Oct. 22, 2021

Bio-integrated Materials Science (Online Lectures)

Bio-integrated Metallic Nanomaterials

Lecture 7

Prof. Jung Heon Lee

Metals in Periodic Table

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

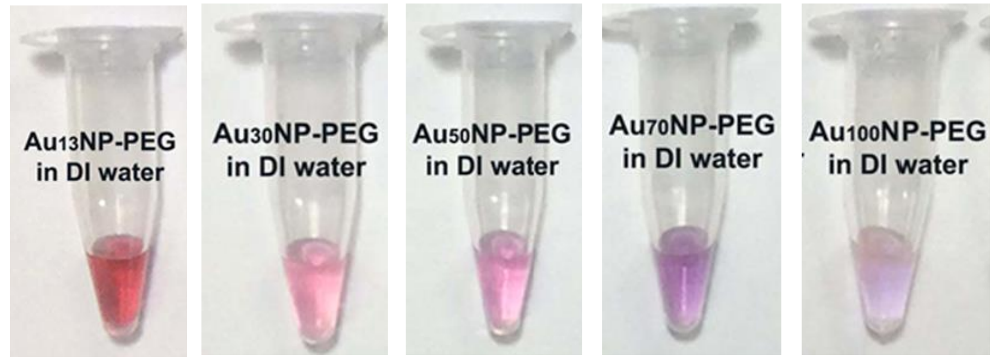
*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
**Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Gold in nanoscale

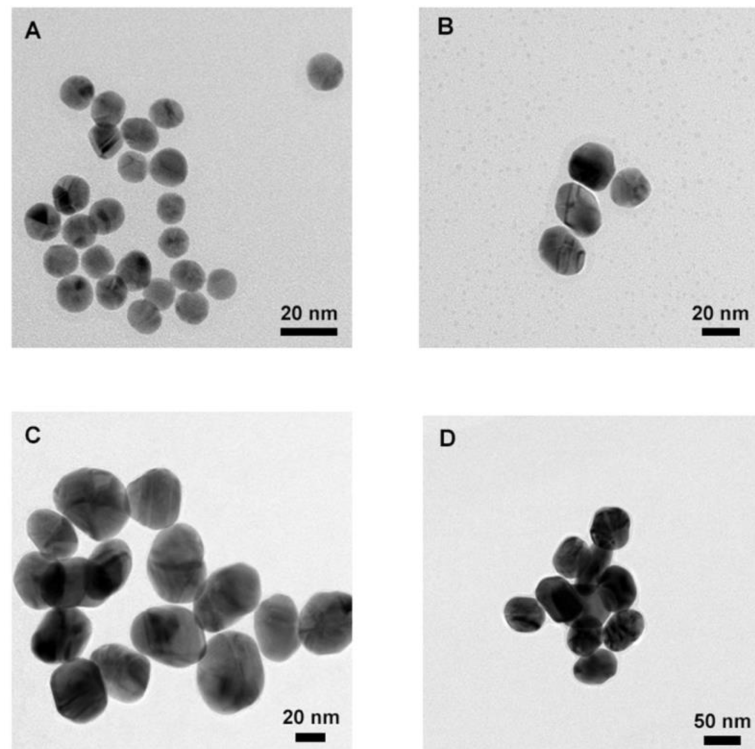
Bulk Gold

- Atomic number 79
- Electron rich
- Chemically inert
- Stable (noncorrosive)
- Great biological compatibility
- Low toxicity
- $$

Nano size →



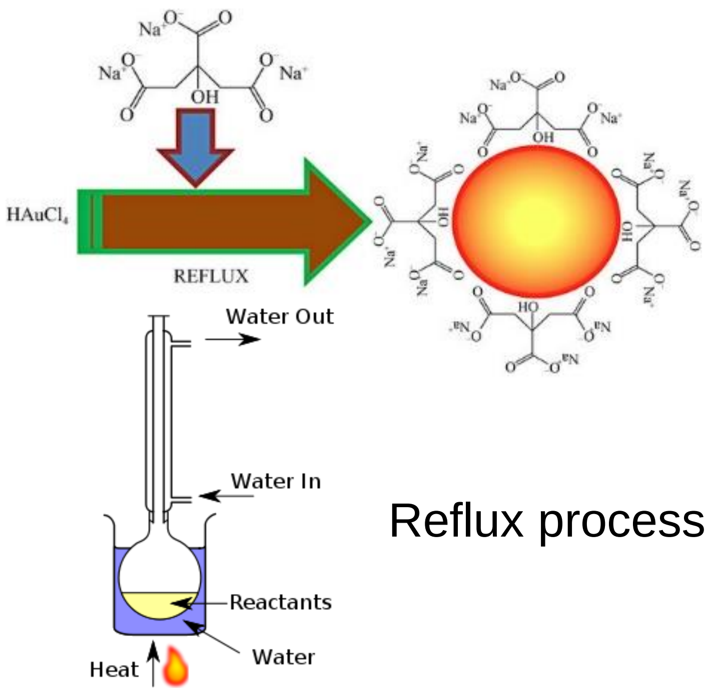
Gold nanoparticles



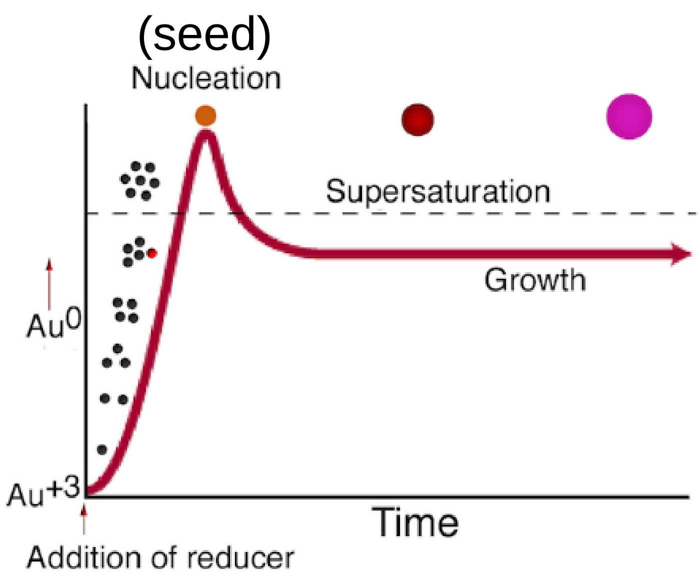
Langmuir, **2015**, 31, 13773

Synthesis of gold nanoparticles

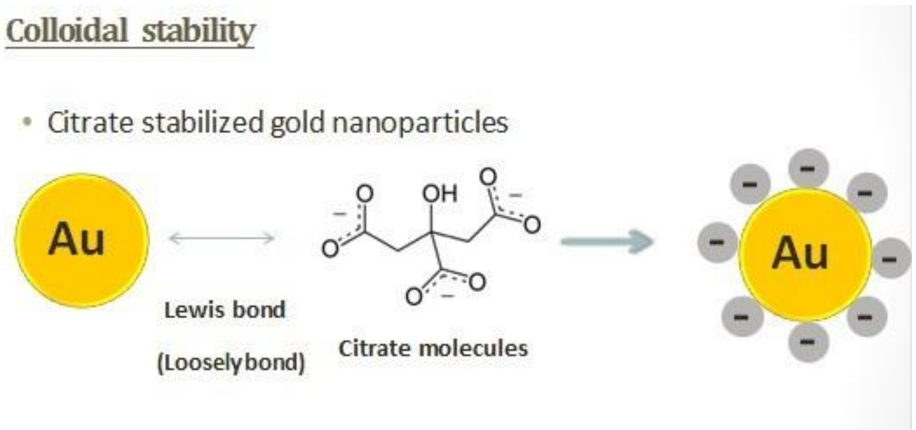
- Citrate reduction method
- Developed by Turkevitch in 1951
- Sodium citrate + $HAuCl_4$
- High yield and monodisperse
- Cheap, easy
- Citrate helps to keep the stability of gold nanoparticles



Reflux process



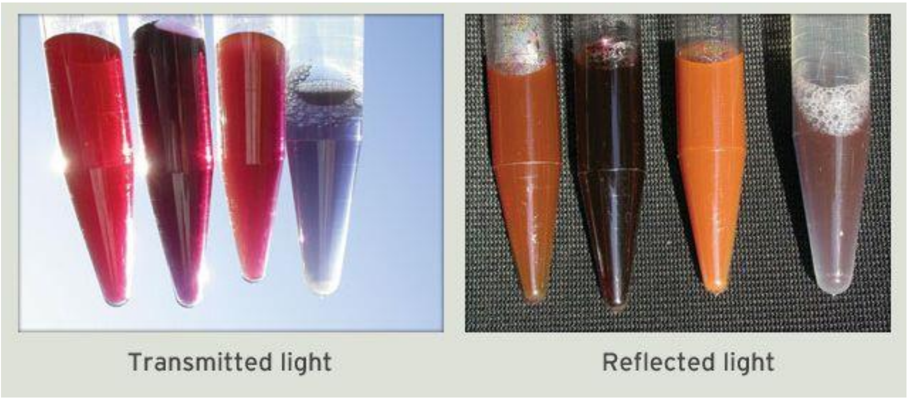
Nucleation and growth



Extinction

Extinction = absorbance + scattering

↳ Absorb light ↳ Reflect light

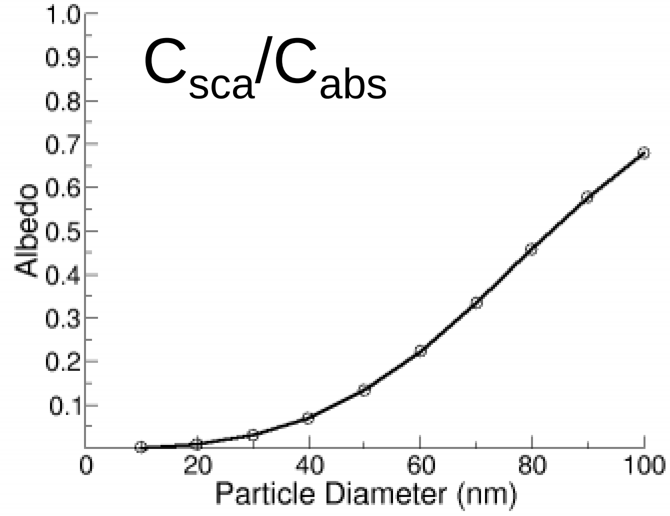


Color of identical gold nanoparticles with transmitted and reflected light

$$C_{abs} = 4\pi k a^3 \mathrm{Im}\left[\frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m}\right]$$

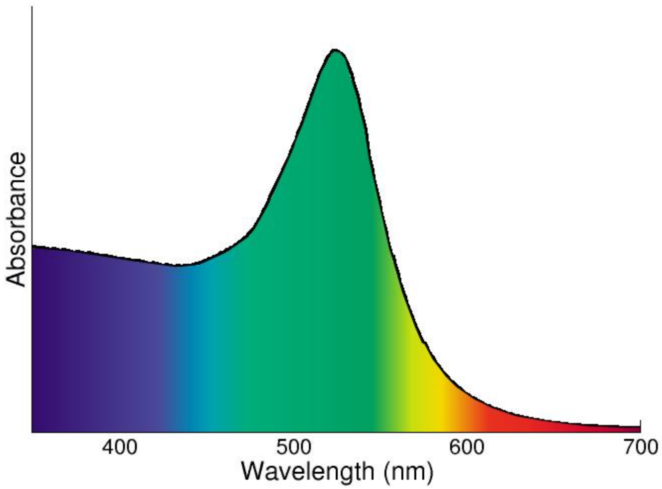
$$C_{sca} = \frac{8\pi}{3} k^4 a^6 \left|\frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m}\right|^2$$

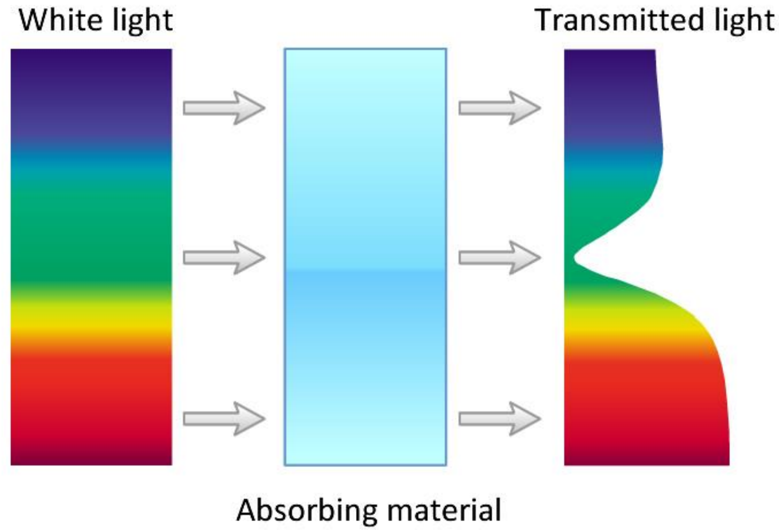
- Absorbance is dominant when a is small
- Scattering is dominant when a is large

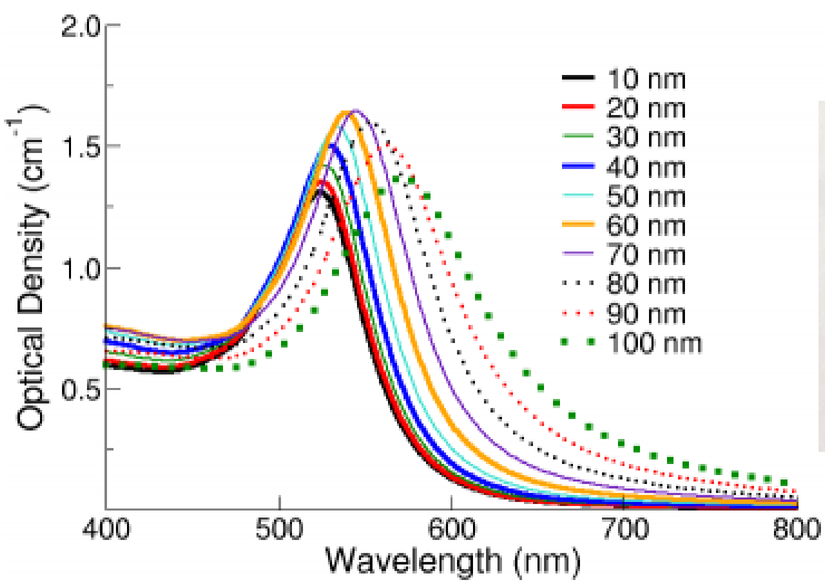


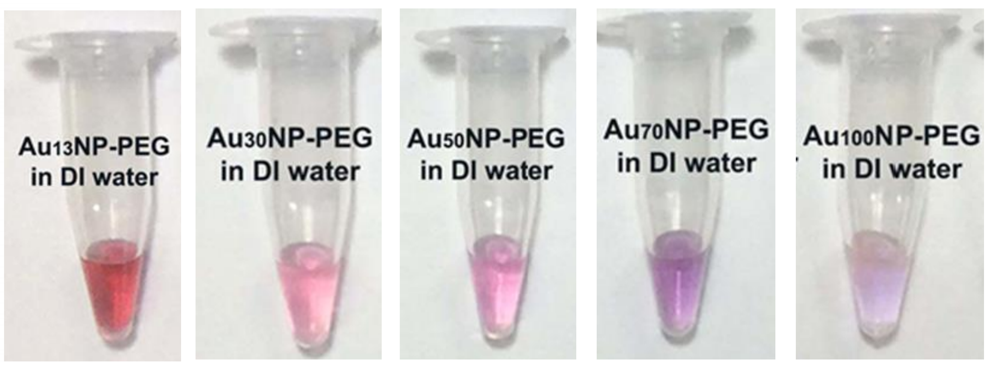
Why is gold nanoparticle red?

Absorbance of gold nanoparticle





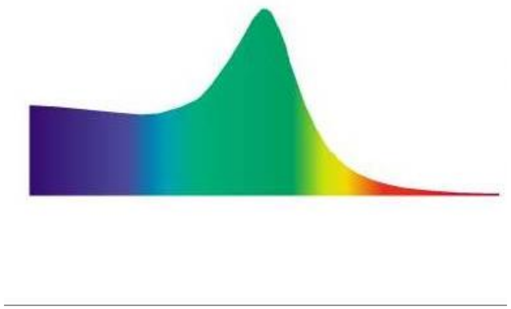


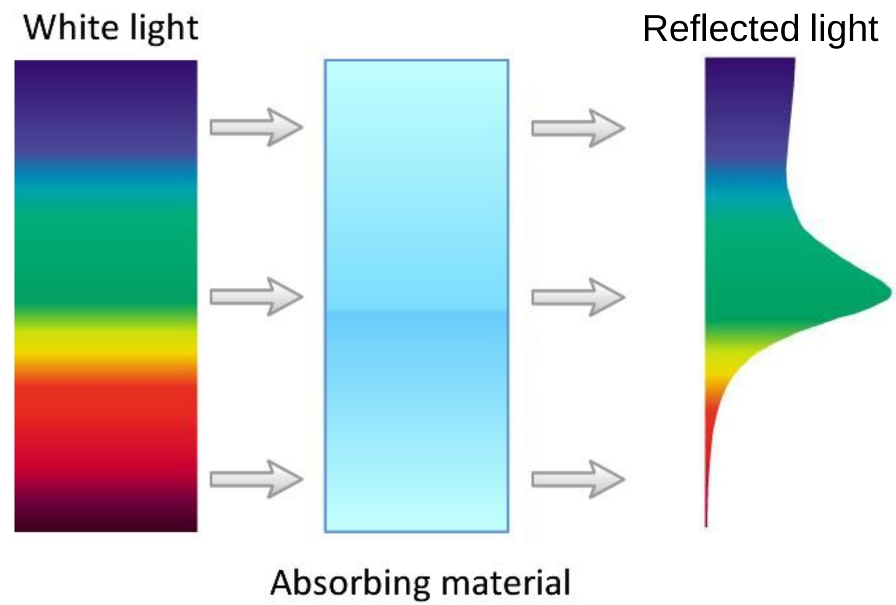


Langmuir, **2015**, 31, 13773

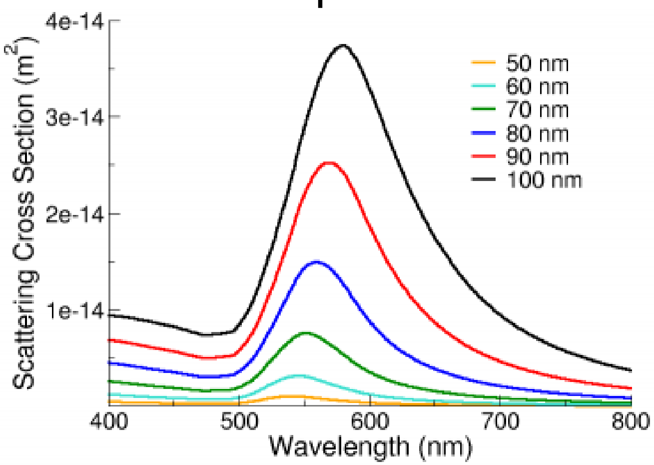
Gold nanoparticles are not always red!

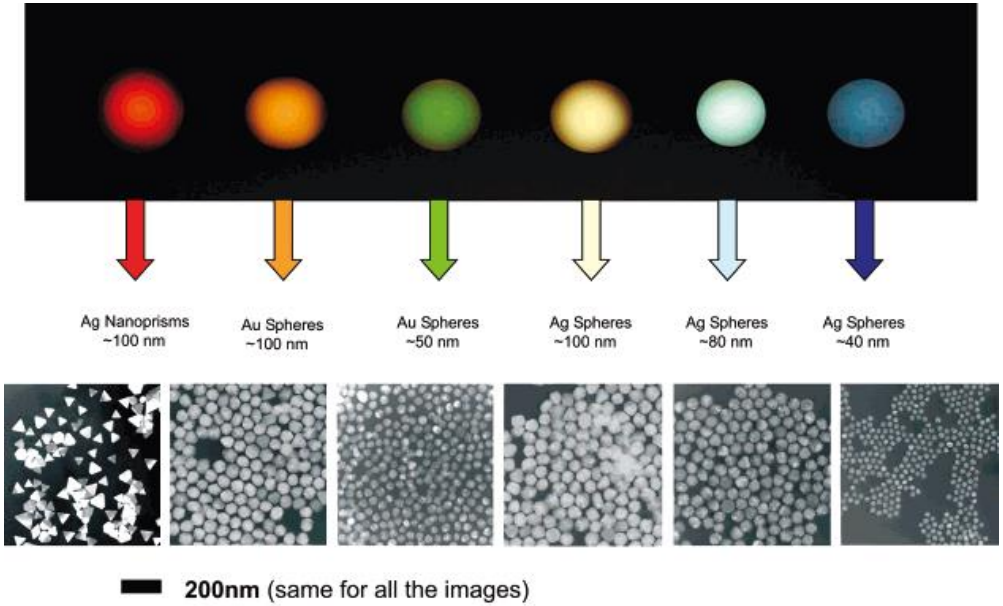
Scattering spectra of a nanoparticle





Scattering spectra of gold nanoparticle





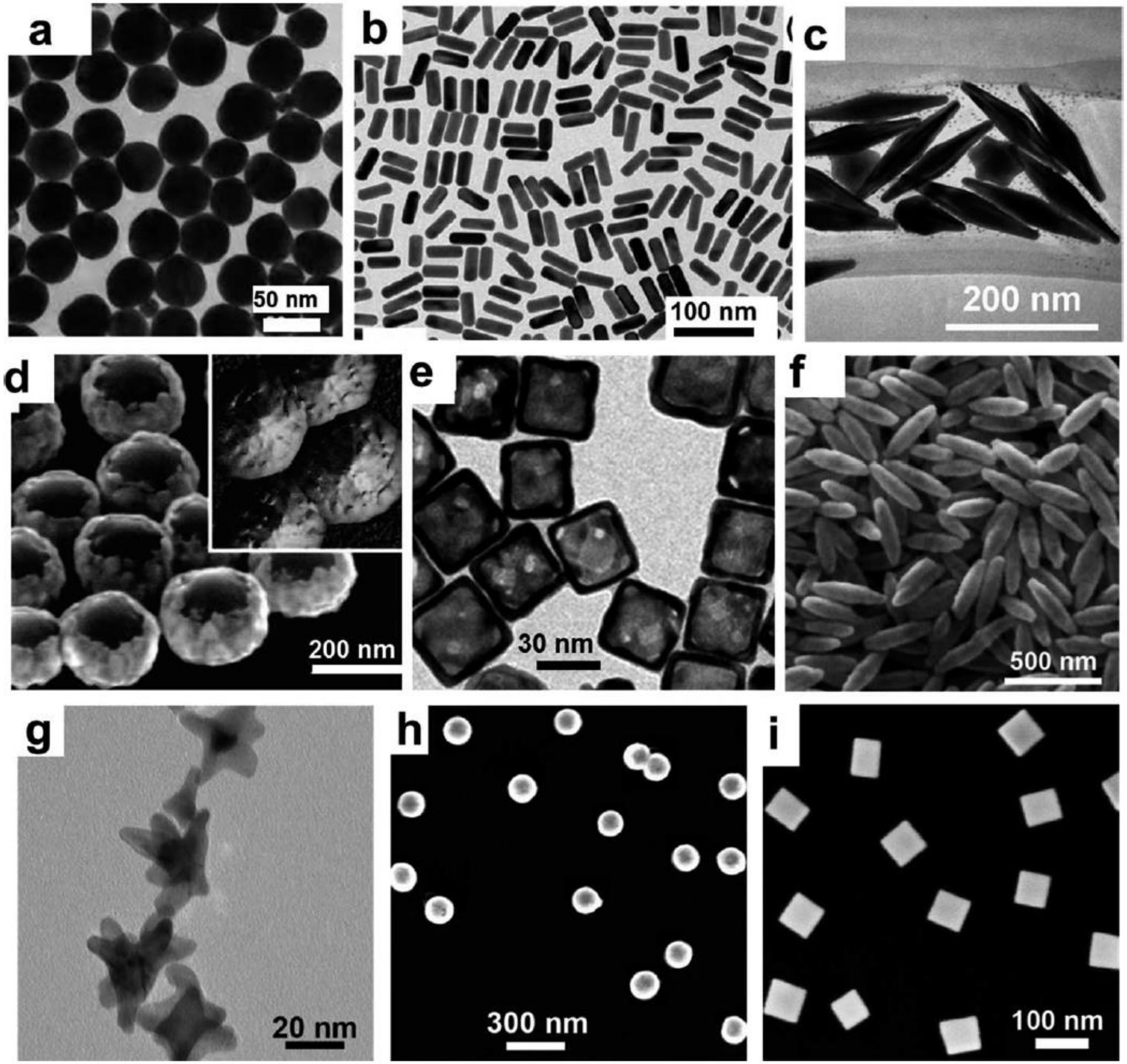
Chem. Rev. **2005,** *105*, 1547

Lycurgus cup

Why does it look different?

Photograph: British Museum Images

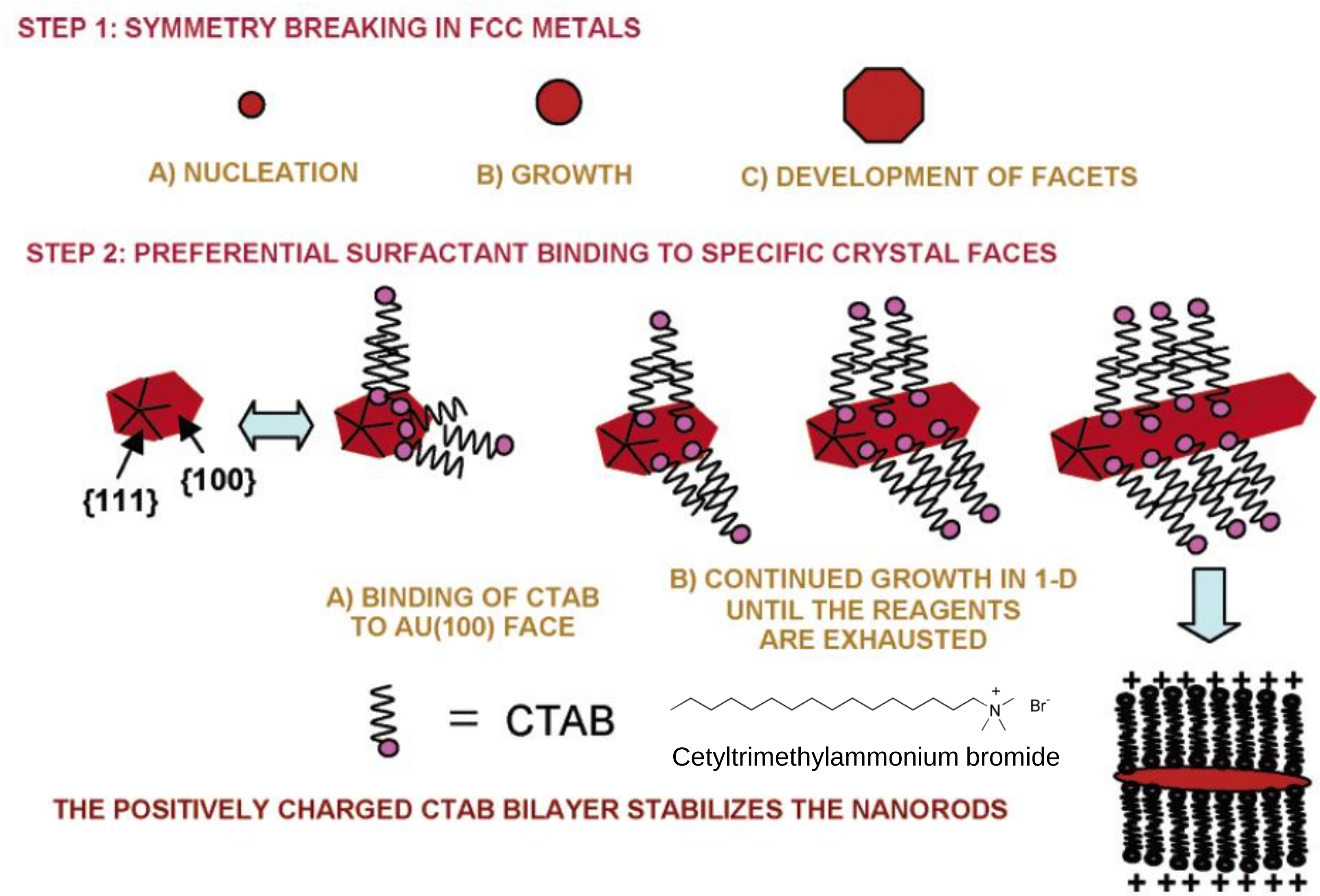
Gold materials of different shapes



→ Each NP has different properties

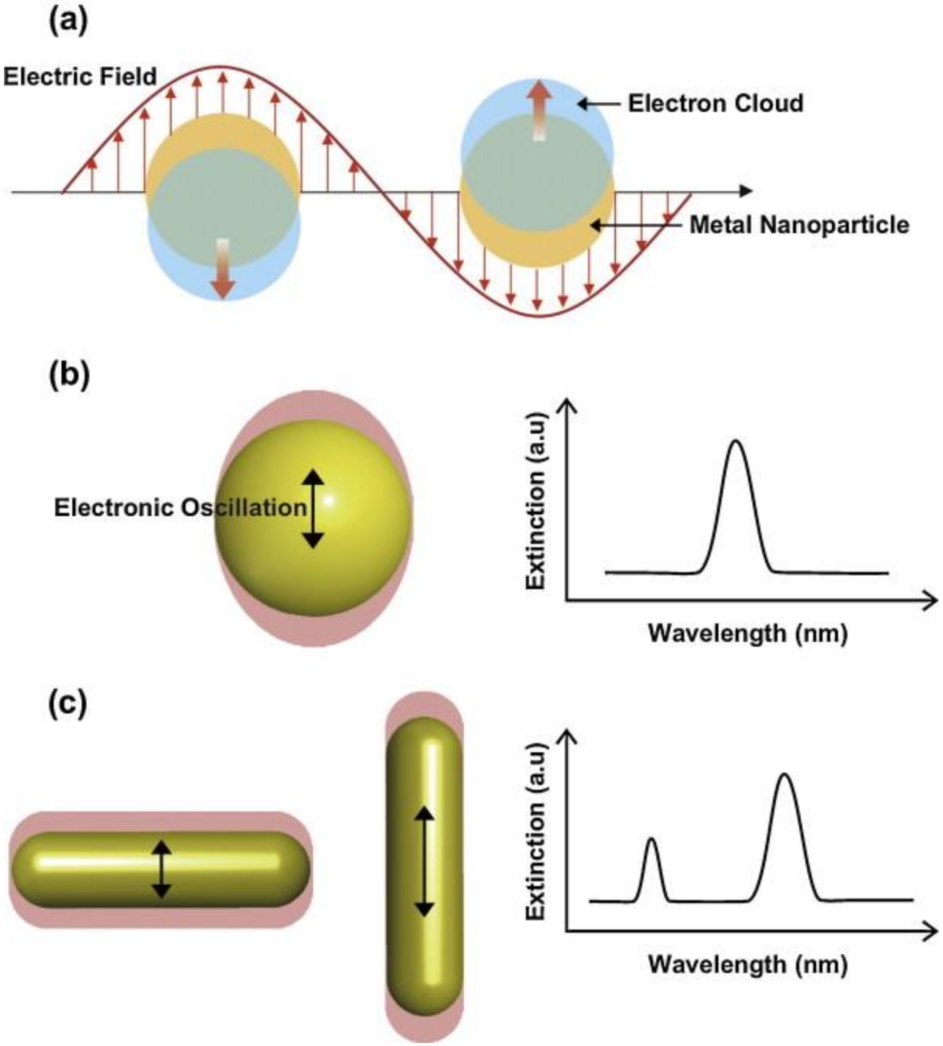
Nanoscale, **2014**, *6*, 2502–2530

Growth mechanism of gold nanorods



J. Phys. Chem. B **2005**, 109, 13857

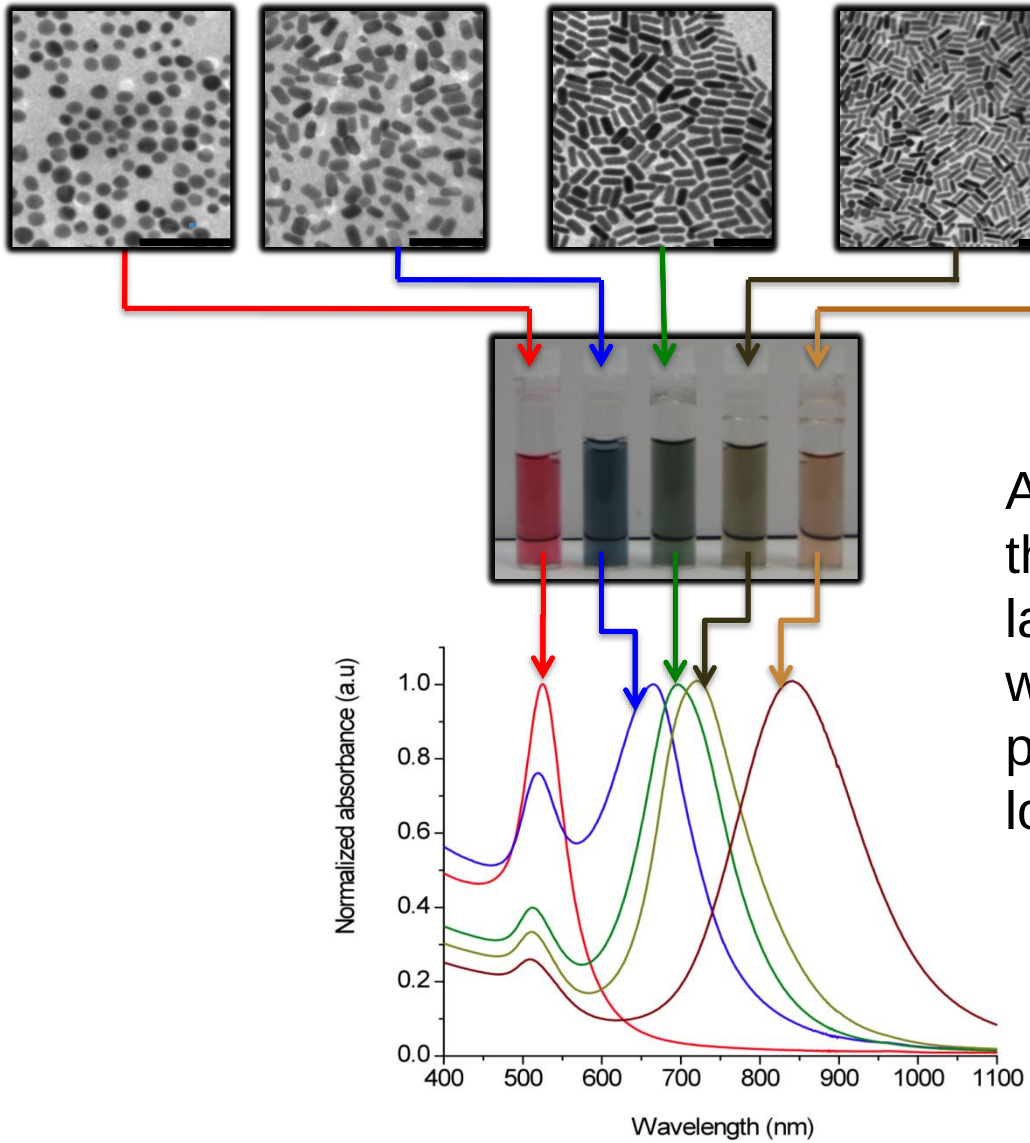
Surface plasmons of nanoparticles



Size and shape of the nanoparticle affect their resonance frequency

Anal. Chim. Acta, **2012**, *716*, 76

Shape variation of gold nanoparticles

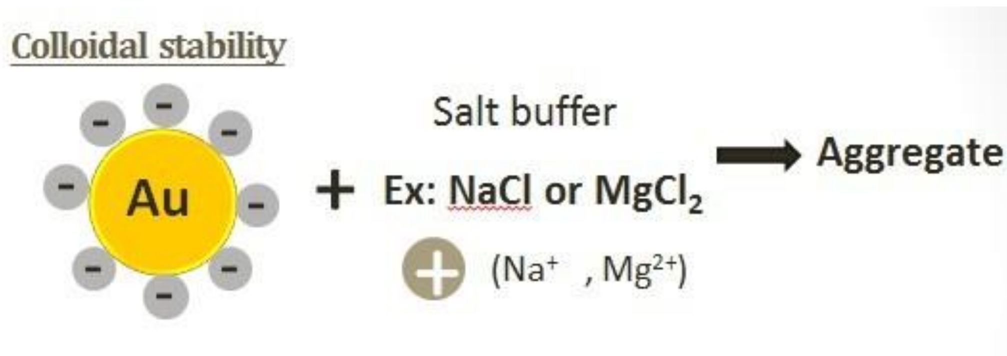


As the aspect ratio of the particle becomes larger, the resonance wavelength of the particle becomes longer

