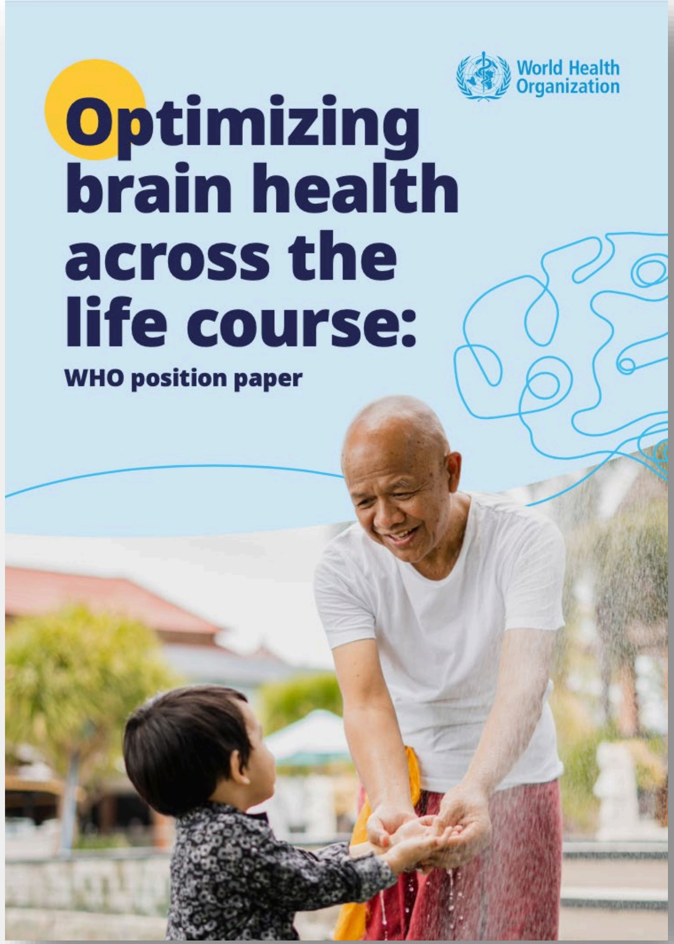
Poznańskie Centrum Superkomputerowo-Sieciowe
Poznan Supercomputing and Networking Center

