Temporal Networks

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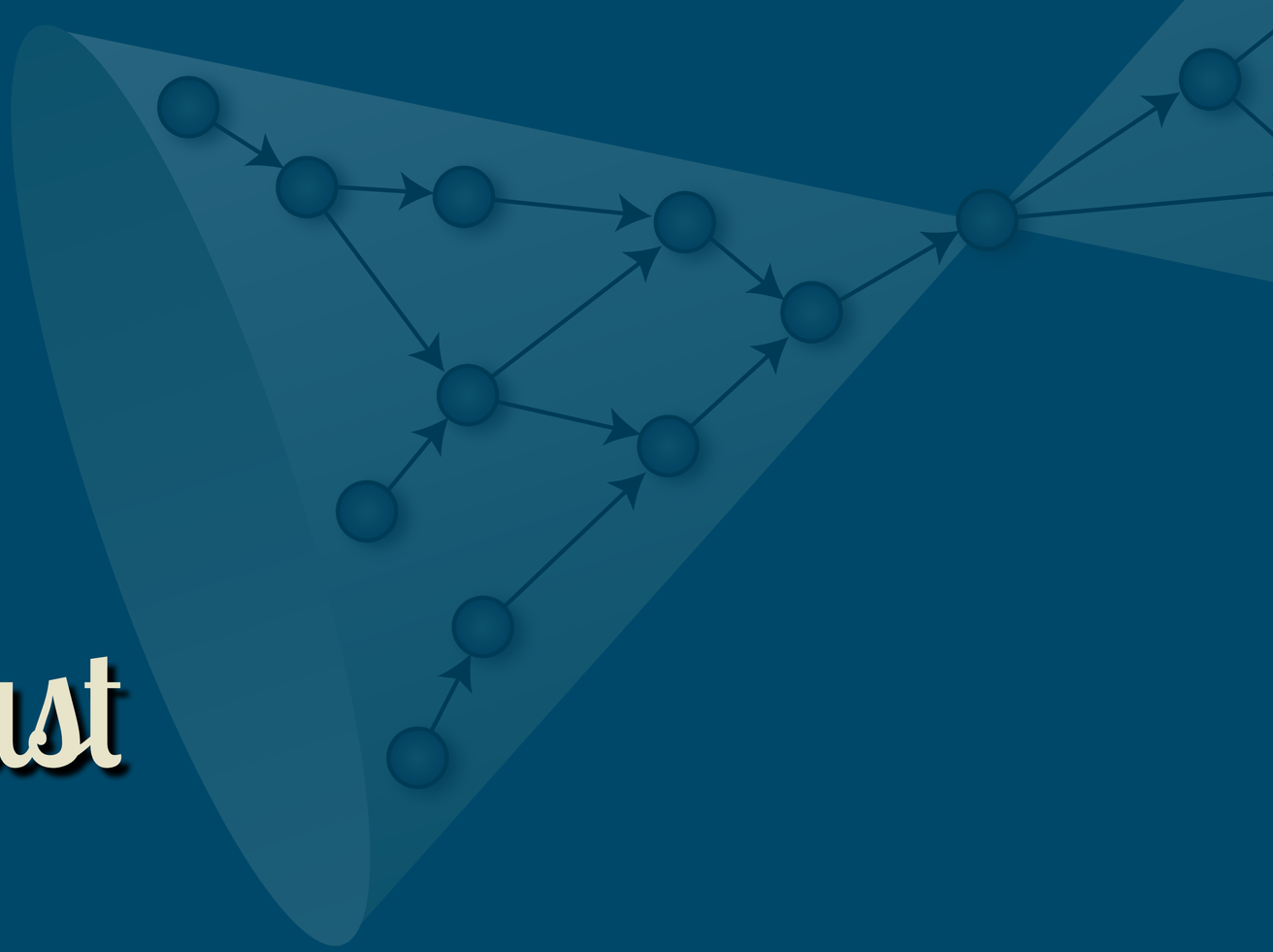
Aalto University, Finland

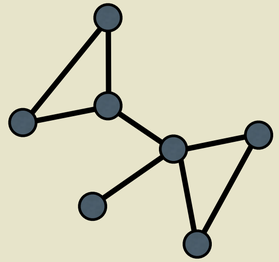
Complex Networks, Lisbon, 11.12.2019

1) Past



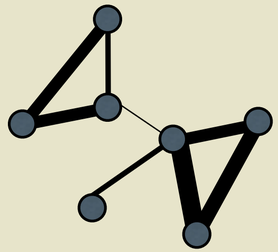
A brief history of network science

static, binary networks



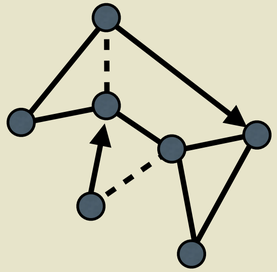
see e.g. Newman, SIAM review **45** (2003)

weighted networks



see e.g. Barrat et al, PNAS **101** (2004) 3747

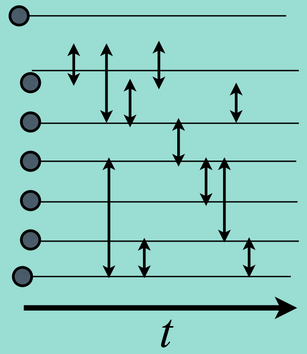
dynamic networks



see e.g. Gautreau et al, PNAS **106** 2009) 8847

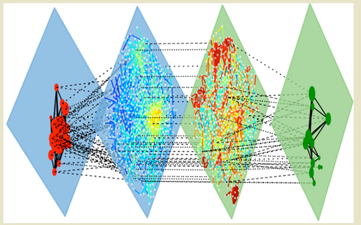
increasing level of detail

temporal networks



see e.g. Holme & Saramäki, Physics Reports **519** (2012)

multilayer networks



see e.g. Kivelä et al, J Complex Networks **2** (2014)

