Universal dielectric breakdown and synaptic behaviour in Mott insulators

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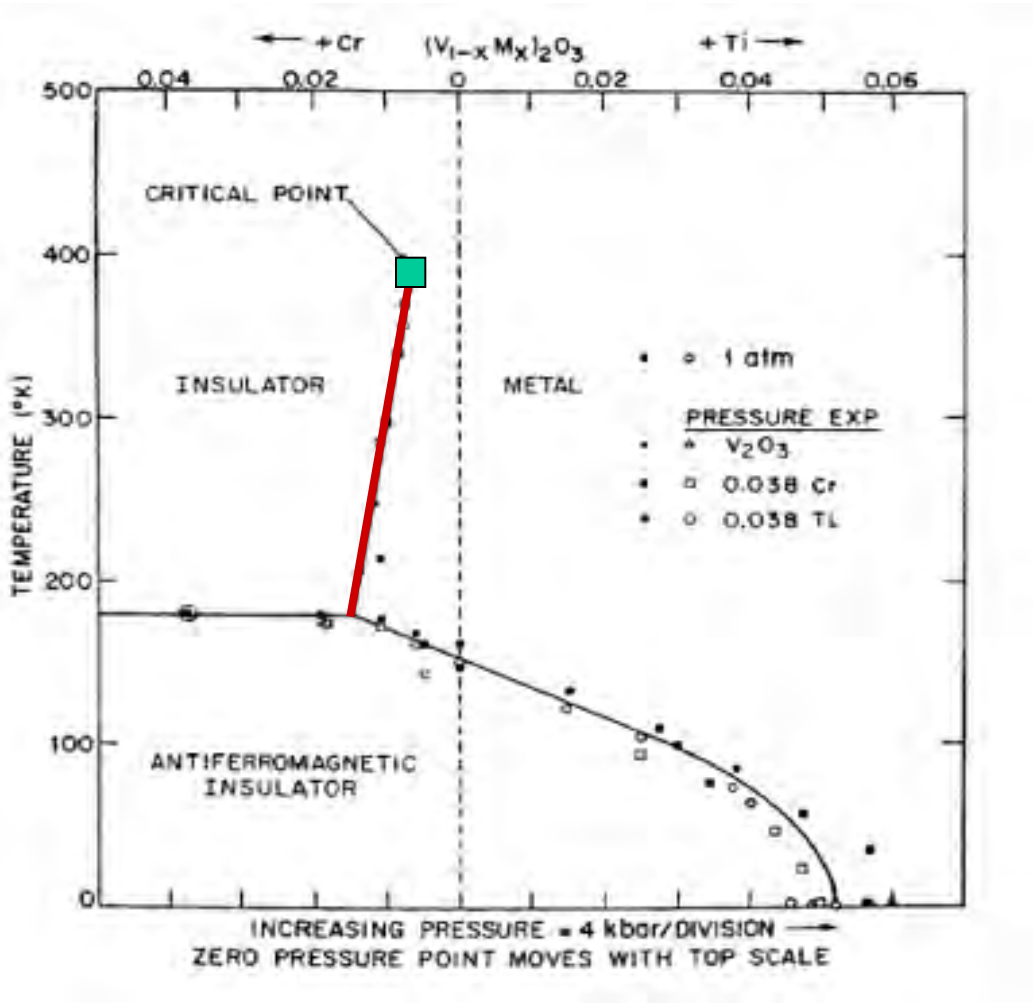
Refs:
V. Guiot et al, Nat Comm (2013)
P. Stoliar et al., Adv. Mat. (2013)
A. Camjayi et al., Phys Rev Lett (2014)
L. Cario et al Adv Func Mat (in press) **Review**

What is a Mott transition?

The classic example: Mott transition in V_2O_3

T



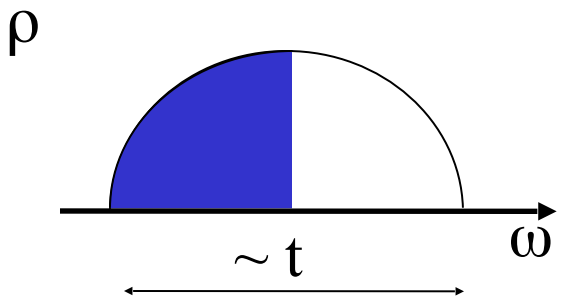
pressure or chemical substitution

McWhan et al PRB ’71 ‘73

The Hubbard model is a minimal model for the metal – insulator transition

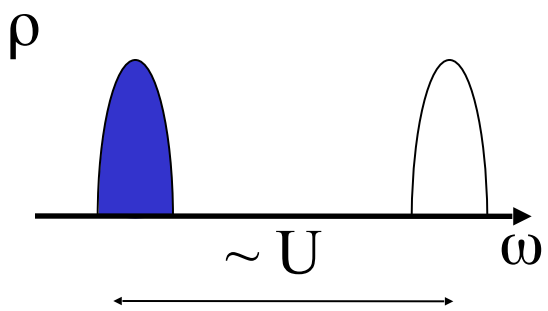
$$H = -\sum_{\langle ij\rangle,\sigma} t_{ij}(c^{+}_{i\sigma}c_{j\sigma} + c^{+}_{j\sigma}c_{i\sigma}) + U\sum_{i} n_{i\uparrow}n_{i\downarrow}$$

