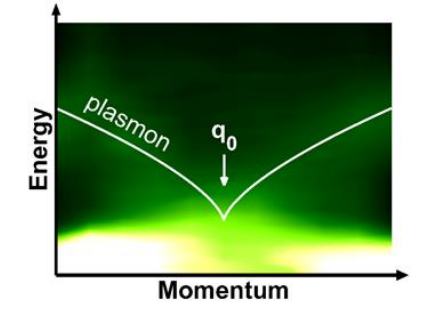
Signatures of exciton condensation in a transition metal dichalcogenide

A. Kogar et al., Science 358, 1314-1317 (2017)



Team 9

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Dec. 7, 2018

Mindy Rak.(Nov. 9, 2018). *Suppression of exciton condensation in Cu-doped $TiSe_2$* . University of Illinois Urbana-Champaign, IL

Outline

1. **Introduction**
2. Background
3. Methods
4. Primary Results
5. Conclusion
6. Critique

What is new about this paper?

- Observation of a thermally equilibrated 3D Bose condensate of excitons in 1T-$TiSe_2$ using a new technique, M-EELS
- New measurement technique that can directly confirm the exciton condensation
- Can unveil the nature of Bose condensate of excitons
- Helps in understanding macroscopic quantum phenomena, as well the classic problem of the metal-insulator transition in band solids

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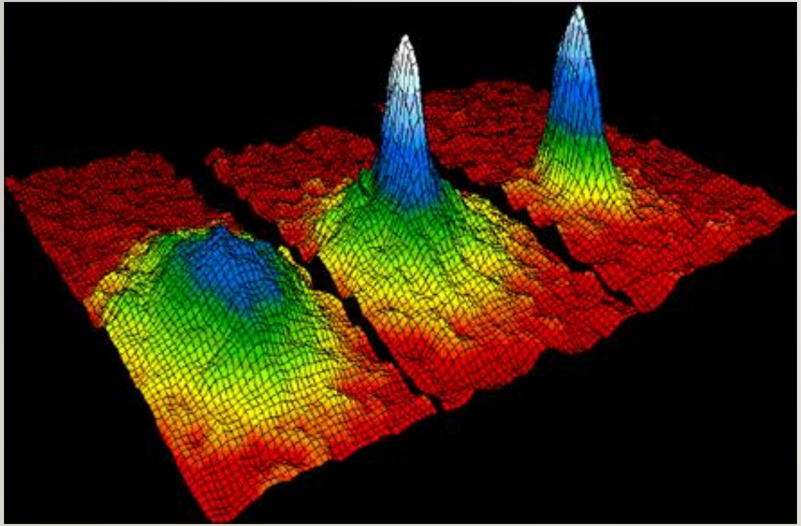
What is the Bose condensate?

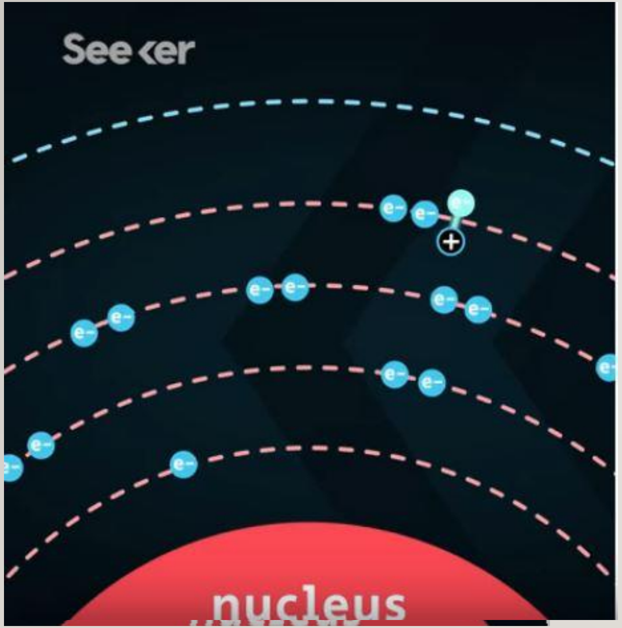


At sufficiently low temperatures, a large portion of stable bosons condense to the lowest quantum energy state

Velocity-distribution of a gas of rubidium atoms

Dalfovo, Franco et al. (1999). Theory of trapped Bose-condensed gases. Rev. Mod. Phys. 71.

Excitons are valence band excitations



Formation of exciton

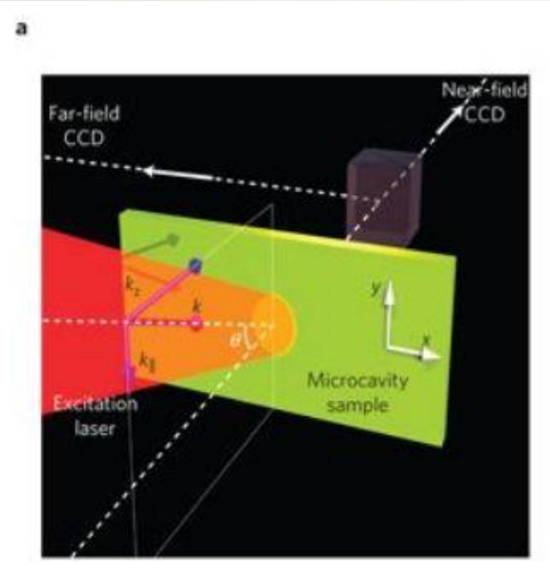
Dominguez, Trace, "There's a New Form of Matter in Town", https://www.youtube.com/watch?v=17Kvxe6v5Ms

