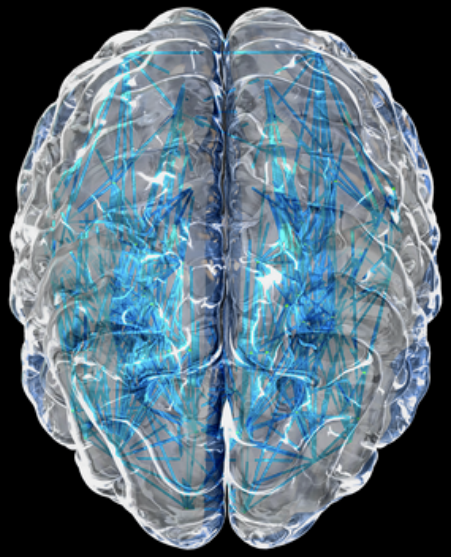
A Tutorial in Connectome Analysis (II): Topological and Spatial Features of Brain Networks



Dr Marcus Kaiser

Professor of Neuroinformatics
School of Computing Science /
Institute of Neuroscience
Newcastle University
United Kingdom

http://www.dynamic-connectome.org

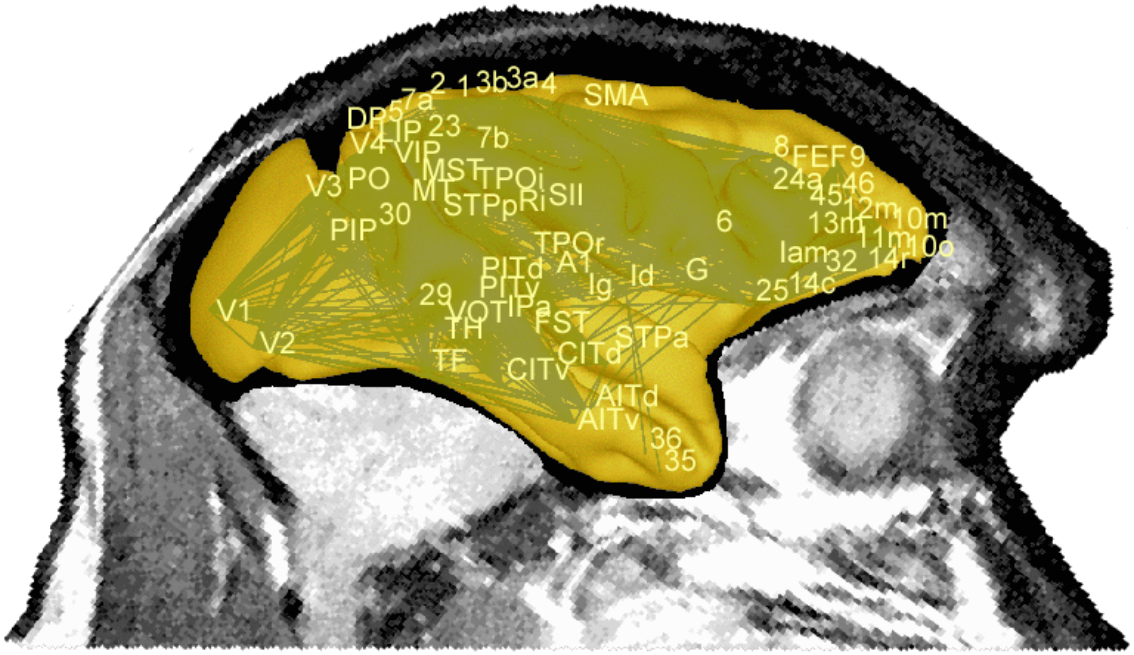
http://neuroinformatics.ncl.ac.uk/

@ConnectomeLab

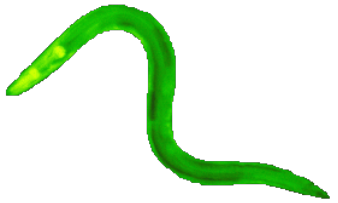
Outline

- Spatial neural networks
- Connection length distributions
- Component placement optimization
- Role of long-distance connections
- Deficits due to changes in long-distance connectivity
  (Alzheimer's disease and IQ)

