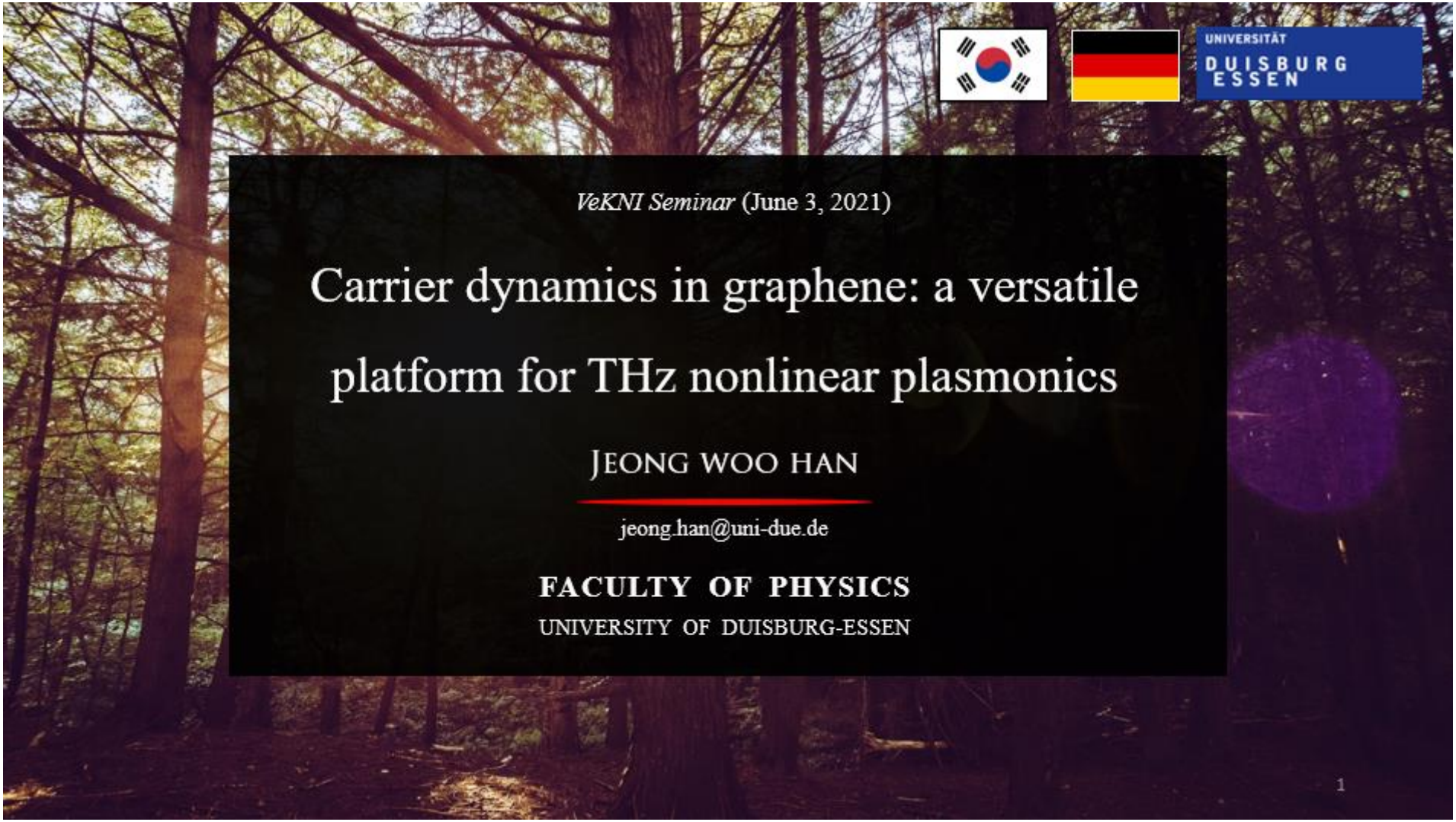
UNIVERSITÄT
DUISBURG
ESSEN
VeKNI Seminar (June 3, 2021)
Carrier dynamics in graphene: a versatile platform for THz nonlinear plasmonics
JEONG WOO HAN
jeong.han@uni-due.de
FACULTY OF PHYSICS
UNIVERSITY OF DUISBURG-ESSEN
1

# OUT LINE

1. Importance of graphene system in condensed matter physics
2. Optical spectroscopy in terahertz frequency range: which physics can we explore?
3. Motivation: plasmonic nonlinearity? how can we observe plasmonic nonlinearity in real material platform
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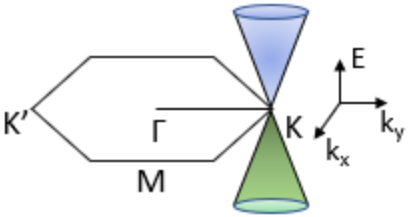
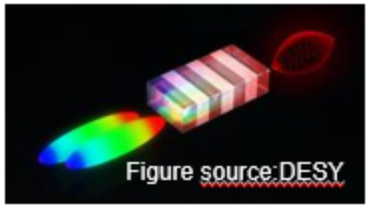
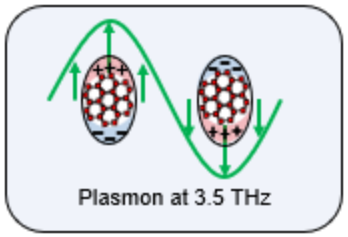
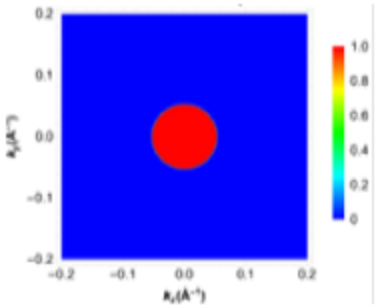
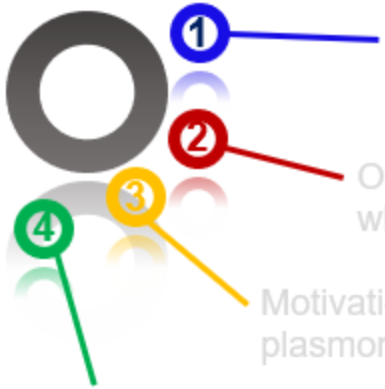


# OUT LINE

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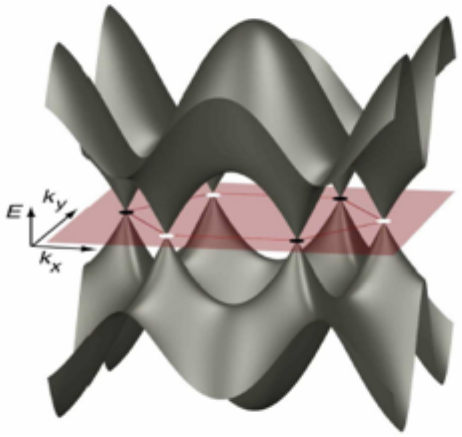
# Graphene – a sheet of carbon atoms

