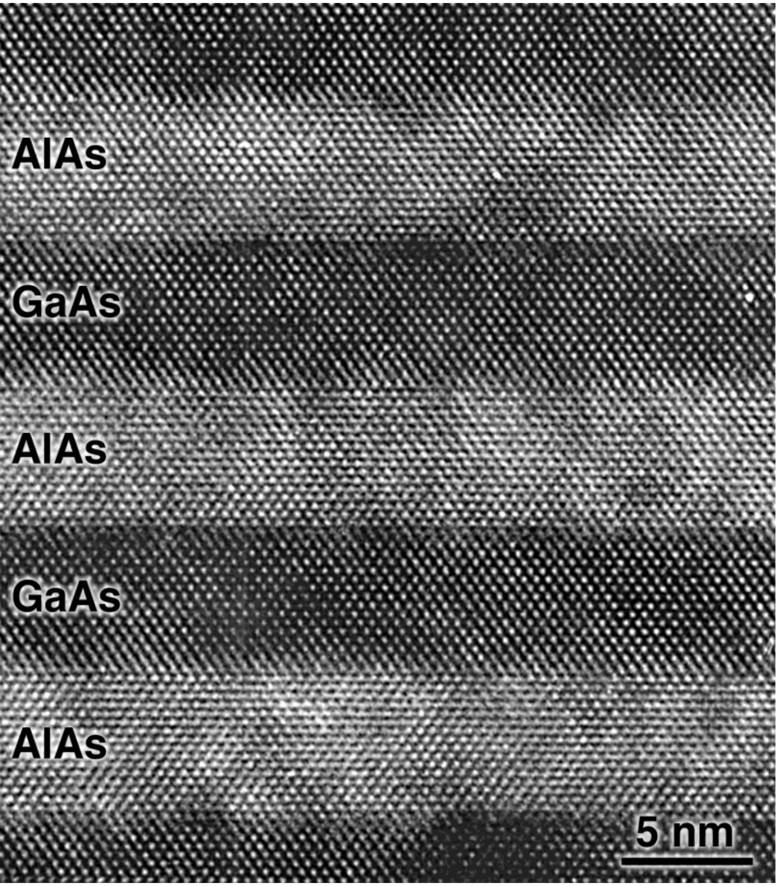
Capacitor-driven pulsed field cuprate measurements



