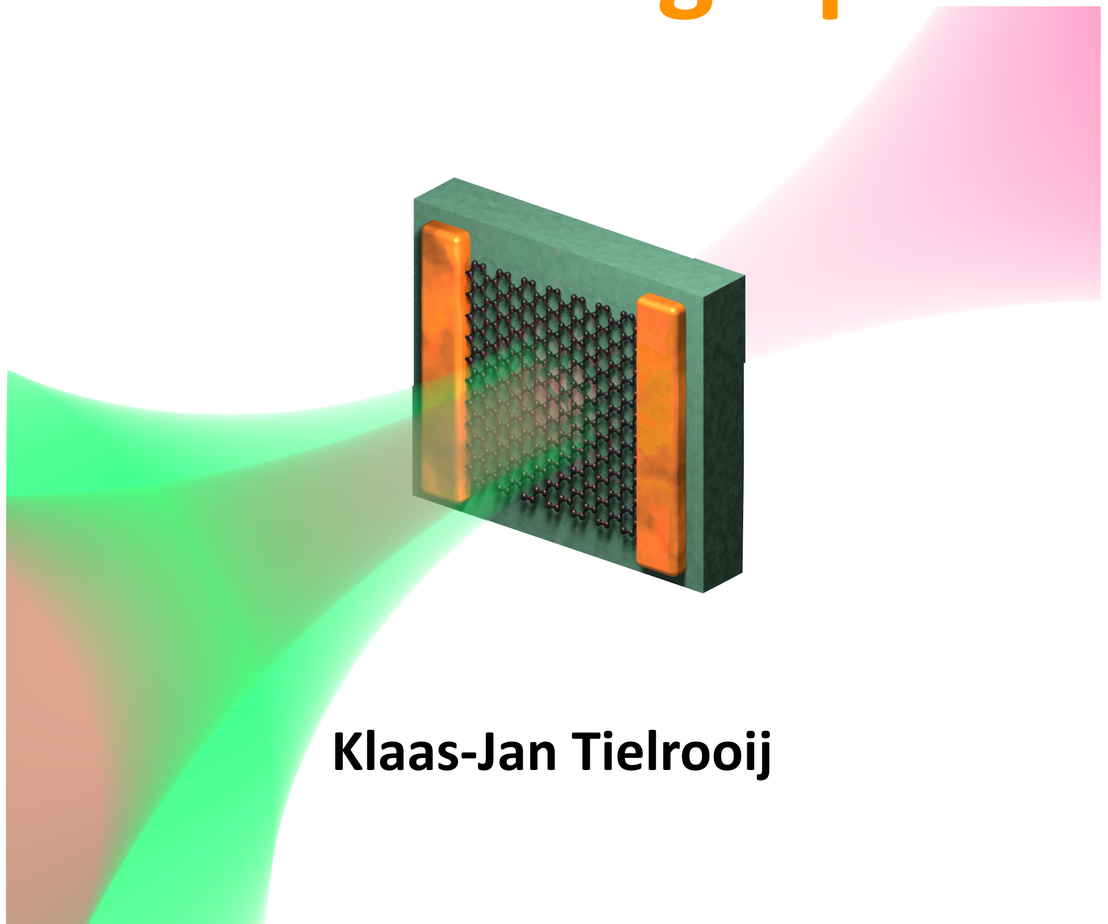
The ultrafast dynamics and conductivity of photoexcited graphene