From Quantum Scales to Virtual Humans

Toward a Transdisciplinary Understanding of Neurodegenerative Mechanisms

Cezary Mazurek, Ph.D, Senior Researcher, Head of Digital Medicine

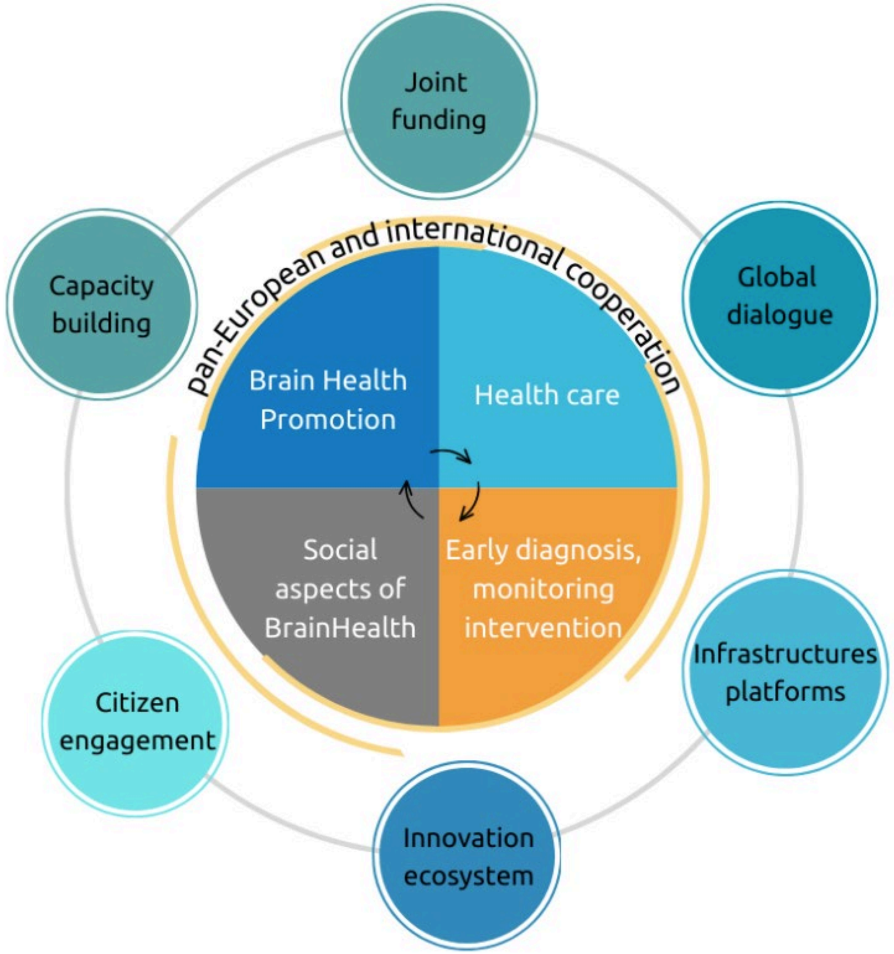
Transdisciplinary call to action

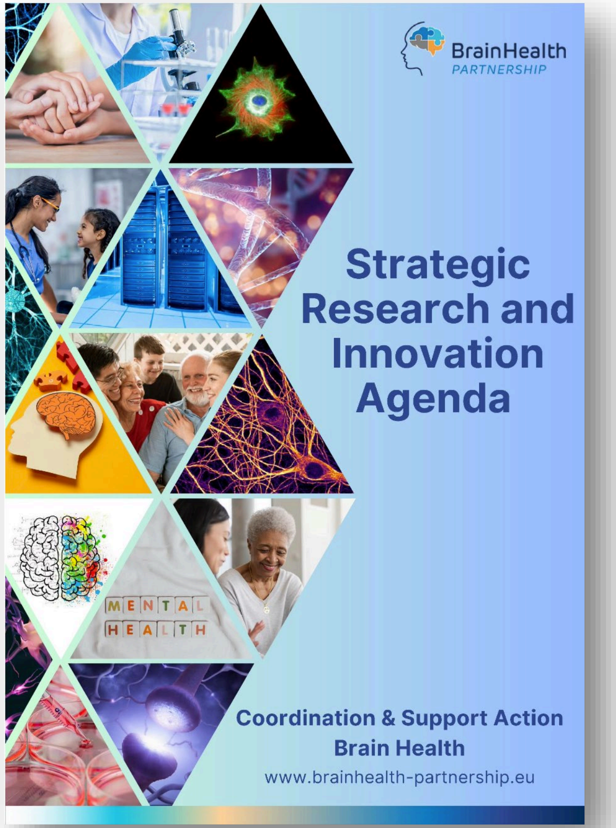


"Advances in neuroscience and neuroimaging – in combination with other disciplines such as artificial intelligence, machine learning and data science – are drivers of research into the human brain, lifting multisectoral discourse and discovery to entirely new levels. This is a cause for great excitement and optimism."*)

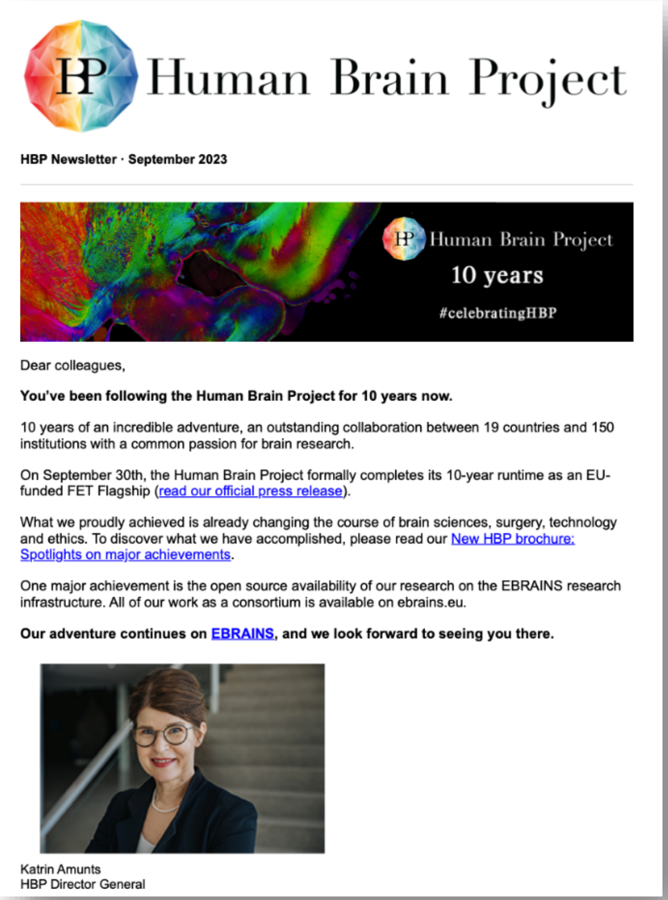
*) Dr REN Minghui, Assistant Director General, Universal Health Coverage/ Communicable and Noncommunicable Diseases, WHO Headquarters

European Partnership for Brain Health (2025)





EBRAINS Λa state-of-the-art ecosystem for neuroscience


HP Human Brain Project

HBP Newsletter · September 2023

Dear colleagues,

You've been following the Human Brain Project for 10 years now.

10 years of an incredible adventure, an outstanding collaboration between 19 countries and 150 institutions with a common passion for brain research.

On September 30th, the Human Brain Project formally completes its 10-year runtime as an EU-funded FET Flagship (read our official press release).

What we proudly achieved is already changing the course of brain sciences, surgery, technology and ethics. To discover what we have accomplished, please read our New HBP brochure: Spotlights on major achievements.

One major achievement is the open source availability of our research on the EBRAINS research infrastructure. All of our work as a consortium is available on ebrains.eu.

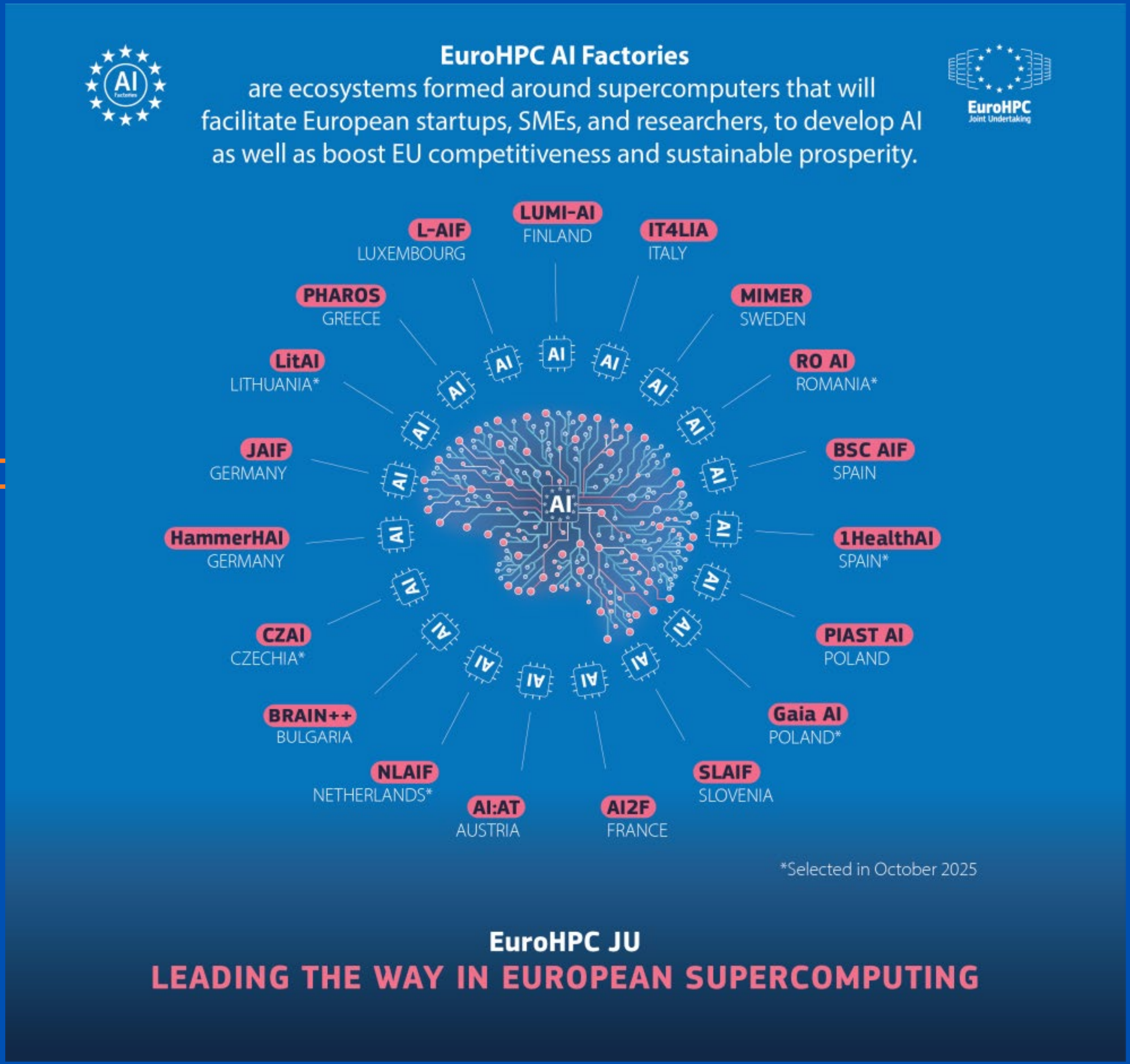
Our adventure continues on EBRAINS, and we look forward to seeing you there.

