Potsdam Institute for
Climate Impact Research

STABILITY AND RESILIENCE OF POWER GRIDS

Jobst Heitzig, joint work with Peter Menck, Paul Schultz,
Anton Plietzsch, Frank Hellmann, Sabine Auer, Peng Ji,
Stefan Schinkel, Carsten Grabow, Kirsten Kleis,
Jürgen Kurths, Hans-Joachim Schellnhuber

Leibniz-Gemeinschaft

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**

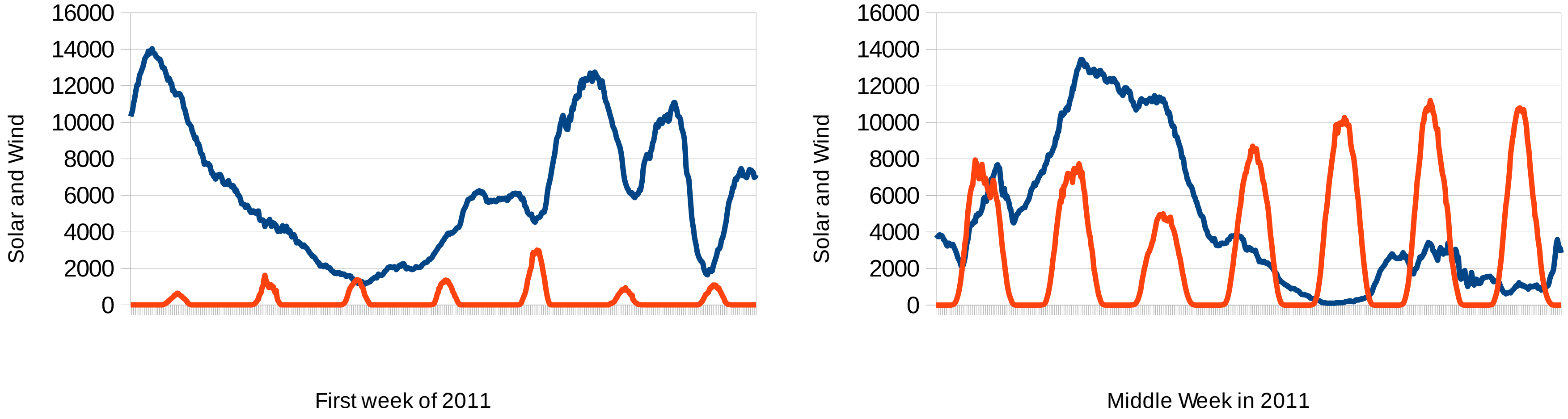
- Renewable energy generation **fluctuates** strongly
  - wind strength/direction, sunshine, cloudiness may vary fast

- 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:



(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**

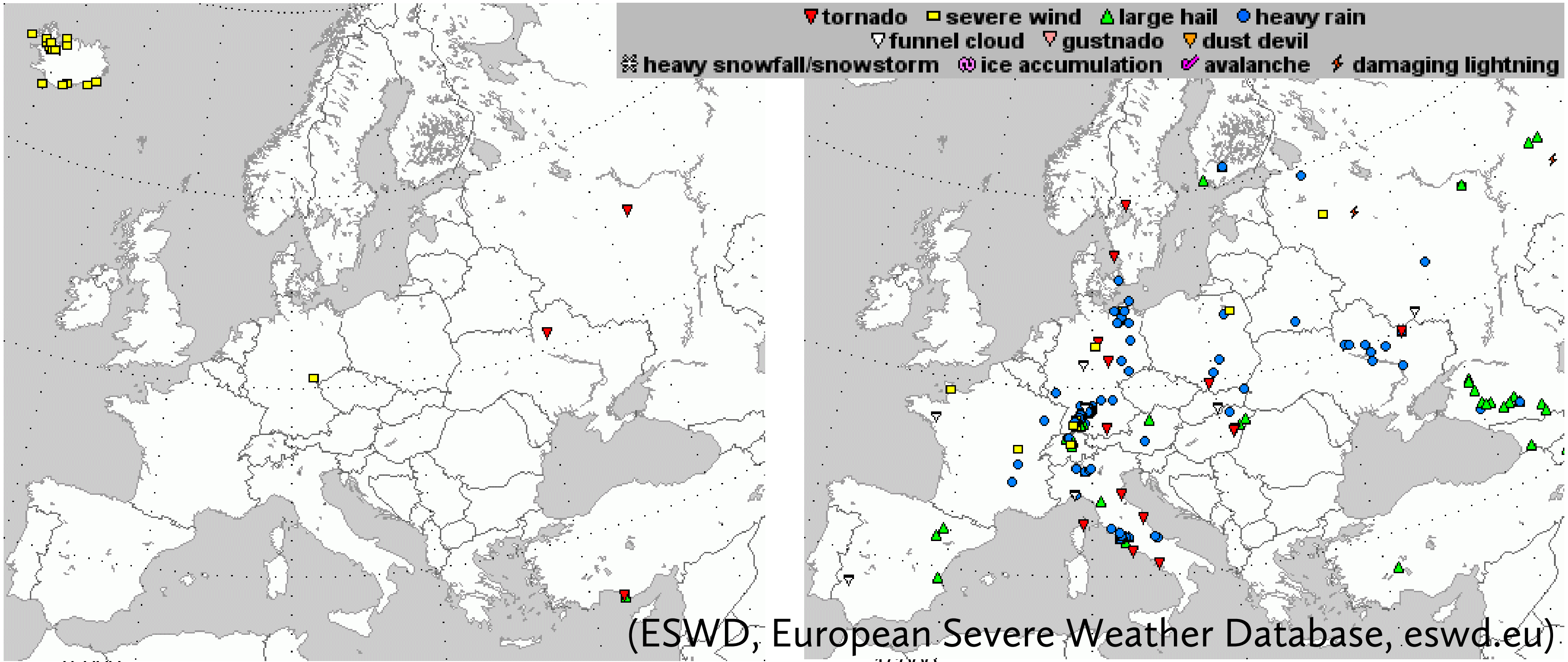
→ **large (local) perturbation** in a power grid

→ local transmission line trips → **redistribution** of power flow

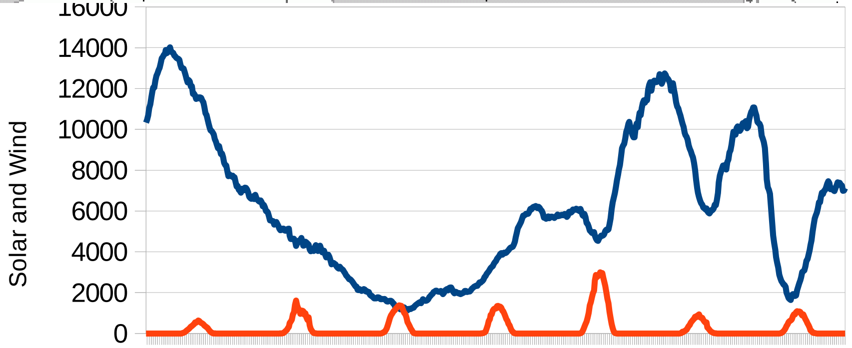
→ If grid is not resilient (cannot cope with the redistribution), further lines trip → **cascading failure** → interregional **blackout**!

→ *Make grid resilient to perturbations of all magnitudes!*

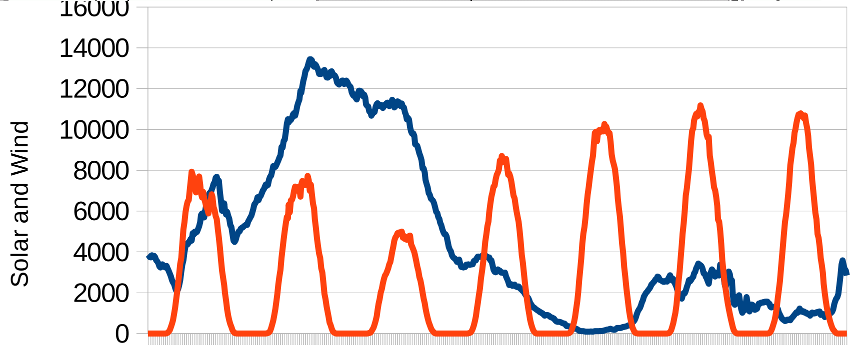
EXTREME WEATHER EVENTS



(ESWD, European Severe Weather Database, eswd.eu)



First week of 2011



Middle Week in 2011

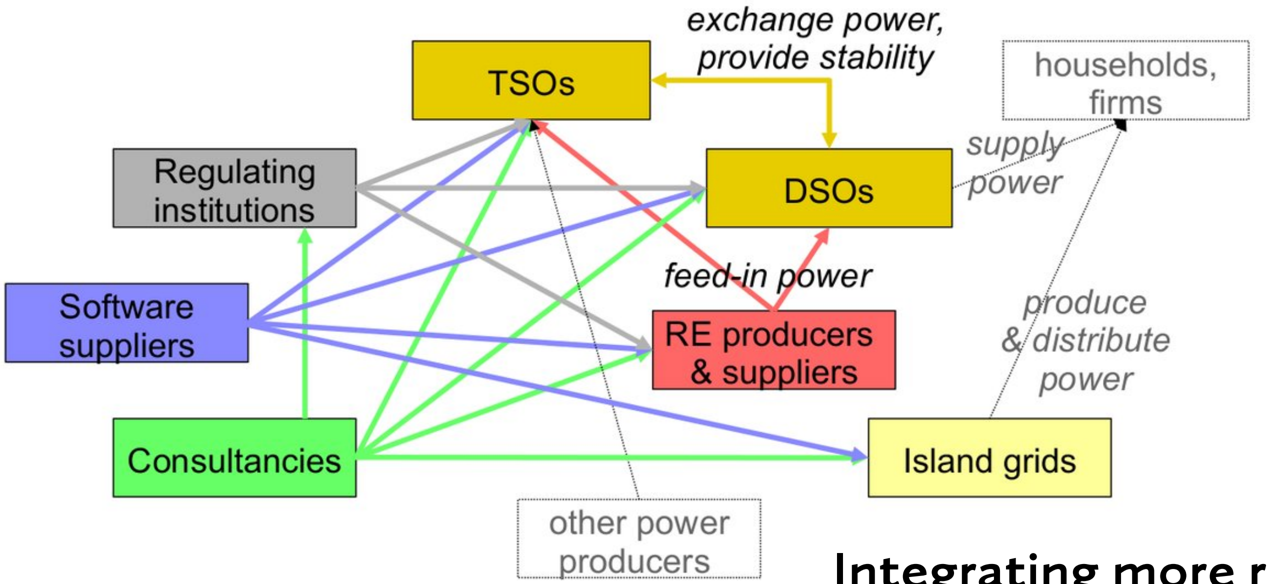
STAKEHOLDER ISSUES

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

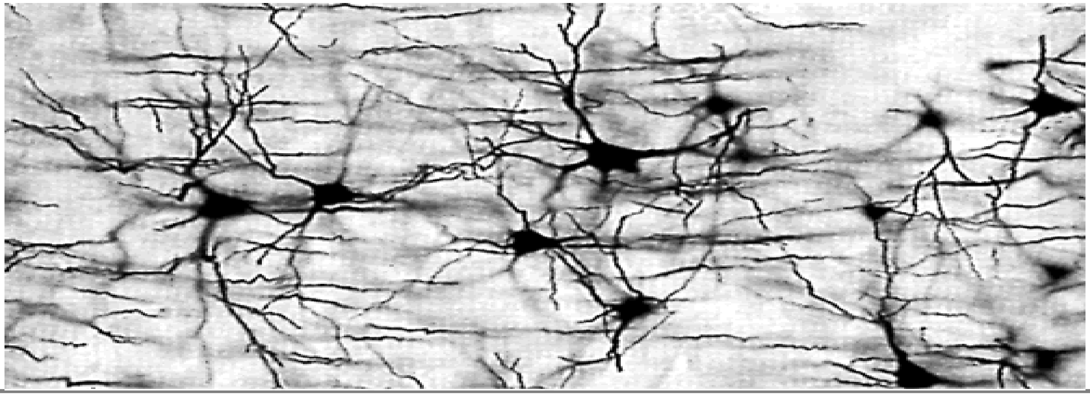
- operations: simulation timing
- planning: no. of considered variants

Integrating more renewables

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

2.

