WWU MÜNSTER

ESAC Seminar 26.07.2018

Complexity Meets Energy

From Power Grids To Turbulence

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Münster

Population (2016-12-31): 311846 (growing)

Students: ~ 60000 (one of few typical „student cities“)

Fifth largest university

Treaty of Westphalia ending the Thirty Years' War in 1648

(starting of rumors about bad weather)

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The Center for Nonlinear Science

Goal: Start / enhance interdisciplinary research, bring ideas from physics and mathematics to other disciplines in Münster

35 groups from 6 departments (physics, mathematics, chemistry, biology medicine, sports science …. maybe economics)

Interdisciplinary workshops, seminars, lectures, ….

My job: Organize, bring people together, build up new lecture series, supervise students that want to do interdisciplinary work

A few examples

Anticipation of critical transitions in biology, ecology, medicine

- Parameter (known or unknown) changes -> leads at a certain point to abrupt change in system behavior (population vanishes, depression starts)
- Can we anticipate this from data?

Detecting collective behavior in sports science and geophysics

- Multidimensional time series (movies) from human motion or turbulent flows
- Can we find a reduced description in terms of patterns?

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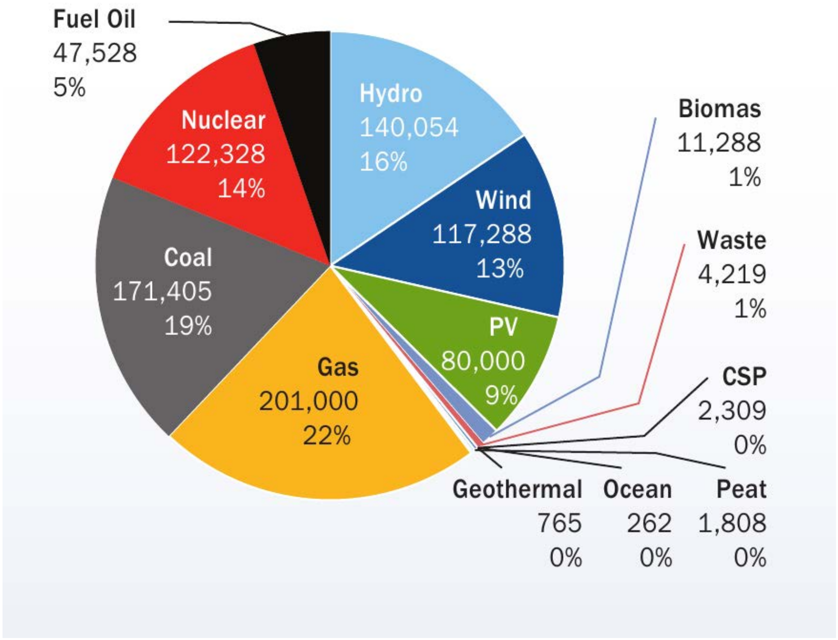
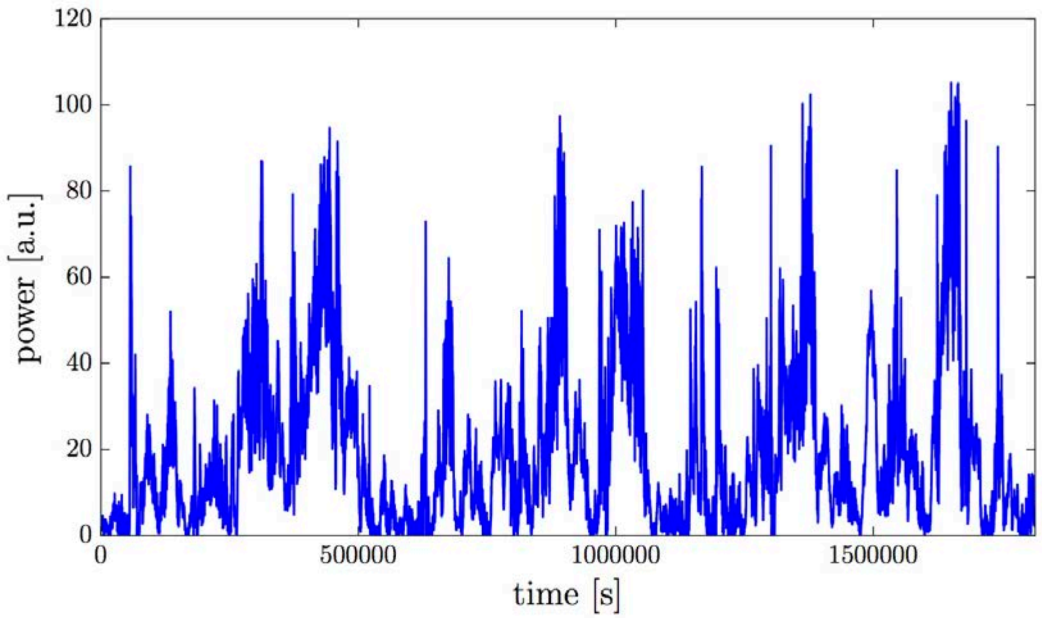
Good news



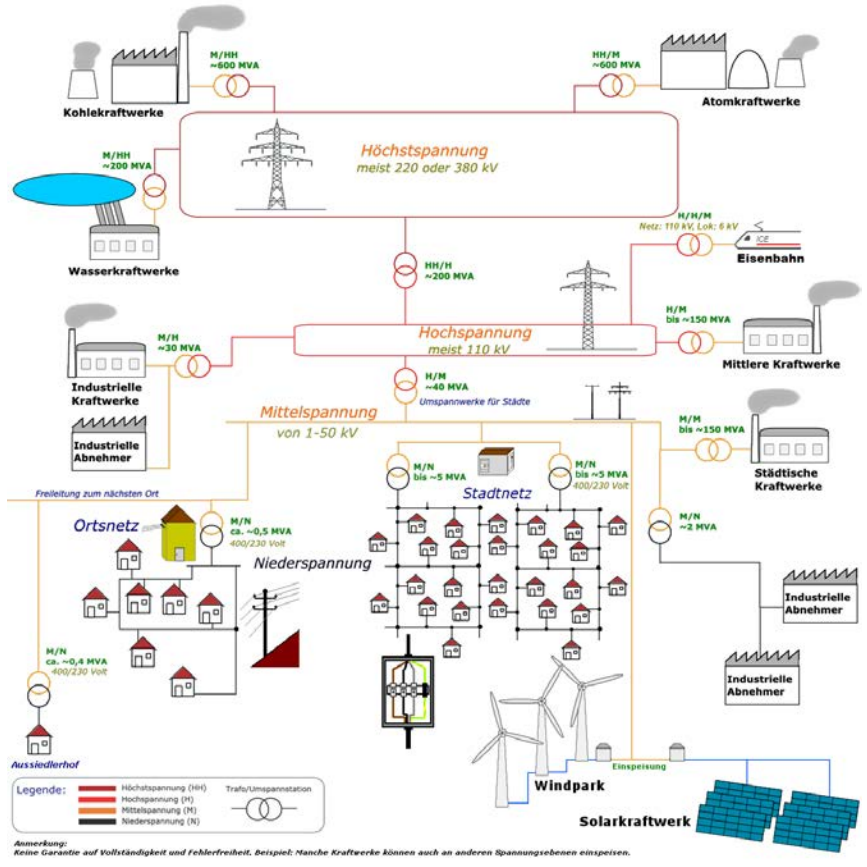
Wind in power – 2013 European statistics

Bad news



Power production of wind park (3 weeks)

The power grid as complex system



Many nonlinear interacting parts

Shows self-organization, critical transitions, fluctuations …

Input of non-Gaussian fluctuations

Theory of complex systems, nonlinear dynamics, statistical physics, network science and stochastic processes meet an engineering problem

Physics can contribute to understand/control collective phenomena and fluctuations

„New“ field / nice playground

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Synchronization

Adjustment of the rhythms of self-sustained oscillators due to a weak coupling

[Youtube]

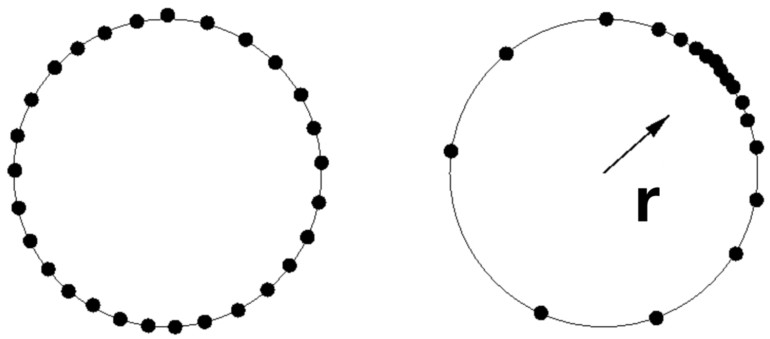
[Youtube]

