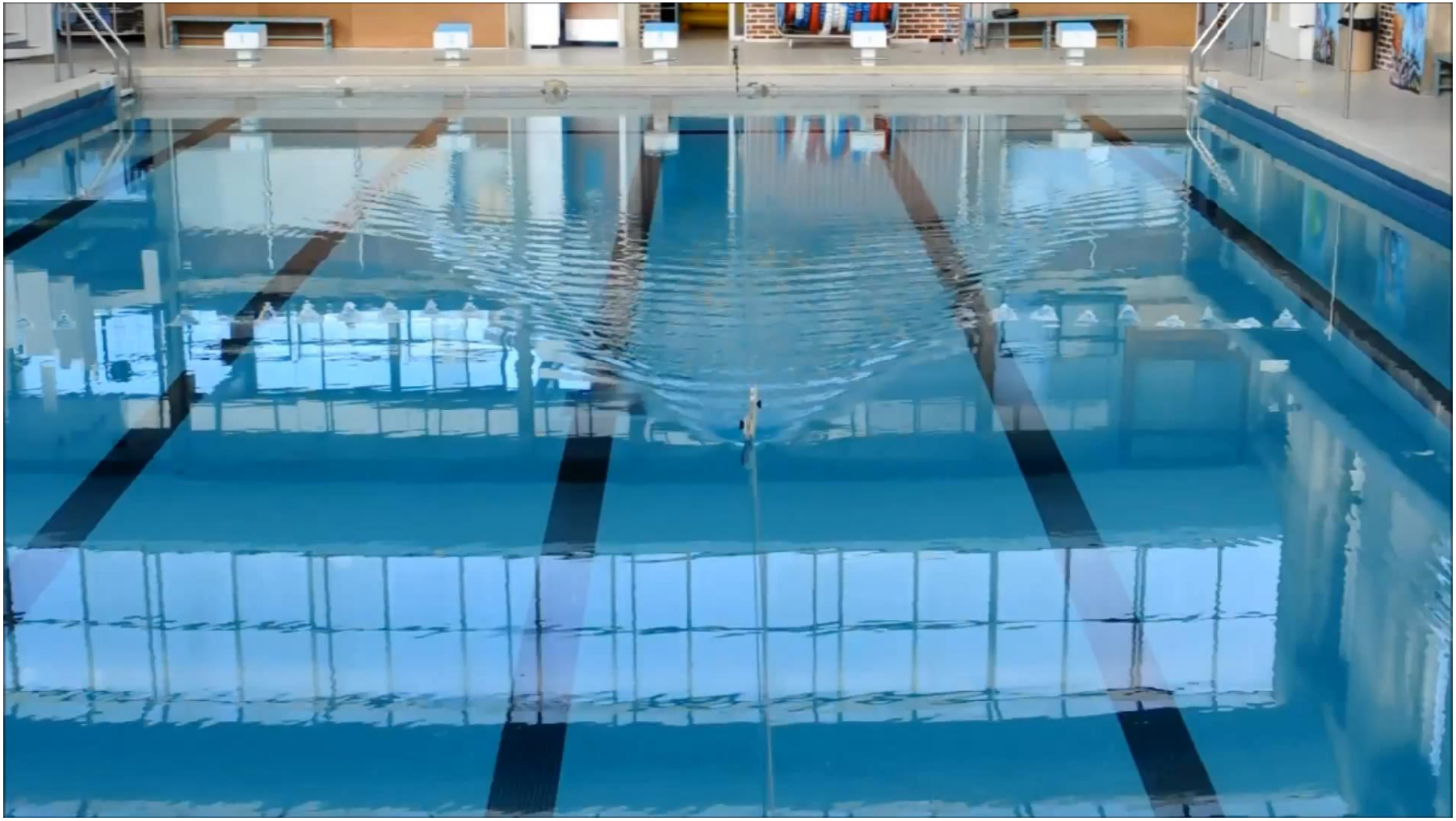
NANYANG TECHNOLOGICAL UNIVERSITY

Fluid mechanics and some novel surface waves
Part II

Baile Zhang

Nanyang Technological University, Singapore

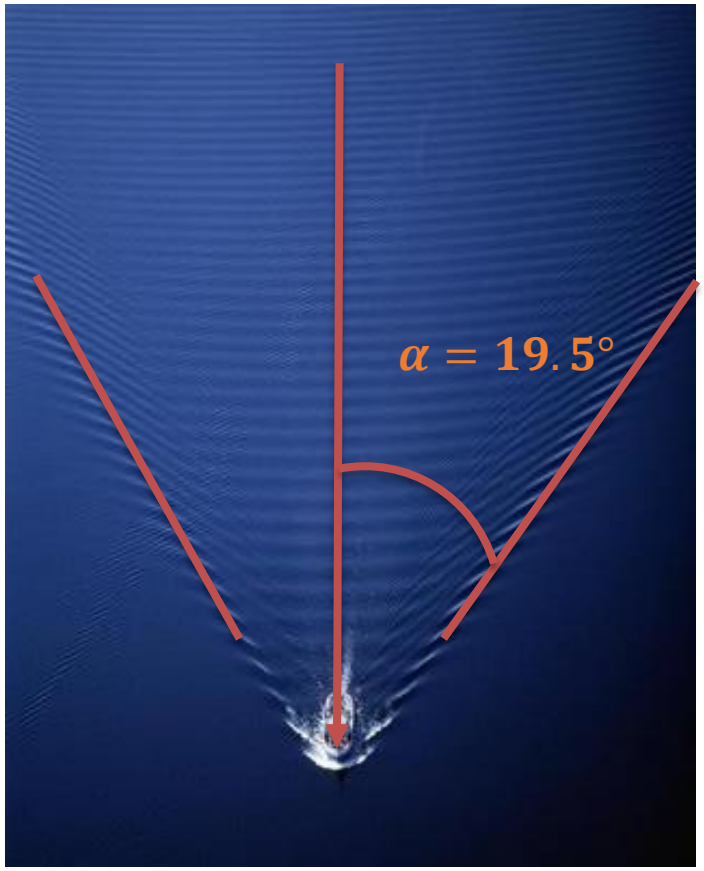


Frederic Moisy and Marc Rabaud, Universite Paris-Sud, CNRS

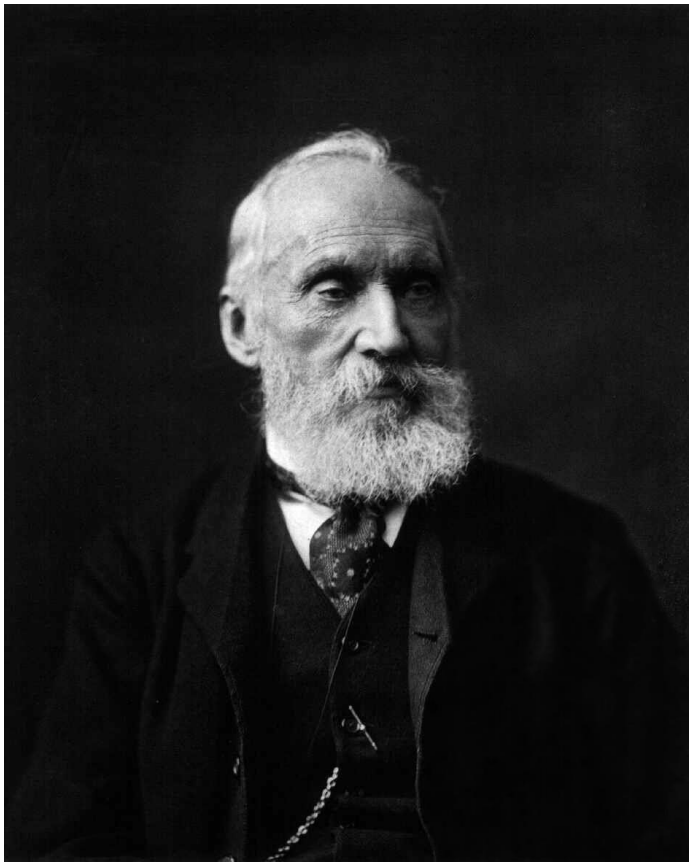
Can we construct this wave on graphene (2D plasmons)?

Deep-water Wave Dispersion: $\boldsymbol{\omega \propto \sqrt{k}}$

Kelvin ship-wave pattern



Kelvin ship-wave pattern



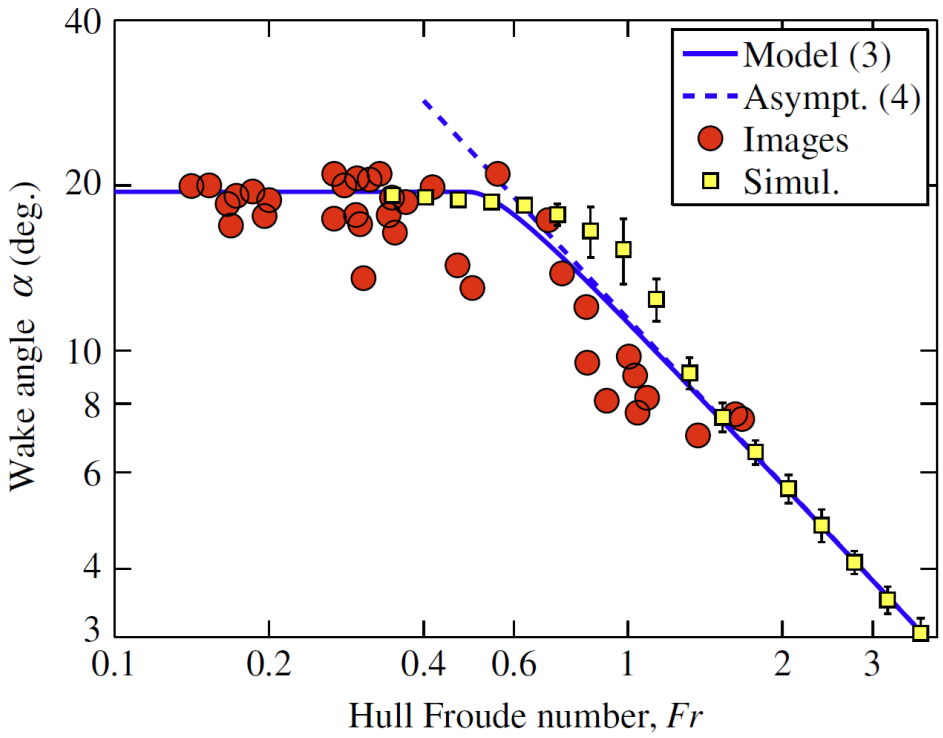
Lord Kelvin (1824 – 1907)

Reawakening the Kelvin wake

PRL 110, 214503 (2013) PHYSICAL REVIEW LETTERS week ending 24 MAY 2013

Ship Wakes: Kelvin or Mach Angle?