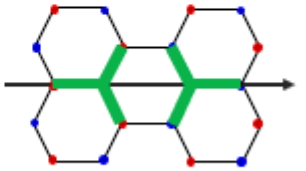
## Electronic structure of graphene



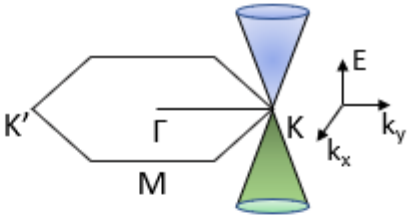

$$H = -t\sum_{i,\delta}\left[A_\sigma^+(j)B_\sigma(j+\delta) + B_\sigma^+(j+\delta)A_\sigma(j)\right]$$

## Pseudospin and energy of graphene (Chirality)

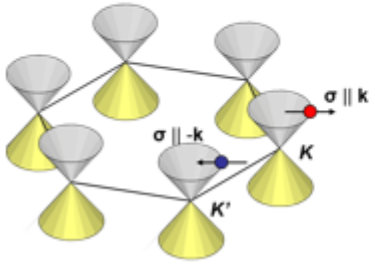
$$|k\rangle = \frac{1}{\sqrt{2}}e^{ik\cdot r}\begin{pmatrix} -ibe^{i\theta_k/2} \\ e^{i\theta_k/s}\end{pmatrix}$$



$$\varepsilon = \hbar v_F|k|$$




## Momentum-spin locking

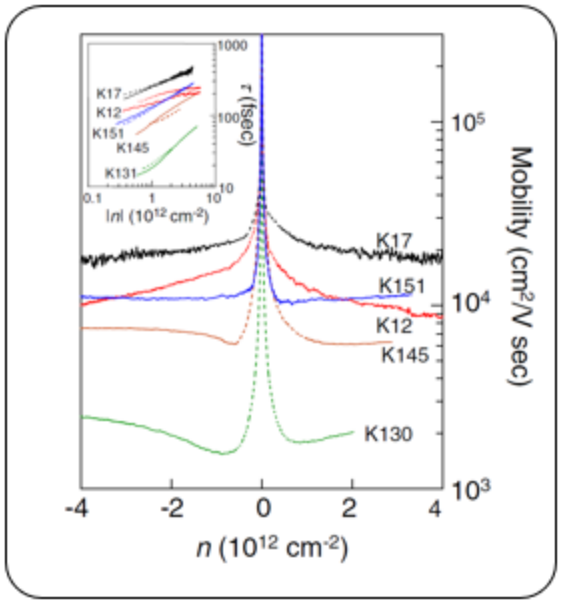



Because of the pseudospin and energy dispersion nature

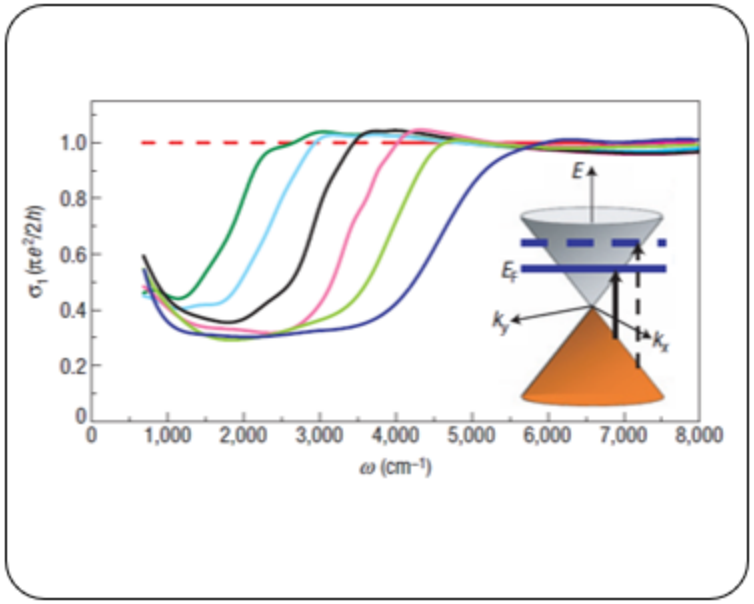
→ Producing relativistic quasi-particle in solid material!!

→ Back-scattering is forbidden

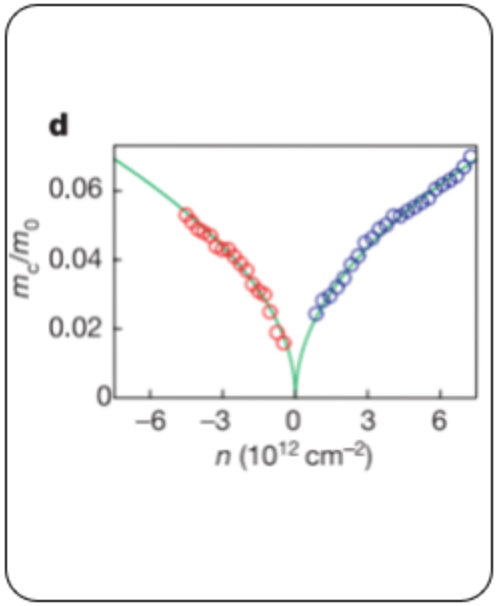
# Experimental studies: ultrafast mobility