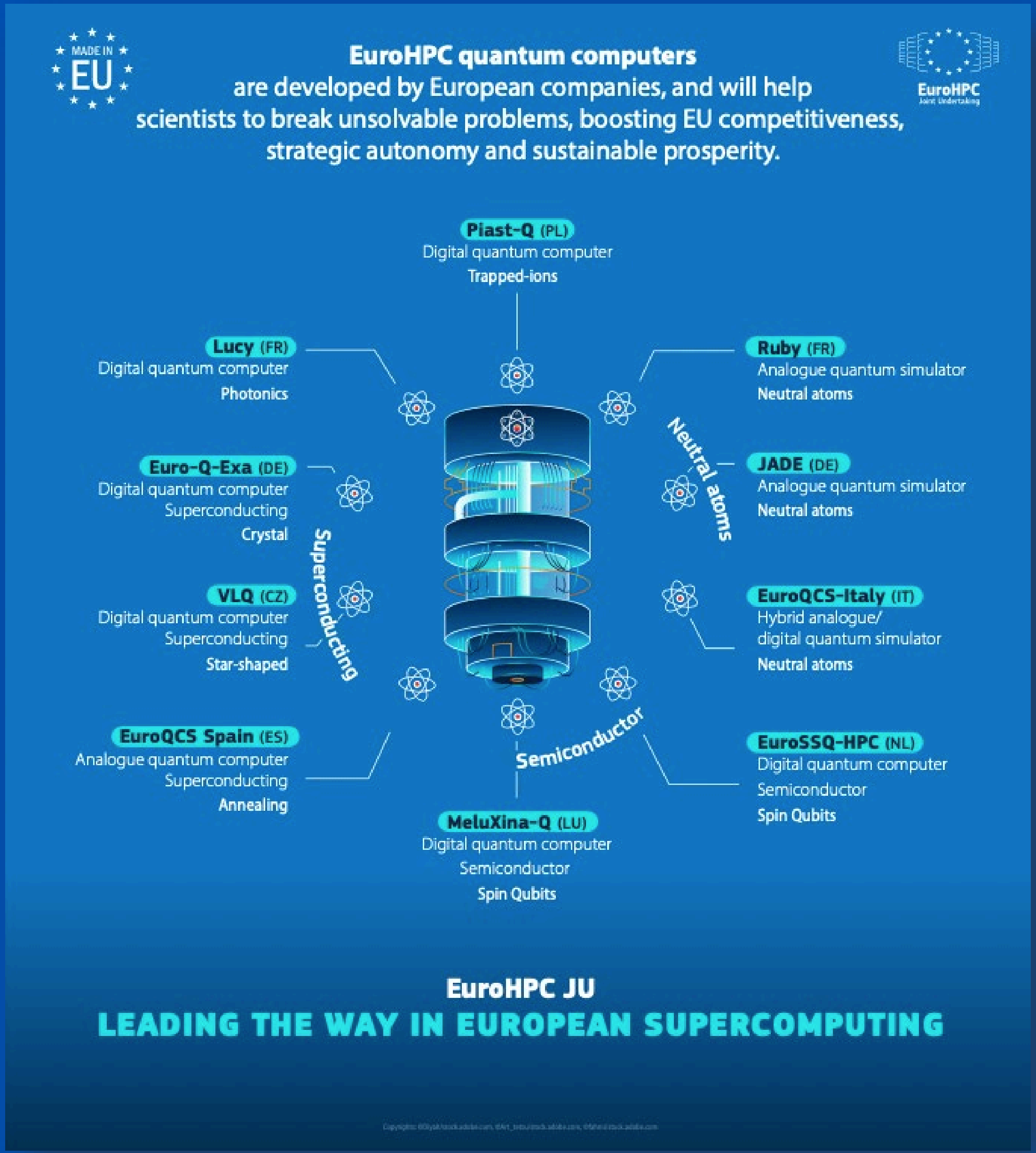
Katrin Amunts
HBP Director General

YOn September 30th, 2023 the Human Brain Project (HBP) has completed its 10-year runtime as an EU-funded FET Flagship. The project has pioneered digital neuroscience,
a new approach to studying the brain based on multidisciplinary collaborations
and high-performance computing.
The HBP will continue to have an impact on neuroscience
for many years through the EBRAINS research infrastructure
and a new way of collaborative work in the Jeld.X

