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## Imaging and therapeutic applications of persistent luminescence nanomaterials

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## Abstract

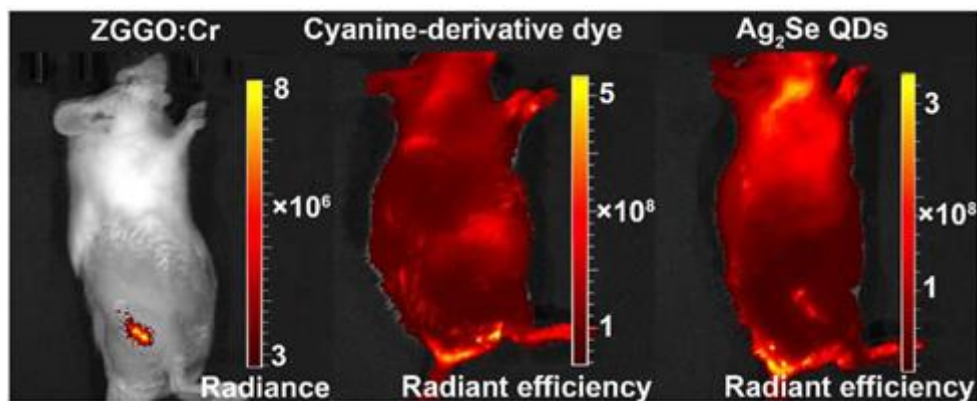
The development of probes for biomolecular imaging and diagnostics is a very active research area. Among the different imaging modalities, optics emerged since it is a noninvasive and cheap imaging technique allowing real time imaging. *In vitro*, this technique is very useful however *in vivo*, fluorescence suffers from low signal-to-noise ratio due to tissue autofluorescence under constant excitation. To address this limitation, novel types of optical nanoproboscopes are actually being developed and among them, persistent luminescence nanoparticles (PLNPs), with long lasting near-infrared (NIR) luminescence capability, allows doing optical imaging without constant excitation and so without autofluorescence. This review will begin by introducing the physical phenomenon associated to the long luminescence decay of such nanoproboscopes, from minutes to hours after ceasing the excitation. Then we will show how this property can be used to develop *in vivo* imaging probes and also more recently nanotheranostic agents. Finally, preliminary data on their biocompatibility will be mentioned and we will conclude by envisioning on the future applications and improvements of such nanomaterials.

Keywords : Persistent luminescence, nanoparticles, surface coating, physical stimulus, *in vivo*, imaging, therapy, nanotheranostics.

## 1. Introduction

The possibility to detect and diagnose diseases earlier than with current imaging methods causes a drastic increase of interest in imaging technologies. A noninvasive, cheap imaging technique, comfortable, portable, highly sensitive and that allows real-time imaging is still to be developed. Among the different existing imaging modalities, optical imaging has largely grown in recent years. This technique is highly complementary to others, such as X-rays or magnetic resonance imaging, since it allows acquisition of data at high speeds, allowing the visualization of biological processes or events in real time.<sup>1</sup> For that purpose, fluorescent probes are often used in order to enable the study of biological processes.<sup>2</sup> Among these probes, semiconductor quantum dots (QDs) exhibiting fluorescence optical properties have emerged as a class of nanoparticles for bioimaging and diagnostics. These crystals are highly fluorescent, allowing their use for *in vitro* and *in vivo* applications.<sup>3,4</sup> Upconversion nanoparticles (UCNPs) doped with rare earth elements, are another type of nanoprobes which emerged for diagnostic applications.<sup>5</sup> UCNPs convert near-infrared (NIR) photons to higher energy (visible or ultraviolet) photons.<sup>6</sup> The NIR excitation light of UCNPs (970-980 nm for trivalent ytterbium or around 810 nm for neodymium) fall into the biological window where light penetration in tissue occurs with minimal absorption and scattering. The phenomenon of upconversion leads to imaging living organisms with lower background autofluorescence in comparison with conventional fluorescent labels.<sup>7</sup> However, despite these advantages, optical imaging is limited because photons are scattered and absorbed by the tissues. The penetration depth of photons inside a tissue depends both on the type of tissue,<sup>8</sup> and on the wavelength ( $\lambda$ ) used. Scattering drastically decreases when  $\lambda$  increases in the so-call tissue transparency window.<sup>9</sup> *In vivo* imaging using fluorescent probes gave interesting results in clinical trials, for example for the detection of breast cancer, for the delimitation of tumor during surgery<sup>10</sup> and for diagnosis of cancer by endoscopy.<sup>11,12</sup> But as already mentioned above this technique is limited by factors such as tissue autofluorescence,<sup>13</sup> which greatly limits the quality of images, especially when working with small amount of fluorescent probe. A review of the state of the art for semiconductors QDs, UCNPs and first results with PLNPs was recently reported.<sup>14</sup> Persistent luminescence is a particular optical phenomenon in which luminescent materials keep emitting light a long time after the excitation is stopped. This phenomenon has intrigued people since several centuries.<sup>15</sup> As this property occurs in inorganic materials when the excitation has been stopped, this is sometimes compared to the bioluminescence mechanism observed in some animals, such as fireflies and jellyfishes.<sup>16</sup> Since a decade, researches are in progress to use this property for the development of *in vivo* optical probes. The main advantage when using this approach for *in vivo* imaging is the total absence of background signal, as represented on Fig. 1 (left). This is in total opposition to what is classically obtained when using most fluorescent probes, with short luminescence decay, in the order of nanoseconds, such as cyanine or QDs (Fig. 1, middle or right respectively) for which autofluorescence signal is very high.<sup>17</sup>

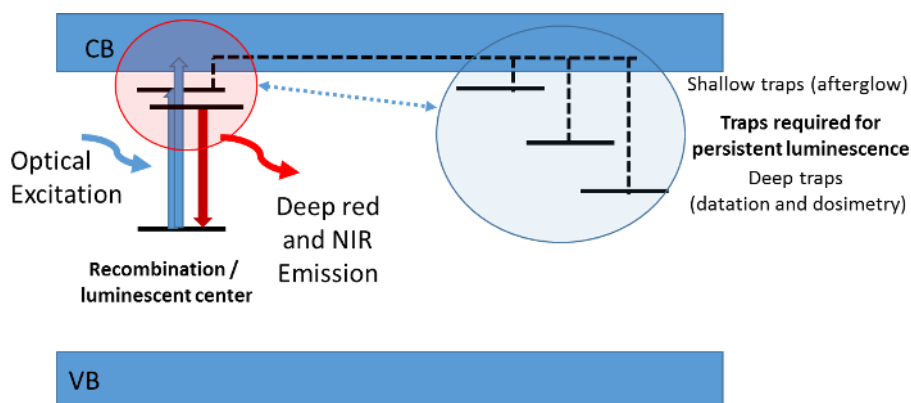
This review manuscript will present this particular optical characteristic of persistent luminescence (section 2) and will report its application in biology, for both imaging (section 3) and therapy (section 4).



**Fig. 1.** Comparison of optical *in vivo* imaging using either persistent luminescence nanoparticles, ZGGO:Cr (left) or conventional fluorescent probes, Cyanine or QDs (middle and right) [17].

## 2. Main characteristics of persistent luminescence materials

Unlike fluorescent probes that emit light for a very short time, a few nanoseconds after excitation, persistent luminescence materials can store the excitation energy into traps or defects under irradiation (Fig. 2). Then, when the excitation is stopped, persistent luminescence is controlled by the slow liberation of trapped charged carriers at room temperature, mainly by a simple thermal de-excitation process. In such conditions, the luminescence which results from traps and holes recombination at the luminescent center can last for several minutes to hours after removal of the excitation source.<sup>18,19</sup> Fig. 2 presents the simplified energy levels of luminescence center and traps responsible for the persistent luminescence. In this figure, the same cation is presented as recombination and excitation centers and trapping and detrapping can occur via the conduction band (CB, dashed black lines) or by direct interaction (dashed blue line). Only traps at energy depths in the bandgap ranging between 0.5 to 1 eV are effective for direct persistent luminescence while deeper traps ( $E > 1$  eV) can be activated by photostimulation or X-ray stimulation, as presented later in this review paper.



**Fig. 2.** Schematic of the energy levels and traps involved in the persistent luminescence mechanisms.

The main applications of this phenomenon, we are used in everyday life, are emergency signs that can be used in case of power failure. This is one of the main applications of persistent phosphors, but others have been reported in night vision such as in watch dials (when radioactive elements were banned more than twenty years ago), decorative objects and toys. Recently our groups have proposed

the application of this phenomenon for *in vivo* optical imaging on small animals. This will be the topic of this review article.

For the materials concerned with persistent luminescence properties, lots of compositions have been tested in the literature with various successes (Table 1). More than two hundred combinations of host materials and activator ions have been depicted in which rare earth (RE) and metal transition (MT) cations have been widely used as dopants to enhance the persistent luminescence properties. The main nanoparticles developed for bioimaging applications, later called PLNPs as an acronym for Persistent Luminescence NanoParticles, using metal transition cations and rare-earth cations for deep red/near infrared emission are reported in Table 1.

Table 1. Main materials used with metal transition (MT) cations and RE (rare earth) cations for red/near infrared persistent emission and bio-applications.

