UNIVERSITÀ DEGLI STUDI DI TERAMO

Nanotecnologies:

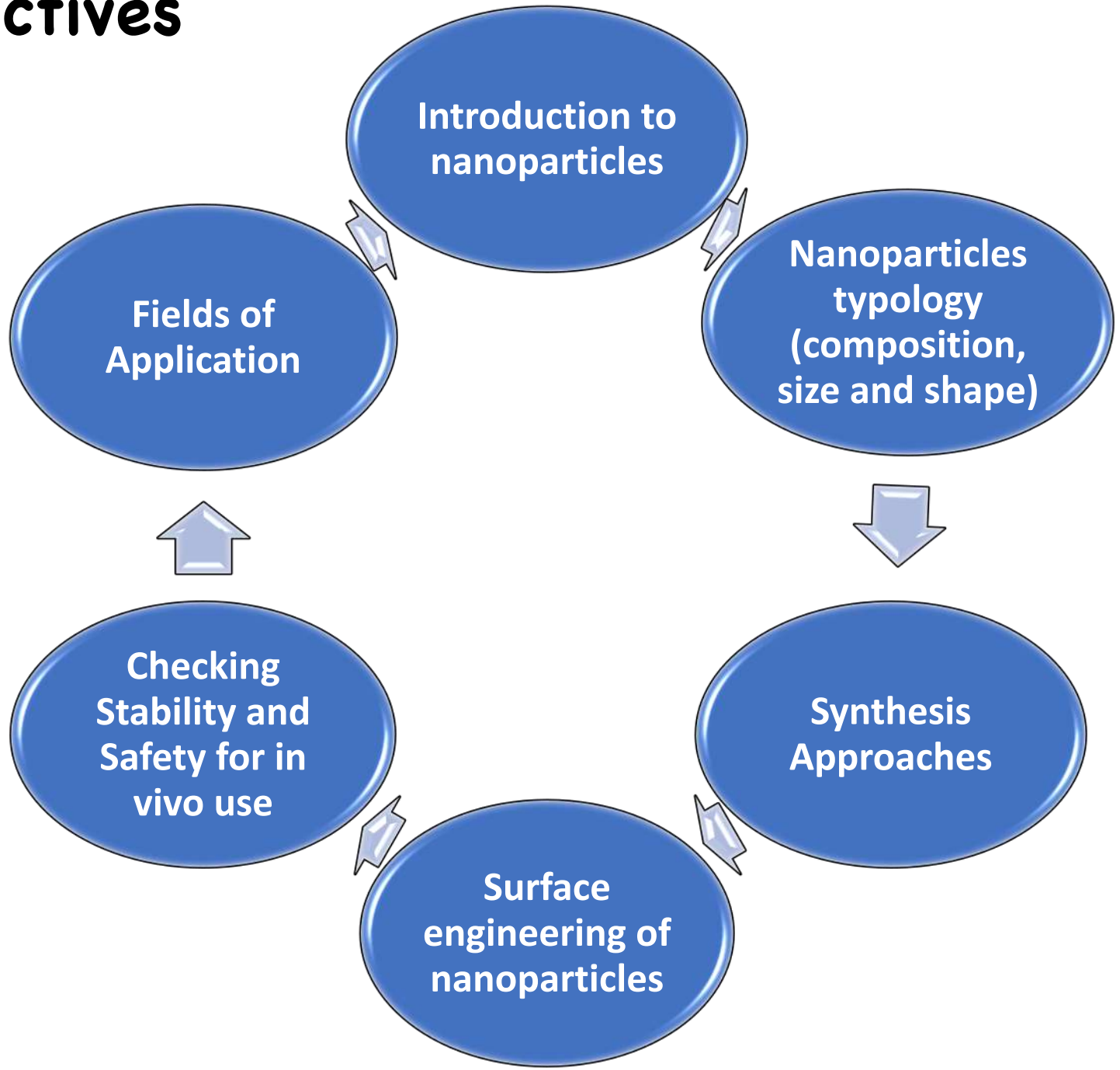
Applications in drug delivery ed imaging

Corso di Laurea Magistrale in Biotecnologie Avanzate

Corso: Tecnologie per la produzione di dispositivi biomimetici (3CFU)

LECTURE 4

Learning objectives



Etymology

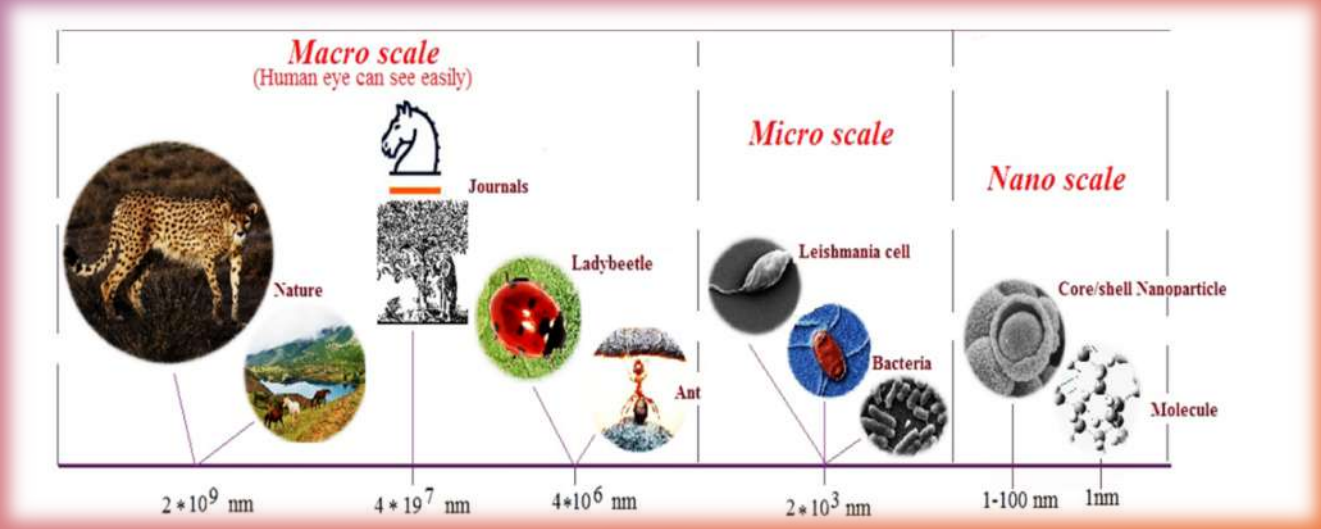
Nanos (greek word):

dwarf or extremely small

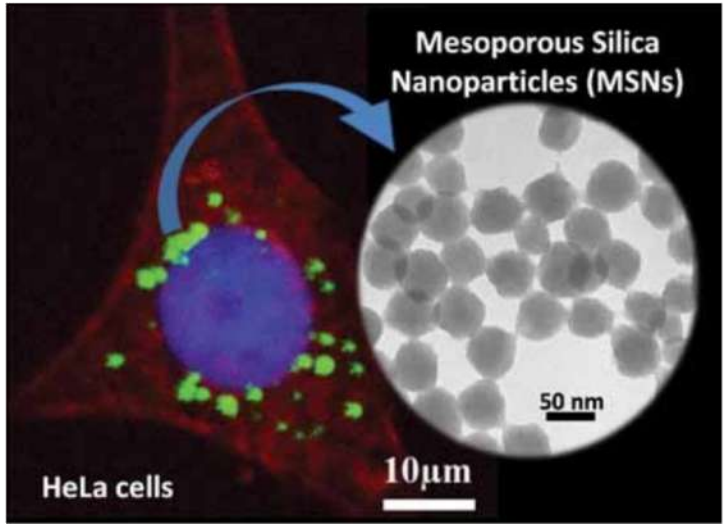
Nanoparticles (NP)

NP are solid colloidal particles ranging from 1 to 1000nm in size, they consist of macromolecular materials in which the active compounds (drugs or biologically active material) could be:

- dissolved;
- entrapped or encapsulated;
- absorbed.



Khatami M e al., 2018



Due to their nanoscale dimensions, NPs can be easily transported across cell membranes and reach subcellular organelles

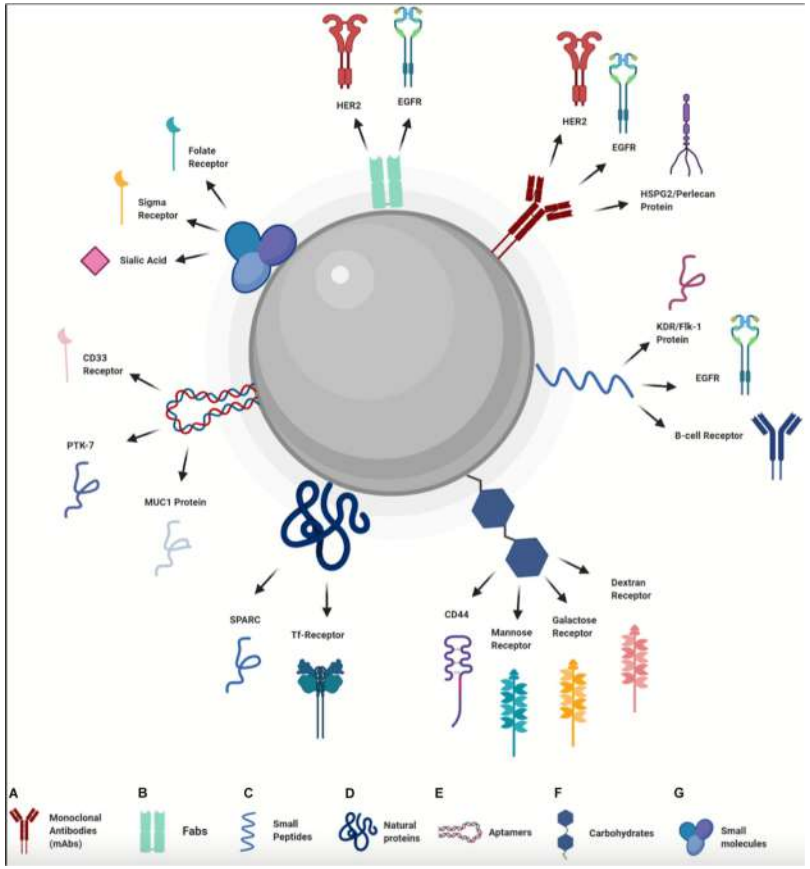
NPs can be modified to facilitate cellular incorporation

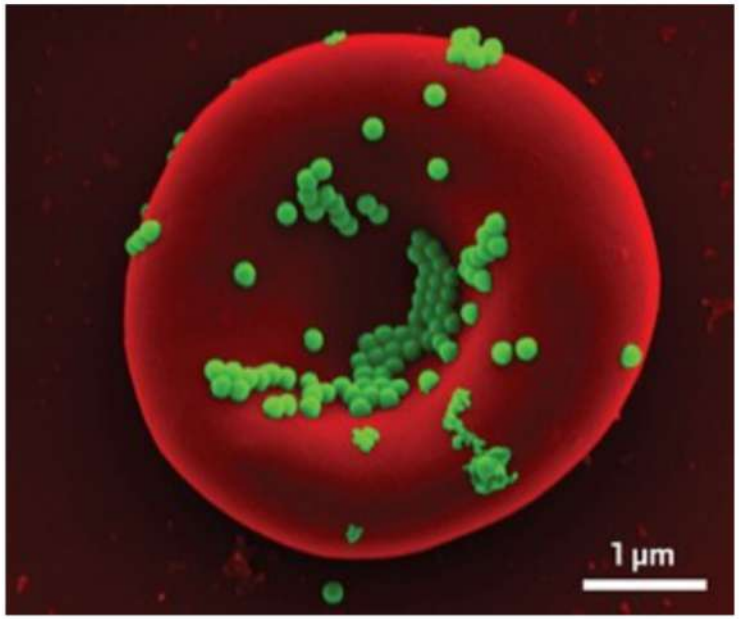
Letting nanoparticles hitchhike on red blood cells

Particles adsorbed on cells accumulate in the first organ downstream from injection site

by ***Celia Henry Arnaud***

July 20, 2018 | A version of this story appeared in **Volume 96, Issue 30**





Credit: ***Nat. Commun.***

Red blood cells carry hitchhiking nanoparticles to target organs. Shown here is a red blood cell with polystyrene nanoparticles.

Classification of NP based on their dimension

Siegel classification

Zero-dimensional nanomaterials	One-dimentional nanomaterials	Two-dimensional nanomaterials	Three-dimensional nanomaterials
Here, all dimensions (x, y, z) are at nanoscale, i.e., no dimensions are greater than 100 nm. It includes nanospheres and nanoclusters.	Here, two dimensions (x, y) are at nanoscale and the other is outside the nanoscale. This leads to needle shaped nanomaterials. It includes nanofibres, nanotubes, nanorods, and nanowires.	Here, one dimension (x) is at nanoscale and the other two are outside the nanoscale. The 2D nanomaterials exhibit platelike shapes. It includes nanofilms, nanolayers and nanocoatings with nanometre thickness.	Not confined to the nanoscale in any dimension. These materials have three arbitrary dimensions above 100 nm. The bulk (3D) nanomaterials are composed of a multiple arrangement of nanosize crystals in different orientations. It includes dispersions of nanoparticles, bundles of nanowires and nanotubes as well as multinanolayers (polycrystals) in which the 0D, 1D and 2D structural elements are in close contact with each other and form interfaces.

0D

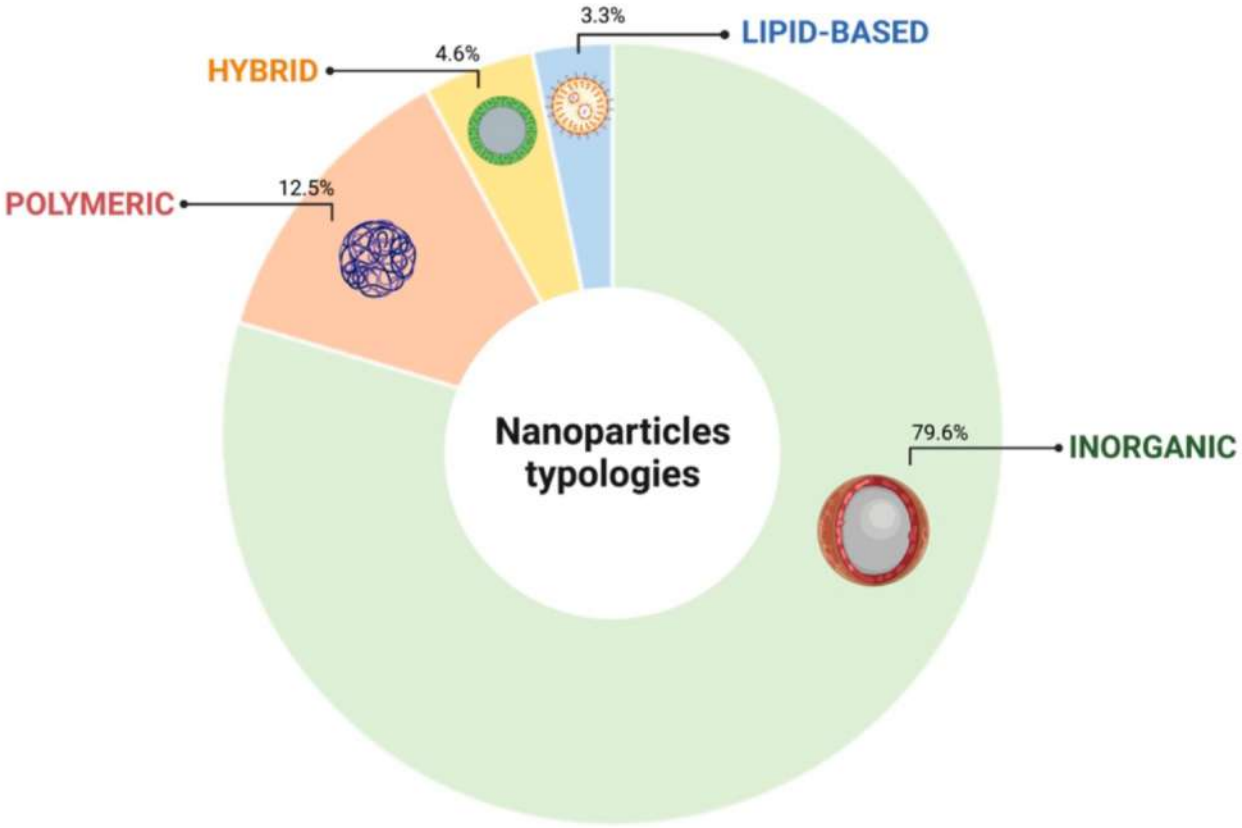
1D

2D

3D

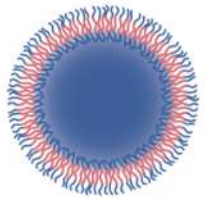
K. Mohapatra, 2020 "Chemistry_Nanomaterials" http://www.gcekjr.ac.in/pdf/lectures/2020/7166--_2nd%20Semester_ALL.pdf

Classification of NP based on their material composition



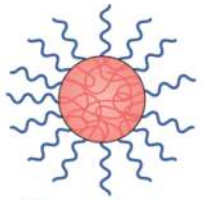
1-1000nm

Polymeric


Polymersome


Dendrimer


Polymer micelle


Nanosphere

20-150nm

Inorganic


Silica NP

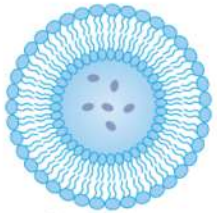

Quantum dot


Iron oxide NP

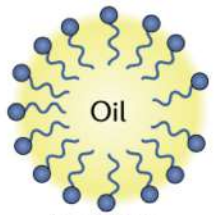

Gold NP

10-1000nm

Lipid-based

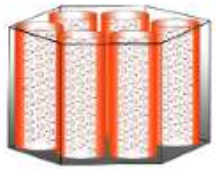
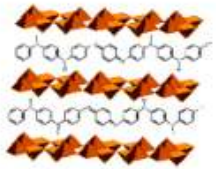

Liposome

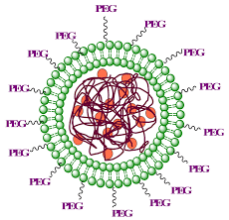

Lipid NP



Emulsion

Hybrid *



Inorganic-Organic


Lipidic-organic

Inorganic NP

shapes

rods or tubes

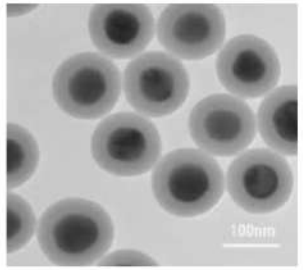
stars

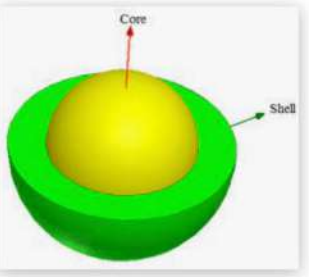
wires

spherical

pyramids

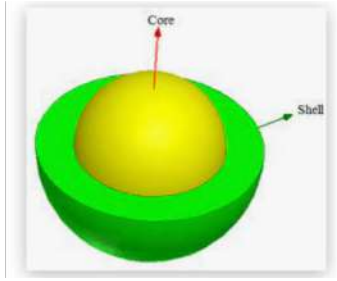
Adapted from Wu Z et al., 2016





Core-shell structure

Adapted form Khatami M e al., 2018



Inorganic NP core composition (3-6 nm):

The core can contain metals, other chemical elements or fluorescent dyes encapsulated in silica. The core defines the magnetic, electronic, fluorescence and optical properties of NPs.