Prof. Dr. med. Katrin Amunts, joint CEO, EBRAINS AISBL

www.ebrains.eu


EuroHPC AI Factories
are ecosystems formed around supercomputers that will facilitate European startups, SMEs, and researchers, to develop AI as well as boost EU competitiveness and sustainable prosperity.
EuroHPC Joint Undertaking
LUMI-AI FINLAND
L-AIF LUXEMBOURG
IT4LIA ITALY
PHAROS GREECE
MIMER SWEDEN
LitAI LITHUANIA*
RO AI ROMANIA*
JAIF GERMANY
BSC AIF SPAIN
HammerHAI GERMANY
1HealthAI SPAIN*
CZAI CZECHIA*
PIAST AI POLAND
BRAIN++ BULGARIA
Gaia AI POLAND*
NLAIF NETHERLANDS*
SLAIF SLOVENIA
AI:AT AUSTRIA
AI2F FRANCE
*Selected in October 2025
EuroHPC JU
LEADING THE WAY IN EUROPEAN SUPERCOMPUTING


MADE IN EU
EuroHPC quantum computers
are developed by European companies, and will help scientists to break unsolvable problems, boosting EU competitiveness, strategic autonomy and sustainable prosperity.
EuroHPC Joint Undertaking
Piast-Q (PL) Digital quantum computer Trapped-ions
Lucy (FR) Digital quantum computer Photonics
Ruby (FR) Analogue quantum simulator Neutral atoms
Euro-Q-Exa (DE) Digital quantum computer Superconducting Crystal
JADE (DE) Analogue quantum simulator Neutral atoms
VLQ (CZ) Digital quantum computer Superconducting Star-shaped
EuroQCS-Italy (IT) Hybrid analogue/ digital quantum simulator Neutral atoms
EuroQCS Spain (ES) Analogue quantum computer Superconducting Annealing
EuroSSQ-HPC (NL) Digital quantum computer Semiconductor Spin Qubits
MeluXina-Q (LU) Digital quantum computer Semiconductor Spin Qubits
Superconducting
Neutral atoms
Semiconductor
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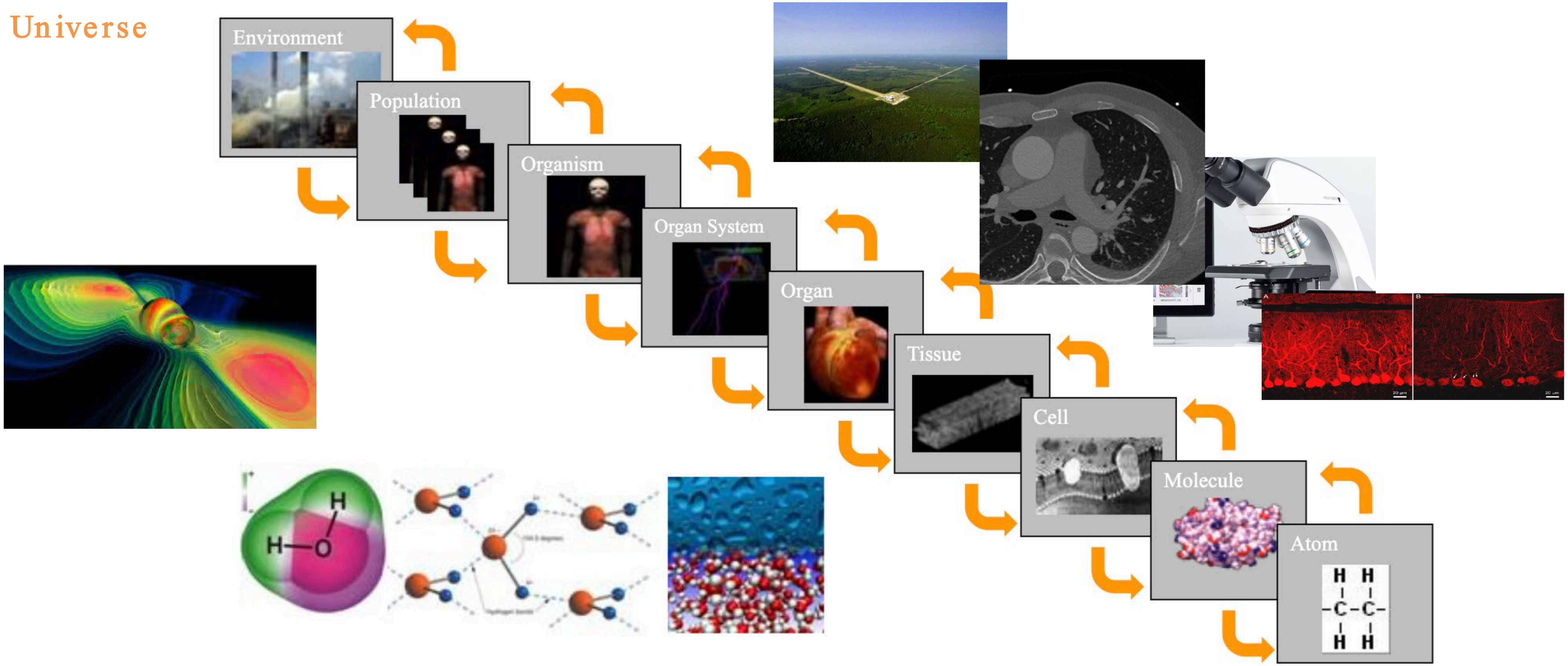
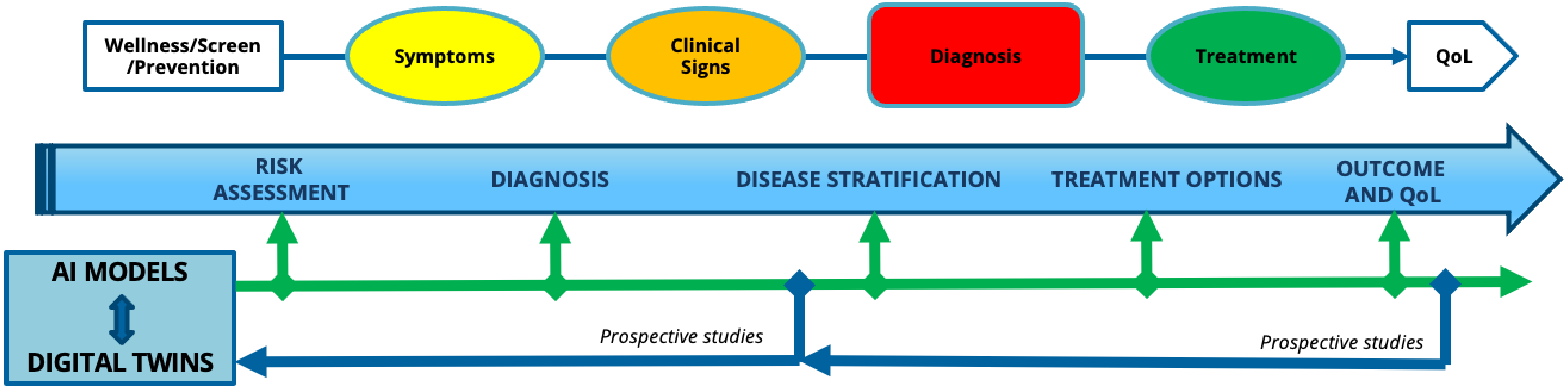
Nature is multiscale

