Complex dynamical networks: from measures to models

Alain Barrat
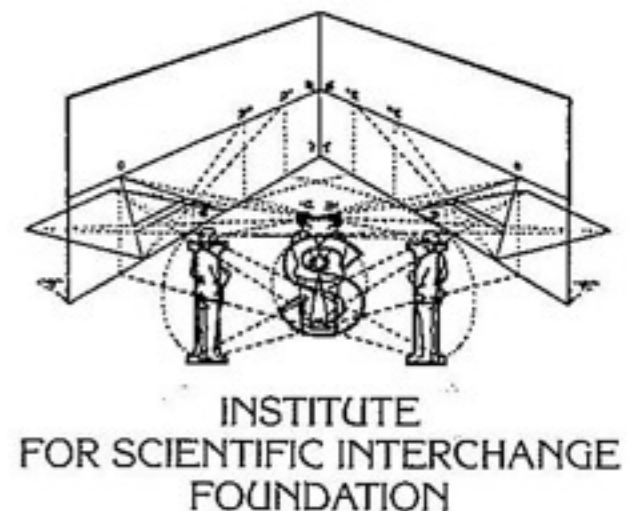
CPT, Marseille, France & ISI, Turin, Italy

http://www.cpt.univ-mrs.fr/~barrat
http://sites.google.com/site/cxnets
http://www.sociopatterns.org

Infrastructure networks
Biological networks
Communication networks
Social networks
Virtual networks

...

DATA

• **Empirical** study and characterization: find generic characteristics (small-world, heterogeneities, hierarchies, communities...) , define statistical characterization tools
• Modeling: understand formation mechanisms
• Consequences of the **empirically** found properties on dynamical phenomena taking place on the networks (epidemic spreading, robustness and resilience, etc…)

Dynamical Processes on
Complex Networks

Alain Barrat, Marc Barthélemy, Alessandro Vespignani
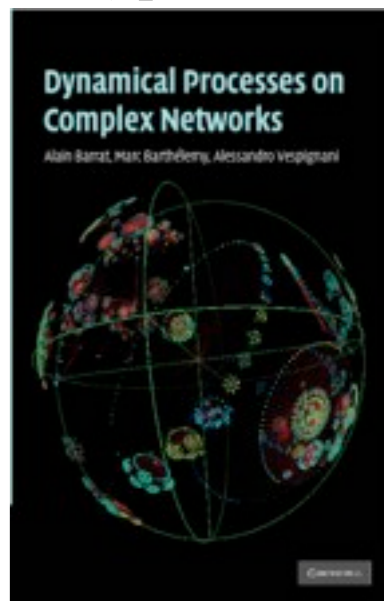
Dynamical networks

Networks= (often) dynamical entities

- Which dynamics?
- Characterization?
- Modeling?
- Consequences on dynamical phenomena?
(e.g. epidemics, information propagation…)
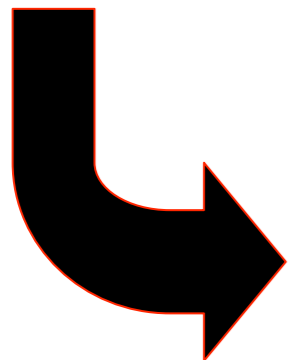
**Back to square one:
Fundamental issue = data gathering!!!**

Outline

- Infrastructure networks
  - Empirics
  - Stationarity and dynamics
  - New characterization tools
- Human contact networks
  - Measuring infrastructure
  - Empirical data
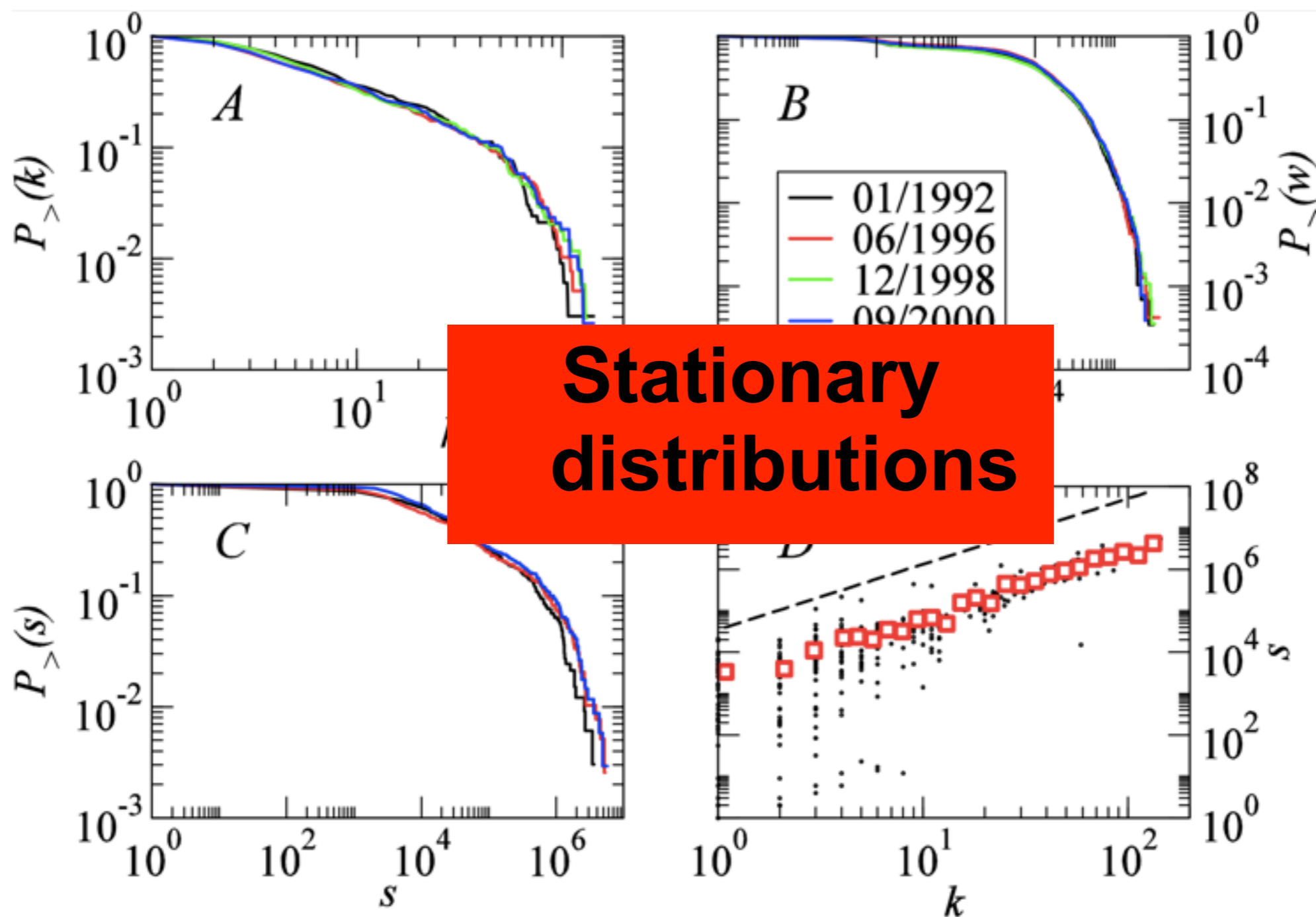 - A model
  - Dynamical processes

Examples of dynamical networks: Infrastructure networks
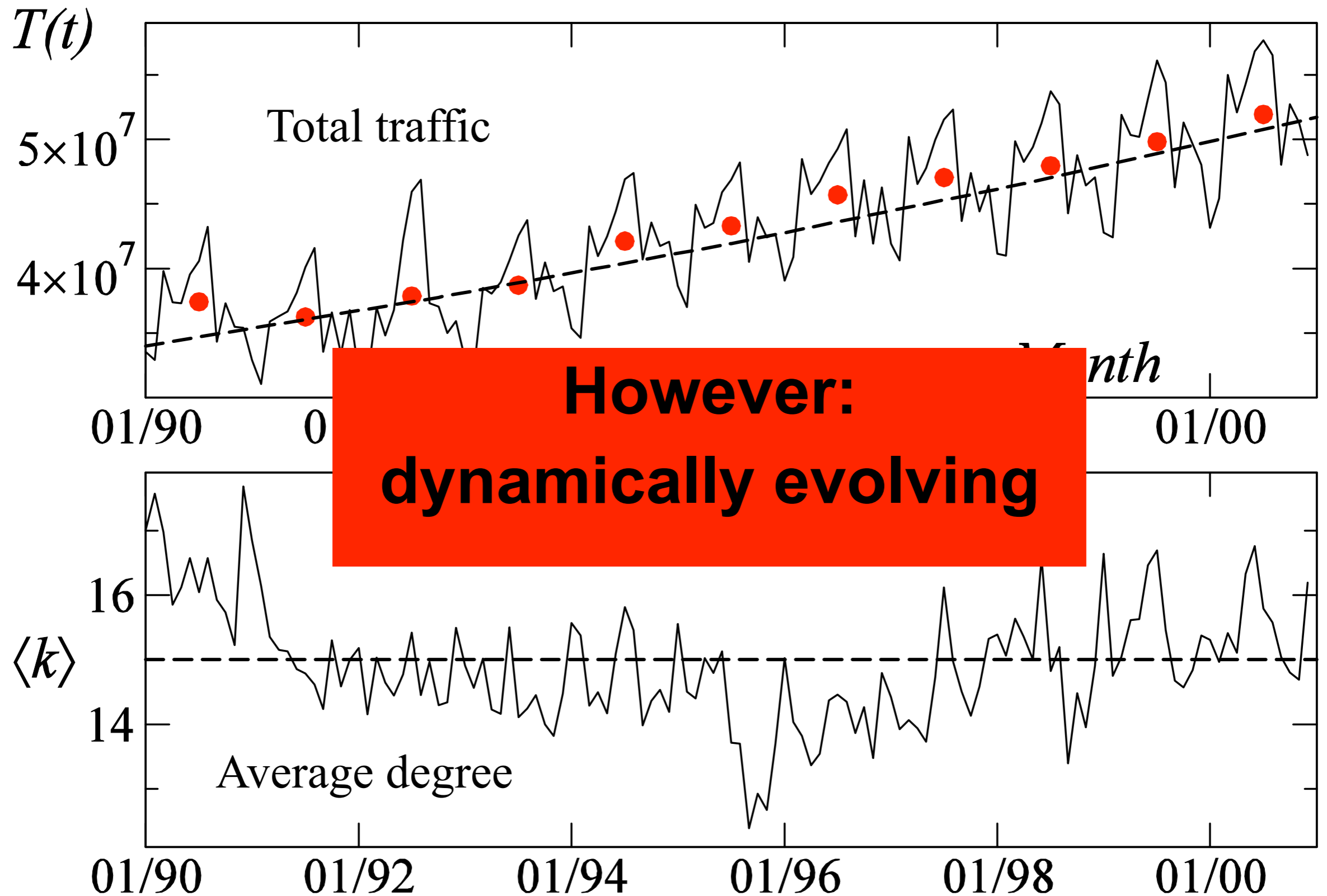
Airport network: dynamically evolving
- Airports opening and closing
- New links appearing
- Links disappearing

Example: the US airport network

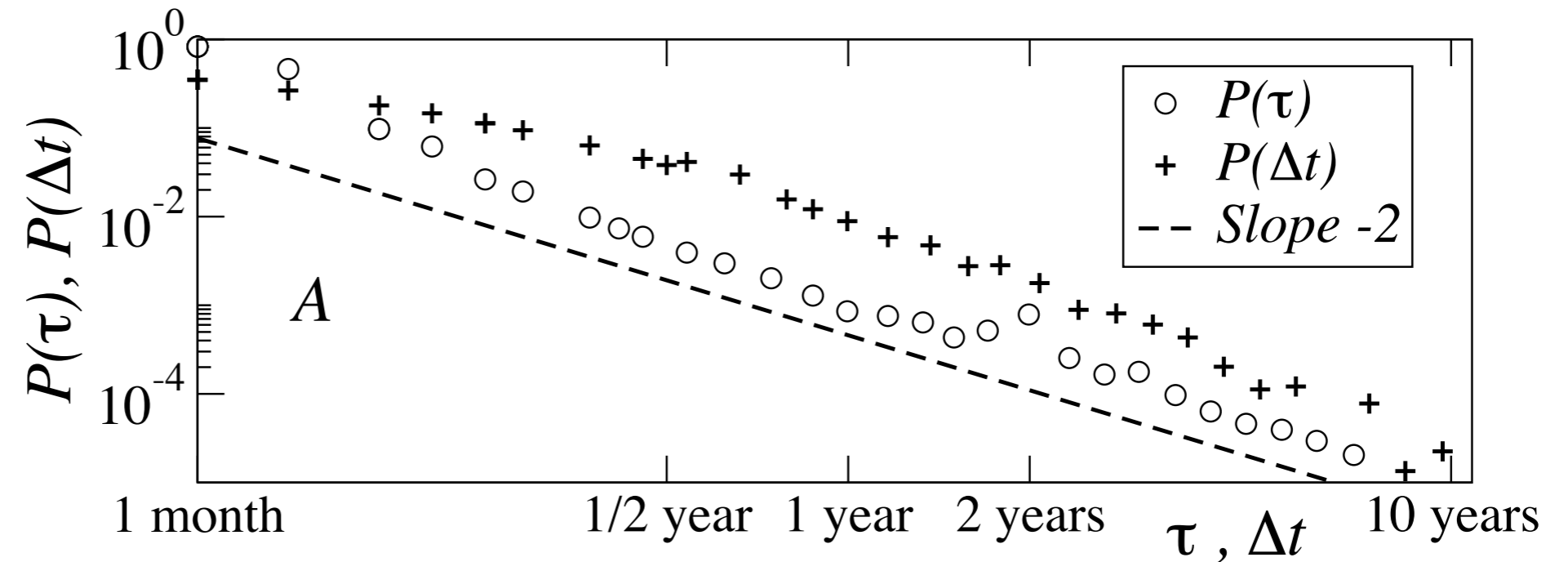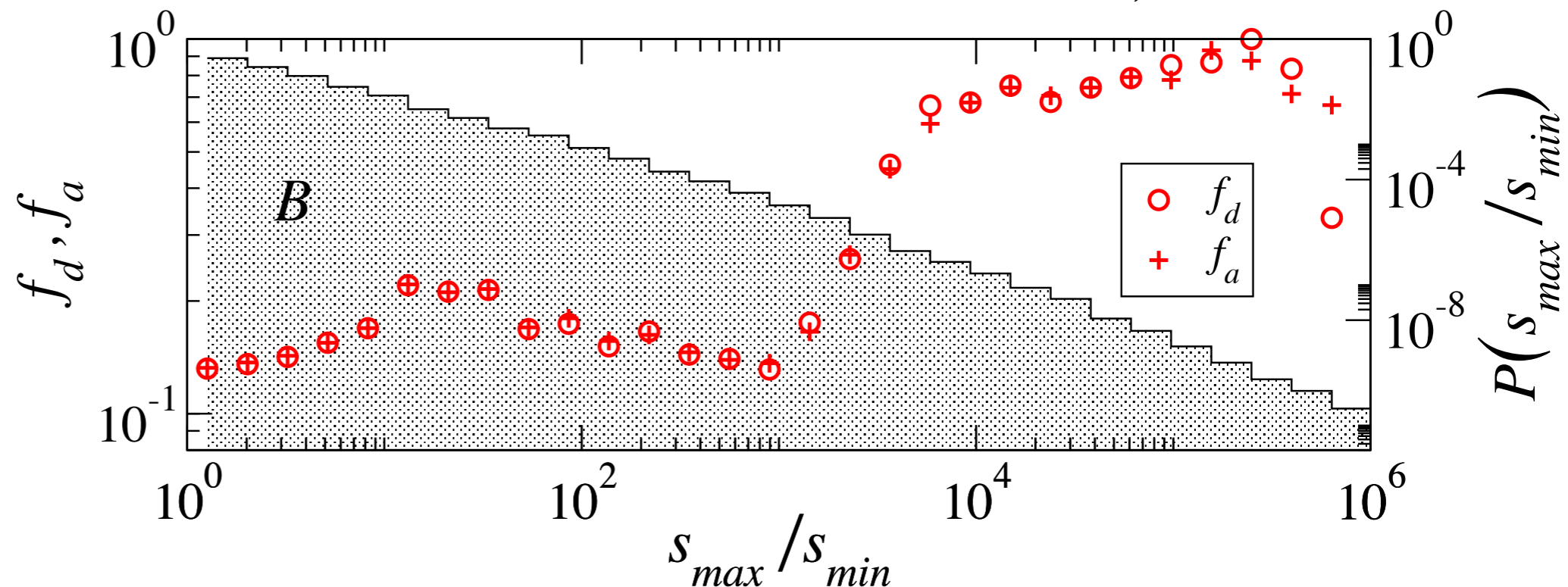*(Gautreau, Barrat, Barthélemy, PNAS (2009))*

US airport network

Stationary distributions

US airport network

$T(t)$

Total traffic

5×10^7

4×10^7

Month

01/90   0

01/00

**However:
dynamically evolving**

16

$\langle k \rangle$

14

Average degree

01/90   01/92   01/94   01/96   01/98   01/00

New characterization tools

τ = duration of a link

Δt = interval between active periods of a link

Fraction of appearing/dis-appearing links

(Gautreau, Barrat, Barthélemy, PNAS (2009))
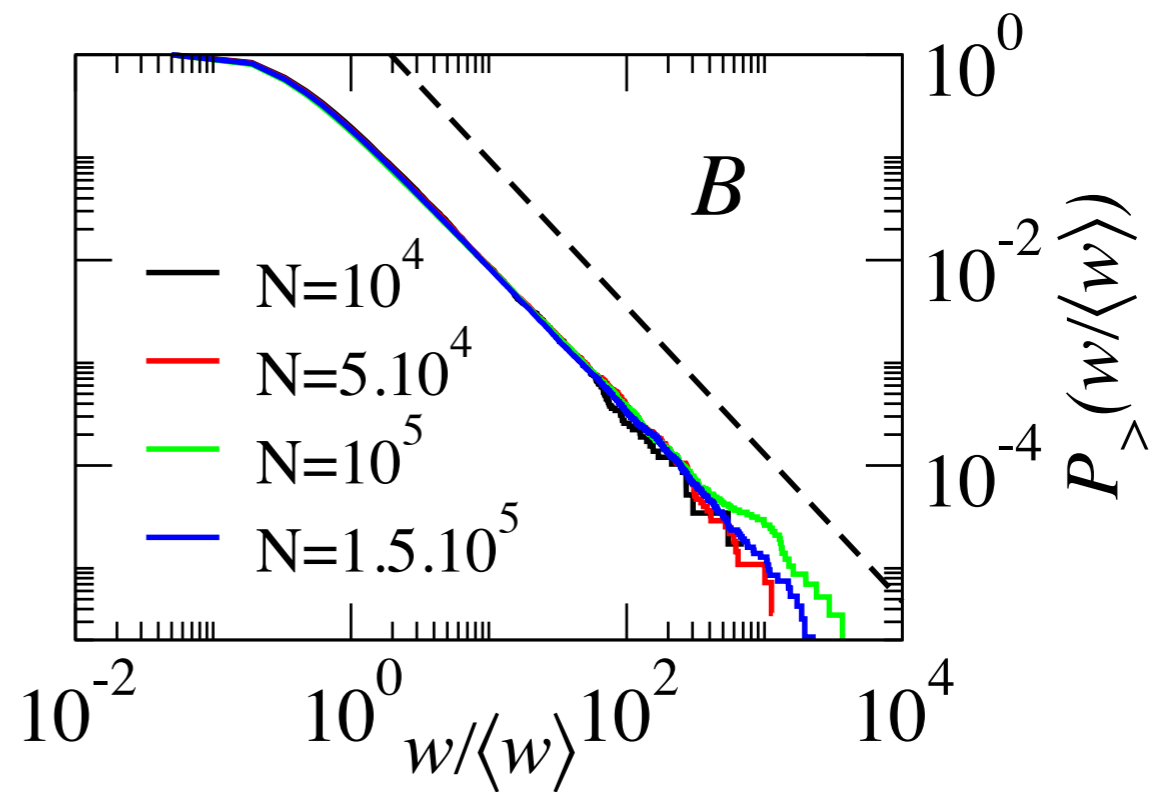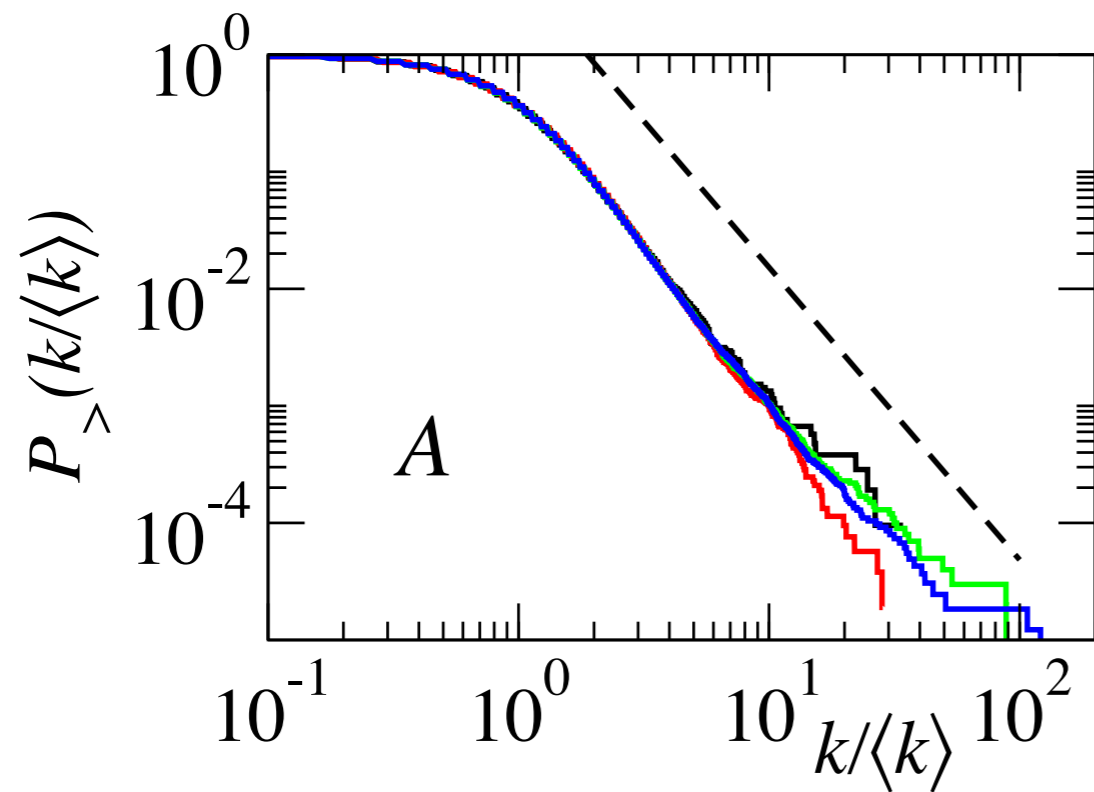
New modeling frameworks

(Simple) model with

• (stochastic) evolution of weights

• deletion of links if weights too small (or strong weight decrease)

• creation of new links if weight increase too large
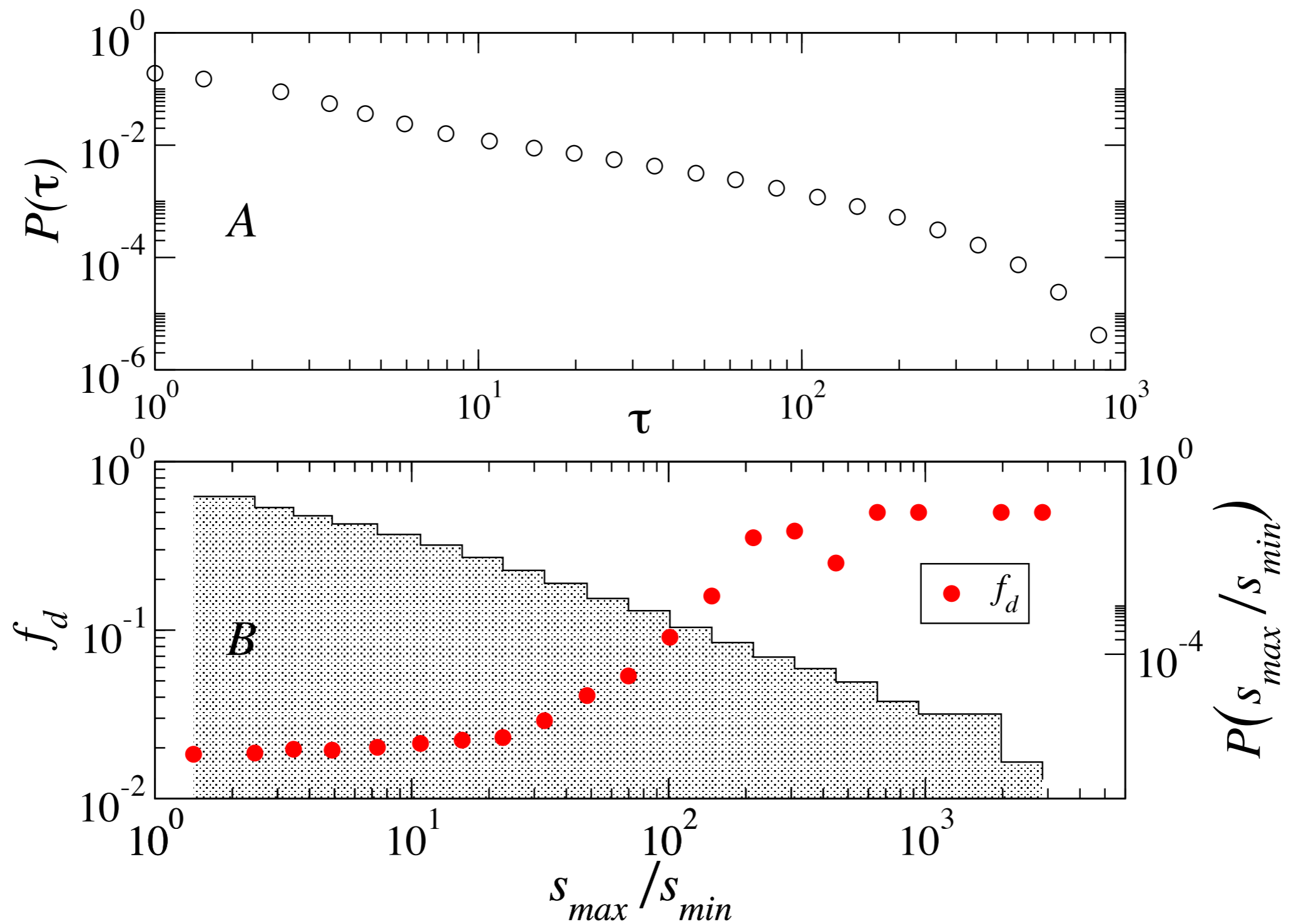
• potentially: addition or removal of nodes

reproduces main empirical facts

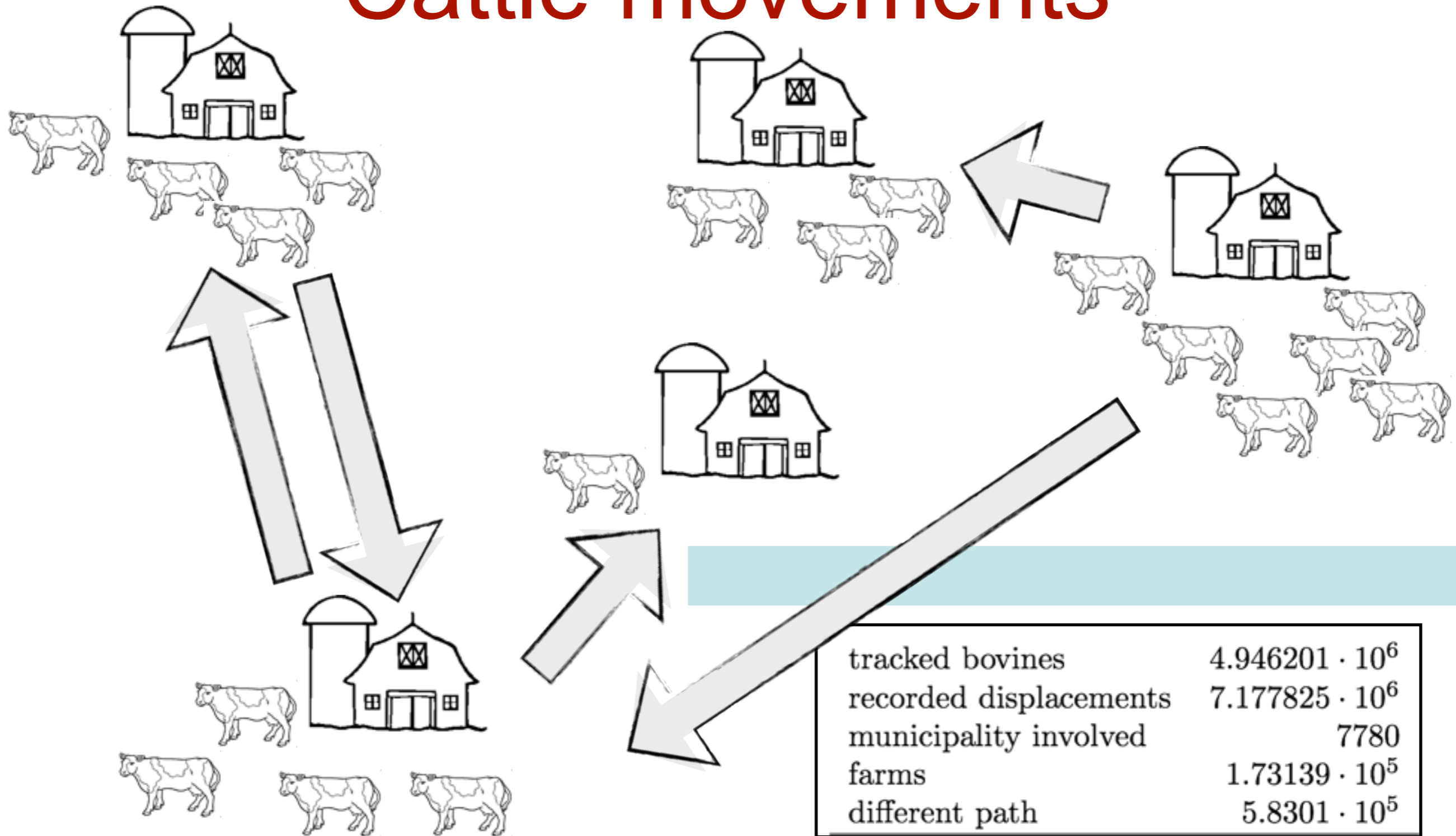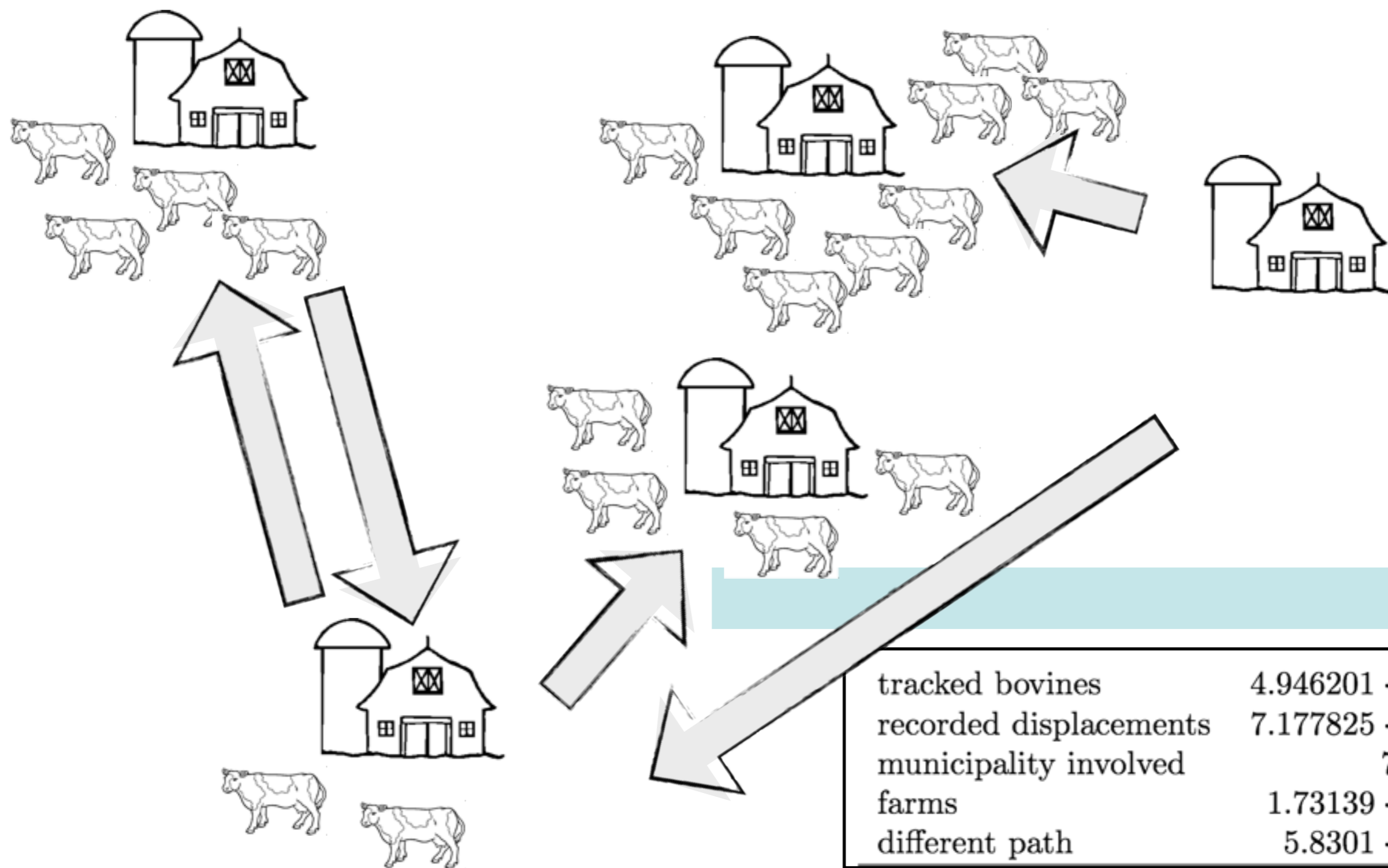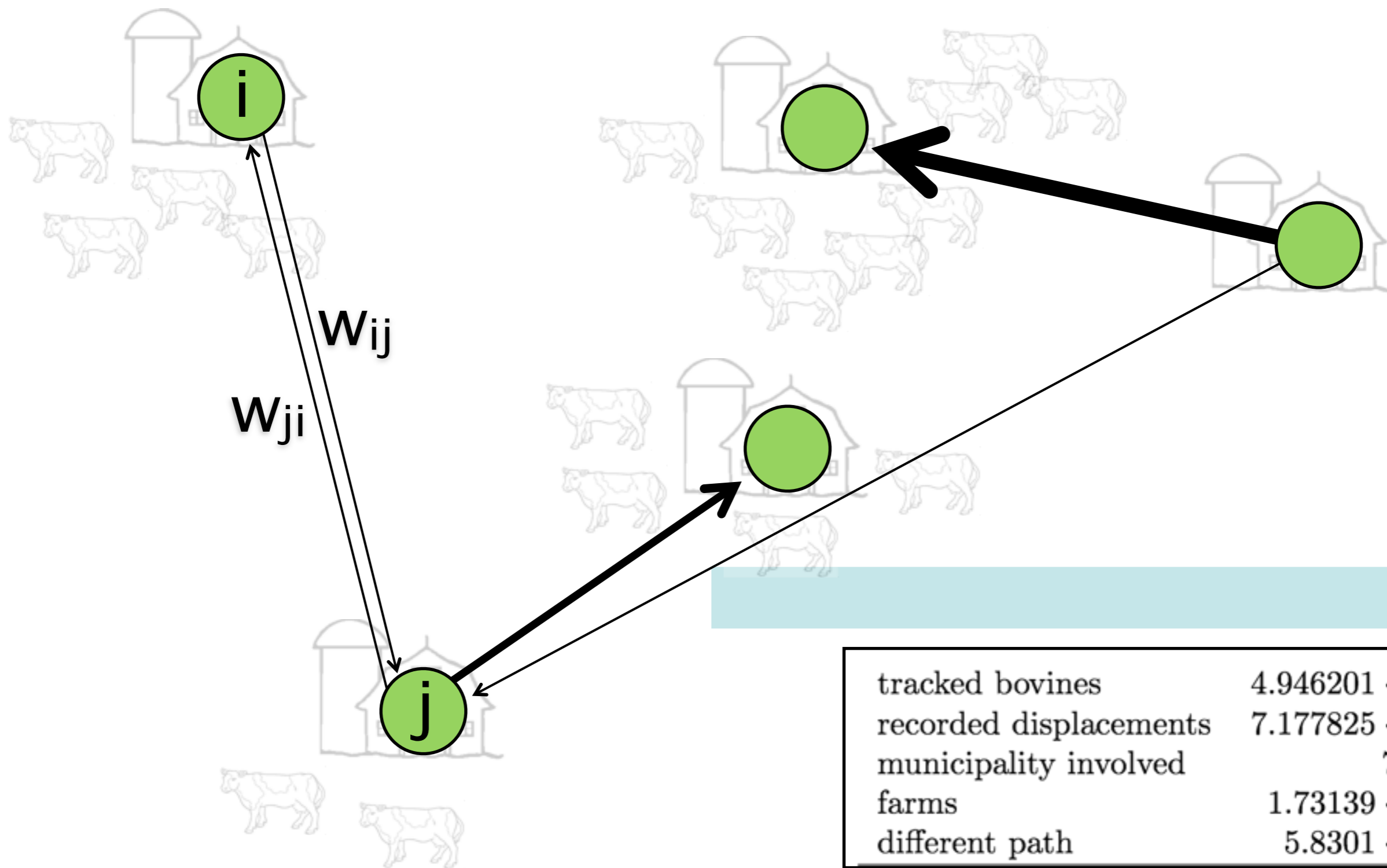*(Gautreau, Barrat, Barthélemy, PNAS (2009))*