U = 0



metal

t = 0

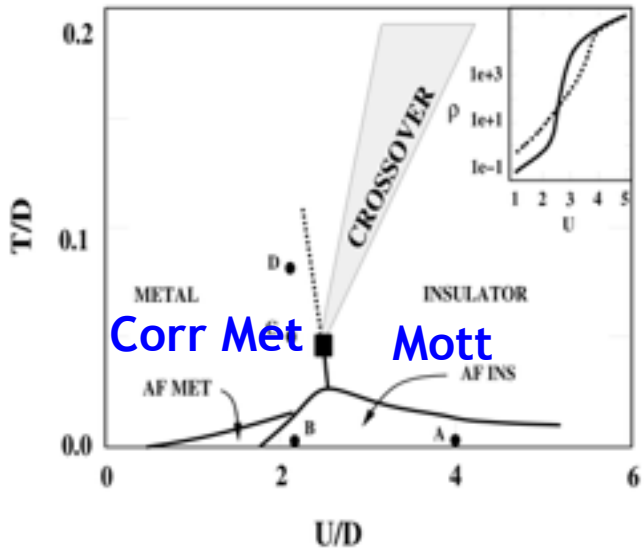


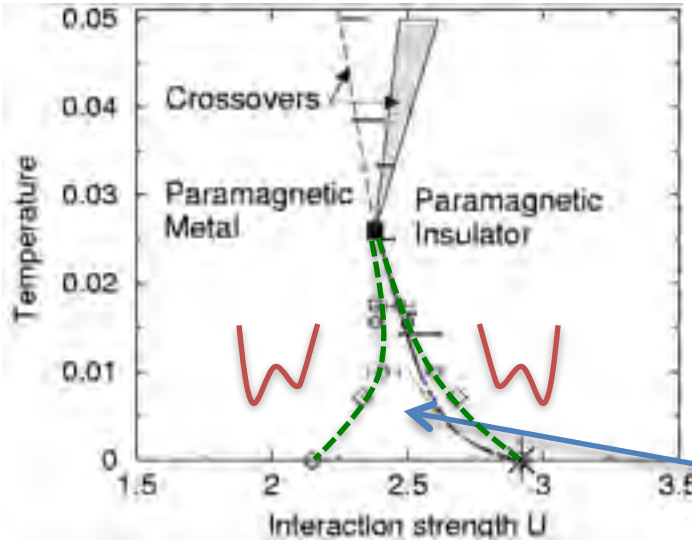
insulator

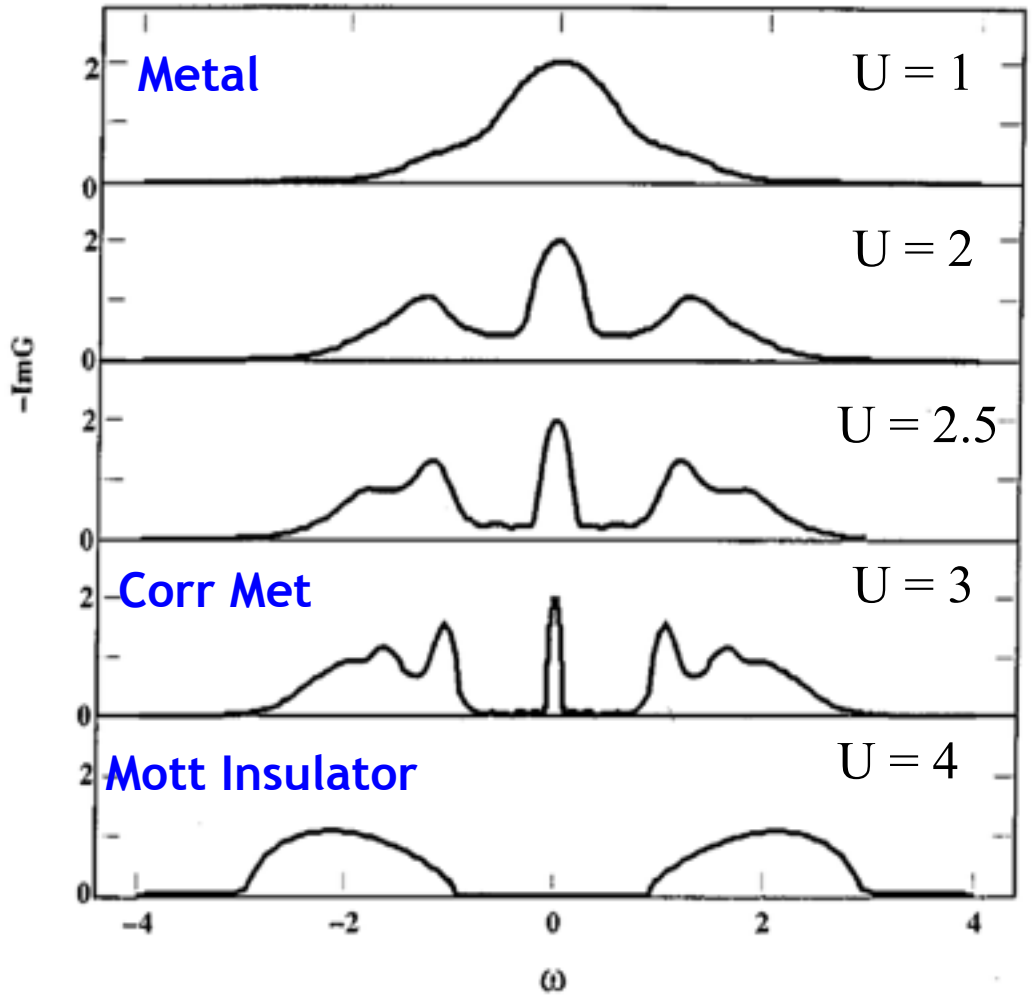
DMFT of the Mott - Hubbard transition

A. Georges et al. RMP '96

XY Zhang, MR, G. Kotliar PRL '92

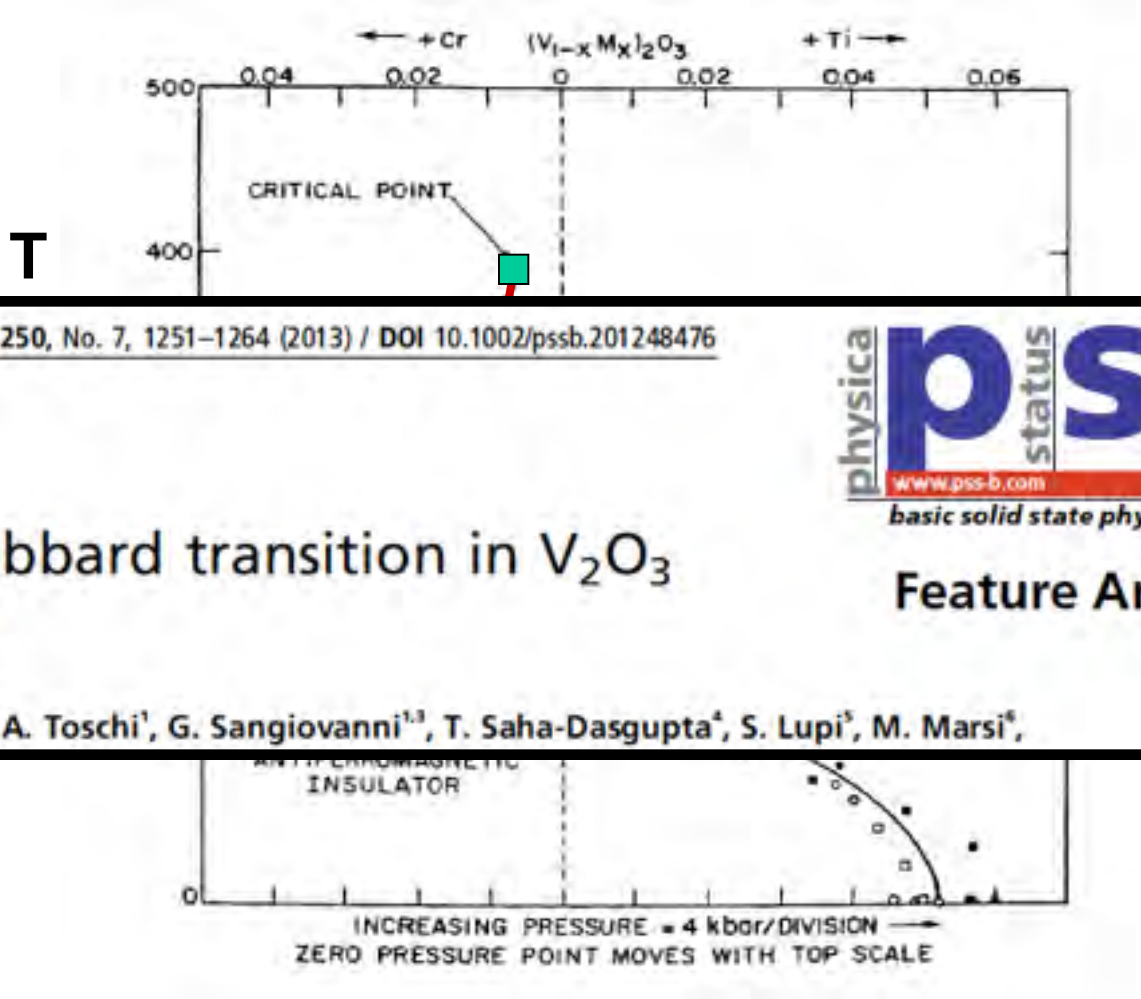






Coexistance region: 2 solutions

The classic example: Mott transition in V_2O_3



Phys. Status Solidi B **250**, No. 7, 1251–1264 (2013) / **DOI** 10.1002/pssb.201248476

physica status solidi b

www.pss-b.com

basic solid state physics

Feature Article

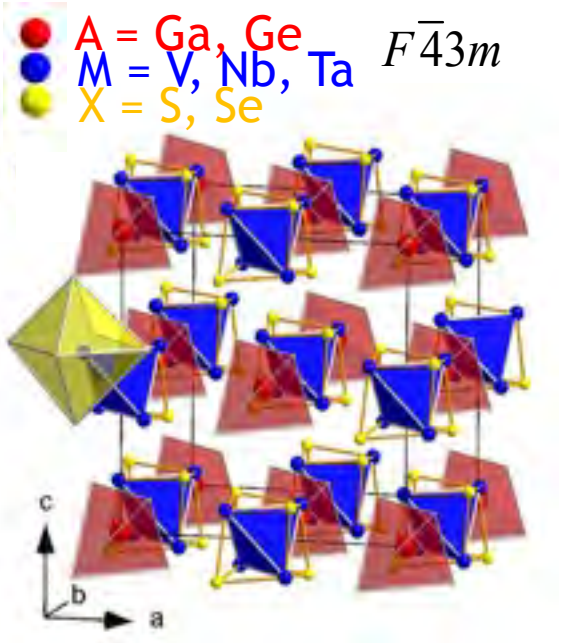
Mott–Hubbard transition in V_2O_3 revisited

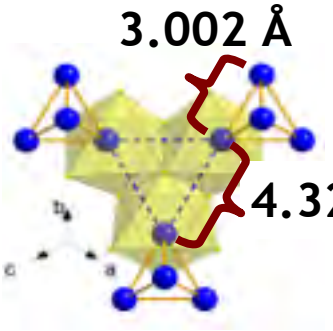
P. Hansmann[1,2], A. Toschi[1], G. Sangiovanni[1,3], T. Saha-Dasgupta[4], S. Lupi[5], M. Marsi[6],

pressure or chemical substitution

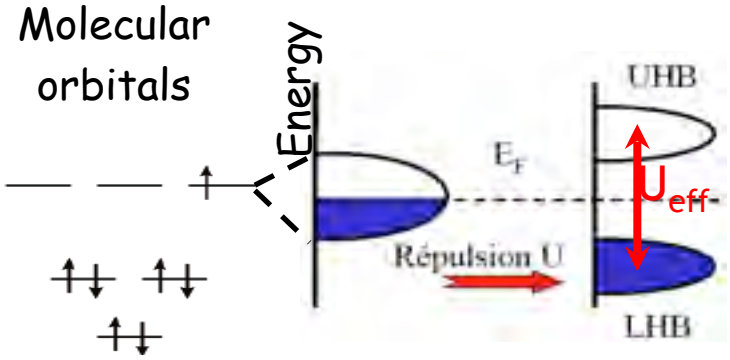
McWhan et al PRB ’71 ‘73

Do Mott – Hubbard systems exist in Nature?
AM_4X_8 family: tailor-made 3D Mott systems





Tetrahedral Clusters

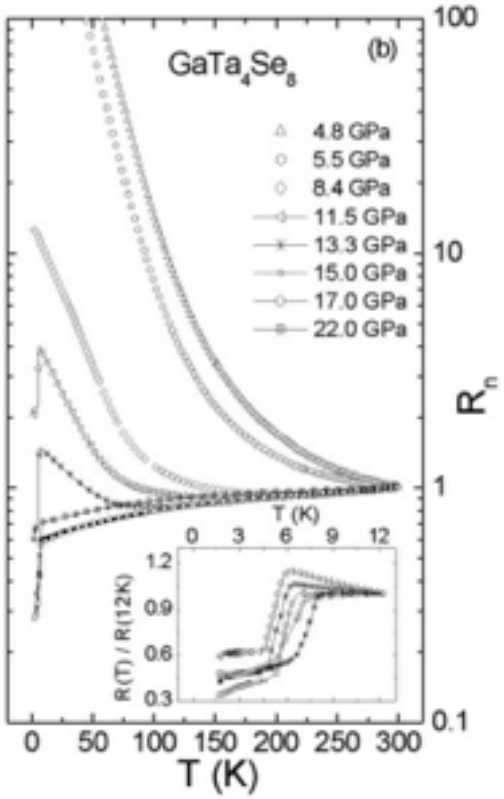


Gap ~ 0.20 eV

Pocha, R. et al., *J. Am. Chem. Soc.* 127, *8732* (2005)

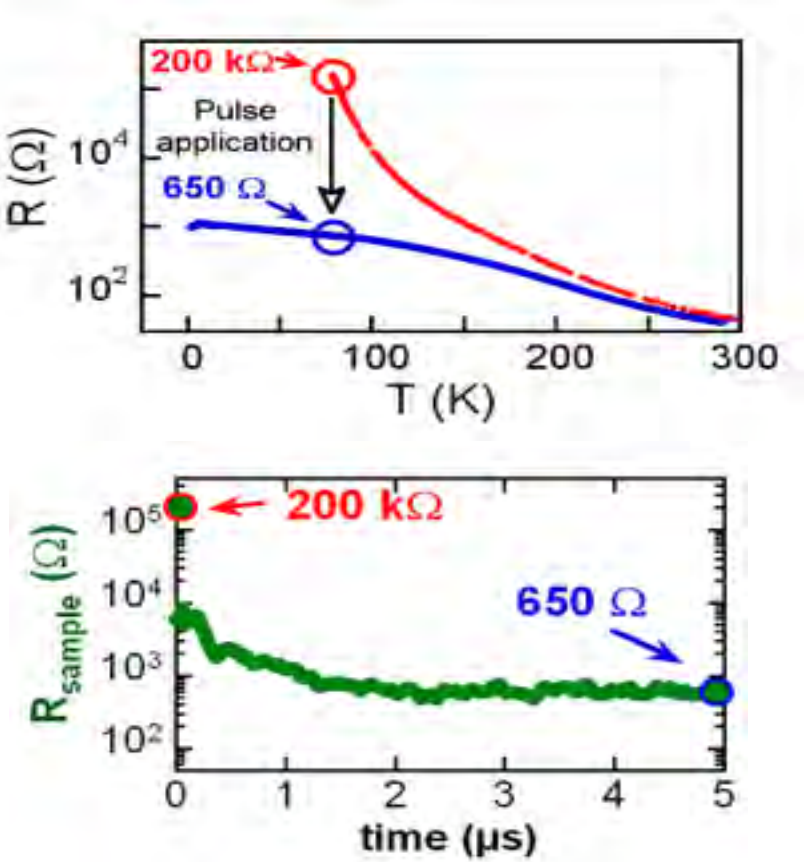
Metal – Insulator transition in GTS

Pressure driven Mott transition



Abd-Elmeguid et al., PRL '04

E-field driven Mott transition



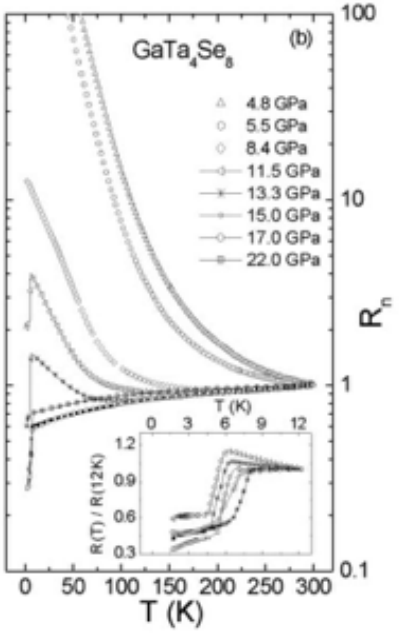
Non Volatile Resistive Switching, t <100 ns

C. Vaju et al., Adv. Mater. '08

Is $GaTa_4Se_8$ (GTS) really a Mott-Hubbard system?

