Sleep, Criticality and Information Processing in the Brain

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National Institute of Mental Health

Sleep Criticality

Information Processing in the Brain

Criticality

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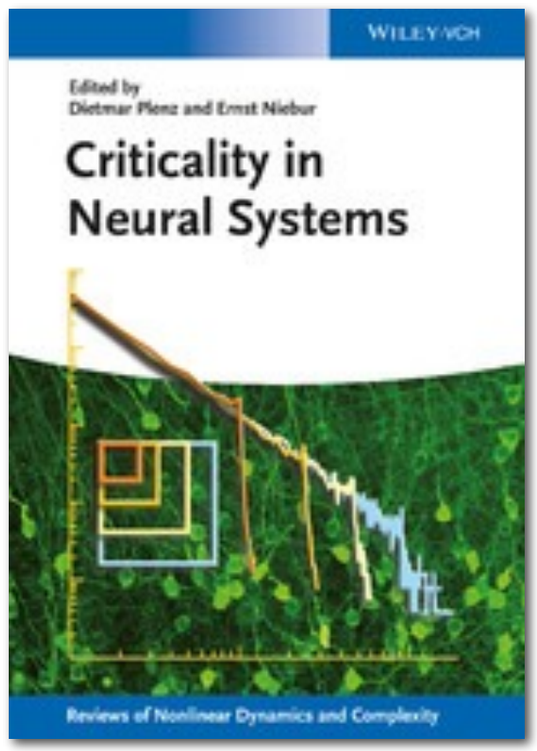
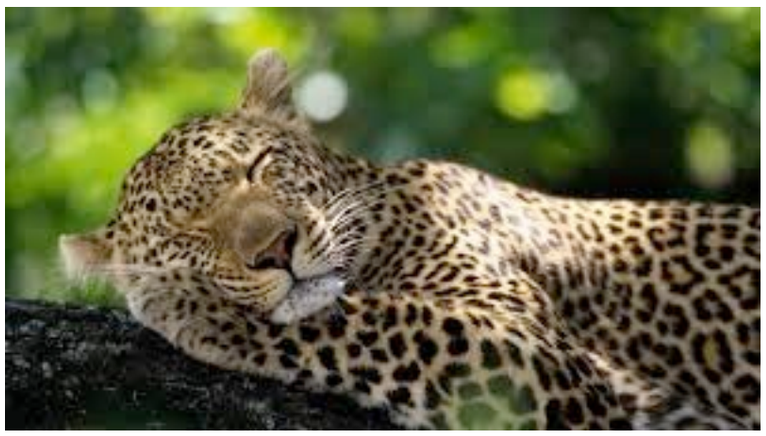
Information Processing in the Brain

Criticality



A Theory for Sleep ?



- observed in all species, from fruitflies to mammals
- about one third of lifetime is spent asleep
- „from the brain, for the brain“
- role unknown

A Theory for Sleep ?

<u>without sleep:</u>

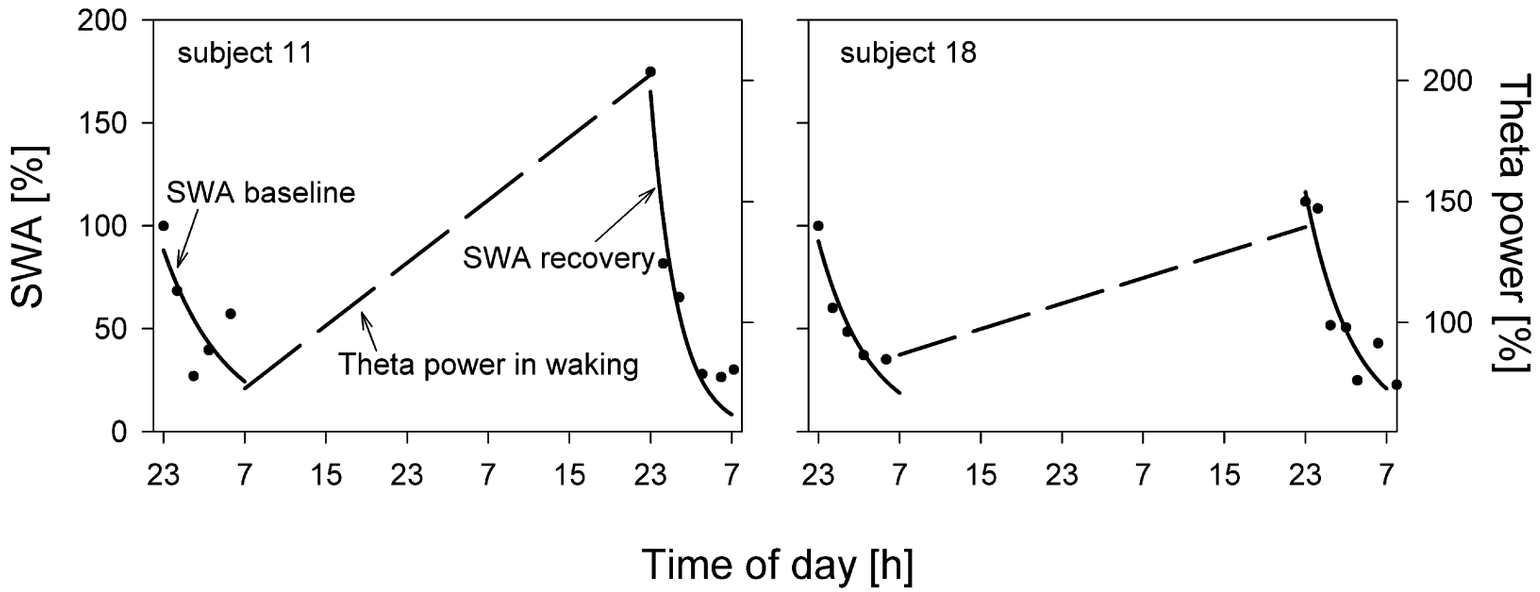
- reduced responsiveness to stimuli
- impaired information processing
- reduced learning ...

Banks, *J Clin Sleep Med*, 2007
Mignot, *PLoS Biol*, 2008

... observations suggest that sleep may play an important role in organizing or reorganizing neuronal <u>networks</u> in the brain toward states where information processing is optimized

Two-process model of sleep

- sleep propensity increases during wake and decreases during sleep
  - *sleep homeostasis* (Achermann, *Brain Res Bul*,1992)
- related to theta and slow-wave activity in the EEG



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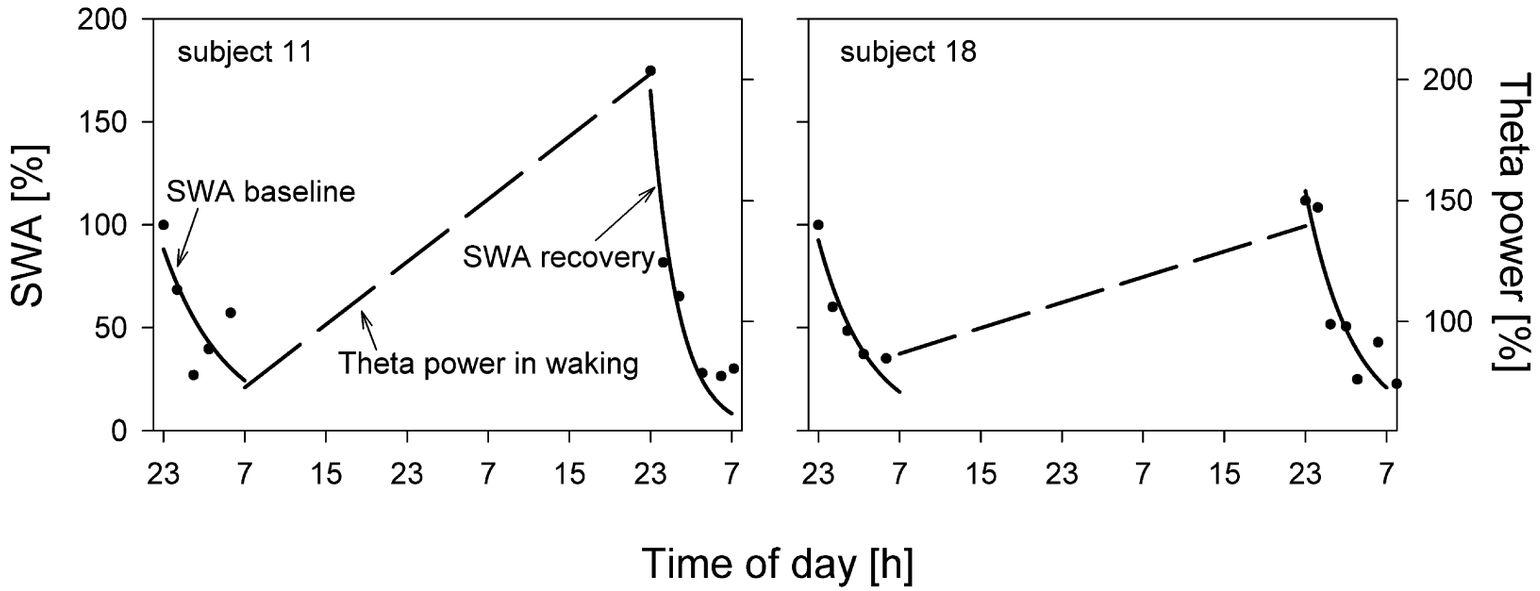
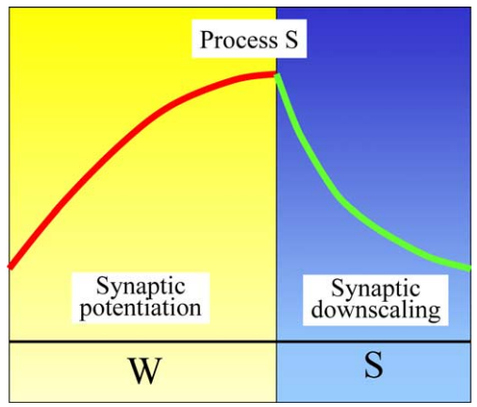
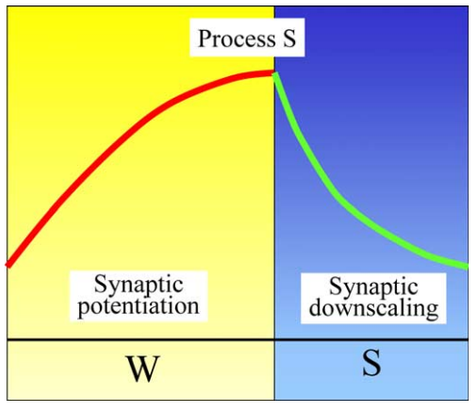
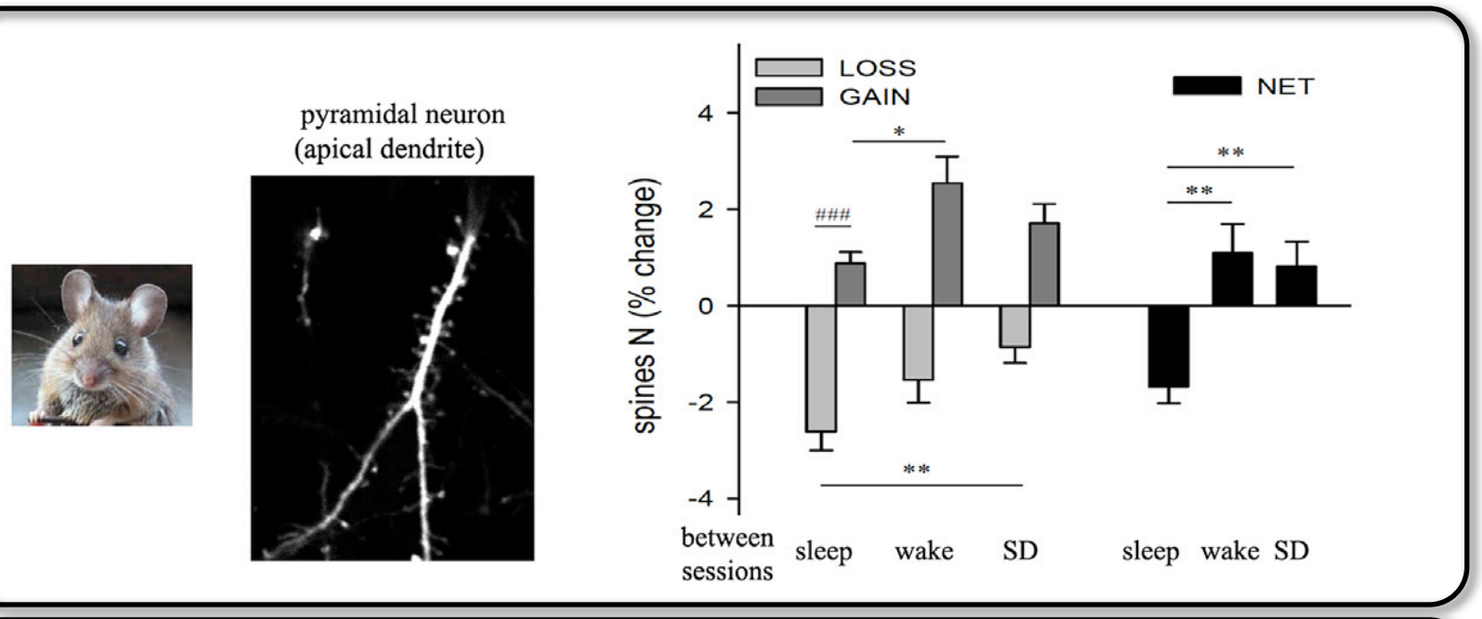


