Bio-inspired plastic spiking neural models engaged in learning and sleep cycles

Pier Stanislao Paolucci

On behalf of APE Lab @ INFN: (R. Ammendola, I. Bernava, A. Biagioni, G. De Bonis, C. Capone, C. Chiarini, P. Cretaro, C. De Luca, O. Frezza, F. Lo Cicero, A. Lonardo, N. Kolodziej, C. Lupo, M. Martinelli, P.S. Paolucci, E. Pastorelli, L. Pontisso, L. Rosati, C. Rossi, F. Simula, L. Tonielli, M. Turisini, P.Vicini)
and B. Golosio, G. Tiddia (INFN Cagliari and Uni Cagliari)

Brain-like plastic spiking network simulations, capable of incremental learning and entering different brain states (wakefulness, REM dreaming and NREM deep-sleep)

INFN
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Simulation
Model

Combining prior knowledge with novel evidence using brain-state specific apical-amplification, apical-drive and apical isolation mechanisms.

Reducing energy consumption and time to response using spiking mechanisms

Spiking Plastic Models & exploration of Hardware IPs on FPGA
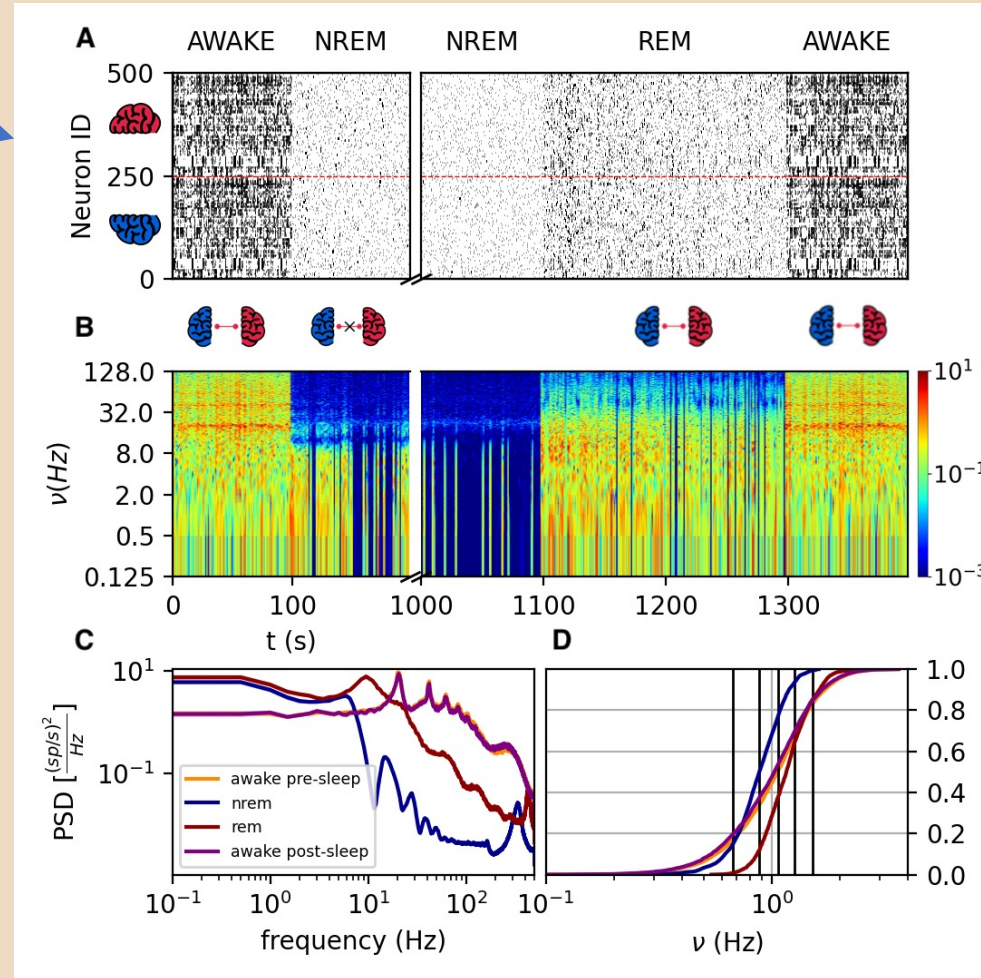
Thalamo-cortical spiking models showing the beneficial cognitive and energetic effects of the interplay among sleep and memories, learned by combining contextual and perceptual information

