Breakdown of semiclassical description of thermoelectricity in twisted bilayer graphene

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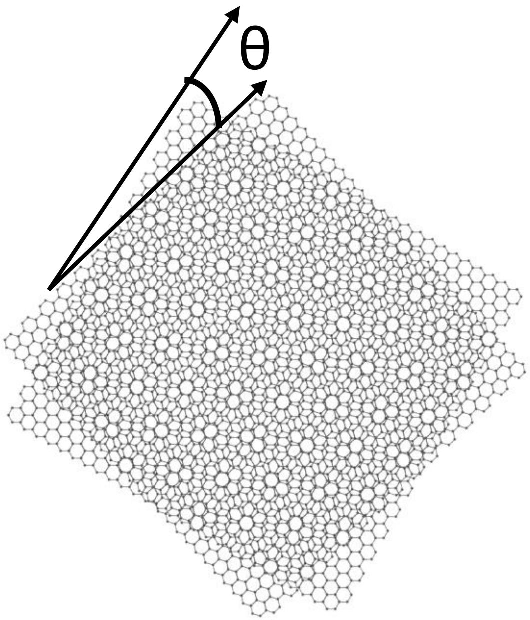
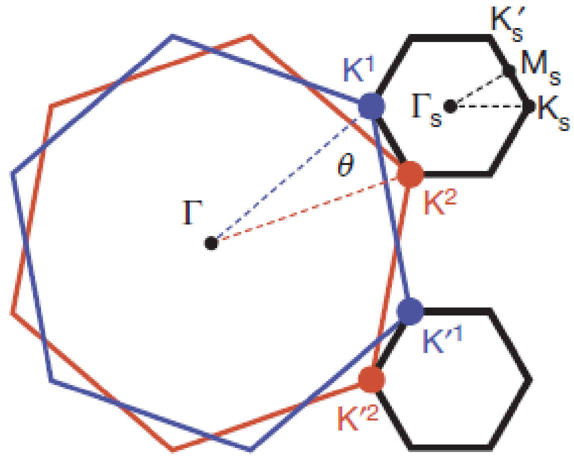
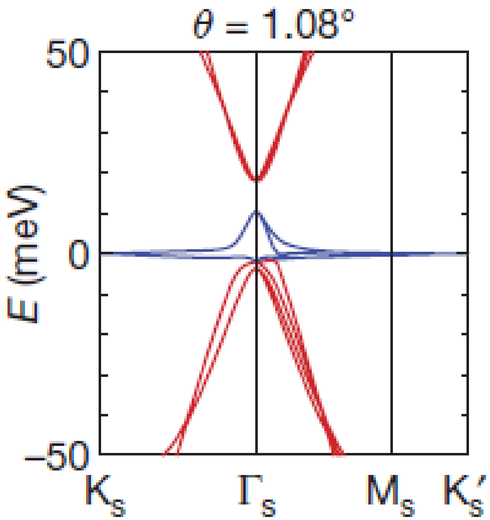
APS SATELLITE MEETING 2022

Twisting two graphene layers







Cao *et al.*, *Nature* 556, 80–84 (2018)

Flat band condition at $\theta_{magic} \approx 1.1^0$

Bistritzer & MacDonald, PNAS 108, 12233–12237 (2011).

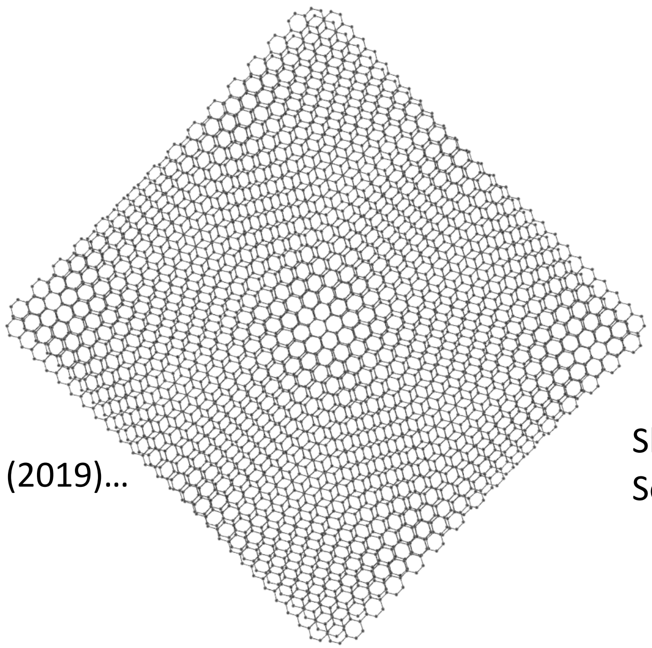
The magic of moiré graphene

Superconductivity

Cao *et al*., *Nature* 556, 80–84 (2018)
Lu *et al*., *Nature* 574, 653–657 (2019)........

Correlated insulators

Cao *et al*., *Nature* 556, 80–84 (2018)
Yankowitz *et al*., Science 363, 1059–1064 (2019)...



Magnetism

Sharpe *et al*., Science 365, 605–608 (2019)
Serlin *et al.,* Science 367, 900-903 (2019)....

Topological phases

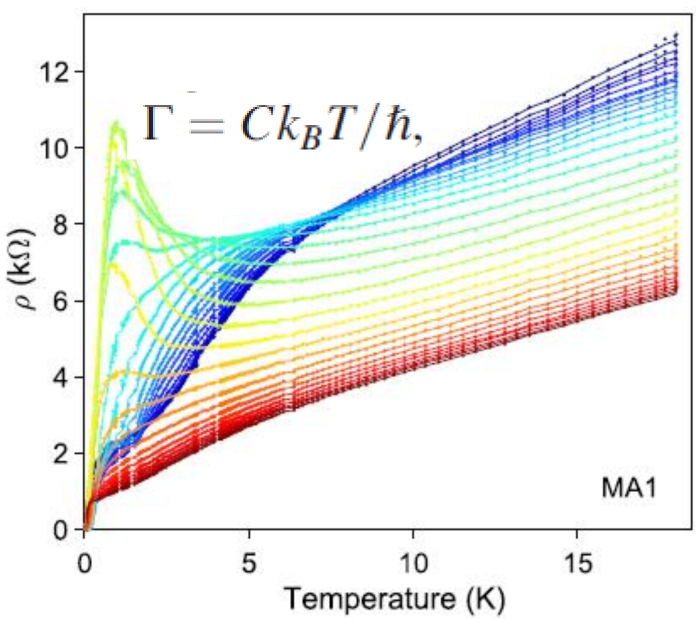
Nuckolls *et al*., *Nature 588,610-615* (2020)
Wu *et al*., *Nat.* materials 20, 488-494 (2021) ....

Open Questions

- Nature of Superconductivity
- **Non-Fermi Liquid behaviour ?**

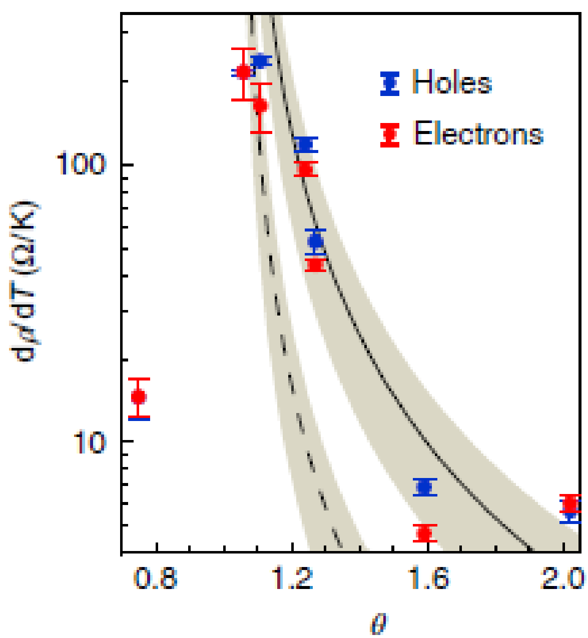
Linear Resistance-Temperature in twisted bilayer graphene

Possible non-Fermi Liquid behaviour



Cao *et al*. PRL 124, 076801 (2020)

Electron-phonon coupling



Polshyn *et al.* Nature Physics (2019)

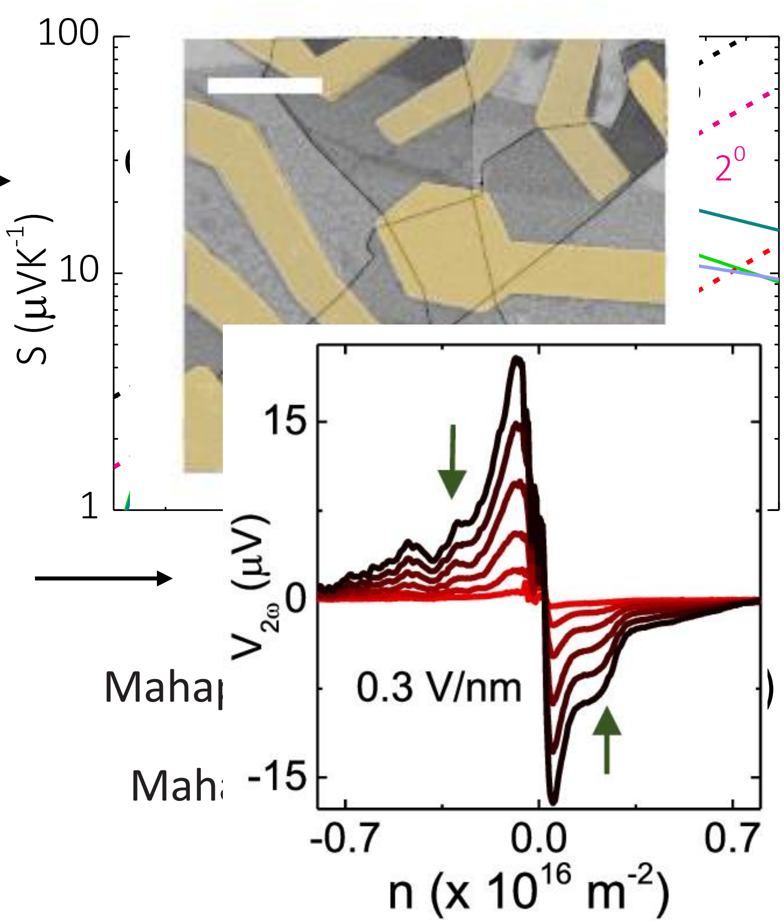
Combining Thermoelectricity with conductivity

Why thermopower ?

