Optical Trapping of Nanostructures

Femtonewton Force Sensing and Ultra-sensitive Spectroscopy

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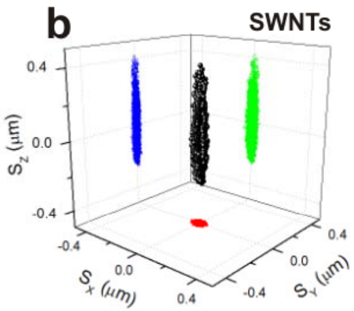
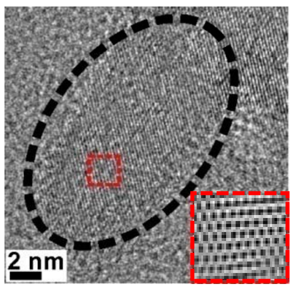
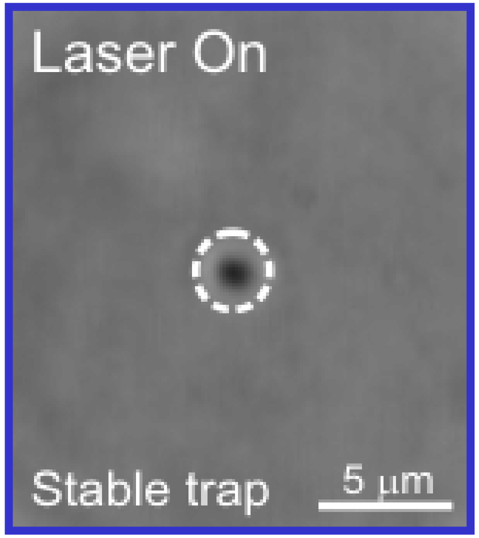
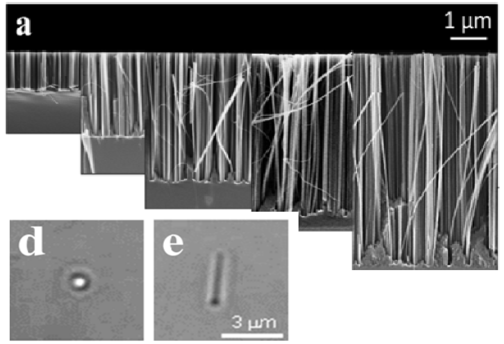








NanoSpain Conf 2012

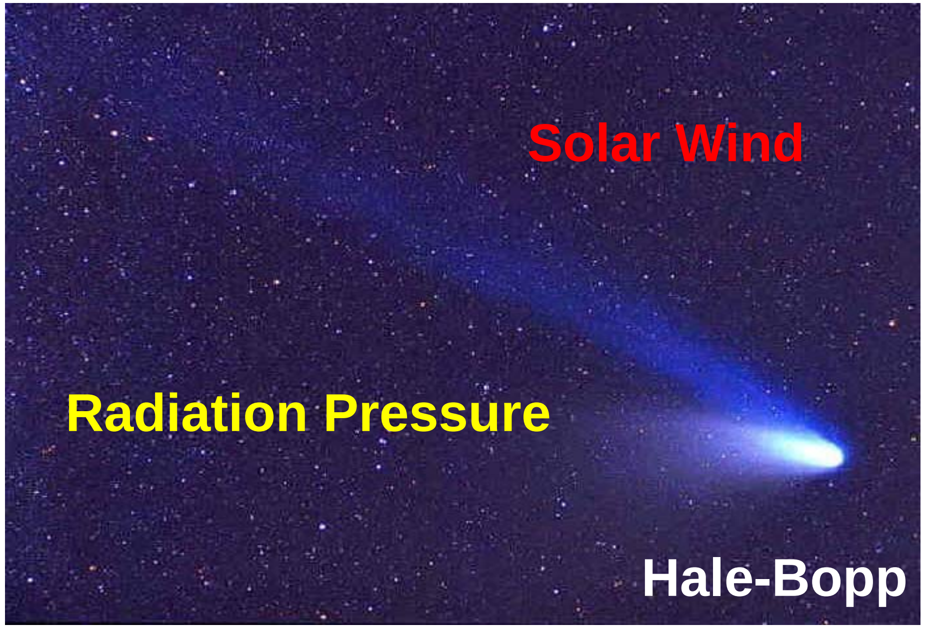
February 27 - March 01, 2012
Santander (Spain)

Outline

- Optical Trapping & Force sensing
- OT of Linear Nanostructures (SWNTs & SiNW)
  - *Brownian motion & Force sensing*
  - *Size-scaling*
  - *Optical Binding*
- OT & Raman OT of Graphene
- Plasmon-Enhanced Forces & Spectroscopy
  - *SERS Tweezers*
  - *Optical Forces on Hybrid Nanostructures, Nanoswimmers*
- Conclusions

Light Moves Matter

- **J Kepler (1610)**
  comet tails are the result of light pressure



- **J C Maxwell (1864)**
  light pressure is explained in electromagnetic theory
- **P Lebedev (1901)**
  measures light pressure for the first time
- **A Ashkin, T Haensch & A Schawlow (1970s)**
  first proposals to manipulate atoms and microparticles, laser cooling
- **A Ashkin & S Chu (1986)**
  at Bell Laboratories moves and traps latex spheres suspended in water using a focused laser beam. Optical Tweezers are born!

A light touch

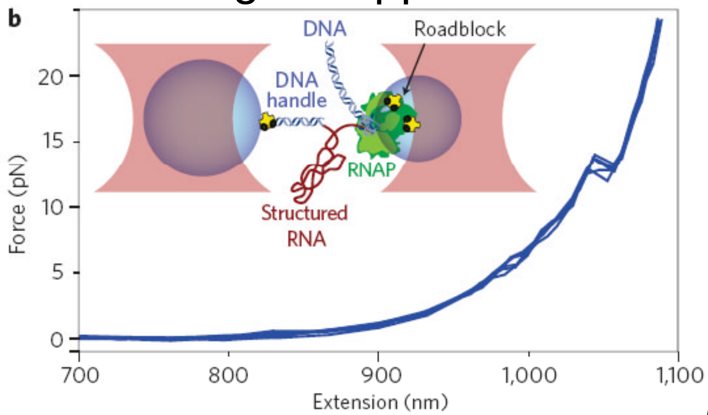
NATURE PHOTONICS | VOL 5 | JUNE 2011 | www.nature.com/naturephotonics

Since the discovery of the optical gradient force in 1970 and the first use of laser beams to manipulate microscopic and atomic systems in 1986, optical manipulation has proved to be a versatile optical tool for uncovering mysteries throughout many fields of science.

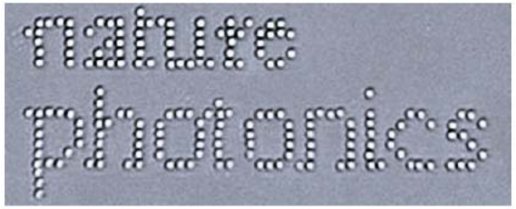
Arthur Ashkin

ICFO

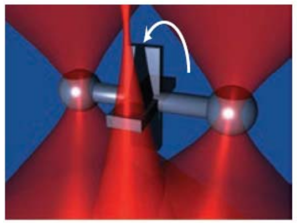
Biological Applications

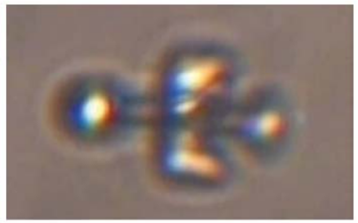


Holographic Tweezers

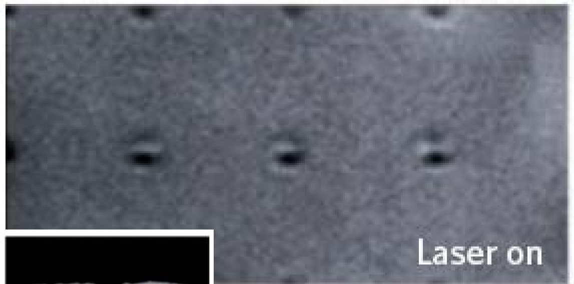


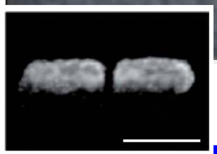
Optofluidics & Lab-on-Chip





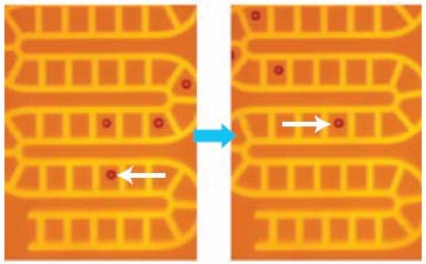
Optical NanoTweezers





Gap-Nanoantenna

OptoelectronicTweezers



Theory of Optical Trapping

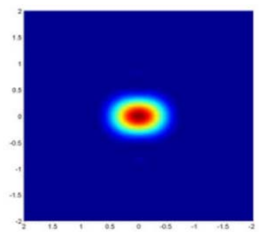
Optical trapping of particles is a consequence of the radiation force that stems from the conservation of electromagnetic momentum.

Rayleigh Regime, d/λ << 1

- **Force divides into two components: <u>gradient force</u> and the <u>scattering force</u>**

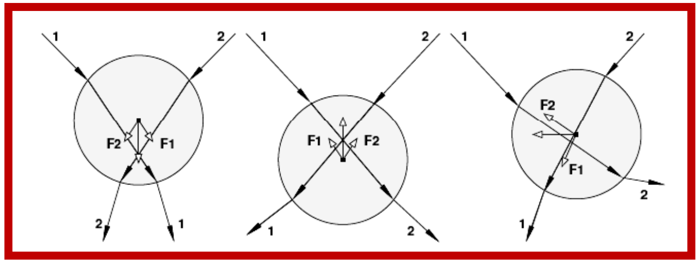
$$\begin{aligned} U_{\text{dip}} &= -\underline{p}\cdot\underline{E} \\ \underline{F}_{\text{grad}} &= -\underline{\nabla} U_{\text{dip}} \\ \propto \underline{\nabla} I(\underline{r}) &= -\kappa_i x_i \end{aligned}$$

x-y plane



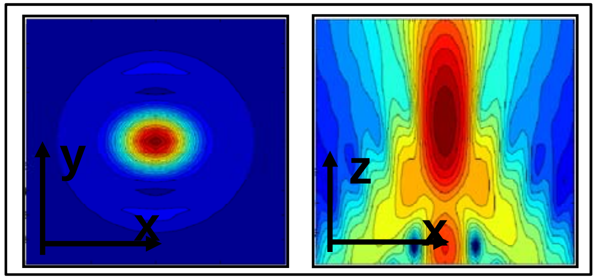
Ray Optics Regime, d/λ >> 1

- **Microsphere acts like a lens**
- **Trapping forces from <u>reflection and refraction of rays</u>**
- **Forces proportional to <u>gradient of intensity</u>**



Complex Region, d/λ ≈ 1

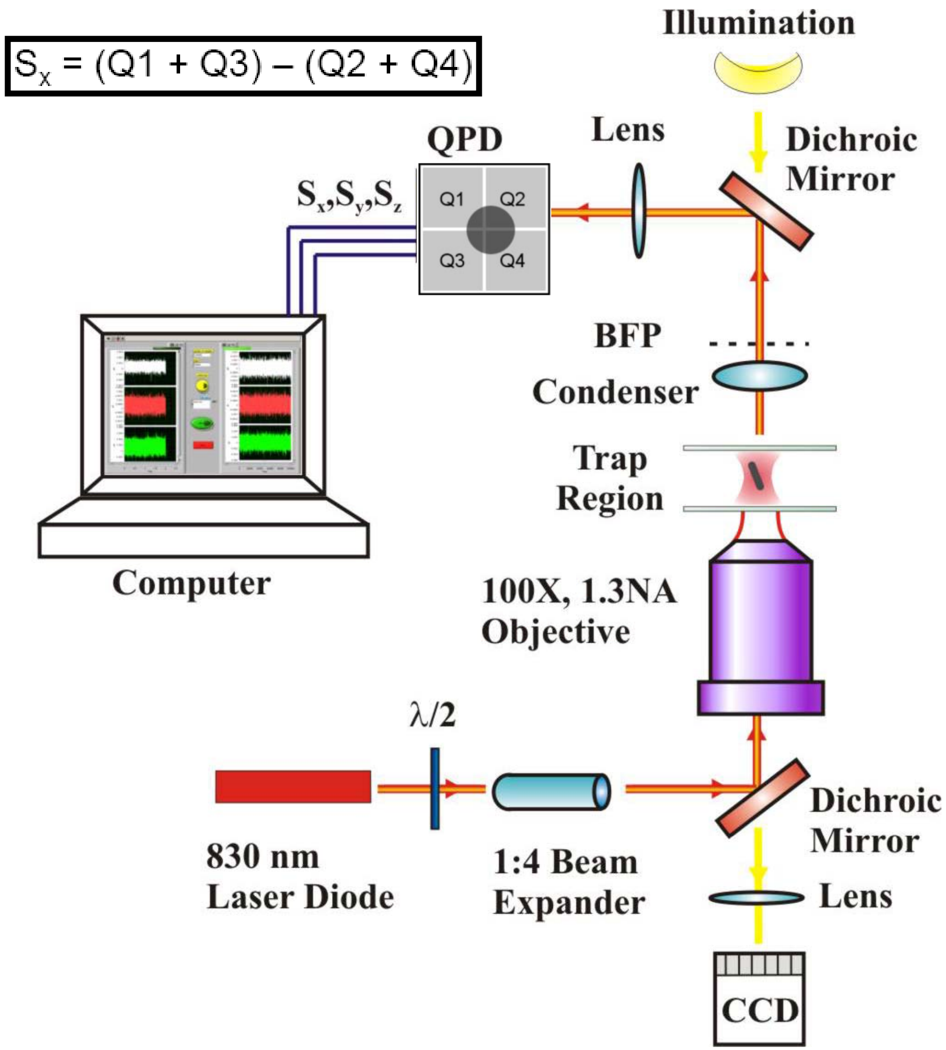
- **Full electromagnetic Theory**
- **Vector character of laser field**
- **Make use of Transition-Matrix approach**
- **Extension to non-spherical particles!**



$$\mathbf{F}_{\text{Rad}} = r'^2 \int_{\Omega'} \hat{\mathbf{r}}' \cdot \langle \mathrm{T_M} \rangle \, d\Omega'$$

Rohrbach, PRL (2005); Singer et al., PR E (2006); Borghese,Denti,Saija,Iatì, Opt. Express (2007); Borghese,Denti,Saija,Iatì,Maragò, Phys Rev Lett (2008); Saija,Denti,Borghese,Maragò,Iatì, Opt. Express (2009); Bareil & Sheng, Opt. Express (2010); Simpson & Hanna, PR E (2010); ...

Optical Tweezers & Force Sensing



- Standard OT with QPD forward or back detection
- Multiwavelength: 830nm (150mW), 785nm (80mW), 633nm (17mW), 417nm (30mW)
- Radial Polarizer (arcoptics)
- Piezostage (1nm resolution)
- Galvomirrors

Back focal plane interferometry combined with a QPD is sensitive to Brownian fluctuations

Brownian motion is a key ingredient in Force Sensing with optical tweezers.

Brownian Motion for a bead

- Equation of motion of a damped harmonic oscillator subject to a randomly fluctuating force:

$$m\cancel{\frac{\mathrm{d}^2x}{\mathrm{d}t^2}} + \gamma\frac{\mathrm{d}x}{\mathrm{d}t} + \kappa x = \xi(t)$$

Stokes

Trap

- The term $\xi(t)$ describes random (uncorrelated) fluctuations in force with zero mean, i.e.

$$\langle \xi(t) \rangle = 0 \qquad \langle \xi(t+\tau)\xi(t) \rangle = \frac{2k_BT}{\gamma}\delta(\tau)$$

