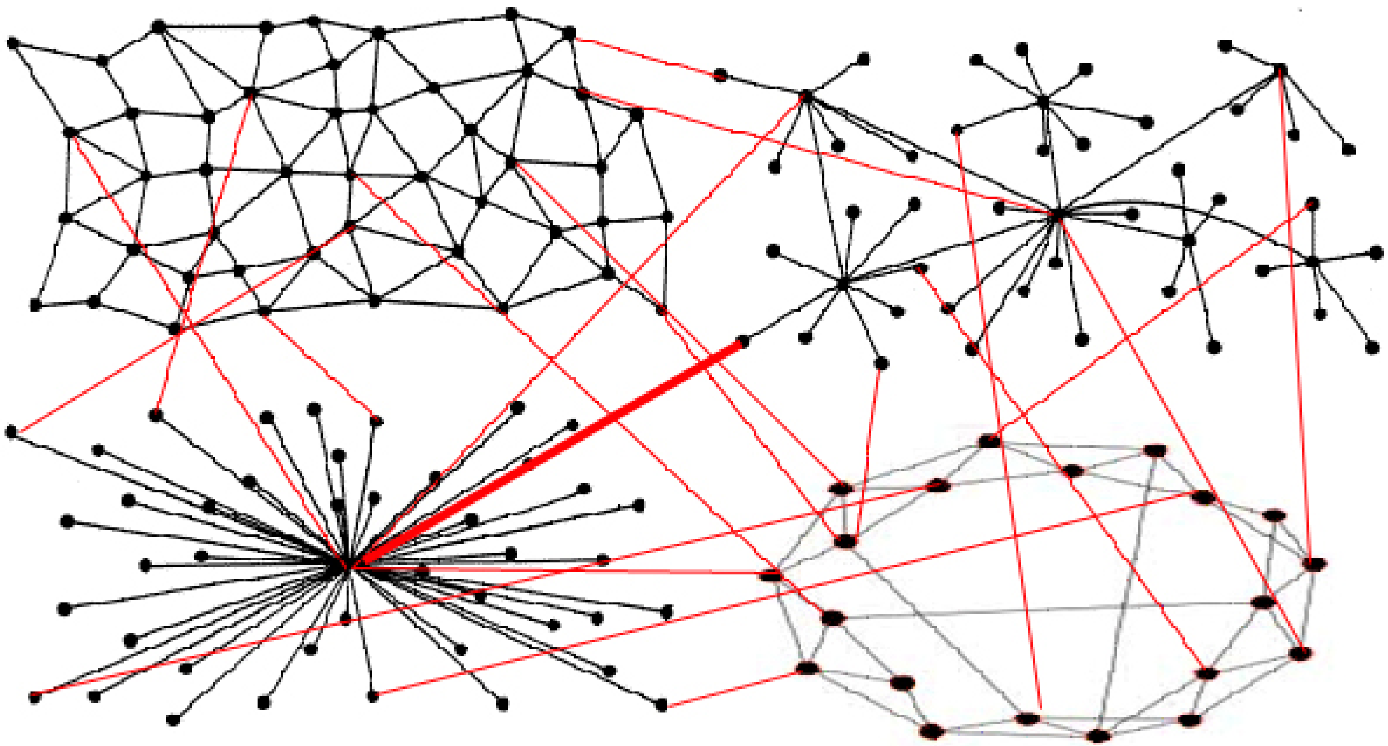
The Extreme Vulnerability of Network of Networks



Shlomo Havlin

Bar-Ilan University

Israel

Two types of links:

1. Connectivity
2. Dependency

Protein networks,
Brain networks
Physiological systems
Infrastructures

Cascading disaster-Sudden collapse

…..

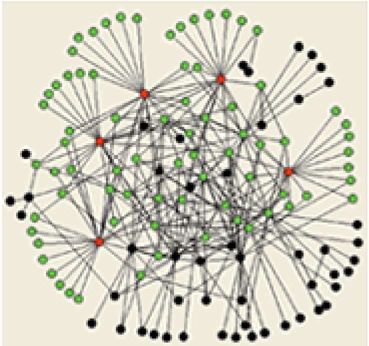
MULTPLEX IS A SPECIAL CASE OF NON

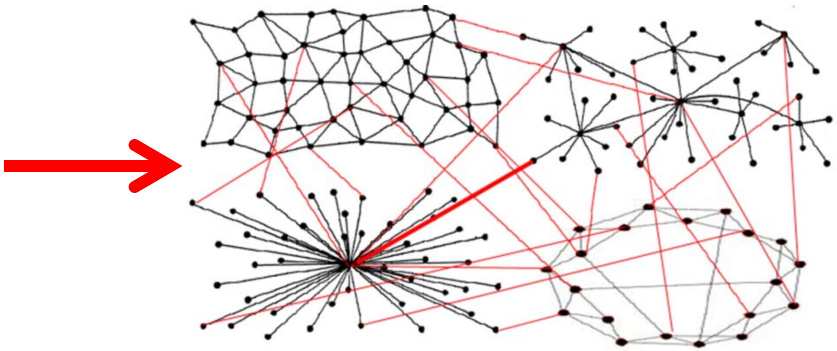
From Single Network to Network of Networks

Collaboration:

Amir Bashan, BIU
Yehiel Berezin, BIU
Sergey Buldyrev, NY
Jianxi Gao: Northeastern
Hans Herrmann, Zurich
Stefano Boccalleti, Florence
Jose Andrade, Fortaleza
Wei Li, BU
Hernan Makse, NY
Xuqing Huang, BU
Roni Parshani: BIU
Nuno Araujo, ETH
Javier M Buldu, Madrid
Irene Sendina–Nadal, Madrid
Christian Schneider, MIT
H. E. Stanley, Boston
PARTIAL LIST

2000 2010





Buldyrev et al, Nature, 464, 1025 (2010)
Parshani et al, PRL ,105, 0484 (2010)
Schneider et PNAS, 108, 3838 (2010)
Parshani et al, PNAS, 108, 1007 (2011)
Gao et al, PRL, 107, 195701 (2011)
Gao et al, Nature Phys.,8, 40 (2012)
Bashan et al, Nature Com., 3, 702, (2012)
Wei Li et al, PRL, 108, 228702 (2012)
Bashan et al, arXiv:1206.2062 (Nature Phys. (2013))
Schneider et al, Scientific Reports (2013)

Extensive Studies Since 2000 -- Single Networks

- A Network is a structure of N nodes and M edges (or 2M links)
- Called usually graph – in Mathematics
- Complex systems can be described

  and understood using networks

  Internet: nodes represent computers

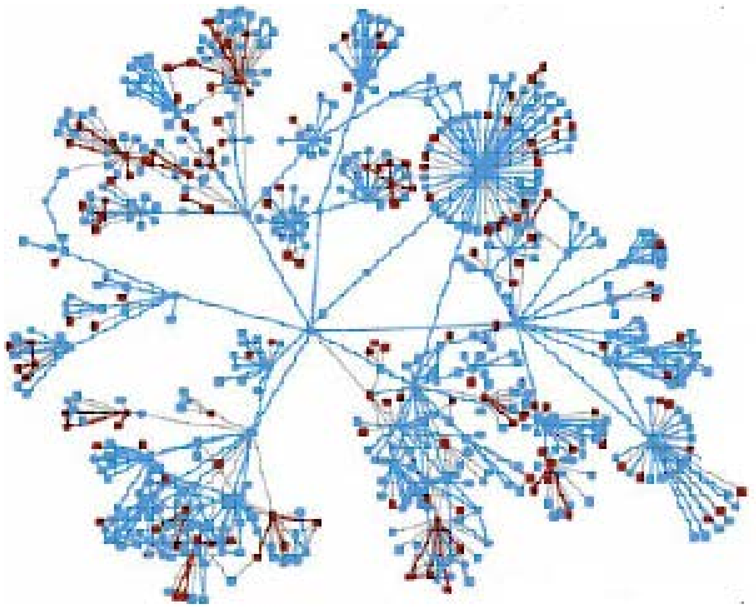
  links the connecting cables

  Biological systems: nodes represent

  proteins links their relations

  Climate system: nodes represent locations

  links similar climate

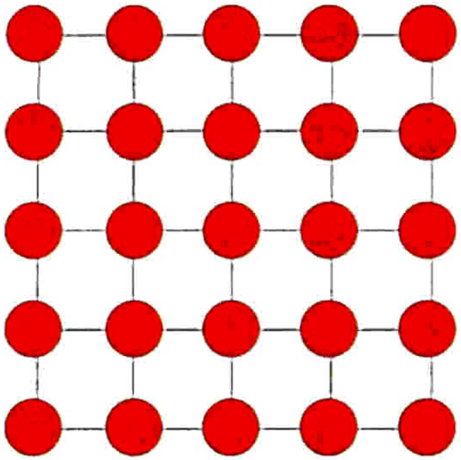


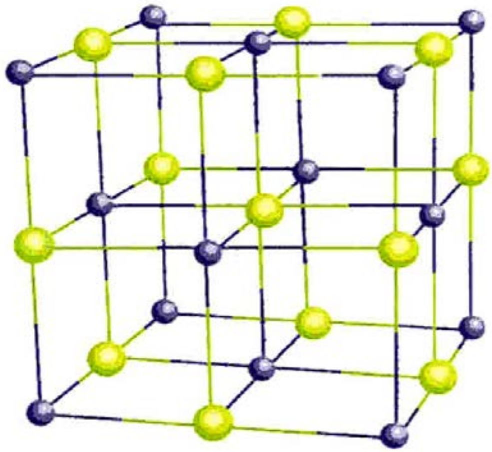
Brown-same operating system-now

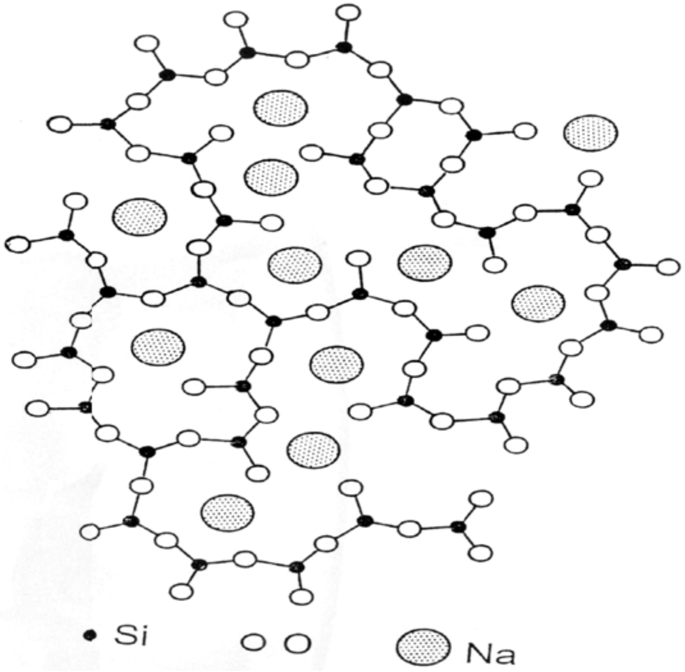
Wang et al (Science 2009)