1. Metal-based NP:
silica, manganese, gold, silver, lanthanide, molybdenum, ruthenium, rubidium, gadolinium, and zinc elements

2. Metal oxide-based NP:
iron oxide, superparamagnetic iron oxide (SPIO), ultrasmall superparamagnetic iron oxide (USPIO), titanium oxide and cobalt iron oxide elements

3. Metal sulfide or phosphide-based NP:
quantum dots

4. Mineral-based NP:
hidroxyapatite and selenium elements

Inorganic NP shell composition (20-150 nm):

The shell is usually made of metals or organic polymers that:

1. protect the core from chemical interactions with the external environment

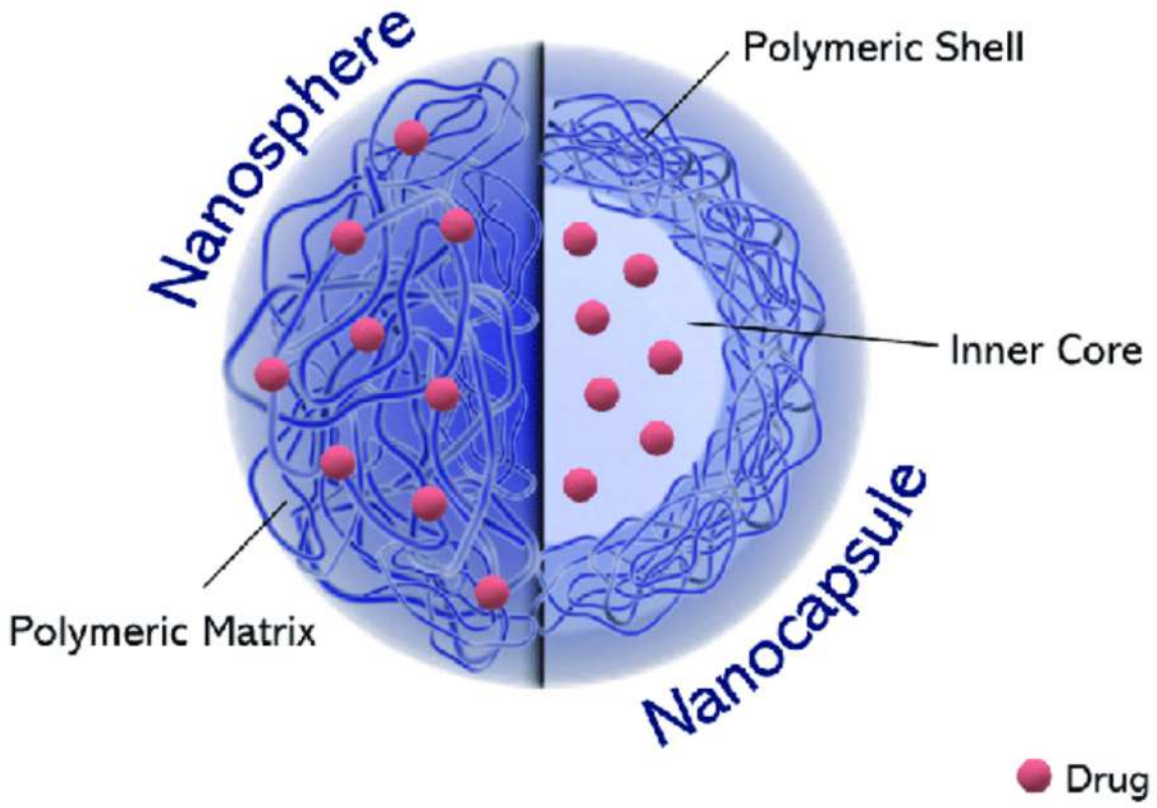
2. serves as a substrate for conjugation with biomolecules such as antibodies, peptides or oligonucleotides (**Functionalization**)

3. preserves NP stability avoiding aggregation

Due to their magnetic, radioactive, X-ray absorption or plasmonic properties, inorganic NPs are used for diagnostics purposes and most of them display good stability and biocompatibility.

Polymeric NP

- Constituted by a polymeric matrix core;
- The polymeric NP can be loaded with bioactive molecules (**functionalization**);
- They are categorized into two forms:
    1. **Spheres** (the bioactive molecule is dispersed within a polymer matrix);
    2. **Capsules** (the bioactive compound is placed in the core of the particle covered by a layer of polymer)



Schematic representation of polymeric nanoparticles as a function of their morphology.

Polysaccharides and proteins are the commonly used materials for the fabrication of polymeric NPs. The polymer provides biocompatibility and protection to the active site. Most used are: PEG, PLGA, PS, PCL, PLA etc..

Lipid-based NP

Defined as colloidal carrier for bioactive molecules

SYNTHETIC FORMULATION:

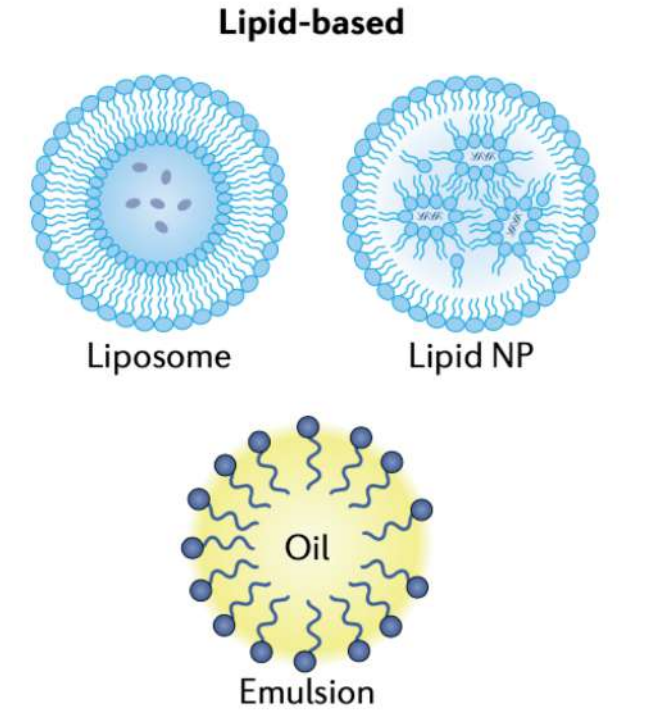
Liposomes: with size < 200 nm, spherical vesicles with an aqueous core and bilayer lipid membrane. They have the capacity to encapsulate diverse bioactive compounds, which can be included into the aqueous core or at the bilayer interface

Solid lipid NP (SLN, solid lipids): spherical in shape and consist of a solid lipid core stabilized by a surfactant. This construct can be used to deliver both hydrophilic and hydrophobic bioactive molecules (functionalization)

Nanostructured lipid carriers (NLC): with sizes ranging from 10–1000 nm, are a combination of liquid and solid lipids.

NATURAL FORMULATION:

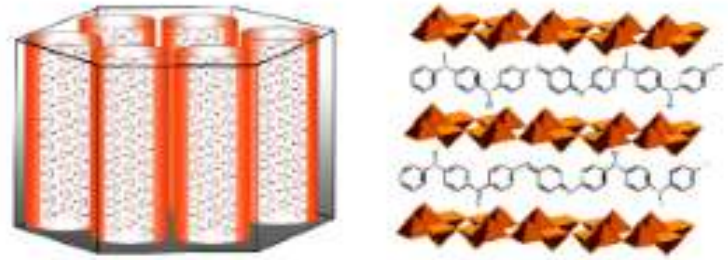
Cell-derived membrane lipidic vesicles, with a small size range (40–100 nm) are naturally derived lipid NP versus the synthetic lipidic formulation



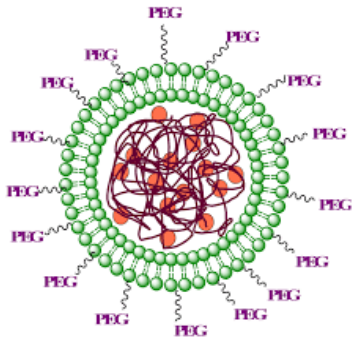
Hybrid NP

Hybrid NPs are constructed from at least two different kind of NP, to overcome the limits of single-component nanoparticles, to improve properties, to achieve new properties not possible for single nanoparticles, and/or to achieve multiple functionalities for single nanoparticles

Hybrid



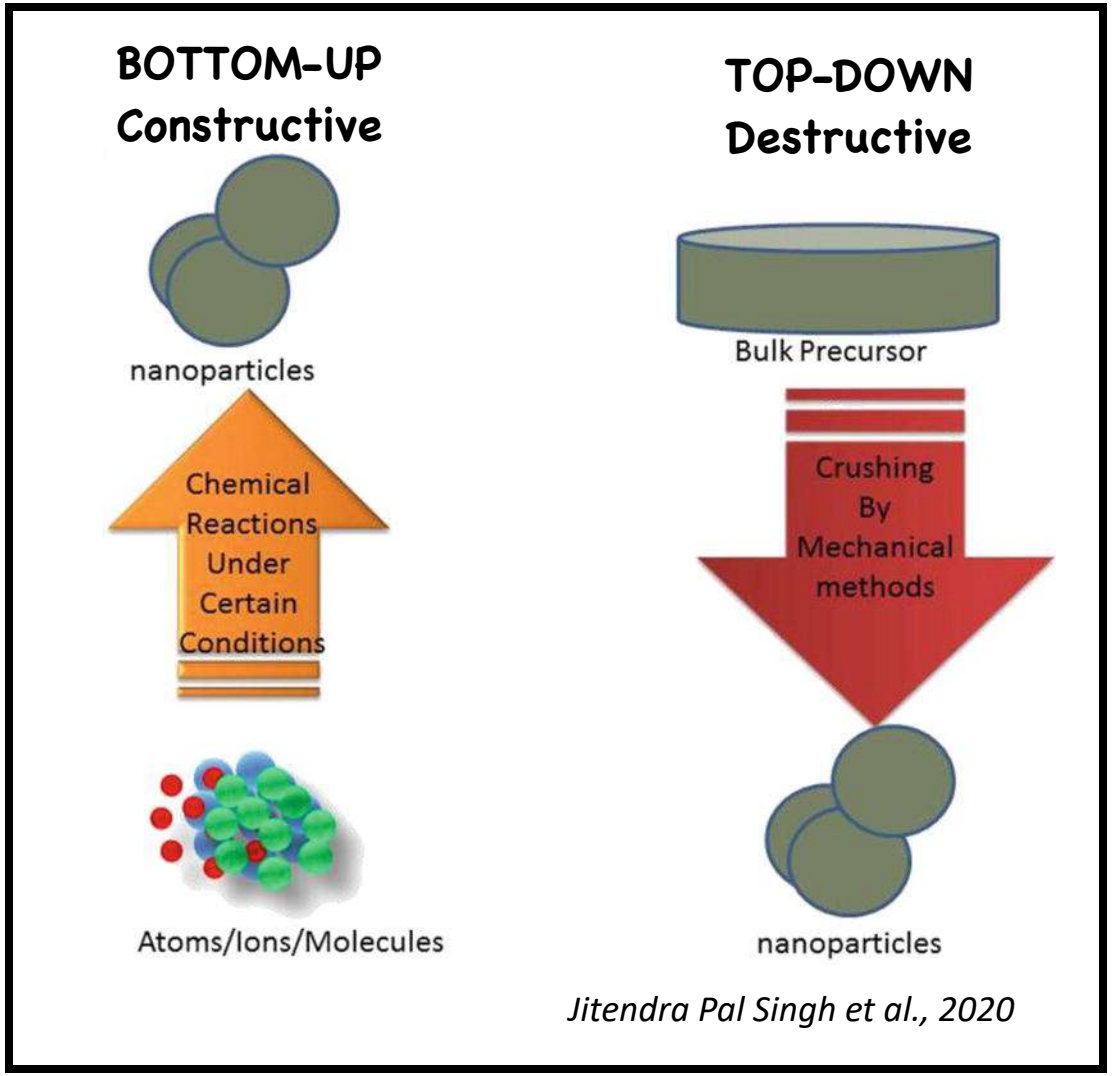
Inorganic-Organic



Lipidic-organic

NP Synthesis Approaches

BOTTOM-UP
NP are produced by the self-assembly of the atoms, the molecules or the clusters

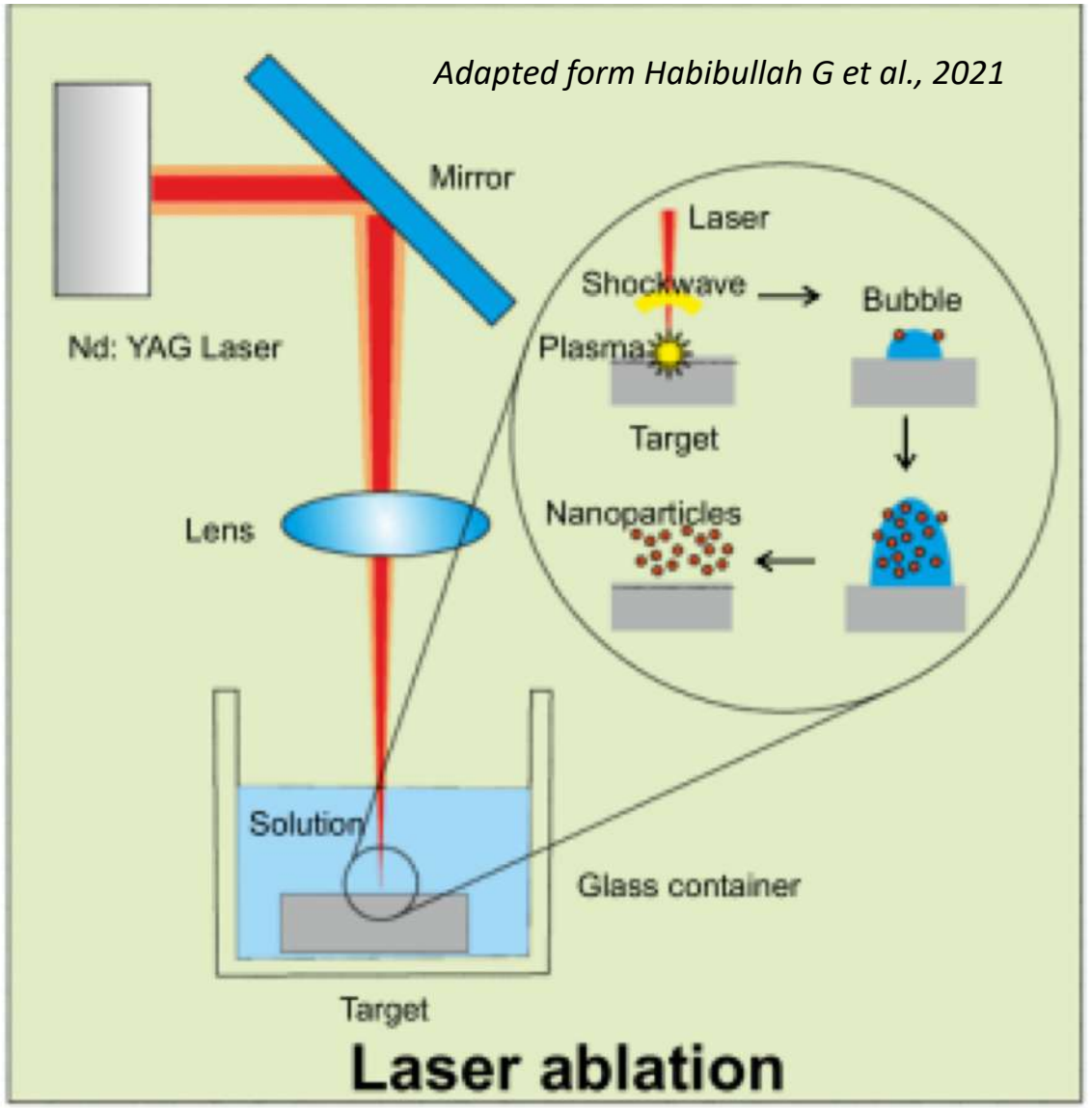


Jitendra Pal Singh et al., 2020

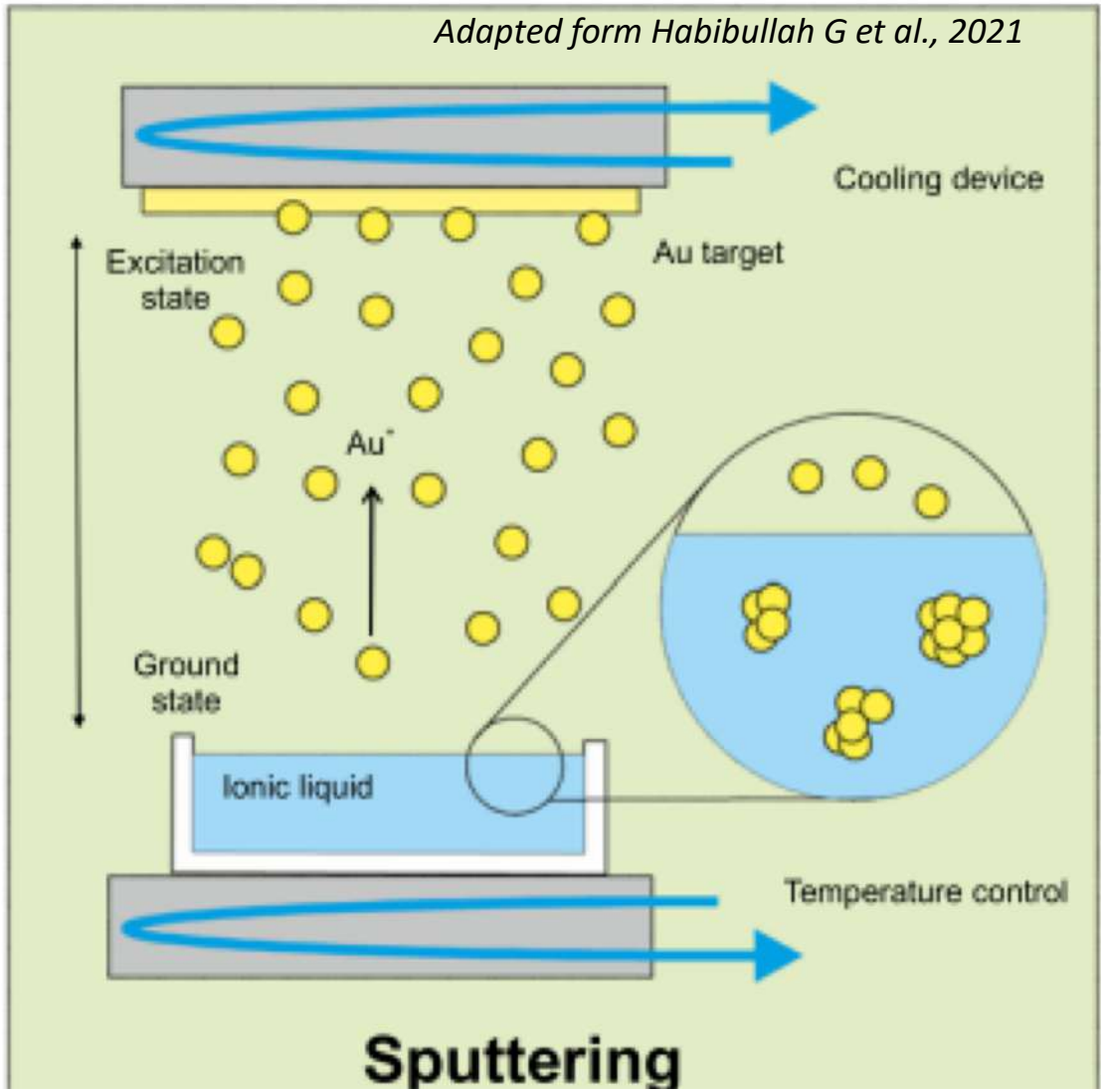
TOP-DOWN
It involves breaking bulk materials into smaller particles of nano-dimensions using various physical and chemical methods