Stability and Resilience of Complex Systems

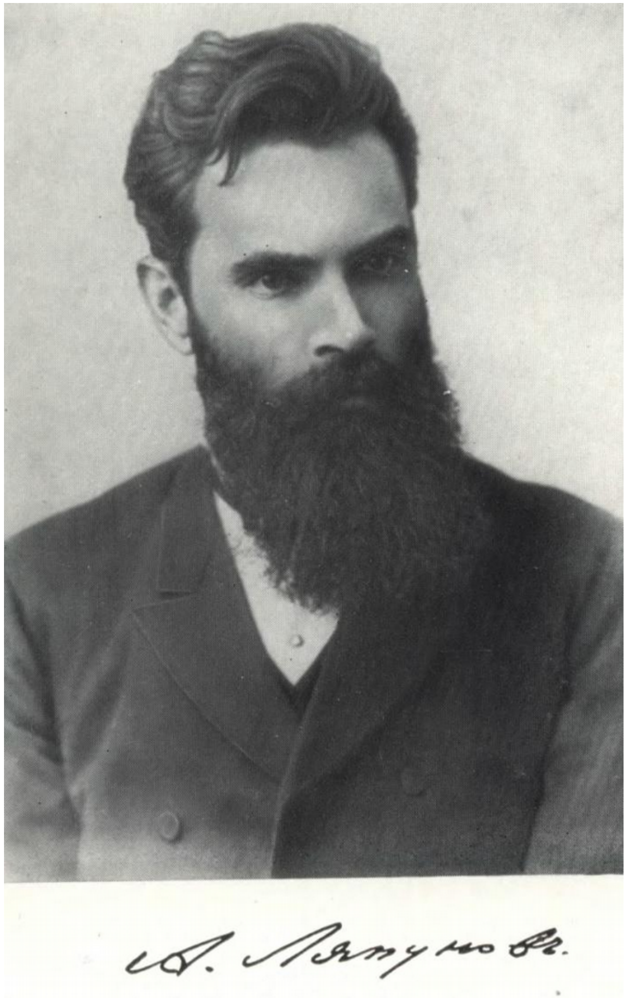


A SUCCESS STORY: STABILITY UNDER *small* PERTURBATIONS

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.



PROBLEMS WITH THIS LINEARIZATION APPROACH

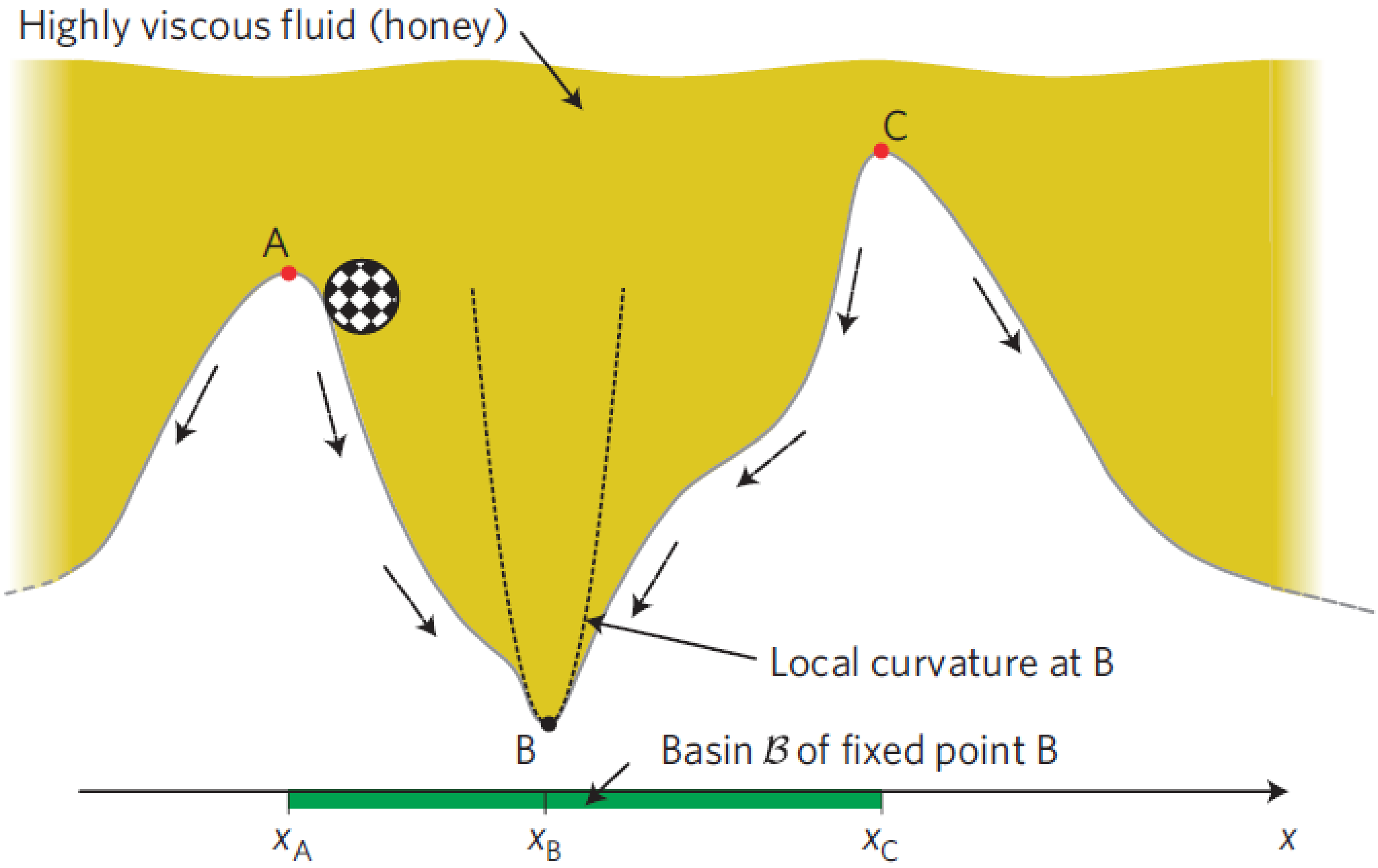
- The classification into stable, semistable, unstable is mainly **qualitative**
- *Quantification* of stability/resilience is more *difficult*

- 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!***

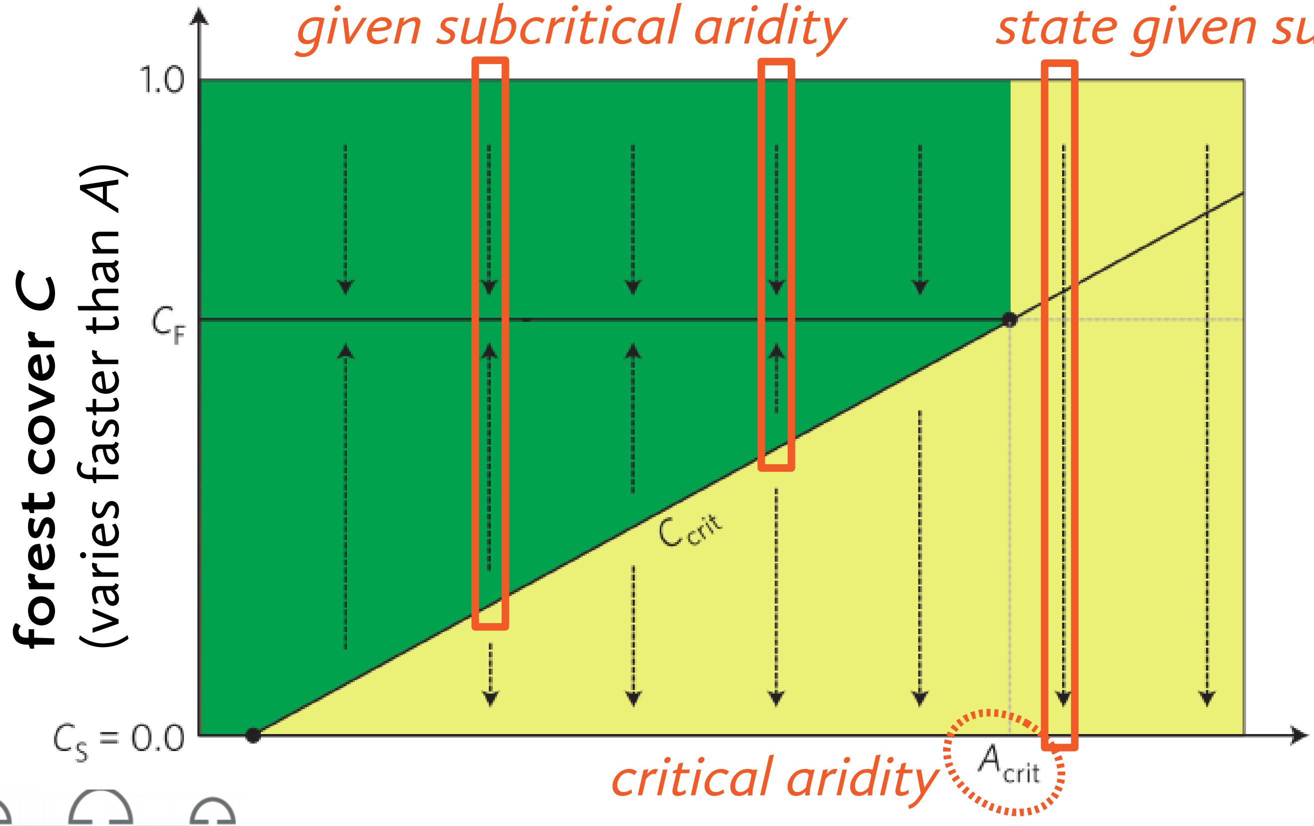
BASINS OF ATTRACTION & THE IMPACT OF *large* PERTURBATIONS

Metaphor: a marble dispersed in honey



BASIN STABILITY = SIZE OF BASIN OF ATTRACTION QUANTIFIES STABILITY

Example: simplistic model of a bistable forest/savanna



basin of attraction of forest state given subcritical aridity

basin of attraction of savanna state given supercritical aridity

forest cover *C* (varies faster than *A*)

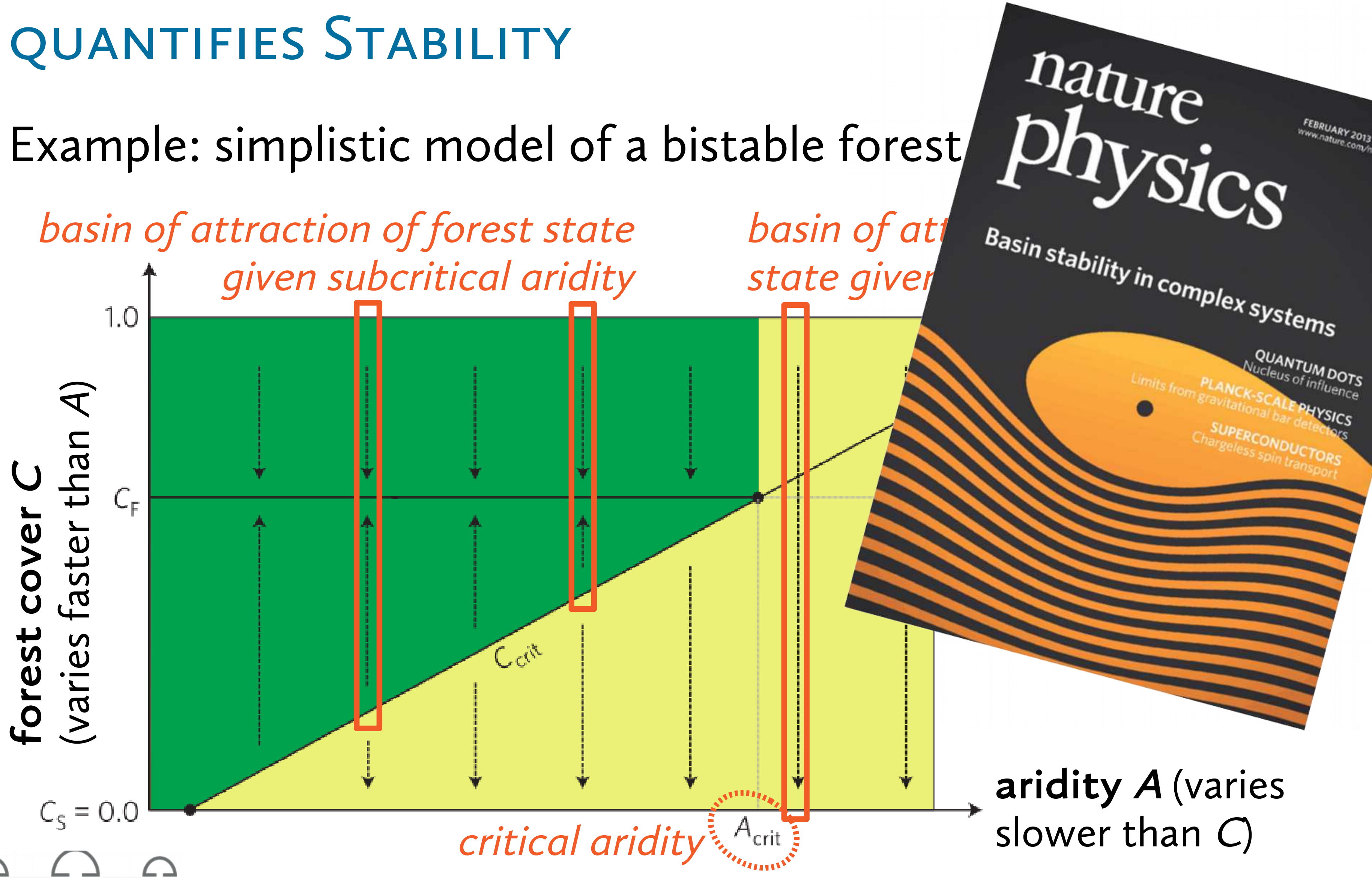
aridity *A* (varies slower than *C*)

critical aridity

Menck et al. (2013) How basin stability complements the linear-stability paradigm. *Nature Physics* 9:89–92

