OPTICAL FORCES FROM PLASMONIC AND CHIRAL FIELDS

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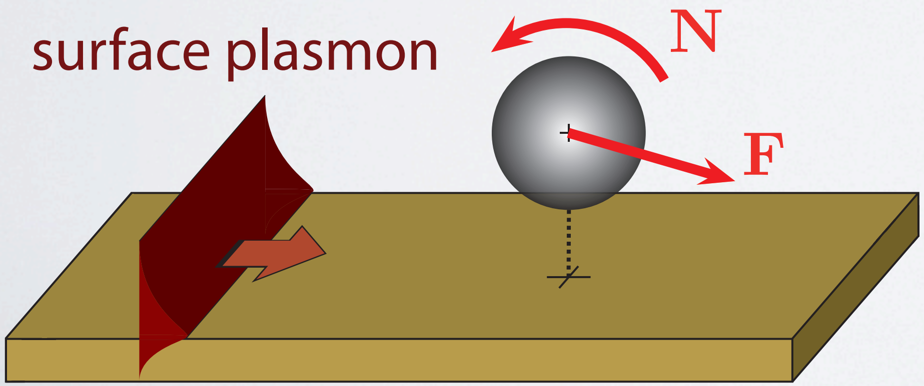
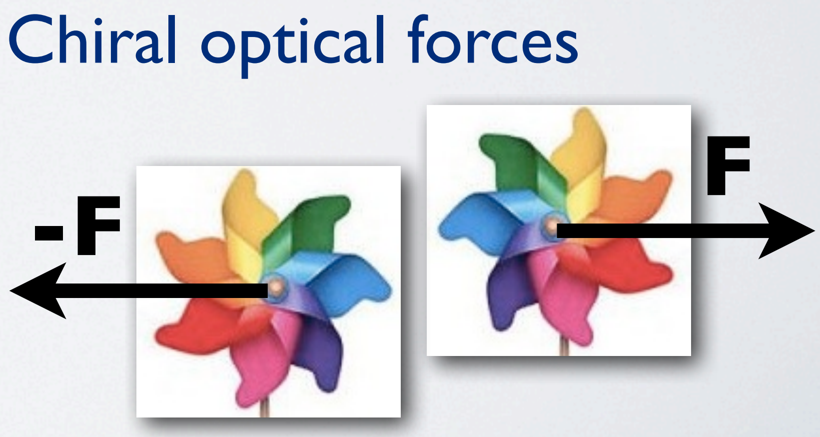
with Aurélien Cuche, James Hutchison, Éloïse Devaux, Jino Georges, Cyriaque Genet and Thomas Ebbesen.

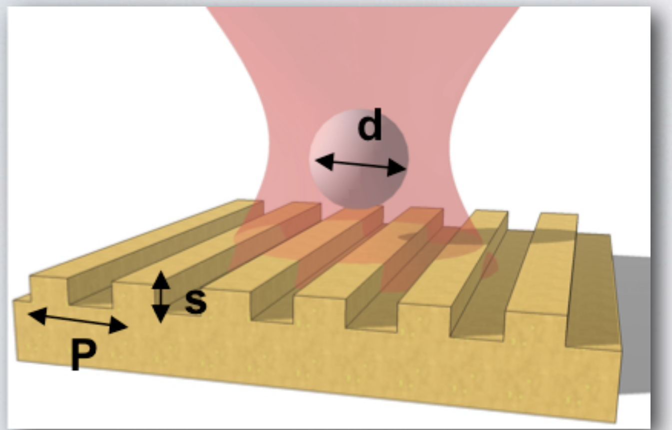




Context: optical manipulation

Optical tweezers

trap and move a NP

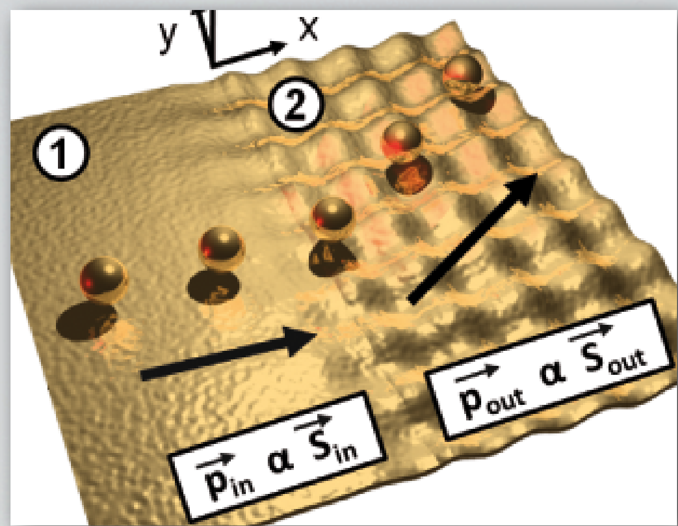


PRL **108**, 026801 (2012)

- biophysics (DNA, ...)
- optomechanical coupling

Optical routing

drive many NPs

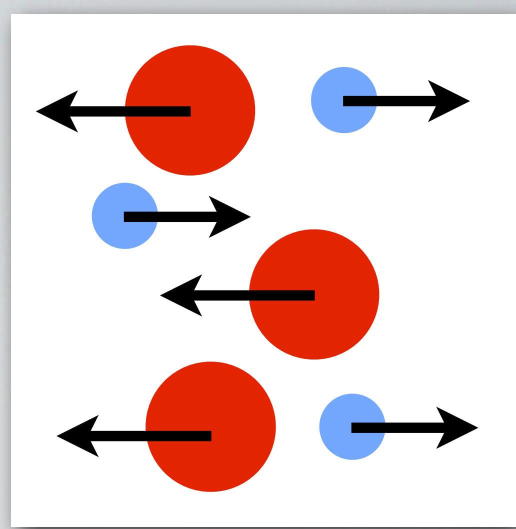


Nano Lett. **12**, 4329 (2012)

- parallel manipulation
- micro/nano-fluidics

Optical sorting

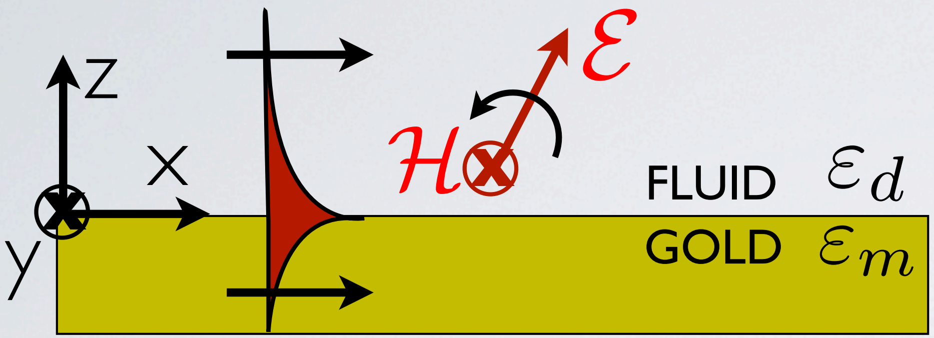
separate NPs



Nano Lett. **13,** 4230 (2013)