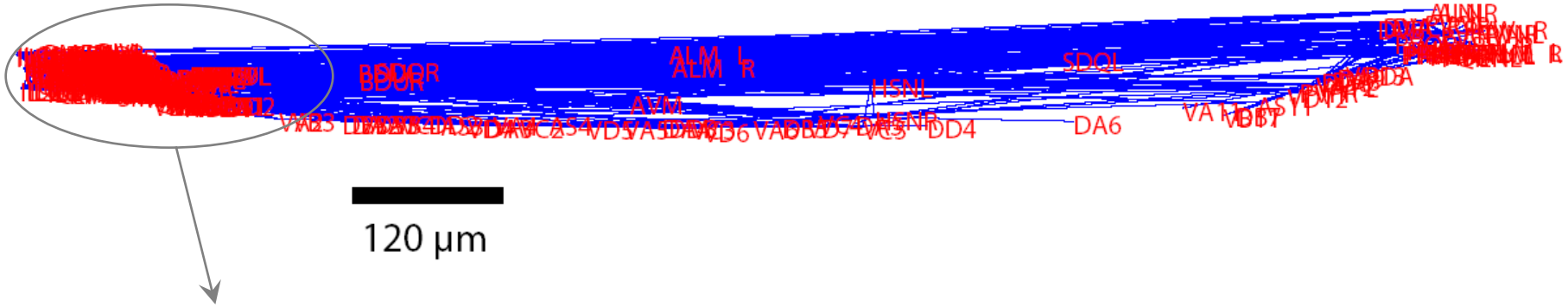
Macaque (rhesus monkey) cortical network

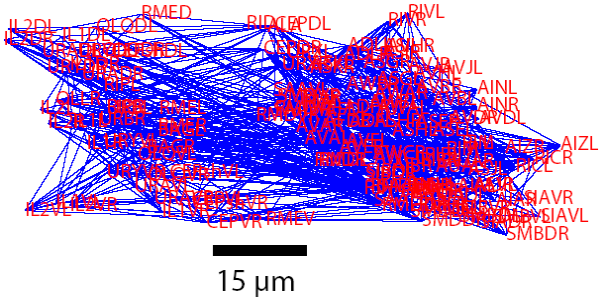


C. elegans neural network



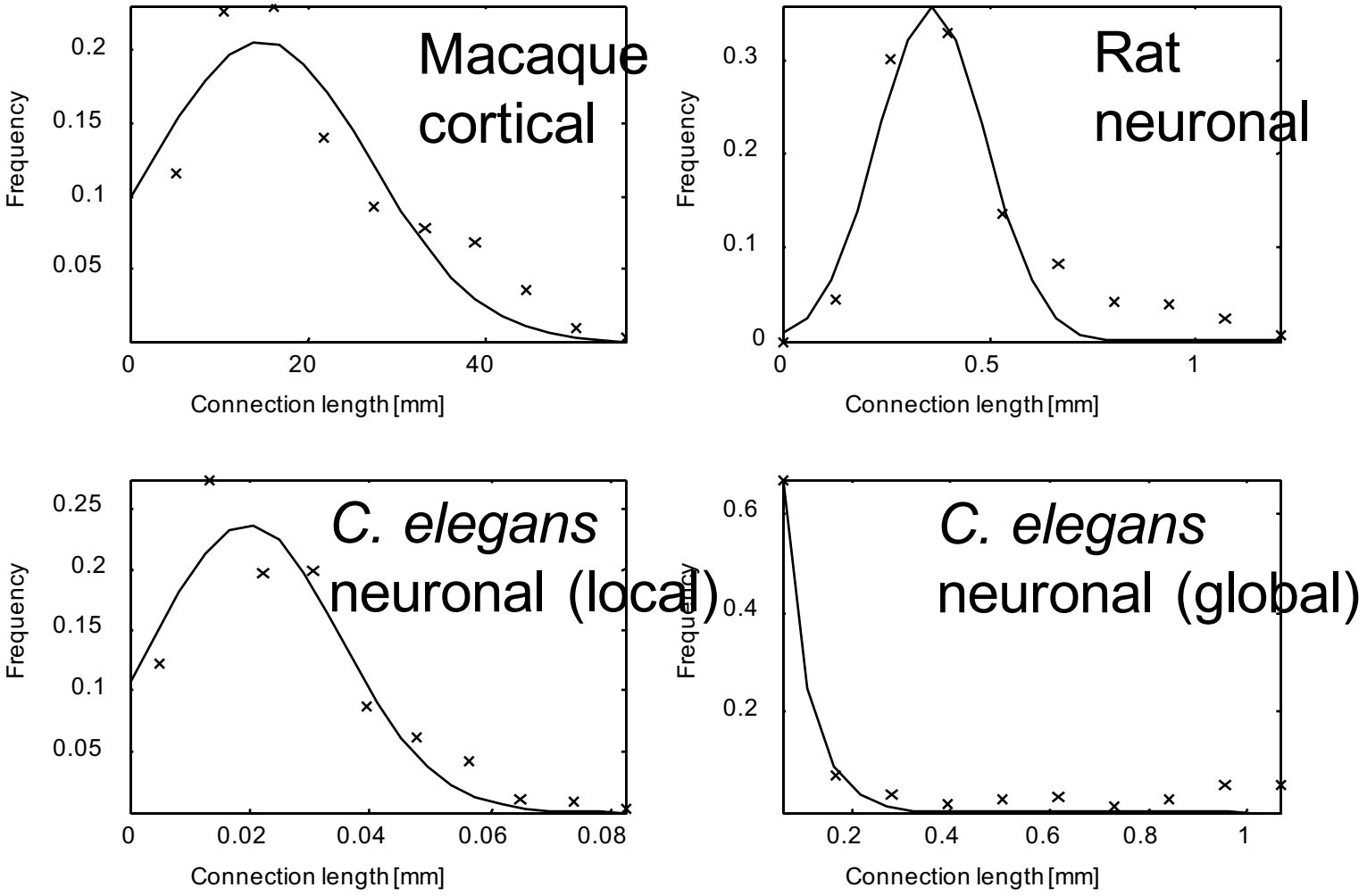
Global level (277 neurons)