- Equation of motion in the overdamped regime:

$$\gamma\partial_t x(t) = -\kappa x(t) + \xi(t)$$

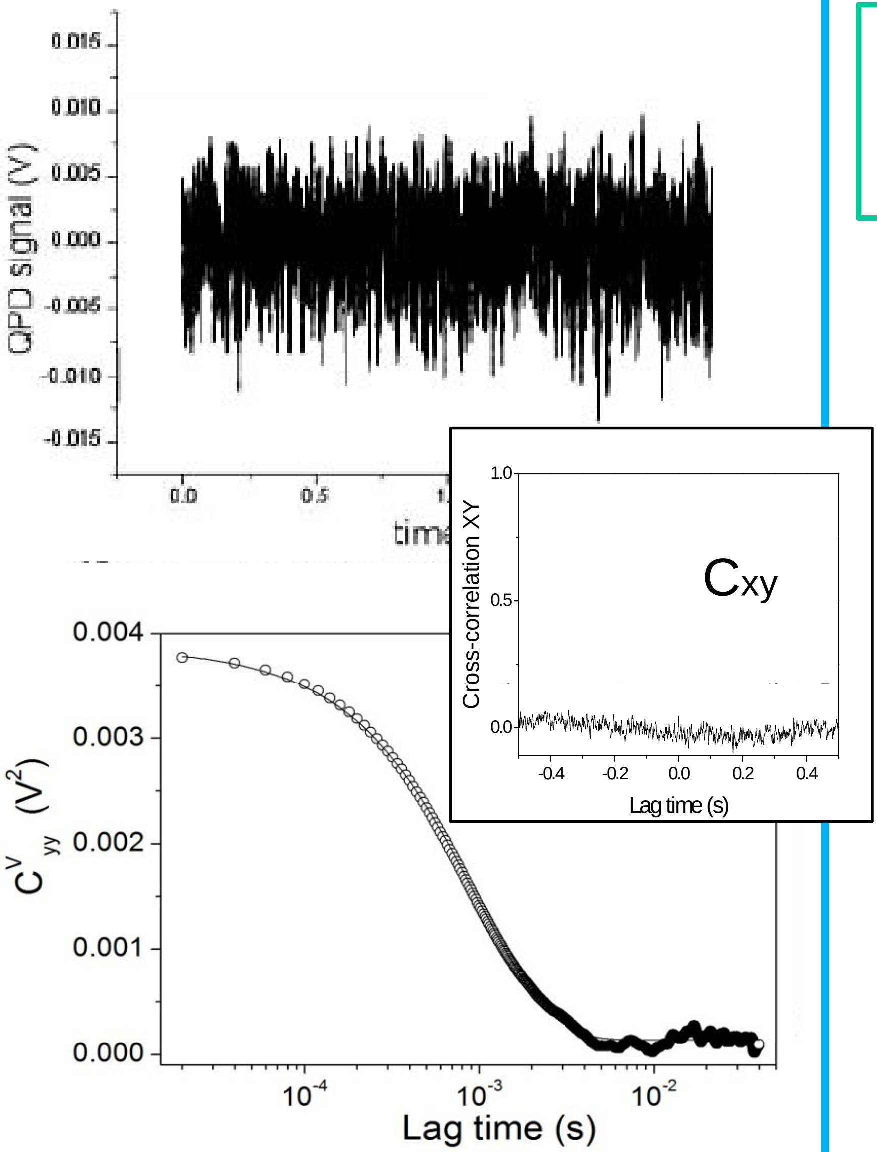
- Calculate the **autocorrelation** of position fluctuations:

$$C_{xx}(\tau) = \langle x(t)x(t+\tau) \rangle$$

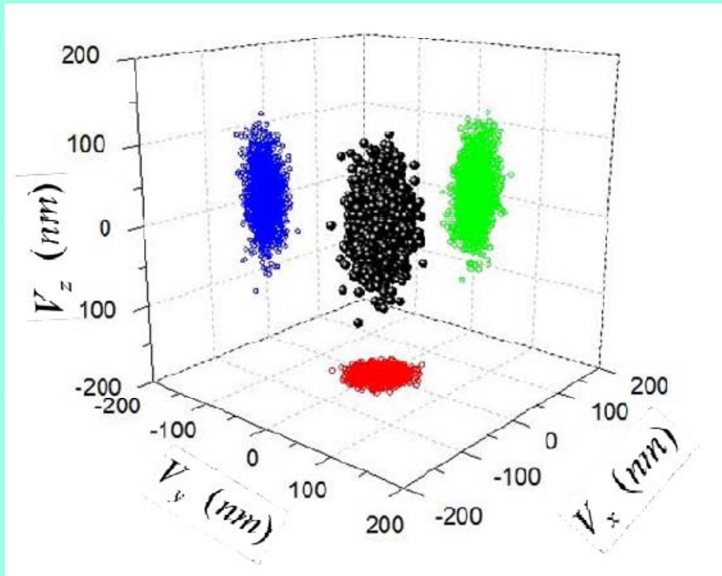
- The solution to which is straightforward:

$$C_{xx}(\tau) = C_{xx}(\tau = 0)\exp(-\omega\tau) \qquad \boxed{\omega = \frac{\kappa}{\gamma}}$$

Calibration for a bead



From QPD tracking signals we get Autocorrelation Functions and eventually the Force Constants

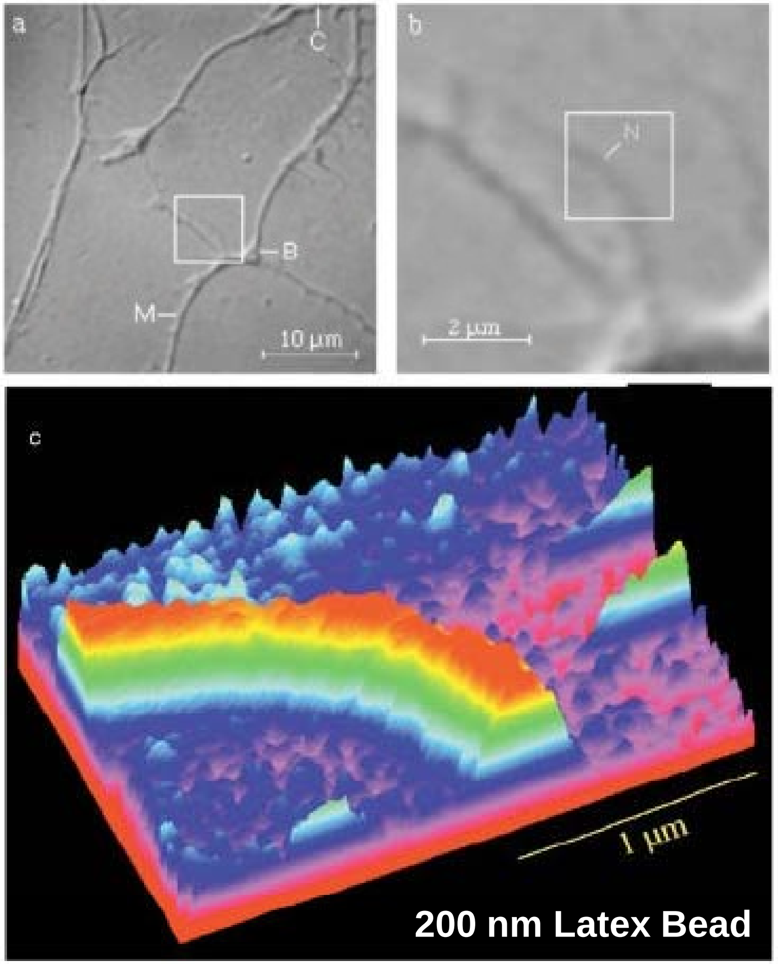


Autocorrelation:
Meiners&Quake, PRL (1999)
Meiners&Quake, PRL (2000)
Rohrbach, PRL (2005)
Volpe&Petrov, PRL (2006)
....

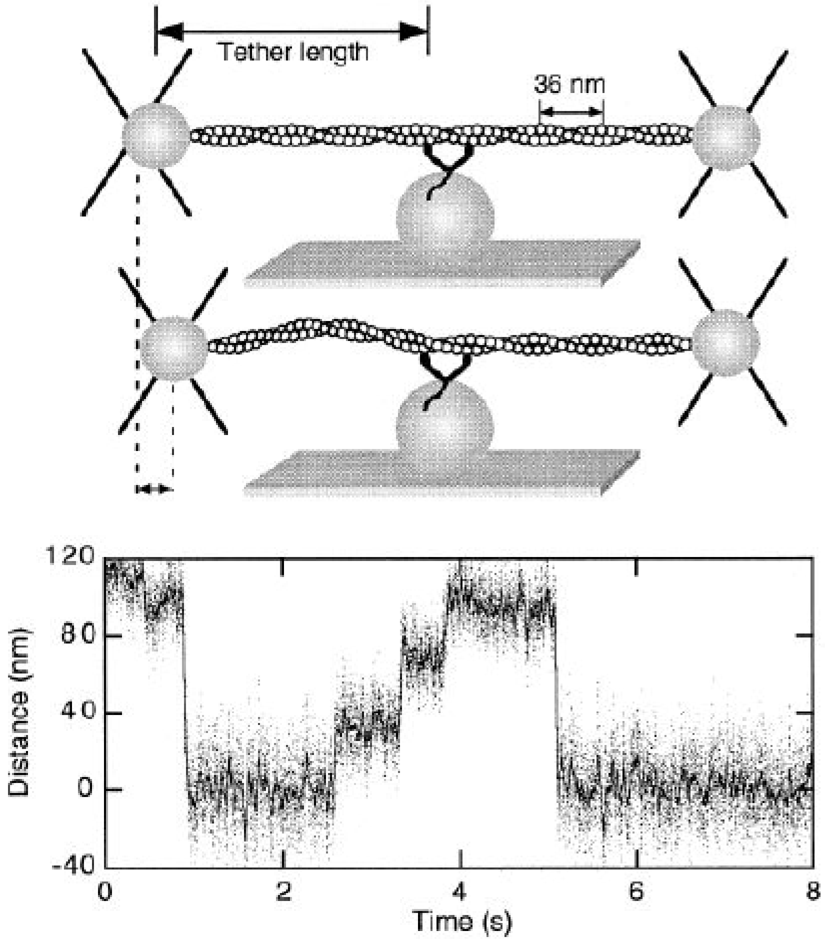
Photonic Force Microscopy

Scanning Probe Technique based on Force Sensing with Optical Tweezers

Dual trap with actin filament
Myosin steps along actin



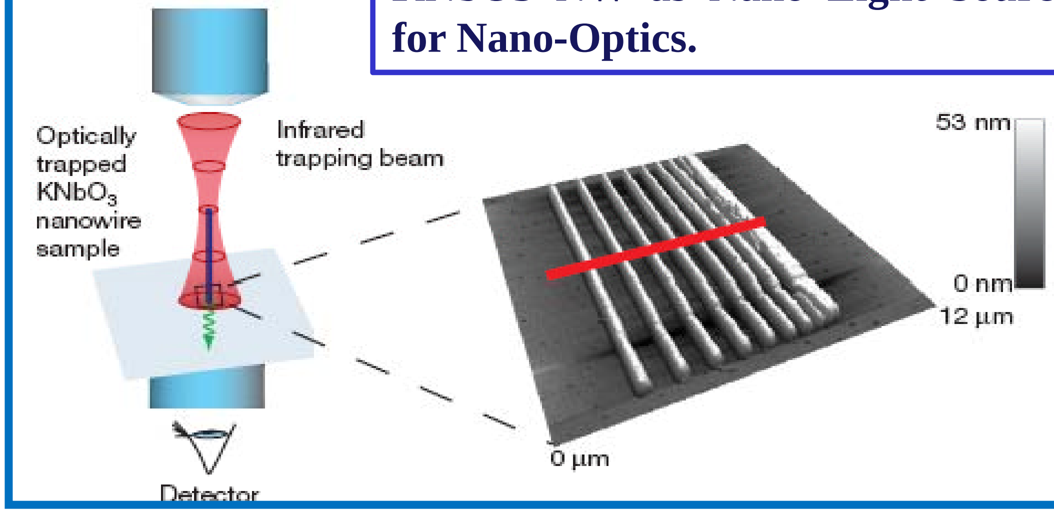
Data from: A. Pralle et al, *Single Mol.* **1** 12 (2000)



Data from: A. Mehta et al, *Nature* **400** 590 (1999)

OT of Linear Nanoprobes

KNbO3 NW as Nano Light Source for Nano-Optics.

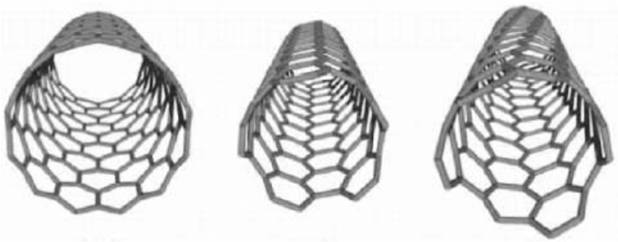


Nanowires:

Agarwal et al., Optics Express (2005)
Pauzauskie et al., Nat. Mat. (2006)
Nakayama et al., Nature (2007)
Borghese et al., Phys. Rev. Lett. (2008)
Carberry et al., Nanotech. (2010)
Simpson&Hanna, JOSA A (2010)
Simpson&Hanna, PR E (2010)
Reece et al., Nano Lett. (2011)
Dutta et al., Nano Lett. (2011)
Irrera et al., Nano Lett. (2011)

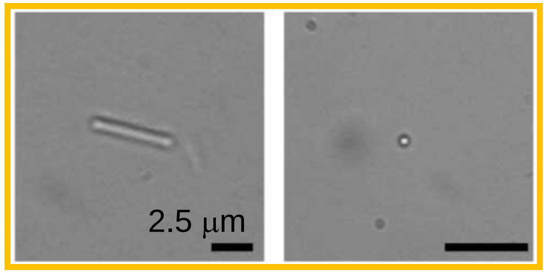
Nanotubes:

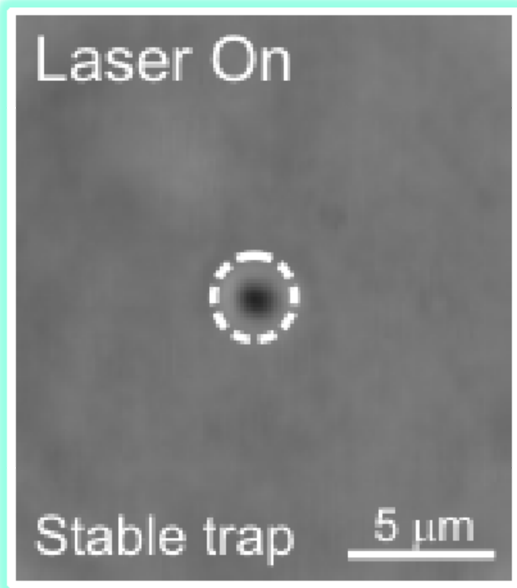
Tan et al., Nano Lett. (2004)
Plewa et al., Optics Express (2004)
Zhang et al., APL (2006)
O.M. Maragò et al., Physica E (2008)
O.M. Maragò et al., Nano Lett. (2008)
P.H. Jones, et al. ACS Nano (2009)
Pauzauskie et al, APL (2009)



Nanofibers:

Neves et al., Optics Express (2010)





OT theory

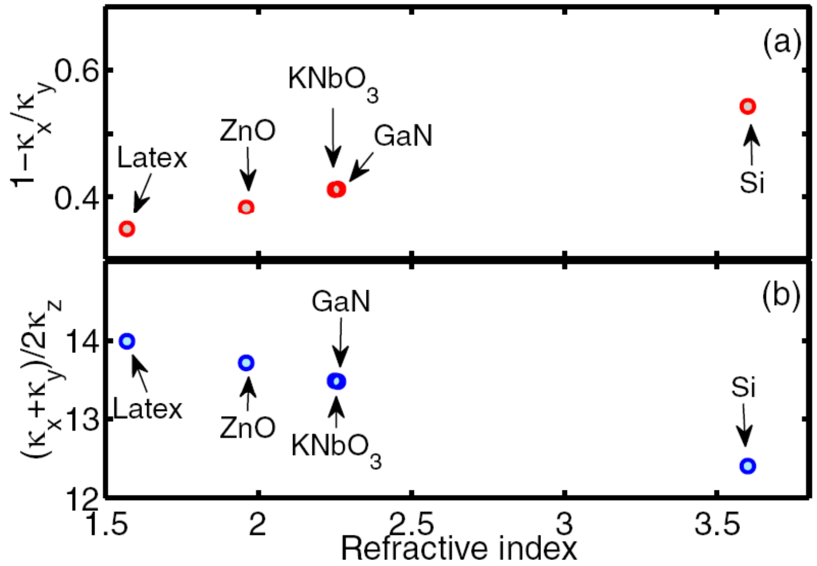
Radiation Force and Torque on non-spherical particles in the T-matrix formalism

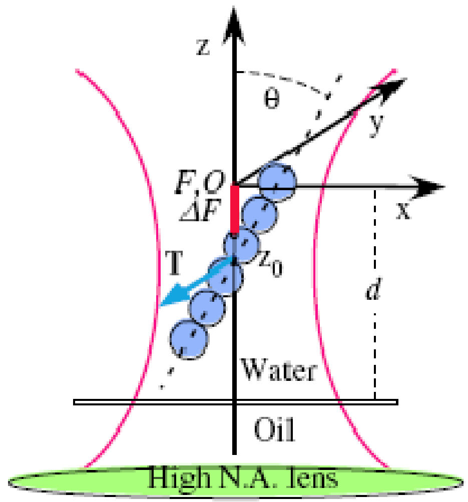
linear nanostructure
$x_{D/2} << 1$ and $x_{L/2} \approx 1$

$$\mathbf{F}_{\rm Rad} = r'^2 \int_{\Omega'} \hat{\mathbf{r}}' \cdot \langle \mathsf{T}_{\rm M} \rangle \, d\Omega'$$

$$\boldsymbol{\Gamma}_{\rm Rad} = -r'^3 \int_{\Omega'} \hat{\mathbf{r}}' \cdot \langle \mathsf{T}_{\rm M} \rangle \times \hat{\mathbf{r}}' \, d\Omega'$$

where $\langle \mathsf{T}_{\rm M} \rangle$ **is the time averaged Maxwell stress tensor**





Polarization and Geometrical asimmetry
$\kappa_P = 1 - \kappa_x/\kappa_y$ $\kappa_G = (\kappa_x + \kappa_y)/2\kappa_z$

Singer et al., Phys Rev E (2006); Borghese et al., Optics Express, (2007); Borghese et al., Phys Rev Lett (2008);
Bareil & Sheng, Opt. Express (2010); Simpson & Hanna, Phys Rev E (2010); ……
S. Albaladejo, J.J. Sáenz, M.I. Marqués *Nano Lett.*, **2011**, *11*,4597–4600 (**Nano Sail**)