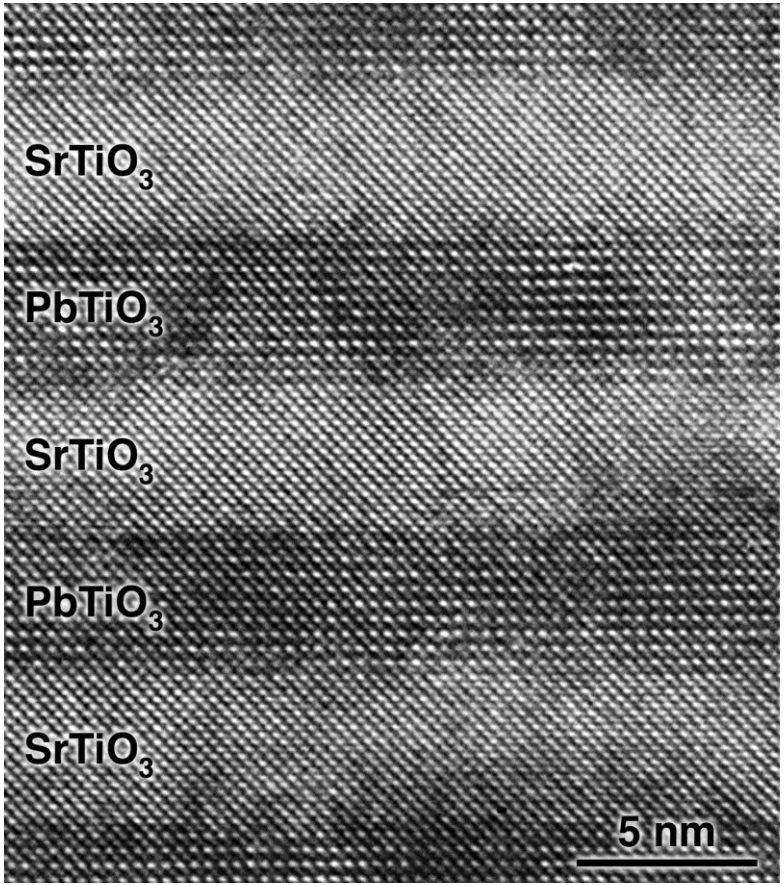


High quality epitaxial perfection is becoming possible

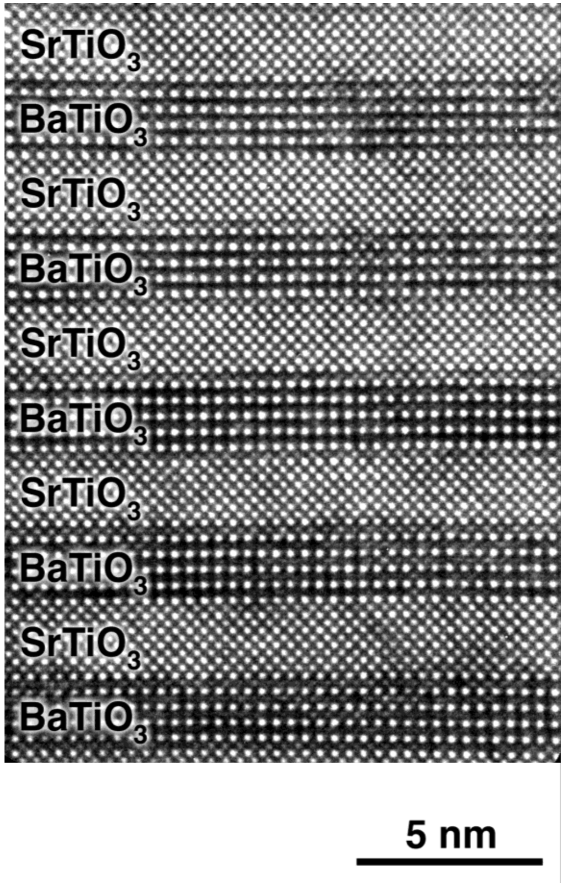
AlAs / GaAs



$PbTiO_3$ / $SrTiO_3$



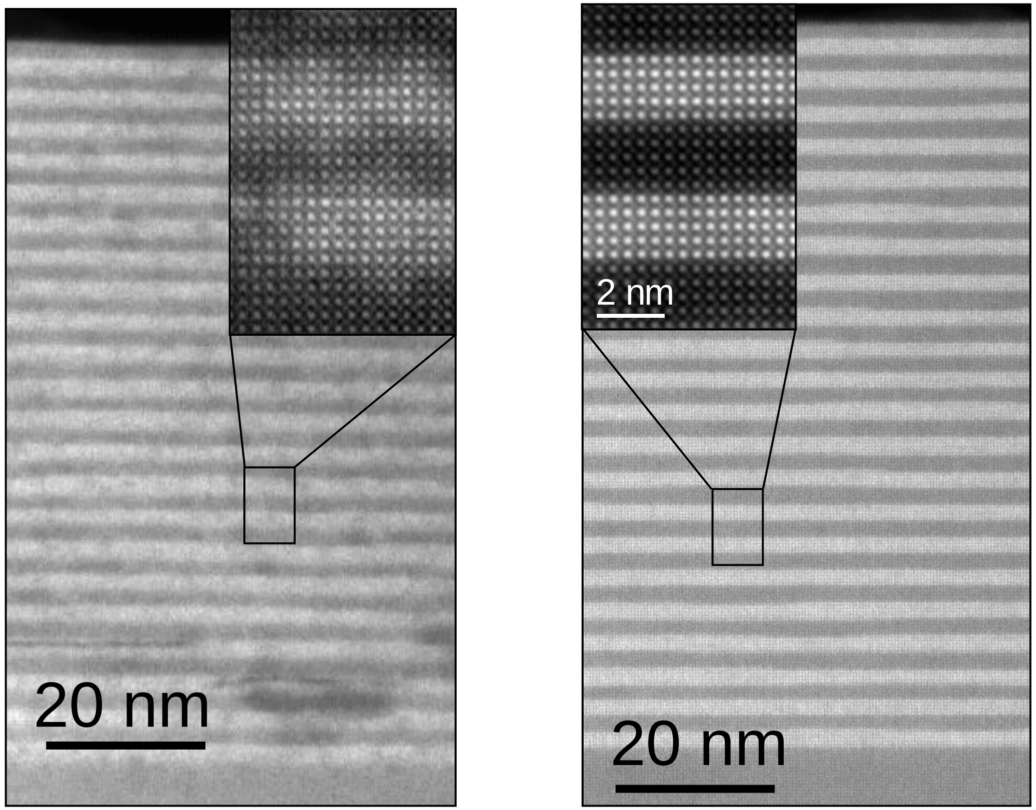
$BaTiO_3$ / $SrTiO_3$

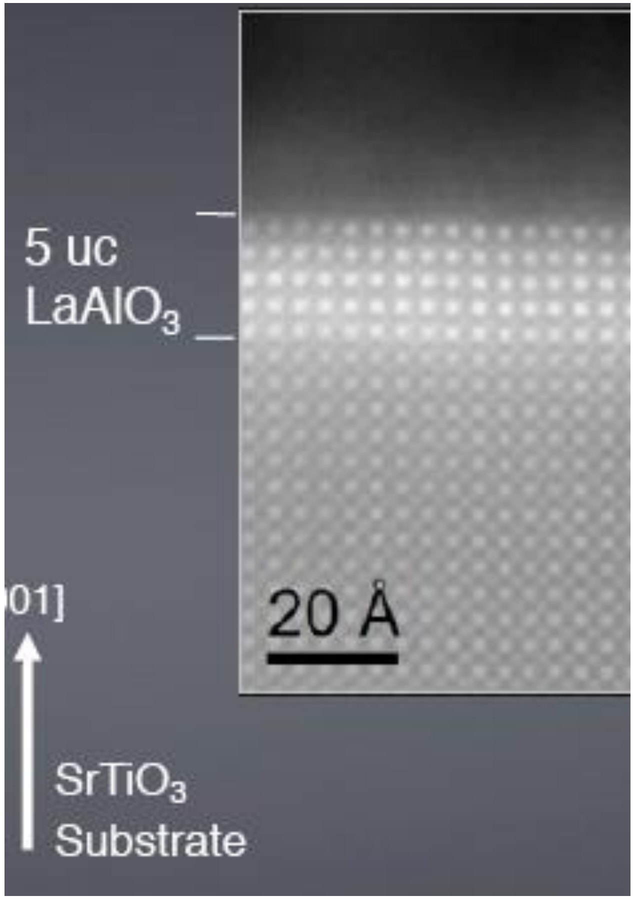


A K Gutakovskii, L I Fedina & A L Aseev, Phys. Stat. Sol. (a) ***150*** *, 127 (1995).*

D G Schlom, J H Haeni, J. Lettieri, C D Theis, W Tian, J C Jiang & X Q Pan, Mater. Sci. Eng. B ***87,*** *282 (2001).*