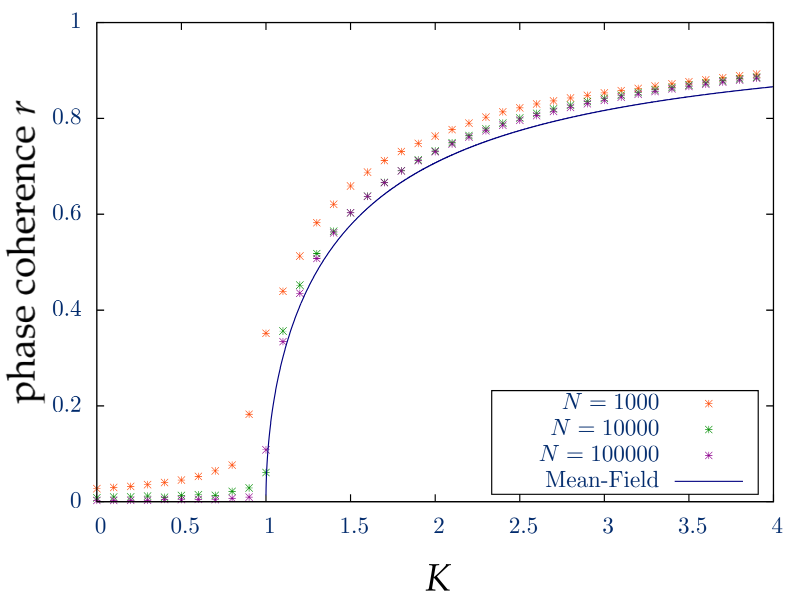
Universal phenomenon in nature: physics, biology, medicine, engineering, ….

The Kuramoto model — describe oscillators by their phase

$$\dot{\delta}_i = \omega_i + \sum_{j=1}^{N} K_{ij} \sin(\delta_j - \delta_i)$$

$$r e^{i\Phi} = \frac{1}{N} \sum_{j=1}^{N} e^{i\delta_j}$$





phase δ_i,

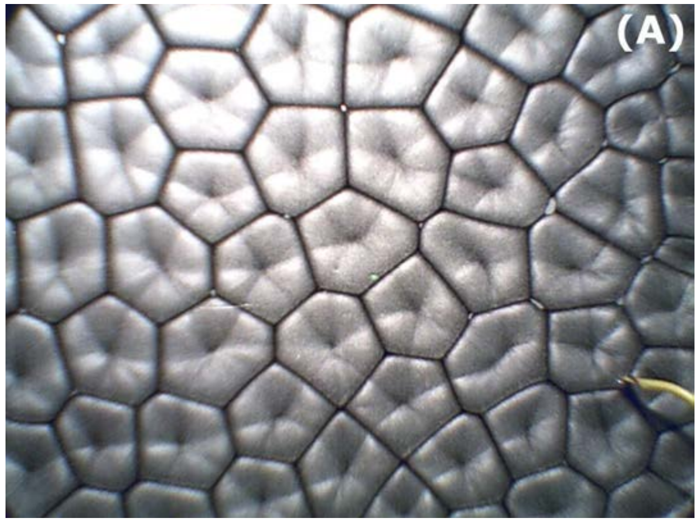
natural frequency ω_i,

coupling K_{ij}

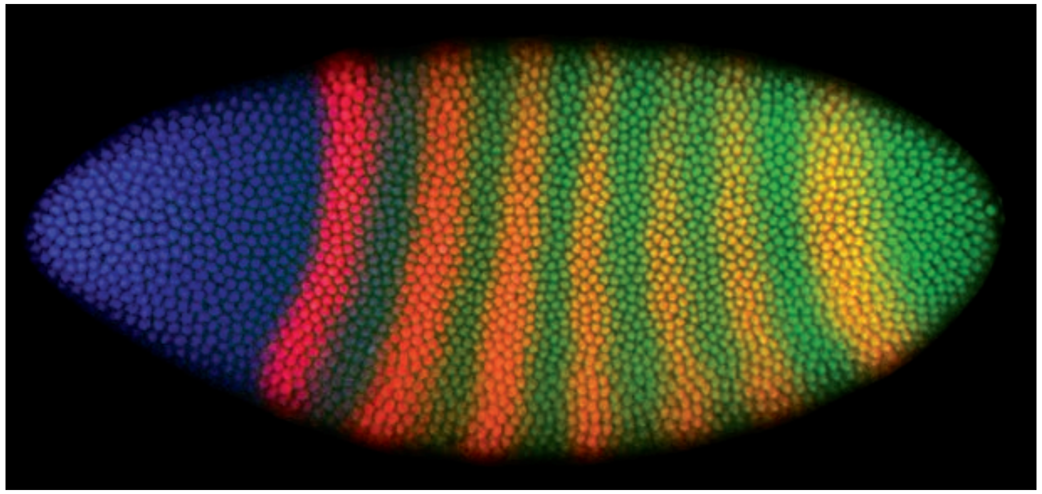
order parameter r (collective variable)

Non-equilibrium phase transition / self-organized synchronization

Comment: Non-equilibrium phase transitions and self-organization



[aus J. A. Maroto et. al.]

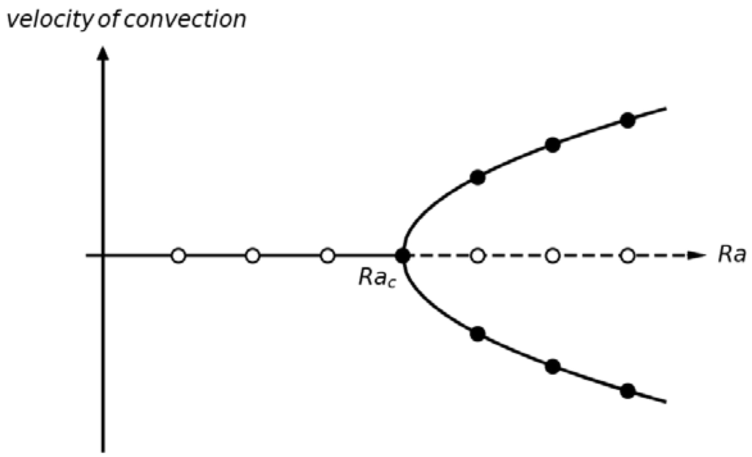


[Gross, Grill]

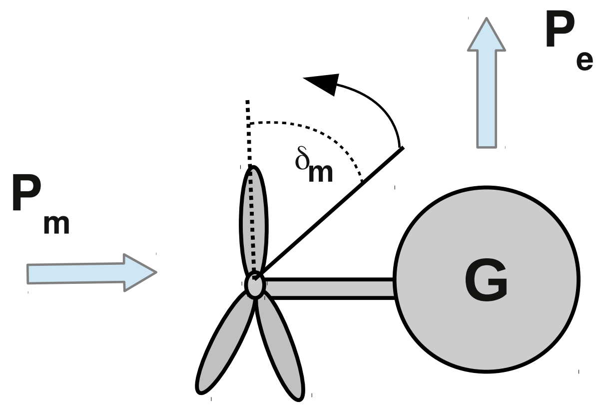
Collective variable (order parameter) undergoes critical transition/bifurcation

Universal behavior in nature

Synchronization is paradigmatic example

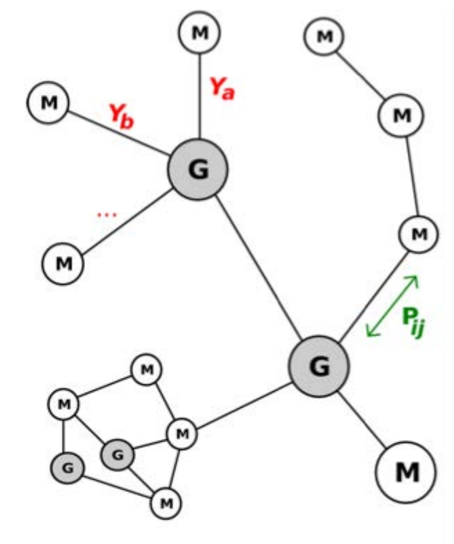


Power grids and the Kuramoto model



$$M\ddot{\delta}_i + D\dot{\delta}_i = P_m - P_e$$

Dynamics of synchronous machine



$$P_{ij} = E_i E_j (B_{ij} \sin(\delta_i - \delta_j) + G_{ij} \cos(\delta_i - \delta_j))$$