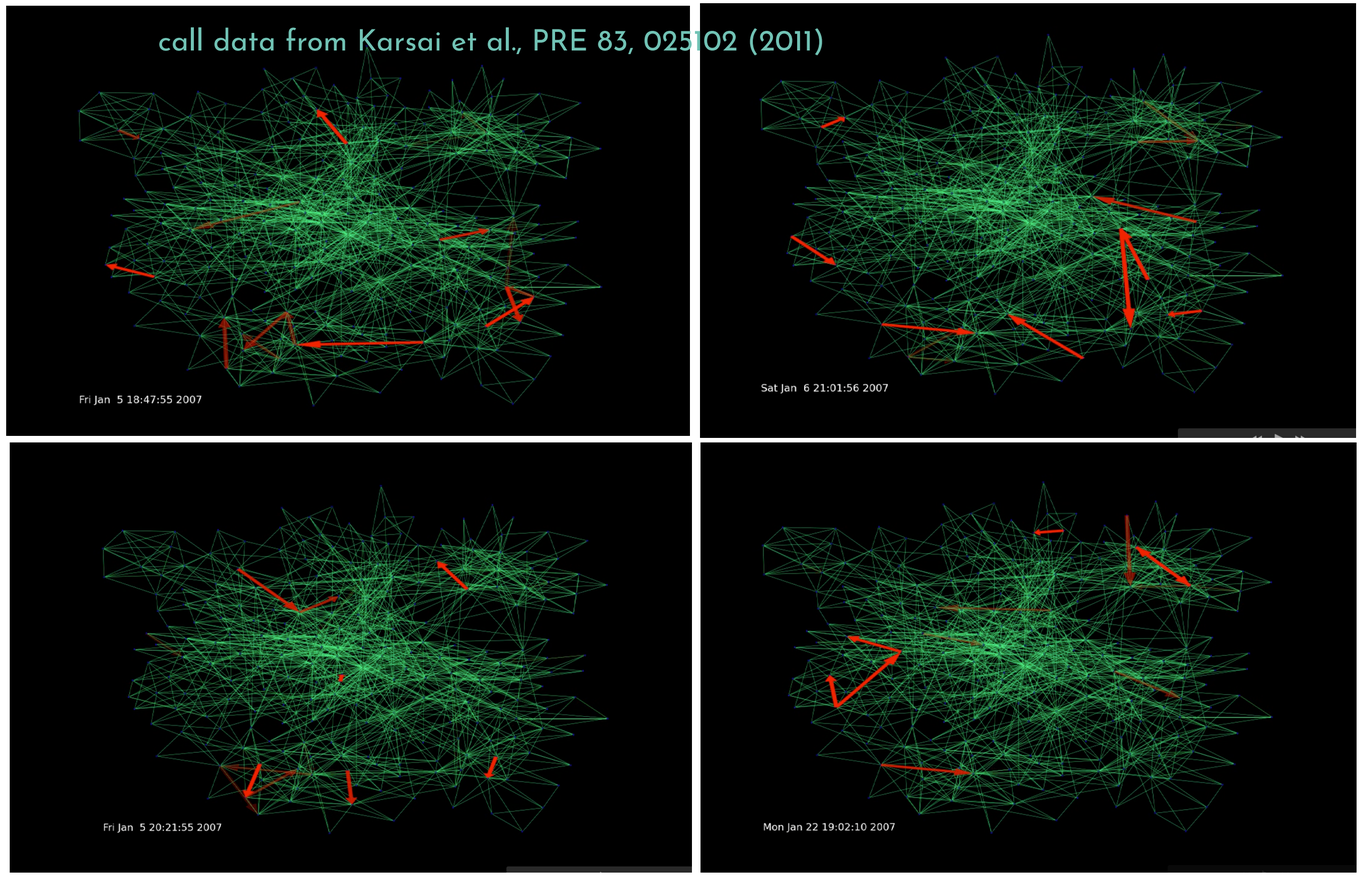
late 2000's & early 2010's:
Data with timestamps → temporal networks

Social interactions:

- Mobile phone calls, text messages (CDRs)
- Emails
- Online interactions
- Sexual encounters
- Proximity (SocioPatterns)

Other:

- Patient-referral/hospital data
- Transport data
- Cattle movement

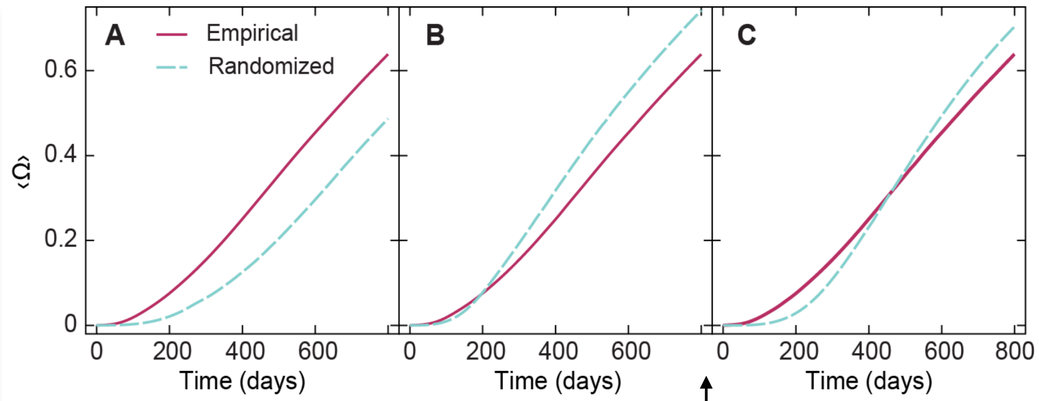


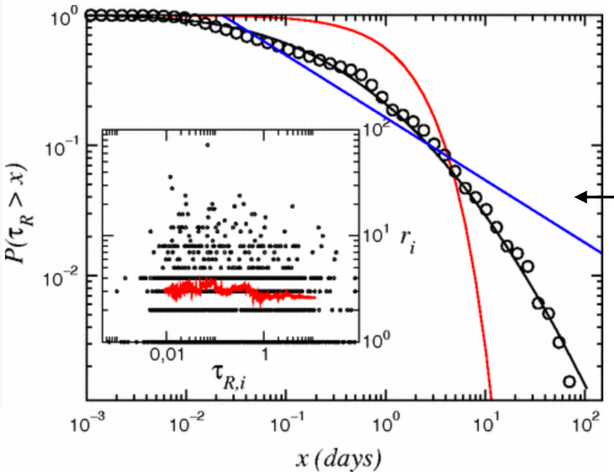
eg Vazquez et al., PRL 98, 158702 (2007) Iribarren & Moro, PRL 103, 038702 (2009) Iribarren & Moro, PRE 84, 046116 (2011) Rocha et al, PLoS Comp Biol 7, e1001109 (2011) Karsai et al., PRE 83, 025102 (2011)

Early temporal-network studies: why?

Two key motivations:

1. Because we have data and because we can!
2. Networks as lattices →spreading dynamics



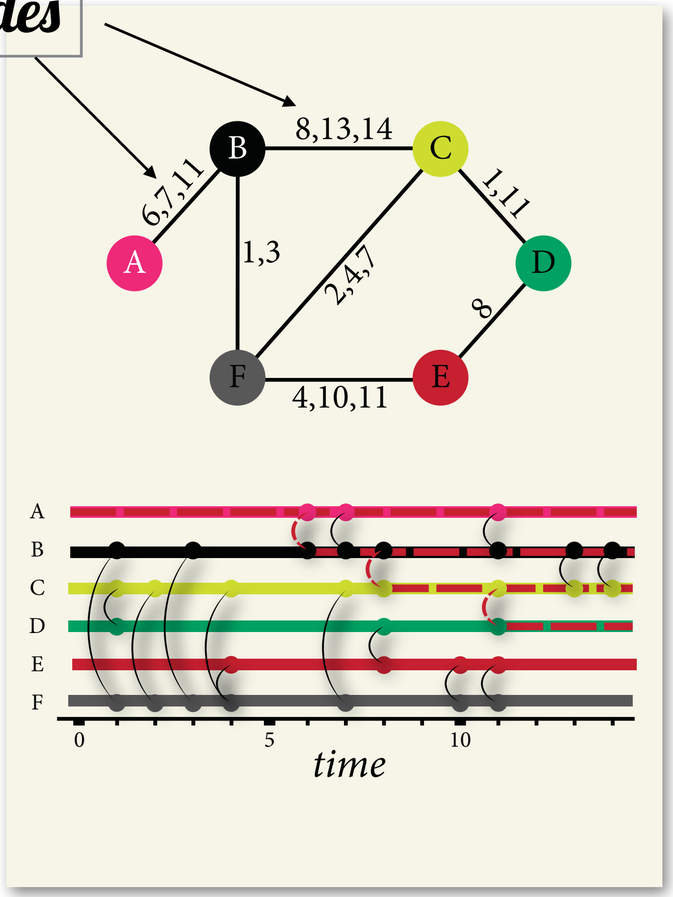


spreading curves from Rocha et al, Plos Comp Biol 2011

viral marketing response times from Iribarren & Moro, PRL 2009

Temporal networks are networks of events

repeated events between nodes

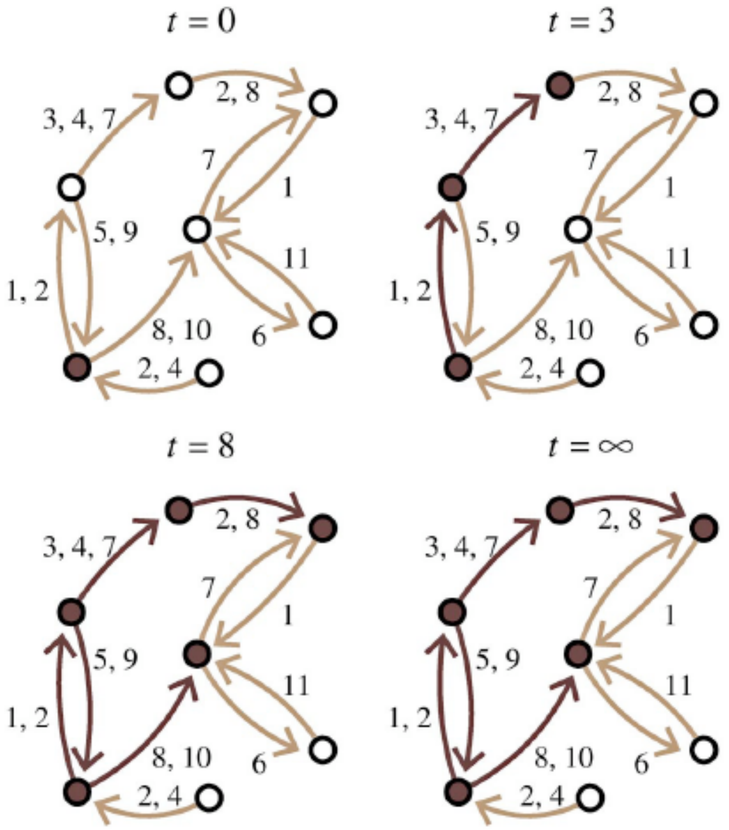


- A **temporal network** is a collection of **events** that link nodes at specified times
- Nodes only interact through events → their times determine everything...
- Because of this, simple representations (e.g. adjacency matrices) no longer work.

see P. Holme & J. Saramäki, *Temporal Networks*, Physics Reports 519 (2012)

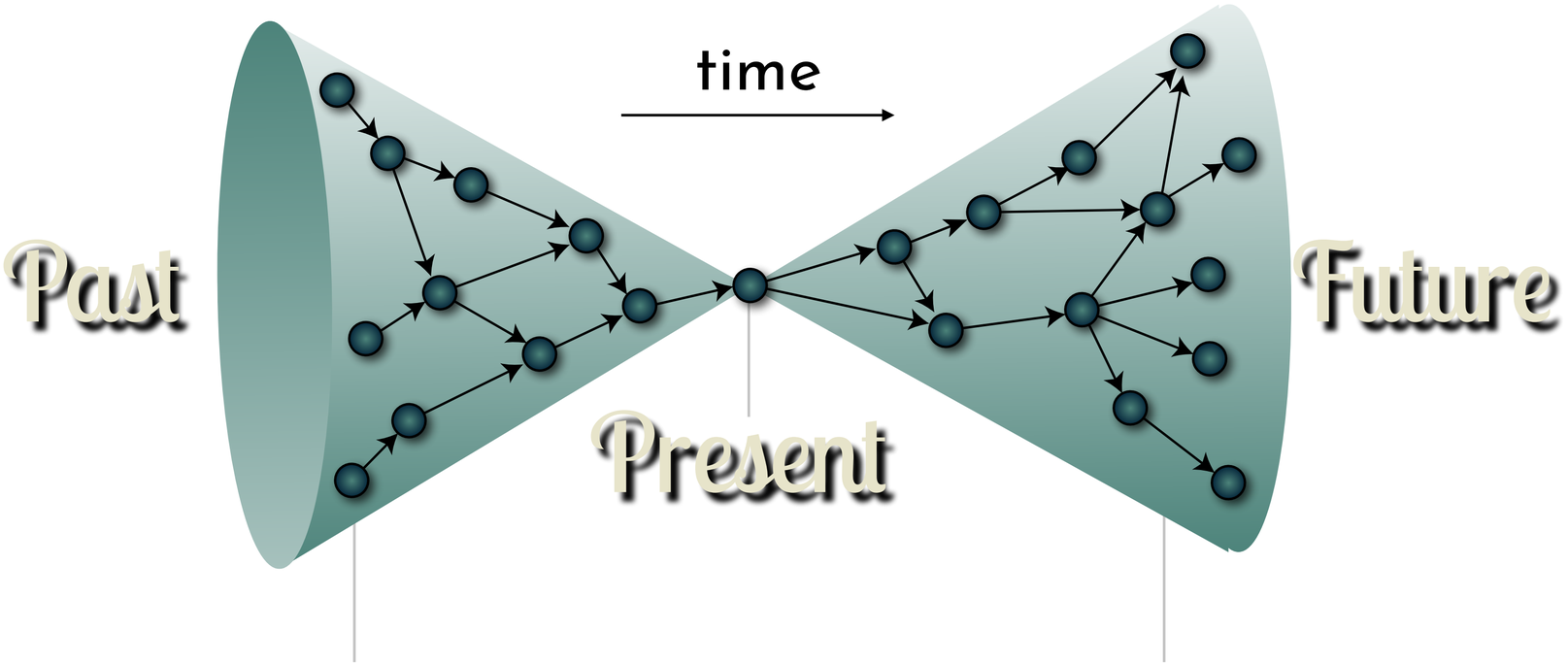
Event sequences determine time-respecting paths

- **Paths = temporal sequences of events** (that respect the direction of time)
- No transitivity, no reciprocity
- Paths exist in time:
  even if there is a path from i to j now, there might be none later.
- Paths take time to traverse;
  they have durations/latencies



P. Holme, Phys. Rev. E 71, 046119 (2005)

Causality: path durations & "light cones"