.. and the quest for improvement continues apace



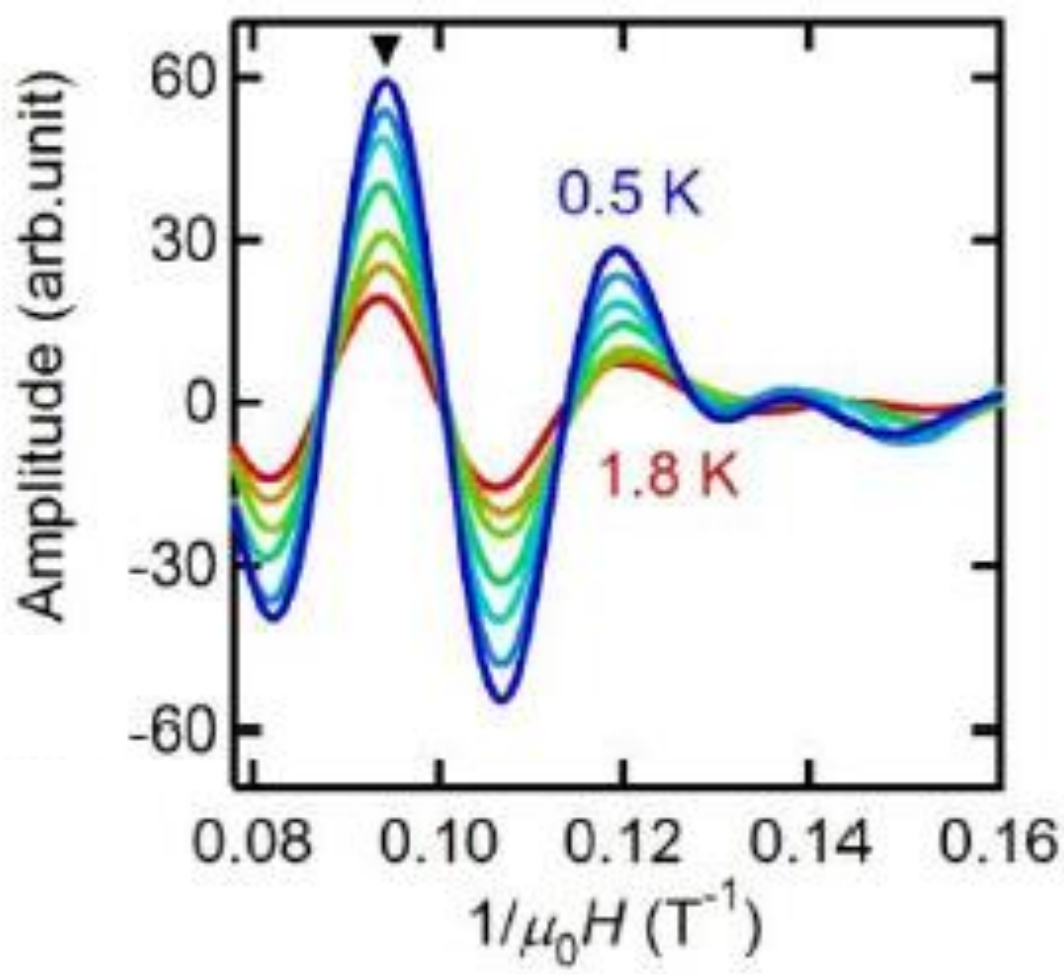


Laser fluence control of extended defects in manganite/titanate superlattices

Hwang group (Tokyo / Stanford)
& Muller group (Cornell)

Mannhart group (Augsburg)
& Muller group (Cornell)

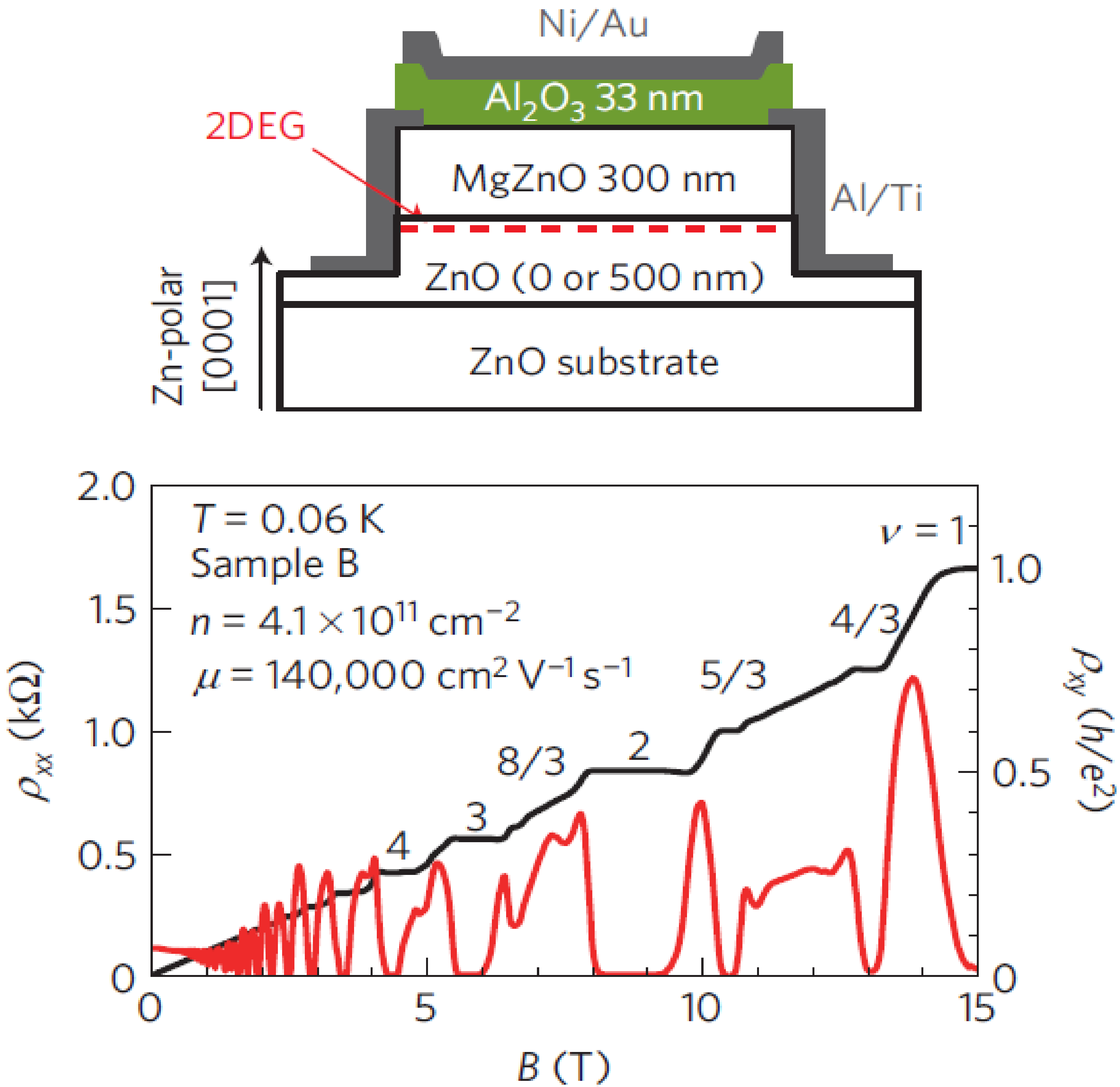
Quantum oscillations observed in an oxide 2DEG