Power flow

- Phase δ_i and voltage E_i of node i
- Power flow P_{ij}
- For high voltage systems G_{ij} can be neglected

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Power grids and the Kuramoto model

$$\ddot{\delta}_i = -\gamma_i \dot{\delta}_i + P_{m,i} + \sum_{j=1}^{N} B_{ij} E_i E_j \sin(\delta_j - \delta_i)$$

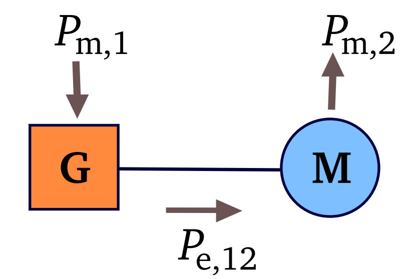
$$\alpha_i \dot{E}_i = E_{\mathrm{f},i} - E_i + X_i \sum_{j=1}^{N} B_{ij} E_j \cos(\delta_j - \delta_i)$$

- $P_{m,i}$ power input, B_{ij} Coupling
- $\alpha_i, \gamma_i, E_{f,i}, X_i$ machine parameters
- Valid up to $\approx$ 10s (then control mechanisms start to act)

Kuramoto model with inertia and time dependent coupling —> Self-organized Synchronization

[Schmietendorf et. al. The European Physical Journal B (2014)]

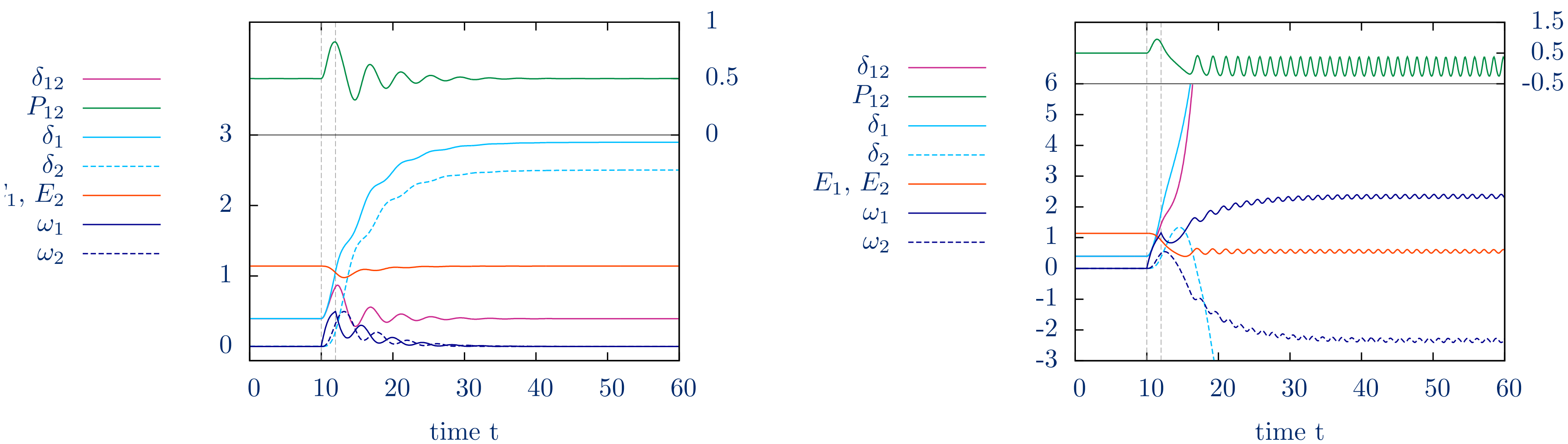
Stability: Case study for N = 2



Basic example: Generator $+P_m$ transfers power to a motor $-P_m$

Stability (phase, voltage):

Ability of the system to return to synchronized state after disturbance



Transition to fixed point or to limit cycle

Analogous behavior when part of complex networks

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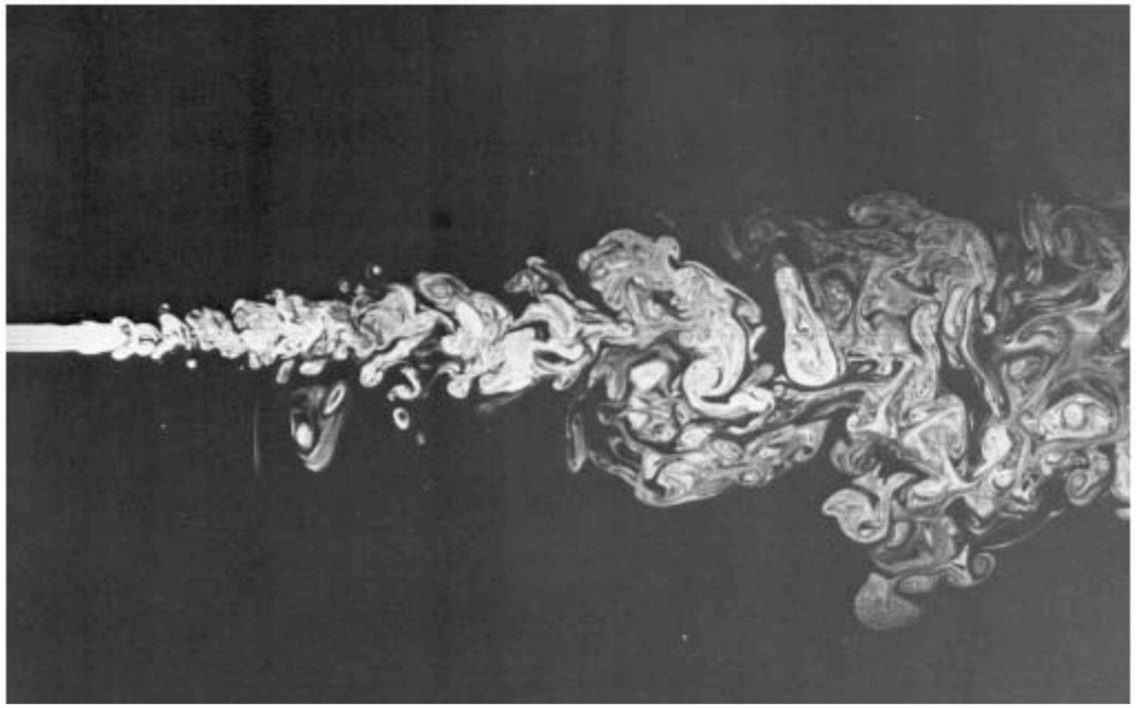
Turbulence

