Human Brain Project

EBRAINS

INFN
Istituto Nazionale di Fisica Nucleare
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@APELab_INFN

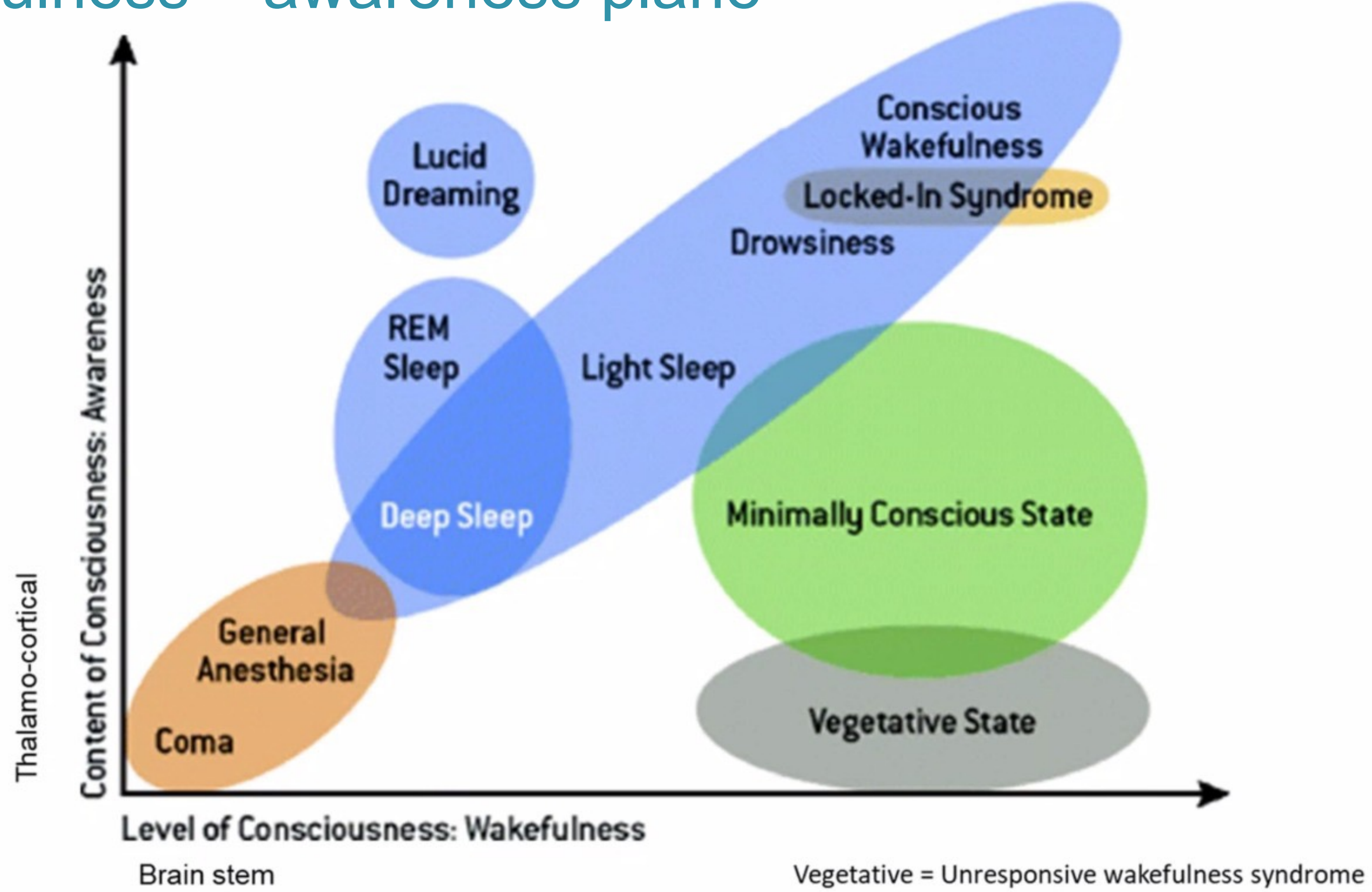
Cognitive and energetic benefits of awake/sleep cycles during incremental learning in spiking neural networks
-> Bio-inspired AI

Pier Stanislao Paolucci

On behalf of APE Lab @ INFN: R. Ammendola, I. Bernava, A. Biagioni, G. De Bonis, C. Capone, P. Cretaro, C. De Luca, O. Frezza, F. Lo Cicero, A. Lonardo, C. Lupo, M. Martinelli, P.S. Paolucci, E. Pastorelli, L. Pontisso, F. Simula, L. Tonielli, M. Turisini, P.Vicini

Co-funded by the European Union

Brain States and Cosciousness: an emerging classification in the wakefulness – awareness plane

