



POTSDAM INSTITUTE FOR
CLIMATE IMPACT RESEARCH

STABILITY AND RESILIENCE OF POWER GRIDS

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Anton Plietzsch, Frank Hellmann, Sabine Auer, Peng Ji,
Stefan Schinkel, Carsten Grabow, Kirsten Kleis,
Jürgen Kurths, Hans-Joachim Schellnhuber

OVERVIEW

Power Grid Stability & Resilience in face of Climate Change

Stability and Resilience of Complex Systems

Network Basin Stability applied to Power Grids

Complex Networks Analysis of Power Grids

Smart Wiring



1. Power Grid Stability & Resilience in face of Climate Change

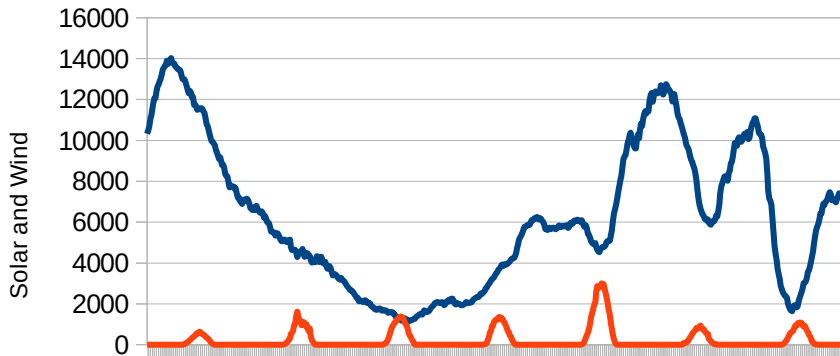


POWER GRID STABILITY AND MITIGATION OF CLIMATE CHANGE

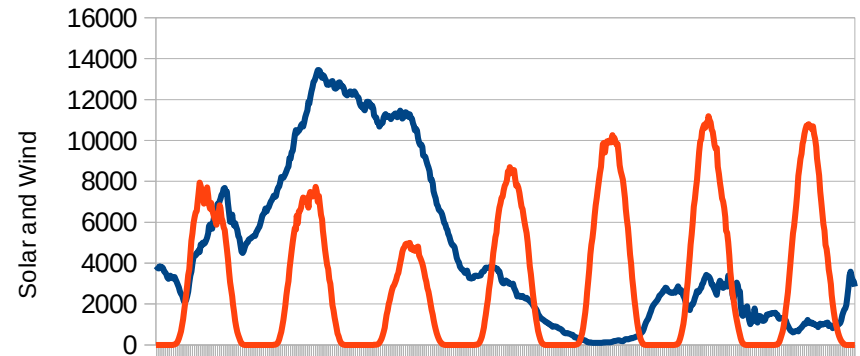
- Mitigation (GHG emissions reduction) requires **renewable energy**
- Renewable energy generation **fluctuates** strongly
 - wind strength/direction, sunshine, cloudiness may vary fast
- Large fluctuations must not **destabilize** the power grid!
- *Make grid stable under largely fluctuating generation!*

FLUCTUATING RENEWABLE GENERATION

Aggregate solar and wind production in Germany:



First week of 2011



Middle Week in 2011

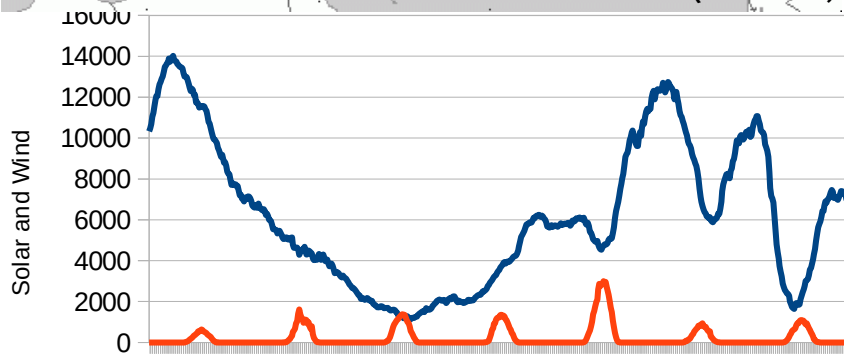
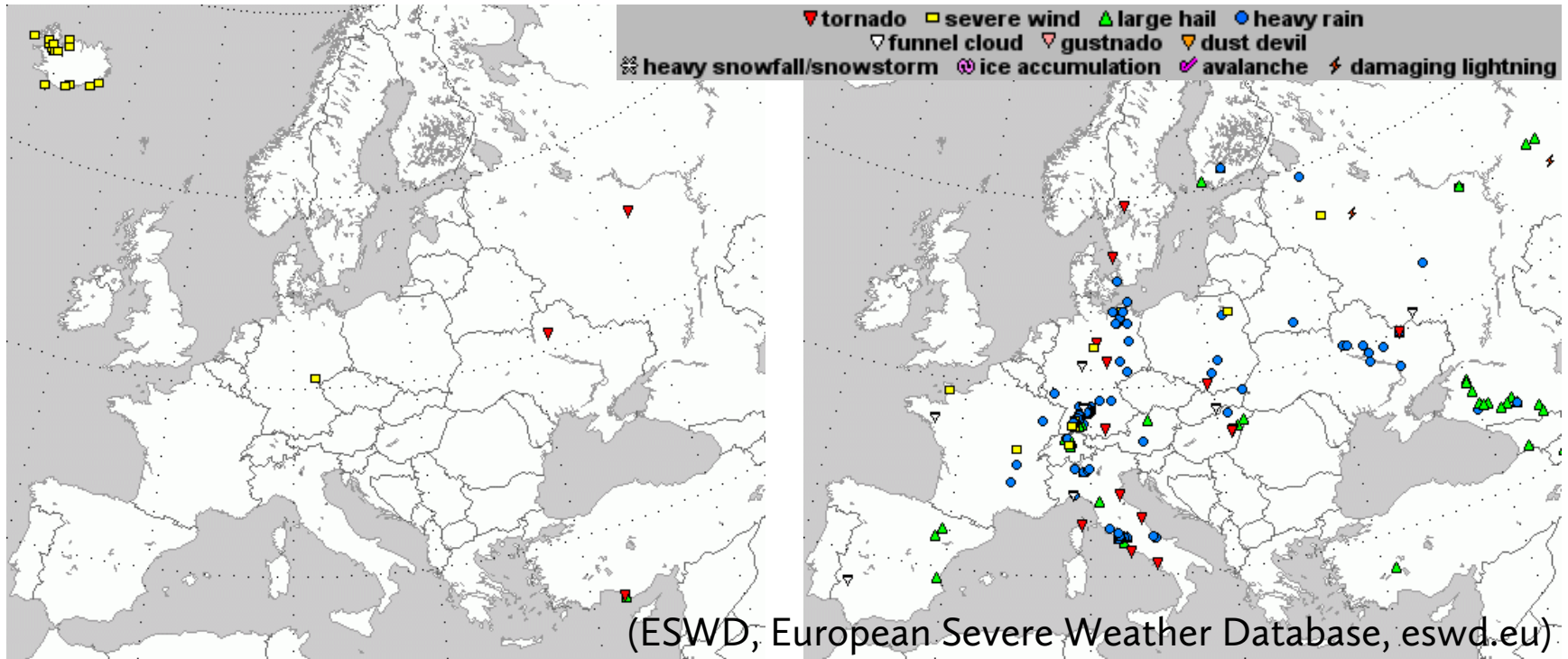
(data provided by grid operators
50Hertz, Amprion, Tennet, and TransnetBW)

(Additional regional fluctuations not shown here)

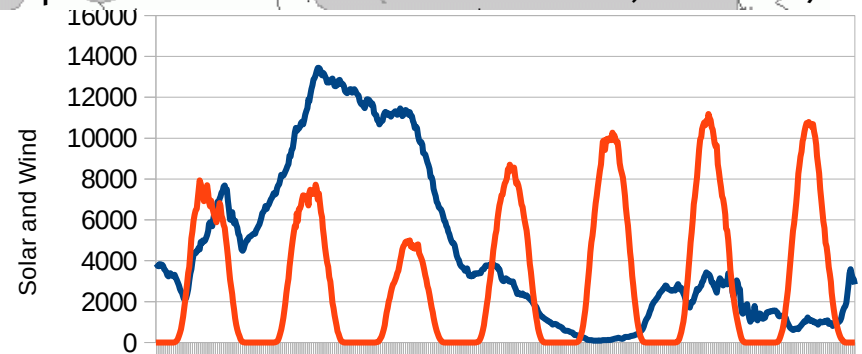
POWER GRID RESILIENCE AND ADAPTATION OF CLIMATE CHANGE

- Climate change will increase frequency and severity of **extreme weather events**
 - **large (local) perturbation** in a power grid
 - local transmission line trips → **redistribution** of power flow
 - If grid is not resilient (cannot cope with the redistribution), further lines trip → **cascading failure** → interregional **blackout!**
 - *Make grid resilient to perturbations of all magnitudes!*

EXTREME WEATHER EVENTS



First week of 2011



Middle Week in 2011

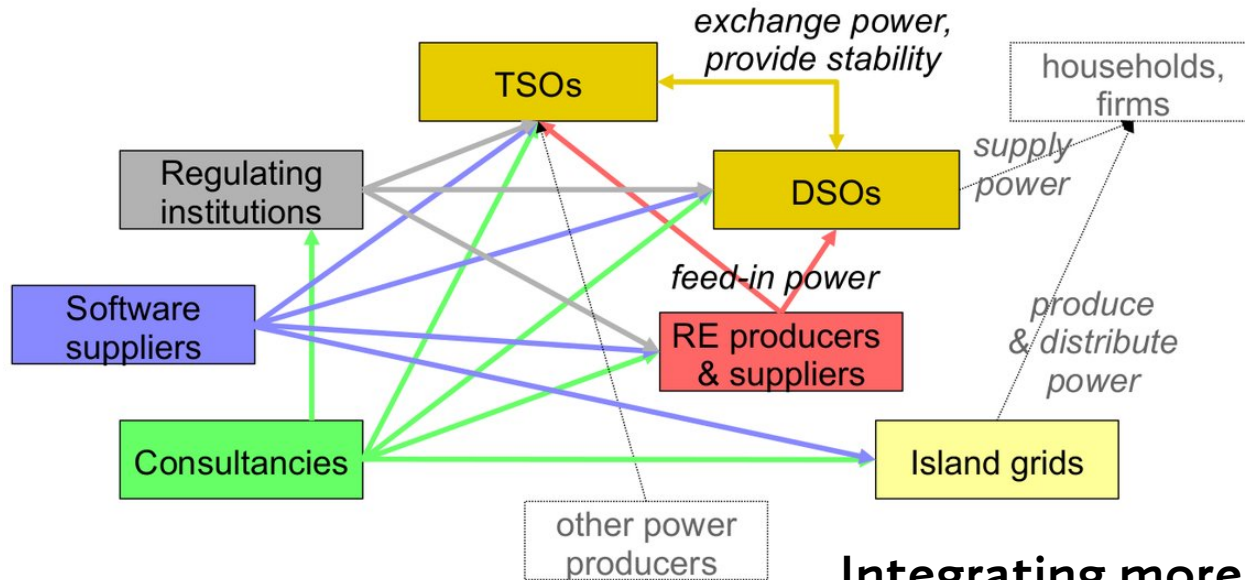
STAKEHOLDER ISSUES

Integrated systemic assessment

- interactions with other energy systems/infrastructure
- “system services”