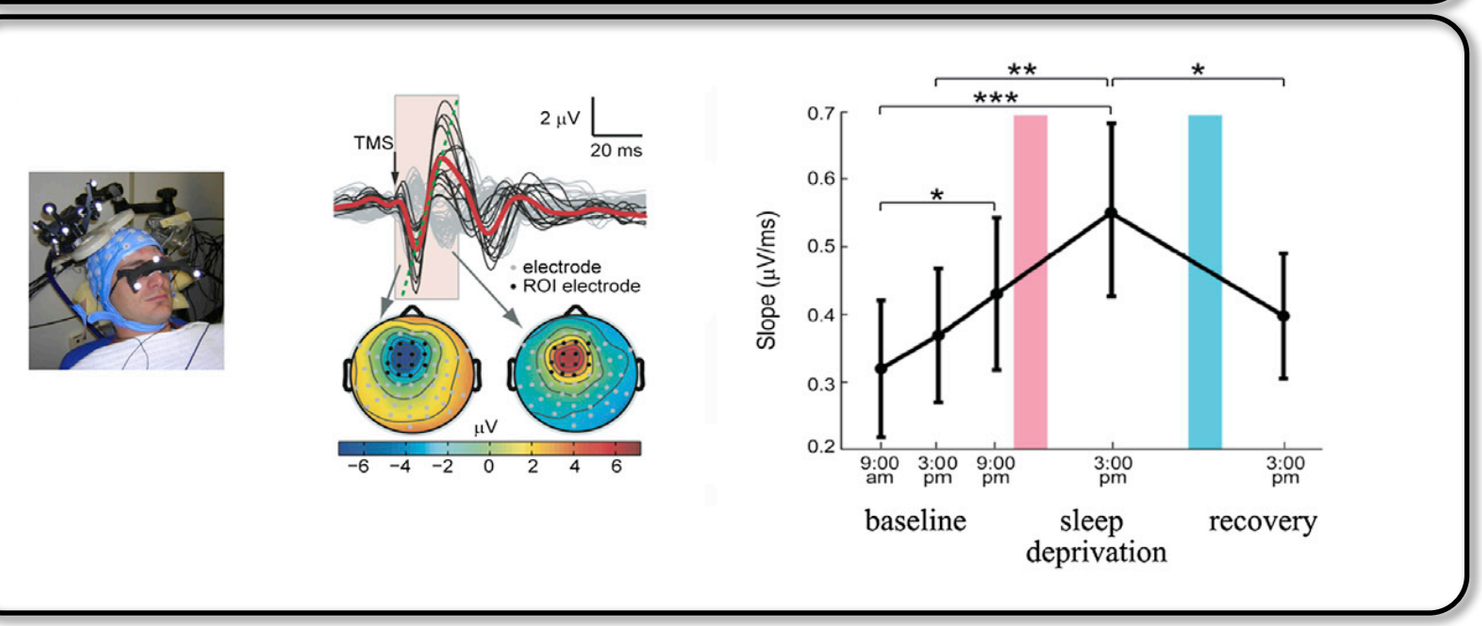
- Tononi: Synaptic homeostasis is underlying sleep homeostasis



Two-process model of sleep





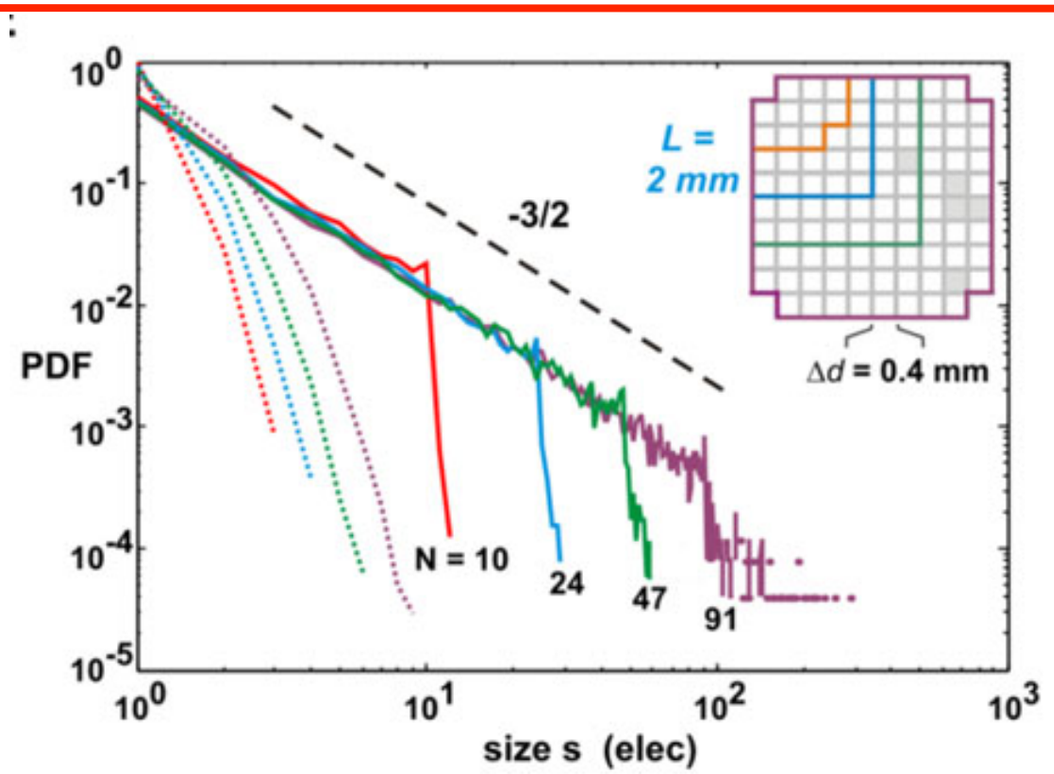


Tononi and Cirelli, *Sleep Med.*, 2006
Bushey et al., *Science*, 2011

Huber et al., *Cereb. Cortex*, 2012
Tononi and Cirelli, *Nat. Neurosc.*, 2014

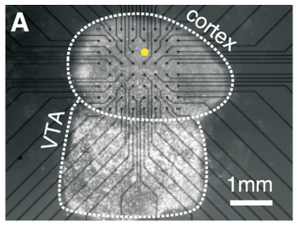
Cortical Network Dynamics

- cortical activity in superficial layers is composed of cascades of activity following a precise scaling relationship



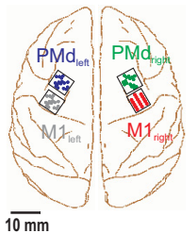
- first observed in organotypic cultures

  Beggs and Plenz, *J. Neurosci*, 2003



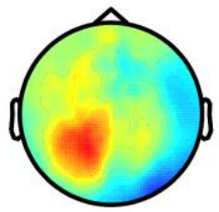
- in awake monkeys

  Peterman et al., *PNAS*, 2009



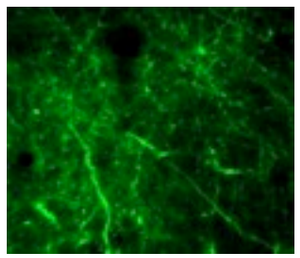
- in human MEG, ECoG, fMRI

  Tagliazucchi et al., *Front. Phys.*, 2012
  Palva et al., *PNAS*, 2013
  Shriki et al., *J. Neurosci*, 2013
  Priesemann et al., *PLoS CB*, 2013

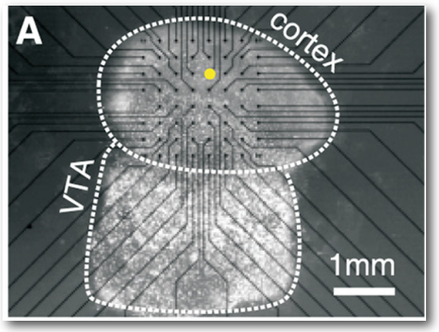


- at the level of individual neurons

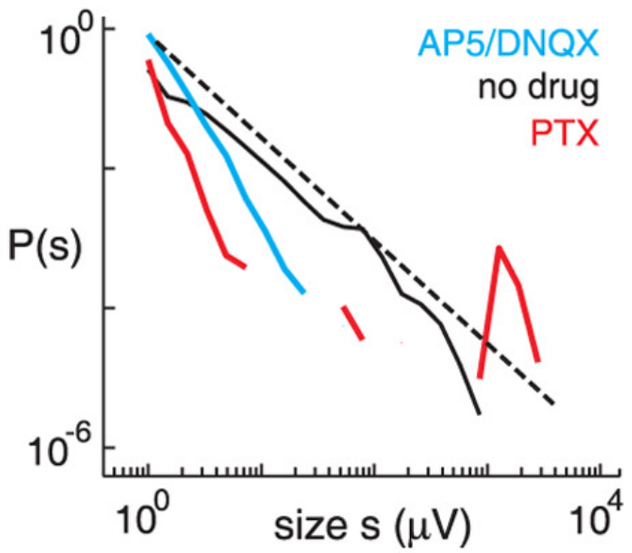
  Bellay et al., *in submission*

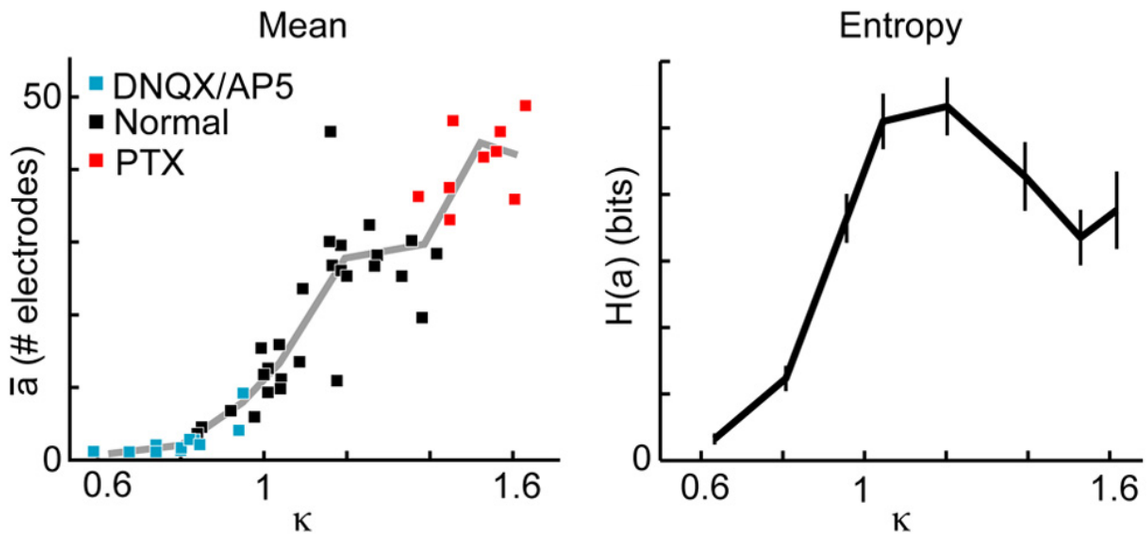


Dependence on E/I balance

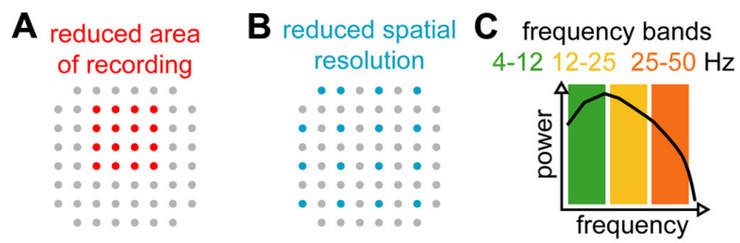


- *in vitro:* systematic control of E/I balance
- control GABAergic and Glutamatergic syn. transm.
- organotypic cortical cultures
- neuronal avalanches characteristic for E/I balance