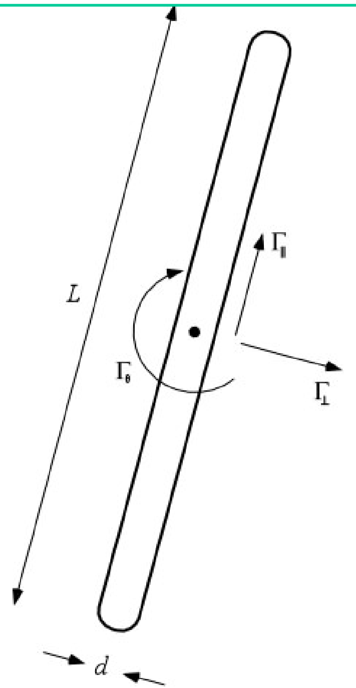
Hydrodynamics

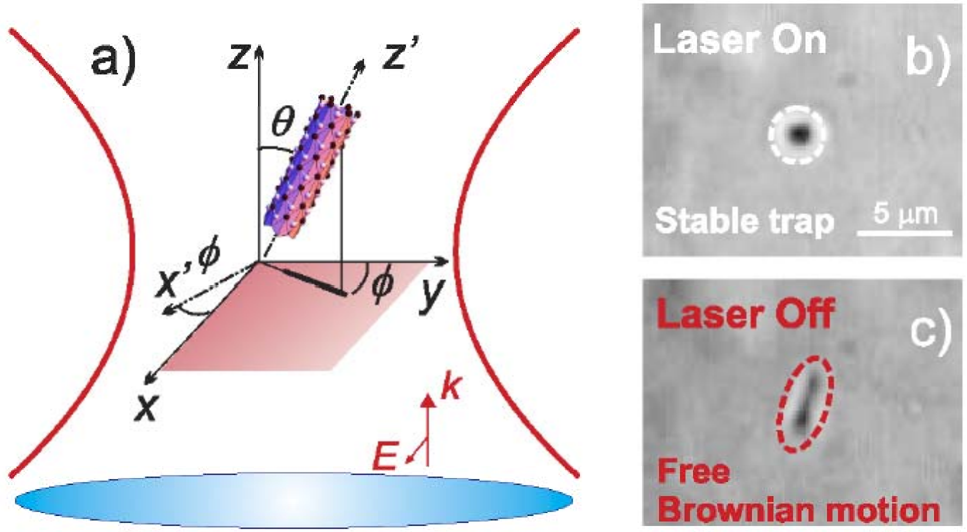
Broersma, J.Chem.Phys. (1981);
Tirado et al. J. Phys Chem C(1984)

Hydrodynamics of a rod-like nanostructure is anisotropic

$$\Gamma_{\perp} = \frac{\ln p + \delta_{\perp}}{4\pi\eta L}, \quad \Gamma_{||} = \frac{\ln p + \delta_{||}}{2\pi\eta L}$$

$$\Gamma_{\Theta} = \frac{3(\ln p + \delta_{\theta})}{\pi\eta L^3}$$





The signals from the QPD are a composition of center of mass Xi and angular motion Θi.

$$S_x \sim \beta_x (X + a\,\Theta_x)\,;\; S_y \sim \beta_y (Y + b\,\Theta_y)\,;\; S_z \sim \beta_z Z$$

Small angle approximation

Brownian Motion is more complex

$$\partial_t X_i(t) = -\omega_i X_i(t) + \xi_i(t), \quad i = x, y, z$$
$$\partial_t \Theta_j(t) = -\Omega_j \Theta_j(t) + \xi_j(t), \quad j = x, y$$

From correlation functions we can extrapolate the <u>force</u> and <u>torque</u> constants on the SWNT bundle

$$C_{X_i X_i}(\tau) = \langle X_i(t) X_i(t+\tau) \rangle$$
$$C_{\Theta_j \Theta_j}(\tau) = \langle \Theta_j(t) \Theta_j(t+\tau) \rangle$$

$$\omega_x = \Gamma_\perp k_x,\ \omega_y = \Gamma_\perp k_y,\ \omega_z = \Gamma_{||} k_z$$
$$\Omega_x = \Gamma_\Theta k_{\Theta_x},\ \Omega_y = \Gamma_\Theta k_{\Theta_y}.$$

Relaxation Frequencies for Translational and Angular Motion

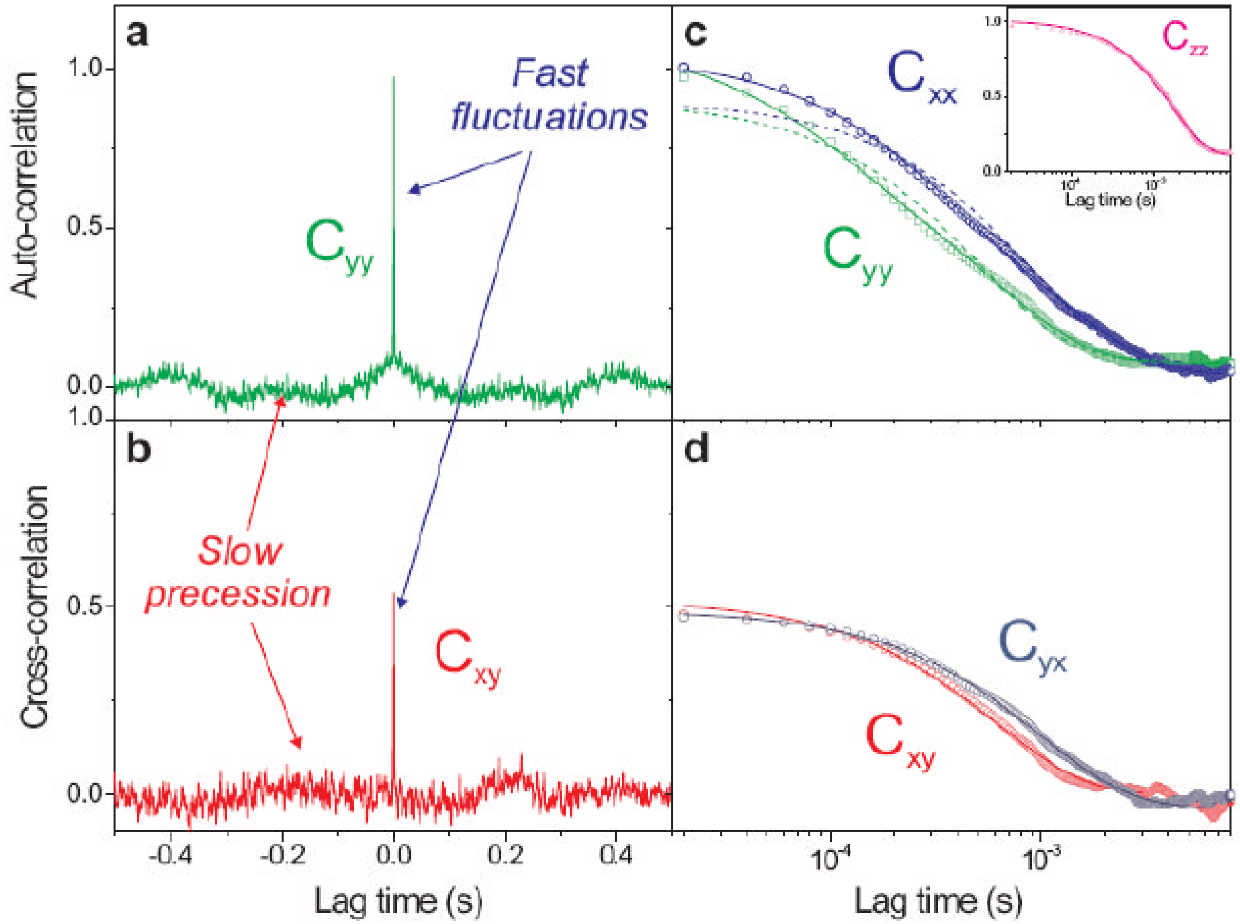
Hydrodynamics of a rod-like nanostructure is embedded in the relaxation frequencies

Correlation Functions

Correlation functions of the tracking signals give information on torque and force constants.

$$C_{ii}(\tau) = \langle S_i(t) S_i(t+\tau) \rangle$$

$$C_{xy}(\tau) = \langle S_x(t) S_y(t+\tau) \rangle$$

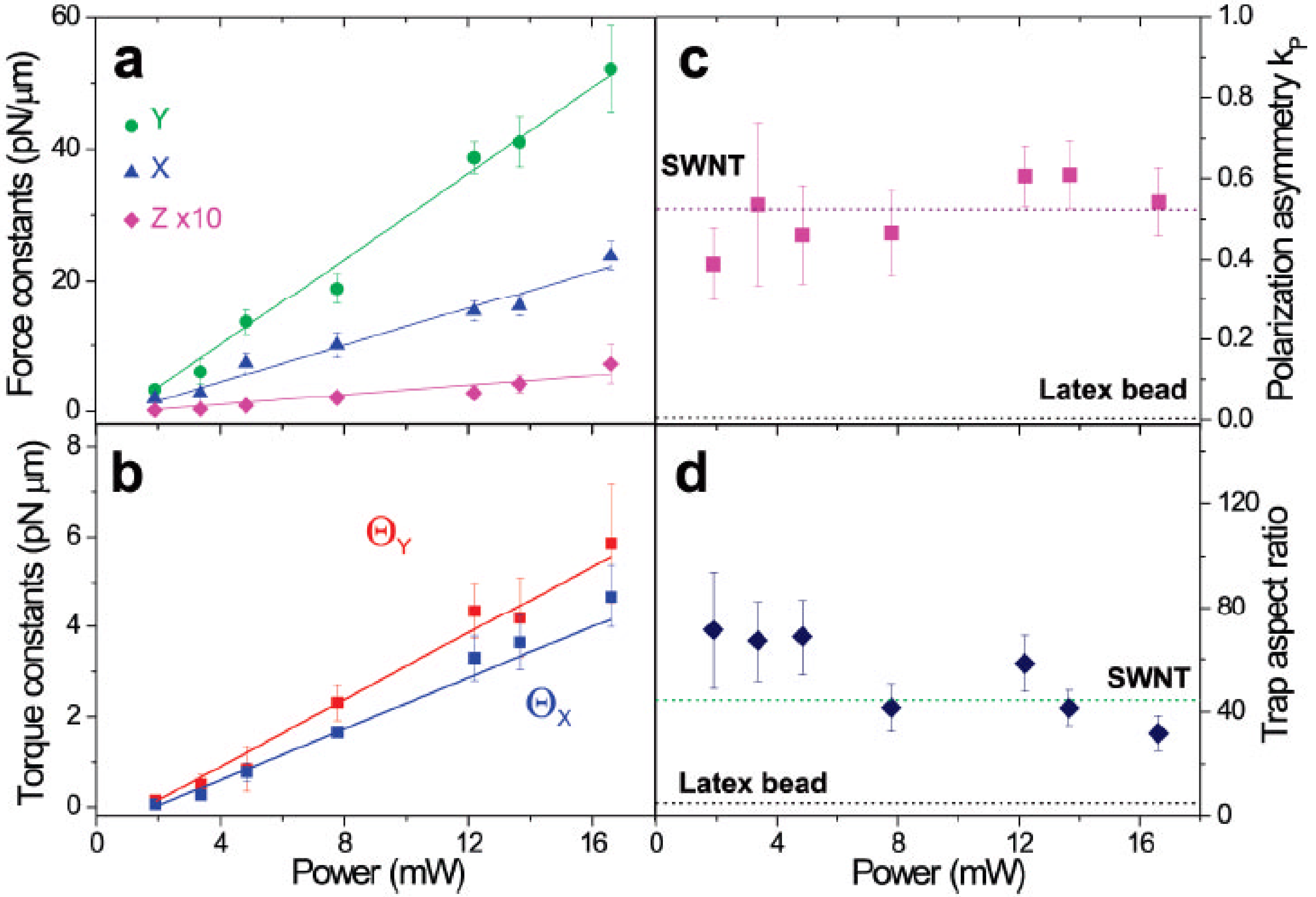


Double Exp for "fast" dynamics

Simple Exp for Z and Cross

Non-conservative forces:
Simpson&Hanna, PR E (2010)

Force and Torque Constants



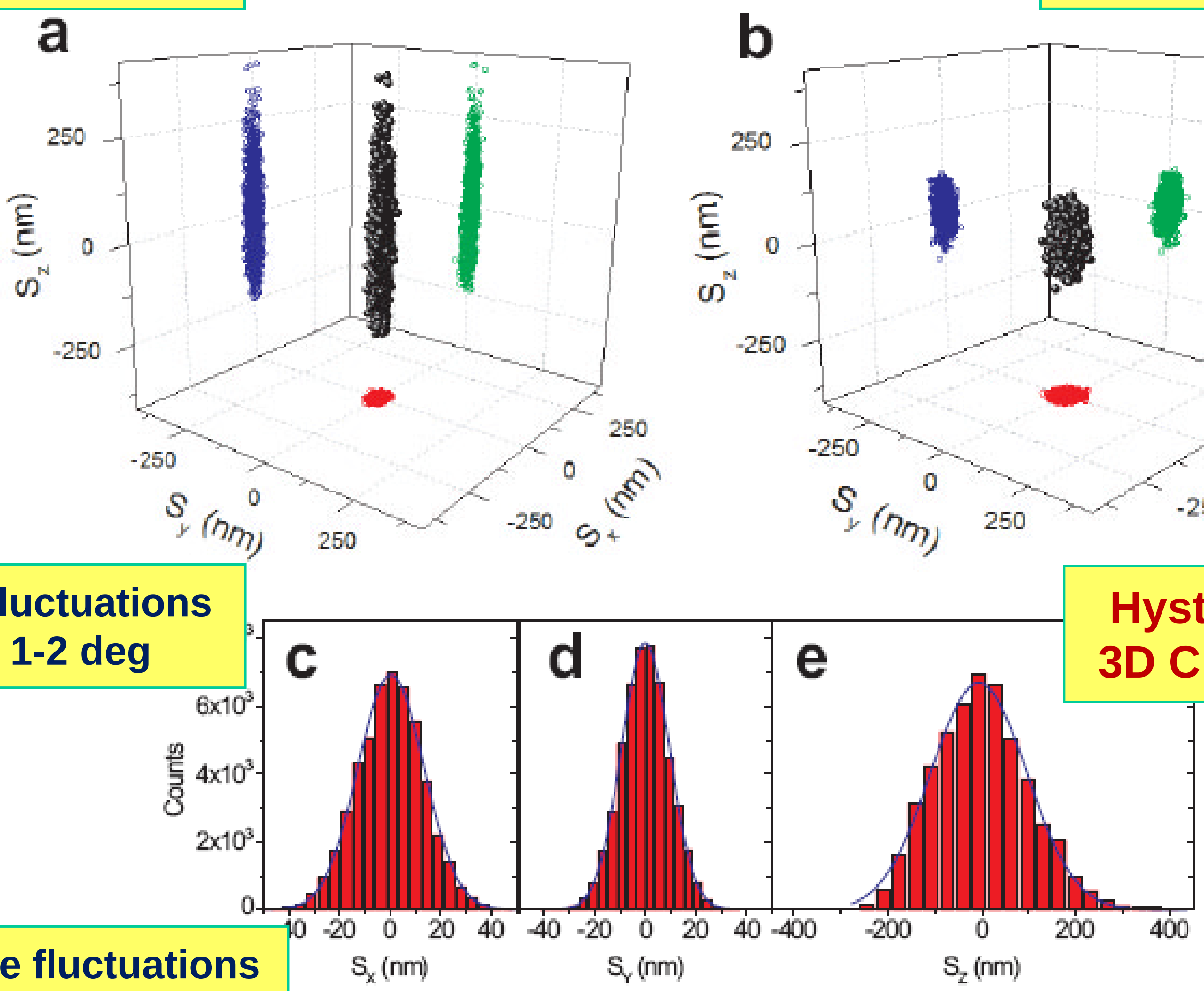
FemtoNewton Regime!

Polarization and Geometrical asimmetry are consistent with OT theory of linear nanostructures

Brownian Motion of Nanotubes

SWNT bundle

Latex Bead 2um



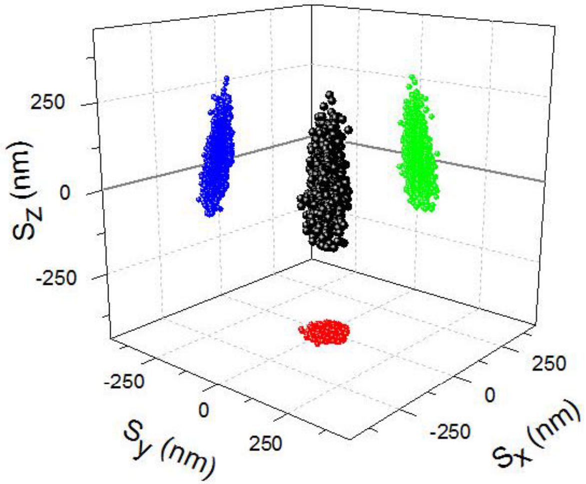
Angular fluctuations within 1-2 deg

Hystograms of 3D CNTtracking

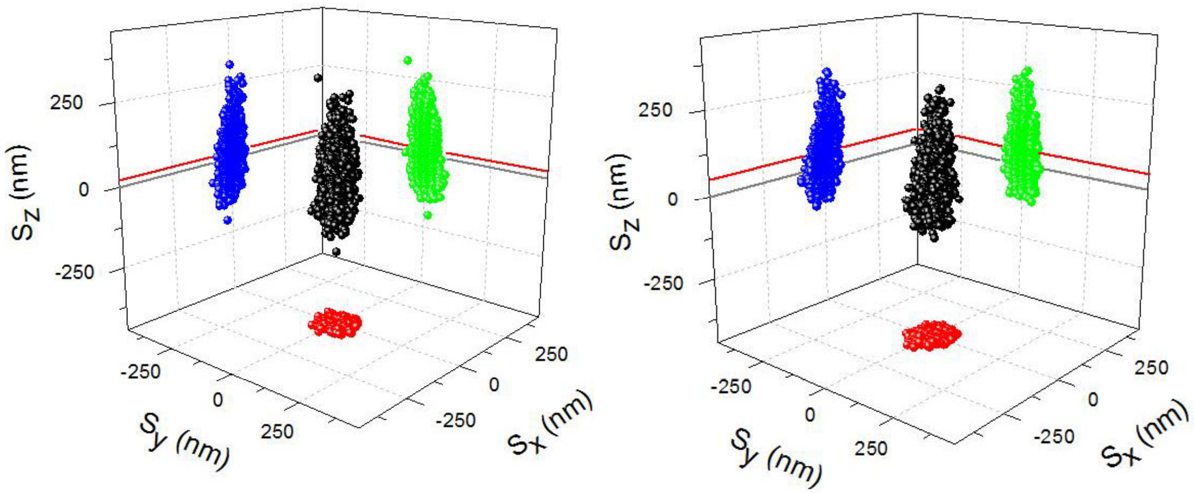
Transverse fluctuations in the 10 nm range

Force sensing blue light

Trapping with 830nm



Pushing with blue 417nm@ low power



Δz=19±2 nm	Δz=44±3 nm
$F_{blue}=k_z\Delta z$=16±3 fN	F_{blue}=45±9 fN
P_{blue}=170 μW	P_{blue}=550 μW

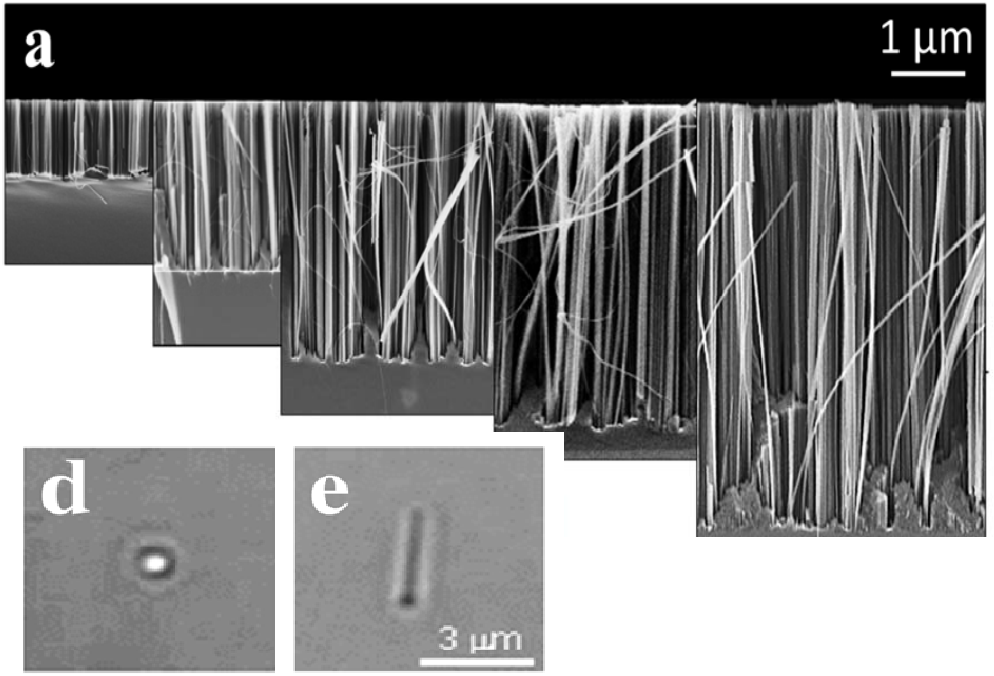
Uncertainty due to Nanotube Length

$C_{ext}=cF/nI_0$=1100±200 nm^2

FemtoNewton Regime!

