Aalto University
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Temporal features of mobile call networks

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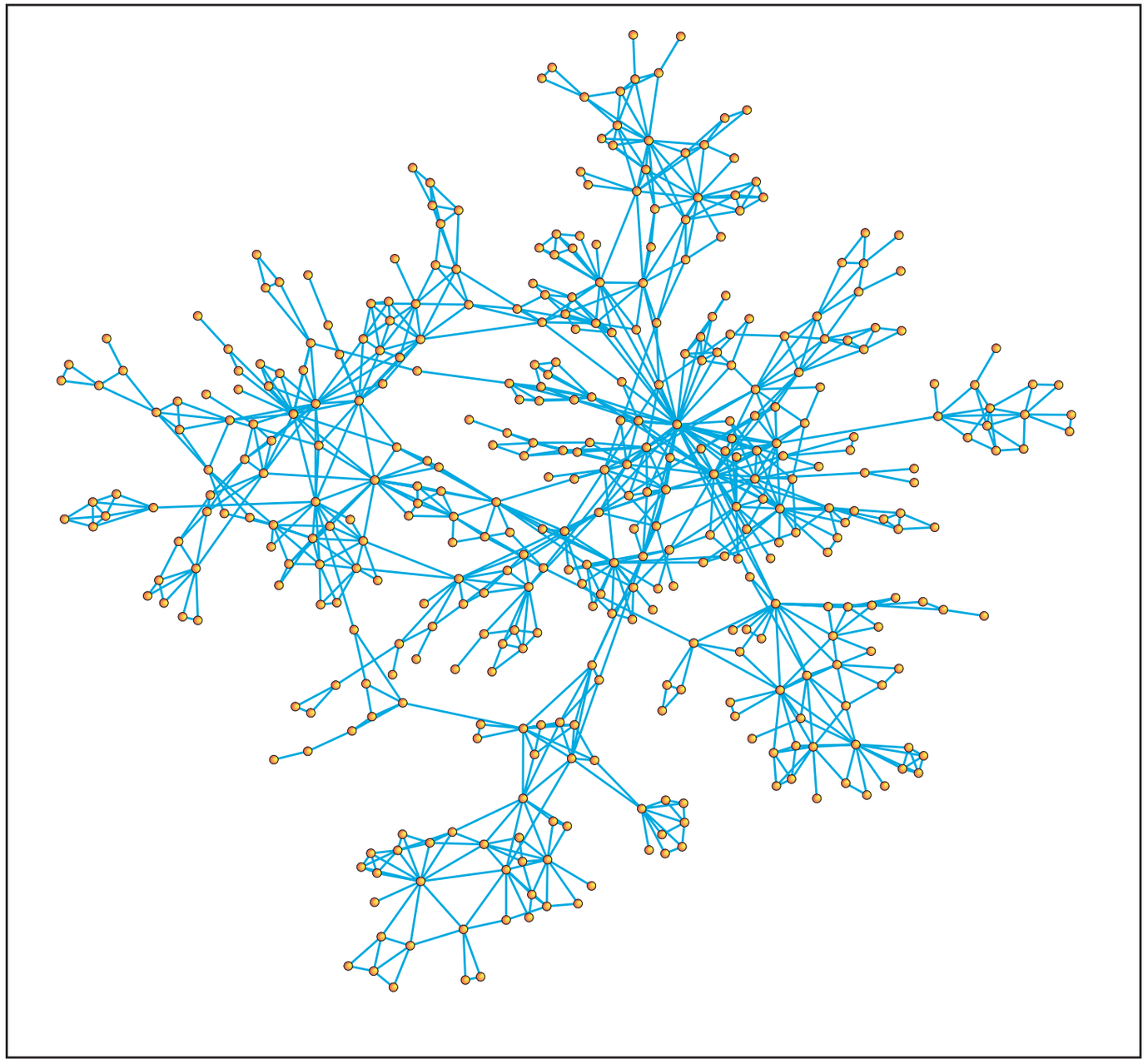
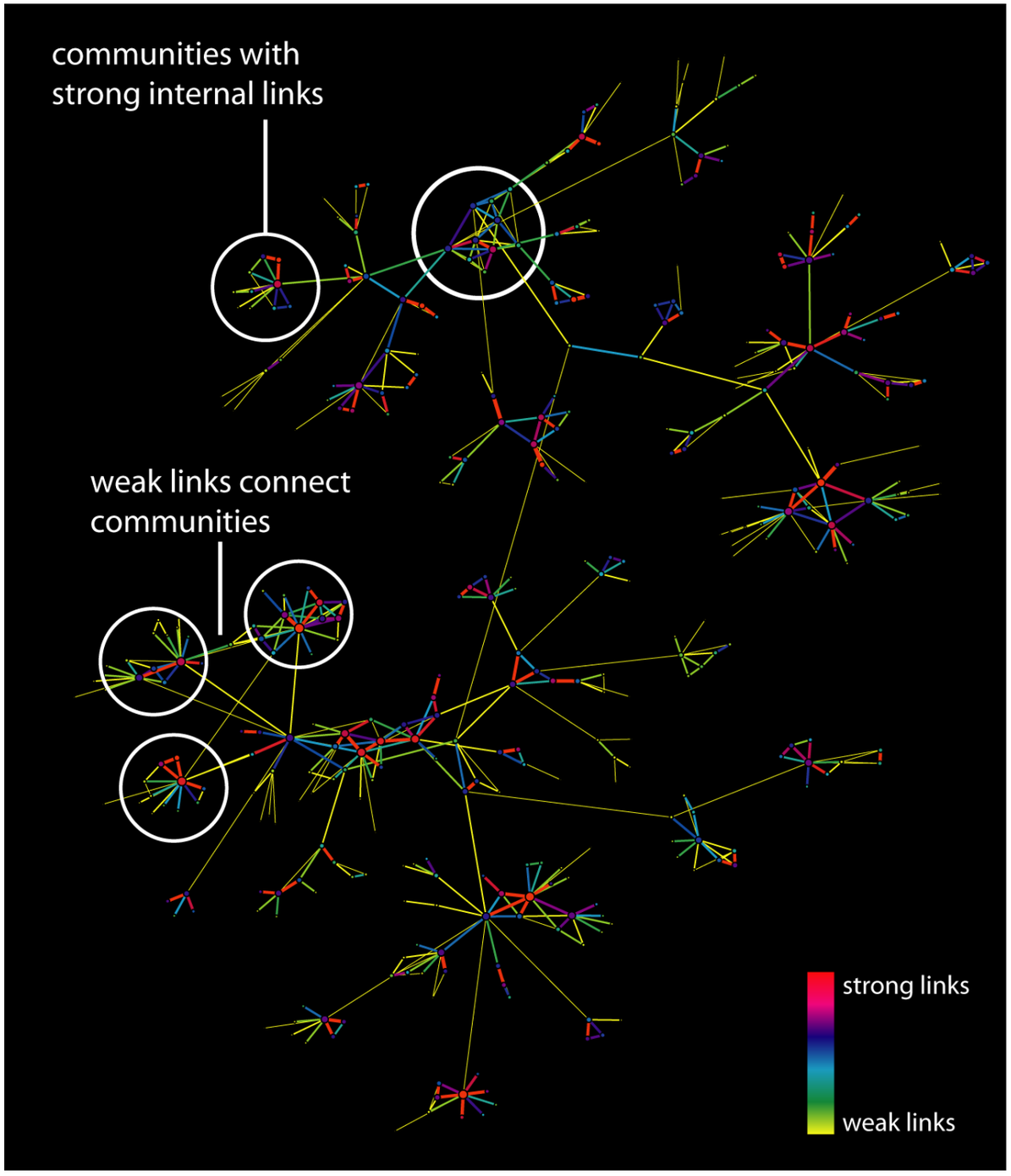
Cambridge, September 19th, 2012