'Delta-doped' $SrTiO_3$-$NbTiO_3$ heterostructures

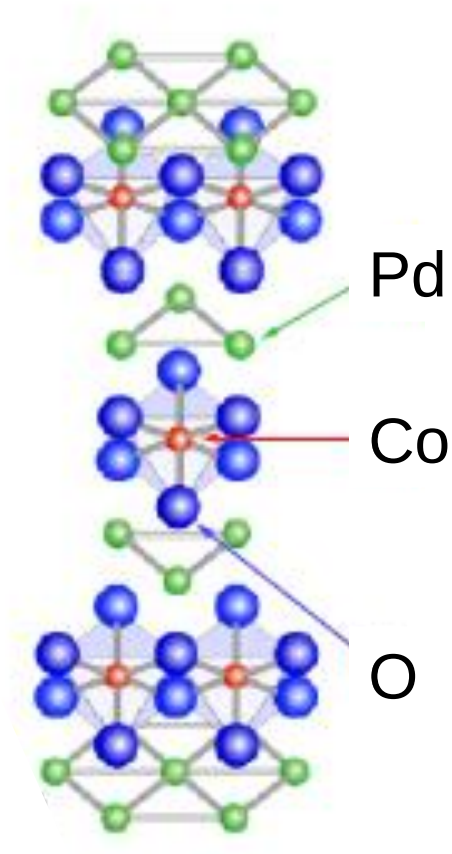
Y. Kozuka, M. Kim, C. Bell, B.G. Kim, Y. Hikata & H.Y. Hwang, Nature ***462****, 487 (2009)*

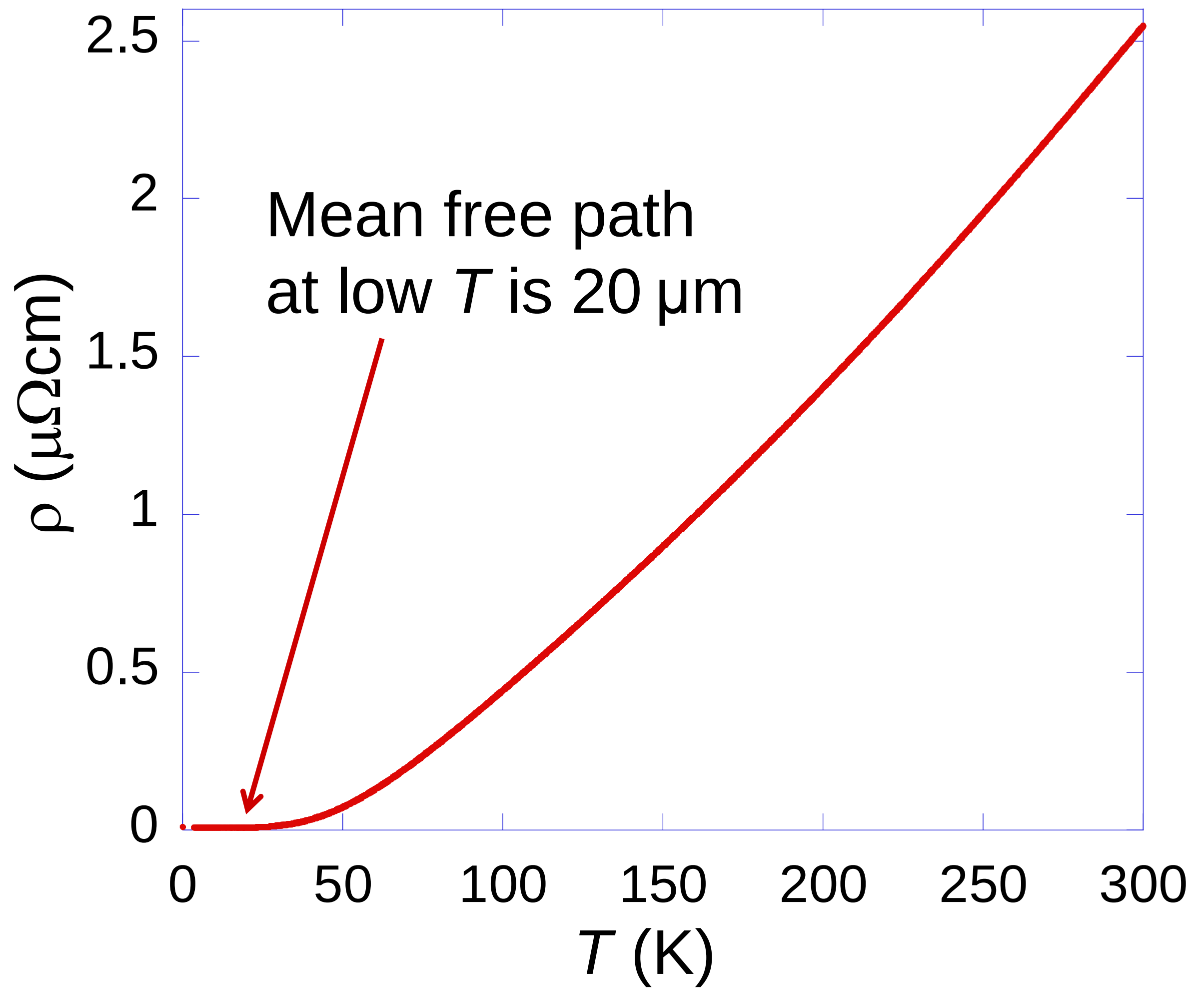
.. and now, even the Fractional Quantum Hall Effect



A. Tsukazaki, S. Akasaka, K. Nakahara, Y. Ohno, H. Ohno, D. Maryenko, A. Ohtomo & M. Kawasaki, Nature Materials ***9****, 889 (2010).*