Model
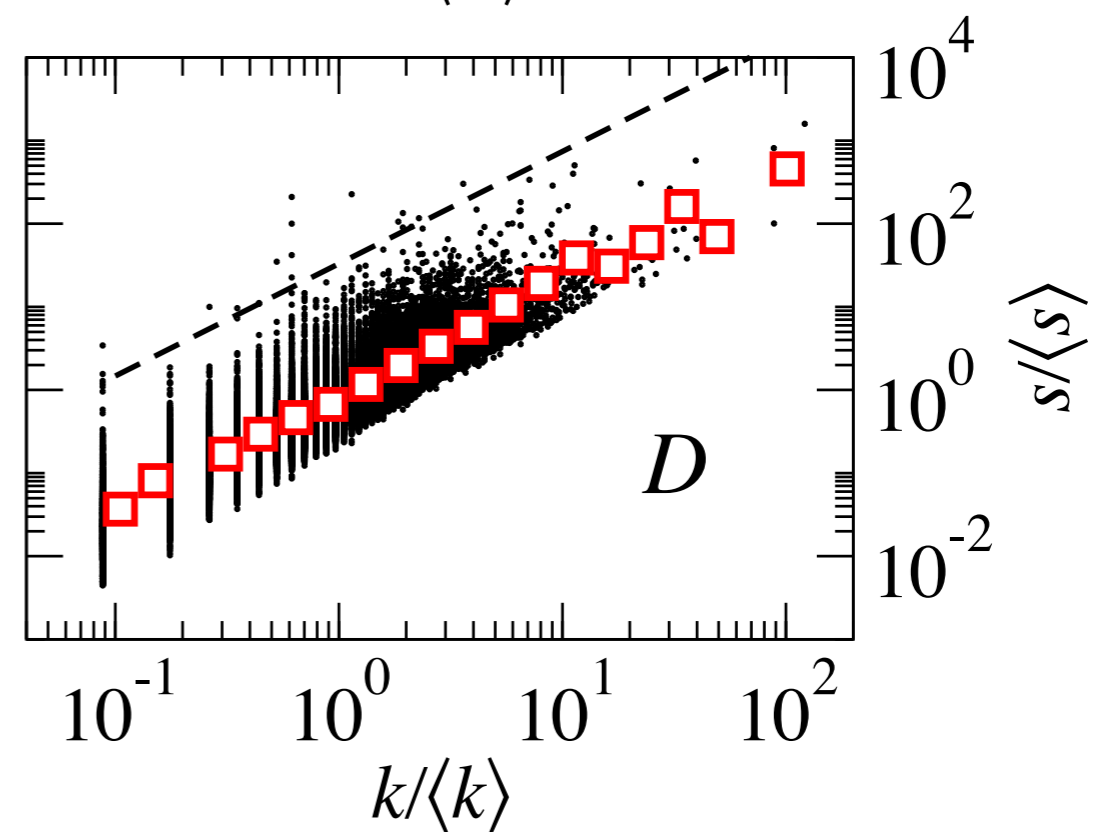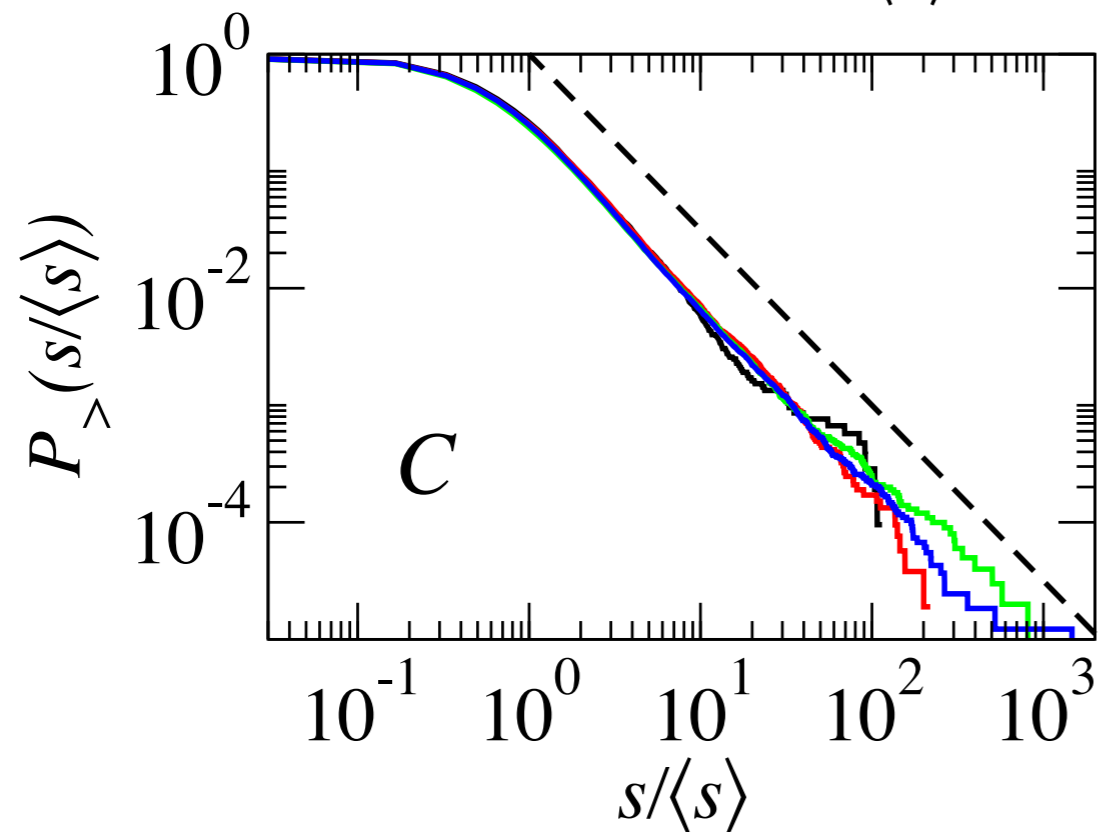
Model
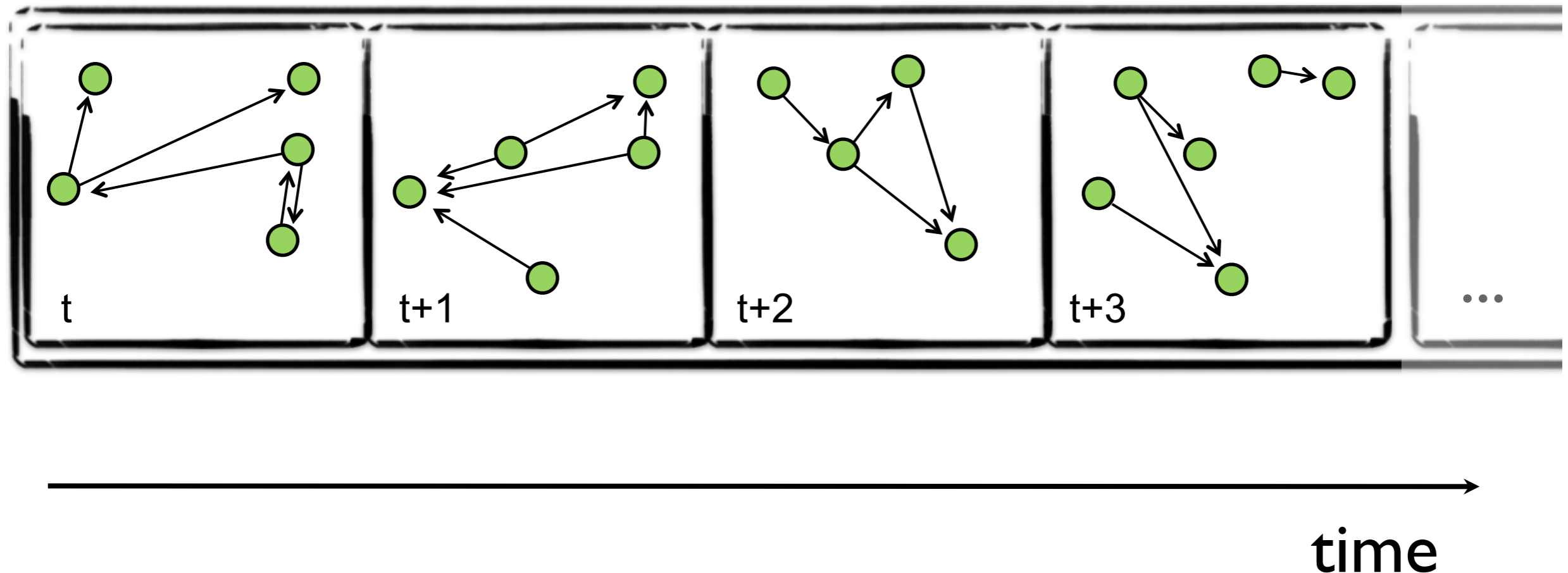
Another example: Cattle movements

tracked bovines	$4.946201 \cdot 10^6$
recorded displacements	$7.177825 \cdot 10^6$
municipality involved	7780
farms	$1.73139 \cdot 10^5$
different path	$5.8301 \cdot 10^5$

Bajardi et al, PLoS ONE (2011)

tracked bovines	$4.946201 \cdot 10^6$
recorded displacements	$7.177825 \cdot 10^6$
municipality involved	7780
farms	$1.73139 \cdot 10^5$
different path	$5.8301 \cdot 10^5$

tracked bovines	$4.946201 \cdot 10^6$
recorded displacements	$7.177825 \cdot 10^6$
municipality involved	7780
farms	$1.73139 \cdot 10^5$
different path	$5.8301 \cdot 10^5$

Aggregate movements within a time window

$$[n\Delta t, (n+1)\Delta t]$$

$\Delta t = 1$

time

=> Time ordered series of directed networks between farms

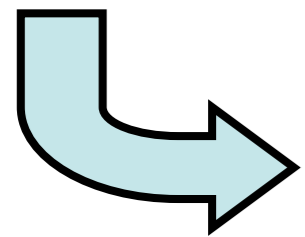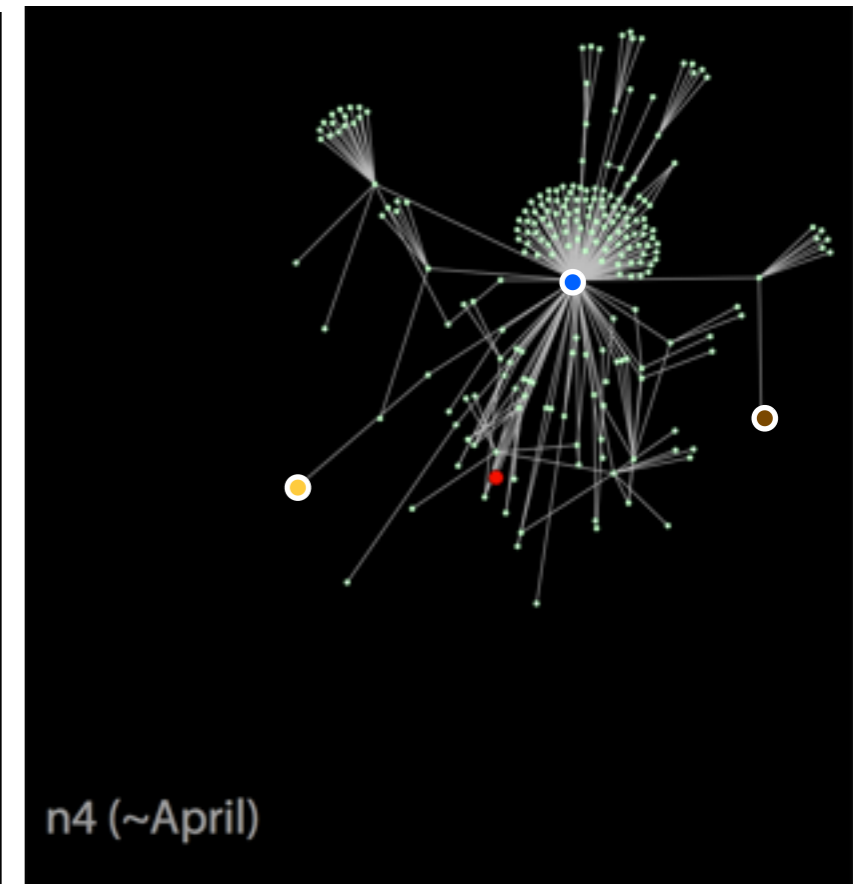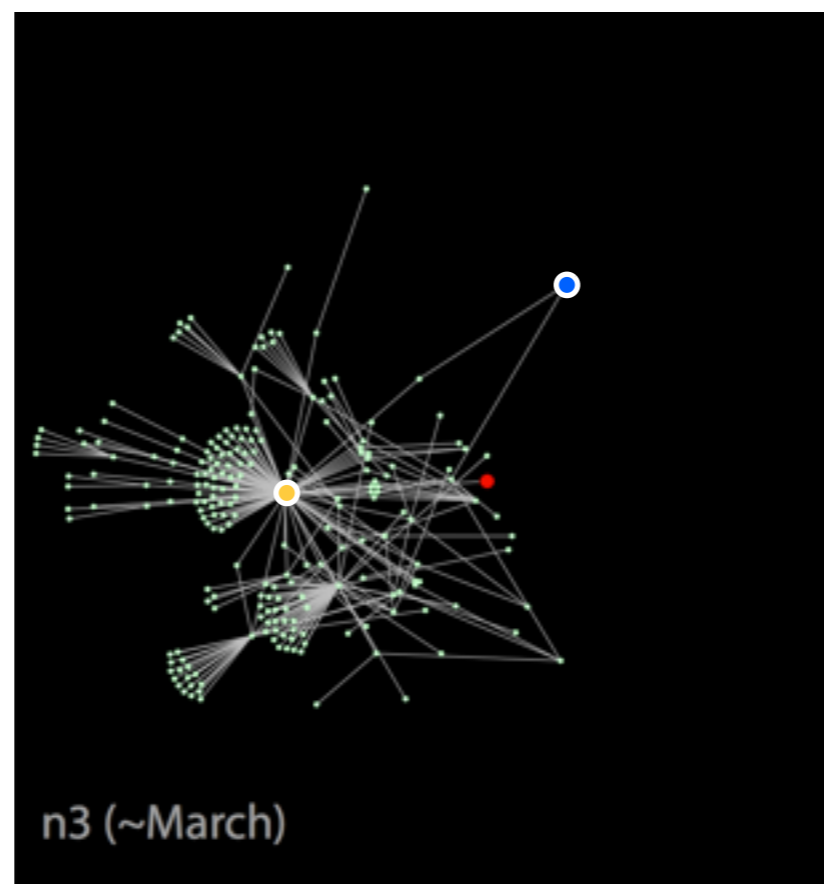# Stationary statistical properties
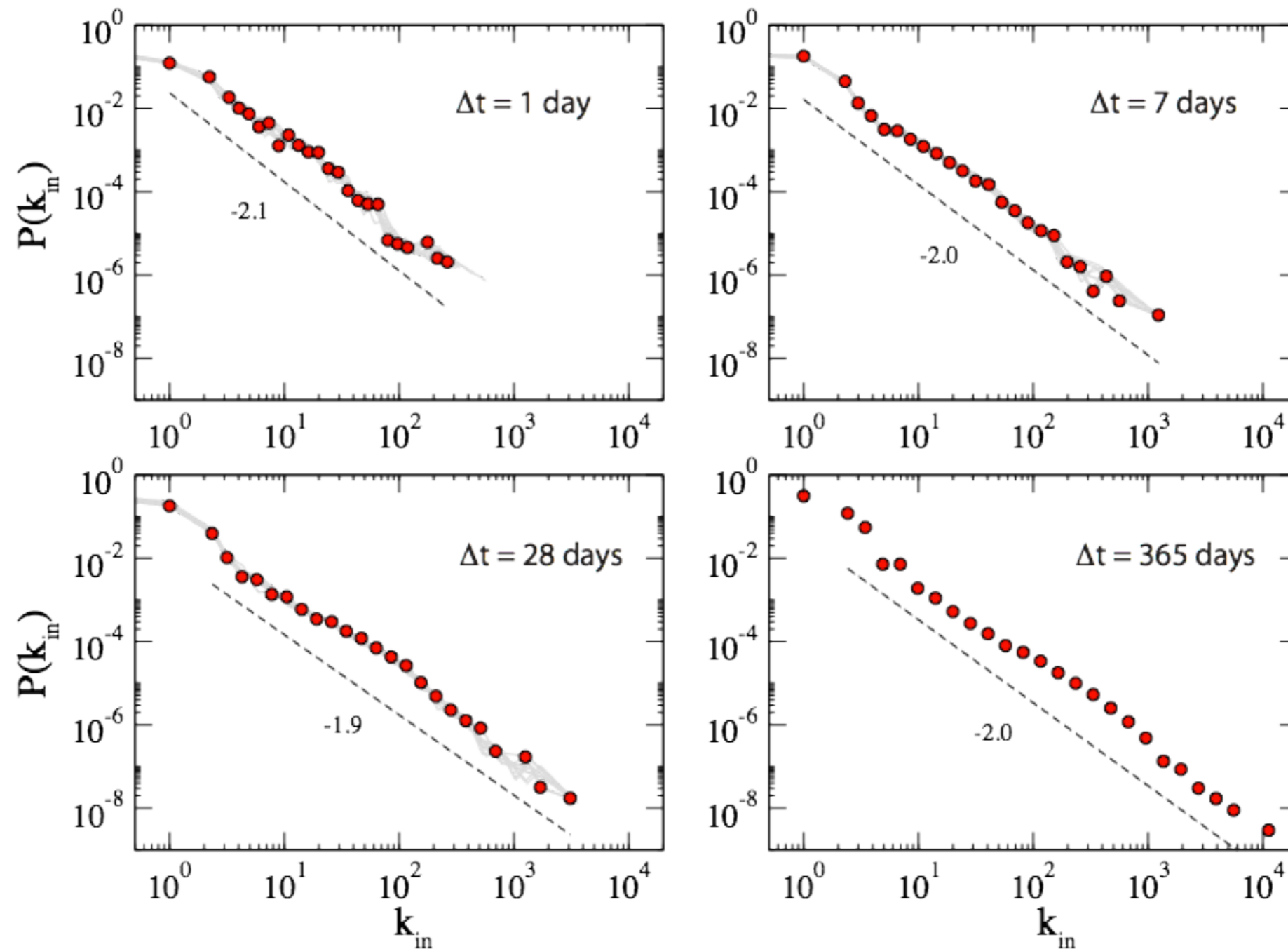
Stationary statistical properties
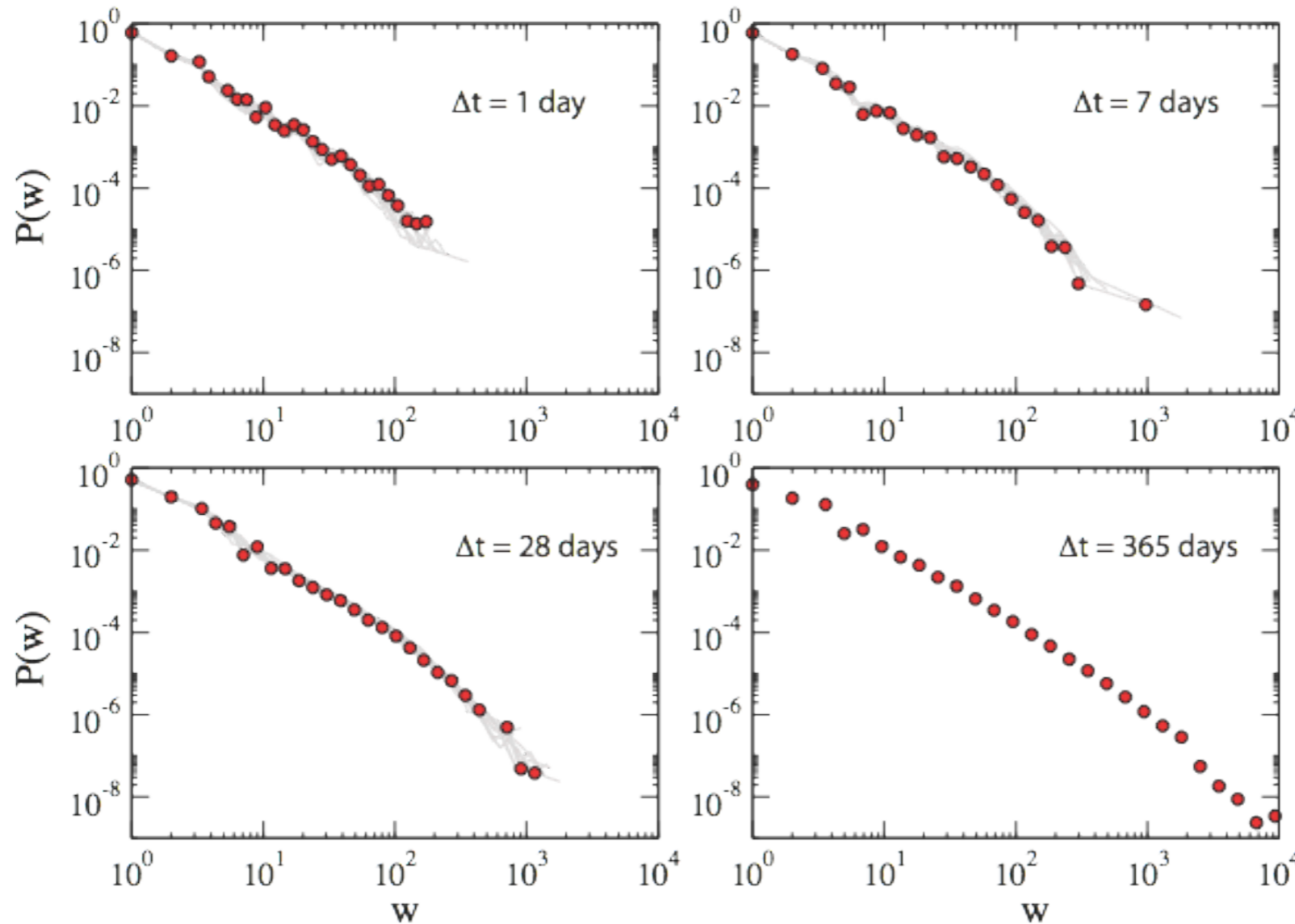
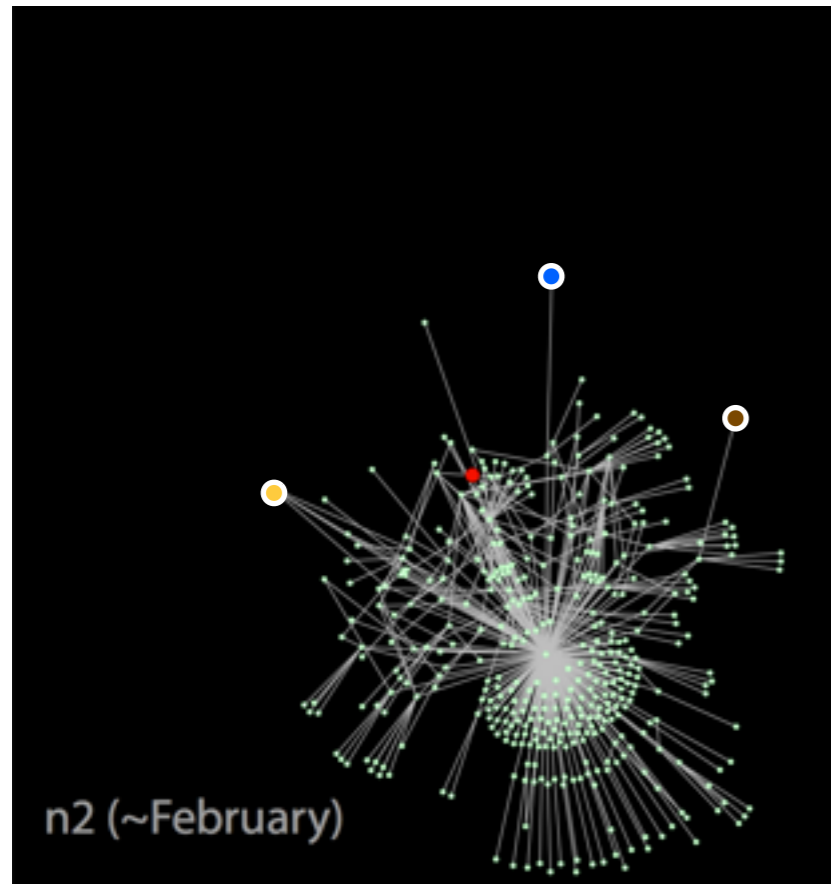$P(k_{in/out})$, $P(s_{in/out})$, $P(w)$, ecc... $\Longrightarrow$ Statistical stationarity of global distributions
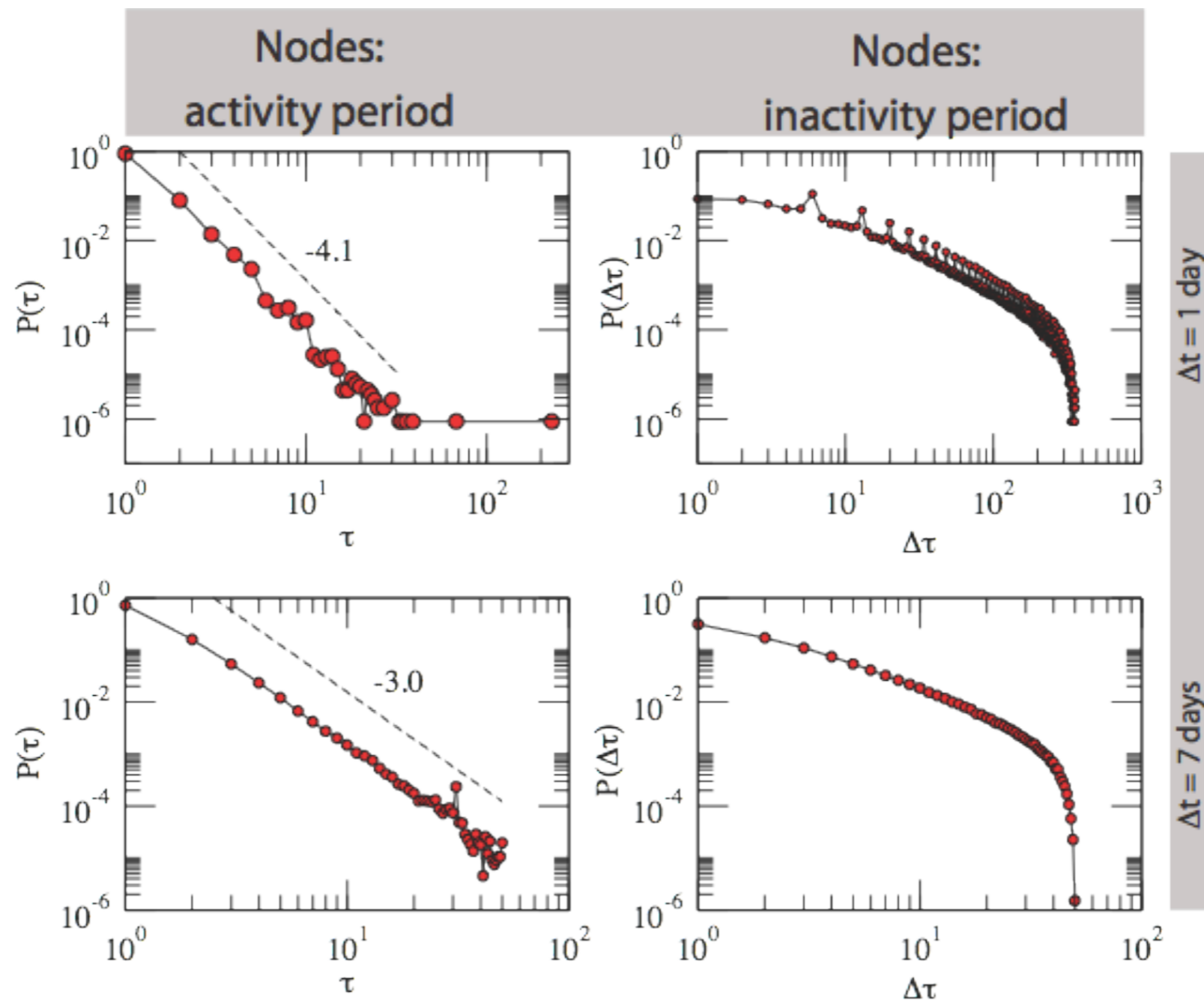
Dynamic behavior of the network