BASIN STABILITY = SIZE OF BASIN OF ATTRACTION QUANTIFIES STABILITY

Example: simplistic model of a bistable forest



Resilience vs. Stability

Working definition here:

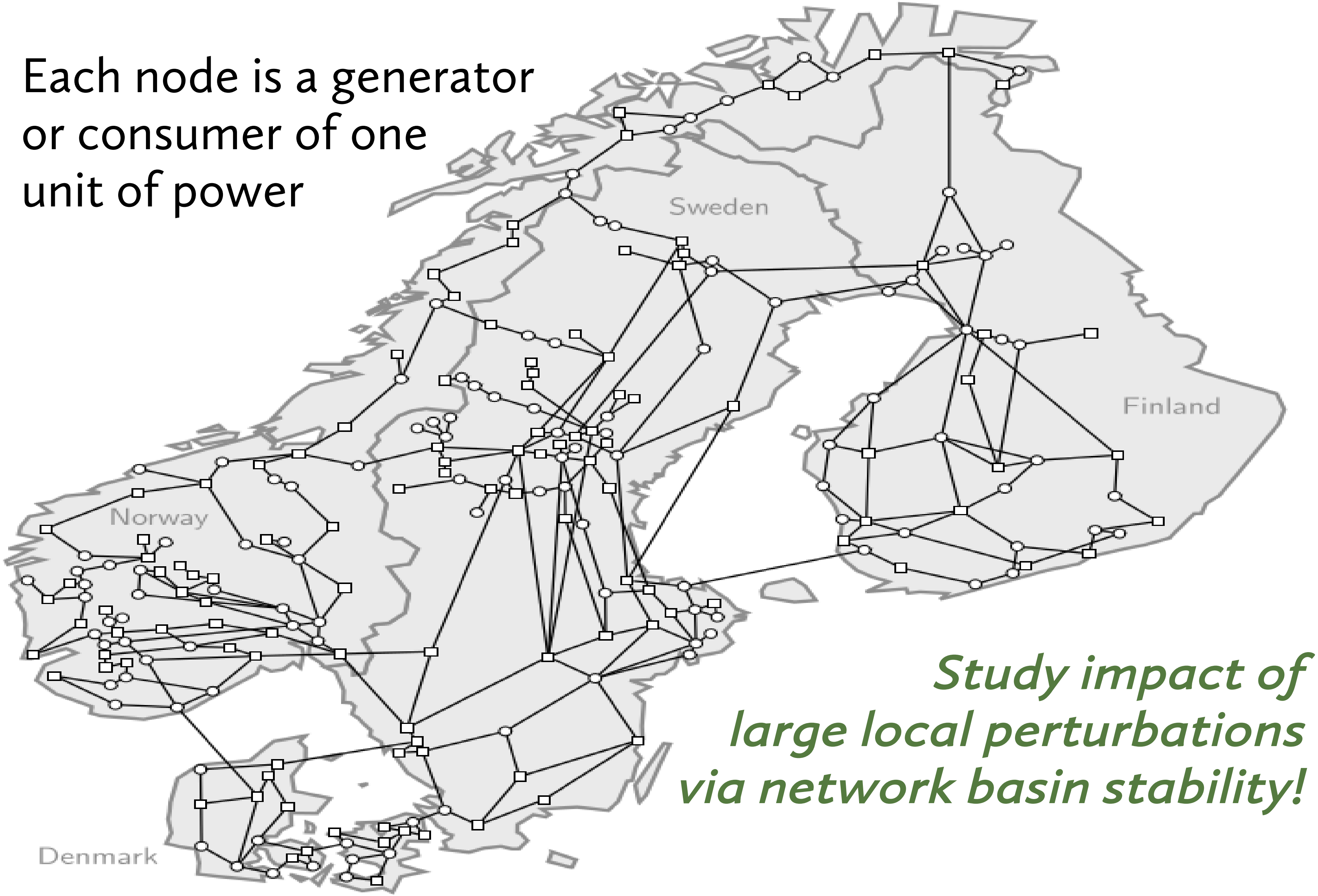
Stability = perturbations will not push the system out of its normal state for long

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

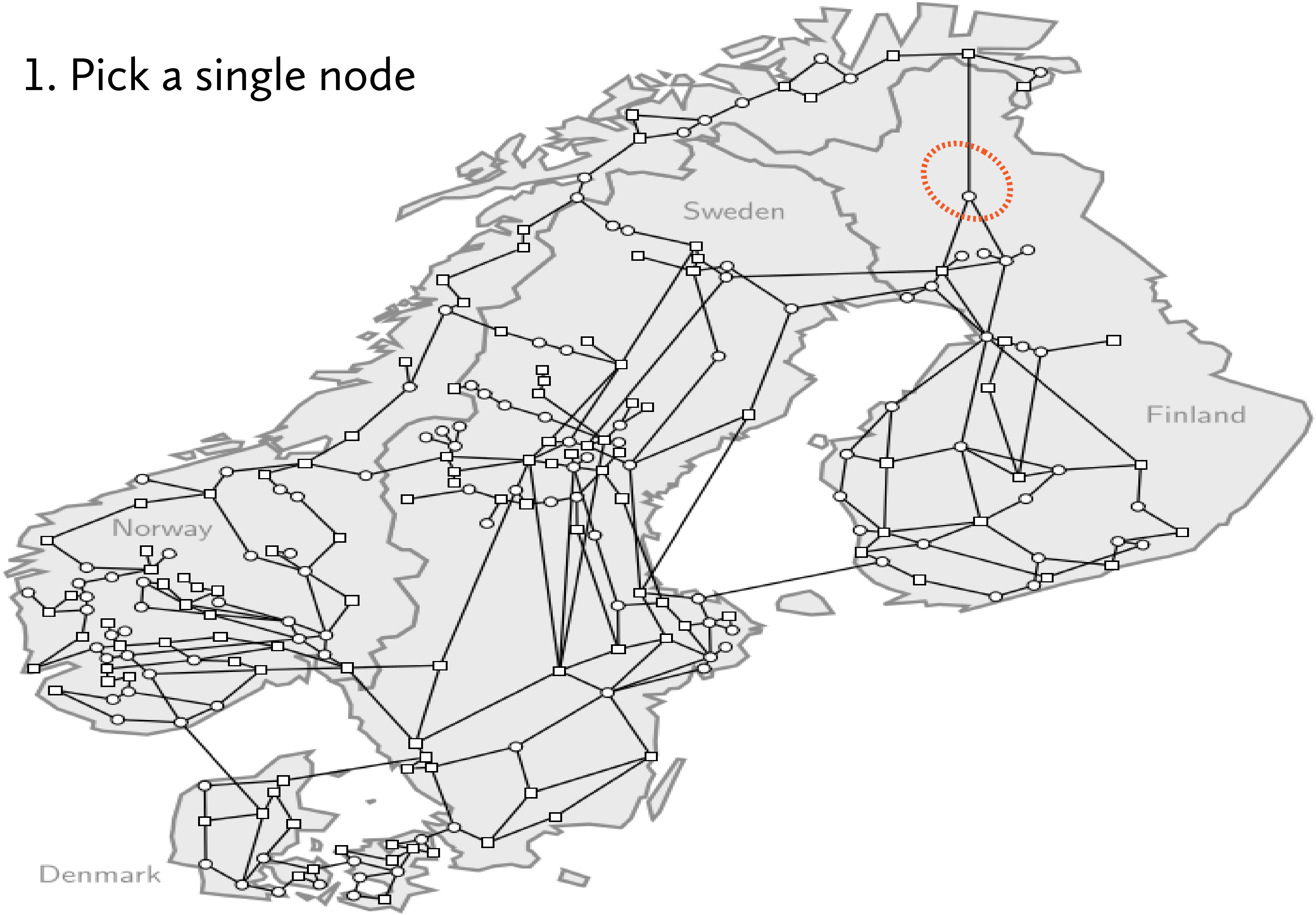


Each node is a generator or consumer of one unit of power

Study impact of large local perturbations via network basin stability!

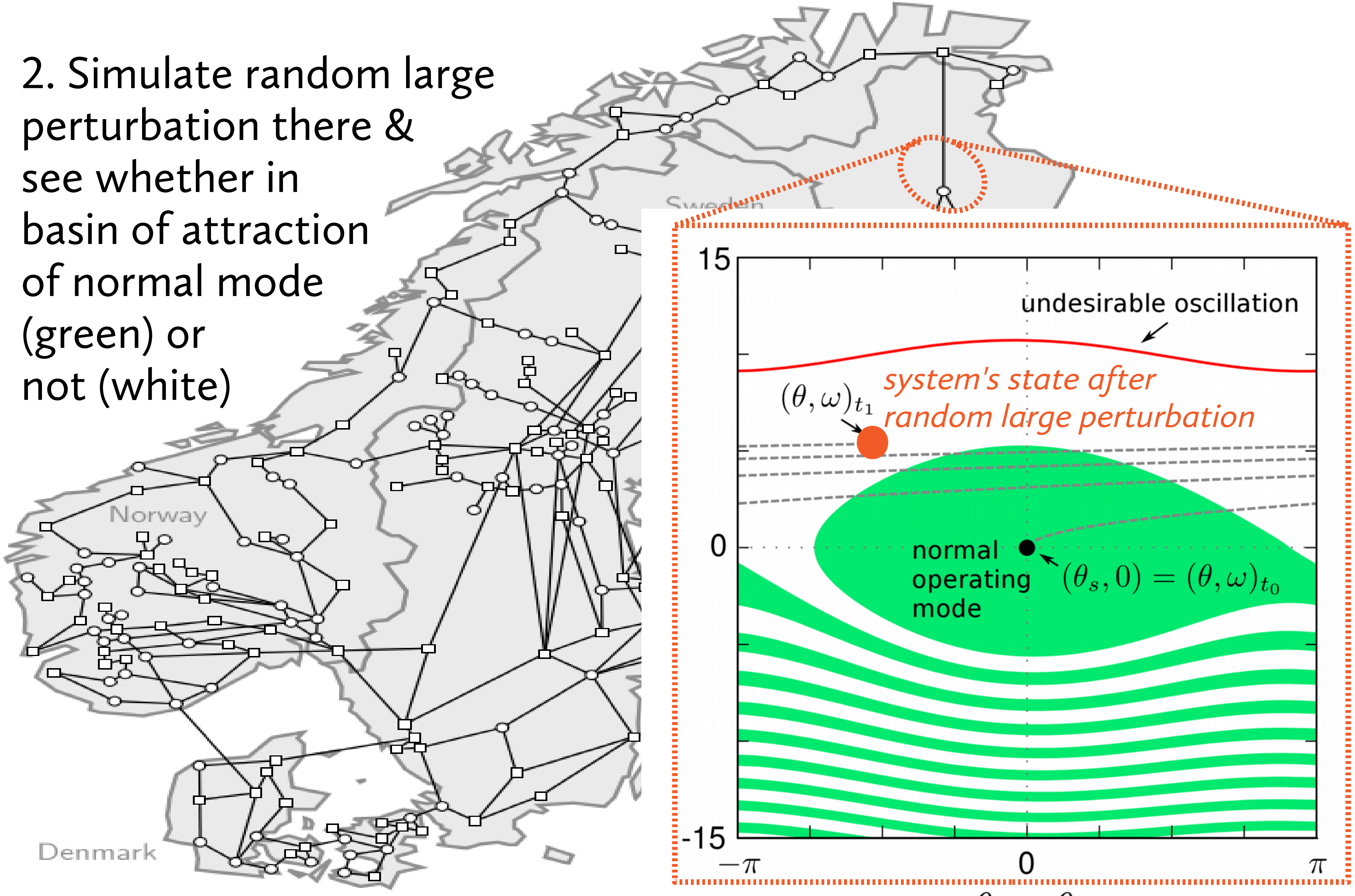
SIMULATE RETURN TO NORMAL OPERATING MODE AFTER A LARGE PERTURBATION AT A SINGLE NODE

