Superlensing with twisted bilayer graphene

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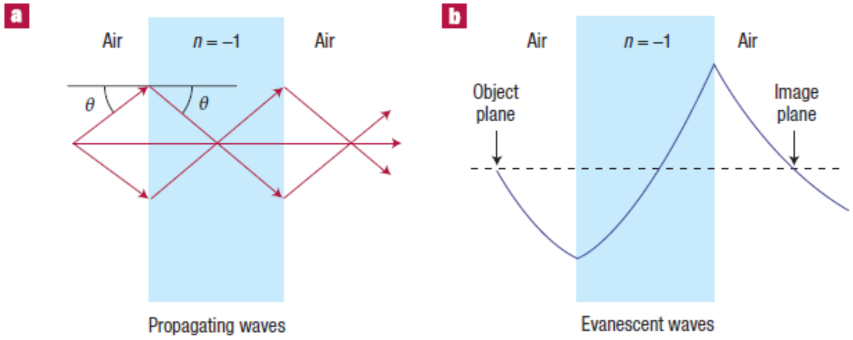
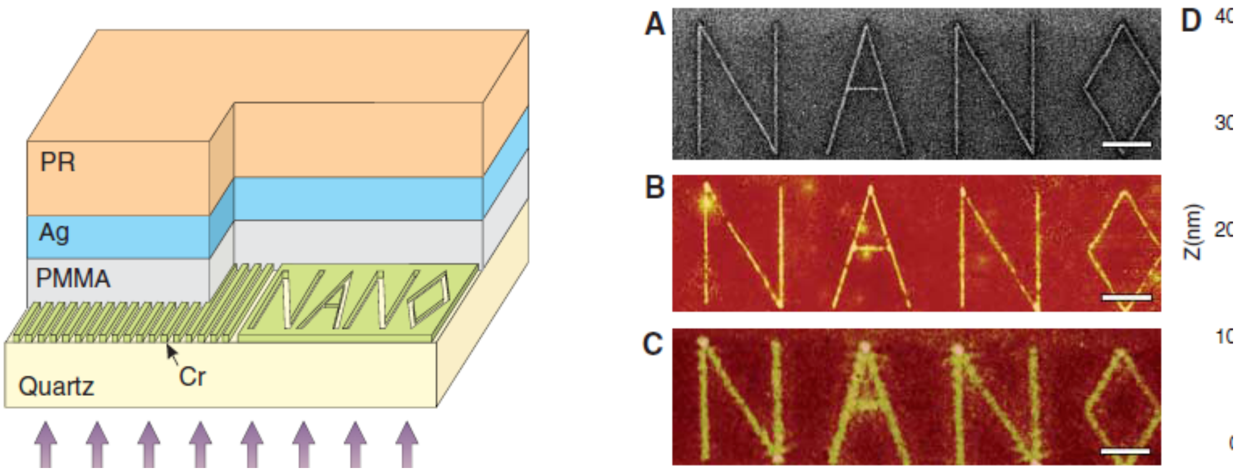
Introduction

Perfect lensing and hyperlensing

Planar superlenses reconstitute the near-field of the source by virtue of resonant surface waves.

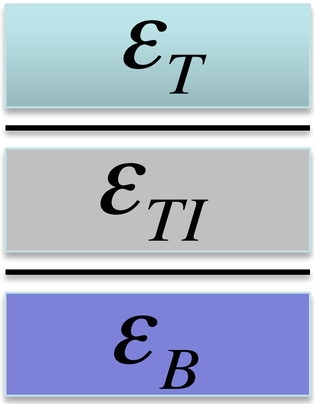


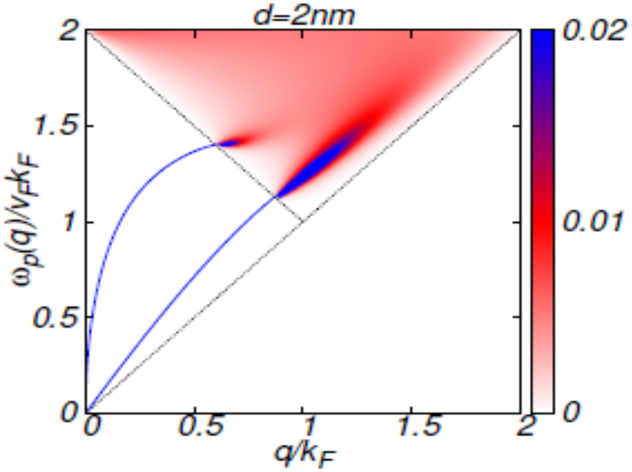
J. B. Pendry, Phys. Rev. Lett. 85, 3966 (2000)



N. Fang et al., Science 308, 534 (2005)

Plasmons in double layer systems, e.g., Topological Insulators





Optical Mode

$$\omega_+^2 = \frac{\alpha v_F^2 (k_F^T + k_F^B)}{(\varepsilon_T + \varepsilon_B)} q$$

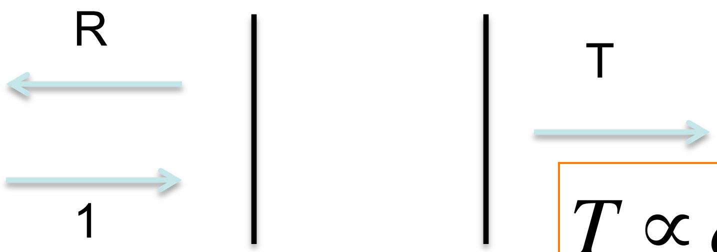
Acoustic Mode

$$\omega_-^2 = \frac{\alpha v_F^2 k_F^T k_F^B}{\varepsilon_{TI} (k_F^T + k_F^B)} q^2$$

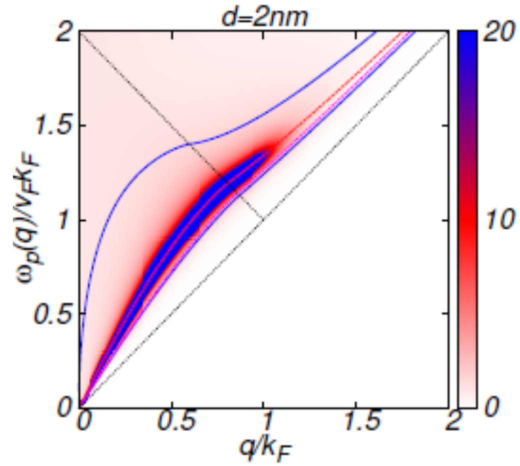
R. E. V. Profumo et al., Phys. Rev. B 85, 085443 (2012)