Klaas-Jan Tielrooij

The Institute of Photonic Sciences

Dresden, 27 June 2018

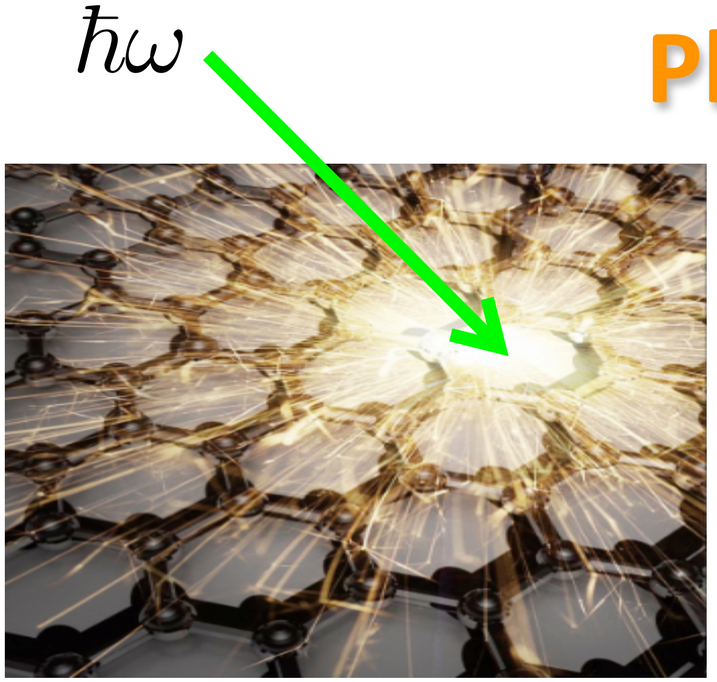
Acknowledgements

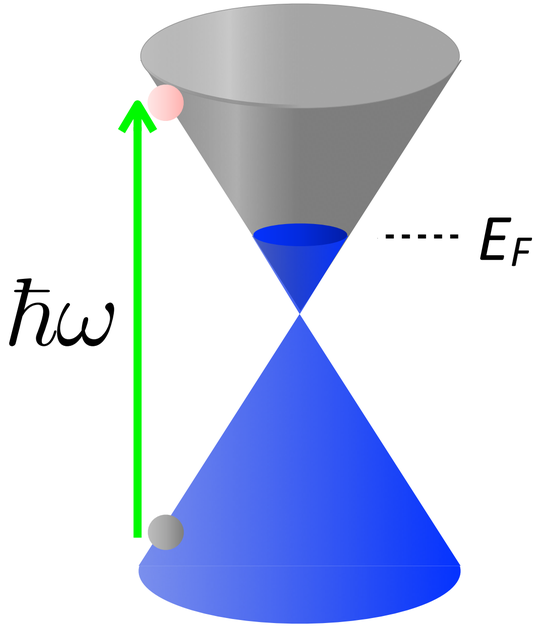
Dr. Andrea Tomadin
Prof. Marco Polini

Dr. Sam Hornett
Prof. Euan Hendry

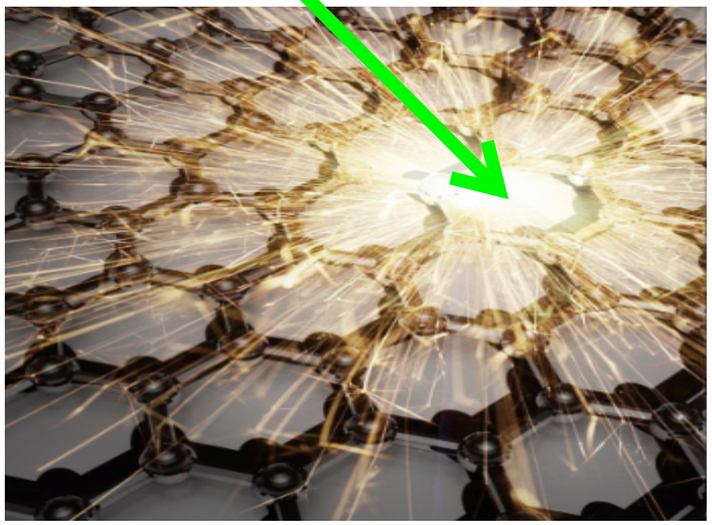
Prof. Frank Koppens

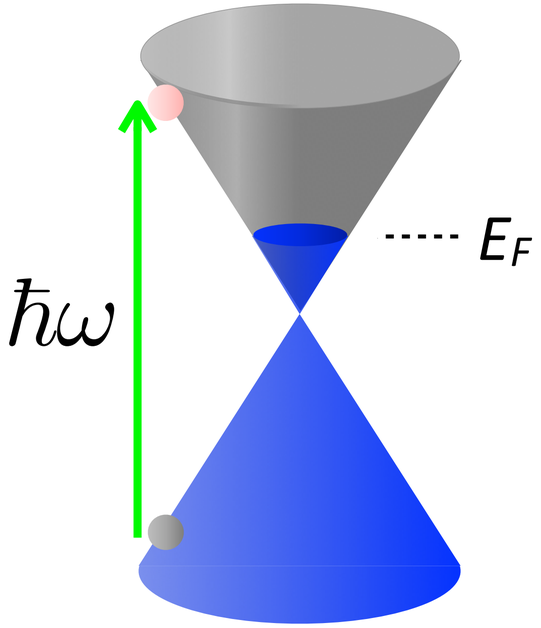
Photoexcited graphene

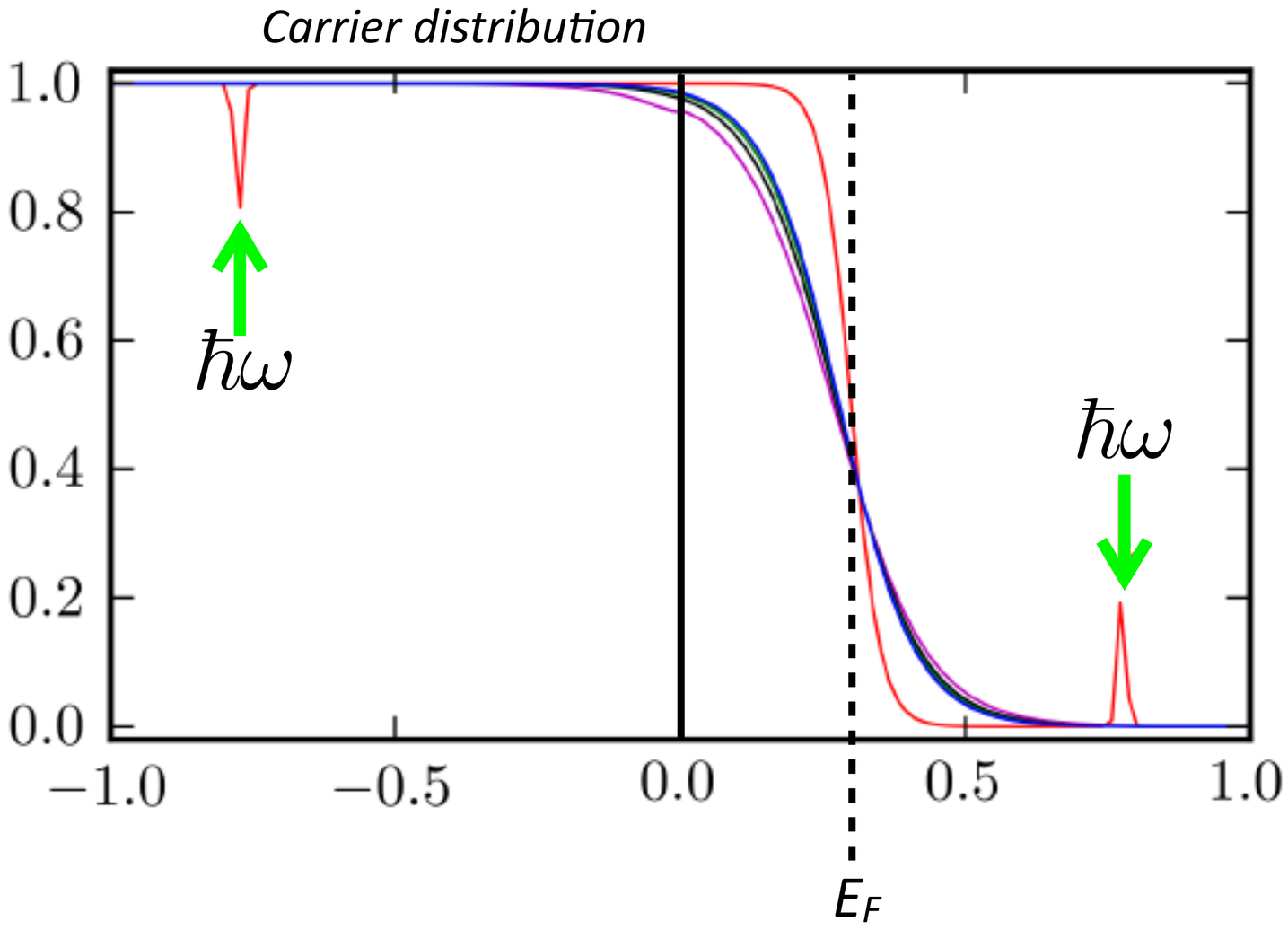




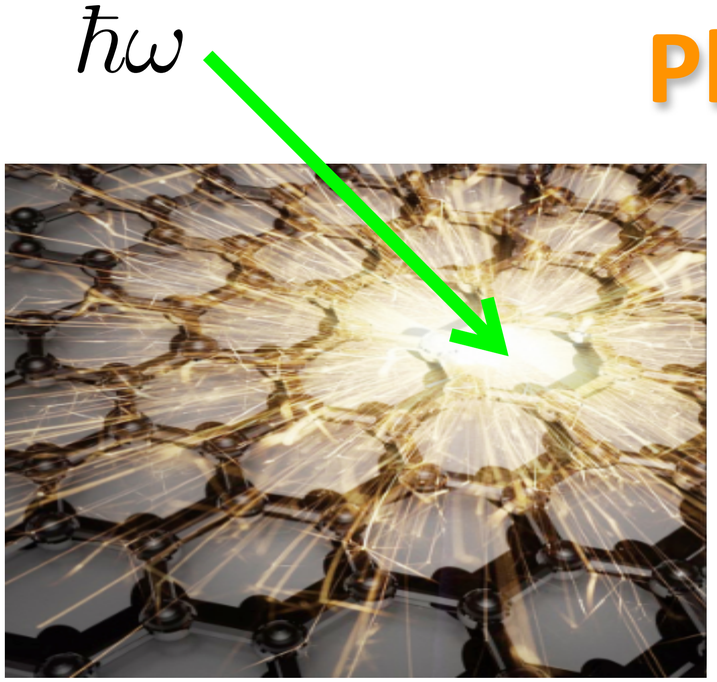
Photoexcited graphene





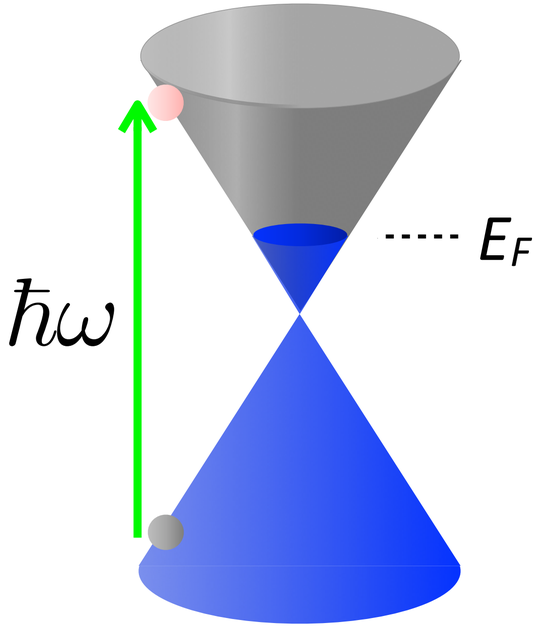


Photoexcited graphene

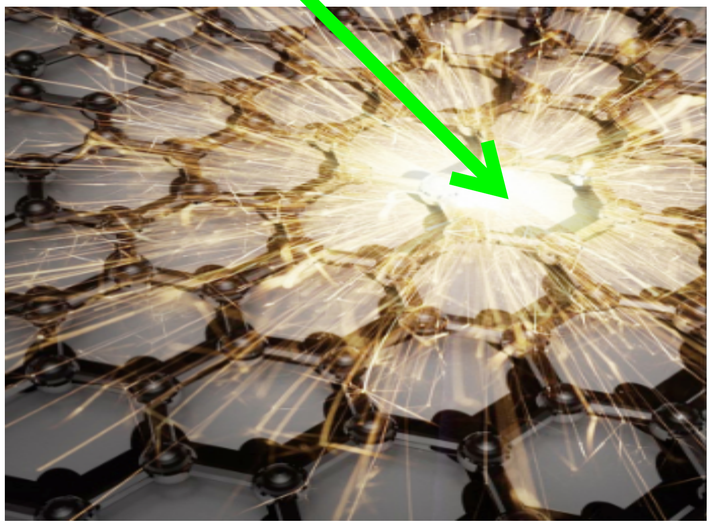


- Heat from absorbed light to electron system
- Ultra-small heat capacity

=> Large increase in electron temperature!



Photoexcited graphene



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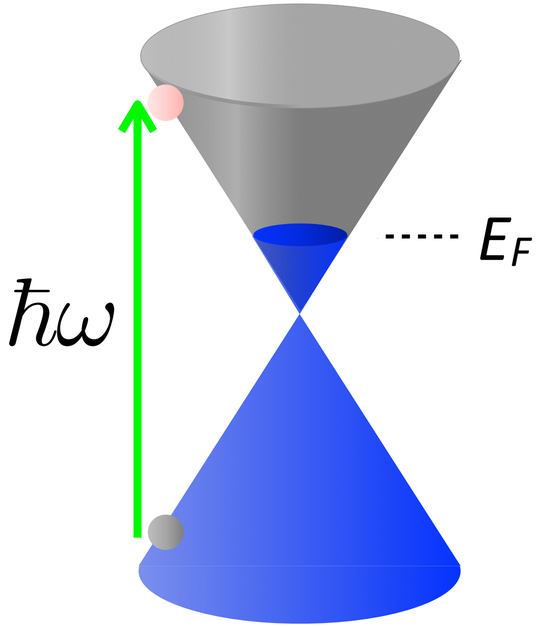
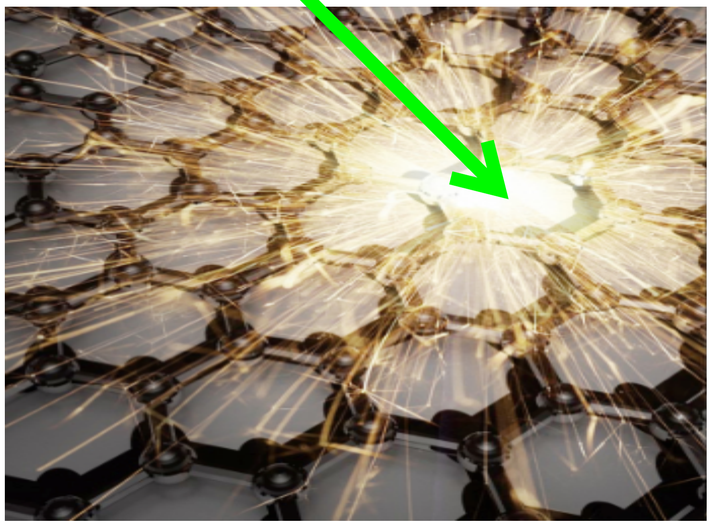


Data communication

Photodetection

Photoexcited graphene



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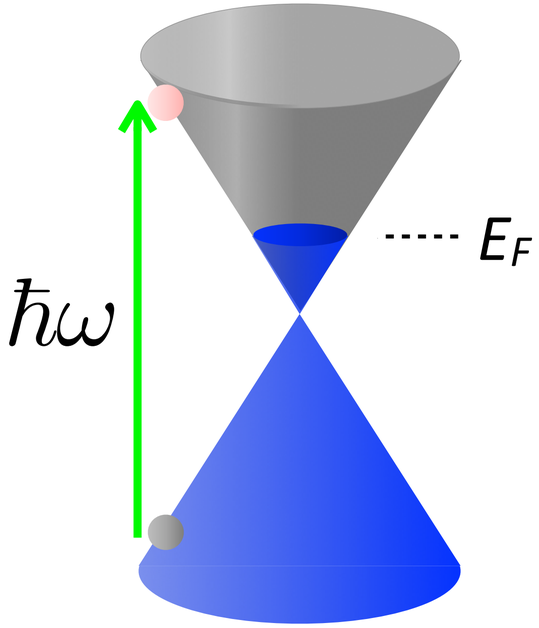

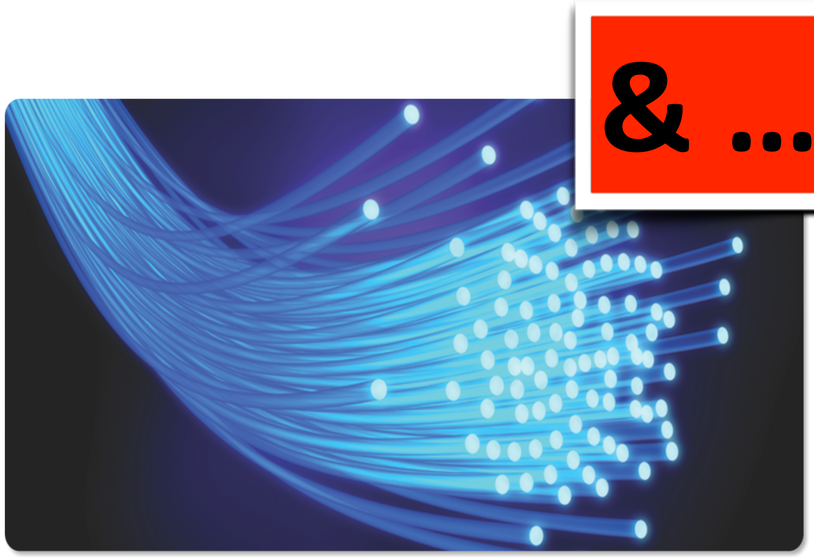

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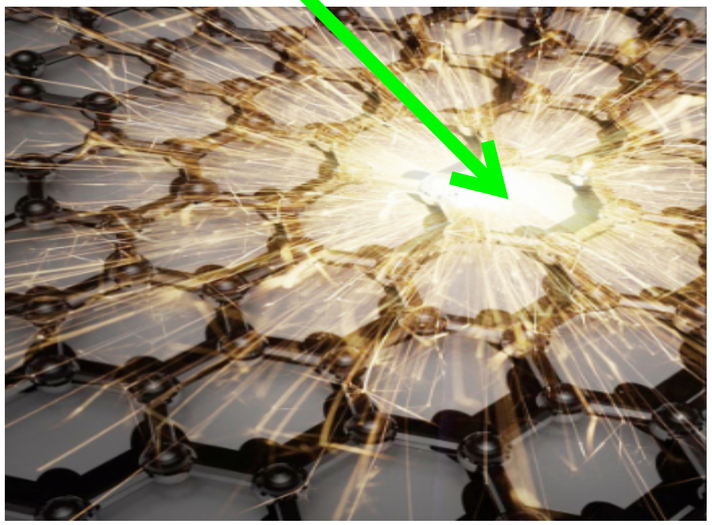
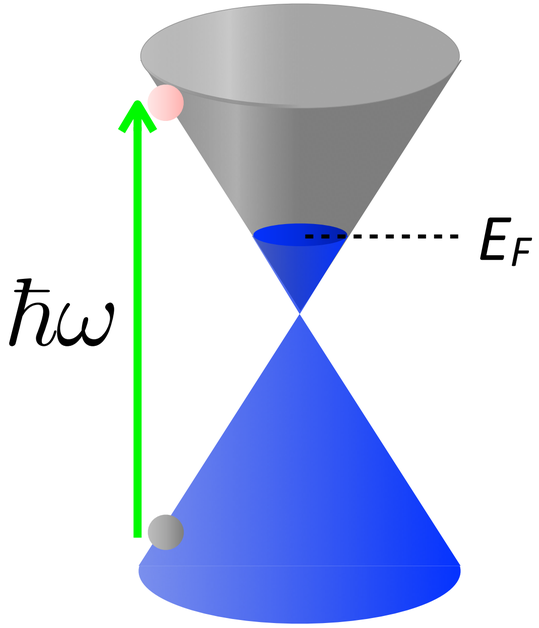
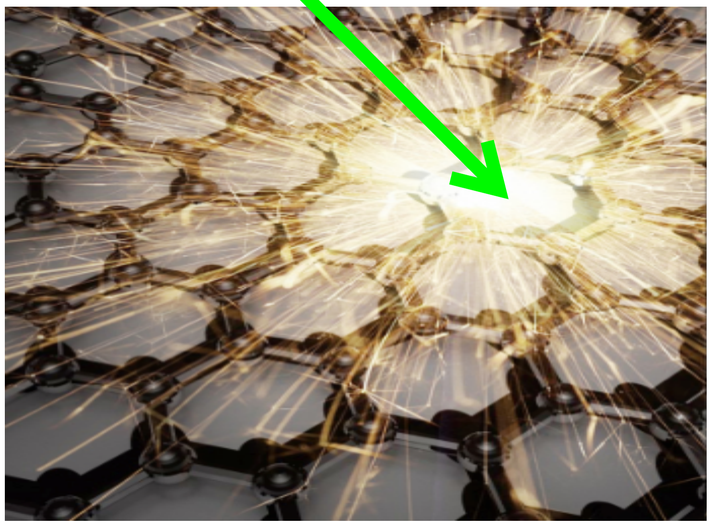
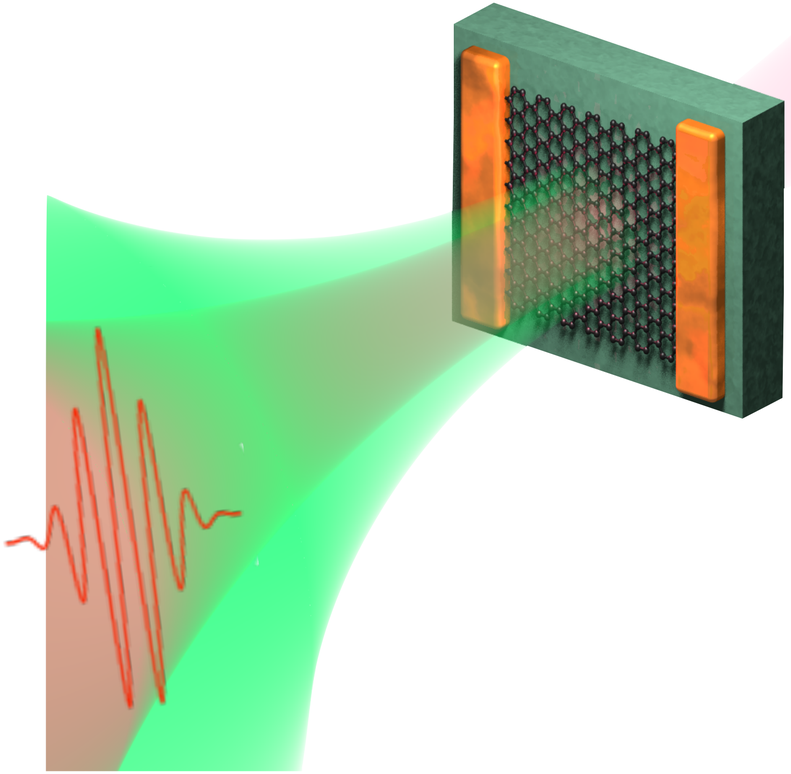


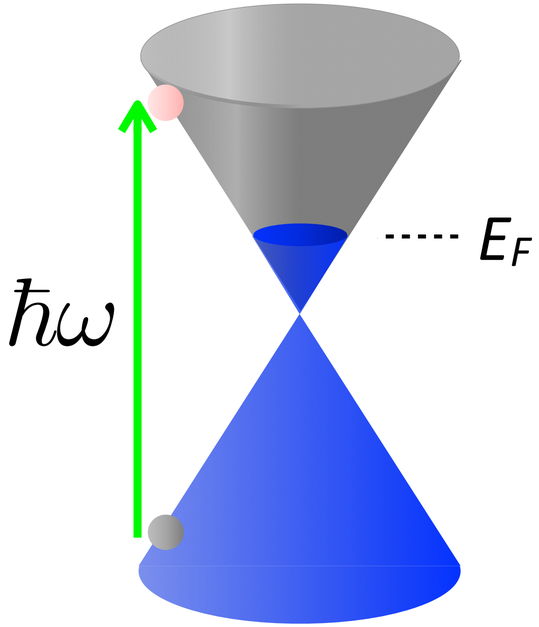


- **Heating dynamics depend on Fermi energy?**
- **Mechanism of modified “hot” conductivity?**
- **Efficiency of heating?**