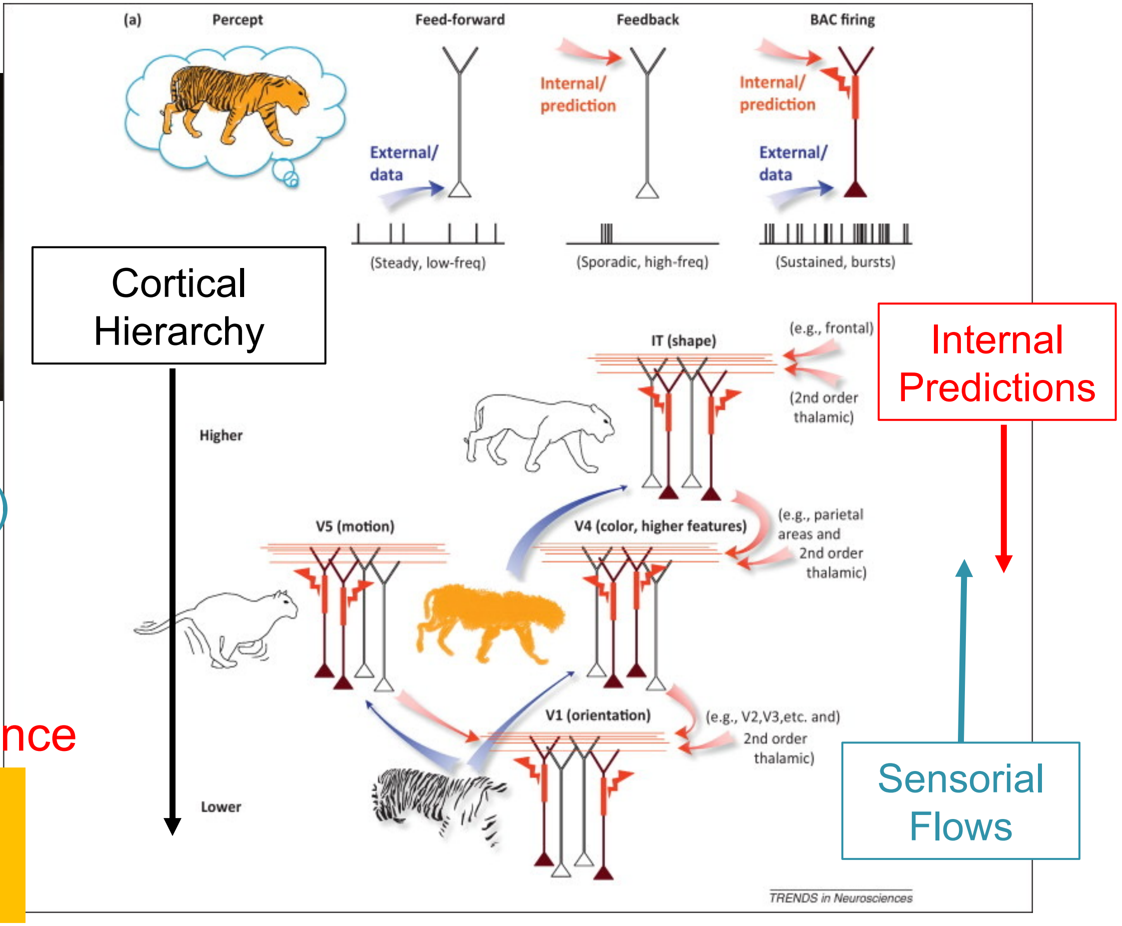


M.V. Sanchez-Vives, M. Massimini, S. Laureys, A. Destexhe, J. Storm, M. Mattia, P.S. Paolucci et al. (2020) kick-off meeting of “Networks Underlying Cognition and Consciousness” Work-package, The Human Brain Project.

Thalamo-cortical spiking models showing the beneficial cognitive and energetic effects of the interplay among sleep and memories, learned by combining contextual and perceptual information

- Sleep essential, in all animal species
- Young humans pass the majority of time sleeping, when learning is faster
- Sleep deprivation detrimental for cognition, even in adults
  - Sleep deprivation, terrible torture

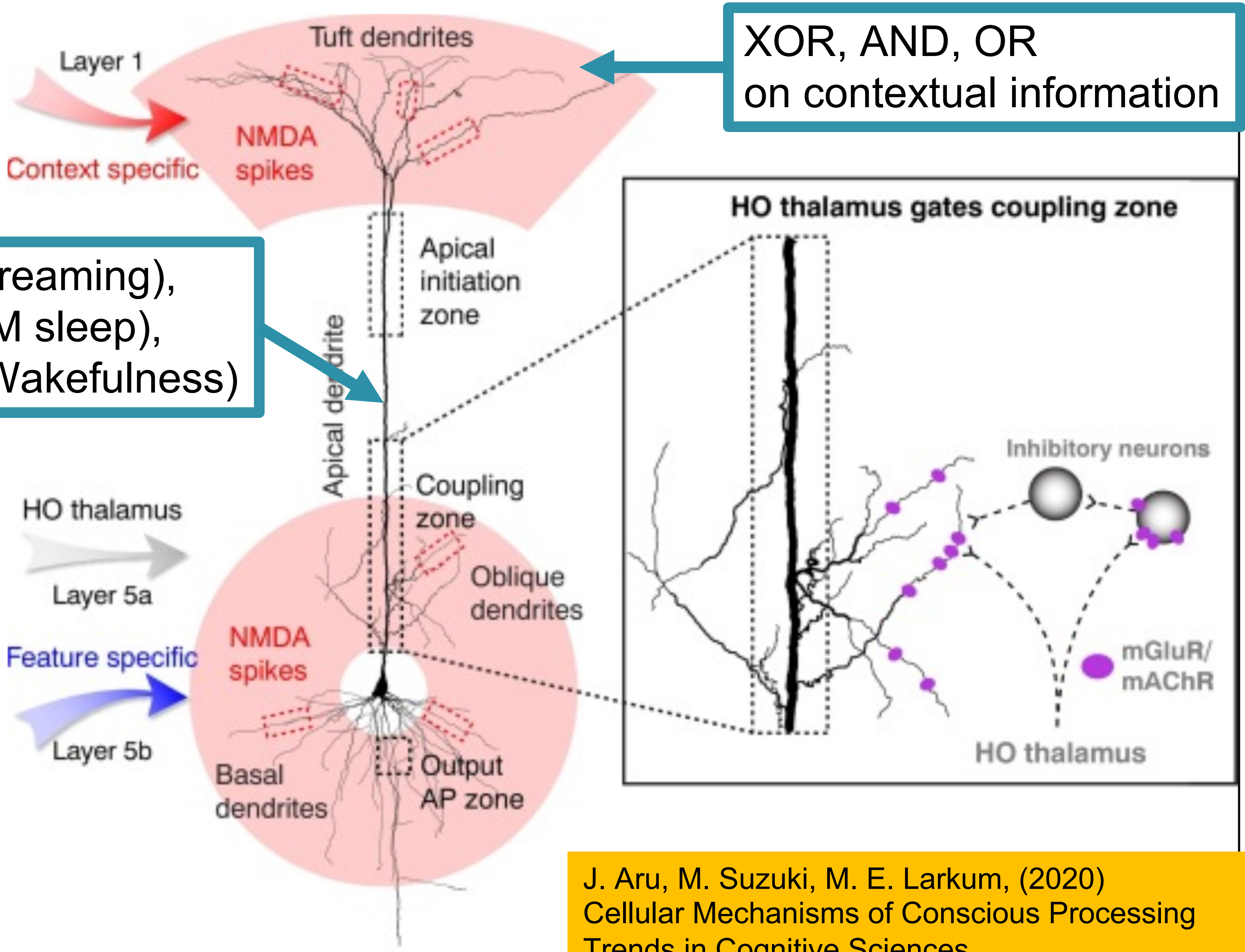
- Roles in *biological intelligence*
  - Optimization of energy consumption
  - Homeostatic processes (normalization of representations)
  - Novel, creative associations and planning
  - Optimization of performances
  - Recovery /restorations of bio-chemical optimality
- (our opinion) Sleep essential for bio-inspired artificial intelligence



Thalamo-cortical spiking model of incremental learning combining perception, context and NREM-sleep ***PLoS Computational Biology*** (2021). *B.Golosio, C. De Luca, C. Capone, …, P.S. Paolucci*. https://doi.org/10.1371/journal.pcbi.1009045

Sleep-like slow oscillations improve visual classification through synaptic homeostasis and memory association in a thalamo-cortical model ***Scientific Reports*** (2019). *C. Capone, E. Pastorelli, B. Golosio, P.S. Paolucci*. https://www.nature.com/articles/s41598-019-45525-0

Larkum, M. A cellular mechanism for cortical associations: an organizing principle for the cerebral cortex. ***Trends in Neurosciences***, 36 (2013), 141.



