VISUALIZING AND UNDERSTANDING COMPLEX SYSTEMS

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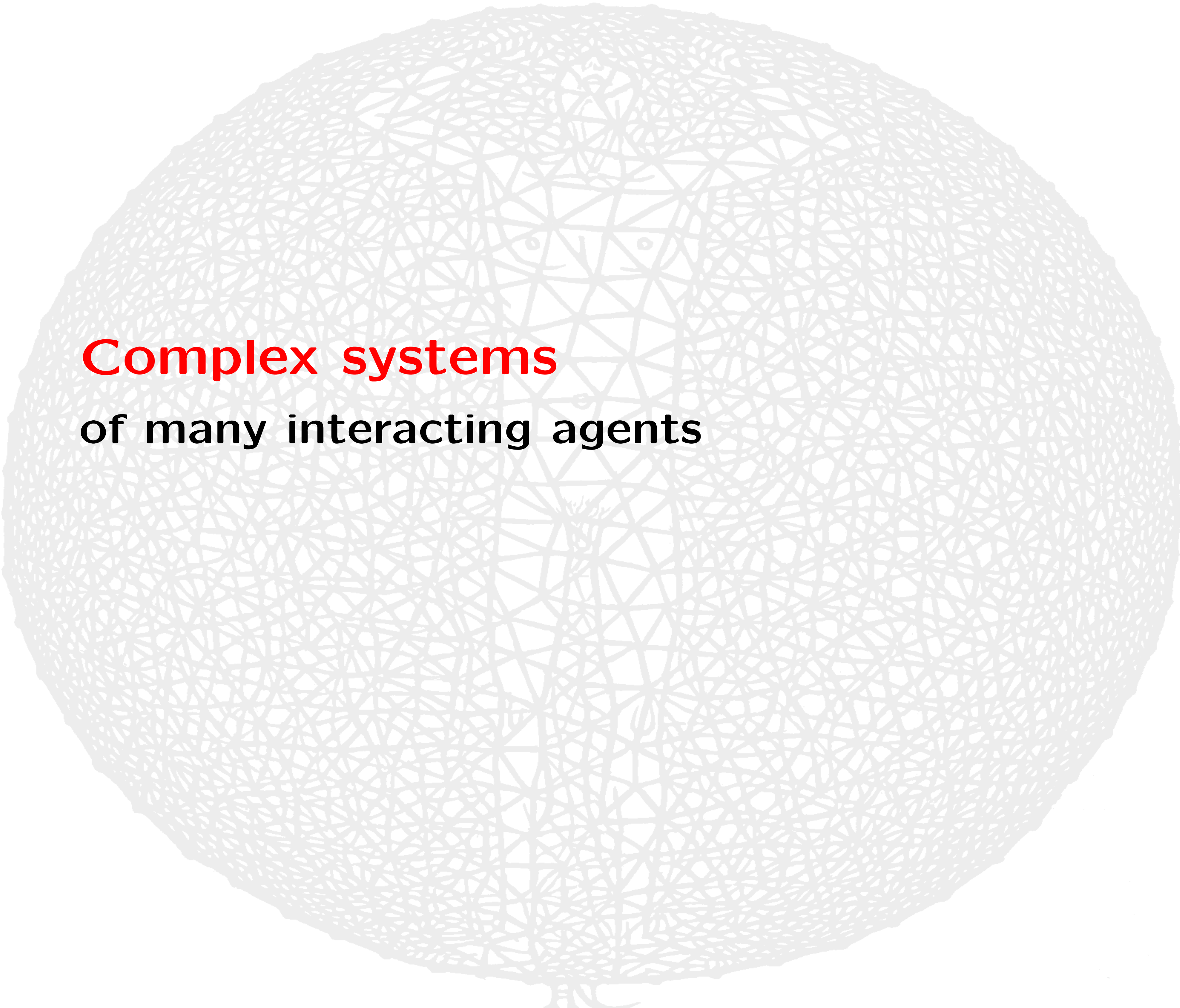
Plan

1. Introduction: Complex systems and Complex networks

2. Case studies:

- Public transport networks
- Online game networks
- Networks of ancient narratives



Complex systems

of many interacting agents

Complex systems

The study of complex systems represents a new approach to science that investigates how relationships between parts give rise to the collective behaviors of a system... The equations from which models of complex systems are developed generally derive from *statistical physics*, information theory and non-linear dynamics.

The whole is greater than the sum of its parts.

Aristotle

Complex systems science bridges the natural and social sciences, enriching both, and reduces the gap between science, engineering, and policy.

CSS Website

More is different.

Philip Anderson

In recent years physicists have been deeply interested in studying the behavior of complex systems. The result of this effort has been a conceptual revolution, a paradigmatic shift that has far reaching consequences for the very definition of physics.

Giorgio Parisi

I think the next century will be the century of complexity.

Stephen Hawking

Complex systems inherent features

- SELF-ORGANIZATION *[into patterns, as occurs with flocks of birds, periodicity in disease outbreaks, or residential segregation.]*

- EMERGENCE *[of functionalities, such as cognition in the brain or the robustness of networks.]*

- CHAOS *[where small changes in initial conditions ("the flapping of a butterfly's wings in Argentina") produce large later changes ("a hurricane in the Caribbean").]*

- "FAT-TAIL"BEHAVIOR *[where rare events occur much more often than would be predicted by a normal (bell-curve) distribution.]*

- ADAPTIVE INTERACTION *[where interacting agents (as in markets or the Prisoner's Dilemma) modify their strategies in diverse ways as experience accumulates to produce cooperative behavior.]*