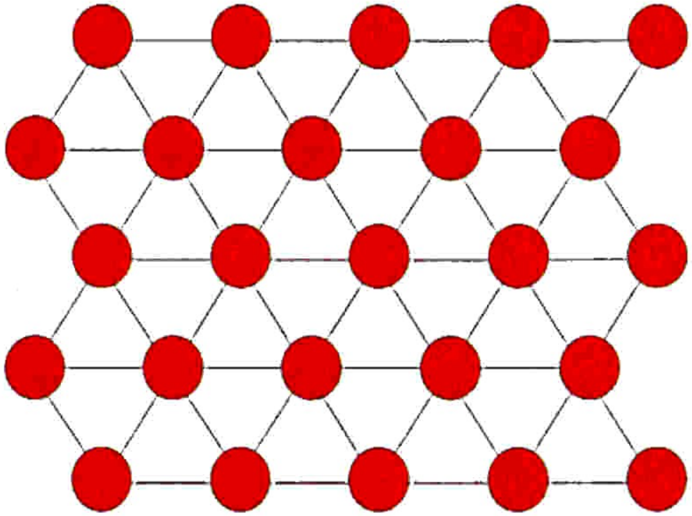
Percolation-Immunization

Networks in Physics



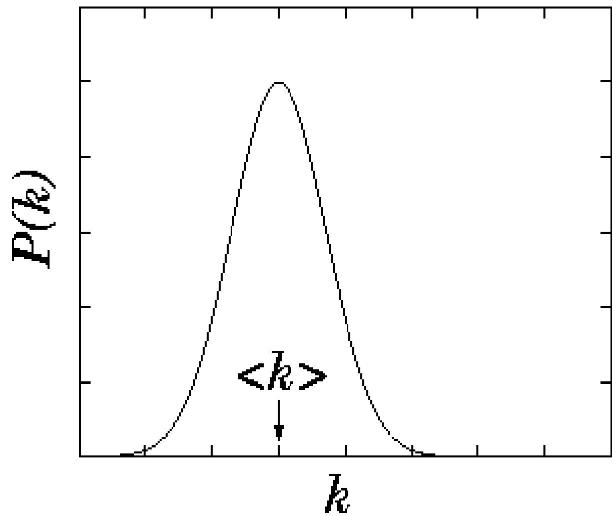




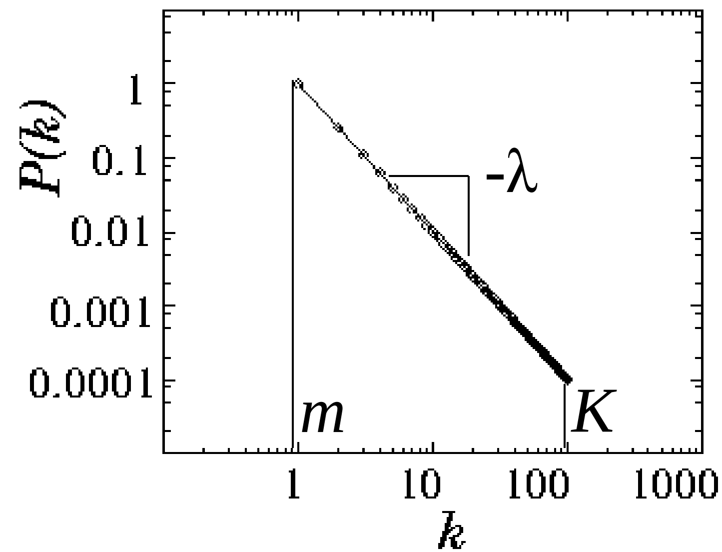


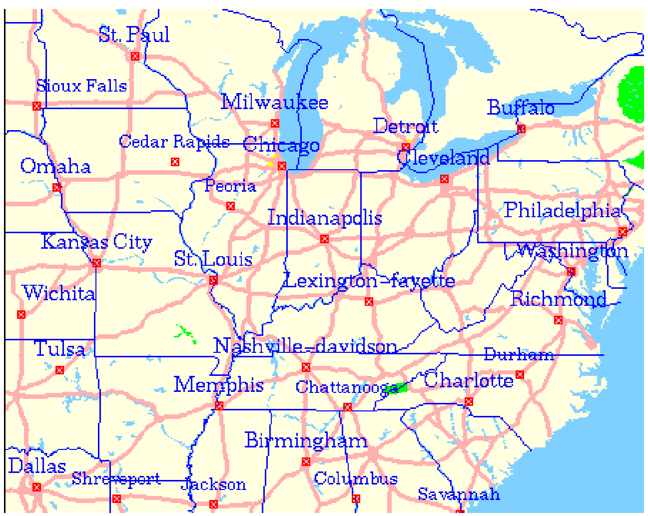
Complex Single Networks- Since 2000

Poisson distribution

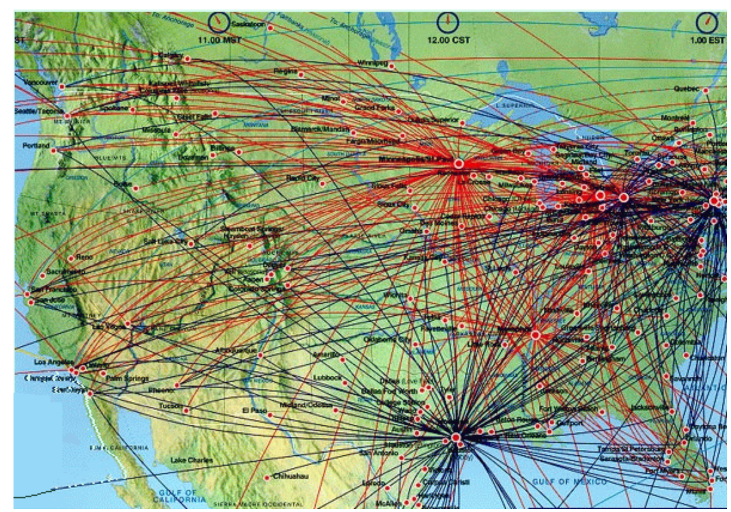


Scale-free distribution





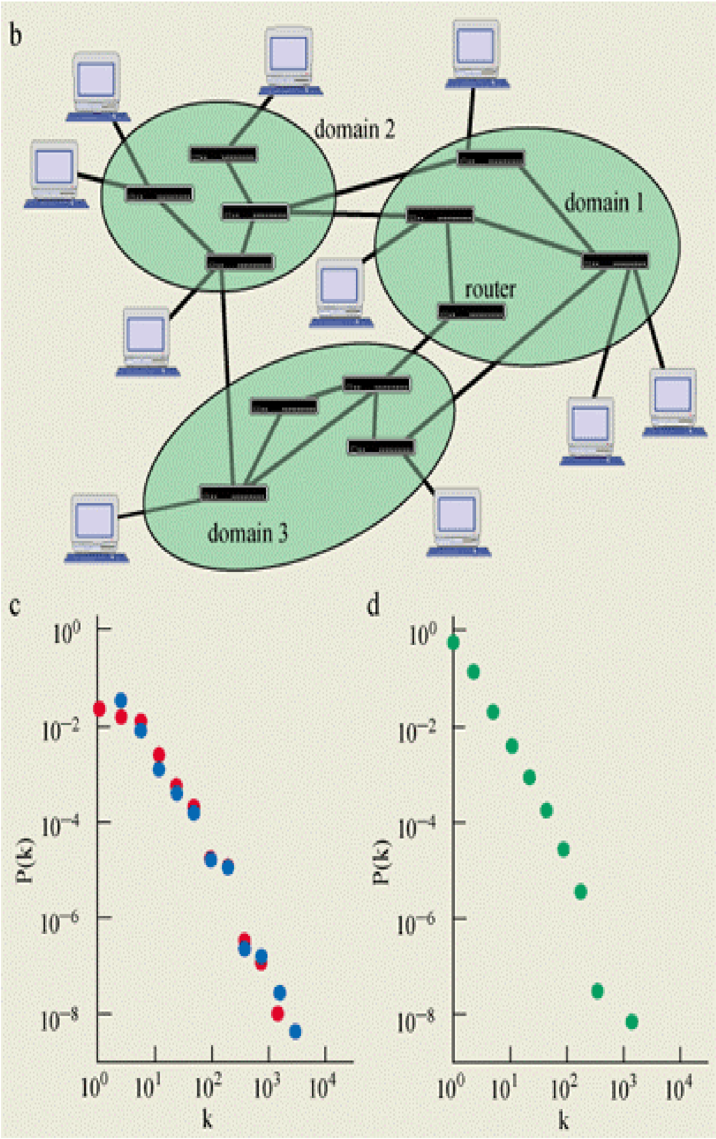
Erdős-Rényi Network

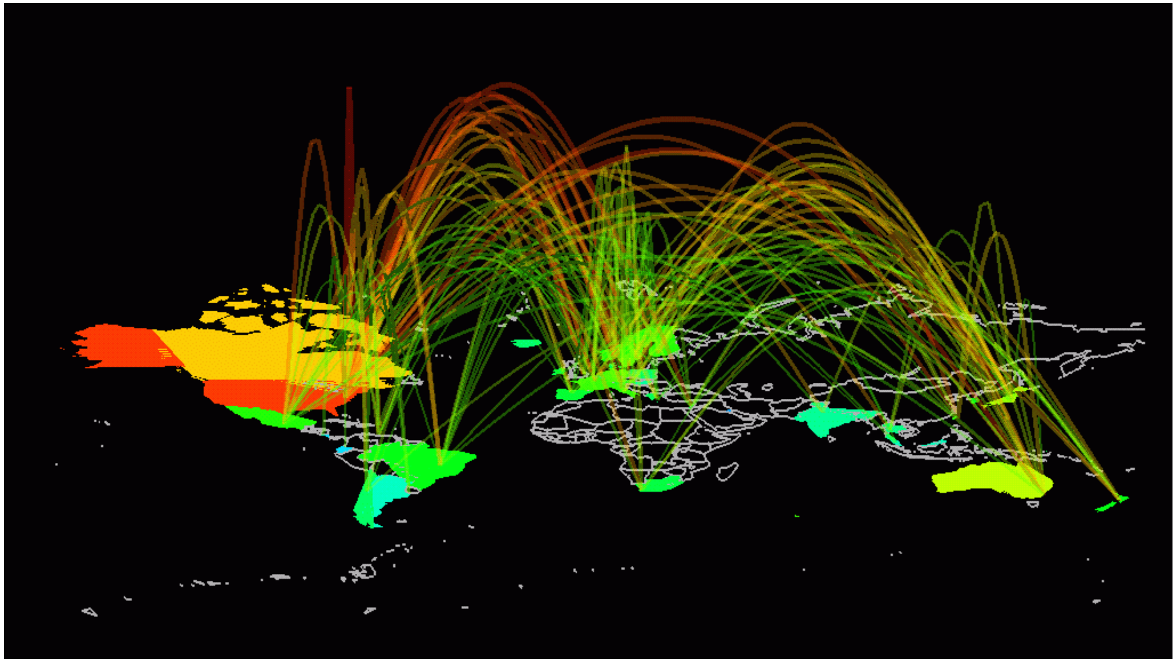


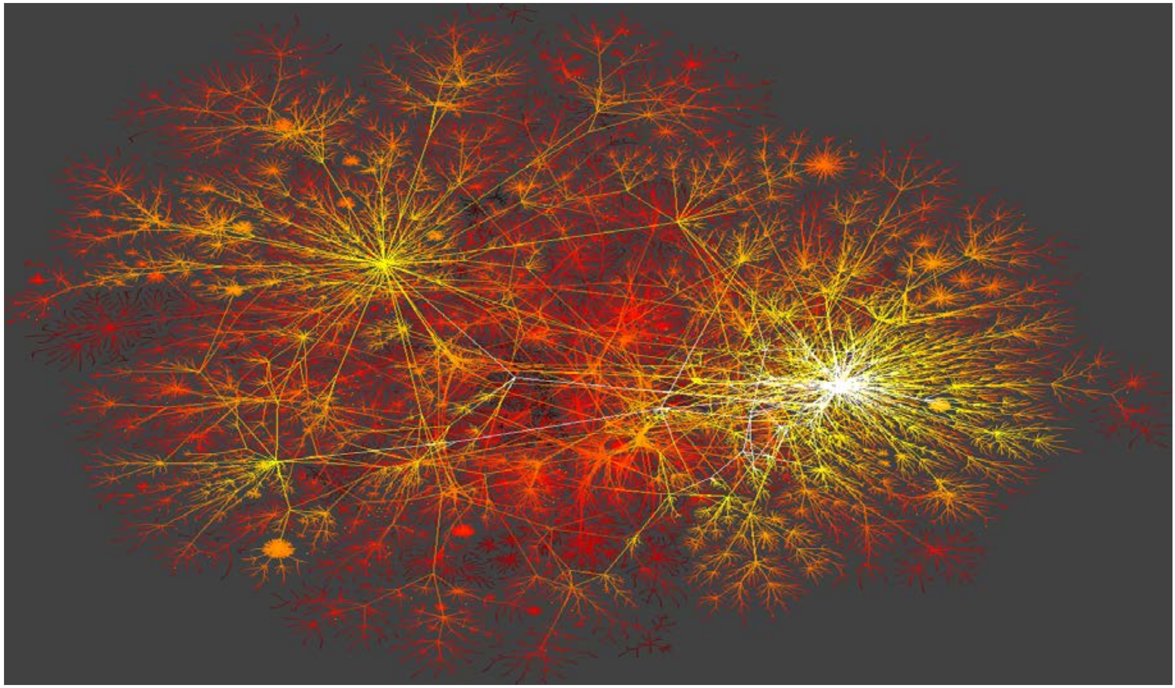
Scale-free Network

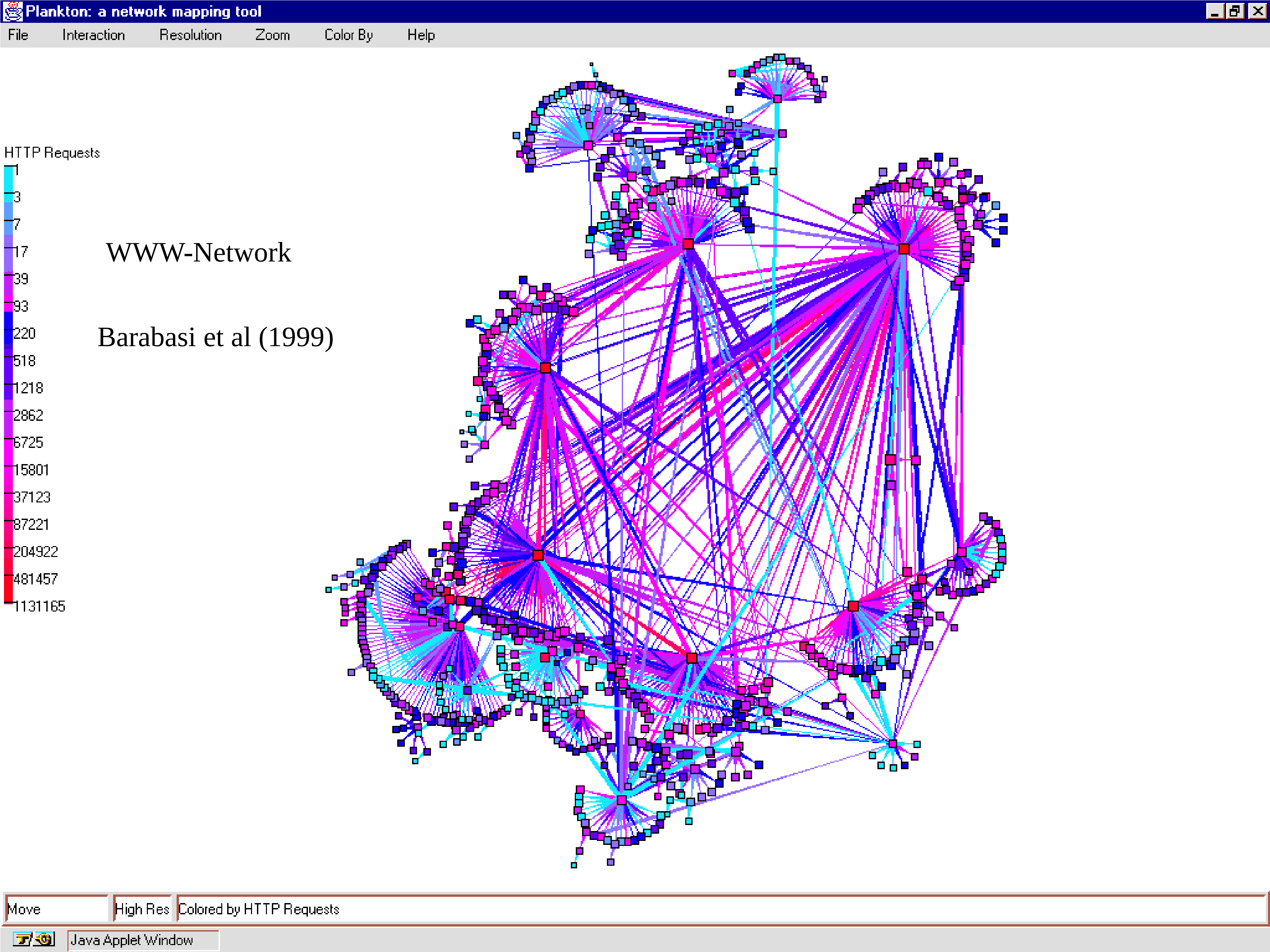
Internet Network

Faloutsos et. al., SIGCOMM '99





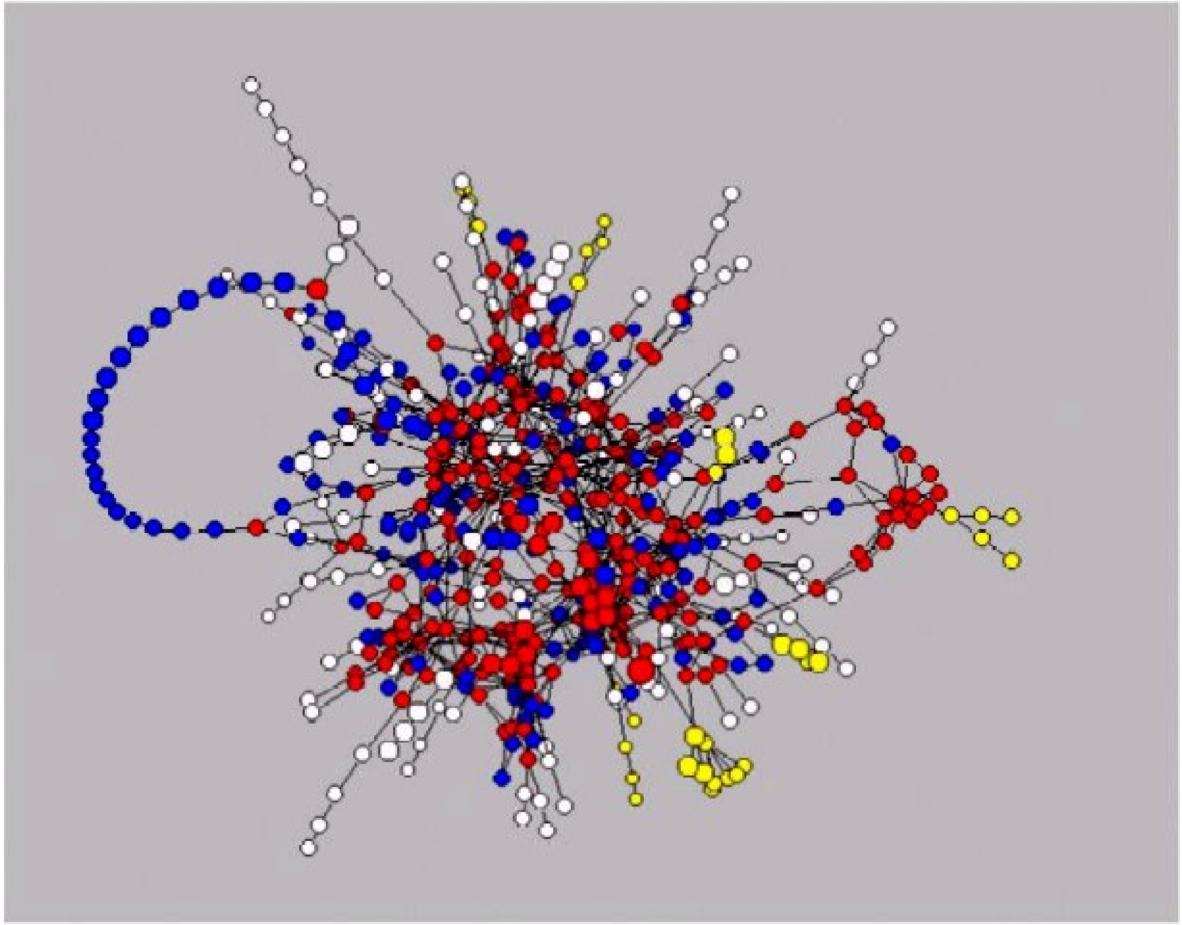



Plankton: a network mapping tool
File
Interaction
Resolution
Zoom
Color By
Help
HTTP Requests
1
3
7
17
39
93
220
518
1218
2862
6725
15801
37123
87221
204922
481457
1131165
WWW-Network
Barabasi et al (1999)
Move
High Res
Colored by HTTP Requests
Java Applet Window

Metabolic Network

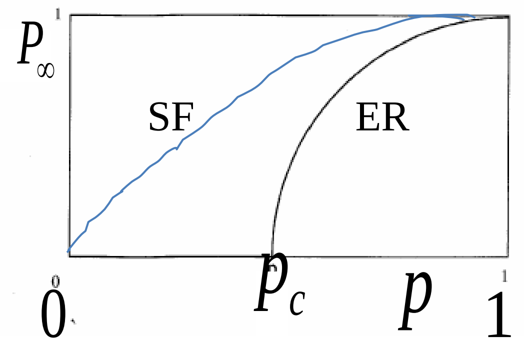
Nodes: chemicals (substrates)

Links: bio-chemical reactions

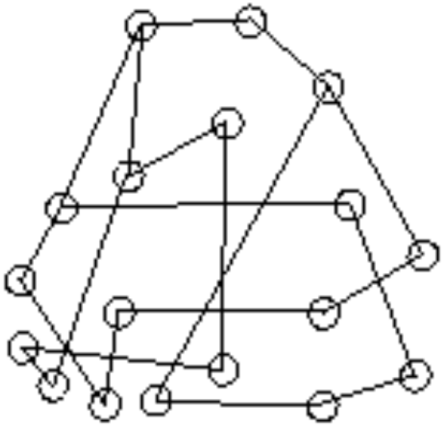


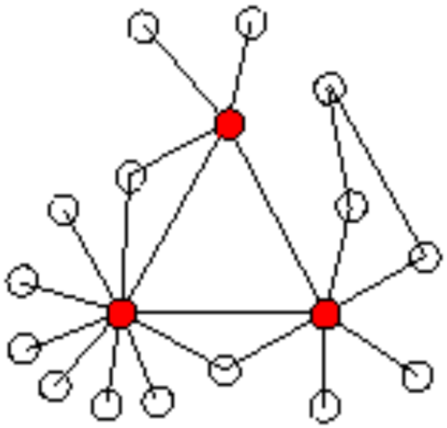
Jeong, Tombor, Albert, Barabasi, Nature (2000)

Many real networks are non-Poissonian



SF more robust!!





$$P(k) = e^{-\langle k \rangle} \frac{\langle k \rangle^k}{k!}$$

$$P(k) = \begin{cases} ck^{-\lambda} & m \le k \le K \\ 0 & otherwise \end{cases}$$

Classical Erdos-Renyi (1960)

Homogeneous, similar to lattices

$d \sim \log N$ -- Small world

$$p_c = 1 - q_c = 1/ < k >$$

$$P_\infty = p[1 - \exp(-\langle k \rangle P_\infty)]$$

Barabasi-Albert (1999)

Heterogeneous-translational symmetry breaks!

Change universality class-many anomalous laws

$e.g.,\quad d \sim \log\log N \; ; \; p_c = 0$

Ultra Small worlds (Cohen and SH, PRL (2003))

Breakthrough in understanding many problems!

WHAT IS DIFFERENT?

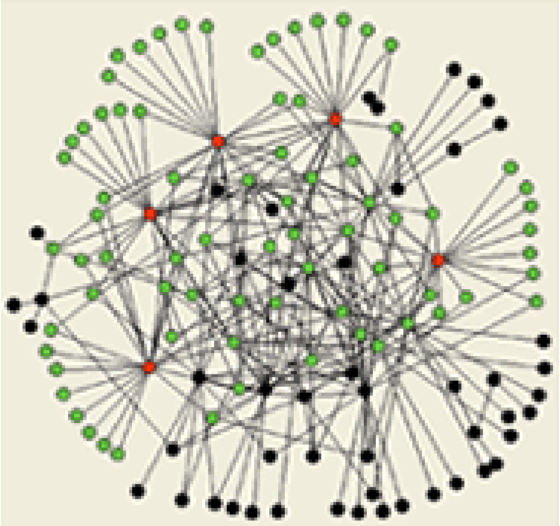
Known values of immunization thresholds:

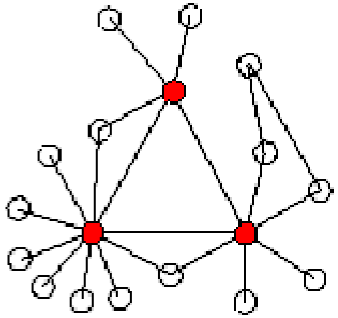
Infectious disease	**Critical Threshold** $q_c = 1 - p_c$
Malaria	99%
Measles	90-95%
Whooping cough	90-95%
Fifths disease	90-95%
Chicken pox	85-90%
Internet	more than 99%

Such immunization thresholds were not understood since they were well above the expected value of percolation in classical random networks:

$$q_c = 1 - p_c = 1 - 1/ < k >$$

This puzzle is solved due to the broad degree distribution (HUBS) of social networks which does not occur in random graphs!



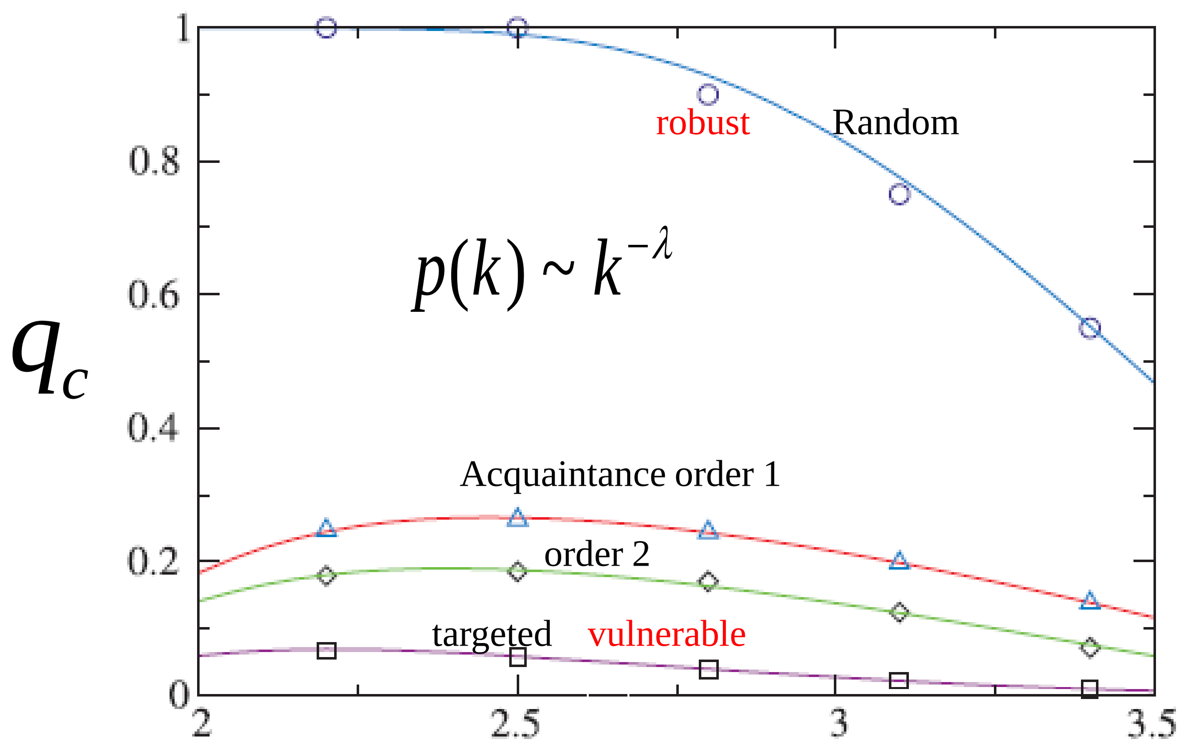


Scale Free networks --immunization strategies

Efficient Immunization Strategy:

Acquaintance Immunization

$q_c -$ critical fraction of removed or immunized nodes



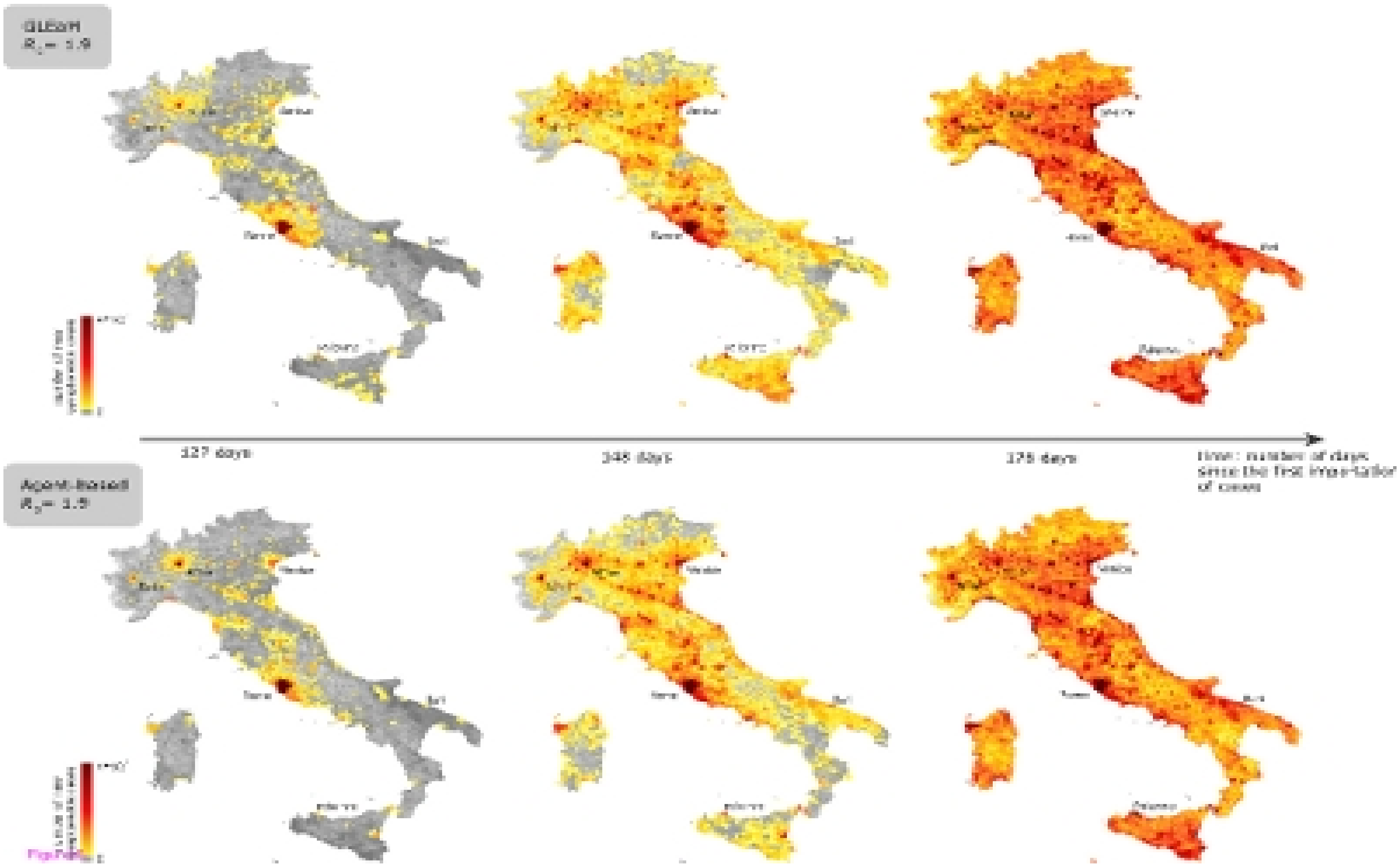
λ

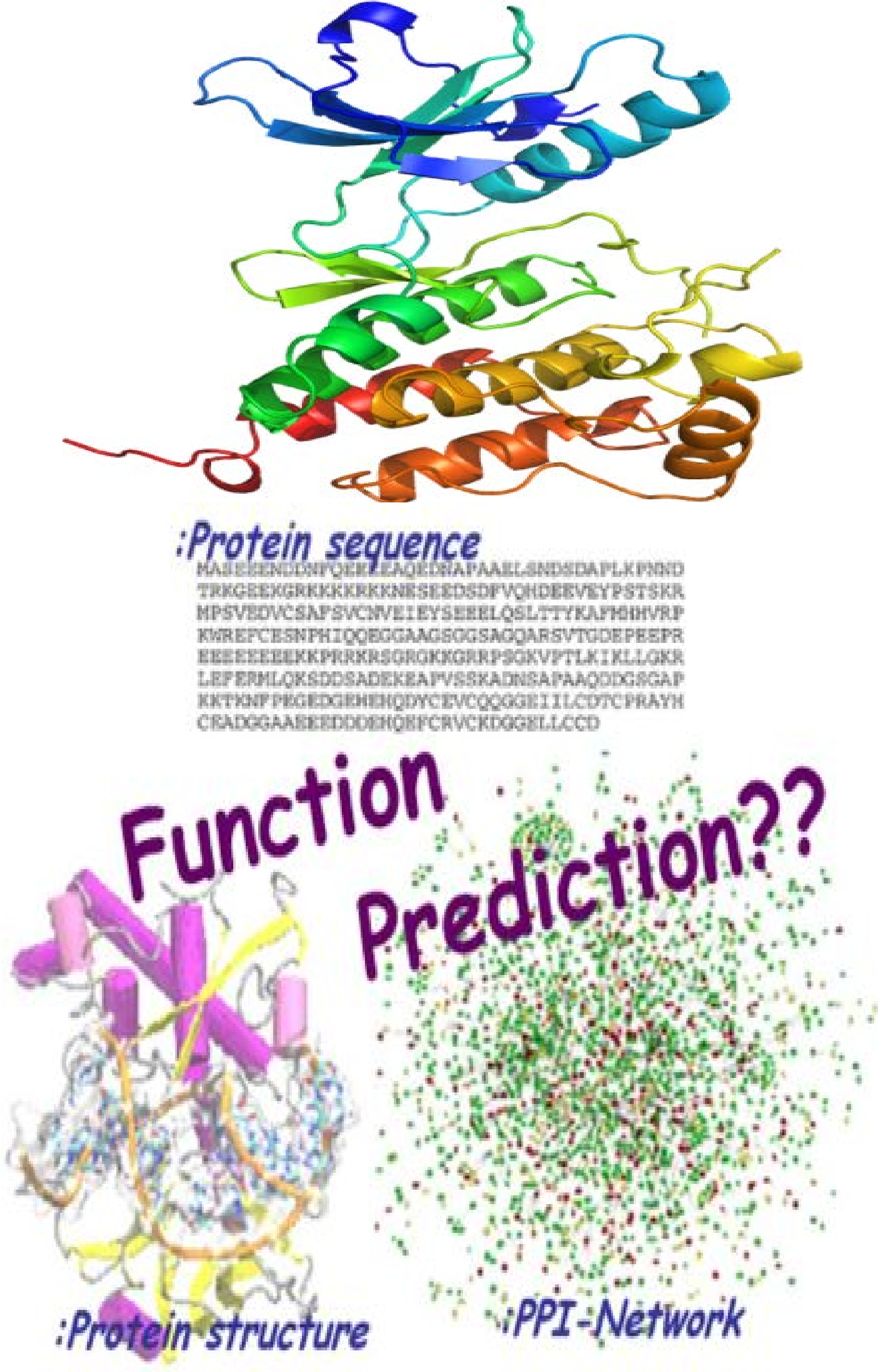
Poor immunization

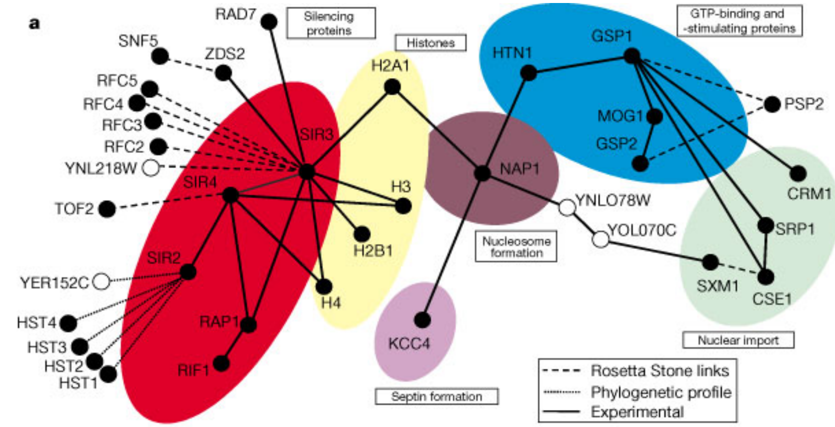
Efficient immunization

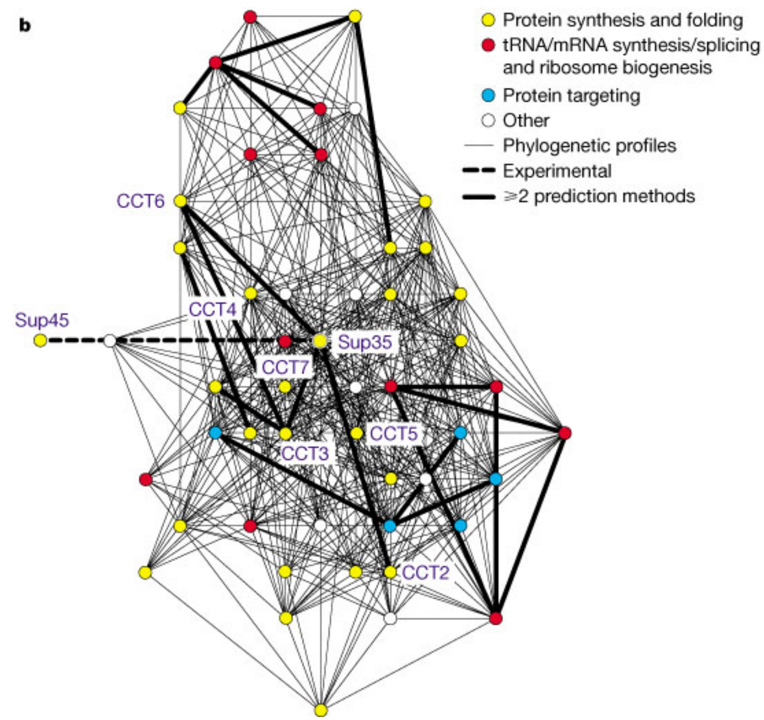
Cohen et al, Phys. Rev. Lett. 91 , 168701 (2003)

EPIWORK

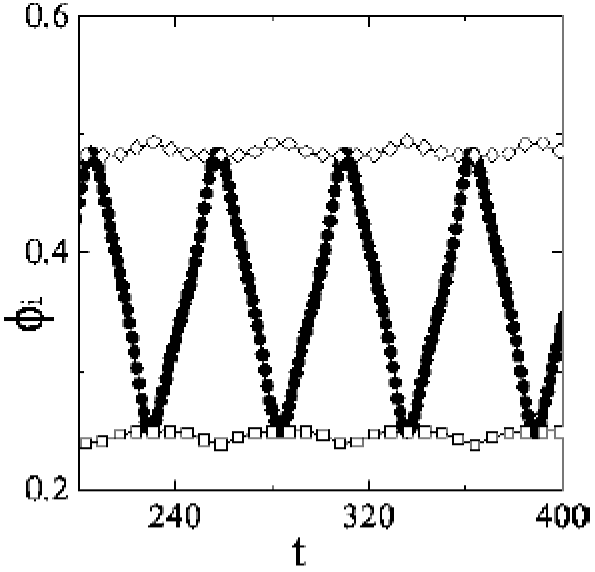

GLEaM
R_0 = 1.9
127 days
146 days
178 days
time: number of days since the first importation of cases
Agent-based
R_0 = 1.9

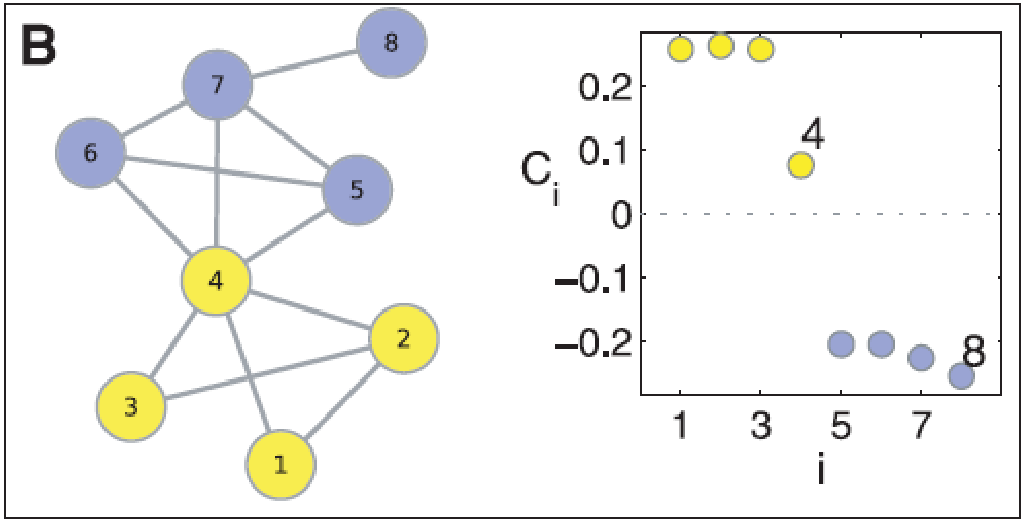

:Protein sequence
Function Prediction??
:Protein structure
:PPI-Network


a
Silencing proteins
Histones
GTP-binding and -stimulating proteins
RAD7
SNF5
ZDS2
RFC5
RFC4
RFC3
RFC2
YNL218W
TOF2
SIR3
SIR4
SIR2
YER152C
HST4
HST3
HST2
HST1
RAP1
RIF1
H2A1
H3
H2B1
H4
KCC4
HTN1
GSP1
MOG1
GSP2
PSP2
NAP1
YNLO78W
YOL070C
CRM1
SRP1
SXM1
CSE1
Nucleosome formation
Nuclear import
Septin formation
Rosetta Stone links
Phylogenetic profile
Experimental


b
Protein synthesis and folding
tRNA/mRNA synthesis/splicing and ribosome biogenesis
Protein targeting
Other
Phylogenetic profiles
Experimental
⩾2 prediction methods
CCT6
CCT4
Sup45
Sup35
CCT7
CCT5
CCT3
CCT2

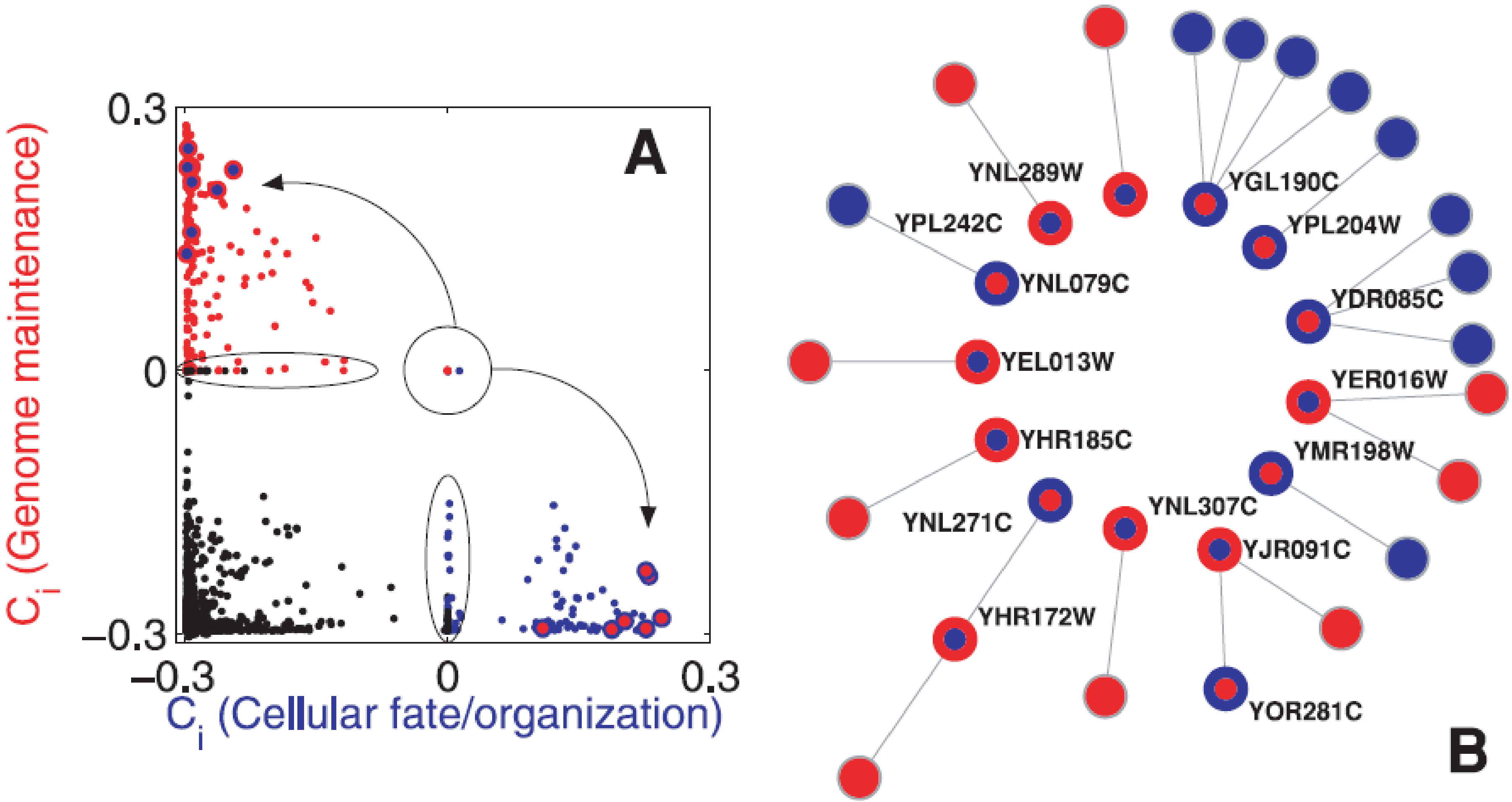
Unveiling Protein Functions by Synchronization in the Interaction Network