- drug industry

The surface plasmon: a spinning field



$$\mathbf{E}_0 = E_0 e^{\imath kx} e^{\imath qz} \left(\tilde{q}, 0, -\tilde{k}\right)^t$$

$$\mathbf{H}_0 = H_0 e^{\imath kx} e^{\imath qz} (0, 1, 0)^t$$

- Complex wavevector: $k = \frac{\omega}{c}\sqrt{\frac{\varepsilon_\mathrm{m}\varepsilon_\mathrm{d}}{\varepsilon_\mathrm{d} + \varepsilon_\mathrm{m}}}$

➡ Evanescent field

➡ Electric ellipticity: $\mathbf{\Phi}_E = \mathcal{E} \times \frac{\dot{\mathcal{E}}}{\omega}$

- Decomposition of the time-averaged Poynting vector:

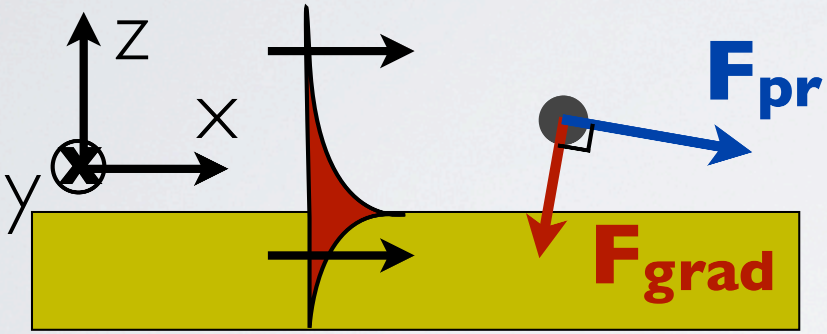
$$\mathbf{\Pi} = \underbrace{\mathbf{\Pi}_O}_{\text{orbital part}} + \underbrace{\frac{\nabla \times \mathbf{\Phi}_E}{2\omega\mu_0}}_{\text{spin part}}$$

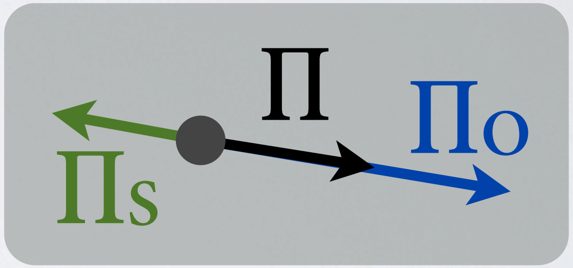
➡ non-zero spin part

Plasmonic force and torque

Dipolar approximation:

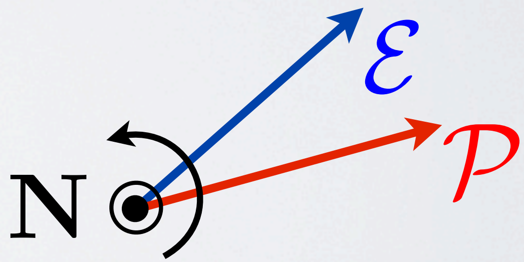
$$\langle \mathbf{F} \rangle_T = \underbrace{\frac{\mathrm{Re}[\alpha]}{4} \nabla \|\mathbf{E}_0\|^2}_{\text{gradient force}} + \underbrace{\mathrm{Im}[\alpha]\omega\mu_0 \mathbf{\Pi}_O}_{\text{radiation pressure}}$$





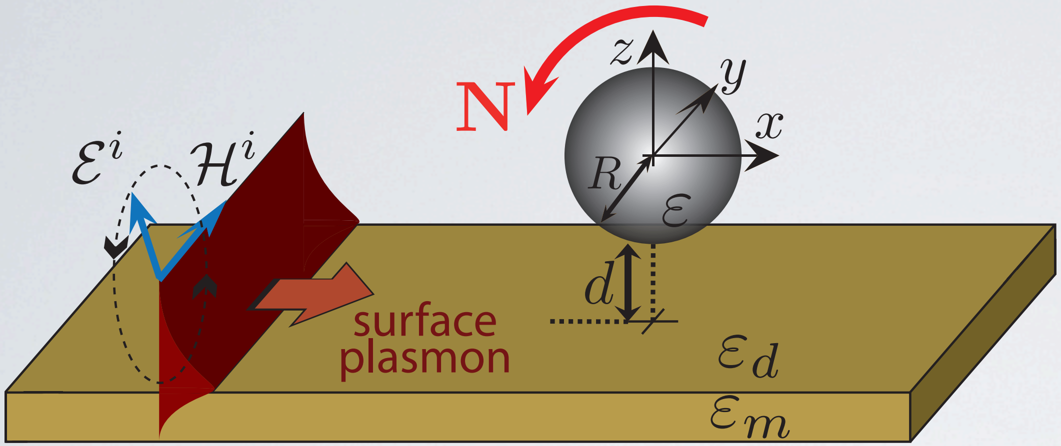
- <u>Optical torque:</u> $\mathbf{N} = \mathcal{P} \times \mathcal{E} = \mathrm{Im}[\alpha]\mathbf{\Phi}_E$

⟶ genuine mechanical rotation?



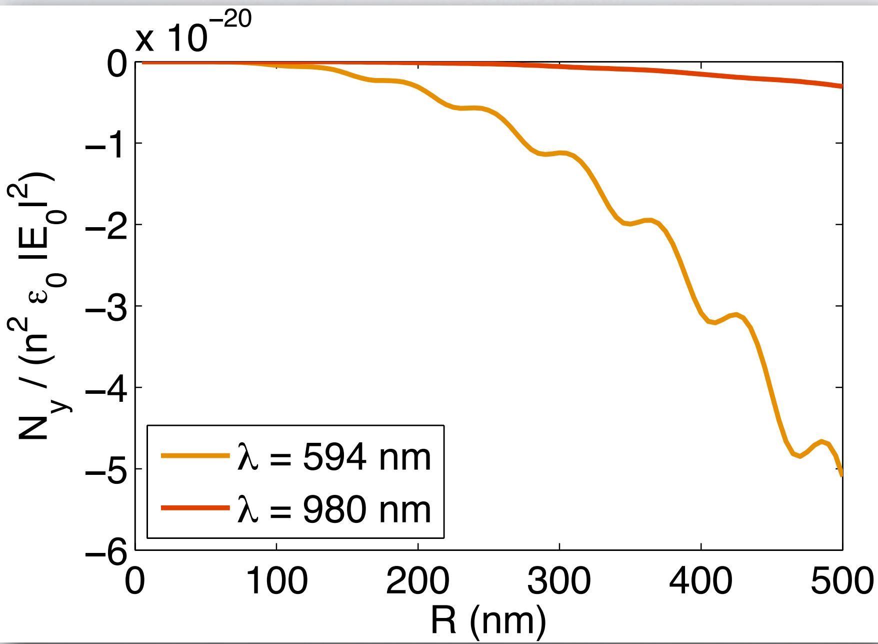
A. Canaguier-Durand, A. Cuche, C. Genet and T.W. Ebbesen, *Phys. Rev. A* **88**, 033831 (2013).