Inorganic NP Synthesis Approaches

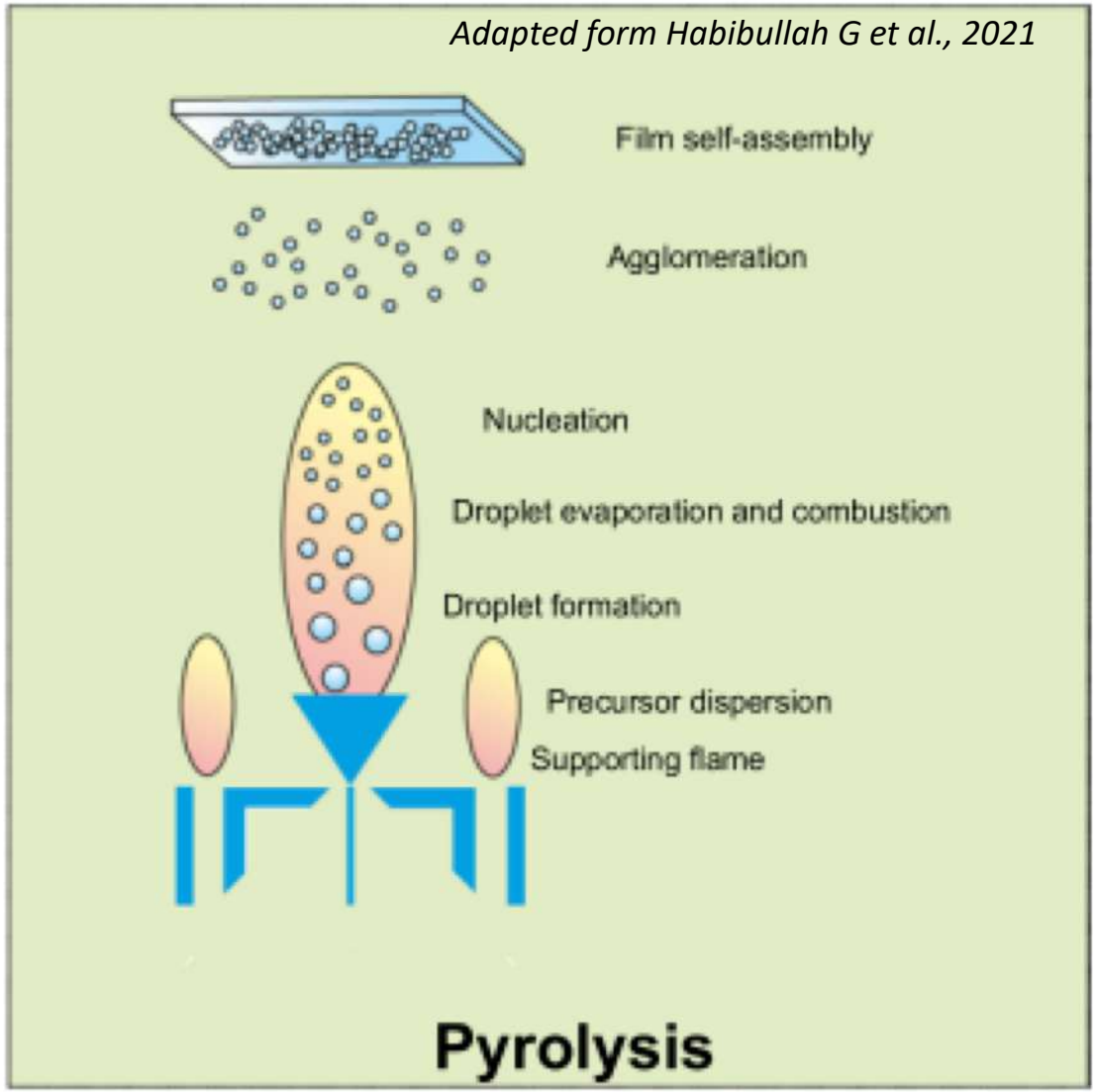
TOP-DOWN



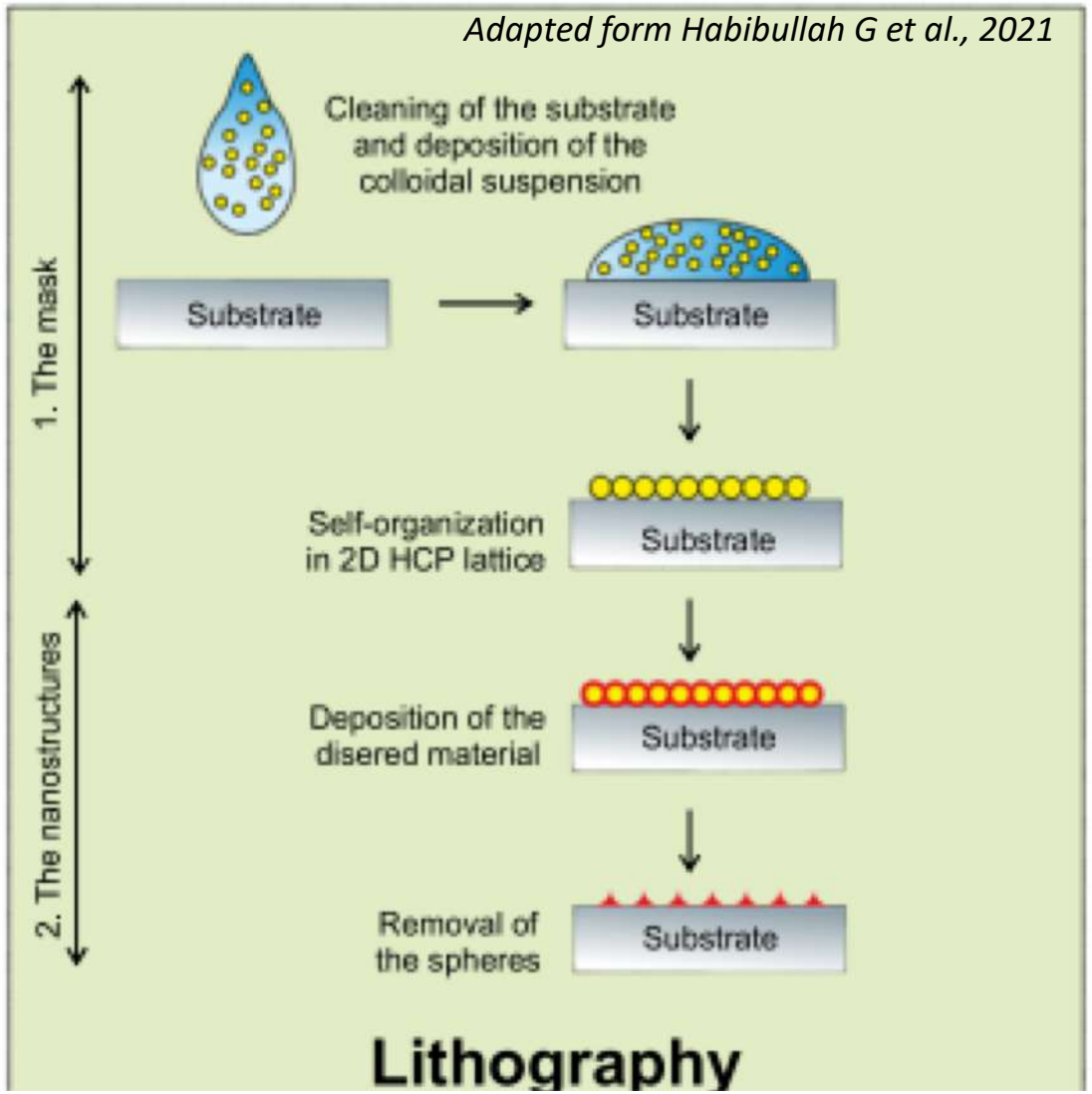
In a laser ablation process, a solid surface (generally a plate of pure metal) is **irradiated** with a laser beam. Nanoparticles are generated by **nucleation and formation of laser-vaporized species** in a background gas.



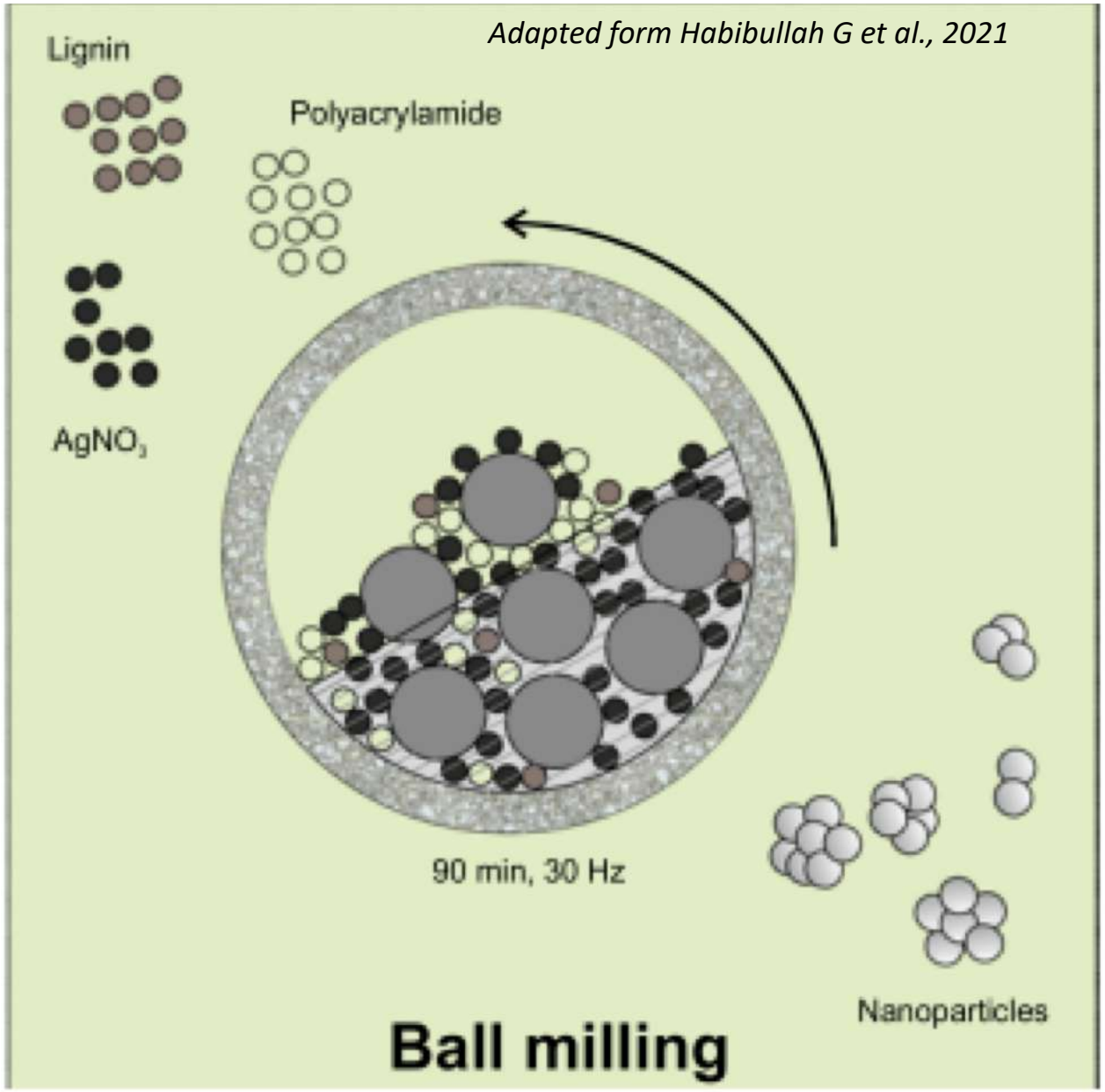
The principle of Sputtering is to use the energy of a plasma (partially ionized gas) on the surface of a target (cathode), to pull the atoms of the material one by one and deposit them on the substrate. Deposition of NPs as a thin layer generated by the **collision of ions over the substrate** and followed by their **aggregation**.



Thermal decomposition. It is an endothermic chemical decomposition process that **uses heat to break the compound's chemical bonds,** resulting in decomposition of the precursor forcing it into a chemical reaction producing NPs along with other by-products in the form of ash.



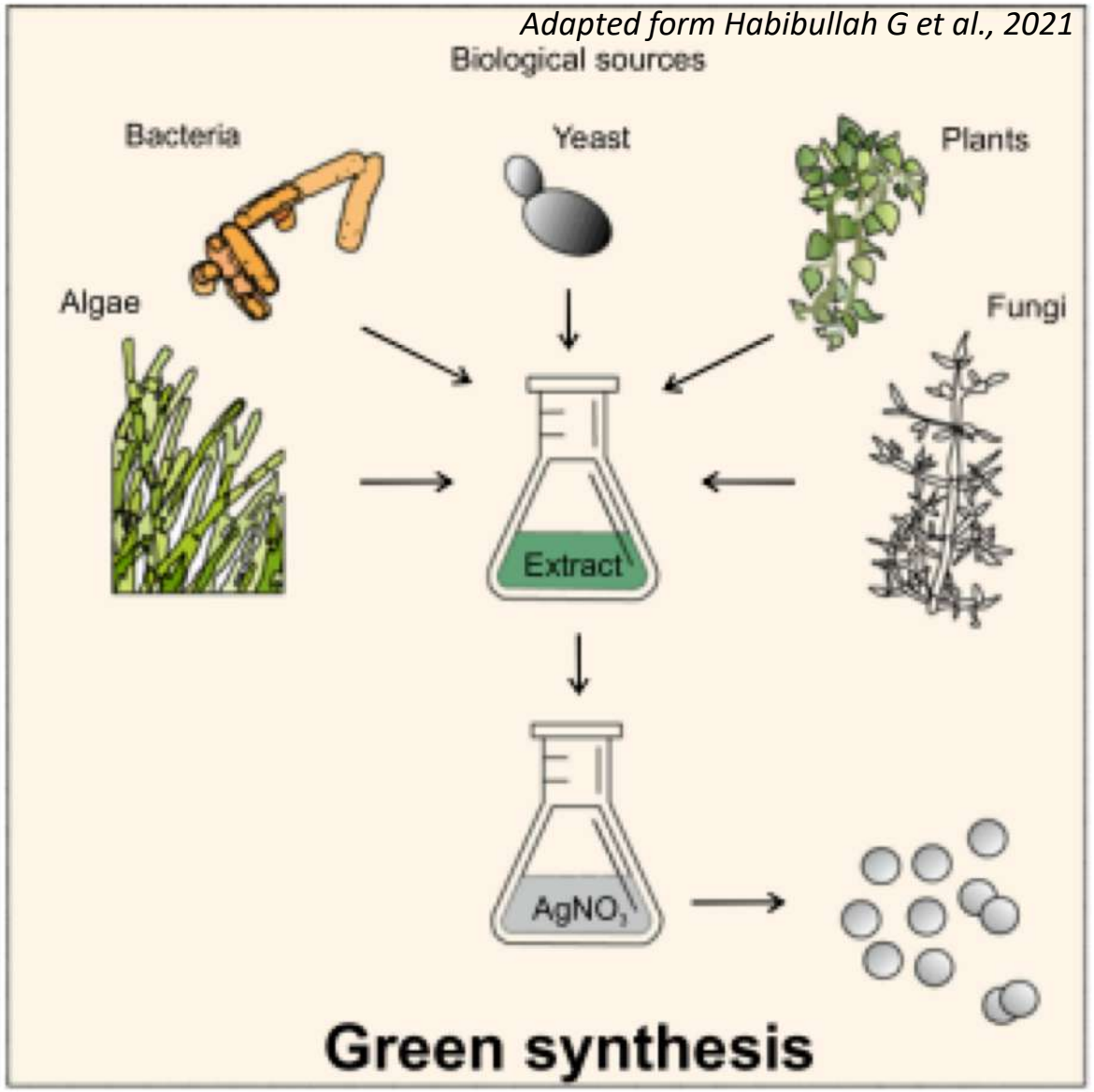
This method is based on the deposition of the **desidered material** on a substrate (e.g.silicon) to produce **regular and homogenous arrays of nanoparticles** with different sizes and with precisely controlled spacings.



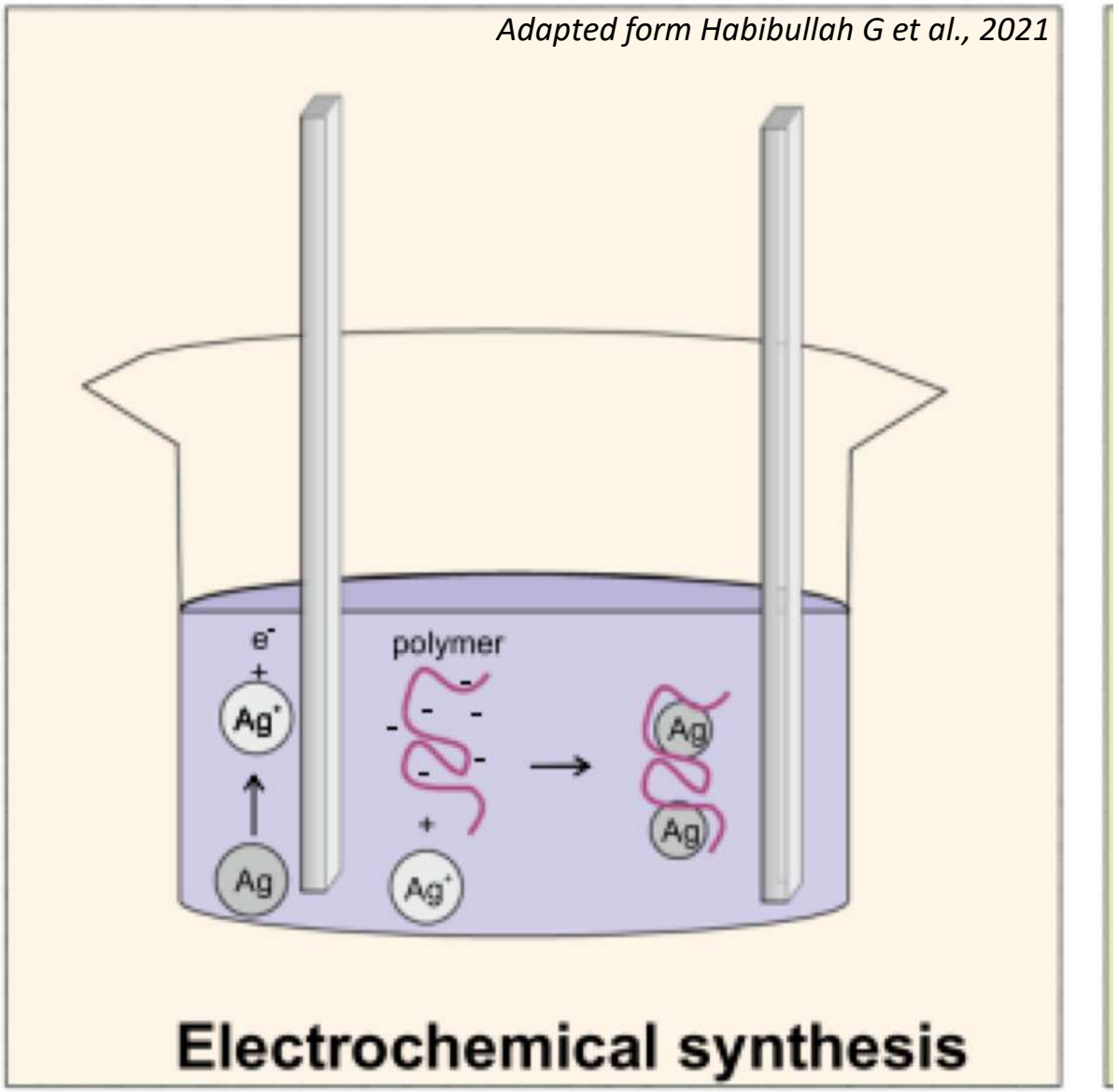
The kinetic energy of the **rollers/balls** (AgNO3, polyacrylammide, lignin) is transferred to the bulk material, which results in the **reduction in grain size**