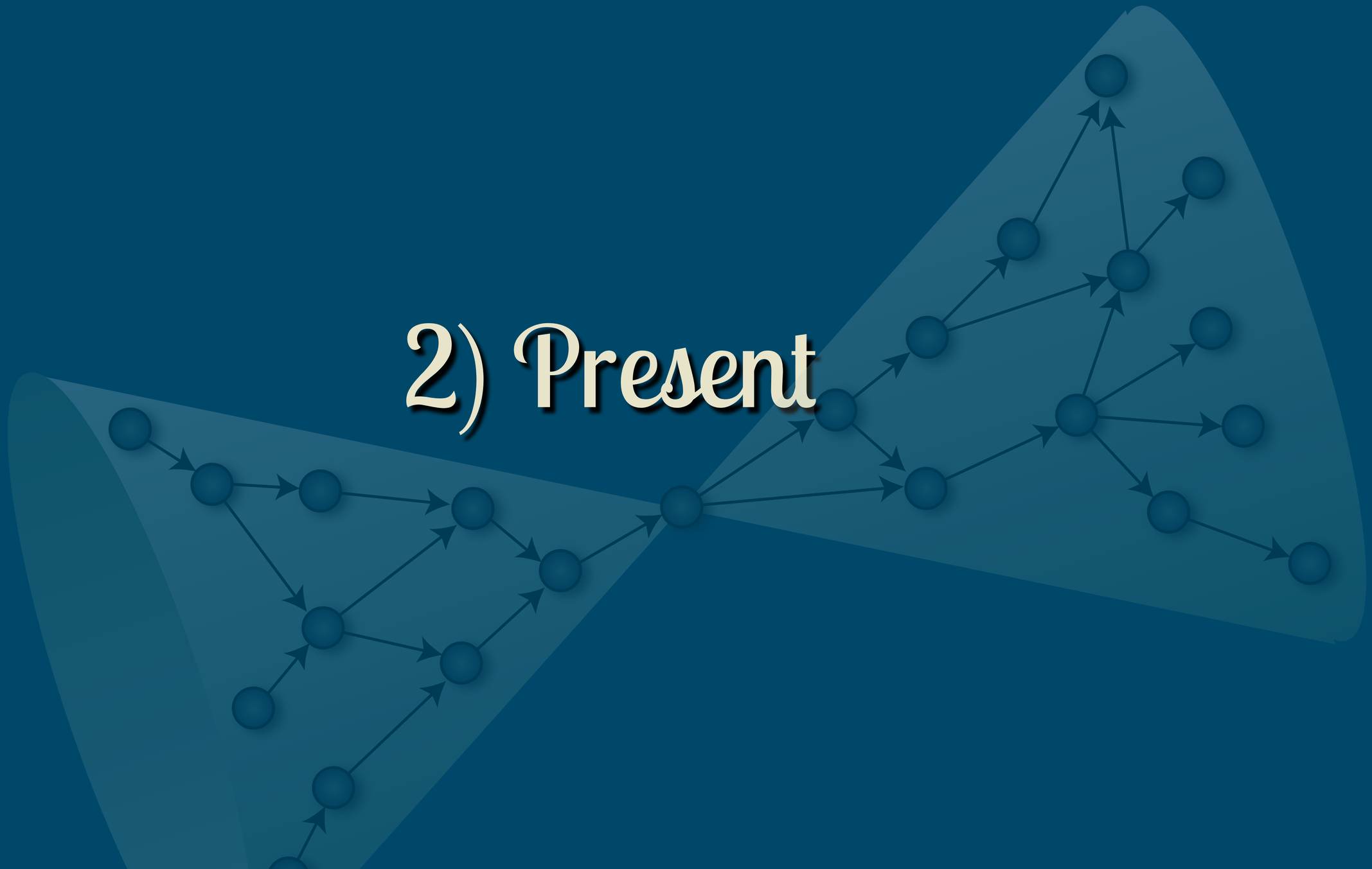
Only these sequences of events can influence focal node.

(A set of *nodetimes* that can influence focal node).

Focal node can influence others only through these sequences.

(A set of *nodetimes* that the focal node can influence in the future).

2) Present



What have people studied?

Early days

- Mobile phone calls, text messages (CDRs)
- Emails
- Online interactions
- Sexual encounters
- Proximity (SocioPatterns)
- Patient-referral/hospital data
- Transport data
- Cattle movement

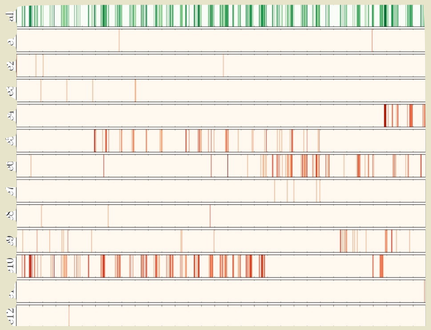
Since then

- Animal networks
- Bike sharing
- Brain networks
- Scientific collaborations
- Bitcoin transactions
- Biological networks
- Archaeological networks
- Networks of narratives
- Investor networks
- Ecological networks
- And many other systems…

What have we learned by 2019?

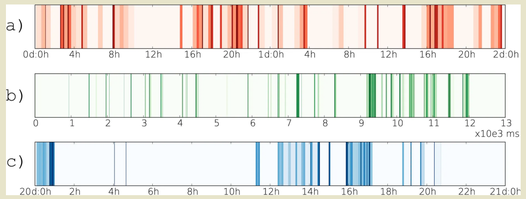
That there are lots of ***temporal inhomogeneities***
that contain information and affect dynamics.

Burstiness



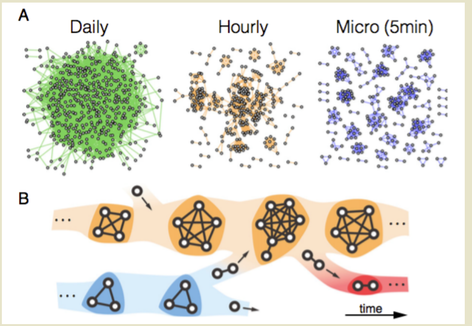
Karsai et al, PLoS One 7, e40612 (2012)

Correlated event times



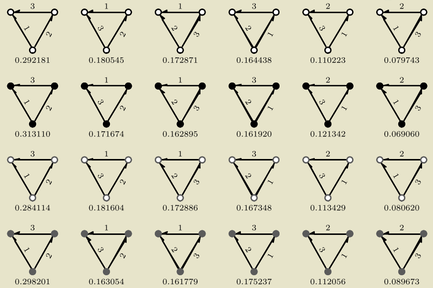
Karsai et al., Sci Rep 2, 397 (2012)

Mesoscopic features



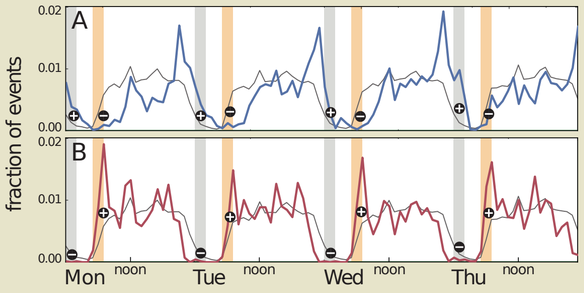
Sekara et al, PNAS 113, 9977 (2016)

Temporal motifs



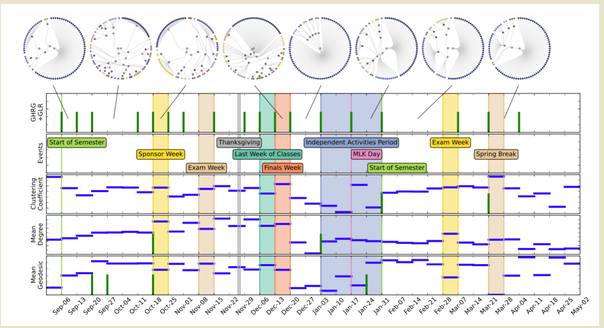
Kovanen et al. in Temporal Networks
(eds. P. Holme & J: Saramäki) (2013)

Daily patterns



Aledavood et al., EPJ Data Sci 7, 46 (2018)