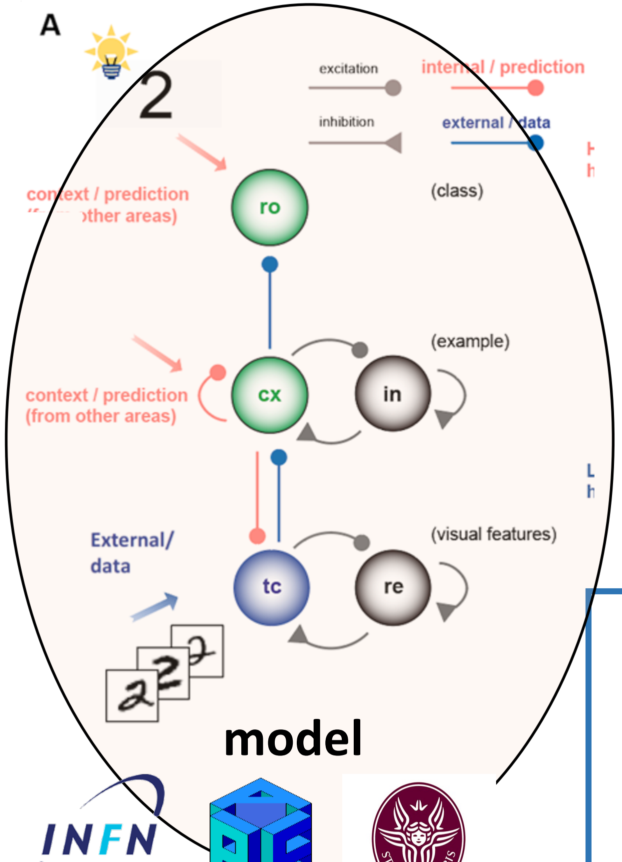
XOR, AND, OR
on contextual information

Apical Drive (Dreaming),
Isolation (NREM sleep),
Amplification (Wakefulness)

Sleep / wake dependent neural mechanisms of conscious / unconscious processing

J. Aru, M. Suzuki, M. E. Larkum, (2020)
Cellular Mechanisms of Conscious Processing
Trends in Cognitive Sciences
https://doi.org/10.1016/j.tics.2020.07.006

Thalamo-cortical INFN models of the energetic and cognitive effects of sleep after awake learning

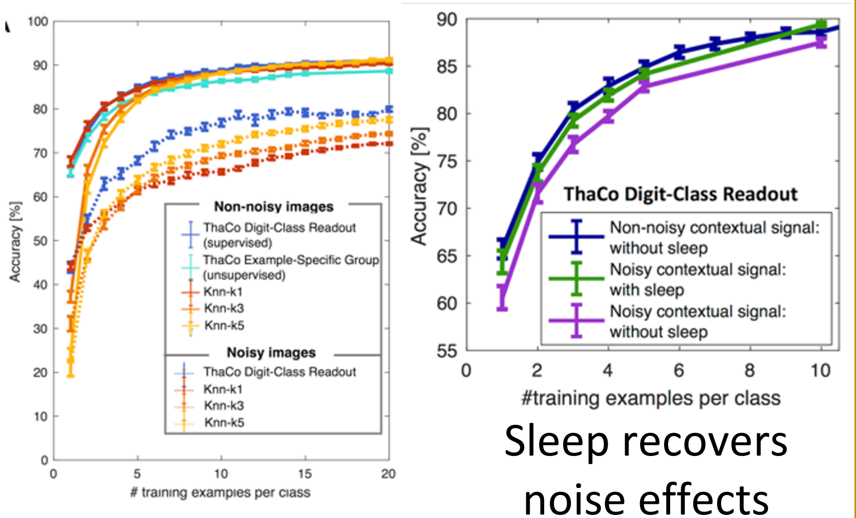


model

Thalamo-cortical … ***PLoS Computational Biology*** *(2021). B.Golosio, C. De Luca, C. Capone, …, P.S. Paolucci.*

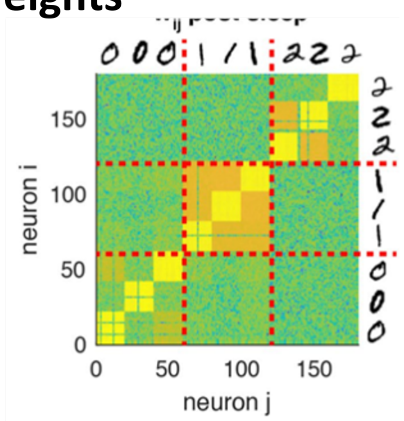
comparable with experiment Watson et al. ***Neuron*** 90 (2016)

