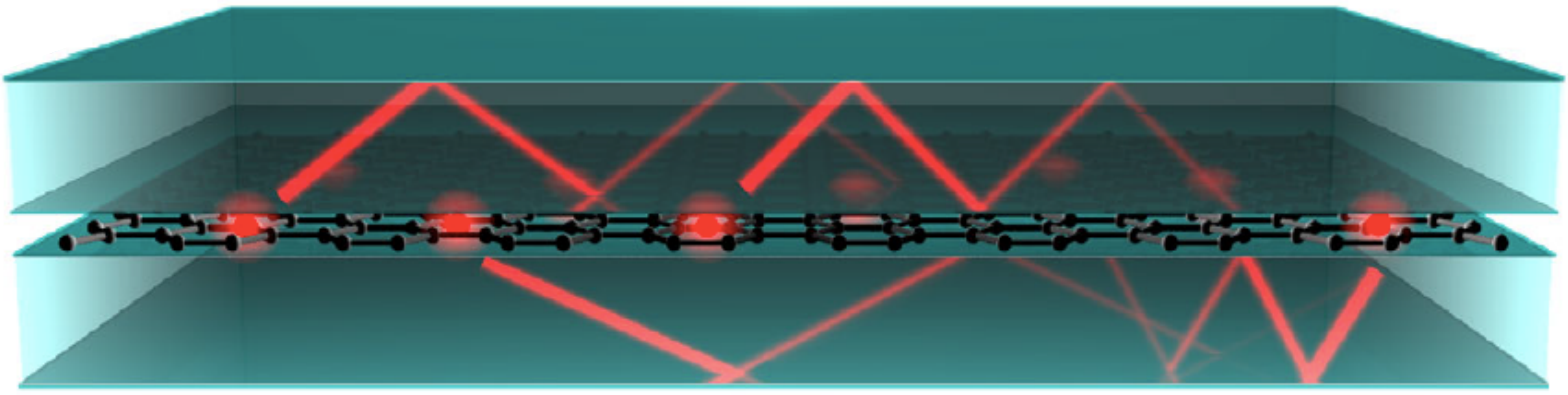
Out-of-plane heat transfer in Van der Waals stacks



The Institute of Photonic Sciences

Klaas-Jan Tielrooij

March 29th 2017

Barcelona, ES

Acknowledgements

ICFO
The Institute of Photonic Sciences

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Frank Koppens
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Peter Schmidt
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Zoltan Mics

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Takashi Taniguchi
Kenji Watanabe

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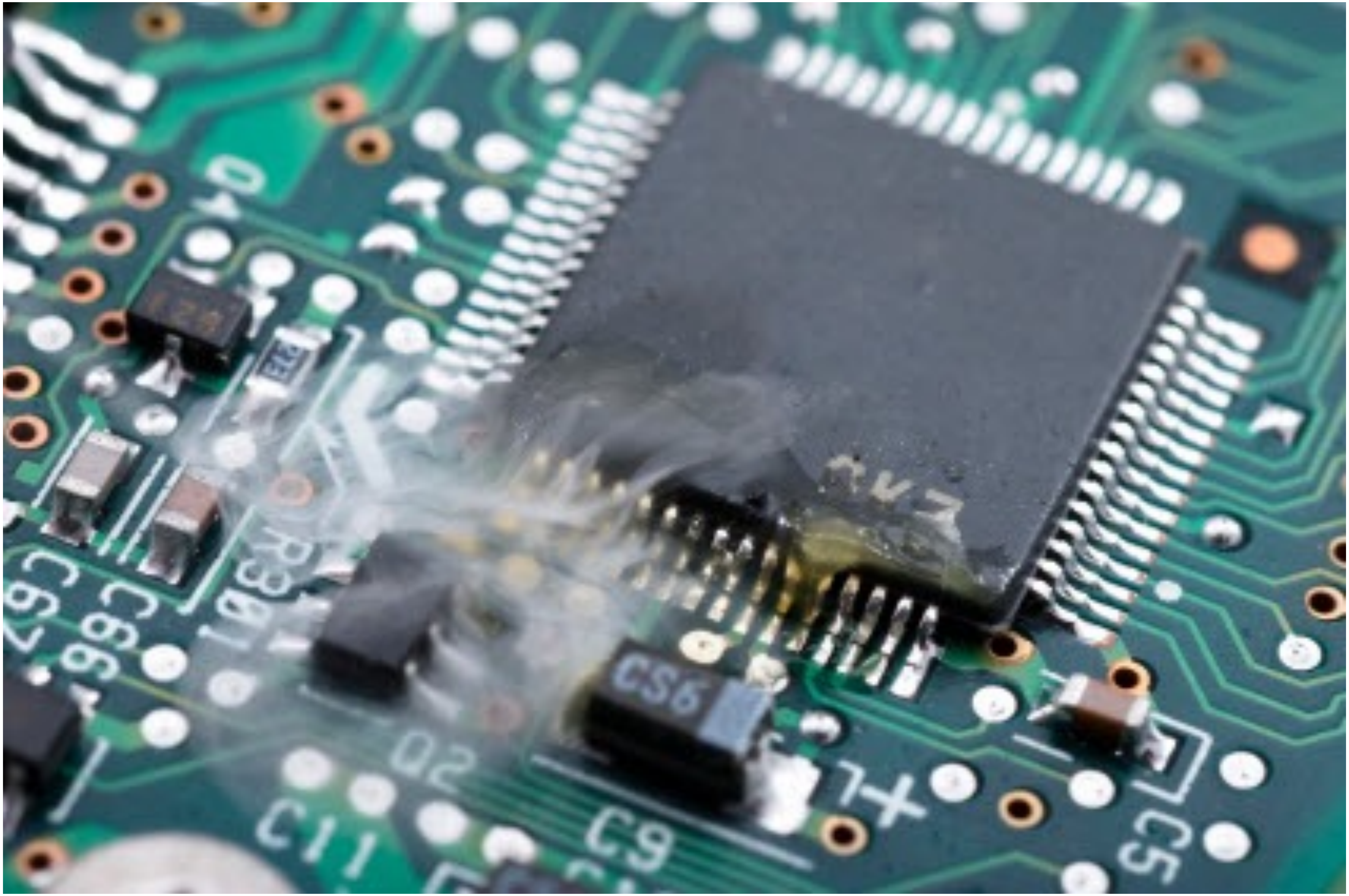
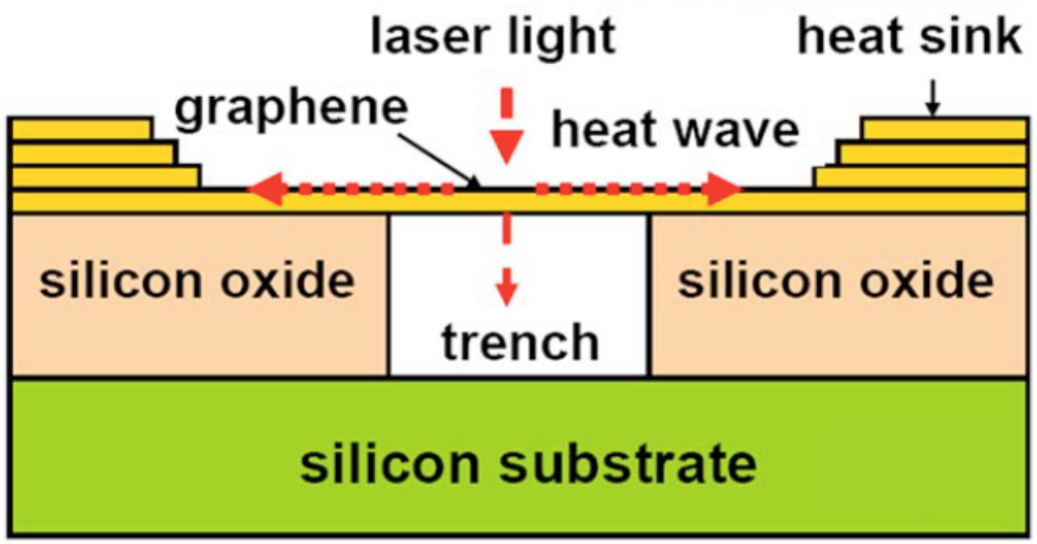
Thermal management



Graphene & thermal management



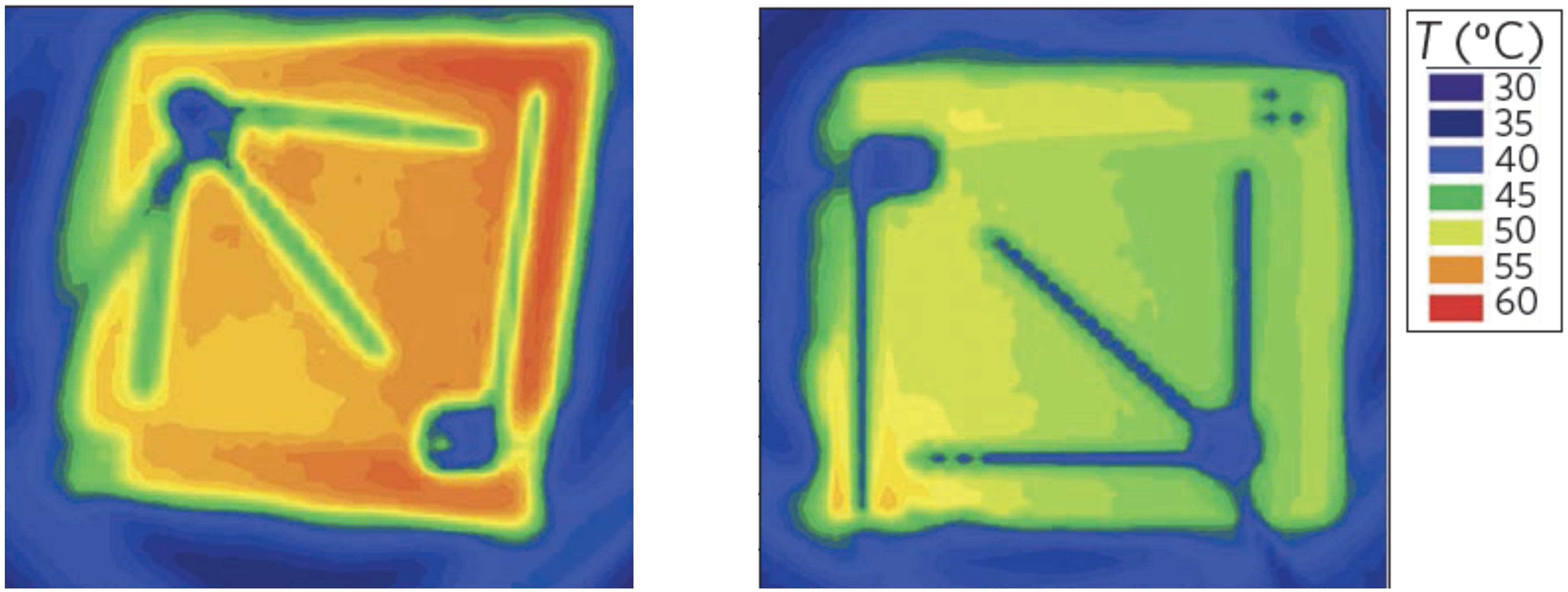
Ghosh et al, *APL 92, 151911* (2008)

→ **Suspended graphene** has a very high in-plane thermal conductivity: >1000 W/mK

→ **Supported graphene: ideal substrate = heat sink!**

Graphene & thermal management

Light-emitting diodes



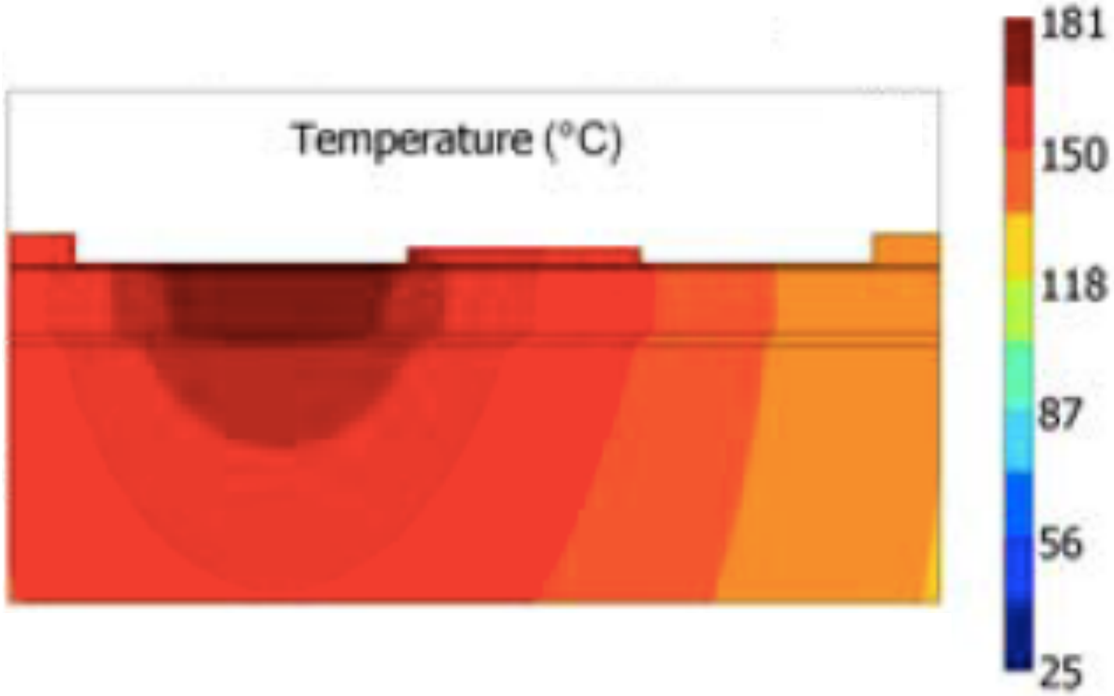
Conventional GaN LED

Embedded graphene layer GaN LED

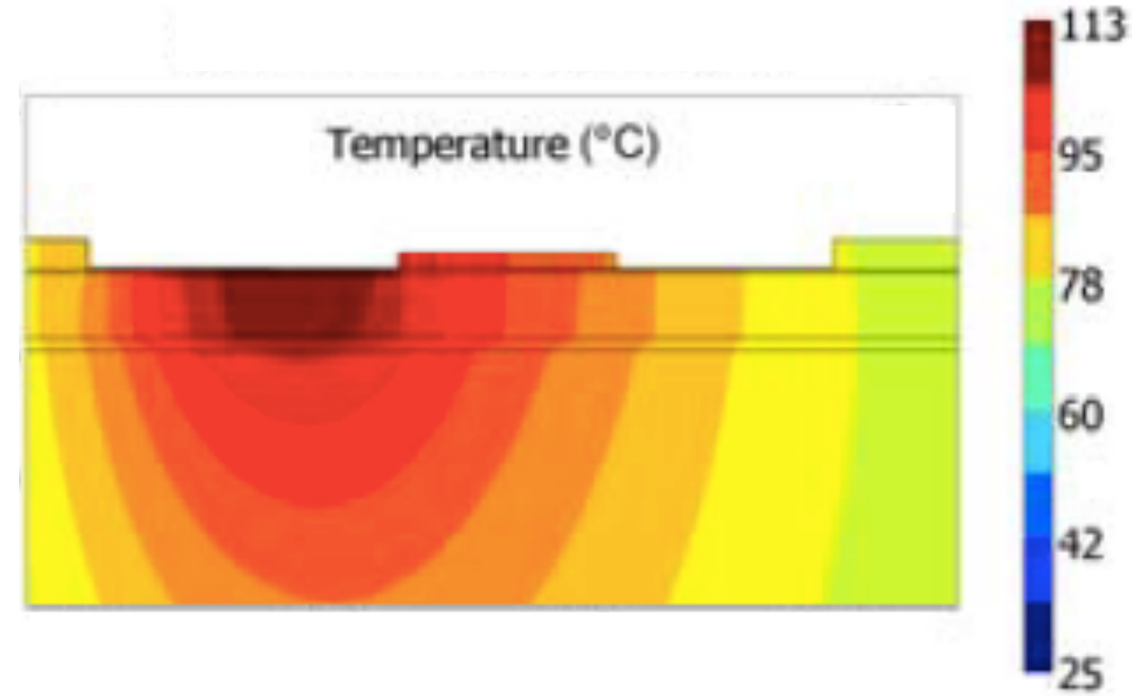
Han et al, *Nature Comm. 4, 1452* (2013)

Graphene & thermal management

Field-effect transistors



AlGaN/GaN FET



AlGaN/GaN FET with graphene/graphite

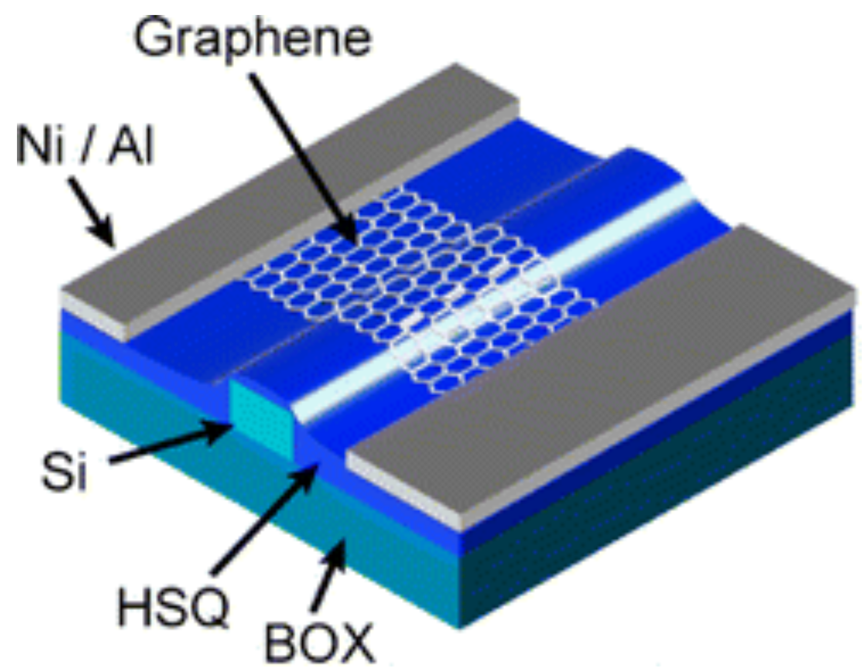
Yan et al, *Nature Comm. 3, 827* (2012)

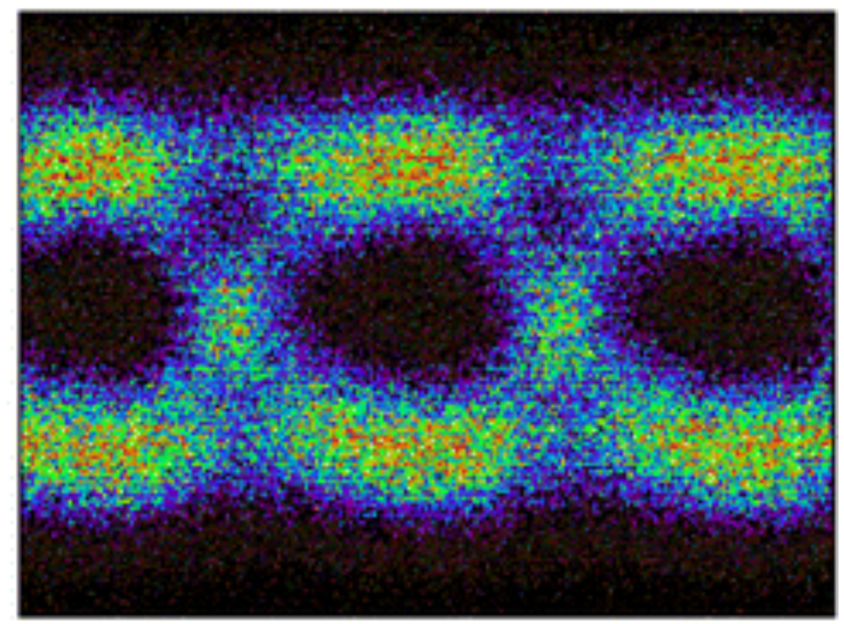
Graphene & thermal management

Fast photodetectors

Fast photodetectors

>50 Gbit/s





Schall et al, *ACS Photonics* (2014)

Fast photodetectors

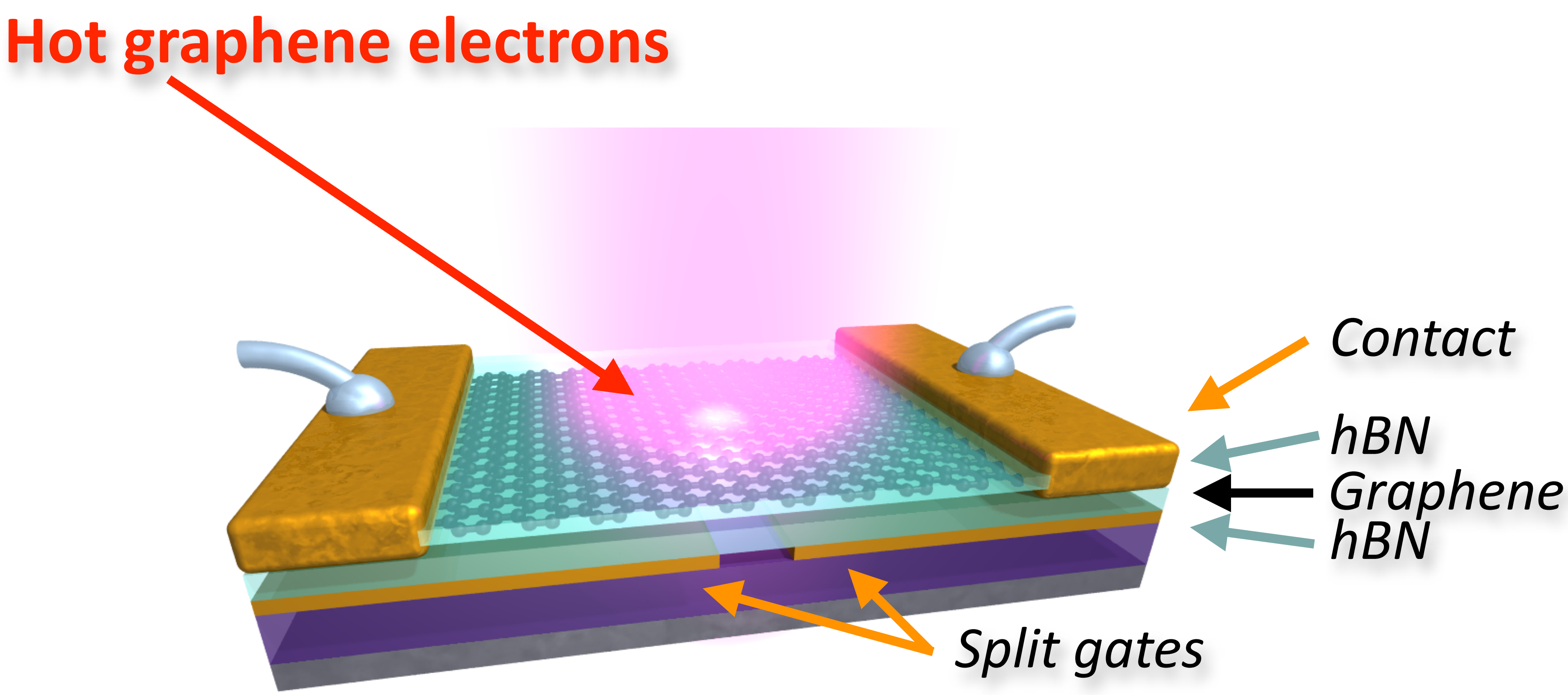


Photo-thermoelectric (PTE) detector

Song et al. *PRL* (2011)
Gabor et al. *Science* (2011)
Koppens et al. *Nature Nano* (2014)

Fast photodetectors

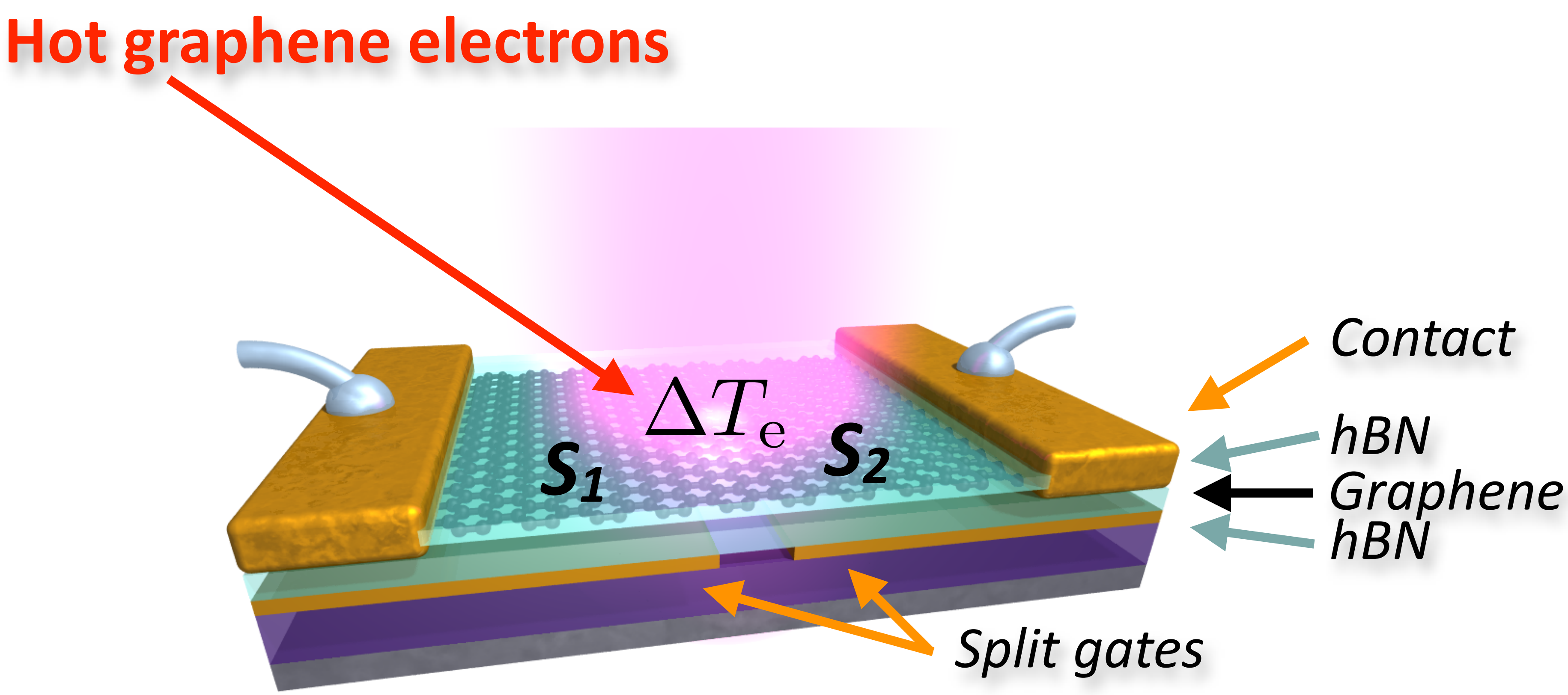
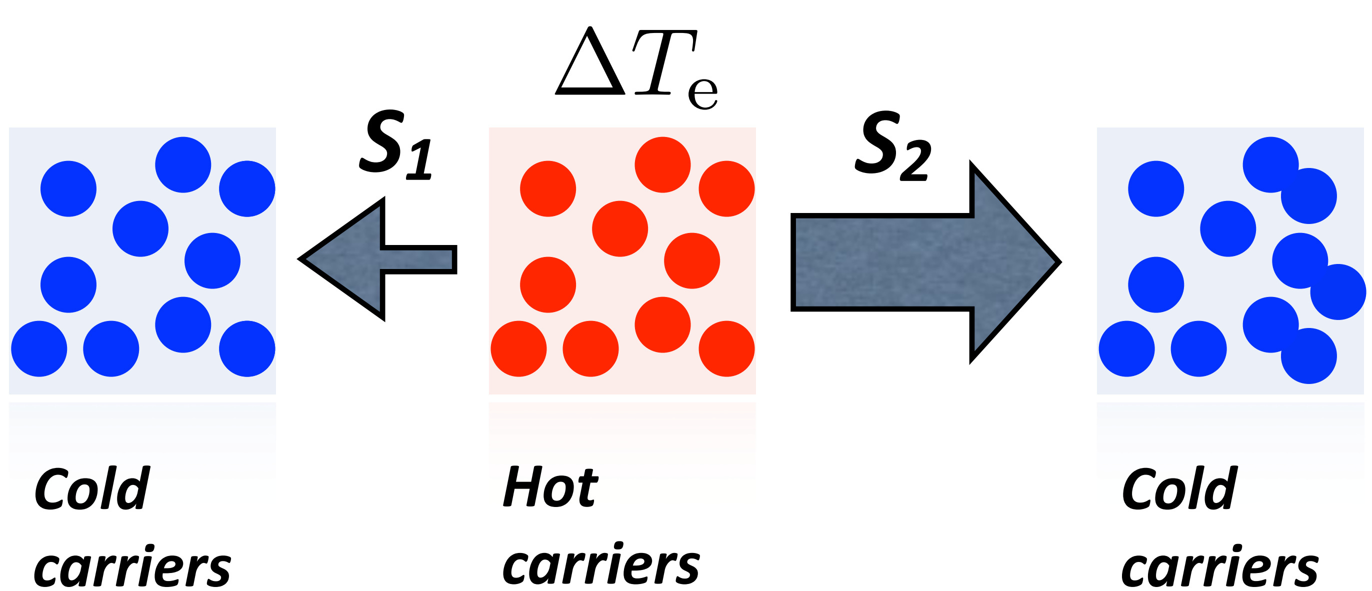


Photo-thermoelectric (PTE) detector



Use the heat!

