INTELLIGENCE TO SHAPE YOUR TOMORROW

The Rise of Neuromorphic Sensing and Computing: Technology Innovations, Ecosystem Evolutions and Market Trends

Edge AI and Vision Alliance Webinar

11 July 2024

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YOLE Intelligence

YOLE GROUP

We provide industrial companies, financial investors and R&D organizations, with market research and marketing analysis, technology, supply chain and cost analysis, as well as performance evaluation, to help our customers in their decision-making about their future business and manufacturing strategy in the semiconductor, photonic and electronic sectors.

3 CORE ACTIVITIES BASED ON DEEP SYNERGIES

Market & Technology	Teardown Reverse engineering and costing	Performance analysis
• Market, technology, and strategy consulting • M&A, Due Diligence and evaluation of companies	• Technology, process & cost analysis • Teardown and reverse engineering • Comparative analysis	• Test of electric and electro-optical performance of devices • Comparison of performances and related technical choice

OUR EXPERTISE

SEMICONDUCTOR INDUSTRY

- Imaging
- Battery
- Display
- Electronic Systems
- Computing and Software
- Compound Semiconductor
- Global Semiconductor Trends

- Memory
- Photonics and Lighting
- Power Electronics
- Radio Frequency
- Semiconductor Equipment
- Semiconductor Packaging
- Sensing and Actuating

COMPUTING AND SENSING EMERGING TECHNOLOGIES
The three emerging technologies analyzed by Yole Group

In 2024, Yole Group will address the three primary emerging new computing methods, with each approach featured in a separate report.
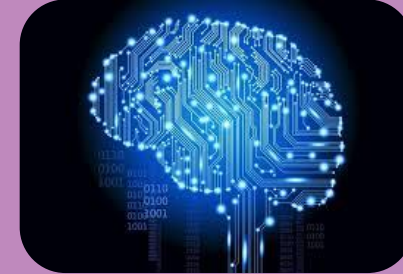
Today Webinar

Quantum Technologies 2024

Optical Computing 2024

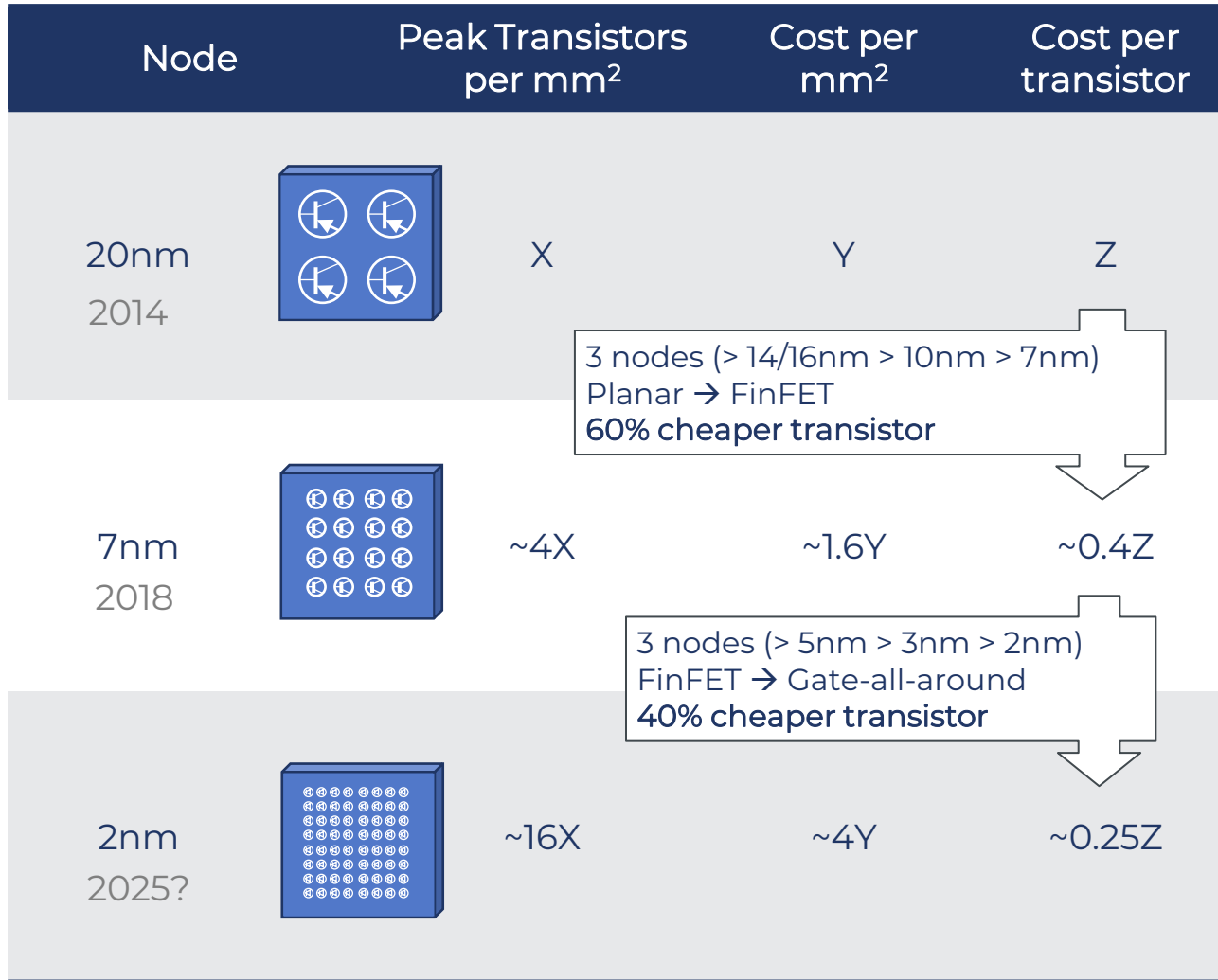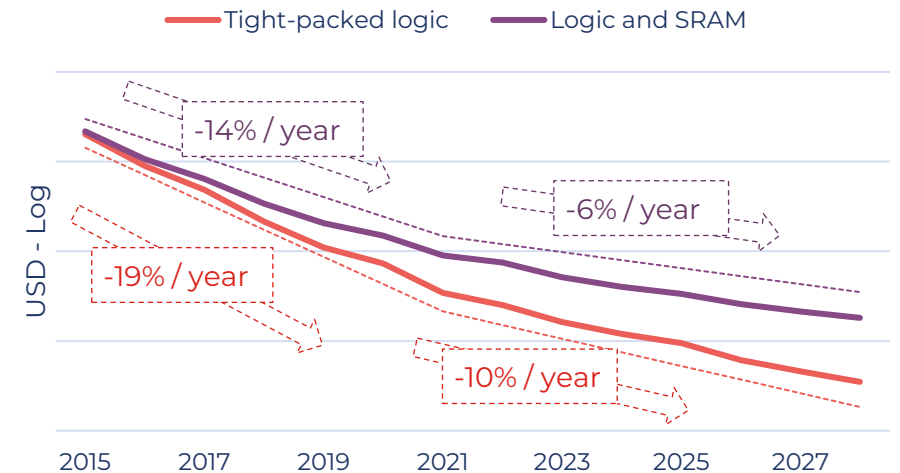Neuromorphic Computing, Memory and Sensing 2024

EMERGING FORMS OF COMPUTING

NEUROMORPHIC PRINCIPLES

CONTEXT
Transistors are getting smaller, but are they still getting cheaper?

Node	Peak Transistors per mm²	Cost per mm²	Cost per transistor
20nm 2014	X	Y	Z
7nm 2018	~4X	~1.6Y	~0.4Z
2nm 2025?	~16X	~4Y	~0.25Z

> 3 nodes (> 14/16nm > 10nm > 7nm)
> Planar → FinFET
> **60% cheaper transistor**

> 3 nodes (> 5nm > 3nm > 2nm)
> FinFET → Gate-all-around
> **40% cheaper transistor**

- The advancement toward more densely packed logic has come with ever-increasing manufacturing complexity and cost.

- Processors are not built purely from logic cells, and the cost scaling for these non-logic building blocks moves even slower.

- From about 2021, we see an inflection in this cost curve from the even higher costs of 5nm and 3nm nodes

Leading Edge Cost per Transistor

— Tight-packed logic — Logic and SRAM

-14% / year
-6% / year
-19% / year
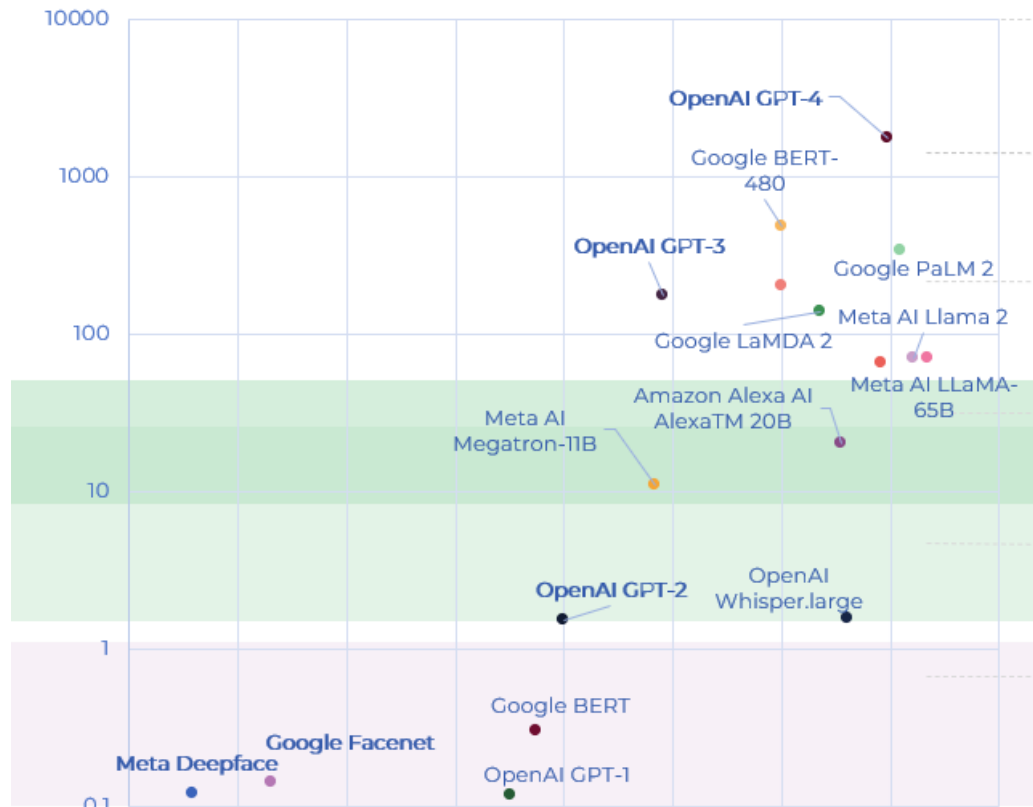-10% / year

USD - Log

2015 2017 2019 2021 2023 2025 2027

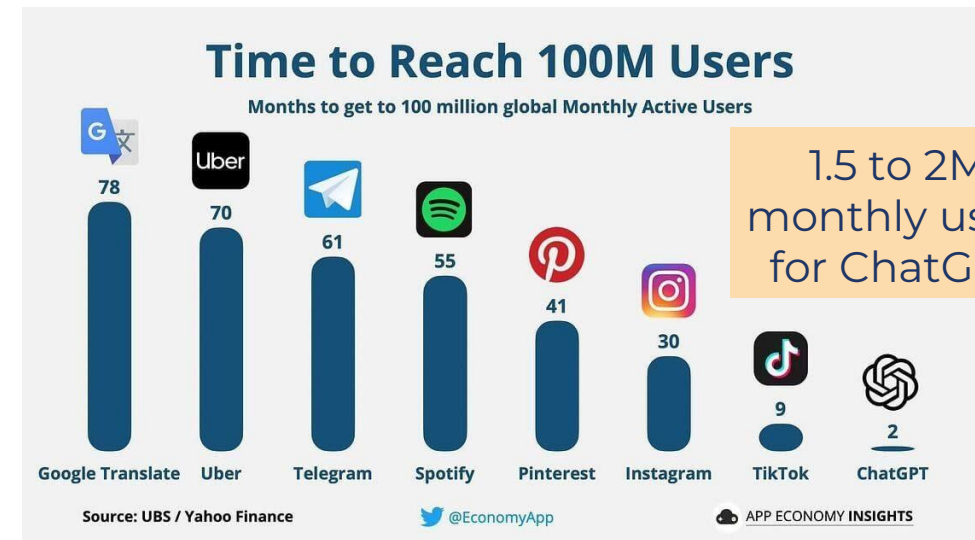# The emergence of LLM and AI models: bigger models more and more used

Bigger and bigger DNNs are being used, especially for Natural Language Processing applications. Transformers are one of the models used explicitly for NLP; the network can be massive with billions of parameters, and the training requires ever-increasing computing resources.