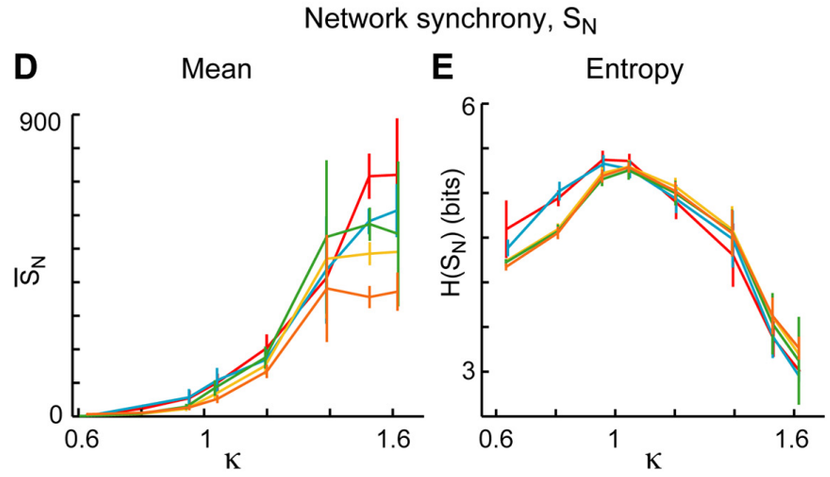




κ ... deviation from a power-law

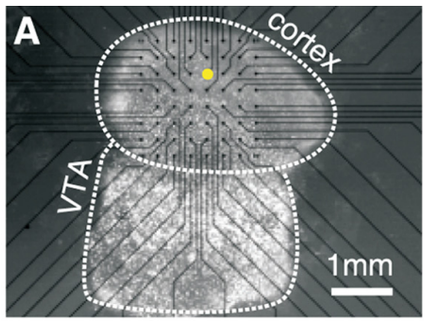


- moderate mean and maximum variability of synchronization

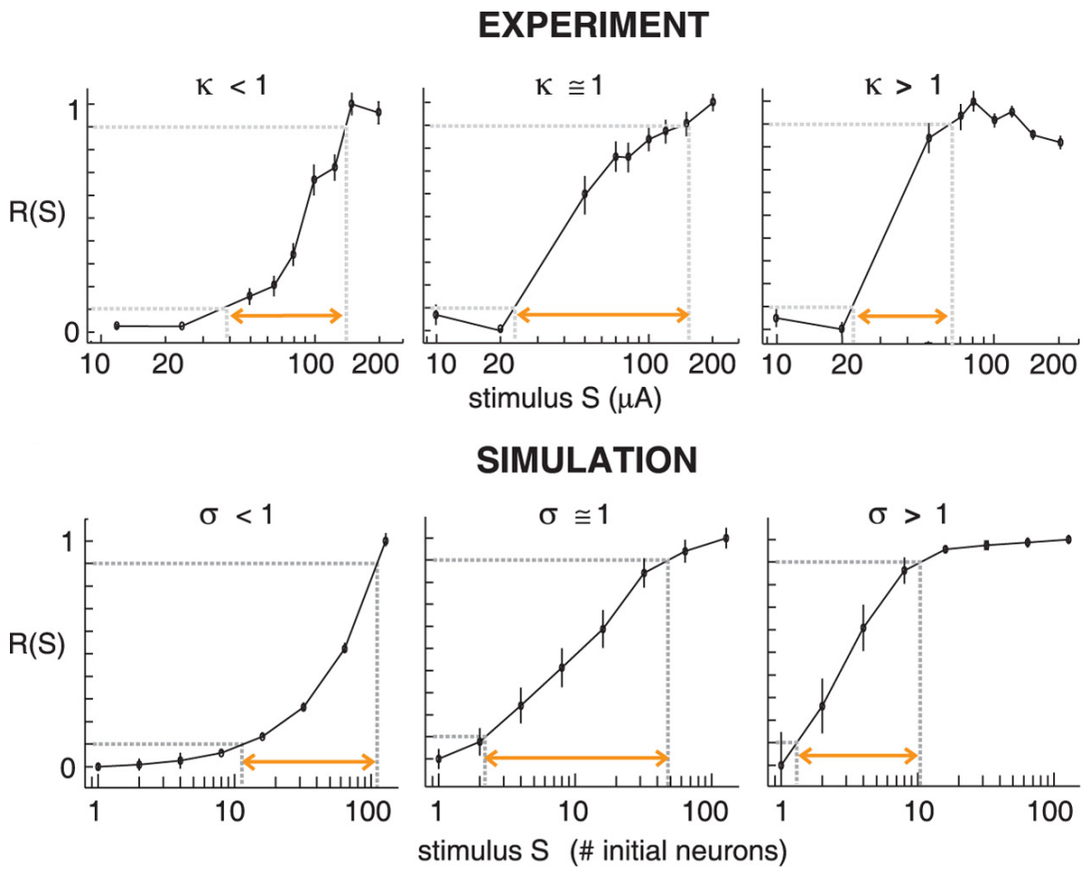


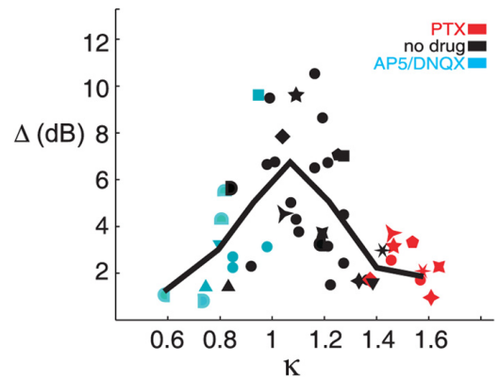
Shew et al., *J. Neurosci*, 2009
Yang et al., *J. Neurosci*, 2012

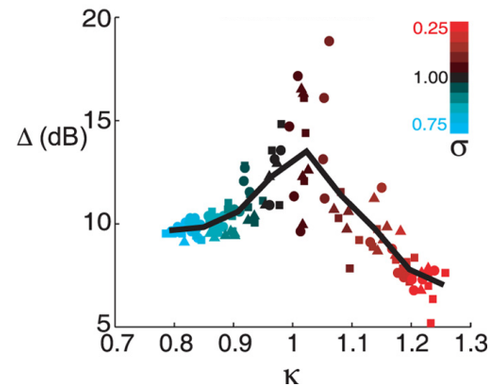
Optimization of certain information processing capabilites



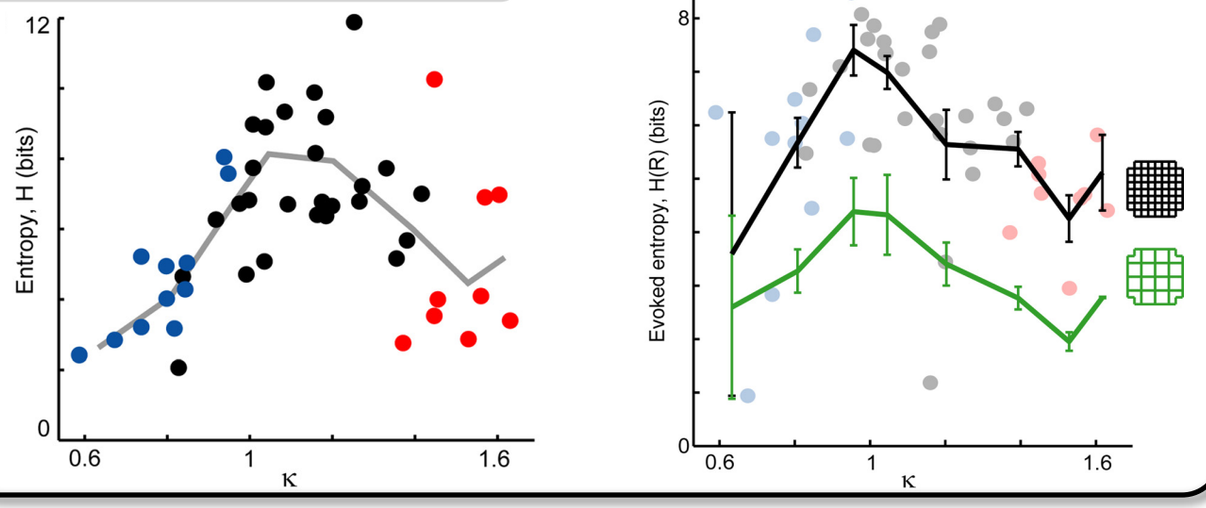
Dynamic Range $\Delta = 10 \log_{10}(S_{max}/S_{min})$



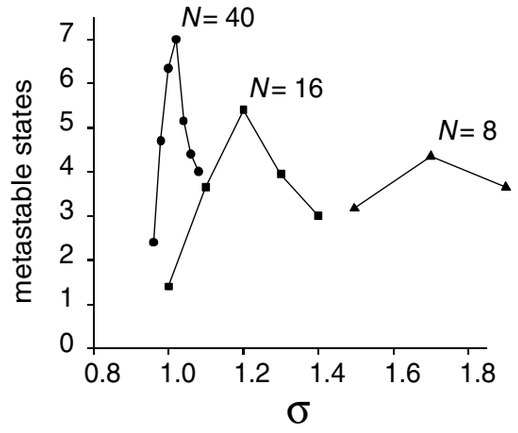




Pattern Entropy



Metastable States



Haldeman and Beggs, *PRL*, 2005
Shew et al., *J. Neurosci*, 2009

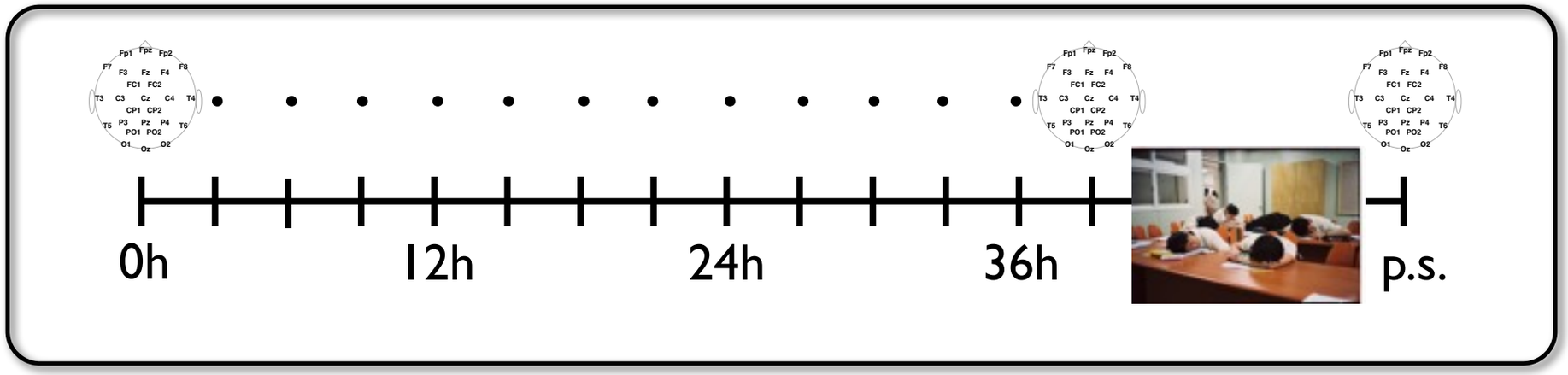
Kinouchi and Copelli, *Nat. Physics*, 2006
Shew et al., *J. Neurosci*, 2011

What are the consequences of changes in synaptic strength and consequently excitability on network dynamics?

Does the sensitivity of neuronal avalanches and related metrics to E/I conditions capture these effects?

Could these effects account for the observed impairments to information processing in cortical networks?