Optical pump - terahertz probe







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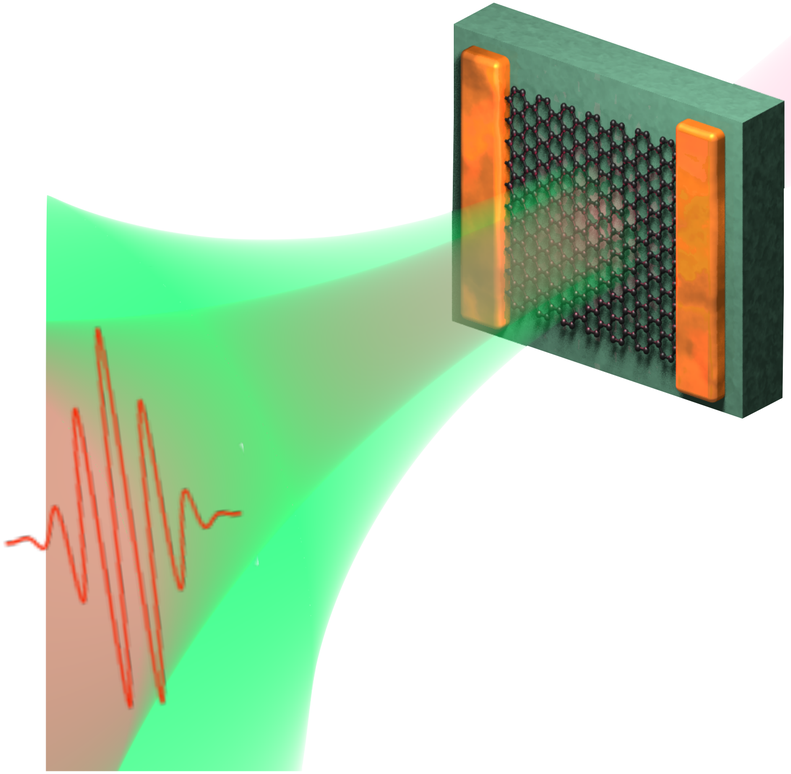
Optical pump - terahertz probe



Carrier distribution

$$\sigma_{\mathrm{THz}}(t) = -\frac{e^2 v_{\mathrm{F}}}{2} \sum_{\lambda} \int_0^{\infty} d\varepsilon \nu(\varepsilon) \frac{\tau(\varepsilon; t)}{1 - i\omega\tau(\varepsilon; t)} \frac{\partial f_{\lambda}(\varepsilon; t)}{\partial \varepsilon}$$

Scattering time

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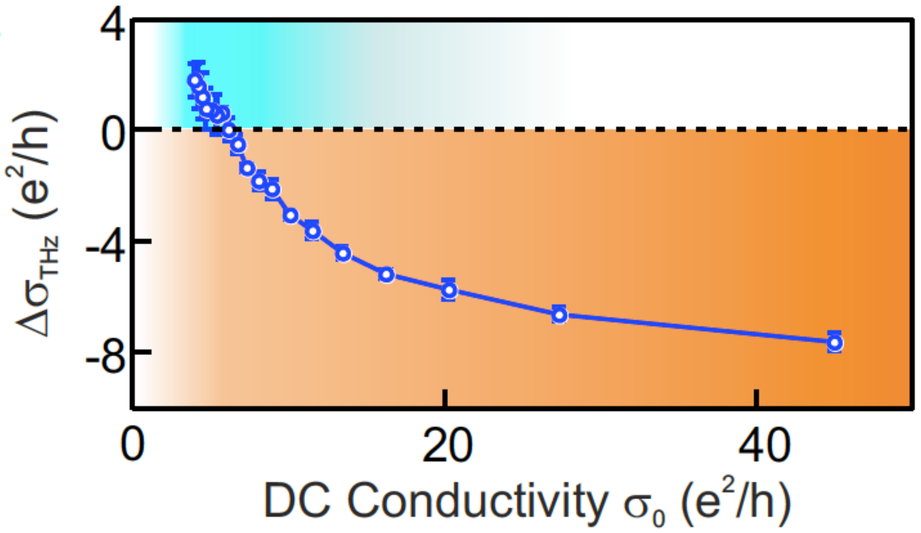
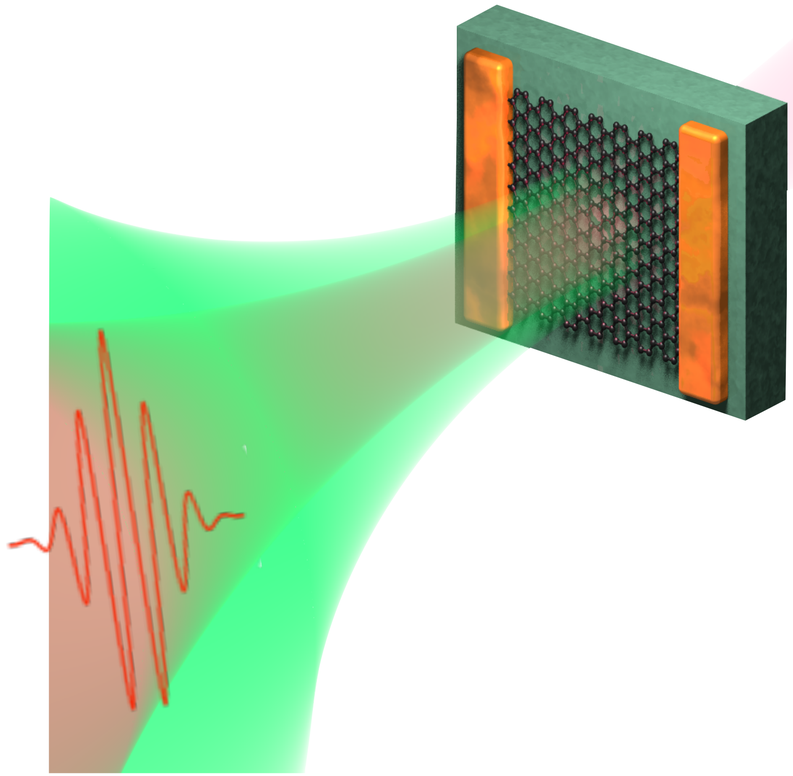
Optical pump - terahertz probe





See also:

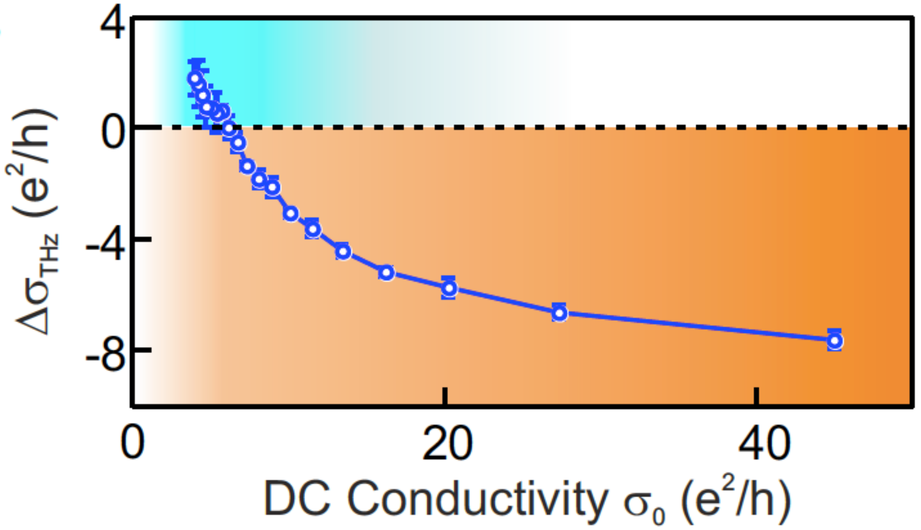
Nano Lett. **14**, 1578 (2014)

Nano Lett. **14**, 5839 (2014)

Phys. Rev. Lett. **113**, 056602 (2014)

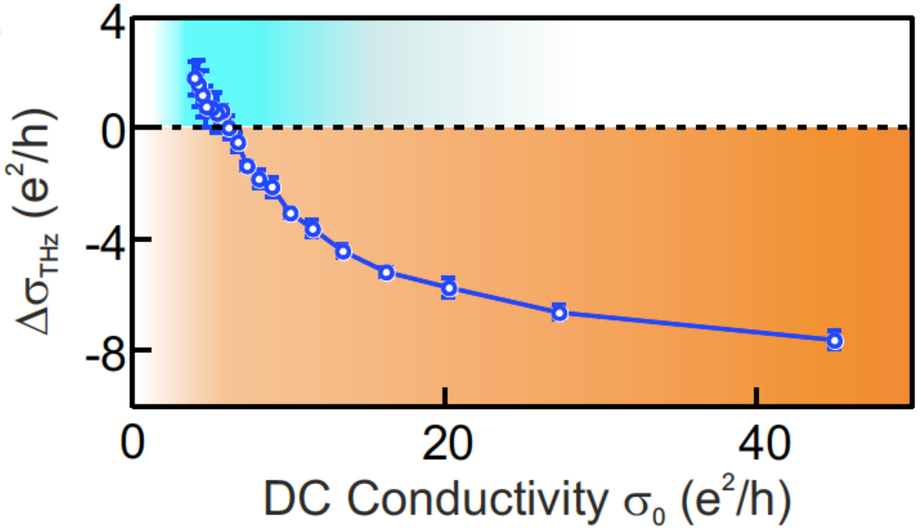
Sci. Adv. **4**, eaar5313 (2018)

Heating dynamics

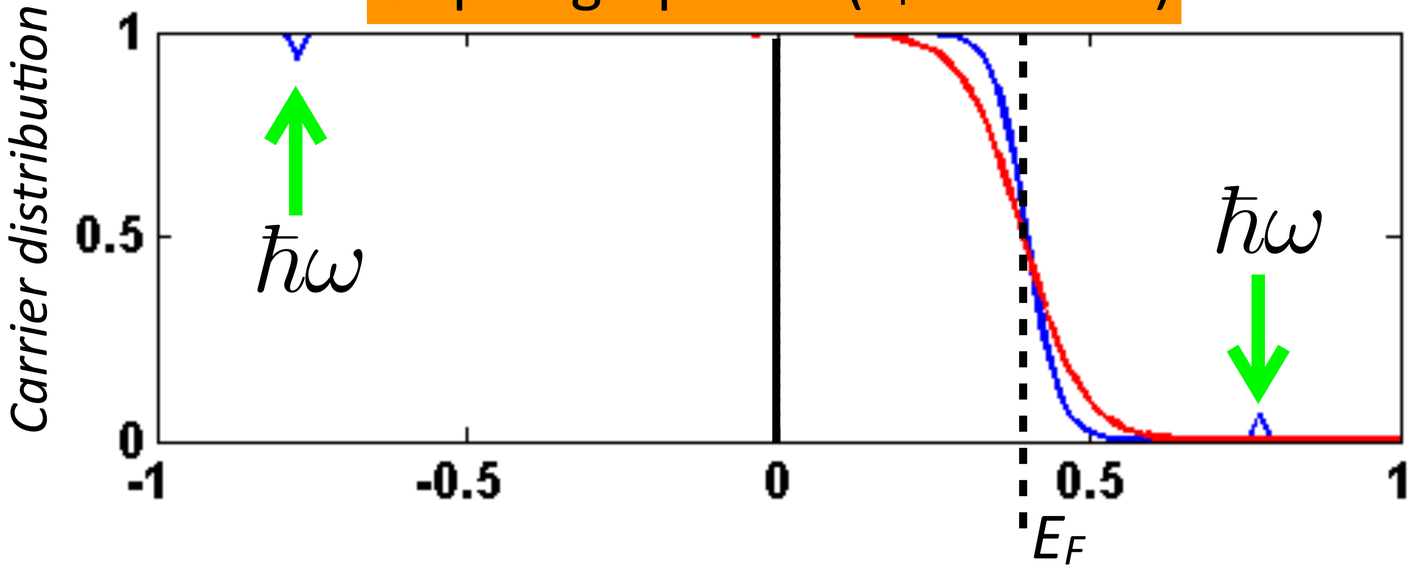


Sci. Adv. **4**, eaar5313 (2018)