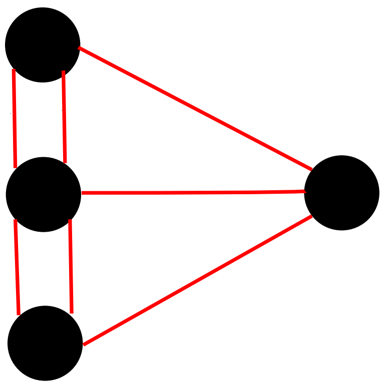
Complex networks

as a tool to visualize, quantify and understand complex systems

Complex networks

A graph: vertices edges

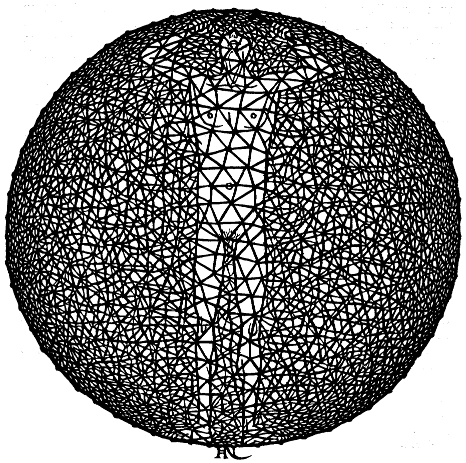
a set of • connected via —-



Complex networks

a set of • connected via —-

A network: nodes links



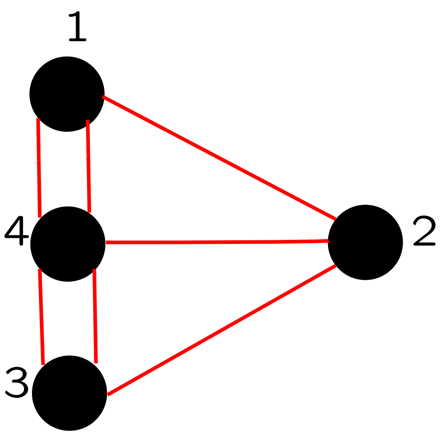
Complex networks

A graph: vertices edges

a set of • connected via —-

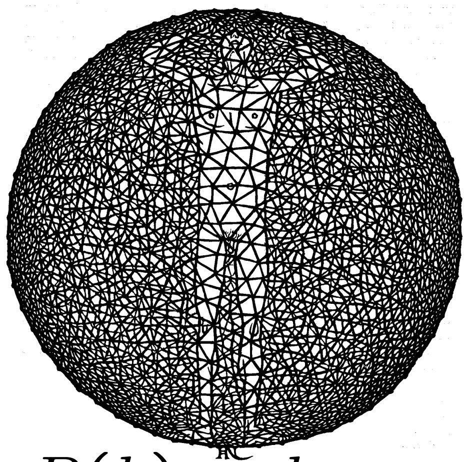
A network: nodes links

$N = 4$



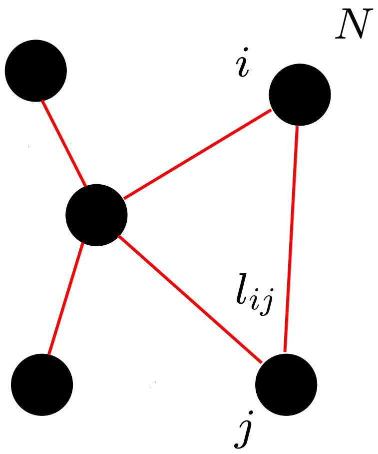
$k_1 = k_2 = k_3 = 3$,
$k_4 = 5$

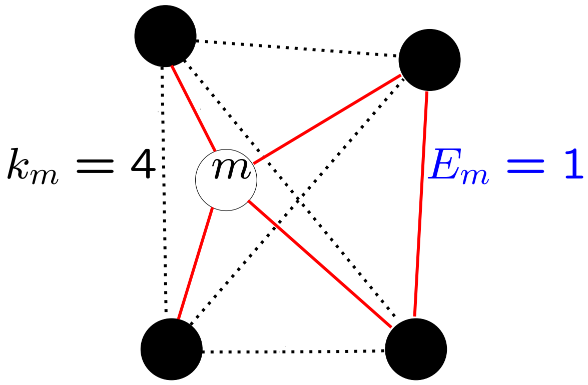
$N \sim 10^3 - 10^9$

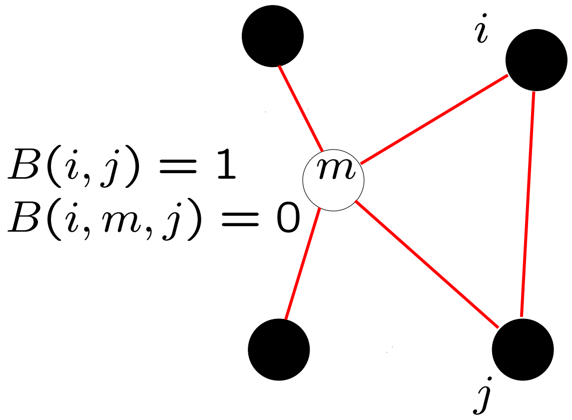


$P(k), < k >, \ldots$

Network features: distance, correlations, centrality







mean shortest path length

clustering coefficient

betweenness

$$\langle l \rangle = \frac{2}{N(N-1)} \sum_{i>j} l_{ij}$$

$$C_m = \frac{2E_m}{k_m(k_m-1)}$$

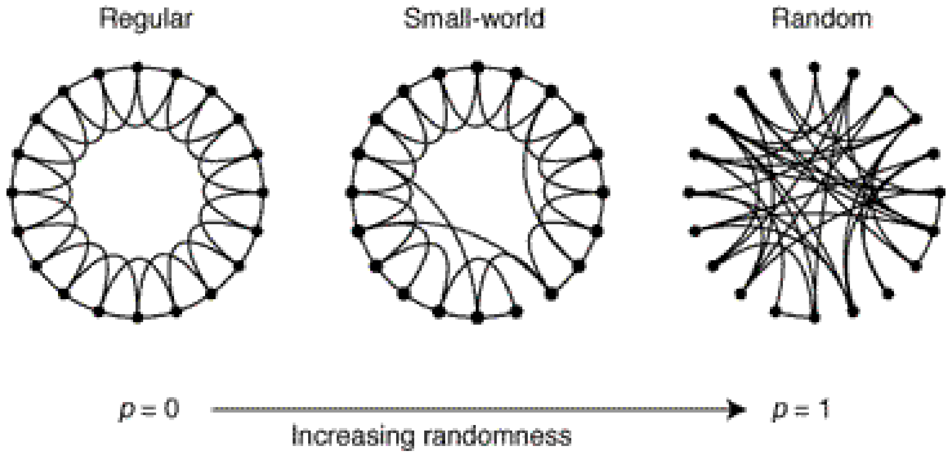
$$\sigma(m) = \sum_{i \neq j} \frac{B(i,m,j)}{B(i,j)}$$

Network features: Small worlds

Watts, Strogats'98:

N vertices of degree k

rewiring probability p



$N = 20$

$k = 4$

Regular	Small-world	Random
$\langle l \rangle \sim \frac{N}{2k} \gg 1$	$\langle l \rangle \sim \langle l \rangle_{\text{rand}}$	$\langle l \rangle_{\text{rand}} \sim \frac{\ln N}{\ln \langle k \rangle}$
$C \sim \frac{3}{4}$	$C \gg C_{\text{rand}}$	$C_{\text{rand}} \sim \frac{\langle k \rangle}{N} \ll 1$

Public transport networks

self-organization

emergence of functionalities

Online game networks

fat-tail behaviour

adaptive interaction

Networks of ancient narratives

In collaboration with:

Bertrand Berche

Christian von Ferber

Public transport networks

Taras Holovatch

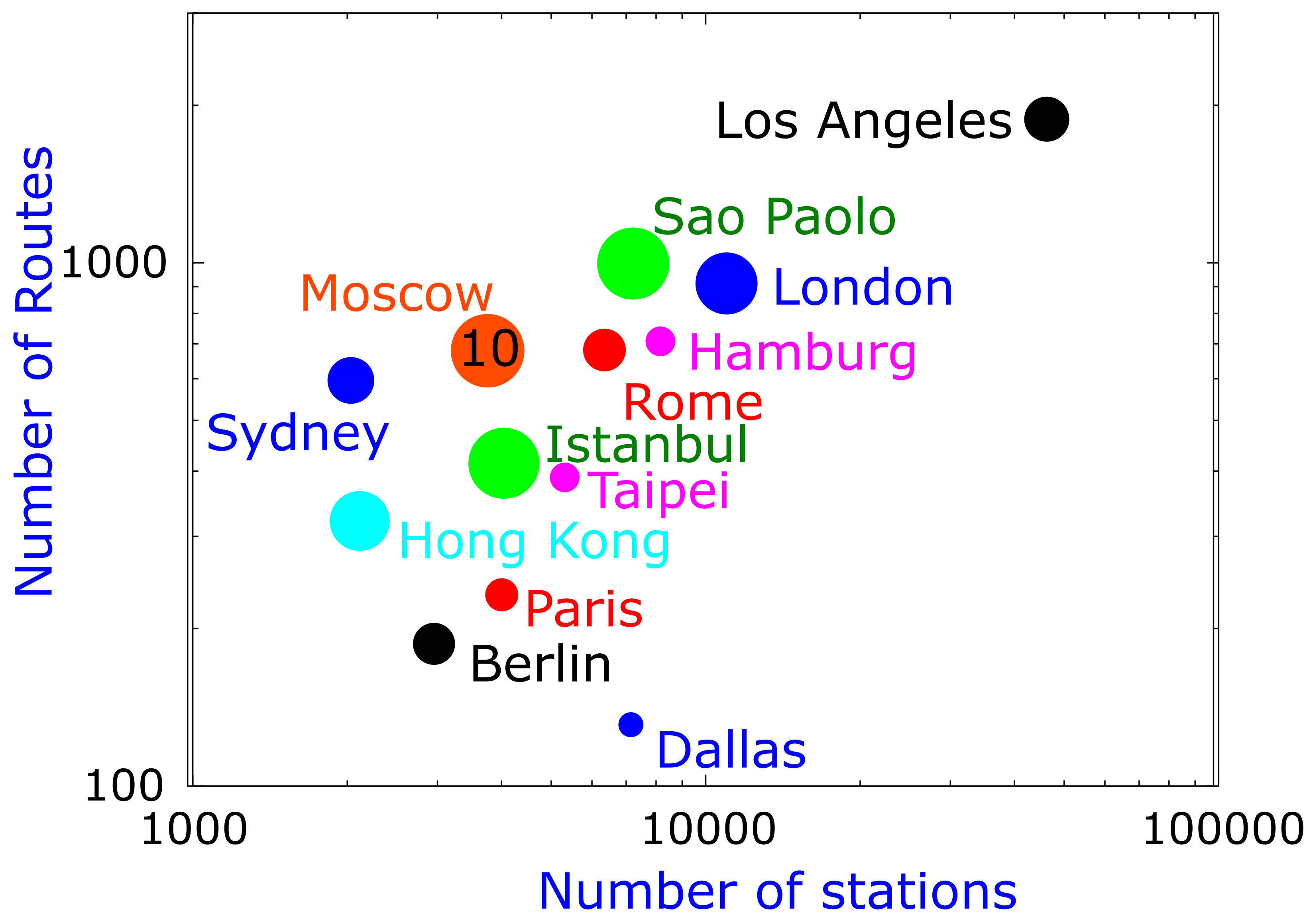
Vasyl Palchykov

Robin de Regt

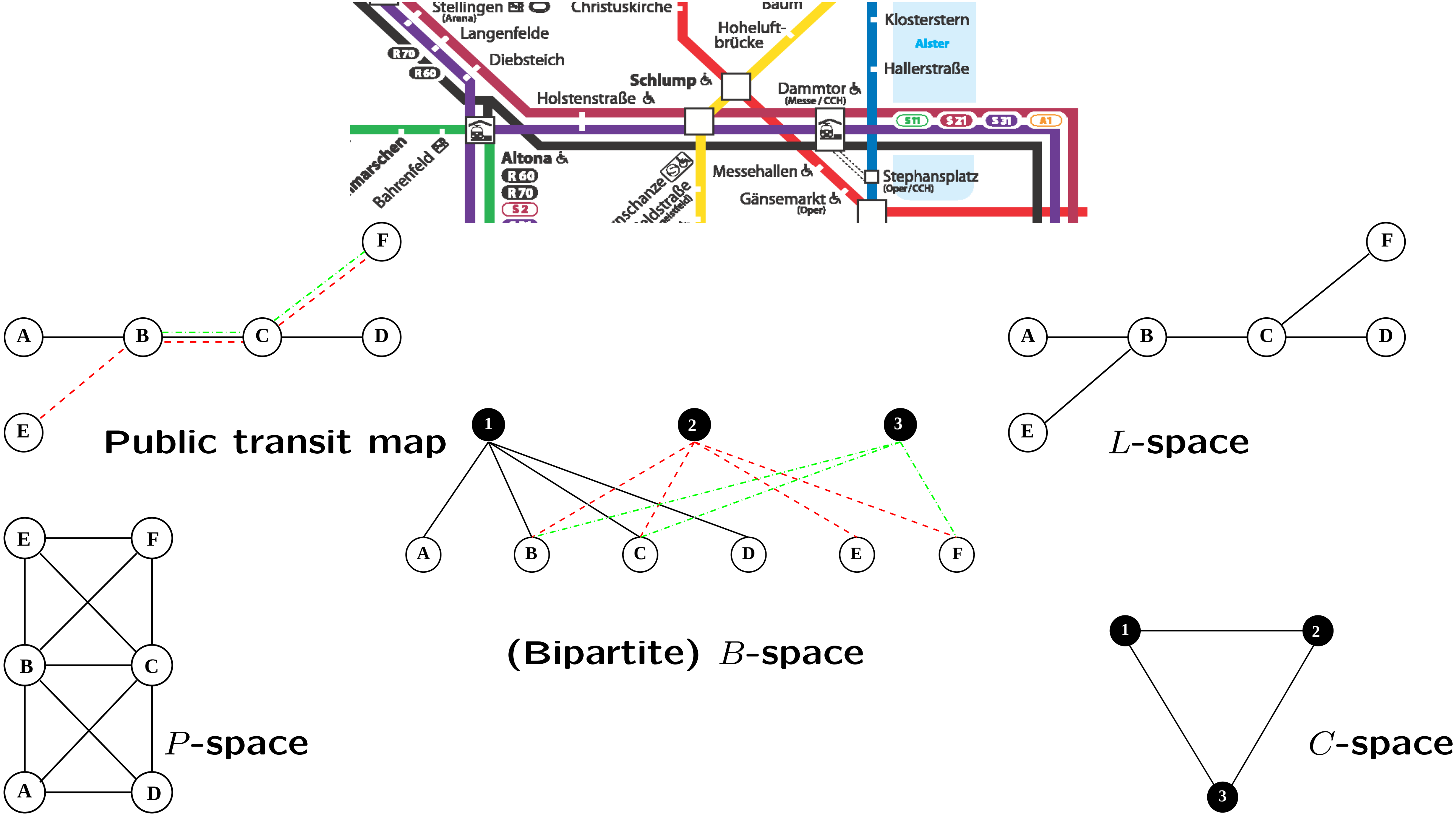
Supported by:

IRSES N269139 (DCP-PhysBio); N295302 (SPIDER)