Capability of awake incremental learning

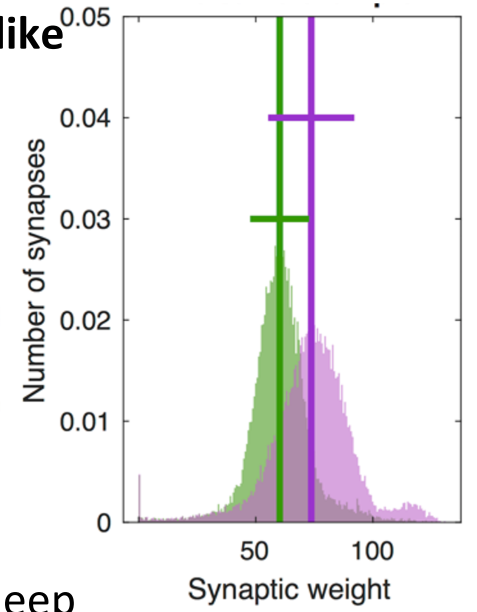


Sleep recovers noise effects

Effects of deep-sleep like activity over synaptic weights



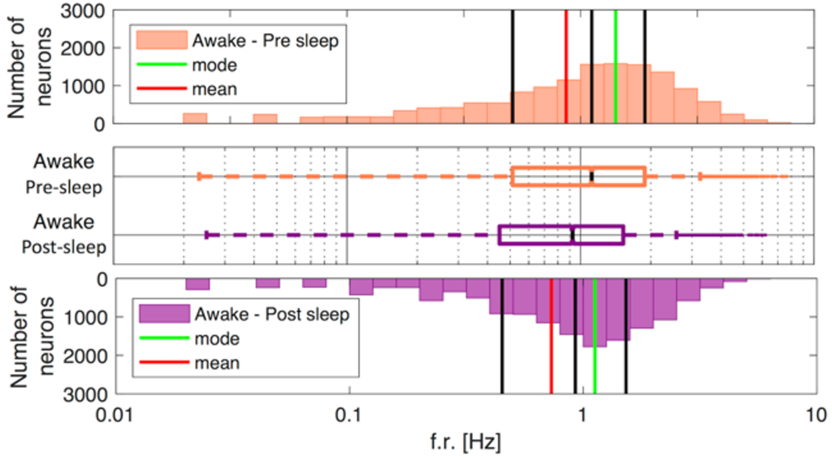
Associative effect of sleep



Homeostatic effect

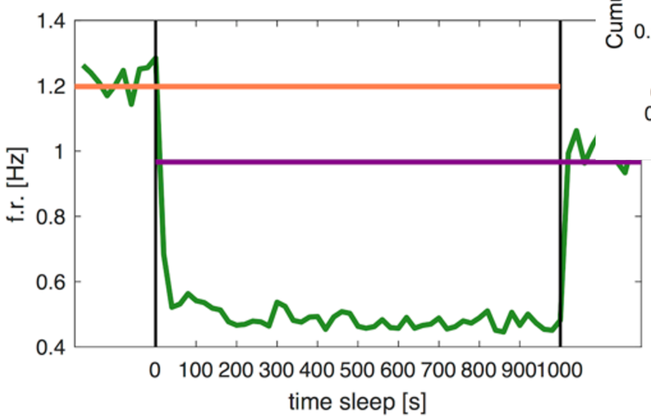
Scientific Reports (2019). *C. Capone et al*

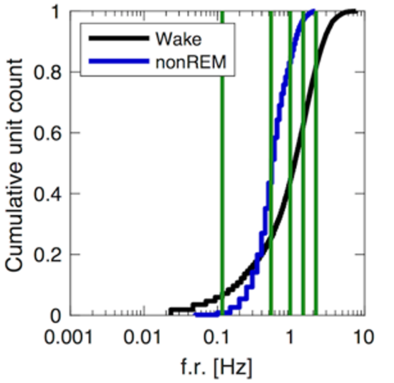
Effects of deep-sleep like activity over neuronal firing rates



Pre-post sleep firing rate distributions

Mean firing rate decreases over time





Cumulative firing rate distribution

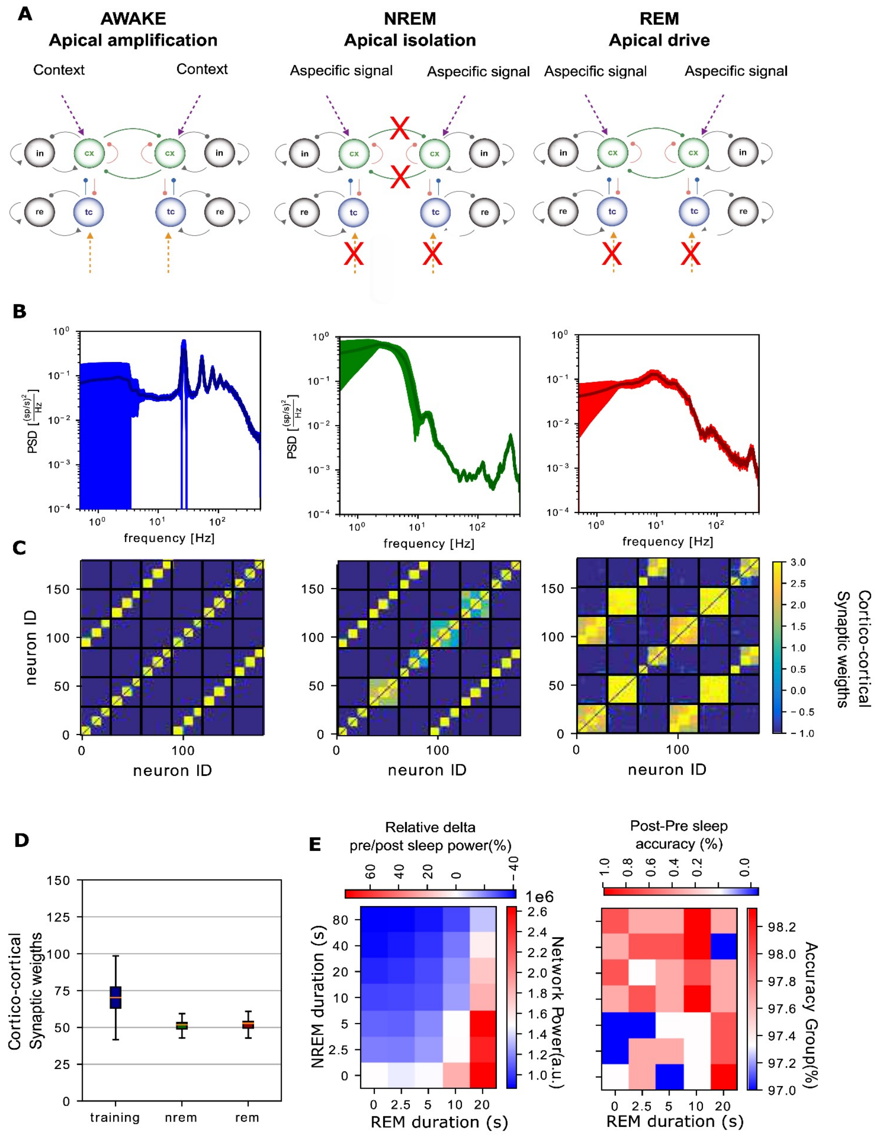
In progress INFN work to add dreaming (REM) to deep-sleep (NREM) and wakefulness modeling