binary social network

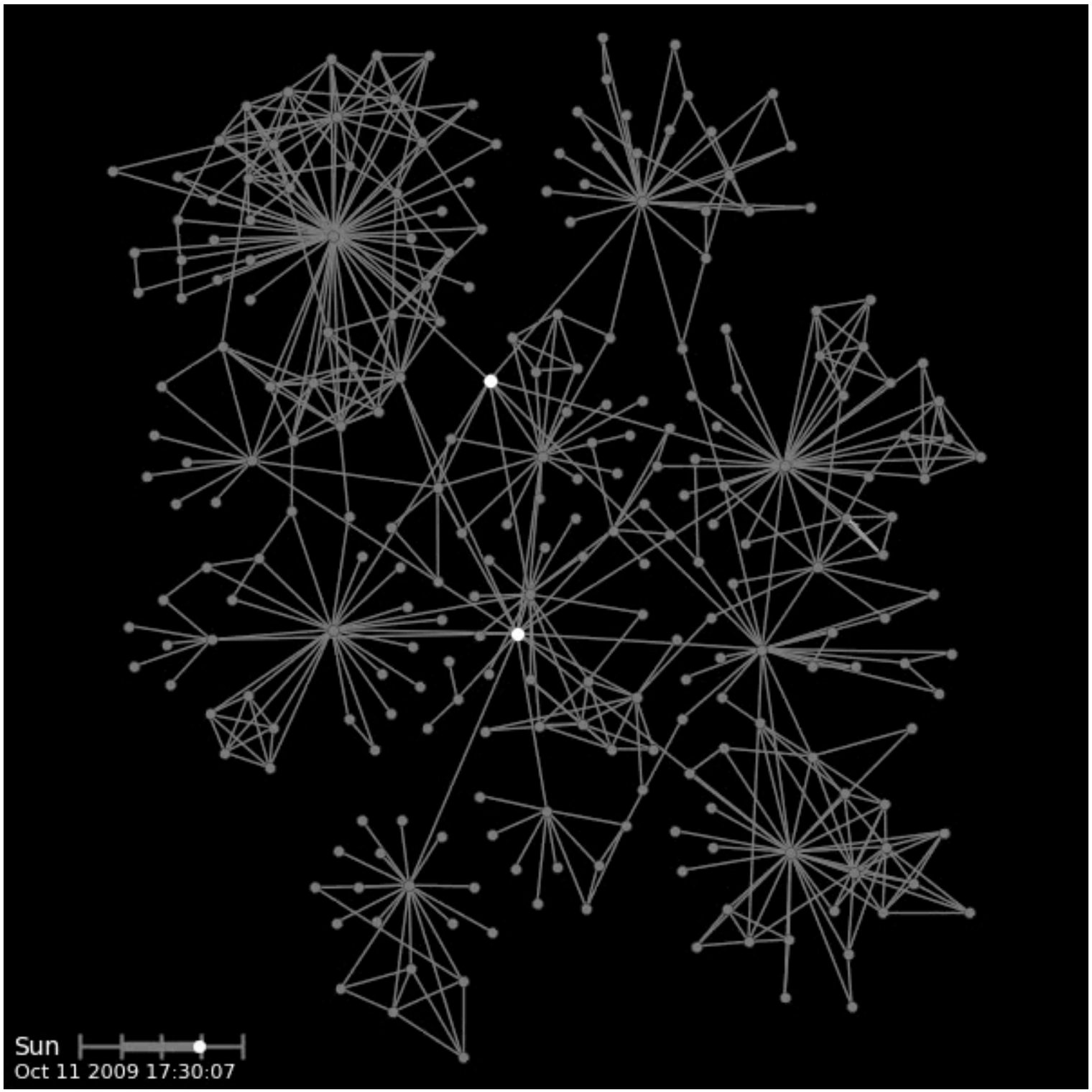


weighted call network



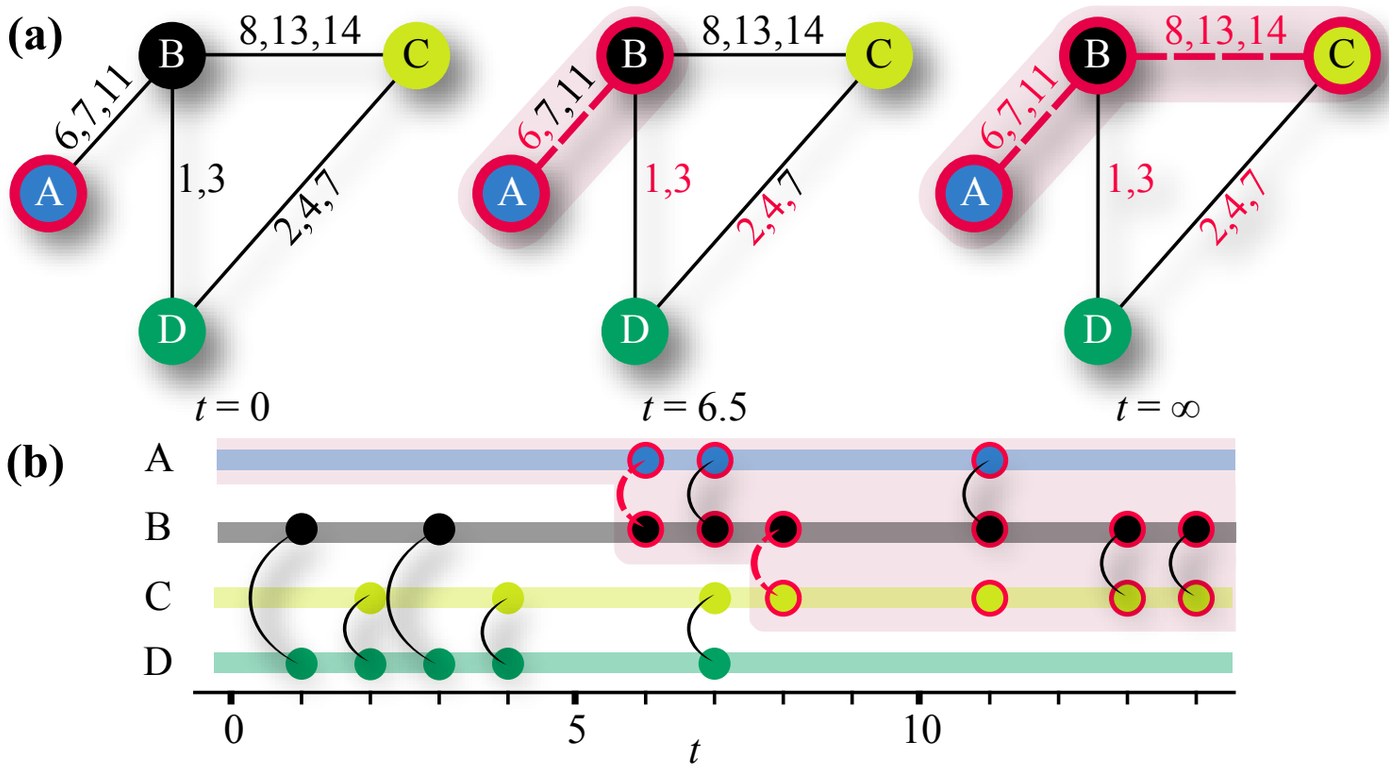
Onnela, Saramäki et al, PNAS 2007

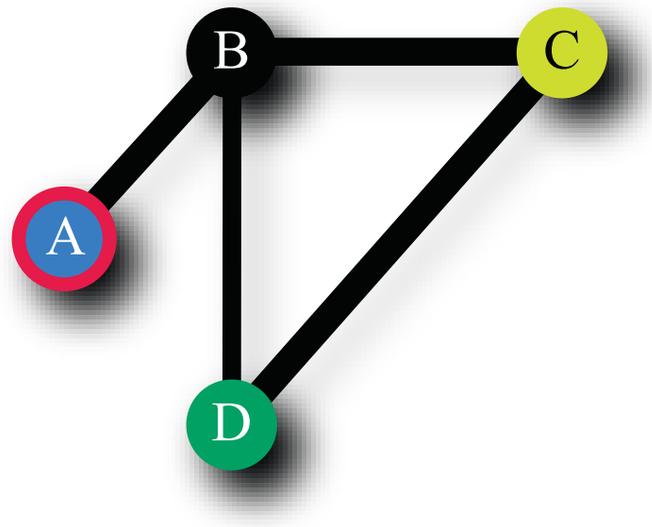
temporal networks: time-stamped calls



temporal network

aggregated weighted network



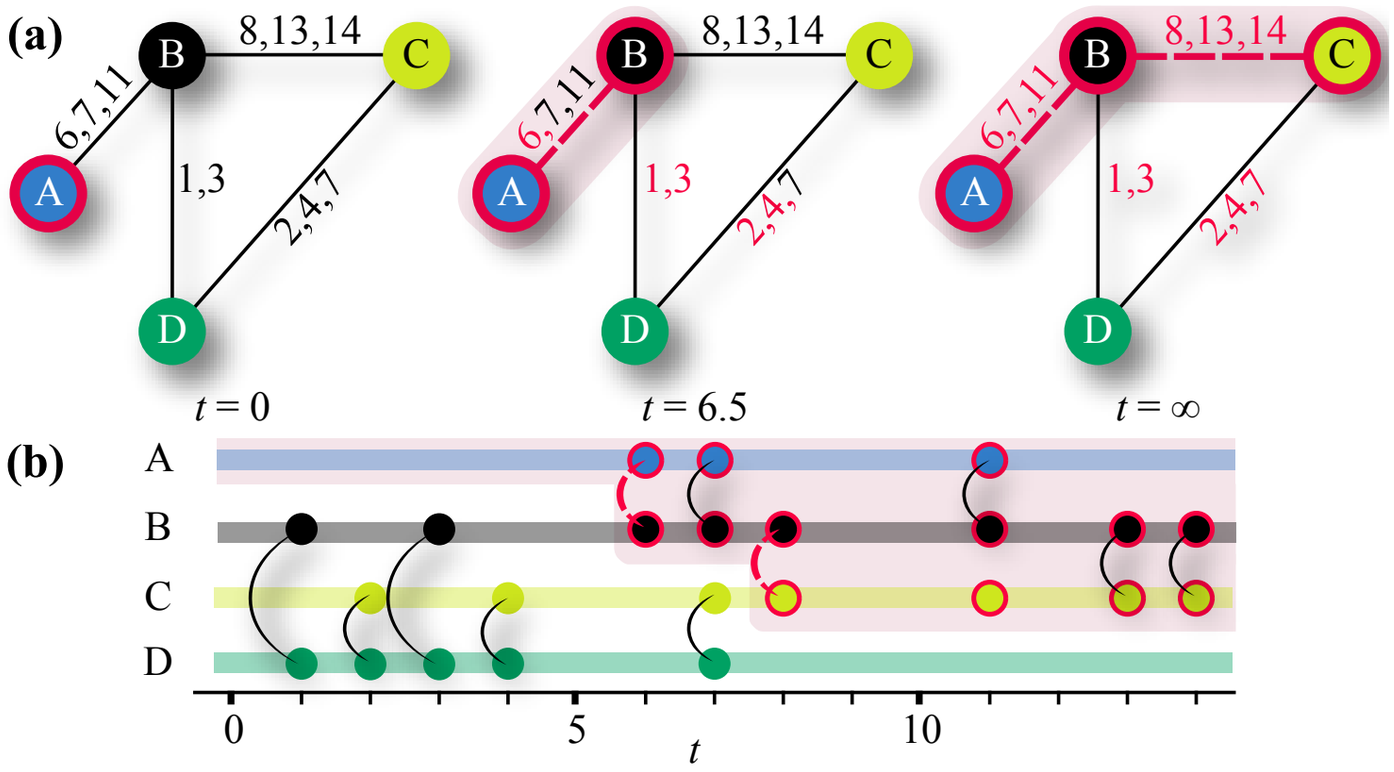


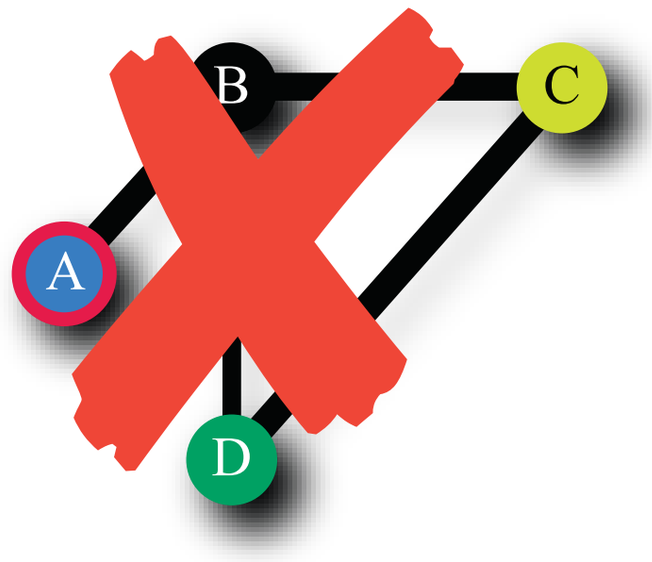
networks are built out of interaction events with specified times; links not permanently "on"

see P. Holme & J. Saramäki, *Temporal Networks*, Physics Reports (in press), arXiv:1108.1780 (2011)

temporal network

aggregated weighted network





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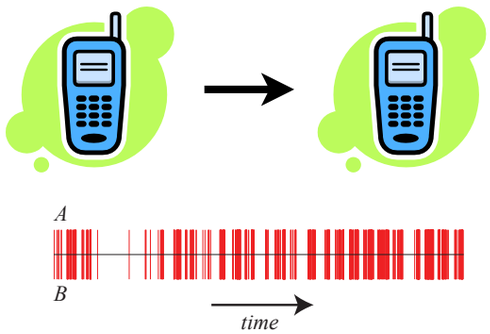
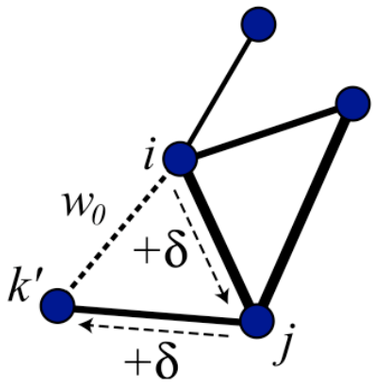
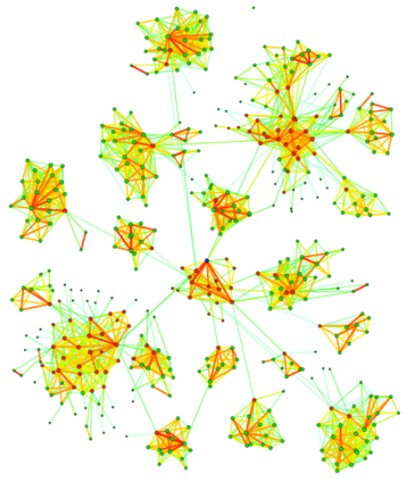
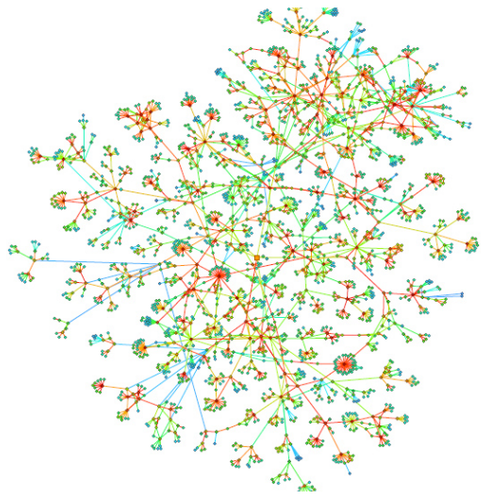








interaction events

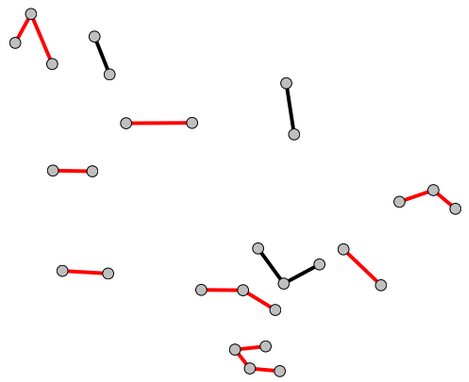
dynamics of ties

dynamics of groups

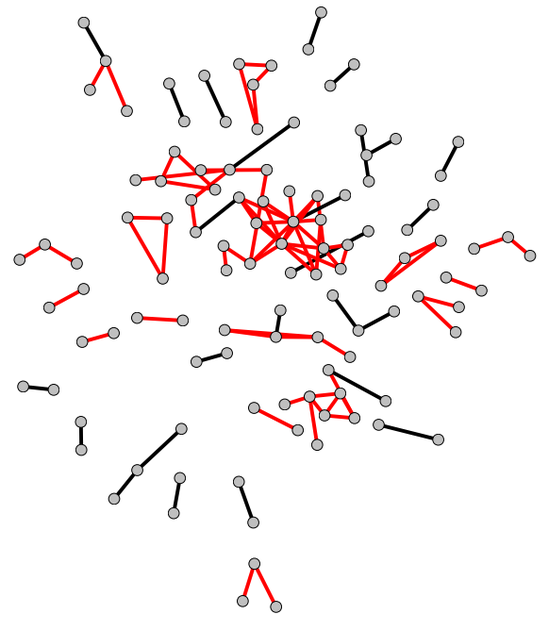
network-level dynamics

...many temporal & structural scales...

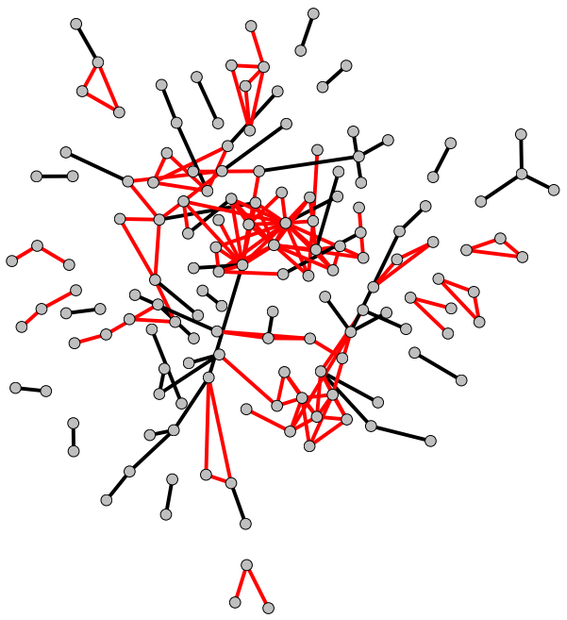
a) t = 1 day



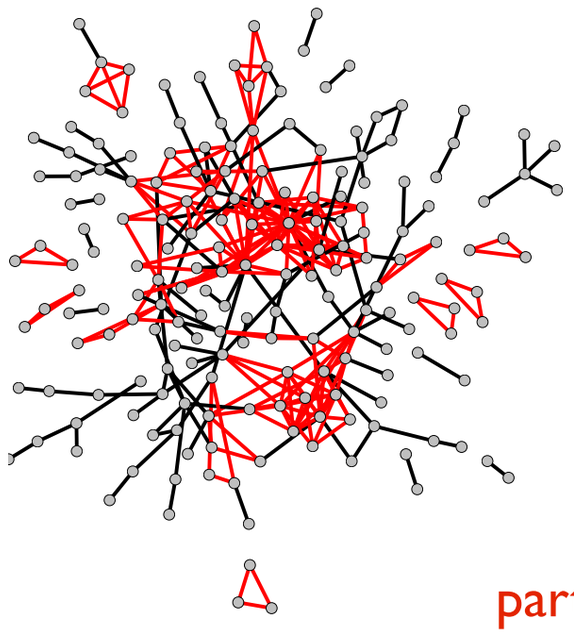
b) t = 1 week



c) t = 4 weeks



d) t = 6 months



red links
participate in triangles

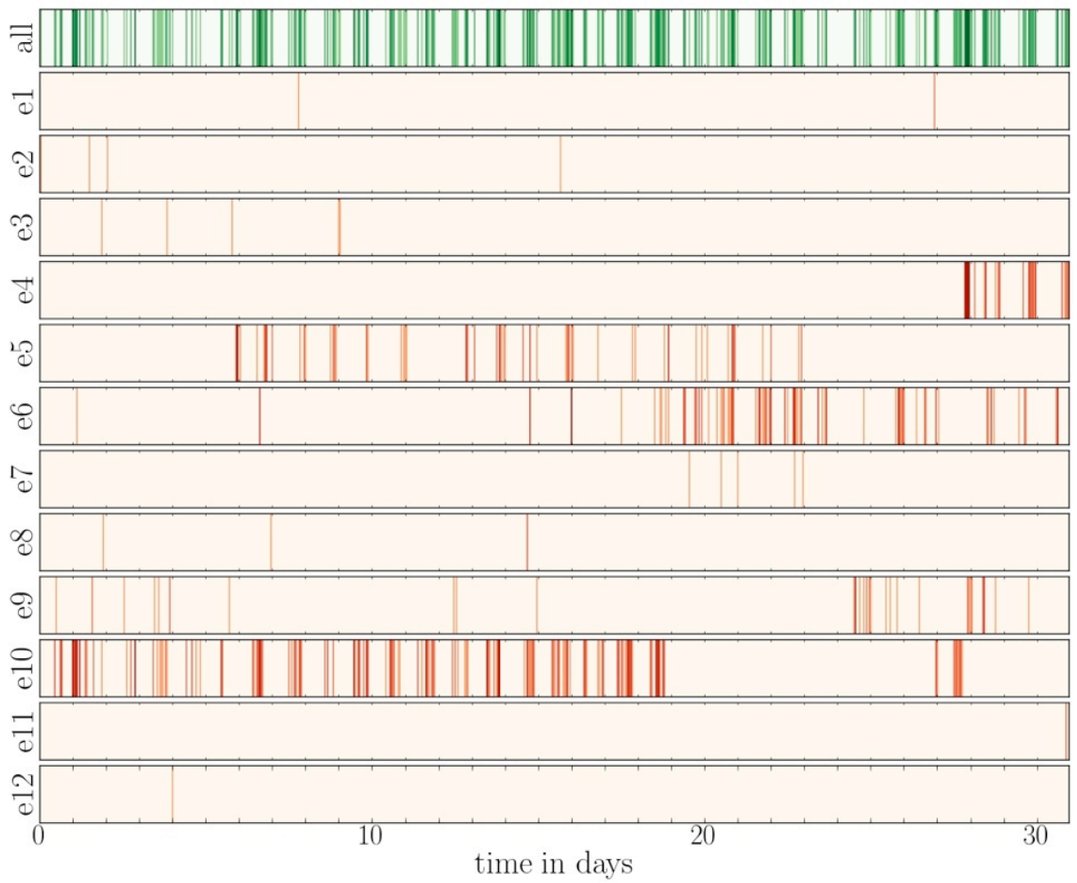
Effects of time window size and placement on the structure of aggregated networks,
G. Krings, M. Karsai, S. Bernardsson, V.D. Blondel, and J. Saramäki, EPJ Data Science 1:4 (2012), arXiv:1202.1145