Increasing fluctuations/dynamics

- temporary supply/demand mismatches
- novel control mechanism
- storage



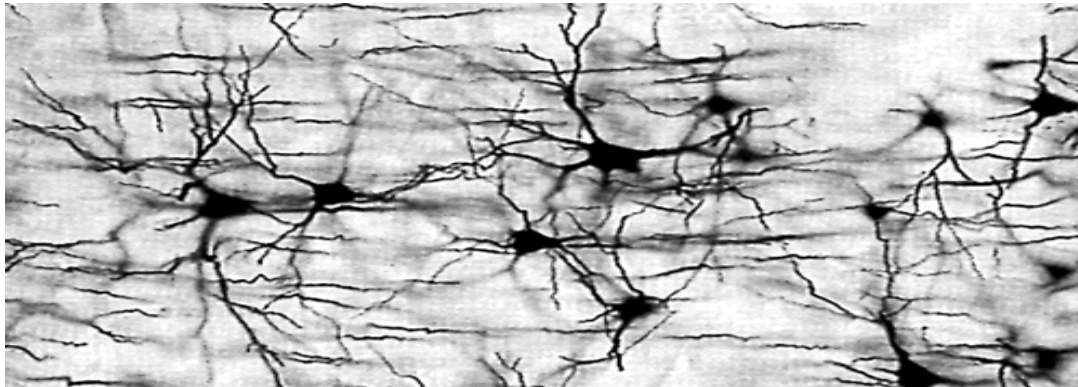
Scarce computational resources

- operations: simulation timing
- planning: no. of considered variants

Integrating more renewables

- changing operational rules
- virtual power plants
- better optimisation of operations
- sharp increase in share

2. Stability and Resilience of Complex Systems

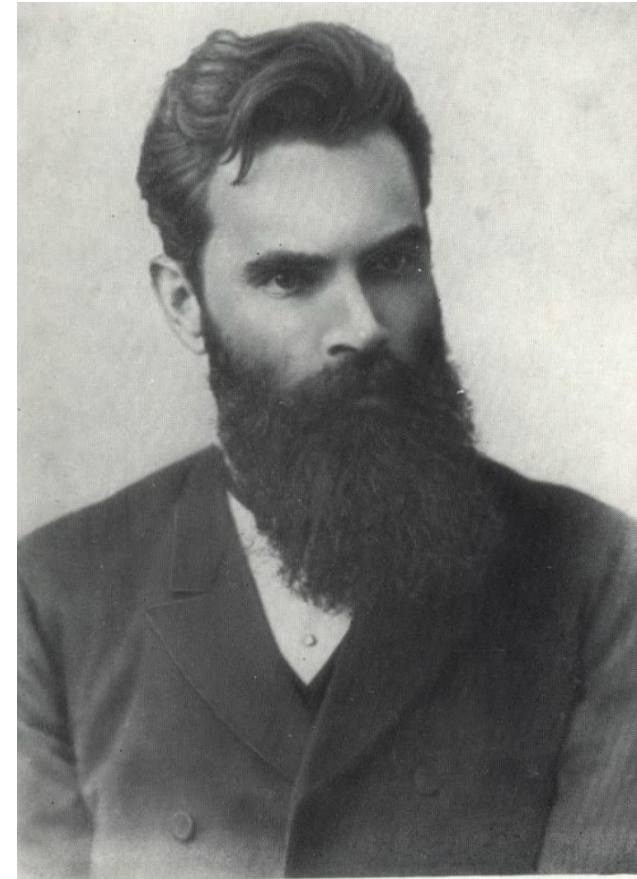


A SUCCESS STORY: STABILITY UNDER *small* PERTURBATIONS

Alexandr M. **Lyapunov** (1857–1918)

Small perturbations are easier to study than large ones!

- if a perturbation is small, the complex system's reaction is equivalent to the reaction of a much simpler, “**linearized**” system
- mathematically, only linear algebra (**eigen value** theory) is needed
- states/modes of a system can be **classified** into “stable”, “semistable”, “unstable”, etc.



A. Lyapunov 1857-1918

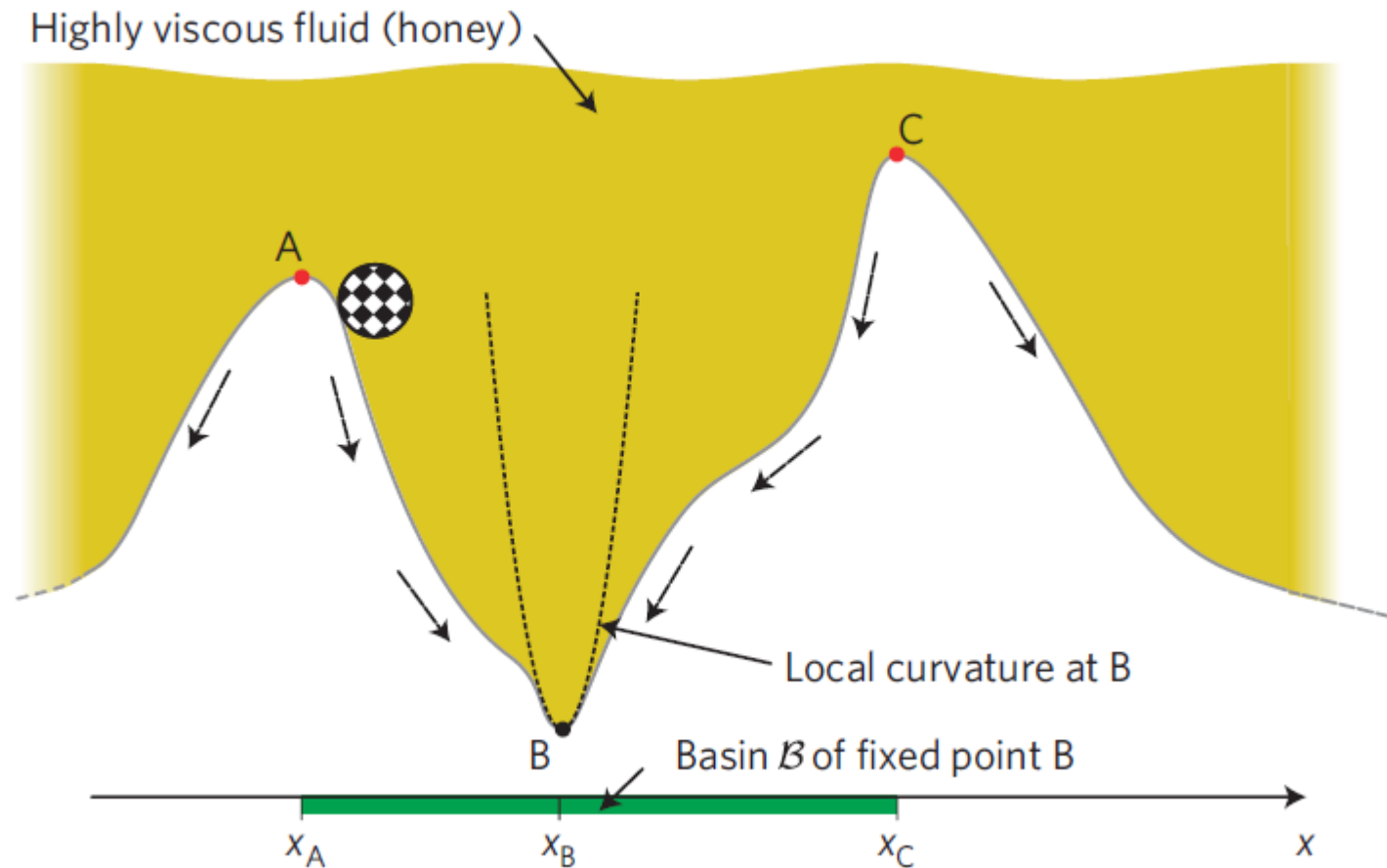
PROBLEMS WITH THIS LINEARIZATION APPROACH

- The classification into stable, semistable, unstable is mainly **qualitative**
 - *Quantification* of stability/resilience is more *difficult*
 - Power grids are complex **non-linear** systems
 - For non-linear systems, the linearization approach tells almost *nothing* about the impact of *large* fluctuations or perturbations!
- ***Other concepts are needed!***



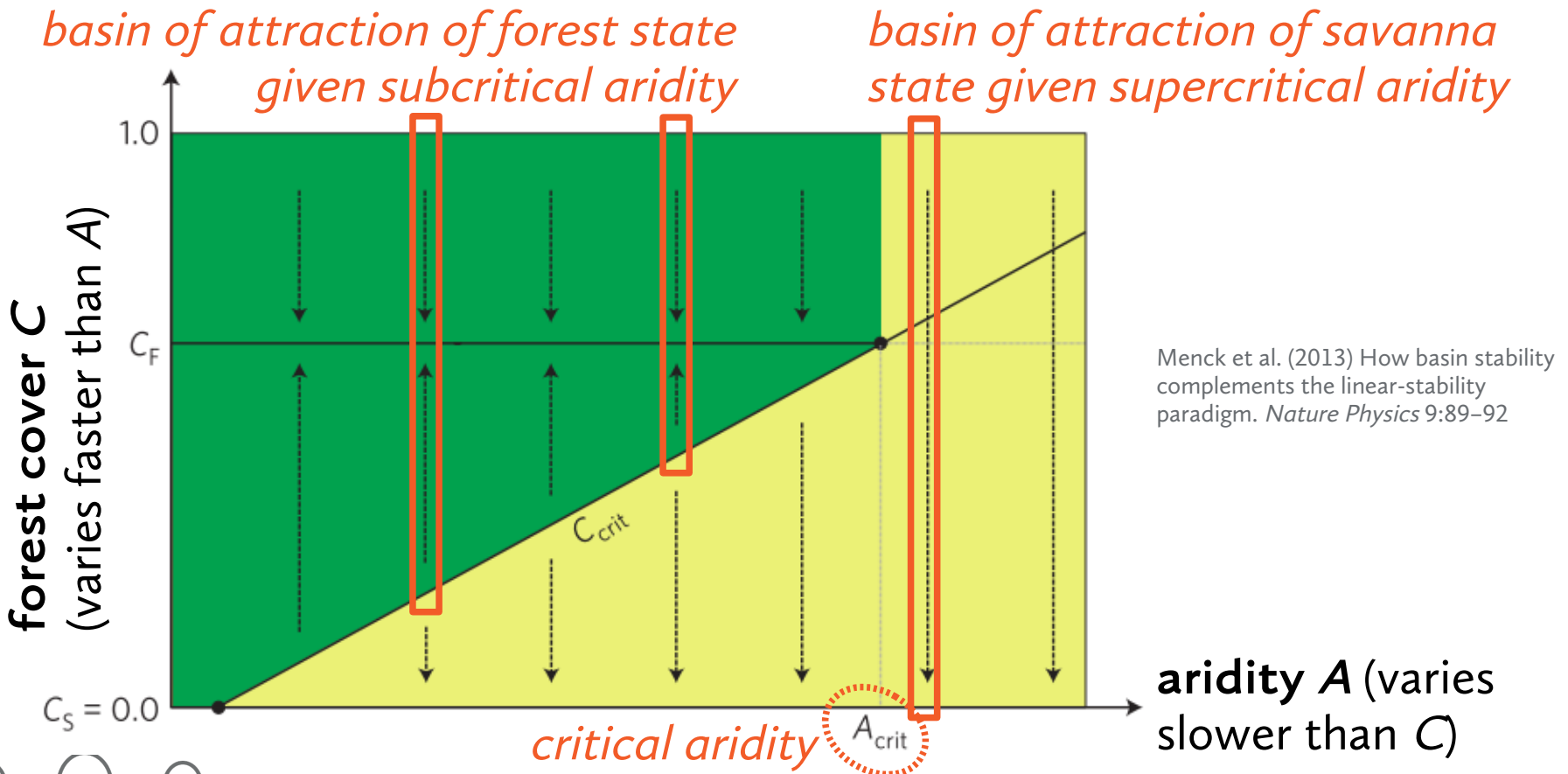
BASINS OF ATTRACTION & THE IMPACT OF *large* PERTURBATIONS