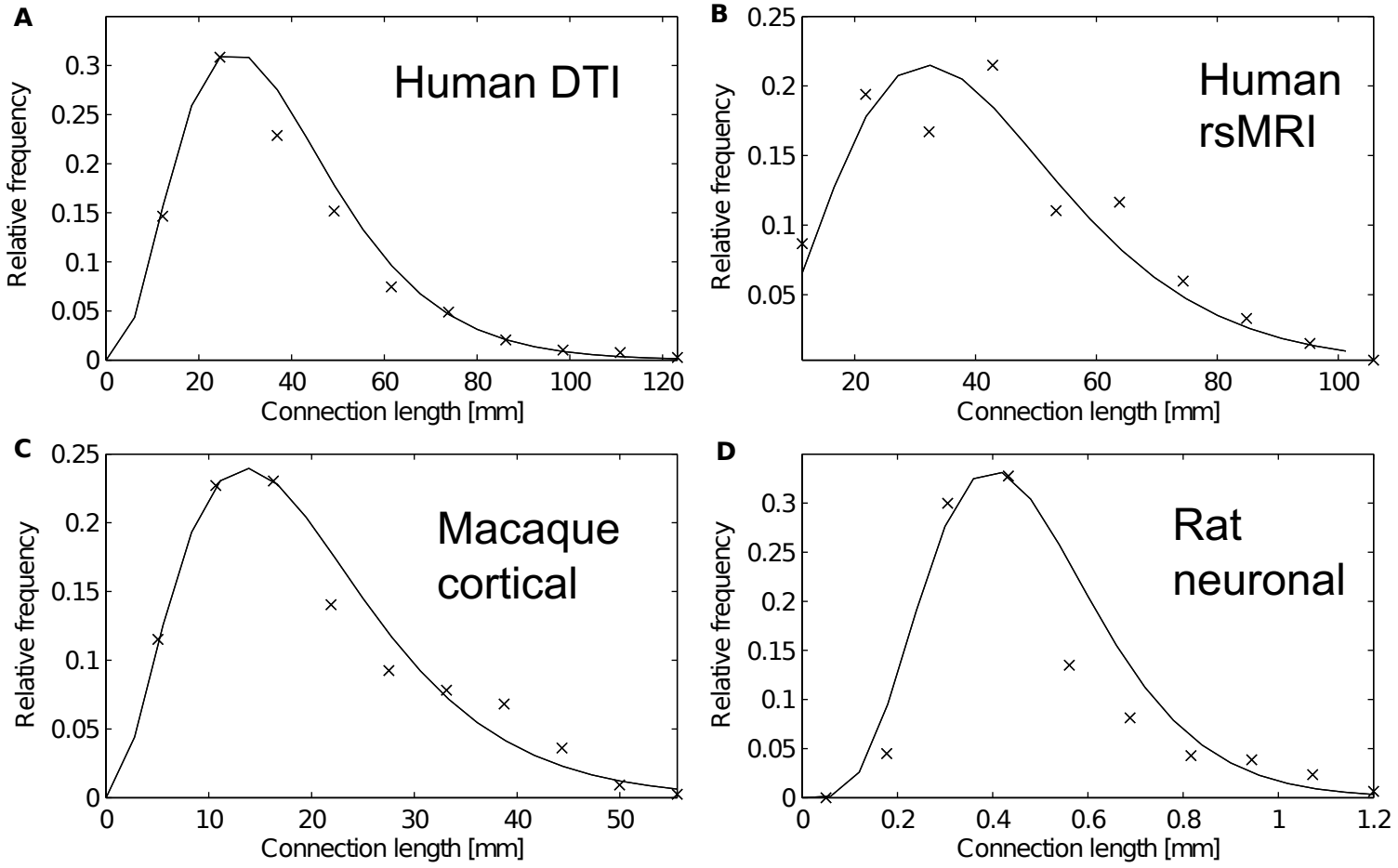
Local level (131 neurons)

Most projections connect adjacent neurons (Gamma function for connection length distribution)