Our data

- **Mobile telephone call & text records of ~7 million individuals**
  - Caller/callee
  - **Time stamp** (1 s resolution)
- Data over a period of >6 months
- After filtering out one-way links etc,

  ~4 million individuals

caller	callee	time
A	B	t=1
C	D	t=3
C	E	t=9
E	A	t=11



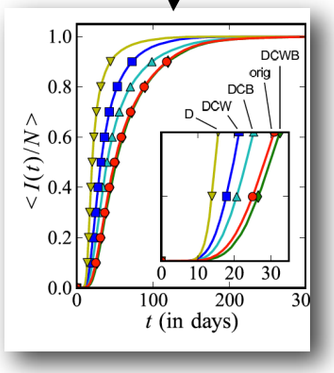
top row: all calls by one person

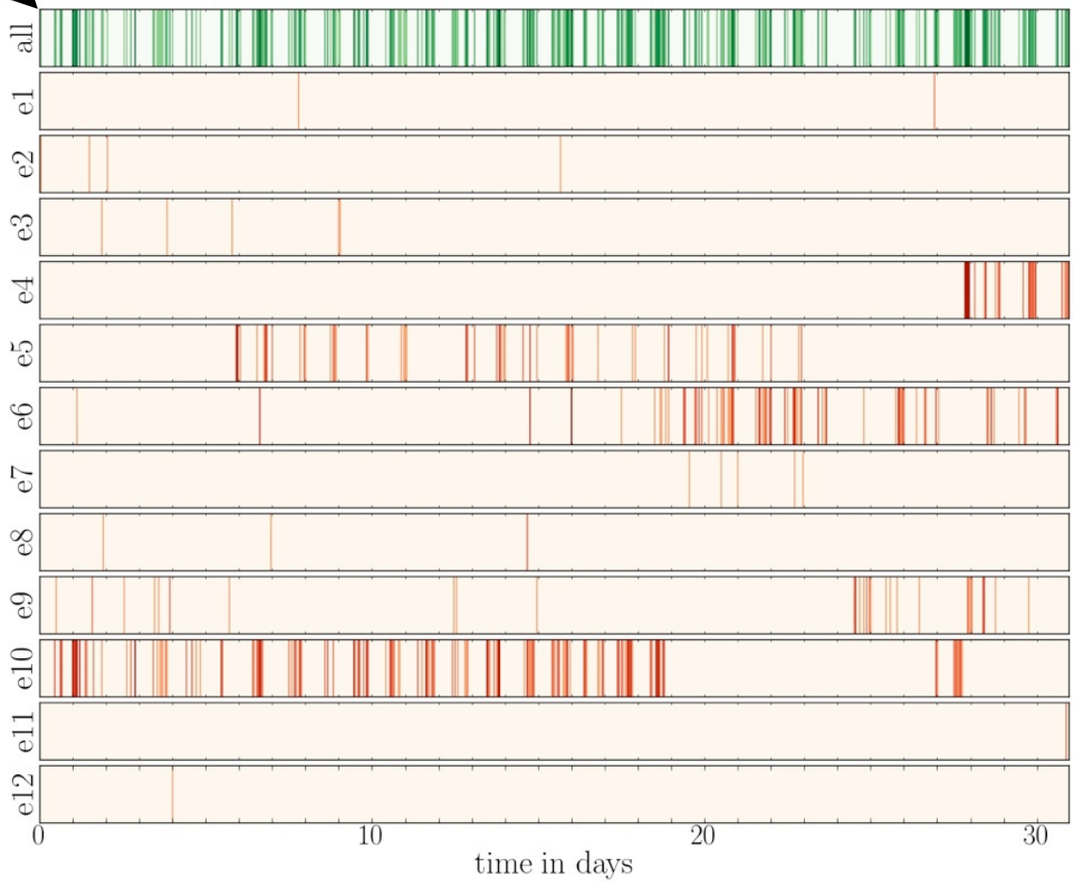
red rows: calls to each alter

time

calls are bursty; this slows down spreading

Karsai et al, *Phys. Rev. E* **83**, 025102(R) (2011)
Pan & Saramäki, *Phys. Rev. E* **84**, 016105 (2011),
Miritello et al., *Phys. Rev. E* **83**, 045102 (2011)





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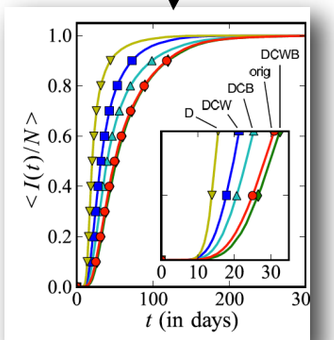
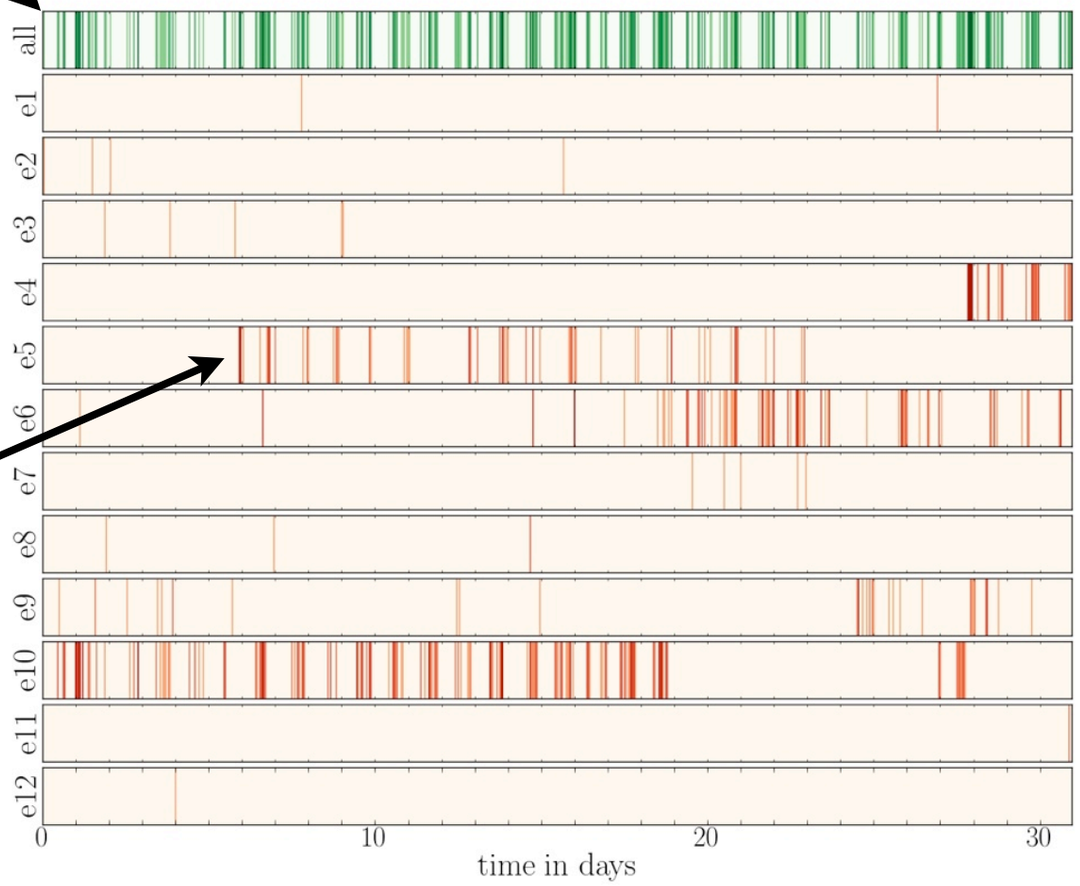


burstiness is associated with *ties*; individuals are bursty because their ties are bursty

Karsai, Kaski, Kertész, PLoS ONE 7(7), e40612 (2012)



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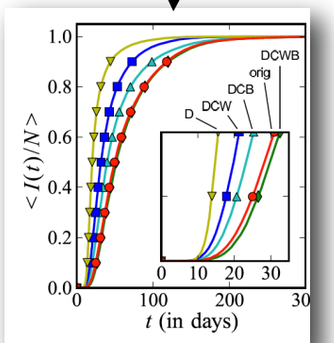
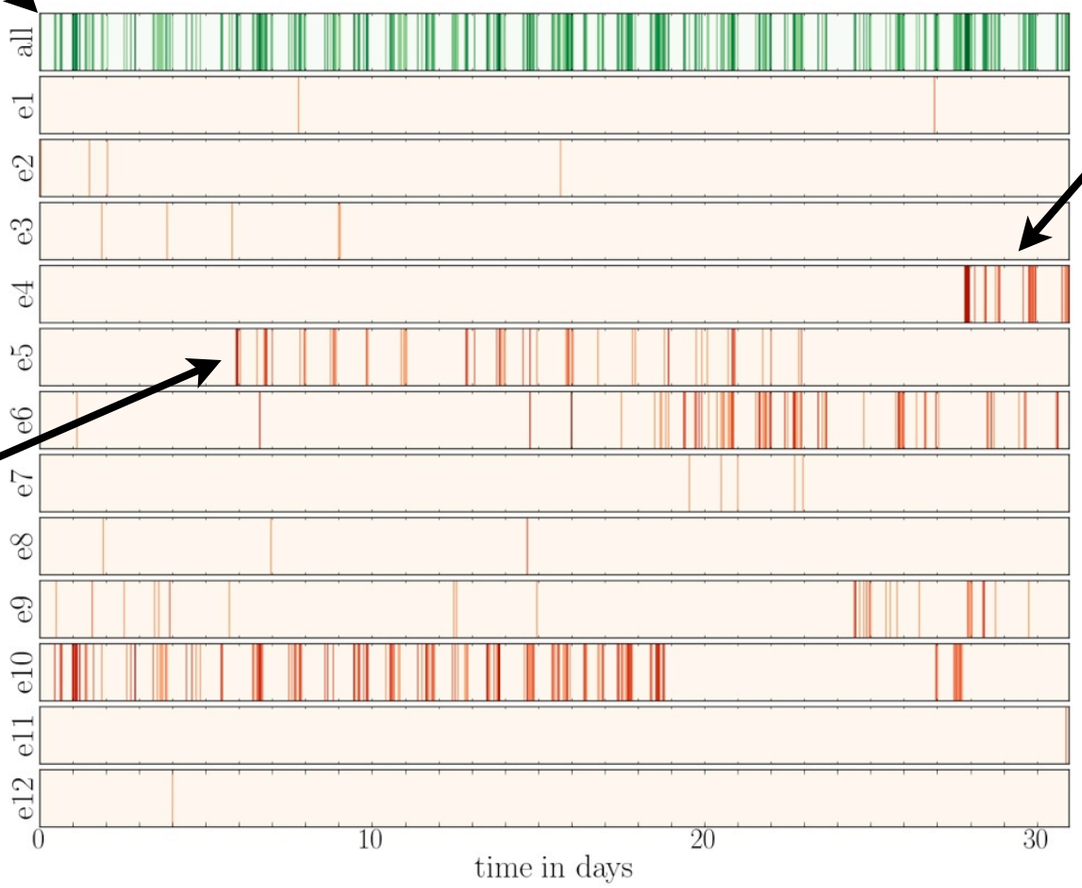


there are *bursty trains*

Karsai, Kaski, Kertész, Barabási, Scientific Reports 2, 397 (2012)



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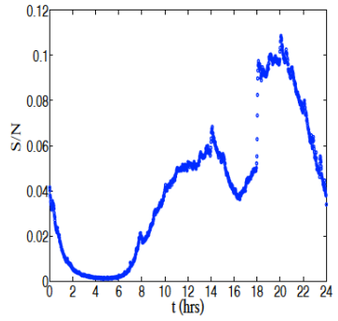

there is a circadian pattern; reflected in entropy and predictability

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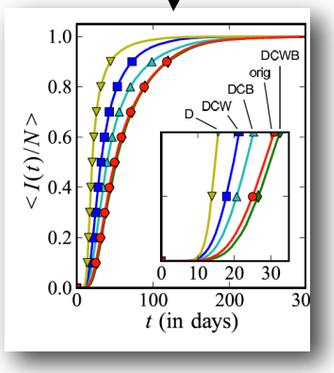