- 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
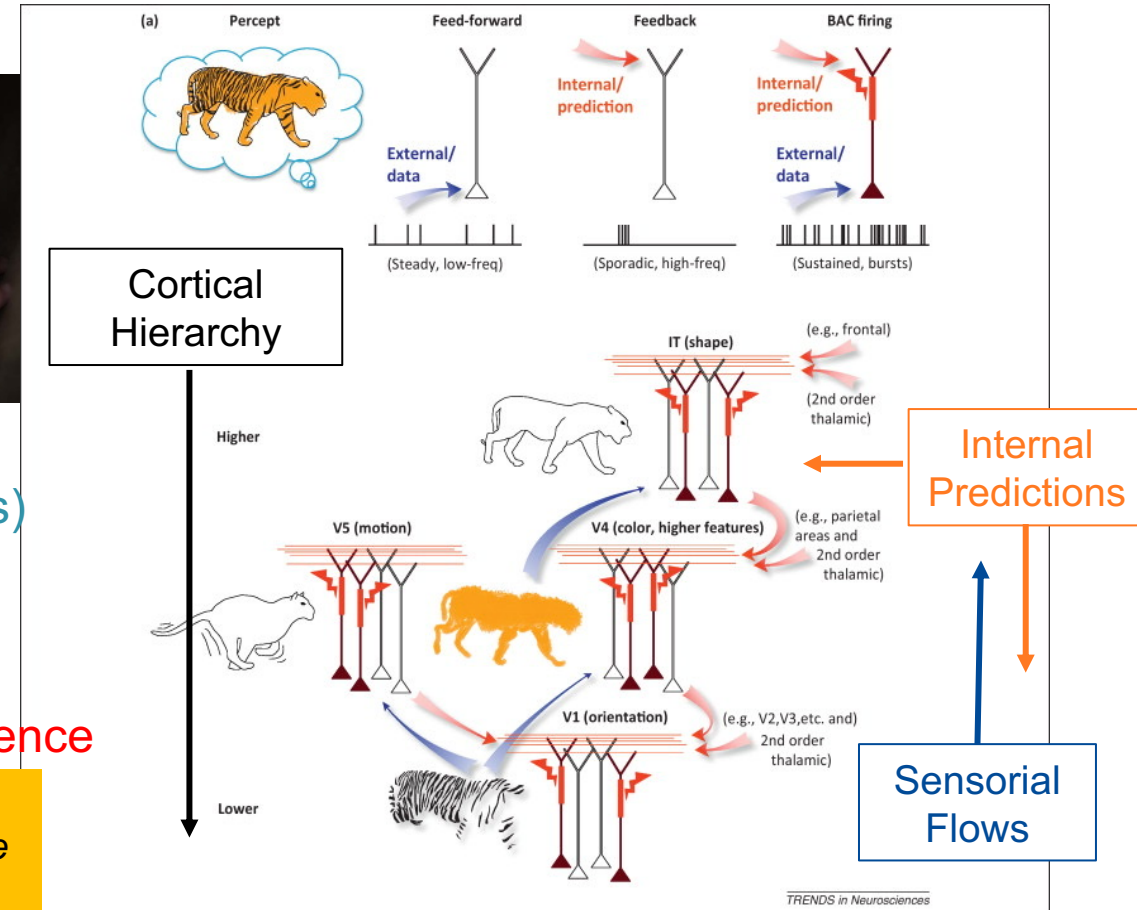
Cortical Hierarchy

Internal Predictions

Sensorial Flows

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.

# Cobrawap (collaborative brain waves analysis pipeline). Open access. Open to contributions.

Analyse spatio-temporal features of waves of neural activity propagating in the brain.

Essential to validate simulation models vs. experimental data.

