Non-Fermi Liquids and Bad Metals in $NdNiO_3$ Thin Films

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University of California, Santa Barbara

Workshop on Bad Metal Behavior in Mott Systems
Schloß Waldthausen, Germany
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Acknowledgements

UCSB

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  - Evgeny Mikheev
  - Adam Hauser
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  - Junwoo Son (now at Postech)
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Quantum Criticality

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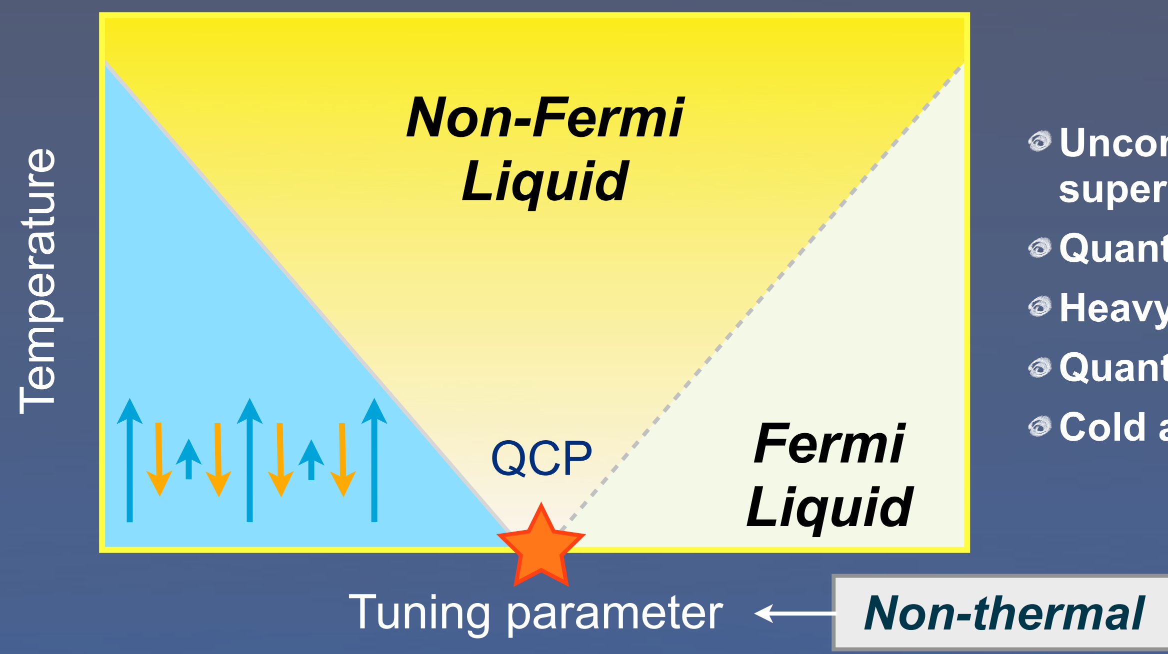


- Unconventional superconductors
- Quantum Hall systems
- Heavy-fermions
- Quantum magnets
- Cold atom gases

- **Continuous phase transition at zero-temperature**
- **Quantum fluctuations influence the material over a wide range of temperatures and across phase diagram**

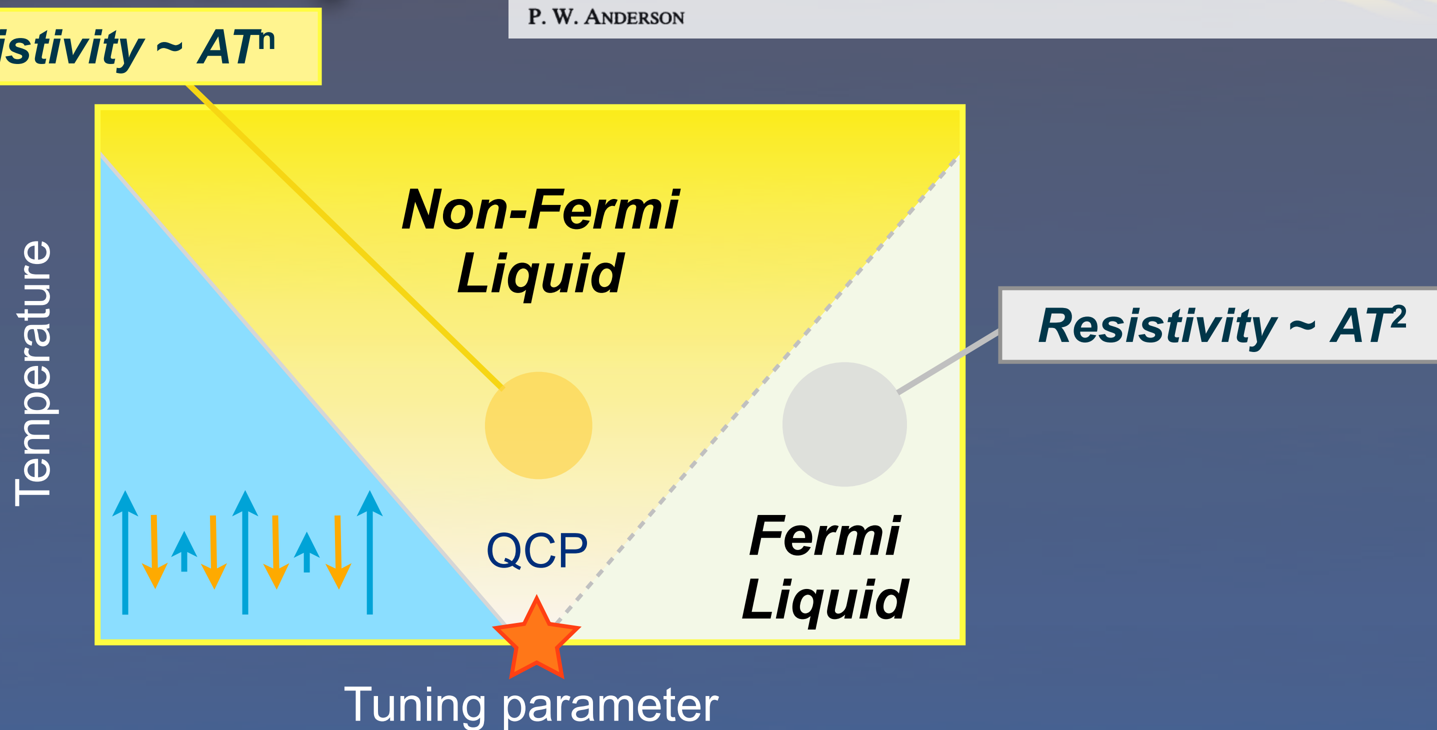
A non-thermal control parameter causing large changes in properties: metal-insulator transitions, magnetic transitions, ...

Quantum Criticality

Proc. Natl. Acad. Sci. USA
Vol. 92, pp. 6668–6674, July 1995
Colloquium Paper

New physics of metals: Fermi surfaces without Fermi liquids

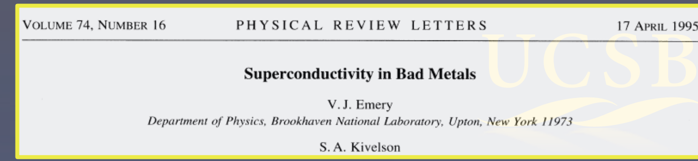
P. W. ANDERSON



Non-Fermi liquid behavior:

- Poorly understood power laws in transport coefficients
- Non-saturating resistances that escalate past the Mott-Ioffe-Regel limit: “Strange Metals”
- Strong temperature dependence of the Hall coefficient (not reflecting a real change in Fermi surface)

Bad Metals


VOLUME 74, NUMBER 16 PHYSICAL REVIEW LETTERS 17 APRIL 1995

Superconductivity in Bad Metals

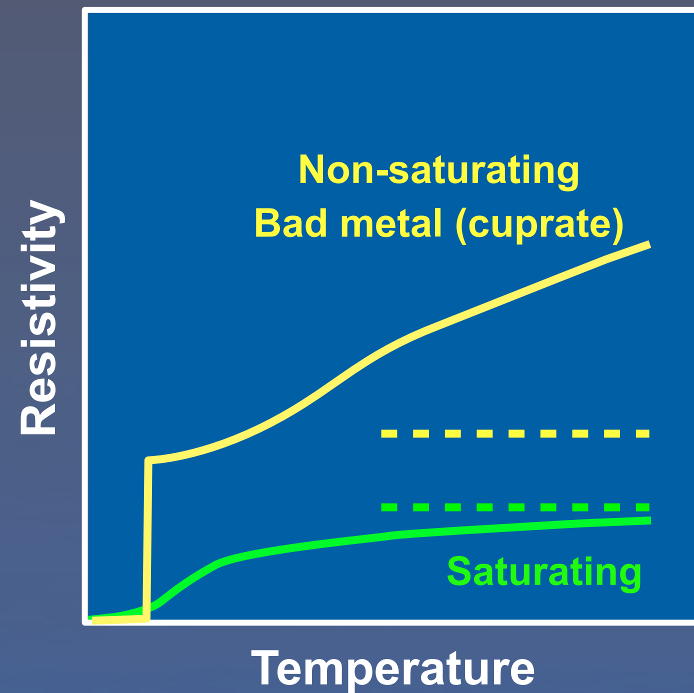
V. J. Emery

Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

S. A. Kivelson

- **Mott-Ioffe-Regel limit: mean free path length ~ lattice spacing**
- **Neither saturating nor non-saturating metals are understood**

P. B. Allen, Physica B 318, 24-27 (2002); O. Gunnarsson, et al., Nature 405, 1027 (2000); B. Chakraborty, and P.B. Allen, Phys. Rev. Lett. 42, 736-738 (1979); M. Calandra, and O. Gunnarsson, Phys. Rev. B 66, 205105 (2002); P. B. Allen, Nature 405, 1007 (2000); Millis, A.J., Hu, J., & Sarma, S.D., Phys. Rev. Lett. 82, 2354-2357 (1999); O. Gunnarsson, et al., RMP 75, 1085 (2003); N. E. Hussey, K. Takenaka, & H. Takagi, Phil. Mag. 84, 2847 (2004).



$$\rho_{MIR} = \frac{3\pi^2\hbar}{q^2 k_F^2 a}$$

Mott-Ioffe-Regel limit

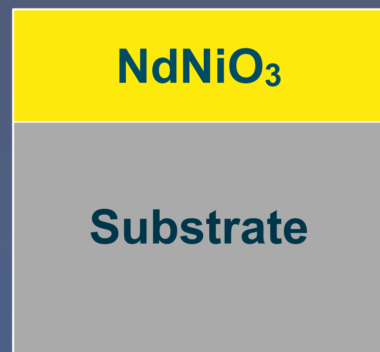
Mott-Ioffe-Regel limit

- **Saturating metals are described by:**

$$\frac{1}{\rho} = \frac{1}{\rho_0 + AT^n} + \frac{1}{\rho_{sat}}$$

- **Electron-electron scattering: n ~ 2**
- **Non-Fermi liquids: n < 2**
- **ρ_0: residual resistance (disorder)**
- **Saturation resistance connected in parallel, serves to reduce resistance**