Heating dynamics

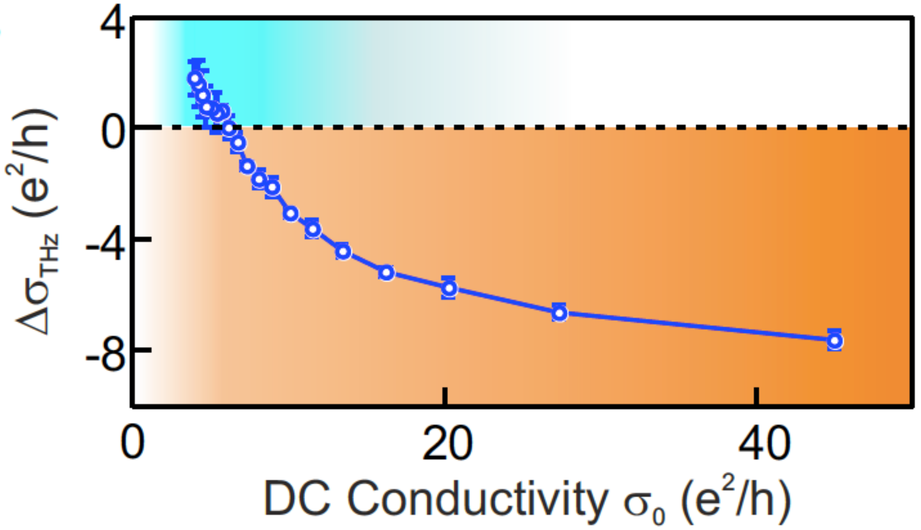


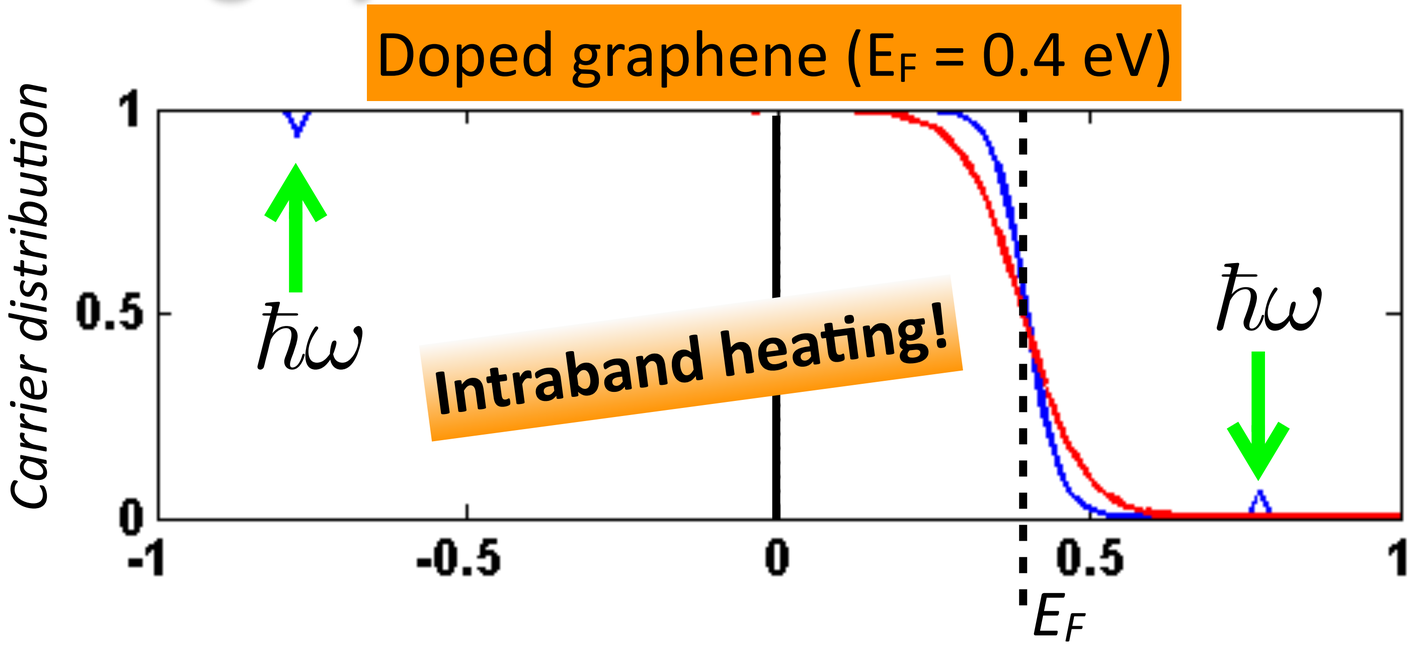
Doped graphene (E_F = 0.4 eV)



Sci. Adv. **4**, eaar5313 (2018)

Heating dynamics





Constant number of Conduction Band carriers

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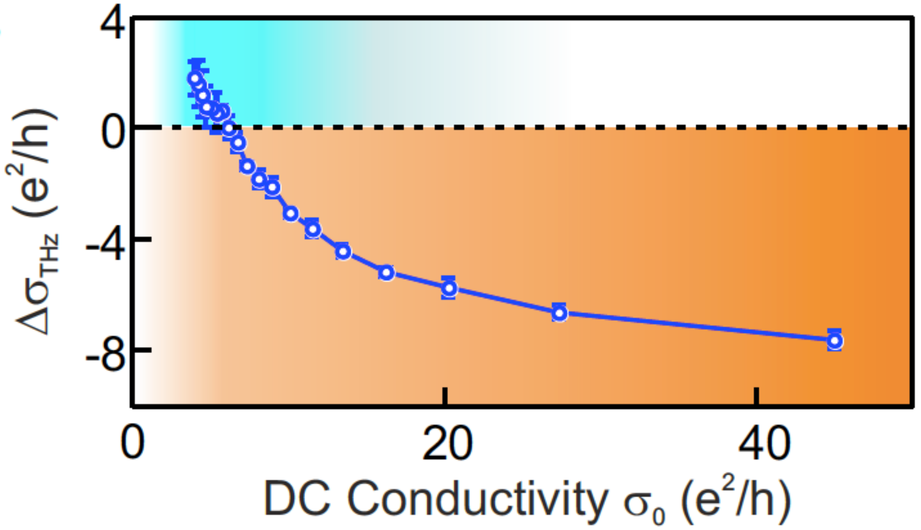
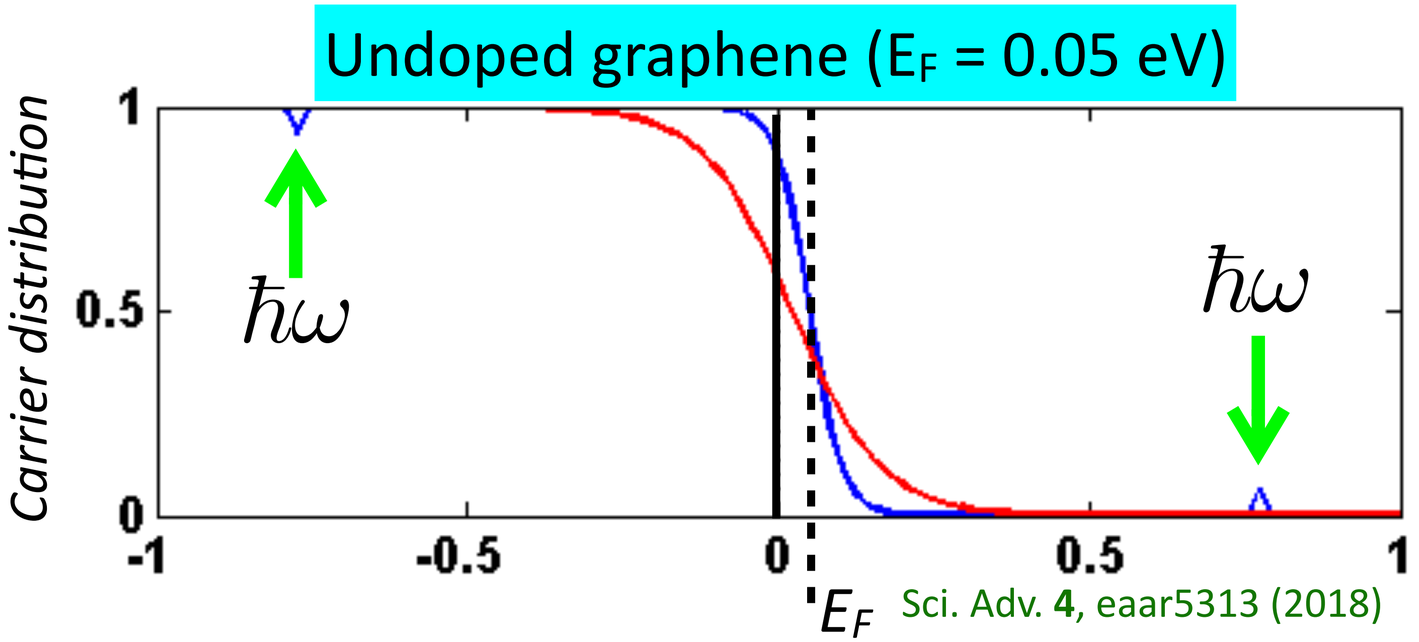
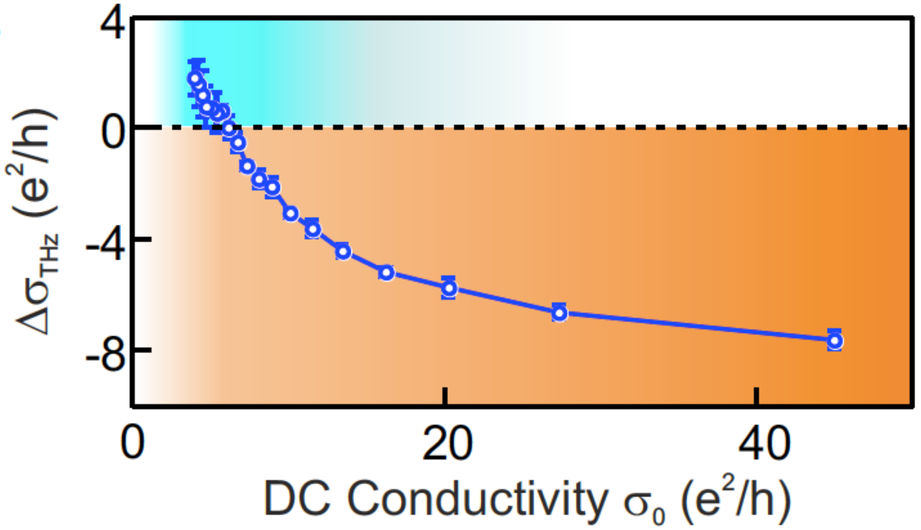
Heating dynamics



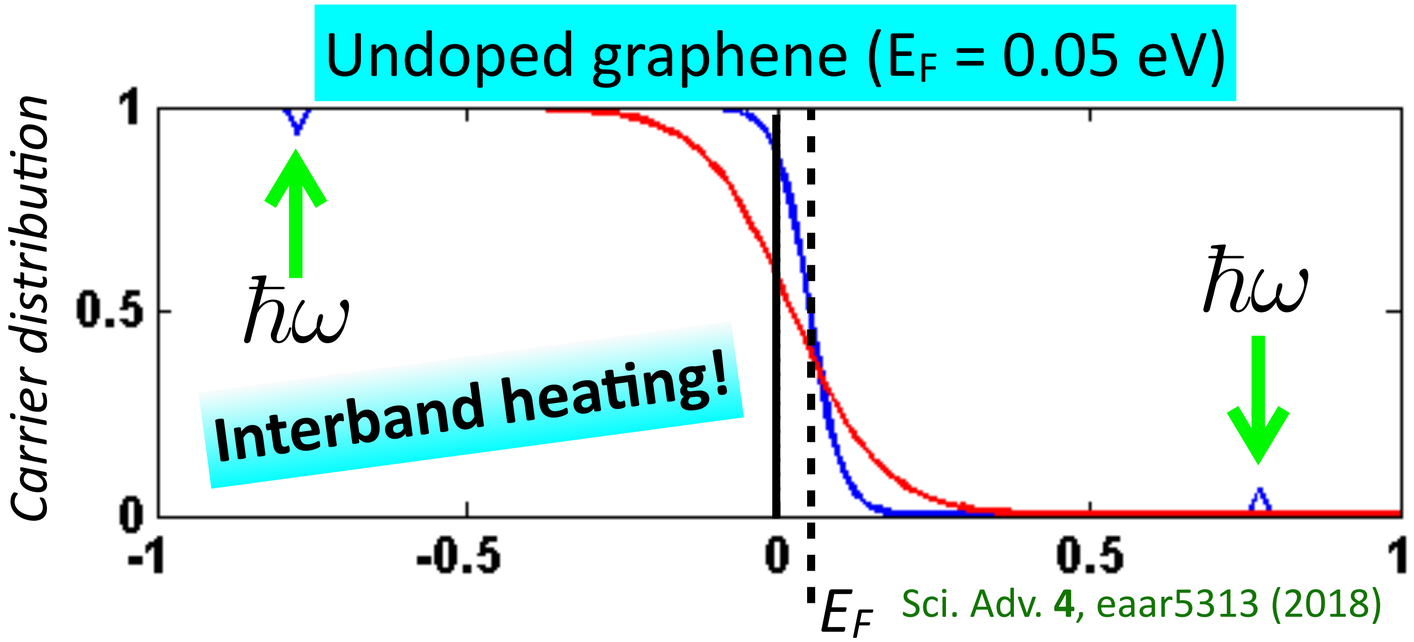


Sci. Adv. **4**, eaar5313 (2018)

Heating dynamics

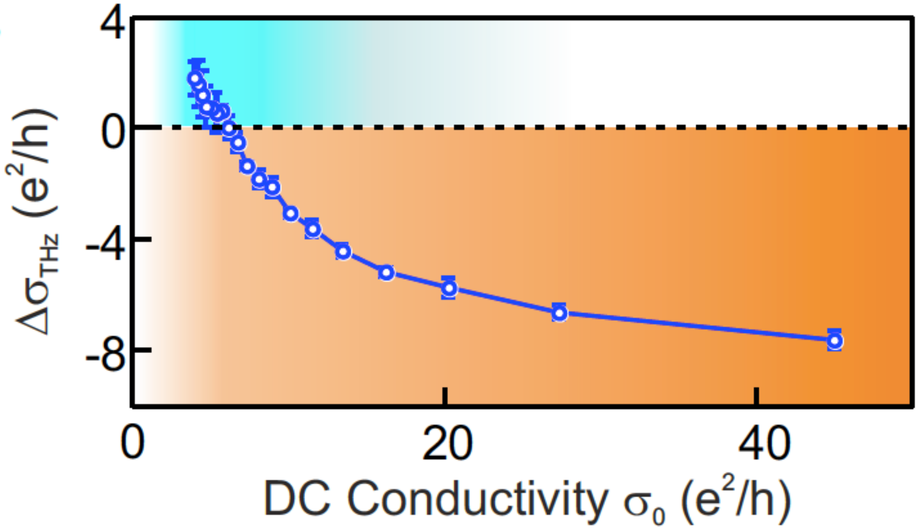


Increase in number of Conduction Band carriers



Sci. Adv. **4**, eaar5313 (2018)