OT of Silicon Nanowires

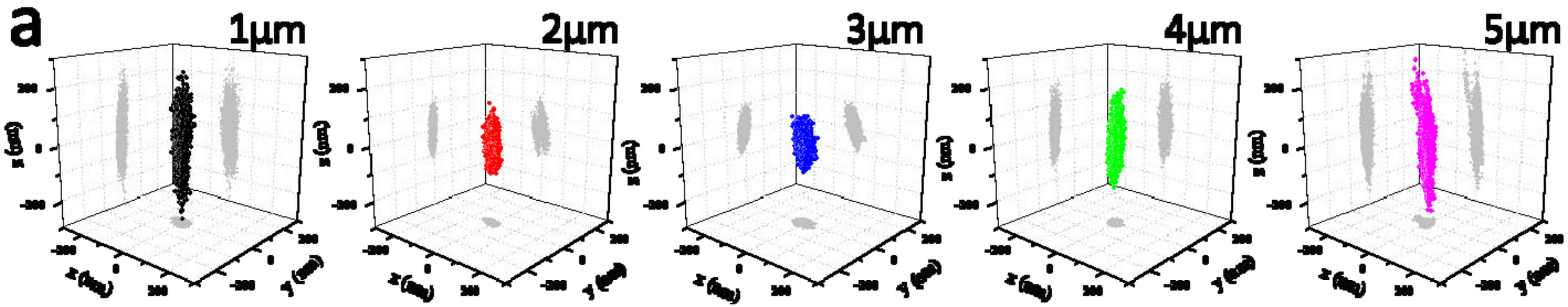
A. Irrera et al., *Nano Letters* **2011**, *11*, 4879



We can now control the length and the diameter

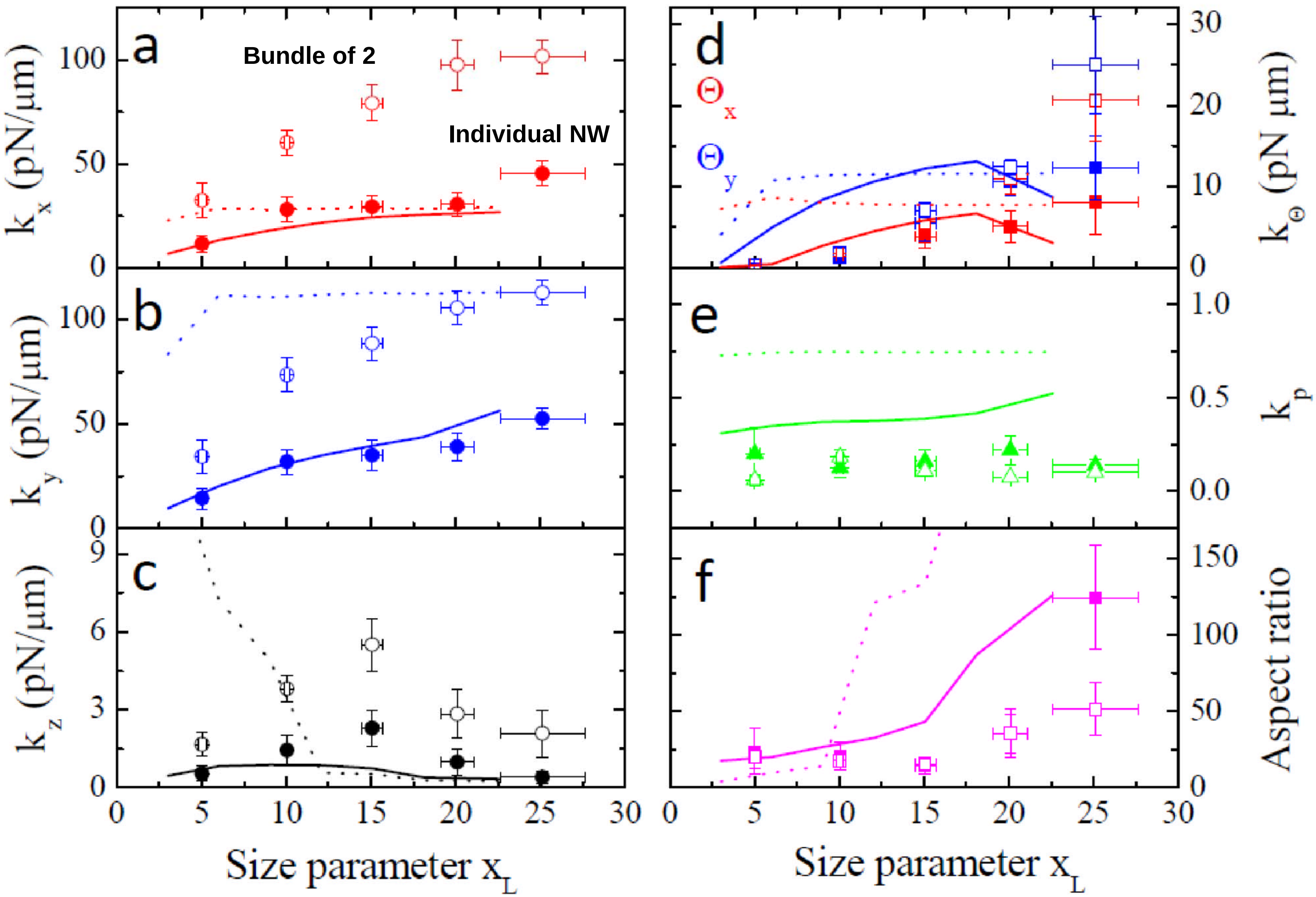
Length controls optical forces and torques

Size-scaling with the size parameter $x_L=\pi nL/\lambda$



Similar behaviour as for nanotube bundles but controlled size

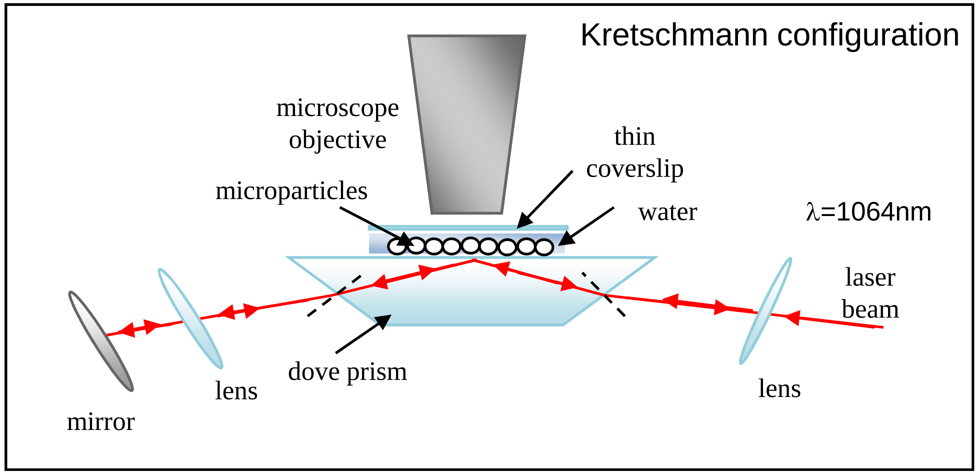
Size-scaling in OT of SiNWs

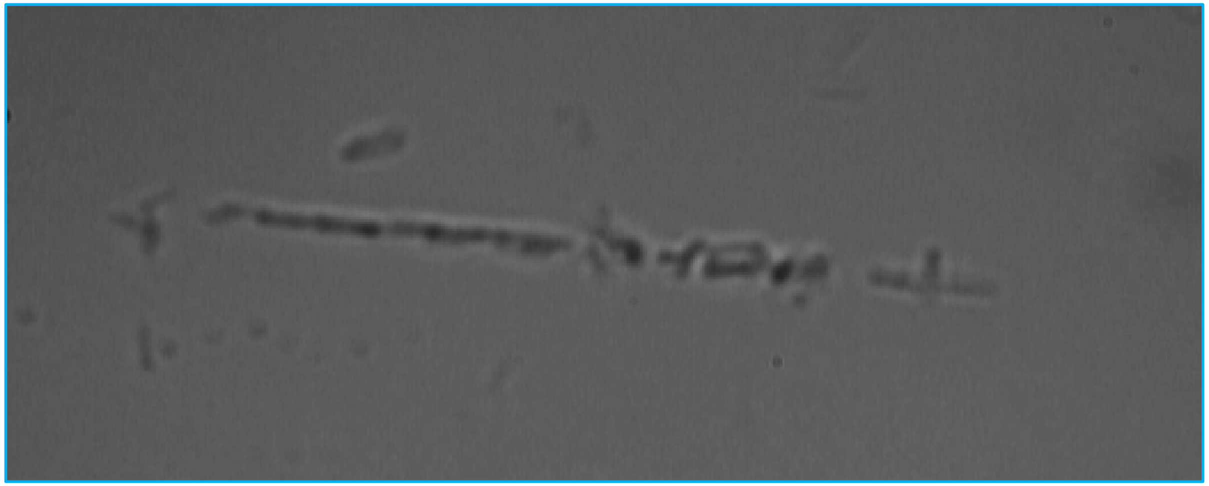


Optical Binding of Nanotubes

(Collaboration with P.H. Jones, UCL)

Optical binding forces arise in the presence of multiple particles. These particles scatter the incoming light and the scattered light induce optical forces on the nearby particles.





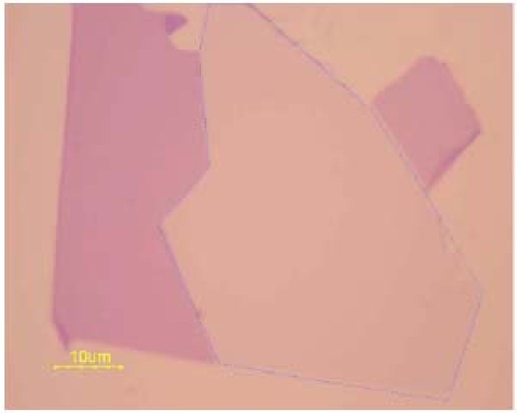
- Nanotubes align end-to-end with **k-vector** of the evanescent standing wave
- Polarization of evanescent field has no effect on alignment

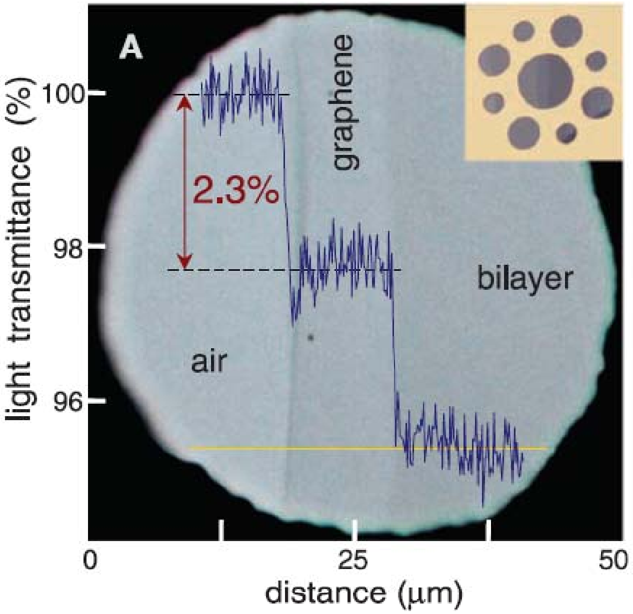
Graphene

Nobel Prize 2010!

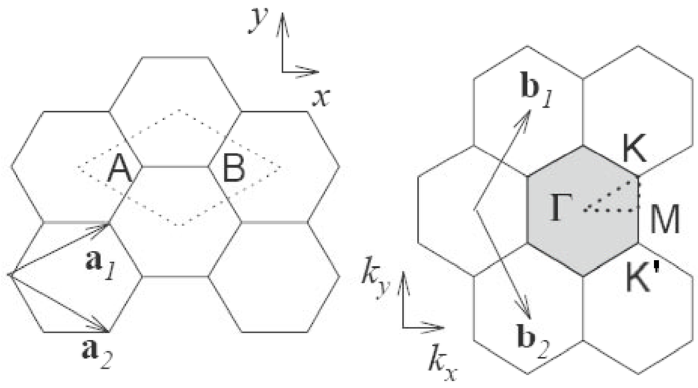
A. Geim

K. Novoselov

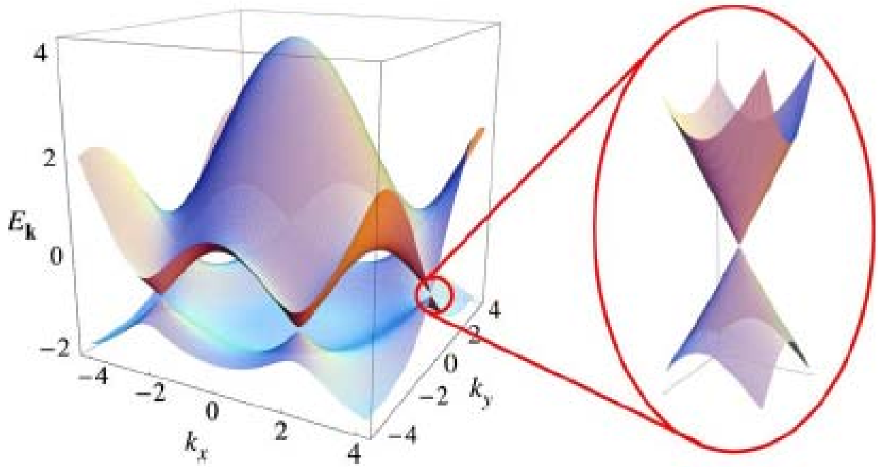




Novoselov, K. S., et al.,Science (2004)



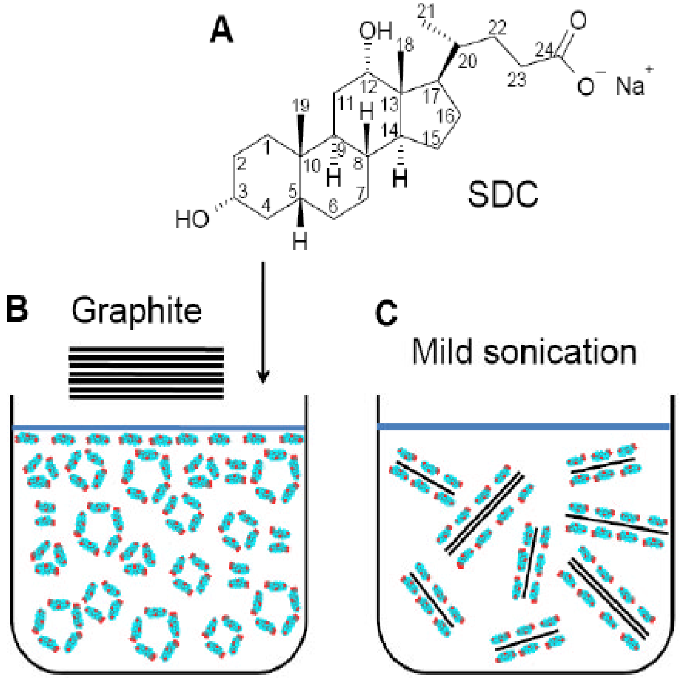
Direct lattice Brillouin zone

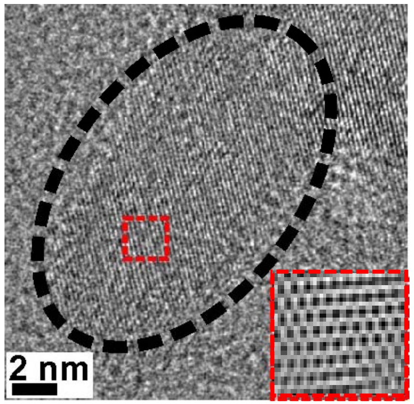


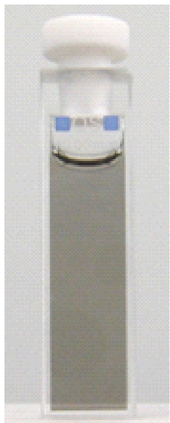
A.H. Castro-Neto et al., Rev. Mod. Phys. (2009)