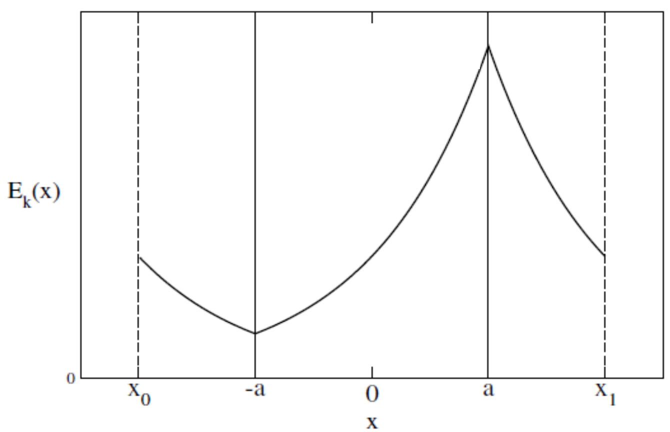
Exponential amplification of evanescent modes

Exponential amplification of evanescent modes for R=0.



$$T \propto e^{2qd}$$





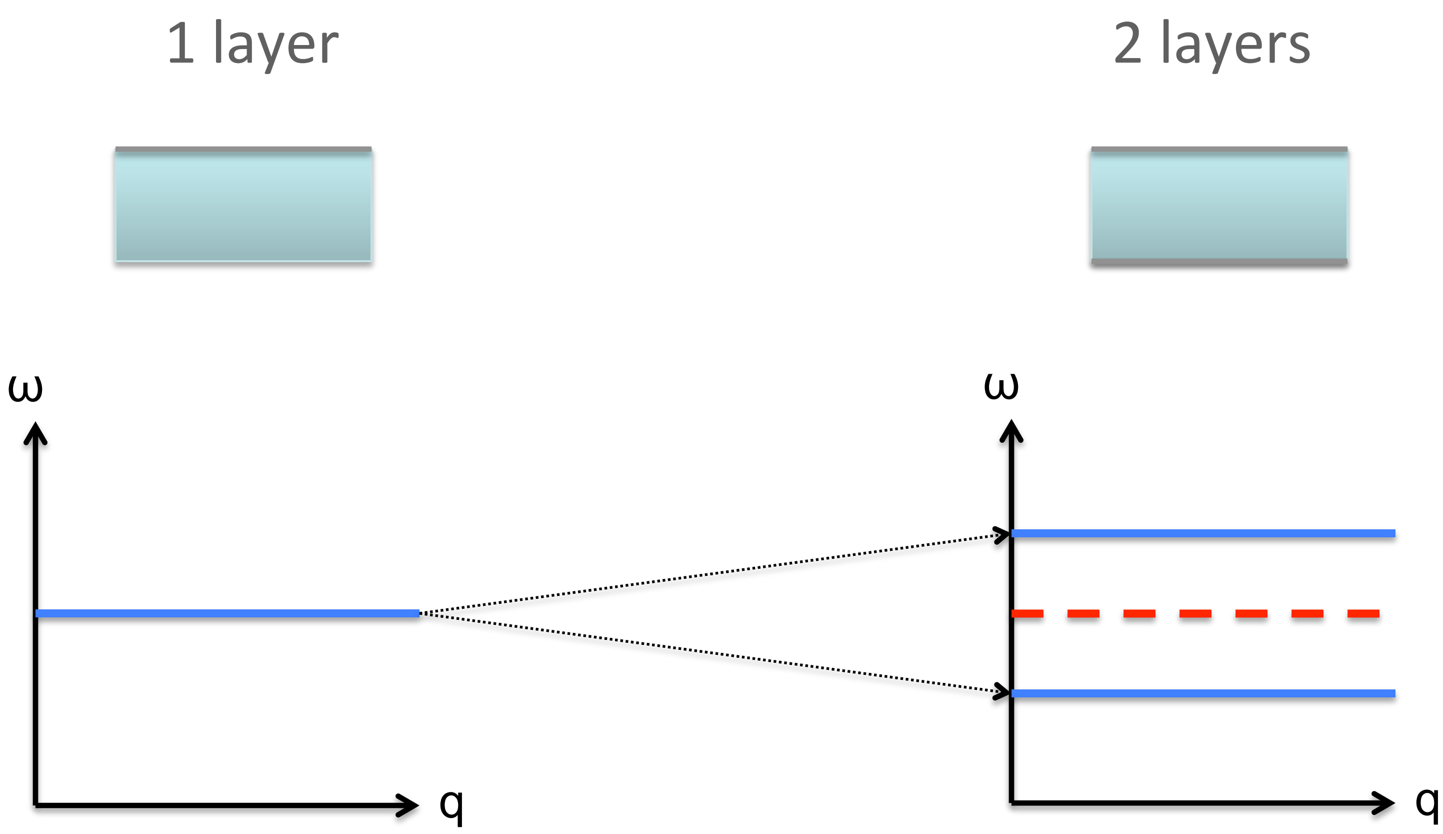
WANTED:

Plasmonic mode with constant energy dispersion

Analogy to Pendry´s perfect lens

T. Stauber and G. Gómez-Santos, Phys. Rev. B 85, 075410 (2012)

Exponential amplification of evanescent modes



Exponential amplification for all modes at constant energy

Hydrodynamic models for 2D systems

Continuity equation and linear response yields:

$$\omega^2 = \chi(\omega,q)\frac{e^2 q}{2\varepsilon_0\kappa}$$

Approximate current repsonse by Drude weight D:

$$D = e^2\chi(\omega \to 0, q = 0)$$

Plasmon dispersion in local approximation for 2D systems:

$$\omega_p = \sqrt{\frac{D}{2\varepsilon_0\kappa}q}$$

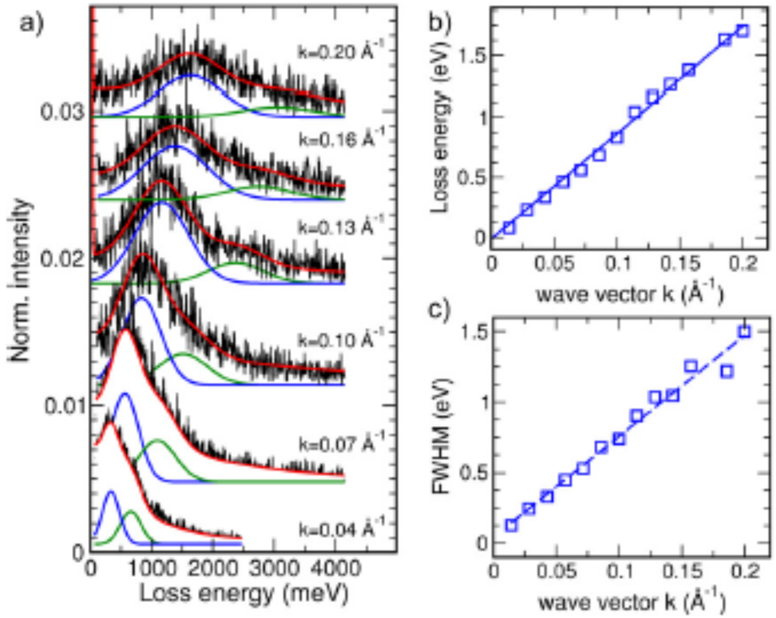
TS, J. Phys.: Condens. Matter **26**, 123201 (2014) Topical Review