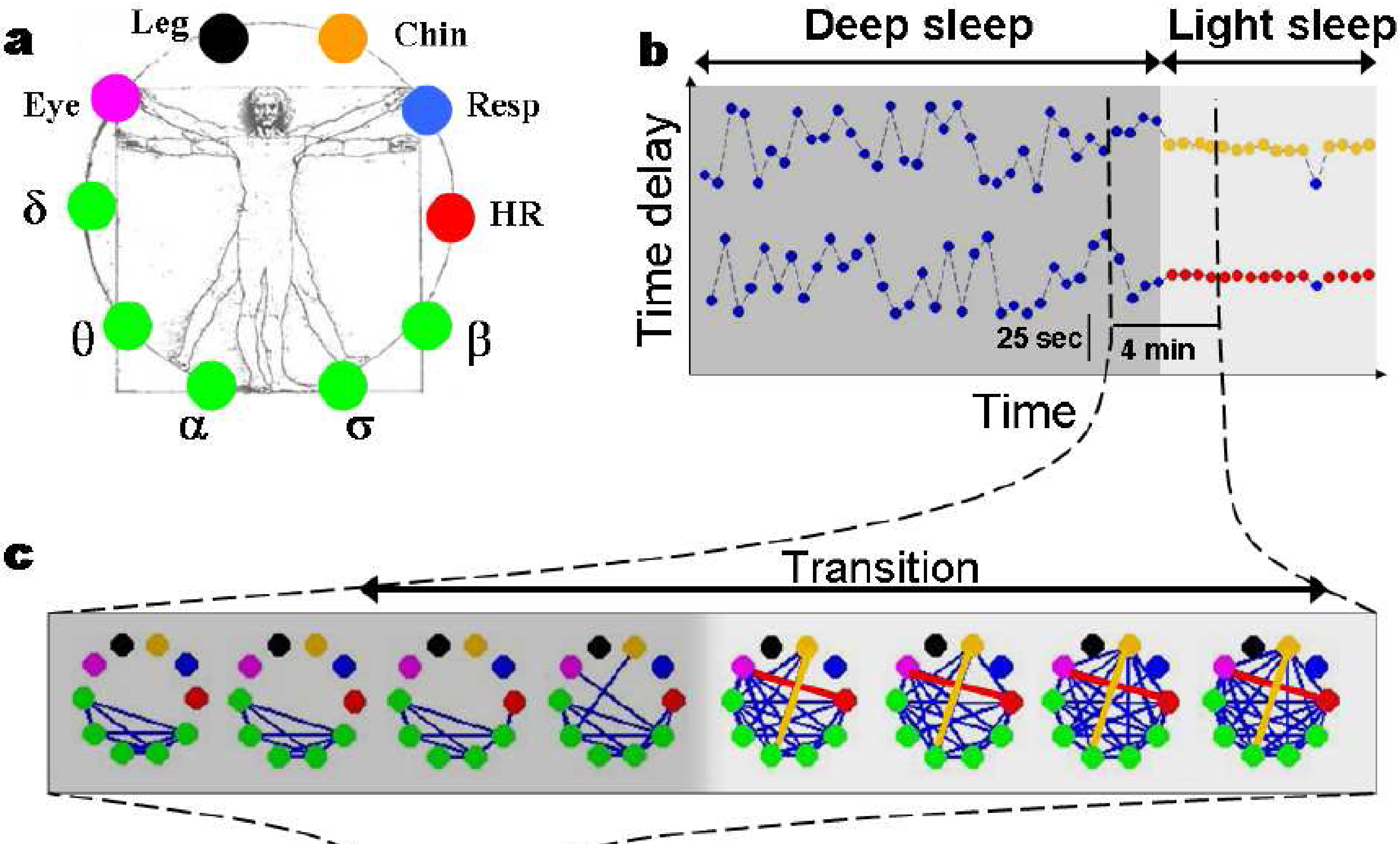


Irene Sendin˜a–Nadal, Yanay Ofran, Juan A. Almendral1, Javier M. Buldu, Inmaculada Leyva, Daqing Li, Shlomo Havlin, Stefano Boccaletti, Plos One (2011)

Unveiling Protein Functions by Synchronization in the Interaction Network



Irene Sendin˜a–Nadal, Yanay Ofran, Juan A. Almendral, Javier M. Buldu, Inmaculada Leyva, Daqing Li, Shlomo Havlin, Stefano Boccaletti, Plos One (2011)



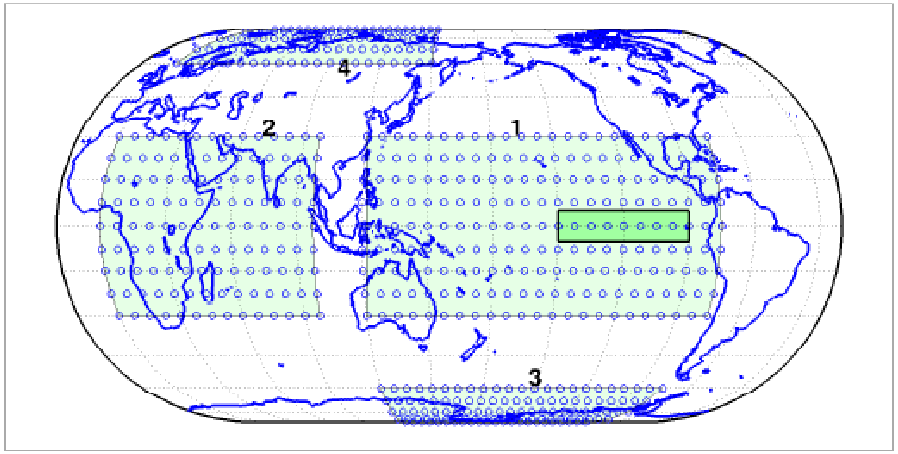
Bashan et al, Nature Communication [2012]

Structure and Function

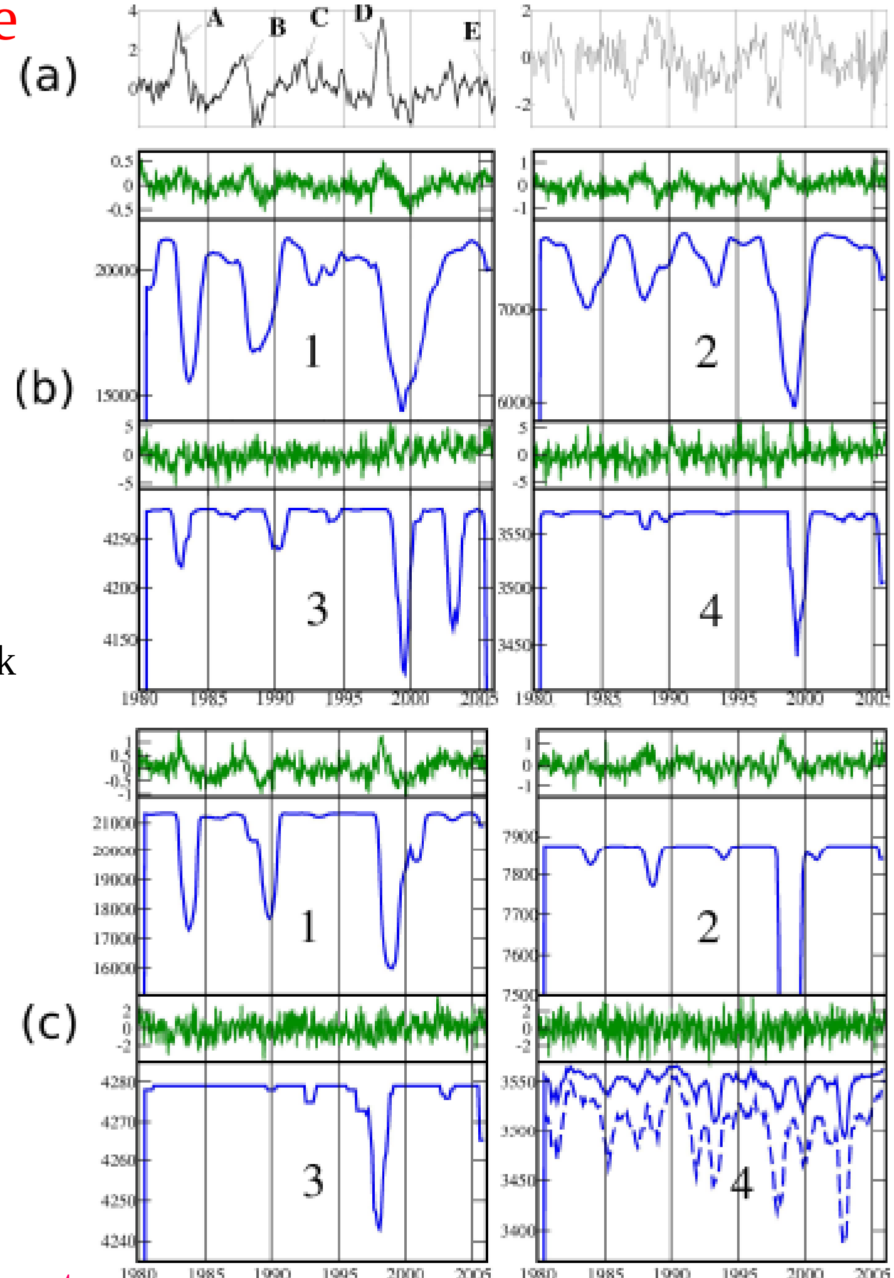
Makse et al, PNAS (2012) optimized transport in brain

(Andrade et al PRL 2010, PRE (2013))

Climate networks are very sensitive to El Nino



Sea surface temperature network

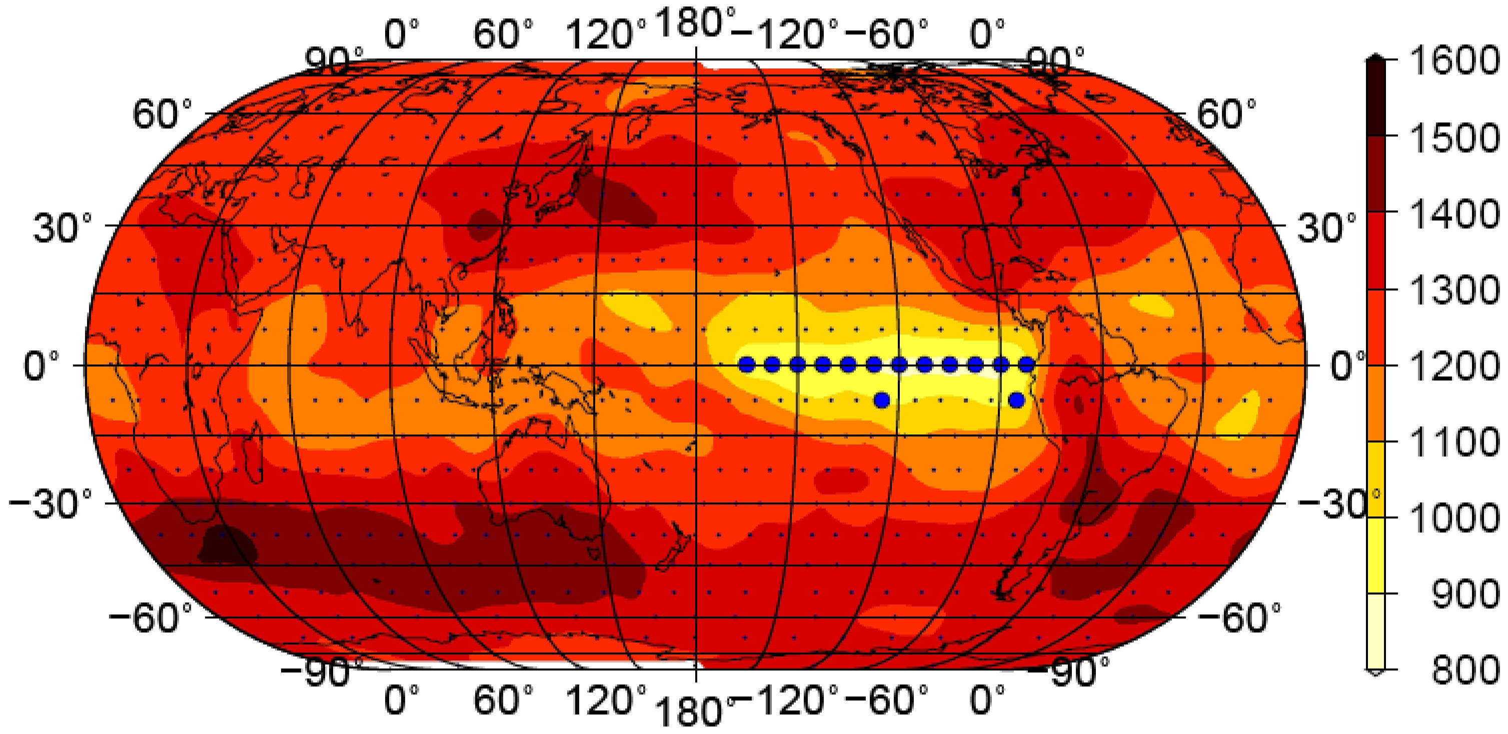


5km height temperature network

Yamasaki, Gozolchiani, SH (PRL 2008, 2011)

Challenge: Predicting El-Nino and other extreme events

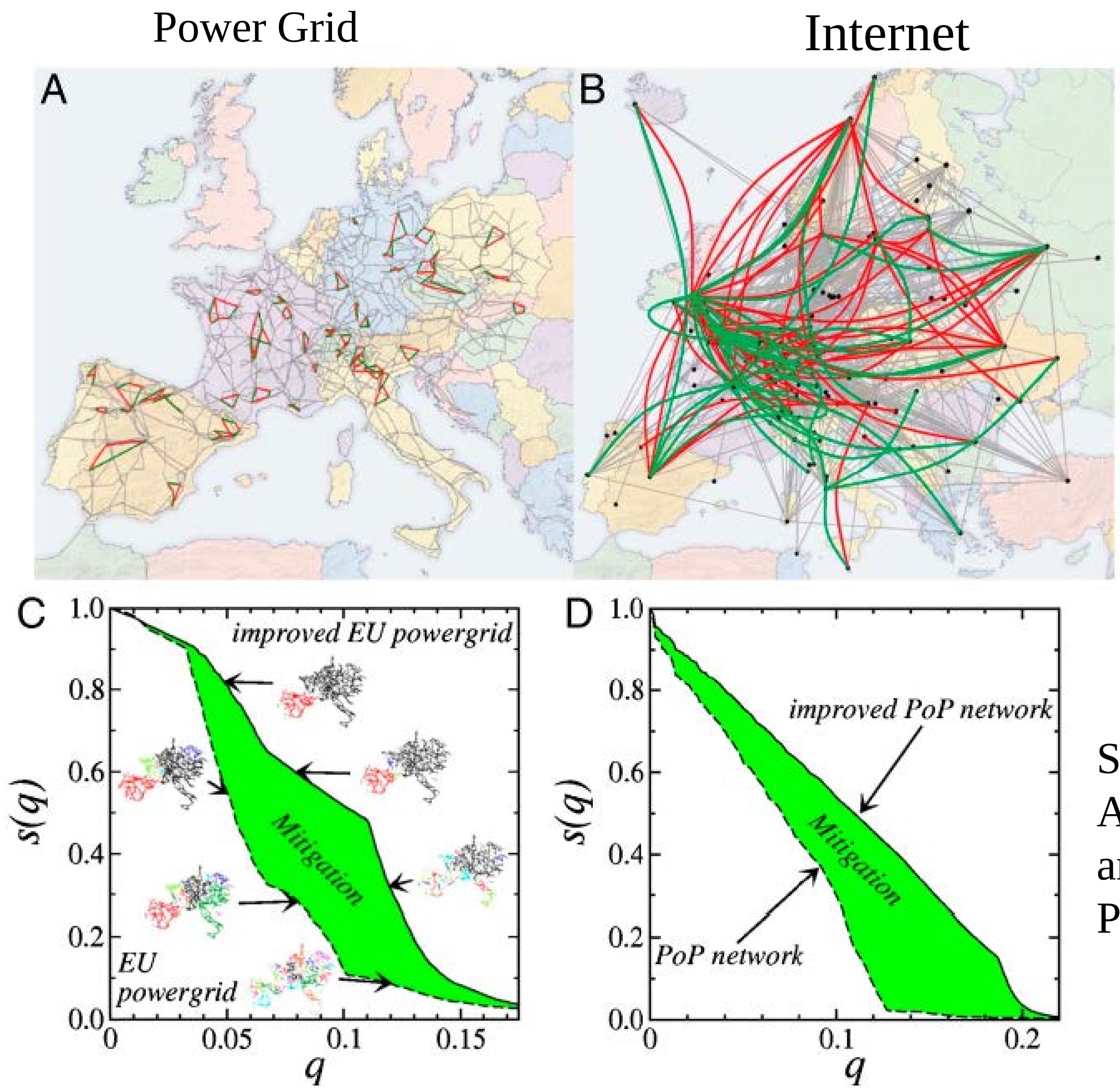
EL-NINO BECOMES AUTONOMOUS: ONLY INFUENCE-NOT INFLUENCED



$$\langle I_l^y \rangle_{y \in El-Nino}$$

Gozolchiani et al PRL (2011)

Mitigation of malicious attacks on networks



Schneider, Moreira, Andrade, SH and Herrmann PNAS (2011)

VOLUME 279
NUMBER 73

Suggested retail price
$1.00
$1.50 outside of
Metro Boston

The Boston Globe

MONDAY, MARCH 14, 2011

A NEW WEAK

TODAY: *Partly sunny and colder. H*
37-42. Low 27-32.
TOMORROW: *Mostly sunny, milde*
High 42-47. Low 32-37.
HIGH TIDE: *6:42 a.m., 7:25 p.m.*
SUNRISE: *6:59* SUNSET: *6:49*
FULL REPORT: PAGE B13

Cascading disaster in Japan

Blast shakes a second reactor death toll soar

By Martin Fackler and Mark McDonald
NEW YORK TIMES

SENDAI, Japan — Japan reel from a rapidly unfolding disaster epic scale yesterday, pummeled by death toll, destruction, and homele ness caused by the earthquake a tsunami and new hazards from da aged nuclear reactors. The prime m ister called it Japan's worst crisis si World War II.

Japan's $5 trillion economy, t world's third largest, was threaten with severe disruptions and partial ralysis as many industries shut do temporarily. The armed forces and v unteers mobilized for the far more gent crisis of finding survivors, eva ating residents near the strick power plants and caring for the v tims of the record 8.9 magnitu quake that struck on Friday.

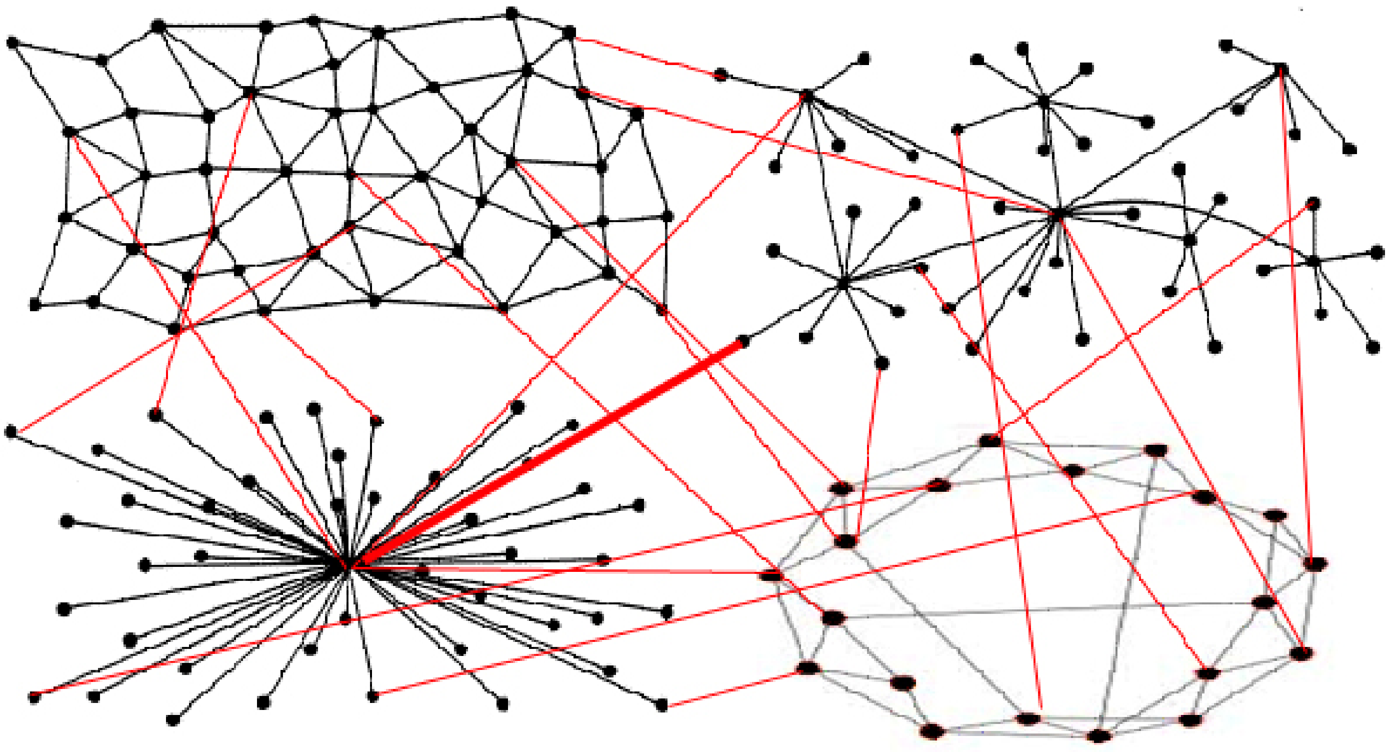
The disaster has left more th 10,000 dead, many thousands hon less, and millions without water, po er, heat, or transportation.