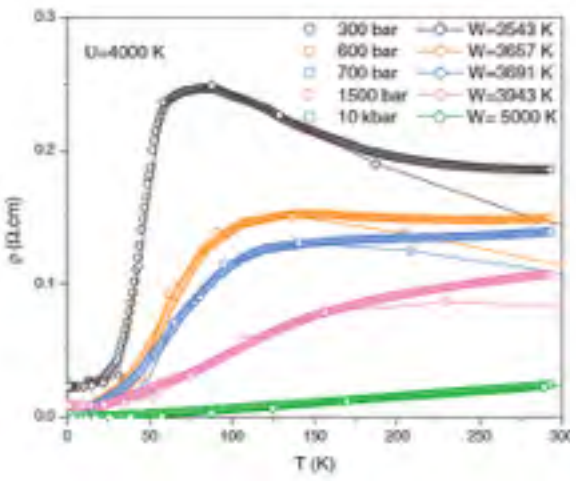
« Ideal system »

- 1 electron per Ta_4 cluster
- 3D fcc lattice
- Paramagnetic
- LDA predicts a metal

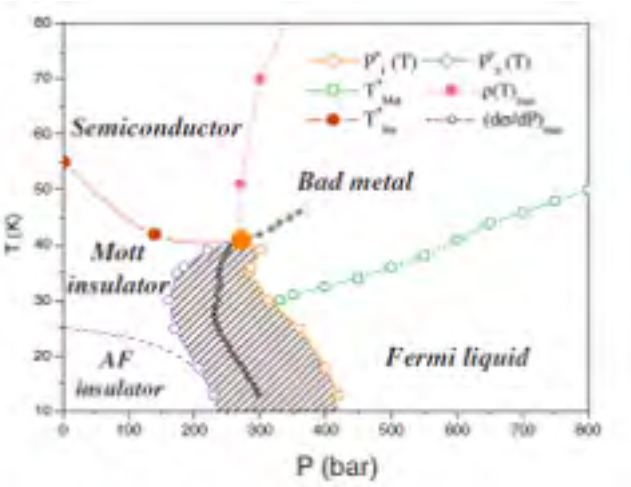


But does not match some DMFT key predictions

- No hysteresis
- ρ(T) does not have non-monotonic behavior

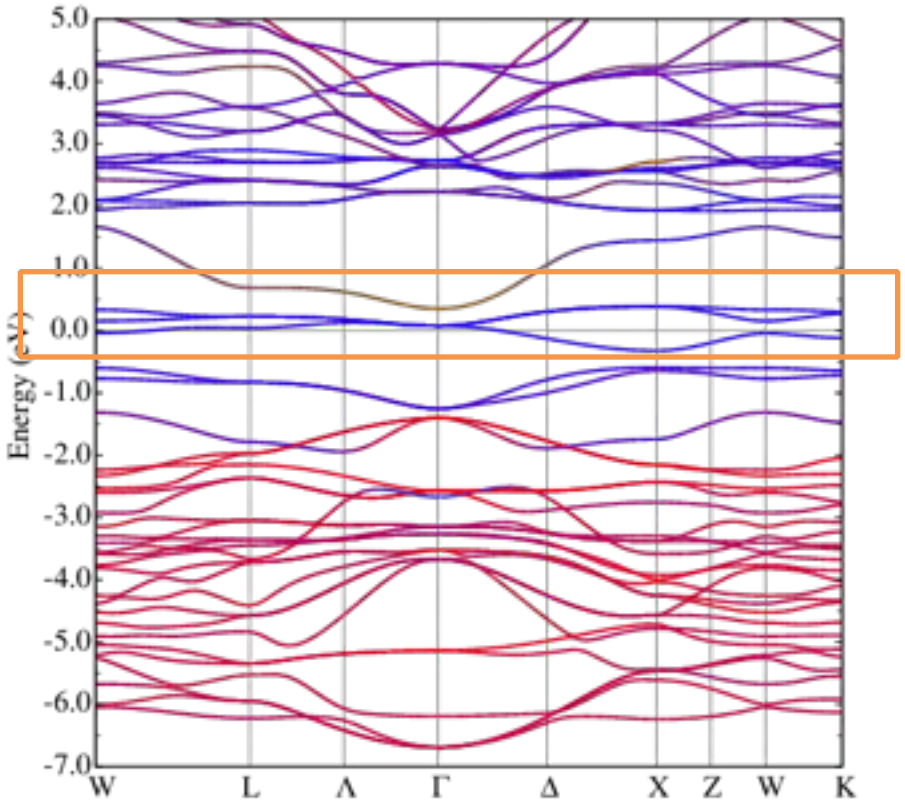


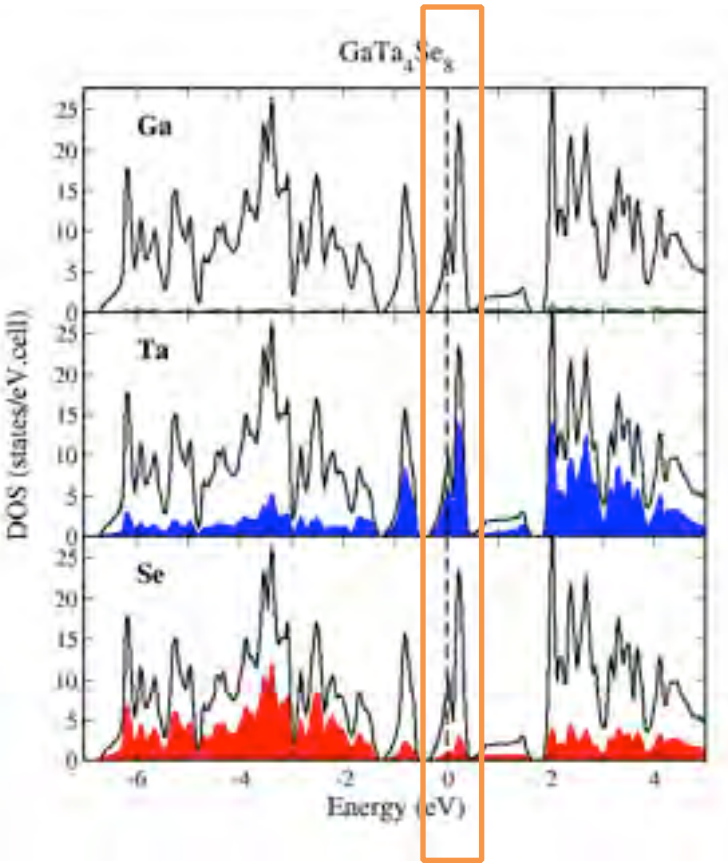
K-organics



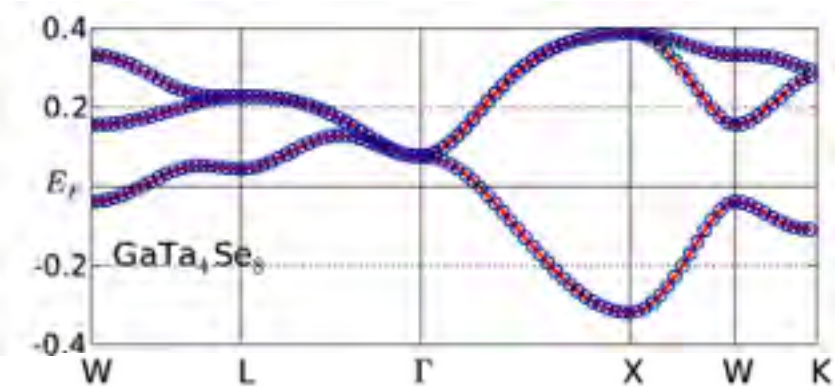
Limelette PRL (2003)

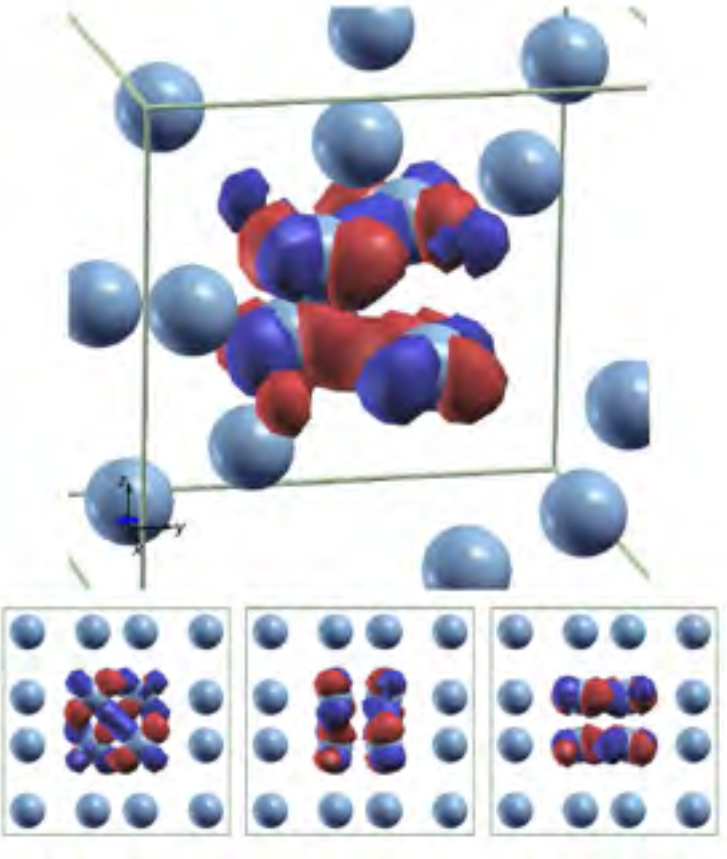
Conduction bands are isolated and have pure Ta character
Nice system for an LDA+DMFT study