Universe



Quantum

Patient Journey as a Multiscale System



Risk Assessment
- Family history
- Genomic profile
- Lifestyle
- Environment
- In utero exposure
- Clinical history
- SDOH

Presentation
- Signs
- Symptoms
- Co-morbidities
  - Active
  - Inactive
  - Undiagnosed
- Medications

Diagnosis
- Guidelines/Criteria
- Biomarkers/Diagnostics
- Disease stage
  - Direction
  - Velocity
- Missed/Mis-diagnosis
- Biopsies

Physician's Characterization
- Specialization
- Pre-disease
- Advanced disease
- Prognosis
- Stratification

Physician's Treatment Decision
- Specialization
- Guidelines
- RW practice
- Off-label use
- Risk/benefit ratio

Patient Compliance
- Side effects
- Adherence
- Perception of risk
- Social/community networks
- Cultural background
- Expectations
- Confidence in HCP

Outcome
- Disease-free survival
- Re-admission
- Management vs. Cure
- Minimum residua disease
- Side effects

Adopted from: Michael Liebman, IPQ Analytis, LLC, Next-Generation Phenotyping: Disease is a Process , Not a State, Bio-IT World Conference, May 17th, 2023

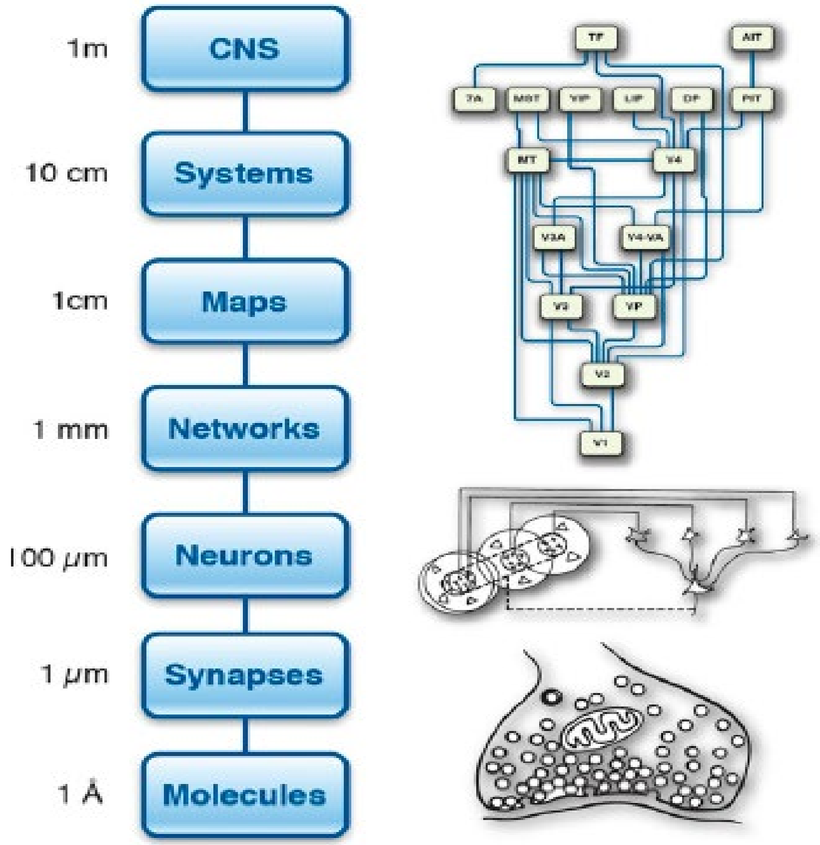
Challenges

- The functions of the brain, including cognitive abilities such as memory, attention, concentration, and language arise from multi-level interaction and as a result of processes occurring at multiple levels simultaneously.
- The study of the brain as a multiscale system requires researchers to pool their knowledge and experience and integrate in a shared research space different types of data,
  collected at multiple scales - both spatial and temporal.
- The ability to store and analyze data is crucial for advancing our understanding of brain structure and the processes occurring within that structure with mapping between different levels - from the molecular level, through receptors and synapses, neurons, neuronal columns, center maps, to a systemic view at the level of the central nervous system and at the behavioral level.

Levels of organization in the brain

- Expansive range of spatial and temporal scales across which relevant mechanisms operate - from quantum/molecular to social/cognitive levels
- Complex behavior spanning nine orders of magnitude scale tiers

	Level	Size (decimal)	Size (m)	Size (m)
1	Nervous system	1	> 1 m	10^{0}
2	Subsystem	0.1	10 cm	10^{-1}
3	Neural network	0.01	1 cm	10^{-2}
4	Microcircuit	0.001	1 nm	10^{-3}
5	Neuron	0.000 1	100 m	10^{-4}
6	Dendritic arbor	0.000 01	10 m	10^{-5}
7	Synapse	0.000 001	1 m	10^{-6}
8	Signaling pathway	0.000 000 001	1 nm	10^{-9}
9	Ion channel	0.000 000 000 001	1 pm	10^{-12}