Electron heat $\neq$ phonon heat

Song et al. *PRL* (2011)
Gabor et al. *Science* (2011)
Koppens et al. *Nature Nano* (2014)

Fast photodetectors

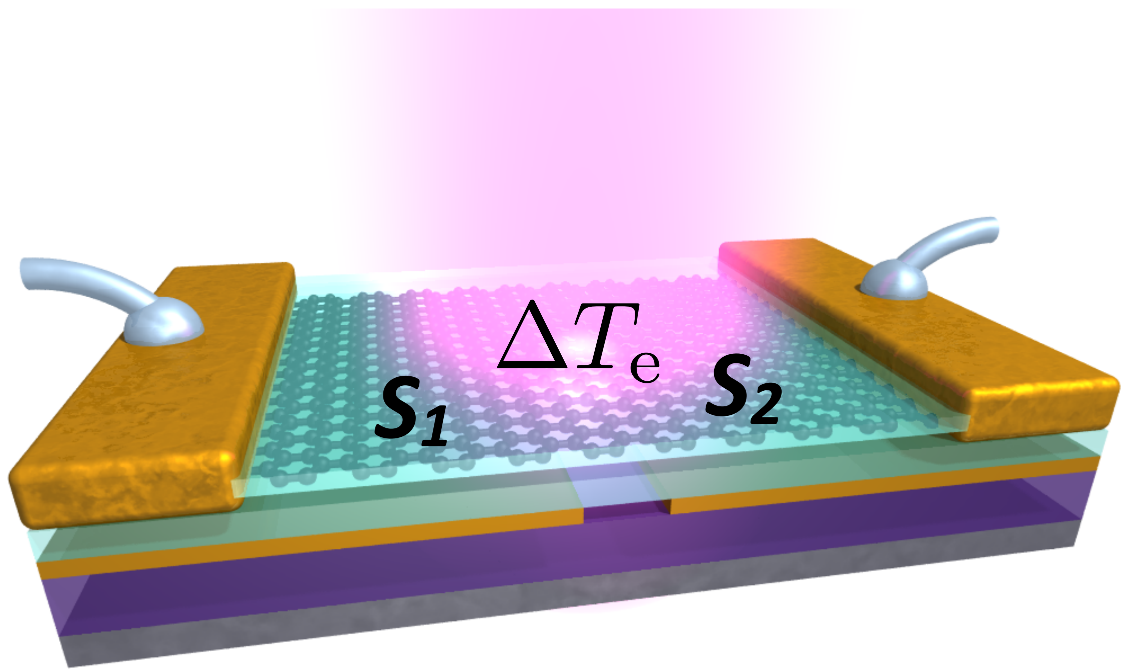


Photo-thermoelectric (PTE) detector

$$V_{PTE} = (S_2 - S_1)\Delta T_e$$

$$\Delta T_e \propto \frac{P_{abs}}{\Gamma_{cool}} = \frac{P_{abs}\tau_{cool}}{C_n}$$

Electron heat → phonon heat

Song et al. *PRL* (2011)
Gabor et al. *Science* (2011)
Koppens et al. *Nature Nano* (2014)

Fast photodetectors

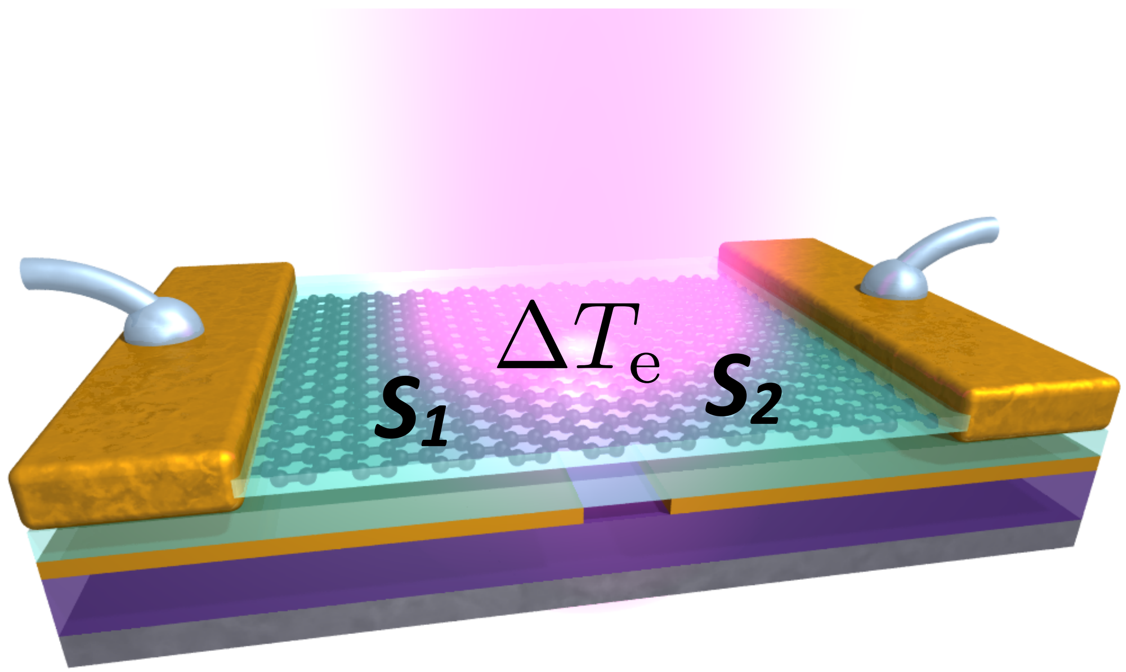


Photo-thermoelectric (PTE) detector

$$V_{\mathrm{PTE}} = (S_2 - S_1)\Delta T_{\mathrm{e}}$$

$$\Delta T_{\mathrm{e}} \propto \frac{P_{\mathrm{abs}}}{\Gamma_{\mathrm{cool}}} = \frac{P_{\mathrm{abs}}\tau_{\mathrm{cool}}}{C_n}$$

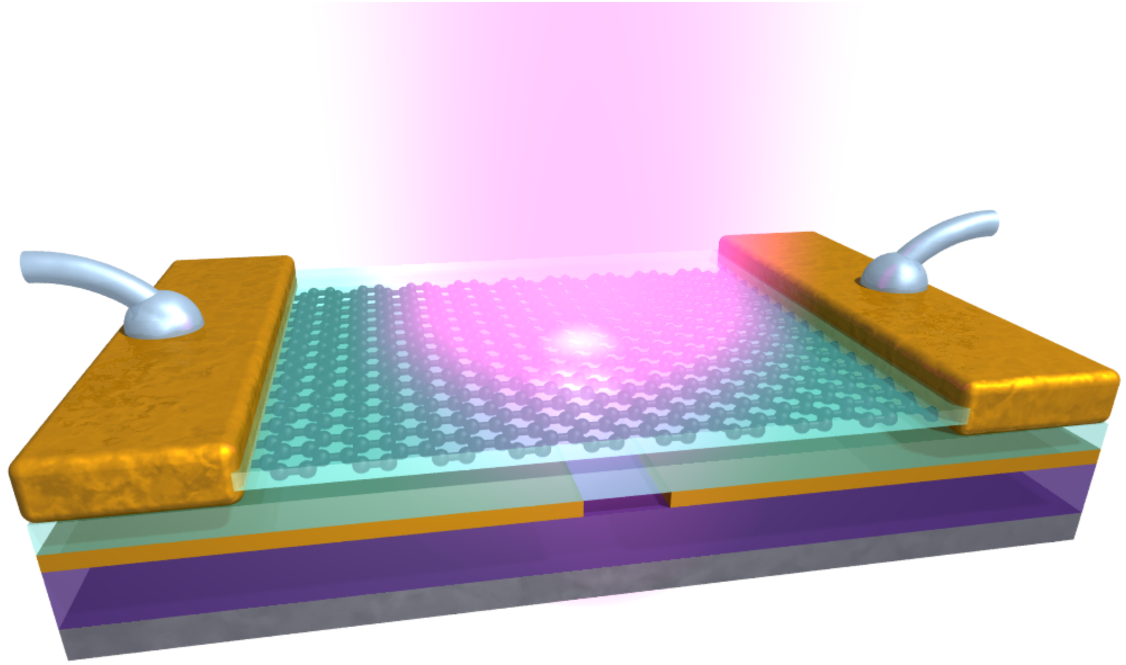
Electron heat → **phonon heat**

→ **Slow electron cooling is beneficial!**

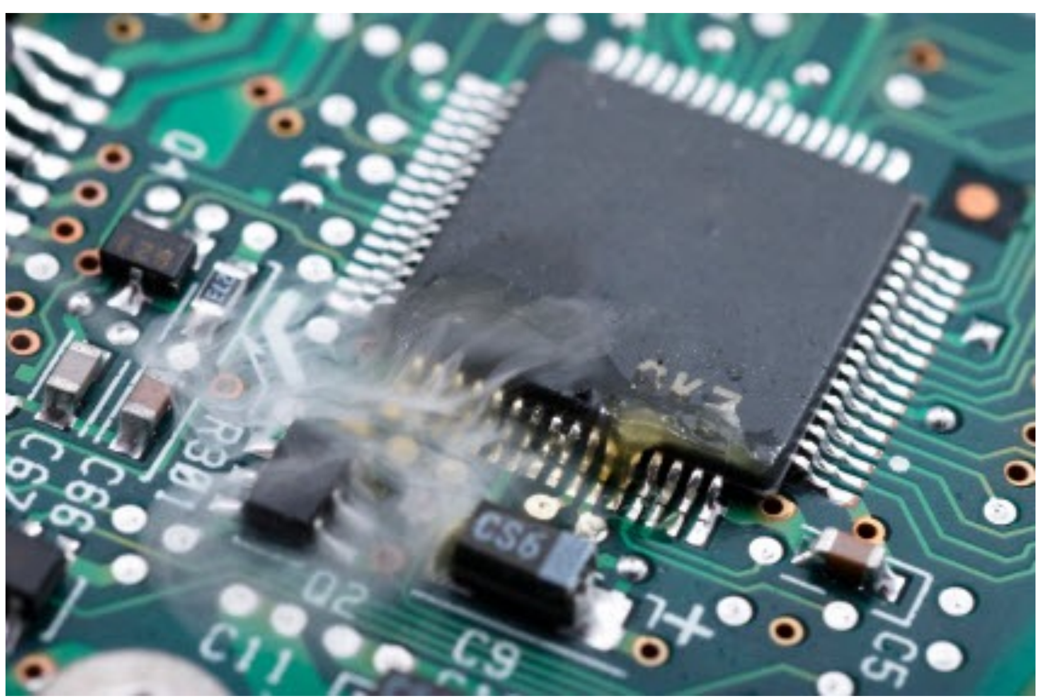
Song et al. *PRL* (2011)
Gabor et al. *Science* (2011)
Koppens et al. *Nature Nano* (2014)

Understand thermal transport

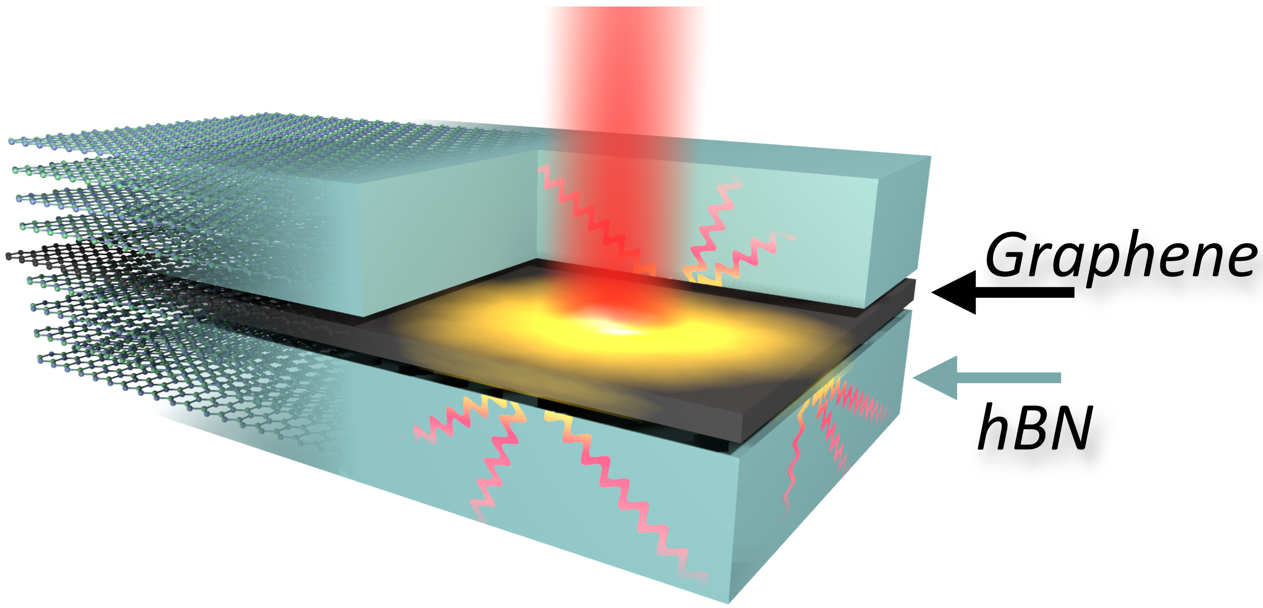
➡ Photodetectors: electron cooling?



➡ Thermal management: ideal substrate = heat sink!

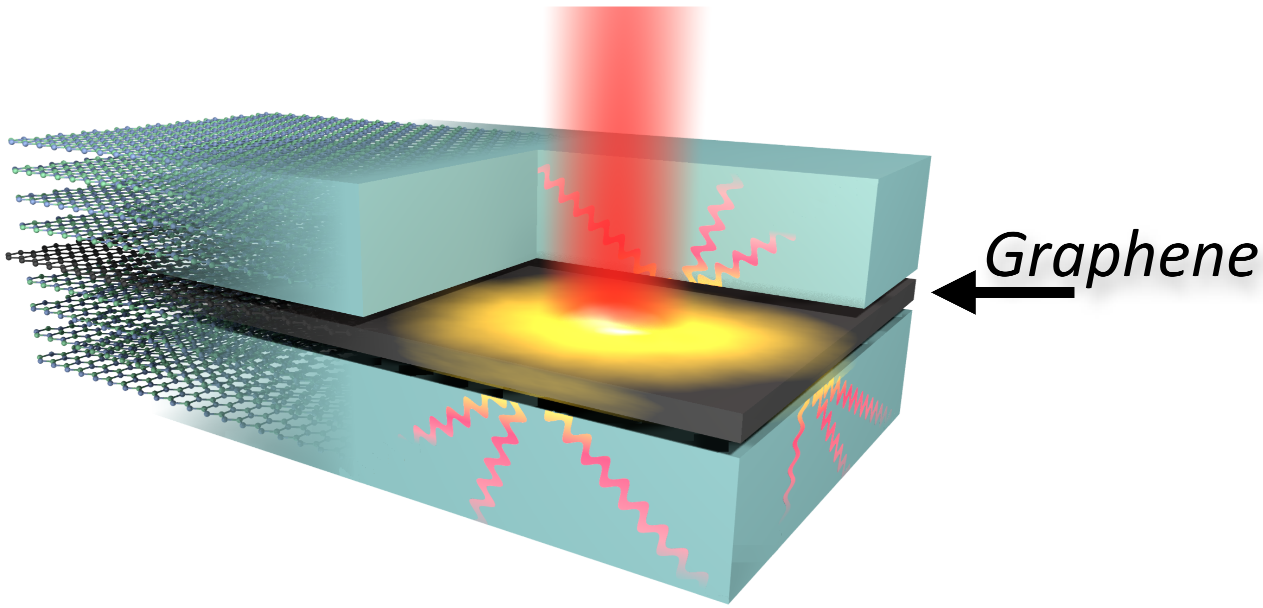


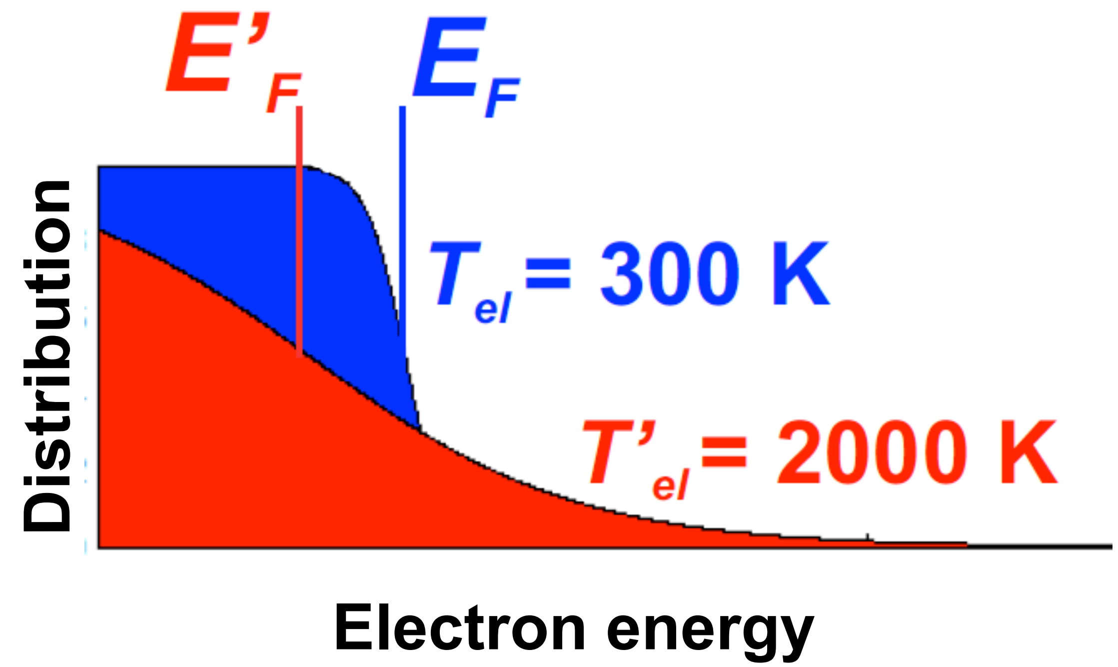
Understand thermal transport



Efficient **out-of-plane** heat transfer:
Hot graphene electrons to **hBN hyperbolic phonon polaritons**

Graphene: Hot electrons

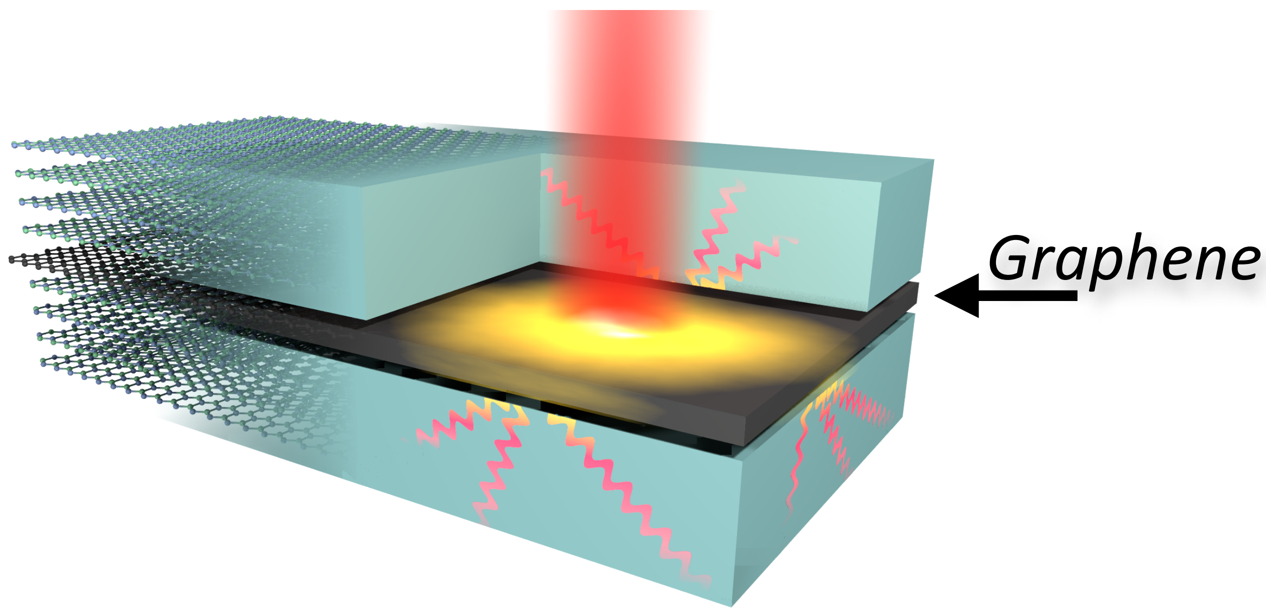


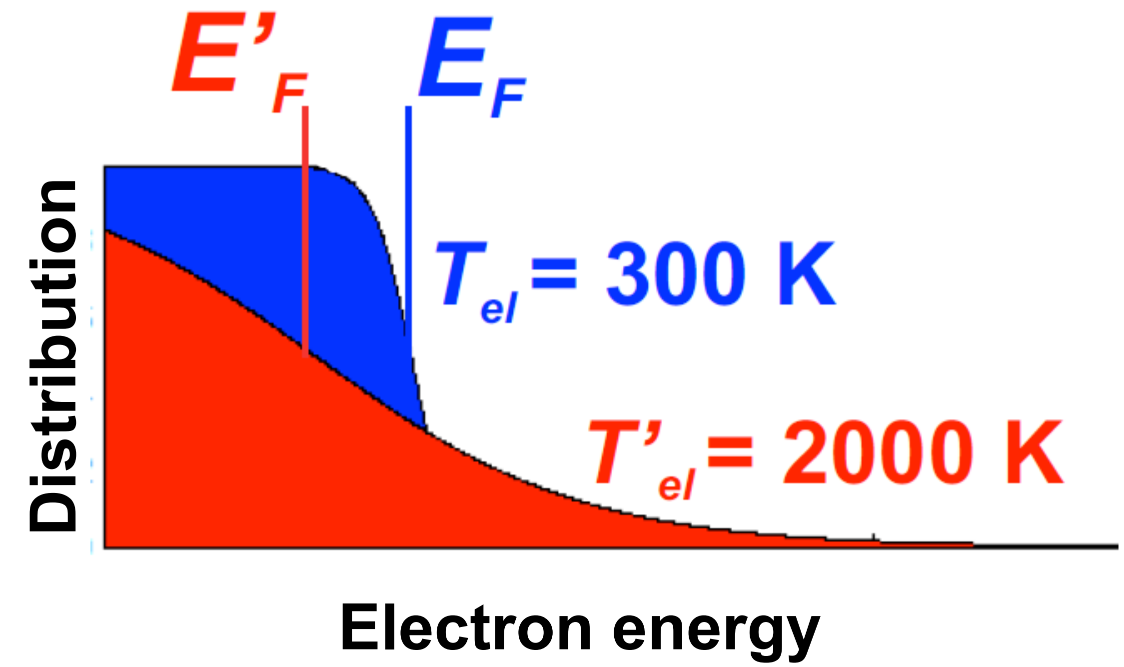


Hot electrons:
broadened Fermi-Dirac distribution

Electron heat ≠ phonon heat

Graphene: Hot electrons

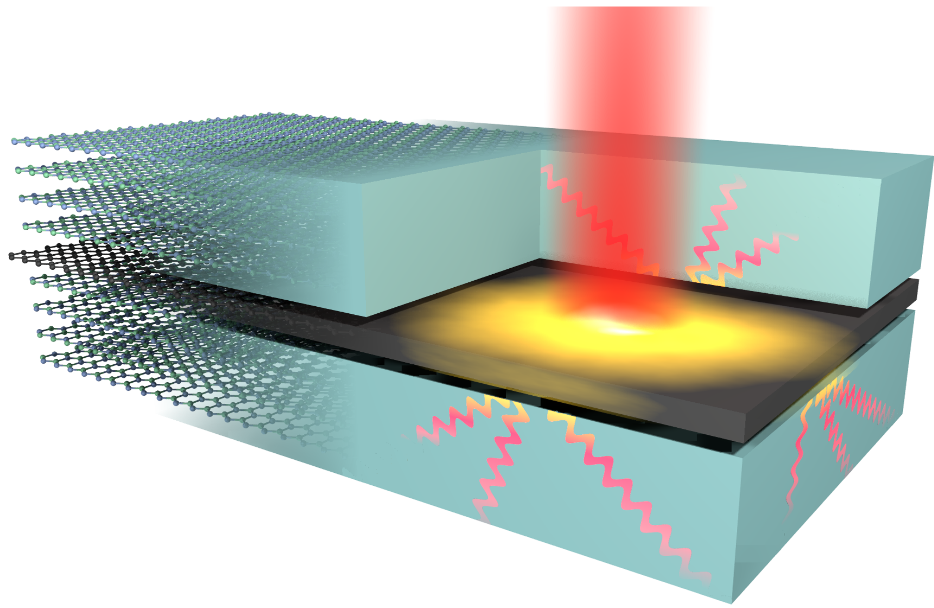


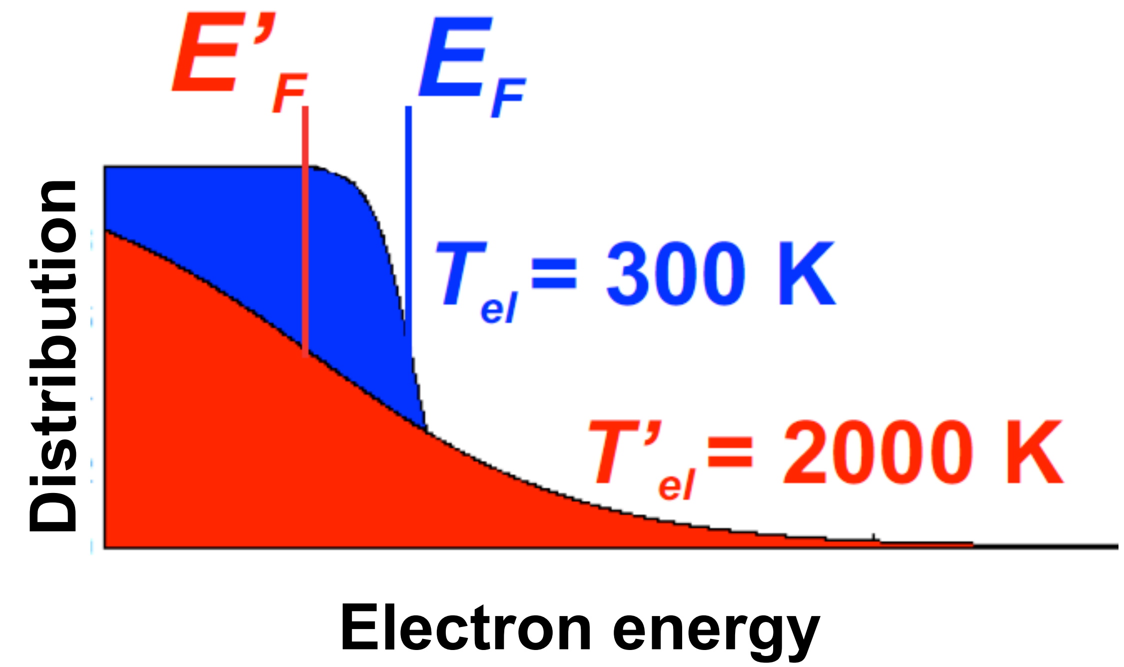


Planck radiation: coupling to *far-field* light in vacuum

$$k < \omega/c$$

Graphene: Hot electrons





Planck radiation: coupling to *far-field* light in vacuum

$$k < \omega/c$$

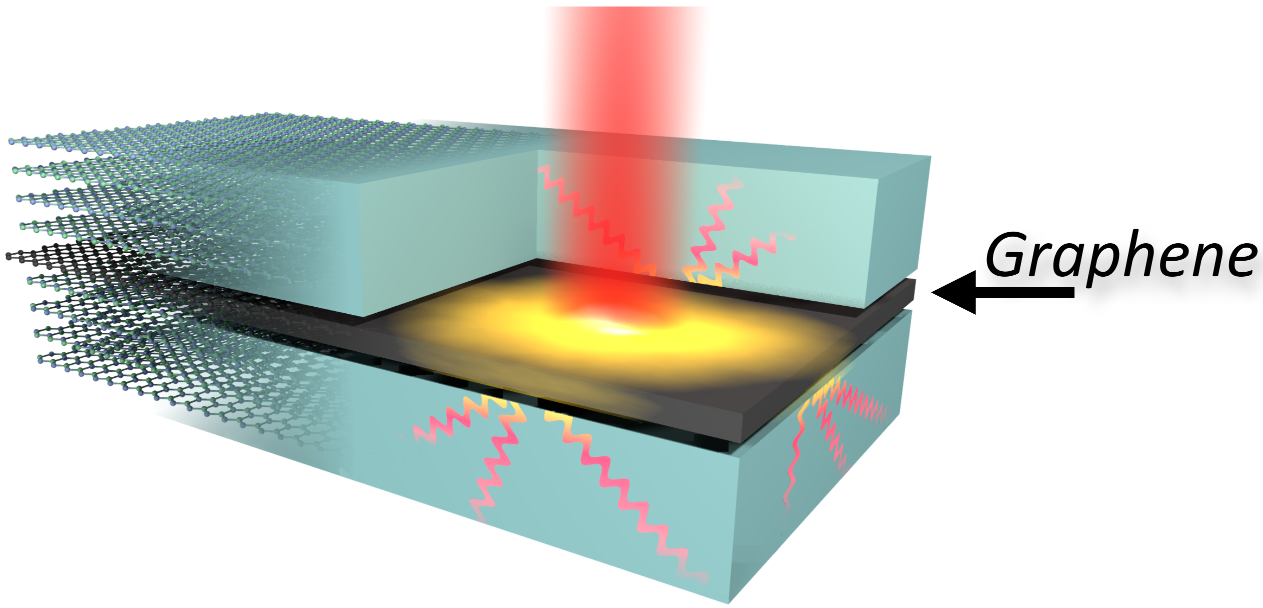
Very inefficient!

