Epsilon-Near-Zero behavior from Plasmonic Dirac Point: Theory and realization using 2D materials

Marios Mattheakis

Collaborators:
C. Valagiannopoulos
E. Kaxiras

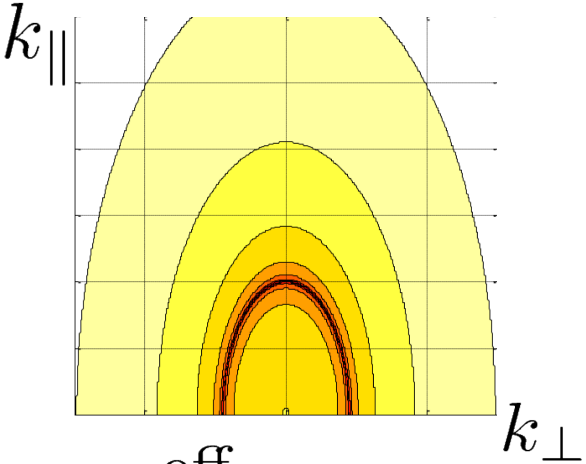
School of **E**ngineering & **A**pplied **P**hysics (SEAS)

APS March Meeting,
March 13, 2017
New Orleans, Louisiana

Periodic Structures

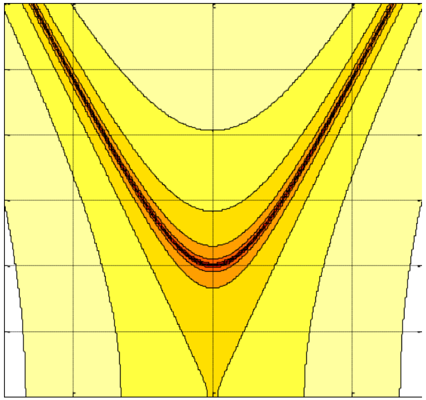
Plasmonic Crystal: Periodic arrangement of dielectric/metal slabs

Optical Bands: The propagation modes form bands in k-space



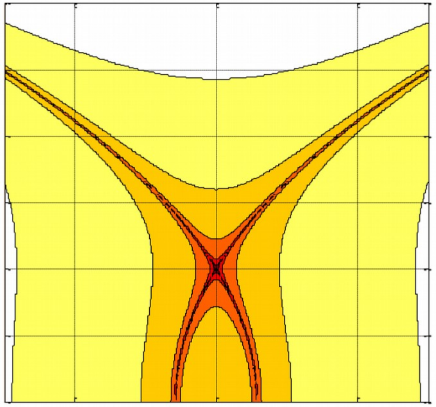
$$\varepsilon_{\|}^{\mathrm{eff}} > 1$$

Normal Refraction



$$\varepsilon_{\|}^{\mathrm{eff}} < -1$$

Negative Refraction



$$-1 < \varepsilon_{\|}^{\mathrm{eff}} < 1$$

Epsilon-Near-Zero (ENZ)

Motivation

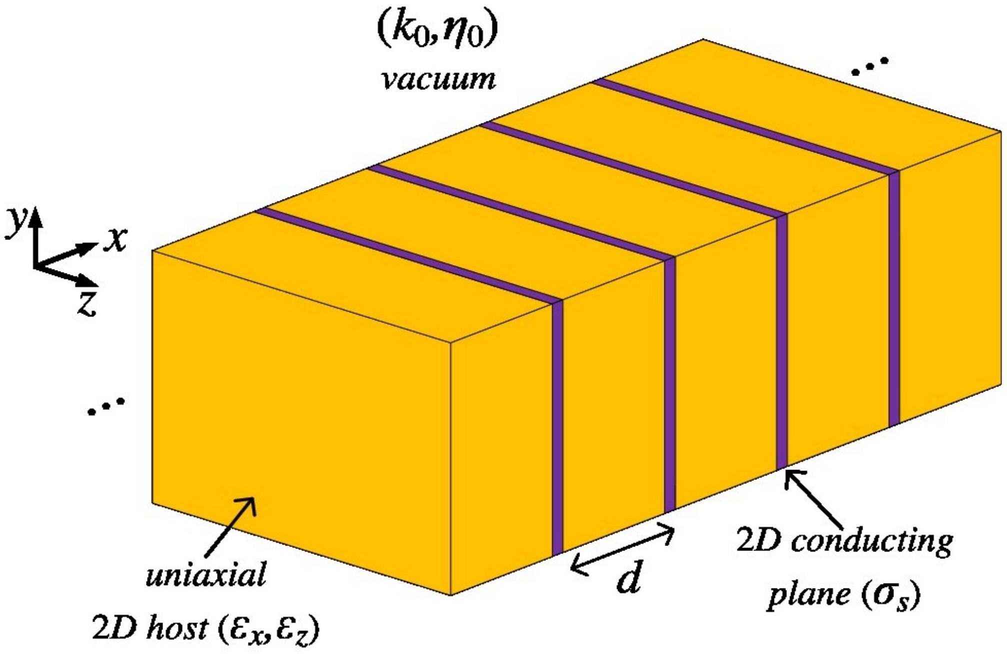
Can we design a structure with dynamically tunable optical bands?