Nature has more to offer: consider the 'delafossite' $PdCoO_2$

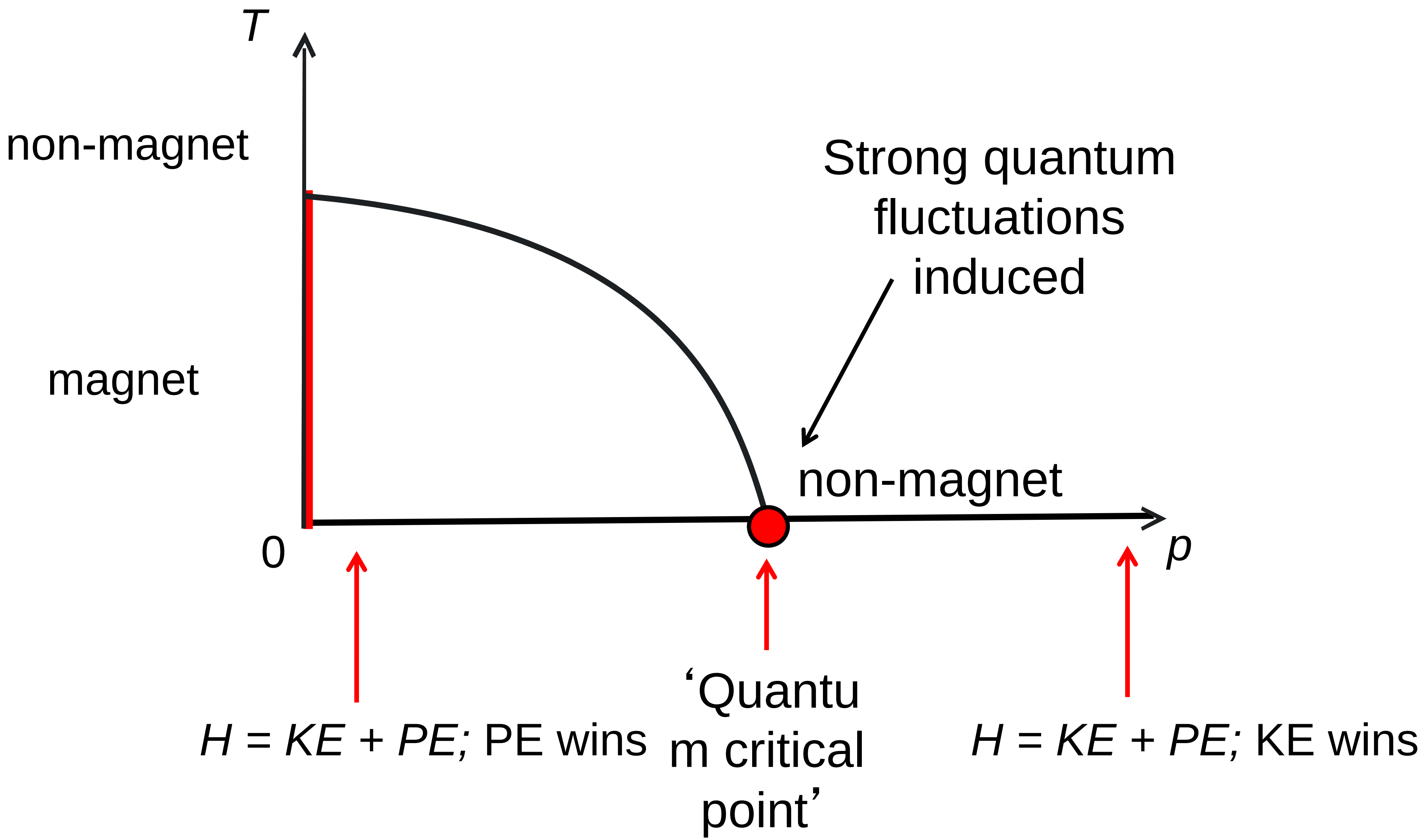




At quantum Hall densities this would require mobility of > 2.10^6 $cm^2V^{-1}s^{-1}$!

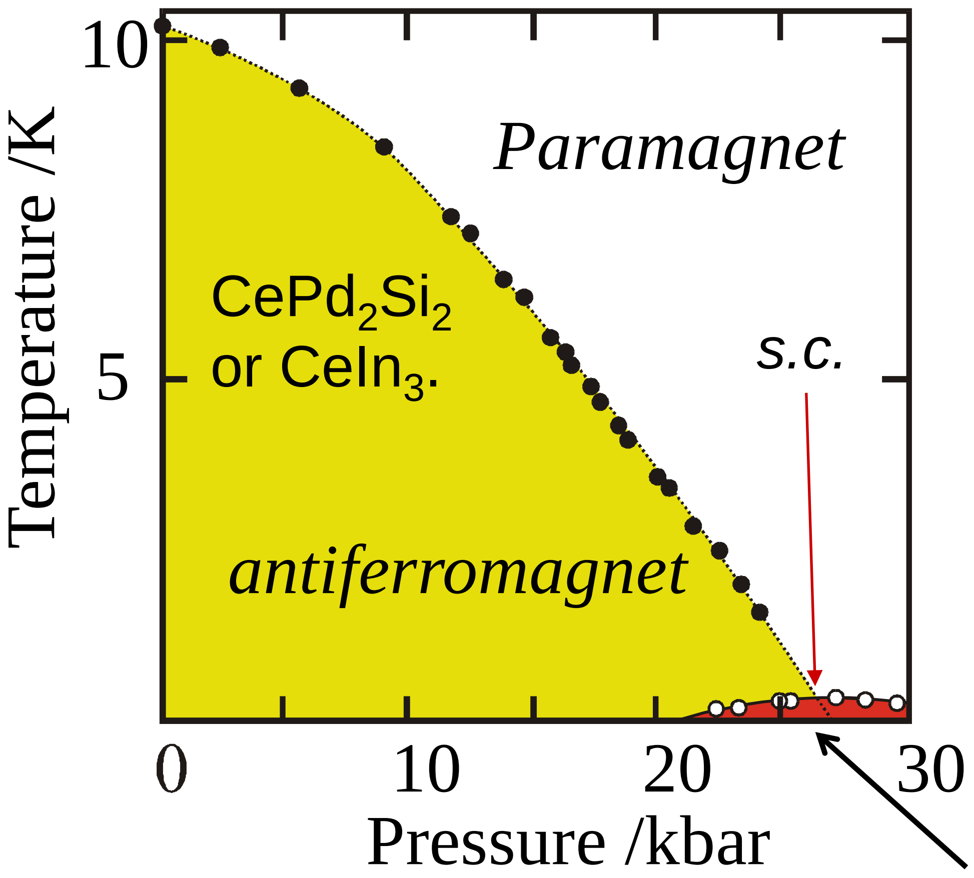
C.W. Hicks, A.S. Gibbs, A.P. Mackenzie, H. Takatsu, Y. Maeno & E.A. Yelland Phys. Rev. Lett. ***109****, 116401 (2012)*