- APE-LAB is a key-designer and developer of cobrawap. Main contributors:
  - INFN APE Lab, Roma
  - Jülich Forschunzentrum, Germany
  - IDIBAPS, Barcellona, Spain
  - LENS, Firenze
  - Università di Firenze
  - ISS (Istituto Superiore di Sanità)
  - collaboration starting with:
    - Athena Res Centre., Greece
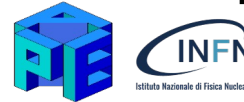
G. De Bonis et al, Analysis Pipeline…. ***Frontiers Systems Neuroscience*** (2019), 141.

M. Celotto et al, Analysis and Model of Cortical Slow Waves...... ***Methods and Protocols*** (2020), 141.

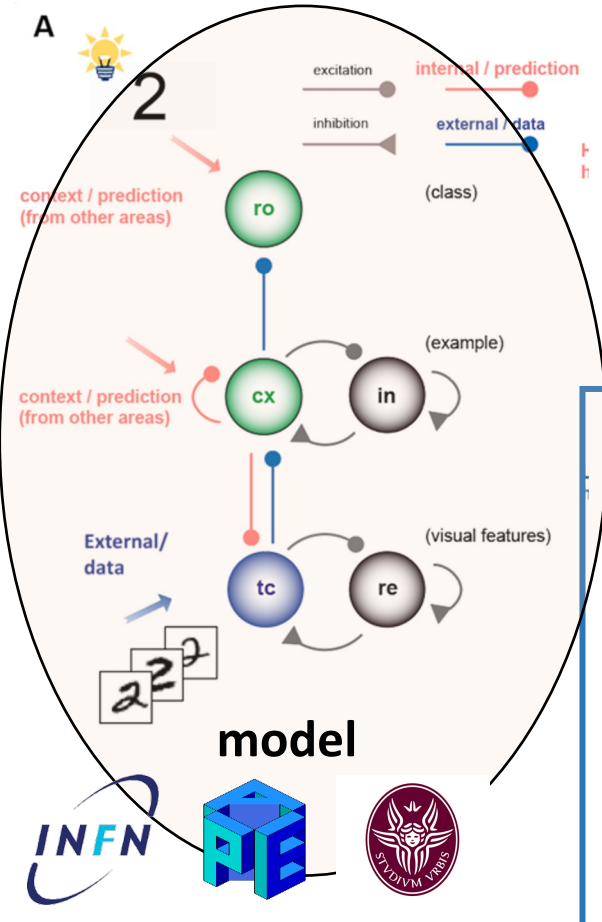*R. Gutzen et al, **arXiv: 2211.08527*** (2021)

C. Capone et al Simulations Approaching data… ***Communications Biology*** (2023) (in press)

Currently developed
In Human Brain Project /
EBRAINS-Europe Project

Future:Main INFN topic in
EBRAINS-ITALY
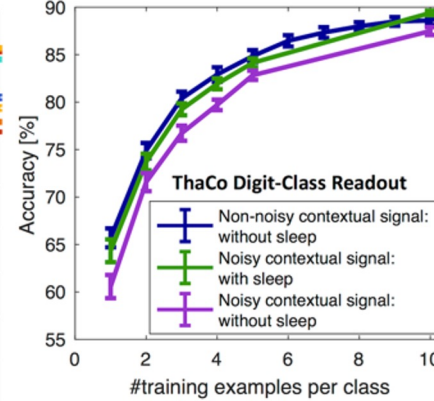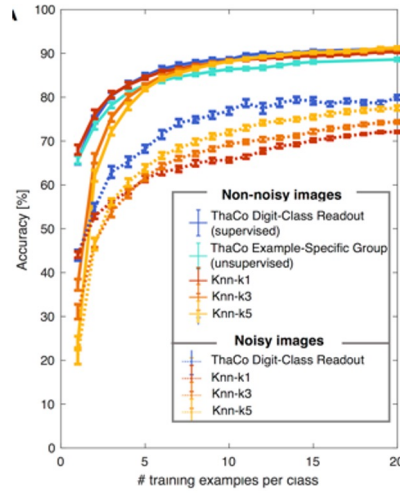PNRR project … - 2025
CUP-B51E22000150006