Dynamic behavior of the network
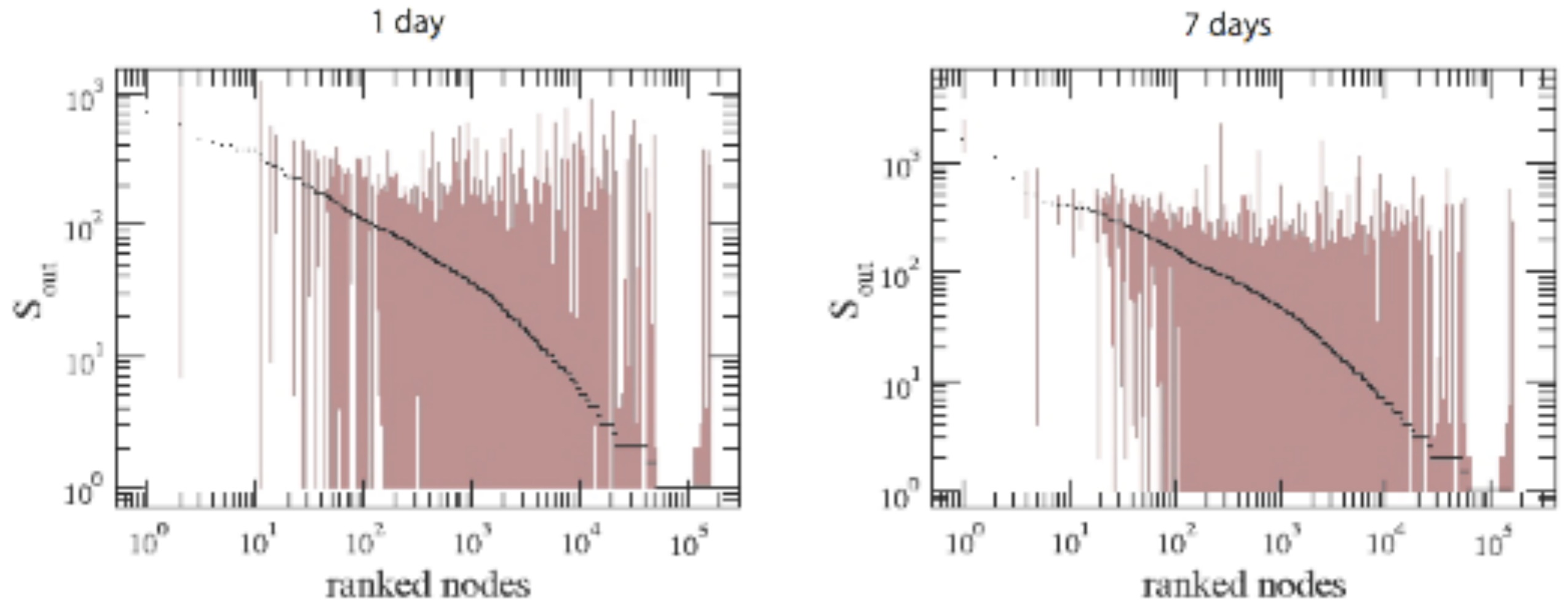

n2 (~February)   n3 (~March)   n4 (~April)
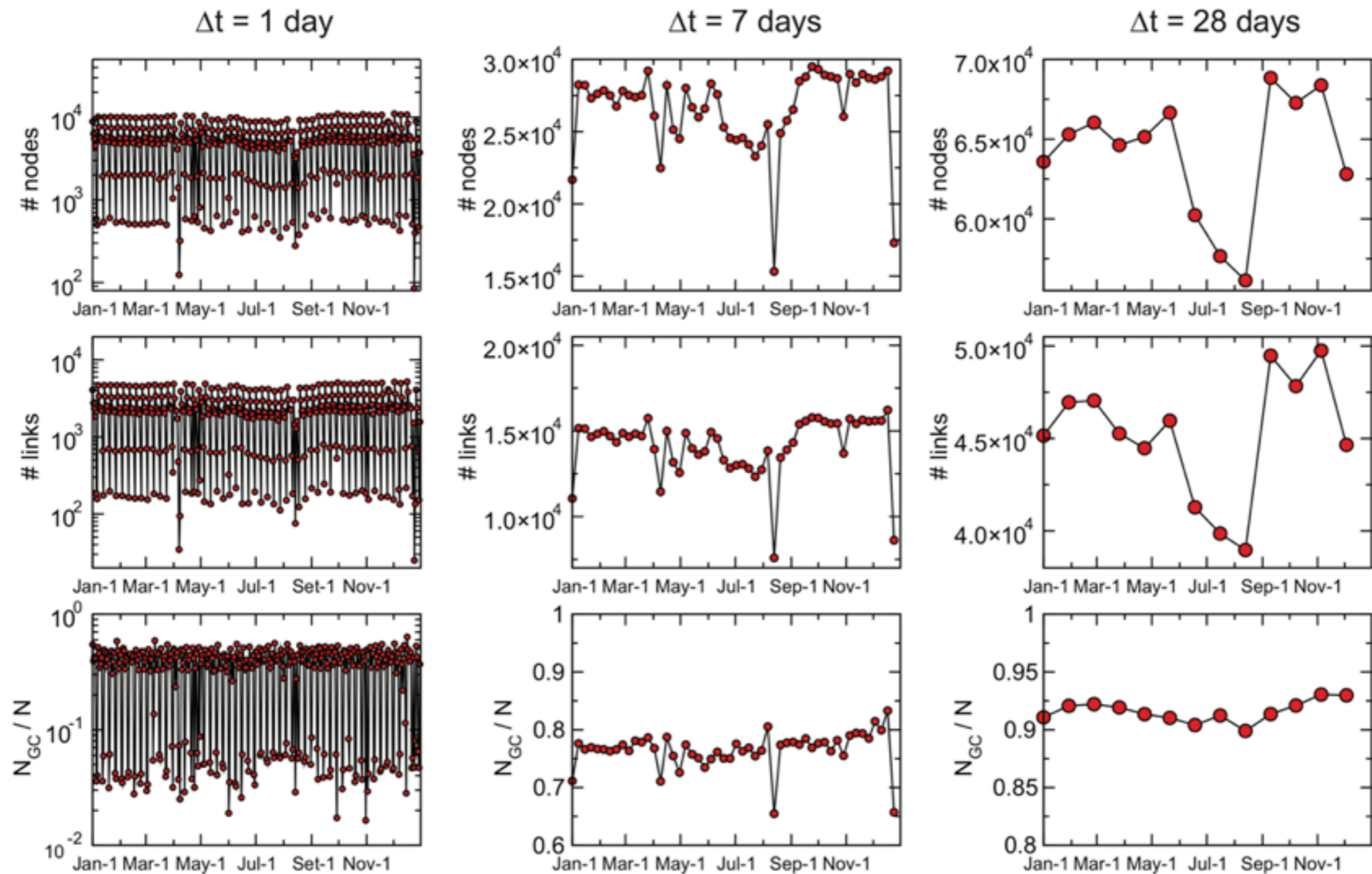
Need to take into account the full dynamical dataset, aggregated views can be misleading

Dynamic behavior of the network

- Lifetime distribution

Fluctuations

Fluctuations of daily/weekly nodes' strengths
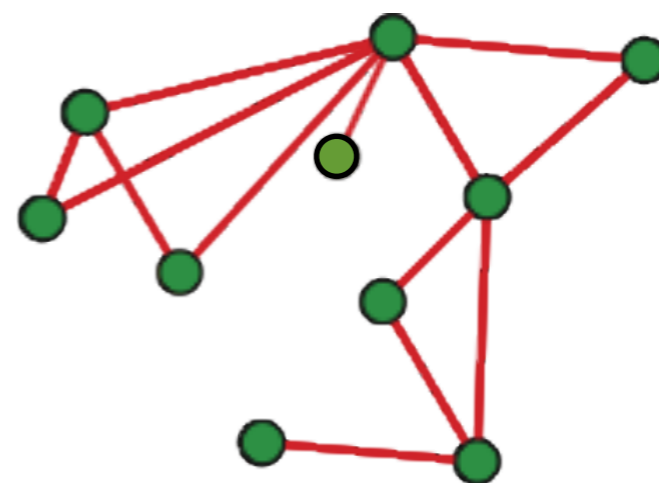
Consequences of temporal fluctuations
Ex: percolation analysis

- used as probe of networks
- identification of most important nodes
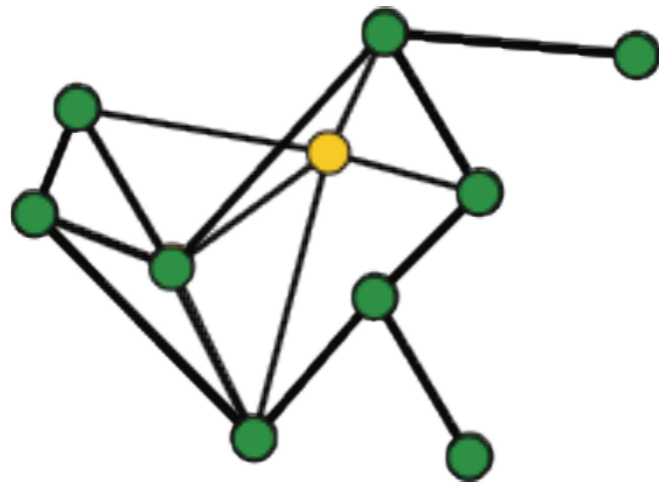- definition of strategies for disease containment
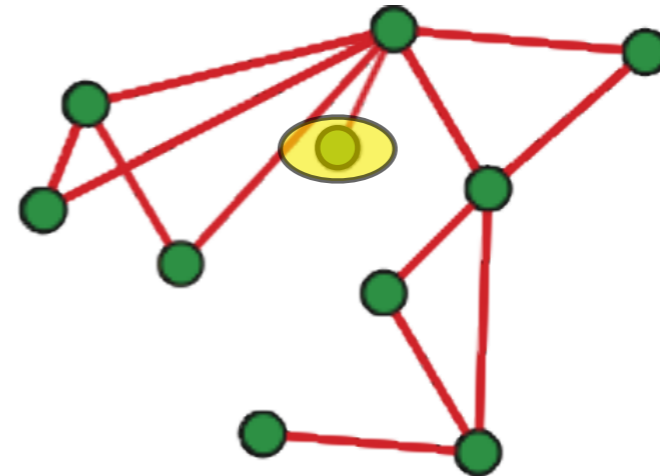
network at time T_1

network at time T_2

Percolation analysis

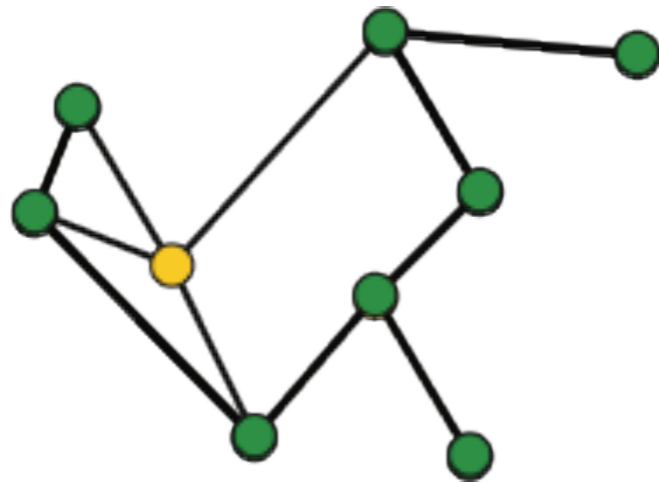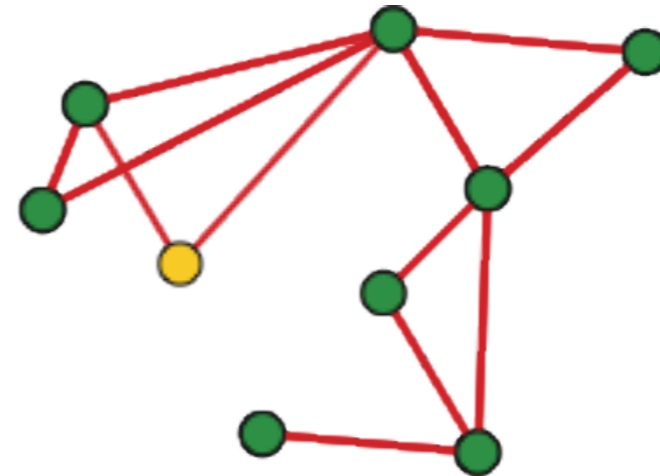network at time T_1

targeted nodes removal

targeted T_1 nodes removal

Percolation analysis

network at time T₁

network at time T_1

network at time T_2

targeted nodes removal

targeted T_1 nodes removal

Percolation analysis

network at time T_1

network at time T_2

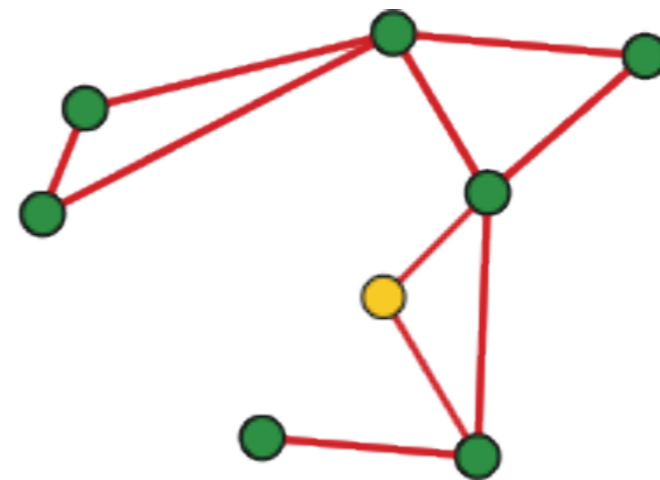targeted nodes removal

targeted T_1 nodes removal

Percolation analysis

network at time T$_1$

network at time T$_2$

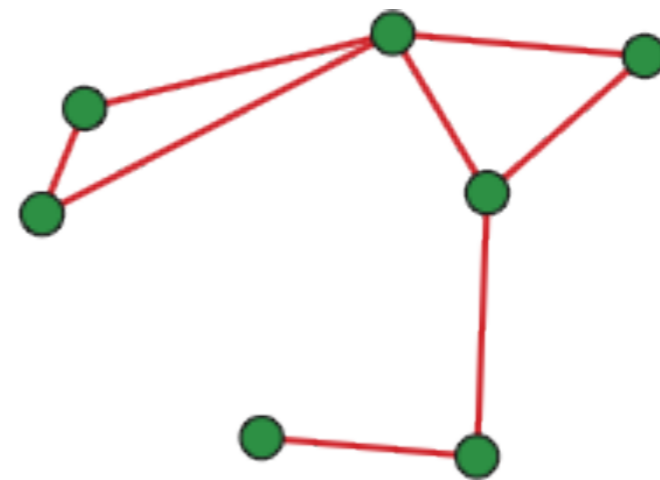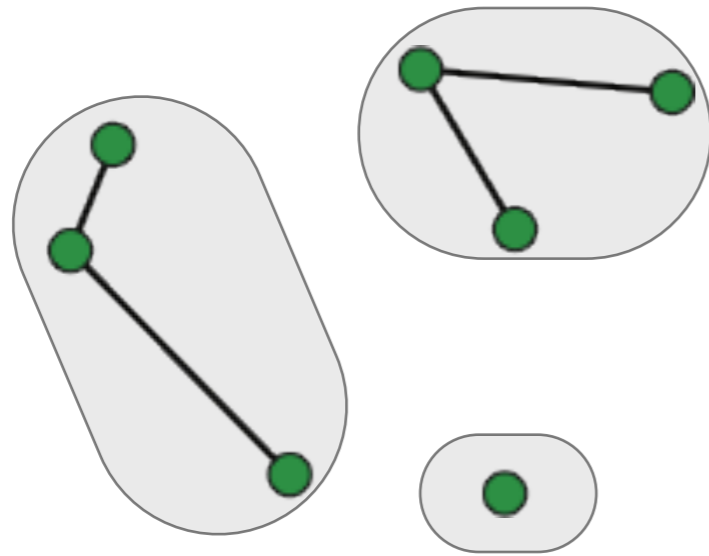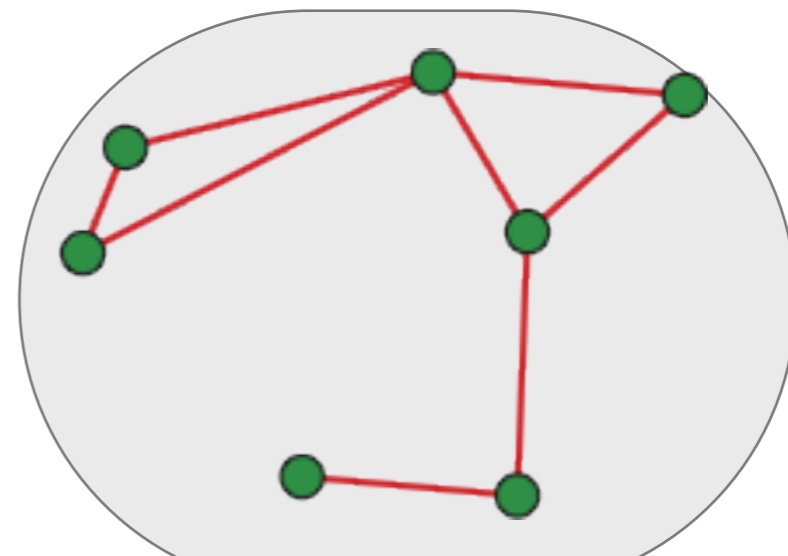targeted nodes removal

targeted T$_1$ nodes removal

Percolation analysis
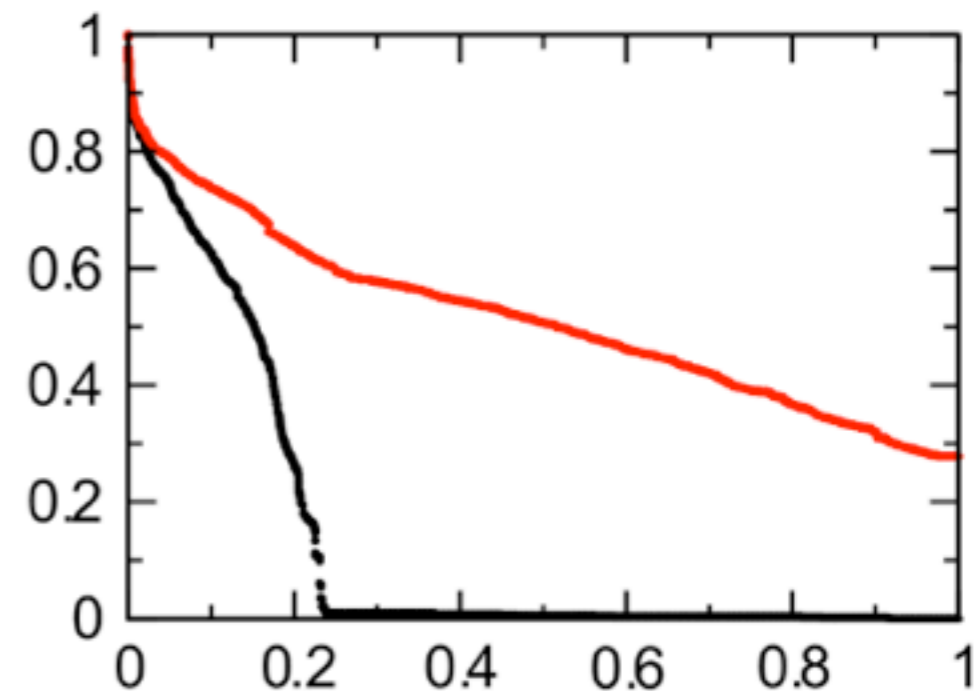
network at time T₁
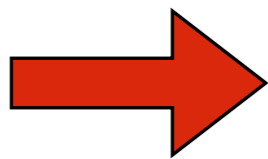
targe...

Targeted attack based on static/ past measures is ineffective

...0.5)

Ex: monthly networks n=3 and n=4

fraction of nodes in the GC
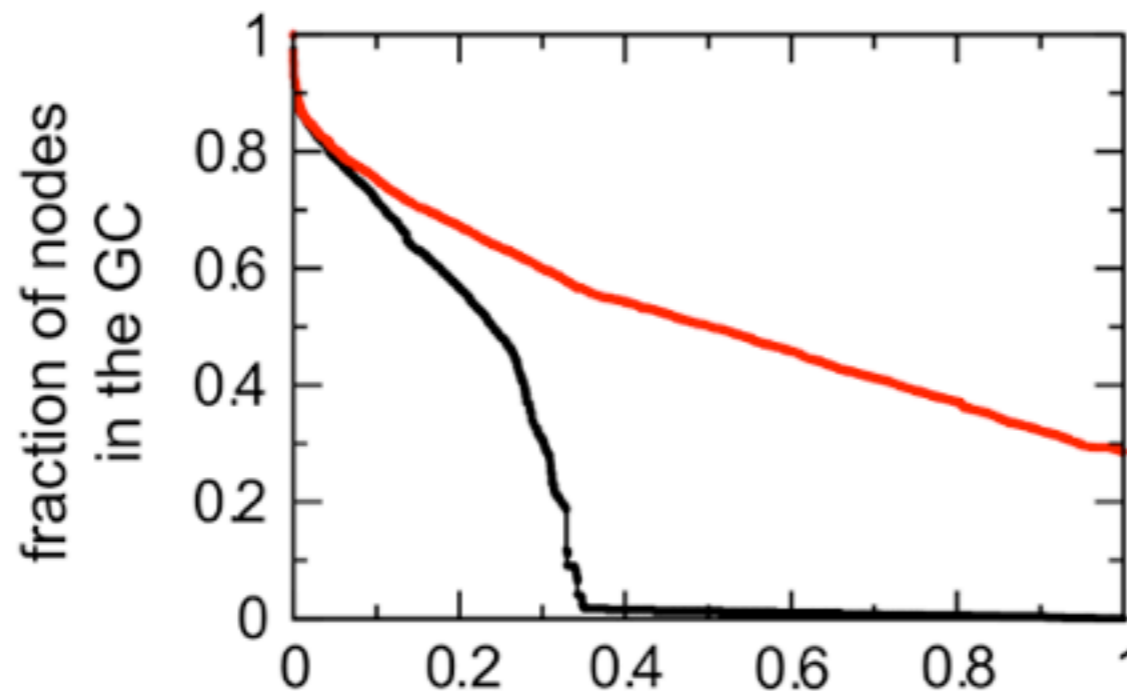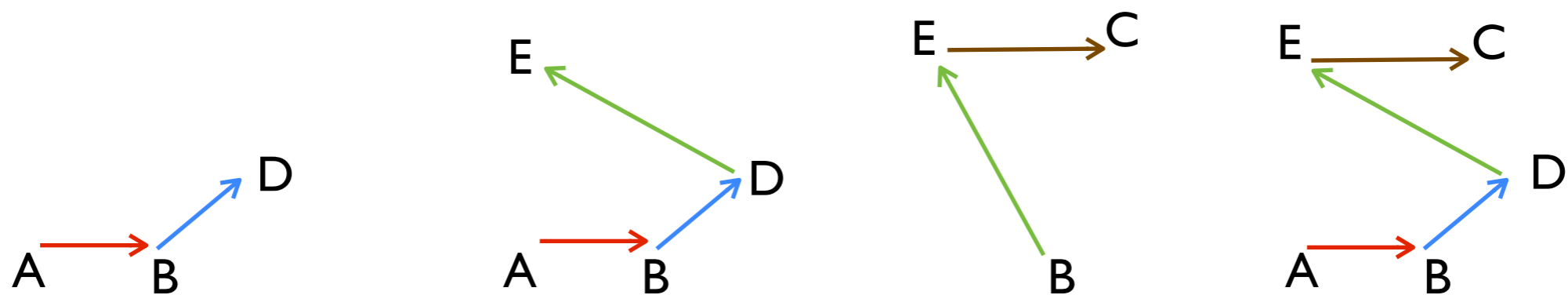
fraction of nodes removed (order= decreasing degree in 3rd monthly network)

New tools: Dynamical motifs

Paths respecting causality:
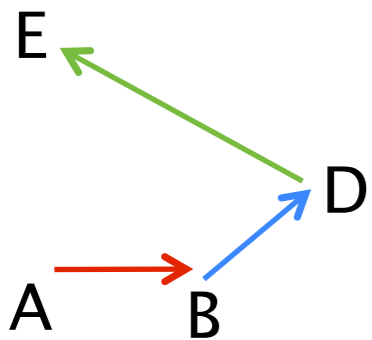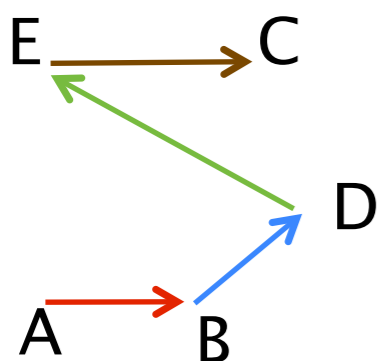
Bajardi et al, PLoS ONE (2011)
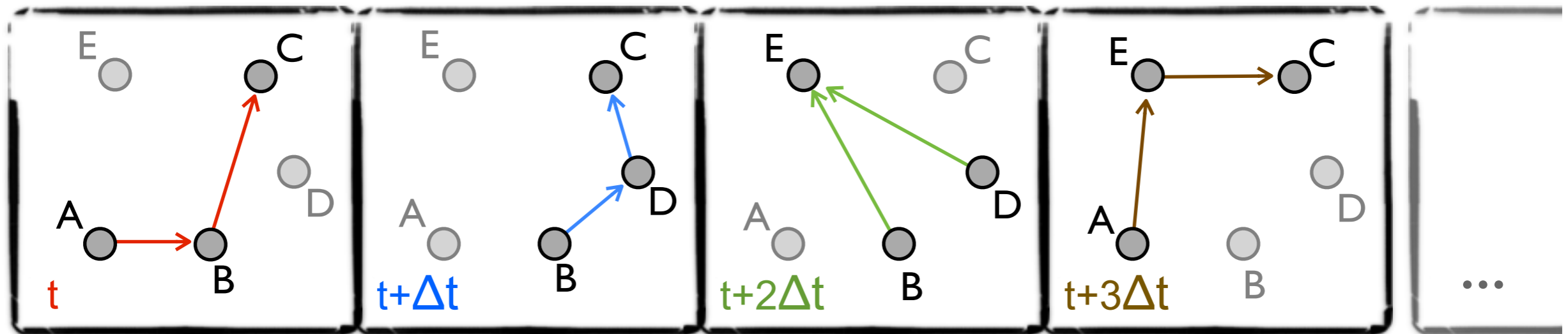
New tools: Dynamical motifs

Paths respecting causality:
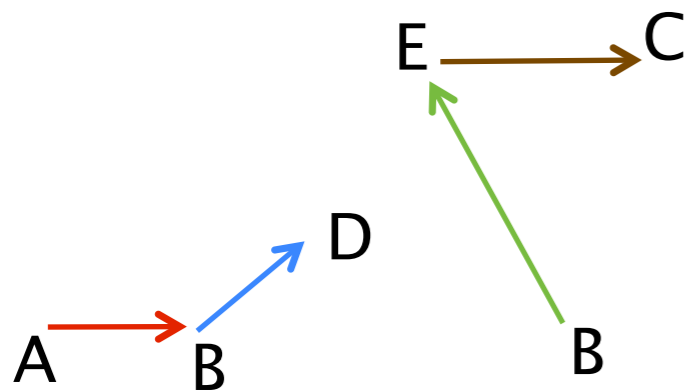
length 2

length 3

length 4

...

Bajardi et al, PLoS ONE (2011)
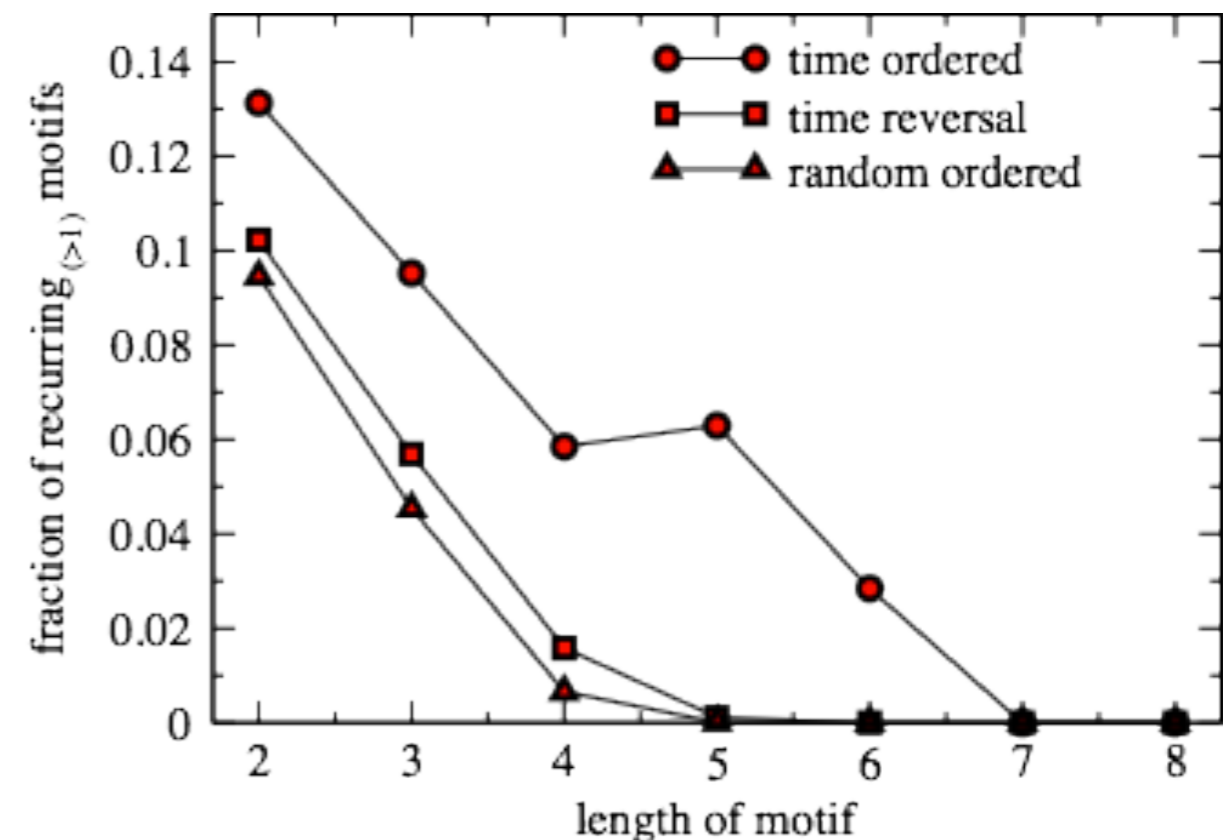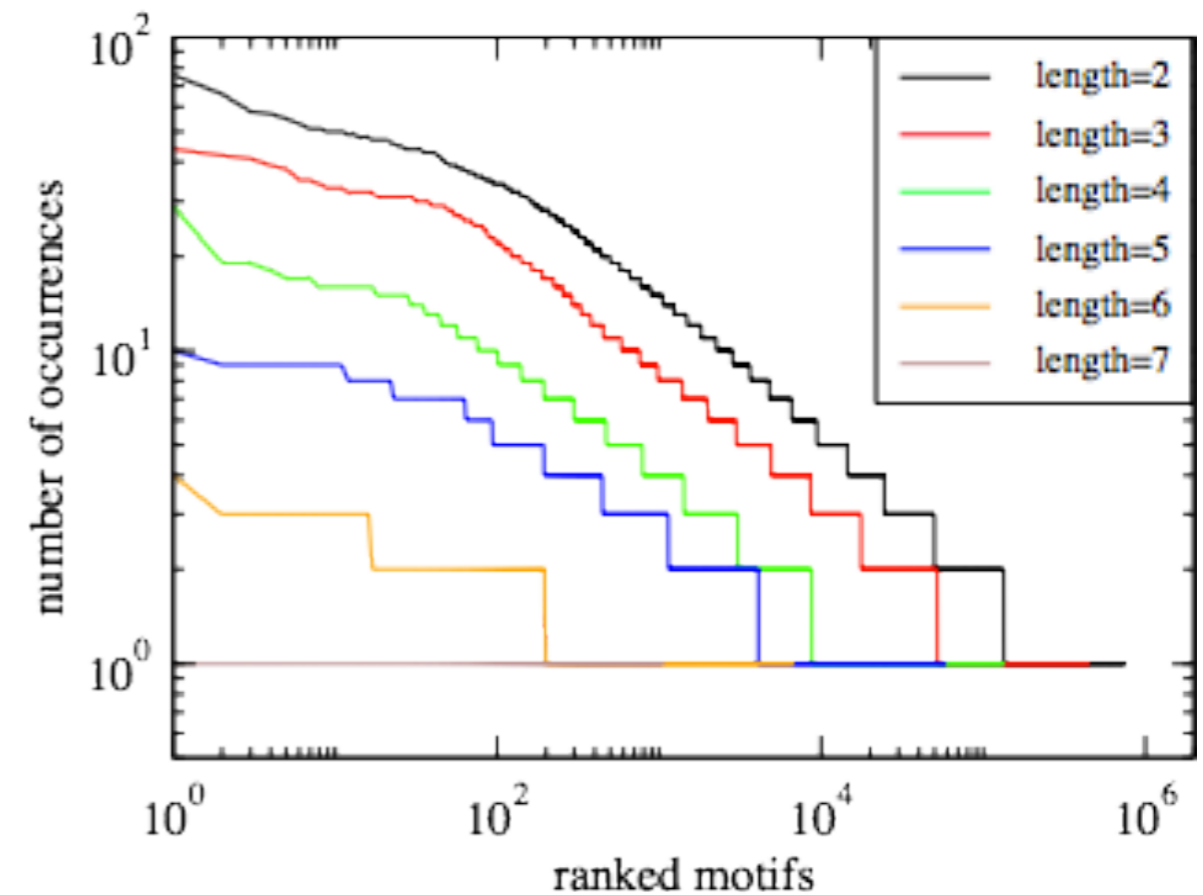
Dynamical networks of human interactions

Data on the dynamics of human interaction networks

- **Mobile phones** (Onnela et al 2007, Gonzalez et al 2009,...)
  - Localisation, mobility patterns, predictability
  - Strength of weak ties
  - ...