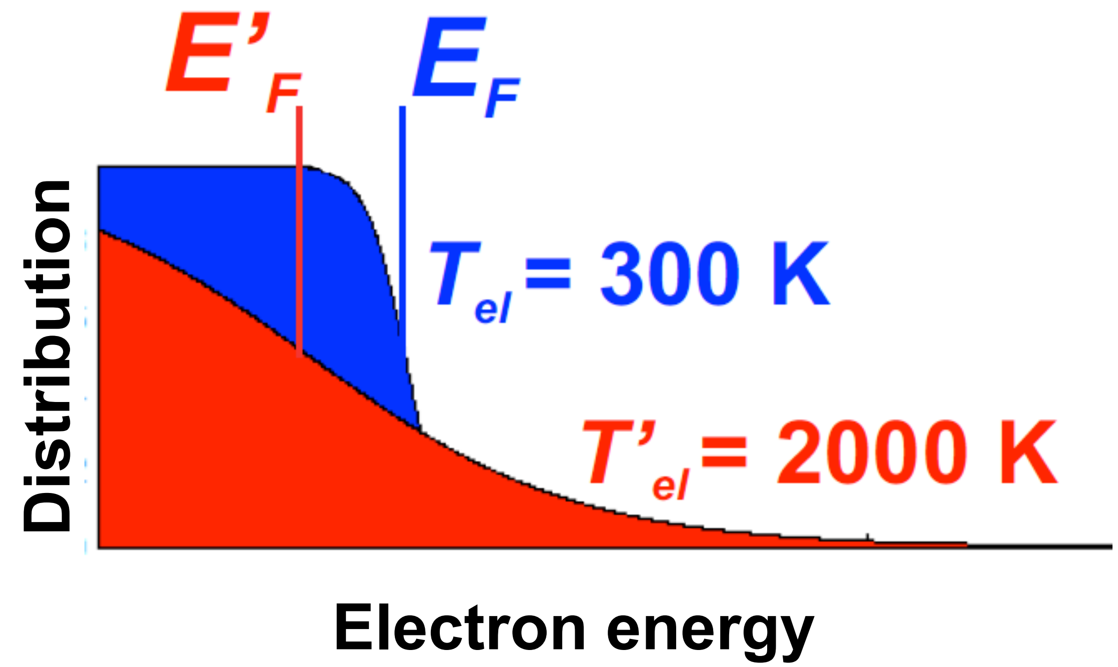
=> Cooling to graphene phonons dominates

(Governed by deformation potential)

Bistritzer and MacDonald, *PRL* (2009)
Song et al. *PRL* (2012)
Graham et al. *Nature Phys.* (2013)
Betz et al. *Nature Phys.* (2013)

Graphene: Hot electrons





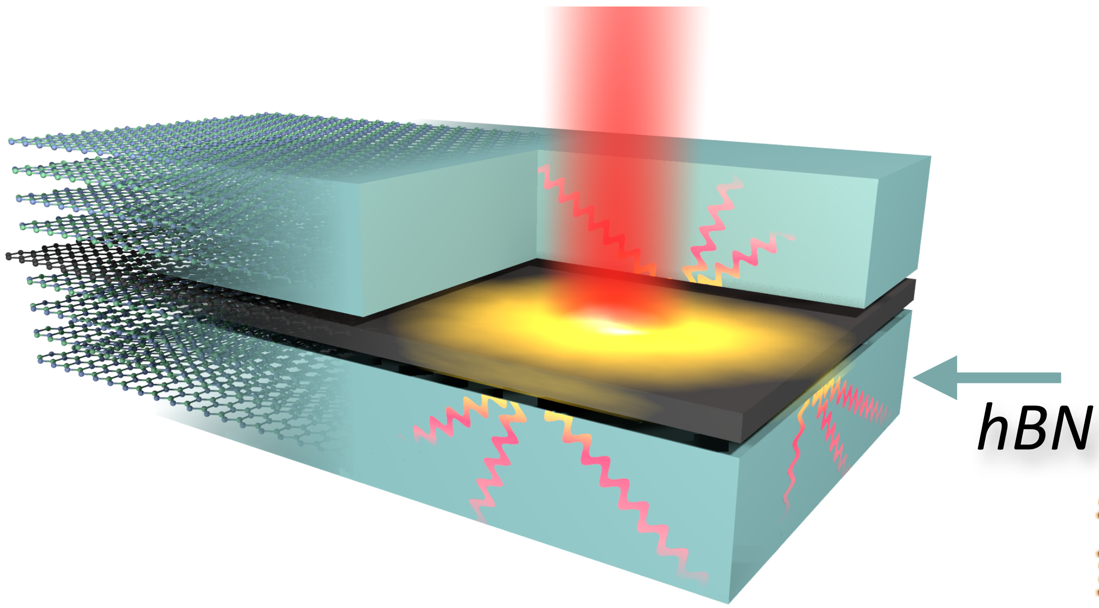
Planck radiation: coupling to *far-field* light in vacuum

$$k < \omega/c$$

Very inefficient!

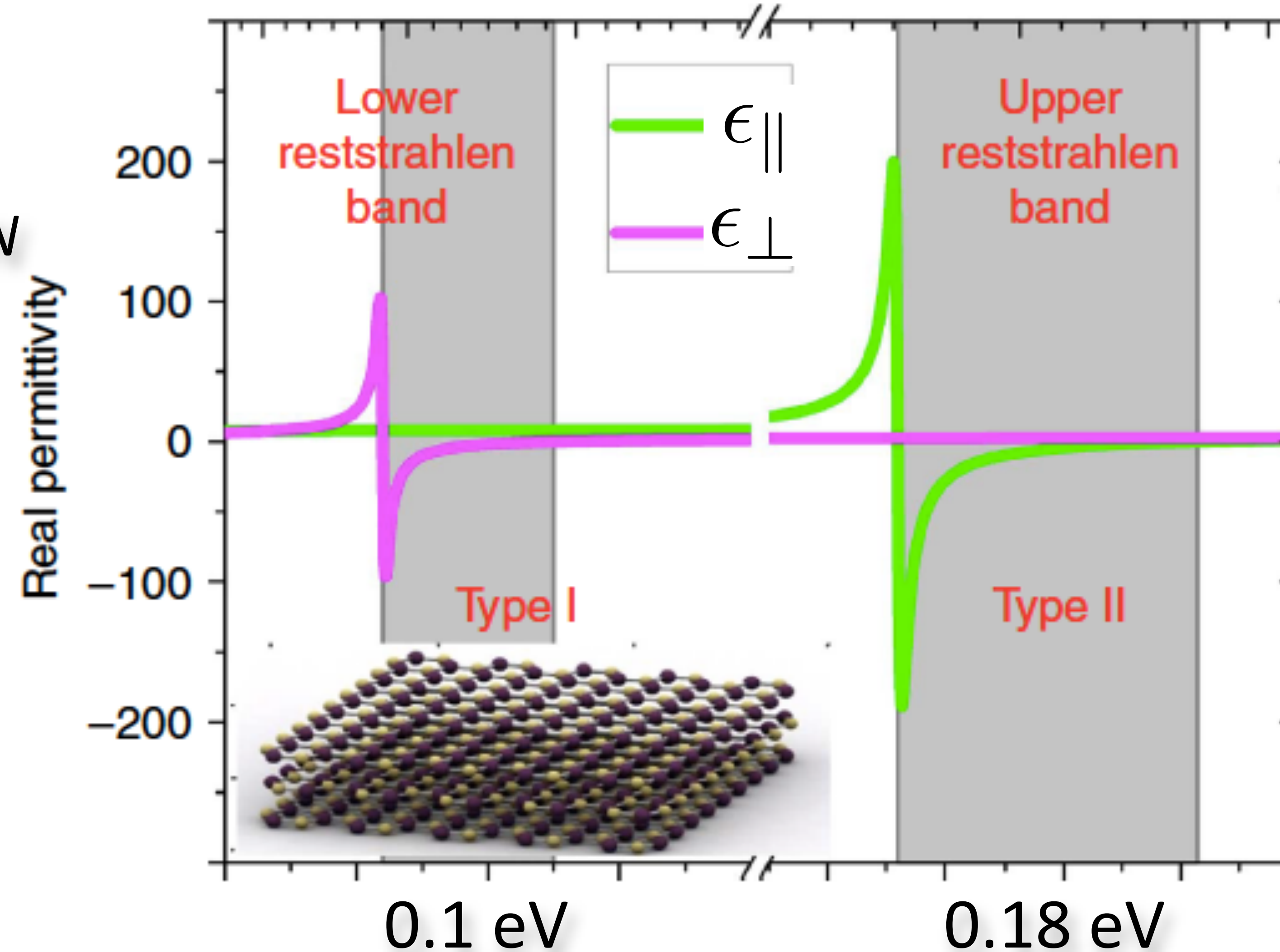
=> What about *near-field* radiation to encapsulant?

hBN: Hyperbolic phonons



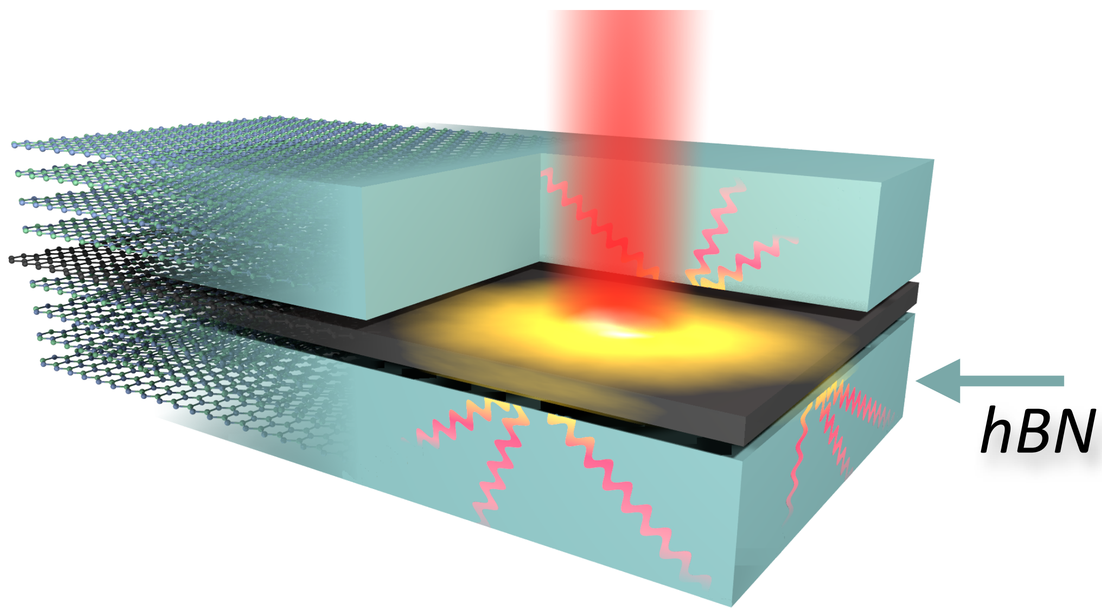
Hyperbolic modes:

$$\mathrm{sgn}(\epsilon_\perp) \neq \mathrm{sgn}(\epsilon_\parallel)$$



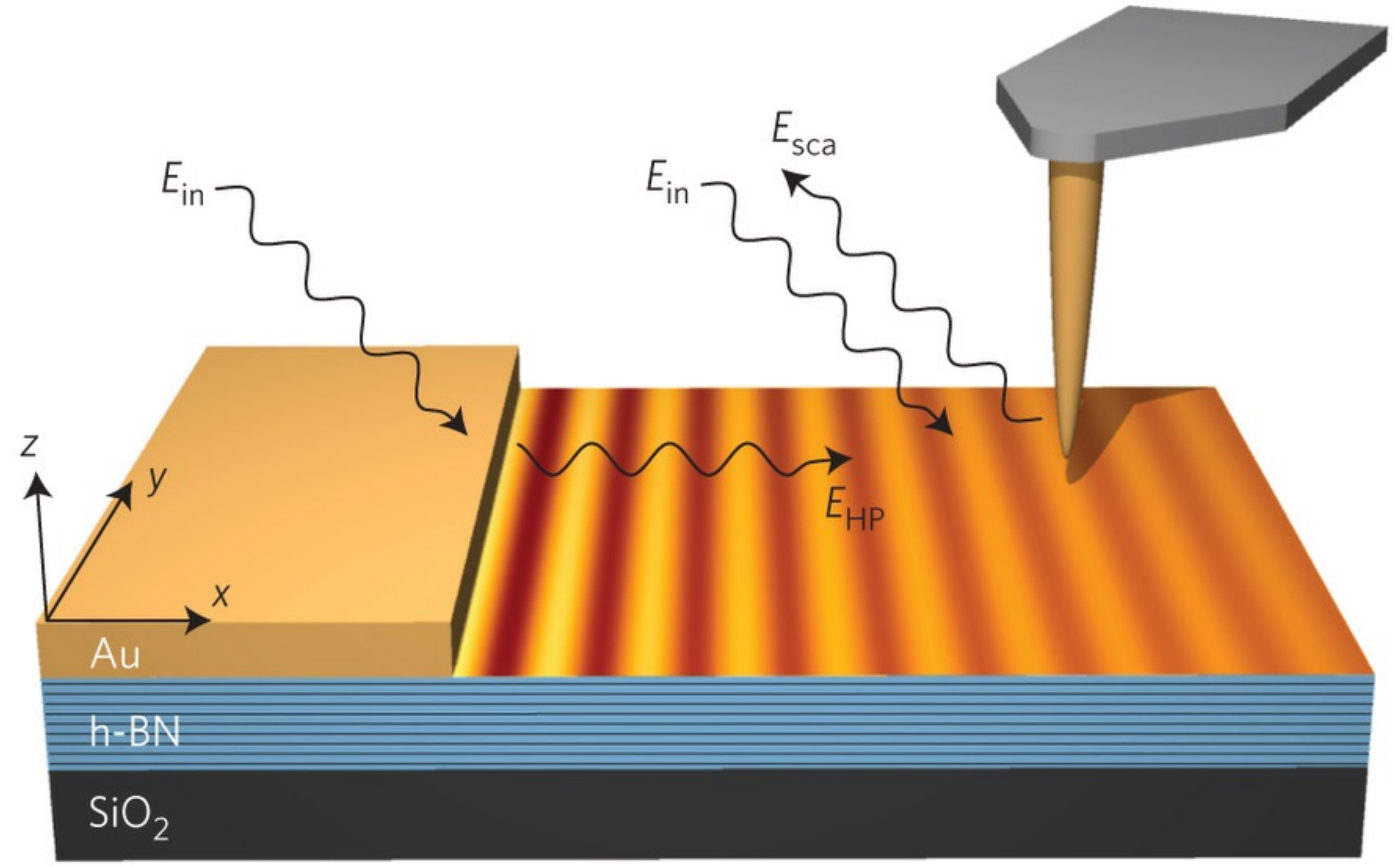
Caldwell et al, *Nature Comm. 5, 5221* (2014)

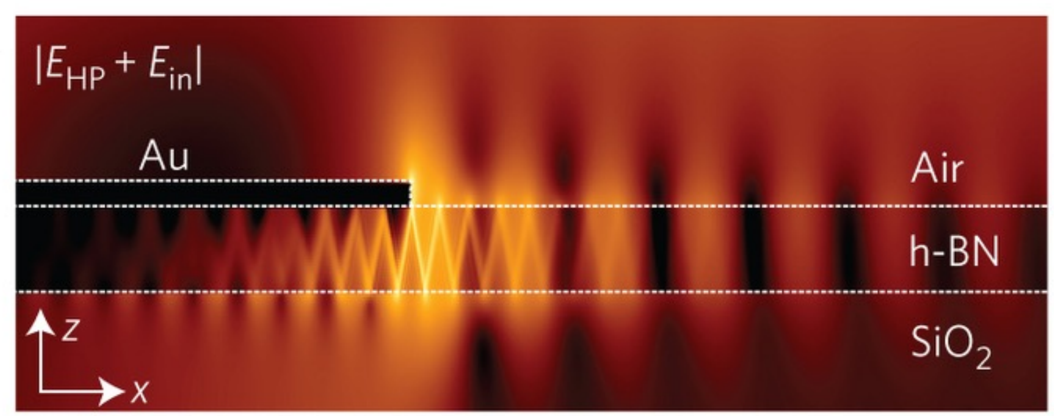
hBN: Hyperbolic phonons



Hyperbolic modes:

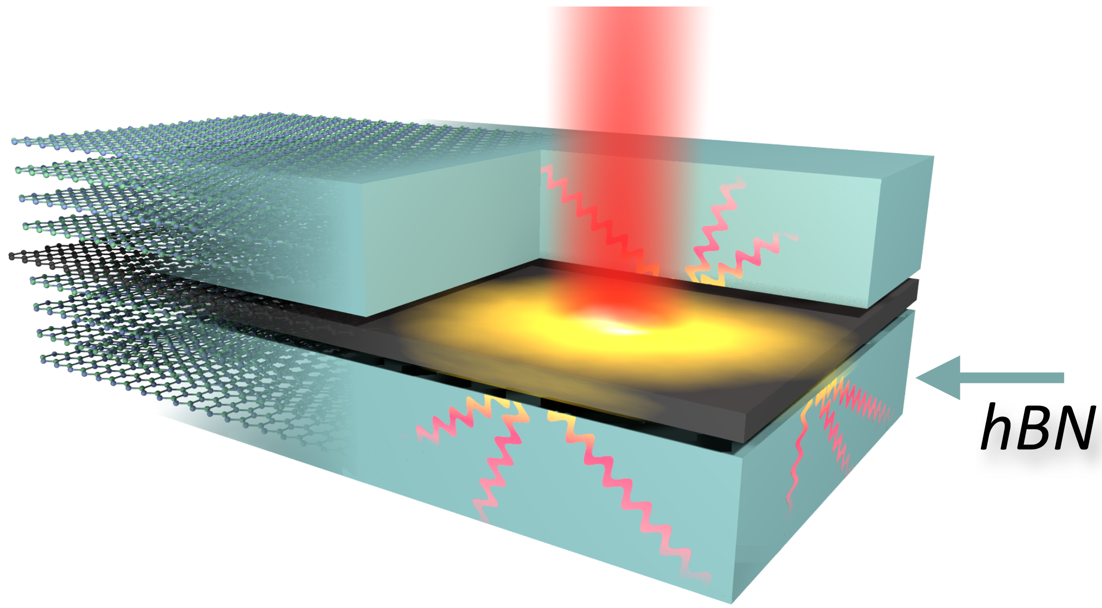
$$\mathrm{sgn}(\epsilon_\perp) \neq \mathrm{sgn}(\epsilon_\parallel)$$





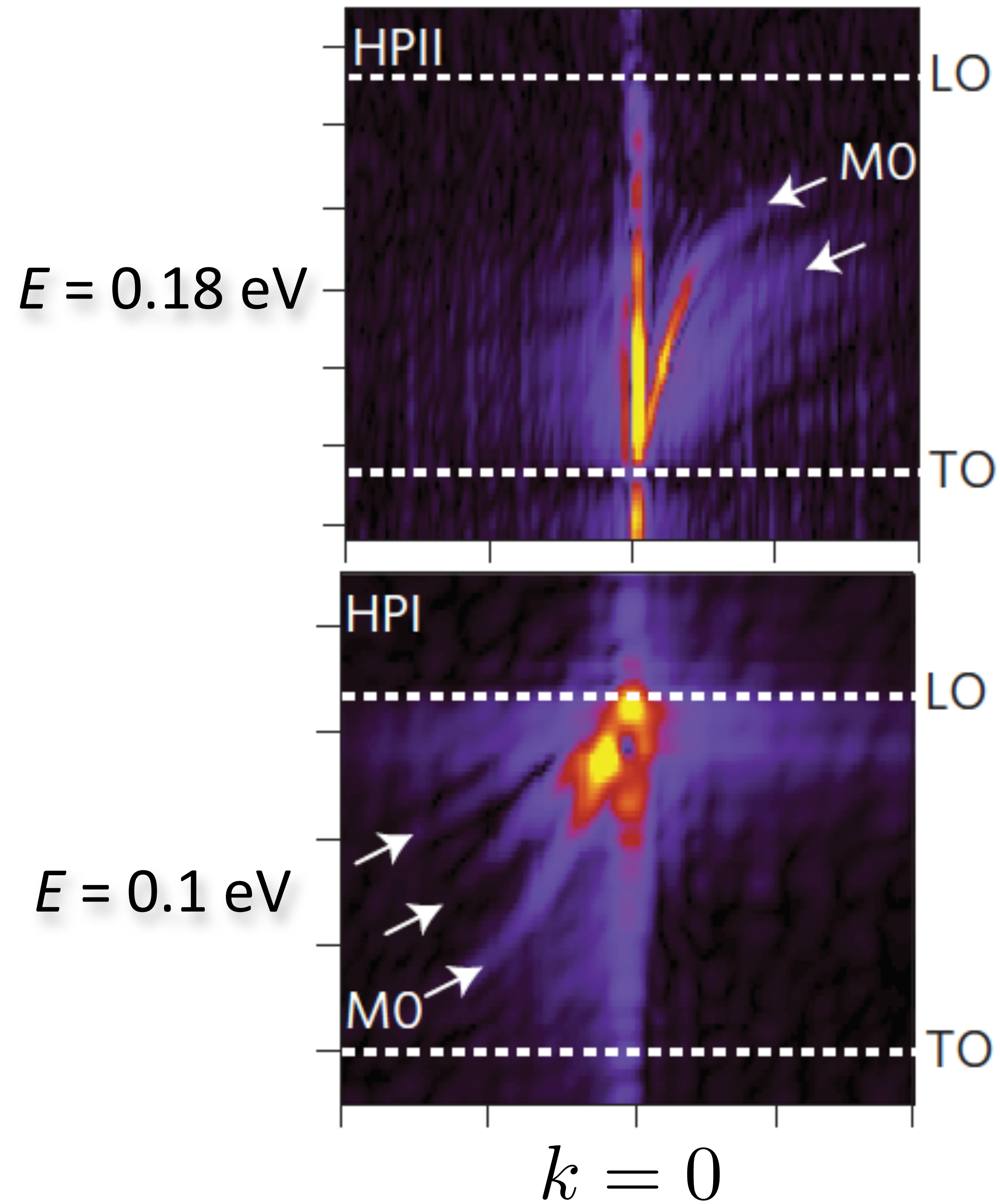
Yoxall et al, *Nature Photon.* (2015)

hBN: Hyperbolic phonons



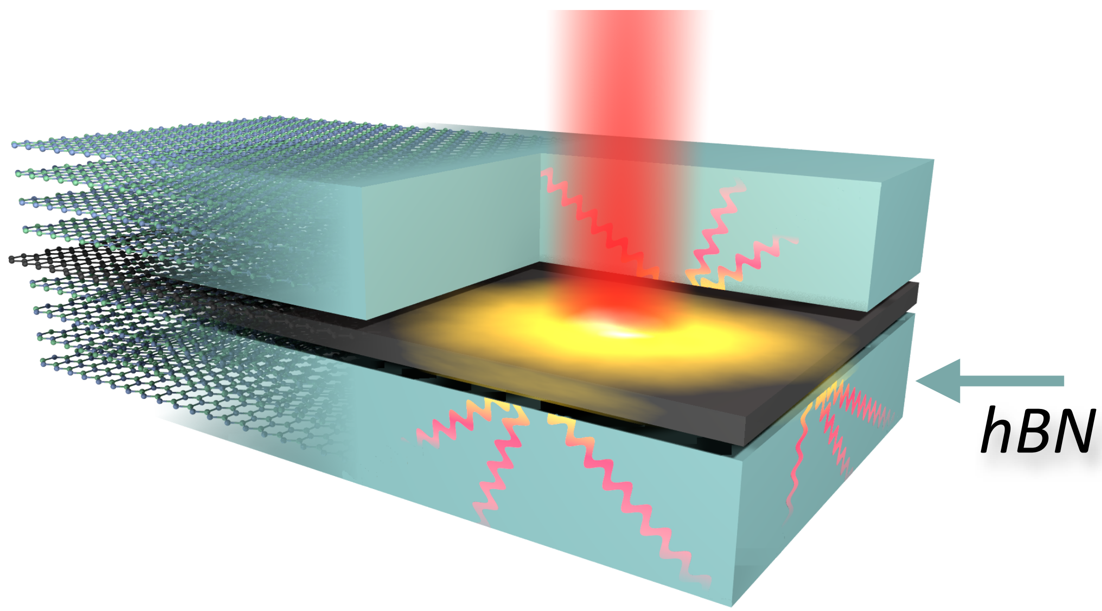
Hyperbolic modes:

$$\mathrm{sgn}(\epsilon_\perp) \neq \mathrm{sgn}(\epsilon_\parallel)$$



Yoxall et al, *Nature Photon.* (2015)

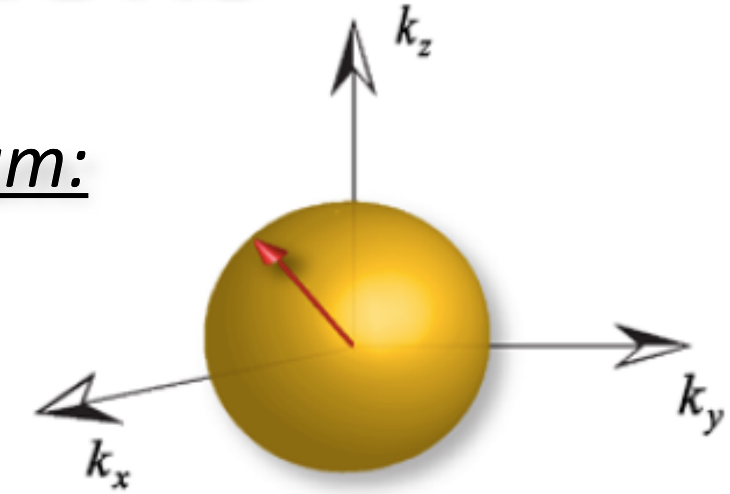
hBN: Hyperbolic phonons



Isotropic medium:

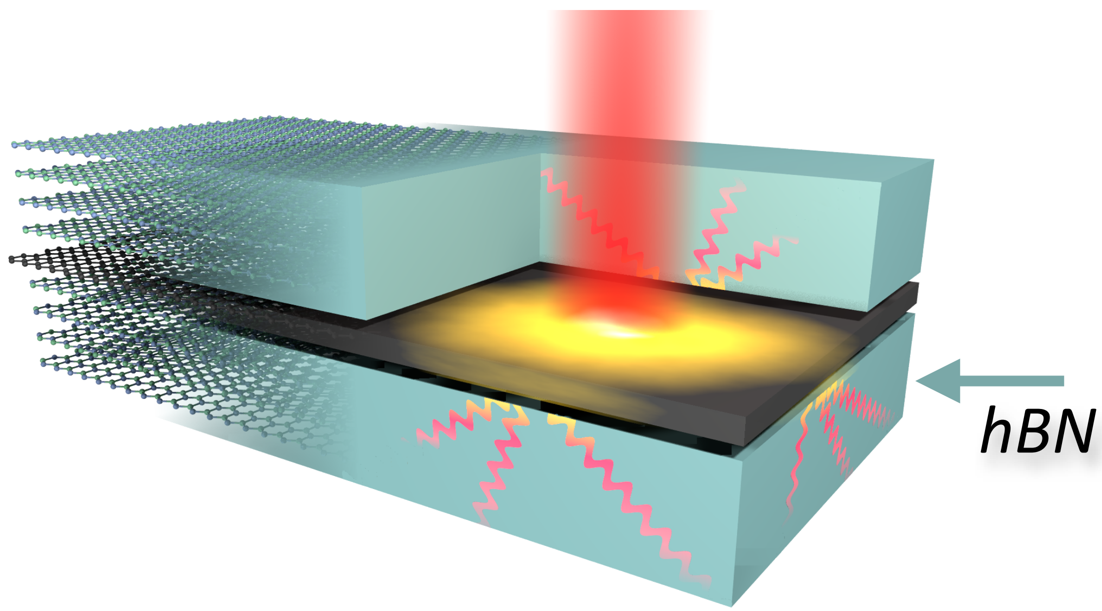
$$\epsilon_\perp = \epsilon_\parallel$$

$$k = \omega / c$$



Jacob et al, *Appl. Phys. B 100, 215* (2010)

