The Nobel Prize in Chemistry

2023

“for the discovery and synthesis of quantum dots”

NOBELPRISET I KEMI 2023
THE NOBEL PRIZE IN CHEMISTRY 2023

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Photo: Massachusetts Institute of Technology

Moungi Bawendi
Massachusetts Institute of Technology (MIT)
USA

Photo: Columbia University

Louis Brus
Columbia University
USA

Alexei Ekimov
Nanocrystals Technology Inc.
USA

Prize amount: 11 million Swedish kronor *(approx. 1 Million US Dollars)*,
to be shared equally between the Laureates.

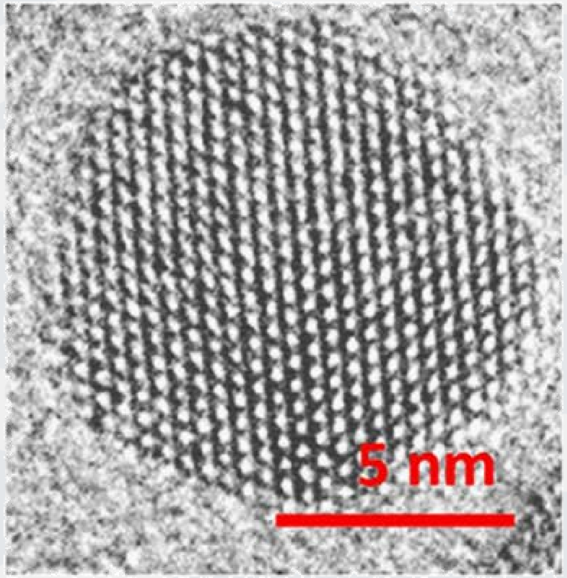
"for the discovery and synthesis of quantum dots"

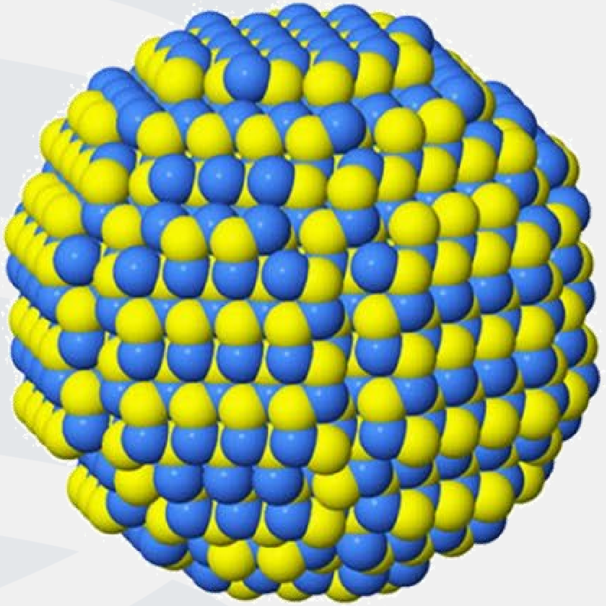
#nobelprize

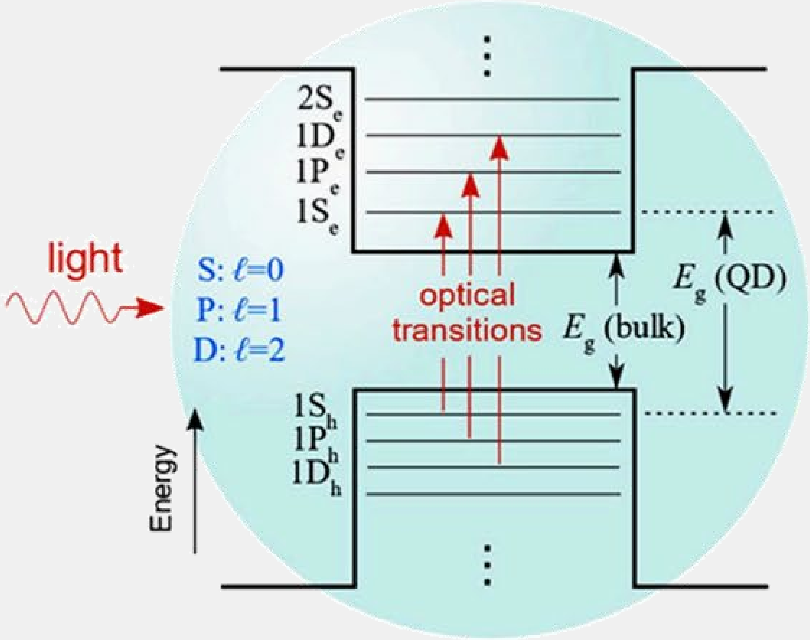
https://www.youtube.com/watch?v=6ilqb5qll8s

What is a Quantum Dot?

- A semiconductor nanocrystal with optical and electronic **properties that depend on particle size** and differ from “bulk” material.

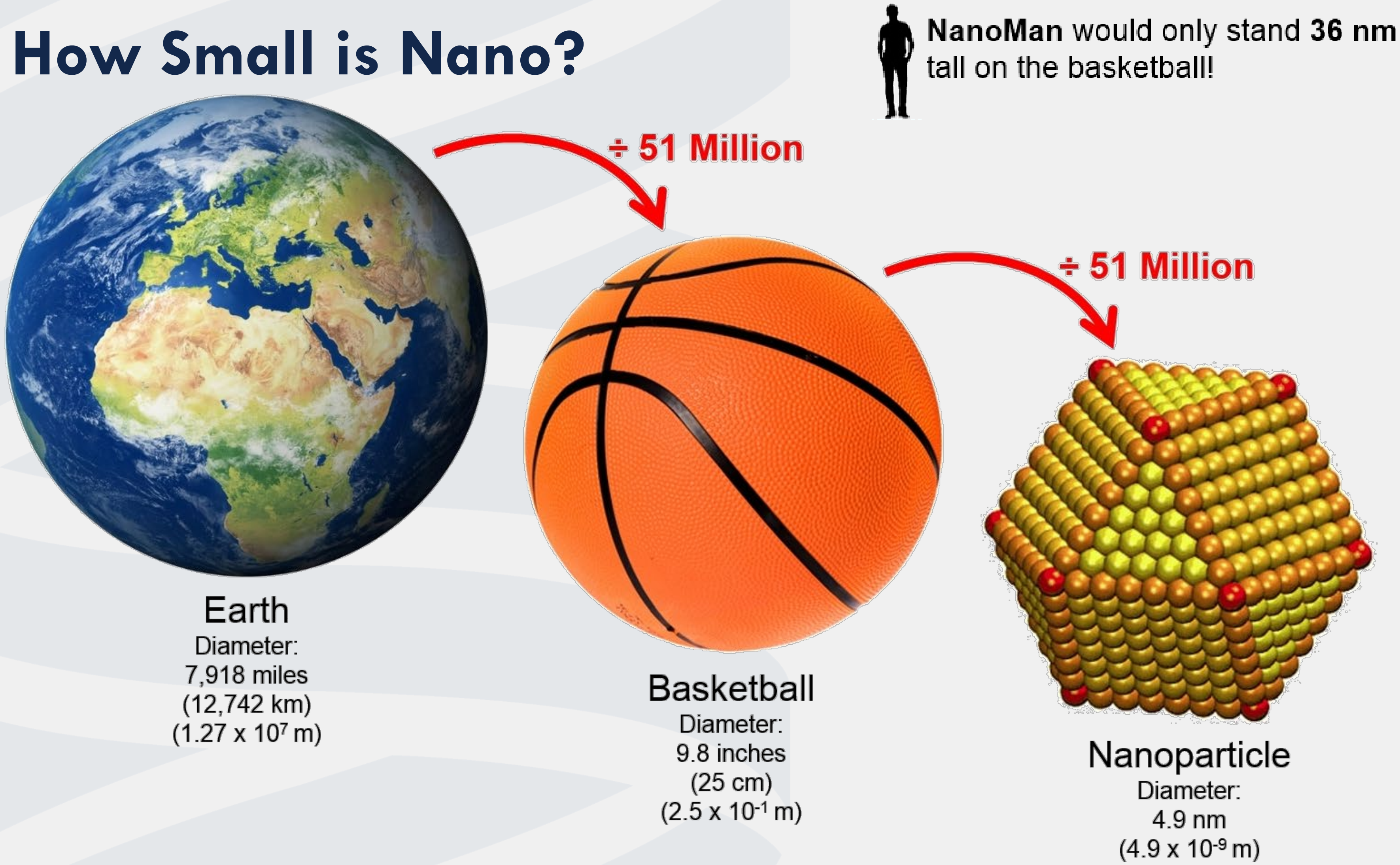






Reproduced from A. L. Efros and L.E. Brus, *ACS Nano* **15**, 6192 (2021).
https://www.nobelprize.org/uploads/2023/10/advanced-chemistryprize2023-3.pdf

How Small is Nano?



At the nano scale, matter is *"pixelated"* because it is approaching the size of atoms!

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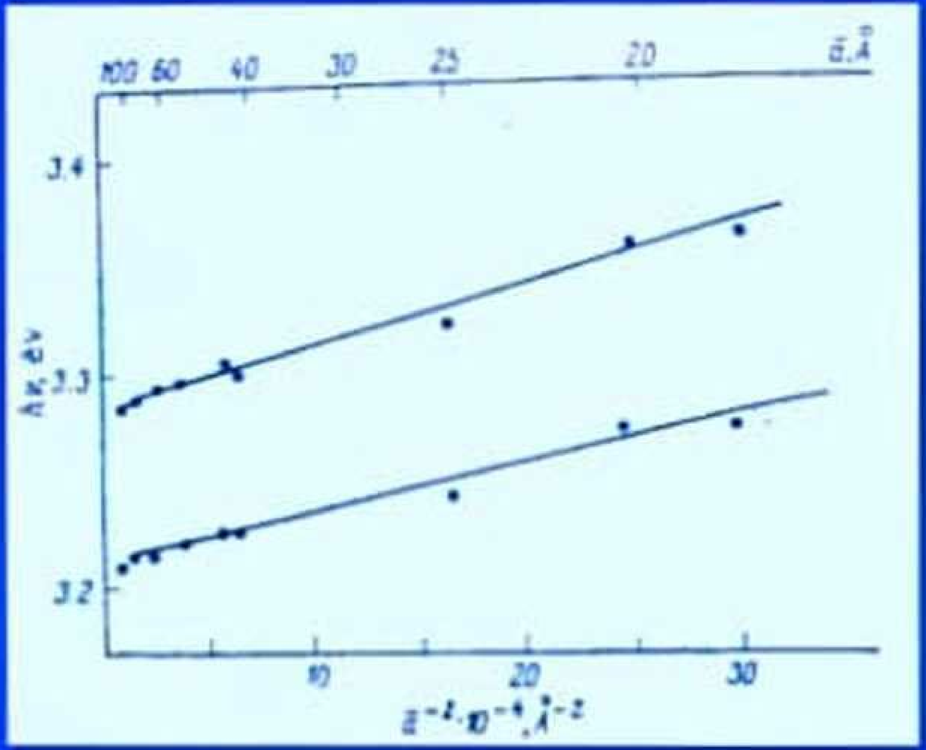

Copper Chloride Nanoparticles in Glass

Alexey Ekimov

. . . In **1981, Alexey Ekimov** succeeded in creating size-dependent quantum effects in **colored glass** at Vavilov State Optical Institute in St Petersburg, Russia. The color came from nanoparticles of copper chloride and Yekimov demonstrated that the particle size affected the color of the glass via quantum effects.

https://www.nobelprize.org/uploads/2023/10/press-chemistryprize2023-3.pdf

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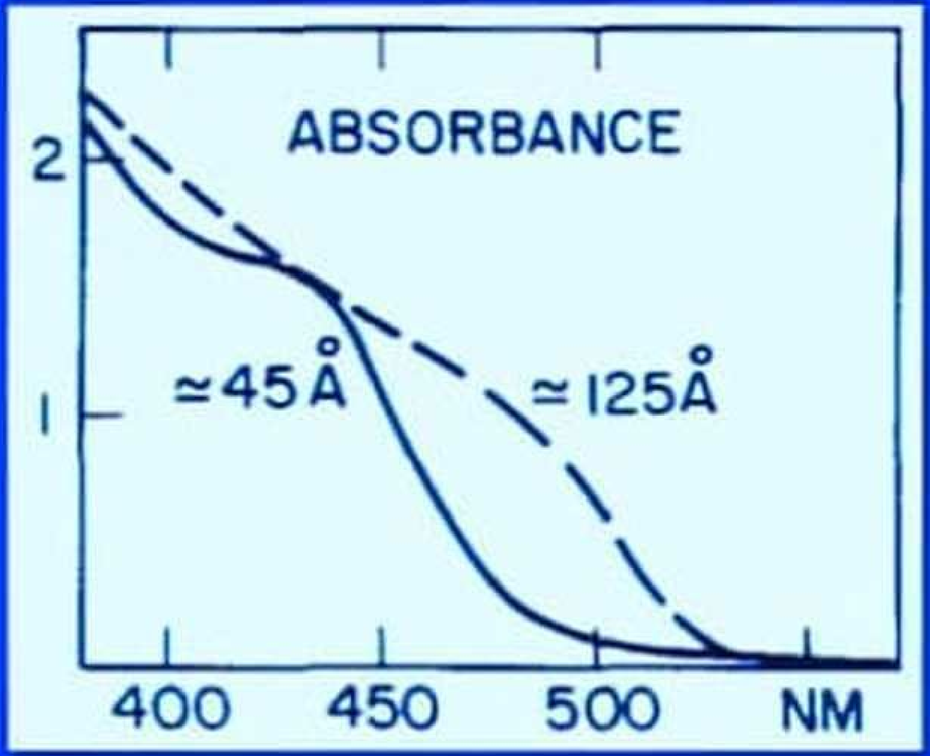
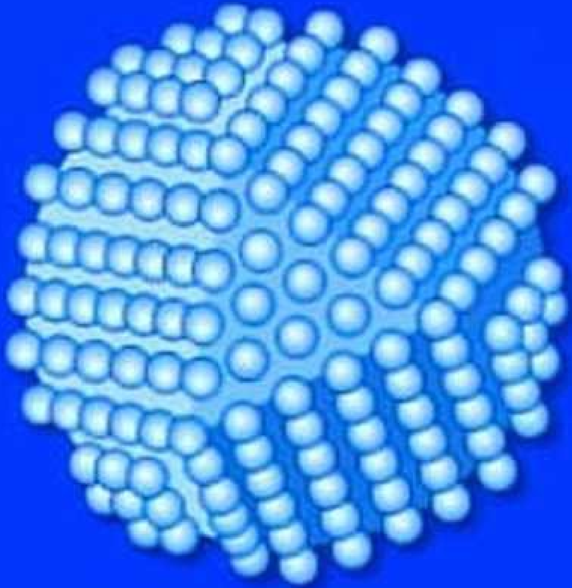


Optical absorbance of CdS quantum dots



Louis Brus

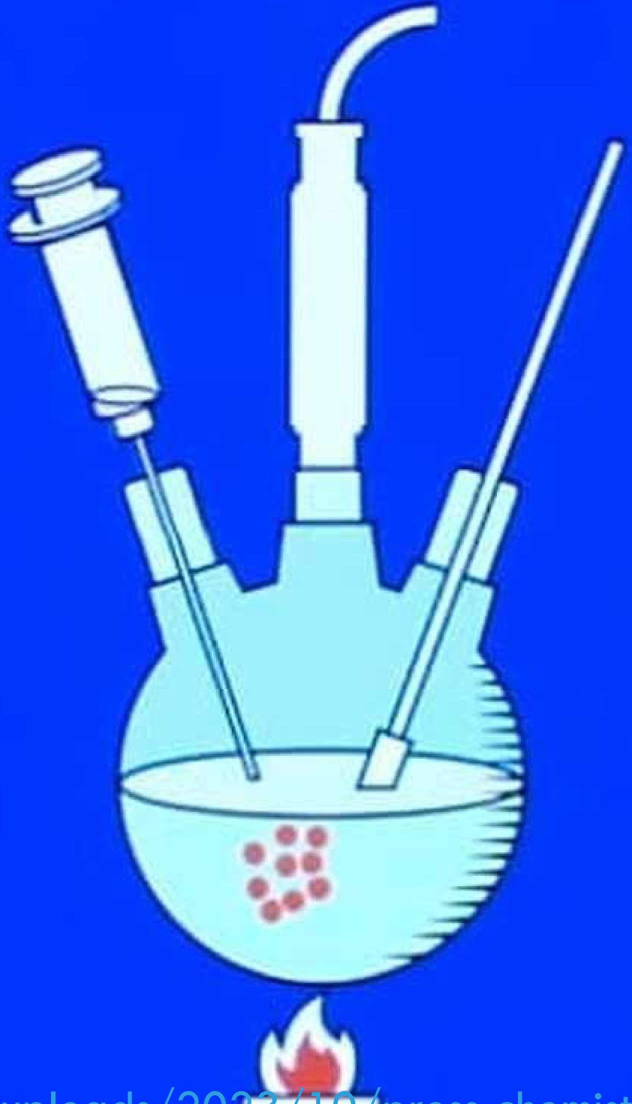
. . . In **1983, Louis Brus** (at AT&T Bell Laboratories) was the first scientist in the world to prove size-dependent quantum effects in particles floating freely in a fluid.