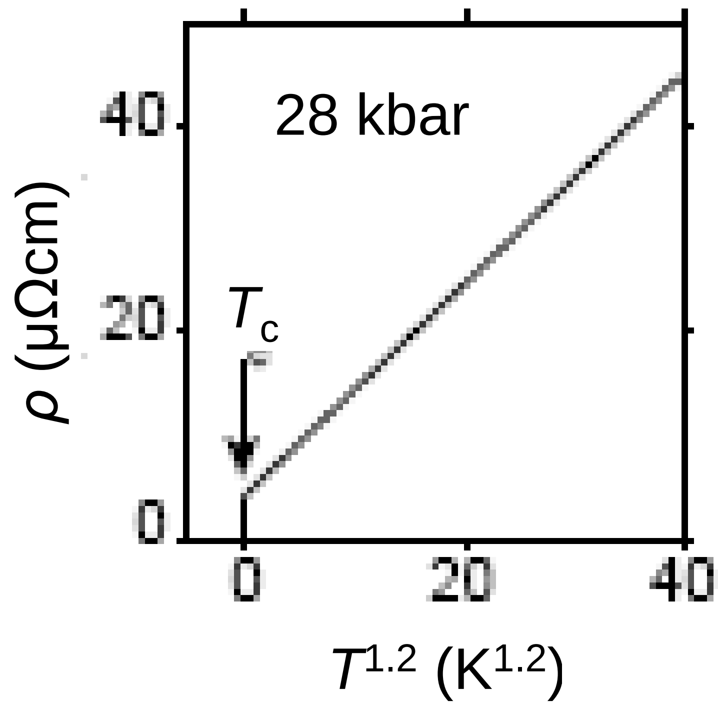
How can we stimulate entirely new physics in these ultra-pure materials?



Superconductivity near antiferromagnetic quantum critical points

Quantum critical superconductivity in two metallic antiferromagnets

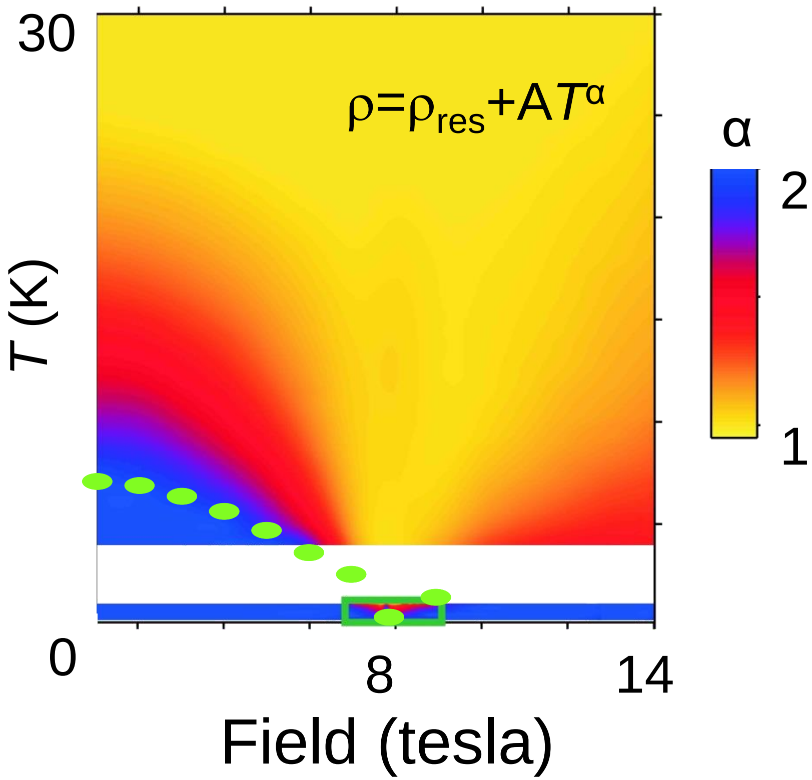


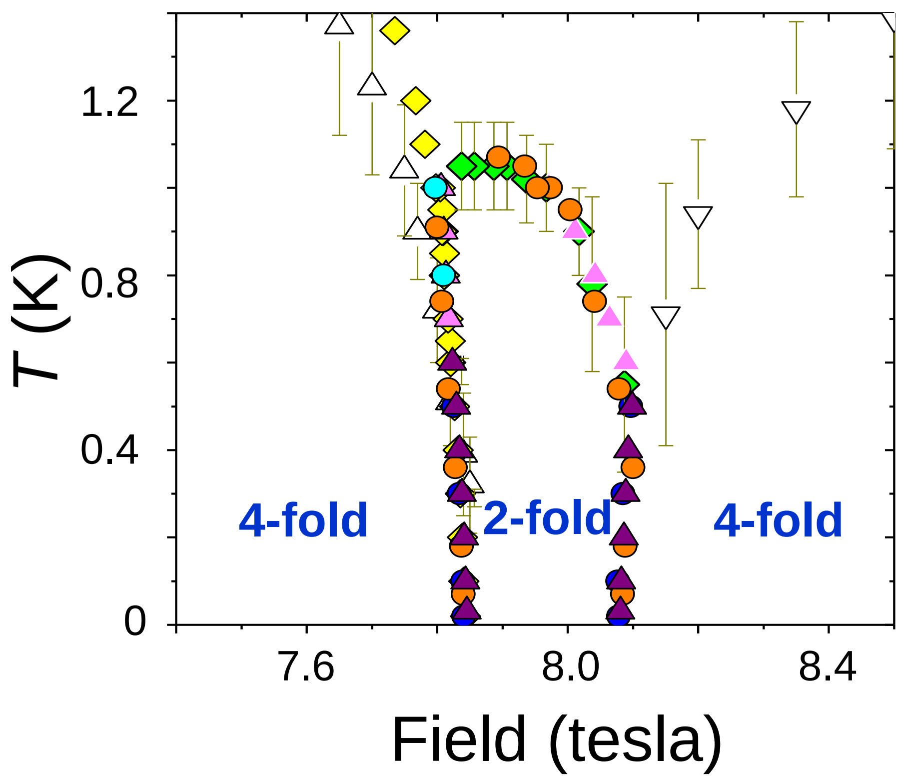


‘Novel quantum order’

*N.D. Mathur, F.M. Grosche, S.R. Julian, I.R. Walker, D.M. Freye, R.K.W. Haselwimmer and G.G. Lonzarich, Nature **394**, 39 (1998)*