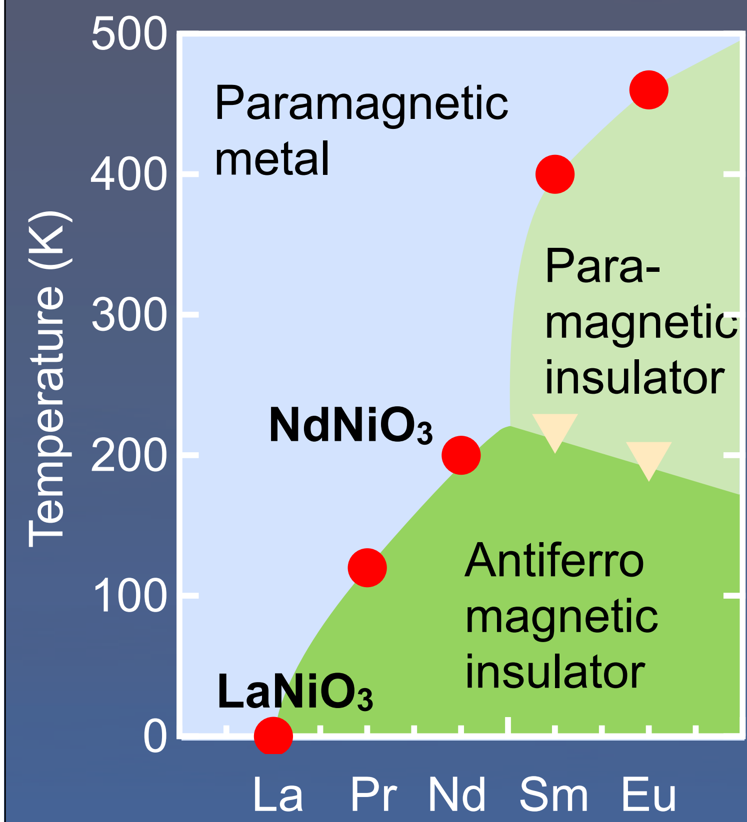
This talk:

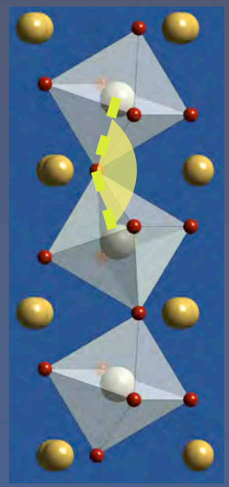


Non-Fermi liquid behavior in strained $NdNiO_3$ thin films:

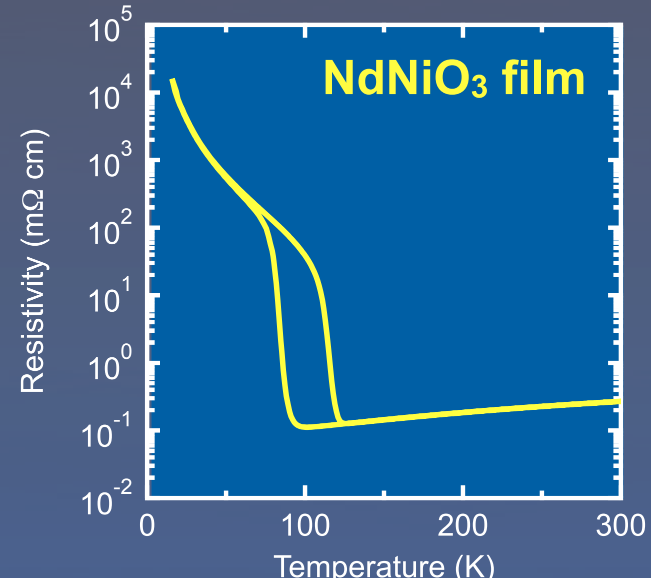
- NFL power law coefficients in resistivity
- Quantum critical point
- Bad metal behavior
- Vary strain and confinement (thickness): relationship to electronic structure

Metal-Insulator Transitions in $RNiO_3$





J. B. Torrance, et al., Phys. Rev. B 45, 8209 (1992). J. M. Rondinelli, S. J. May, and J. W. Freeland, MRS Bulletin (March 2012).



A. J. Hauser, et al., Appl. Phys. Lett. 106, 092104 (2015).

- **Quantum phase transition**
- **Size of the rare earth ion is the tuning parameter: "band-width driven metal-insulator transition"**
- **Expect the transition to be sensitive to strain**
- **Is the transition quantum critical?**
- **Non-Fermi liquid behavior?**

Orbital Engineering in $RNiO_3$

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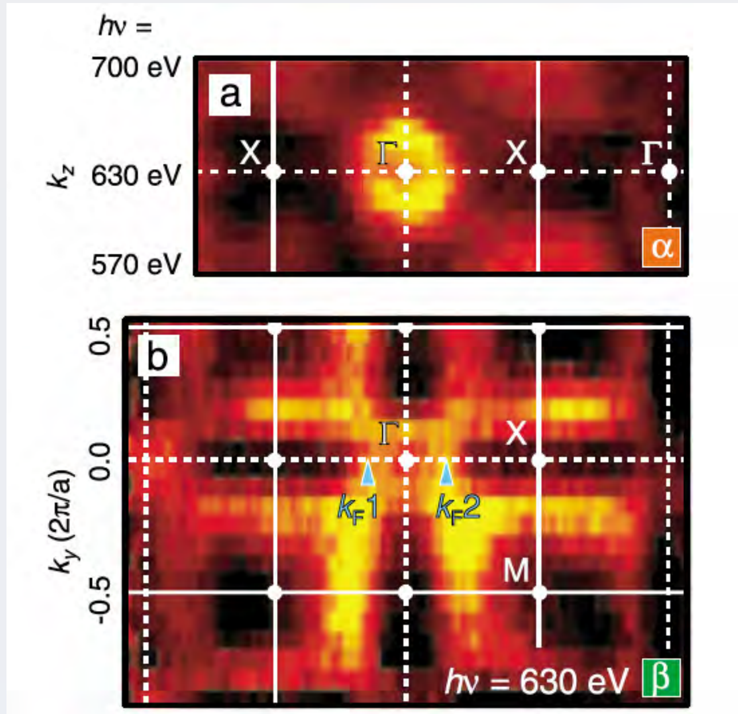


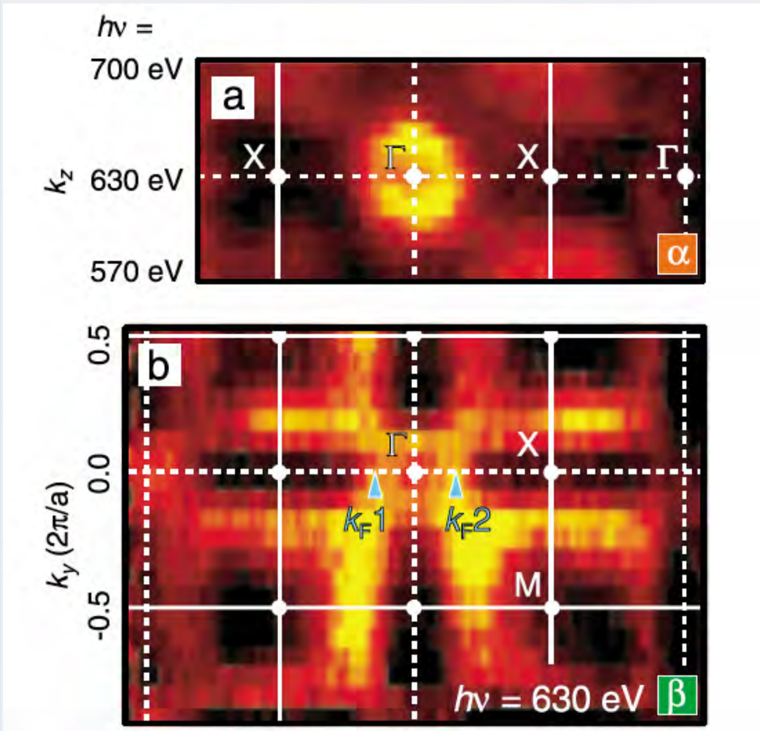
R. Eguchi, et al., Phys. Rev. B 79, 115122 (2009).

PRL **103,** 016401 (2009) PHYSICAL REVIEW LETTERS week ending 3 JULY 2009

Turning a Nickelate Fermi Surface into a Cupratelike One through Heterostructuring