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

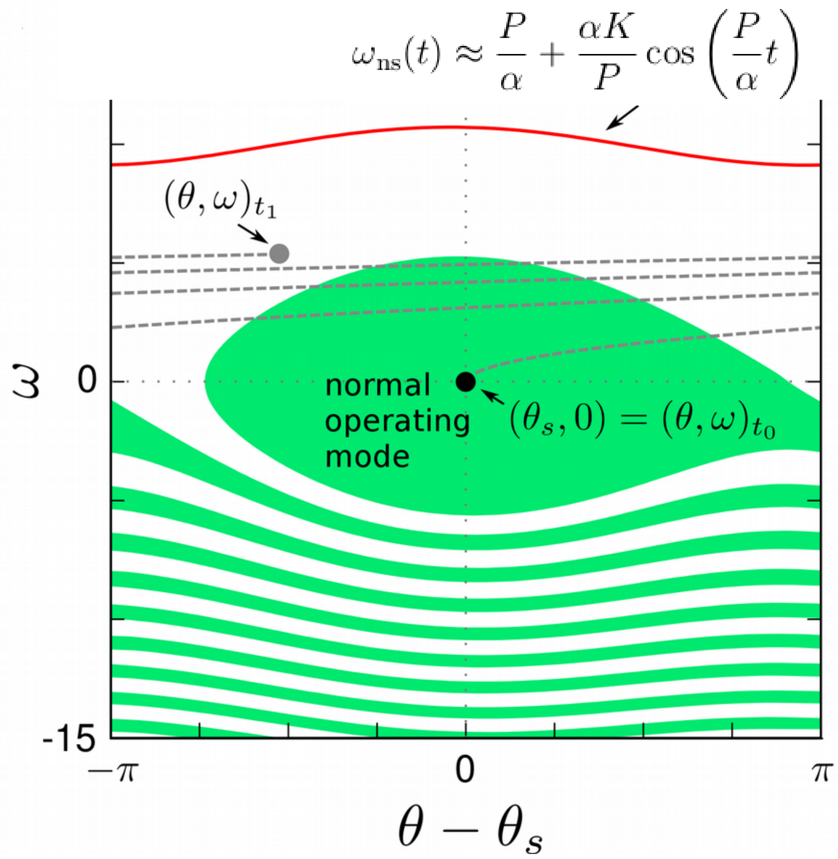
Dynamics of grid node i (simplest approx., "swing equation"/ 2nd order Kuramoto):

phase: $\frac{\mathrm{d}}{\mathrm{d}t}\theta_i = \omega_i$

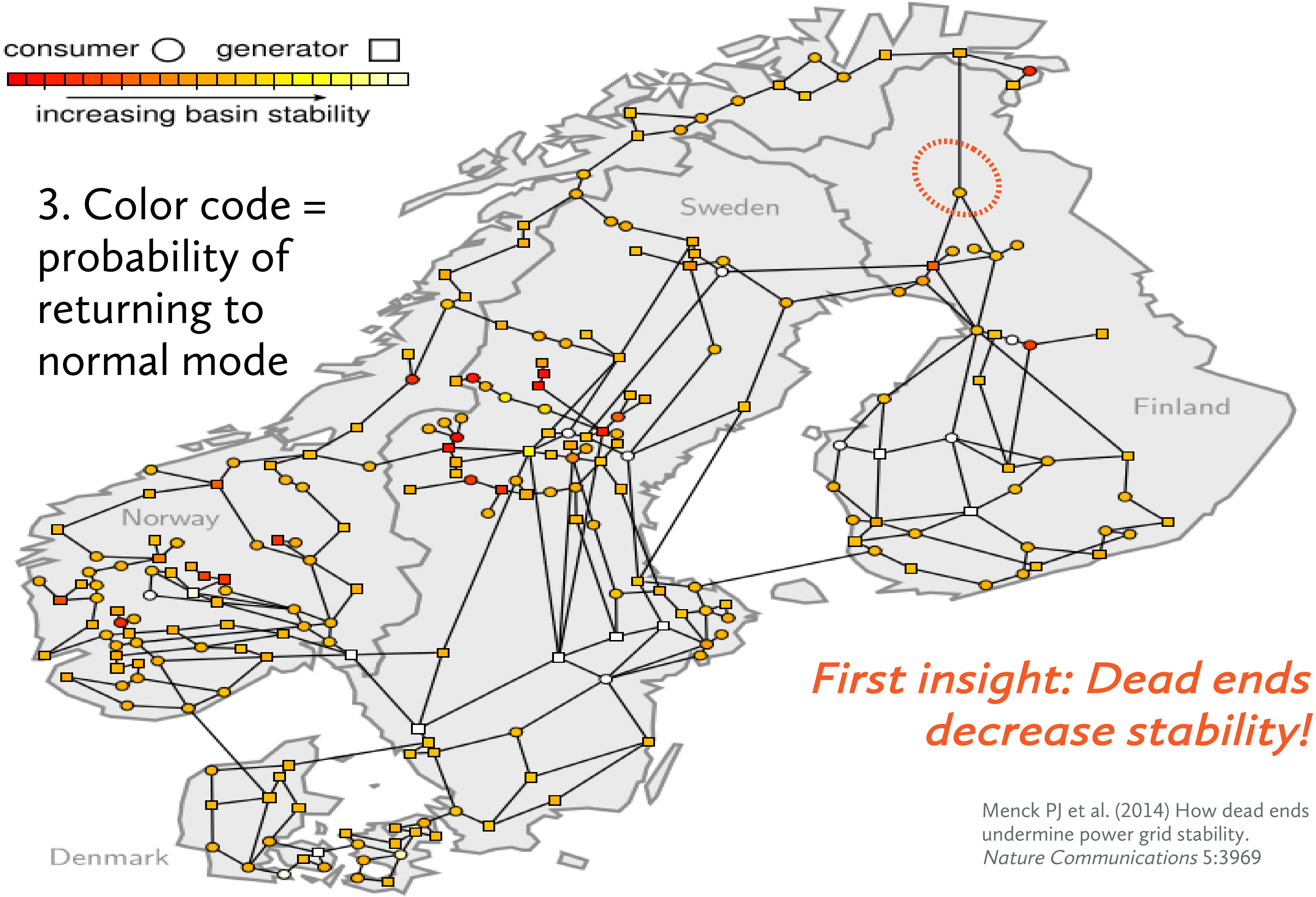
frequency: $\frac{\mathrm{d}}{\mathrm{d}t}\omega_i = P_i - D\omega_i - K \cdot \sum_j A_{ij} \sin(\theta_i - \theta_j)$

Parameters:

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



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

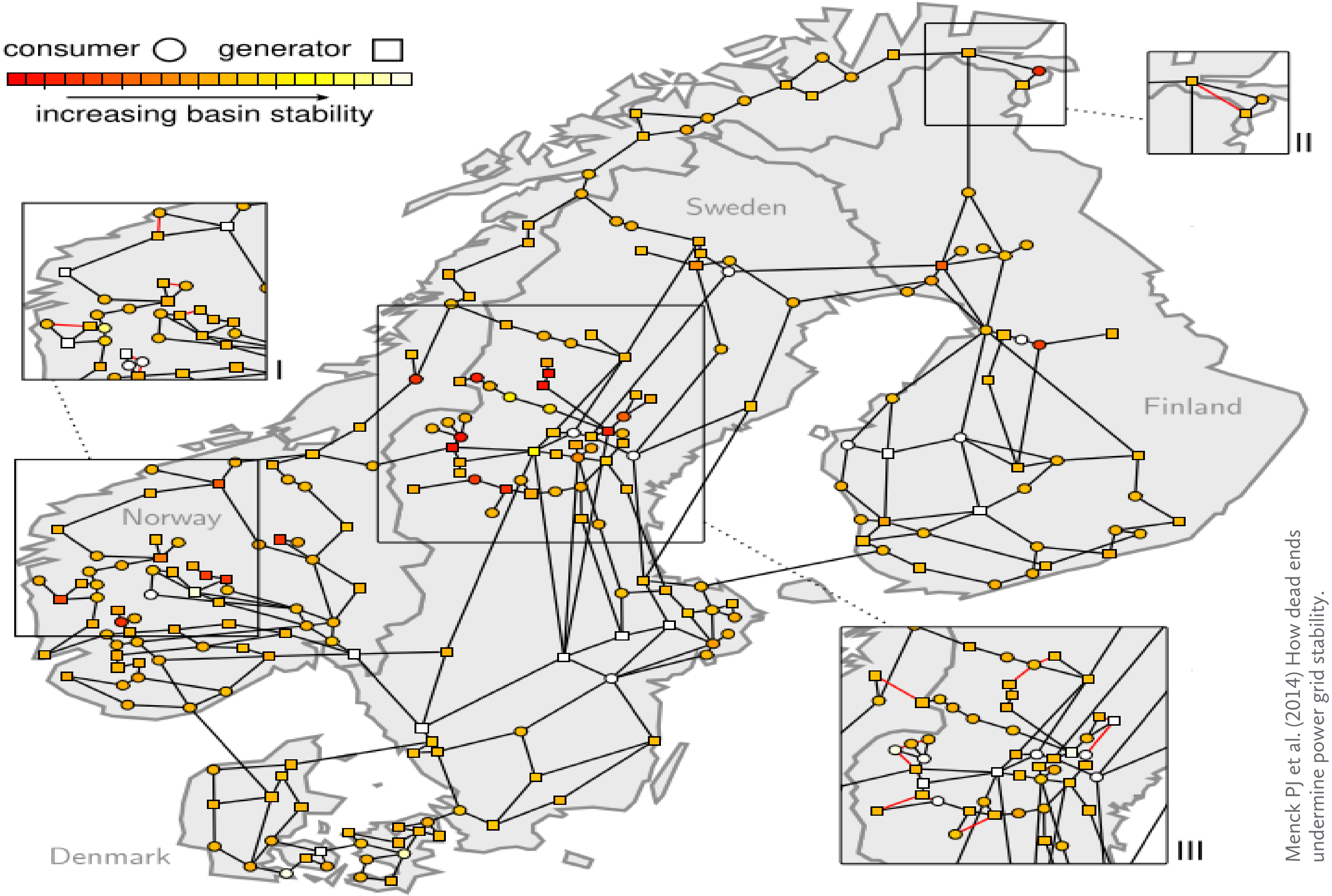


3. Color code = probability of returning to normal mode

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

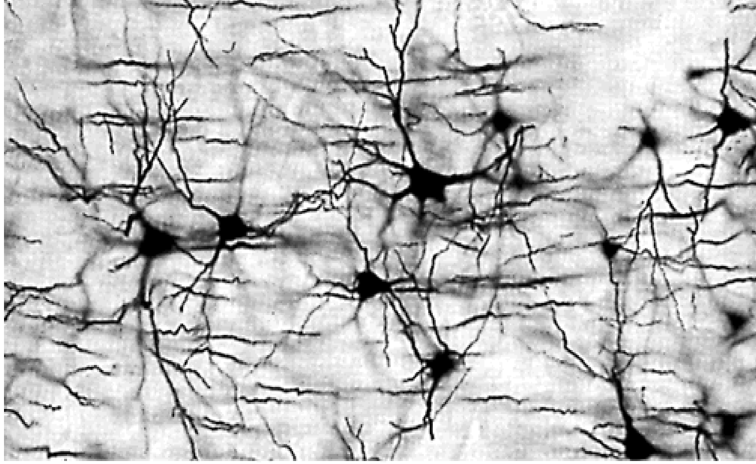


Menck PJ et al. (2014) How dead ends undermine power grid stability. *Nature Communications* 5:3969

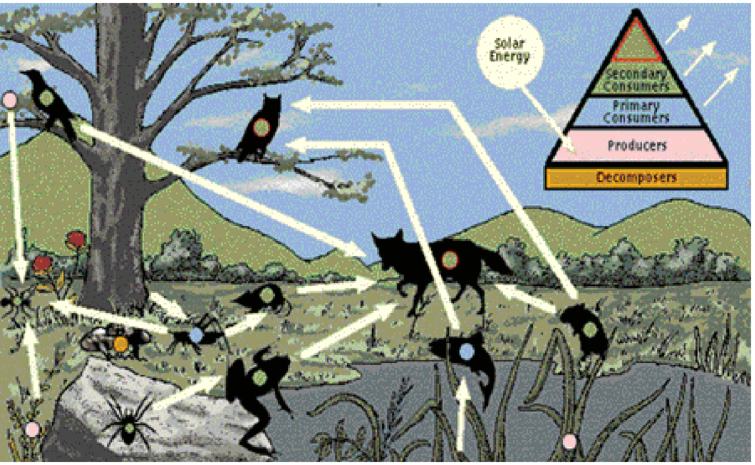
4.