- Social interaction networks
  - Bluetooth, wifi (O' Neill et al 2006; Scherrer et al 2008; Eagle, Pentland 2009)
  - MIT Reality mining project (sociometric badges)
  - MOSAR european project (hospitals)
  - Salathé et al. 2010 (highschool)
  - ...

LACKING: large-scale time-resolved data on f2f proximity across a variety of contexts

Gathering data:
The SocioPatterns project

what are the statistical and dynamical properties
of the networks of contact and co-presence
of people in social interaction?
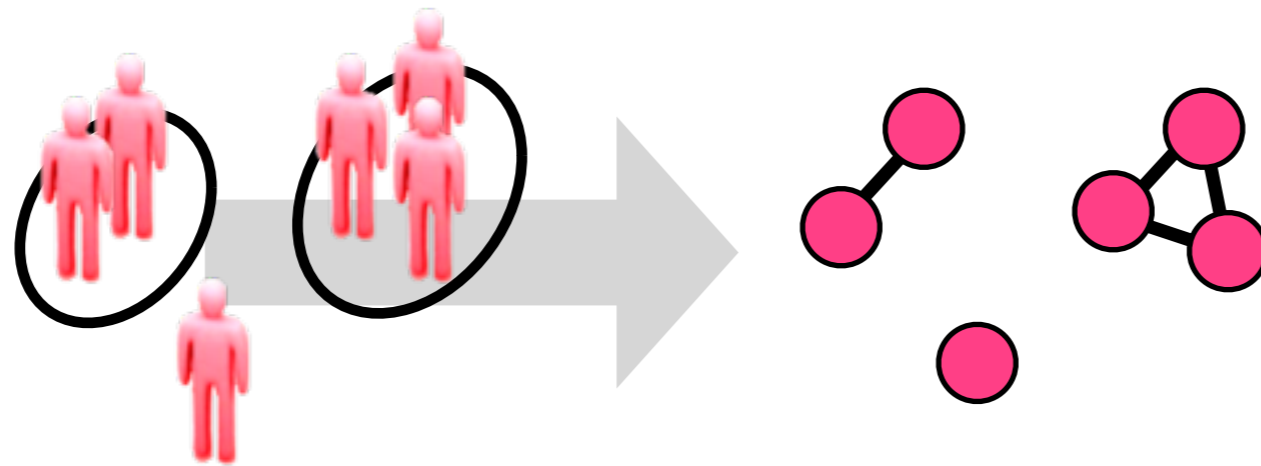
fine-grained **spatial** (~ m) and **temporal** (<min) resolution

Motivations
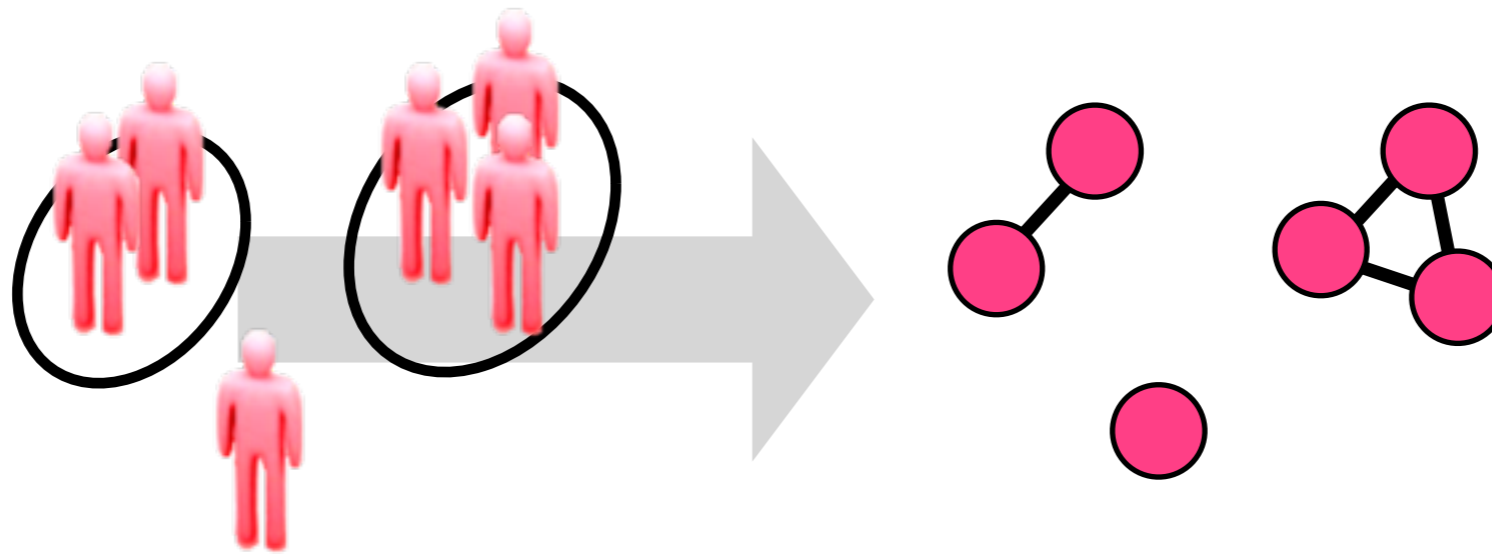
★ fundamental knowledge on human contact
★ epidemiology
★ social sciences
★ ad-hoc networks
★ integration with on-line information
★ ...

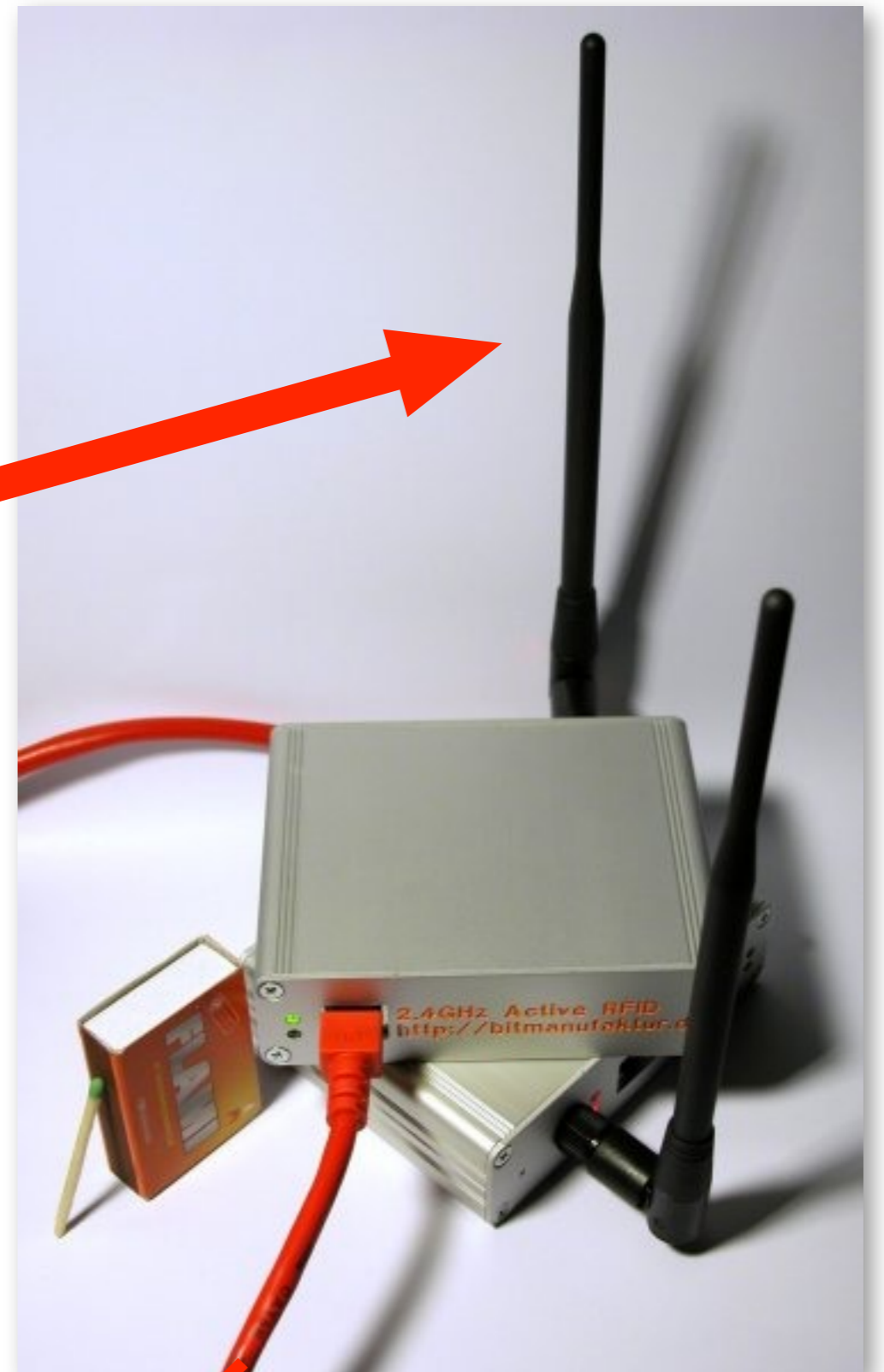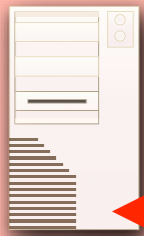(not your usual) active RFID

standard active RFID behavior

"I am 42 !"

42

LAN

Contact detection

10

42

Short distance (~1-2m):
Exchange of very low power
data packets
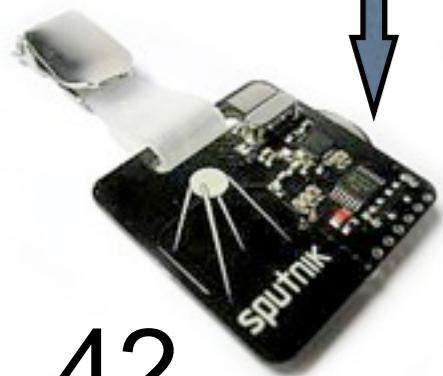
"42 saw 10 at power 0"
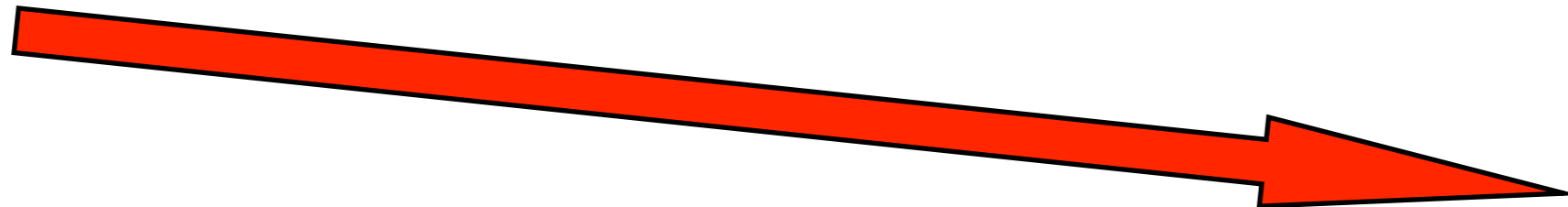
- Two power levels => 2 detection ranges
- Face to face situation
- Statistical detection => 20s time resolution
- Small,
- Scalable

2.4GHz Active RFID
http://bitmanufaktur...

From event stream to dynamical network

distributed proximity scan

time-stamped star-shaped proximity sub-graphs

temporal aggregation over sliding window to produce global proximity graph
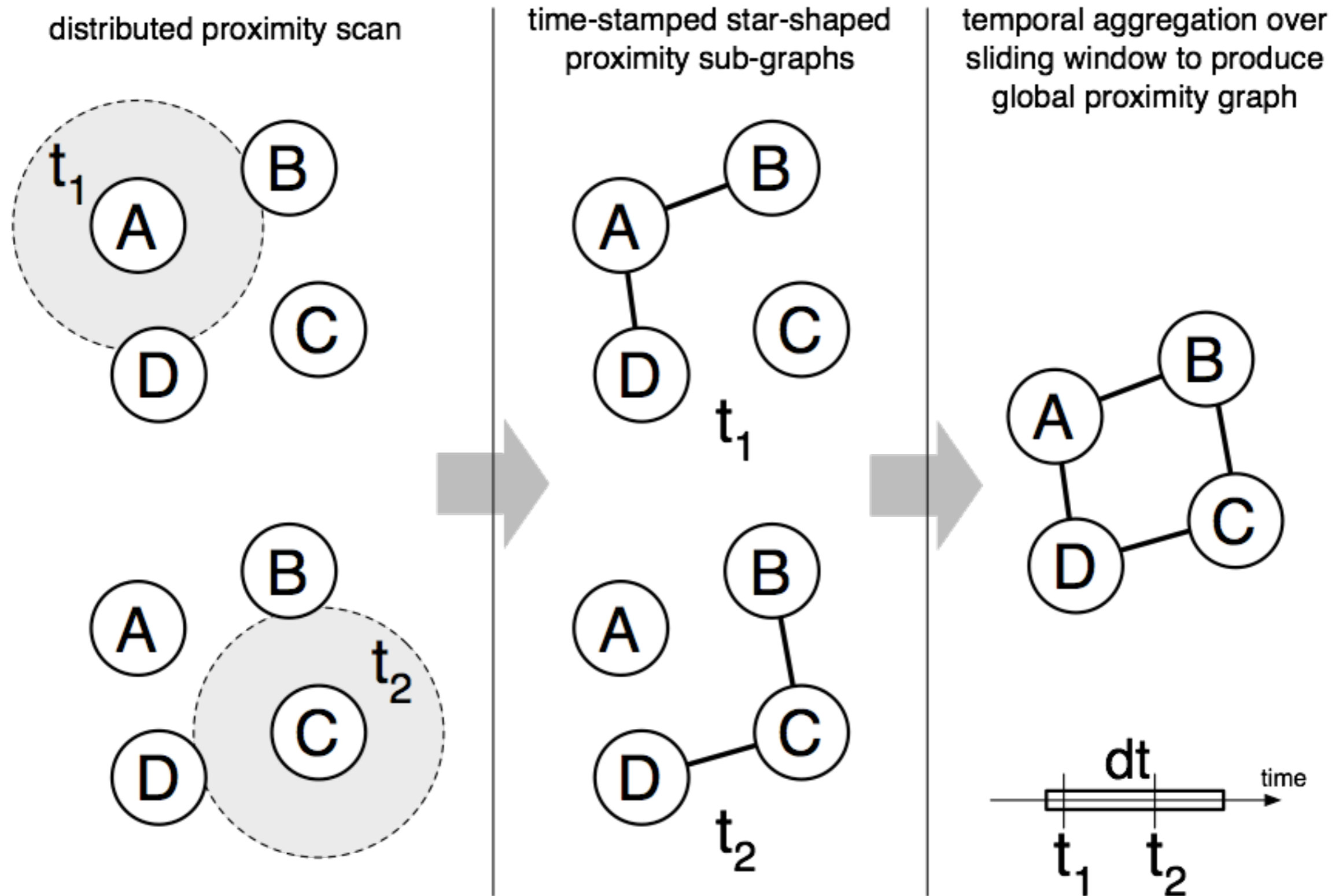
dynamical network of f2f proximity

http://www.vimeo.com/6590604

DATE	EVENT	SIZE	DURATION
May 2008	Socio-physics workshop, Torino, IT	~65	3 days
Jun 2008	ISI offices, Torino, IT	~25	3 weeks
Oct 2008	ISI workshop, Torino, IT	~75	3 days
Dec 2008	Chaos Comm. Congress, Berlin, DE	~600	4 days
Apr-Jul 2009	Science Gallery, Dublin, IE	~30,000	3 months
Jun 2009	ESWC09, Crete, GR	~180	4 days
Jun 2009	SFHH, Nice, FR	~360	2 days
Jul 2009	ACM HT2009, Torino, IT	~120	3 days
Oct 2009	Primary school, Lyon, FR	~250	2 days
Nov 2009	Bambino Gesù Hospital, Rome, IT	~250	10 days
Jun 2010	ESWC10, Crete, GR	~200	4 days
Apr 2010	Practice Mapping, Gijon, ES	~100	10 days
Jul 2010	H-Farm, Treviso, IT	~200	6 weeks

>a glimpse of data
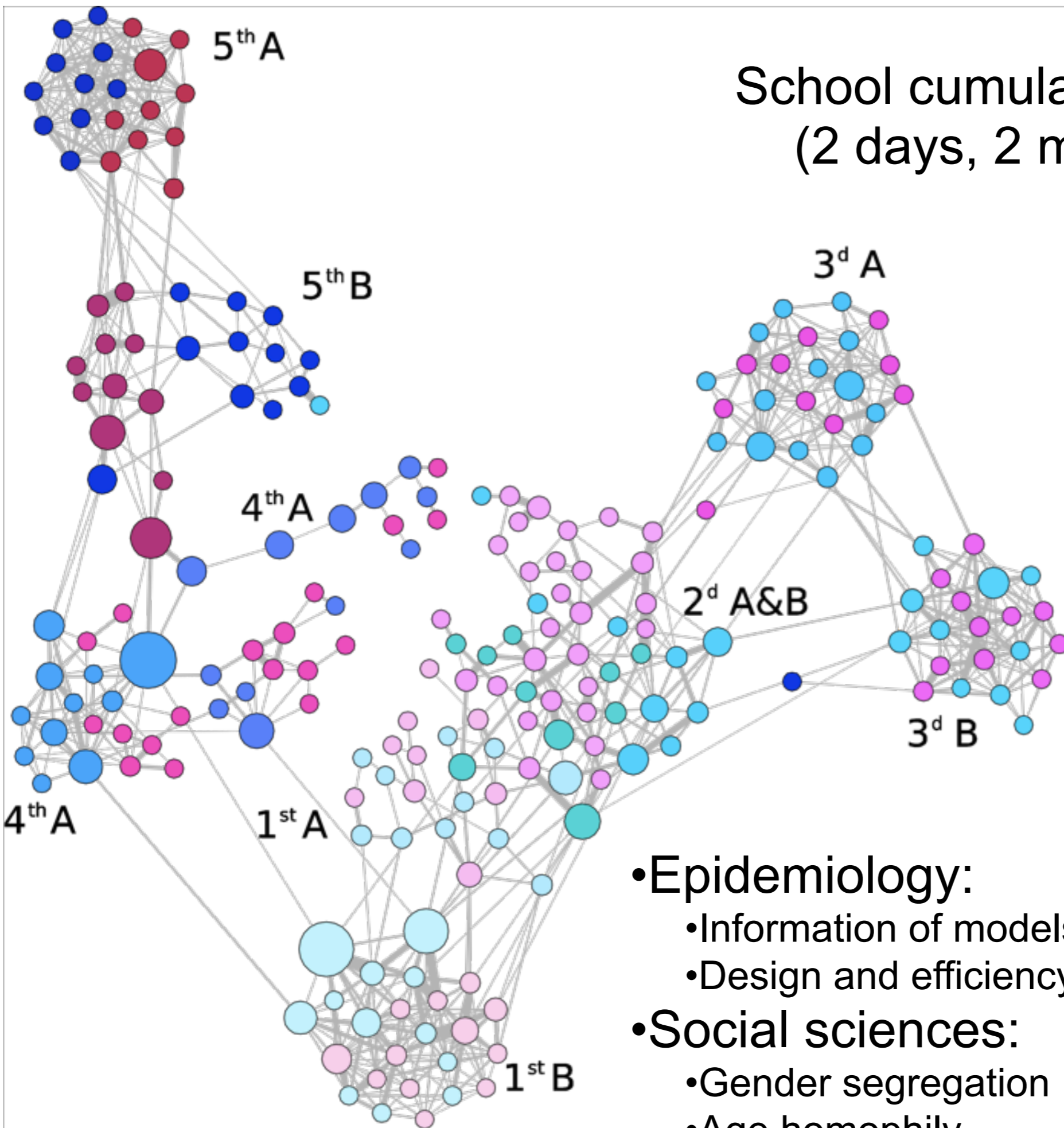
Several data sets available at
www.sociopatterns.org

>school

contacts in a primary school

2nd grade

3rd grade

1st grade

4th grade

5th grade
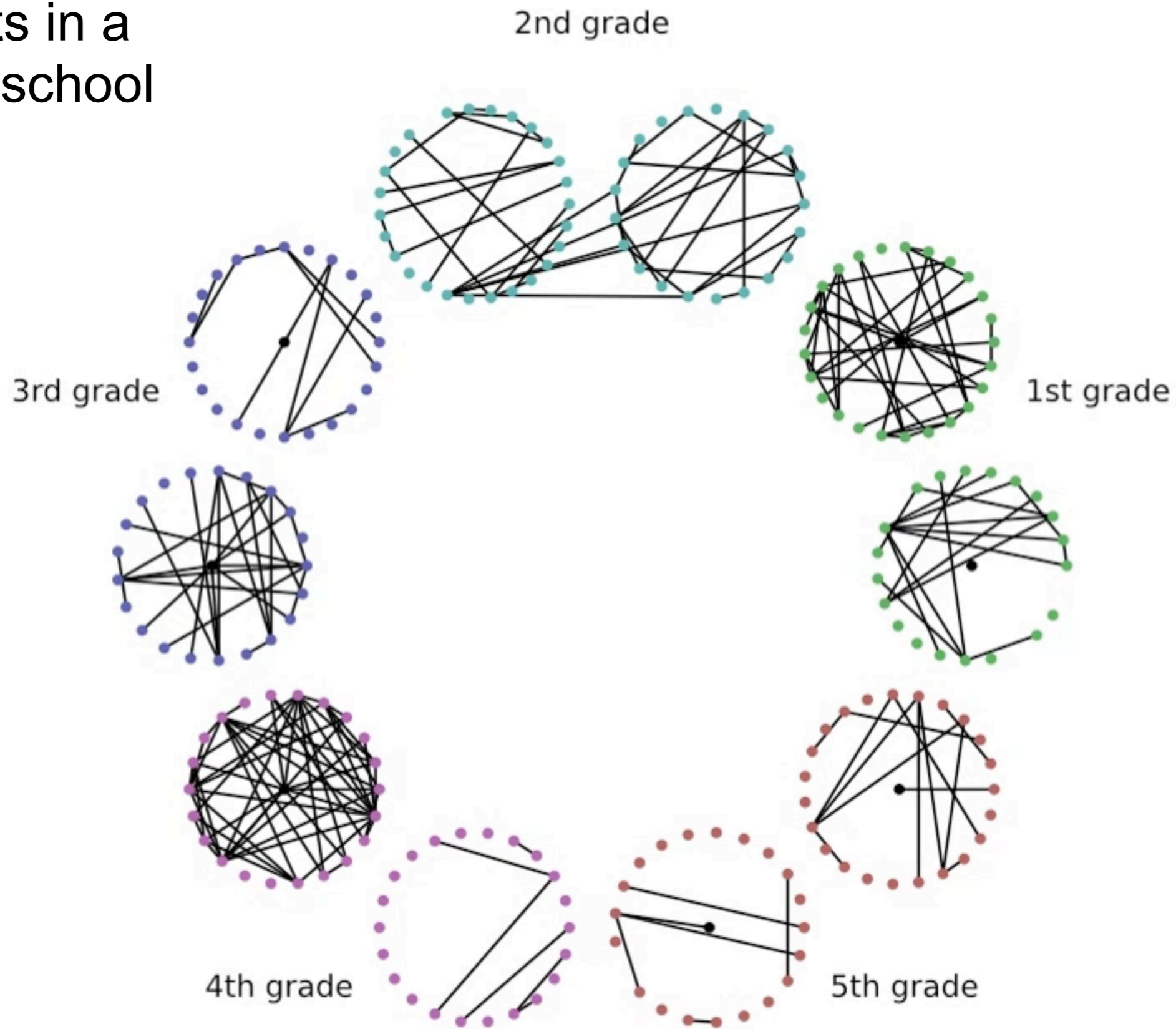
Thu, 11:20- 12:00

School cumulative f2f network
(2 days, 2 min threshold)

J. Stehlé et al. PLoS ONE
6(8):e23176 (2011)

5th A

5th B

3d A

4th A

2d A&B

3d B

4th A

1st A

1st B

- Epidemiology:
  - Information of models
  - Design and efficiency of containment measures
- Social sciences:
  - Gender segregation
  - Age homophily

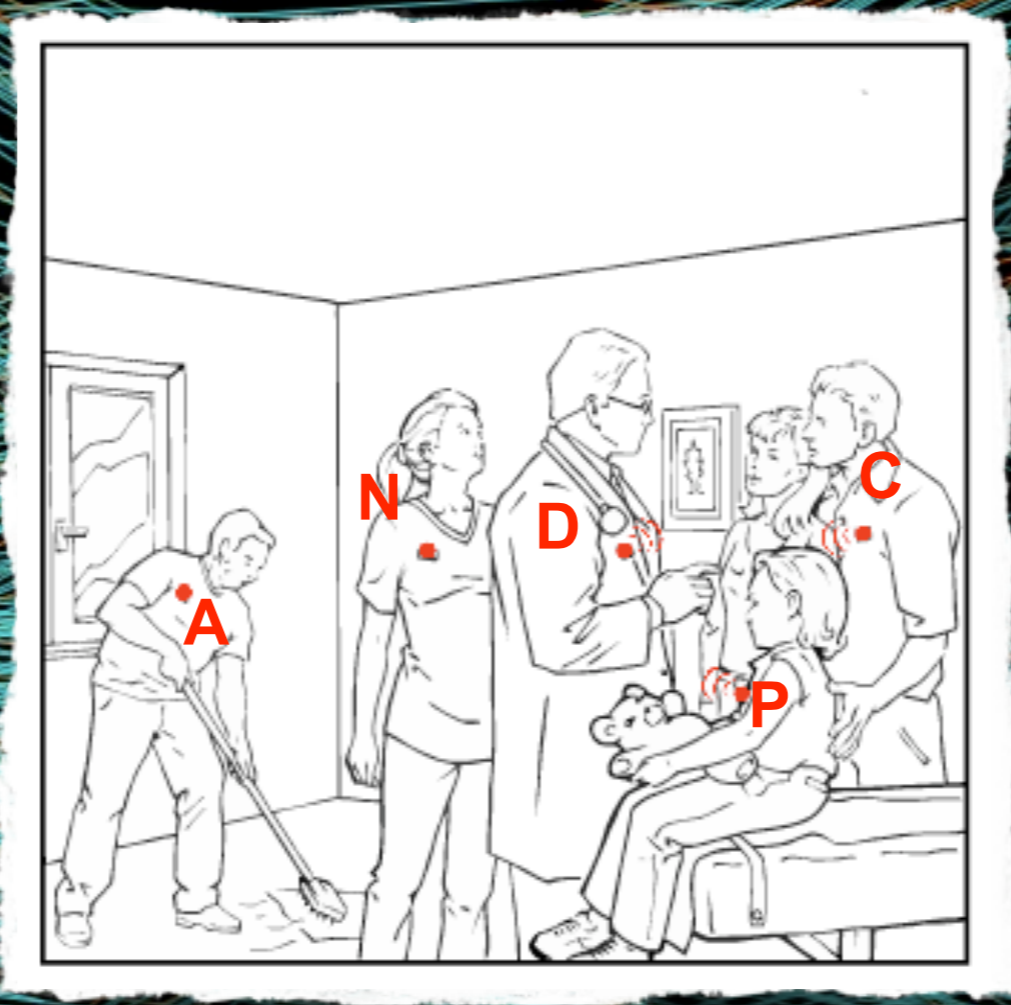# class contact matrix
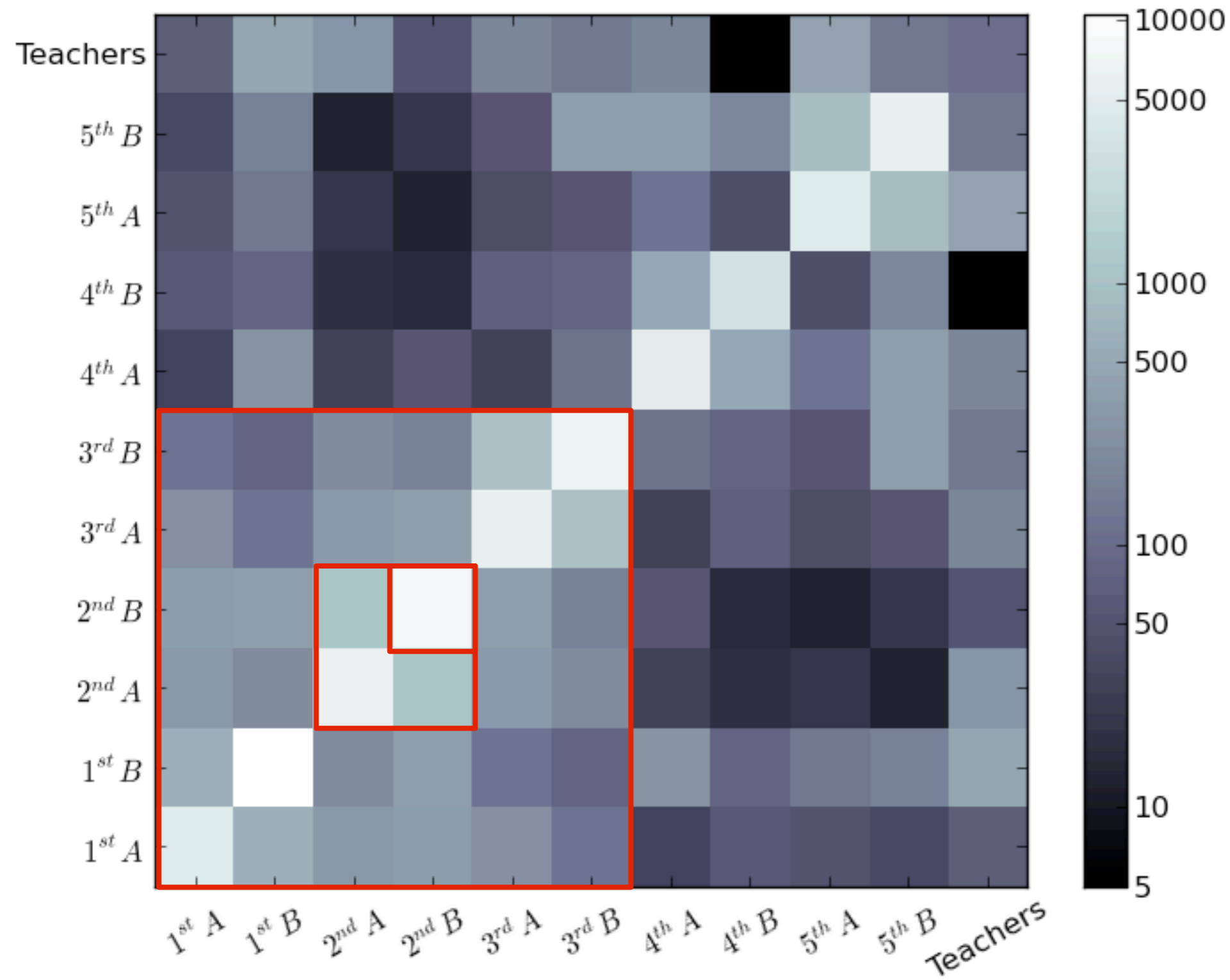
J. Stehle, et al.
High-Resolution Measurements of Face-to-Face Contact Patterns in a Primary School
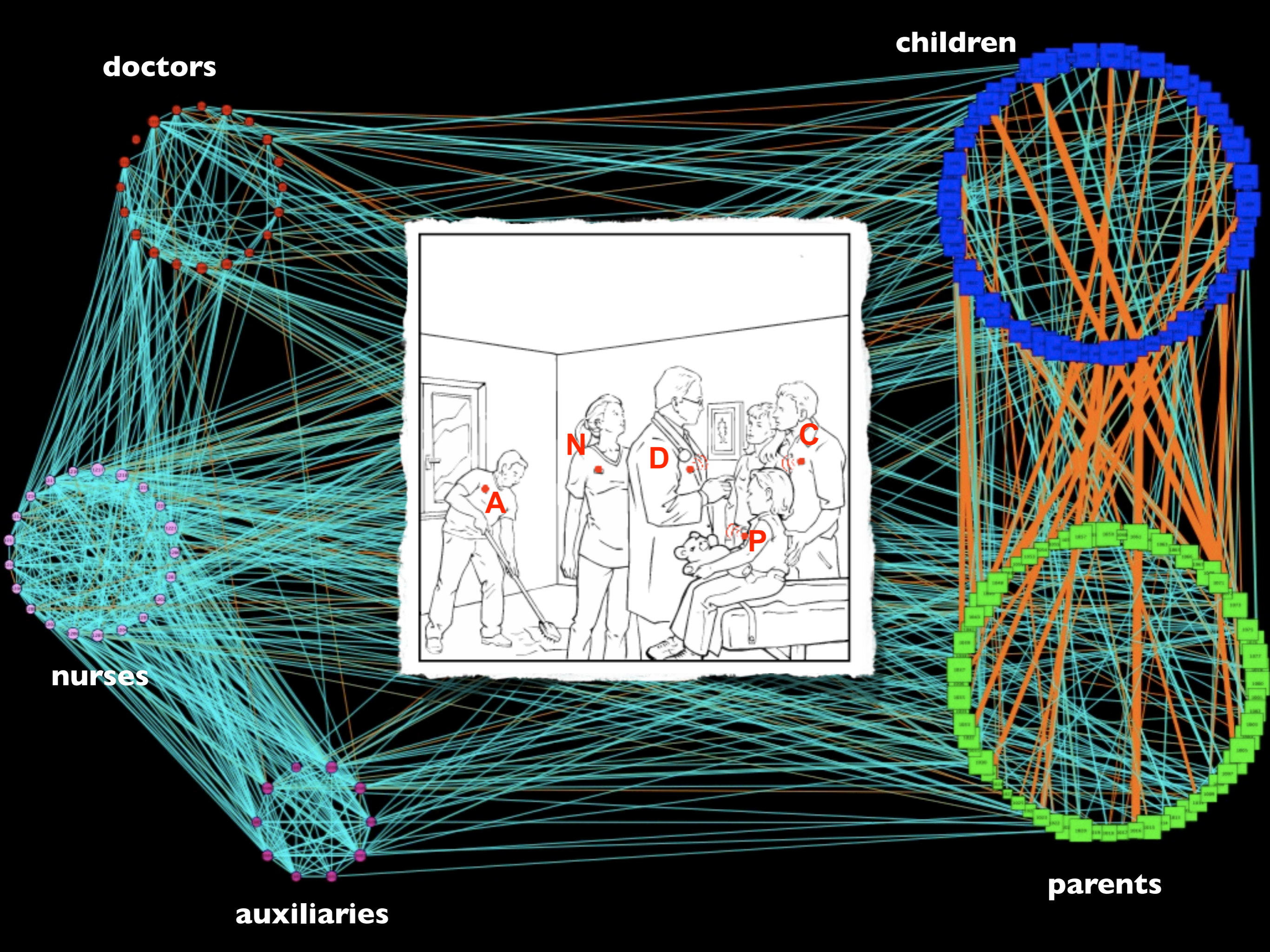PLoS ONE 6(8), e23176 (2011)
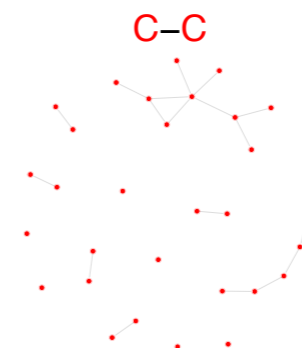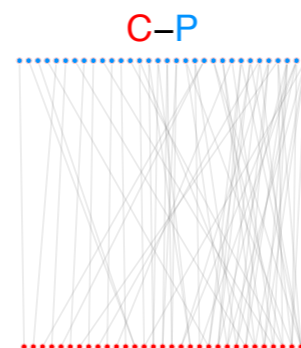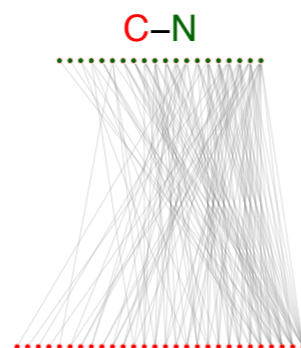
>hospital