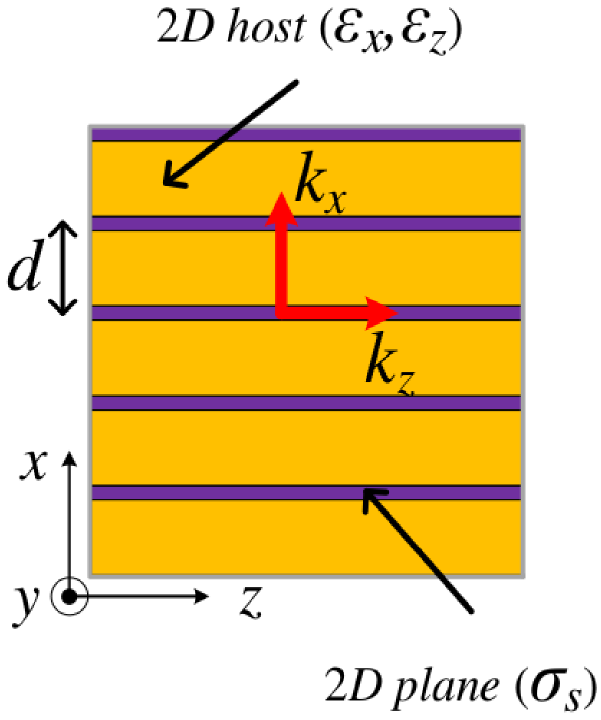
Can we have ENZ behavior between normal and negative refraction regimes?

What the shape of ENZ band will be?

Structure

2D metals are embedded periodically in an anisotropic dielectric host





Maxwell Equations

Transverse Magnetic (TM) monochromatic EM waves

$$-\mathrm{i}\frac{\partial}{\partial z}\boldsymbol{\Psi} = \mathcal{M}\cdot\boldsymbol{\Psi} \Leftrightarrow$$

$$-\mathrm{i}\frac{\partial}{\partial z}\begin{pmatrix} E_x \\ H_y \end{pmatrix} = k_0\eta_0 \begin{pmatrix} 0 & 1+\frac{1}{k_0^2}\frac{\partial}{\partial x}\frac{1}{\varepsilon_z}\frac{\partial}{\partial x} \\ \frac{\varepsilon_x}{\eta_0^2} & 0 \end{pmatrix}\begin{pmatrix} E_x \\ H_y \end{pmatrix}.$$

$$E_z = \frac{\mathrm{i}\eta_0}{k_0\varepsilon_z}\frac{\partial H_y}{\partial x}$$