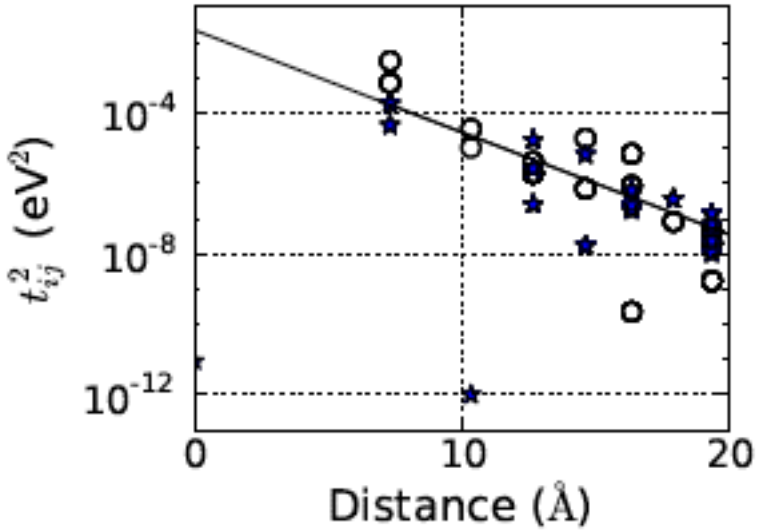




Wannier maximally localized **molecular** orbitals for Ta_4 tetrahedra



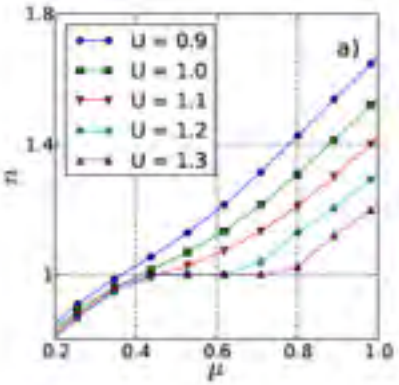




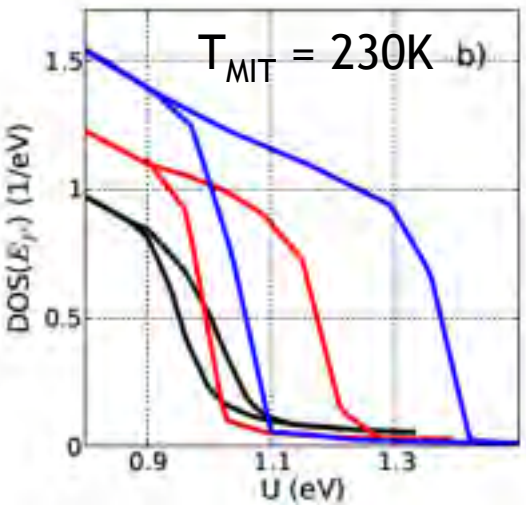
Cubic FCC structure, t_{2g} symmetry

What is U?

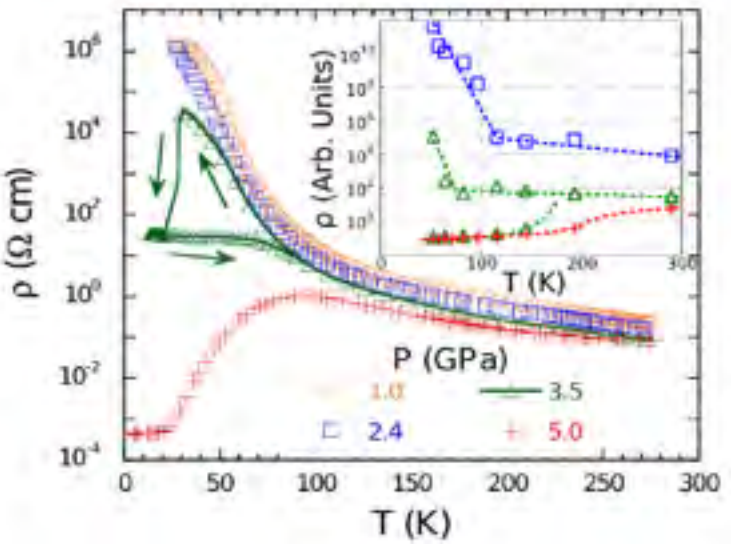
Uc = 1.2 eV

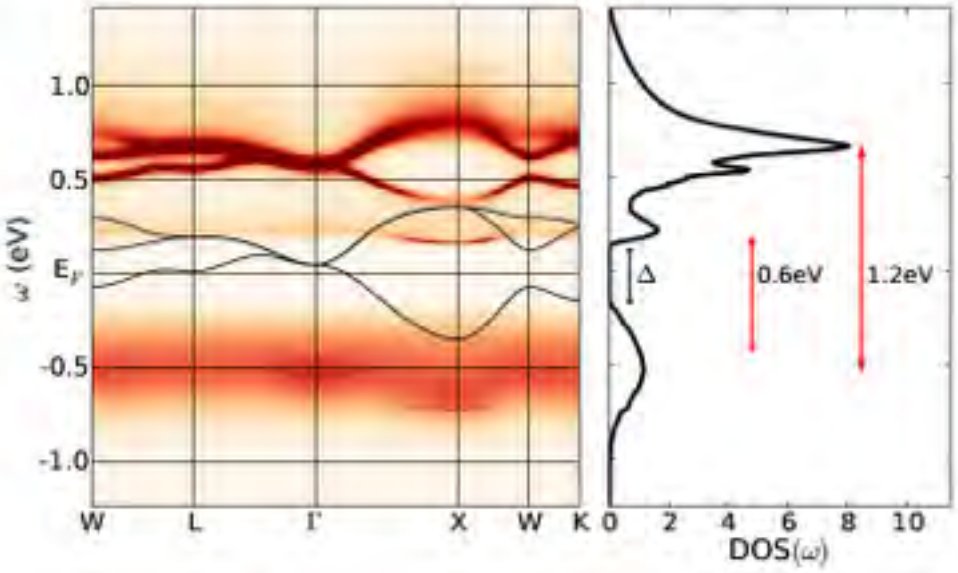


hysteresis



resisivity

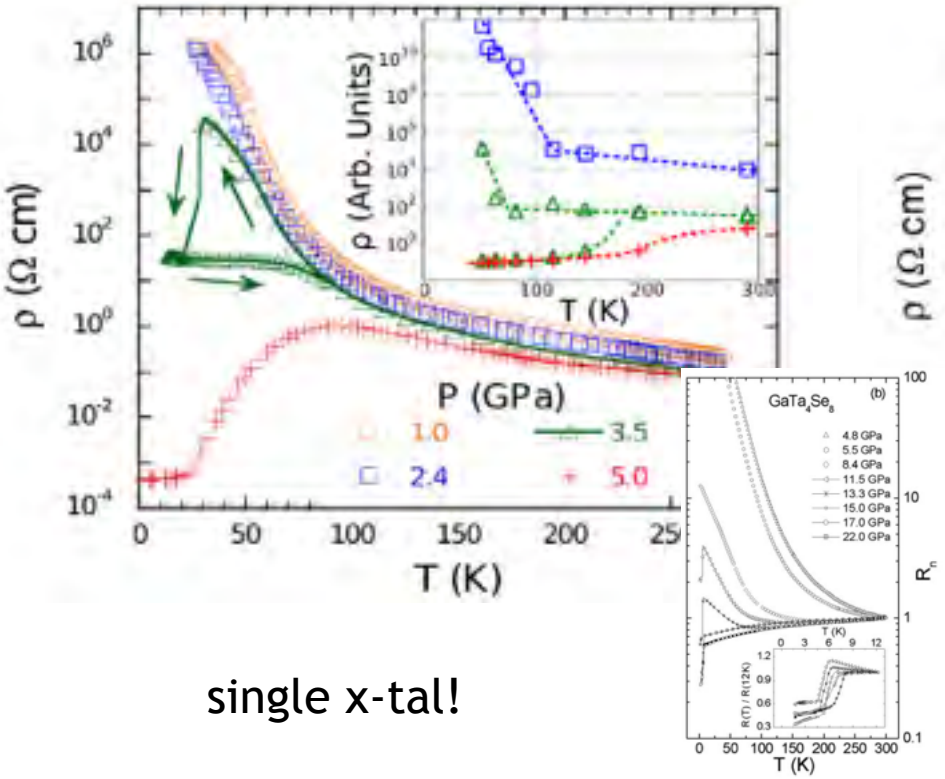




- 1st order transition T
- Optical conductivity
- Resistivity (activation gap)

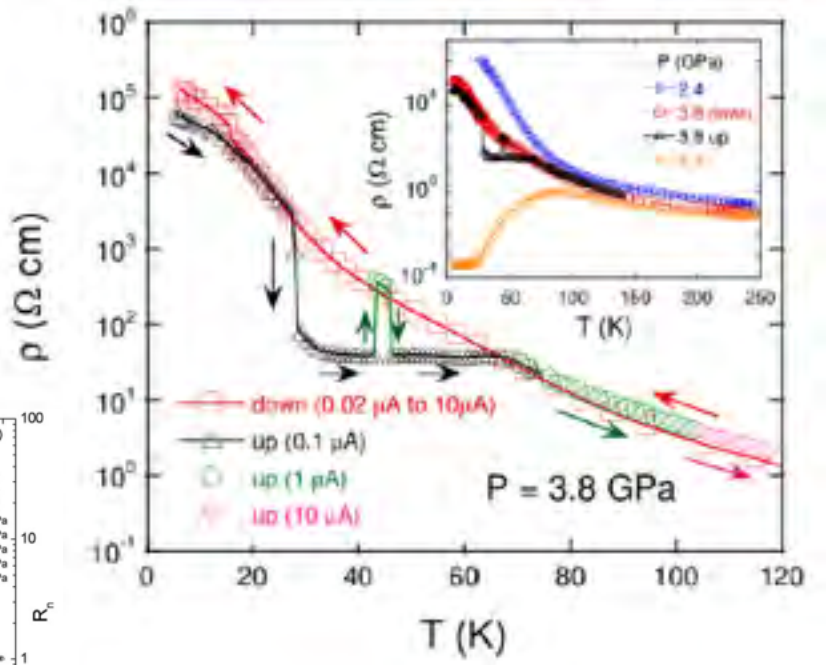
A. Camjayi et al., Phys Rev Lett (2014)

Resistivity is **nonmonotonic** in the metal and has **hysteresis** at the IMT



single x-tal!

Abd-Elmeguid et al., PRL '04



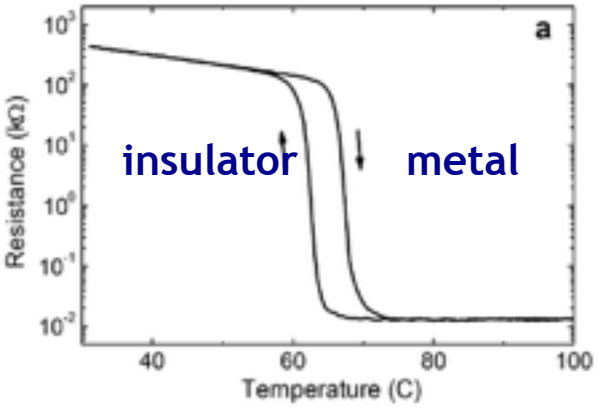
A. Camjayi et al., Phys Rev Lett (2014)

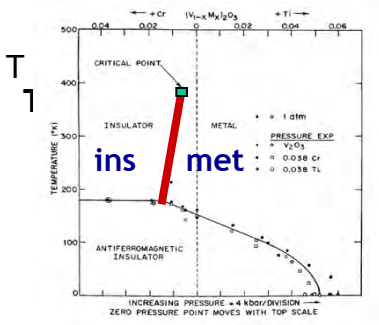
Mott physics + electronics
« Mottronics »

