Deliverable 7.10

# D7.10 Update to the exploitation plan: iteration 1

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NEUROPULS

Neuromorphic energy-efficient secure accelerators

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# Document Abstract

This report presents the first update of Exploitation Plan of the NEUROPULS Horizon Europe project (Grant Agreement n° 101070238).

This deliverable is part of WP7, which is the main interface between the project and the outside world, academics, and industrials playing a role in the value network underpinning scientific breakthroughs in the photonic neuromorphic computing area, linked to the main drivers of AI and Edge computing.

Towards this goal, Exploitation activities aim to define the Key Exploitable Results of the project, and plan the actions and measures to execute the corresponding exploitation routes.

First focus will concern Indirect routes, via IP generation, open access to the research data, and use of results for further research activity for a wider knowledge dissemination and building a common European scientific and technological area.

Second focus will be to set the foundations for potential commercial exploitation and opportunities with the identified stakeholders. In spite of low TRL of NEUROPULS technology building blocks (2 and 3), this deliverable, during its lifecycle (4 years) will leverage the strong engagement of industrial partners, and academic stakeholders of international visibility, to convert generated knowledge and technology demonstrations into products or services.

In this first version, we propose to explain the technical background (Section 1), before outlining the methodology employed for setting up the exploitation routes for both academics and industrials (Section 2). A specific focus will be done, in Section 4 on the business cases led by the industrials: technology positioning and competitive advantage that will prompt us to fill initial lean business canvas, building the foundations for potential commercial exploitation and opportunities. Because one of the strongest hypotheses of exploitation is based on strong R&D signals in the field of photonic neuromorphic architectures, we will address a bibliometric study in the Section 5, to layout the research landscape. This will be complemented by some initial elements from market projections, and involvement of the industrials in filing patents and publications. Moreover, this landscape would guide the consortium in new partnerships and collaborations expanding the exploitation routes and increasing the NEUROPULS impact.

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# 1. Introduction

## 1.1 The project

Optical communications have been the backbone of the world's digitalization for several decades. The complex nature of transceiver PICs (Photonic Integrated Circuits) was, in the past, the main driver for technological advances in the whole Integrated Photonics value chain. However, emerging markets for Integrated Photonics may have completely different requirements and are not optimally served by the existing technologies and solutions.

Along with the rapid developments in communication technologies and the surge in the use of IoT devices, a brand-new computation paradigm, Edge Computing, has surged in popularity. Meanwhile, Artificial Intelligence (AI) applications are thriving with the breakthroughs in deep learning and are substantially increasing the volumes of data generated both in the cloud and at the edge. New constraints are strongly emerging in terms of algorithms optimization and HW architectures: energy efficiency, latency, data security and data rate.

Thus, the NEUROPULS project will provide a proof of the concept of disruptive performances achieved on a low-power and secure RISC-V interfaced neuromorphic accelerator, paving the way for new advances in the field of this new computing paradigm.

The consortium is formed by 14 partners:

- 3 RTO: CEA, CNRS, BARCELONA SUPERCOMPUTING CENTER-CENTRO NACIONAL DE SUPERCOMPUTACION (BSC)
- 3 Industrials: HPE, ALBORA Tech, ARGOTECH
- 8 academics

## 1.2 Objectives

Exploitation activities are implemented within WP7 "Dissemination and exploitation activities", led by HPE. Main purpose is to define the Key Exploitable Results of the project, and plan the actions and measures to execute the corresponding Exploitation Routes. This will ensure scientific, social and economic impacts based on the results. The Exploitation framework will operate during the project duration (48 months), involving all the partners, and considering the low TRL of the technology building blocks and generated risk factors.

In this first version, we will be targeting the main following objectives:

- Understand the Unique Value proposal of NEUROPULS via its technological positioning, which constitutes the main hypothesis for a viable Exploitation plan

- Outline the individual exploitation routes, based on the contributions of the identified partners, industrials, and academics, in the light of their advantages in terms of positioning, resources and local/international impact
- Highlight the relevancy of NEUROPULS to the identified business cases, with respect to existing technological solutions. This constitutes a strong hypothesis for further commercial exploitation
- Set up initial Lean business Canvas for the industrial partners, as a first methodological foundation for a commercial exploitation
- Assess the R&I worldwide landscape around photonic neuromorphic computing, to better anticipate the market penetration, and scout for potential future competitors or partners

# 2. Technical Background: Development of hardware for AI

The objective of this section is to highlight how NEUROPULS is positioned in the technological roadmap of hardware development for AI, driven essentially by the boom of edge computing and IoT.

Considering the neuromorphic architecture, which is in the core of this project, we will demonstrate how photonics' approach is providing key advantages in term of energy efficiency, data rate, and high degree of parallelism for processing. Toward pushing for efficient exploitation of NEUROPULS technology, we will consider a holistic approach taking care of drawing the full photonics' ecosystem attractiveness (advancements in interconnections, main challenges in scalability, packaging, and integration).

## 2.1 Edge computing gaining momentum

AI applications are based on training and inference tasks:

**Training** is the initial phase for an AI model, during which the model learns from data to create a representation that can make accurate predictions or classifications.

**Inference** involves running a trained machine-learning model on new, unlabeled live data to make predictions or classifications

***BEFORE:*** Training of hyperscale models that act as foundations in latent spaces for solving a multitude of downstream tasks have been dominating computation in cloud AI. Prominent examples include Large Language Models (LLMs), text-to-image generation (out-painting) or even generative image composition (in-painting). At inference, these hyperscale models had to run on the cloud, similarly.

Workloads have been pushing the compute and memory requirements to unprecedented scale, along with their data ingestion needs. However, edge devices capabilities have not scaled at the same pace.

***NOW:*** Currently, the surge of IoT devices, with the increase of connectivity, is generating substantial data by widespread and geographically distributed mobile and IoT devices, other than the mega-scale cloud datacenters.

Many more application scenarios, such as intelligent networked vehicles, autonomous driving, smart home, smart city and real-time data processing in public security, will drive a substantial increase in AI edge devices. This number is expected to reach 300 Million units in 2025 and 2.5 Billion units in 2030 (Fig.2).

With inference, AI algorithms handle less data but must generate responses more rapidly. A self-driving car doesn't have time to send images to the cloud for processing once it detects an object in the road, nor do medical applications that evaluate critically ill patients have leeway when interpreting brain scans after a hemorrhage. That makes the edge, the best choice for inference. A new framework for edge inference, is being developed with a new hardware architecture adapted to the splitting/partitioning of the model, and the management of adapted models


***Fig 1: AI, why edge computing***
Source: ABI research, 2021

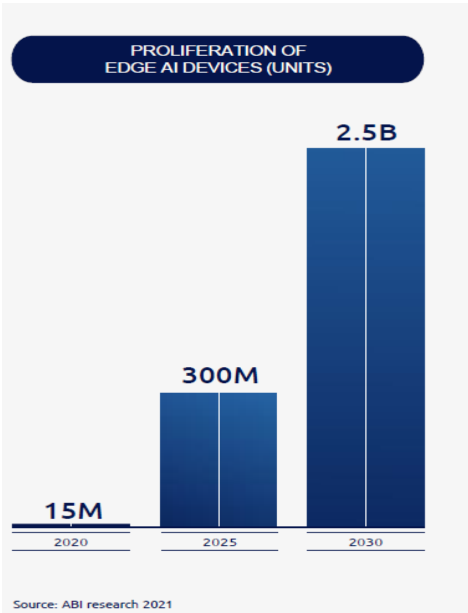



***Fig 2: Proliferation of Edge AI devices***
Source: ABI research, 2021

However, model training in the edge seems to be more challenging, due to 2 conflicting facts:

- AI training models' size in number of parameters has increased exponentially and compute usage in Petaflops/s has strongly increased in recent years, leading to strong requirements in density of memory computing, memory, and bandwidth.

- AI hardware for edge computing has not scaled to these performances, in addition to intrinsic strong constraints, linked to power consumption, reliability and form factor.

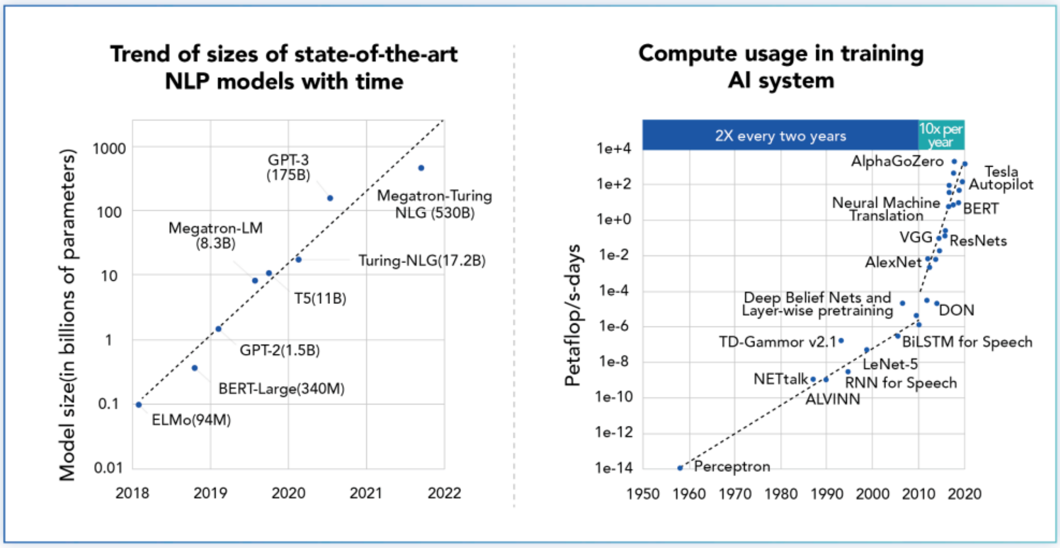



*Fig 3: AI Model size and compute usage in training AI systems*

***FUTURE:*** AI's new area of research is to move toward new approaches for model training, to address the bottleneck arising today in edge computing.

Integrated photonics are one of the main emergent solutions to deal with this requirement:

- First, photonics interconnection technologies can efficiently move data among computing resources, thanks to their ability to directly route light instead of electronic signals, which dramatically reduces latency and power consumption, improving the overall bandwidth at all levels of communication. Therefore, transceivers designs that are used in AI/ML infrastructure are moving from pluggable optics to co-packaged optics (CPO), that co-package the optical engine chip into the switch or accelerator modules. This will potentially answer the bandwidth and energy efficiency challenges. **This field is gaining the most focus and attraction from academia and industry**.

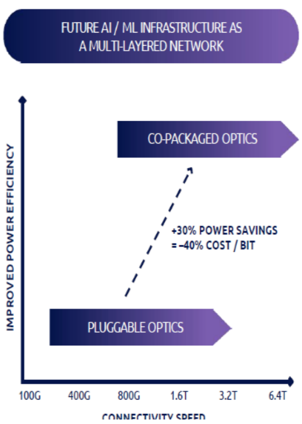



***Fig 4: FUTURE AI / ML infrastructure as a multi-layered network.***
Source: ResearchandMarkets

- A second area, which is still emergent, compare to the first one, is linked to computing architectures. This will

be leveraging new computing paradigms like photonics
for neuromorphic and quantum computing.

These two areas are currently enabling multiple technological innovations in new materials, advanced packaging solutions, new frameworks for design flows and wafer-scale testing solutions. **The photonics' ecosystem is expected to continue growing and strengthening.**

In addition, one major evolution will concern the topology of Edge AI scope. Taking into account the amount of data available on end-user devices, edge servers, and cloud servers, research is also tending to bring AI tasks as close as possible to the user, where data volumes are most massive. **On-device computing will constitute a major evolution in the coming years.**

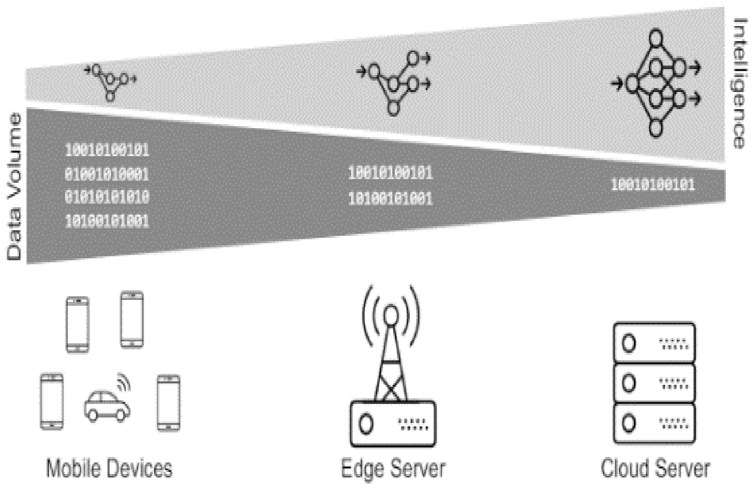



***Fig 5: Scope of Edge AI***
Source: Roadmap for Edge AI, A Dagstuhl Perspective, Delft University of Technology, 2022

# 2.2 Photonic Neuromorphic for AI

## 2.2.1 Neuromorphic architecture to go beyond the "Memory Wall" & Moore's Law

Conventional computer technology is facing two important bottlenecks: the memory wall effect of the "Von Neumann" architecture causes low energy efficiency and Moore's Law, which leads the development of semiconductors, is expected to expire in the next few years.

On one hand, the traditional processor architecture converts the processing of high-dimensional information into a one-dimensional processing of pure time dimension, which has low efficiency and high-energy consumption. This architecture cannot construct appropriate algorithms when processing unstructured information, especially when processing intelligent problems in real time. In addition, the information processing happens using a physically separated CPU and memory. Programs and data are sequentially read from the memory into the CPU for processing, and then sent back to the memory. This process causes a large amount of energy consumption.