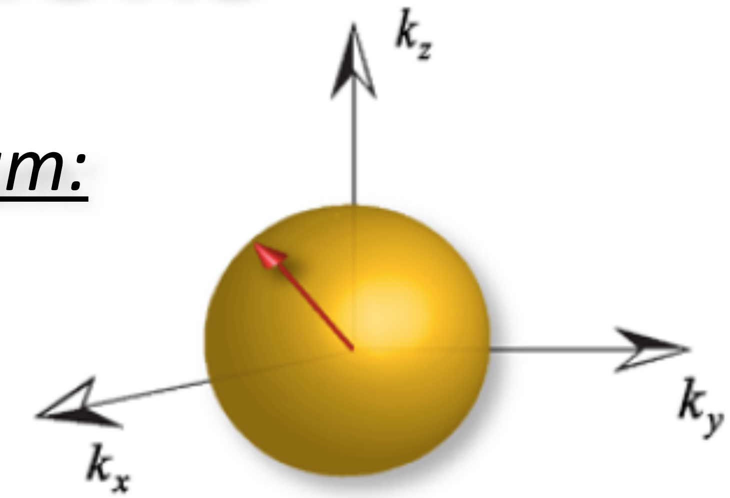
hBN: Hyperbolic phonons



<u>*Isotropic medium:*</u>

$$\epsilon_\perp = \epsilon_\parallel$$

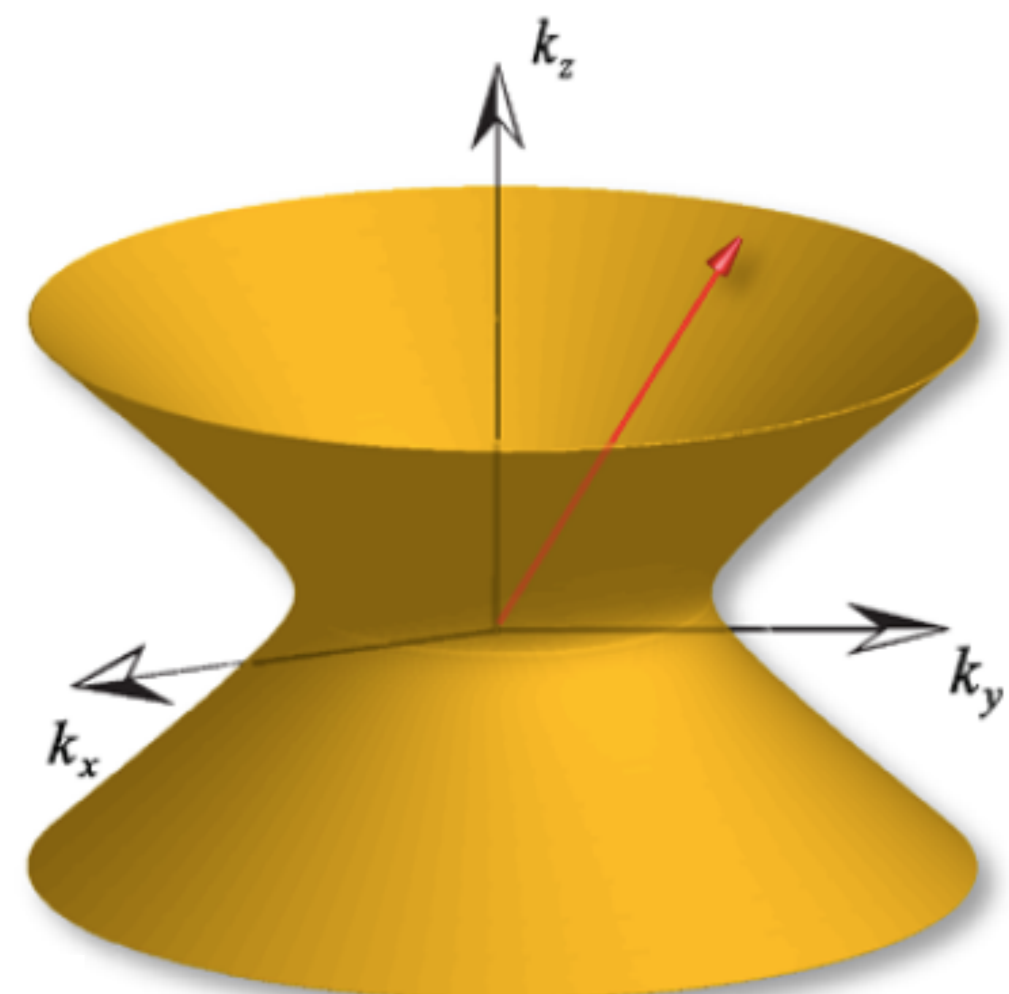
$$k = \omega/c$$



<u>*Hyperbolic mode (Type II):*</u>

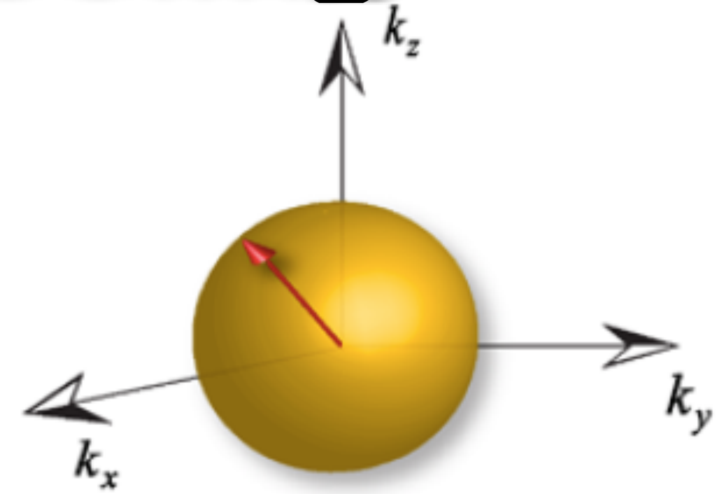
$$\mathrm{sgn}(\epsilon_\perp) \neq \mathrm{sgn}(\epsilon_\parallel)$$

$$k \gg \omega/c$$



Jacob et al, *Appl. Phys. B 100, 215* (2010)

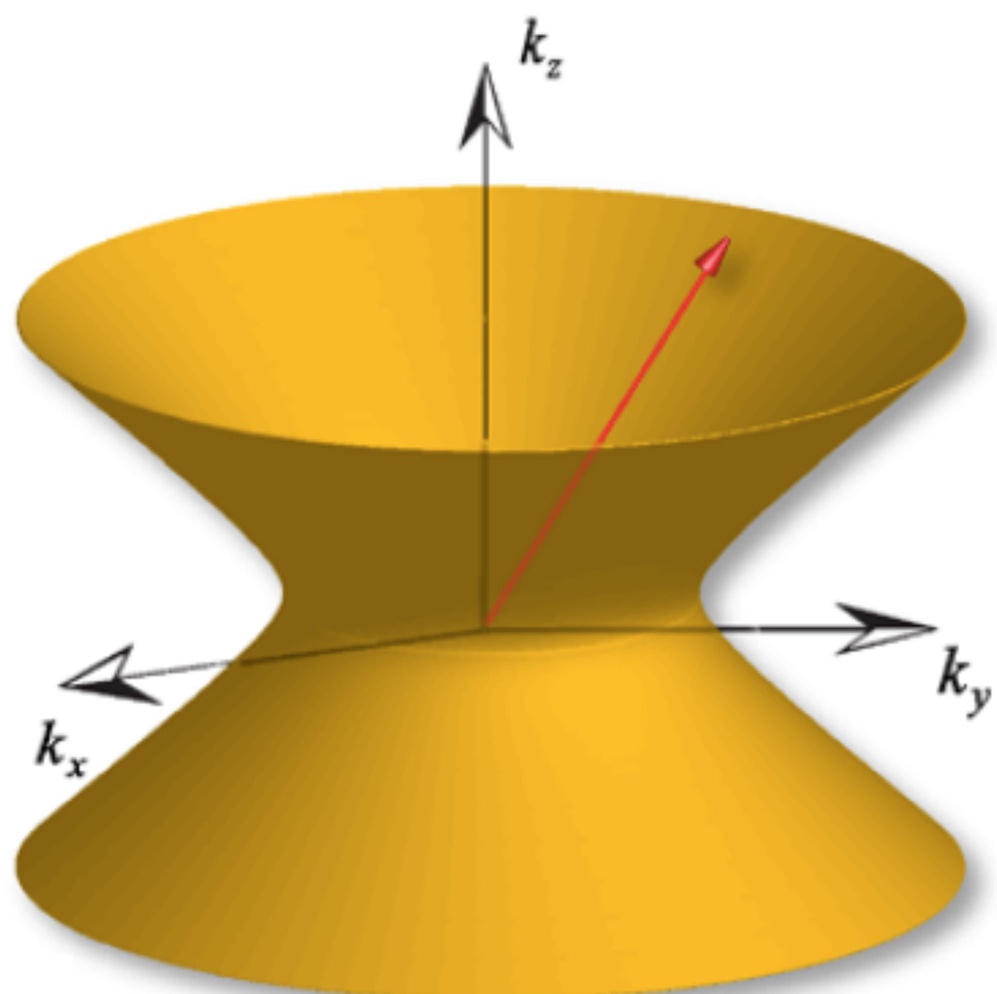
Near-field, hyperbolic cooling



Graphene in vacuum

- Light cone with restricted *k*-vectors
- *Low thermal energy density*

→ **Blackbody Planck radiation (inefficient)**



Near-field, hyperbolic cooling

Graphene in vacuum

- Light cone with restricted *k*-vectors
- *Low thermal energy density*

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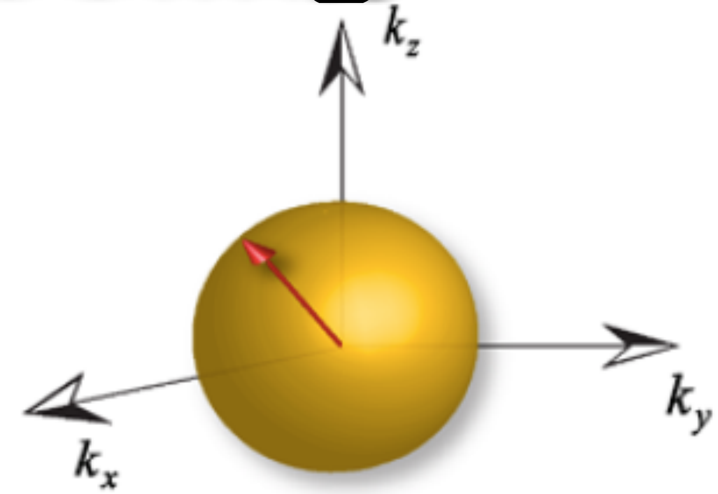
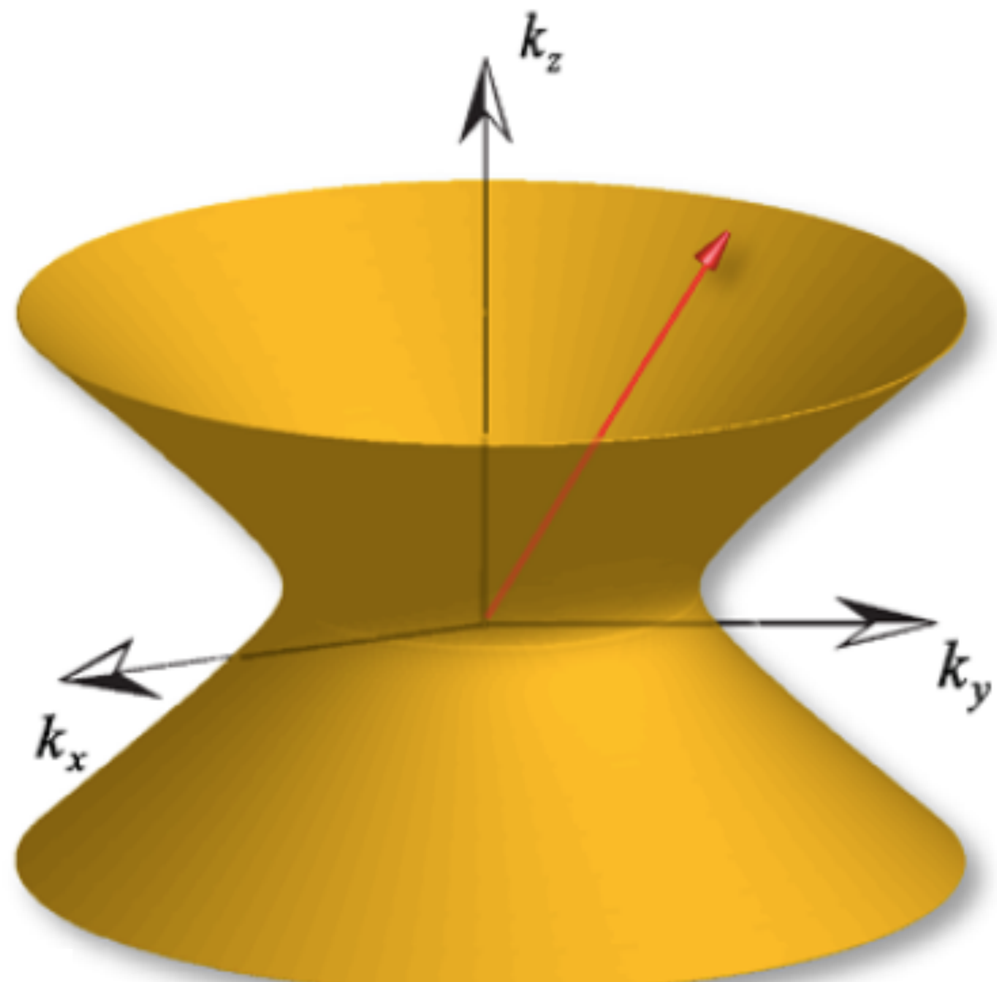


hBN-encapsulated graphene

- Hyperbolic modes with near-infinite range of *k*-vectors
- *High thermal energy density*

→ **Super-Planckian radiation (very efficient)**



More efficient than graphene phonon cooling?

Experiment

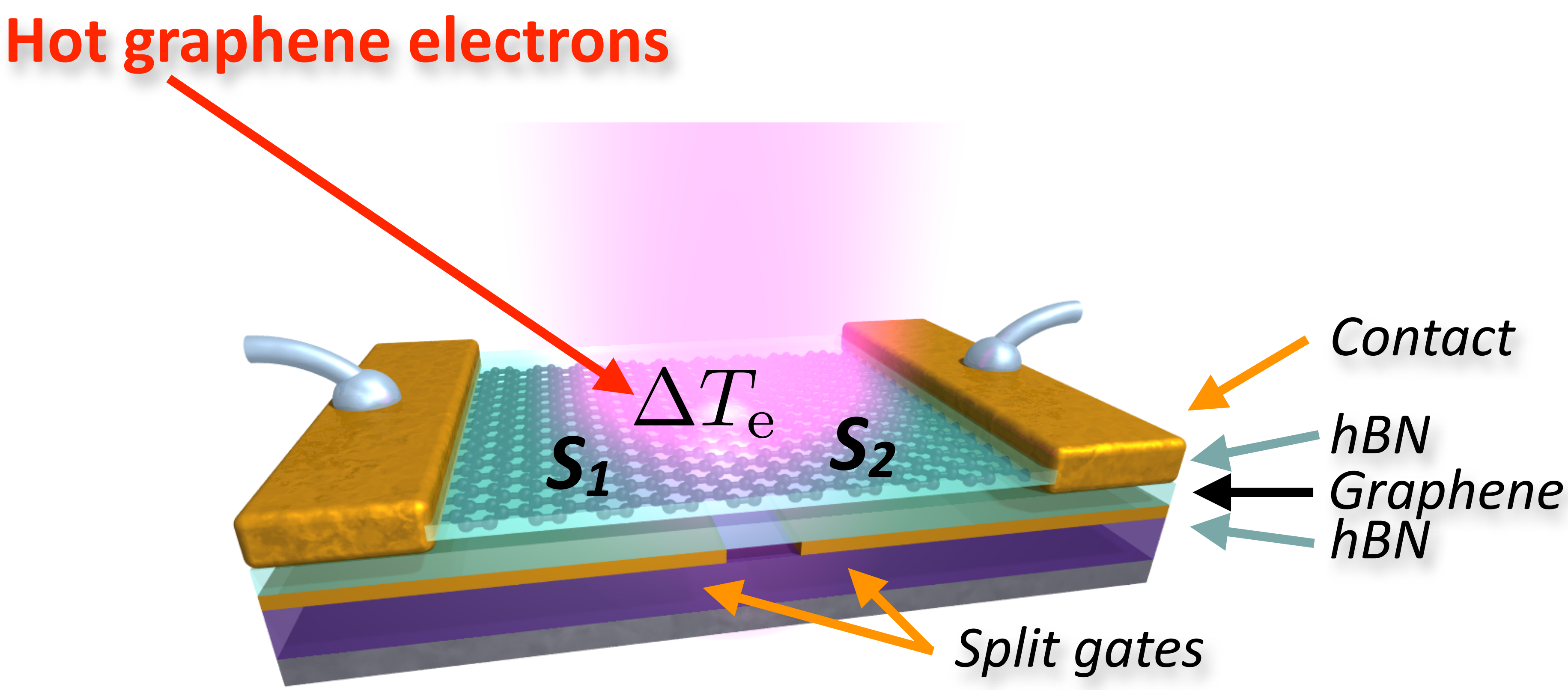
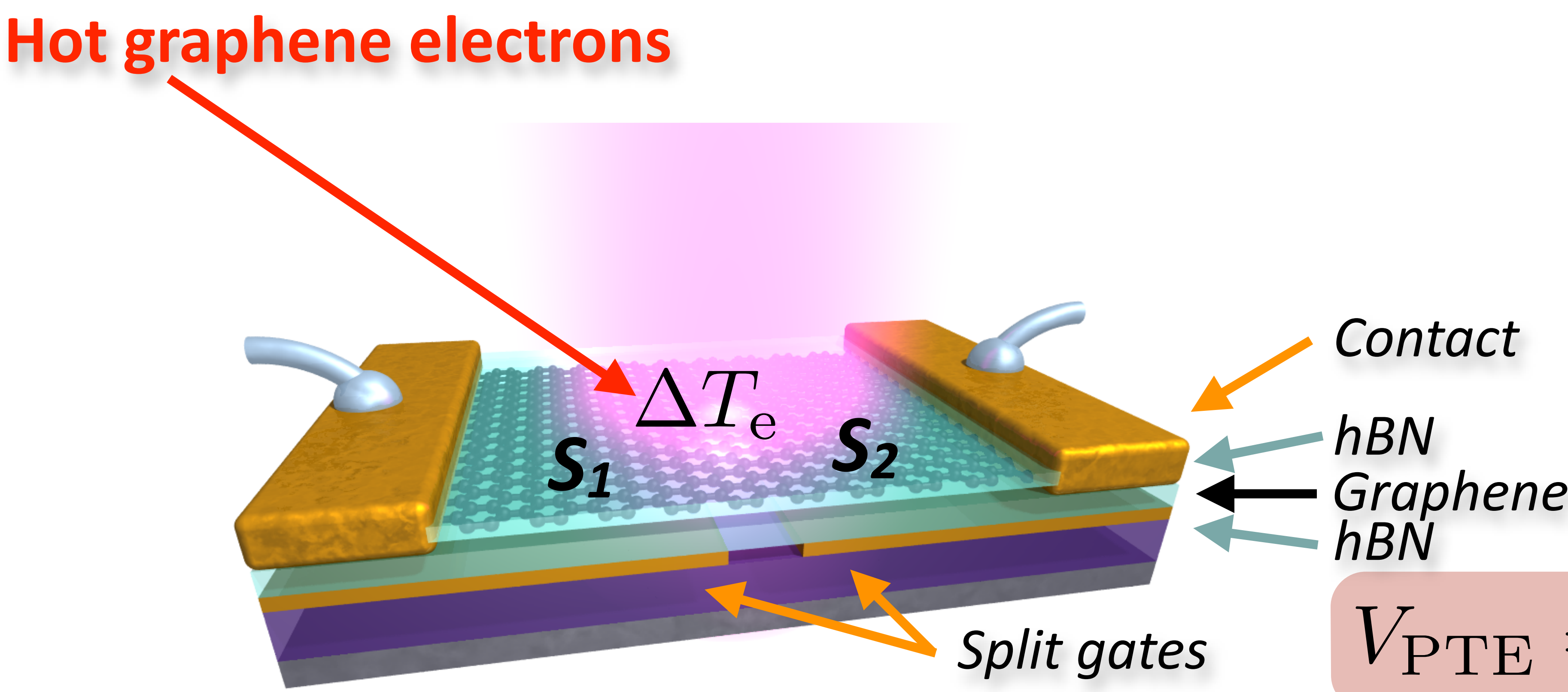


Photo-thermoelectric (PTE) detector

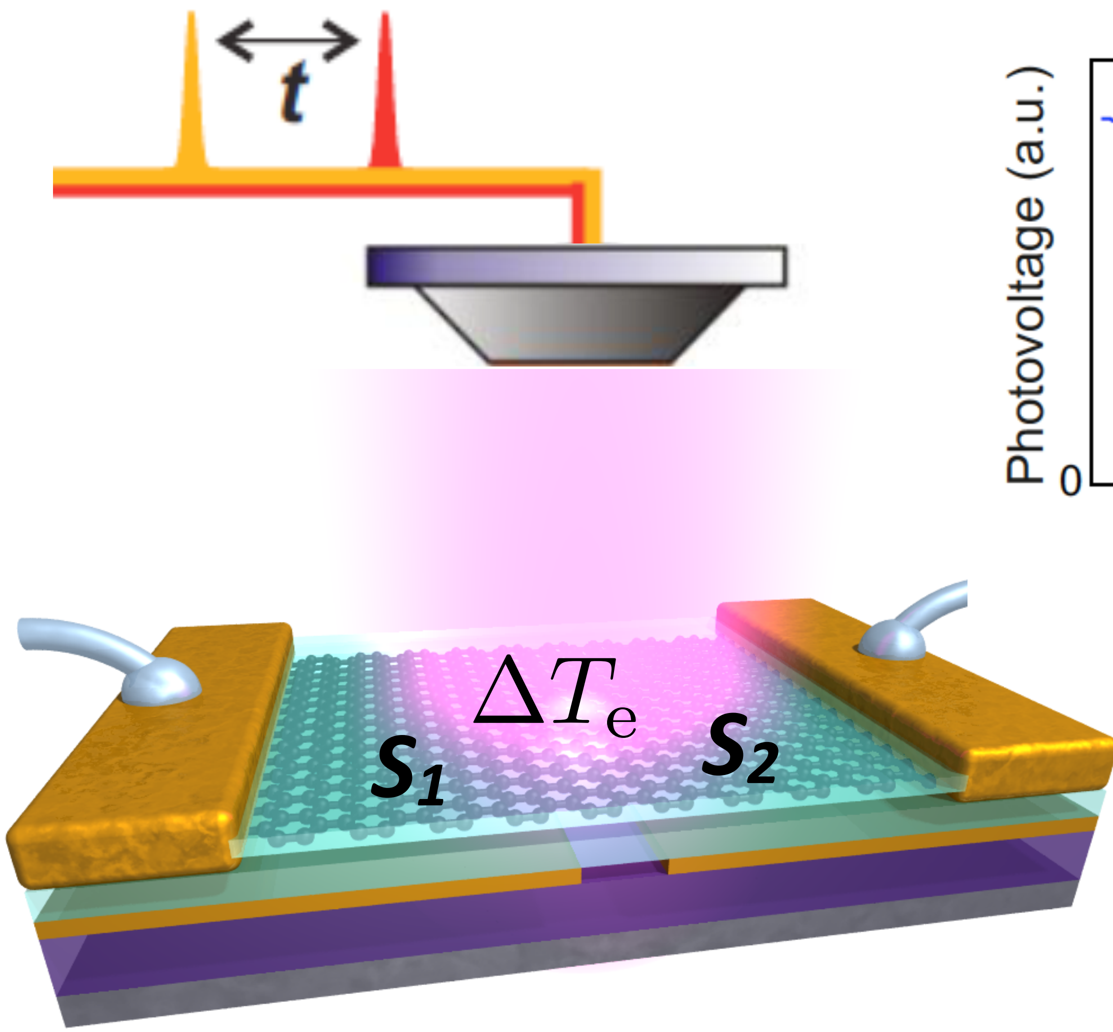
Experiment

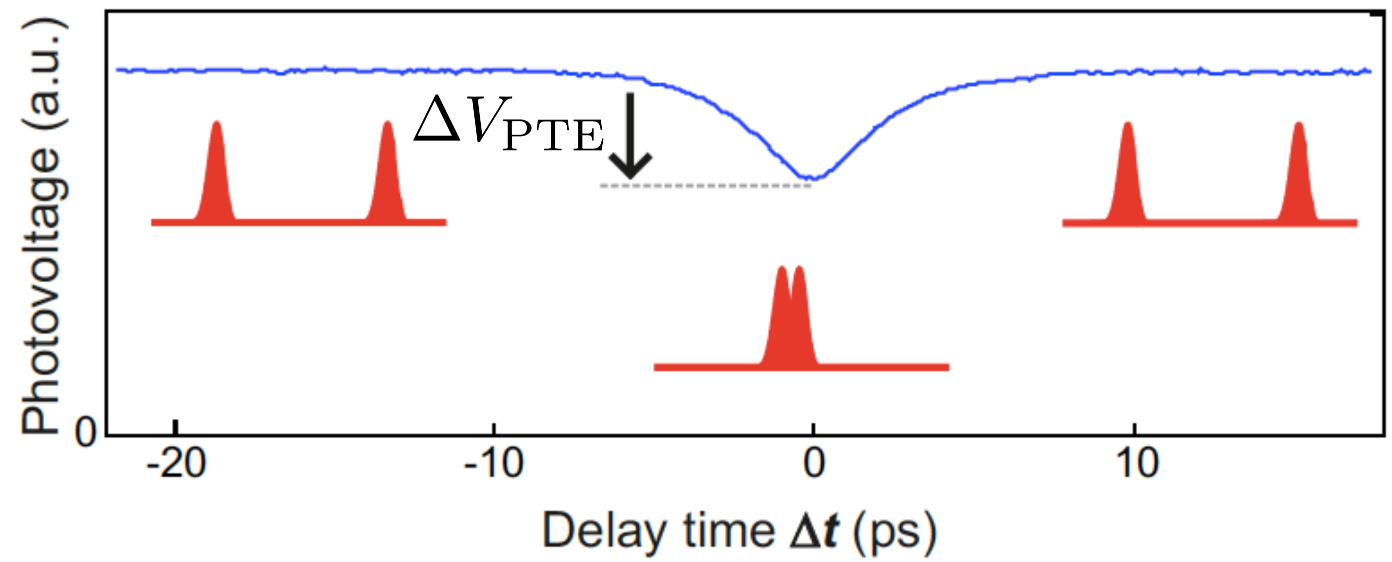


$$V_{PTE} = (S_2 - S_1)\Delta T_e$$

Photo-thermoelectric (PTE) detector

Experiment



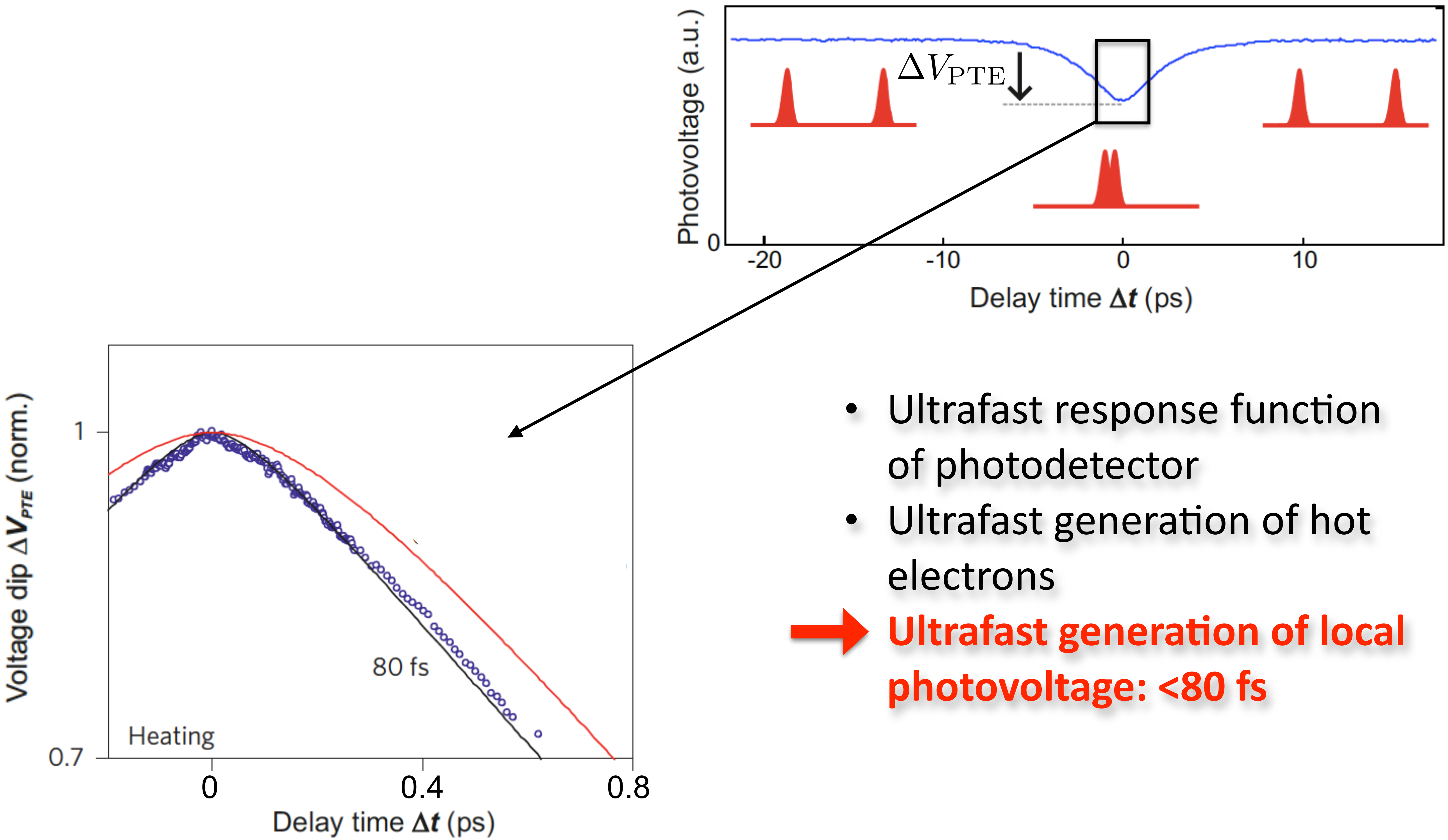


$$V_{\mathrm{PTE}} = (S_2 - S_1)\Delta T_{\mathrm{e}}$$

$$\Delta V_{\mathrm{PTE}}(\Delta t) \sim \Delta T_{\mathrm{e}}(\Delta t)$$

Access to temperature dynamics!