Study design



- 8 healthy subjects
- sleep deprivation for a total of 40 hours
- EEG every 3 hours, 27 channels
- we used artefact free 20s segments (eyes open condition)

- distribution of neuronal avalanches
- mean and variability of synchronization
- distribution of phase-lock intervals

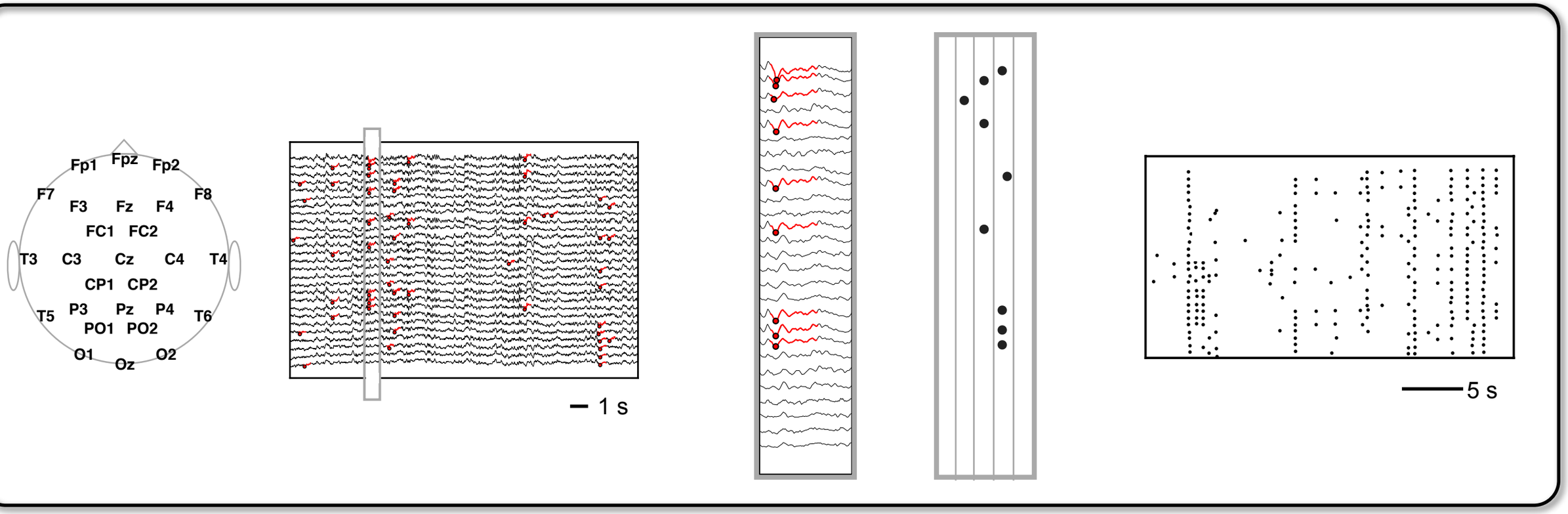
Neuronal avalanches

Cascades of activity identified by two methods:

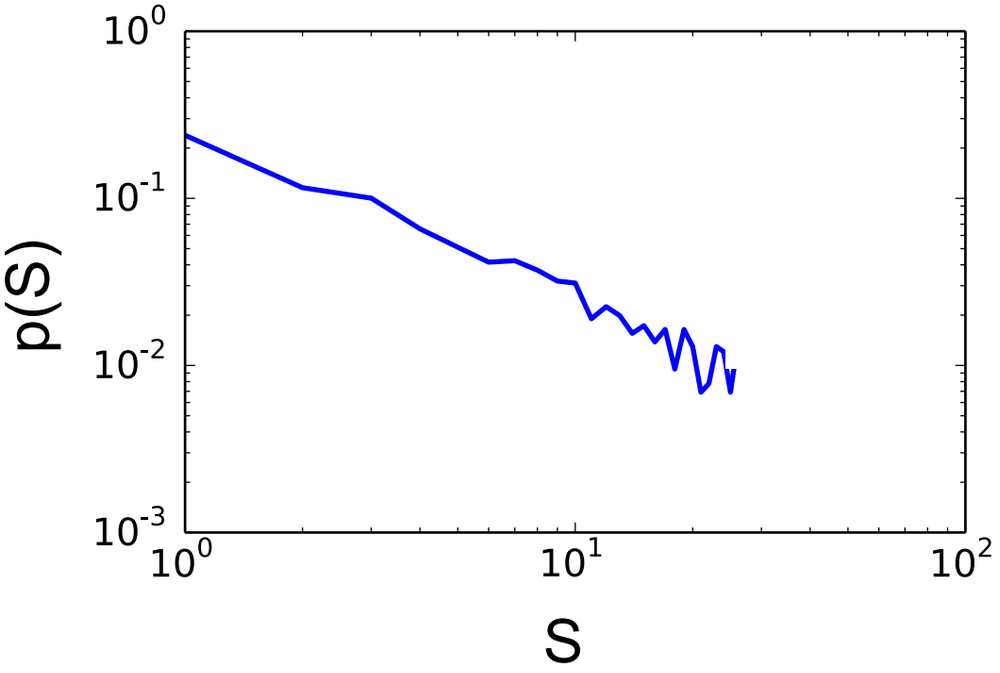
(A) Large positive or negative events on each channel exceeding a certain threshold

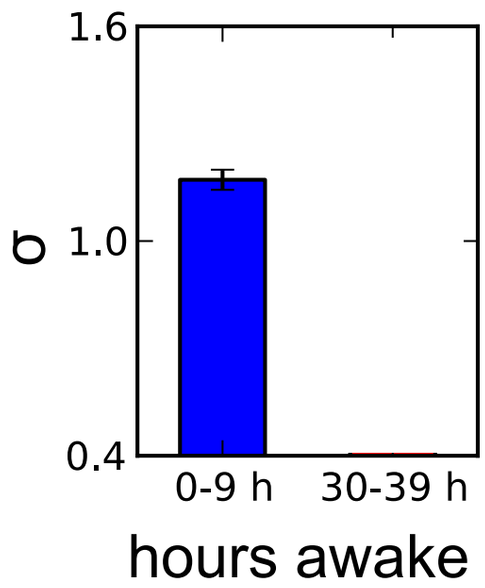
(B) Events with high similarity - „coherence potentials“

Thiagarajan, *PLoS Biol*, 2010



Neuronal avalanches

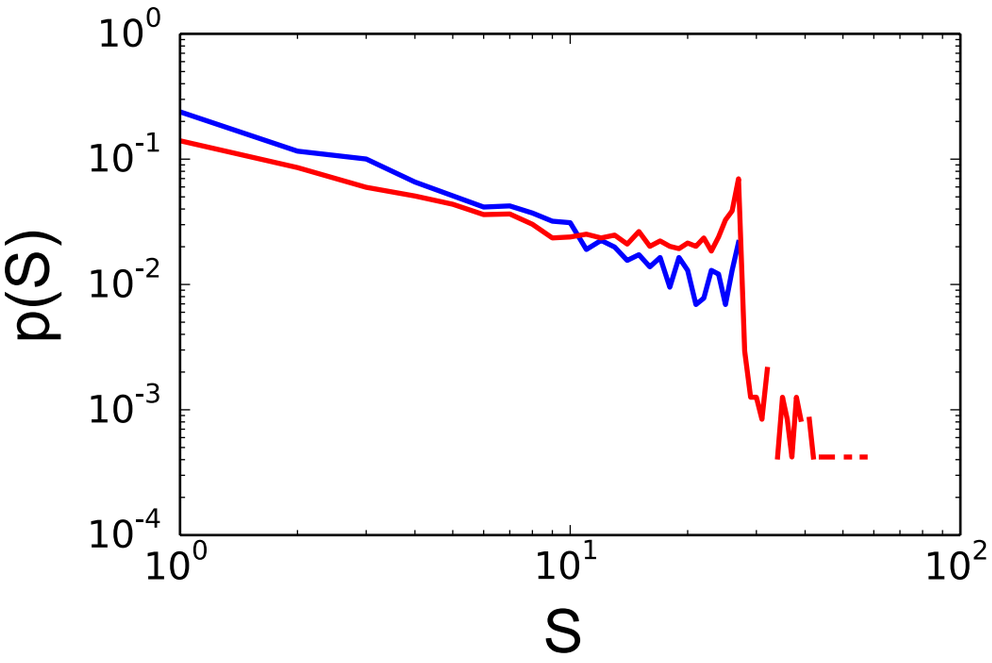


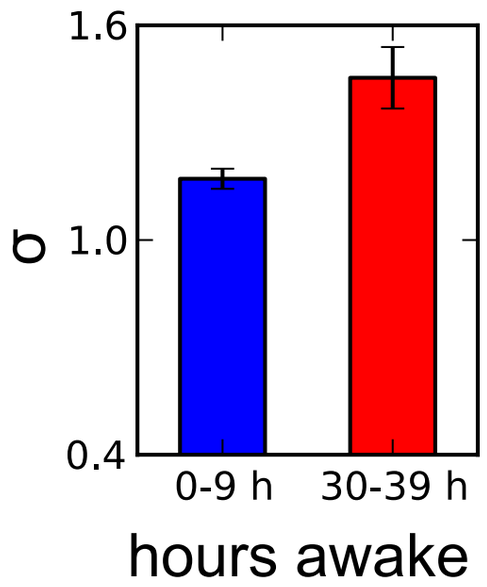


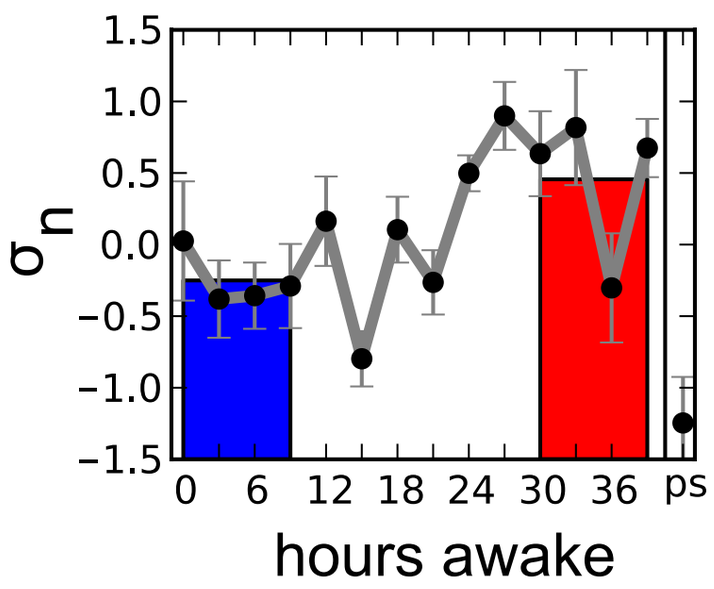
ΔD ... deviation from a power-law

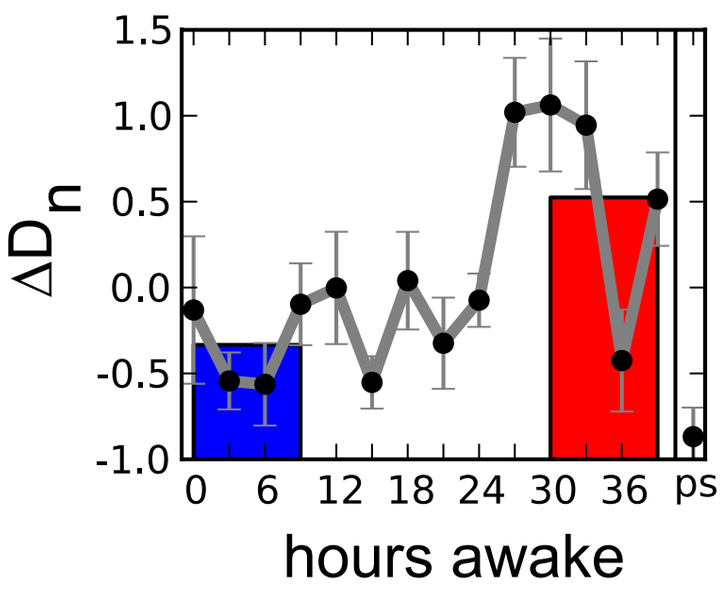
σ ... branching parameter $\sigma = \frac{n(\text{2nd time bin})}{n(\text{1st time bin})}$