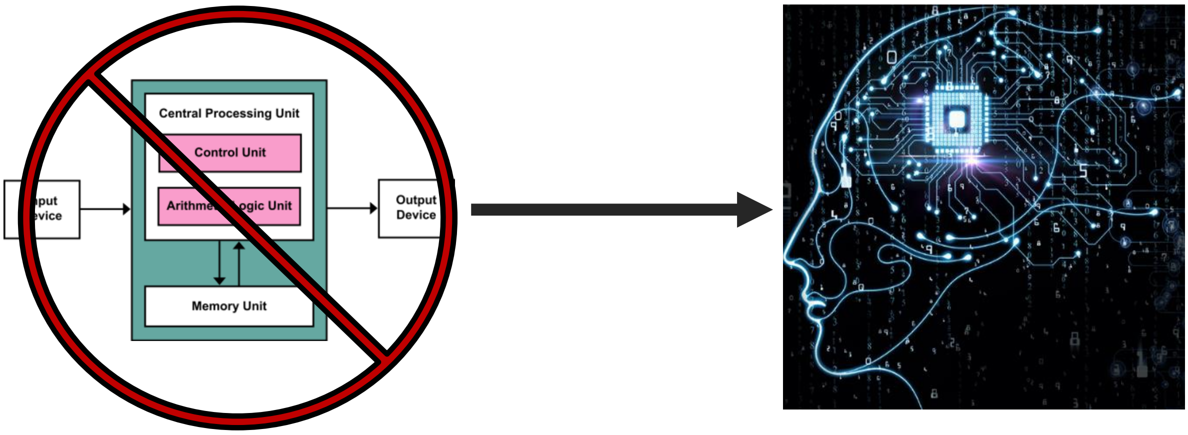



*Fig 6: From "Von Neumann" architecture to Neuromorphic architecture*

Neuromorphic computing, an emerging field of research focuses on developing computational systems inspired by the structural and functional characteristics of the human brain. This discipline strives to overcome the limitations of conventional computing by mimicking the parallelism, fault tolerance, and energy efficiency observed in biological neural networks. At its core, neuromorphic computing aims to create hardware and software architectures that replicate the behavior of neurons and synapses. These architectures enable the processing of information using spiking neural networks and specialized neuromorphic chips, which offer real-time handling of complex data and the potential for accelerated machine learning algorithms (Fig.7). **The primary advantage of neuromorphic computing lies in its ability to process information in a massively parallel manner, leading to enhanced computational and**

**energy efficiency**. By leveraging the inherent capabilities of neurons and synapses, neuromorphic systems demonstrate potential AI applications in areas such as pattern recognition, image classification, autonomous driving, and LLM.

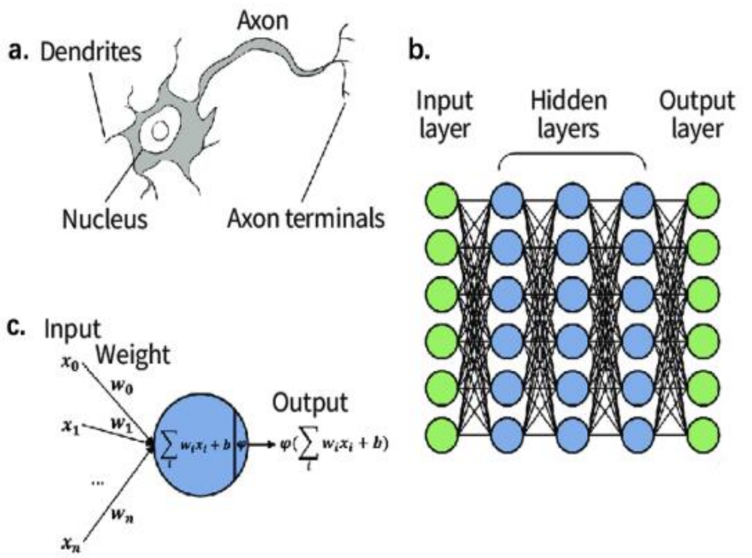



***Fig 7: a. biological neuron in animals;***
***b. multi-layer perception neural networks (MLP) or***
***fully-connected (FC) layers; c. Forward propagation of artificial neurons in MLP, including the input,***
***weights, summation, activation function, and the output. Data obtained from online image libraries.***
Source: New advancements, challenges and opportunities of nanophotonics for neuromorphic computing: A

## 2.2.2 Silicon Photonics for Neuromorphic architecture

### 2.2.2.1 Photonics vs. conventional electronic neuromorphic

The implementation of neuromorphic computing at the hardware level can be achieved through oxide based (CMOS) devices such as memristors, spin electronic memories, threshold switches, transistors, etc. Some examples are illustrated in Fig 8.

In these implementations, due to the conductivity and resistivity characteristics of conventional conductors, a large amount of energy loss will inevitably occur during the transmission of electrical currents. Moreover, the size factor is also limiting the energy consumption limit of traditional conductive materials. As neuromorphic computing devices continue to shrink in size, quantum and thermal effects may become more pronounced, affecting energy efficiency. We can see clearly in Fig 8, that these electronic implementations consume three orders of magnitude more energy than biological systems and photonic systems.

**Parallelism and synchronization** face several major limitations in these implementations. First, in terms of parallelism, electronic devices are often limited by circuit bandwidth, which affects their ability to perform parallel processing that is required for AI workflows. Additionally, electromagnetic interference can become a serious problem, limiting overall performance. Second, in terms of synchronization, maintaining global clock synchronization can be very complex and energy-intensive in large-scale electronic systems. The propagation speed of electronic signals in wires is limited, which further affects the accuracy of system synchronization.

**Photonic systems, on the other hand, can achieve high-degree of parallelism using the inherent fan-out and WDM (Wavelength Division Multiplexing) techniques. They can transmit data at a high rate and a low energy level independent of distance, which essentially solves the communication overhead of electronic systems**.

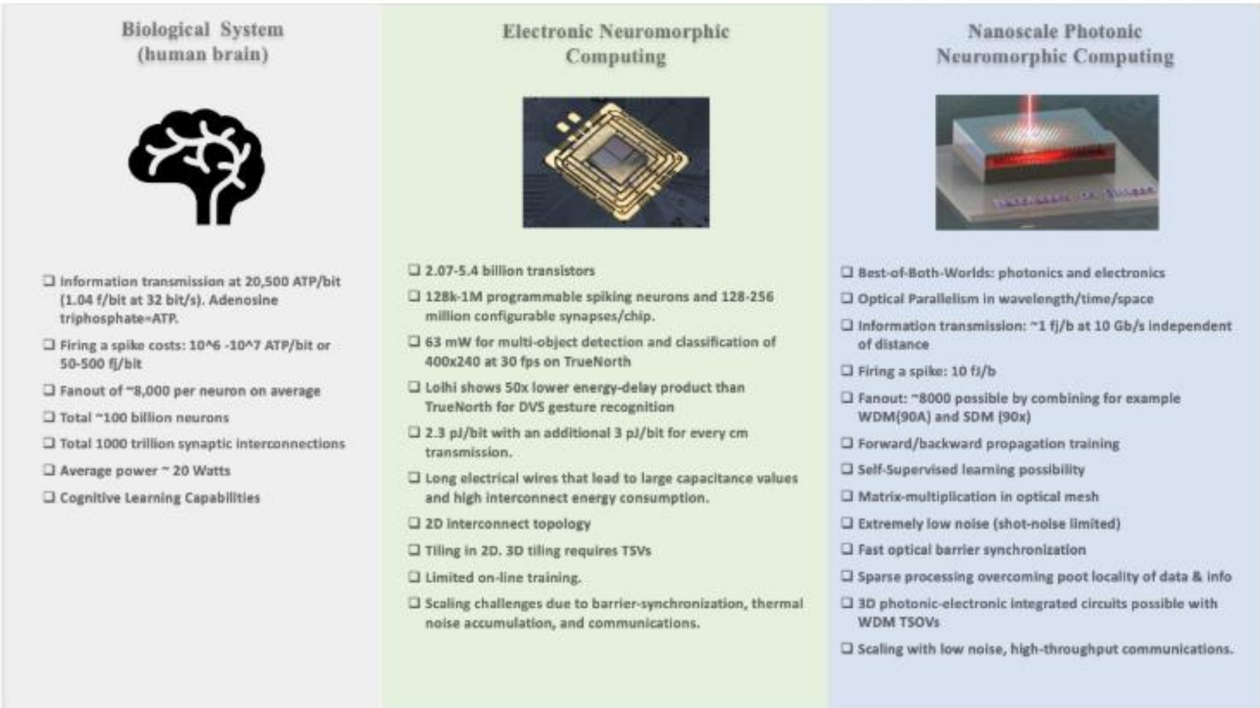



***Fig 8: Comparisons of a biological cognitive system, CMOS based electronic neuromorphic computing (Ex. IBM TrueNorth and Intel Loihi), and nanoscale photonic neuromorphic computing***

Source: New advancements, challenges and opportunities of nanophotonics for neuromorphic computing: A state of the art review

### 2.2.2.2 Photonic Integration for neuromorphic architecture: main challenges

Fundamentally, photonic neuromorphic architecture is a neural network composed of connected artificial neurons. Each neuron corresponds to a node of the ANN and is capable of only three fundamental mathematical operations: vector multiplication (weighting), spatial summation (addition) and a nonlinear transformation (activation function).

These neural networks are based on “spike processes” mimicking physiological neurons, which communicate with each other using trains of electrical pulses called action potentials or spikes.

The artificial neurons can be realized with optoelectronics devices such as excitable lasers (which is the option used in NEUROPULS project) or integrated modulators. They are interconnected with optical waveguides forming a network; these connections must be reconfigurable and provide the weighting functionality. Thus during the training the weights that connect each neuron are adjusted until the neural network achieves the targeted performance.

HW implementation is based on a set of key photonic active devices (lasers, optical modulators, photodetectors …) and passive devices (waveguides, resonant cavity, photonic crystal …). Fabrication platforms is a field that has grown rapidly, as requires advanced manufacturing techniques capable of precise design of nanostructures. Still many challenges are there:

- ***Integration:*** efficient integration of various nano-photonic components into functional systems, such as a PIC, is a complex task that requires interdisciplinary collaboration. Some existing integration methods include heterogeneous, monolithic, hybrid integration etc.
- ***Scalability***: many manufacturing methods need to be adapted to large-scale production to meet the growing demand for nano-photonic devices. Current photonic manufacturing has relatively poor scalability compared to electronic ICs.
- ***Materials innovation:*** the development of new materials with tailored optical properties will expand the design possibilities of nano-photonic devices. Core semiconductor materials, besides the typical silicon, are Gallium Arsenide, Indium Phosphide, Silicon Nitride, and Transition-metal dichalcogenide (TMDCs).
- ***Cost-Efficiency:*** reducing the cost of fabrication techniques, especially for lithography, 3D printing and self-assembly, is essential for widespread adoption of photonic devices. This could also call for cheaper fabrication tools and equipment.
- ***Hybrid Platforms:*** combining different fabrication methods can offer unique advantages, leading to hybrid nano-photonic platforms. Common semiconductor platforms include CMOS, carbon systems including carbon nanotubes and graphene, and the latest magnetoelectric spin–orbit (MESO) …

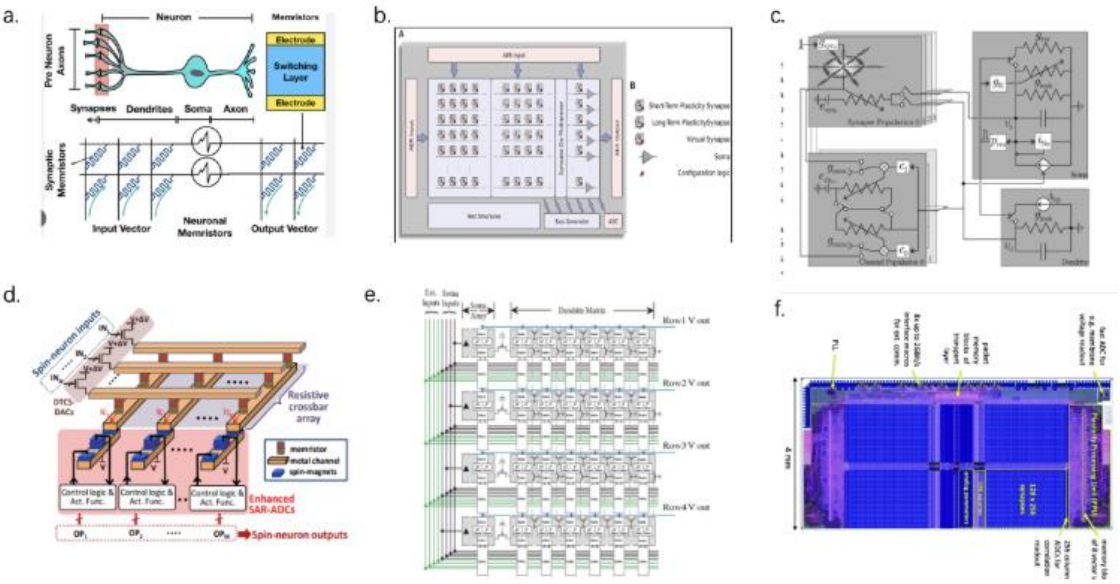



***Fig 9: Conventional neuromorphic computing systems, utilizing electronics rather than photonics. a. Neuromorphic Computing with Memristor Crossbar, b. A reconfigurable on-line learning spiking neuromorphic processor comprising 256 neurons and 128K synapses, c. Neurogrid: A mixed-analog-digital multi-chip system for large-scale neural simulations, d. SPINDLE: SPINtronic deep learning engine for large-scale neuromorphic computing e. A field programmable neural array (FPNA), f. Layout of the current BrainScaleS-2 full-size ASIC***

Source: New advancements, challenges and opportunities of nanophotonics for neuromorphic computing: A state of the art review

# 3. Exploitation Activities

The main objective of this section is to submit a proven model and associated methodology to ensure industrial exploitation and take-up of the results generated in future European projects providing guidelines for all stakeholders including partners, project initiators and the European Commission.