- Nature of interlayer coupling

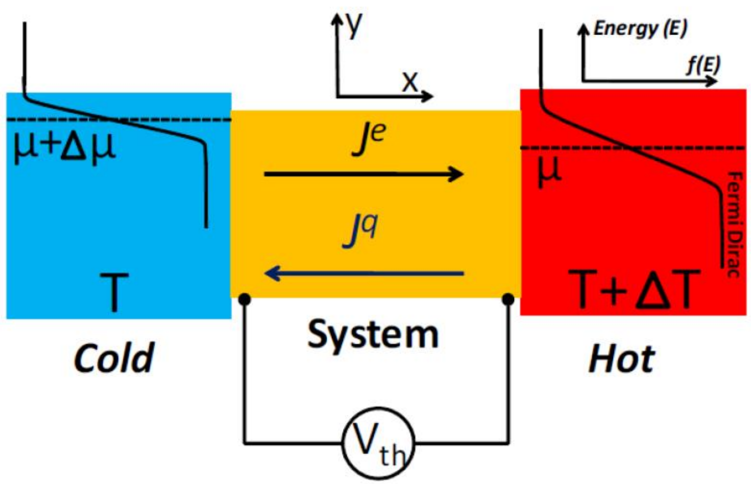
- Low energy structures in density of states

- Strong correlation effects



Jayaraman et al. Nano Lett. (2021)

Thermoelectricity and Seebeck effect



Charge and Heat current equation:

$$\Delta\mu/e = RI + S\Delta T$$

$$Q = \Pi I - K\Delta T$$

Sivan et al. Phys. Rev. B **33**, 551 (1986)

Mott Relation

Seebeck Coefficient, $S = \frac{\Delta V}{\Delta T} = S_{ph} + S_d$

$$S_{\mathrm{Mott}} = \frac{\pi^2 k_B^2 T}{3|e|} \frac{\mathrm{d}\ln R(E)}{\mathrm{d}E}\bigg|_{E_F}$$

$$S_{\mathrm{Mott}} = \frac{\pi^2 k_B^2 T}{3|e|} \frac{1}{R}\frac{\mathrm{d}R}{\mathrm{d}V_{tg}}\frac{\mathrm{d}V_{tg}}{\mathrm{d}n}\frac{\mathrm{d}n}{\mathrm{d}E}\bigg|_{E_F}$$