doctors

children

nurses

auxiliaries

parents

class-level contact networks
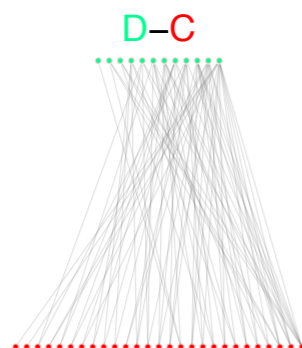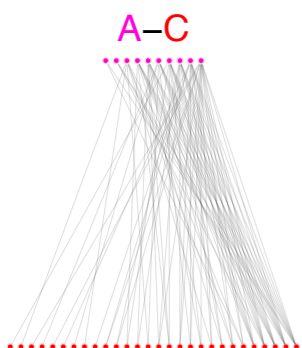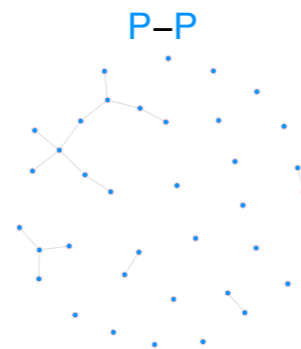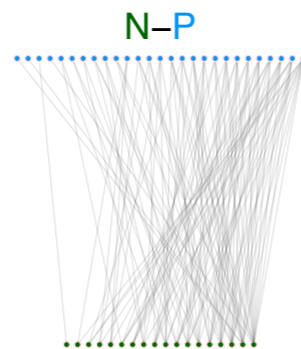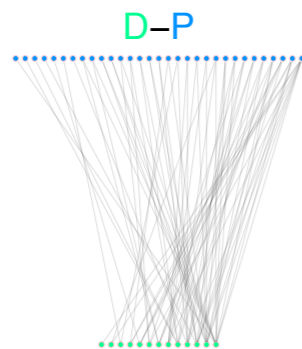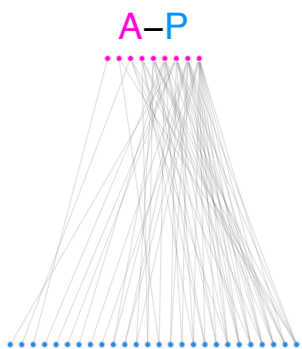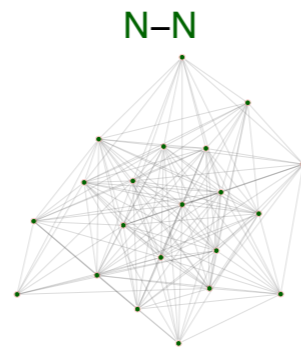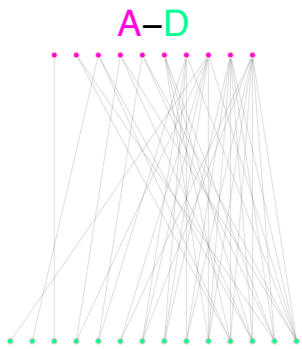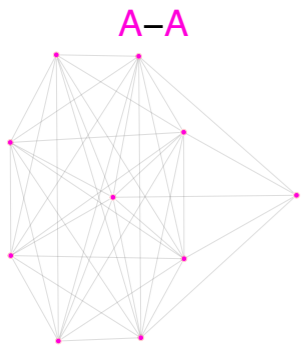
Epidemiology: Contact matrices
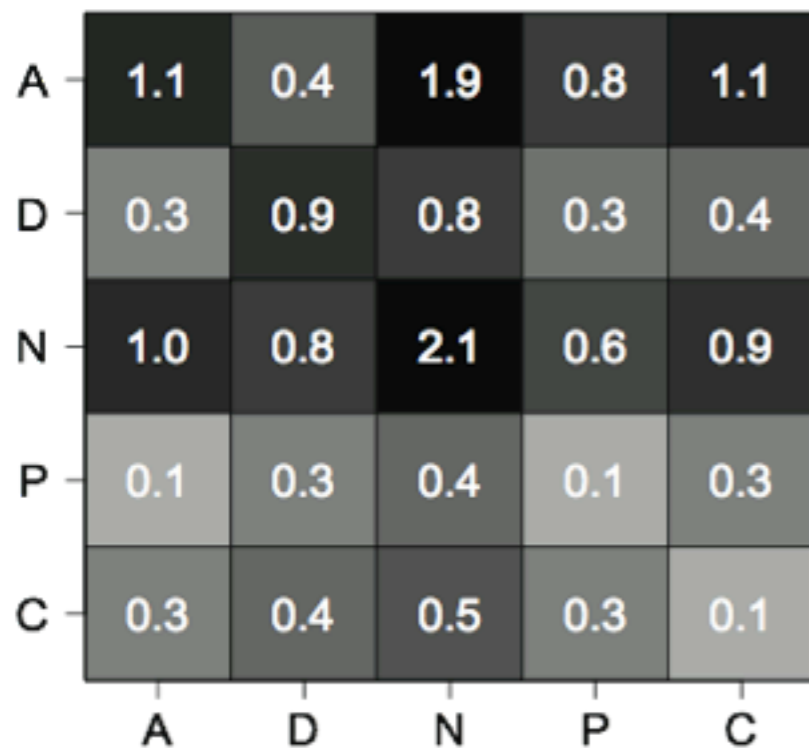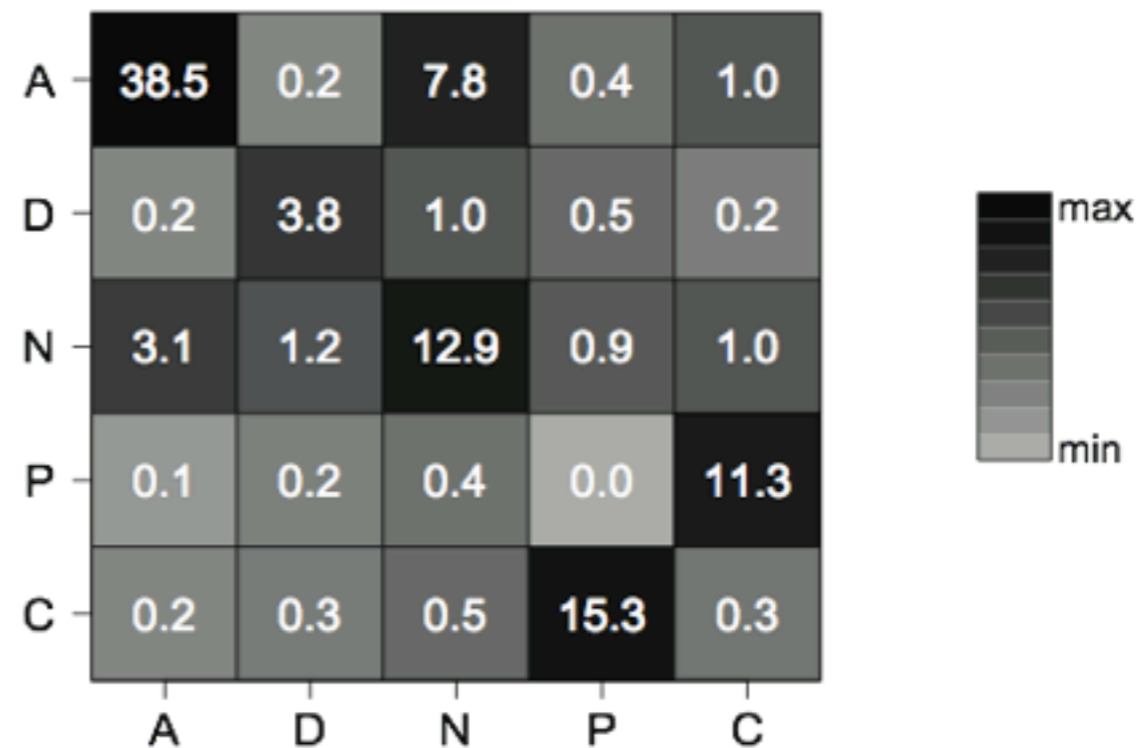
>dealing with data: similarities and differences across contexts

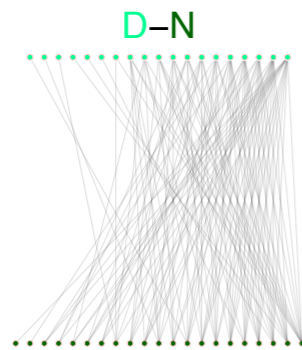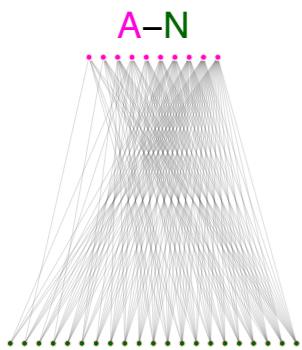| DATE	EVENT	SIZE	DURATION
May 2008	Socio-physics workshop, Torino, IT	~65	3 days
Jun 2008	ISI offices, Torino, IT	~25	3 weeks
Oct 2008	ISI workshop, Torino, IT	~75	3 days
Dec 2008	Chaos Comm. Congress, Berlin, DE	~600	4 days
Apr-Jul 2009	Science Gallery, Dublin, IE	~30,000	3 months
Jun 2009	ESWC09, Crete, GR	~180	4 days
Jun 2009	SFHH, Nice, FR	~400	2 days
Jul 2009	ACM HT2009, Torino, IT	~120	3 days
Oct 2009	Primary school, Lyon, FR	~250	2 days
Nov 2009	Bambino Gesù Hospital, Rome, IT	~250	10 days
Jun 2010	ESWC10, Crete, GR	~200	4 days
Apr 2010	Practice Mapping, Gijon, ES	~100	10 days
Jul 2010	H-Farm, Treviso, IT	~200	6 weeks

Different contexts

- Conference (HT09)
  - Fixed number of attendees
  - Unconstrained mobility

- Museum (SG)
  - Flux of individuals
  - Predefined visiting path

- School
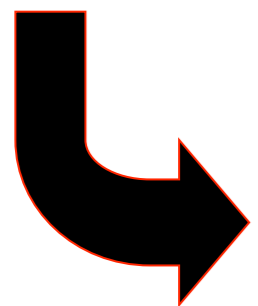
↪ Similarities/differences in the f2f proximity patterns?

Daily cumulated networks

Museum

Non small-world
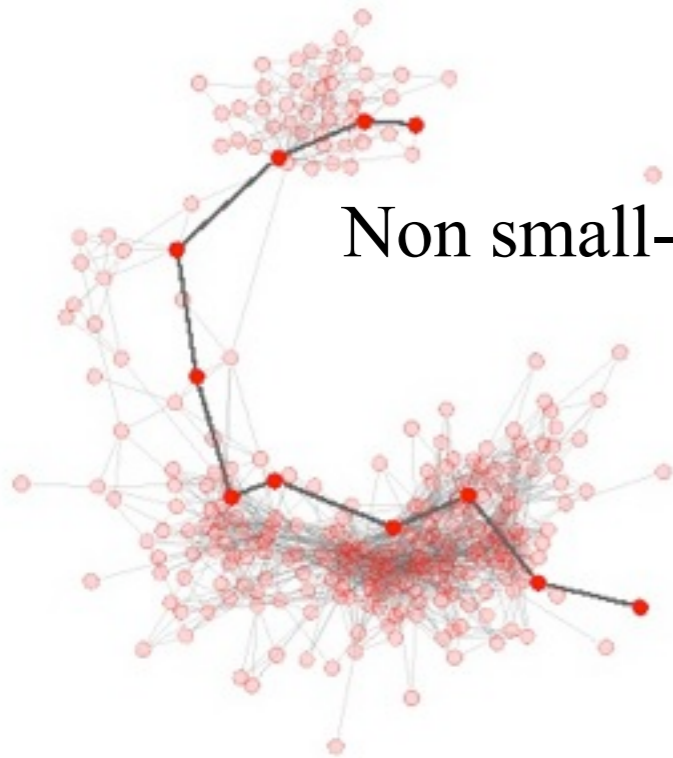
Conference
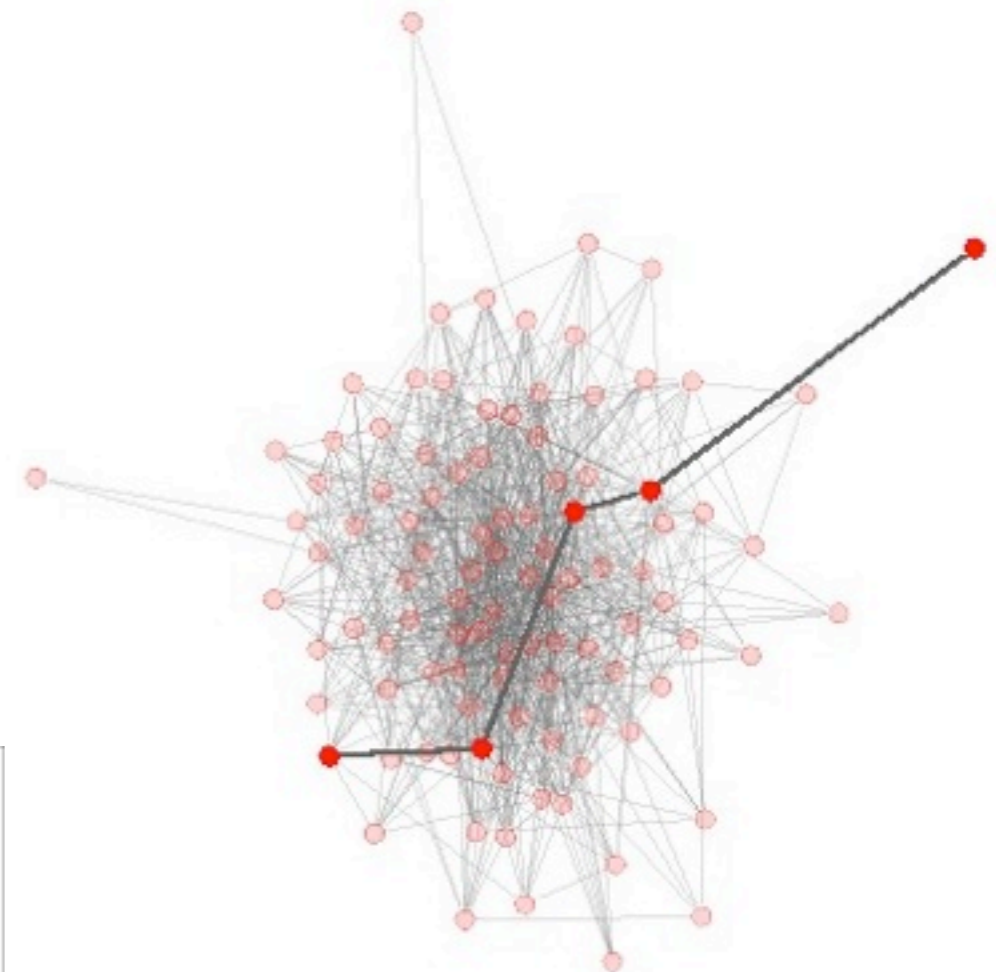
Small-world

School
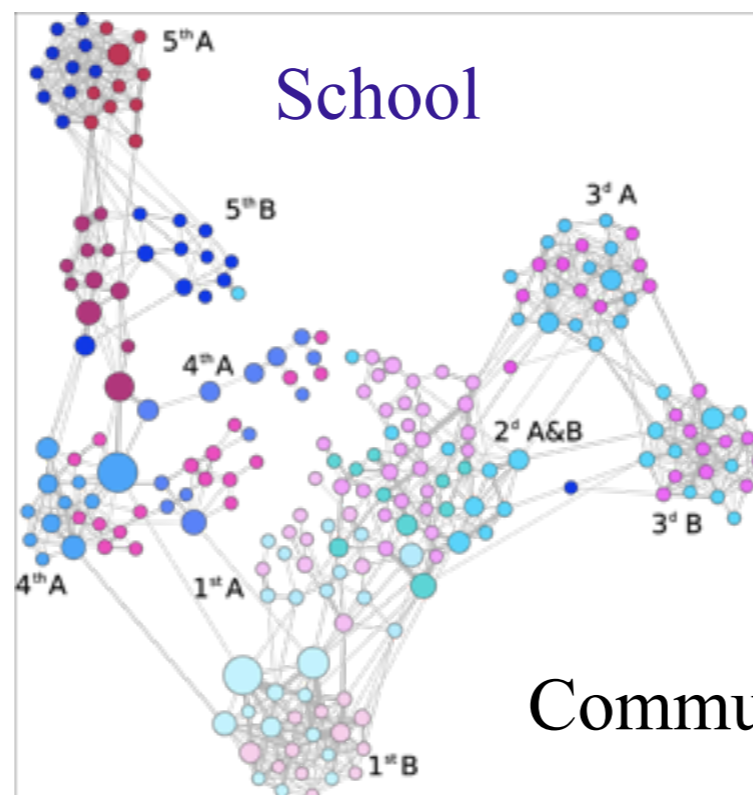
Communities

cumulative contact networks

- color encodes the time of day
- node are colored by arrival time
- several groups (guided tours)

3/6 4/6 5/6 6/6 7/6

10/6 11/6 12/6 13/6 14/6

17/6 18/6 19/6 20/6 21/6

http://www.sociopatterns.org/gallery/infectious-sociopatterns-poster

24/6 25/6 26/6 27/6 28/6
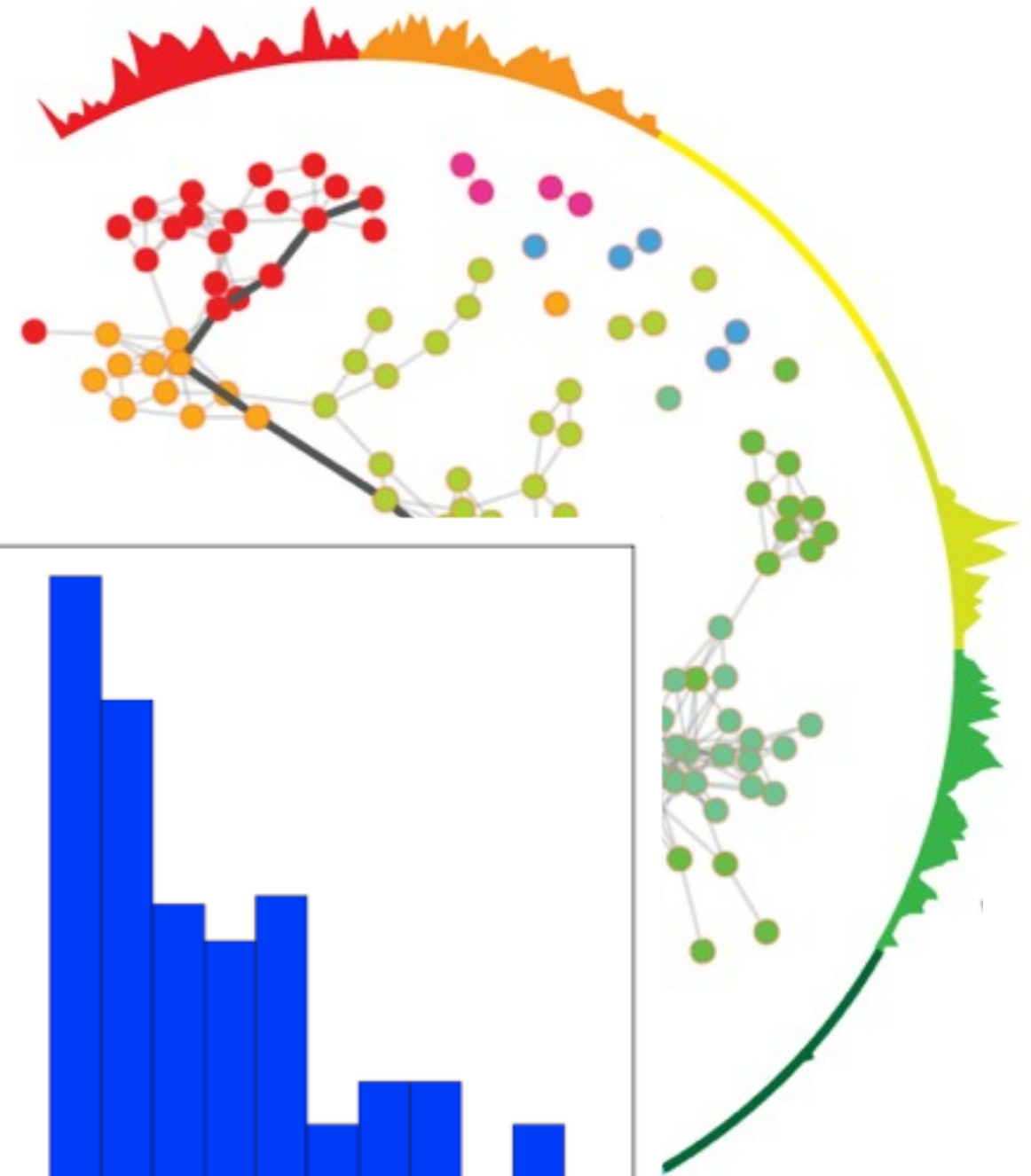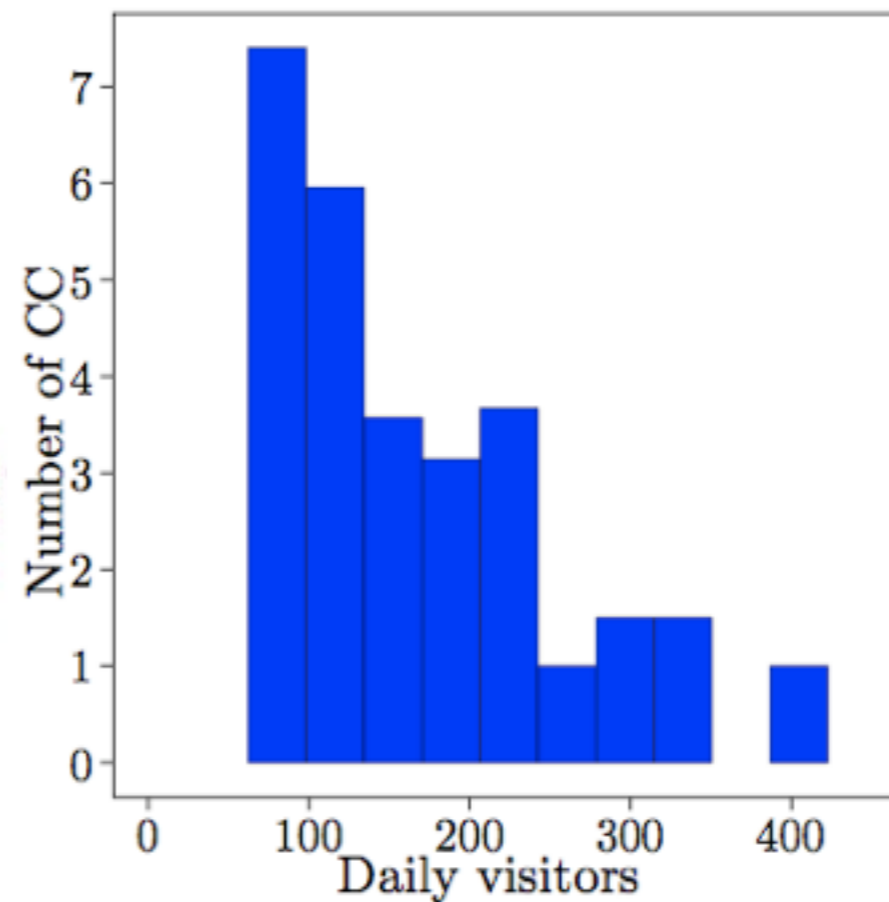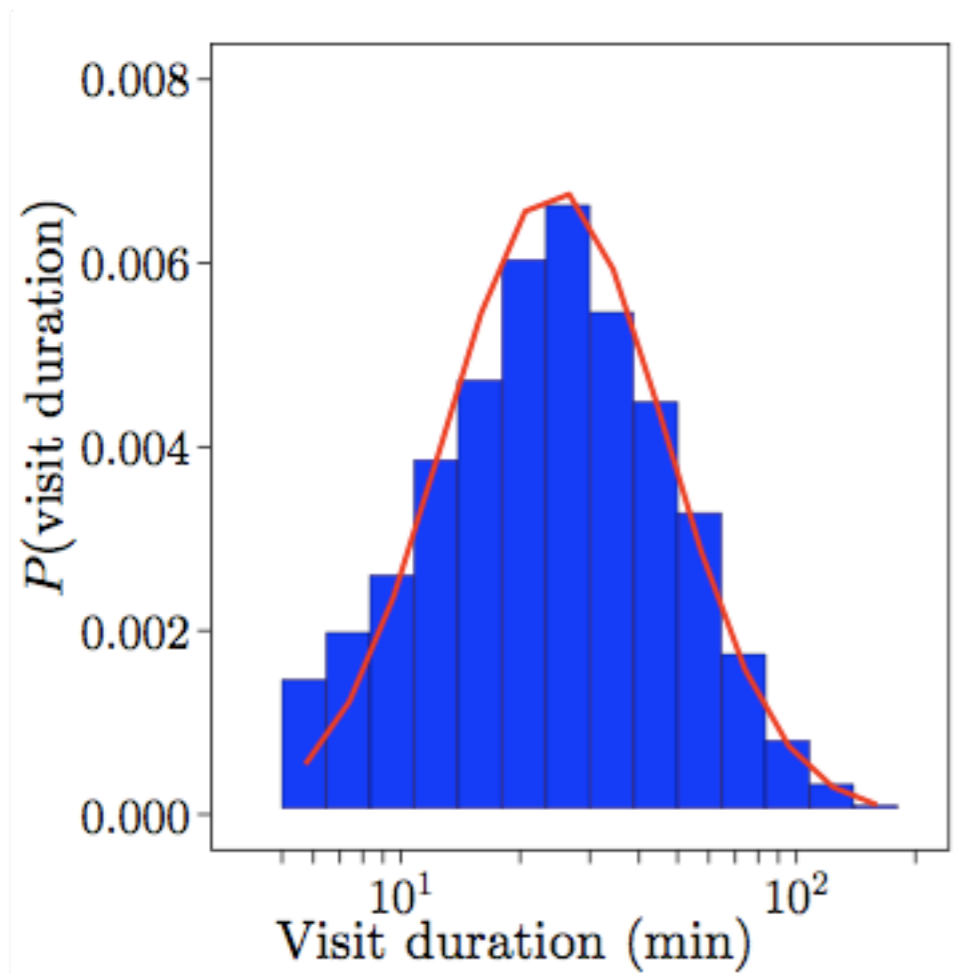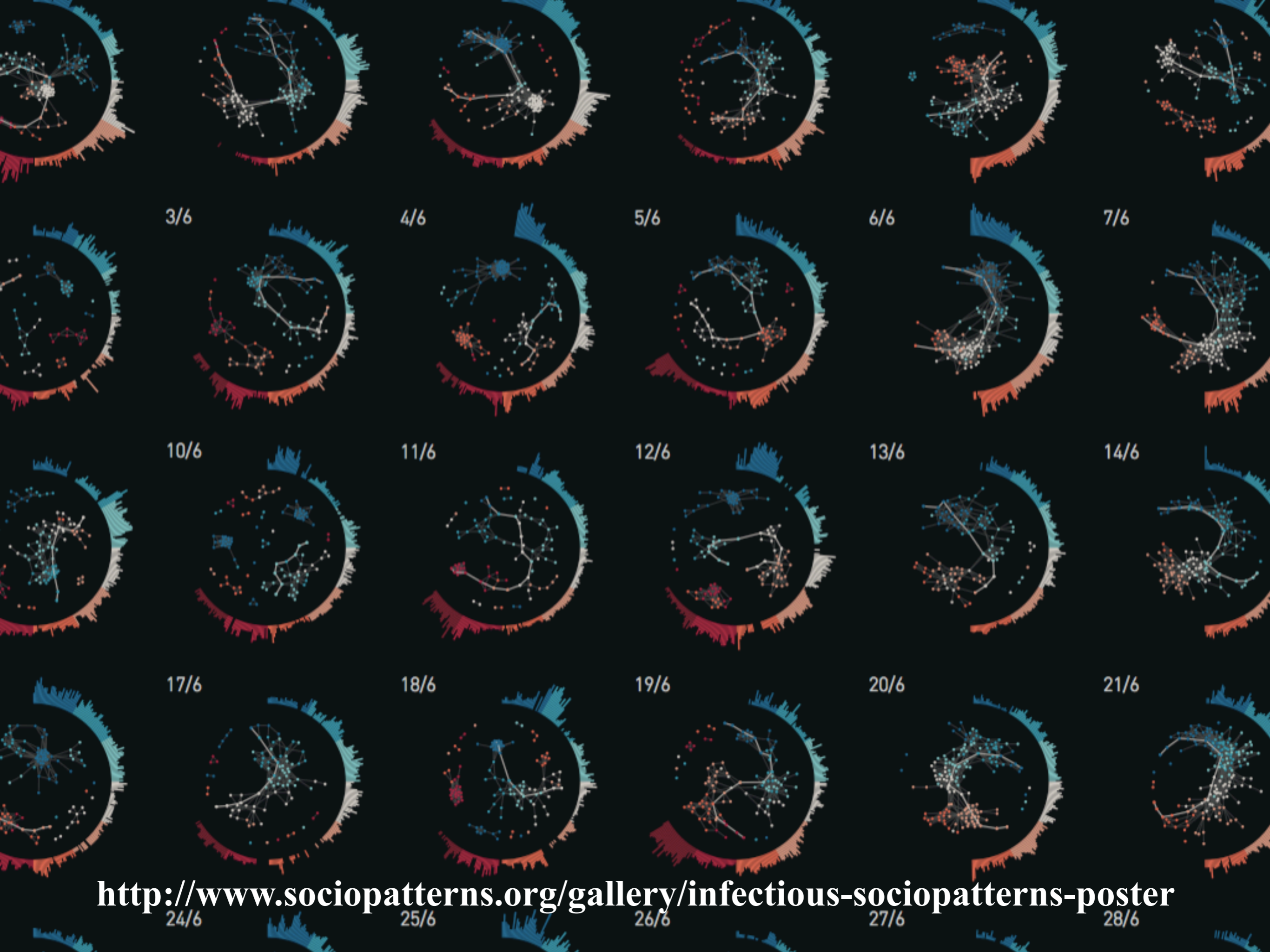
Exp. degree distributions