- Bound state between an electron and hole
- Neutral quasiparticle and a boson
- Predicted to Bose condense but debate on the nature of Bose condensate of excitons (excitonium):

  -Superfluid vs. Innately Insulating

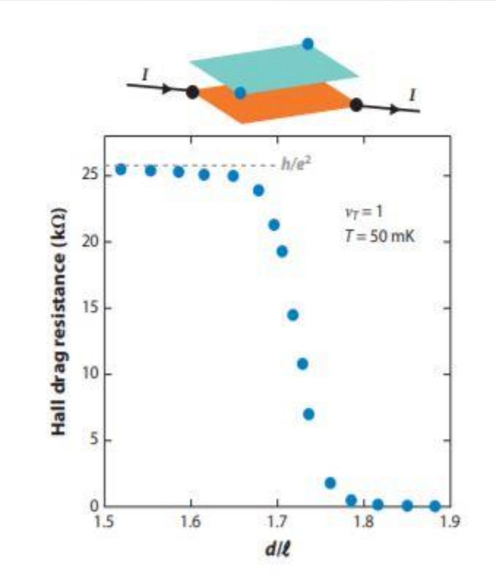
Previous experimental works on exciton condensation

Photogenerated excitonic condensates



Experimental setup for semiconductor quantum wells

Excitonic phases in 2D structures

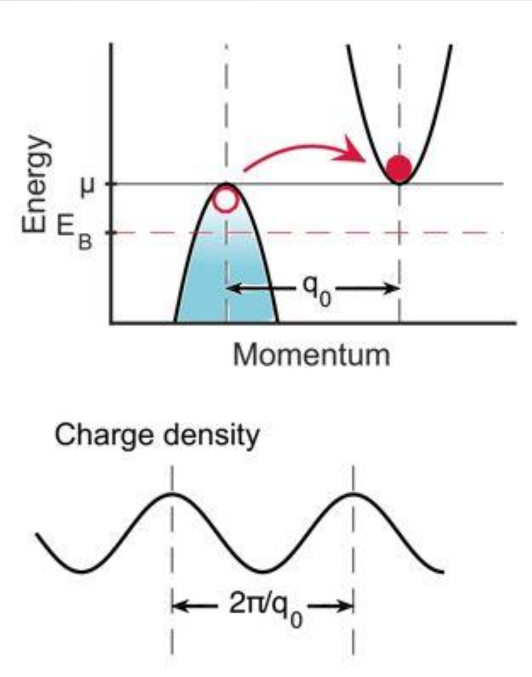


Indicative of excitons for quantum Hall bilayer in perpendicular magnetic field

A. Amo et al., Superfluidity of polaritons in semiconductor microcavities. *Nat. Phys.* 5, 805–810 (2009)

J. P. Eisenstein, Exciton condensation in bilayer quantum Hall systems. *Annu. Rev. Condens. Matter Phys.* 5, 159–181 (2014)

Experimental Signature of Exciton condensate



- Formation of charge density wave (CDW)
- Two types of CDW modulation
  - Plasmons: Oscillation of decoupled electron density with respect to the fixed positive ion
  - Phonons: Distortion of the underlying lattice

L. V. Keldysh, Sov. Phys. Solid State **6**, 2219 (1965); N. F. Mott, Phil. Mag. **6**, 287 (1961)

Problem: Peierls charge density wave

- Spontaneous crystal distortion from electron-phonon interaction

	Exciton condensate	**Peierls phase**
Charge modulation caused by...	Electronic instability (Coulomb interactions)	Lattice instability and electron-phonon coupling
Experimental signatures	Superlattice, opening of an energy gap	Superlattice, opening of an energy gap

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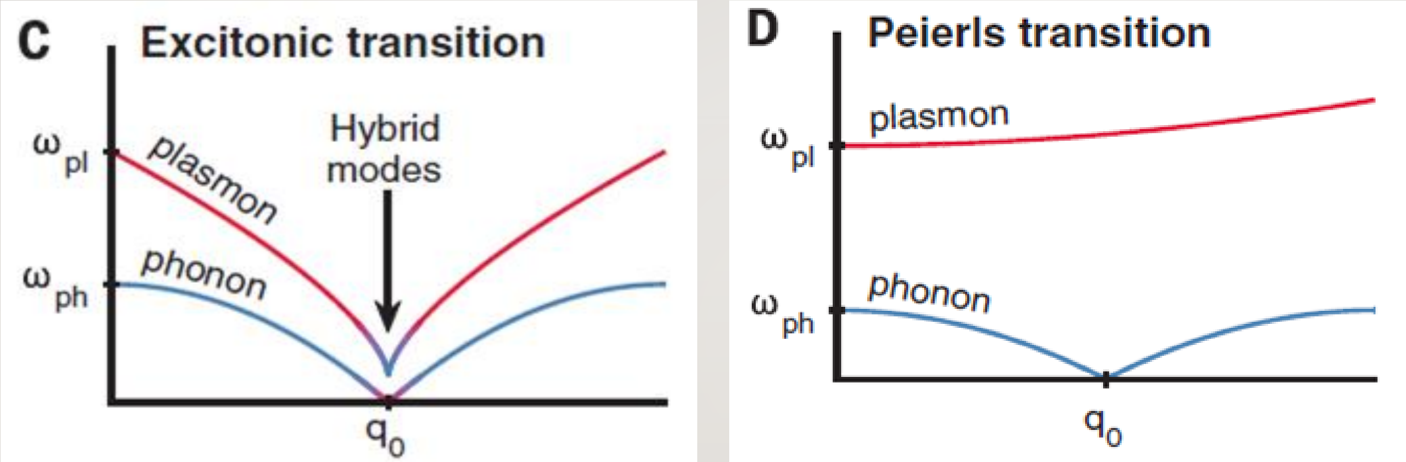
Excitonic state compared to peierls charge density wave