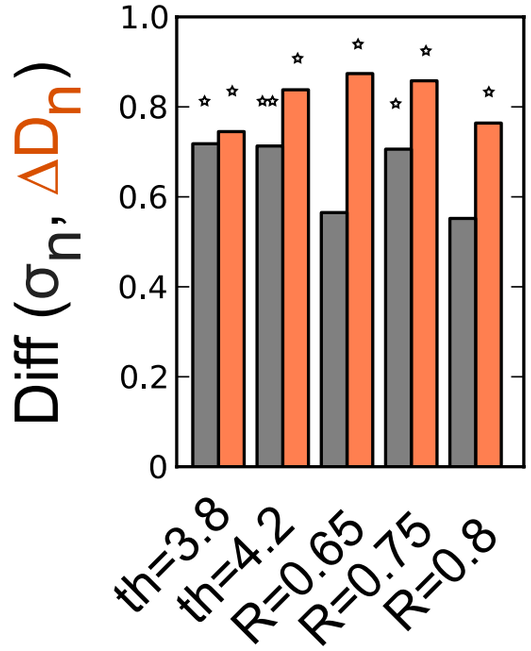
Neuronal avalanches









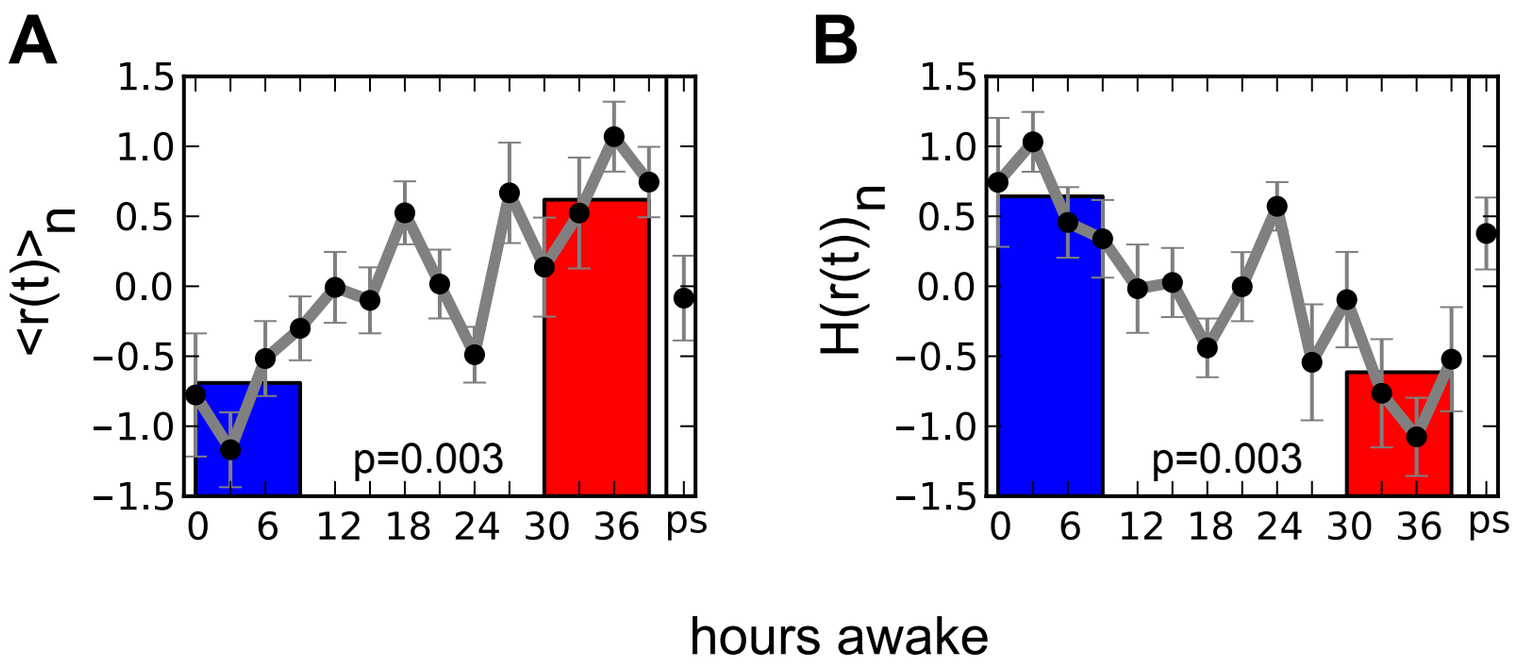


ΔD ... deviation from a power-law

σ ... branching parameter

Variability and mean of synchronization

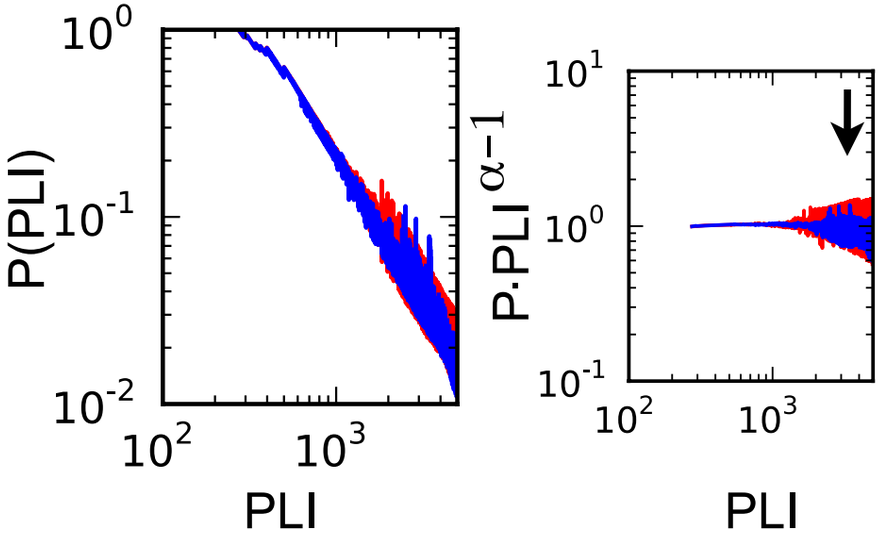
- phase synchronization in the alpha (8-16 Hz) and theta (4-8 Hz) frequency bands
- phase ... $\theta_i(t) = \arctan \frac{\mathrm{H}[\mathrm{F_i(t)}]}{\mathrm{F_i(t)}}$
- Kuramoto orderparameter ... $r(t) = \frac{1}{n} \left| \sum_{j=1}^{n} e^{i\theta_j(t)} \right|$
- mean synchronization ... $\langle r(t) \rangle = \frac{1}{L} \sum_{t=1}^{L} r(t)$
- variability of synchronization ... $H(r(t)) = -\sum_{i=1}^{B} p_i \log_2 p_i$

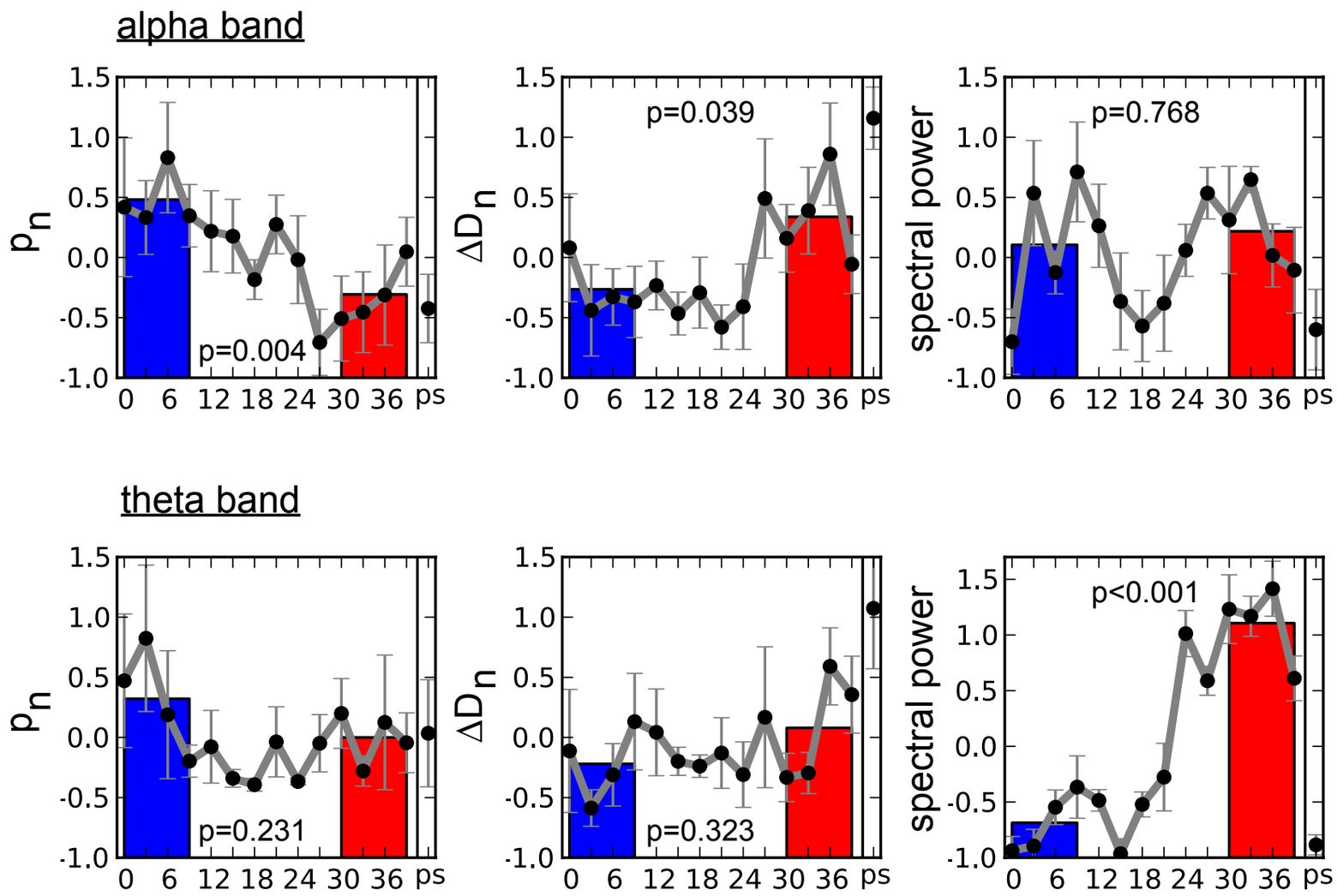


- effect observed in both frequency bands (stronger in alpha)

Variability and mean of synchronization

- distribution of phase-lock intervals in the alpha (8-16 Hz) and theta (4-8 Hz) frequency bands
- PLI ... continuous intervals with $|\Delta\Phi i, j(t)| \leq \pi/4$