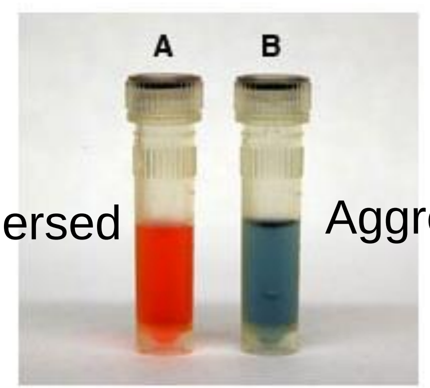
Catherine Murphy *et al.*

Aggregation of gold nanoparticles

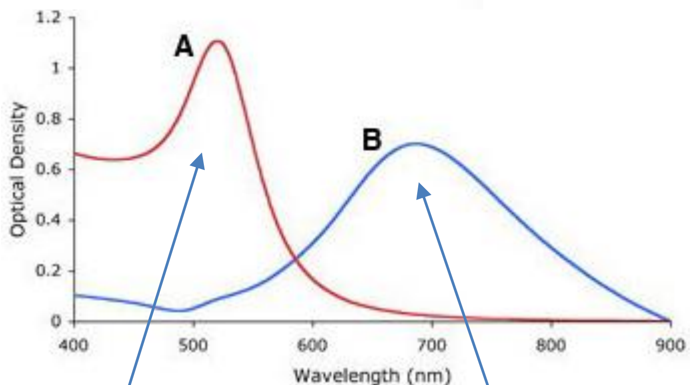
- Dispersed gold nanoparticles will have a red color in solution.
- If the particles aggregate, the solution will appear blue/purple and can progress to a clear solution with black precipitates.
- Why? Plasmonic coupling!



Dispersed



Aggregated



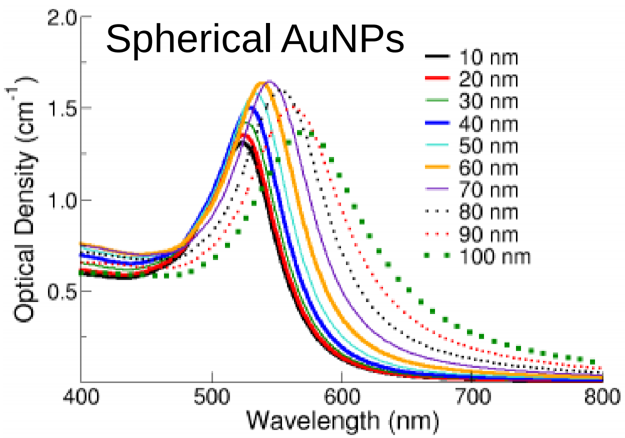
Absorbance

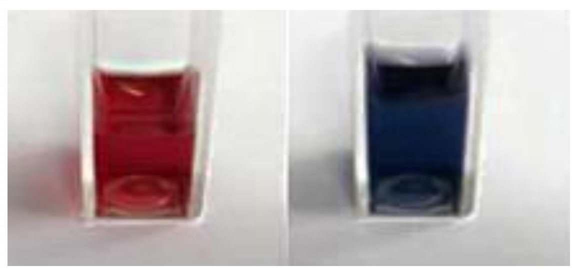
Scattering

Metallic nanoparticles

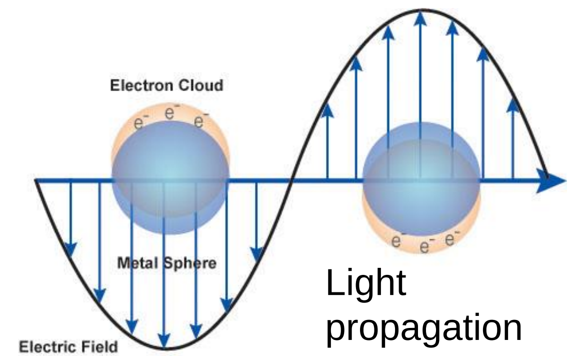
Surface plasmon resonance

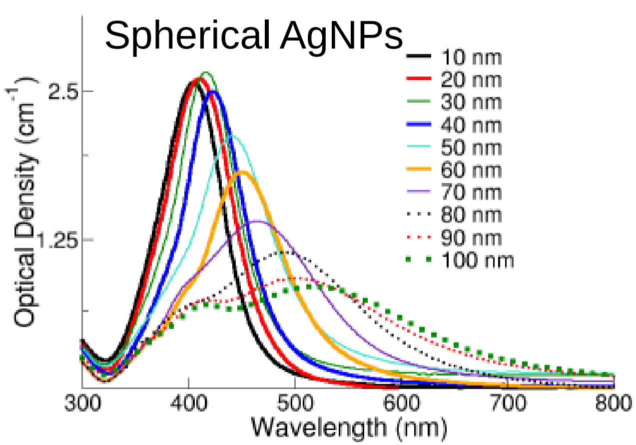
- Free electrons oscillate collectively at the interface of metal and surrounding medium in resonance with external EM fields
- Dyes, SERS, fluorescence amplification, colorimetric sensing
- Can be applied in various biomedical imaging

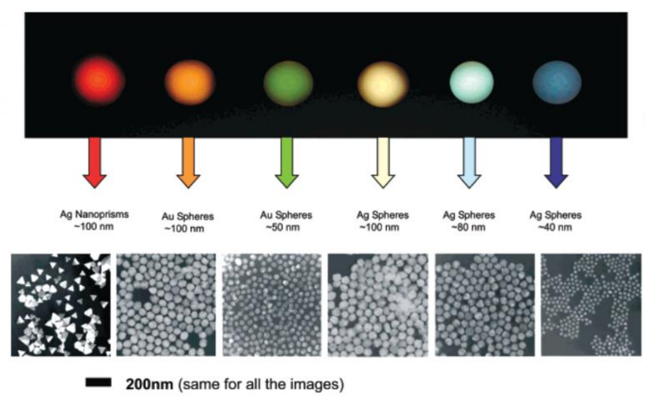


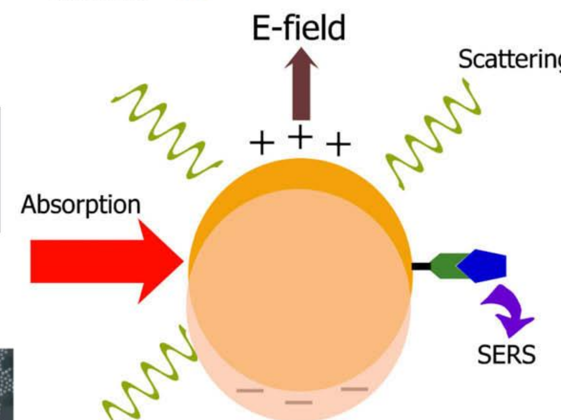


Dispersed Aggregated





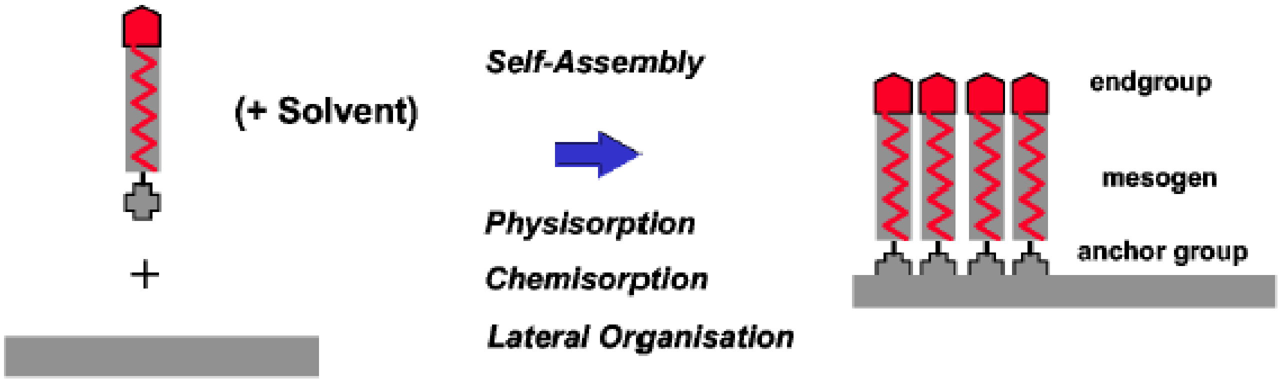




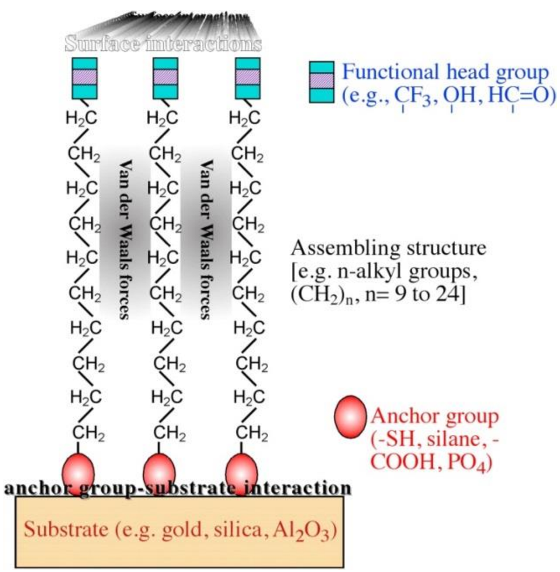
Chem. Phys. Lett. **2010**, *487*, 153

Self assembled monolayers (SAM)

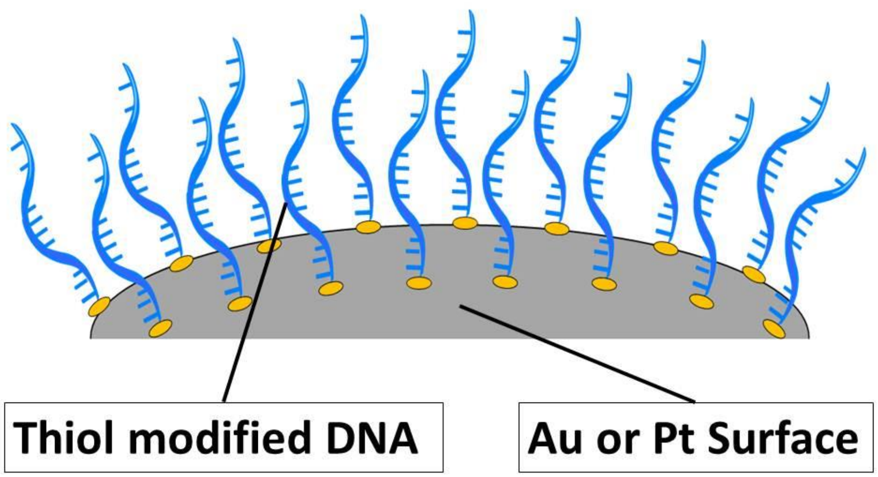
SAM (self-assembled monolayers): adsorption of molecules from solution onto solid substrates to form ordered molecular monolayers (e.g. alkylthiols on gold)



Gold-thiol chemistry

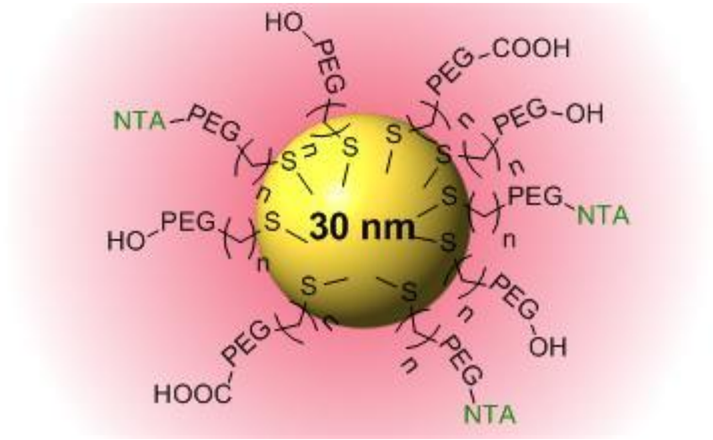


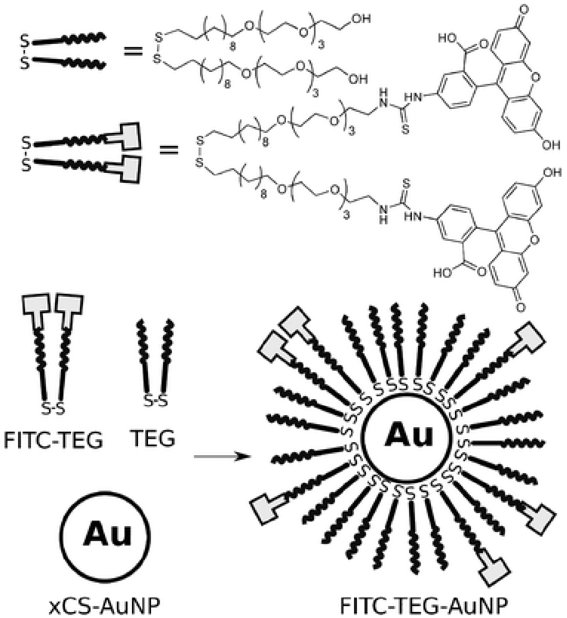
SAM conjugation



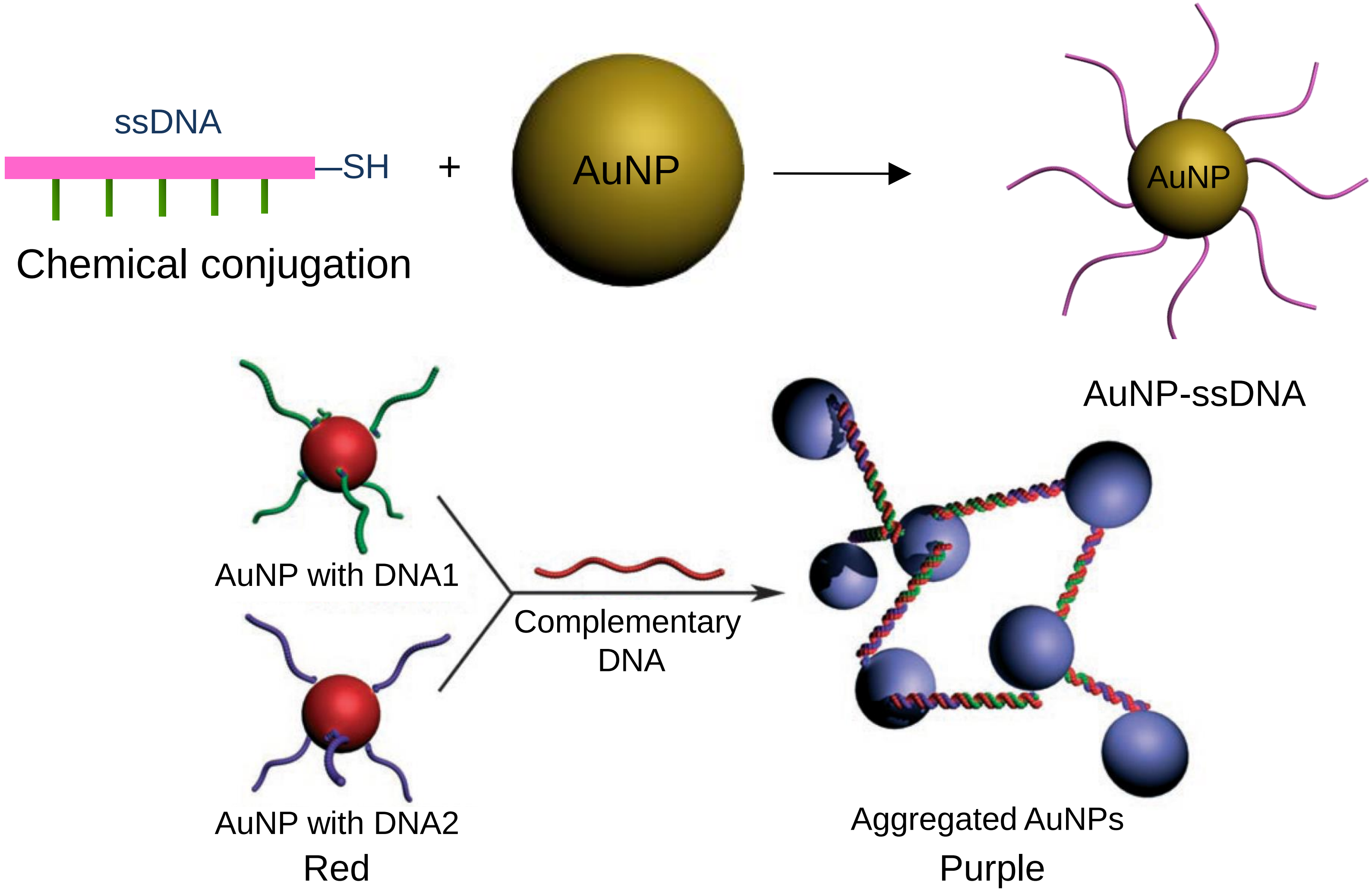
Chemical conjugation of AuNPs

Use SAM (Self assembled monolayer) on the surface of AuNP surface





Chemical conjugation between AuNP and ssDNA

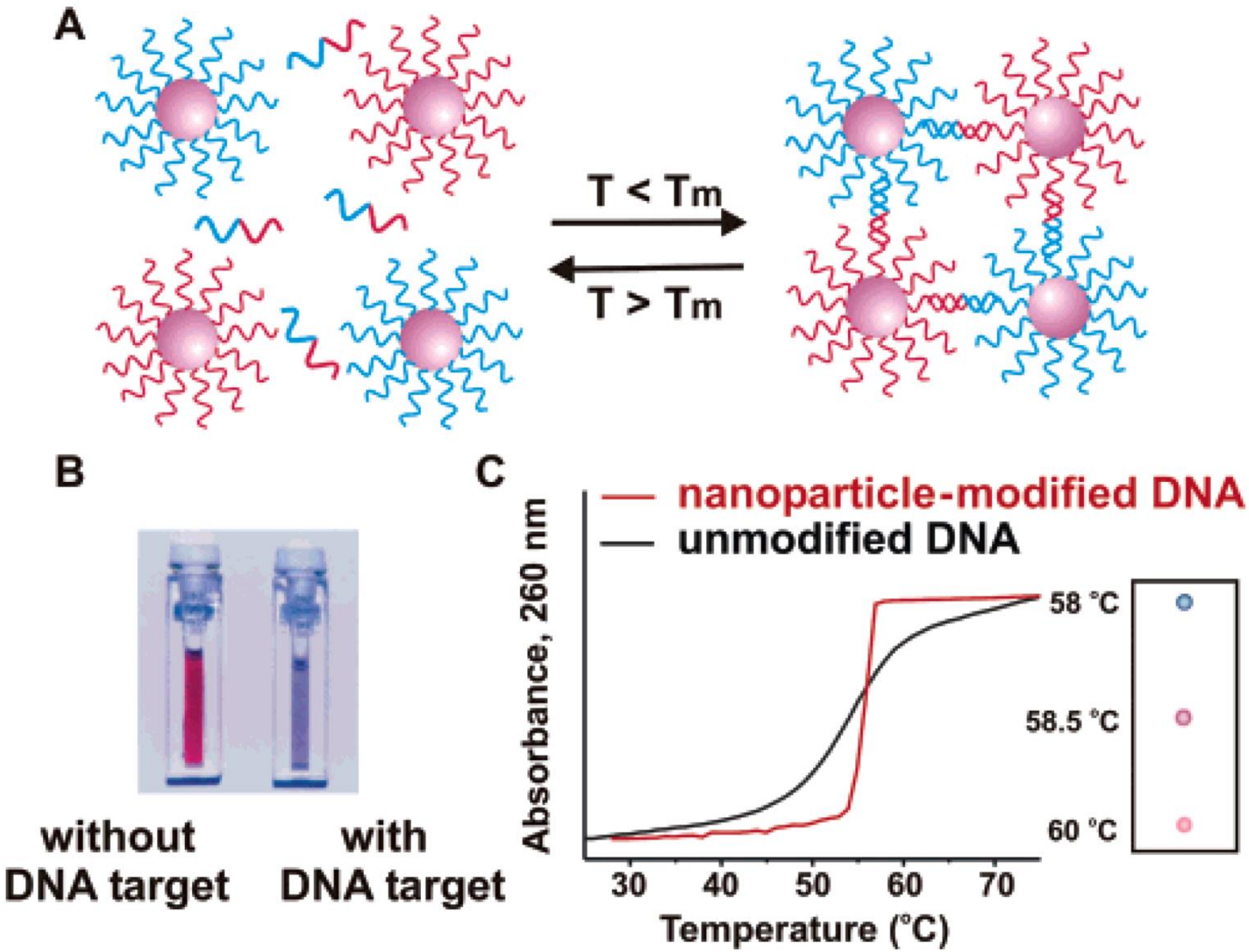


Single stranded (ss) DNA can be chemically attached on AuNP based on SAM

J. Am. Chem. Soc., **2008**, *130*, 14217
Adv. Mater. **2008**, *20*, 3263

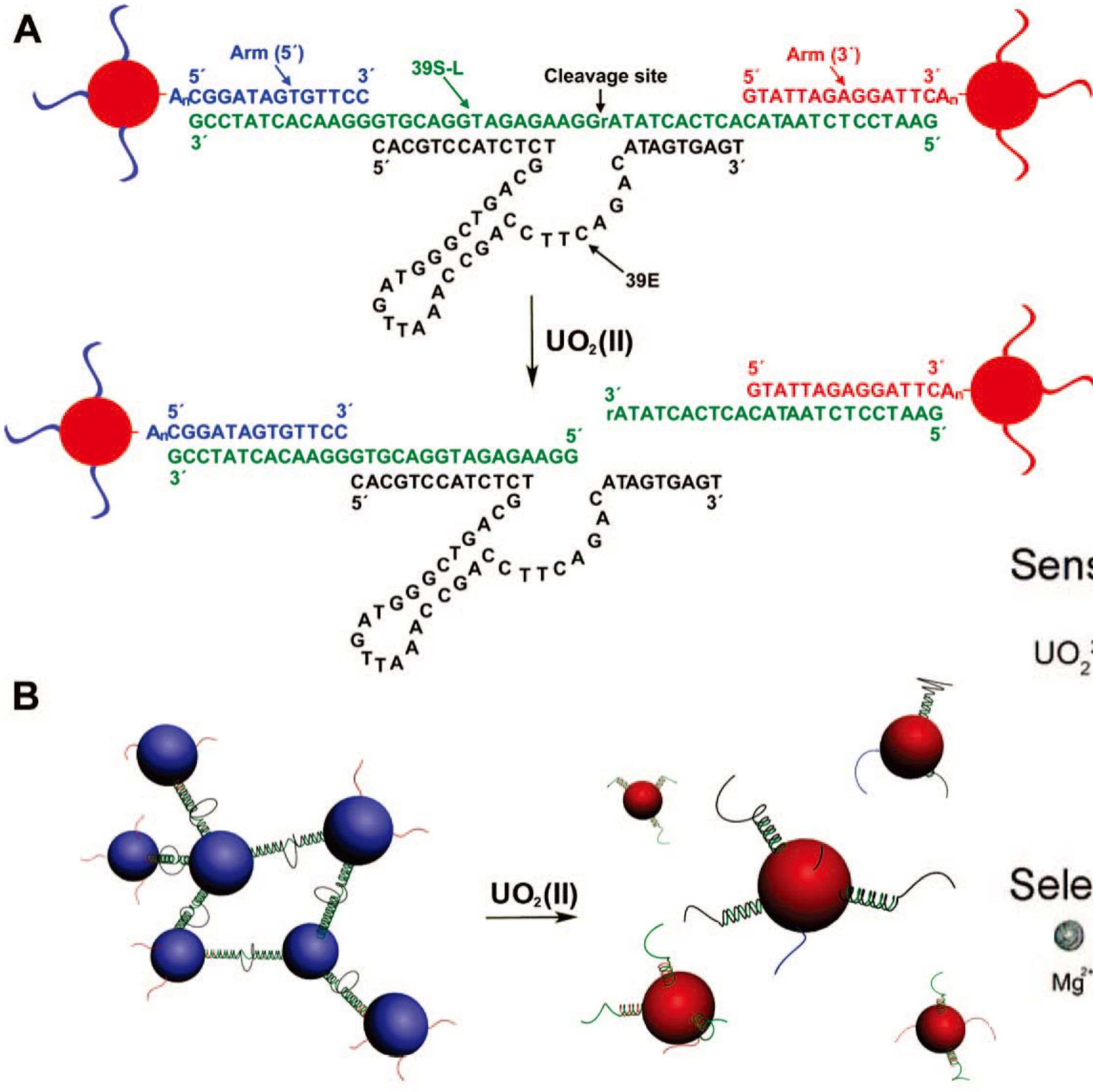
DNA conjugation on AuNPs

- The behavior of AuNPs can be controlled by the functionalized DNA

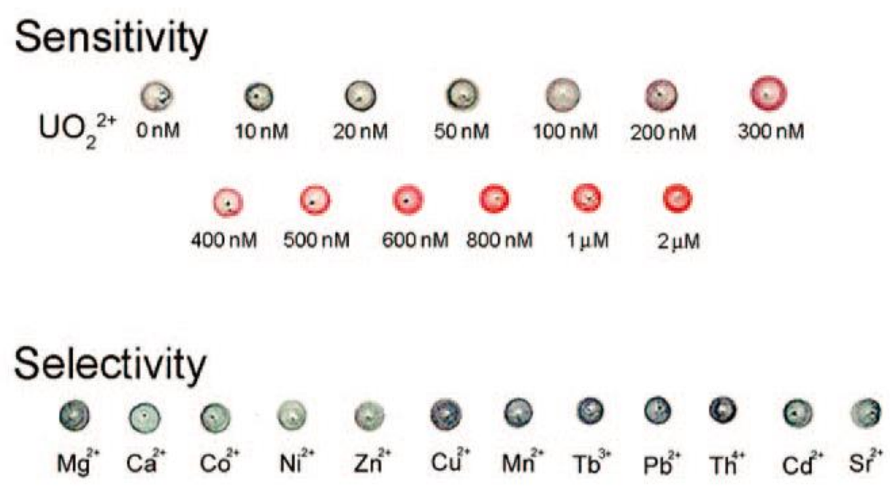


Nature. **1996**, 382, 607

AuNP-DNA system for metal ion sensing

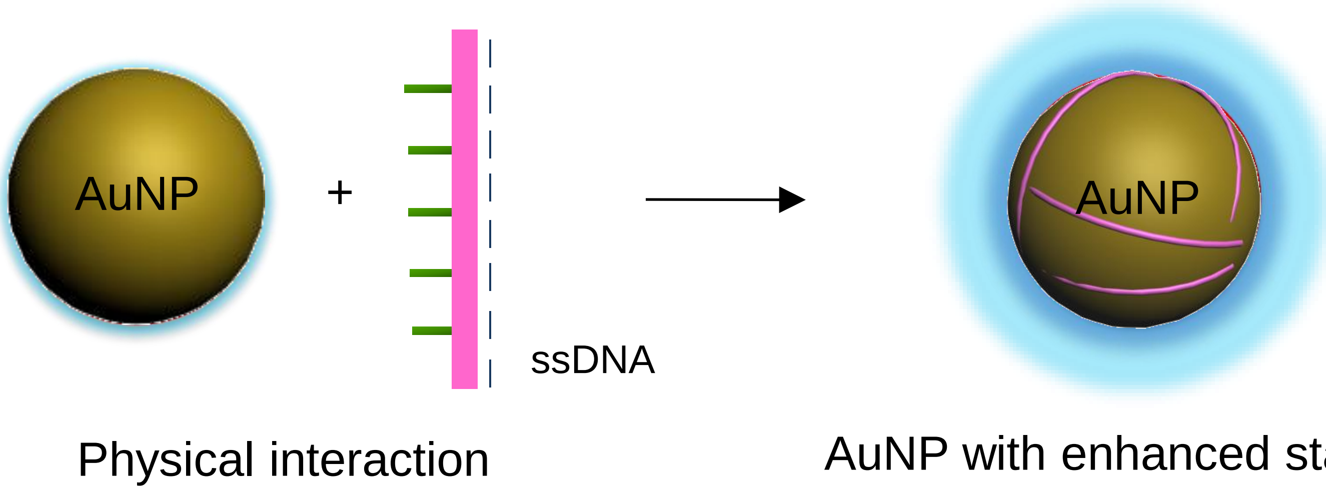


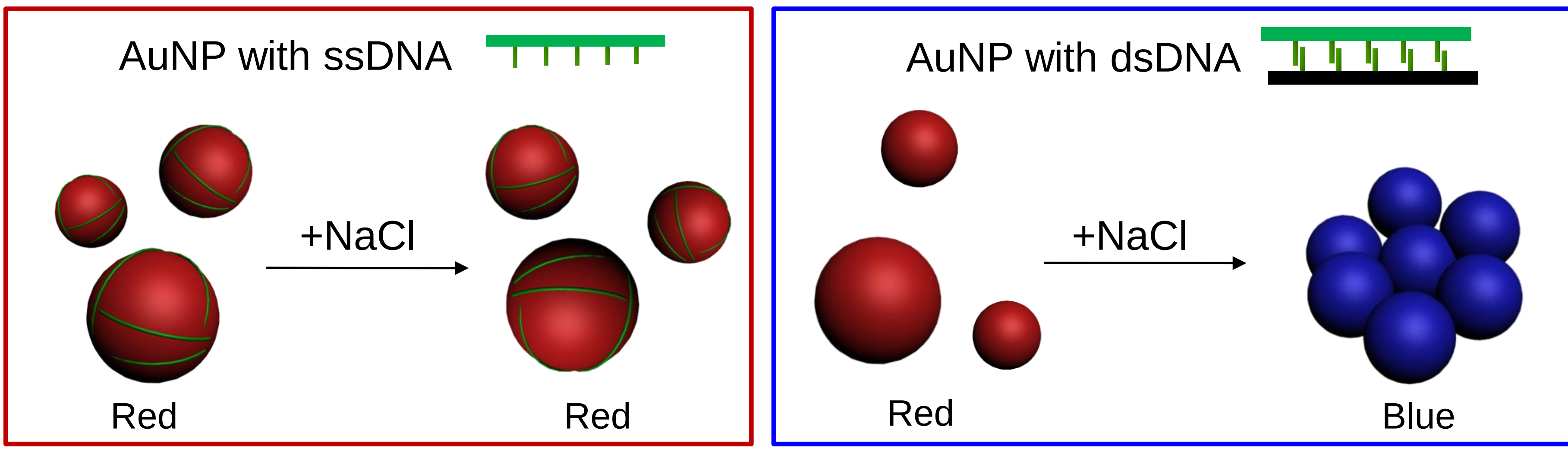
Metal ion specific aptamers integrated to AuNP system for colorimetric detection of metal ions