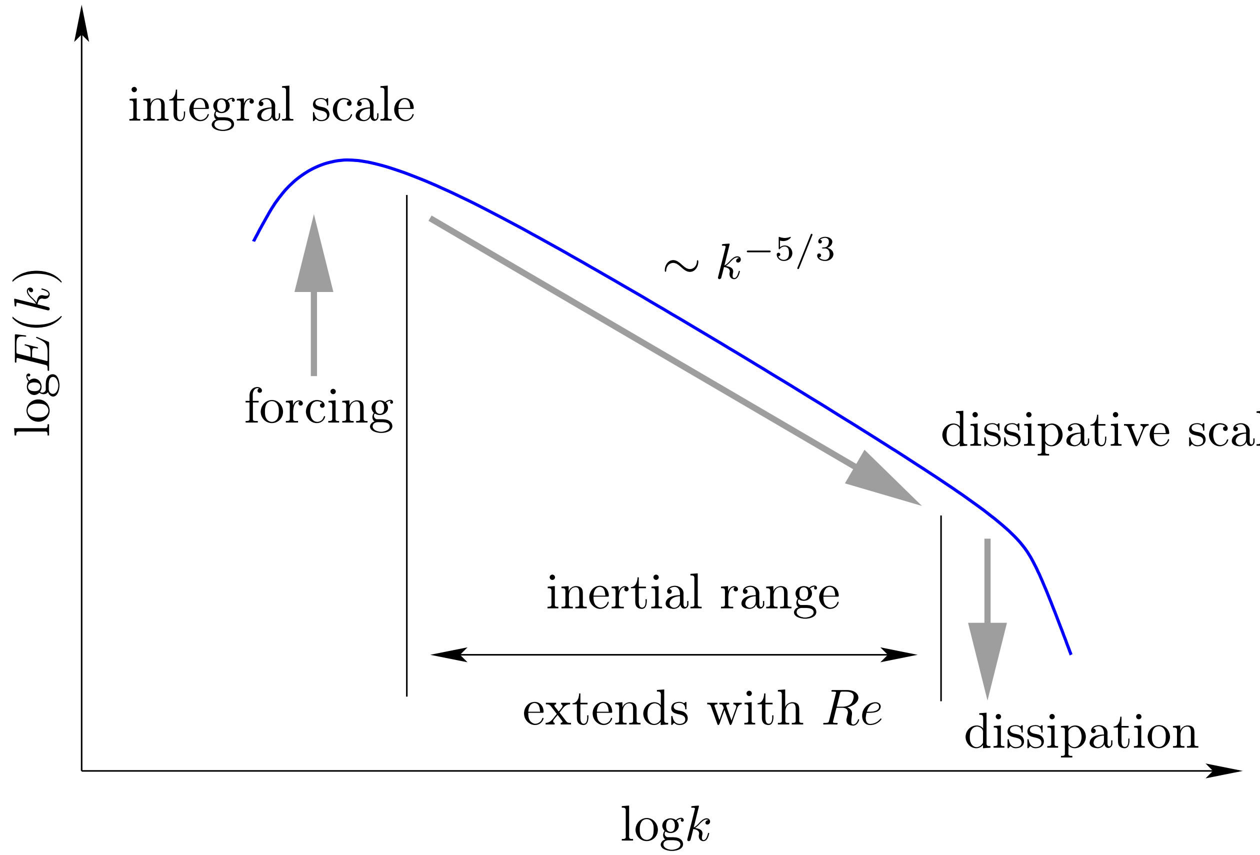


Universal phenomenon in nature (also astrophysics)

Turbulence — The cascade picture

$$\dot{\boldsymbol{v}} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\nabla p + \frac{1}{\mathrm{Re}} \Delta \boldsymbol{v}$$

$$\nabla \cdot \boldsymbol{v} = 0$$



Scaling of energy spectrum from dimensional analysis (Kolmogorov, Heisenberg)

Turbulence

Sample $v_1(t_1), v_2(t_2), \ldots, v_N(t_N) \rightarrow p(v_1(t_1), v_2(t_2), \ldots, v_N(t_N))$

$$\dot{\boldsymbol{v}} + \boldsymbol{v} \cdot \nabla \boldsymbol{v} = -\nabla p + \frac{1}{\mathrm{Re}} \Delta \boldsymbol{v}$$

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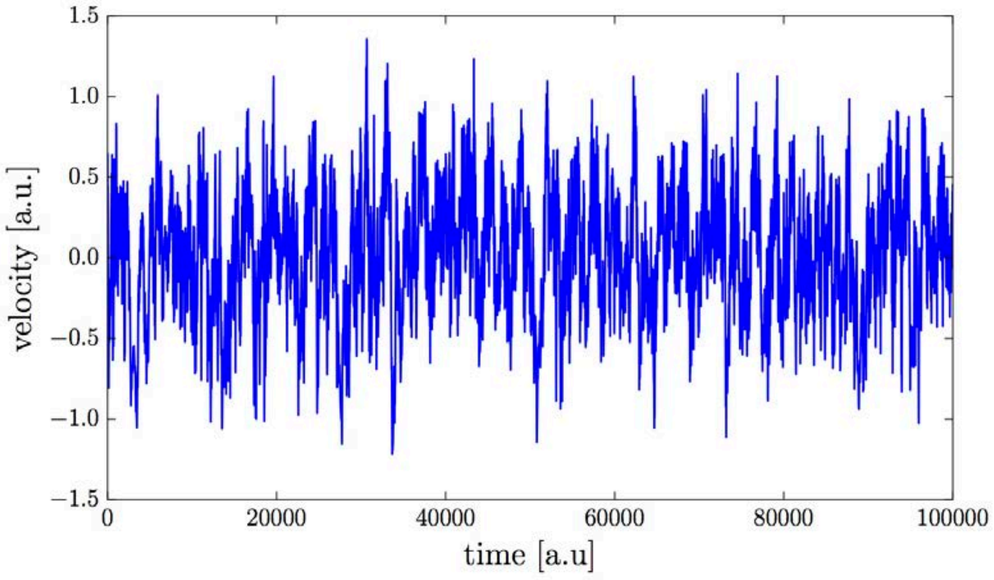

Idea to characterize complexity by increments: $v(\tau)=u(t+\tau)-u(t) \rightarrow$ N one-point PDFs $p_i(u,\tau)$

Turbulence

Sample $v_1(t_1), v_2(t_2), \ldots, v_N(t_N) \rightarrow p(v_1(t_1), v_2(t_2), \ldots, v_N(t_N))$

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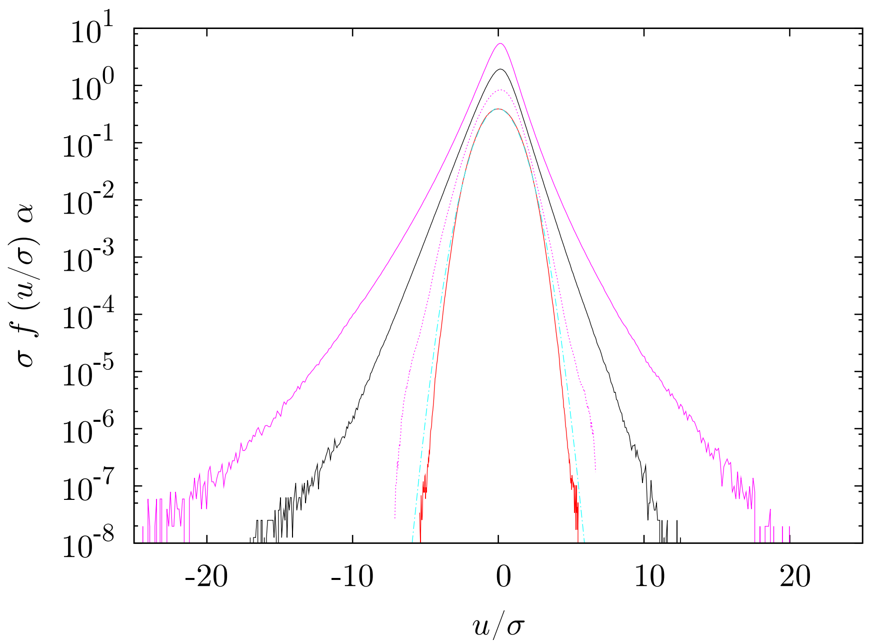
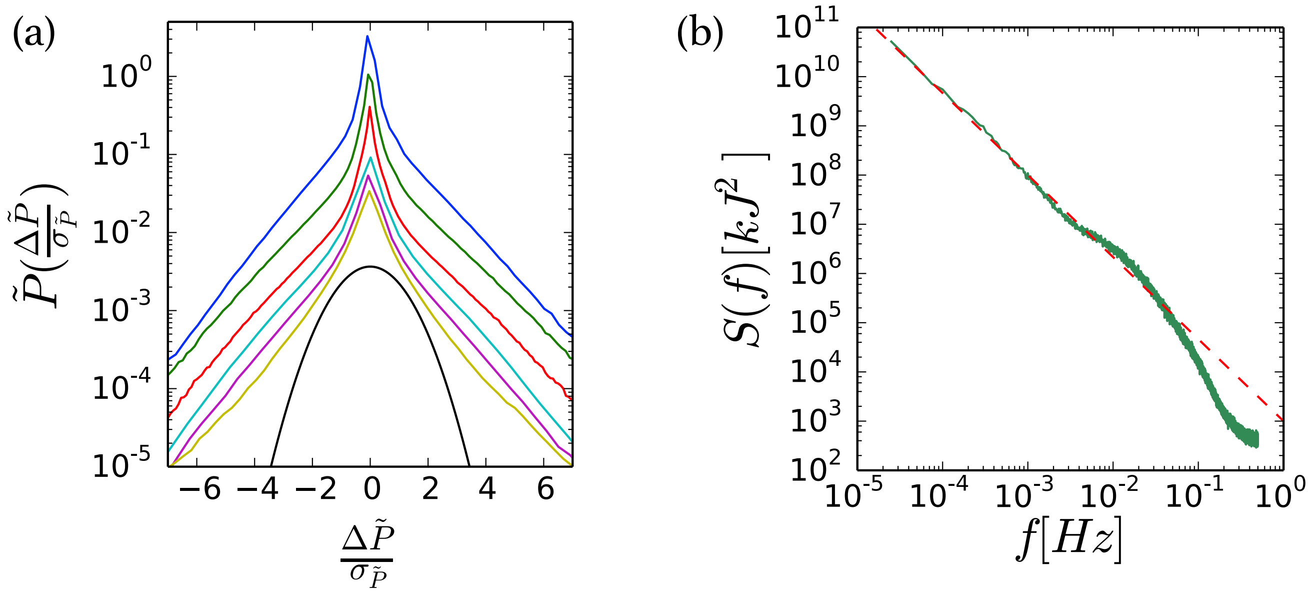