BOTTOM-UP

Adapted form Habibullah G et al., 2021

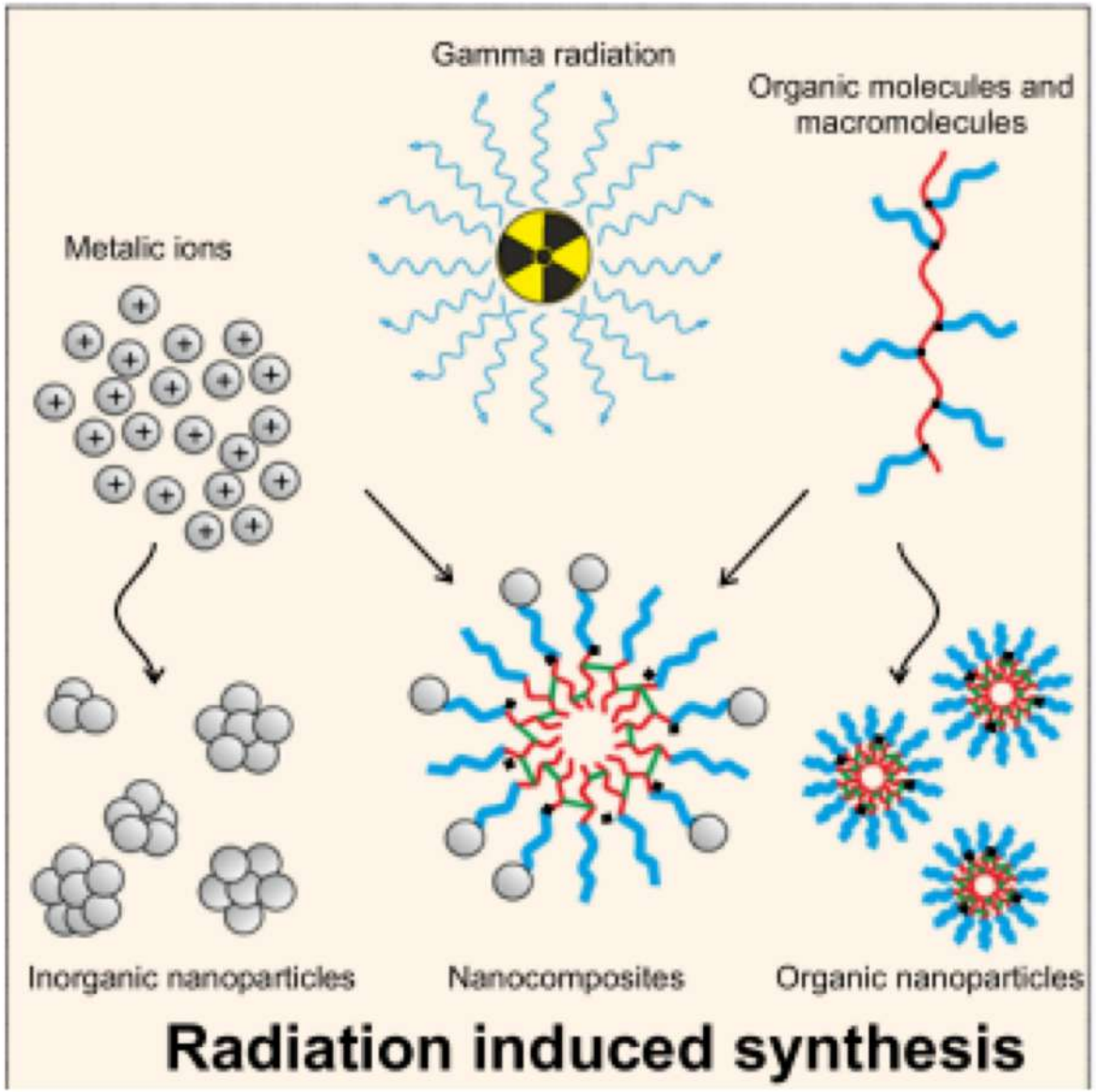


Green synthetic methods employing plant extracts, microorganisms and biopolymers have proven to be potent candidates for replacing chemical methods of NP synthesis (reaction catalisis by enzymes or specific chemical elements)

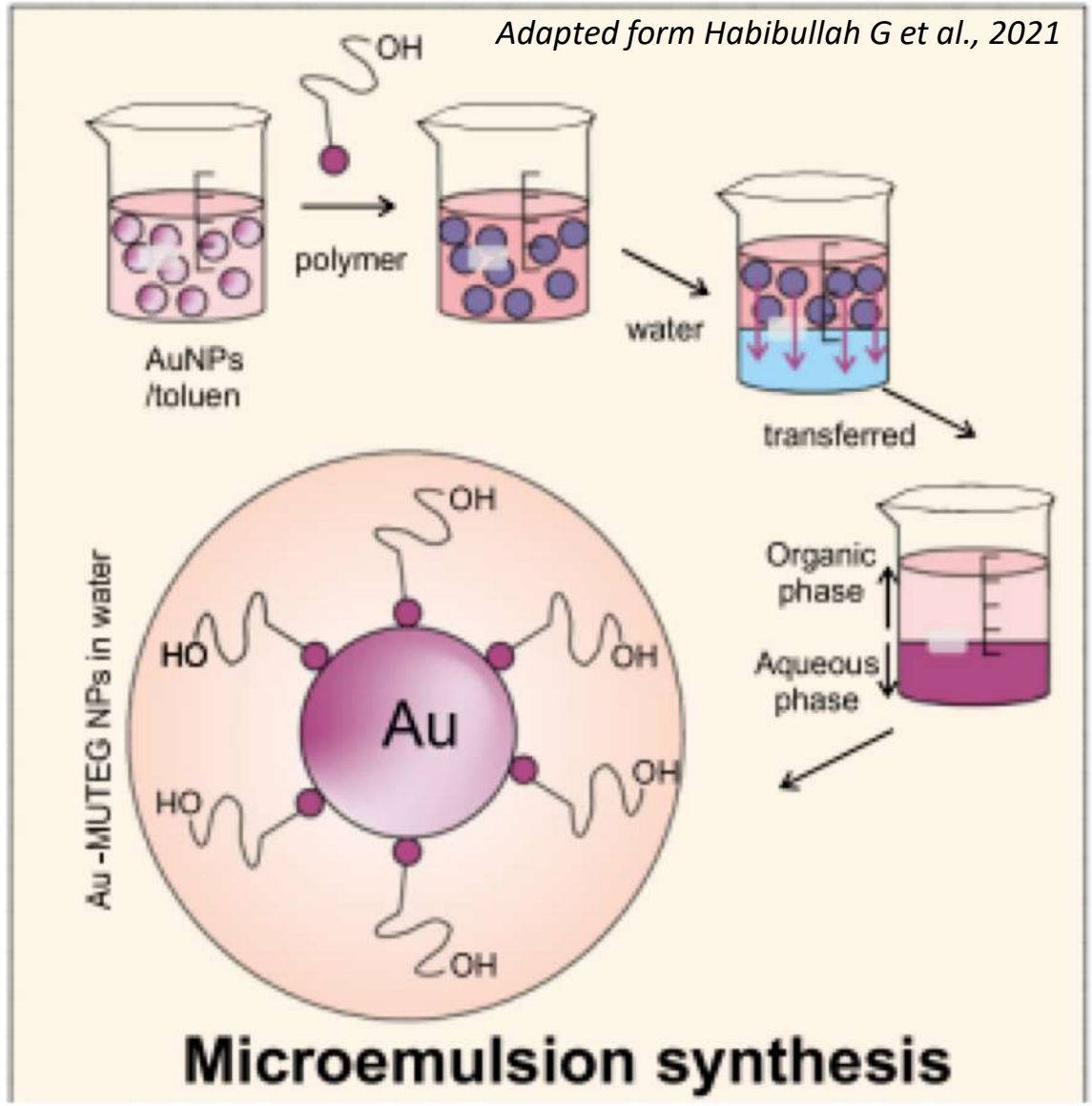


Dissolution of a metal sheet from the anode to achieve the **deposition of metal salt on the cathode** of an electrochemical cell in the presence of an electrolyte to produce nanoparticles

Adapted form Habibullah G et al., 2021



For metal NP. This method employs **ionizing radiation** (gamma and X-rays and UV-light) for the synthesis of **metal nanoparticles**. Reaction occours in aqueous solutions.

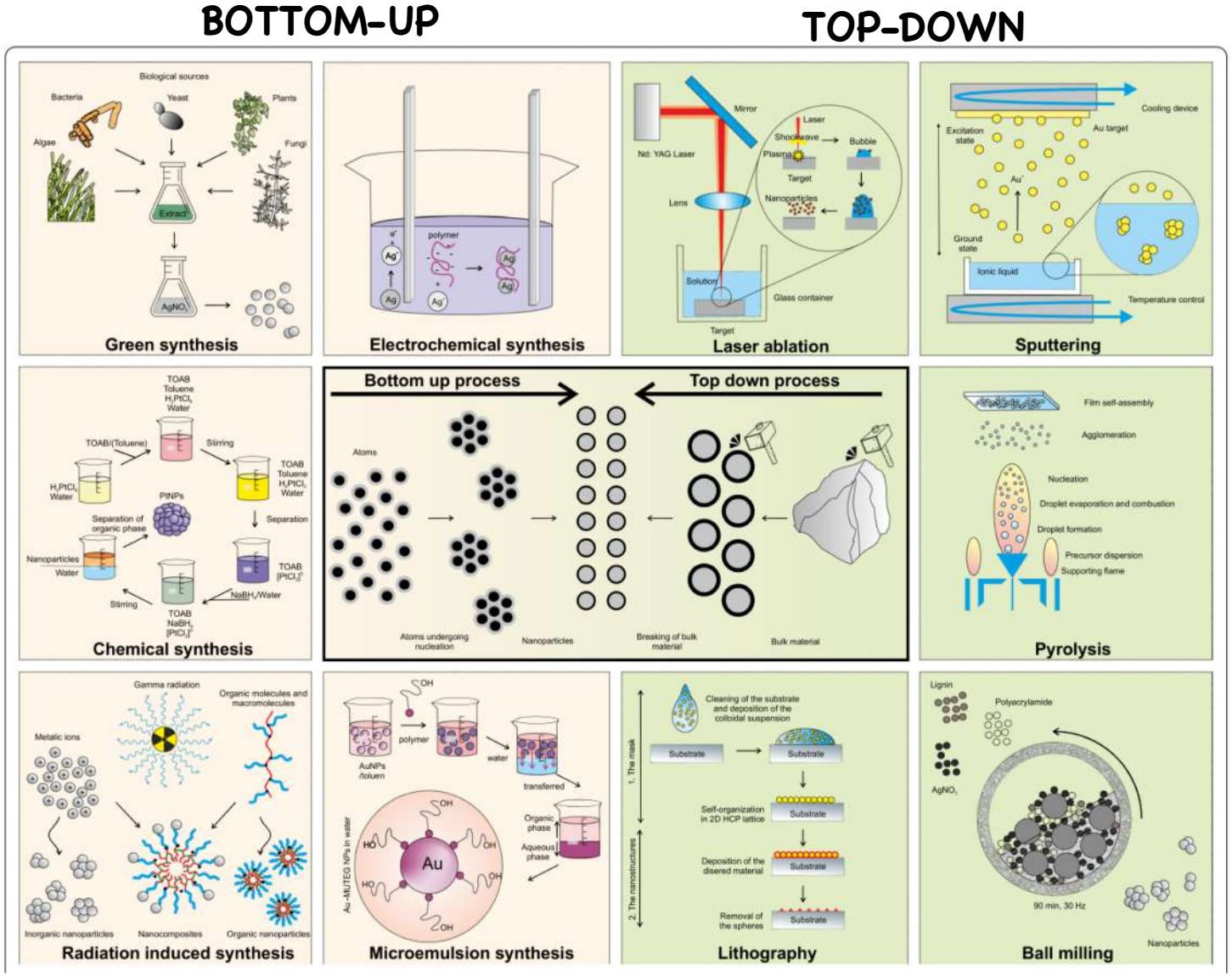


It consists in a mixtures of two immiscible liquids in the presence of a surfactant. **Two separate microemulsions** are prepared, one containing the **ionic salt** and another containing the **reducing agent** produced in an amphiphilic environment.

Advantages:

1. provides control over the final product formation with more **homogeneous size, shape** (physical parameters) and **chemical composition**

2. Less expensive



Habibullah G et al., 2021

Involve externally controlled processes of **cutting, milling and shaping** the materials into the desired order and shape

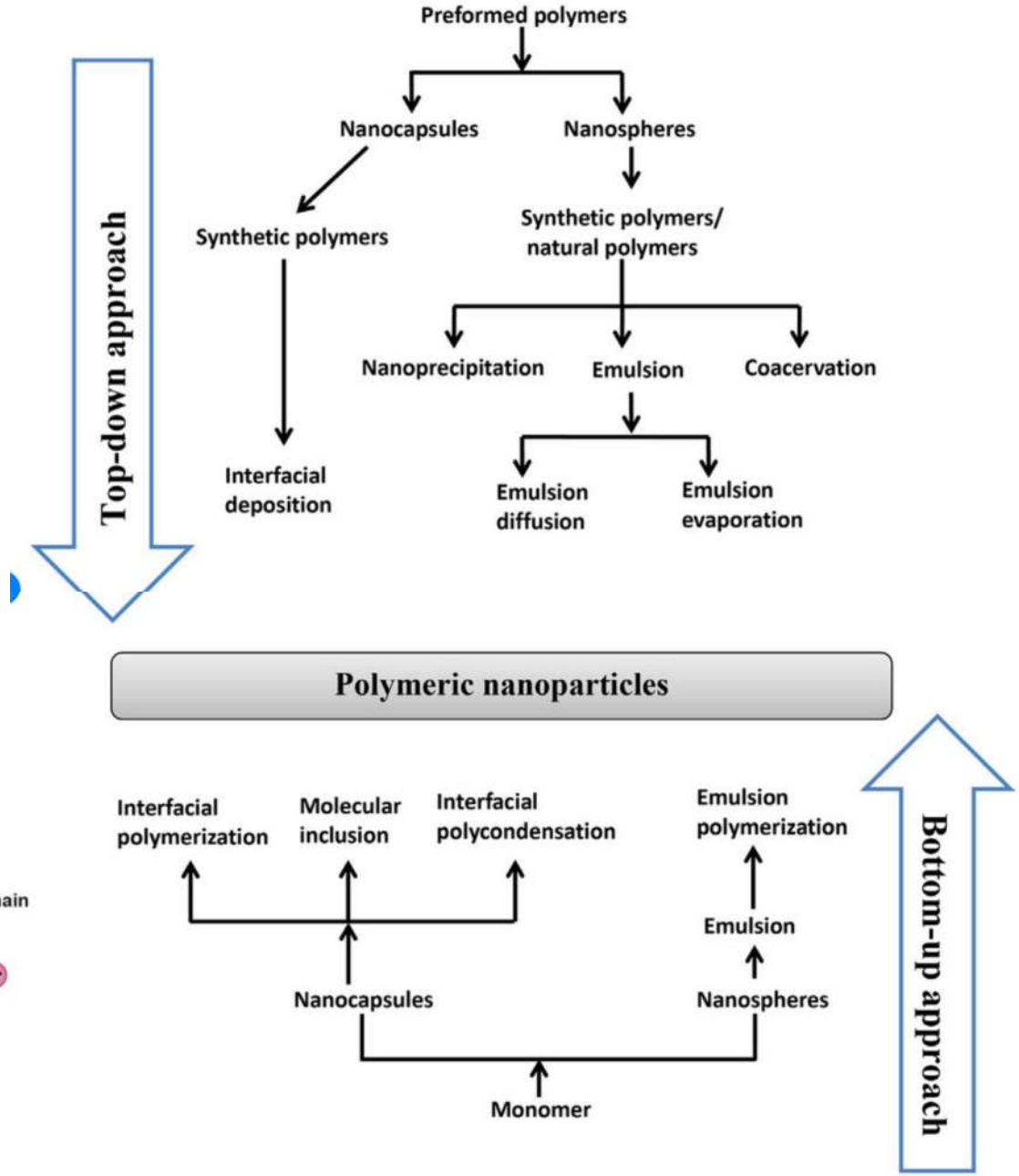
Major limitations:

1. the imperfect surface structure of the resulting NP, which substantially affects their physical and chemical properties

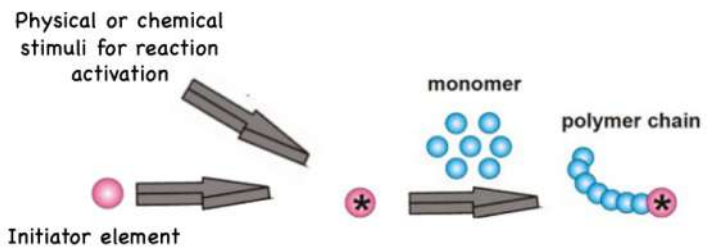
2. this method requires an enormous amount of energy to maintain the high-pressure and high-temperature conditions during the synthetic procedure, making the process expensive

Polymeric NP Synthesis Approaches

Dispersion approaches of preformed polymers



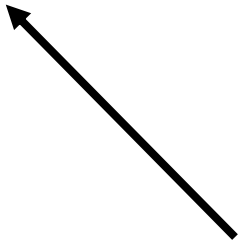
Polymerization of monomers



Reaction ambient: Non-solvent phase or solvent phase

Stabilizators: tensioactive or surfactants

Synthesis approaches and material composition should guarantee NP … overtime



STABILITY PRESERVATION

FACTORS INFLUENCING NP STABILITY:

Environmental stresses
such as extended storage, pH and mineral composition, thermal processing, freeze–thaw cycling, dehydration, mechanical stress and light exposure

Table 5. Key parameters defining NP stability and strategies to determine stability preservation.