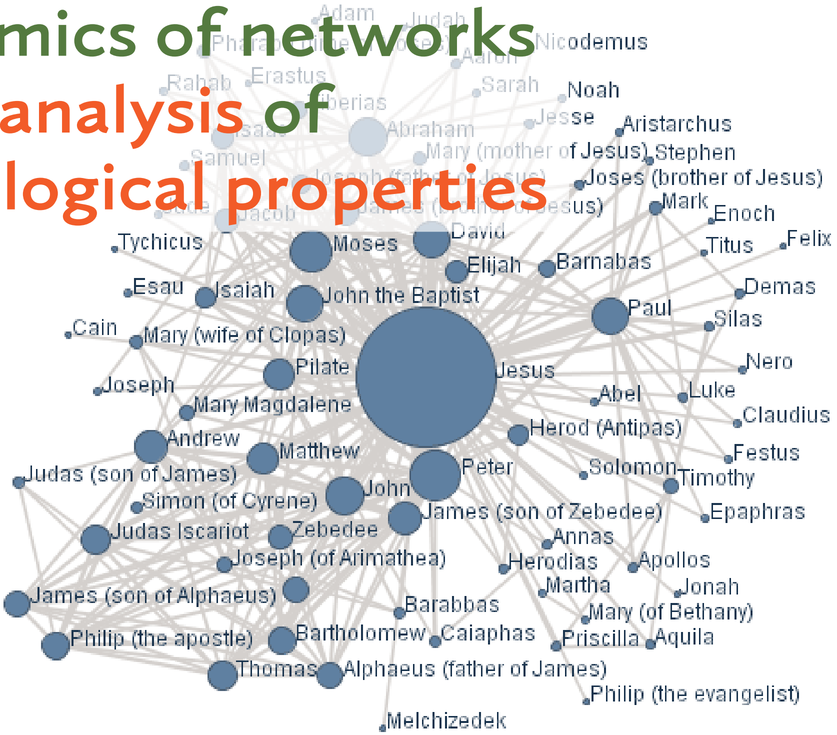
Complex Networks Analysis of Power Grids

COMPLEX NETWORK THEORY

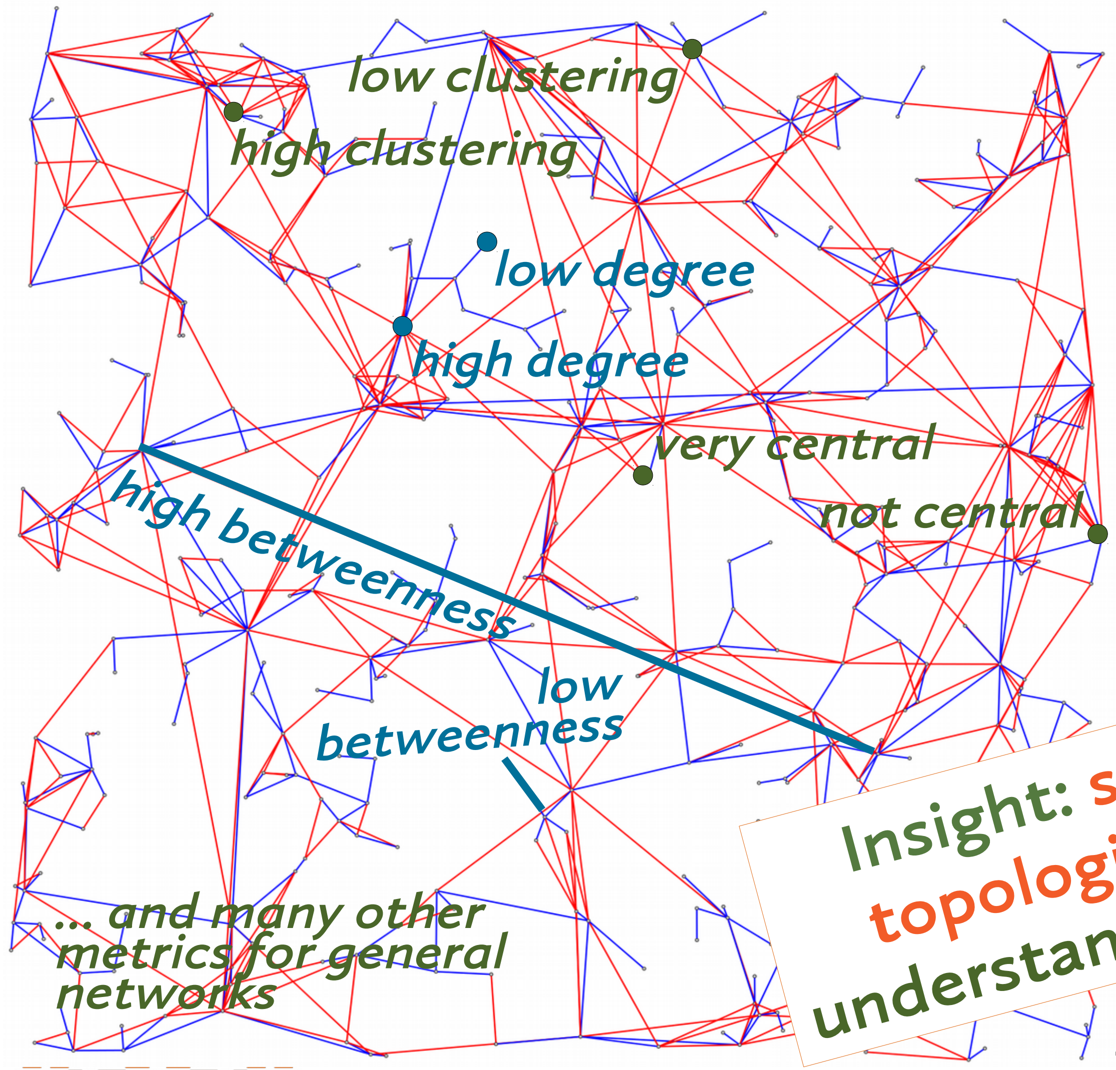


Method: study dynamics of networks via **statistical analysis** of global and local **topological properties**





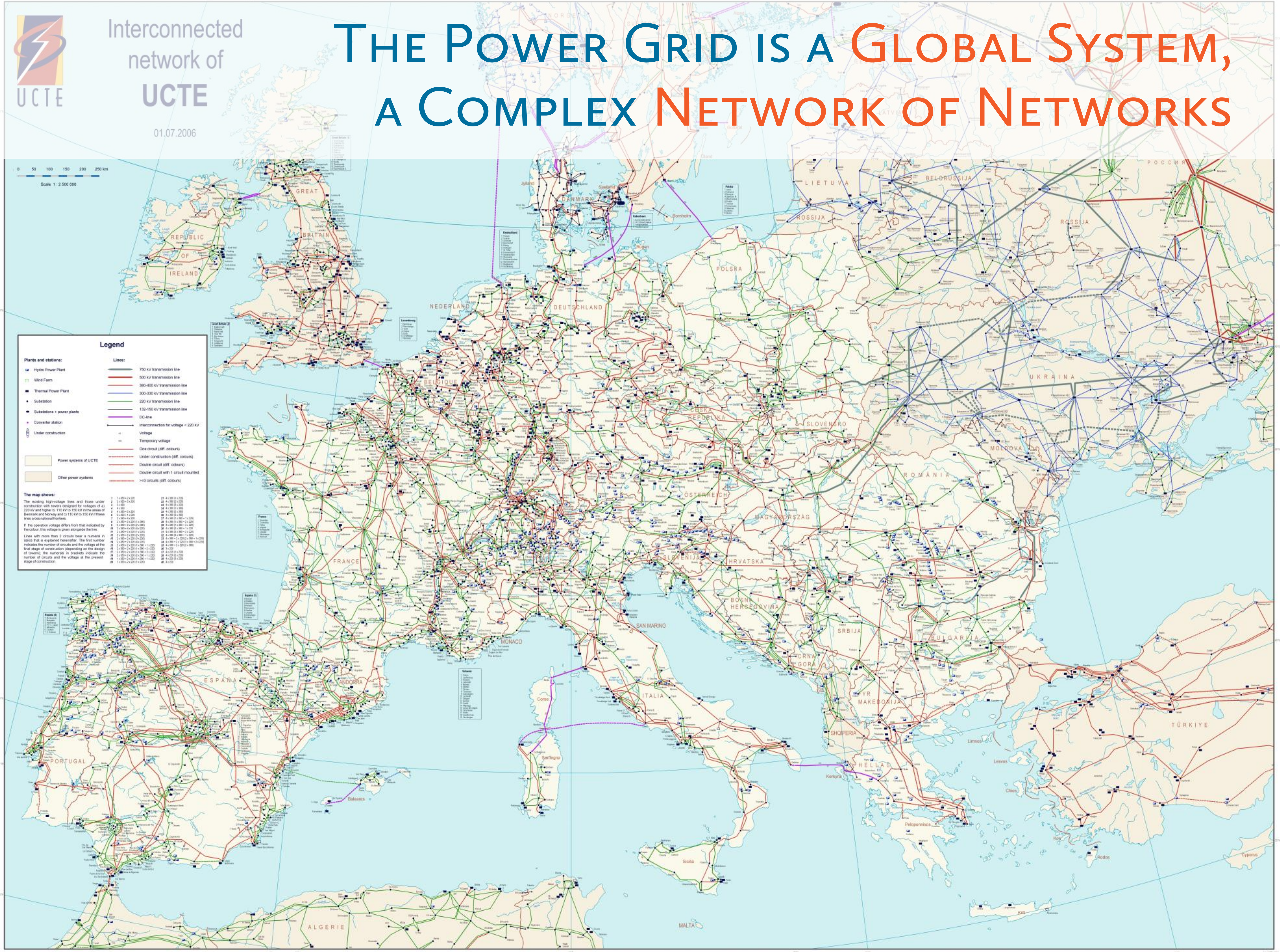
STATISTICAL ANALYSIS OF NETWORK TOPOLOGIES



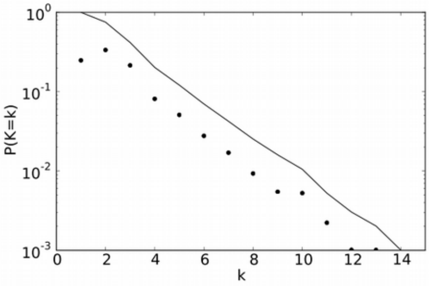
so far successfully applied to climate dynamics, neuro, trade, ...

Insight: statistical analysis of topological properties helps understanding network dynamics

The Power Grid is a Global System, a Complex Network of Networks



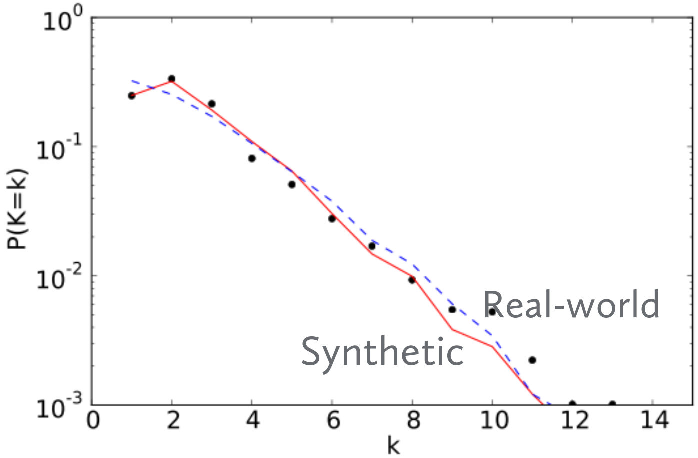
CHARACTERISTICS OF POWER GRID TOPOLOGIES



- 50 – 10,000 nodes
- Exponential degree distribution $p_k \sim e^{-k/\gamma}$ with 1.5 < γ < 2 → *not Erdös-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(√N) due to spatial embedding → *not small-world*
- **Low clustering** coefficient → *not "random geometric"*