- Exciton has a coupling of a soft phonon and a soft plasmon
- Peierls has a soft phonon without a soft plasmon
- We need an instrument that can measure both energy and momentum that is sensitive to valence electron modes

Previous measurement techniques were inadequate

	Energy Resolution	Momentum Resolution	Valence Band Sensitivity
EELS	**X**		**X**
IR Spectroscopy	**X**	**X**	
Neutron, X-ray Scattering	**X**	**X**	
Low energy electron diffraction (LEED)		**X**	**X**

- Previous measurement techniques lacked a key element needed to measure a soft plasmon

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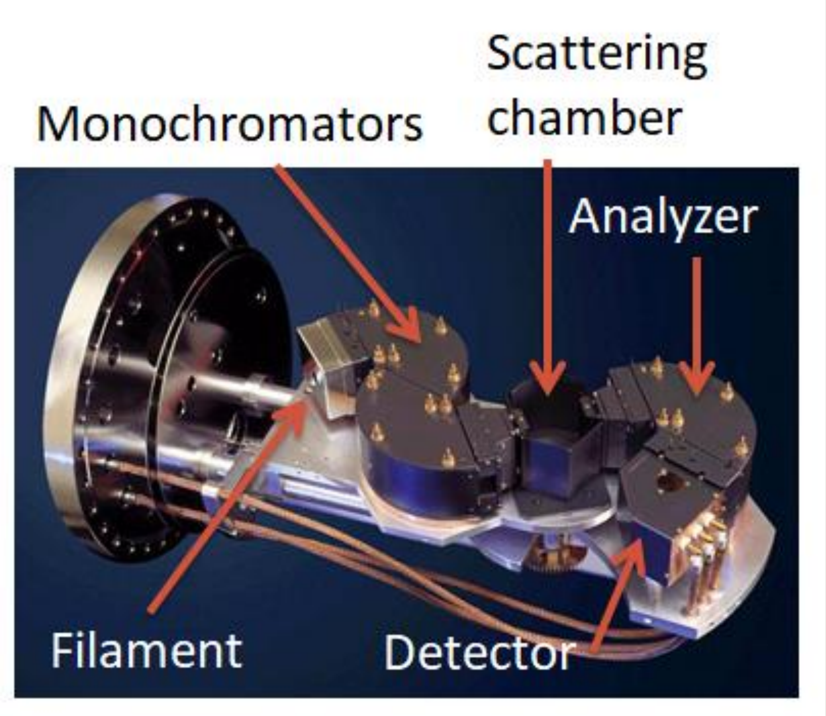
What is Electron Energy-Loss Spectroscopy (EELS)?

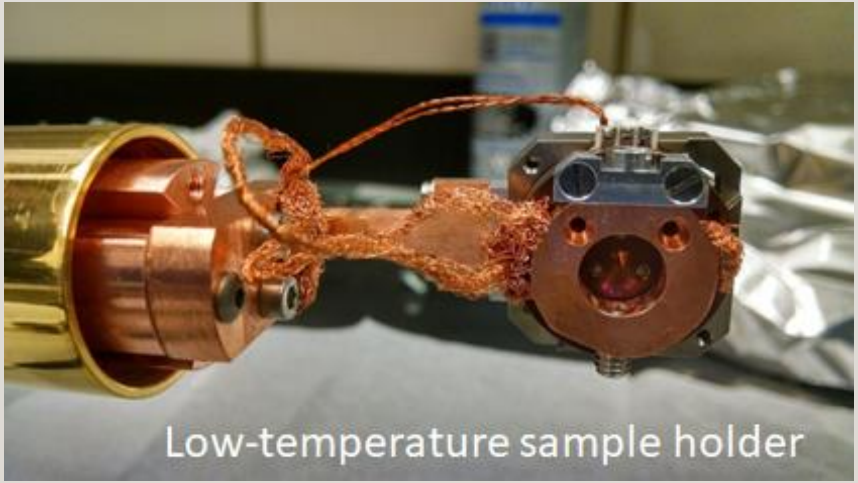


- EELS scatters electrons off of the sample surface and measures the energy loss to determine valence band distortions

Mindy Rak.(Nov. 9, 2018). *Suppression of exciton condensation in Cu-doped $TiSe_2$* . University of Illinois Urbana-Champaign, IL

What is Momentum-resolved Electron Energy-Loss Spectroscopy (M-EELS)?