Applying strong E-fields to Mott systems

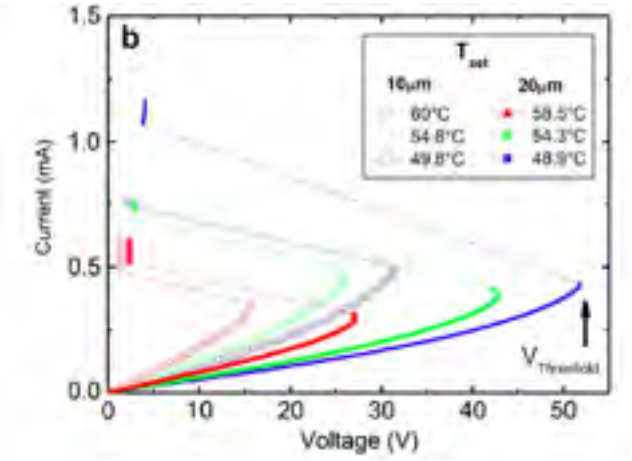
Do not mix up with the Mott transition in VO_2

1st order transition driven by T



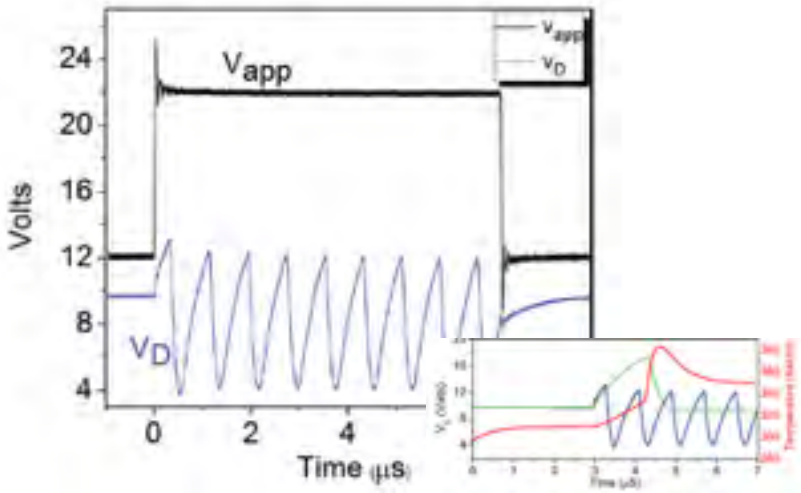


Joule heating effect



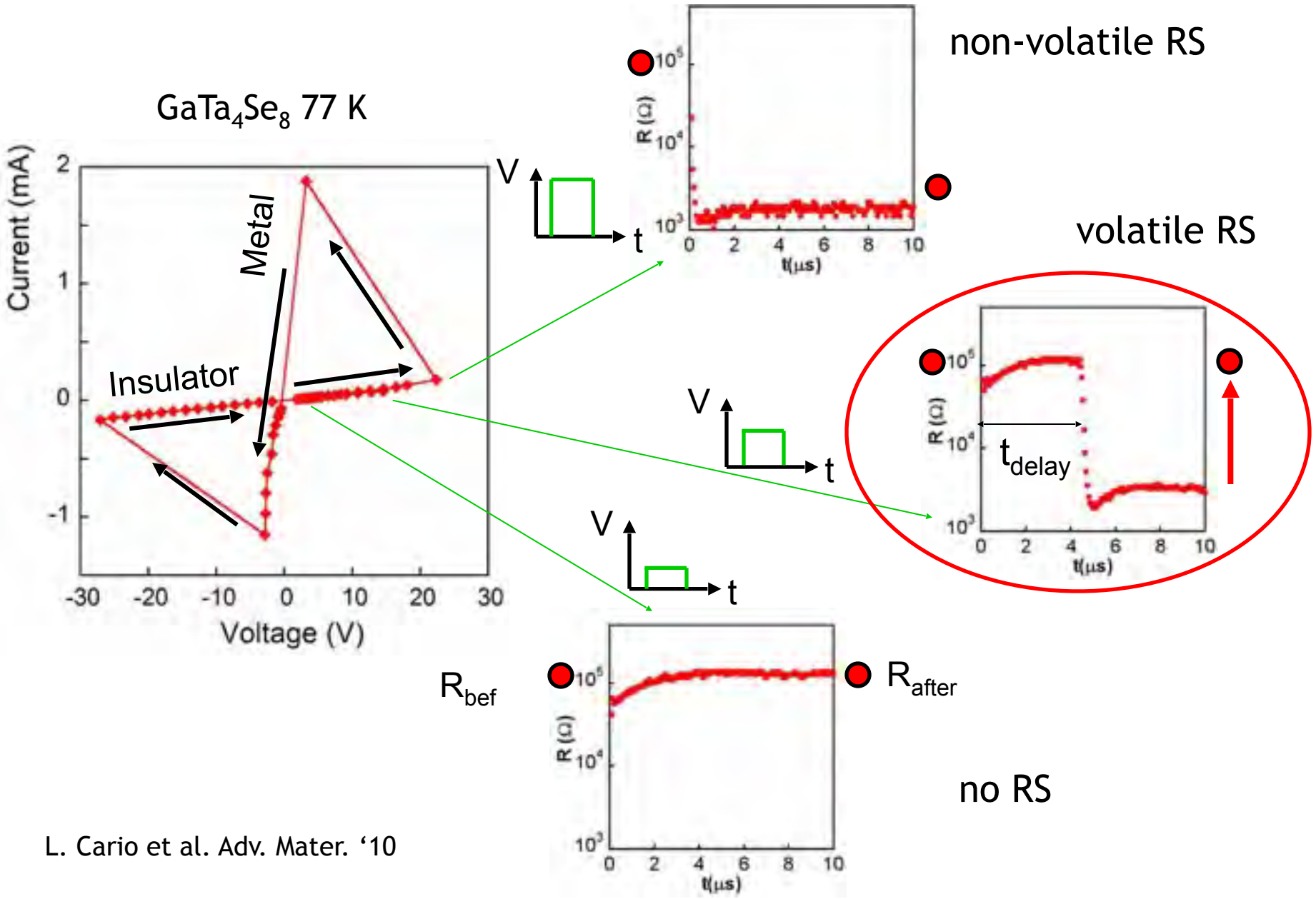
Zimmers et al PRL '13

E-field effect



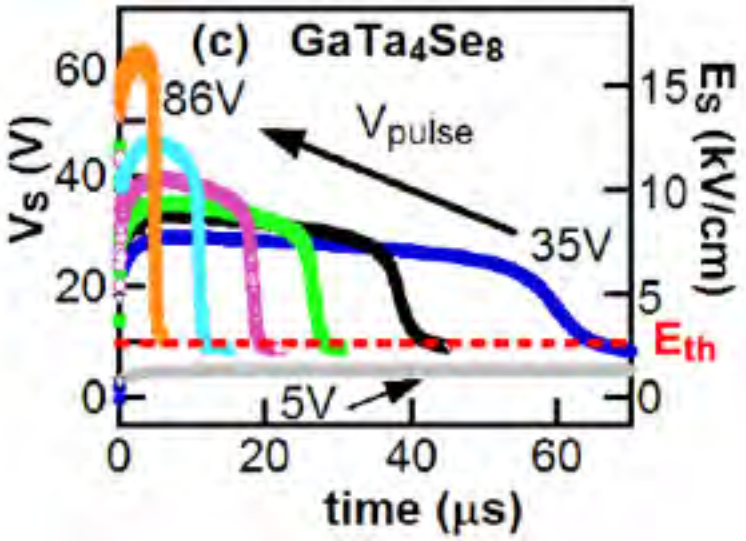
Driscoll PRB '12

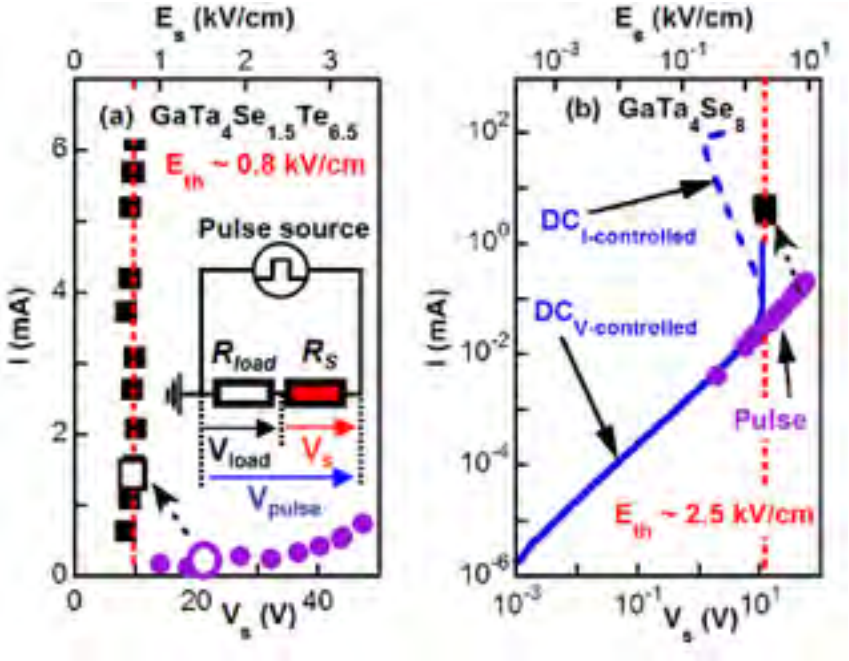
Three different regimes



L. Cario et al. Adv. Mater. '10

E-field driven Mott transition in GTS





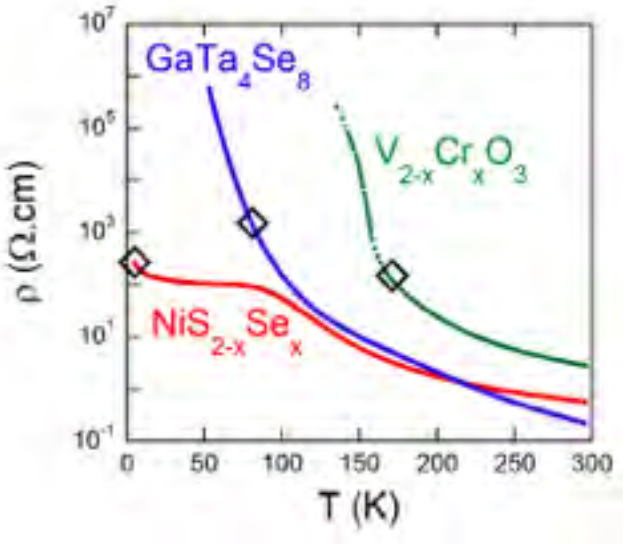
E-field threshold

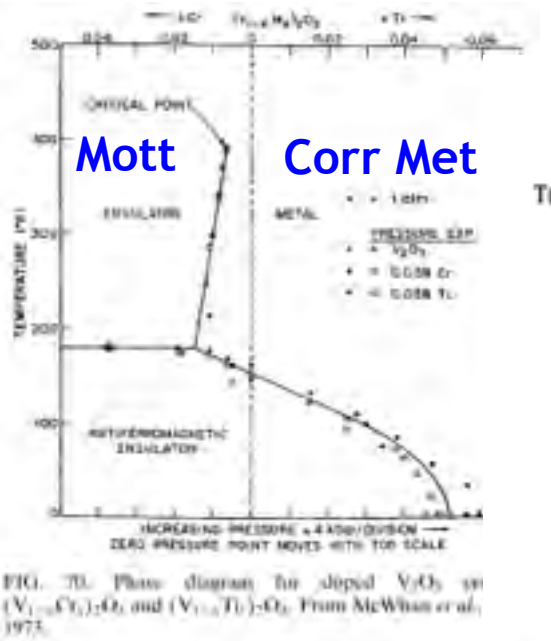
V. Guiot et al. Nat Comm (2013)