Conference

Museum

$< k > \simeq 20$
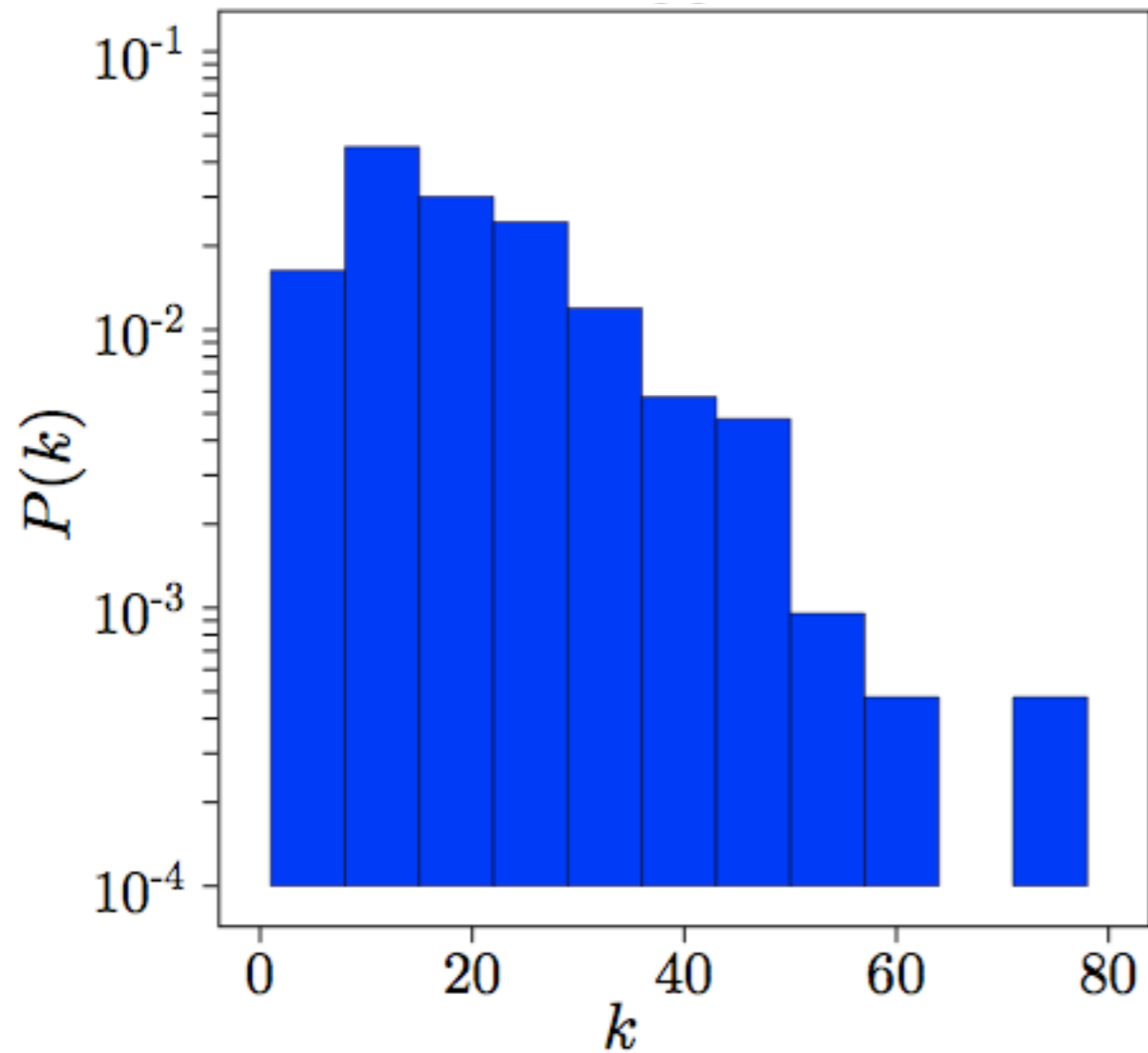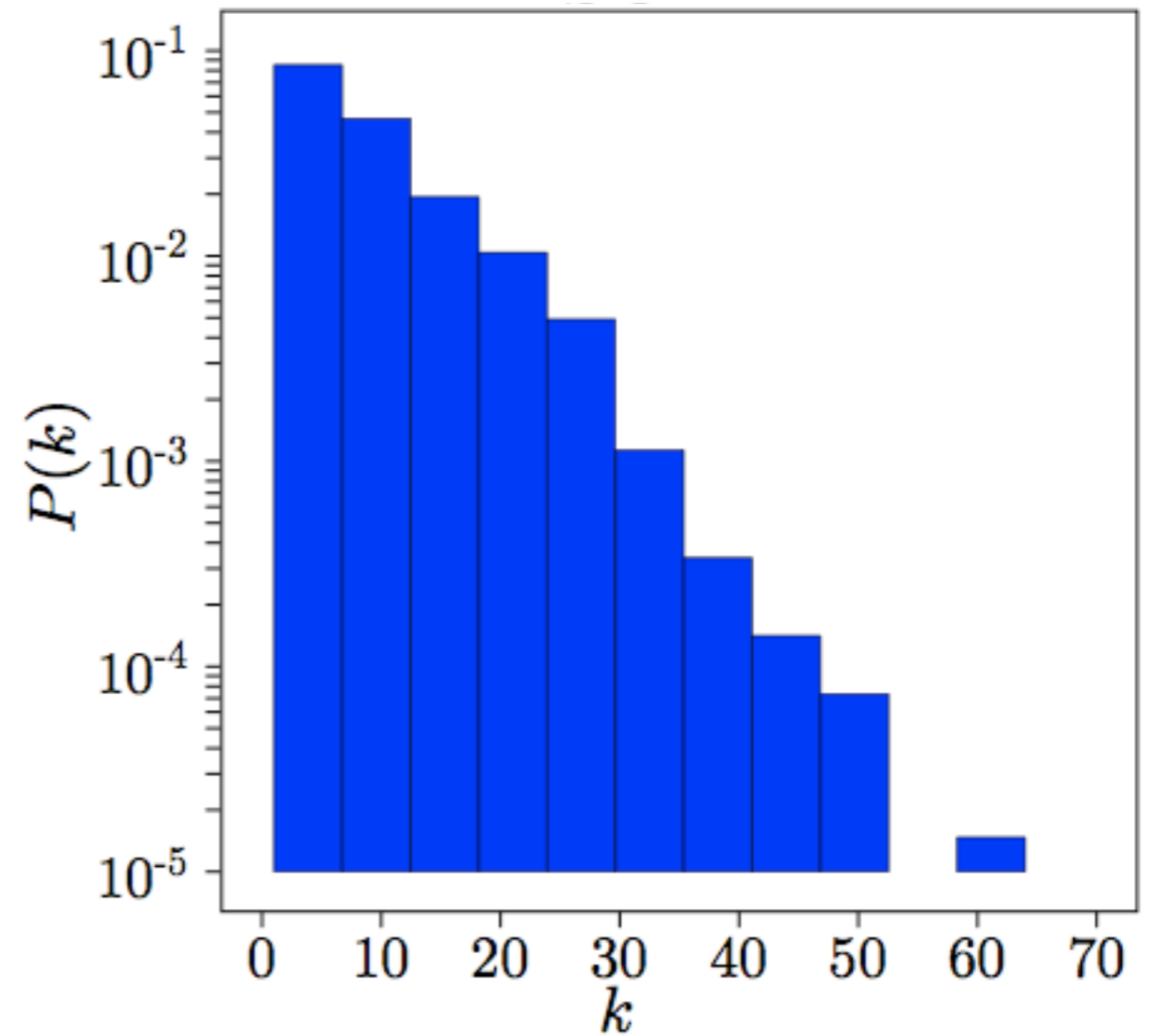
$< k > \simeq 8$

Similar contact durations distributions
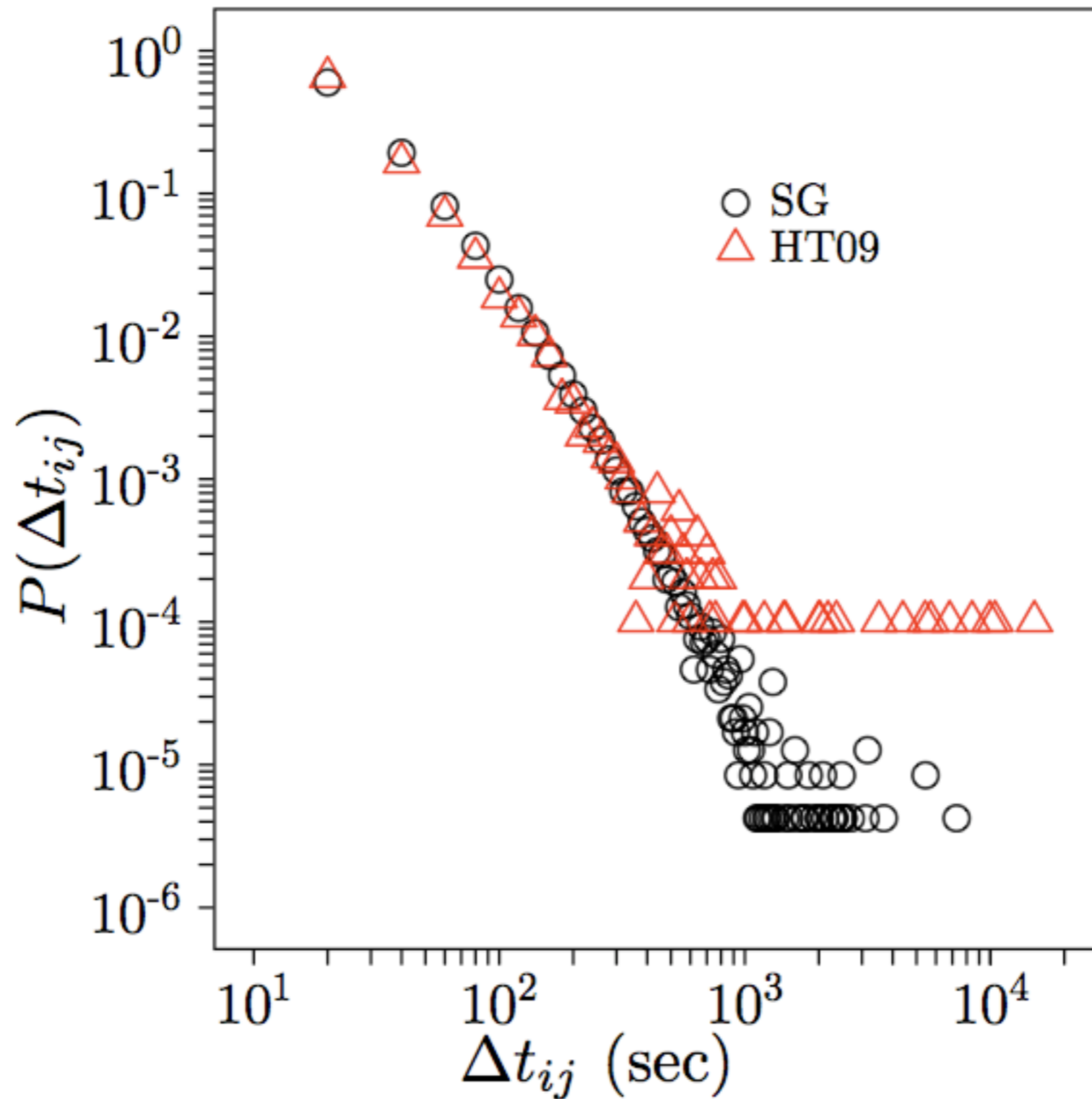
Similar contact durations distributions
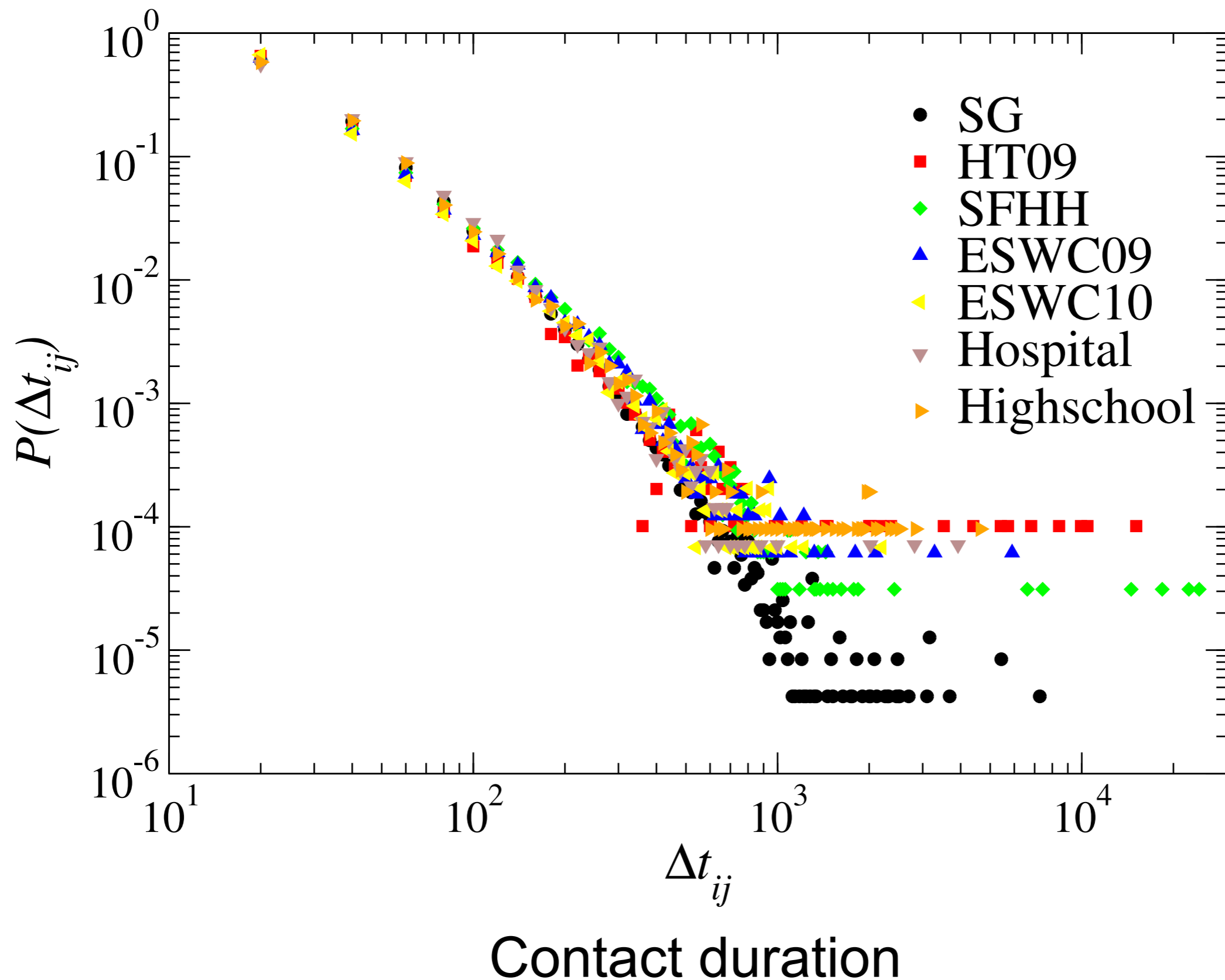
Weight (cumulative contact time) distributions
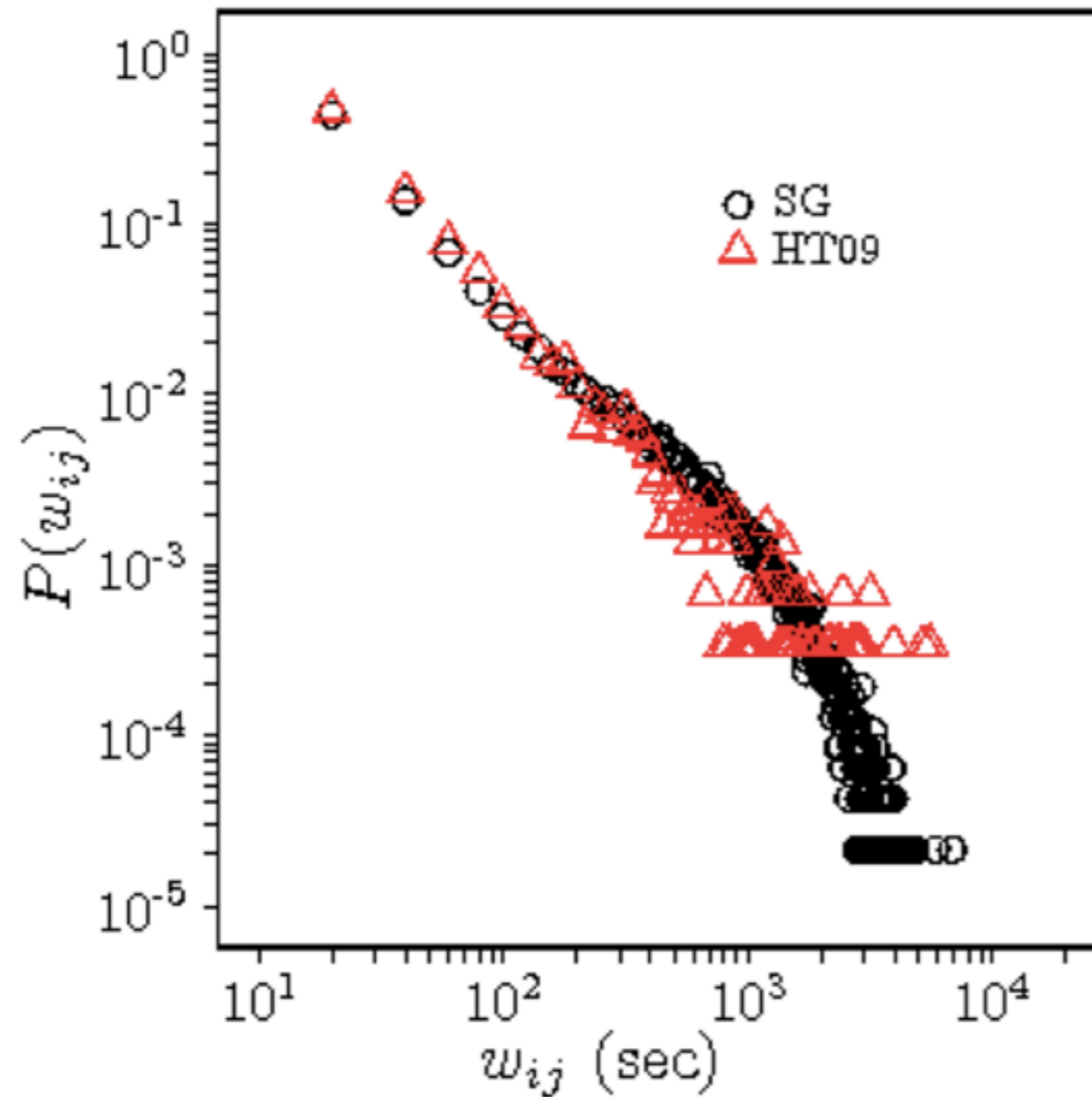
Different "superspreading" patterns

Conference
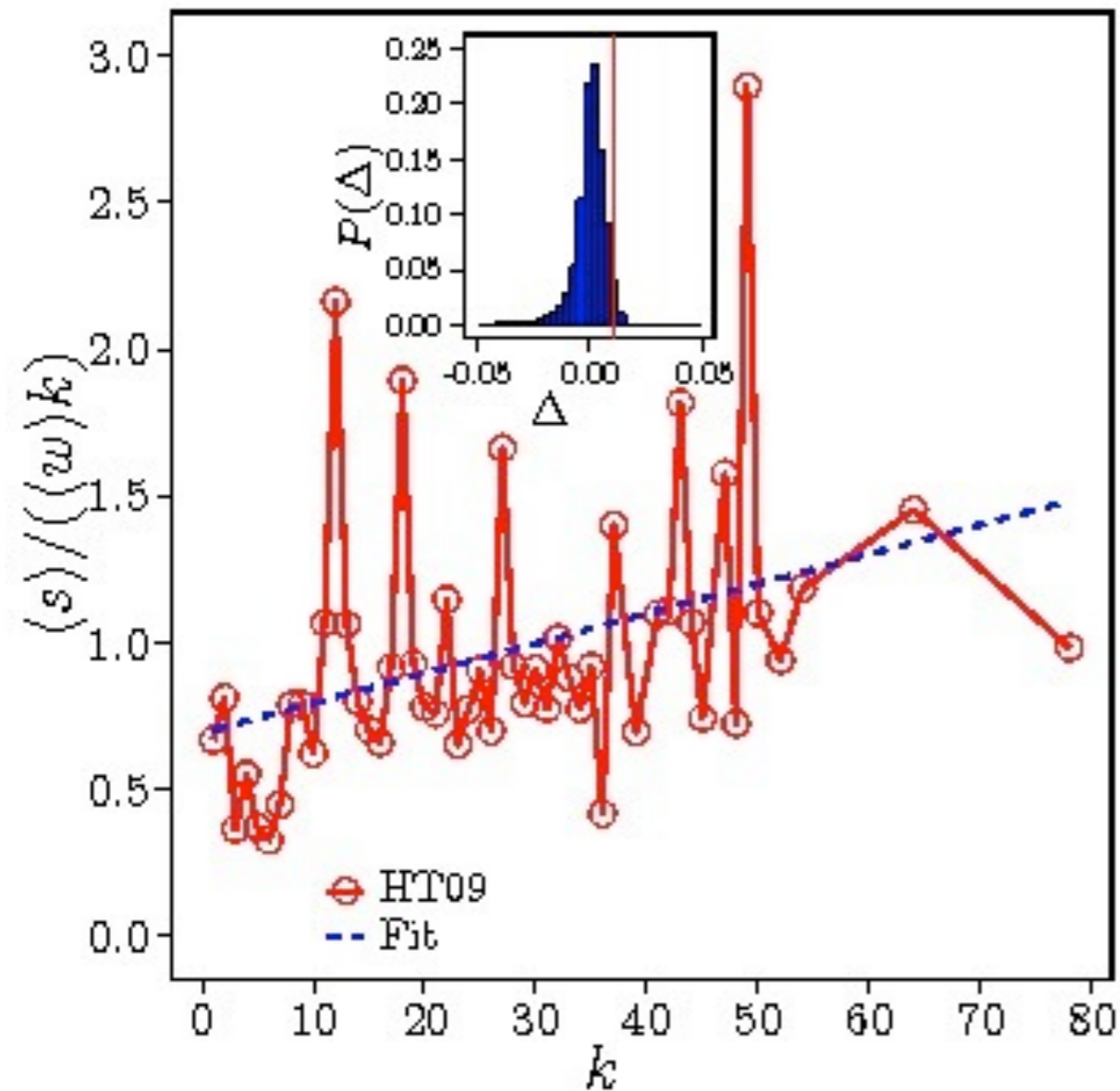
Museum

Superspreading
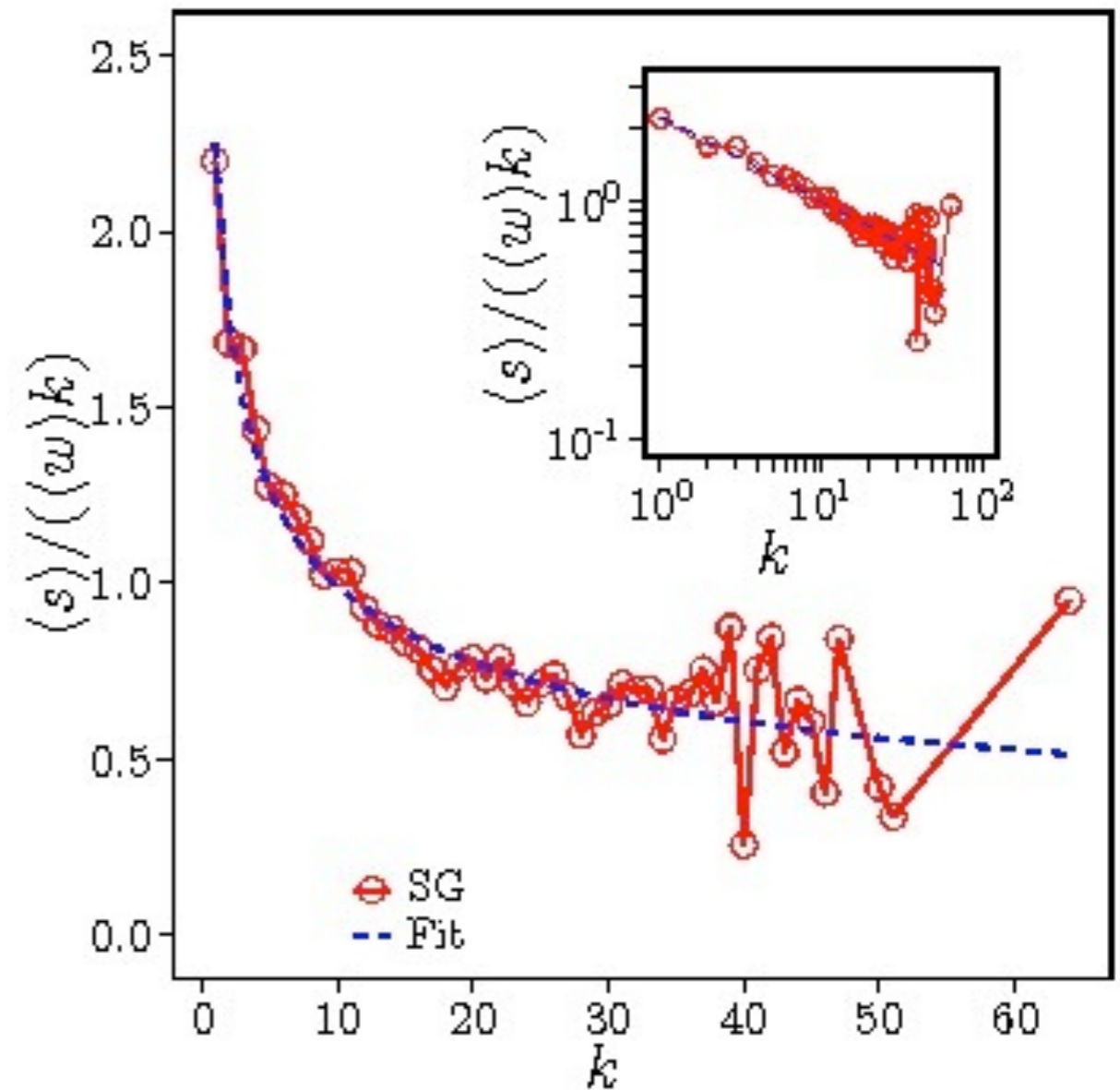
Opposite trend

k=number of distinct persons contacted
s=total time spent in contact
Random weights: s ~ <w>k

L. Isella *et al.*, Journal of Theoretical Biology 271, 166 (2011)

>how to go beyond?

"synopsis" of dynamic network data
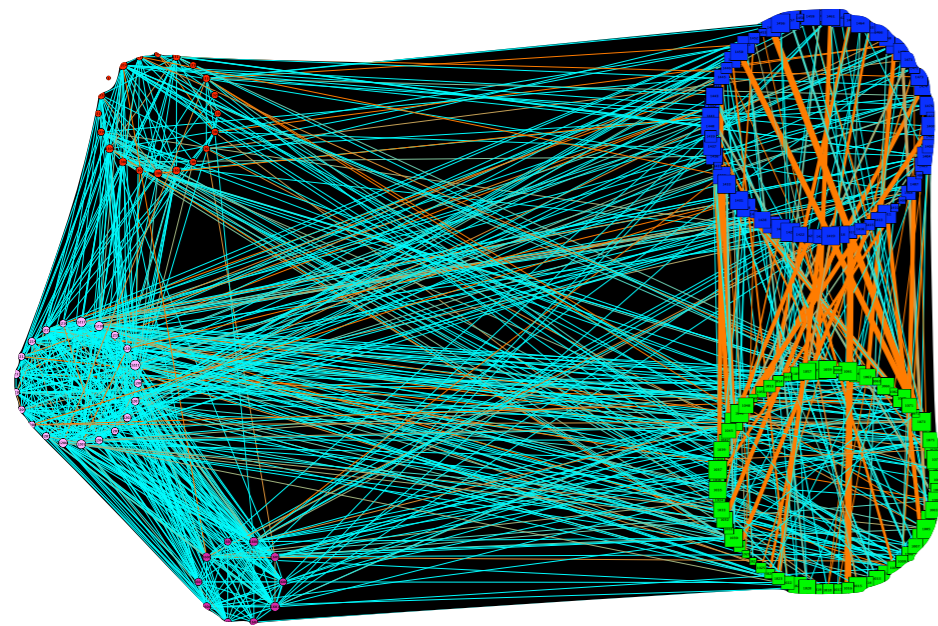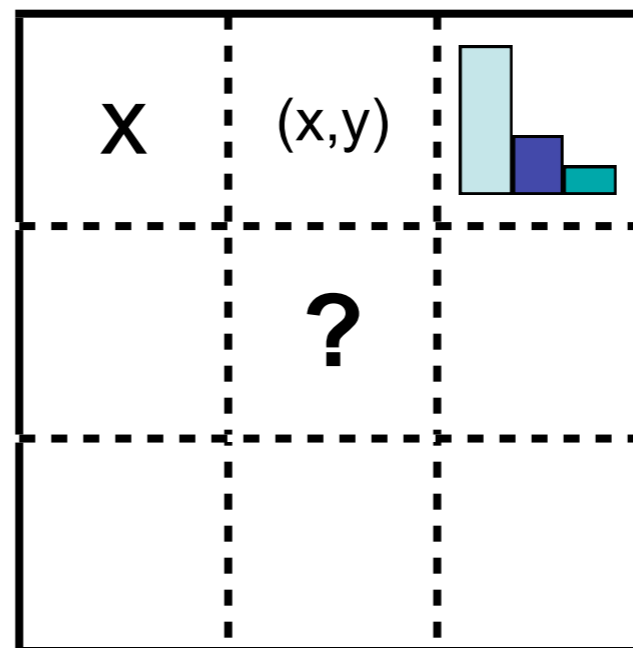
discovery of behavioral classes

A simple model of interacting agents

Time *t*

Time *t+1*

Transition probabilities depending on:
-present state
-time of last state change

Time *t+2*

Time *t+3*
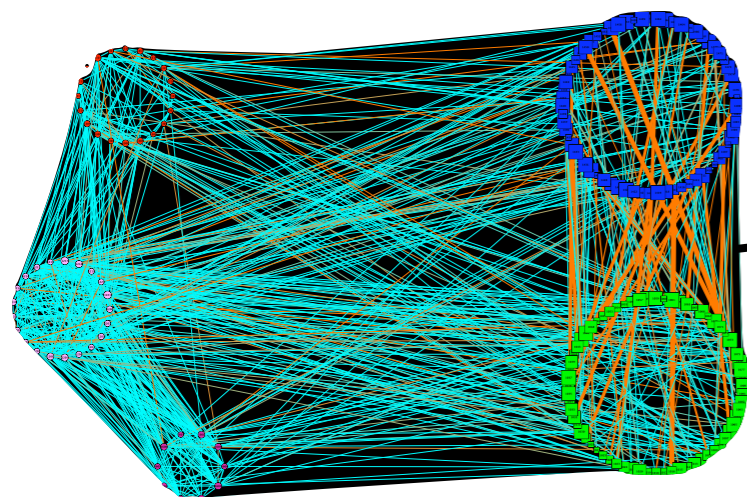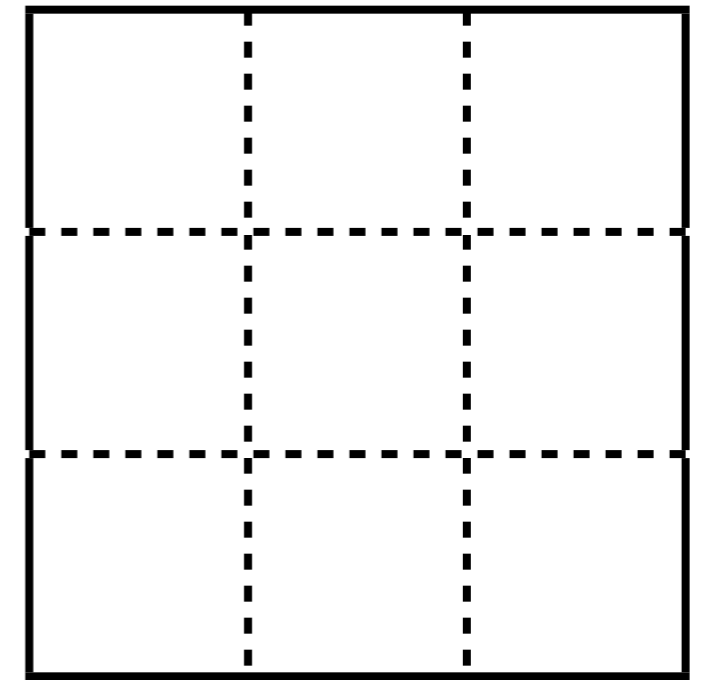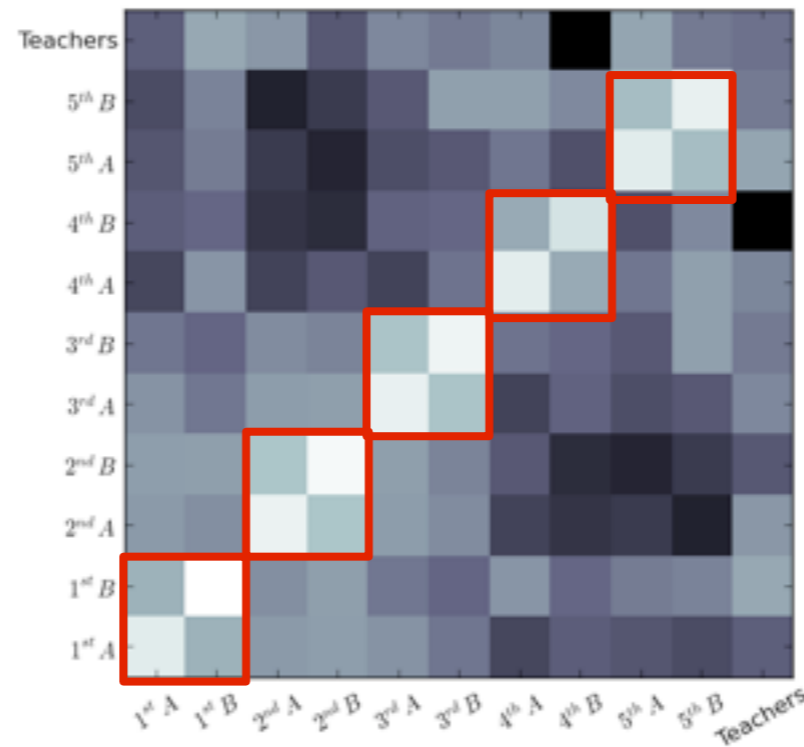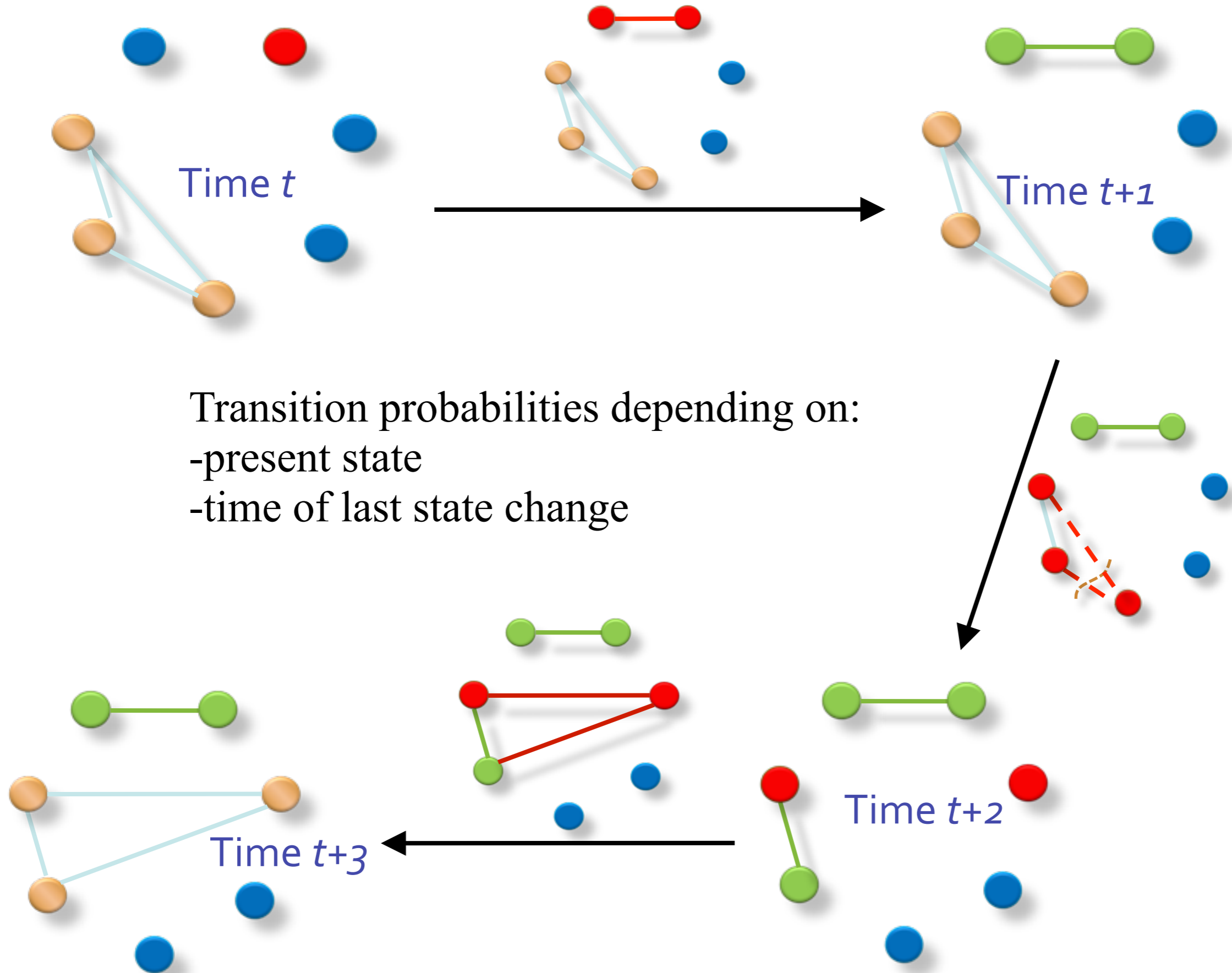
A simple model of interacting agents