Heating dynamics



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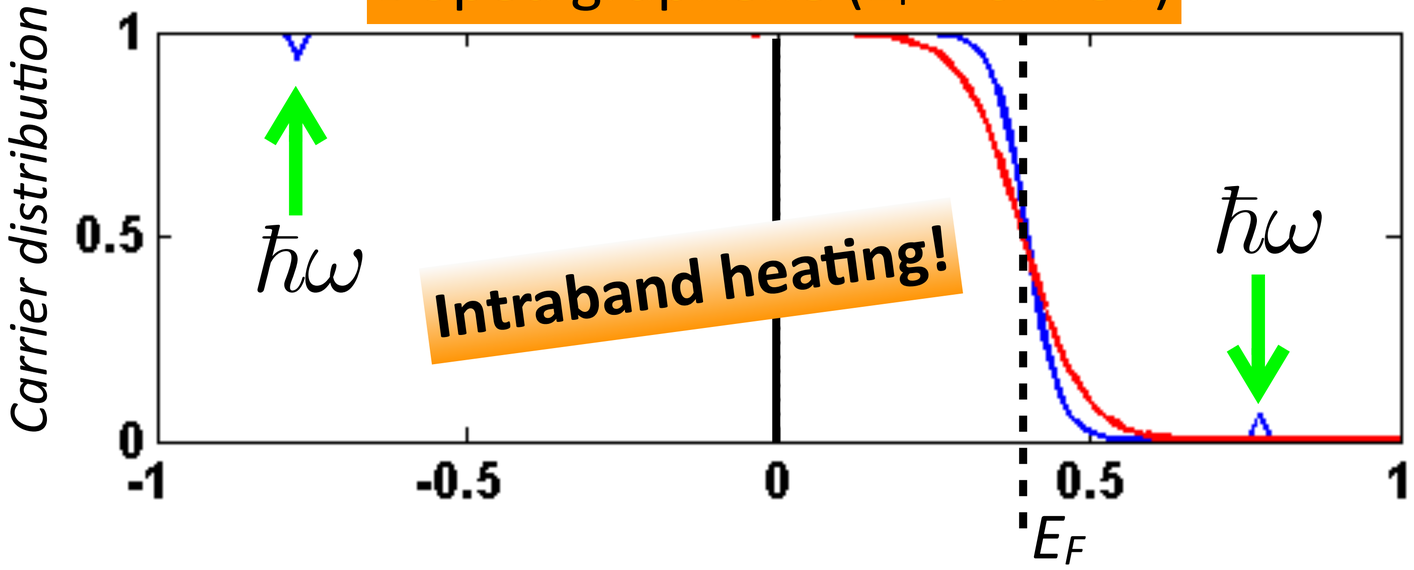
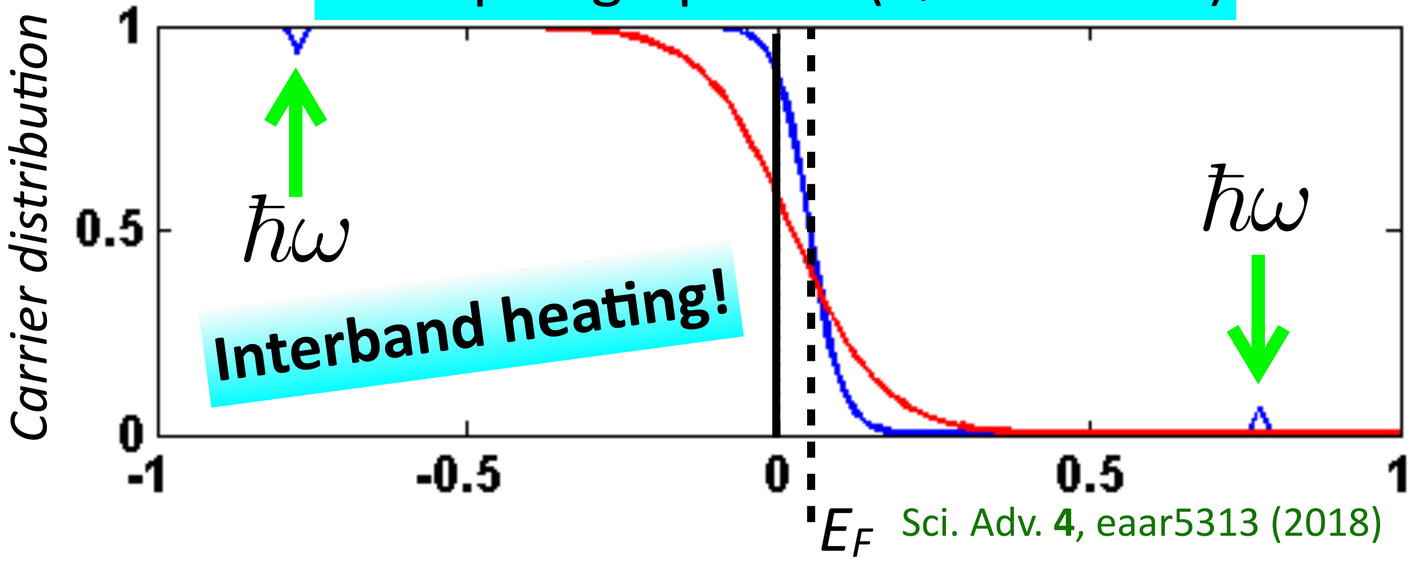


Undoped graphene (E_F = 0.05 eV)



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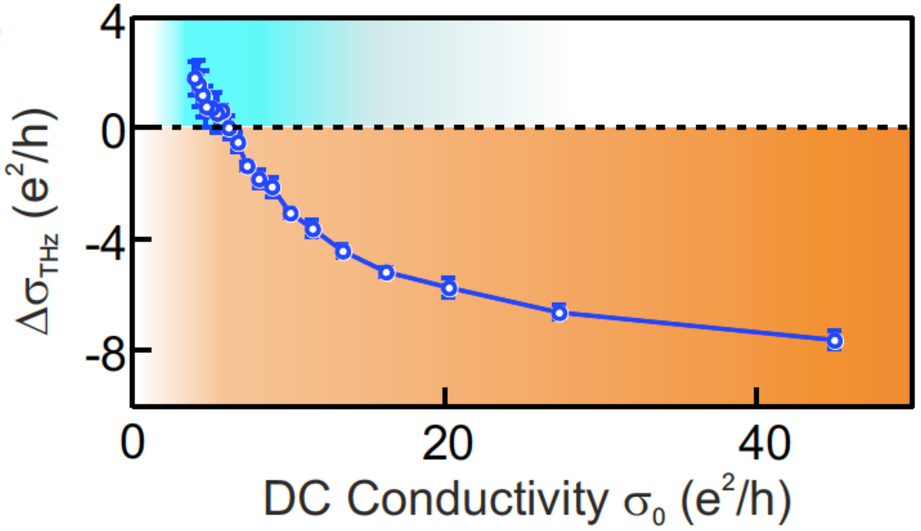
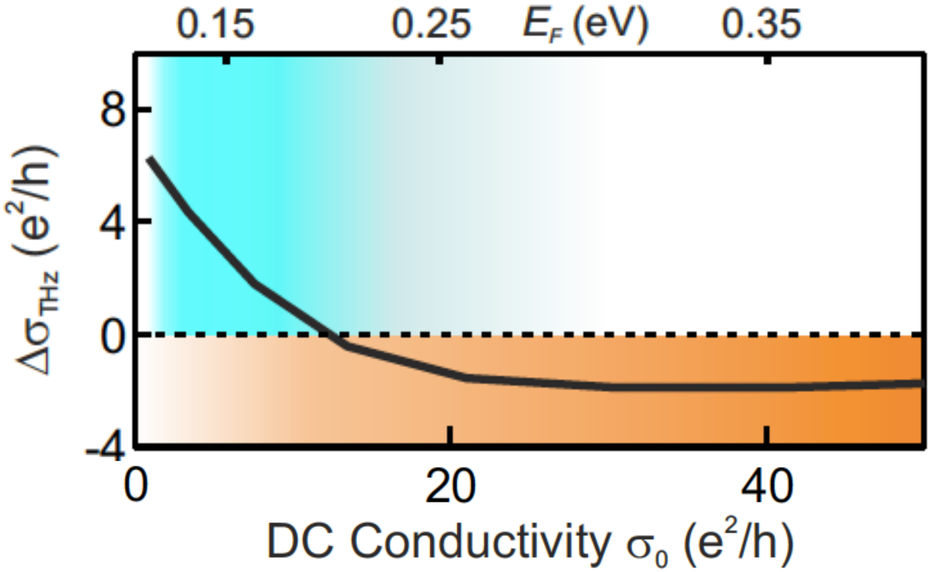
Photoexcited “hot” conductivity





Only purely electronic effects taken into account:

Long-range Coulomb impurity scattering

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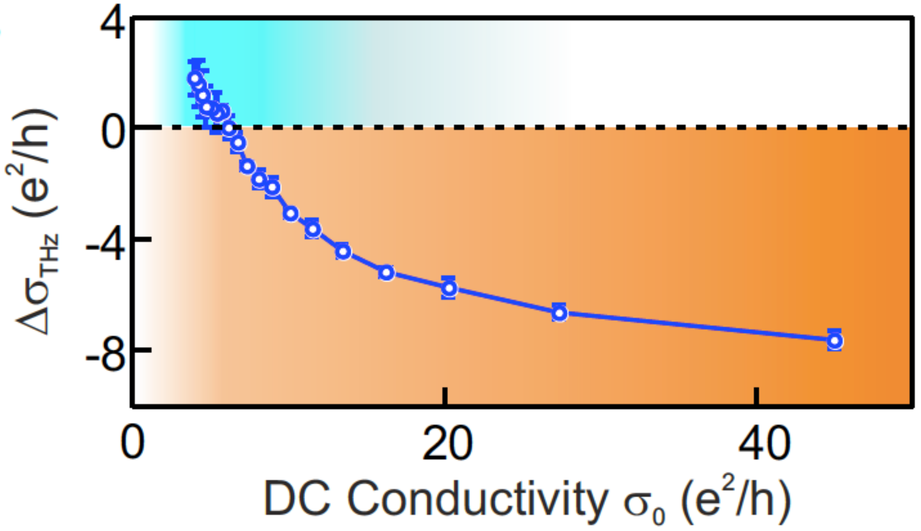
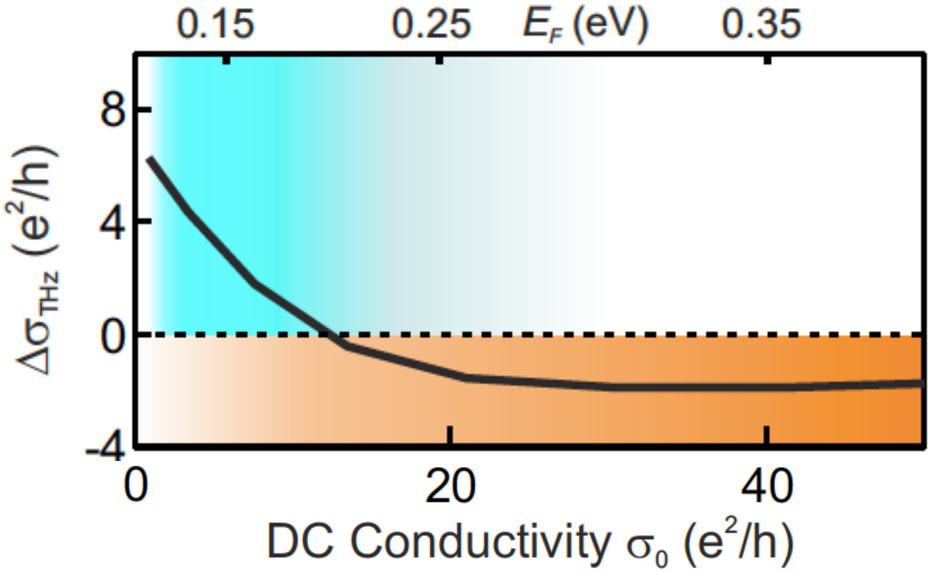
Photoexcited “hot” conductivity



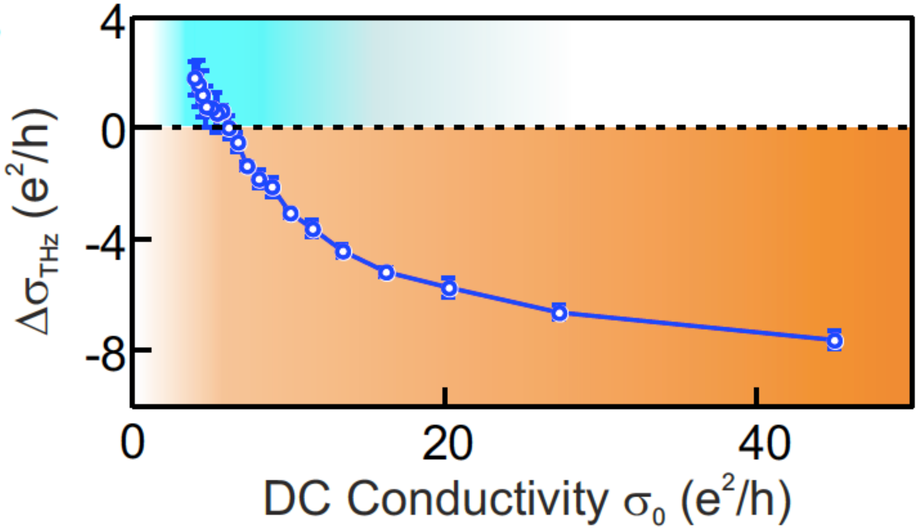


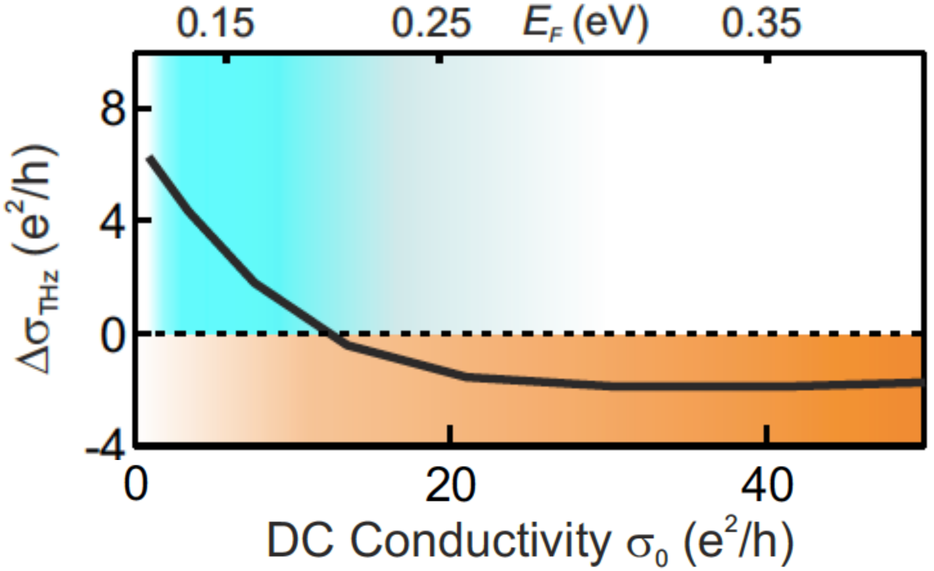
Undoped graphene (E_F = 0.05 eV)