Y. W. Tan *et al.*, Phys. Rev. Lett. **99**, 246803 (2007)

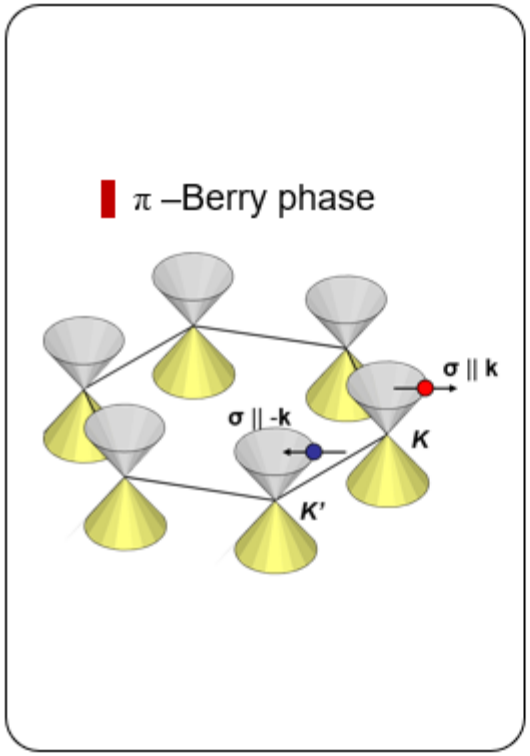


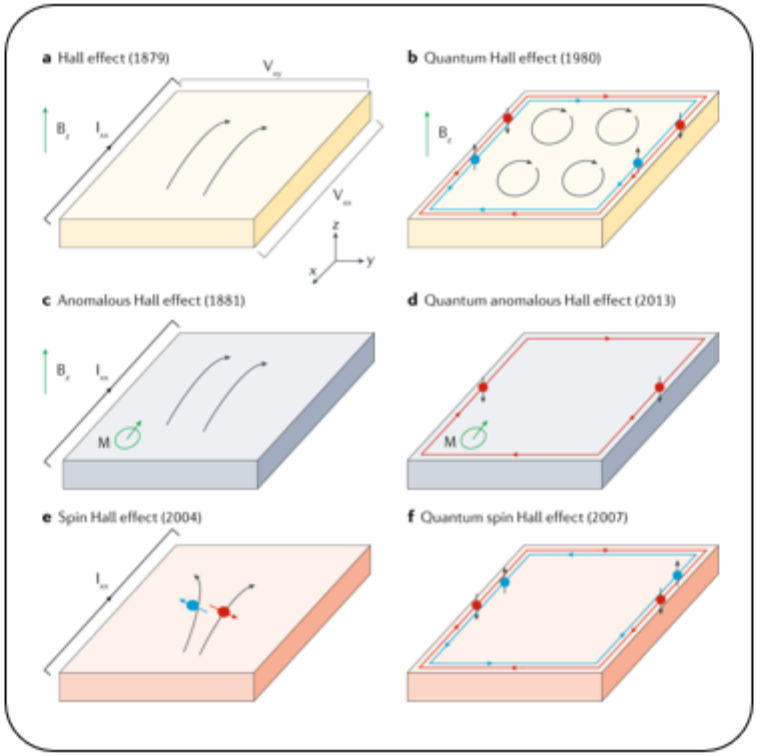

Z. Q. Li *et al.*, Nat. Phys. **4**, 532 (2008)



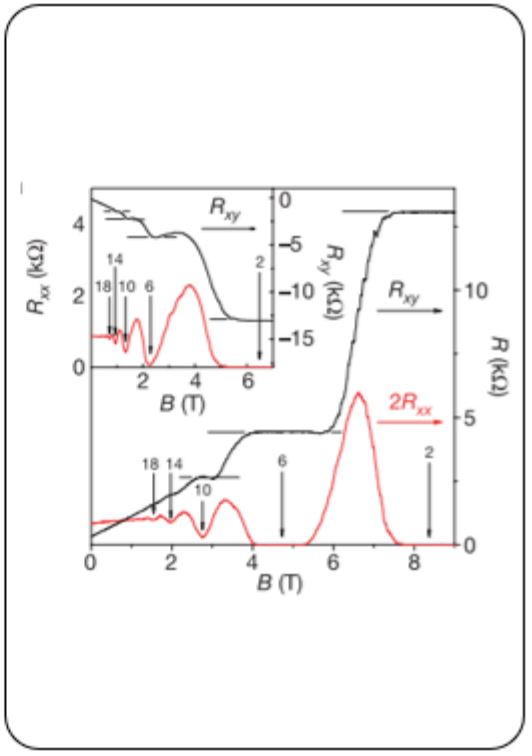

K. S. Novoselov *et al.*, Nature **438**, 197 (2005)

# Experimental studies: pseudospin




K. V. Klitzig *et al.*, Nat. Rev. Phys. **2**, 397 (2020)




Y. Zhang *et al.*, Nature. **483**, 201 (2005)

# Summary of chapter 1

Because of the extraordinary properties (massless particle, pseudospin, and charity), graphene has attracted much attentions as a versatile material platform, enabling to explore the physical properties predicted from Dirac equation.

**Flexibility**

**Ultra-high mobility**

**Ultra-high thermal conductivity**

# OUT LINE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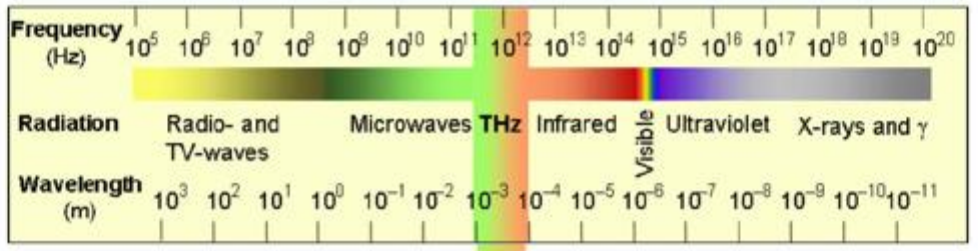
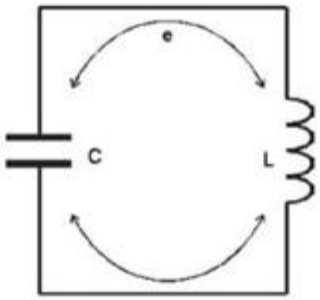
# Terahertz (THz) frequency range





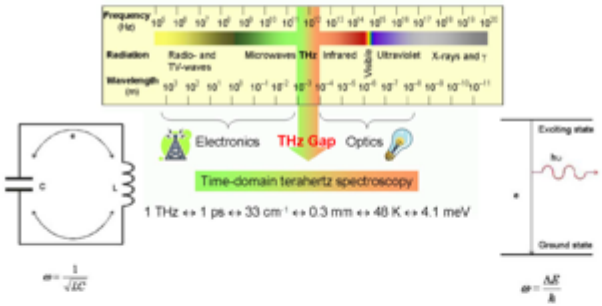
1 THz ↔ 1 ps ↔ 33 $cm^{-1}$ ↔ 0.3 mm ↔ 48 K ↔ 4.1 meV