## 3.1 Main objectives

- Embed project results into the practices of participants
- Make available the knowledge generated through the project to all interested organisations
- Establish links with related on-going research initiatives
- Trigger further development and researches linked to photonic neuromorphic area
- Set the foundation for further commercial exploitation and opportunities

- Help to attract additional funding to increase TRL level of technologies and tools developed
- Make the project's work widely known, attract civil society attention and generate interest for exploitation of the results
- Inform decision makers about NEUROPULS important outcomes

## 3.2 Project Key Exploitable Results (KER)

The exploitation aims to describe how the results arising from the project will be used and more generally concretizes the value and impact of the R&I activity for societal challenges.

### 3.2.1 Methodology

This step intends to answer the following questions:

- What are the expected key exploitable results of the project?
- How are they going to be used and by whom?
- Which means to ensure their exploitation?

The scope of this first version of the exploitation plan at M12 is based on a synthesis of the elements formalized in the grant agreement. Based on that, each partner has already defined an exploitation path or paths for the use of the project's results to fully maximise the impact of the project. These paths are described in the table below (Table 1).

At this level, he exploitation plan aims to draw up the landscape of these exploitation paths, and assess their feasibility with respect to the partner's ecosystem and the consortium agreement rules. A focus will be given to the industrial stakeholders, via their use cases. In spite of low TRL of the technological bricks (2 and 3), we will provide a business Canvas for each use case, and identify the competitive advantage that NEUROPULS could provide in terms of positioning, and market opportunities. Risk analysis will be provided from exploitation point of view.

For M24, and M36, we will be monitoring first the evolution of technical KPIs of the project with respect to the state of the art evolution, and market dynamics. Based on that we will be working closely with partners to review and/or update their initial KER definitions. We will support them in building & executing their exploitation routes in this time frame.

Further updates at M48 will be based on effective results coming from industrial use cases benchmarks. Exploitation activities will support industrial stakeholders in enhancing their commercial activities related to their KERs, and academic partners in enhancing further research activities linked to their contributions. This phase will ensure the effective realization of exploitation routes, that are planned in the project time frame, and matching the partners with their initial ambitions/goals.

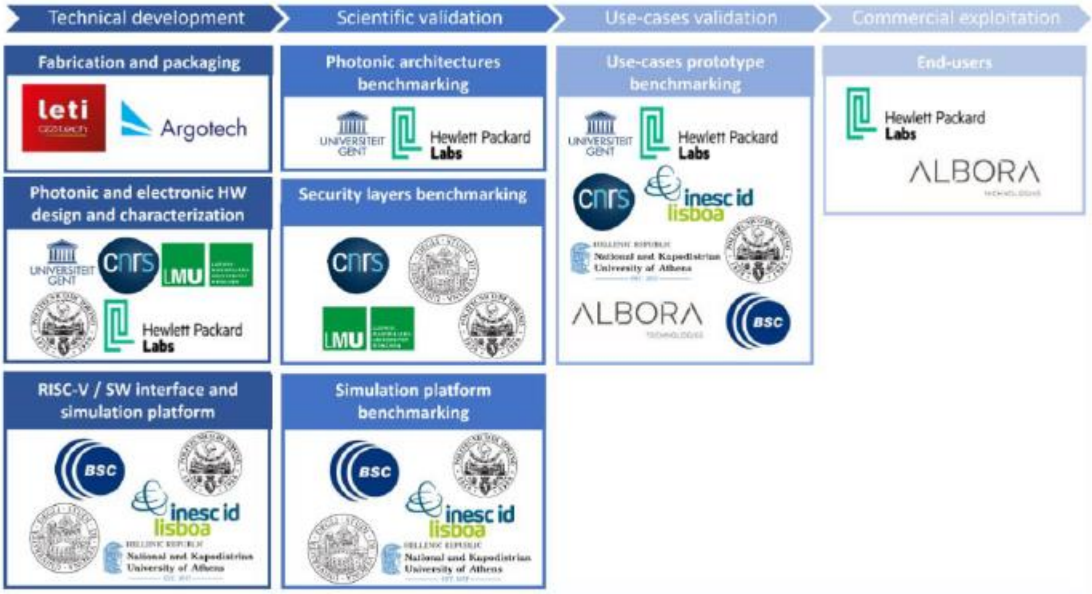



*Fig 10: NEUROPULS Value Chain*
Source: NEUROPULS, Grant Agreement

| Partners | Project results & Application domain | Exploitation |
|---|---|---|
| **CNRS** | Models for PCMs integrated with photonic waveguides; optoelectronic devices for neuromorphic computing; novel algorithms for NNs, and photonic security primitives | Publications, conferences, future device development, application in graduate-level courses |
| **CEA** | New optical PCM and their integration in optoelectronic devices | Patents, publications, conferences, future applications |
| **UGENT** | Novel architectures and training algorithms for neuromorphic computing | Patents, publications, conferences, future applications |
| **INESC-ID** | Methods for automatic generation of system-level models of the photonic components, PUFs and NNs, photonic architecture accelerator interface. | Patents, publications, conferences, future applications and academic developments |
| **BSC** | Statistics Unit to support safety and security-related systems (SafeSU). An automotive application of the neuromorphic accelerator | Open hardware releases, publications (conferences, journals). |
| **POLITO** | Simulation platform for the dependability analysis of neuromorphic components | Patents, publications, conferences, and academic developments |

| | | |
|---|---|---|
| **HPE** | New Q-switched laser source, photonic neuromorphic architectures, and edge-centric use-case of the neuromorphic accelerator. | Patents, publications, conferences, future research & customer applications |
| **AT** | Platform for efficient GNSS radio frequency signals jamming detection and/or mitigation with NNs. | Patents, publications, future research, customer applications, and integration with industry GNSS products |
| **NKUA** | Full-system model and tools of computing system stack with neuromorphic accelerators. Performance, robustness, energy, and security assessment framework. | Publications (conferences and journals), open tools releases, future research and academic developments, new content in graduate courses. |
| **LMU** | Security, entropy, and complexity analysis of the implemented optical PUFs. Error correction and transformation techniques for short, stable, and highly entropic bit strings from raw PUF-responses. | Publications in conferences and journals, organization of special sessions or workshops, inclusion in teaching (graduate courses...) |
| **ARGO** | Fully customized platform for hosting FPGA driving circuit connected to photonic chip | Enhanced portfolio of company's assembly and packaging processes |
| **UNIVR** | Novel interface to support secure interaction between the software and hardware layers | Patents, publications, future research and academic development |

***Table 1: Individual partner exploitation plans***
Source: NEUROPULS, Grant Agreement

### 3.2.2 Indirect Exploitation Paths

NEUROPULS has considerable research challenges and many academic partners, reason for which we can notice that the exploitation paths noted within the exploitation plan are frequently in the form of publications, patents, conference presentations and so on.

We talk of these types of exploitation as being ***indirect*** because commercial exploitation (providing a final commercial product or service) is not part of the partner's exploitation plan, though this does not mean that commercial exploitation is not possible by third parties, either other partners within the project or outside. A case in point would be the creation of a patent as part of the project, whereby the academic party could license the patent to a third party that would look to valorise the patent to create a product or service. Valorisation occurs indirectly based on the existence of a third-party that is involved in the commercialisation.

#### 3.2.2.1 IP rights & management

IP strategy aims to secure and manage project results. To formalize this strategy, several points must be taken into account:

- Ownership of the results (principle = results belong to the beneficiary generating them; if they have been generated by several partners jointly = joint ownership)
- Access rights of the results (open access as a general principle of scientific dissemination).
- Whether or not they have to be protected (can reasonably be expected to be commercially or industrially exploited and protecting them is possible, reasonable and justified).
- Which protection measures will be chosen.

At this level, we can highlight the achieved and ongoing actions regarding this area of exploitation:

- Patent filed on how to adjust reliably weights with a single heater (**CNRS**)
- Patent in filing about methods to achieve faster cooling for PCM-based devices (**CNRS, CEA-LETI**)
- Patent in filing about a chiplet approach to connect different photonic chips with different characteristics (**CNRS, ARGOTECH**)
- Patent on security protocols for encryption and system identification based on PUFs + software protection solutions to secure the software components interacting with the neuromorphic processor (**UNIV OF VERONA**)

#### 3.2.2.2 Open access to research data

According, to article 39 (Dissemination and Exploitation), of Horizon Europe, it has been stipulated that: ***“Open access to research data shall be the general rule under the terms and conditions laid down in the grant agreement, ensuring the possibility of exceptions following the principle 'as open as possible, as closed as necessary', taking into consideration the legitimate interests of the beneficiaries including commercial exploitation and any other constraints, such as data protection rules, privacy, confidentiality, trade secrets, Union competitive interests, security rules or intellectual property rights.”***

In addition to open science practices mentioned in the agreement proposal, to comply with Horizon Europe, number of partners have included this approach in their KER strategy:

- Open-source tools for modelling and simulation of the full system computing with neuromorphic accelerators, in gem5 platform (**NKUA**)
- Open-source simulation tools for modelling of PCM integrated platform (**CNRS**)

We mention also the fact that these open-source approaches, do not preclude protection some features of these simulation tools.

### 3.2.2.3 Use of the results in further research activities

The use of results in further research activities helps to maximize the impact of research, enabling the effect of results to be potentially wider than the original focuses. It enables a wider knowledge dissemination and building a common European scientific and technological area. Encouraging the use of results in further research activities fosters the free movement of researchers, scientific knowledge, and innovation, and encourages a more competitive European area. Therefore, considering most of the partners, they own dynamic research ecosystems linked to the computing field, or to the different technological bricks characterizing NEUROPULS: photonics, neuromorphic architecture, advanced security layer. We suggest here to mention those with the most notoriety in term of number of scientific publications, and number of collaborative research projects around the field of neuromorphic photonics (cf. Section 5).

**CEA-LETI** has a silicon photonics 300 mm wafer platform, and represents France's largest R&D center for the development, characterization and simulation of optoelectronic systems and components. Its activities range from component design through component fabrication, integration into systems and packaging. With NEUROPULS this platform will be enriched with PCMs and III-V materials.

Its process design kit (PDK) contains the design rules and building blocks for photonics design, available into the Synopsys PhoeniX OptoDesigner suite. Used by more than 300 designers worldwide, this PDK gives access to a complete set of passive components, such as couplers, silicon waveguides, and active components, such as high-speed Mach Zehnder modulators and high-speed germanium photodiodes based on Leti's fab. Therefore, CEA LETI will be exploiting its augmented silicon photonics platfrom for further research activities, following its working model with the phtonics players (through its PDK).

Beyond its impact on the photonics community, CEA-LETI will be using the results of NEUROPULS for further European projects to upgrade the exploitation of photonics neurmorphic architecture, into quantum and bio-inspired new paradigms. PROMETHEUS (PROgraMmable integrated photonic nEuromorphic and quanTum networks for High-speed imaging, communications and sEcUrity applicationS) is one of the projects under Horizon Europe, aiming to shatter the boundaries between neuromorphic and quantum engineering and merge them to a common disruptive photonic integrated platform.

- **CNRS** is the European leader in the area of photonics neuromorphic in term of publications (the 5th worldwide) with many collaborations in France, Germany (**UNIV TECHNISCHE BERLIN**), and Spain (**UNIV ILLES BALEARS**) (cf. Section 5)
  CNRS is involved with all of its laboratories (CROMA/INL/TIMA/ICB) around novel devices and systems, particularly exploiting CMOS-compatible platforms and the integration of electronics and photonics for applications in security and computing. In particular, CNRS is focusing on the development of electronic-photonic systems exploiting phase change materials (PCMs) which have a

threshold-dependent activation and memory-dependent response that can mimic the behavior of a neuron or a synapse as well as reconfigurable photonic physical unclonable functions.

CNRS will leverage NEUROPULS results for Horizon Europe projects, in which they are currently involved, around photonics & neuromorphic areas:

- III-V seMiconductor on sILicon nano opticaL ampIIfier for signal regenerAtion and computing, 2023
- Time-based single molecule nanolocalization for live cell imaging, 2023
- Neuromorphic computing Enabled by Heavily doped semiconductor Optics, 2023
- Quantum Optical Networks based on Exciton-polaritons, 2023

The **University of Ghent**, specifically the Photonics Research Group, is significantly involved in the field of Photonic Neuromorphic Computing. They have been conducting fundamental research on novel concepts for quantum and neuromorphic computing.

They have a number of research projects and vacancies related to Photonic Neuromorphic Computing. University of Ghent will leverage NEUROPULS results in the perimeter of Horizon Europe
projects, in which they are currently involved around photonics & neuromorphic area:

- Reconfigurable superconducting and photonic technologies of the future, 2023
- Neuromorphic computing Enabled by Heavily doped semiconductor Optics, 2023

We have identified University of Ghent as a key player, in research ecosystem with multiple collaborations in Belgium (**IMEC**), Germany (**university of Munster**), UK (**university of Oxford**...). and with **IBM** (cf. Section 5).

- **Barcelona Supercomputing Center (BSC)** has a strong potential to exploit NEUROPULS results to support the “Future of Computing” . With a total staff of more than 400 R&D experts and professionals, BSC is an essential tool for international research & competitiveness in science and engineering within the framework of European funding programmes, and in the context of Advanced Computing in Europe (PRACE) initiative. The center collaborates with leading companies such as **IBM**, **Microsoft, Intel, Nvidia, Repsol** and **Iberdrola**. The partnership with **IBM,** aims to develop new and more efficient and energy sustainable

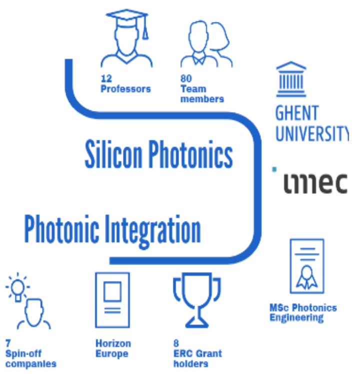



*Fig 11: Ghent University, Research ecosystem*
Source::https://photonics.intec.ugent.be/

processors with European technology. The main segment, which is targeted, is HPC (High Performing Computing) but the initiative aims to expand its use to all kind of business loads. As part of the partnership with IBM, BSC has received 3 million Euros in scholarships for Education and Research activities over 5 years.


