The economics of brain network organization

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gsk

An economical model of brain networks

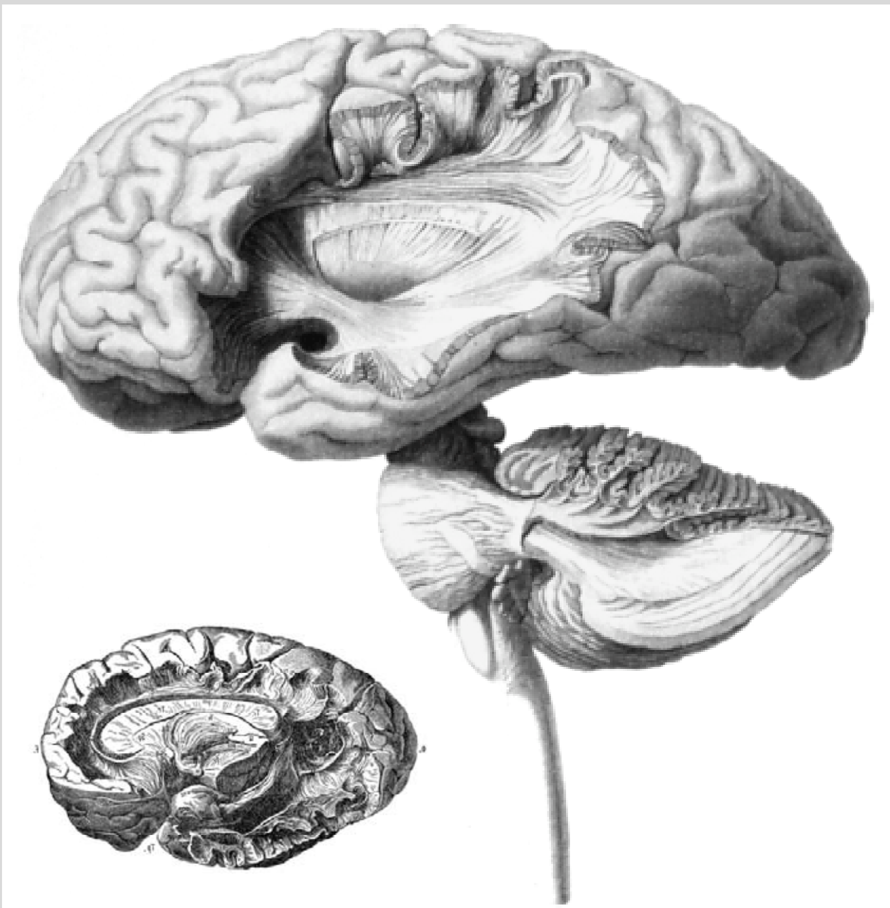
- Brains make adaptive value at some physical cost
  - *Adaptive value:* perceptions, cognitions, behaviours that help the organism survive in a changing, competitive environment
  - *Physical cost:* volume, wiring and metabolic costs of nervous systems

- In brain networks, the topological properties that add the most adaptive value are often the most costly
  - Long distance connections needed for integrative processing
  - Central hubs that mediate a lot of inter-modular connections

- Like profitable businesses, brain networks negotiate an economic trade-off between adding value and controlling production costs

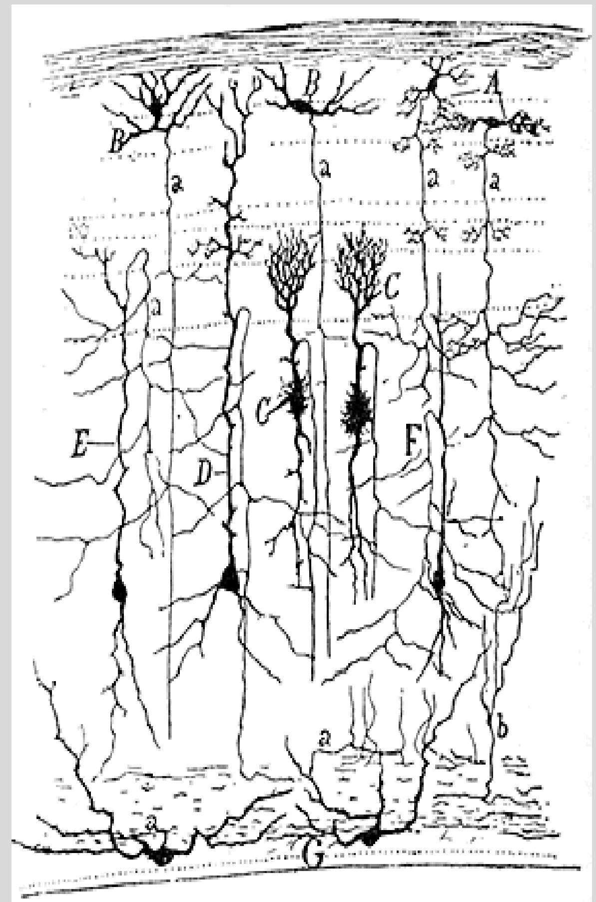
How did we start thinking about brain networks?

Macro



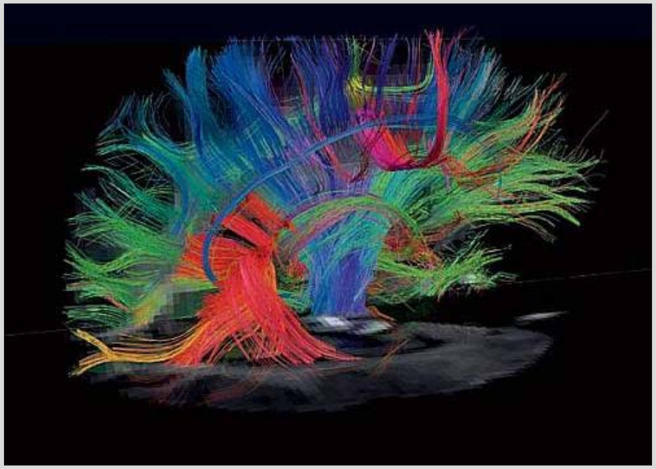
Mayo, Meynert
(1827, 1870)

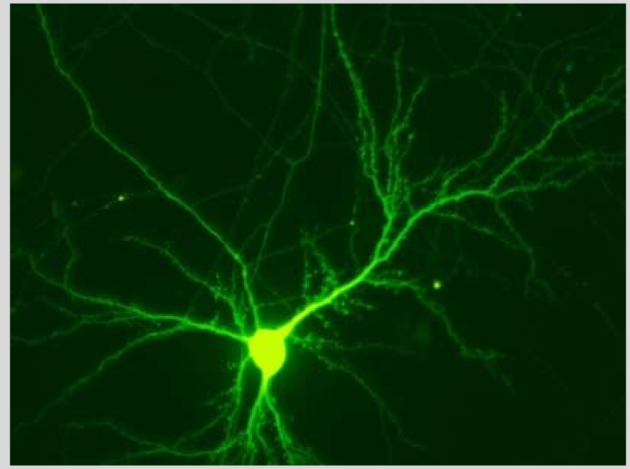
Micro



Ramón y Cajal
(1890)

Explosion of high quality neuroimaging data now makes connectomes dauntingly accessible





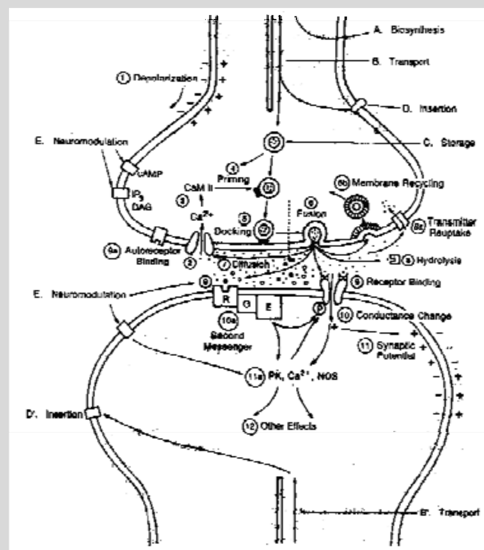
About 100,000,000,000 neurons in the human brain (100 billion)