J. Am. Chem. Soc., **2008**, *130*, 14217
Adv. Mater. **2008**, *20*, 3263

Physical interaction between AuNP and ssDNA





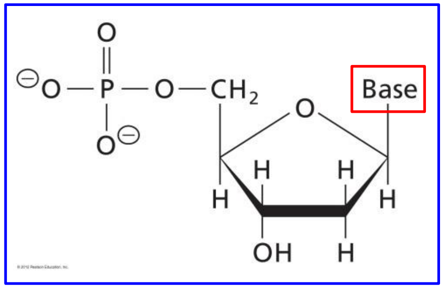
ssDNA can bind to AuNPs, but double stranded DNA cannot

ssDNA can improve the stability of AuNPs

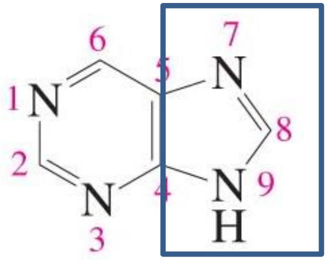
J. Am. Chem. Soc., **2008**, *130*, 14217

Adv. Mater. **2008**, *20*, 3263

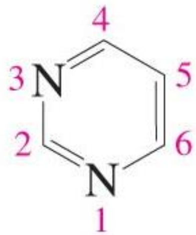
Bases



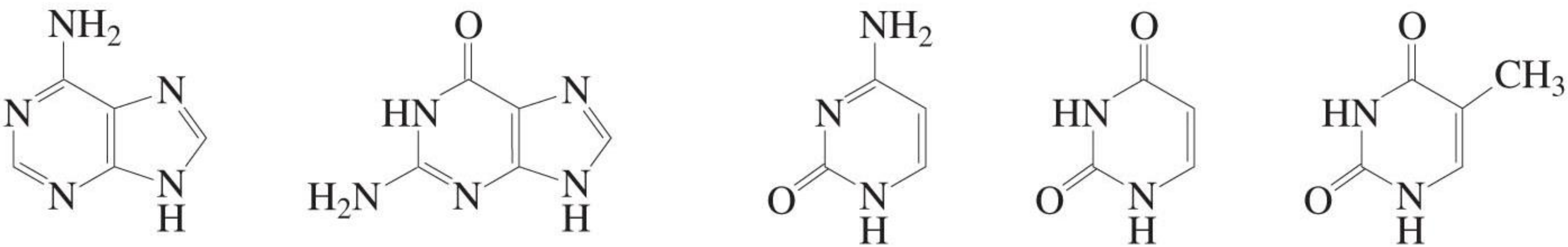
Imidazol binds to Au surface



purine : Two rings with four “N”



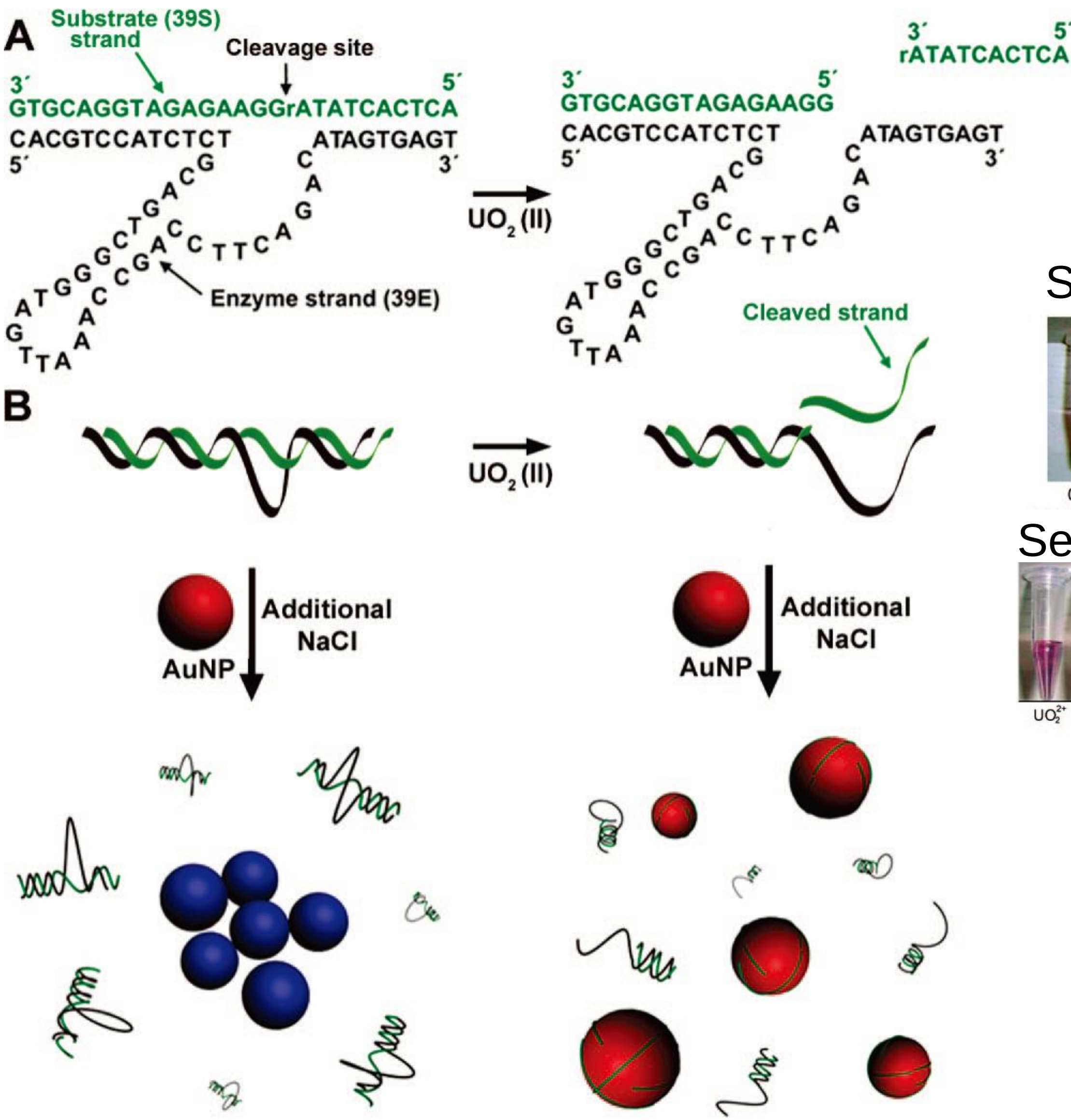
pyrimidine : One ring with two “N”



adenine **guanine** **cytosine** **uracil** **thymine**

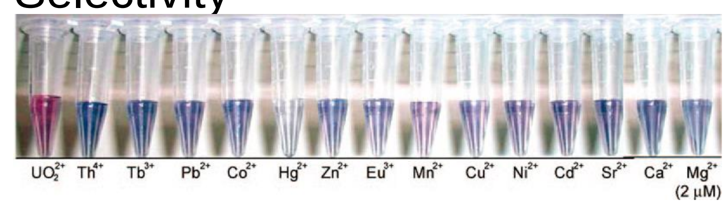
- Adenine (A), guanine (G), cytosine (C), and thymine (T) are found in DNA.
- Adenine, guanine, cytosine, and uracil (U) are found in RNA
- Bases have ring structure → hydrophobic

Colorimetric sensors for detection of metal ions



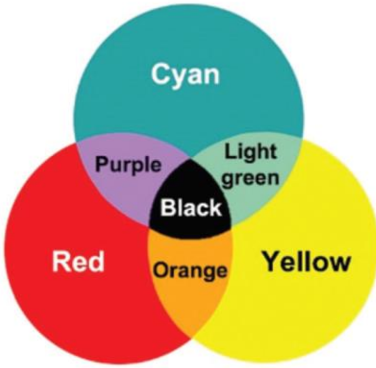
Sensitivity (DL: 1 nM)

Selectivity



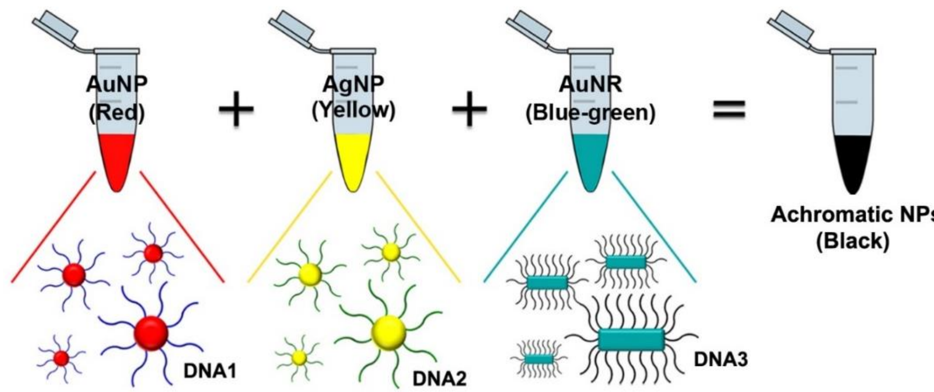
J. Am. Chem. Soc., **2008**, *130*, 14217
Adv. Mater. **2008**, *20*, 3263

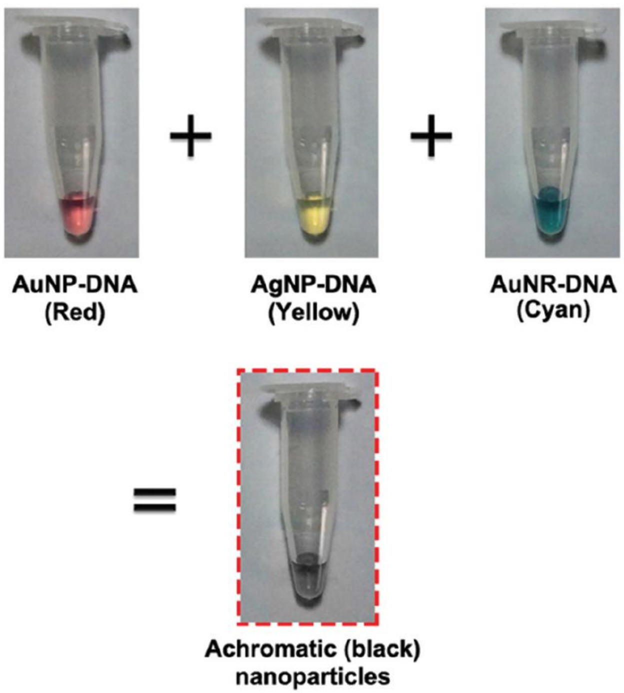
Achromatic (black) nanosensors based on CRYK model

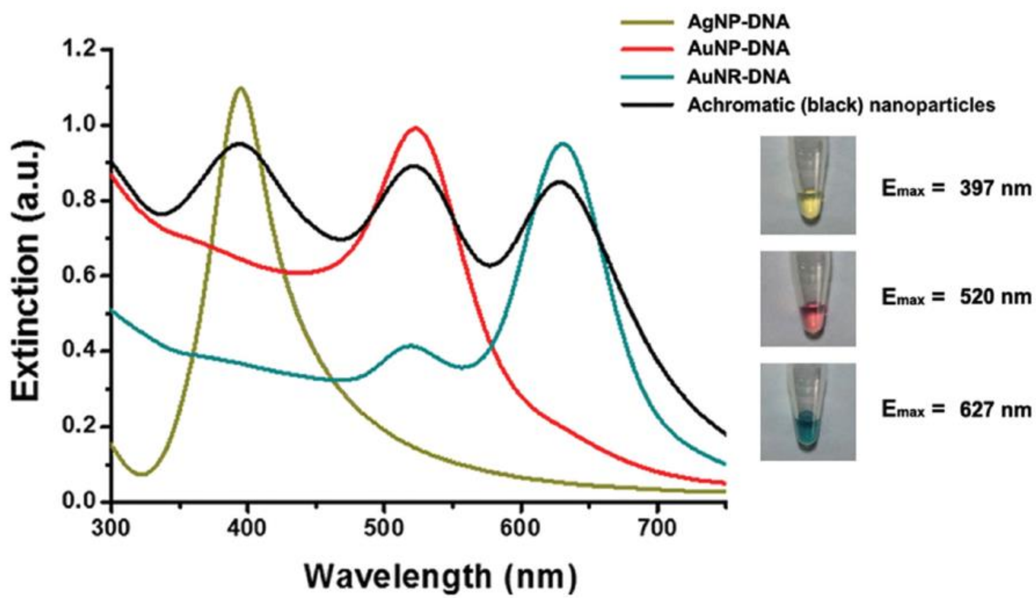


CRYK Color Model

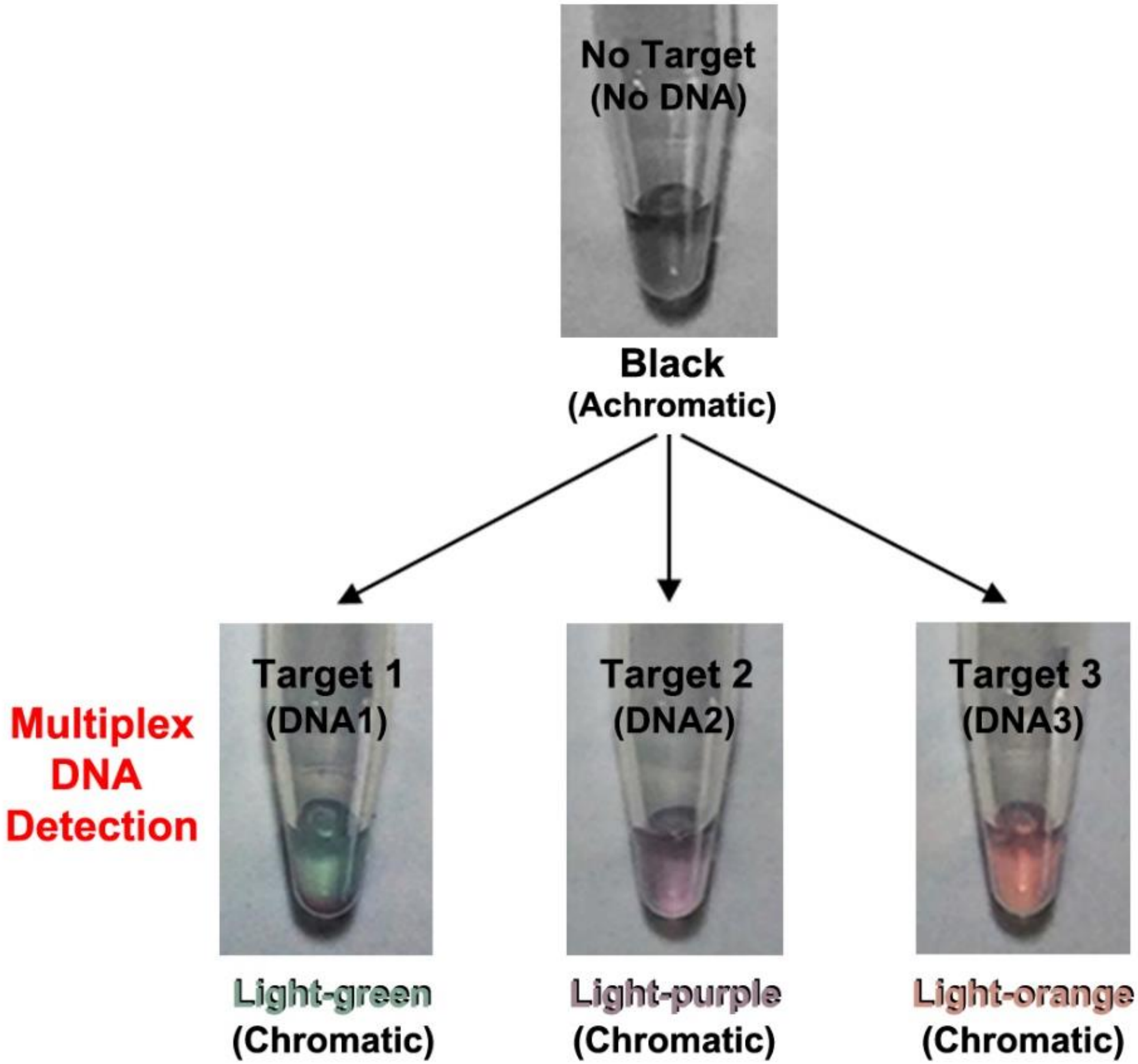
Achromatic nanoparticles (Achromatic NPs)





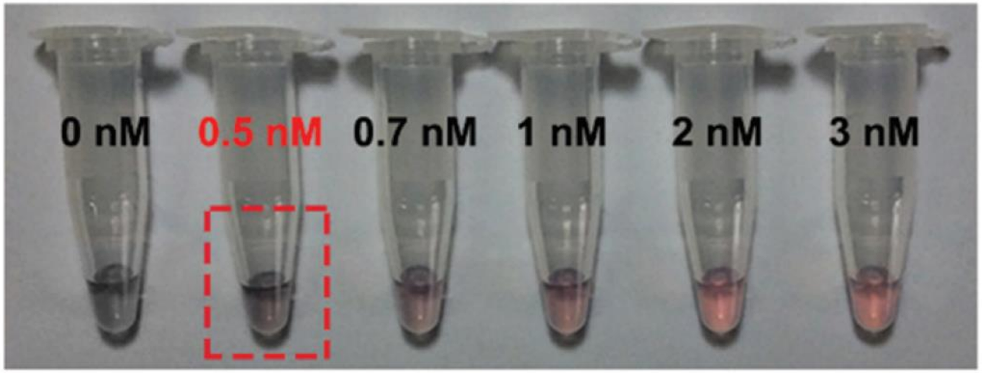


Achromatic (black) nanosensor for multiplexed detection

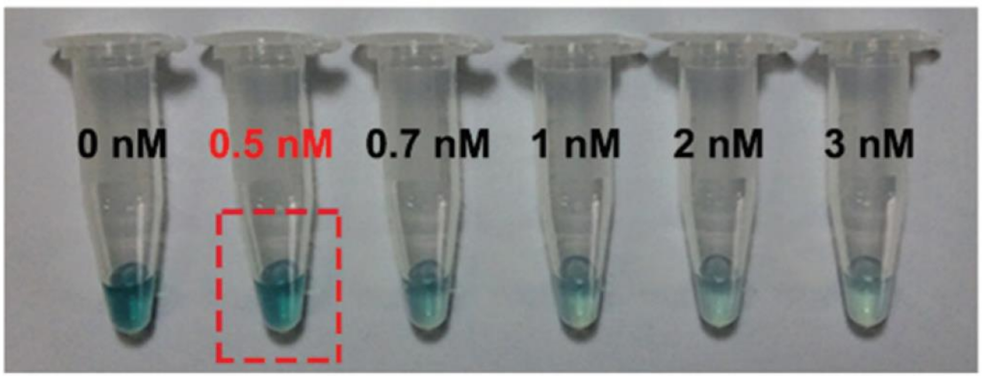


Enhancement of color transition with naked eyes

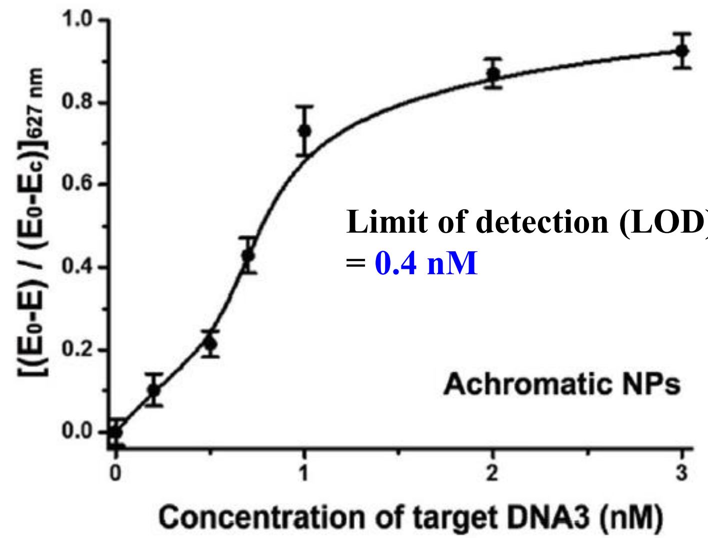
Achromatic nanoparticles (Achromatic NPs)

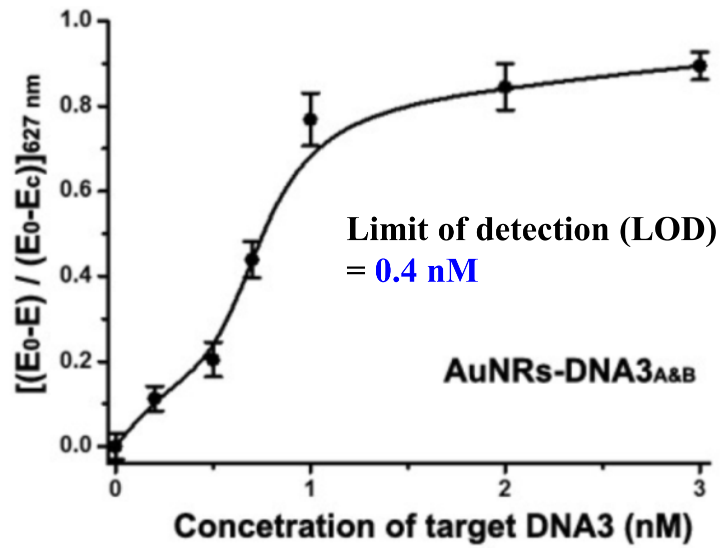


AuNRs-DNA3A&B



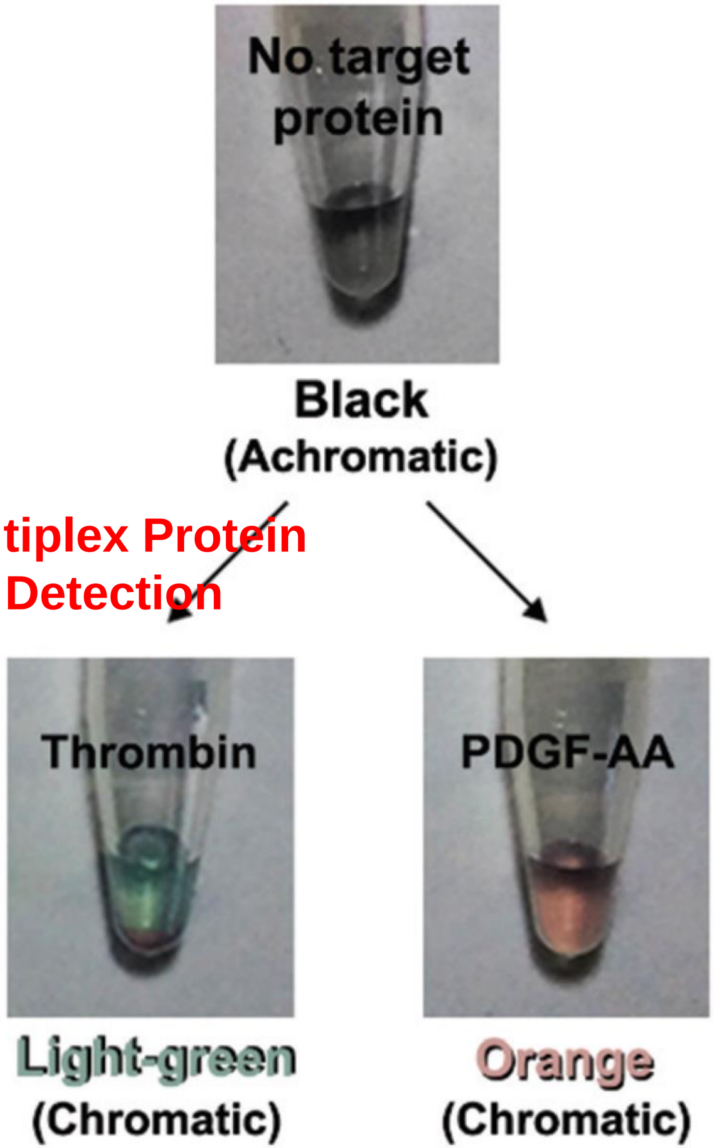
(Concentration of target DNA3 : 0 - 3 nM)