Interband "plasmons" in Graphene on Ir(111)

Do plasmons exist in a neutral system (D=0)

EELS of Graphene on Ir

Ir



T. Langer et al., New J. Phys. **13**, 053006 (2011)

Interband "plasmons" in Graphene on Ir(111)

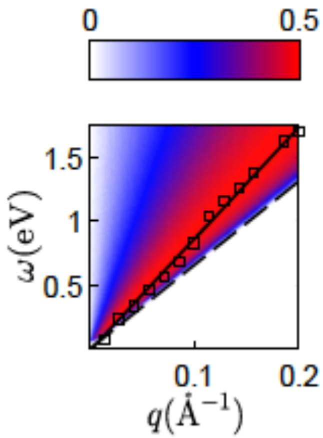
In pure Dirac systems, there are no interband plasmons because the charge response is always negative.

$$\chi_\rho(q,\omega) = -\frac{1}{4\hbar}\frac{q^2}{\sqrt{(v_F q)^2 - \omega^2}} < 0$$

$$\omega^2 \neq \chi(q,\omega)\frac{e^2 q}{2\varepsilon_0 \kappa}$$

But there can be an enhanced charge response as seen in the maximum of the loss function.

$$S(q,\omega) = -\mathrm{Im}\frac{1}{1 - v_q \chi_\rho(q,\omega)}$$



TS, J. Phys.: Condens. Matter **26**, 123201 (2014)

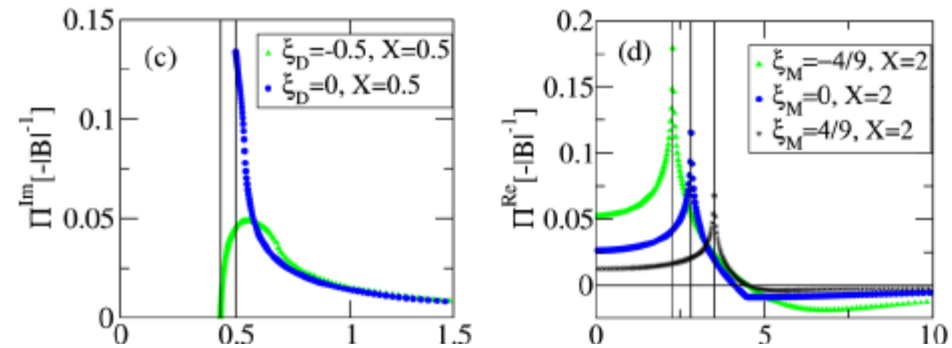
Are interband plasmons possible?

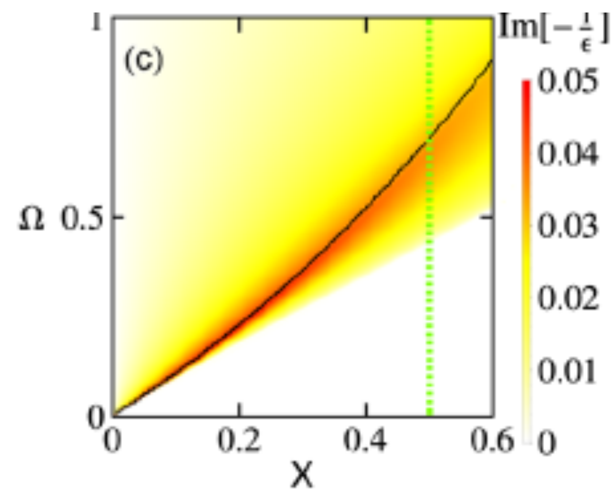
BHZ-model for fermions in Hg(Cd)Te:

$$H = \mathbf{d}_{\mathbf{k}} \cdot \vec{\sigma}$$

$$\mathbf{d}_{\mathbf{k}} = (v_F k_x, v_F k_y, M - Bk^2)$$

Mixture between Dirac and Schrödinger electrons yields plasmons at zero doping

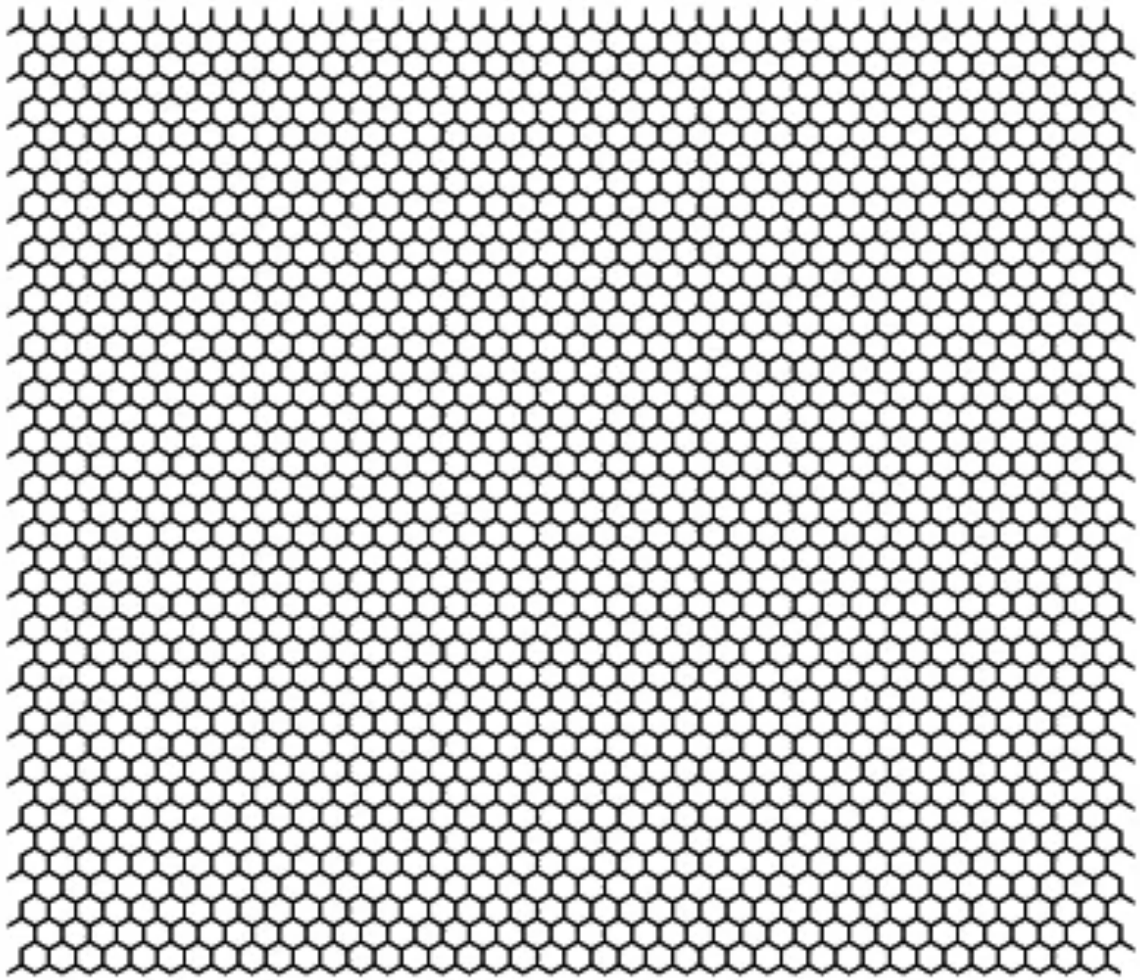




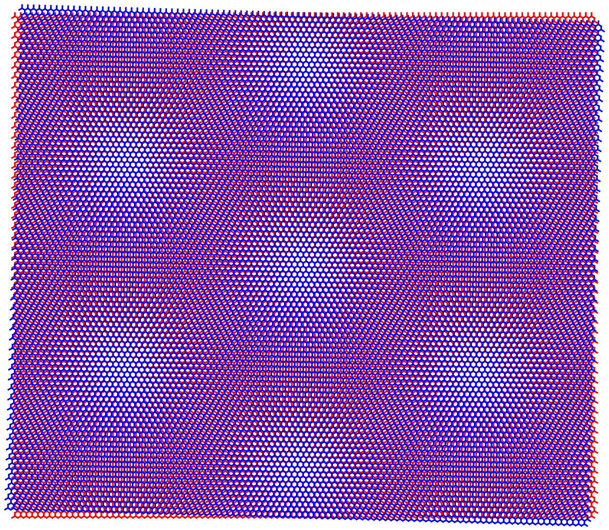
S. Juergens, P. Michetti, and B. Trauzettel, Phys. Rev. Lett. 112, 076804 (2014)

Twisted bilayer graphene

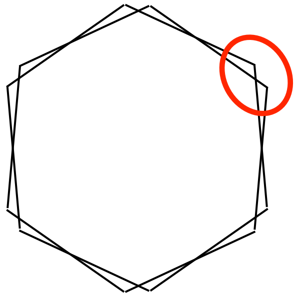
Twisted bilayer graphene

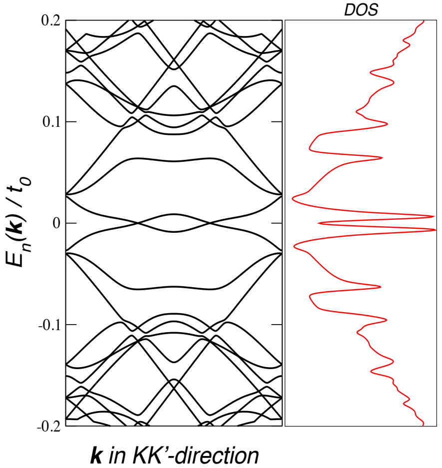


Brillouin zone for twisted bilayer grahene



Two Dirac cones





Twist angle parameterized by i

$$\cos\theta_i = 1 - \frac{1}{2A_i}$$

$$A_i = 3i^2 + 3i + 1$$

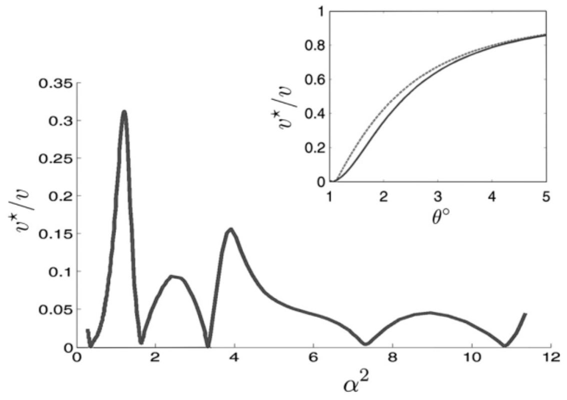
Fermi velocity renormalization

Renormalization of the Fermi velocity:

$$v = v_F\left(1 - 9\frac{t_\perp}{v_F \Delta K}\right)$$

J. M. B. Lopes dos Santos et al., Phys. Rev. Lett. **99**, 256802 (2007).

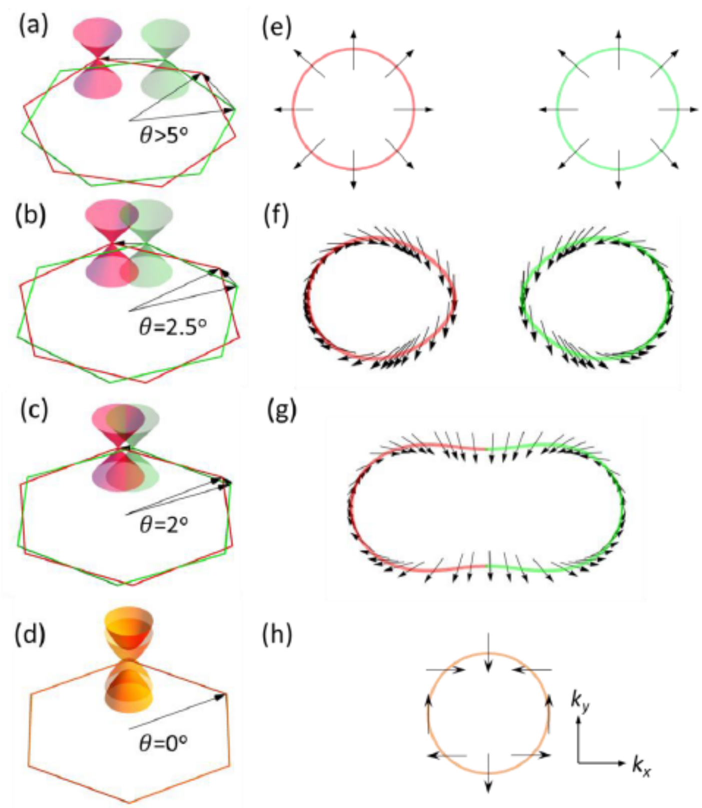
Appearance of magic angles for i>31



R. Bistritzer and A. H. MacDonald , PNAS **108**, 174108 (2011).

Merging of the pseudo-spin texture

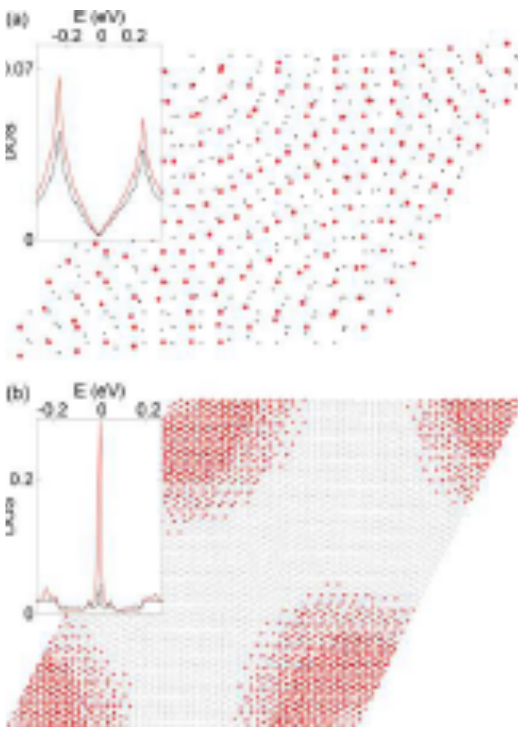
Crossover from large angle regime to low angle regime