	NP Stability	Definition	Approaches Used for Characterization of NP Stability	
			Physical	Chemical
1	Aggregation	Preservation of NPs upon collisions	Dynamic light scattering	Single particle inductively coupled plasma mass spectrometry UV–visible spectroscopy
2	Core Composition	Unchanged chemistry of the core during the use	X-ray diffraction	Single particle inductively coupled plasma mass spectrometry UV–visible spectroscopy Surface-enhanced Raman scattering X-ray photoelectron spectroscopy Energy dispersive X-ray
3	Shape	Preservation of NP architecture during the use	Transmission electron microscopy Scanning electron microscopy X-ray diffraction Atomic force microscopy	Single particle inductively coupled plasma-mass spectrometry UV–visible spectroscopy
4	Size	Preservation of NP dimension during use or storage	Dynamic light scattering Scanning electron microscopy Transmission electron microscopy Small-angle X-ray scattering Atomic force microscopy	Single particle inductively coupled plasma-mass spectrometry UV–visible spectroscopy
5	Surface chemistry	Preservation of the native surface functionality	Low energy ion scattering X-ray photoelectron spectroscopy	Single particle inductively coupled plasma-mass spectrometry UV–visible spectroscopy Surface-enhanced Raman scattering X-ray photoelectron spectroscopy Energy dispersive X-ray

Peserico A et al., 2022

NP functionalization

NP conjugation with bioactive molecules (MOIETIES)

- **TARGETING/UPTAKE**

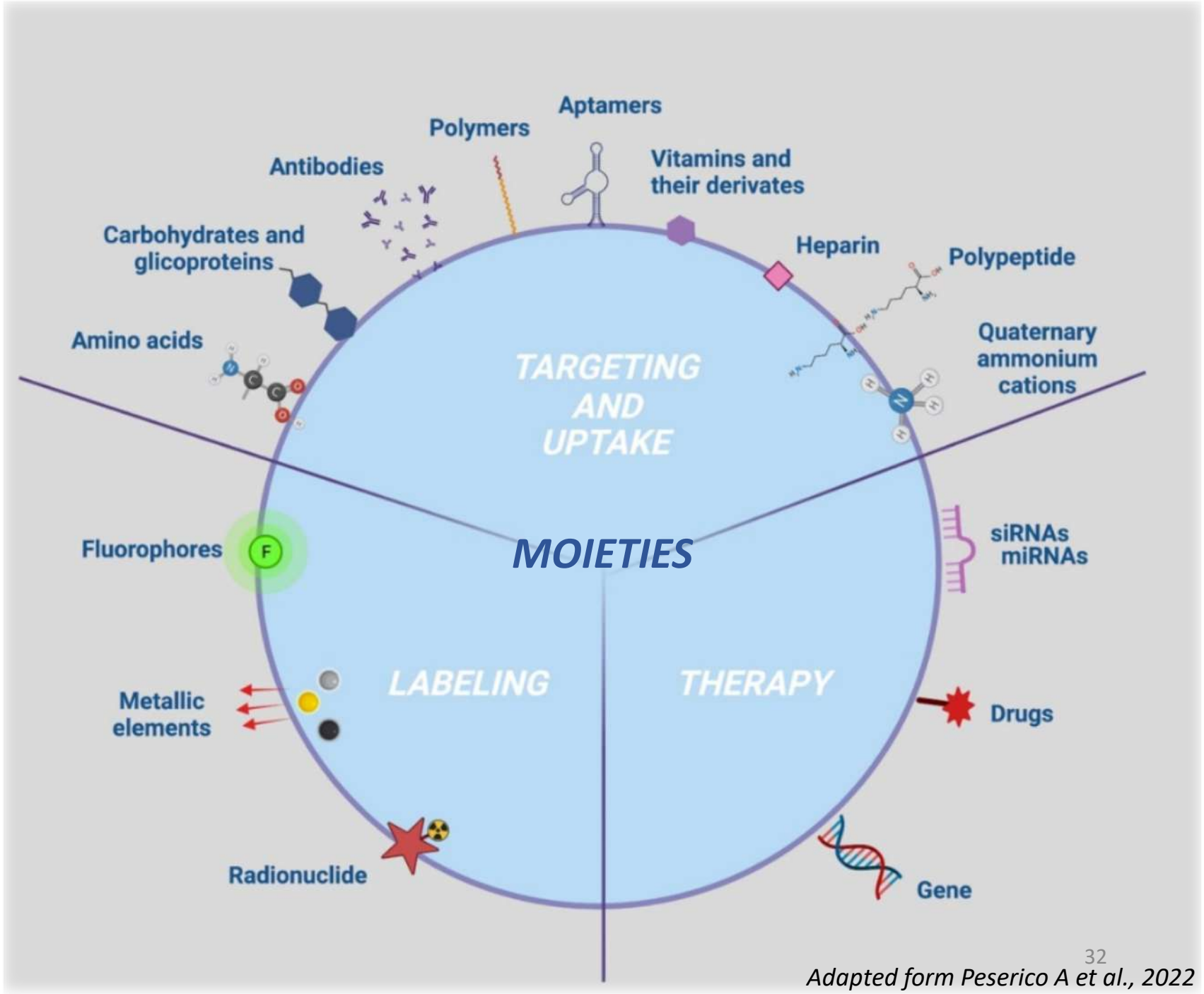
Selection of cells to be targeted and facilitation of NP internalization

- **THERAPY**

Affect positively or negatively target cell functions

- **LABELING**

Tracking of NP delivery



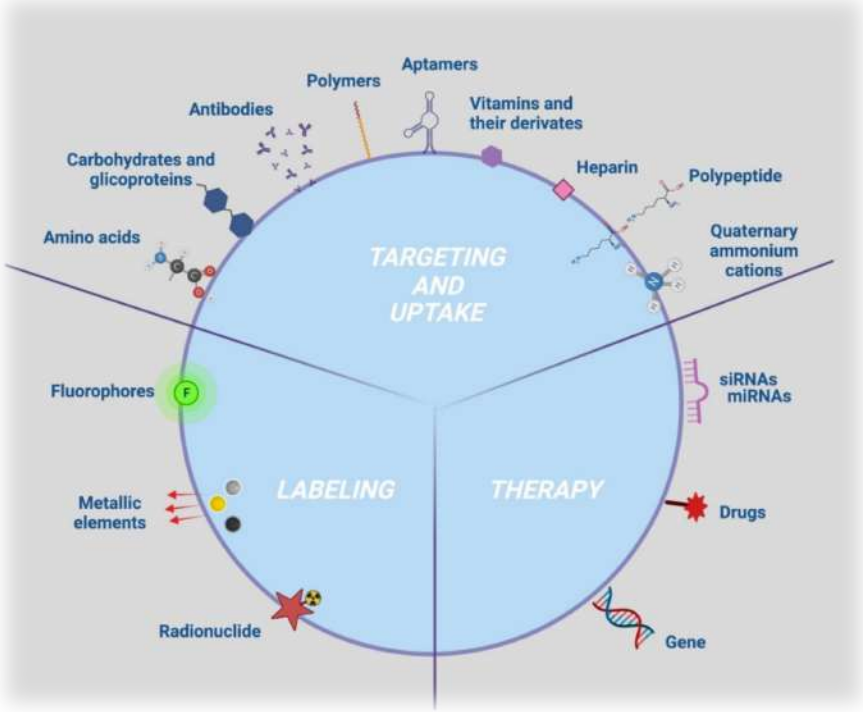
Adapted form Peserico A et al., 2022

Targeting and uptake moieties

MOIETIES WITH ACTIVE ACTION

Elicit a targeted NP uptake (internalization) by capturing specific cell biomarkers such as antigens/receptors

- **Antibodies** for specific cancer cell antigens
- **Folic acid** and **riboflavin vitamins** due to overexpression of their receptors on cancer cells
- **Aptamers** which recognize specific receptors on the cell surface
- **Carbohydrates** (dextran, carbodextran, chitosan, glucose, beta cyclodextrin, and transferrin) to avoid immune response



Peserico A et al., 2022

MOIETIES WITH PASSIVE ACTION

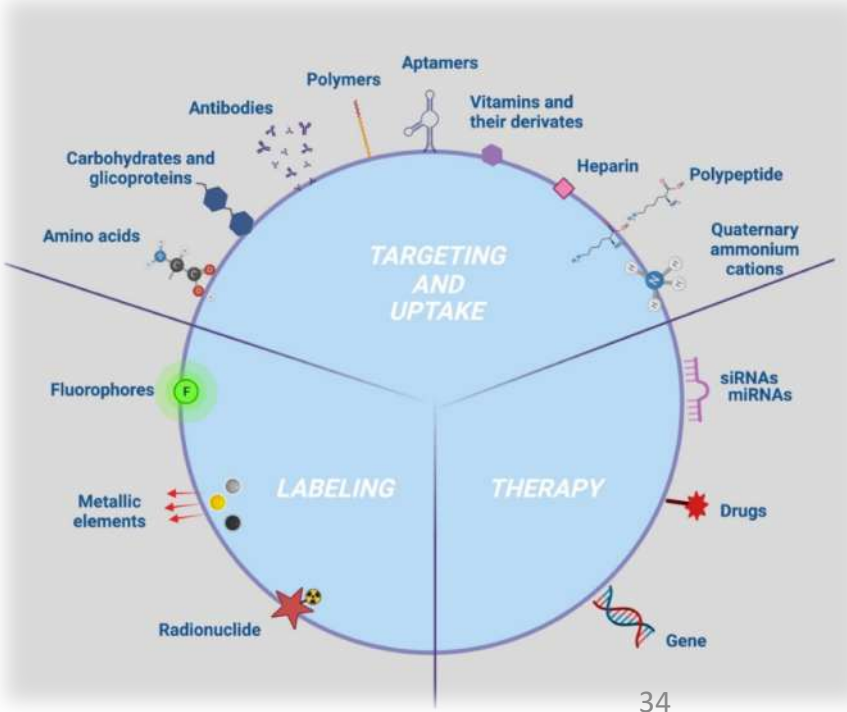
Enhance NP permeation and retention based on their biocompatibility

- **Polymers**
- **Heparin**
- **Quaternary ammonium cations**
- **Polypeptide polylysine**
- **Histidine** amino acid, which, thanks to their positive charge, stabilize NP and mediate the electrostatic interaction with the cell membrane, improving the endocytosis

Terapheutic moieties

Several therapeutic NP have been developed for both self-reporting disease and/or tissue damage and delivering therapy.
Therapy followed by imaging might be useful to test reactions in order to treat and identify patients in which therapy has an effect with the goal of providing personalized therapy for individual patients.

miRNA
siRNA
genes
drugs or **compounds**
with key roles in the modulation of cell proliferation and differentiation



AntimiR-138 was shown to significantly promote the expression of osteogenesis-related genes and its conjugation to the NPs used to label the MSCs was found to efficiently enhance the osteogenic differentiation of transplanted MSCs and direct cranial bone regeneration in preclinical mouse models

BCL2 and BIRC5 as well as genes with regulatory roles in sustaining cancer cell proliferation and migration, were used for NP functionalization and were found to selectively blockade the cancer cell proliferation of oral and glioblastoma cancer cell models

Peserico A et al., 2022

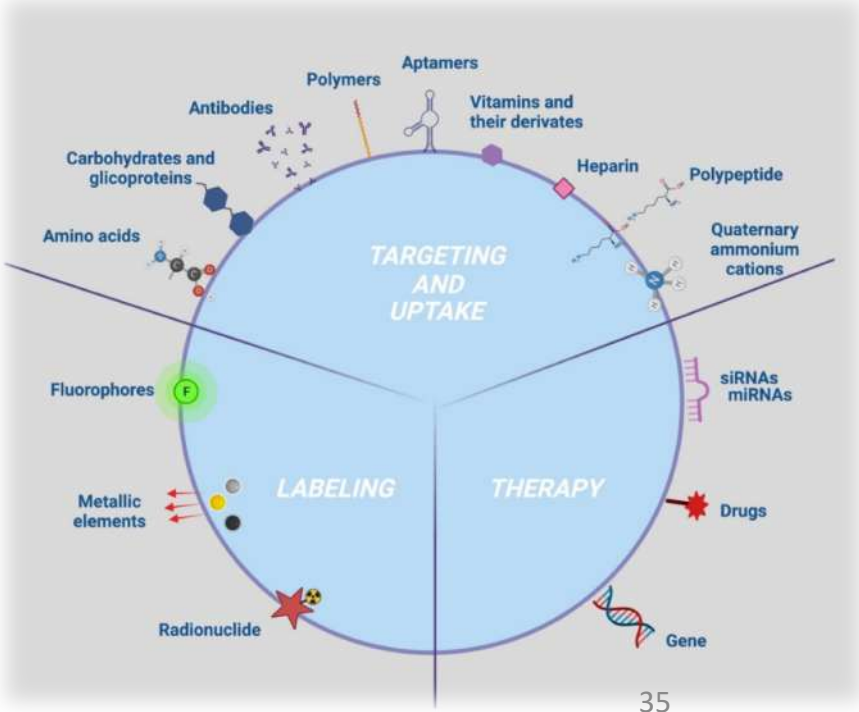
Labeling moieties

Molecules with optical properties working as contrast agent:

- **Fluorophore**
- **Bioluminescent dyes**
- **Isotopes** *or* **chemical elements with high molecular weight or magnetic properties**

For inorganic NP, a combinatorial usage of contrast agents represents an effective strategy for multimodal in vitro and/or in vivo tracking, as it could allow the limitations found with the use of a single-tracking approach to be overcome.

miRNA -26a-5p to label MSCs to be transplanted for tissue regeneration purposes



Peserico A et al., 2022

NP Sterilization prior in vivo delivery

- Nanoparticles intended for parenteral use should be sterilized to be pyrogen free before using on animals or humans.
- Sterilization is achieved by using aseptic technique throughout preparation, processing and formulation or by autoclaving or using γ- irradiation.
- Autoclaving and γ- irradiation show impact on the physicochemical properties of the particles with modification of particle size stability and drug release characteristics.
- Sterilization is a critical step and should be systematically investigated during formulation development stage.

NP applications in biomedicine

CANCER MEDICINE

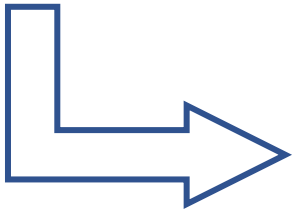
Aim: diagnosis and/or treatment of cancer

- Tracking of tumor foci
- Drug delivery

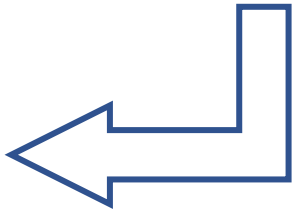
REGENERATIVE MEDICINE

Aim: monitoring cell trasplantation procedures and/or enhancing tissue regeneration

- Tracking of trasplanted cells
- Immunomodulatory factors delivery



HOW?



HOW

DIAGNOSIS?

NP works as a contrast agent to be followed by imaging techniques

HOW

THERAPY?

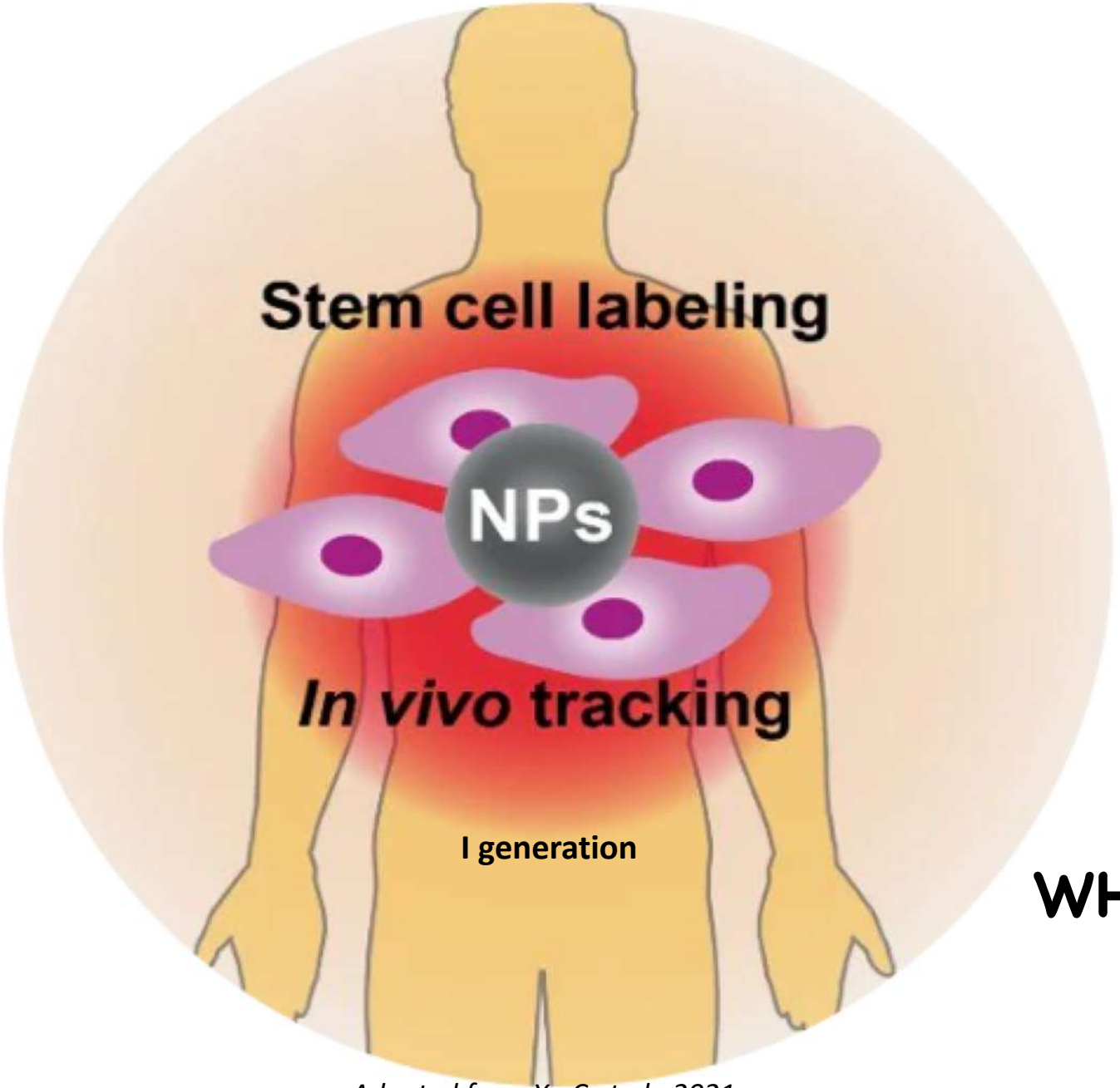
NP carries a drug

HOW

How to find its application in other most suitable tissue?

NP finds its application in other most suitable tissue when incorporated by a cell able to home

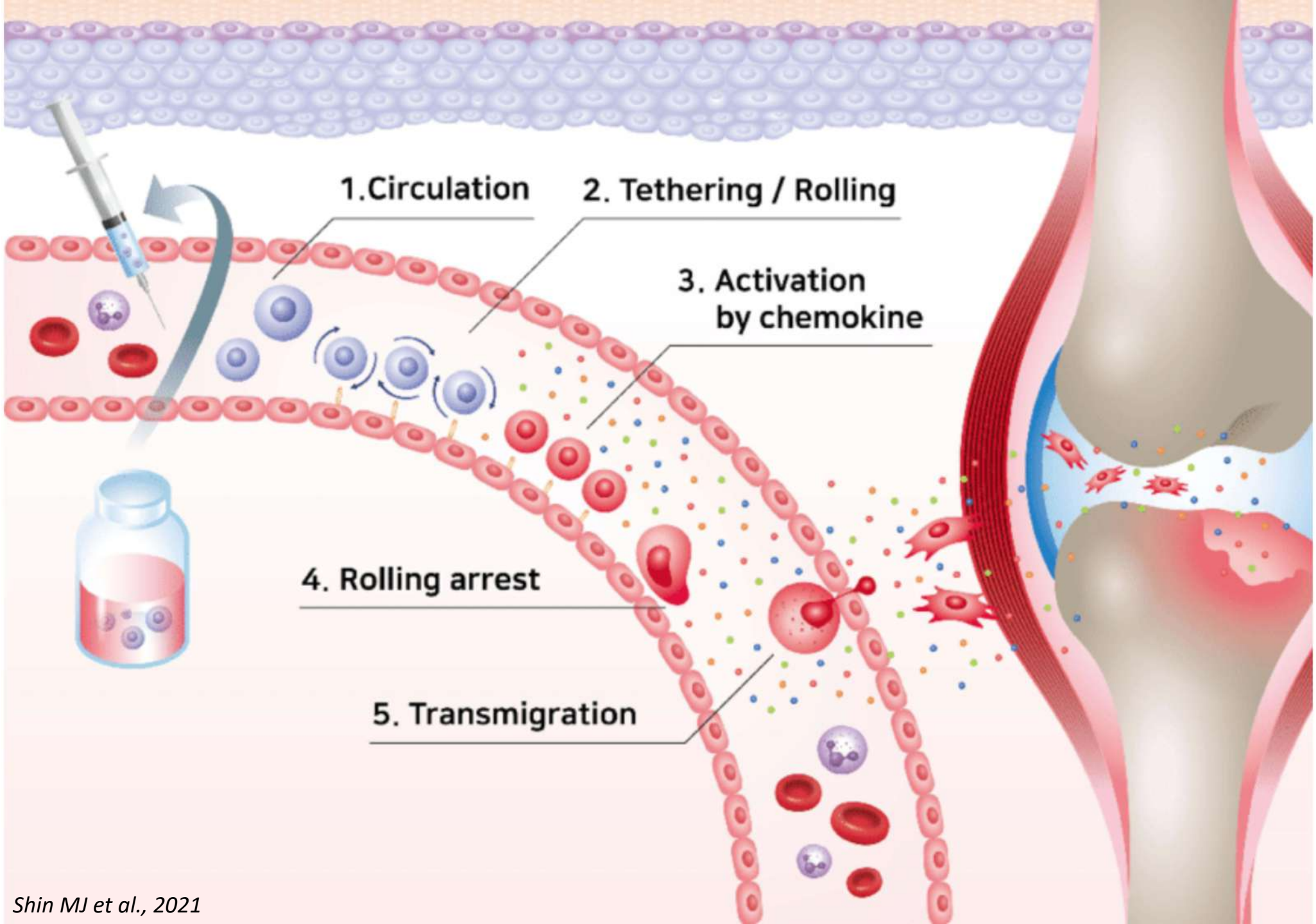
systemic NP administration



WHY STEM CELLS?