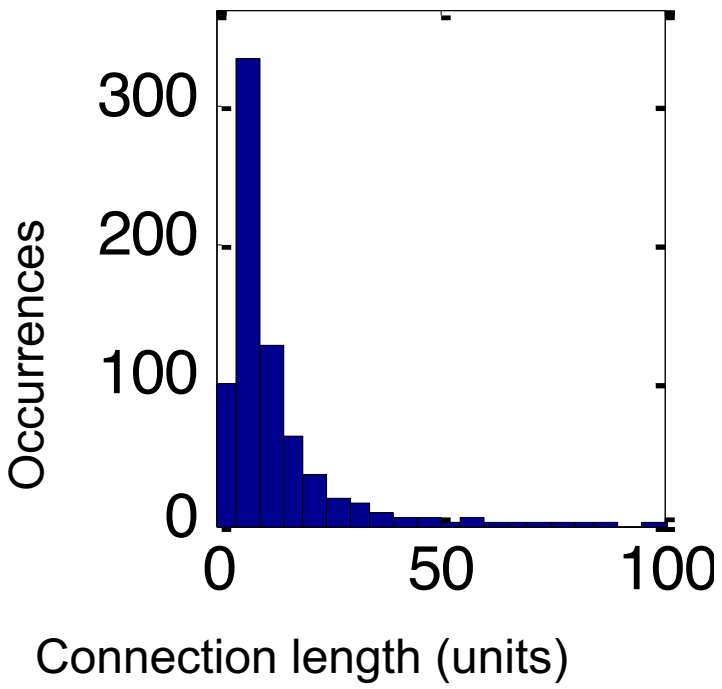
Kaiser et al. (2009) *Cerebral Cortex*

Also true for human structural and functional connectivity

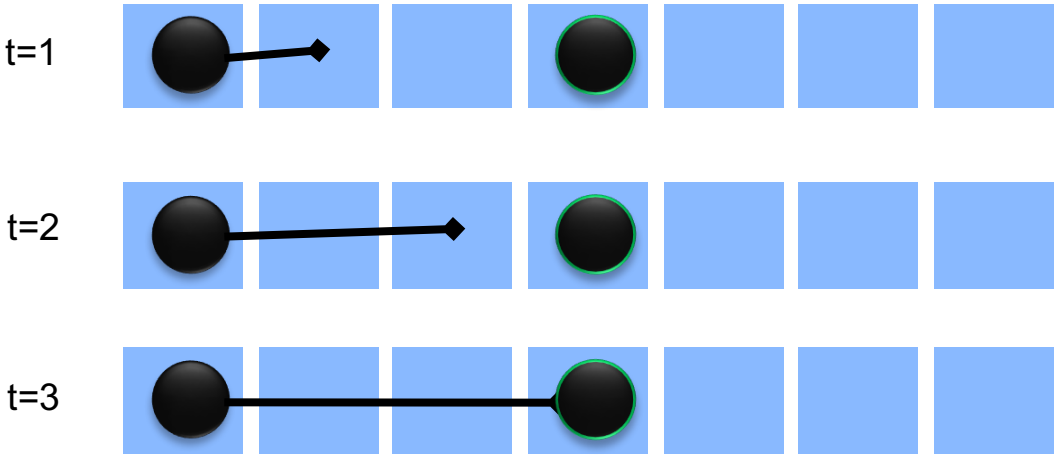


Kaiser (2011) *Neuroimage*

Why is there an exponential tail?



X: number of steps until another neuron
is in the range of the axonal growth cone
p: probability that unit space contains a neuron
q = 1 - p