Catastrophic Cascading Failures in Interdependent Networks

Work with:

A. Bashan (BIU)
Y. Berezin (BIU)
S. Buldyrev (NY)
R. Parshani (BIU)
J. Gao (BU)
H. E. Stanley (BU)

Nature, 464, 1025 (2010)
PRL ,105, 0484 (2010)
PNAS, 108, 1007 (2011)
PRL, 107, 195701 (2011)
Nature Physics (2012)
Nature Comm. (2012)



Electric grid,
Communication
Transportation
Services …..

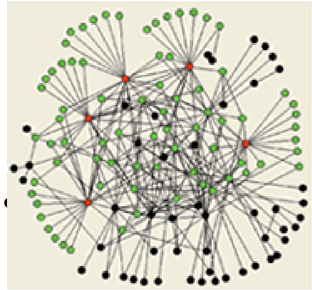
Two types of links:
1. Connectivity
2. Dependency

Cascading disaster

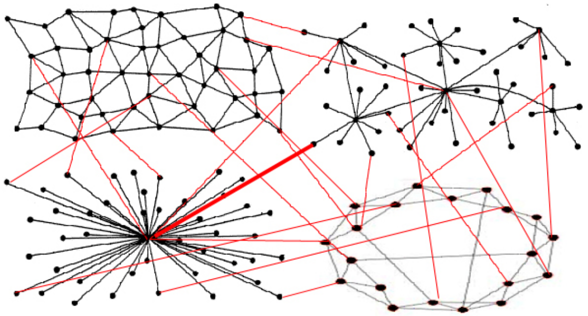
Raissa D'sousa-same type

Interdependent Networks

- Until recently (2010) studies focused on a single network which is isolated AND does not interact or influenced by other systems.

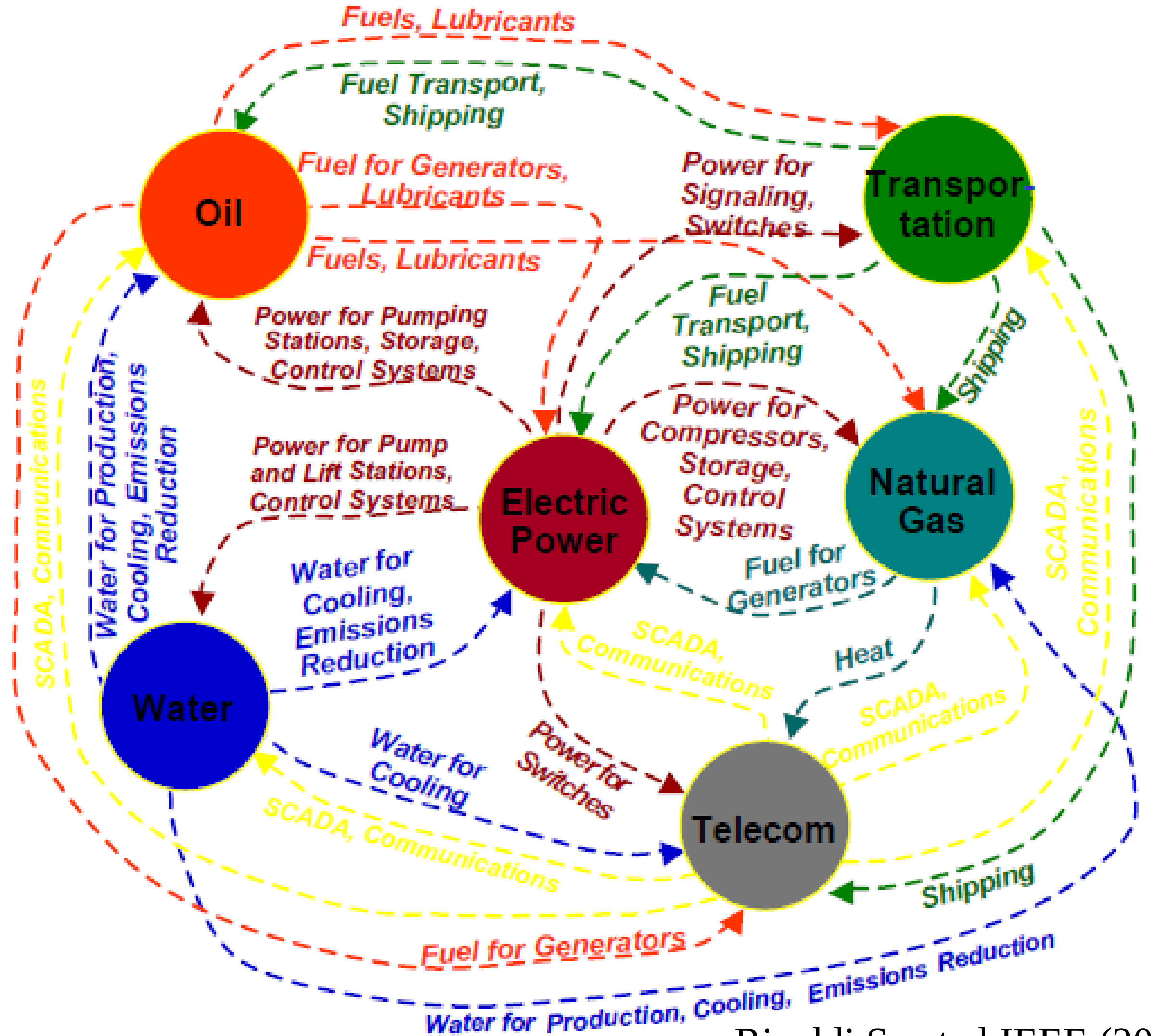


- Isolated systems rarely occur in nature or in technology -- analogous to non-interacting particles (molecules, spins).



- Results for interacting networks are strikingly different from those of single networks.

How interdependent are infrastructures?

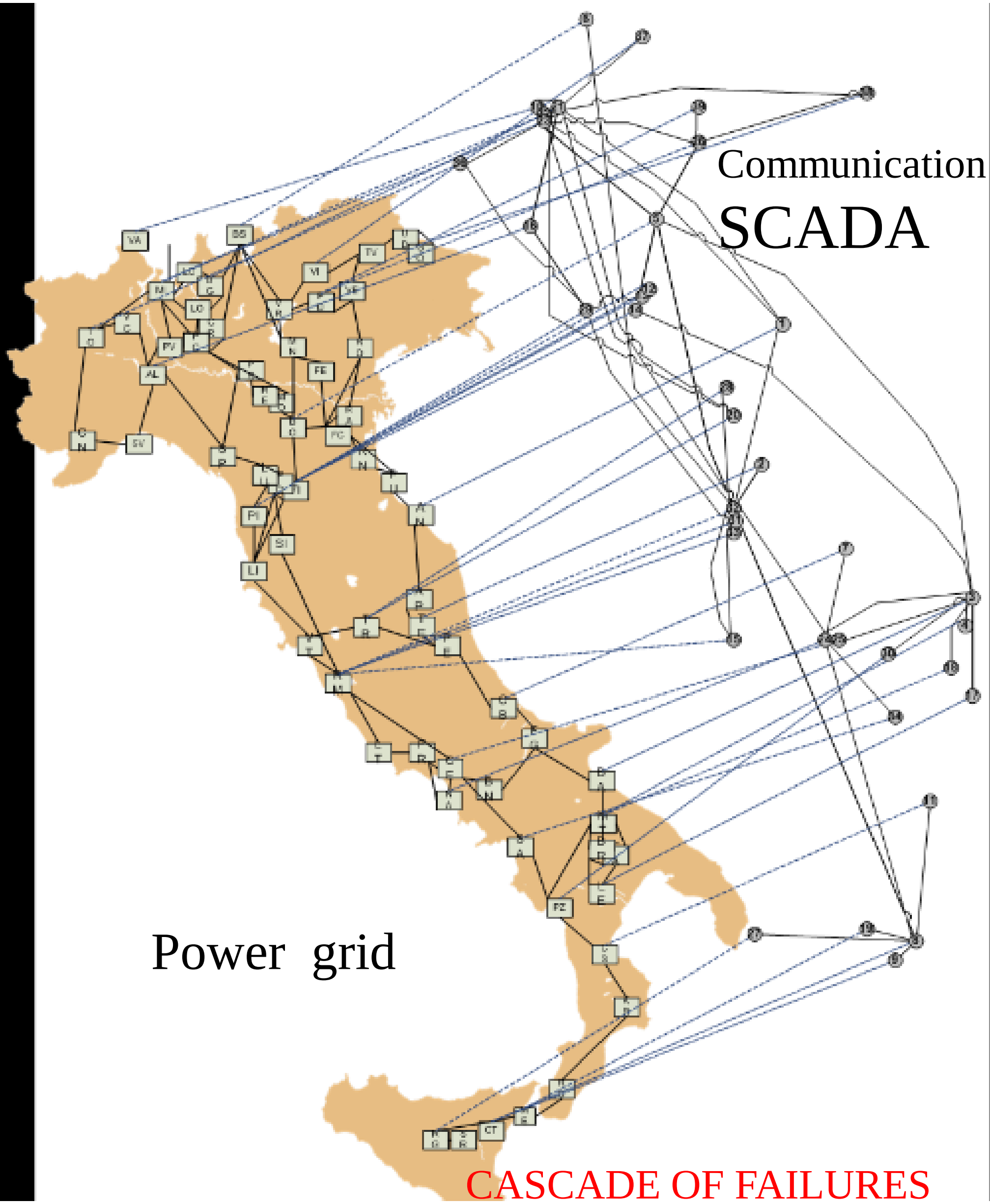


Rinaldi S, et al IEEE (2001)

Blackout in Italy (28 September 2003)

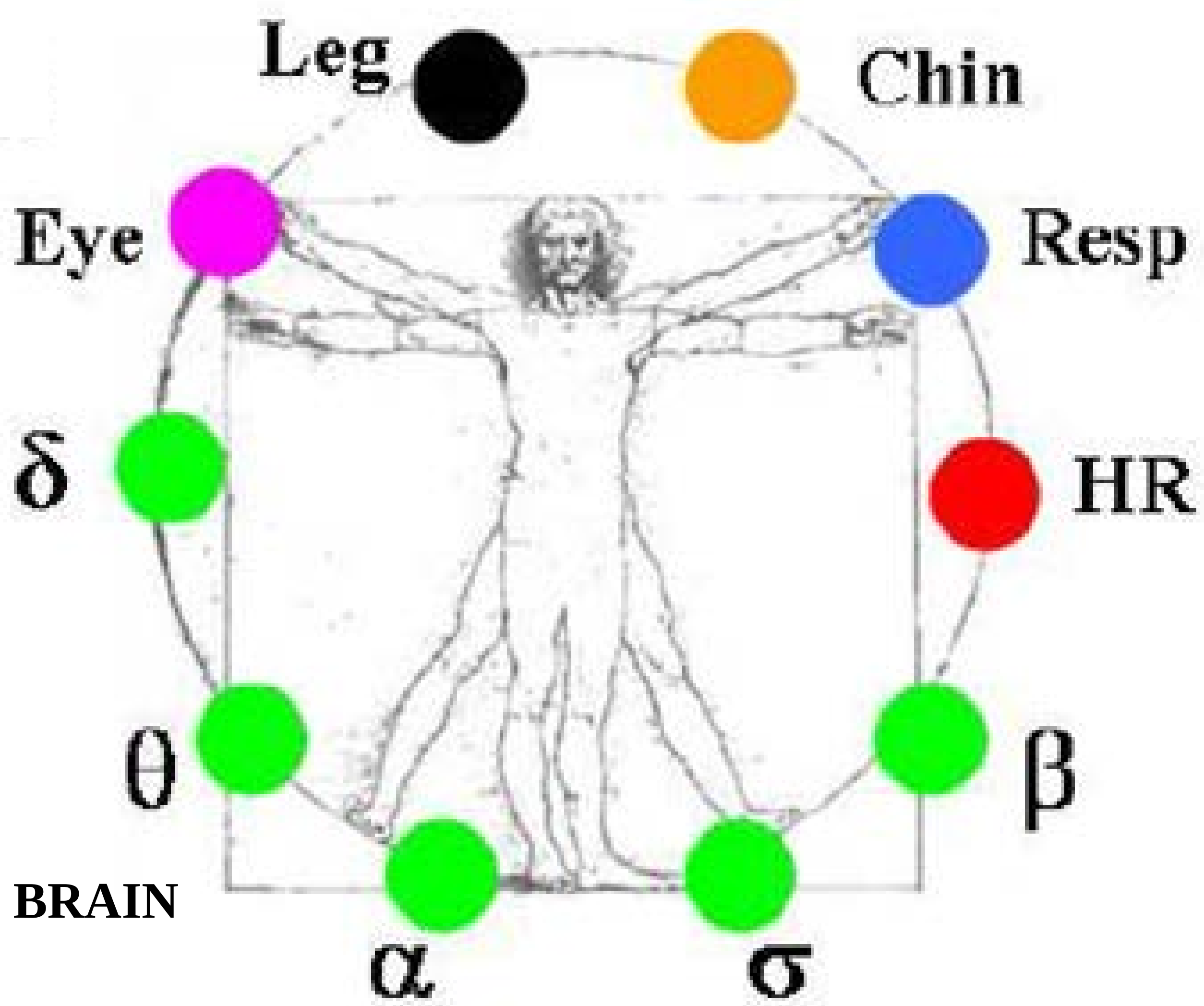
Cyber Attacks-CNN Simulation (2010)

Rosato et al Int. J. of Crit. Infrastruct. 4, 63 (2008)



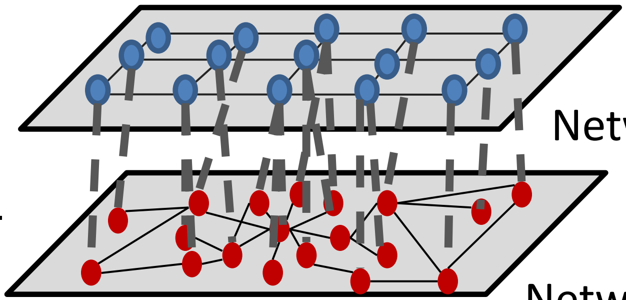
Railway network, health care systems, financial services, communication systems

HUMAN BODY: NETWORK OF NETWORKS



Further Examples of Interdependent Networks

Appear in all aspects of life, nature and technology



- *Physiology*: The human body can be seen as inter-dependent networks. For example, the cardio-vascular network system, the respiratory system, the brain network, and the nervous system all depend on each other.

•*Biology*: A specific cellular function is performed by a network of interacting proteins. Such networks depend on each other through proteins that perform several functions.

•*Transportation* : Railway networks, airline networks and other transportation systems are interdependent.

Critical Breakdown Threshold of Interdependent Networks

Failure in network A
causes failure in B, C, D… → causes further failure in A …..CASCADES
What are the critical percolation thresholds for such interdependent networks?
What are the sizes of cascade failures?

Buldyrev, Parshani, Paul, Stanley, S.H., Nature (2010); Parshani, Buldyrev, S.H. , Phys. Rev. Lett., (2010)

Comparing single and coupled networks: Robustness

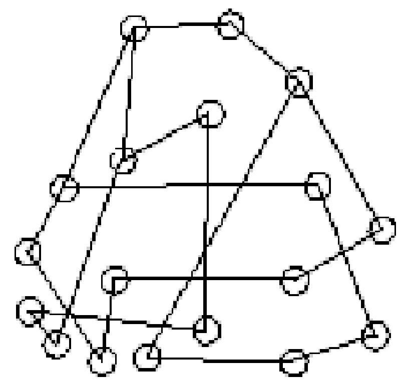
Remove randomly (or targeted) a fraction $1-p$ nodes

P_∞ Size of the largest connected component (cluster)

p_c Breakdown threshold

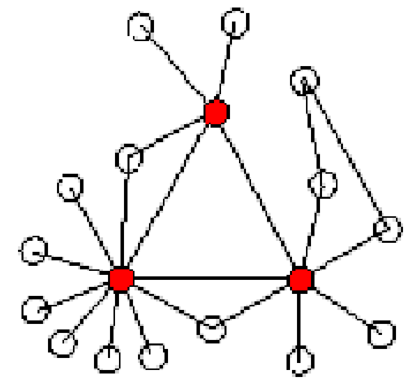
Single networks:
Continuous transition

Exponential (ER)

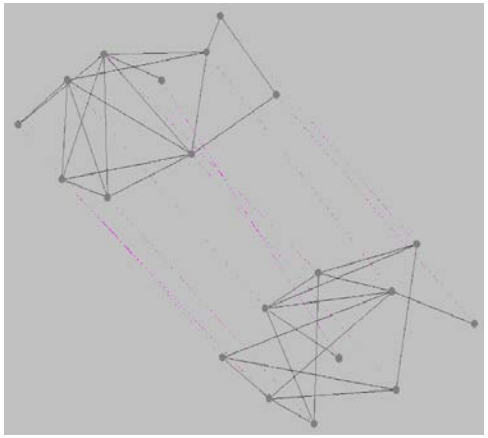


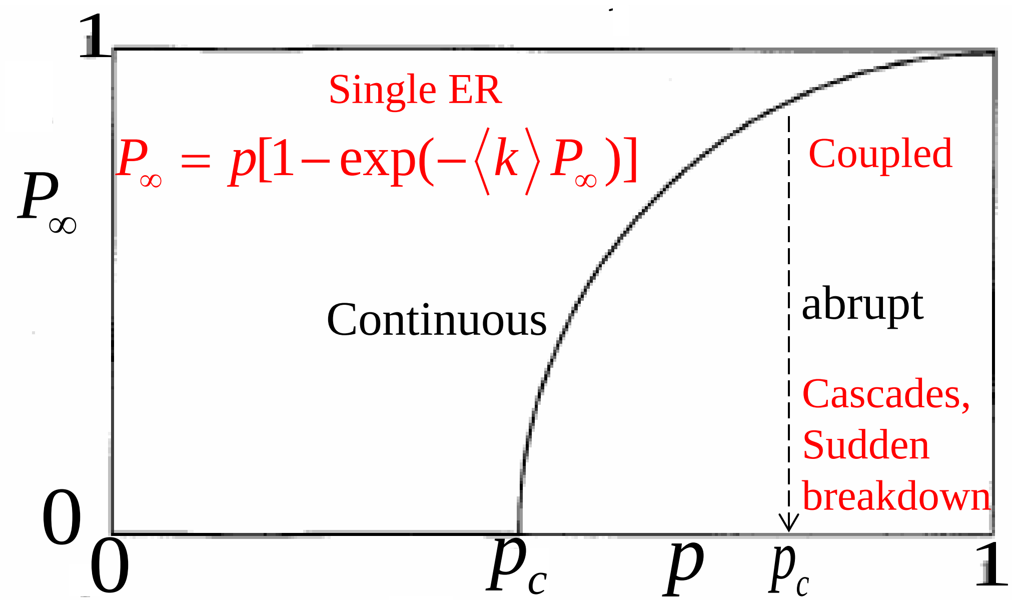
$$P(k) = e^{-\langle k \rangle} \frac{\langle k \rangle^k}{k!}$$

Scale-free (SF)