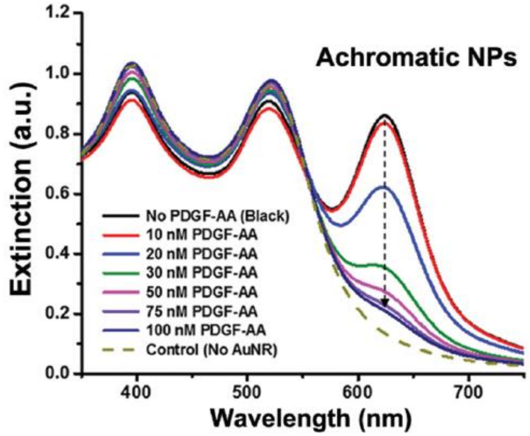


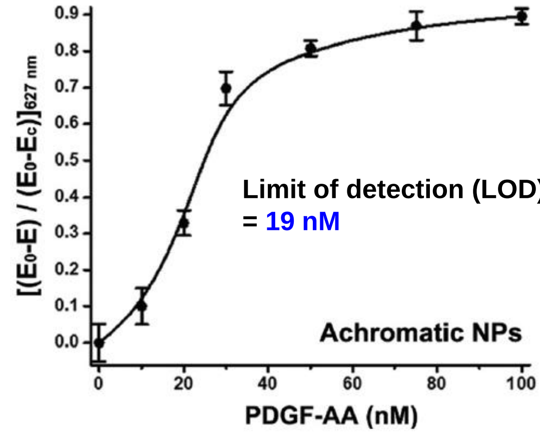


Achromatic sensors for biomarker detection

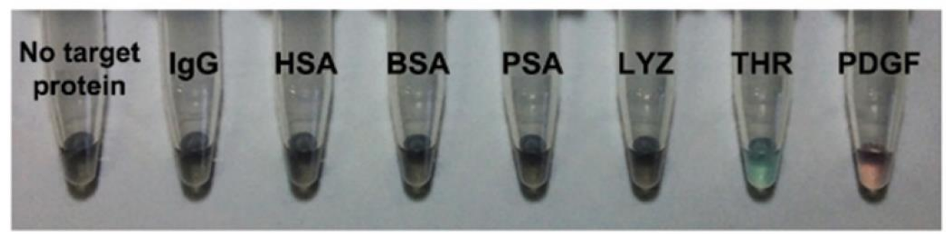
Multiplex Protein Detection



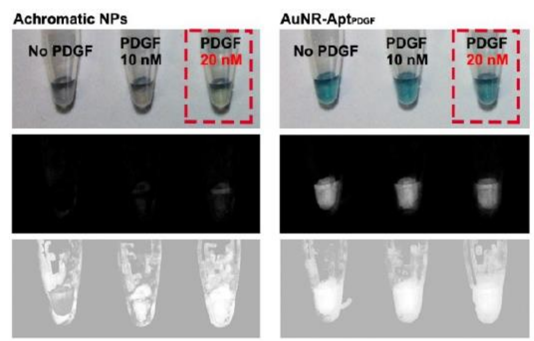


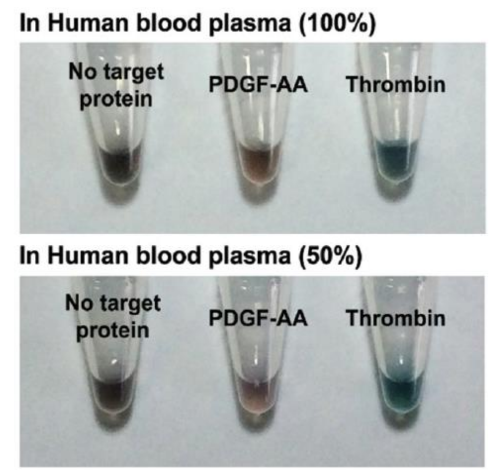


Selectivity



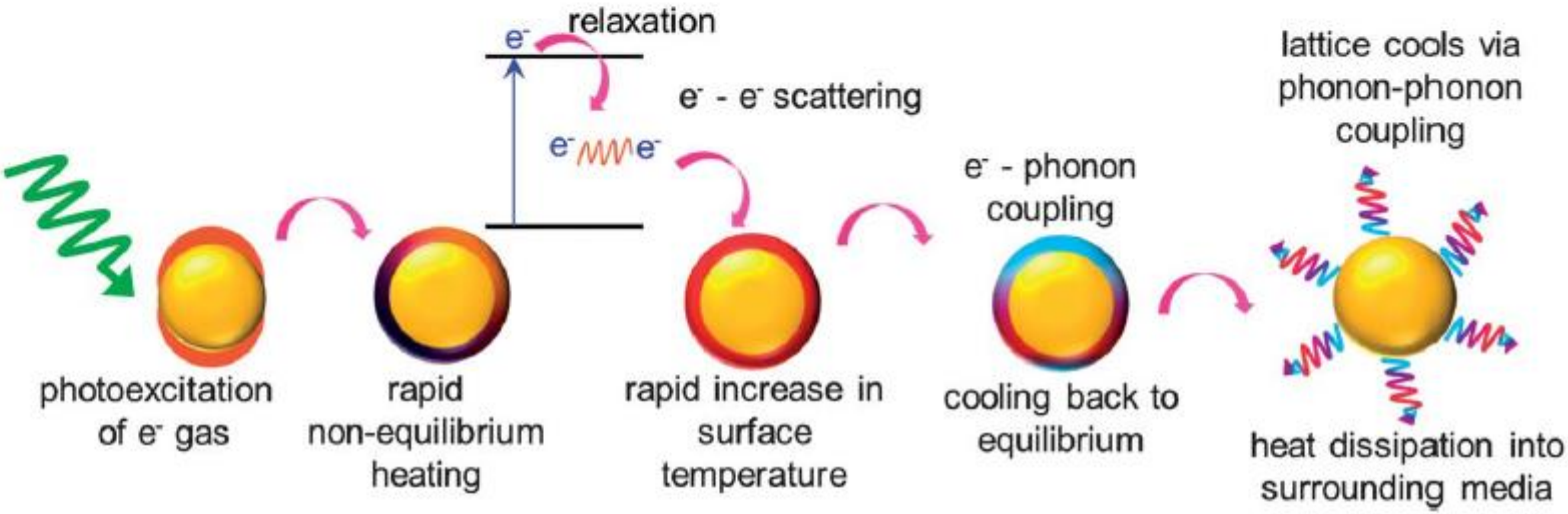
Color analysis





J. H. Heo *et al.*,*Nanoscale*, **2016**, *8*, 1834

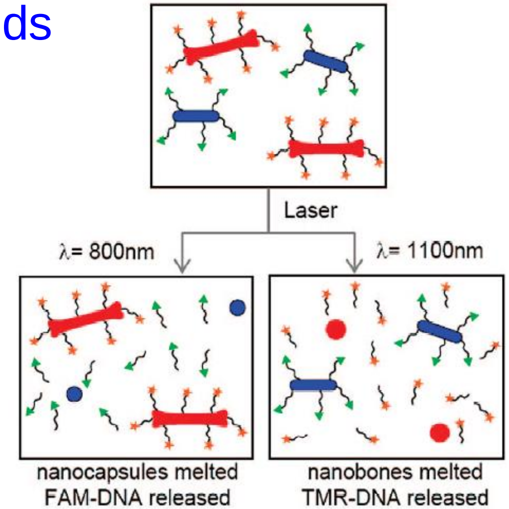
Photothermal phenomenon

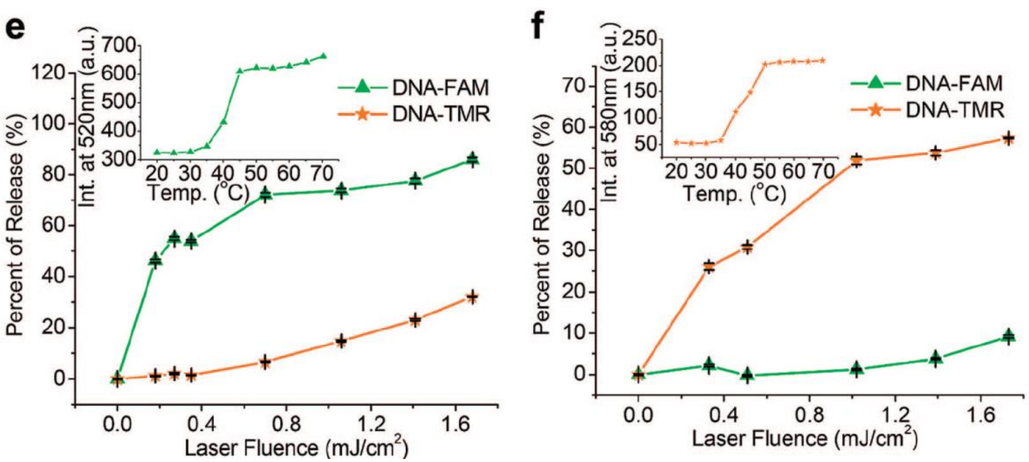


Nanoscale, **2014**, 6, 2502–2530

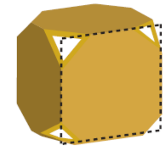
Photothermal driven release

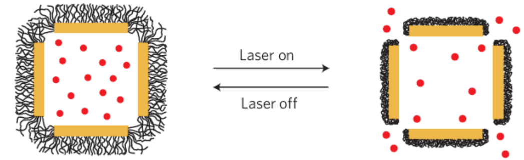
Nanorods



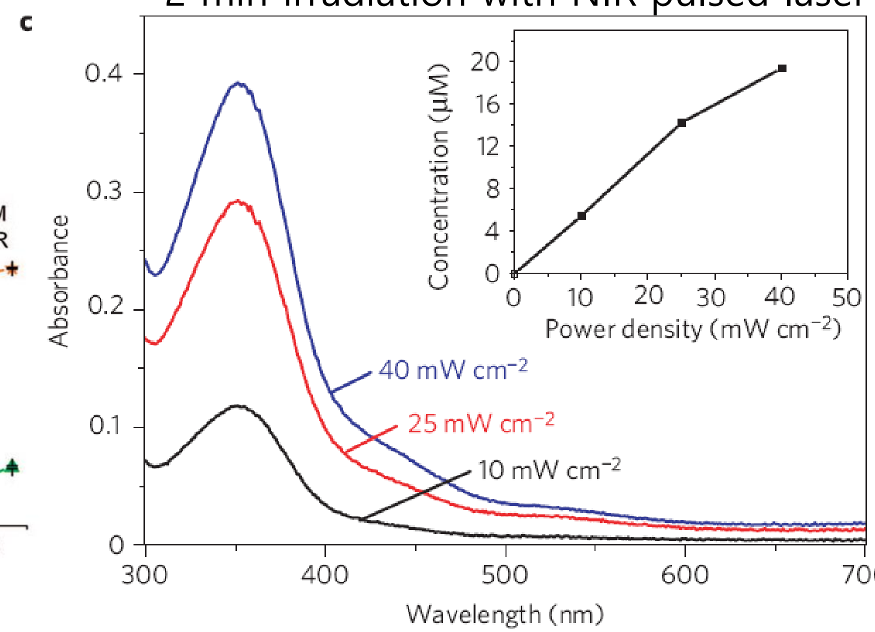


Nanocages



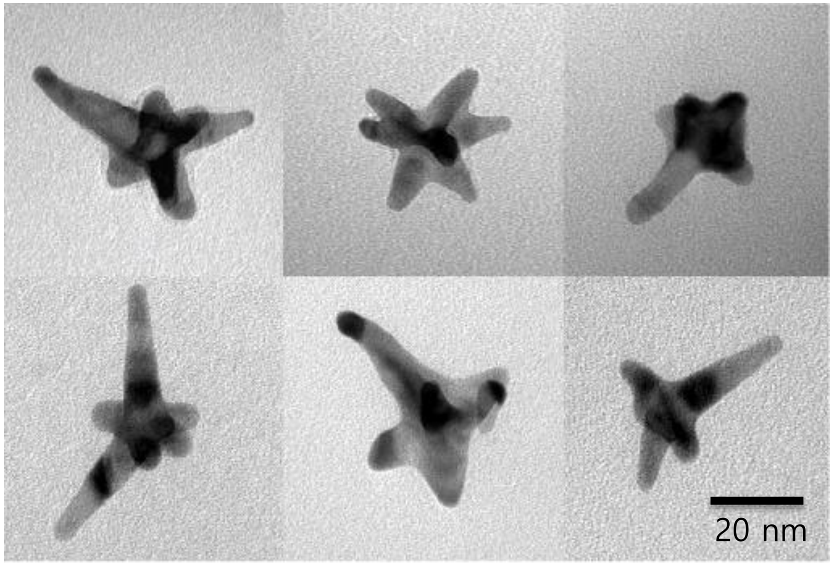


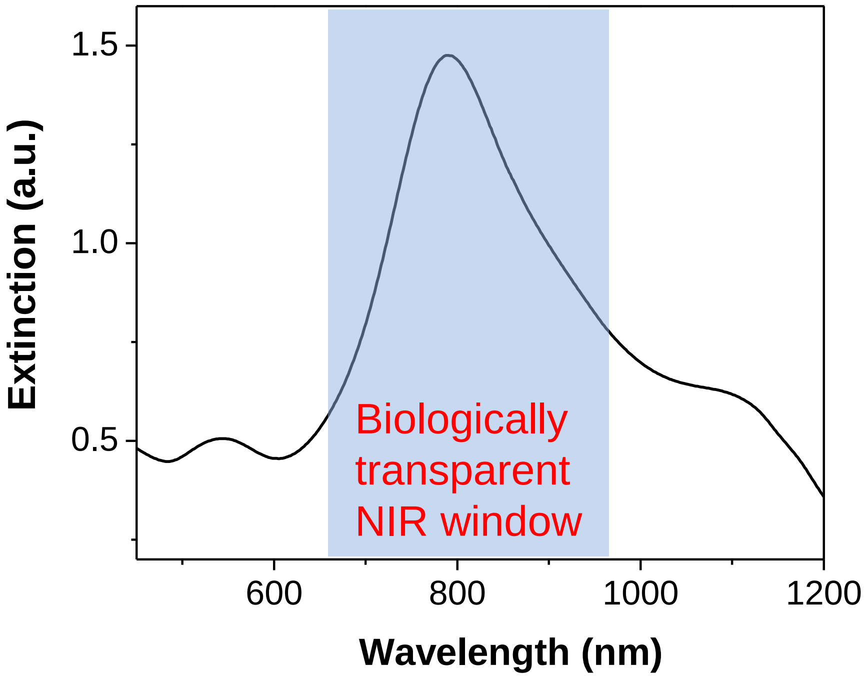
2 min irradiation with NIR pulsed laser



ACS Nano, **2009**, 3 ,80–86
Nature Mater. **2009**, *8*, 935 - 939

Gold nanostars





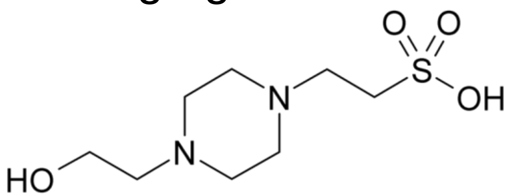
$HAuCl_3^- + HEPES \longrightarrow AuNS$

- ❑ Biocompatibility (HEPES is a buffer)
- ❑ Surface plasmon resonance at ~750-800 nm
- ❑ Small size (~30-40 nm)

ACS Nano, **2012**, *6, 3318*

HEPES gold nanostars

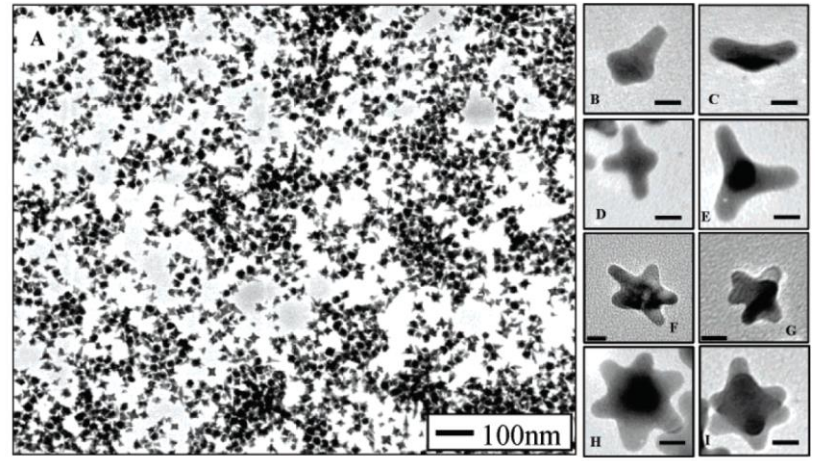
- 2-[4-(2-hydroxyethyl)-1-piperazinyl]ethanesulfonic acid (HEPES) is used as both reducing and shape-directing agents.

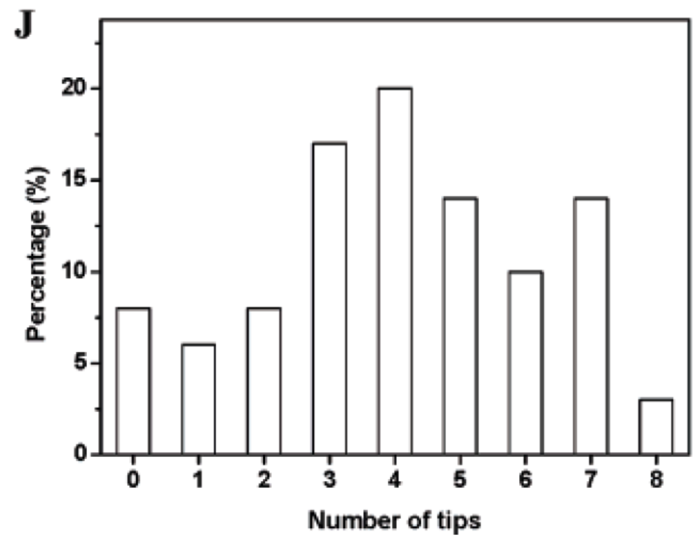


HEPES

- Branched gold nanocrystals were formed by selective tip growth in the <111> directions, suggesting relatively weak or no adsorption of HEPES on the {111} planes compared with the {100} planes

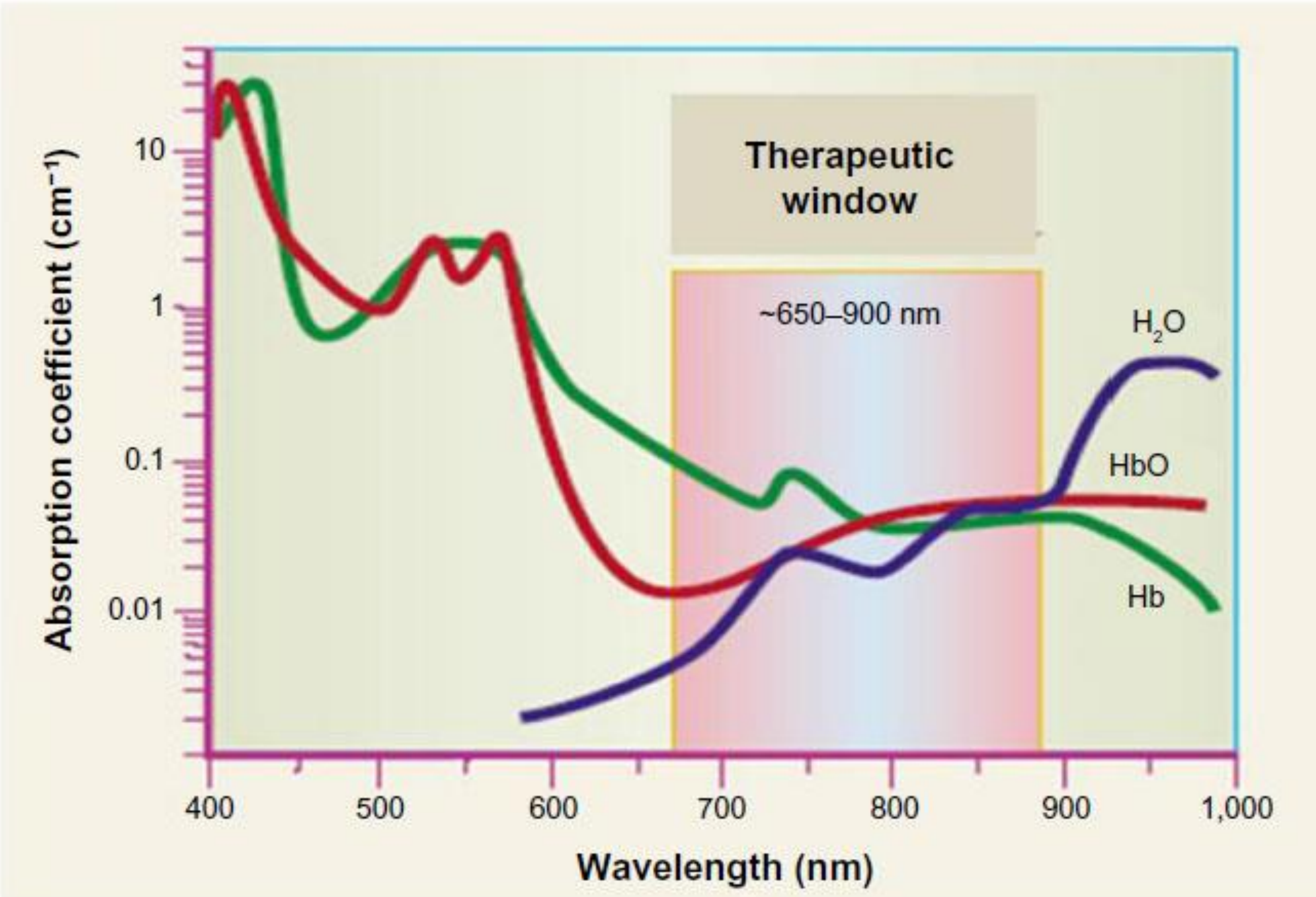
- Among three functional groups in the HEPES molecule (hydroxyl, sulfonate, and piperazine), piperazine is responsible for generating branched structure





DIC Wang *et al*., *Chem. Mater.* **2007,** *19,* 2823-2830

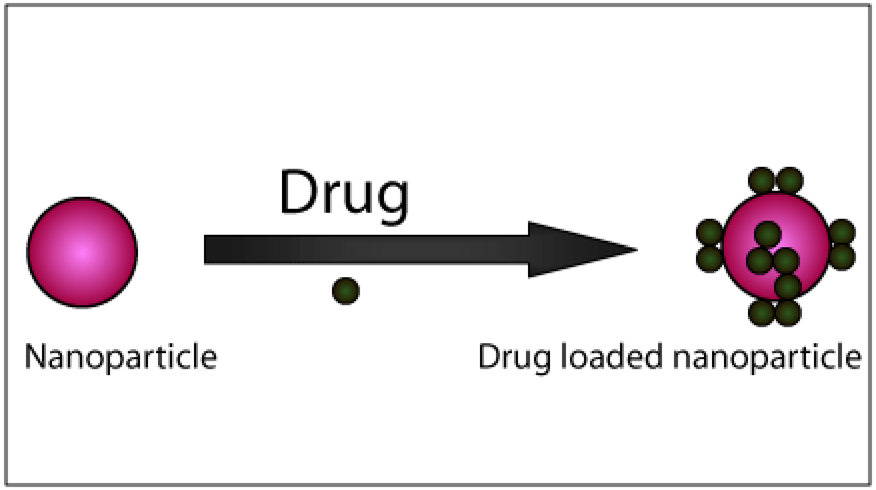
Biologically transparent window

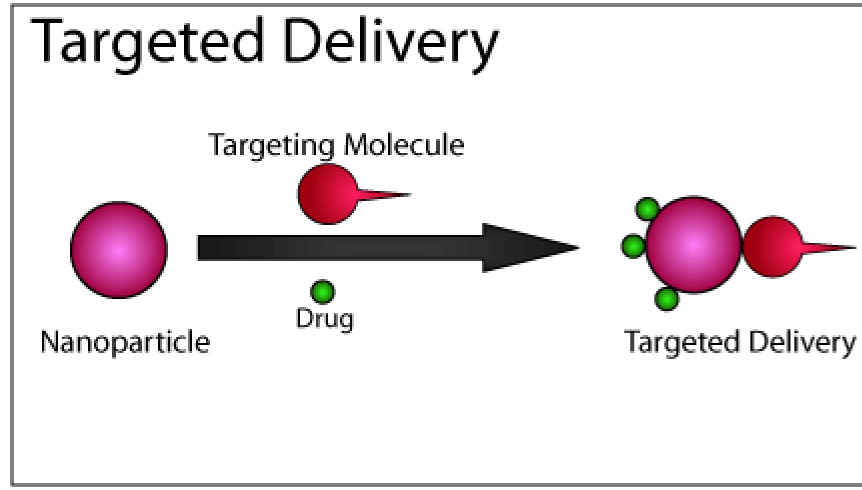


- Wavelengths of light from 650 nm to 900 nm are minimally absorbed and preferentially scattered upon interaction with tissue allowing for deeper light penetration than possible at other optical wavelengths

Dovepress, **2015**, 7, 193-209

Targeted drug delivery





Nonspecific

Targeted to the specific part to treat in the body

Type and property of various targeting molecules for NPs. Modified from ref. [242].

Type	MW (kDa)	Diameter (nm)	Features
Monoclonal antibodies			
Whole antibodies	150	15–20	High affinity, divalent, many clinically approved examples, contains biologically active constant (Fc) region, long circulation
Engineered fragments (monovalent)			
ScFv	25	3–5	Lowered affinity, rapid clearance from circulation, renal retention, reduced stability, reduced immunogenicity
Fab′	50	5–10	Can be produced genetically or enzymatically by cleavage of monoclonal antibodies
Nanobody	15	2–3	Smallest antigen-binding fragment, single domain, can bind cryptic epitopes
Engineered fragments (divalent)			
$F(ab')_2$	100	10–15	Improved affinity, can be engineered to a variety of sizes and arrangements of protein domains
Diabodies	50–80	5–10	Mono-specific or bi-specific dimer of ScFv
Minibodies	80	10	Can be produced genetically
Aptamers			
RNA/DNA	10–30	2–3	Rapid clearance, automated chemical synthesis, susceptible to nucleases without chemical modification
Receptor-ligands			
Whole proteins	30–150	Variable	Produced using recombinant DNA technologies, can be biologically active, susceptible to proteases
Peptides	0.5–10	Variable	Facile synthesis and modification, diverse libraries and screening technologies, susceptible to peptidases, renal retention
Small molecules	0.1–1.0	0.5–2.0	Chemical synthesis, simple modification and coupling chemistries, can be biologically active, highly variable affinities

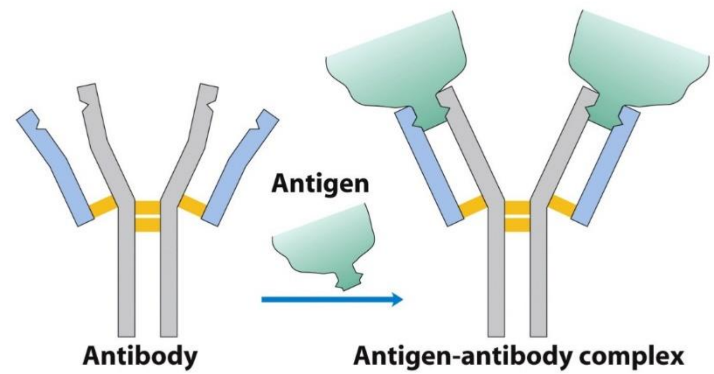
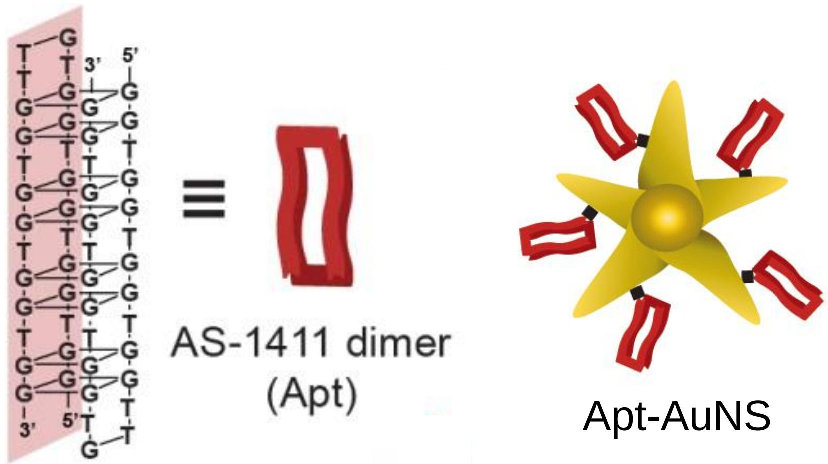
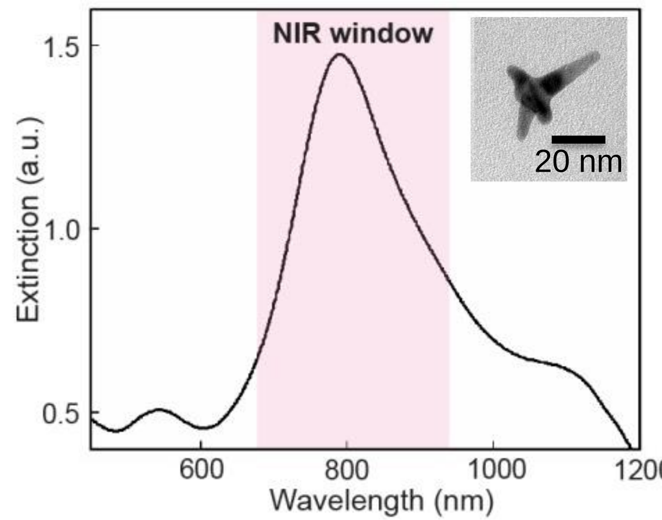
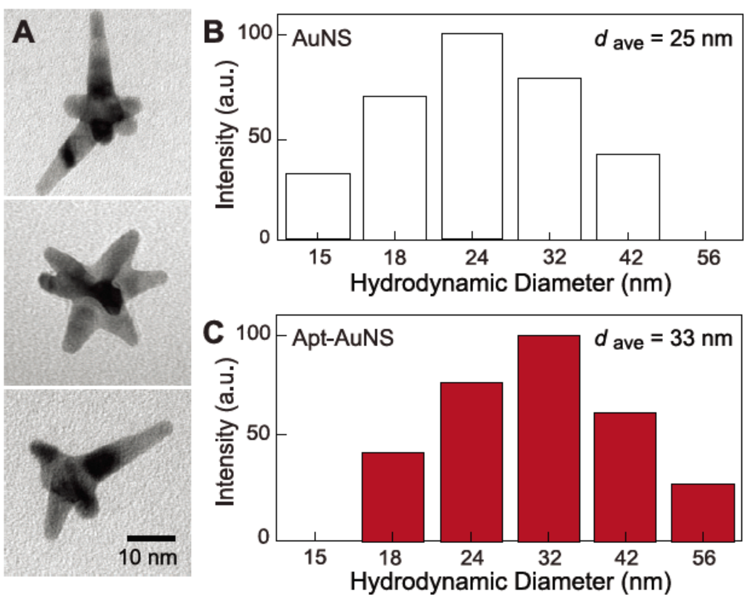


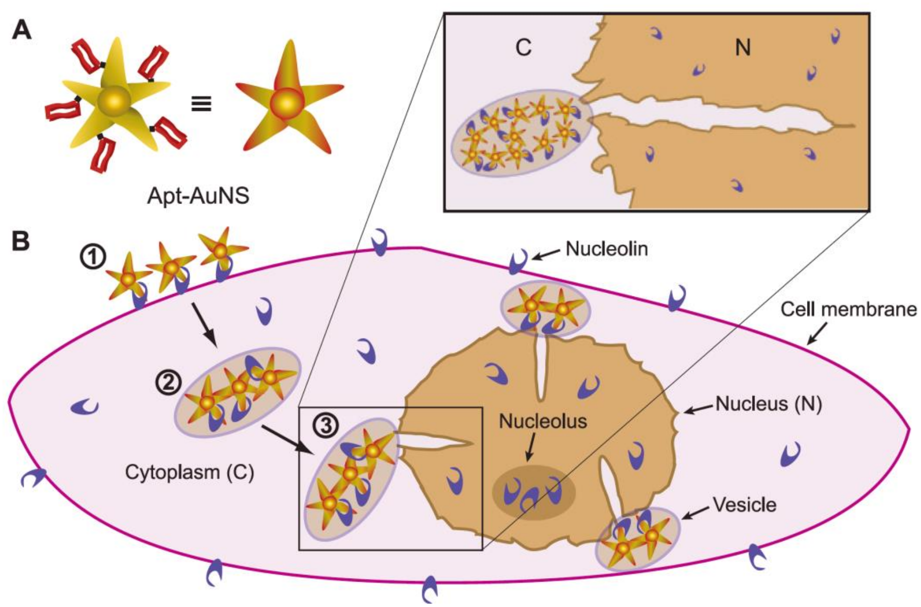
Figure 5-22
Lehninger Principles of Biochemistry, Fifth Edition

Gold nanostar based DDS-release of drug









ACS Nano, **2012**, *6, 3318*

Cell image

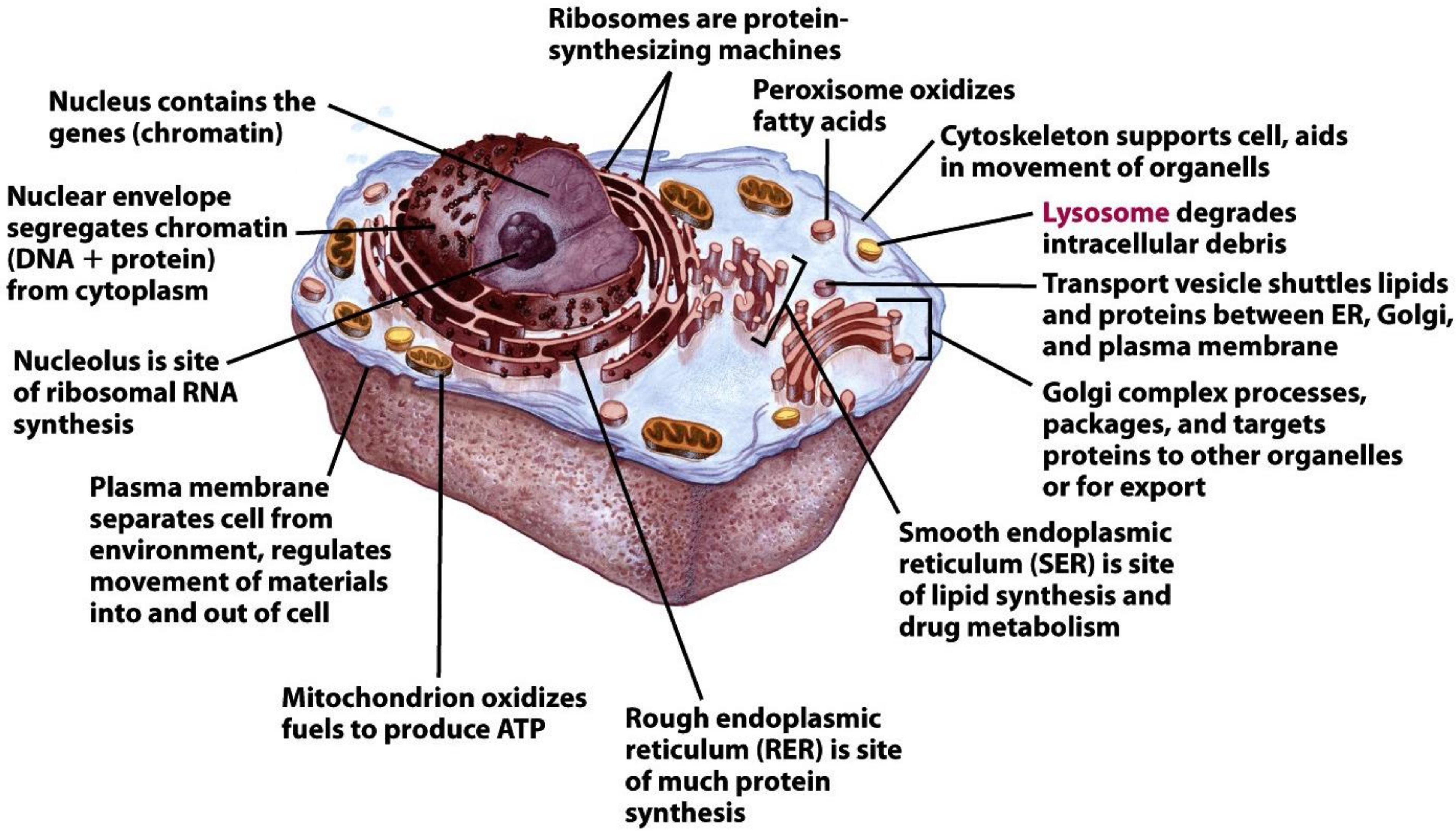
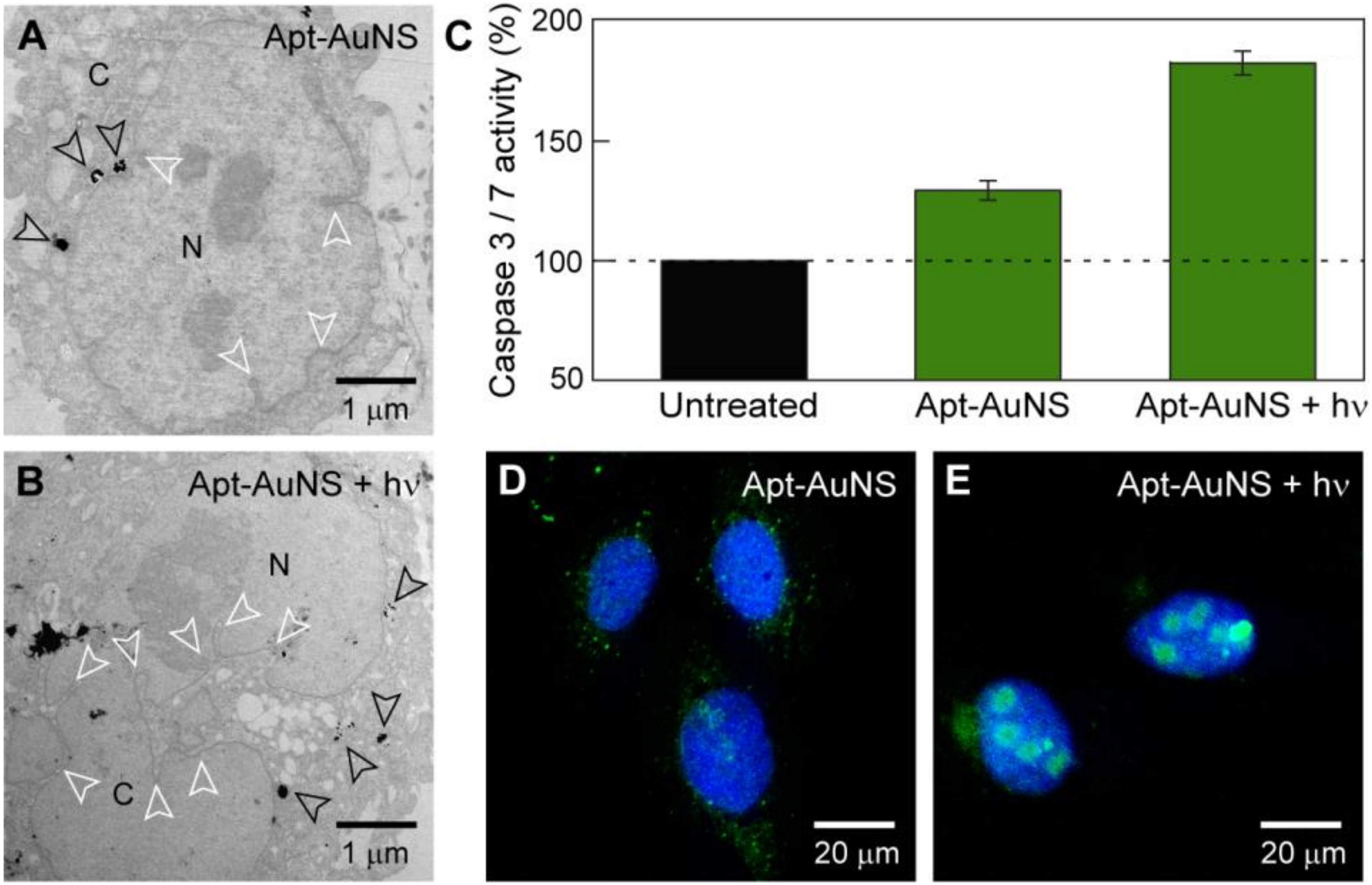