Quantum computing - scale and complexity of modeling the brain

The brain is the killer app of quantum computing

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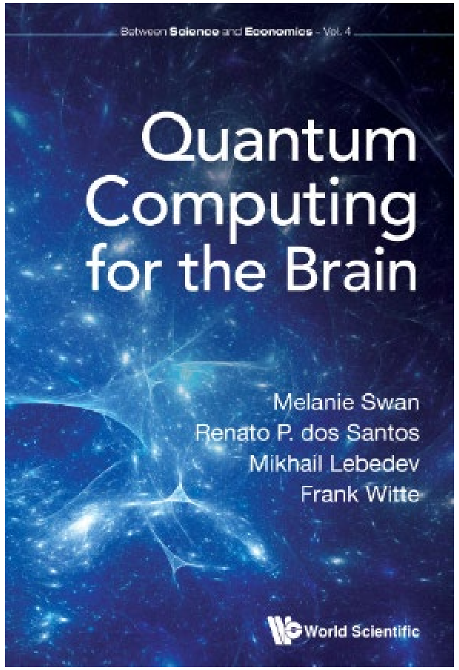
the outer limits case deЛning the requirements of the medium

Quantum neuroscience:

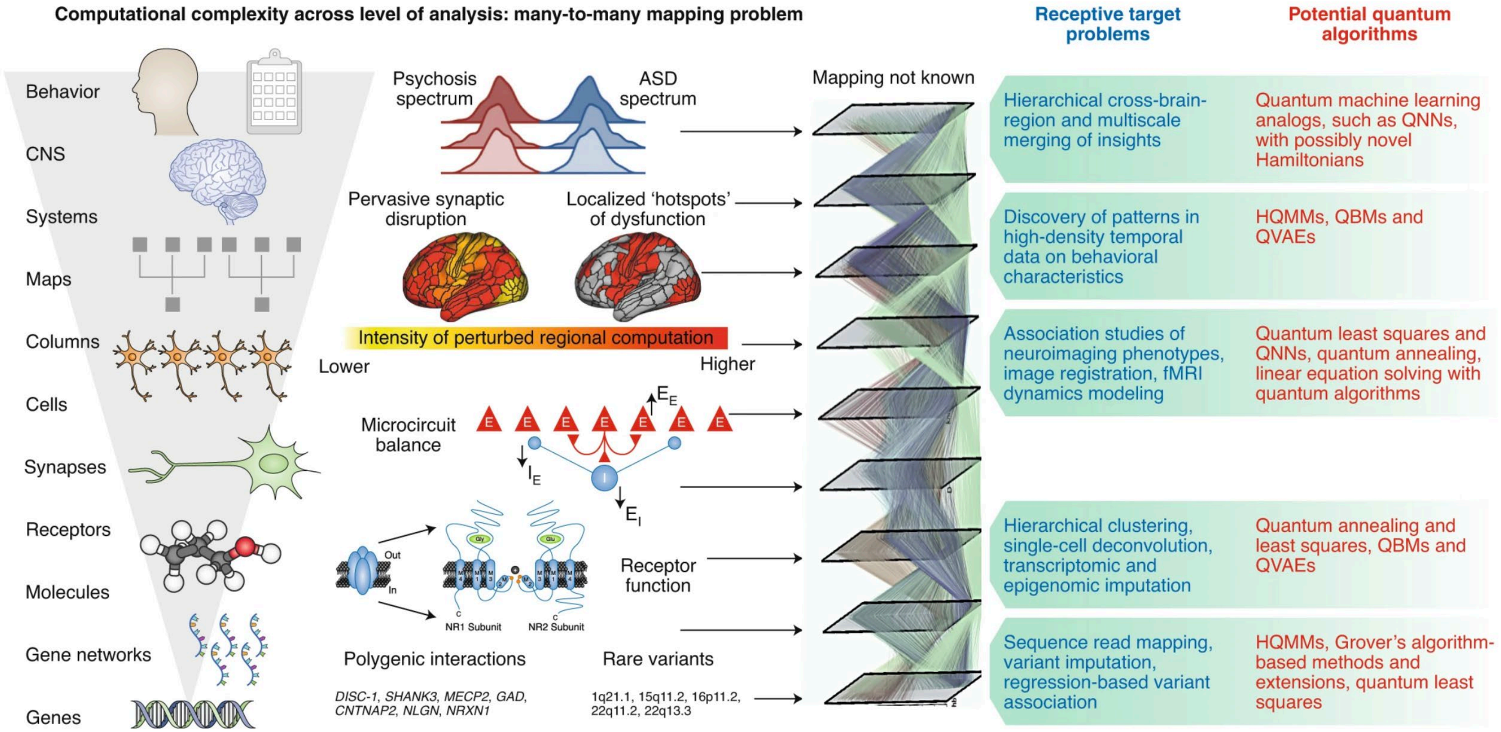
Application of quantum computing methods to computational neuroscience problems such as:

- EEG waveform-based analysis
- Quantum biology state modeling
- Physics of neuroscience



The complexity of combining levels of analysis from genetics to human behavior

From: Quantum computing at the frontiers of biological sciences



The challenge consists, in part, of the need to interrogate the enormous search space for determining the mapping across levels, which constitutes a many-to-many probabilistic problem. Computational innovation will be a key effort to help close these gaps. Portion of figure adapted with permission from ref. [62], Elsevier. Also shown are some of the ways in which QC can aid in the interrogation of these levels.

Emani, P.S., Warrell, J., Anticevic, A. et al. Quantum computing at the frontiers of biological sciences. Nat Methods 18, 701–709 (2021). https://doi.org/10.1038/s41592-020-01004-3

Case 1: Glaucoma Prediction

First in class, functional, independent of the IOP attribute, intelligent decision support system in the diagnosis and therapy of glaucomatous neuropathy, based on the description of dynamic phenomena and interactions occurring between the eyeball and the cardiovascular system

1. **Predicting the development and progression of glaucomatous neuropathy**
2. **Evaluation of the therapy effectiveness**
3. Identification of therapeutical targets different from IOP reduction

Świerczyński, H., Pukacki, J., Szczęsny, S., Mazurek, C., Wasilewicz, R. Application of machine learning techniques in GlaucomAI system for glaucoma diagnosis and collaborative research support. Sci Rep 15, 7940 (2025). https://doi.org/10.1038/s41598-025-89893-2


特　許　証
(CERTIFICATE OF PATENT)

特許第７２７８３２３号
(PATENT NUMBER)

発明の名称 (TITLE OF THE INVENTION)
対象者の緑内障のリスクを予測する予測モデルを生成する方法、当該予測モデルを用いて対象者の緑内障リスクを決定する方法、対象者の緑
その他別紙記載

