

Blackout risk, cascading failure and complex systems dynamics

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Cascading failure; large blackouts

- Rare, unanticipated, dependent events
+ huge number of possibilities and combinations
- Mechanisms include: hidden failures, overloads, oscillations, transients, control or operator error, ...
but all depend on loading

Detailed postmortem analysis of a particular blackout

- arduous (months of simulation and analysis)
but very useful
- a basis for strengthening weak parts of
system
- motivates good practice in reliability:
“Blackouts cause reliability”

Our general approach

- Instead of looking at postmortem details of particular blackouts, look at statistics and risk of series of blackouts
- Global top-down analysis; look at bulk system properties and statistics.
- Complementary to detailed analysis

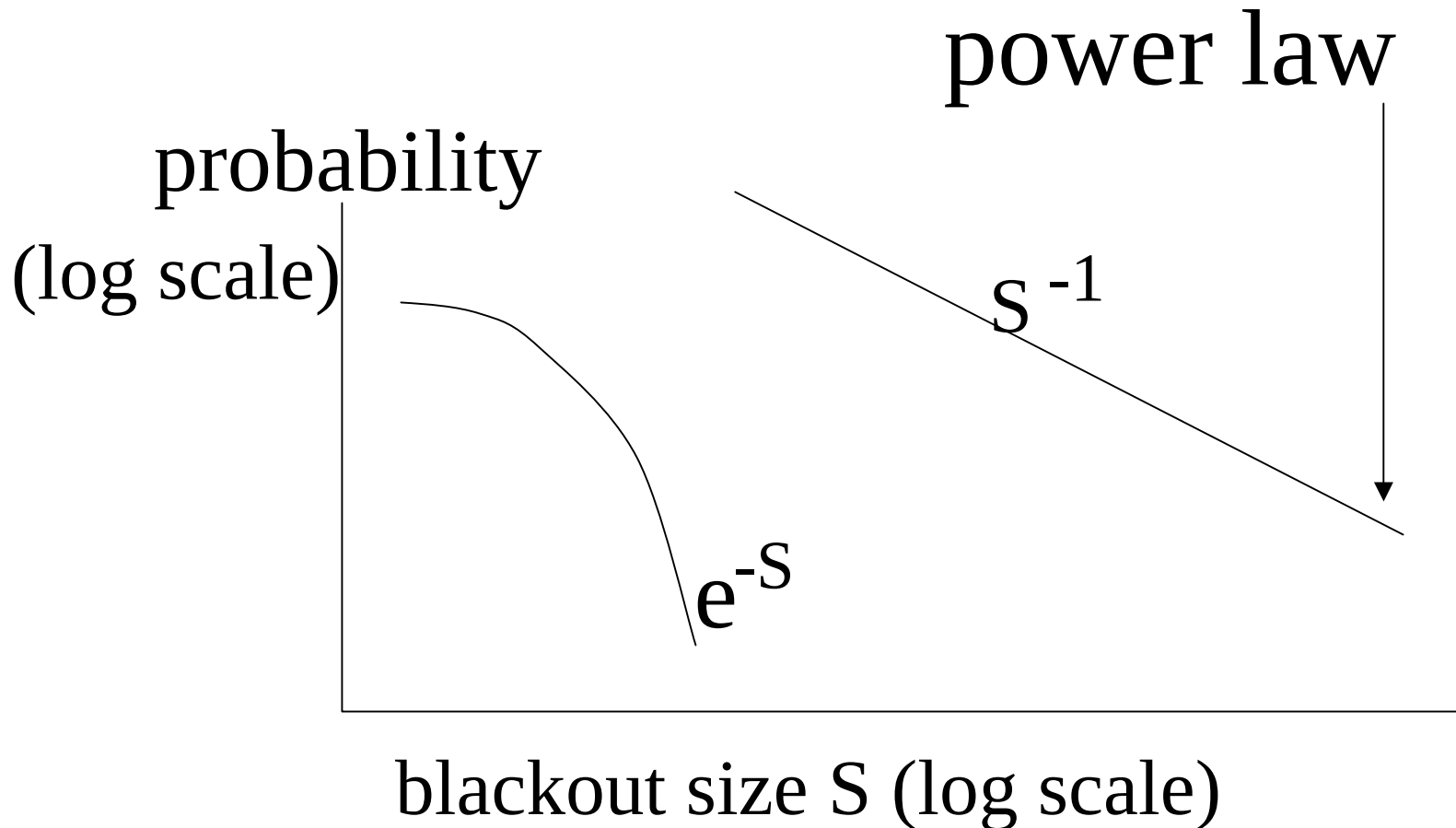
Who pays the blackout cost?

- Public and business. Halts the economy + indirect costs + harms other infrastructures
- Utilities. Reputational, legal, regulatory costs, cost of upgrade or personnel to avoid similar blackouts
- Government. Political risk

Blackout risk as size increases

$$\text{risk} = \text{probability} \times \text{cost}$$

- Cost increases with blackout size.
example: direct cost proportional to size
- How does blackout probability decrease as size increases? ... a crucial consideration for blackout risk!



power laws have huge impact
on large blackout risk.

risk = probability $\times$ cost

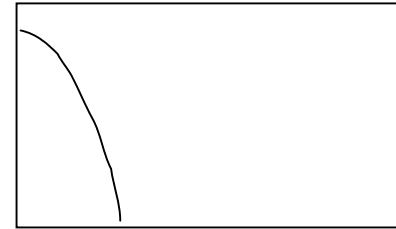
If probability of blackout decreases as a power law with exponent near -1, then risk of large blackouts is comparable to (or even exceeding) the risk of small blackouts.

Effect of Loading

log log plots

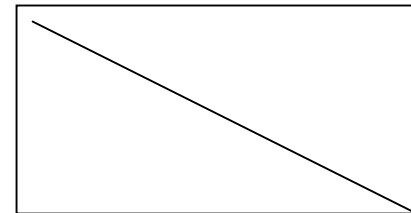
probability

- VERY LOW LOAD
 - failures independent
 - exponential dependence

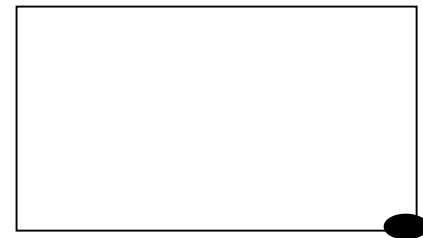


blackout size

- CRITICAL LOAD
 - power law dependence



- VERY HIGH LOAD
 - total blackout likely



Cascading failure probabilistic models

- CASCADE
- Branching process

Cascading failure power system simulations

- OPA (Dobson Carreras Newman)
- Hidden failure (Thorp)
- Manchester (Kirschen)
- Carnegie-Mellon (Talukdar, Apt)
- TRELSS (EPRI)