P. Hansmann,[1,2] Xiaoping Yang,[1] A. Toschi,[1,2] G. Khaliullin,[1] O. K. Andersen,[1] and K. Held[2]

Orbital Engineering in $RNiO_3$



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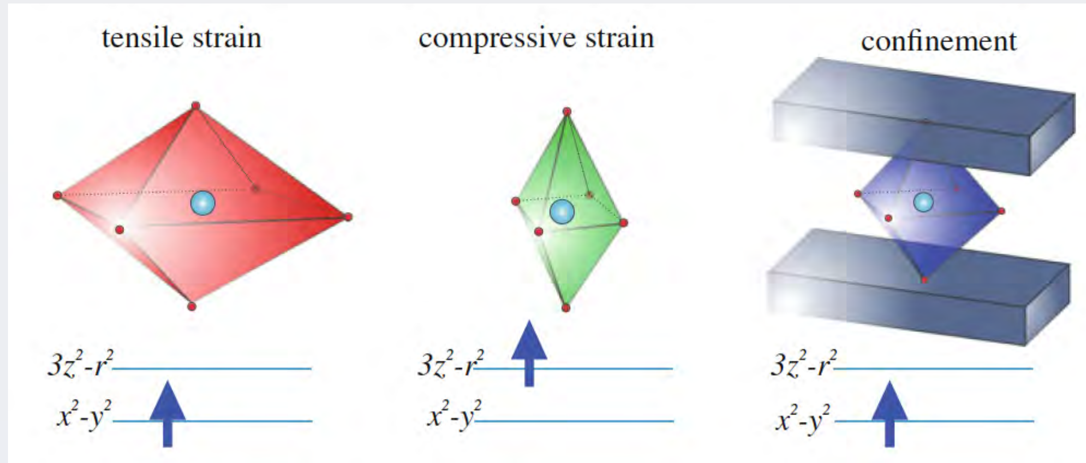
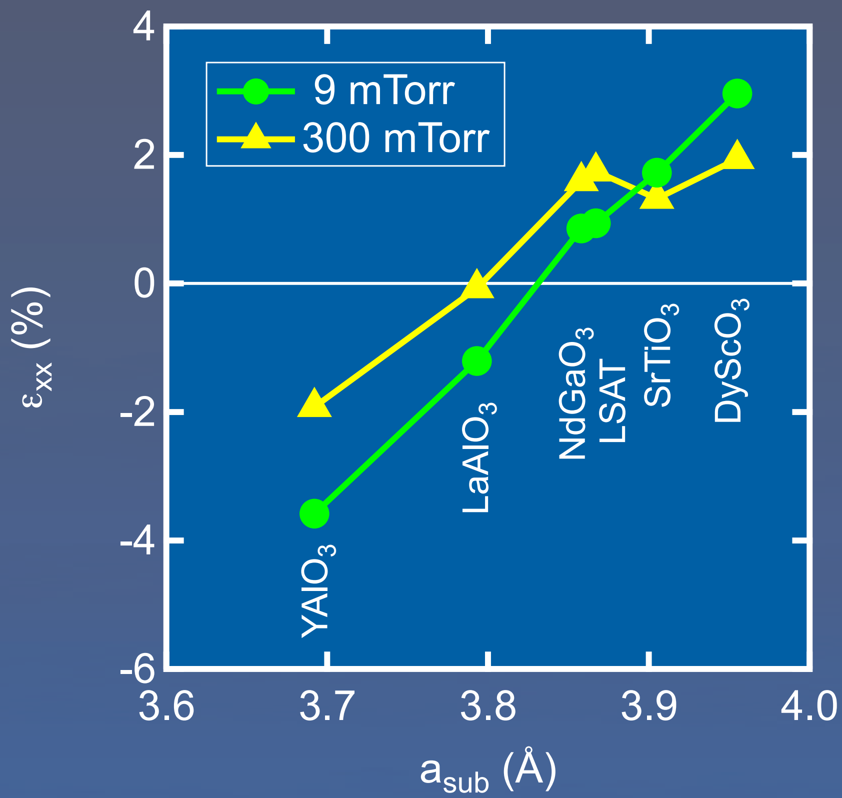


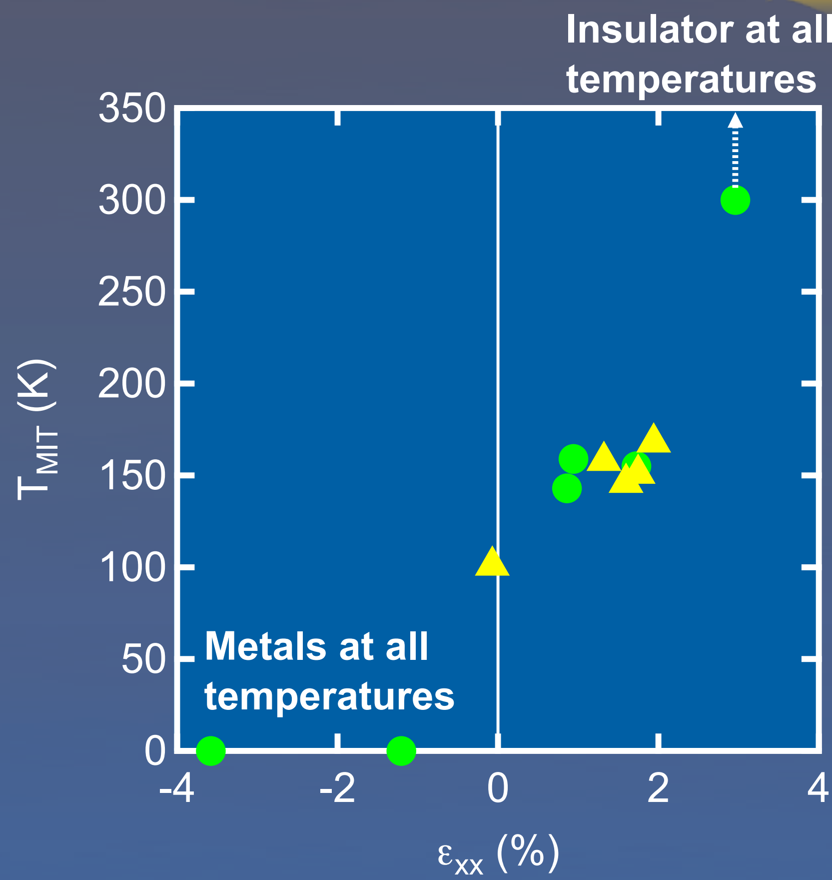
A. Frano, Spin Spirals and Charge Textures in Transition-Metal-Oxide Heterostructures (Ph.D. thesis, 2014), Springer.

O. E. Peil et al., Phys. Rev. B 90, 045128 (2014); E. Benckiser, et al., Nat. Mater. 10, 189 (2011); J.W. Freeland, et al., EPL 96, 57004 (2011); A.V. Boris, et al., Science 332, 937 (2011); M. Wu et al., Phys. Rev. B 88, 125124 (2013); H. K. Yoo, et al., Sci. Rep. 5, 8746 (2015); S. B. Lee et al., Phys. Rev. Lett. 106, 016405 (2011).

- **Tensile strains and confinement favor the large hole surface**
- **Promotes a spin density wave instability and insulating state**
- **Confinement and tensile strains have qualitatively similar effects**

Strain as a Tuning Parameter





A. J. Hauser, et al., Appl. Phys. Lett. 106, 092104 (2015).

- Epitaxial strain systematically shifts the MIT
- MIT is relatively independent of deposition conditions, which affect the stoichiometry
- Low-pressure films can be strained to larger strains without relaxing

Orbital Engineering in $RNiO_3$

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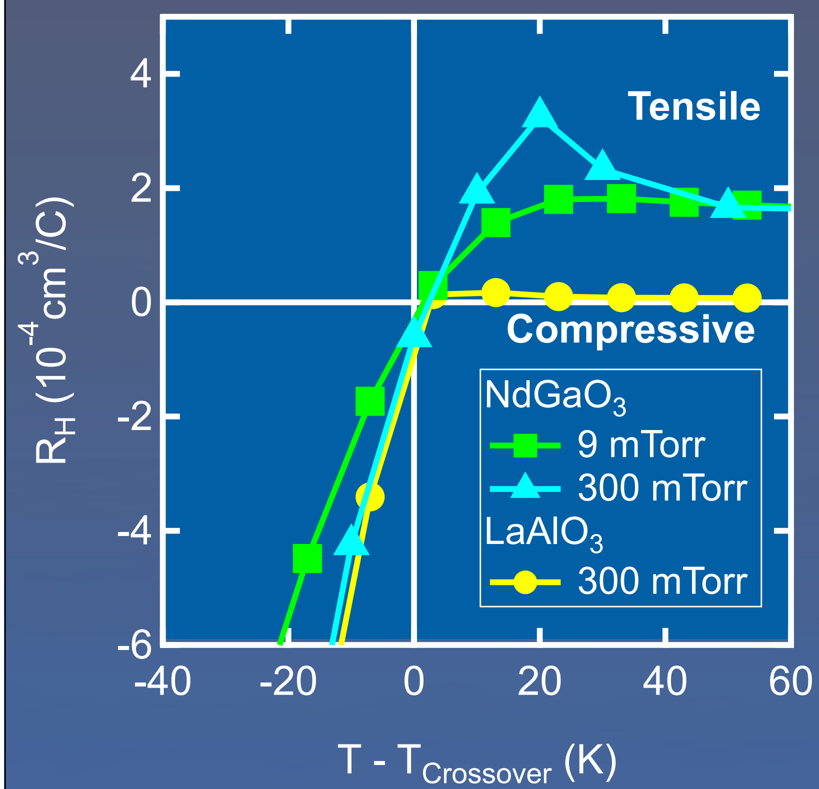

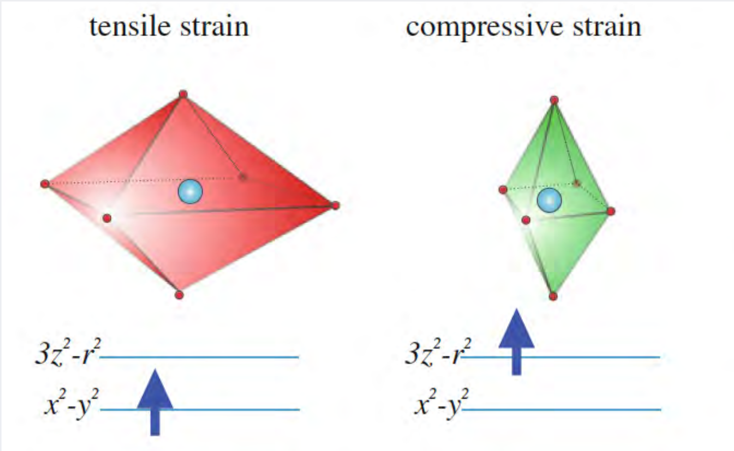

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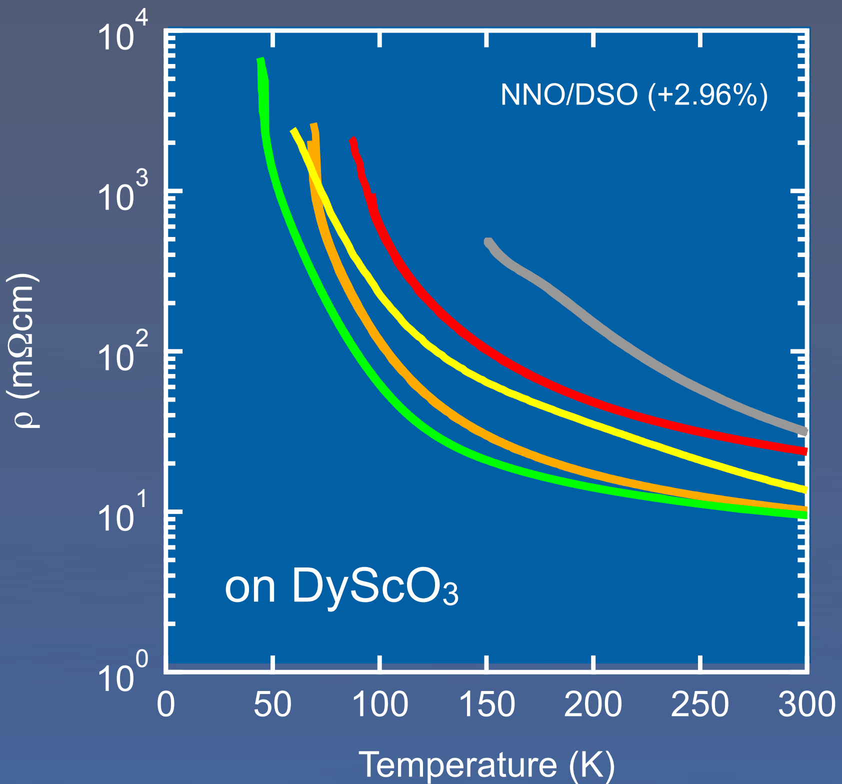