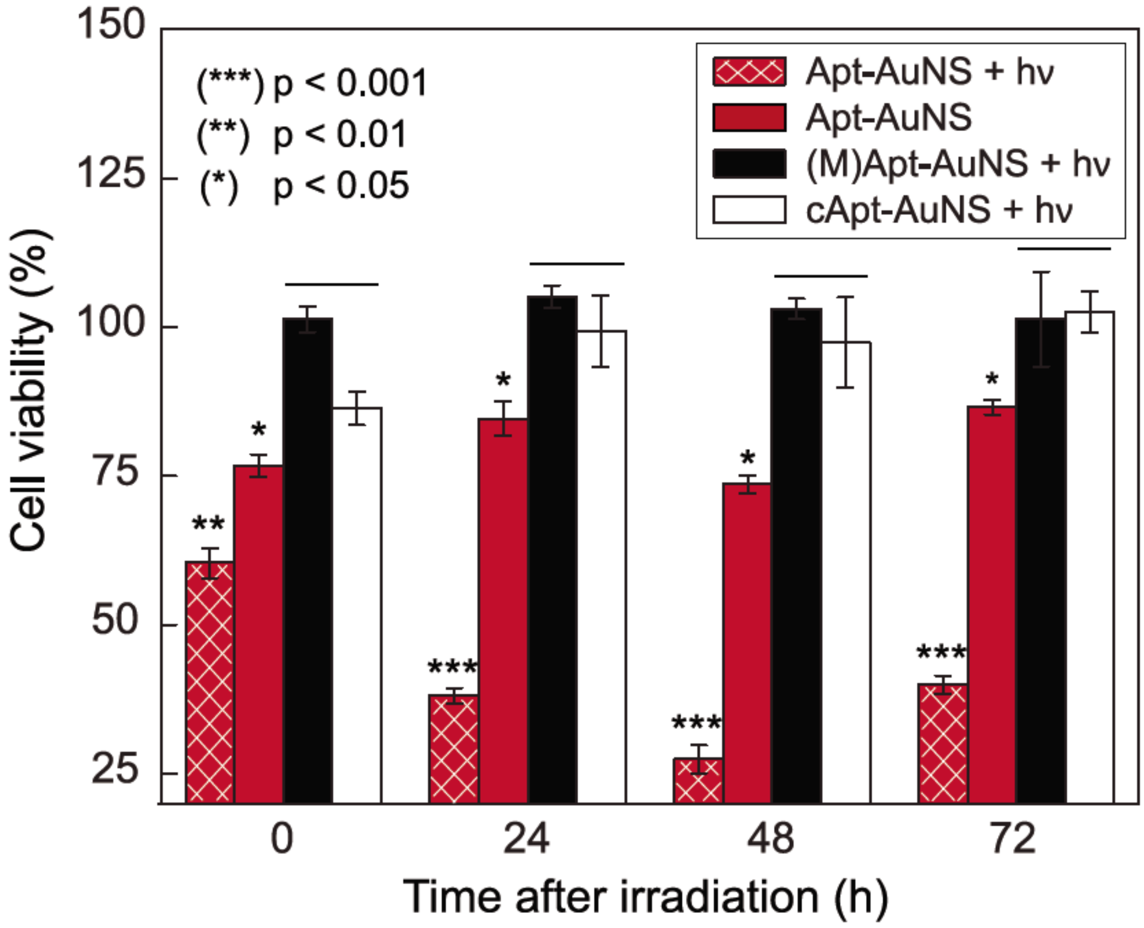
Figure 1-7a
Lehninger Principles of Biochemistry, Fifth Edition

Gold nanostar based cancer treatment



ACS Nano, **2012**, *6, 3318*

Cell viability assay

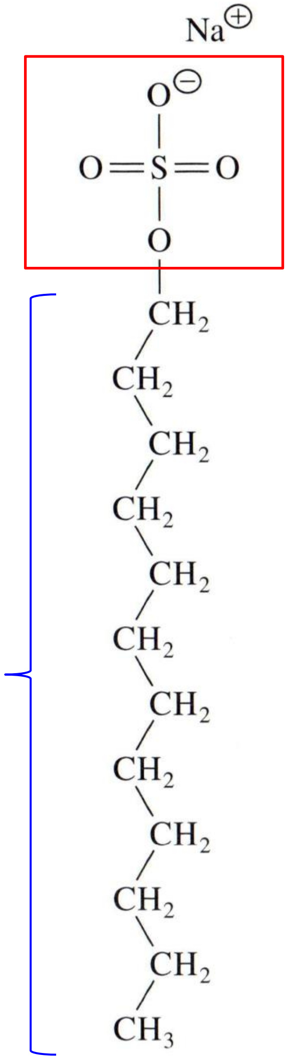


ACS Nano, **2012**, *6, 3318*

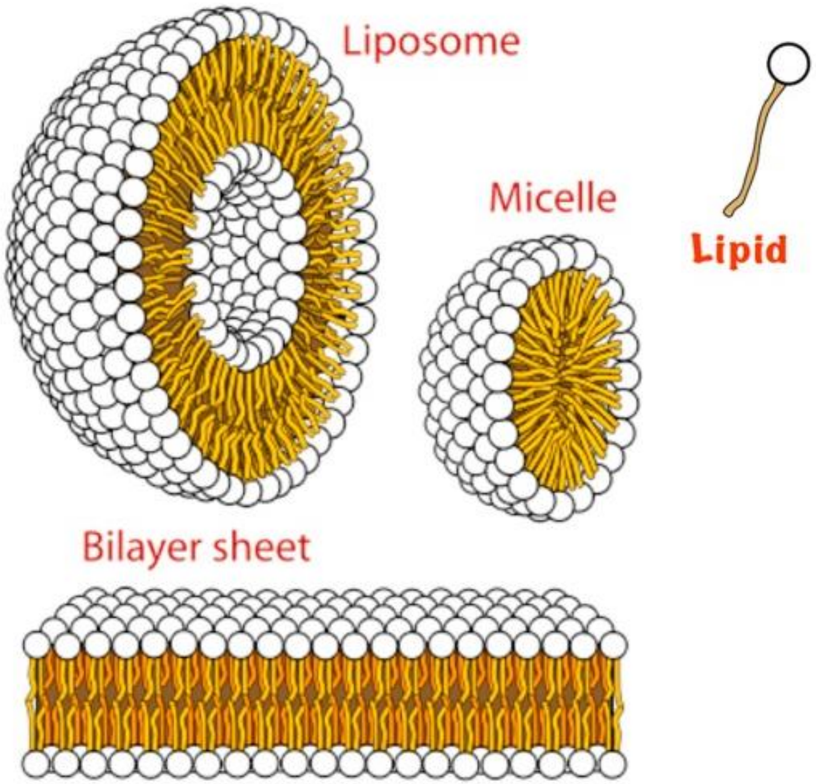
Self assembly of surfactants

Synthetic detergent commonly used in biochemistry: Sodium dodecyl sulfate (SDS)

Polar “sulfate” group



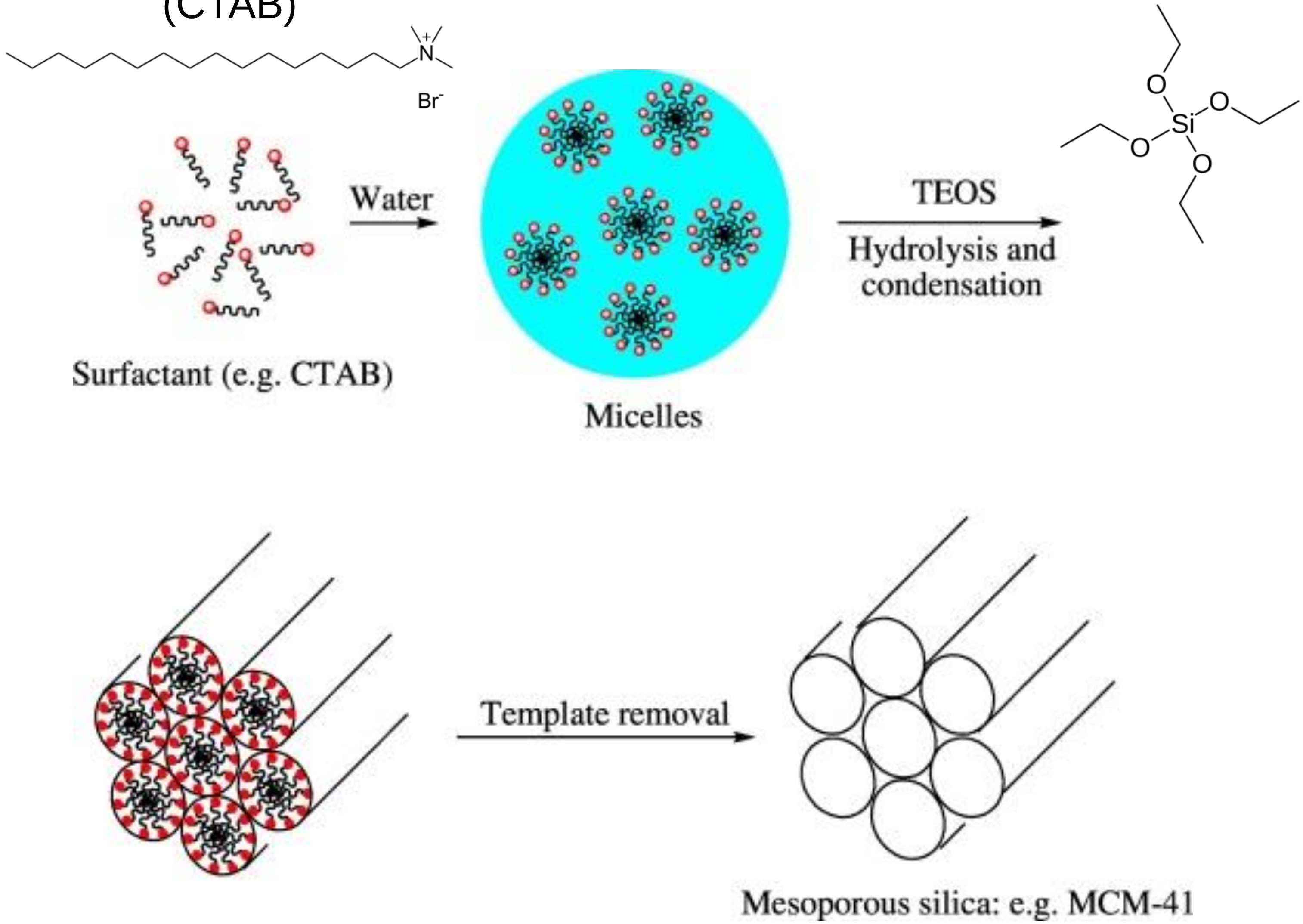
Nonpolar “$(CH_2)_{12}$” chain



Synthesis of mesoporous materials using surfactants

Cetyl trimethylammonium bromide (CTAB)

Tetraethyl orthosilicate (TEOS)



J. Control. Release **2017**, *262 (28)*, 329

Synthesis of AuNR/mSiO_2 core/shell structure

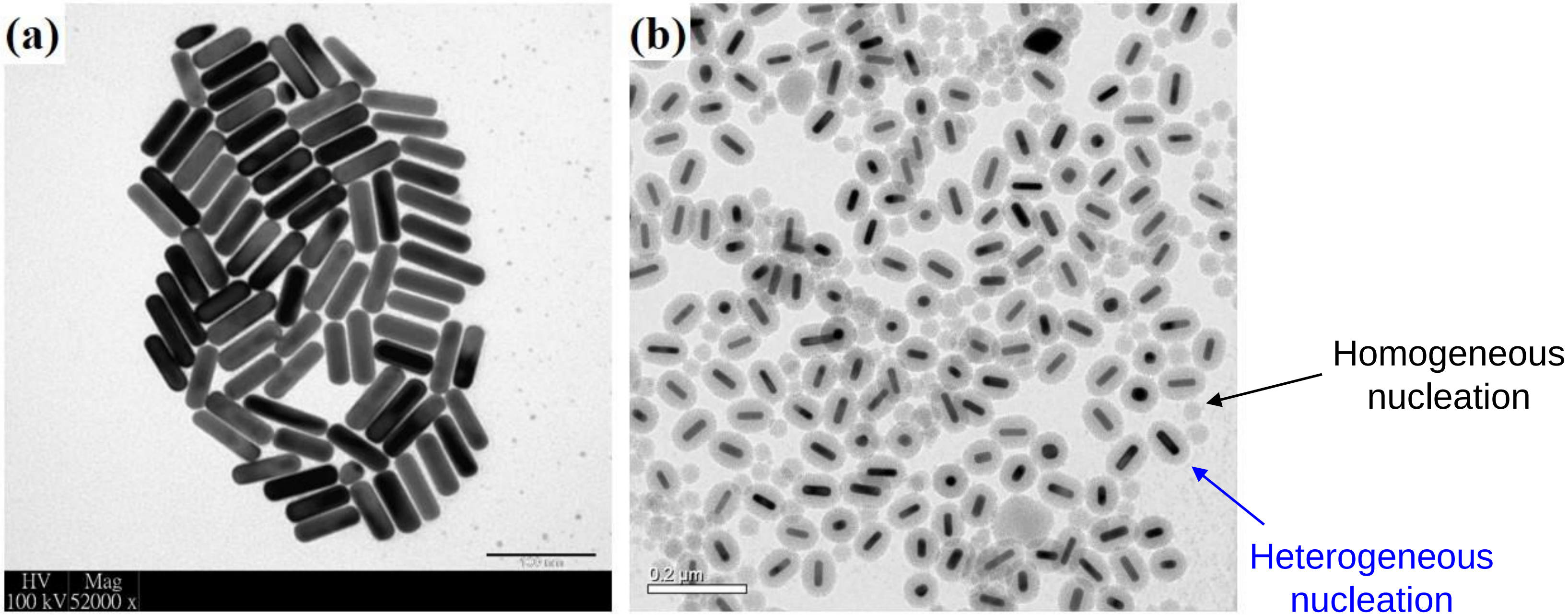
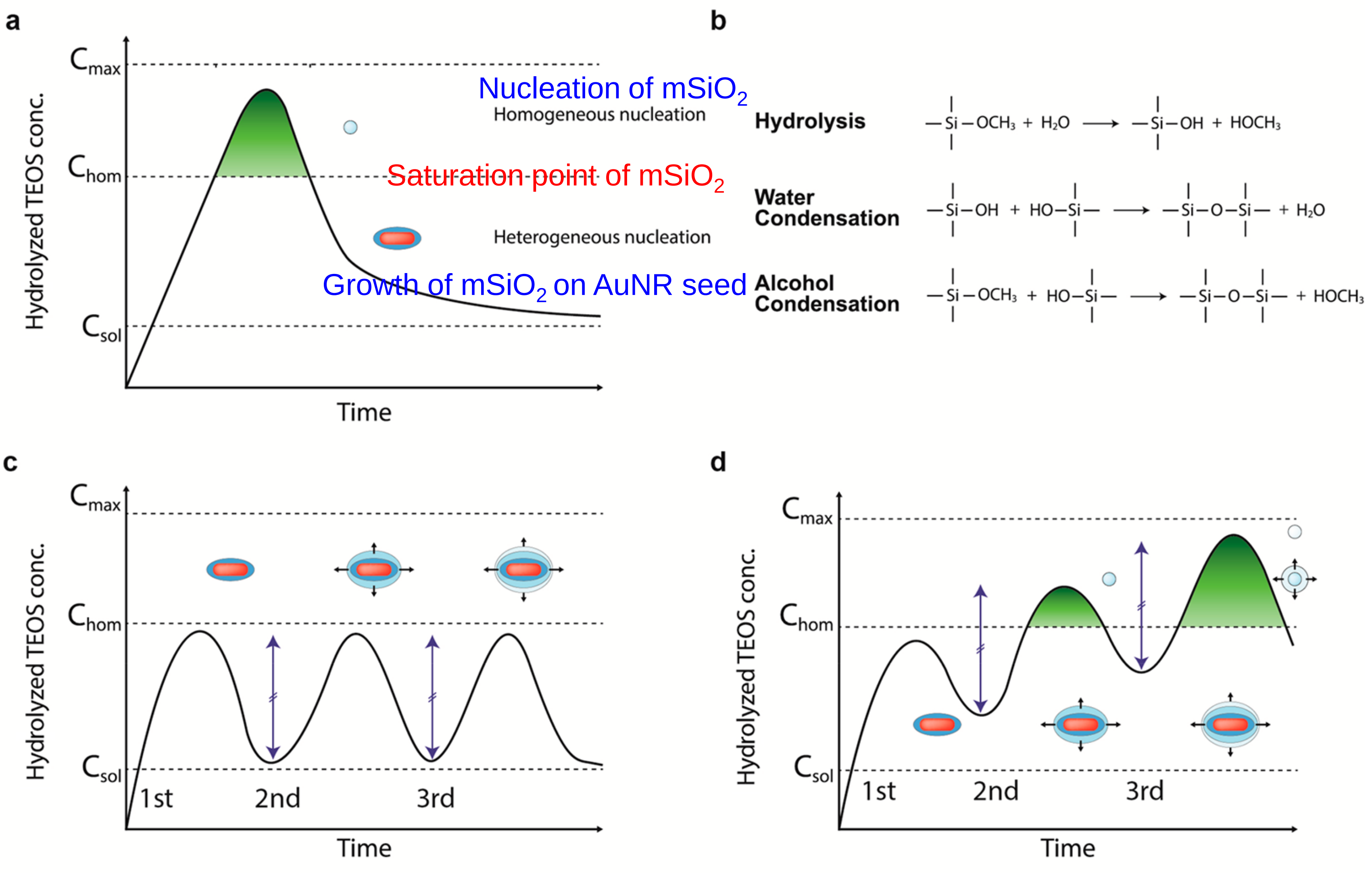


Fig. 1. TEM images of (a) AuNRs and (b) AuNR@mSiO_2 nanoparticles.

- Homogeneous nucleation: nuclei that are spontaneously generated and grow irreversibly to form a new phase.
- Heterogeneous nucleation: nuclei are formed on alien surfaces or particles, or pre-existing nuclei in the old phase.

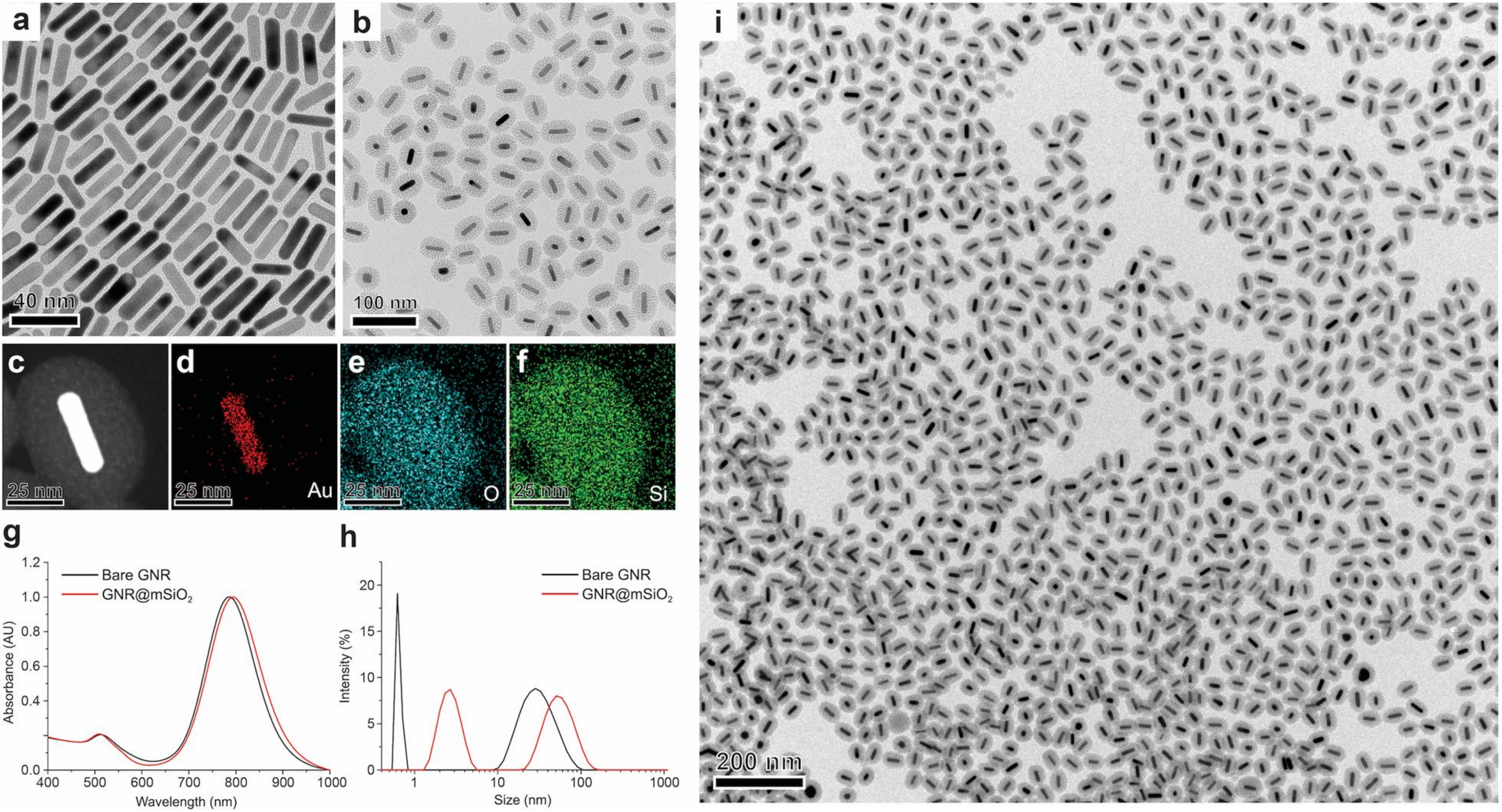
https://www.frontiersin.org/10.3389/conf.FBIOE.2016.01.01053/event_abstract

AuNR/mSiO$_2$ core/shell structure



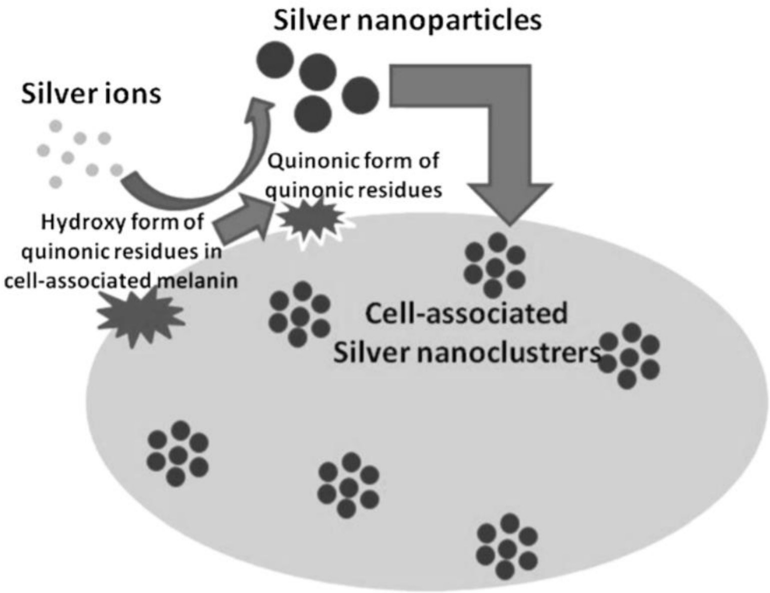
Cryst. Growth Des. **2018**, *18 (8)*, 4731