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.*
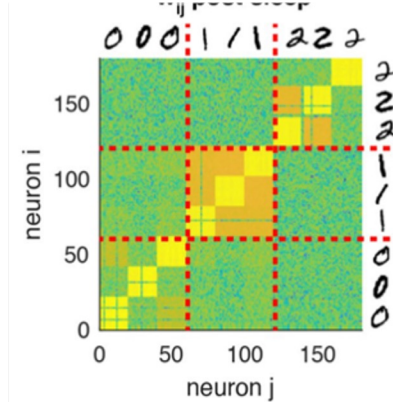
Capability of awake incremental learning
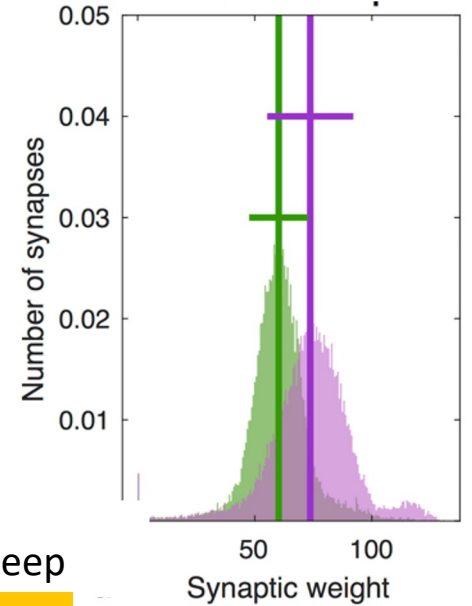
Sleep recovers noise effects

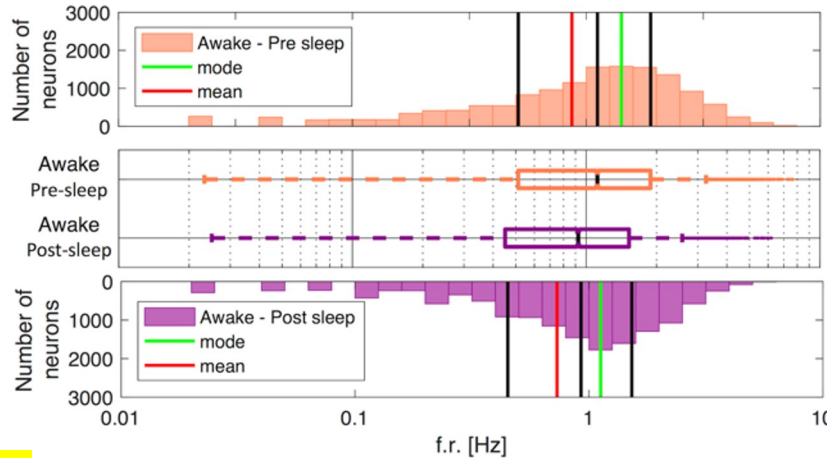learning MNIST: from 1 to 20 examples per class

Effects of NREM on synapses

Associative effect of sleep

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

Homeostatic effect

Effects of deep-sleep like activity over neuronal firing rates

Mean firing rate decreases over time

Pre-post sleep firing rate distributions
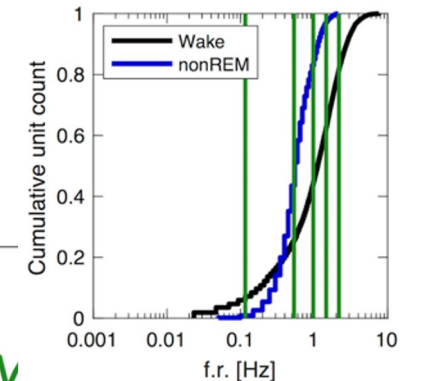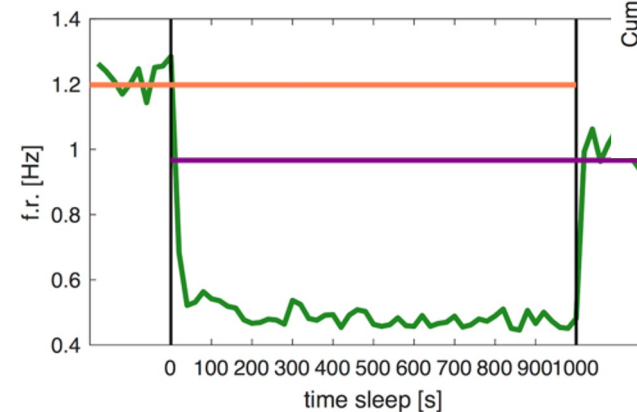
Cumulative firing rate distribution