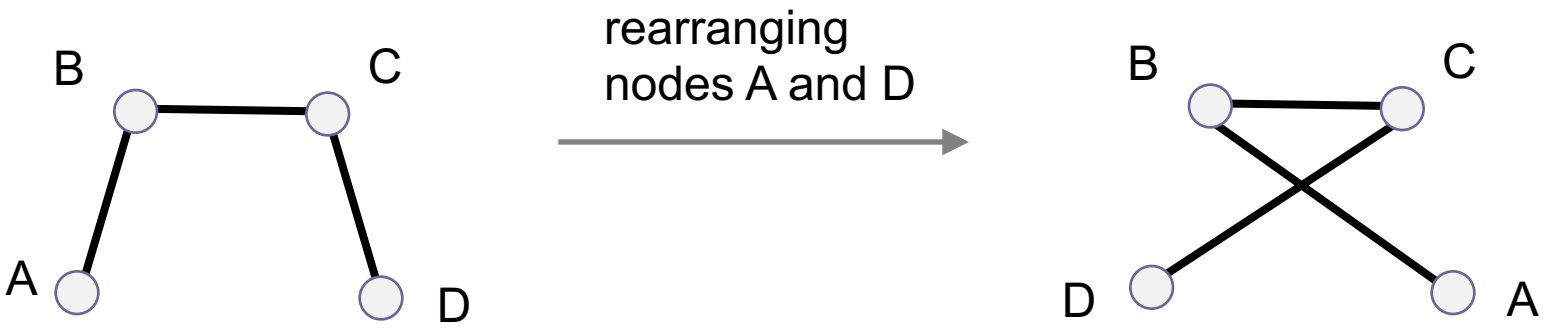
$P(X = n) = p * q^{n-1}$

-> exponential distribution

Kaiser et al. (2009) *Cerebral Cortex*

Reducing neural wiring costs

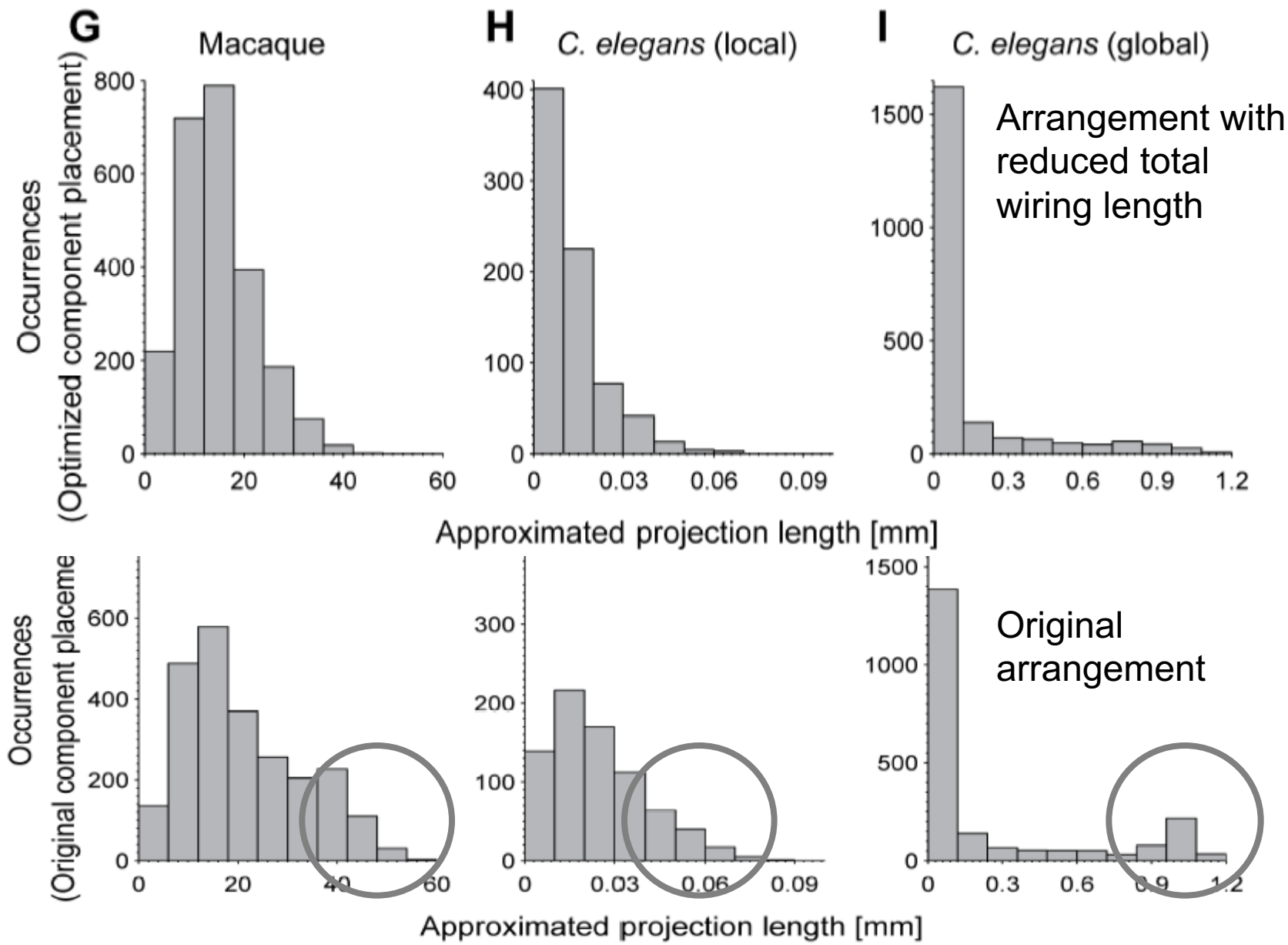
- Minimizing total wire length reduces metabolic costs for connection establishment and signal propagation
- *Component Placement Optimization, CPO*
  Every alternative arrangement of network nodes will lead to a higher total wiring length