***Fig 12: BSC Research in numbers, 2023***
Source: BSC Summary, 2023

Moreover, the center is committed to advancing autonomous driving technologies and contributing to the development of safer and more efficient autonomous vehicles. BSC is collaborating with **Lenovo** and **Intel**, to develop AI algorithms for machine learning of autonomous vehicles from changes in the environment.
This partnership includes also an innovative data set for large scale object detection benchmark, called "SODA 10M" (Self/semi-supervised Object Detection dataset for Autonomous driving).

### 3.2.3 Direct Exploitation Paths

Due to the TRL of the technology (2 & 3 to 5), activities aiming at direct commercialization and industrial implementation during the project are premature and will have to take place following further technologies developments and prototypes.

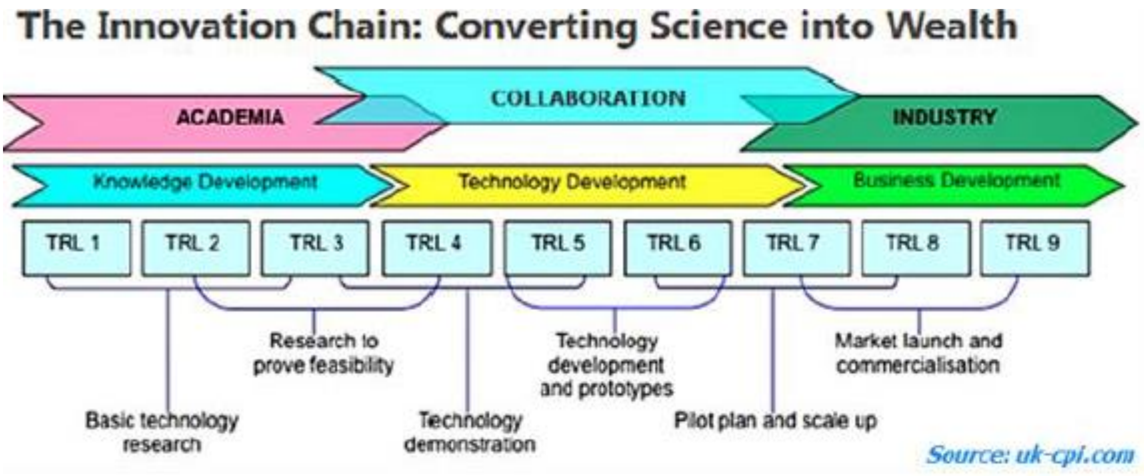



*Fig 13: Technology Readiness Level scale*

Nevertheless, the exploitation plan must lead reflection to anticipate and prepare relevant actions in order to convert generated knowledge and technology demonstrations into products or services. In later updates of the document, we will set up a marketing strategy and business plans for the industrial use cases that are driving NEUROPULS. This will be based on a consortium brainstorming session, and ideally involving the Knowledge Transfer and Partner Relations Departments of the academic centers involved in the project.

### 3.2.3.1 Methodology

At this stage, we propose the analysis of the business cases, from technology positioning perspective, and the usage of business lean Canvas approach (Fig 14).
This tool is a strategic management feature for developing new business models. It supports researchers and innovators in collecting information for the exploitation plan and helps them focus on the most important steps towards use and commercialization.
A questionnary has been proposed to support the industrial partners, in filling this business Canvas (Table 2).

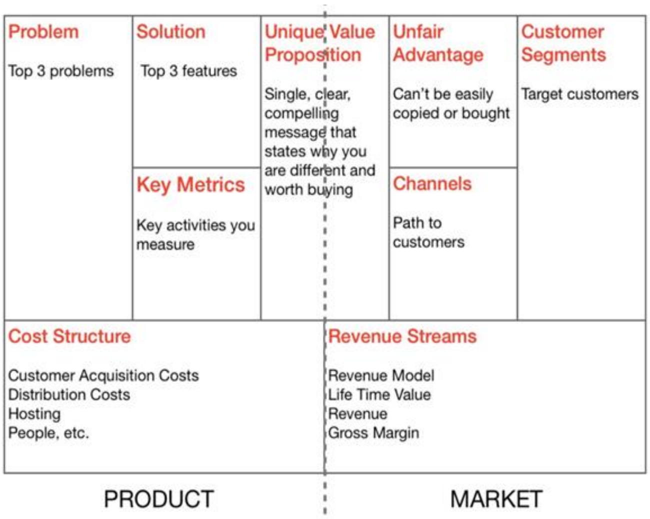



*Fig 14: Lean business Canvas template*

| | ***Business Case & Industrial Owner*** | |
|---|---|---|
| 1 | **Opportunity description** | Describe the opportunity / Key Exploitable Result in a few sentences. |
| 2 | **Problem identified** | Describe the 3 main problems you are addressing. Describe existing alternatives - Find out how they are solving the problem now (today's alternatives) |
| 3 | **Solution proposed** | Outline the main features of your solution. What are the current solutions (if any) and what are the points of difference! |
| 4 | **Who are the customers /users?** | What customers are you targeting: market segmentation, customer type? |
| 5 | **(Unique) Value Proposition** | Define your UVP based on today's alternative: what makes your product better or more efficient to the customer, a single and compelling sentence. Provide facts and data in support. |
| 6 | **Unfair Advantage** | What real key advantage do you have compared to anyone else developing the KER. This could be excellent channels to market, a unique technology, strong IP. |
| 7 | **Revenue Streams (how you generate value from the KER)** | What will be the main revenue streams when the solution is ready for the market? Estimate revenues (try to quantify amounts and prices). |
| 8 | **Channels** | How does your product/service get to the customer? Do you need channel partners, distributors, a new sales/marketing dept., or an ecommerce platform? |
| 9 | **Metrics** | Key aspects/activities you need to measure to get feedback on exploitation development |

| | | |
|---|---|---|
| 10 | **Cost structure** | What are the key cost components relating to your KER? Is there a high cost of equipment, materials, or sales? What things can input the cost structure? Do you need a high-volume market? |
| | | |
| 11 | **Risk Factors** | What are the main risks (technical and market) you see in developing the KER? |

*Table 2: How to fill the Lean Business Canvas?*

#### 3.2.3.2 Industrial partners: the main drivers for direct exploitation paths

Direct exploitation routes in the project relate to the chosen use cases for the secure photonic neuromorphic accelerator and the activities of two of the industrial partners, **HPE** and **Albora technologies**. Here, it is envisaged that the industrials would provide direct services to clients in anomaly detection (in different market verticals) and in GNSS signal jamming detection that are a threat to position, navigation and time solutions.

Detailed analysis of these use cases will be exposed in Section 4. Trajectory prediction is one of the challenging use cases, which could enable autonomous driving. Although this use case is not carried by an industrial, we propose to analyse it, and monitor its attractiveness with respect to current investigations led by the market leaders.

A further direct form of exploitation comes from the industrial partner and packaging house **Argotech.** By taking part in the project, the company anticipates it will enhance its packaging portfolio allowing it to offer new assembly and packaging services. In other words, either through specific patents or increased process know-how, Argotech would provide an impact in terms of addressing new types of packaging solution and/or new clients. Considering initial elements shared by Argotech, we propose the following lean business Canvas.

| Lean Canvas | Designed for: Argotech | Designed by: Nour POPOFF | Date: 20-04-2024 | Version: #1 |
|---|---|---|---|---|
| **Problem**<br>PICs are coupled with fibers (fiber arrays) equipped with ceramics ferrules or fiber array blocks, MFD (Mode Field Diameter) adaptors if is needed and lenses if is necessary. This solution is not optimal in term of compacity and performannces (losses).<br>. | **Solution**<br>PIC to PIC coupling is based on direct edge connection between chips. MFD adaptors can be used optionally. | **Unique Value Proposition**<br>Argotech solution will provide more compact solution with less components needed. Better optical performances are expec ted. | **Unfair Advantage**<br>• Compactness<br>• Mode field matching techniques<br>• Scalability | **Customer Segments**<br>industrial, , aerospace, defense, computing, automotive and healthcare segments |
| | **Key Metrics**<br>•Optical performances<br>•Cooling and mechanical stability<br>•Manufacturing process mastering | | **Channels**<br>Current customers ( for confidentiality reasons, customers can not be named) | |
| **Cost Structure**<br>• Purchase of :<br>-Tools and jigs for adjustment machine<br>-New adhesive<br>• Hiring ~ 100 PM technicians to set machines and processes | | **Revenue Structure**<br>Revenues from production volumes<br>Revenues from getting new customers | | |

# 4. Business cases Analysis

The objective of this section is to provide a comprehensive understanding of each use case, from technology positioning perspective. On top of that, we will consider the competitive advantage and the potential of market opportunities. These elements constitute key hypothesis that we must recurrently validate for a viable commercial use of NEUROPULS results (during the project duration). Based on that, and considering market elements and initial data collected from the industrial partners, we will provide a first version of lean business canvas. This may evolve in the future updates of the Exploitation plan document.

## 4.1 Anomaly Detection in IoT devices: HPE

### 4.1.1 Anomaly Detection System for IoT

IoT is a significantly diverse ecosystem, including many layers and a wide variety of devices and network technologies. As the number of devices multiplies, a shift from centralized to decentralized will likely occur in security management. As the sheer volume of data required to manage devices increases, there will be a point when centralized management is no longer effective and efficient. Instead, the scalable and secure option is to embed security into each piece of equipment and empower the

equipment with the security context required to make safe decisions. This is where the potential for security at the edge becomes important.
Considering the architecture for IoT Systems and security layers, the business case led by HPE is linked to Network Connectivity.

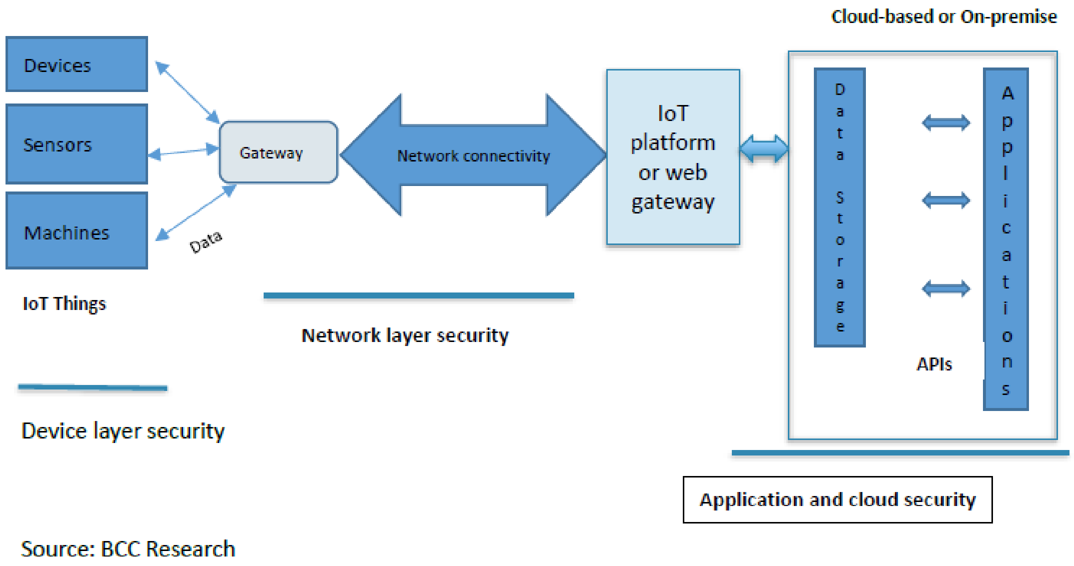



*Fig 15: Typical Architecture for IoT systems and security layers*
Source: BCC Research

Network security combines all the activities designed to protect the integrity and operation of data, applications, systems, and devices connected to the network. It uses various layers of defenses at the edge and in the network; every defense layer works on control and policies to ensure authentic access to the network. This security type offers safety from network intrusions, distributed denial-of-service (DDoS) attacks, and malware and allow secure platform access to computers, program, and users to perform a specific task.
Within the global IoT security market, Network security layer represents around 7.7 $B in 2023, and is expected to grow with 23% CAGR (2022-2027), to reach 17.7 $B in 2027.

Global Market for IoT Security Technologies, by Type of Security, Through 2027
($ Millions)

| Type of Security | 2021 | 2022 | 2023 | 2025 | 2027 | CAGR% 2022-2027 |
|---|---|---|---|---|---|---|
| Endpoint security | 6,095.8 | 7,553.0 | 9,323.0 | 14,412.5 | 22,429.5 | 24.3 |
| Network security | 5,154.2 | 6,316.7 | 7,712.2 | 11,665.5 | 17,763.9 | 23.0 |
| Application security | 3,352.9 | 4,232.2 | 5,321.6 | 8,535.5 | 13,779.2 | 26.6 |
| Cloud security | 3,049.1 | 3,886.0 | 4,934.1 | 8,068.7 | 13,280.7 | 27.9 |
| Others | 1,735.5 | 2,118.5 | 2,569.7 | 3,803.3 | 5,595.1 | 21.4 |
| Total | 19,387.5 | 24,106.4 | 29,860.6 | 46,485.5 | 72,848.4 | 24.8 |

***Fig 16: Global IoT Security Technologies market***
Source: BCC Research

***How is Anomaly Based Detection positioned in the Network Security Layer?***
The use case we are considering, the Anomaly Based Detection, belongs to one feature of Network security, named Intrusion Detection System (IDS). This feature offers an extra and second layer of protection from attacks.