Intermittency — non-selfsimilar scaling

Idea to characterize complexity by increments: $v(\tau)=u(t+\tau)-u(t) \rightarrow$ N one-point PDFs $p_i(u,\tau)$

Turbulence and wind power production

Intermittent increment statistics is transferred from atmospheric turbulence to wind energy / also for solar power



Conversion process : P ~ u^3, Spectrum is preserved S(f) ~ $f^{-5/3}$

[P. Milan et. al., Phys. Rev. Lett. (2013) , M. Anvari et. al., New Journal of Physics (2016)]

A simple model

$$\dot{y}_i = -\gamma y_i + \Gamma$$ Ornstein-Uhlenbeck

$$\dot{x}_i = x_i\left(g - \frac{x_i}{x_0}\right) + \sqrt{D x_i^2}\, y_i$$

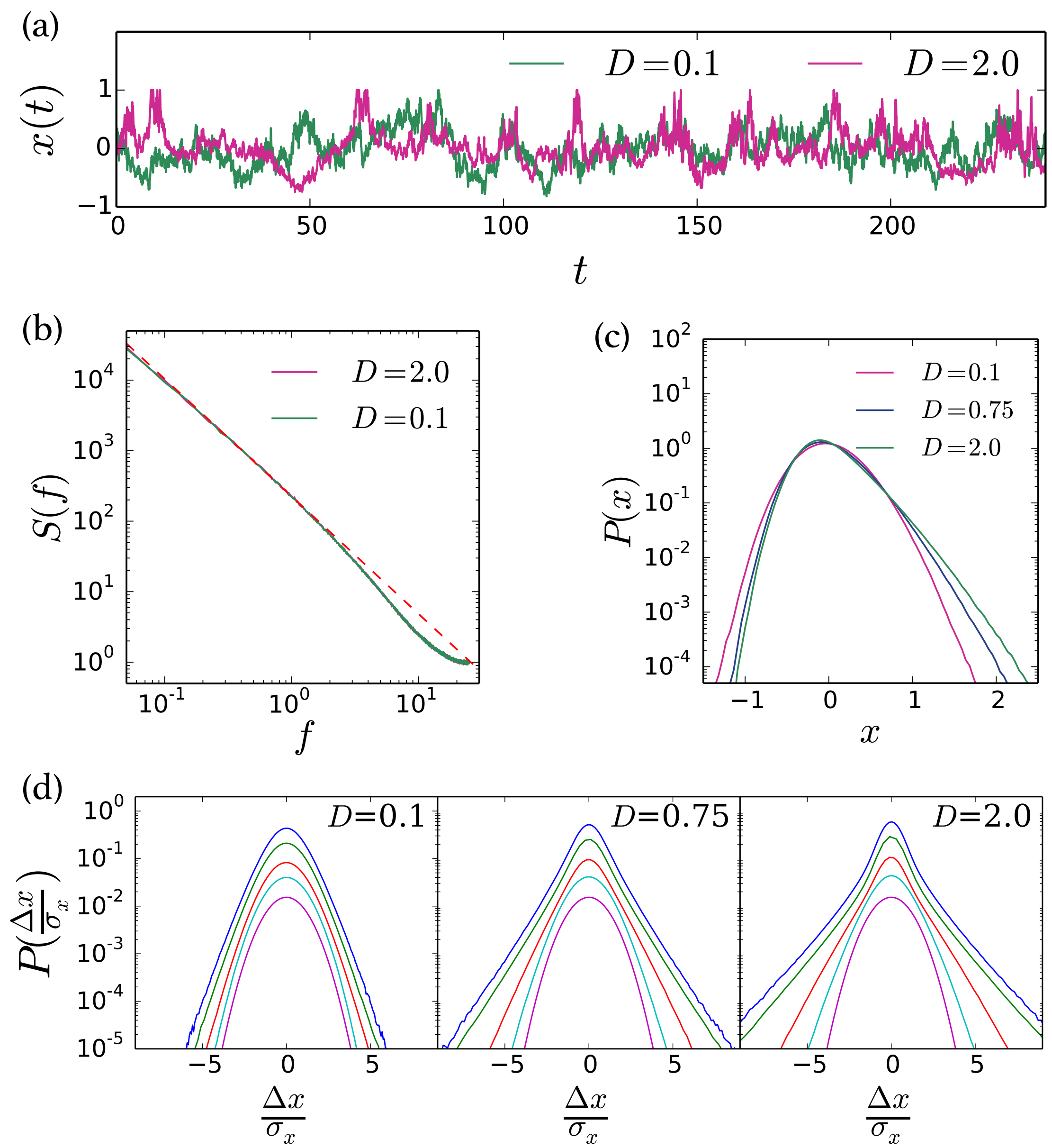
„intermittency strength“

- second step: modify power spectrum

  S(f) ~ -5/3

- *D*=0.1: weakly intermittent
- *D*=2.0: strongly intermittent

Main characteristics of real power data are reproduced.



Introducing fluctuations

Three scenarios:

(i) realistic noise: intermittent, temporally correlated, -5/3 power spectrum

(ii) correlated Gaussian noise, -5/3 power spectrum

(iii) uncorrelated Gaussian white noise

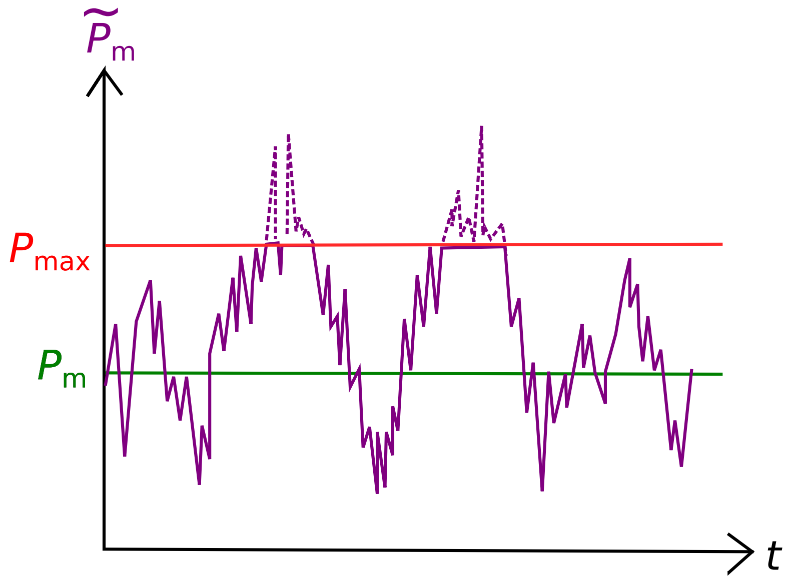
$$\ddot{\delta}_i = -\gamma_i \dot{\delta}_i + P_{m,i} + \sum_{j=1}^{N} B_{ij} E_i E_j \sin(\delta_j - \delta_i)$$

$$\alpha_i \dot{E}_i = E_{\mathrm{f},i} - E_i + X_i \sum_{j=1}^{N} B_{ij} E_j \cos(\delta_j - \delta_i)$$

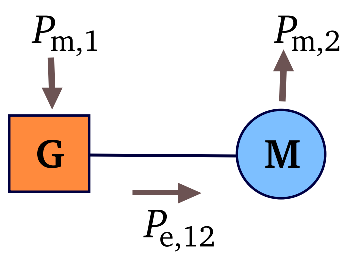
Parameter fluctuations:

P_m —> $P_m - p\,(x(t) - 1)$

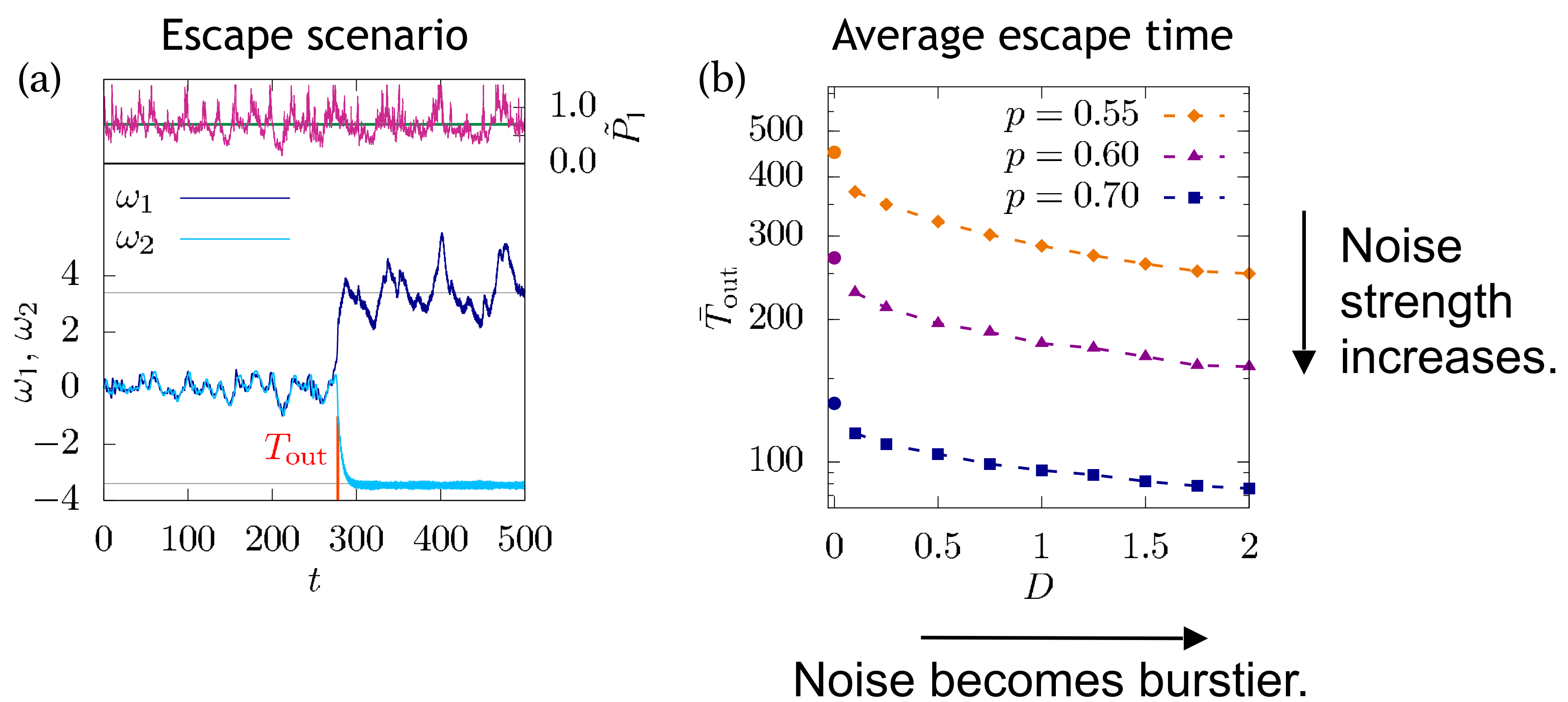
- p : penetration
- $\langle x \rangle = 1$, i. e. power balance in long-term limit
- maximum (rated) power



Results for two machine system



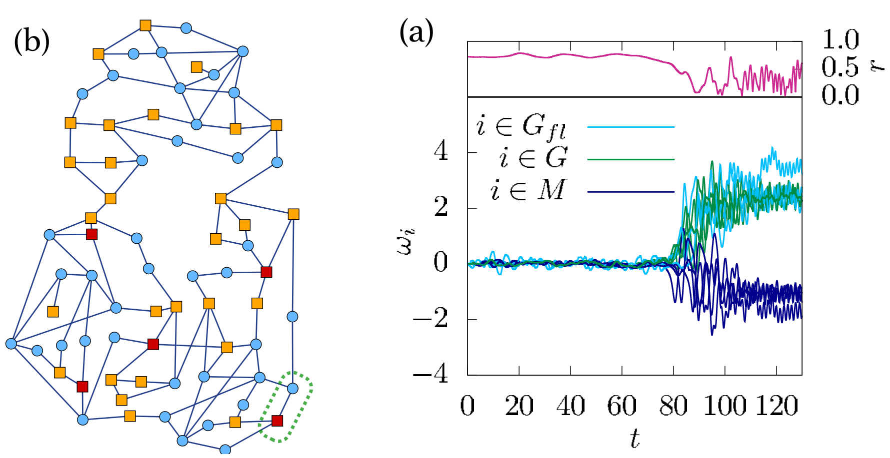
generator frequency
motor frequency
noise



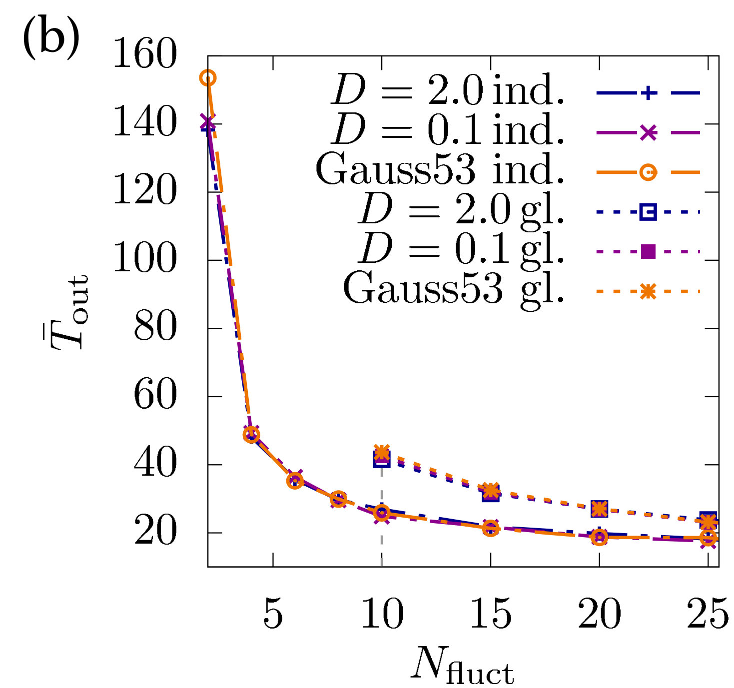
Gaussian white noise: no escapes observed for simulations $O(10^6)$.

Complex grid

IEEE grid, 33 generators, 40 consumers



- ensemble average: positions of N_{fluct} generators randomly selected, different noise time series
- single-node stability varies



Temporal correlations are essential, intermittency plays a minor role.

[Schmietendorf et. al. The European Physical Journal B (2017)]

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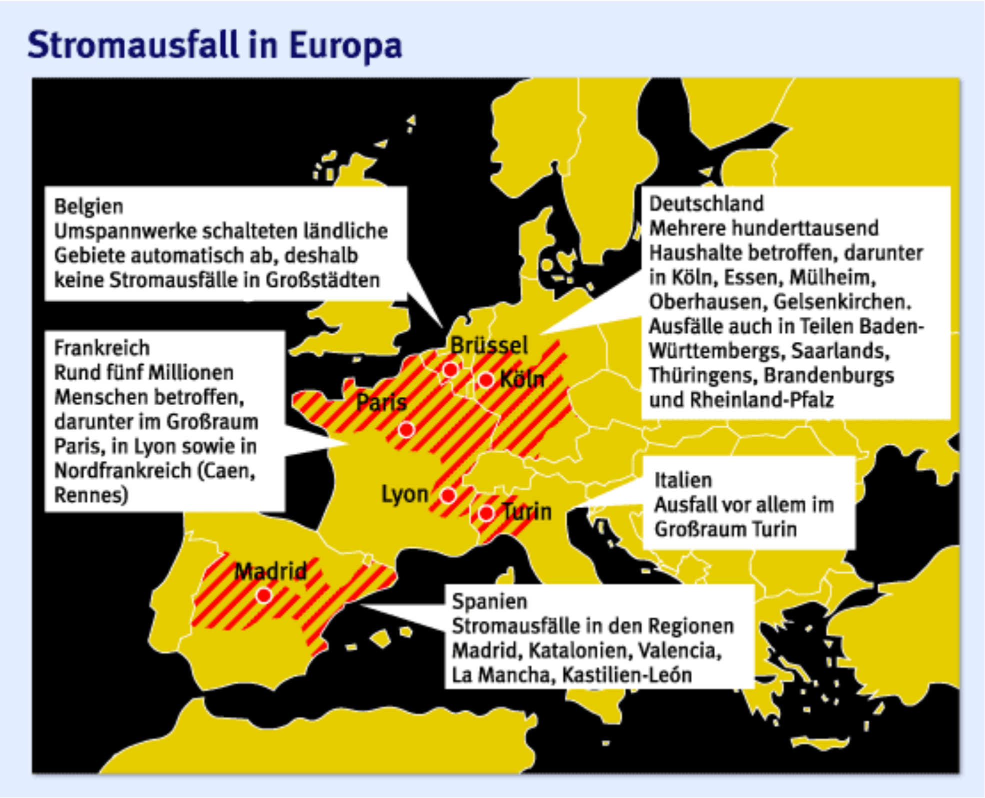
Cascading failure — An example