LLM and generative AI models are becoming very popular. This massive growth in AI usage is new, and the direct consequence is that associated inferences require more and more computing resources.

AI Models size evolution (in Billion parameters)

The success of Chat-GPT

Time to Reach 100M Users
Months to get to 100 million global Monthly Active Users

1.5 to 2M monthly users for ChatGPT

Google Translate	Uber	Telegram	Spotify	Pinterest	Instagram	TikTok	ChatGPT
78	70	61	55	41	30	9	2

Source: UBS / Yahoo Finance   @EconomyApp   APP ECONOMY INSIGHTS

THE BRAIN AS A MODEL
Improve performance, reduce consumption

The brain is capable of far more than the classic AI architecture.

Brain simulation by traditional computing hardware

100 billion neurons
x
~10,000 synapses
=
1 quadrillion synapses

1.5 million processors
+
1.6 petabytes of high-speed memory

2L volume

~20W
480Wh in one day

2 buildings

~10MW
240MWh in one day
~ 100GWh in 1 year

1 ExaFLOP of performance
1 billion calculations/second

Needs **years** to simulate one day of brain activity

2. In-memory computing

3. Analog computing

1. Parallelism

4. Plasticity

5. Probabilistic computing

10. Non-linearity

6. Scalability

9. Causality
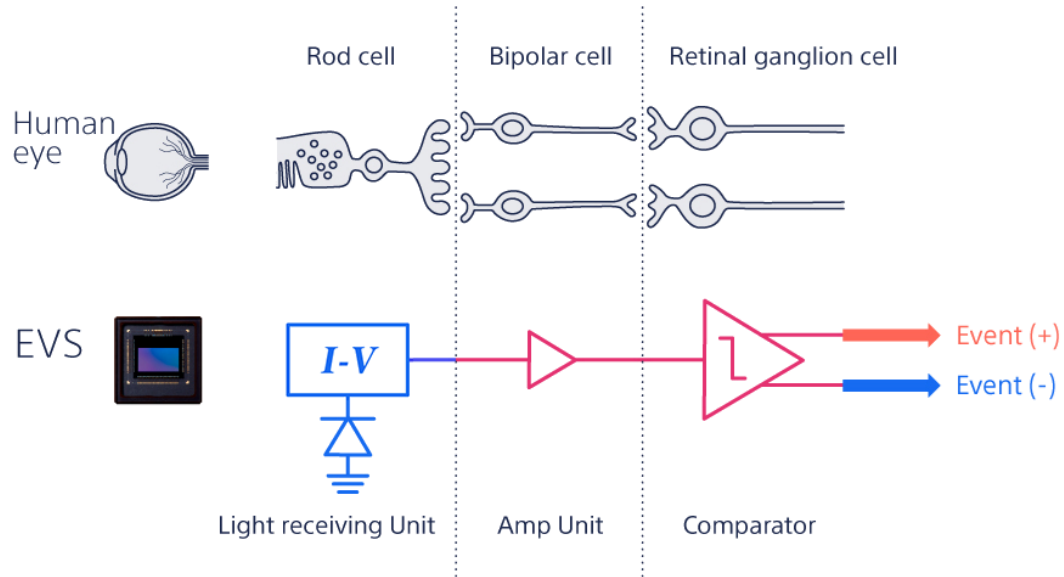
8. Learning

7. Sparsity
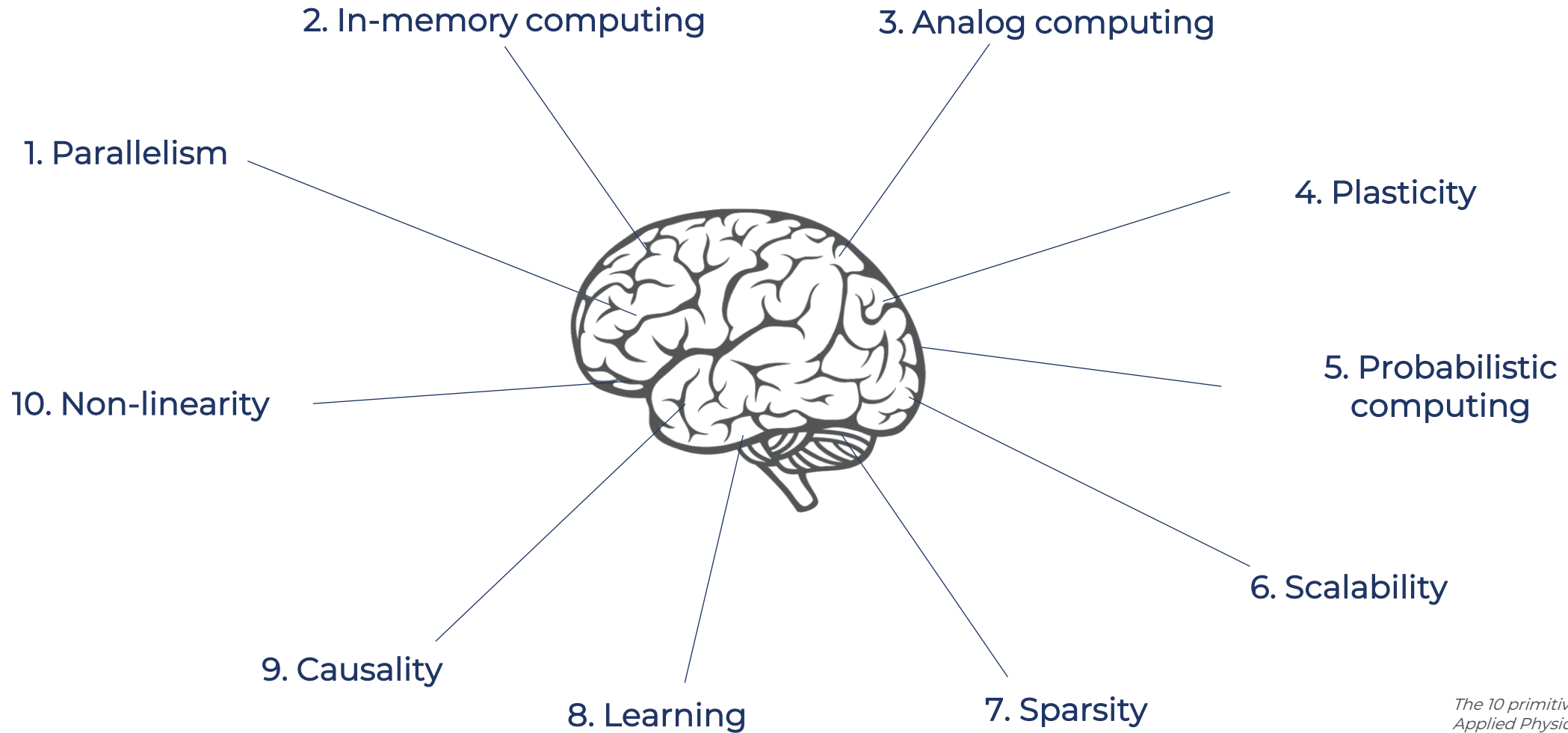
The 10 primitives are extracted from Applied Physics Reviews "The building blocks of a brain-inspired computer" Jack D. Kendall and Suhas Kumar, Rain Neuromorphics and HP Labs, respectively. Year 2020
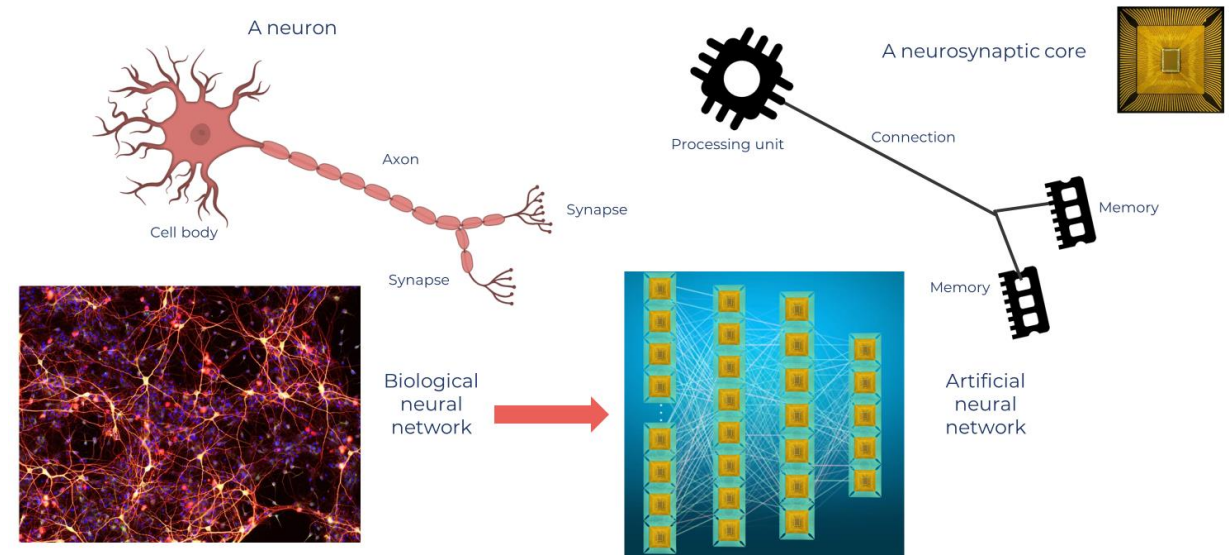
Sensing: Mimicking the human retina