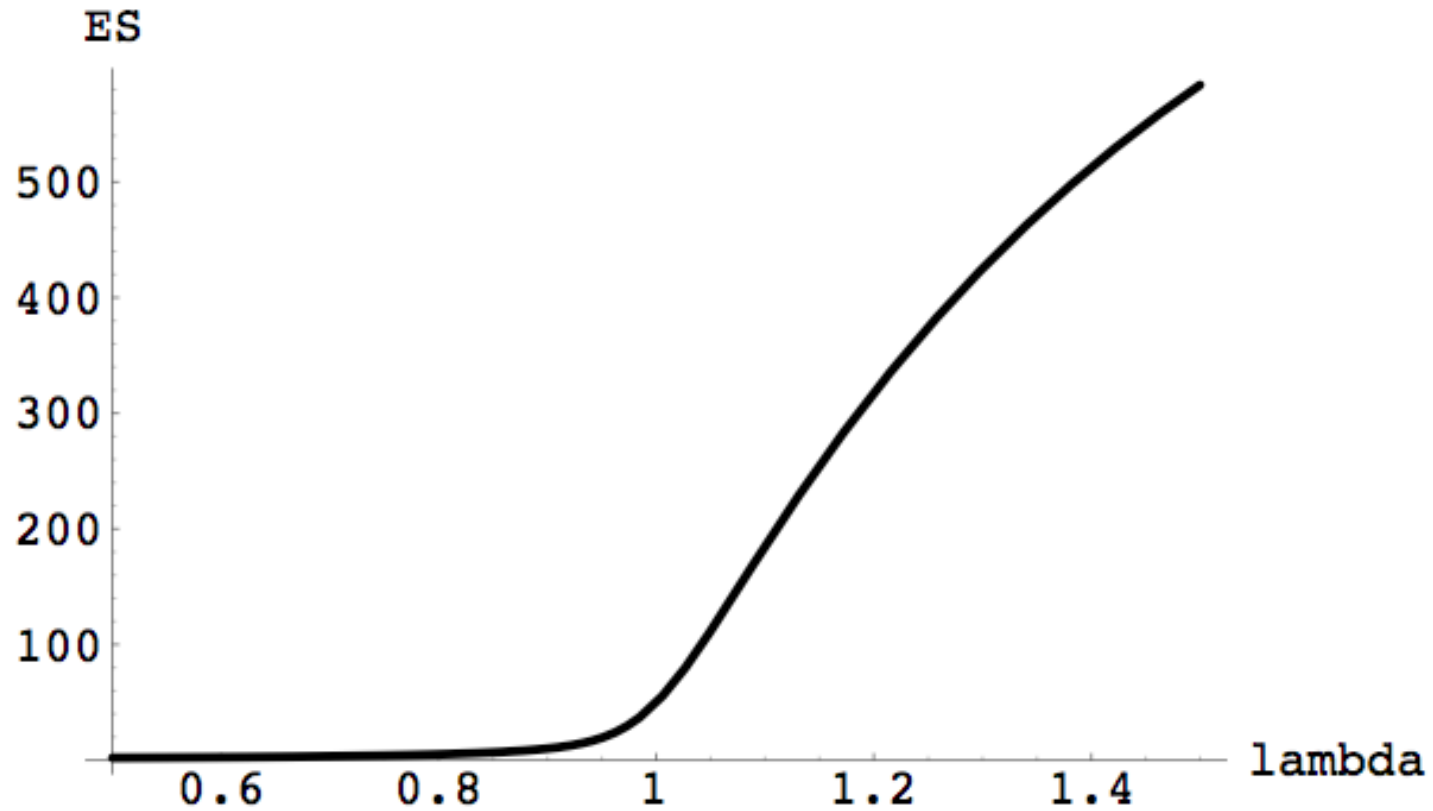
The probability of cascading failure
blackout increases with system loading

Exactly how does it increase?

How does the average blackout size increase?

How does the probability distribution of blackout
sizes change?

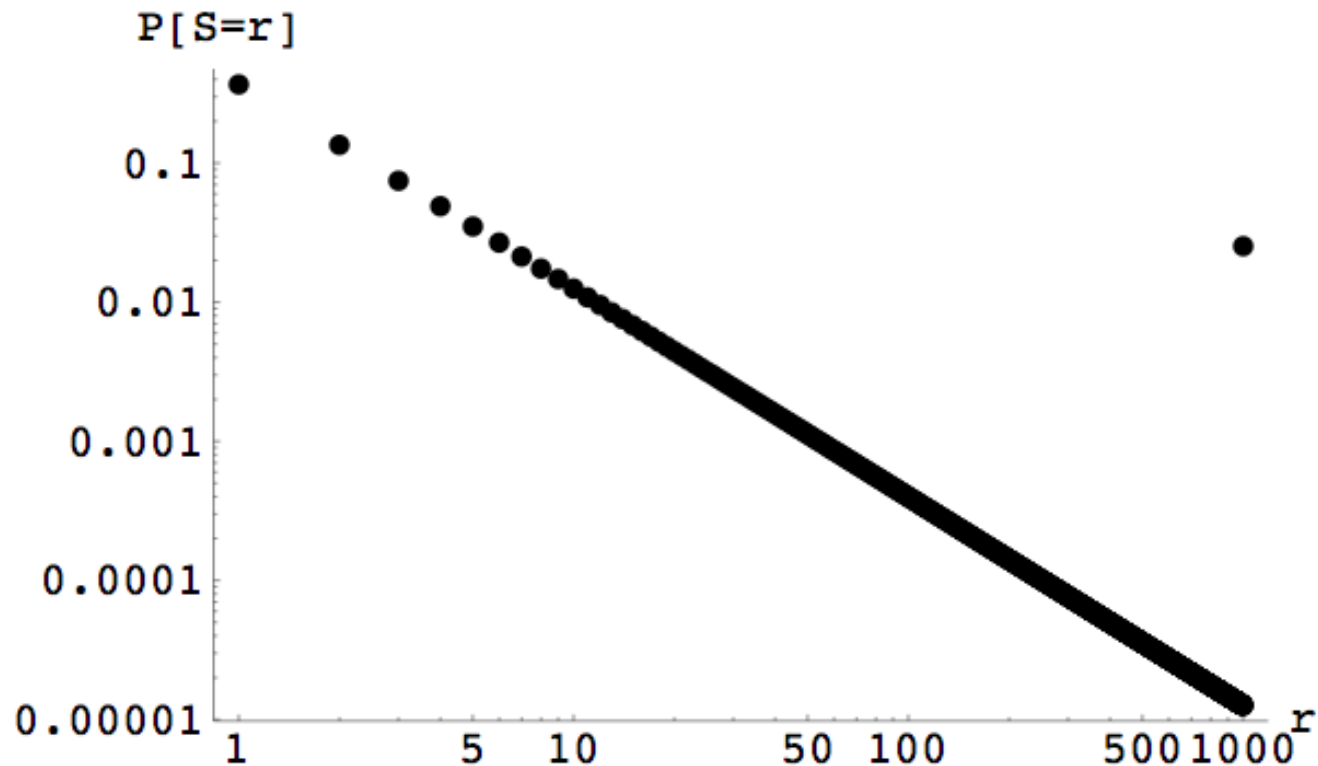
Mean number of failures



criticality λ ; system stress

Branching model with 1000 components

probability

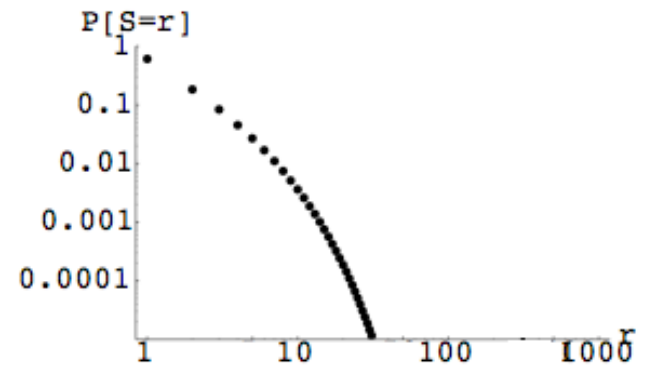


number of failures

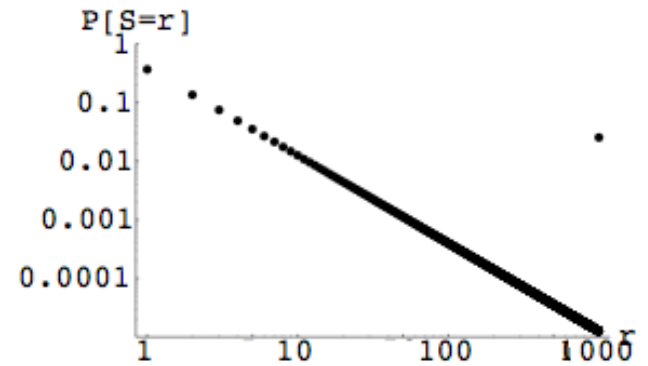
Branching model with 1000 components at criticality

