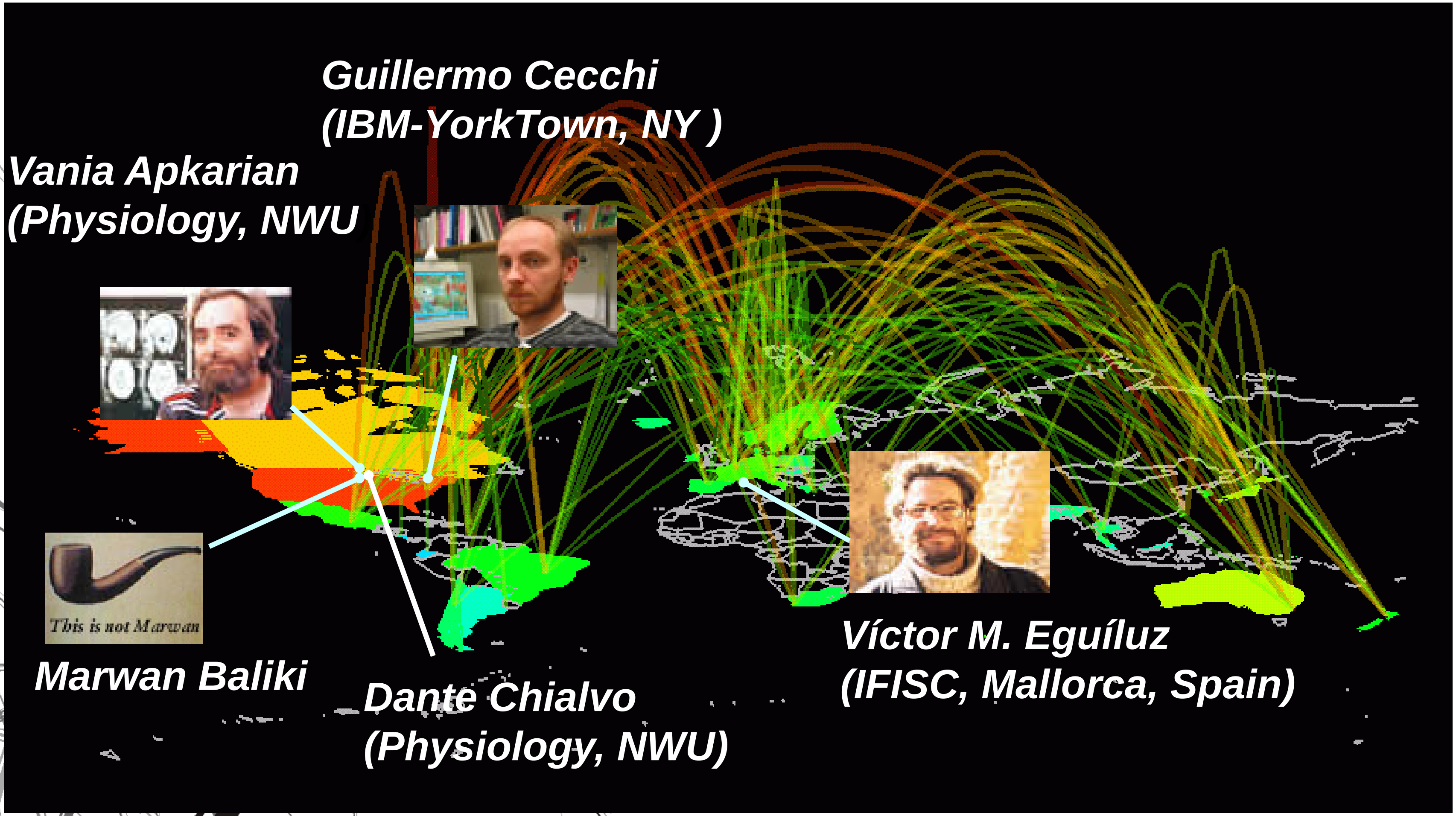
Scale-free Brain Functional Networks



victor@ifisc.uib-csic.es
ifisc.uib-csic.es/victor

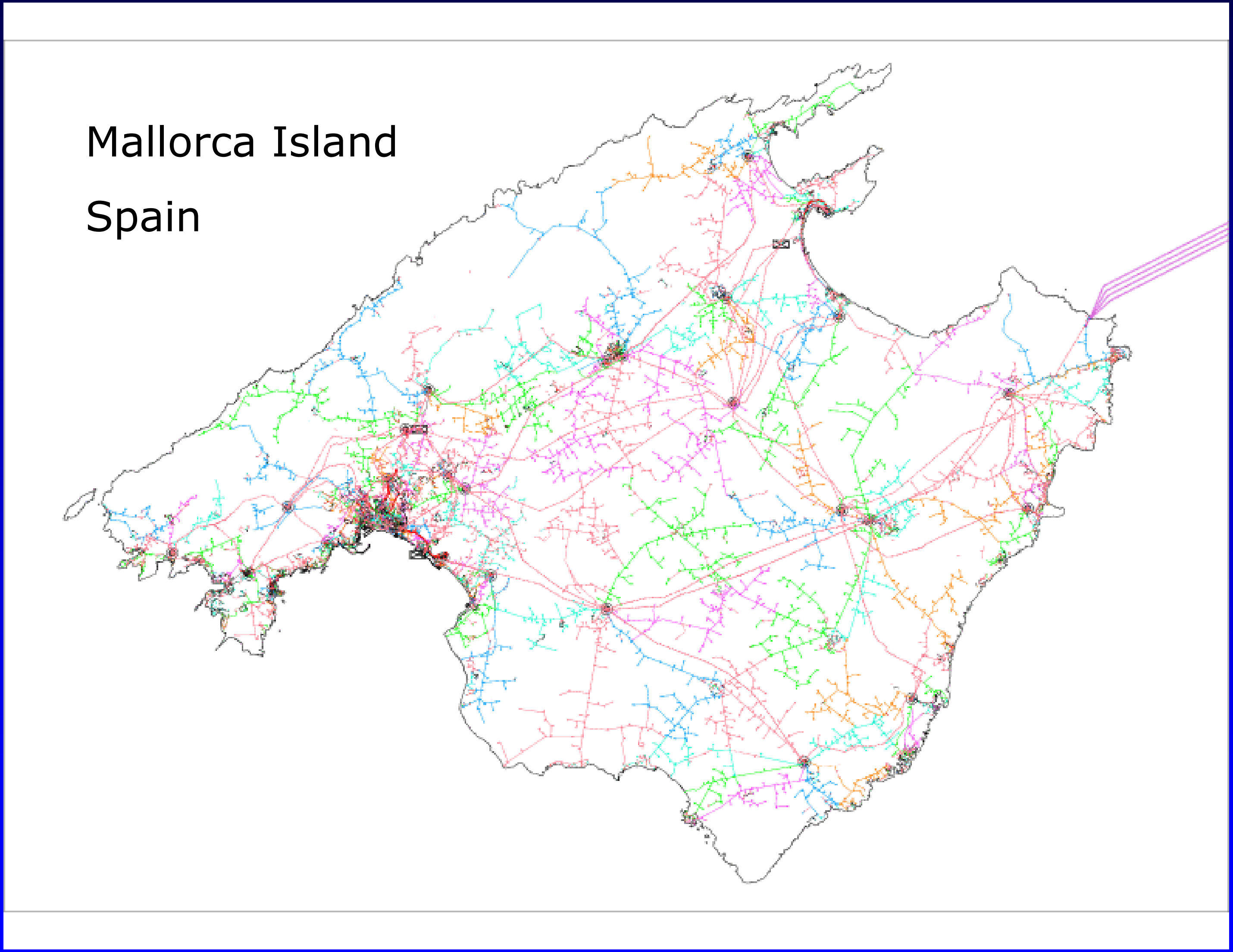
IFISC

Eguíluz et al, PRL 94, 018102 (2005)

Plan

- Motivation: Networks & Brain
- How to get functional networks from fMRI
- Characterization of brain functional networks
- Conclusions and open problems…

Power grid



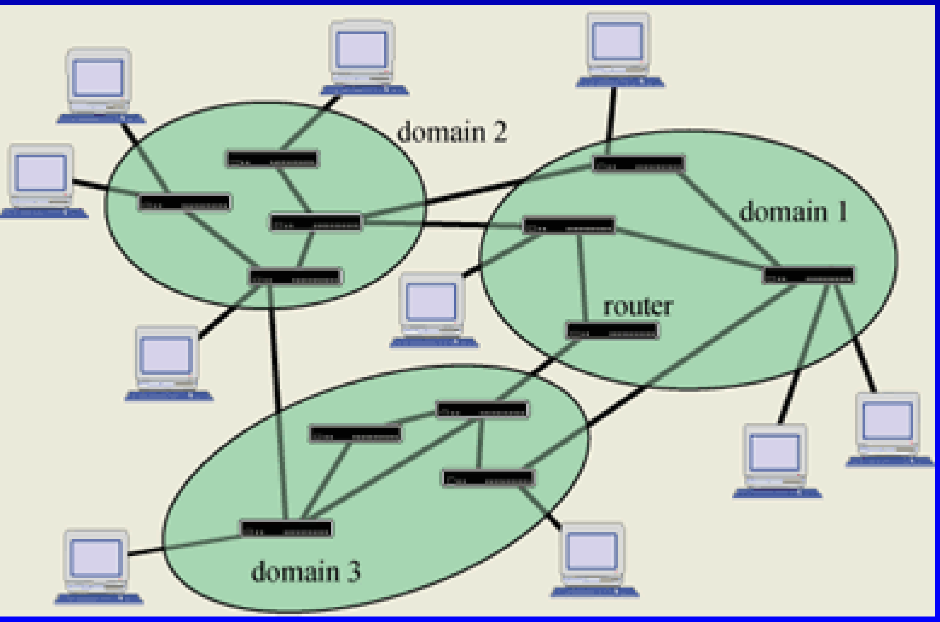
Scire et al, EPL (2005)