Source: Sony

Computing: Mimicking the human neurons

NEUROMORPHIC APPLICATION DRIVERS
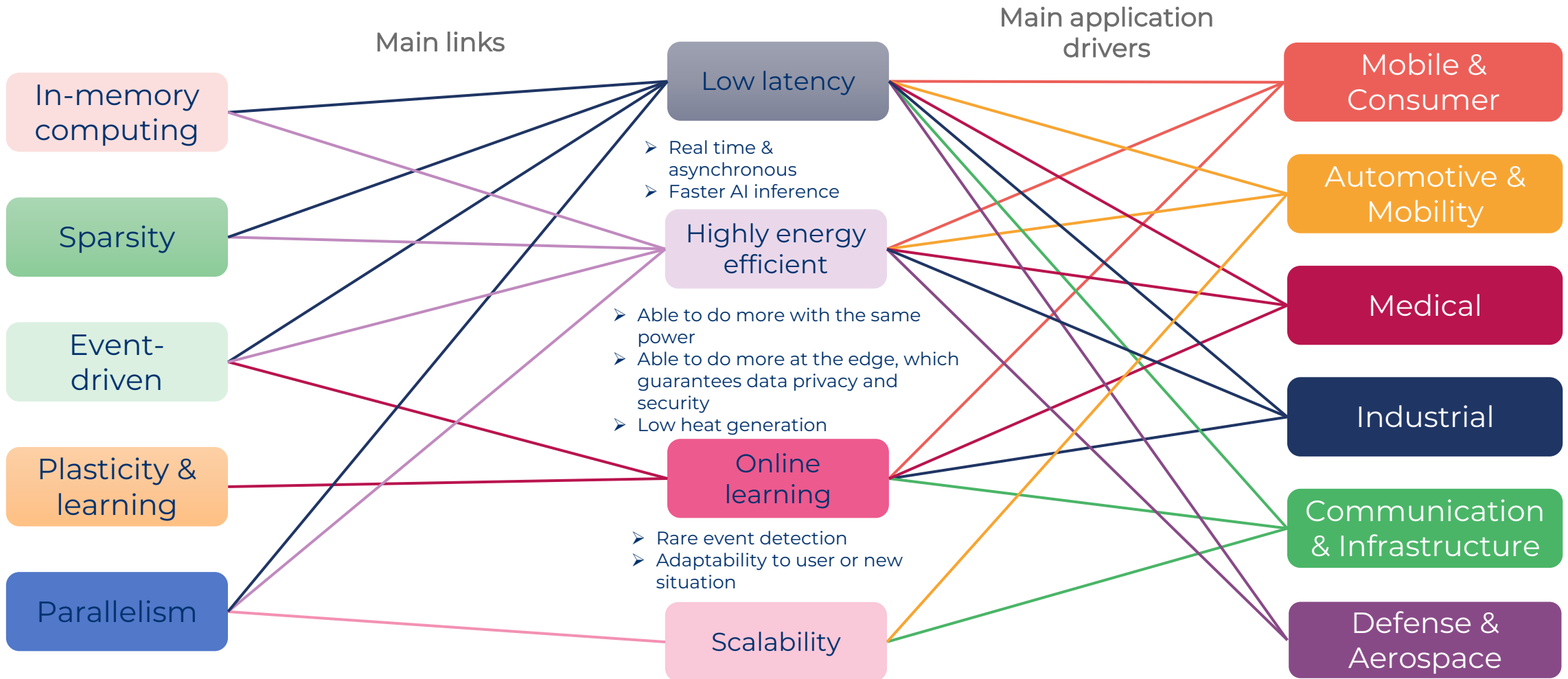## Neuromorphic attributes, assets and applications

Main attributes

Neuromorphic assets

Market

Main links

Main application drivers

In-memory computing

Sparsity

Event-driven

Plasticity & learning

Parallelism

Low latency
➢ Real time & asynchronous
➢ Faster AI inference

Highly energy efficient
➢ Able to do more with the same power
➢ Able to do more at the edge, which guarantees data privacy and security
➢ Low heat generation

Online learning
➢ Rare event detection
➢ Adaptability to user or new situation

Scalability

Mobile & Consumer

Automotive & Mobility

Medical

Industrial

Communication & Infrastructure

Defense & Aerospace

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WHAT IS THE NEUROMORPHIC PROMISE?

For cameras sensors, improving image quality, data monitoring and compactness…

IMAGE QUALITY

- Increased low light sensitivity
- Wider dynamic range
- More robust

DATA MONITORING

- More significant data
- Lower latency
- More intelligence
- More privacy

COMPACTNESS

- Smaller footprint
- Lower power

TECHNOLOGY TRENDS
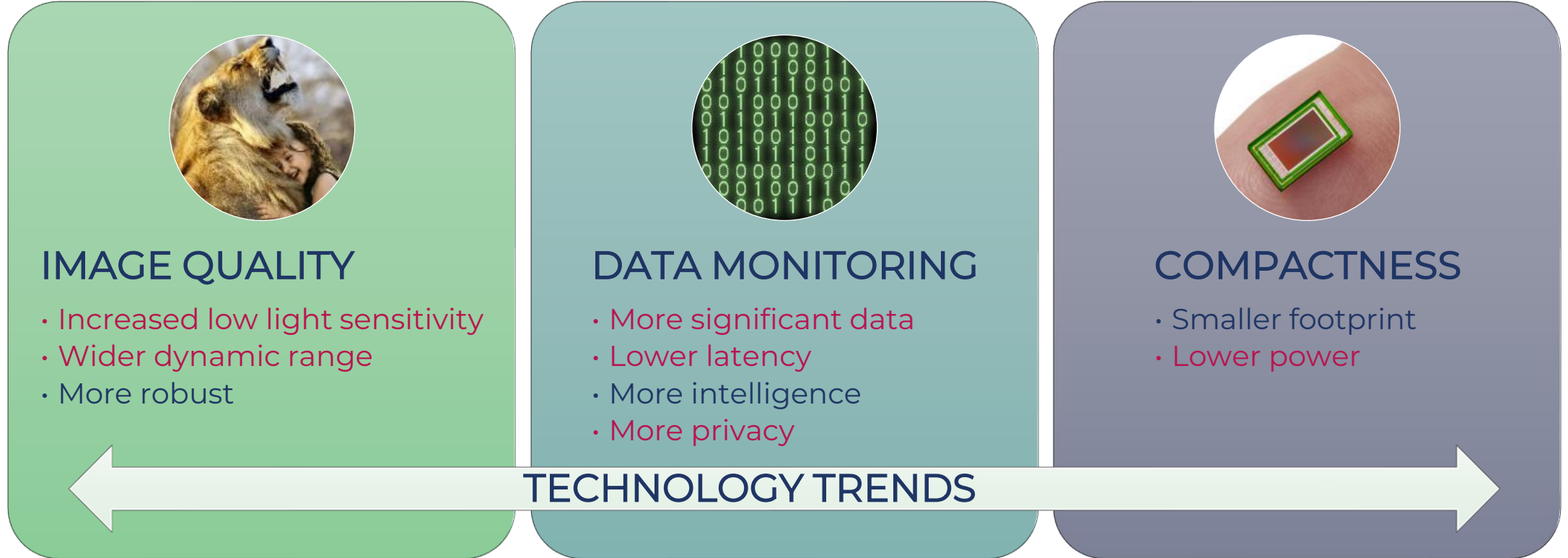
- Neuromorphic sensing is addressing numerous desired technological challenges in CMOS image sensor technology evolution: low light sensitivity and dynamic range improvements, lower latency and power consumption, and favoring better data privacy.

WHAT IS THE NEUROMORPHIC PROMISE?
Neuromorphic computing: More and better AI

Sustainable innovation

Disruptive innovation

Improve existing AI

Expand existing AI

Go beyond existing AI

➢ **More efficient AI**
- Lower power
- Lower latency

➢ **More adaptable AI**
- Fault tolerant
- More robust

➢ **Bring AI to the edge and extreme edge,** where power or heat constraints prevent conventional AI from being deployed.
- Lower power
- Lower heat
- Privacy respected

➢ **Enable always-on AI**
- Energy efficient always-on sensing

➢ **Enable edge online learning**
- Improve AI personalization
- Make possible new use-cases

➢ **Enable learning with little data**
- More efficient learning

✓ Run existing DNN/CNN faster and much **more power-efficiently.**
✓ Make AI more environmental-friendly.

✓ **Distributed intelligence** through a **network of edge sensors.**
✓ Good environmental understanding for robots.

✓ More **natural human/robot interaction** with voice command or gesture recognition.
✓ Enable more **robot autonomy.**

NEUROMORPHIC APPLICATIONS

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MARKET SEGMENTATION OF NEUROMORPHIC TECHNOLOGIES

13 applications with 29 corresponding end markets and end systems have been analyzed.

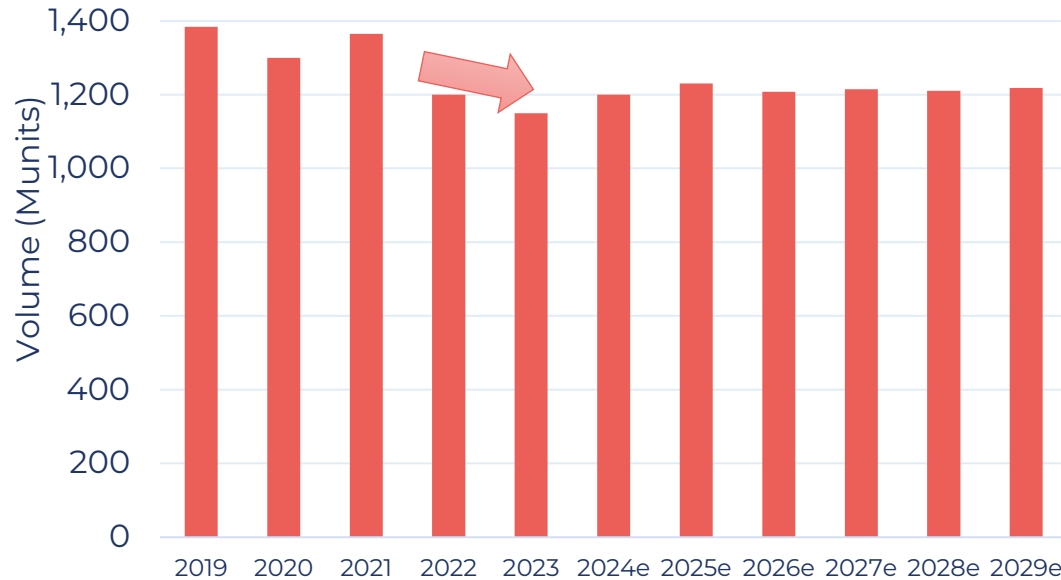| Market	Application	End-system
Mobile and Consumer	Mobile	Smartphone
	Entertainment	Consumer Drone, Action Cam, Headset – Earbud, AR/VR Headset
	Health	Smartwatch
	Home	Personal Robotics, Household Camera, Smart Speaker
	Productivity	Tablet, Laptop
Automotive and Mobility	Automotive	Forward Camera ADAS, Surround ADAS, In-cabin Camera, ADAS Domain Controller, Infotainment System, Sensor Monitoring
	Robotic vehicle	Robotic Vehicle
Medical	Diagnostic wearable	Vital Signs Monitor, Fall Detector
Communication and Infrastructure	Datacenter	Computing Server
Industrial	Logistics	Heavy Truck, AGV & AMR, Indus – Drone,
	Smart City/Building	Security Camera
	Manufacturing	Fixed Camera, Indus – Sensor Monitor
Defense and Aerospace	Defense and Aerospace	Defense and Aerospace

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NEUROMORPHIC APPLICATIONS - SENSING
The recent mobile market dynamics

What is the future of mobile imaging and sensing?