Change points



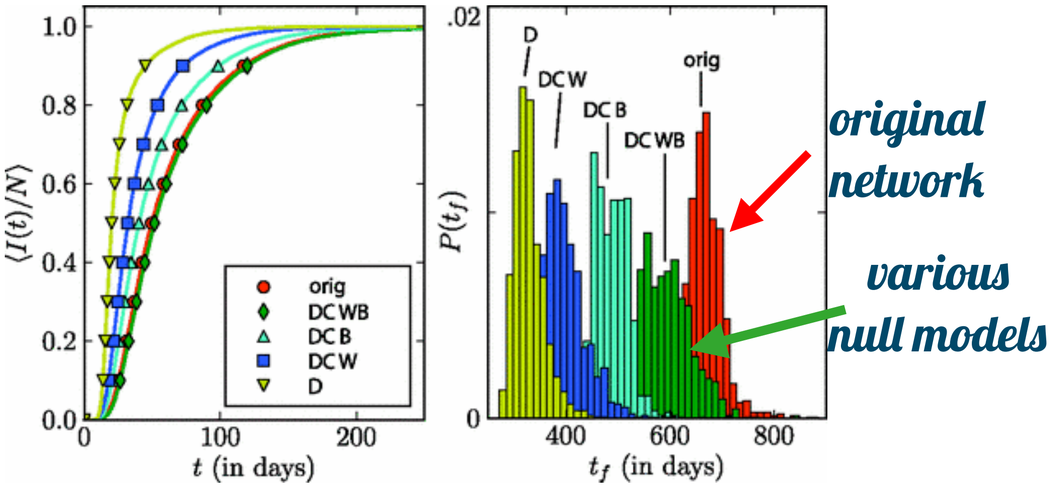
Peel & Clauset, Proc of the 29th AAAI Conf.
on Artificial Intelligence, 2015

Example: Burstiness & Spreading

- Early result: burstiness slows down spreading dynamics
- But, unfortunately, it is **more complicated** than that…
- Horváth & Kertész 2015: *"We have demonstrated that the question of the speed of spreading is a complex one. The IETD, the topology and the age of the temporal process have all impact on it"*
- Delvenne & Lambiotte 2015 (Random walks): *"Except for SEX42 and POK data sets, in the other cases the temporal heterogeneity substantially increases the mixing times (see slowdown factor Θ in Table 1). Table 2 shows that in these networks the dominant factor regulating the mixing time depends on the characteristics of the system. Fat tails of the waiting-time distribution drive the relaxation for the cases of face-to-face contacts (SPM, SPC and SPH). However, the structure is the leading mechanism behind the networks corresponding to other situations of human communication (EMA, SEX and POK)."*

No simple explanations; summary: "it depends."

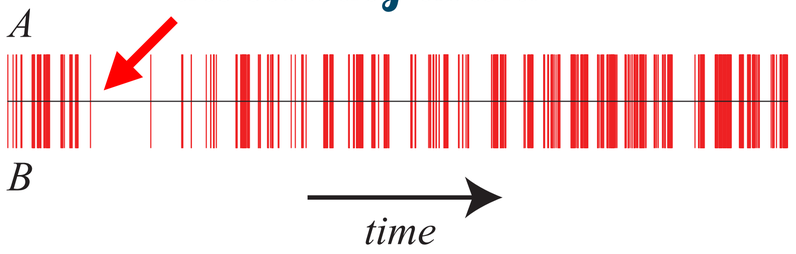
Karsai et al., PRE 83, 025102 (2011)



original network

various null models

these gaps are behind the slowing-down.



Epidemic Thresholds

Many studies:

TEMPORAL NET MODEL ∈{activity-driven, random, ...}

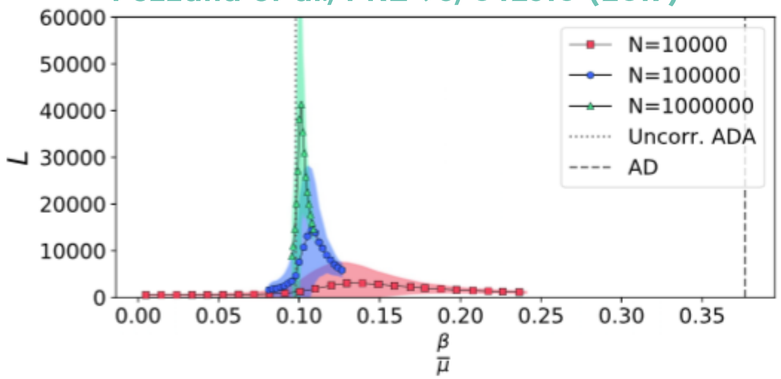
X

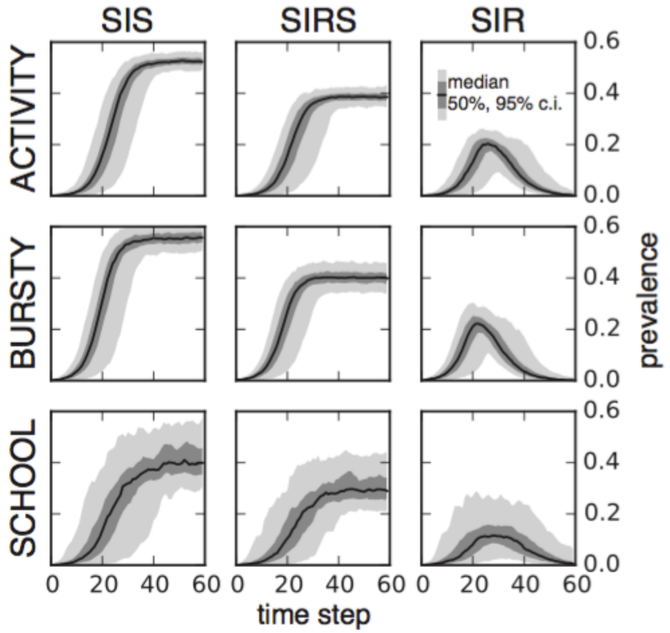
SPREADING MODEL ∈{SI, SIS, SIR, ...}

Outcome so far:
no big, single, universal result

...except that most of the time, time matters!

Pozzana et al., PRE 96, 042310 (2017)





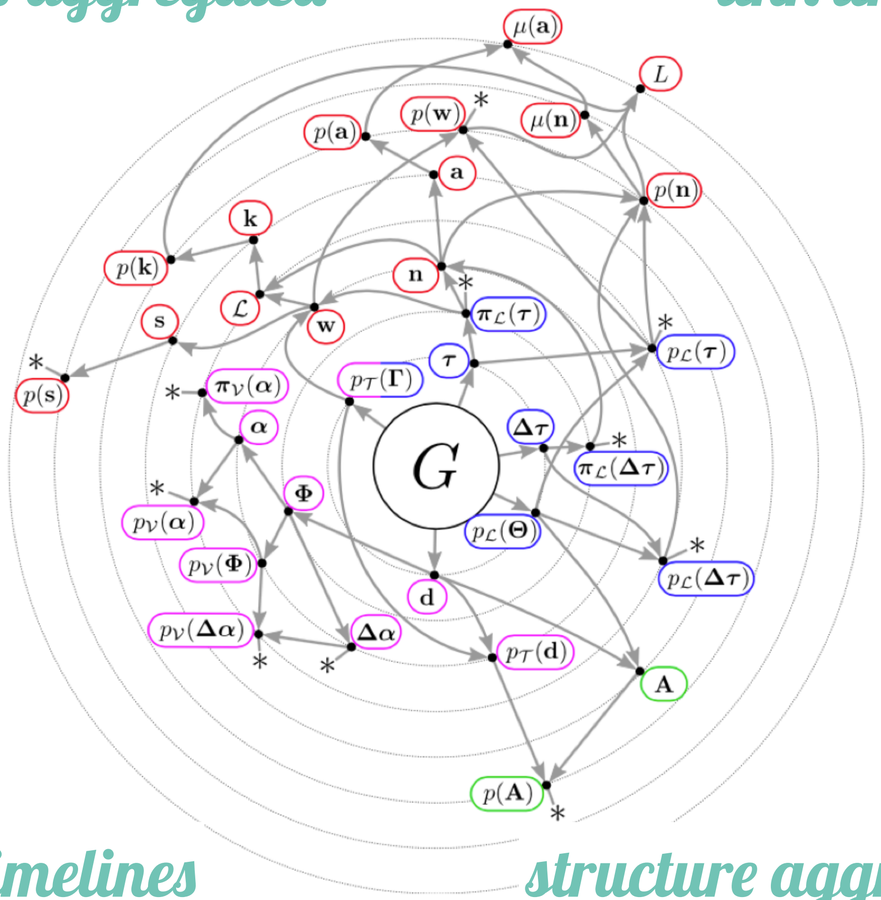
Valdano et al., Eur. Phys. J. B (2015) 88: 341