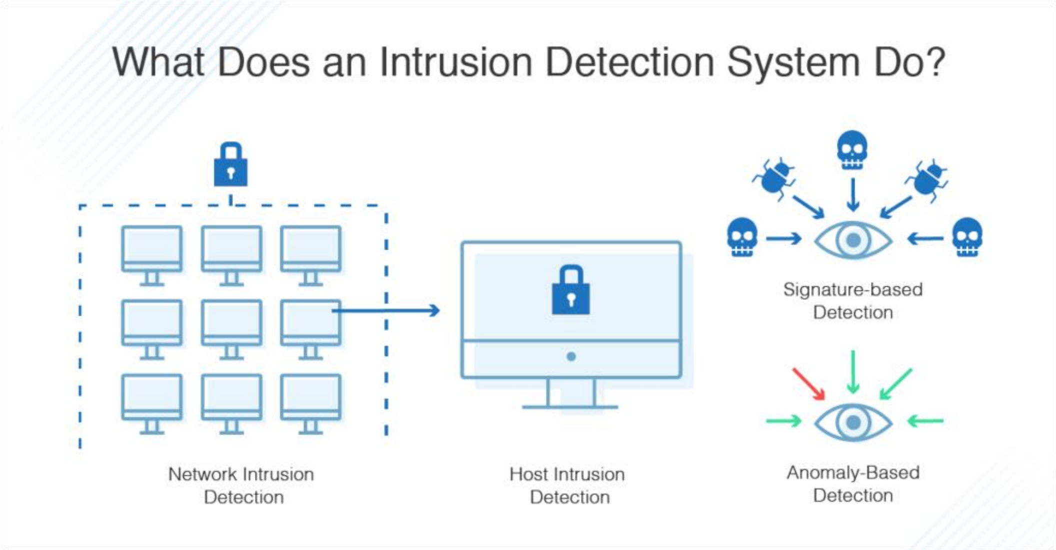



***Fig 17: Intrusion Detection System (IDS)***
Source: BCC Research

***Why are we considering Anomaly Based Detection, specifically for photonic neuromorphic accelerator?***

As mentioned in the Fig 17, Signature based detection is the second mechanism of IDS, which is more popular and traditional than Anomaly Based Detection. Acting as antivirus software, it relies on a preprogrammed list of **known attack behaviors.** These “signatures” can include subject lines and attachments on emails known to carry viruses, remote logins in violation of organizational policy, and certain byte sequences.

At the opposite, **Anomaly-based,** begins with a model of normal behavior on the network, then alerts an admin anytime it detects any deviation from that model of normal behavior. Anomaly-based IDS begins at installation with a training phase where it “learns” normal behavior. **AI and machine learning have been very effective in this phase of anomaly-based systems, due to their ability to automatically identify anomalies, uncover hidden patterns, handle large-scale data, and enhance decision making,**

In term of existing solutions, Anomaly detection is still subject to inaccuracy leading to false positive detection alerts.
NEUROPULS will train deep learning models on recurrent neural networks to achieve sufficient accuracy, which consists the main challenge for this type of security system.
Therefore, by using deep learning approach, it is enabling models to automatically learn new attack patterns without the need for explicit rules. Deep learning models can recognize patterns of suspicious behavior even when attacks take never-before-seen forms, making network defenses more **robust and adaptable**.

***What is the total addressable market for anomaly-based solutions ?***
This TAM will follow very closely the global IoT Intrusion Detection Systems (IDS) market. It represents a total of 1.2 $B in 2023, and is expected to grow with 20.6% CAGR (2022-2027) to reach 2.6 $B in 2027. This can be explained by increasing cyberattacks, with sophisticated techniques such as signature evasion and camouflage of malicious activity.

Global Market for IoT Intrusion Detection System and Intrusion Prevention System Solutions, by Region, Through 2027
($ Millions)

| Region | 2021 | 2022 | 2023 | 2025 | 2027 | CAGR% 2022-2027 |
|---|---|---|---|---|---|---|
| North America | 278.6 | 336.2 | 404.5 | 592.9 | 875.4 | 21.1 |
| Europe | 283.3 | 338.1 | 401.9 | 576.0 | 830.9 | 19.7 |
| Asia-Pacific | 222.9 | 271.5 | 329.2 | 492.4 | 740.6 | 22.2 |
| Rest of the World | 65.9 | 76.5 | 88.4 | 118.6 | 158.1 | 15.6 |
| Total | 850.7 | 1,022.3 | 1,224.0 | 1,779.9 | 2,605.0 | 20.6 |

***Fig 18: Global Intrusion Detection System market***
Source: BCC Research

### 4.1.2 HPE Lean Business Canvas

**HPE** provides security and digital protection services for enterprise security and adaptive protection that fortify end-users' data confidentiality, integrity and availability in hybrid IT and at the edge. Additionally, HPE through its subsidiary **Aruba Networks** offers Aruba IntroSpect User and Entity Behavior Analytics, which identifies advanced cyberattacks through the use of AI-based machine learning. This product identifies threats that have evaded traditional security protections.

Considering the business model of HPE, 3 segments have been identified for Anomaly based detection use case:

- Heavy' Edge computing infrastructure (e.g., as part of an AI for science infrastructure that spans from Edge)
- 5G/6G (optical accelerator can be placed between light-weight antenna and Edge data center)
- Anomaly/intrusion detection in in-vehicle networks for the automotive

| Lean Canvas | Designed for: HPE | Designed by: Nour POPOFF | Date: 20-04-2024 | Version: #1 |
|---|---|---|---|---|
| **Problem**<br>Anomaly Based Intrusion Detection Systems are susceptible of false positive alerts, because of lack of accuracy .<br>This is beacoming more crucial with increased cyberattacks with sophisticated techniques such as signature evasion and camouflage of malicious activity. | **Solution**<br>HPE's solution is based on deep learning models on feedforward neural networks, to achieve sufficient accuracy. This will enable models to learn automatically new attack patterns without the need for explicit rules.<br><br>**Key Metrics**<br>• Latency<br>• Reliability<br>• Low power consumption<br>• Accuracy | **Unique Value Proposition**<br>HPE's solution will be integrated to IoT Network Systems and security layers, benefitting from low power consumption, while maintaining equivalent inference accuracy with respect to state of the art (LOihi from Intel) | **Unfair Advantage**<br>• Low power consumption<br>• Accuracy<br>• Easy integration in Aruba Networks' security solutions and framework<br><br>**Channels**<br>Licensing IPs to appropriate vendors in HPE's supply chain eco-system. These vendors will take care of the fabrication and packaging of the silicon photonic dies and electronic control ASICs. | **Customer Segments**<br>**1. Edge Infrastructure**<br>**2. 5G/6G infrastructure**<br>**3. Autonomous Driving** |
| **Cost Structure**<br>Costs corresponding to the software stack development and integration of the full solution.<br>Will be managed by a business unit inside HPE | | **Revenue Structure**<br>Revenues from licensing the technology to appropriate HPE's vendors<br>Revenues from the commercialization of the full solution | | |

## 4.2 Anti-jamming GNSS: Albora

### 4.2.1 Albora solution vs. existing solutions

***Why GNSS anti-jamming ?***

GNSS receivers, which use GPS signals (as well as GLONASS, Galileo and other constellations – hence the name "GNSS" – Global Navigation Satellite System), are notoriously vulnerable. This is due to the nature of the signals themselves, which emanate from orbiting satellites located 20,000km above the Earth's surface.

Besides the vast distance the signals have to travel, the satellites themselves have limited energy. Signal disruption can be the result of physical barriers between the receiver and the satellites, such as mountains, buildings or a roof, an intentional jamming (an adjacent frequency used, such as Ligado, which overlaps with GPS) or intentional jamming.

Therefore, GNSS anti-jamming solutions are crucial for mitigating the intentional and unintentional interference of GNSS signals. They provide mission-critical defense systems with continuous, assured access to GNSS position, navigation, and timing information

***What about the exiting market of anti-jamming solutions?***

3 main approaches exist in the market:

- Beamforming: focuses a wireless signal towards a specific receiving device, rather than having the signal spread in all directions. Beamforming requires precise, real-time channel state information (CSI) from the user equipment (UE) to customize the beam. It needs full digital control of the amplitude and phase at every antenna element.
- Beam Steering: to control the direction of the overall beam formed by an array antenna. Beamsteering refers to the simplest use of large antenna arrays at the base station. It creates narrow beams within a cell to direct signals to specific locations. Beam steering is usually implemented with phase shifters
- Null Steering: This is a technique used in conjunction with beamforming to improve the signal quality and reduce interference. Nulls are created in the direction or vector of interference, in such a way that any signal from it, is attenuated.

The anti-jamming GNSS market represents a value of 5.28 B$ in 2024, and is forecasted to grow with a CAGR of 9.58% to reach 8.35 B$ in 2029.

Main leaders are **Thales Group** and **infiniDome** who have developed advanced technologies to ensure the reliability of GNSS systems in the face of increasing jamming threats. Their solutions are designed especially for military, and defense applications.
Here is an example of TopShield solution from **Thales**, showing how it functions to cancel the jamming signals at antenna level.

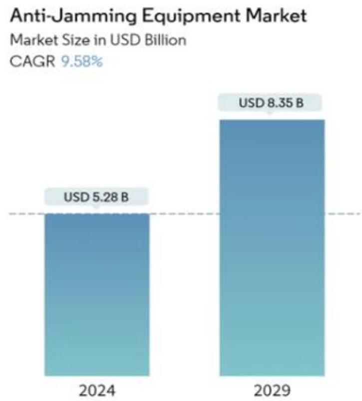



***Fig 19: Anti-jamming market (2024-2029)***
Source: Morodor Intelligence

***What novelty with Albora Technology?***

First, we should mention a fundamental functional difference. While the existing solutions handle the mitigation tasks of the interference management, Albora's solution will tackle the detection and classification tasks, to either alert the user or switch on countermeasures. One strong competitive advantage is related to the fact that this detection can operate dynamically.

Moreover, Albora's use case, implemented on NEUROPULS accelerator will overcome to the power consumption issue of most of the existing solutions. Actually, the latter are extremely power hungry as they employ a lot of digital signal processing, and require high-end analog to digital solutions components.
Digital null steering solutions also add a substantial amount of latency to the signal (RF) path. The number of calculations and possible nulls for jamming protection increases (exponentially) with each additional antenna. Consequently, the size of the anti-jamming unit (due to the quantity of electronics needed) directly correlates to the number of nulls and complexity of calculation.

On the other hand, in NEUROPULS, implementing Albora's solution allows us to demonstrate a new field of integrated microwave photonics, beyond their efficiency in the communication field such as radio-over-fiber systems.
From the RF carriers, NEUROPULS will be exploring the potential of programmable photonics, leveraging the performances of the RF-Optical link, the abundant processing bandwidth obtained from upconverting the radiofrequencies to the optical frequencies.
On top of that, neuromorphic architectures, will provide to Albora the competitive advantage of demonstrating anti jamming deep learning algorithms.

### 4.2.2 Albora Lean business canvas

**Lean Canvas**

| Designed for: | Designed by: | Date: | Version: |
|---|---|---|---|
| ALBORA | Anselm Adams | 28-03-2024 | #1 |

**Problem**
Current GNSS solutions do not address dynamic GNSS anti-jamming attacks for critical infrastructure and safety applications

**Solution**
Albora's neural network software-based and hardware agnostic solution allows the GNSS receiver to detect and classify jamming signals.

**Key Metrics**
- Reliability
- Accuracy
- Detection probability
- False alarm probability

**Unique Value Proposition**
Using Albora's softwarebased AI neural networks allows a dynamic solution as opposed to current static, once built, hardwarebased solutions on the market.

**Unfair Advantage**
- Software based
- Hardware agnostic
- Price
- Easy integration

**Channels**
B2B to GNSS receiver manufacturers

**Customer Segments**
**1. Critical infrastructures**:
- Power grid
- Financial services
- Broadcasting
- Wireless communications.

**2. Safety-critical:**
- Autonomous driving
- Aviation
- UAVs

**Cost Structure**
- HR:65% (wages & salaries)
- Productization: 10% (HW&SW)
- Commercialization: 15%
- G&A costs: 10% (finances, travel expenses, brands, domains, transaction costs, offices, supplies,..)

**Revenue Structure**
Revenues from licensing the technology to GNSS receiver manufacturers.

## 4.3 Trajectory prediction for autonomous driving: BSC

### 4.3.1 Understanding the use case & BSC's solution positioning

During recent decades, automobile manufacturers have been consistently working on improving the driving experience and making road vehicles safer by developing driver assistance technologies. In order to evaluate the extent of advances in driver assistance technology, 6 levels of autonomy have been defined by the Society of Automotive Engineers (SAE).

These levels range from 0, which corresponds to fully manual driving, to 5 the fully autonomous which is the ultimate goal of the recent research made both by the automotive industry and institutions. Today's transportation systems have intermediate autonomy levels going from the ability to control both steering and accelerating/decelerating, to environmental detection and decision making capabilities, to intervening in critical situations. However, they have significant room for improvement in order to reach the full automation level.

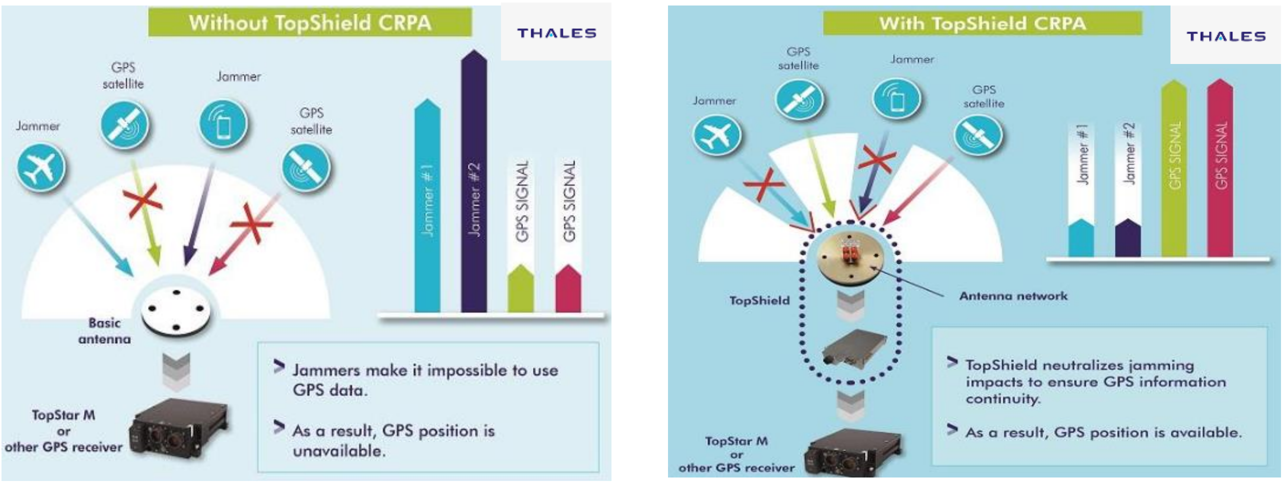



***Fig 20: TopShield Anti-jamming solution from Thales Group***
Source: https://www.thalesgroup.com/fr/global/activites/aeronautique/solutions-de-navigation/topshield-crpa-solution-against-gps-jamming

### *How Trajectory Prediction task is positioned in the autonomous driving pipeline?*

In order to understand NEUROPULS use case, it is important to remind the typical autonomous driving pipeline, which is constituted of perception, prediction, planning, and control.