Plasmonic torque on a sphere



<u>Method: multipolar calculation</u>

- scattered field (Mie theory)
- optical force and torque from Maxwell stress tensor



Results for gold nanospheres:

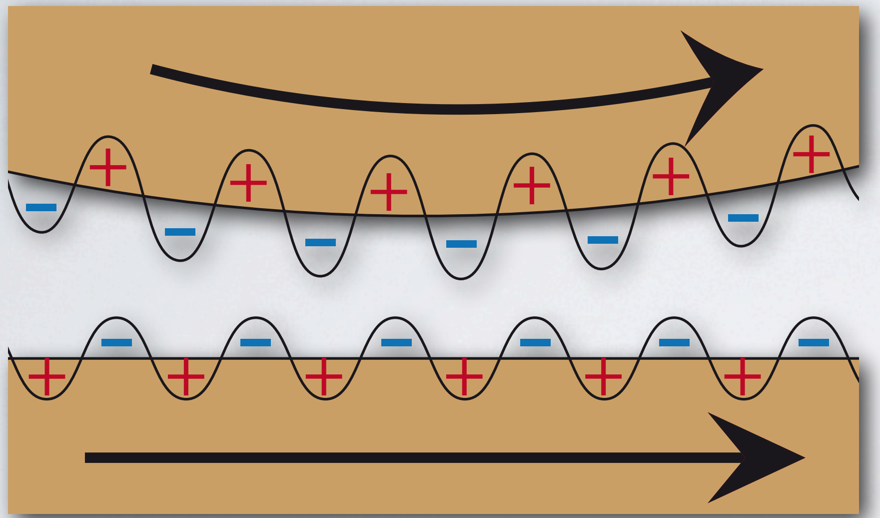
- strong dependance on R and λ
- <u>transverse spinning</u>

➡ new tool for optical manipulation

A. Canaguier-Durand and C. Genet, *submitted* [arXiv:1311.7481].

Role of dissipation in the torque

Electronic point of view:



- induced movement of electrons
- dissipation transfers momentum

➡ Non-contact gears

Test:

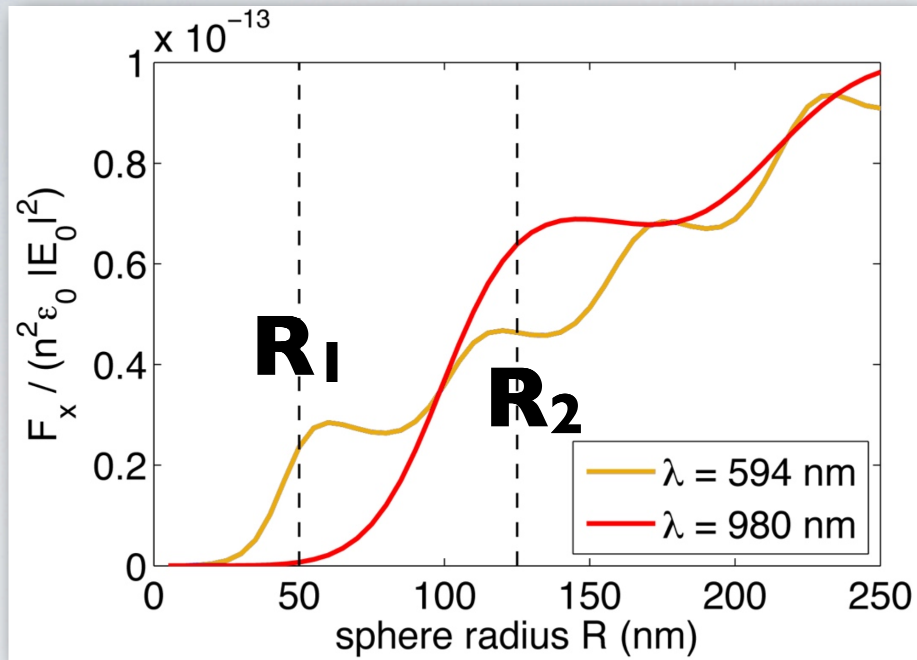
Case of a dielectric sphere with refractive index $n = 1.5 + \imath n''$

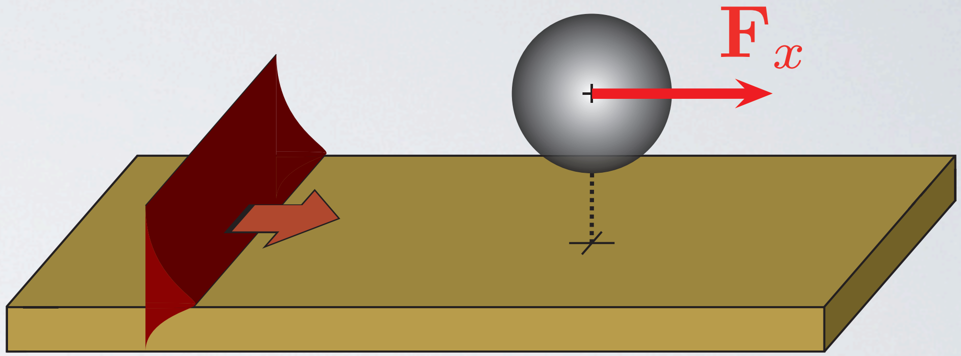
➡ torque is proportional to dissipation

A. Canaguier-Durand and C. Genet, *submitted* [arXiv:1311.7481].

Plasmonic force on a sphere

Results for the longitudinal force:

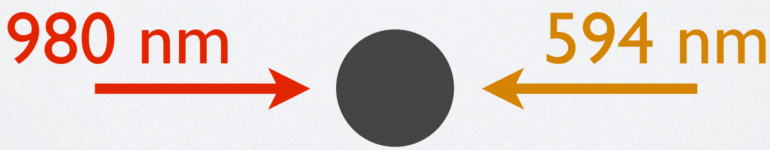




- confirms dipolar result for small R
- resonance effects (gold sphere)

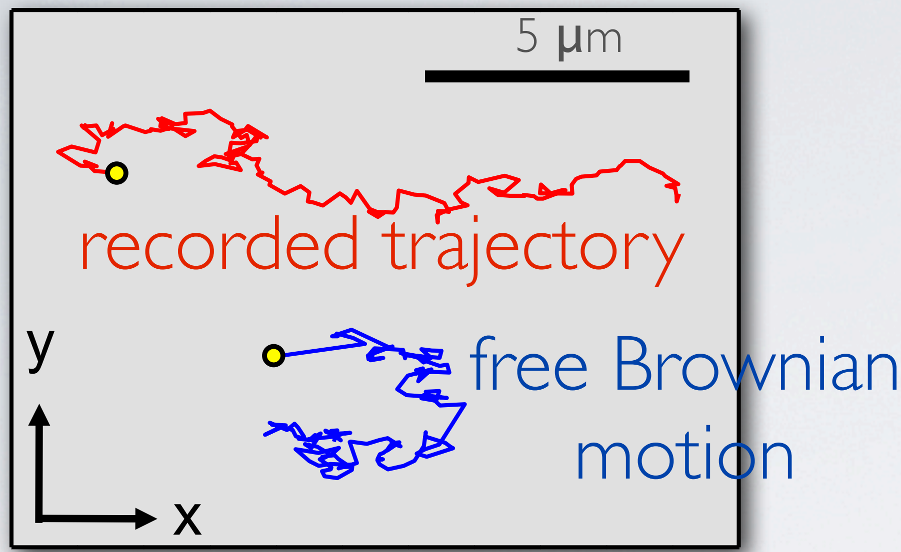
potential for optical sorting **R_1-R_2**