Cadmium Sulfide Nanoparticles in Solution

https://www.nobelprize.org/uploads/2023/10/press-chemistryprize2023-3.pdf

NOBELPRISET I KEMI 2023
THE NOBEL PRIZE IN CHEMISTRY 2023

KUNGL. VETENSKAPS AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES



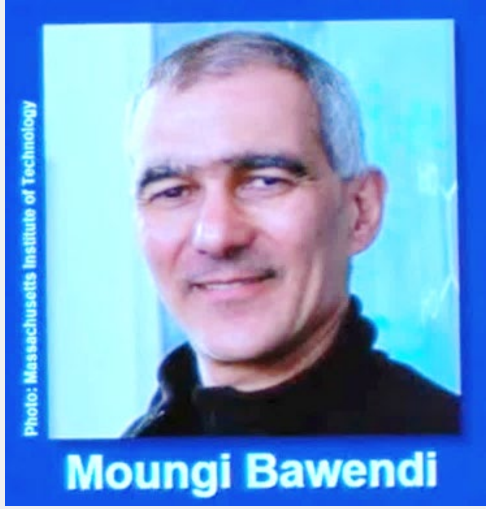
Improved Synthesis of Cadmium Selenide Nanoparticles in Solution

Moungi Bawendi

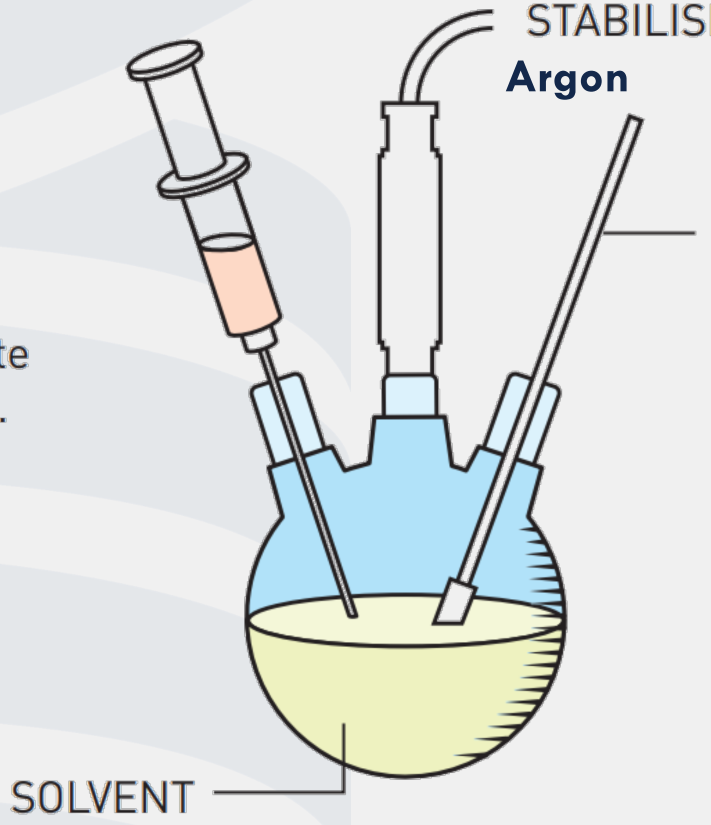
In **1993, Moungi Bawendi** (at MIT *but* was former postdoctoral researcher with Louis Brus at Bell labs) revolutionized the chemical production of quantum dots, resulting in almost perfect particles. This high quality was necessary for them to be utilized in applications.

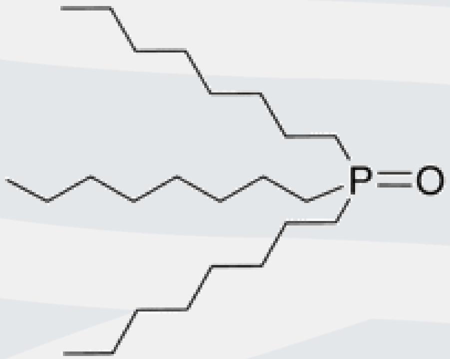
https://www.nobelprize.org/uploads/2023/10/press-chemistryprize2023-3.pdf

How Moungi Bawendi produced CdSe quantum dots

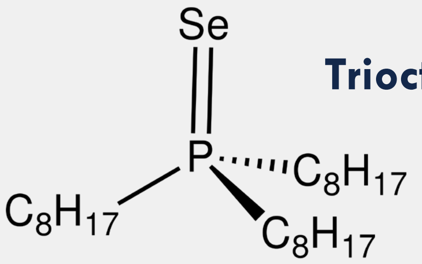


1 Bawendi injected substances that can form cadmium selenide into hot solvent. The volume was enough to saturate the solvent around the needle.





Trioctylphosphine oxide (TOPO)



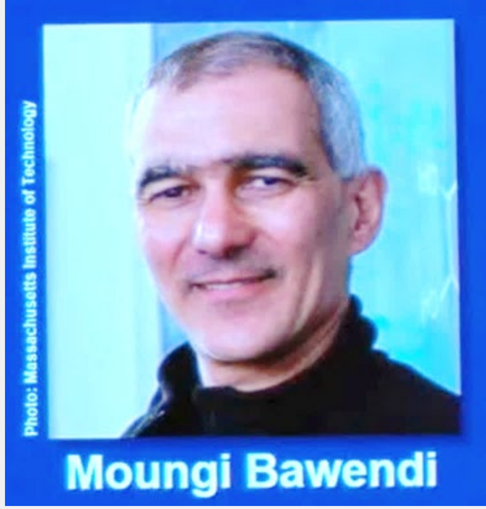
Trioctylphosphine selenide (TOPSe)

in Trioctylphosphine solvent

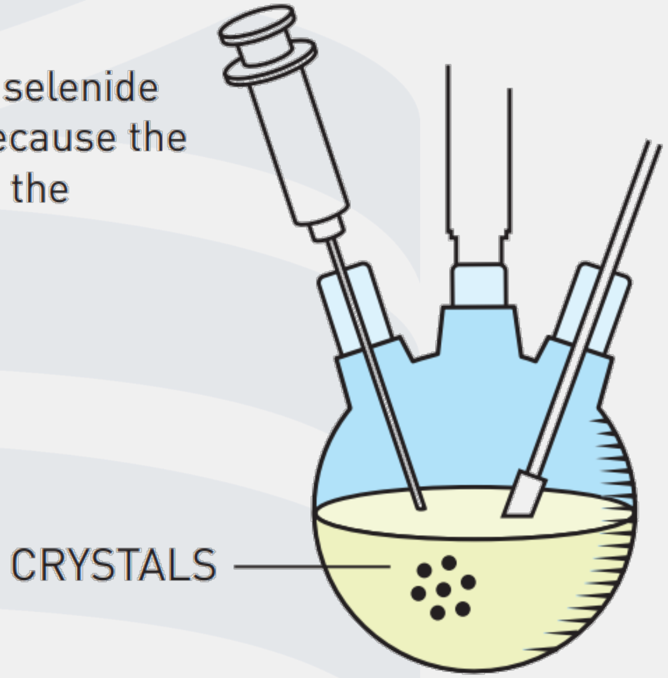
$H_3C{-}Cd{-}CH_3$ Dimethylcadmium

https://www.nobelprize.org/uploads/2023/10/fig4_ke_en_23.pdf

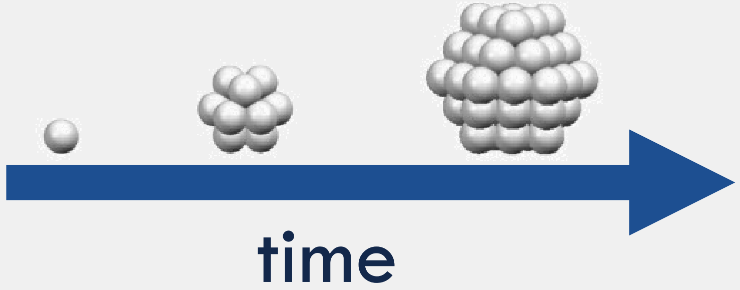
How Moungi Bawendi produced quantum dots



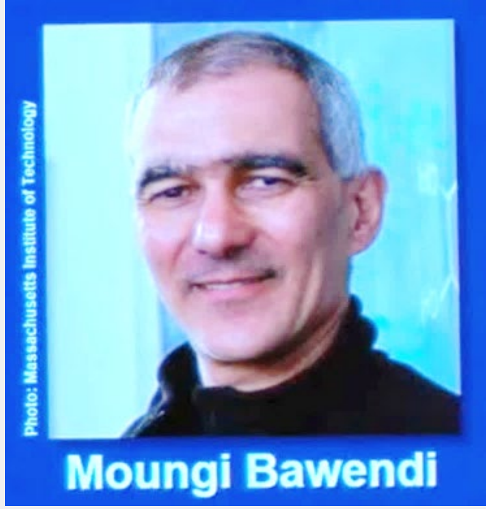
2 Small crystals of cadmium selenide immediately formed, but because the injection cooled the solvent the crystals stopped forming.



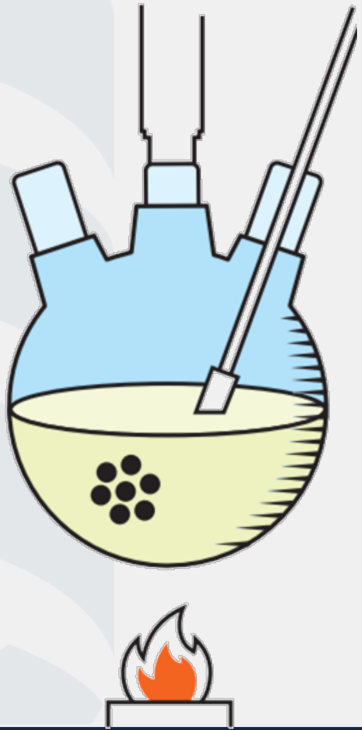
180°C

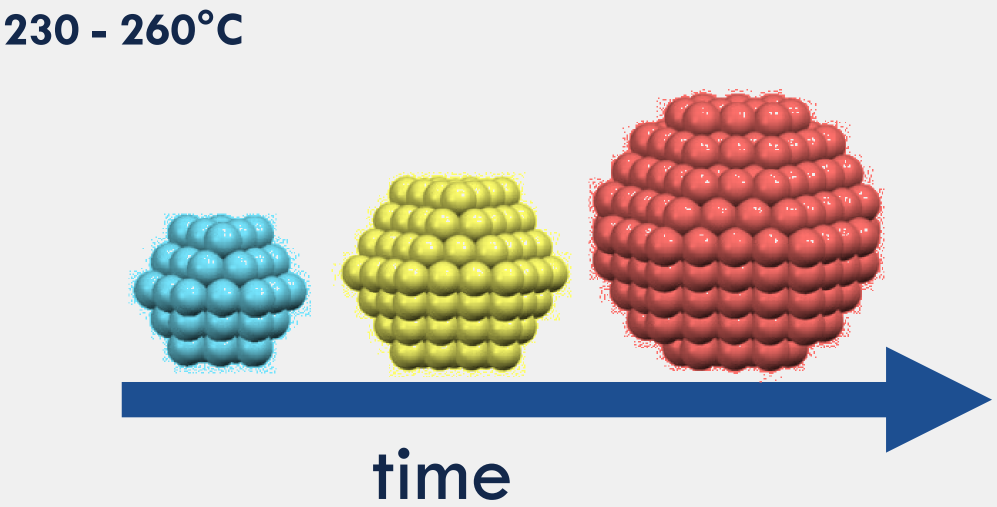


How Moungi Bawendi produced quantum dots



3 When Bawendi increased the temperature of the solvent, the crystals once again started to grow. The longer this continued, the larger the crystals became.

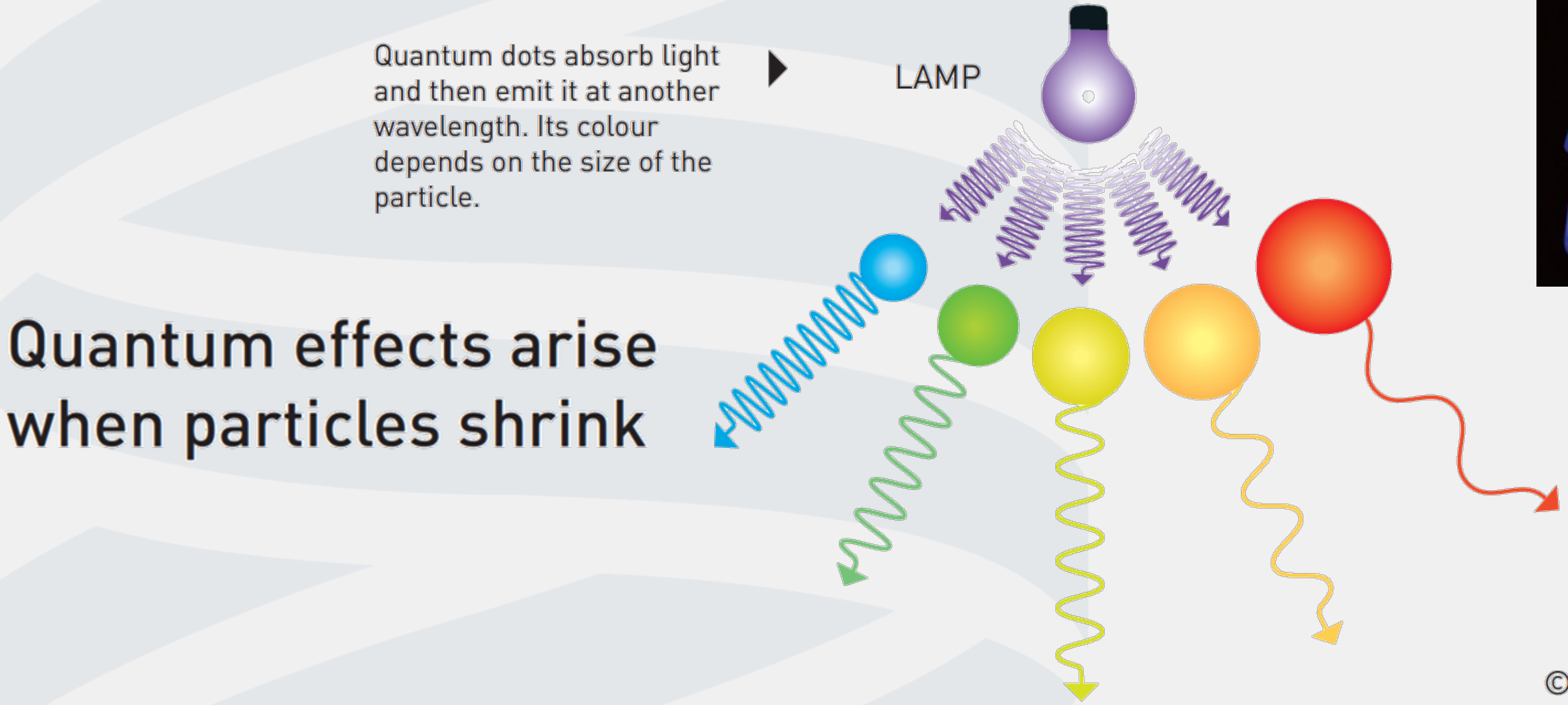


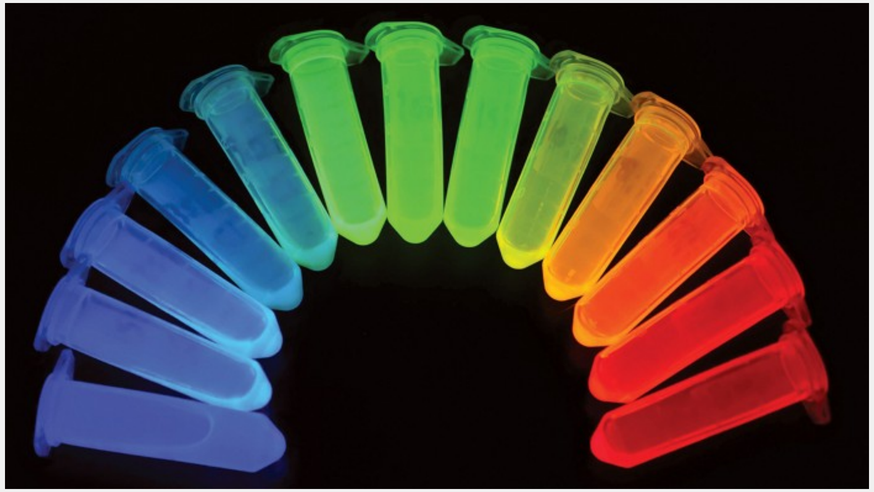


https://www.nobelprize.org/uploads/2023/10/fig4_ke_en_23.pdf

Size-Dependent Photoluminescence and Electroluminescence

"Black Light"
Ultraviolet





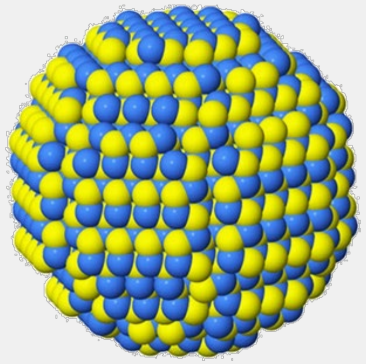
Fluorescence

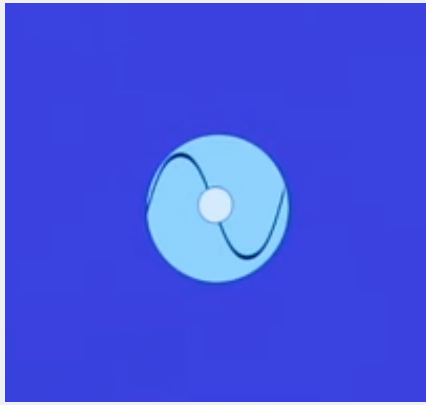
https://www.nobelprize.org/uploads/2023/10/fig3_ke_en_23.pdf