Marc Rabaud and Frédéric Moisy
Laboratoire FAST, Université Paris-Sud, UPMC Université Paris 6, CNRS, Bâtiment 502, Campus Universitaire, 91405 Orsay, France



$$Fr = U/\sqrt{gL}$$

J. Fluid Mech. (2014), *vol.* 738, R3, doi:10.1017/jfm.2013.607



Kelvin wake pattern at large Froude numbers

Alexandre Darmon[1,2], Michael Benzaquen[1] and Elie Raphaël[1,†]

[1]PCT, UMR CNRS 7083 Gulliver, ESPCI ParisTech, 10 rue Vauquelin, 75005 Paris, France
[2]EC2M, UMR CNRS 7083 Gulliver, ESPCI ParisTech, 10 rue Vauquelin, 75005 Paris, France

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Physicists rethink celebrated Kelvin wake pattern for ships

May 30, 2013 4 comments

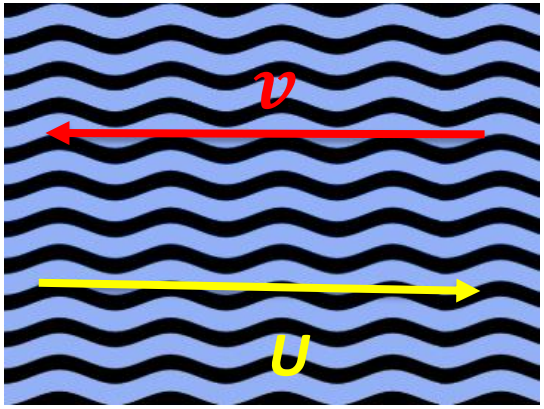
Stationary wave pattern in steady stream

Steady stream: the fluid velocity does NOT change with time

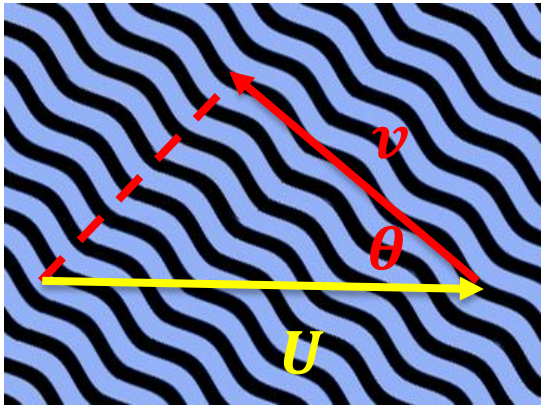
Stationary wave pattern: pattern shows NO change with time

$\boldsymbol{v}$: velocity of wave

$\boldsymbol{U}$: velocity of stream



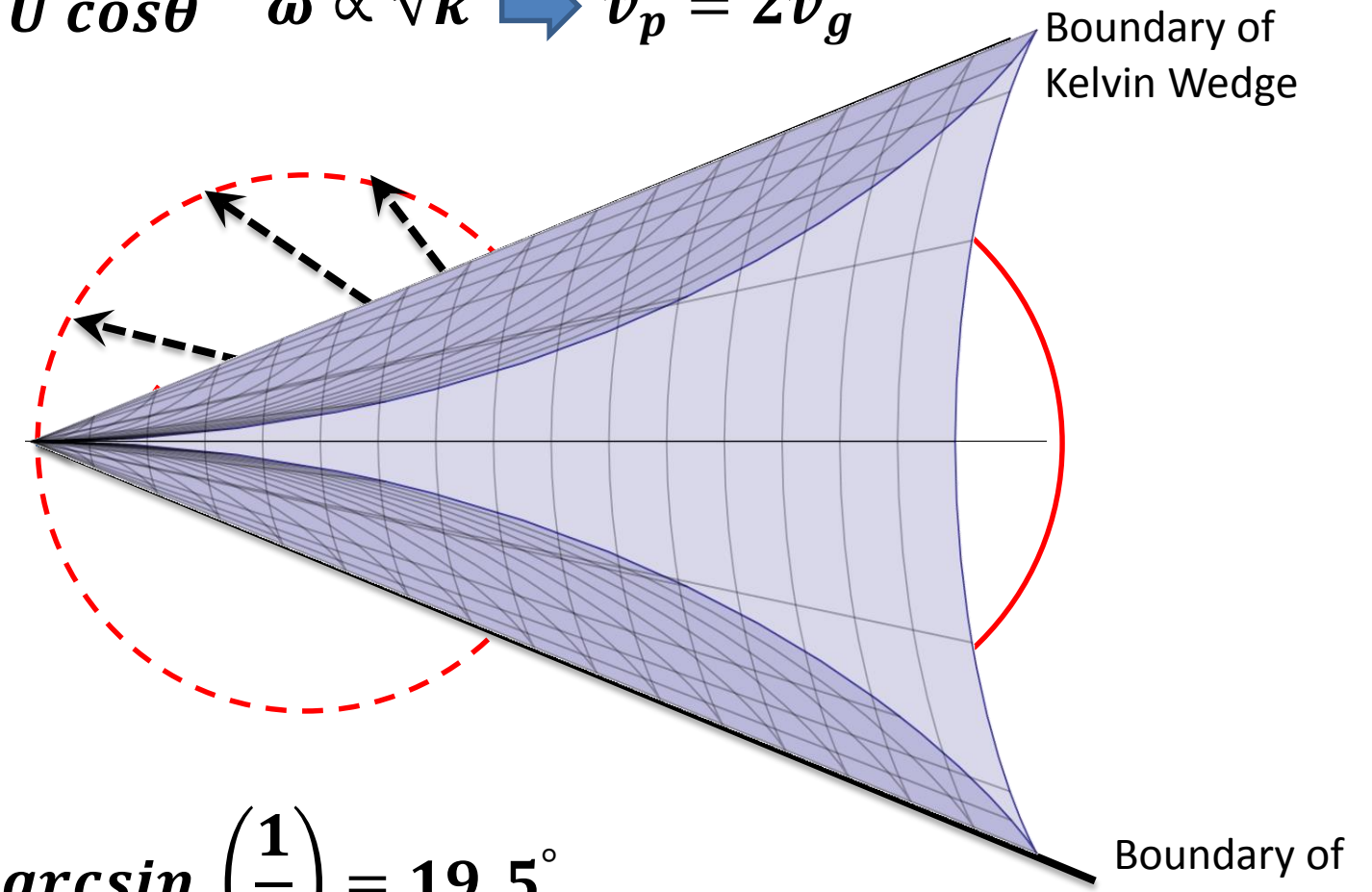
$$\boldsymbol{v = U}$$



$$\boldsymbol{v = U\,cos\theta}$$

Model of Kelvin angle

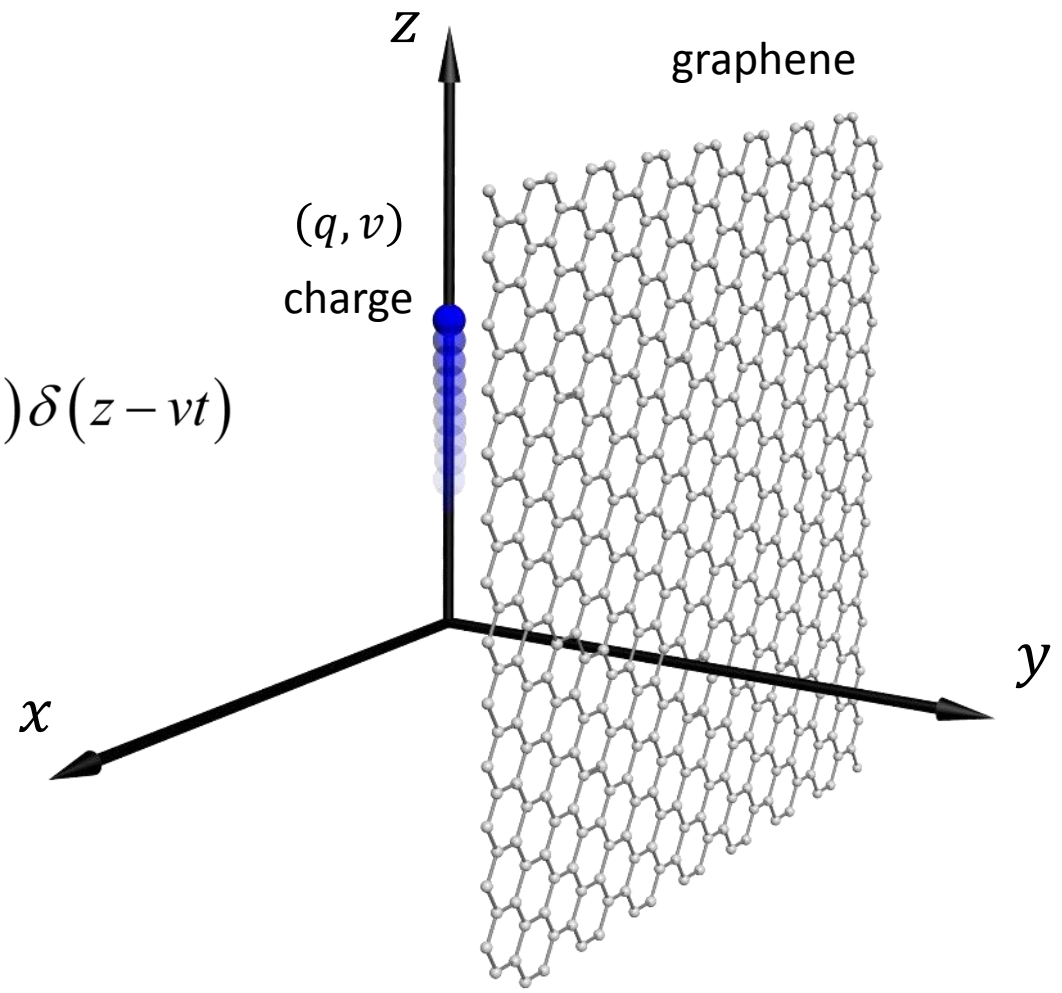
$$v_p = U\cos\theta \qquad \omega \propto \sqrt{k} \Rightarrow v_p = 2v_g$$



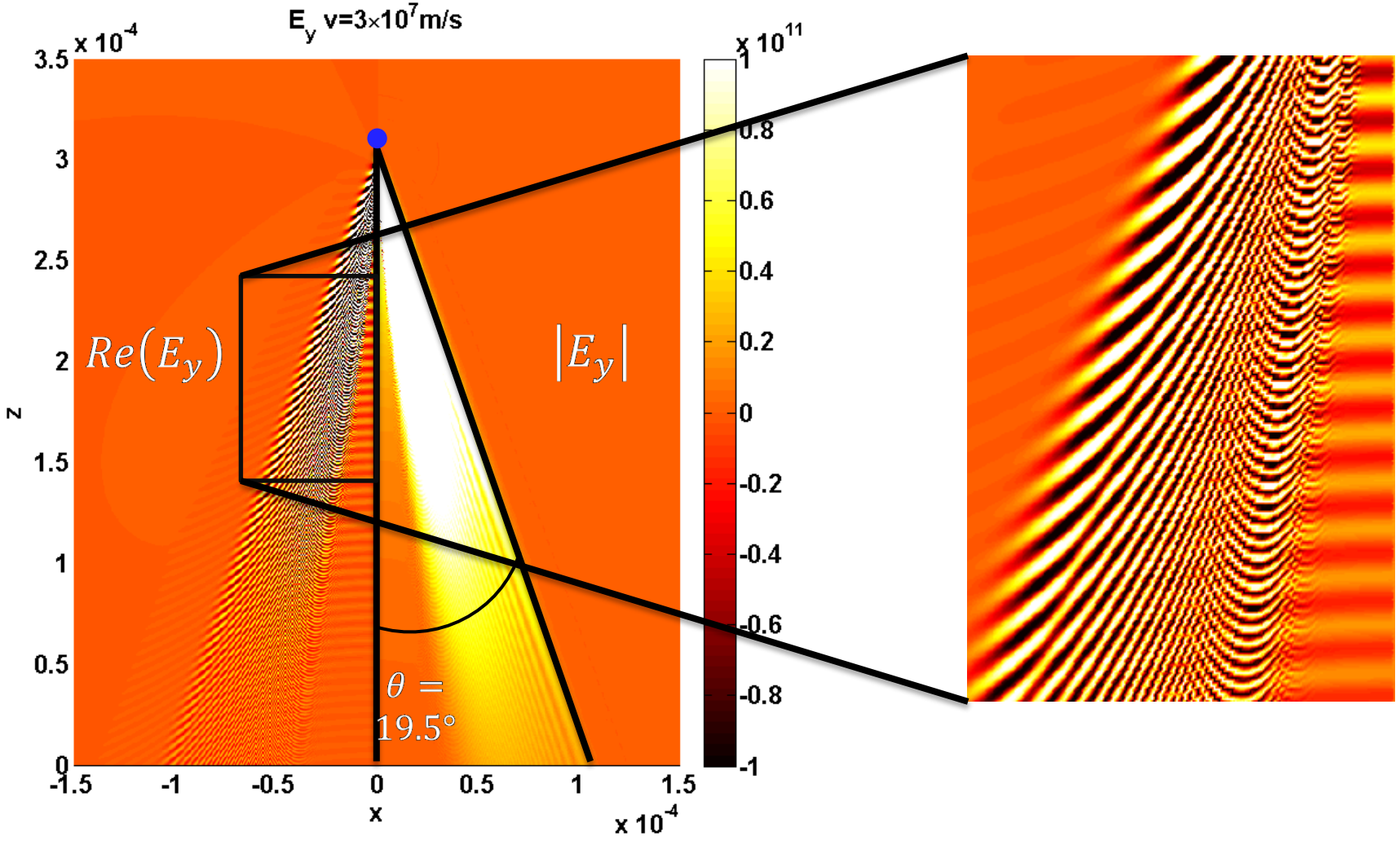
$$\alpha = arcsin\left(\frac{1}{3}\right) = 19.5^{\circ}$$