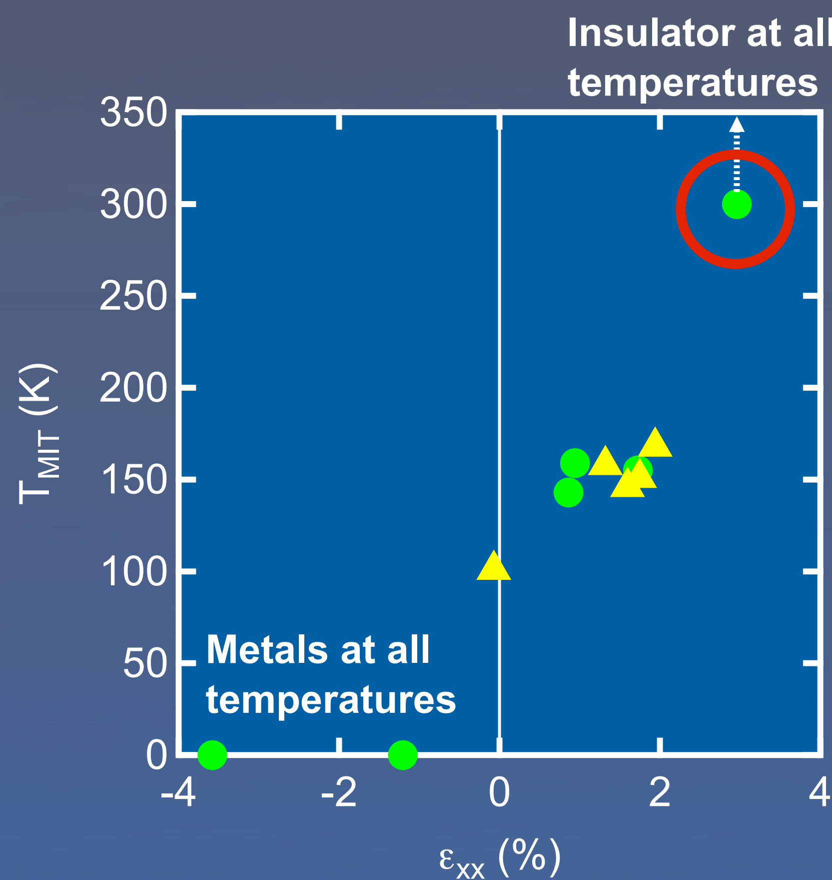

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Likely more complex reasons for films with insulating state at all temperature than simple band width tuning

Role of disorder?

Criterion for Anderson transition in this system?

Metal-Insulator Transitions in $NdNiO_3$

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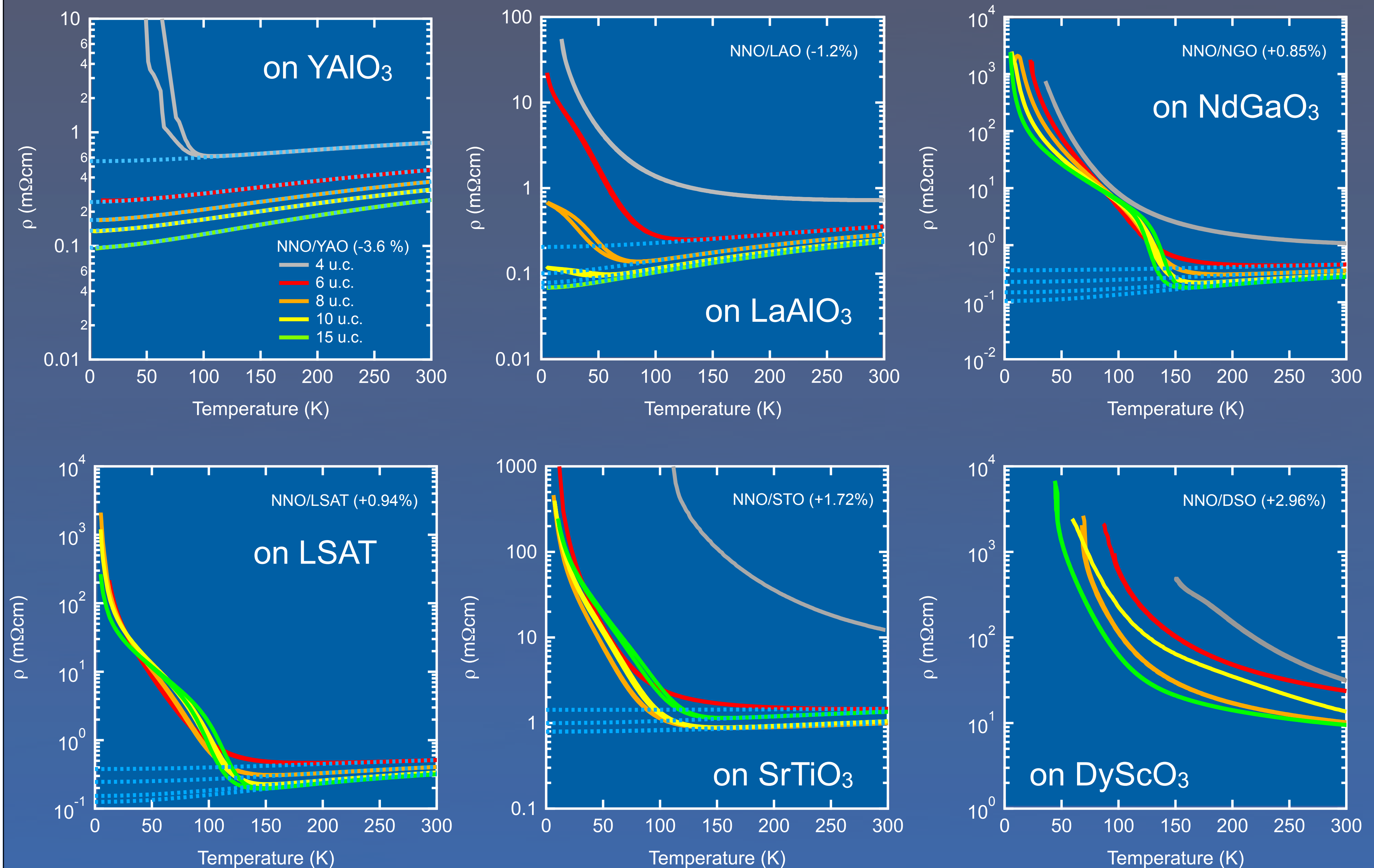

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]

Metal-Insulator Transitions in $NdNiO_3$

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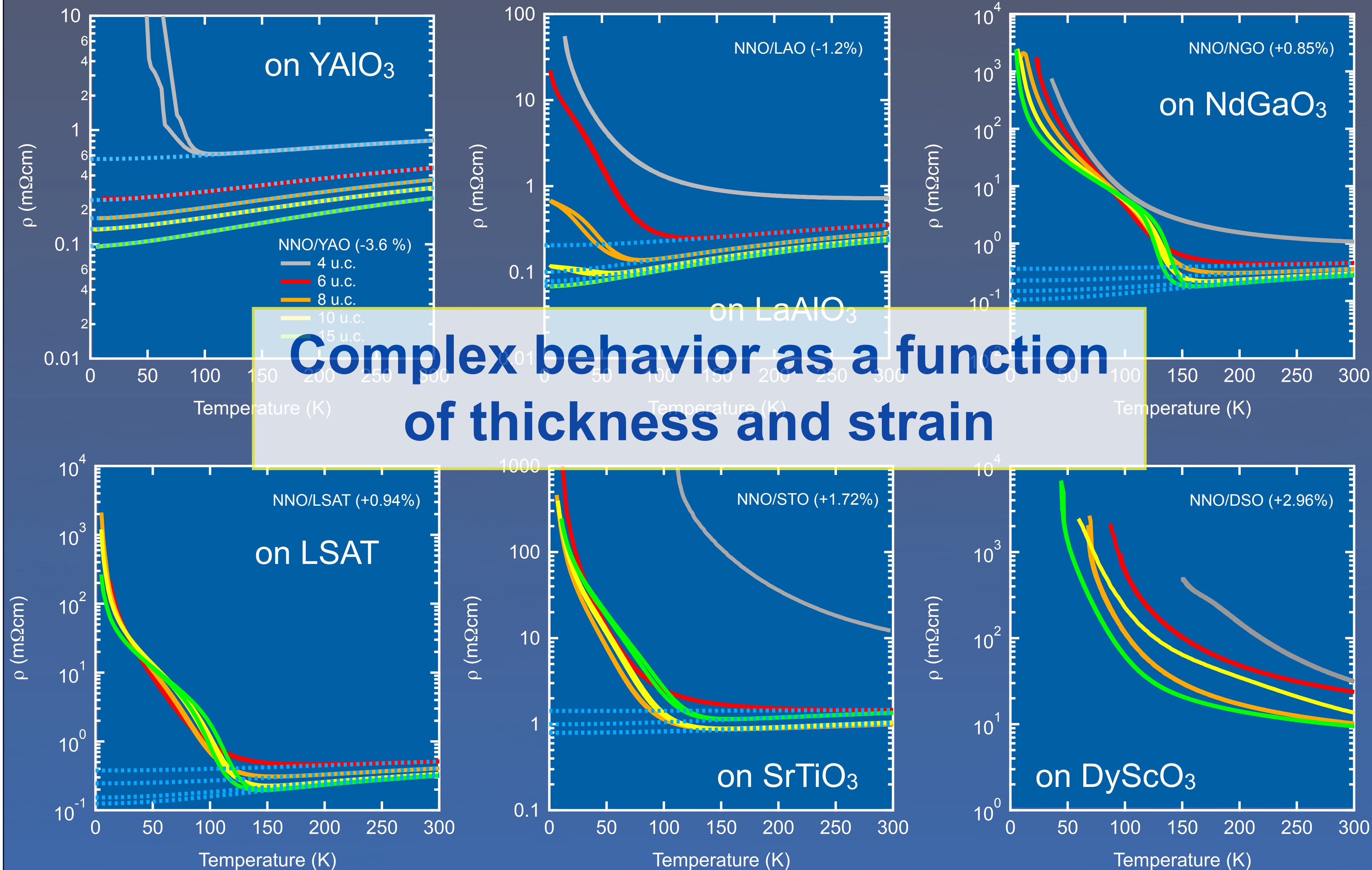
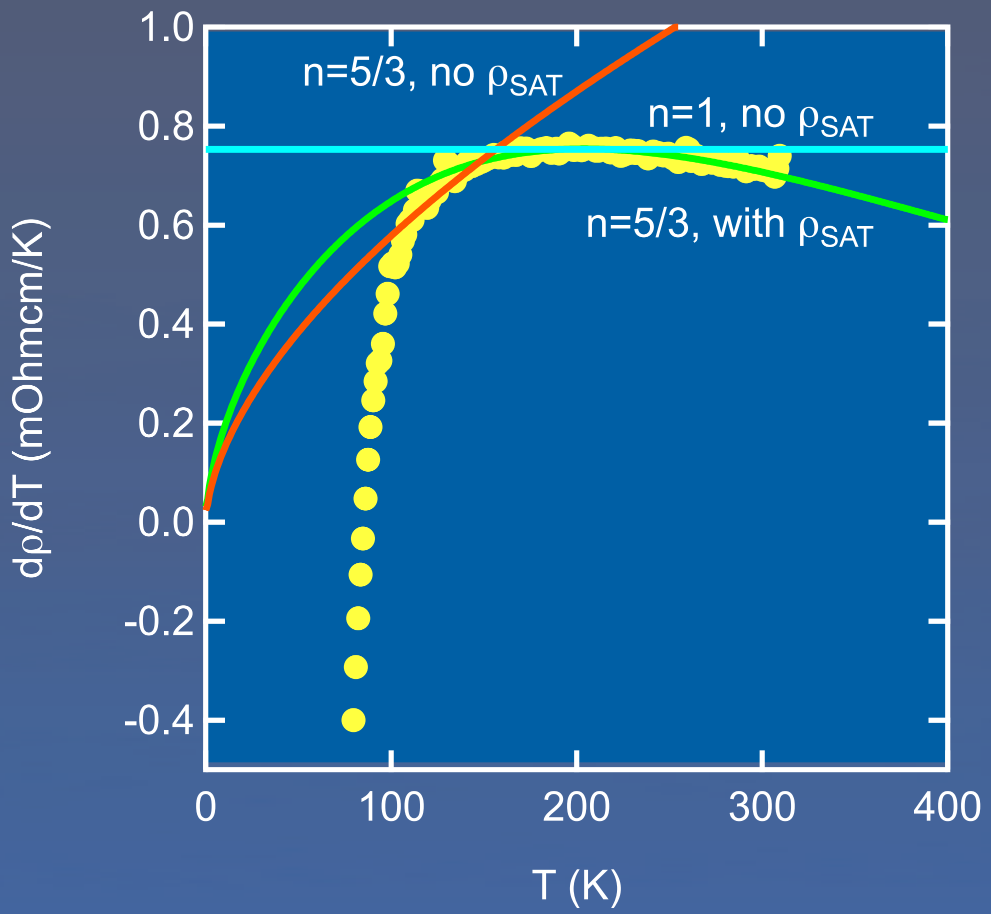