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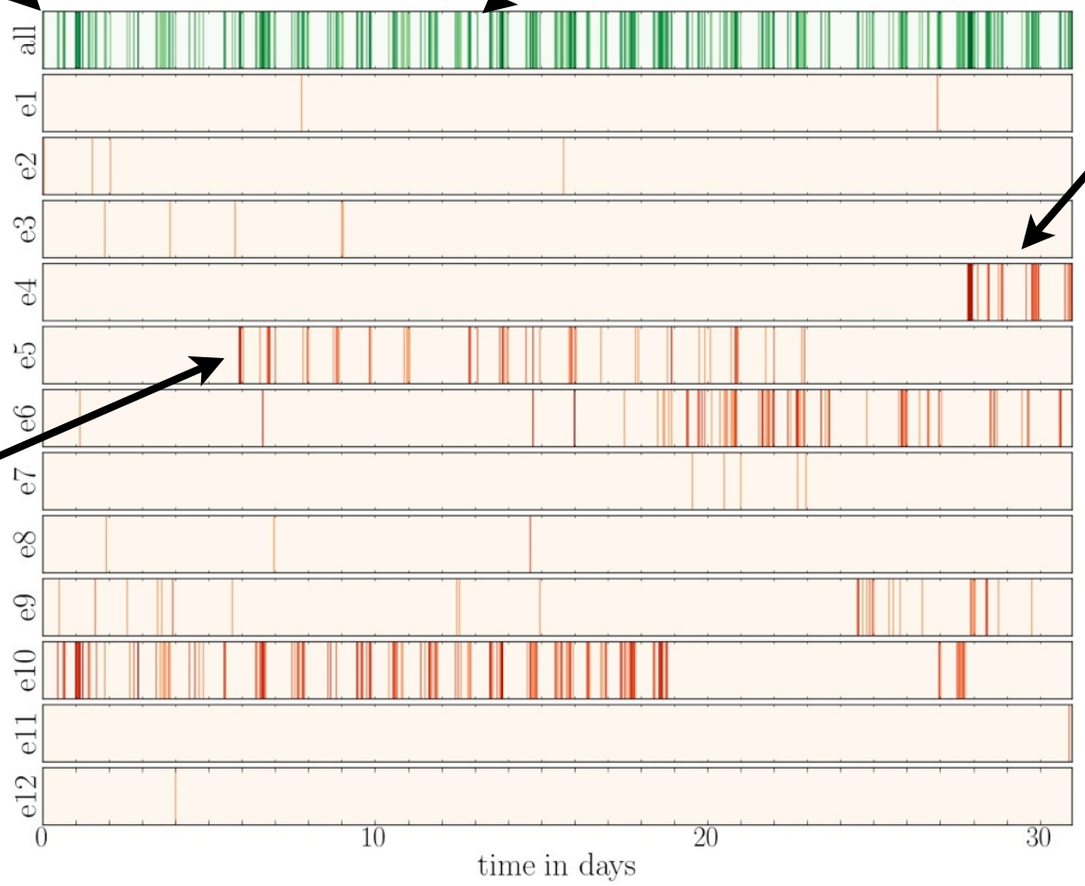

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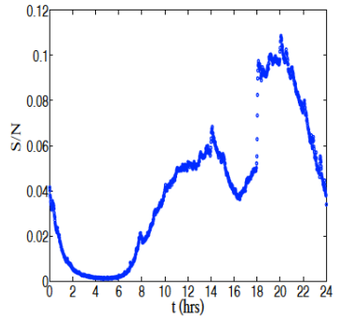

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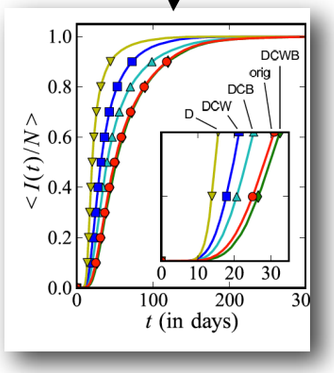

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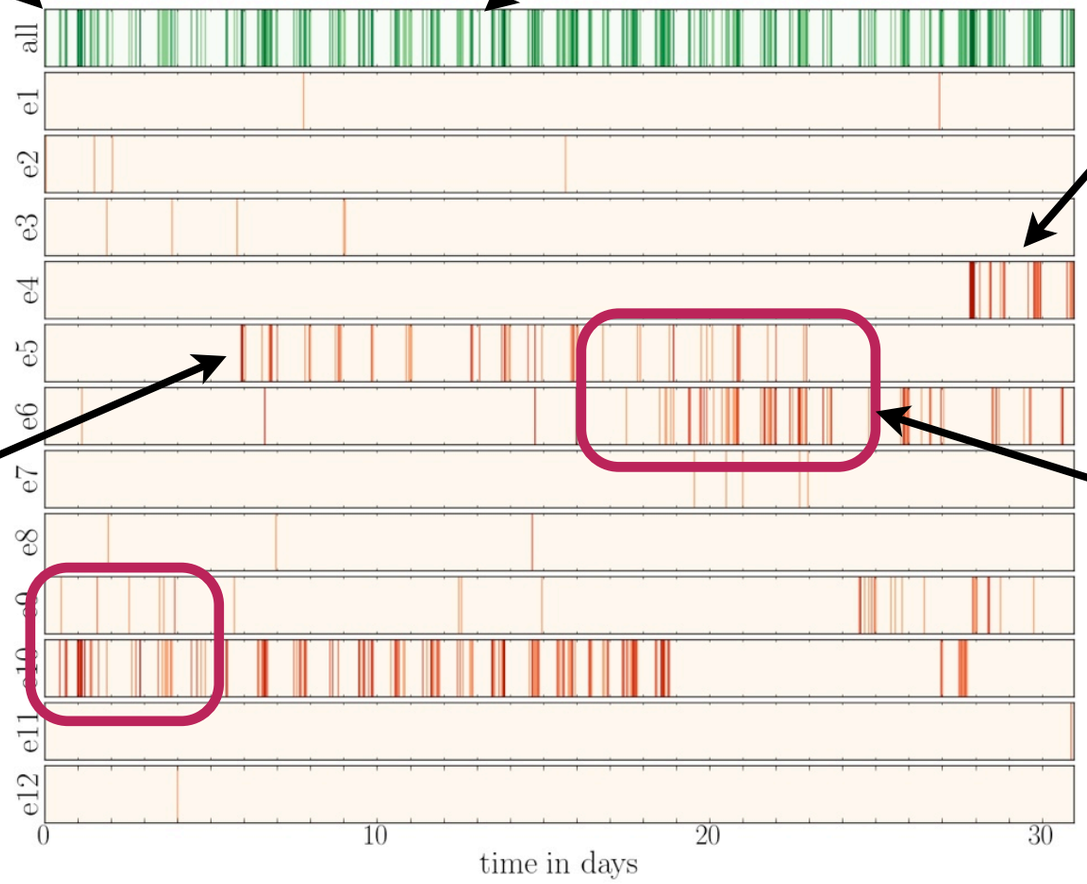
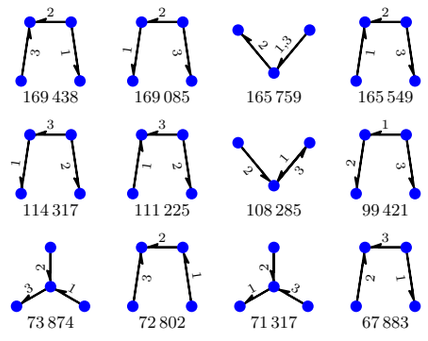


burstiness is associated with *ties*; individuals are bursty because their ties are bursty

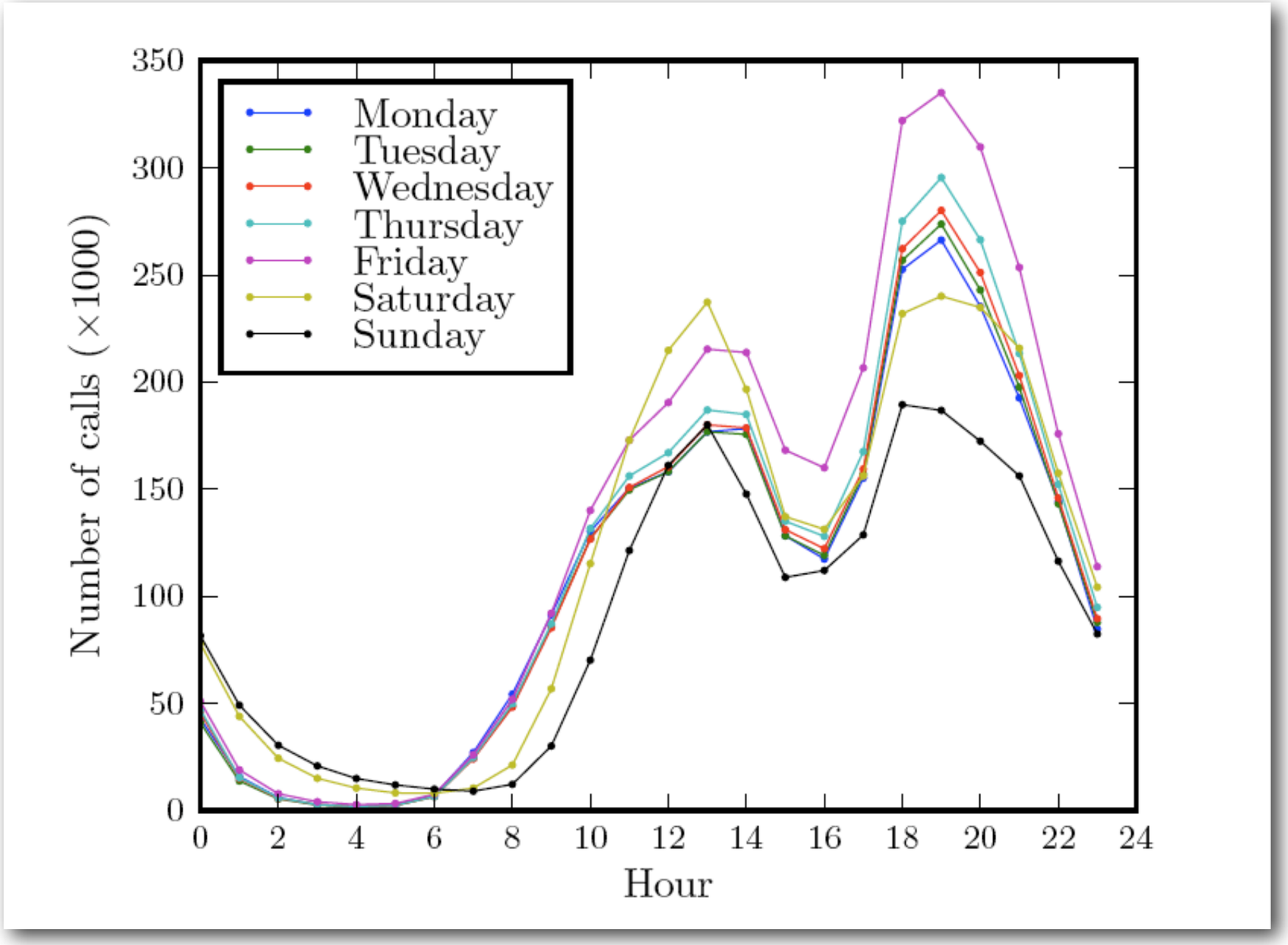
Karsai, Kaski, Kertész, PLoS ONE 7(7), e40612 (2012)

there are patterns involving several individuals

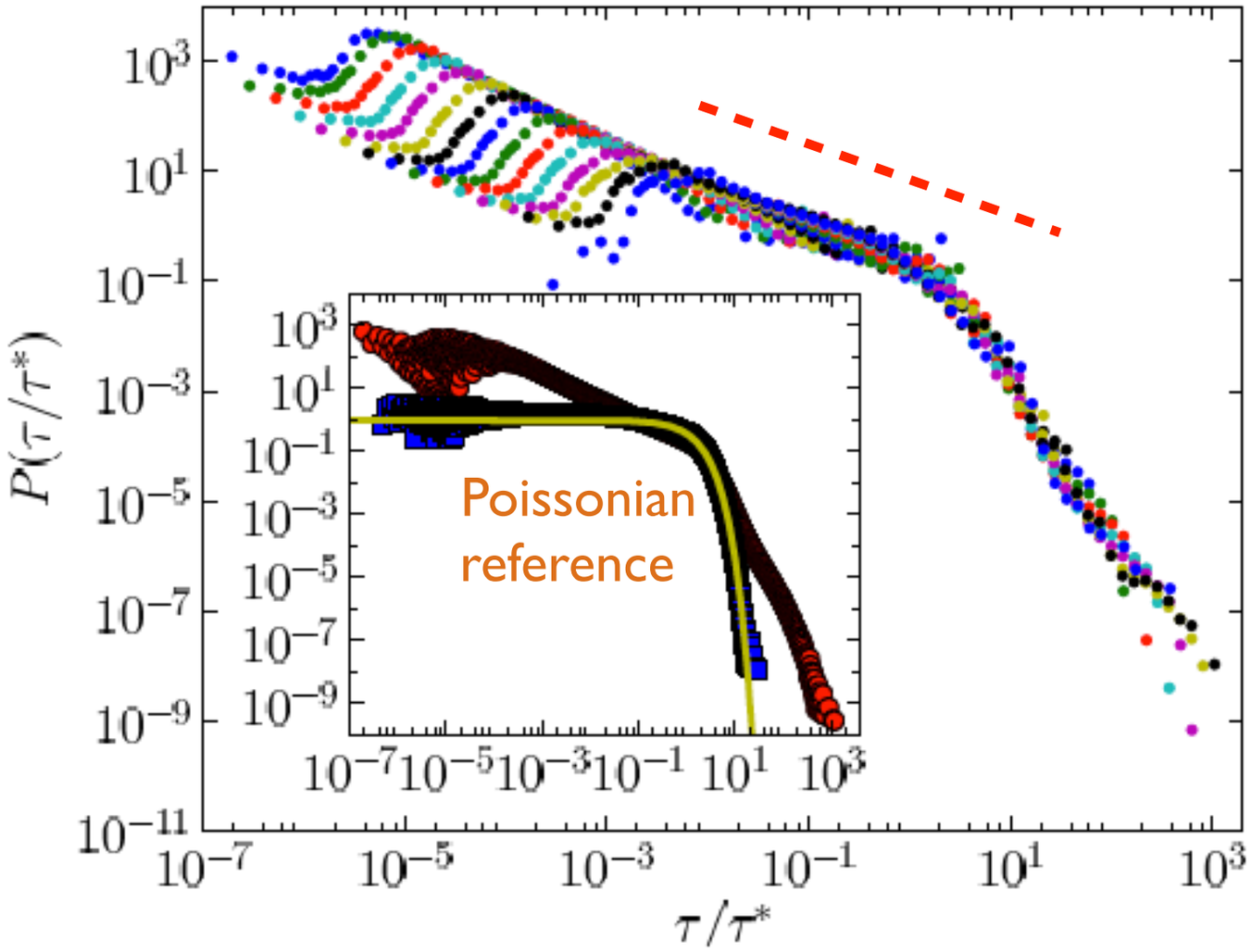
Kovanen et al, J Stat Mech, P11005 (2011)