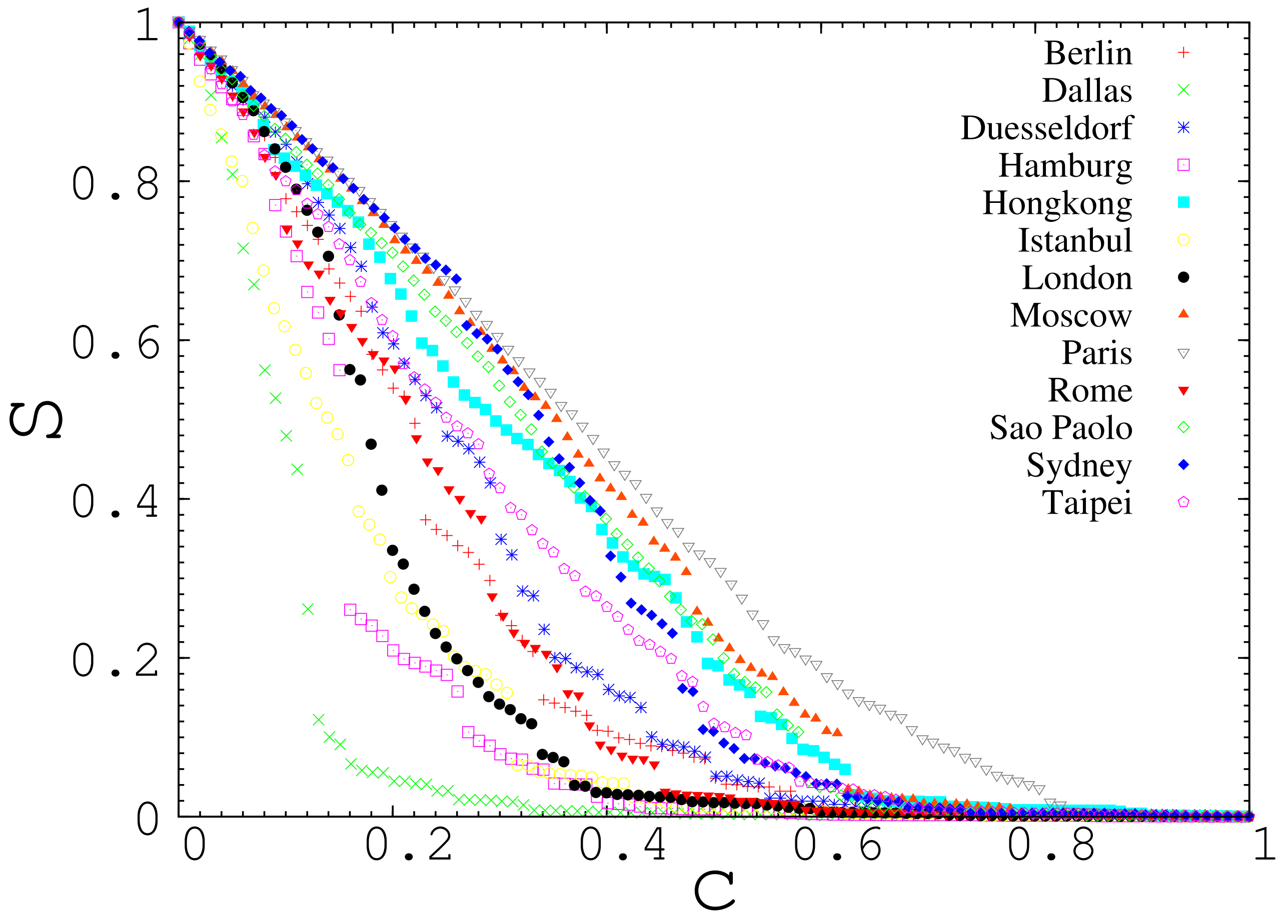
Our database

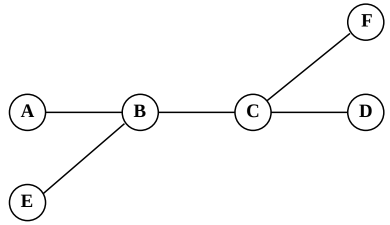


Network interpretation



Robustness vs vunerability





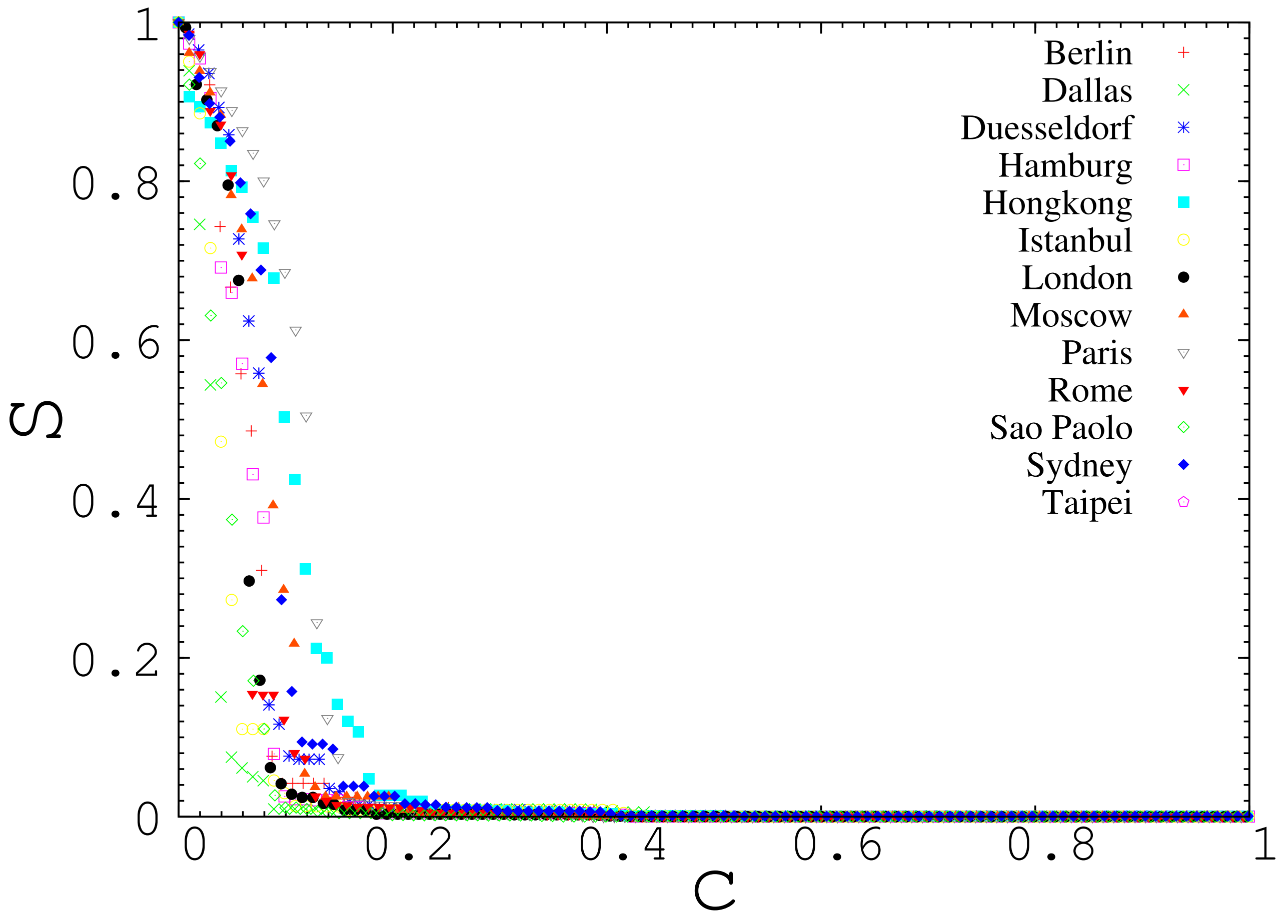
L-**space**

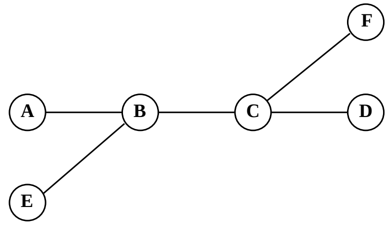
Largest cluster size S as function of removed node share c.

Scenario "random".