ΔD ... deviation from a power-law

p ... likelihood for power-law

Variability and mean of synchronization

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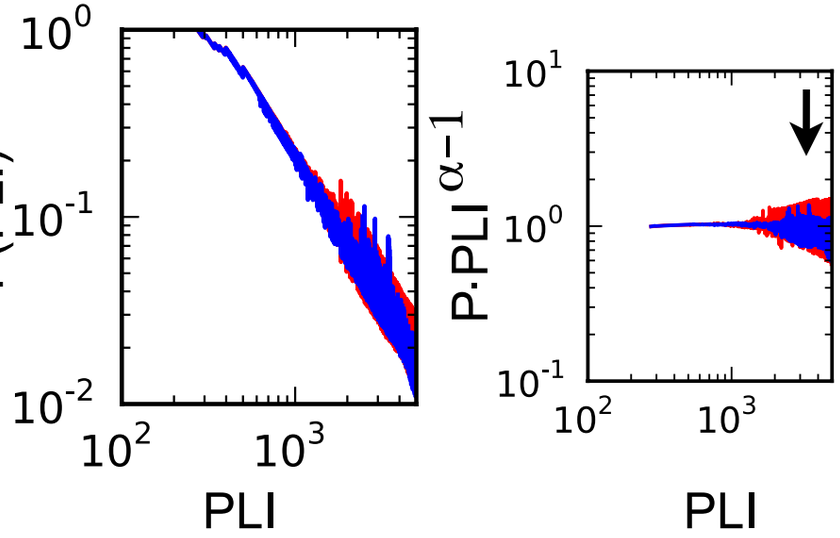
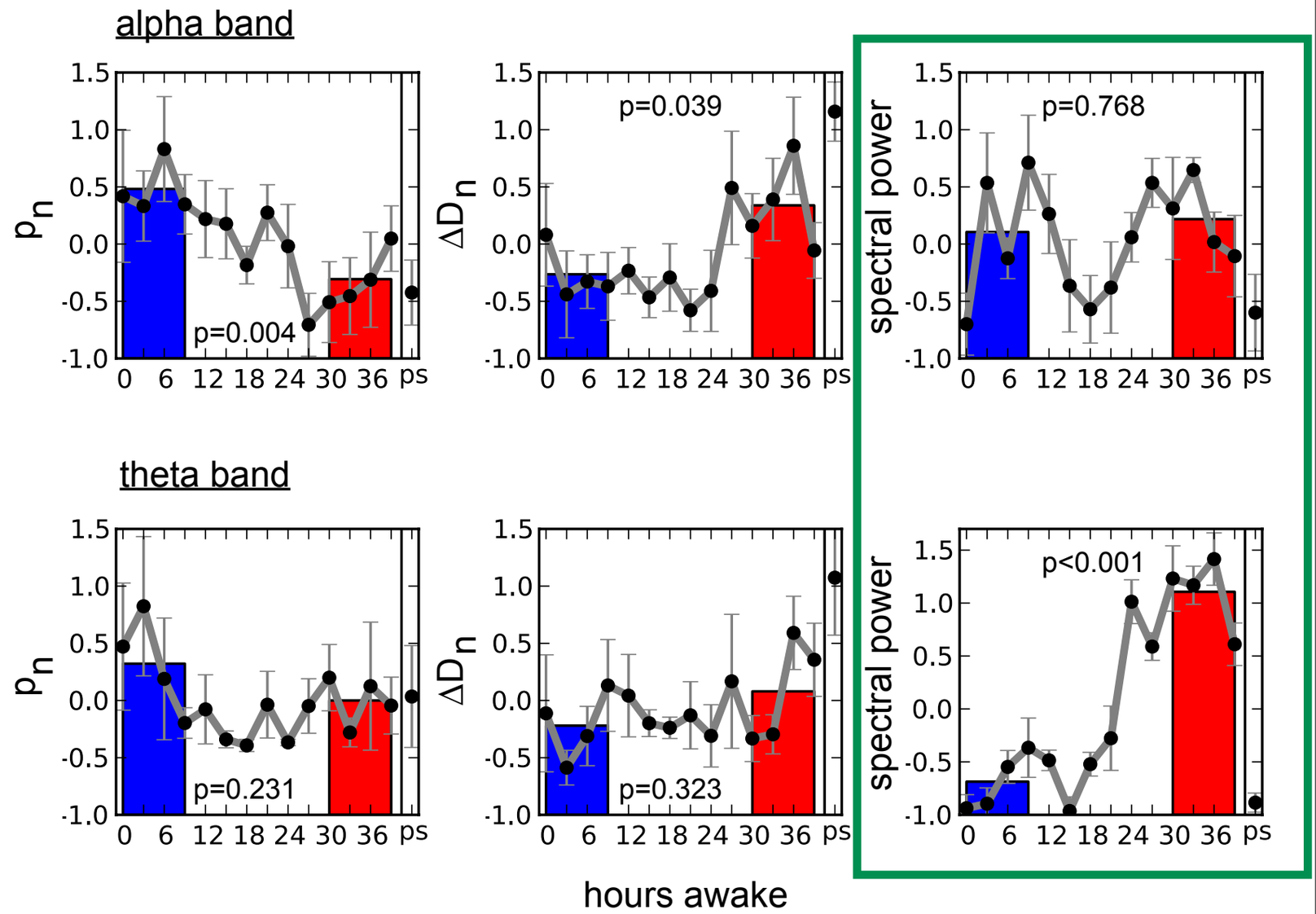
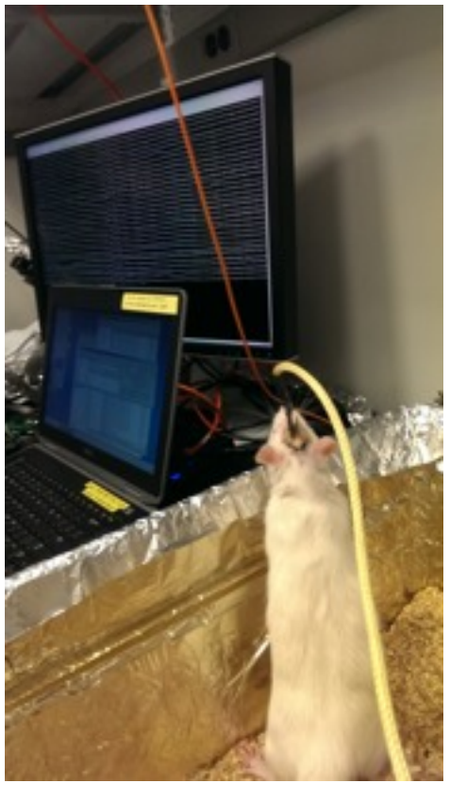
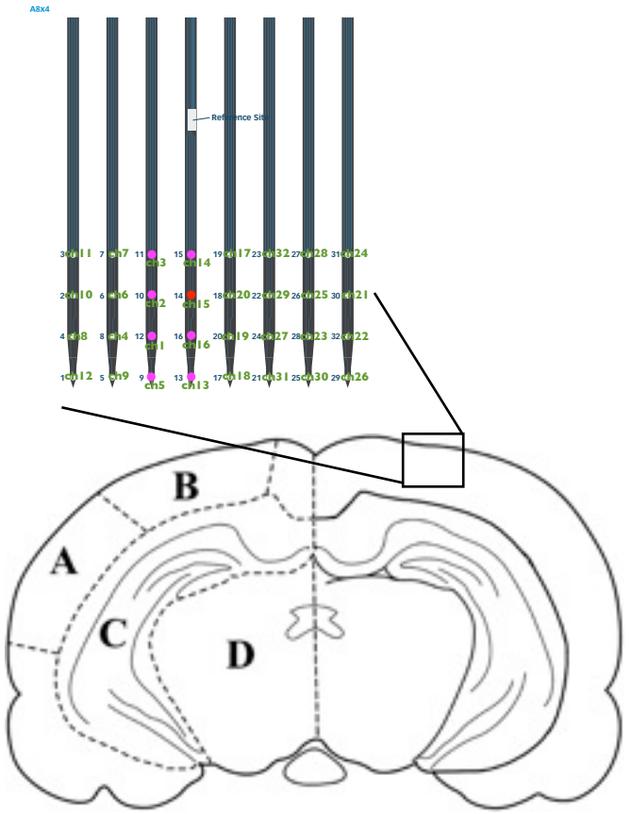


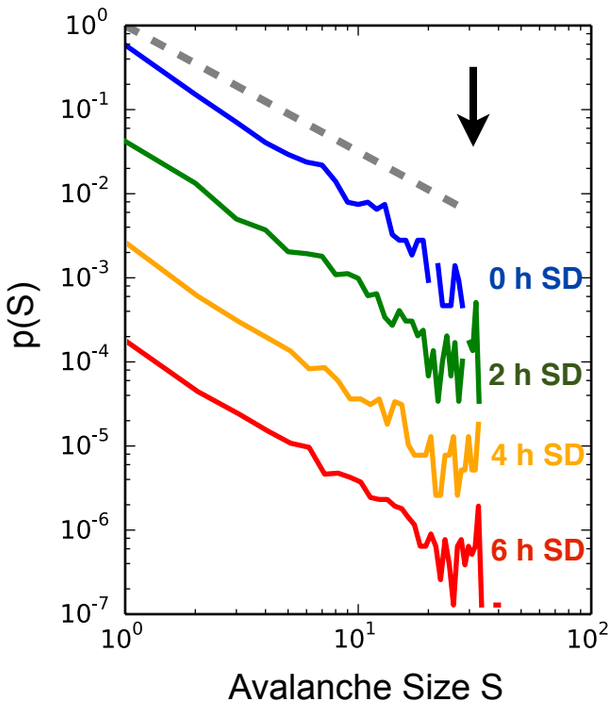


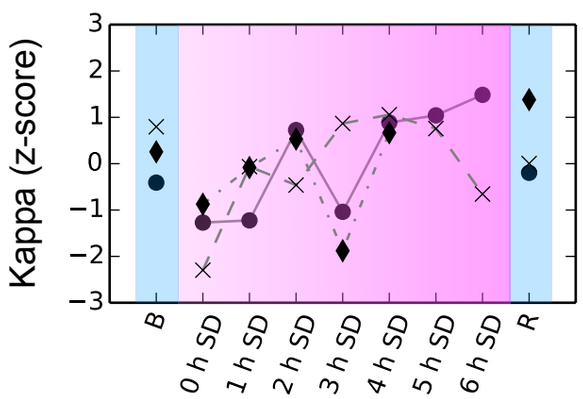
- Again: effect observed in both frequency bands
- Cannot be explained by changes in power alone

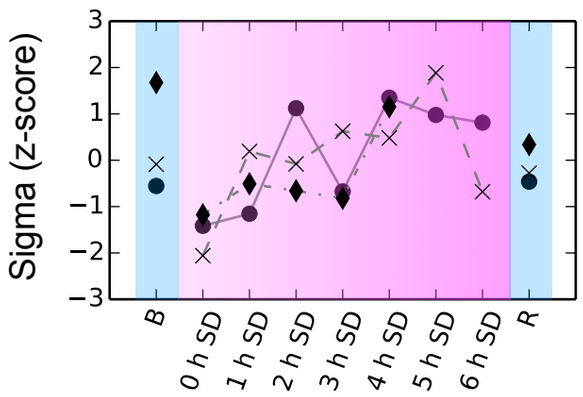
Microelectrode recording under sleep deprivation