- Added goniometer to rotate sample while performing EELS, enabling momentum resolution
- Measures both energy and momentum while being sensitive to electron valence band excitations
- Measured $TiSe_2$



Mindy Rak.(Nov. 9, 2018). *Suppression of exciton condensation in Cu-doped* $TiSe_2$. University of Illinois Urbana-Champaign, IL

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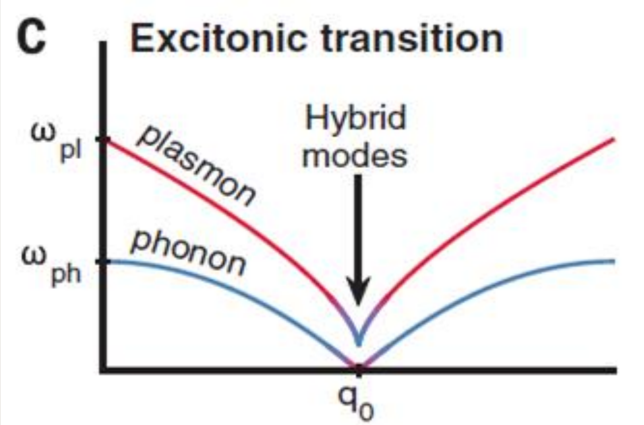
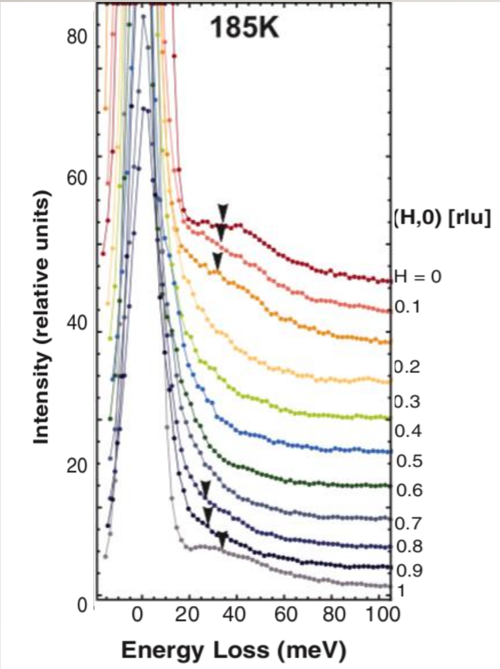
What do we expect to see relative to Tc = 185K?

- T~Tc: Energy required to create electron-hole pair is zero
  - We should see an energy loss of zero at phonon momentum values matching the charge density momentum, q_0
- T<Tc: Electronic mode begins to harden
- T<<Tc: Excitonic condensate becomes macroscopic
  - Electronic and lattice modes are now distinguishable

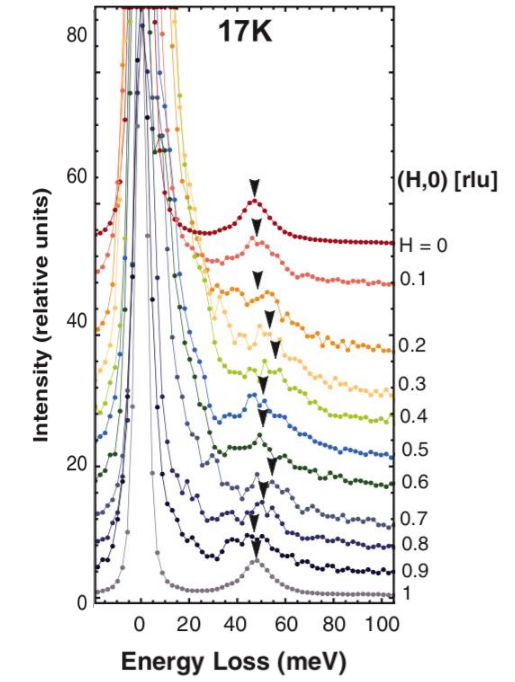


Soft plasmon behavior at 185K ~ Tc



- Electronic and lattice excitation energies are now indistinguishable
- Finite population of excitons forms near the ordering wave vector q_0 = (0.5,0)
- This is the behavior of the soft plasmonic and soft phononic modes in an excitonic condensate

Hard plasmon mode at 17K << Tc



- Electronic and lattice excitations energies are now distinguishable
- We observe a fully hardened mode at ~47meV
  - Corresponds to an excitonic energy state
- The highest phononic energy state would be ~36meV, according to IR spectroscopy studies of 1T-$TiSe_2$

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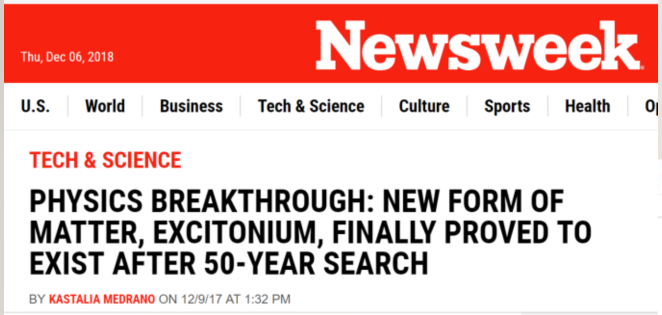
Conclusions