Experiment

Density of states/ Electronic dispersion

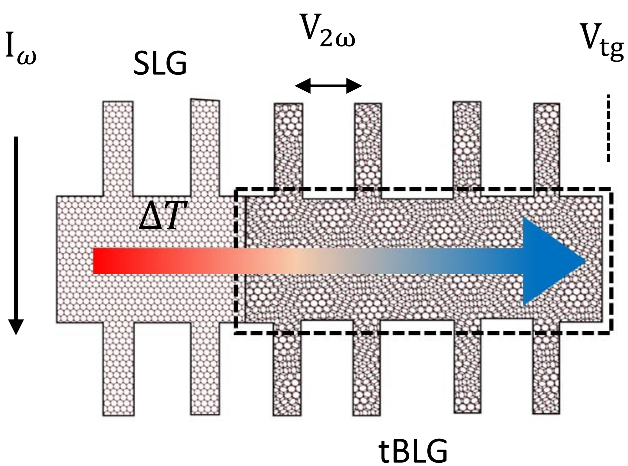
S_{ph}: $f[\phi(q), n(q)]$

e-ph coupling

$$\frac{1}{\exp\left(\frac{\hbar\omega}{k_B T}\right) - 1}$$

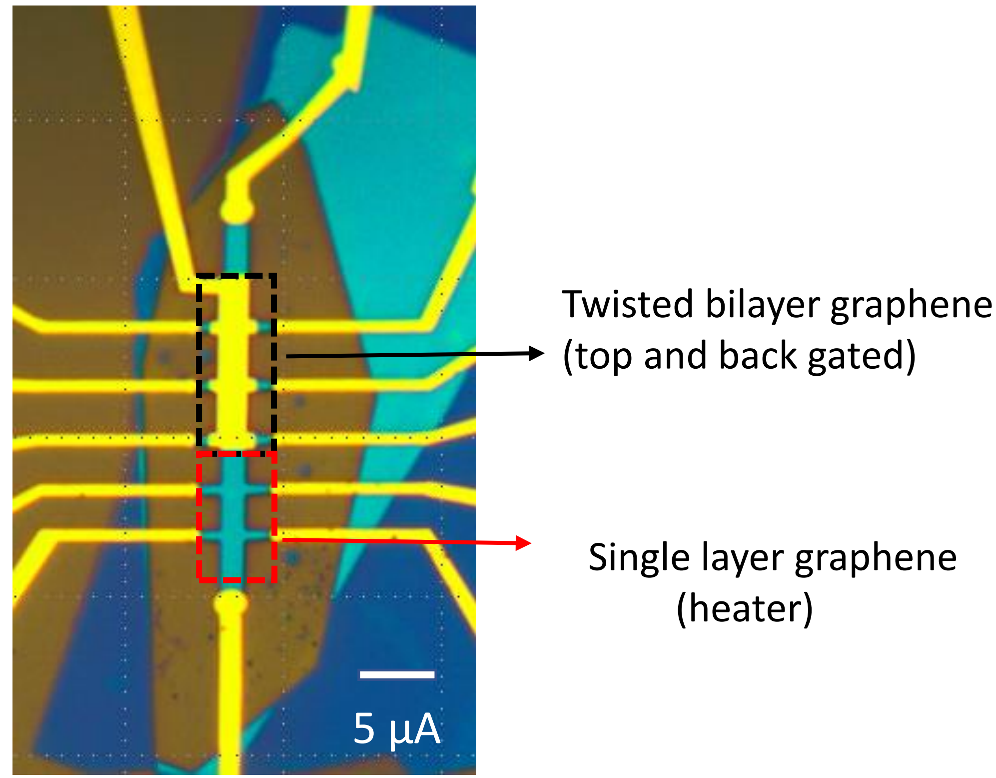
Thermopower in twisted bilayer graphene

- Correlation effects close to magic angle

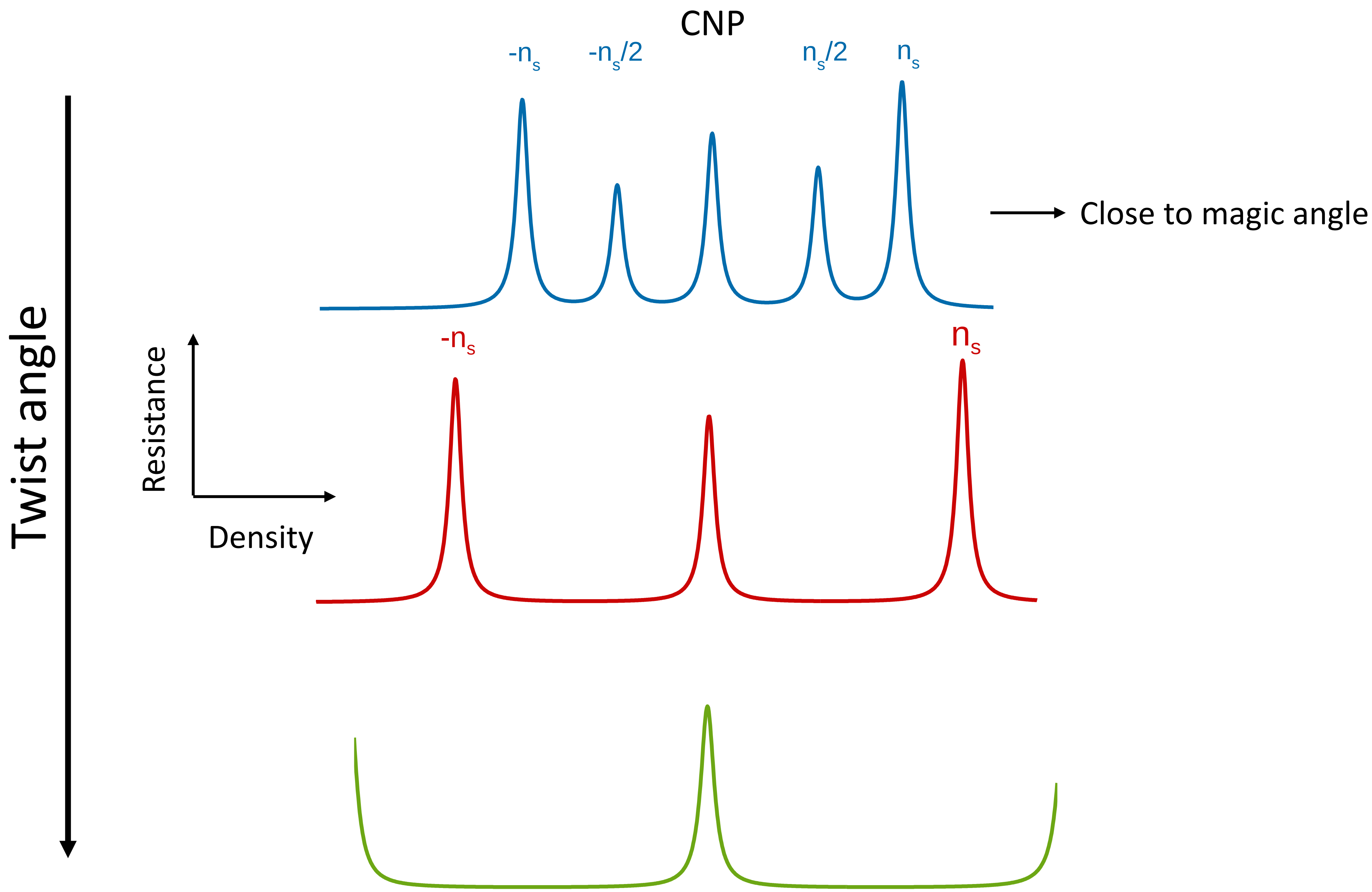


$V_{2\omega} \rightarrow$ sign of charge carriers

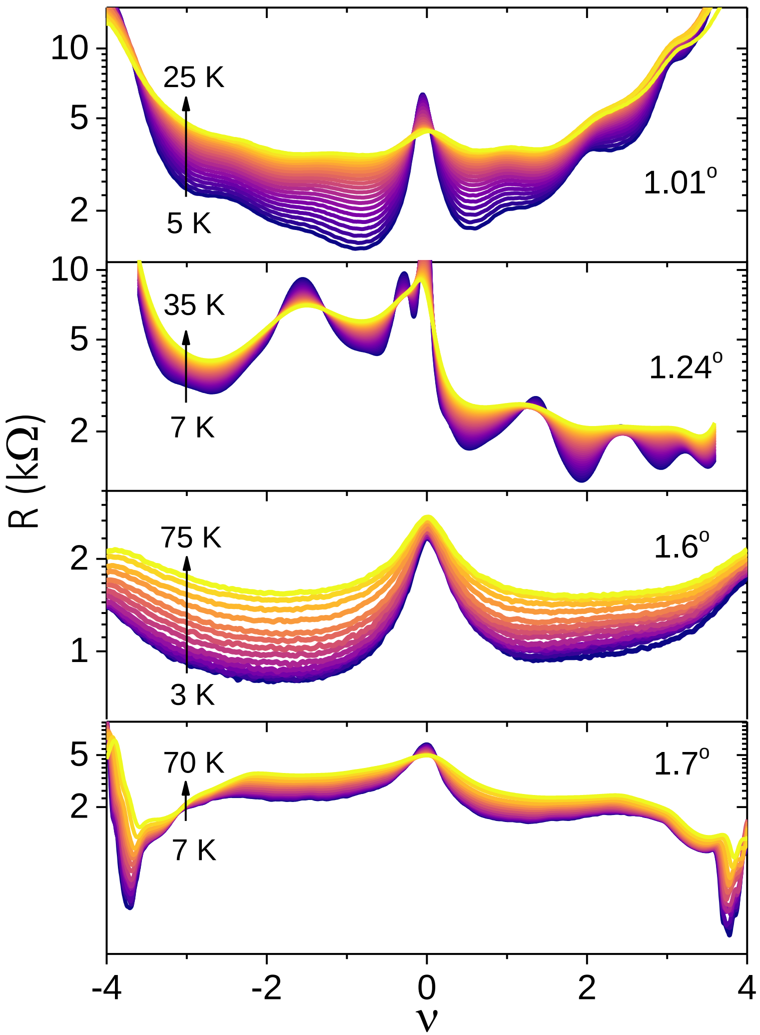
$V_{2\omega} \propto P \rightarrow \ (\Delta T \ll T)$