Hosts	Dopants	Comments and applications in bio-imaging	Year <sup>Ref</sup>
Gd <sub>2</sub> O <sub>2</sub> S	Eu <sup>3+</sup> , Mg <sup>2+</sup> , Ti <sup>4+</sup>	NPs regular shape, bimodality optical / MRI	2015 <sup>20</sup>
Ca <sub>3</sub> (PO <sub>4</sub> ) <sub>2</sub> / Hydroxyapatite	Mn <sup>2+</sup> , Tb <sup>3+</sup> , Dy <sup>3+</sup>	Fully biocompatible, NPs and <i>in vivo</i> imaging	2015 <sup>20</sup>
Ca <sub>2</sub> Si <sub>5</sub> N <sub>8</sub>	Eu <sup>2+</sup> , Tm <sup>3+</sup>	Bioimaging applications	2012 <sup>21</sup>
SrAl <sub>2</sub> O <sub>4</sub>	Eu <sup>2+</sup> , Dy <sup>3+</sup>	NPs, functionalization, Bioimaging applications, <i>green emission</i>	2014, 2018 <sup>22</sup>
Ca <sub>0.2</sub> Zn <sub>0.9</sub> Mg <sub>0.9</sub> Si <sub>2</sub> O <sub>6</sub>	Mn <sup>2+</sup> , Eu <sup>2+</sup> , Dy <sup>3+</sup>	NPs, functionalization, pioneer work for bio-imaging: cancer cells imaging, cell targeting	2007, <sup>23</sup> 2011, 2012
Ca <sub>1.86</sub> Mg <sub>0.14</sub> ZnSi <sub>2</sub> O <sub>7</sub>	Eu <sup>2+</sup> , Dy <sup>3+</sup>	FRET and various bio-sensing applications	2018 <sup>24</sup>
CaMgSi <sub>2</sub> O <sub>6</sub>	Mn <sup>2+</sup> , Eu <sup>2+</sup> , Pr <sup>3+</sup>	NPs, functionalization, bio-imaging	2011 <sup>25</sup>
MAIO <sub>3</sub> (M=La, Gd)	Mn <sup>4+</sup> /Ge <sup>4+</sup>	Bio-imaging in pork tissue	2016 <sup>26</sup>
GdAlO <sub>3</sub>	Mn <sup>4+</sup> , Ge <sup>4+</sup> @Au Sm <sup>3+</sup> , Cr <sup>3+</sup>	Trimodality imaging Optical and magnetic dual mode imaging	2016 <sup>26</sup> 2018 <sup>27</sup>
ZnGa <sub>2</sub> O <sub>4</sub>	Cr <sup>3+</sup>	NPs, functionalization, bio-imaging (cancer cells imaging), Cell targeting, cytotoxicity, visible Light NIR photostimulation, X-rays activation Oral administration & breast cancer imaging Toxicology analysis Probiotic analysis	2014 <sup>28</sup>  2013 <sup>29</sup> 2018 <sup>30</sup> 2018 <sup>31</sup>  2017 <sup>32</sup> 2018 <sup>33</sup>
ZnGa <sub>2</sub> O <sub>4</sub> in hollow cavity	Cr <sup>3+</sup>	Photodynamic therapies	2018 <sup>34</sup>
ZnGa <sub>2</sub> O <sub>4</sub>	Cr <sup>3+</sup> , Gd <sup>3+</sup>	NPs, functionalization, bimodality optical/NMR imaging	2015 <sup>35</sup>
ZnGa <sub>2</sub> O <sub>4</sub> /SiO <sub>2</sub> ZnGa <sub>2</sub> O <sub>4</sub> /Fe <sub>2</sub> O <sub>3</sub> ZGOCS@m-SiO <sub>2</sub> @Gd <sub>2</sub> O <sub>3</sub>	Cr <sup>3+</sup> Cr <sup>3+</sup> Cr <sup>3+</sup>	Core-shell structure, drug delivery Cell labelling and magnetic vectorization, multimodal nanoprobe	2014 <sup>36</sup> 2015, <sup>37</sup> 2018 <sup>38</sup> 2017 <sup>39</sup>
Zn <sub>1.1</sub> Ga <sub>1.8</sub> Ge <sub>0.1</sub> O <sub>4</sub> /SiO <sub>2</sub>	Cr <sup>3+</sup> , Eu <sup>3+</sup>	NPs, core-shell structure, drug delivery	2015 <sup>40</sup>
Zn <sub>3</sub> Ga <sub>2</sub> Ge <sub>2</sub> O <sub>10</sub>	Cr <sup>3+</sup>	Imaging of pork tissue, Photostimulation, cytotoxicity	2014 <sup>41</sup>
Zn <sub>1.1</sub> Ga <sub>1.8</sub> Ge <sub>0.1</sub> O <sub>4</sub> @SiO <sub>2</sub> Zn <sub>1.25</sub> Ga <sub>1.5</sub> Ge <sub>0.25</sub> O <sub>4</sub>	Cr <sup>3+</sup> Cr <sup>3+</sup> , Yb <sup>3+</sup> , Er <sup>3+</sup>	Bio-imaging and drug delivery Metastasis tracking and chemophotodynamic therapy	2018 <sup>42</sup> 2018 <sup>43</sup>
Zn <sub>1.1</sub> Ga <sub>1.8</sub> Ge <sub>0.1</sub> O <sub>4</sub>	Cr <sup>3+</sup>	Nanothermometry	2017 <sup>44</sup>
Zn <sub>3</sub> Ga <sub>2</sub> Sn <sub>1</sub> O <sub>10</sub>	Cr <sup>3+</sup>	Imaging of goldfish	2014 <sup>45</sup>
Zn <sub>2.94</sub> Ga <sub>1.96</sub> Ge <sub>2</sub> O <sub>10</sub> Zn <sub>3</sub> Ga <sub>2</sub> Ge <sub>2</sub> O <sub>10</sub>	Cr <sup>3+</sup> , Pr <sup>3+</sup> Cr <sup>3+</sup>	NPs, functionalization Recognition of breast cancer cells	2013 <sup>46</sup> 2015 <sup>47</sup>
Zn <sub>3</sub> Ga <sub>2</sub> GeO <sub>8</sub>	Cr <sup>3+</sup> , Yb <sup>3+</sup> , Er <sup>3+</sup>	Upconversion	2014 <sup>48</sup>
LiGa <sub>5</sub> O <sub>8</sub>	Cr <sup>3+</sup> /PEG-OCH <sub>3</sub>	NPs, functionalization, bio-imaging, Visible light stimulation, photostimulation	2013, <sup>49</sup> 2014 <sup>50</sup>
Ca <sub>3</sub> Ga <sub>2</sub> Ge <sub>3</sub> O <sub>12</sub>	Cr <sup>3+</sup> , Yb <sup>3+</sup> , Tm <sup>3+</sup> Pr <sup>3+</sup> , Yb <sup>3+</sup>	NIR stimulation, upconversion <i>In vivo</i> imaging	2014 <sup>51</sup> 2017 <sup>52</sup>
m-SiO <sub>2</sub> @Gd <sub>3</sub> Ga <sub>5</sub> O <sub>12</sub>	Cr <sup>3+</sup> , Nd <sup>3+</sup>	multimodal imaging and cancer therapy	2018 <sup>53</sup>
Sr <sub>2</sub> SnO <sub>4</sub>	Nd <sup>3+</sup>	Finger image	2014 <sup>54</sup>
SiO <sub>2</sub> /CaMgSi <sub>2</sub> O <sub>6</sub>	Eu <sup>2+</sup> , Pr <sup>3+</sup> , Mn <sup>2+</sup>	Bio-imaging, intraperitoneal injection Photostimulation imaging of pork tissue	2014 <sup>55</sup>
YAGG (garnet)	Er <sup>3+</sup> , Cr <sup>3+</sup>	Imaging in the second biological window	2018 <sup>56</sup>
NaYF <sub>4</sub> + SrAl <sub>2</sub> O <sub>4</sub>	Yb <sup>3+</sup> , Tm <sup>3+</sup> , Eu <sup>2+</sup> , Dy <sup>3+</sup>	Upconversion & photodynamic therapy	2018 <sup>57</sup>
Sr <sub>2</sub> MgSi <sub>2</sub> O <sub>7</sub>	Eu <sup>2+/3+</sup> , Dy <sup>3+</sup>	Photodynamic activation Visualization of abdominal inflammation	2016 <sup>58</sup> 2018 <sup>59</sup>
La <sub>3</sub> Ga <sub>5</sub> GeO <sub>14</sub> @SiO <sub>2</sub> @Van (vancomycin)	Cr <sup>3+</sup> , Zn <sup>2+</sup>	Bio-imaging-guided <i>in vivo</i> & drug delivery	2018 <sup>60</sup>
CaTiO <sub>3</sub>	Pr <sup>3+</sup> , Yb <sup>3+</sup> , Tm <sup>3+</sup>	Up converting and guided photothermal therapy	2017 <sup>61</sup>
ZnSn <sub>2</sub> O <sub>4</sub>	Cr <sup>3+</sup> , Eu <sup>3+</sup>	Cellular and deep tissue imaging	2017 <sup>62</sup>

$\text{Sr}_3\text{Sn}_2\text{O}_7$	$\text{Nd}^{3+}$	Second window imaging	2017 <sup>63</sup>
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The reader could further see reviews and book chapter on the persistent luminescence topic.<sup>64,65,66</sup> Concerning bioimaging and *in vivo* applications, the past ten years have witnessed several major advances to establish deep red/near-infrared emitting PLNPs as a novel approach for real-time *in vivo* imaging in small animal.<sup>67,68,69</sup> For that application both size and emission wavelength should be controlled (see section 2 and 3).

### 2.1 Persistent luminescence mechanisms

The physics related to the phenomenon of persistent luminescence is not simple and lots of research has been going on for years to understand it. For the trapping process which is the primary very important step, two kinds of traps are envisioned: (i) extrinsic defects obtained by adding dopants during the synthesis of the material or (ii) intrinsic defects which correspond either to anions vacancies (such as oxygen) or cations deficiencies.<sup>70,71</sup> In some compounds, antisite defects corresponding to cationic exchanges are very likely, varying some chemical bonds and creating low energy traps (shallow traps) in the conduction band (see Fig. 2). For example, authors have proposed the existence of antisite defects near  $\text{Cr}^{3+}$  ions in order to explain the persistent luminescence of the zinc gallate ( $\text{ZnGa}_2\text{O}_4$ , ZGO) spinel host used in section 3.<sup>72,73,74,75</sup> It must be also emphasized that thermal annealing with or without reducing atmosphere can create or increase the number of intrinsic traps such as oxygen vacancies leading to persistent luminescence.<sup>76,77</sup>

### 2.2 Traps and co-doping

Co-doping (extrinsic defect) is another strategy largely used to enhance the persistent luminescence, for example by co-doping the material with one or two lanthanides cations. For instance,  $\text{Dy}^{3+}$  was used as electrons trap in the first hybrid enstatite/diopside silicate developed for proof of concept of *in vivo* bioimaging with PLNPs.<sup>23</sup> Later it appeared that co-doping with  $\text{Pr}^{3+}$  was indeed better when the diopside bandgap was considered.<sup>25</sup> The variation of traps depths strongly depend of the couple host/dopant and corresponds to a so-call bandgap engineering as introduced in previous works,<sup>78,79</sup> with the prediction of the energy level diagram.<sup>80,81</sup> Such bandgap engineering was proposed in various hosts used for persistent luminescence but was also tested with success for others photonic applications such as scintillation and lighting.<sup>82</sup> To improve the persistent luminescence performance, it is possible to vary the position of the conduction band and the traps depth by varying the composition, or by playing with cationic and anionic substitutions or by a careful choice of the doping cation for an optimal couple composition/dopant.

To go in deeper understanding, knowledge of the energy formation of defects, defects stability and defects energy position are required, through band structure and defects calculations.<sup>83</sup> Several spectroscopic techniques have been used to study the persistent luminescence mechanism such as: optical, Electron Paramagnetic Resonance (EPR) to control the origin and defects intensity,<sup>84</sup> X-rays spectroscopies to give insight to the mechanism,<sup>85</sup> thermoluminescence and photoconductivity<sup>86,87</sup> to measure the traps depth.<sup>88</sup> In the case of electrons traps and holes traps,<sup>89</sup> the stored charges can be released by various processes, as presented in the following part of this review, such as thermal,<sup>90</sup> optical<sup>91</sup> or others physical stimulations,<sup>92</sup> resulting in stimulated emissions from the active recombination centers.