There is a network-wide daily pattern

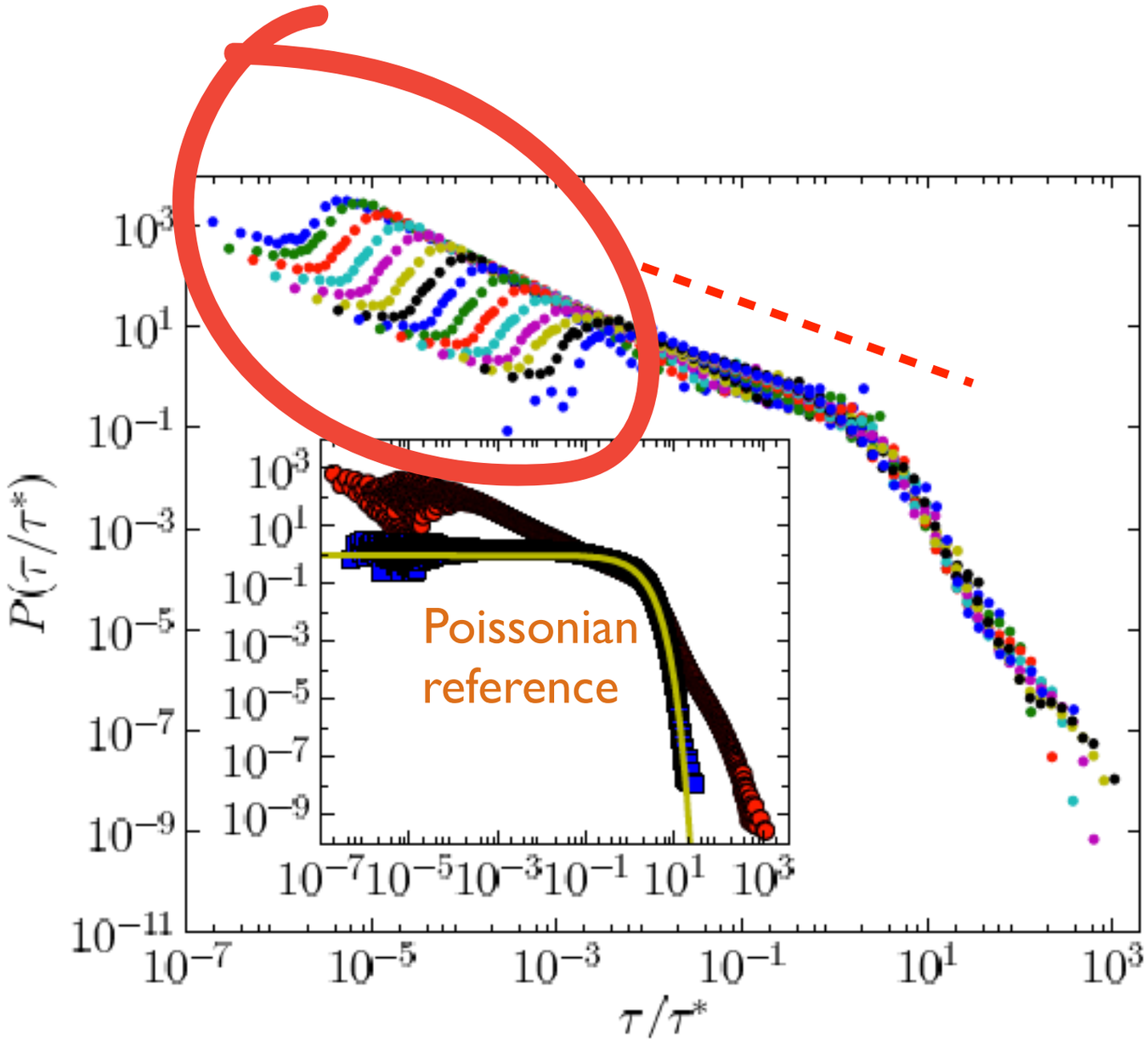


Burstiness: broad inter-call time distributions



- Nodes binned according to # of calls of node
- Interevent time distribution scaled by avg interevent time in bin

Burstiness: broad inter-call time distributions



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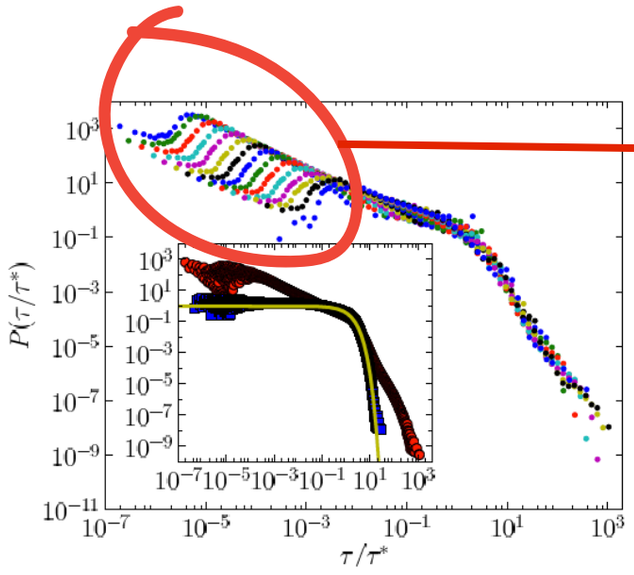
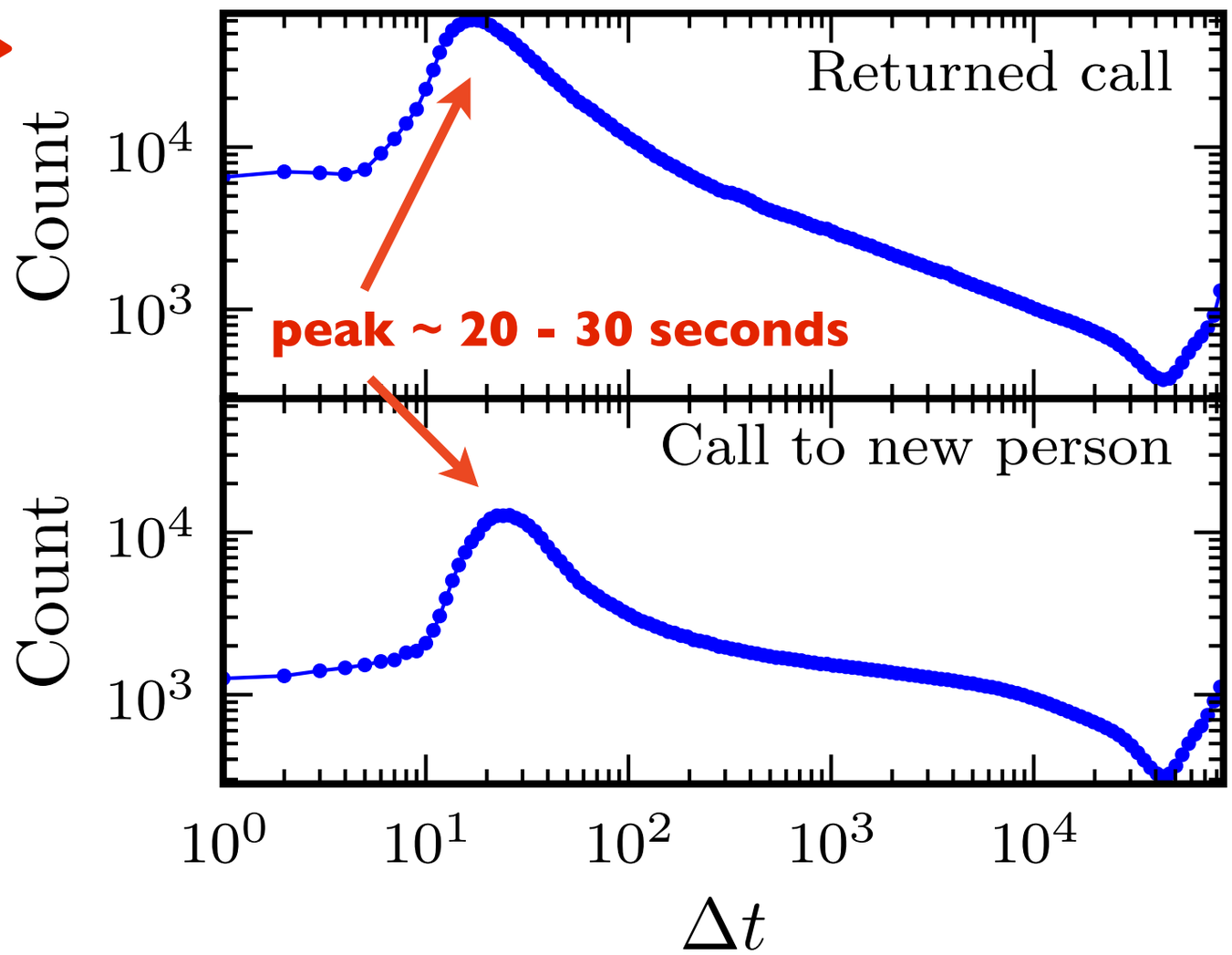
Calls trigger calls

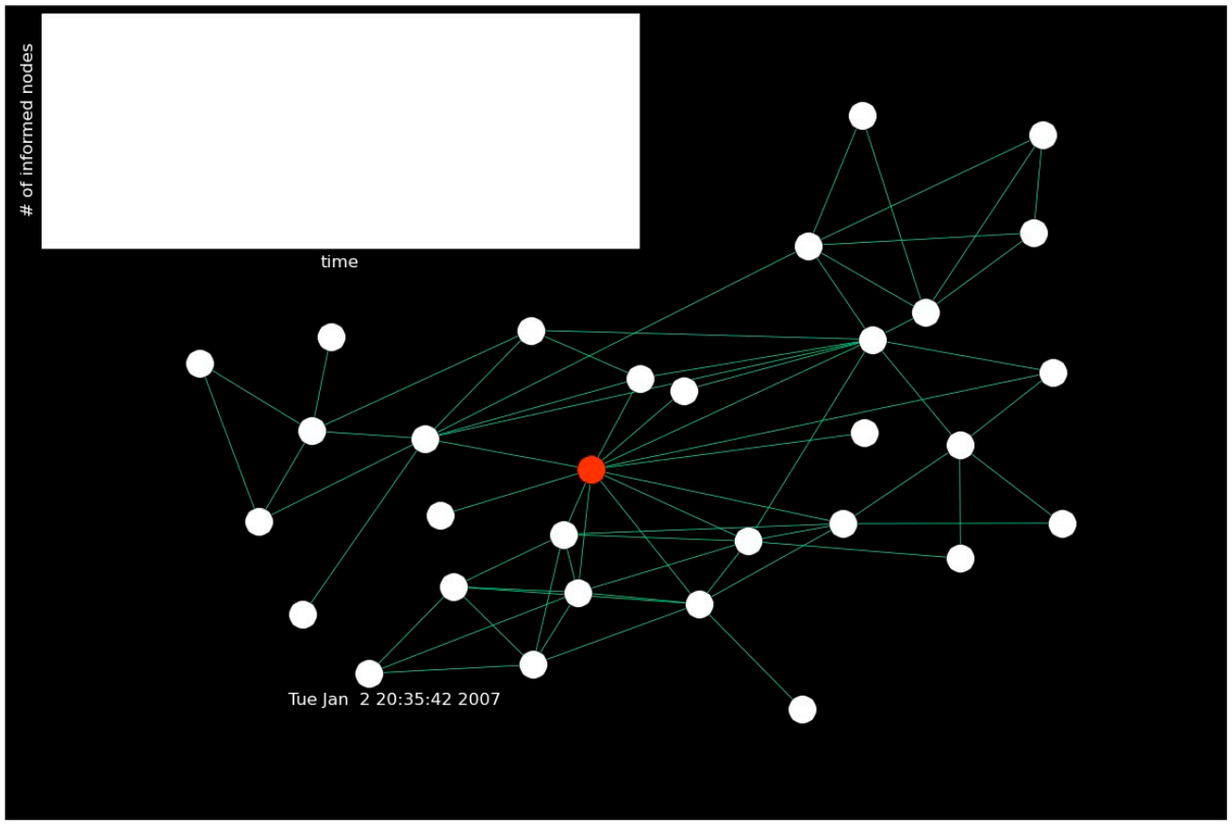




to previous
incoming call

Dynamics at the network level: SI spreading

- (S)usceptible-(I)nfectious
- Represents maximum velocity of information spreading

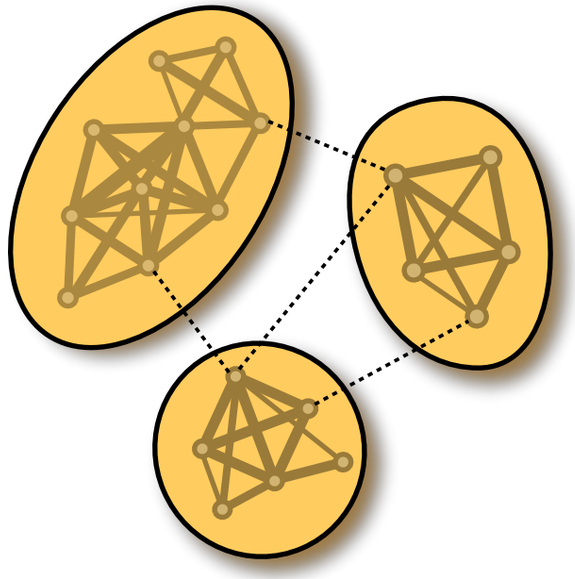


Features that affect spreading dynamics

TOPOLOGICAL

C: Community structure

W: Weight-topology correlations

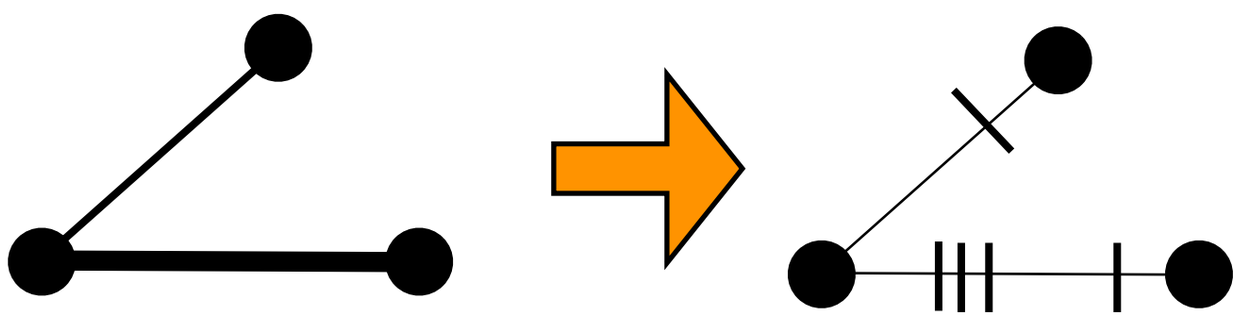


TEMPORAL

B: Bursty single-edge dynamics ("ping-pong")