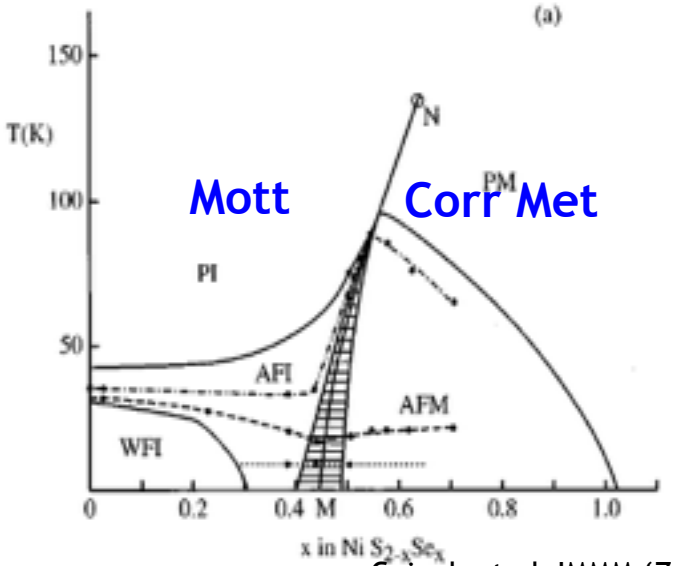
Is the Mott electric-breakdown universal?

Three different Mott-insulators:

$GaTa_4Se_8$ $V_{2-x}Cr_xO_3$ $NiS_{2-x}Se_x$

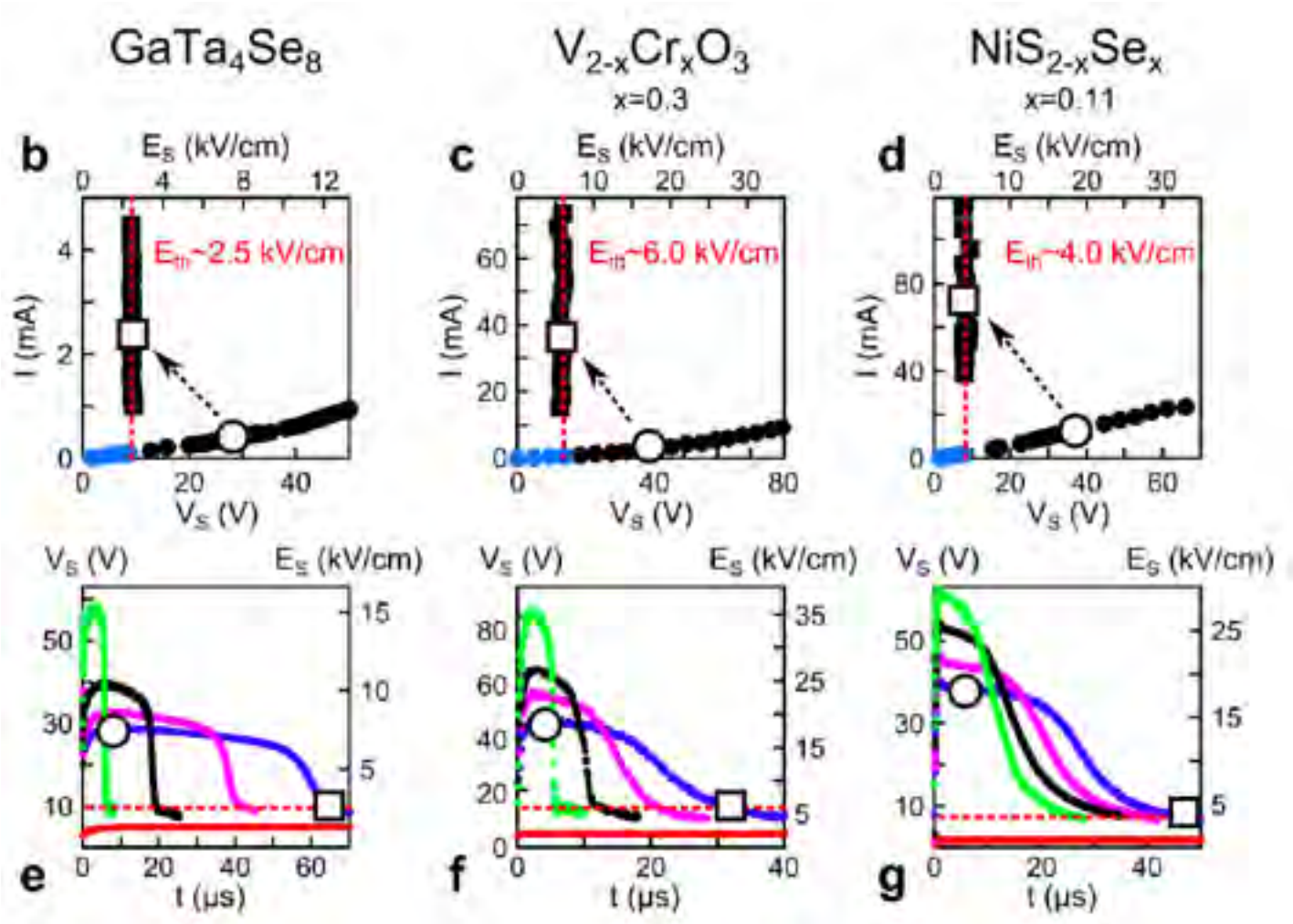






Czjzek et al JMMM '76

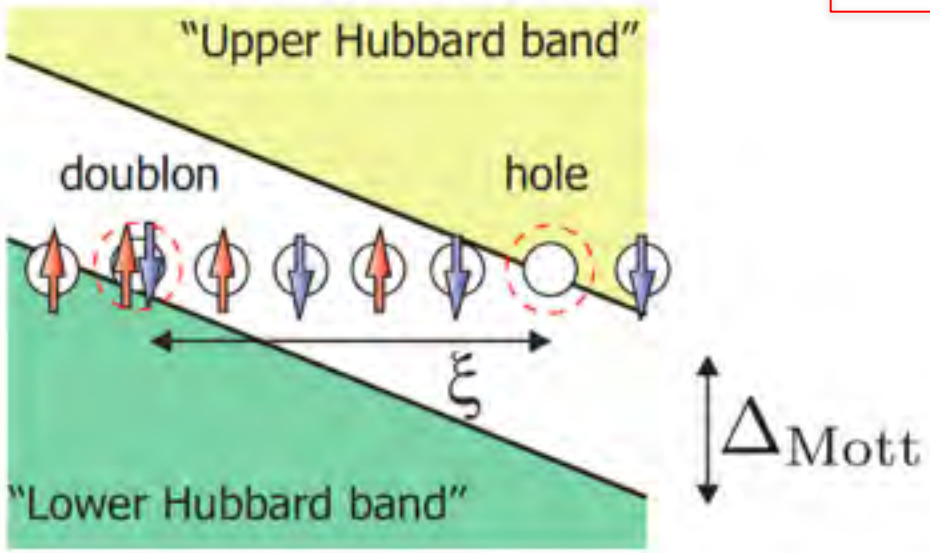
Universal behavior: three different Mott Insulators



P. Stoliar et al Adv. Mater. (2013)

What is the origin of the Mott electric-breakdown?

Hubbard model 1D

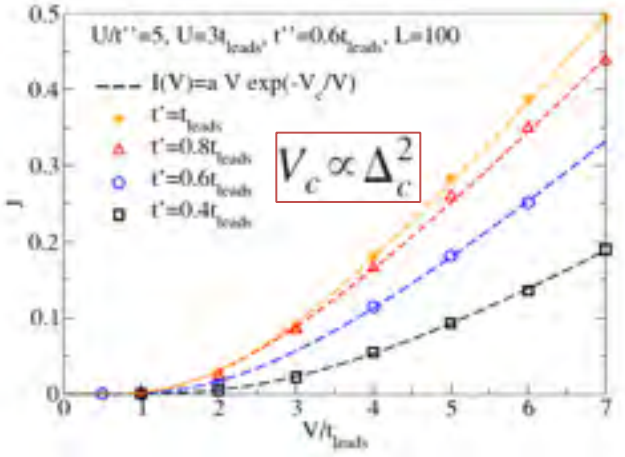


$F_{th} \propto \Delta_{Mott}^2$

$1/\xi \sim \Delta_{Mott}$ (1D)

$$F_{th} \simeq \frac{\Delta_{Mott}}{2\xi}$$

$$J \sim \Gamma_p = \frac{F_0}{2\pi} \exp\left(-\pi \frac{F_{th}}{F_0}\right)$$



T. Oka et al. '03 '05 '10 '12
F. Heidrich-Meisner et al '10

M. Eckstein et al. '10 '11 (DMFT)
A. Amaricci et al. '12 (DMFT)

??? $1/\xi \sim \Delta_{Mott}$ (3D)

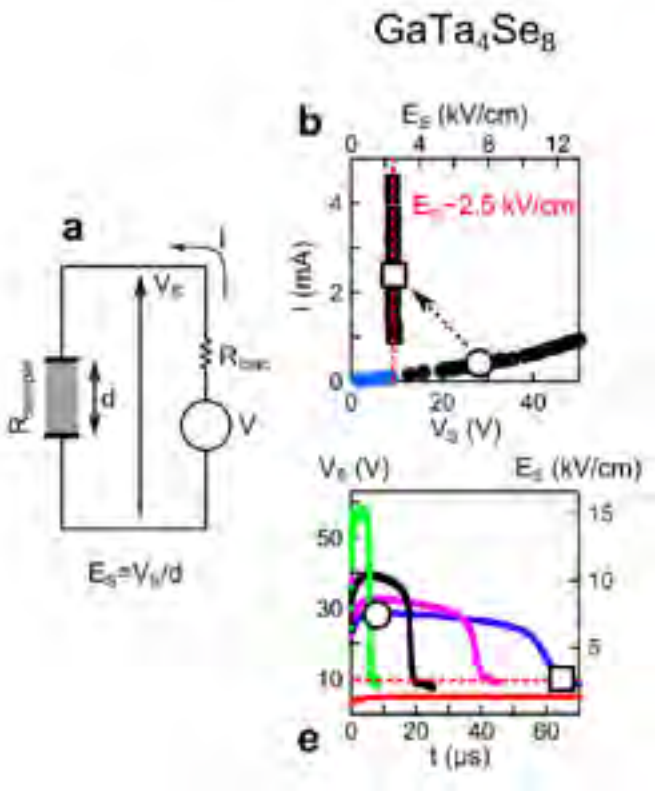
??? $\xi \sim \mu m$ (3D)