Apical Amplification – Isolation – Drive vs Wakefulness, NREM, REM

Cellular mechanism supporting “brain state specific” combination/decoupling of contextual information (i.e. internal information, flowing either Top-Down from areas higher in the abstraction Hierarchy and/or Laterally from other areas at similar level of abstraction
With
bottom-up evidence from sensory system or areas lower in the abstraction hierarchy

J. Aru, F. Siclari, W. A. Phillips, J. F. Storm (2020)
Apical drive—A cellular mechanism of dreaming?
Neuroscience & Biobehavioral Reviews

J. Aru, M. Suzuki, M. E. Larkum, (2020)
Cellular Mechanisms of Conscious Processing
Trends in Cognitive Sciences



INFN APE Lab in Human Brain Project - EBRAINS

HBP (2014-2023). budget > 500M€. (https://www.humanbrainproject.eu) >120 research institutions

- Mission: understand structure and mechanisms supporting brain functions: since ever a major philosophical challenge. Turned by experimental tools and HPC simulation in a scientific challenge
  - Physicists and HPC scientists central: complex systems, massive data analysis, models on HPC
- Societal motivations:
  - 800 B€/year in Europe, cost of neurologic traumatic and clinic diseases
  - Next-generqtion Bio-inspired AI
- Deliver of first release EBRAINS Research Infrastructure. (https://ebrains.eu/)
  - Open access / reproducible brain research. FAIR methodology. Integration of experimental data (atlases and activity) and models. (2023-...) EBRAINS European ESFRI: central structure + national nodes

APELab - INFN Roma: 2.1 M€ from HBP (2016-2023), “Networks underlying cognition and consciousness”

- Modeling cognitive, entropic and energetic optimizations effects produced by wakefulness, deep sleep (NREM), dreaming (REM) + high resolution cortical modelling on parallel/distributed computing systems
- Analysis of experimental data and high-resolution modeling of spatio-temporal features of brain activity waves
- Synergy with APELab “traditional” HPC projects. Benchmarks for next computing and networking architectures
- -> PNRR: EBRAINS Italian Node (2023-2026) proposal submitted Feb 2022 + Bio-Inspired AI (TBC)

BASSES Workshop

Organized by APELab/LENS on behalf of the Human Brain Project – EBRAINS Research Infrastructure

BASSES:= Brain Activity across Scales and Species: Analysis of Experiments and Simulations

When
13-15 June 2022

Where
RomaEventi Fontana di Trevi
Piazza della Pilotta 4, Roma

Hybrid format (on-line & on-site)

Free of charge (no conference fee)

Call for abstract open (poster session)

applied sciences

an Open Access Journal by MDPI

IMPACT FACTOR 2.679

CITESCORE 3.0 SCOPUS

New Insights into Computational Neuroscience

Guest Editor
Dr. Giulia De Bonis

Deadline
20 September 2022

Special Issue

mdpi.com/si/104727

Invitation to submit

INFN Istituto Nazionale di Fisica Nucleare

lens European Laboratory for Non-Linear Spectroscopy

Human Brain Project Education Programme

EBRAINS Workshop

Brain Activity across Scales and Species: Analysis of Experiments and Simulations (BASSES)

13 – 15 June 2022

ROME (ITALY) AND ONLINE

Abstract Submission Deadline
6 MAY 2022

Registration Deadline
27 MAY 2022

The goal of the BASSES Workshop is to provide an overview of the scientific topics of brain states and complexity, state transitions, and their connection with cognitive functions, and to demonstrate the achievements in this field obtained within the Human Brain Project thanks to the functionalities provided by the EBRAINS research platforms.

BASSES will allow people with different expertises, from experimental and theoretical neuroscientists to computer scientists, to share results and ideas and connect into a wider community.

Scientific chairs

Anna Letizia Allegra Mascaro | LENS
Giulia De Bonis | INFN

Hands-on sessions

Handling EBRAINS data
Lyuba Zehl | Forschungszentrum Jülich

Running analysis in EBRAINS
Michael Denker | Forschungszentrum Jülich

Simulating spatially organised networks with NEST
Johanna Senk | Forschungszentrum Jülich