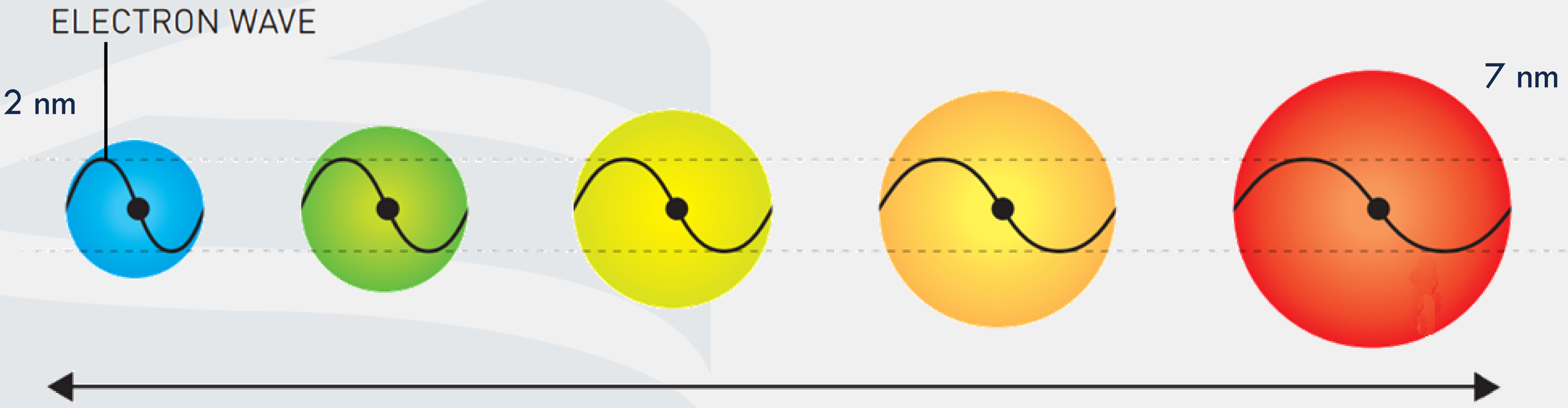
https://cen.acs.org/people/nobel-prize/Podcast-race-report-Nobel-Prizes/101/web/2023/10

Quantum effects arise when particles shrink

When particles are just a few nanometres in diameter, the space available to electrons shrinks. This affects the particle's optical properties.



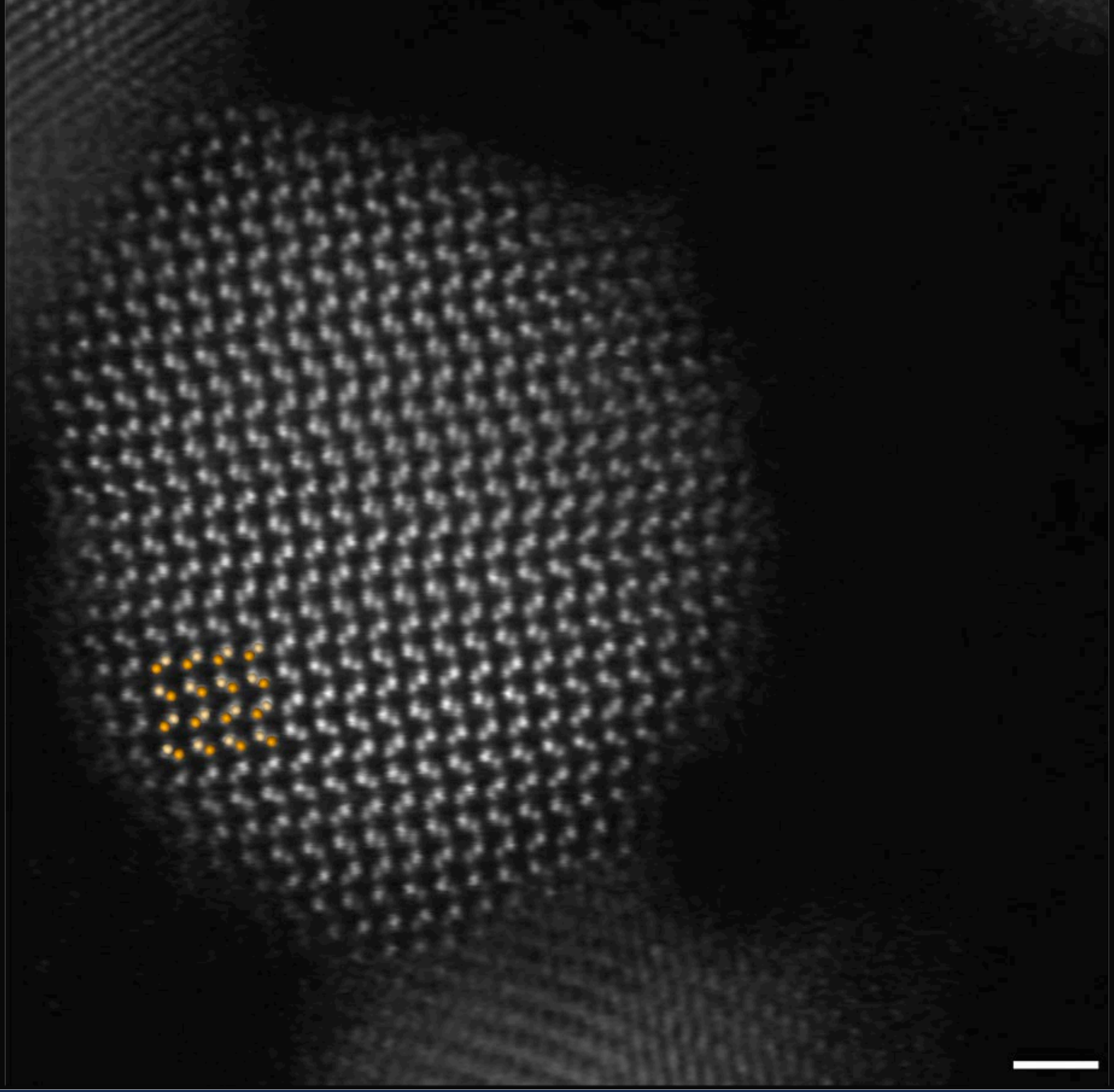




Smaller nanoparticle, less space for the electron wave

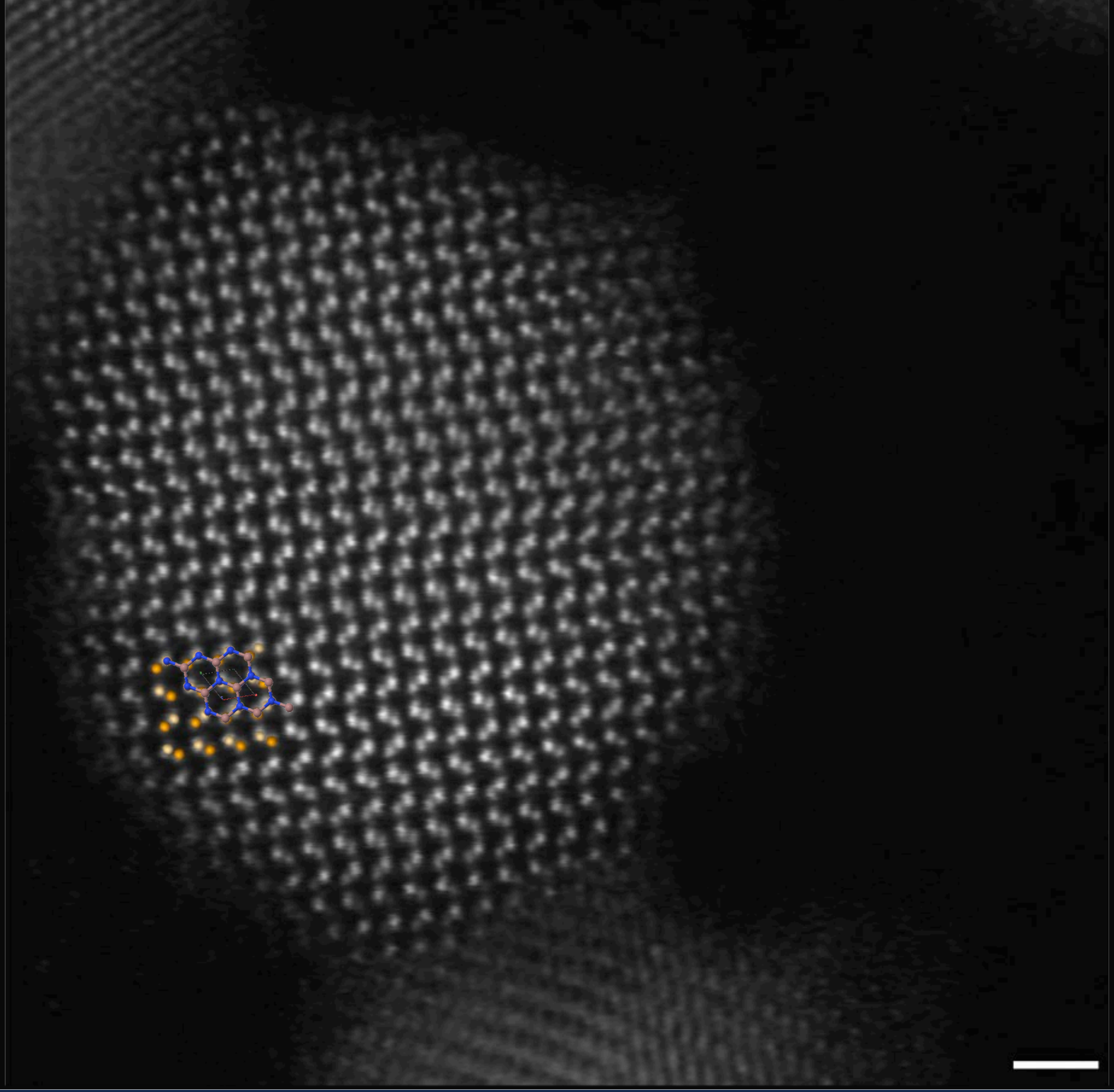
Larger nanoparticle, more space for the electron wave

https://www.nobelprize.org/uploads/2023/10/fig3_ke_en_23.pdf



This image shows a CdSe nanoparticle with atomic resolution. It is a projection image of the nanoparticle where darker atomic columns represent Se columns while the brighter columns are Cd (atomic structure has been partially overlayed to highlight the atomic arrangement). Scale bar is 1nm. This micrograph is part of the CdSe research that appeared in "Surfactant Ligand Removal and Rational Fabrication of Inorganically Connected Quantum Dots", Nanoletters (2011). DOI: 10.1021/nl202892p

https://en.wikipedia.org/wiki/Cadmium_selenide#/media/File:CdSe_Nanoparticle.png



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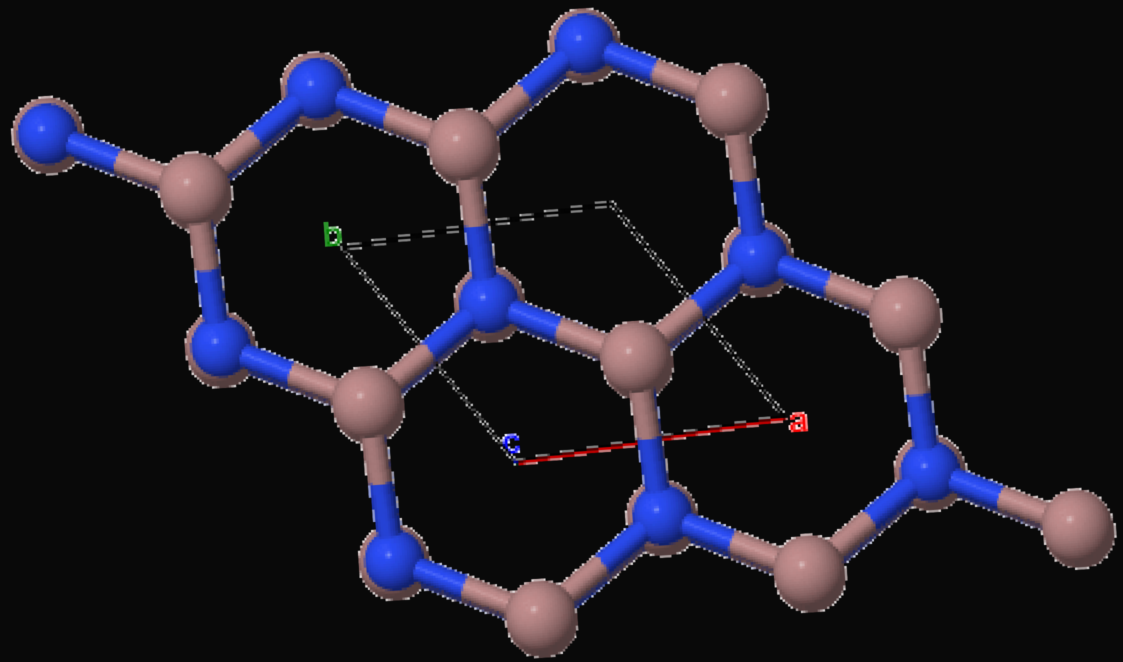
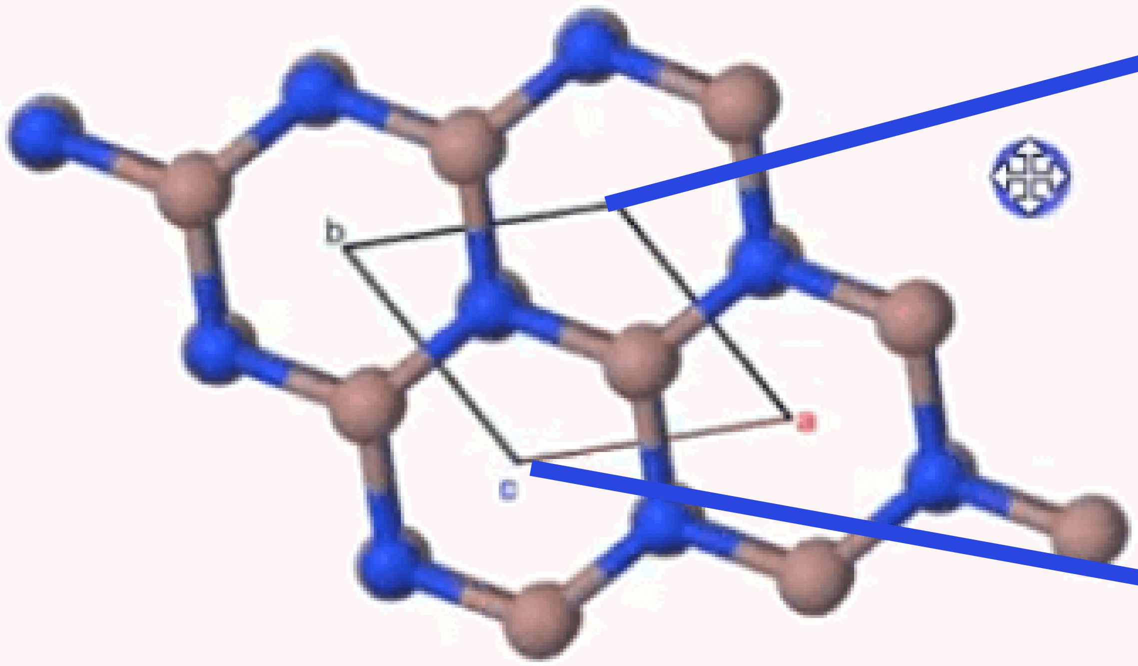
https://en.wikipedia.org/wiki/Cadmium_selenide#/media/File:CdSe_Nanoparticle.png