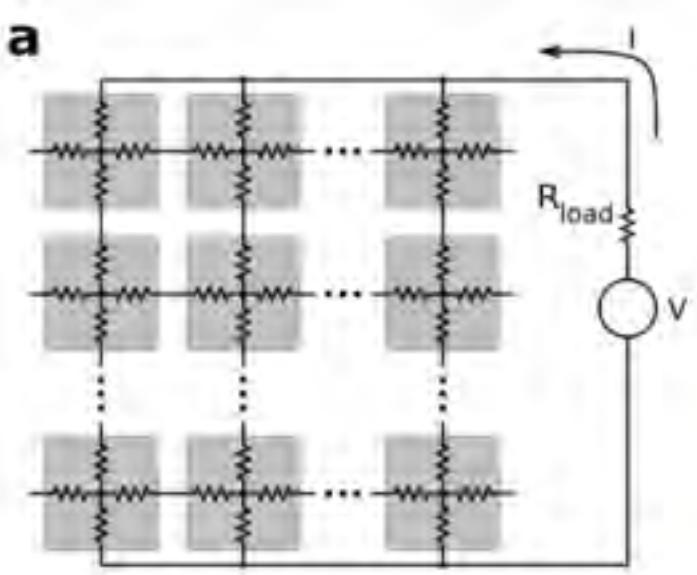
$\Delta \sim 10^{-1}$ eV
$\xi \sim 1$ nm $= 10^{-7}$ cm
$F_{Th} \sim 1$ MV/cm

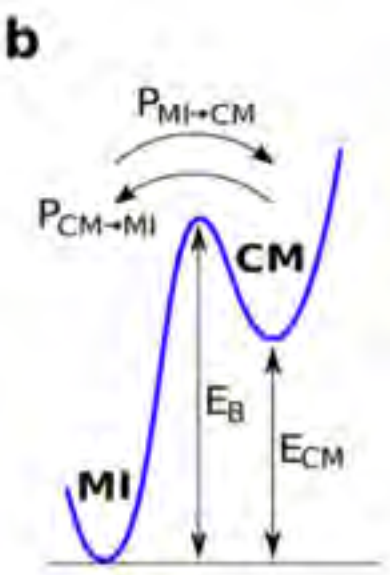
$E_{Th} \sim 1$ KV/cm !!!!

Model of the Mott resistive transition

P. Stoliar et al Adv. Mater. (2013)







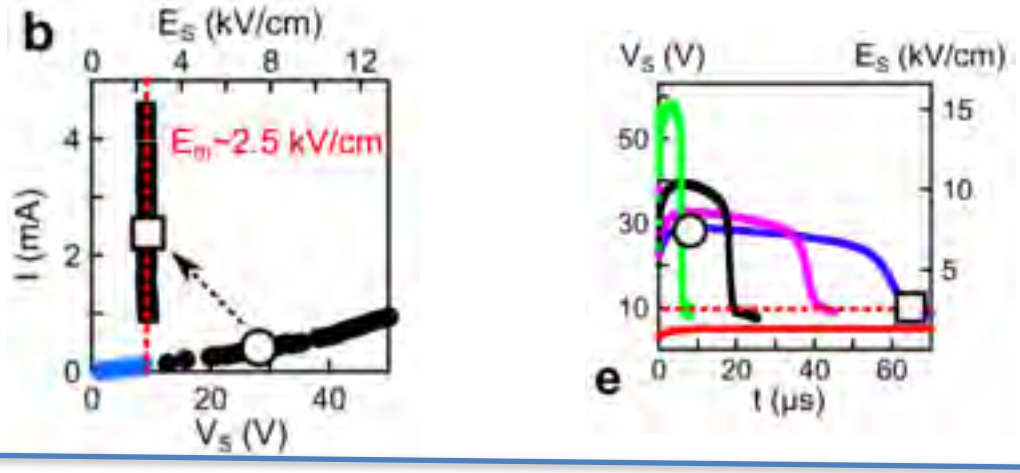
Two states: MI – Mott insulator
CM – Correlated metal
$R_{MI} >> R_{CM}$

$P_{MI->CM}$ and $P_{CM->MI}$ are transition probabilities

$$P_{MI\to CM} = \nu e^{-(E_B - q\Delta V)/kT} \qquad P_{CM\to MI} = \nu e^{-(E_B - E_{CM})/kT}$$

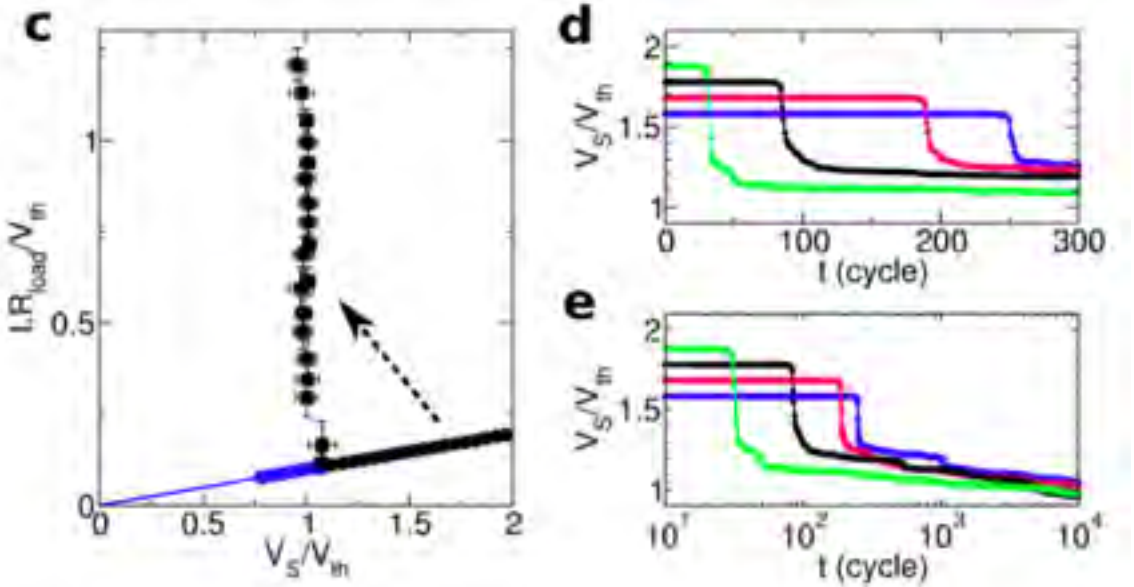
Model results: Threshold Mott resistive transition

Experiment

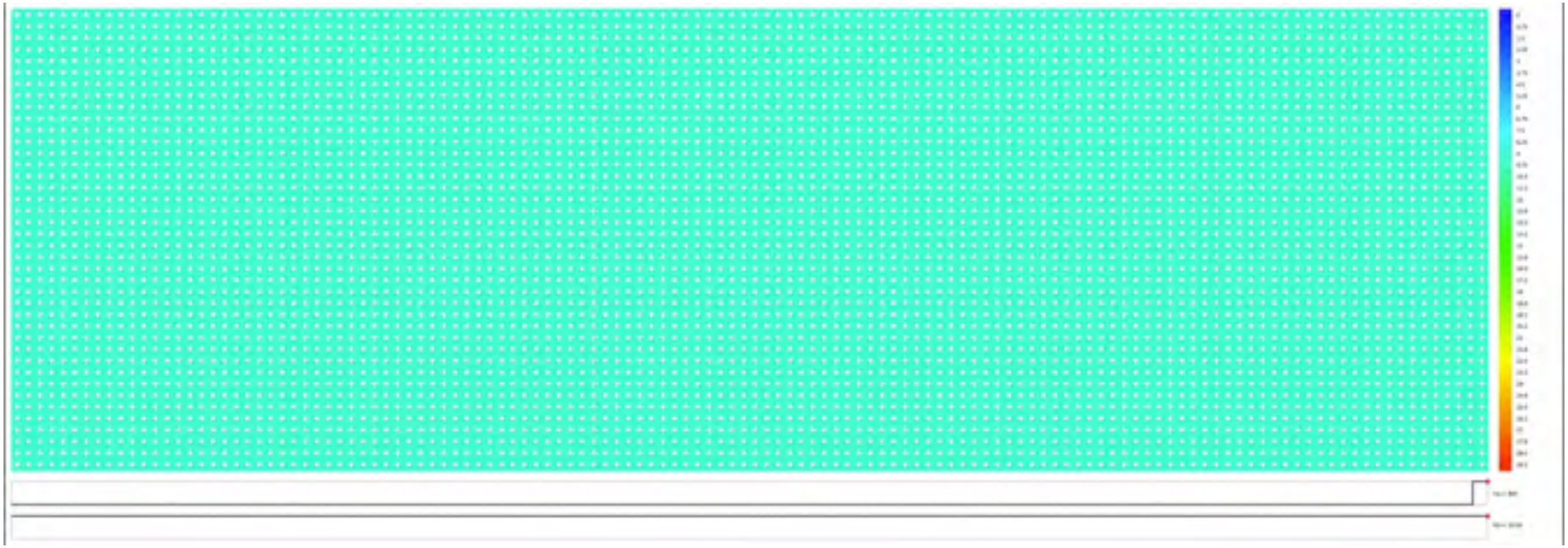


V_S/V_{Th} = 1.74, 1.84 1.95, 2.06

Theory



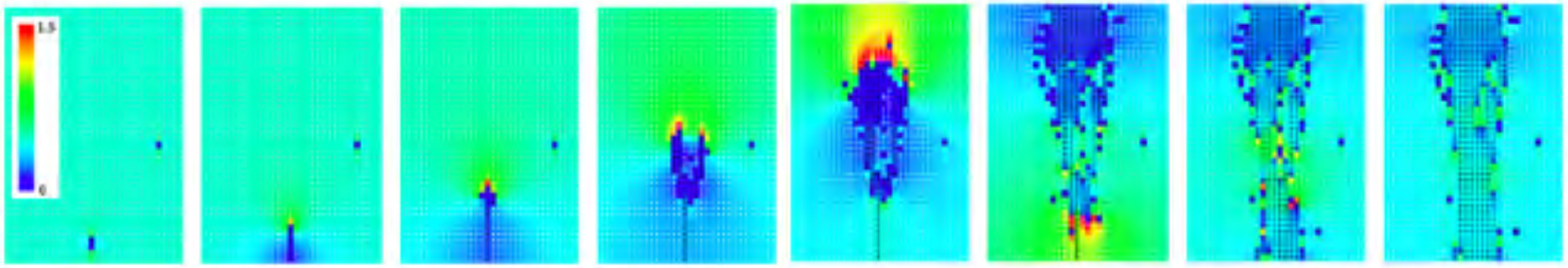
How the transition evolves in time?