M. Zhu et al., 2D Mater. 4, 011013 (2017)

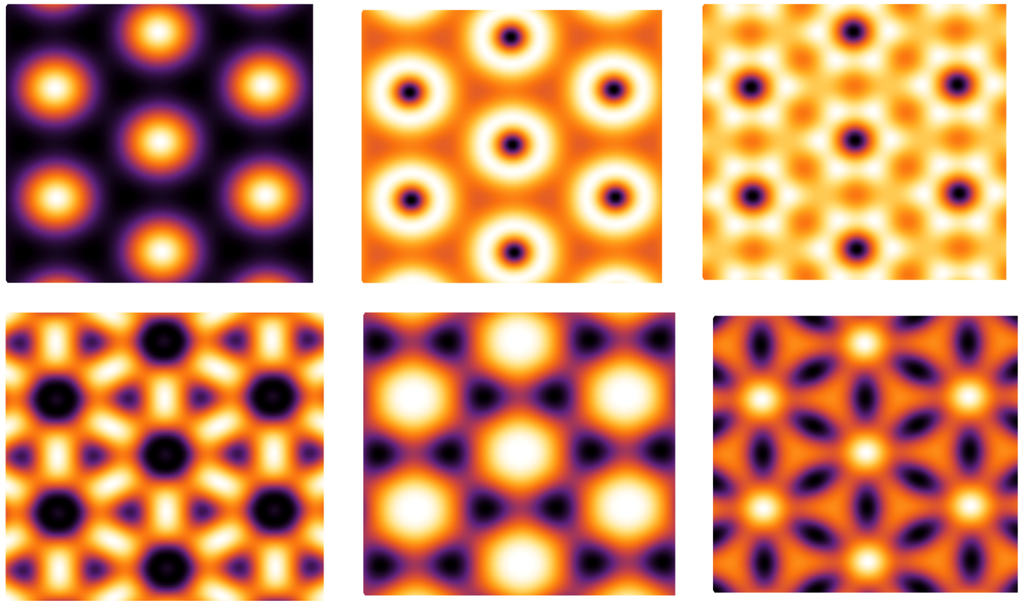
Localized states around AA-stacked islands

Crossover from extended to localized states



G. T. Trambly de Laissardiere, D. Mayou, L. Magaud, Nano Lett. 10, 804 (2010)

Local density of first six conduction bands:

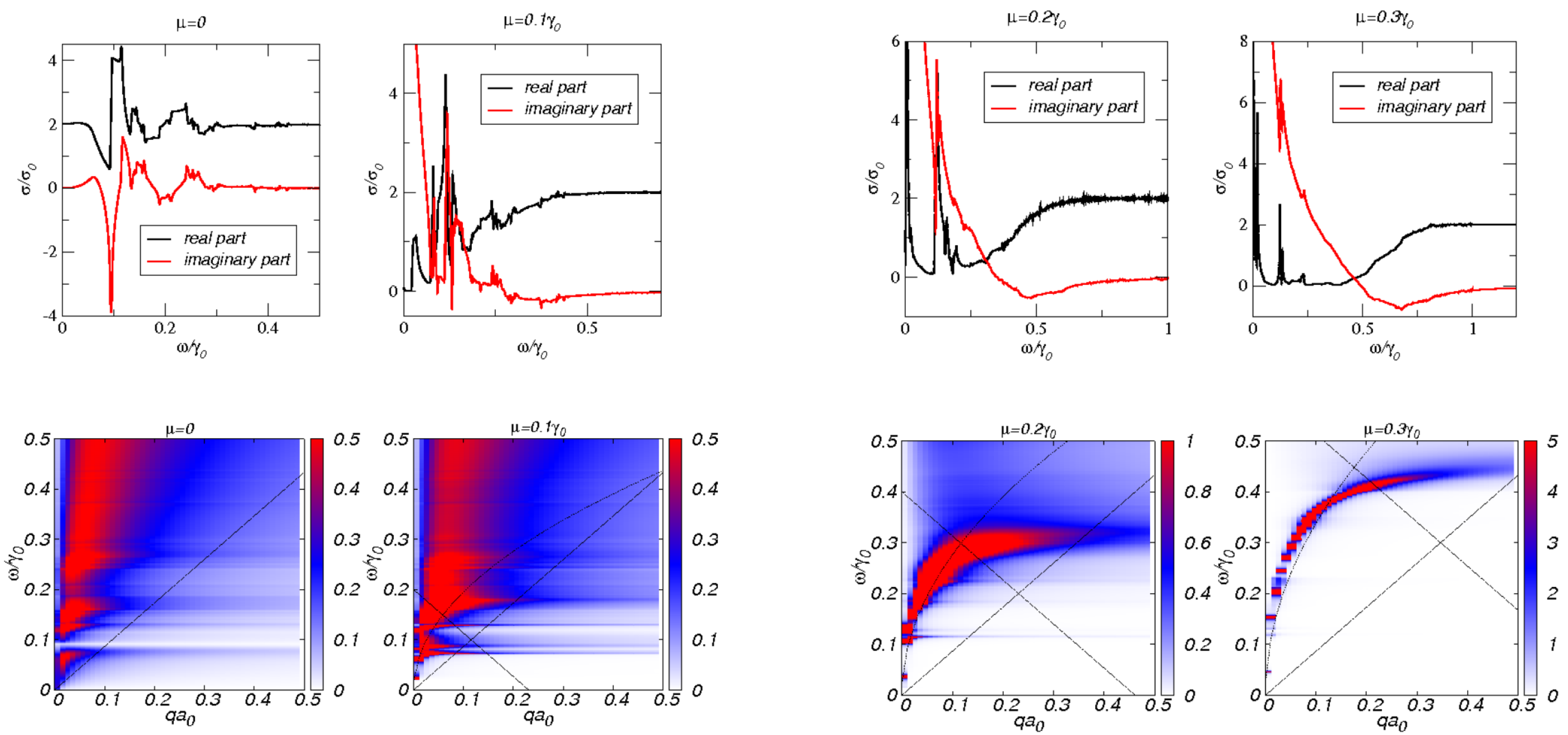


T. Stauber and H. Kohler, Nano Lett. **16**, 6844 (2016)

Plasmons in twisted bilayer graphene

Local optical response of twisted bilayer graphene

Plasmons in local approximation



T. Stauber, P. San-Jose, and L. Brey, New J. Phys. , 804 (2013)

Charge response with local field effects

Incoming momentum couples to reciprocal lattice vectors

$$V_{ext}(\mathbf{r}) = v_{\mathbf{q}} e^{i\mathbf{q}\cdot\mathbf{r}}$$

$$\Rightarrow$$

$$\delta\rho(\mathbf{r}) = \sum_{\mathbf{G}} \delta\rho(\mathbf{q},\mathbf{G}) e^{i(\mathbf{q}+\mathbf{G})\cdot\mathbf{r}}$$