B. Berche, C. von Ferber, T. Holovatch, Yu.H. Eur. Phys. J. B ***71*** *(2009) 125; Dyn. Soc.-Econ. Syst.* ***2*** *(2010) 42; Adv. Compl. Syst.* ***15*** *(2012) 1250063 Journ. Transport. Security* ***5*** *(2012) 199*

Robustness vs vunerability





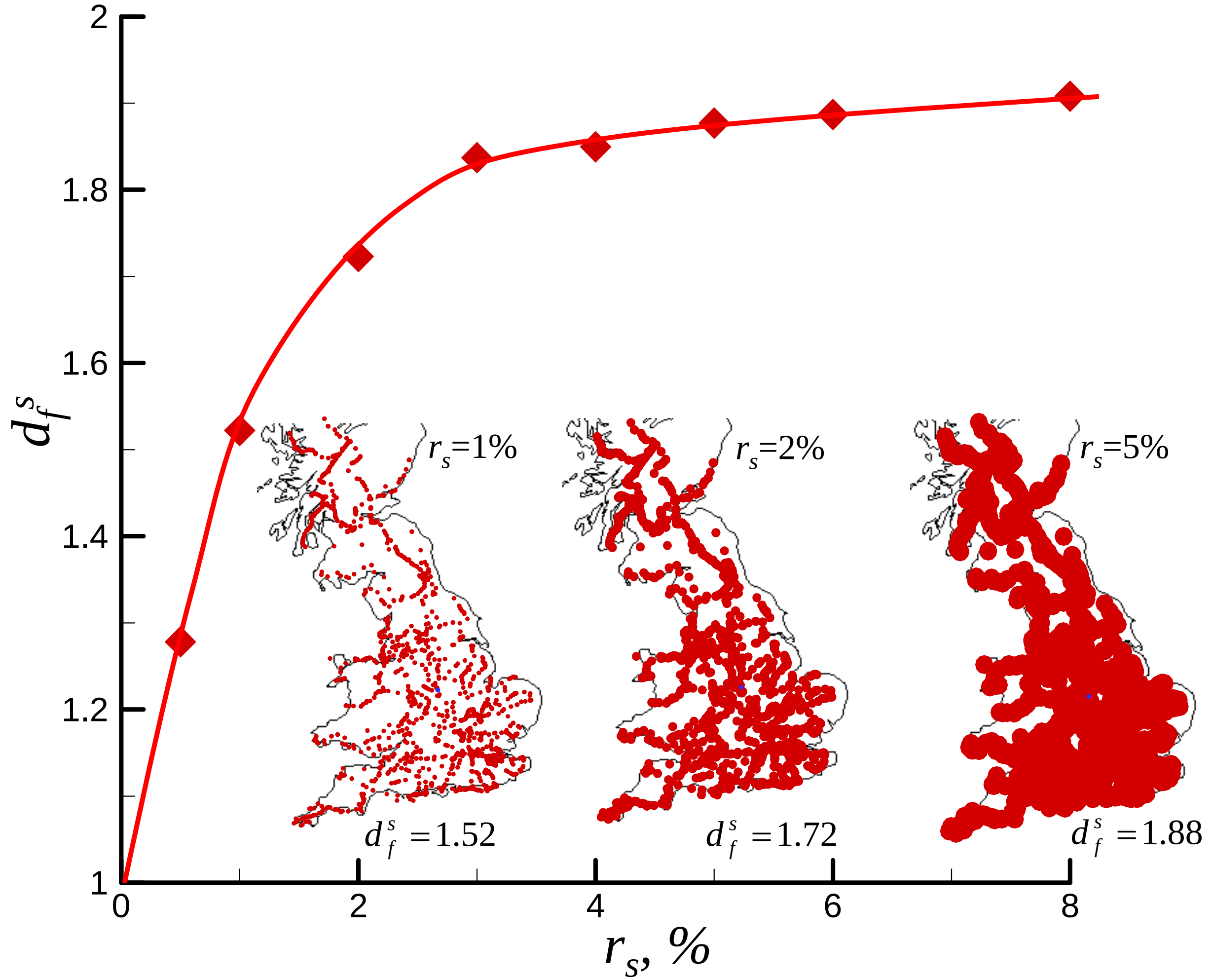
L-**space**

Largest cluster size S as function of removed node share c.

Scenario "recalculated node degree".

B. Berche, C. von Ferber, T. Holovatch, Yu.H. Eur. Phys. J. B ***71*** *(2009) 125; Dyn. Soc.-Econ. Syst.* ***2*** *(2010) 42; Adv. Compl. Syst.* ***15*** *(2012) 1250063 Journ. Transport. Security* ***5*** *(2012) 199*

Transportation network seen as a fractal



Fractal dimension of the UK coach network calculated by considering a boxing method

R. de Regt, C. von Ferber, Yu.H., M. Lebovka. Transportation Research E (2017)

In collaboration with:

Benedikt Fuchs

Olesya Mryglod

Online game networks

Michael Szell

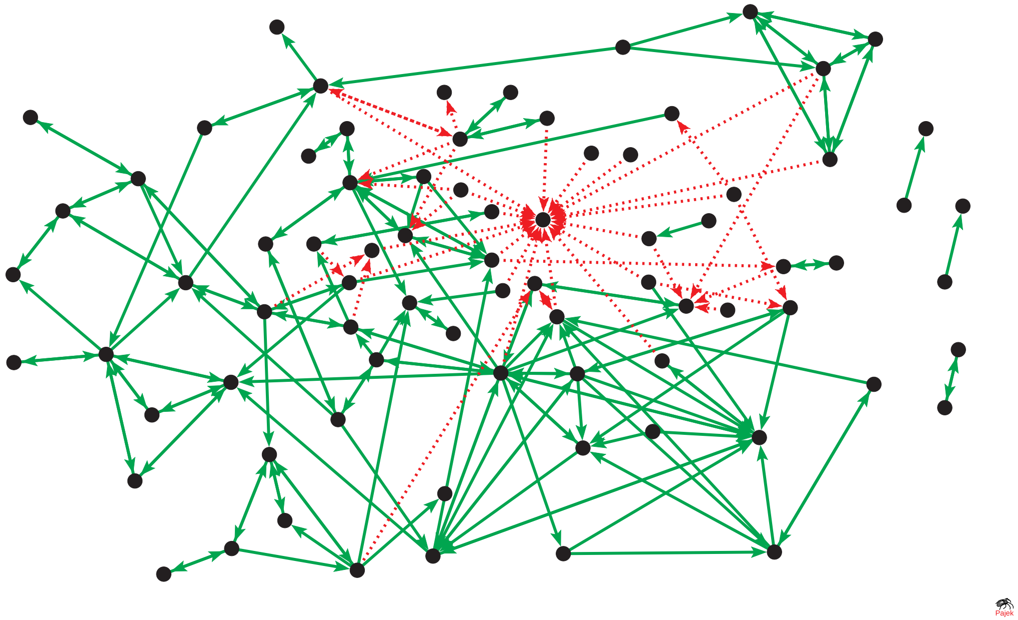
Stefan Thurner

Supported by:

IRSES N612707 (DIONICOS); COST TD1210 (KNOWSCAPE)

Sociophysics. Analysis of a virtual world

MMOG (online game, launched in 2004, $\sim$ 400 000 players)



Friendly (green) and hostile (red) relations
between 72 randomly chosen players, 445-th day