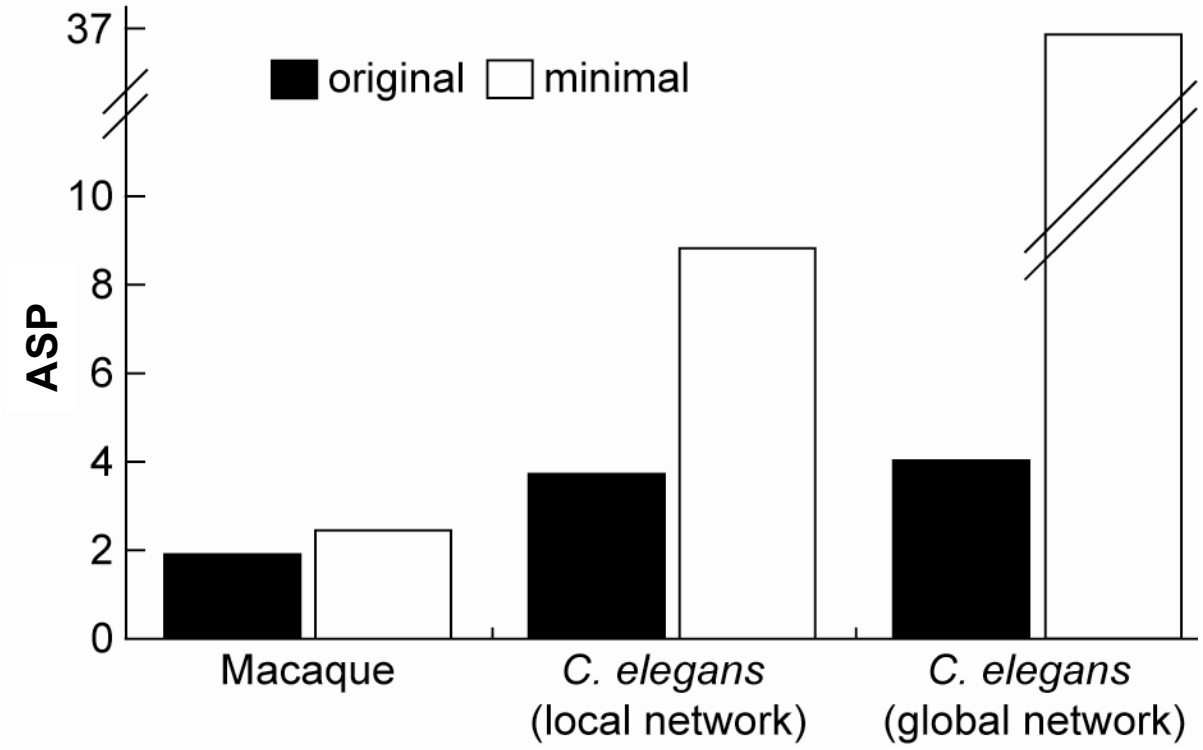
- Not the case! Reductions by 30-50% possible

Kaiser & Hilgetag (2006) *PLoS Computational Biology*, 7:e95

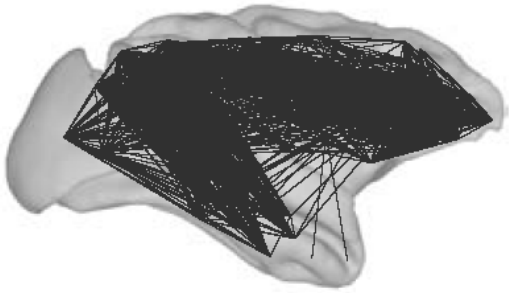
More long-distance projections than expected



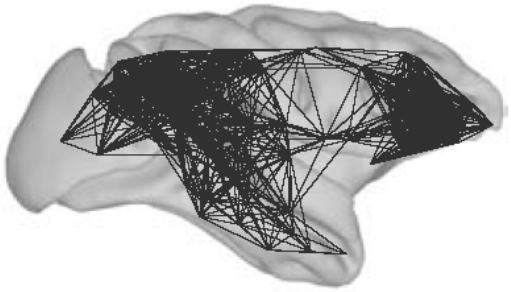
When long-distance fibers are missing (minimal):



original



minimal

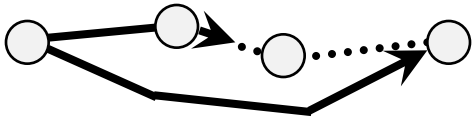


Long-distance connections are short-cuts that help to reduce the characteristic path length (or average shortets path, ASP):
Less long-distance connections -> longer path lengths

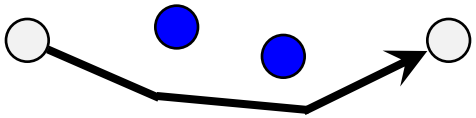
Low path lengths = few intermediate processing steps are beneficial