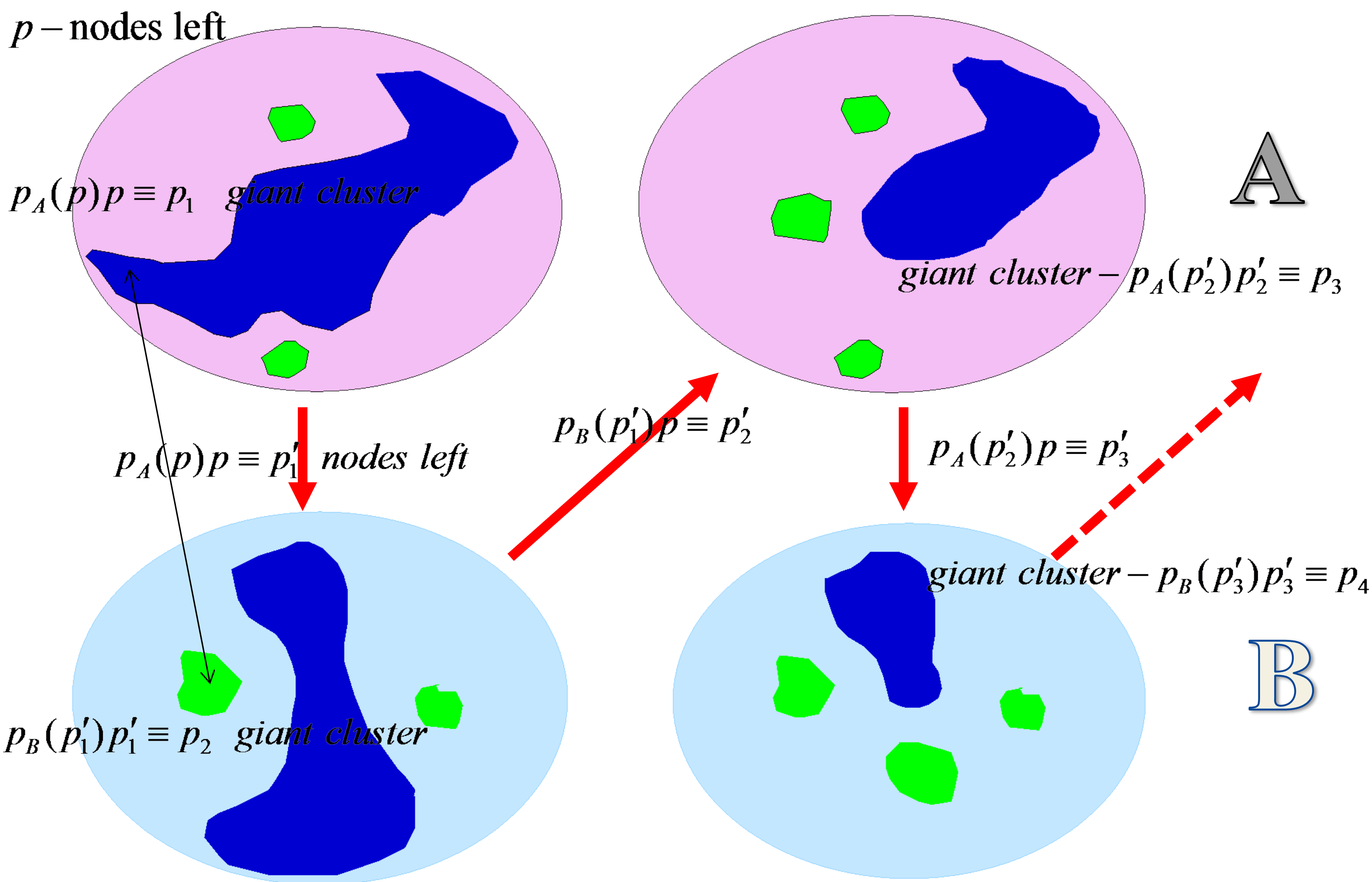
$$P(k) = \begin{cases} ck^{-\lambda} & m \le k \le K \\ 0 & otherwise \end{cases}$$





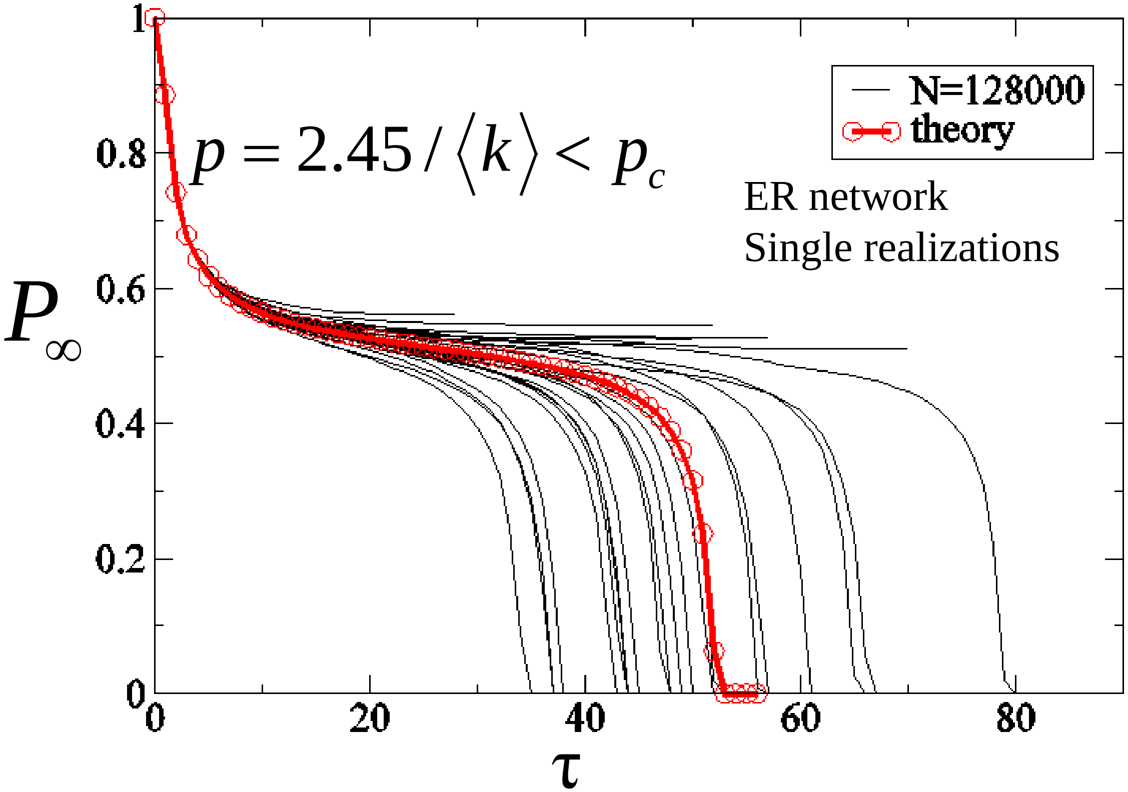
Coupled networks:
New paradigm-Abrupt transition
Cascading Failures

RANDOM REMOVAL – PERCOLATION FRAMEWORK

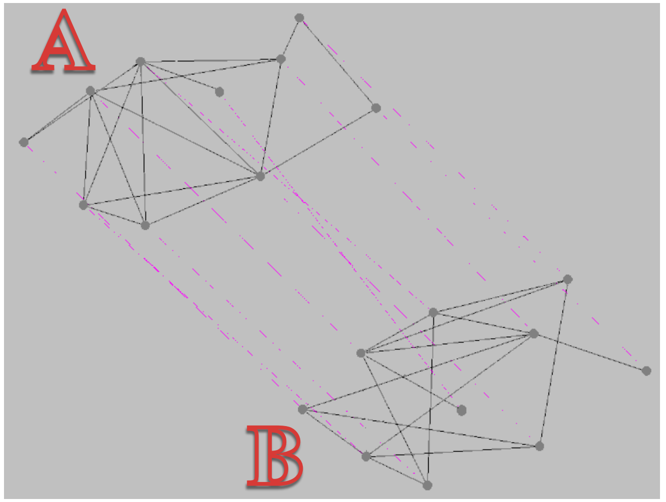


RESULTS: THEORY and SIMULATIONS: ER Networks

P_∞ after τ-cascades of failures



Removing 1-p nodes in A



Catastrophic cascades just below p_c

ABRUPT TRANSITION (1st order)

$p_c = 2.4554/\langle k \rangle$ For a single network $p_c = 1/\langle k \rangle$

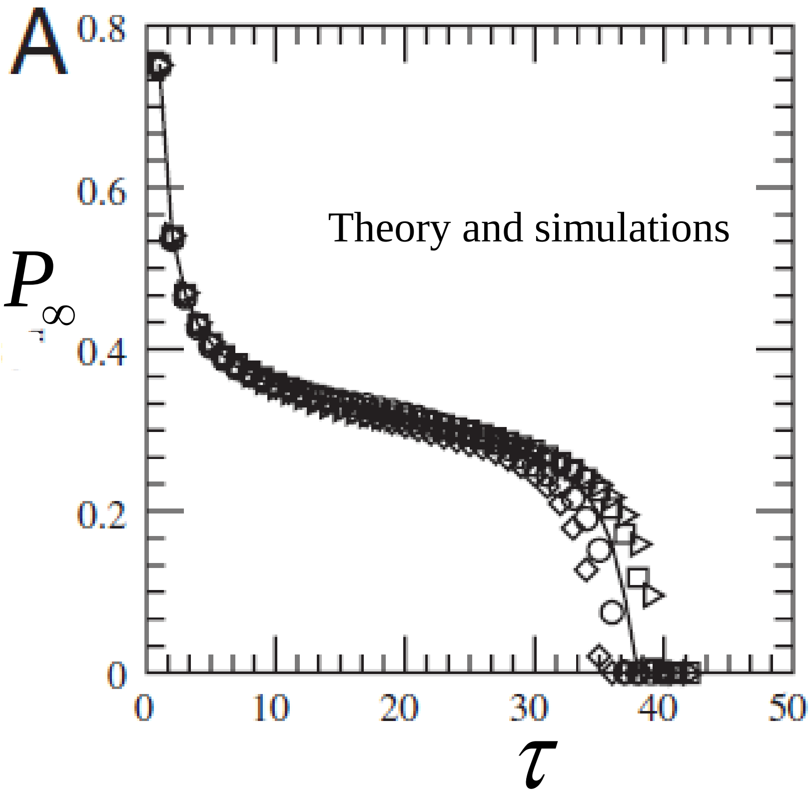
$\langle k \rangle_{\min} = 2.4554$ for single network $\langle k \rangle_{\min} = 1$

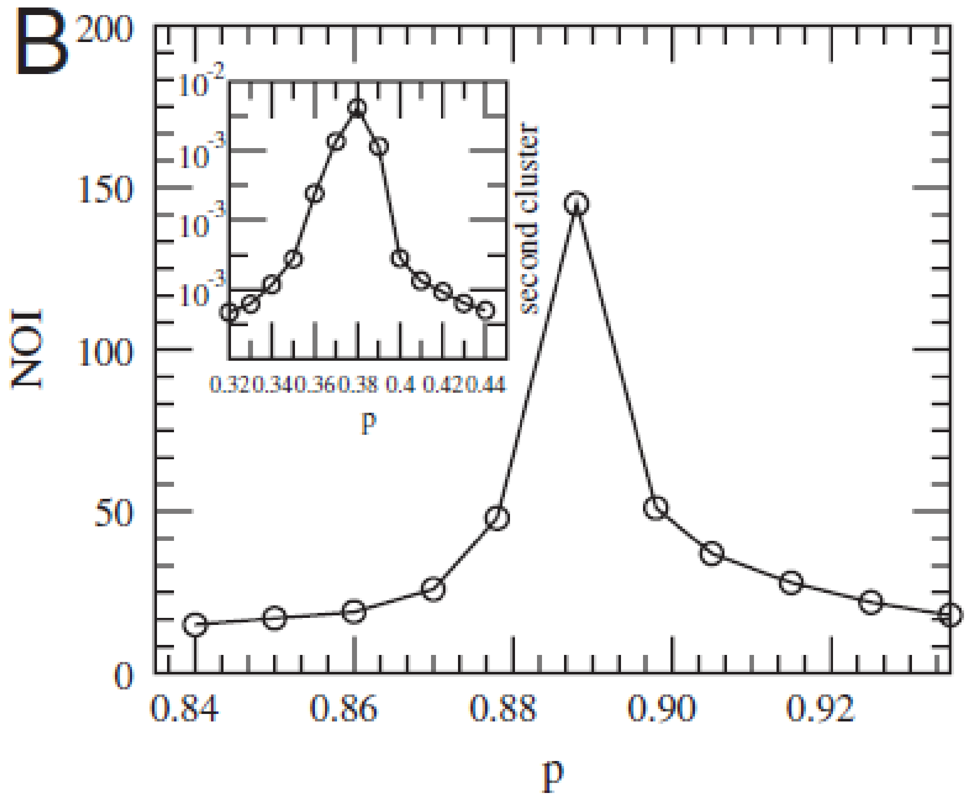
$\langle \tau \rangle \sim N^{1/3}$

Dong Zhou et al (2013)

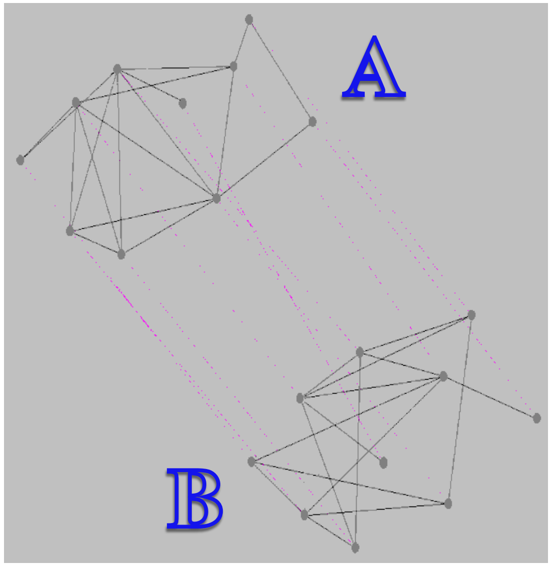
Partial Interdependent Networks

Determining p_c in simulations:





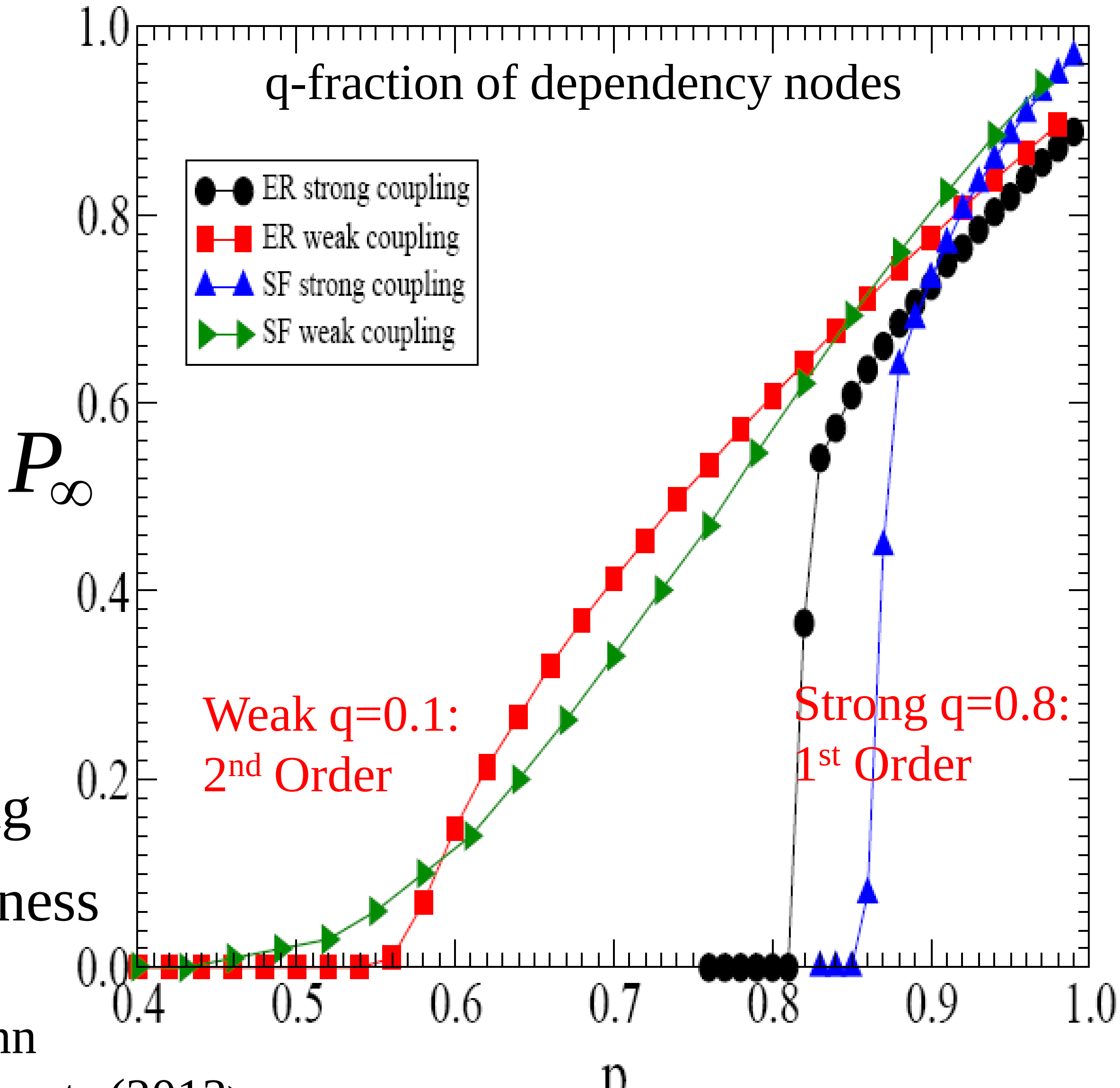
GENERALIZATION: PARTIAL DEPENDENCE: Theory and Simulations



Parshani, Buldyrev, S.H.
PRL, **105**, 048701 (2010)

$q_c \cong 0.2$ for random coupling

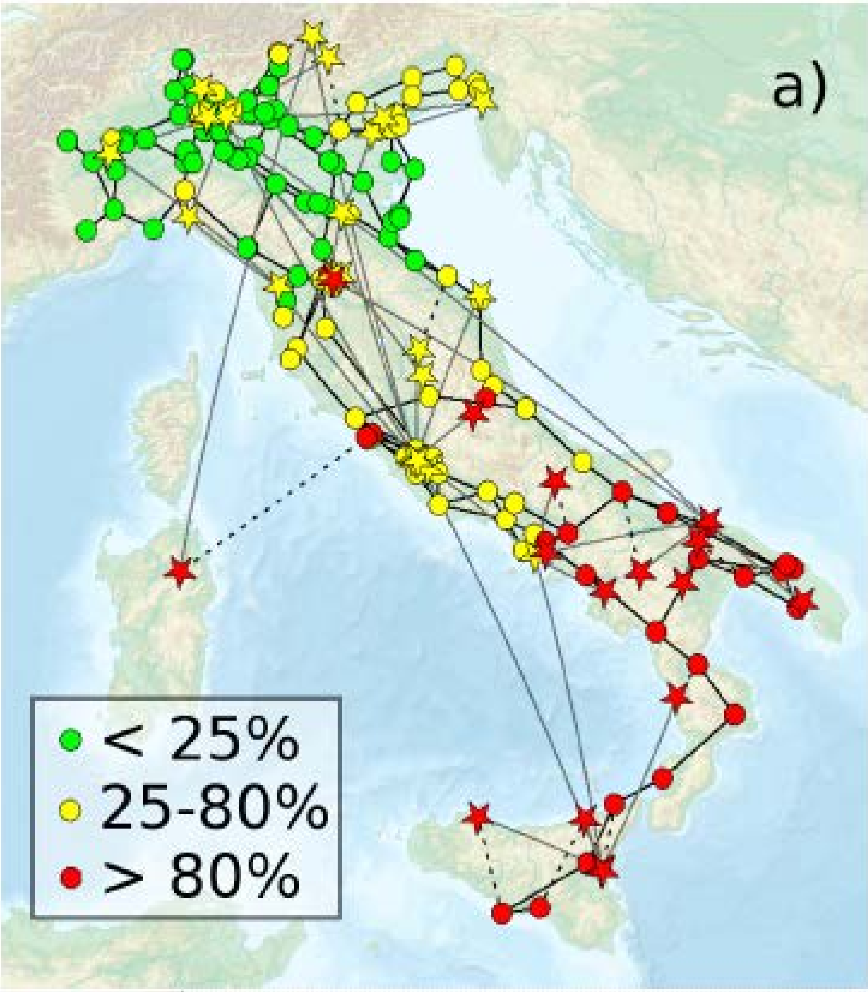
$q_c \to 0.9$ for optimal robustness



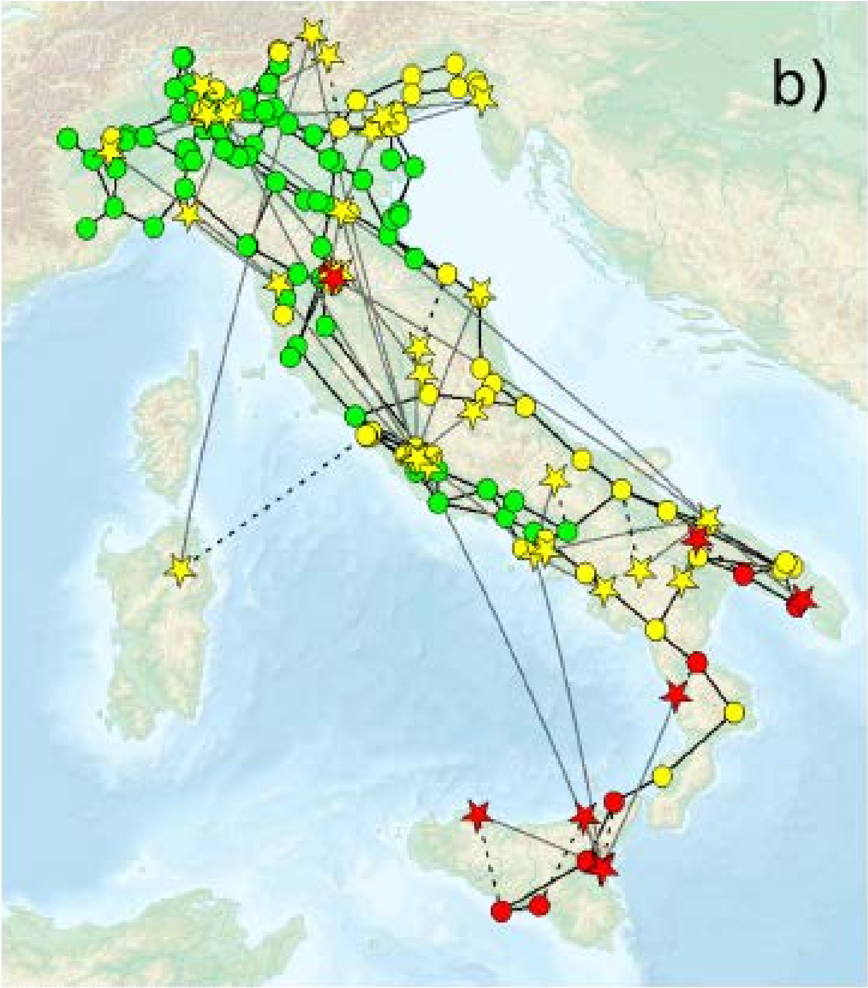
Schneider, Araujo, SH, Herrmann
arXiv:1106.3234, Scientific Reports (2013)