Thu, Dec 06, 2018

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Citation Analysis

- 22 papers in total (1 paper to be published, 1 self-citation)
- While the discovery made in this paper is significant, there are not many follow-up papers yet:

  1. Studies on direct gap semimetal/2D structures

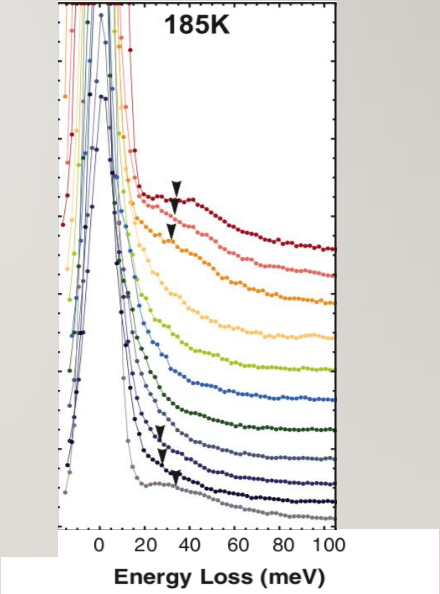
  2. Theoretical study on hybrid mode

Critical Analysis - Journal Article

- **Clear background** on theory and previous related experimental measurements
- **Figures are well-placed and meaningful**: first figure introduces problem and predictions, second figure places new method in context, third figure shows key results, fourth figure summarizes results and compares to predictions
- Article is **dense**; this may possibly be due to journal constraints
- **Limited explanation of M-EELS**, a novel experimental method, which adapts techniques from X-ray diffraction for application with EELS

Critical Analysis - Methods and Results

- **Novel adaptation of established technique**, EELS
- **Fitting methods not justified**: reasons for fitting with Gaussian form and Lorentzian forms not clear, along with power law fit in certain regions
- Values for energy loss provided, for example, but **error ranges not stated** in article for any measurements (discussed in Supplemental Information)
- **Supplementary results with real-space measurements not provided**; such data would help corroborate reciprocal-space M-EELS measurements



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4. Dominguez, Trace, "There's a New Form of Matter in Town", https://www.youtube.com/watch?v=17Kvxe6v5Ms
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9. Jiang, Z., Li, Y., Zhang, S., & Duan, W. (2018). Realizing an intrinsic excitonic insulator by decoupling exciton binding energy from the minimum band gap. Physical Review B, 98(8)
10. B. I. Halperin, Rev. Mod. Phys. 40, 755 (1968)
11. W. Kohn, Rev. Mod. Phys. 42, 1 (1970)

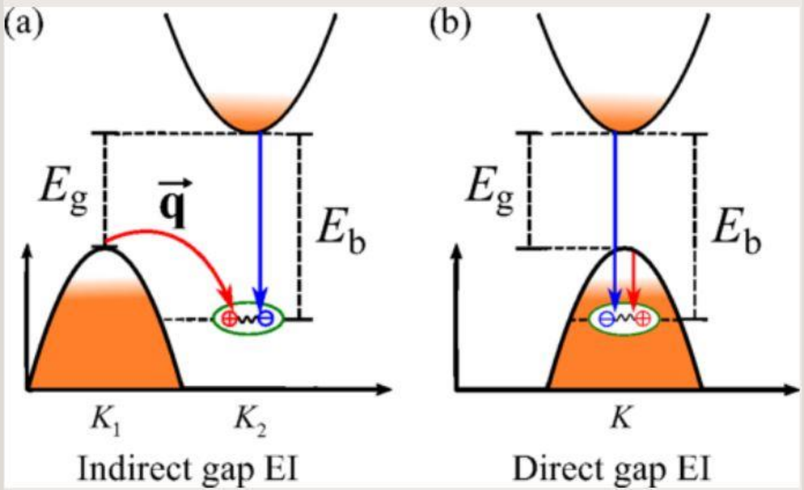
Thank you :)