EigenValue Problem

$$\boldsymbol{\Psi}(x,z) = \boldsymbol{\Psi}(x)e^{\mathrm{i}k_z z}$$

$$k_z\boldsymbol{\Psi} = \mathcal{M}\boldsymbol{\Psi}$$

Dispersion Relation

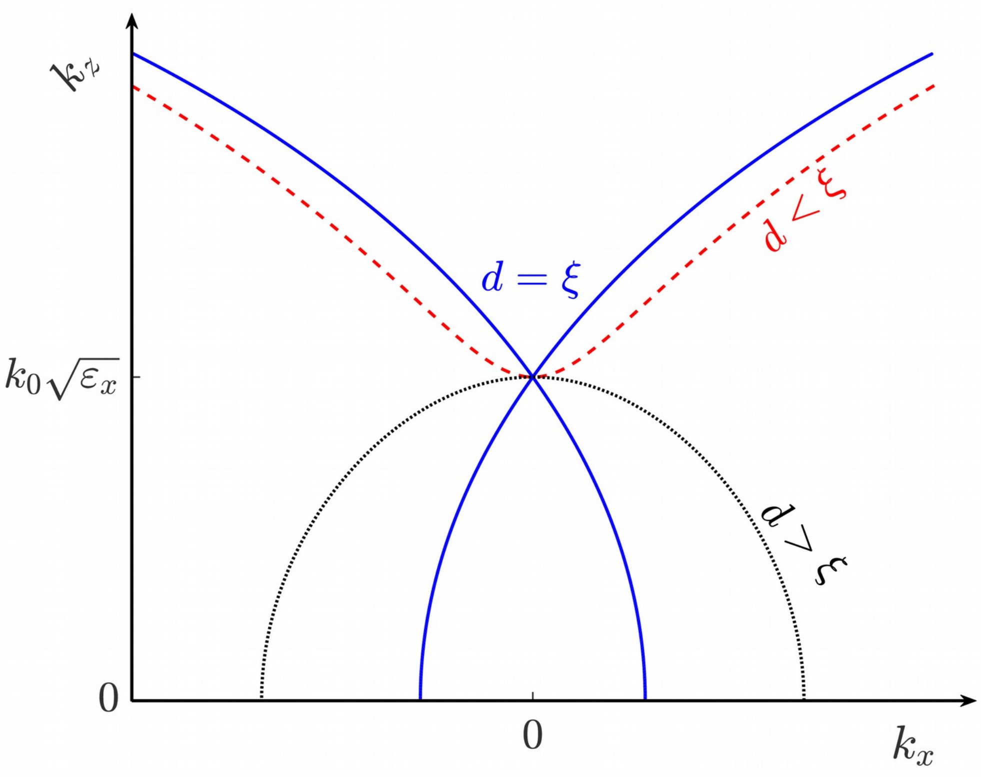
Dense grid λ >> d:

$$\frac{k_z^2}{\varepsilon_x} + \frac{d}{(d-\xi)\varepsilon_z} k_x^2 = k_0^2$$

Plasmonic Thickness

$$\xi = -\frac{i\sigma_s \eta_0}{k_0 \varepsilon_z} = 2\delta$$

(B.Wang *et. al.* PRL 109, 2012)



Plasmonic Dirac Point (PDP)

A Plasmonic Dirac Point leads to ENZ

Effective medium (metamaterial) approach

$$\varepsilon_z^{\text{eff}} = \varepsilon_z \frac{d-\xi}{d} \quad , \quad \varepsilon_x^{\text{eff}} = \varepsilon_x$$

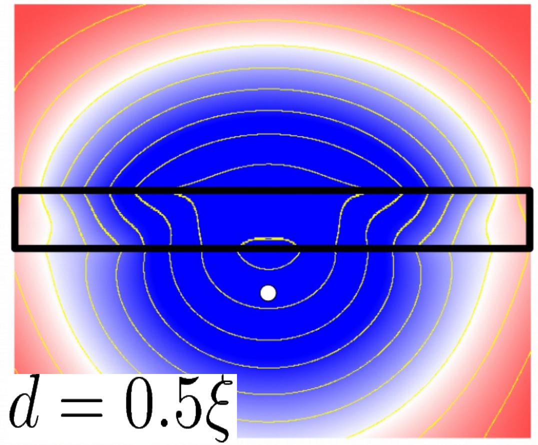
Plasmonic Dirac Point leads to Epsilon-Near-Zero behavior

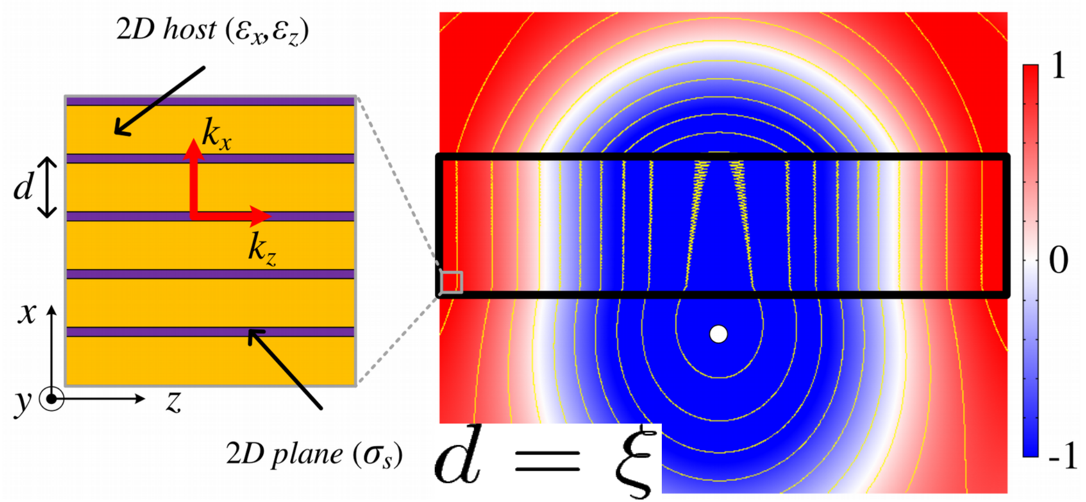
$$d = \xi \Rightarrow \varepsilon_z^{\text{eff}} = 0$$