Branching
model with
1000
components

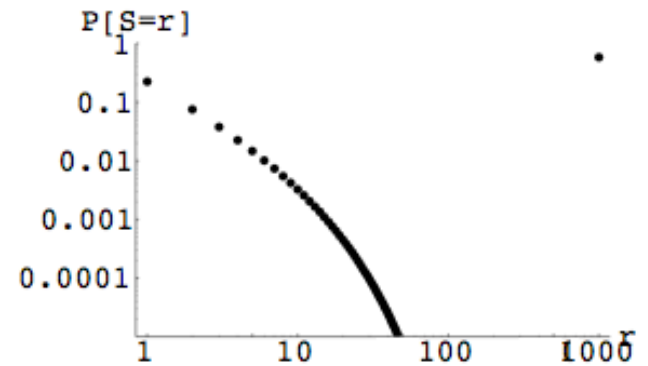
probability
**well below
criticality**



**at
criticality**

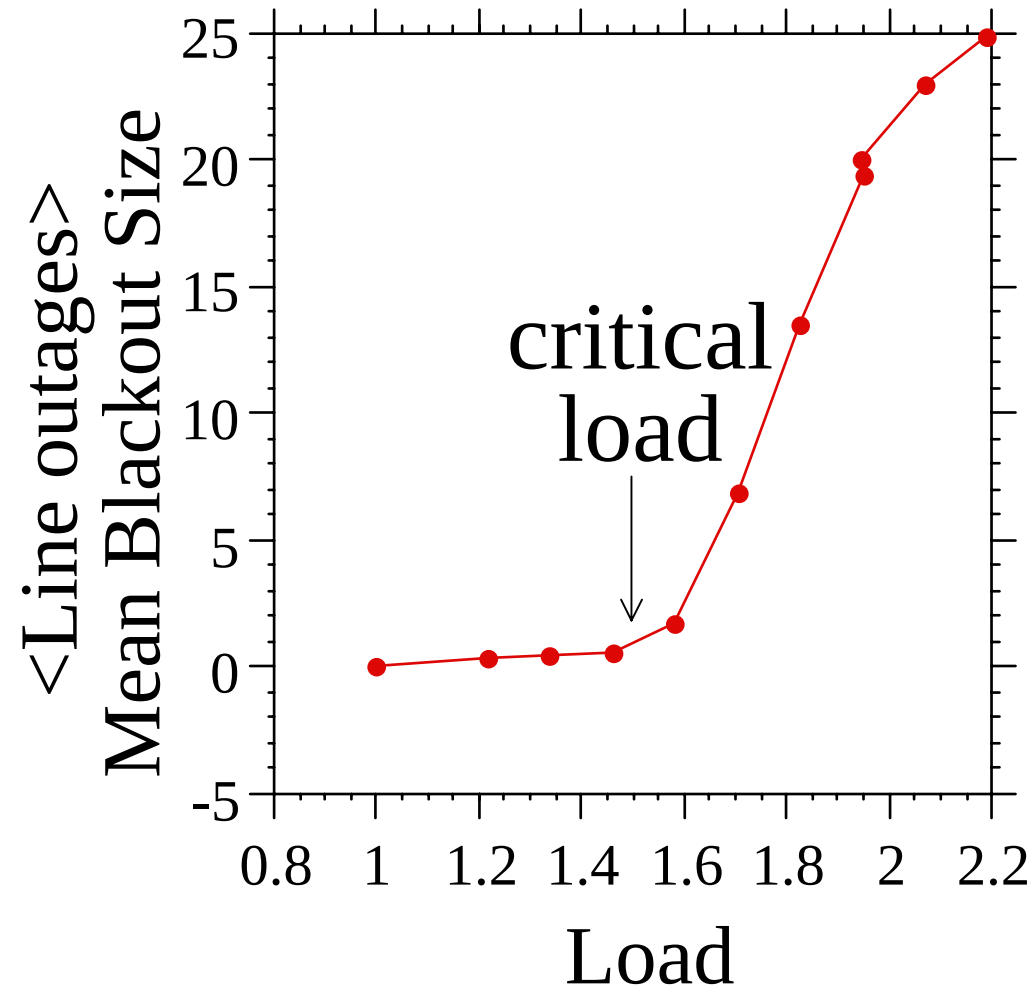


**above
criticality**



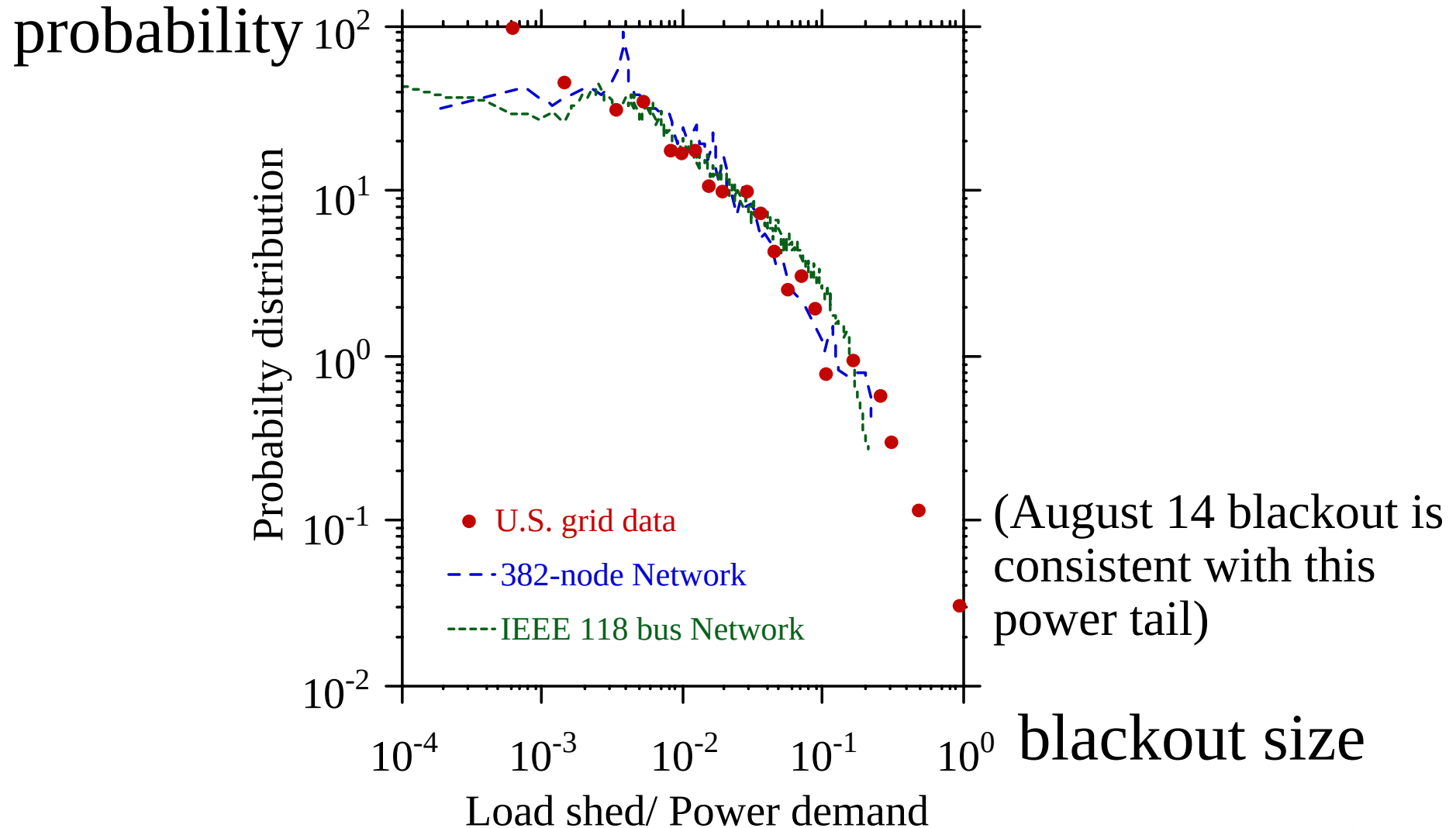
number of failures

Critical loading in OPA blackout model



Mean blackout size sharply increases at critical loading; increasing risk of cascading failure.