Designing Robust Coupled Networks:
Italy 2003 blackout

Random interdependencies



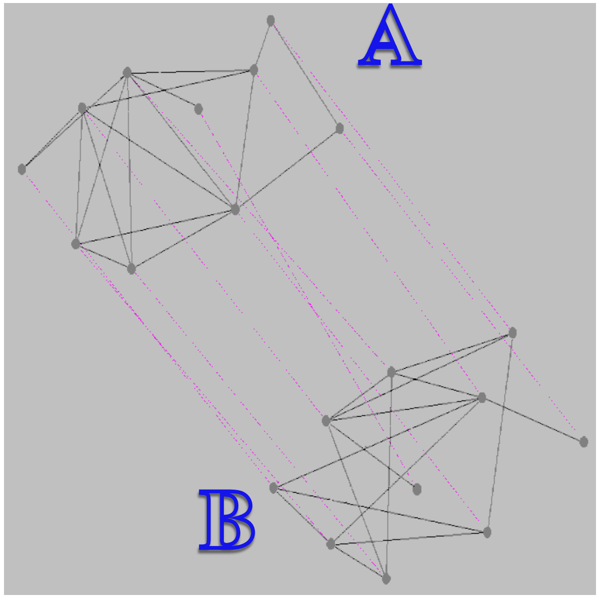
Nearly optimal interdependencies



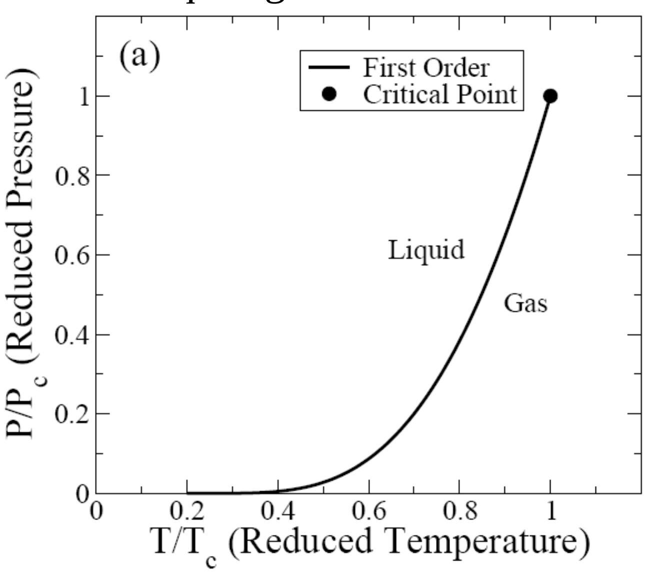
Schneider, Araujo, Havlin , Herrmann, Designing Robust Coupled Networks, Scientific Reports (2013)

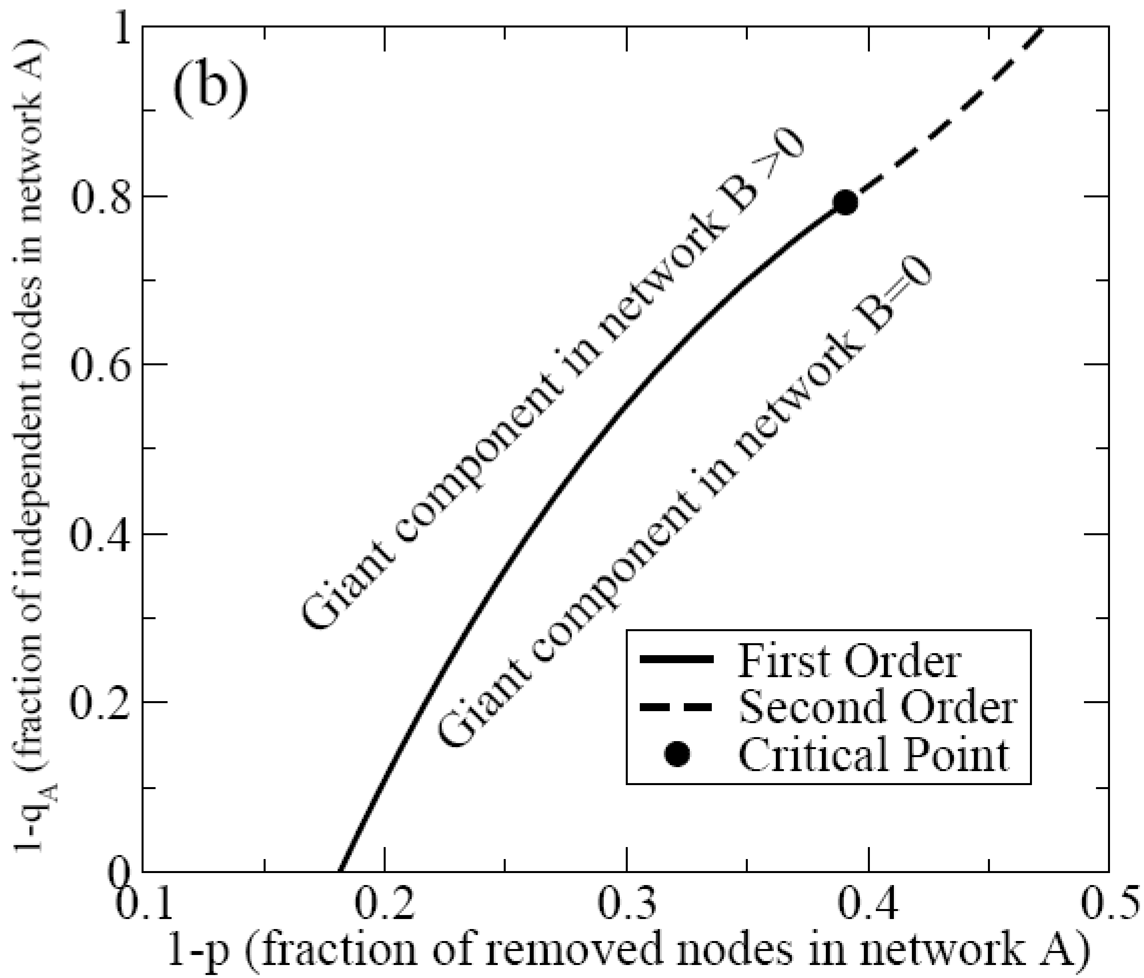
PARTIAL DEPENDENCE: critical point

Parshani et al
PRL, **105**, 048701 (2010)

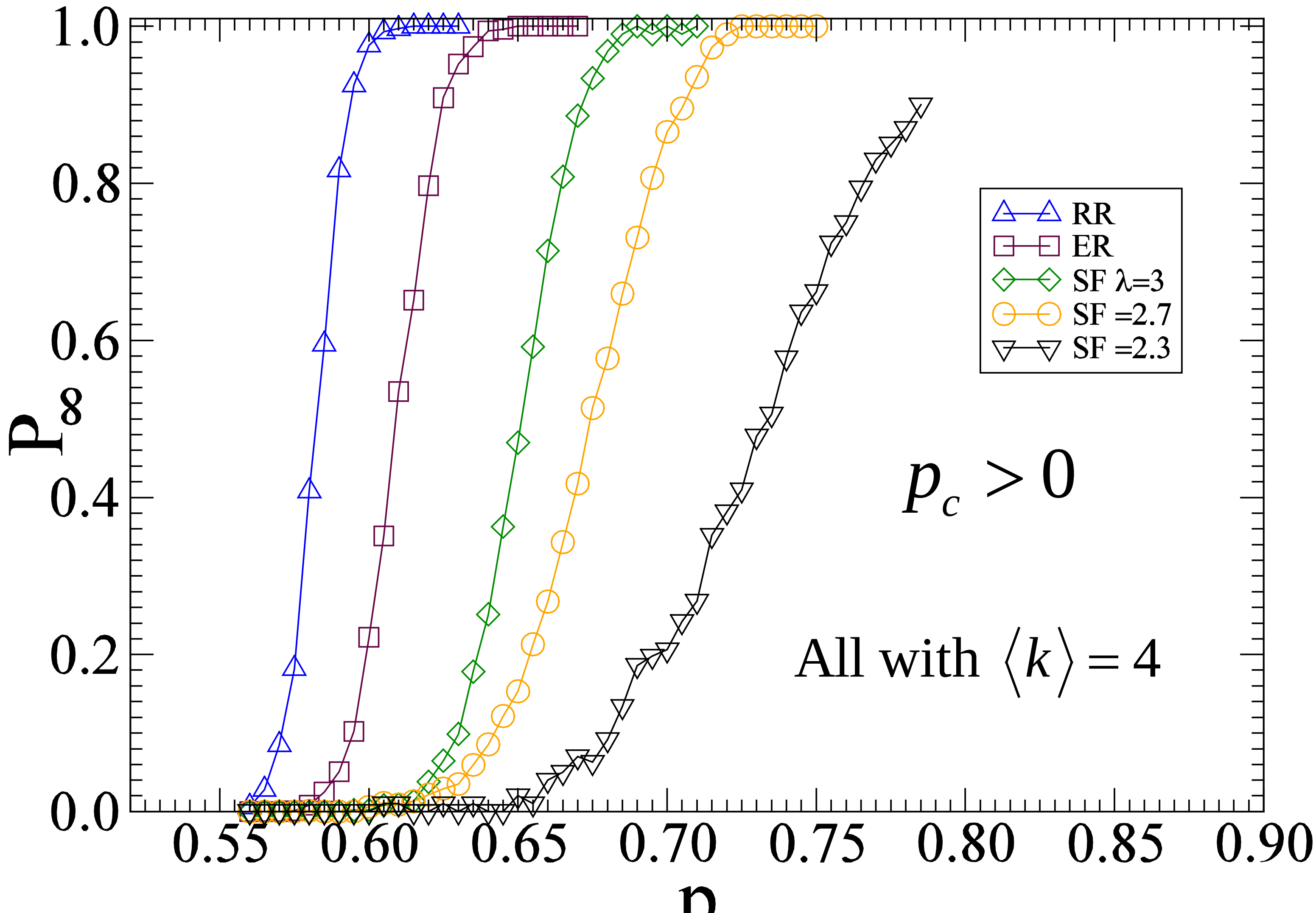


Analogous to critical point
in liquid-gas transition:





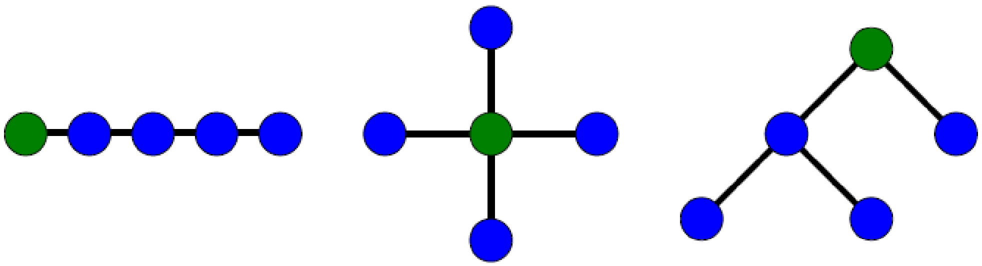
IN CONTRAST TO SINGLE NETWORKS, COUPLED NETWORKS ARE MORE VULNERABLE WHEN DEGREE DIST. IS BROADER

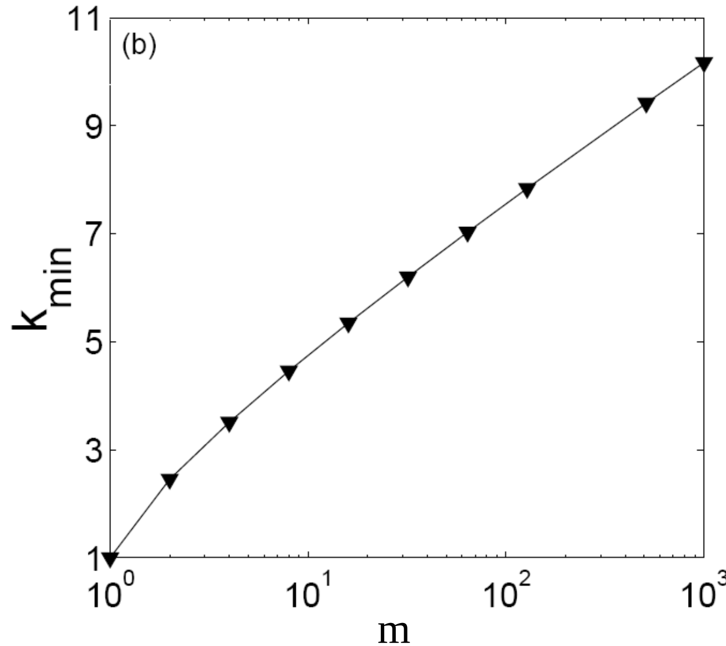


Buldyrev, Parshani, Paul, Stanley, S.H. Nature (2010)

Network of Networks (tree)

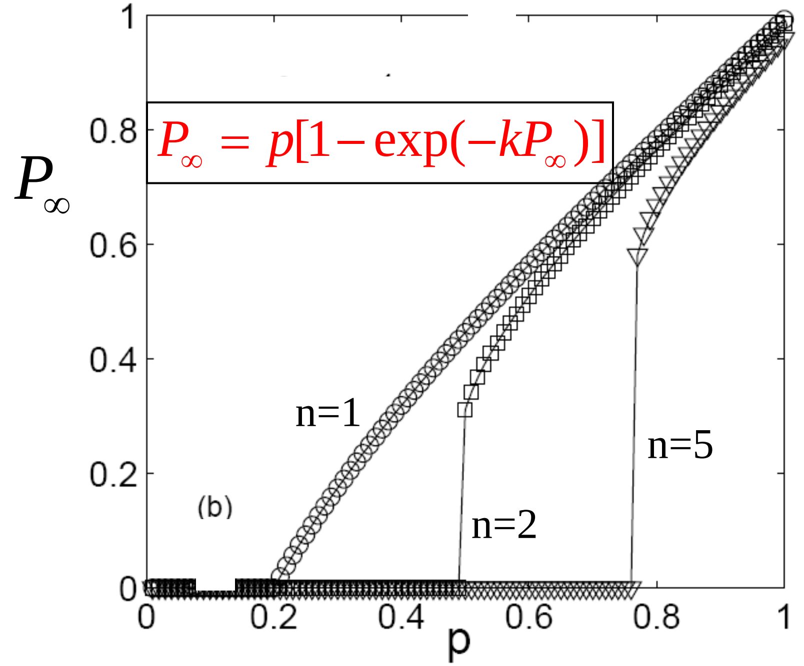
n=5





For ER, $\langle k_i \rangle = k$, full coupling ,
ALL loopless topologies (chain, star, tree):

$$P_\infty = p[1-\exp(-kP_\infty)]^n$$



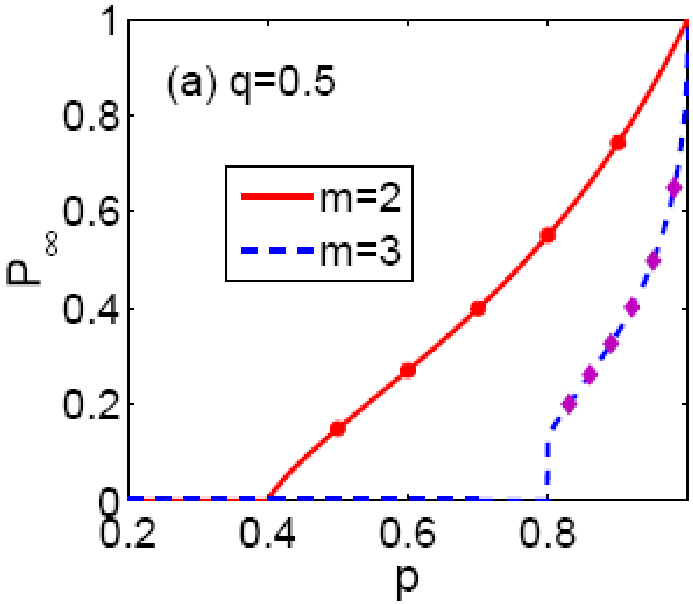
n=1 known ER- 2nd order

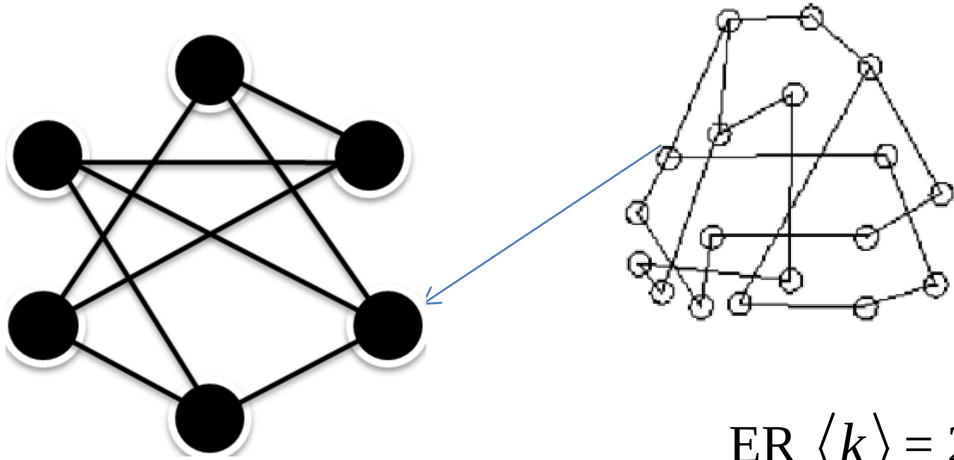
$$p_c = 1/\langle k \rangle$$

Gao et al PRL (2011)