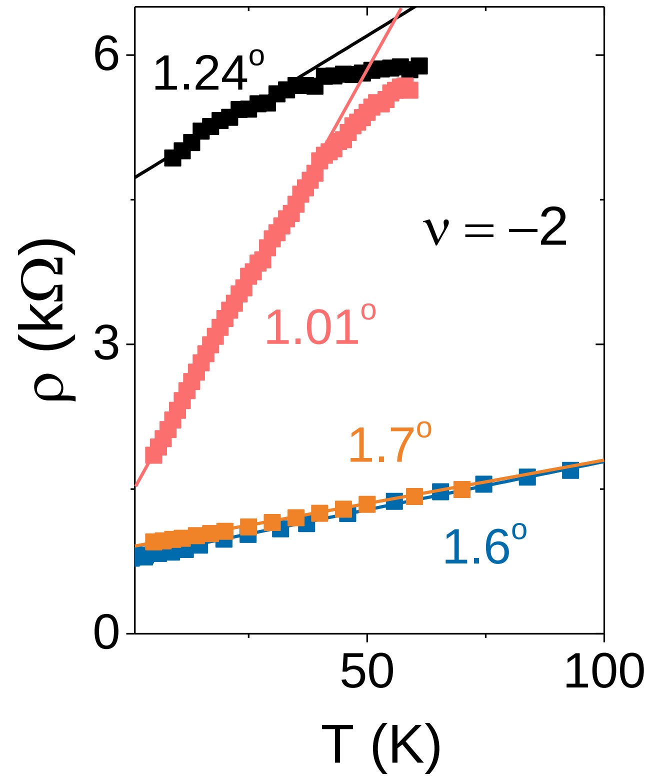


Finding the right twist angle



Electrical transport: Temperature dependence of resistance

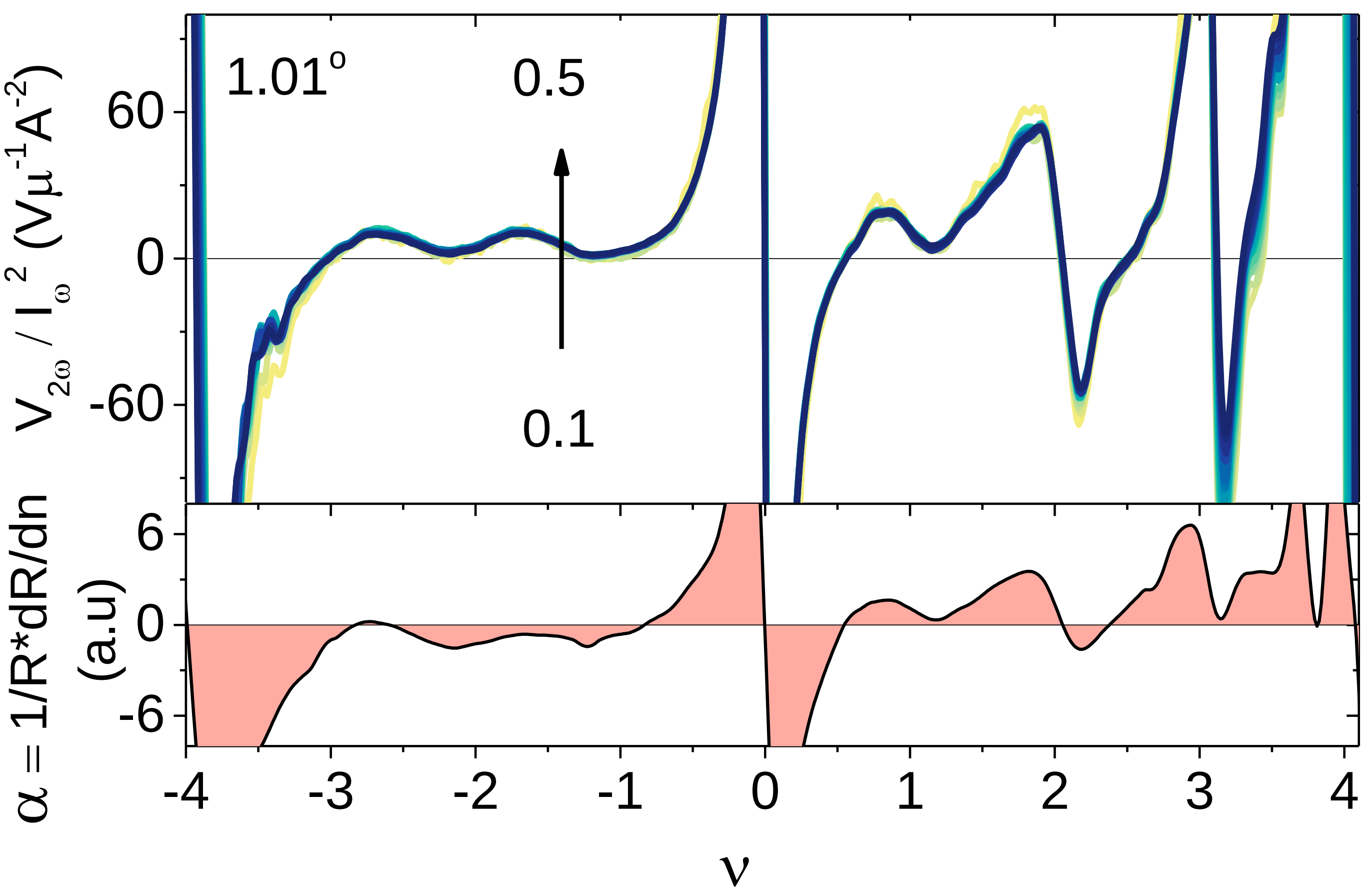




- Linear R-T for all devices at low T

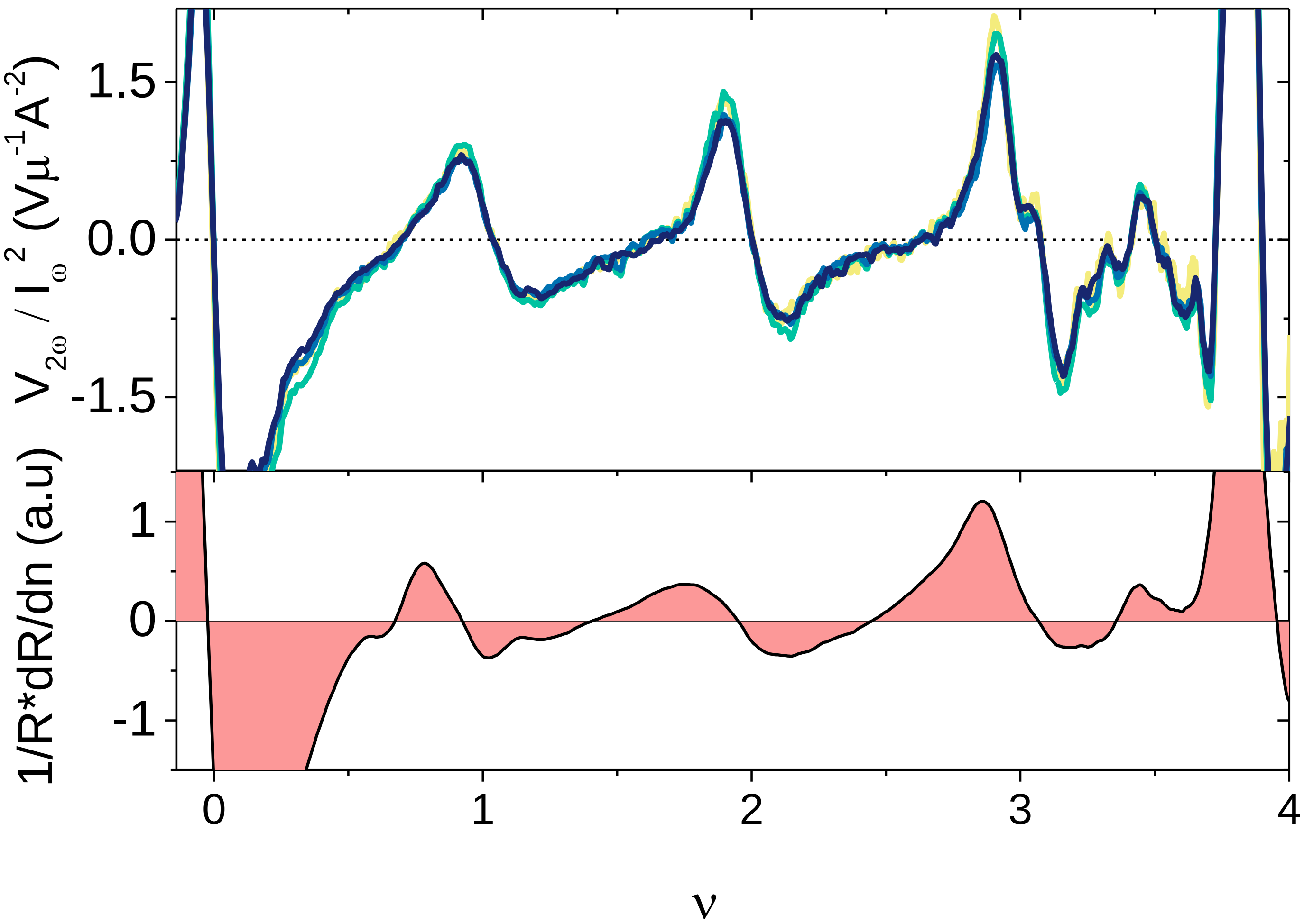
Ghawri et al. arXiv:2004.12356
(in press, Nature Communications)

Thermopower in twisted bilayer graphene $\theta = 1.01^0$



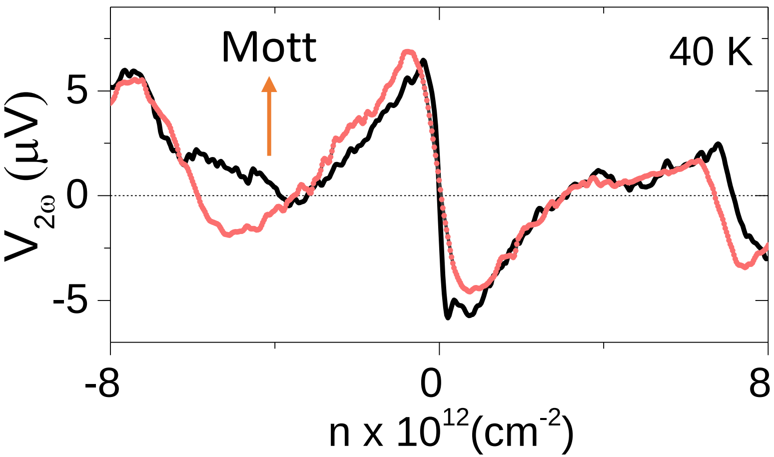
- Qualitative correspondence in the oscillations and sign reversals of the measured $V_{2\omega}$ and α.
- Quantitative estimation of the deviation of the measured thermopower from that expected from the semiclassical model not possible.

Thermopower in twisted bilayer graphene θ = 1.16⁰



Bhowmik et al. arXiv:2108.12689
(in press, Nature Physics)

Thermopower in twisted bilayer graphene $\theta = 1.6^0$

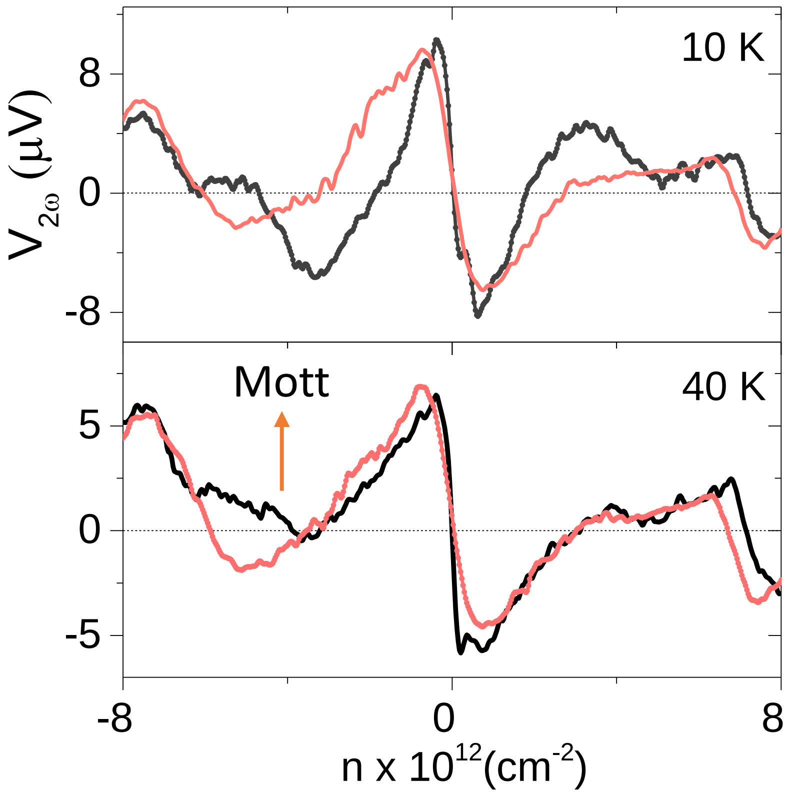


Ghawri et al. arXiv:2004.12356
(in press, Nature Communications)

Density of states calculation by
Shinjan and Prof. Manish Jain

Thermopower in twisted bilayer graphene $\theta = 1.6^0$

Violation of Mott formula



Ghawri et al. arXiv:2004.12356
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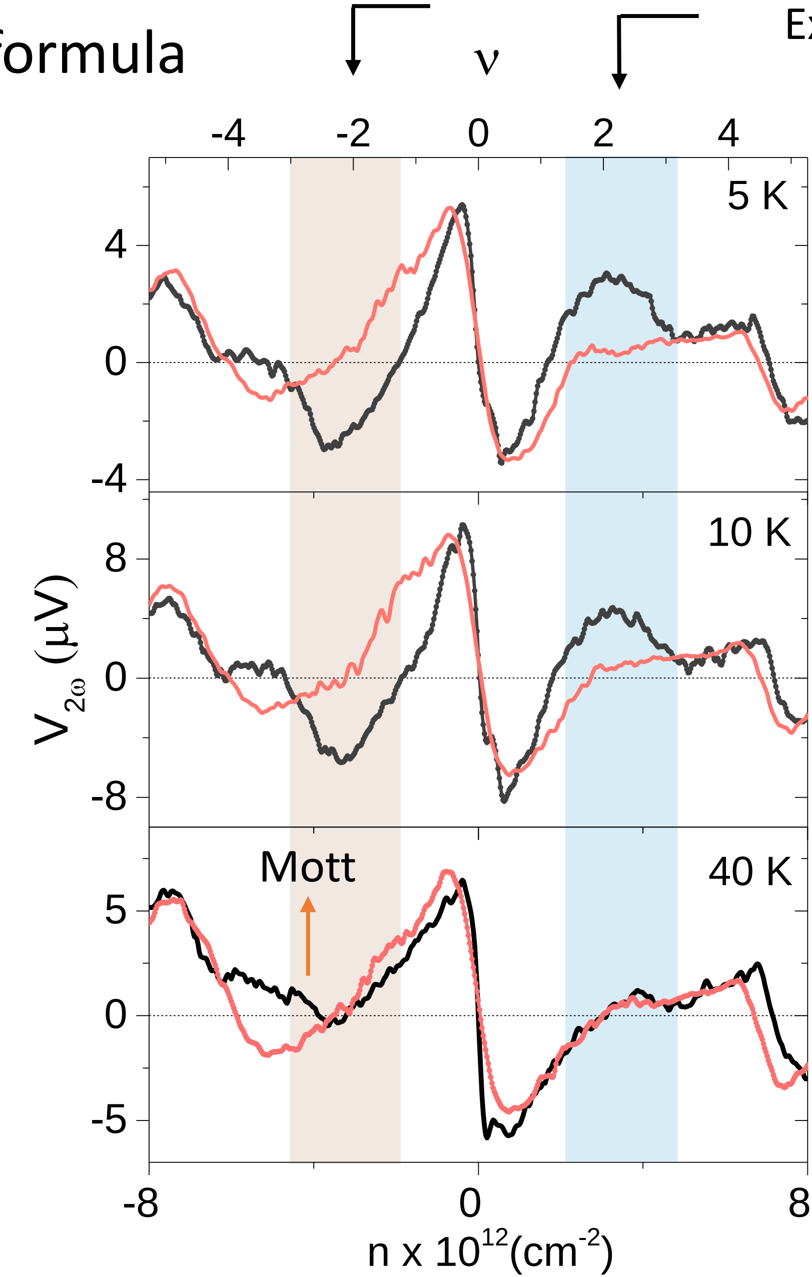
Density of states calculation by Shinjan and Prof. Manish Jain