A charged particle moves parallel to graphene

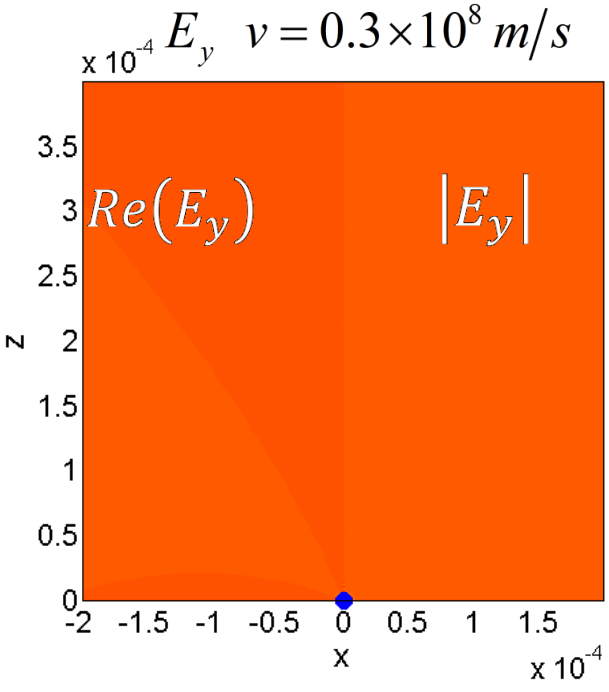
$$\bar{J}(\bar{r},t) = \hat{z}qv\delta(x)\delta(y)\delta(z-vt)$$