→ *how to generate synthetic grids for simulations?*

MODEL FOR GENERATING SYNTHETIC POWER GRID TOPOLOGIES



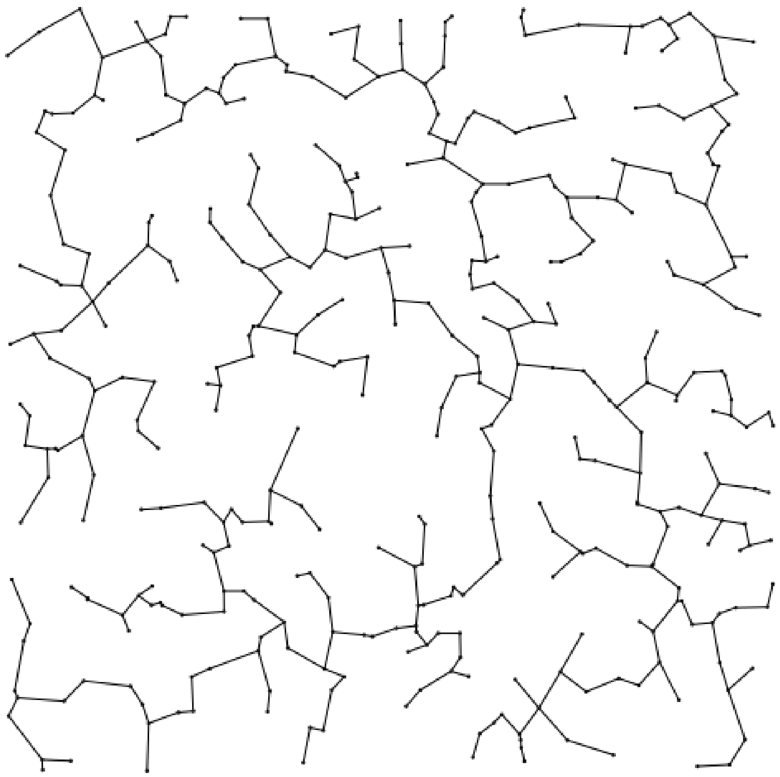
- **Initial layout**
  - given initial node locations,
  - construct the “minimal spanning tree
  - then add some redundant lines
- **Growth phase**
  - either connect a new node to the closest existing node
  - and to some other node for redundancy
  - or put a new node somewhere along an existing line
- **Trade off between global and local redundancy**
  - by maximizing $(1 + \textit{internal grid distance})^r / (\textit{spatial distance})$
  - where r is a redundancy control parameter

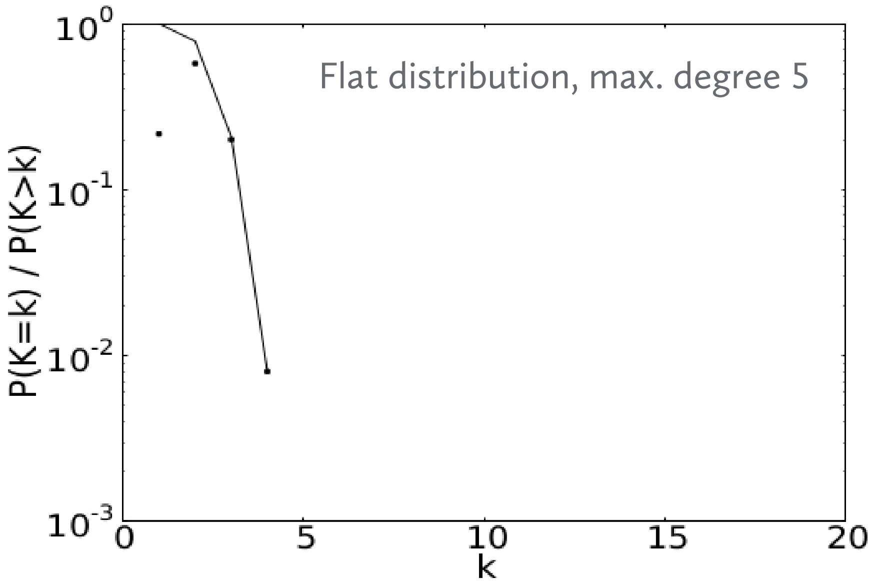
Schultz et al. (2014) A Random Growth Model for Power Grids and Other Spatially Embedded Infrastructure Networks. *EPJ ST* 223(12):2593–2610

MINIMAL SPANNING TREE (MST)

- optimizes one-time construction costs
- no redundant lines

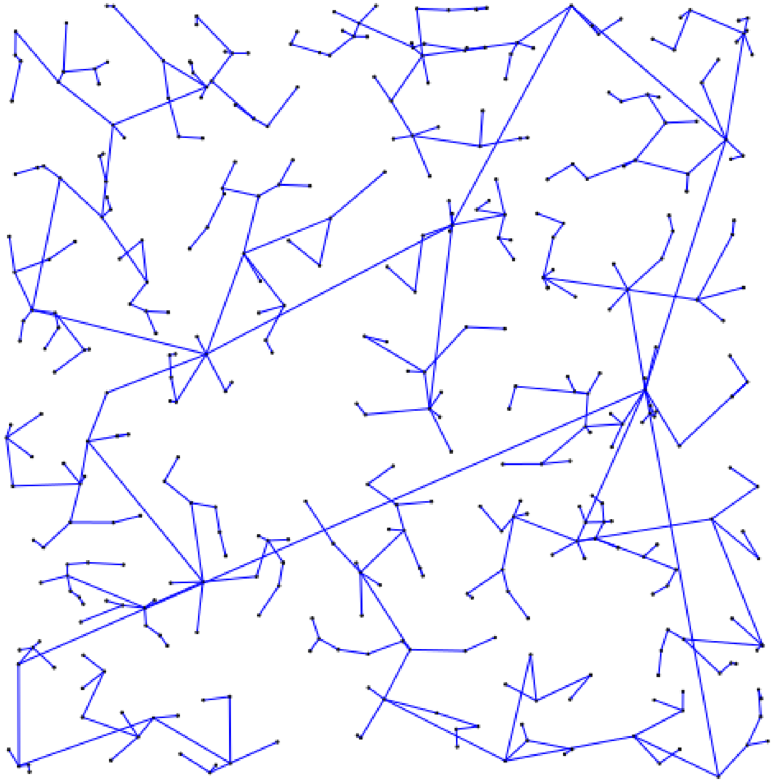
→ one tripping line already causes a partial blackout

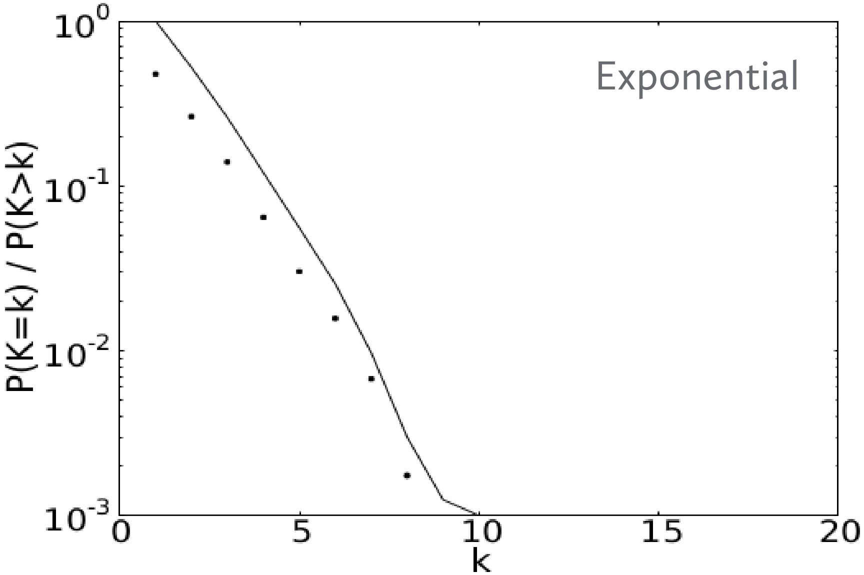



Flat distribution, max. degree 5

GROWN TREE, LINK TO NEAREST NEIGHBOUR

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





MST +
Global Redundant Lines

(large *r* parameter)

- meshlike structure, many “large” circles

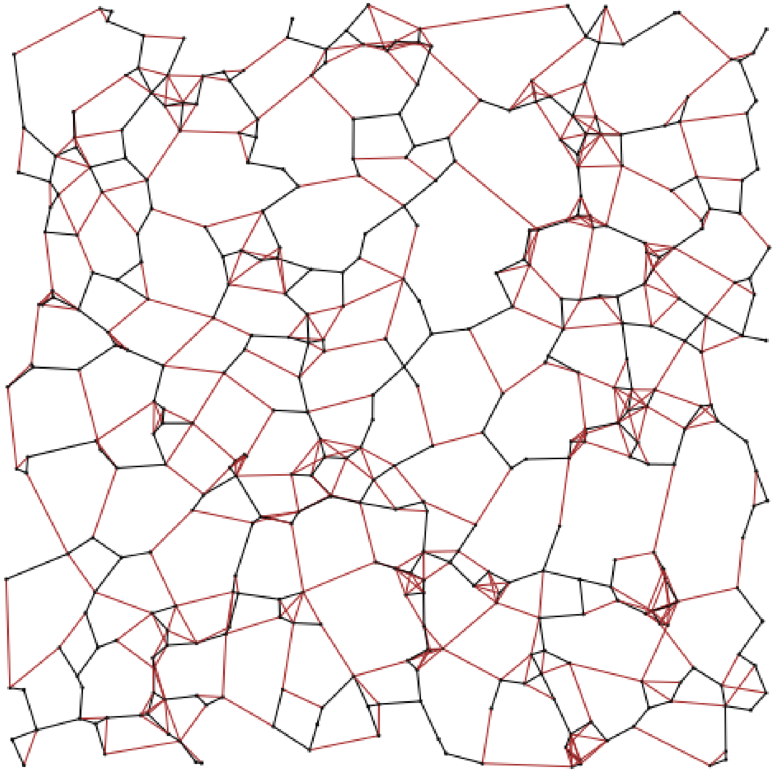
→ very few dead ends

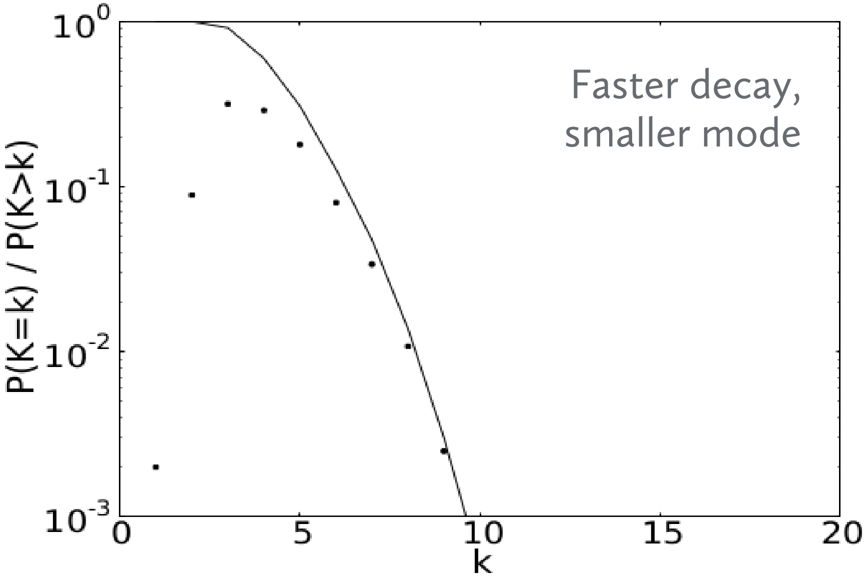
→ improved basin stability

but:

- few triangles

→ cascading failures may occur





Faster decay, smaller mode

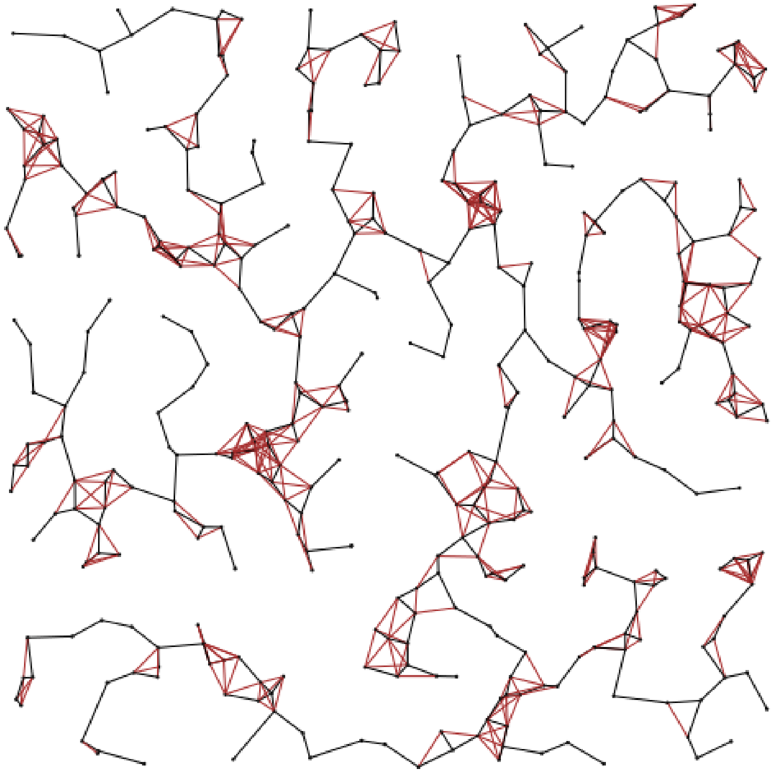
MST + LOCAL REDUNDANT LINES

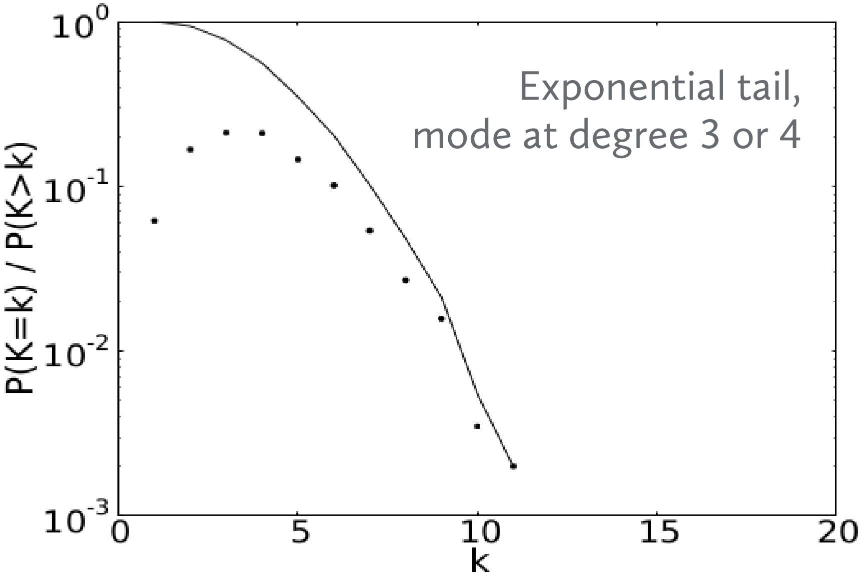
(small *r* parameter)

- many triangles

→ flow through tripping line
  is redistributed to
  few other lines

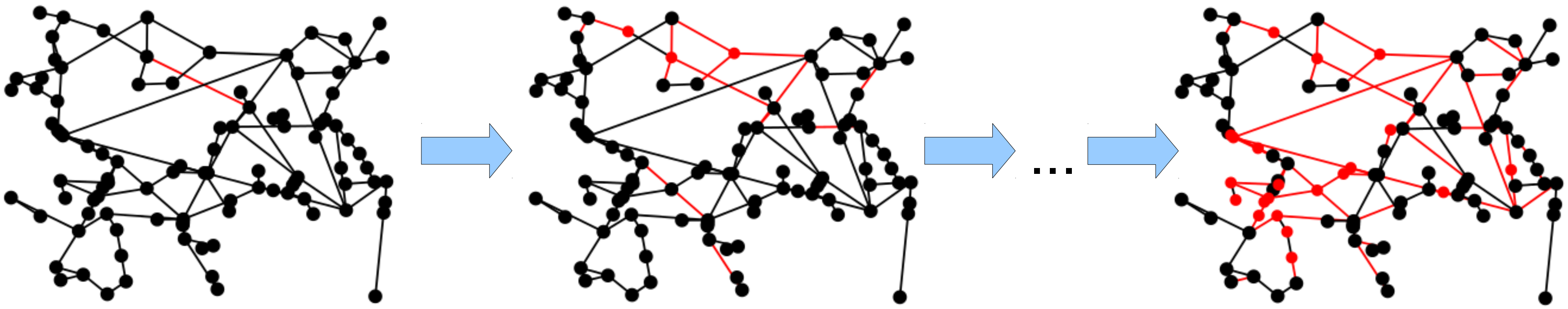
→ long failure cascades less likely

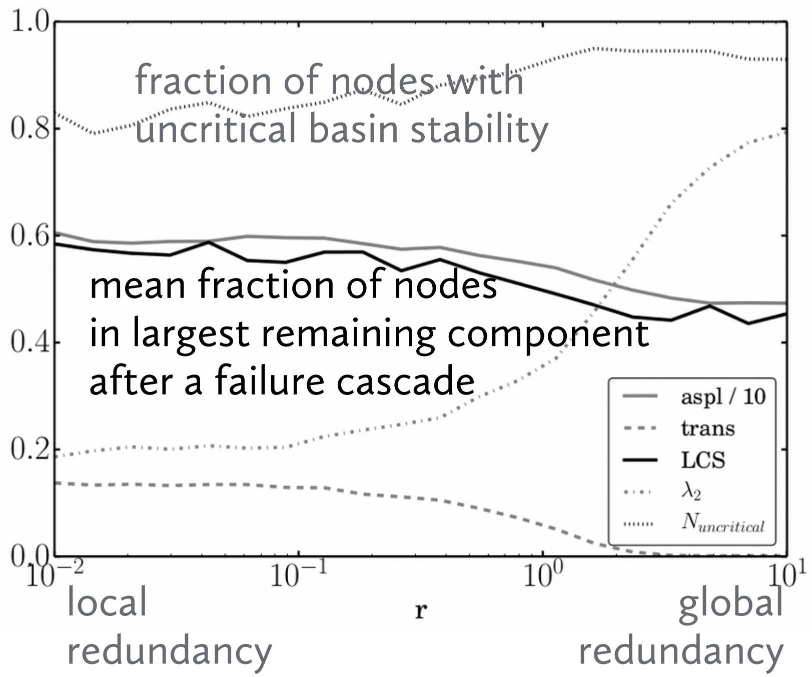




Exponential tail,
mode at degree 3 or 4

Resilience Against Cascading Failures vs. Basin Stability




fraction of nodes with uncritical basin stability

mean fraction of nodes in largest remaining component after a failure cascade

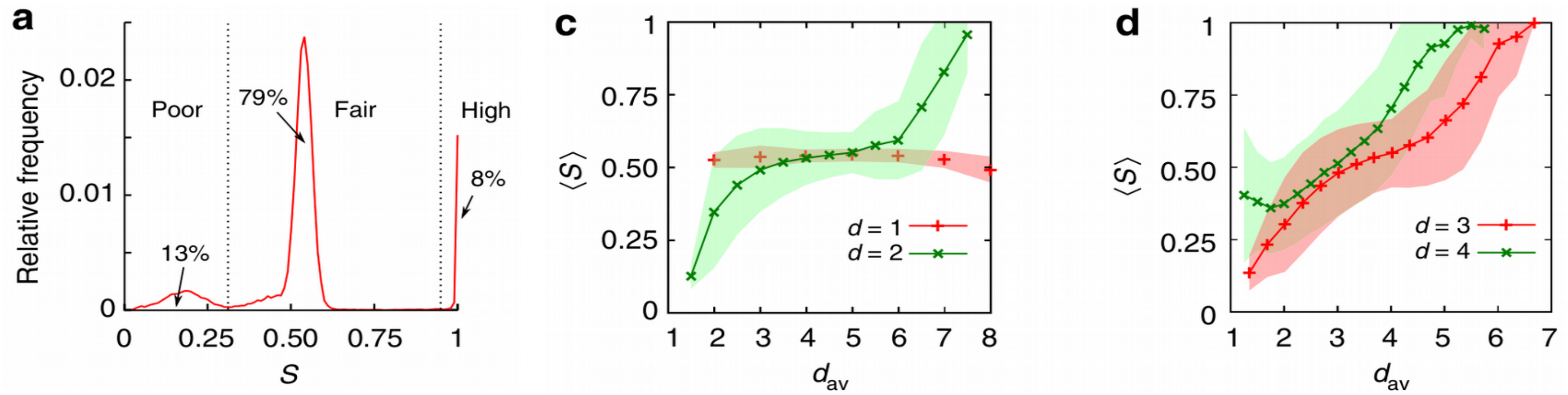
local redundancy

global redundancy

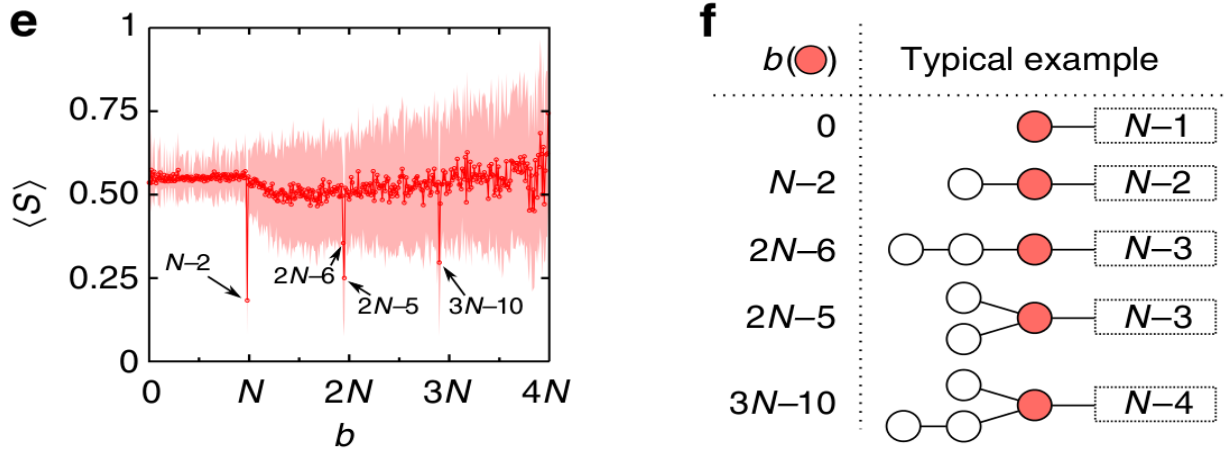
Plietzsch A, Schultz P, Heitzig J, Kurths J (2015) Local vs global redundancy – tradeoffs between resilience against cascading failures and frequency stability. Submitted to *EPJ ST*

RELATIONSHIP BETWEEN BASIN STABILITY AND STANDARD NETWORK STATISTICS

Relationship to *average neighbour's degree*



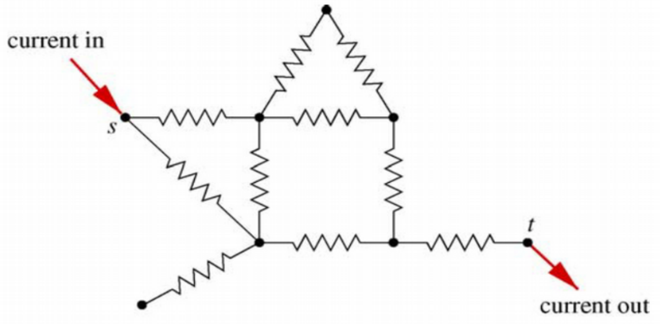
Relationship to *shortest path betweenness*

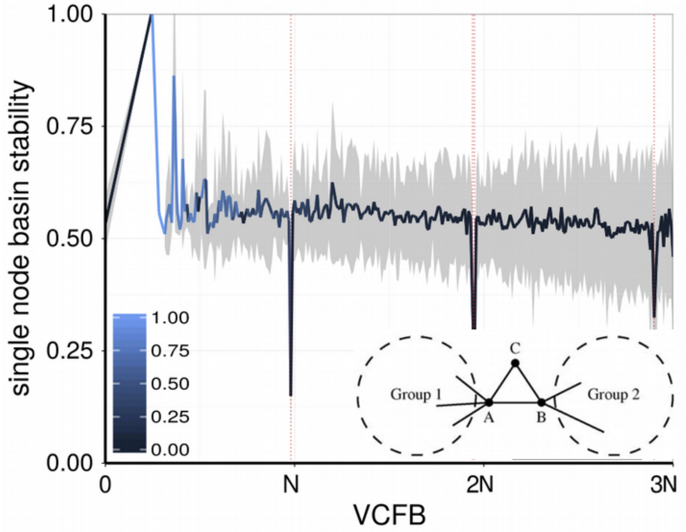


Menck PJ et al. (2014) How dead ends undermine power grid stability. *Nature Communications* 5:3969