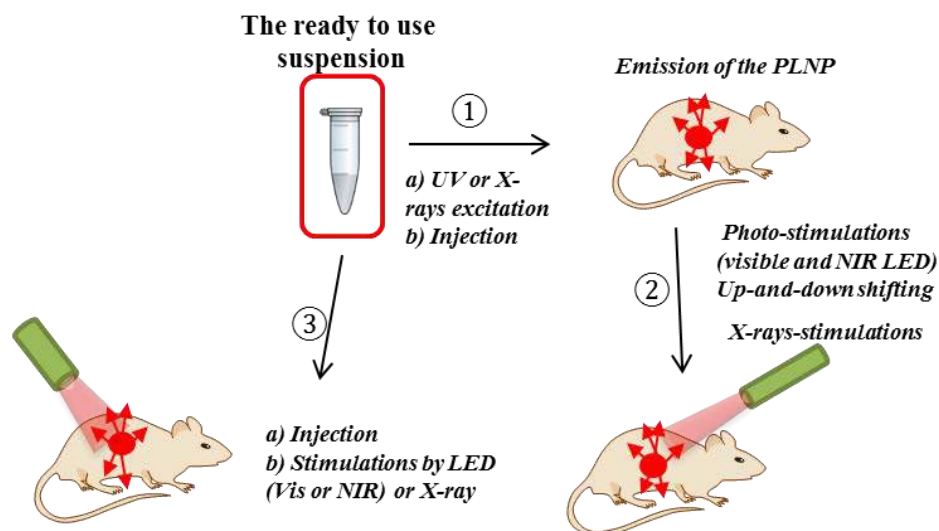
### 2.3 Excitation sources (physical stimuli) used to charge/discharge nanoprobe

The first generation of PLNPs was only excitable (charged) *ex vivo* using UV light before its injection,<sup>23</sup> allowing *in vivo* optical imaging (see section 3). This procedure has a limit for some applications such as the visualization of accumulation of the probe within tumors which usually

requires several hours after injection.<sup>93</sup> This was too long compared to the duration of persistent luminescence, which doesn't go beyond one hour *in vivo*.

To overcome this major restriction, developments of new materials and new excitation modalities have been undertaken. First, efforts to optimize compositions and enhanced optical characteristics have been made. In that sense, compounds based on new host materials such as gallate and gallo-germanate spinels have attracted great attention, mainly due to their bright deep persistent luminescence when doped with trivalent chromium ( $\text{Cr}^{3+}$ ) and excite with UV compared to previously used silicate nanoprobles (see section 3). However, the main breakthrough was the possibility to reexcite the persistent luminescence material at lower energy in the biological window, through the animal body, allowing longer time observations. For that purpose, new modalities have been proposed, as seen in Figure 3.

This figure summarizes the various approaches that can be followed for long term *in vivo* imaging with persistent luminescent nanoparticles. Indeed, PLNPs dispersed in biological buffer, such as PBS or glucose, can be pre-excited in a syringe *ex situ*, injected into small animal and then the persistent luminescence signal emitted by the probe can be collected by a photon-counting system (step 1, Fig. 3). Depending on their composition, some PLNPs can be excited or re-excited *in vivo* through the animal body (step 2, Fig. 3). This way of proceeding allows the recovery of persistent luminescence signal whenever wanted. The efficiency is however weaker than for the persistent luminescence under UV excitation (step 1) but it is indeed enough to detect and localize the probe *in vivo* over long time. Furthermore for some persistent luminescent nanoprobles, when deeper traps are observed in the thermoluminescence spectra, such as in garnet or spinel hosts (Table 1), deep-red persistent emission can be activated or stimulated using near infrared light, in such a process we are talking about photostimulated persistent luminescence (PSPL).<sup>94,95,96</sup> Charging of the persistent phosphors is also possible through second order effects.<sup>97</sup> The photostimulation capability of several materials is widely reported and researchers have focused their attention on the  $\text{Cr}^{3+}$  doped samples. This technique is highly used for UV dosimetry, as well as in geology and archeology for dating.<sup>98</sup> One can adjust the depth of the traps responsible for the persistent luminescence and therefore control carefully the composition. In that case, the release of the traps and thus the emission of light could be started at the convenience of the user, using a red/near infrared LED for instance which will be in the best transparency range. The first preliminary tests carried out have shown the originality and feasibility of this new modality.<sup>99</sup>



**Fig 3:** Different physical strategies (stimuli) allowing performing *in vivo* optical imaging with persistent luminescence nanoparticles (PLNPs). (1) *Ex situ* excitation of a suspension of nanoparticles with UV followed by tail vein injection and optical imaging using a photon counting camera. (2) Once the *in vivo* persistent luminescence signal has completely disappeared, some PLNPs can give further activated either by photo or X-rays stimulations. (3) Some PLNPs can be directly excited in the animal body using visible, near infrared or X-rays photons without preliminary *ex-situ* excitation. [14]

The energy needed for electron detrapping vary from red to NIR (LED or laser sources).<sup>100,101,102</sup> However, *in vivo* excitation is hindered by its limited penetration in tissue even in the near infrared. An alternative way is to use other excitation source, such as X-ray. Compared to the traditional excitation source (UV/visible/NIR), X-ray has a number of advantages such as weaker scattering and deeper penetration in tissues, as well as simplified image reconstruction in tomography.<sup>103</sup> This allows achieving deeper tissue and higher sensitivity imaging with better spatial resolution. With these additional excitation pathways, the charges can be released from deep traps and redistributed to shallow traps in order to produce a persistent luminescence signal.<sup>104,105</sup>

The following section 3 and 4 present several examples from the literature using different physical stimuli discussed previously (UV, visible, photostimulation, NIR, X-rays) to excite PLNPs for *in vivo* bioimaging or therapy.

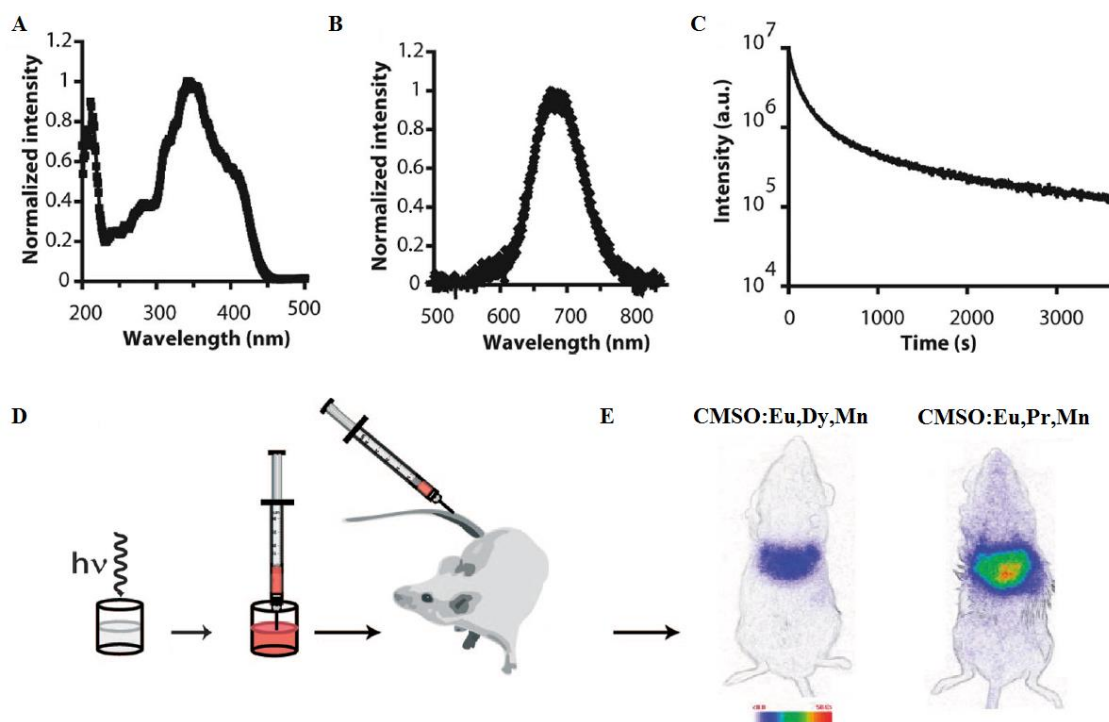
### 3. *In vivo* bioimaging

The main features that a probe has to fulfill for *in vivo* applications are the following: (i) it must be prepared as nanoparticles (PLNPs with size < 100 nm), (ii) with an intensive emission extending in the deep red toward the near infrared range corresponding to the tissue window transparency,<sup>106</sup> (iii) efficient functionalization,<sup>107,108,109</sup> (iv) stability in biological media,<sup>110</sup> (v) persistent emission. These points are the reasons why applications of persistent phosphors for bio-applications were little investigated at the beginning of the development of the persistent phosphors in 1996 and the investigation started later in 2007, after our pioneer paper was published.<sup>23</sup> Since that time, several materials have been developed for imaging applications (see review papers [24, 68] and Table 1). Notice that at first all the researches were focused in the deep-red range (high transmission range of

the living tissue) where the silicon detectors of the cameras also reach their maximal sensitivity. But very recently, researchers expand the range to the second and third biological windows (BW-II and BW-III) even if the results are still very preliminary.<sup>111</sup> For the development of new nanomaterials with long persistent luminescence for bio-applications, we must have in mind that different strategies are developed to get small size PLNPs but also with the maximum of defects at the origin of the persistent luminescence (section 2). For this purpose, hydrothermal, solvothermal, sol-gel, co-precipitation and microwaves methods have been developed.<sup>69</sup> Finally, surface functionalization is required to make these probes biocompatible in order to be used for *in vivo* applications. This section presents a selection of works developed in our group and latest works by colleagues concerning the use of persistent luminescence nanoparticles as efficient nanoprobes for *in vivo* imaging.<sup>112</sup>

### 3.1 Proof of concept : UV excitable nanoprobes

The first article reporting the use of persistent luminescence nanoparticles (PLNPs) for optical *in vivo* imaging was published in 2007 by Scherman and co-workers.<sup>23</sup> As discussed previously, to be used *in vivo*, the probe must have a nanometric size and must emit radiation in the biological window ( $> 650$  nm). In their work, the authors prepared a silicate enriched with RE ( $\text{Eu}^{2+}$ ,  $\text{Dy}^{3+}$ ) and MT: ( $\text{Mn}^{2+}$ ). This material has the characteristics for the envisioned application: excitation of  $\text{Eu}^{2+}$  with UV light creates charges stored by electron traps ( $\text{Dy}^{3+}$ ) and after thermal activation (by the animal body), persistent luminescence signal at 700 nm occurs due to recombination of charges at the emission center ( $\text{Mn}^{2+}$ ) (Fig. 4A-B).<sup>113</sup> The long lasting luminescence of this material, several hours after excitation (Fig. 4C) has been used by the authors *in vivo*. Thanks to the persistent luminescence signal, the authors proposed an alternative procedure to perform *in vivo* imaging (Fig. 4D). Unlike what is classically done with fluorescent probes which are excited in the animal body at the same time as the signal is recorded, suspension of PLNPs dispersed in physiological serum is excited *ex vivo*, outside the animal body, with a UV light, then the excited probe is injected into the mouse and the photons emitted are captured by a sensitive camera (Fig. 4D-E). In such conditions, *in vivo* imaging without any background (without any autofluorescence signal) can be performed for about 30 min to 1 hour (Fig 4E).