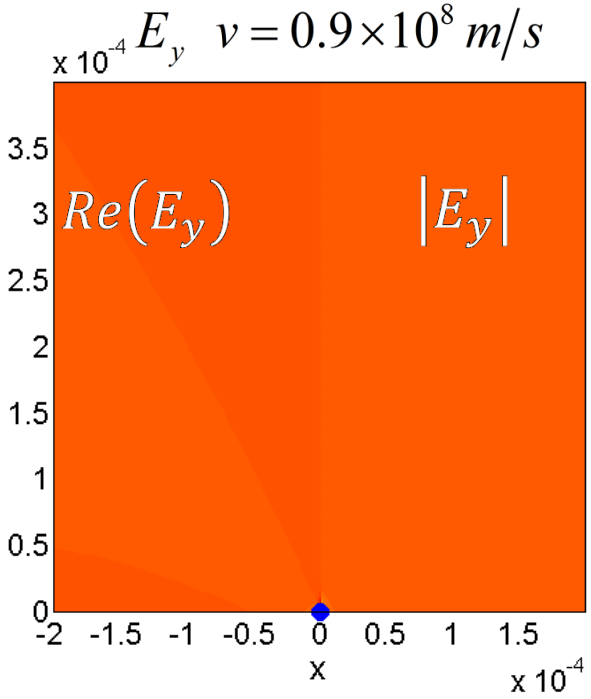


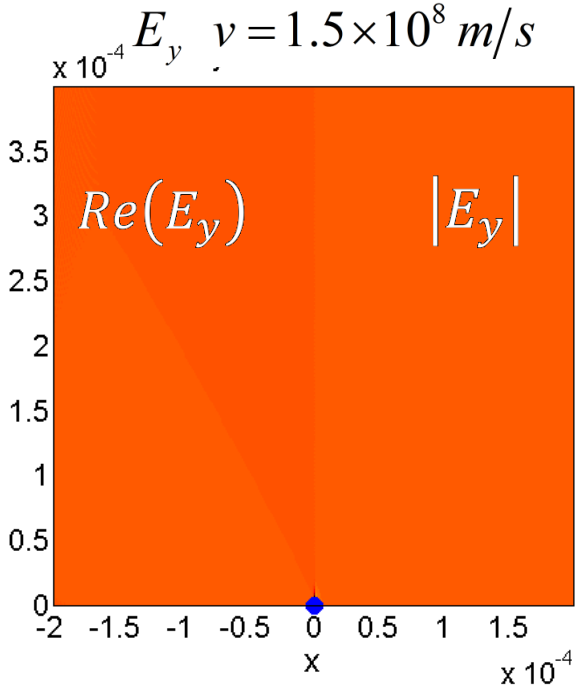
Plasmonic ship wake on graphene



Plasmonic ship wake on graphene

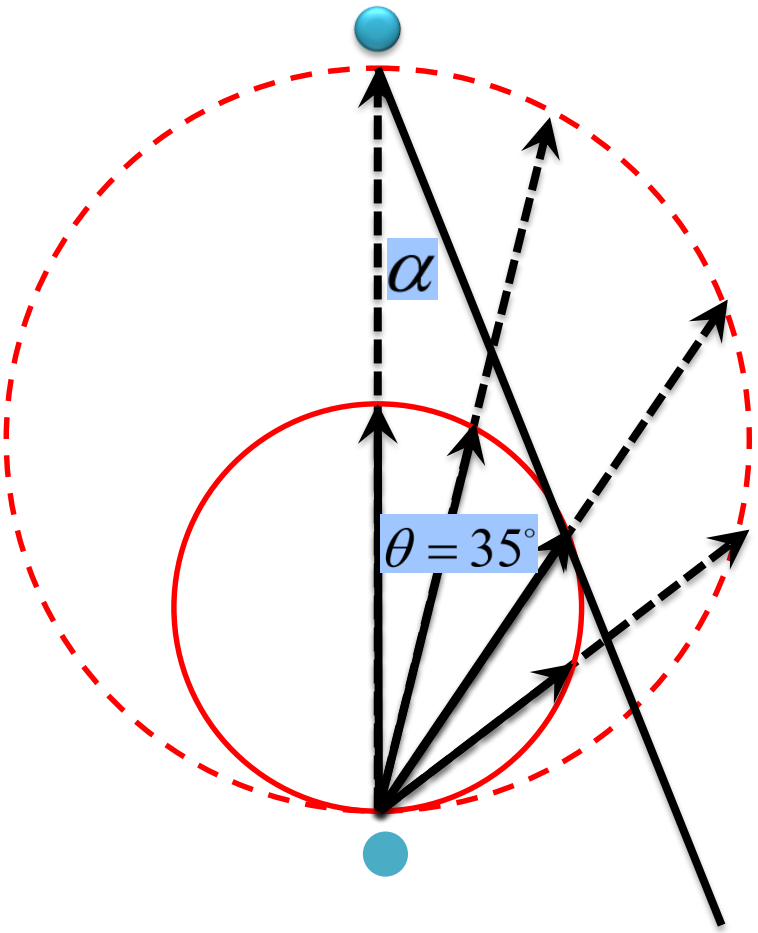




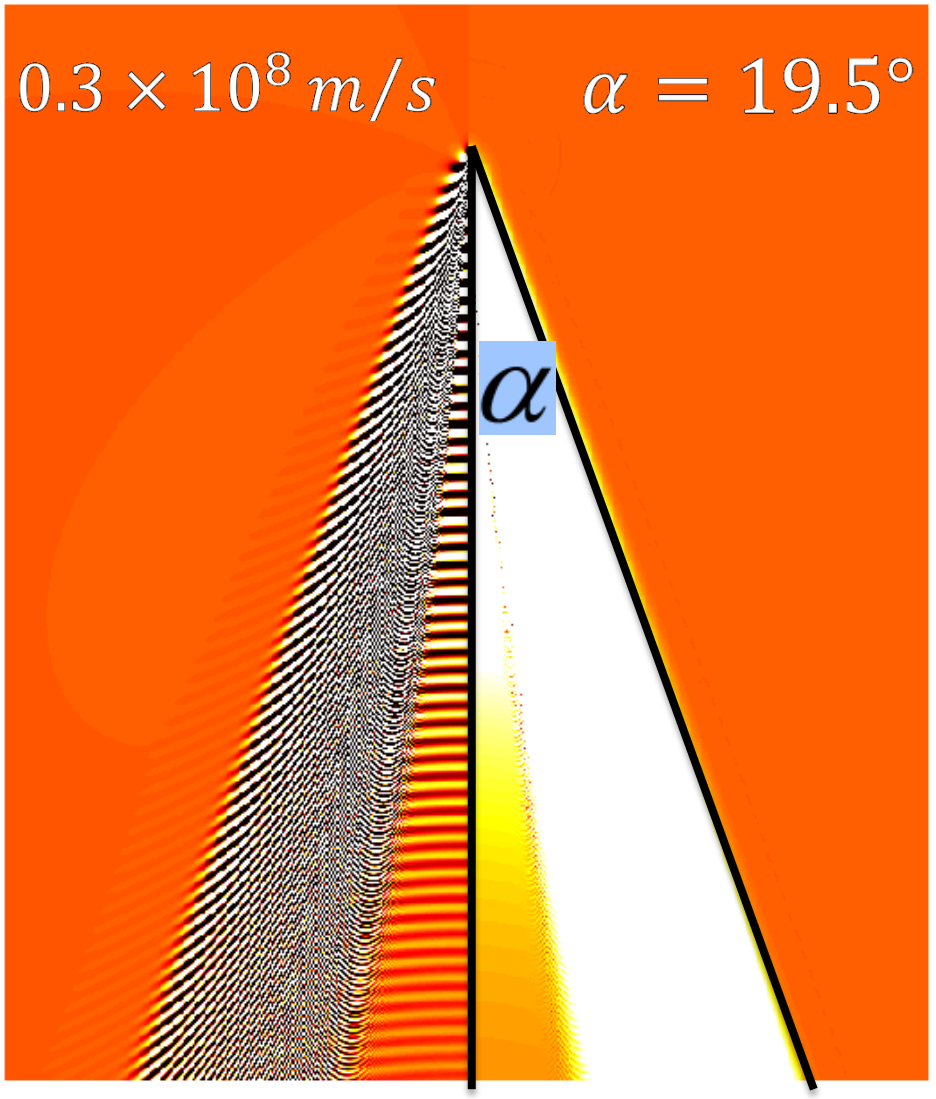


$\alpha = 19.5^\circ$ $\alpha = 13.5^\circ$ $\alpha = 8.7^\circ$

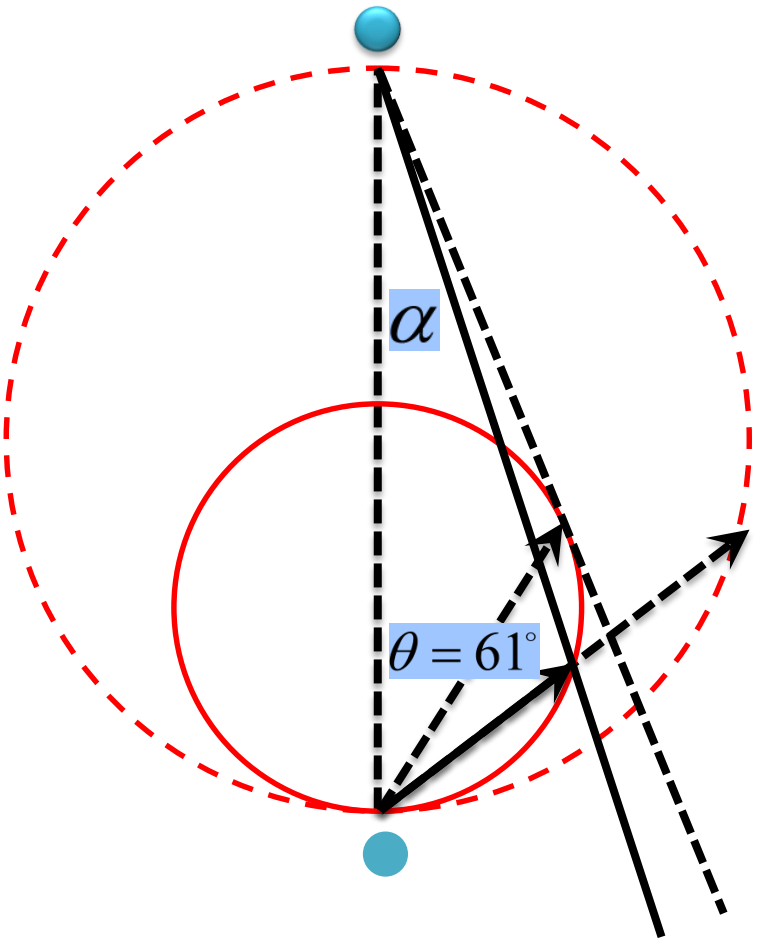
Plasmonic Kelvin angle



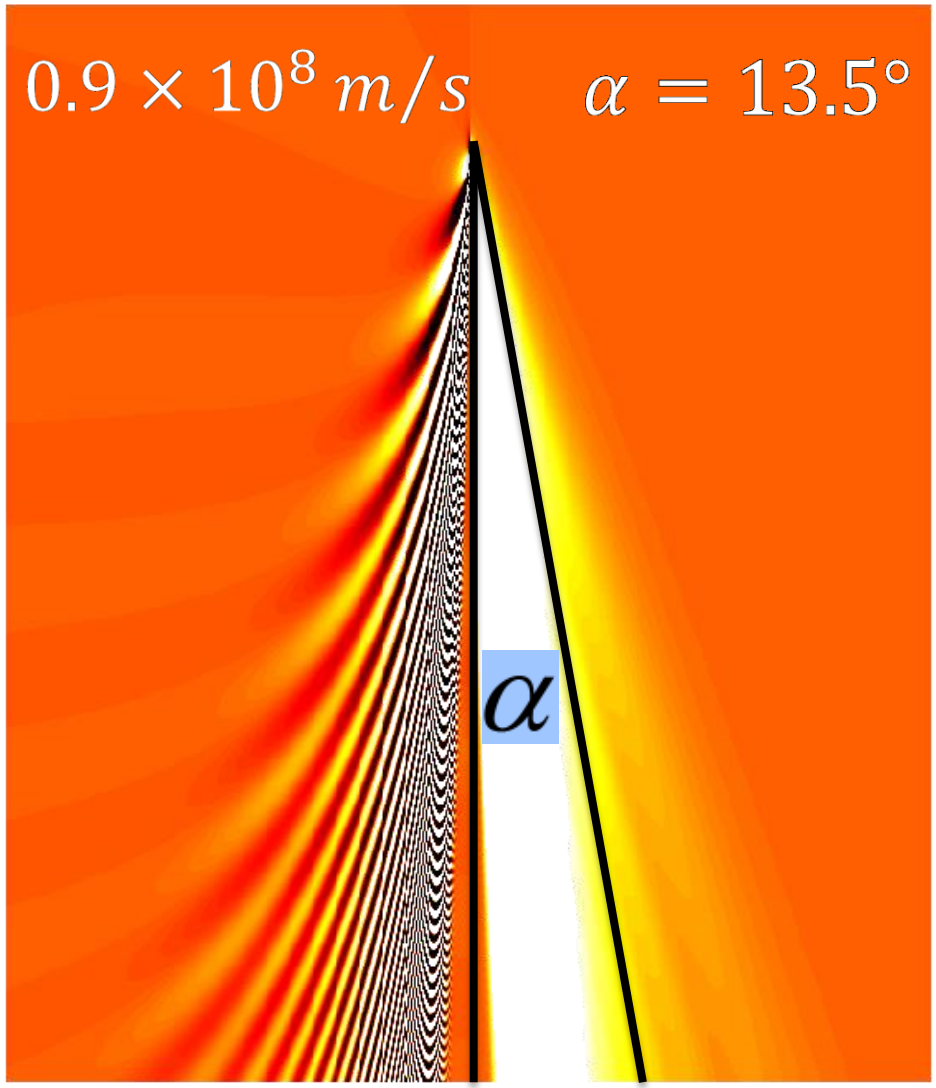
$$v_p = V\,cos\theta$$



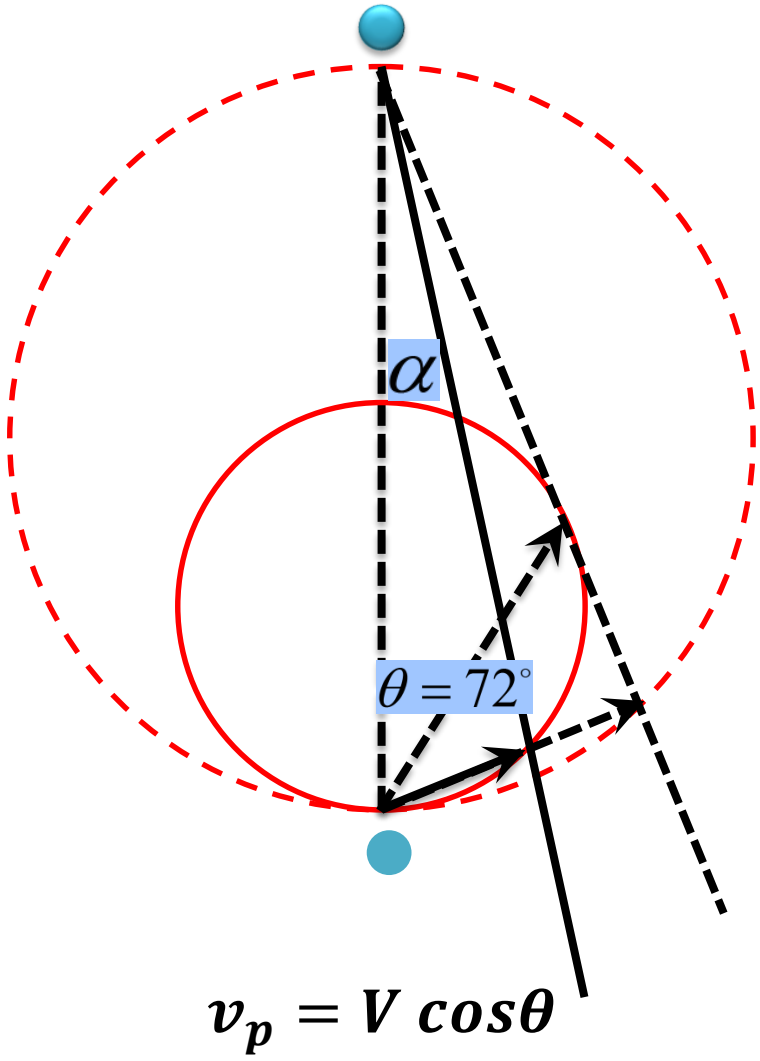
Plasmonic Kelvin angle

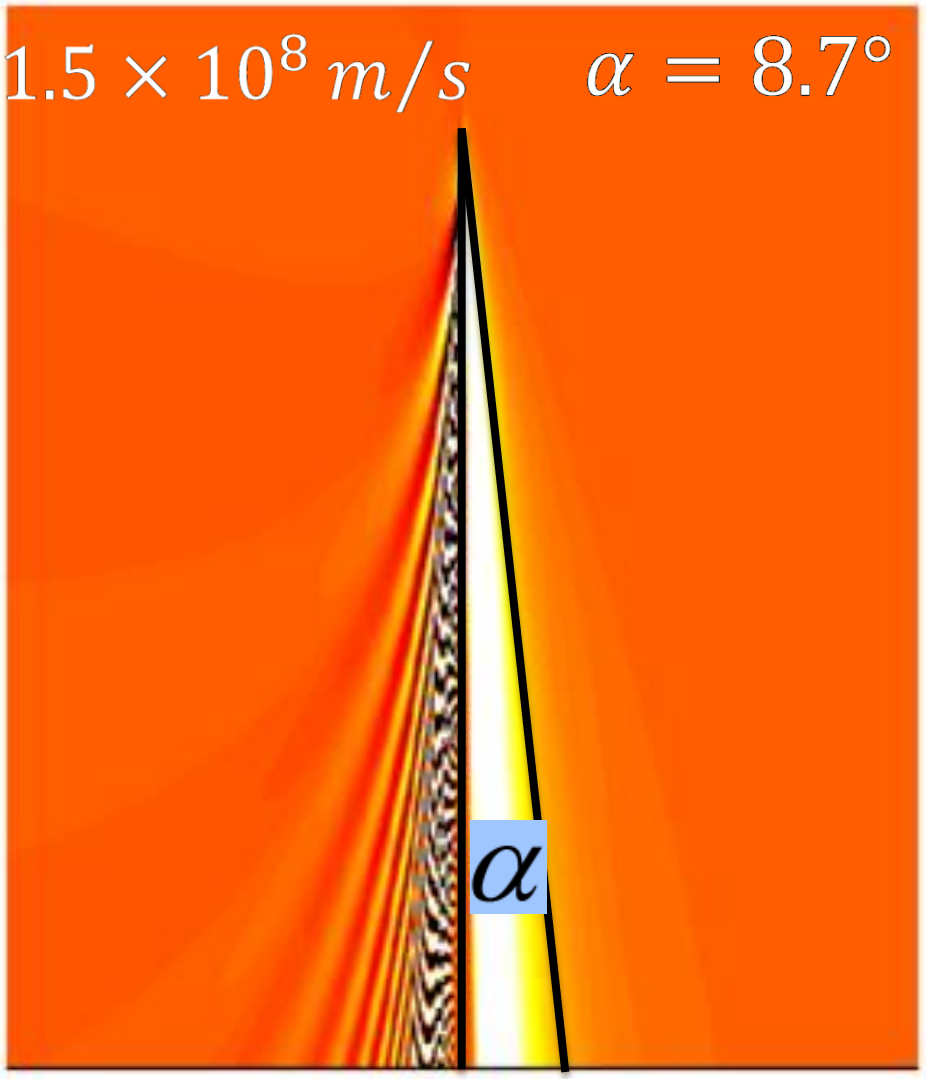


$$v_p = V\cos\theta$$



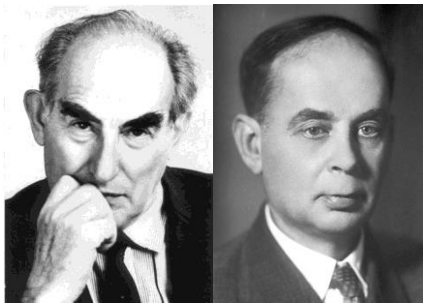
Plasmonic Kelvin angle





What else?