Metaphor: a marble dispersed in honey



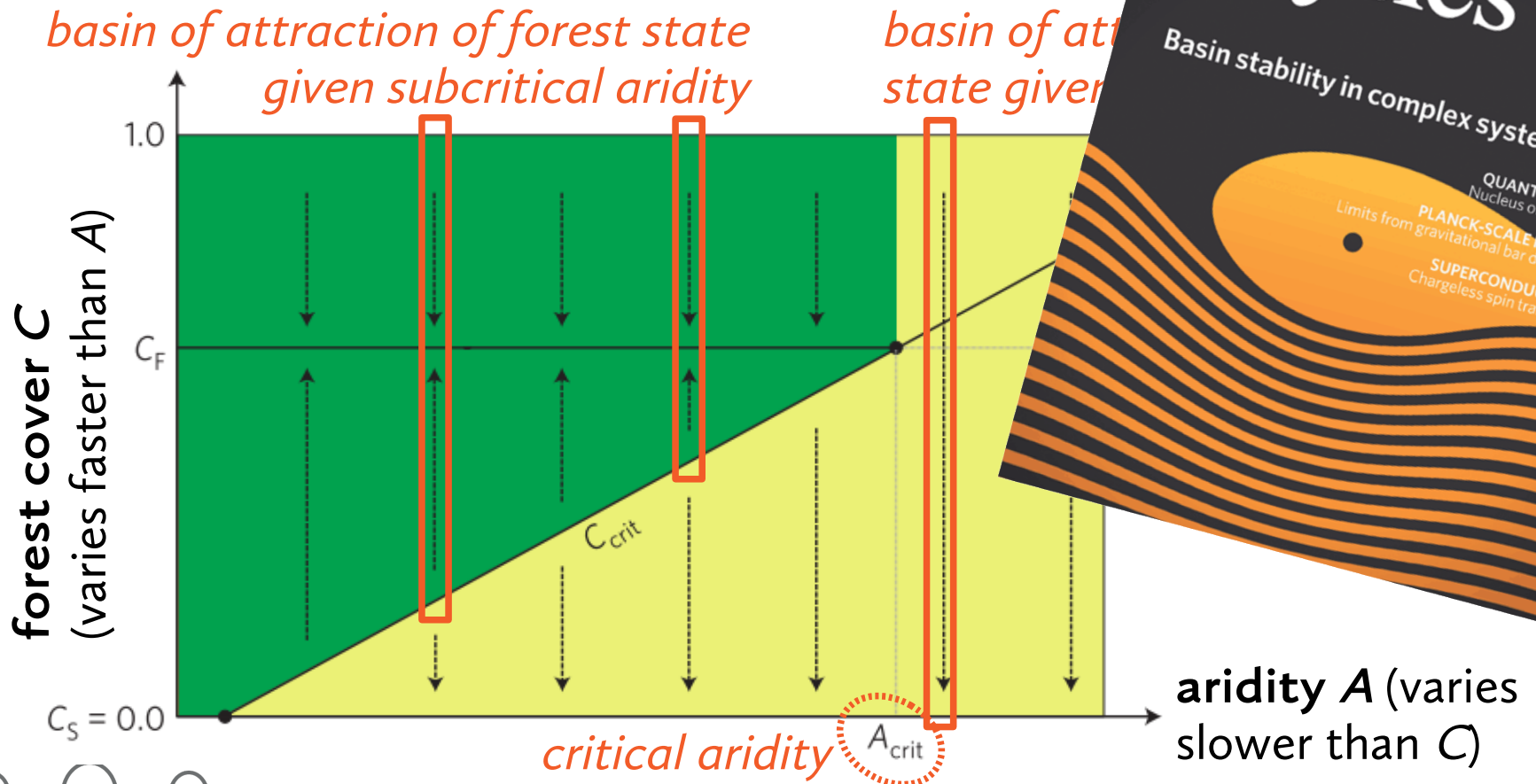
BASIN STABILITY = SIZE OF BASIN OF ATTRACTION QUANTIFIES STABILITY

Example: simplistic model of a bistable forest/savanna



BASIN STABILITY = SIZE OF BASIN OF ATTRACTION QUANTIFIES STABILITY

Example: simplistic model of a bistable forest



RESILIENCE VS. STABILITY

Working definition here:

Stability = perturbations will not push the system out of its normal state for long

Resilience = the system can find a new stable states by reorganizing itself (automatically)

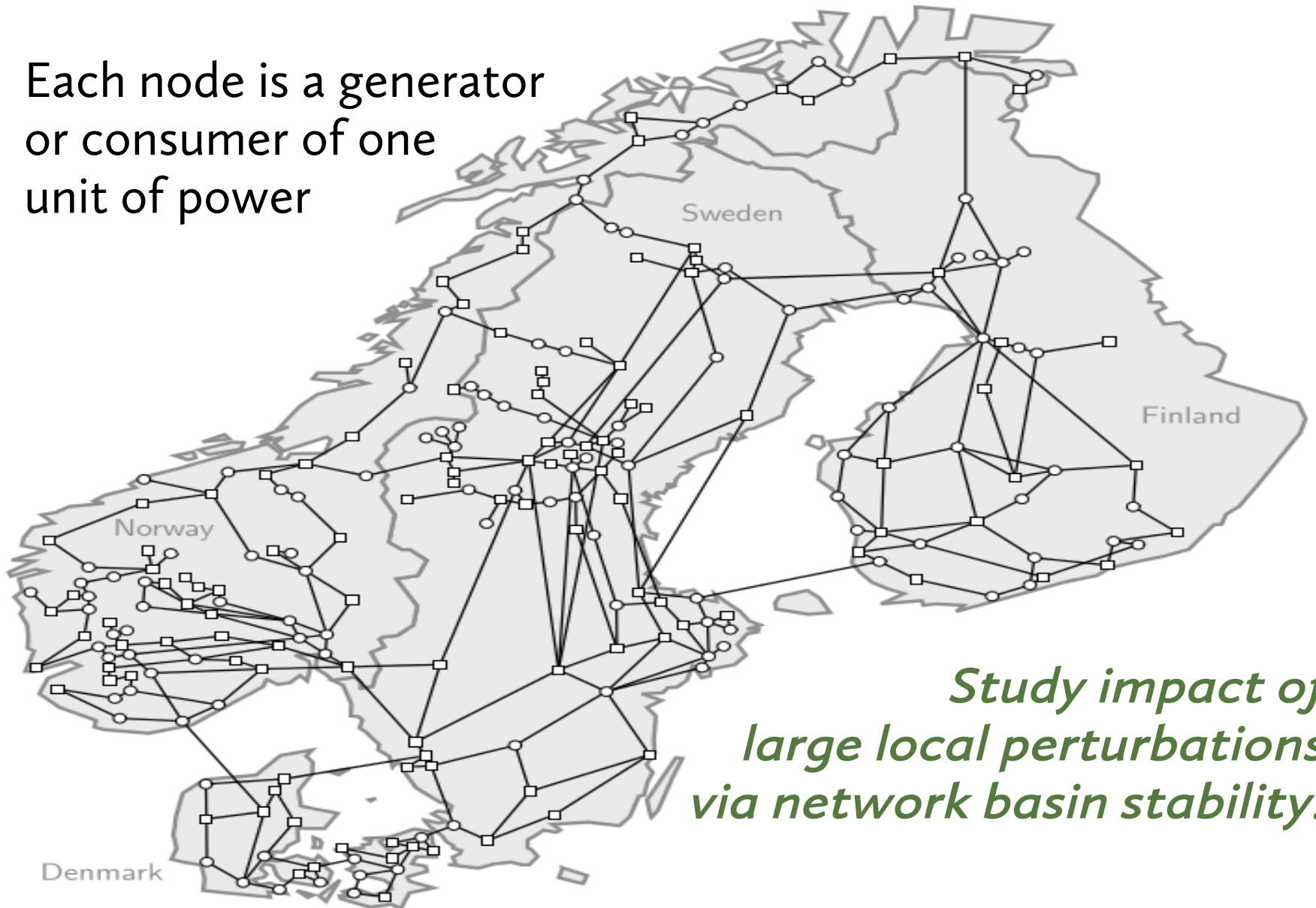
3.

Network Basin Stability applied to Power Grids



CASE STUDY: STYLIZED SCANDINAVIAN TRANSMISSION GRID

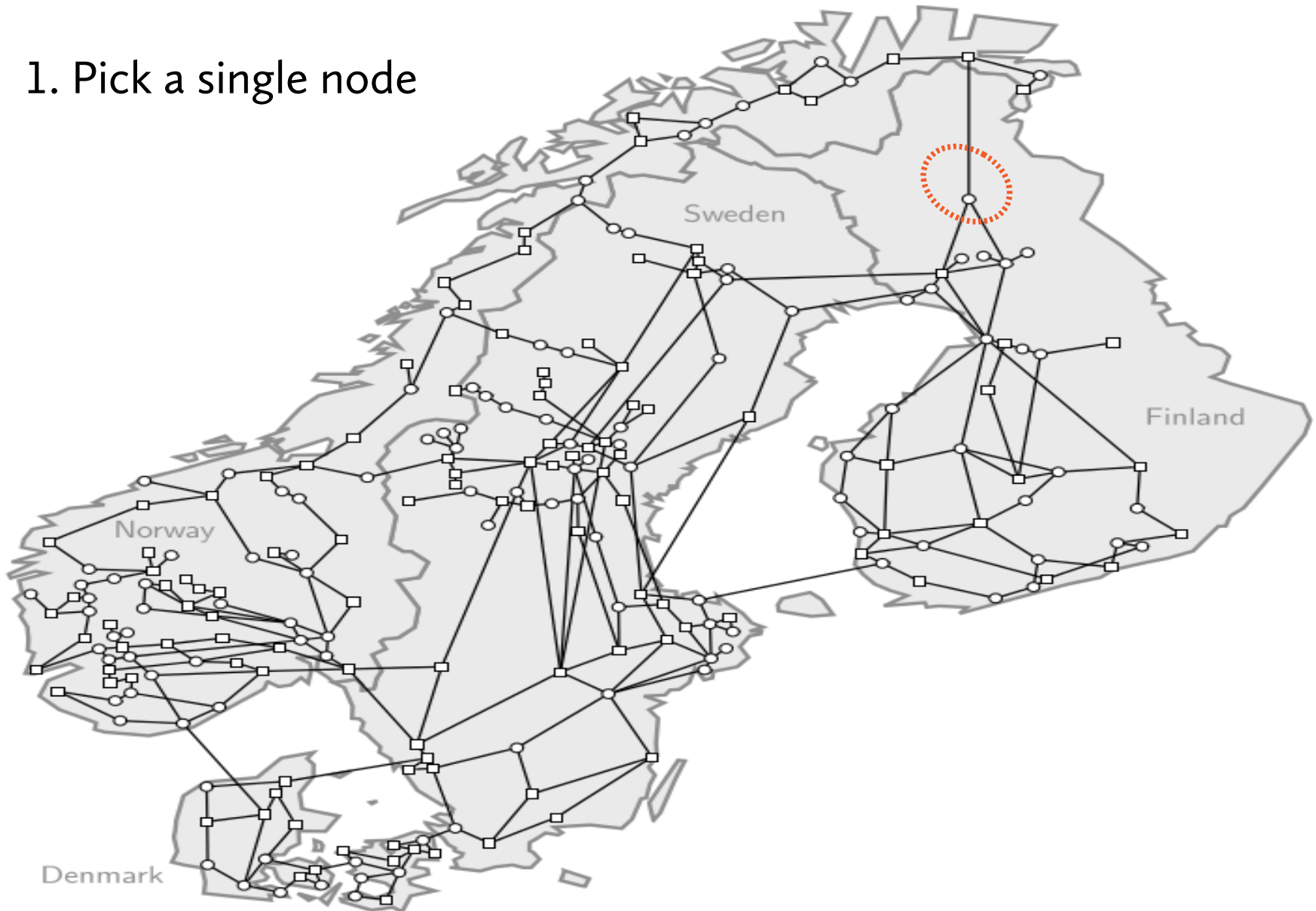
Each node is a generator
or consumer of one
unit of power