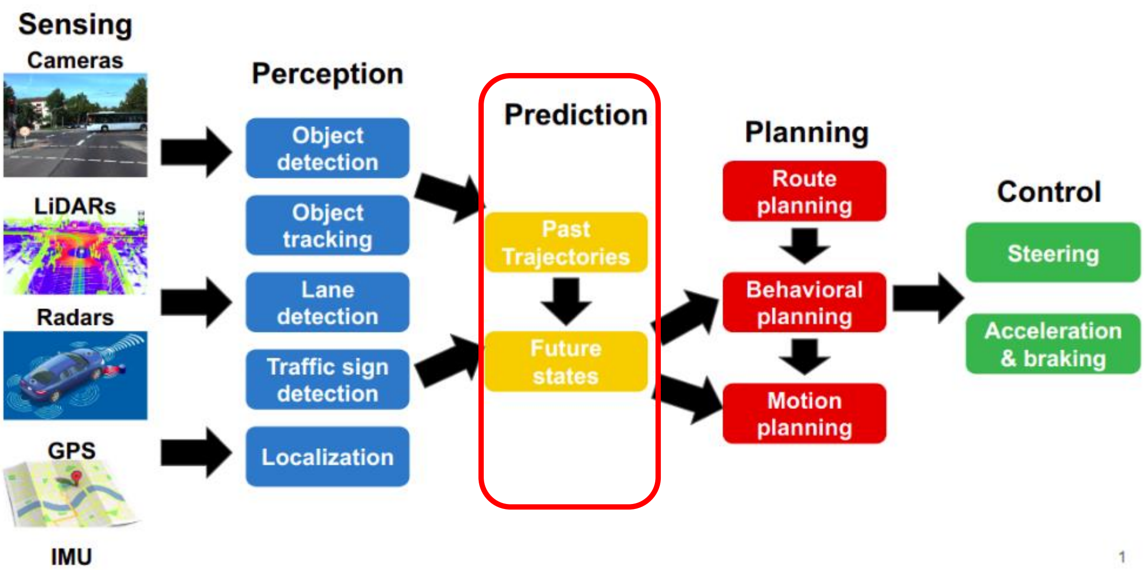



***Fig 21: Automated Driving Pipeline***
Source "Challenges and Tradeoffs in Trajectory Prediction for Autonomous Driving", Electrical Engineering and Computer Sciences, 2020

In order to perceive the surrounding environment, multiple exteroceptive sensors such as cameras, LiDARs, radars and ultrasonic sensors are mounted on the vehicle to scan the environment. The perception module examines the raw sensor data, detects and identifies the static and dynamic scene objects; the different parts of the road structure (drivable area, lanes etc.) and the other road users (cars, cyclists, pedestrians, etc.). Once the perception task is completed, it outputs an estimation of the location of each detected object. For a fully automated driving in complex urban scenes or high-speed scenarios, estimating the current location alone is insufficient to be able to interact with those objects. **Therefore, a prediction module is required to forecast the future behaviors of the surrounding agents, i.e. future maneuvers or trajectories.** Based on these predictions and on the final destination, the appropriate trajectory is planned and translated to the actuators.

***How BSC's solution is positioned from a technology perspective?***

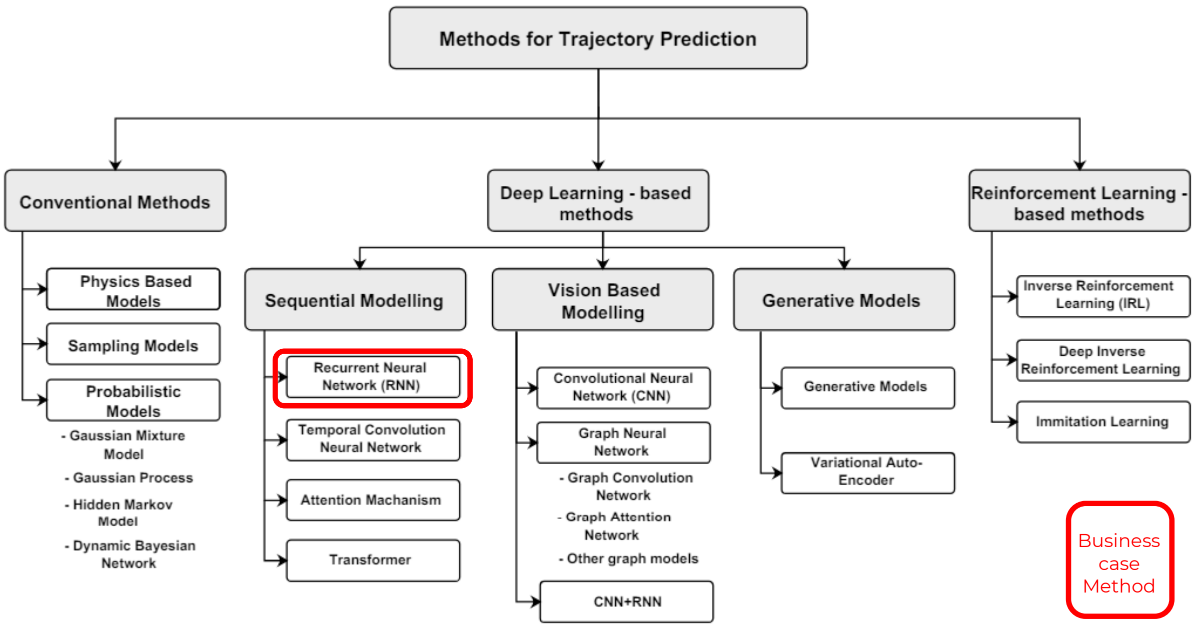



***Fig 22: Categorization of methods for trajectory prediction task***
Source: Machine Learning for Autonomous Vehicle's Trajectory Prediction: A comprehensive survey, Challenges, and Future Research Directions.

Conventional prediction techniques are only effective in basic prediction scenarios and short-term prediction assignments. **Deep learning-based trajectory prediction models have gained popularity due to their ability to consider various factors that contribute to accurate predictions**. These models take into account physical factors, such as the position, velocity, acceleration, size, and shape of vehicles. They also consider road related factors like traffic signs, traffic lights, road geometry, and road obstacles. Additionally, interaction-related factors, including the distance between vehicles, relative speeds, and the presence of communication systems, are considered. These models have been largely discussed in the literature, with different network architectures and approaches.

NEUROPULS use case is using the sequential modeling, as depicted in Figure 23, based on RNN model to handle the temporal sequence of object locations. This approach is the most popular in the research around autonomous driving (Fig 24). Two of the most commonly used metrics to evaluate the quality of these models are **average displacement error (ADE)** and **final displacement error (FDE).**

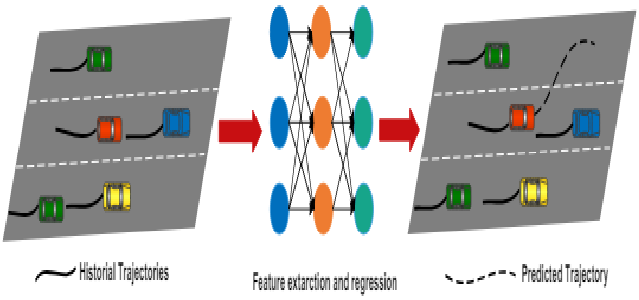



***Fig 23: The illustration of Deep Learning based methods***

Source: Machine Learning for Autonomous Vehicle's Trajectory Prediction: A comprehensive survey, Challenges, and Future Research Directions, Vibha Bharilya, and Neetesh Kumar, Member, IEEE, 2023

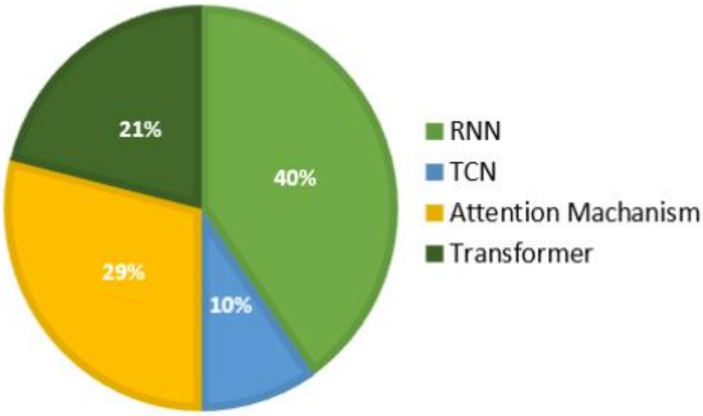



***Fig 24: Segmentation of research articles in trajectory prediction task***

Source: Machine Learning for Autonomous Vehicle's Trajectory Prediction: A comprehensive survey, Challenges, and Future Research Directions, Vibha Bharilya, and Neetesh Kumar, Member, IEEE, 2023

From HW perspective, this use case will leverage the advantages of NEUROPULS accelerator, breaking the CMOS bottleneck around picojoule/ (multiply-accumulate) operation. Considering a KPI of < 0.06 pJ / MAC OP (as agreed in the agreement proposal), this use case will be fulfilling to HW research requirements in term of energy efficiency for autonomous driving.

# 4.3.1Autonomous Driving Trajectory Prediction R&D Key players

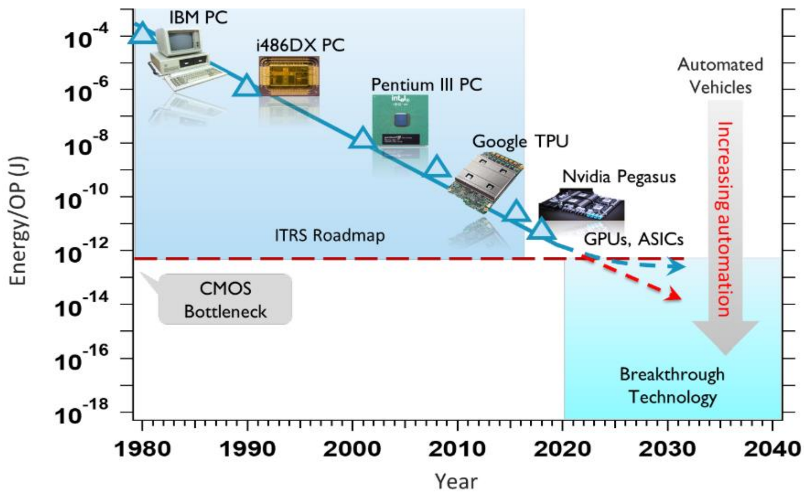



***Fig 25: Energy per Operation (OP) plotted versus Year. A new co-design paradigm will be needed to meet the energy efficient computing requirements of highly automated driving.***
Source: Energy Efficient Computing R&D Roadmap Outline for Automated Vehicles, Sandia National Laboratories, 2021

At the difference of the precedent use cases, we don't propose a lean business Caneva for trajectory prediction. This is due to the fact that BSC is not an industrial, and cannot go to a commercial exploitation. We believe that transfer to the market can follow one of the 2 following scenarios:

- Technology transfer from BSC to the market via its dynamic involvement in the field of autonomous driving.
- Implication of HPE in this use case, in addition to anomaly-based detection system for autonomous driving segment. This will constitute two main technological bricks that would strengthen HPE's position in this field.

According to future decisions that will be taken, we will work more carefully on the selected scenario. At this level, we propose to consider the R&D ecosystem for trajectory prediction solutions.

From Global Data Patent Analytics, we can highlight the main market leaders that are filing patents on this field. They are split according to:

- "Application diversity" measures the number of applications identified for each patent. It broadly splits companies into either 'niche' or 'diversified' innovators
- "Geographic reach" refers to the number of countries each patent is registered in. It reflects the breadth of geographic application intended, ranging from 'global' to 'local'.