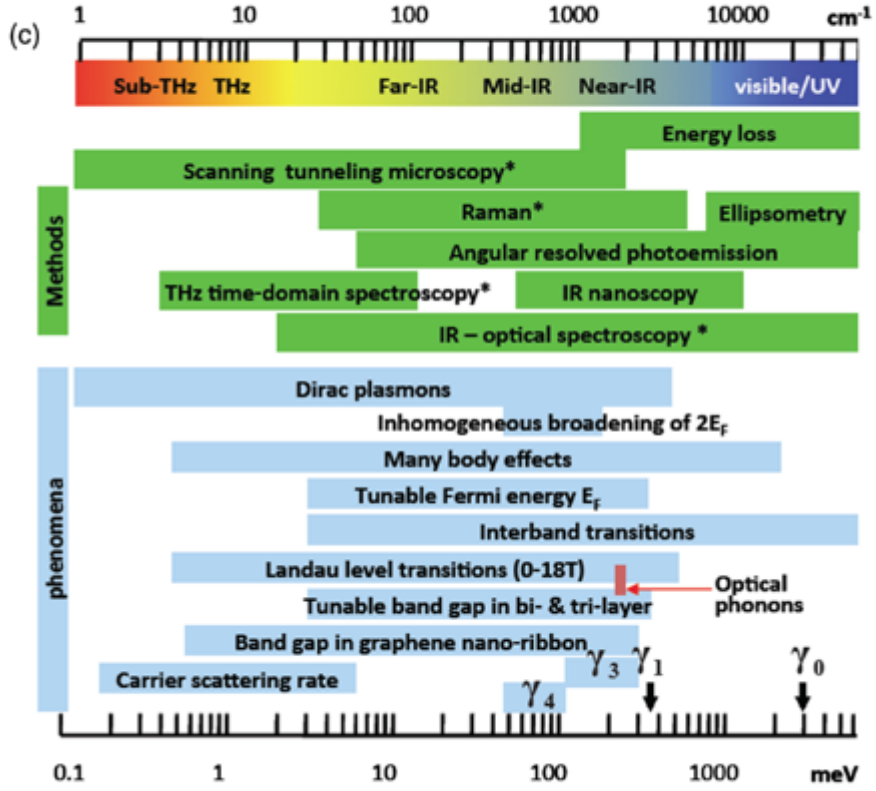



$$\omega = \frac{1}{\sqrt{LC}}$$


$$\omega = \frac{\Delta E}{\hbar}$$

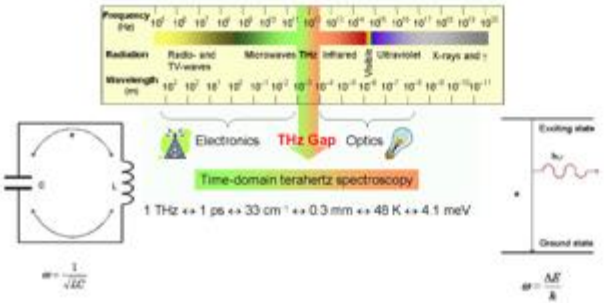
# Physical phenomena in THz range

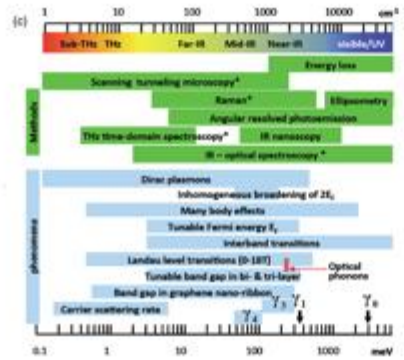



D. N. Basov *et al.*, Reviews of Modern Physics 86, 959 (2014)

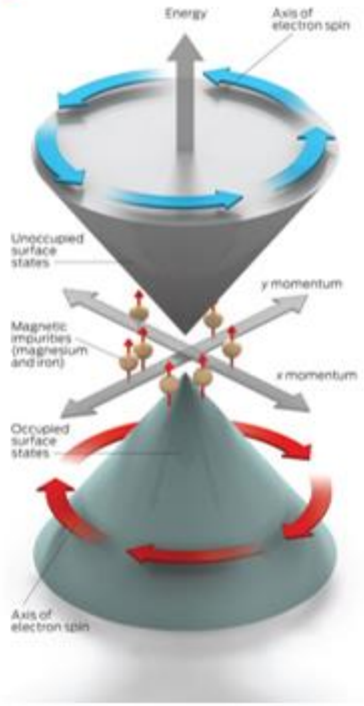
# THz range: providing unique opportunity!!



D. N. Basov *et al.*, Reviews of Modern Physics 86, 959 (2014)

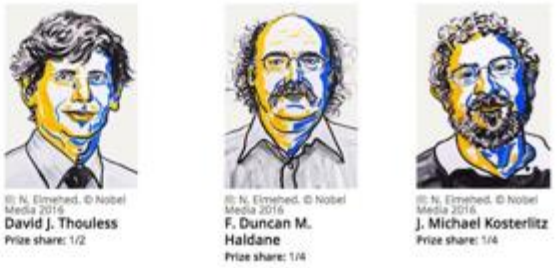
Topological insulator




Joel E. Moore, IEEE Spectrum


Graphene (Nobel prize 2010)

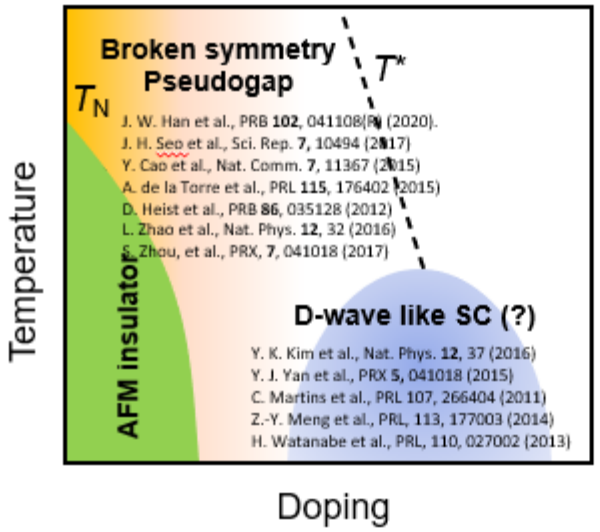
The Nobel Prize in Physics 2016



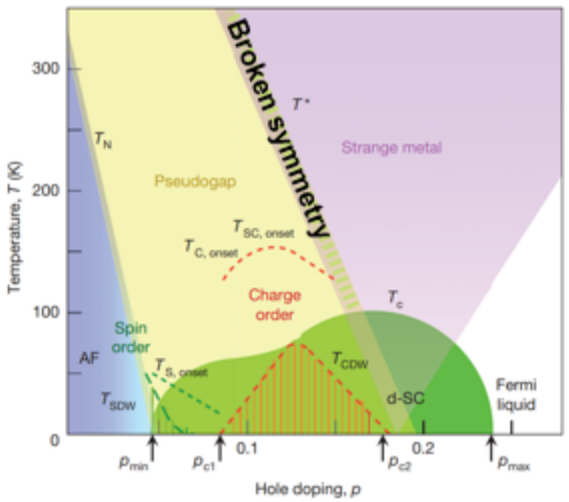

Topological insulator (Nobel prize 2016)

# Another proper tool for verifying the origin of High-temperature superconductivity

## Iridate




## Cuprate




B. Keimer *et al.*, Nature **518**, 179 (2015)

## Contributions

### Papers related to THz science

J. W. Han *et al.*, Opt. Lett. **39**, 5531 (2014).
J. W. Han *et al.*, Appl. Opt. **56**, 2529 (2017).
J. W. Han *et al.*, Sci. Rep. **8**, 8613 (2018).
J. W. Han *et al.*, J. Opt. Soc. B **36**, 1551 (2019)
J. W. Han *et al.*, Phys. Rev. B **102**, 041108(R) (2020).
S. Izadi*, J. W. Han* *et al.*, Small accepted (2021).
J. W. Han *et al.*, Adv. Photon. Res accepted (2021)

# Summary of chapter 2

Because of the low-energy nature of THz light, one can explore the novel physical phenomena using terahertz spectroscopy from weakly correlated system (graphene, topological insulator...) to strongly correlated system (Iridate, cuprate....).