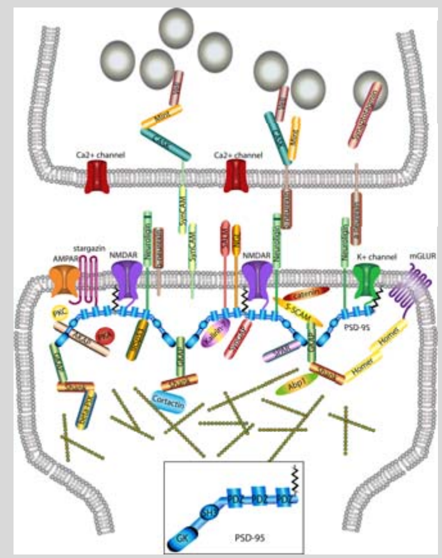
About 100,000 synapses per neuron

1 quadrillion cellular connections (10^{15}) in human brain connectome

1000s of structural and signalling proteins per synaptic connection

Sporns, Tononi & Kotter (2005) *PLoS Comp Biol*





Graph theory powerfully simplifies the topology of complex systems

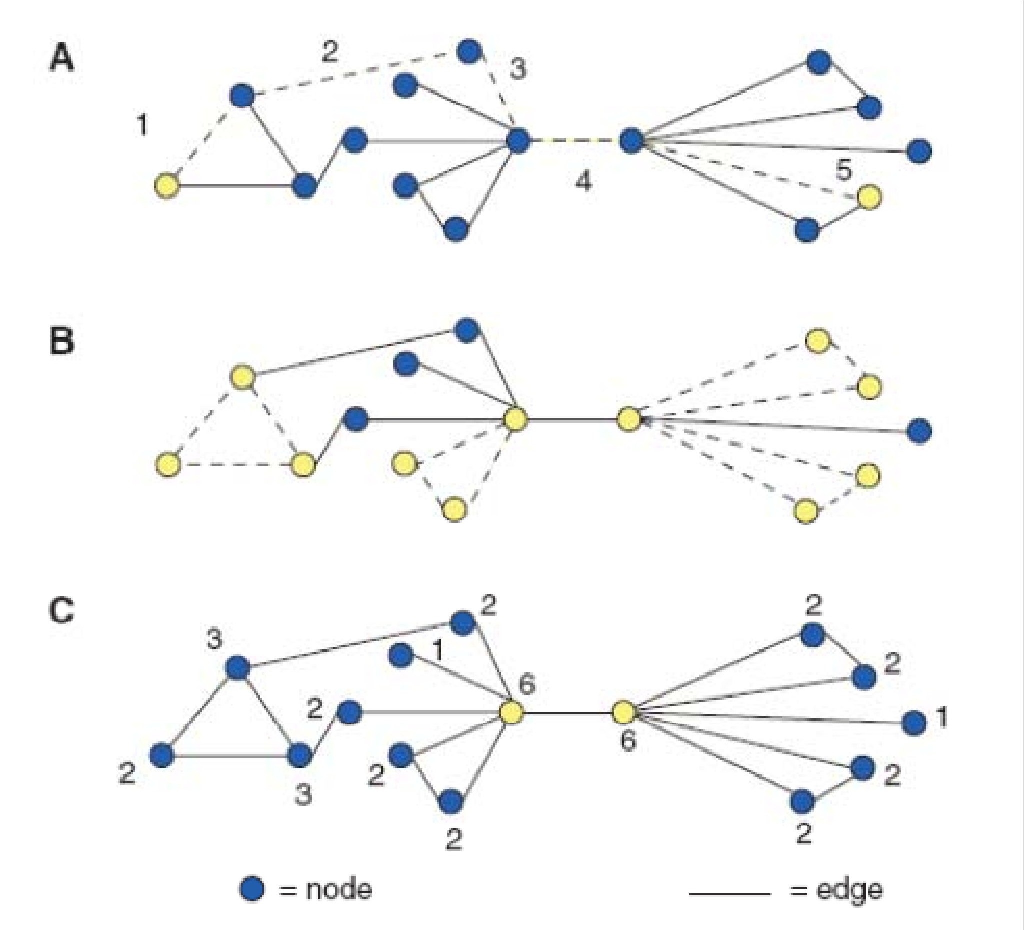
Path length

Efficiency

Clustering

Degree

Hubs

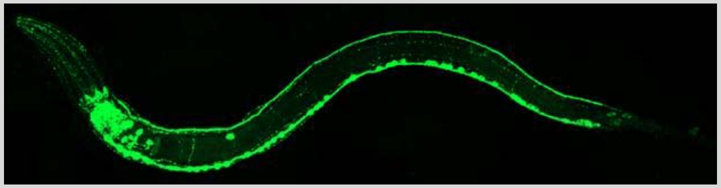


Bassett & Bullmore (2006) *Neuroscientist*

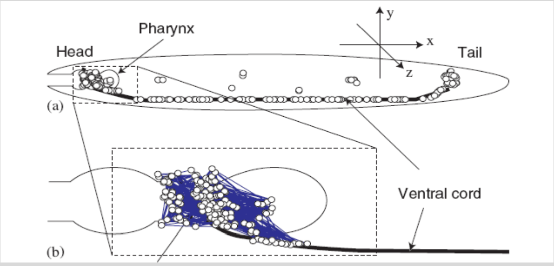
Topology: the study of properties that are preserved under continuous deformation of objects

The small world of the worm's brain

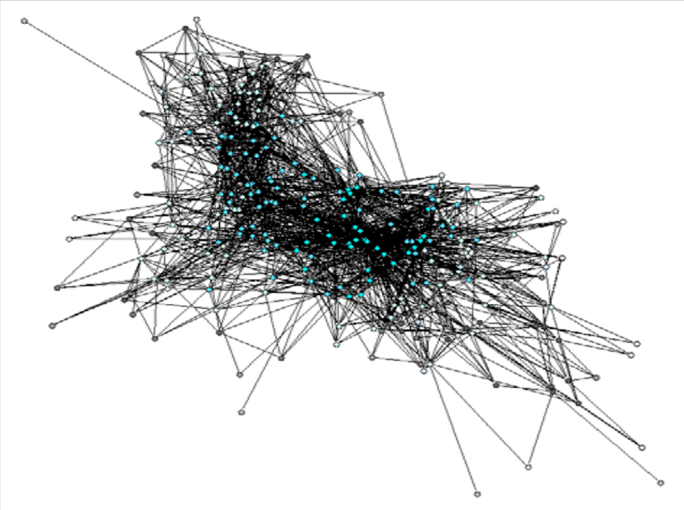
Caenorhabditis elegans



Anatomy (277 neurons, 7000 synapses)

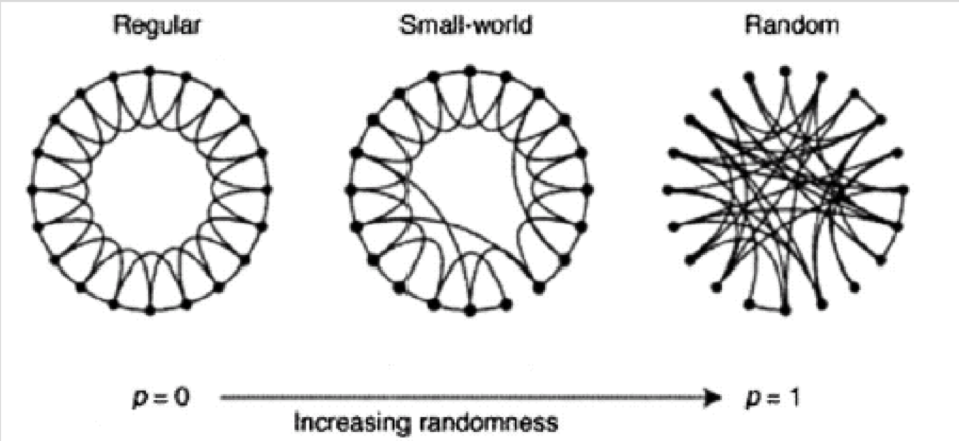


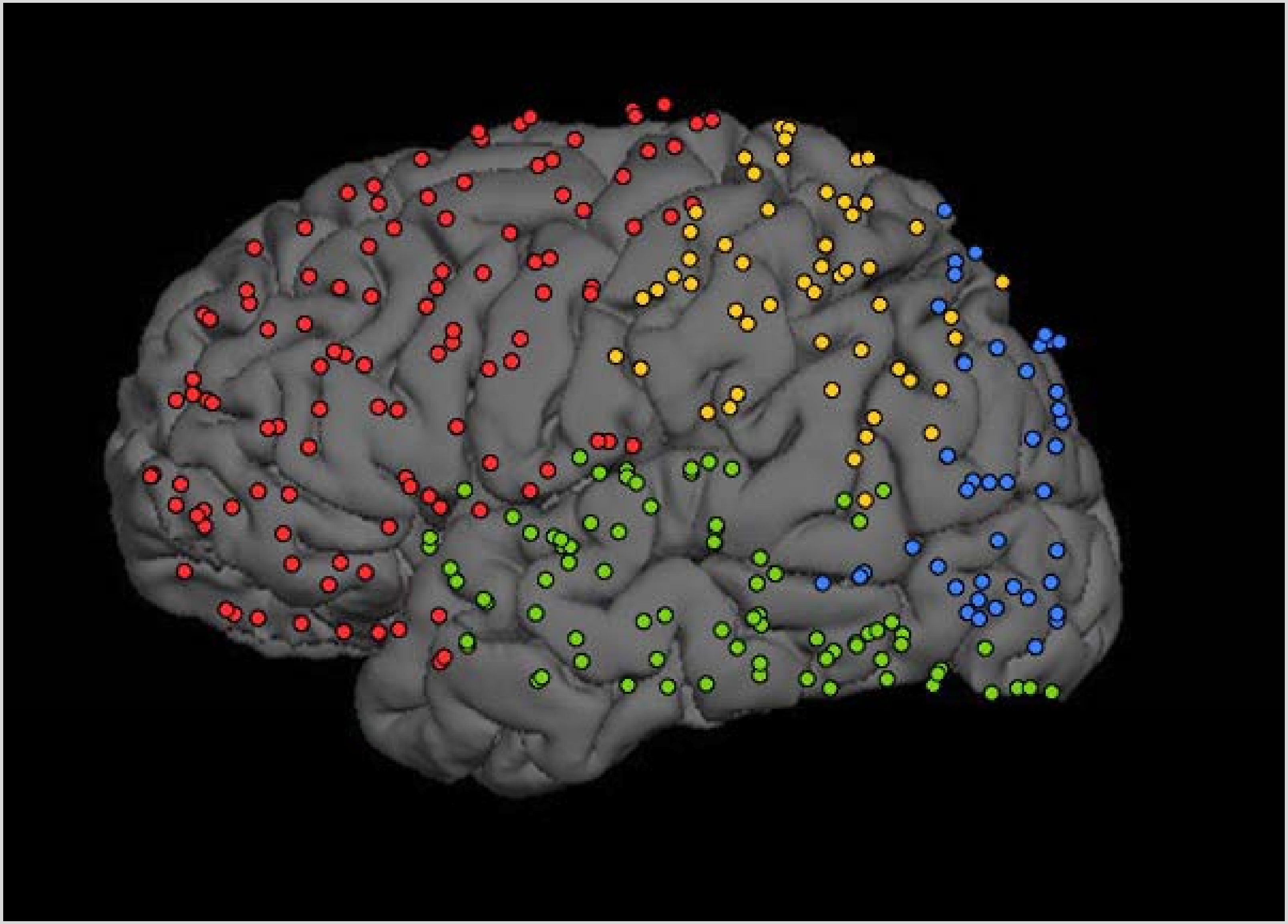
Topology (277 nodes, 7000 edges)