Power outage on 4th November 2006

Shutdown of transmission line
Conneforde-Diele for the passage of
a ship from shipyard in Papenburg

Cascading failure — An example

Power outage on 4th November 2006

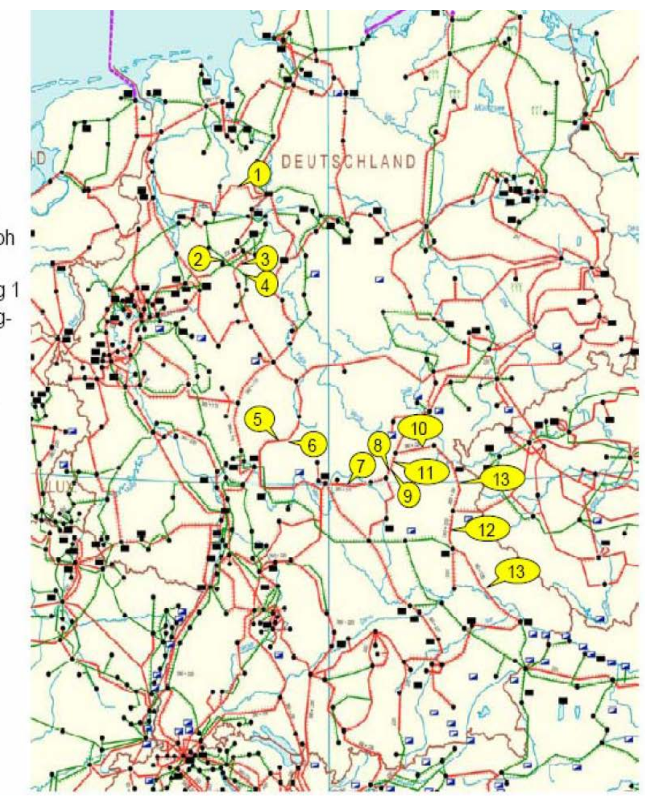


Shutdown of transmission line Conneforde-Diele for the passage of a ship from shipyard in Papenburg

Cascading failure — An example

Power outage on 4th November 2006

Nr.	Zeit	kV	Leitung
1	22:10:13	380	Wehrendorf-Landesbergen
2	22:10:15	220	Bielefeld/Ost-Spexard
3	22:10:19	380	Bechterdissen-Elsen
4	22:10:22	220	Paderborn/Süd-Bechterdissen/Gütersloh
5	22:10:22	380	Dipperz-Großkrotzenburg 1
6	22:10:25	380	Großkrotzenburg-Dipperz 2
7	22:10:27	380	Oberhaid-Grafenrheinfeld
8	22:10:27	380	Redwitz-Raitersaich
9	22:10:27	380	Redwitz-Oberhaid
10	22:10:27	380	Redwitz-Etzenricht
11	22:10:27	220	Würgau-Redwitz
12	22:10:27	380	Etzenricht-Schwandorf
13	22:10:27	220	Mechlenreuth-Schwandorf
14	22:10:27	380	Schwandorf-Pleinting



Shutdown of transmission line Conneforde-Diele for the passage of a ship from shipyard in Papenburg

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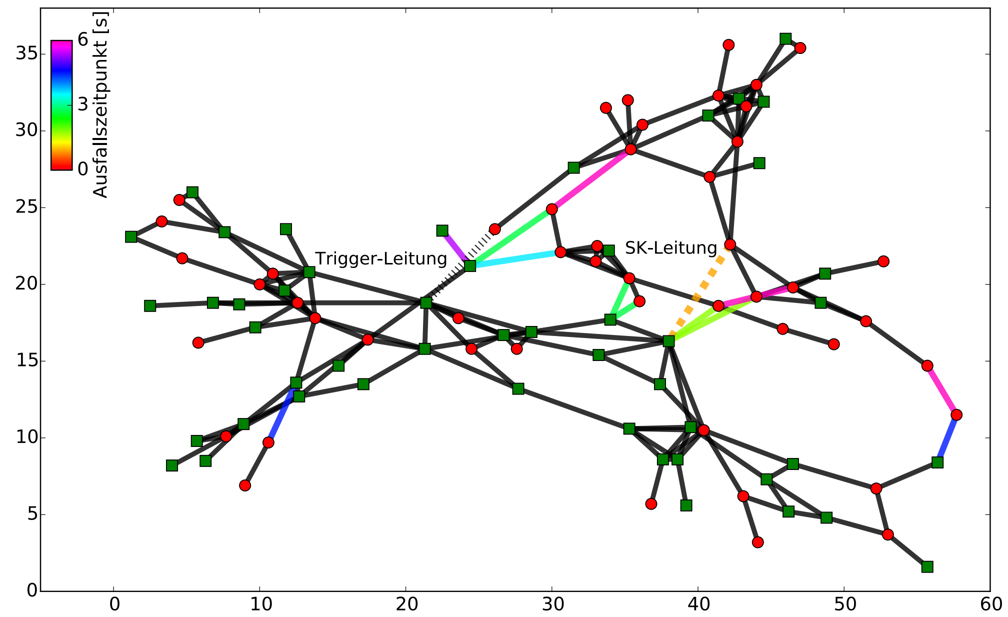
Cascading failure — In general

Consider transportation Network (Traffic, Internet, Power)

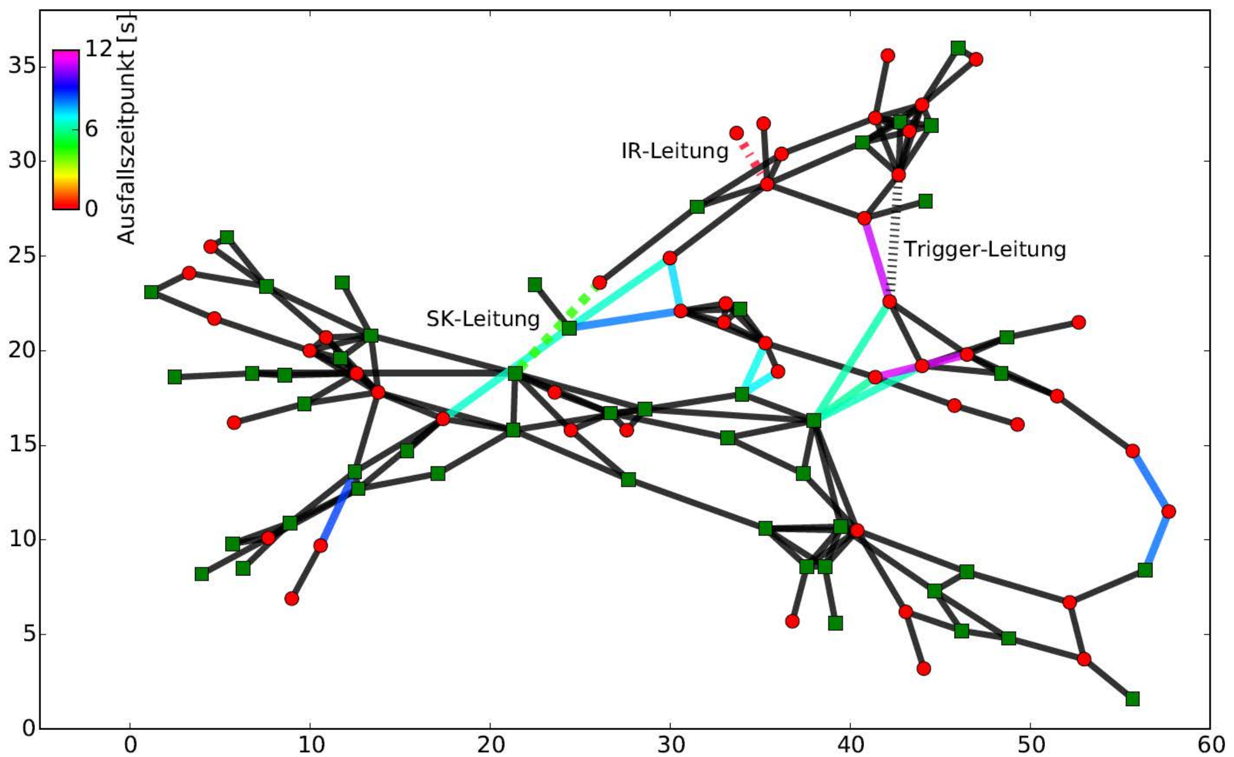
- Line failure (accident, overload,….)
- „Traffic“ has to reroute, use other lines
- Can lead to overload on other line ->
- More „traffic“ has to reroute, use other lines
- ……