Thermopower in twisted bilayer graphene θ = 1.6^0

Violation of Mott formula

Excess thermopower



Ghawri et al. arXiv:2004.12356
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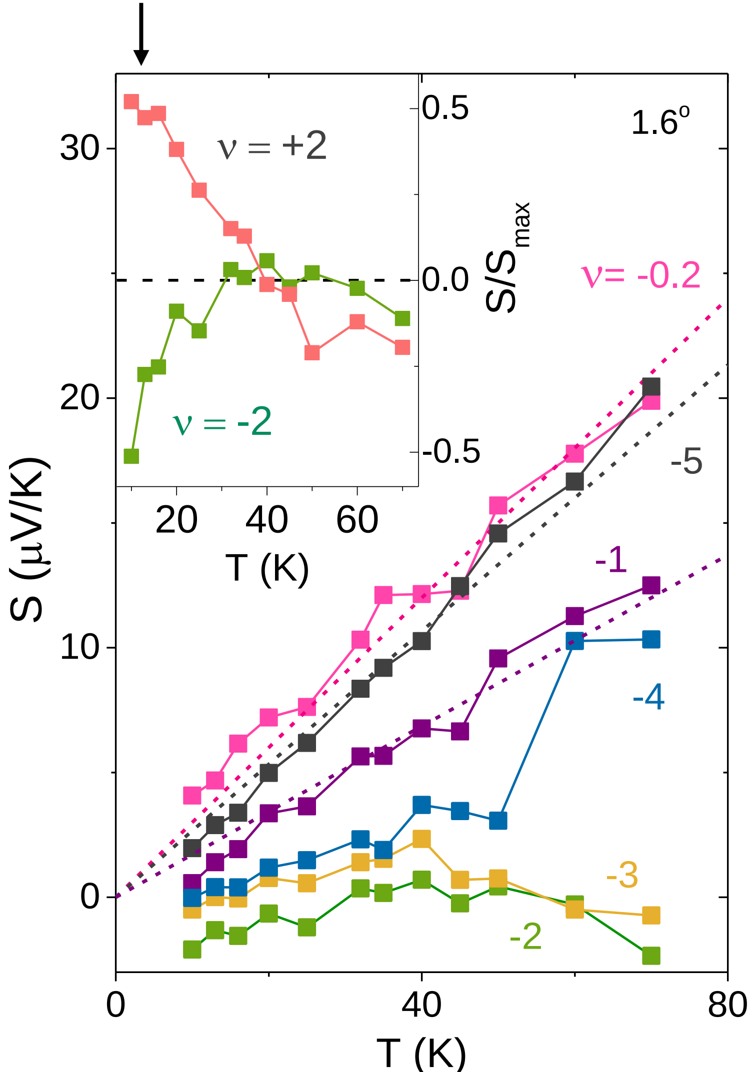
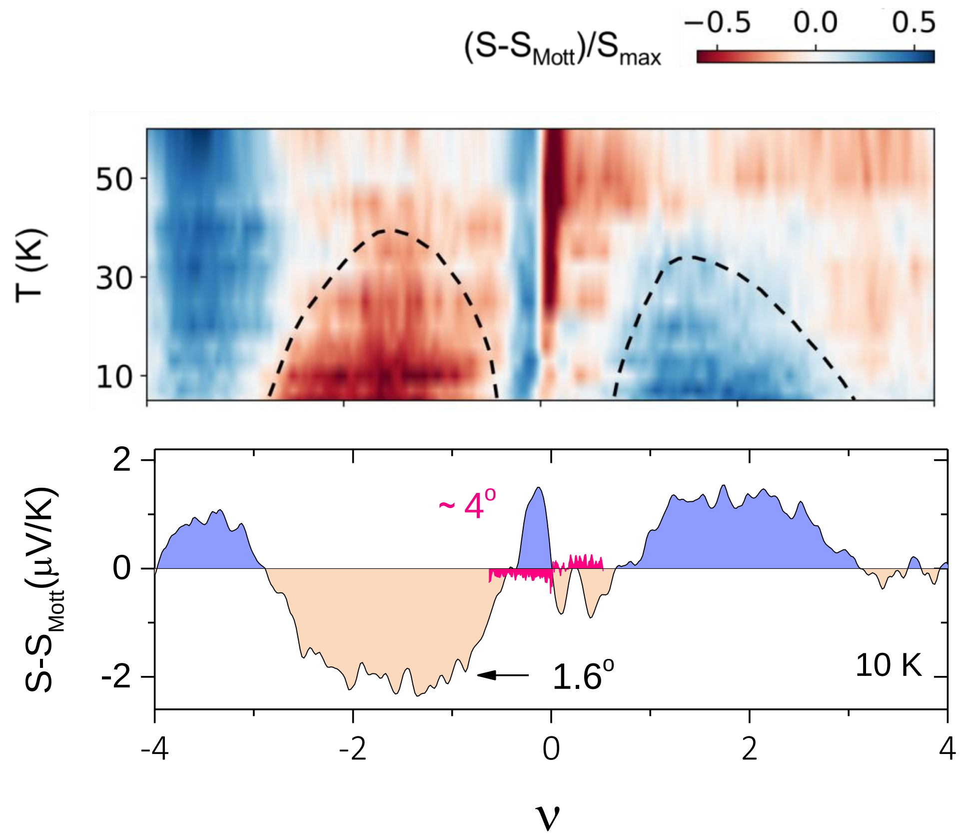
Violation of Mott formula

