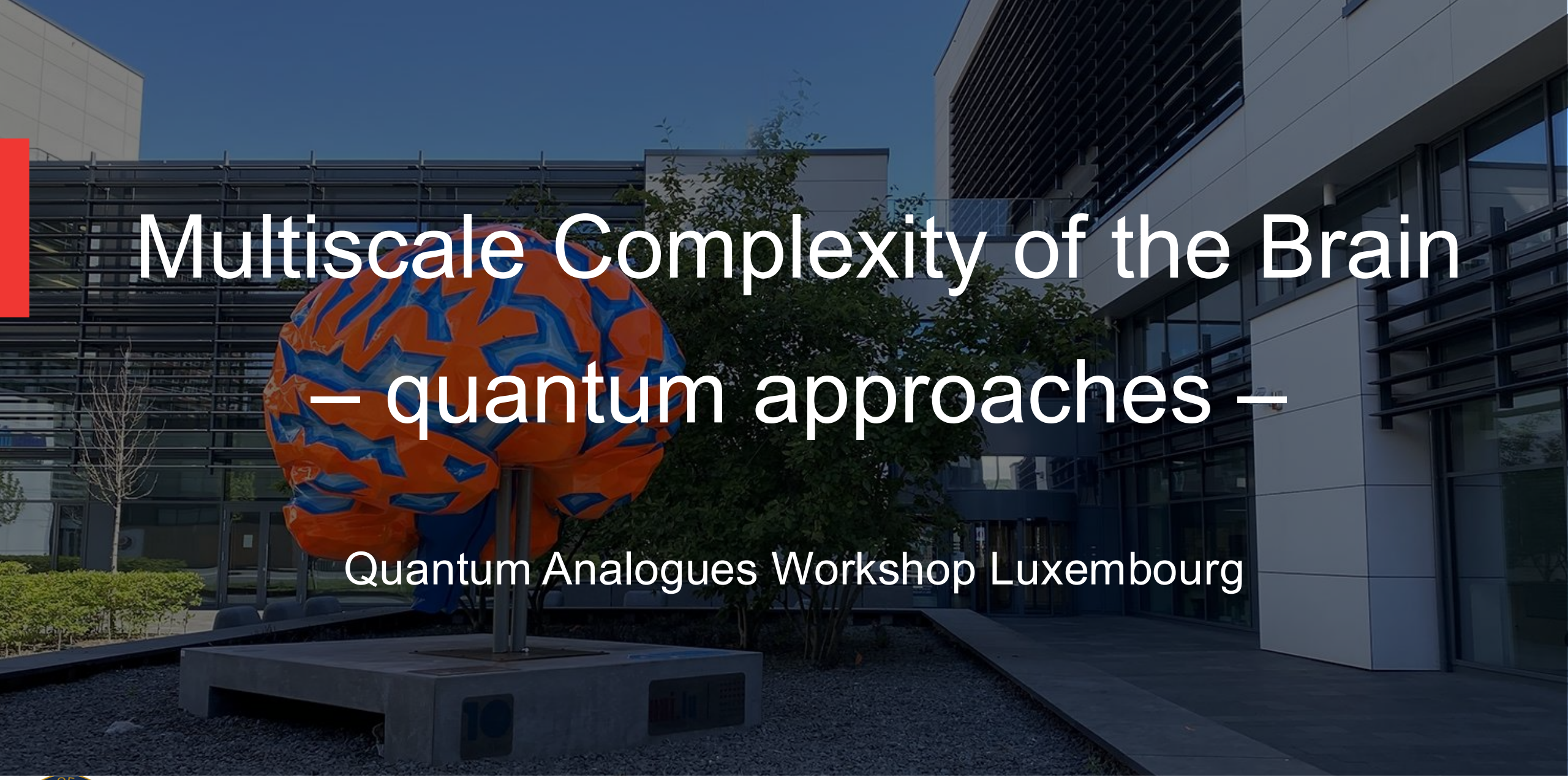


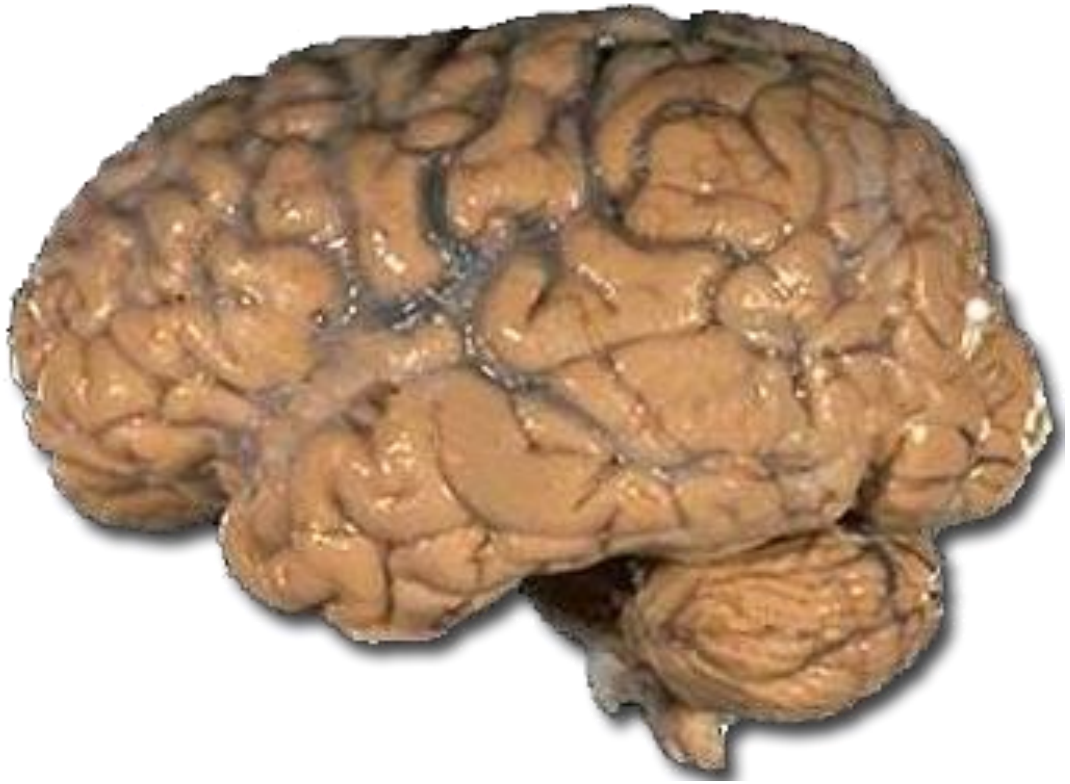
Multiscale Complexity of the Brain – quantum approaches –

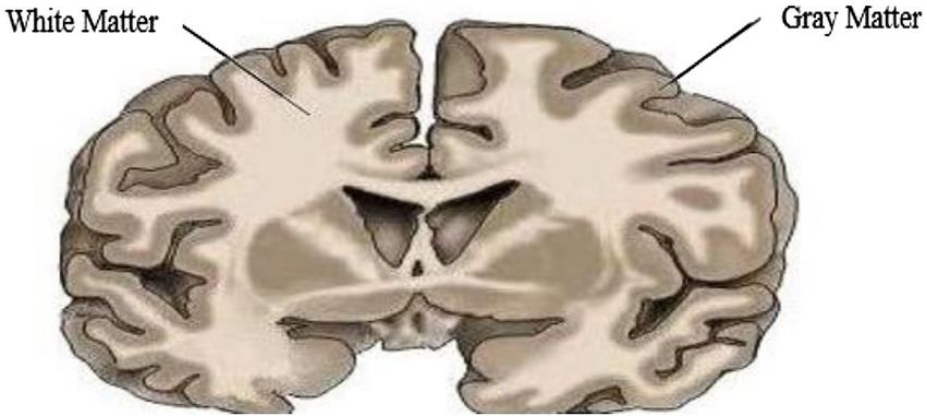
Quantum Analogues Workshop Luxembourg

Alexander Skupin

September 2025

The brain – white and grey matter was dark matter in 19th century





Most complex organ of ~1.5 kg
Source of consciousness and body control
(instead of Aristotle's cooling the heart idea)

Analogous discussion: homogenous vs discrete brain activity

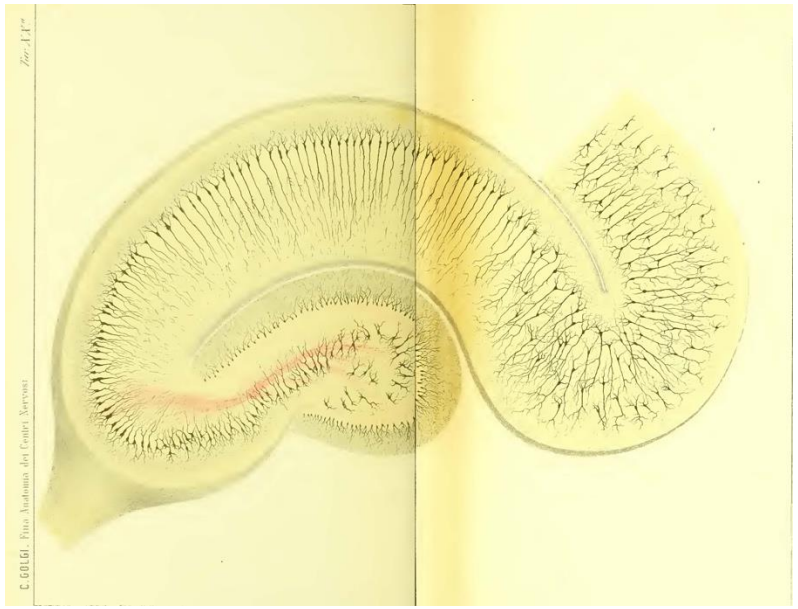
Camillo Golgi (1843–1926)

Reticular theory suggested that the nervous system consists of a continuous, fused network of neurons