**Fig. 4.** *In vivo* imaging using the first generation of PLNPs. (a-c) Optical properties of silicate-based PLNPs. (d) Principle of *in vivo* imaging using PLNPs. (e) *In vivo* persistent luminescence signals obtained using a Biospace photon-counting camera and bioluminescence acquisition mode [23,25]

This was the first example showing that persistent luminescence nanoprobes could be used in small animal and detected without any background signal. With this first generation of PLNPs, *in vivo* imaging could be done for about 1 h, luminescence intensity varying with the size of nanoprobes.<sup>65</sup> This may be sufficient for some applications, but for others it can be necessary to do imaging for longer time. For that purpose, as discussed in section 2, a possibility was to change the nature of the electron traps, to favor both the trapping and the electron detrapping at the animal body temperature. For that purpose, the same research group synthesized other silicates in which they replaced the electrons trap of the first synthesized nanomaterial (i.e  $\text{Dy}^{3+}$ ) by other RE ions such as  $\text{Nd}^{3+}$ ,  $\text{Pr}^{3+}$  or  $\text{Ce}^{3+}$ . Among these, they found that the silicate doped with  $\text{Pr}^{3+}$  was 5 times more efficient in term of luminescence intensity and decay, allowing doing imaging for longer time, about 3 hours after UV excitation and injection (Fig. 4E, right).<sup>25114,115,116</sup>

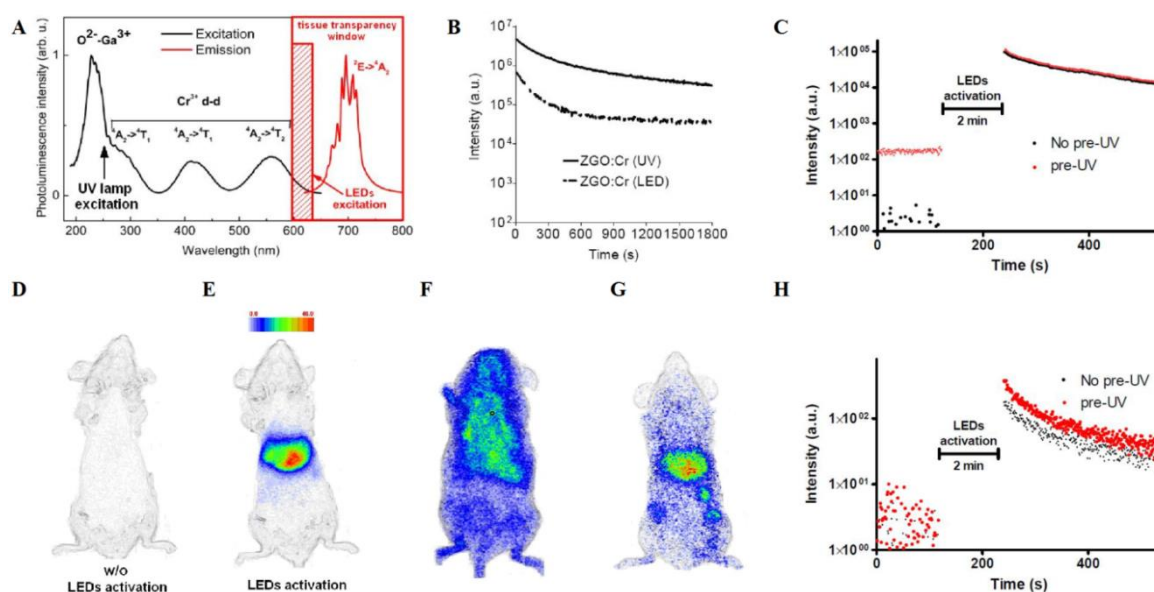
In 2012, Smet and co-workers<sup>21</sup> proposed an alternative solution to do *in vivo* experiments with other PLNPs using a nitridosilicate matrix ( $\text{Ca}_2\text{Si}_5\text{N}_8$ ) doped with  $\text{Eu}^{2+}$  and  $\text{Tm}^{3+}$  as RE elements. In that case  $\text{Tm}^{3+}$  was the electrons trap and  $\text{Eu}^{2+}$  both activator and emitting center. The authors reported that this material could emit persistent luminescence light at 640 nm (BW-I) after UV excitation and they have evaluated its efficacy *in vivo*. However, *in vivo*, this material is not more efficient than the previous one in term of luminescence intensity and decay time. However, the main point to emphasize here is that these first examples highlighted the possibility of using persistent luminescence nanoprobes *in vivo*, as alternatives to conventional fluorescence probes in order to improve the diagnostic. However for long term imaging, their disadvantage was their excitation mode, using UV light, which limits their detection to a few hours after their excitation and injection to mice. However, these pioneer works opened the door to a new type of nanoprobes with oxides, nitrides and sulfide-

based NPs<sup>117</sup> and since that time, lots of bio-applications with various excitation modalities and compositions have been proposed, as seen in Table 1. Some of them will be detailed in the following part of the paper, using different physical methods (stimuli) to trigger the persistent luminescence.

### 3.2 Strategies developed to perform longer time imaging

#### 3.2.1 LED excitation

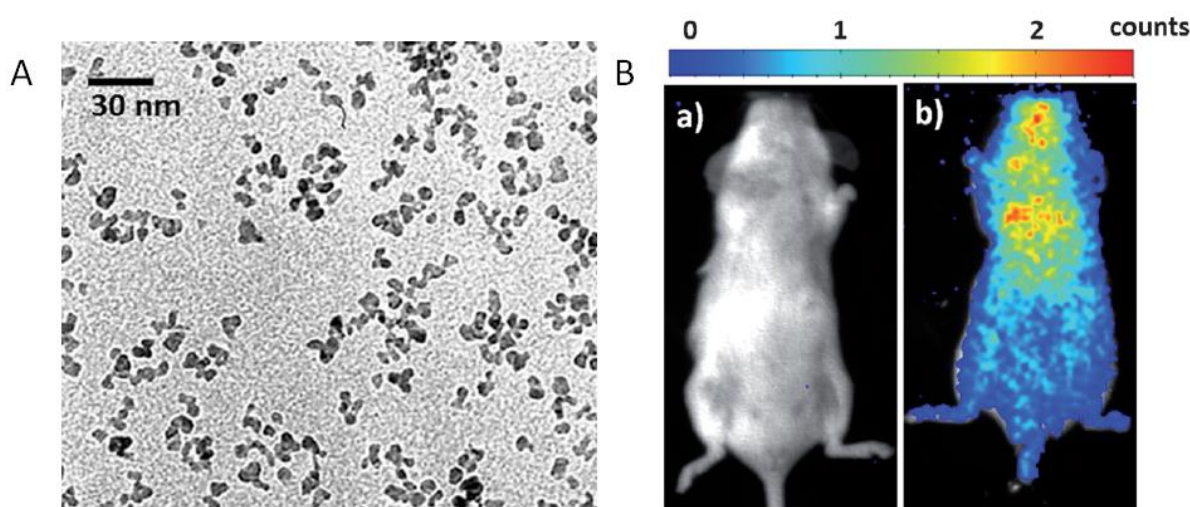
To overcome the major restriction of the first generation of PLNPs, and to allow longer time imaging (> few hours), in 2014 Maldiney *et al.* have changed the matrix and have proposed the use of zinc gallium oxide doped with Cr<sup>3+</sup>.<sup>28,118,119,120</sup> As can be seen in Fig. 5, contrary to previous first generation silicates, this probe has three excitation bands, among which one being close to the tissue transparency window (Fig. 5A, hatched red rectangle). The authors synthesized ZnGa<sub>2</sub>O<sub>4</sub>:Cr (ZGO) in the form of nanoparticles and first characterized the powder. They observed a persistent luminescence decay signal after both UV (Fig. 5B, continuous line) and also after excitation with LEDs (Fig. 5B, dashed line). To evaluate the superiority of this probe *in vivo*, a suspension of this material dispersed into 5% glucose was injected into mice, and for the first time the authors have shown that the probe could be activated *in vivo* with orange/red light-emitting diodes (Fig. 5E). The authors have also shown that *ex situ* UV pre-excitation before LED re-activation was not necessary (Fig. 5C and 5H). In these conditions, there is no more time constraint and the probe can be observed *in vivo* when desired thanks to excitation with the LEDs (Fig. 5E-G). The authors successfully reported that such nanoproboscopes could be used *in vivo*, after a proper functionalization, to target and image tumors (Fig. 5G).



**Fig. 5.** *In vivo* imaging with *in situ* excitable PLNPs. (a-c) Optical properties of ZGO powder after either UV or visible excitation. (d-h) *In vivo* excitation of unfunctionalized ZGO, (f) PEGylated ZGO in healthy mice, (g) PEGylated ZGO in tumor bearing mice. [28]

This new PLNPs composition opened the way to new researches.<sup>121</sup> Before ZGO is published (< 2014), very few articles were reported in the literature using PLNPs. However after ZGO is published (> 2014), the interest of the community for PLNPs applications in biology changed drastically. For

example, some research groups changed the synthetic procedure in order to get smaller ZGO PLNPs, initial work having been done with 80 nm nanoparticles. Indeed in 2015 the first synthesis of small ZGO ( $< 10$  nm) was reported.<sup>122</sup> The authors have used a biphasic approach with toluene and water to control the size of ZGO NPs. The same year, Teston *et al.* proposed another approach to synthesis ultra-small  $\text{ZnGa}_2\text{O}_4:\text{Cr}^{3+}$  with a diameter close to 6 nm based on the dissolution of precursors in benzylalcohol followed by microwave irradiation,<sup>123</sup> offering a reduction of time (30 min) compared to traditional autoclave conditions (24 hours).<sup>28</sup> This procedure does not require high-temperature heating, allowing the control of the growth of the crystal. The authors showed that these very small particles could be detected *in vivo* (Fig. 6). Han and co-workers proposed a third strategy to get small water-dispersable ZGO NPs, based on the use of a hydrothermal treatment at 220°C with a molar ratio of Zn/Ga of 2/2.<sup>124</sup>

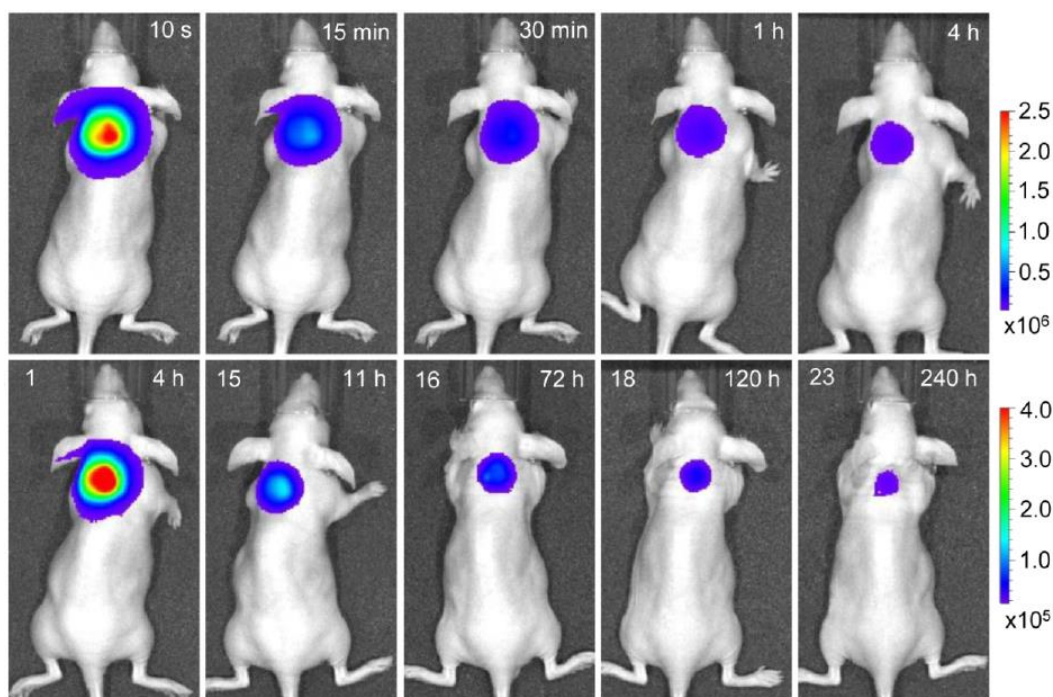


**Fig. 6.** Ultrasmall PLNPs. (a) Characterisation by TEM. (b) *In vivo* imaging application [127]

In 2018, Ai *et al.*, from Department of Hepatobiliary Surgery in Zhujiang Hospital (Guangzhou, China), reported the use of small ( $\sim 10$  nm) ZGO nanoparticles in luminescence guided surgery. In their work, the authors used light emitted by ZGO nanoparticles captured in the liver to help surgeon to remove hepatocellular carcinoma (HCC).<sup>125</sup> Other authors changed the composition of PLNPs or used other physical stimuli such as photostimulation, X-rays, NIR to perform *in vivo* imaging. This will be highlighted in the following.