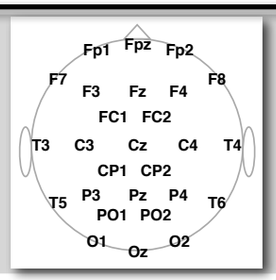


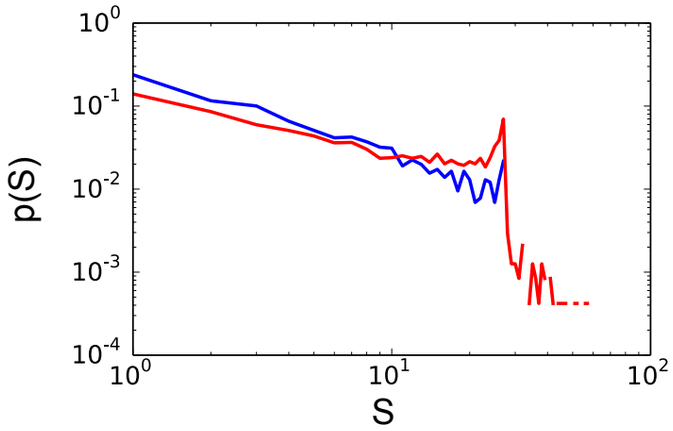


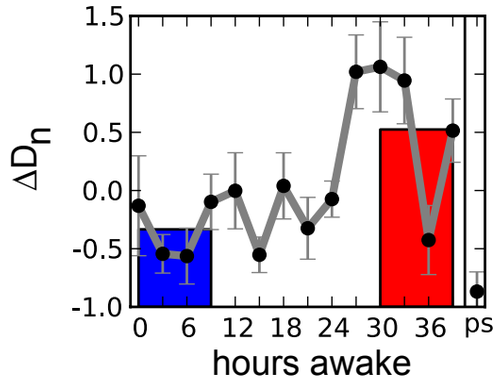


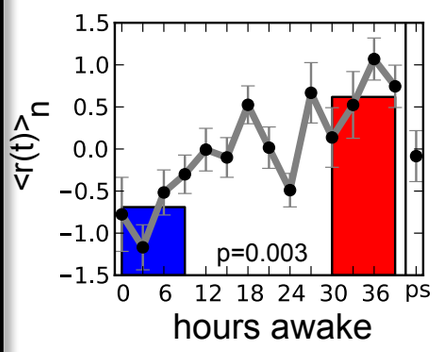


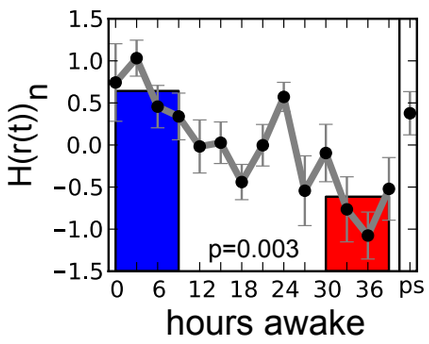
EEG

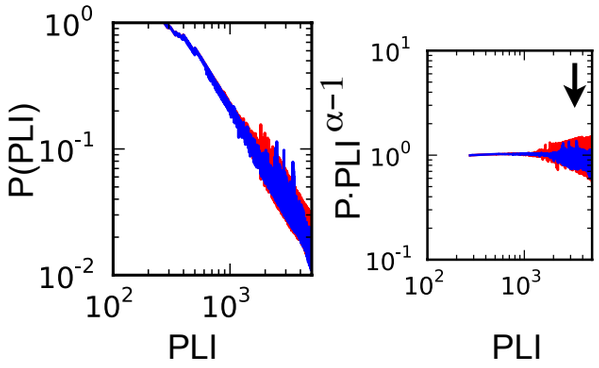

Fp1 Fpz Fp2
F7 F3 Fz F4 F8
FC1 FC2
T3 C3 Cz C4 T4
CP1 CP2
T5 P3 Pz P4 T6
PO1 PO2
O1 Oz O2


p(S)
S

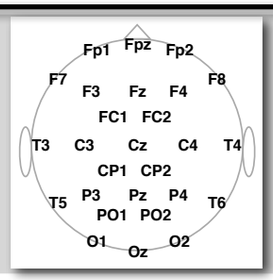

ΔDn
hours awake

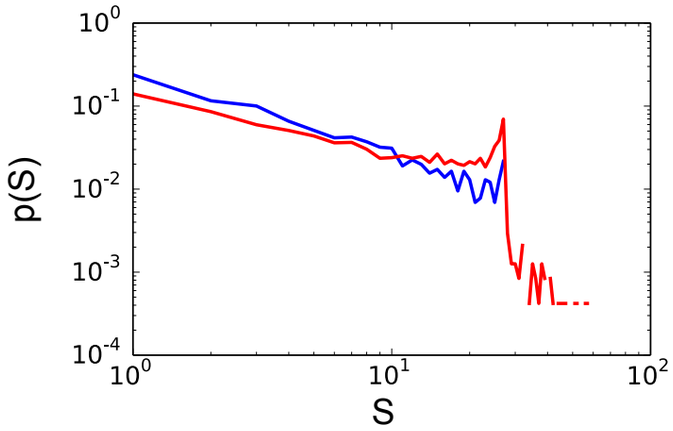

<r(t)>n
p=0.003
hours awake

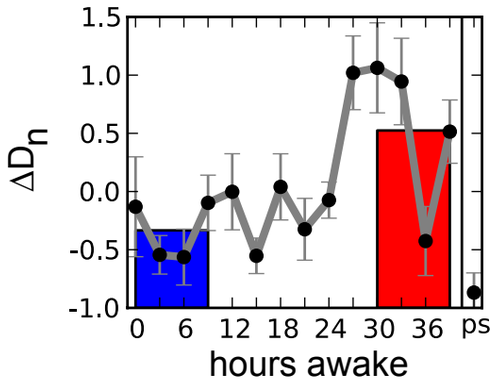

H(r(t))n
p=0.003
hours awake

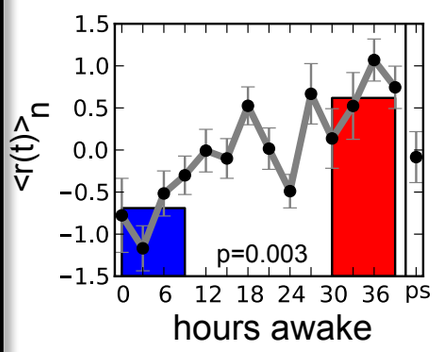

P(PLI)
P·PLI α−1
PLI
PLI

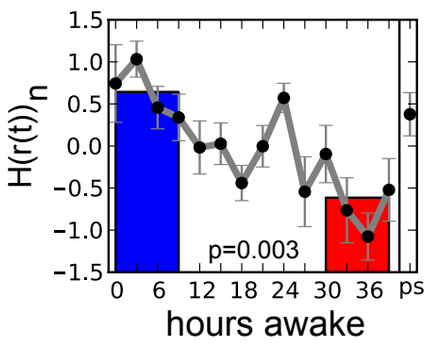
EEG

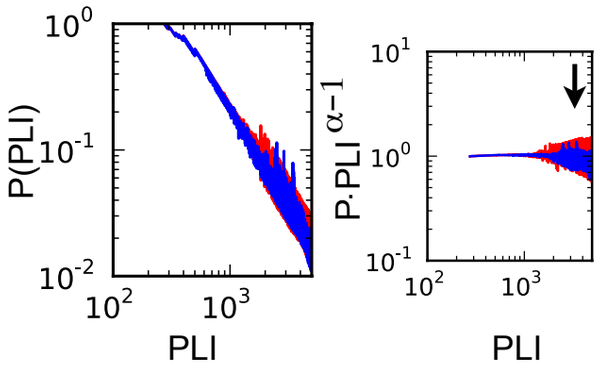




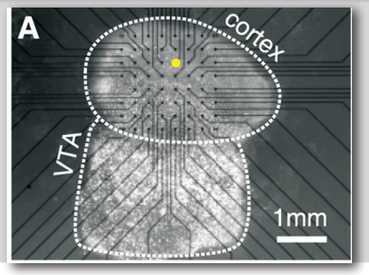


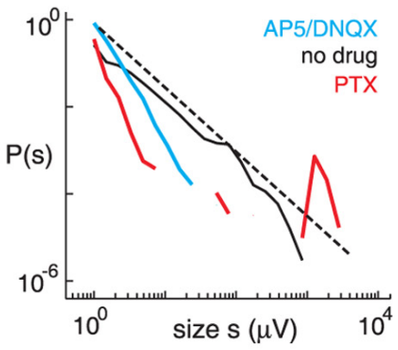


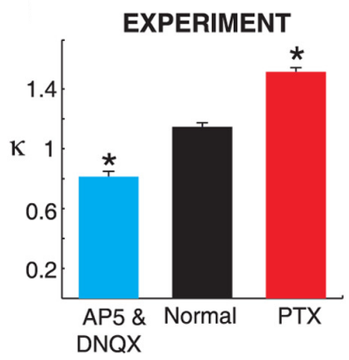


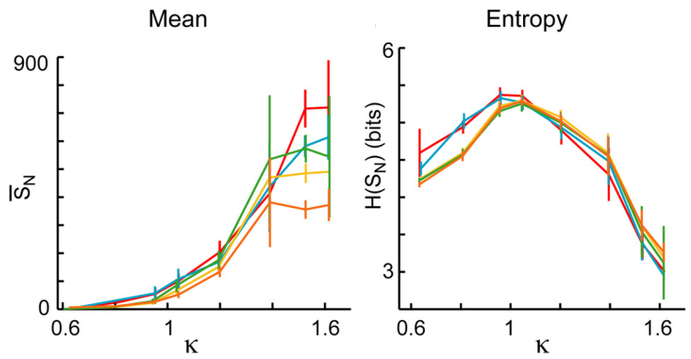


in vitro







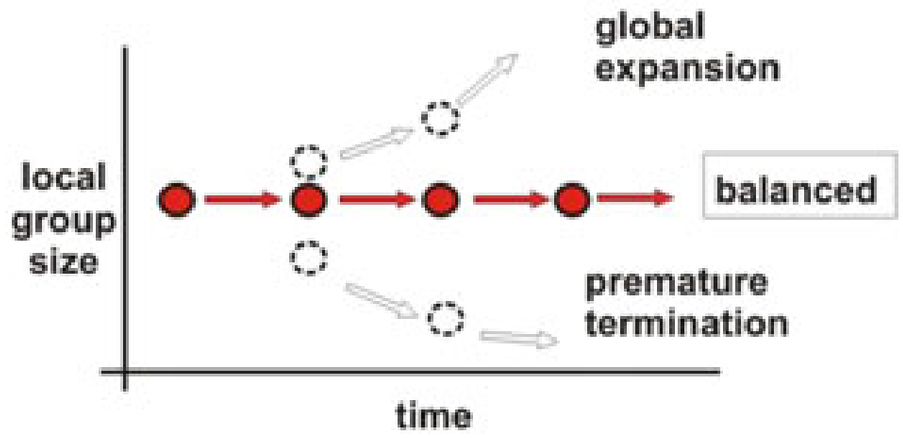


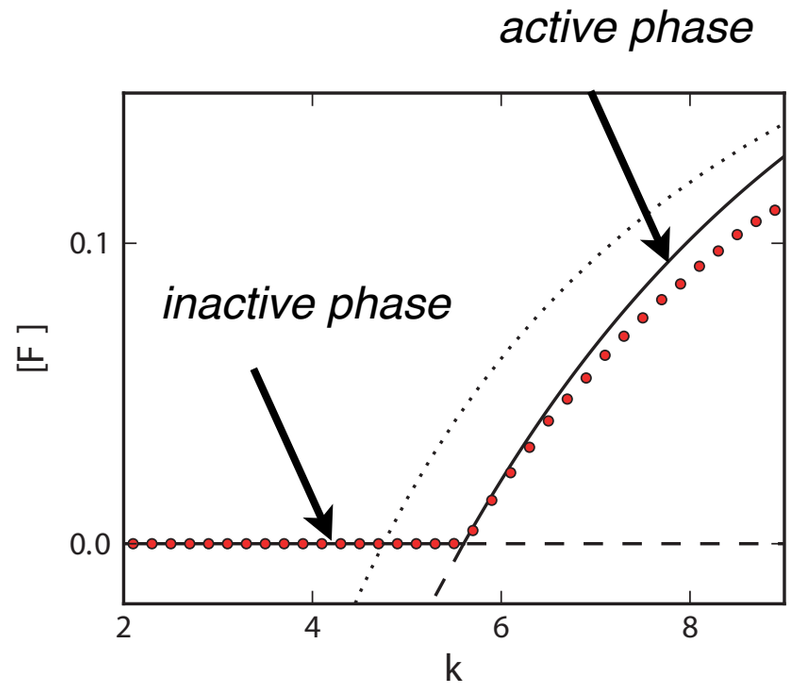
Beggs and Plenz, *J. Neurosci*, 2003
Shew et al., *J. Neurosci*, 2009
Yang et al., *J. Neurosci*, 2012

- observations in EEG during sleep deprivation are in agreement with a shift towards increased excitability where larger events dominate dynamics

Interpretation: Criticality ?

(1) All those seemingly different findings are precisely captured by *a critical branching process.*





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Haldeman and Beggs, *PRL*, 2005

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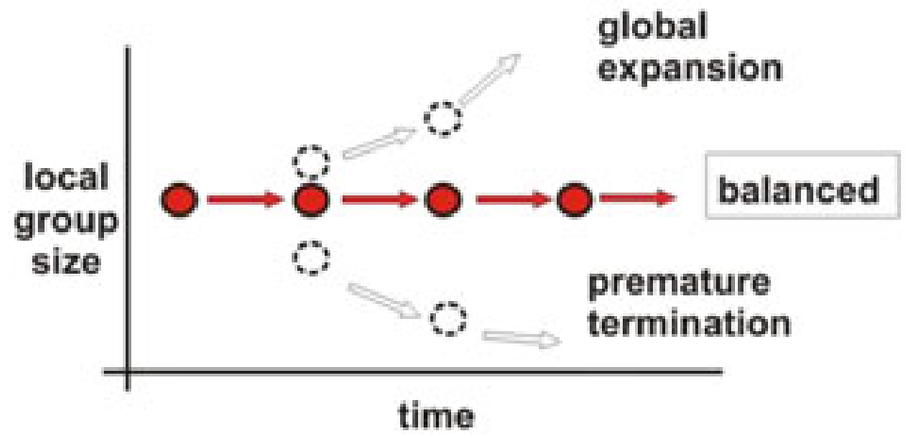