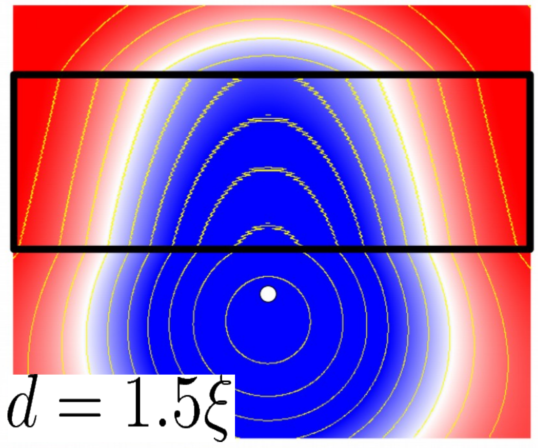
M. Mattheakis *et. al*., Phys. Rev. B, 94, 201404(R), 2016.

EM wave simulations

- 40 periods structure: doped graphene layers embedded in MoS_2 host (ε_x=3.5, ε_z=13)
  (R.K. Defo *et. al.* PRB **94,** 2016)
- 2D magnetic dipole source
- λ_0 = 12 μm (f = 25 THz), ξ=20.8 nm



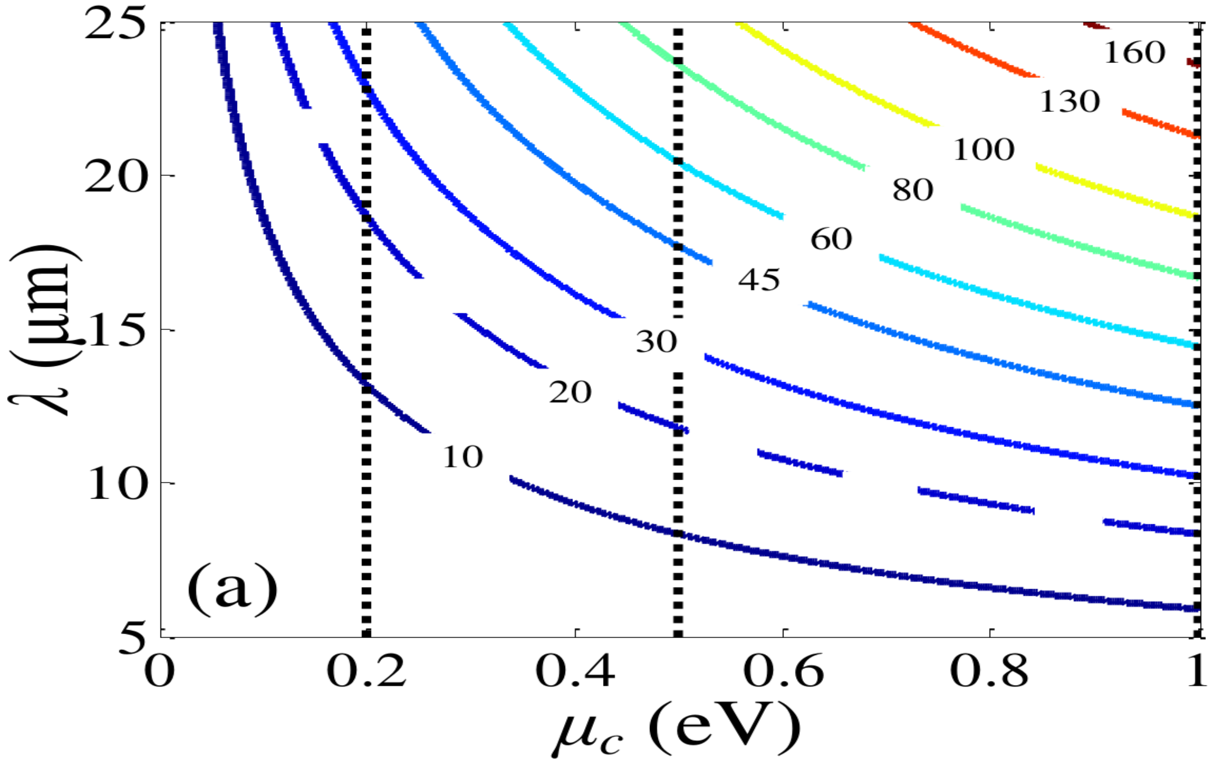