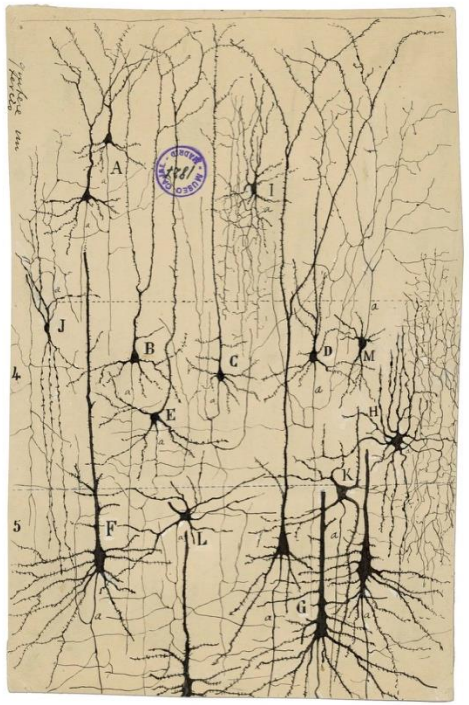
vs

Santiago Ramón y Cajal (1852–1934)

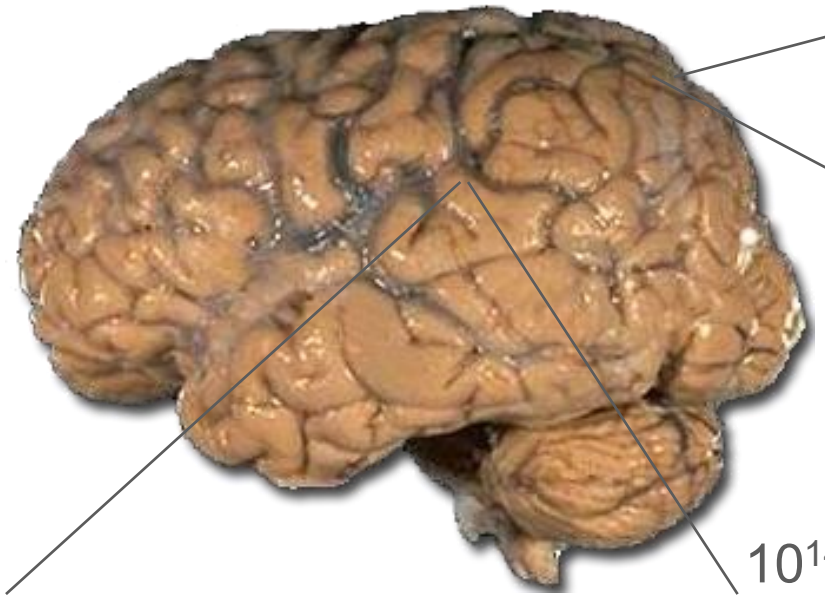
Neuron doctrine stated that the nervous system is composed of discrete cells that communicate with each other.

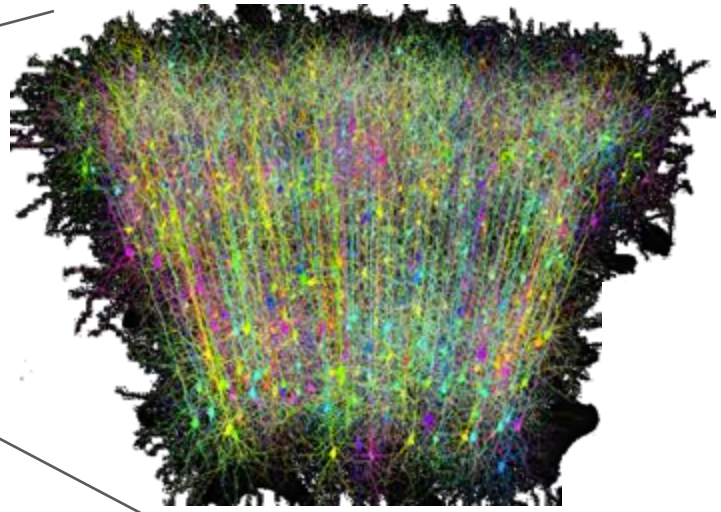


Shared Nobel Prize 1906

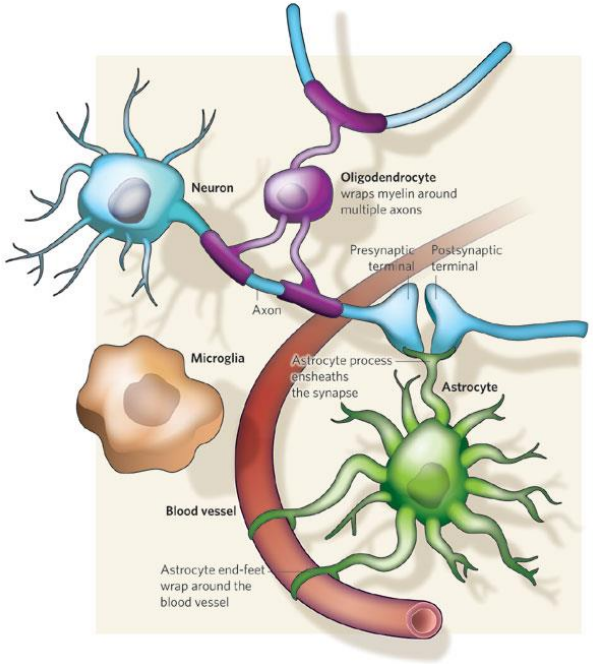


The brain in a nutshell



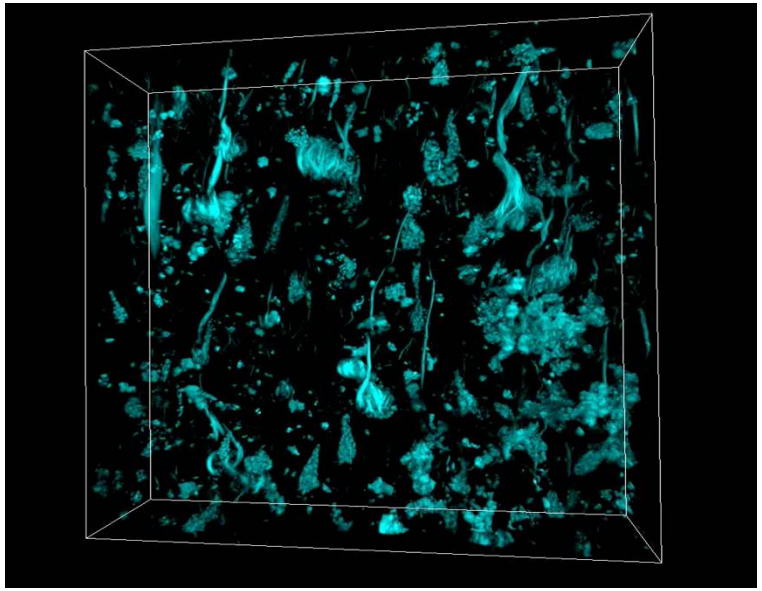


10^{11} neurons and
10^{14} synaptic connections
(Petabytes)



Brain is an ecosystem

(Allen, Nature 457, 675-677, 2009)

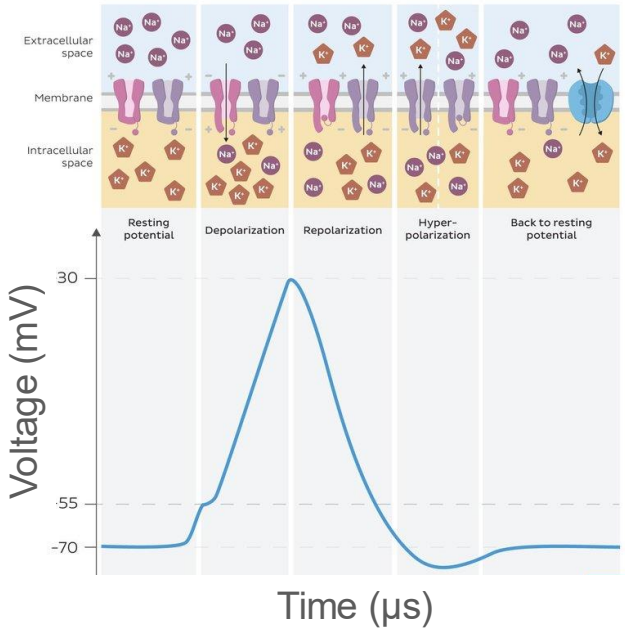


Human Alzheimer Brain

Neurons: special cells with special needs

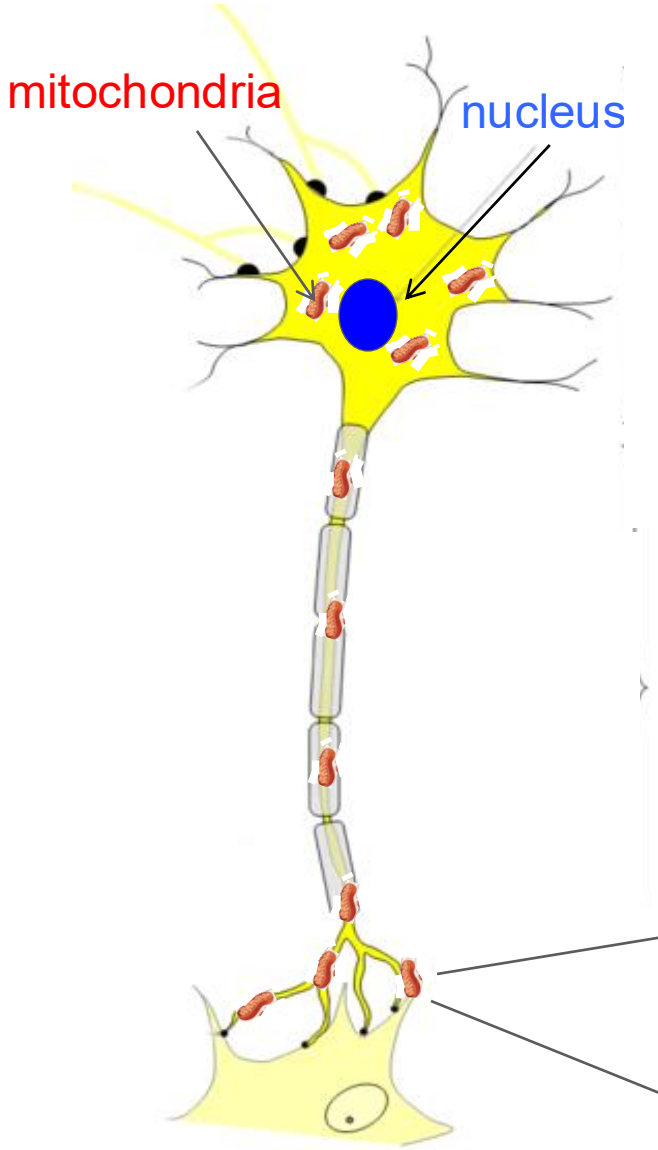
- Neurons communicate by fast electric impulses

→ High energy demand!