2019-2029 Smartphone total production *(in Munits)*

Volume (Munits)

1,400	
1,200	
1,000	
800	
600	
400	
200	
0	

2019 2020 2021 2022 2023 2024e 2025e 2026e 2027e 2028e 2029e

2019 - 2029 average number of cameras per smartphone handset

350%
300%
250%
200%
150%
100%
50%
0%

237%   261%   279%   281%   283%   287%   293%   297%   303%   310%

— Smartphones Rear camera   — Smartphones Front camera

- - - Previous forecast
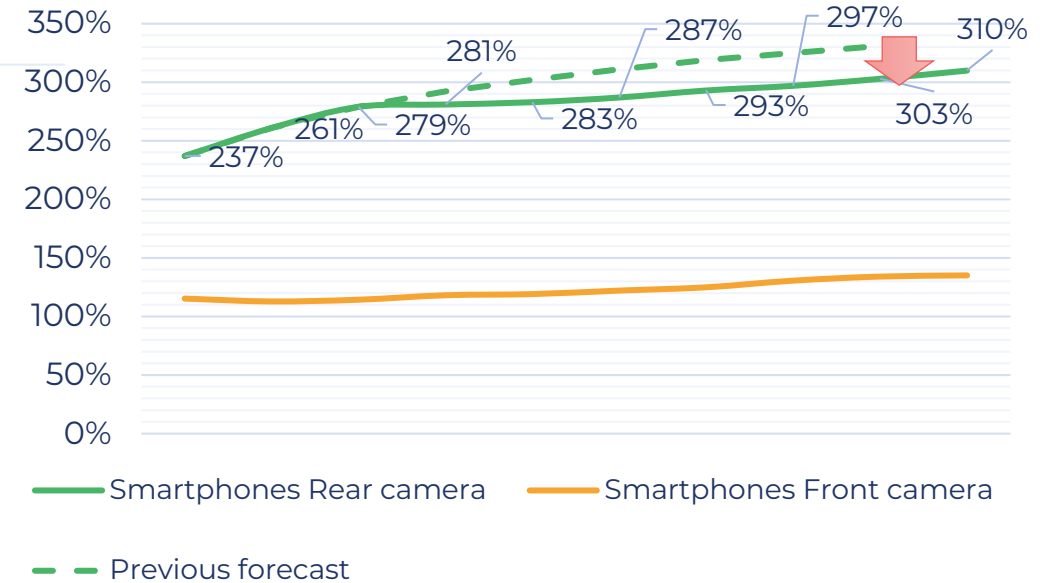
Decrease in 2022 and longer-term expectations for smartphone shipments by about 10%.

Deceleration in the increase of the average number of cameras per smartphone.

Nokia 9 PureView

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NEUROMORPHIC APPLICATIONS - SENSING

Event-based and multispectral cameras expected in flagship smartphones...

Courtesy of Nokia

> 2020   **> 2024**   **> 2028**

More 3D sensing cameras

+ Event-based cameras

+ Multispectral cameras

New imaging and sensing opportunities?

Front camera:
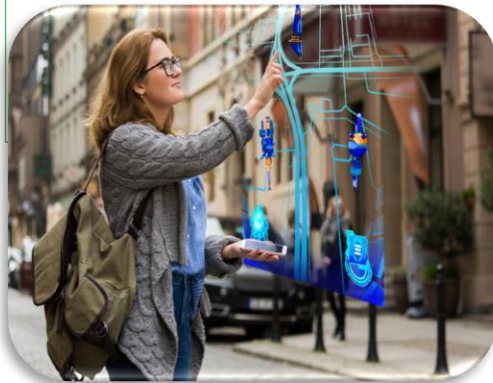Face identification
Rear camera:
Photography, bokeh effect
Augmented reality
Gaming...

Rear camera:
Live deblurring
Slow motion
SLAM...
Front camera:
Always-on user interface

Front camera:
Face identification
Rear camera:
Skin care, cosmetics
Accurate color photography...

NEUROMORPHIC APPLICATIONS - SENSING
Frame-based cameras are not good enough...

Motion blur, except for art, is limiting photograph quality

- Over the past decades, efforts have been made to improve the quality of frame-based cameras. Among the current imitations: motion blur, limited dynamic range, ghosting, flickering and color artifacts.
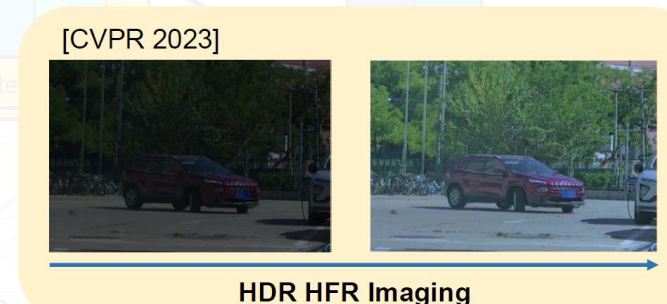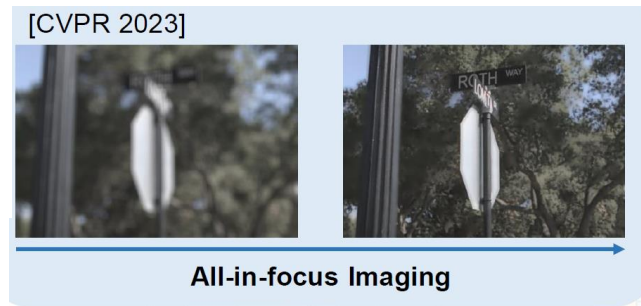
Neuromorphic image sensors' low latency and high bandwidth permit advanced features such as foveation, refocus, motion deblur, and high frame rate HDR to photography and video applications.

From: Boxin Shi, Peking University, CVPR 2023

Input Events   Input Image   Refocus Results

[CVPR 2023]

All-in-focus Imaging

[CVPR 2023]

HDR Imaging

[CVPR 2022]

GS Imaging

[CVPR 2023]

HDR HFR Imaging
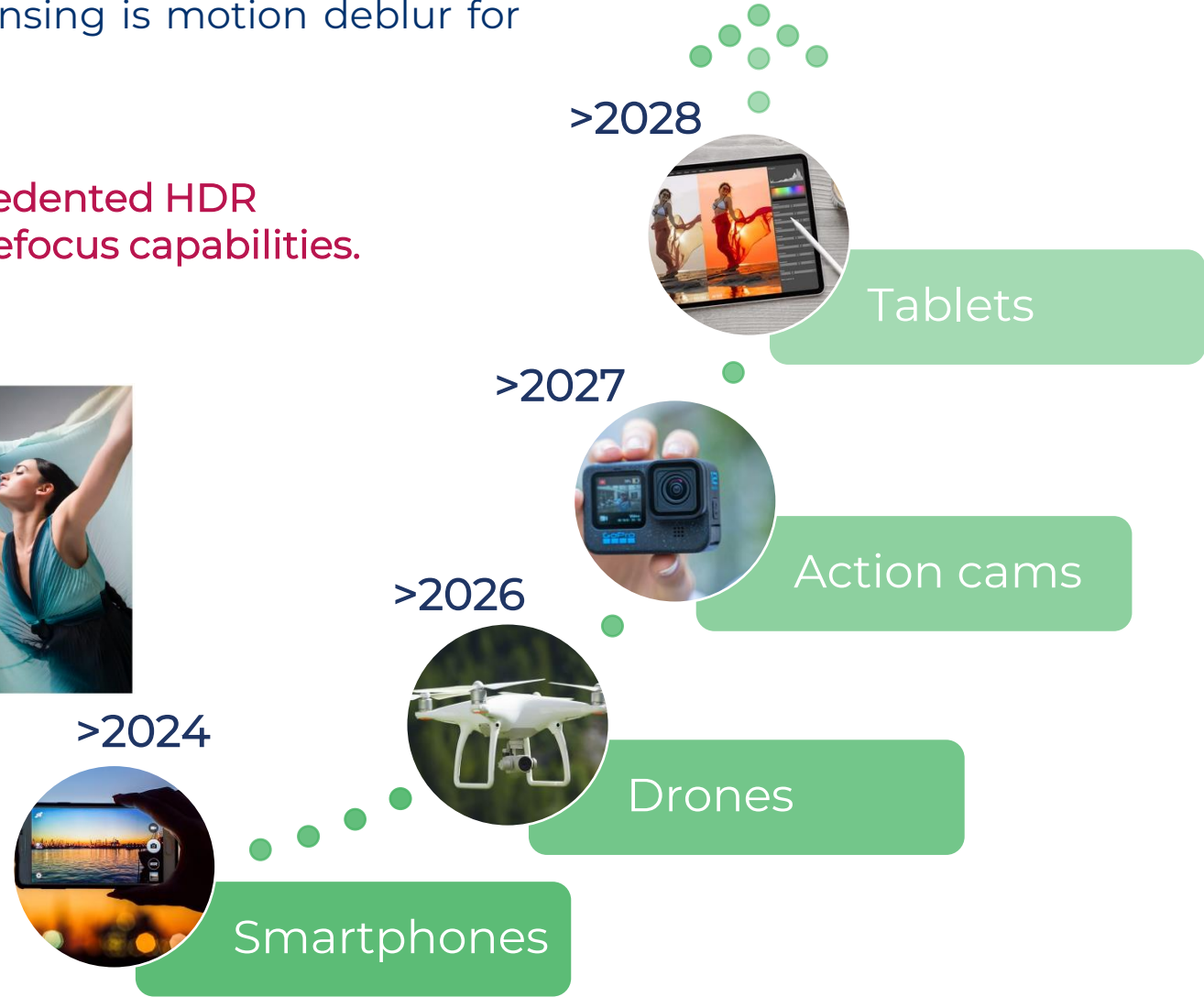
NEUROMORPHIC APPLICATIONS - SENSING
Going beyond smartphone photography

- The next opportunity coming for neuromorphic sensing is motion deblur for smartphone photography applications.

Neuromorphic image sensor will allow unprecedented HDR photography and video, motion deblur and image refocus capabilities.
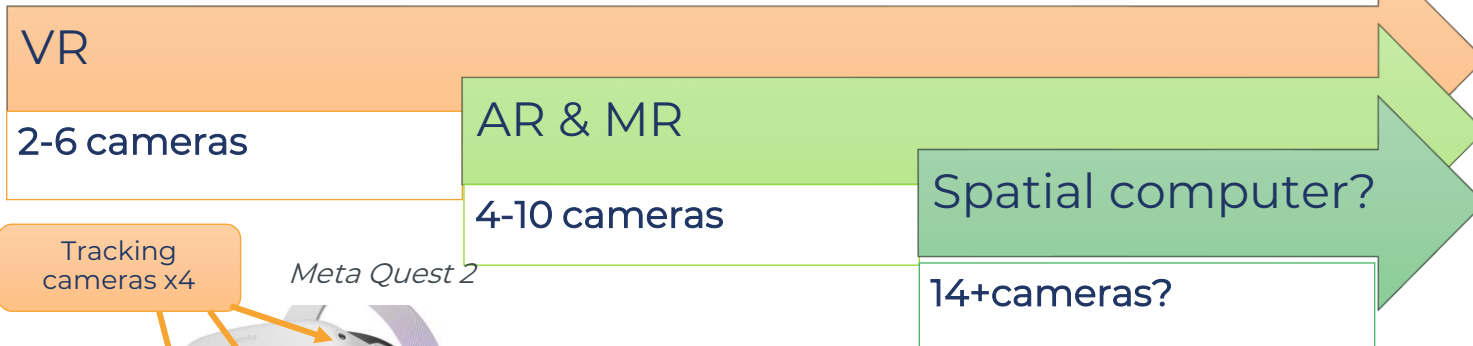

Source: Prophesee

>2028 — Tablets

>2027 — Action cams

>2026 — Drones

>2024 — Smartphones

NEUROMORPHIC APPLICATIONS – COMPUTING AND SENSING
Neuromorphics is key to moving to spatial computing era

Proliferation of sensors for XR

VR
2-6 cameras

AR & MR
4-10 cameras

Spatial computer?
14+cameras?

New imaging paradigm to unlock lower power and latency sensing approaches: neuromorphics

Will the next AR/VR processor be neuromorphic?

