Estimating and Mitigating Cascading Failure Risk

Paul Hines
JST-NSF-DFG-RCN Workshop
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Credits
Good ideas: P. Rezaei, M. Eppstein, Ian Dobson
Funding: Dept. of Energy, National Science Foundation
Errors and omissions: Paul Hines

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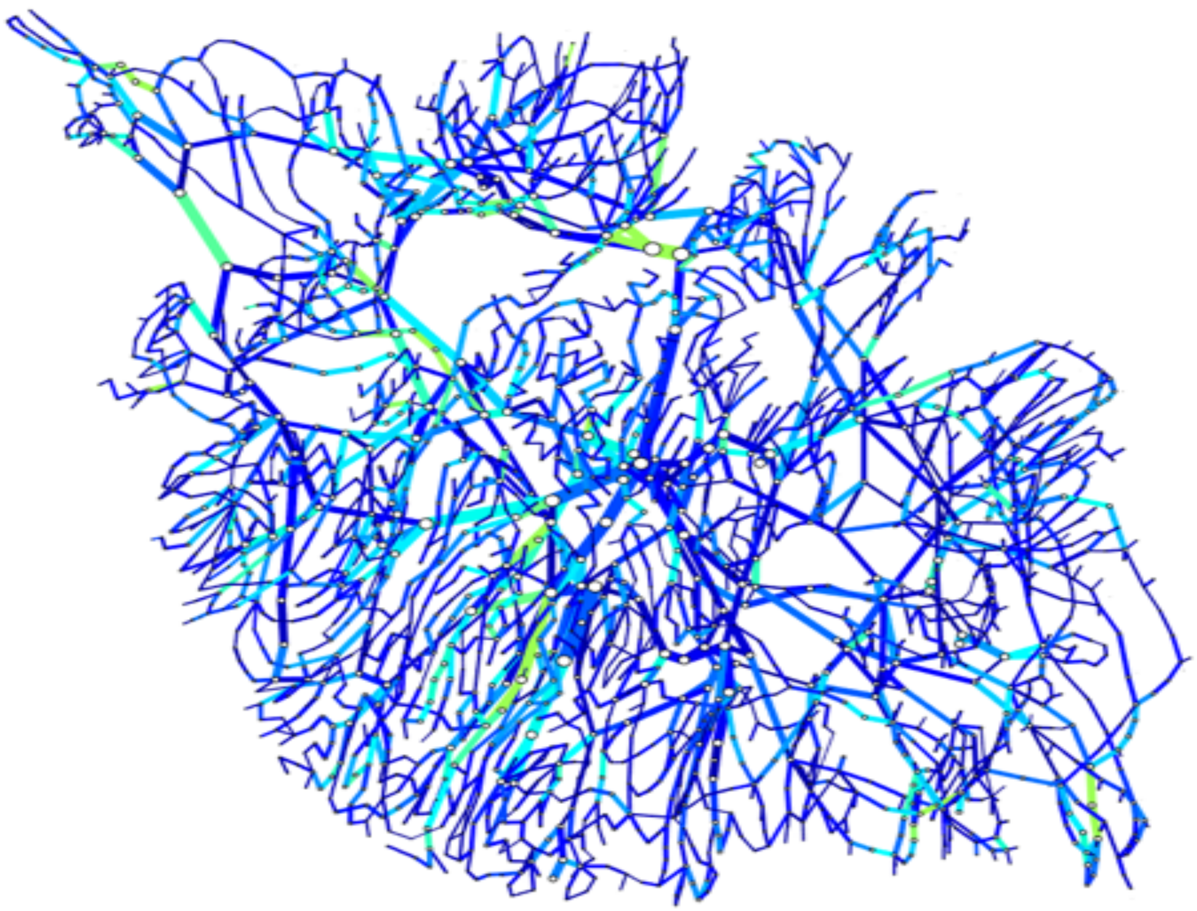
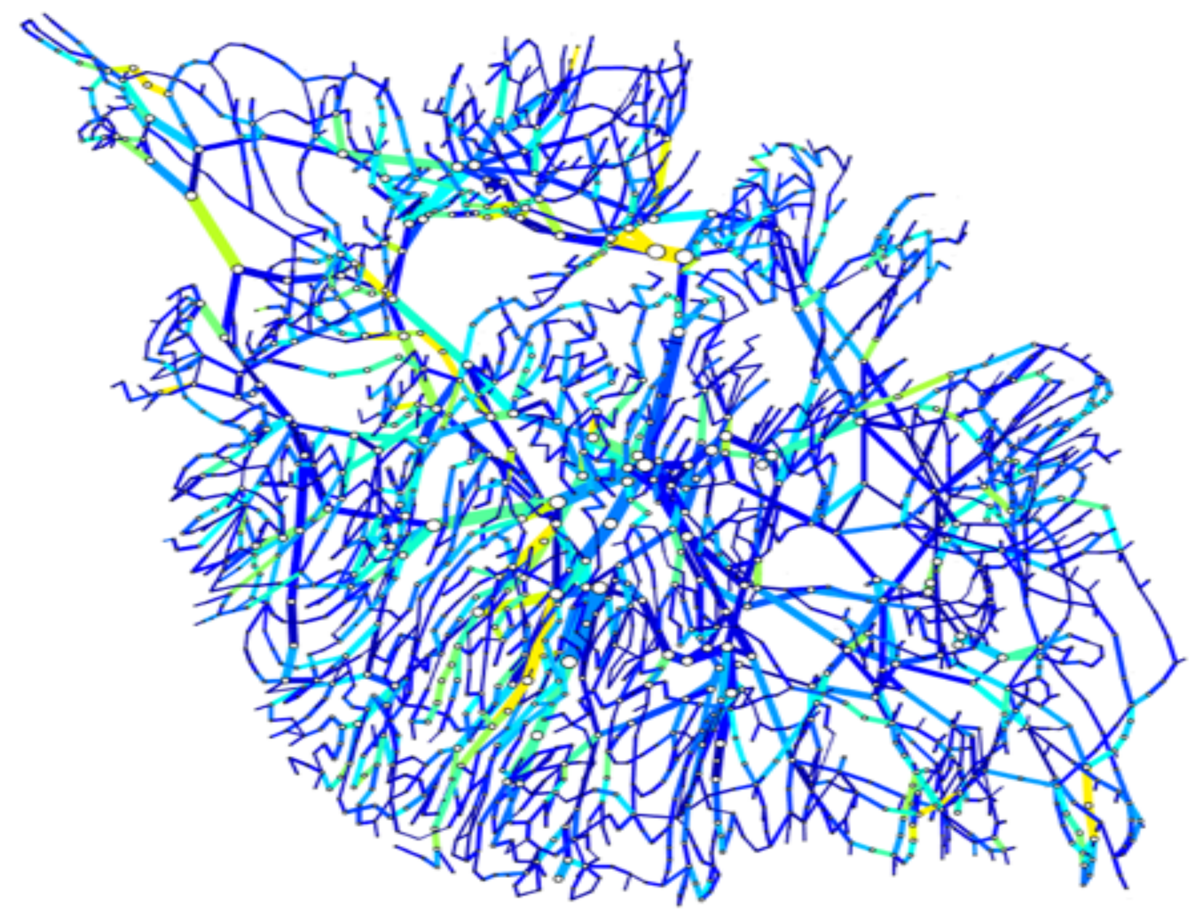
The cascading failure risk estimation problem