Temporal Reference models

- Randomize/shuffle temporal networks in ways that retain some temporal and/or structural features and destroy others
- Main outcome: **it's complicated...**
- This is (partially) behind the lack of universal results.

time aggregated

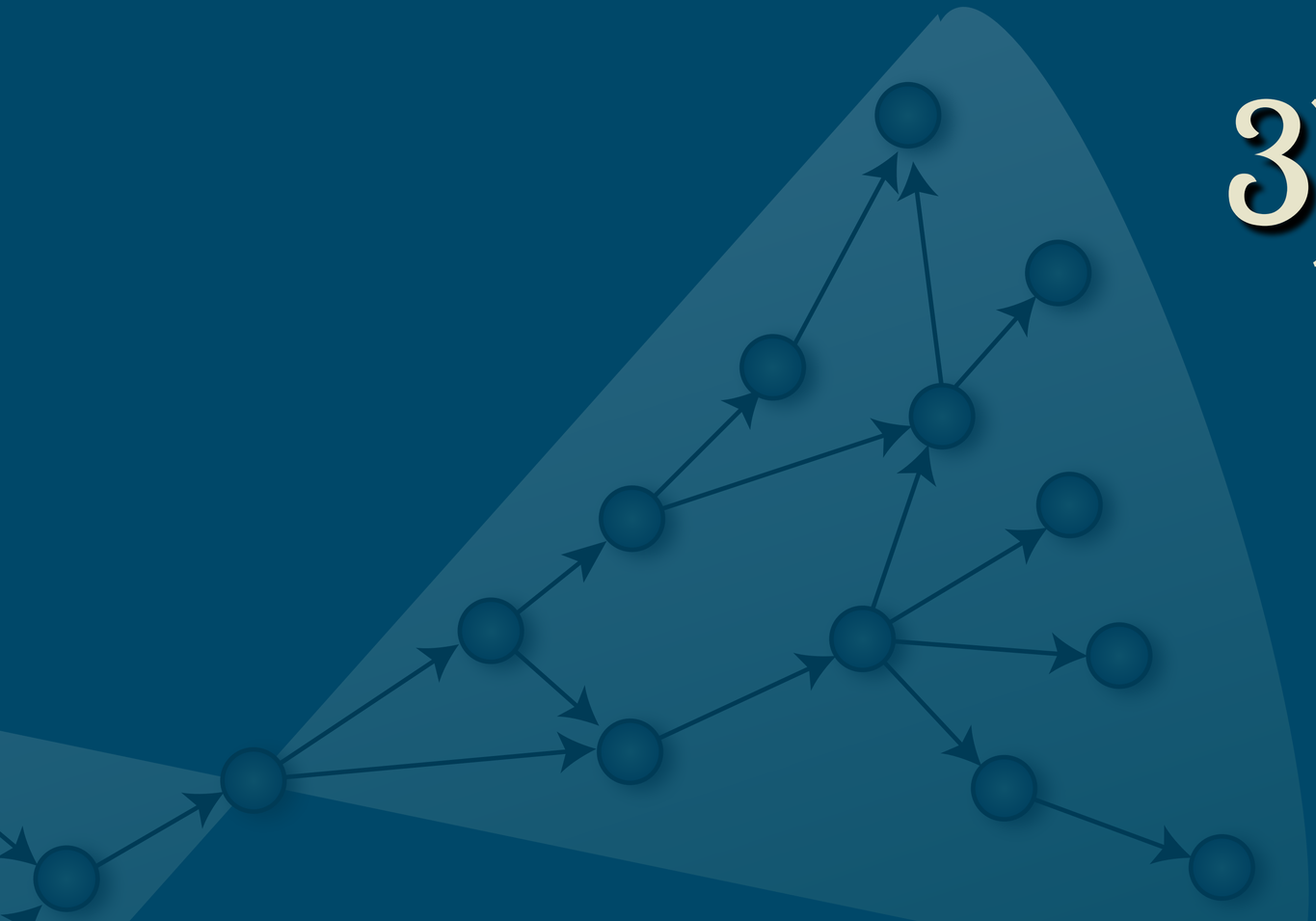
link timelines



node timelines

structure aggregated

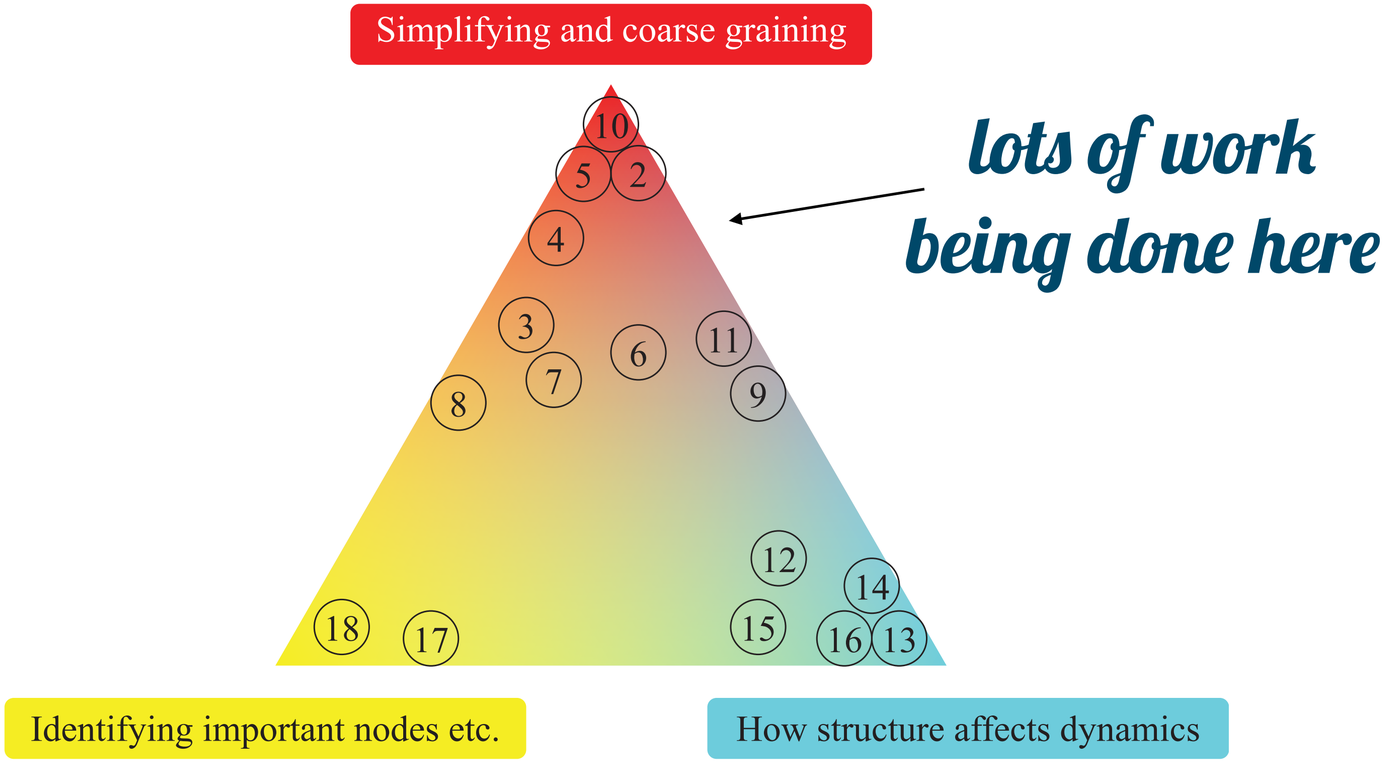
From Gauvin et al, arXiv:1806.04032



3) Future

(One possible) map of approaches

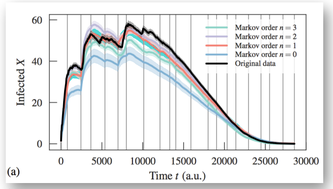
Map of the chapters of our recent book, Temporal Network Theory (Springer, 2019)

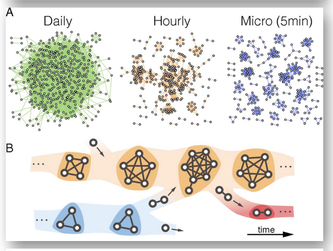


P. Holme & J. Saramäki (eds), *Temporal Network Theory*, Springer (2019)

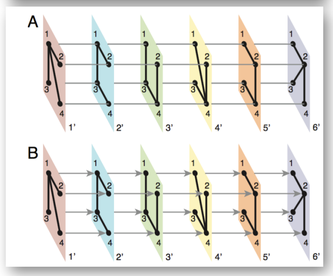
Current trends: simplifying/coarse-graining

- Higher-order models
- Mesoscopic models/ structures
- Multilayer/multiplex representations
- Event graphs

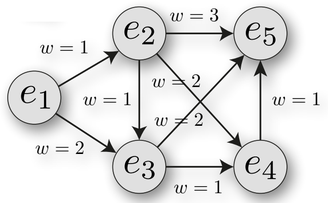




e.g. Lambiotte, Rosvall, Scholtes, Perspective in Nat. Phys. 15, 313 (2019)