- Synchrony of near and distant regions

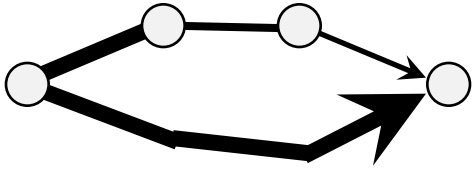
- Reduced transmission delays



- Less (cross-modal) interference

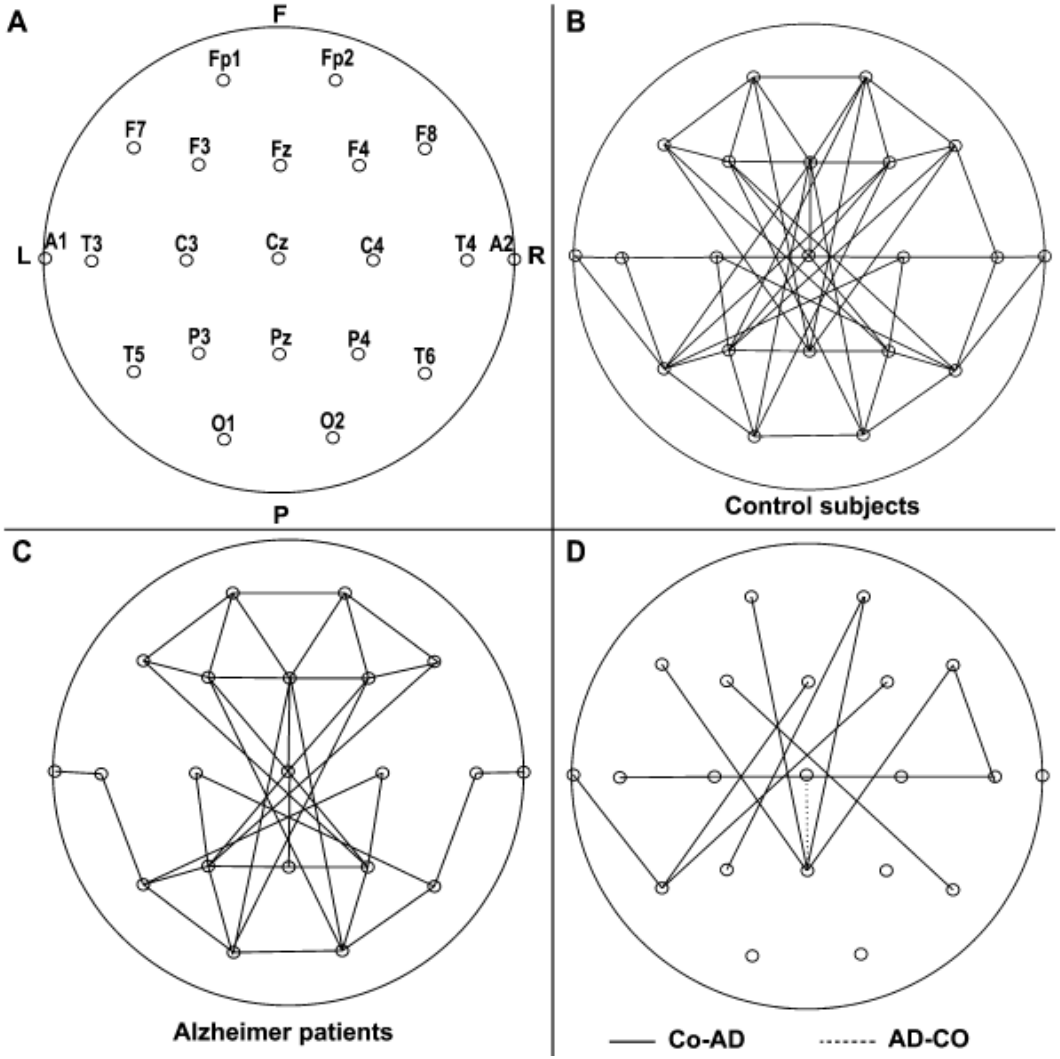


- Higher reliability of transmission



Linking structure and function

Small-world properties



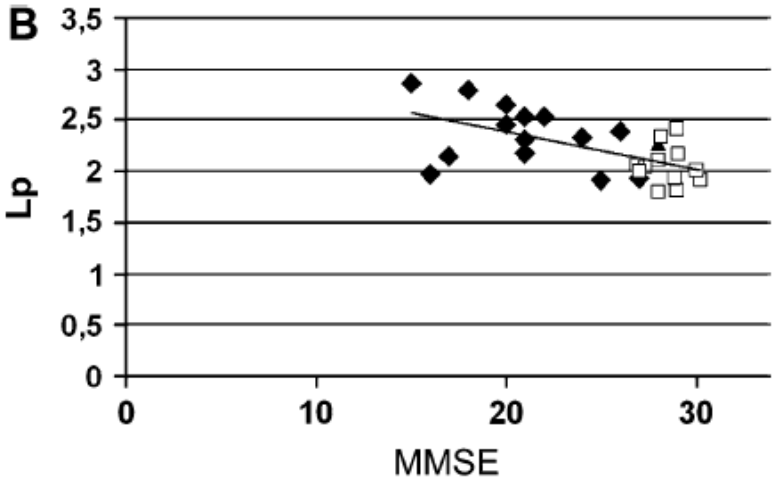
EEG synchronization Network (functional connectivity)

in Alzheimer's patients and control group

Stam et al. *Cerebral Cortex* (2007)