**Low-energy**

**Strong coupling**


**Transparent**

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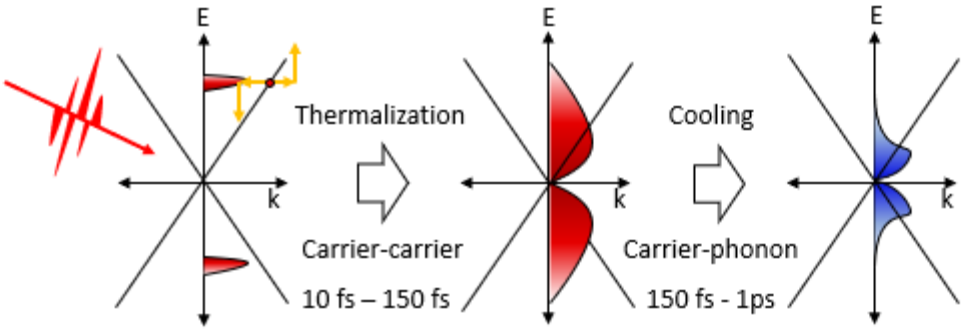
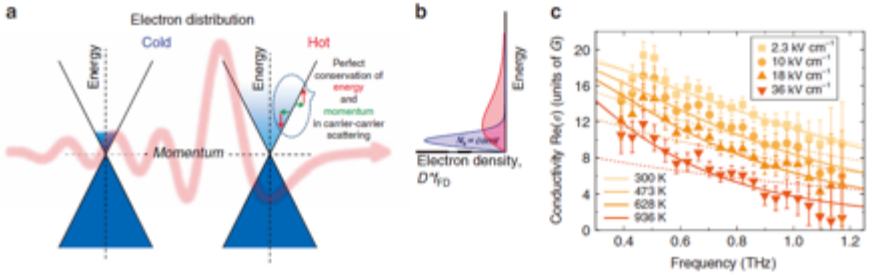
# Graphene: versatile platform for thermal nonlinearity

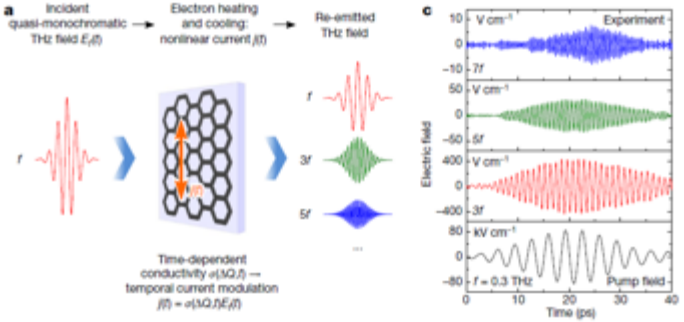
Fast/Strong thermalization




Momentum can be conserved easily → Emission efficiency of phonon ↑ → Fast/Strong thermalization