Increased “hot” conductivity mainly due to additional carriers

Sci. Adv. **4**, eaar5313 (2018)

Photoexcited “hot” conductivity





Undoped graphene (E_F = 0.05 eV)

Increased “hot” conductivity mainly due to additional carriers

Doped graphene (E_F = 0.4 eV)

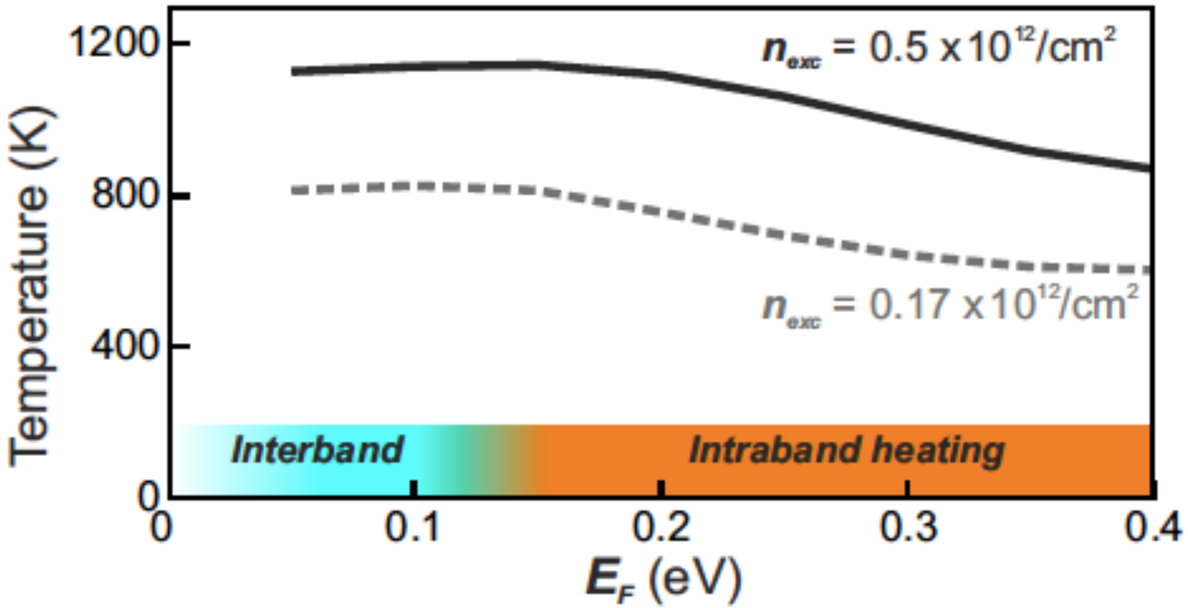
Decreased “hot” conductivity mainly due to decreased screening

Sci. Adv. **4**, eaar5313 (2018)

Efficient heating?

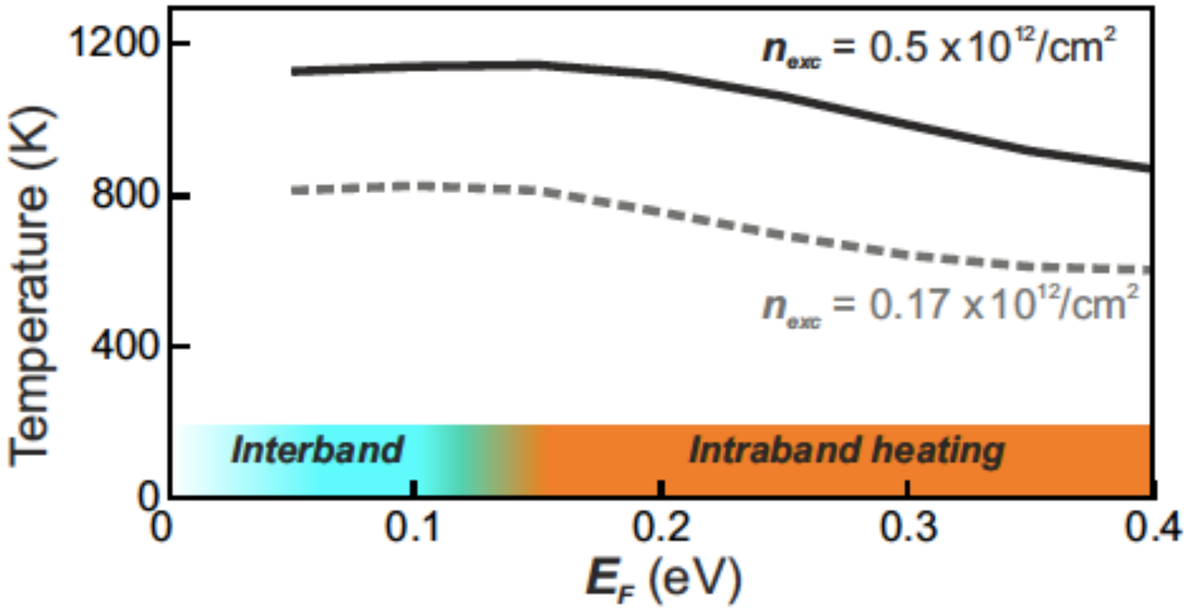
Sci. Adv. **4**, eaar5313 (2018)

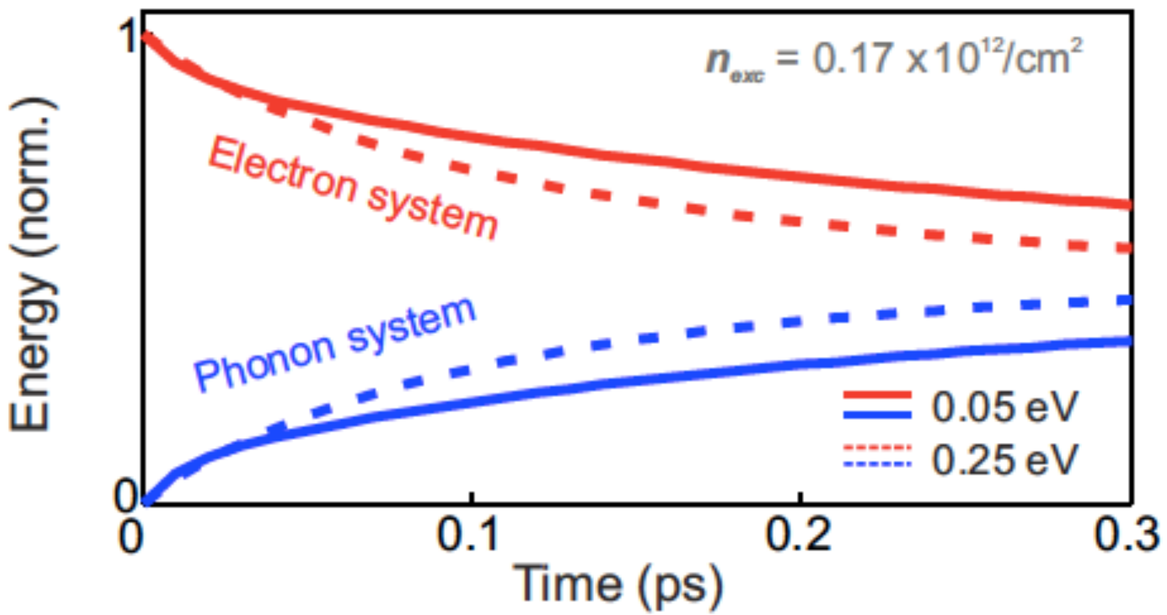
Efficient heating?



Sci. Adv. **4**, eaar5313 (2018)

Efficient heating?





Highly efficient flow of energy from photons to electron system!

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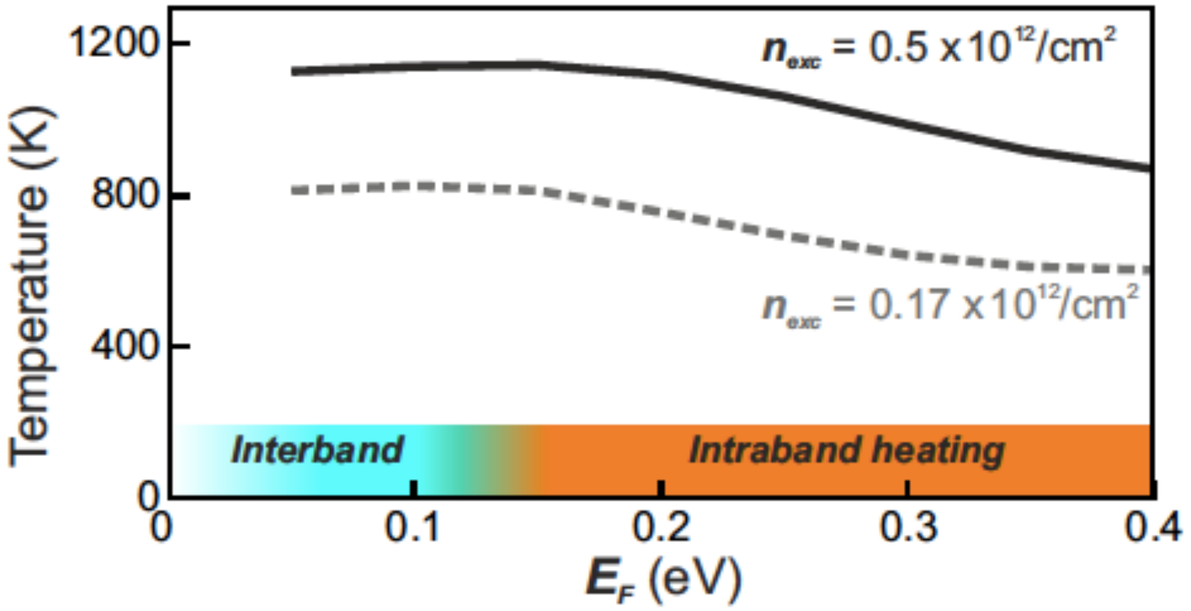
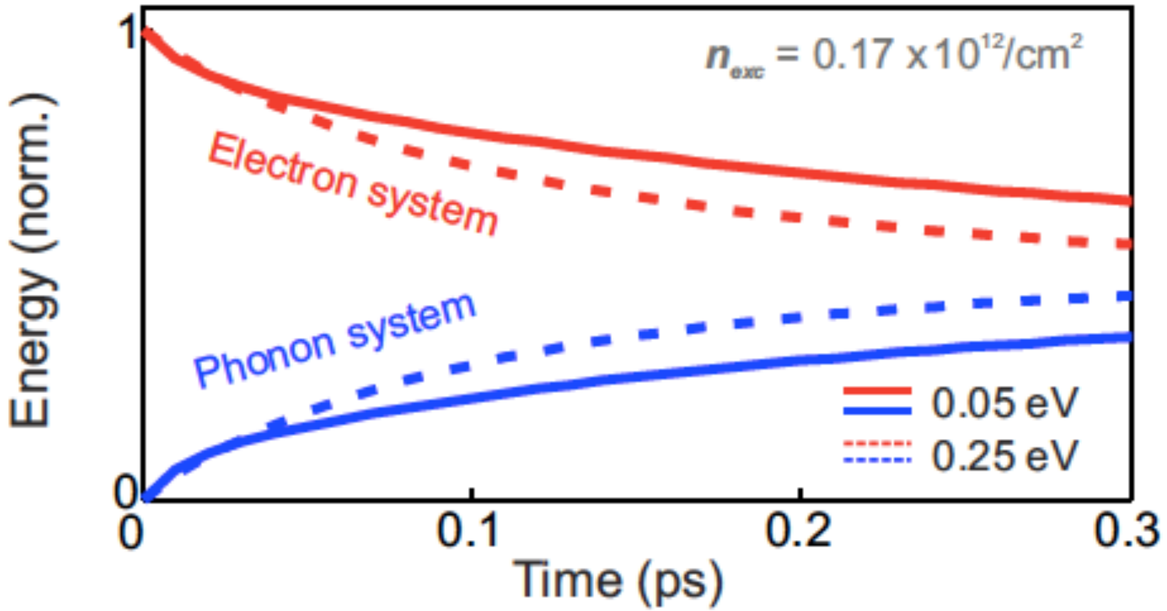
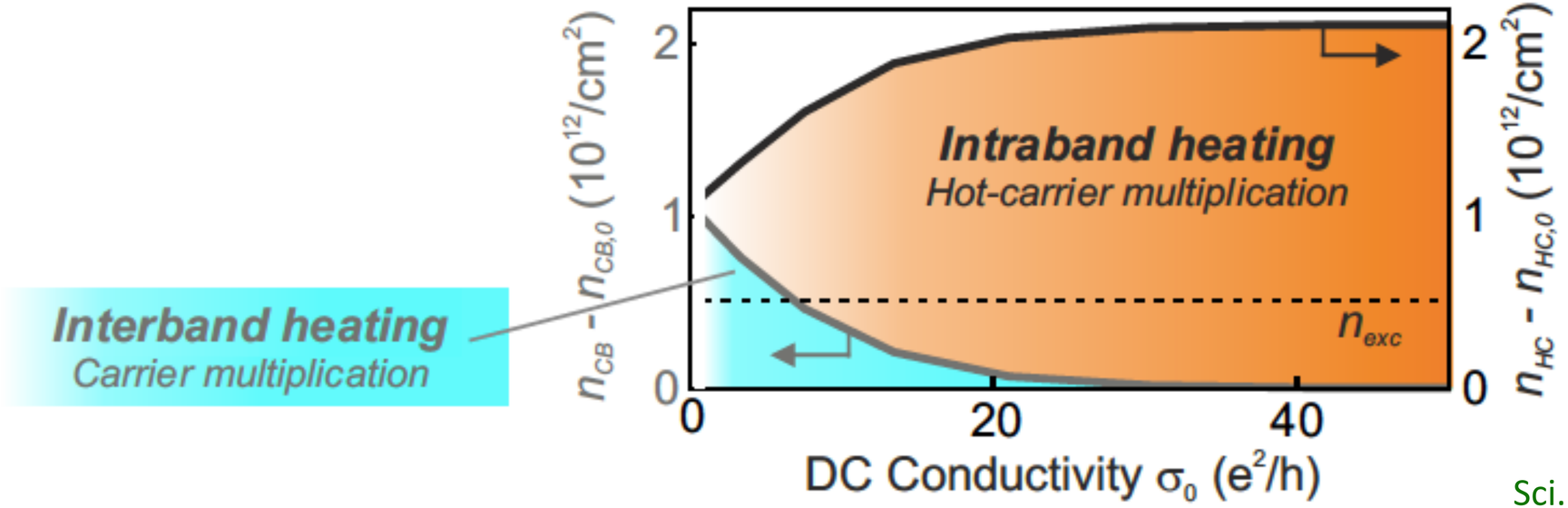
Efficient heating?