Notes

- M-EELS article: https://scipost.org/SciPostPhys.3.4.026/pdf

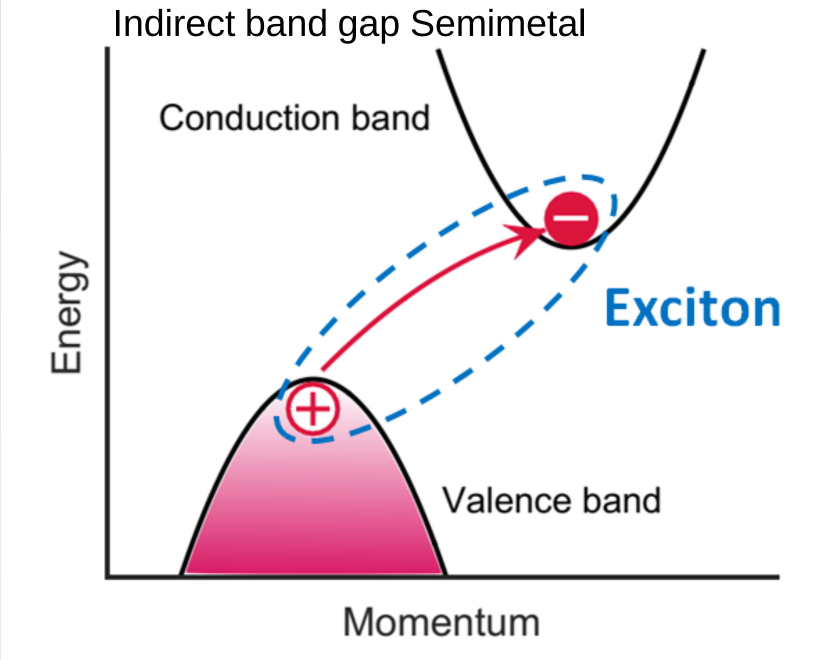
Direct v.s. Indirect bandgap Semi metal?

	Direct	Indirect
Lattice Distortion	negligible	significant
Energy condition	Eg and Eb coupled	Eg and Eb independent



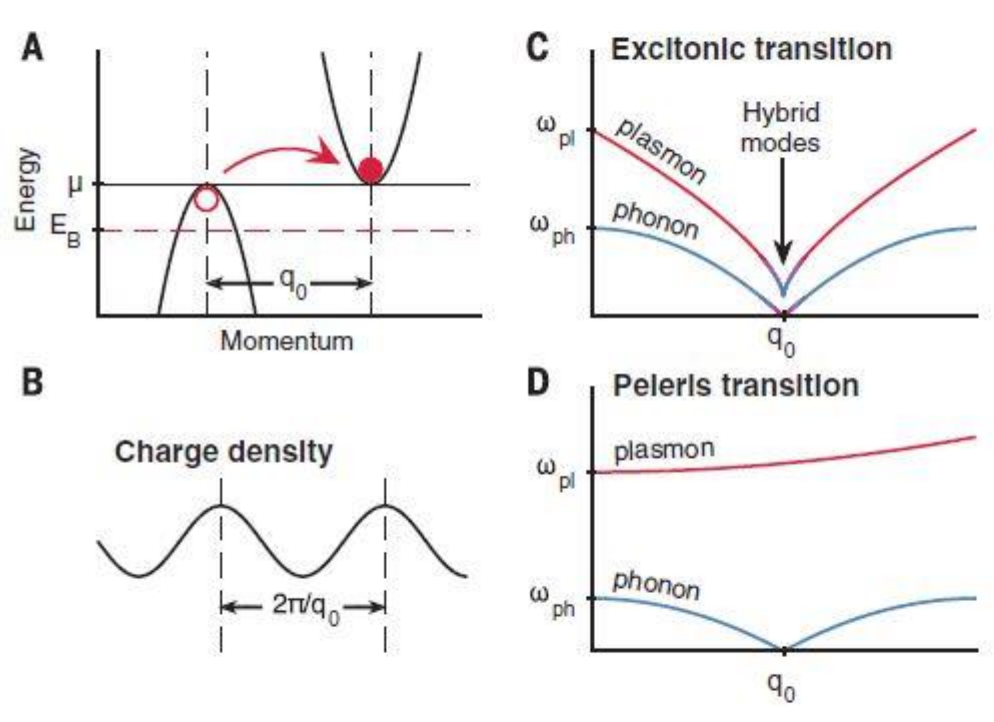
Jiang, Z., Li, Y., Zhang, S., & Duan, W. (2018). Realizing an intrinsic excitonic insulator by decoupling exciton binding energy from the minimum band gap. *Physical Review B, 98*(8)