At each timestep: choose an agent i at random:

- i isolated: with proba $b_0 f(t, t_i)$, agent i changes its state, and chooses an agent j with probability $\Pi(t, t_j)$

- i in a group: with probability $b_1 f(t, t_i)$, agent i changes its state :
  - with probability λ, agent i leaves the group
  - with probability $1-\lambda$, it introduces an isolated agent n choosen with probability $\Pi(t, t_n)$ to the group

Parameters: b_0, b_1, λ

Analytical and numerical results

$$P_0(\tau) \propto (\tau + 1)^{-1-b_0\frac{3\lambda-1}{2\lambda-1}}$$

$$P_p(\tau) \propto (\tau + 1)^{-1-b_1(p+1)}$$

where $\tau = \dfrac{t - t_p}{N}$
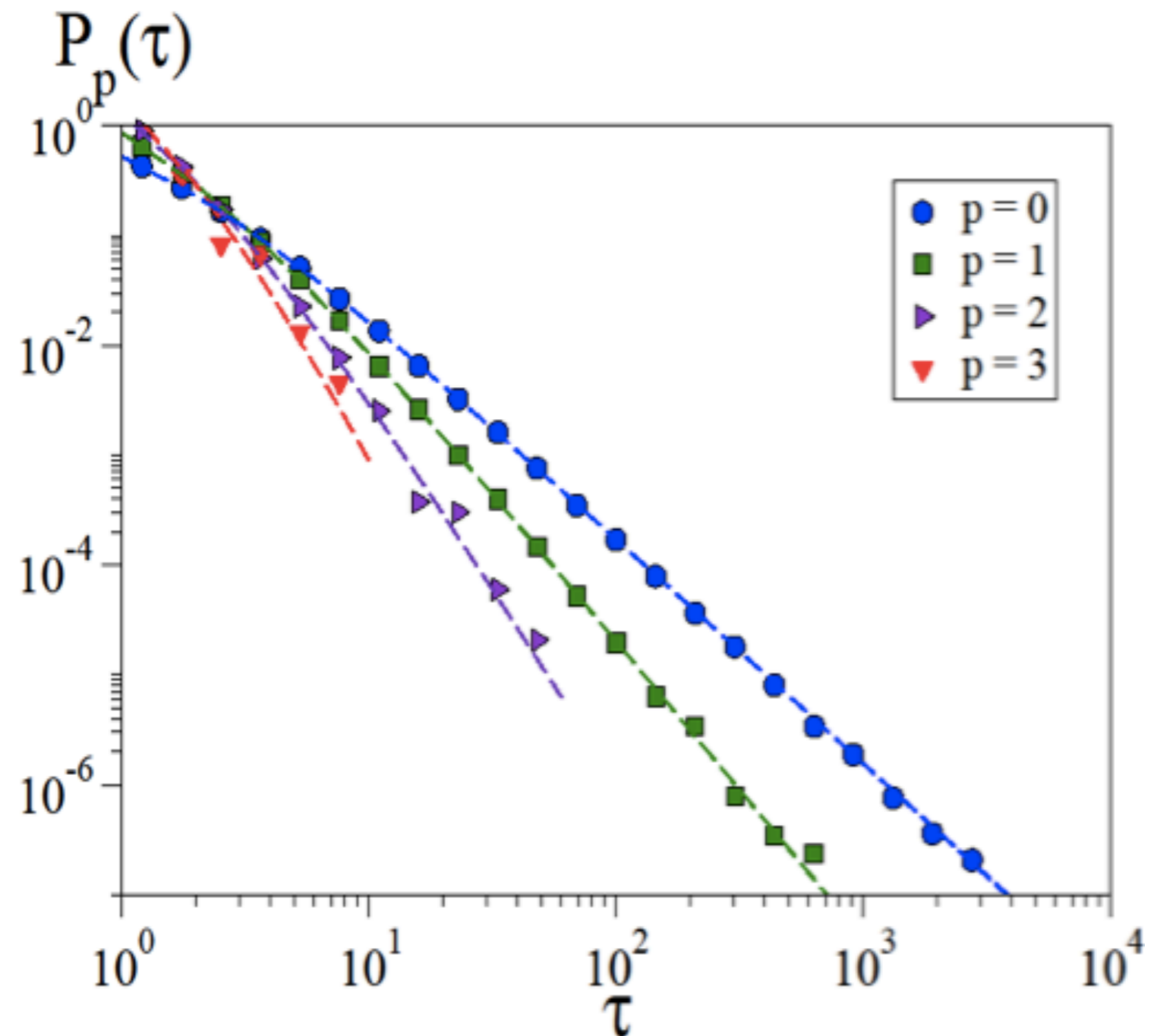
Distributions of times spent with p neighbours

SocioPatterns data
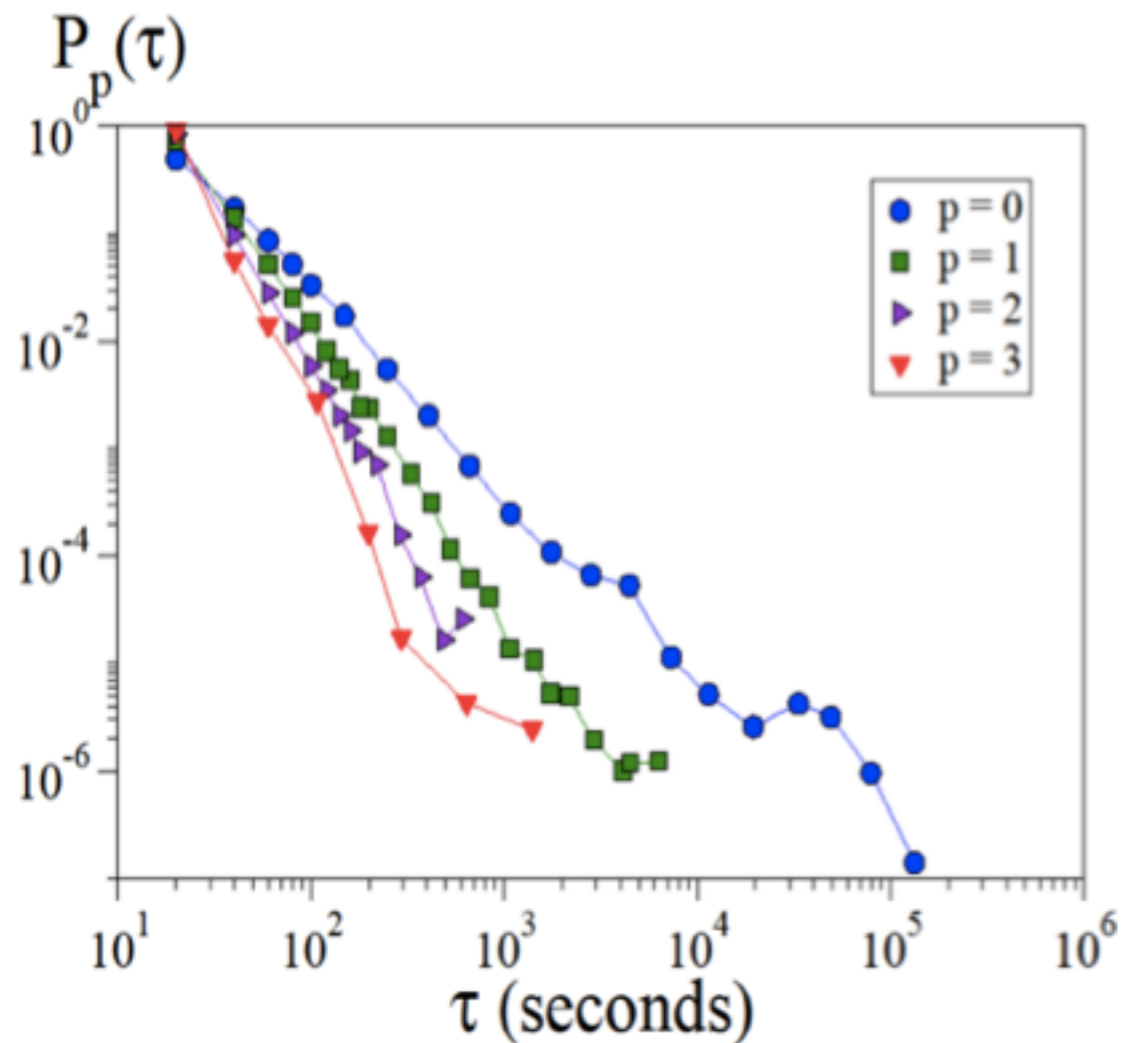
Model
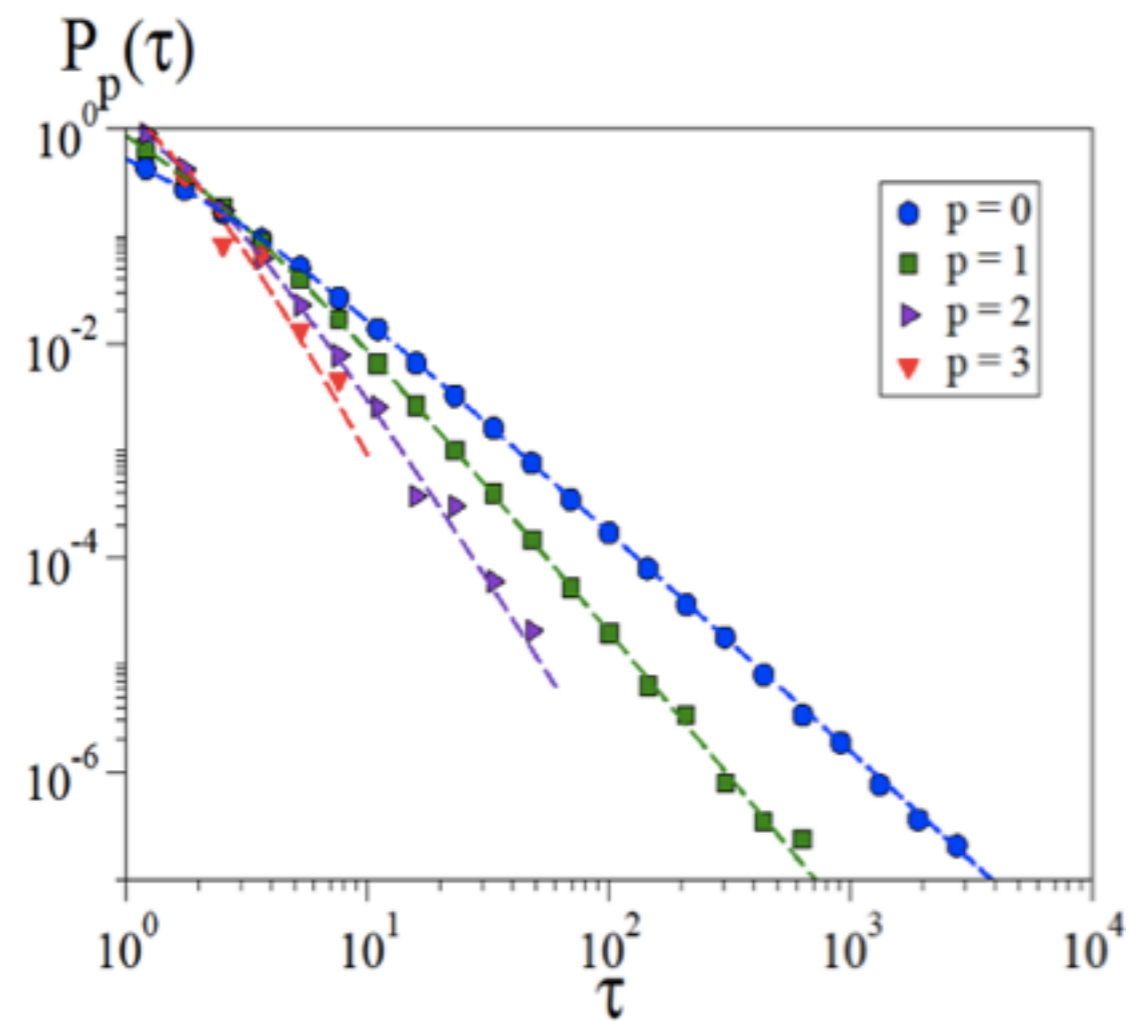
Generalizations

- Heterogeneous agents
  - Heterogeneous tendency to socialize

- Non-stationary dynamics
  - Number of agents depending on time

- Flux of agents
  - Museum-like situation

Flux of agents
(museum-like situation)
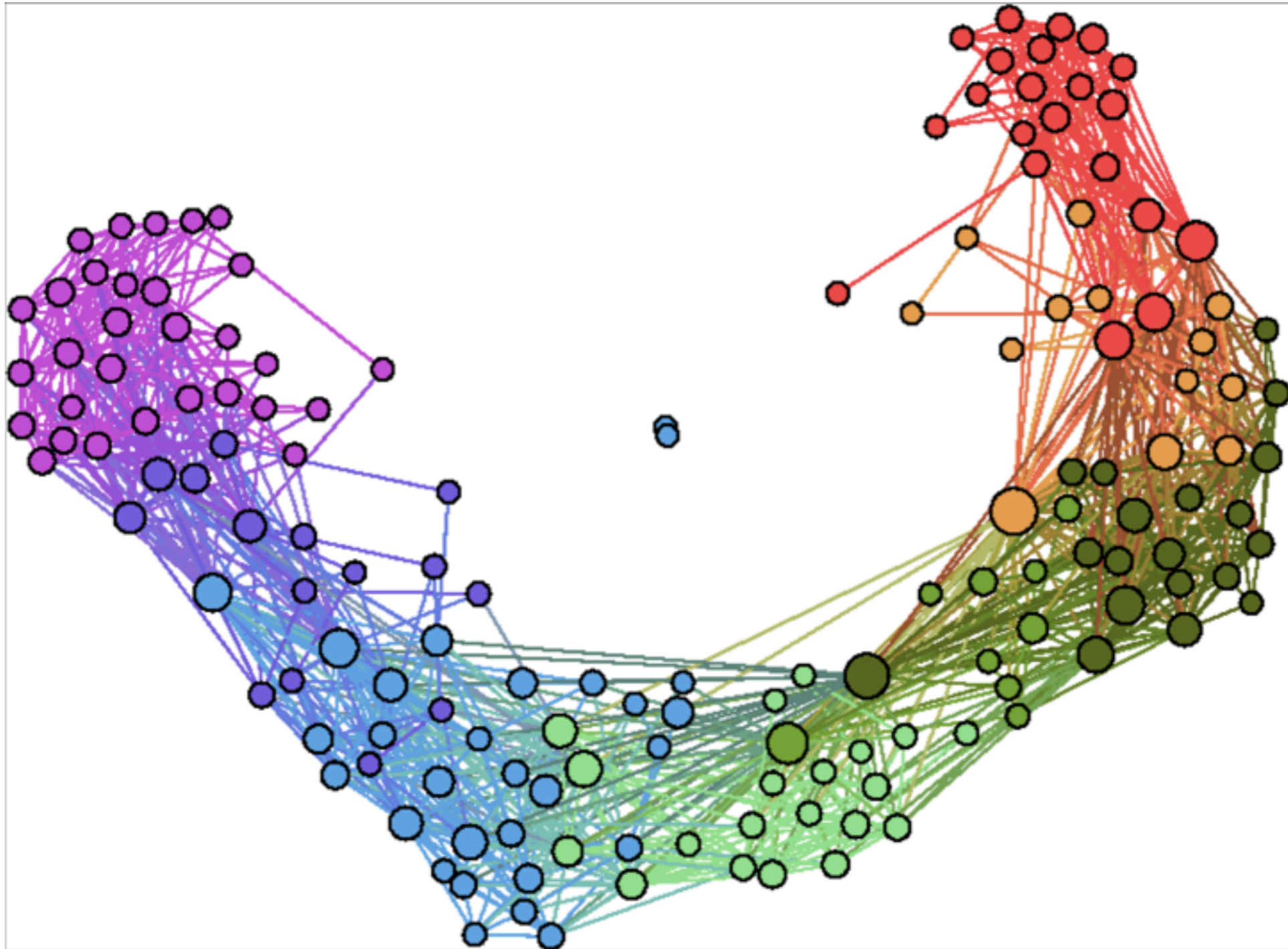
>(Toy) dynamical processes on dynamical networks

dynamical process

S ▸ I

+
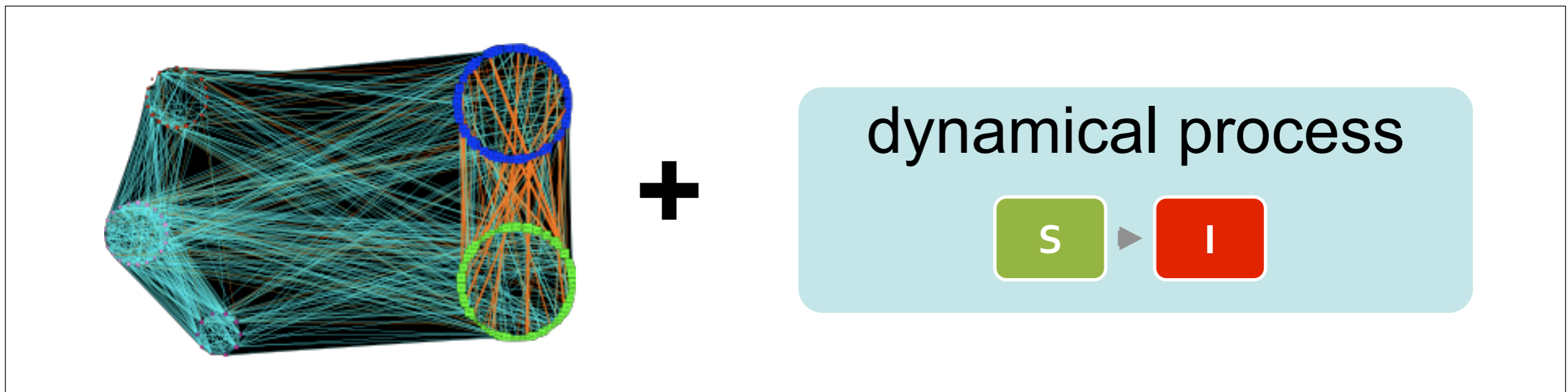
epidemic processes as probes
for the structure of temporal networks

Toy processes on dynamical networks

- deterministic SI process to probe the causal structure of the dynamical network

- **fastest paths ≠ shortest paths**
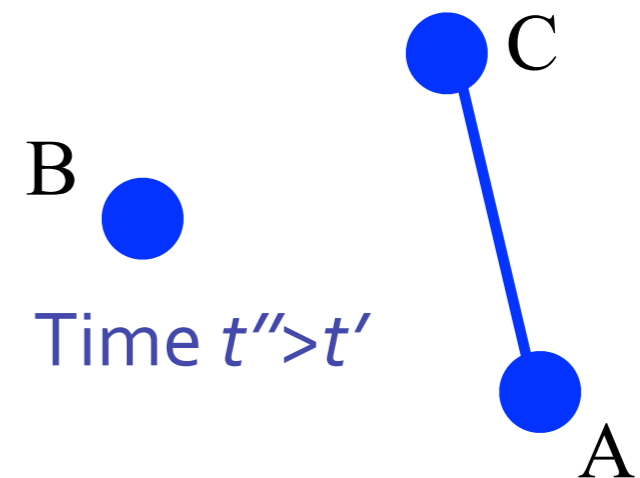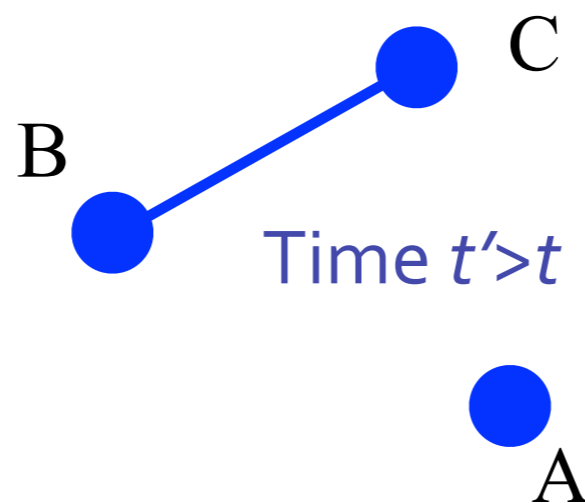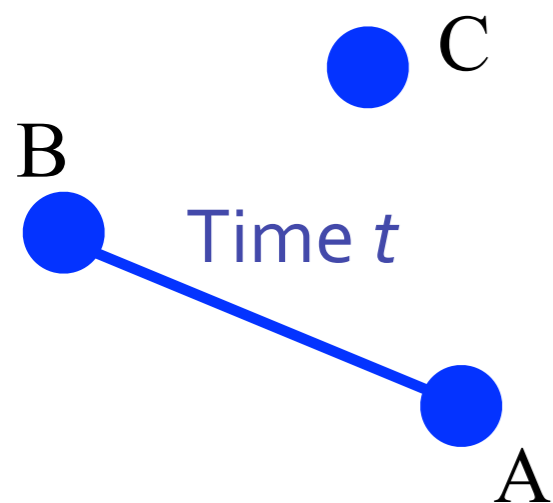
Fastest path= A->B->C
Shortest path= A-C

paths: shortest vs fastest
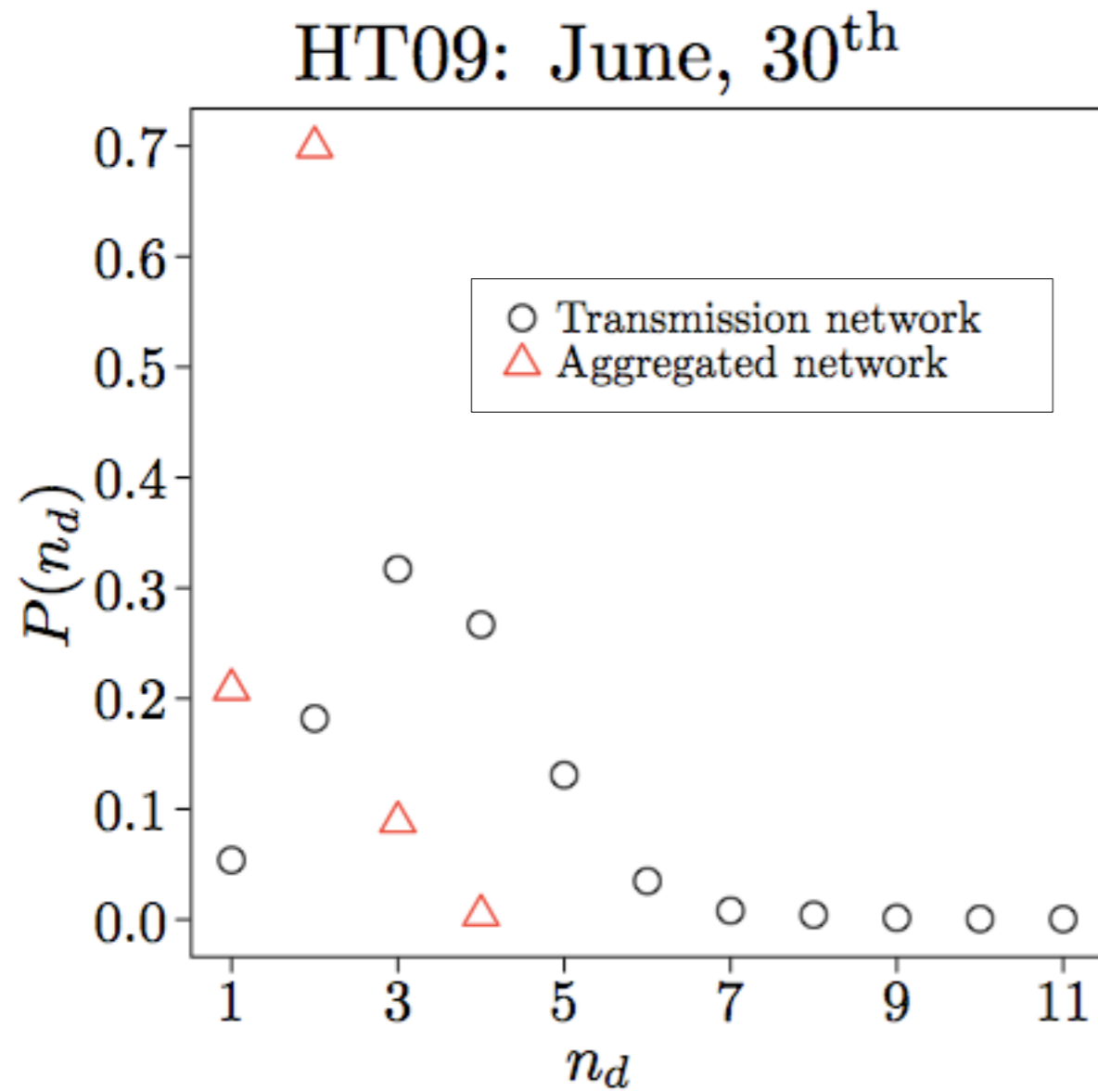
Conference
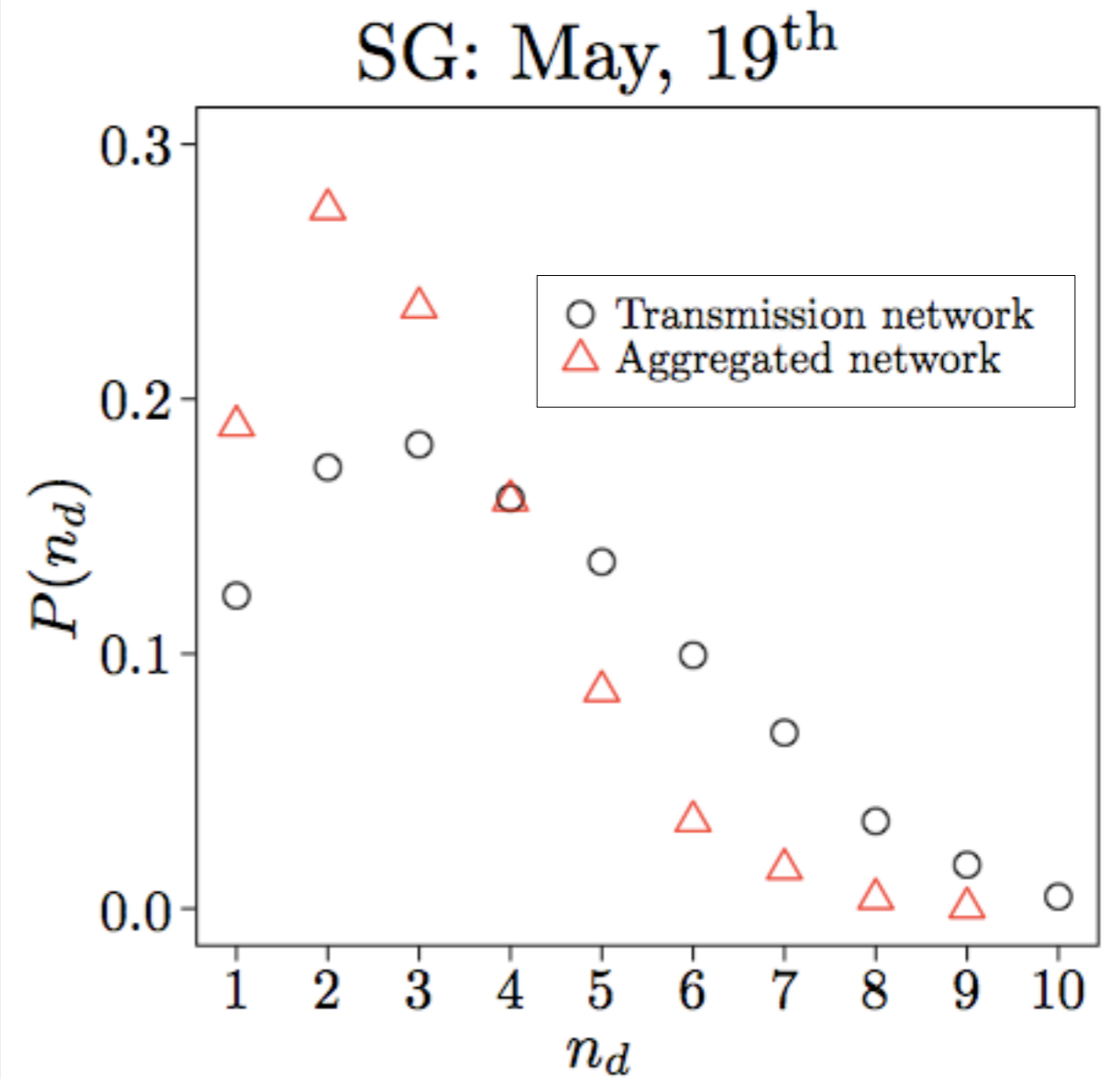
Museum