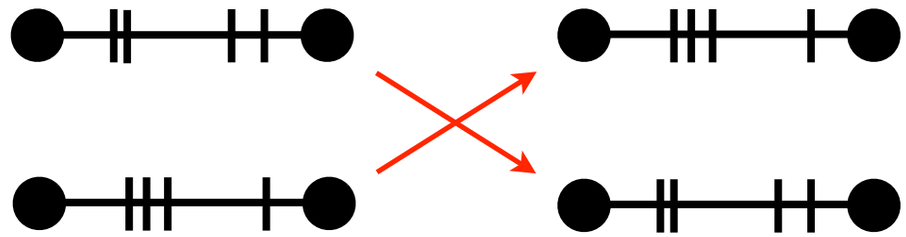
E: link-link correlations (calls trigger calls, A to B to C)

D: Daily pattern (more calls around lunchtime, etc)

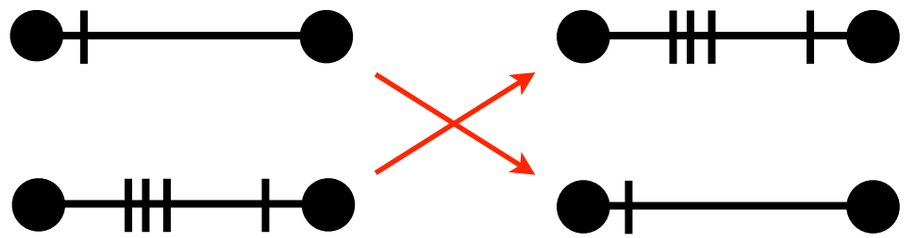


Randomized reference models for removing correlations

Destroy link-link correlations



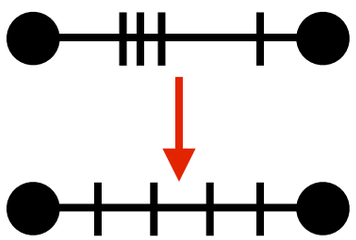
Destroy link-link correlations + weight-topology correlations



Destroy all temporal correlations except daily pattern, retain weights

caller	callee	time
A	B	I
D	E	3
D	F	9
F	A	II

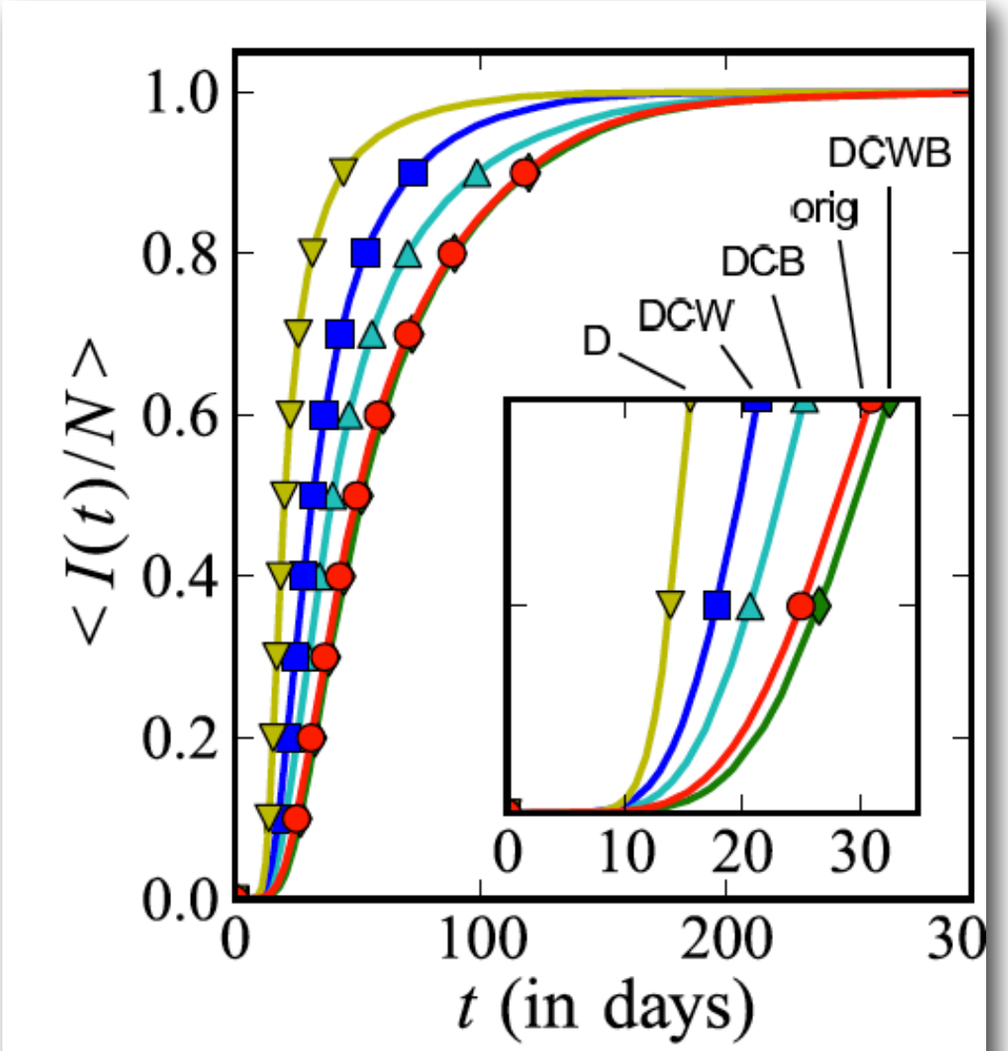
caller	callee	time
A	B	9
D	E	II
D	F	3
F	A	I



Destroy all

Configuration model topological rewiring + random link sequence placement + time stamp shuffling

prevalence vs time
- curves for null models



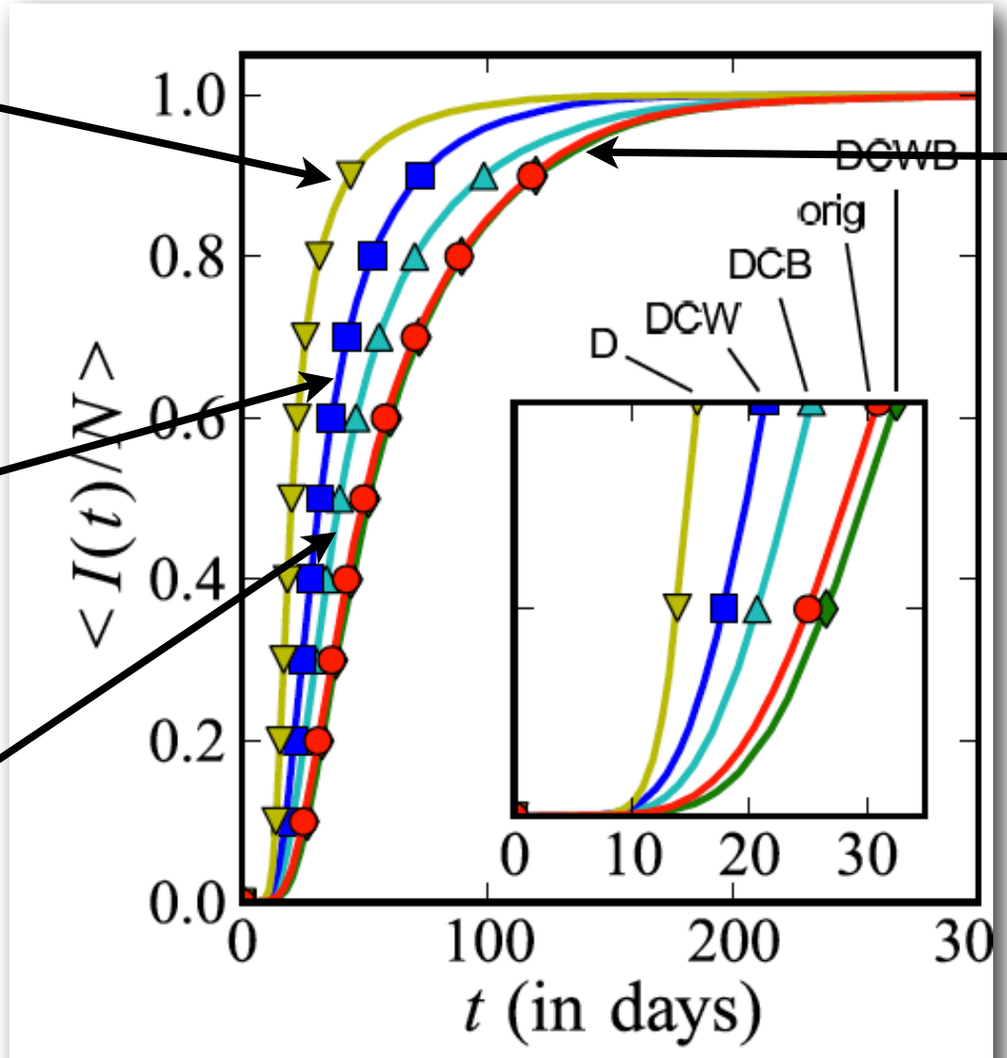
Small but slow world: how network topology and burstiness slow down spreading, M. Karsai, M. Kivelä, R. K. Pan, K. Kaski, J. Kertész, A.-L. Barabási, and J. Saramäki, Phys Rev E **83**, 025102(R) (2011)

prevalence vs time
- curves for null models

most correlations removed

link burstiness removed

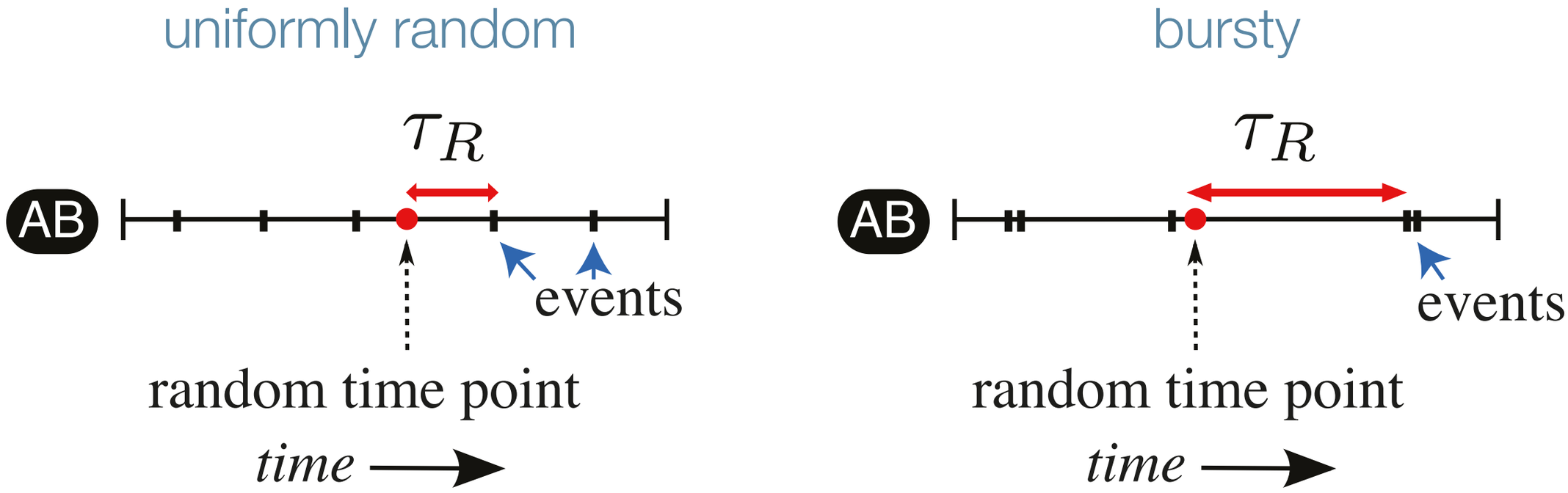
burstiness on, weak-link bottleneck removed



original call sequence

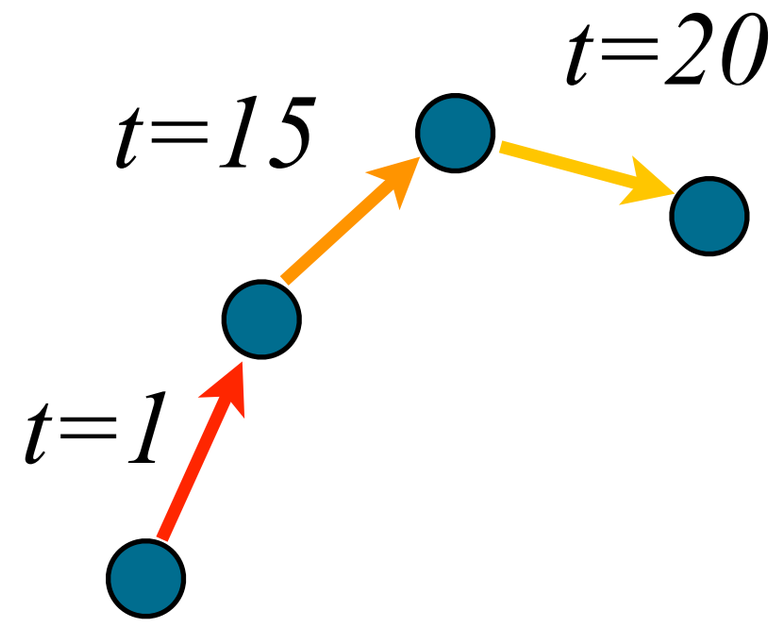
Bursty dynamics slows down spreading a lot!