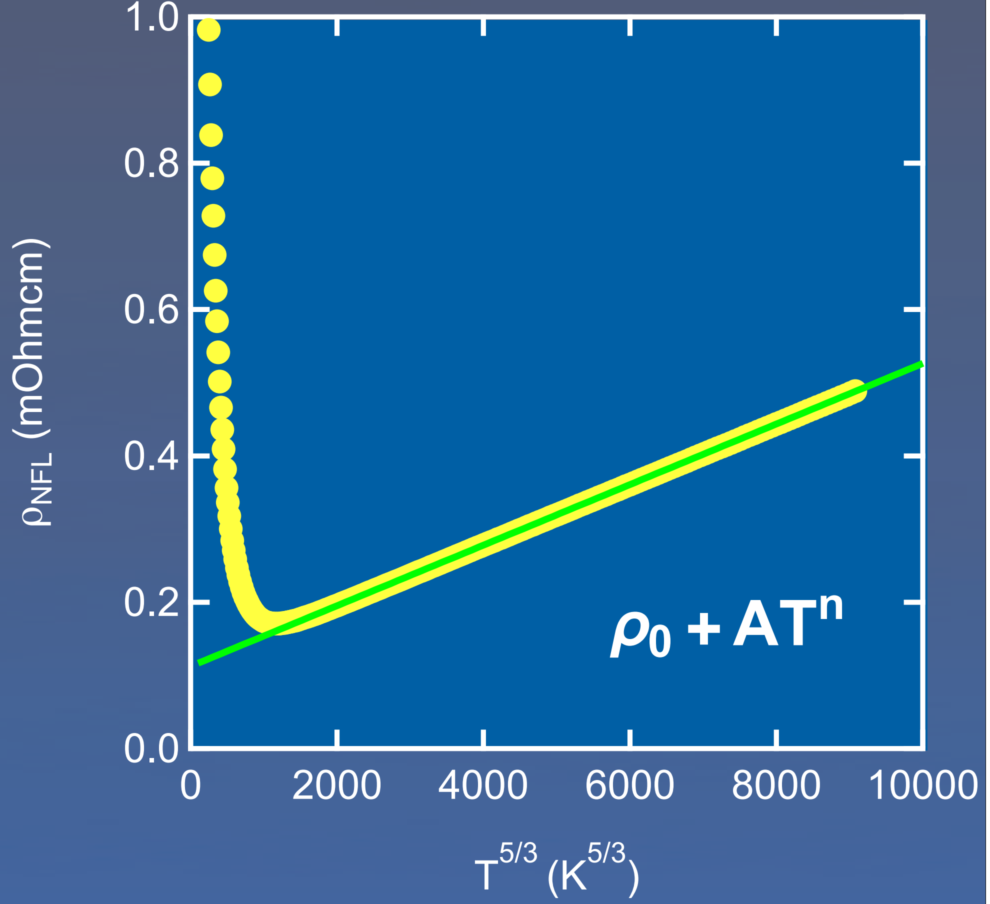
Complex behavior as a function of thickness and strain

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]

MITs and Non-Fermi Liquids

$$\frac{1}{\rho} = \frac{1}{\rho_0 + AT^n} + \frac{1}{\rho_{sat}}$$



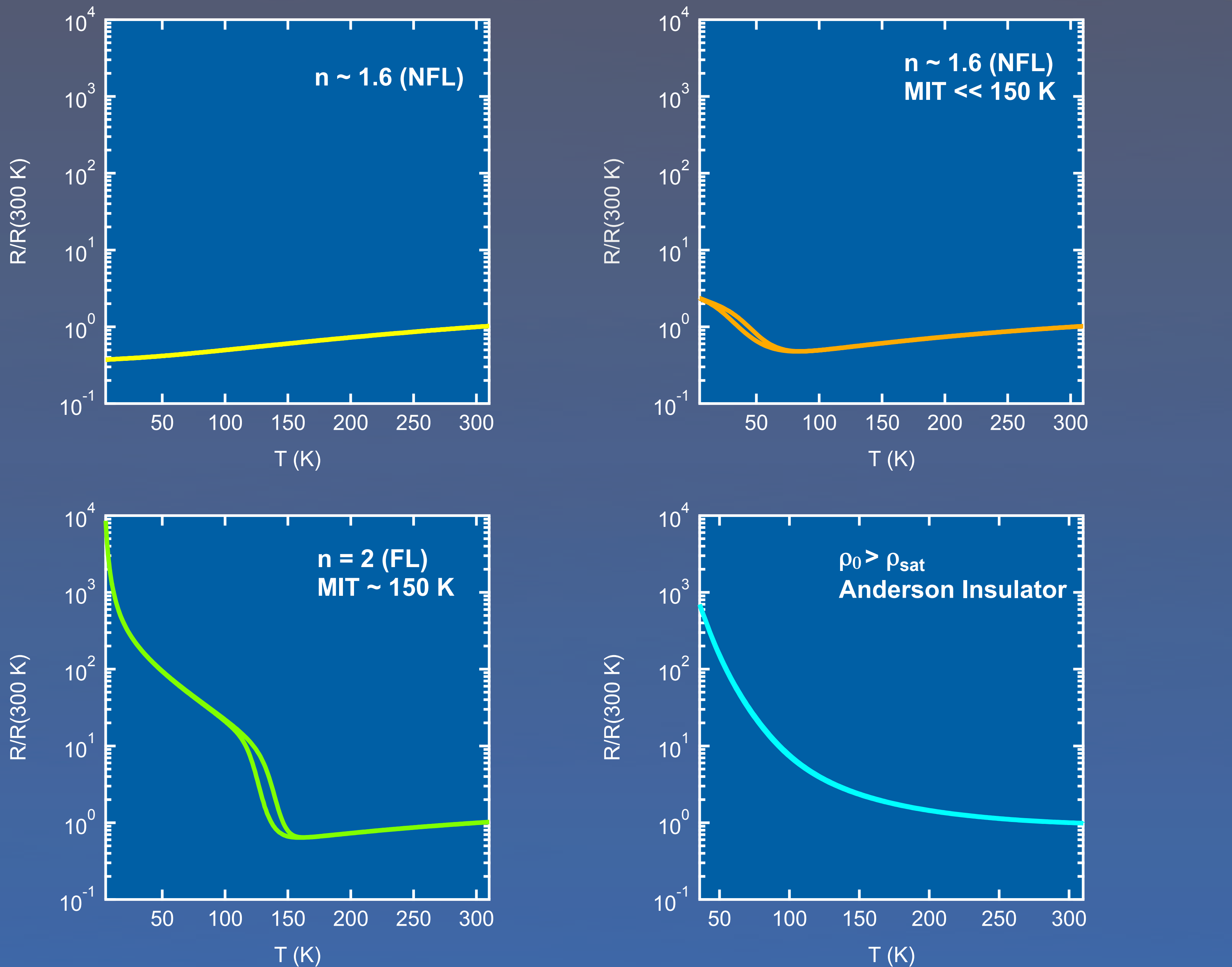


E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]

- **Metallic phase exhibits saturating resistance**
- **Need to take into account to get correct NFL exponent**