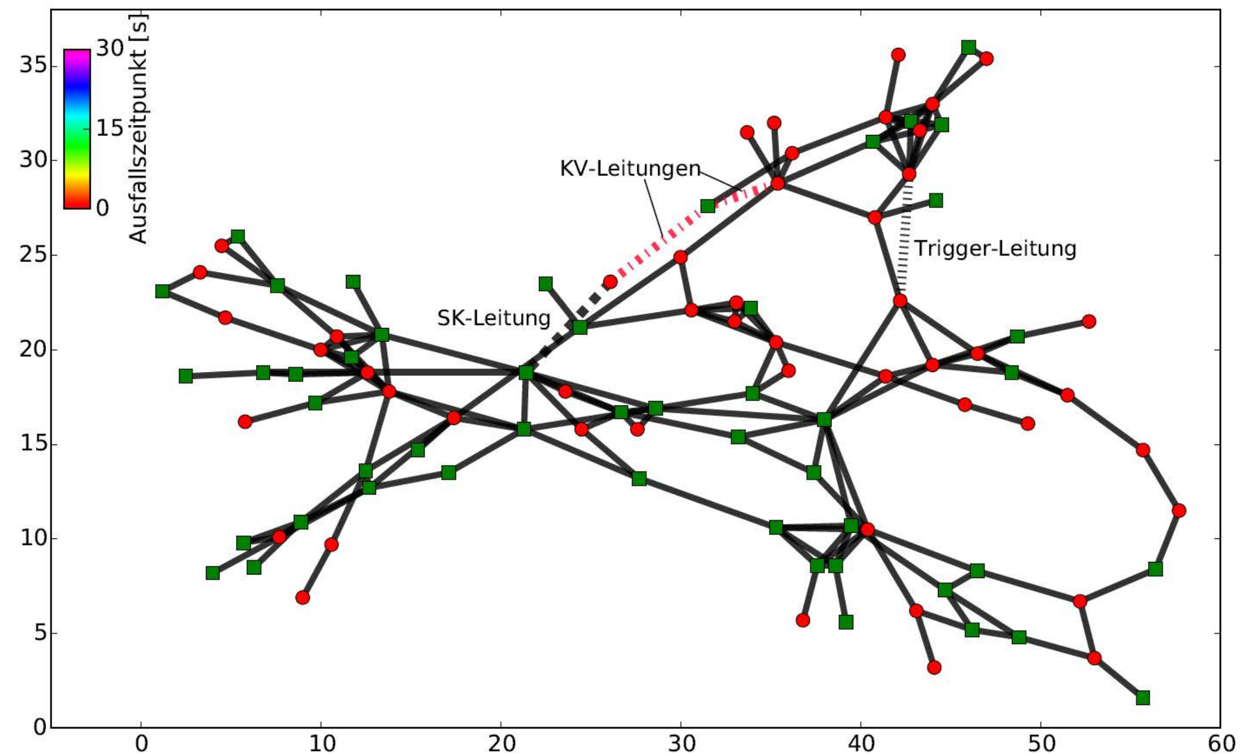


[A. Motter et. al. Physical Review E (2002)]

Our strategy — The Spanish high voltage grid

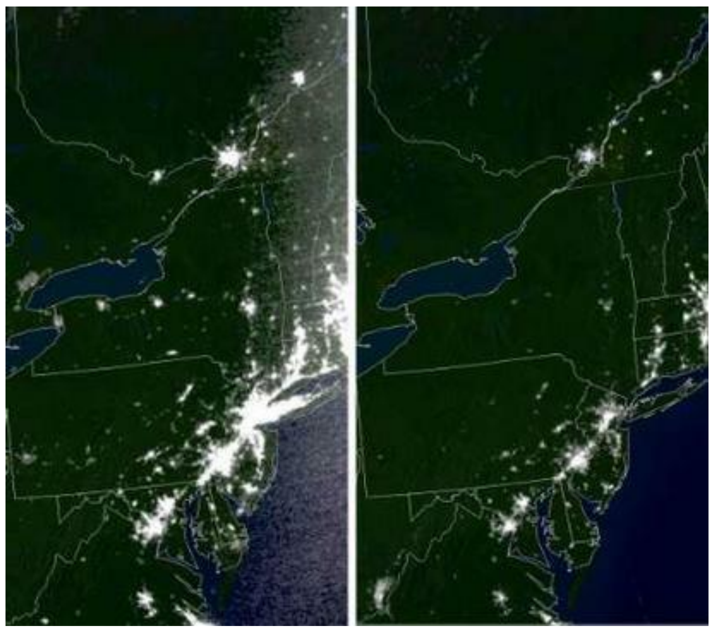
Counteraction: Intentional removal of certain lines to rescue part of the network



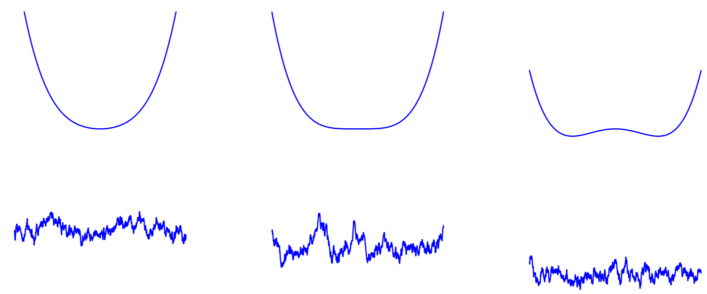


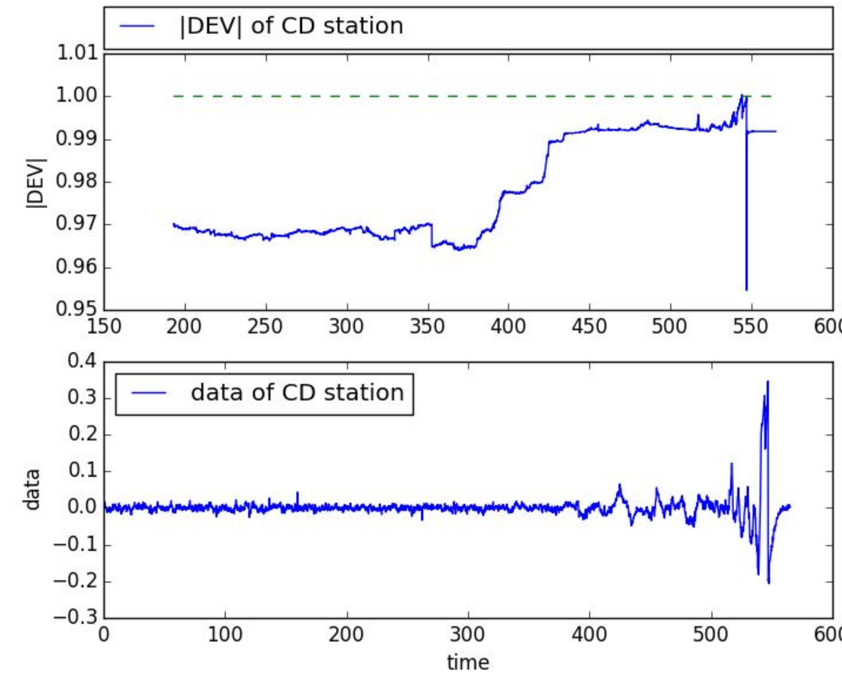
Our idea: Damping of certain lines to rescue the whole net

Anticipation of outages



NOAA satellite image





Growing interdisciplinary field, see e.g. M. Scheffer et. al., Nature (2009)

Conclusion

Physics of power grids is a very interesting field combining different ideas

Level of modeling plays a big role

The nature of fluctuations is important for stability

Maybe it is possible to stop cascading failures