Tracking cameras x4

Meta Quest 2

~$350

Tracking cameras x4

RGB camera

3D camera

Microsoft HoloLens 2

~$3,500

Eye tracking cameras x2

M2 APU   R1 co-processor

dToF 3D camera "LiDAR"

Structured light 3D camera

RGB cameras x2

LiDAR Scanner
TrueDepth camera
Downward cameras
IR illuminators
Side cameras
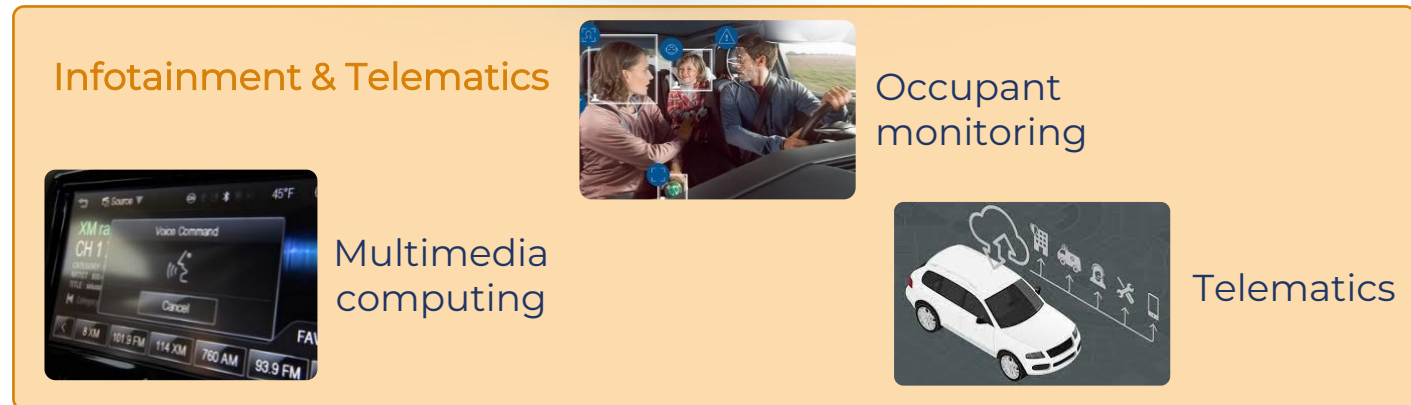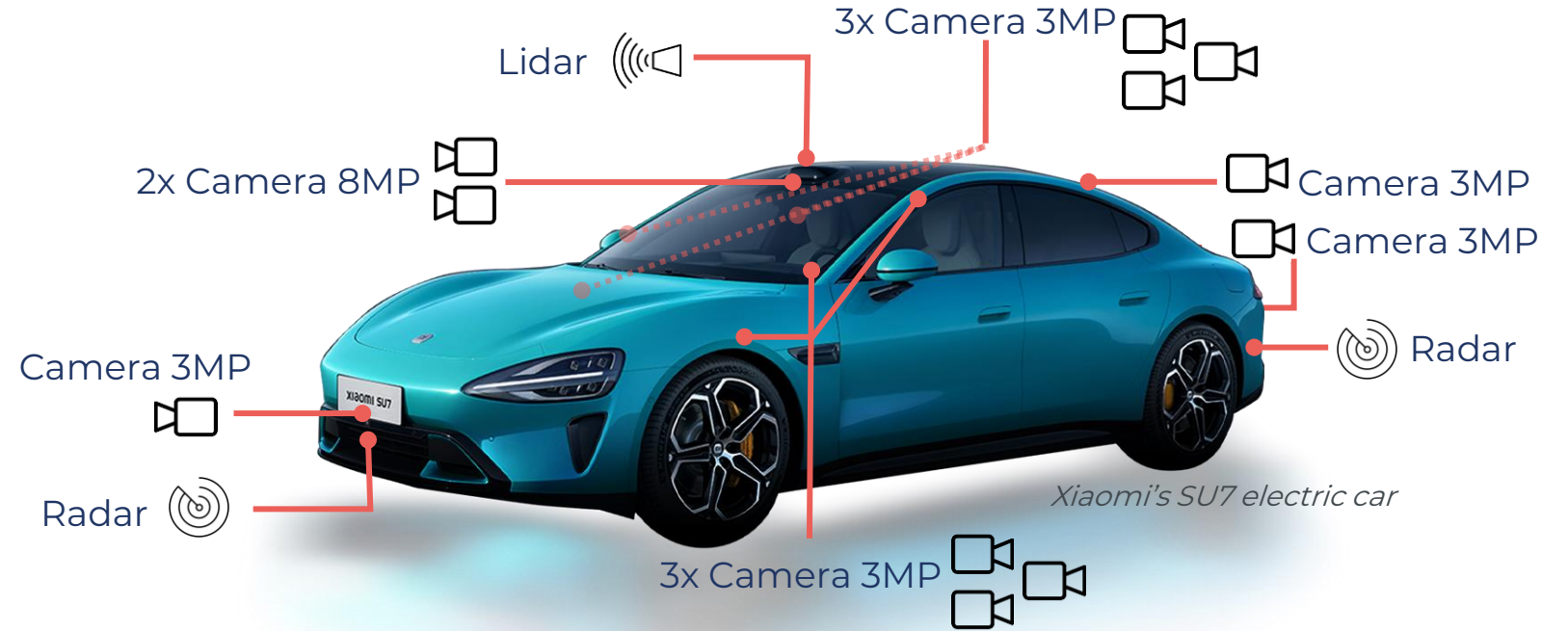
Tracking cameras x6

Apple Vision Pro

~$3,500

Eye tracking cameras x4

Battery

~$1,200

Meta Quest Pro

ultraleap | PROPHESEE | TCL RayNeo

low power tracking technology for AR glasses

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Automotive domains

ADAS & Safety

Level 5
Level 4

Autonomous driving - AD
Centralized computing

Level 3
Level 2

Advanced Driver Assistance Systems - ADAS

Computing close to sensor

Driver monitoring

Lidar

3x Camera 3MP

2x Camera 8MP

Camera 3MP

Camera 3MP

Camera 3MP

Radar

Radar

3x Camera 3MP

Xiaomi's SU7 electric car

Infotainment & Telematics

Occupant monitoring

Multimedia computing

Telematics
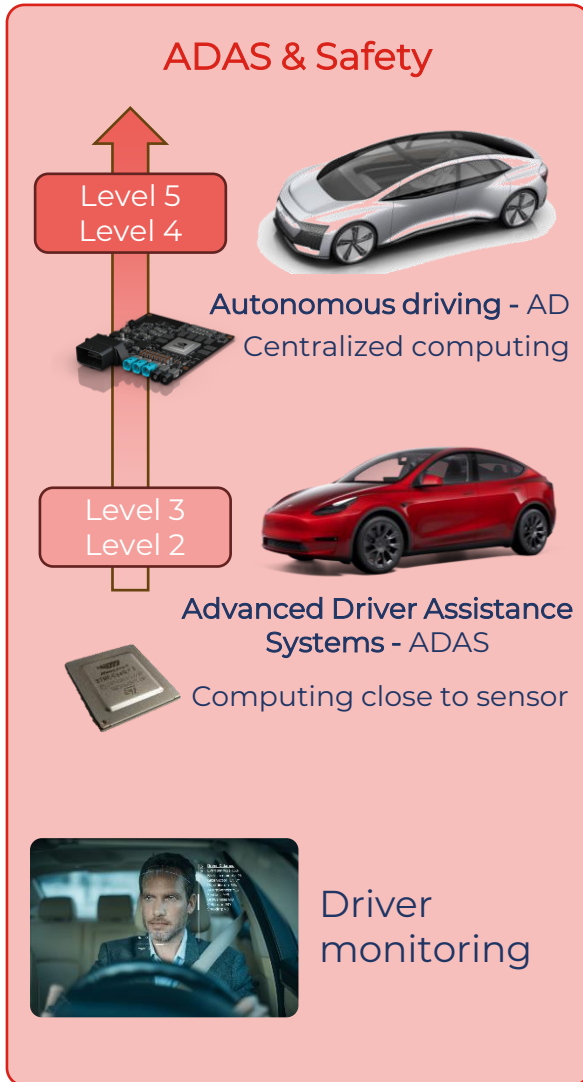
NEUROMORPHIC APPLICATIONS – COMPUTING AND SENSING
Why neuromorphic technologies for ADAS?

Running child: 8 km/h

Distance when pedestrian is visible: 10m

Vehicle velocity: 40 km/h

Distance when pedestrian is detected: 9.4m

Distance when pedestrian is detected: 8.4m

Note: 40kph = 25mph

Distance when pedestrian is detected: 6m

Event camera:
Sensor detection: 5ms
Internal delay (computing): 50ms

30fps:
Sensor detection: 100ms
Internal delay (computing): 50ms

10fps:
Sensor detection: 300ms
Internal delay (computing): 50ms

State of the art ADAS 2021

-3.2 m
Distance after
Automated Emergency Braking

Collision
Velocity: 30 km/h

VoxelFlow™

0.6 m
Distance after
Automated Emergency Braking

Collision Avoidance

terranet™

Mercedes-Benz

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NEUROMORPHIC APPLICATIONS – COMPUTING AND SENSING
Driver Monitoring Systems (DMS) and infotainment

Child presence detection
- Presence detection
- Presence classification
- Vital signs detection

Driver monitoring
- Distraction and drowsiness detection
- Head orientation and position
- Eye direction monitoring
- Smart seatbelt detection
- Object detection
- Hand positions on the wheel
- Position on the seat
- Face recognition
- Smart airbag deployment

HIGHER LOW LIGHT PERFORMANCE

FAST RESPONSE TIME

ENERGY-EFFICIENCY

PERSONALIZATION
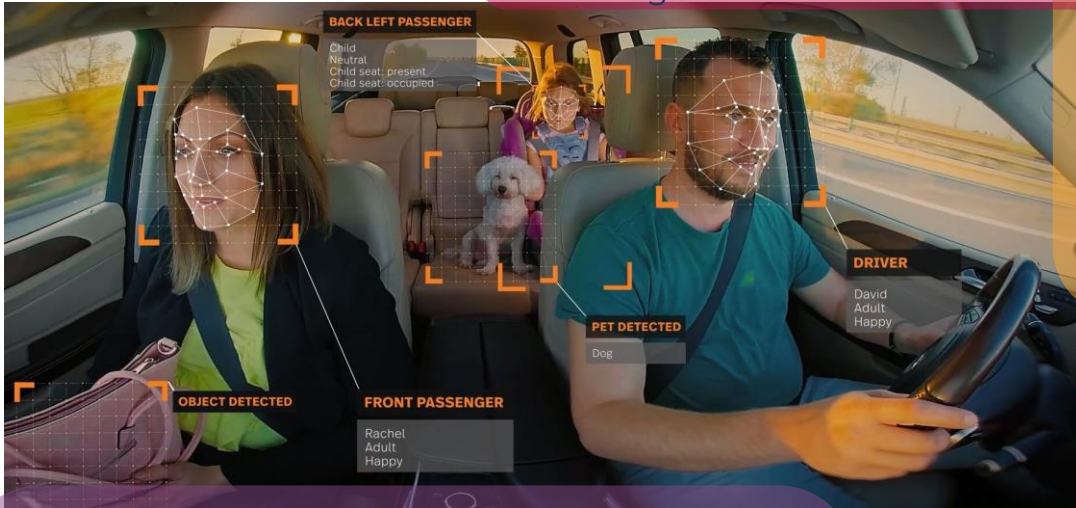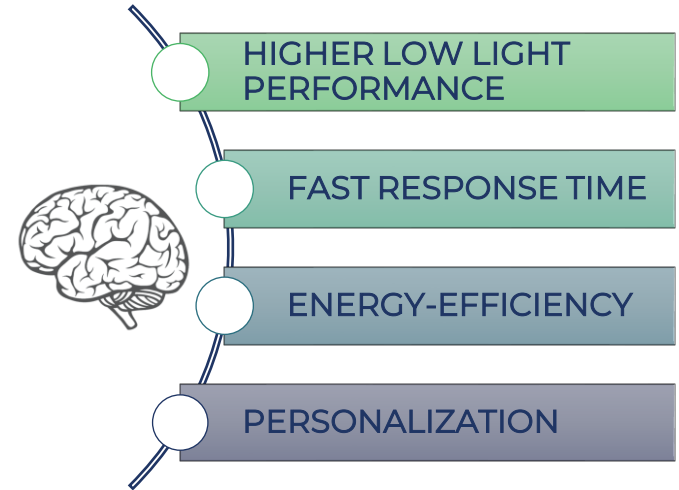
Occupant monitoring
- Occupant detection, identification, classification
- Position on seat
- Feet on dashboard detection
- Seatbelt detection
- Object detection
- HVAC control
- Emotion detection
- Conference call, selfies
- Heart and respiration rate
- Blood flow measurement