*Study impact of
large local perturbations
via network basin stability!*

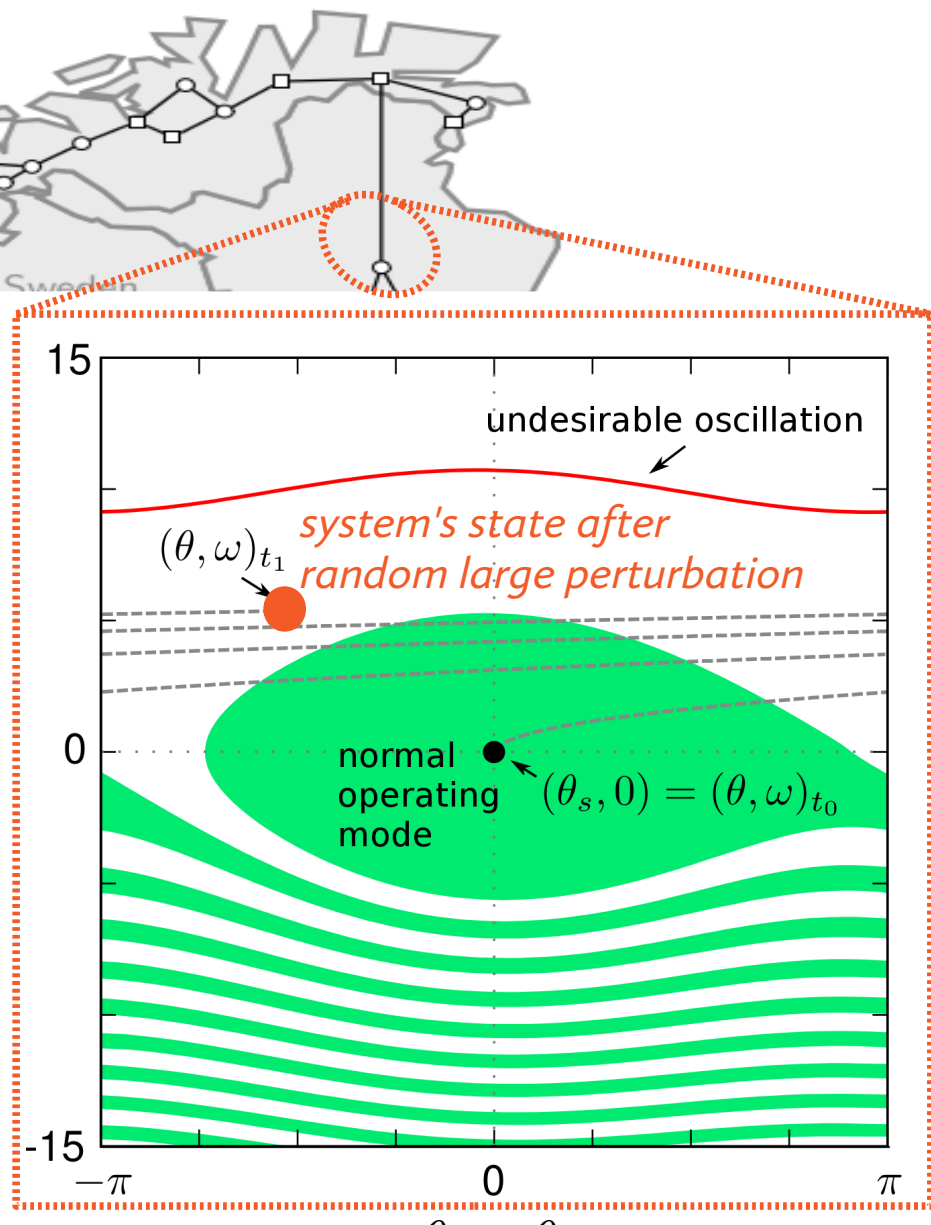
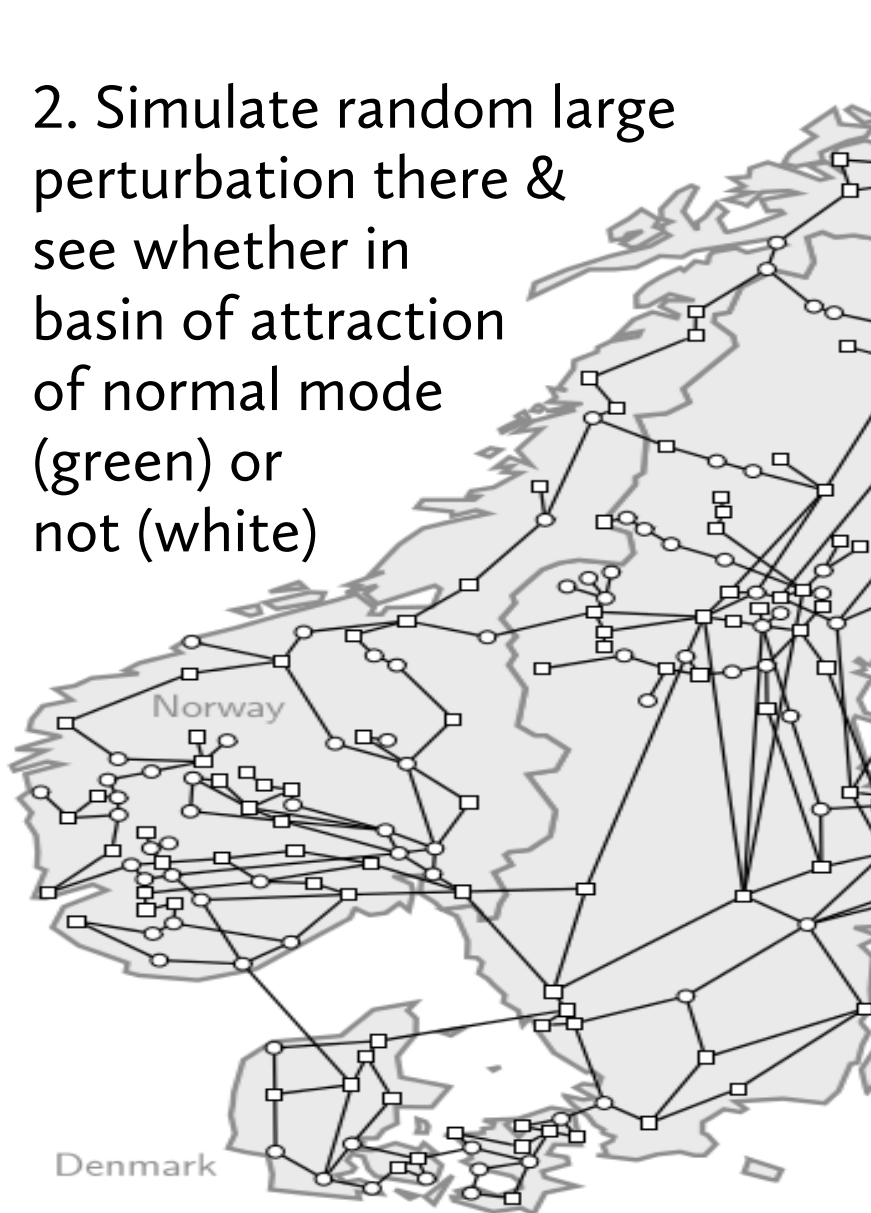
SIMULATE RETURN TO NORMAL OPERATING MODE AFTER A LARGE PERTURBATION AT A SINGLE NODE

1. Pick a single node



SIMULATE RETURN TO NORMAL OPERATING MODE AFTER A LARGE PERTURBATION AT A SINGLE NODE

2. Simulate random large perturbation there & see whether in basin of attraction of normal mode (green) or not (white)



SIMULATE RETURN TO NORMAL OPERATING MODE AFTER A LARGE PERTURBATION AT A SINGLE NODE

Dynamics of grid node i (simplest approx., “swing equation”):

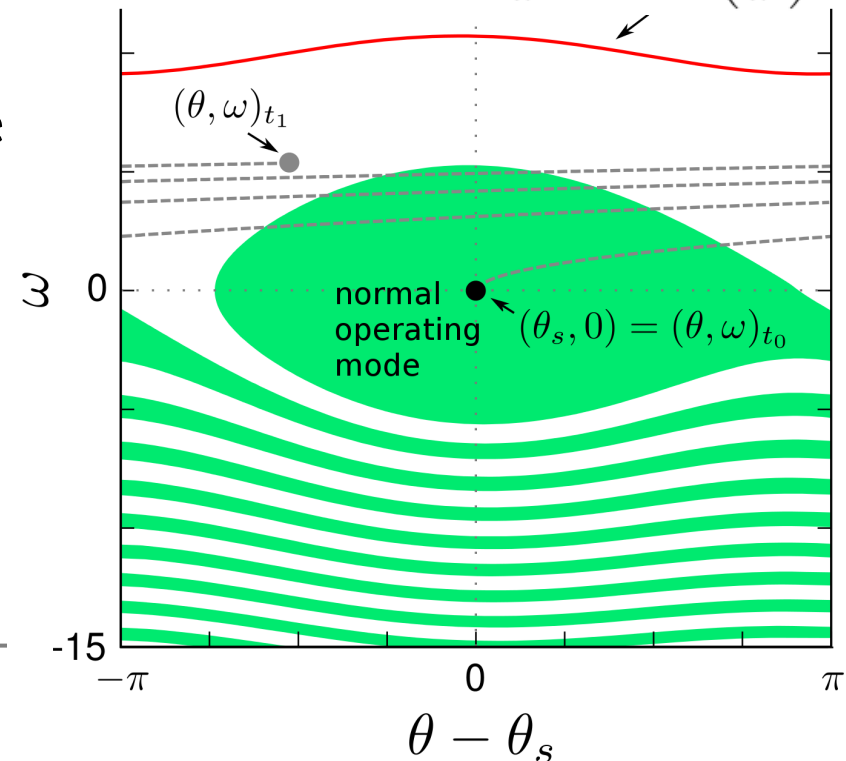
phase: $\frac{d}{dt}\theta_i = \omega_i$

frequency: $\frac{d}{dt}\omega_i = P_i - D\omega_i - K \cdot \sum_j A_{ij} \sin(\theta_i - \theta_j)$

Parameters:

- P_i net power input at node
- α dissipation constant
- K coupling constant
- A_{ij} adjacency matrix
(1 if linked, 0 otherwise)

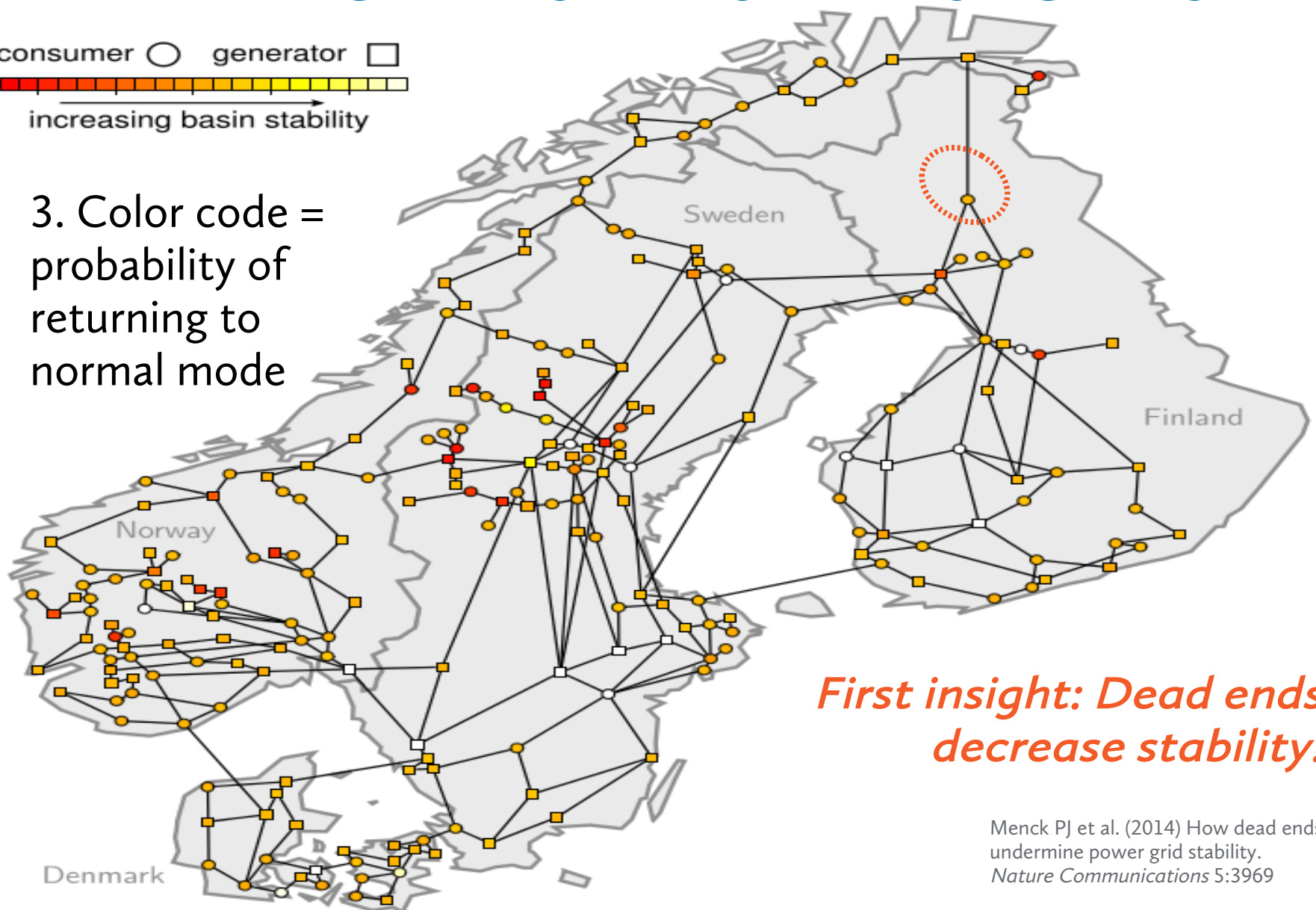
$$\omega_{ns}(t) \approx \frac{P}{\alpha} + \frac{\alpha K}{P} \cos\left(\frac{P}{\alpha}t\right)$$