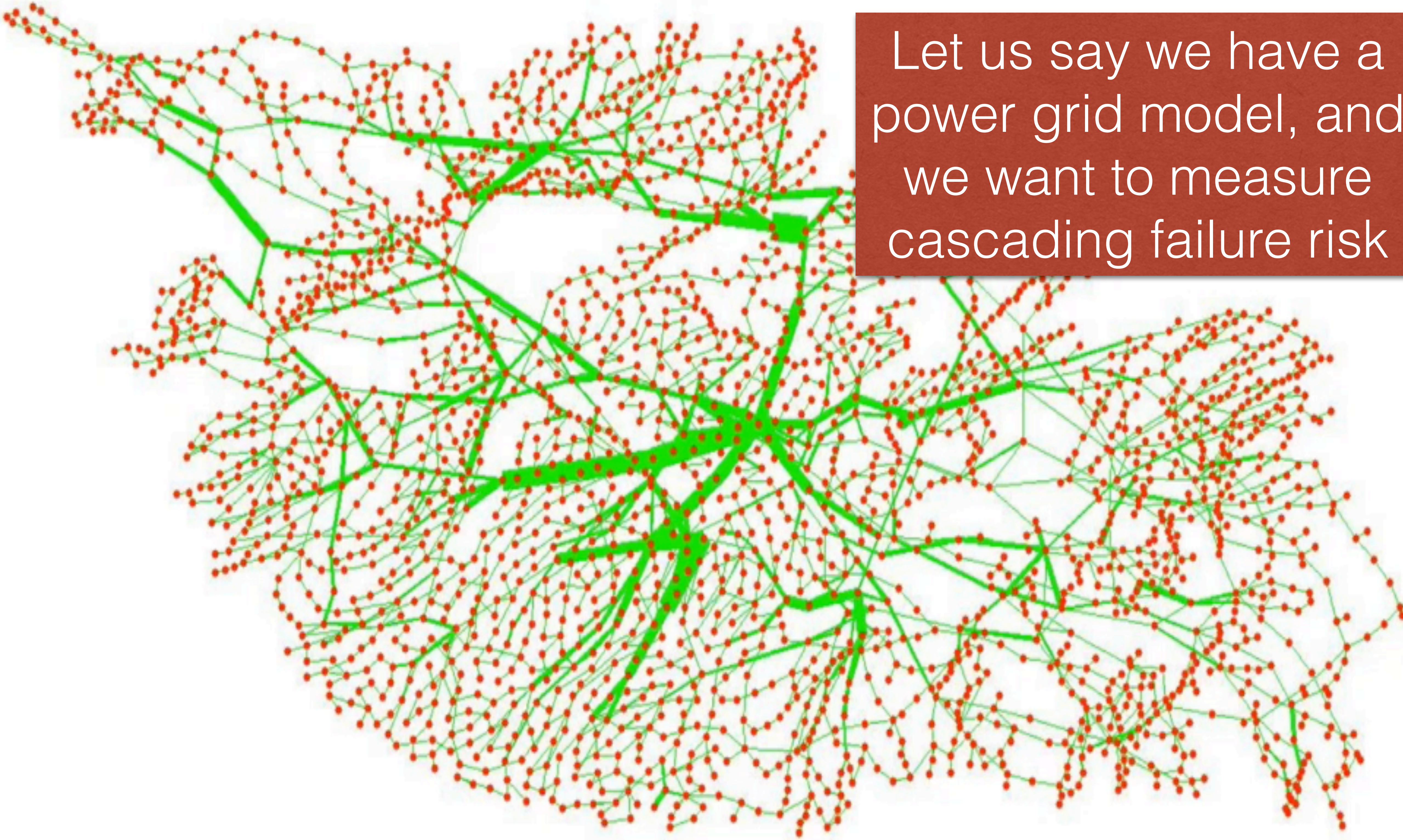


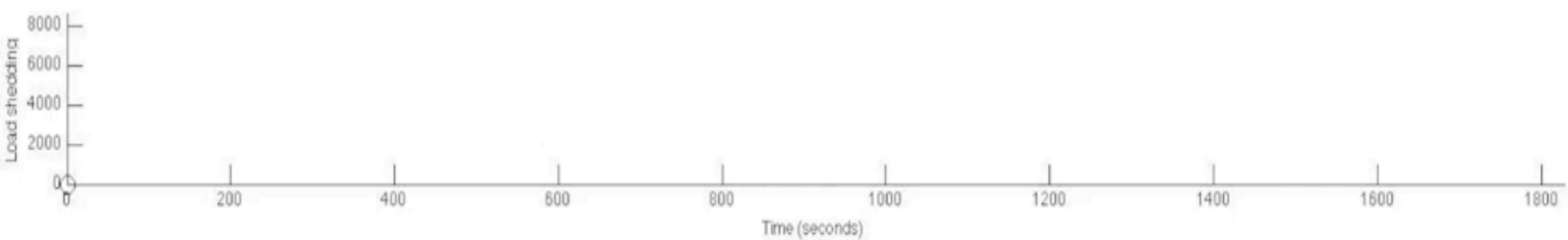


Both cases are N-1 secure.
How can we compare, understand, and mitigate blackout risk in the two systems?