- Brain uses 2/3 of the resting body's energy

→ 50 Watt thinking

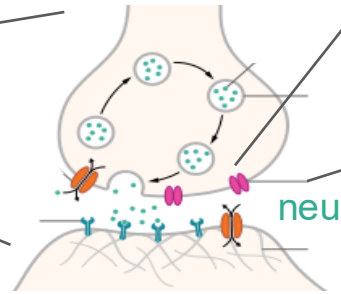


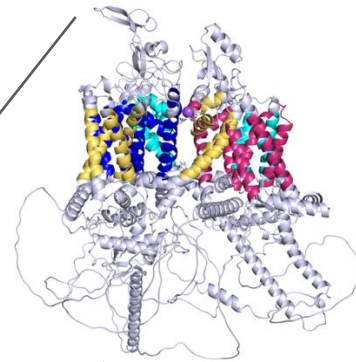
Dendrites
- Antenna

Cell body
- Coordination
- Production

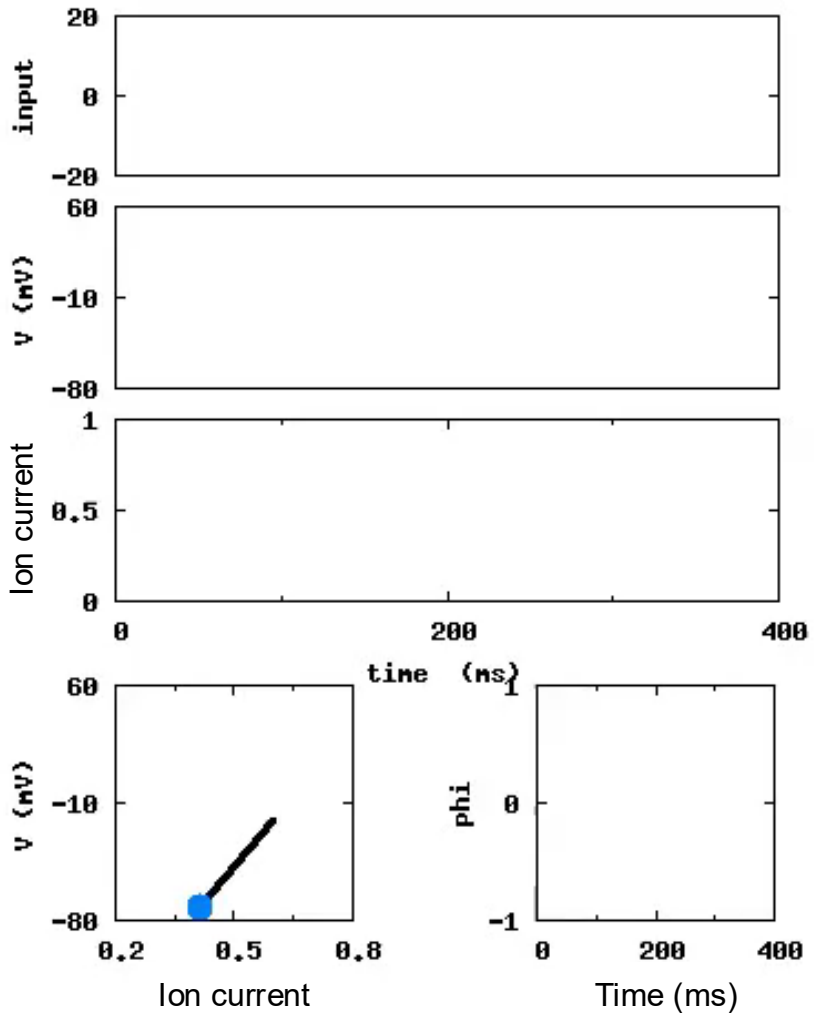
Axon
- Signal Propagation
- Information Transition

Synapse





Neuronal dynamics



- Neuron dynamics by Hodgkin-Huxley (Nobel Price 1963)

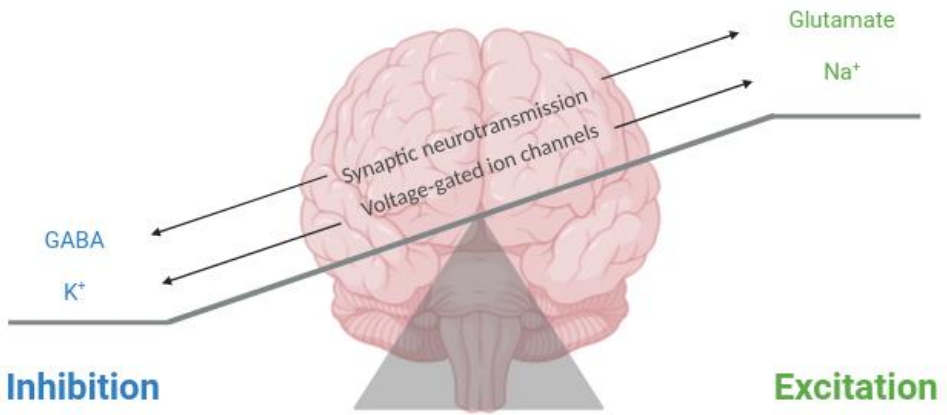
$$
\begin{aligned}
-\frac{dV}{dt} &= \frac{\bar{g}_{\mathrm{K}} n^4 (V - E_{\mathrm{K}}) + \bar{g}_{\mathrm{Na}} m^3 h (V - E_{\mathrm{Na}}) + \bar{g}_L (V - E_L)}{C_M} \\
\frac{dn}{dt} &= \alpha_n (1 - n) - \beta_n n \\
\frac{dm}{dt} &= \alpha_m (1 - m) - \beta_m m \\
\frac{dh}{dt} &= \alpha_h (1 - h) - \beta_h h \quad .
\end{aligned}
$$

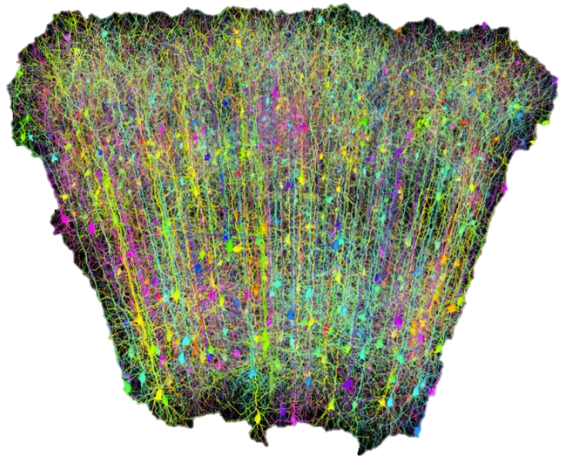
- Heraklit's: *"Panta rhei" (everything is floating)*

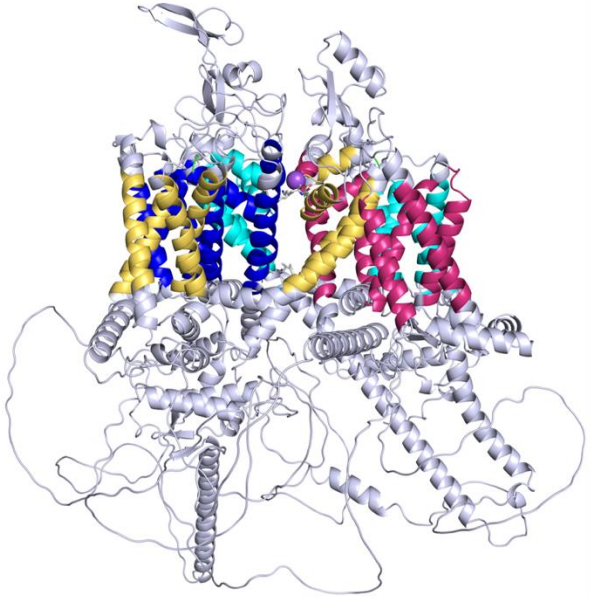
  turned in life to

  "Everything is oscillating"

Outline: Along the multiscale complexity of the brain







Brain homeostasis
- space: centimeters (10^{-1} m)
- time: seconds to years

Nerve cells
- space: micrometers (10^{-6} m)
- time: milliseconds to seconds

Ion channel
- space: nanometers (10^{-9} m)
- time: nanoseconds

Quantum brain memory (cm scale)

Ricciardi & Umezawa (1967): “Brain and Physics of Many-Body Problems”

Information is encoded as stable ordered patterns (vacua $|0(\theta)\rangle\rangle$ in the quantum fields with Hamiltonian

$$H = \sum_i \hbar\omega_i \left(a_i^\dagger a_i + \tfrac{1}{2}\right) + \sum_{i\neq j} g_{ij}\left(a_i^\dagger a_j + a_j^\dagger a_i\right) + \sum_{i\neq j} h_{ij}\left(a_i a_j + a_i^\dagger a_j^\dagger\right)$$

Each memory corresponds to a distinct vacuum configuration created by **spontaneous symmetry breaking**.