PROPHESEE dts XPERI

brainchip   Mercedes-Benz

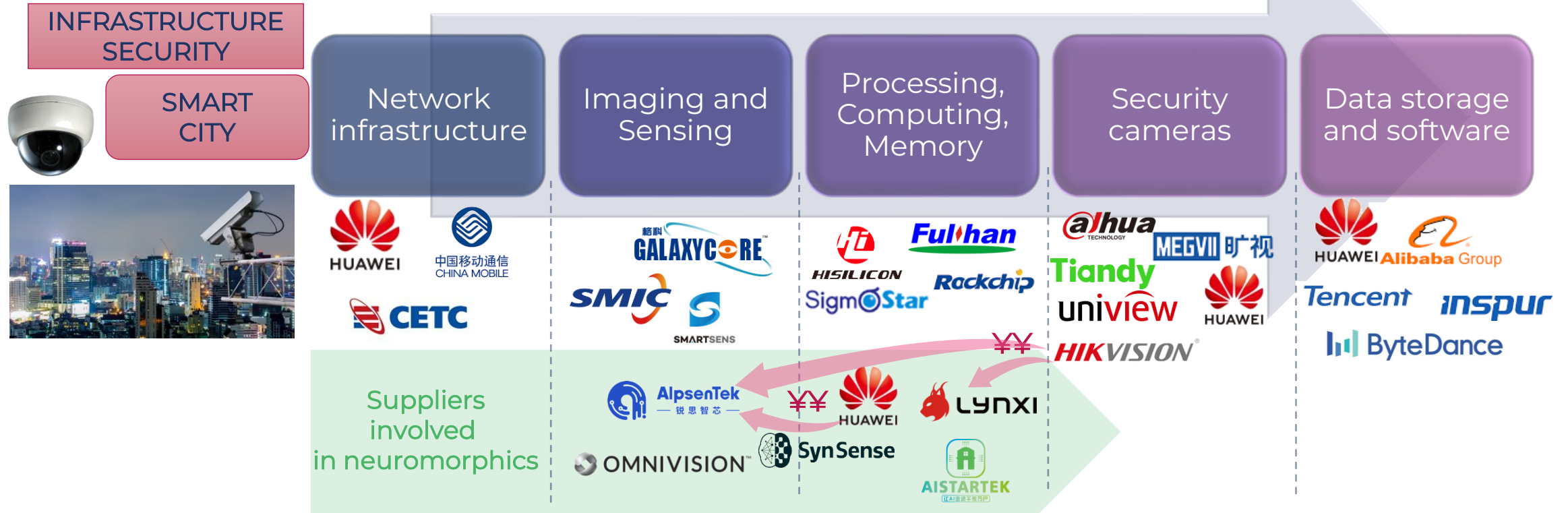DMS with equivalent frame rate of 10,000fps without requiring active illumination

Keyword spotting 5 to 10 times more energy-efficient

NEUROMORPHIC APPLICATIONS – COMPUTING AND SENSING
A powerful security imaging ecosystem in China eyeing neuromorphics

INFRASTRUCTURE SECURITY

SMART CITY

| Network infrastructure | Imaging and Sensing | Processing, Computing, Memory | Security cameras | Data storage and software |

Suppliers involved in neuromorphics

We expect security cameras will represent a $1.1B neuromorphic market by 2034.

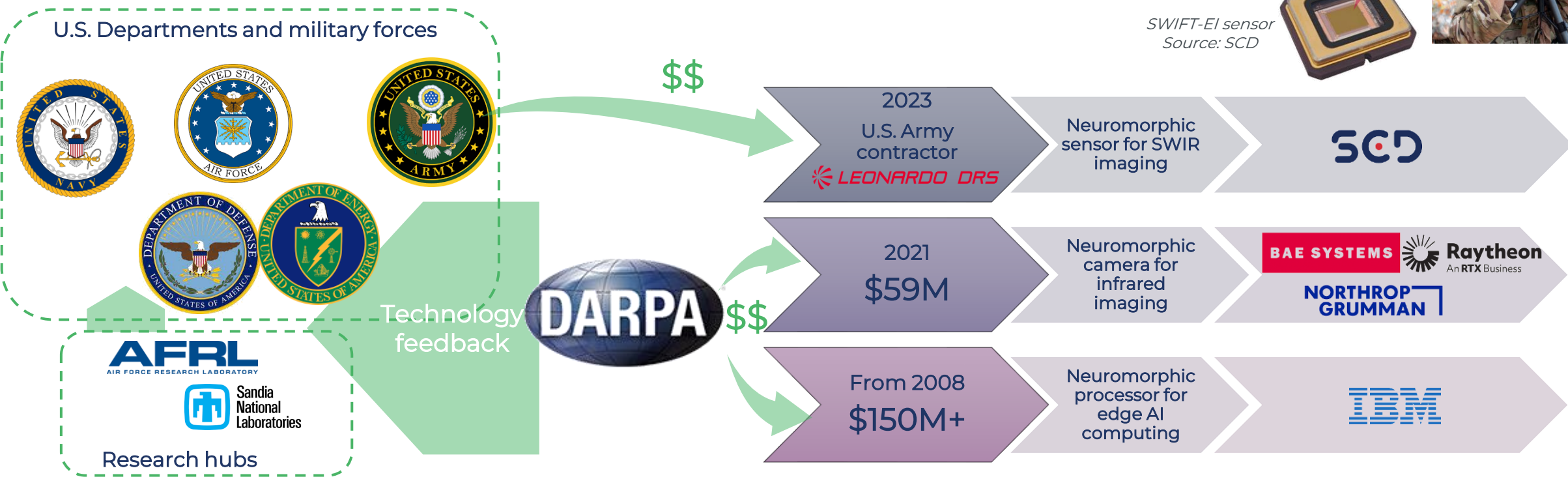Neuromorphics could allow to design high performance chips at larger nodes than legacy processor technologies.

NEUROMORPHIC APPLICATIONS – COMPUTING AND SENSING
## Defense sector has long supported neuromorphic technologies

- DARPA Fast Event-based Neuromorphic Camera and Electronics (FENCE) program.

- DARPA Neuromorphic Adaptive Plastic Scalable Electronics (SyNAPSE): 2018 demonstration of **3D stereo vision high-performance processing, coupling neuromorphic event-based cameras with a TrueNorth neuromorphic processor**.

- According to the Assistant Secretary of Defense for Critical Technologies, Maynard Holliday, there is a **crucial need for edge AI computing to be unlocked by neuromorphic technology, expected to be related to image and video processing and recognition tasks**.

JETS II hand-held precision laser targeting system
Source: Leonardo DRS

SWIFT-EI sensor
Source: SCD

U.S. Departments and military forces

Technology feedback

DARPA

AFRL
AIR FORCE RESEARCH LABORATORY
Sandia National Laboratories

Research hubs

$$

2023
U.S. Army contractor
LEONARDO DRS

Neuromorphic sensor for SWIR imaging

SCD

$$

2021
$59M

Neuromorphic camera for infrared imaging

BAE SYSTEMS | **Raytheon** An RTX Business
NORTHROP GRUMMAN

From 2008
$150M+

Neuromorphic processor for edge AI computing

IBM

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NEUROMORPHIC APPLICATIONS – COMPUTING
Health – Neuromorphics can enable low-power data analytics at the edge
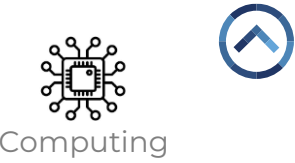
- In November 2023, **Polyn Technology entered into a partnership with Medicalps,** a healthcare industry cluster located in the French Alps. This collaboration aims to help startups accelerate their entry into international markets and strengthen connections within the local healthcare ecosystem.

- Polyn Technology's NeuroSense is a Tiny AI chip based on a Neuromorphic Analog Signal Processor. It can process signals such as heart rate measurements using simple sensors, like two LEDs and one photodiode, among other features. The key advantage of this technology is its **higher accuracy and lower power consumption compared to traditional methods**.

- This technology can be integrated into **medical wristbands** to monitor the health of individuals with medical conditions. Moreover, it can potentially revolutionize the mass consumer wearable market by offering advanced health monitoring capabilities like better heart rate accuracy measurement, advanced oxygen saturation and stress monitoring.

- Furthermore, this technology can be combined with IMU sensors for applications like **fall monitoring**, which is becoming increasingly important as populations age. Since these devices are battery-powered, leveraging neuromorphic sensors to extend battery life makes perfect sense.

Courtesy of Polyn

NeuroSense integration block diagram
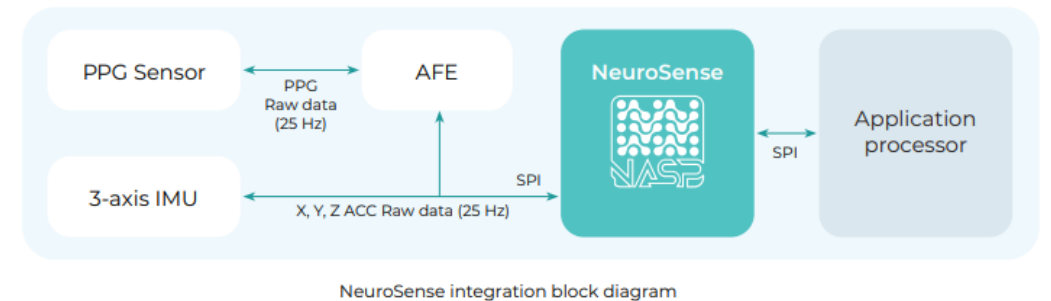
NEUROMORPHIC APPLICATIONS – COMPUTING
Data center – Fighting cyber crime and threat detection

- In May 2023, BrainChip partnered with Quantum Ventura to develop cutting-edge cyber threat-detection tools. This collaboration will leverage **BrainChip's Akida neuromorphic** processor to create cybersecurity applications for the U.S. Department of Energy.

- The Akida neural processor and AI neuromorphic IP offer advantages for threat detection, including its **small size, low power consumption, accuracy, and ability to learn and adapt to new patterns**. By identifying unknown, repeating patterns in vast amounts of noisy data, Akida can effectively **detect malware, attack signatures, and other types of malicious activity in network traffic**.

- Moreover, BrainChip's IP supports **incremental learning**, on-chip learning, and high-speed inference within micro-watt to milli-watt power budgets.