Performance index/risk-based methods (McCalley, Edjebe, others) are useful, but not based on explicit blackout simulations

Let us say we have a power grid model, and we want to measure cascading failure risk





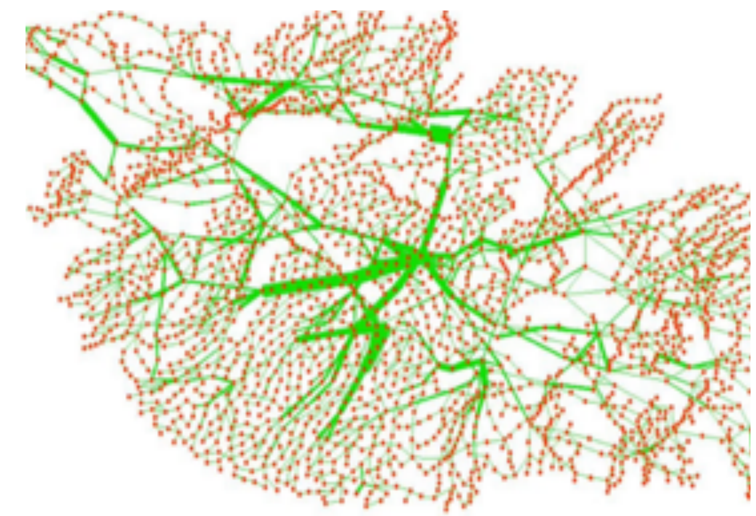
The Risk Analysis Challenge

- N-1 security analysis has been the guiding risk analysis principle for >50 years
- But:
  - The probability of a single line outage is ~10^{-4}
  - Large systems have ~10^{4} lines; ~1 failure/hour
  - Even if outages are uncorrelated (false) N-2 events are ~1x/year
- ~1970s, Monte Carlo methods were developed for probabilistic reliability analysis
- But, Monte Carlo is super-slow:
  - Combinatorial number of possible triggering combinations, each with very small probabilities
  - Event costs (blackout sizes) span 4+ orders of magnitude

But most combinations are benign, only a few are “malignant”

<u>Evidence</u>

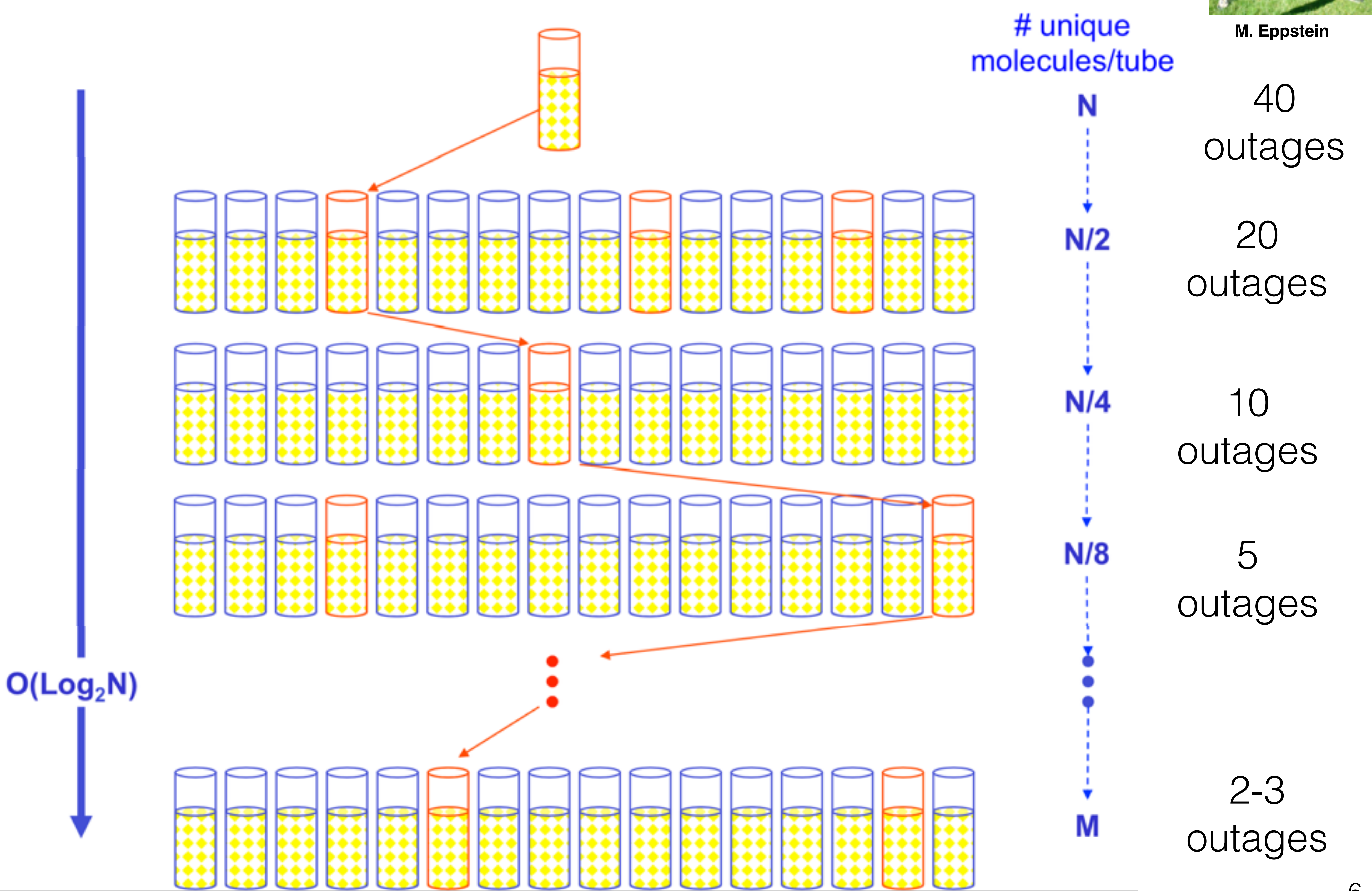
There are 4.2 million n-2 combinations in the“Polish” grid.
Only 300-400 of these cause large blackouts.