### 3.2.2 Photostimulation

*In vivo*, PLNPs often use thermoluminescence, i.e. the temperature of the animal body to release the trapped charges in order to lead to light emission. In 2013, a group synthesized PLNPs able to be detrapped by using low energy light. This process called photostimulating persistent luminescence (PSPL, Fig. 3, step 2) is another possible physical stimulus. For that purpose,  $\text{LiGa}_5\text{O}_8:\text{Cr}^{3+}$  was prepared and used for cell labelling and tracking *in vivo*.<sup>29,126</sup> To favor their internalization into cells,  $\text{LiGa}_5\text{O}_8:\text{Cr}^{3+}$  nanoparticles were coated with polyethylene imine (PEI), a cationic polymer,<sup>127,128</sup> and labelled cells were excited *ex vivo* with UV light and injected into mice. Their localization *in vivo* was followed over the time without (Fig. 7, top) or with photostimulation (Fig. 7, bottom).

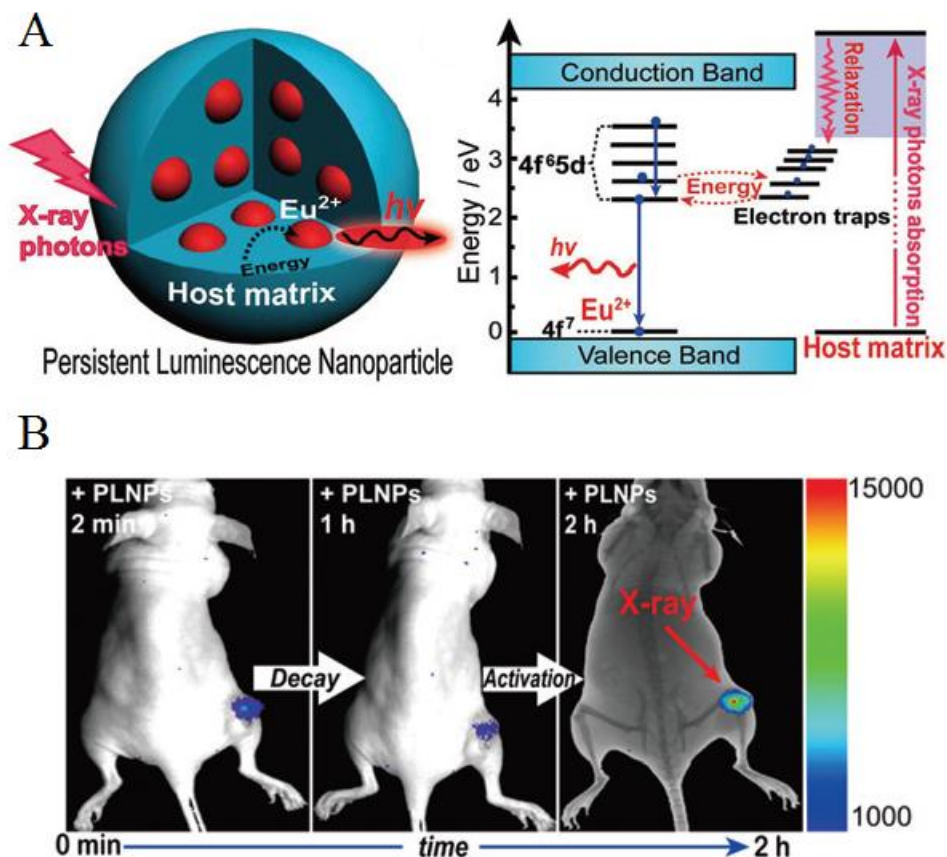


**Fig. 7.** *In vivo* imaging using photostimulated  $\text{LiGa}_5\text{O}_8:\text{Cr}$  PLNPs in order to track labeled cells *in vivo* at different time after injection [131].

### 3.2.3 X-rays excitation

As discussed in section 2, a limit of visible light to excite NPs is its low penetration into tissues. So it is very important to develop probes and excitation sources able to exceed this limit. Among the different possible excitation sources, we can mention X-rays.<sup>129</sup> X-rays are one possible physical stimulus able to excite luminescent centers and also host matrix (Fig. 2 and Fig. 8A) in order to produce light. Compared to classical methods of excitation (UV/visible/NIR), X-rays have the advantages of weaker diffusion and higher penetration in tissues. Moreover easier reconstruction occurs for tomography,<sup>130</sup> and more precise localization of the probe in the animal happens (Fig. 8B). As a proof of concept, Xue *et al.* used  $\text{ZnGa}_2\text{O}_4:\text{Cr}^{3+}$  NPs and evaluated the efficacy of low excitation X-rays source to excite ZGO *in vivo* (Fig. 8).<sup>30</sup>





**Fig. 8.** (a) Principle of *in vivo* imaging using X-rays excitation. (b) Application *in vivo*. [30]

### 3.2.4 NIR excitation

Another strategy to effectively excite the probe *in vivo*, as presented in physical section 2 (Fig. 3) is to get PLNPs with both excitation and emission bands localized in the biological window. Hao and co-workers recently used this strategy in order to propose another stimulation strategy using upconversion PLNPs (named UC-PLNPs) by using  $\text{Zn}_3\text{Ga}_2\text{GeO}_8:\text{Cr}^{3+}, \text{Yb}^{3+}, \text{Er}^{3+}$  NPs. The presence of  $\text{Yb}^{3+}$  into the nanomaterial allows doing excitation at 980 nm. This wavelength excite  $\text{Yb}^{3+}$  which then transferred its energy to  $\text{Er}^{3+}$  and which is finally stored into the traps.<sup>131</sup> In 2018, Chang and co-workers used the same idea with another matrix, made of  $\text{Zn}_2\text{SiO}_4:\text{Mn}$  doped with  $\text{Y}^{3+}, \text{Yb}^{3+}, \text{Tm}^{3+}$ . Here again  $\text{Yb}^{3+}$  can be excited by a laser at 980 nm and can transfer its energy to  $\text{Tm}^{3+}$  before being stored into electron traps. The authors have used such UC-PLNPs to label macrophages *ex vivo* in order to target and image tumor *in vivo*.<sup>132</sup> This strategy can be of particular interest in cell-based therapy applications.

### 3.3 Multimodal imaging nanoprobles

Multimodal imaging is a relatively new strategy used in bioimaging in order to provide more accurate information.<sup>133,134</sup> Insofar as each imaging modality has advantages and disadvantages in terms of sensitivity, resolution,<sup>135</sup> the concept of multimodal imaging is to combine into the same imaging tool

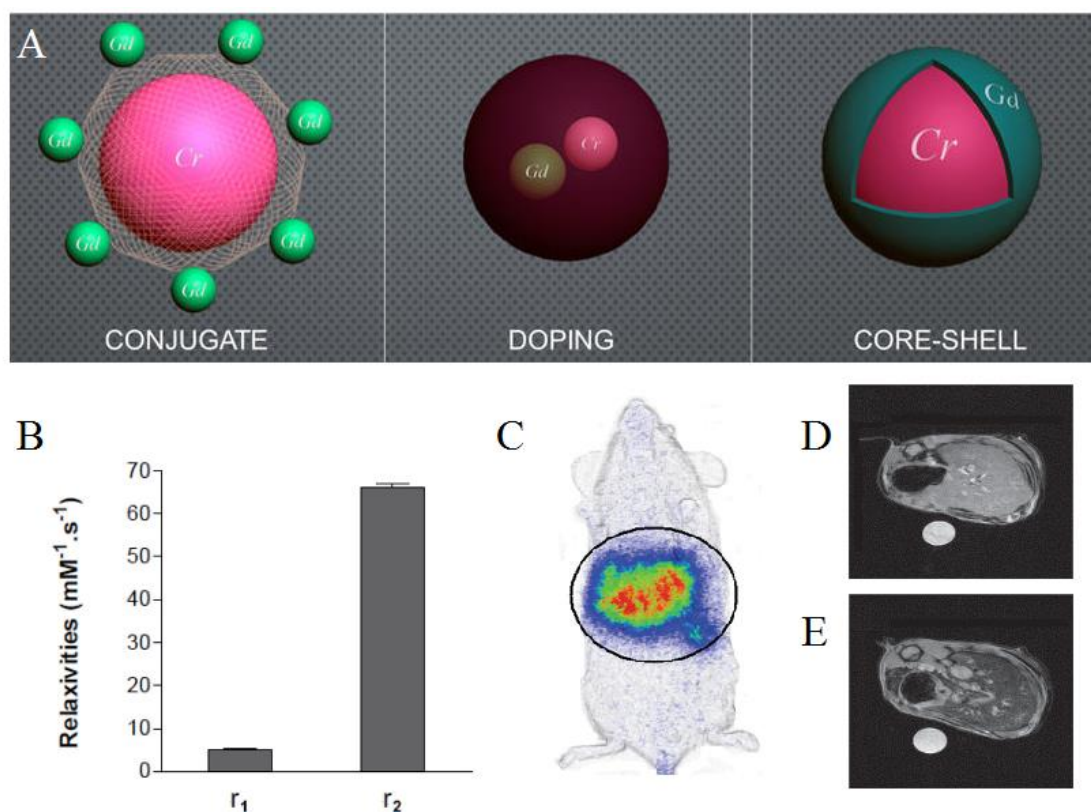
different modalities that are complementary, for example optical imaging with MRI in order to benefit from each. For that purpose, different alternatives have been reported.

### 3.3.1 Gd containing PLNPs

Gadolinium is an MRI contrast agent largely used in clinic. Several strategies have been reported using this cation to have access to bimodal imaging PLNPs (Fig. 9). In 2014, Yan et al. introduced DTPA/Gd complexes on the surface of  $\text{Zn}_{1.1}\text{Ga}_{1.8}\text{Ge}_{0.1}\text{O}_4$  NPs in order to get a bimodal imaging agent, that could be detected by optical imaging (thanks to the PLNPs) and by MRI (thanks to  $\text{Gd}^{3+}$ ) (Fig. 9A, left).<sup>136</sup>

In 2015, other authors reported another strategy to also have a bimodal imaging agent. In that case, the authors incorporated various amount of  $\text{Gd}^{3+}$  ions at the beginning of the synthesis, in order to substitute some  $\text{Ga}^{3+}$  ions of the matrix by  $\text{Gd}^{3+}$  ions (Fig. 9A, middle).<sup>35</sup> In such conditions, contrary to the previous strategy, the surface of the NPs remains accessible for further functionalization. The authors have shown that such nanoprobe could be easily detected by optical imaging (Fig. 9C) and by MRI giving a negative contrast into the liver (Fig. 9B, D-E).