Problem of capacity: only a small number of memory states could coexist stably because new memory states tend to overwrite previous ones since:

$$\langle 0(\theta)|0(\theta')\rangle \approx e^{-N|\theta-\theta'|^2} \neq 0,$$ (N numbers of field modes)

Giuseppe Vitiello Hiroomi Umezawa

Extension to dissipative system by Vitiello (1990)

Operators:

$$[A_\kappa, A_\lambda^\dagger] = \delta_{\kappa,\lambda} = [\tilde{A}_\kappa, \tilde{A}_\lambda^\dagger] \quad ; \quad [A_\kappa, \tilde{A}_\lambda^\dagger] = 0 = [A_\kappa, \tilde{A}_\lambda]$$

Damped harmonic oscillators

$$H = H_0 + H_I \quad ,$$

$$H_0 = \sum_\kappa \hbar\Omega_\kappa \left(A_\kappa^\dagger A_\kappa - \tilde{A}_\kappa^\dagger \tilde{A}_\kappa\right)$$

$$H_I = i\sum_\kappa \hbar\Gamma_\kappa \left(A_\kappa^\dagger \tilde{A}_\kappa^\dagger - A_\kappa \tilde{A}_\kappa\right)$$

→

Memory state (vacua) (with SU(1,1) group)

$$|0>_{\mathcal{N}} = \exp\left(-iG(\theta)\right)|0>_0 = \prod_\kappa \frac{1}{\cosh\theta_\kappa} \exp\left(-\tanh\theta_\kappa J_+^{(\kappa)}\right)|0>_0$$

with: $J_+^{(\kappa)} \equiv A_\kappa^\dagger \tilde{A}_\kappa^\dagger \qquad G(\theta) = -i\sum_\kappa \theta_\kappa \left(A_\kappa^\dagger \tilde{A}_\kappa^\dagger - A_\kappa \tilde{A}_\kappa\right)$

Leads to: $|0(t)>_{\mathcal{N}} = \exp\left(-it\frac{H}{\hbar}\right)|0>_{\mathcal{N}} = \exp\left(-it\frac{H_I}{\hbar}\right)|0>_{\mathcal{N}}$

$$= \prod_\kappa \frac{1}{\cosh\left(\Gamma_\kappa t - \theta_\kappa\right)} \exp\left(\tanh\left(\Gamma_\kappa t - \theta_\kappa\right) J_+^{(\kappa)}\right)|0>_0$$

And thus vacua $|0(\Theta)\rangle, \quad \Theta = \{\theta_k\}$

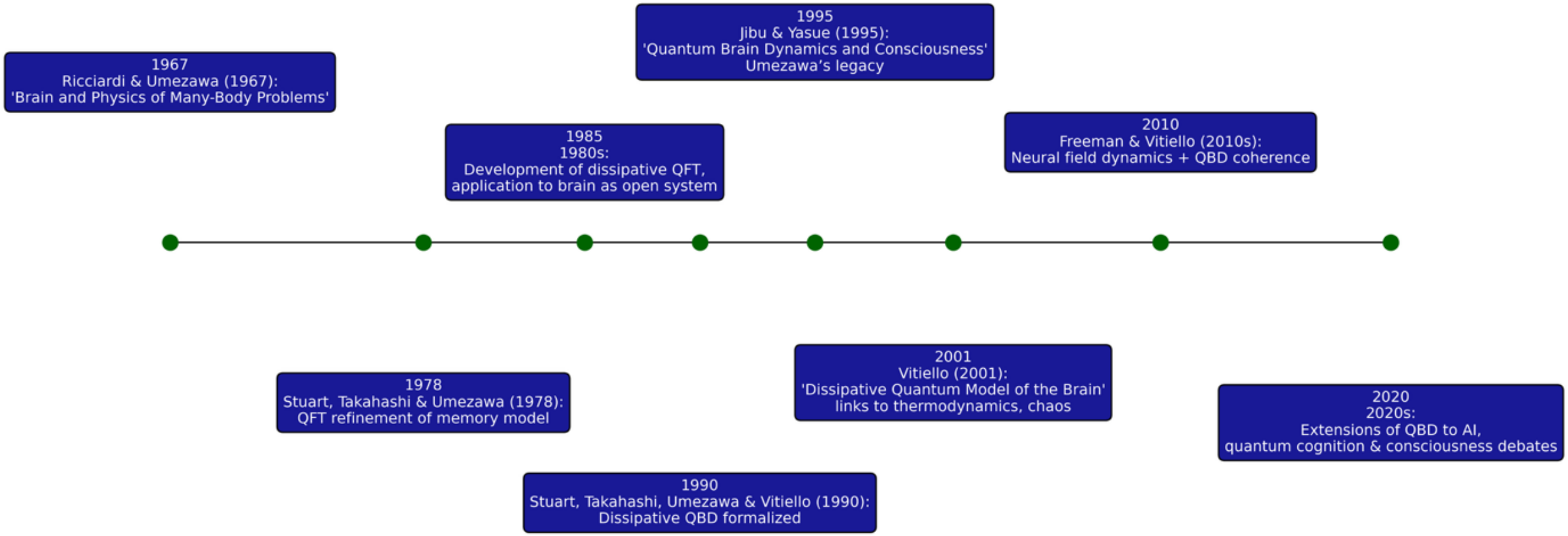
with θ_k coupling with environmental modes

$\langle 0(\Theta) \mid 0(\Theta')\rangle \rightarrow 0 \quad$ for $\Theta \neq \Theta'$

$\langle 0(\theta, \tilde{\theta}) \mid 0(\theta', \tilde{\theta}')\rangle = \delta_{\theta,\theta'}\, \delta_{\tilde{\theta},\tilde{\theta}'}$

→ exponential memory increase with N

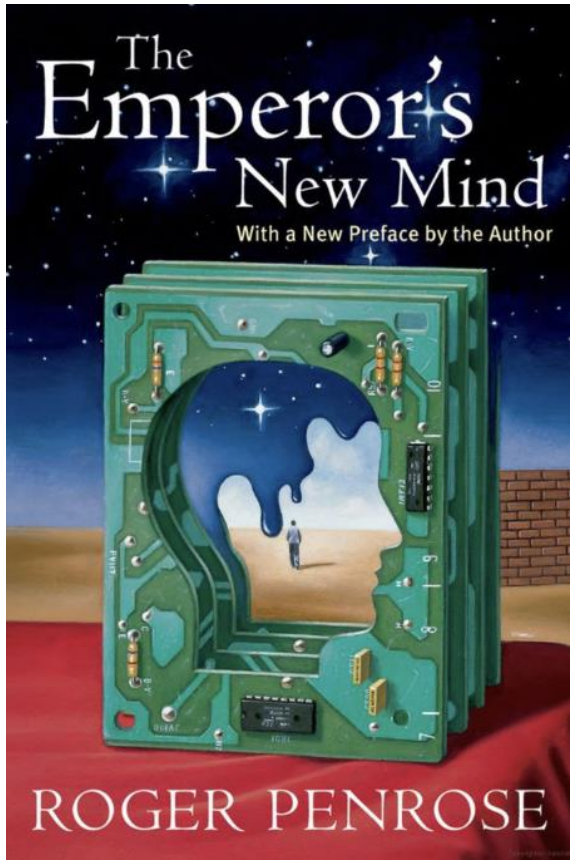
Quantum brain memory timeline



Consciousness as collapse of wave function

Roger Penrose

Based on Gödel's *Incompleteness Theorem*, Penrose argues that, since human recognize truth of certain unprovable statements, consciousness requires non-algorithmic physical processes.



(1989)

Objective reduction (OR): wavefunction collapse not by measurement but due to gravity for different mass distributions with:

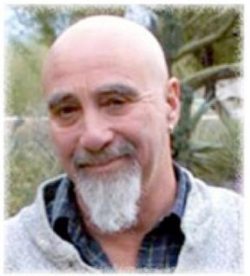
$$\tau \sim \frac{\hbar}{E_G}$$

E_G = the **gravitational self-energy**

→ spacetime geometry is central to consciousness

When & How?

Consciousness in microtubules



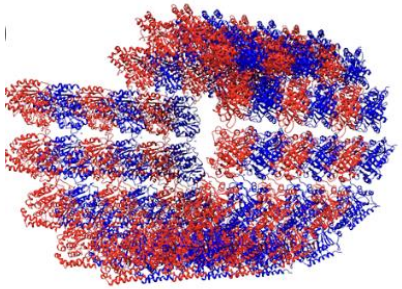
Steward Hameroff

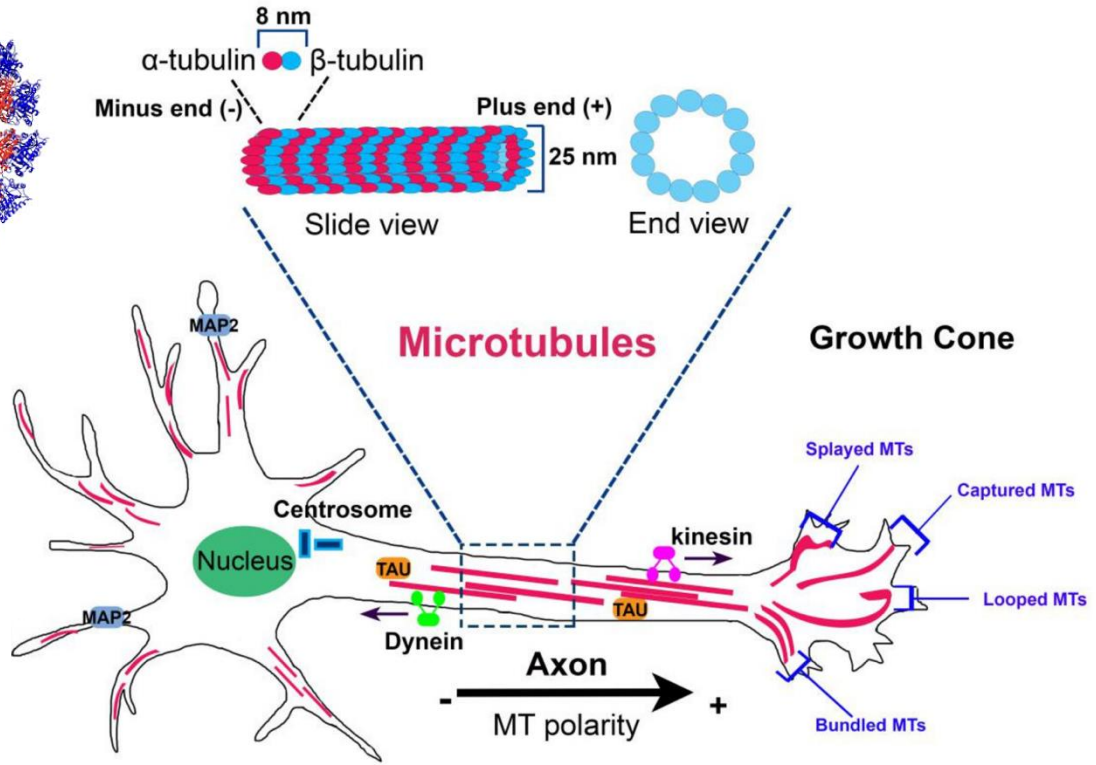
Hameroff proposed microtubules as substrate since tubulin proteins can exist in **quantum superpositions of conformational states**, and that networks of microtubules could maintain quantum coherence.