- Small-world
  - *High clustering or cliquishness of connections between neighboring nodes*
  - *Short path length or high efficiency of communication between any pair of nodes*
- Cost-efficient
  - *46% maximum efficiency of information transfer for about 4% maximum connection cost*

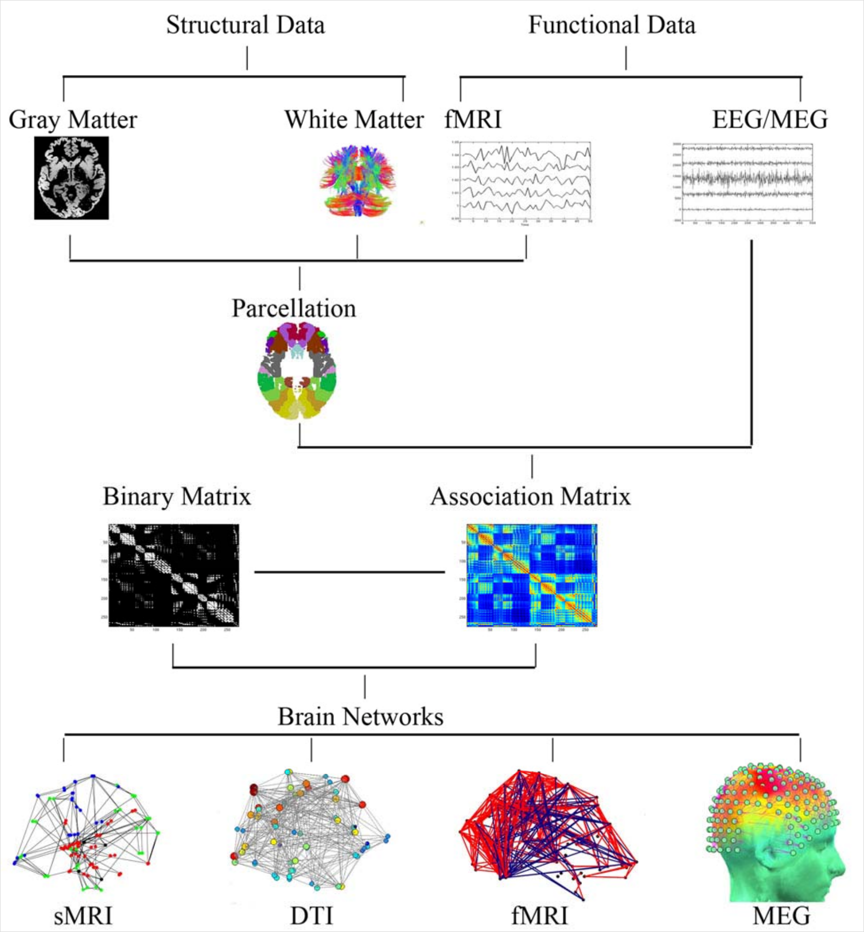
Watts & Strogatz (1998) *Nature;* Latora & Marchiori (2001) *Phys Rev Lett*





Vertes et al (2011) *YouTube*
(search on neuro tweets)

From neuroimaging to brain graphs



1. Estimate an association matrix from the data
   - What are the nodes?
   - What metric of connectivity?
2. Generate an adjacency matrix from the association matrix
   - What are the edges?
3. Measure topological properties of each graph
4. Make comparisons between graphs

Brain graphs are statistical models entailing assumptions and trade-offs which influence parameter values

Brain graph parameters make sense relativistically, not absolutely; comparison between graphs is not trivial

Bassett & Bullmore (2010) *Curr Op Neurol;* Bullmore & Bassett (2011) *Annu Rev Clin Psychol*

Many network properties are conserved across many scales and kinds and species of brain graphs

Small worldness

- high clustering
- short path length or high efficiency

Cost-efficiency

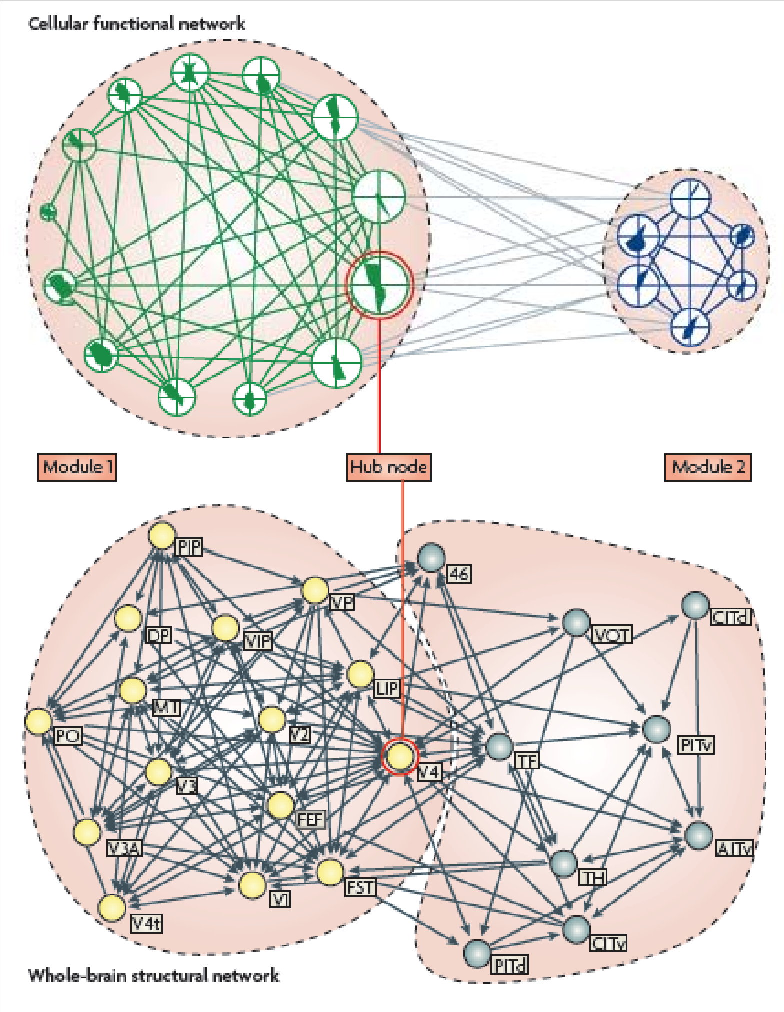
- high efficiency of information transfer for relatively low connection cost

Hub nodes

- fat-tailed degree distributions

Modularity

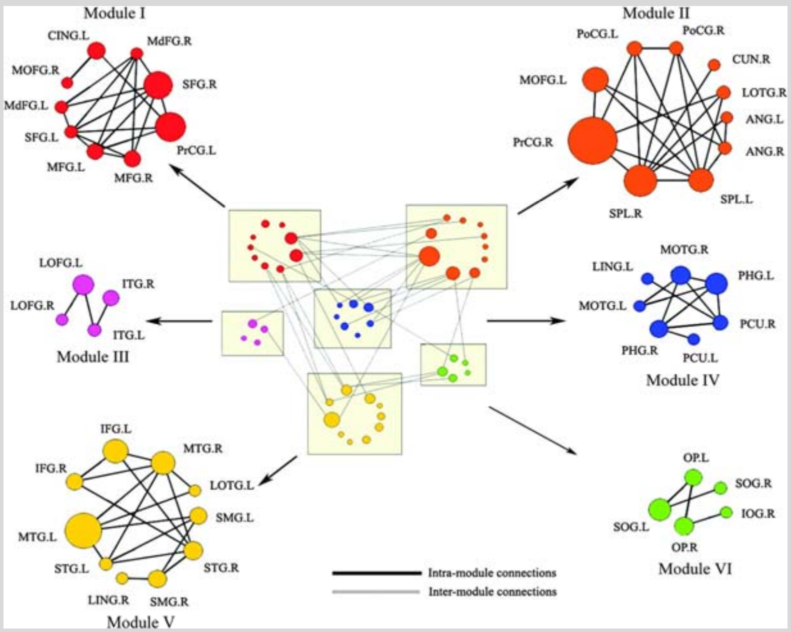
- nodes are more densely connected to other nodes in the same module than to nodes in other modules