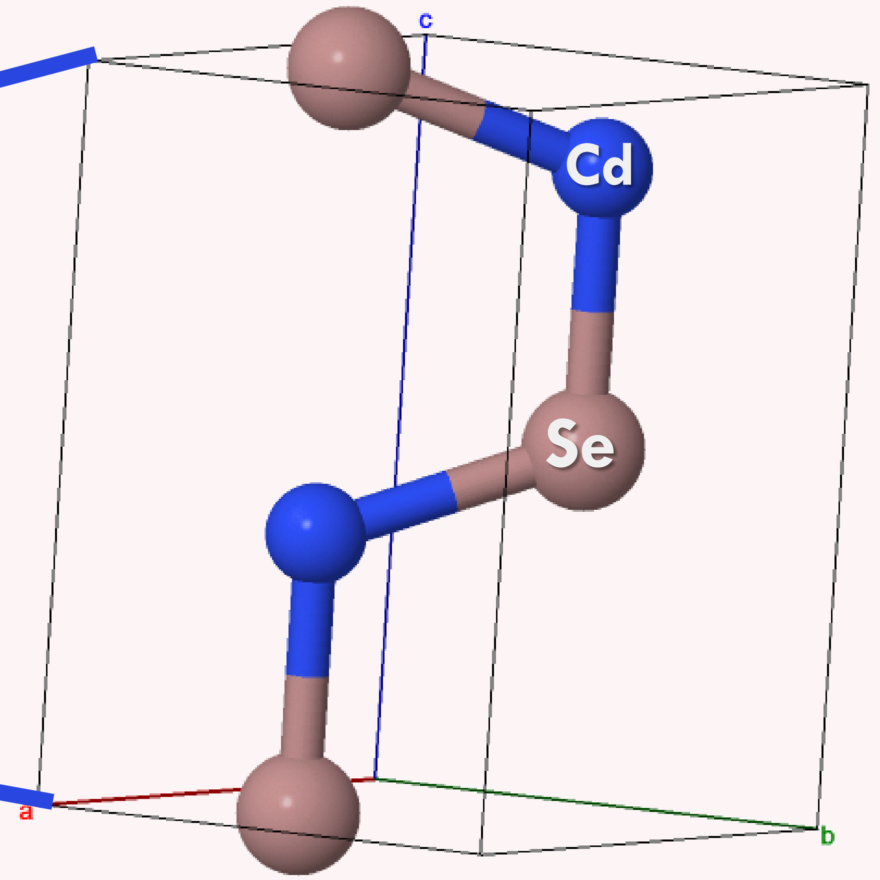
Cadmium Selenide (CdSe)



Cadmium Selenide (CdSe)

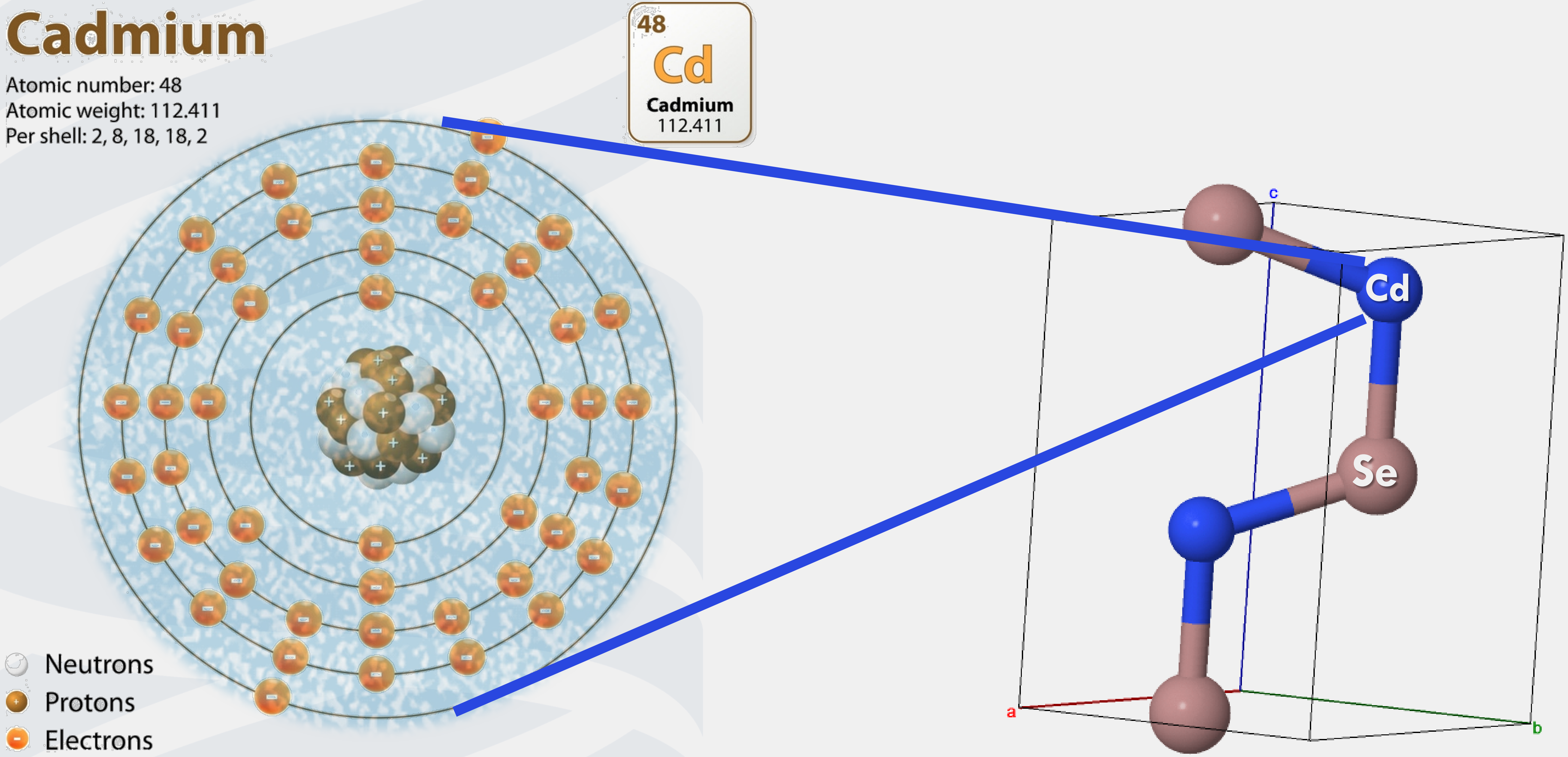


Wurtzite
Crystal Structure



Cadmium

Atomic number: 48
Atomic weight: 112.411
Per shell: 2, 8, 18, 18, 2



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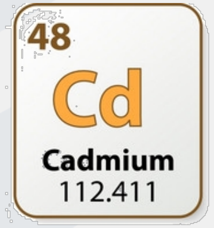

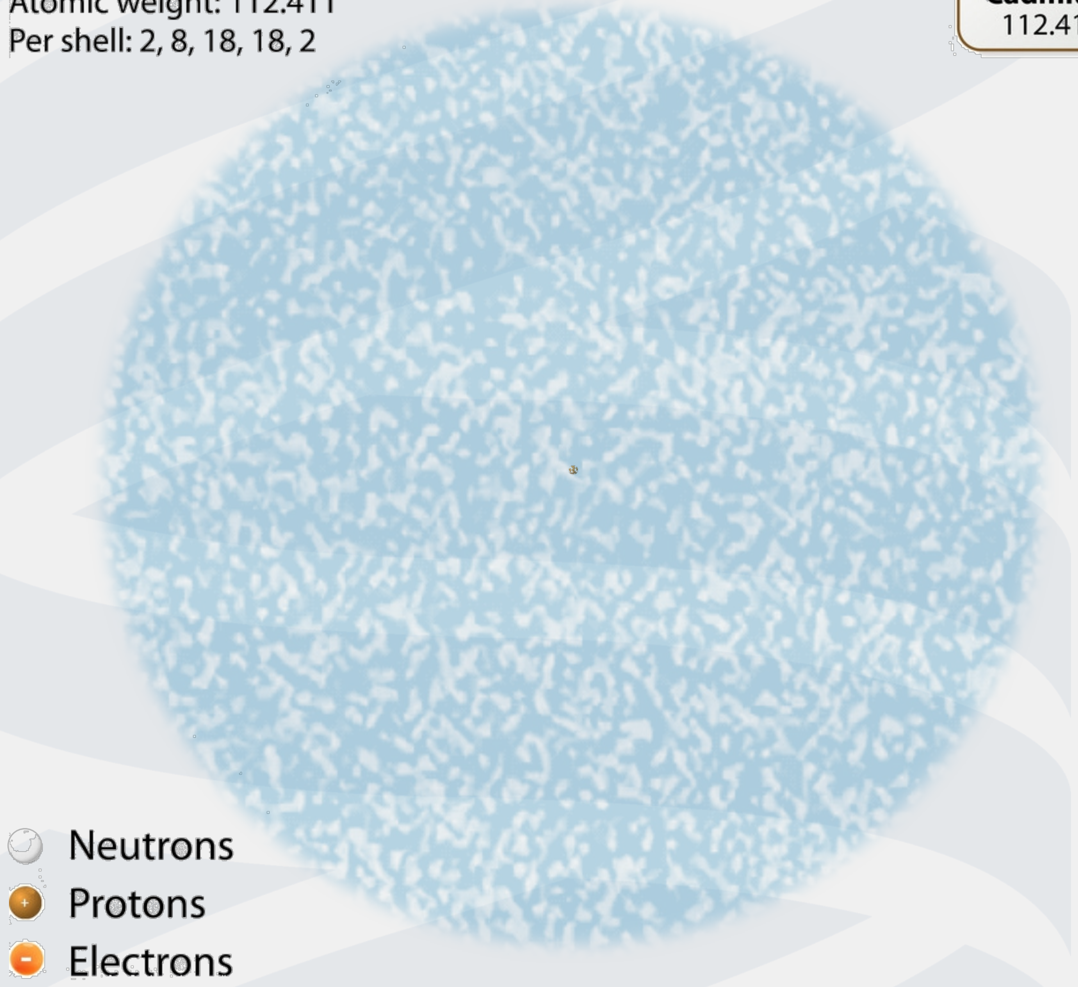

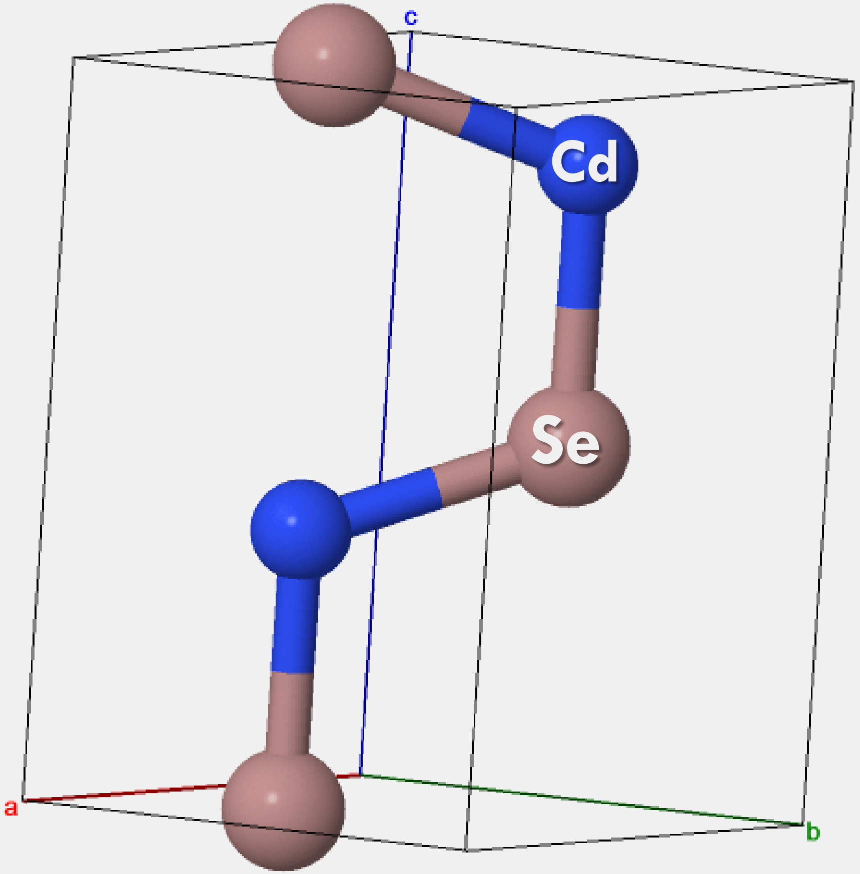

https://ssd.phys.strath.ac.uk/resources/crystallography/crystal_models/wurtzite_structure/

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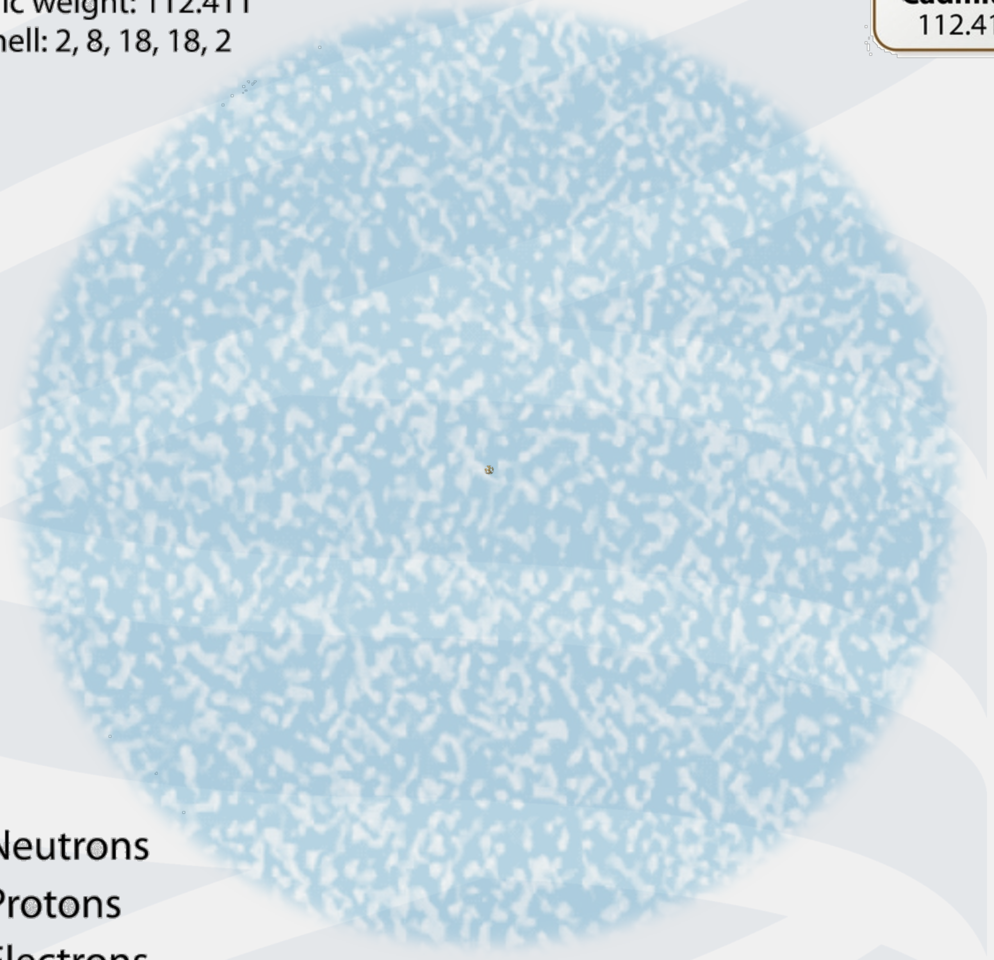
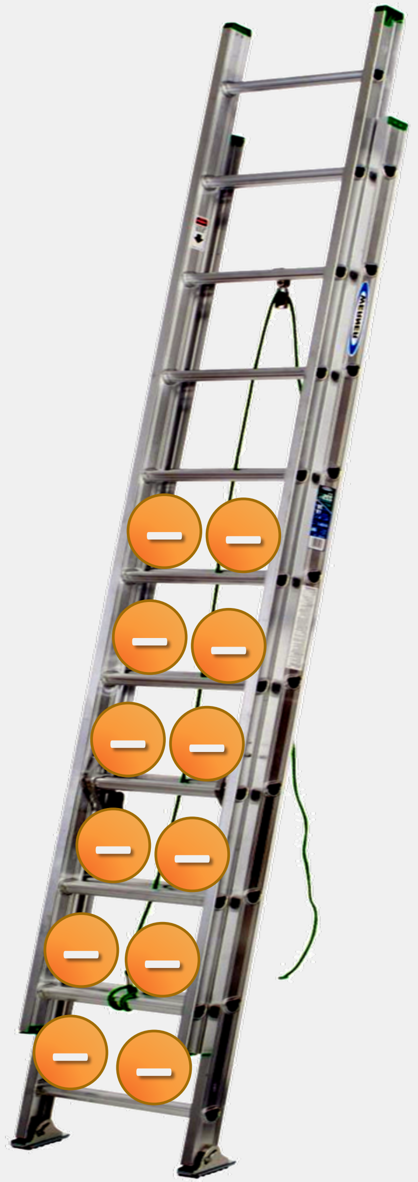
48
Cd
Cadmium
112.411