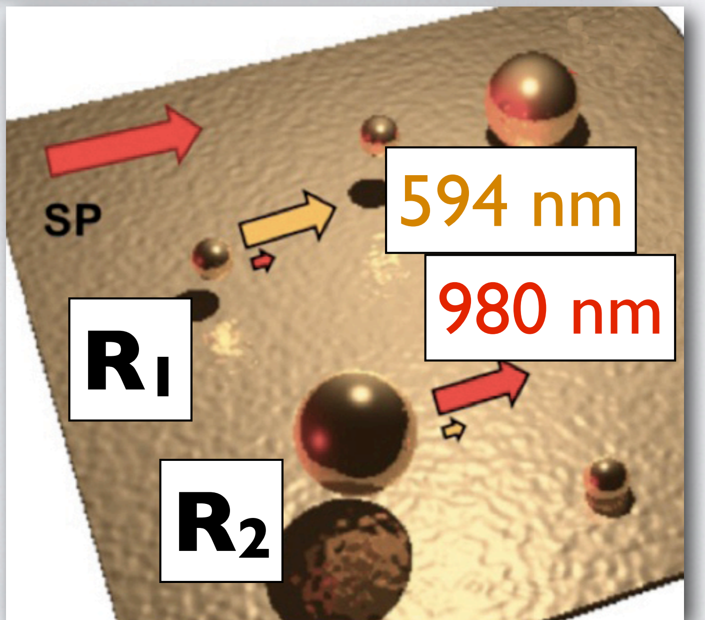
counter-propagating scheme:



A. Canaguier-Durand and C. Genet, *submitted* [arXiv:1311.7481].

Plasmonic sorting demonstrated





Experiment in the group at ISIS: force observed through statistical analysis of particles' motion.

$$F_x = \mu \frac{\gamma}{\Delta t}$$

friction by the liquid (γ)

μ: mean displacement during Δt

Experimental confirmation for the potential of SP for sorting NPs.

A. Cuche, A. Canaguier-Durand, É. Devaux, J.A. Hutchison, C. Genet and T.W. Ebbesen, *Nano Letters* **13,** 4230-4235 (2013).

Chiral objects

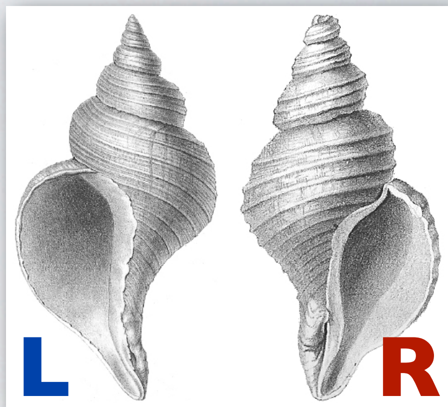
→ objects without spatial symmetry on a plane

In everyday life:

In gastropods:

L: Neptunea angulata

R: Neptunea despecta

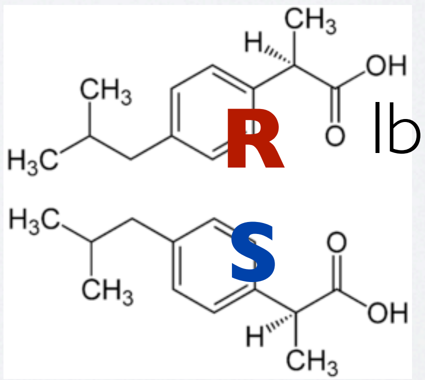


(10%) (90%)

In fundamental science:

- DNA, proteins
- weak interactions
- creation of life
- homochirality

In drug industry:



Ibuprofene (pain reliever)

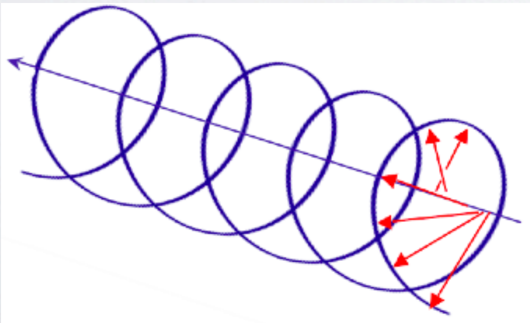
S: active **R**: inactive

→ sold as racemate

Optical chirality

	Energy	Chirality
Density	$W(\mathbf{r},t) = \frac{\varepsilon_0}{2}\mathcal{E}\cdot\mathcal{E} + \frac{\mu_0}{2}\mathcal{H}\cdot\mathcal{H}$	$K(\mathbf{r},t) = \frac{\varepsilon_0}{2}\mathcal{E}\cdot(\nabla\times\mathcal{E}) + \frac{\mu_0}{2}\mathcal{H}\cdot(\nabla\times\mathcal{H})$
Flux	$\mathbf{S}(\mathbf{r},t) = \mathcal{E}\times\mathcal{H}$	$\mathbf{\Phi}(\mathbf{r},t) = \frac{\mathcal{E}\times(\nabla\times\mathcal{H}) - \mathcal{H}\times(\nabla\times\mathcal{E})}{2}$
Conservation	$\nabla\cdot\mathbf{S} + \frac{\partial W}{\partial t} = 0$	$\nabla\cdot\mathbf{\Phi} + \frac{\partial K}{\partial t} = 0$

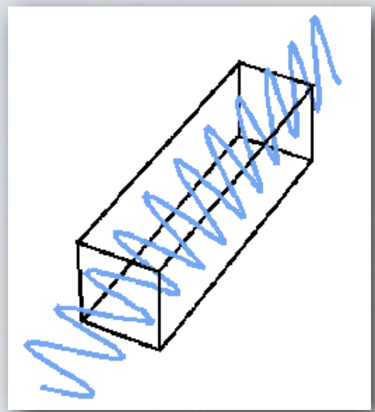
Circularly polarized wave



$$\mathbf{\Phi} = \frac{\omega I_0}{2c}\hat{\mathbf{z}} \qquad K = \frac{\omega I_0}{2c^2}$$

Chirality in light-matter interactions

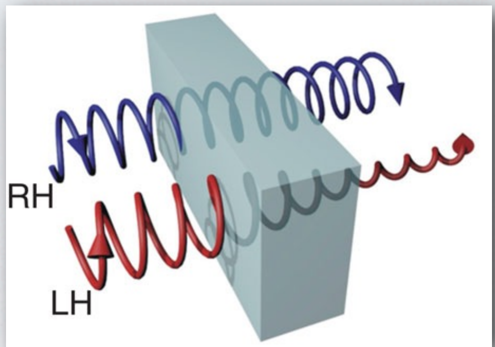
- Chiral matter on light:



Optical rotation

$\mathrm{Re}[\chi]$

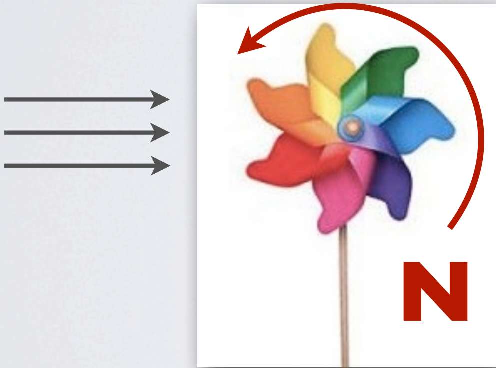
- Chiral matter on chiral light:



Circular dichroism

$\mathrm{Im}[\chi]$

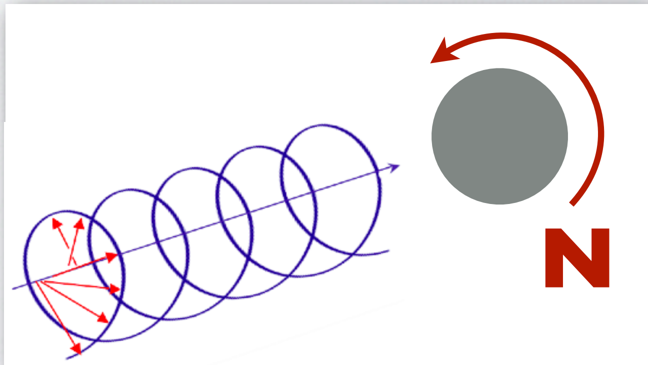
- Light on chiral matter:



Torque

$\mathrm{Im}[\chi]$

- Chiral light on matter:



Torque

$\mathrm{Im}[\alpha]$

➡ Optical force of chiral light on chiral objects?

Optical force on a chiral dipole

- Chiral dipole with moments: $\begin{cases} \mathbf{p}_0 = \alpha \mathbf{E}_0 + \imath\chi \mathbf{H}_0 \\ \mathbf{m}_0 = -\imath\chi \mathbf{E}_0 + \beta \mathbf{H}_0 \end{cases}$
- Optical force: $\mathbf{F} = (\mathcal{P} \cdot \nabla)\,\mathcal{E} + (\mathcal{M} \cdot \nabla)\,\mathcal{H} + \mu_0 \dot{\mathcal{P}} \times \mathcal{H} + \varepsilon_0 \dot{\mathcal{M}} \times \mathcal{E}$

$$\longrightarrow \langle \mathbf{F} \rangle_T = \mathrm{Re}\left[\alpha \mathbf{f}_0 + \beta \mathbf{g}_0 + \chi \mathbf{h}_0\right]/2$$

chiral optical force

- $\mathrm{Re}[\chi] \longleftrightarrow \mathrm{Re}[\mathbf{h}_0] = \dfrac{2c^2}{\omega} \nabla K \longrightarrow$ reactive part
- $\mathrm{Im}[\chi] \longleftrightarrow \mathrm{Im}[\mathbf{h}_0^*] = 4\left(\mathbf{\Phi} - \dfrac{\nabla \times \mathbf{\Pi}}{2}\right) \longrightarrow$ dissipative part

A. Canaguier-Durand, J.A. Hutchison, C. Genet and T.W. Ebbesen, *New J. Phys.* **15**, 123037 (2013).

Optical enantioseparation

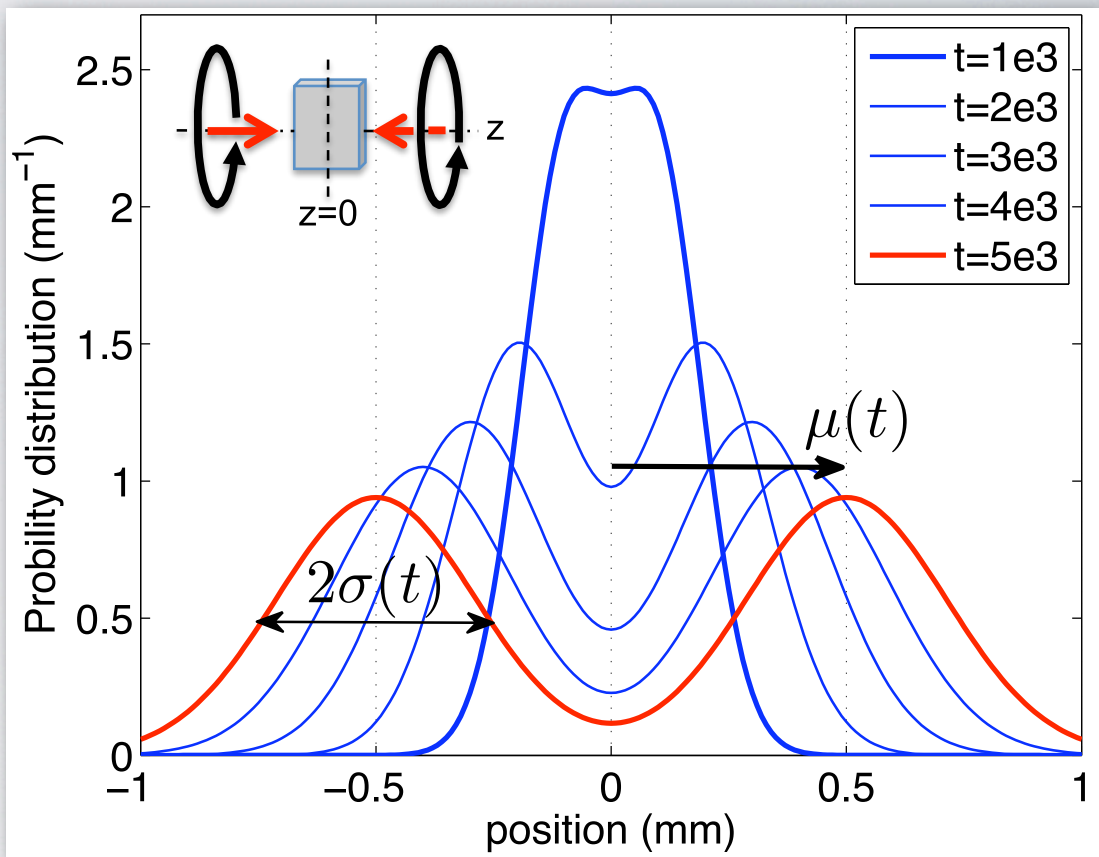
- counter-propagating CPL's
- opposite handedness
- incoherent fields

➡ only dissipative chiral force

$$\langle F \rangle_T = \frac{\omega I_0}{c} \mathrm{Im}[\chi] \hat{\mathbf{z}}$$