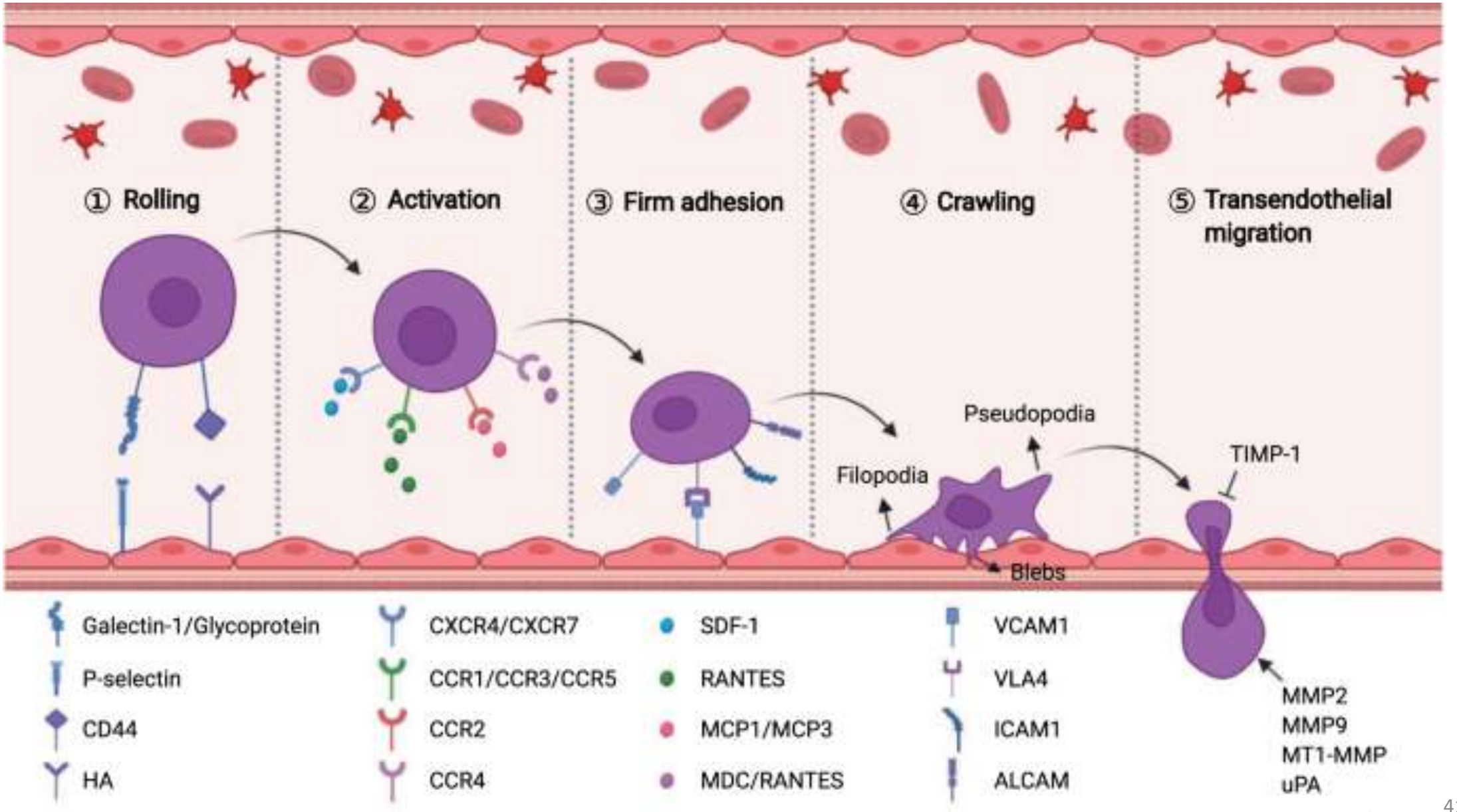
Adapted from Xu C et al., 2021

STEM CELL HOMING



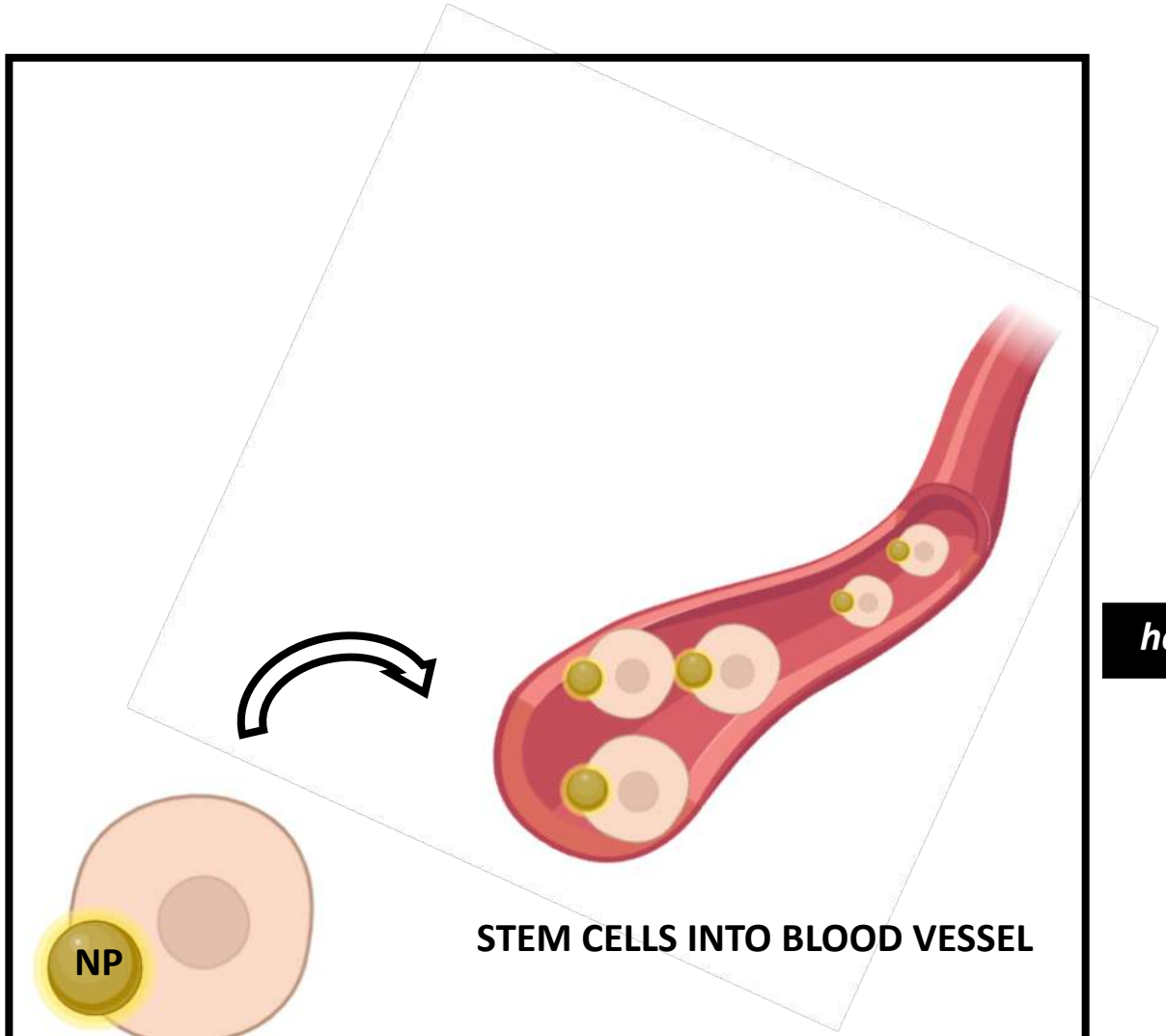
Shin MJ et al., 2021

HOW DO STEM CELLS FIND THEIR WAY HOME?



Yuan M et al., 2022

REGENERATIVE MEDICINE

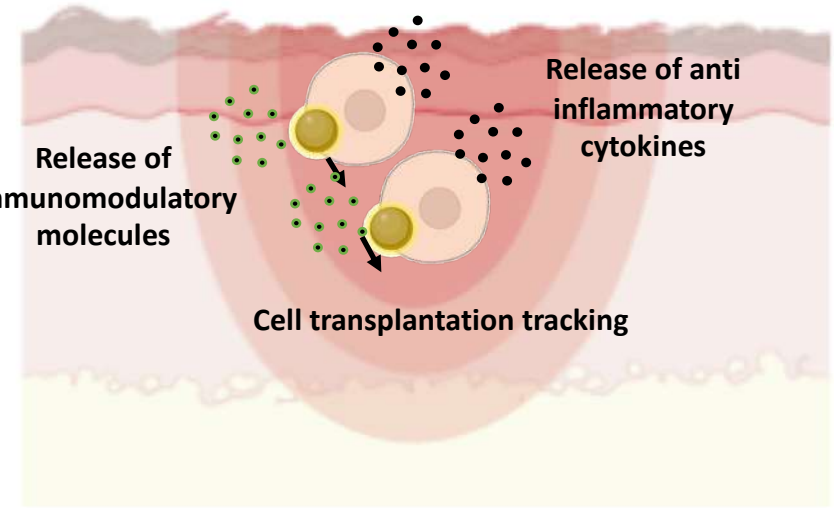


STEM CELL

STEM CELLS INTO BLOOD VESSEL

homing

DAMAGED TISSUE

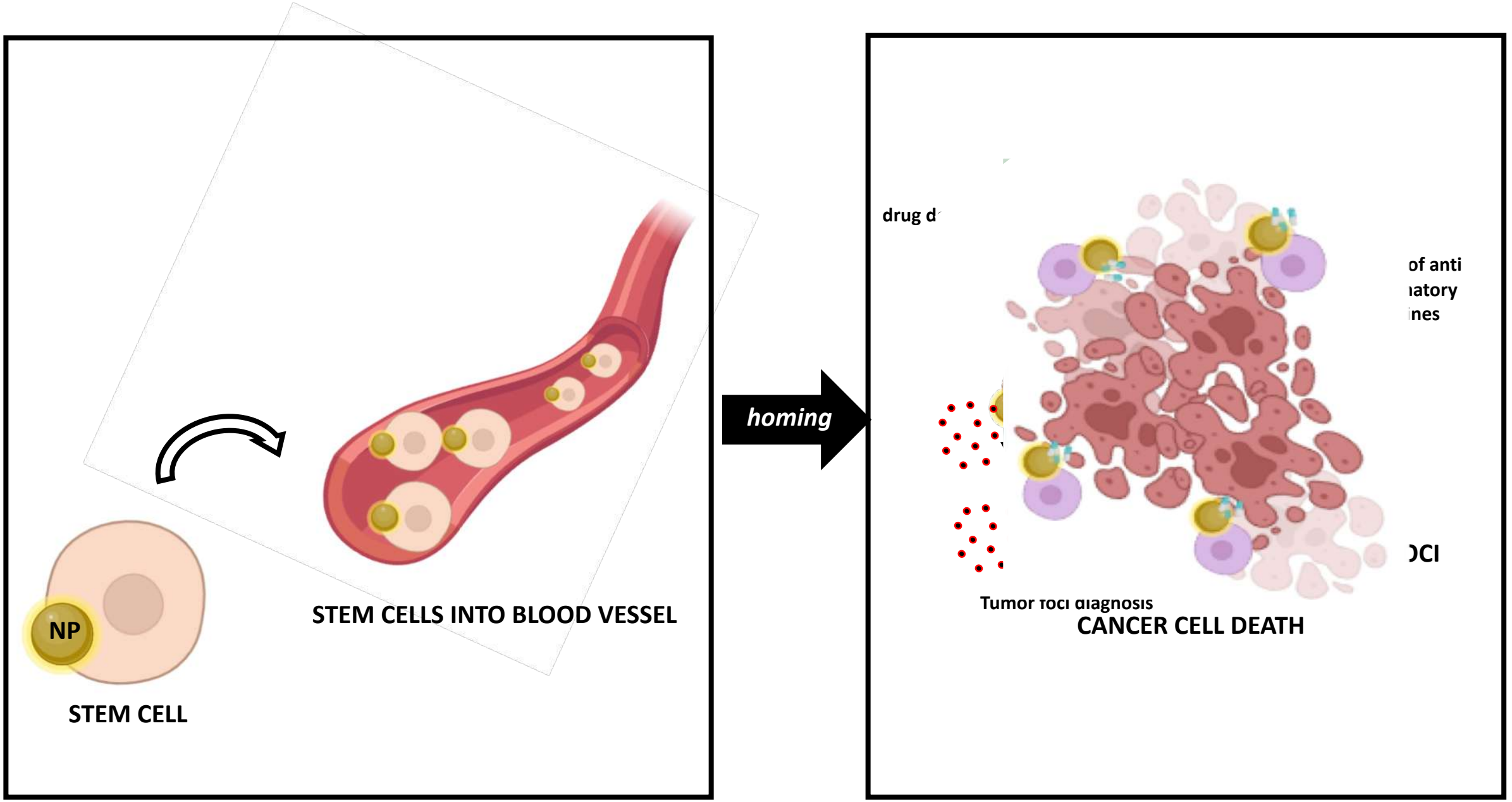


EXPLOITATION OF STEM CELL PROPERTIES

- Self renewing
- Undifferentiated cells differentiate into any organ-specific cell depending on their origin
- **Immunomodulation**

ENHANCED TISSUE REGENERATION IN A DAMAGED SITE

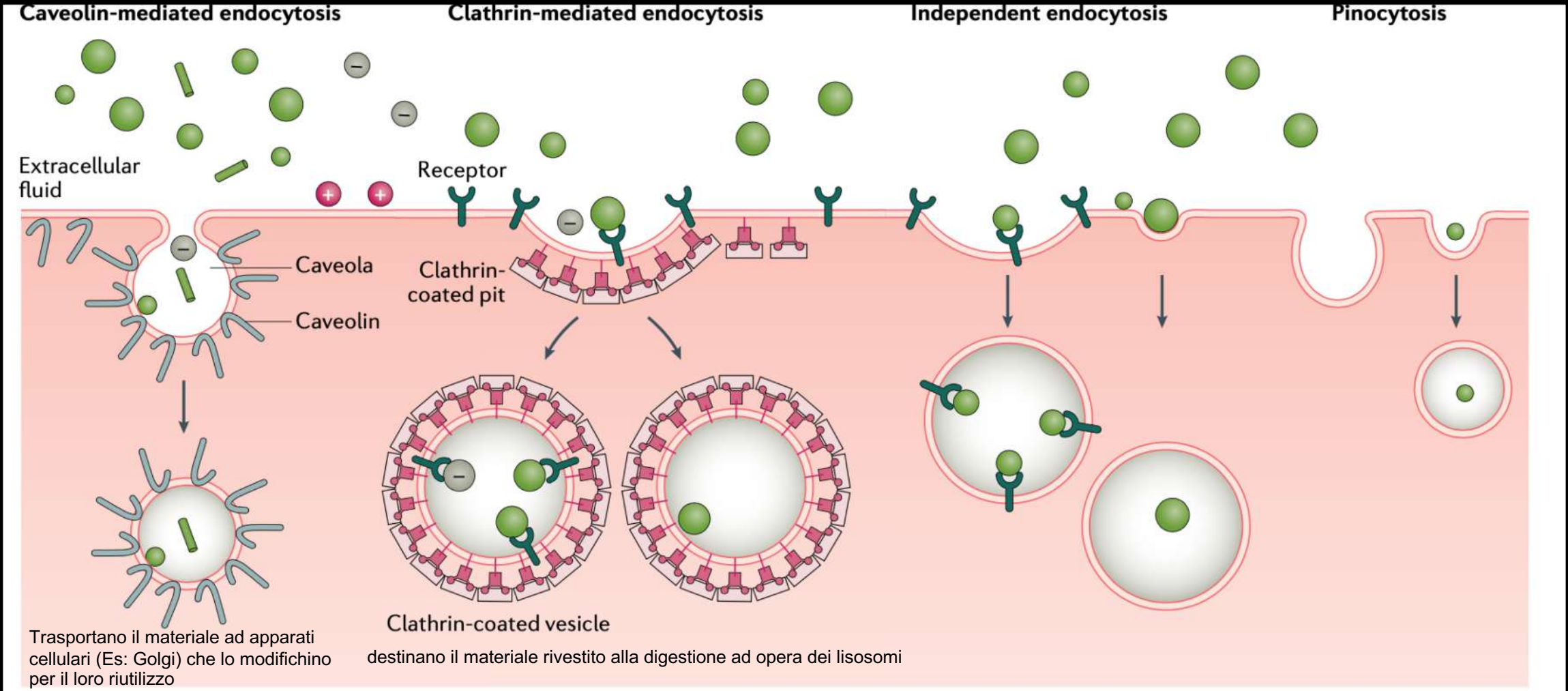
CANCER MEDICINE



Key features defyning a cell as good carrier of NP

- The cells must be able to incorporate exogenous material not requiring particular in vitro manipulation
- Migratory and homing ability
- Immunomodulatory capacity
- Doubling time should not affect the NP incorporated to each cell division

FIND THE RIGHT RATIO!