Input → quantum computing

↓

Orchestrated objective reduction (Orch-OR) as moment of conscious awareness





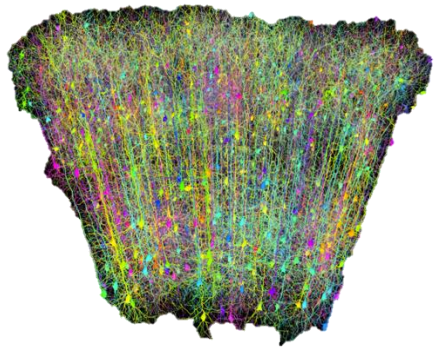
Excitation transport within microtubules:

$$H_{eff} = H_0 + \Delta - \frac{i}{2}G \qquad H_{eff} = \sum_{\mathcal{E}} \mathcal{E}|\mathcal{E}^R\rangle\langle\mathcal{E}^L|$$

$$\rho_{\text{th}} = \sum \frac{e^{-\beta\epsilon}}{Z}|\epsilon^R\rangle\langle\epsilon^L| \quad \rightarrow \quad C_{l_1}[\rho] = \sum_{k\neq k'} |\langle k|\rho|k'\rangle| \quad \sim 20\text{-}50 \text{ ms}$$

(Celerada NJP 2019)

Model for neuronal columns (µm scale)

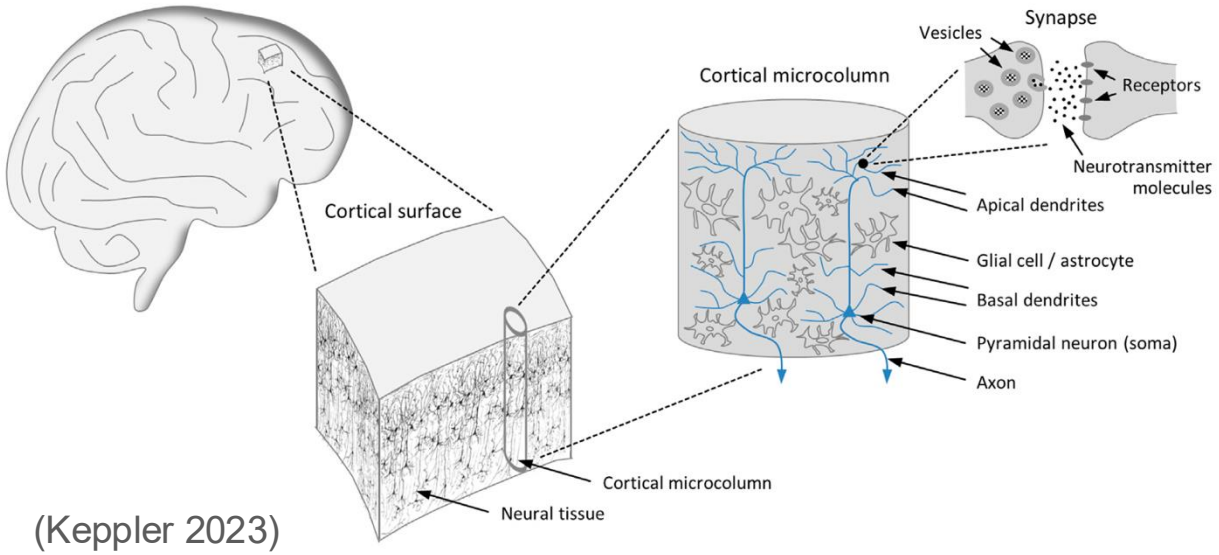


Interaction of neurotransmitter with the vacuum fluctuations of the electromagnetic field, termed zero-point field (ZPF)

Field: $$\vec{A}(\vec{x},t) = \sum_{\vec{k}} \sum_{\sigma} \sqrt{\frac{\hbar}{2\varepsilon_0 \omega V}}\, \vec{\varepsilon}_{\vec{k},\sigma} \left(a_{\vec{k},\sigma} e^{i(\vec{k}\cdot\vec{x}-\omega t)} + a^{\dagger}_{\vec{k},\sigma} e^{-i(\vec{k}\cdot\vec{x}-\omega t)} \right)$$

$$\left[a_{\vec{k},\sigma}(t), a^{\dagger}_{\vec{k}',\sigma'}(t) \right] = \delta_{\vec{k}\vec{k}'}\delta_{\sigma\sigma'} \qquad \left[a_{\vec{k},\sigma}(t), a_{\vec{k}',\sigma'}(t) \right] = 0$$

$$\left[a^{\dagger}_{\vec{k},\sigma}(t), a^{\dagger}_{\vec{k}',\sigma'}(t) \right] = 0$$



(Keppler 2023)

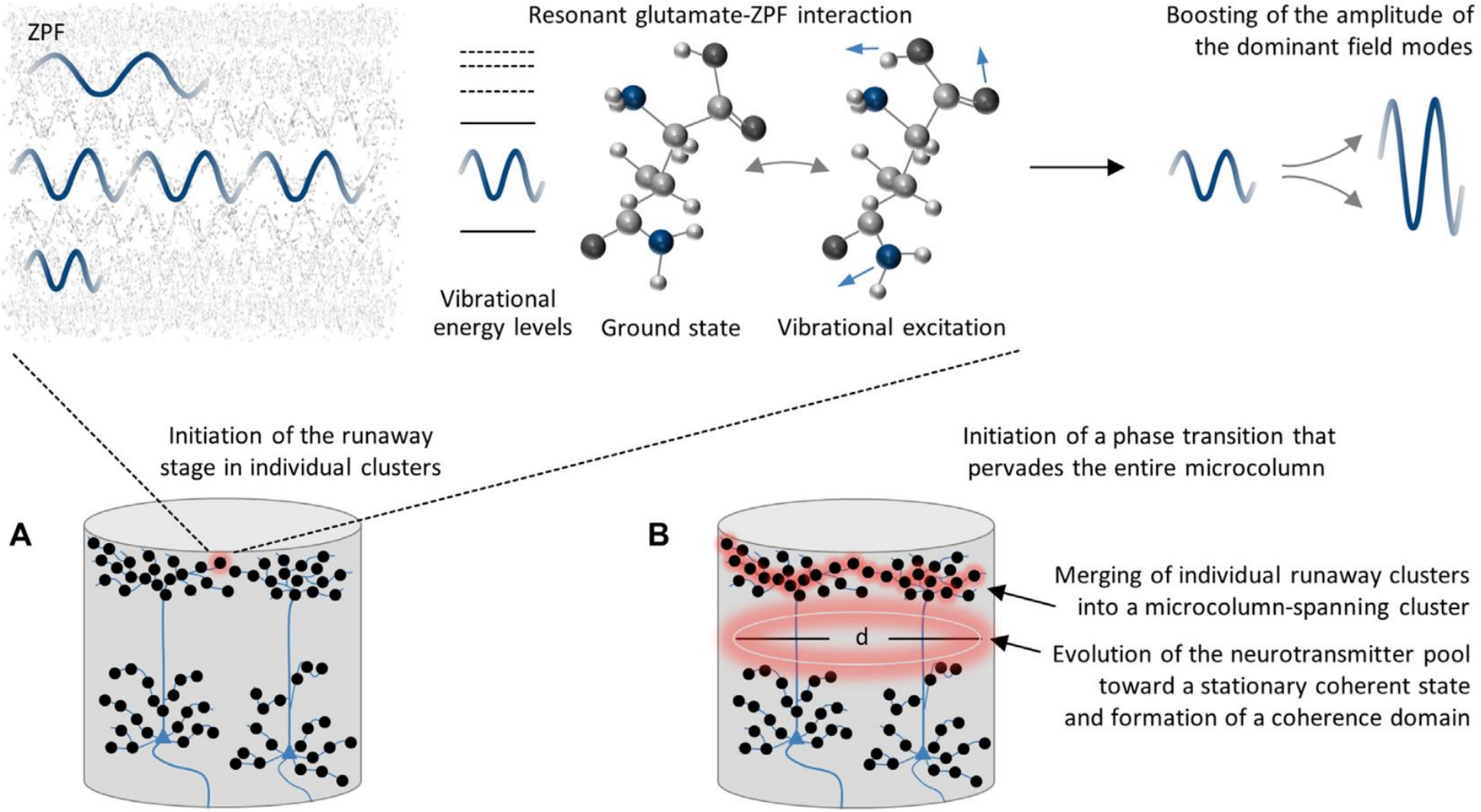
Lagrangian:

$$\begin{aligned} L &= L_{matter} + L^{(1)}_{int} + L^{(2)}_{int} + L_{field} \\ &= i\hbar \int \psi^{\dagger}(\vec{x},t) \frac{\partial}{\partial t} \psi(\vec{x},t)\, d^3x - \int \psi^{\dagger}(\vec{x},t)(H_0 + H_{SR})\psi(\vec{x},t)\, d^3x \\ &\quad -q \int \vec{A}(\vec{x},t)\, \psi^{\dagger}(\vec{x},t)\, \vec{J}\, \psi(\vec{x},t)\, d^3x - \lambda q^2 \int \vec{A}^{\,2}(\vec{x},t)\, \psi^{\dagger}(\vec{x},t)\, \psi(\vec{x},t)\, d^3x + L_{field} \\ &= i\hbar \int \psi^{\dagger}(\vec{x},t) \frac{\partial}{\partial t} \psi(\vec{x},t)\, d^3x - \int \psi^{\dagger}(\vec{x},t)(H_0 + H_{SR})\psi(\vec{x},t)\, d^3x \\ &\quad -q \sum_{\vec{k}} \sum_{\sigma} \sqrt{\frac{\hbar}{2\varepsilon_0 \omega V}}\, \vec{\varepsilon}_{\vec{k},\sigma} \int \left(a_{\vec{k},\sigma}(t)\, e^{i(\vec{k}\cdot\vec{x}-\omega t)} + a^{\dagger}_{\vec{k},\sigma}(t)\, e^{-i(\vec{k}\cdot\vec{x}-\omega t)} \right) \psi^{\dagger}(\vec{x},t)\, \vec{J}\, \psi(\vec{x},t)\, d^3x \\ &\quad -\lambda q^2 \sum_{\vec{k}} \sum_{\sigma} \frac{\hbar}{\varepsilon_0 \omega V} \left(a^{\dagger}_{\vec{k},\sigma}(t)\, a_{\vec{k},\sigma}(t) + \frac{1}{2} \right) \int \psi^{\dagger}(\vec{x},t)\, \psi(\vec{x},t)\, d^3x \\ &\quad +\hbar \sum_{\vec{k}} \sum_{\sigma} \left[\frac{i}{2} \left(a^{\dagger}_{\vec{k},\sigma}(t)\, \dot{a}_{\vec{k},\sigma}(t) - \dot{a}^{\dagger}_{\vec{k},\sigma}(t)\, a_{\vec{k},\sigma}(t) \right) + \frac{1}{2\omega}\, \dot{a}^{\dagger}_{\vec{k},\sigma}(t)\, \dot{a}_{\vec{k},\sigma}(t) \right], \end{aligned}$$

leads to macroscopic wave function:

$$i\hbar \frac{\partial}{\partial t} \psi(\vec{x},t) = q \sqrt{\frac{\hbar}{2\varepsilon_0 \omega_k V}}\, \vec{\varepsilon}_{\vec{k},\sigma}\, e^{i\omega_k t} \int e^{-i\vec{k}\cdot\vec{x}}\, \psi^{\star}(\vec{x},t)\, \vec{J}\, \psi(\vec{x},t)\, d^3x$$