OPA model and NERC data



Significance of criticality

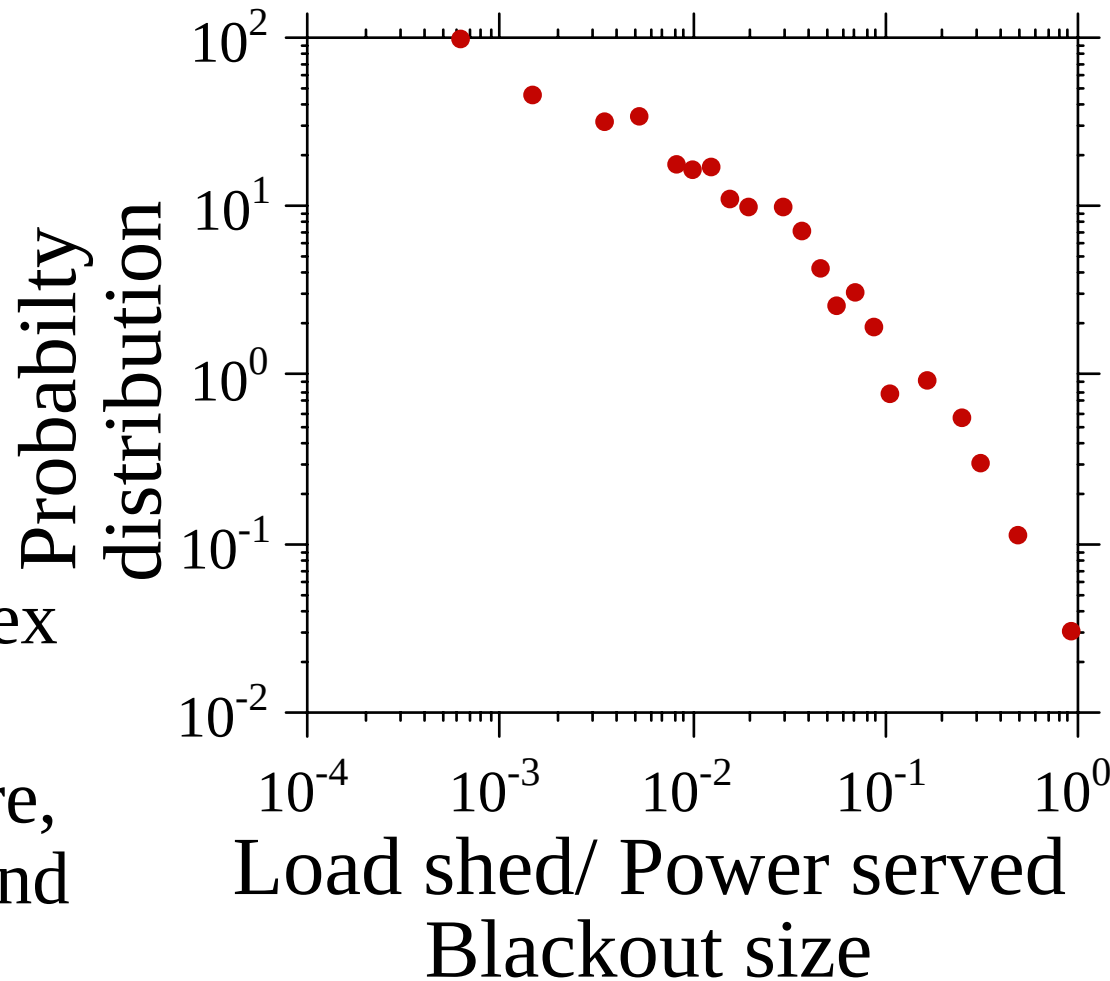
- At criticality there is a power law dependence, a sharp increase in mean blackout size, and an increasing risk of cascading failure.
- Criticality gives a power system limit or reference point or “edge” with respect to cascading failure.
- Margin to criticality determines probability distribution of blackout sizes and risk

Ongoing research on margin to criticality

- One approach is to increase loading in blackout simulation until criticality is detected by sharp increase in average blackout size.
- Another approach is to monitor or measure how much failures propagate (λ) from real or simulated data.

NERC blackout data shows power law

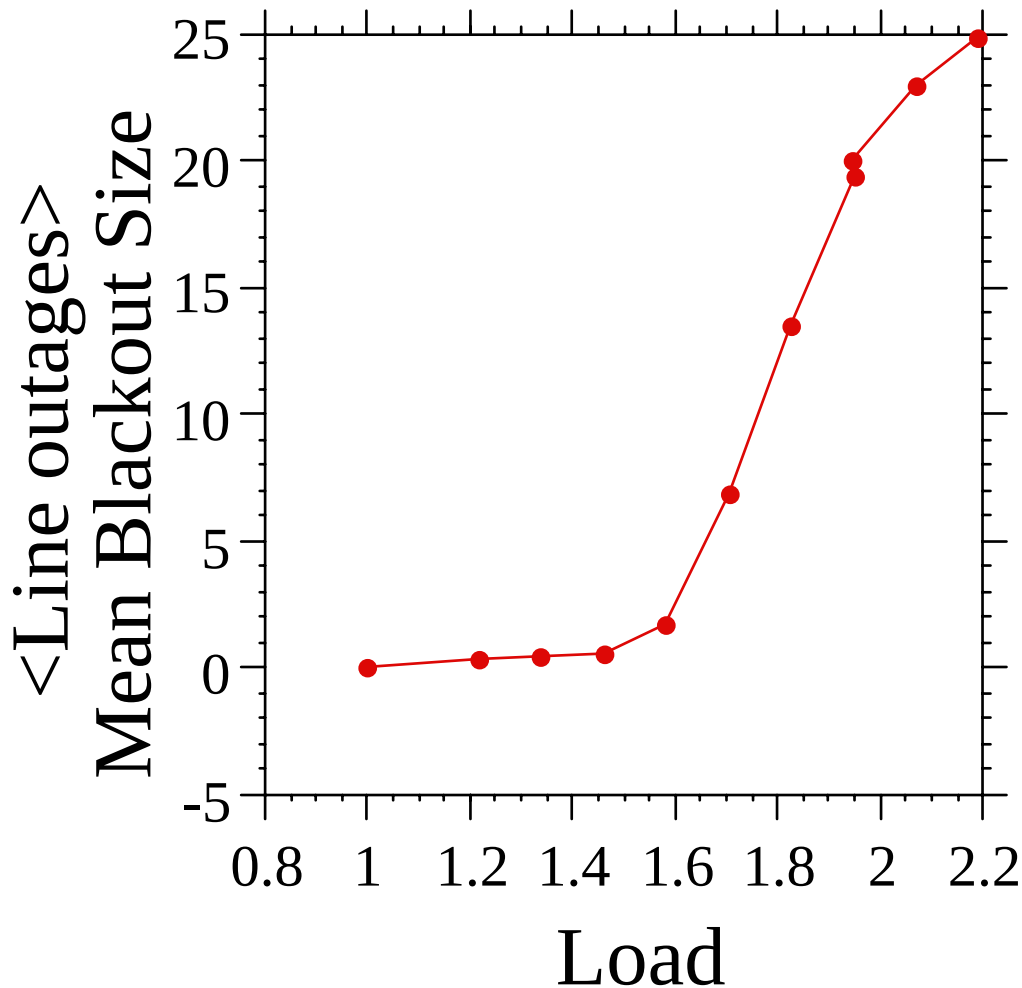
- Large blackouts more likely than expected
- Conventional risk analysis tools do not apply; new approaches needed
- Consistent with complex system near criticality
- Large blackouts are rare, but have high impact and significant risk



COMPLEX SYSTEM DYNAMICS

- We have been looking at “fast” cascade dynamics; now look at slow dynamics as network upgrades
- Network slowly upgrades as load increases and engineers respond to real or simulated blackouts by strengthening parts of network involved in blackout.
- We will see that the complex dynamics can make power system evolve to near criticality (a form of self-organized criticality)