$Sr_3Ru_2O_7$: phase formation from a quantum critical soup





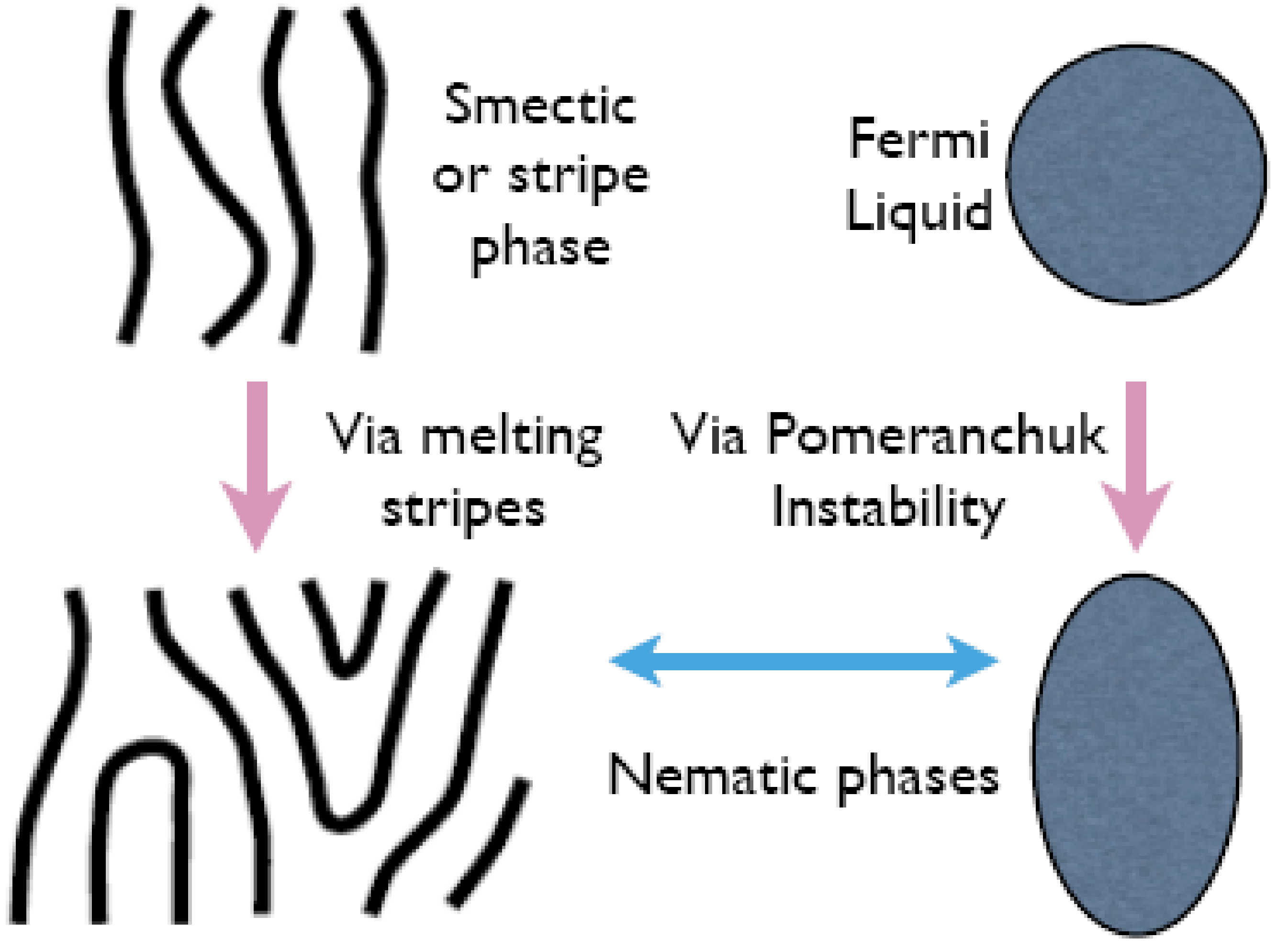
Seen in samples with ℓ ~ 3000 Å

*S.A. Grigera, P. Gegenwart, R. A. Borzi, F. Weickert, A. J. Schofield, R.S. Perry, T. Tayama, T. Sakakibara, Y. Maeno, A. G. Green & APM, Science **306**, 1154 (2004)*

*R.A. Borzi, S.A. Grigera, J. Farrell, R.S. Perry, S. Lister, S.L. Lee, D.A. Tennant, Y. Maeno & APM, Science **315**, 214 (2007)*

*J.A.N. Bruin, R.A. Borzi, S.A. Grigera, A.W. Rost, R.S. Perry and A.P. Mackenzie, Phys. Rev. B **87**, 161106 (2013)*

‘Liquid crystals’ of correlated electrons



Real space limit Momentum space limit

E. Fradkin, S.A. Kivelson, M.J. Lawler, J.P. Eisenstein & APM, Annual Review of Condensed Matter Physics ***1****, 153 (2010)*

Conclusions

Oxide metals are ideal playgrounds for the study of quantum complexity due to:

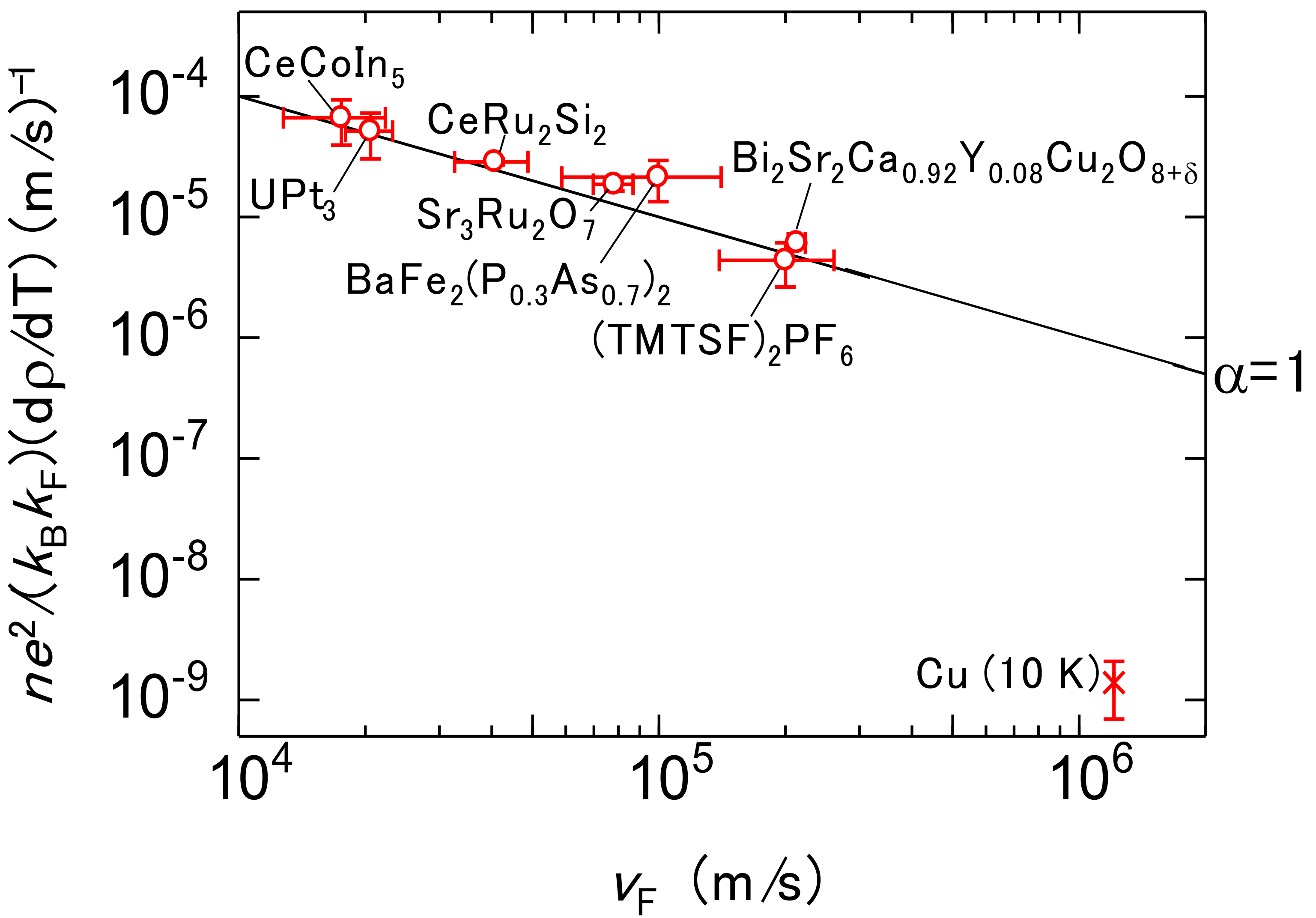
a) Rapid advances in material purity.