Neutrons
Protons
Electrons



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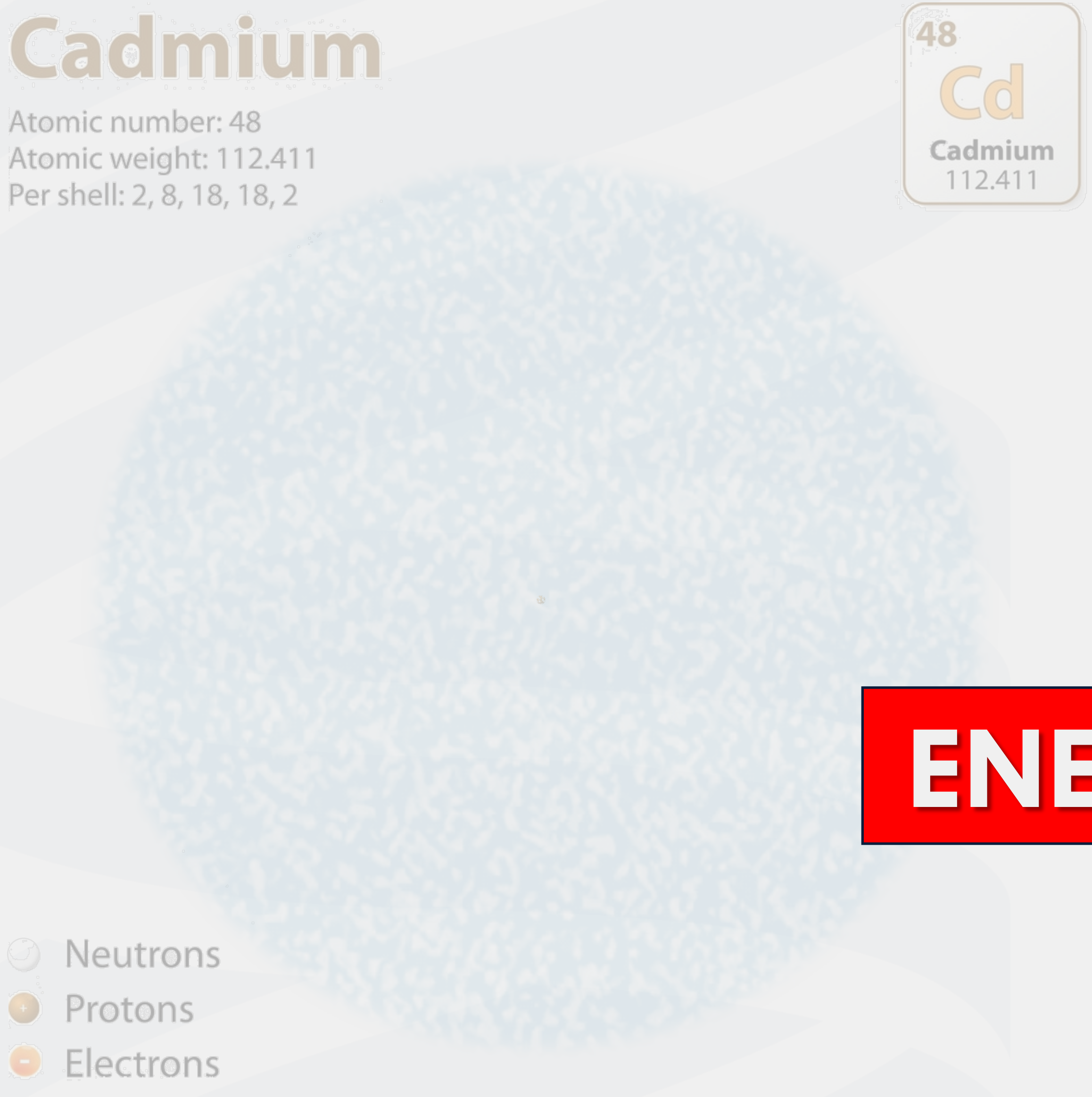
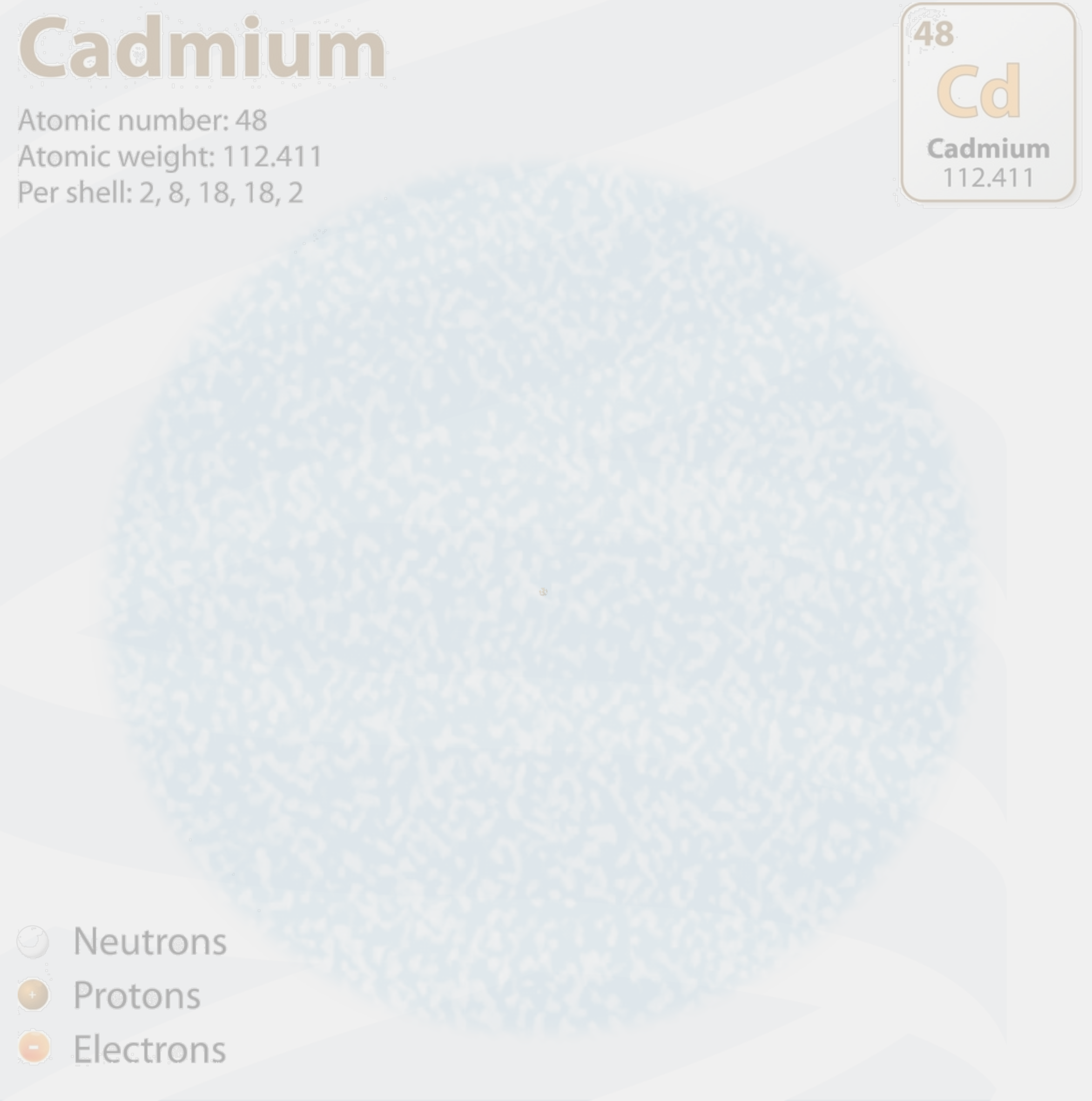

Cadmium
Atomic number: 48
Atomic weight: 112.411
Per shell: 2, 8, 18, 18, 2
48
Cd
Cadmium
112.411
Neutrons
Protons
Electrons


ENERGY


Cadmium
Atomic number: 48
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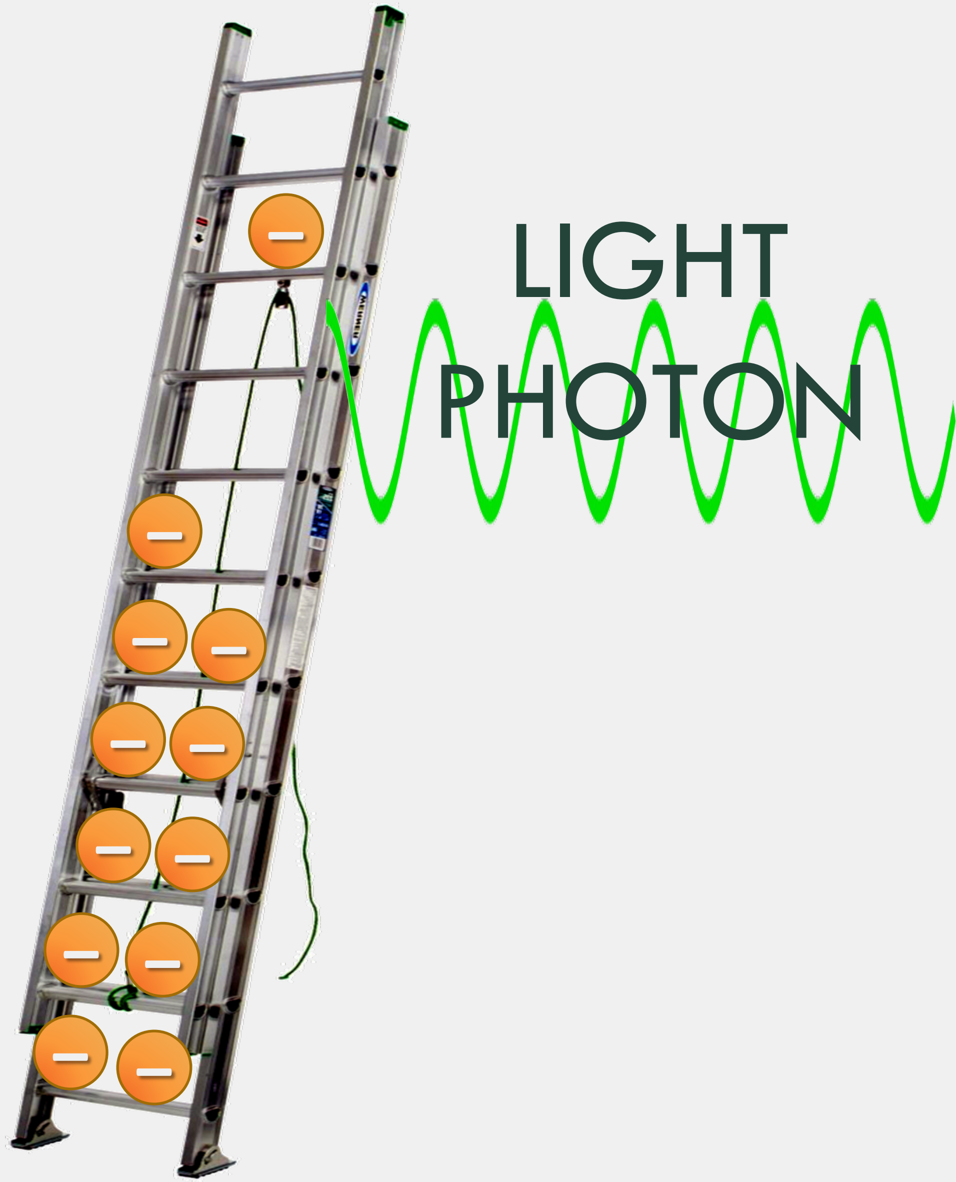
48
Cd
Cadmium
112.411
Neutrons
Protons
Electrons

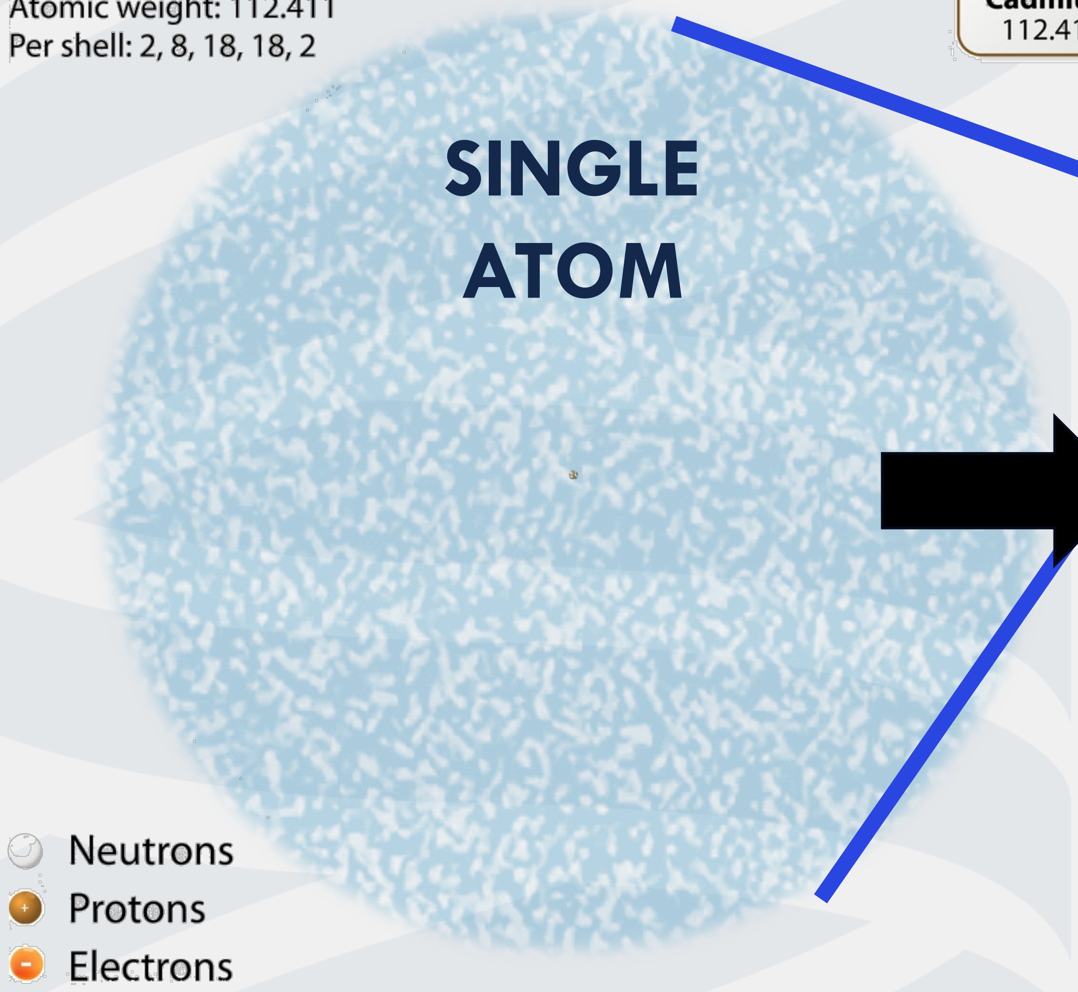

LIGHT
PHOTON

Cadmium

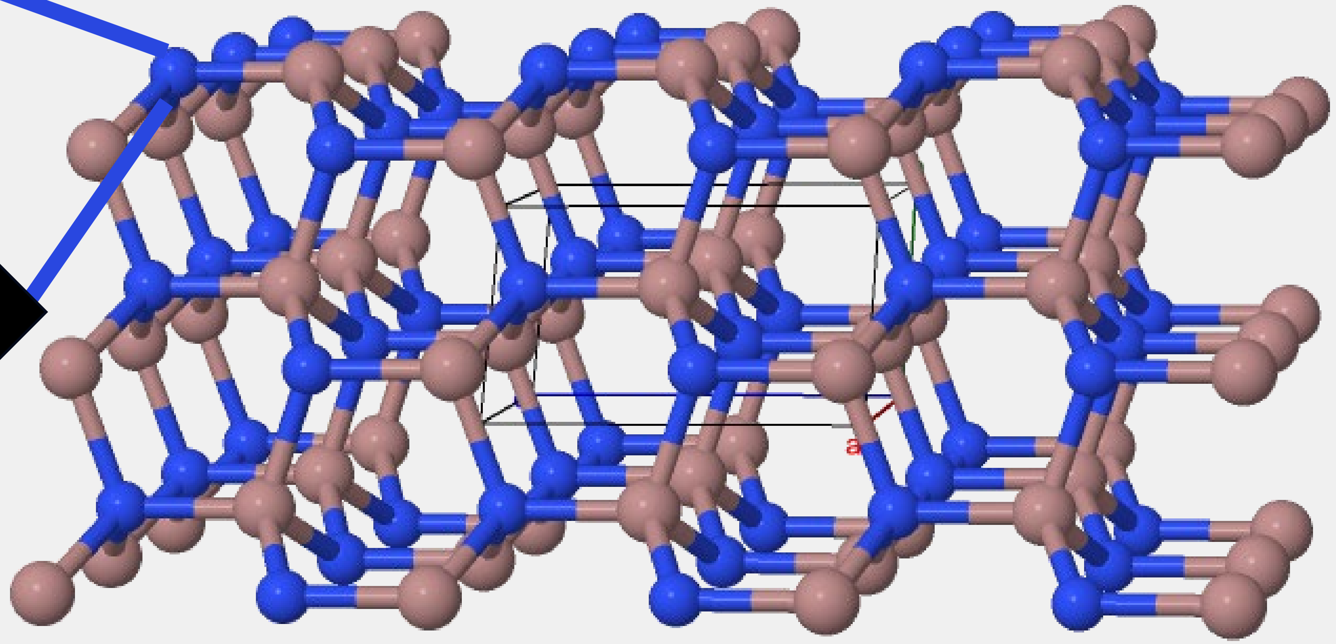
Atomic number: 48
Atomic weight: 112.411
Per shell: 2, 8, 18, 18, 2