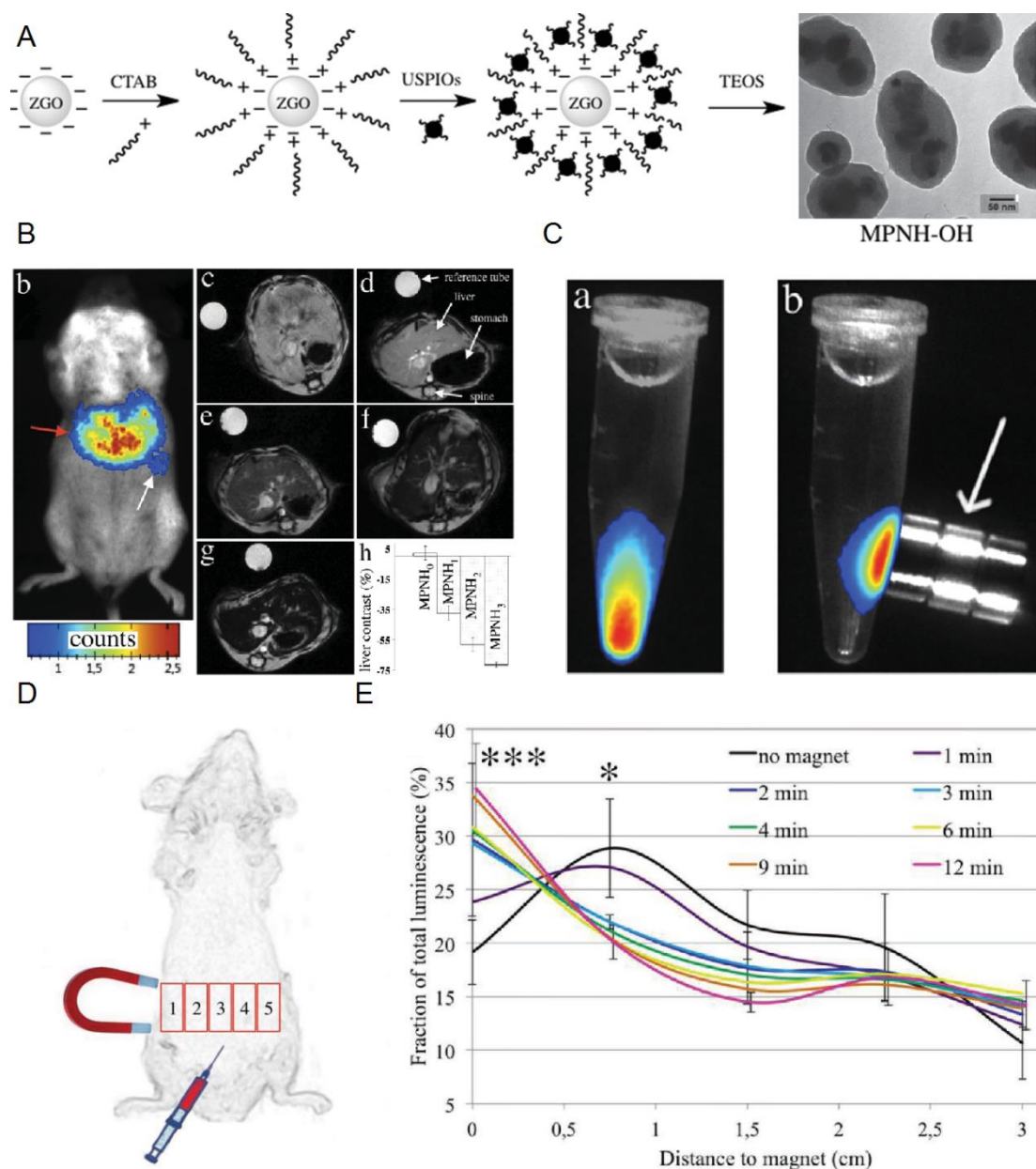
In 2017, a third strategy was proposed based on the use of ZGO doped with  $\text{Cr}^{3+}$  and  $\text{Sn}^{4+}$  incorporated into silica (ZGOCS@MSNs) and the all wrapped by a shell of  $\text{Gd}_2\text{O}_3$  (Fig. 9A, right)<sup>39</sup>. In that case, contrary to the previous strategy, a positive contrast was obtained after capture by the liver.



**Fig. 9.** (a) Strategies to prepare  $\text{Gd}^{3+}$  containing PLNPs. (b-e) Examples of *in vivo* bimodal imaging applications. [35, 39, 142]

## 3.3.2 Iron oxide/PLNPs nanohybrids

In addition to gadolinium, ultrasmall iron oxide nanoparticles (USPIO) are also used in clinic as negative ( $T_2$ ) MRI contrast agents. In 2015, Teston *et al* synthesized the first mesoporous nanohybrids (MPNHs) made of PLNPs and USPIOs incorporated into mesoporous silica to get a bimodal imaging agent (Fig. 10).<sup>37</sup> In addition to its efficiency as a bimodal imaging probe (Fig. 10B), the authors observed that these nanohybrids could be attracted by a magnet (Fig. 10C). They have later used this property to label cells and have demonstrated that such labeled cells could be attracted *in vivo* using a magnet (Fig. 10D-E).<sup>38</sup> This result opens alternative approaches in cells based therapy trials.



**Fig. 10.** Nanohybrids (MPNHs) made from iron oxide NPs and PLNPs. (a-c) Synthesis and characteristics. (d-e) Cell labelling and *in vivo* magnetic targeting. [37, 38]

This section has highlighted some of the main applications of PLNPs, reported since 2007, using different physical stimuli (UV, visible, NIR, X-rays) in bioimaging. More recently such NPs have also shown interest in therapy. This approach will be presented in the following section.

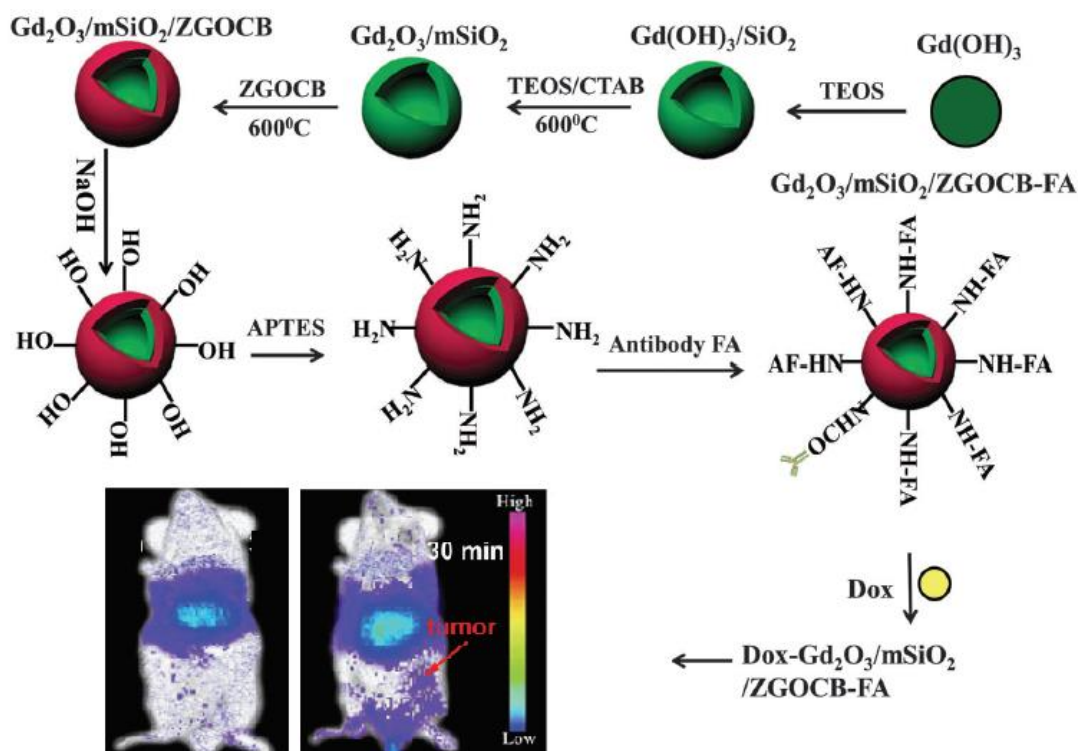
#### 4. Nanotheranostics

With the development of nanomedicine, the conception of nanoparticles able to be used not only for imaging as presented in section 3, but also as a therapeutic agent has emerged, by incorporating into the same nanosystem both imaging and therapeutic property. Such hybrids are called nanotheranostics.<sup>137</sup> To be used *in vivo*, such nanomaterials should have several advantages:<sup>138</sup> (i) preferential accumulation of the nanotheranostics in the organ to be imaged/treated, (ii) ability to deliver the therapeutic agent at the action site, and (iii) the nanotheranostics must be as safe as possible. This approach is actually under investigation for the treatment of several diseases.<sup>139,140,141,142</sup> In this section, we will highlight the emerging applications of persistent luminescence for the development of new nanotheranostics using as before different physical stimuli (X-rays, LED, NIR) to detect and follow the distribution and efficacy of therapeutic agents.

##### 4.1 DOX loaded nanotheranostics

Because of its biocompatibility, mesoporous silica (mSiO<sub>2</sub>) which consists of silica nanoparticles containing a large number of pores in its structure is often used as a carrier in order to deliver drugs.<sup>143</sup> But a limit of this approach is the inability to monitor the biodistribution of mesoporous silica because it is undetectable by any imaging method. In 2014, Maldiney *et al.* proposed a solution based on the use of persistent luminescence as a powerful property to follow *in vivo* the biodistribution of mSiO<sub>2</sub> loaded with doxorubicin (DOX).<sup>144</sup> *In vitro*, the authors have shown that such nanotheranostics can be used on cancer cells in order to induce a cytotoxic effect, contrary to the non-loaded system. *In vivo*, the presence of DOX has a little effect on the luminescence of the nanoprobles.<sup>108</sup>

In 2016, Zhang and co-workers developed a variant of the previous system in which mesoporous silica can be made not only with PLNPs (ZGO) as before but also with an MRI contrast agent (Gd<sub>2</sub>O<sub>3</sub>) (Fig. 11).<sup>145</sup> This nanotheranostic was loaded with DOX in order to monitor its biodistribution in healthy and in tumor bearing mice (Fig. 11, bottom left).