Applications to Photonics: F.Bonaccorso et al., Nature Photon. (2010)

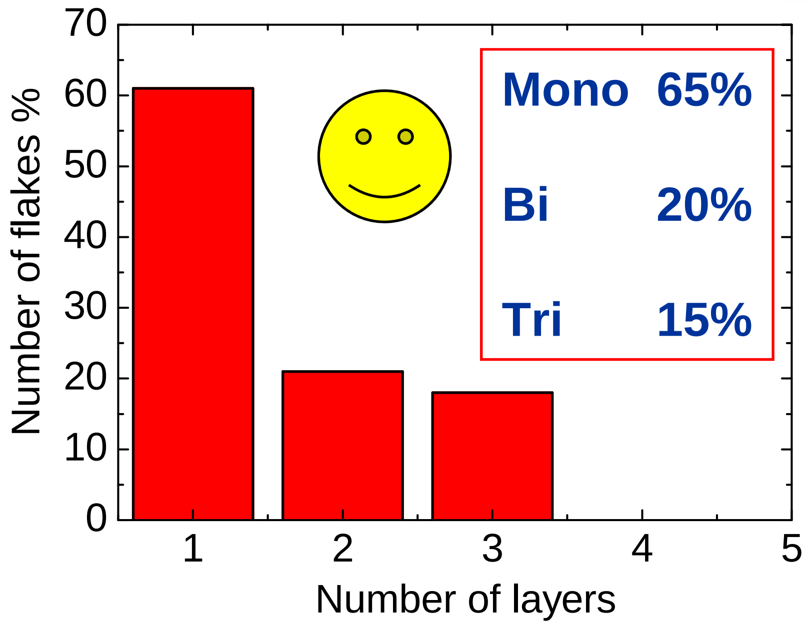
Graphene: Liquid Phase Exfoliation

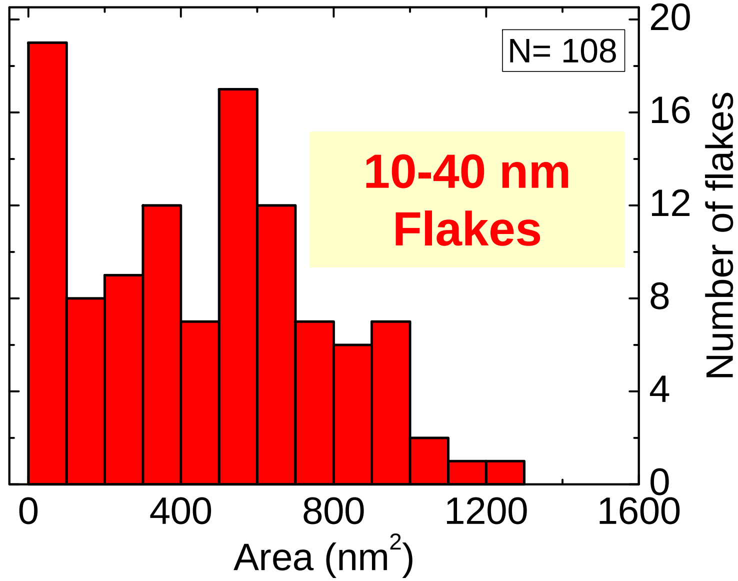






Y. Hernandez et al. Nature Nanotech. 3, 563 (2008)





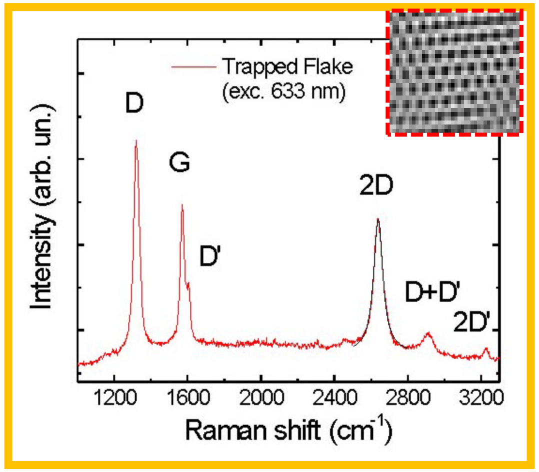
O.M. Maragò et al. ACS Nano **4**, 7515 (2010)

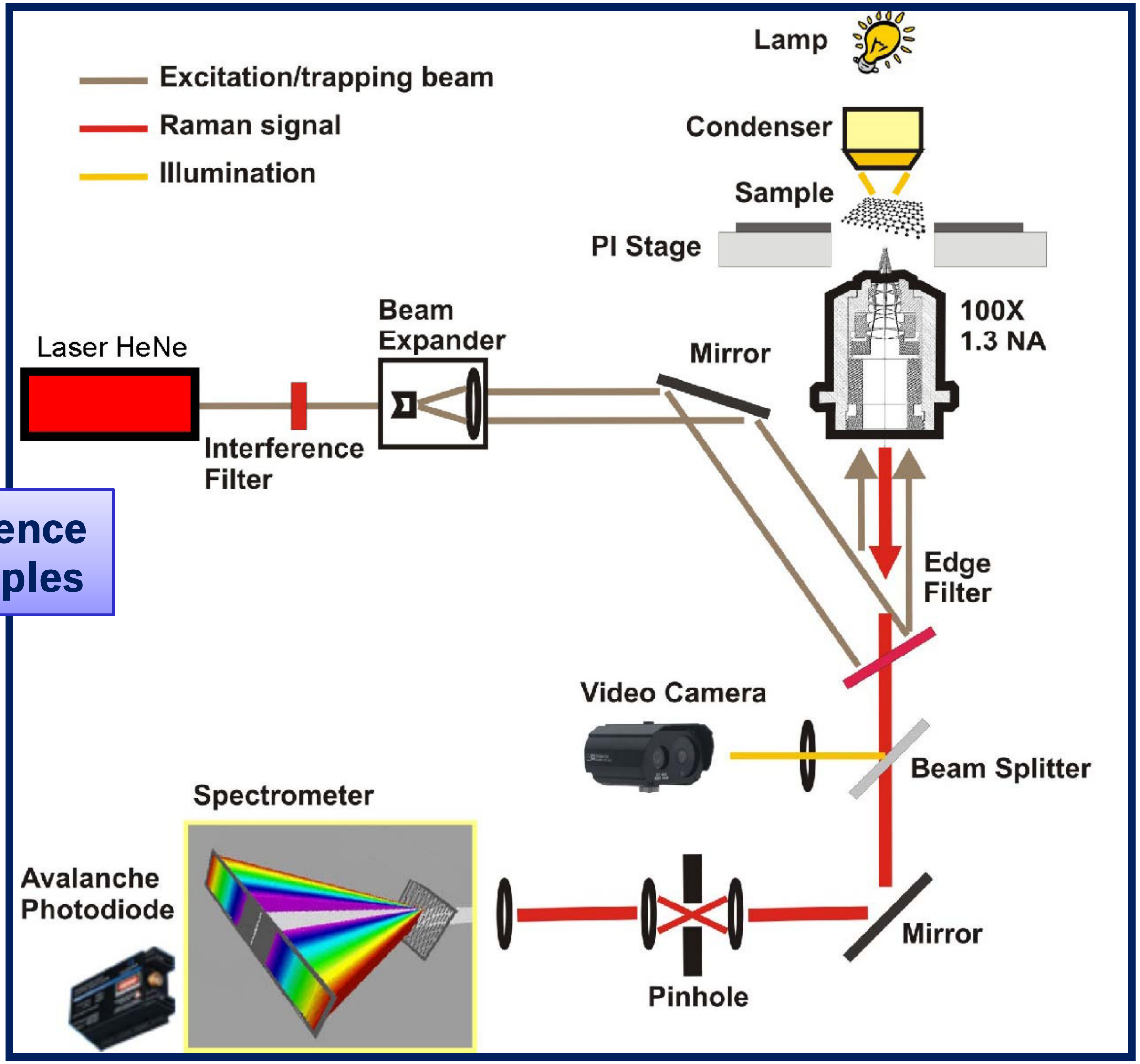
Raman Tweezers Setup

- HeNe 633nm, 10 mW
- Edge filter@633nm
- Jobin-Yvon Triax 190 spectrometer
- Avalanche photodiode, SPC (Perkin Elmer)

Raman & Photoluminescence inspection of trapped samples

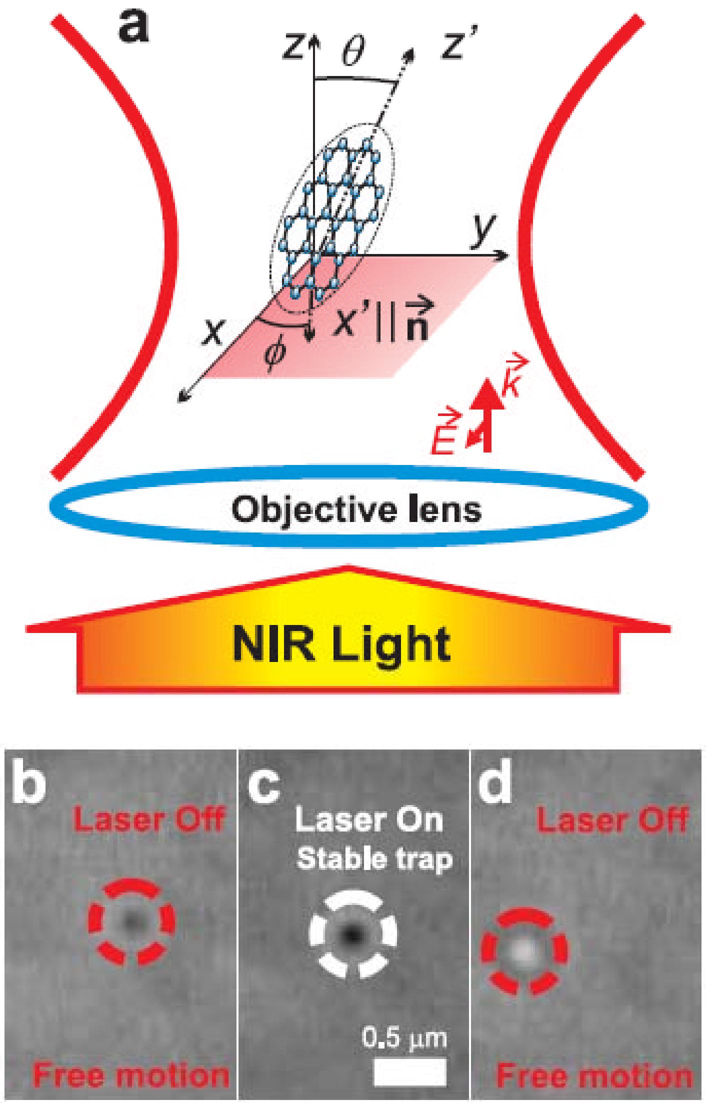
E.g., Inspection of **Graphene** flakes



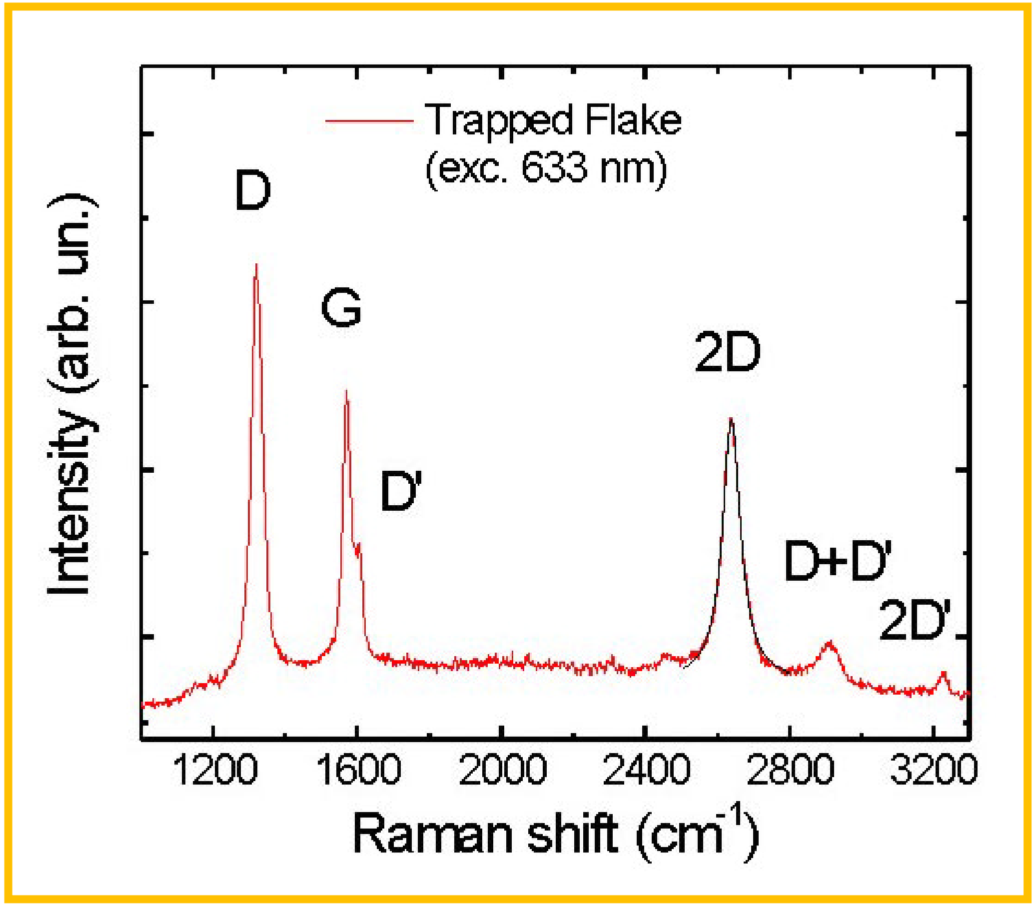


Maragò, O.M., et al.,*ACS Nano* **4**, 7515 (2010)

OT & RT of Graphene

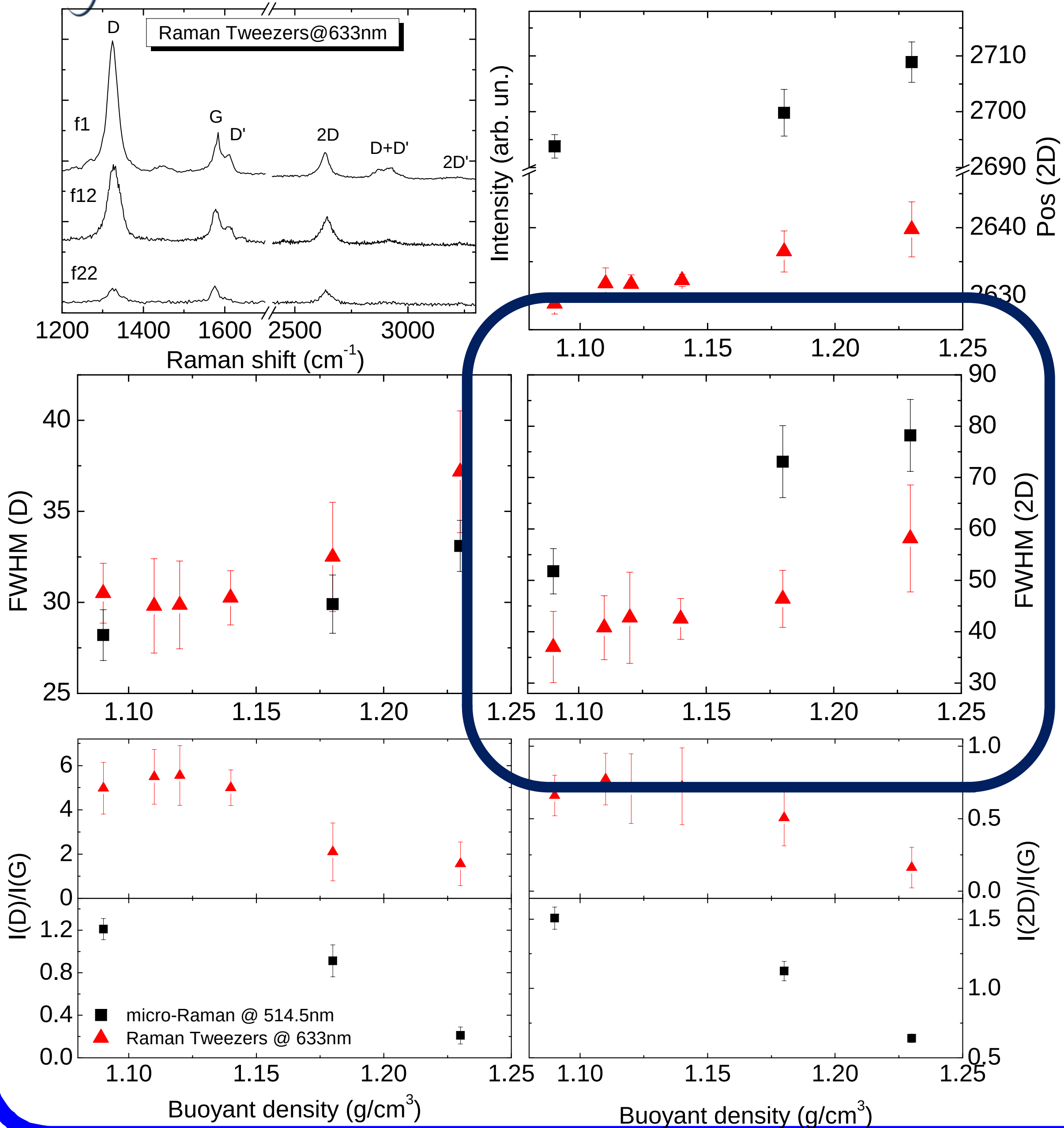


Low power (2 mW) for stable OT AND Raman@633nm



Maragò, O.M., et al.,ACS Nano (2010)