Source:
Planificació i Qualitat de Xarxa,
GESA-ENDESA
Spain

Network:
set of nodes connected by links

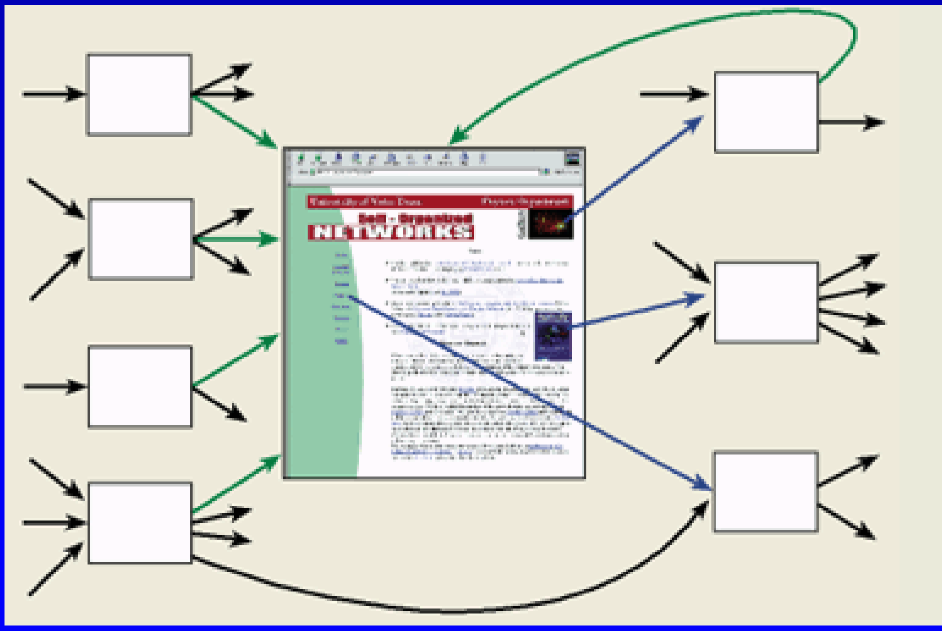
Internet

Nodes: computers, routers, …
Links: physical connections

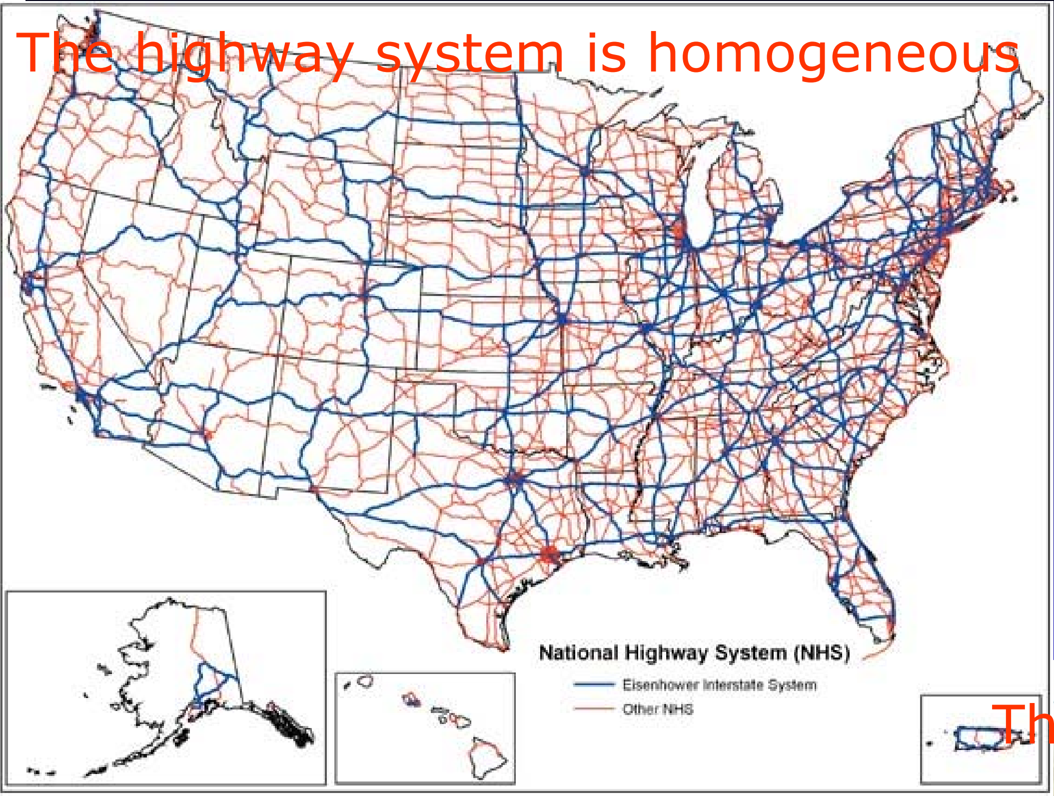


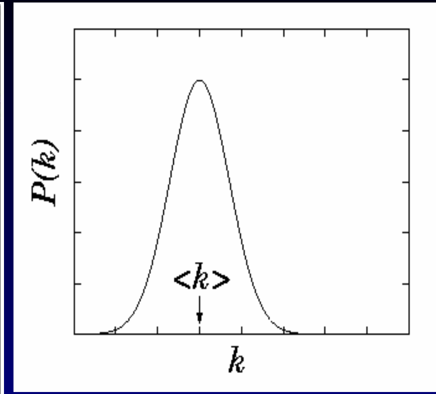
WWW

Nodes: web pages
Links: links



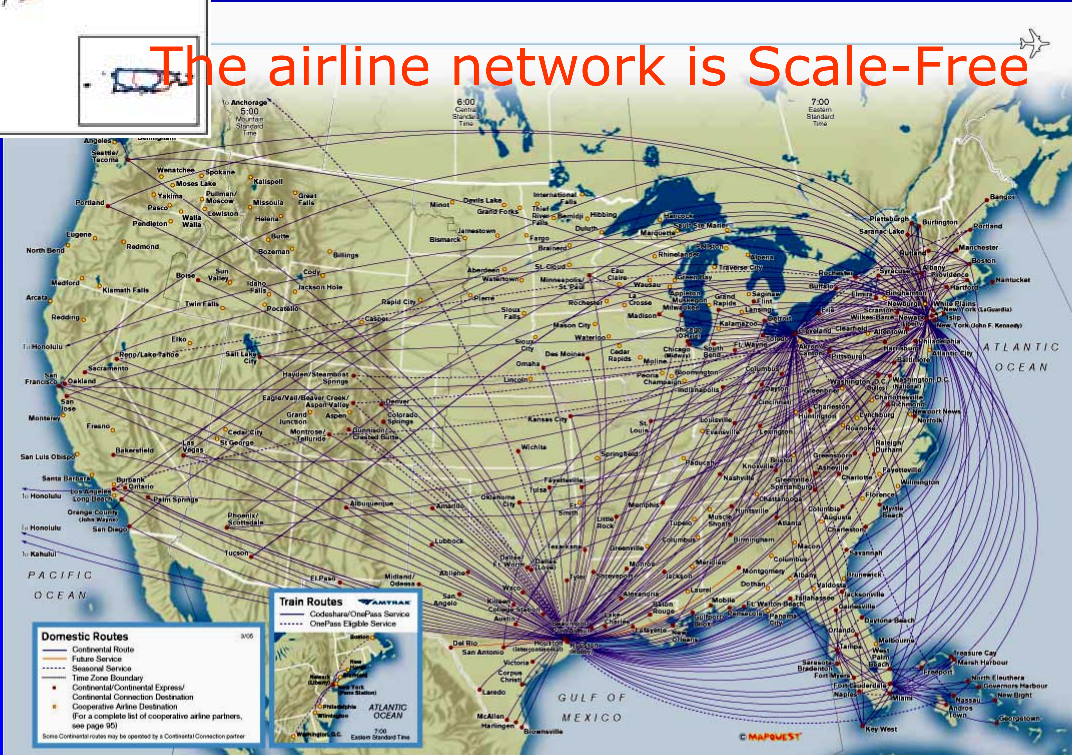
The highway system is homogeneous



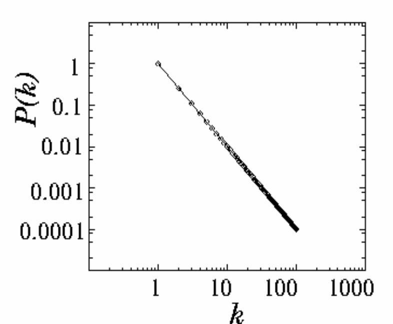


The consequence of deleting a node (city or airport) is dramatically different in these two cases.

The airline network is Scale-Free

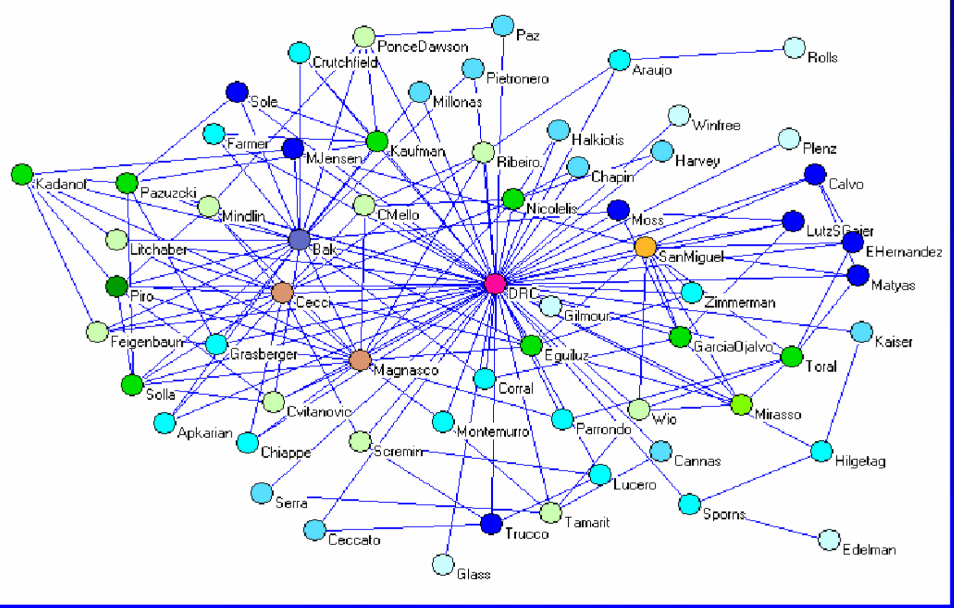


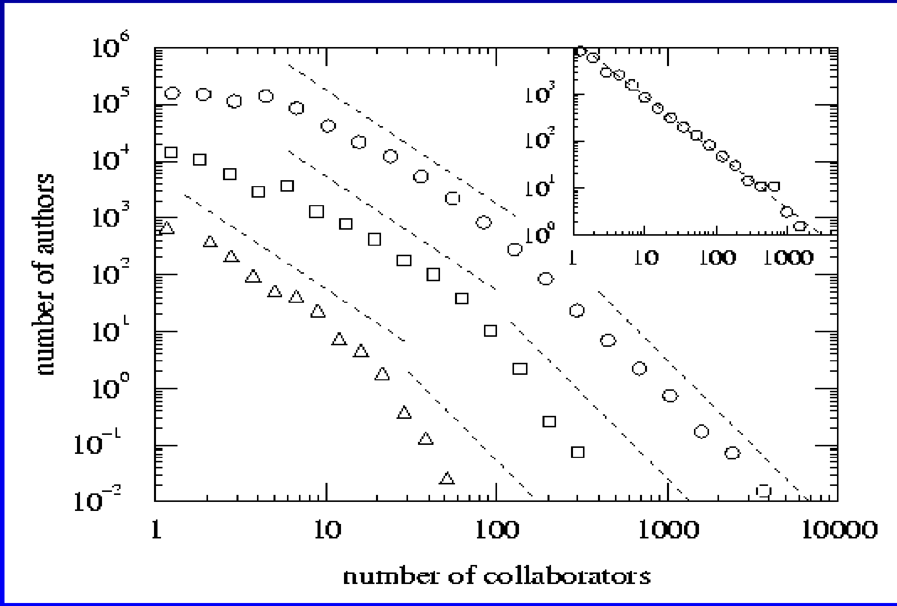
Scale-free nets, in terms of resistance to damage: are Robust (to random) but Fragile (to targeted attack).



Co-authorship of scientific papers

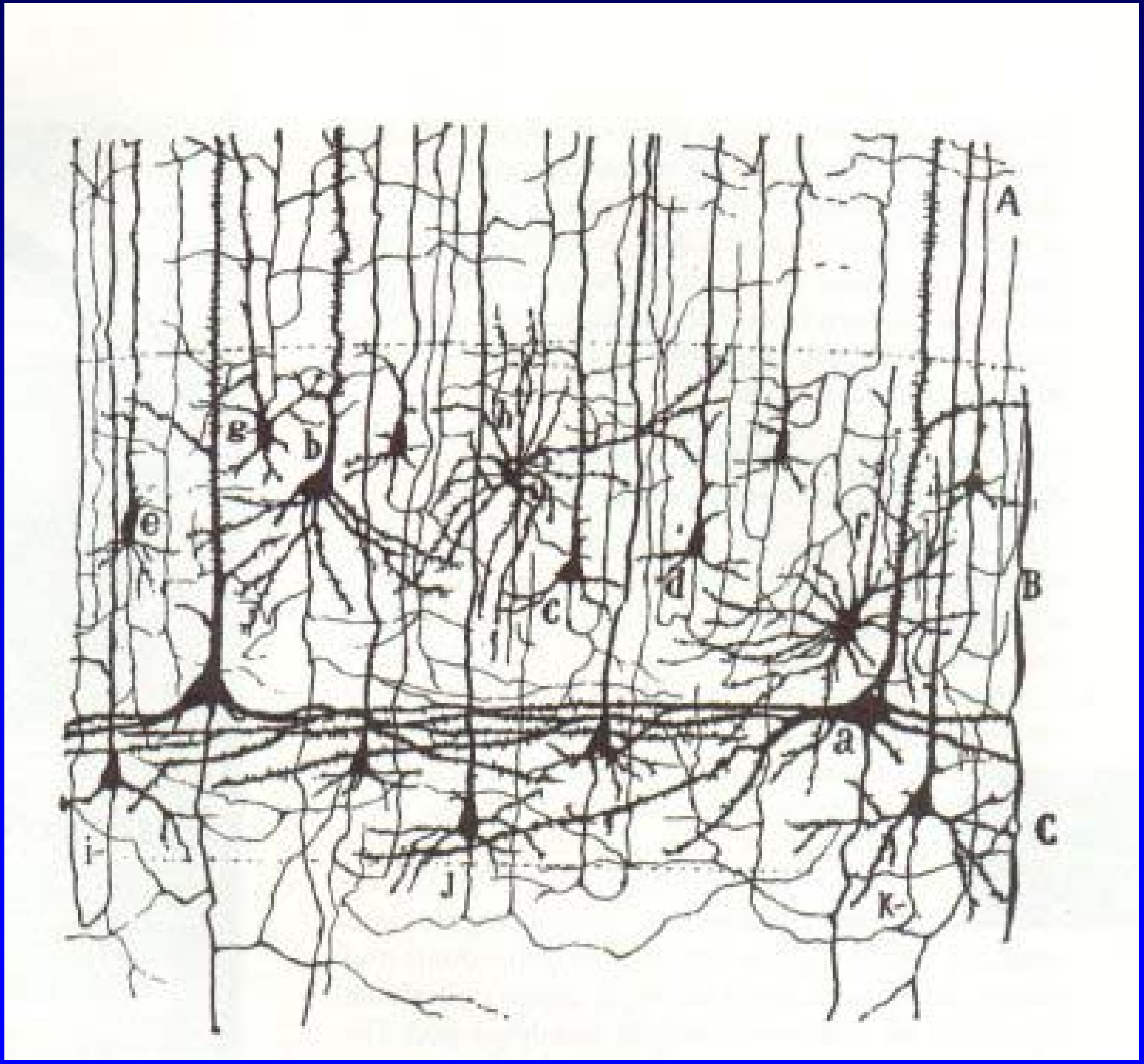
Nodes: scientists (authors)
Links: write a paper together