Can we somehow quickly find the malignant combinations, and then use their probabilities to estimate risk?

The Random Chemistry algorithm

M. Eppstein



Estimating risk from RC (1)

The estimated number of malignancies of size k

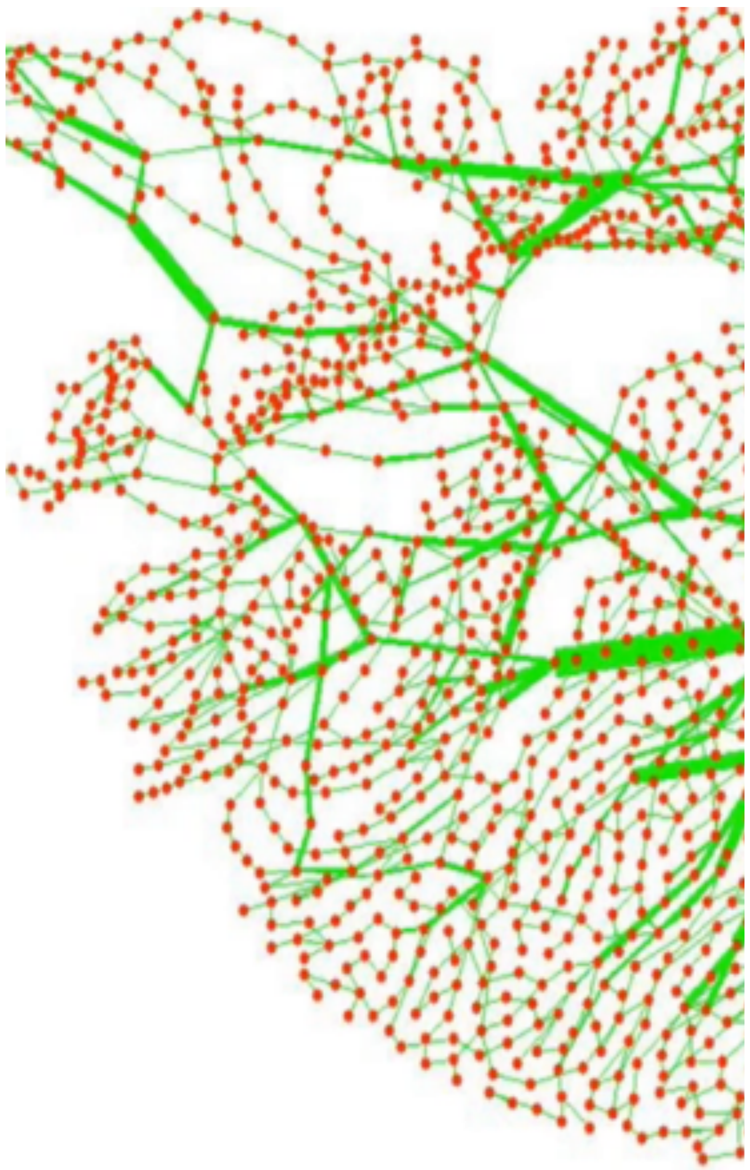
Blackout sizes

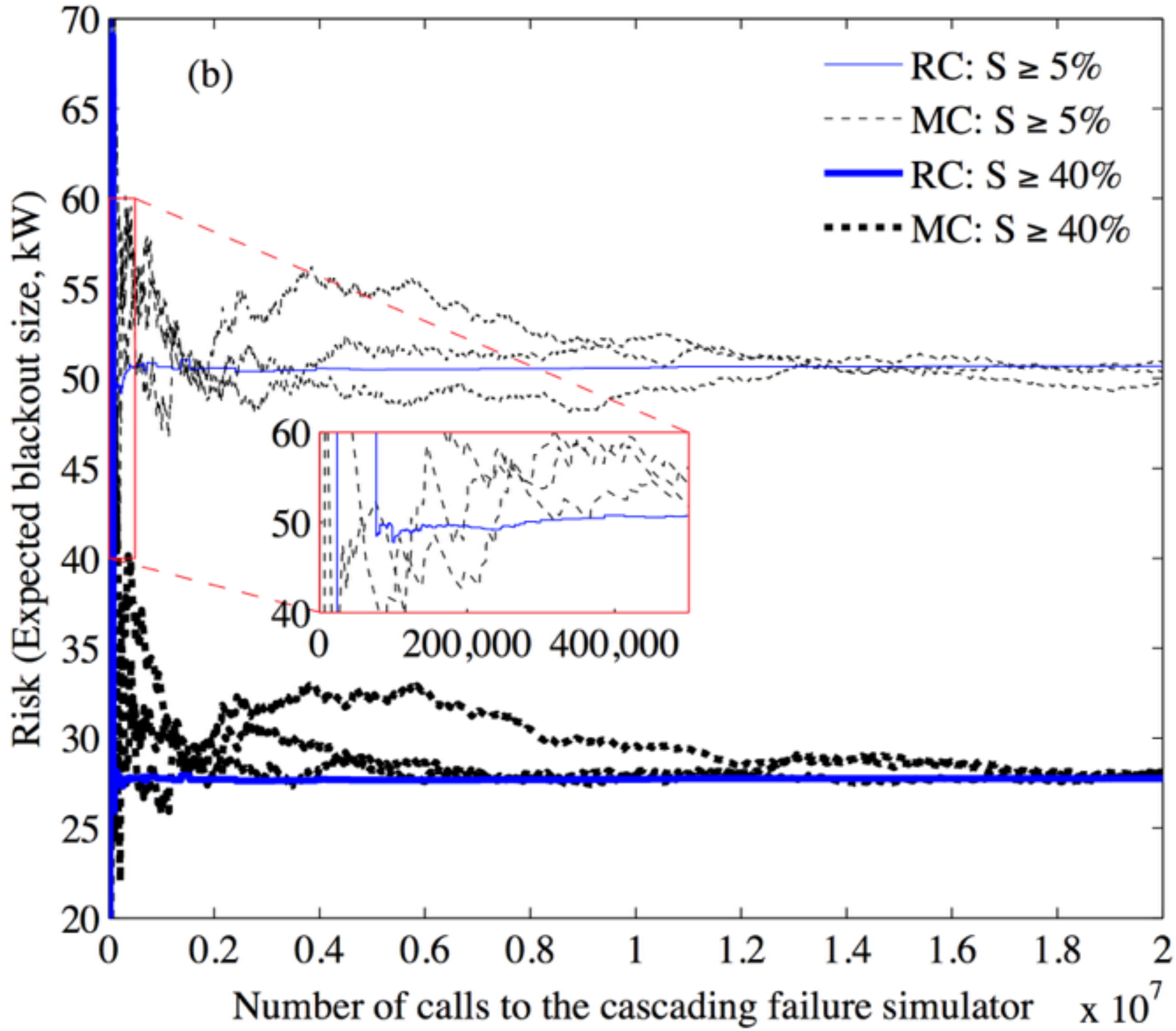
$$\hat{R}_{RC,k}(x) = \frac{\hat{m}_k}{|\Omega_{RC,k}|} \sum_{d \in \Omega_{RC,k}} S(d,x) \left(\prod_{i \in d} p_i \right)$$