- separation $\mu(t) \propto t$
- Brownian motion causes

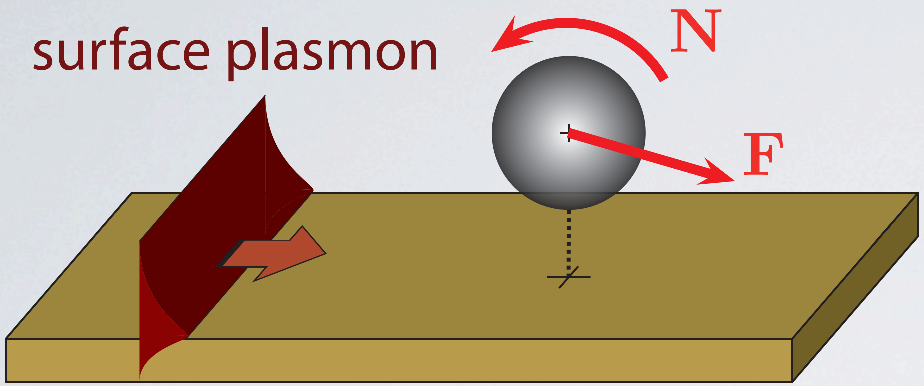
a variance $\sigma(t) \propto \sqrt{t}$



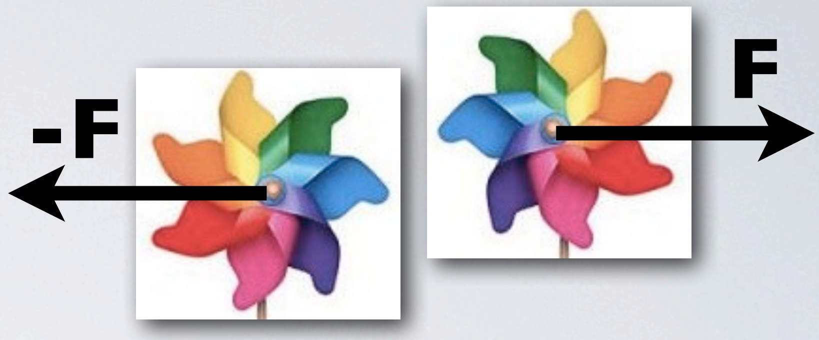
⟶ separation of ~1mm in one hour could be achieved

(50 mW on 1 μm^2, for a 50 nm object with high chirality)

A. Canaguier-Durand, J.A. Hutchison, C. Genet and T.W. Ebbesen, *New J. Phys.* **15**, 123037 (2013).



Chiral optical forces



conclusions:

- radiation pressure given by Π_O , not Π !
- plasmonic torque able to spin NP transversely
- chiral light exerts chiral optical force on chiral objects

perspectives: towards the near-field

➡ surface plasmons for efficient optical separation

OPTICAL FORCES IN THE NEAR-FIELD

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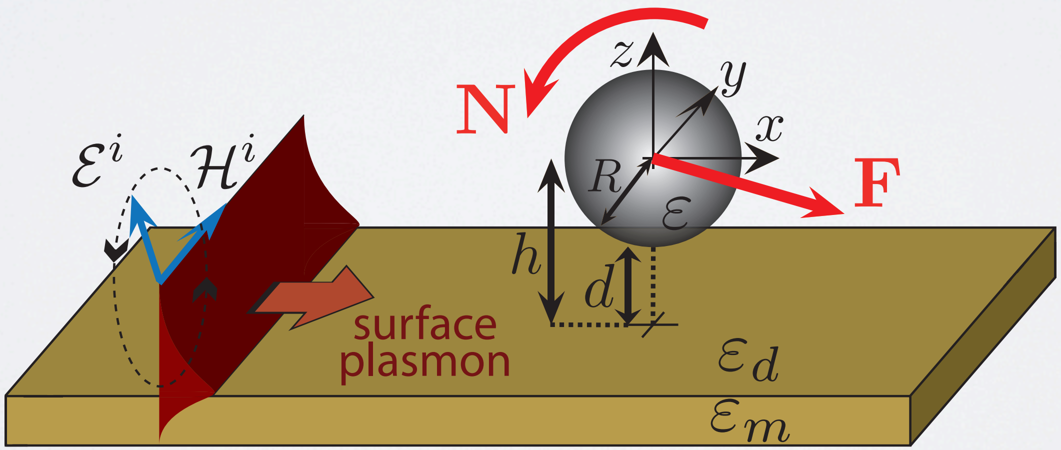
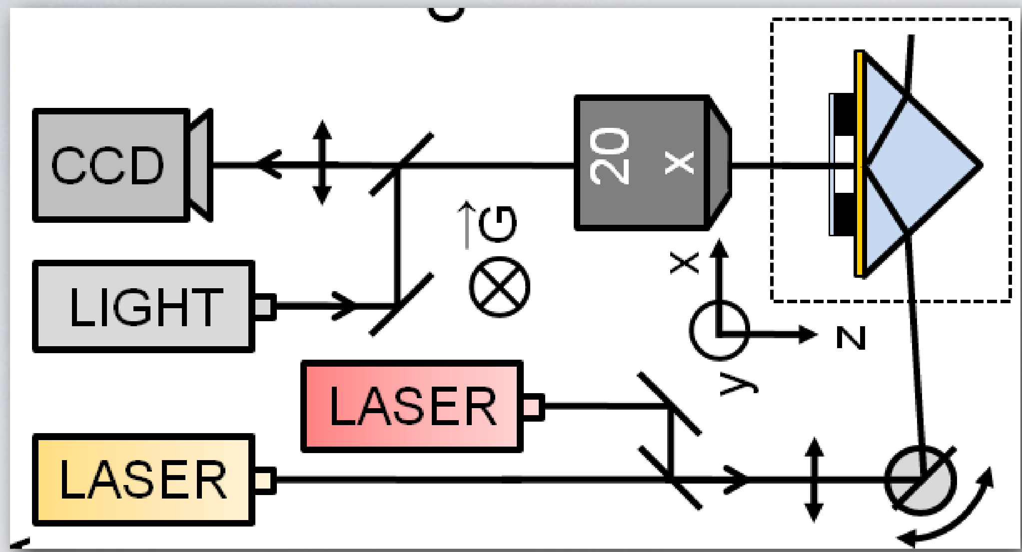
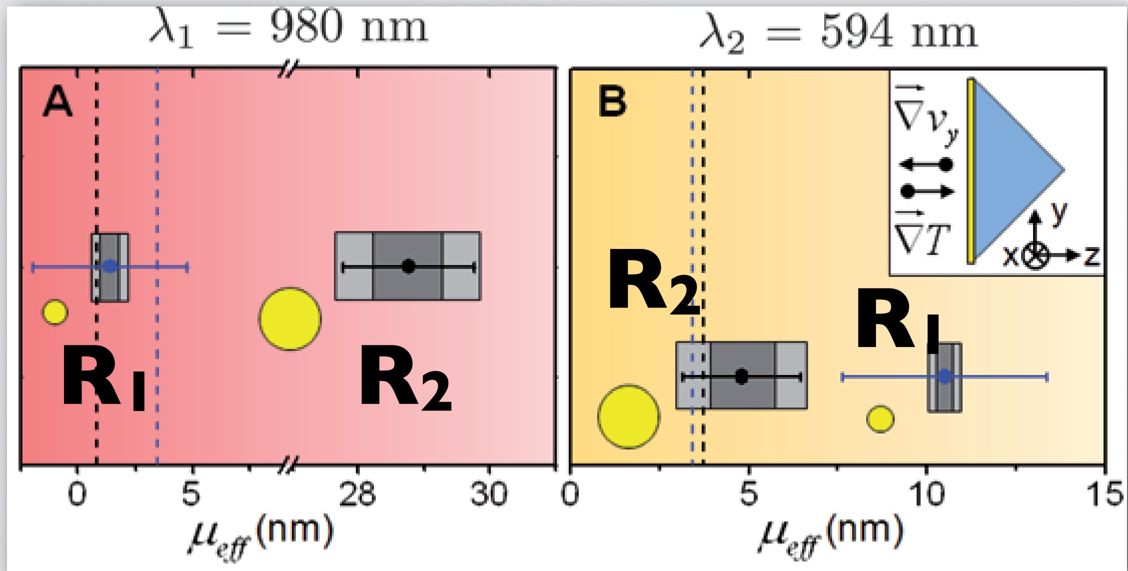
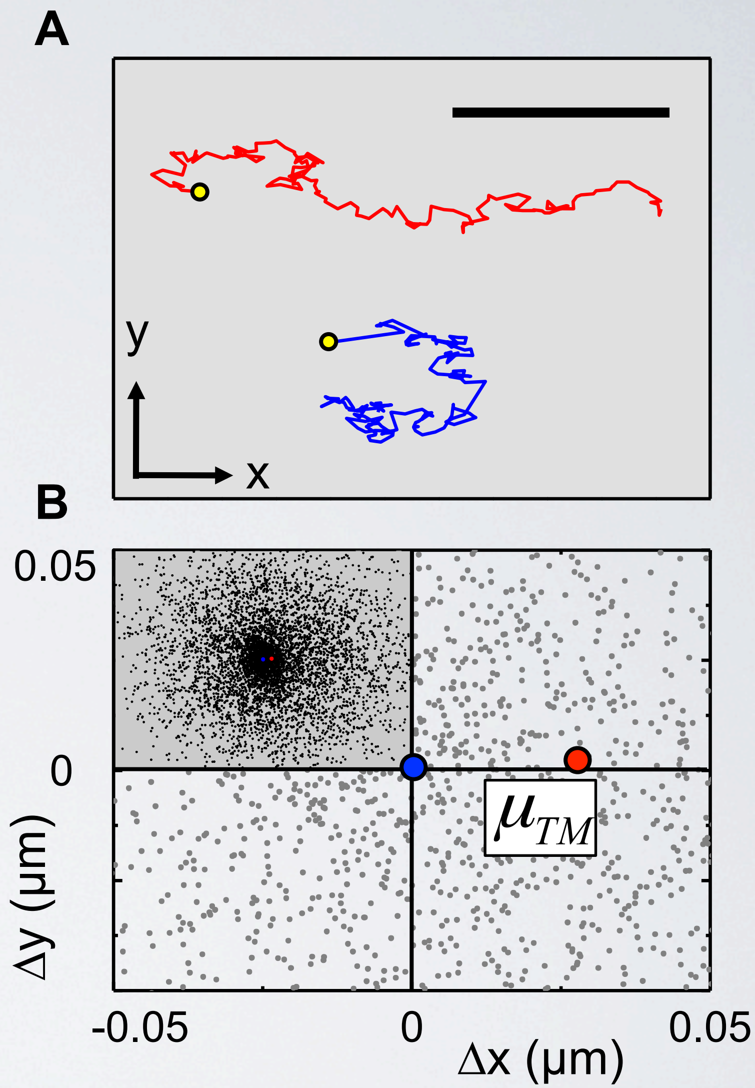