M. Mattheakis *et. al*., Phys. Rev. B, 94, 201404(R), 2016.

Tunability in terms of λ, μ_c & d

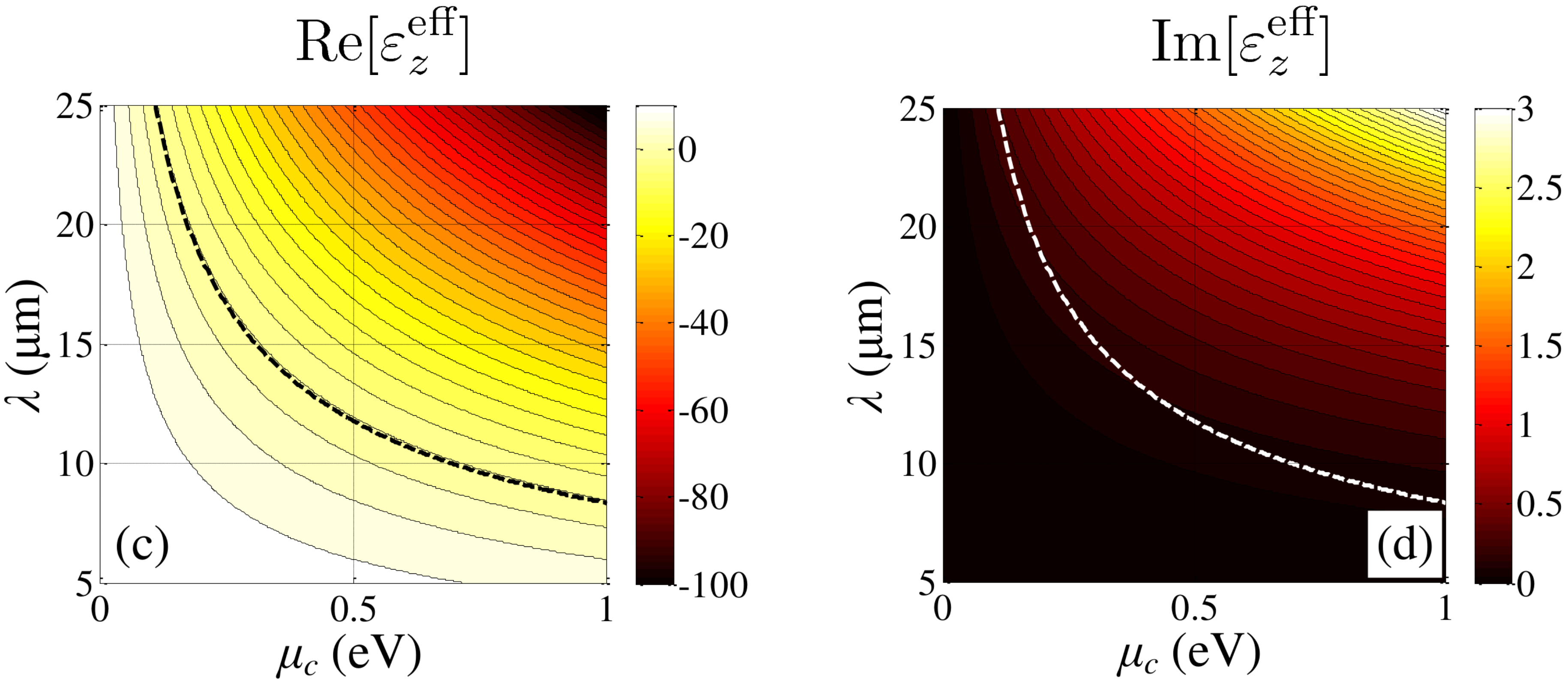
Combinations of μ_c and λ leading to PDP & ENZ (d is plotted in nm).



M. Mattheakis *et. al*., Phys. Rev. B, 94, 201404(R), 2016.

Effective Permittivity

Combinations of λ and μ_c at fixed period d=20nm. Dashed lines indicate ENZ regime.