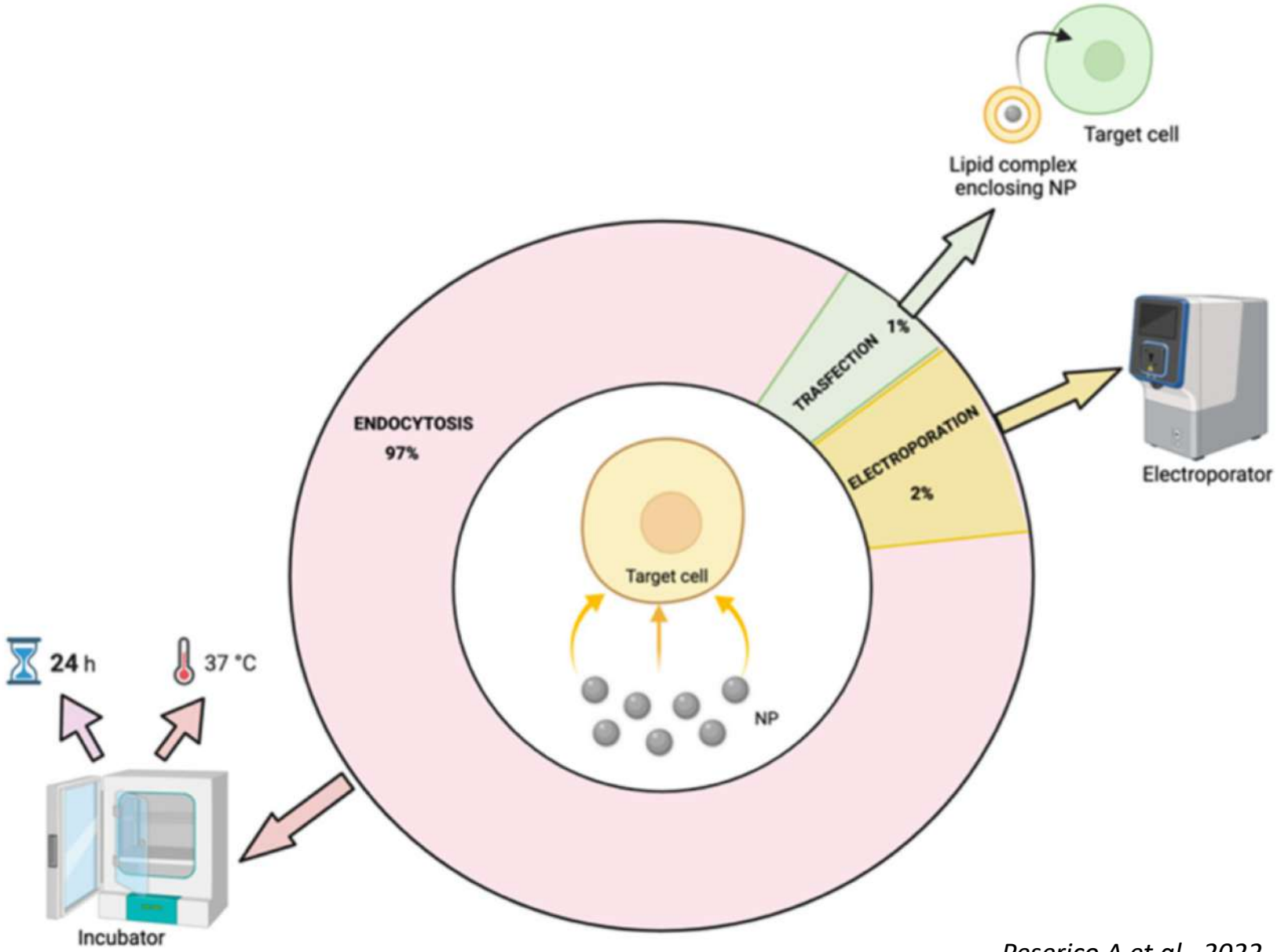


Trasportano il materiale ad apparati cellulari (Es: Golgi) che lo modifichino per il loro riutilizzo

destinano il materiale rivestito alla digestione ad opera dei lisosomi

Michell MJ et al., 2021

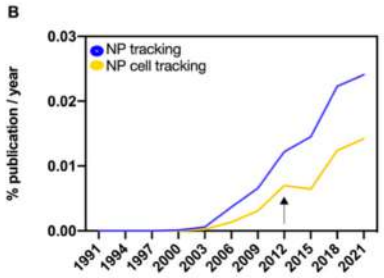
NP CELL INTERNALIZATION MECHANISMS



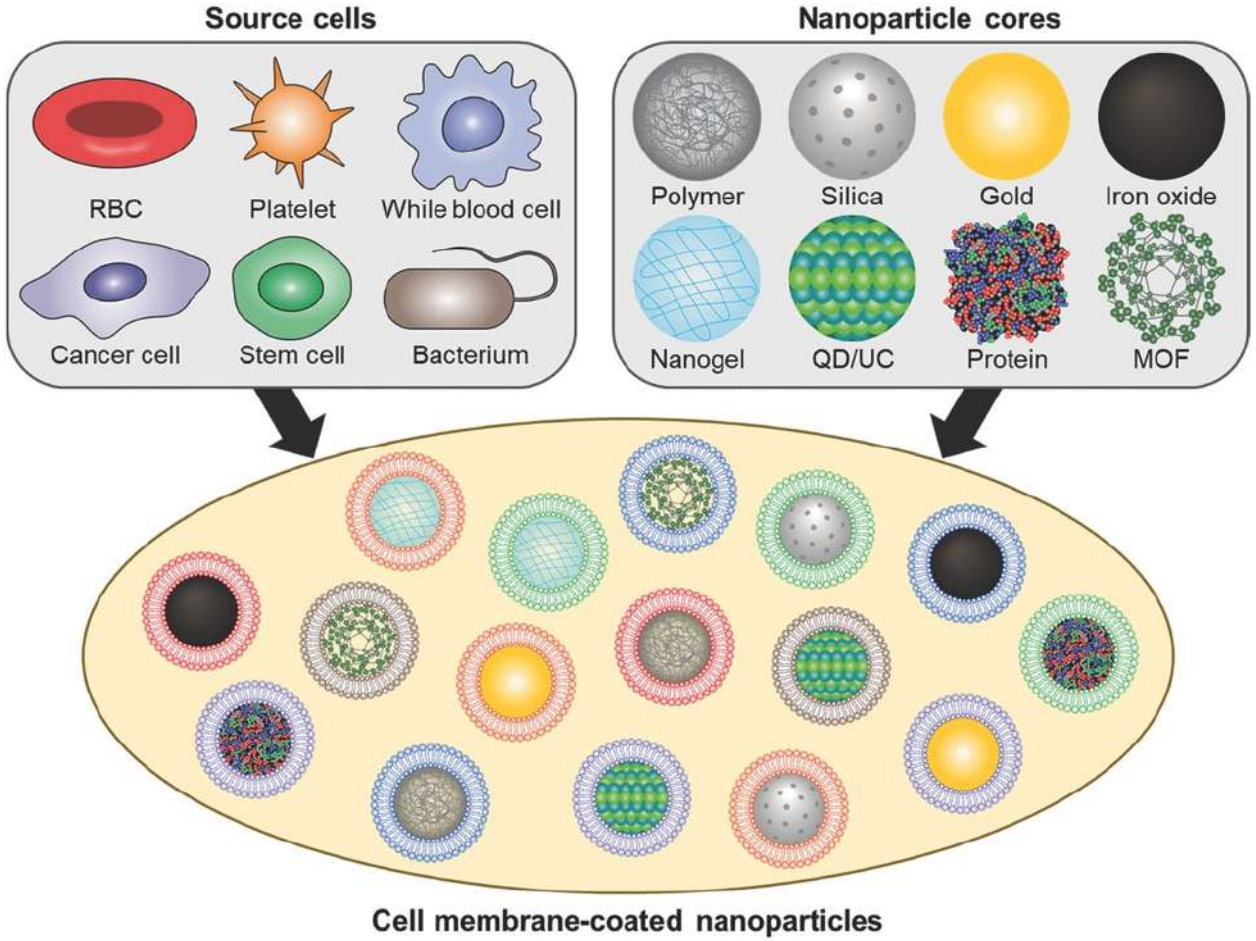
Peserico A et al., 2022

Cell Membrane-coated NP

II generation of NP for cell tracking (diagnosis) and therapy



Peserico A et al., 2022



Cell membrane coating is an emerging nanotechnology. By cloaking nanomaterials in a layer of natural cell membrane, which can be derived from a variety of cell types, it is possible to fabricate nanoplatforms with enhanced surface functionality. This can lead to increased nanoparticle performance in complex biological environments, which can benefit applications like drug delivery, imaging, phototherapies, immunotherapies, and detoxification.

Fang RH et al., 2018

NP systems and imaging techniques for tracking

The cell-tracking imaging platform choice relies on the tyope of contrast agent used for cell labeling and vicecersa

1. Magnetic resonance imaging (MRI) (in vivo)

2. X-ray, also known as X-ray computed tomography (CT) (in vivo)

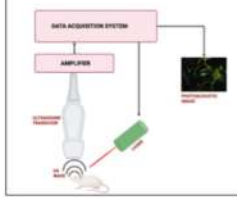
3. Optical imaging (endoscopy and fluorescence near-infrared or bioluminescence-based imaging methodologies)

4. Ultrasound

5. Radionuclide molecular imaging

6. Photoacoustic imaging (PAI)

Imaging devices in vivo

IMAGING DEVICE	OPERATIONAL PRINCIPLE	TARGET TISSUE	ADVANTAGES AND DISADVANTAGES
MAGNETIC RESONANCE IMAGING * 	Magnetic resonance imaging (MRI) uses powerful magnets to create a strong magnetic field that compels protons in the body to align with it. The MRI sensors can detect the energy produced as the protons realign with the magnetic field when the radiofrequency field is switched off and build a picture of these signals.	Soft tissue	Advantages: High spatial resolution; Detailed anatomical information of specific organs; Non-ionizing radiation. Disadvantages: Slow imaging speed; Long scanning time.
COMPUTED TOMOGRAPHY 	CT employs a narrow beam of X-rays that is targeted at a patient and swiftly rotated around the body, creating signals that are analyzed by the machine's computer to create cross-sectional pictures of the body.	Hard tissues	Advantages: High temporal resolution; No depth penetration limit; Inexpensive; Offers quantitative information on contrast agents in vivo. Commonly available in hospitals and research facilities.
* PHOTOACOUSTIC IMAGING 	PAI irradiates tissues using pulsed laser light, which causes pressure waves because to the elevated warmth and volume. These pressure waves are monitored using a high-frequency ultrasound transducer, and a 3D reconstruction is done.	It adapts very well to structures that contain blood.	Advantages: Excellent contrast; High spatial resolution; High sensitivity. Disadvantages: Shallow detection depth; Lack of stability.
OPTICAL IMAGING 	In vivo optical imaging is involved in the collection of a photographic picture of the body under white light, which allows for the quantification of a bioluminescent (BLI) or fluorescent (FI) signal overlaid on the image. The bioluminescent or fluorescent signal is represented as an intensity map and expressed in photons per second.	Different biological samples: in vitro cells, ex vivo tissue, in vivo imaging of living organism.	Advantages: Semi-quantitative planar image; Signal intensity proportional to the number of viable or actively expressing cells; Disadvantages: Without background anatomical information.

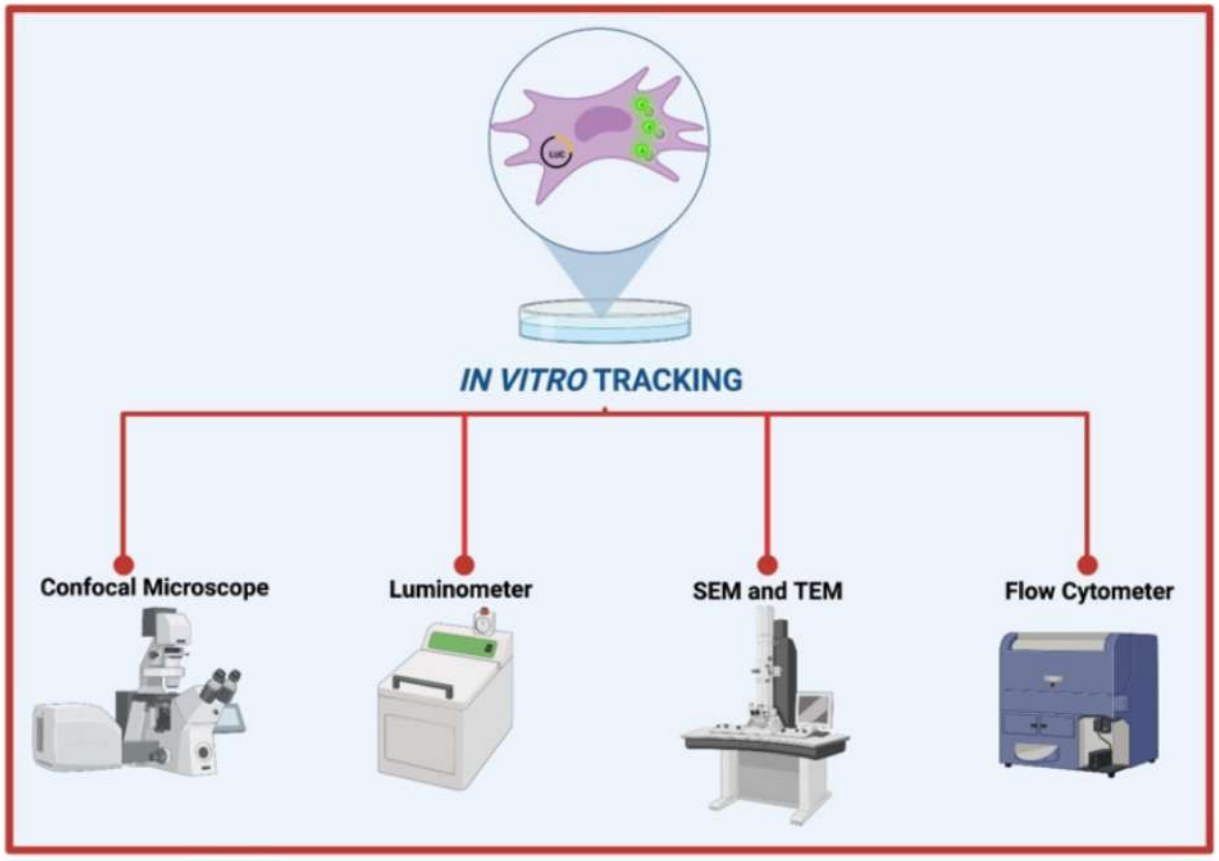
Chemical elements with magnetic properties

Chemical elements (expecially Gold NP) with high molecular weight

Chemical elements with high molecular weight; Carbon elements

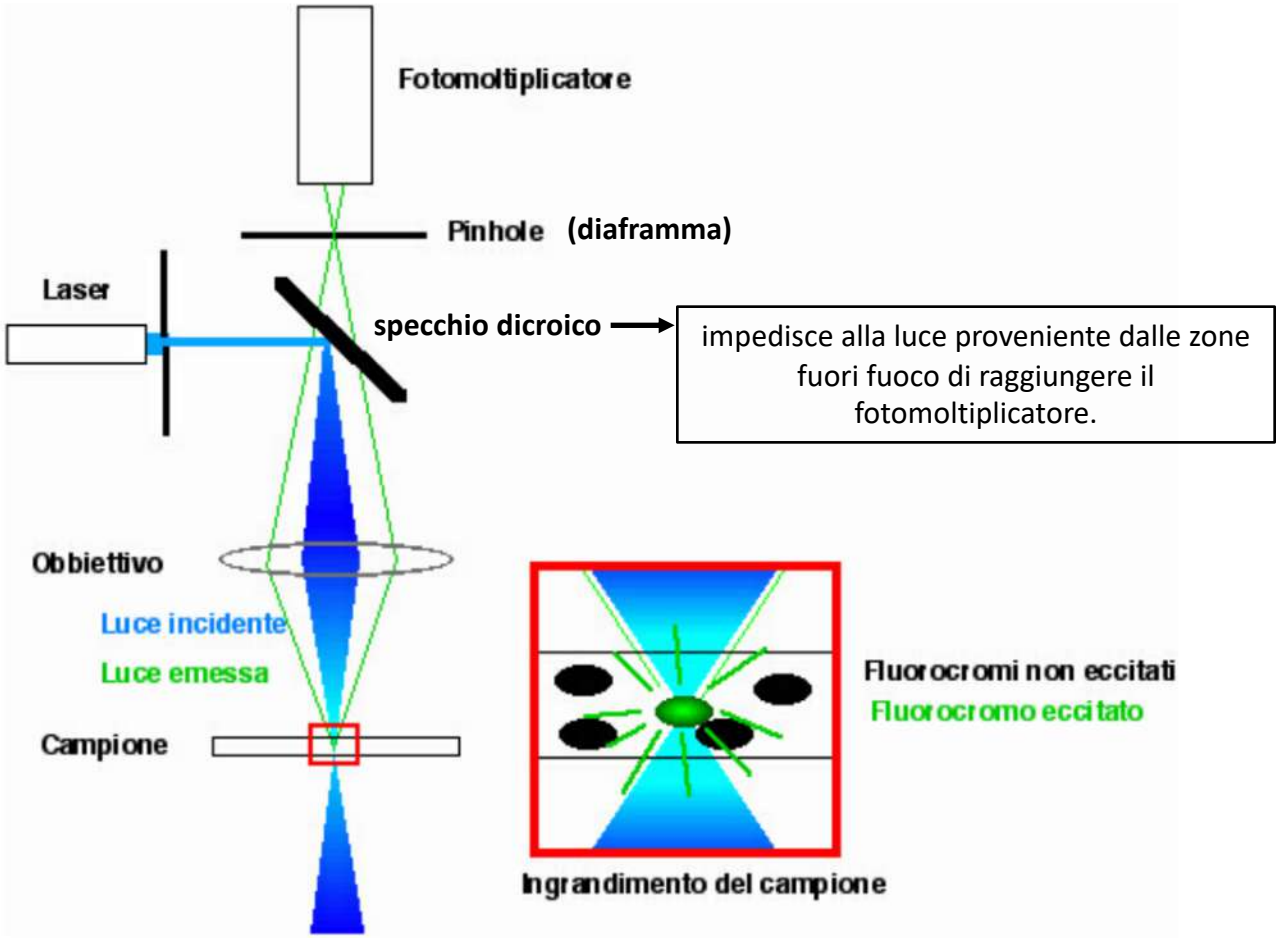
Fluorophores and Bioluminescents

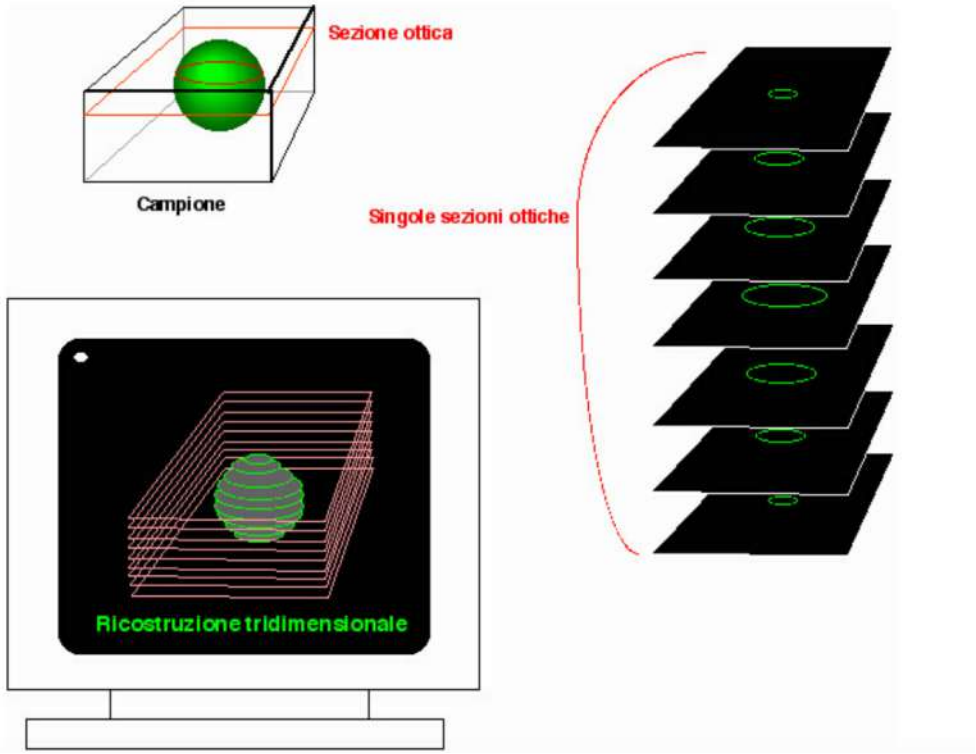
Imaging devices in vitro



Confocal Microscope

La luce emessa dai fluorocromi presenti nel campione viene catturata dalle lenti dell'obbiettivo e deviata da uno specchio dicroico su un fotomoltiplicatore, che trasforma l'intensità luminosa rilevata in un segnale elettrico di intensità proporzionale, segnale digitalizzato per la costruzione dell'immagine.





Ogni punto del campione verrà a corrispondere ad un pixel dello schermo. L'accostamento di tutti i singoli pixel corrispondenti ai punti scanditi dal fascio laser nel campione darà così l'immagina finale.