Ultrafast heating

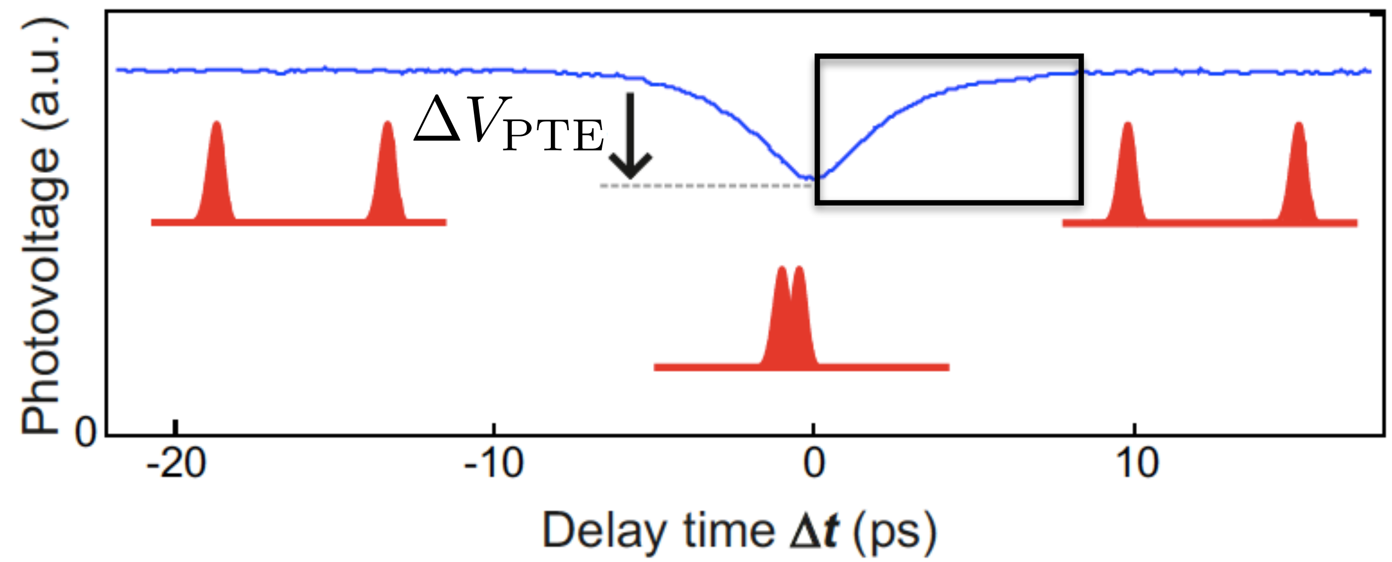


- Ultrafast response function of photodetector
- Ultrafast generation of hot electrons

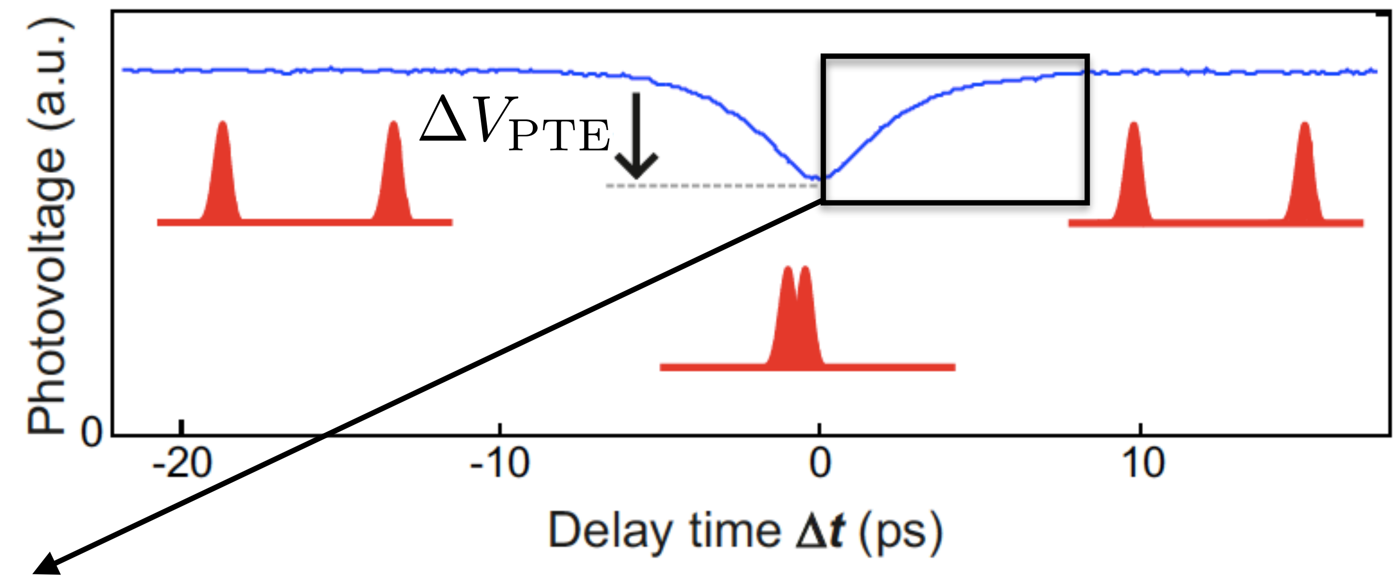
➡ **Ultrafast generation of local photovoltage: <80 fs**

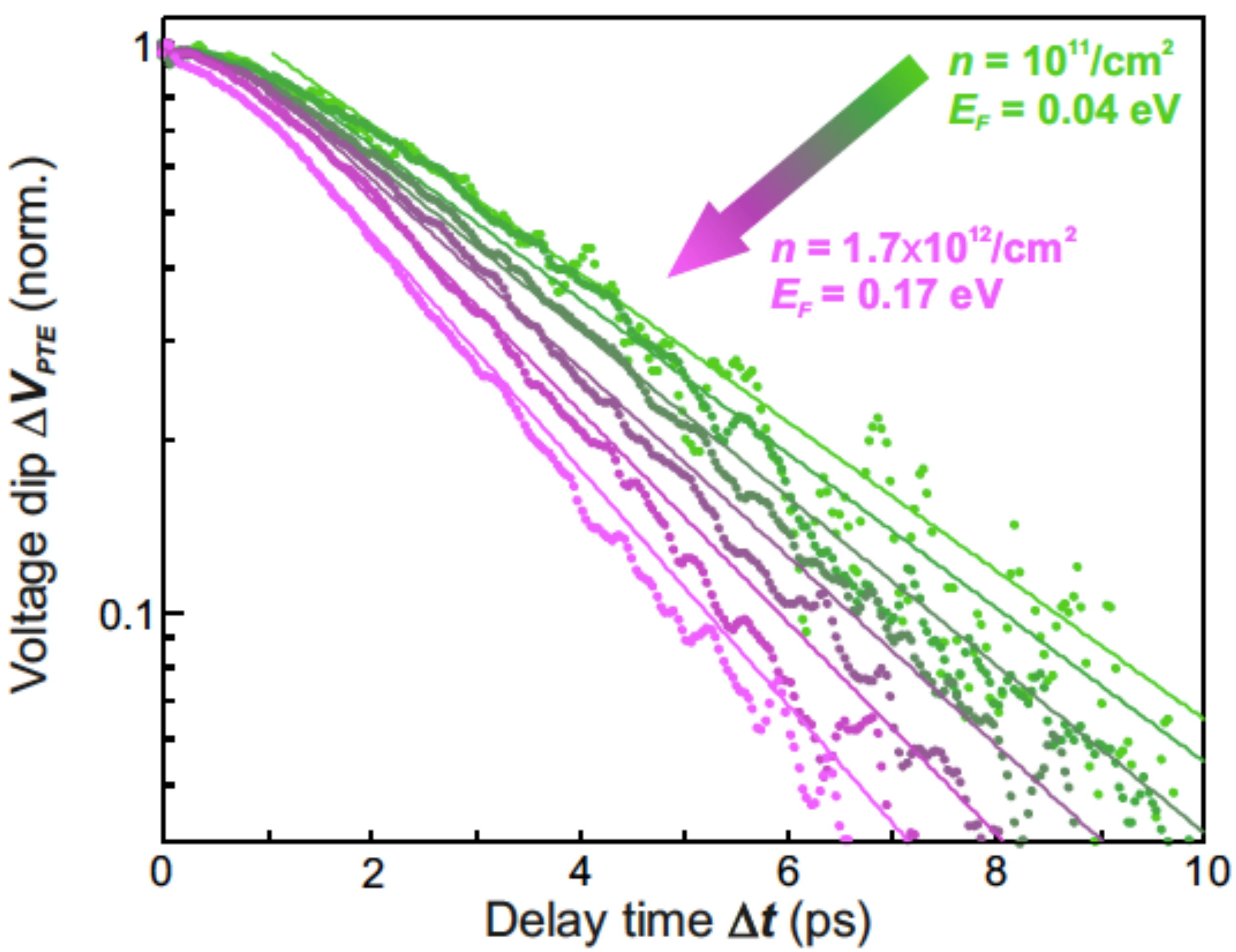
Tielrooij et al. *Nature Nano 10, 437* (2015)

Cooling: varying carrier density



Cooling: varying carrier density





→ **Cooling time ~2-3 ps**

→ **Faster cooling for *higher* density**

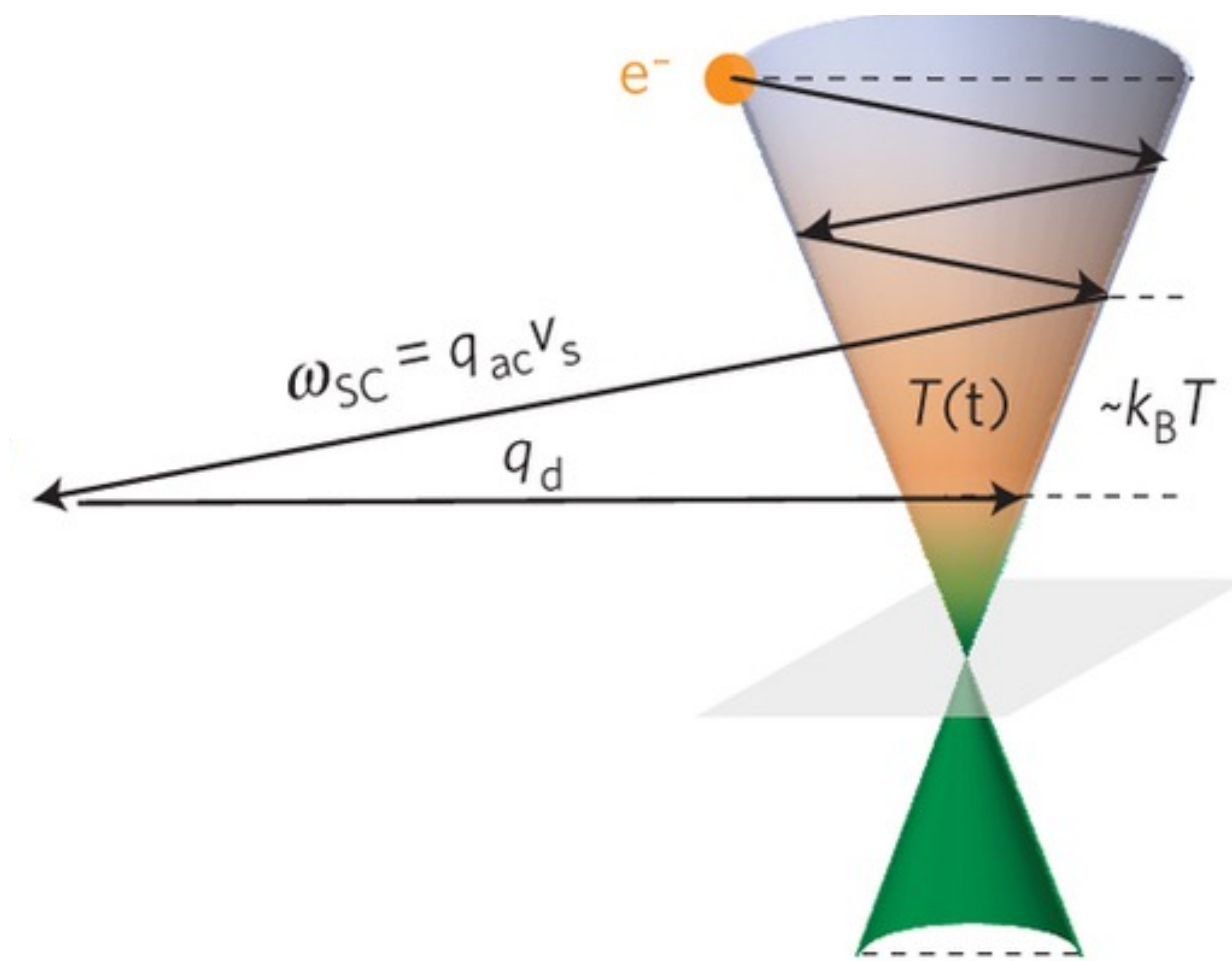
Tielrooij et al, *Arxiv*:1702.03766 (2017)

Super-collision cooling?

Disorder-assisted scattering with acoustic graphene phonons:

Graham et al. *Nature Phys* (2013)
Song et al. *PRL* (2012)

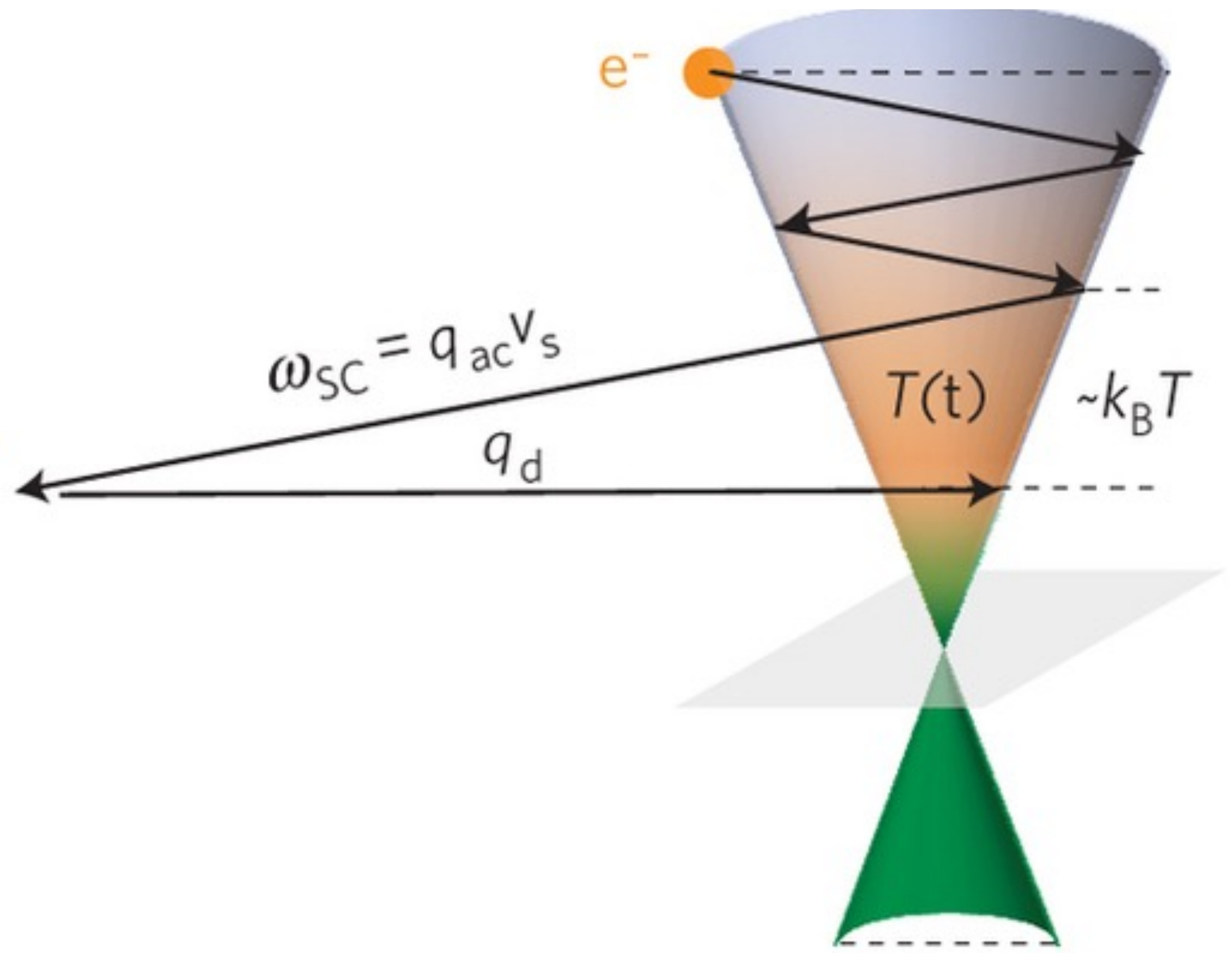
- Deformation potential
- Disorder density



Super-collision cooling?

- Super-collision cooling is faster for *lower* carrier density

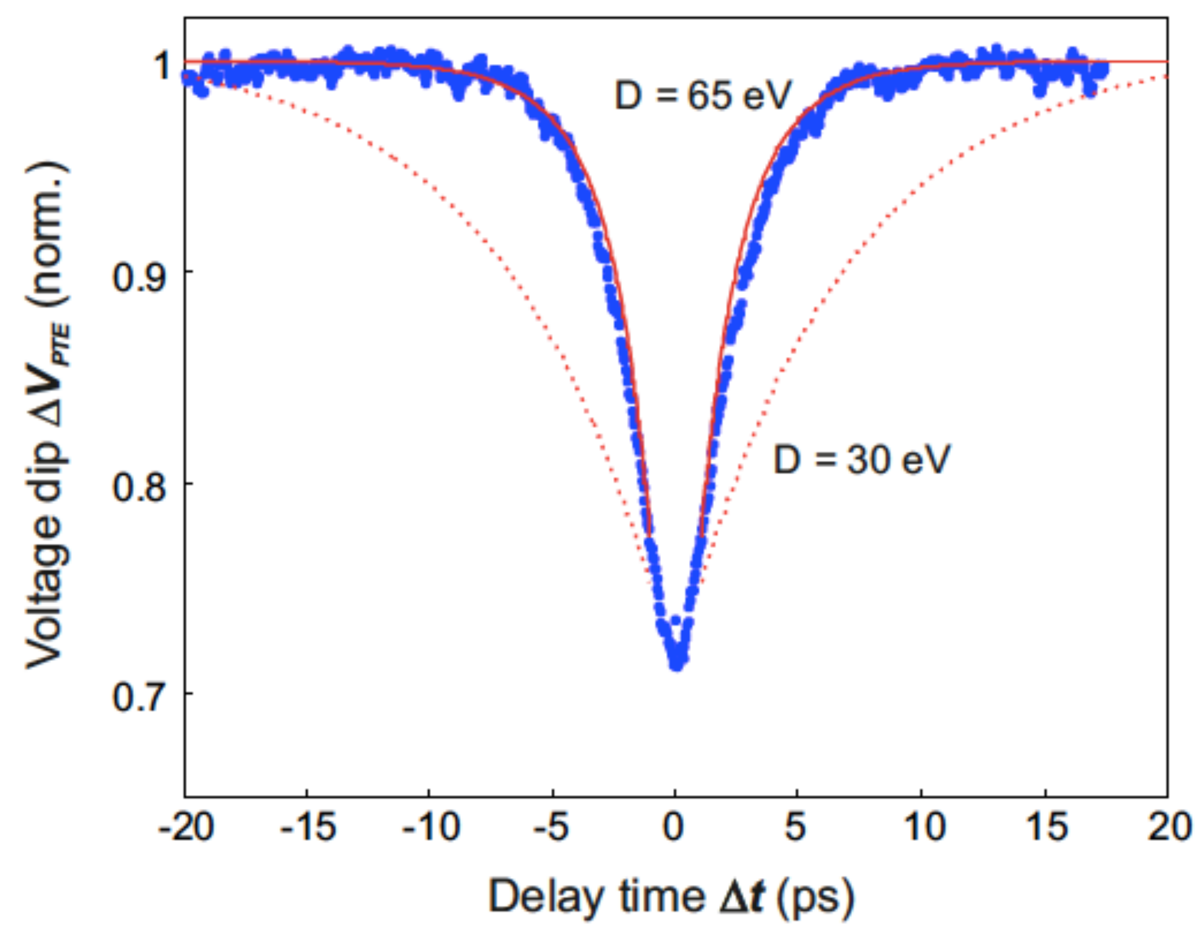
Graham et al. *Nature Phys* (2013)



Super-collision cooling?

- Super-collision cooling is faster for *lower* carrier density

- Super-collision cooling requires an unrealistic deformation potential of **65 eV**



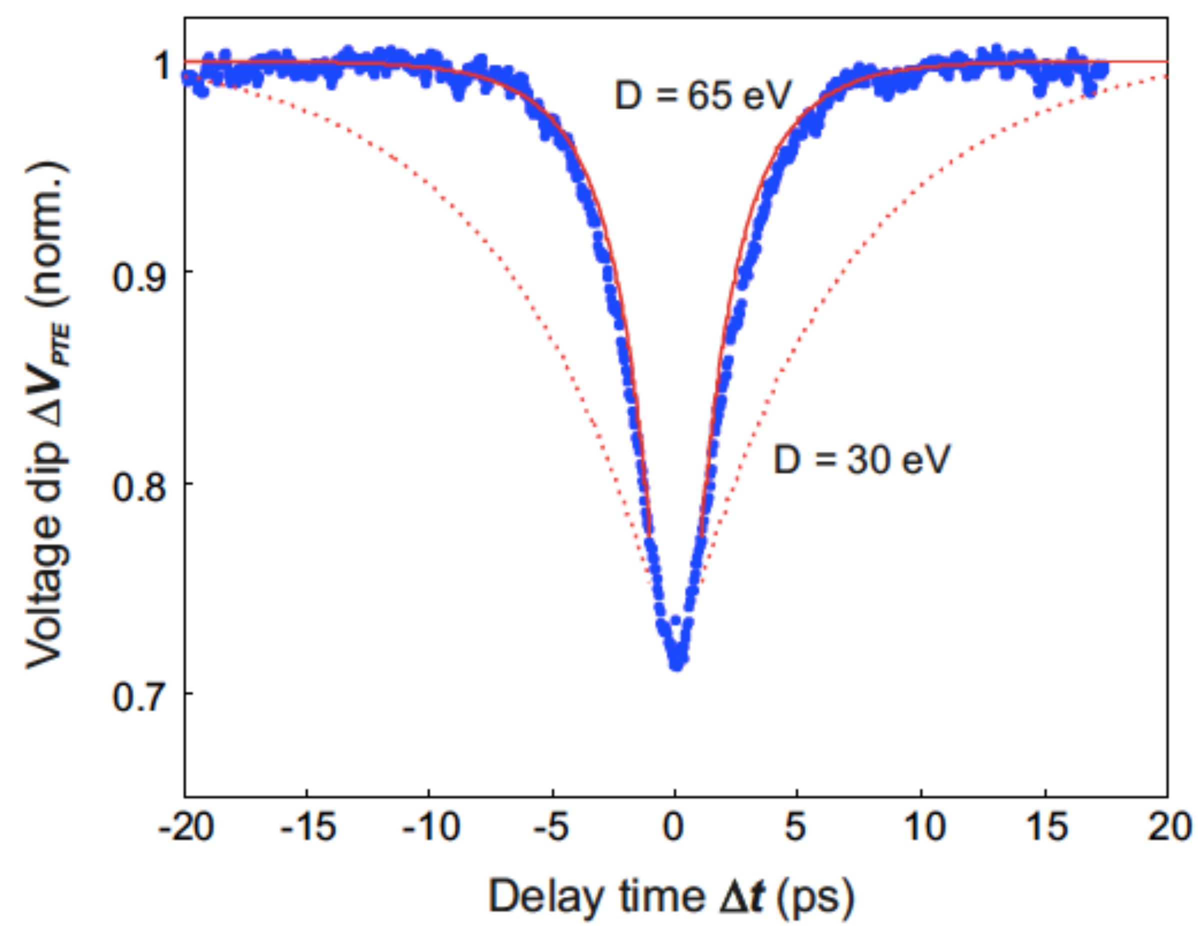
Tielrooij et al, *Arxiv*:1702.03766 (2017)

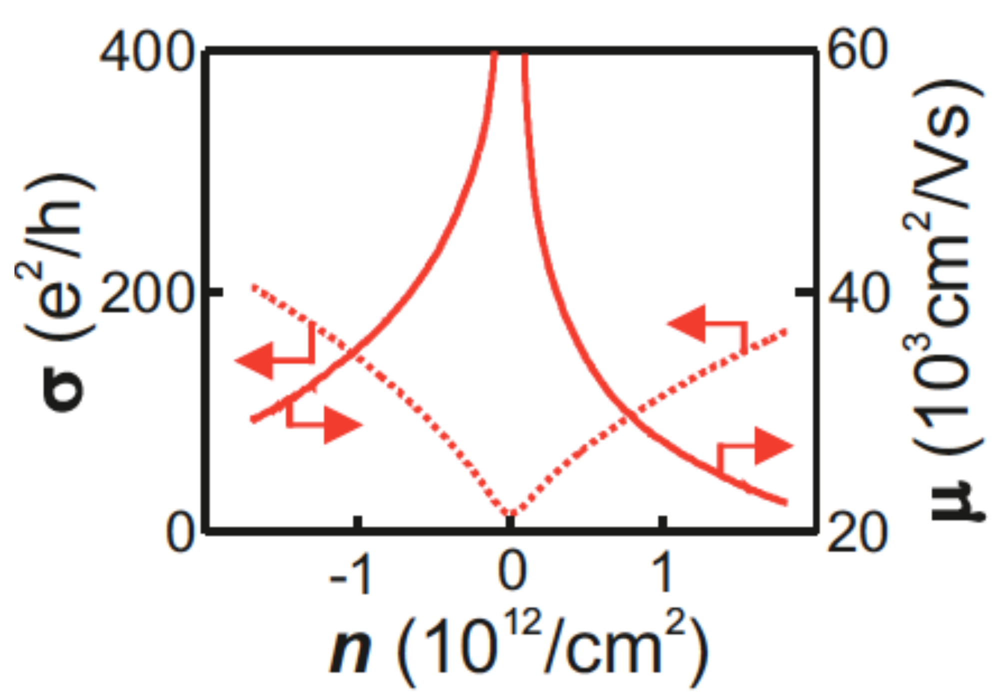
~~Super-collision cooling?~~

- Super-collision cooling is faster for *lower* carrier density

- Super-collision cooling requires an unrealistic deformation potential of **65 eV**

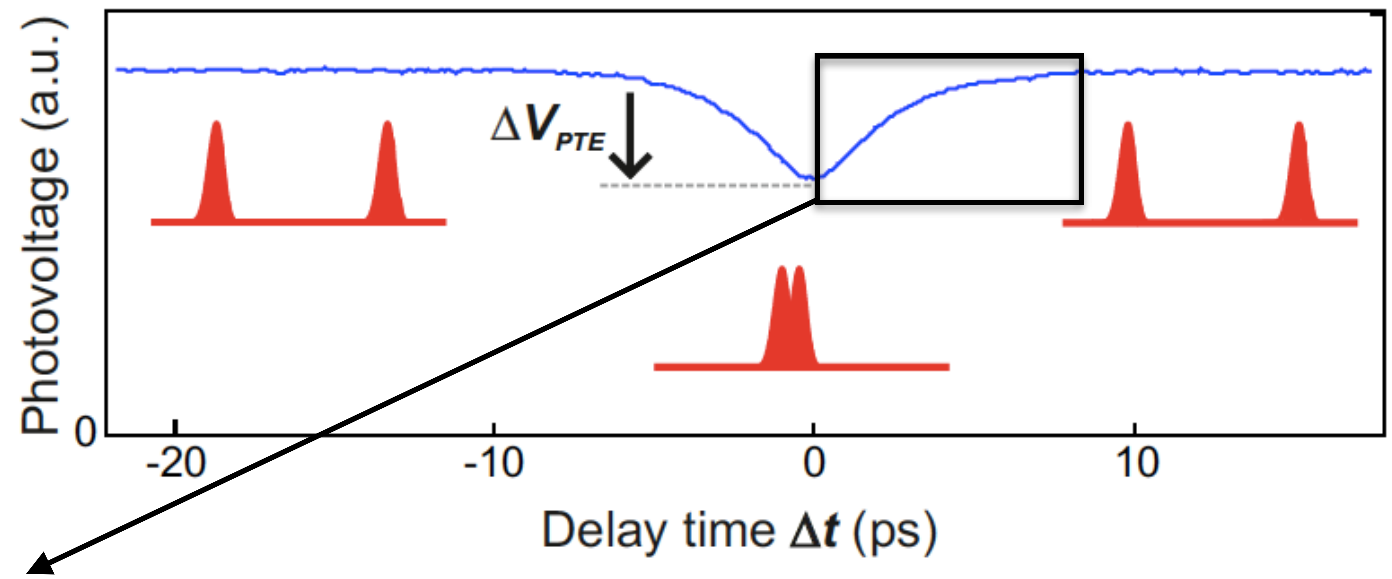
- Our device has a deformation potential **<35 eV**

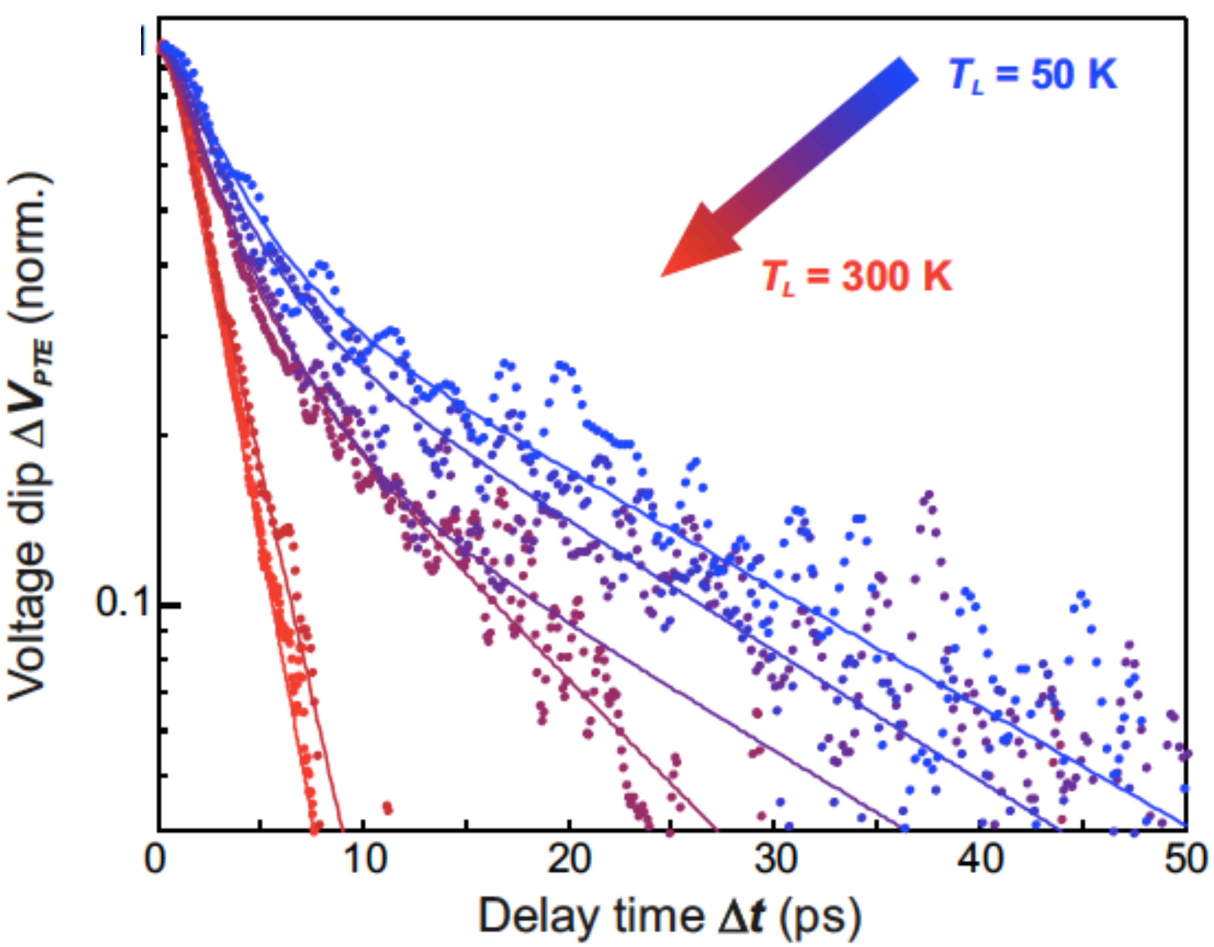




Tielrooij et al, *Arxiv*:1702.03766 (2017)

Cooling: varying lattice temperature





→ **Faster cooling for *higher* lattice temperature**

Tielrooij et al, *Arxiv*:1702.03766 (2017)

Normal collision cooling?