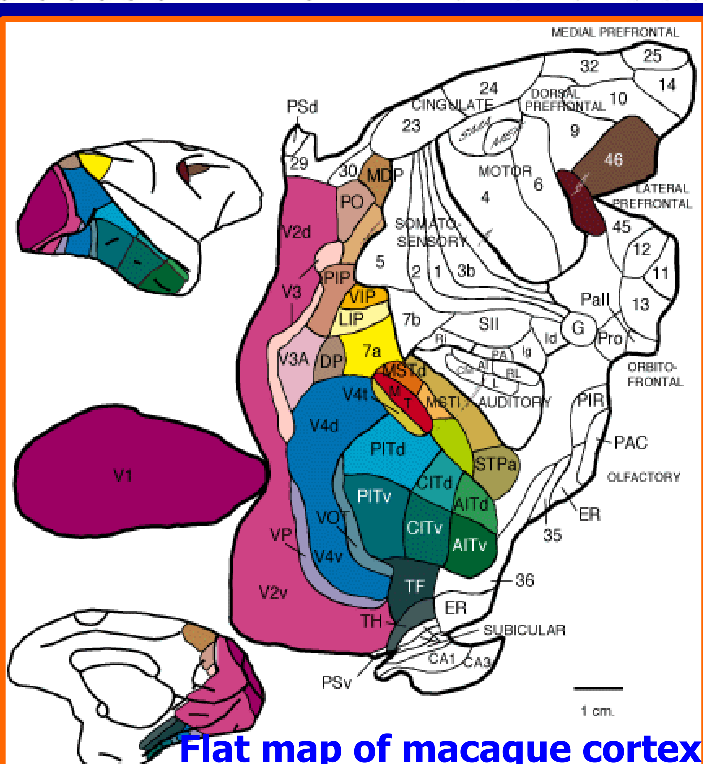
(Newman, 2000, H. Jeong et al 2001)

… and the brain



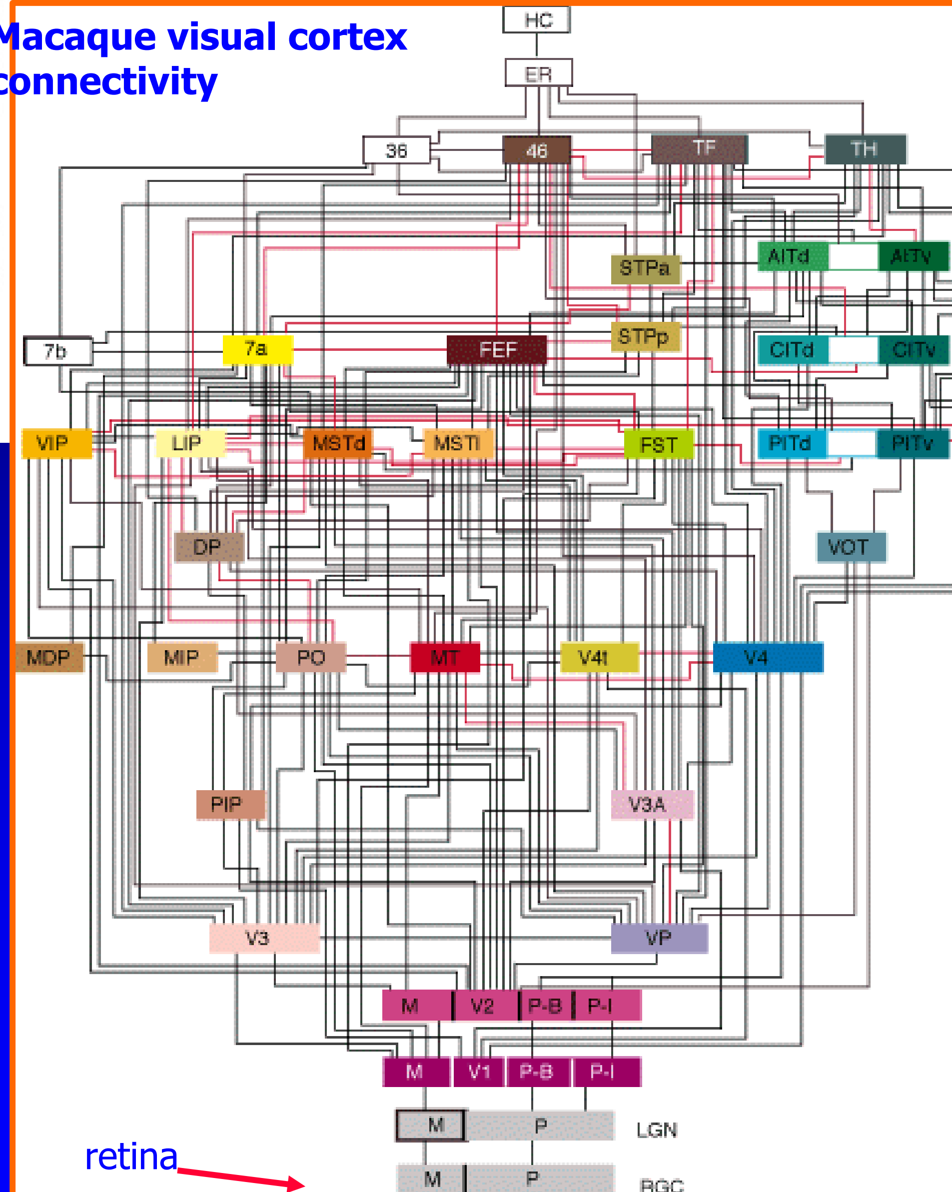
“In catalogue” cortical nets

	V1	V2	V3	VP	V3A	V4	VOT	V4t	MT	FST	PITd	PIT	PITv	CITd	CIT	CITv	AITd	AITv	STPp	STP	STPa	TF	TH	MSTd	MSTl	PO	PIP	LIP	VIP	MIP	MDP	DP	7a	FEF	46
V1		1	1	0	1	1	0	0	1	0	0		0	0		0	0	0	0		0	0	0	0		1	1	0	0	0					
V2	1		1	1	1	1	1	1	1	1	0		0	0		0	0	0	0		0	0	0	1	1	1	1	0	1	0					
V3	1	1			1	1	0	1	1	1	0		0	0		0	0	0	0		0	1	0	1	0	1	1	1	1	0					
VP	0	1	1		1	1	1	0	1	1	0		0	0		0	0	0	0		0	1	0	1	0	1	1		1	0					
V3A	1	1	1	1		1			1	1	0		0	0		0	0	0	0		0	0	0	1	1	1				0					
V4	1	1	1	1	1			1	1	1	1		1	1		1	0	1	0		0	1	1	0	0	0	1	1	0	0					
VOT	0	1	0	1		1					1		1																						
V4t	1		1	0		1			1	1														0	1	1									
MT	1	1	1	1	1	1		1		1	0		0	0		0	0	0	0		0	0	0	1	1		1	1	1	0					
FST	0	0	1	0	1	1		1	1			1		0		0	0	0	1			1		1	1	0	0	1	1						
PITd	0	0	0	0	0	1			0							1	1	1							0	0	0	0	0						
PIT										1														1											
PITv	0	0	0	0	0	1			0							1		1							0	0	0		0						
CITd	0	0	0	0	0	1			0				1				1	1						0	0	0	0	0	0						
CIT																																			
CITv	0	0	0	0	0	1			0				1				1	1						0	0	0	0	0	0						
AITd	0	0	0	0	0	0			0	0			1			1								0	0	0	0	0	0	0					
AITv	0	0	0	0	0	1			0	0			1			1					0	1	1	0	0	0	0	0	0	0					
STPp	0	0	0	0	0	0			0	1					1		0				1	1	1	1	1	0	0	0	0	0					
STP																																			
STPa	0	0	0	0	0	0			0								1	0	1			1	1			0	0	0	0	0					
TF	0	0	1	1	0	1			0	1			1			1	1	1	1		1			1		0	0		0	0					
TH	0	0	0	0	0	1			0				1		1		1	1	1		1			0	0	0	0	0	0	0					
MSTd	0	1	1	1	1	0		1	1	1		1		0		0	0	0	1							1		1	1						
MSTl	0	1	0	0	1	0		0	1	1	0	0	0	0		0	0	0	1							1	0		1						
PO	1					0			1	0	0		0	0		0	0	0	0		0	0	0	1	1			1	1						
PIP	1		1	1		1			1		0		0	0		0	0	0	0		0					1									
LIP	0		1	1	1	1			1	1	0		1	0		0	0	0				1	0	1	1	1			1						
VIP	0		1						1	1	0		0	0		0	0	0						1	1	1		1							
MIP	0	0	0	0	0	0			0	0	0		0	0		0	0	0						0	0	1									
MDP	0	0	0	0	0	0			0	0	0		0	0		0	0	0						0	0	1									
DP	0	0	0	0	1	1			0	1	0		0	0		0	0	0	0		0	0	0	1	1	1	1	1							
7a	0	0	0	0	0	0			0		0		0	0		0	1			1		1	1	1		1		1							
FEF	0									1					1		1		1					1	1	1		1	1						
46	0	0	0	0	0					0					1		1		1		1	1	1	0											