Spontaneous formation of exciton in a gapped system

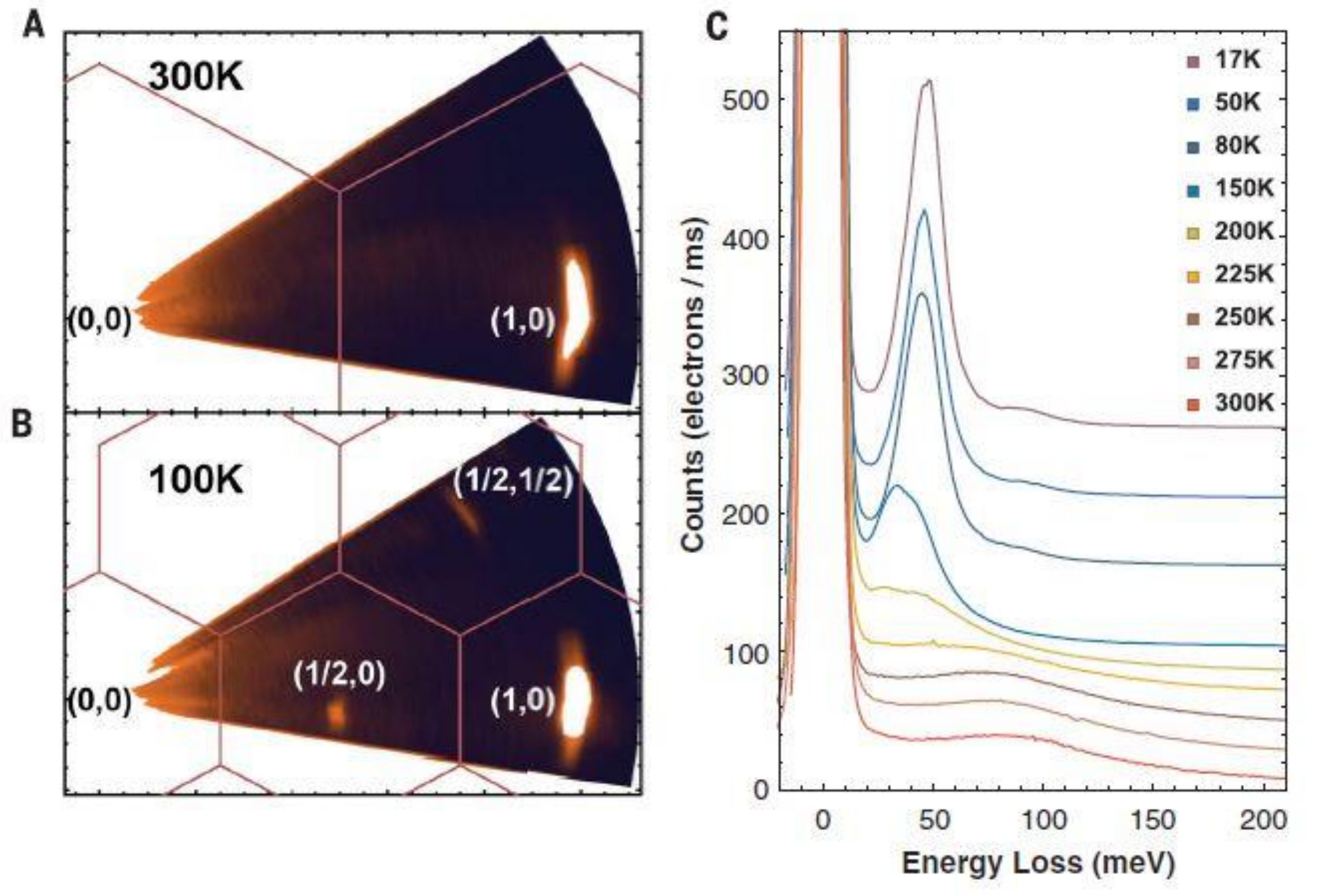


- Necessary energy condition:
  Gap energy < Binding energy
  → Formation of charge density wave
- Plasmons=Oscillation of electron density with respect to the fixed positive ion
- Problem: Any other factors resulting in CDW?
- Distortion of the lattice itself! (Phonons)

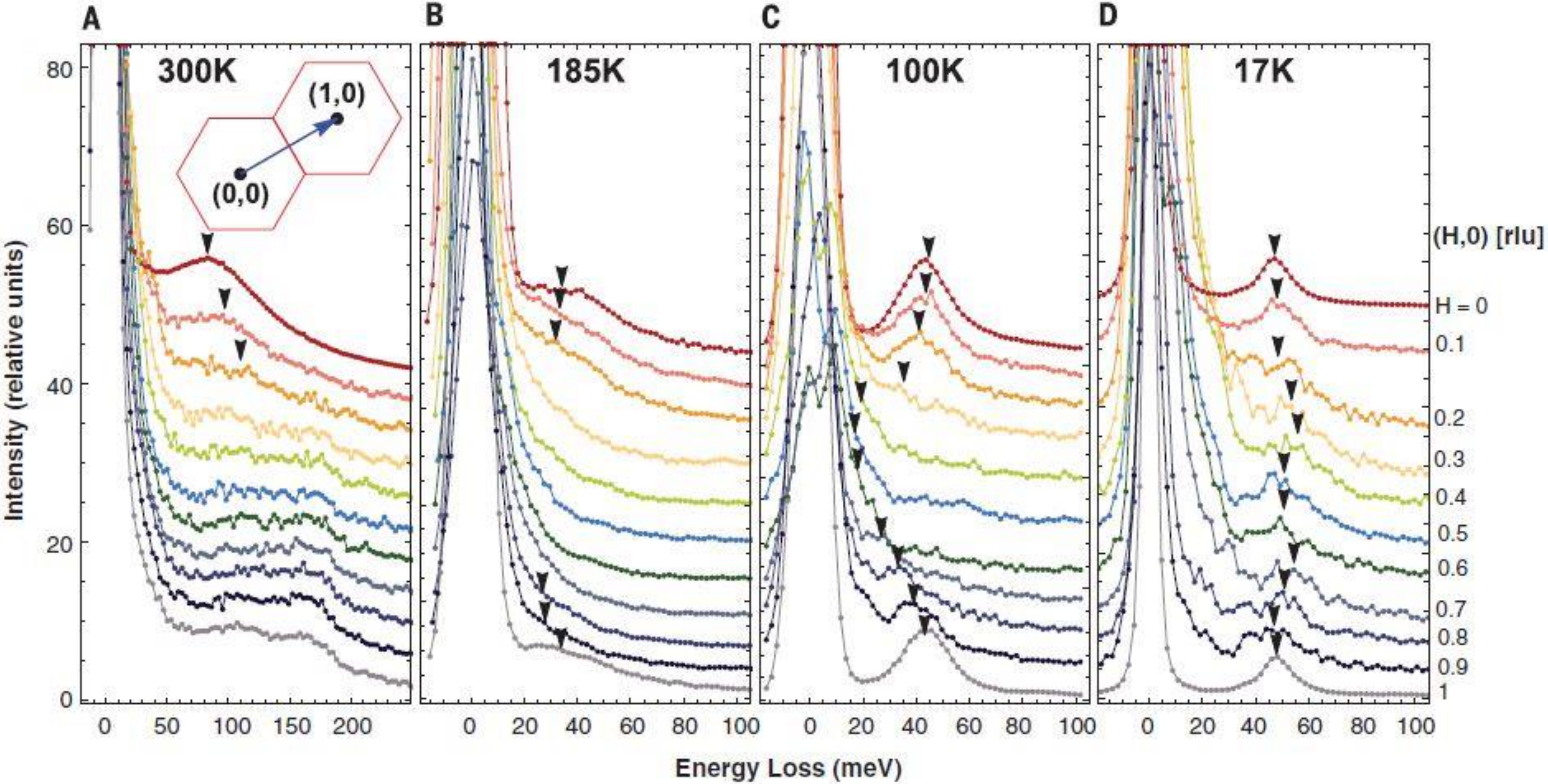
N. F. Mott, Phil. Mag. **6**, 287 (1961); L. V. Keldysh, Sov. Phys. Solid State **6**, 2219 (1965);
B. I. Halperin, Rev. Mod. Phys. **40**, 755 (1968); W. Kohn, Rev. Mod. Phys. **42**, 1 (1970)