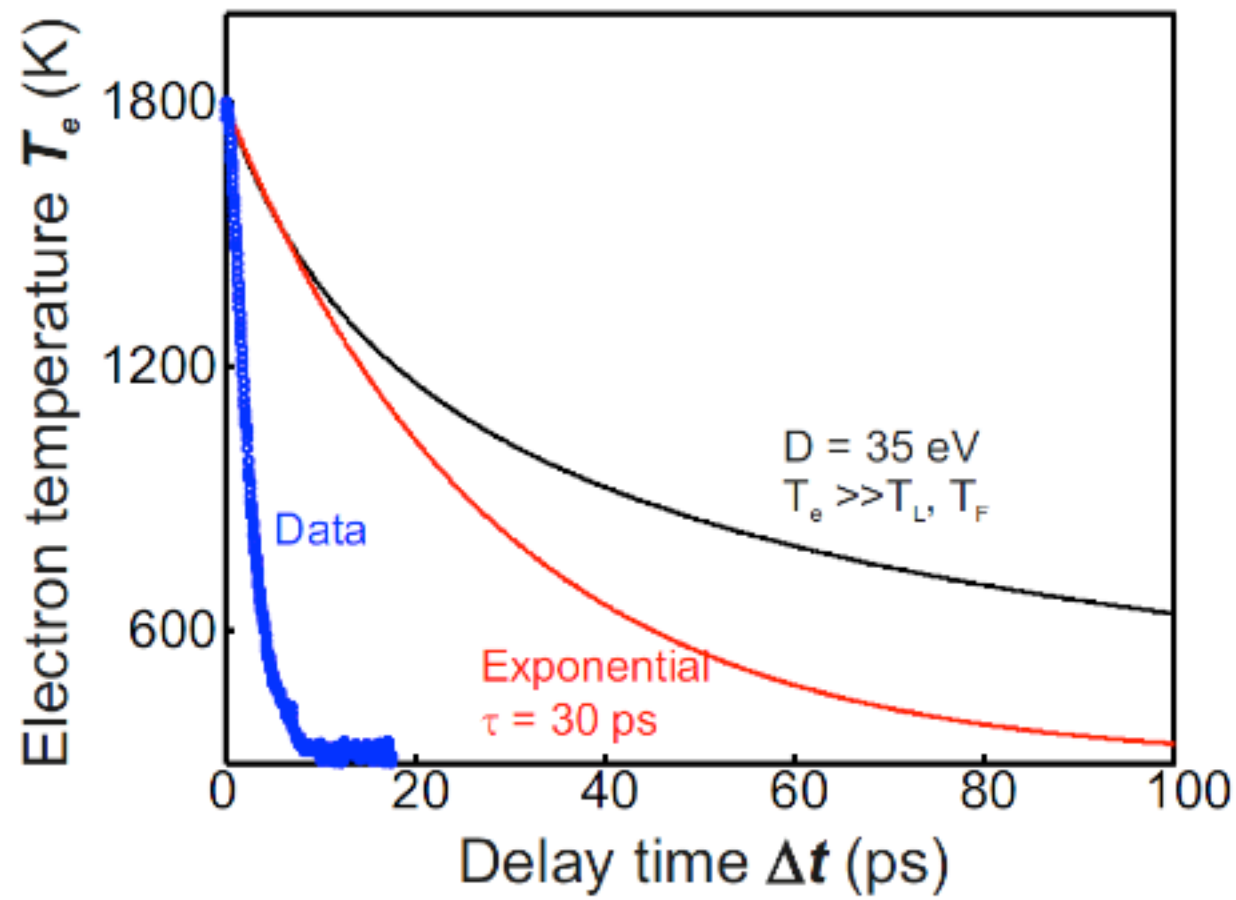
- Normal collision cooling (in overheating) is not dependent on lattice temperature

Bistritzer and MacDonald *PRL 102, 206410* (2009)

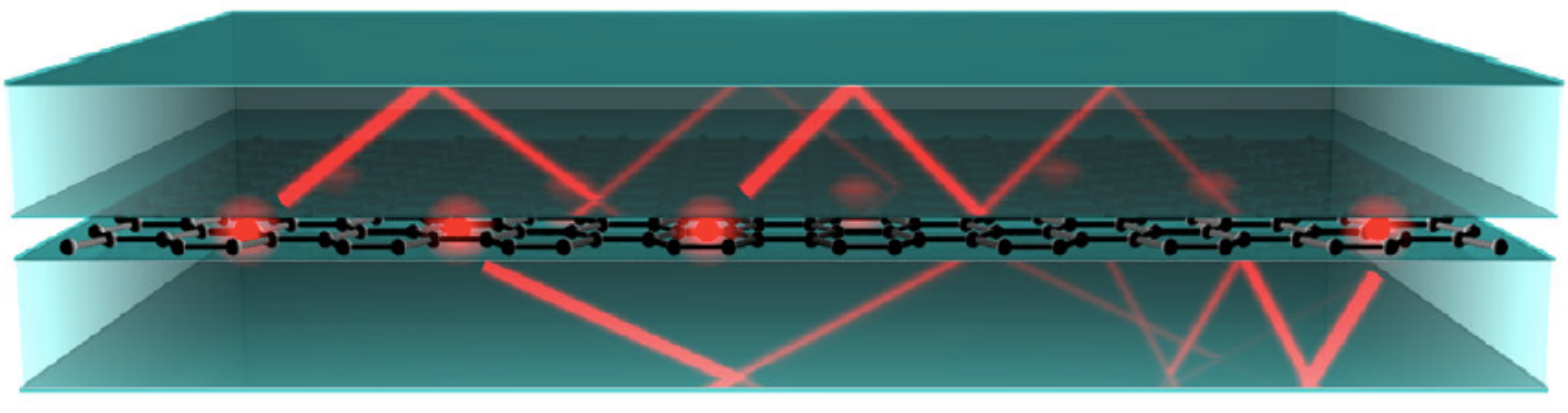
~~Normal collision cooling?~~

- Normal collision cooling (in overheating) is not dependent on lattice temperature
- Normal collision cooling gives non-exponential cooling with a timescale >30 ps at RT

Bistritzer and MacDonald *PRL 102, 206410* (2009)



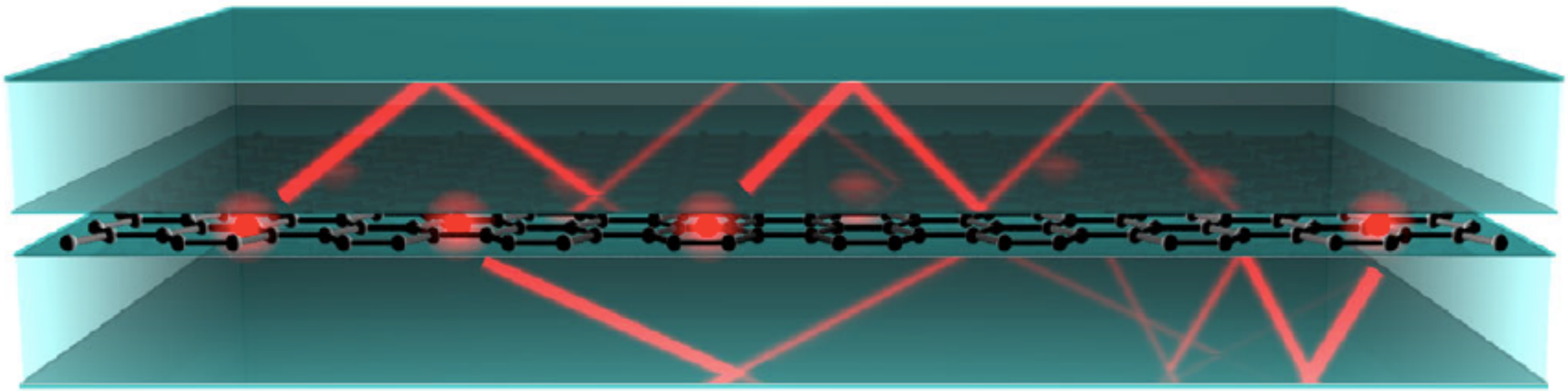
Tielrooij et al, *Arxiv*:1702.03766 (2017)



In-plane cooling mechanisms are not consistent with data

Tielrooij et al, *Arxiv*:1702.03766 (2017)

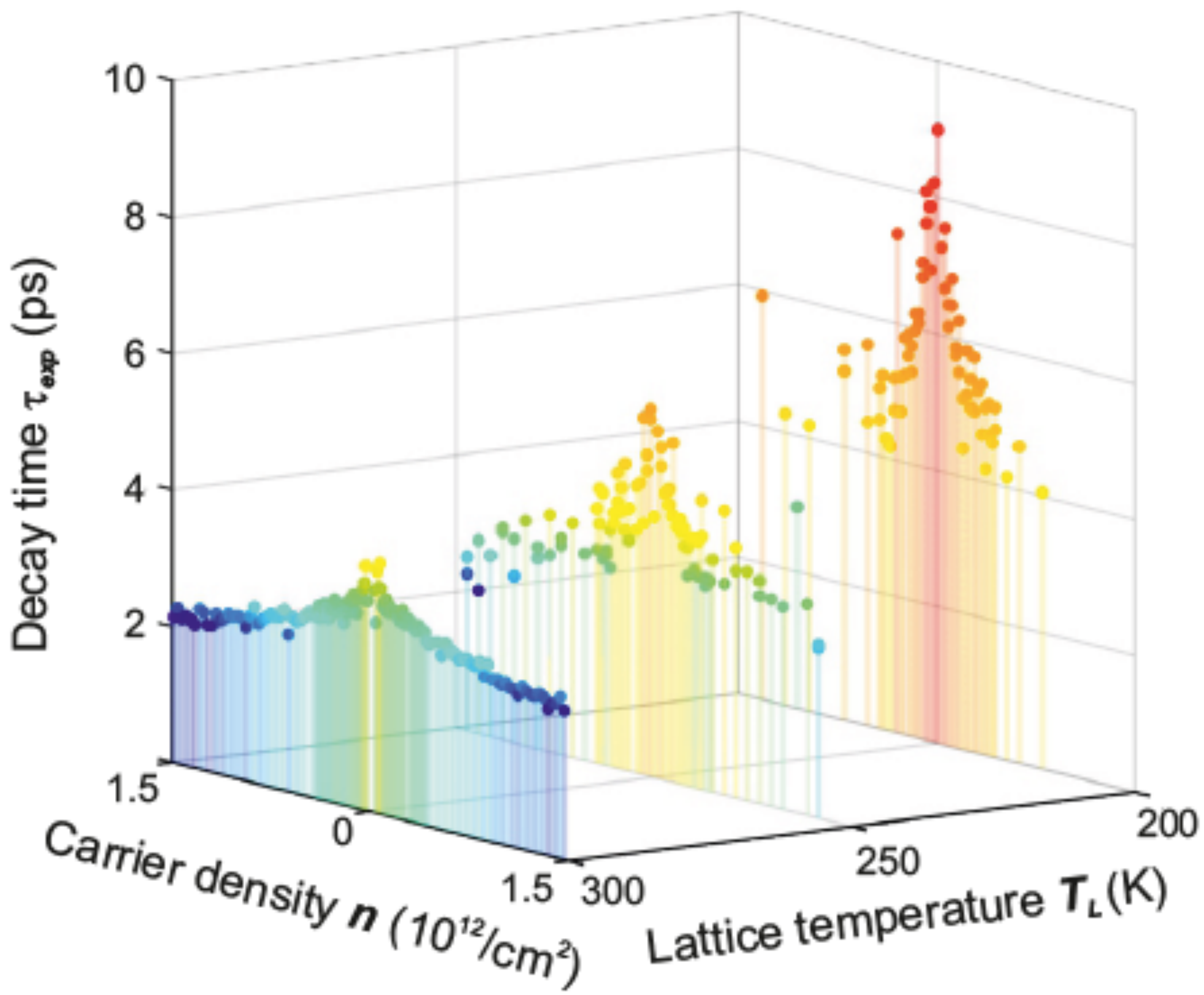
Out-of-plane transport!



→ In-plane cooling mechanisms are not consistent with data

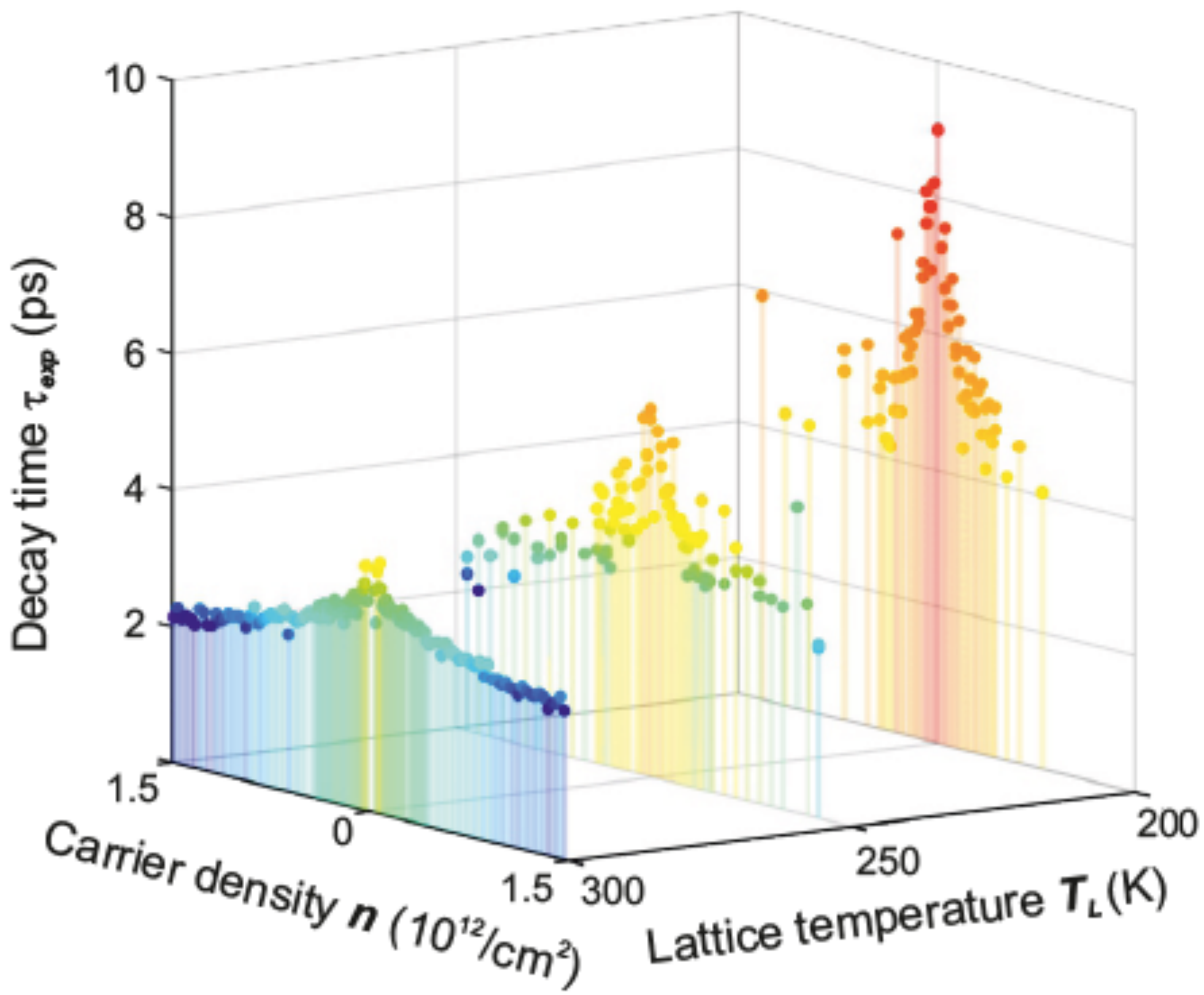
Tielrooij et al, *Arxiv*:1702.03766 (2017)

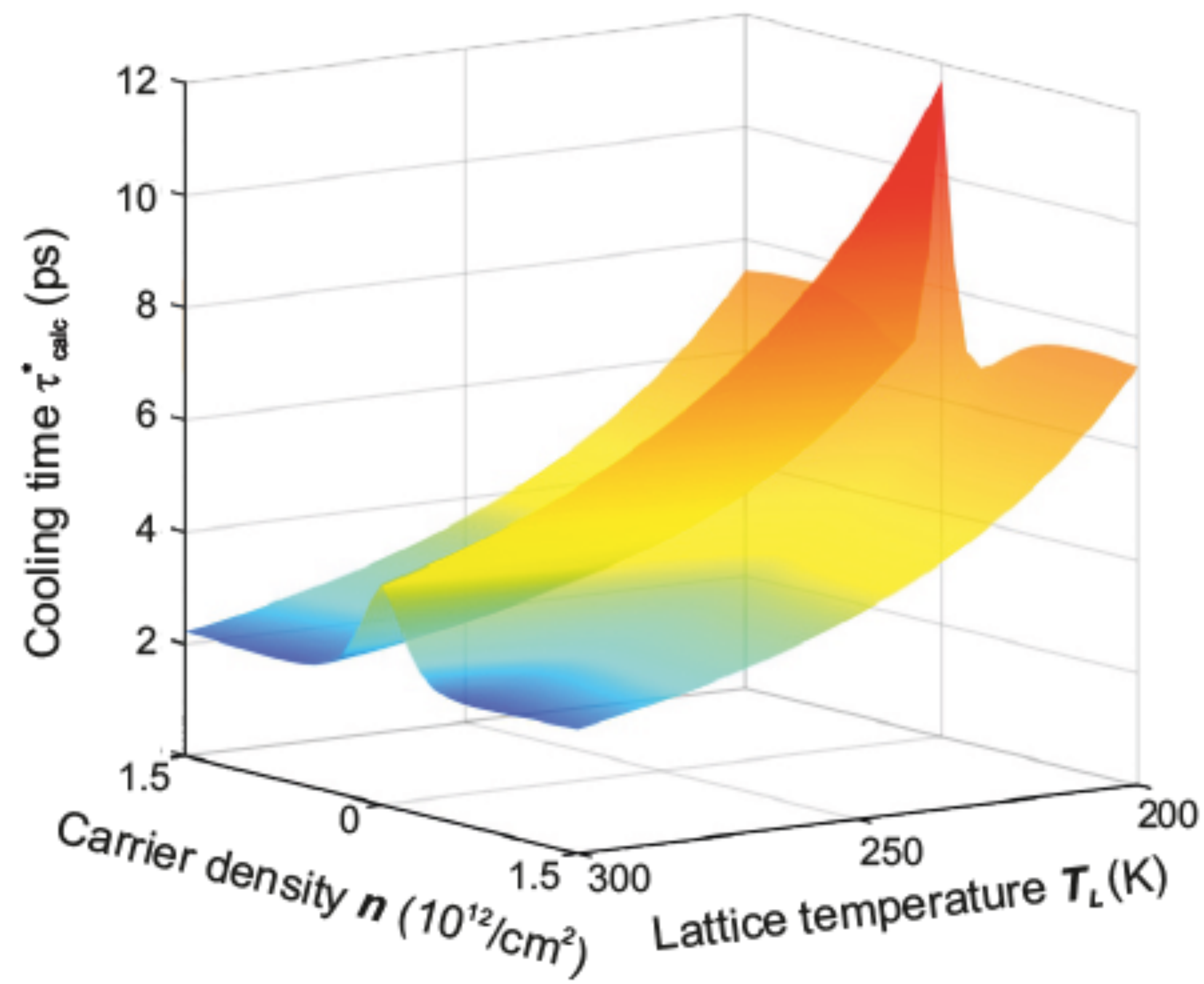
Compare with hyperbolic cooling



Tielrooij et al, *Arxiv*:1702.03766 (2017)

Compare with hyperbolic cooling





➡ Cooling to hyperbolic hBN phonon polaritons reproduces the trends

Principi et al, *PRL 118, 126804* (2017)
Tielrooij et al, *Arxiv*:1702.03766 (2017)

Hyperbolic cooling

$$\mathcal{Q} = \iiint_{-\infty}^{\infty} \frac{d\omega dk_x dk_y}{(2\pi)^3} [n_B(\omega, T_{\rm e}) - n_B(\omega, T_{\rm L})] M(\omega, k)$$

Energy transfer rate

Marco Polini

Mark Lundeberg

Alessandro Principi

Principi et al, *PRL 118, 126804* (2017)

Hyperbolic cooling

$$\mathcal{Q} = \iiint_{-\infty}^{\infty} \frac{d\omega dk_x dk_y}{(2\pi)^3}[n_B(\omega, T_e) - n_B(\omega, T_L)]M(\omega, k)$$

Energy transfer rate

$$M(\omega, k) = 4\frac{\mathcal{R}\{Y(\omega,k)\}\mathcal{R}\{\sigma(\omega,k)\}}{|Y(\omega,k)+\sigma(\omega,k)|^2}$$

Impedance matching function between graphene electrons and hBN phonon polaritons

Marco Polini

Mark Lundeberg

Alessandro Principi

Principi et al, *PRL 118, 126804* (2017)

→ **No adjustable fit parameters**

Hyperbolic cooling

$$\mathcal{Q} = \iiint_{-\infty}^{\infty} \frac{d\omega dk_x dk_y}{(2\pi)^3} [n_B(\omega, T_\mathrm{e}) - n_B(\omega, T_\mathrm{L})] M(\omega, k)$$

Energy transfer rate

$$\Gamma_\mathrm{cool} = \left.\frac{\partial \mathcal{Q}}{\partial T_\mathrm{e}}\right|_{T_\mathrm{e}=T_\mathrm{L}}$$

Interfacial heat conductivity

$$\tau^*_\mathrm{calc} = C_\mathrm{n}/\Gamma_\mathrm{cool}$$

Near-equilibrium cooling time

Marco Polini

Mark Lundeberg

Alessandro Principi

Principi et al, *PRL 118, 126804* (2017)

Hyperbolic cooling

$$\mathcal{Q} = \iiint_{-\infty}^{\infty} \frac{d\omega dk_x dk_y}{(2\pi)^3} [n_B(\omega, T_e) - n_B(\omega, T_L)] M(\omega, k)$$

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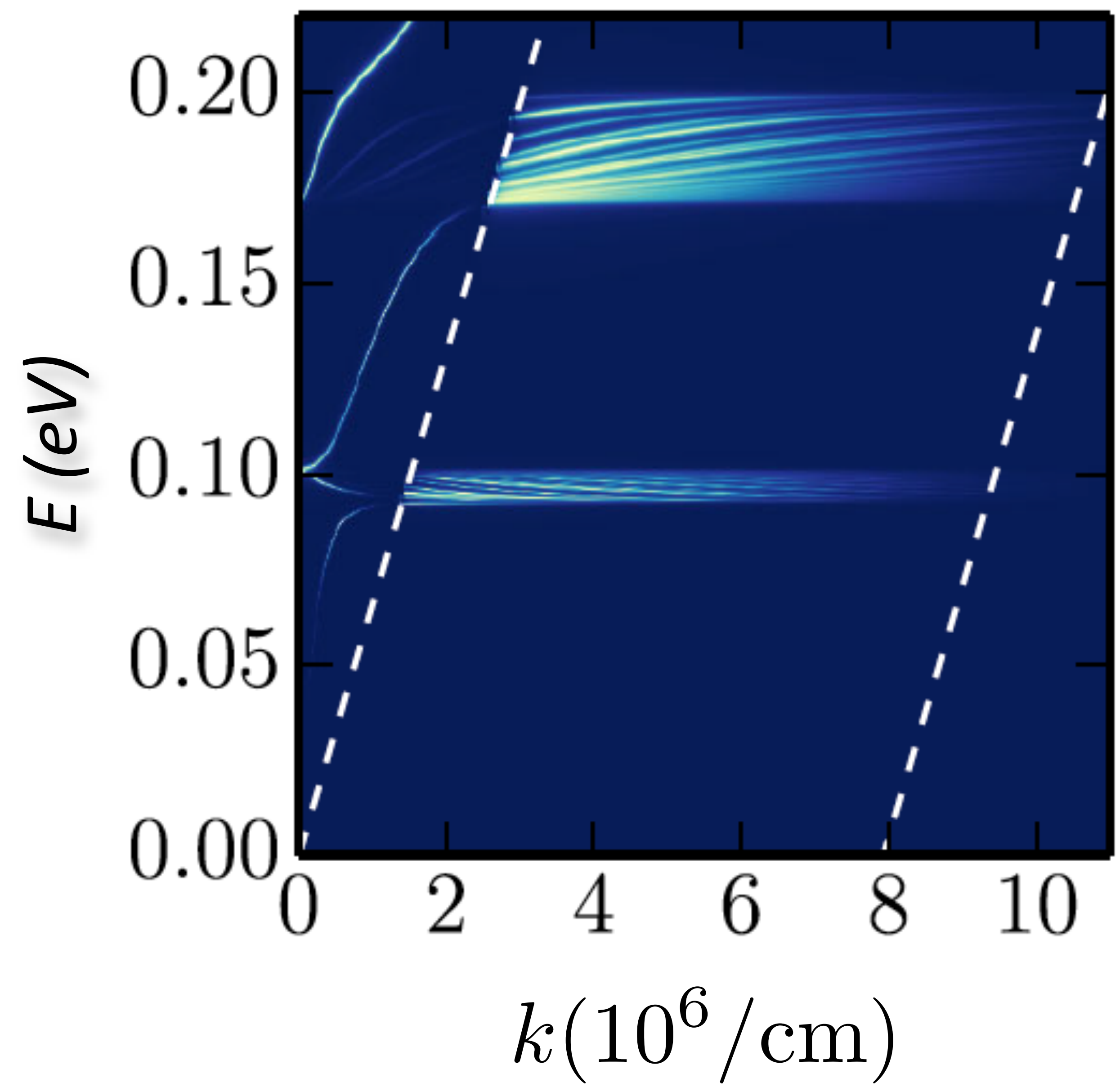
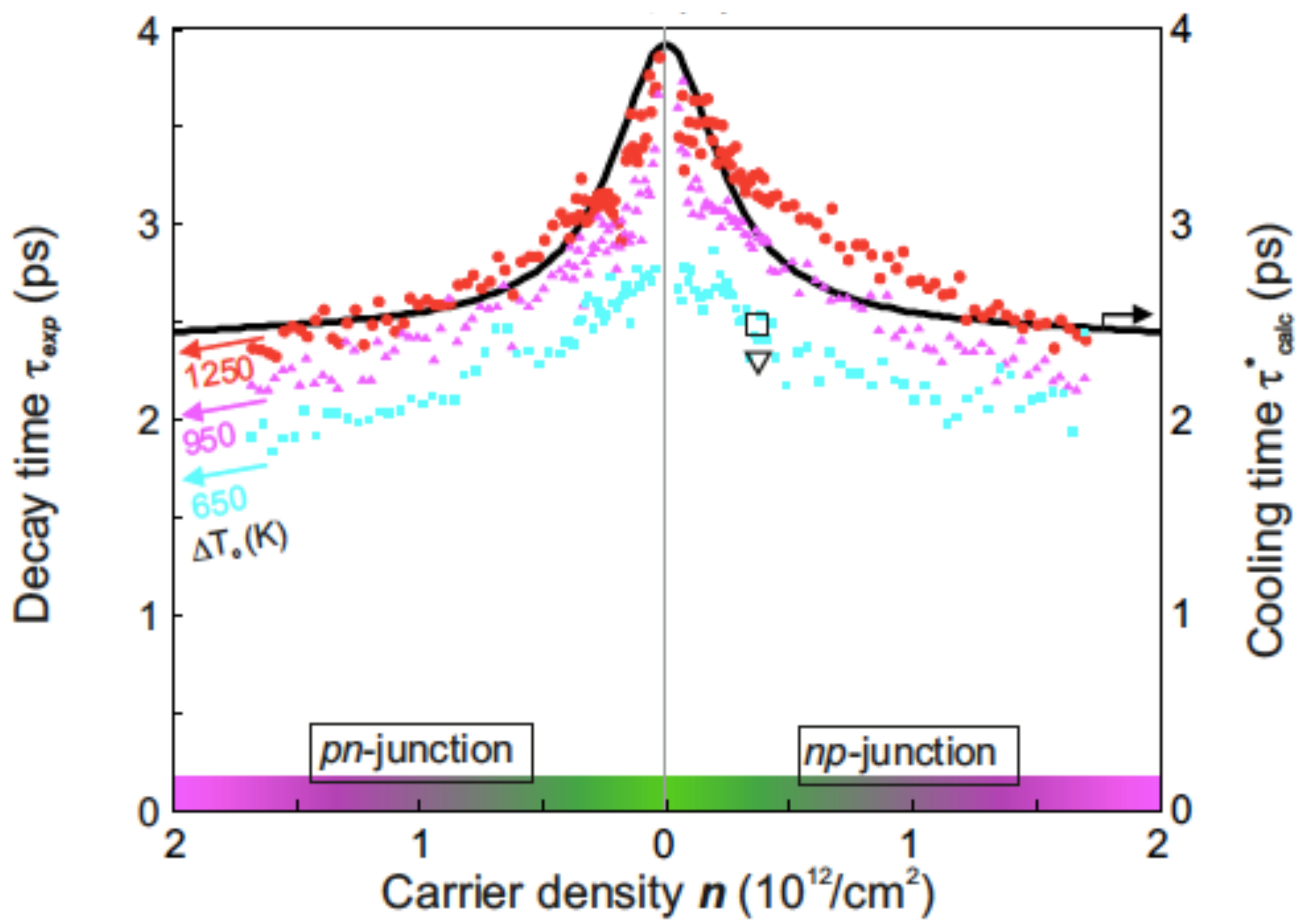