M. Szell, S. Thurner, Social Networks ***32*** *(2010) 313*

Quantitative features of PARDUS universe

- M.S. Granovetter'73, *The Strength of Weak Ties*

Overlap O of two neighbouring nodes as function of weight w and betweenness b of their connecting link:

$$O(w) \simeq \sqrt[3]{w} \qquad\qquad O(b) \simeq \frac{1}{\sqrt{b}}$$

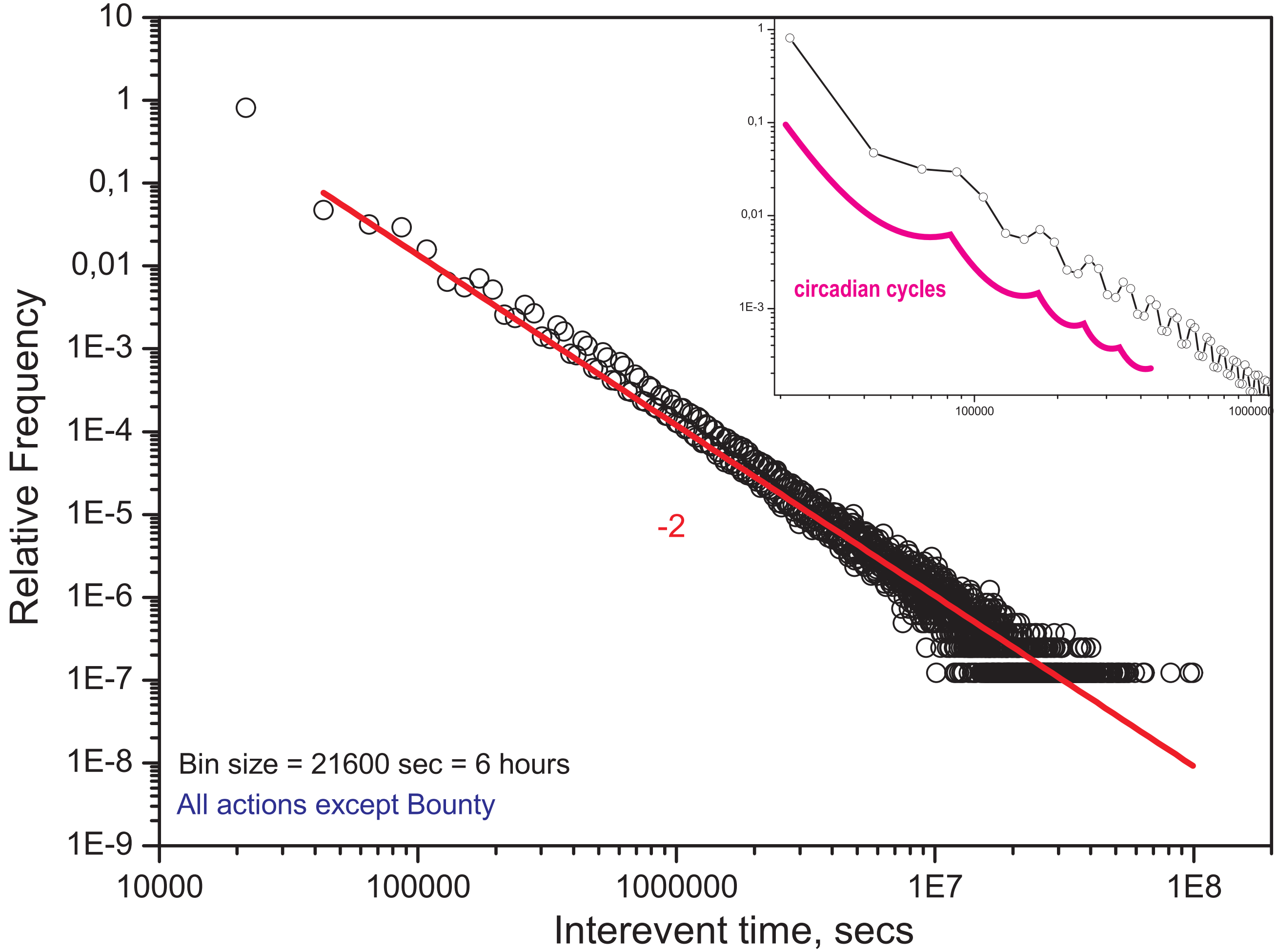
- R. Dunbar'93, *Co-Evolution of Neocortex Size, Group Size and Language in Humans*

Maximal node degree (Dunbar number):