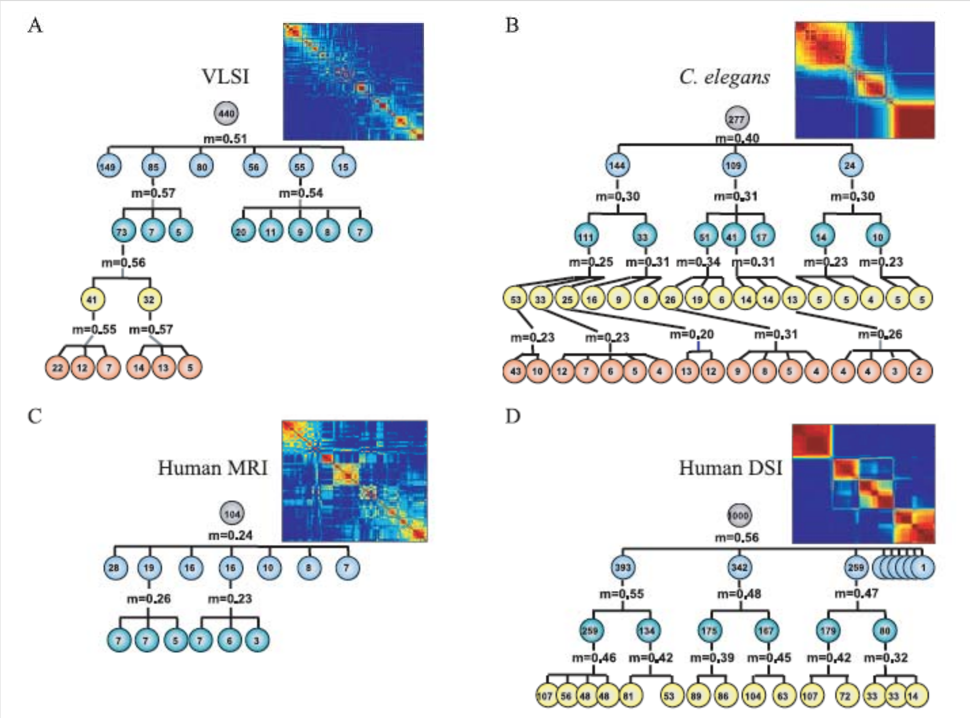


Bullmore & Sporns (2009) *Nat Rev Neurosci*

Sporns et al (2007) *PLoS ONE;* Yu et al (2008) *Cereb Cortex;* Meunier et al (2010*) Front Neurosci*

Human brain graphs and other information processing networks are hierarchically modular



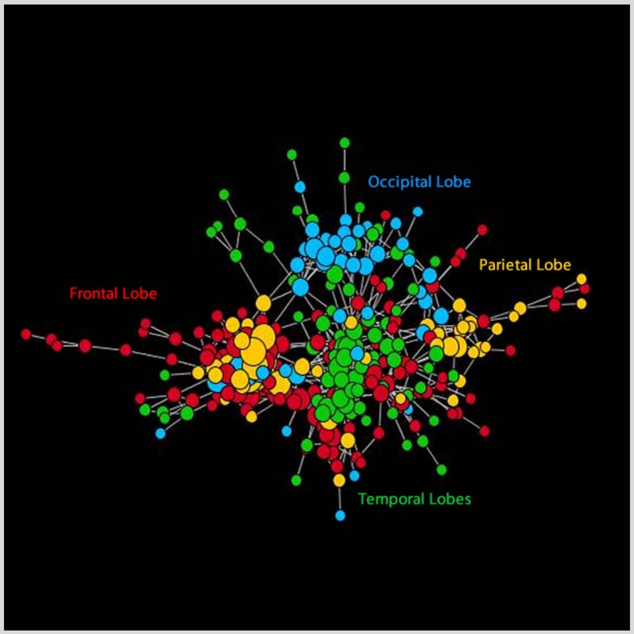


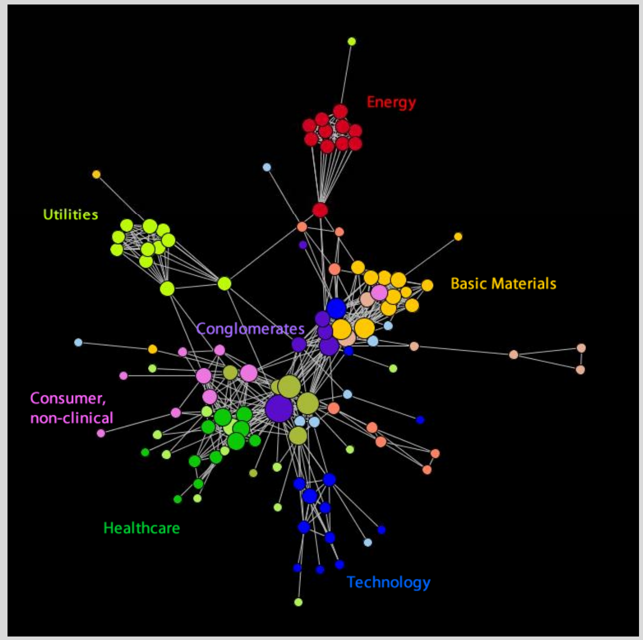
Nodes in the same module are often, but not always, anatomical as well as topological neighbours: so intra-modular edges will be shorter distance than inter-modular edges

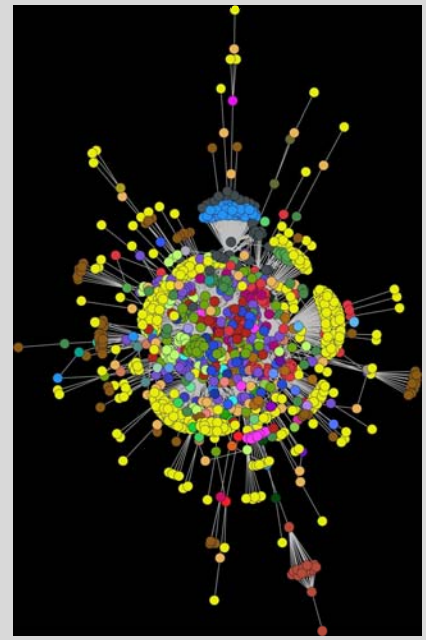
Brain graphs typically have modules within modules

Meunier et al (2010) *Front Neurosci*; Bassett et al (2010) *PLoS Comp Biol;* Chen et al (2008) *Cereb Cortex*

What’s special and what’s universal about human brains compared to other information networks?





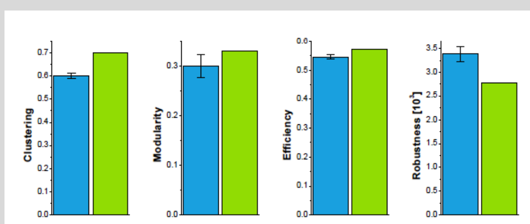


Human Brain Network
Resting state FMRI

Economic Network
New York Stock Exchange

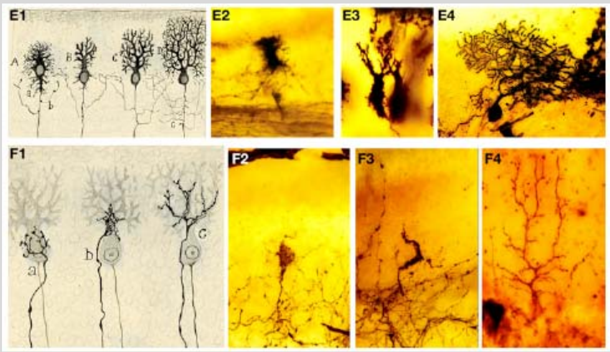
Social Network
Twitter #gadaffi

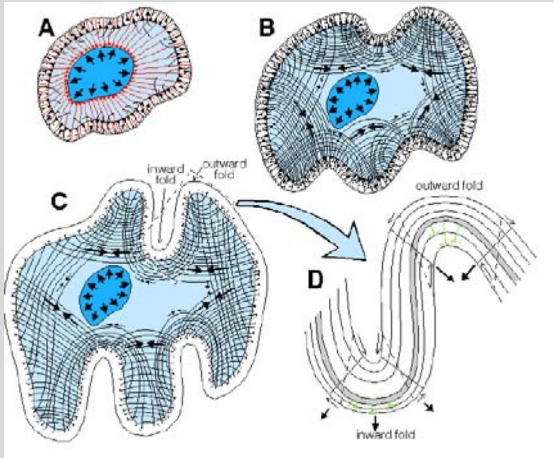
Blue = Brain
Green = Market

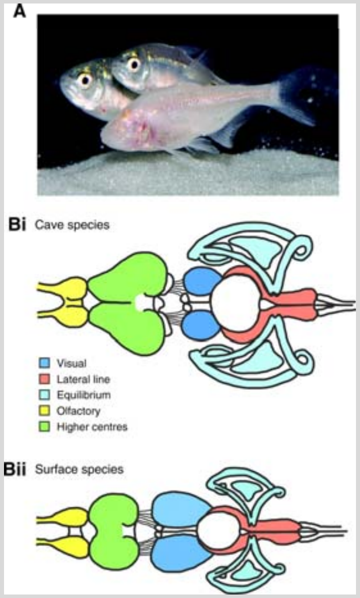


Vertes et al (2011) *Front Sys Neurosci*

“Back to anatomy”
Counting the material and metabolic costs of brain networks







Cajal’s economical principle:

“We realized that all of the various conformations of the neuron and its various components are simply morphological adaptations governed by laws of conservation for time, space, and material.”