Peixoto, Gauvin, Sci. Rep. 8 15511 (2018)
Peixoto, Rosvall, Nat. Comm. 8, 582 (2017)
Sekara, Stopczynski, Lehmann, PNAS 113, 9977 (2016)
Galimberti et al., CIKM 2018

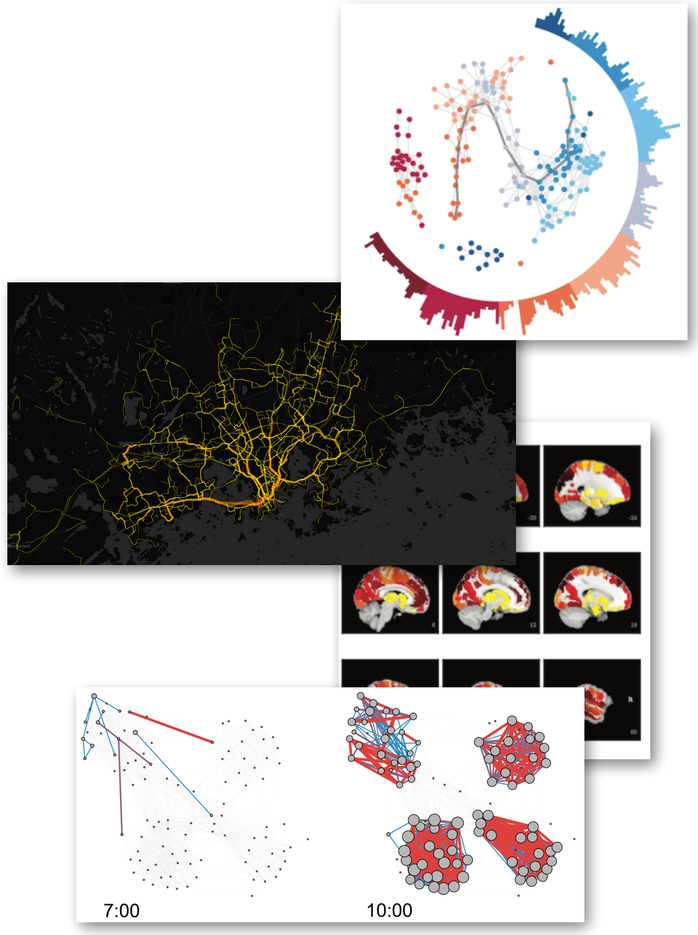


e.g. Taylor, Porter, Mucha in Temporal Network Theory (2019), arXiv:1904.02059, arXiv:1906.06366



e.g. Mellor, J Compl Netw 6, 639 (2017)
Kivelä, Cambe, Saramäki, Karsai, Sci Rep 8, 12357 (2018)
Saramäki, Kivelä, Karsai in Temporal Network Theory (2019)

Current trends: data-driven applications

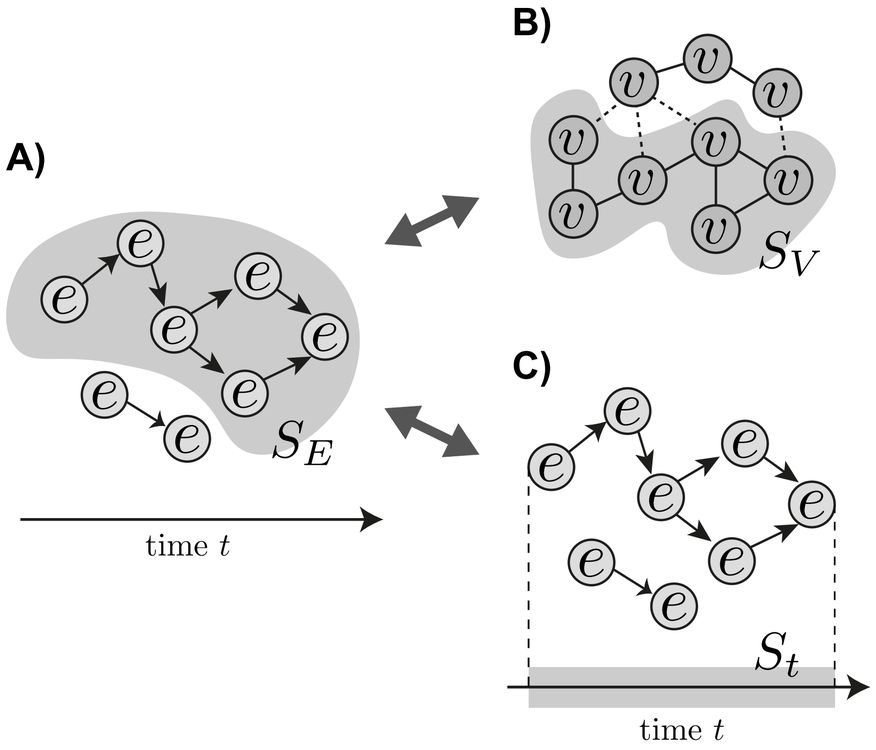


Some examples

- RFIDs: Sociopatterns
  (Face-to-face human interactions, even animal networks!)
  https://sociopatterns.org/
- Transport data sets
  e.g. Gallotti & Barthelemy, Sci Data 2, 140056 (2015)
  Kujala et al, Sci Data 5, 180089 (2018)
- Brain imaging data
  e.g. ABIDE I & II
- Various smartphone tracking experiments
  e.g. SensibleDTU
  ...but no publicly available data
- Hospital referrals
  work underway in the Nordics
  ...but no publicly available data