$$k_{\text{max}} \simeq 150$$

M. Szell, S. Thurner, Social Networks **32** *(2010) 313*

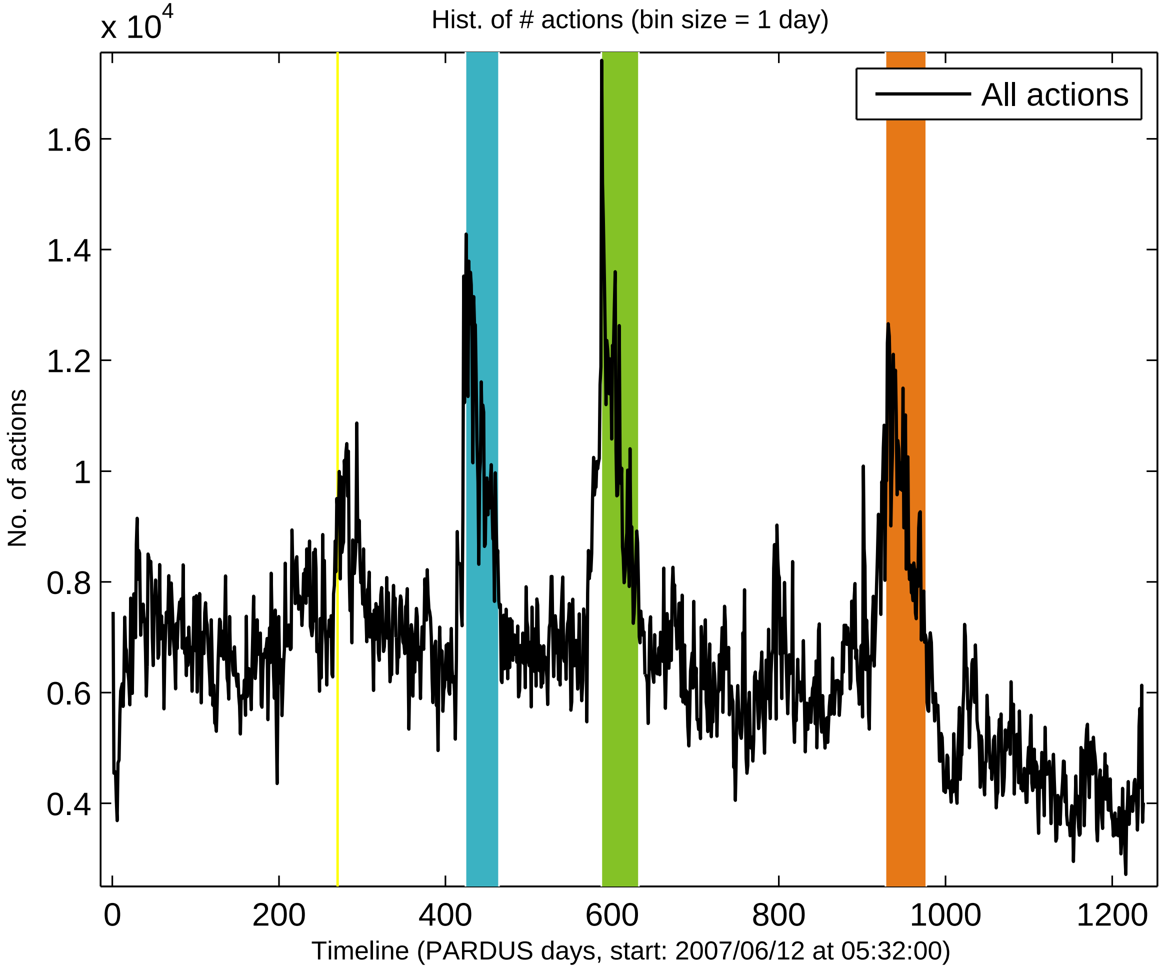
Power laws and universality



Social dynamics: interevent time distribution $P \sim \tau^{-2}$

O. Mryglod, B. Fuchs, M. Szell, Yu.H., S. Thurner, Physica A **419** *(2014) 681.*

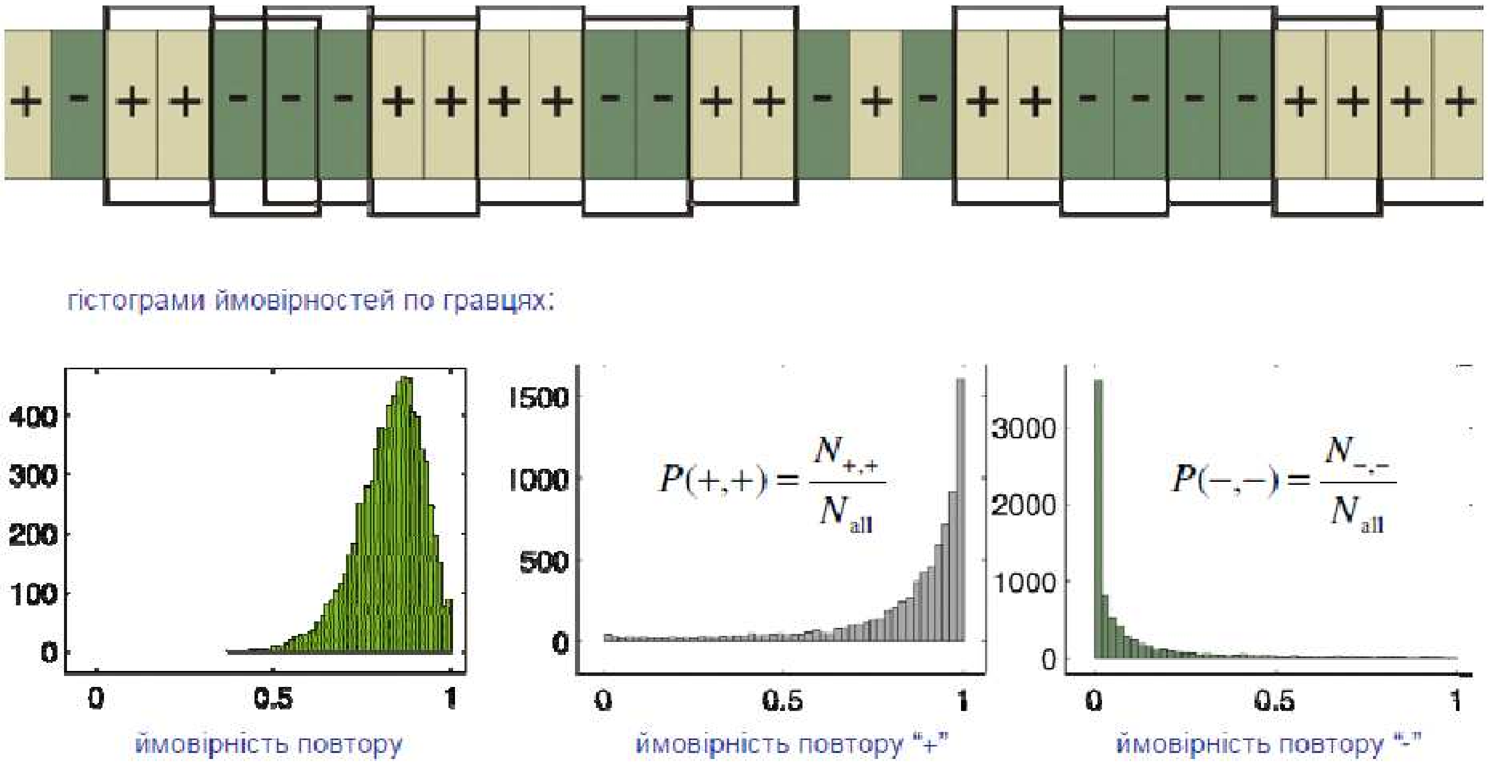
Self-organization and chaos



Extreme event statistics: wars in Pardus universe

O. Mryglod, B. Fuchs, M. Szell, Yu.H., S. Thurner, Physica A **419** *(2014) 681.*

Emergence of structures in social networks



Action streams in virtual world

In collaboration with:

Ralph Kenna

Pádraig Mac Carron

Networks of ancient narratives

UNIVERSITY OF OXFORD

Petro Sarkanych

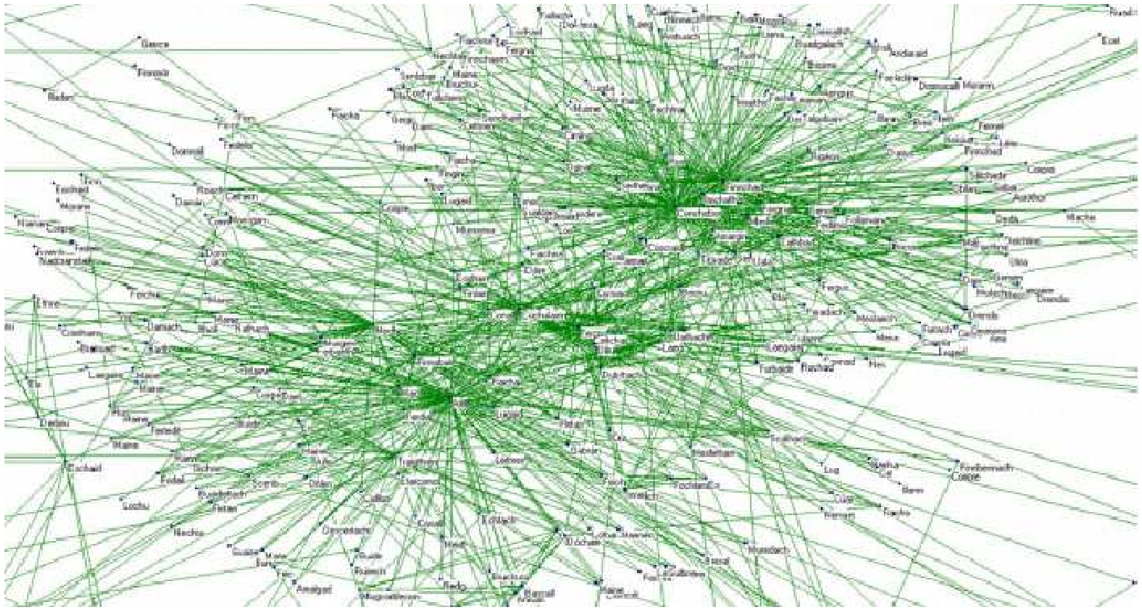
Supported by:

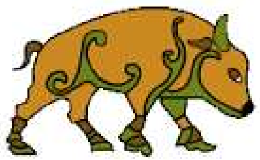
SEVENTH FRAMEWORK PROGRAMME

IRSES N269139 (DCP-PhysBio); N295302 (SPIDER)