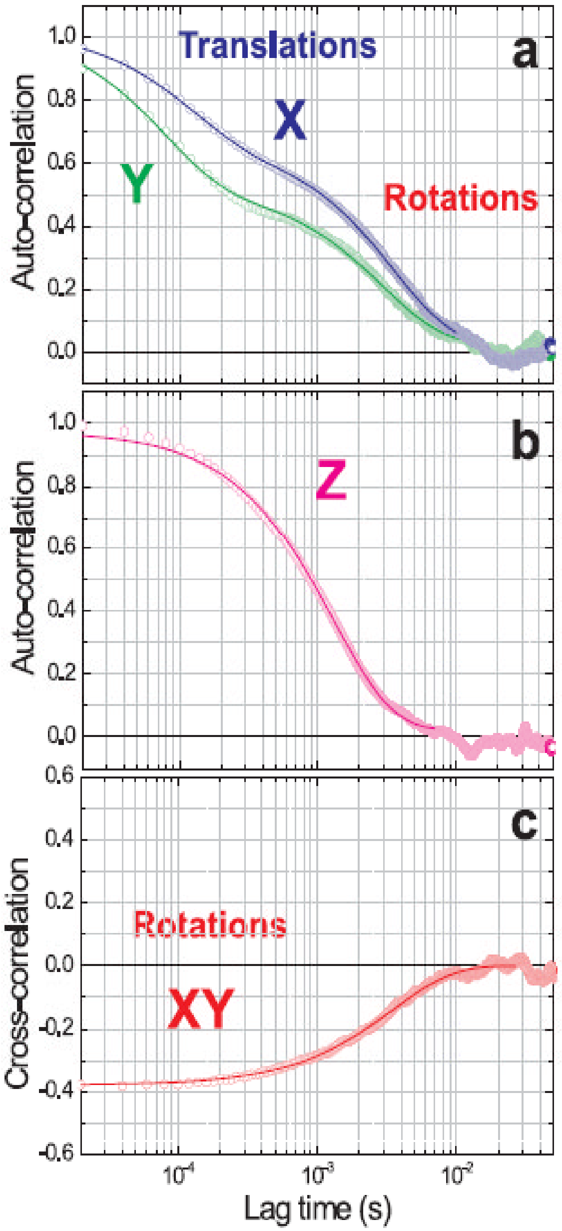
RT Spectroscopy on DGU Flakes



- We trap individual flakes and measure smaller FWHM than micro-Raman on a substrate

- Top fractions show up to 70% monolayer flakes consistent with TEM analysis

Brownian Motion of Graphene



Hydrodynamics

$$
\begin{aligned}
\gamma_{||} &= 8\eta D \\
\gamma_{\perp} &= \frac{16}{3}\eta D \\
\gamma^{r} &= \frac{4}{3}\eta D^{3}
\end{aligned}
$$

Langevin

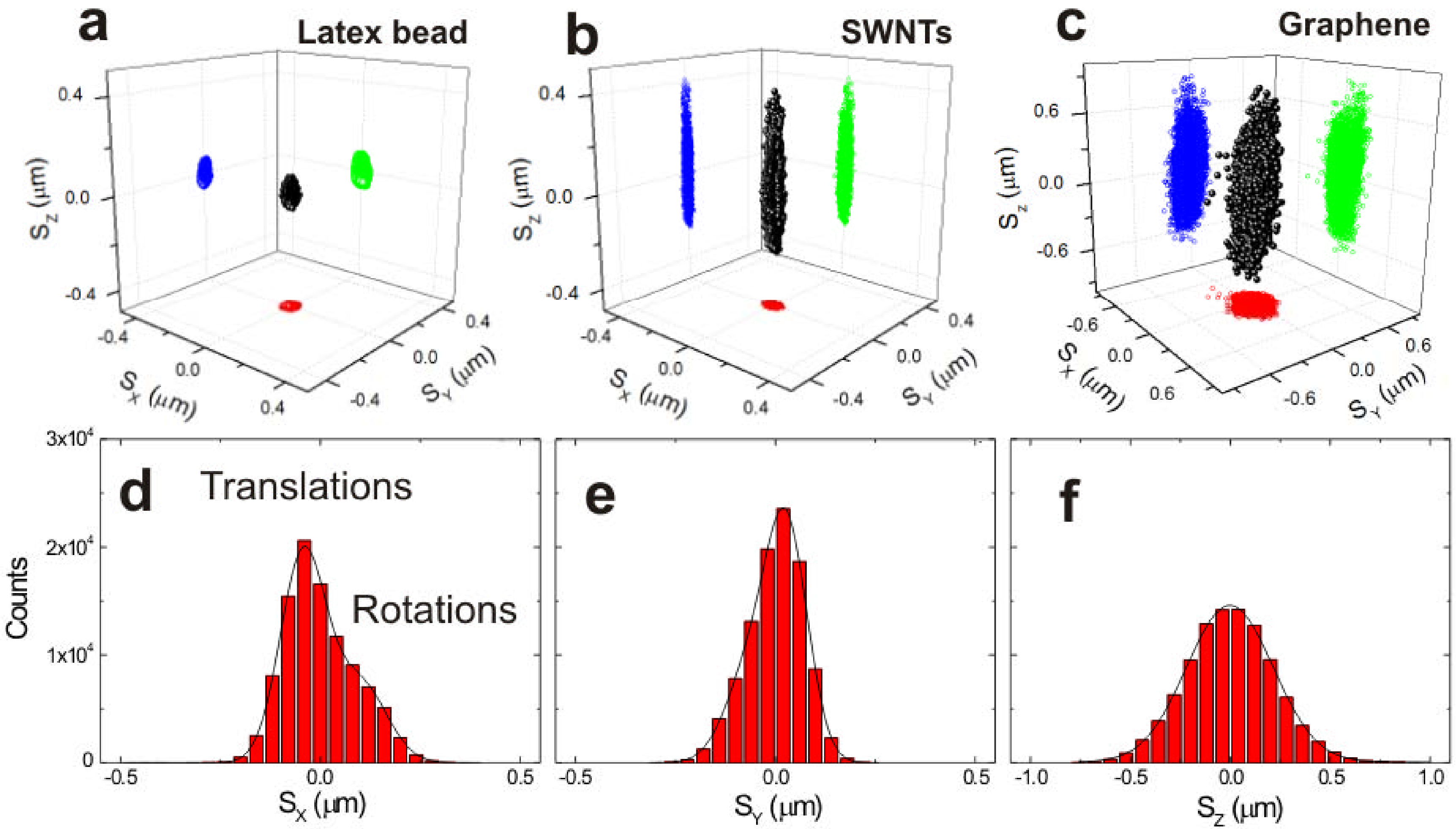
$$
\begin{aligned}
\partial_t X(t) &= -\Gamma_{\perp} k_x X(t) + \xi_x(t) \\
\partial_t Y(t) &= -\Gamma_{||} k_y Y(t) + \xi_y(t) \\
\partial_t Z(t) &= -\Gamma_{\perp} k_z Z(t) + \xi_z(t) \\
\partial_t \phi(t) &= -\Gamma^{r} k_{\phi} \phi(t) + \xi_{\phi}(t) \\
\partial_t \theta(t) &= -\Gamma^{r} k_{\theta} \theta(t) + \xi_{\theta}(t)
\end{aligned}
$$

QPD Signals and Correlations

$$
S_x \sim \beta_x \left(X - \mathrm{a}\,\phi + \mathrm{b}\,\theta\right); \; S_y \sim \beta_y \left(Y + \mathrm{c}\,\phi\right); \; S_z \sim \beta_z Z
$$

$$
\begin{aligned}
C_{xx} &\approx \beta_x^2 \left[C_{XX} + \mathrm{A}^2\, C_{\phi\phi} + \mathrm{B}^2\, C_{\theta\theta}\right] \\
C_{yy} &\approx \beta_y^2 \left[C_{YY} + \mathrm{C}^2\, C_{\phi\phi}\right] \\
C_{zz} &\approx \beta_z^2\, C_{ZZ} \\
C_{xy} &\approx -\beta_x \beta_y \mathrm{AC}\, C_{\phi\phi}
\end{aligned}
$$

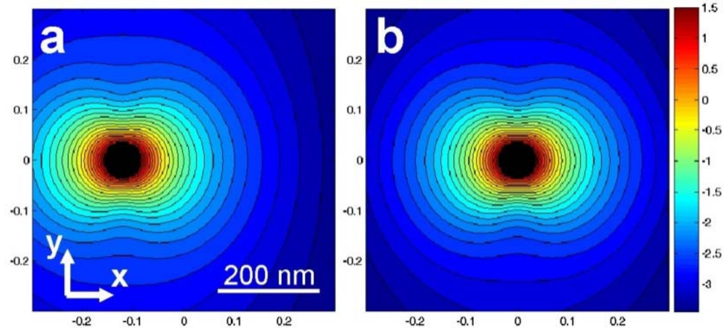
Brownian Motion of Graphene



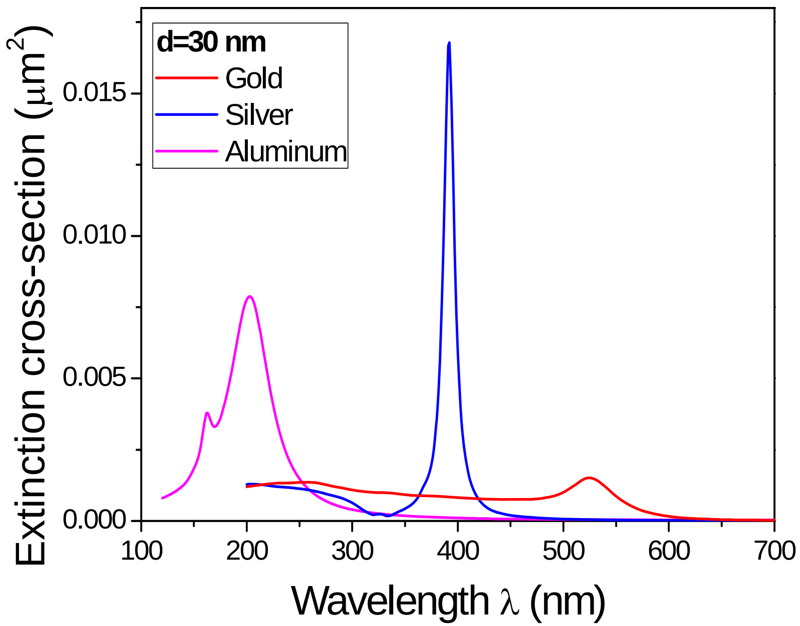
Angular fluctuations within **7 deg**
Transverse fluctuations **50 nm**
Axial fluctuations **200 nm**

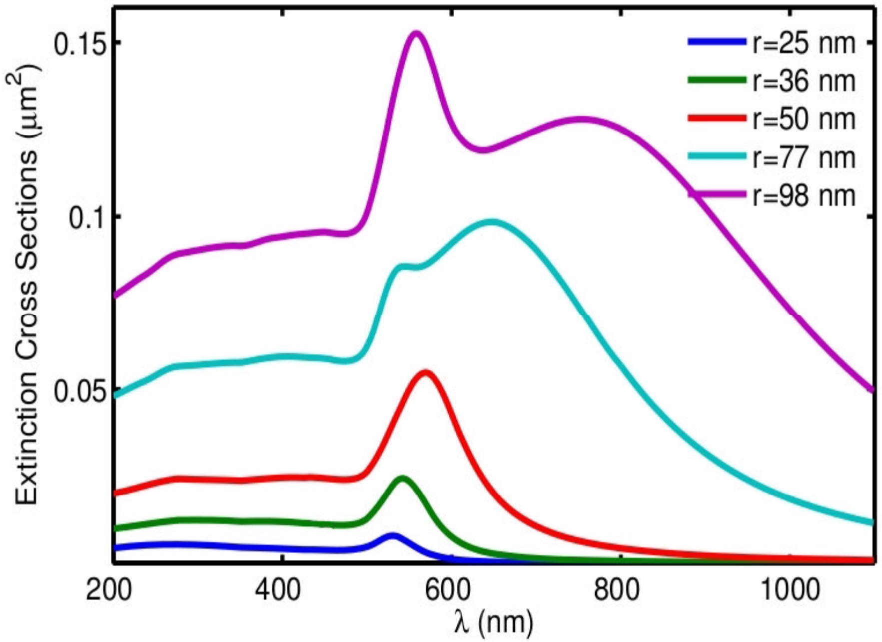
Torque **6 fN nm/rad**
Transverse Force **1.5 pN/μm**
Axial Force **0.1 pN/μm**

Plasmon-enhanced Optical Trapping (1)



For **metal nanoparticles**, the presence of **plasmon resonances** leads to their optical trapping with a wavelength in the **red side** of the spectrum.





Saija R et al. Optics Express (2009)

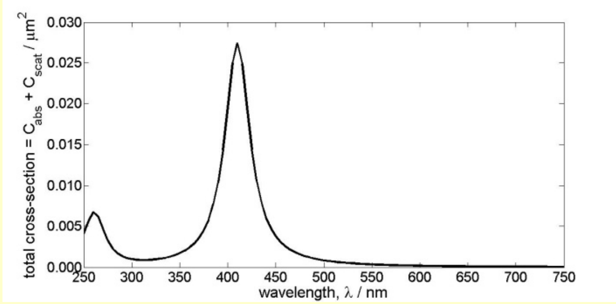
Plasmon-enhanced Optical Trapping (2)

Lorentz-Drude model for dielectric constant using tabulated fit parameters that agrees well with experimental data and exploit plasmon resonance to enhance optical forces

$$\varepsilon(\omega) = \varepsilon_\infty + \sum_{k=1}^{K} \frac{f_k \omega_p^2}{\omega_k^2 - \omega^2 + i\omega\Gamma_k}$$

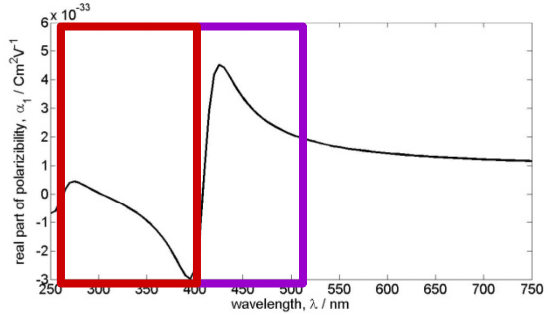
$$\boxed{\alpha(\omega) = 4\pi\varepsilon_0 a^3 \frac{\varepsilon_1(\omega) - \varepsilon_2}{\varepsilon_1(\omega) + 2\varepsilon_2}}$$

$$C_{abs} = \frac{k}{\varepsilon_0} \mathrm{Im}\{\alpha(\omega)\}; \quad C_{scat} = \frac{k^4}{6\pi\varepsilon_0^2} |\alpha(\omega)|^2$$

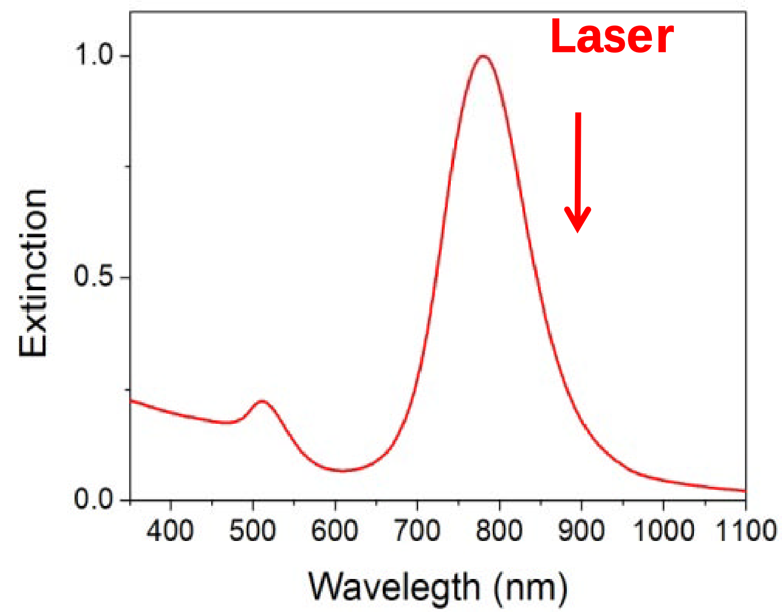


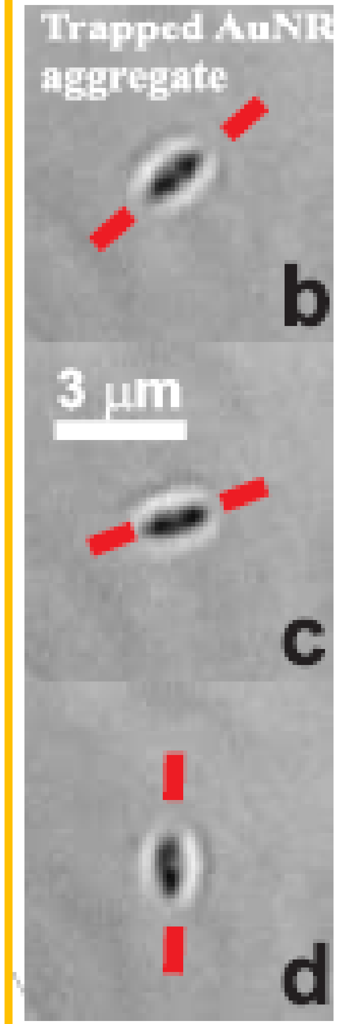
$$F_{scat.}(r) = \frac{k^4 \alpha^2}{6\pi c n^3 \varepsilon_0^2} I(r)$$

$$\langle F_{grad} \rangle = \tfrac{1}{2} \mathrm{Re}\{\alpha(\omega)\} \nabla \langle |E|^2 \rangle$$



Polarization Orientation of Nanorods (Shape Matters!)