- As an event-based technology, Akida is inherently more **energy-efficient** than conventional neural network accelerators, providing high performance with low power consumption. This efficiency allows partners like Quantum Ventura to deliver AI solutions previously unattainable on battery-operated or fan-less embedded edge devices.
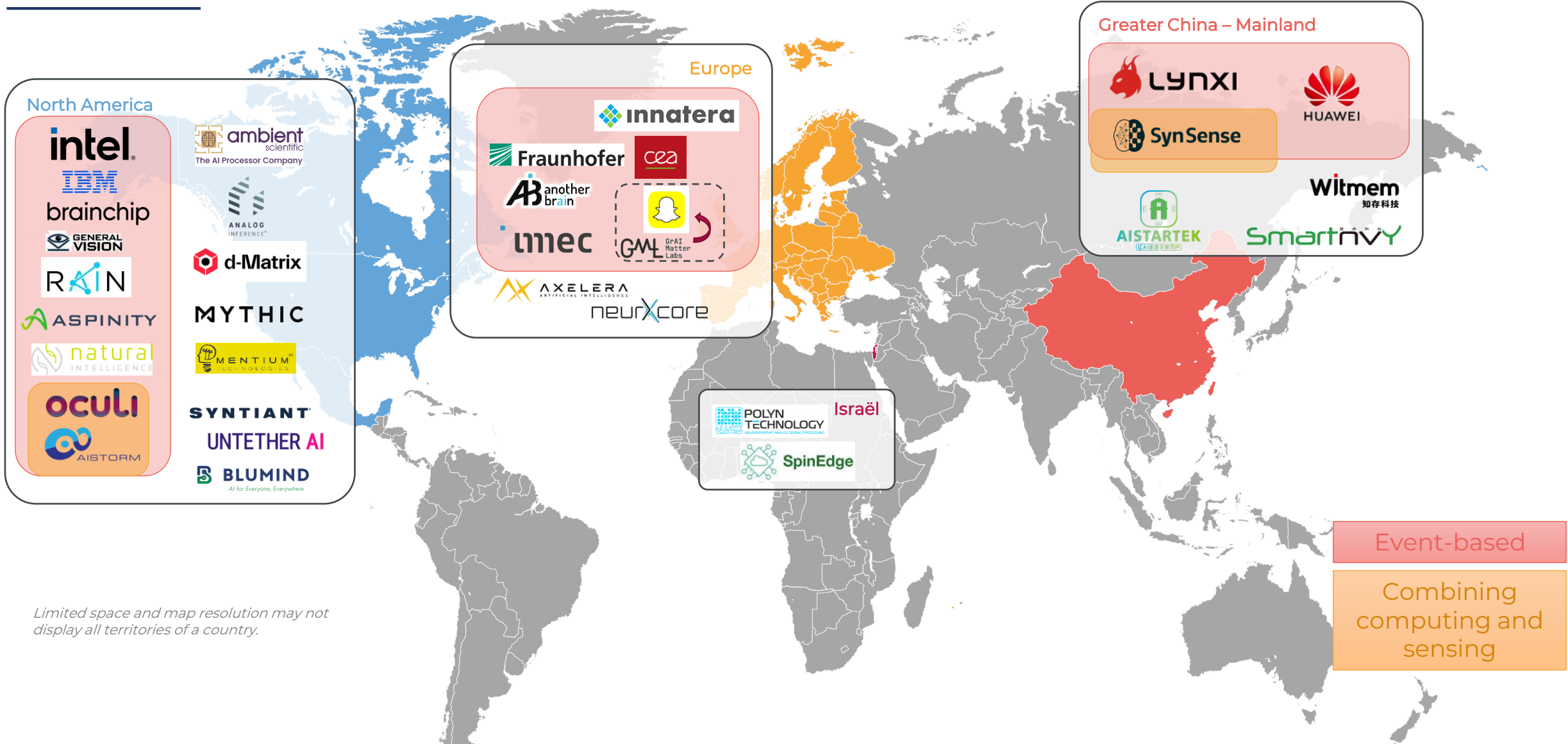
Low latency

Highly energy efficient

Online learning

NEUROMORPHIC ECOSYSTEM AND TECHNOLOGY

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NEUROMORPHIC AND IN-MEMORY COMPUTING
The US, Europe and China are the three most active areas

North America
- intel
- IBM
- brainchip
- GENERAL VISION
- RAIN
- ASPINITY
- natural INTELLIGENCE
- oculi
- AISTORM
- ambient scientific — The AI Processor Company
- ANALOG INFERENCE
- d-Matrix
- MYTHIC
- MENTIUM TECHNOLOGIES
- SYNTIANT
- UNTETHER AI
- BLUMIND — AI for Everyone, Everywhere

Europe
- innatera
- Fraunhofer
- cea
- AB another brain
- imec
- GML GrAI Matter Labs
- AXELERA ARTIFICIAL INTELLIGENCE
- neurXcore

Israël
- POLYN TECHNOLOGY — NEUROMORPHIC ANALOG SIGNAL PROCESSING
- SpinEdge

Greater China – Mainland
- LYNXI
- HUAWEI
- SynSense
- Witmem 知存科技
- AISTARTEK
- SmartNVY

Legend:
- Event-based
- Combining computing and sensing

Limited space and map resolution may not display all territories of a country.

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TECHNOLOGY TRENDS – NEUROMORPHIC COMPUTING
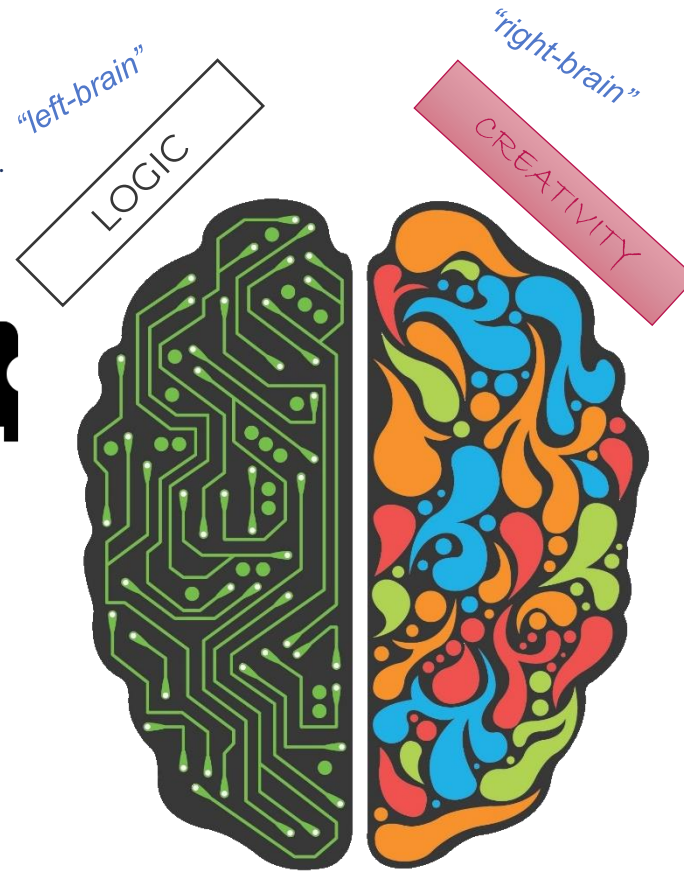## Von Neumann and neuromorphic architecture combined in one processor

Von Neumann architecture consists of two different components: computing and memory with connections between the two.
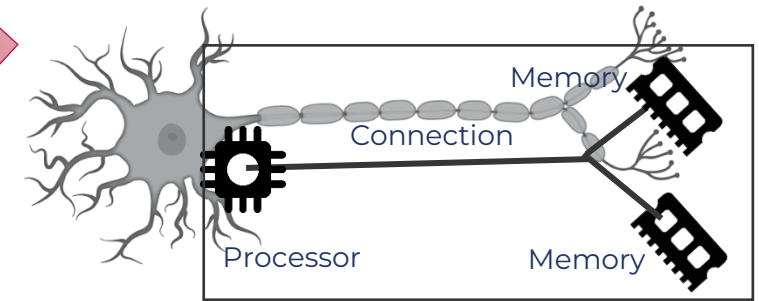
"left-brain"

LOGIC

"right-brain"

CREATIVITY

Neuromorphic architecture consists of embedded computing and memory in one component/core.

Memory

Connection

Processor   Memory

Toward a heterogeneous architecture?

Connection

Processor   Memory
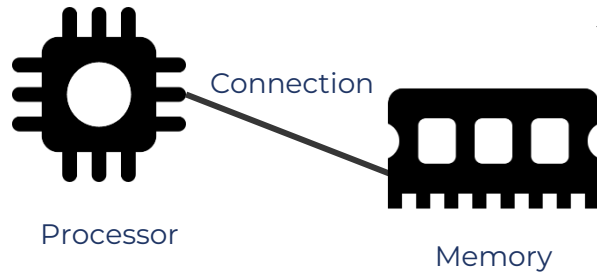
- Analytical thinking
- Language
- Etc.

- Pattern recognition
  - Learning
  - Reasoning
    - Etc.

FLOPS-driven
Floating-point Operations Per Second

Converts senses to actions.
SOPS-driven
Synaptic Operations Per Second

Analysis
Control
Decision

Model creation
High reactivity

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Example of hybrid processors

➤ **Lynxi KA200 Neuromorphic chip**

- It is a hybrid chip that can compute both classic algorithms and SNN

- 250,000 neurons and 25 million synapses (in dense mode)

- There is also a **sparse mode** that enables scaling to support integrated computing with 2 million neurons and 2 billion synapses