Non vanishing thermopower

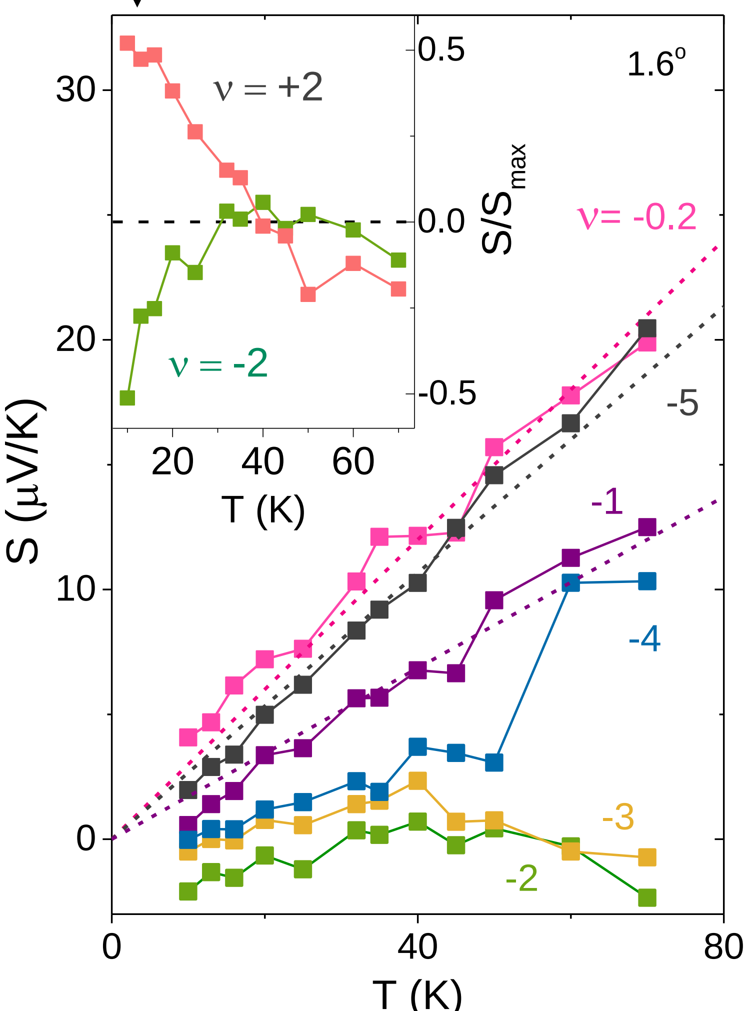


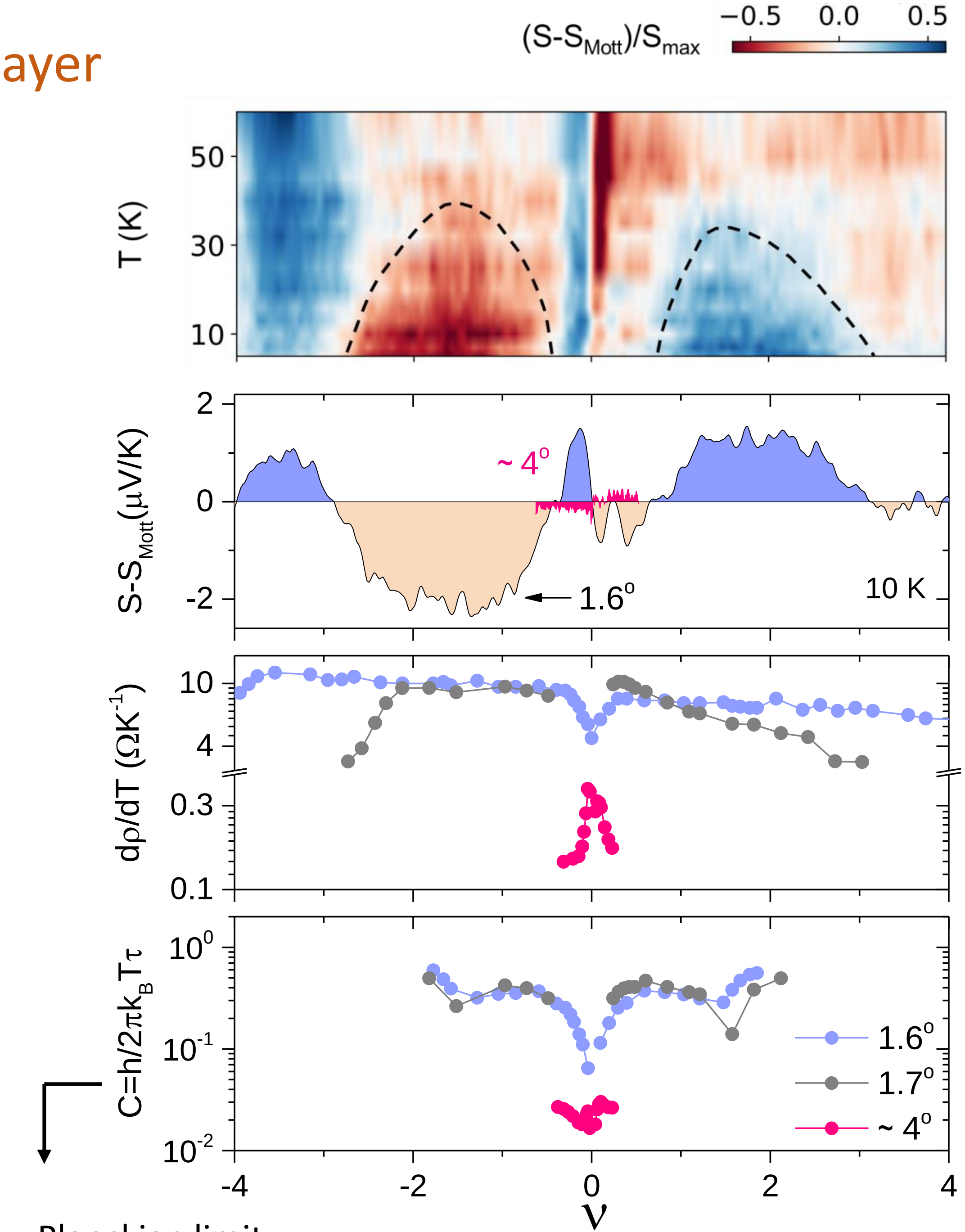


Thermopower in twisted bilayer graphene $\theta = 1.6^0$

Violation of Mott formula

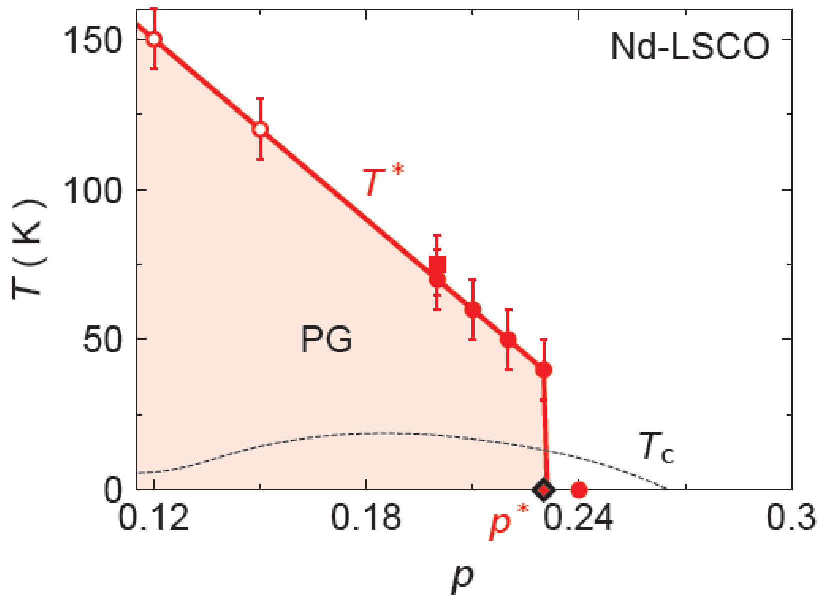
Non vanishing thermopower

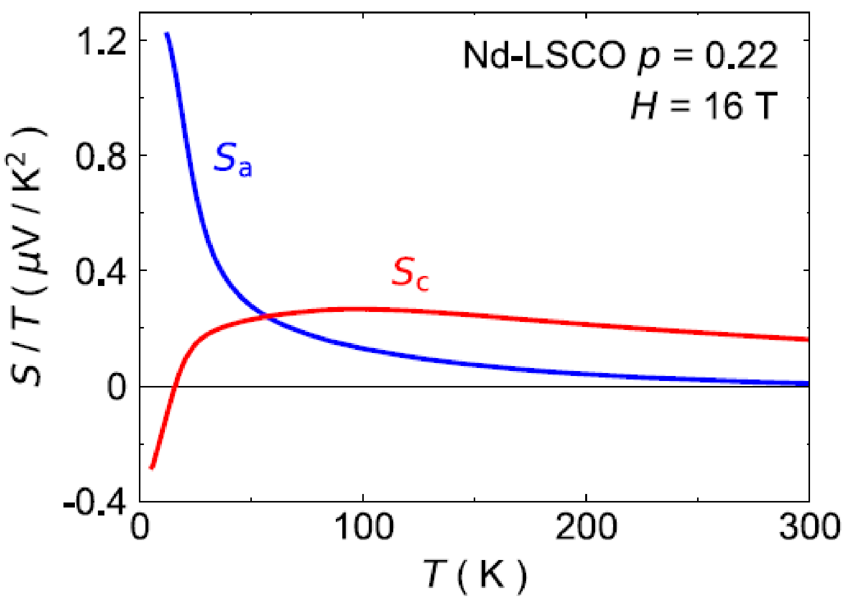




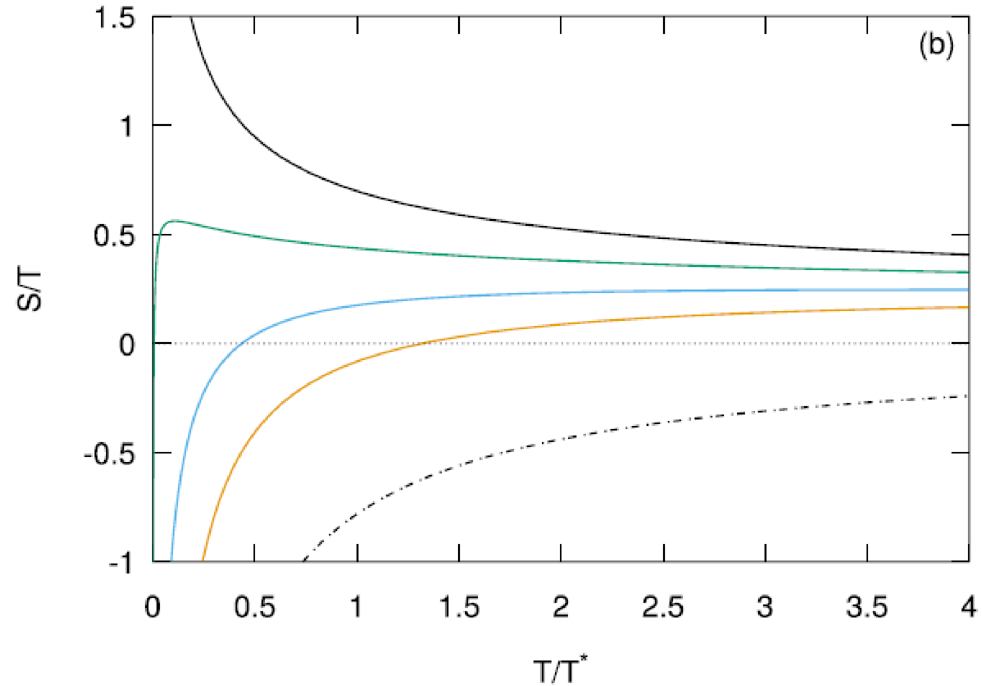
Planckian limit

Skewed non-Fermi liquids





Gourgout et al. Phys. Rev. X 12, 011037 (2022)



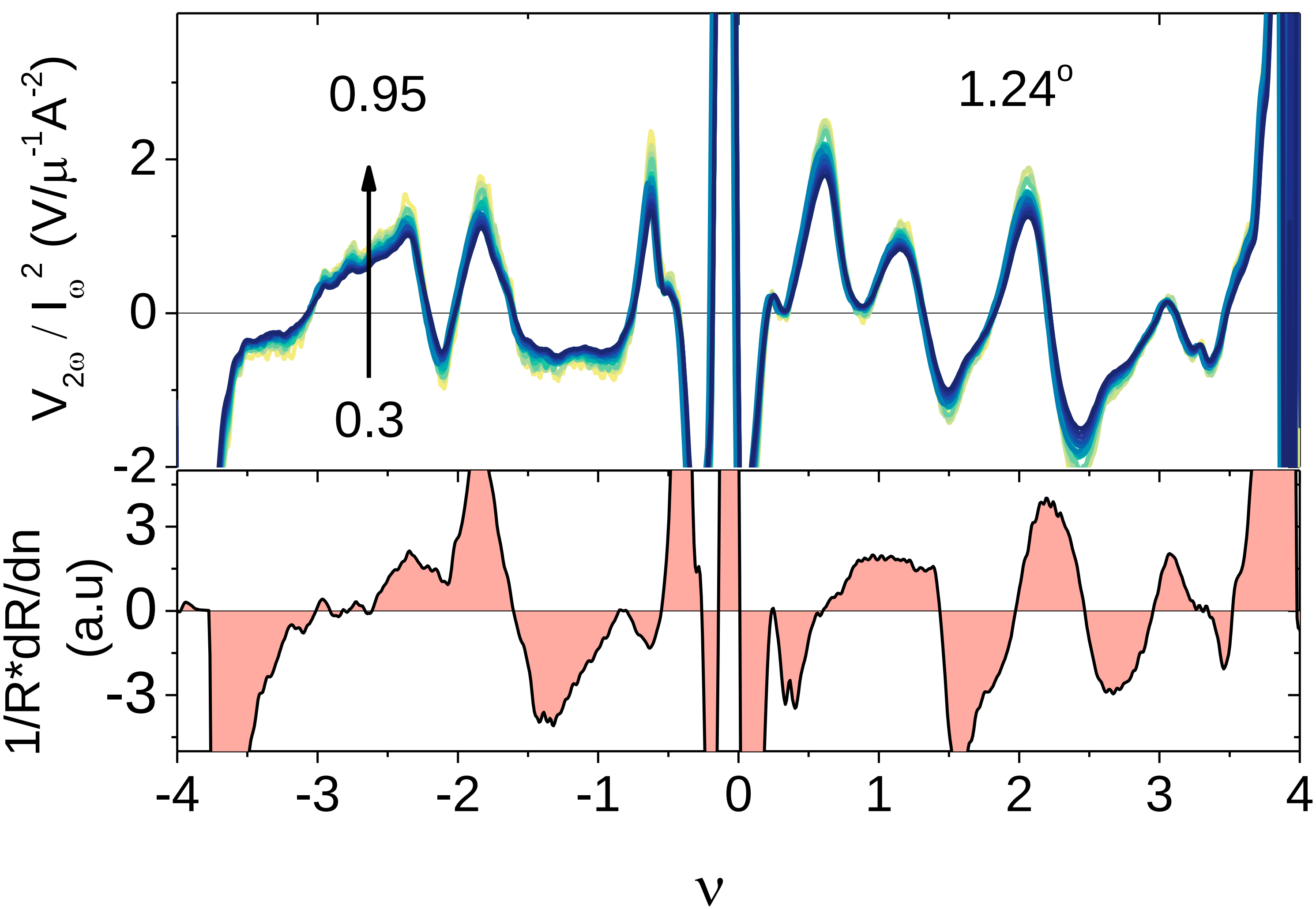
Georges et al. Phys. Rev. Research 3, 043132 (2021)