Highly monodisperse AuNR/mSiO$_2$

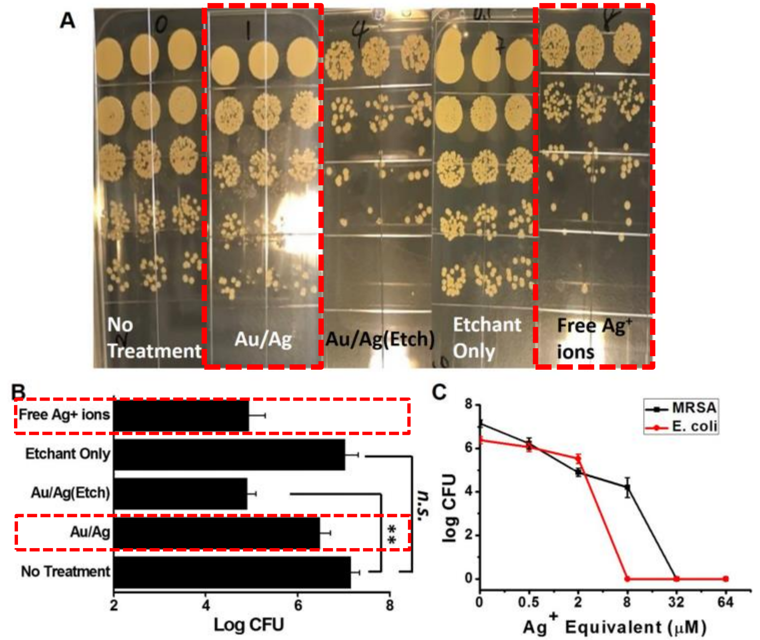


Cryst. Growth Des. **2018**, *18 (8)*, 4731

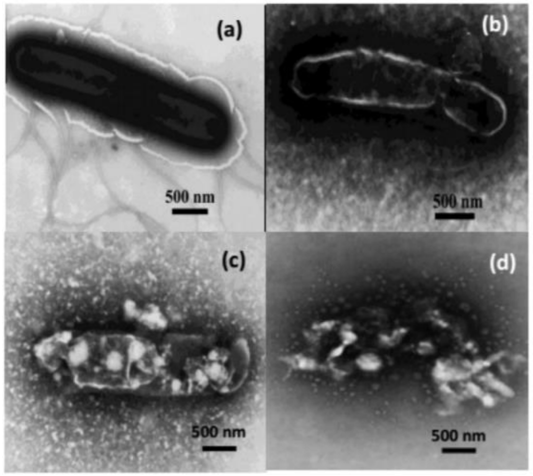
Antibacterial property of AgNP



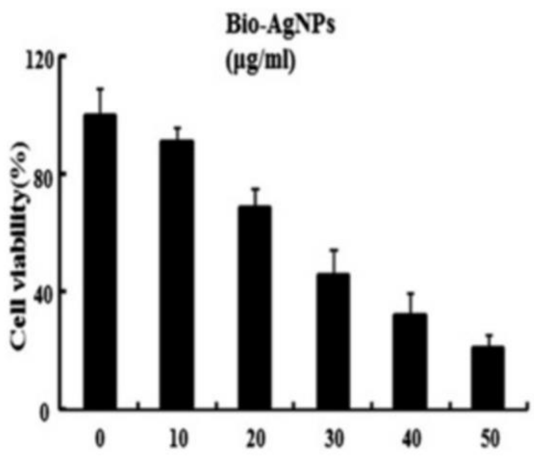
AMB Express, **2013**, 3-32



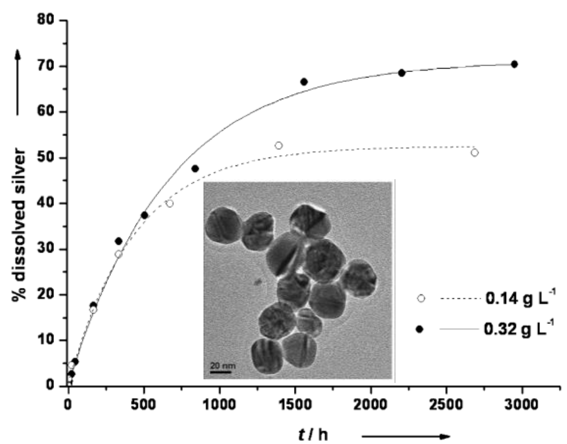
ACS Nano, **2018**, 12, 5615−5625



Text. Res. J., **2017,** 1377–1386

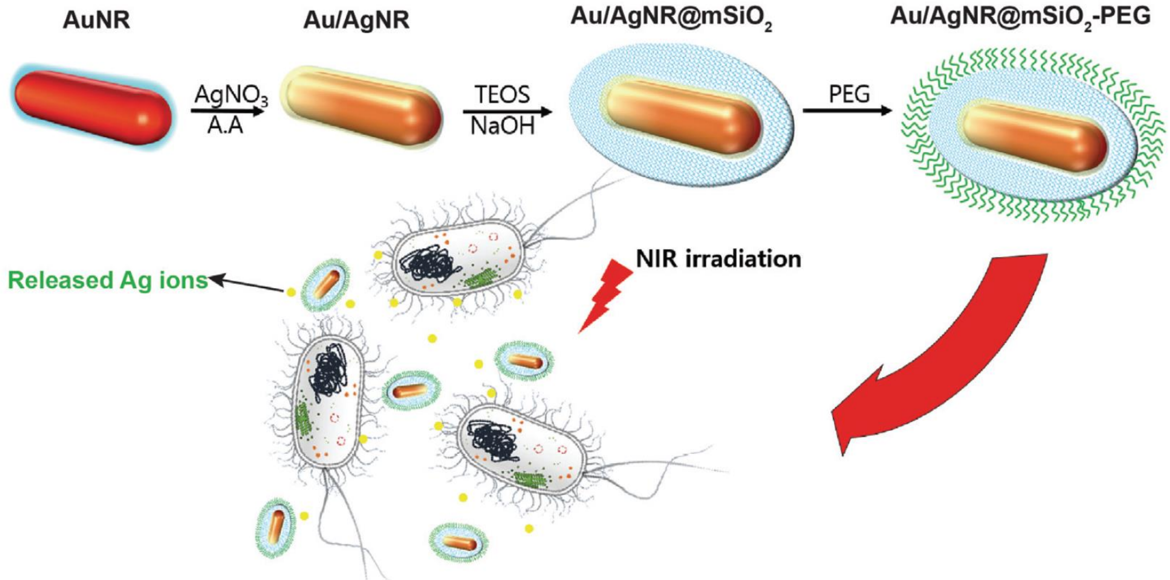


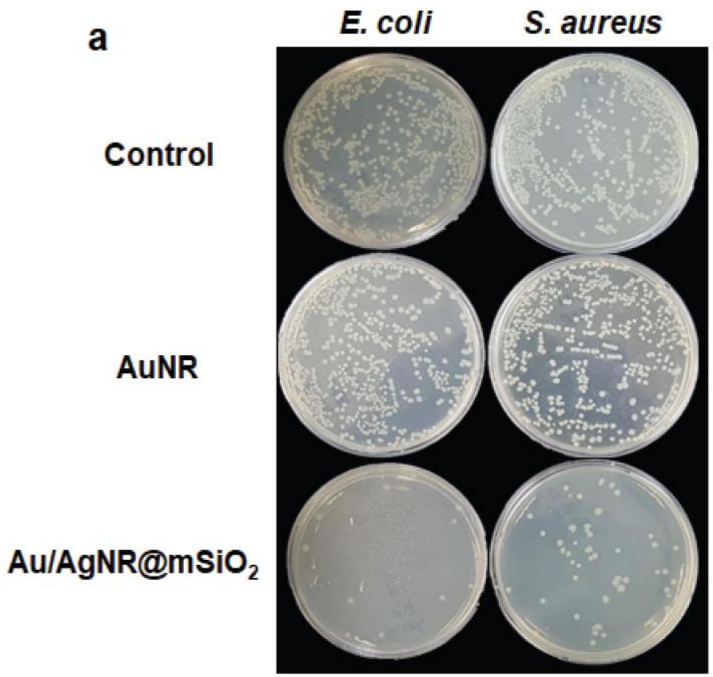
Nanoscale Res. Lett, **2014,** 9, 459

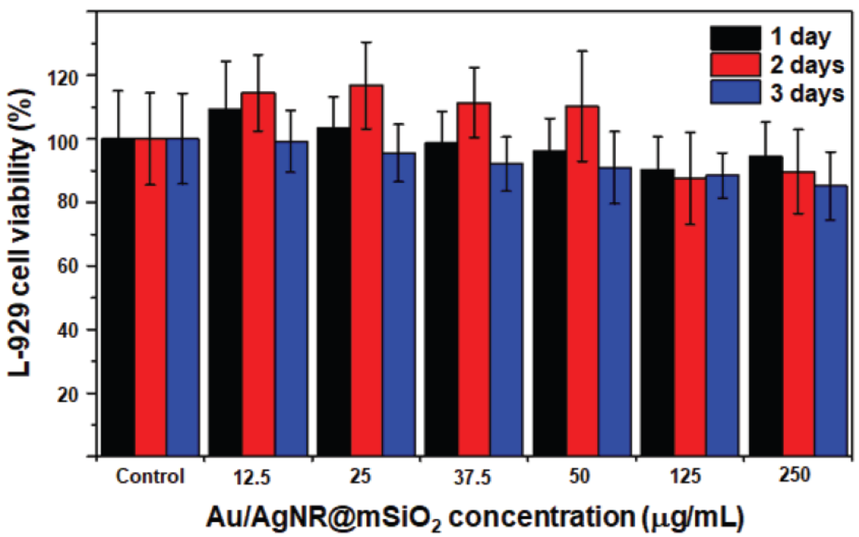


Angew. Chem, **2013,** 52, 1636–1653

Gold/silver nanorod for anti-bacterial applications

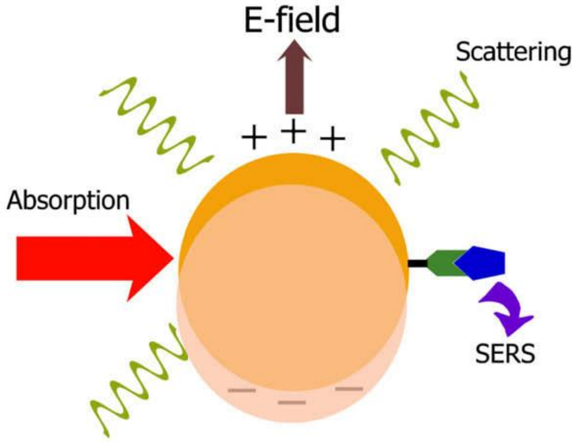




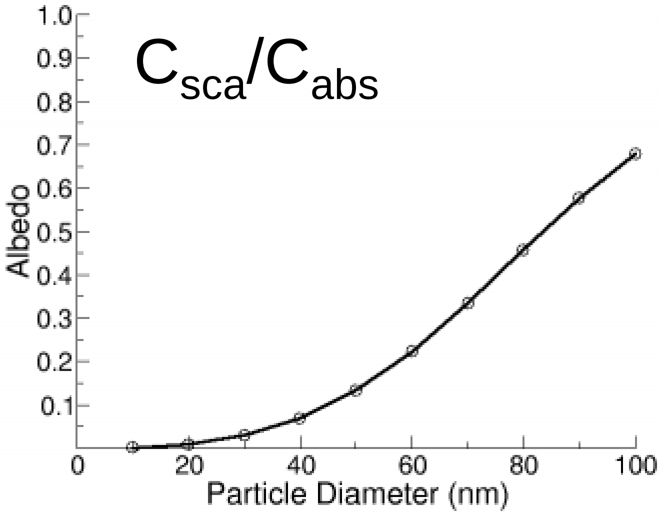


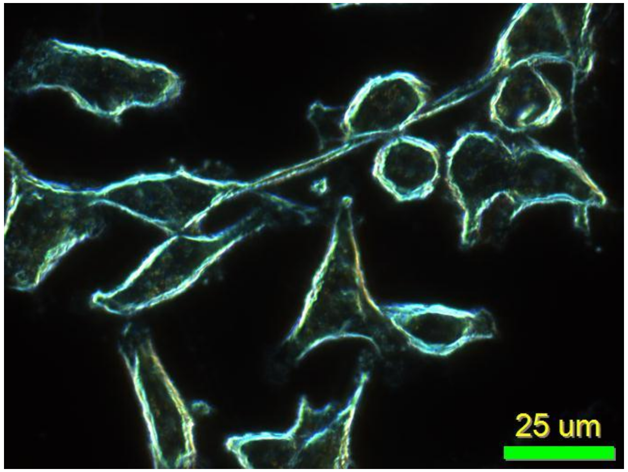
BioChip J., **2019,** *13 (4)*, 362

Dark field imaging of cancer cells

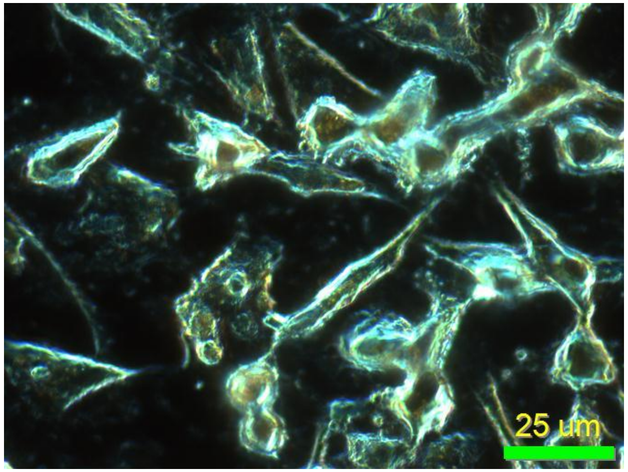


Chem. Phys. Lett. **2010**, *487*, 153

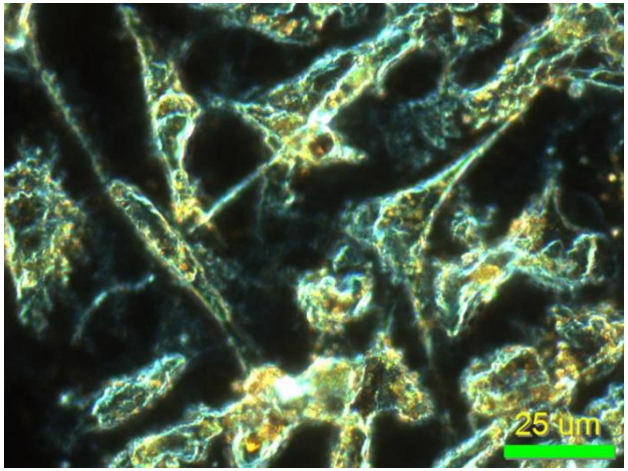




13 nm AuNP
x 20 times concentrated



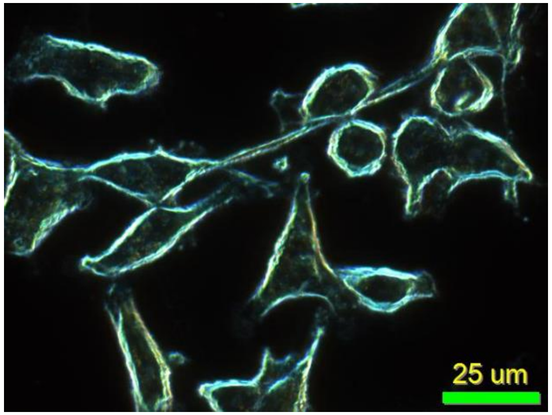
50 nm AuNP



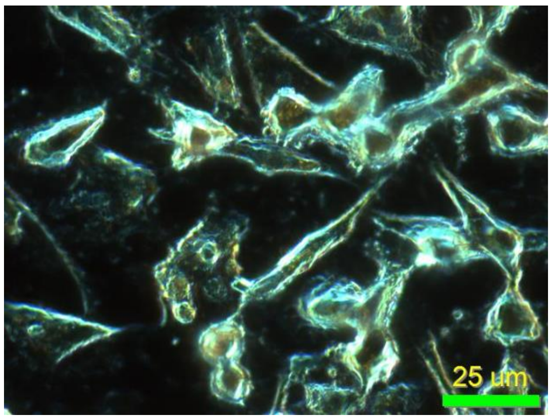
100 nm AuNP

Langmuir, **2015**, 31, 13773

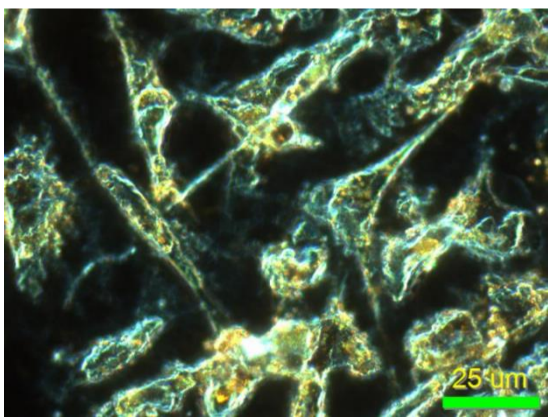
Dark field imaging of NPs



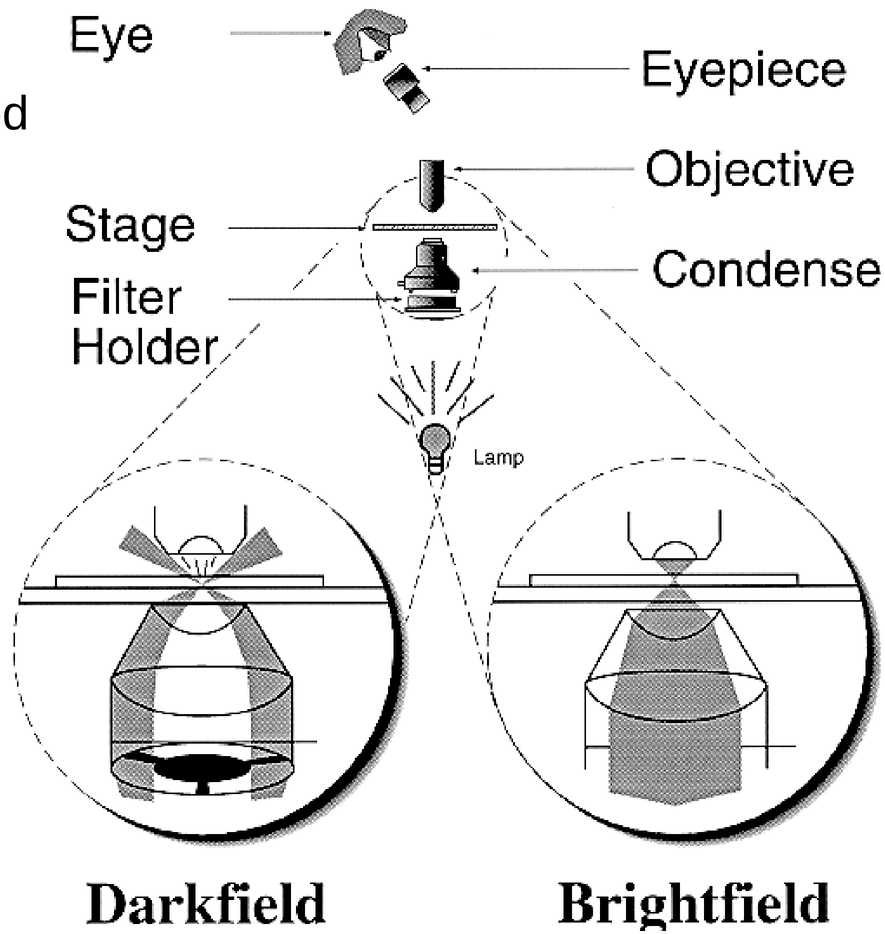
13 nm AuNP
x 20 concentrated



50 nm AuNP

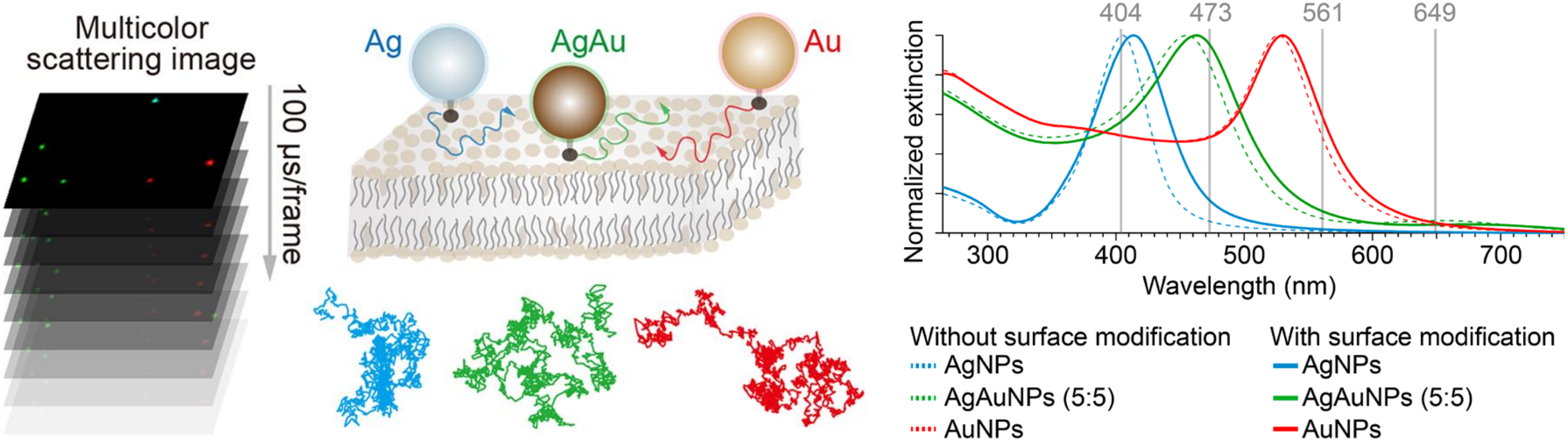


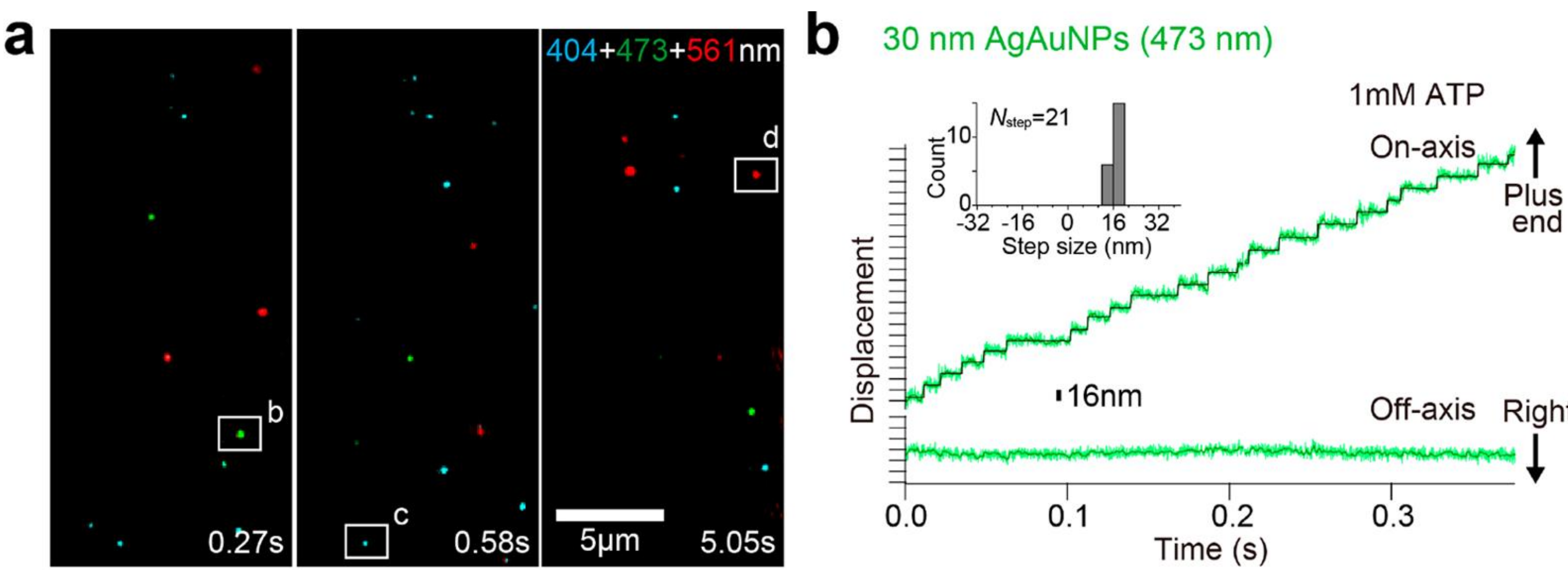
100 nm AuNP



Imaging single molecule movement

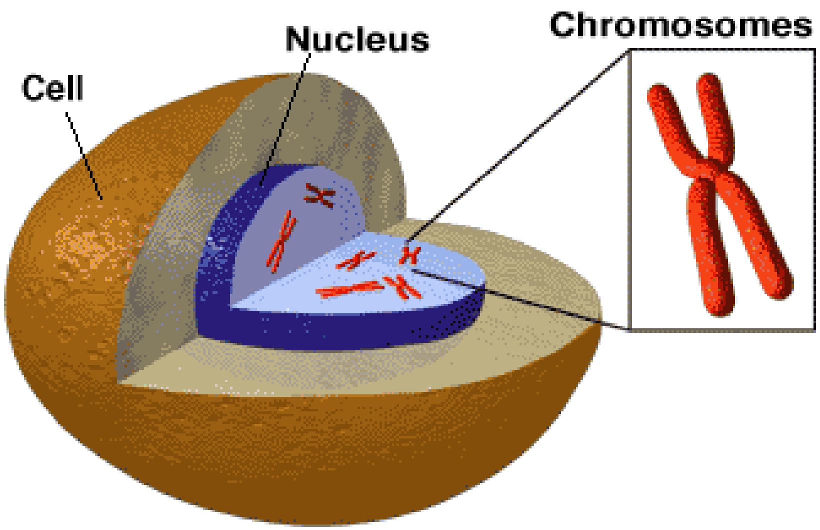
Multicolor tracking of single biomolecules using plasmonic NPs



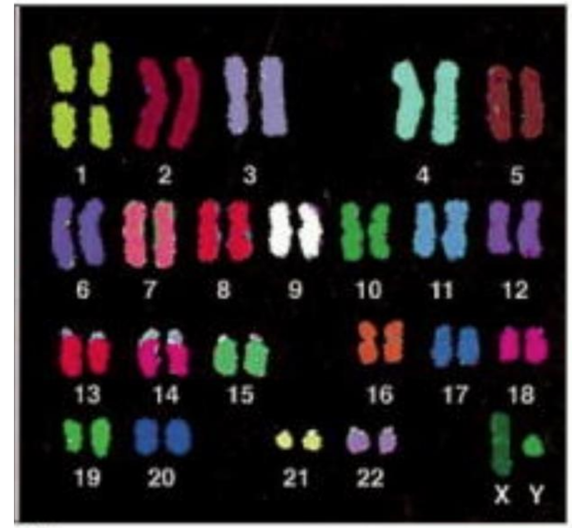


ACS Photonics **2019**, *6*, 2870−2883

Dimension of genomic DNA molecules

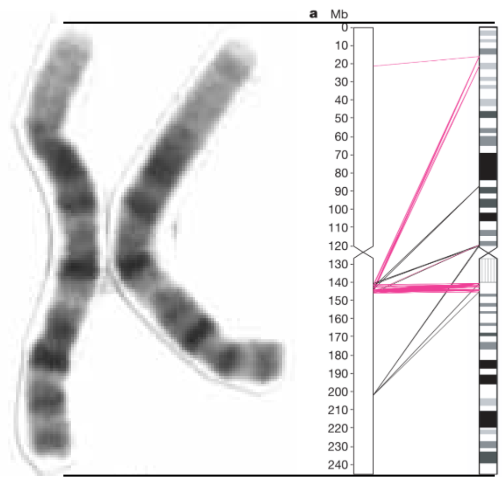


Iowa Public Television, 2004

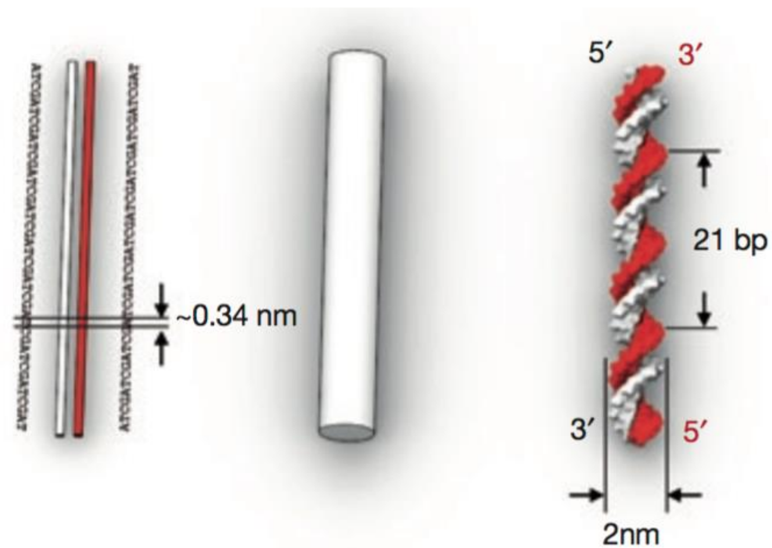


Science, **1996**, 273, 494–497

Chromosome no.1
2.5×10^8 bp= 85 mm
(0.34 nm/1 bp)



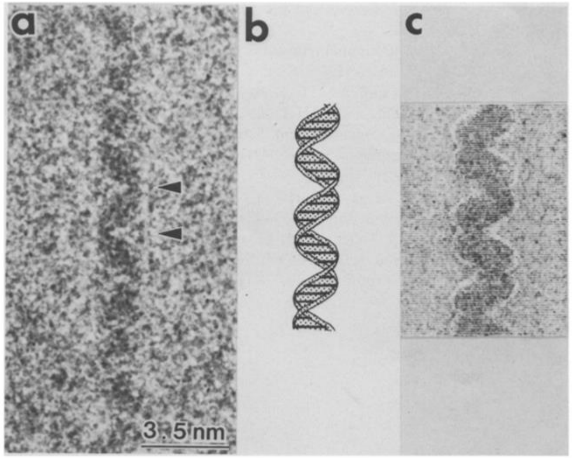
Nature. **2006**, 441, 7091, 315–321



Nat. Methods, **2011**, 8, 221–229

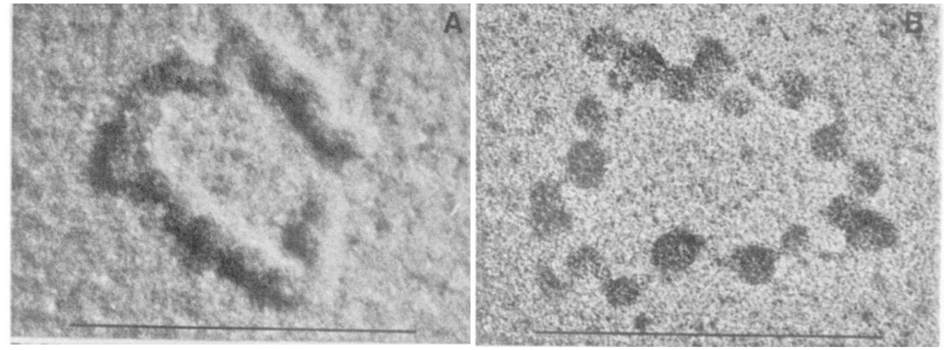
Transmission Electron Microscopy (TEM) based DNA visualization

Double helical B-form DNA structure



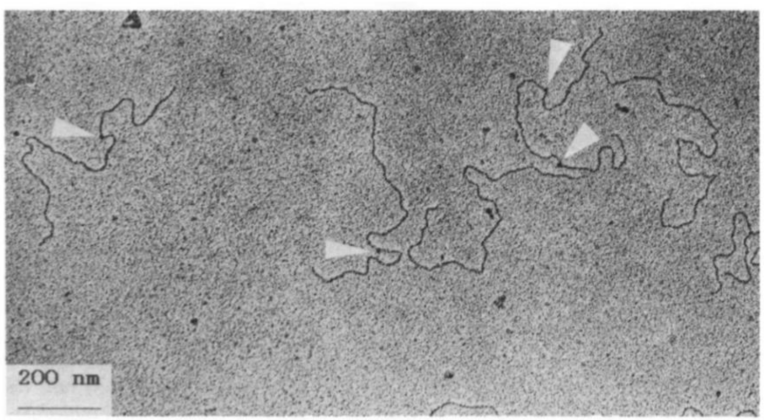
Ultramicroscopy, **1981**, 7, 189

DNA-protein complex (chromatin)



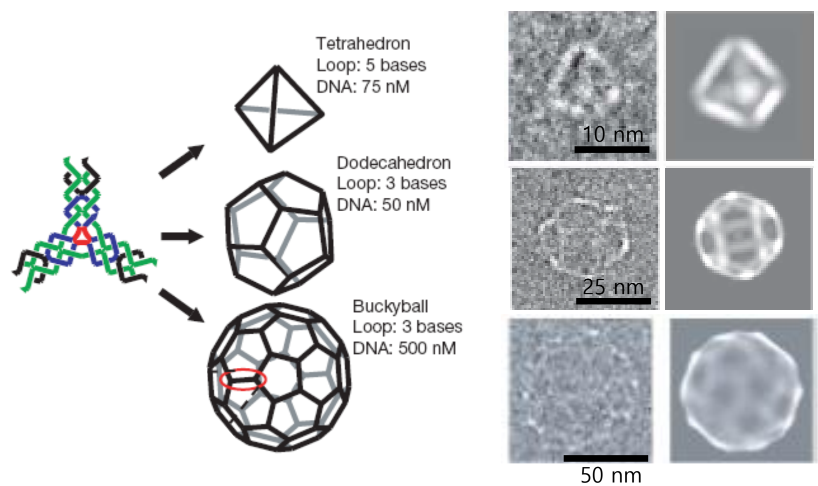
Science, **1975**, 187, 1202

Sequence specific mapping



Nucl. Acids Res., **1994**, 22, 5218

DNA nanostructures

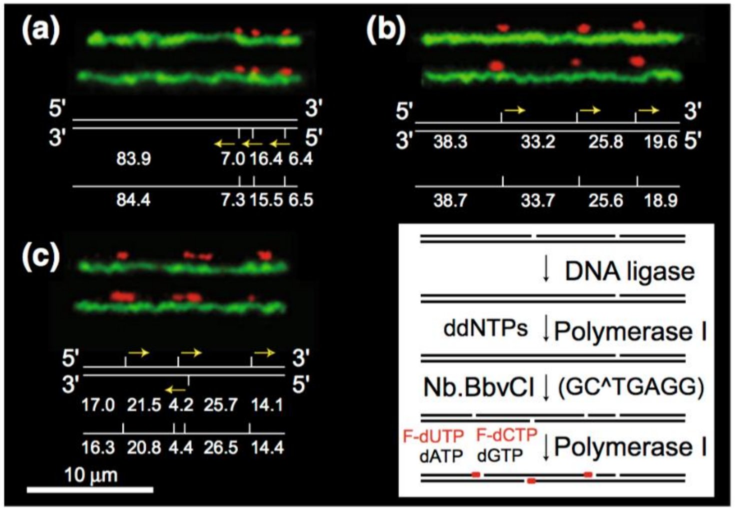


Nature, **2008**, *452*, 198

SUNG KYUN KWAN UNIVERSITY (SKKU)

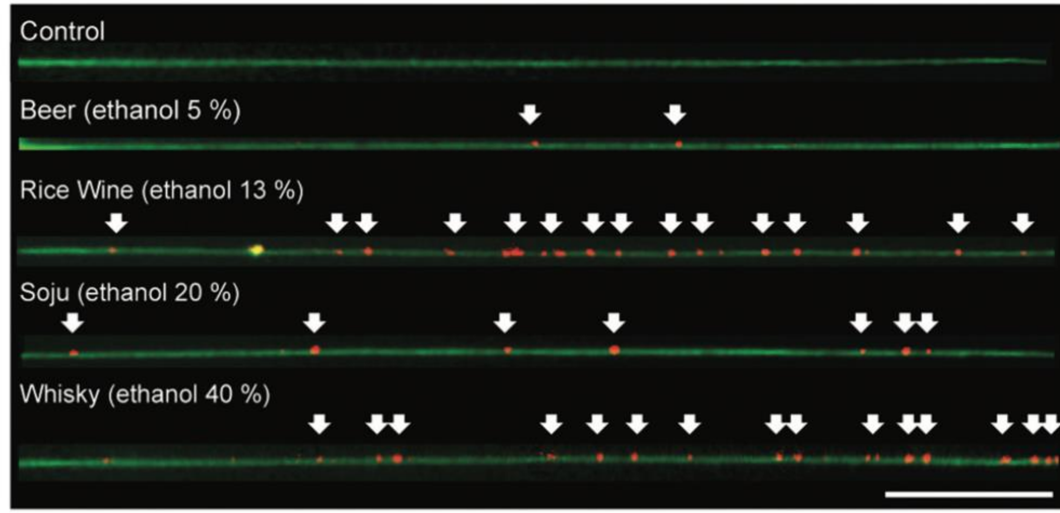
Fluorescence imaging for genomic DNA studies

High-throughput sequencing



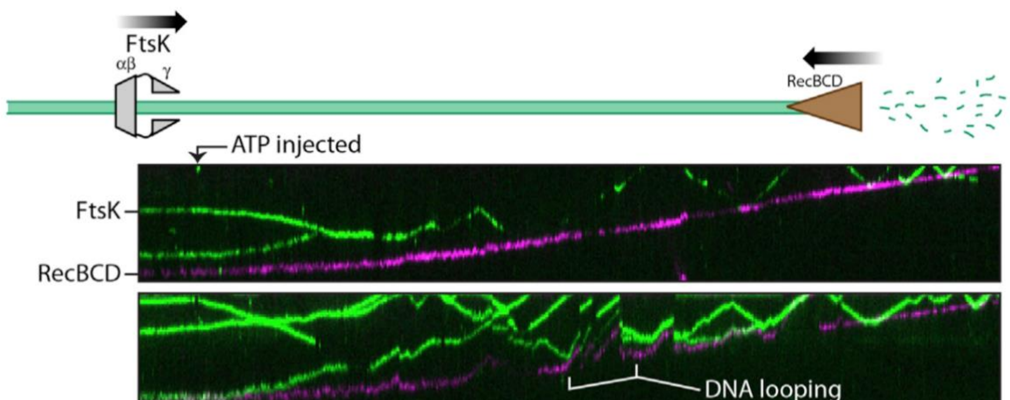
PNAS, **2007**, 104, 2673-2678

DNA damages



Analyst, **2016**, 141, 4326–4331

DNA-protein interactions



Mol. Cell., **2014**, 54, 832–843

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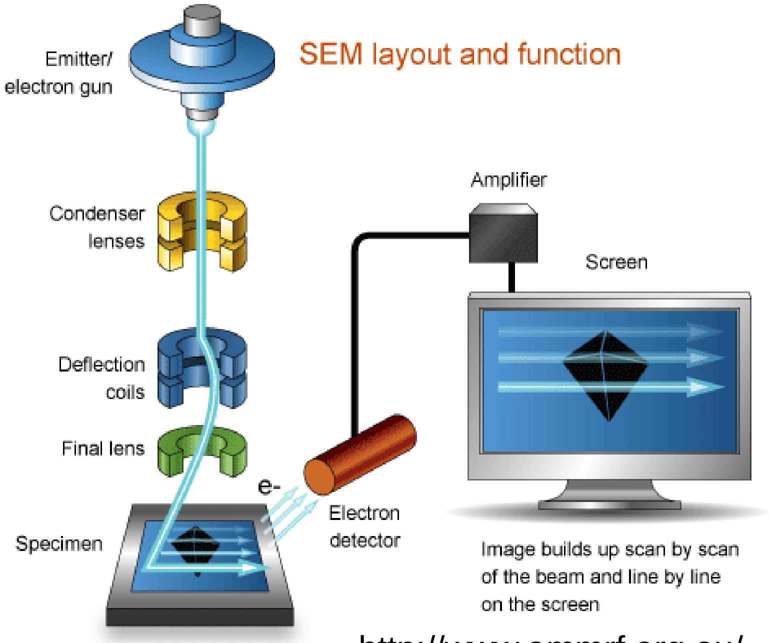
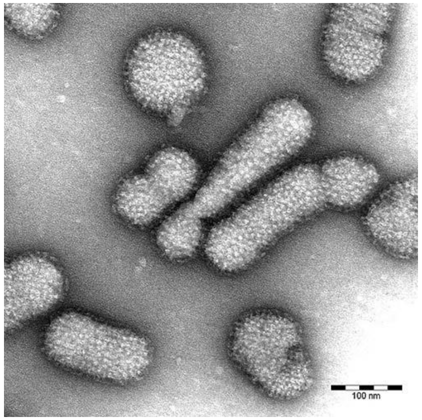
Scanning Electron Microscopy (SEM) imaging