Flat map of macaque cortex

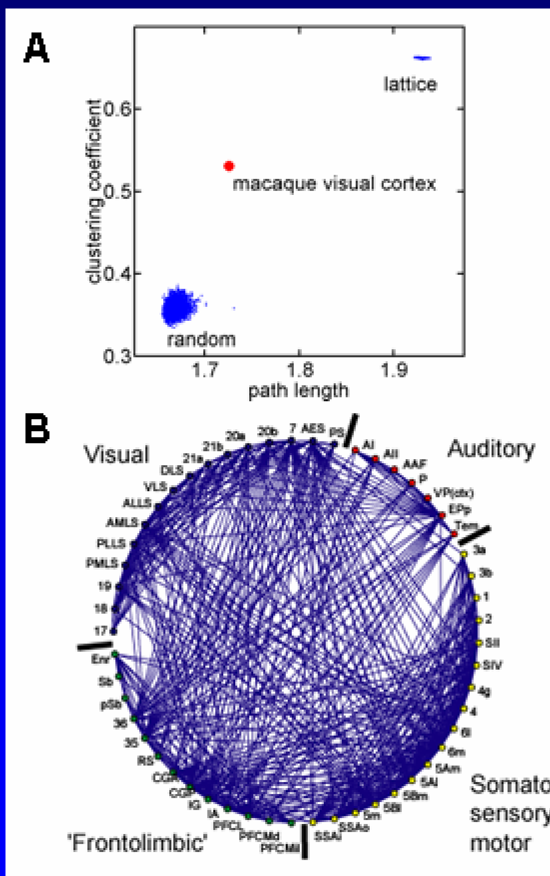
Macaque visual cortex connectivity

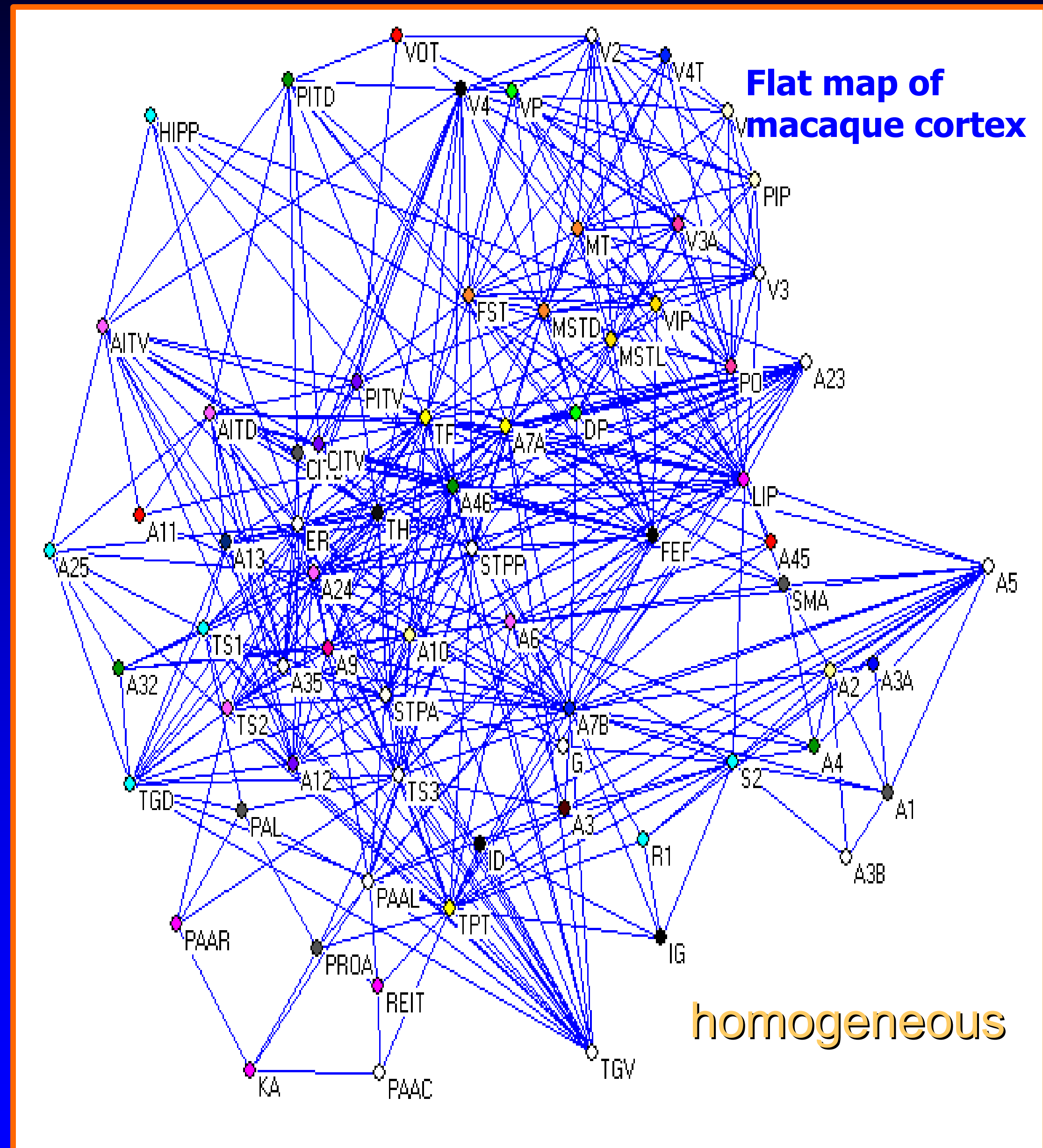


Felleman and Van Essen, Cerebral Cortex 1, 1 (1991).

The macaque cortical network

Entire macaque cerebral cortex
(71 nodes, 755 links)





From Sporns et al, Cerebral Cortex , 10:127-141(2000).

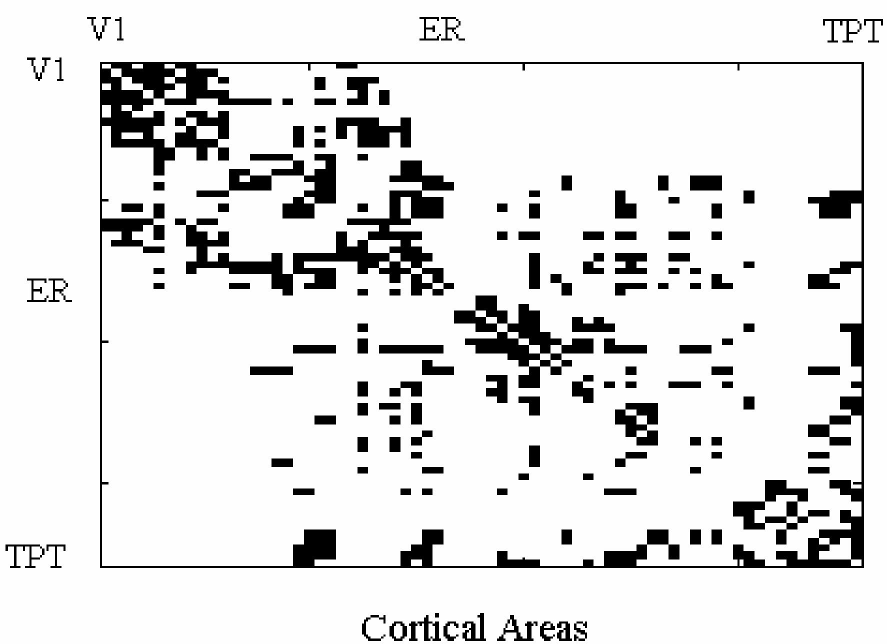
“In Catalogue” brain nets are small-world but not scale-free (very homogeneous)

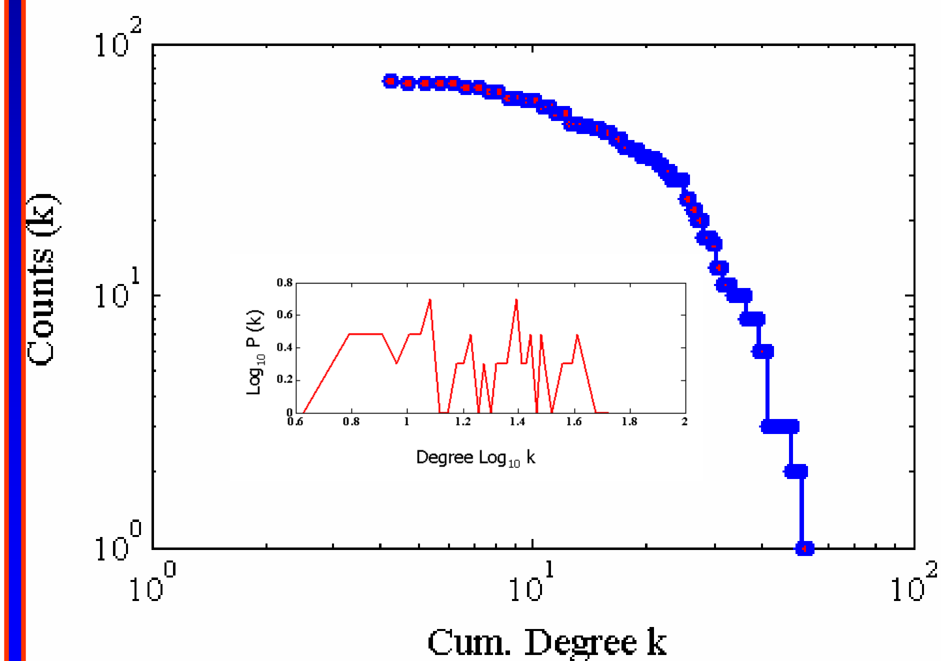
Network	*N*	*C*	*L*	*<k>*	.	C_{rand}	L_{rand}
Macaque CC	71	0.46	2.3	10.6	.	0.15	2.0

“Small-world”

- $C >> C_{rand}$
- $L \sim L_{rand}$

Macaque cerebral cortex





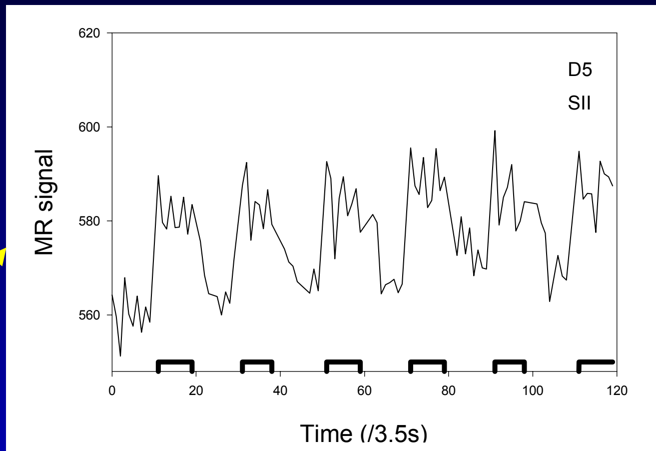
Chialvo, Physica A, (2004)

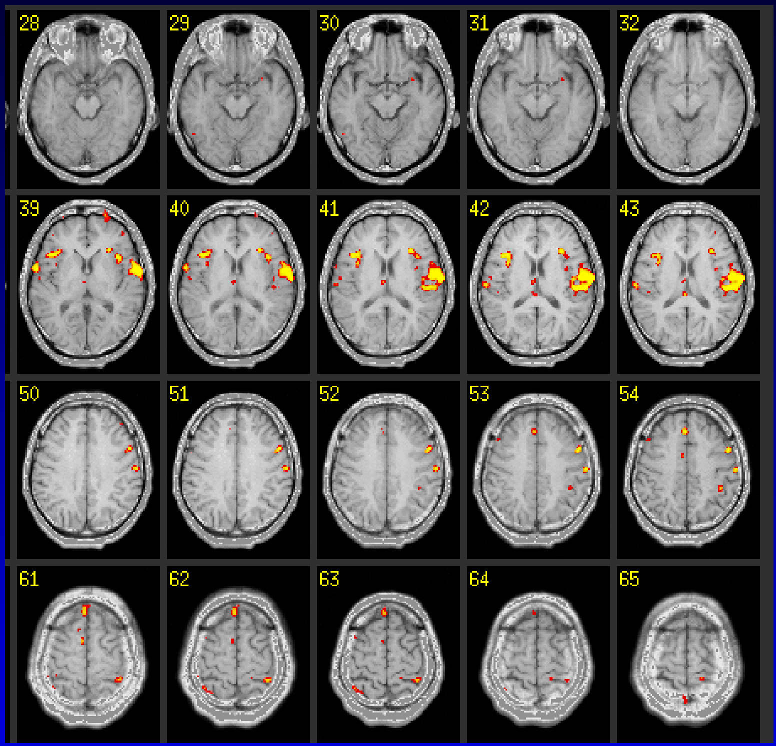
What is the Problem?

- Emotion, pain, pleasure… are examples of brain states where regions are dynamically co-active; like in a dance.
- Can we capture the dance?…

Functional Magnetic Resonance Imaging ("fMRI")

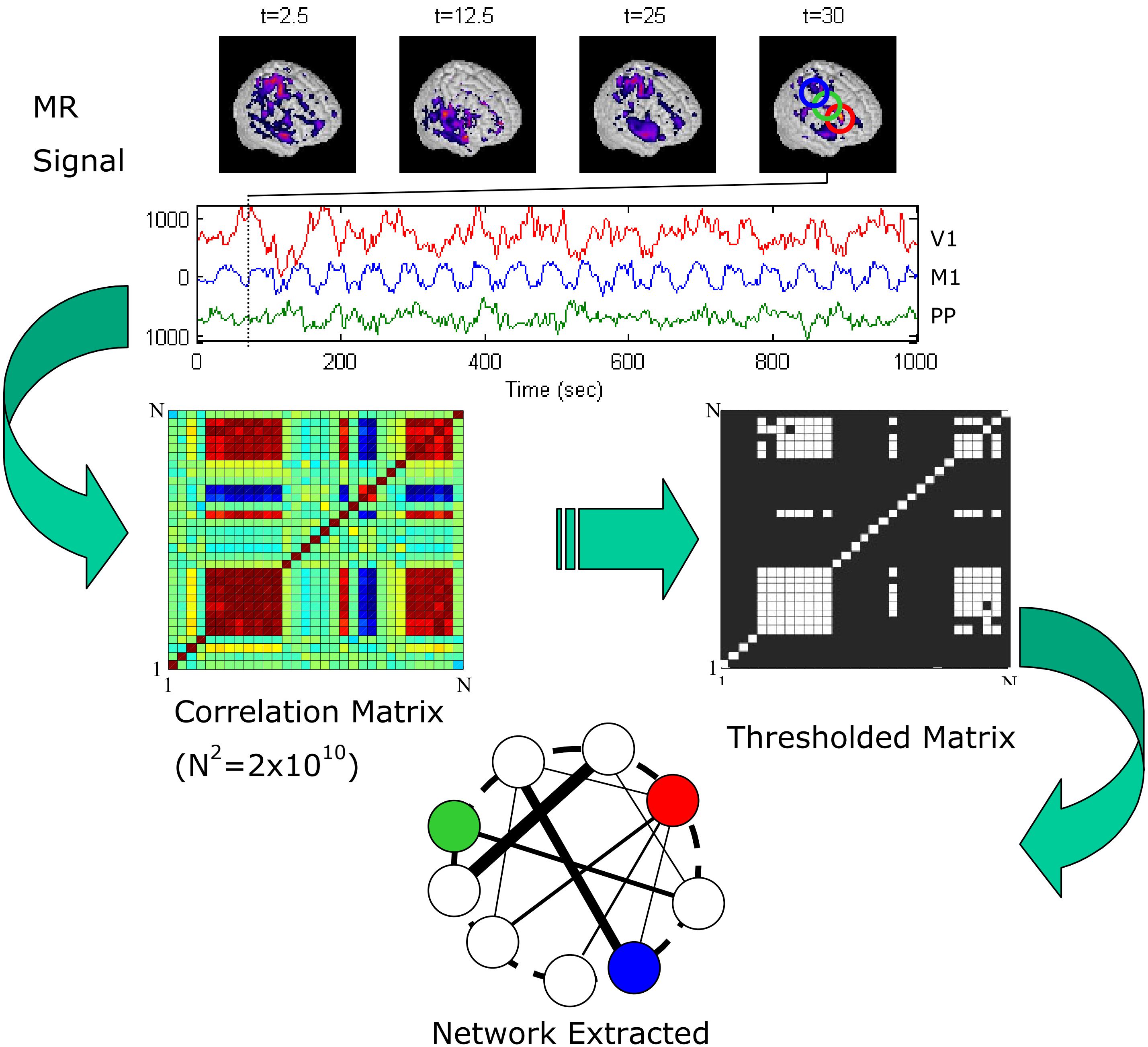
fMRI Analysis = "This Minus That"