Summary

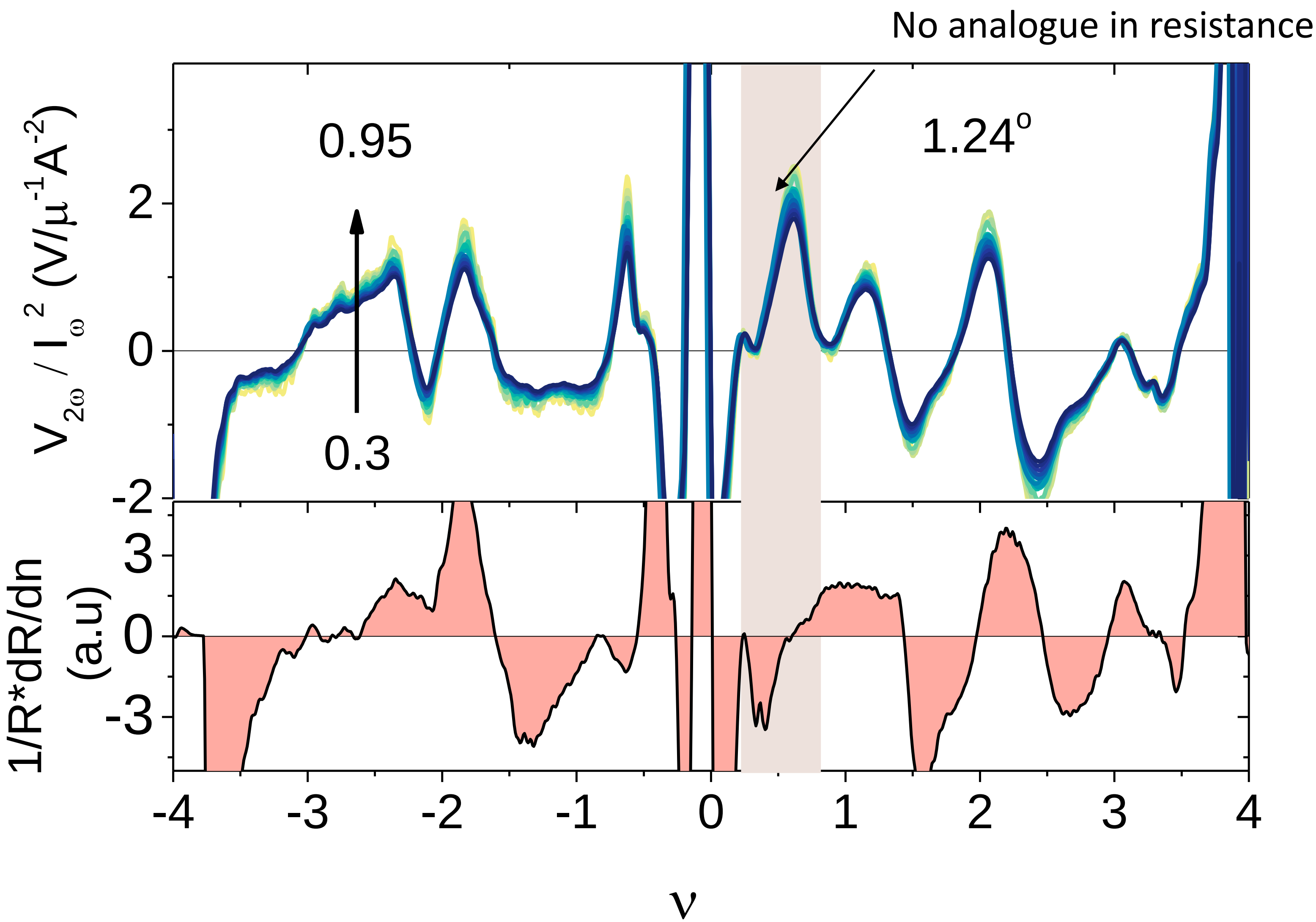
- Thermopower can be used as an effective probe to study diverse phenomenology in twisted bilayer graphene.
- Violation of Mott formula near half filling close to magic angle.
- Possibility of non-Fermi Liquid behaviour