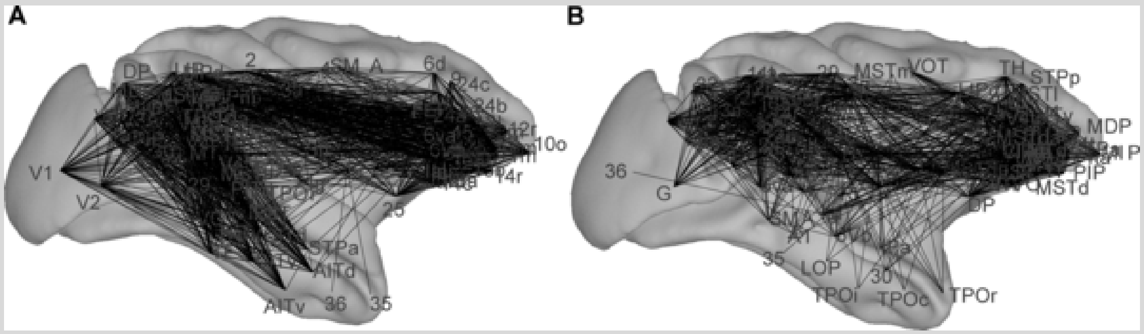
Increasing awareness also of the metabolic or energy costs of the nervous system and the biological drive to control metabolic as well as material costs of brains

Van Essen (1997) *Nature*
Niven & Laughlin (2008) *J Exp Biol*
Garcia-Lopez (2010) *Front Neuroanatomy*

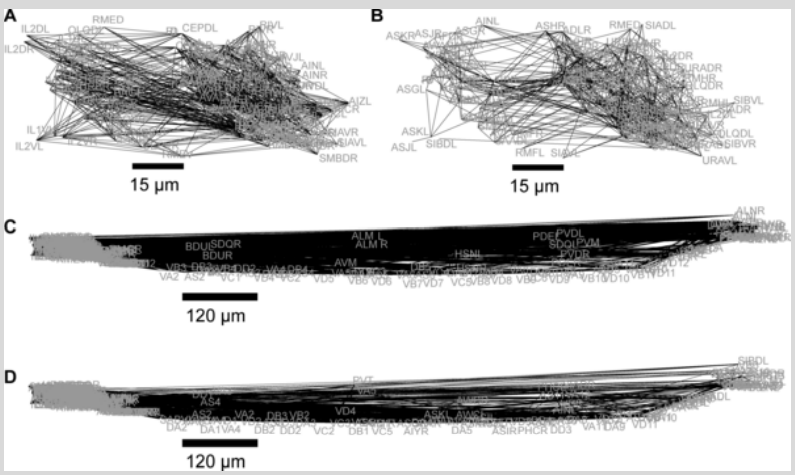
Brain networks are economically wired but do *not* strictly minimise wiring cost

Original

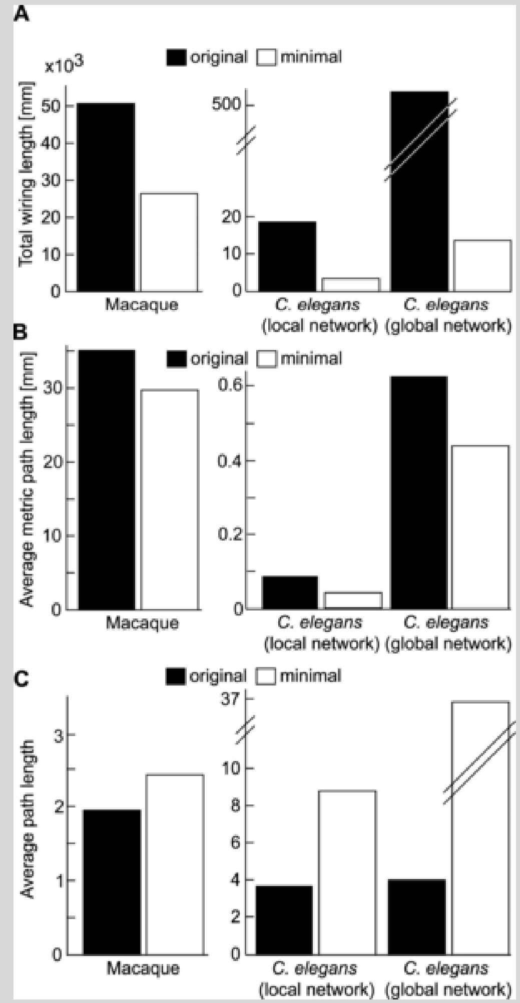
Minimal



Macaque

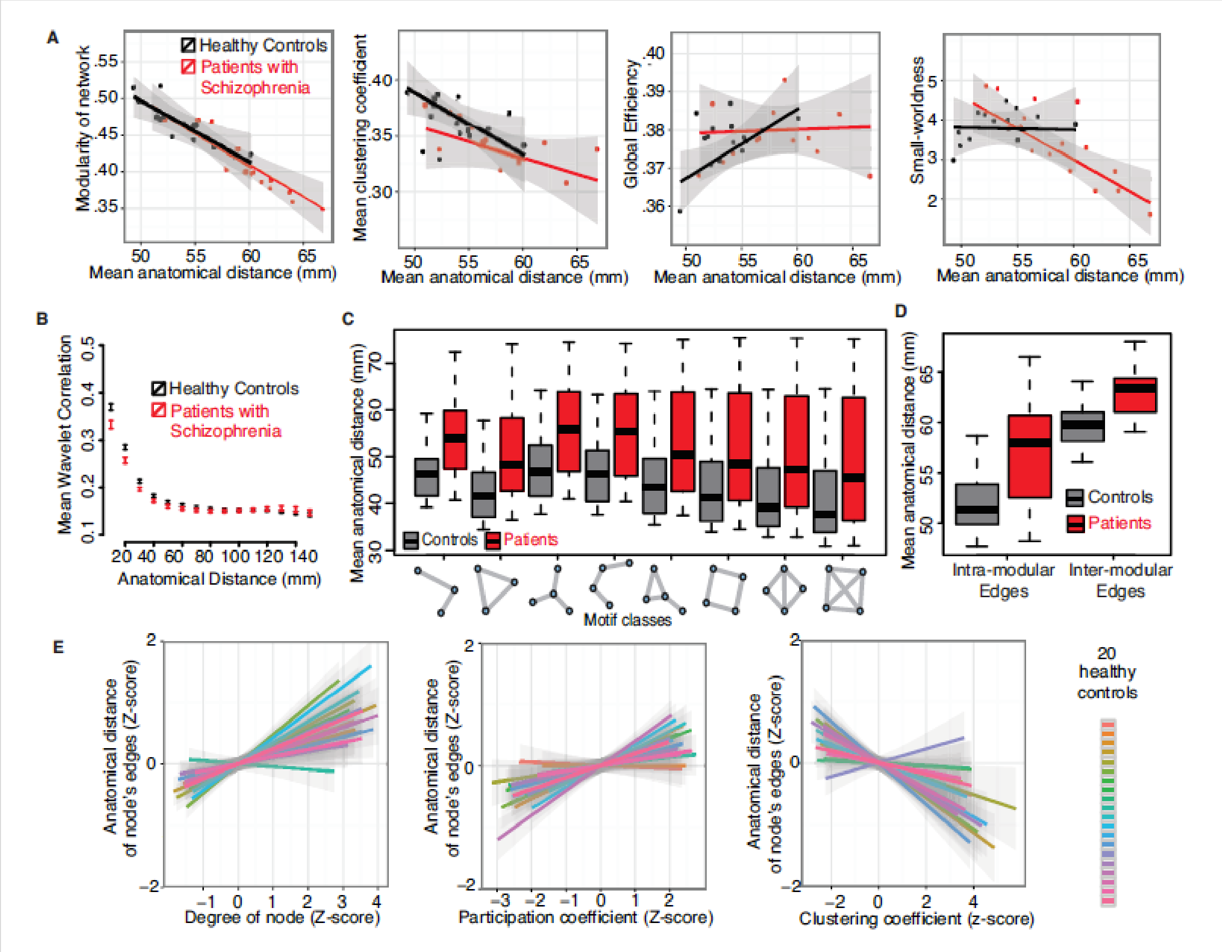


C. elegans



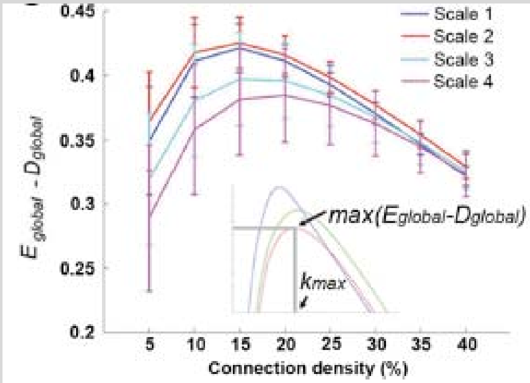
Kaiser & Hilgetag (2006) *PLoS Comp Biol*

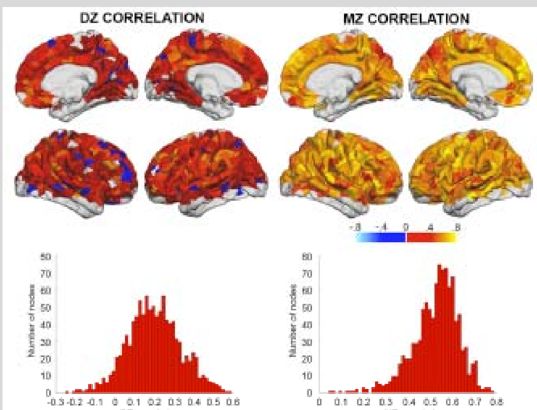
Trade-offs between connection distance and topology in human brain networks