Coherent domain of cortical microdomains



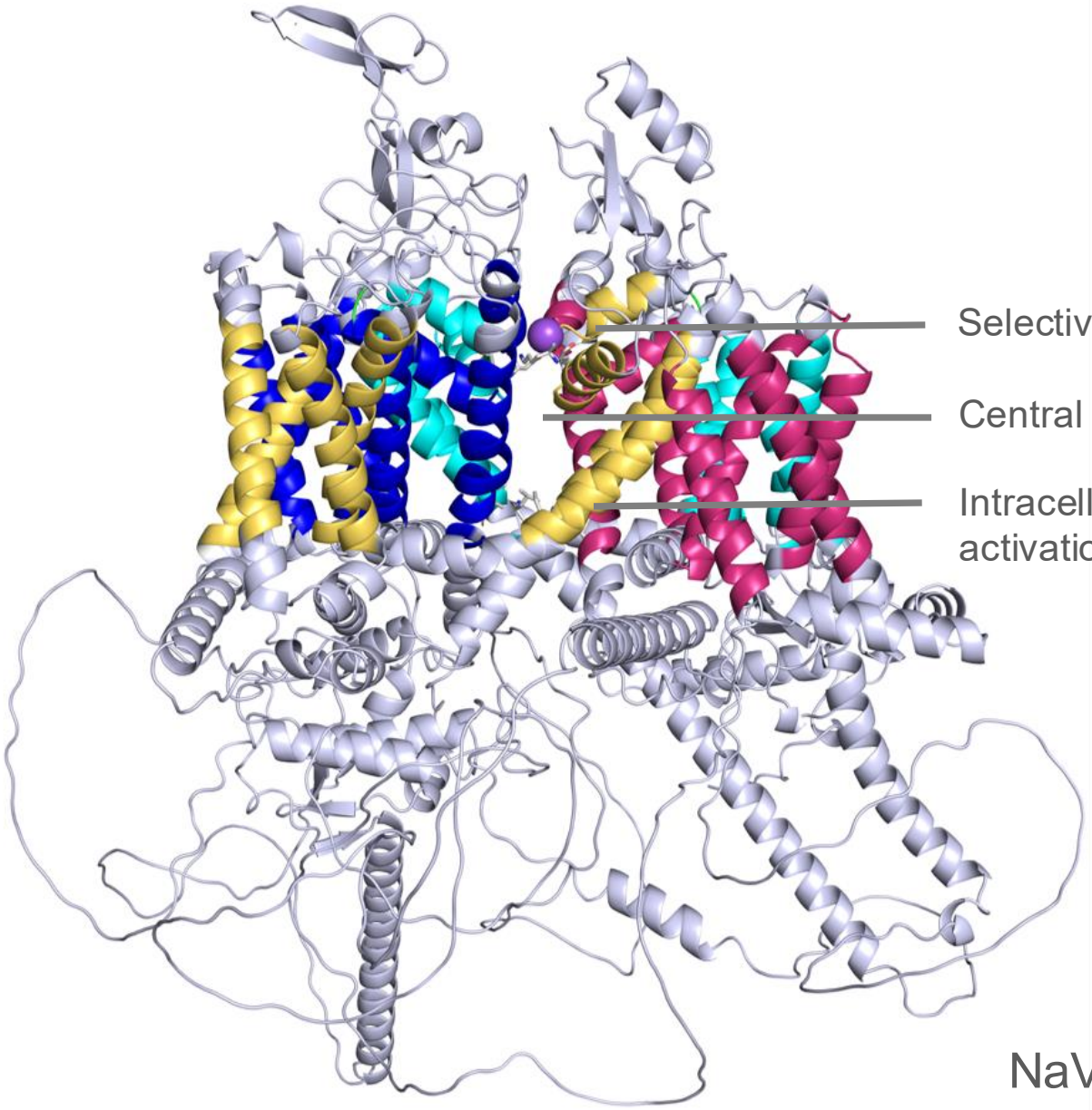
Ion channels (nm scale)

Ions (Na^+, K^+, Ca^{2+}, Cl^-) move through pores with diameters ~0.3–1 nm, comparable to their de Broglie wavelength $\lambda = \frac{h}{mv} = \frac{h}{p}$

Potential quantum effects:

- **Tunneling**
  (ions or protons crossing barriers),
- **Coherence**
  (delocalized ion states in selectivity filters),
- **Quantum gating**
  (protein conformations as quantum transitions).

These effects may explain the extraordinary **speed + selectivity** of ion channels.



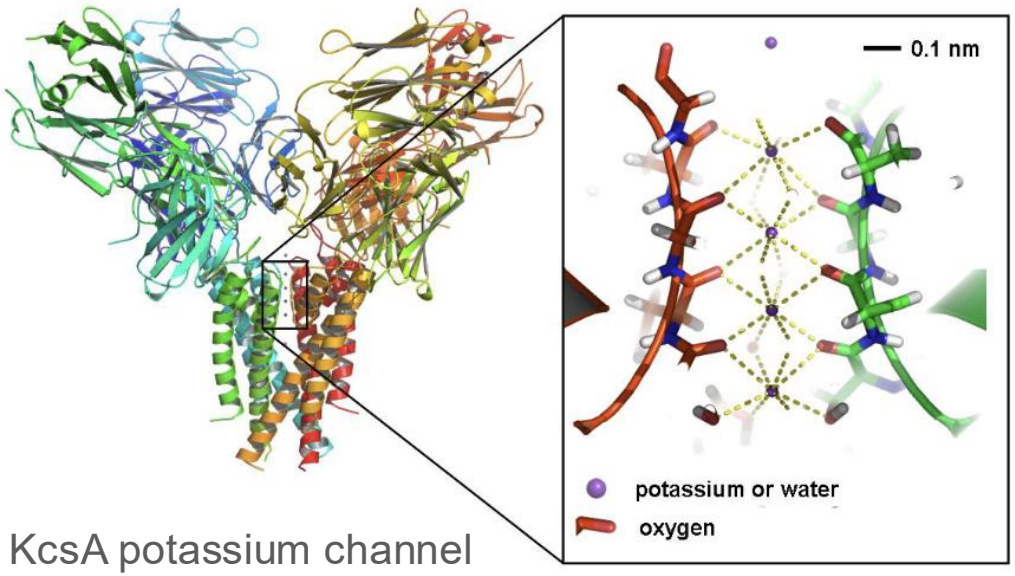
NaV1.1

Ion channels coherence

Quantum coherence in ion channels: Resonances, Transport and Verification

Alipasha Vaziri
Janelia Farm Research Campus, Howard Hughes Medical Institute 19700 Helix Drive Ashburn, VA 20147, USA

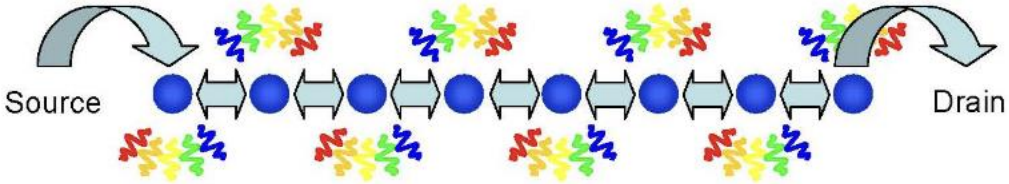
Martin B. Plenio
Institut für Theoretische Physik, Albert-Einstein Allee 11, Universität Ulm, Germany