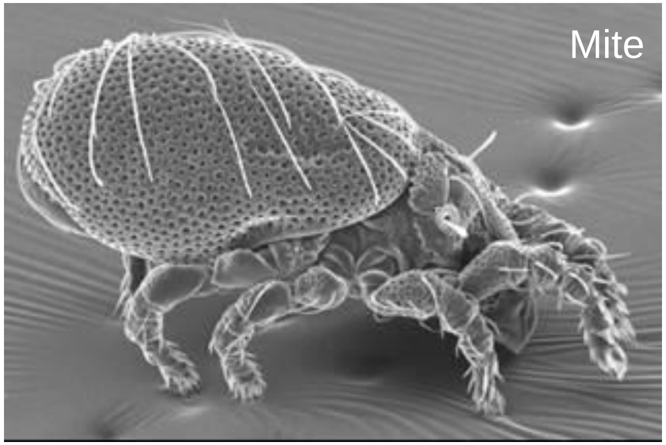


http://www.ammrf.org.au/

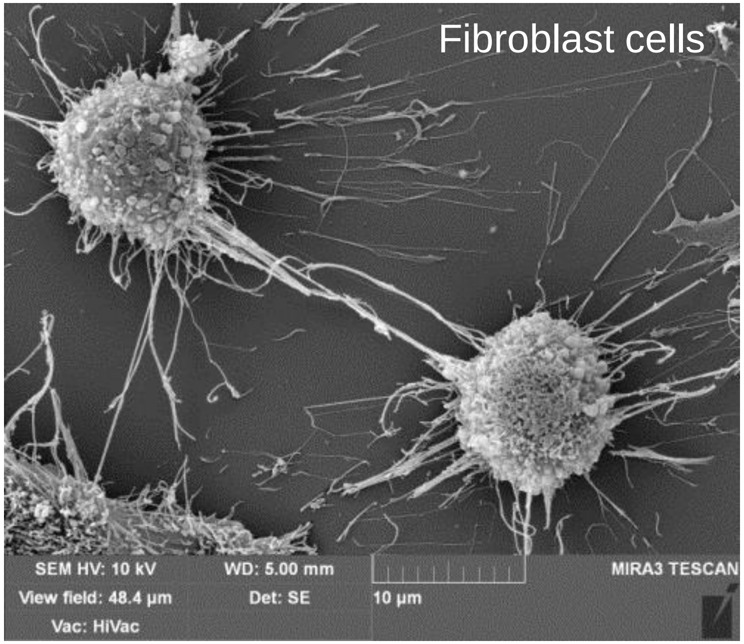
Avian flu virus



UAF Center for Distance Education

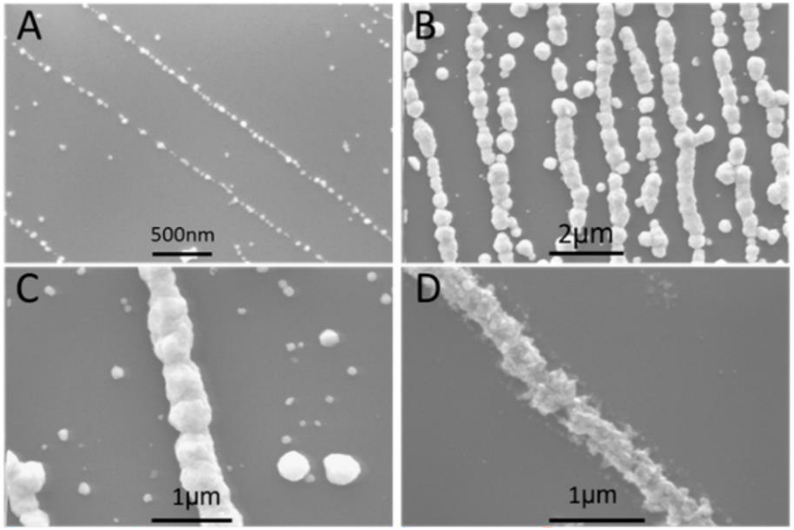


The James Hutton Institute

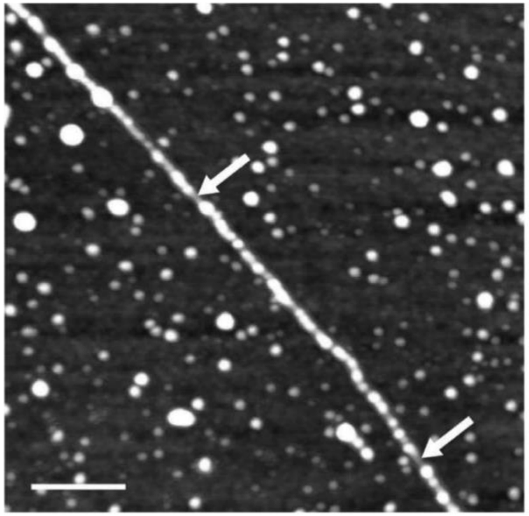


www.tescan.com

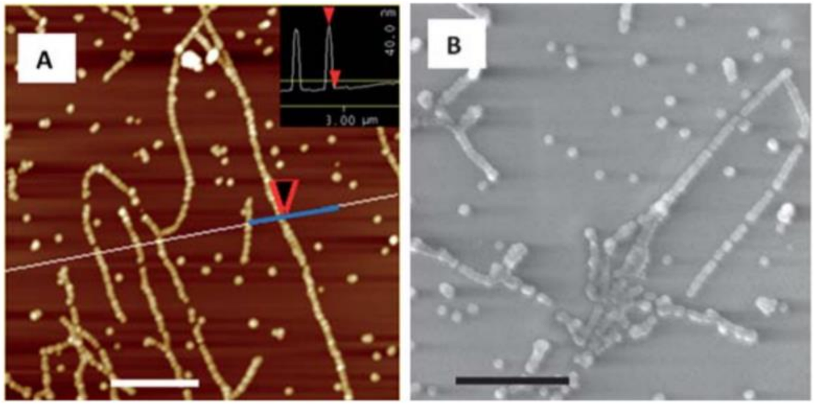
Limitation of current DNA metallization strategies

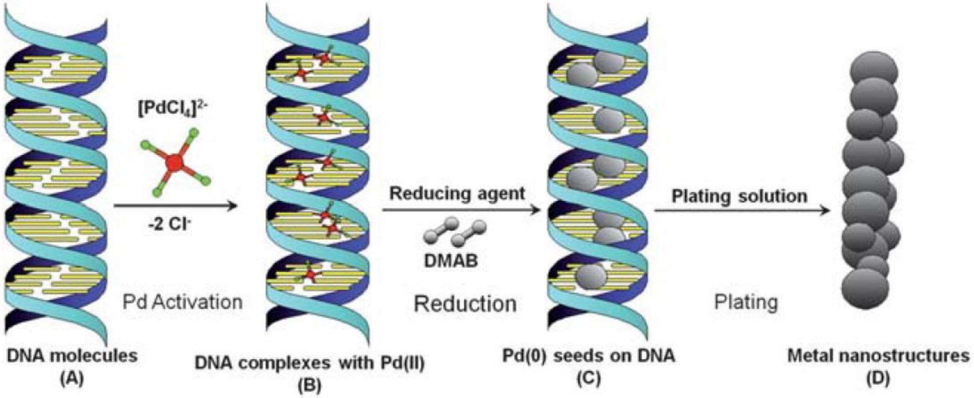


Langmuir, **2013**, 29, 11176−11184



Langmuir, **2010**, 26(3), 2068–2075





J. Mater. Chem., **2011**, 21, 12126–12131

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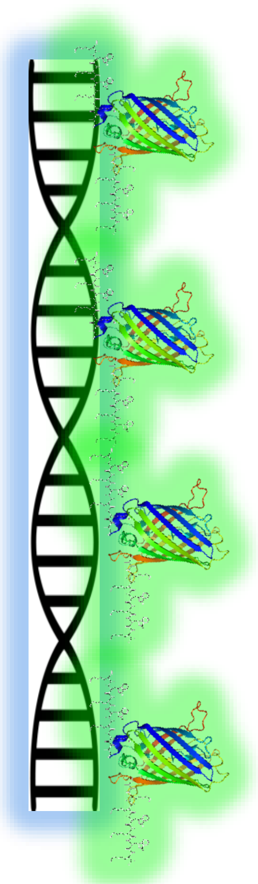
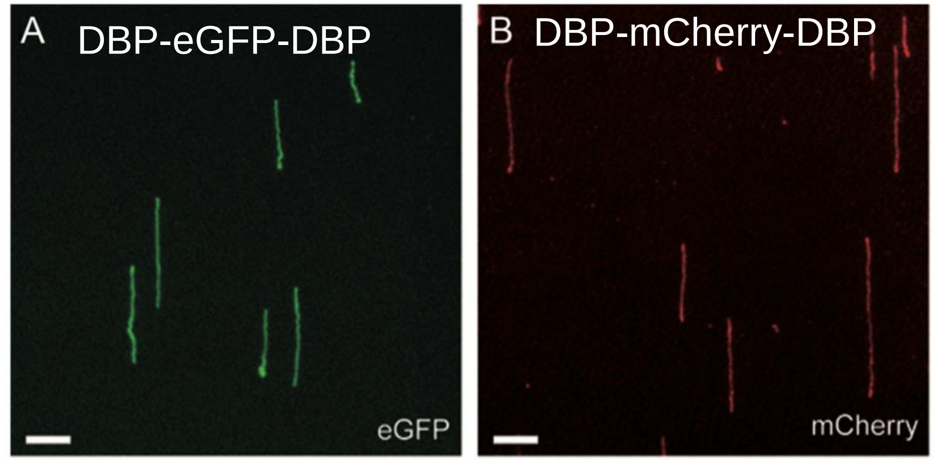
DNA binding peptide (DBP) based DNA imaging

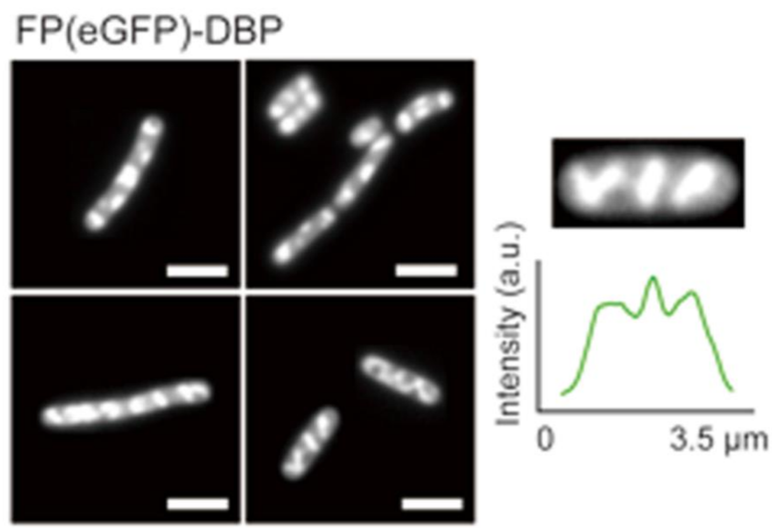
KWKWKKA-FP-AKKWKWK
FP: eGFP, mCherry



Design of DBP based fluorescence imaging



Imaging DNA of live *E.coli* cells



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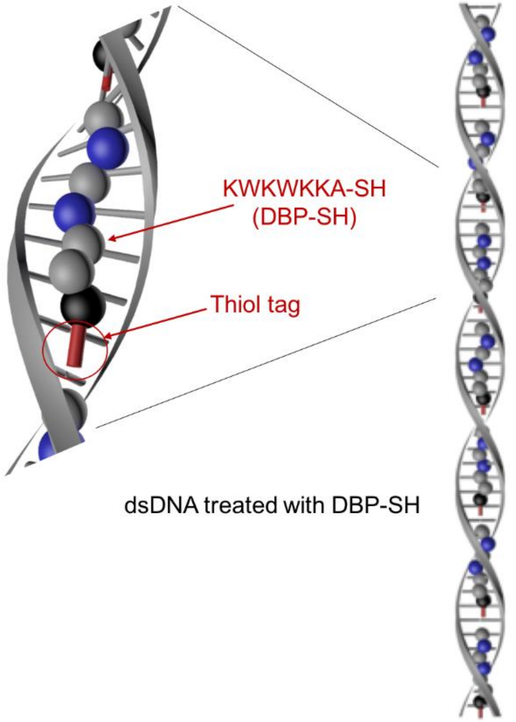
Nucleic Acids Res., **2016**, 44, 1

DNA metallization strategy

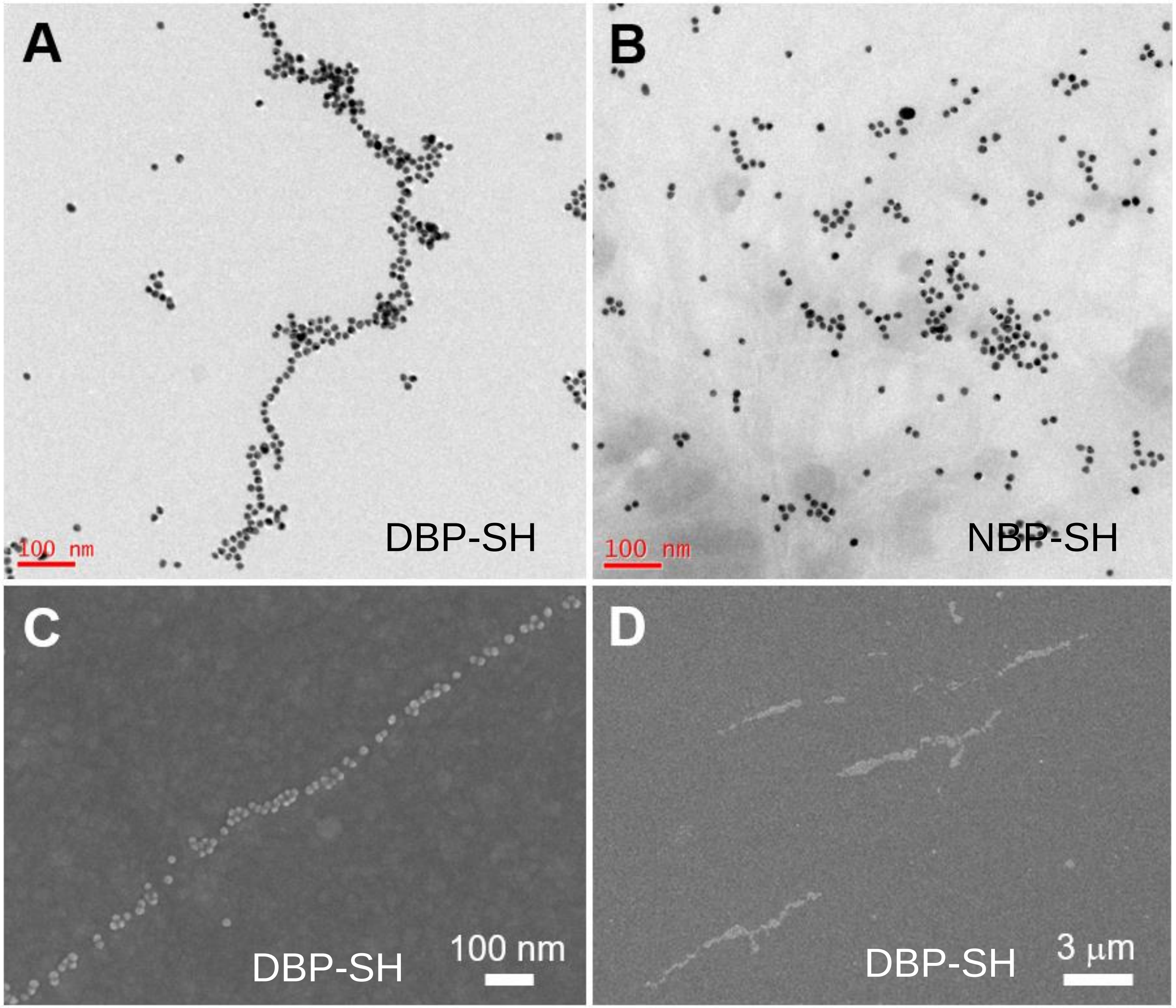


DNA with high density thiol groups

- Interaction with dsDNA and DNA binding peptide with thiol tag (DBP-SH) for the introduction of functional groups
- Covalent bonding of thiol group onto the gold surface and nanoparticle

Small, **2017**, 13, 1601926

AuNP assembly on DBP-SH treated λ-DNA



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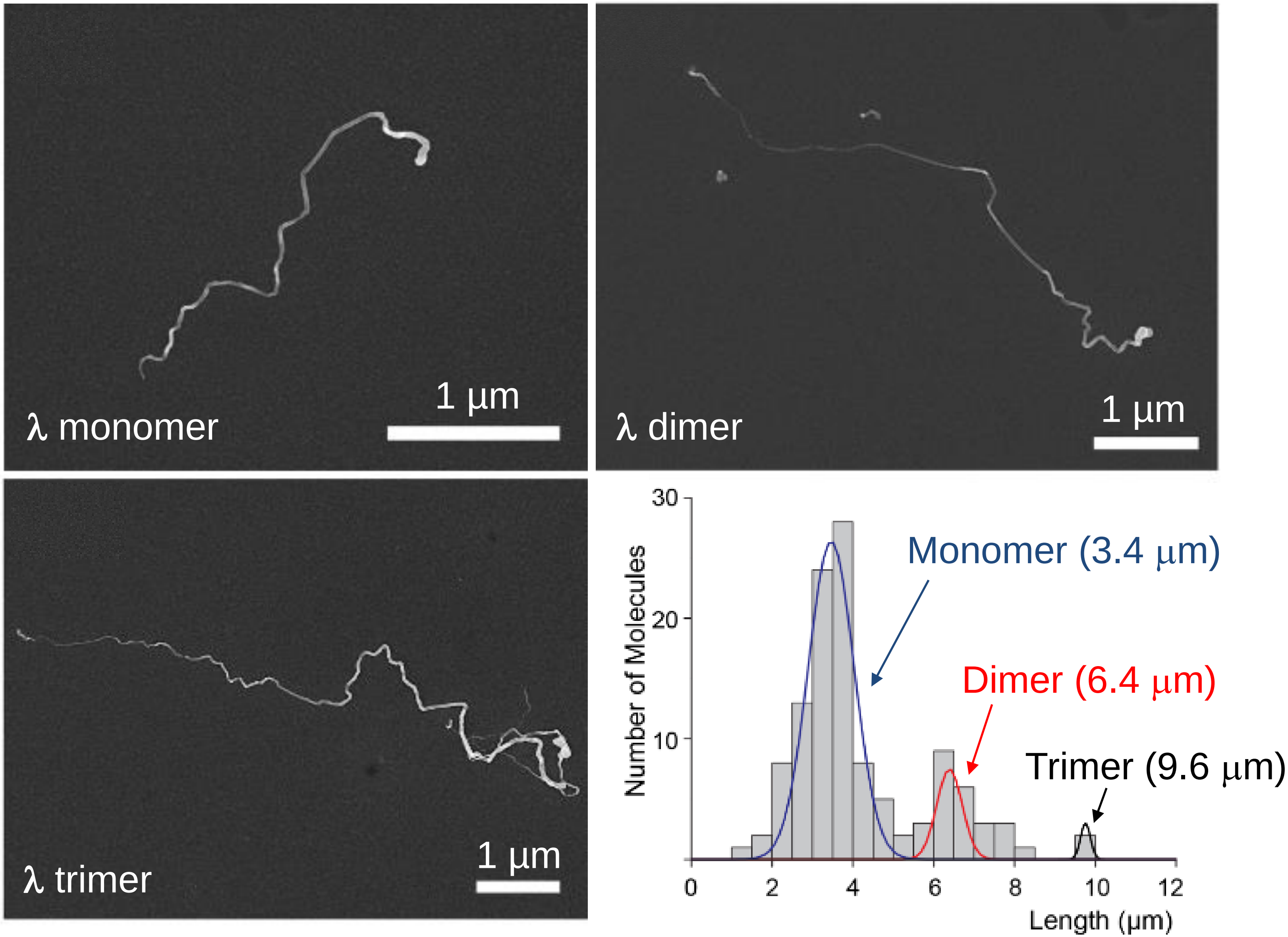
Au nanowires grown on λ-DNA templates



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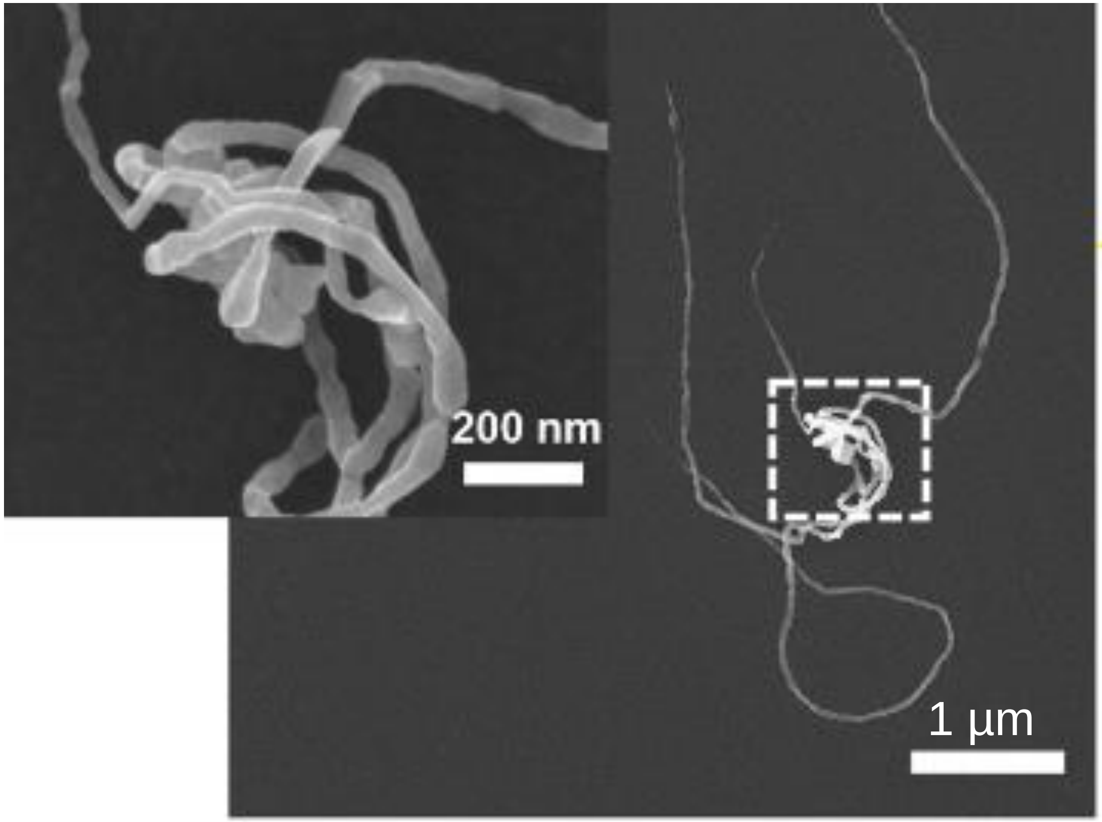
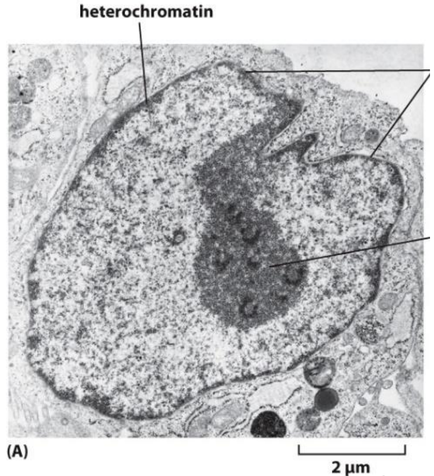
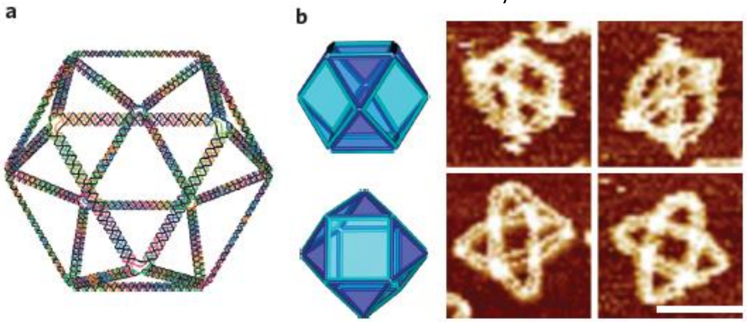
Imaging 3D entangled DNA structures

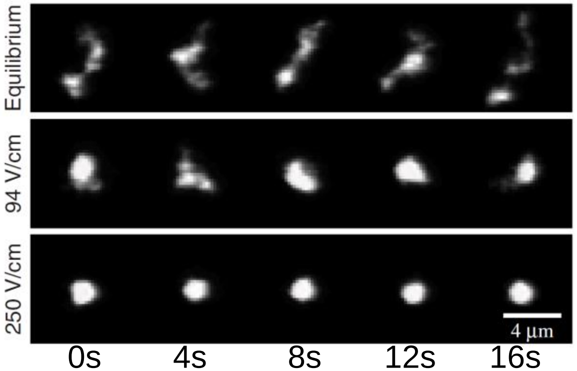




Mol. Biol. of the Cell, 6th Ed.



Nat. Nanotechnol., **2015**, 10, 779



PNAS., **2011**, 108 (39), 16153-16158

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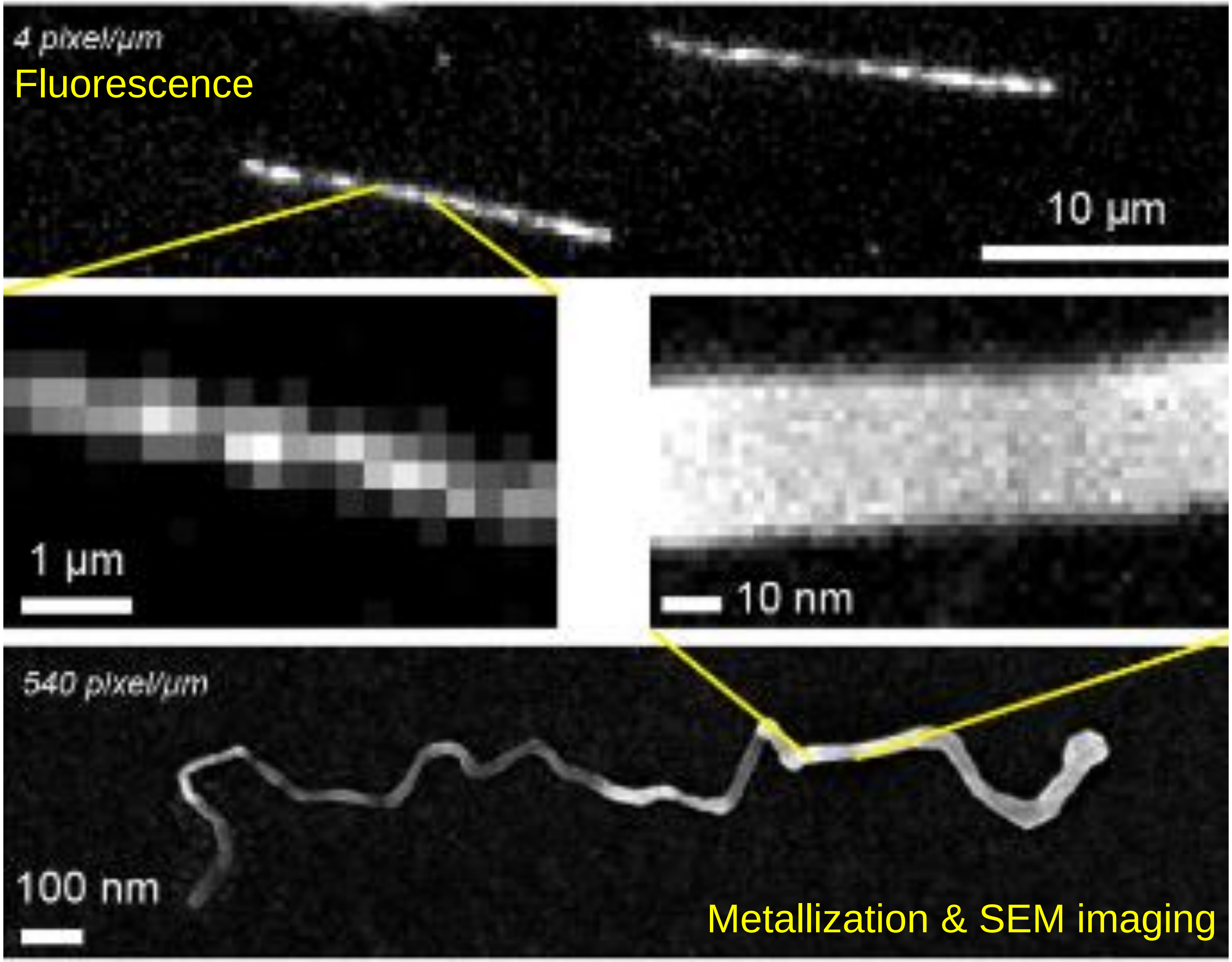
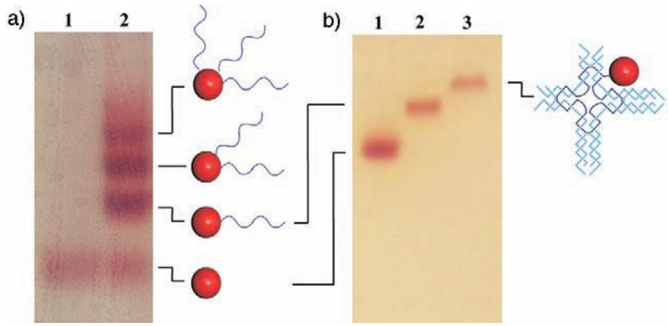
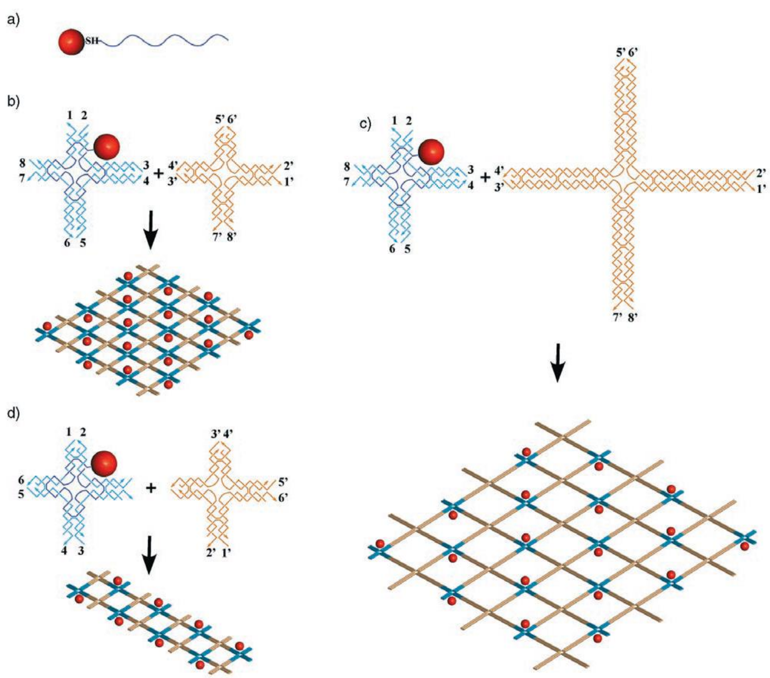
Comparison of fluorescence & SEM images of DNA