特許権者 (PATENTEE)
ポーランド６１－７０４ポズナン、ノスコフスキエゴ１２／１４番、ポズナンスキエ・セントルム・スーペルコンプテロヴォ－シェチョヴェ
国籍・地域　ポーランド共和国
インスティトゥト・ヘミー・ビオオルガニチネイ・ペアエヌ
その他別紙記載

発明者 (INVENTOR)
ロベルト・ヘンリク・ヴァシレヴィチ
チェザリ・マズレク
ユリウシュ・プカツキ
その他別紙記載

出願番号 (APPLICATION NUMBER)　特願２０２１－０６５７９８
出願日 (FILING DATE)　令和　３年　４月　８日(April 8, 2021)
登録日 (REGISTRATION DATE)　令和　５年　５月１１日(May 11, 2023)

この発明は、特許するものと確定し、特許原簿に登録されたことを証する。
(THIS IS TO CERTIFY THAT THE PATENT IS REGISTERED ON THE REGISTER OF THE JAPAN PATENT OFFICE.)

令和　５年　５月１１日(May 11, 2023)

特許庁長官
(COMMISSIONER, JAPAN PATENT OFFICE)

濱野幸一

Case 2: Brain dynamics

Why study brain dynamics (with our extensions):

- Dynamical-systems + **physics descriptors** effectively capture brain□s spatiotemporal richness
- **Data □shared space □descriptors □phase localisation** enables **virtual experimentation** (e.g., neuromodulation/lesion what-ifs)

Where alternative methods fall short (spatiotemporal complexity and current limitations):

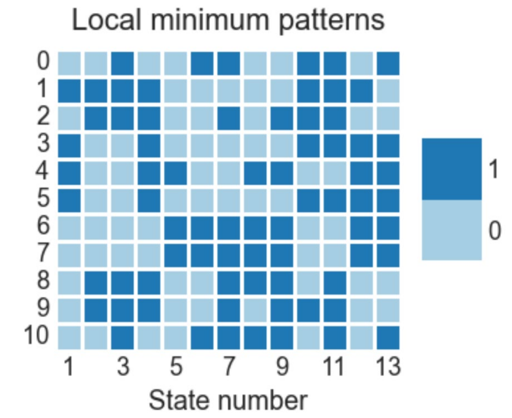
- Brain activity is high-dimensional, multiscale, and metastable: patterns reconfigure over space (millimetres □networks □whole brain) and time (milliseconds □minutes)
- **Idiosyncratic feature spaces** across subjects/modalities make cohort-level comparison hard (apples vs oranges). Virtual whole-brain models exist, but standard coordinates for dynamics are scarce.
- **Sampling & optimisation** for high-dimensional, rugged energy landscapes are computationally demanding; classical methods can struggle to explore rare transitions at scale. Specialised tools may help Λ**virtual models** (calibrated from descriptors) and **quantum** accelerators for hard inference/sampling (Ising/QUBO)

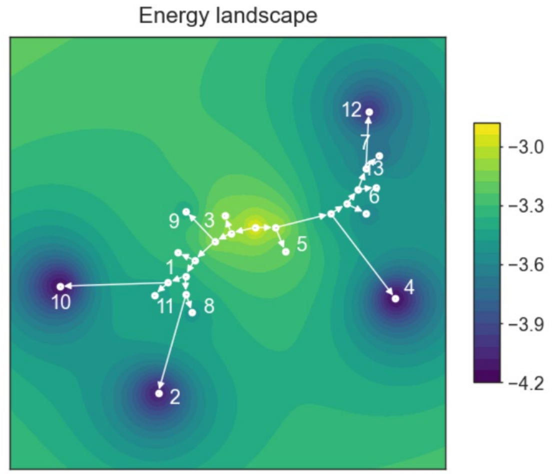
Proposed method:

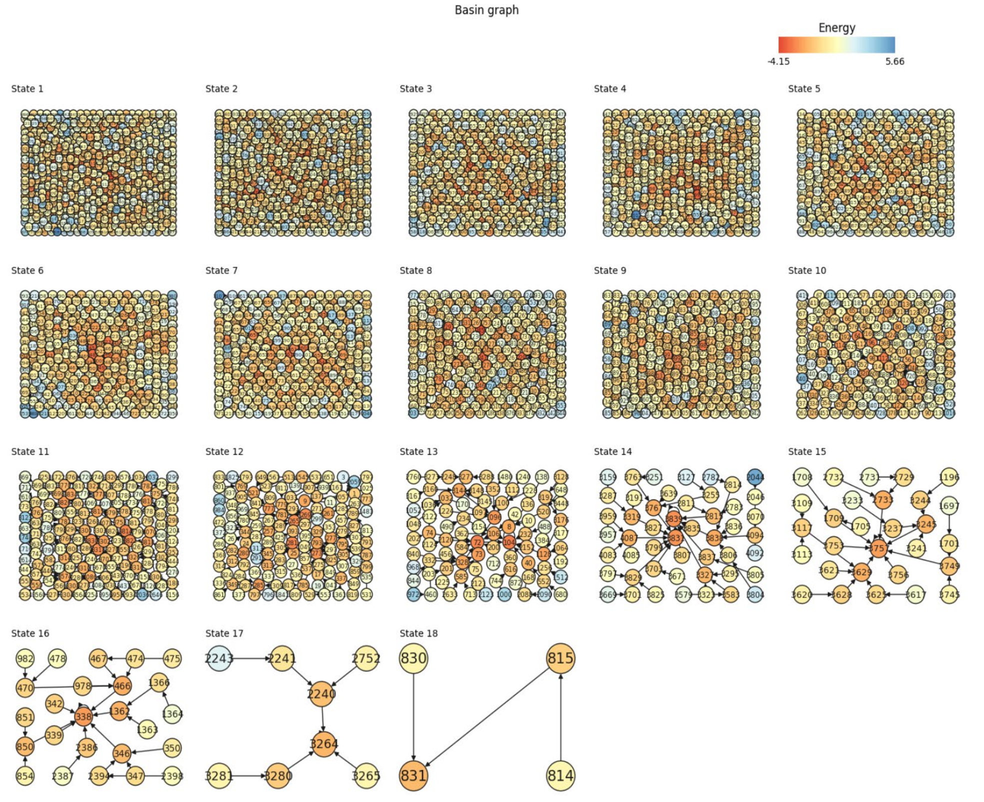
- Shared, population-trained representational space
- Energy landscape analysis (ELA) of each subject's latent representation
- Common-reference phase diagram analysis (PDA) of the cohort