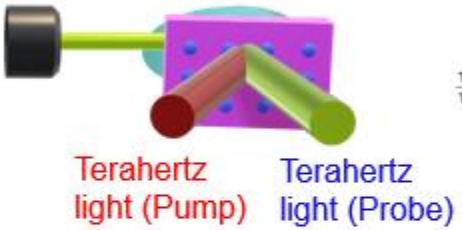


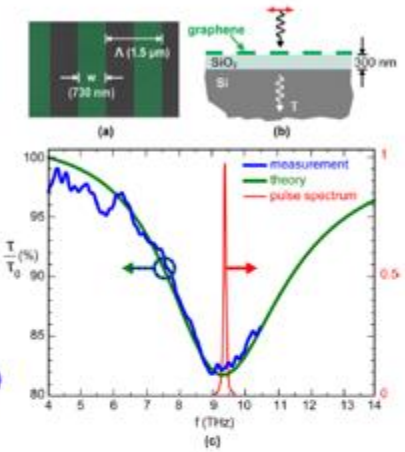

Z. Mics *et al.*, Nat. Commun. **6**, 7655 (2015)

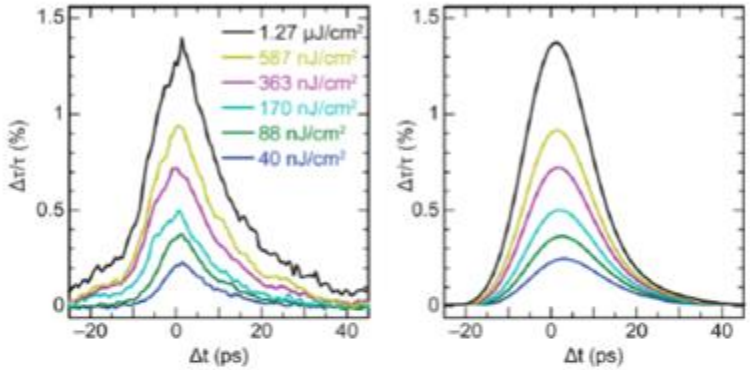



H. Hafez *et al.*, Nature **561**, 507 (2018)

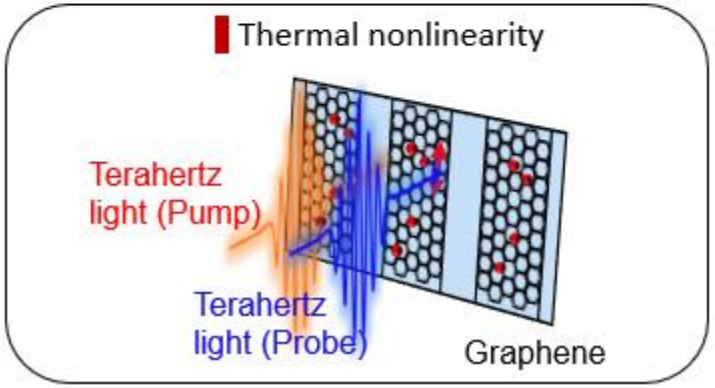
# Graphene: thermal nonlinearity

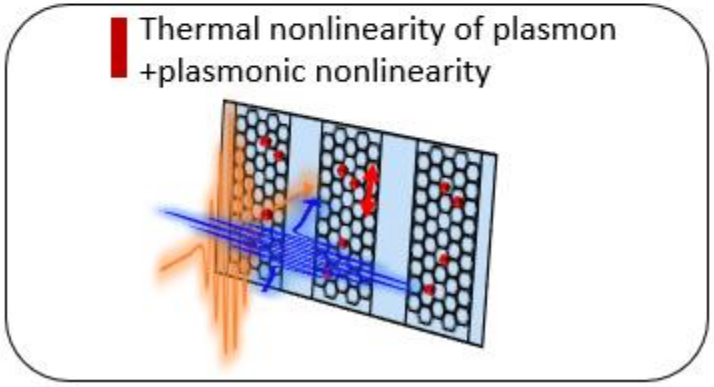


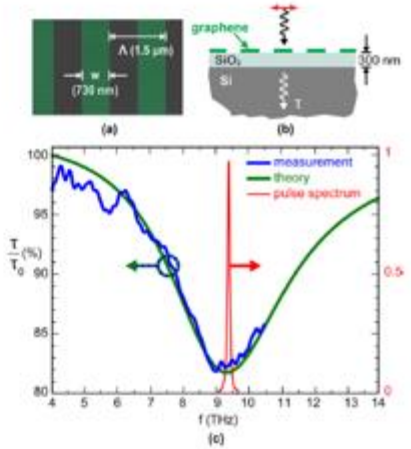



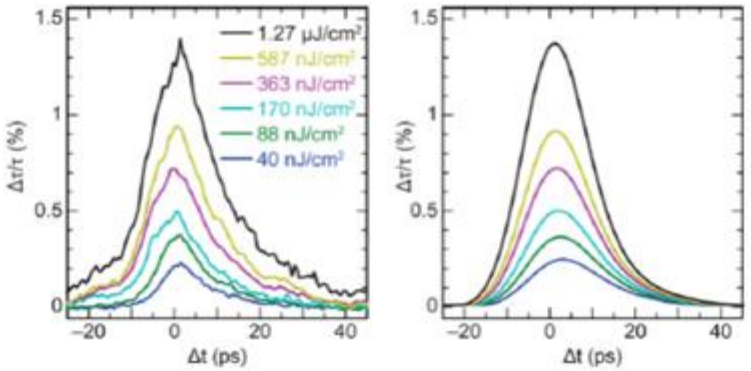

M. M. Jadidi *et al.*, ACS nano **16**, 2734 (2018)



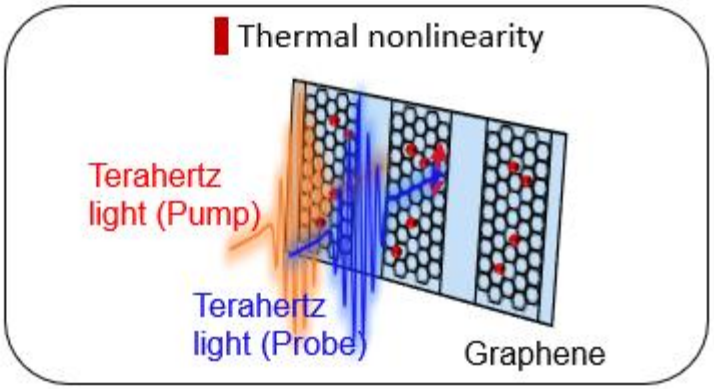



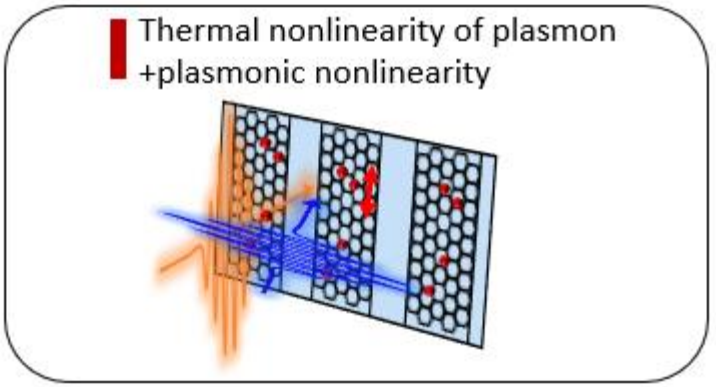
# Graphene: thermal nonlinearity



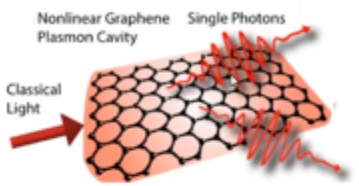




M. M. Jadidi *et al.*, ACS nano **16**, 2734 (2018)

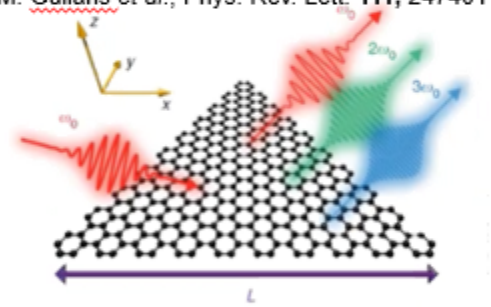


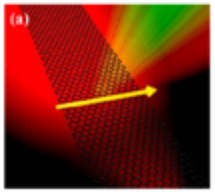
# Graphene: plasmonic nonlinearity (1)



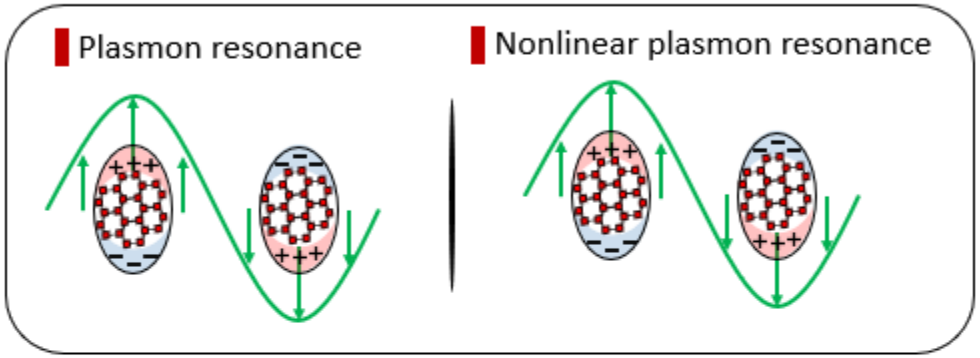

M. Gullans *et al.*, Phys. Rev. Lett. **111,** 247401 (2013).

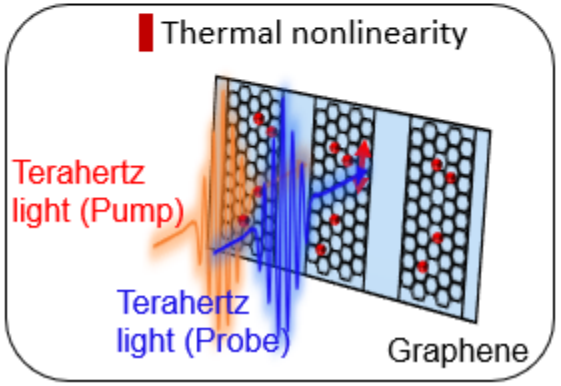


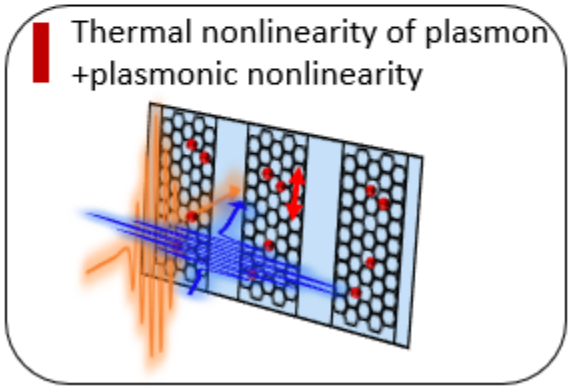
J. D. Cox *et al.*, Nat. Comm. **5,** 5725 (2014).