48
Cd
Cadmium
112.411

SINGLE ATOM

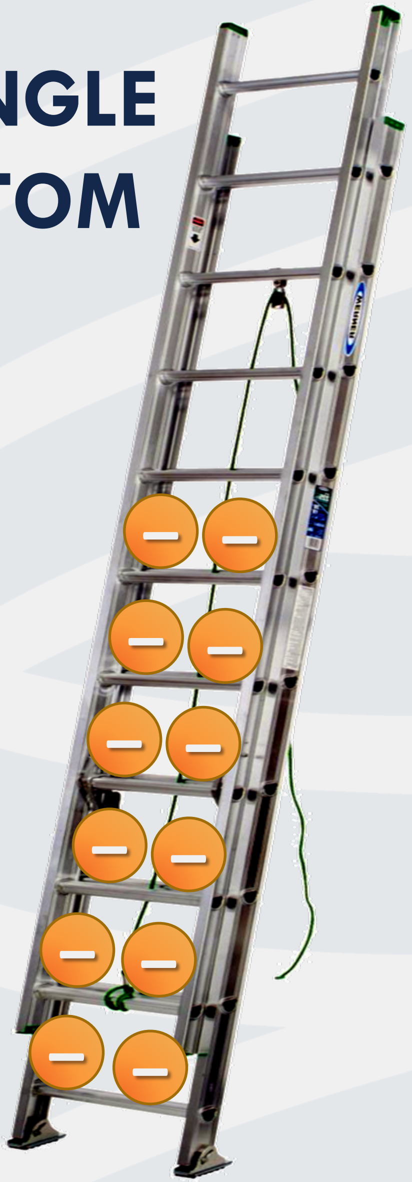


CRYSTAL LATTICE



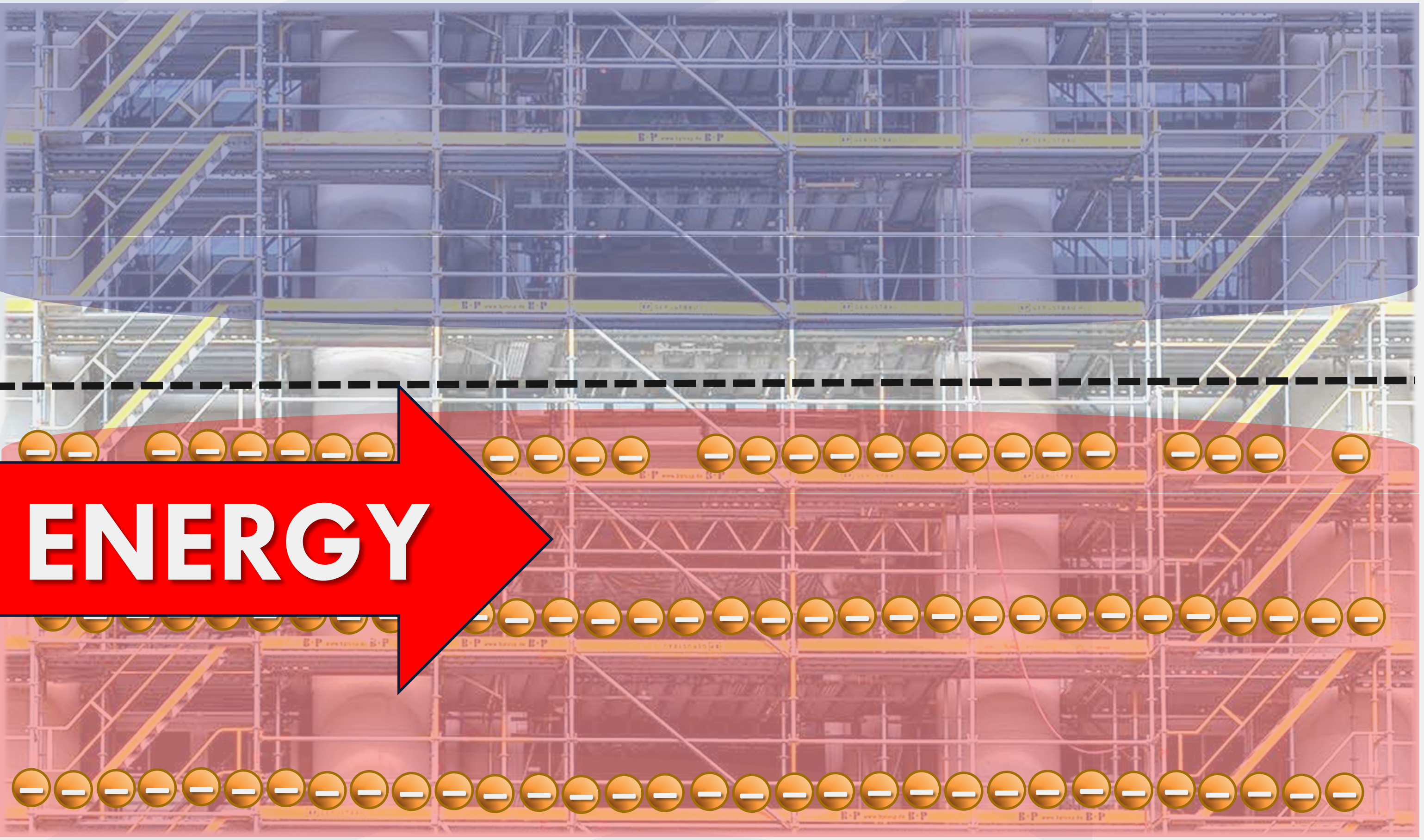
https://ssd.phys.strath.ac.uk/resources/crystallography/crystal_models/wurtzite_structure/

SINGLE ATOM

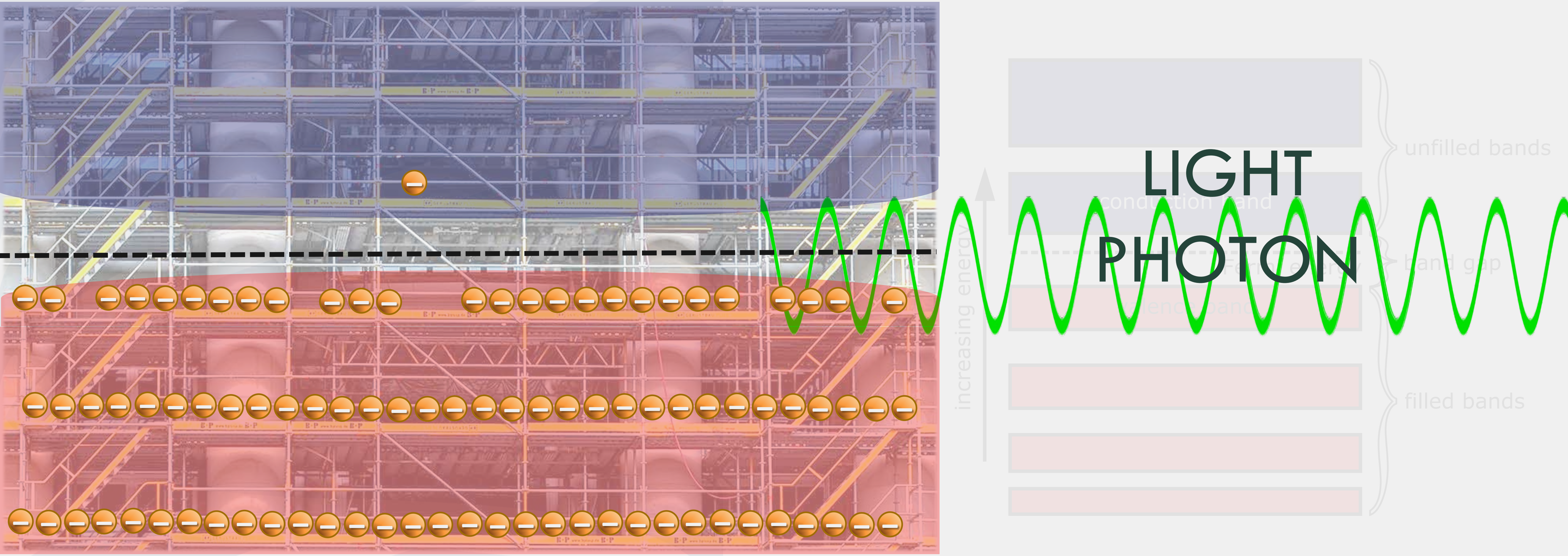


CRYSTAL LATTICE

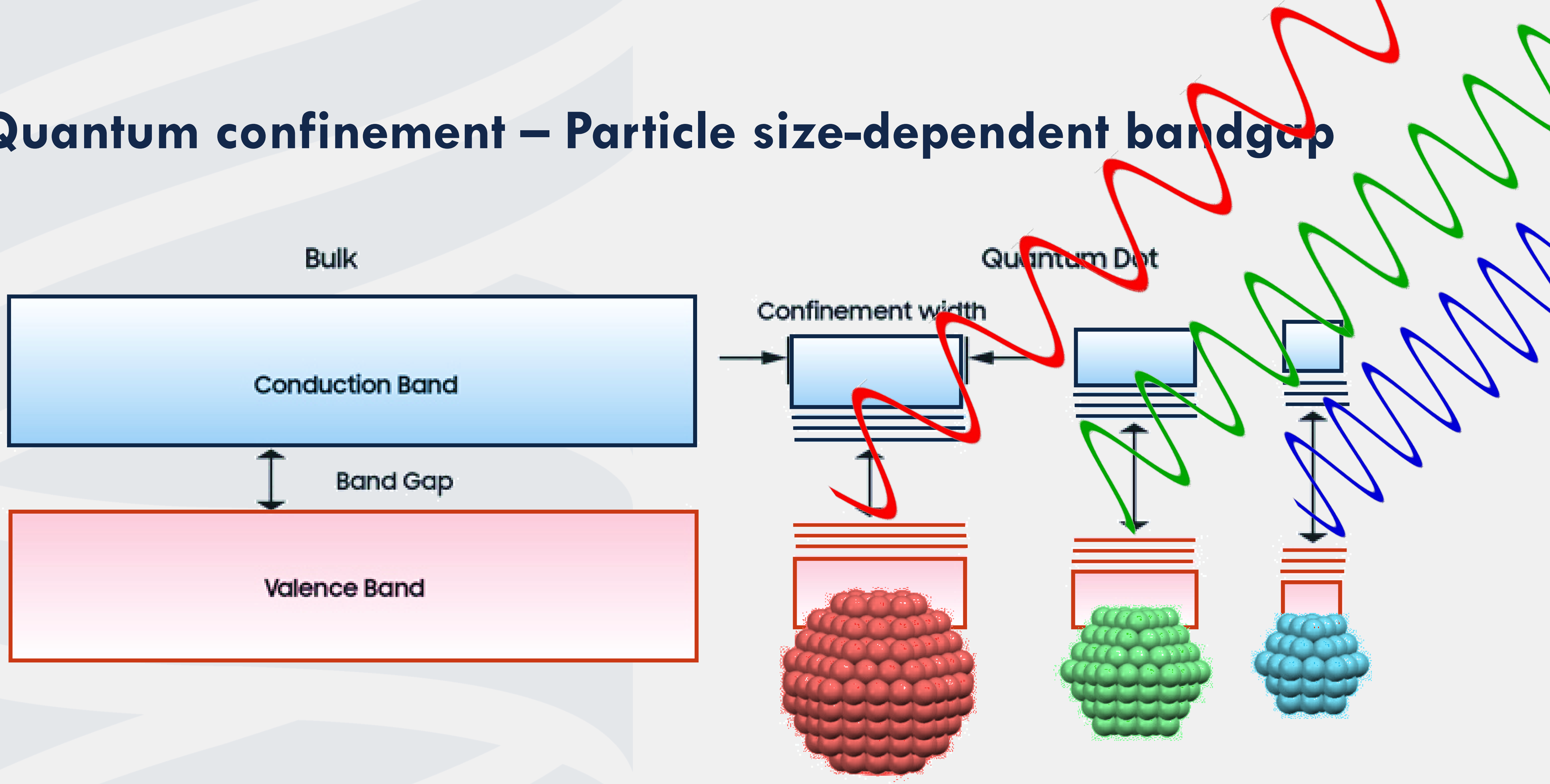
ELECTRONIC BAND STRUCTURE



ELECTRONIC BAND STRUCTURE

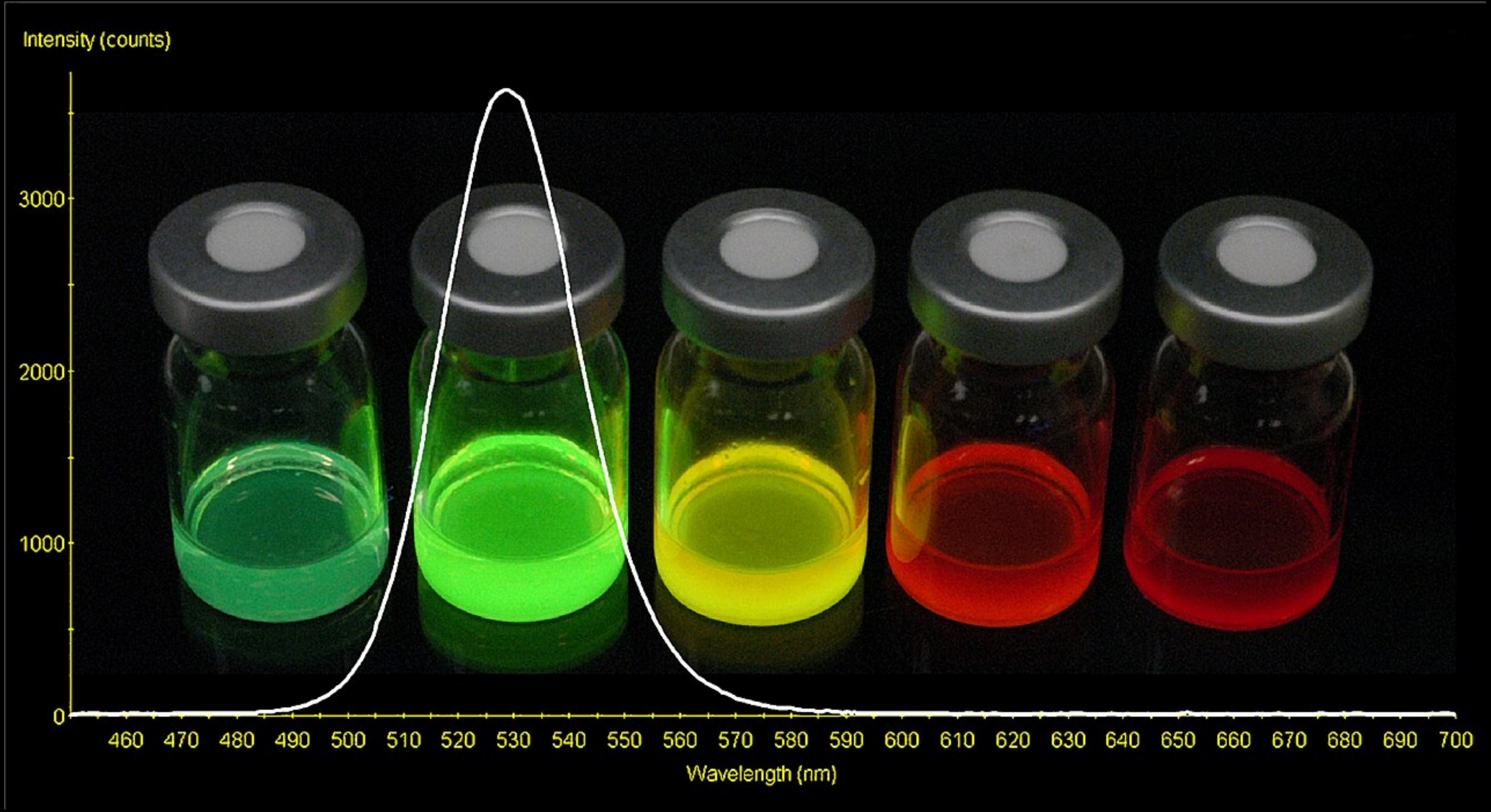


Quantum confinement – Particle size-dependent bandgap



https://innovate.samsungdisplay.com/blog/understanding-quantum-dots/

Quantum confinement – Particle size-dependent bandgap



Cadmium selenium Quantum Dots (QDs) are metal nanoparticles that fluoresce in a variety of colors determined by their size. QDs are solid state structures made of semiconductors or metals that confine a countable, small number of electrons into a small space. The confinement of electrons is achieved by the placement of some insulating material(s) around a central, well conducted region. Coupling QDs with antibodies can be used to make spectrally multiplexed immunoassays that test for a number of microbial contaminants using a single test.

https://en.wikipedia.org/wiki/Cadmium_selenide#/media/File:CdSeqdots.jpg

What are the Applications?