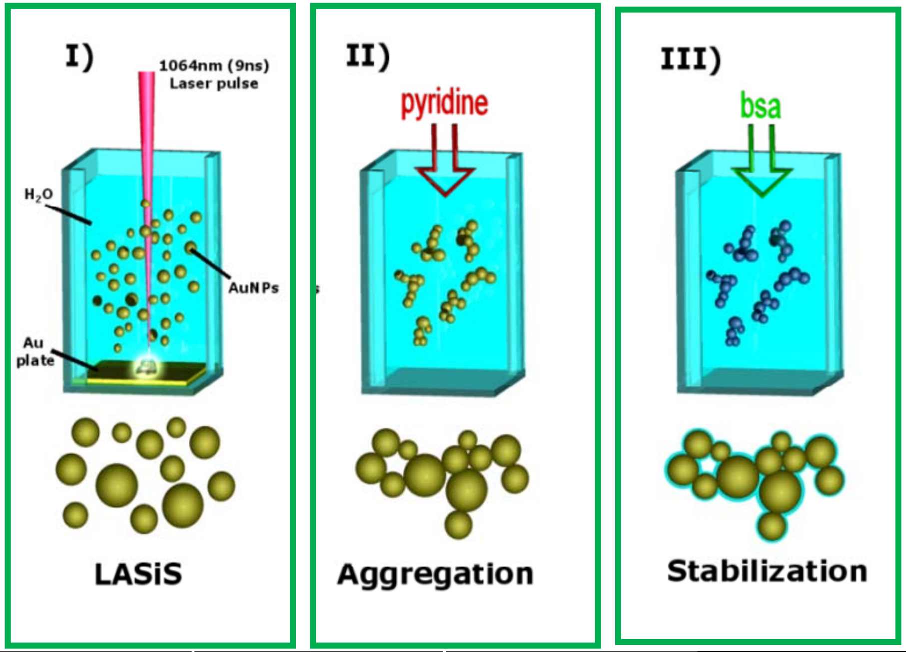


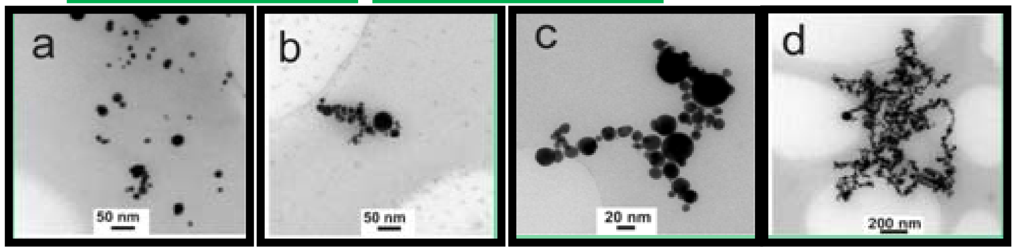
Gold Nanorods align with polarization in the trap and they can be easily rotated.

Jones et al., *ACS Nano* **(2009)** *3*, 3077–3084

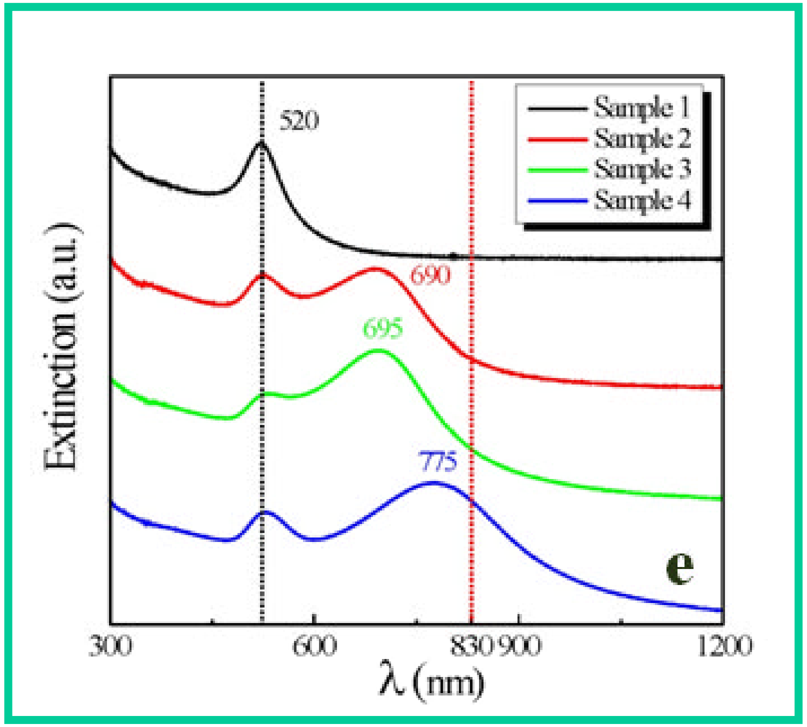
OT of Au NanoAggregates

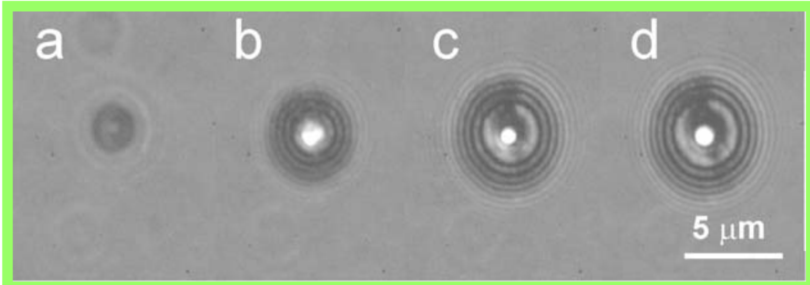
LASiS





Messina et al., *ACS Nano* 5, 905 (2011)

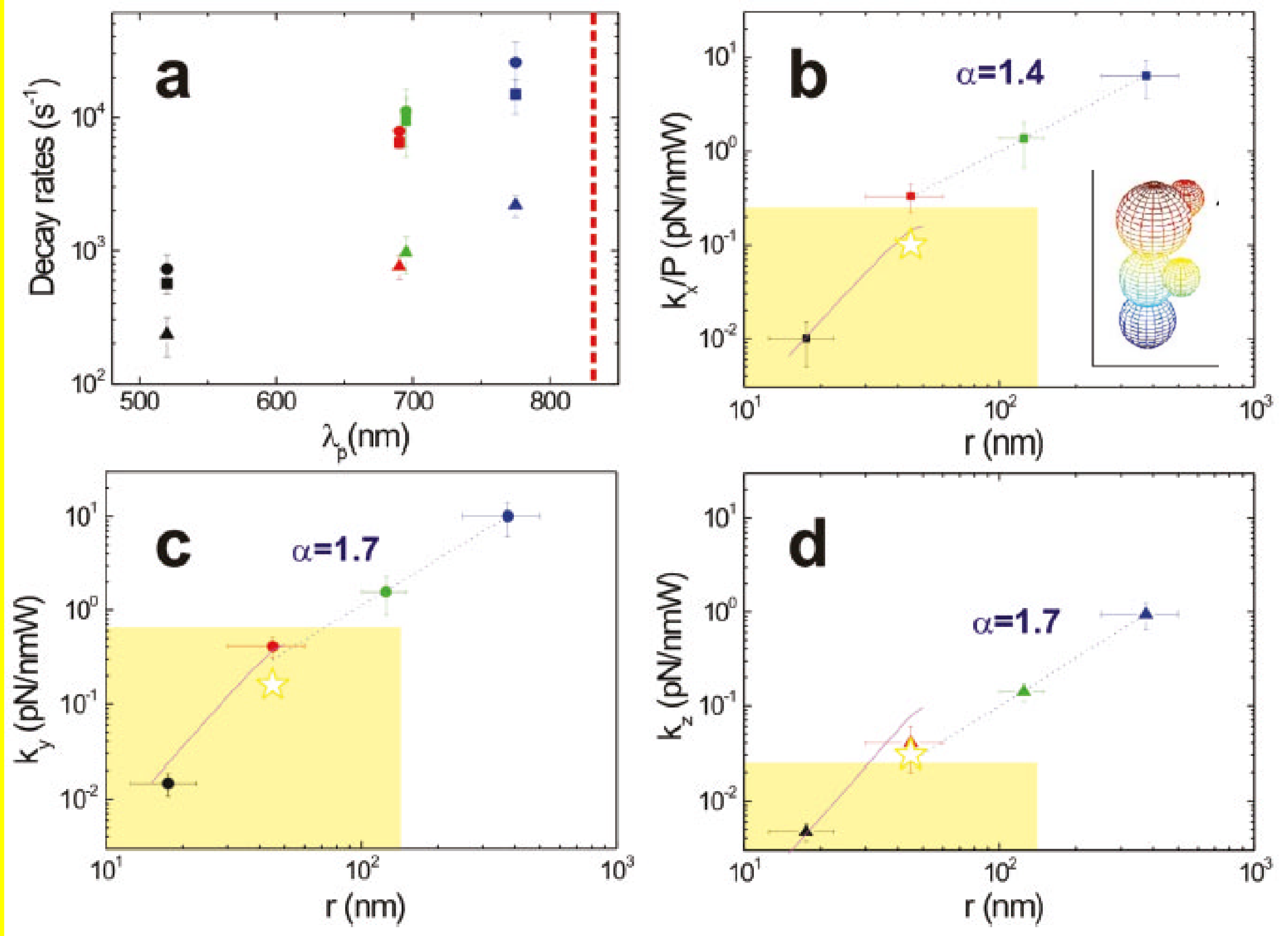




Also used for **Magneto-Plasmonic** (Au-Fe) Nanostructures!

Enhanced Forces on Aggregates

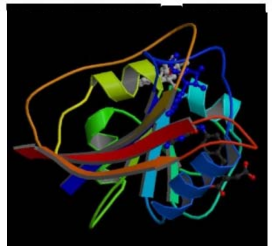
Messina et al., *ACS Nano* 5, 905 (2011)



Force on a sphere has volumetric scaling, while for an **Aggregate Scaling** reflects its **Fractal** structure

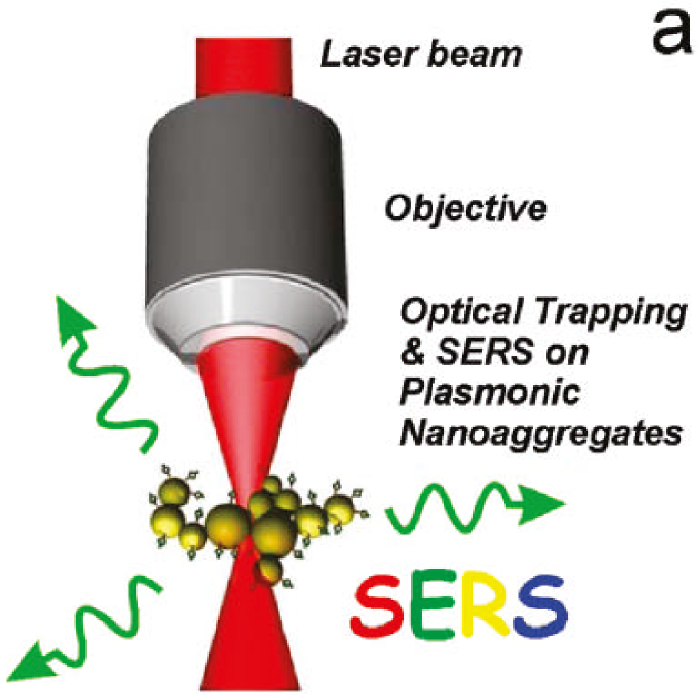
Surface-Enhanced Raman Tweezers

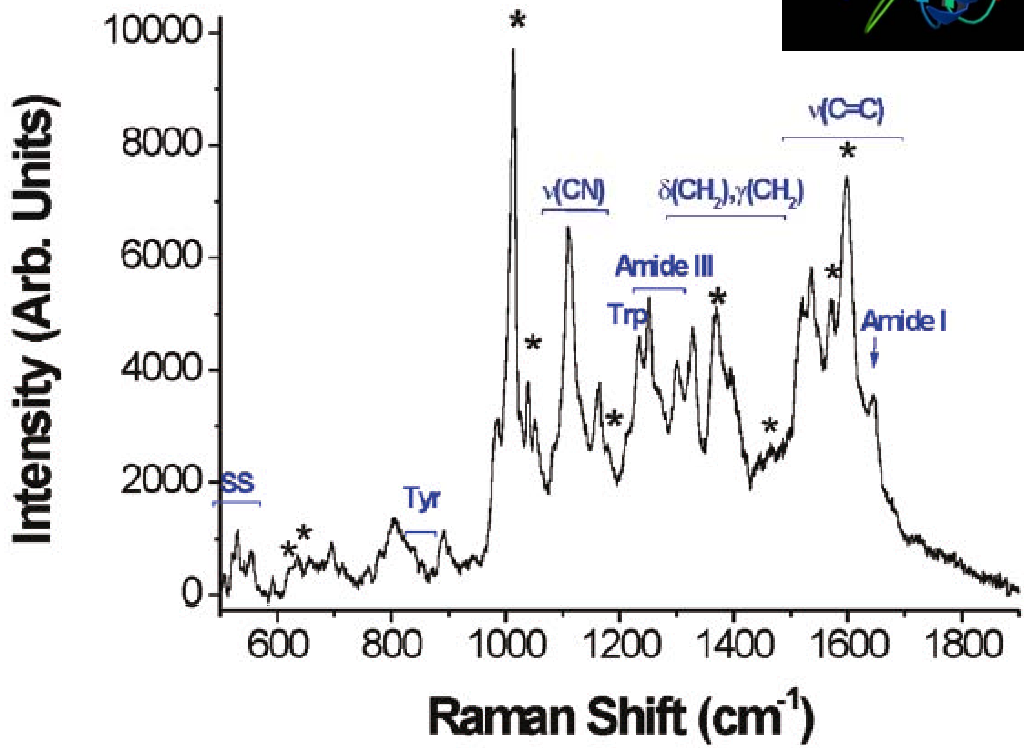
BOVINE SERUM ALBUMIN (BSA)



Use the SAME light to trap and excite SERS

Trapping wavelength 785nm > 695nm MNP Aggregate SPR

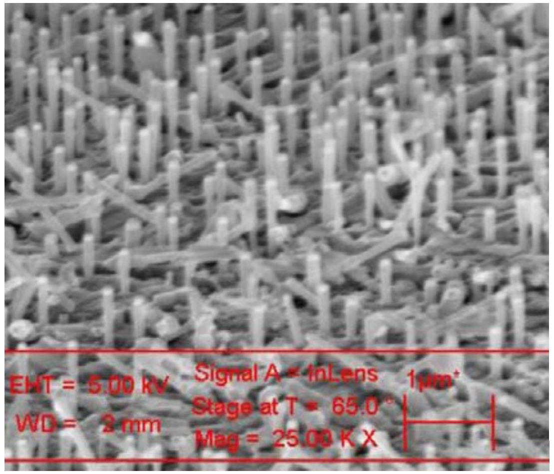


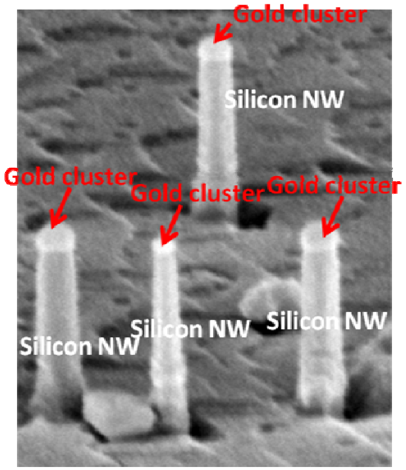


Messina et al., *J Phys Chem C* 115, 5115 (2011)

Active Plasmonic Nanoswimmers

Collaboration with F. Priolo (Catania) & G. Volpe (Bilkent)



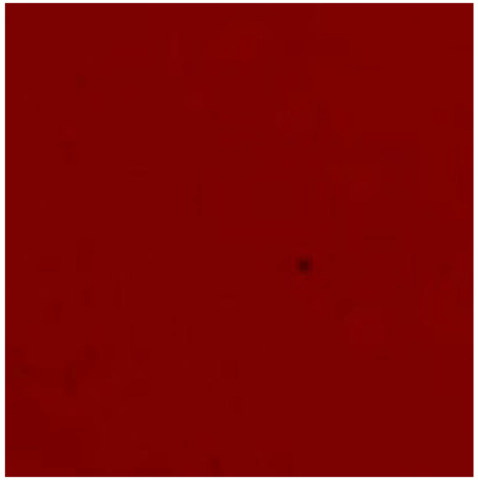


Si Nanowires with a Gold NP
Length=800 nm
Width= 100 nm

Interesting for optical trapping, probing, spectroscopy, …

Green Laser off
Sad nanoswimmer!