Validating models against data in EBRAINS
Andrew Davison | CNRS

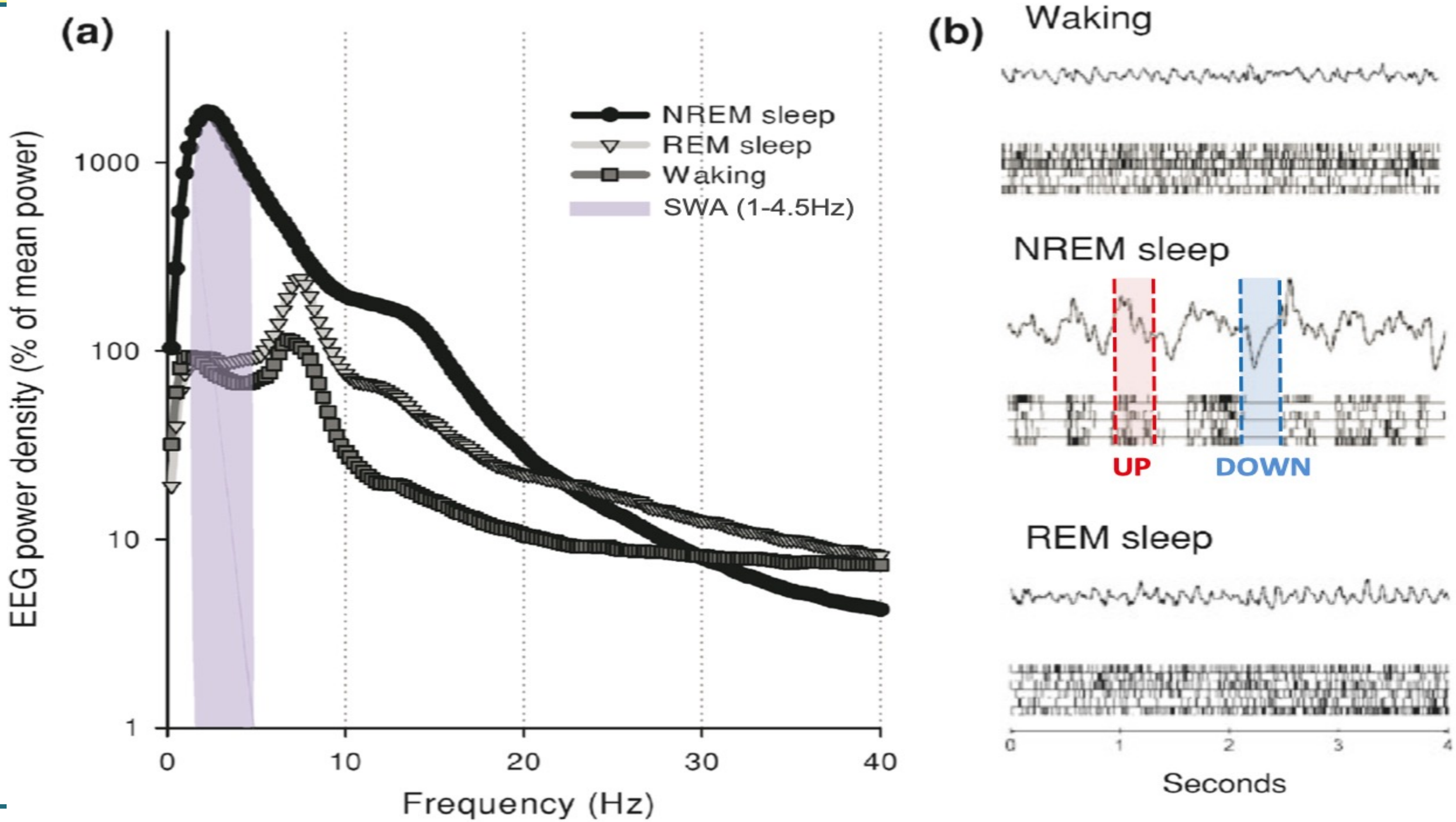
Confirmed speakers

Jan Bjaalie (University of Oslo)
Alessandra Camassa (IDIBAPS)
Cristiano Capone (INFN)
Chiara De Luca (INFN)
Alain Destexhe (CNRS)
Jennifer Goldman (INFN)
Bruno Golosio (University of Cagliari)
Robin Gutzen (Forschungszentrum Jülich)
Viktor Jirsa (Aix-Marseille University)
Arnau Manasanch (IDIBAPS)
Thierry Nieus (University of Milan)
Marcello Massimini (University of Milan)
Maurizio Mattia (ISS)
Elena Montagni (LENS)
Pier Stanislao Paolucci (INFN)
Francesco Pavone (LENS)
Elena Pastorelli (INFN)
Andrea Pigorini (University of Milan)
Mavi Sanchez-Vives (IDIBAPS)
Johan Storm (Unversity of Oslo)
Gianni Valerio Vinci (ISS)
Sacha van Albada (Forschungszentrum Jülich)

Further information
www.humanbrainproject.eu/en/education/ebrains-workshops/basses

EBRAINS Human Brain Project Co-funded by the European Union

Deep-sleep NonREM <-> Unconscious state, Slow Waves in Delta band
REM (dreaming) and Wake <-> Conscious, Asyncronous Irregular activity



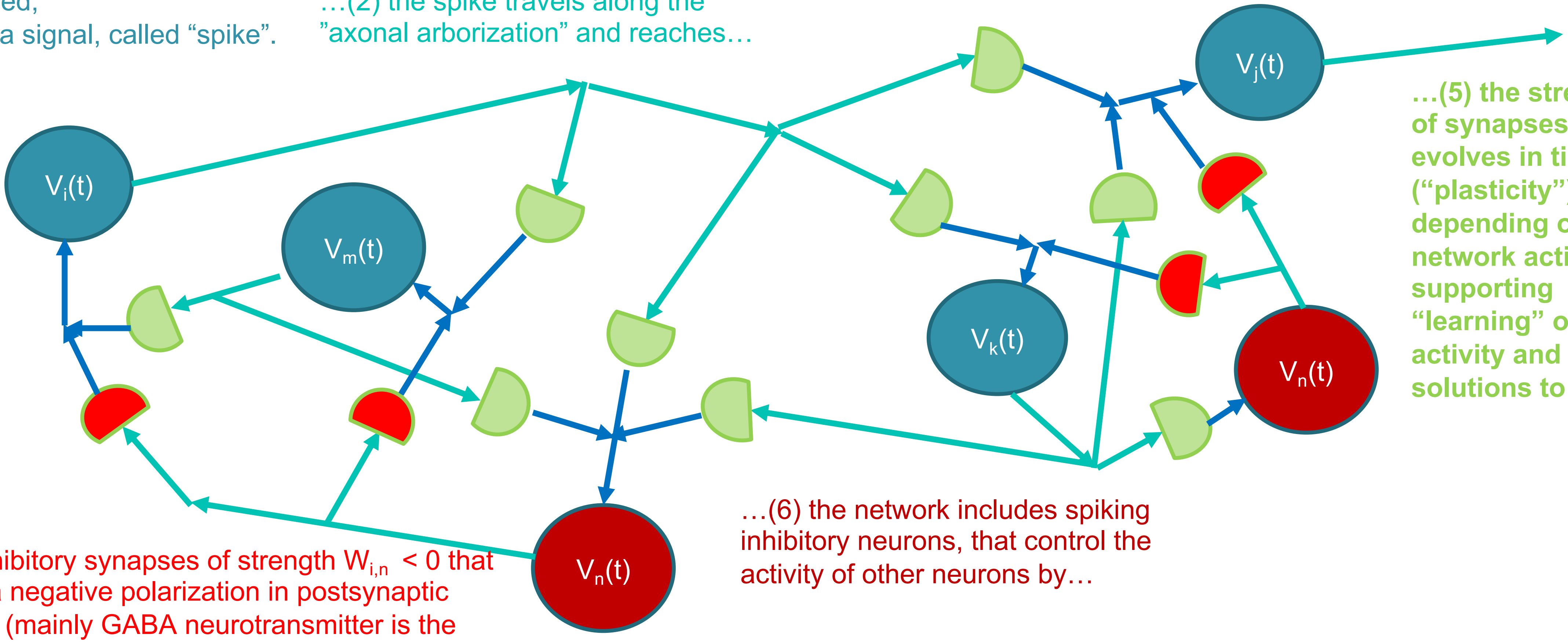
Toy spiking model with plastic synapses

(1) Excitatory Neuron i, and its membrane potential V_i (t).
If a threshold potential is surpassed,
it emits a signal, called "spike".