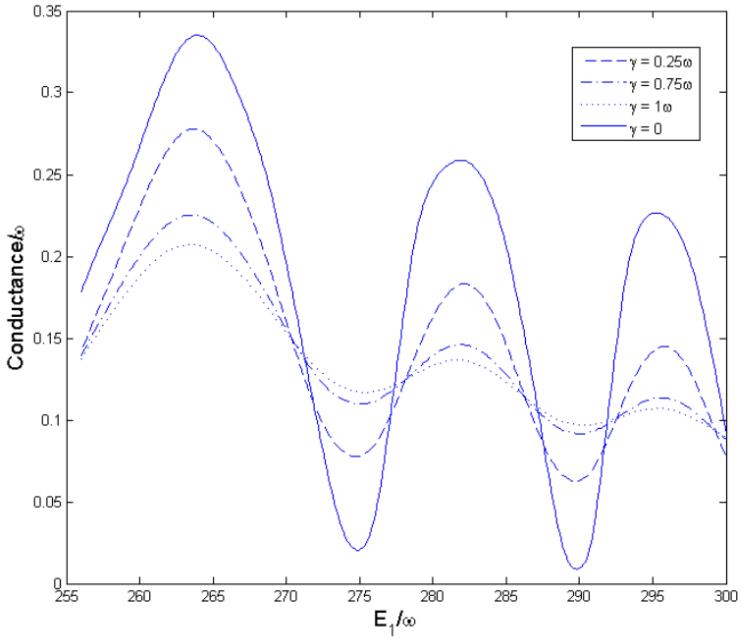
KcsA potassium channel

→ Suppression of transport depends on coherence
Supporting selectivity

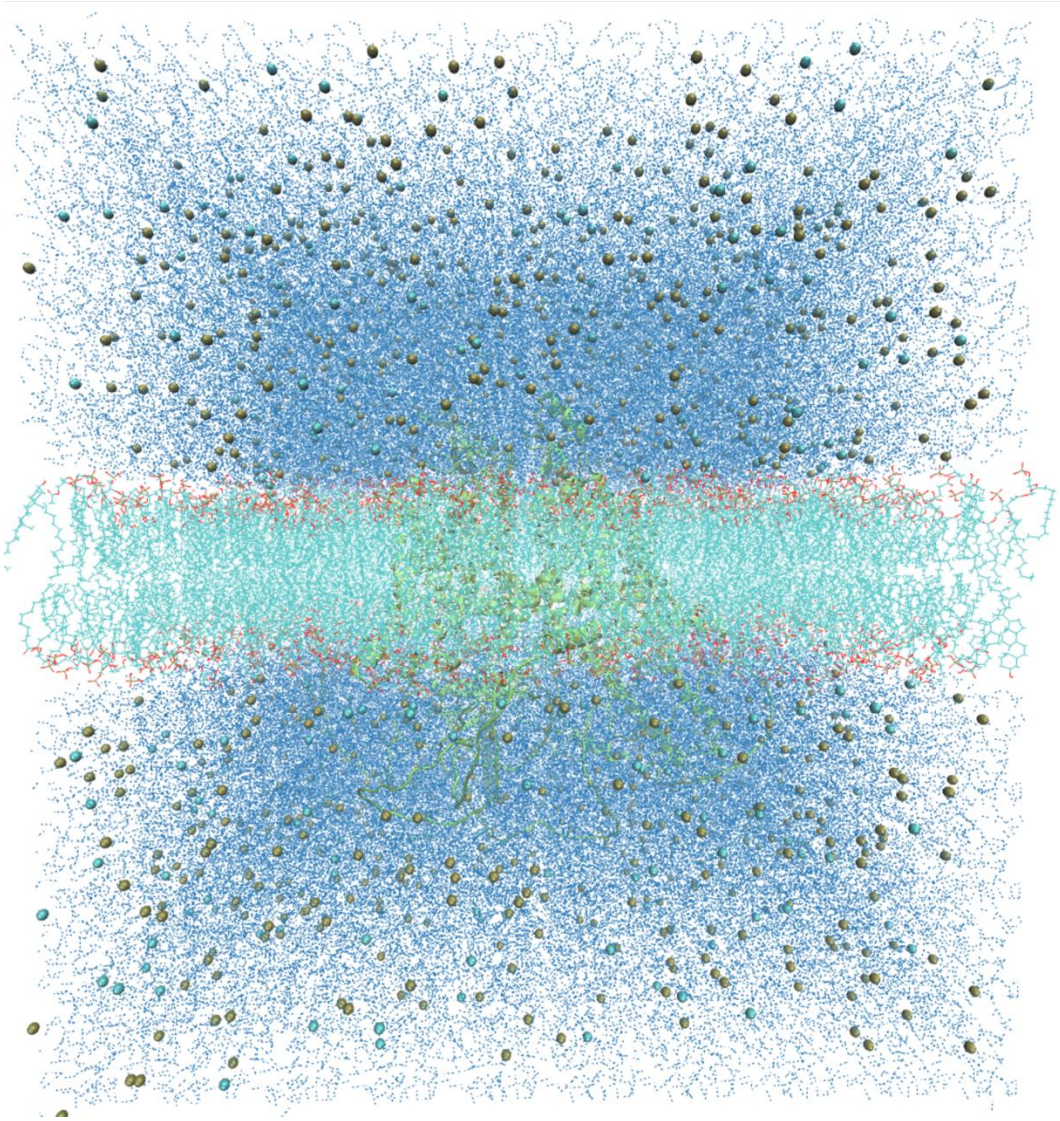
Transport as excitation of linear chain

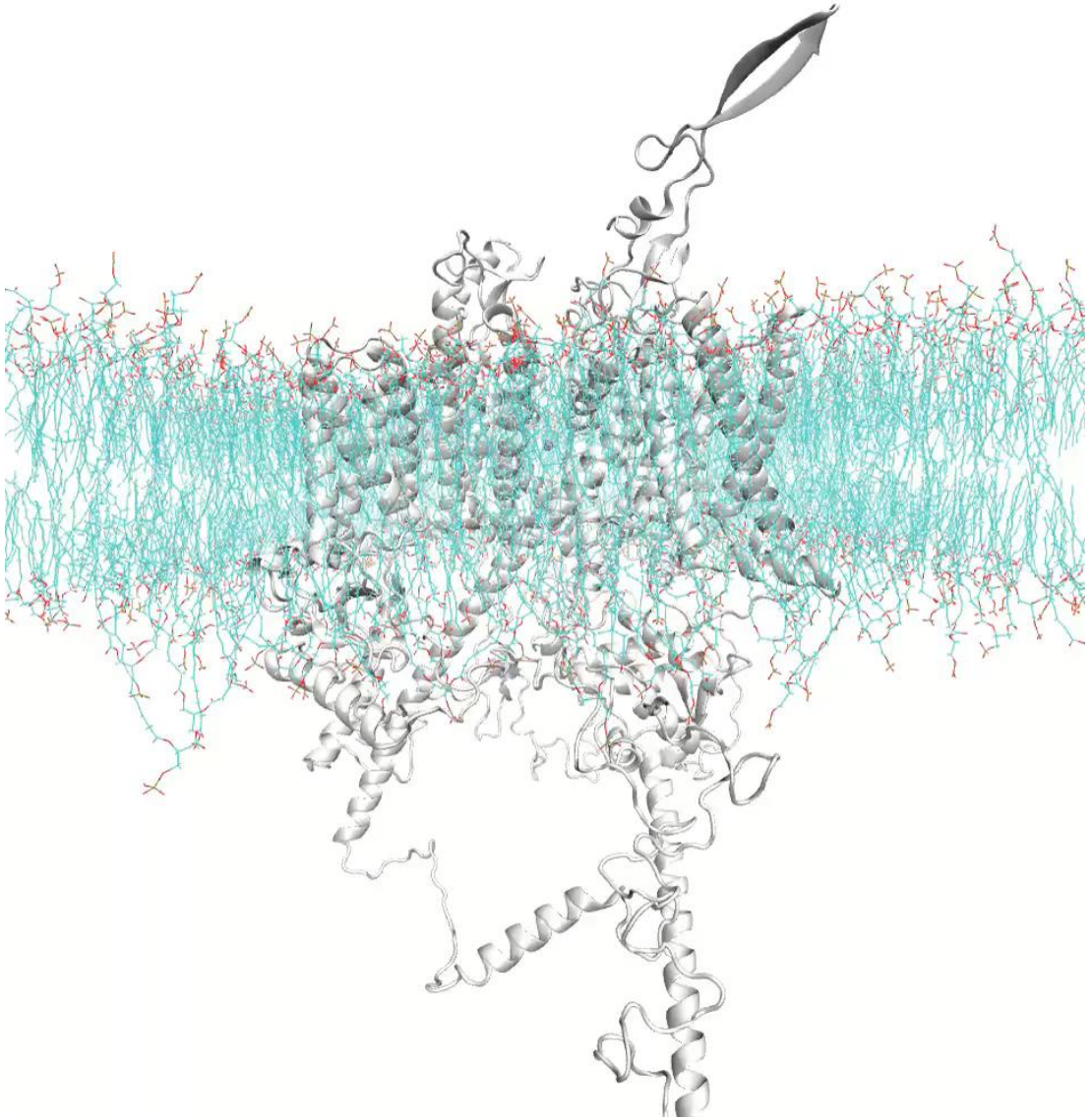


$$H_I/\hbar = \sum_{k=1}^{N-1} cJ_{\frac{\Omega_0}{\omega}}\left(\frac{\Omega_1}{\omega}\right)\left(\sigma_k^+\sigma_{k+1}^- + \sigma_k^-\sigma_{k+1}^+\right)$$