1945, transition radiation by Ginzburg and Frank

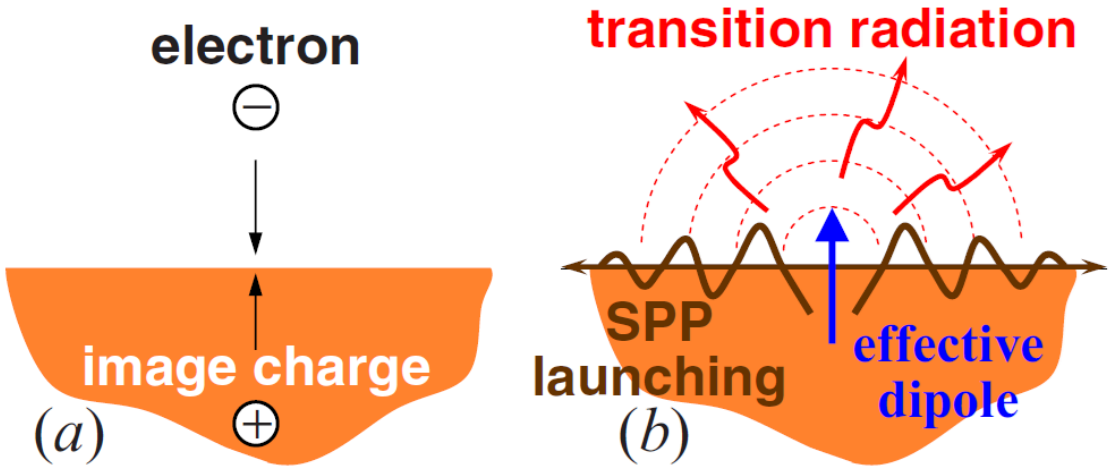


High energy physics

- 1952, 'it takes a relatively long time and therefore a long distance for an energetic electron to create a photon' by Ter-Mikayelian;
- 1956, Landau-Pomeranchuk-Migdal (LPM) effect

Plasmonics

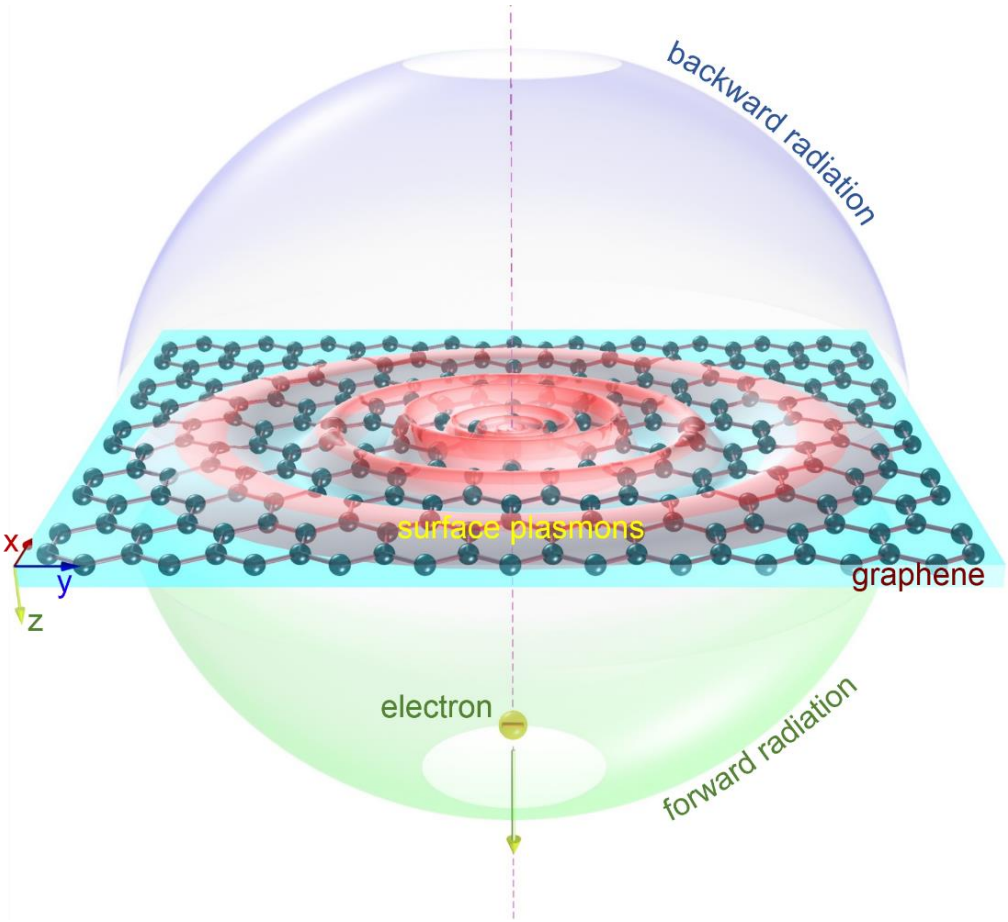
- Since 1950s, electron-energy-loss for plasmons on thin metal films
- **How is SPP generated?**



V. L. Ginzburg, et al. *Phys. Rep*. **49**, 1 (1979).
García de Abajo, F. J. *Rev. Mod. Phys.* **82**, 209 (2010).
V. L. Ginzburg & V. N. Tsytovich. *Transition Radiation and Transition Scattering* (Adam Hilger, 1990).

Splashing?



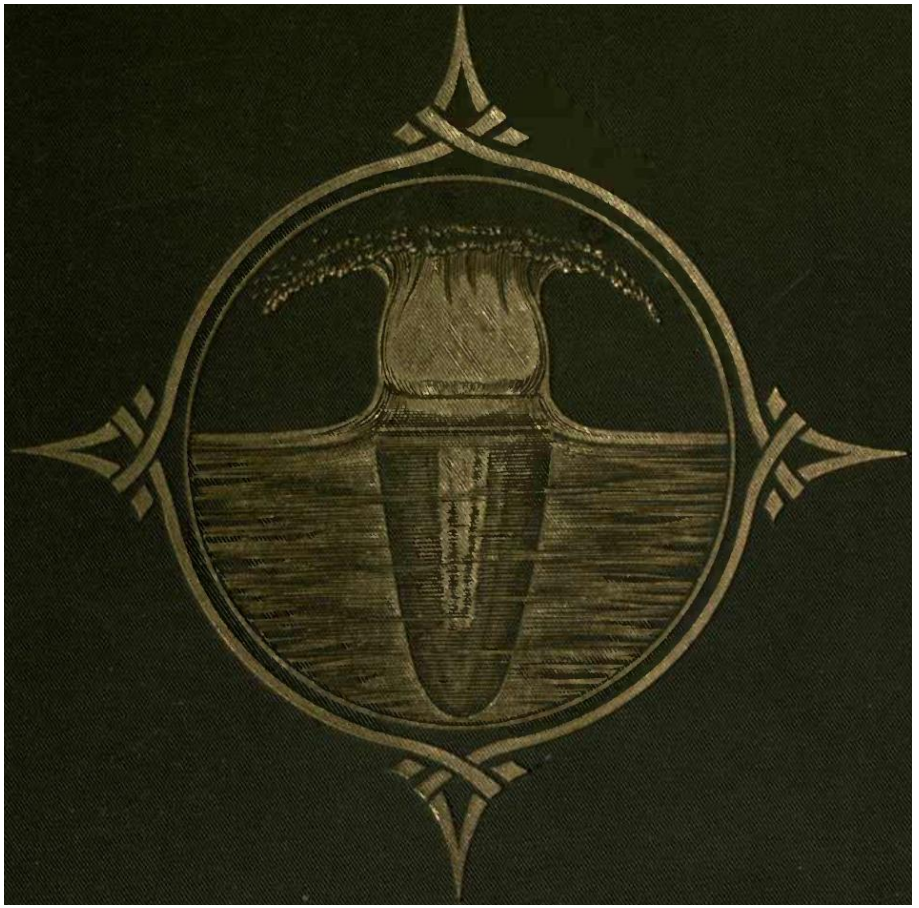

backward radiation
surface plasmons
graphene
x
y
z
electron
forward radiation

Worthington jet (Rayleigh jet)





http://www.youtube.com/user/ultraslo

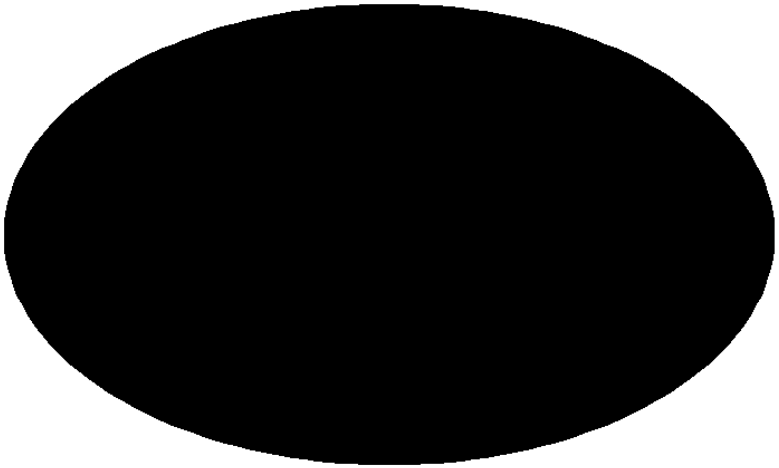


cover page for ***A study of splashes*** by **A. M. Worthington** in 1908

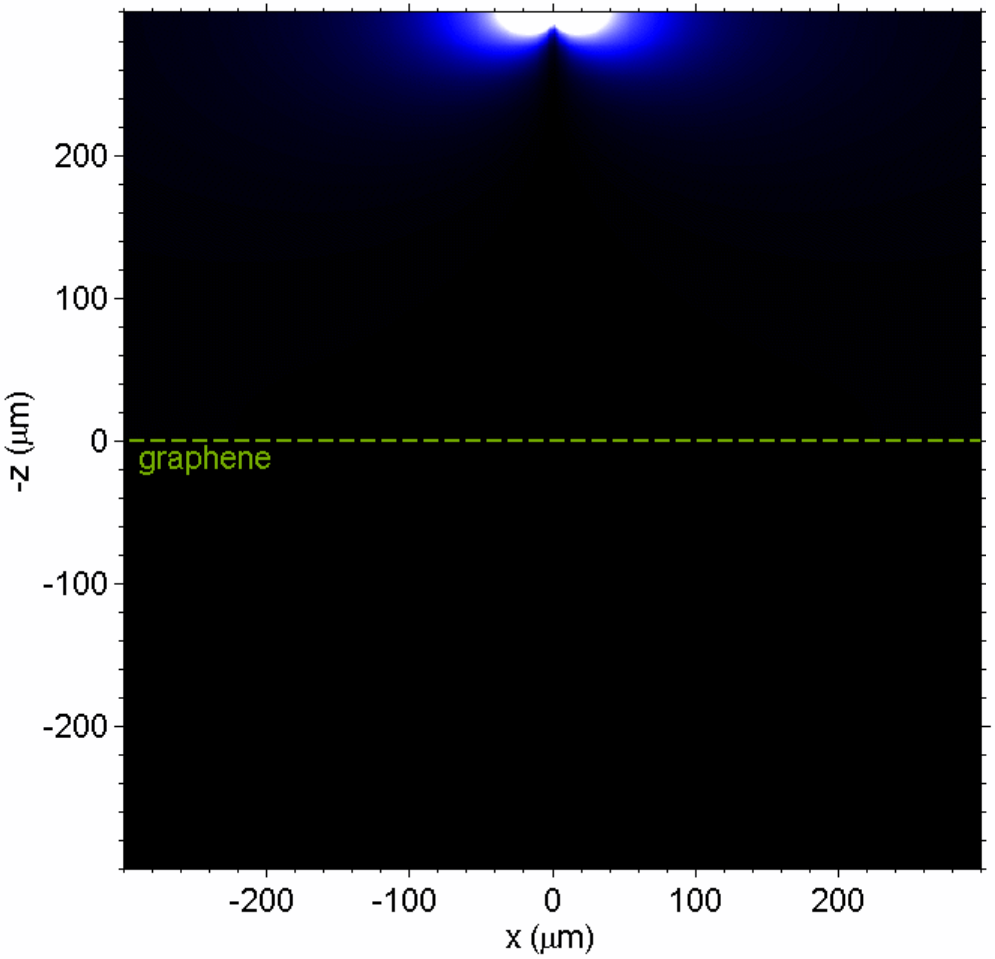
Graphene plasmon launching

$\delta n(\bar{r}, t)$: deviation of electron density from its average value on graphene plane

(x-y plane with radius = 200 μm)