Alzheimer: Path length vs. task performance

Mini Mental State Examination
(attention, memory, language)

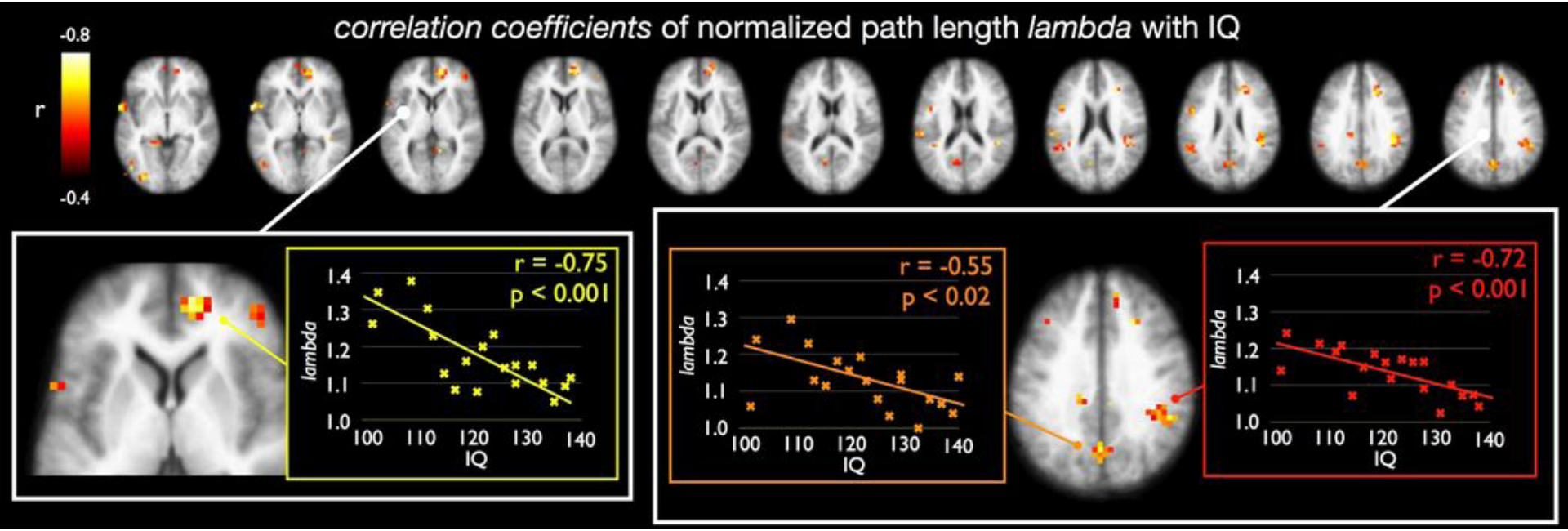


Diamonds:
Alzheimer patients

Empty squares:
Control

Cognition: Path length vs. IQ

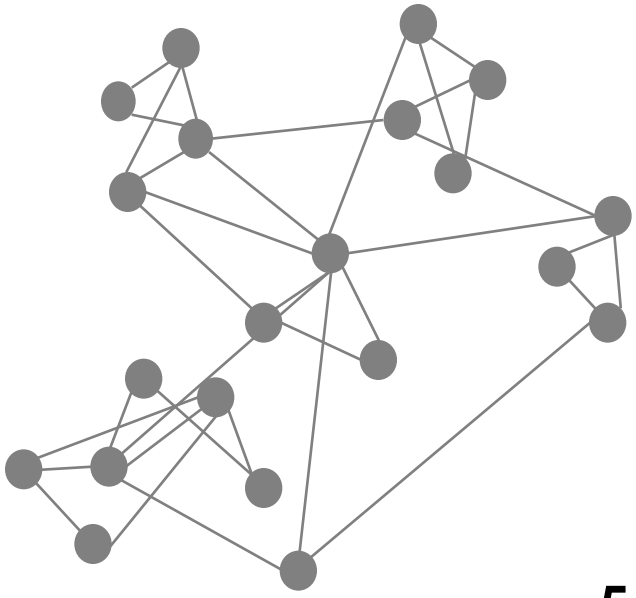
Resting state fMRI in 19 subjects (functional connectivity based on coherence)



Correlations between local path length lambda (shortest path length from one node to any other node) and IQ (Intelligence Quotient) for medial prefrontal cortex, bilateral inferior parietal cortex and precuneus / posterior cingulate regions ($p < 0.05$, corrected for age).

Van den Heuvel (2009) *J. Neurosci.* 29: 7619

Summary



4. Spatial properties:
- Preference for connections to neighbours
- Fast processing due to long-distance connections

5. Linking structure and function:
- Alzheimer's disease: path lengths
- IQ: path lengths