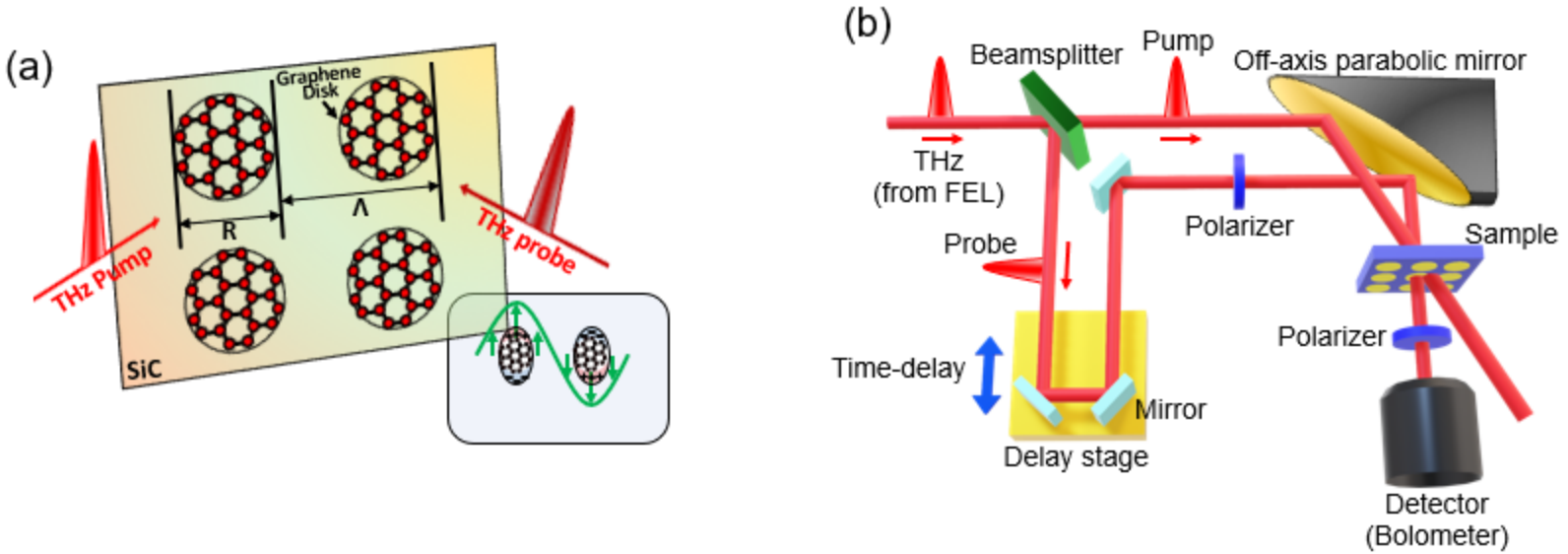
J. D. Cox *et al.*, ACS Nano **10,** 1995 (2016).



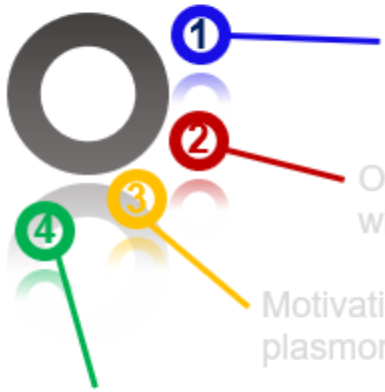
# Graphene: plasmonic nonlinearity (2)




Using graphene disks, we expect that strong plasmonic nonlinearity can be observed.

→ Which will be the first experimental evidence for observing the plasmonic nonlinearity

# OUT LINE

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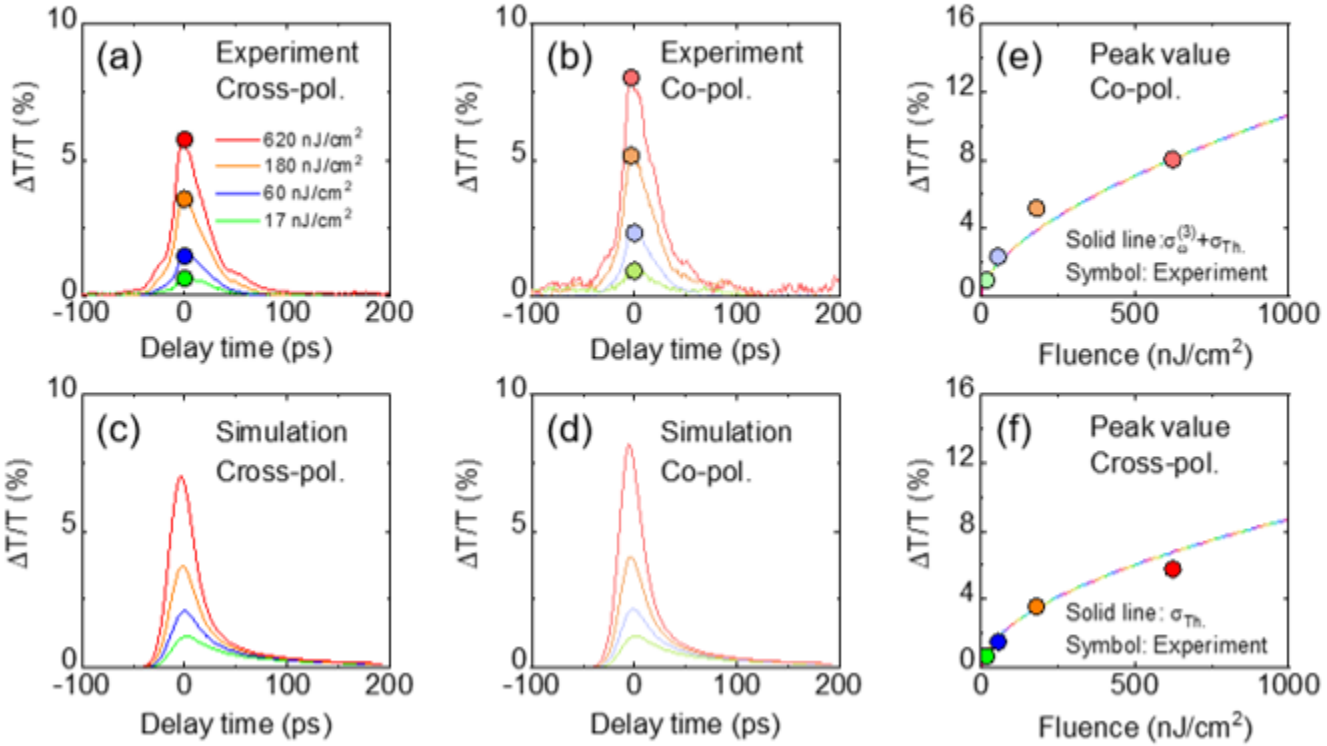
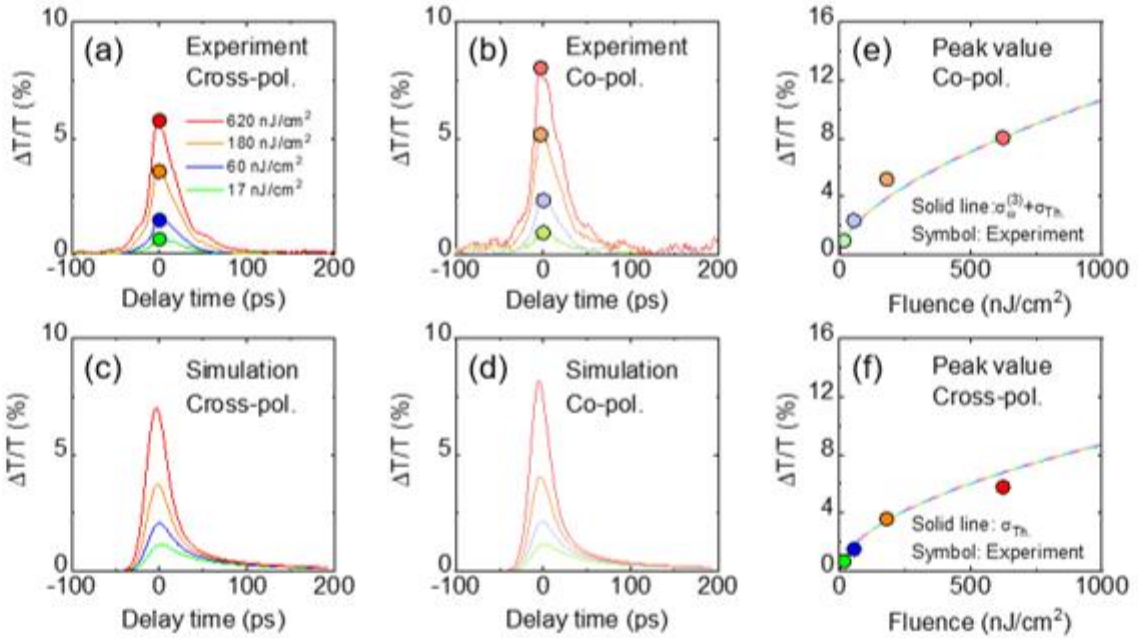
# Experimental result on graphene disk