An explanation of power system operating near criticality



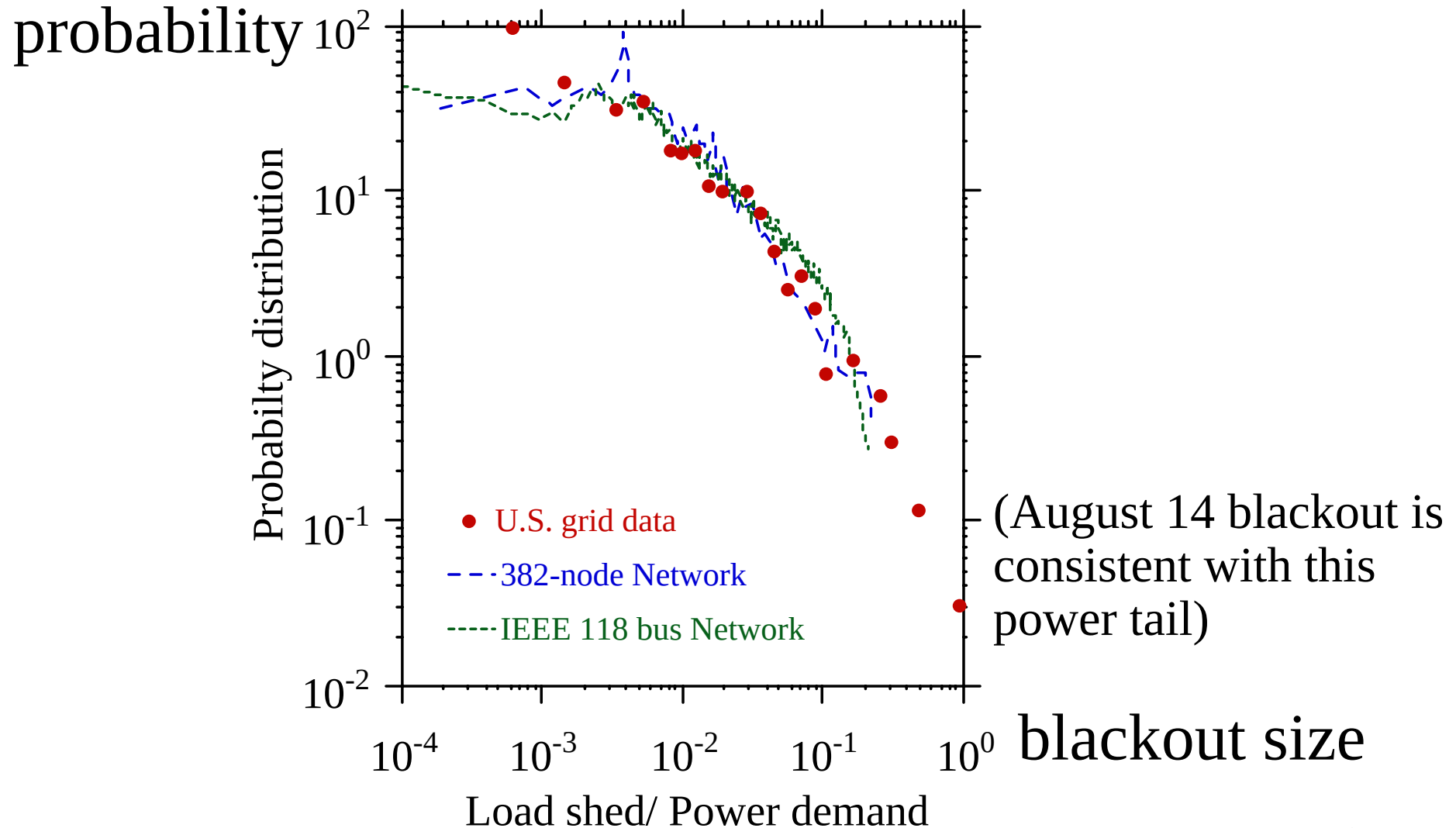
Mean blackout size sharply increases at critical loading; increased risk of cascading failure.

Economic and engineering forces drive system to near critical loading

Summary of OPA blackout model

- transmission system network modeled with DC load flow and LP dispatch
- random initial disturbances and probabilistic cascading line outages and overloads
- slow load increase
- upgrade lines that are part of a blackout; upgrade generation.
That is, upgrade weakest parts
- Run until a “complex systems steady state” is reached.

OPA model and NERC data



Effect of mitigation methods on probability distribution of blackout size

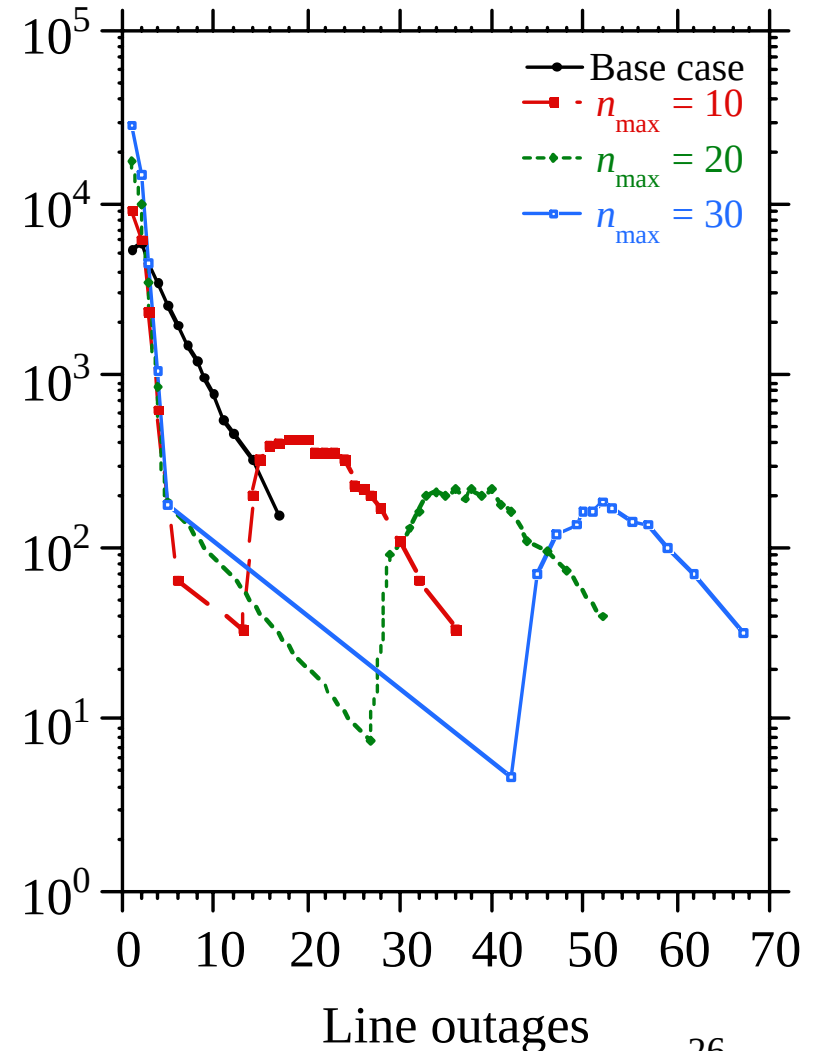
“obvious” methods can have
counterintuitive effects
in complex systems

Blackout mitigation example

- In the OPA model, overloaded lines outage with a given probability.
- Mitigation method requires a certain minimum number of transmission lines to overload before any overloaded lines outage.

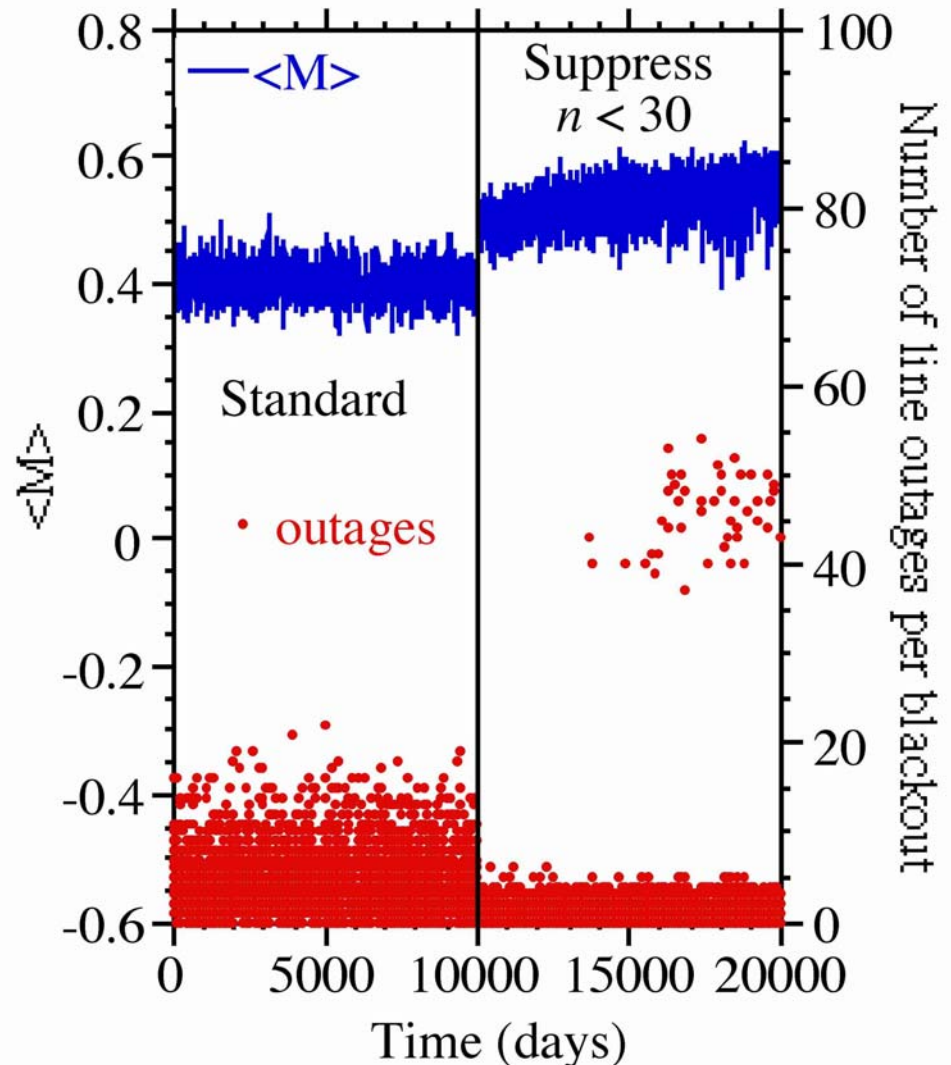
A minimum number of line overloads before any line outages

- In base case, there are blackouts with line outages ranging from zero up to 20.
- When we suppress outages unless there are $n > n_{\max}$ overloaded lines, there is eventually an increase in the number of large blackouts because the network readjusts itself.