Combined probability

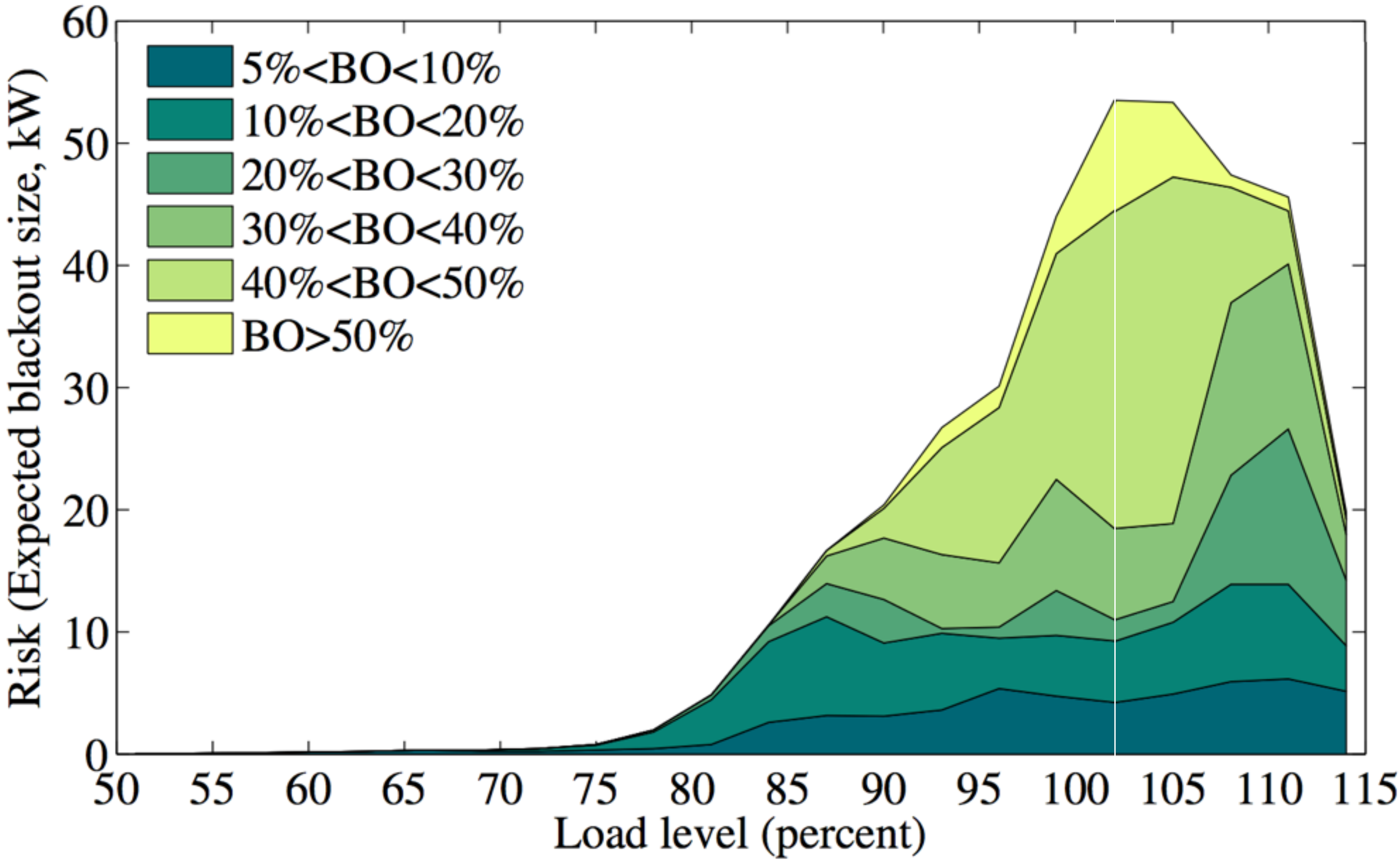
The number of malignancies of size k found by RC

Comparing RC to Monte Carlo





Risk vs. load, given SCOPF



Why?