…(2) the spike travels along the "axonal arborization" and reaches…

…(3) excitatory synapses of strength $W_{j,l} > 0$ that inject a positive current in postsynaptic neurons (typically, Glutammate neurotransmitter opens the channels)

(4) Contributing to the dynamics of postsynaptic neurons, and to the emission of spikes



…(5) the strength of synapses evolves in time ("plasticity") depending on the network activity, supporting "learning" of past activity and novel solutions to tasks

…(6) the network includes spiking inhibitory neurons, that control the activity of other neurons by…

…(7) inhibitory synapses of strength $W_{i,n} < 0$ that induce a negative polarization in postsynaptic neurons (mainly GABA neurotransmitter is the channel opener)

Toy model: networks of neurons with Spike Frequency Adaptation can enter and exit from the NREM Slow Wave Activity regime

$V(t)$, membrane potential of the neuron
C_m, the membrane capacitance of the neuron

ω, the neural *fatigue* due to the emission of spikes

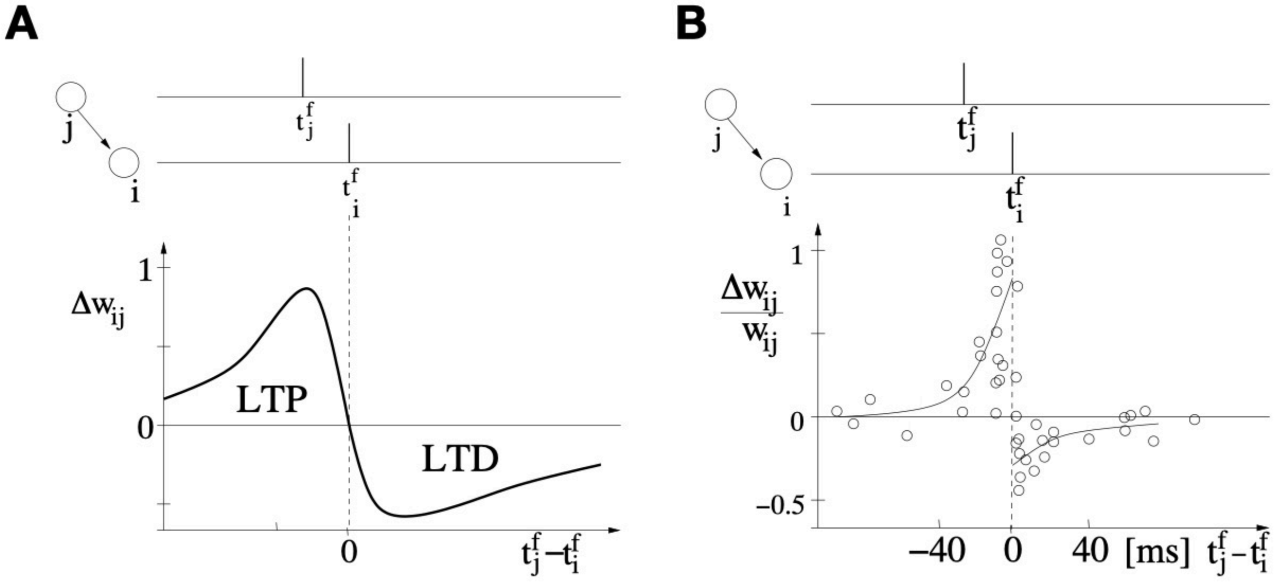
I_{system}, the input current, spikes from other neurons injected by synapses

$$\left\{\begin{array}{ll} V(t) \geq V_{treshold} \rightarrow & \text{spike emission, axonal transmission to} \\ & \text{synapses that injects current in other neurons} \\ & \text{reset potential to afterspike } V_{afterspike} \\ & \text{increase the fatigue } \omega \\ C_m \frac{dV}{dt} & = -g_L\,(V - E_L) + g_L \Delta_T e^{\frac{(V - V_{th})}{\Delta_T}} + I_{system} - \omega \\ \tau_\omega \frac{d\omega}{dt} & = a\,(V - E_L) + b \sum_k \delta(t - t_k) - \omega \end{array}\right\} \quad (1)$$

Change b parameter in last equation to enter and exit NREM Slow Wave Regime

Neuromodulation proxy

Learning in a toy spiking model: Spike Timining Dependent Plasticity (STDP)



- Synapses are engines that are able to detect both causality and anti-causality.
- They can reward themselves, by increasing their values when causality is detected,
- and depress themselves when anti-causality is detected.

General form of synaptic
Spiking Time Dependent synaptic Plasticity (STDP)