SIMULATE RETURN TO NORMAL OPERATING MODE AFTER A LARGE PERTURBATION AT A SINGLE NODE

consumer ○ generator □
increasing basin stability

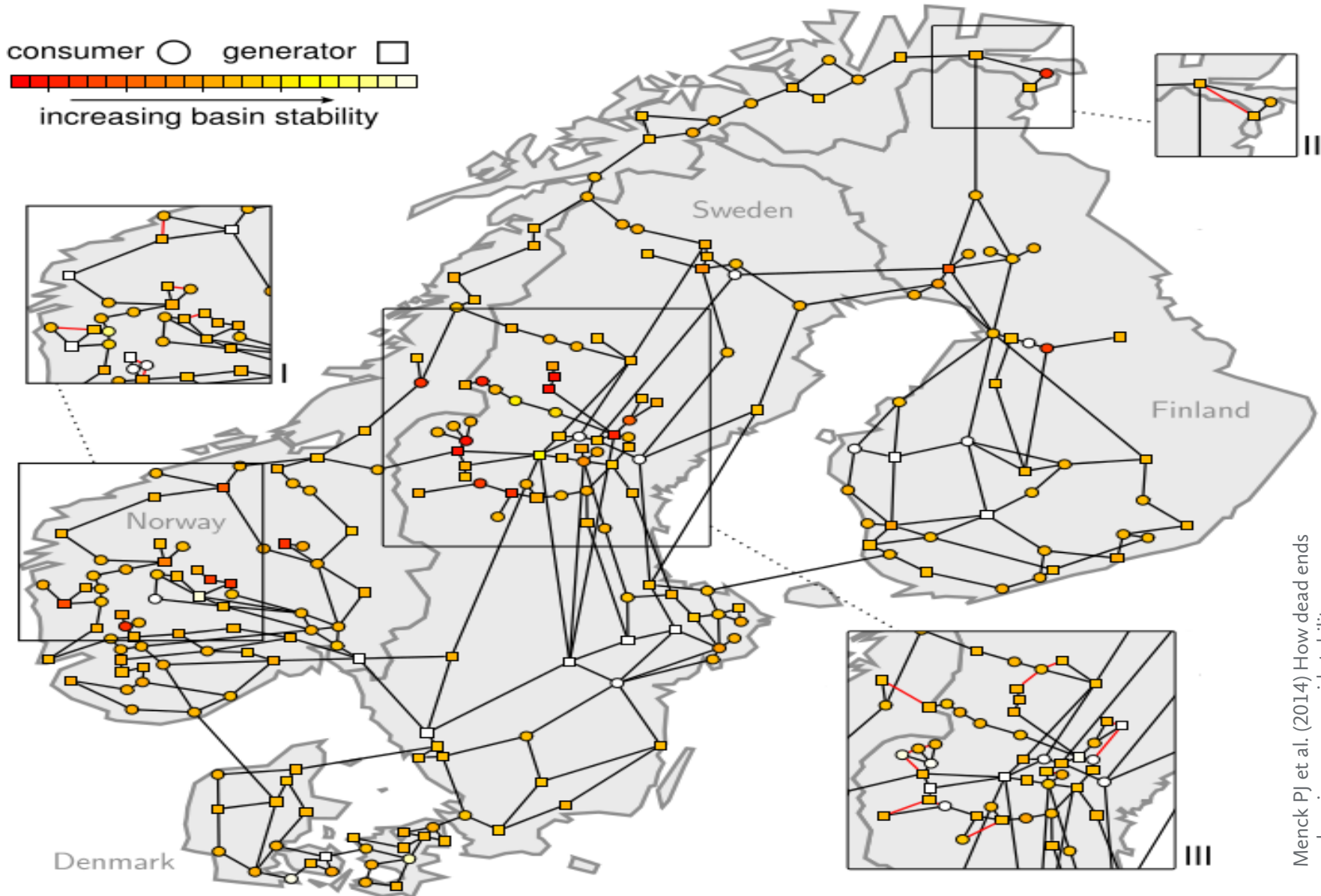
3. Color code =
probability of
returning to
normal mode



*First insight: Dead ends
decrease stability!*

Menck PJ et al. (2014) How dead ends
undermine power grid stability.
Nature Communications 5:3969

SMART WIRING = ADD A FEW LINES AT OPTIMAL POSITIONS

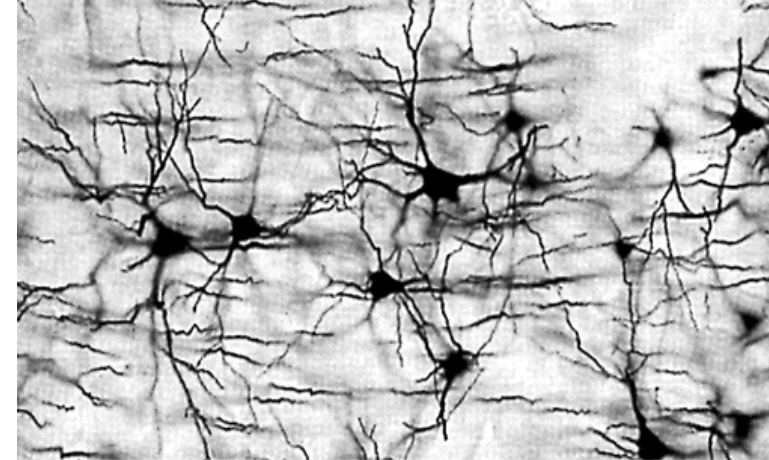


Menck PJ et al. (2014) How dead ends undermine power grid stability. *Nature Communications* 5:3969

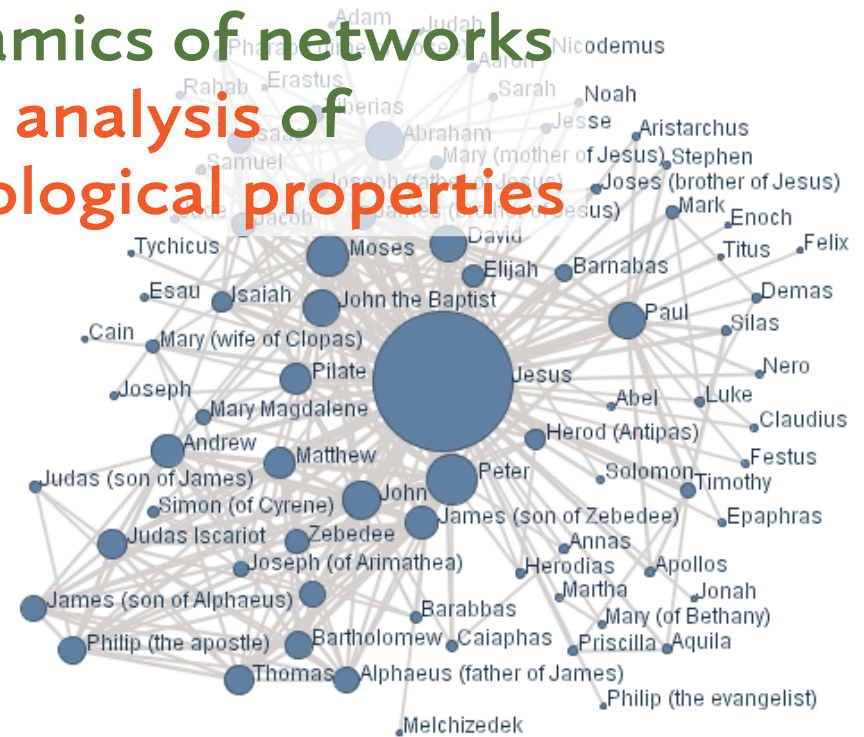
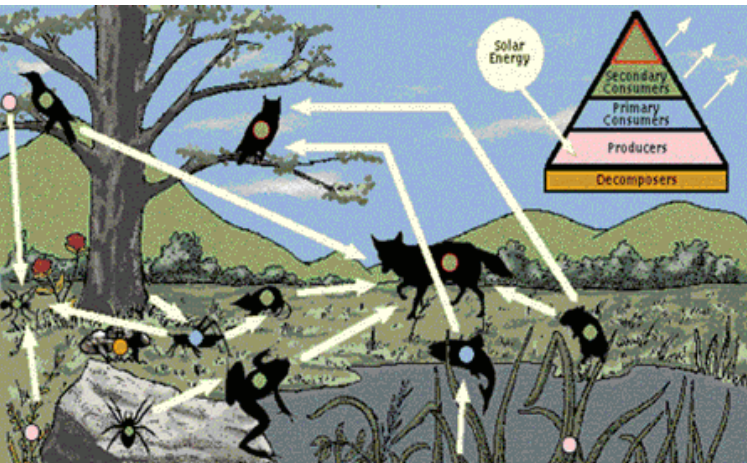
4.