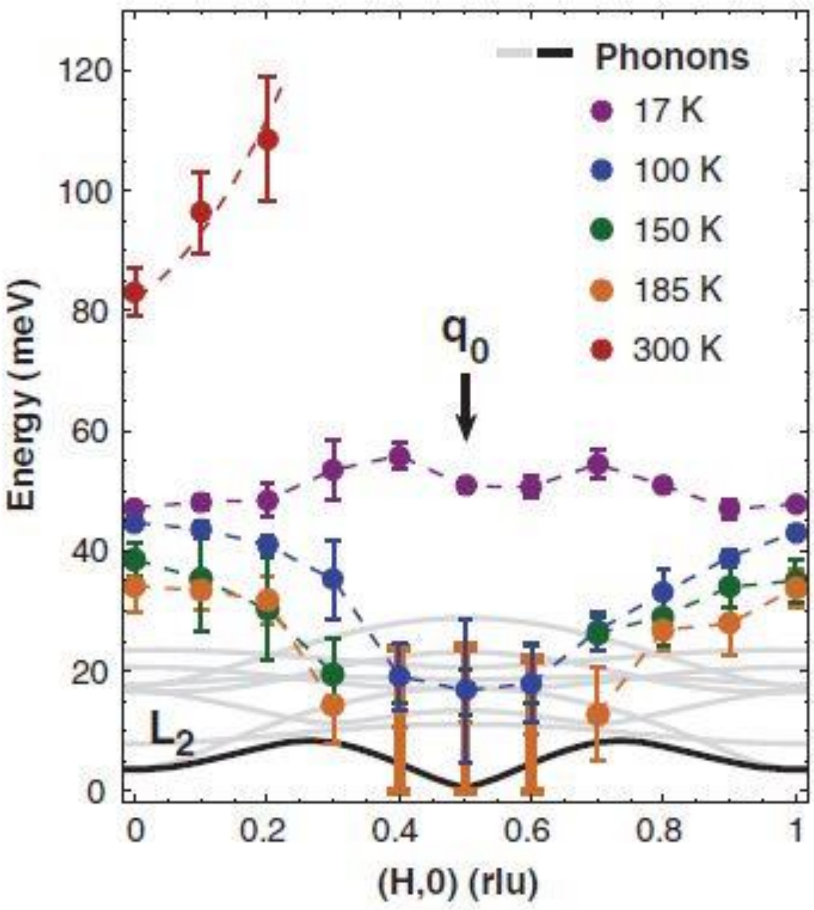
A
Energy
μ
E_B
q_0
Momentum
B
Charge density
$2\pi/q_0$
C
Excitonic transition
ω_{pl}
plasmon
Hybrid
modes
ω_{ph}
phonon
q_0
D
Peierls transition
ω_{pl}
plasmon
ω_{ph}
phonon
q_0



A
300K
(0,0)
(1,0)
B
100K
(1/2,1/2)
(1/2,0)
(0,0)
(1,0)
C
17K
50K
80K
150K
200K
225K
250K
275K
300K
Counts (electrons / ms)
500
400
300
200
100
0
0
50
100
150
200
Energy Loss (meV)



A
B
C
D
300K
185K
100K
17K
(1,0)
(0,0)
Intensity (relative units)
(H,0) [rlu]
H = 0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Energy Loss (meV)


Phonons
17 K
100 K
150 K
185 K
300 K
q0
L2
Energy (meV)
(H,0) (rlu)
0
20
40
60
80
100
120
0
0.2
0.4
0.6
0.8
1