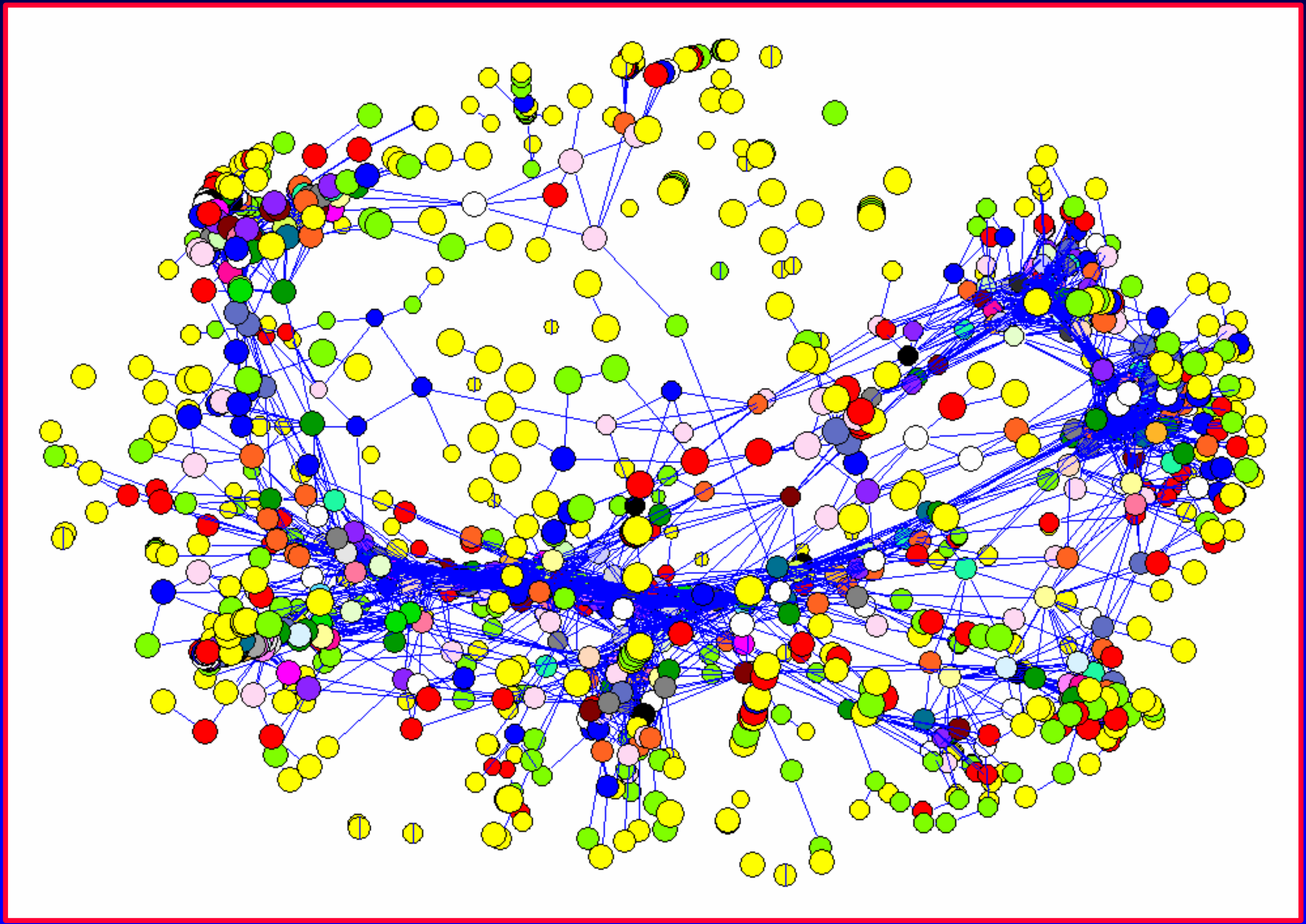
Yu ftpn2

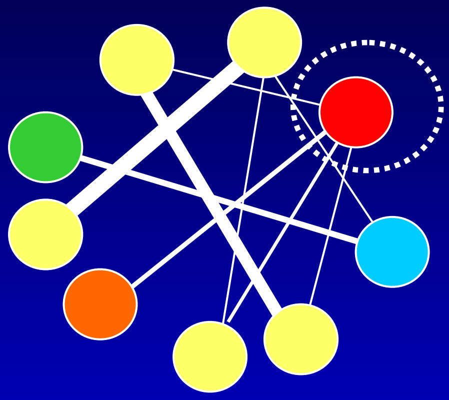
"metabolic activity"=
electrical+blood flow +...
(BOLD="Blood Oxygen Level
Dependent")



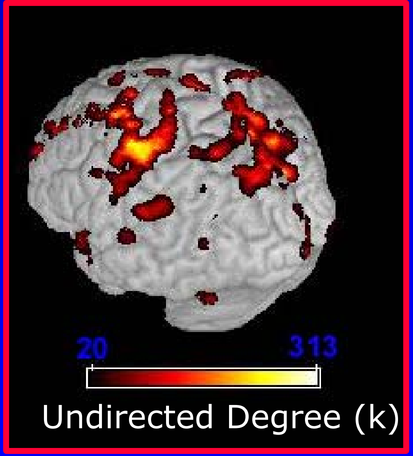
Extracting the Net

Brain' Net (during finger tapping)



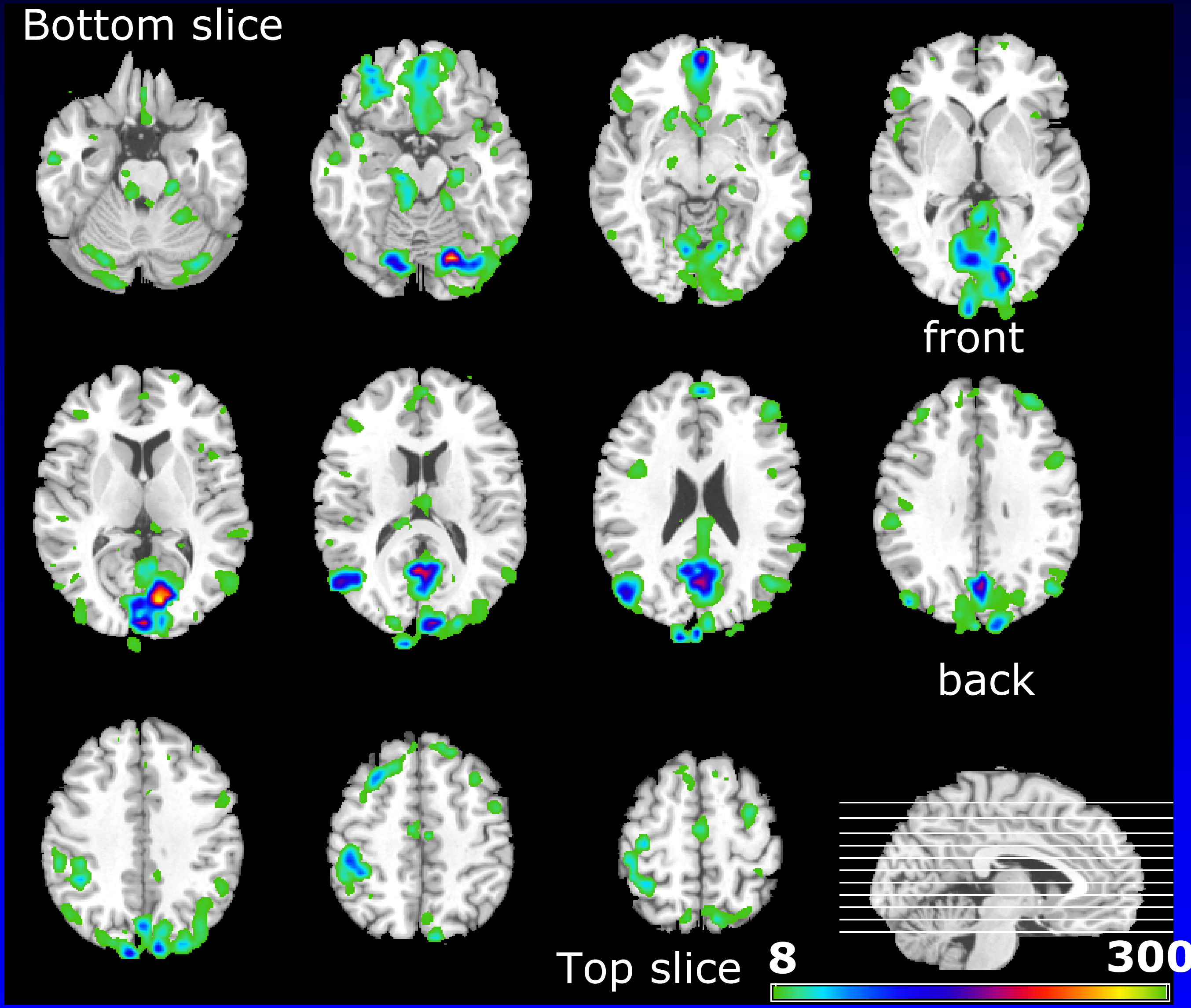


Nodes spatial location



Colors indicate the number of links (or "degree") of each node. yellow=1, green 2, red=3, blue=4, etc

Hubs



Colors indicate number of links (degree) of each site

Statistical Properties

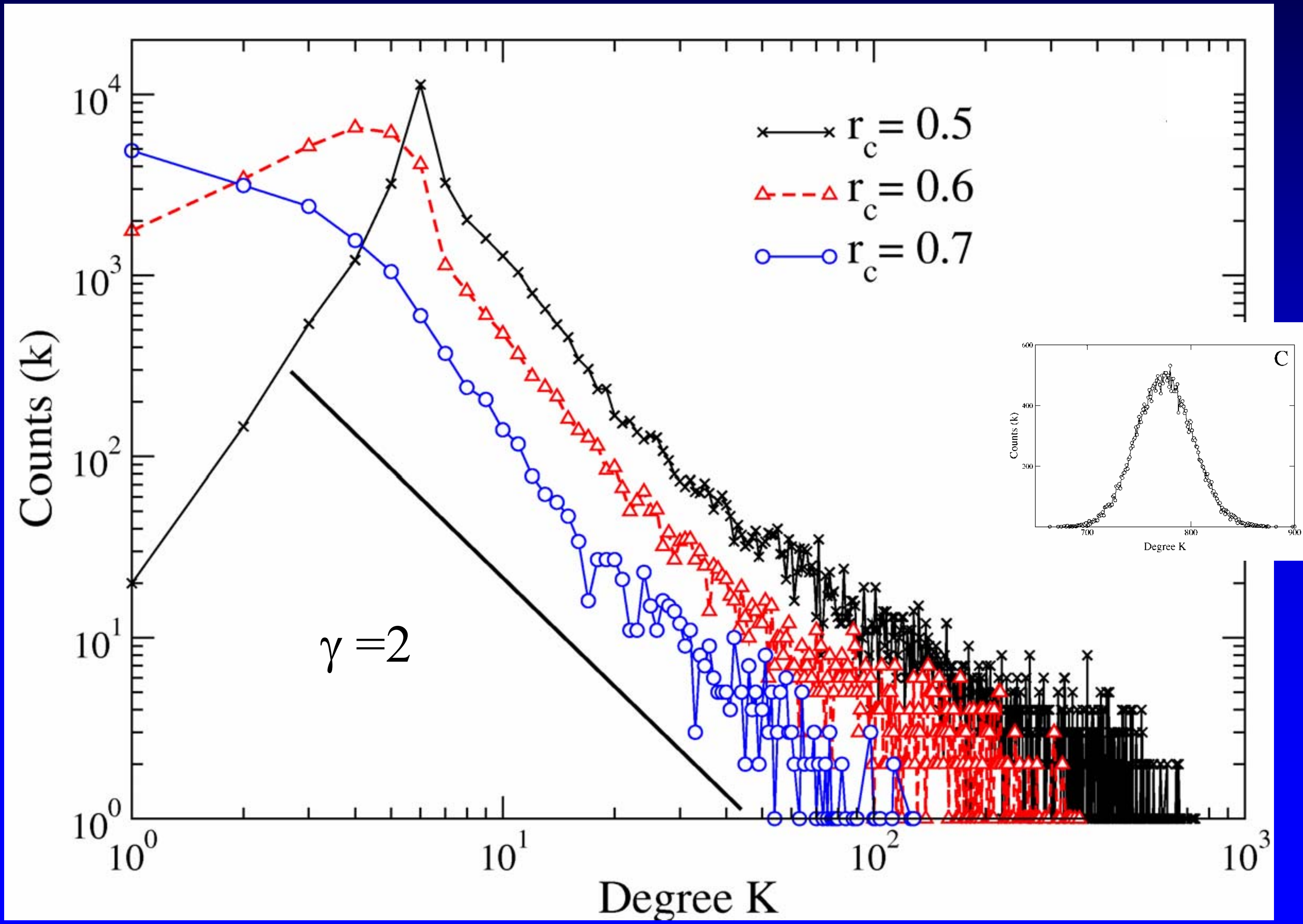
- <u>Degree distribution:</u> $P(k) \sim k^{-\gamma}$
  (how many links each node have)
- <u>Average shortest distance:</u> $L \sim Ln(N)$
  (shortest distance between any two nodes)
- <u>Clustering:</u> $C(k) \sim k^{-\mu}$
  (how many of your links are also mutually linked)