Principi et al, ***PRL 118, 126804*** (2017)

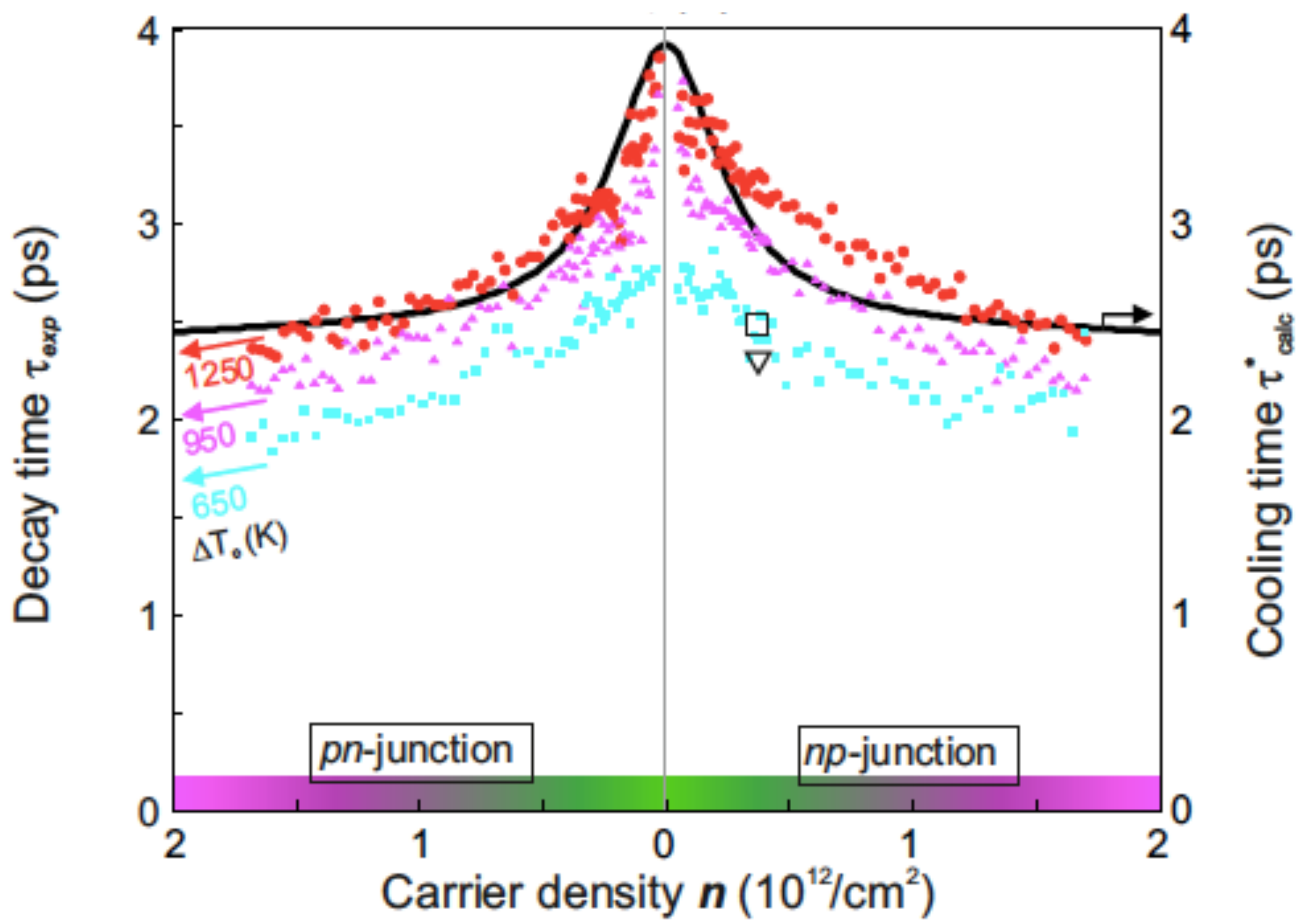
Quantitative comparison

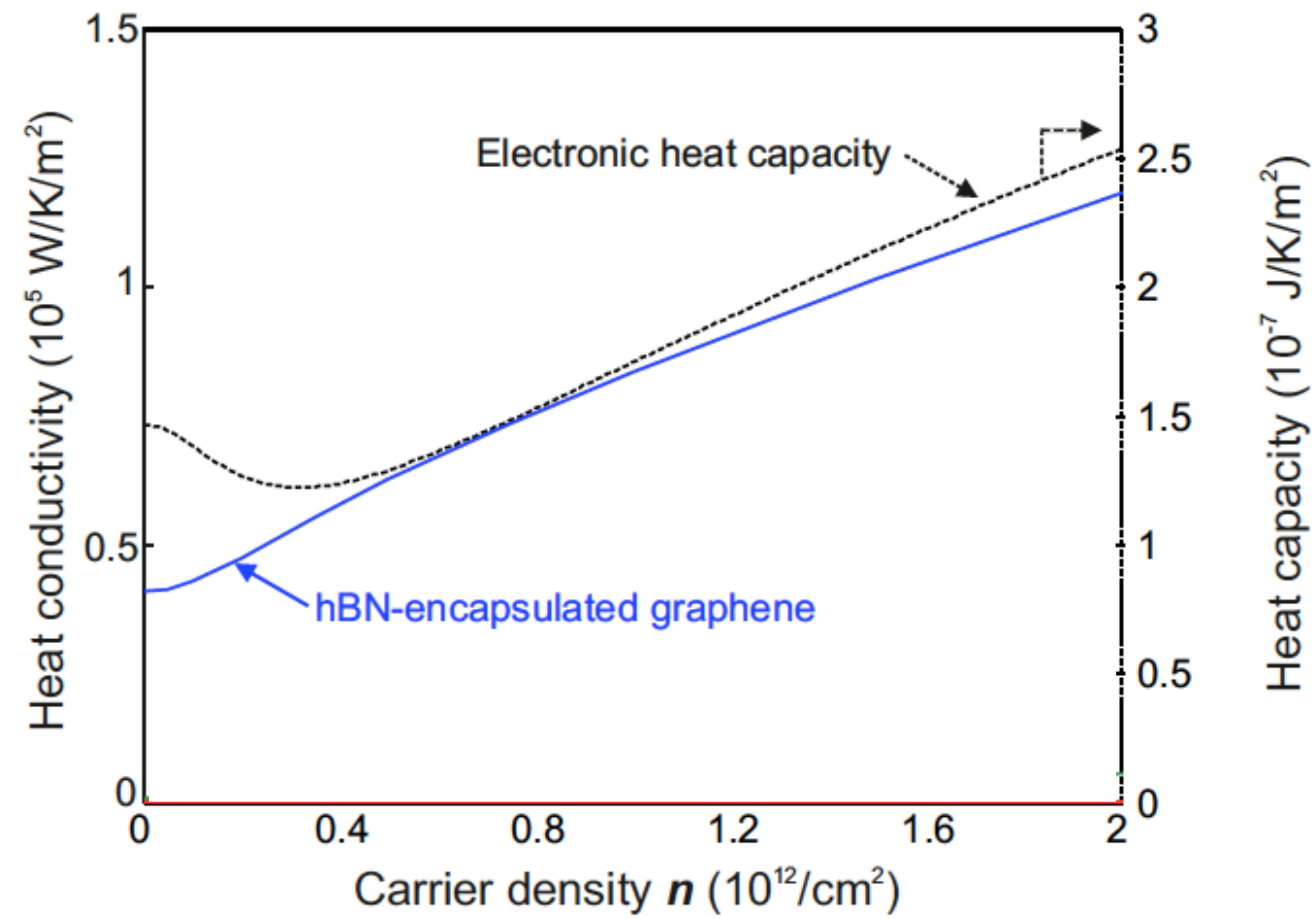


- Origin of the low-density peak?
- Effect of laser power?

Tielrooij et al, *Arxiv*:1702.03766 (2017)

Quantitative comparison





- **Origin of the low-density peak?**

$$\Gamma_{\rm cool} = \frac{\partial \mathcal{Q}}{\partial T_{\rm e}}\bigg|_{T_{\rm e}=T_{\rm L}}$$

$$\tau^*_{\rm calc} = C_{\rm n}/\Gamma_{\rm cool}$$

Interfacial heat conductivity

Tielrooij et al, *Arxiv*:1702.03766 (2017)

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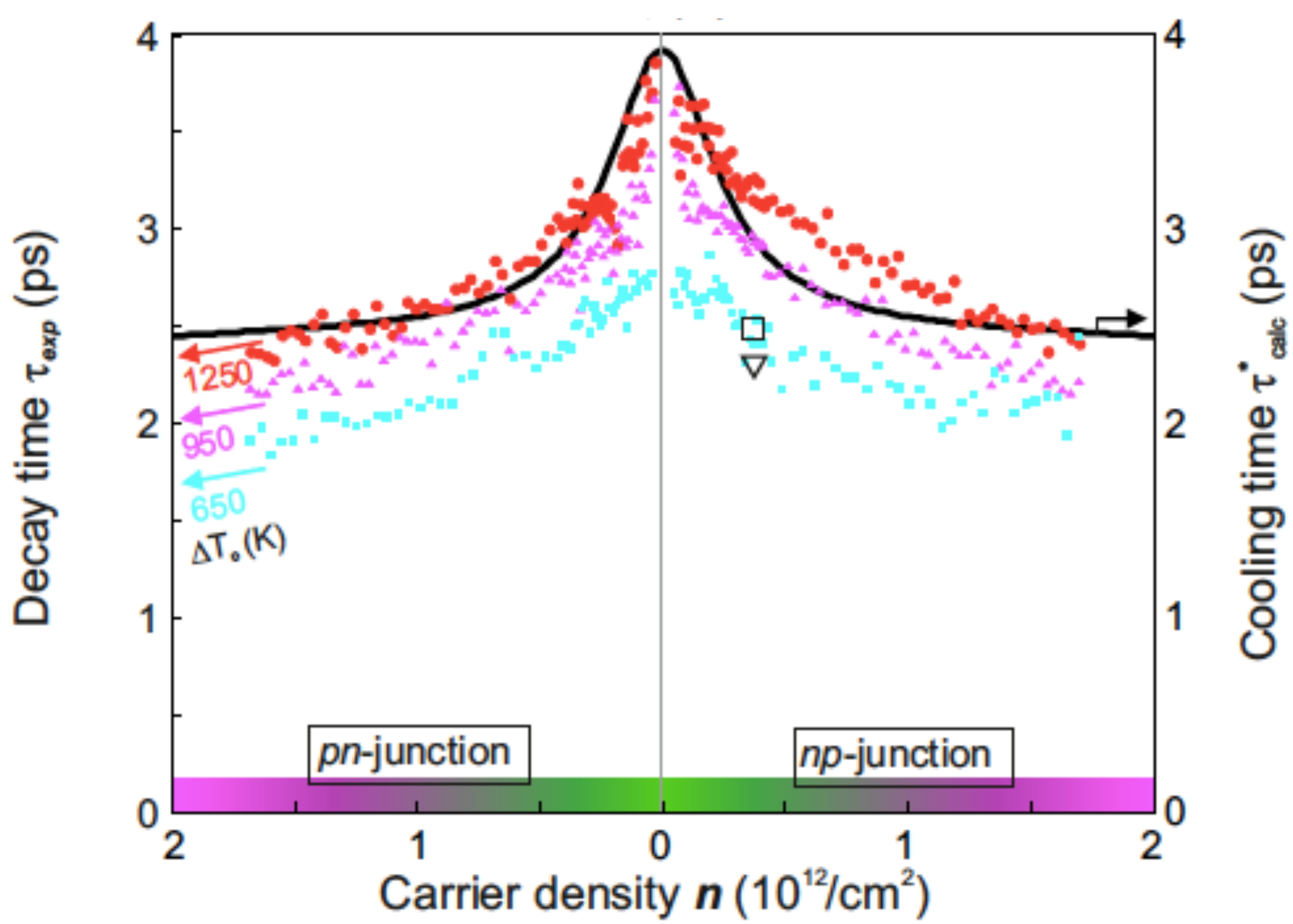

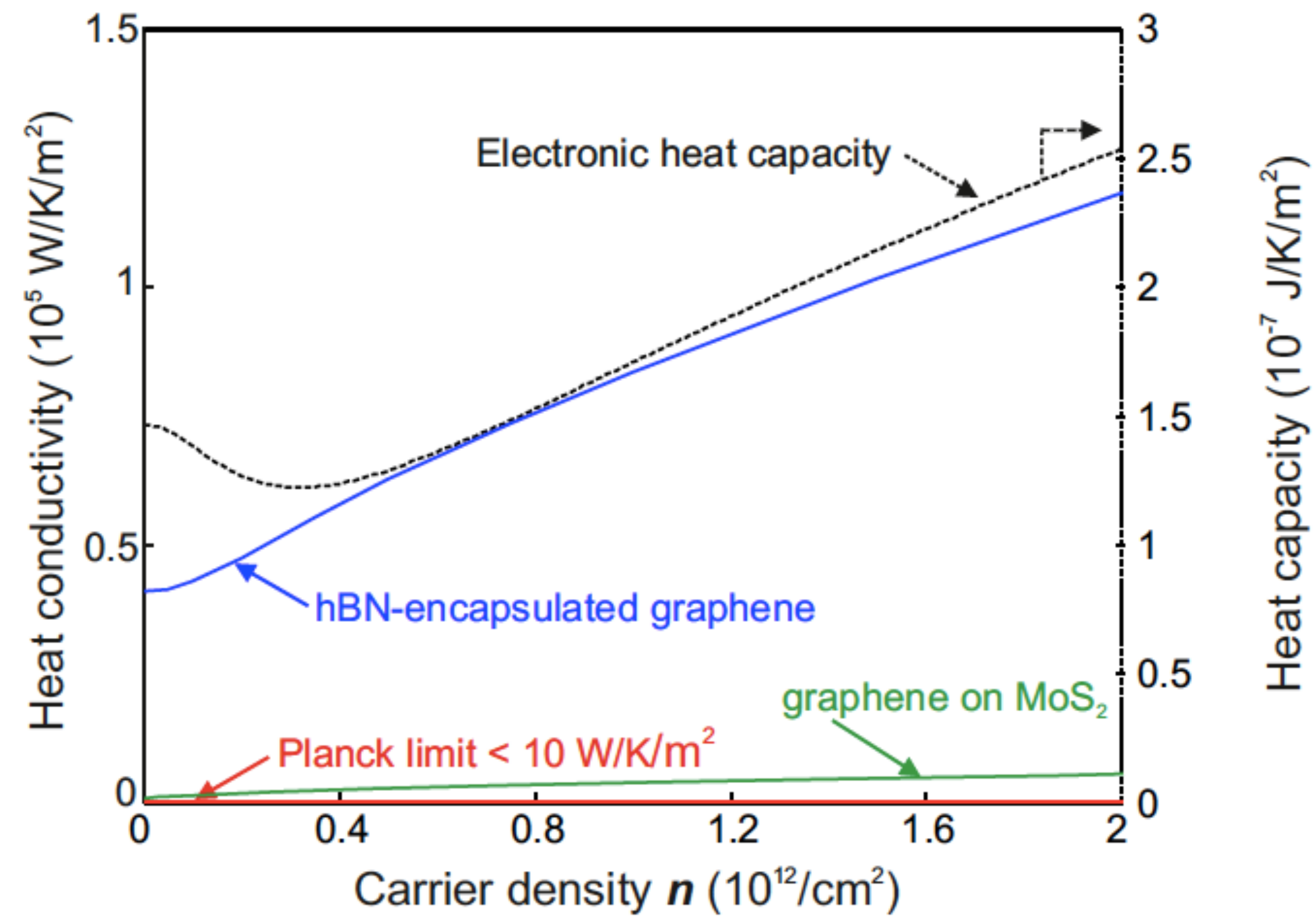

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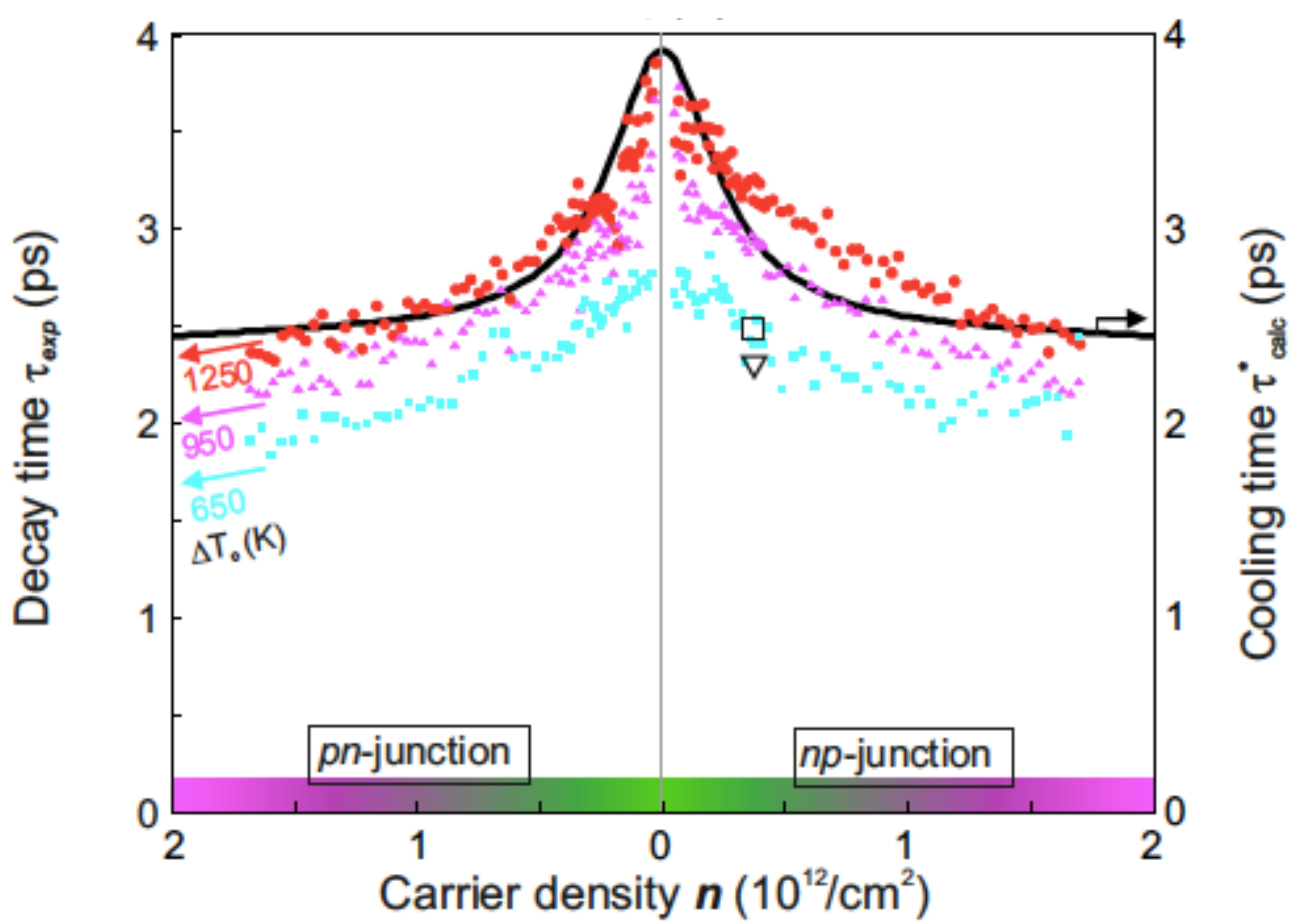


- Origin of the low-density peak?

- **Effect of laser power?**

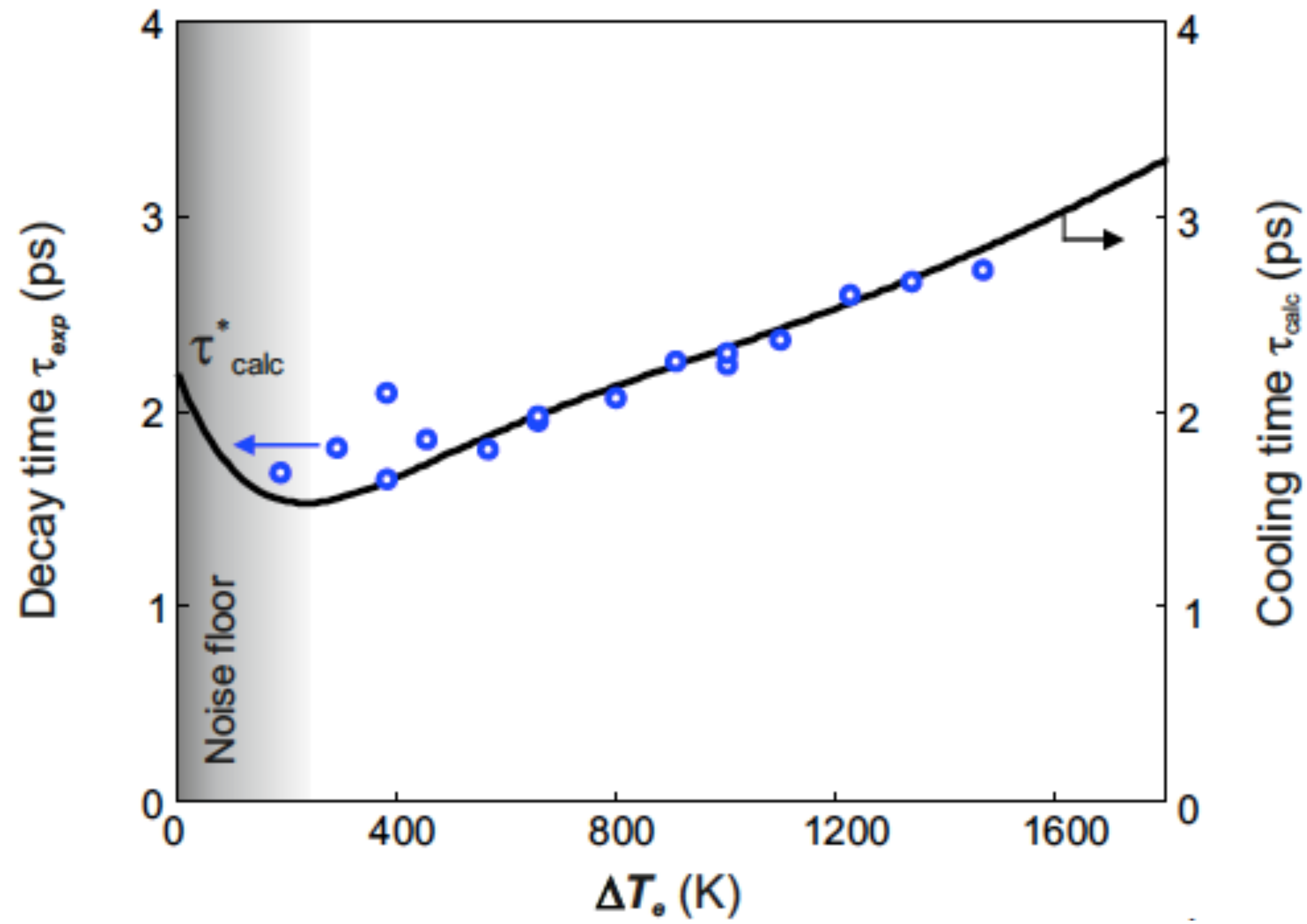
Tielrooij et al, *Arxiv*:1702.03766 (2017)

Quantitative comparison

$$\tau_{\mathrm{calc}}(T_{\mathrm{e}}, T_{\mathrm{L}}) = C_{\mathrm{n}} \frac{T_{\mathrm{e}} - T_{\mathrm{L}}}{Q}$$

Cooling time in overheating regime

Principi et al, *PRL 118, 126804* (2017)

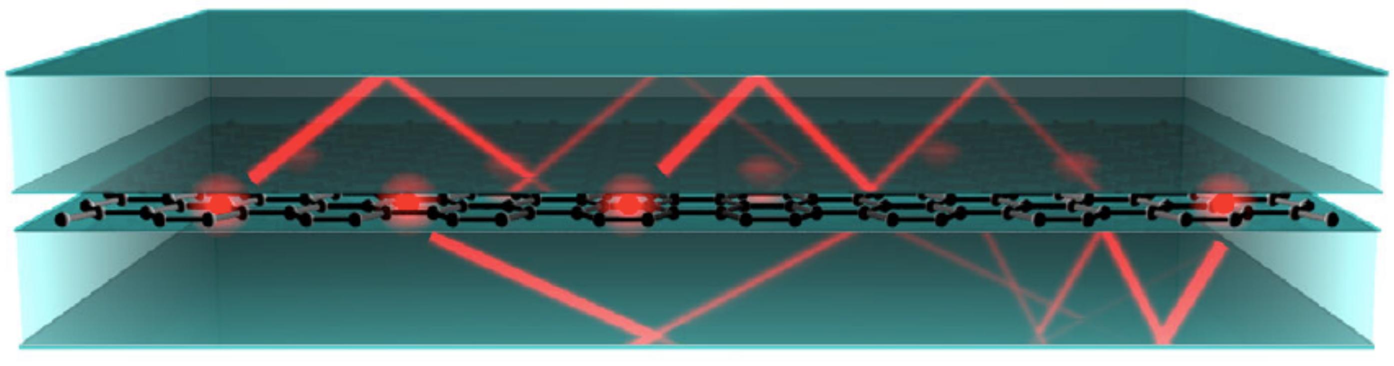


- **Longer cooling time with increasing laser power**
- **Consistent with hyperbolic phonon cooling**

Tielrooij et al, *Arxiv*:1702.03766 (2017)

Summary

Graphene encapsulated by hBN:
Cooling of hot graphene carriers through **out-of-plane heat transfer** to hBN hyperbolic phonons



Tielrooij et al, *Arxiv*:1702.03766 (2017)