Plasmonic sorting: experiment







A. Cuche, A. Canaguier-Durand, É. Devaux, J.A. Hutchison, C. Genet and T.W. Ebbesen, *Nano Letters* **13,** 4230-4235 (2013).

Plasmonic sorting: details

- Gold nanospheres of radii 50 and 125 nm in a 70 μm thick fluidic cell.
- Incident laser: 10^5-10^6 W.m^{-2} @ 594 and 980 nm.
- 50 nm gold film evaporated on nanostructured ITO coated glass substrate.
- 5 nm SiO_2 layer evaporated on top of gold film to prevent electrostatic adhesion.
- Kretschmann configuration with metal/fluid interface (gold/water).
- Illumination angles θ = 64.3° [594] and 76.5° [980], TM polarization.
- Evanescent tail of ~ 200 nm in the fluid.
- NP positions recorded with a high speed CCD camera (f = 100 Hz).

A. Cuche, A. Canaguier-Durand, É. Devaux, J.A. Hutchison, C. Genet and T.W. Ebbesen, *Nano Letters* **13,** 4230-4235 (2013).

Π_O natural generalization of the phase-gradient

$$\langle \mathbf{F} \rangle_T = \frac{1}{2} \mathrm{Re}\left[\alpha \mathbf{f}_0\right] \;,\; \mathbf{f}_0 = \mathbf{E}_0 \cdot (\nabla)\, \mathbf{E}_0^* = \sum_i E_i \nabla E_i^*$$

- linear polarization: $\mathbf{\Pi} = \mathbf{\Pi}_O$

$$\mathbf{E}_0(\mathbf{r}) = \rho(\mathbf{r}) e^{\imath\phi(\mathbf{r})} \hat{\mathbf{x}} \longrightarrow \mathrm{Re}[\mathbf{f}_0] = \frac{1}{2} \nabla \rho^2$$

$$\longrightarrow \mathrm{Im}[\mathbf{f}_0^*] = 2\omega\mu_0 \mathbf{\Pi}_O = \rho^2 \nabla \phi$$

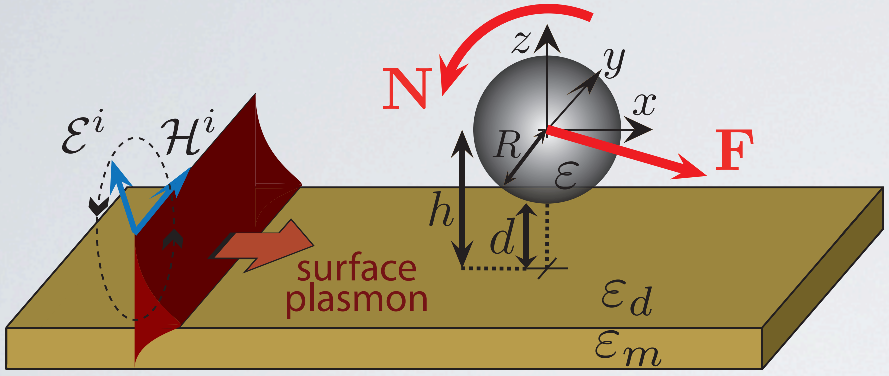
- general field: $\mathbf{\Pi} \neq \mathbf{\Pi}_O$

$$E^j = \rho_j e^{\imath\phi_j} \qquad \longrightarrow \mathrm{Re}[\mathbf{f}_0] = \frac{1}{2} \nabla \sum_j \rho_j^2$$

$$\longrightarrow \mathrm{Im}[\mathbf{f}_0^*] = 2\omega\mu_0 \mathbf{\Pi}_O = \sum_j \rho_j^2 \nabla \phi_j$$