Knowledge gap: percolation & component structure

- Temporal-network percolation not even conceptually ready
- My take: components are events (that map to nodetimes)
- Event graphs may help

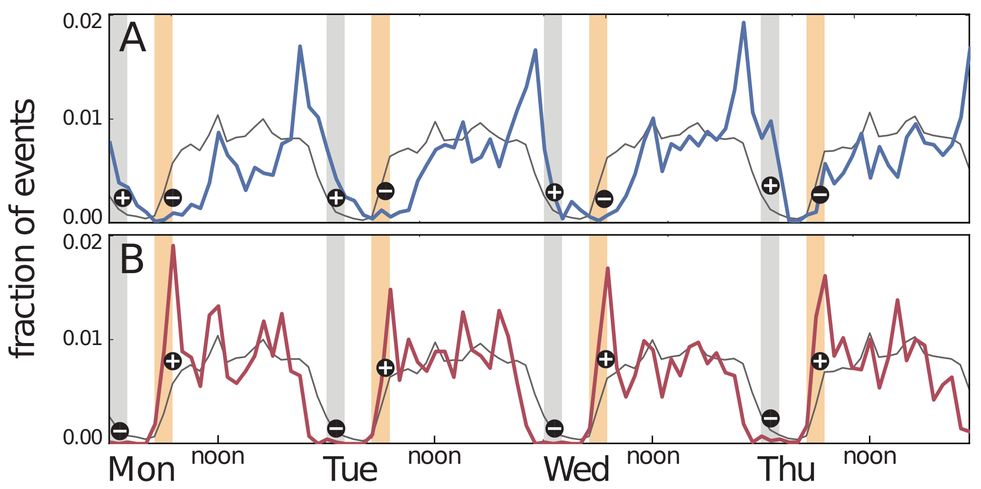


Saramäki, Kivelä, Karsai in Temporal Network Theory (2019), http://arxiv.org/abs/1912.03904

Knowledge gap: extracting information from event times

- "Traditional" temporal network view: networks = lattices that affect dynamics
- But the **times of events contain lots of information on** various dynamics
- E.g.: use time series of events to understand people's behavioural patterns & individual differences

example: circadian rhythms from phone use

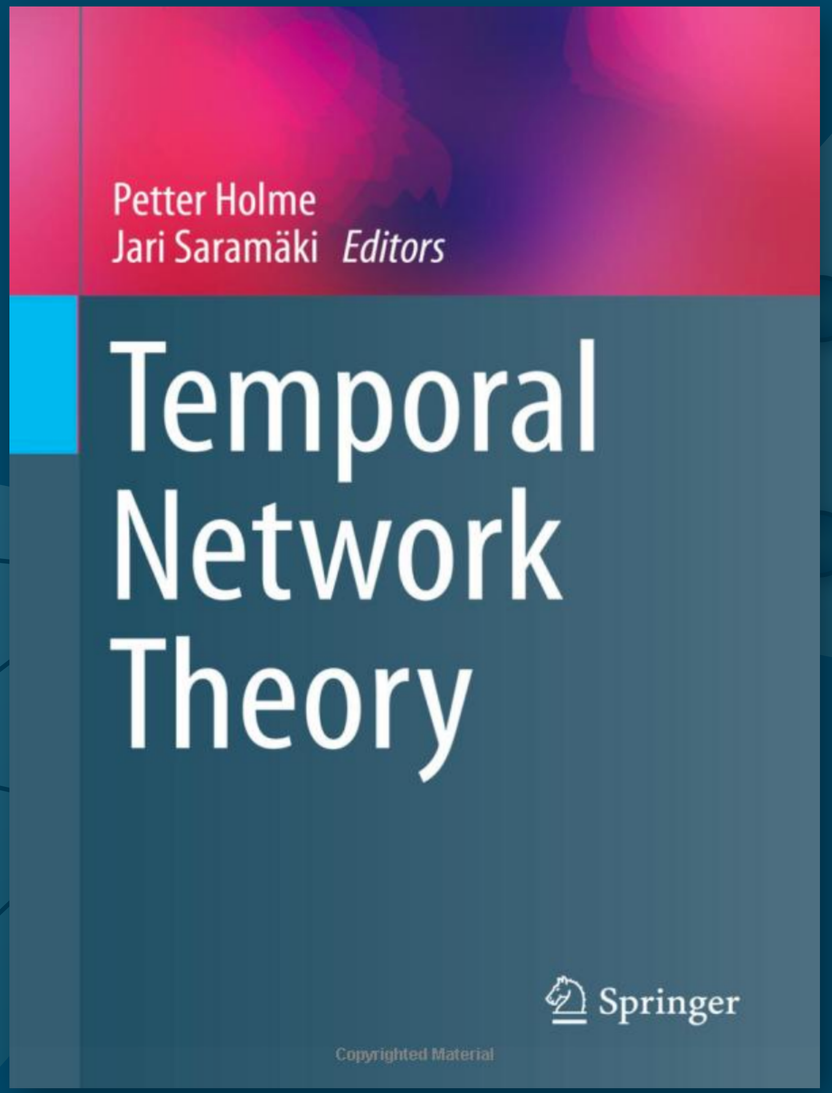


Aledavood et al., EPJ Data Sci 7, 46 (2018)

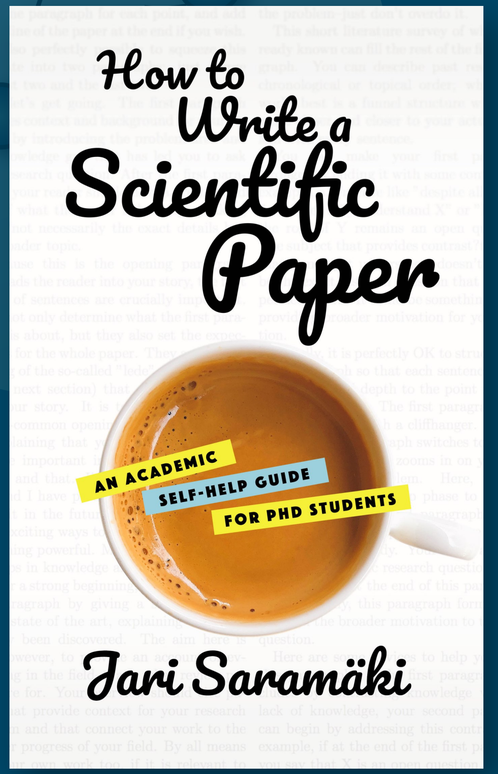
Thank You!

- For these slides, go to https://jarisaramaki.fi/
- Follow me on Twitter: @JariSaramaki

BOOKS:



https://amazon.com/dp/3030234940/



https://www.amazon.com/dp/B07K1C2K23