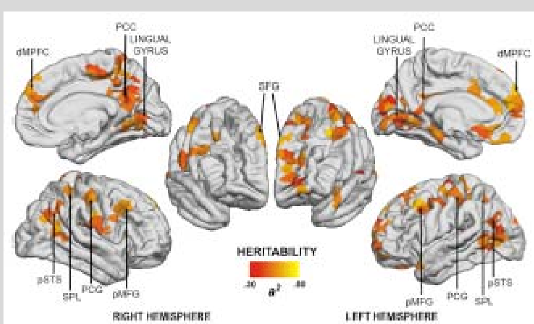


Alexander-Bloch et al (2011) *in review*

Cost-efficiency and its heritability in human brain networks



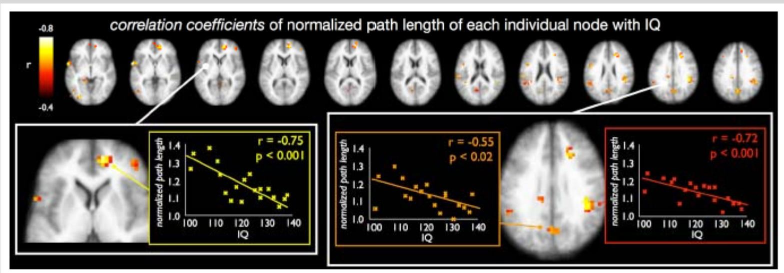




- If brain networks had been selected by competitive criteria of minimising cost and maximising efficiency we might predict that cost-efficiency is heritable
- Trade-off between topological efficiency and "connection cost" (Euclidean distance between functionally connected regions) was measured in 16 MZ and 13 DZ twin pairs
- Global cost-efficiency was heritable ~0.6 and nodal cost-efficiency was heritable ~0.8 in symmetrical cortical regions, including DMN components

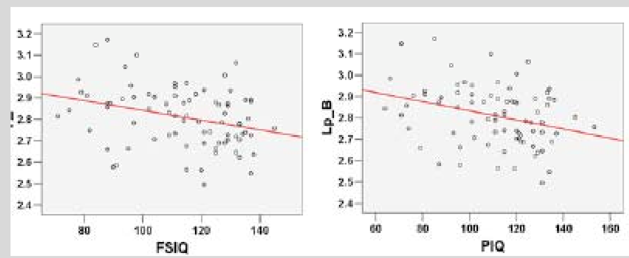
Fornito et al (2011) *J Neurosci*

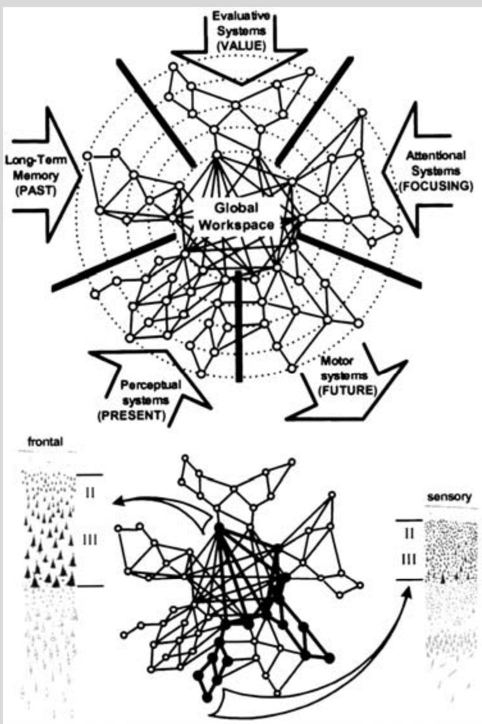
Expensive, long-range integrative connections may be "worth it" for extra cognitive capacity



- Greater efficiency (or shorter path length) of human brain networks is correlated with higher IQ

Van den Heuvel et al (2009) *J Neurosci*; Li et al (2009) *PLoS Comp Biol;* Bassett et al (2010) *PLos Comp Biol*;





- Global (neuronal) workspace theory predicts integrative networks will be required for conscious, effortful processing

Dehaene et al (1998) *Proc Natl Acad Sci*

Baars (1993) *A cognitive theory of consciousness*

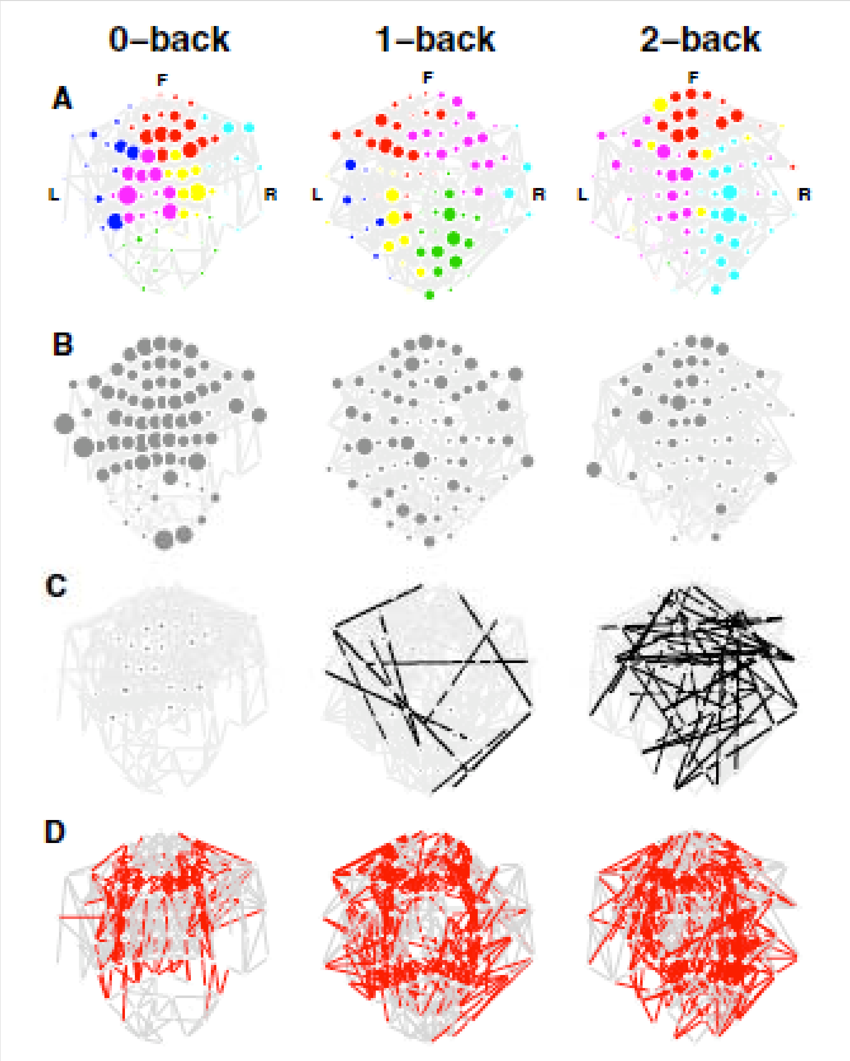
Working memory load "breaks modularity" and drives workspace configuration of functional brain networks

Modules

Clustering

Long-distance edges

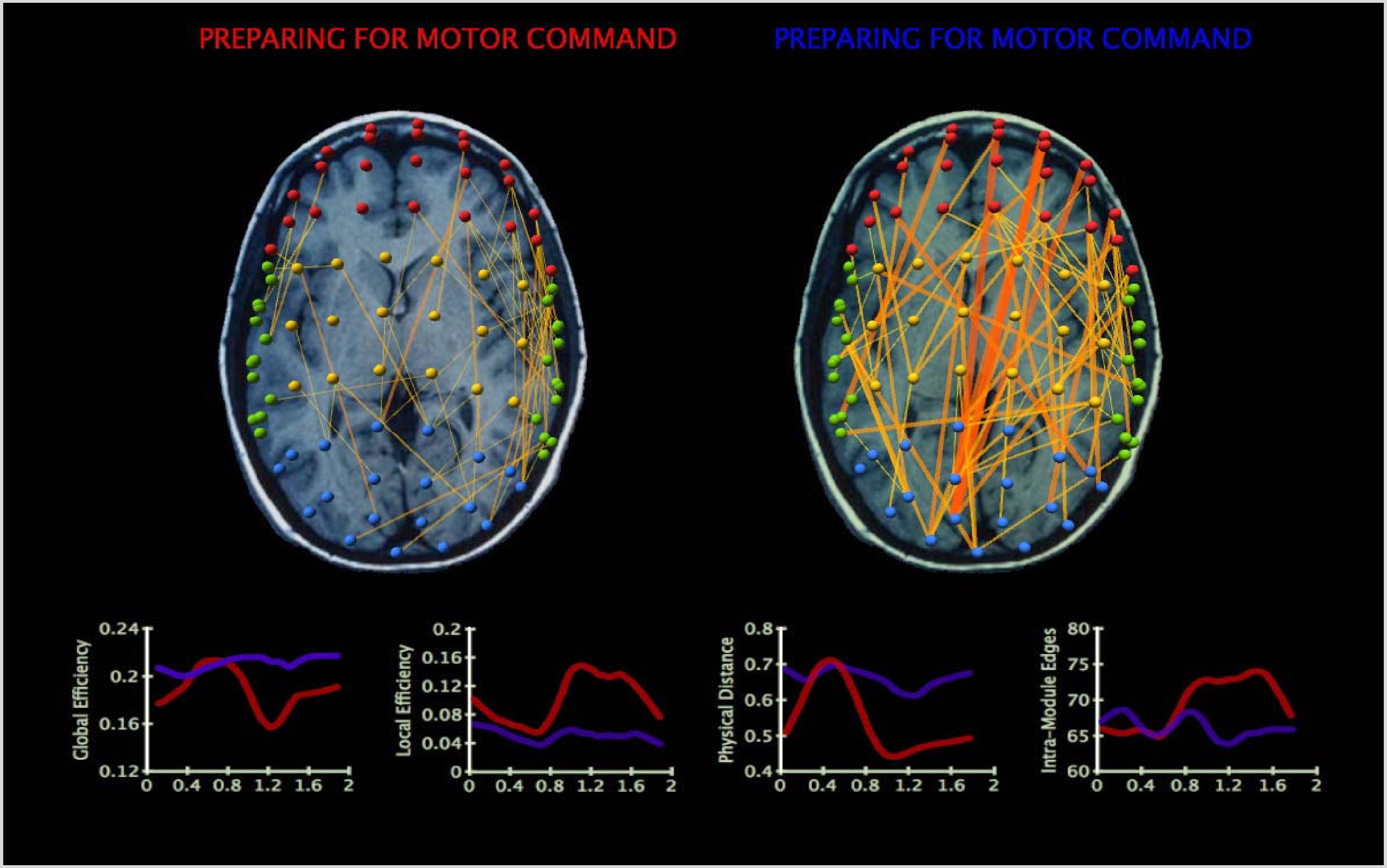
Inter-modular edges



β-band frequency networks recorded using MEG in healthy volunteers performing N-back working memory task