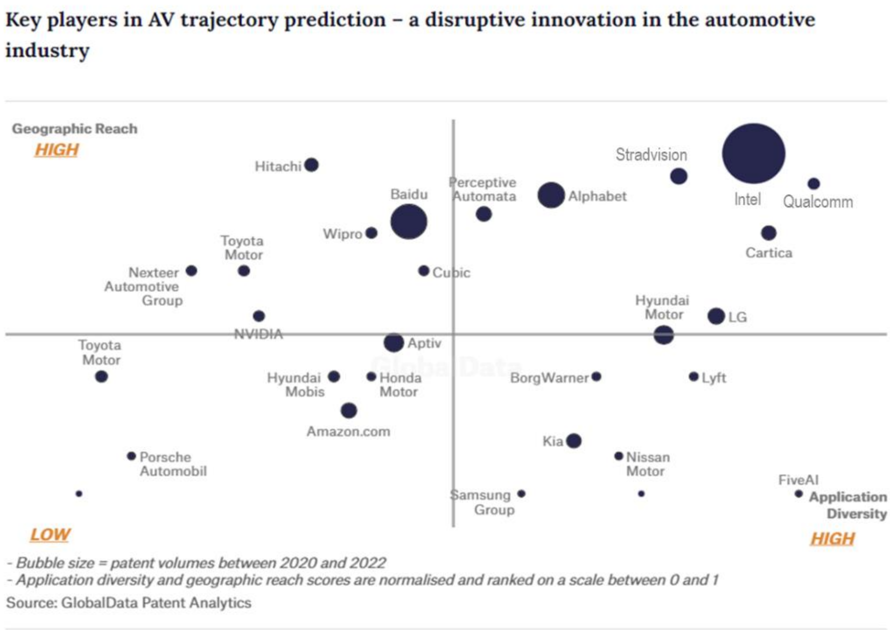



***Fig 25: Patenting Activity in AV trajectory prediction***
Source: Global Data Patent Analytics

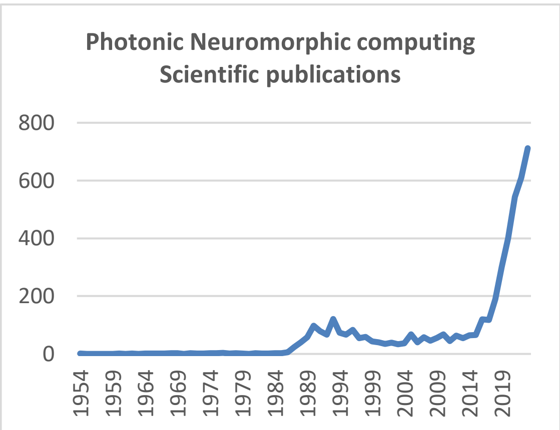
**Intel,** the top patent filer in autonomous vehicle trajectory prediction, has filed a system and method for autonomous vehicle trajectory prediction using a hybrid deep learning model. This innovative approach combines a neural network trained to predict other vehicles and pedestrians trajectories with a second network trained to predict the autonomous vehicle's trajectory. This patent is part of Intel's ongoing efforts to advance autonomous vehicle technology. **Baidu** and **Alphabet** are some of the other key patent filers in AV trajectory prediction. In terms of application diversity, **Qualcomm** leads the pack. **FiveAI** and **Cartica** stood in the second and third positions respectively. By means of geographic reach, **Intel** held the top position followed by **Hitachi** and **Stradvision.**

# 5. Photonic Neuromorphic computing: R&I landscape & market projections

The objectives of this section is first to provide an overview of Research ecosystem around the specific area of neuromorphic photonic computing, whose technological building blocks have low TRLs (2 and 3). This is key to guide the academics and research centers in the consortium, in their indirect exploitation routes, towards the most relevant players. We are proposing a bibliometric study to tackle this objective, considering worldwide data (patents & publications). Complemented by some available data, this section aims to assess the market readiness, and better anticipate the scenarios that photonic neuromorphic computing would penetrate the market. Additionally, by identifying the main dynamics and key players, we will have a vision of potential partners (direct or indirect) and/or competitors that exploitation activities should monitor cautiously during the project duration. It is to mention that, due to the early stages of NEUROPULS technology, we will restrict our consideration to this first general outlook, without going into a marketing study in this first update of the document.

## 5.1 R&D key indicators: main dynamics

Photonic neuromorphic computing has sparked a wave of research, and consequently an increasing number of scientific publications. Performing a bibliometric study, we can notice that this number has been accelerating since 2017, with a CAGR of +35% between 2017 and 2023. The number of patents has also grown in the same period with a CAGR of +24% (between 2017 and 2022).



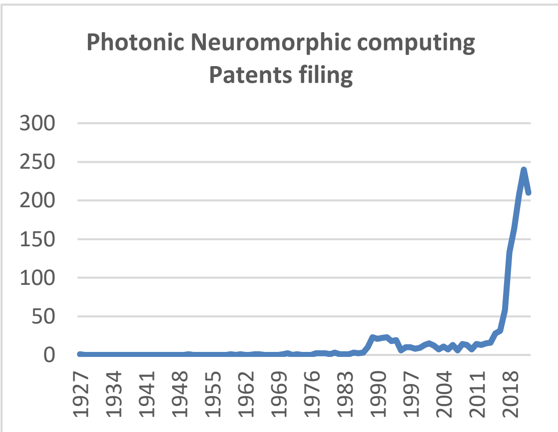
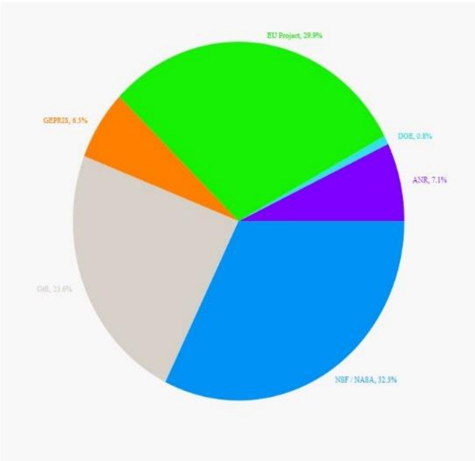




*Fig 26: R&D indicators for photonic neuromorphic computing technology*
Source: Internal analysis, IPMETRIX tool

Regarding collaborative projects, since 2019, we have accounted in our data base 127 projects coming from:

- European Projects: (Horizon, H2020)
- GEPRIS: European Group for the Promotion of Systems Engineering Research
- GtR refers to "Großforschungsprojekt des Bundes und der Länder", which are major collaborative research projects jointly funded by the German federal and state governments.
- ANR refers to "Agence Nationale de Recherche" is the main funding agency for research projects in France.
- DOE refers to projects funded by the US Department Of Energy.
- NSF/NASA refers to projects jointly funded by the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) in the US. NSF is the main federal funding agency for non-medical basic research in the US



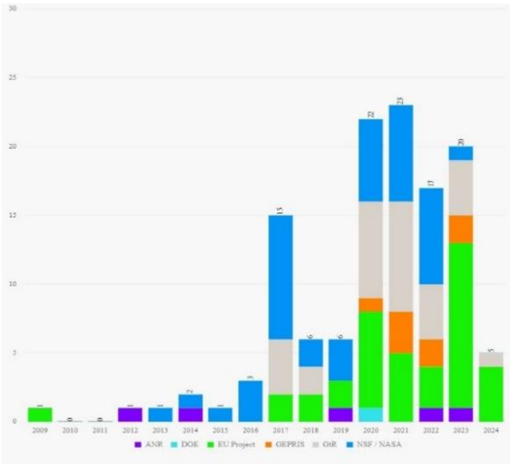




***Fig 27: Collaborative projects for photonic neuromorphic computing technology development***

Source: Internal analysis, IPMETRIX tool

It is to highlight that European commission is funding 30% of total number of collaborative projects regarding this area, just after NSF/NASA (Fig 27). Completed with GEPRIS, Europe seems to offer the most dynamic financing programs generating the most collaborative projects. This trend has accelerated during last 4 years, which confirms the priority given to this technology. Across national programs, NSF/NASA is the main one in the US, and its programs have been carried out much earlier, since 10 years. Regarding other countries, we have identified GtR in Germany funding almost quarter of total number of programs, followed by ANR in France with 7%.

## 5.2 Main players from Research Perspective

### 5.2.1 Main players from bibliometric study

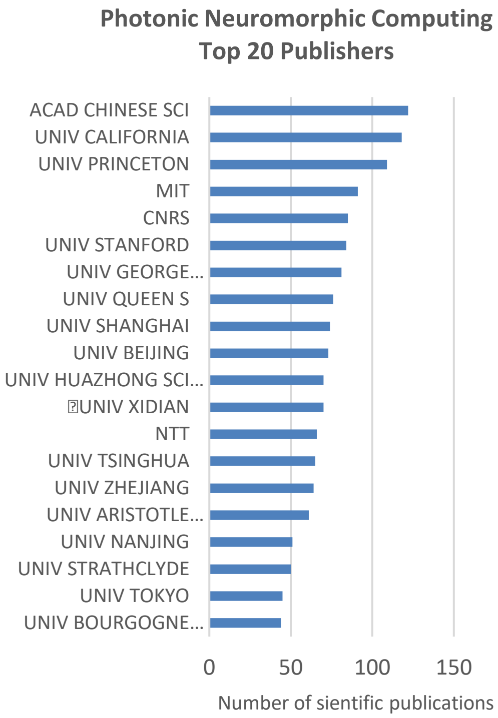



***Fig 28: Top 20 publishers in photonic neuromorphic computing technology***
Source: Internal analysis, IPMETRIX tool

Following this bibliometric study, we can identify main players that have been publishing or contributing to collaborative projects or filing patents, regarding photonic neuromorphic computing.

*20 top players out of a large number of publishers have 1468 documents out of 4825 scientific publications. This highlights that they are dominating the research landscape with **ACAD CHINESE SCI**, in the first ranking (122 publications), followed by American universities: **university CALIFORNIA** (118) **university PRINCETON** (109), **MIT** (91), university **STANFORD** (84) and **G.WASHINGTON** (81). Many Chinese universities are coming in the top players (**Beijing, Xidian, Huazhong, Shanghai, Tsinguha…**). In the European ecosystem, we can identify **CNRS**, university **of Arhistotle of Thessaloniki** and university of **Strathclyde**, followed by **university of Ghent**.

Moving to patents landscape (Fig 29), we highlight those 20 top players out of a large number of patents filers, have 442 out of 1640 patents. Similar to scientific publications, the landscape is oligopolistic, but top players are composed of companies and academics. Chinese academics are coming in the first ranking, especially with **University of BEIJING**, having 68 patents. Among top industrials, we can highlight **IBM**(18), in addition to number of players especially in Japan (**NTT, KODAK, Hitachi**) and in South Korea(**RICOCH, ETRI, SAMSUNG**).

*Regarding players who have been involved into collaborative projects, we recognize academics who have already cited above in scientific publications and patenting in European and US ecosystems. Additionally, UK academics arise within multiple organizations: University College of London, Imperial College London, university Southampton, college Cork, university Oxford and Manchester. German academics are also there with Fraunhofer and university Heidelberg Ruprecht Karl.

Few companies seem to be involved a part from **IBM**, who has the strongest number of collaborative projects (13), **HPE** and the swiss **Lumiphase**.

## 5.2.2 Collaborative networks

In order to understand the landscape dynamics, it is important to identify inter- and intra- ecosystems networks, especially regarding academics and research technology organizations that seem to be at this level, the most active to bring the maturity level of photonic neuromorphic to the next stage, and transfer it to industrial players.

We propose to split the ecosystems across regional repartition:

- Europe
- North America
- Asia Pacific (APAC)

We consider all collaborative options, either via co-publications, or co-patenting, or via collaborative projects consortium. As criteria, we consider only links > 4 documents in common (patents and/or publications)

*European ecosystem seems to be very dynamic, especially in France, UK, and Belgium. Other local ecosystems are operating in Italy, Spain, Greece and Russia. The main organizations with the strongest number of documents, and which are building networks at national, European and even international level, are:

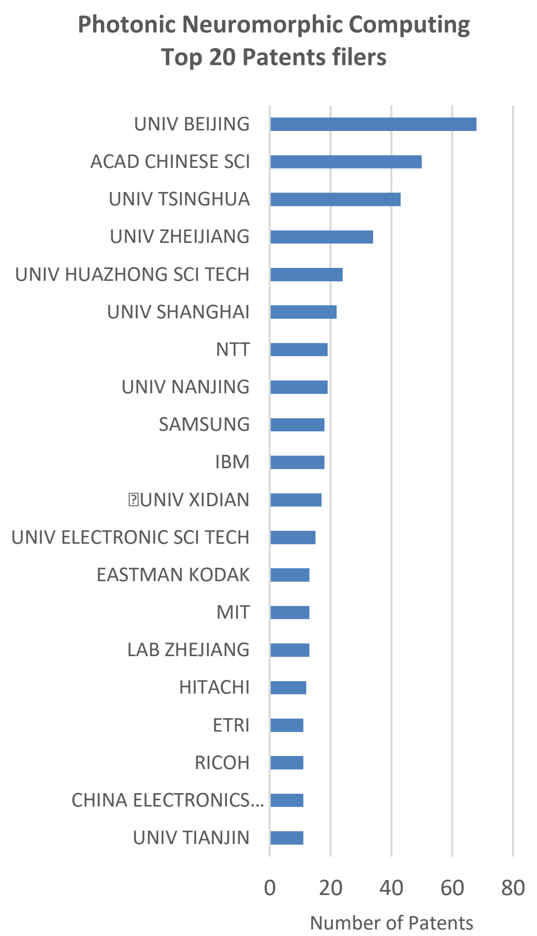



***Fig 29: Top 20 patents filers in photonic neuromorphic computing technology***
Source: Internal analysis, IPMETRIX tool

- **CNRS** with many collaborations in France, Germany (**UNIV TECHNISCHE BERLIN**), and Spain (**UNIV ILLES BALEARS**)
- **University of Ghent** with collaborations in Belgium (**IMEC**), Germany (**university of Munster**), UK (**university of Oxford**...). It is also collaborating with **IBM**
- **University Strathclyde and University Oxford** (UK) with many collaborations oriented to academics in Europe. Both of them are also operating in the local system. University Strathclyde is collaborating with the Chinese university Southwest.

*APAC ecosystem is strongly dominated by Chinese academics that are multiplying collaborations in China, at their head **ACAD CHINESE SCI**. Universities of **Shenzhen, Xidian, Nanjing, Fudan and Shanghai** are playing also a predominant role. Only the universities **City Hong Kong** and **University Electronic Sci Tech** are extending their collaborations outside of China, mainly with Australian universities (**RMT, Monash, Swinburne…**).