b) The marriage of experiment and theory common to all correlated electron systems.

c) The appearance in a single class of materials of a unique range of ground states.

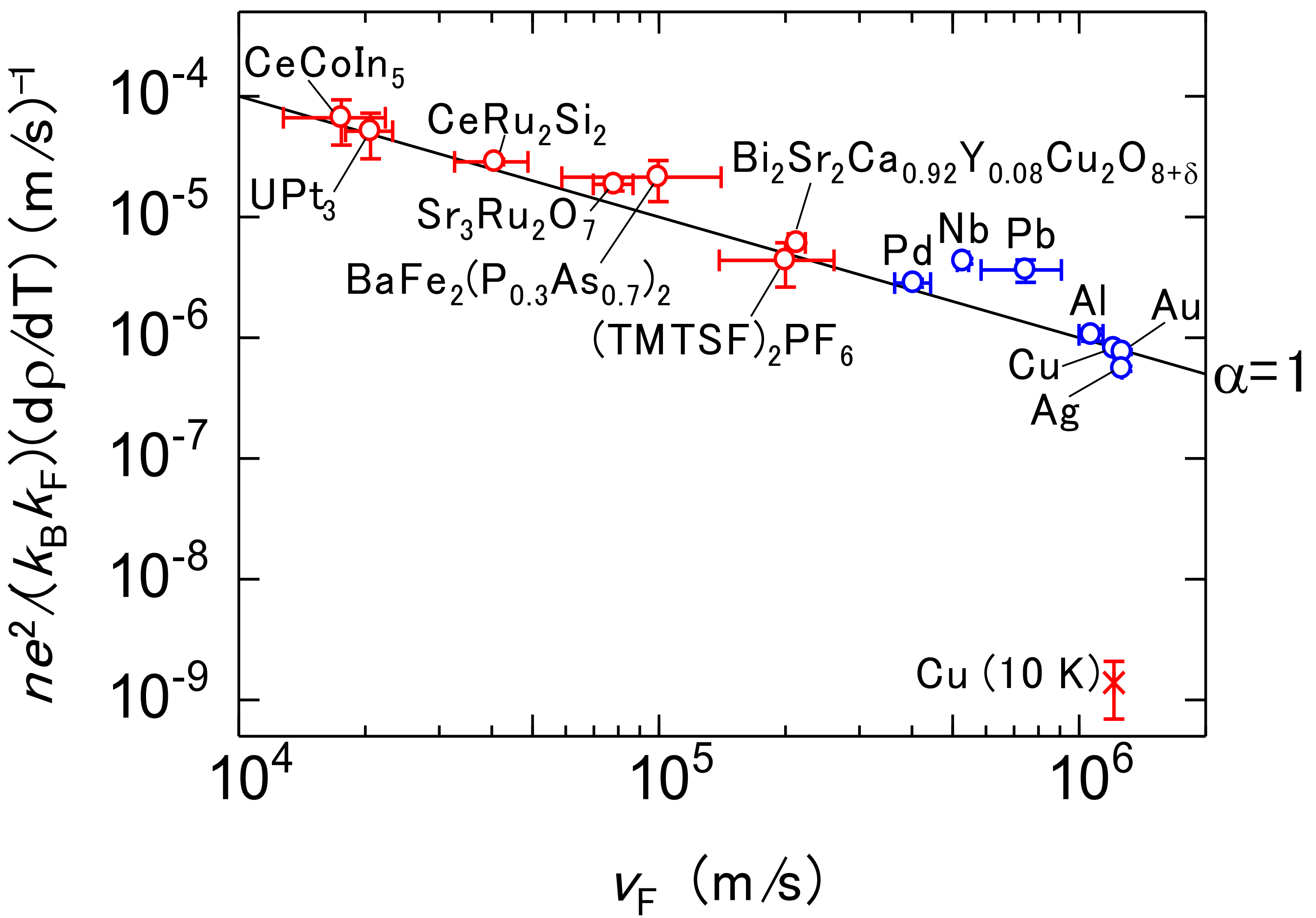
d) The increasingly realistic prospect of being able to use these many-body ground states in entirely new classes of electronics technologies.

‘Universal’ behaviour seen in heavy fermions, oxides, pnictides and organics



When ρ is T-linear, $(\tau T)^{-1} \cong k_B/\hbar$ in all these systems in spite of the range of microscopic physics and dimensionality.

Comparison with electron-phonon coupled materials at high *T*



In the language of electron-phonon scattering $\alpha = 2\pi\lambda$ where λ is the dimensionless coupling constant.