M. Mattheakis *et. al*., Phys. Rev. B, 94, 201404(R), 2016.

Conclusion

- ➢ Any periodic structure of 2D plasmonic materials (e.g. doped graphene) exhibits **P**lasmonic **D**irac **P**oint in k-space.

- ➢ A Plasmonic Dirac Point leads to **E**psilon-**N**ear-**Z**ero metamaterial.
  - ✔ A systematic method for designing ENZ metamaterials.

- ➢ Optical properties can be tuned dynamically via doping and frequency.
  - ✔ Tunable Metamaterial.

Relevant Publication:

M. Mattheakis, C.A. Valagianopoulos and E. Kaxiras, Phys. Rev. B, **94**, 201404(R), 2016.

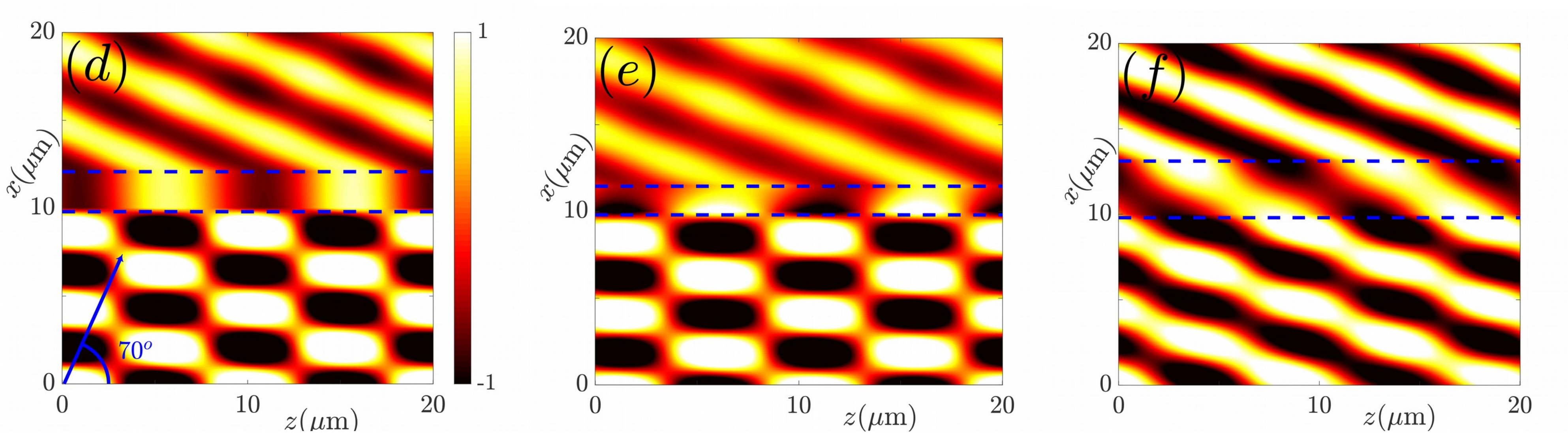
Acknowledgment

H2020-MSCA-RISE-2015

M. Mattheakis *et. al*., Phys. Rev. B, 94, 201404(R), 2016.

Plasmonic Metamaterial (simulations)

100 periods structure is excited by a plane wave source of f=25 THz (λ=12μm).



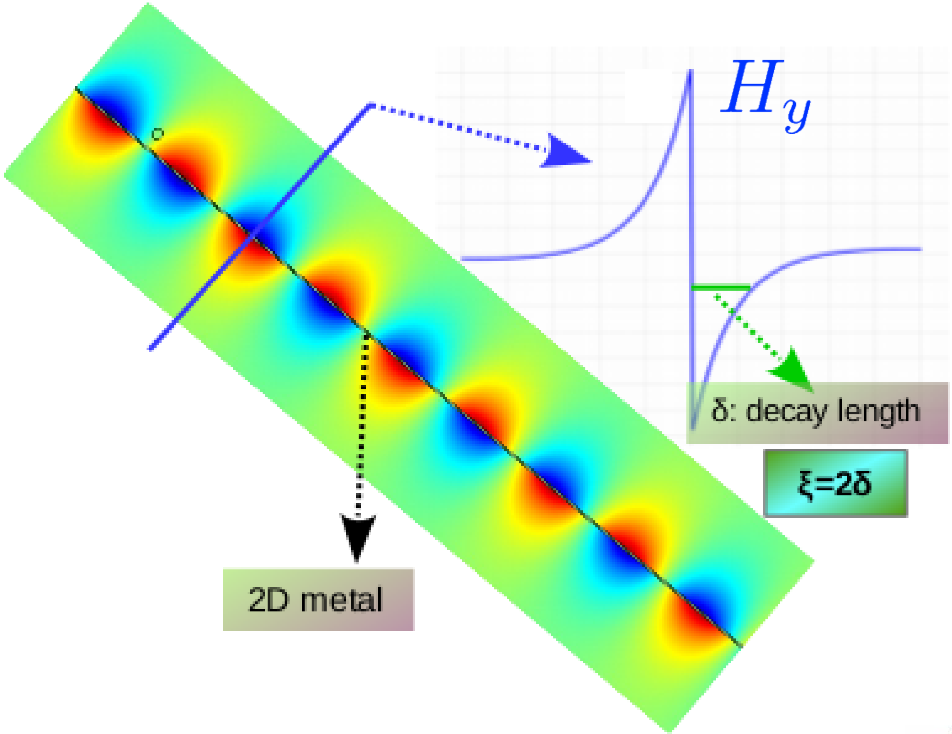
d=ξ=20,8 nm (linear) **d<ξ (hyperbolic)** **d>ξ (elliptic)**