Long term effect of complex dynamics on mitigation

- Start in “steady state”
- Try mitigation method requiring 30 lines to overload before outages occur.
- Mitigation works in short term, but in long term system adjusts to have more large blackouts.



Mitigation of blackouts

- Formulate problem as jointly reducing small and large blackout frequency.
- Complex systems dynamics arise from strong economic and societal forces and may be hard or costly to influence.

KEY POINTS: cascading failure

- North American data shows relatively high risk of large blackouts
- Criticality is a “limit” for increasing risk of cascading failure
- We are exploring and developing practical tools to quantify and monitor margin to criticality and hence risk of blackouts of all sizes.

KEY POINTS: complex dynamics

- Complex dynamics of network upgrade involve slow load growth and engineering responses.
- Complex dynamics can organize to near criticality.
- Some methods of suppressing small blackouts may eventually increase large blackouts.
- Problem of blackout mitigation is to jointly reduce frequency of small and large blackouts.
- For more information see papers at <http://eceserv0.ece.wisc.edu/~dobson/home.html>

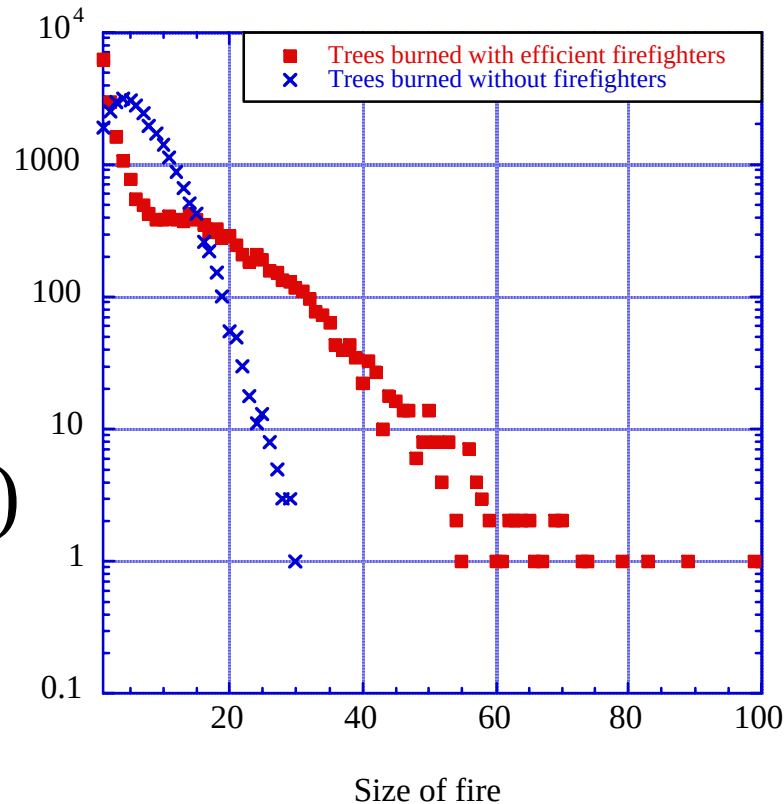
EXTRA SLIDES FOLLOW

Forest fire mitigation simulation

red = efficient fire fighting

blue = no fire fighting

number of
fires of
given size
(proportional
to probability)



size of fire

Upgrading transmission does not necessarily improve security

- The (eventual) changes in system loading are also important

- Example is based on

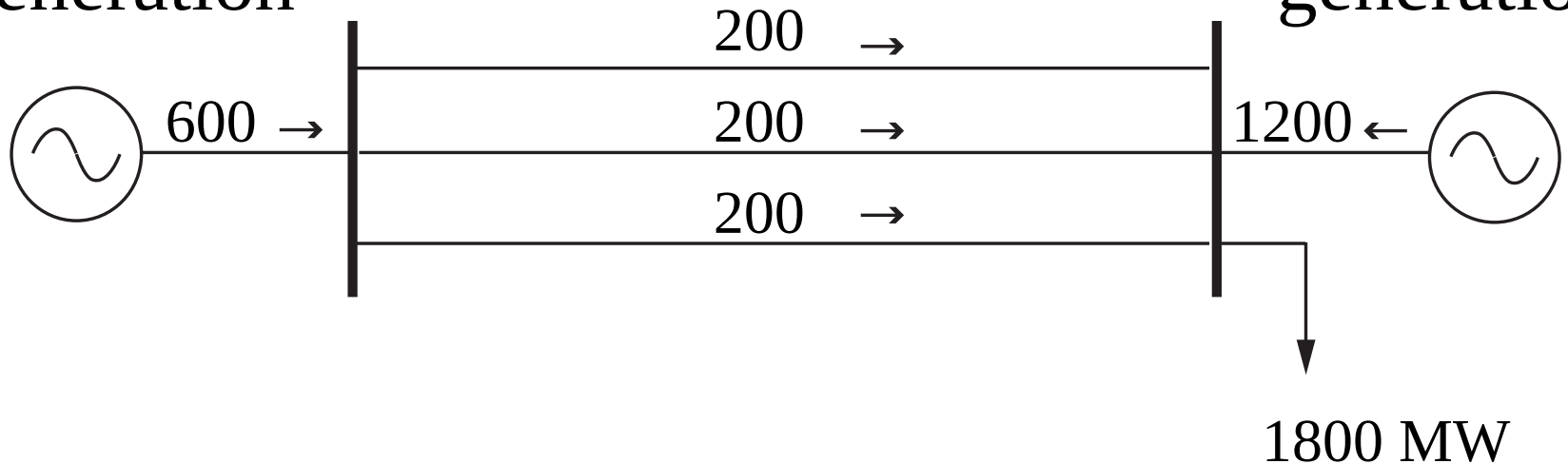
D. Kirschen, G. Strbac, Why investments do not prevent blackouts, UMIST 2003

www.ksg.harvard.edu/hepg/Standard_Mkt_dsgn/Blackout_Kirschen_Strbac_082703.pdf

N-1 secure system; line limit 300 MW

cheap
generation

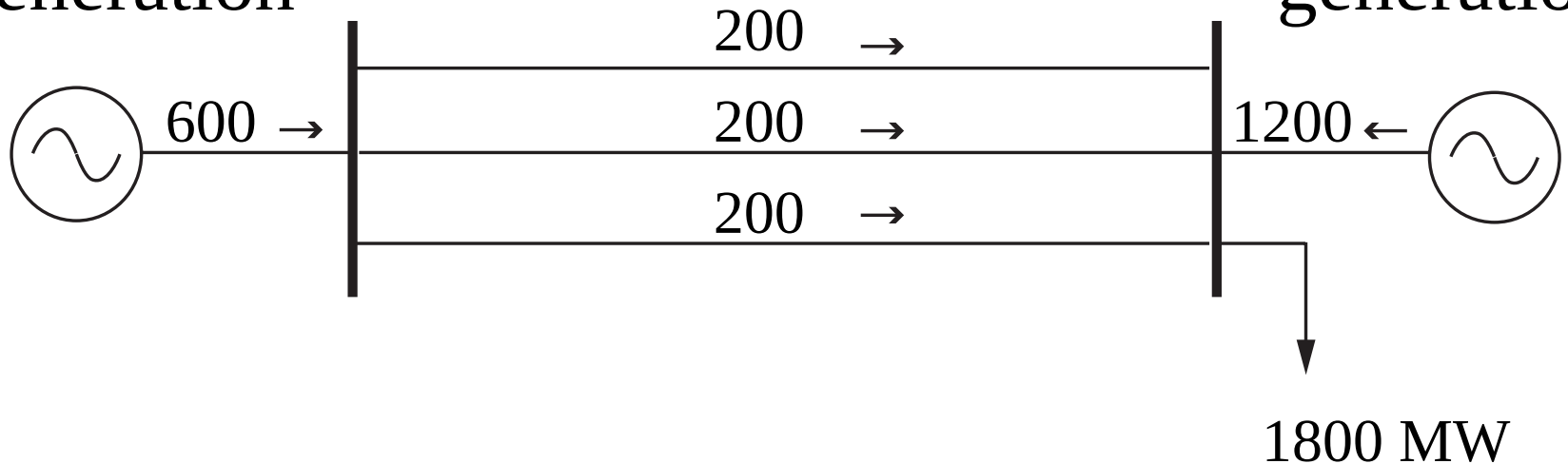
expensive
generation



upgraded lines 600 MW; increased security?