- Two bottles of quantum dots in a liquid solution emit red and green light when illuminated with blue light. The technology powers Samsung's QD OLED TVs.

  --Stephen Shankland/CNET

https://www.cnet.com/tech/home-entertainment/samsung-qd-led-tv-tech-explained-welcome-quantum-dot-era/

https://www.cnet.com/tech/home-entertainment/oled-vs-led-vs-miniled-vs-lcd-whats-the-best/

SAMSUNG 17 YEARS Global No.1 TV brand

ACSI American Customer Satisfaction Index

No. 1 in Overall Customer Satisfaction

SAMSUNG DISPLAY

Total

$39,999.99

With Samsung Financing

$1,111.11/mo for 36 mos⊕

98" Class Samsung Neo QLED 8K QN990C

QN98QN990CF / QN98QN990CFXZA ★★★★★ 5.0 (1) Write a review

Infinity-all-metal design

Quantum Matrix Pro with Mini LEDs

Neural Quantum Processor 8K

Dolby Atmos and Cinema Object Tracking Sound

- Immerse yourself in a next level viewing experience with an impossibly slim 360 degree metal profile with Infinity-all-metal design.
- See worlds within worlds, with unparalleled 8K precision made possible by a universe of tiny lights with Quantum Matrix Pro with Mini LEDs.
- Upscale every movie night—and be ready for the future of 8K TV—with our prestigiously detail-oriented processor with Neural Quantum Processor 8K.
- Hear what happens where it happens with speakers that track the action from all corners with Dolby Atmos with Cinema Object Tracking Sound.

https://www.samsung.com/us/televisions-home-theater/tvs/samsung-neo-qled-8k/98-class-samsung-neo-qled-8k-qn990c-qn98qn990cfxza/

SAMSUNG
17 YEARS
Global No.1 TV brand*

ACSI
American Customer Satisfaction Index

No. 1 in Overall Quality

SAMSUNG DISPLAY

Total	With Samsung Financing
$3,599.99 ~~$4,499.99~~	$150.00/mo ~~$187.50/mo~~ for 24 mos

77" Class OLED S95C

QN77S95CAF / QN77S95CAFXZA ★★★★★ 4.5 (133) Write a review

Samsung OLED Technology

Infinity One Design with Slim One Connect

Quantum HDR OLED+

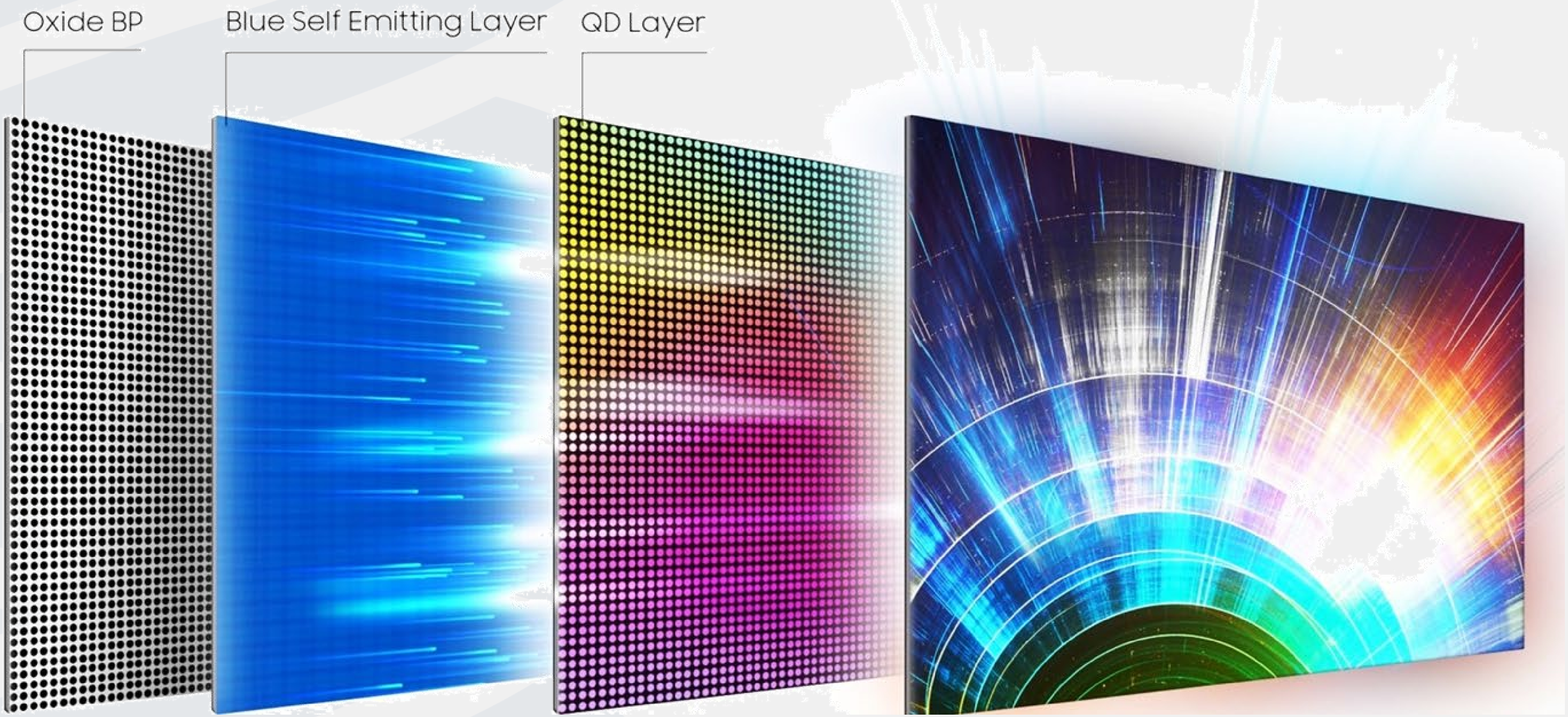
Neural Quantum Processor with 4K Upscaling*

- Steal the show with the bold contrast, dramatic sound and the vibrant colors with Samsung OLED Technology.
- Sit back and be mesmerized as your content is transformed to 4K with Neural Quantum Processor with 4K Upscaling.
- Witness the difference detail can make, with fine-tuned brightness and optimized contrast made possible by self-illuminating pixels with Quantum HDR OLED.

https://www.samsung.com/us/televisions-home-theater/tvs/oled-tvs/77-class-s95c-oled-4k-smart-tv-2023-qn77s95cafxza/?r=true&referrer=usnewsroom

QD-Display

SAMSUNG DISPLAY

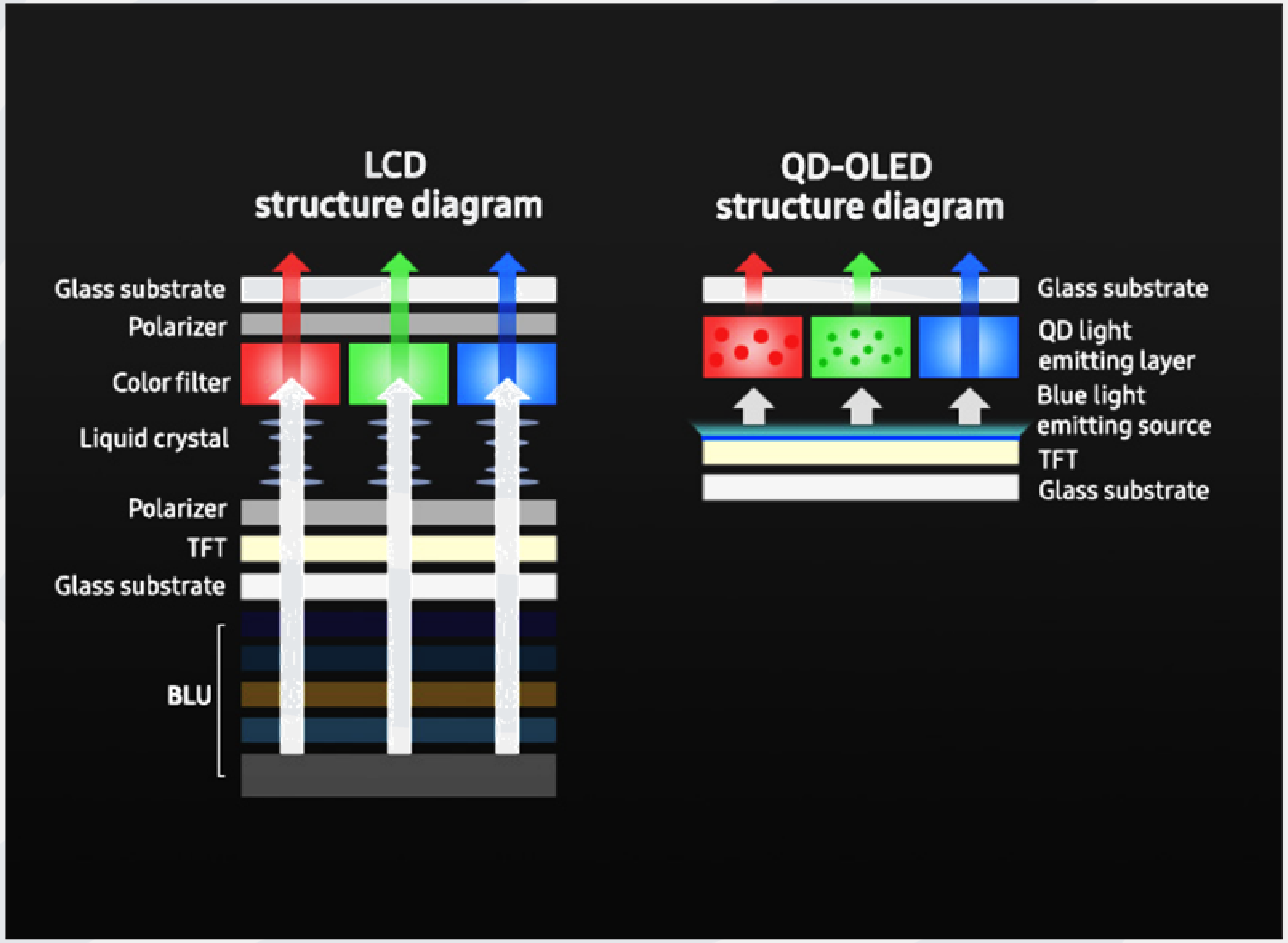


University of Wisconsin-Stout

https://www.samsungdisplay.com/eng/tech/quantum-dot.jsp#

SAMSUNG DISPLAY

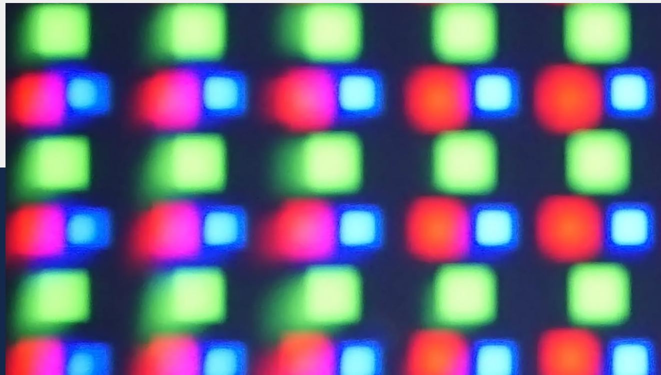
LCD vs. QD-OLED



QD-OLED, a self-luminous display, consists of **a TFT layer**, which is an electronic circuit that controls **the light emitting layer**, a light source that emits light, and **a QD light emitting layer** that expresses colors using the light emitted from the light source.

QD-OLED uses blue, which has the strongest light energy, as a light source, so it can achieve relatively bright luminance.

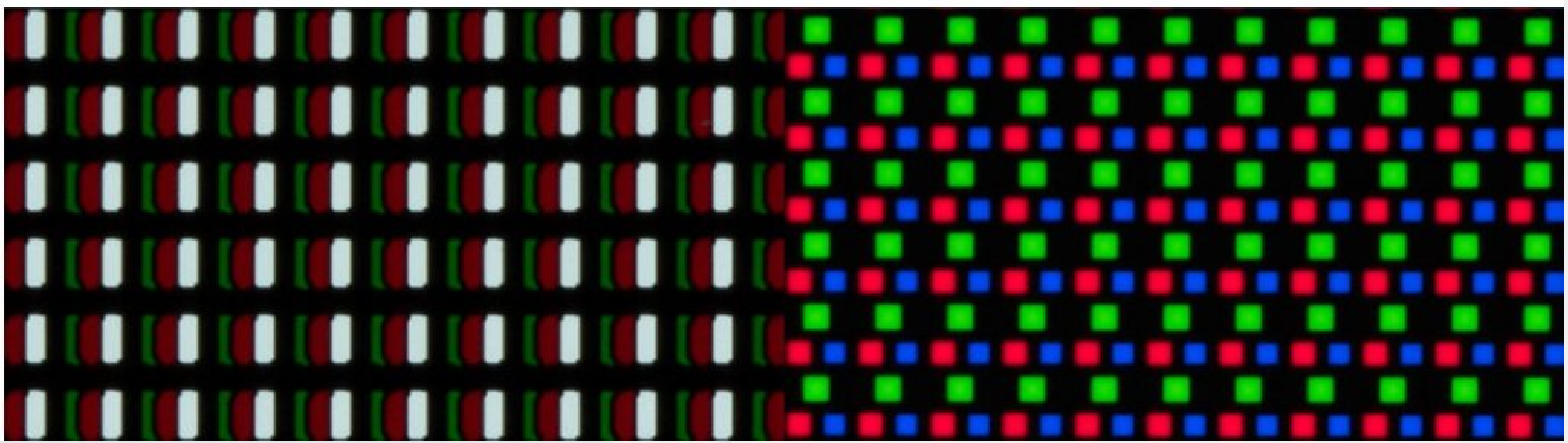
In particular, Samsung Display's QD technology utilizes a front light-emitting method that efficiently utilizes light, enabling a simpler and more efficient structure, unlike LCDs that require a backlight, providing a **thin and light display**.