Small but slow world: how network topology and burstiness slow down spreading, M. Karsai, M. Kivelä, R. K. Pan, K. Kaski, J. Kertész, A.-L. Barabási, and J. Saramäki, Phys Rev E **83**, 025102(R) (2011)


uniformly random
τ_R
AB
events
random time point
time
bursty
τ_R
AB
events
random time point
time

Slow spreading = slow temporal paths

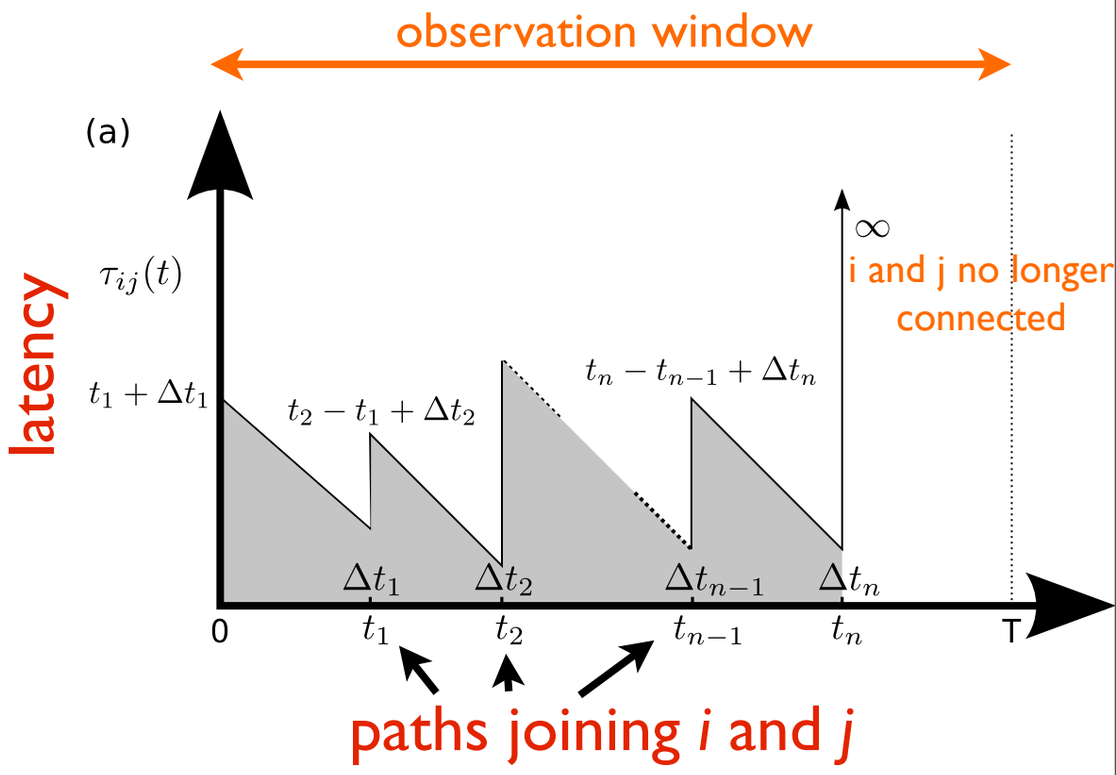
- One can characterize a temporal graph by measuring average latencies between nodes
- Temporal latency τ_{ij}: the time it takes to reach j from i via a time-respecting path, beginning at time t



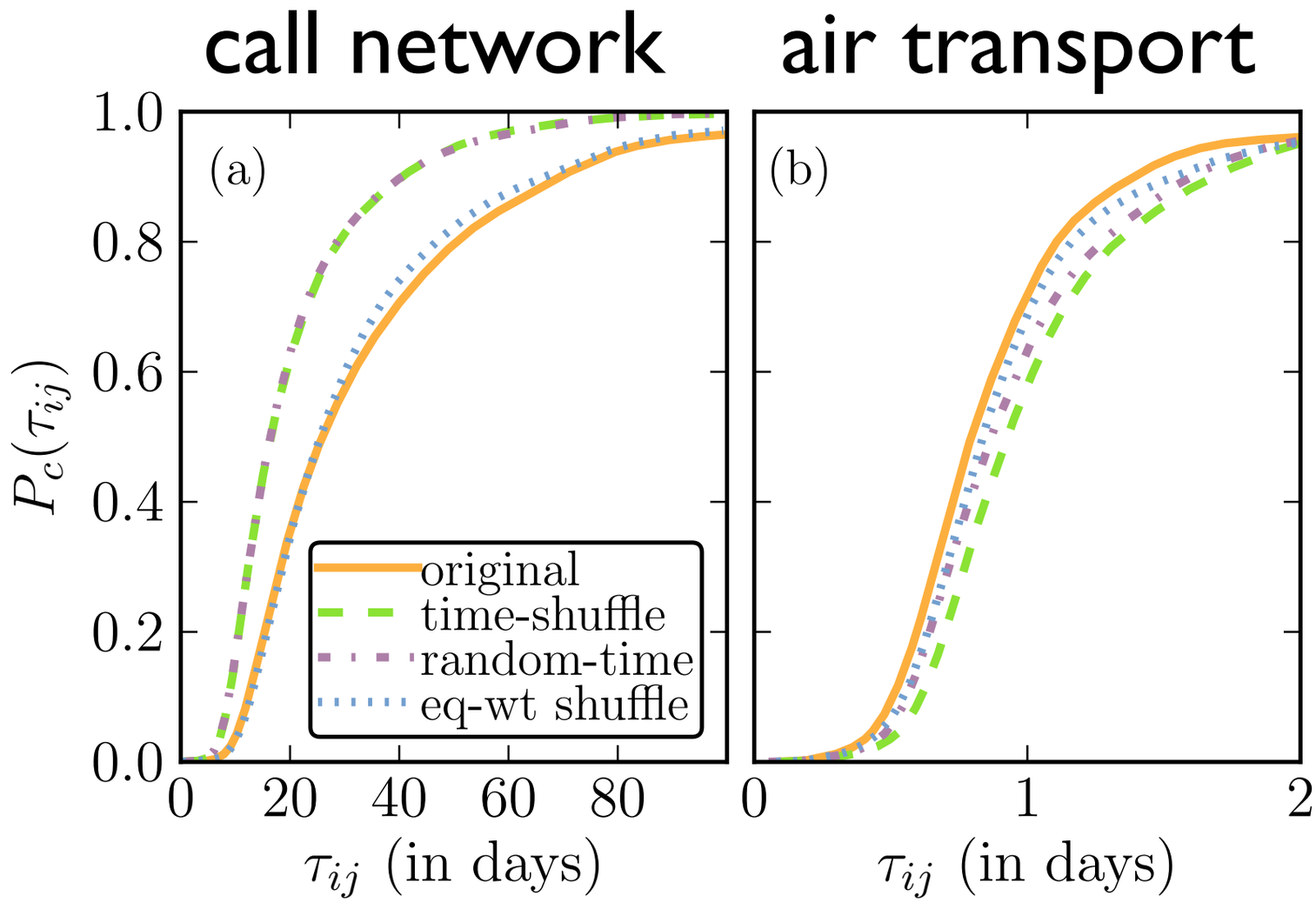
- The statement "*i* and *j* are connected via a temporal path" is not enough
  - need to know ***when, how often, and how long*** does it take to traverse the paths

- Average quantities: ***finite observation window!***

- See *Path lengths, correlations, and centrality in temporal networks*, R.K. Pan and J. Saramäki, Phys. Rev. E 84, 016105 (2011), arXiv:1101.5913

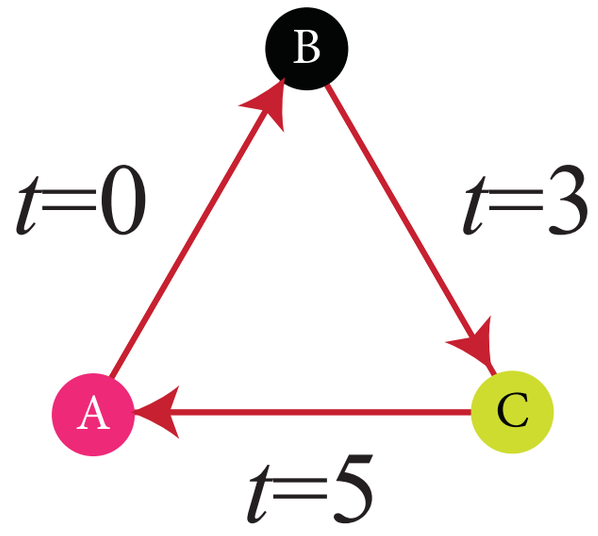


cumulative latency distributions



For the air transport network, temporal correlations give rise to *faster* paths

temporal motifs

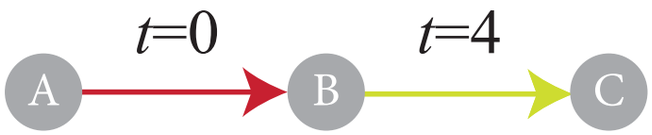


- We want to detect **temporal patterns, where links activate within short time periods**

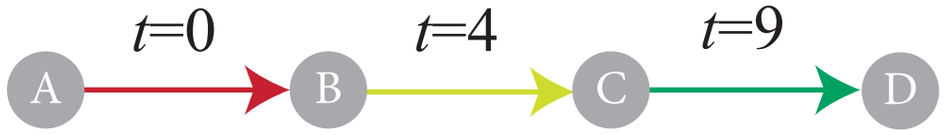
- Patterns should be grouped into equivalence classes (motifs) that take event order into account

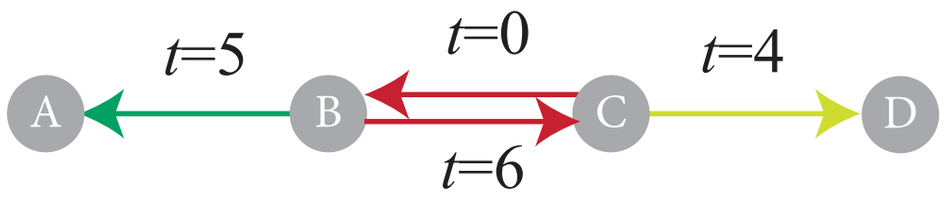
Δt-adjacent and Δt-connected events

these two are temporal subgraphs



Δt-adjacent
for $\Delta t=5$





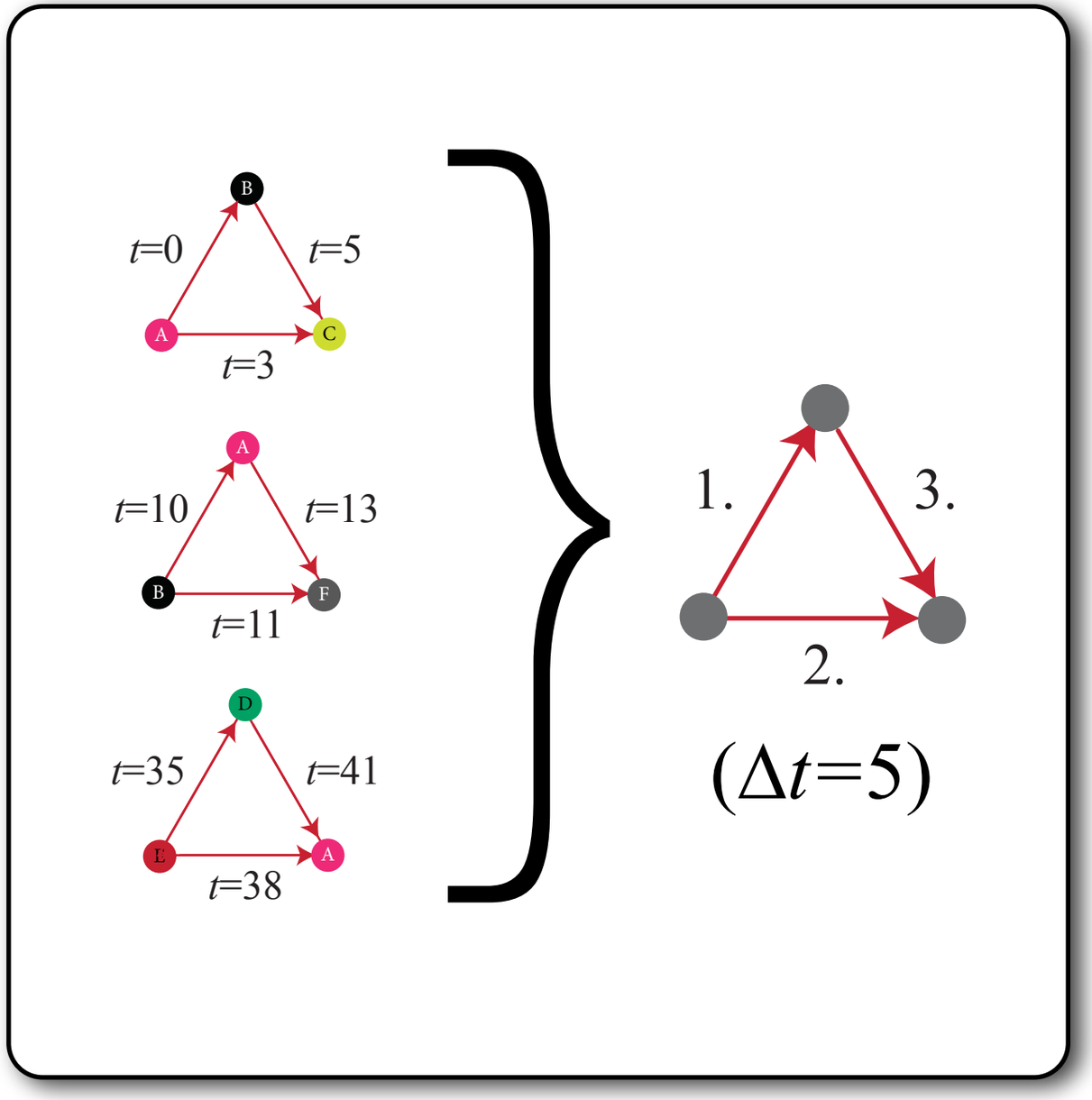
Δt-connected
for $\Delta t=5$

Temporal motifs: definition

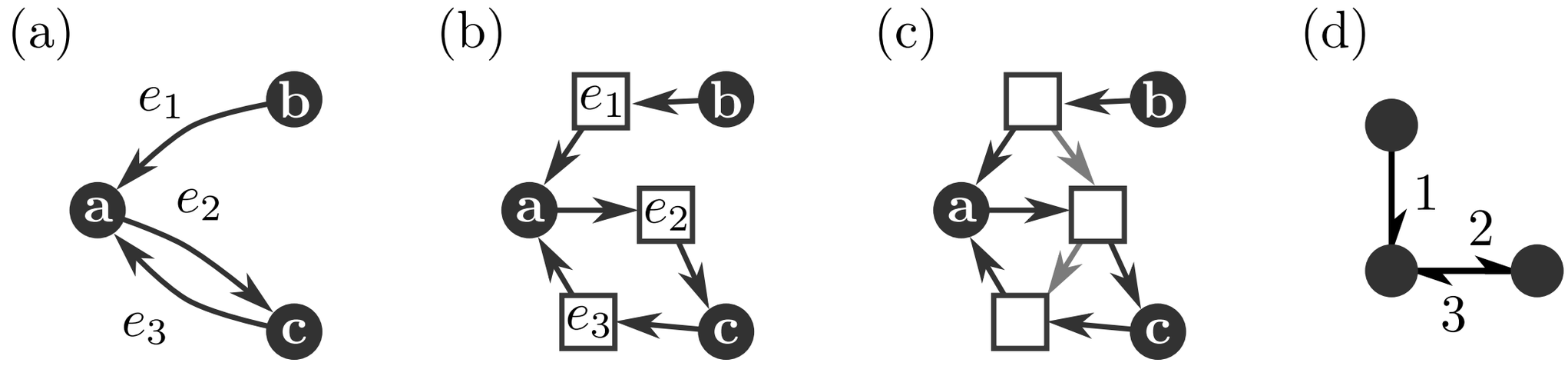
- **temporal motifs** = **equivalence classes** of **valid** temporal subgraphs