Charge response with local field effects

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Charge susceptibility

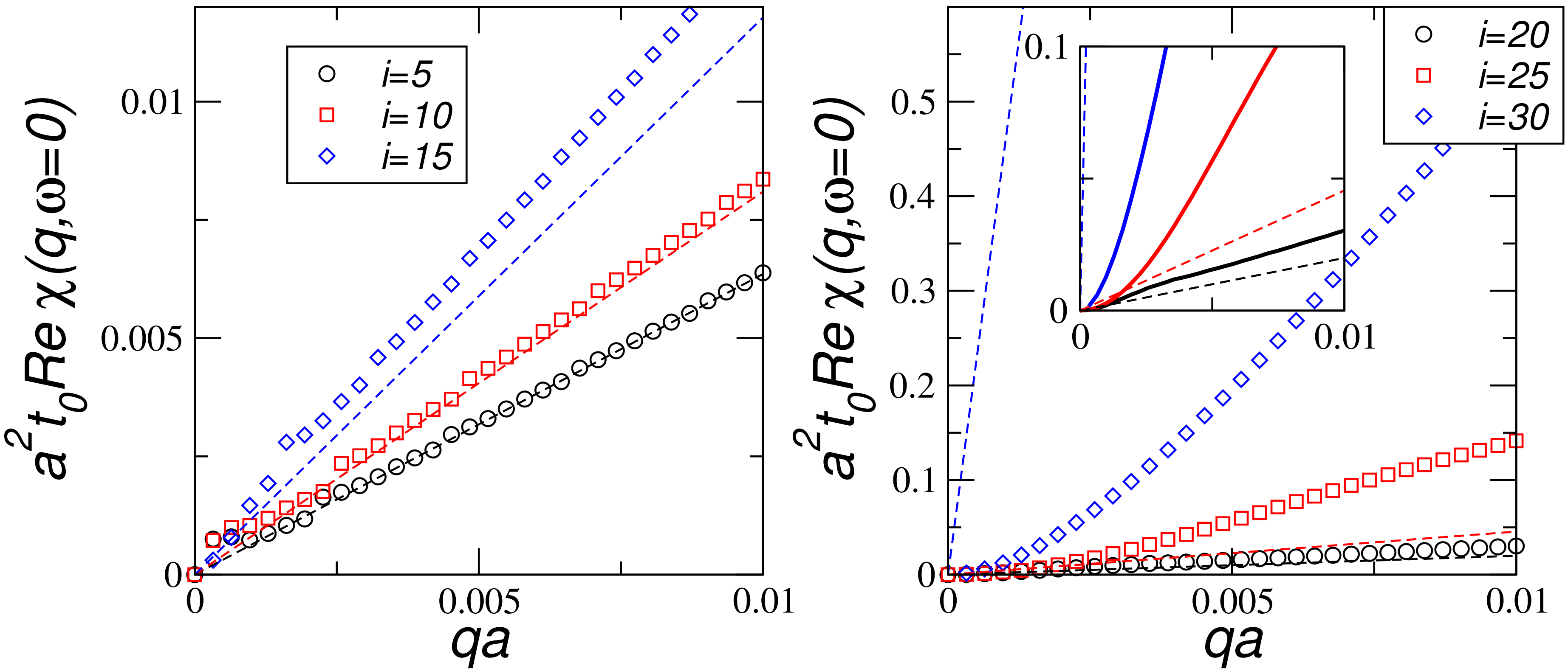
$$\chi_{\mathbf{G},\mathbf{G}'}(\mathbf{q},\omega) = \frac{g_s}{(2\pi)^2} \int_{1.\mathrm{BZ}} \mathrm{d}^2k \sum_{n,m;\kappa=\pm} f^{n,m;\kappa}_{\mathbf{G},\mathbf{G}'}(\mathbf{k},\mathbf{q}) \left[\frac{n_F(E^s_{\mathbf{k}}) - n_F(E^{s'}_{\mathbf{k}+\mathbf{q}})}{E^s_{\mathbf{k}} - E^{s'}_{\mathbf{k}+\mathbf{q}} + \hbar\omega + i\delta} \right]$$

Band overlap including local field effects

$$f^{n,m;\kappa}_{\mathbf{G},\mathbf{G}'}(\mathbf{k},\mathbf{q}) = \left\langle \mathbf{k},n;\kappa \middle| e^{-i(\mathbf{q}+\mathbf{G})\cdot\hat{\mathbf{r}}} \middle| \mathbf{k}+\mathbf{q},m;\kappa \right\rangle \left\langle \mathbf{k}+\mathbf{q},m;\kappa \middle| e^{i(\mathbf{q}+\mathbf{G}')\cdot\hat{\mathbf{r}}} \middle| \mathbf{k},n;\kappa \right\rangle$$

Static response of twisted bilayer graphene

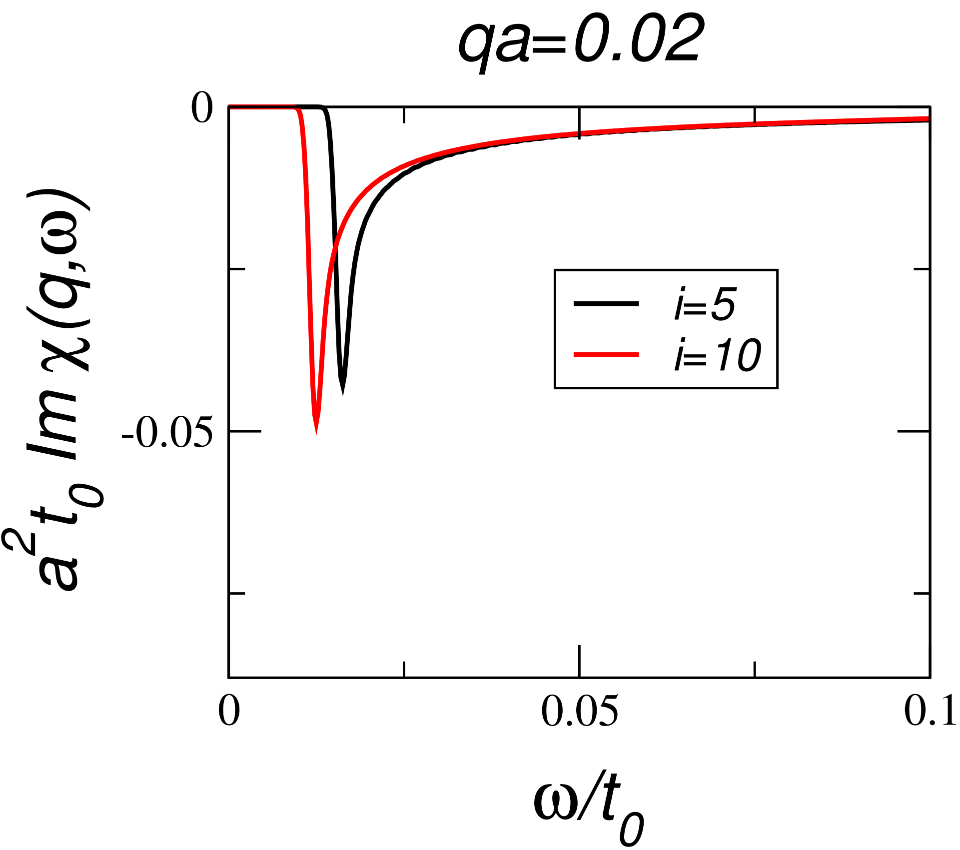
Crossover from linear to quadratic behavior