cheap
generation

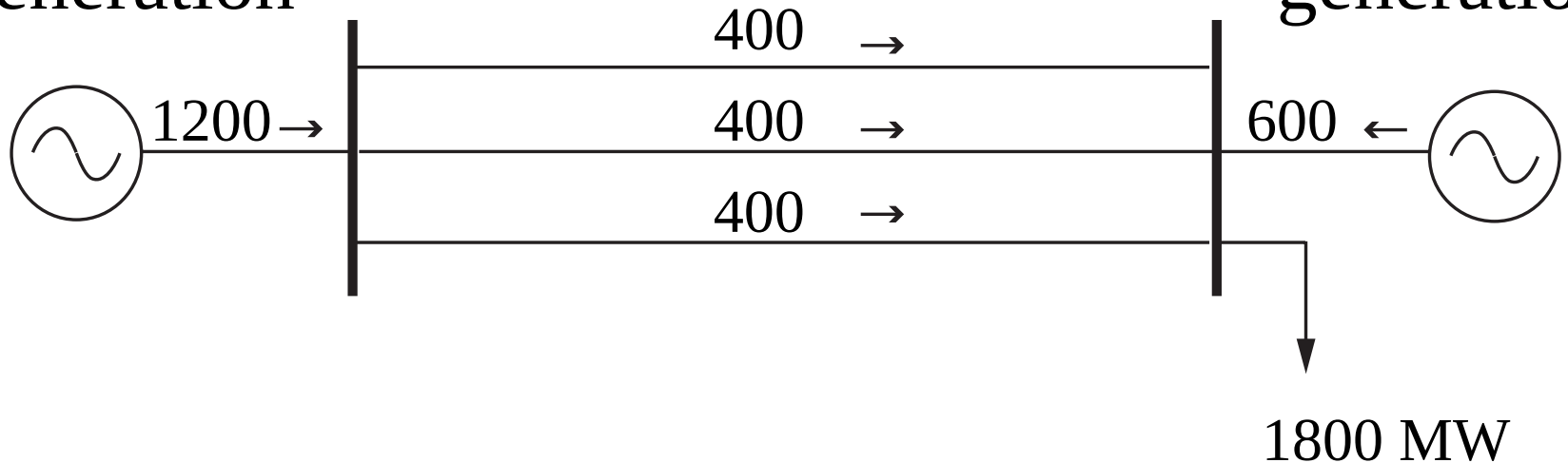
expensive
generation



Economics can change the flows to again minimally satisfy N-1 criterion

cheap
generation

expensive
generation

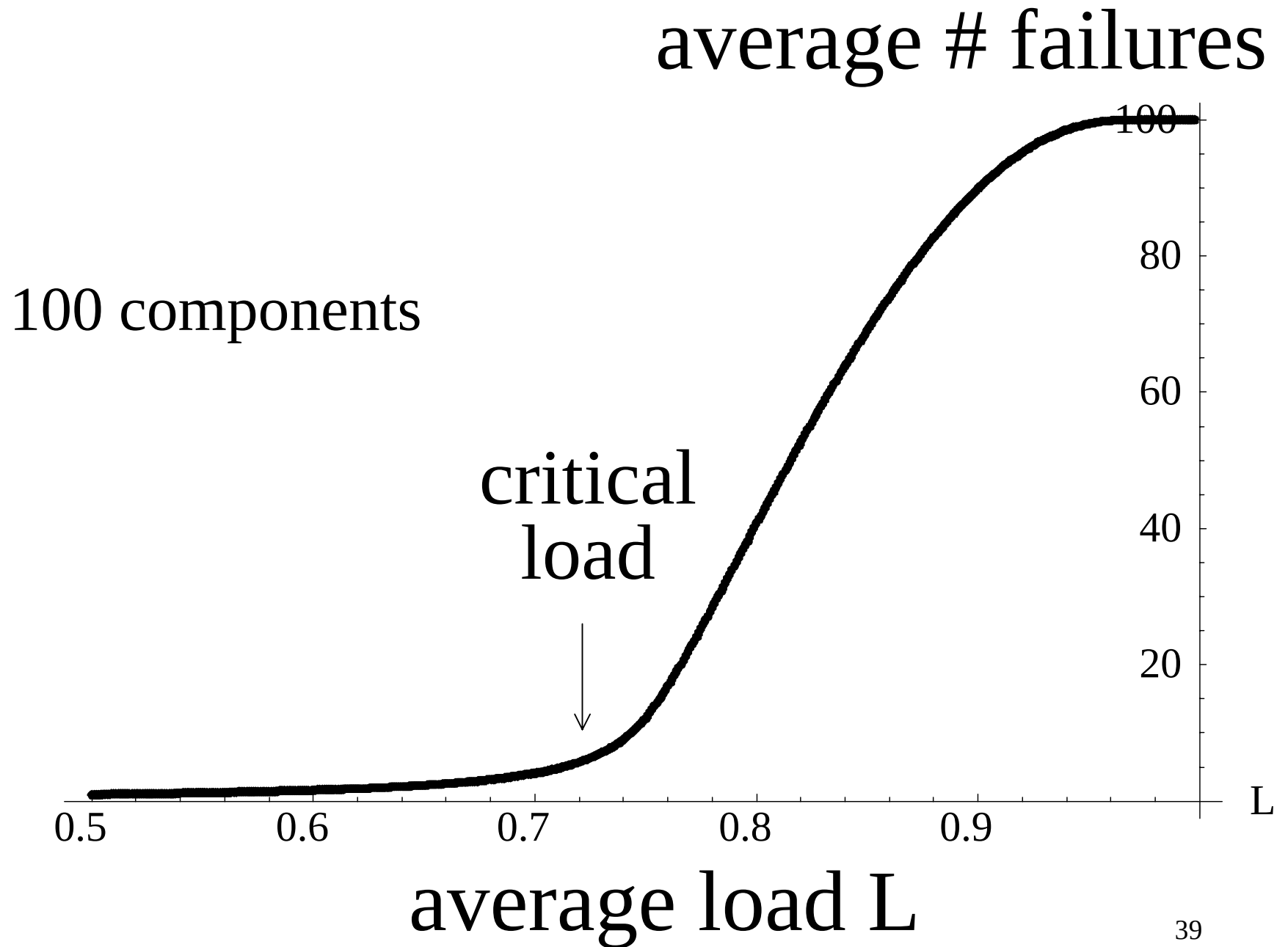


Summary of CASCADE model

- A probabilistic loading-dependent model of cascading failure --- captures system weakening as successive failures occur.
- Identical components that trip when overloaded and further load all other components; start with random loadings.
- There is an explicit formula for the probability distribution of number of failed components.
- Captures some salient features of cascading failure in a tractable model.