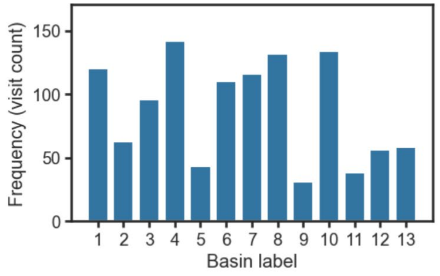
Energy Landscape Analysis (ELA):

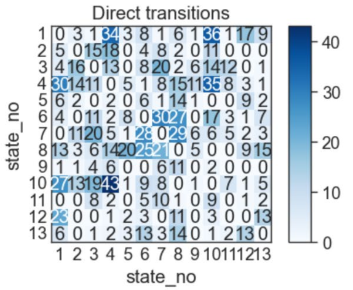
Local minimum patterns: Fingerprints of attractor states (columns = basins, rows = regions; dark = active).
Energy landscape: 2-D surface with labelled minima and saddle crossings; valleys = stability, ridges = barriers.
Basin graph: node-level patterns per basin; one-step reachability between minima (who neighbors whom).
Visit frequency: How often each basin is expressed in the data (common vs rare states).
Direct transitions: One-step jump probabilities between basins (preferred moves).
Direct + indirect transitions: Multi-step reachability; alternative routes and funnels.
Barrier-height distribution: Histogram of saddle energies; overall ease/hardness of switching.
Disconnectivity graph: Dendrogram organised by barrier heights; vertical gaps = separation; clusters = families of states.

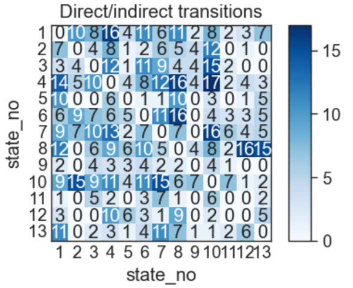


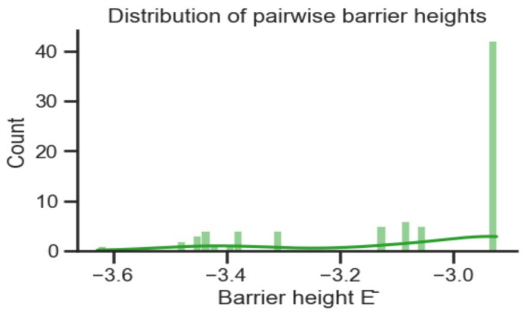


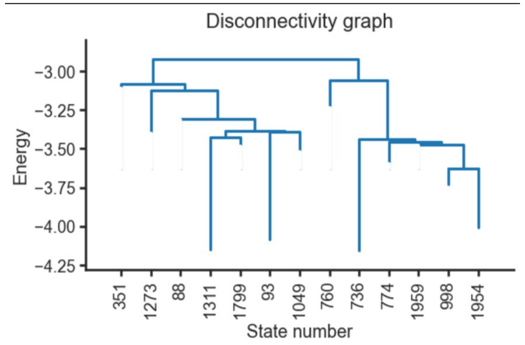












Usecase takeway

Our pipeline places each brain in a common, physics-grounded map and reads out simple, interpretable markers of dynamics - global drive, pattern rigidity/flexibility, sensitivity to local vs. global input, distance to tipping points - plus landscape features (basins, barriers, transition paths).

Why this matters (clinical & research):

- Detect failure modes: fragmented coordination, over/under coupling, rigid or unstable dynamics; localise them in phase space.
- Clinical use: screen/stratify patients, track treatment response, and select/personalise stimulation or drug targets using basin depth and barrier structure.
- Basic/Translational research: compare people, modalities, species, and tasks on the same coordinates; generate/test mechanistic hypotheses; run virtual what-if experiments with individualised models.
- Practical strengths: works on real recordings; provides uncertainty on every readout; classical pipeline now, quantum-ready for heavy sampling/optimisation.

Kedys, J. Mazurek, C. Phenotyping whole-brain dynamics with modality-agnostic energy landscapes and cohort embeddings. HIBALL 9th BigBrain Workshop. 27-29.10.2025, Berlin, https://events.hifis.net/event/2171/contributions/19174/

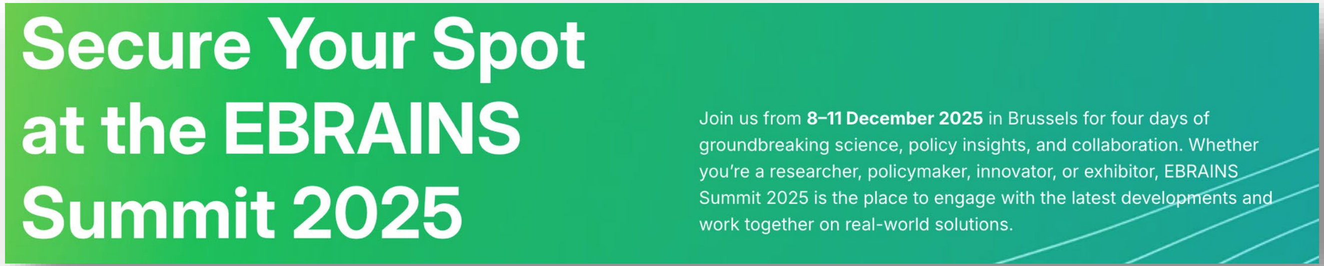
Conlusions

The journey from predicting glaucoma to simulating the brain as a virtual twin shows that we are entering an era where biology, computation, and cognition converge.

The challenge ahead is beyond the brain modeling:

to understand the human being it represents, across all scales of complexity.

From data to undestanding, from models to meaning



Poznańskie Centrum Superkomputerowo-Sieciowe
Poznan Supercomputing and Networking Center

From Quantum Scales to Virtual Humans

Thank you!

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