- Technology node: 12nm

- Performance:
  - Neuromorphic 24 TSOPS
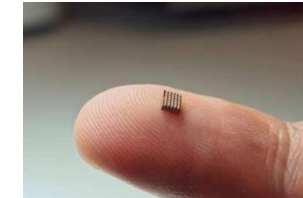 - Traditional: 48TOPS @INT8, 24TFLOPS @FP16
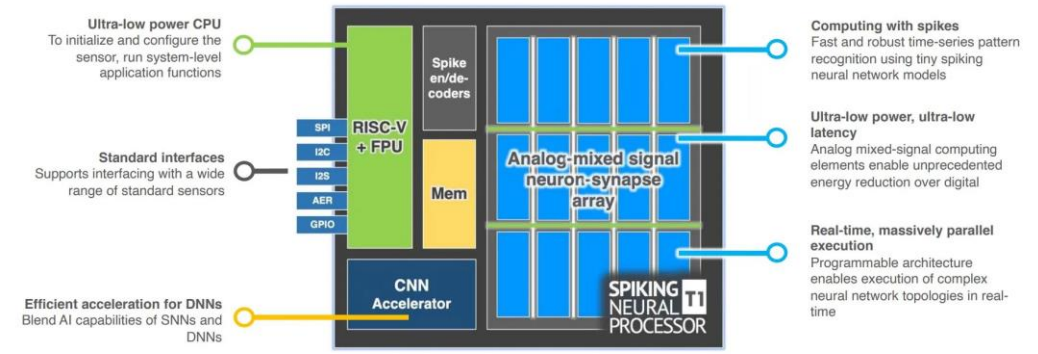
Spiking Neural Processor T1 diagram   *Courtesy of Innatera*
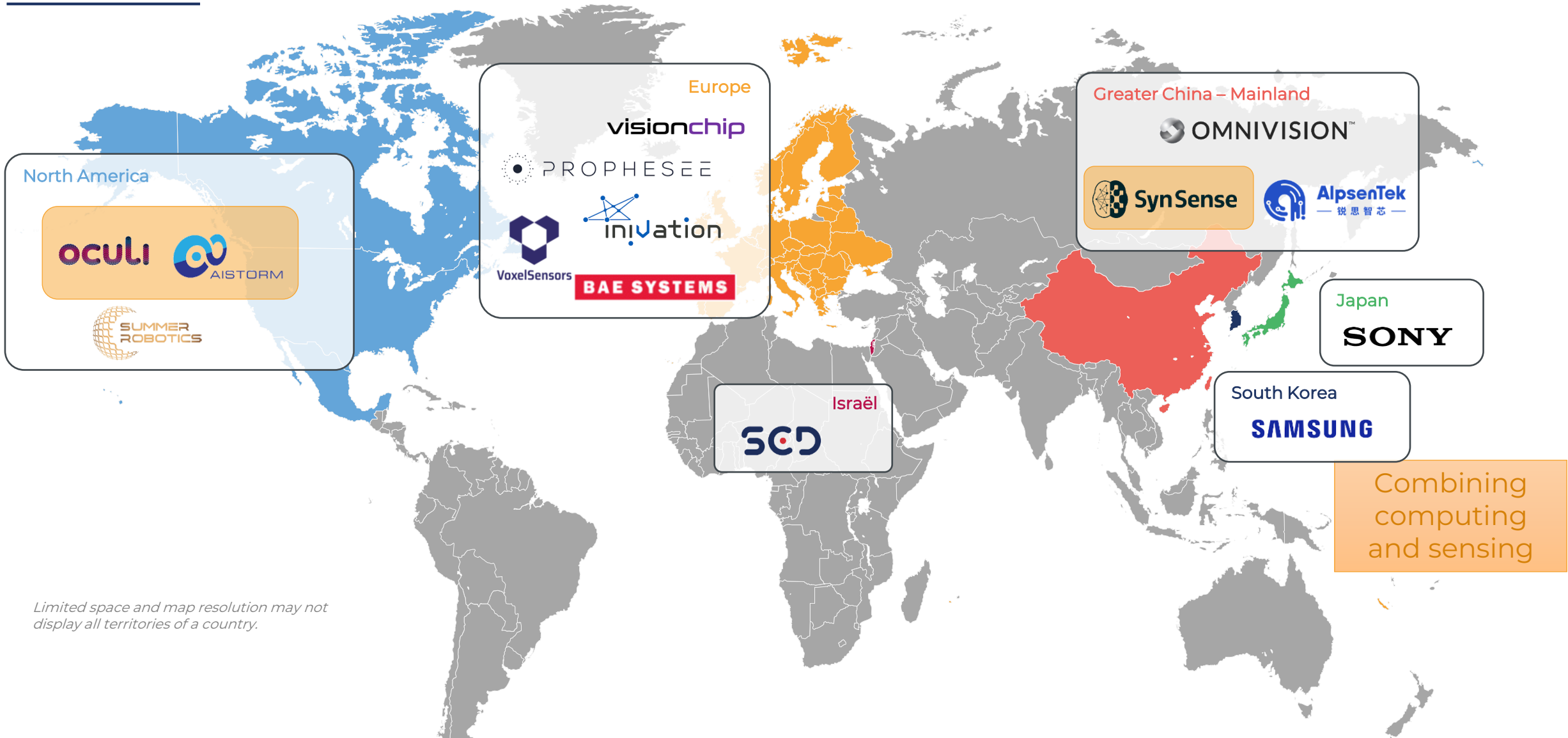
Innatera T1 chip

- BrainChip is a fabless semiconductor company founded in 2013 in California, US.

- Today, **BrainChip defines itself as more like an IP company than a chip company**.

- Chips are still designed to demonstrate their performance and for some specific customers.

- They promote more the IP approach, with the vision of **integrating IP into existing hardware as a neuromorphic unit**
  This approach is potentially much more scalable as they work with partners.

brainchip

NEUROMORPHIC SENSING ECOSYSTEM
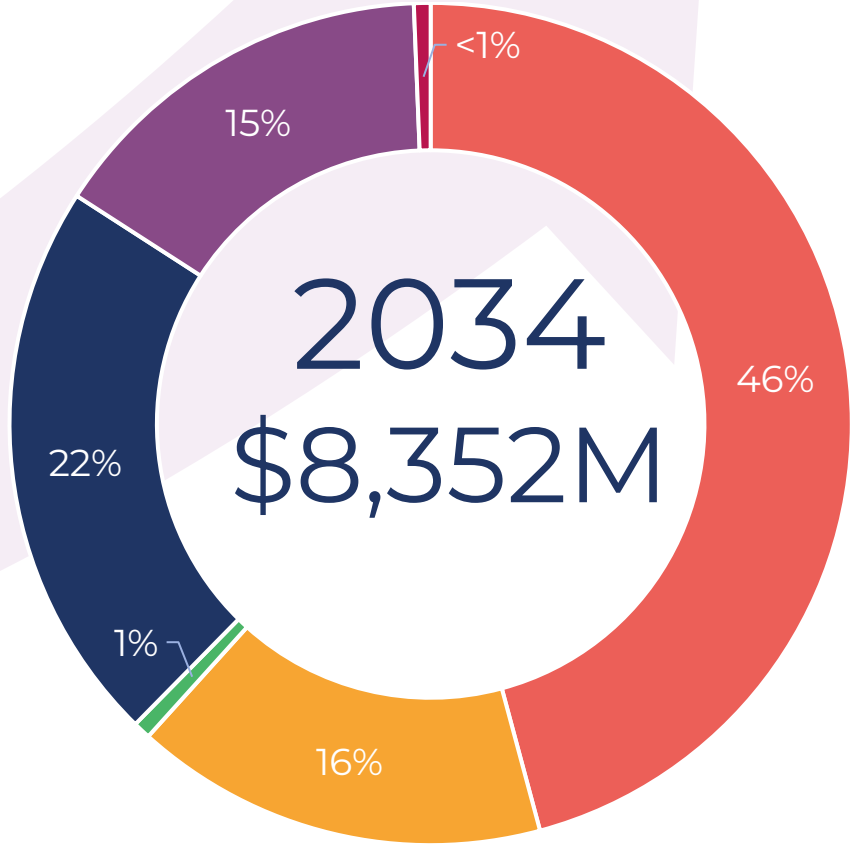## The top 3 CMOS image sensor suppliers followed by numerous startups

North America
- oculi
- AISTORM
- SUMMER ROBOTICS

Europe
- visionchip
- PROPHESEE
- iniVation
- VoxelSensors
- BAE SYSTEMS

Greater China – Mainland
- OMNIVISION
- SynSense
- AlpsenTek 锐思智芯

Japan
- SONY

South Korea
- SAMSUNG

Israël
- SCD

Combining computing and sensing

Limited space and map resolution may not display all territories of a country.

Different strategies to address mobile photography

- Currently, Prophesee, Alpsentek, and Omnivision are actively offering solutions for mobile photography motion deblur.

Pure event-based

- A classical camera along with a dedicated event mode camera

Hybrid RGB-event

- One single camera operating in both modes with dedicated event pixels

26,7 mm

14,9 mm

OMS

PROPHESEE

inivation   SONY

?   SAMSUNG

OMNIVISION   **or**

Top wafer   Middle wafer   Bottom wafer

EVS pix

AUX   MIPI

scan   ESP

ADC   ISP

HVS pixel

1 EVS pixel
15 CIS pixels

M. Guo et al. "A 3-Wafer-Stacked Hybrid 15MPixel CIS + 1MPixel EVS with 4.6GEvent/s Readout, In-Pixel TDC and On-Chip ISP and ESP Function", ISSCC 2023

AlpsenTek
锐思智芯

HVS pixel

it can output image and EVS data

NEUROMORPHIC MARKET FORECAST

2024-2034 NEUROMORPHIC SENSING AND COMPUTING FORECAST

Legend:
- Mobile and Consumer
- Automotive and Mobility
- Medical
- Communication and Infrastructure
- Industrial
- Defense and Aerospace

2024 $28M: 83%, 10%, 7%

2029 $822M: 48%, 7%, 1%, 28%, 14%, 2%

2034 $8,352M: 46%, 16%, 1%, 22%, 15%, <1%

YOLE Intelligence

KEY TAKEAWAYS
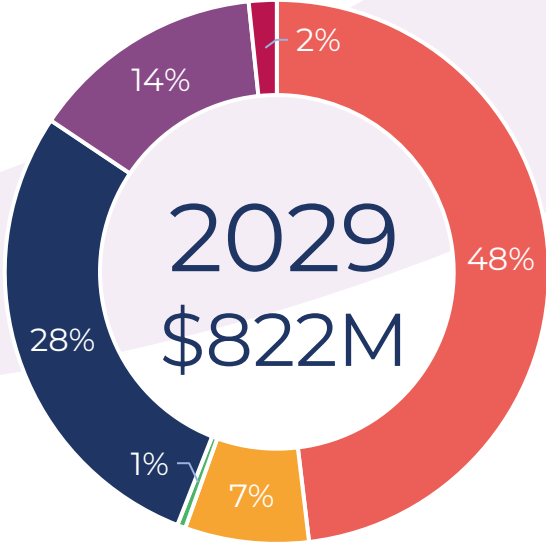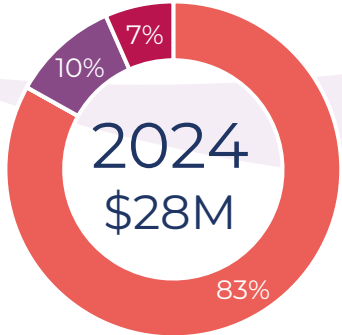
- The brain is an incredibly **energy-efficient device** and possesses key attributes that can be used for sensors and processors, it is the main idea behind neuromorphic technologies. The key assets of such technologies are **low latency**, **energy efficiency**, **online learning**, and **high scalability**.

- The next opportunity coming for neuromorphic sensing is **motion deblur for smartphone photography** applications. Neuromorphic is expected as a new imaging and computing paradigm in **power-constrained consumer applications such as AR/VR**, in the context of sensors proliferation. Security cameras could be one of the most promising markets for neuromorphic technologies as the powerful **security imaging ecosystem in China is investing in this technology**.

- Neuromorphic technology facilitates the implementation of **extreme-edge AI**, allowing intelligence to be integrated directly into sensors for low-power predictive maintenance and health monitoring applications.

- Datacenter applications are increasingly sensitive to power consumption today, as the energy footprint of datacenter is strongly growing, and the associated workload is still expected to grow. Neuromorphic technologies could enable to tackle this growing issue.

- The US, Europe, and China are the three most active areas for neuromorphic computing. **Hybrid approaches** are an interesting path to leverage the best of both worlds, and it is chosen by several competitors.

- The top 3 CMOS image sensor suppliers are involved in neuromorphic sensing: Sony, Samsung and Omnivision, followed by numerous startups. Two main sensor design approaches have been proposed for imaging-related applications: **standalone event-based sensors and mixed RGB with event-based pixel hybrid sensors**. With neuromorphic AI smart vision sensors, specific architectures are proposed to target **ultra-low power always-on use cases**, such as 3D sensing, sometimes bringing advanced processing at the pixel level.

- We expected the neuromorphic market will reach $822M in 2029 and $8.4B in 2034.
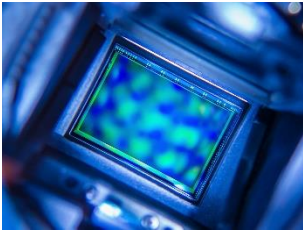
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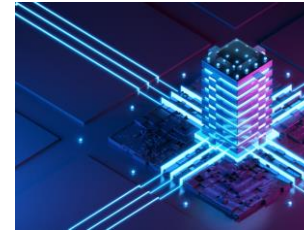
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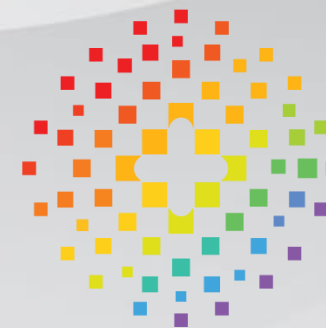
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