Complex Networks Analysis of Power Grids

COMPLEX NETWORK THEORY

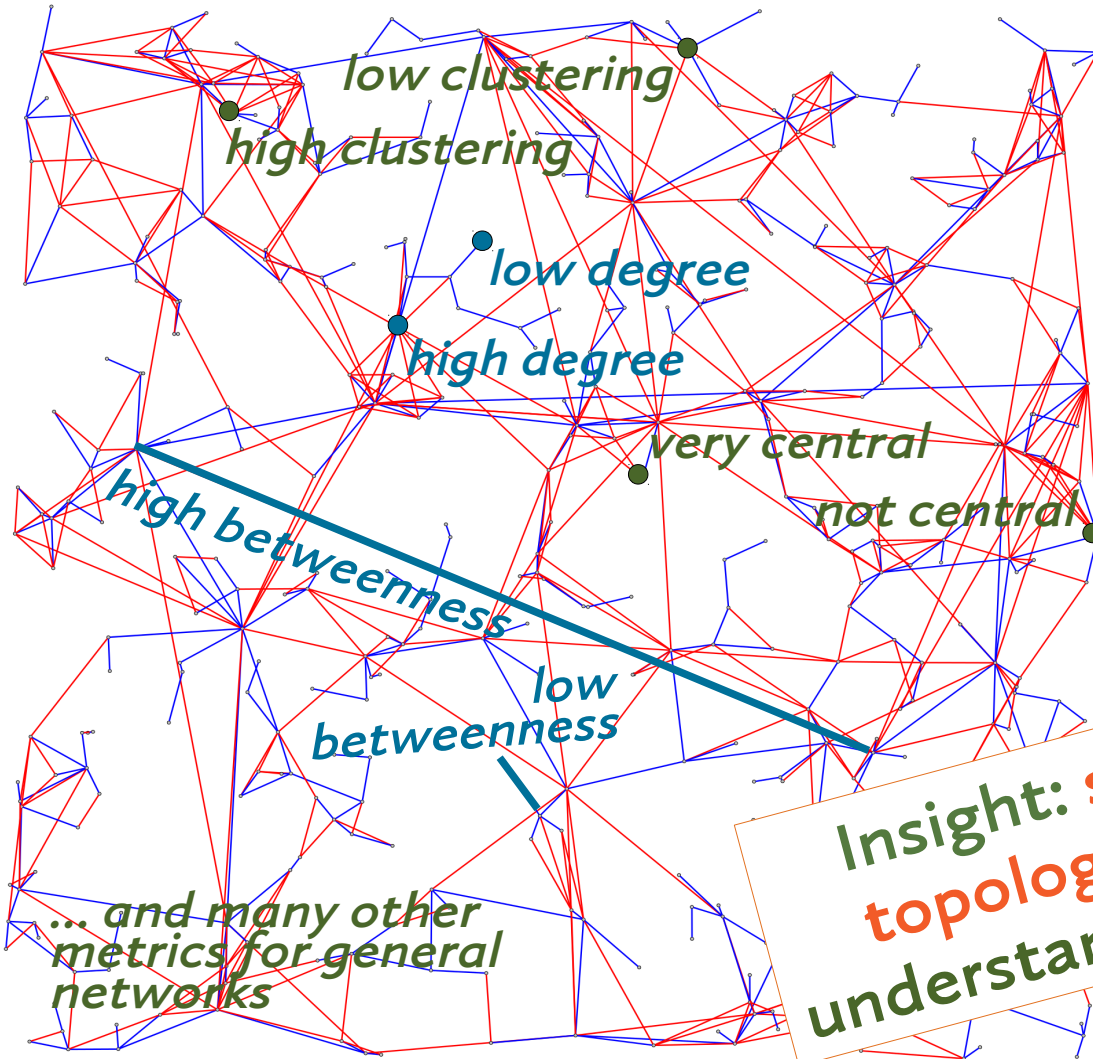


Method: study dynamics of networks
via statistical analysis of
global and local topological properties



STATISTICAL ANALYSIS OF NETWORK TOPOLOGIES

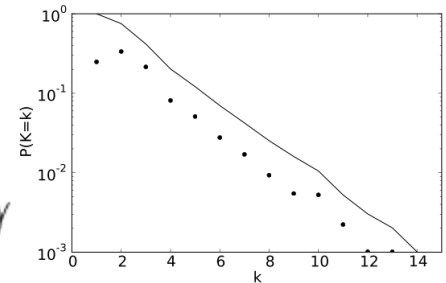
so far successfully applied to climate dynamics, neuro, trade, ...



Insight: statistical analysis of topological properties helps understanding network dynamics

CHARACTERISTICS OF POWER GRID TOPOLOGIES

- 50 – 10,000 nodes
- **Exponential** degree distribution $p_k \sim e^{-k/\gamma}$
with $1.5 < \gamma < 2 \rightarrow$ *not Erdős-Renyi random or scale-free*
- **Very sparse: average node degree approx.**
 - 2.8 for transmission grids (tree + 40% additional lines)
 - 2 (tree) for distribution grids (almost no redundant lines)
- **Large average path length** $O(\sqrt{N})$
due to spatial embedding \rightarrow *not small-world*
- **Low clustering coefficient** \rightarrow *not “random geometric”*



\rightarrow how to generate synthetic grids for simulations?



MODEL FOR GENERATING SYNTHETIC POWER GRID TOPOLOGIES

- **Initial layout**

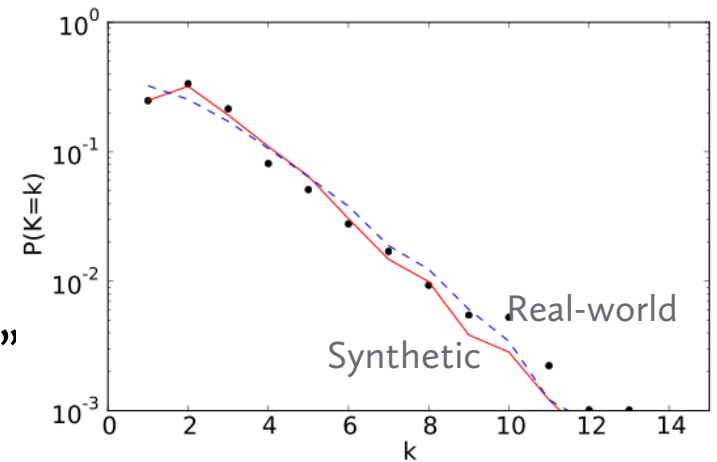
- given initial node locations,
- construct the “minimal spanning tree”
- then add some redundant lines

- **Growth phase**

- either connect a new node to the closest existing node
- and to some other node for redundancy
- or put a new node somewhere along an existing line

- **Trade off between global and local redundancy**

- by maximizing $(1 + \text{internal grid distance})^r / (\text{spatial distance})$
- where r is a redundancy control parameter

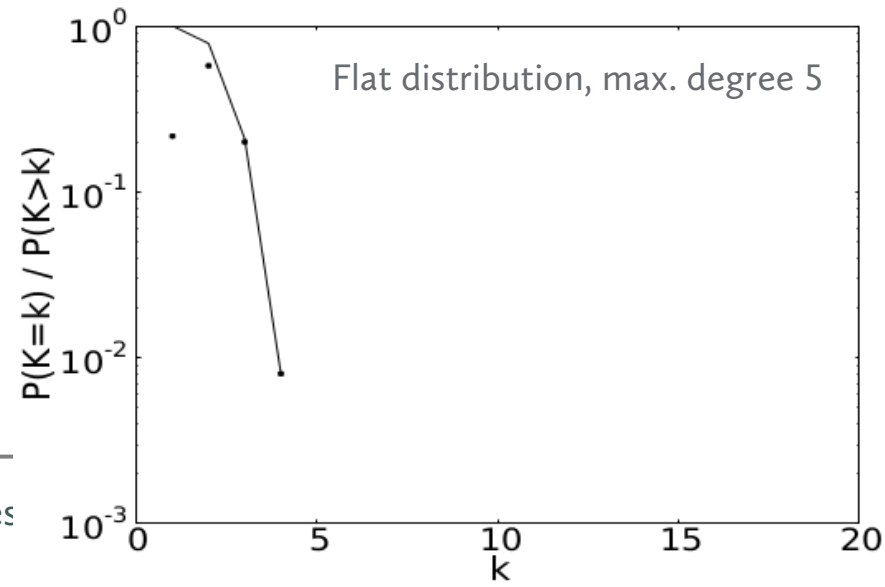
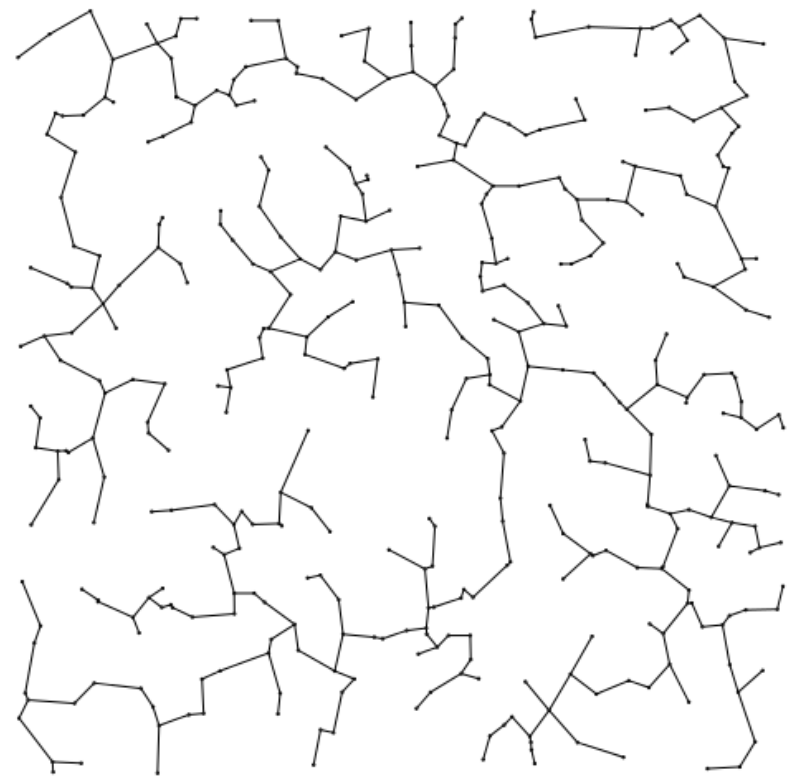


Schultz et al. (2014) A Random Growth Model for Power Grids and Other Spatially Embedded Infrastructure Networks. *EPJ ST* 223(12):2593–2610



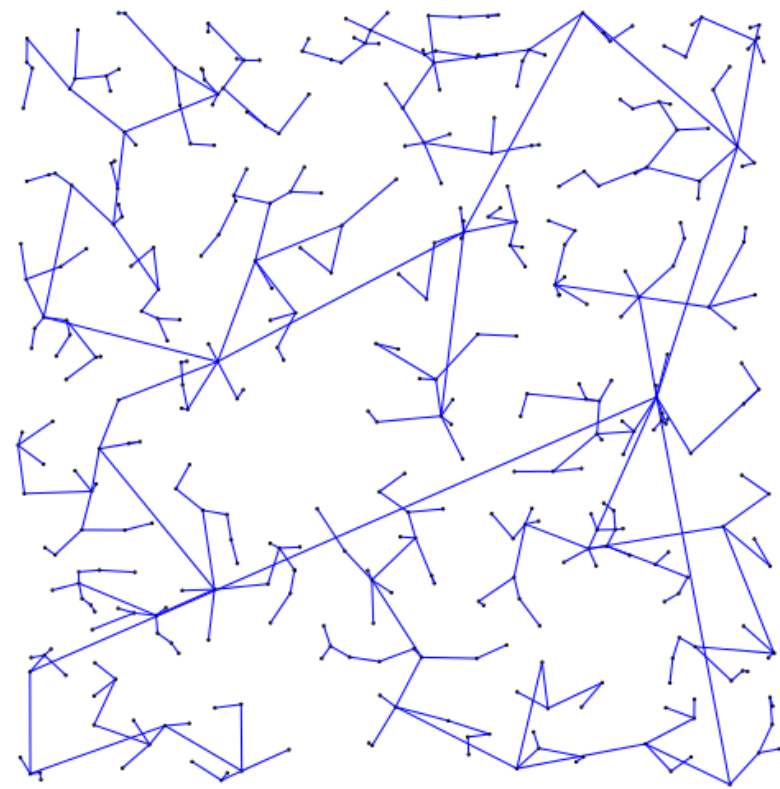
MINIMAL SPANNING TREE (MST)

- optimizes one-time construction costs
 - no redundant lines
- one tripping line already causes a partial blackout