Spreading process; conference vs museum
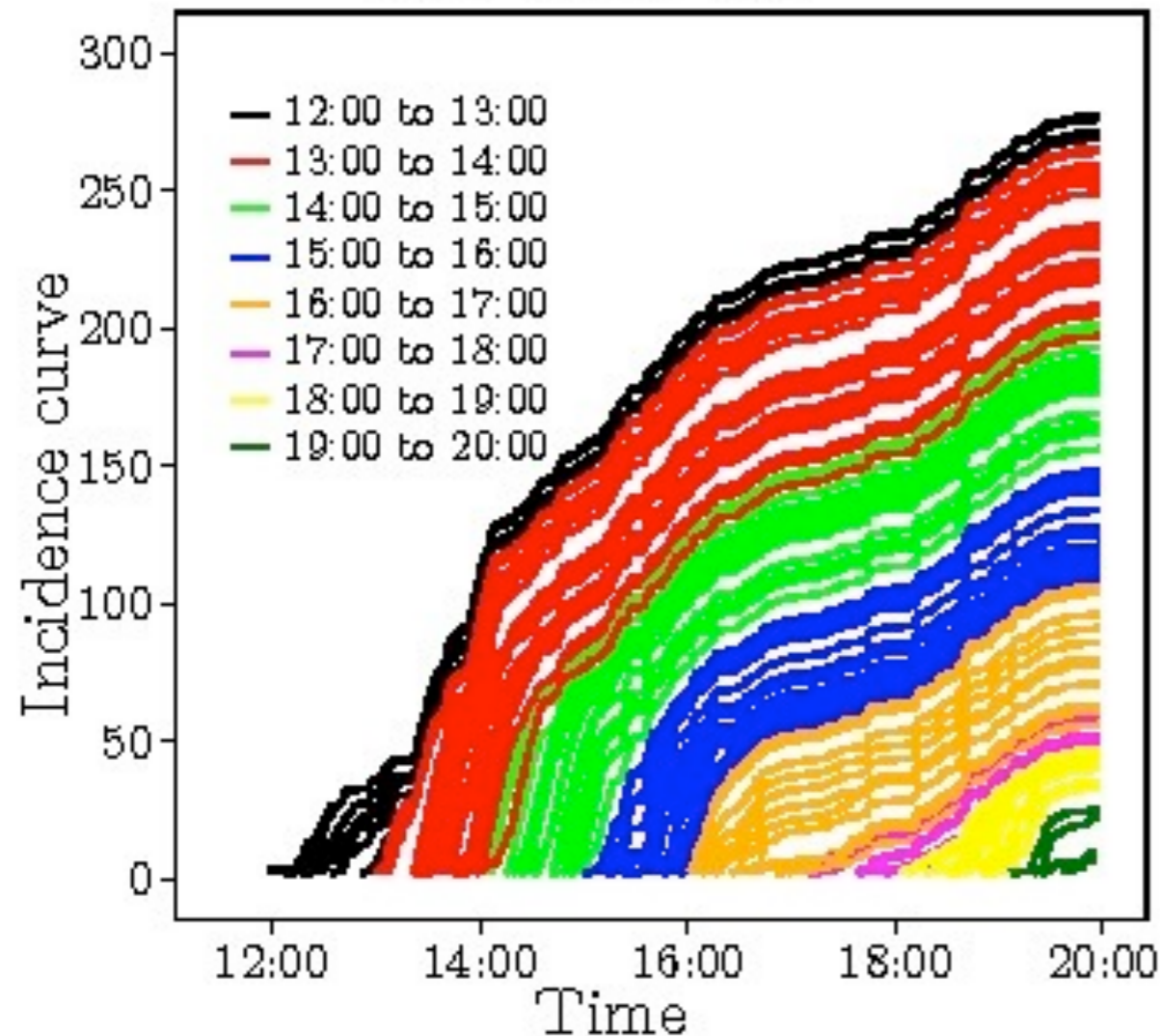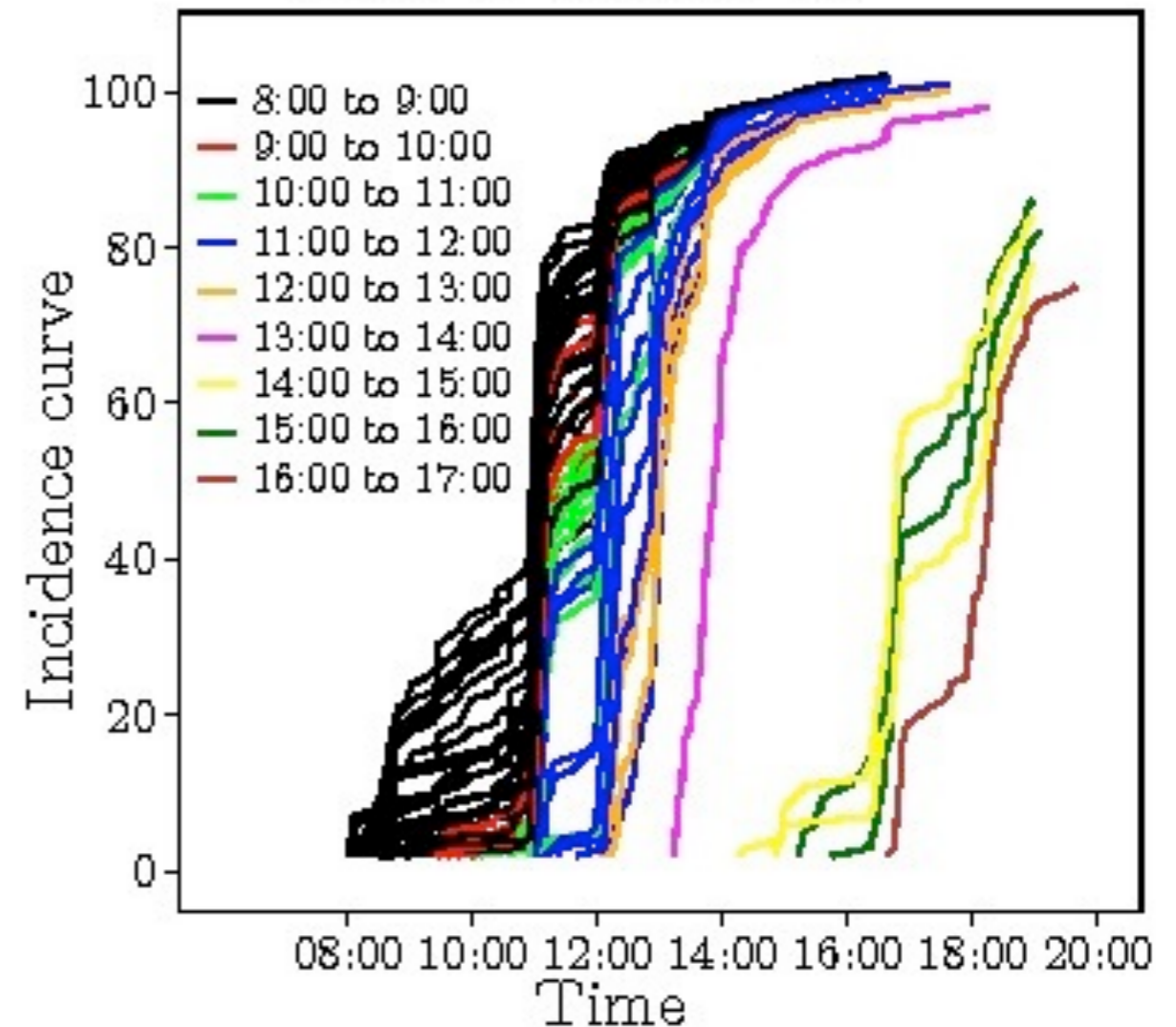
SI deterministic spreading process

Spreading process; school
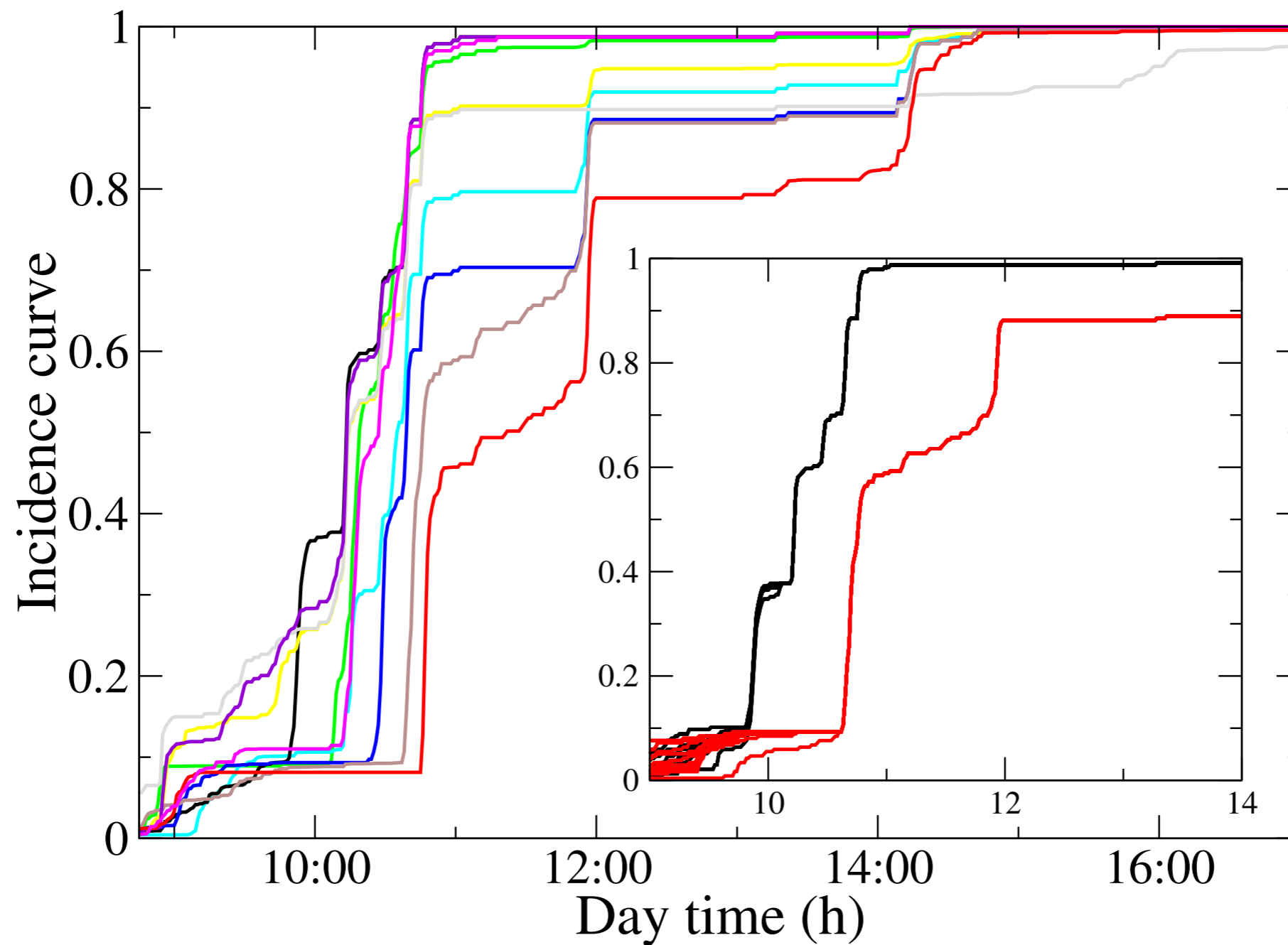
"temporal communities" detection?

Spreading process; conference vs museum
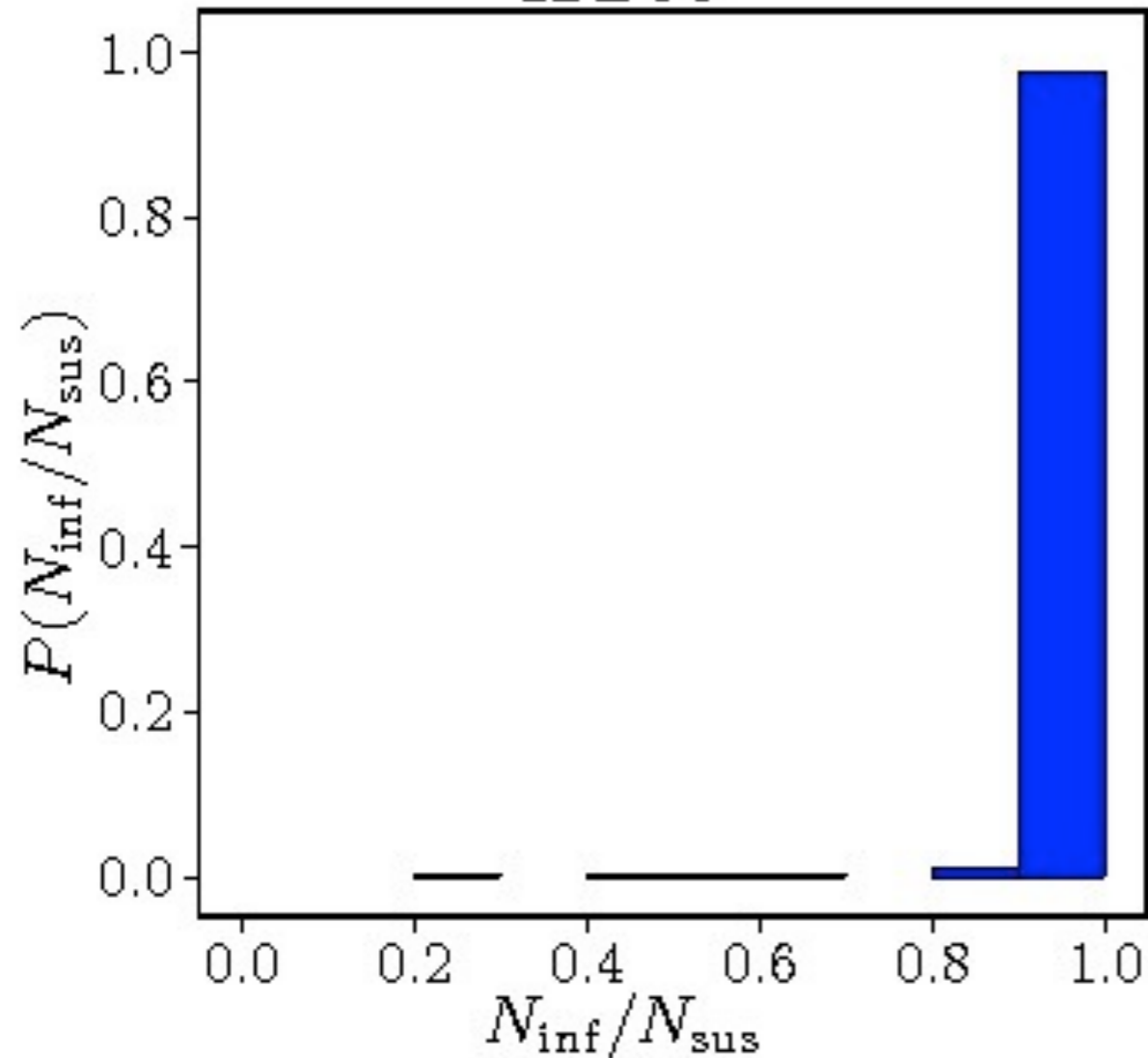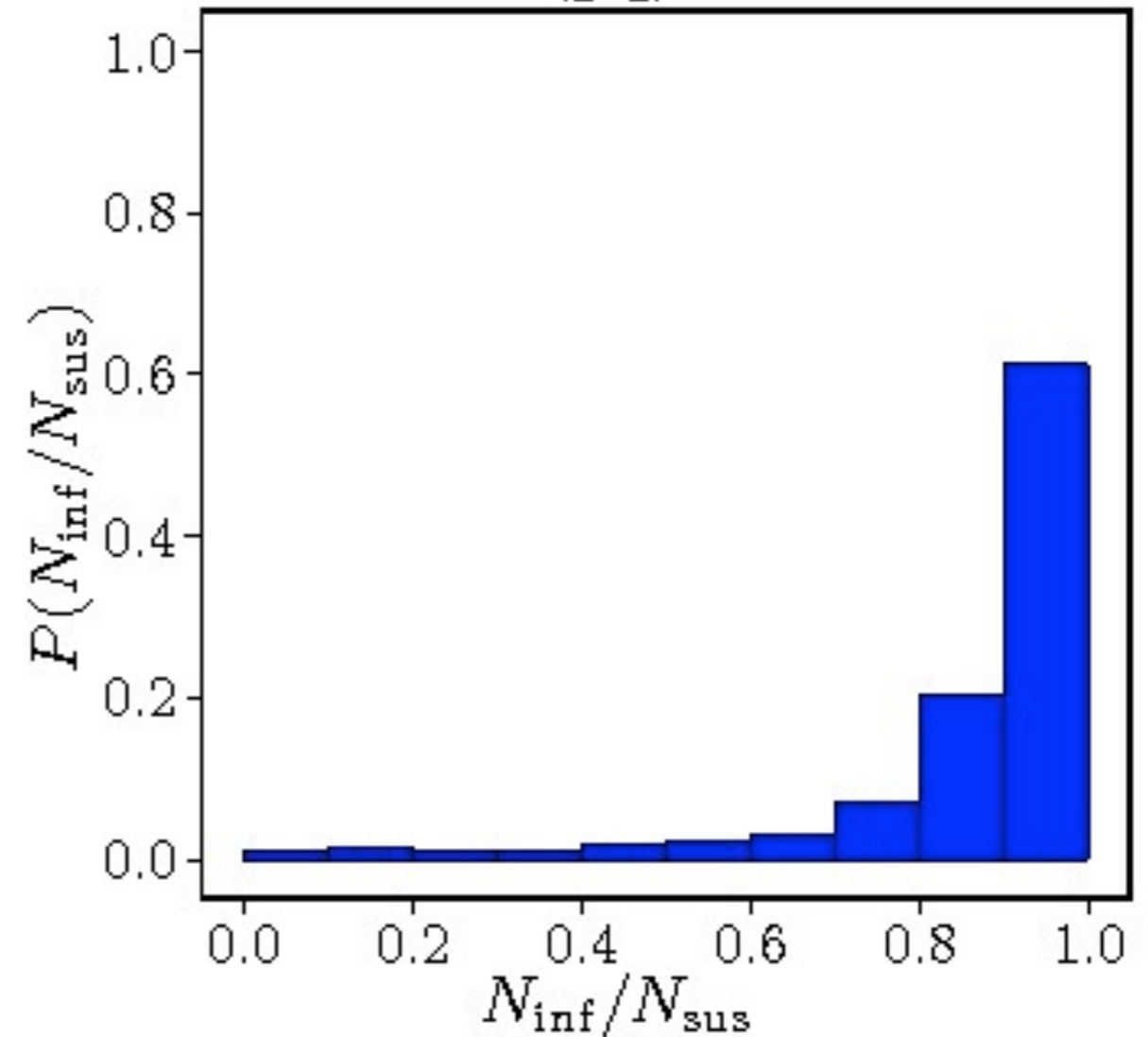
SI deterministic spreading process:
Ratio of infected nodes w.r.t. nodes which could have been infected

Performance of spreading processes on dynamical networks

Performance of a dissemination process

(context: ad-hoc networks):

usually measured as the average time (or the distr. of times) between creation time of a message at a node and its arrival time at the other nodes

However: burstiness, non-stationarity => measured performance depends on initial time, on the contact patterns rather than on the diffusion mechanism

Performance of spreading processes on dynamical networks

Example: 3 days conference, SI spreading process, time delays between generation of message and arrival of message to a node

Time= wall-clock time

A. Panisson et al., Ad Hoc Networks (2012), arXiv:1106.5992
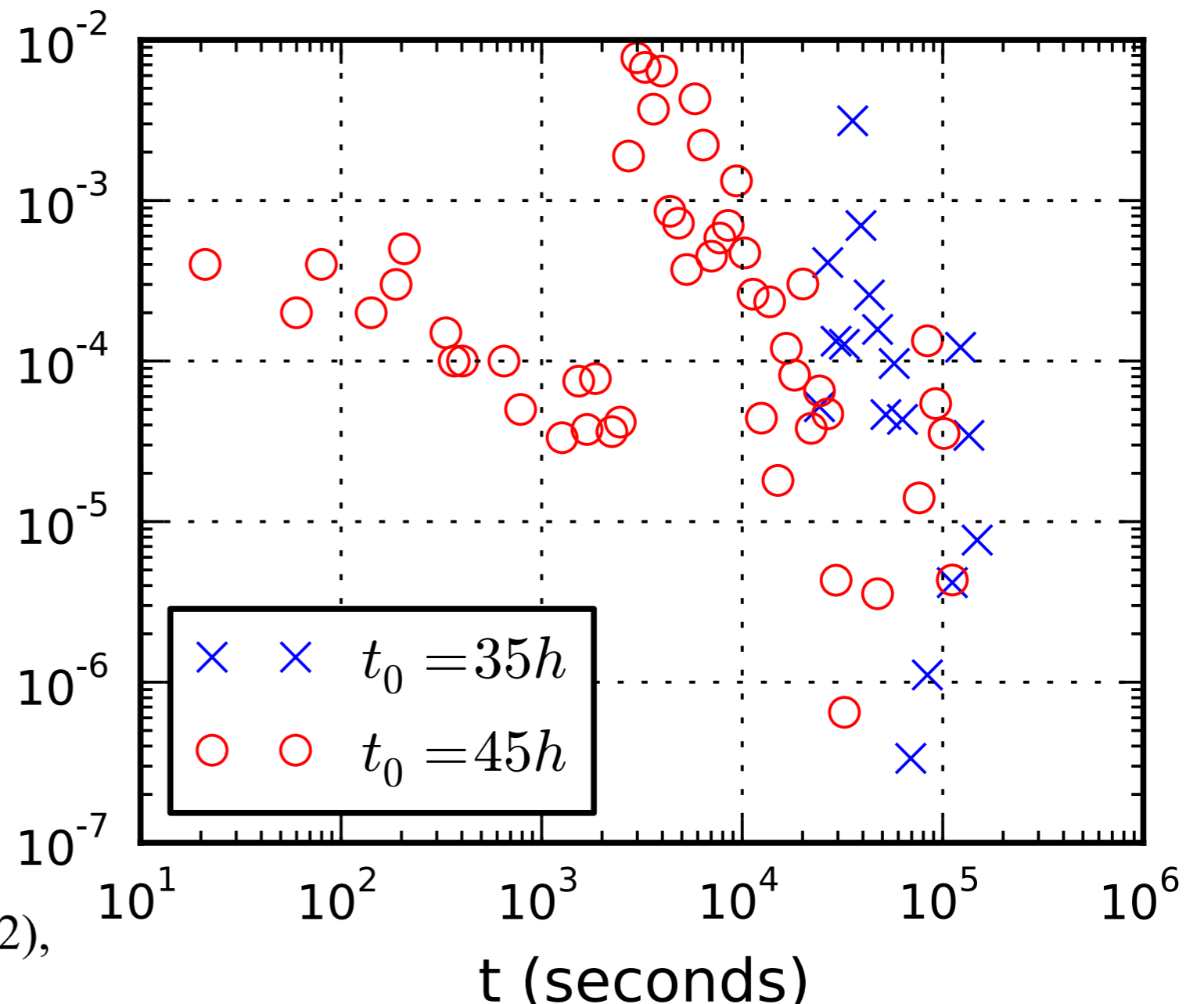
Activity clocks

New notion of time= **intrinsic time** of each node,
incremented only when the node is in contact
with at least another node

t*=10

A Δt=3 B

Δt=7 Δt=5

C
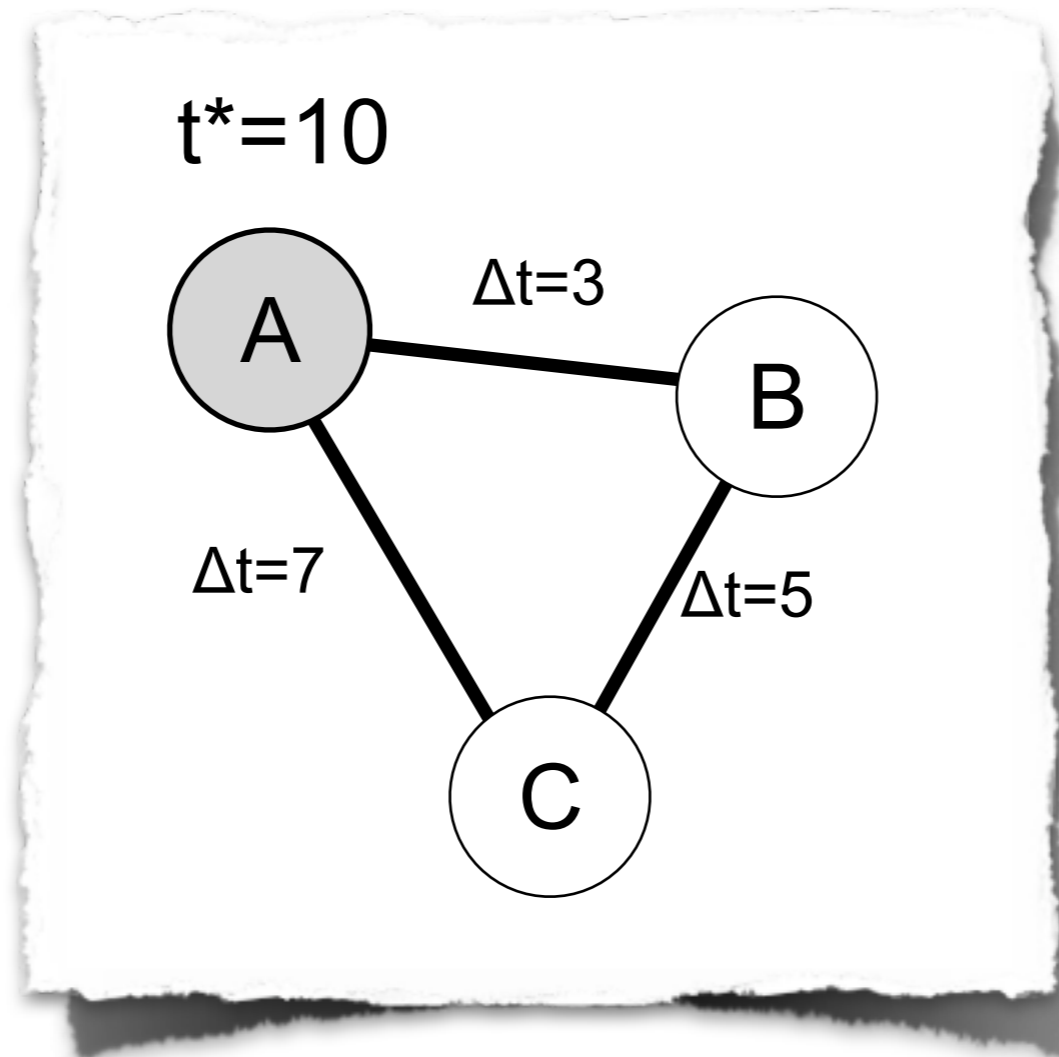
Performance of spreading processes on dynamical networks

Example: 3 days conference, SI spreading process, time delays between generation of message and arrival of message to a node

New notion of time= **intrinsic time** of each node, **incremented only when the node is in contact** with at least another node

A. Panisson et al., Ad Hoc Networks (2012), arXiv:1106.5992
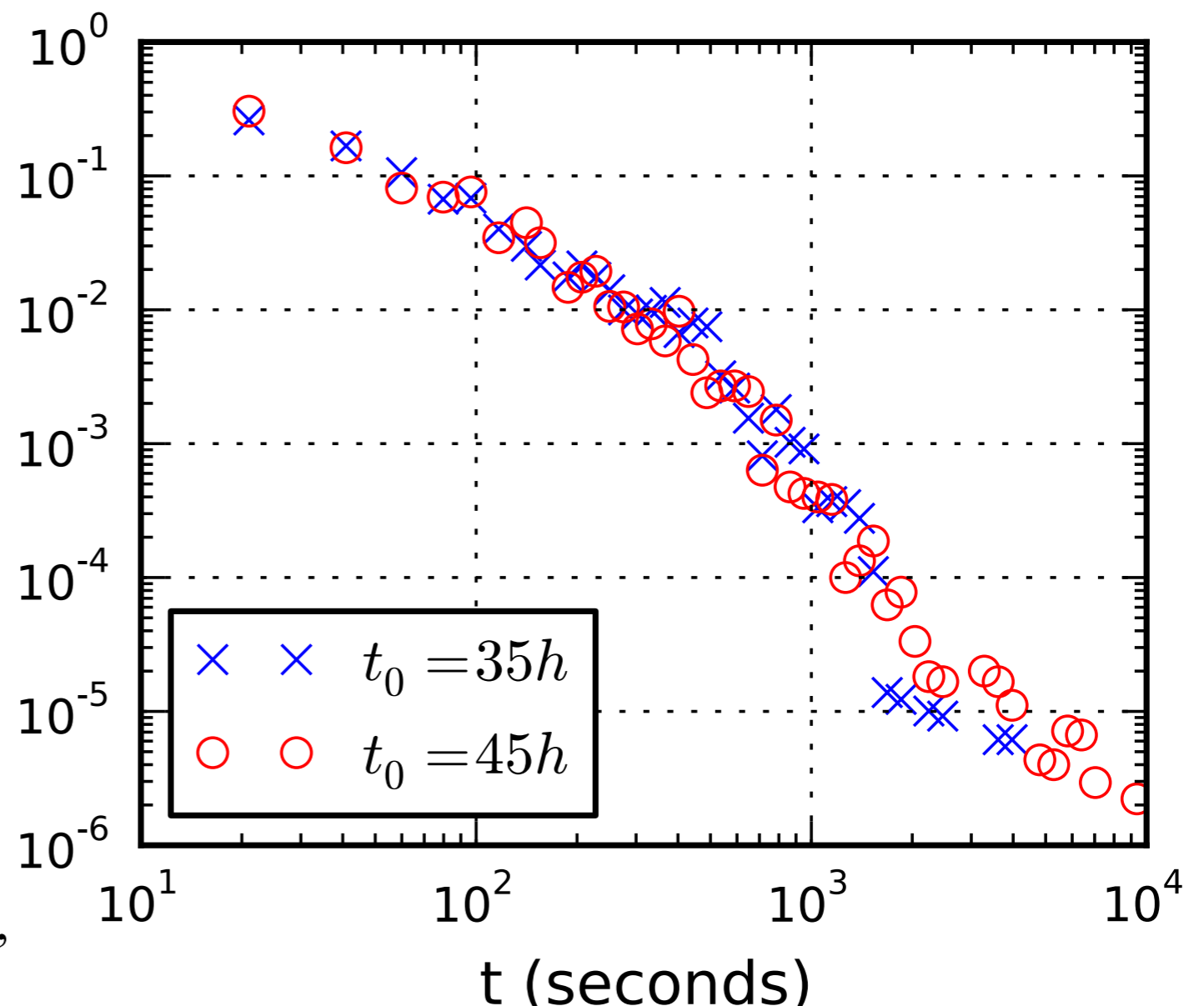
Other/work in progress

Dynamical networks
- Coexistence of stationary properties and local dynamics
- New characterization tools; from statistical physics to signal processing
- Impact of network's dynamics on the quantification of centrality/importance of nodes
- New modeling frameworks

SocioPatterns
- Towards an "Atlas" of human interactions
(Conferences/Museums/Schools/Hospitals...)
- Information of epidemic models (contact networks/matrices)
- Social sciences
(e.g. school: gender segregation, age homophily; firms: organizational science)

Dynamical processes on dynamical networks (social+infrastructure networks)
- interplay of timescales
- role of temporal resolution
- concepts of intrinsic time
- summaries of data, how much detail is needed (whole network, contact matrices, intermediate levels...)?
- inform public health measures (evaluation of containment strategies)
- role of initial conditions
- identification of important nodes

Collaborators

- Airport network

  A. Gautreau, M. Barthélemy

- Bovines

  P. Bajardi, V. Colizza, F. Natale, L. Savini

- SocioPatterns

  www.sociopatterns.org

SocioPatterns team and collaborators

Ciro Cattuto (ISI Foundation, Turin)
Wouter Van Den Broeck (ISI Foundation, Turin)

Vittoria Colizza (INSERM, Paris & ISI Foundation, Turin)
Lorenzo Isella (ISI Foundation, Turin)
Anna Machens (CPT Marseille)
André Panisson (ISI & University of Turin)
Jean-François Pinton (ENS Lyon)
Marco Quaggiotto (ISI & Politecnico di Milano)
Juliette Stehlé (CPT Marseille)
Alessandro Vespignani (Northeastern University & ISI)

Milosch Meriac and Brita Meriac (Bitmanufaktur)

ISI Foundation + CPT Marseille + ENS Lyon + Bitmanufaktur

collaborators

Harith Alani
Martin Szomsor

Alberto Tozzi
Caterina Rizzo
+ staff

Ginestra Bianconi
Kun Zhao

Michael John Gorman
Don Pohlman
+ staff

Philippe Vanhems
Nicolas Voirin
+ staff

the organizers of:
25C3, ESWC09,
HT09, ESWC10,
Epiwork, SFHH, ...

A. Gautreau, A. Barrat, M. Barthélemy,
Microdynamics in stationary complex networks, PNAS 106:8847 (2009)

C. Cattuto, W. Van den Broeck, A. Barrat, V. Colizza, J.-F. Pinton, A. Vespignani.
Dynamics of Person-to-Person Interactions from Distributed RFID Sensor Networks,
PLoS ONE 5(7), e11596 (2010)

L. Isella, M. Romano, A. Barrat, et al.,
Close Encounters in a Pediatric Ward: Measuring Face-to-Face Proximity and Mixing Patterns
 with Wearable Sensors, PLoS ONE 6(2), e17144 (2011)

J. Stehlé, A. Barrat, G. Bianconi
Dynamical and bursty interactions in social networks, Physical Review E 81, 035101 (2010)

L. Isella, J. Stehle, A. Barrat, C Cattuto, J.-F. Pinton, W. Van den Broeck
What's in a crowd? Analysis of face-to-face behavioral networks, Journal of Theoretical Biology 271, 166 (2011)

K. Zhao, J. Stehlé, G. Bianconi, A. Barrat
Social networks dynamics of face-to-face interactions, Physical Review E 83, 056109 (2011)

P. Bajardi, A. Barrat, F. Natale, L. Savini, V. Colizza
Dynamical patterns of cattle trade movements, PLoS ONE 6(5):e19869 (2011)

J. Stehlé, N. Voirin, A. Barrat, C Cattuto, et al.
Simulation of a SEIR infectious disease model on the dynamic contact network of conference attendees, BMC Medicine 9:87 (2011)

J. Stehlé, N. Voirin, A. Barrat, C Cattuto, et al.
High-resolution measurements of face-to-face contact patterns in a primary school, PLoS ONE 6(8):e23176 (2011)

A. Panisson, A. Barrat, C. Cattuto, G. Ruffo, R. Schifanella,
On the Dynamics of Human Proximity for Data Diffusion in Ad-Hoc Networks, Ad Hoc Networks 10, 1532 (2012)