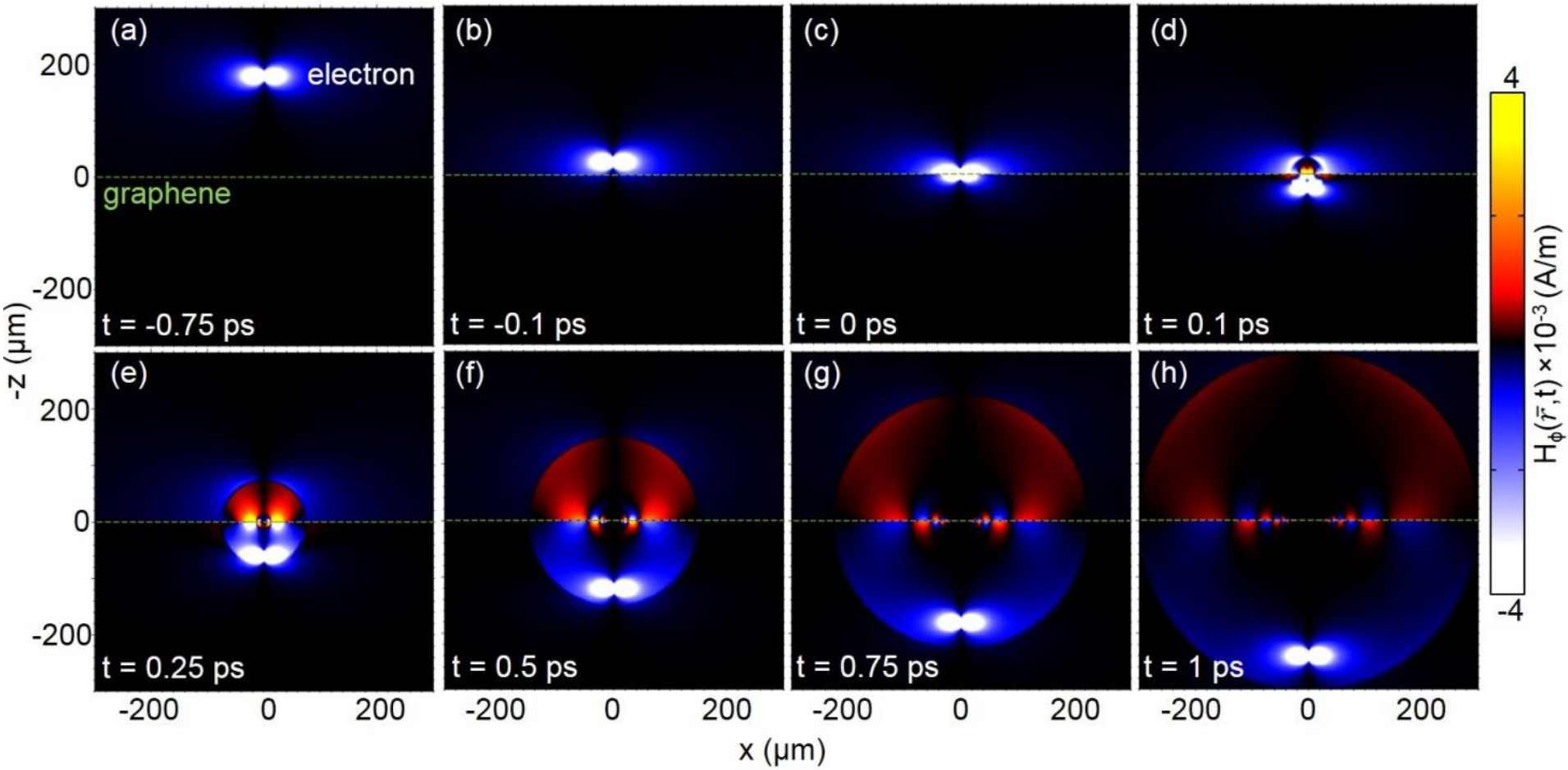
$H_\phi(\bar{r}, t)$ in x-z plane at y = 0 μm



Hydrodynamic splashing and Worthington jet



http://www.youtube.com/user/ultraslo


(a)
electron
graphene
t = -0.75 ps
(b)
t = -0.1 ps
(c)
t = 0 ps
(d)
t = 0.1 ps
(e)
t = 0.25 ps
(f)
t = 0.5 ps
(g)
t = 0.75 ps
(h)
t = 1 ps
200
0
-200
-z (μm)
-200
0
200
x (μm)
4
-4
$H_\phi(\vec{r},t) \times 10^{-3}$ (A/m)

Ginzburg's model of formation zone/time

Electron's current

$$\bar{J}^q(\bar{r},t) = \hat{z}J_z^q(\bar{r},t) = \hat{z}qv\delta(\bar{r}-\bar{v}t)$$

Fourier expansion of fields

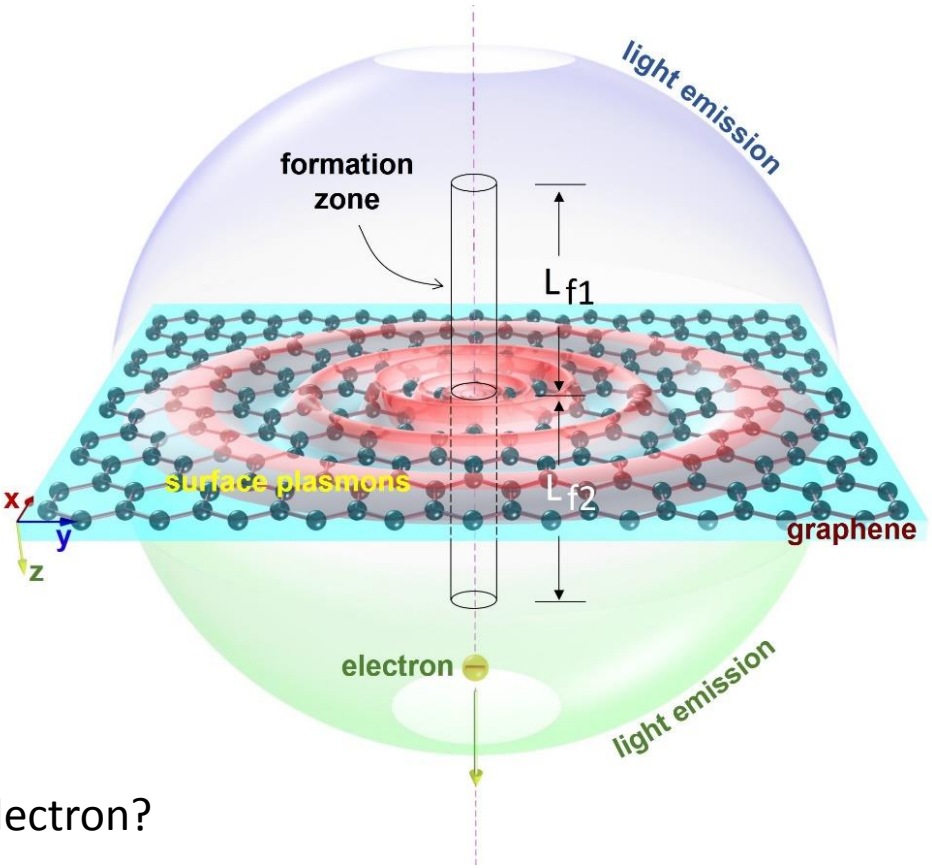
$$J_z^q(\bar{r},t) = \int j^q_{\bar{\kappa}_\perp,\omega}(z)e^{i(\bar{\kappa}_\perp\cdot\bar{r}_\perp-\omega t)}d\bar{\kappa}_\perp d\omega$$

$$E_z(\bar{r},t) = \int E_{\bar{\kappa}_\perp,\omega}(z)e^{i(\bar{\kappa}_\perp\cdot\bar{r}_\perp-\omega t)}d\bar{\kappa}_\perp d\omega$$

Matching boundary conditions

$$E^q_{\bar{\kappa}_\perp,\omega}\sim\exp(i\omega z/v)$$

$$E^{1,2}_{\bar{\kappa}_\perp,\omega}\sim\exp(\mp i\omega z/c\sqrt{1-\kappa_\perp^2c^2/\omega^2})$$



Q: When does a photon separate from the electron?

A: When $\frac{\omega L_f}{v} \mp \frac{\omega L_f}{c\sqrt{1-\frac{\kappa_\perp^2c^2}{\omega^2}}} = 2\pi$

$$L_{f1} = \frac{2\pi}{|\frac{\omega}{v}-\omega/c\sqrt{1-\frac{\kappa_\perp^2c^2}{\omega^2}}|},\quad L_{f2} = \frac{2\pi}{|\frac{\omega}{v}+\omega/c\sqrt{1-\frac{\kappa_\perp^2c^2}{\omega^2}}|}$$

Example: v=0.8 c, 10 THz Backward $\frac{L_{f1}}{v} = 0.05$ ps Forward $\frac{L_{f2}}{v} = 0.5$ ps

Ginzburg's model of formation zone/time

Electron's current

$$\bar{J}^q(\bar{r},t) = \hat{z}J_z^q(\bar{r},t) = \hat{z}qv\delta(\bar{r}-\bar{v}t)$$

Fourier expansion of fields

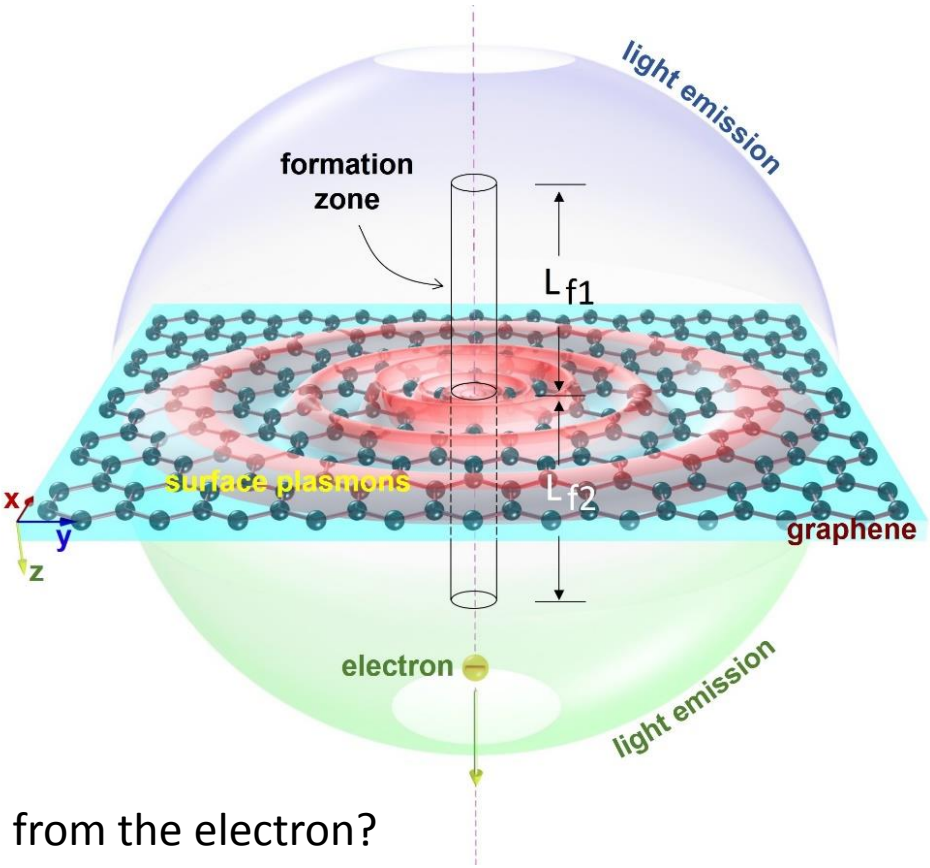
$$J_z^q(\bar{r},t) = \int j^q_{\bar{\kappa}_\perp,\omega}(z)e^{i(\bar{\kappa}_\perp\cdot\bar{r}_\perp-\omega t)}d\bar{\kappa}_\perp d\omega$$

$$E_z(\bar{r},t) = \int E_{\bar{\kappa}_\perp,\omega}(z)e^{i(\bar{\kappa}_\perp\cdot\bar{r}_\perp-\omega t)}d\bar{\kappa}_\perp d\omega$$