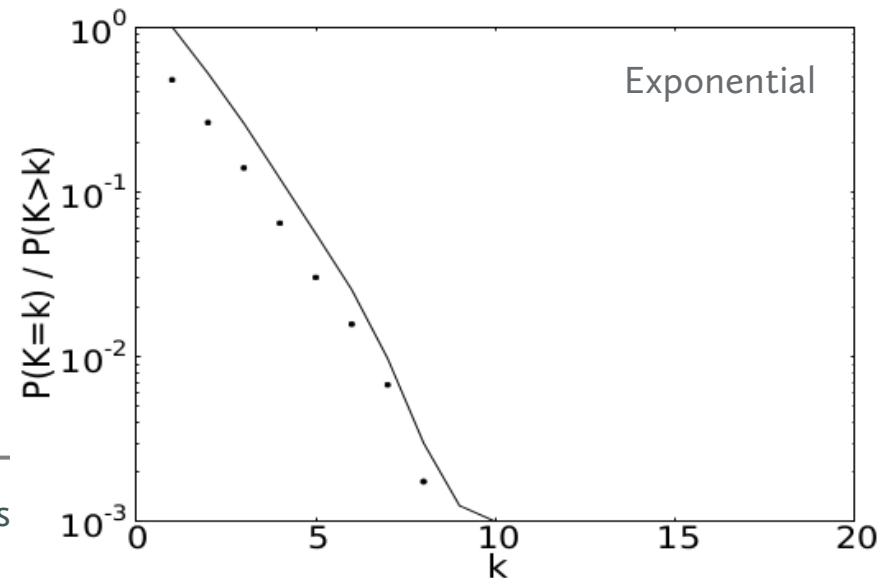


GROWN TREE, LINK TO NEAREST NEIGHBOUR

- optimizes node-wise extension costs
- initial long lines appear sub-optimal later
- still no redundant lines



Jobst Heitzig et al. Stability and Res



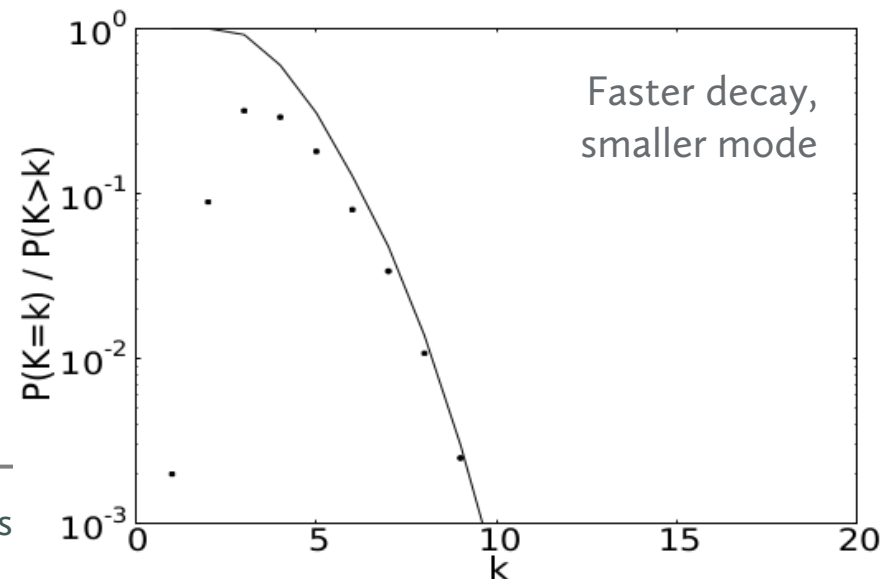
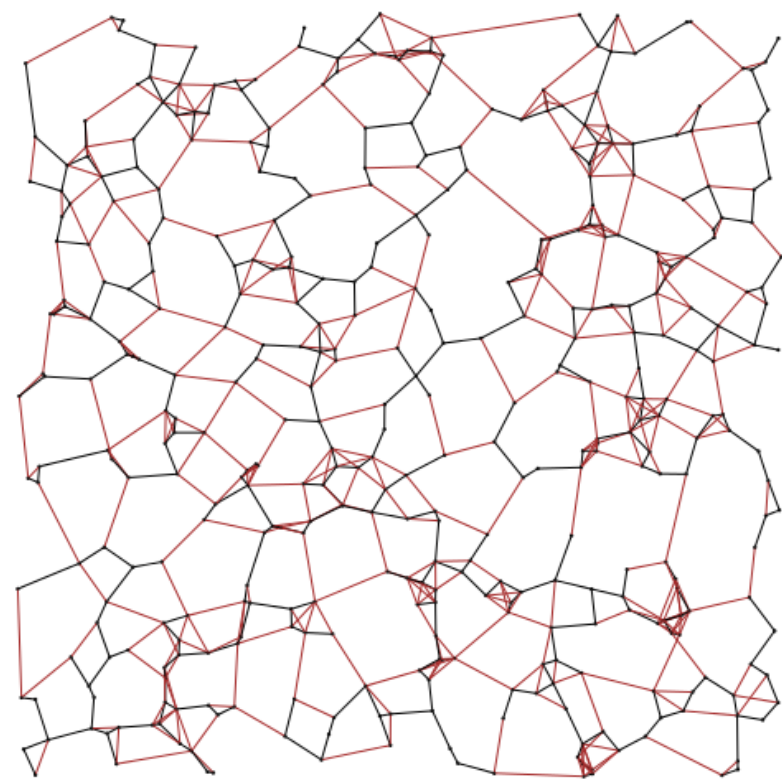
MST + GLOBAL REDUNDANT LINES

(large r parameter)

- meshlike structure,
many “large” circles
→ very few dead ends
→ improved basin stability

but:

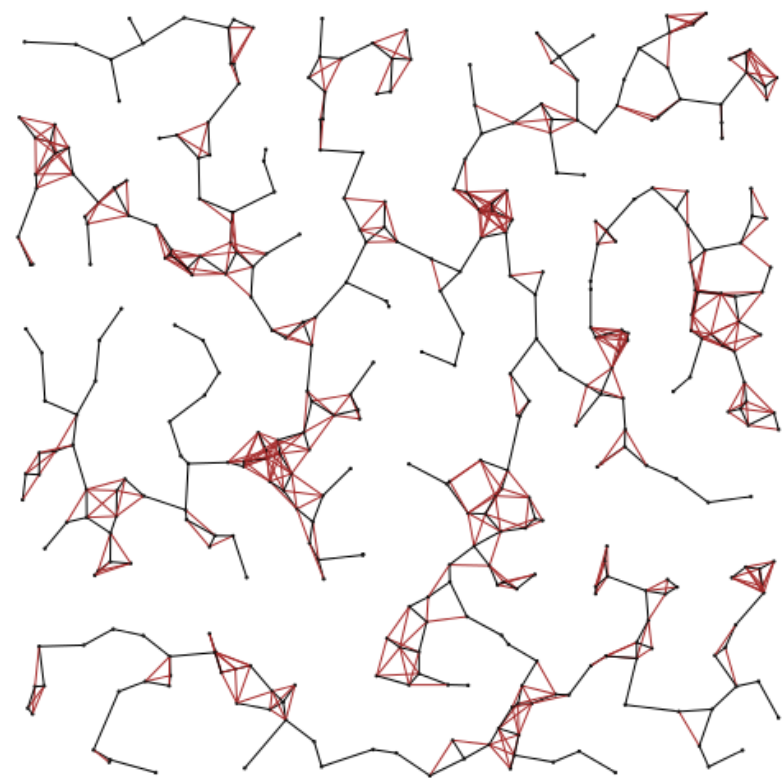
- few triangles
→ cascading failures may occur



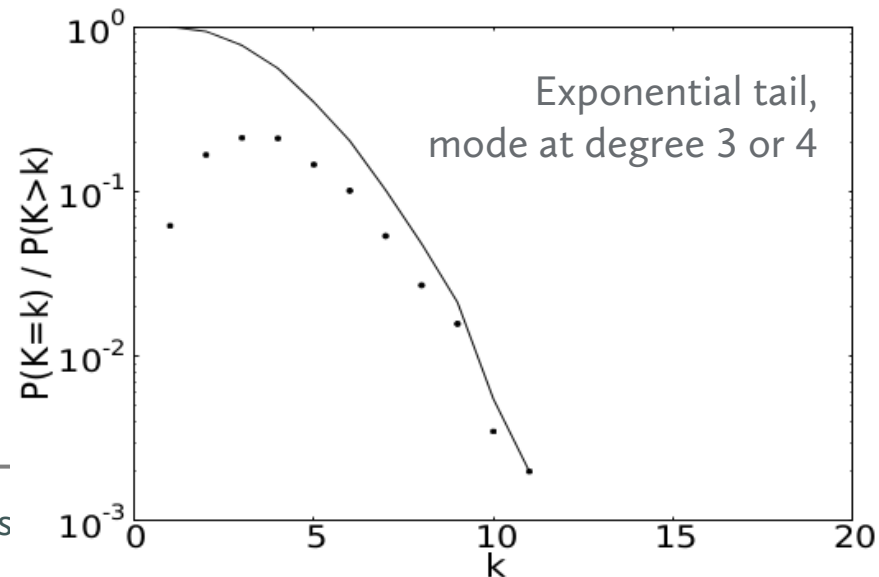
MST + LOCAL REDUNDANT LINES

(small r parameter)

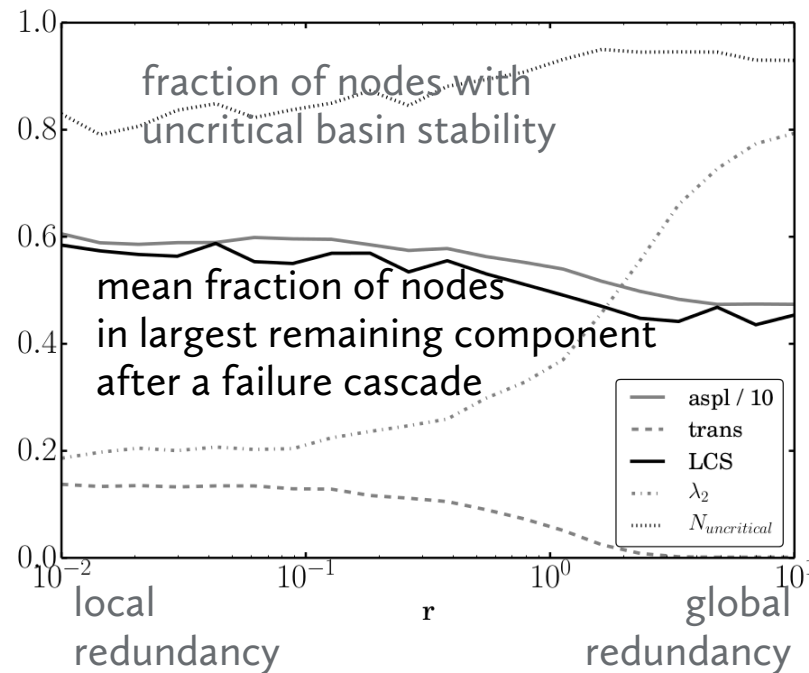
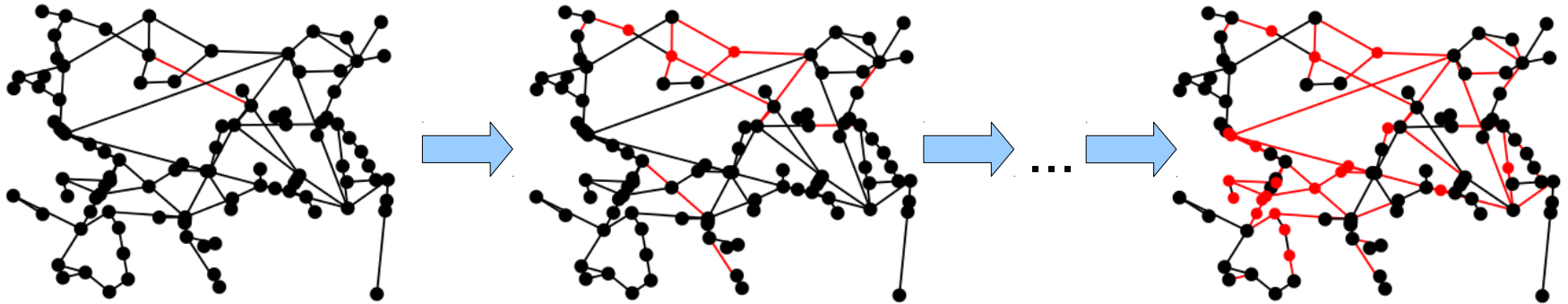
- many triangles
- flow through tripping line is redistributed to few other lines
- long failure cascades less likely