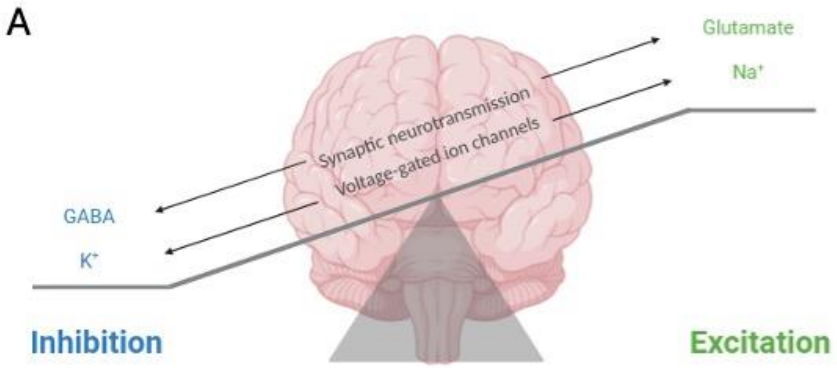


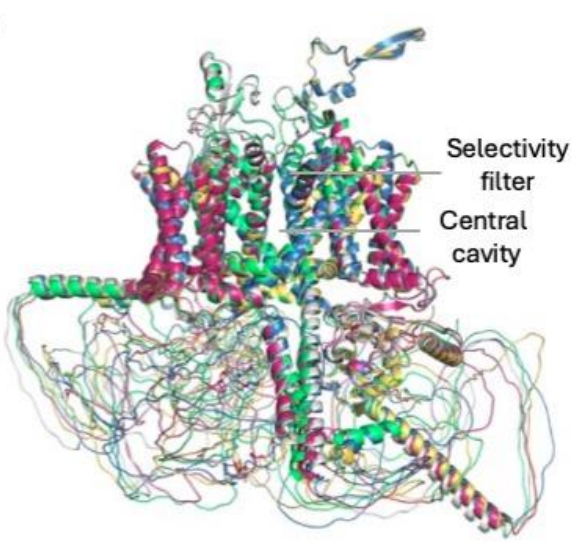
Molecular dynamics of Nav1.1

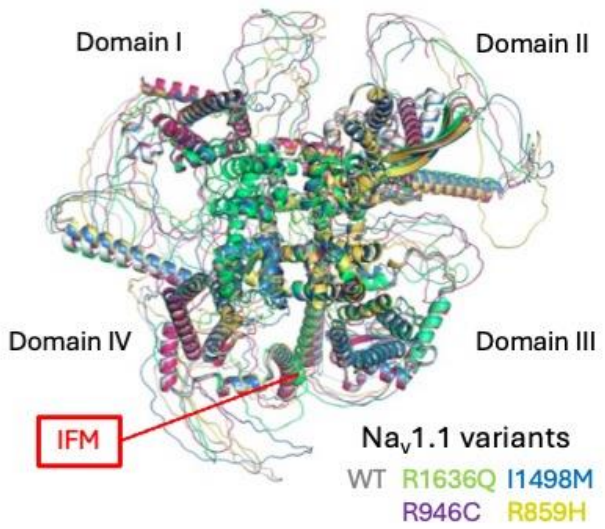


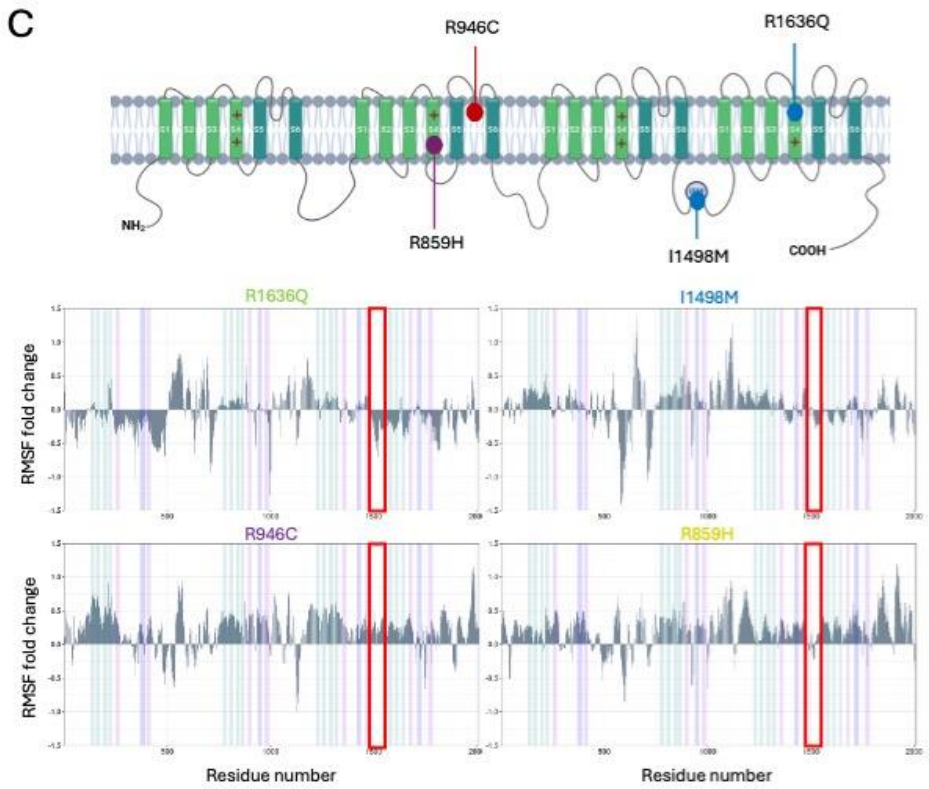


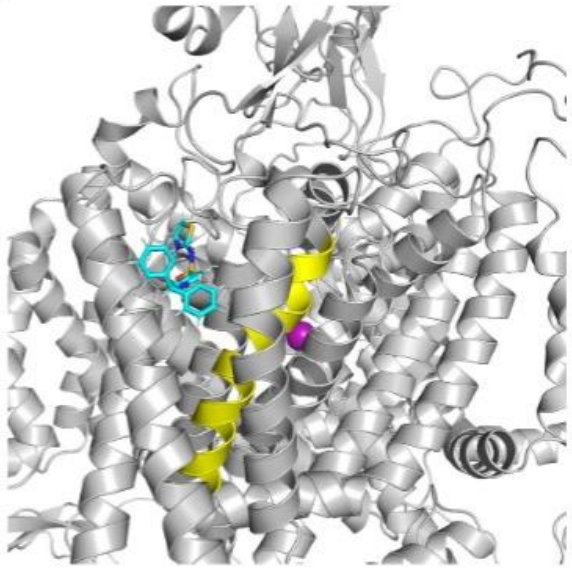
Drug evaluation in simulations

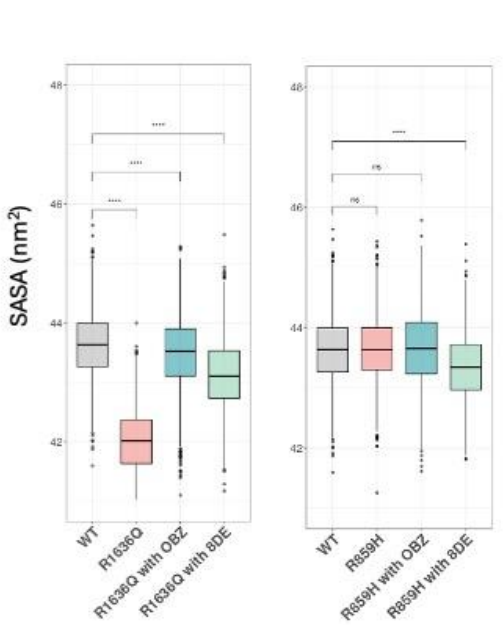




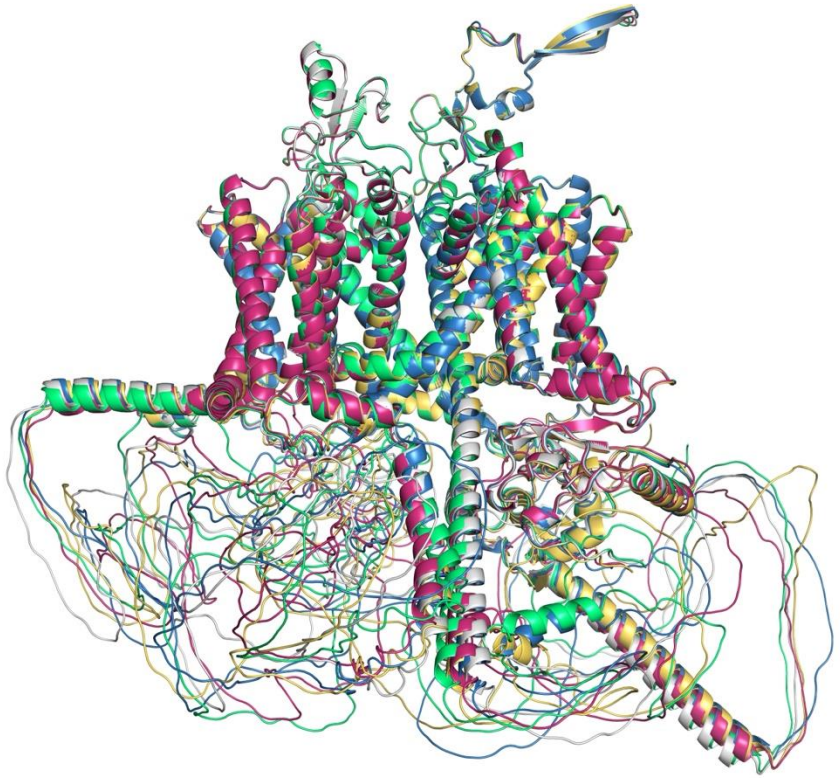


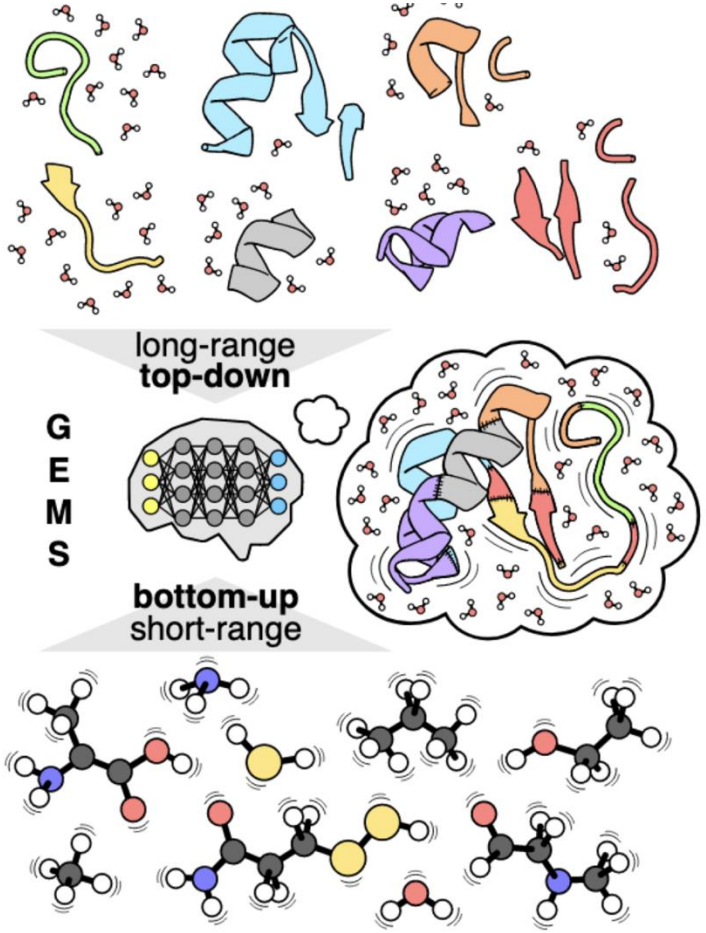






IonMolDyn project to evaluate quantum force fields





Concluding remarks

- Brain is complex multiscale entity
- Quantum Brain Dynamics can describe memory states

  → warm, wet and noisy environment & lack to explain spatial organization, capacity
- *Orchestrated Objective Reduction* for non-computable foundation of consciousness

  → environment, overinterpretation of Gödel, microtubules, classical alternatives
- Electromagnetic fields of neurons can couple to vacuum fluctuations and induce a phase transition

  → environment, organization of intrinsic noise, unfalsifiability
- Ion channels are the central entities of neuronal dynamics and have scales relevant for quantum mechanisms

  → contribution to fast transport and selectivity but has to be validated

  → intramolecular residue interactions (VdW) can lead coherent domains - to be done

Acknowledgement

Ellisman lab (San Diego) Huang lab (Seattle) Dudley lab (Seattle) van Steen lab (Liege)
Falcke lab (Berlin) Esguera lab (Oslo) Lerche lab (Tübingen) Sejnovski lab (San Diego)

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Luxembourg National Research Fund
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