Vulnerability increases significantly with n

Random Regular Network of ER networks





RR, m=3

ER $\langle k \rangle = 2.2$

$$P_\infty = \frac{p}{2^m}(1 - e^{-\langle k \rangle P_\infty})[1 - q + \sqrt{(1-q)^2 + 4qP_\infty}]^m$$

$$p_c = \frac{1}{\langle k \rangle (1-q)^m}$$

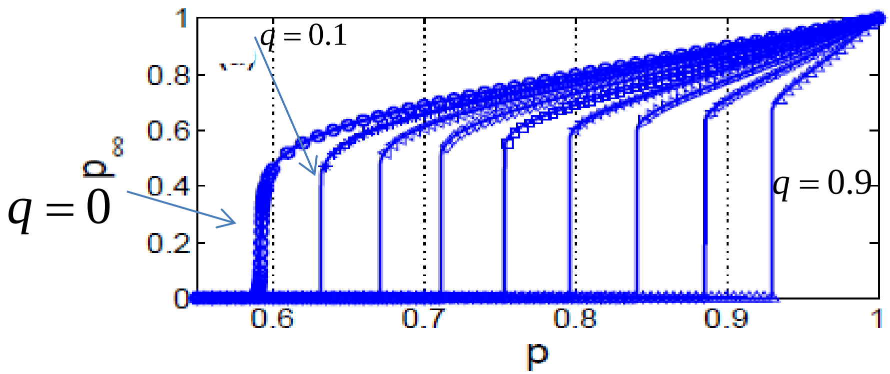
$$q_c = \frac{\langle k \rangle + m - \sqrt{m^2 + 2\langle k \rangle m}}{\langle k \rangle}$$

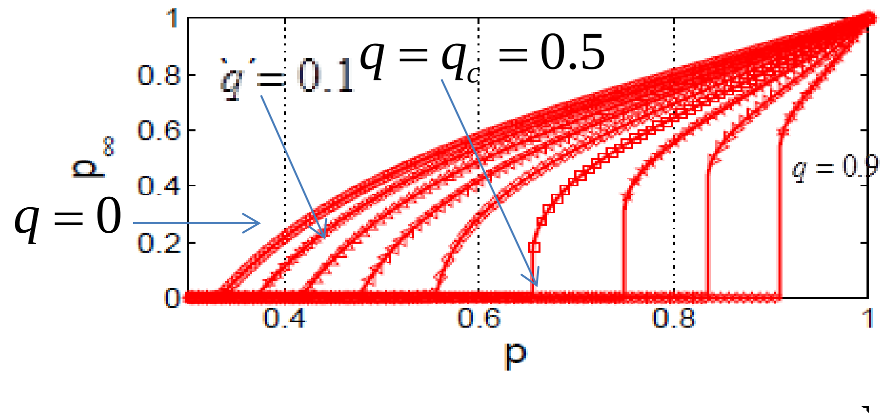
Surprisingly Independent on n!

For $m = 0$ OR $q = 0$ the single network is obtained!

$$P_\infty = p[1 - \exp(-\langle k \rangle P_\infty)]$$

Spatial embedded compared to random coupled networks when q changes





EXTREMELY VULNERABLE!!

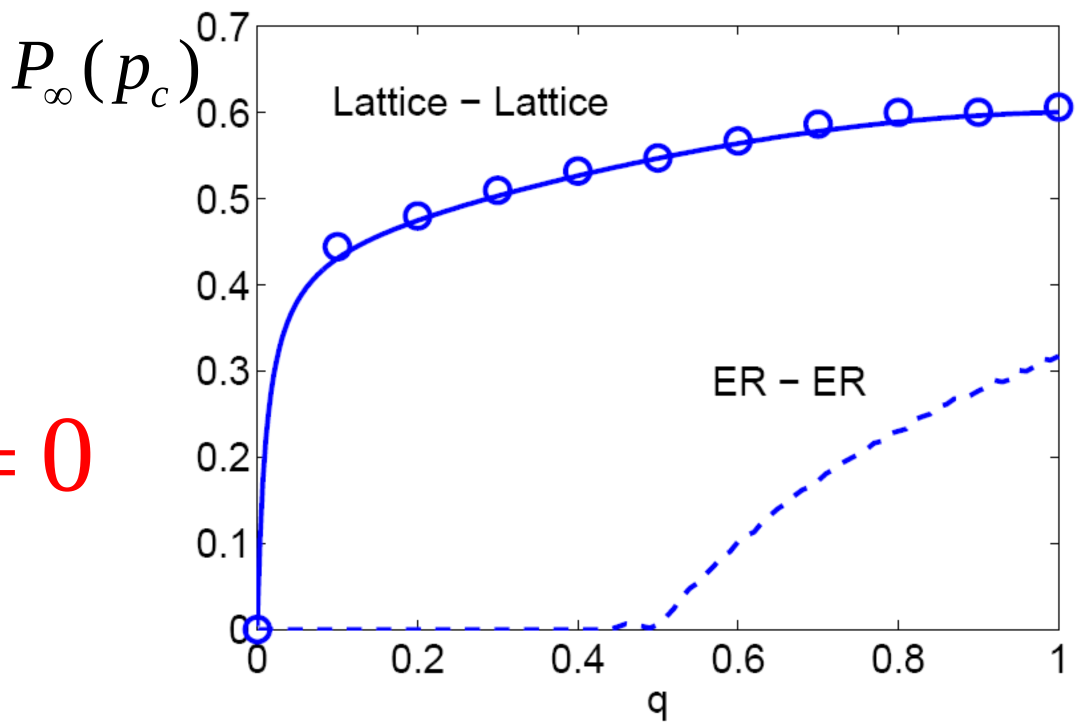
$$1 = p_c q_c P'_\infty(p_c)$$

$P_\infty \sim (p - p_c)^\beta$

$\beta = 5/36 < 1$ for d=2

For ER and d=6, β=1

$$q_c = 0$$



Bashan et al

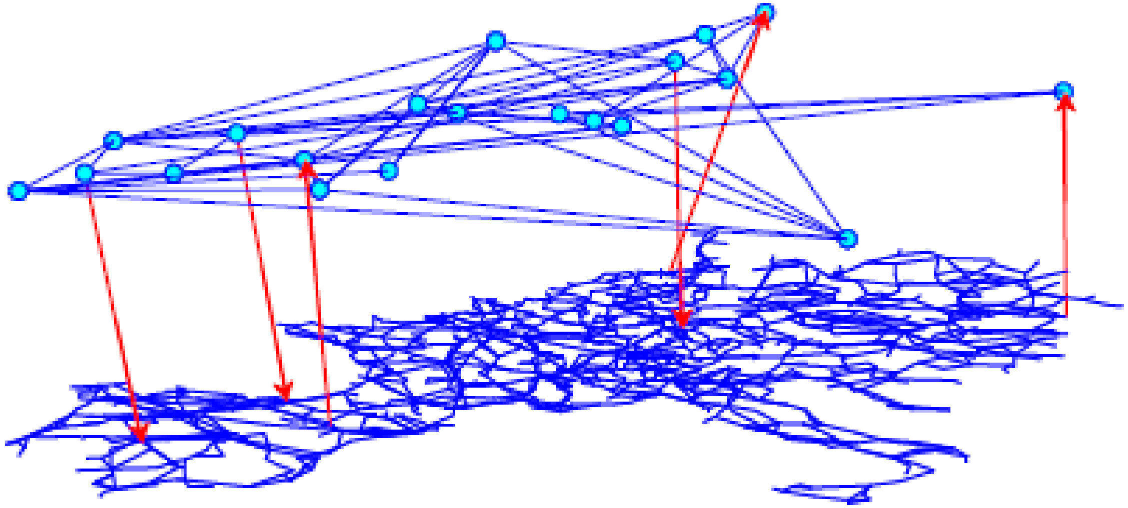
http://arxiv.org/abs/1206.2062

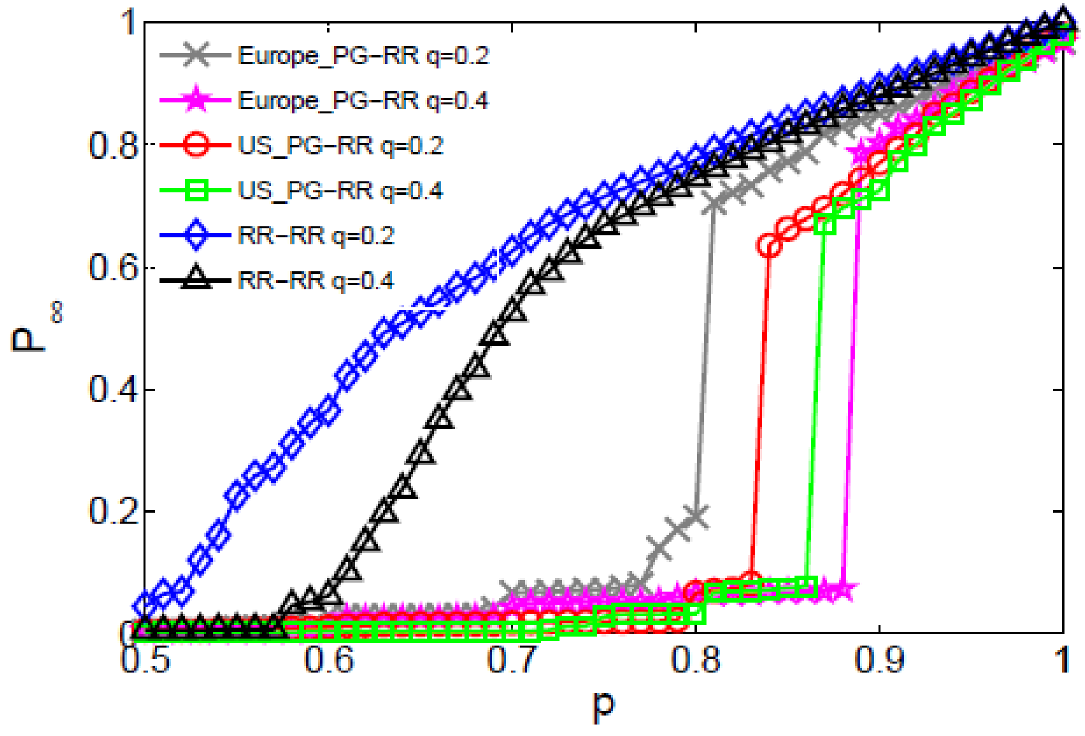
Nature Physics, (2013)

Message: our world is extremely **unsafe!-no safe zone!**

Test on real spatial embedded coupled networks

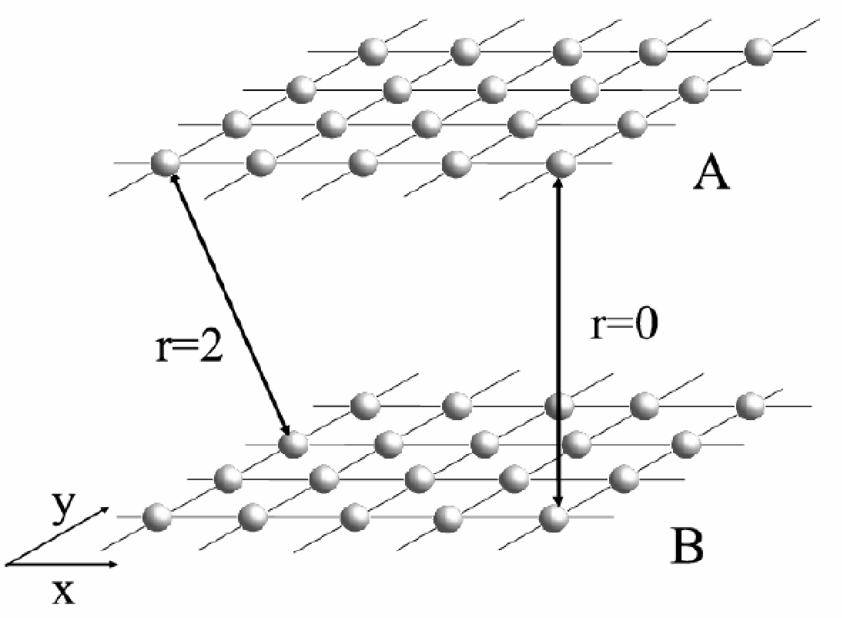
US-POWER GRID
EUROPE POWER GREED



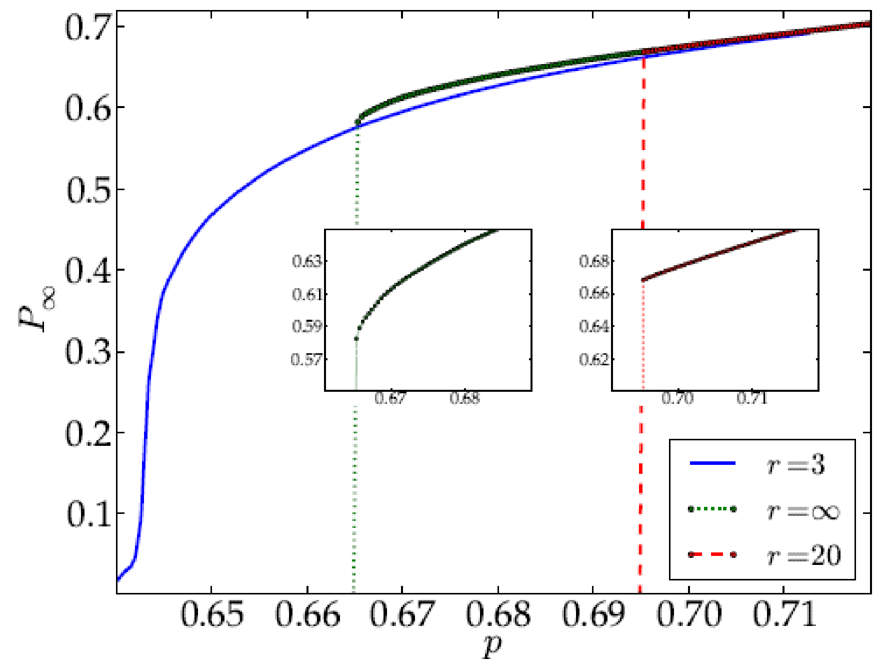


Bashan et al, Nature Physics (2013)
http://arxiv.org/a*bs/1206.206*2

Interdependent Spatially Embedded Networks



Many networks are spatially embedded: Internet, Power grid, Transportation etc



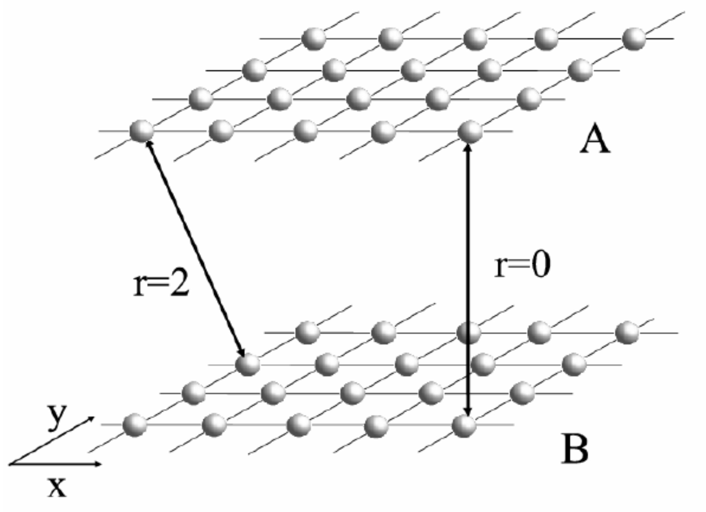
When connectivity links are limited in their length---same universality class as lattices!

THREE DIFFERENT BEHAVIORS DEPENDING ON r

Wei et al, PRL, 108, 228702 (2012)

Bashan et al, http://arxiv.org/abs/1206.2062

Interdependent Spatially Embedded Networks



Many networks are spatially embedded:
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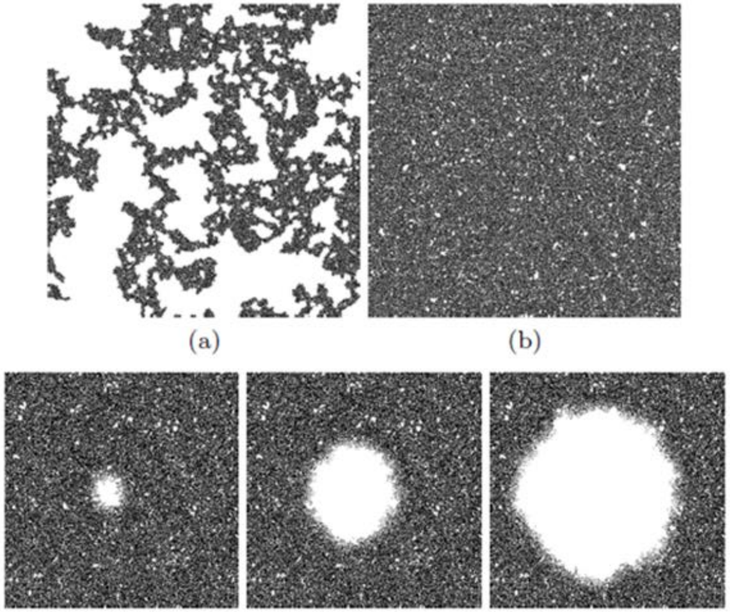
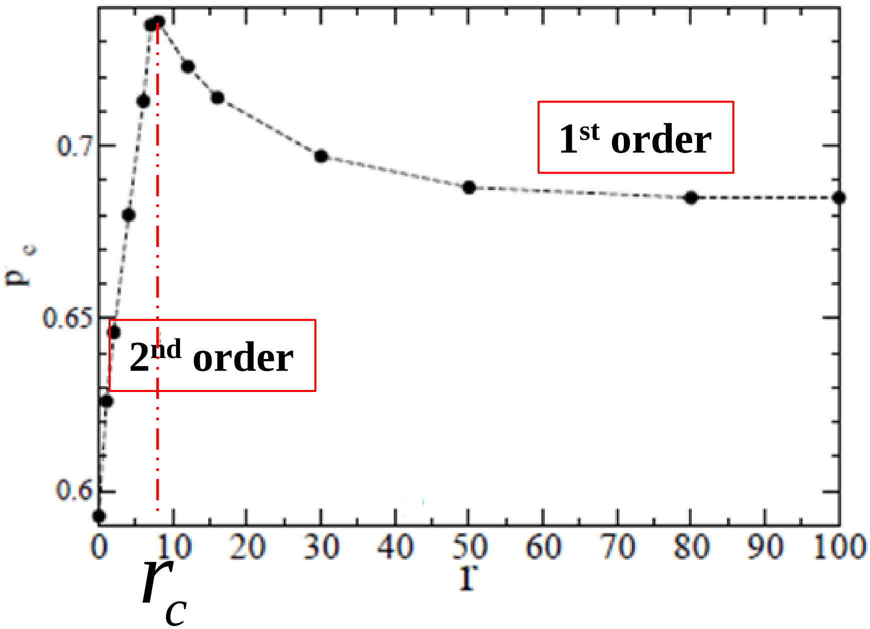


(a) (b)

(c) (d) (e)



Wei et al, PRL, 108, 228702 (2012)

Bashan et al, http://arxiv.org/abs/1206.2062

Summary and Conclusions

• First statistical physics approach for robustness of Networks of Interdependent Networks—cascading failures

•New paradigm: abrupt collapse compared to continuous in single network

• Generalization to "Network of Networks": n interdependent networks-
50y of graph theory and percolation is only a limited case!
Larger n is more vulnerable–spatial embedding-extremely unsafe: $q_c = 0$

Rich problem: different types of networks and interconnections.

Buldyrev et al., NATURE (2010)
Parshani et al., PRL (2010)
Gao et al, PRL (2011)
Parshani et al, PNAS (2011)
Wei et al, PRL (2012)
Gao et al., Nature Phys. (2012)
Bashan et al, Nature Phys. (2013)