Each pixel is a cell of the resistor network model

Color intensity indicates the local ΔV drops (ie local E)

How the transition evolves in time? (snapshots)

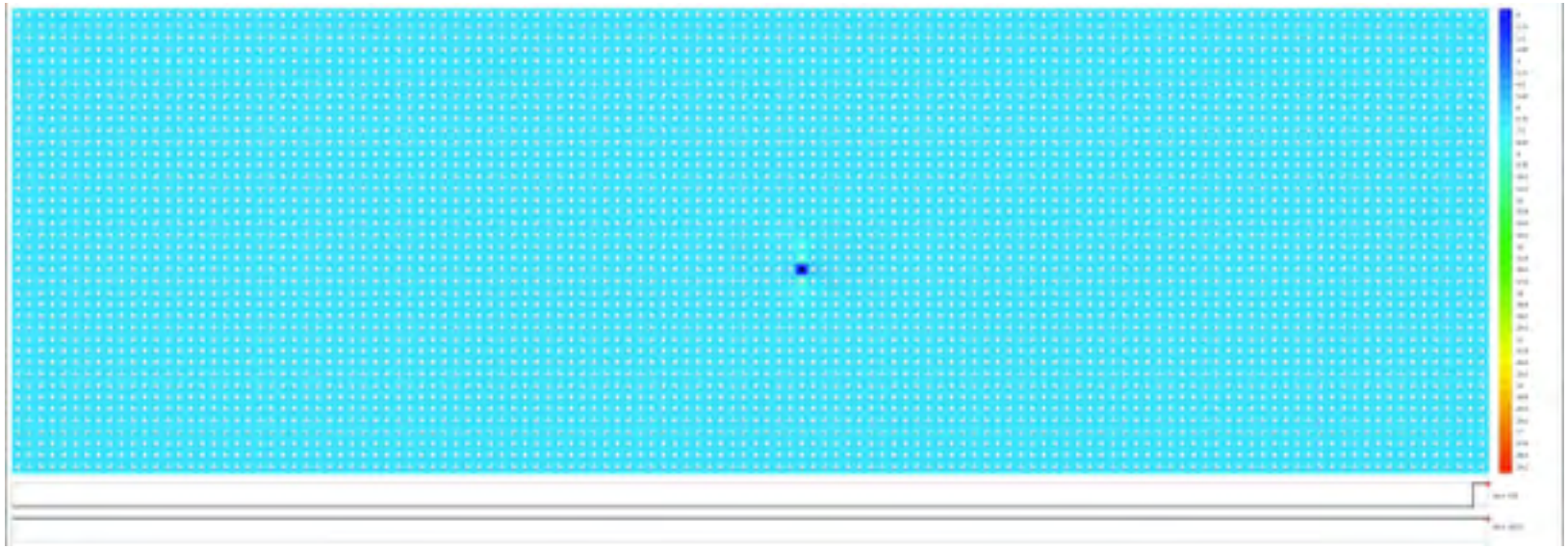


time

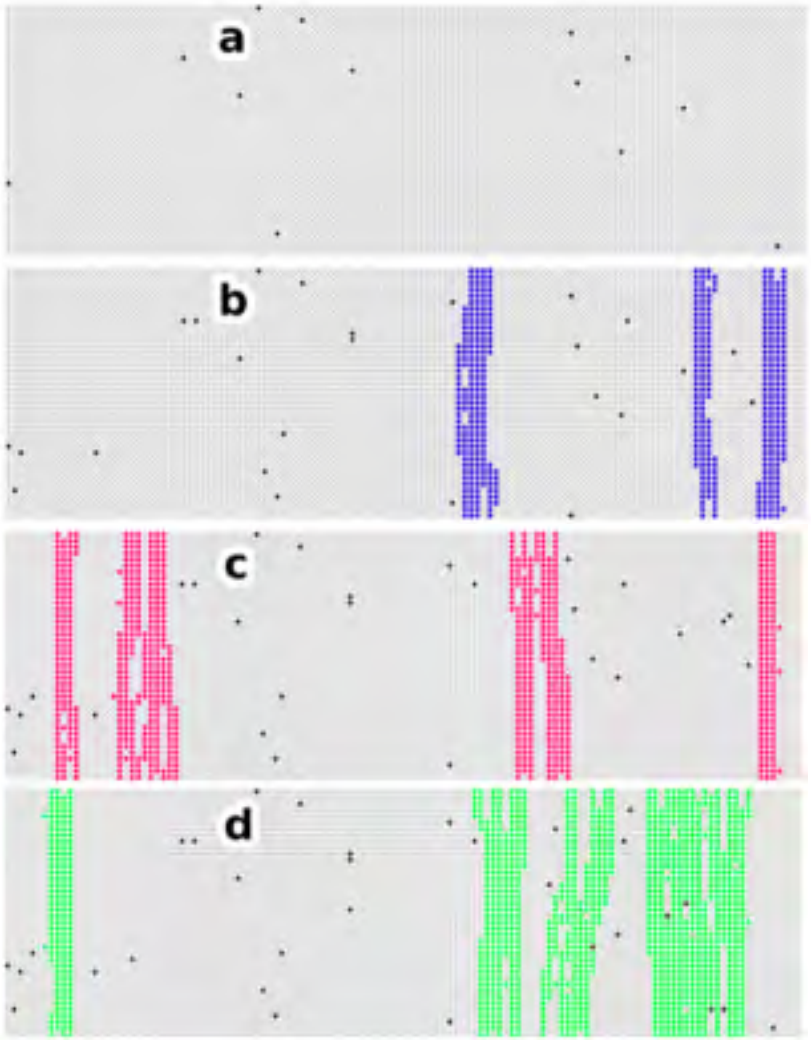
Threshold effect

Below threshold

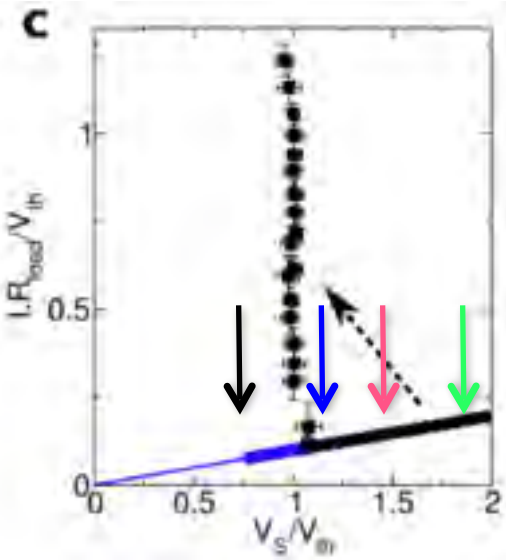
Above threshold

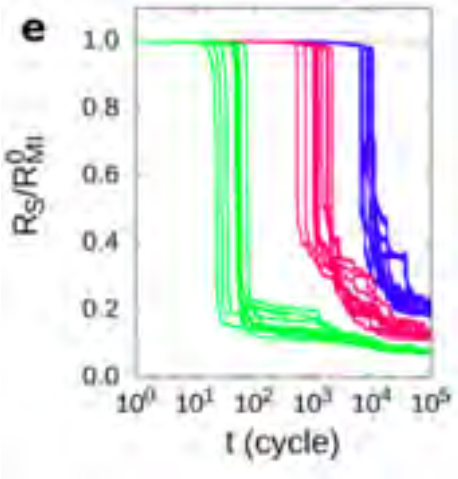


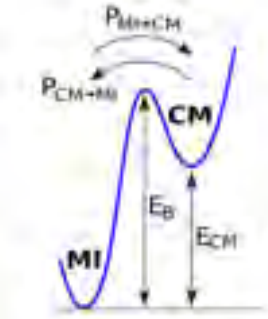
Threshold effect



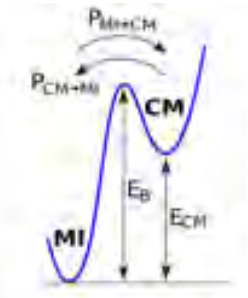
V_S/V_{Th} = 0.7, 1.1, 1.4, 1.8







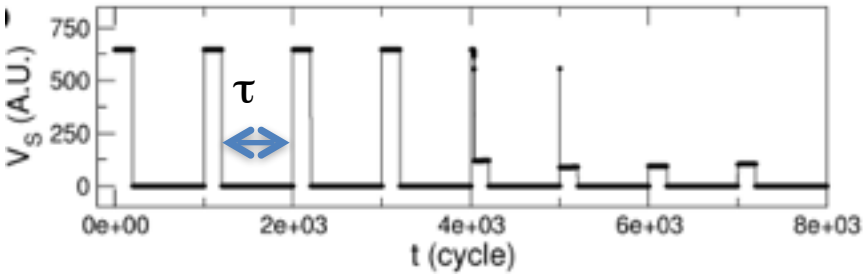
Model prediction: **Neuromorphic** behaviour!

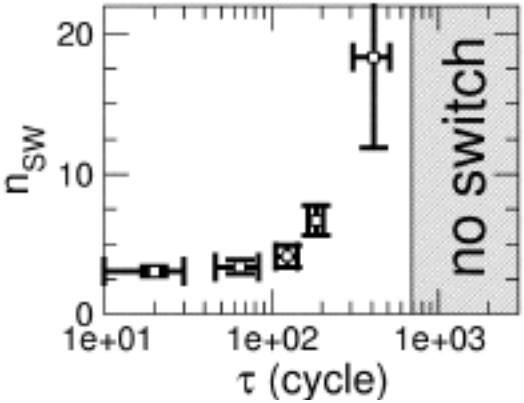


Transition rates imply the existence of a relaxation time scale t_{relax}

Short pulses ($< t_{delay}$) are sent at intervals $\tau < t_{relax}$

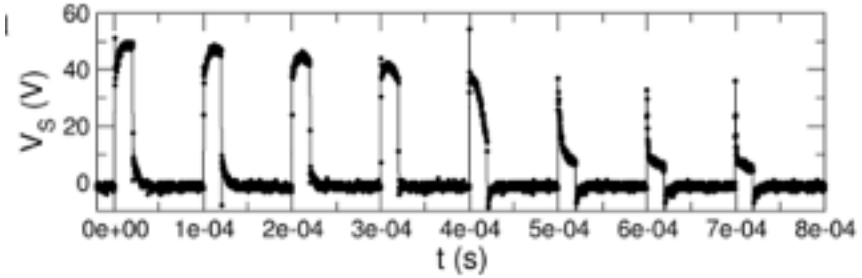
Model prediction

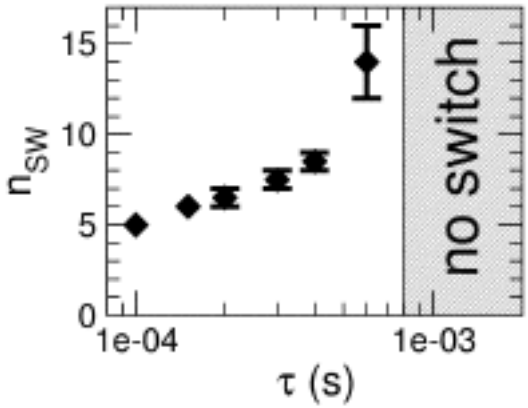




Transition after 5 pulses

Experiment





P. Stoliar et al., Adv. Mat. (2013)

Summary

- $GaTa_4Se_8$ is a new Mott-Hubbard system
- E-field driven Mott insulators show a universal resistive transition with threshold behavior
- A phenomenological model based on DMFT Mott-Hubbard physics captures the qualitative behavior of the Mott resistive transition
- New electronic emergent behavior: neuromorphic

Refs:
V. Guiot et al, Nat Comm (2013)
P. Stoliar et al., Adv. Mat. (2013)
A. Camjayi et al., Phys Rev Lett (2014)
L. Cario et al Adv Func Mat (in press) **Review**