Spostando lungo l'asse verticale il campione dopo ogni scansione, è possibile eseguire serie di scansioni successive corrispondenti a piani focali via via più profondi all'interno del campione. Queste scansioni prendono il nome di **sezioni ottiche** e la loro sovrapposizione ordinata consente di ricostruire un'immagine complessiva dell'intero volume scandito, in cui tutti i piani sono contemporaneamente a fuoco.

Luminometer

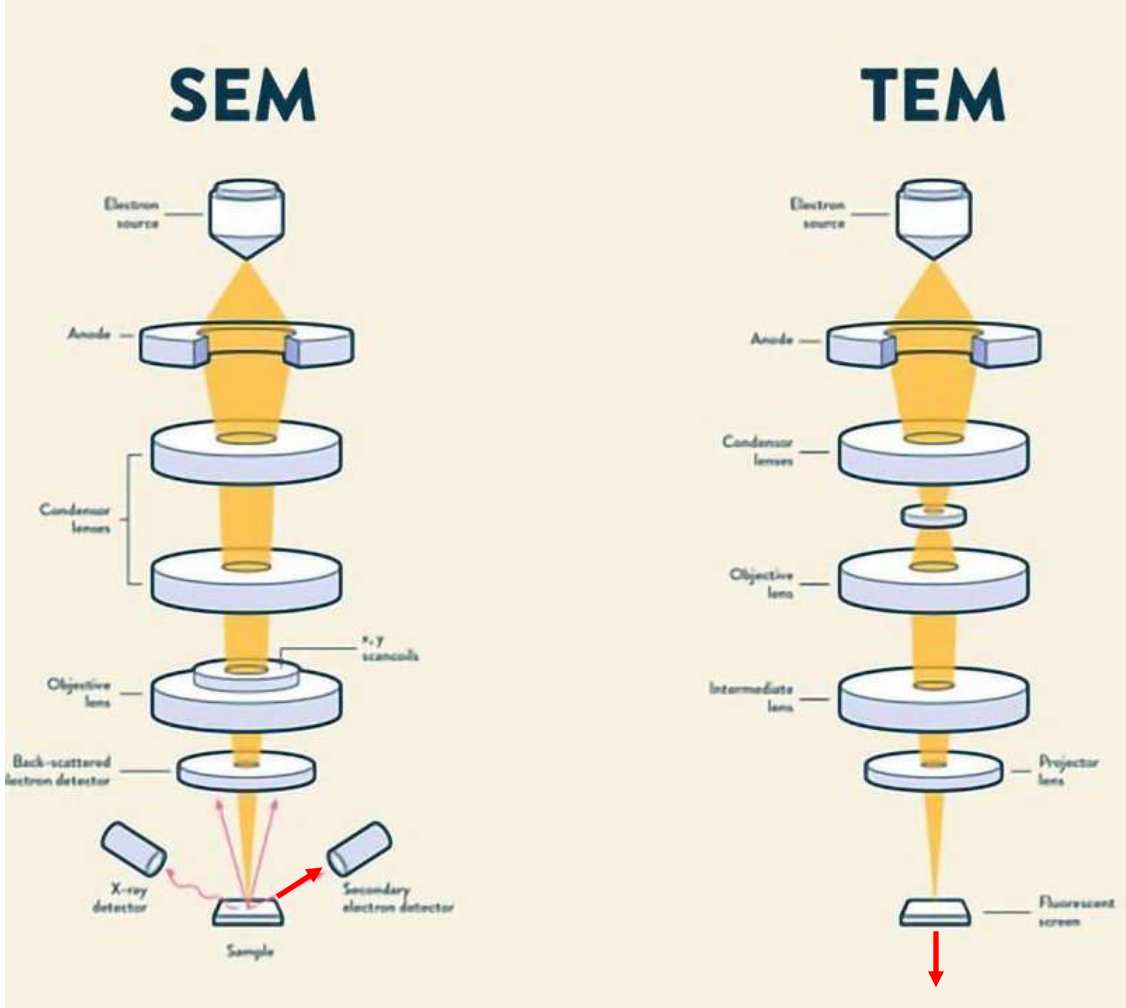
Lettura dell'emissione di fotoni nello spettro visibile.

Sfrutta il fenomeno della bioluminescenza in cui giocano un ruolo chiave 2 elementi:

- substrato organico che emette la luce (luciferina)
- enzima catalizzatore (luciferasi)

Nella maggior parte dei casi il fenomeno è appunto dovuto alla luciferina, che in presenza di ATP (adenosintrifosfato), magnesio e dell'enzima luciferasi, cede elettroni, i quali, passando ad un livello minore di energia, liberano energia sotto forma di luce.

Scanning Electron Microscopy (SEM) and Transmission electron Microscopy (TEM)



SEM creates an image by detecting reflected electrons

TEM uses transmitted electrons (electrons that are passing through the sample) to create an image.

As a result, TEM offers valuable information on the inner structure of the sample, such as crystal structure, morphology and stress state information, while SEM provides information on the sample's surface and its composition.

Signal source: electrons beam
How the signal is transmitted: electron beam pass trought electromagnetic and electrostatic lenses in a high vacuum chamber.

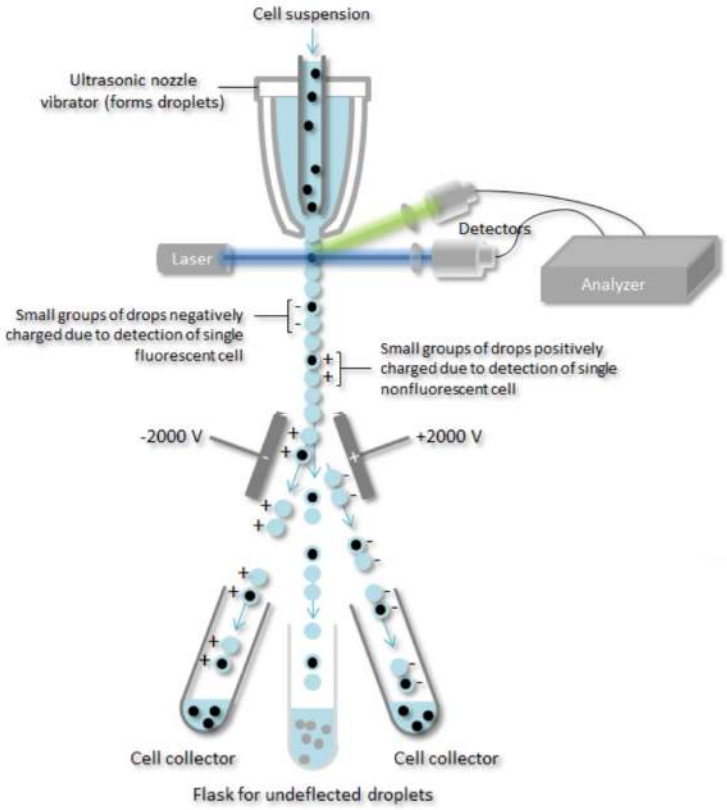
Flow Cytometer

- Caratterizzazione sia a livello qualitativo sia quantitativo di una sospensione cellulare o di particelle.

- Analisi contemporanea di molteplici parametri sia fisici (dimensione e complessità cellulare) sia biochimici/molecolari (es. presenza di specifici antigeni cellulari).

Operational principle:
Il principio si basa sull'impiego di una sorgente luminosa che emette a lunghezza d'onda variabile intercettando perpendicolarmente le singole cellule che fluiscono in un flusso costante e lineare:

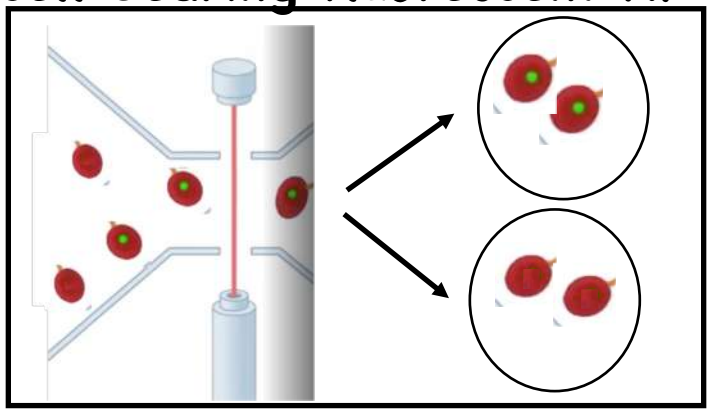
- i raggi direttamente deviati dalla cellula "scatter" forniscono le informazioni fisiche.
- le fluorescenze di emissione forniscono le informazioni legate al target cellulare che si è deciso di studiare (es. particelle incorporate, sottopopolazioni cell).
- 2 detector, uno che misura la dimensione (forward scatter; FSC) ed uno che misura la complessita o granulosità cellulare (side scatter; SSC)



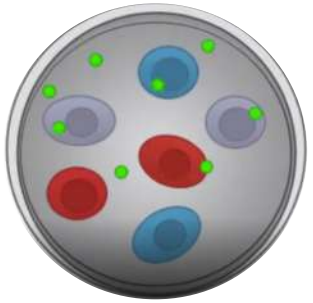
N.B. Esistono due tipi di citometria a flusso: una di tipo "non-sorting" che raccoglie i dati di "scatter" ed emissioni di fluorescenza, ed una di tipo "sorting" che sfrutta tali informazioni per poter separare singole sottopopolazioni cellulari con determinati parametri, partendo dalla popolazione eterogenea iniziale.

Flow cytometry Application examples:

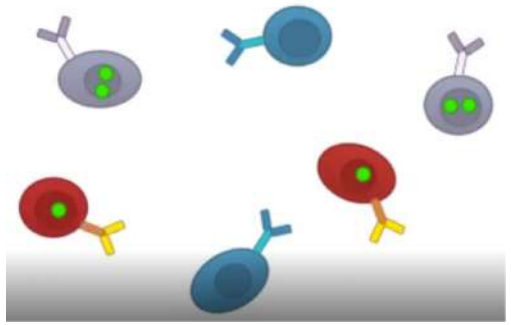
1. Sorting and quantification of cell bearing fluorescent NP prior in vivo administration



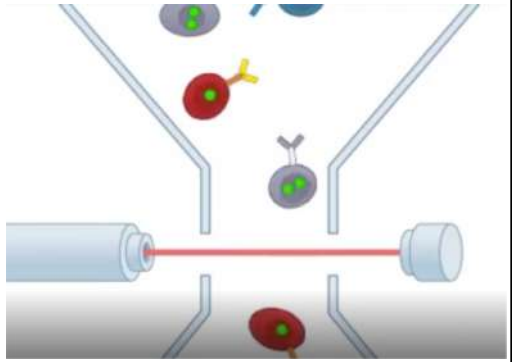
2. Identification of fluorescent NP interaction with different cell populations



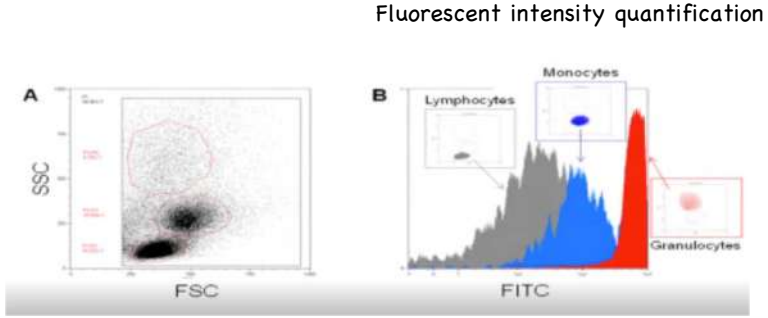
NP cell uptake



Cell labeling with ab against specific cell type markers



Flow cytometry analysis



Interaction of each cell type with NP can be measured

STUDY QUESTIONS

- Ho un paziente con tumore alla mammella in stadio avanzato, occorre valutare la presenza di eventuali metastasi. Primo tessuto target di metastatizzazione del tumore alla mammella è l'osso.

1. Quale approccio diagnostico supportato da NP?
2. Quale NP?

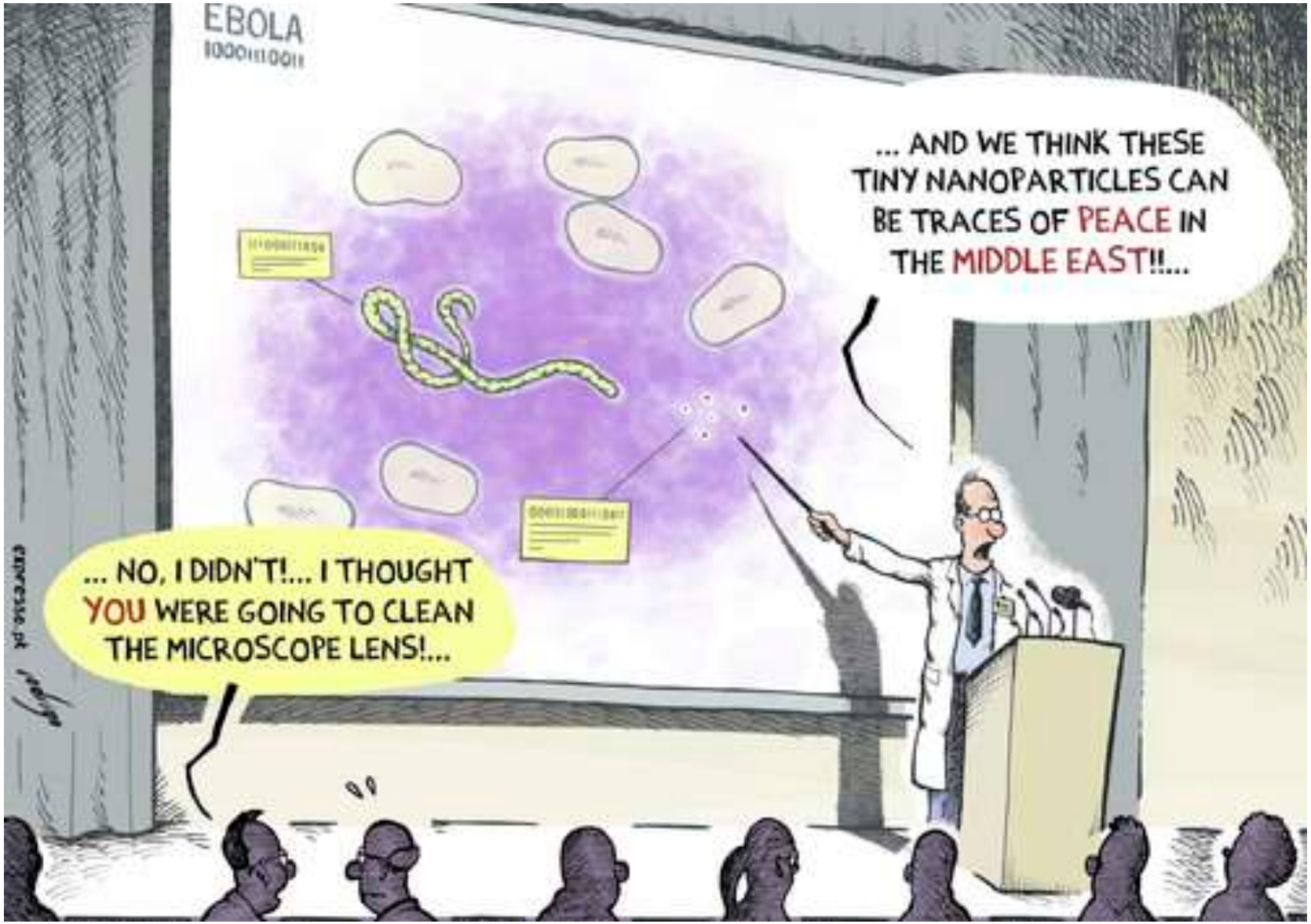
Se volessi far terapia?

- Ho un paziente con danno tissutale al fegato che necessita di trapianto per risoluzione.

1. Come posso monitorare il trapianto cellulare?
2. Posso fare terapia anti-infiammatoria?

Bibliography (websites and databases)

- Fang RH, Kroll AV, Gao W, Zhang L. Cell Membrane Coating Nanotechnology. Adv Mater. 2018 Jun;30(23):e1706759. doi: 10.1002/adma.201706759. Epub 2018 Mar 27. PMID: 29582476; PMCID: PMC5984176.
- Khatami M et al., 2018. Core@shell Nanoparticles: Greener Synthesis Using Natural Plant Products. Appl. Sci. 2018, 8, 411; doi:10.3390/app8030411
- Yuan M, Hu X, Yao L, Jiang Y, Li L. Mesenchymal stem cell homing to improve therapeutic efficacy in liver disease. Stem Cell Res Ther. 2022 May 3;13(1):179. doi: 10.1186/s13287-022-02858-4. PMID: 35505419; PMCID: PMC9066724.
- Shin MJ, Park JY, Lee DH, Khang D. Stem Cell Mimicking Nanoencapsulation for Targeting Arthritis. Int J Nanomedicine. 2021 Dec 31;16:8485-8507. doi: 10.2147/IJN.S334298. PMID: 35002240; PMCID: PMC8725870.
- Mitchell MJ, Billingsley MM, Haley RM, Wechsler ME, Peppas NA, Langer R. Engineering precision nanoparticles for drug delivery. Nat Rev Drug Discov. 2021 Feb;20(2):101-124. doi: 10.1038/s41573-020-0090-8. Epub 2020 Dec 4. PMID: 33277608; PMCID: PMC7717100.
- *K. Mohapatra, 2020 "Chemistry_Nanomaterials" http://www.gcekjr.ac.in/pdf/lectures/2020/7166--_2nd%20Semester_ALL.pdf*
- Wu Z, Yang S, Wu W. Shape control of inorganic nanoparticles from solution. Nanoscale. 2016 Jan 21;8(3):1237-59. doi: 10.1039/c5nr07681a. PMID: 26696235.
- Jitendra Pal Singh, Manish Kumar, Aditya Sharma, Ganesh Pandey, Keun Hwa Chae and Sangsul Lee. Bottom-Up and Top-Down Approaches for MgO. Feb 2020. DOI: 10.5772/intechopen.91182
- Habibullah G, Viktorova J, Ruml T. Current Strategies for Noble Metal Nanoparticle Synthesis. Nanoscale Res Lett. 2021 Mar 15;16(1):47. doi: 10.1186/s11671-021-03480-8. PMID: 33721118; PMCID: PMC7960878.
- Xu C et al., 2021. https://www.sigmaaldrich.com/IT/it/technical-documents/technical-article/materials-science-and-engineering/biosensors-and-imaging/advances-nanoparticle-based-imaging-contrast-agents
- Peserico A, Di Berardino C, Russo V, Capacchietti G, Di Giacinto O, Canciello A, Camerano Spelta Rapini C, Barboni B. Nanotechnology-Assisted Cell Tracking. Nanomaterials (Basel). 2022 Apr 20;12(9):1414. doi: 10.3390/nano12091414. PMID: 35564123; PMCID: PMC9103829.
- Sustainable Delivery Systems Through Green Nanotechnology. 2017 Kiruba Krishnaswamy, Valérie Orsat. Nano- and Microscale Drug Delivery Systems. http://dx.doi.org/10.1016/B978-0-323-52727-9.00002-9.
- Link to MRI operational principles: https://www.youtube.com/watch?v=_TkIEyIoO38
- Link to TC operational principles: https://www.youtube.com/watch?v=IH49HLC-wYg
- Link to PA imaging operational principles: https://www.youtube.com/watch?v=sJ9ZWnvZkRI


EBOLA
... AND WE THINK THESE TINY NANOPARTICLES CAN BE TRACES OF PEACE IN THE MIDDLE EAST!!...
... NO, I DIDN'T!... I THOUGHT YOU WERE GOING TO CLEAN THE MICROSCOPE LENS!...