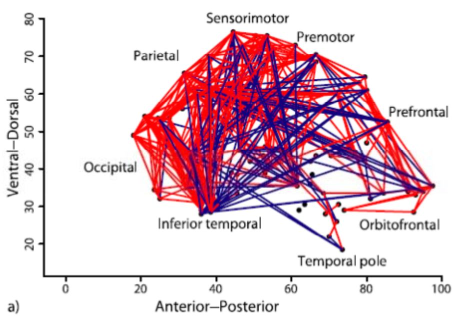
Kitzbichler et al (2011) *J Neurosci*

Changes in cognitive load are associated with rapid reconfiguration of network topology and connection distance



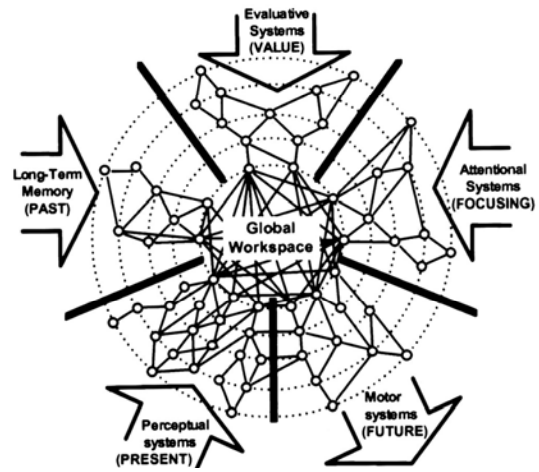
Kitzbichler et al (2011) *J Neurosci*

Cartoon interpretation of economical small-world architecture in terms of cognitive processes



High efficiency
Short path length
(Higher cost)

High clustering
Modularity
(Lower cost)



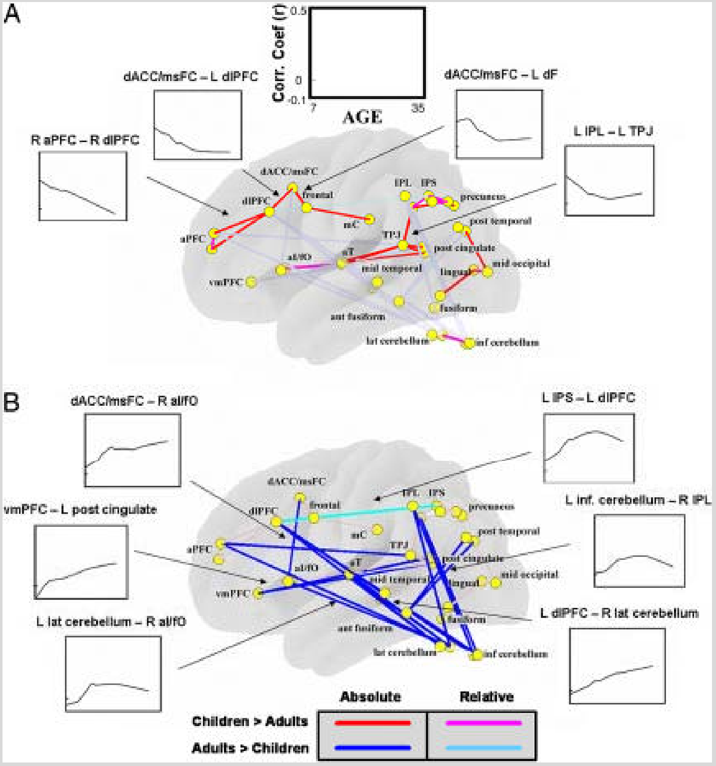
Integrated processes

General – eg "executive"
Isotropic (IQ)
Distributed
Conscious
Effortful

Segregated processes

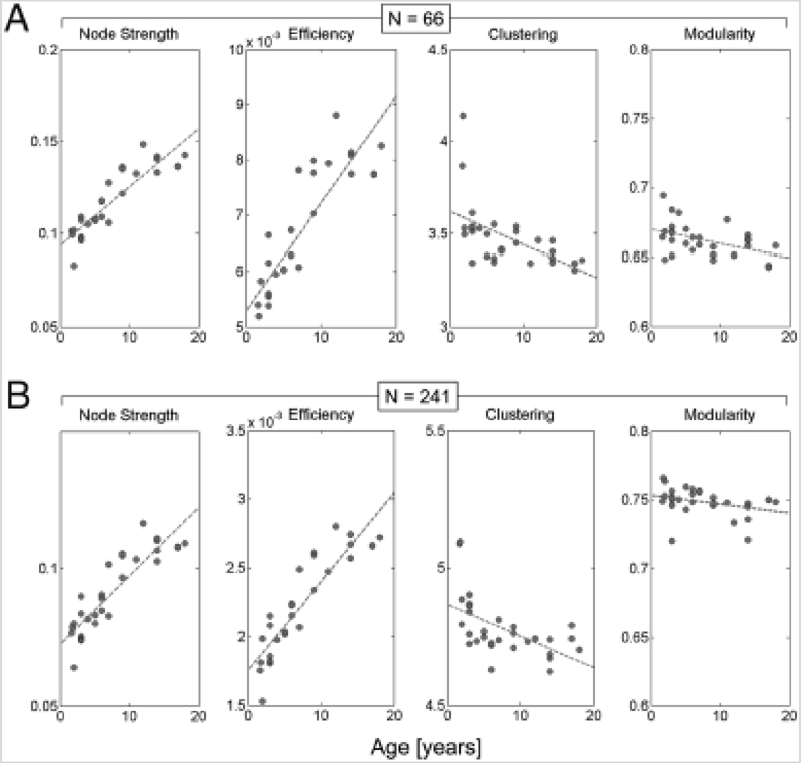
Specialised – eg face vision
Encapsulated
Localised
Unconscious
Automatic

Normal brain development is associated with changes in network efficiency and connection cost