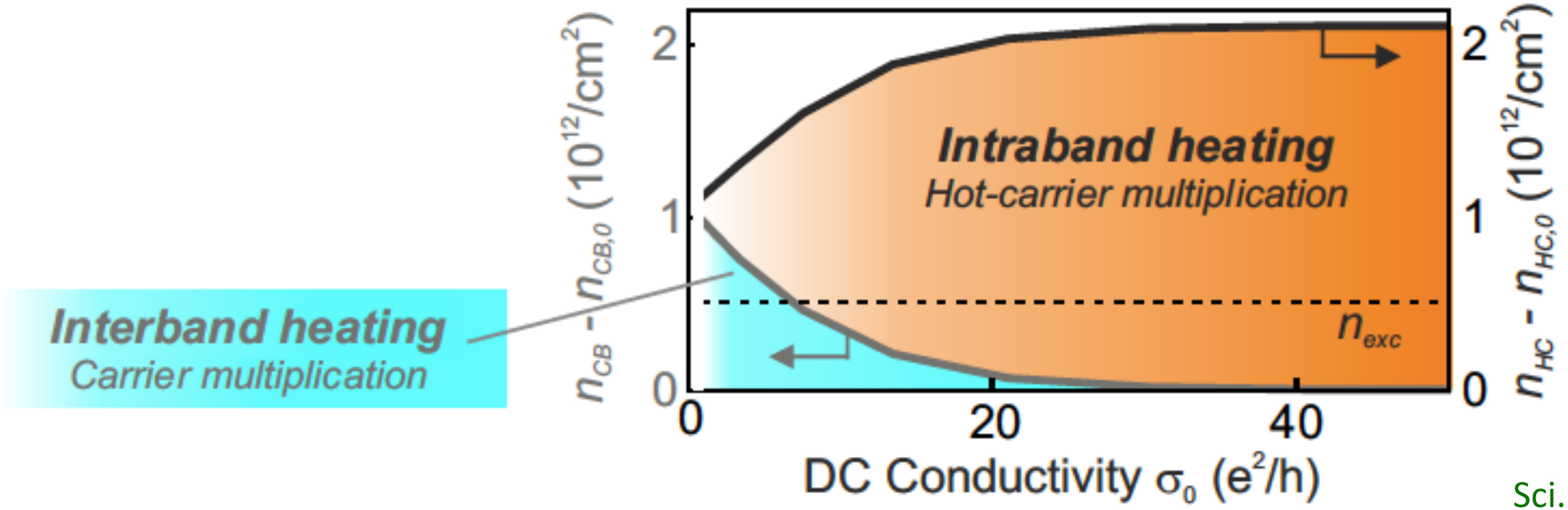
Sci. Adv. **4**, eaar5313 (2018)

Efficient heating?

Undoped graphene (E_F = 0.05 eV)

Possible: carrier multiplication

See also
Theory: Nano Lett. **10**, 4839 (2010)
Experiment: Nano Lett. **14**, 5371 (2014)



Sci. Adv. **4**, eaar5313 (2018)

Efficient heating?

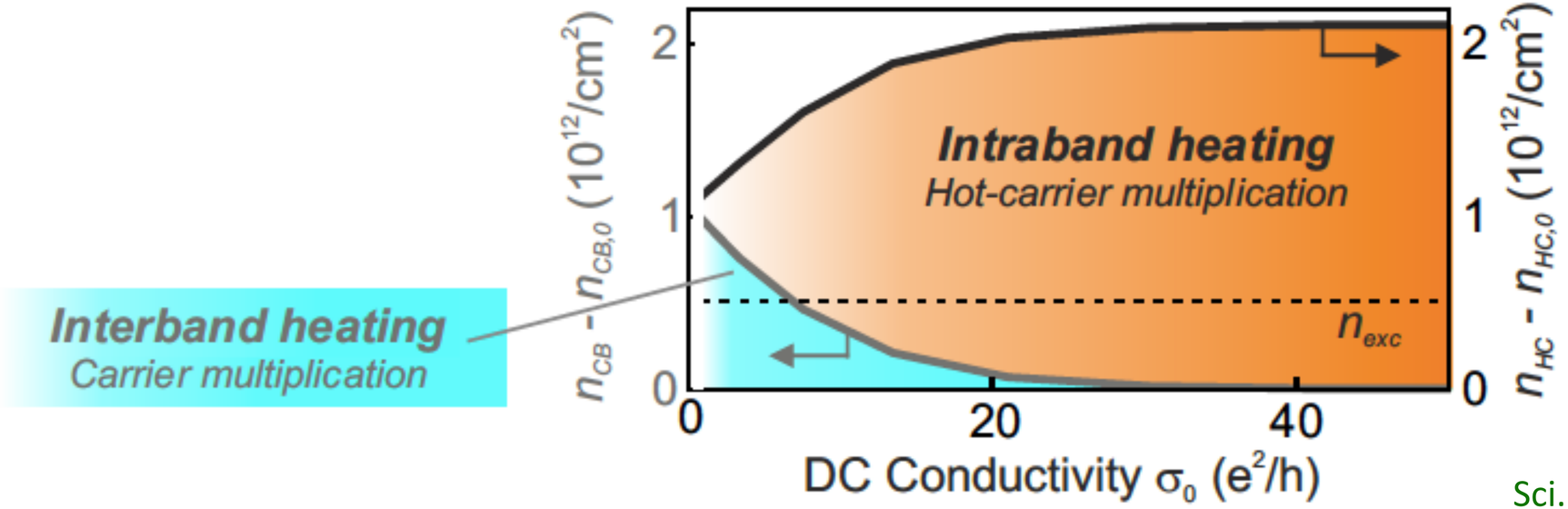
Undoped graphene (E_F = 0.05 eV)

Possible: carrier multiplication

Doped graphene (E_F = 0.4 eV)

See also
Theory: Nat. Phys. **9**, 248 (2013)
Experiment: Science Adv. **2**, e160002 (2016)

Possible: hot-carrier multiplication



Sci. Adv. **4**, eaar5313 (2018)

Efficient heating?

Undoped graphene (E_F = 0.05 eV)

Possible: carrier multiplication

Doped graphene (E_F = 0.4 eV)

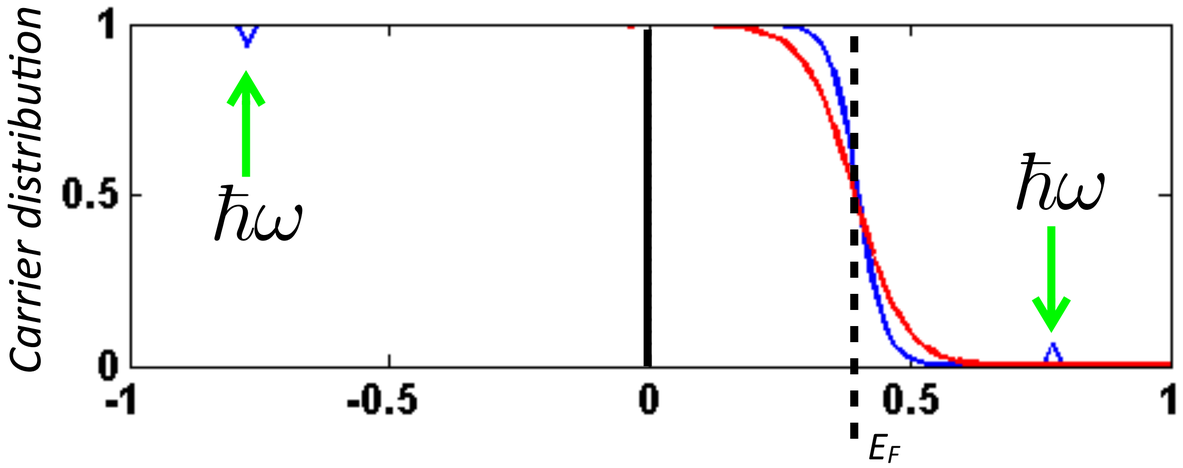
Possible: hot-carrier multiplication

CM and hot-CM are the result of efficient heating!

Sci. Adv. **4**, eaar5313 (2018)

Summary

Doped graphene (E_F = 0.4 eV)

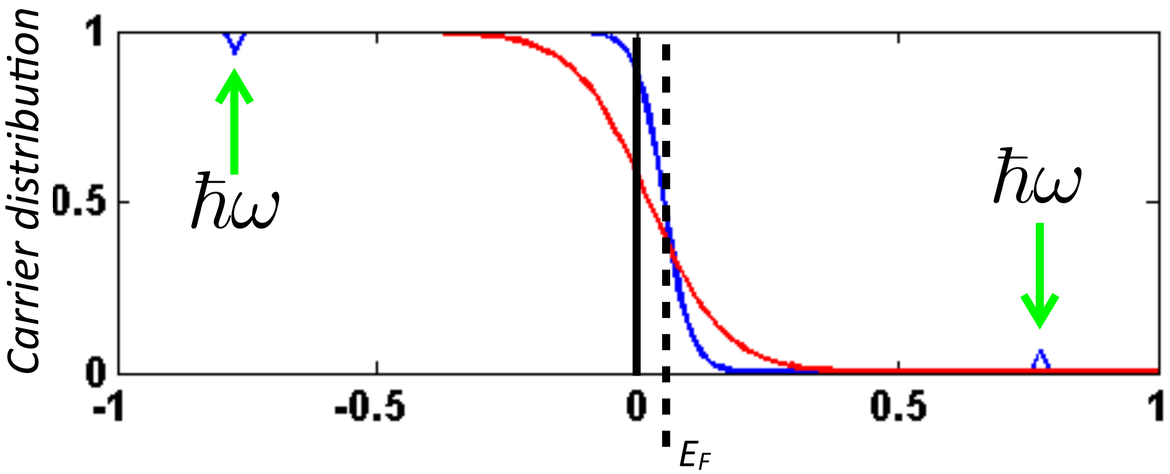


Efficient intraband heating

Hot-carrier multiplication possible

Decreased conductivity mainly due to reduced screening

Undoped graphene (E_F = 0.05 eV)



Efficient interband heating

Carrier multiplication possible

Increased conductivity mainly due to additional CB carriers

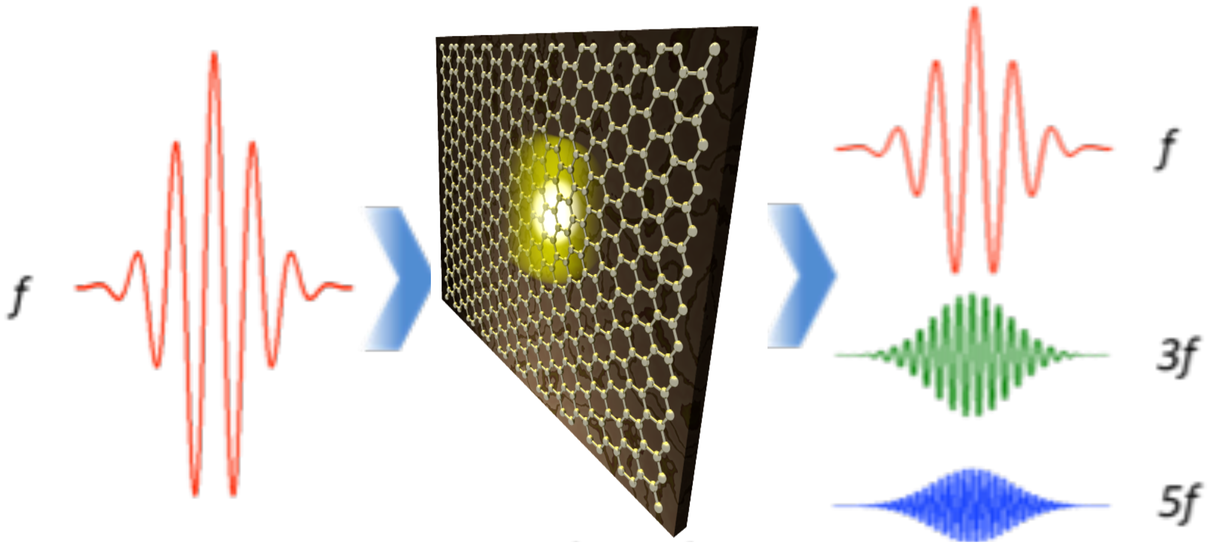
Sci. Adv. **4**, eaar5313 (2018)

& … ???