A. Canaguier-Durand, A. Cuche, C. Genet and T.W. Ebbesen, *Phys. Rev. A* **88**, 033831 (2013).

Transverse spinning of a NP in a fluid



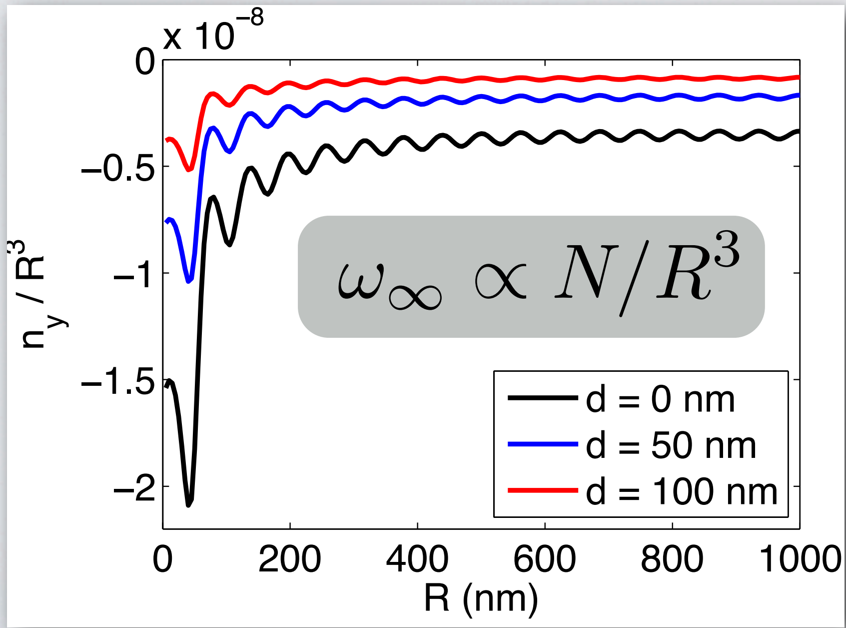
$$I\dot{\omega} = N + N_{\text{drag}}$$

applied torque (N)

friction torque (N_{drag}):

$$N_{\text{drag}} = -\gamma\omega$$
$$\gamma = 8\pi\eta R^3$$

➡ final angular frequency: $\omega_\infty = N/\gamma$ reached in time I/γ.



➡ independent on R for R≥200 nm

➡ for 1mW on 1μm², λ=594 nm: up to 20 Hz in water, 400 Hz in air

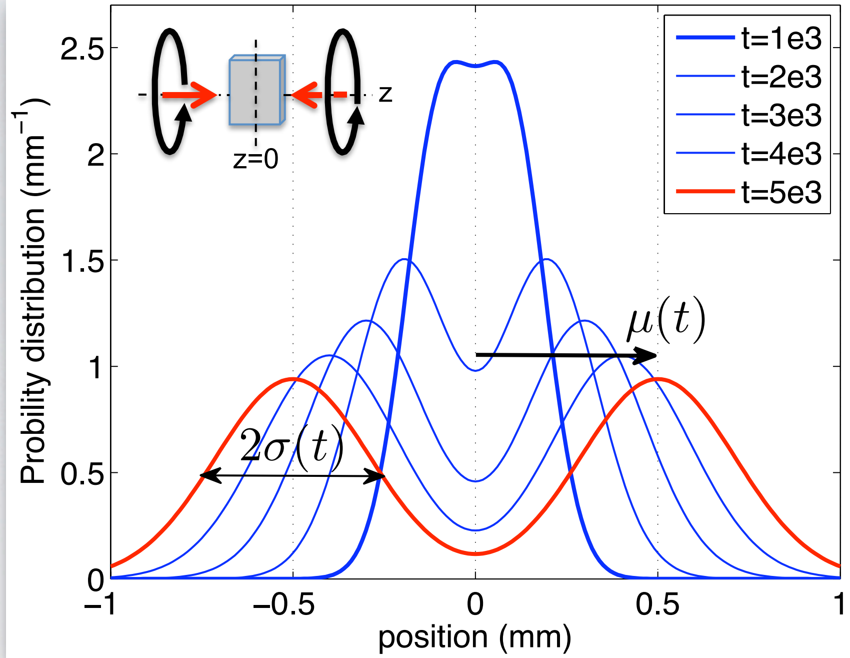
➡ transverse spinning for optical manipulation

A. Canaguier-Durand and C. Genet, *submitted* [arXiv:1311.7481].

Optical enantioseparation

- counter-propagating CPL's
- opposite handedness
- incoherent fields

$$\langle F \rangle_T = \frac{\omega I_0}{c} \mathrm{Im}[\chi] \hat{\mathbf{z}}$$



separation of ~1mm in one hour could be achieved

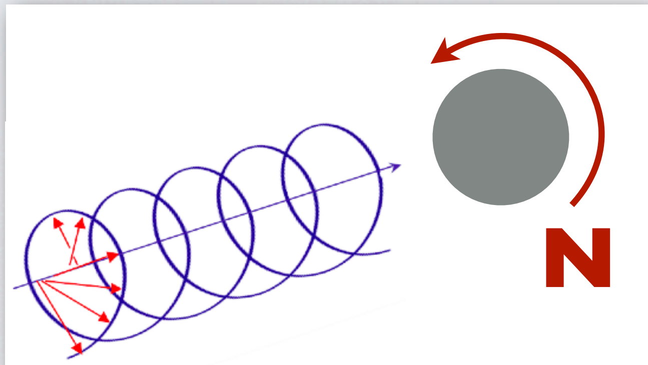
- incident intensity: 50 mW on 1 μm^2 ⟶ $I_0 = 5 \cdot 10^{10}$ W · m^{-2}
- very chirality object: Im[c χ]=10^{-2} · Im[α/ε_0] (W. Yan et. al. 2012)
- 20 nm radius gold nanoparticles: Im[α/ε_0] ~10^{-22}
- optical chiral force: F ~ 1fN ⟶ $\Delta x = F \cdot \Delta t/\gamma \sim 10^{-6} \Delta t$

A. Canaguier-Durand, J.A. Hutchison, C. Genet and T.W. Ebbesen, *New J. Phys.* **15**, 123037 (2013).

Optical torque on a chiral dipole

- Chiral dipole with moments: $\begin{cases} \mathbf{p}_0 = \alpha \mathbf{E}_0 + \imath\chi \mathbf{H}_0 \\ \mathbf{m}_0 = -\imath\chi \mathbf{E}_0 + \beta \mathbf{H}_0 \end{cases}$
- Optical torque: $\mathbf{\Gamma} = \mathcal{P} \times \mathcal{E} + \mathcal{M} \times \mathcal{H}$

$$\longrightarrow \langle \mathbf{\Gamma} \rangle_T = \mathrm{Im}[\alpha]\mathbf{\Phi}_E + \mathrm{Im}[\beta]\mathbf{\Phi}_H + 2\mathrm{Im}[\chi]\mathbf{\Pi}$$



Non-chiral torque

$\mathrm{Im}[\alpha]$

Chiral torque

$\mathrm{Im}[\chi]$

A. Canaguier-Durand, J.A. Hutchison, C. Genet and T.W. Ebbesen, *New J. Phys.* **15**, 123037 (2013).