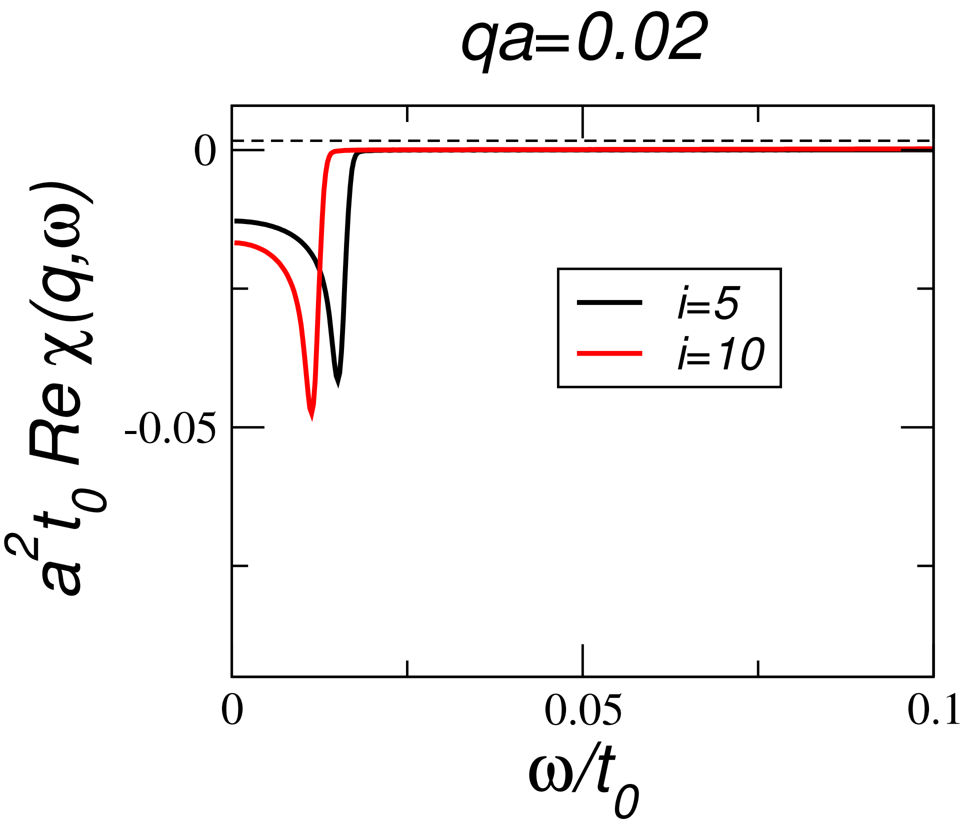


T. Stauber and H. Kohler, Nano Lett. **16**, 6844 (2016)

Dynamical response of twisted bilayer graphene

Crossover at i=15-20:





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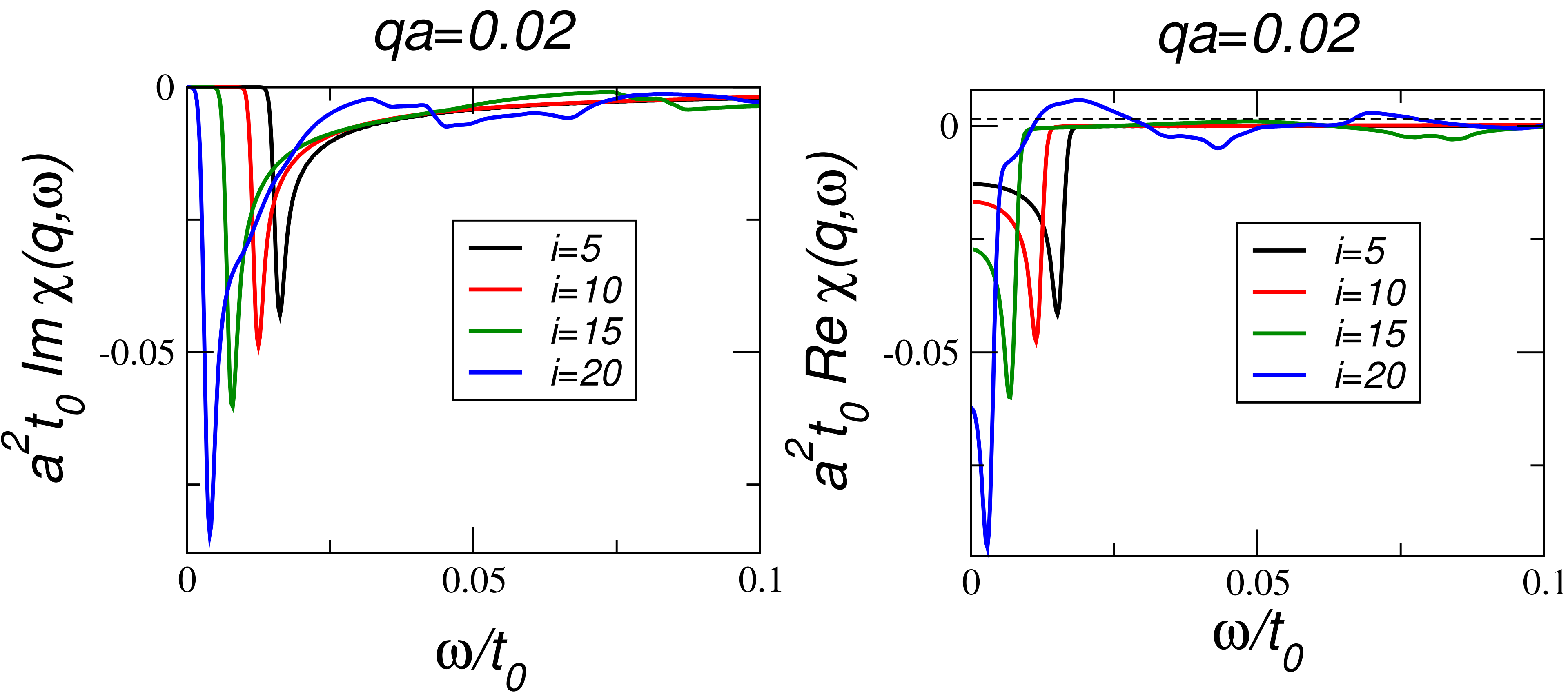
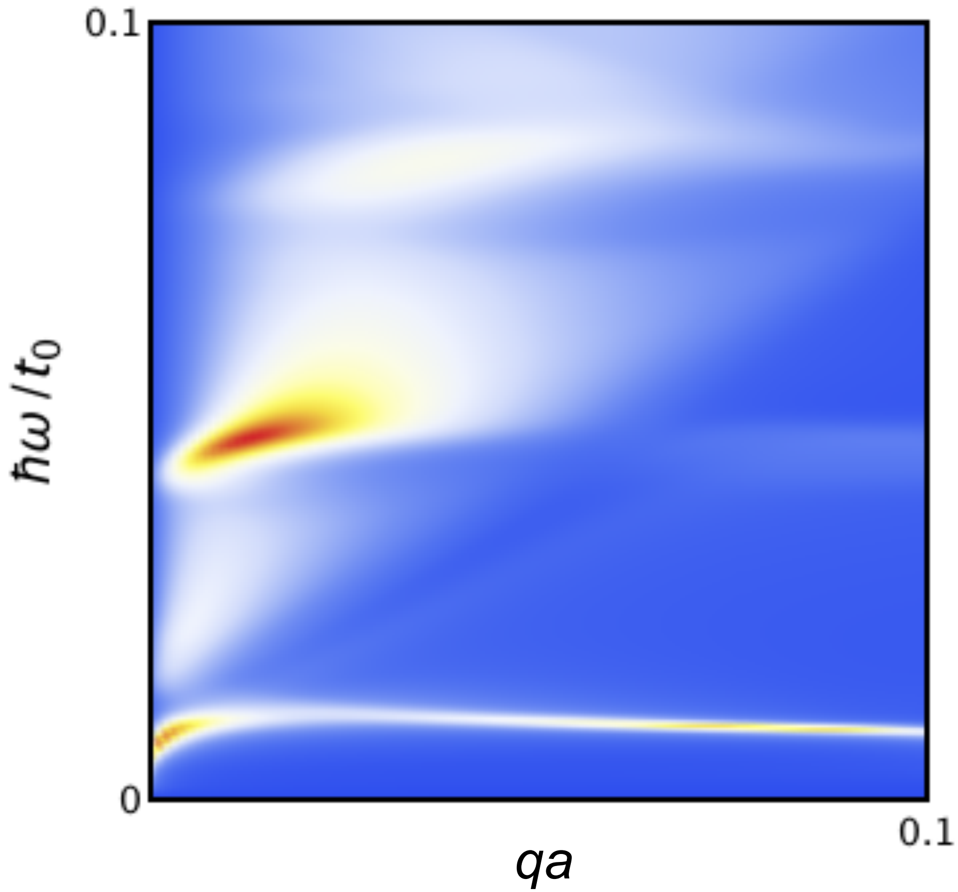


T. Stauber and H. Kohler, Nano Lett. **16**, 6844 (2016)

Loss function for i=25

Quasi-flat plasmonic bands for θ≈1.6°:



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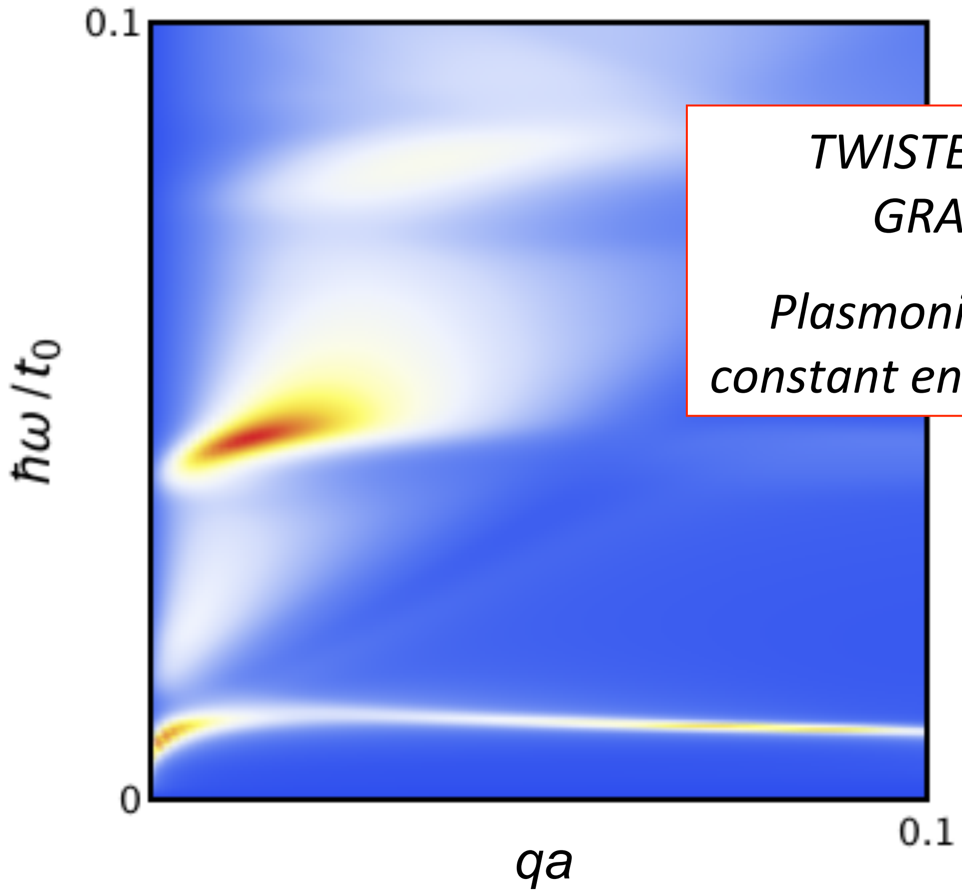

TWISTED BILAYER GRAPHENE:

Plasmonic mode with constant energy dispersion

T. Stauber and H. Kohler, Nano Lett. **16**, 6844 (2016)

1. For small enough twist angle, we find a novel plasmonic resonance of almost constant energy at zero doping. This mode can be tuned and quenched/enhanced by changing the twist angle and chemical potential, respectively.

2. The novel mode can be characterised as collective excitonic in-phase oscillations in a periodic, but quasi-confining potential surrounding the AA-stacked regions.

3. Twisted bilayer graphene resembles a new metamaterial with extraordinary properties in the THz to mid-infrared region leading to enhanced absorption and exponential amplification at constant energy reminiscent to Pendry's perfect lens, but without the need of left-handed materials.

Thank you for your attention!