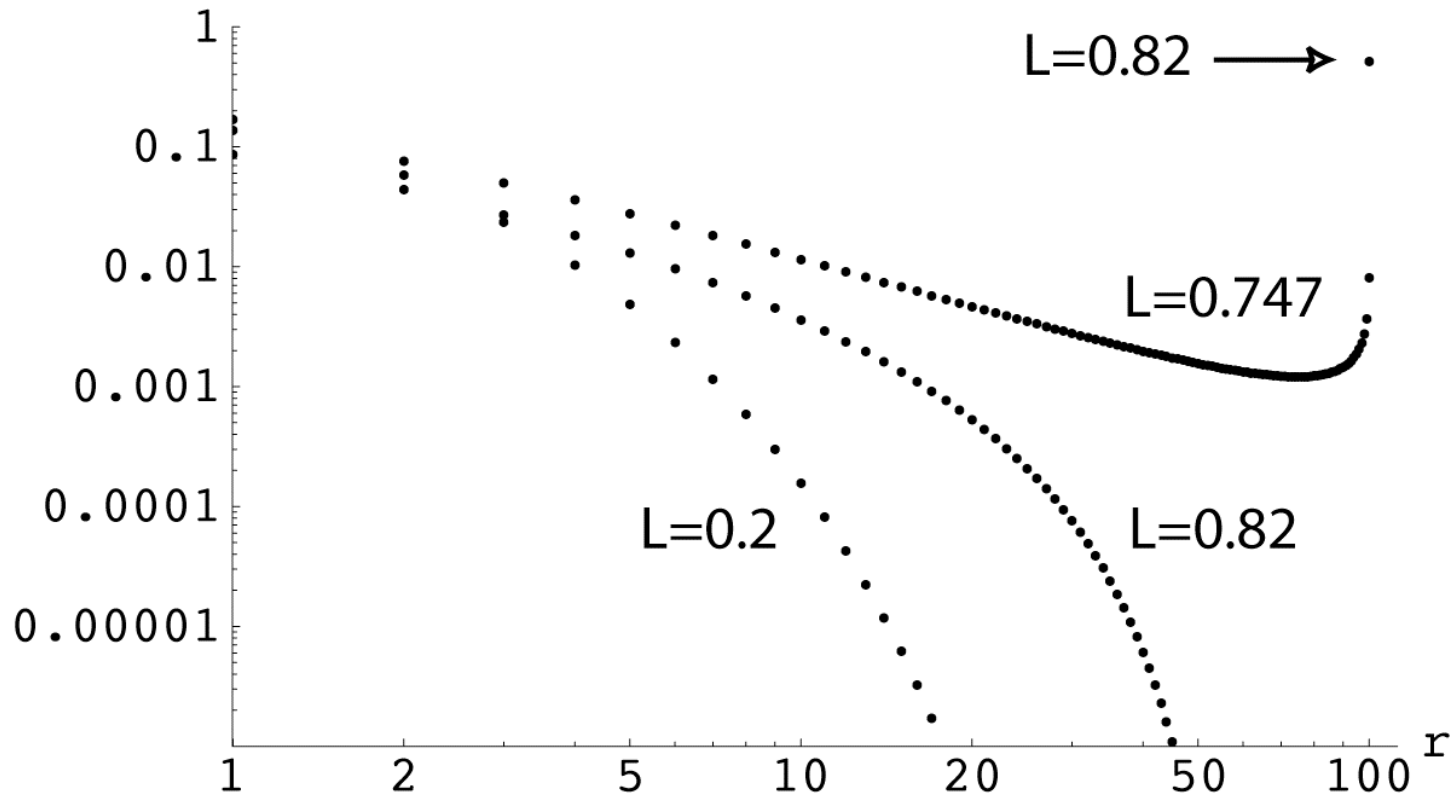
CASCADE model

- n identical components with random initial load uniform in $[L_{\min}, L_{\max}]$
- initial disturbance D adds load to each component
- component fails when its load exceeds threshold L_{fail} and then adds load P to every other component. Load transfer amount P measures component coupling, dependency
- iterate until no further failures



probability distribution as average load L increases

probability



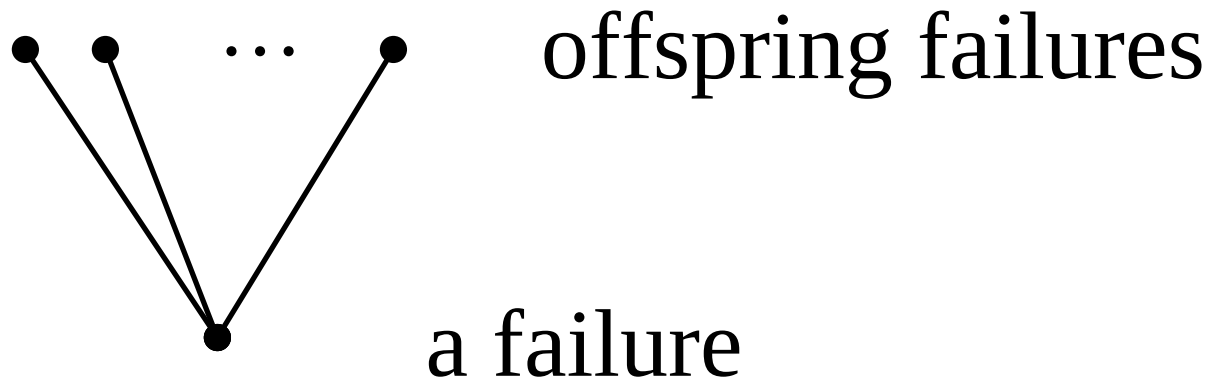
number of failures

Context

- We suggest adding an “increased risk of cascading failure” limit to usual power system operating limits such as thermal, voltage, transient stability etc.
- Cascading failure limit measures overall system stress in terms of how failures propagate once started; complementary to measures to limit cascading failure by inhibiting start of cascade such as n-1, n-2 criterion.

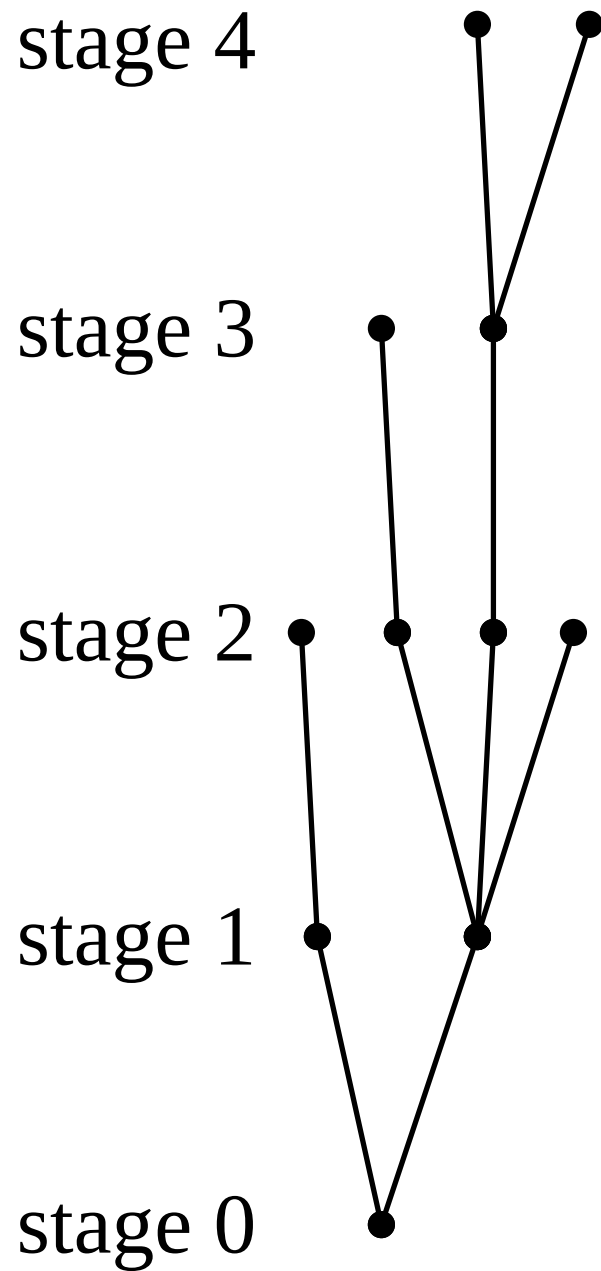
Summary of branching process model

Branching from one failure:



number of offspring $\sim \text{Poisson}(\lambda)$

mean number of failures $= \lambda$



Branching Process

- each failure independently has random number of offspring in next stage according to $\text{Poisson}(\lambda)$
- $\lambda = \text{mean number failures per previous stage failure}$
- $\lambda^k = \text{mean number of failures in stage } k$

λ controls failure propagation

- Subcritical case $\lambda < 1$:
failures die out
- Critical case $\lambda = 1$:
probability distribution of total number of failures
has power tail
- Supercritical case $\lambda > 1$:
failures can proceed to system size

Cumulative Line Trips from August 2003 Blackout Final Report

Figure 6.1. Rate of Line and Generator Trips During the Cascade