Jobst Heitzig et al. Stability and Res

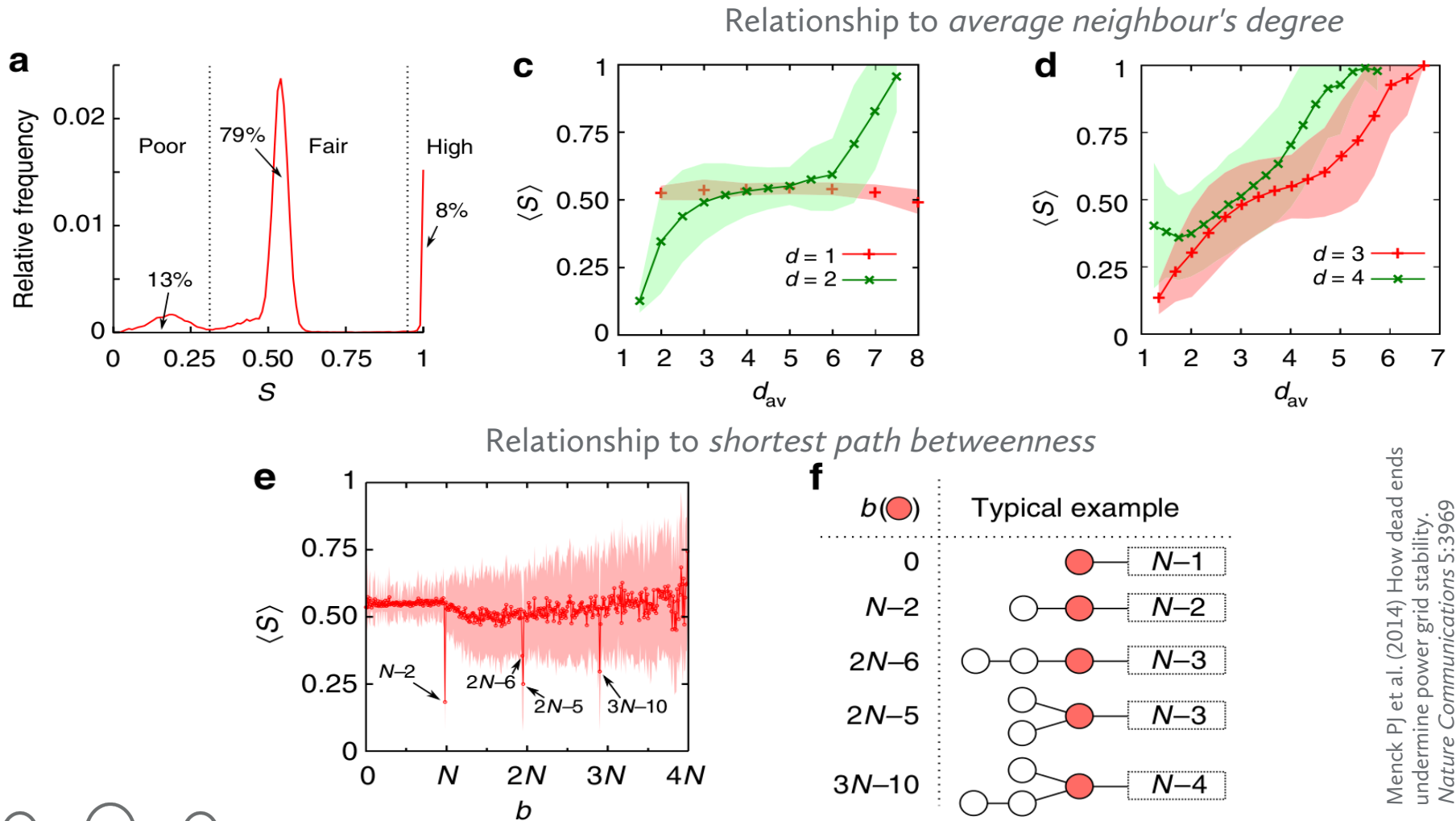


RESILIENCE AGAINST CASCADING FAILURES VS. BASIN STABILITY



Plietzsch A, Schultz P, Heitzig J, Kurths J (2015)
 Local vs global redundancy – tradeoffs between
 resilience against cascading failures and
 frequency stability. Submitted to EPJ ST

RELATIONSHIP BETWEEN BASIN STABILITY AND STANDARD NETWORK STATISTICS

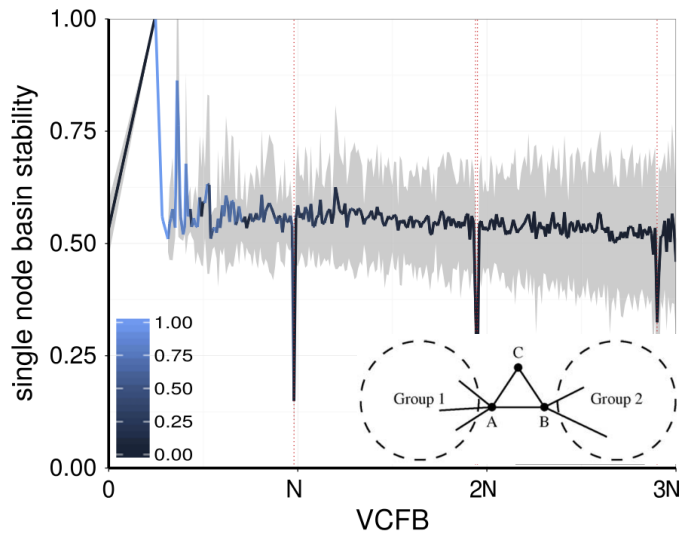
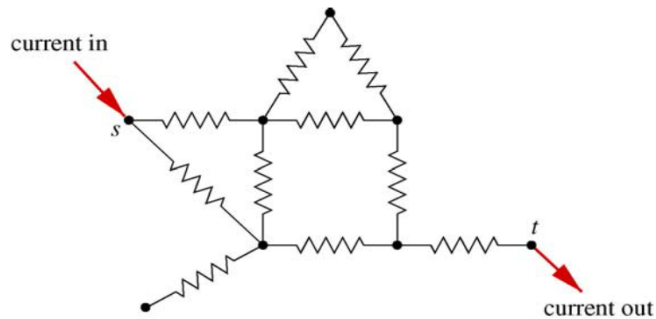


Menck PJ et al. (2014) How dead ends undermine power grid stability. *Nature Communications* 5:3969

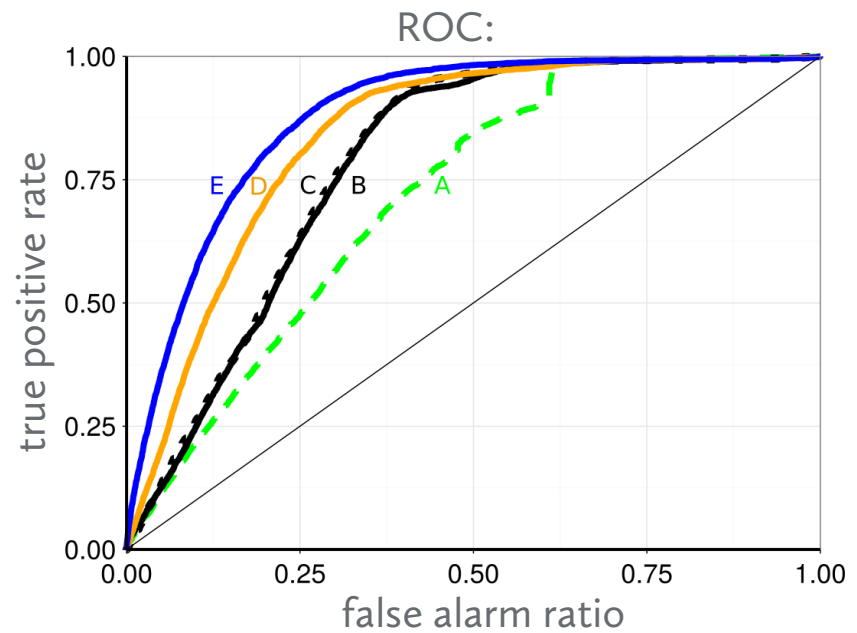


EVEN CLEARER RELATIONSHIP TO SPECIALLY ADAPTED NETWORK STATISTICS

current flow betweenness
(Newman, Social Networks 2005)



predicting “poor” basin stability nodes
from topology only, using
node strength,
average neighbours' strength,
a capacity-weighted clustering coefficient
and *effective resistance closeness centrality*



Schultz P, Heitzig J, Kurths J (2014)
Detours around basin stability in power networks.
New Journal of Physics



5.

Smart Wiring

LESSON: KNOW WHICH TYPE OF REDUNDANCY AFFECTS WHICH ASPECT OF STABILITY/RESILIENCE!

- In general, additional (“redundant”) lines improve stability
 - Traditional “N–1” criterion:
grid must stay connected when one appliance/line fails
 - But: adding a line may also *destabilise* another grid region (Braess' paradox)
- Different **types of redundancy**:
 - **local** redundancy (high clustering, short detours) helps avoiding long **failure cascades** leading to large blackouts
 - **global** redundancy (high connectivity, low path length, long-range connections) more important for **dynamic stability**
 - in view of economic constraints: good **trade-off** needed

LESSON: SOME “MOTIFS” SHOULD BE AVOIDED OR PRODUCED

- **Hub nodes:** *use as “stability anchors”!*
 - connect new lines preferably to them than to their immediate neighbours
- **Dead ends/dead trees:** *avoid!*
 - connect pairs of leaf nodes (improves local redundancy)
 - connect leaf node to a hub in another part of grid (global redundancy)
- **“Detour” nodes:** *produce!*
 - e.g. connect neighbours of hubs with each other (local redundancy)

PUBLICATIONS

- Menck PJ, [Heitzig J](#), Marwan N, Kurths J (2013) How basin stability complements the linear-stability paradigm. *Nature Physics* 9:89–92. doi:10.1038/nphys2516
- Ji P, Peron TKD, Menck PJ, Rodrigues F, Kurths J (2013) Cluster explosive synchronization in complex networks. *Physical Review Letters* 110(21):1–5. doi:10.1103/PhysRevLett.110.218701
- Menck PJ, [Heitzig J](#), Kurths J, Schellnhuber HJ (2014) How dead ends undermine power grid stability. *Nature Communications* 5:3969. doi:10.1038/ncomms4969
- Schultz P, [Heitzig J](#), Kurths J (2014)
A Random Growth Model for Power Grids and Other Spatially Embedded Infrastructure Networks. *EPJ ST Resilient Power Grids and Extreme Events* 223(12):2593–2610. doi:10.1140/epjst/e2014-02279-6
- Schultz P, [Heitzig J](#), Kurths J (2014) Detours around basin stability in power networks. *New Journal of Physics* 16:125001. doi:10.1088/1367-2630/16/12/125001
- [Heitzig J](#), Fujiwara N, Aihara K, Kurths J (2014) Editorial: Interdisciplinary challenges in the study of power grid resilience and stability and their relation to extreme weather events. In: [Heitzig J](#), Fujiwara N, Aihara K, Kurths J (eds.) Resilient Power Grids and Extreme Events, *EPJ Special Topics* 223(12):2383–2386
- Plietzsch A, Schultz P, [Heitzig J](#), Kurths J (2015) Local vs global redundancy – tradeoffs between resilience against cascading failures and frequency stability. Submitted to *EPJ ST*
- Hellmann F, Schultz P, Grabow C, [Heitzig J](#), Kurths J (2015)
Survivability: a unifying concept for the transient resilience of deterministic dynamical systems. *In revision*
- Kleis K, Auer S, Hellmann F, Schultz P, Kurths J (2015).
The impact of model detail on power grid resilience measures. *In preparation for EPJ ST*

TAKE HOME MESSAGES

The **(node-wise) basin stability** concept can help to find weak points in power grids by simulation.

Adjusted **topological statistics** can speed this up by preselecting potentially critical nodes.

Suitable **random generators** for power grid topologies enable ensemble simulations in power grid research.

*Thank you for your attention –
I'm curious for your comments!*

Contact: heitzig | hellmann | schultz @pik-potsdam.de