**Fig. 11.** Synthesis of mesoporous  $Gd_2O_3/ZGO$  nanostructure, loading with DOX and example of *in vivo* application. [155]

#### 4.2 Photodynamic therapy with PLNPs

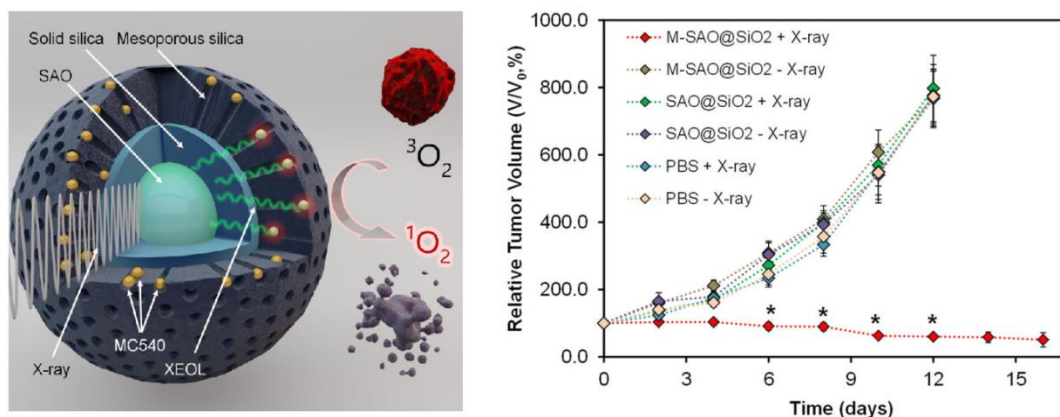
Photodynamic therapy (PDT) is a technique used for the treatment of certain cancers, such as skin cancers.<sup>146</sup> It is based on the use of a photosensitizer (PS), which most of the time is a polyaromatic organometallic complex such as porphyrins, phthalocyanines, able to be excited by light. Among the different PS, Porfimer has been approved by the United States Food and Drug Administration (FDA).<sup>147</sup> In the dark such molecules are not toxic, but upon excitation, the photosensitizer absorbs light and transfer part of this energy to surrounding oxygen molecules generating reactive oxygen species (ROS) such as  $^1O_2$  or  $O_2^-$ . When produced into cells, these highly instable species react rapidly with surrounding molecules such as unsaturated lipids or DNA resulting in cell death.<sup>148,149</sup> However a limit of this technique is the difficulty to excite the PS in deep tissues.<sup>150</sup> Several strategies have been proposed to solve this problem, such as the use of endoscopic technologies allowing illuminating internal cavities, such as bladder, prostate, and esophagus.<sup>151</sup> Other strategies are based on the use of high-dose of X-rays.<sup>152</sup> But such irradiations can cause damage to healthy tissues.<sup>153</sup>

As discussed in section 2 and 3, persistent luminescence is an innovative phenomenon in which the excitation energy can be stored and then used over very long period of time. PLNPs alone have limited impact on cancer cells.<sup>154</sup> The following paragraph will show how it is possible to use PLNPs in PDT.

##### 4.2.1 X-rays excitable nanotheranostics

In 2015, Xie and co-workers have designed a nanosystem composed of PLNPs made of  $SrAl_2O_4:Eu^{2+}$  (SAO) and a photosensitizer (MW540) incorporated into mesoporous silica.<sup>155</sup> The authors have

shown that such a nanosystem is able to absorb X-ray photons in order to excite SAO NPs and the visible photons emitted by the PLNPs are able to activate photosensitizers (MW540) present into the nanosystem in order to produce ROS. In this work, the authors have shown that such nanosystem can efficiency reduce the tumor growth, compared to X-rays treatment alone or PLNPs alone (Fig. 12).



**Fig. 12.** Nanosystem made of PLNPs (SAO) and a PS agent (MC540) incorporated into mesoporous silica. [165]

In 2018, Yang and co-workers have used another strategy to develop X-ray excitable PDT/PLNPs. They have shown that another photosensitizer (PS) such as Zn (II) phthalocyanine tetrasulfonic acid (ZnPcS4) can be covalently linked to ZGO PLNPs to fabricate PDT nanosystem (ZGO:Cr/ZnPcS4). When the X-ray irradiation is stopped, the persistent luminescence light emitted by ZGO is able to excite in continuously the PS allowing reducing the dose of X-ray and in plus minimizing the side effects of X-ray treatments.<sup>156</sup>

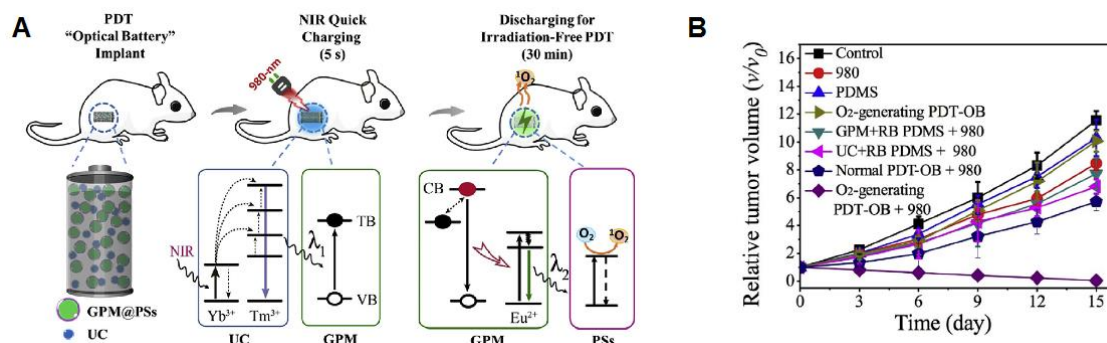
#### 4.2.2 LED excitable nanotheranostics

In 2018, Zhang and co-workers developed another strategy for tumor imaging and photodynamic therapy based on the use of LED as an alternative physical stimulus.<sup>157</sup> To be able to load therapeutic molecules, they used carbon spheres as a template to absorb the different cations precursors of luminescence on the surface of carbon spheres. After calcination at about 800°C the carbon spheres are degraded allowing forming porous PLNPs. This porous material was used to load a PS made of silicon porphyrin (Si-Pc). Excitation at 650 nm allows the transfer of the persistent luminescent signal to Si-Pc. Such phenomenon was used *in vivo* and its efficacy was evaluated on tumor bearing mice and compared to non-treated mice.<sup>167</sup>

#### 4.2.3 NIR excitable nanotheranostics

Zhang *et al.* used another strategy based on UC-PLNPs loaded with photosensitizers to generate ROS. For that purpose, the authors prepared a nanohybrid made of UC-PLNPs composed of NaYF<sub>4</sub> doped with 25% of Yb<sup>3+</sup>, and 0.5% of Tm<sup>3+</sup>, a persistent luminescence material made of SrAl<sub>2</sub>O<sub>4</sub>:Eu<sup>2+</sup>,Dy<sup>3+</sup> (SAO), and a photosensitizer made of rose Bengal, the whole incorporated into a biocompatible polymer made of polydimethylsiloxane (PDMS).<sup>158</sup> In such system, NIR light (980 nm laser) can be used as a physical stimulus to excite UC-PLNPs (Fig. 13 A). The blue light emitted by

UC-PLNPs is used to excite SAO which in turn emits green light able to excite the PS (rose Bengal). The main advantage of this process is that ROS can be produced for about 30 min without constant irradiation (Fig. 13). Thanks to the good tissue penetration of NIR laser, generation of singlet oxygen in deep tissue ( $\sim 4$  mm) is possible. The efficacy of such nanohybrid for the inhibition of tumor proliferation was evaluated on subcutaneous 4T1 tumor bearing mice (Fig. 13B).



**Fig. 13.** Optical battery made of GPM, UC and PS activated by NIR light. [168]

### 4.3 Photothermal therapy

Another strategy developed in recent years for the treatment of cancers is the conversion of light radiations to generate heat to destroy cancer cells. This technique is called PTT for photothermal therapy.<sup>159</sup> For that purpose, a molecule able to convert light excitation into heat (ideally beyond  $42^{\circ}\text{C}$ ) in order to kill cancer cells is used. Among the FDA-approved molecules for PTT, indocyanine green (ICG) is often used in hyperthermia since it can absorb near-infrared light to produce heat where it is present.<sup>160</sup> To improve the local delivery of ICG in order to enhance its efficacy *in vivo*, different nanosystems are under development.<sup>161,162</sup> Among the emerging strategy, the use of persistent luminescence to extend the *in vivo* production of heat is considered.

#### 4.3.1 PTT induced by LED excitation

In 2017, Chang and co-workers developed a nanosystem based on ZGO NPs and ICG incorporated into mesoporous silica (Fig. 14A).<sup>163</sup> In such system, ZGO is both used to visualize the nanosystem *in vivo* after injection and also to excite ICG. Indeed the persistent luminescence signal emitted between 680 to 730 nm by ZGO after excitation can be absorb by ICG which in return will produce heat at the site of action (Fig. 14B). Using such nanosystem, the authors have shown that after irradiation, they were able to increase the local temperature in order to kill cancer cells. The authors have shown that such nanosystem is much more efficient than when using the irradiation source alone or with ICG (Fig. 14C).

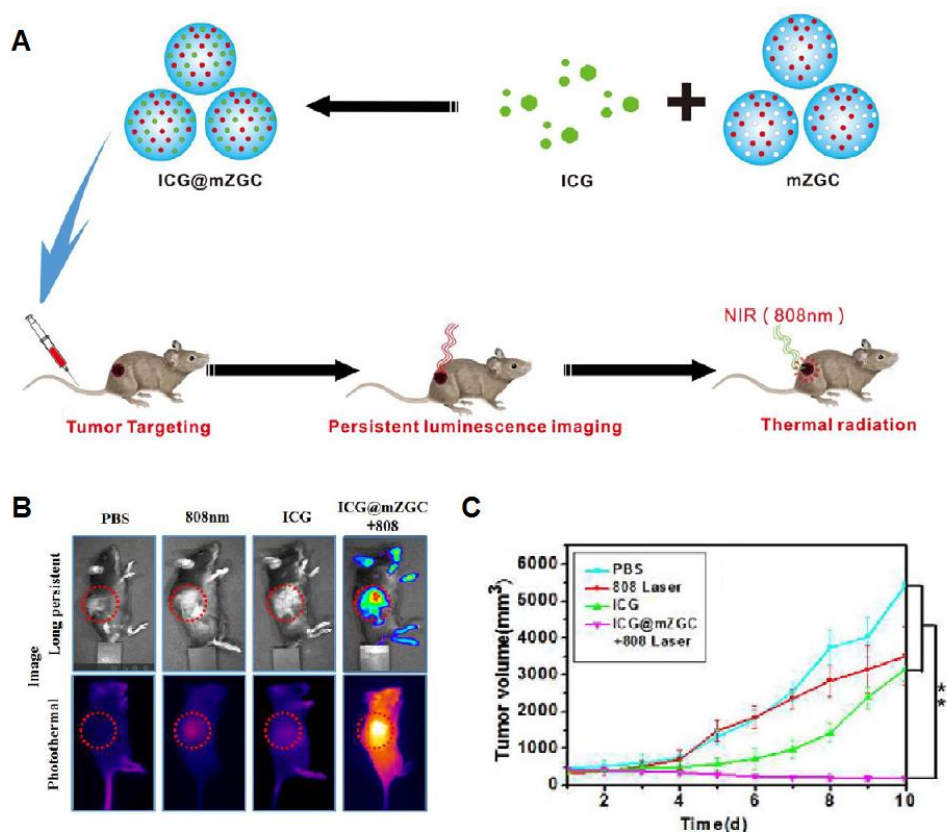


Fig. 14. PTT induced by using ICG loaded in PLNPs. [173]

#### 4.3.2 PTT induced by NIR excitation

Finally, Cao and co-workers developed an alternative strategy to favor heat production in deeper tissues based on the use of upconverting PLNPs.<sup>61</sup> For this purpose, the UC-PLNPs were doped with  $\text{Er}^{3+}$  and  $\text{Tm}^{3+}$  in order to allow excitation at 980 nm. The photons emitted by UC-PLNPs at about 650 nm can be then absorbed by ICG to produce heat. Using thus nanosystem, the authors have shown that the local temperature measured by an external thermal camera can be increased (Fig. 15, bottom), and this was successfully used to control the tumor growth *in vivo*.