A number of Japanese industrials collaborating with academics characterizes APAC ecosystem also:

- **NTT:** collaborating with MIT, UNIV Nagoya & Tokyo, Cornell, and UNIV Technische Berlin
- **MITSUBISHI:** collaborating with UNIV Purdue
- **TECHX** collaborating with UNIV Colorado and Stanford
- **NEC** collaborating with UNIV Princeton

*North American ecosystem appears very dynamic with American universities: **university California, Princeton, George Washington, MIT,** which are actively publishing (> 100 documents), and they are leading the academic landscape. **University Queen's** (Canada) is also very active. One specific characteristic of the North American ecosystem the presence of many industrials that are collaborating in the local and international landscape:

- **IBM:** collaborating with UNIV GHENT and the swiss LUMIPHASE
- **Optelligence:** collaborating with UNIV California and UNIV G. WASHIGTON
- **Omga Optics** collaborating with UNIV Texas and UNIV G. WASHIGTON
- **Synopsys & Alpine Optoelectronics** collaborating with UNIV Texas
- **NVIDIA** collaborating with MIT
- **CELESTIAL AI:** collaborating with UNIV ARISTOTLE THESSALONIKI

**NIST (National Institute of Standards and Technology),** a non-regulatory agency of the US Department of Commerce that promotes innovation and industrial competitiveness, is the second American player.

**In Summary,** European commission is funding 30% of total number of collaborative projects in the field of photonic neuromorphic computing just after NSF/NASA. Compared to other ecosystems, Europe's dynamism is strongly led by RTOs and academics of international notoriety. APAC and North American ecosystems possess strong industrials from the semiconductor and telecommunication fields, that are driving the R&I and could give them a step ahead of European players. Among these industrials, some leaders in the computing field (e.g. NVIDIA, IBM) or Startups (e.g.

# 5.3 Market Overview

## 5.3.1 Market Size & Forecast

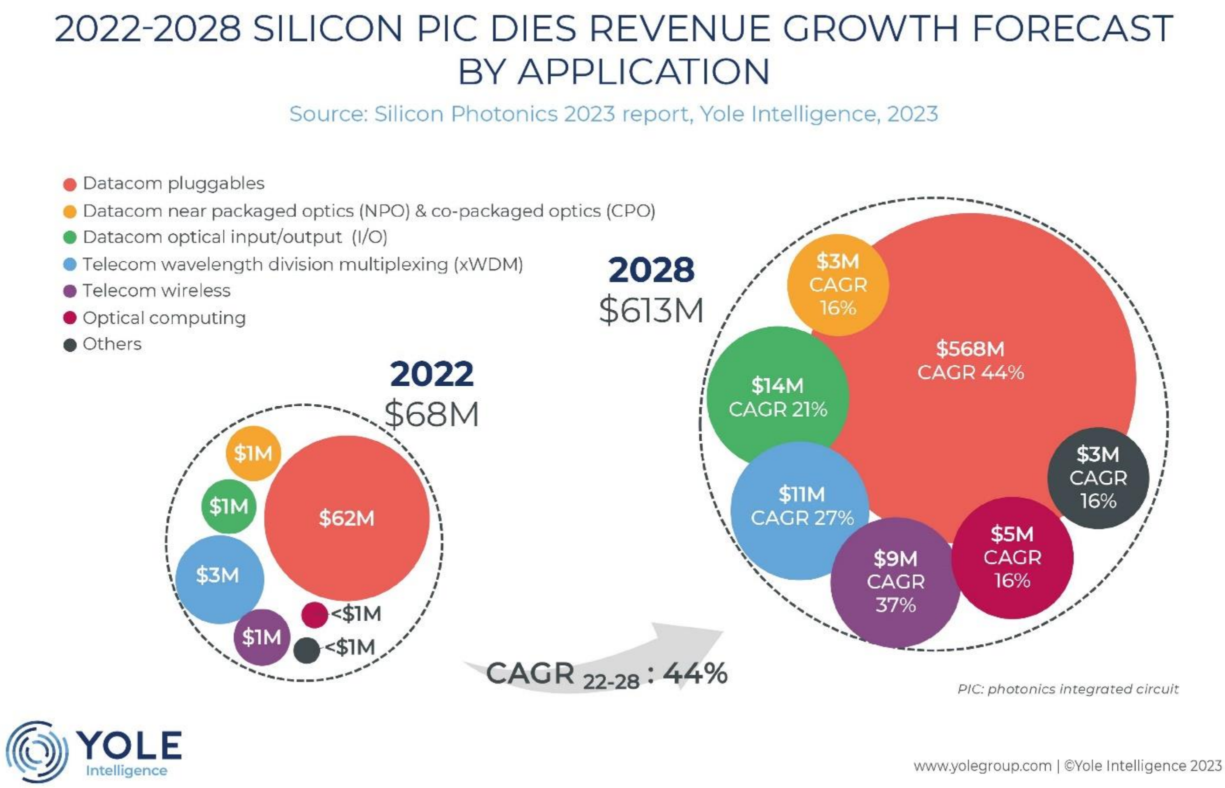



*Fig 30: Silicon Photonics Market (2022-2028)*
Source: Yole, Silicon Photonics report, 2023

According to Yole, silicon photonic processing segment should penetrate the global silicon photonic die market, to reach 5 Million $ in 2028.

### 5.3.2 Main industrials with the highest R&I indicators

We highlighted from the bibliometric study that main R&I indicators, are coming from academy. Photonic Neuromorphic is still at early TRL levels.

Nevertheless, it is worth examining the trends of some industrials and startups concerning their publishing and patenting activities (Fig31).

We can identify different players, of different sizes, business models and operating differently in the value chain. Quantitatively, giants from the semiconductor industry are the most involved. But we notice a large number of new entrants and startups in this field. Some key players, from Telecom field have a leading position (NTT). Photonic chips have been historically linked to networks & communication.

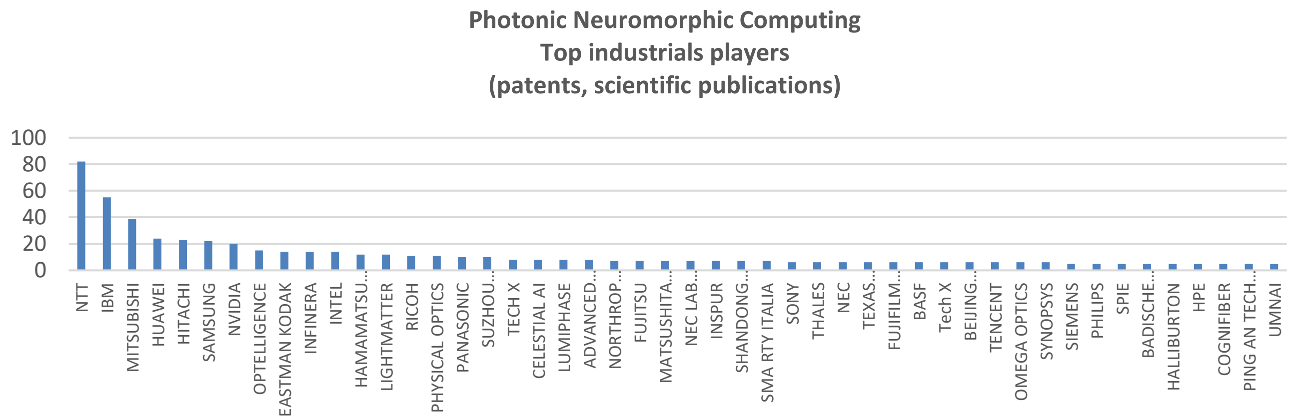



*Fig 31: Top industrials from bibliometric study*
Source: Internal analysis, IPMETRIX tool

### 5.3.3 Startups and New entrants:

In recent years, a number of startups, developing new solutions for optical I/O & optical accelerator chips for AI, has strongly entered the landscape of Si Photonics. We don't consider here adjacent domains such as optical transceivers, or optical LIDARs, experiencing the same dynamics.

Following is an overview of fundraising, showing an acceleration towards commercialization. Strong leaders are investing in these startups.


*Fig 32: Segmentation of industrial players*

| Company | Date | Product | Raised funds (in USD) | Investors | National Transaction |
|---|---|---|---|---|---|
| Lightmatter | May 2023 | Optical I/O & Photonic processor | $154M | SIP Global, Fidelity Management & Research Company, Viking Global Investors, GV (Google Ventures), HPE Pathfinder and existing investors | Will leverage this new financing to arm some of the largest cloud providers, semiconductor companies, and enterprises with the power of photonic technology to bring a new level of performance and energy savings to the most advanced AI and HPC workloads |
| AyarLabs | May 2023 | Optical I/O | $25M | Boardman Bay Capital Management, HPE, Nvidia, Applied Ventures LLC, GlobalFoundries, Intel Capital, and Lockheed Martin Ventures, Agave SPV, Atreides Capital, Berkeley Frontier Fund, IAG Capital Partners, Infinitum Capital, Nautilus Venture Partners, and Tyche Partners, BlueSky Capital, Founders Fund, Playground Global, and TechU Venture Partners | The funding will be used to accelerate commercialization of Ayar Labs' silicon photonics technology, which uses light instead of electricity to transfer data between chips or servers, it added |
| iPronics | July 2022 | Photonic processor | €3.7M | Amadeus Capital Partners, with participation from Caixa Capital Risc | To back the team to advance the concept of programmable photonics |
| Salience Labs | May 2022 | Photonic computing | $11.5M | Cambridge Innovation Capital and Oxford Sciences Enterprises, with Oxford Investment Consultants, former Dialog Semiconductor CEO Jalal Bagherli, ex–Temasek Board Member Yew Lin Goh, and Arm–backed Deeptech Labs | Seed round. |
| AyarLabs | April 2022 | Optical I/O | $130M | Boardman Bay Capital Management, HPE, Nvidia, Applied Ventures LLC, GlobalFoundries, Intel Capital, and Lockheed Martin Ventures, Agave SPV, Atreides Capital, Berkeley Frontier Fund, IAG Capital Partners, Infinitum Capital, Nautilus Venture Partners, and Tyche Partners, BlueSky Capital, Founders Fund, Playground Global, and TechU Venture Partners | Accelerate commercialization. |
| Luminous Computing | March 2022 | Light-based AI accelerator chip | $105M | Microsoft cofounder Bill Gates, Gigafund, 8090 Partners, Neo, Third Kind Venture Capital, Alumni Ventures Group, Strawberry Creek Ventures, Horsley Bridge, and Modern Venture Partners | Funds will primarily go towards doubling the size of the engineering team, building out Luminous' chips and software, and gearing up for "commercial-scale" production. |
| Celestial AI | February 2022 | Photonic AI accelerator chips | $56M | Temasek's Xora Fund, The Engine, Tyche Partners, M-Ventures, IMEC XPand, and Fitz Gate | To commercialize its Orion AI accelerator product. |
| Alpine Optoelectronics Inc. | August 2021 | Silicon photonic optical engines | $44.4M | optolink | To acquire Si photonics technology. |

***Table 3: Fundraising in Si Photonics for Computing***
Source: Si Photonics 2023, Yole

**In Summary,** we foresee a strong positive signal from market projections: silicon photonics dies market for computing will emerge and reach 5 Million$ in 2028. From R&I indicators, we highlight a strong involvement from giants in the semiconductor and Telecom players: the silicon photonics for neuromorphic computing value chain seems to progress in a positive way. Meanwhile, multitude of startups have flourished in the recent years, with promising solutions for silicon photonics computing, providing the different puzzle pieces that are still missing for a robust, scalable and integrated silicon photonics ecosystem.

Although these startups can accelerate the market penetration, we believe that commercial scale would involve strong industry leaders in the emergent applications (autonomous driving, edge cybersecurity …).

# 6. Conclusion & Perspectives

At this stage of the project, Exploitation activities have validated the main hypothesis for a potential use of the expected results and outcomes.

- Positioning of NEUROPULS core technology, the photonic neuromorphic computing, considering the expected performances, is very promising for secure AI workloads running on the Edge.
- Positioning of NEUROPULS, as a whole platform, exploiting the core technologies and flexible infrastructure and modular design, for the industrial business cases, presents functional and technical relevancy. Moreover, it may provide the industrial leaders, in the consortium, with a competitive advantage in case of commercial rollout.
- R&I indicators from the bibliometric study, attest to high level of dynamics in the different ecosystems. Involvement of giants from the semiconductor and Telecom sectors, in publishing and filing patents, demonstrates the attractiveness of the photonic neuromorphic architectures for an industrial exploitation.

Considering these hypothesis, we identified main indirect and direct routes for Exploitation Key Results (KER) :

- IP generation, open-source tools & data, and use of results for further research activities. At this level, we have emphasized the advantages that partners bring in terms of resources, connections, and international notoriety, which can accelerate their already identified routes. In term of content, beyond the technology building blocks for the photonic IC development, we have identified the quantum photonics with photonic qubits as promising area to exploit the Integrated PCMs and III-V photonic platform.
- Business canvas for GNSS-antijamming and anomaly-based detection business cases, as methodological foundations for a potential commercial exploitation. The Autonomous Driving business case was analyzed, but without a business canvas at this stage. This will be considered depending on whether an industrialization scenario arrives from an industrial player later in the project.
- A business canvas for Argotech to leverage its optic coupling solution, to enhance its portfolio of packaging solutions.

Finally, some market data regarding the projections in terms of revenues, and key players, make us aware both of the acceleration of the market, but also of the threats that this can represent to our exploitation activities over the project duration. While a "game changer" is still missing, if the market takes off strongly, our industrial partners, would adapt to a new market context, and risk losing their competitive advantage. We can flag a further risk factor linked to the relevancy of our KPIs, during the project period. Although the promising performances of photonic neuromorphic architectures, that seem to attract a considerable interest from academia, industry and investors, we can note assume immunity from innovative approaches, or technologies that make our KPIs obsolete. A mitigation plan should be investigated to overcome these scenarios.

Naturally, the intrinsic risk factors of NEUROPULS exploitation is linked to the project success in term of convergence between the different layers: material development and fabrication, device, architecture and prototype development, security layers development, full system simulation platform & use cases implementation. Mitigation actions do not have the same severity depending on the disconnect that could arise.

Thus, in the coming reporting period, we will work on monitoring the risk factors that may hinder our exploitation plan. This will include mitigation actions that we should set, individually for each partner. In addition to that, we will set a roadmap for the identified exploitation routes, to plan the execution of the exploitation activities during and after the project. Last but not least, we will follow up the advancements of the operational aspects.