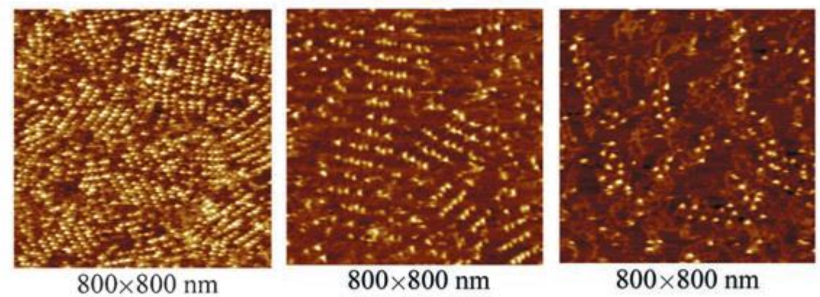


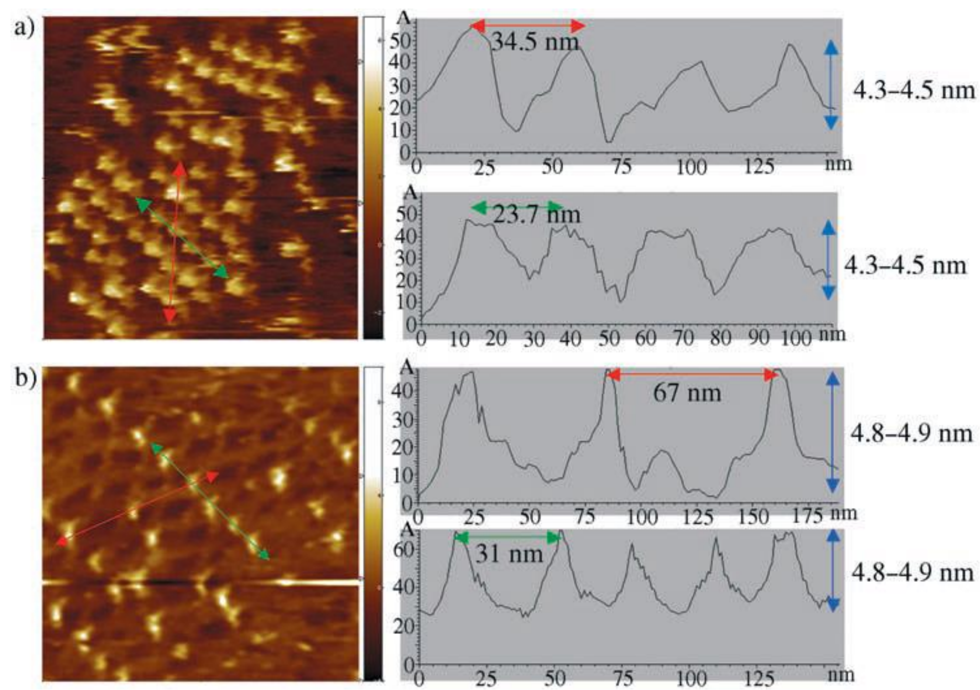
DNA nanostructures for NP patterning

Patterning NPs on DNA nanostructures





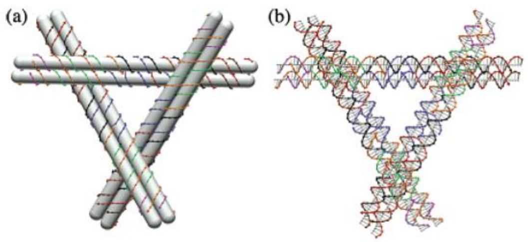


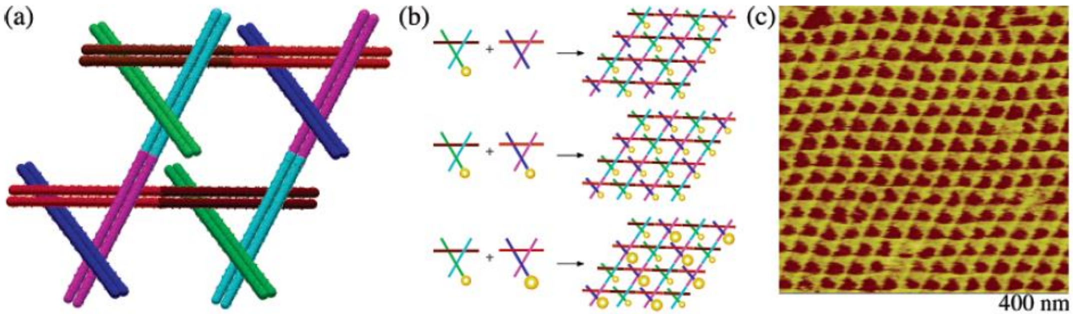


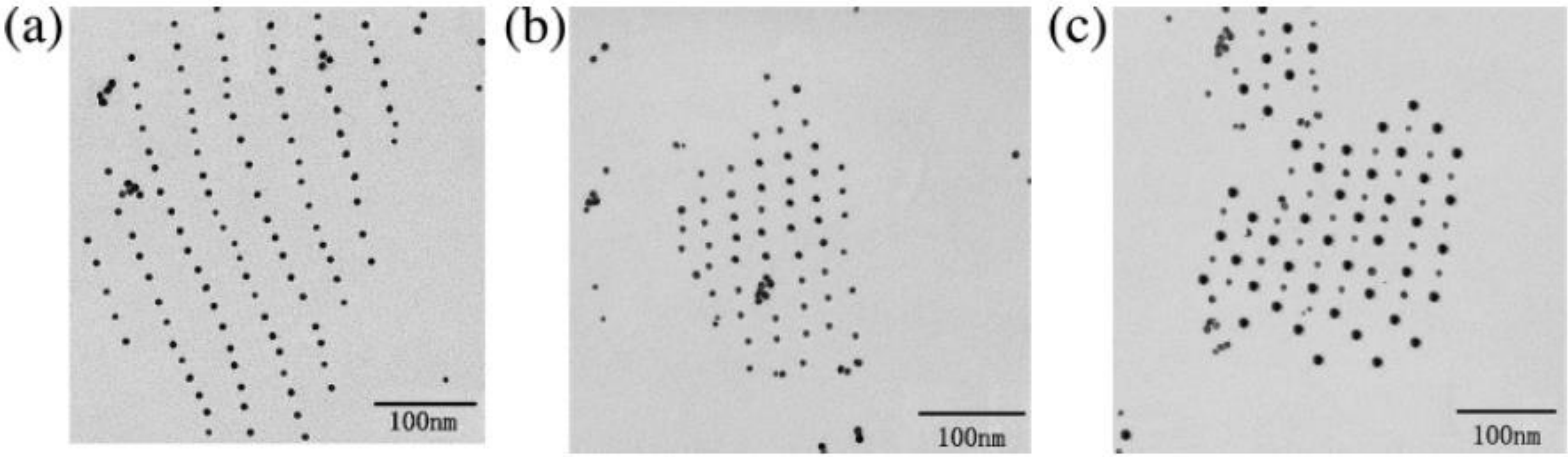
H. Yan *et al*., *Angew Chem*., 2006, 45, 730

DNA nanostructures for NP patterning

Patterning NPs on DNA nanostructures

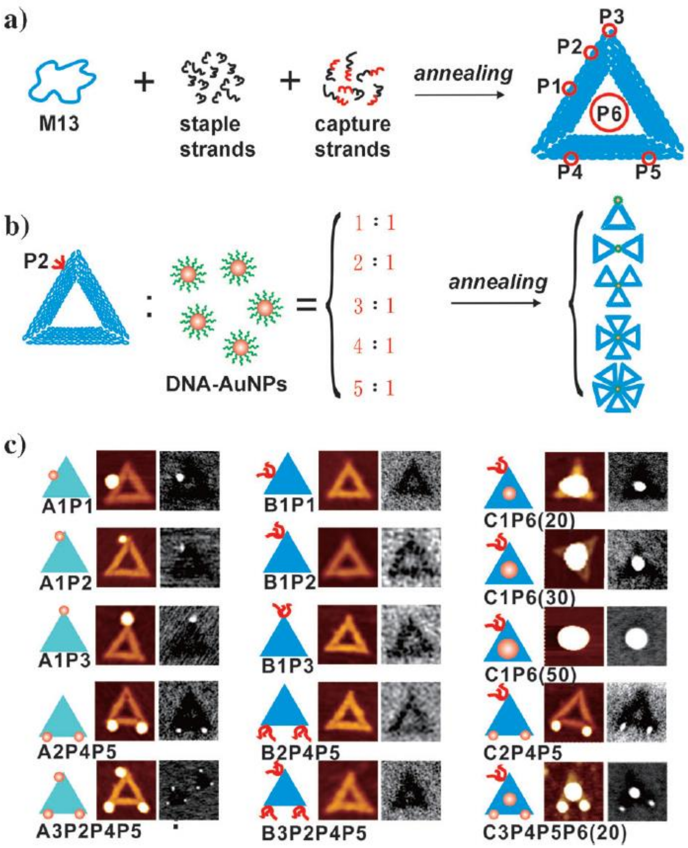


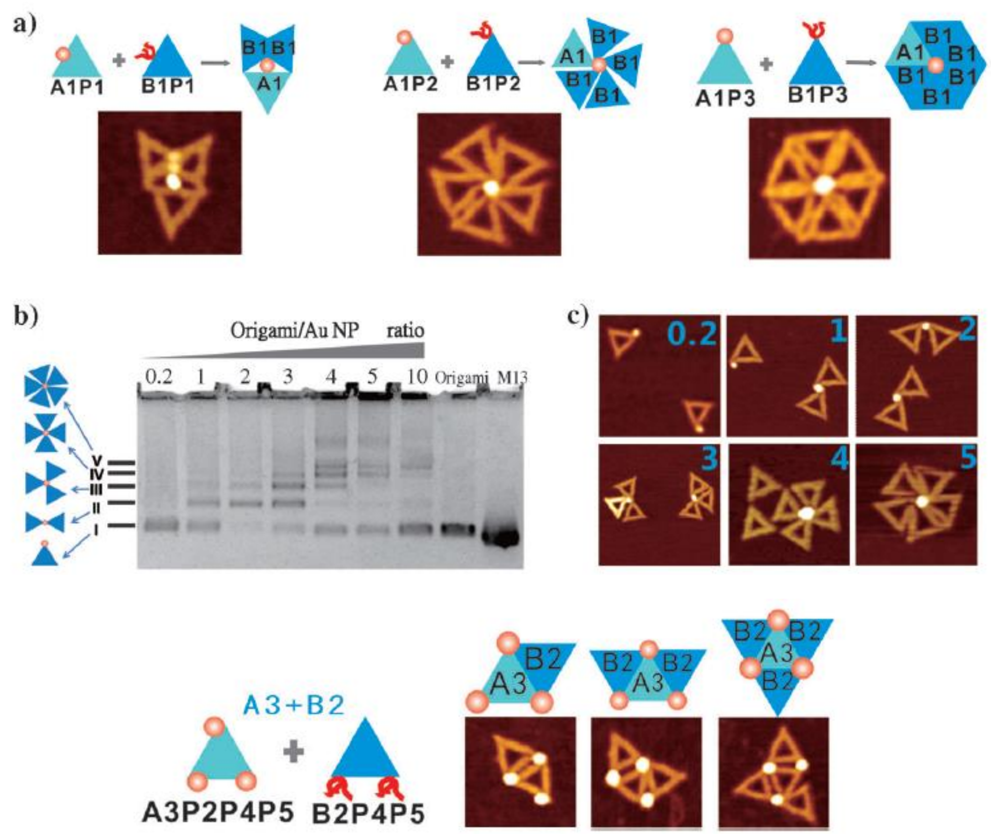




Nano Lett., **2006**, 6, 7, 1502

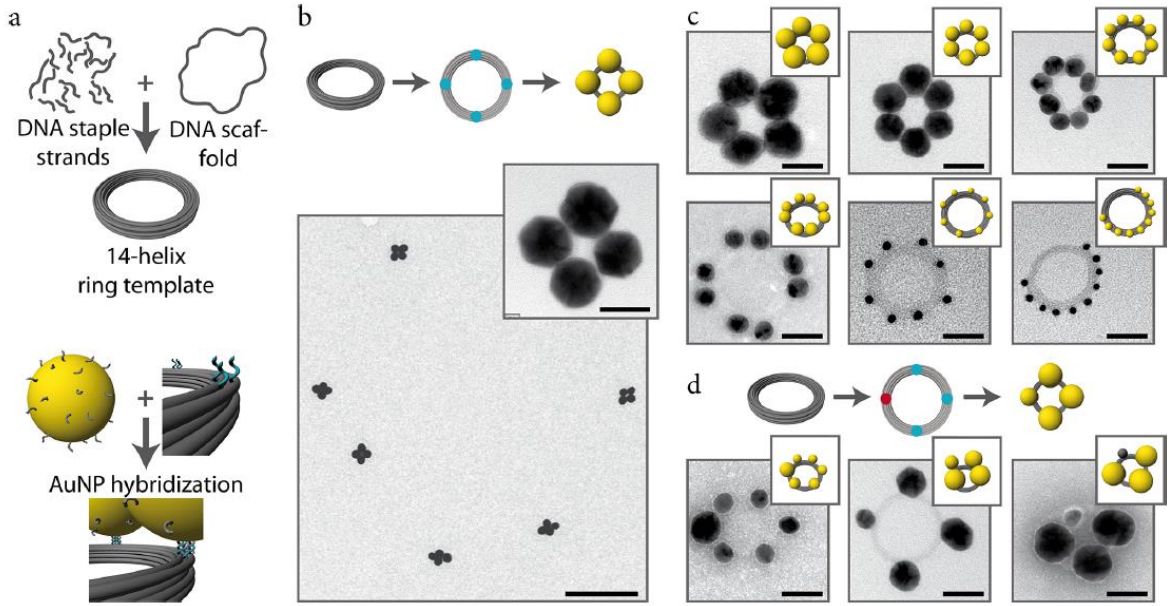
NP patterning on DNA origami

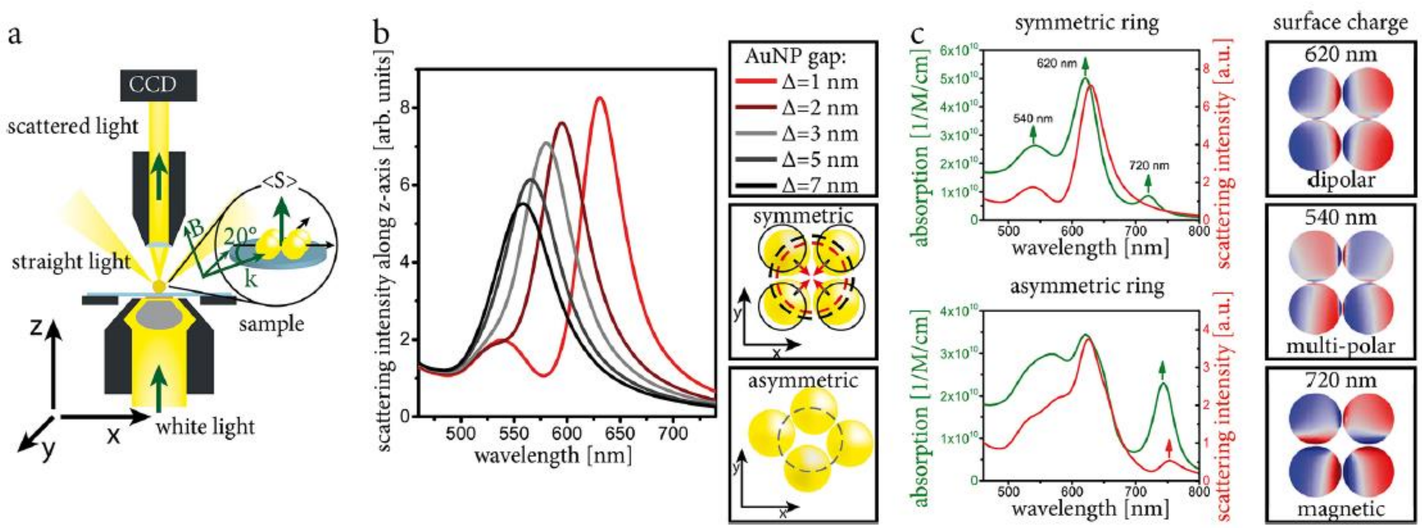




Angew Chem., **2015**, *54*, 2966

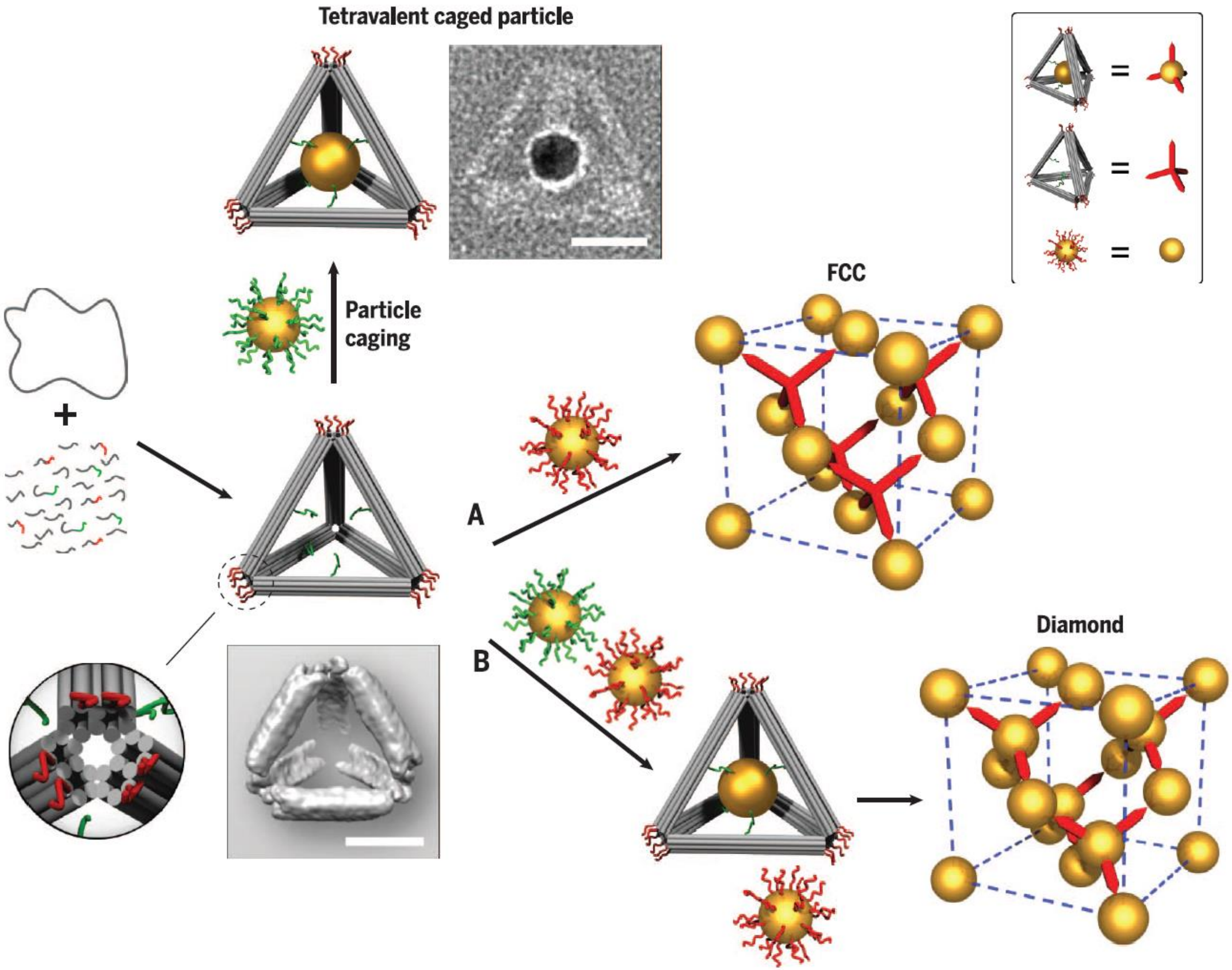
Self assembly of NPs using DNA origami





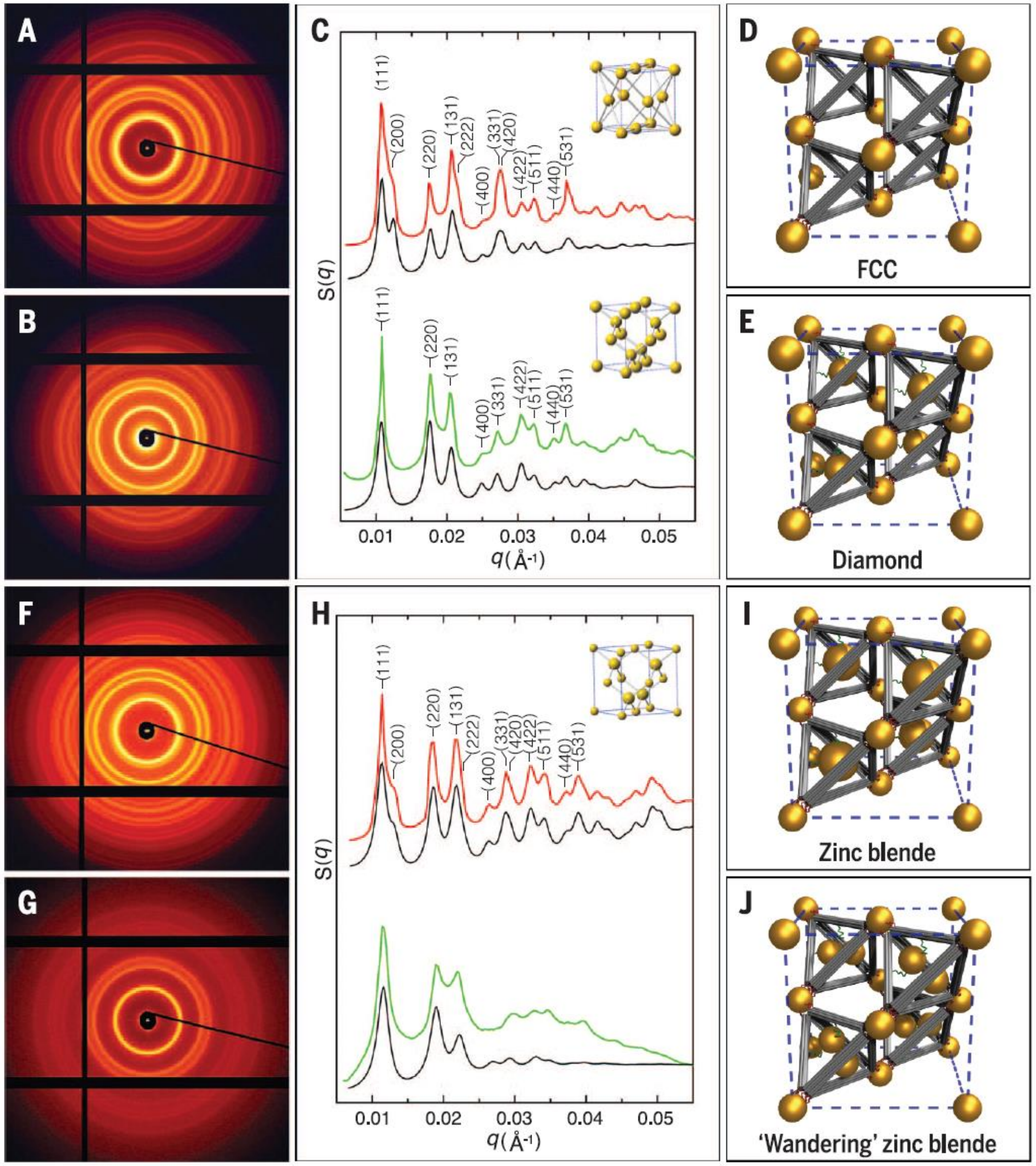
Nano Lett. **2015**, *15*, 1368

Lattice structures formed using DNA origami



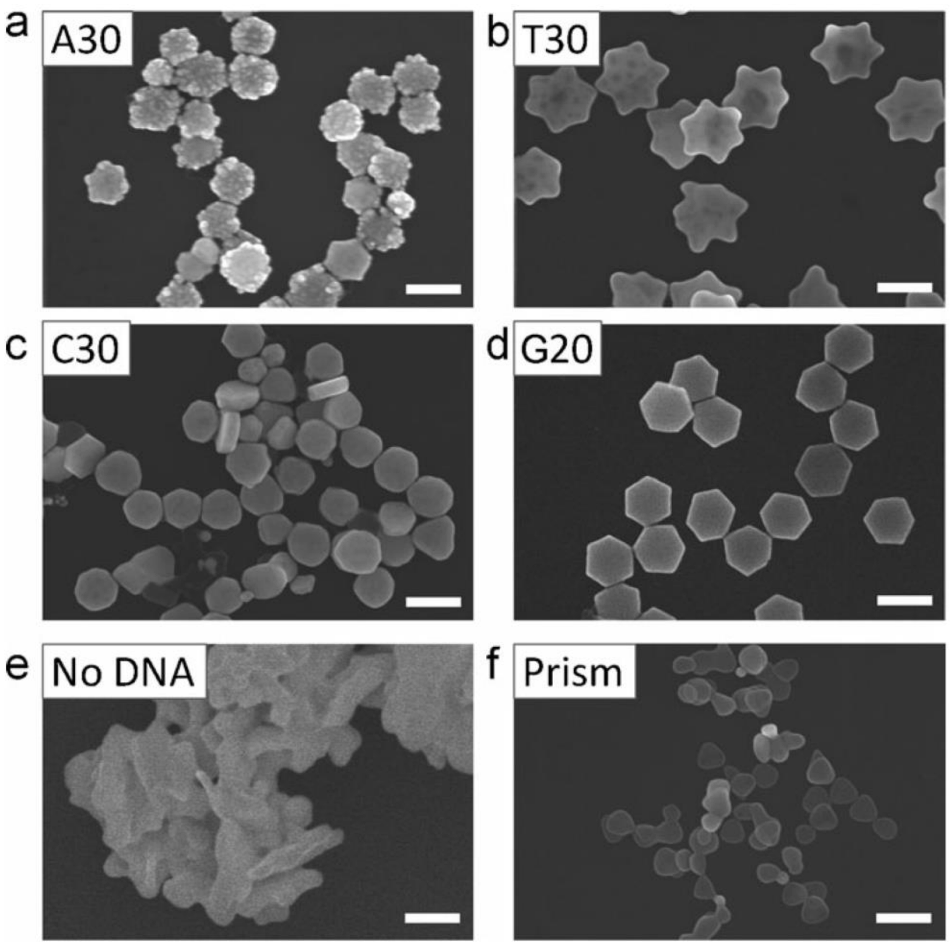
Science, **2016**, *351 (6273),* 582

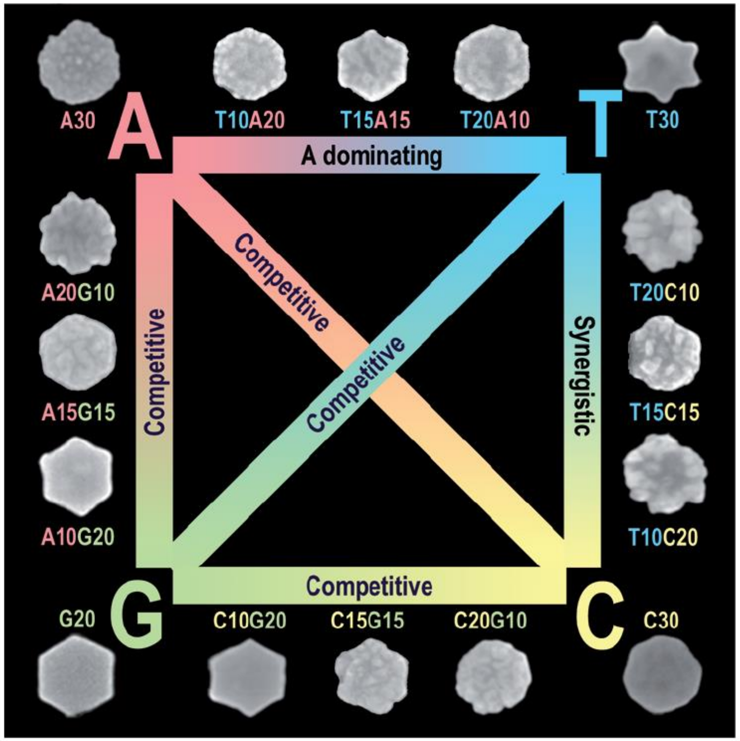
Lattice structures formed using DNA origami

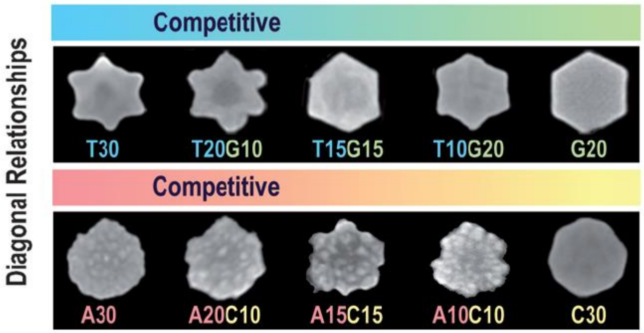


Science, **2016**, *351 (6273),* 582

DNA base directed AuNP morphologies changes

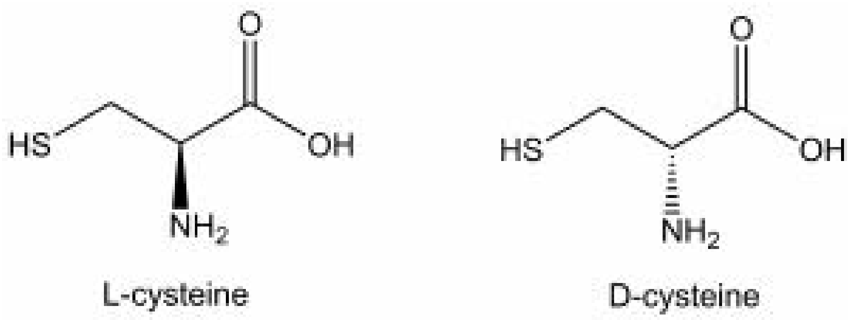




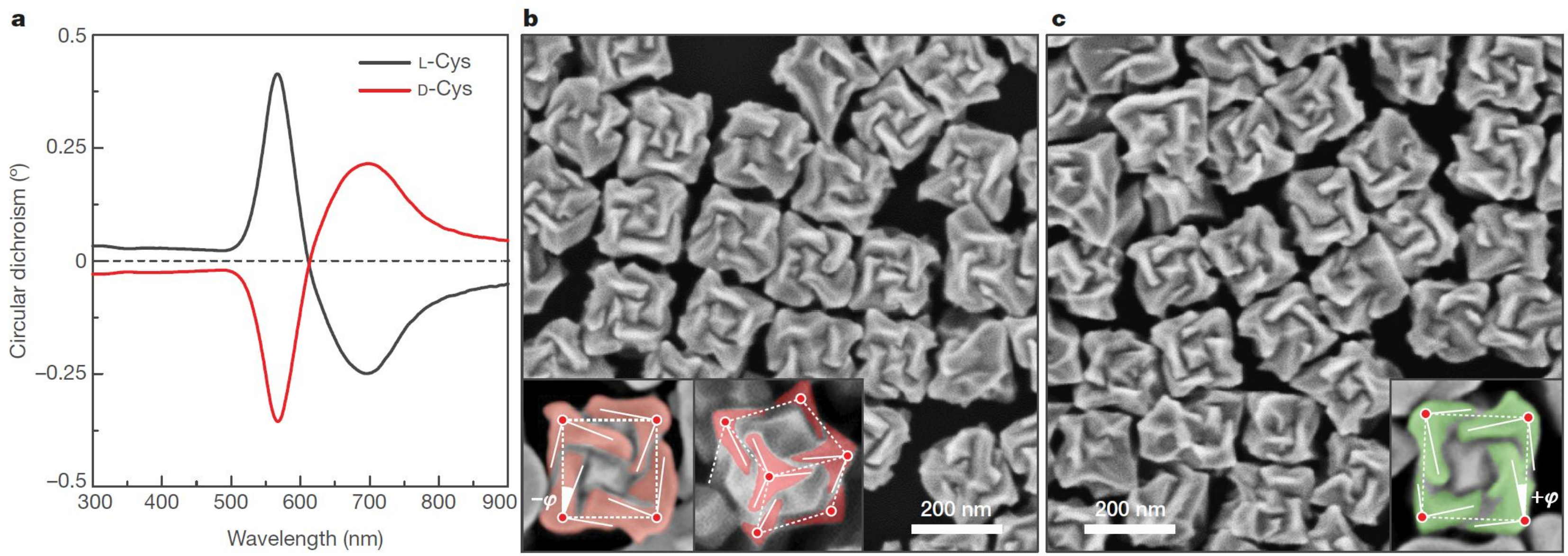


Angew. Chem. Int. Ed. **2012**, *51*, 9078

Synthesis of chiral AuNPs using AA/peptides



Use chiral amino acids or peptide to guide synthesis of chiral materials



Chembites.org
Nature, **2018**, *556*, 360