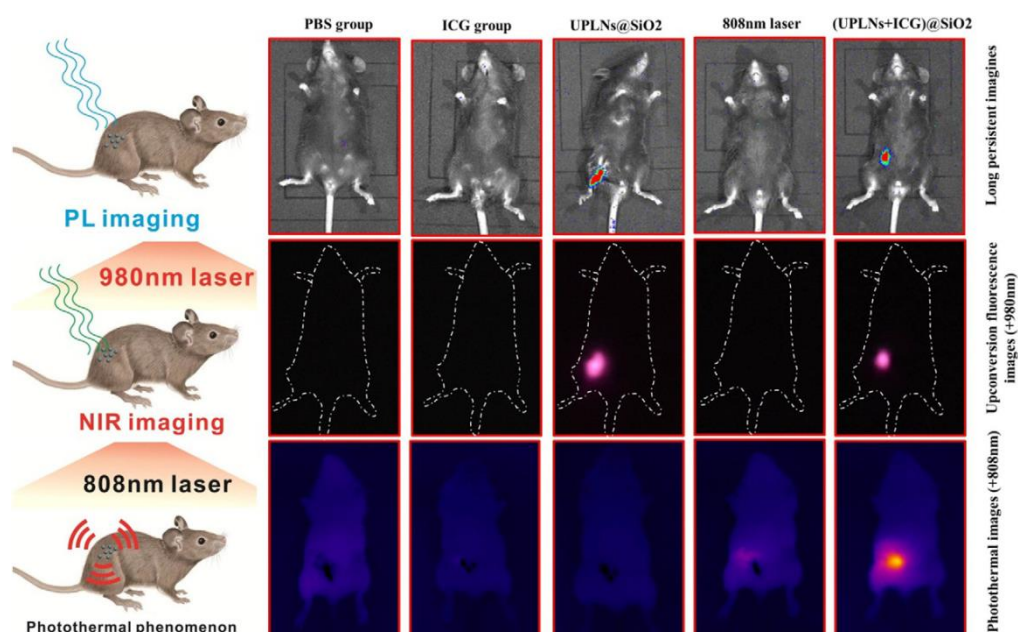


Fig. 15. PTT induced by NIR excitable PLNPs. [61]

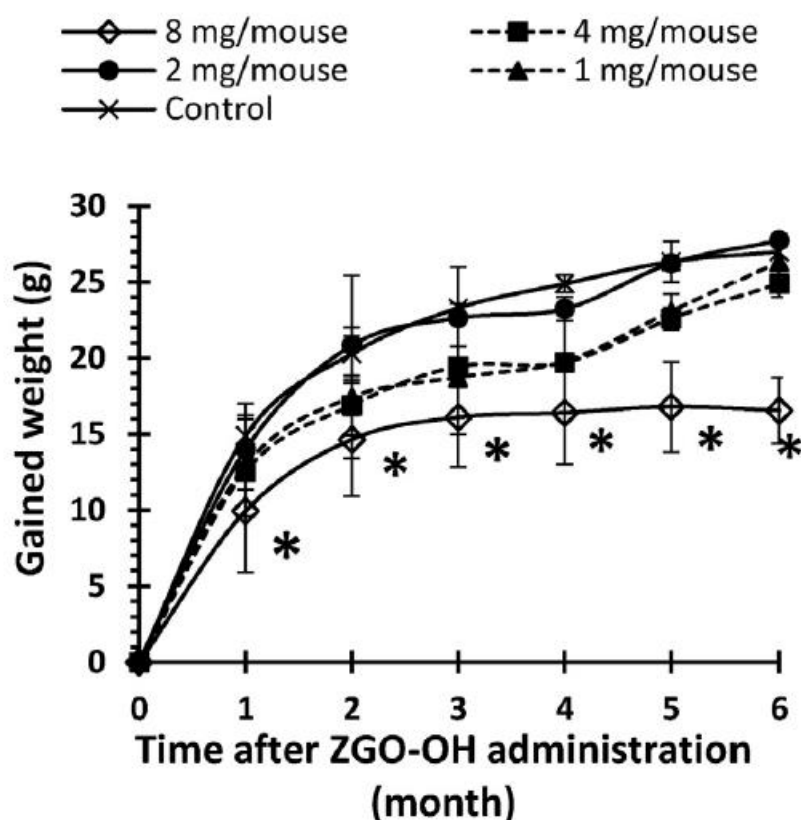
## 5. Biocompatibility of PLNPs

To be used *in vivo*, all these potent nanosystems should be highly biocompatible. In general, good biocompatibility is obtained when a nanomaterial interacts with the body without inducing toxicity.<sup>164</sup> Once injected into the blood stream, the physico-chemical properties of nanoparticles, known as their “synthetic identity” will change a lot, mainly due to interactions with biomolecules such as lipids, sugars and proteins.<sup>165</sup> This forms a corona around the surface of nanoparticles, known as the “biological identity”.<sup>176</sup> Such identity is what the biological system sees, and it also determines the distribution, metabolism, excretion, and toxicity of the nanomaterials. Different parameters such as the nanoparticle size and the coating greatly affect the biodistribution.<sup>166</sup> Nanoparticle with size < 6 nm (hydrodynamic diameter) are able to pass through the pores of the glomerulus in the kidneys and cleared by renal filtration. On the contrary, nanoparticles > 6 nm (hydrodynamic diameter) will stay in the body and be sequestered by the reticulo-endothelial system (RES) and macrophages present in the liver, spleen and lungs.<sup>167</sup> In liver, nanoparticles can be captured either in Kupffer cells, which are liver resident macrophages or in hepatocytes. In the last case the nanoparticles will be cleared by the hepatobiliary system. This could be realized in hours to weeks.<sup>168</sup> On the contrary, if the nanoparticles are captured in Kupffer cells, they could stay for months to years.<sup>169</sup> In order to reduce the adsorption of serum proteins on the nanoparticles to avoid captured of nanoparticles by hepatic tissue, efforts are employed to delay or reduce their phagocytosis. Different strategies to coat the surface of NPs by molecules or polymers have been developed.<sup>170171</sup> Many studies have demonstrated that the PEG-functionalized NPs adsorb fewer proteins and are less ingested by cells.<sup>172</sup> Precoating NPs with proteins or the formation of a protein corona on their surface could shield NPs from binding with membrane proteins and therefore reduce cellular uptake of NPs.<sup>173</sup> Thereby, biocompatibility is an important prerequisite for nanoparticles being used *in vivo*.

The main matrixes presented above are either zinc gallium oxide ZGO NPs, or derivatives, incorporated into mesoporous silica. The toxicity of mesoporous silica is well known since this material is used since more than a decade.

The biocompatibility of mesoporous silica has been highly investigated.<sup>174,175</sup> For example it has been shown that no abnormality could be observed in various tissues such as heart, liver, spleen, lung and kidney after intravenous injection into mice. This suggests that the mesoporous silica has not significant tissue toxicity. The same conclusion was obtained by Zink and Tamanoi after intraperitoneal injection.<sup>176</sup> Even after high dose injection (50 mg.kg<sup>-1</sup>/day), the acute toxicity of this material was negligible. It's only at very high dose (> 1000 mg.kg<sup>-1</sup>) that this material was toxic either after intravenous or intraperitoneal injection.<sup>177</sup>

Concerning persistent luminescence nanoparticles by themselves, one article has been published by Ramirez-Garcia *et al.* concerning the biocompatibility and toxicity of ZGO *in vivo*. Indeed, this information is of great importance for future applications of such nanomaterials. In their study, mice were injected once with increasing amounts of ZGO (from 1 and 8 mg of ZGO per mice). The effect was analyzed in the short term (24 hours), middle term (30 days) and longer term (6 months) after injection. As could be seen in Fig. 16, only elevated amount of ZGO (8 mg/mouse), which is about 5 times higher than the amount classically used for *in vivo* imaging, causes a significant variation of weight of animals.



**Fig. 16.** Influence of injected dose of ZGO-OH on mice body weight over a 6 months period [32].

In addition to that, a set of factors were measured such as oxidative stress, and the hematic biometry.<sup>32</sup> The authors observed that only high concentrations of nanoparticles with hydroxyl groups on their surface (ZGO-OH) generate oxidative stress in liver, as well as increase the number of white blood cells 24h after injection. No toxicological effects were observed with PEGylated ZGO showing the protective effect of such hydrophilic polymer. It would be also interesting to evaluate the genotoxic

effect of PLNPs. More investigations are also required to evaluate the biotransformation of such nanoprobes over the time.

## 6. Conclusions and perspectives

In a decade, persistent luminescence has emerged as a useful property for the design of new optical imaging nanoprobes. Thanks to the long lasting luminescence, from few minutes to several hours after the end of excitation, imaging in the first transparency window (BW-I) with high sensitivity was reported by several research groups. Nowadays, more than 40 research groups all over the world use this strategy to develop optical nanoprobes and more than 200 papers have been published.

Beyond to their uses for imaging, and more recently for therapy, new applications based on this technology are emerging. The first one concerns their interest for the development of sensitive *in vitro* biosensors for the detection of small amount of analytes.<sup>178,179</sup> As a second example, we can cite the emerging use of persistent luminescence for the development of nanothermometers, for which the idea is to link the luminescence (intensity, decay profile) emitted by the nanoprobes to temperature variations *in vivo* at the nanoscale (thermoluminescence). The decay profiles in persistent phosphors strongly depend on the temperature as the traps released are temperature dependent. In that case, the time scale can be in the order of the seconds rather than microseconds/milliseconds for the usual lifetime decays measurements. This allows the emission to be recorded with quite simple optical devices. Indeed temperature measurement is an important parameter to control in hyperthermia (as presented in section 4), since this precision nanomedicine method used to kill malignant cells by thermal ablation has received European regulatory approval for tumours' treatment.<sup>180,181,182,183,184</sup> Actually the temperature is only measured on the surface of the body using a NIR-camera, which doesn't allow to access the *in situ* local temperature.

Future works on persistent luminescence concern the development of new probes compositions and also new detectors able to be used in the second biological window (NIR –II, > 1000 nm). Indeed, optical imaging in this biological window (BW-II, BW-III, from 1.0 to 1.7  $\mu\text{m}$ ) has showed significant attention. Indeed a limit of imaging in BW-I is the scattering of light. On the contrary, beyond 1000 nm, photons can provide high spatial resolution, deeper tissue penetration and reduced scattering.<sup>185,186,187</sup> Furthermore, imaging in this region addresses several challenges: minimal autofluorescence of biological tissue leading to increased sensitivity.<sup>188</sup> In such conditions, a whole mouse can be rendered translucent.<sup>189,190</sup> But for that purpose, probes with new compositions must be developed. Recently, Qiu and co-workers reported a strategy for moving the emission of persistent phosphors at around 1270 to 1430 nm by synthesizing  $\text{Ni}^{2+}$  doped  $\text{Zn}_{1+y}\text{Sn}_y\text{Ga}_{2-x-2y}\text{O}_4$ .<sup>191</sup> In the same idea, Ueda,<sup>192</sup> Tanabe<sup>193</sup> and our groups recently reported new compositions able to be used in the second transparency window.<sup>194</sup> Biological applications of persistent luminescence are probably just beginning. Other applications of luminescent materials have also been reported in other area, such as in light emitting diodes (LEDs).<sup>195,196</sup>

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