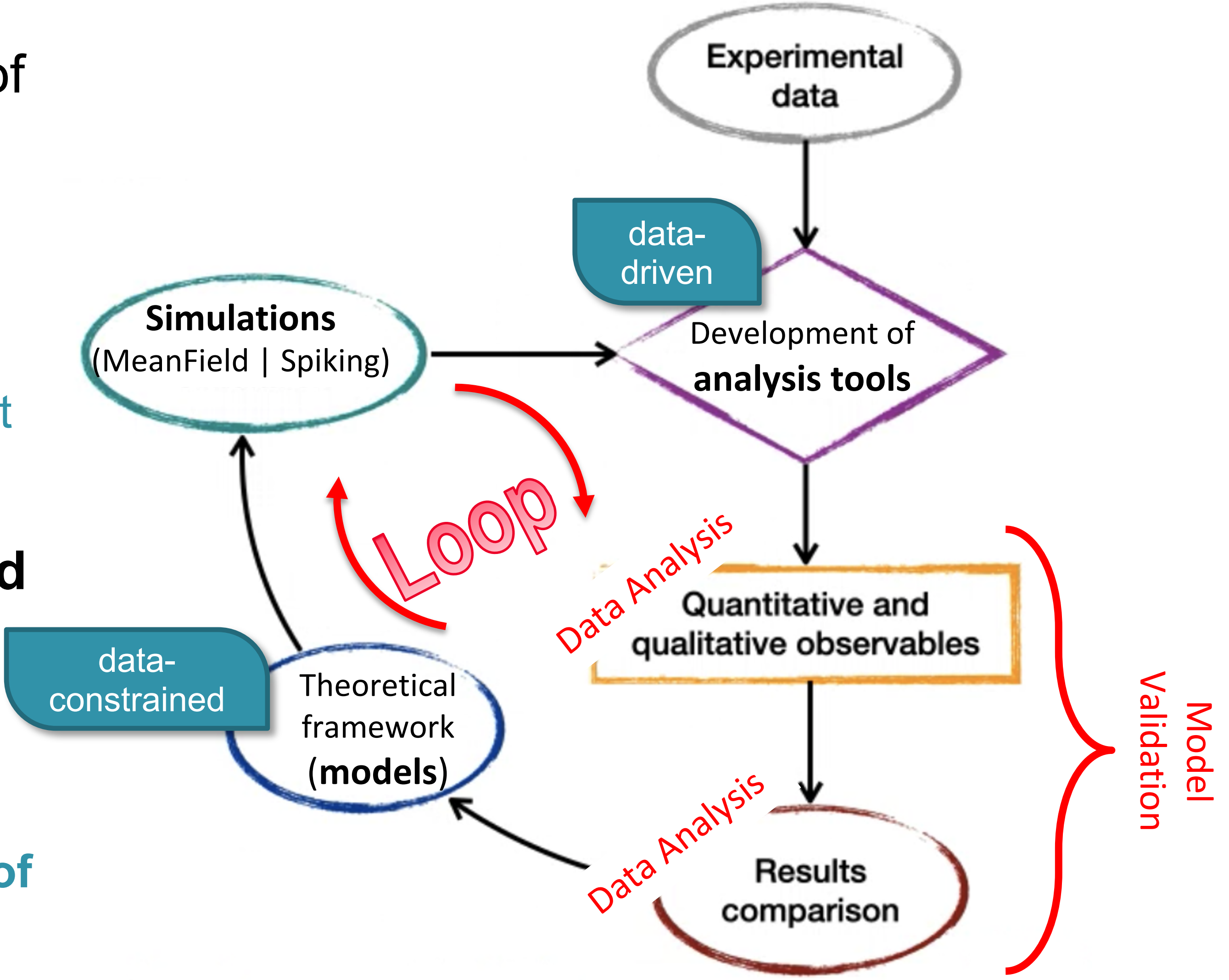
$$\Delta w(\Delta t) = \begin{cases} A_+ e^{\frac{\Delta t}{\tau_+}} & \Delta t > 0 \\ A_- e^{\frac{\Delta t}{\tau_-}} & \Delta t \leq 0 \end{cases}$$

Specific form used in many of our simulations:
NLTAH-STDP

$$\Delta w(\Delta t) = \begin{cases} -\lambda \alpha w^{\mu} e^{-\frac{\Delta t}{\tau}} & \Delta t \leq 0 \\ \lambda (1-w)^{\mu} e^{-\frac{\Delta t}{\tau}} & \Delta t > 0 \end{cases}$$

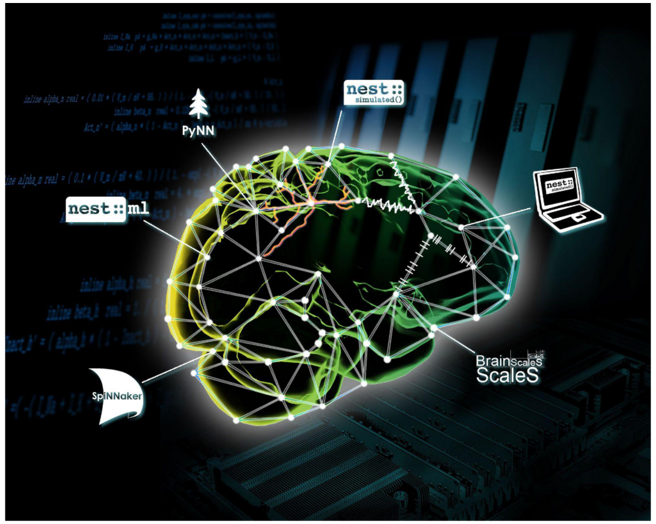
Interplay DataAnalysis – Models – Simulations

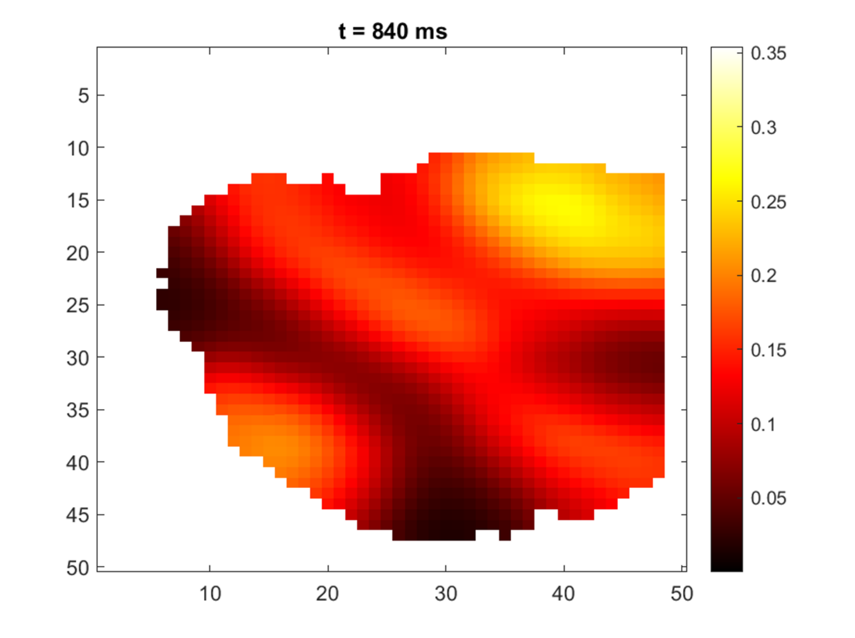
- understand mechanisms and features of the brain dynamics from **observation** and **interpretation** of **experimental data**
  - define **benchmark observables** and design **data-driven analysis tools**, for **comparing and combining different datasets**, aiming at general claims and at statistically significant assessments
- extract results from experimental recordings for feeding **data-constrained simulations** and **refining theoretical models**
  - define **methods and procedures** for the **validation of theoretical models** (comparison of experimental and simulated data) and for the **comparison of models**



INFN: large scale simulations

- Spiking and mean field neural network simulations reproducing models of **cortical slow wave activity** at the scale of mouse hemisphere
- Data-driven model: simulation **parameters inferred from experimental data** (wide-field calcium imaging)





- Near to **biological resolution** (54K neuron/mm2 and about 5K synapses per neuron in rat neocortex area)
- Simulated and experimental behavior compared using **analysis tools**
- Model used as a **benchmark** to drive the development of future interconnects for platforms including millions of embedded ARM cores

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