- <u>Average connectivity of neighbors</u>: $K_{nn}(k) \sim k^{-\delta}$
  (how many links my neighbors have)
- <u>Betweeness:</u> $B(k) \sim k^{-\beta}$, with $\beta=2.2, 2.0$
  (how many short-cuts pass trough one node)

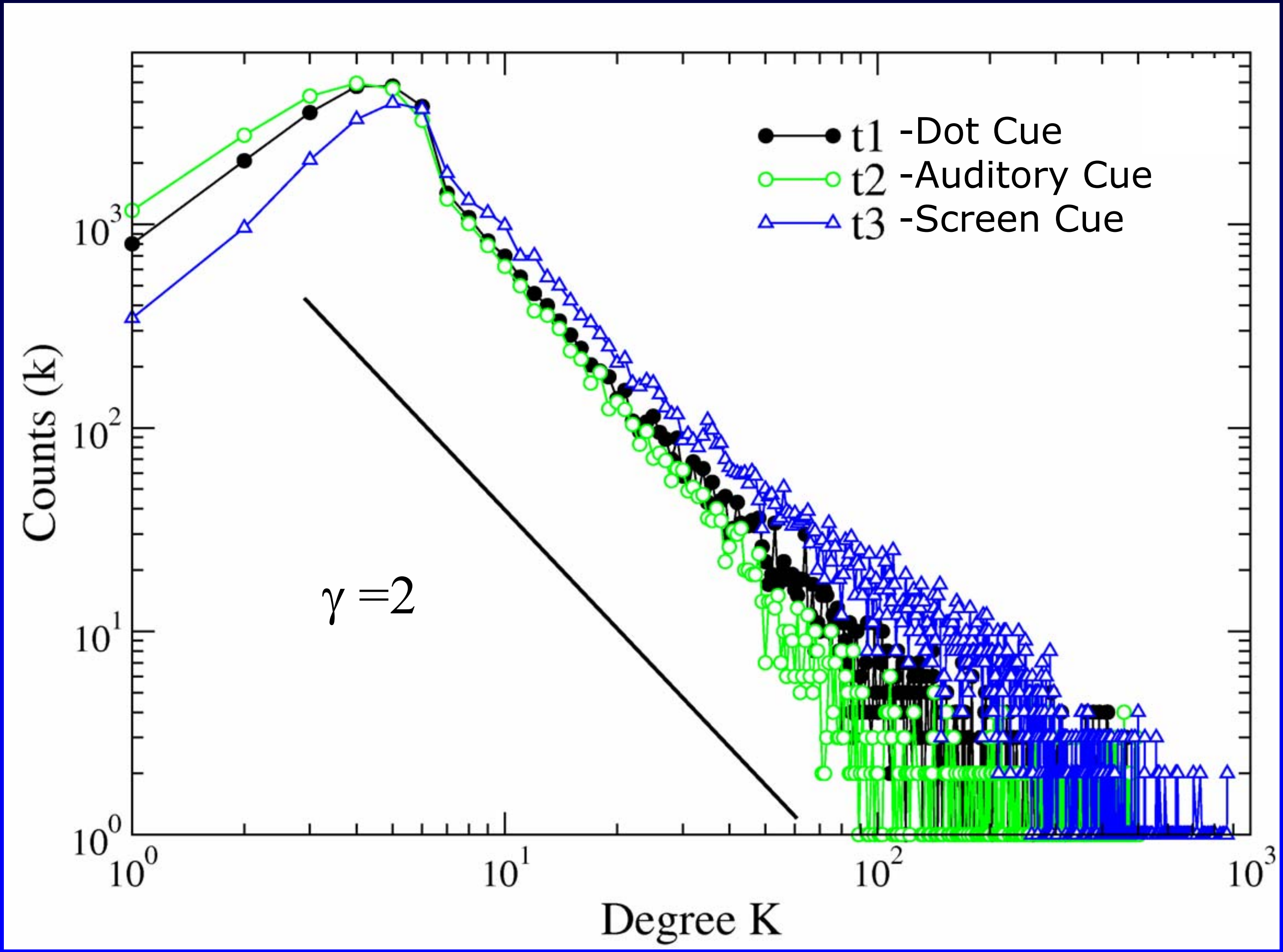
(Rev. Mod. Phys. 74, 47 (2002); Adv. in Physics 51, 4 (2002); SIAM Rev. 45, 167 (2003))

Degree Distribution …

Scale-free $k^{-\gamma}$ with $\gamma \sim 2$

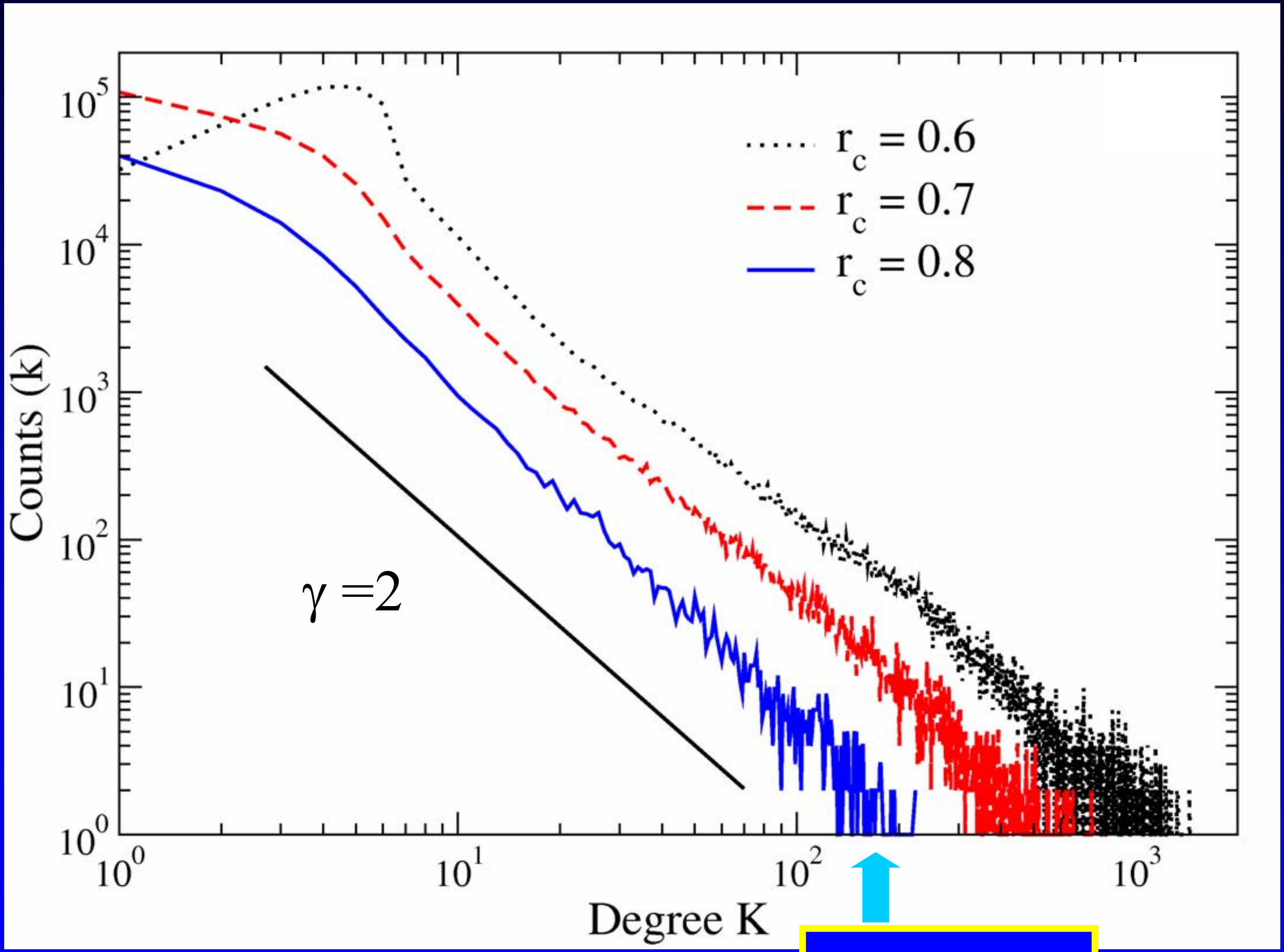


Another subject in different tasks:



Similar tail decay in different finger tapping tasks

Average Degree Distribution



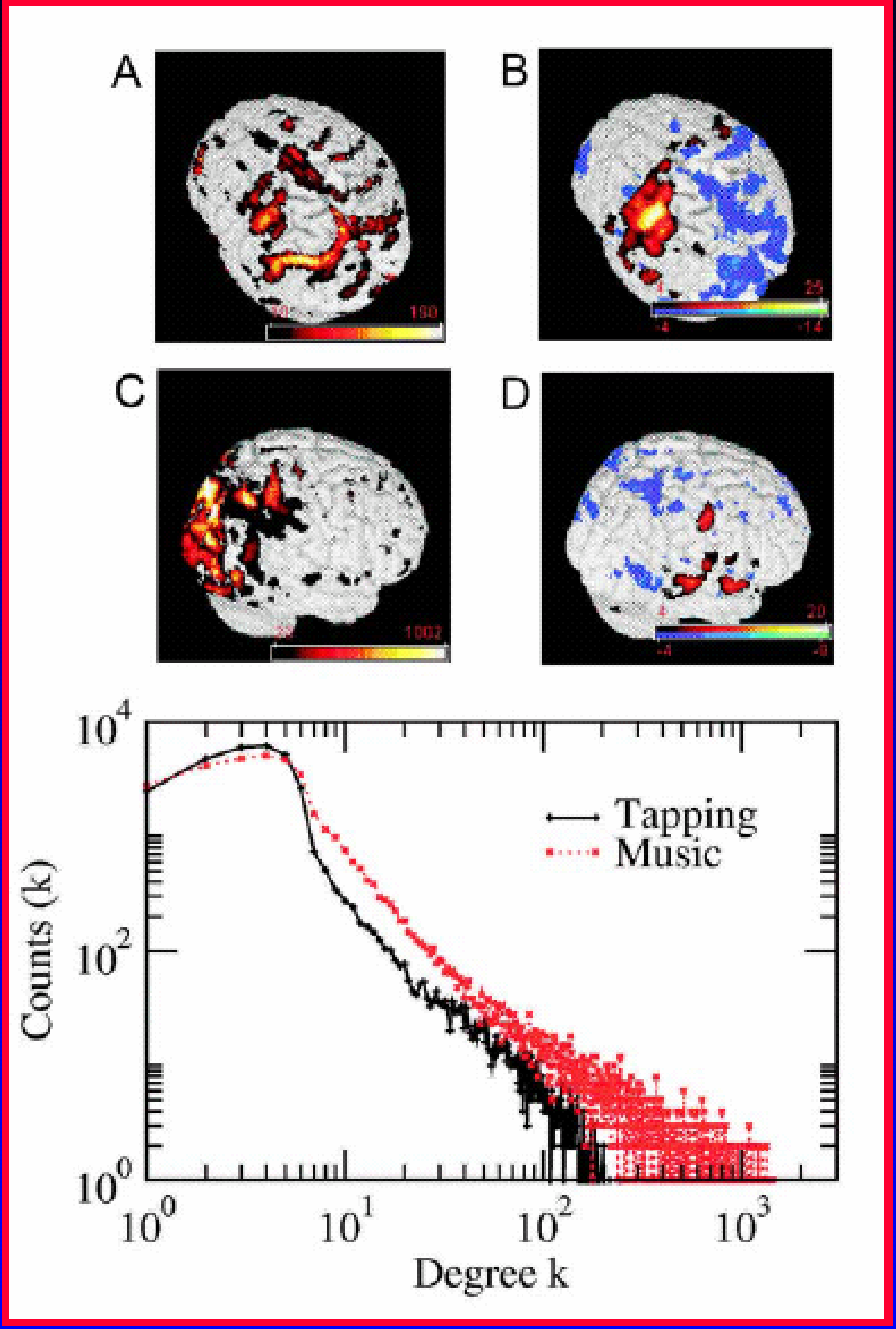
Few brain sites are very well connected

n=22 from 7 subjects

-Different task

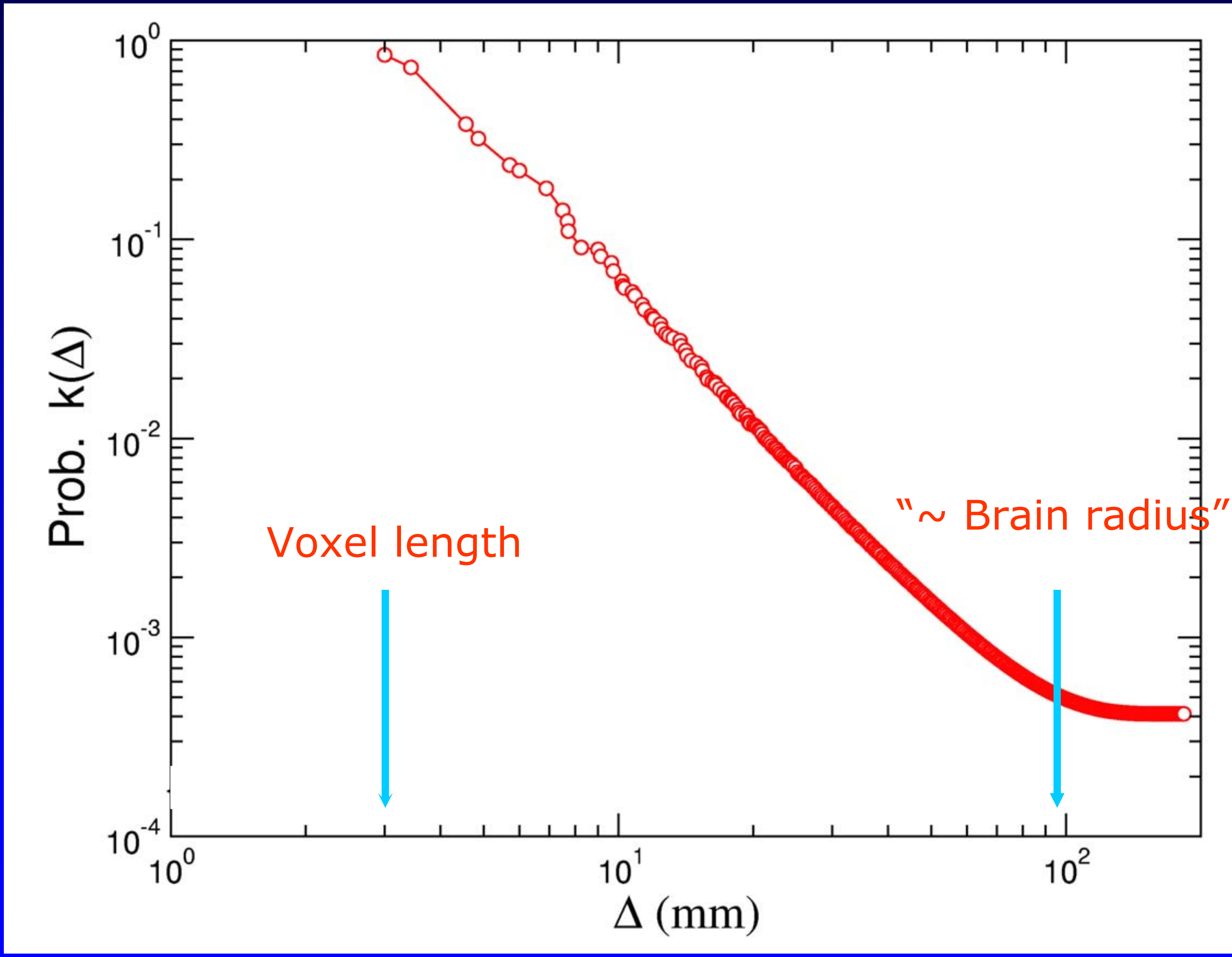
-Different nets

-Similar scaling

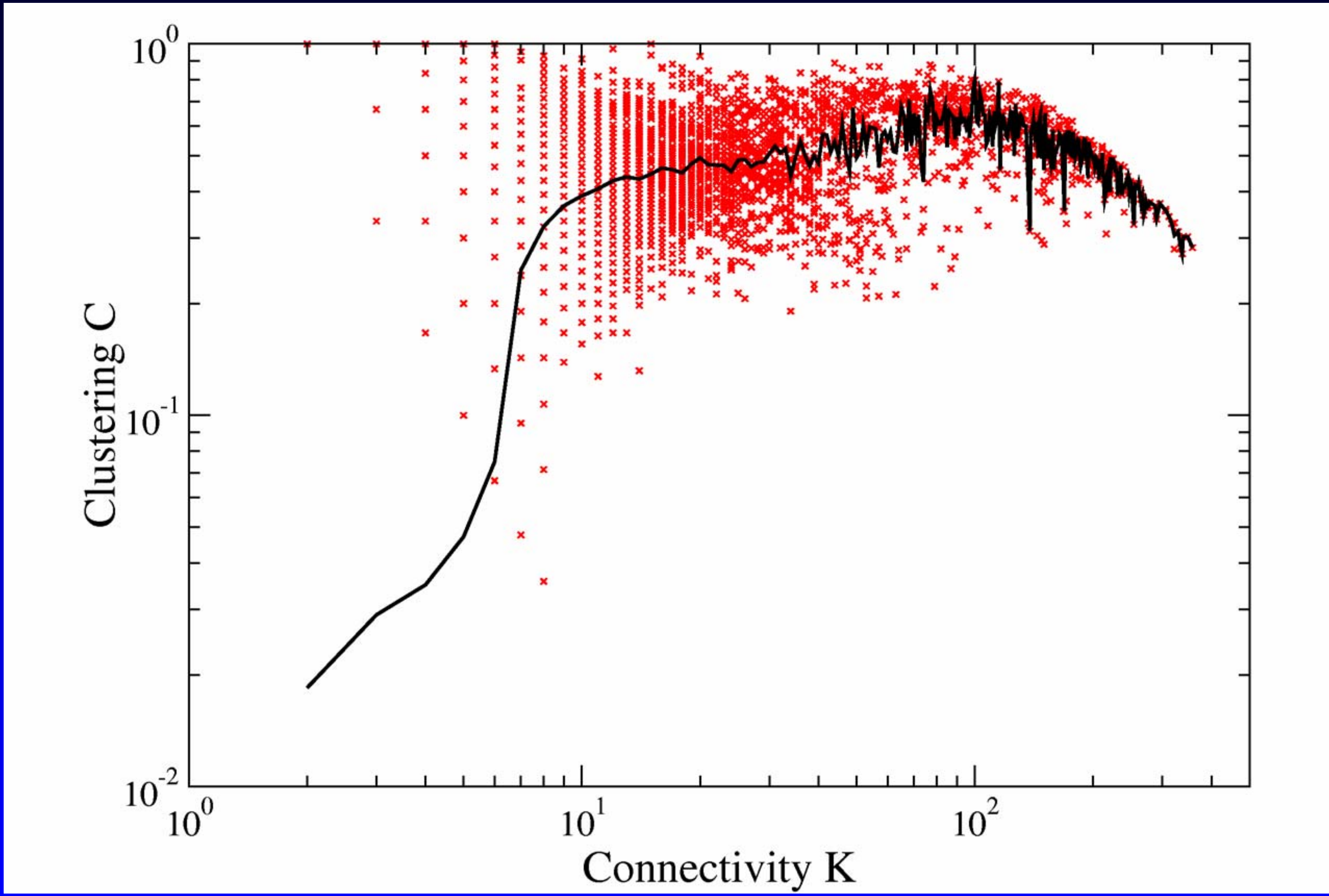


Average Links Length Distribution

Probability of finding a link between two nodes separated by a distance **x >** Δ

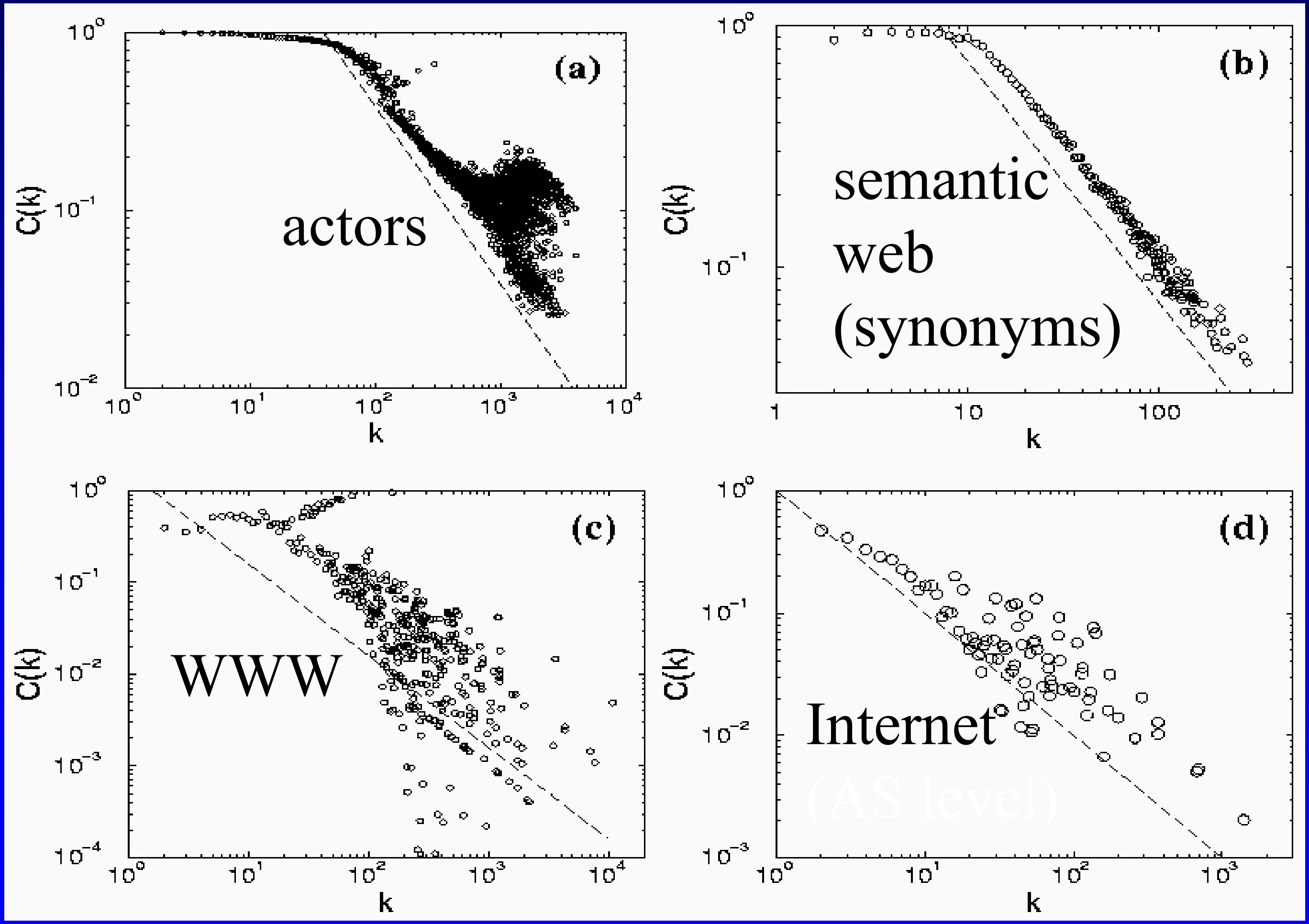


Degree vs. clustering



- Clustering is rel. independent of connectivity.