https://www.samsungdisplay.com/eng/tech/quantum-dot.jsp#

SAMSUNG DISPLAY

LCD vs. QD-OLED



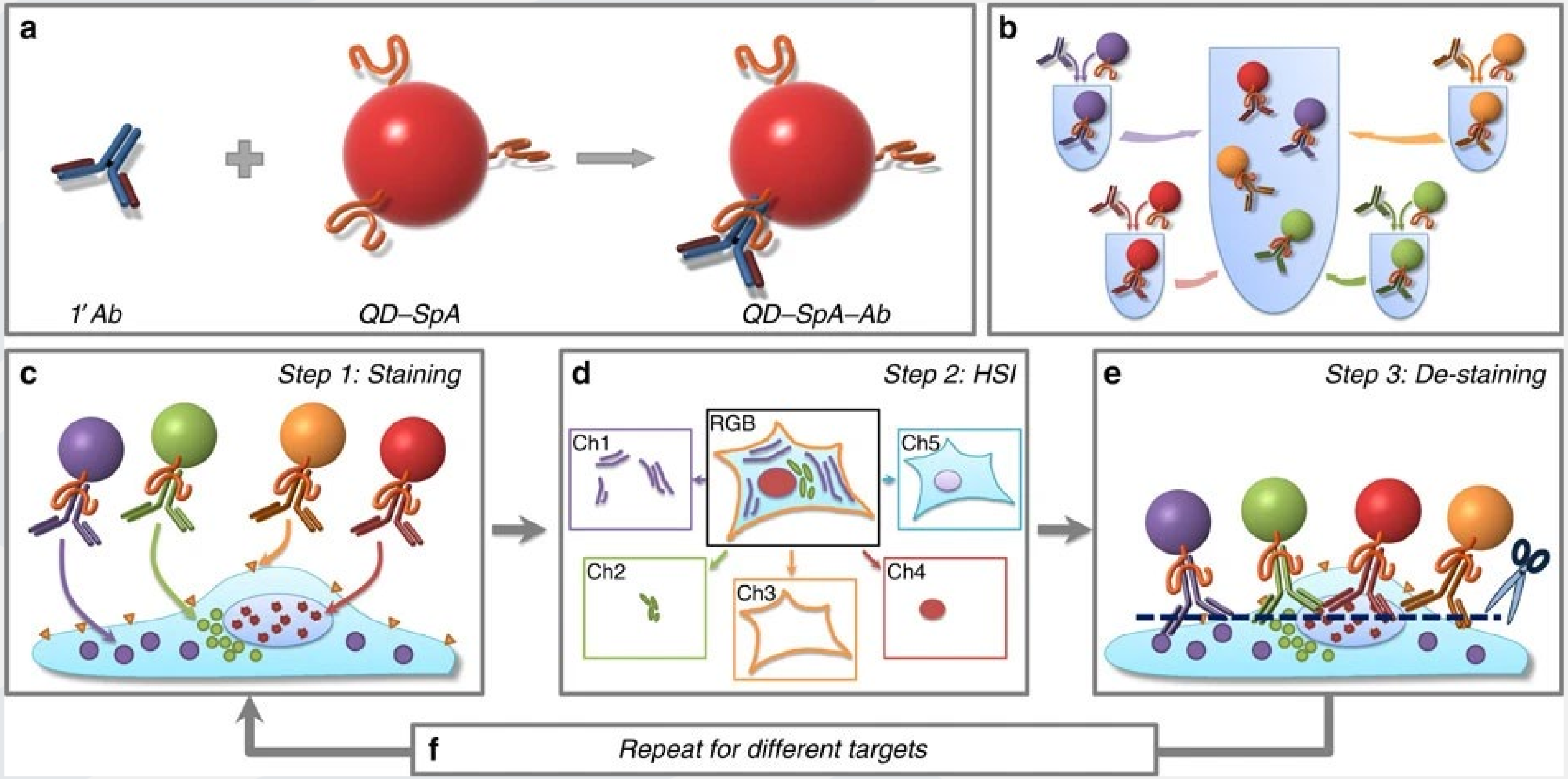
(L) The subpixel array on LG OLED is Red, Green, Blue (looks black above) and White.
(R) The Sub-pixel array on Samsung QD OLED is red and green only. Blue is a transparent layer – not a QD and black means no subpixel in that space (solid)

LCD vs. QD-OLED

the Samsung QD OLED TV, center, offered richer colors in bright and dark areas than the conventional OLED TV to the left and the LCD TV to the right. However, the Samsung-arranged demonstration wasn't a formal test, and this photo of one scene doesn't capture the full range of image quality attributes.
--Stephen Shankland/CNET - Jan. 6, 2022

https://www.cnet.com/tech/home-entertainment/samsung-qd-led-tv-tech-explained-welcome-quantum-dot-era/

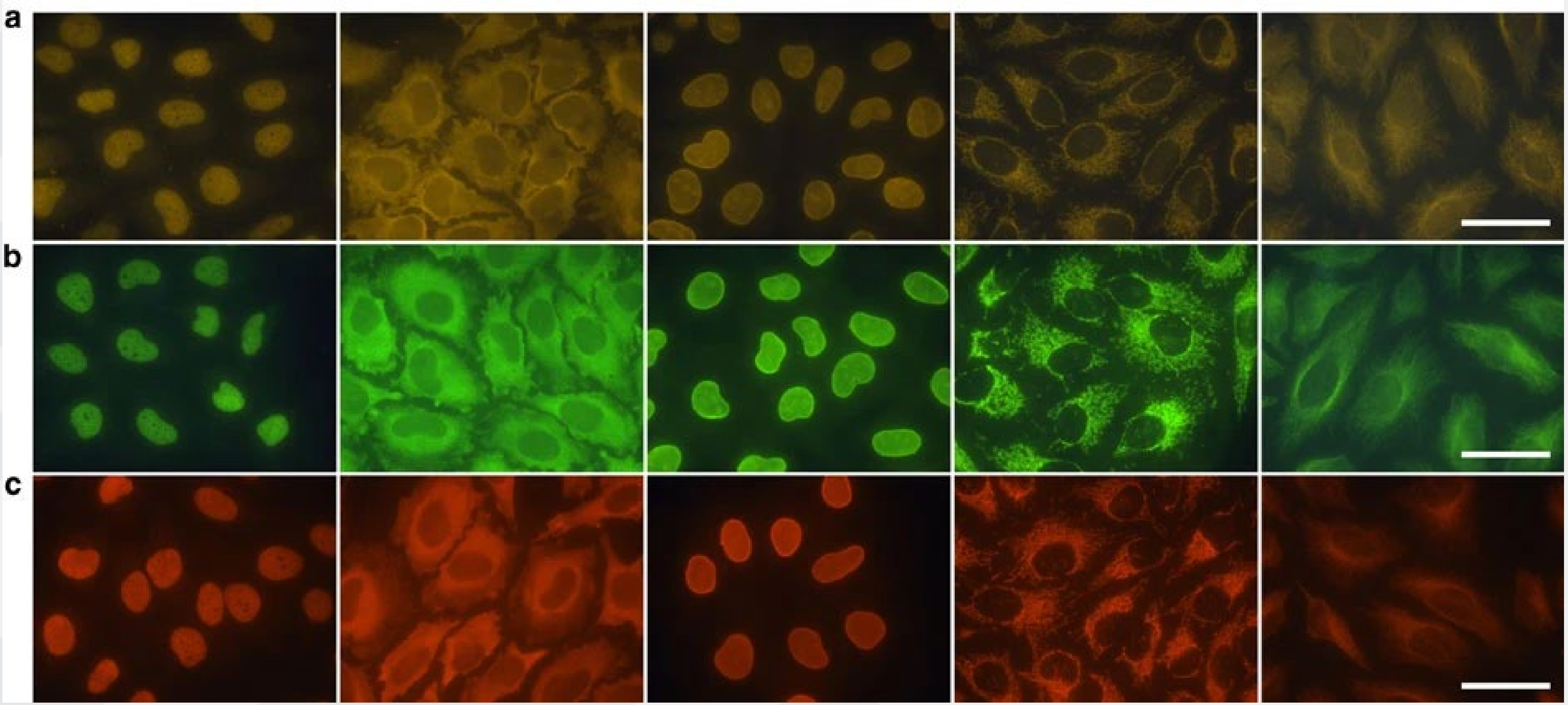
Quantum dot imaging platform for single-cell molecular profiling



(**a**) A universal QD-SpA platform is used for single-step purification-free assembly of functional QD-SpA-Ab probes via capture of free antibodies from solution by SpA. (**b**) Once bound, Abs cannot be exchanged between QD-SpA probes, thus enabling mixing of multicolour probes within a single cocktail. (**c**) The QD-SpA-Ab cocktail is used for single-step parallel multiplexed staining. (**d**) Spectral imaging is performed for unmixing individual QD colours, quantitative analysis of target expression and depiction of relative target distribution within the specimen. (**e**) Complete de-staining restores specimen for another staining cycle. (**f**) Sequential repetition of *N*-colour parallel staining for *M* cycles enables analysis of $N \times M$ molecular targets.

Zrazhevskiy, P., Gao, X. Quantum dot imaging platform for single-cell molecular profiling. *Nat Commun* **4**, 1619 (2013). https://doi.org/10.1038/ncomms2635

Quantum dot imaging platform for single-cell molecular profiling



(**a**) Five model targets (Ki-67, HSP90, Lamin A, Cox-4 and β-tubulin, from left to right) are labelled with QD585-SpA-Ab probes in a single-step procedure, producing staining patterns consistent with those obtained with either QD565-labelled (**b**) or Alexa Fluor 568-labelled (**c**) 2′Abs in a conventional two-step staining. Scale bar, 50 µm.

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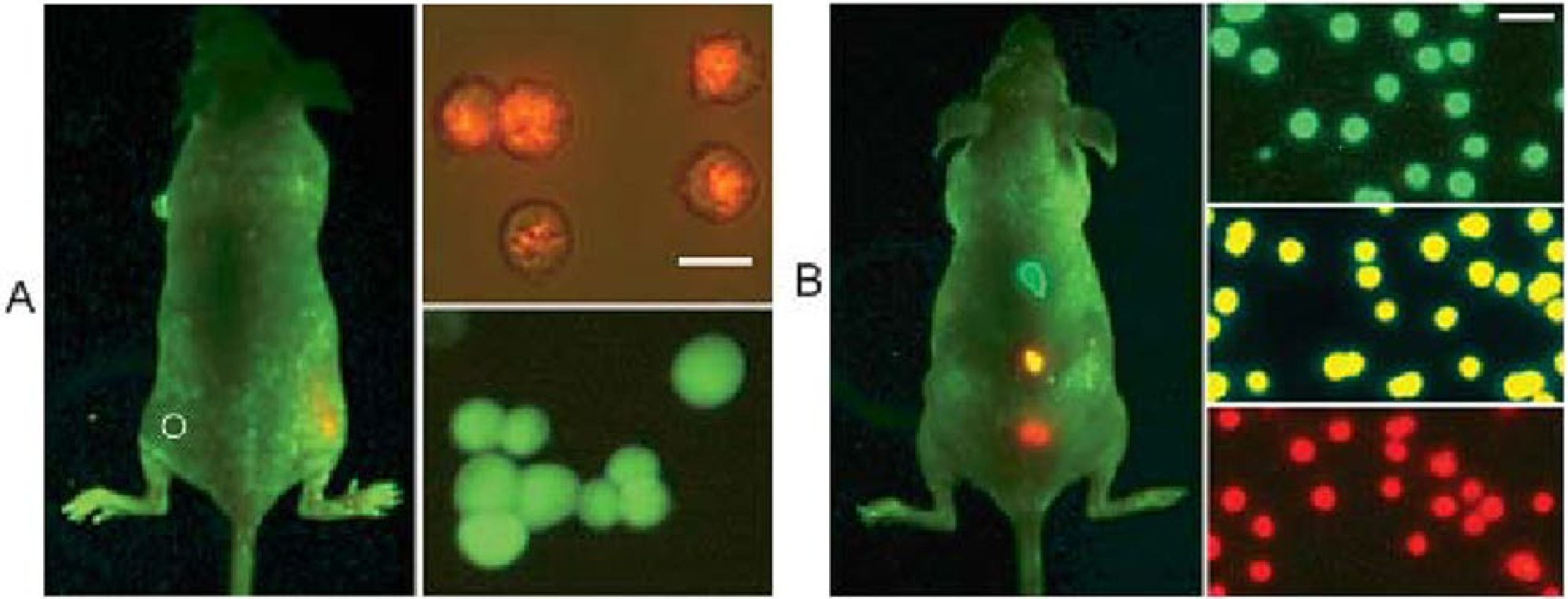
Quantum Dots for Live Cell and In Vivo Imaging



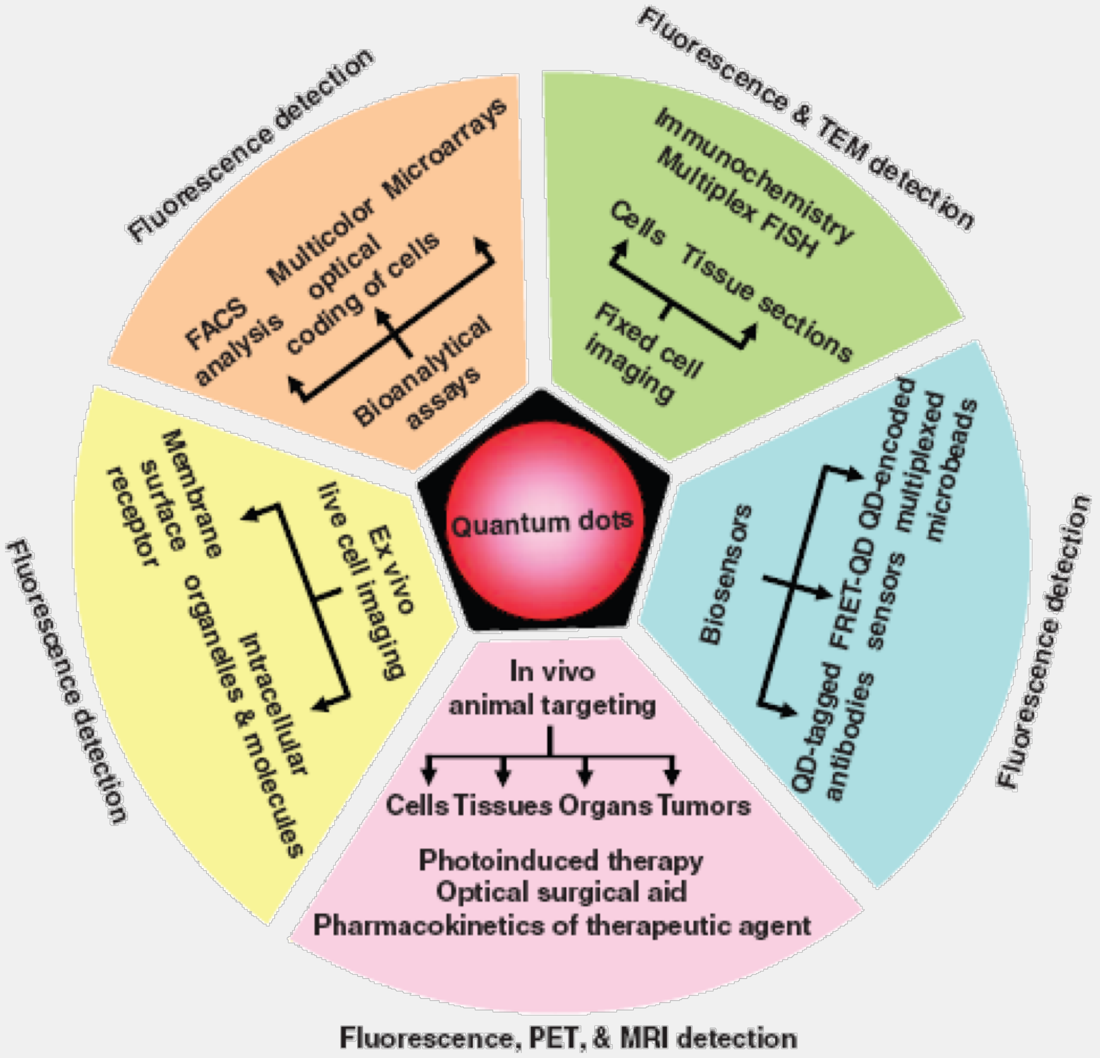
QD imaging in live animals. (A,B) Sensitivity and spectral comparison between QD-tagged and GFP transfected cancer cells

Walling, M.A.; Novak, J.A.; Shepard, J.R.E. Quantum Dots for Live Cell and *In Vivo* Imaging. *Int. J. Mol. Sci.* **2009**, *10*, 441-491. https://doi.org/10.3390/ijms10020441

Quantum Dots for In Vivo Imaging

Quantum Dots (QDs) for In Vivo Imaging			
QD Type	Type Core/Shell QD	Wavelength Range (nm)	Dispersed In
Heavy-Metal	CDSe/ZnS	540-660	Aqueous Solvents
	CdSeTe/ZnS	680-880	Aqueous Solvents
	PbS/CdS	700-1400	Aqueous Solvents
Heavy-Metal-Free	CuInZnS/ZnS, CuInS/ZnS	530-680	Aqueous Solvents
	InP/ZnS	520-750	Aqueous Solvents
	Ag_2S	750-1300	Aqueous Solvents

https://www.photonics.com/Article.aspx?AID=60801



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