MITs and Non-Fermi Liquids

$R = R_0 + AT^n$



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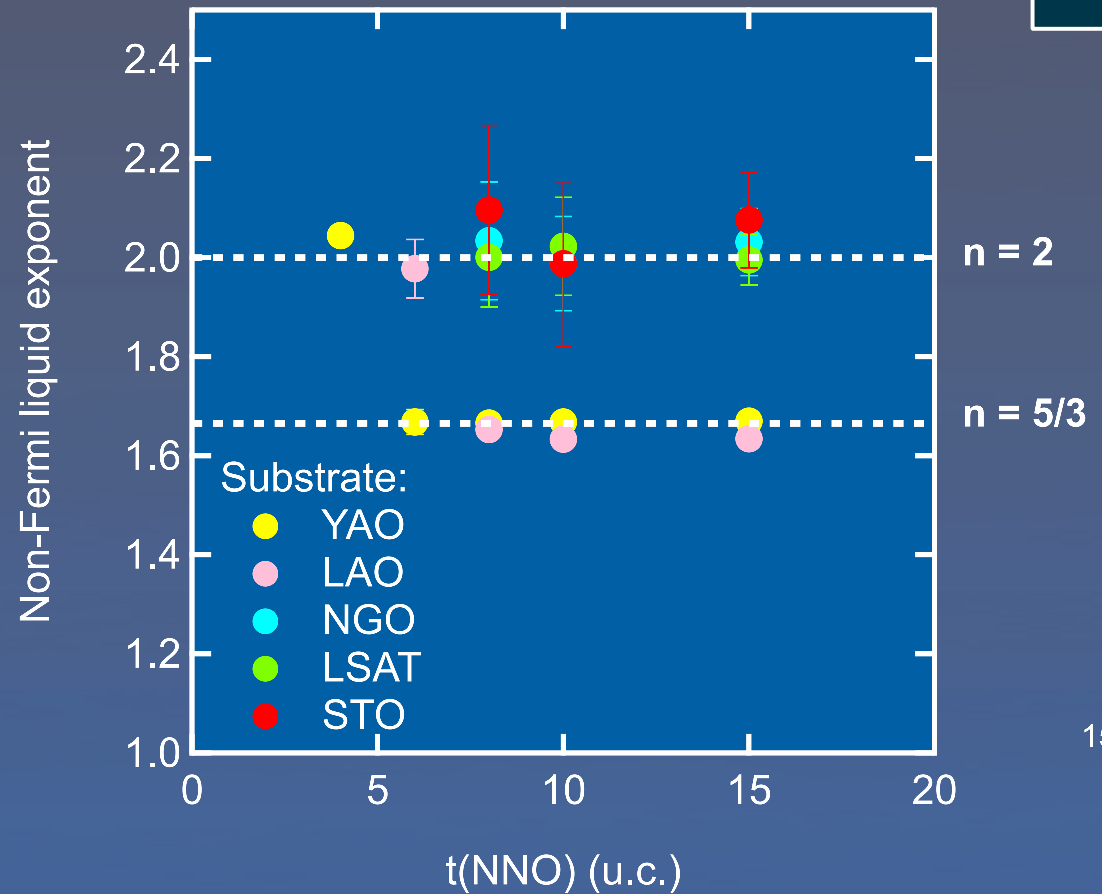
MITs and Non-Fermi Liquids

$$\frac{1}{\rho} = \frac{1}{\rho_0 + AT^n} + \frac{1}{\rho_{sat}}$$

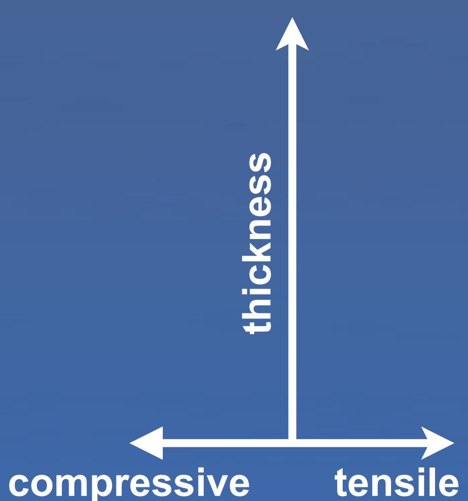


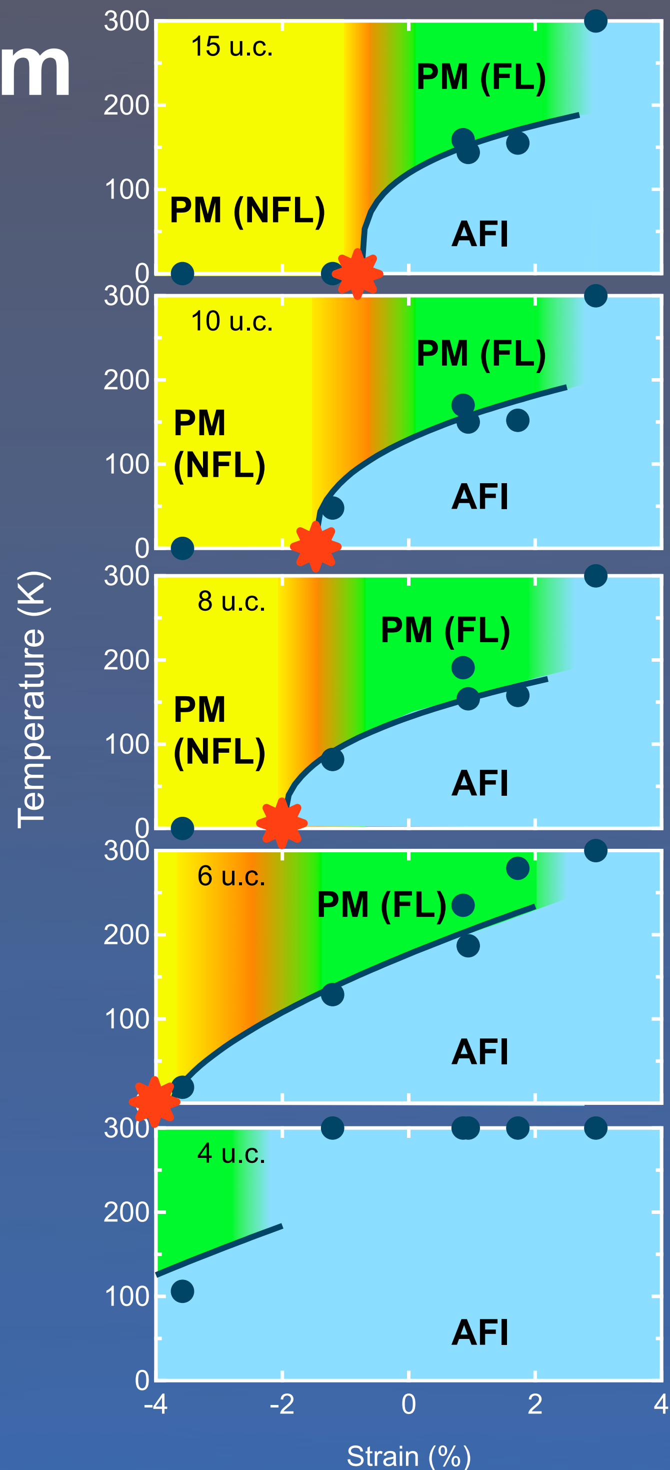
E. Mikheev, et al., arXiv: 1507.06619 [cond-mat.str-el]

- **Non-Fermi liquid behavior *only* if MIT is suppressed**
- **Same exponent (5/3) across the entire sample series**
- ***n* is independent of disorder**
- **Need to take resistance saturation into account to get correct *n***

Phase Diagram

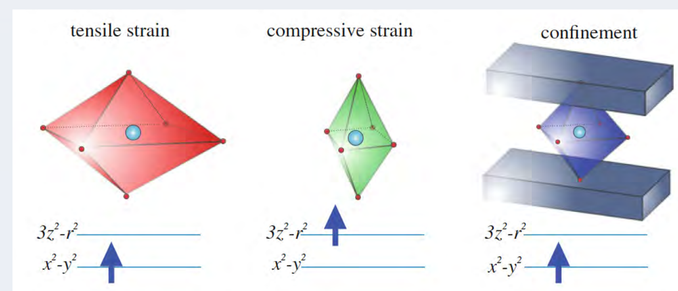
$$\frac{1}{\rho} = \frac{1}{\rho_0 + AT^n} + \frac{1}{\rho_{sat}}$$





- **Quantum critical point shifts to more compressive strains with decreasing film thickness**
- **Confinement promotes x^2-y^2 orbital polarization, which favors spin density wave and the AFM insulator**
- **Suppression of MIT leads to NFL behavior**

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]



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Bad Metals

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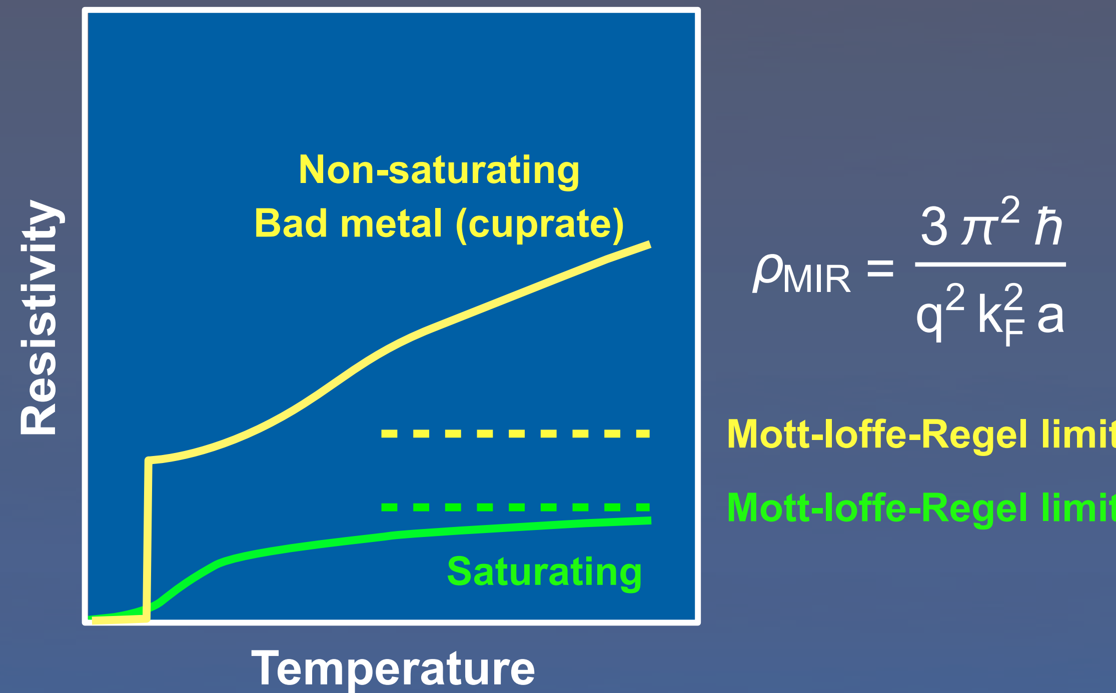
- **Mott-Ioffe-Regel limit: mean free path length ~ lattice spacing**
- **Neither saturating nor non-saturating metals are understood**