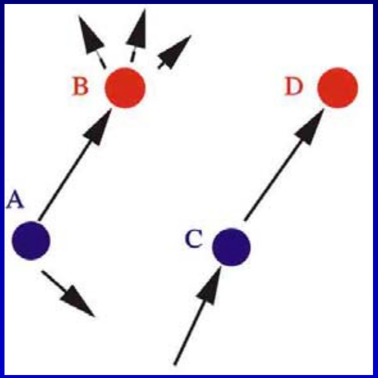
Modularity in real networks



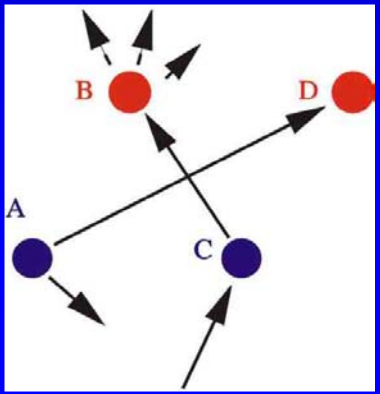
Ravasz and Barabási, cond-mat/0206130

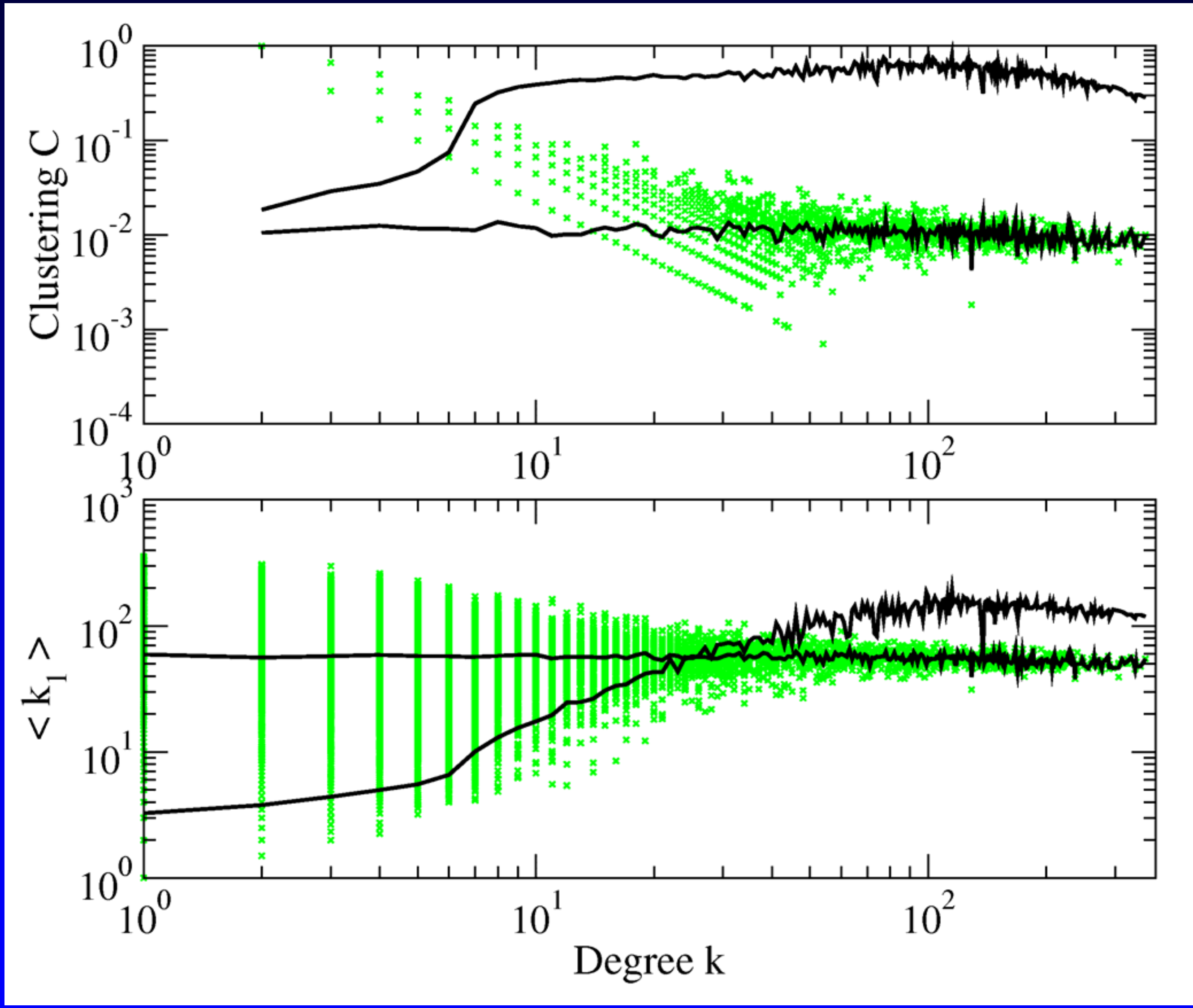
K_1, and Degree vs. Clustering

Maslov's rewiring



Switch partners





Statistics

fMRI-results

r_c	N	C	L	<*k*>	ρ *	γ
0.6	31503	0.14	11.42	13.41	0.000428	2.0
0.7	17174	0.13	12.95	6.29	0.000369	2.1
0.8	4891	0.16	5.96	4.12	0.000893	2.2

- C >> ρ
- Small L

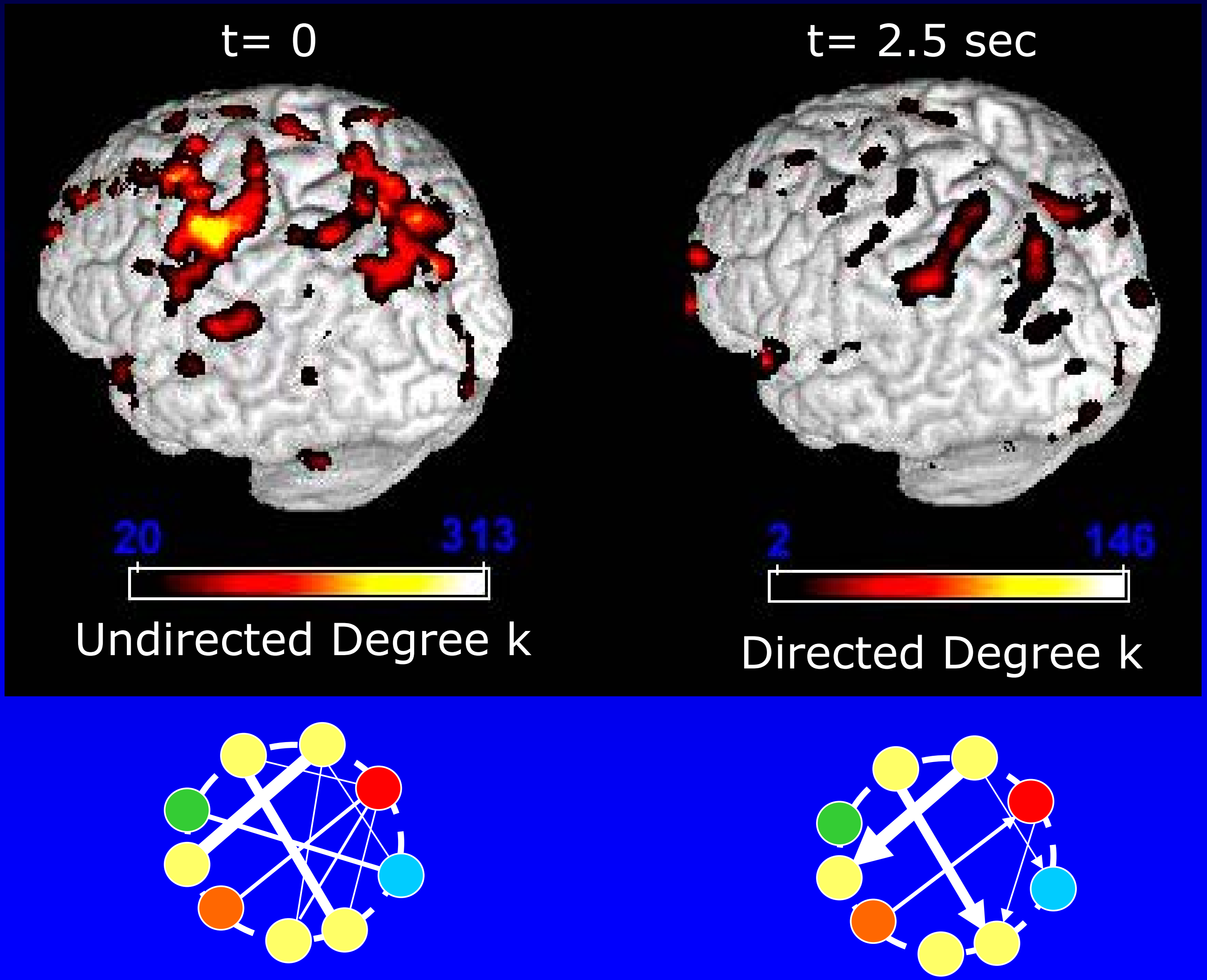
Previous results

Network	N	C	L	<*k*>	ρ
C. Elegans [1]	307	0.28	3.97	7.68	0.025
Macaque VC [2]	32	0.55	1.77	9.85	0.318
Cat Cortex [2]	65	0.54	1.87	17.48	0.273

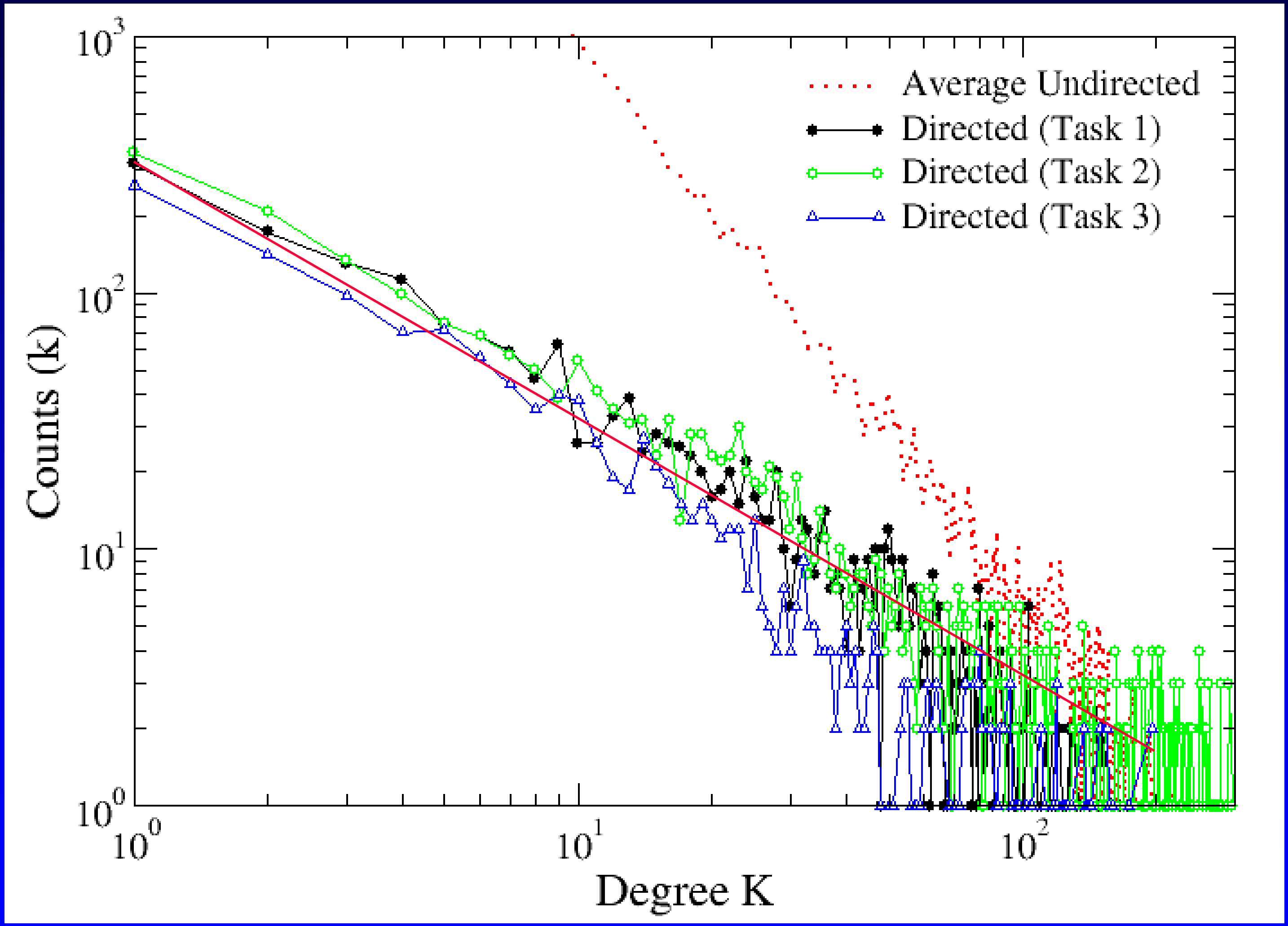
* $\rho \sim \langle k \rangle / N$

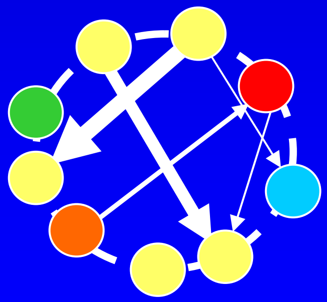
(1) Watts & Strogatz (1998).
(2) Osporn et al (2003).

Hubs II



Directed degrees distr.





Summary:

- Brain activity does not have a characteristic scale.
- Some physicists will be happy to know that, after all, the brain is a scale-free network with small-world properties. ($C >> \rho$).
- MODELS: We would like to know from where are coming all these exponents???
- Are we reinventing the wheel? (networks as "skeleton of an underlying fractal")
- The absence of scale emphasize the need to talk in terms of networks of interaction, rather that in term of regions, at least for any relevant behavior (emotion, pain, pleasure, uncooperative patients, coma etc).
- This unsupervised method can be a powerful window into the brain in particular when no clear external correlators can be identified.
- The method allows, in principle, to study the brain in a dance rather than a pose.
- Repeat same calculations with magneto-encephalography (128 sites)
- Plan to study pleasure and pain with this approach