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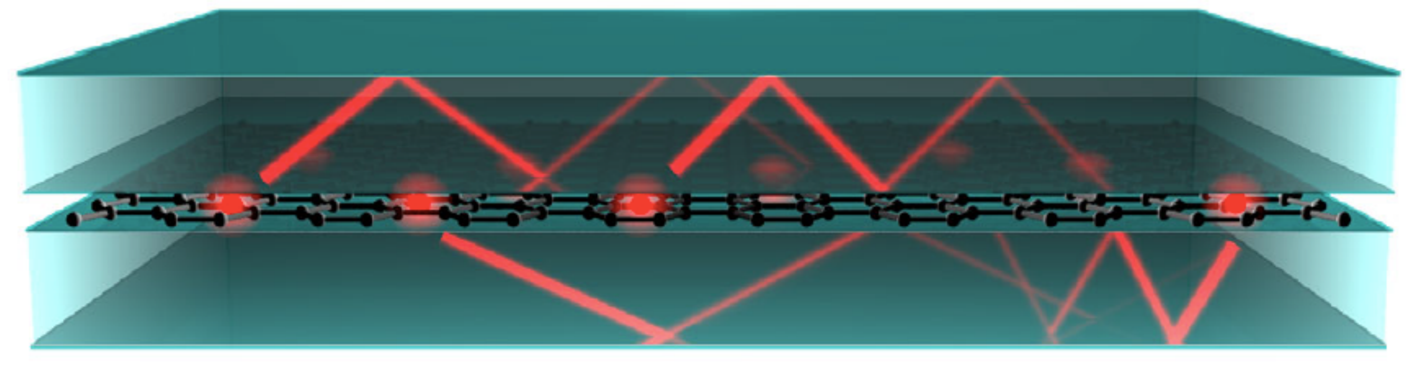
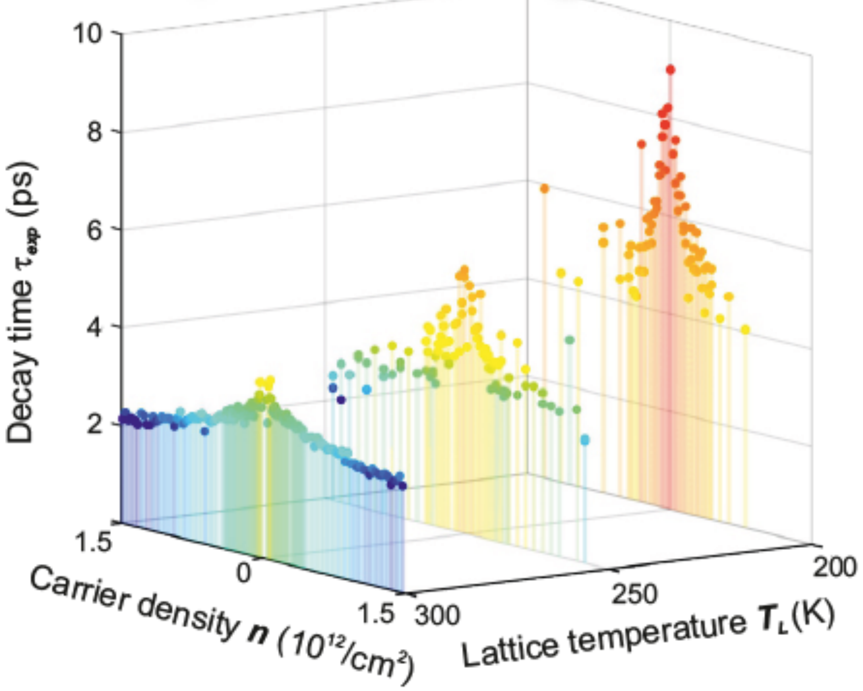
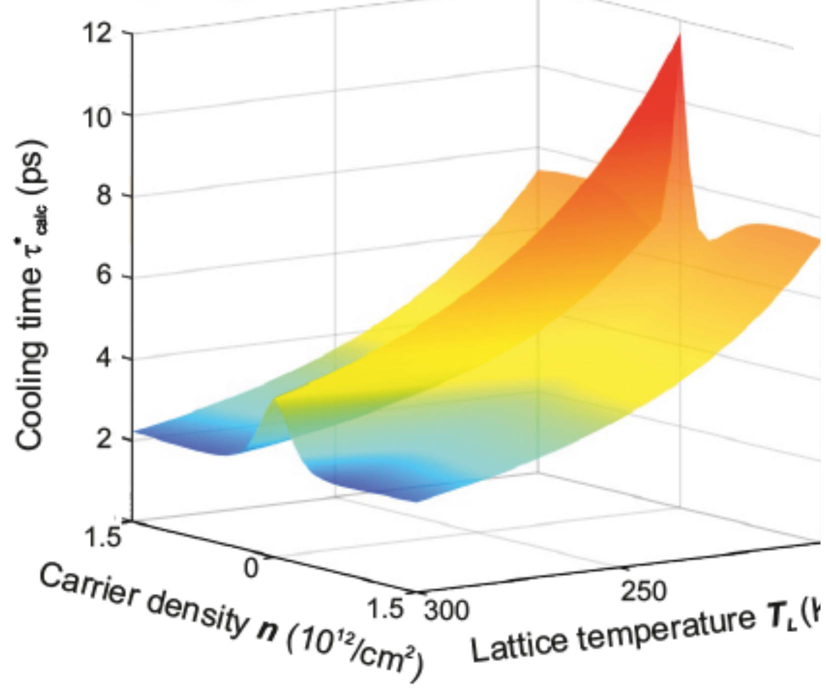
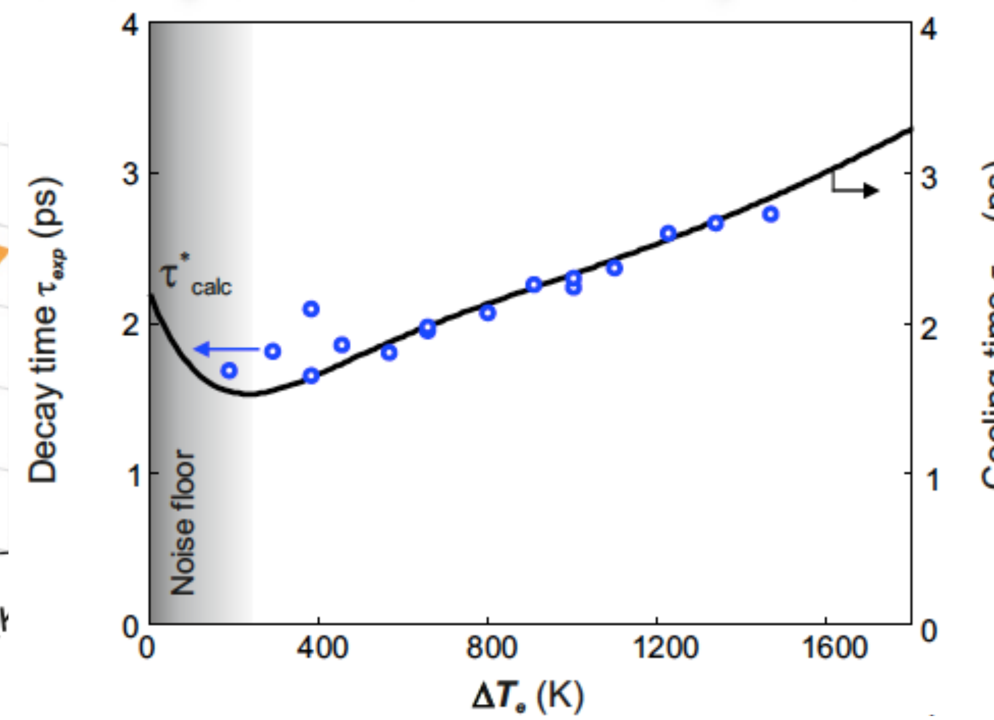


Experimental agreement for varying *carrier density, lattice temperature and laser power*







Tielrooij et al, *Arxiv*:1702.03766 (2017)

Outlook

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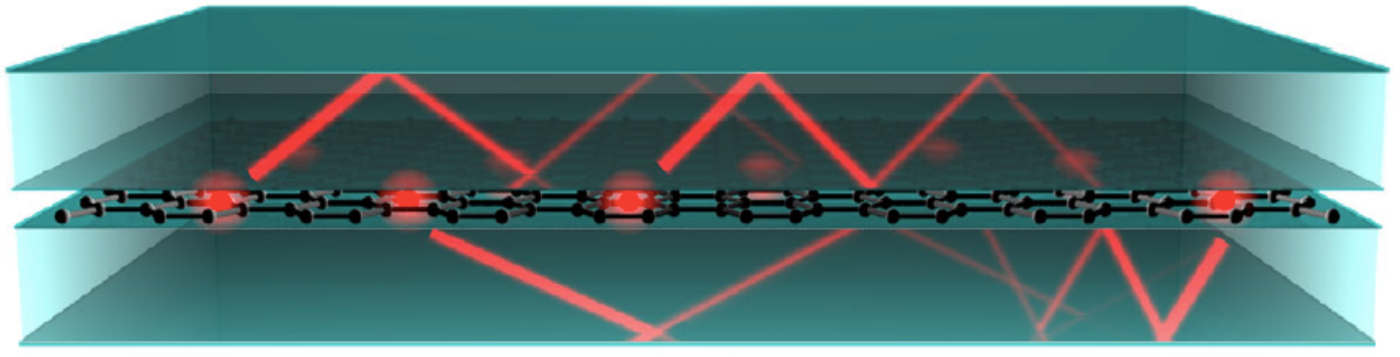

➡ Thermal management: ideal substrate = heat sink!

Tielrooij et al, *Arxiv*:1702.03766 (2017)

Outlook

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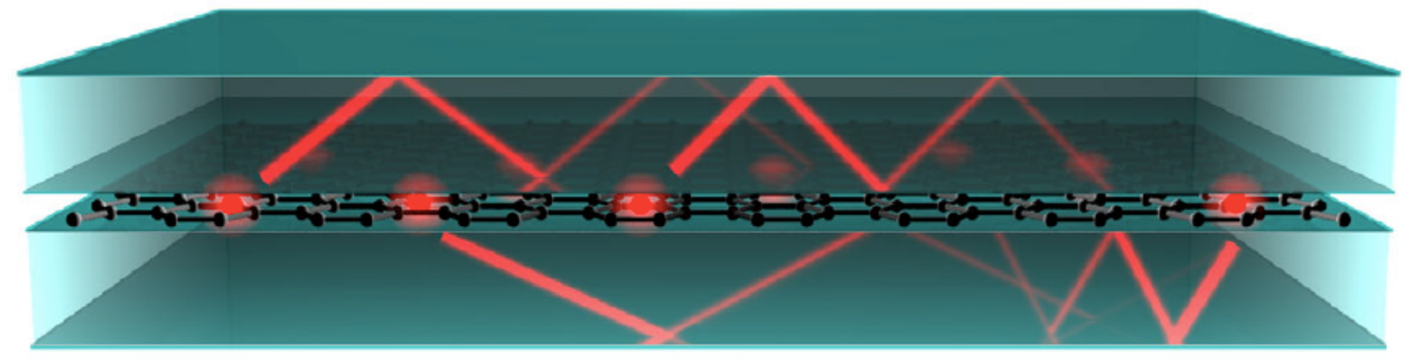

→ **Photodetectors: electron cooling?**

Tielrooij et al, *Arxiv*:1702.03766 (2017)

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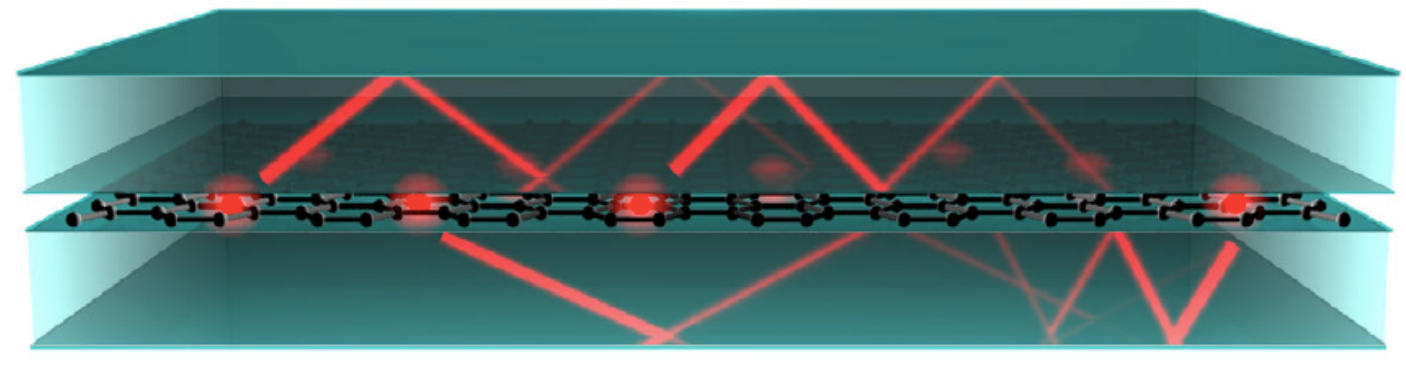

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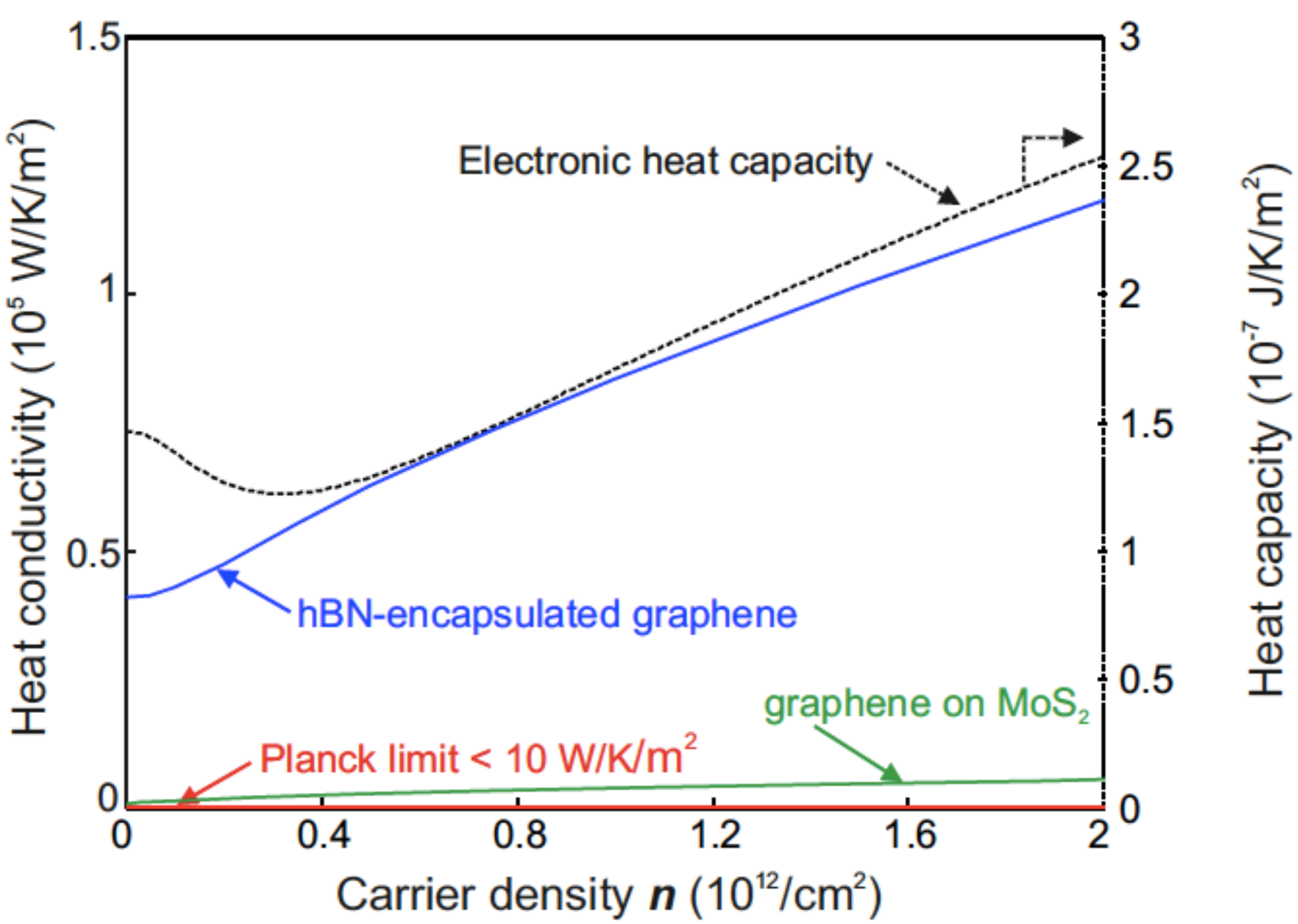

Tielrooij et al, *Arxiv*:1702.03766 (2017)

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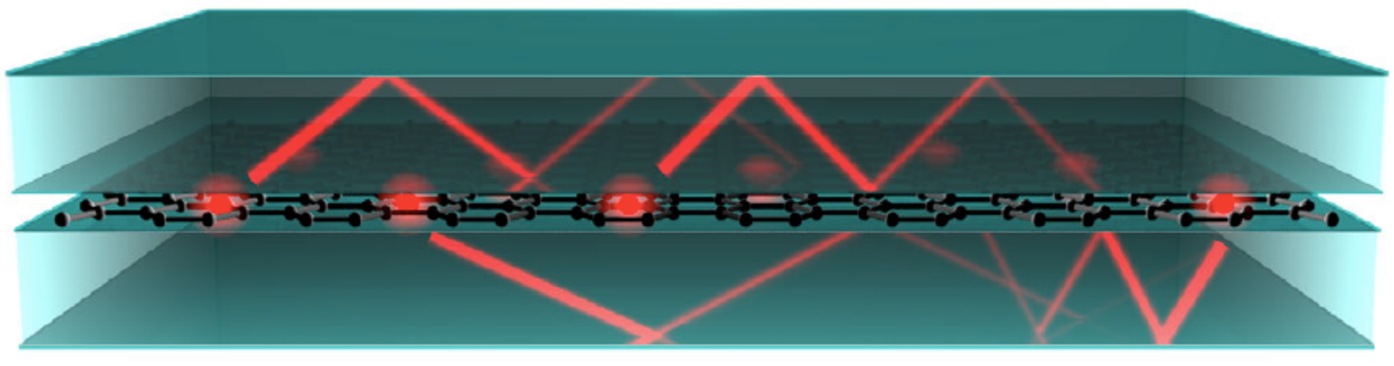

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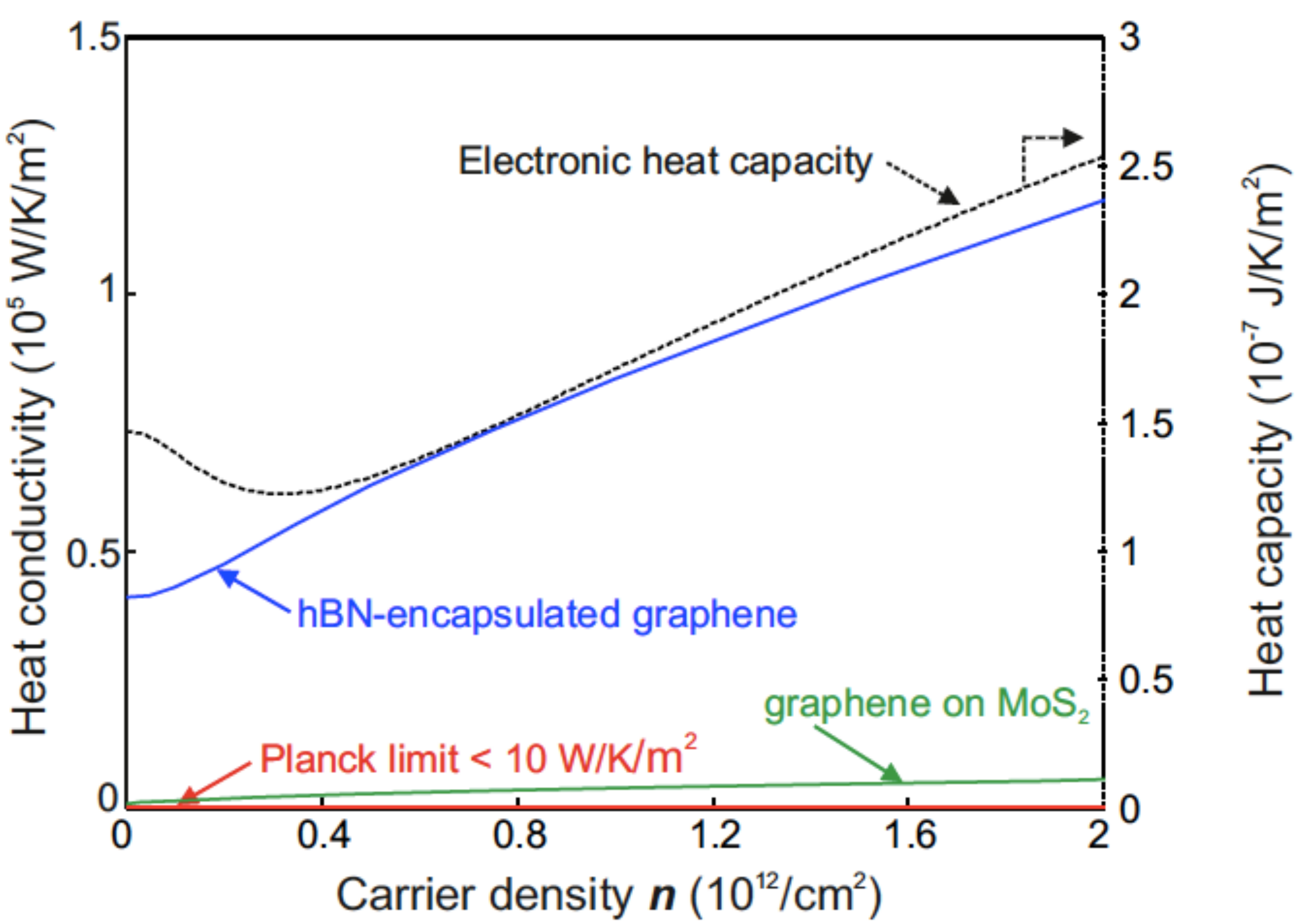

Different encapsulant!

Tielrooij et al, *Arxiv*:1702.03766 (2017)

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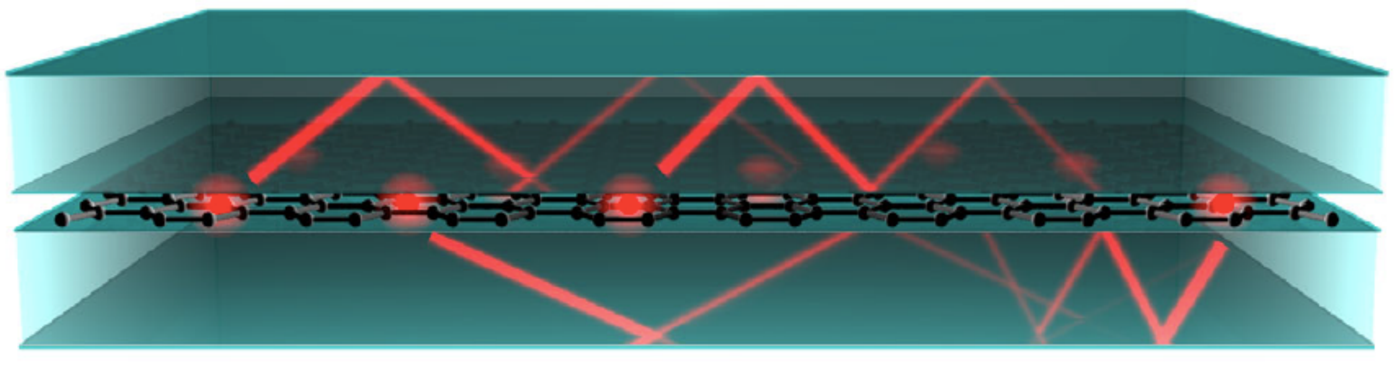

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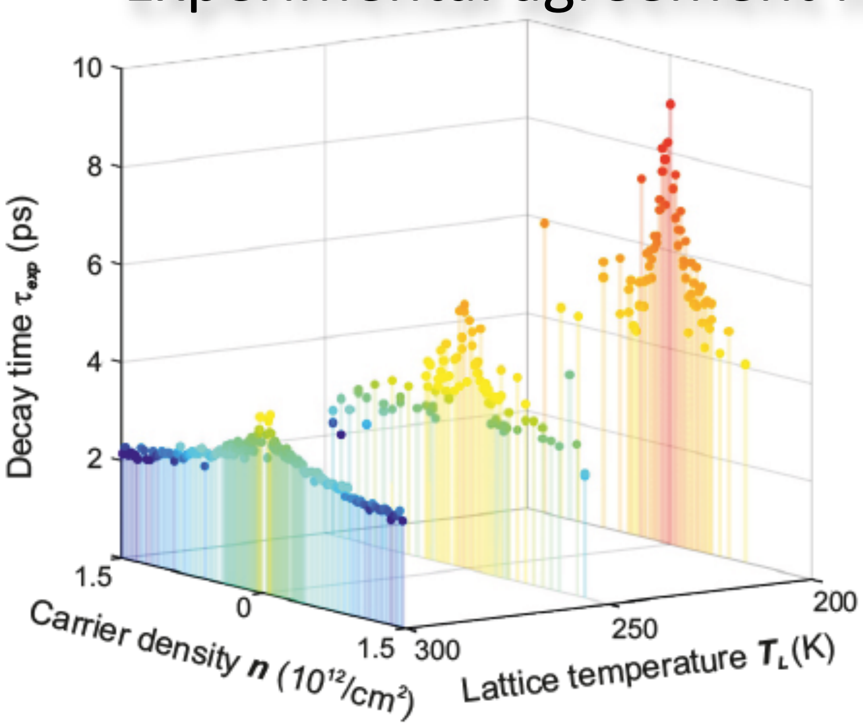

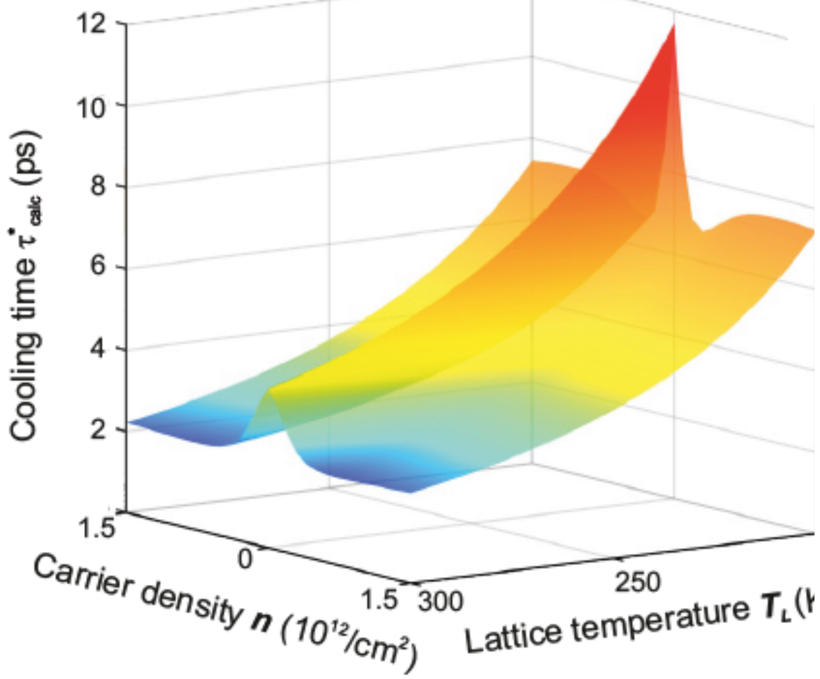

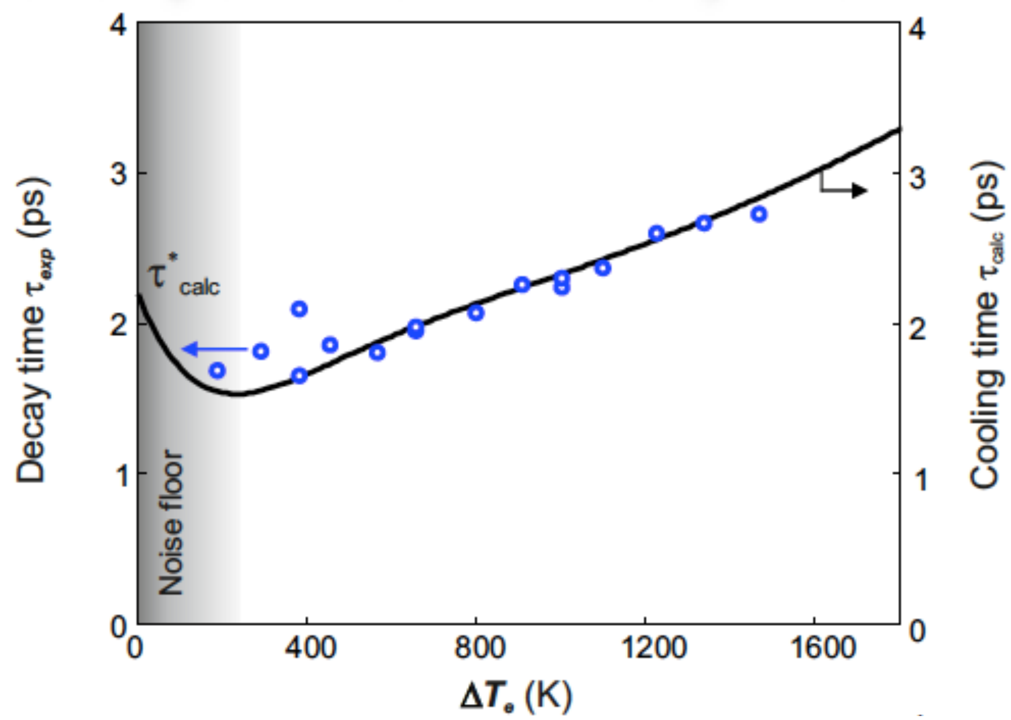

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