Functional MRI networks

Connection distance increases with age



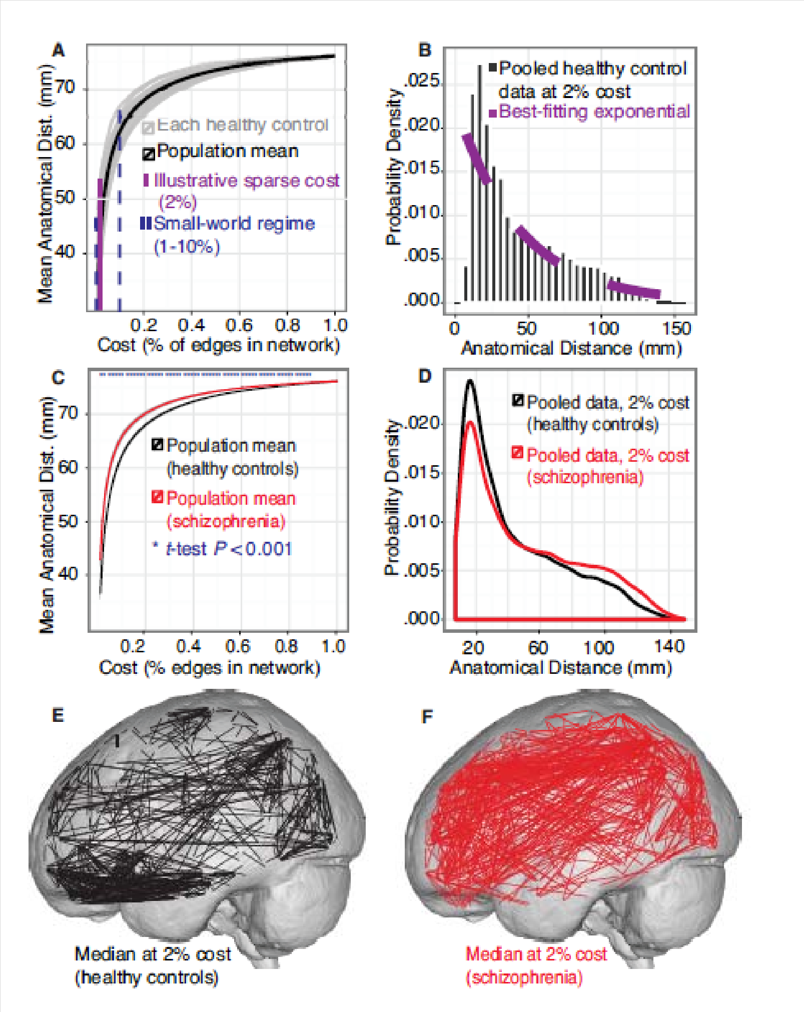
Anatomical DTI networks

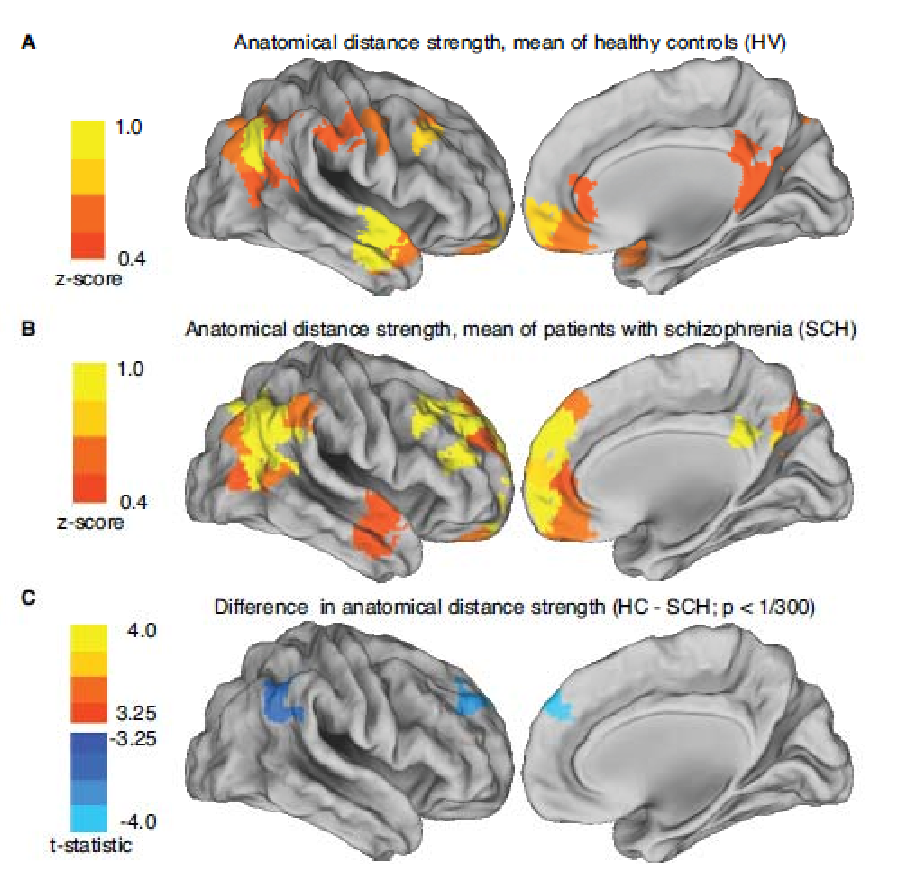
Topological efficiency increases with age

Fair et al (2007) *Proc Natl Acad Sci*

Hagmann et al (2010) *Proc Natl Acad Sci*

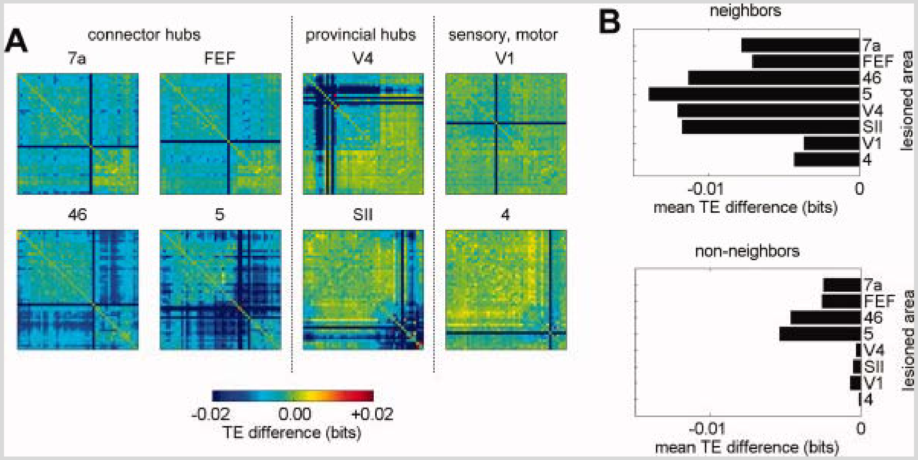
Functional networks and connector hubs are less parsimoniously connected in schizophrenia





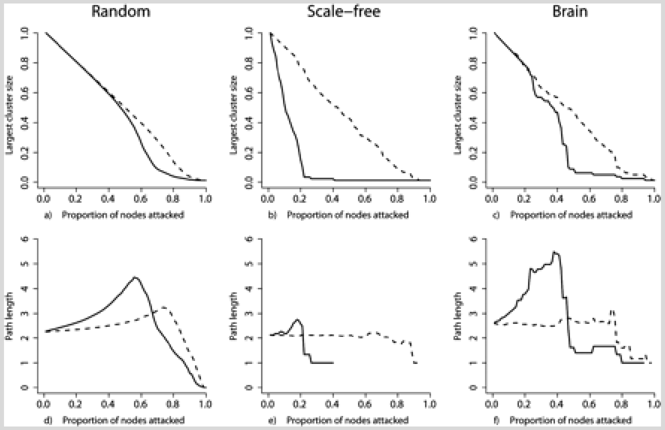
Alexander-Bloch et al (2011) *in review*

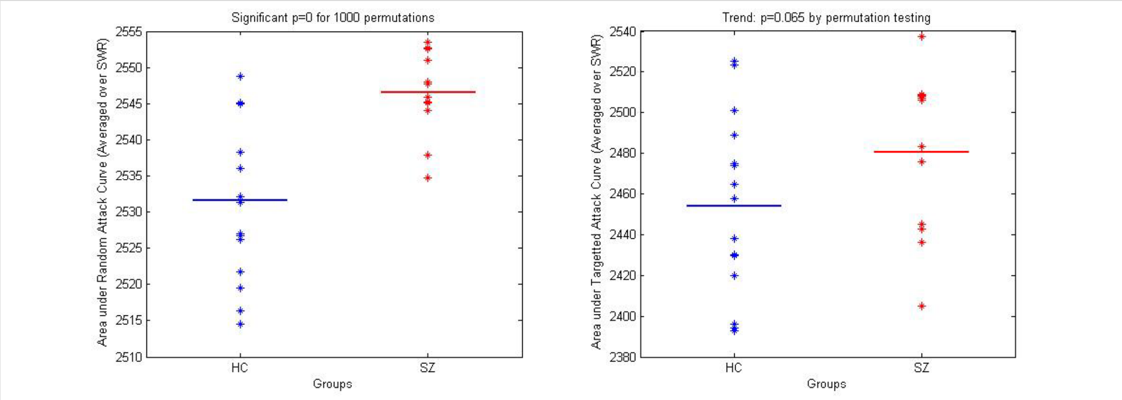
What could be *good* about the schizophrenia connectome?



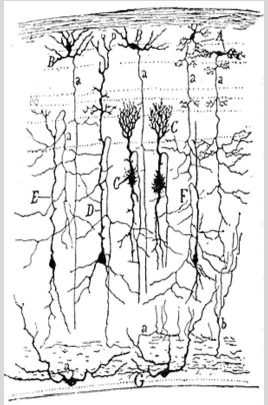
Connector hubs add value but are also points of vulnerability if the network is attacked or lesioned

Schizophrenic brain networks have greater robustness, perhaps representing greater resilience against pathological attack

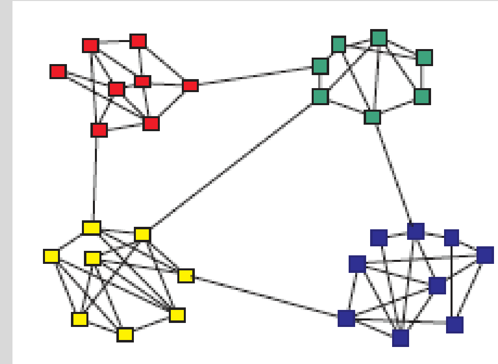




Achard et al (2006), *J Neurosci;* Honey & Sporns (2008) *Hum Brain Mapp*; Lynall et al (2010) *J Neurosci*; Vertes et al (2011), *in review*



Conclusions



- Brains make adaptive value at some physical cost
- In brain networks, the topological properties that add the most adaptive value are often the most costly
- Like profitable businesses, brain networks negotiate an economic trade-off between adding value and controlling production costs
- Brain networks have complex topology embedded in anatomical space
  - Long distance connections, often between modules, are important for efficiency of information transfer and formation of workspaces
  - Topological properties such as efficiency and robustness have adaptive value in terms of supporting effortful cognitive processes and resilience to adverse perturbation
  - Brains can rapidly and slowly reconfigure themselves in terms of connection distance and topology
  - Trade-offs between wiring cost and topological efficiency have been demonstrated directly in C elegans and, less directly, in humans
  - It is plausible that an economical trade-off between topological and spatial properties is an important criterion for developmental and evolutionary selection of brain networks
  - Brain disorders impacting on cognitive function have abnormal network properties, spatially and topologically, suggesting that neurological and psychiatric symptoms arise especially when the more costly components of networks are lesioned or develop abnormally
- An economical model of brain network organization is not yet refuted and could benefit from further testing
  - More precise characterization of wiring cost in human networks
  - More studies of brain networks in experimentally tractable animal models
  - More computational modeling of network selection by economic criteria
  - More comprehensive and larger-sample mapping of network abnormalities across a range of brain disorders

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