P. B. Allen, Physica B 318, 24-27 (2002); O. Gunnarsson, et al., Nature 405, 1027 (2000); B. Chakraborty, and P.B. Allen, Phys. Rev. Lett. 42, 736-738 (1979); M. Calandra, and O. Gunnarsson, Phys. Rev. B 66, 205105 (2002); P. B. Allen, Nature 405, 1007 (2000); Millis, A.J., Hu, J., & Sarma, S.D., Phys. Rev. Lett. 82, 2354-2357 (1999); O. Gunnarsson, et al., RMP 75, 1085 (2003); N. E. Hussey, K. Takenaka, & H. Takagi, Phil. Mag. 84, 2847 (2004).



$$\rho_{MIR} = \frac{3\pi^2\hbar}{q^2 k_F^2 a}$$

- **Saturating metals are described by:**

$$\frac{1}{\rho} = \frac{1}{\rho_0 + AT^n} + \frac{1}{\rho_{sat}}$$

- **Electron-electron scattering: n ~ 2**
- **Non-Fermi liquids: n < 2**
- **ρ_0: residual resistance (disorder)**
- **Saturation resistance connected in parallel, serves to reduce resistance**

Saturating Metallic Phase

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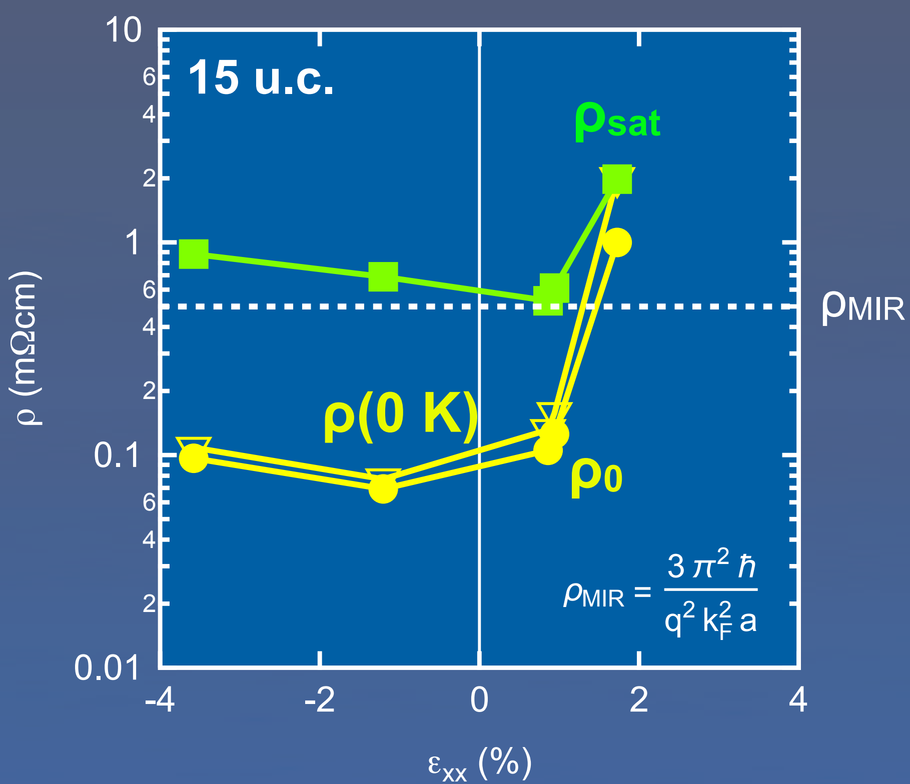
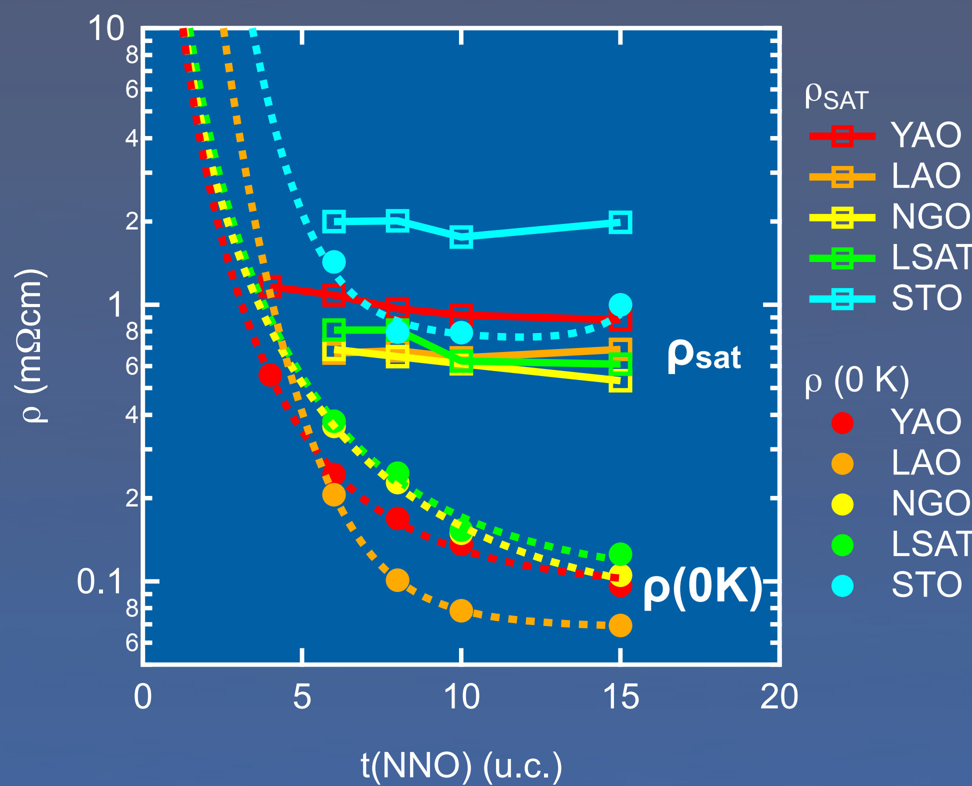
In the 0-K limit: $$\frac{1}{\rho\,(0\,\mathrm{K})} = \frac{1}{\rho_0} + \frac{1}{\rho_{sat}}$$

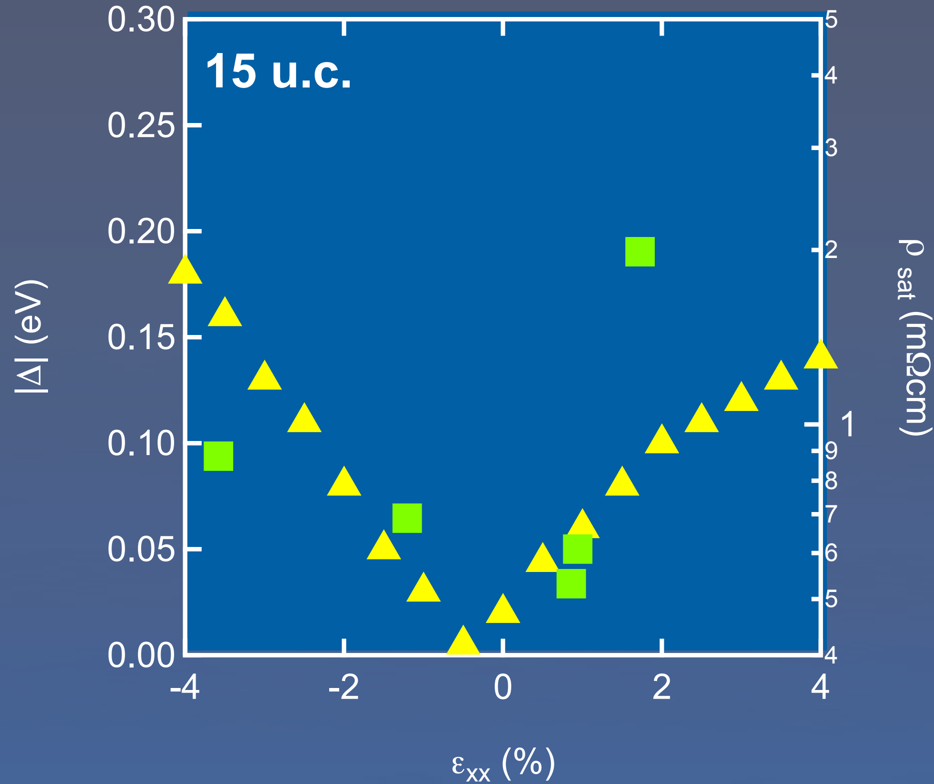




- ρ_{sat} and ρ_0 depend on the magnitude of the mismatch strain
- ρ_{sat} is independent of thickness (confinement, disorder)
- ρ_0 strongly depends on thickness

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]

Saturation and Orbital Polarization



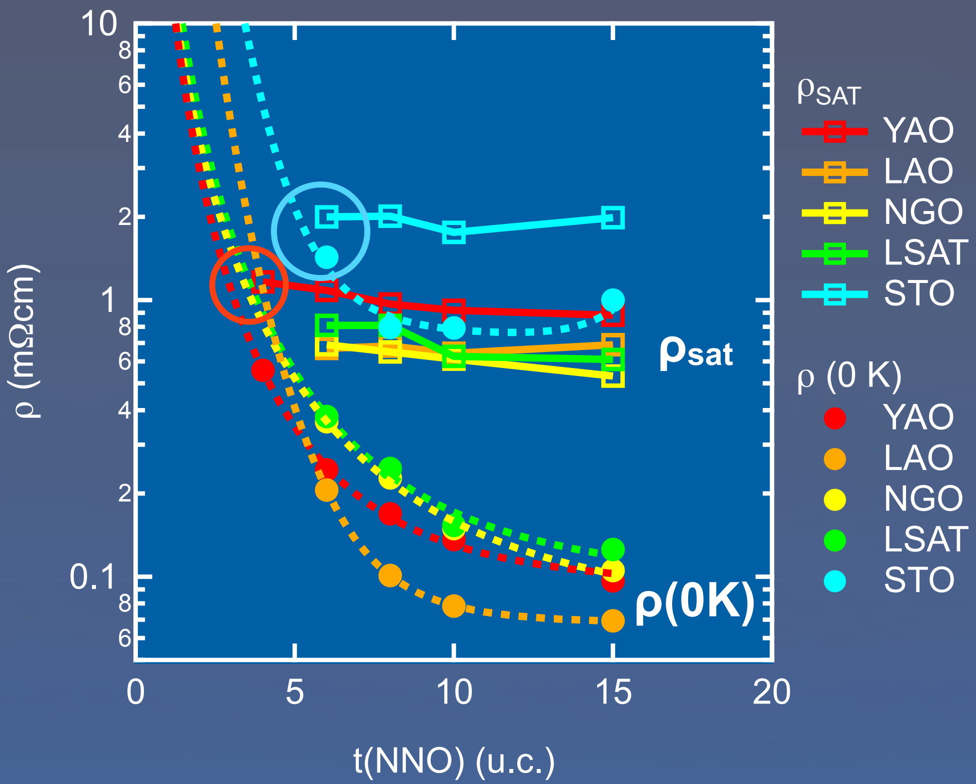
- ρ_{sat} depends on the magnitude of orbital polarization
- A parallel channel due to interband scattering
- Conversely, predict that materials with a single band at the Fermi level show no saturation (i.e., cuprates)

- **Consistent with theoretical predictions (modified Boltzmann transport models that account for interband scattering and QMC simulations)**

  P. B. Allen, Physica B 318, 24-27 (2002); O. Gunnarsson, et al., Nature 405, 1027 (2000); B. Chakraborty, and P.B. Allen, Phys. Rev. Lett. 42, 736-738 (1979); M. Calandra, et al., Phys. Rev. B 66, 205105 (2002).