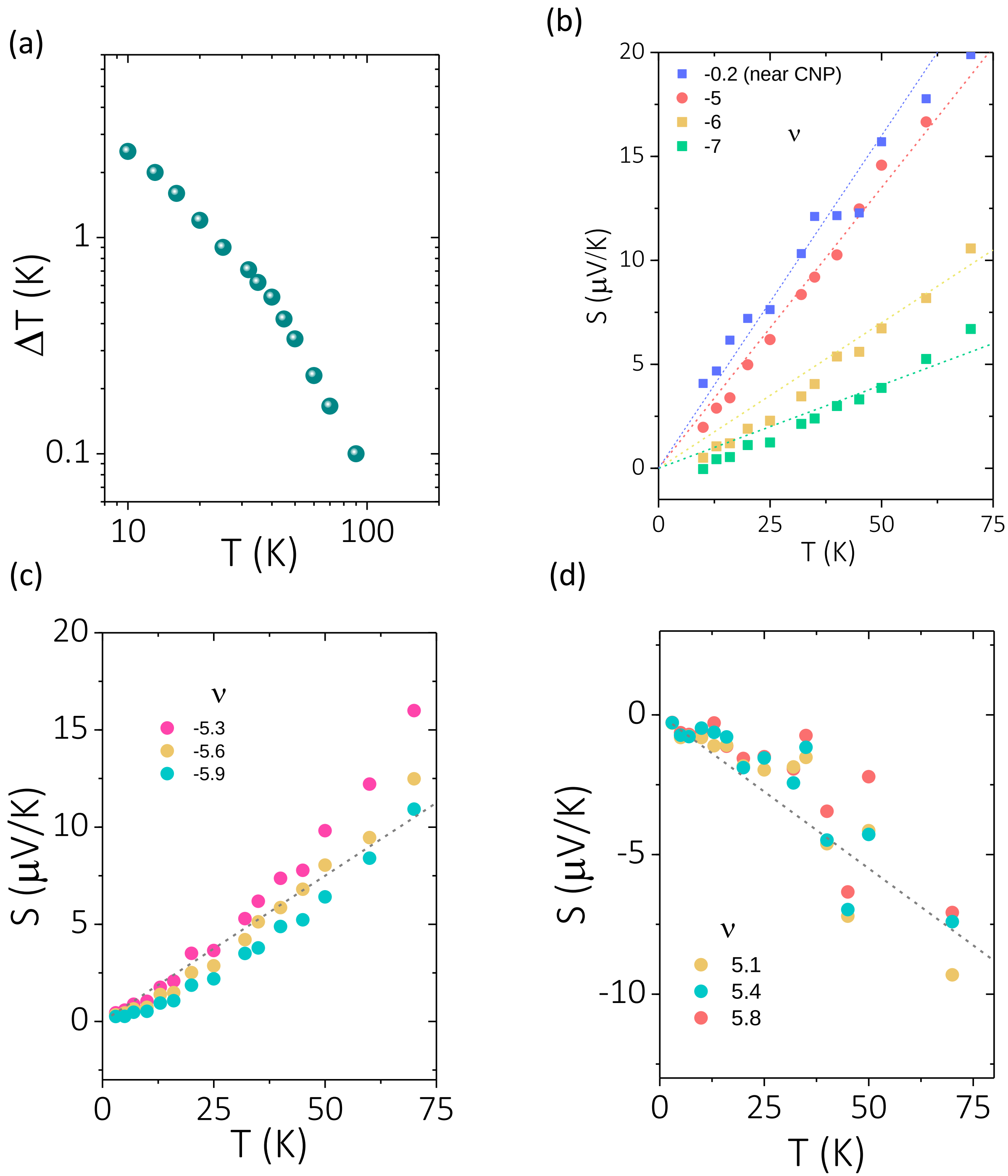
Thank you

Thermopower in twisted bilayer graphene θ = 1.24⁰

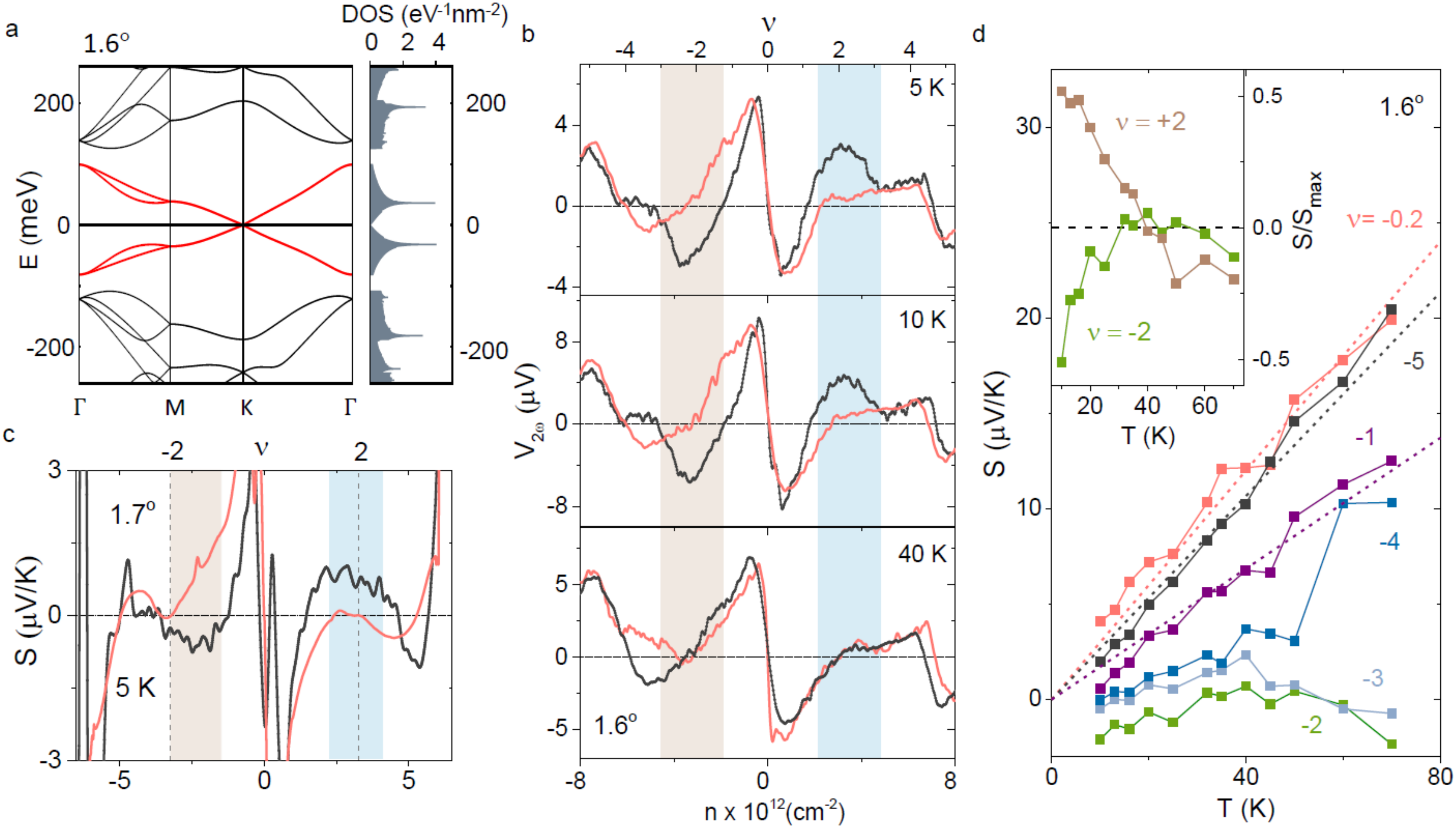


Thermopower in twisted bilayer graphene θ = 1.24^0



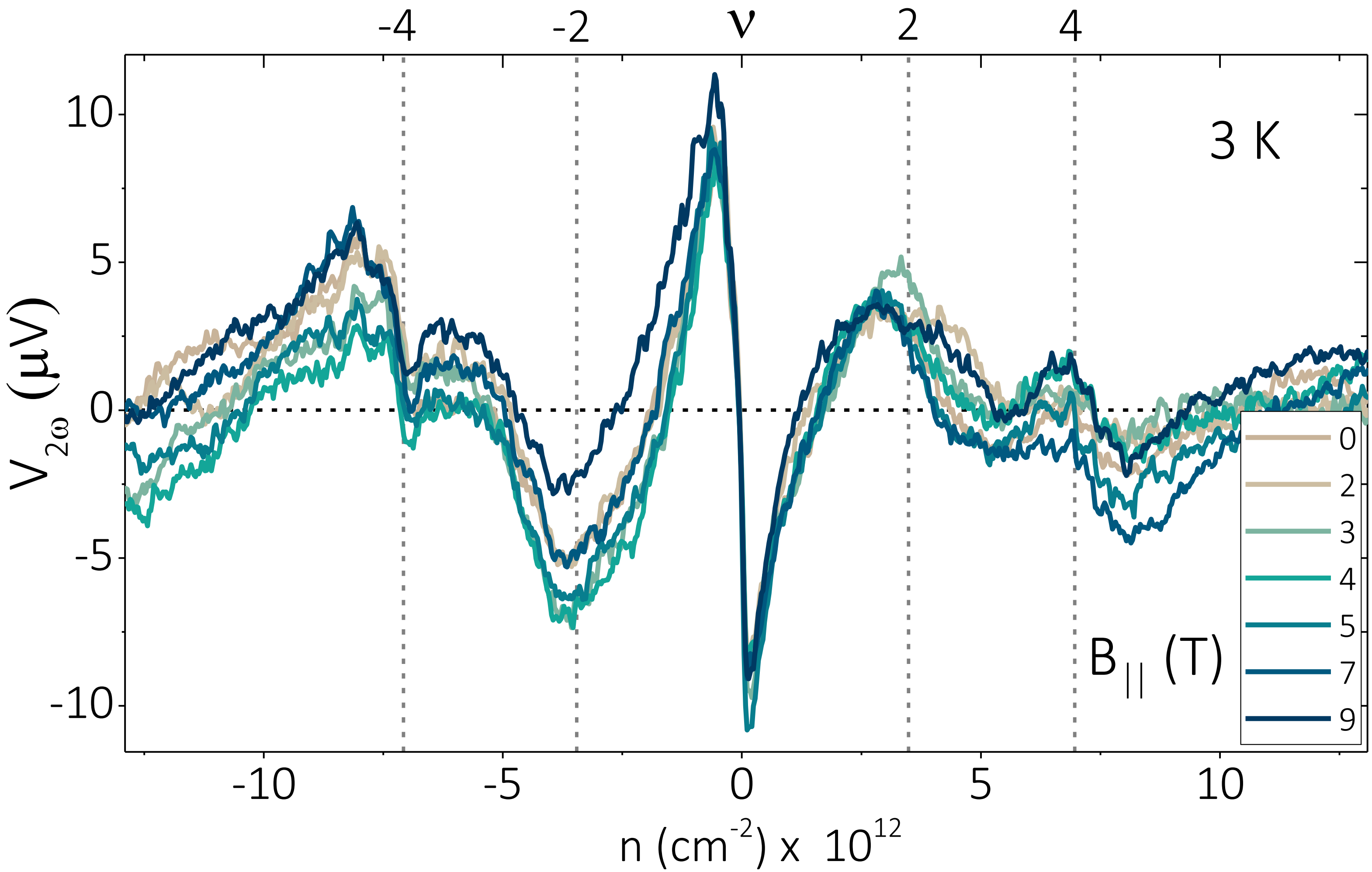


(a)
ΔT (K)
T (K)
1
0.1
10
100
(b)
S (μV/K)
T (K)
-0.2 (near CNP)
-5
-6
-7
ν
0
5
10
15
20
25
50
75
(c)
S (μV/K)
T (K)
ν
-5.3
-5.6
-5.9
(d)
S (μV/K)
T (K)
ν
5.1
5.4
5.8
-5
-10

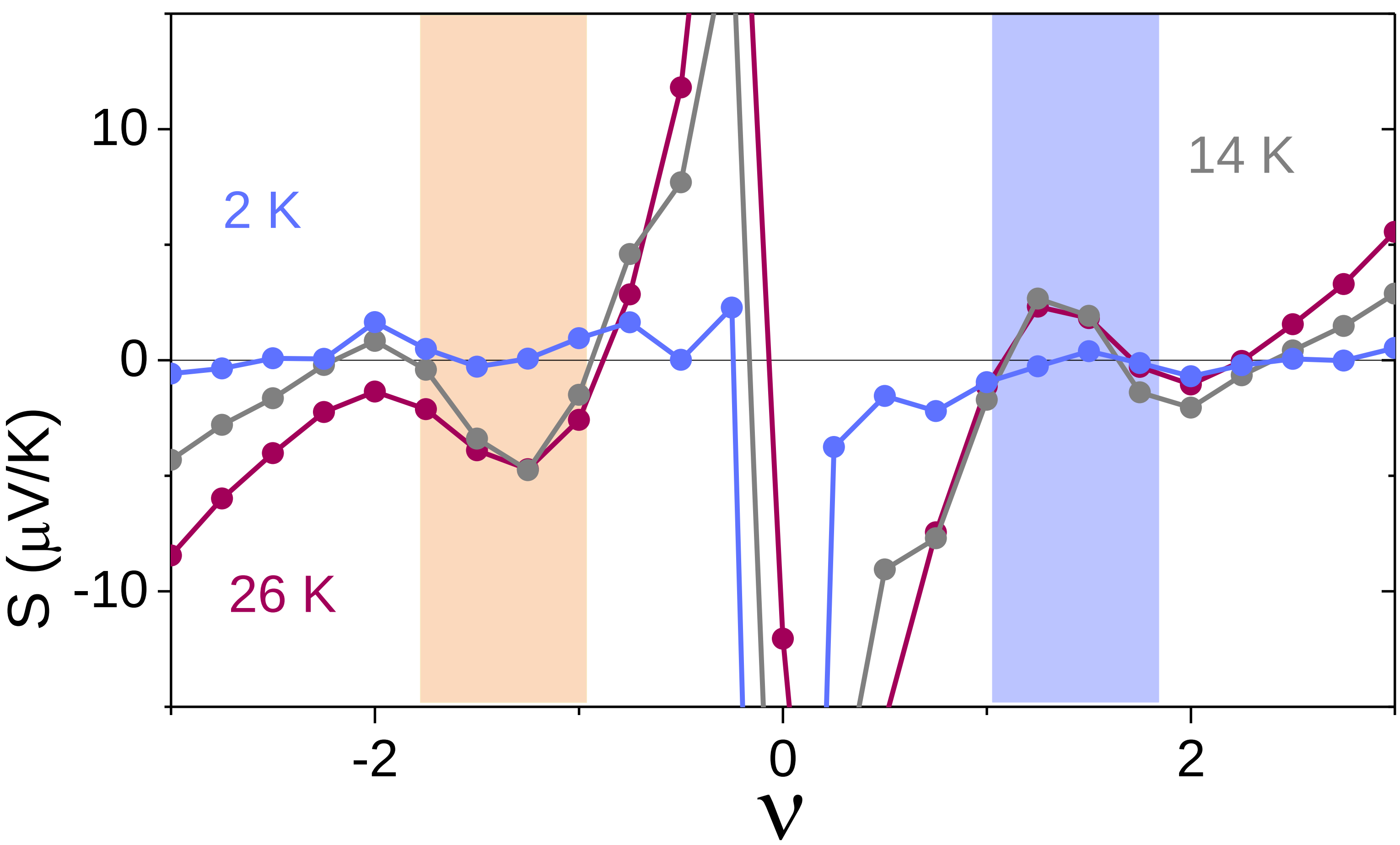


a
1.6°
DOS (eV-1nm-2)
E (meV)
Γ
M
K
Γ
b
ν
5 K
10 K
40 K
1.6°
V2ω (μV)
n x 10^12(cm-2)
c
1.7°
5 K
S (μV/K)
d
1.6°
ν = +2
ν = -2
S/Smax
T (K)
ν= -0.2
-5
-1
-4
-3
-2
S (μV/K)
T (K)

Magnetic field dependence



DMFT calculation



DMFT calculation