- equivalence: order of events matters, exact timings don't

- **valid** = no events are skipped at nodes



From subgraphs to equivalence classes



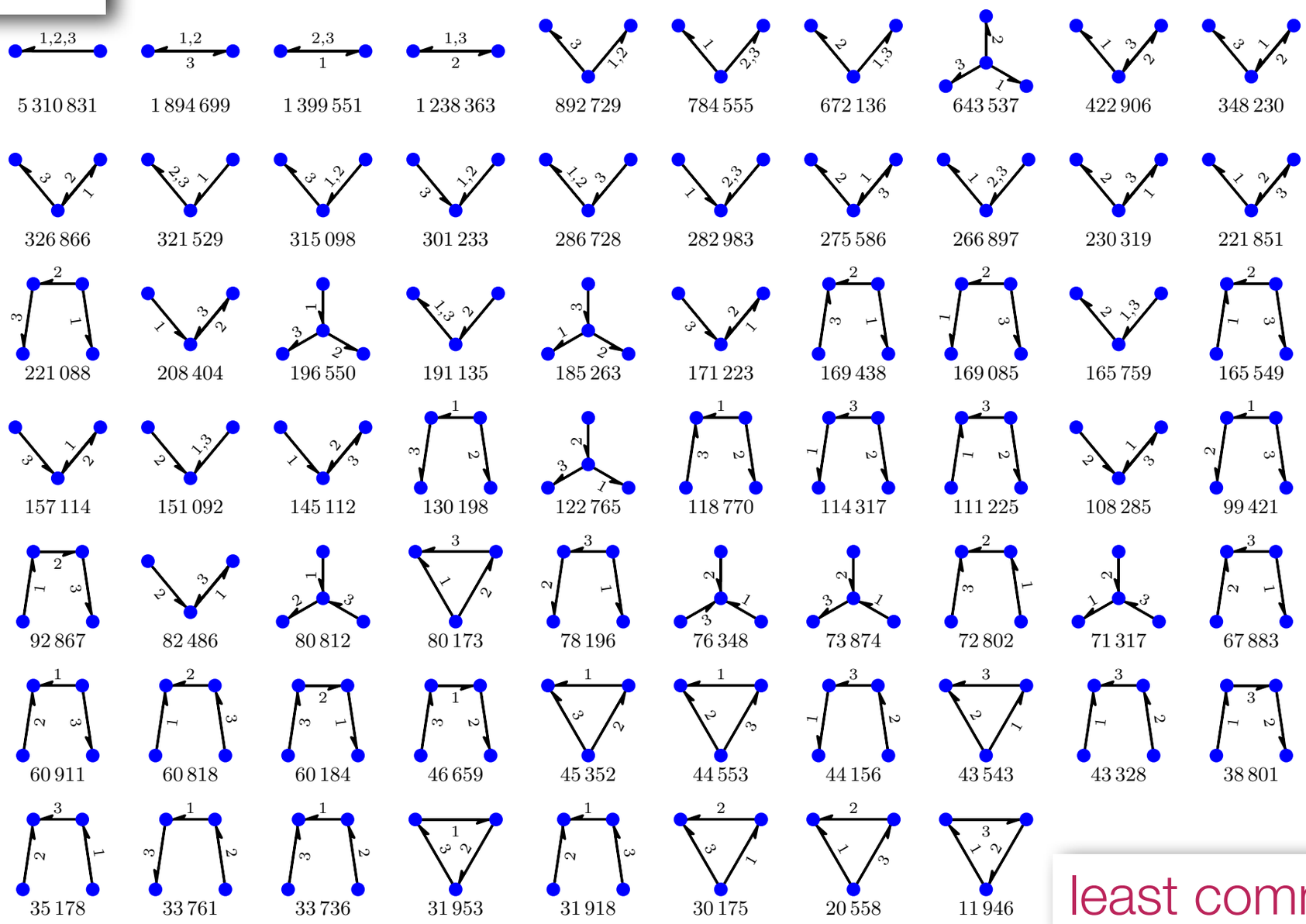
- Temporal subgraphs are mapped into directed, coloured graphs
- Isomorphism algorithms are used for assigning equivalence classes

See Kovanen et al., J Stat Mech P11005 (2011), arXiv:1107.5646 (2011)

Motifs in call data

most common

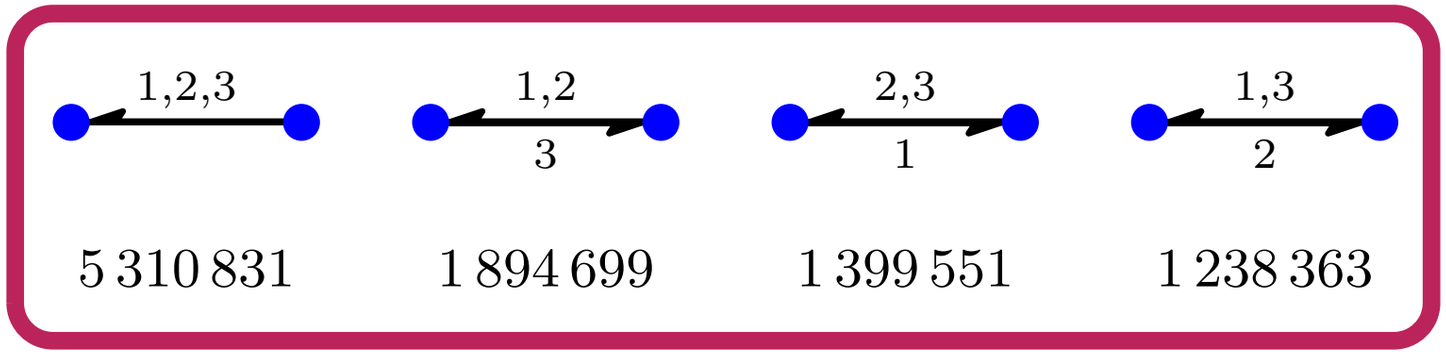
all 3-call motifs

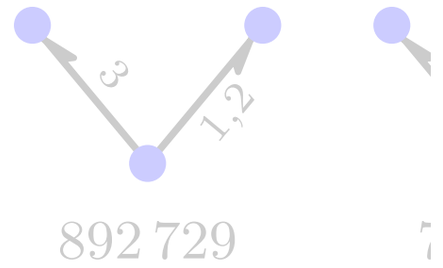


least common

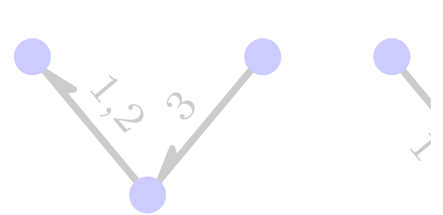
(motifs from ~320 mill. call events, with Δt=10 min → 35% of events are time-adjacent with some other event)

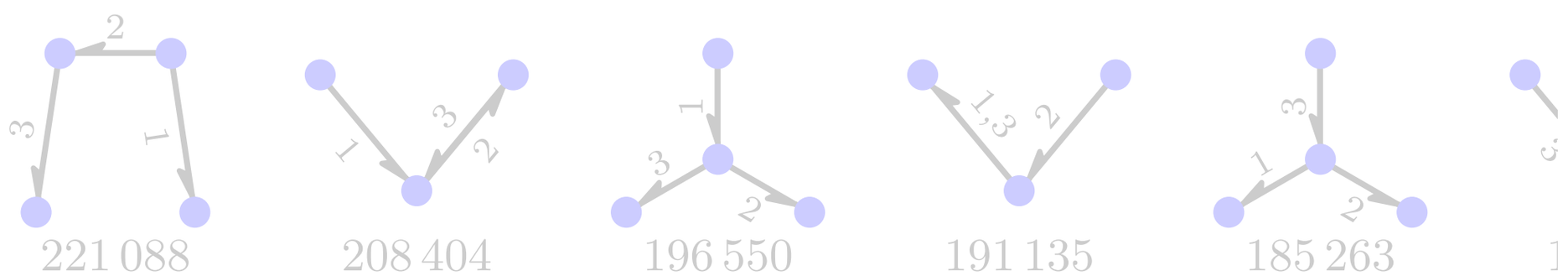
Motifs in call data



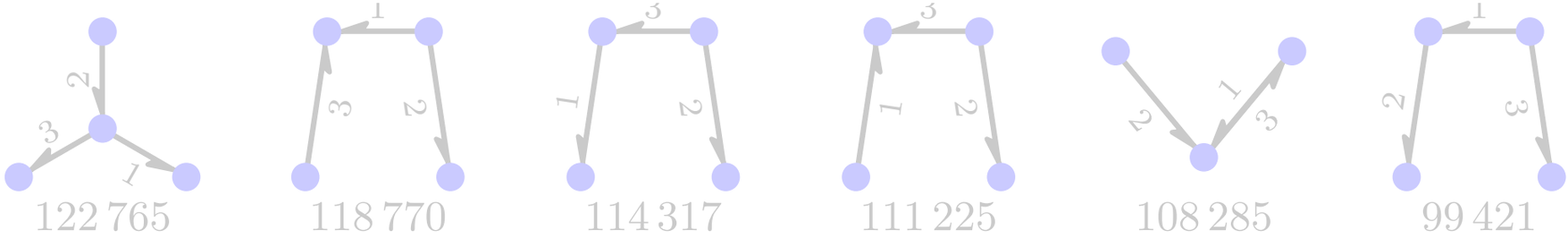


THE MOST COMMON MOTIFS REFLECT BURSTINESS





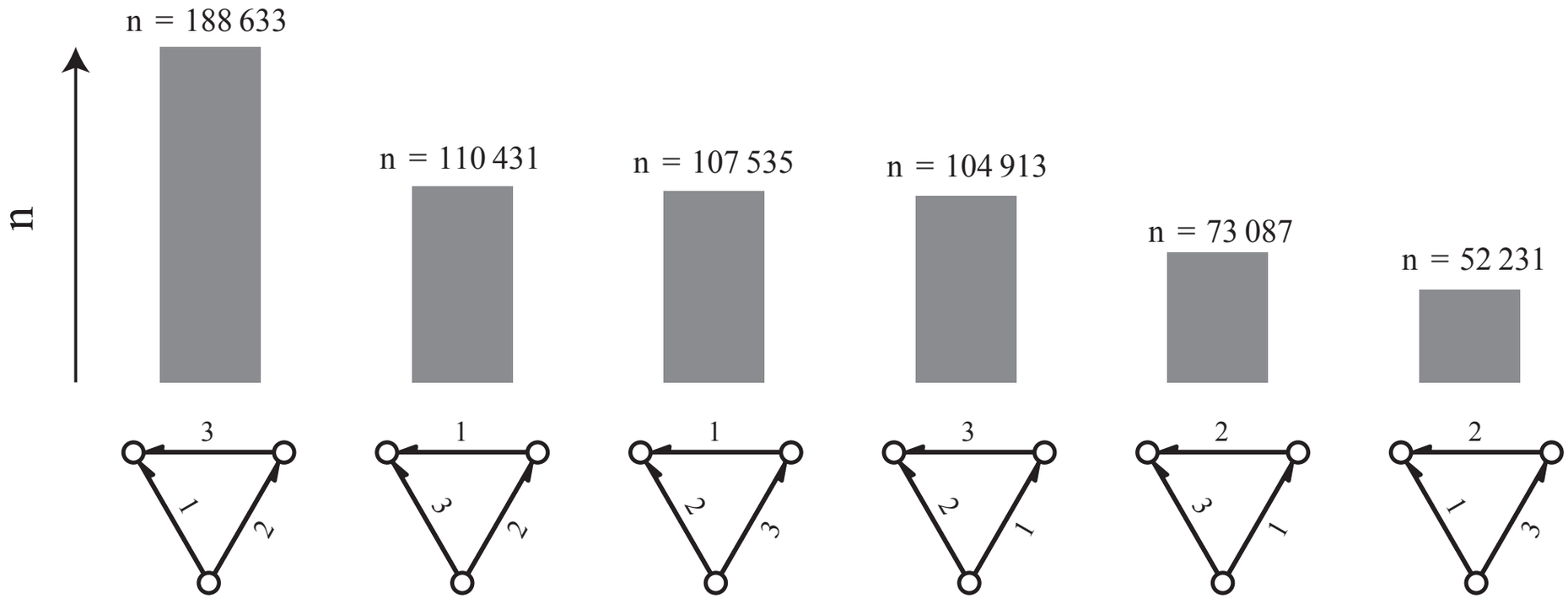
Motifs in call data



"A calls B, then C calls A, then B calls C"

THE LEAST COMMON MOTIFS ARE (probably) NOT CAUSAL SEQUENCES

triangular motifs in call data



“A calls B,
A calls C,
C calls B”

“A calls B,
C calls B,
A calls C”

THANK YOU!

Some related papers by the Aalto Complex Networks group:

- *Small but slow world: how network topology and burstiness slow down spreading*, M. Karsai, M. Kivelä, R. K. Pan, K. Kaski, J. Kertész, A.-L. Barabási, and J. Saramäki, Phys. Rev. E **83**, 025102(R) (2011)

- *Path lengths, correlations, and centrality in temporal networks*, R.K. Pan and J. Saramäki, Phys. Rev. E **84**, 016105 (2011)

- *Temporal motifs in time-dependent networks,* L. Kovanen, M. Karsai, K. Kaski, J. Kertész, and J. Saramäki, J. Stat. Mech. P11005 (2011), arXiv:1107.5646 (2011)

- *Multi-scale analysis of spreading in a large communication network*, M. Kivelä, R.K. Pan, K. Kaski, J. Kertész, J. Saramäki, and M. Karsai, J. Stat. Mech. P03005 (2012), arXiv:1112.4312

- *Temporal networks*, P. Holme and J. Saramäki, to appear in Physics Reports (2012), arXiv: 1108.1780 (2011)

- *Temporal motifs,* L. Kovanen, M. Karsai, K. Kaski, J. Kertész, and J. Saramäki, to appear in Temporal networks, eds. P. Holme and J. Saramäki, Springer Complexity Series

- *Universal features of correlated bursty behaviour*, M. Karsái, K. Kaski, A.-L. Barabási, J. Kertész, Scientific Reports 2, 397 (2012)