model

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

Selection of background works from APE Lab @ INFN

PLOS COMPUTATIONAL BIOLOGY

2021 doi: 10.1371/journal.pcbi.1009045

RESEARCH ARTICLE

Thalamo-cortical spiking model of incremental learning combining perception, context and NREM-sleep

Bruno Golosio[1,2], Chiara De Luca[3,4]*, Cristiano Capone[4], Elena Pastorelli[3,4], Giovanni Stegel[5], Gianmarco Tiddia[1,2], Giulia De Bonis[4], Pier Stanislao Paolucci[4]

SCIENTIFIC REPORTS

OPEN

Sleep-like slow oscillations improve visual classification through synaptic homeostasis and memory association in a thalamo-cortical model

d: 24 January 2019
d: 3 June 2019
d online: 20 June 2019

Cristiano Capone[1], Elena Pastorelli[1,2], Bruno Golosio[3,4] & Pier Stanislao Paolucci[1]

frontiers in Systems Neuroscience

Analysis Pipeline for Extracting Features of Cortical Slow Oscillations

Giulia De Bonis[1]*, Miguel Dasilva[2], Antonio Pazienti[3], Maria V. Sanchez-Vives[2,4], Maurizio Mattia[3] and Pier Stanislao Paolucci[1]

PMLR Proceedings of Machine Learning

2022 **Research**

Burst-Dependent Plasticity and Dendritic Amplification Support Target-Based Learning and Hierarchical Imitation Learning

PLOS COMPUTATIONAL BIOLOGY

🔓 OPEN ACCESS   ⬚ PEER-REVIEWED

RESEARCH ARTICLE

Error-based or target-based? A unified framework for learning in recurrent spiking networks

Cristiano Capone, Paolo Muratore, Pier Stanislao Paolucci

Version 2 ▾   Published: June 21, 2022 • https://doi.org/10.1371/journal.pcbi.1010221

PLOS ONE

🔓 OPEN ACCESS   ⬚ PEER-REVIEWED

RESEARCH ARTICLE

Target spike patterns enable efficient and biologically plausible learning for complex temporal tasks

Paolo Muratore, Cristiano Capone, Pier Stanislao Paolucci

Published: February 16, 2021 • https://doi.org/10.1371/journal.pone.0247014

EuroEXA Custom Switch: an innovative FPGA-based system for extreme scale computing in Europe

Andrea Biagioni[1], Paolo Cretaro[1], Ottorino Frezza[1], Francesca Lo Cicero[1], Alessandro Lonardo[1], Pier Stanislao Paolucci[1], Luca Pontisso[1], Francesco Simula[1], and Piero Vicini[1,*]

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Towards EXtreme scale technologies and accelerators for euROhpc hw/Sw supercomputing applications for exascale: The TEXTAROSSA approach ☆

Giovanni Agosta[a] ✉, Marco Aldinucci[f] ✉, Carlos Alvarez[h] ✉, Roberto Ammendola[n] ✉, Yasir Arfat[f] ✉, Olivier Beaumont[g] ✉, Massimo Bernaschi[c] ✉, Andrea Biagioni[i] ✉, Tommaso Boccali[i] ✉, Berenger Bramas[g] ✉, Carlo Brandolese[a] ✉, Barbara Cantalupo[f] ✉, Mauro Carrozzo[c] ✉, Daniele Cattaneo[a] ✉, Alessandro Celestini[c] ✉, Massimo Celino[b] ✉, Iacopo Colonnelli[f] ✉, Paolo Cretaro[j] ✉, Pasqua D'Ambra[d] ✉, Marco Danelutto[e] ✉ ... Giuseppe Zummo[b] ✉