- **ρ_{sat} is tunable by orbital polarization**

Criterion for the "Anderson Insulator": $\rho_{sat} \sim \rho_0$



$$\frac{1}{\rho} = \frac{1}{\rho_0 + AT^n} + \frac{1}{\rho_{sat}}$$

- **ρ_{sat} is independent of thickness but depends on strain**
- **ρ_0 depends on thickness**
- **Predict that material is insulating at all temperatures when $\rho_{sat} \sim \rho_0$**
- **Correct to within 1 u.c.**
- **This Anderson insulator is strain and thickness tunable**

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]

MITs and Non-Fermi Liquids

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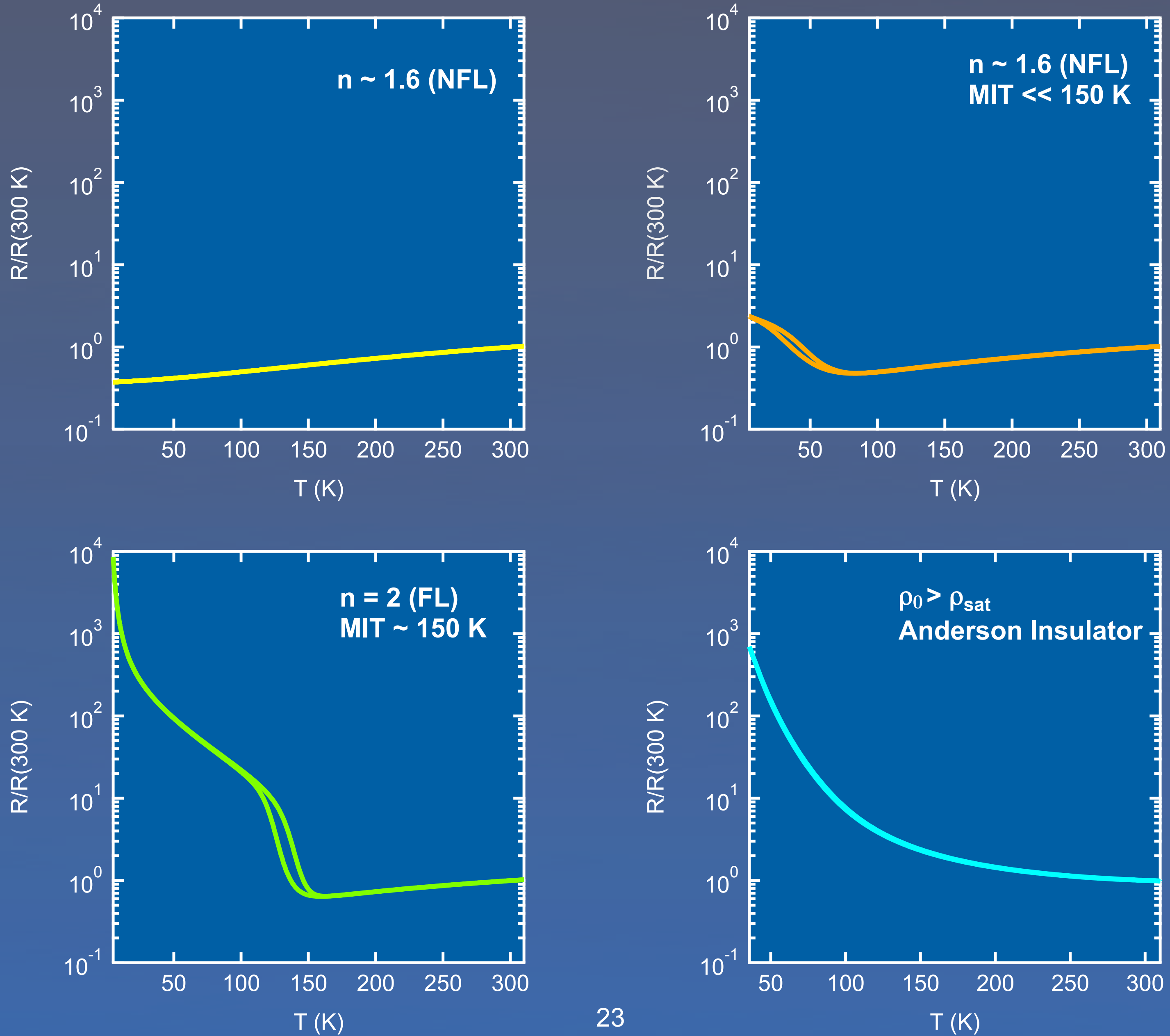

Phase Diagram

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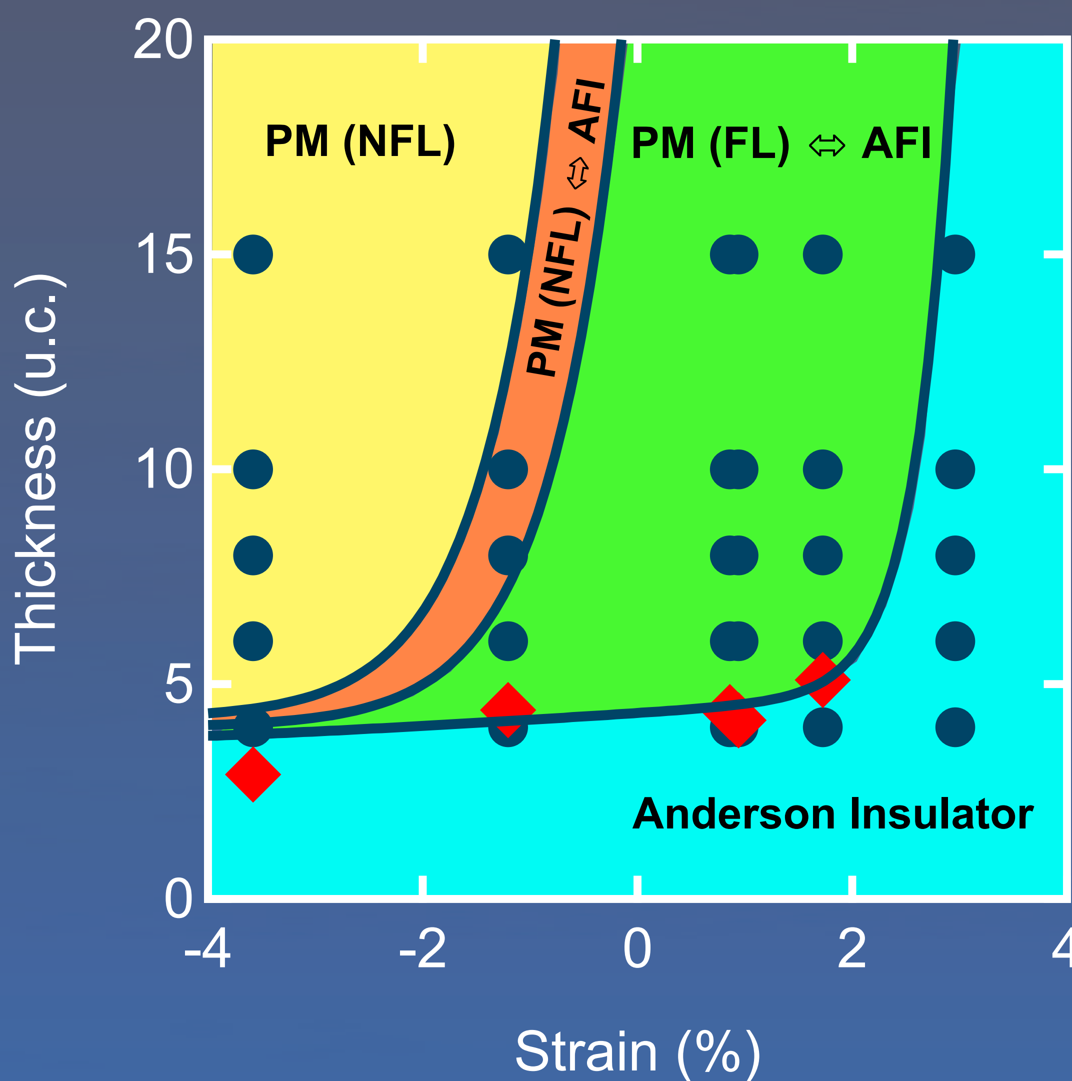

◆ $\rho_{sat} \sim \rho_0$

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]

Summary

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- Single non-Fermi liquid exponent (5/3) across the entire series, if MIT is suppressed
- Non-Fermi liquid phase or quantum critical point?
- Need to take resistance saturation into account to get correct NFL exponent
- $NdNiO_3$ is a saturating metal, but Ioffe Regel Limit is exceeded
- Degree of “bad metal” behavior depends on orbital polarization (strain)
- Large orbital polarization increases ρ_{sat} and makes the material increasingly “non-saturating” → resistivity escalates past the Mott-Ioffe-Regel limit
- Can be tuned by strain and confinement
- Metals with large degeneracy have large ρ_{sat} and are thus non-saturating
- Quantitative understanding of the role of electronic structure in strongly correlated phenomena is desirable
- New routes to controlling MITs:
  - Confinement stabilizes spin-density wave and insulating state ⇒ modulate confinement
  - Strain can modulate transition between Anderson insulator and metal

E. Mikheev, et al., arXiv:1507.06619 [cond-mat.str-el]

Thank you