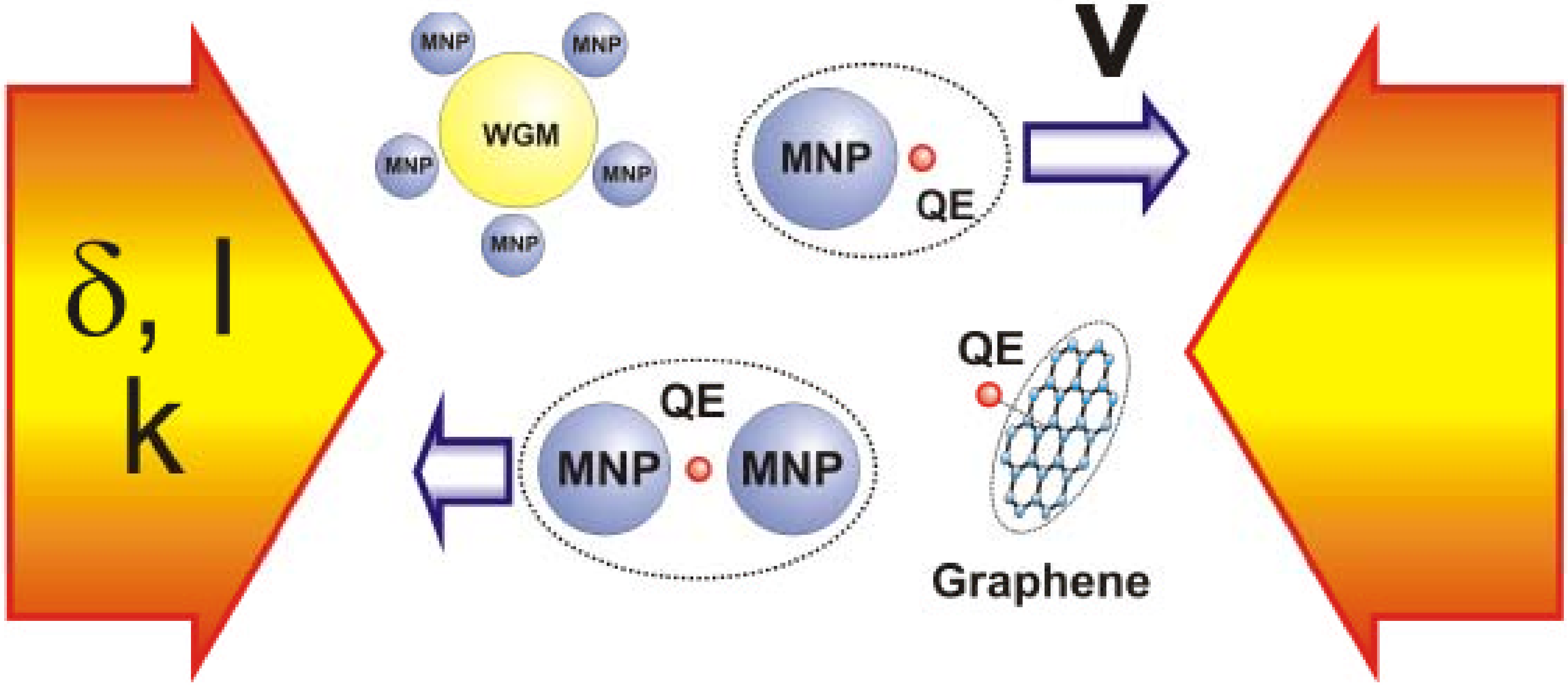
Green Laser on
Happy nanoswimmer!



Tunable & Directional Brownian Motion

Self-Diffusionphoresis in a critical mixture

Can we apply Laser Cooling to Nanostructures?

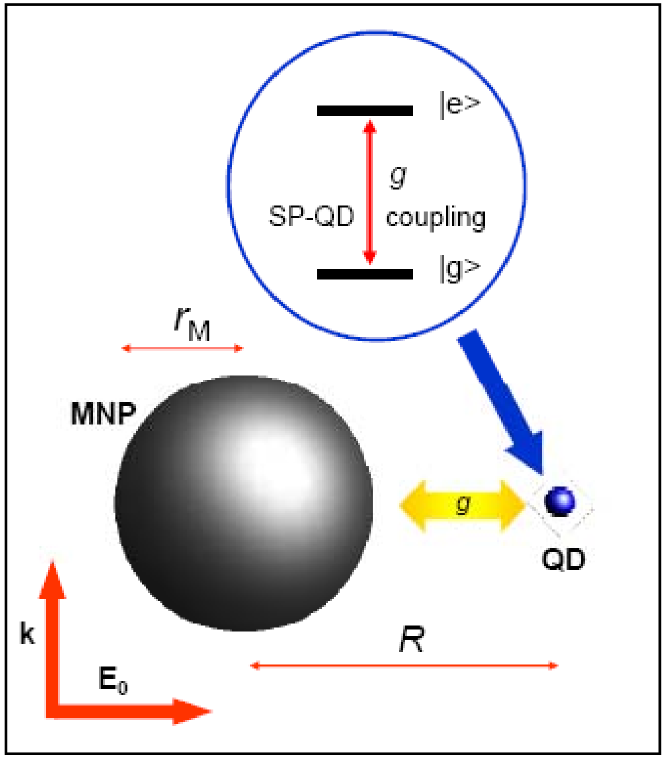


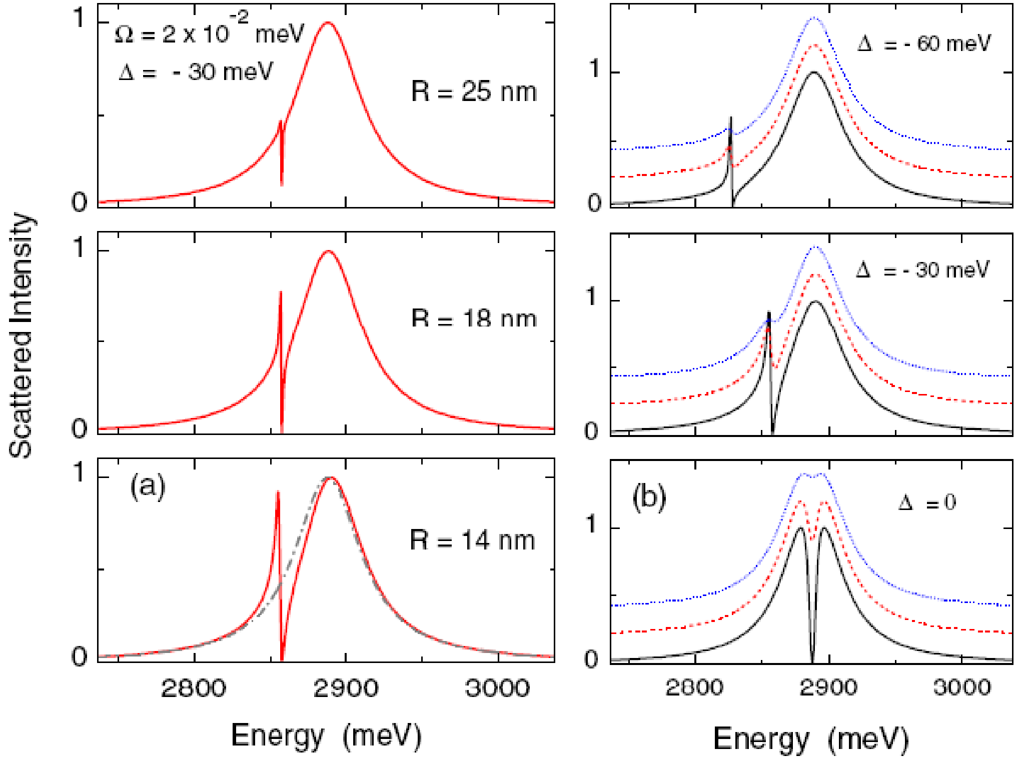
Hybdridization of Nanostructures plays a crucial role in getting Quantum resonances that can help the Laser Cooling.

A. Ridolfo, et al. *ACS Nano* **2011,** *5,* 7354

Quantum Plasmonics: Quantum Interference in the Continuum

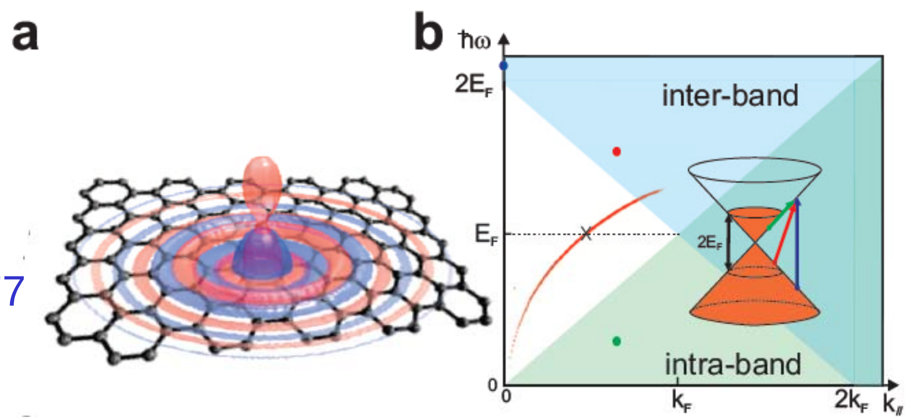
A. Ridolfo et al., PRL (2010);
S. Savasta et al., ACS Nano (2010)





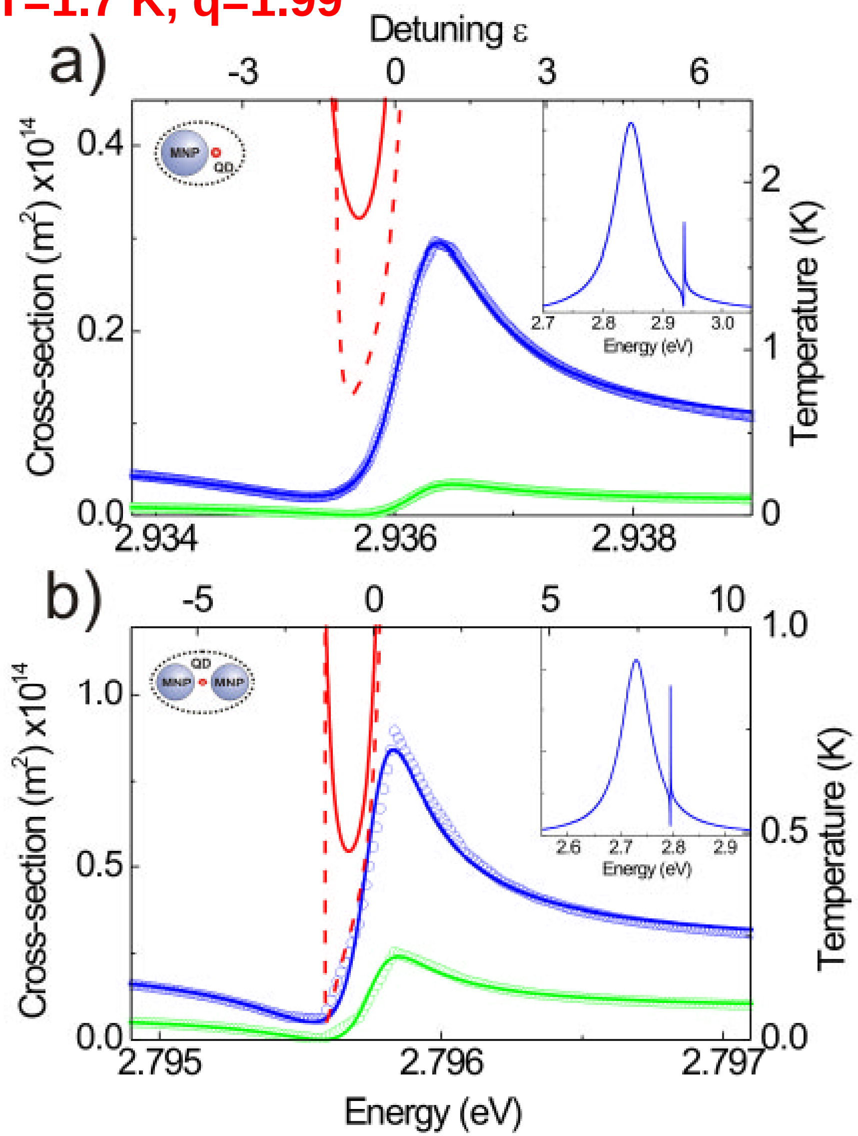
The MNP-QD molecule is a saturable scatterer

Koppens et al., *Nano Lett.*, **2011**, *11*, 3370–3377



Sub-Doppler Temperature

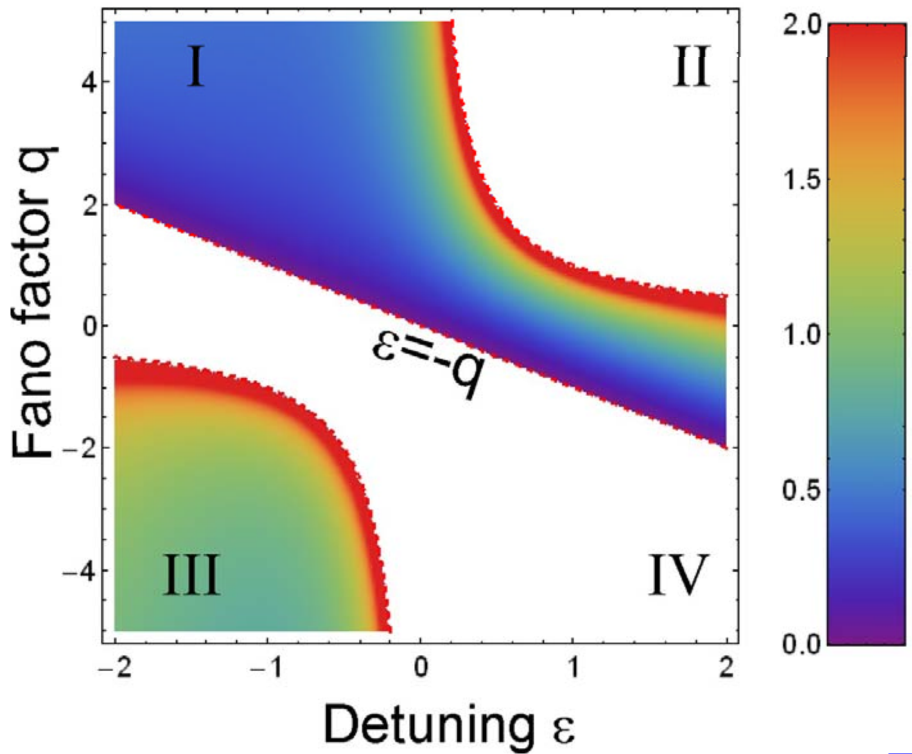
T=1.7 K, q=1.99



T=450 mK, q=1.71

Temperature from the diffusion process in momentum space. Balance between cooling and scattering processes.

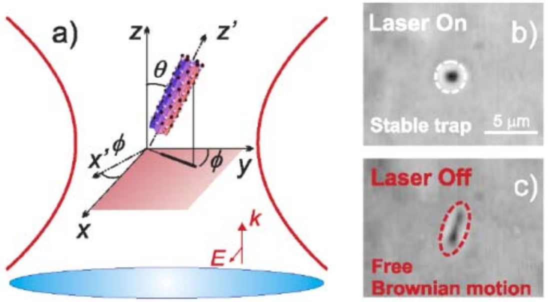
$$\frac{T_F}{T_D} = \frac{(q+\epsilon)\,(\epsilon^2+1)}{2\,(1-\epsilon q)}$$



Conclusions

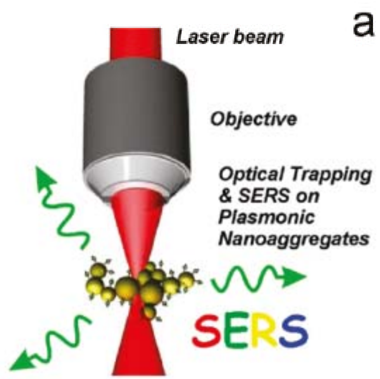
Optical Trapping of Linear Nanostructures (Nanotubes & Nanowires)

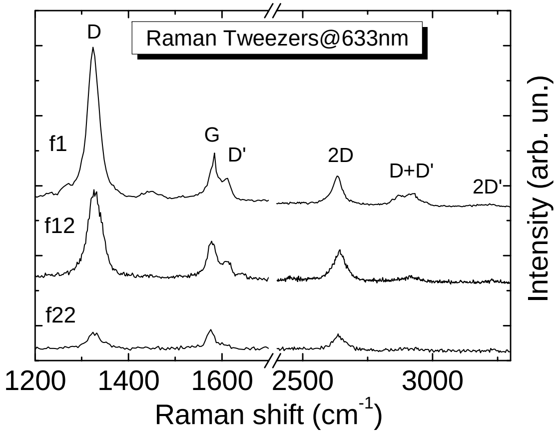
- Brownian Motion – Role of 1D Geometry
- Force Sensing with Nanotubes (Nanotube-PFM)
- Raman & PL Tweezers (Individual bundle spectroscopy)
- Size-Scaling in OT of Linear Nanostructures



Plasmon-enhanced Optical Trapping of MNPs

- Measure of Optical Forces & Rotations
- Force Calculations and Scaling Laws
- SERS with Trapped Nanoaggregates

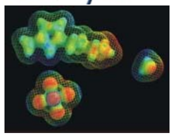




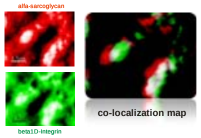
Optical Trapping of Graphene

- Brownian Motion – Role of 2D Geometry
- Light forces on Graphene flakes
- Raman Tweezers (Individual flake spectroscopy)

Acknowledgements



NanoSoftLab



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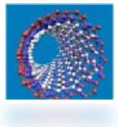
E. Messina (Post-doc)

C. D'Andrea (PhD), **A. Foti** (Diploma)



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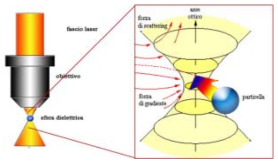
A. Cacciola (PhD, Theory)

A. Irrera (Nanostructured Semiconductors)

O. M. Maragò (Optical Trapping)

M. Monaca & R. Sayed (PhD)

S. Vasi & R. Stornante (Diploma)



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S. Savasta (UniMessina, Quantum Optics Theory)

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F. Priolo
G. Compagnini

G. Volpe

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THE ROYAL SOCIETY

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Thank You!!!