Matching boundary conditions

$$E^q_{\bar{\kappa}_\perp,\omega}\sim\exp(i\omega z/v)$$

$$E^{1,2}_{\bar{\kappa}_\perp,\omega}\sim\exp(\mp i\omega z/c\sqrt{1-\kappa_\perp^2c^2/\omega^2})$$

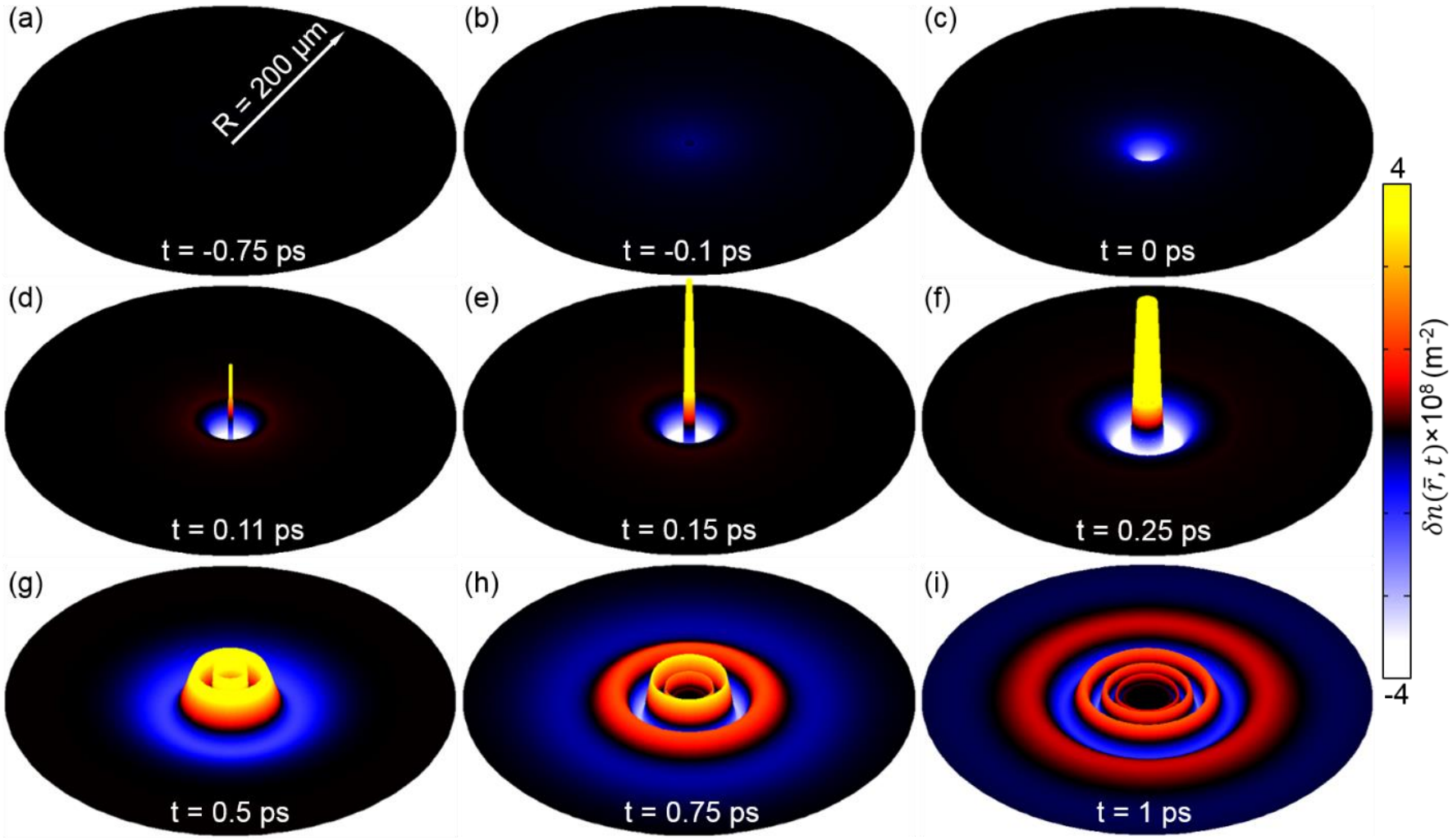


Q: When does a surface plasmon separate from the electron?

A: When $\frac{\omega L_f}{v} = 2\pi$ $\qquad L_{f1} = L_{f2} = \frac{2\pi v}{\omega}$

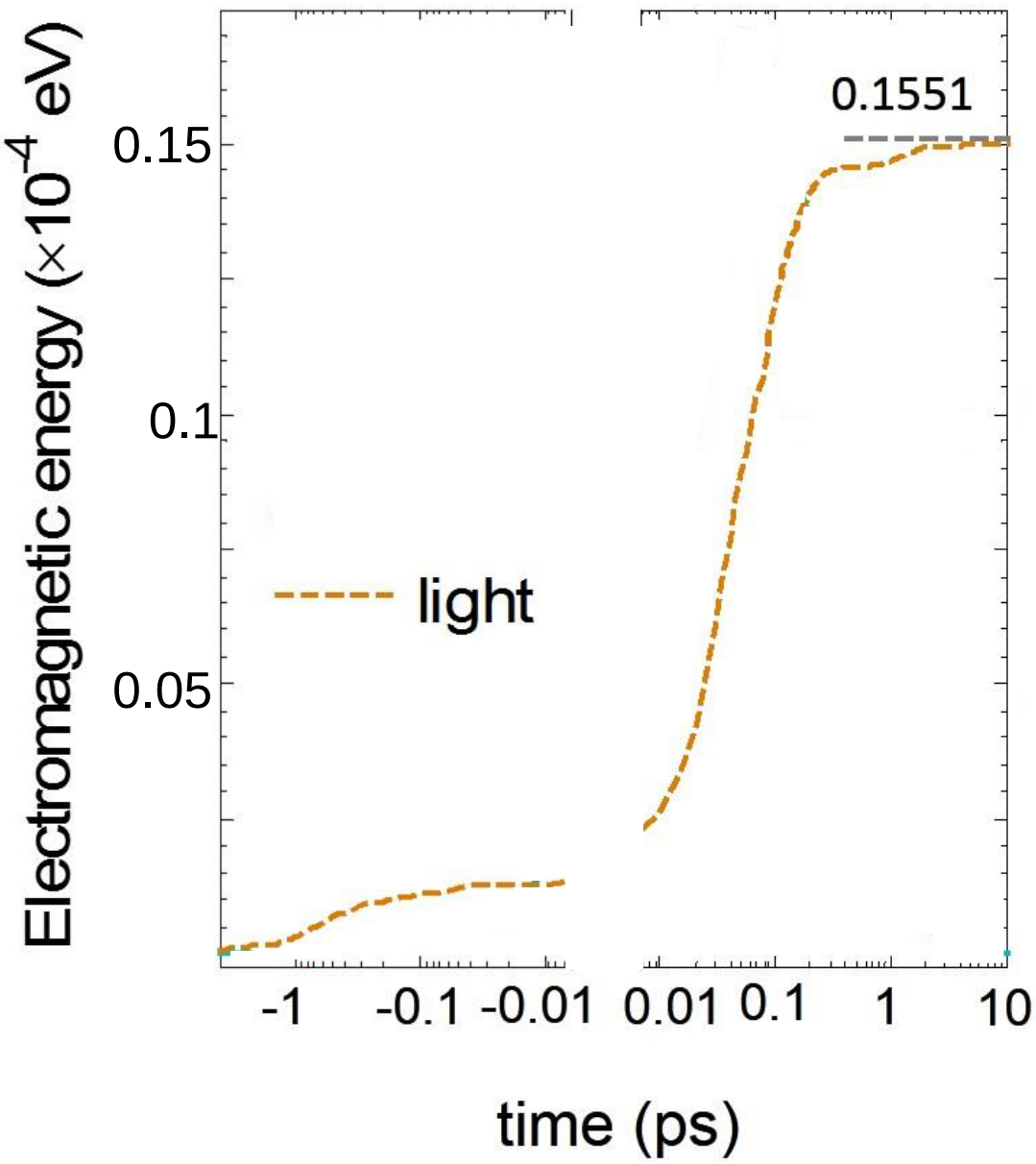
Example: v=0.8 c, 10 THz $\qquad (L_{f1}+L_{f2})/v = 0.2$ ps

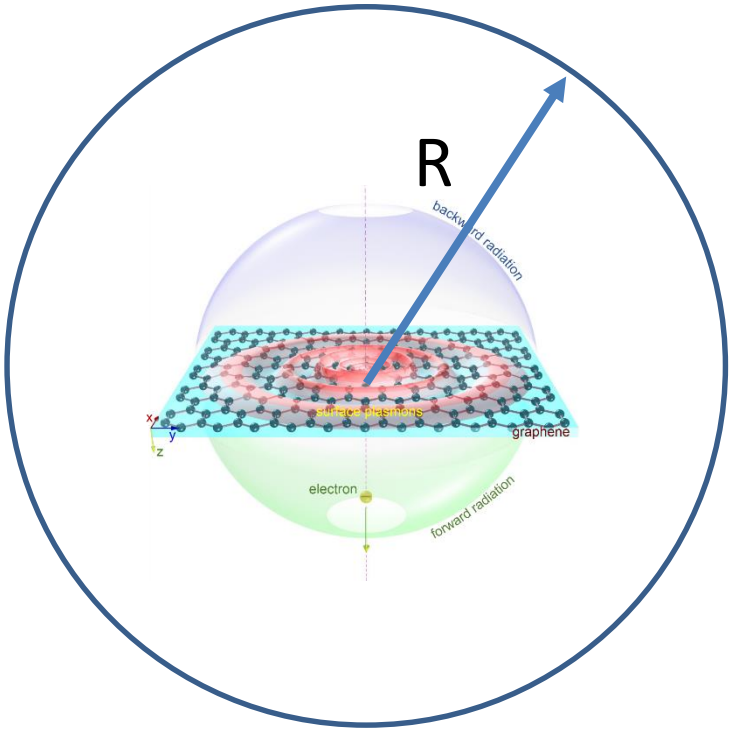
Plasmonic jet on graphene



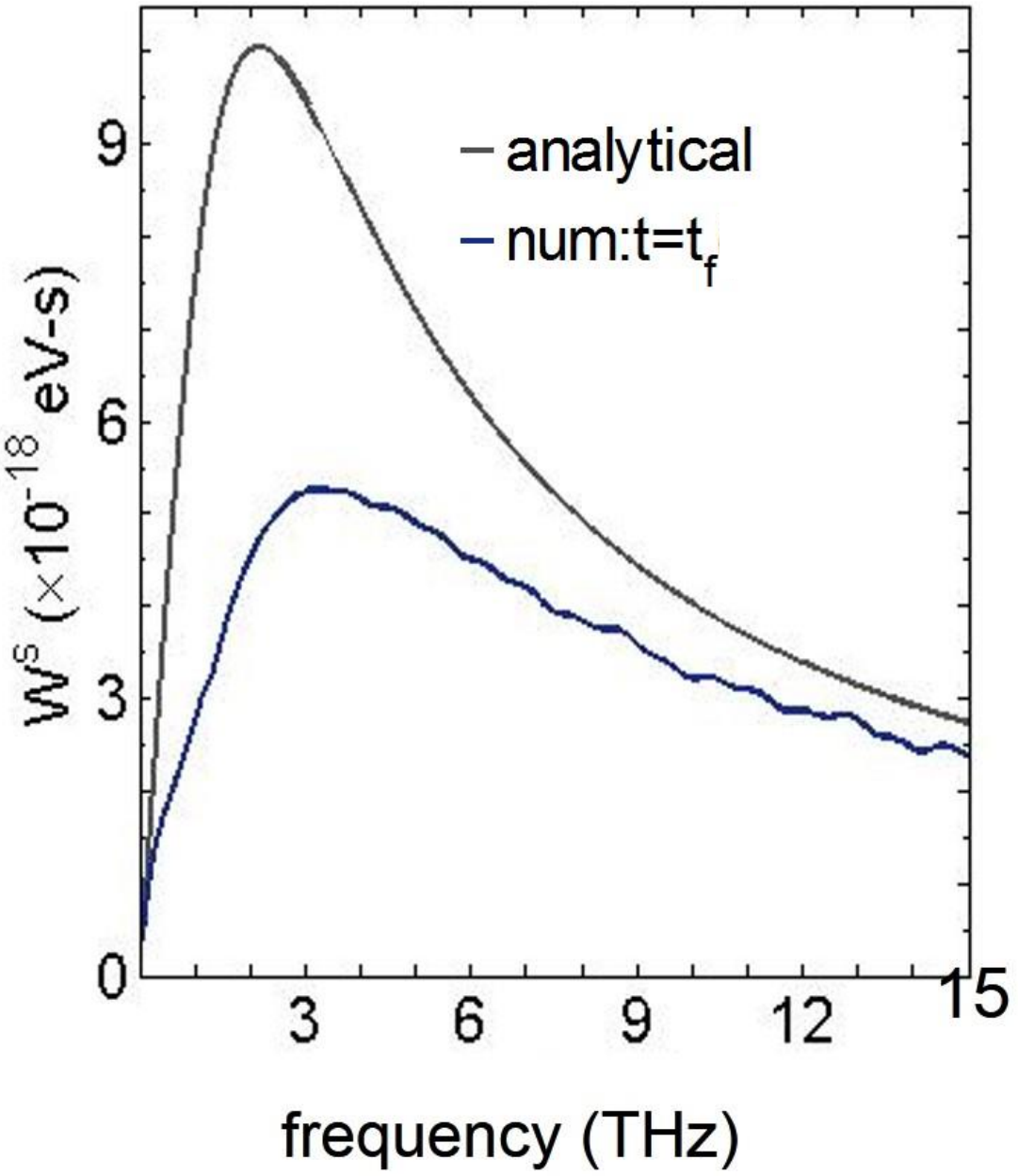
Plasmonic ‘jet’ ‘shakes off’ transition radiation before launching SPP.