M. Mattheakis *et. al*., Phys. Rev. B, 94, 201404(R), 2016.

Dispersion Relation

Assuming a very dense grid λ >> d:

$$\frac{k_z^2}{\varepsilon_x} + \frac{d}{(d-\xi)\varepsilon_z} k_x^2 = k_0^2$$

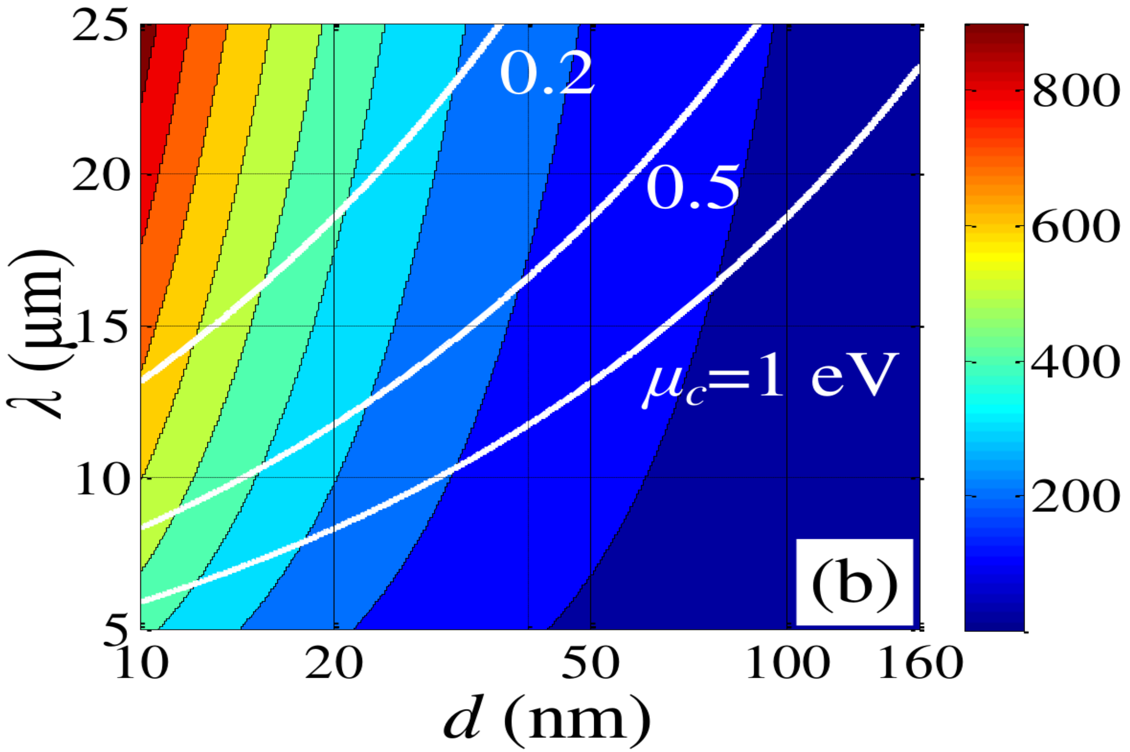


Plasmonic Thickness

$$\xi = -\frac{\mathrm{i}\sigma_s \eta_0}{k_0 \varepsilon_z}$$

Propagation Length

Propagation length L/d for combinations of λ, d & μ_c leading to ENZ.