The Cattle Raid of Cooley

Táin Bó Cúailnge (The Tain): the most famous epics of Irish mythology

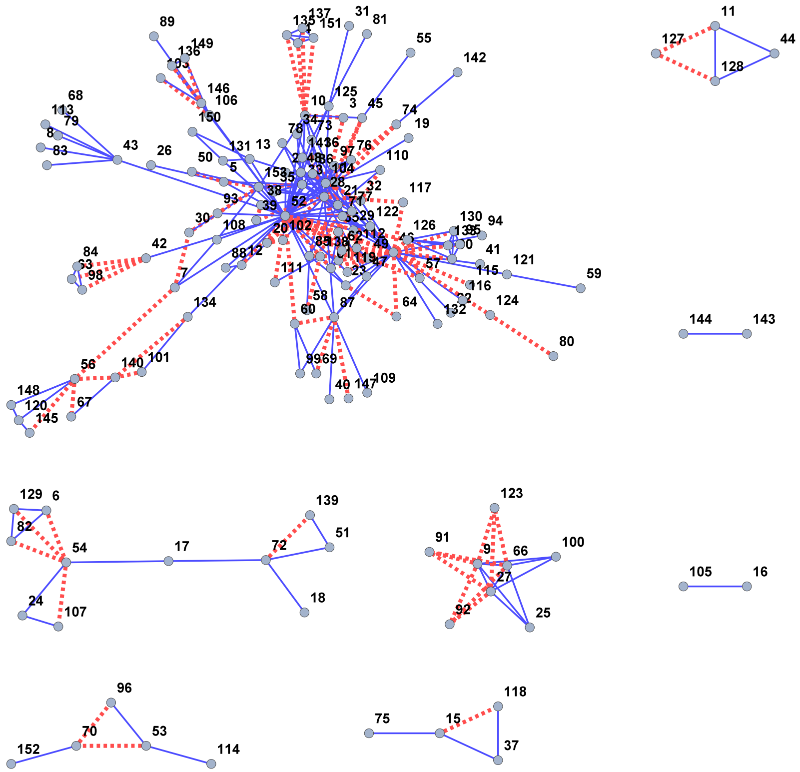




Network of friends

P. Mac Carron, R. Kenna, Eur. Phys. Lett. ***99*** *(2012) 9928002.*

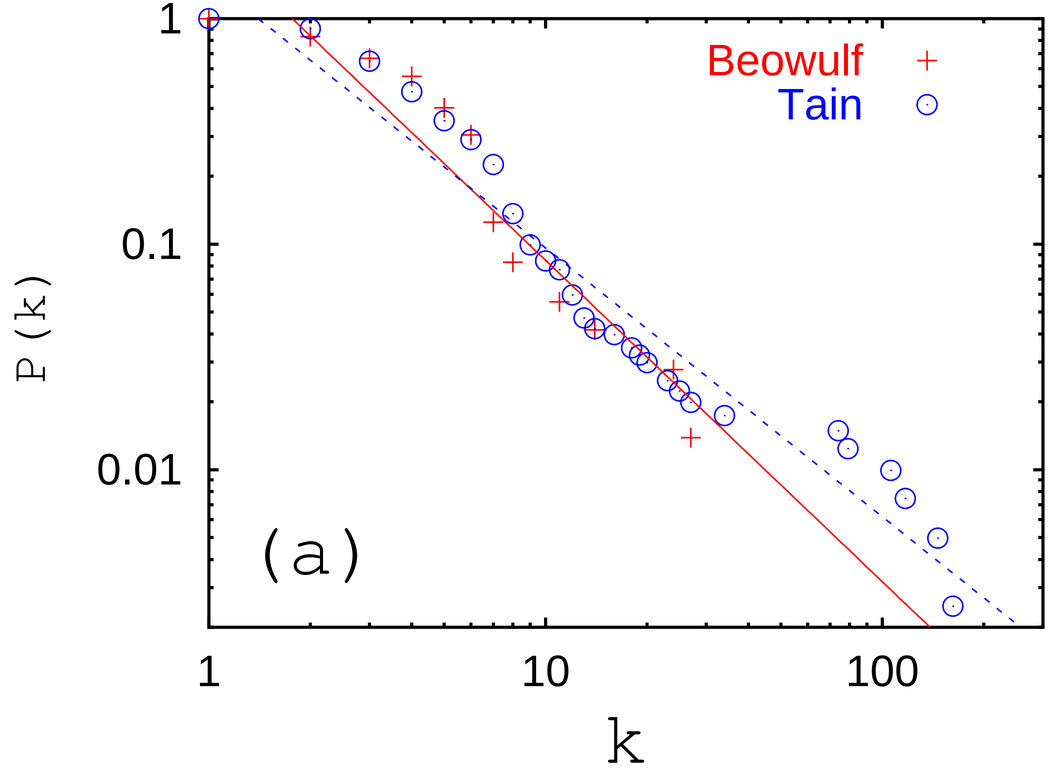
Social network of bylyny characters

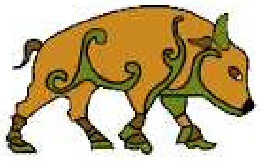


Hostile (red) and friendly (blue) bylyny characters networks of Kievan period

P. Sarkanych, Yu.H., R. Kenna, P. Mac Carron, J. Phys. Stud. **20** *(2016) 4801.*

Universal properties of myth networks

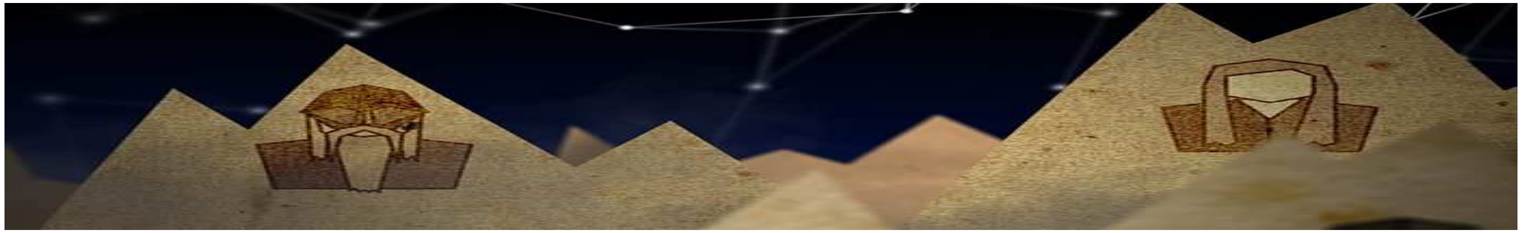




Node degree distribution (The Tain)

P. Mac Carron, R. Kenna, Eur. Phys. Lett. **99** *(2012) 9928002.*

Universal properties of myth networks



	Social	Myth (friendly)	Fiction
Small world	Yes	Yes	Yes
Hierarchy	Yes	Yes	Yes
$p(k)$	Power law	Power law	Exp.
Scale free	Yes	Yes	No
G_c	$<90\%$	$<90\%$	$>90\%$
TA	Vulnerable	Vulnerable	Robust
RA	Robust	Robust	Robust
Assortative	Yes	Yes	No

P. Mac Carron, R. Kenna, Eur. Phys. Lett. **99** *(2012) 9928002.*

Complex systems

of many interacting agents

self-organization

phase transition

emergence of functionalities

percolation

can be visualized, quantified and understood by tools of

fat-tail behaviour

scaling, universality

Complex networks

adaptive interaction

diffusion, RW, SAW

Yu. Holovatch, R. Kenna, S. Thurner, Complex systems: physics beyond physics. Eur. J. Phys. **38** *(2017) 023002*