Time evolution of emitted photon energy





Energy of generated plasmons



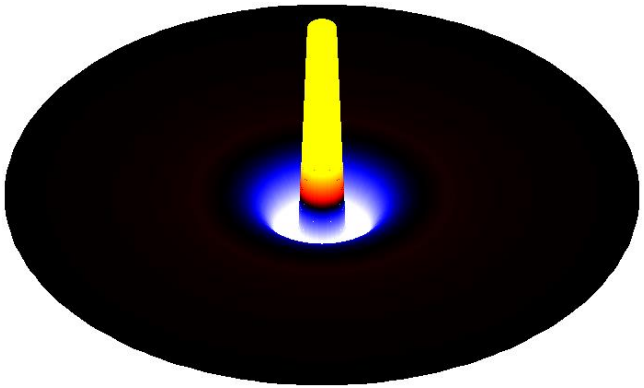
All previous estimates on graphene plasmon yields in EELS calculation were overestimated.

Similarity between two dynamic processes

Hydrodynamics **Graphene plasmons**

Jet



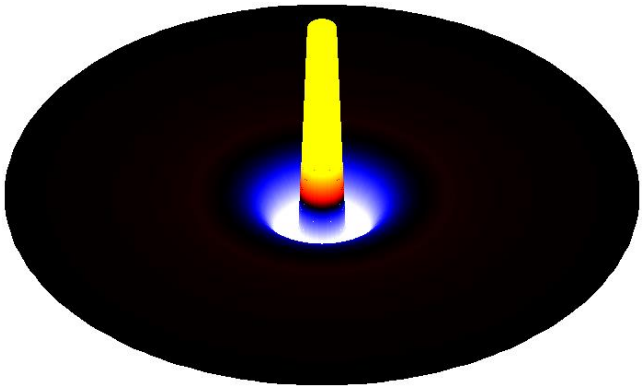


Similarity between two dynamic processes

Hydrodynamics **Graphene plasmons**

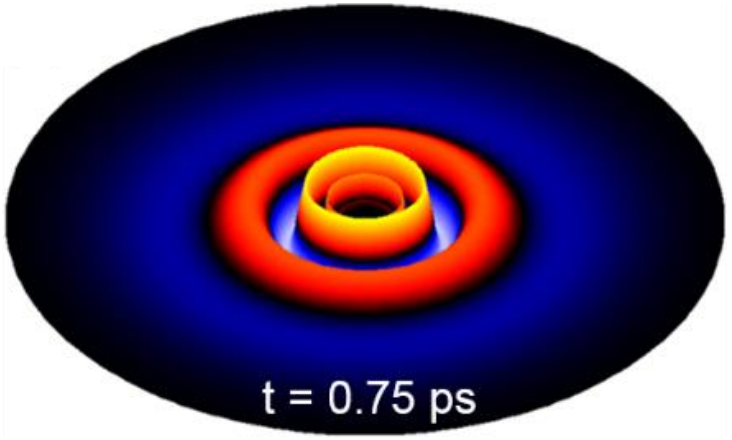
Jet





Ripple



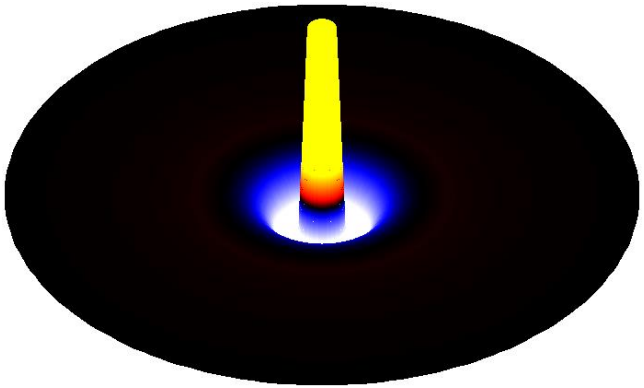


Similarity between two dynamic processes

Hydrodynamics **Graphene plasmons**

Jet

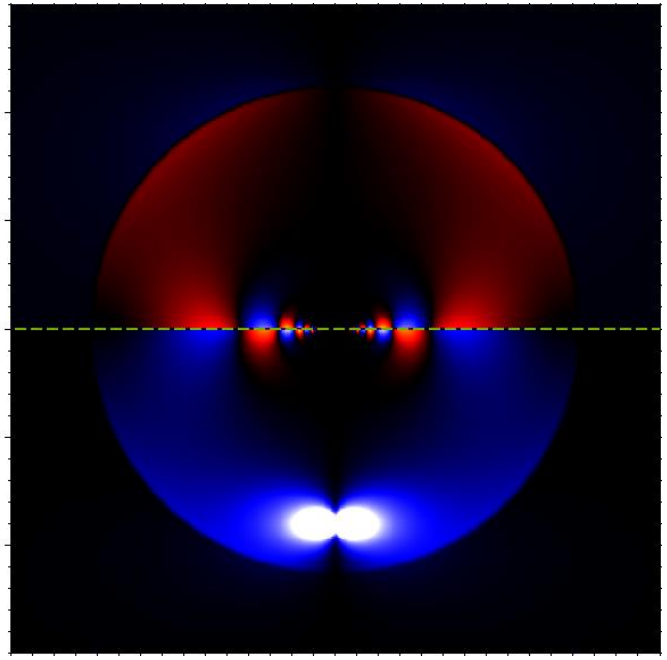




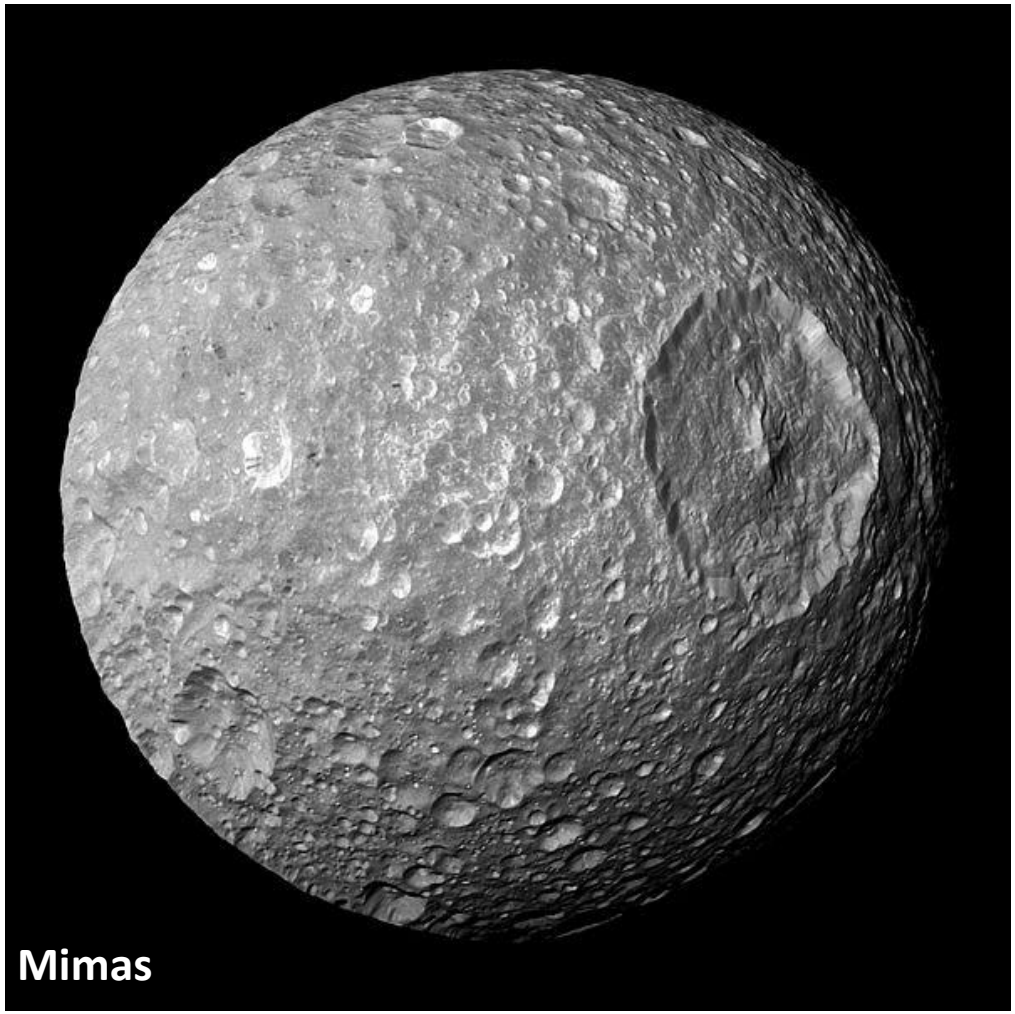
Ripple

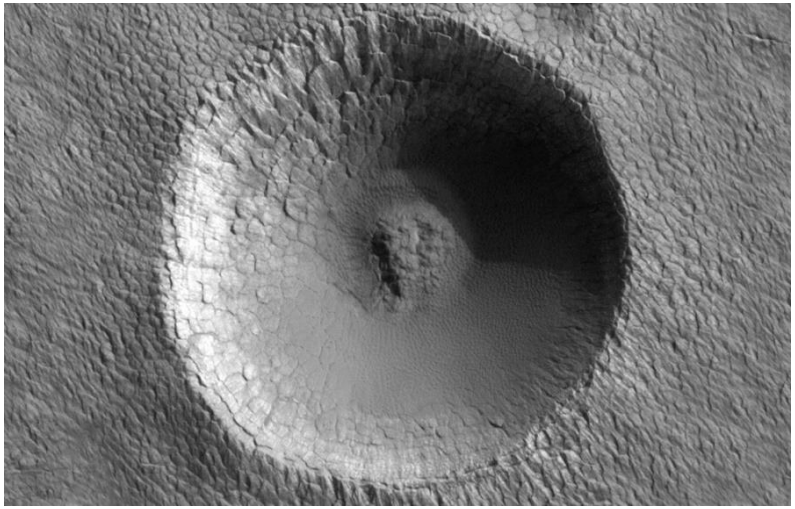
Sound/Light





Worthington Jet in meteor impact





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Thanks!