Plasmonic Metamaterial

Doped graphene surface conductivity:

$$\sigma_s = \frac{\mathrm{i}e^2 \mu_c}{\pi \hbar^2 (\omega + \mathrm{i}/\tau)} \quad (\tau = 0.5ps)$$

PDP is extremely sensitive to structural defects:

$$\frac{\Delta k_z}{k_0 \sqrt{\varepsilon_x}} = -\frac{6}{(k_0 d)^2 \varepsilon_z} \frac{\Delta \xi}{d}.$$

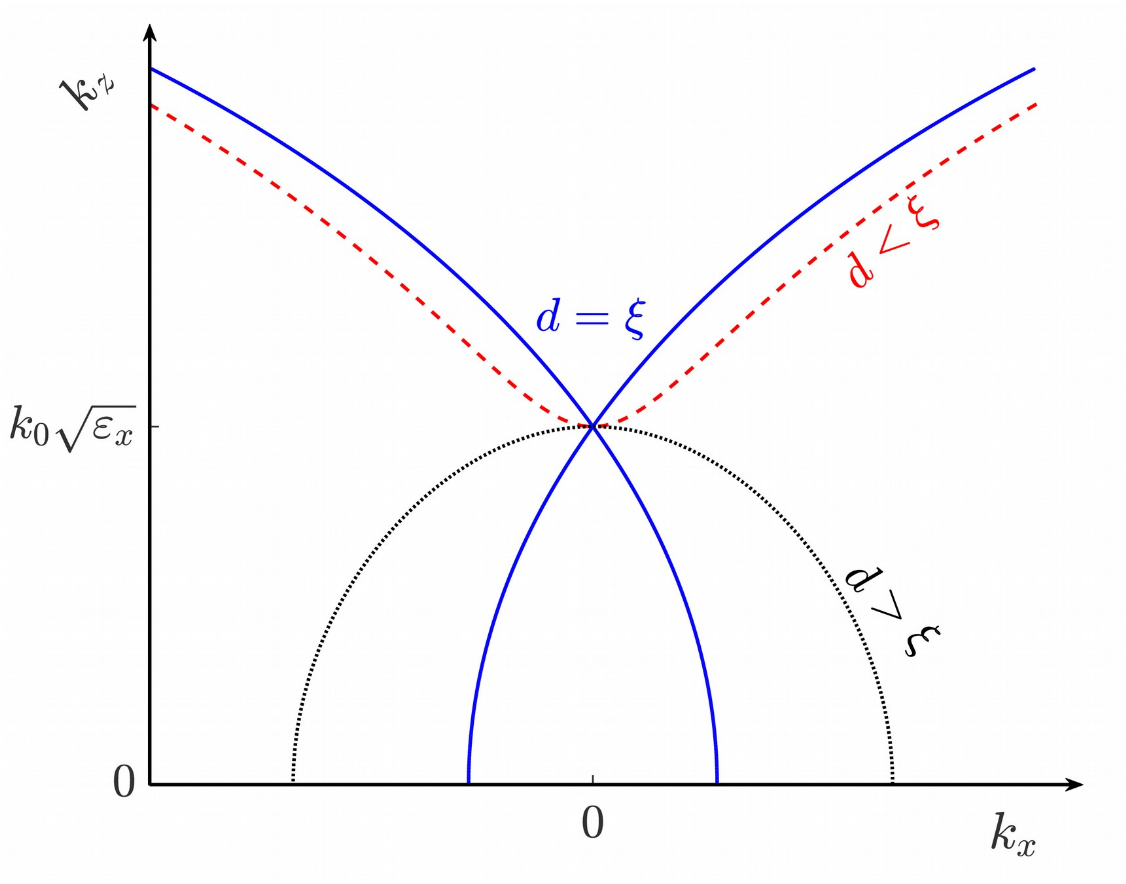
Stacking of 2D materials provides essentially perfect planarity.

Stacking of MoS2 builds a anisotropic dielectric:

$$\varepsilon_x = 3.5 \quad , \quad \varepsilon_y = \varepsilon_z = 13$$

(R.K. Defo *et. al.* PRB **94,** 2016)

Optical Bands



Weak plasmon coupling

Strong plasmon coupling

Critical plasmon coupling

Plasmonic Dirac Point (PDP)

$$k_z^2 \approx \frac{\varepsilon_x d}{\varepsilon_z(\xi - d)} k_x^2$$

M. Mattheakis *et. al*., Phys. Rev. B, 94, 201404(R), 2016.