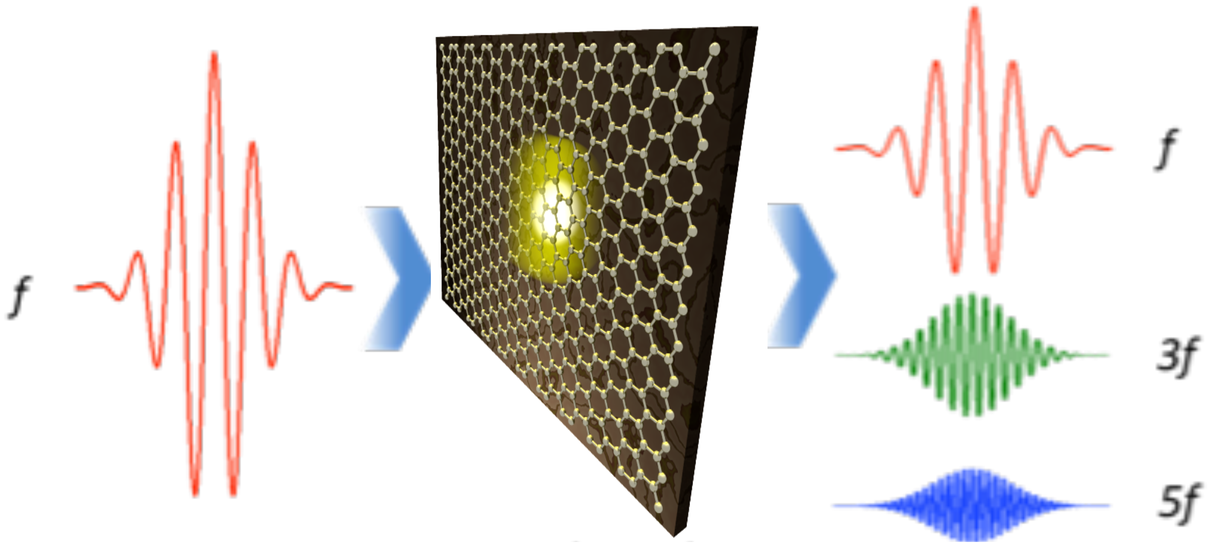
Data communication

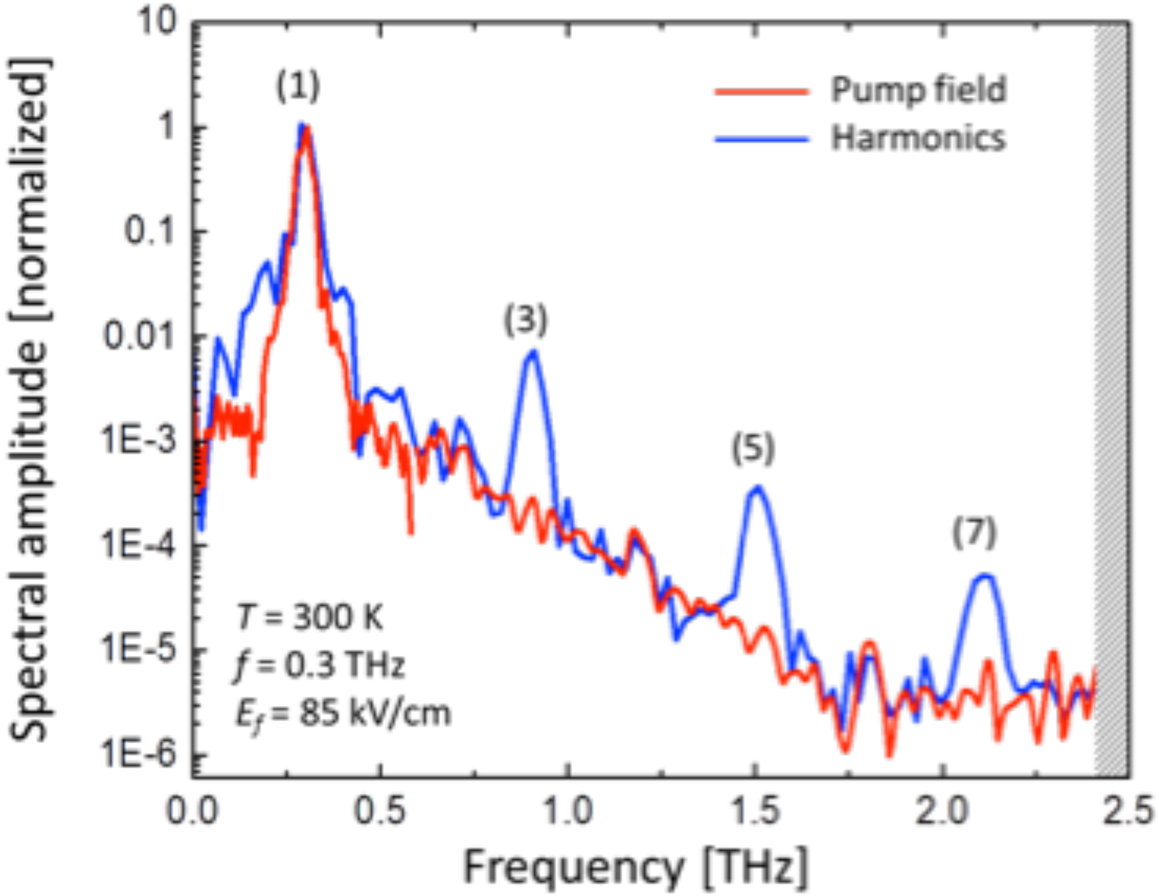
Photodetection

THz harmonics via carrier heating!

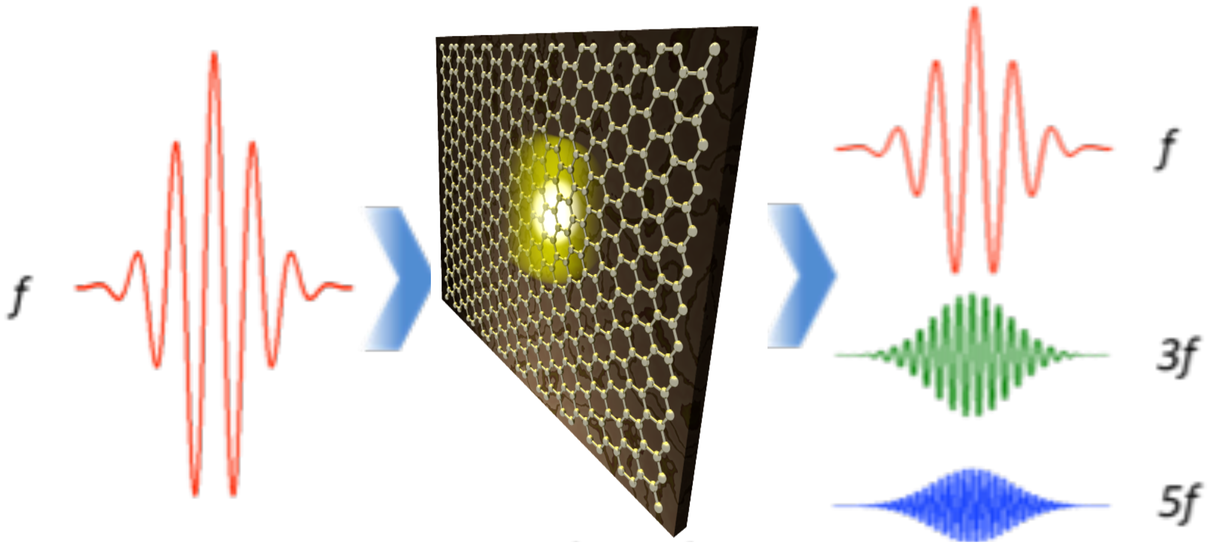


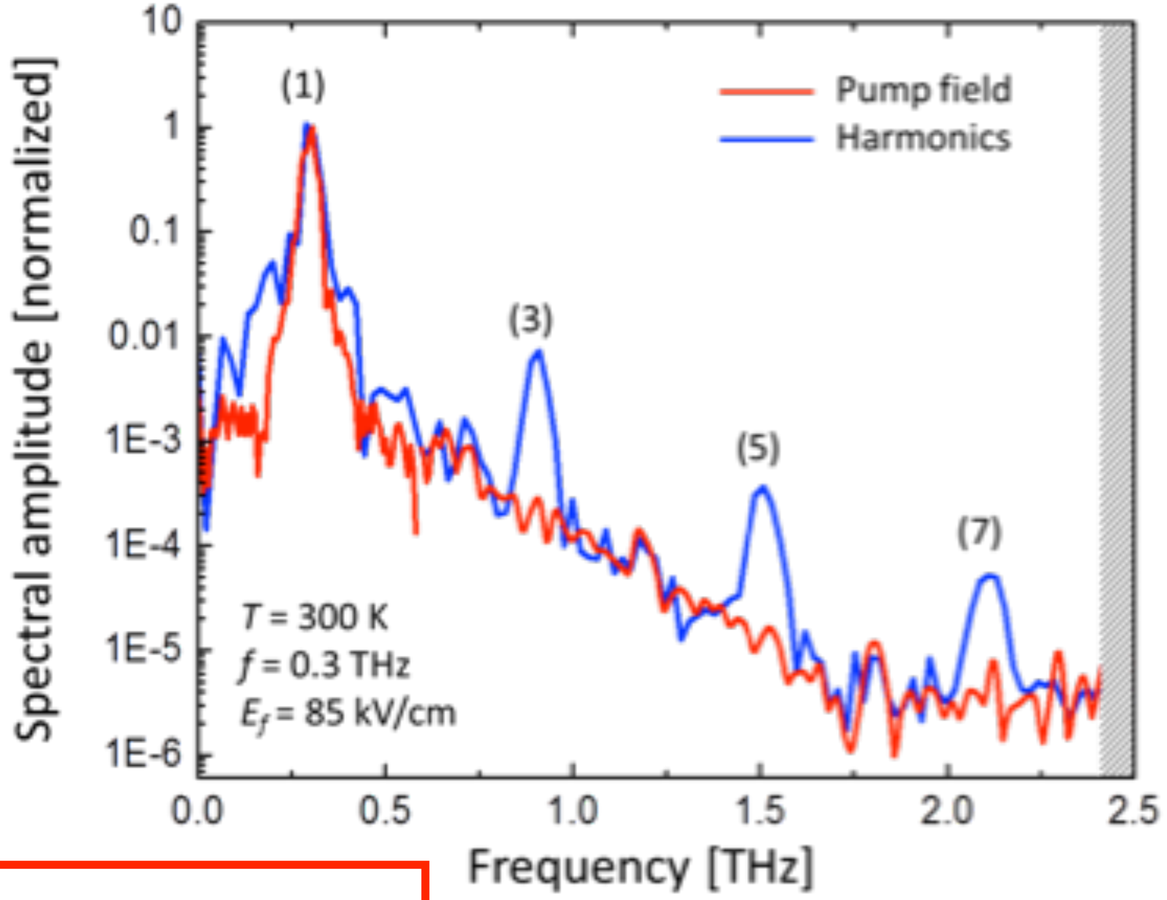
THz harmonics via carrier heating!





THz harmonics via carrier heating!





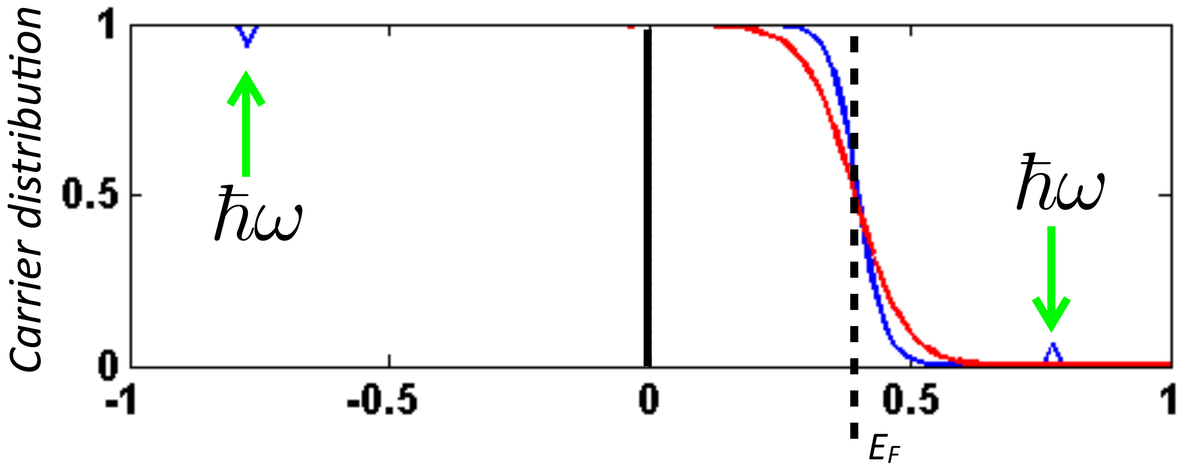
See: Poster 127

"Efficient Terahertz High Harmonic Generation in Single-Layer Graphene"

Presenter: Sergey Kovalev (Helmholtz Zentrum Dresden Rossendorf, Germany)

Summary

Doped graphene (E_F = 0.4 eV)

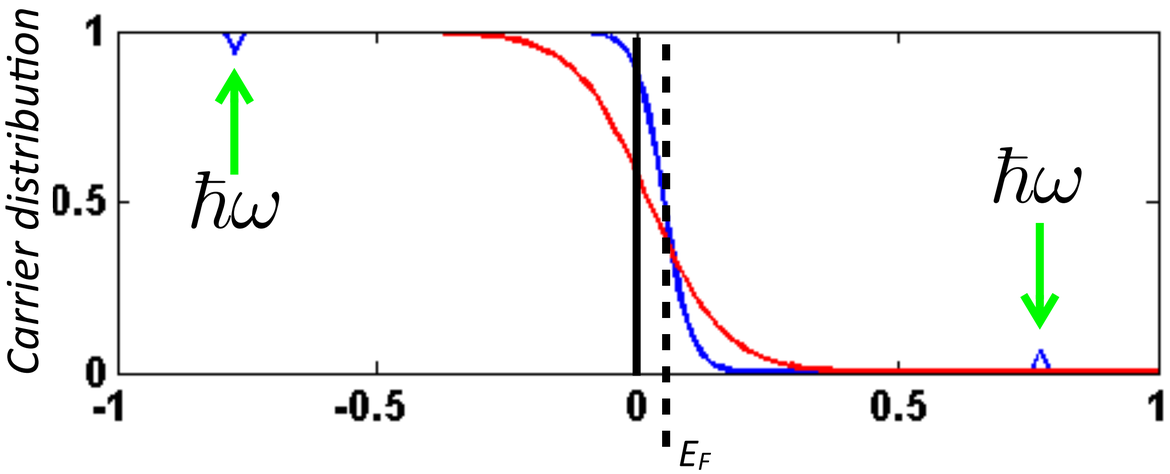


Efficient intraband heating

Hot-carrier multiplication possible

Decreased conductivity mainly due to reduced screening

Undoped graphene (E_F = 0.05 eV)



Efficient interband heating

Carrier multiplication possible

Increased conductivity mainly due to additional CB carriers

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