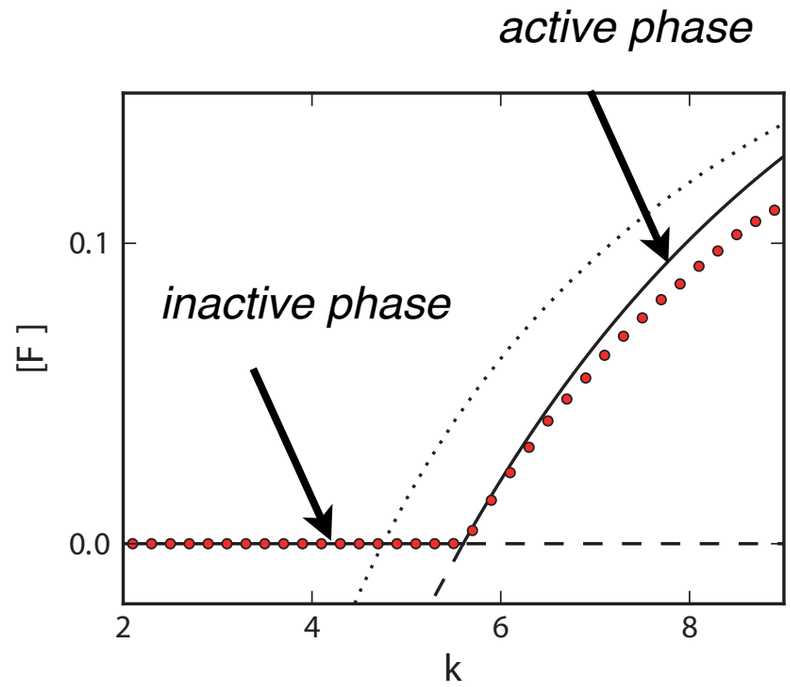

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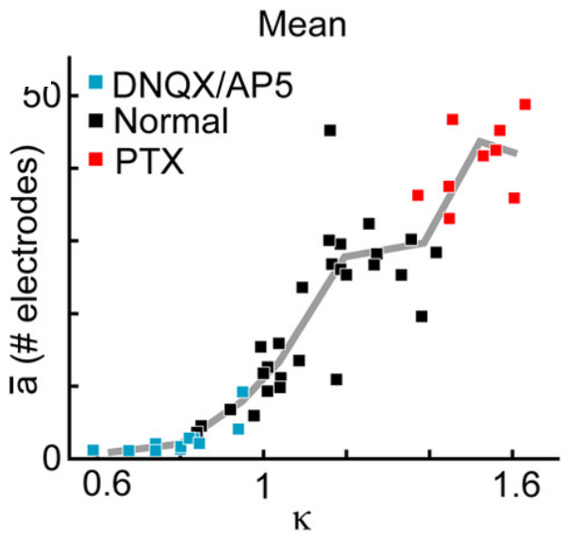

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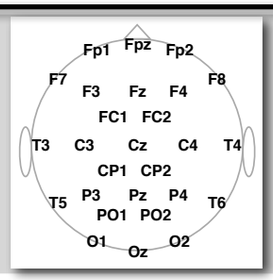
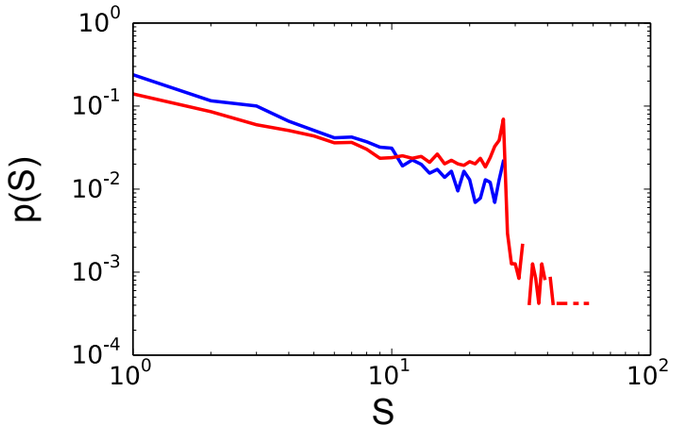
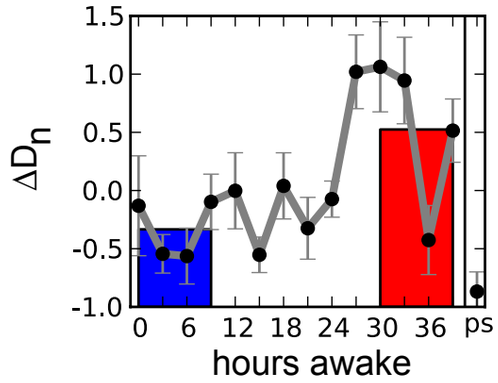
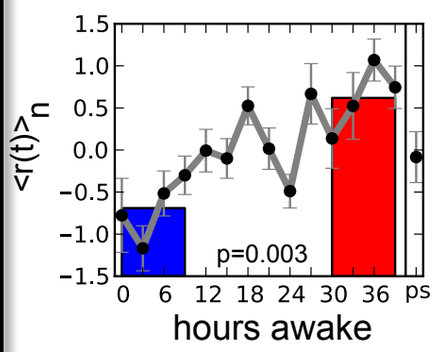
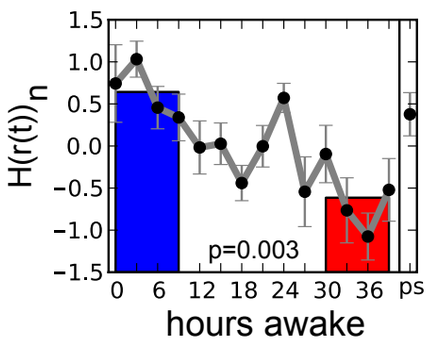
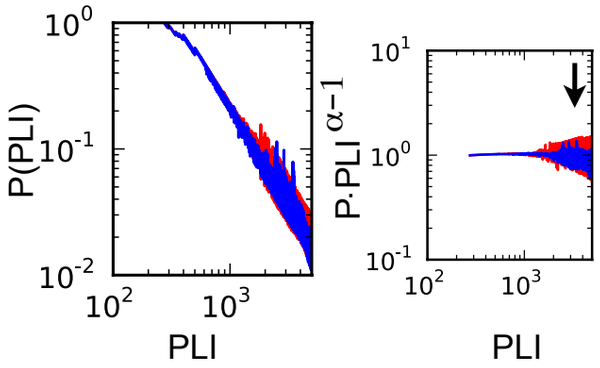




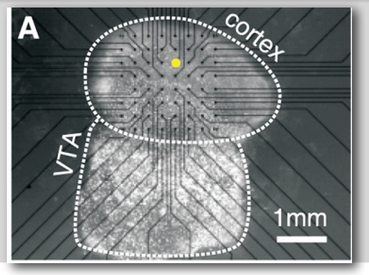


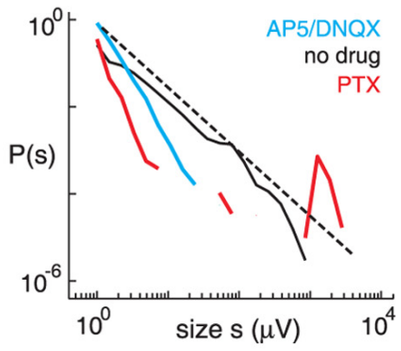


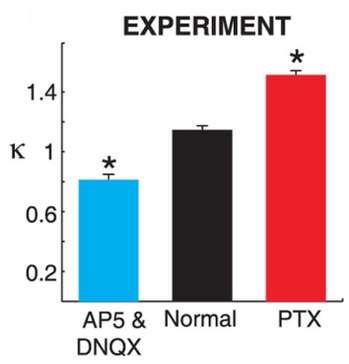


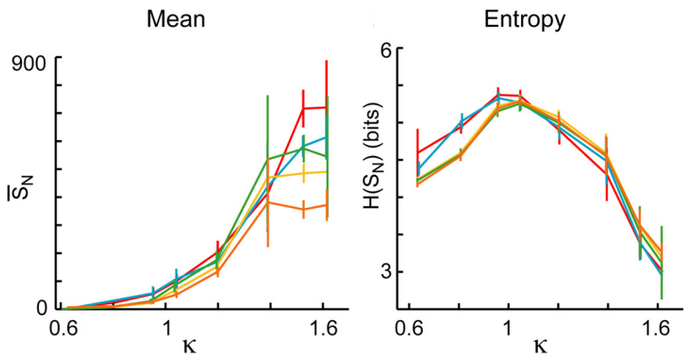


in vitro









Beggs and Plenz, *J. Neurosci*, 2003
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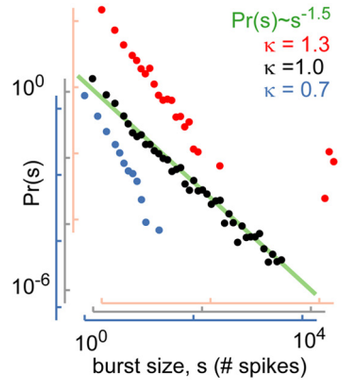
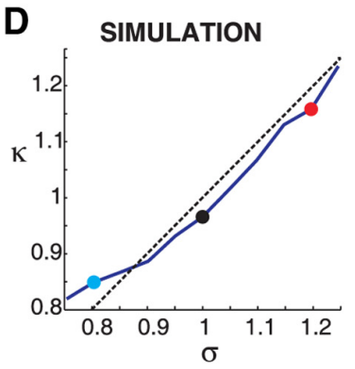
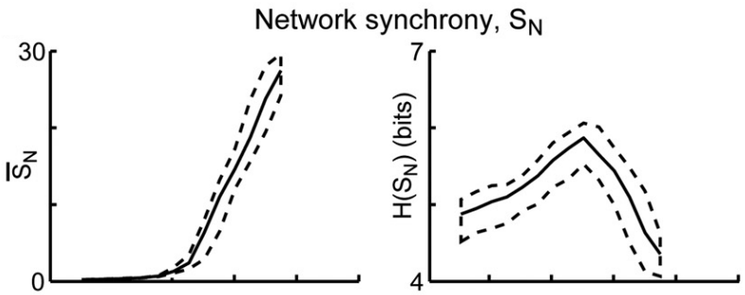
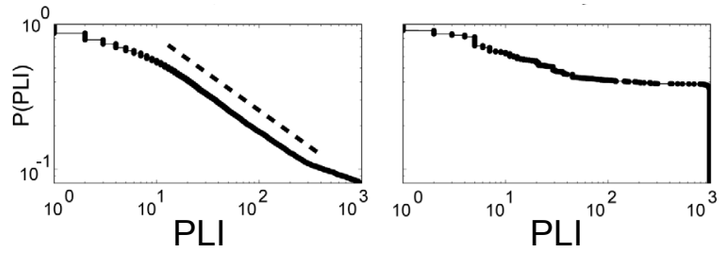
Model









Yang et al., *J. Neurosci*, 2012
Meisel et al., *PLoS CB*, 2012

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the balance between excitation and inhibition

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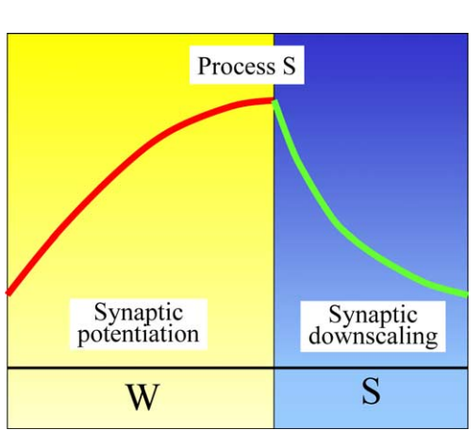

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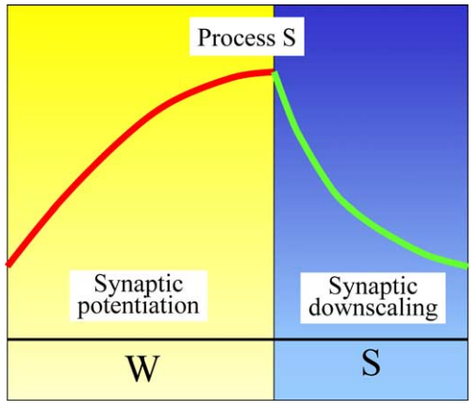

(4) A critical branching process captures other experimental observations: *maximal dynamic range, maximal pattern entropy, power-law scaling of avalanche durations, relations between scaling exponents, optimal information transmission (mutual information between stimulus and response), ...*

Hypothesis:

Sleep reorganizes cortical network dynamics to a critical state and thereby assures optimal computational capabilities for the time awake.

The Journal of Neuroscience, October 30, 2013 • 33(44):17363–17372 • **17363**

Systems/Circuits

Fading Signatures of Critical Brain Dynamics during Sustained Wakefulness in Humans

Christian Meisel,[1,2,3] Eckehard Olbrich,[4] Oren Shriki,[3] and Peter Achermann[5,6]

[1]Max Planck Institute for the Physics of Complex Systems, 01187 Dresden, Germany, [2]Department of Neurology, University Clinic Carl Gustav Carus, 01307 Dresden, Germany, [3]Section on Critical Brain Dynamics, National Institute of Mental Health, Bethesda, Maryland, [4]Max Planck Institute for Mathematics in the Sciences, 04103 Leipzig, Germany, [5]Institute of Pharmacology and Toxicology and Zurich Center for Integrative Human Psychology, University of Zurich, 8057 Zurich, Switzerland, and [6]Neuroscience Center Zurich, University and ETH Zurich, Zurich, Switzerland