Even Clearer Relationship to Specially Adapted Network Statistics

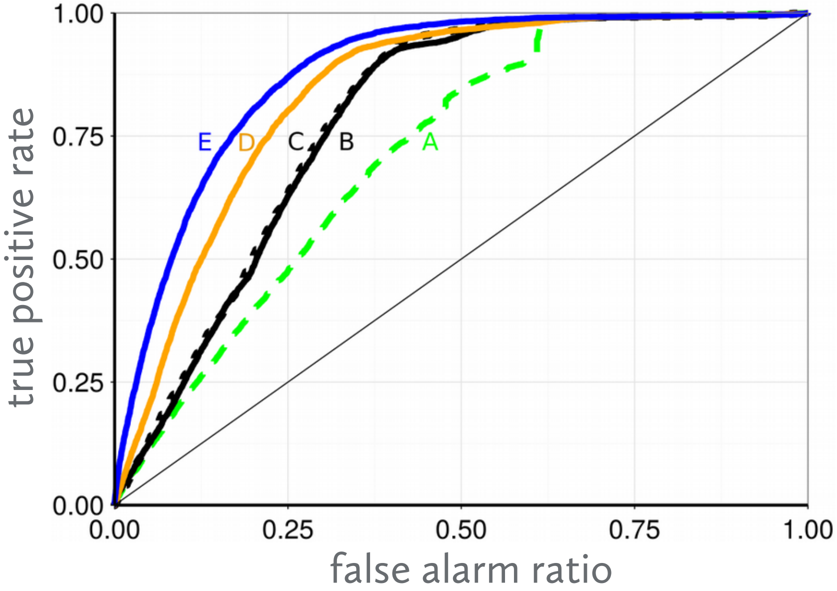
current flow betweenness
(Newman, Social Networks 2005)





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

ROC:



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)

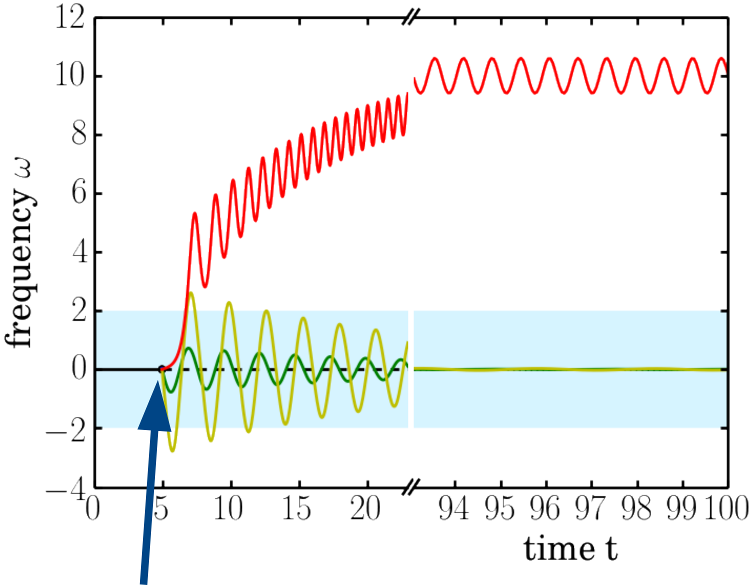
- **"Detour" nodes**: *produce!*
  - e.g. connect neighbours of hubs with each other (local redundancy)

6.

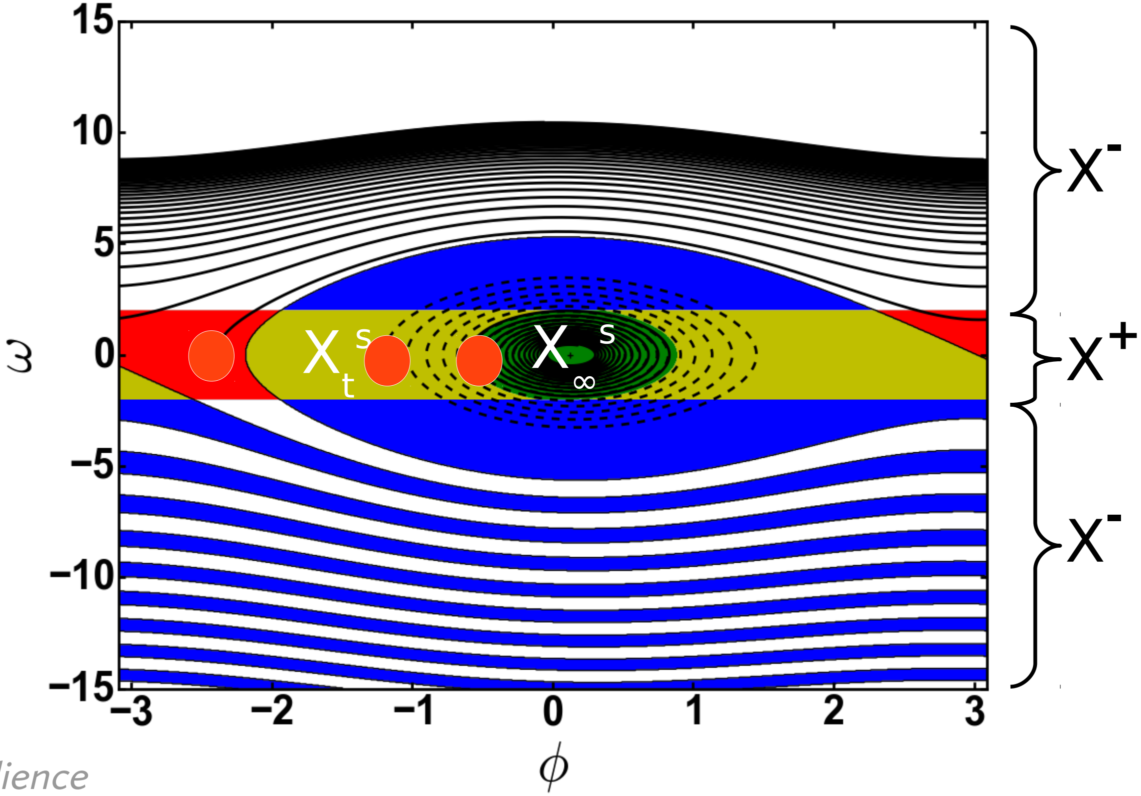
Outlook

TRANSIENT BEHAVIOUR: FROM BASIN STABILITY TO *SURVIVABILITY*

survivability = P (system stays in desired region | random perturbation)



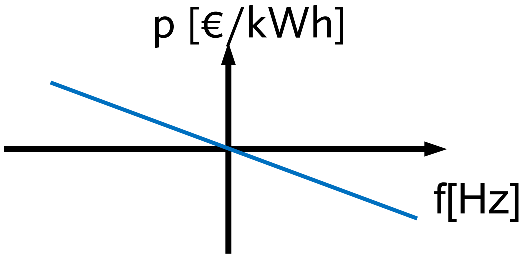
three different perturbations



F. Hellmann, P. Schultz, C. Grabow, J. Heitzig and J. Kurths: *Survivability: A Unifying Concept for the Transient Resilience of Deterministic Dynamical Systems.* arXiv:1506.01257 [nlin.AO]

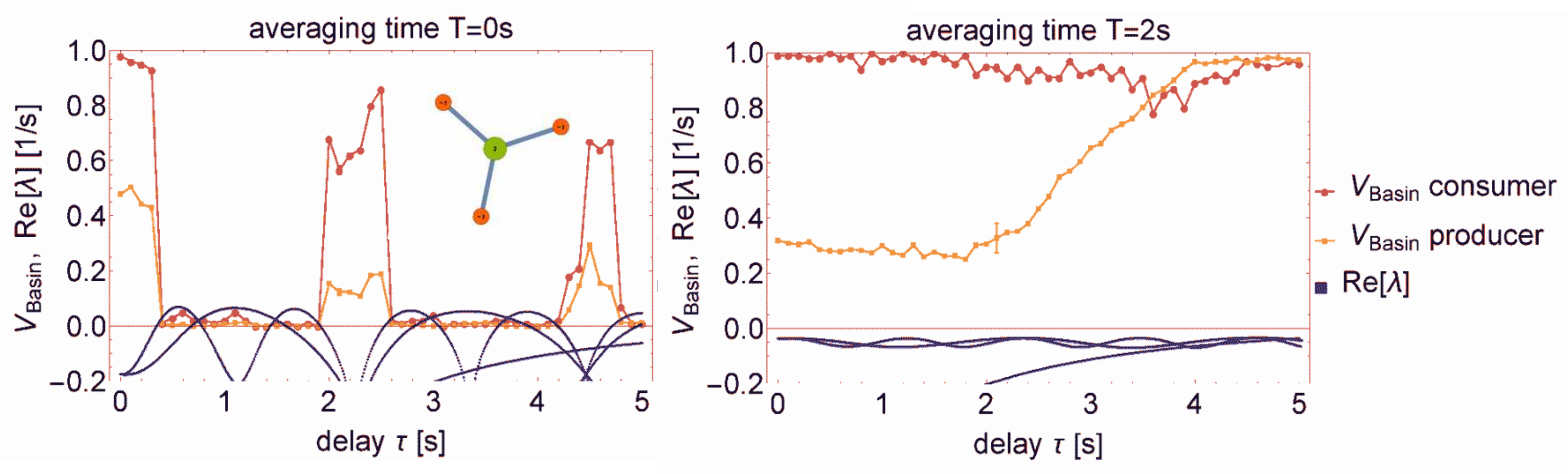
Decentral Smart Grid Control

Idea: make *price* (and thus demand) a linear function of past *frequency*



$$\dot{\omega}_i = \boxed{P_i - \gamma\omega_i(t-\tau)} - D\omega_i - K\sum_j A_{ij}\sin(\theta_i - \theta_j)$$

Delay induces resonances → „healed“ by averaging



B. Schäfer, C. Grabow, S. Auer, D. Witthaut, M. Timme. Taming Instabilities in Power Grid Networks by Decentralized Control (2015). Submitted to EPJ.

MORE REALISTIC MODEL OF NODE DYNAMICS: PHASE & FREQ. → PHASE, FREQ. & *VOLTAGE*

$$V = E_d + iE_q$$

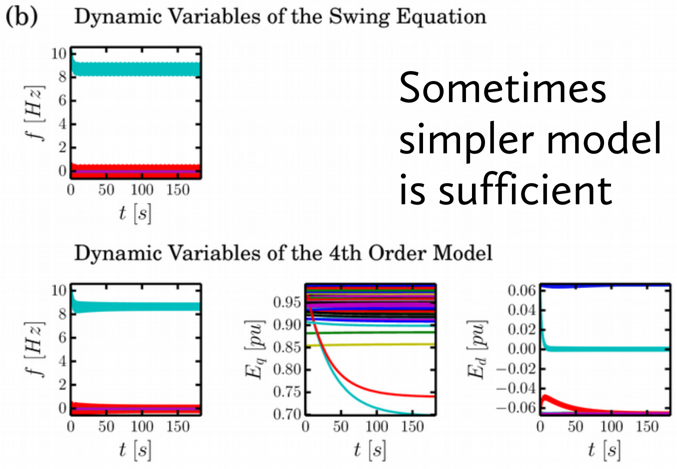
$$\frac{d\phi_i}{d\tau} = \omega_i,$$

$$\frac{d^2\phi}{d\tau^2} = P_i - (E_{q,i}I_{q,i} - E_{d,i}I_{d,i}) - \alpha_i\omega_i$$

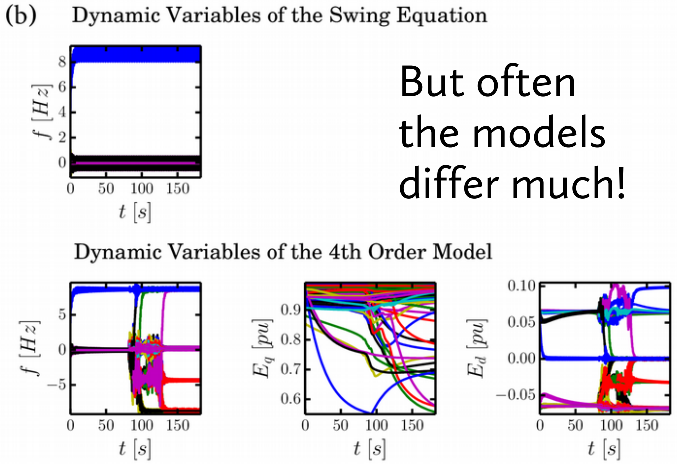
$$T_{d,i}\frac{dE_{q,i}}{d\tau} = -E_{q,i} + X_{d,i}I_{d,i} + E_f,$$

$$T_{q,i}\frac{dE_{d,i}}{d\tau} = -E_{d,i} + X_{q,i}I_{q,i},$$

$$I_i = \sum_{j=1}^{N} K_{ij}V_j e^{i(\phi_j - \phi_i)}$$



Sometimes simpler model is sufficient



But often the models differ much!

S. Auer, K. Kleis, P. Schultz, J. Kurths, F. Hellmann: Model Detail for large perturbation studies of power grids. *In preparation*.

Publications

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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!

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