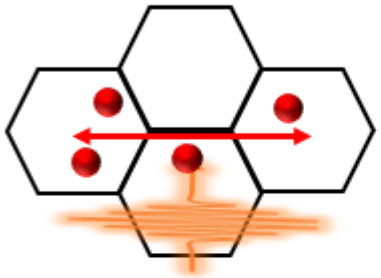
# Experimental result on graphene disk

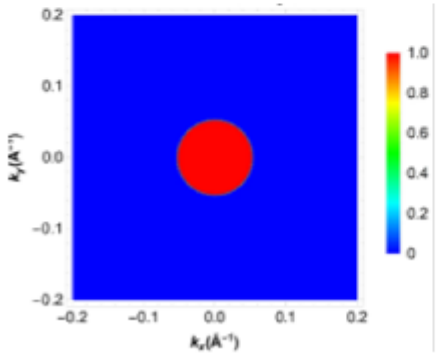


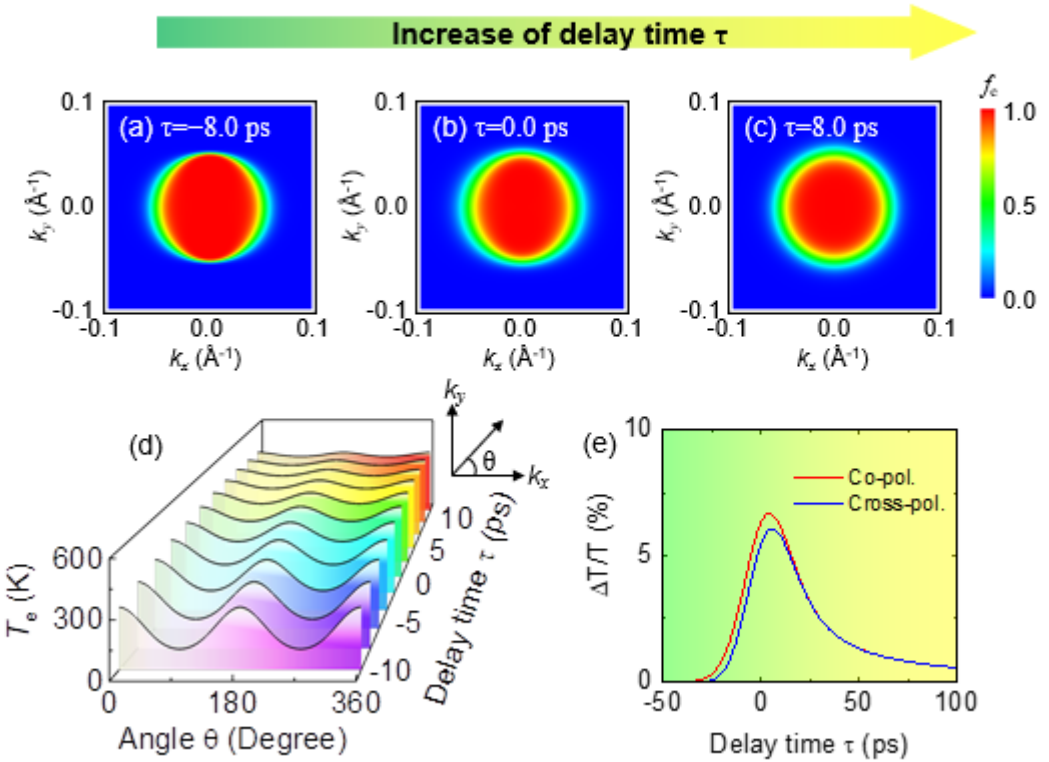

Our simulation result (nonlinear thermal + nonlinear plasmonic nonlinearities) well reproduce the experimental result, suggesting that we observed the first experimental result regarding plasmonic nonlinearity.

# Is it cased by the thermal anisotropic?

## Thermal anisotropic







# Summary

Using graphene disks

→ Experimentally, we observed different response on FEL experiment depending on the polarization-configuration.

→ Using simulation framework, we can nail down this difference observed stemming from the plasmonic nonlinearity.

→ This is the first experimental evidence, making the cornerstone to apply plasmonic nonlinearity for real devices.