- At high load levels SCOPF leaves larger margins on long inter-area tie lines (to allow for potential contingencies)

Total absolute flow on lines with large (>200MW) base case flow

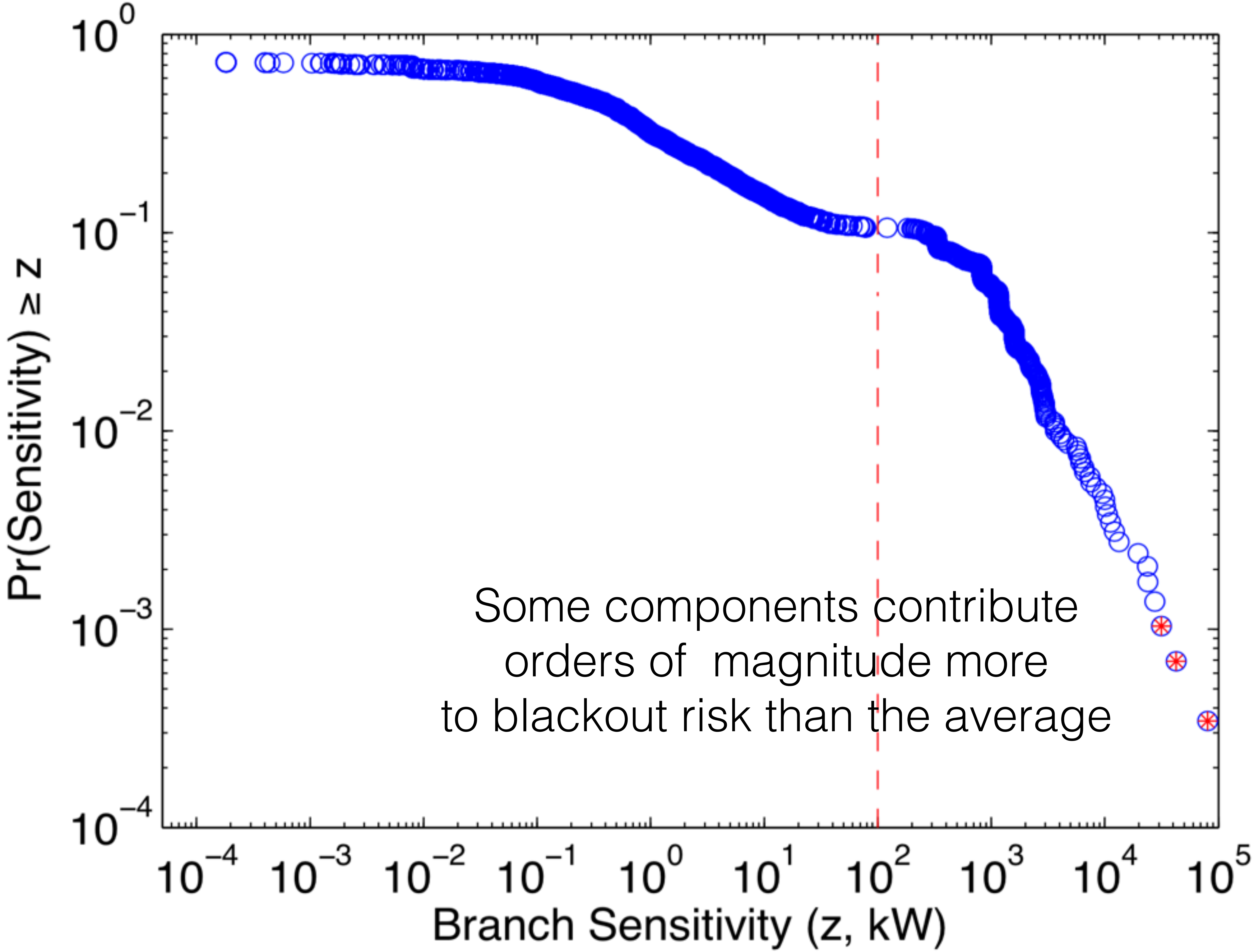
Load level	95%	100%	105%	110%	115%
MW flow	16,312	17,032	17,102	16,869	15,916

Finding the contribution of elements to risk

Differentiate the risk equation with respect to element outage probabilities

$$\hat{R}_{RC}(x) = \sum_{k=2}^{k_{\max}} \frac{\hat{M}_k}{|\Omega_{RC,k}|} \sum_{m \in \Omega_{RC,k}} \Pr(m) S(m,x)$$

$$\frac{\partial \hat{R}_{RC,k}}{\partial p_i} = \frac{\hat{M}_k}{|\Omega_{RC,k}|} \sum_{m \in \Omega_{RC,k}} S(m,x) \frac{\partial}{\partial p_i} \Pr(m)$$

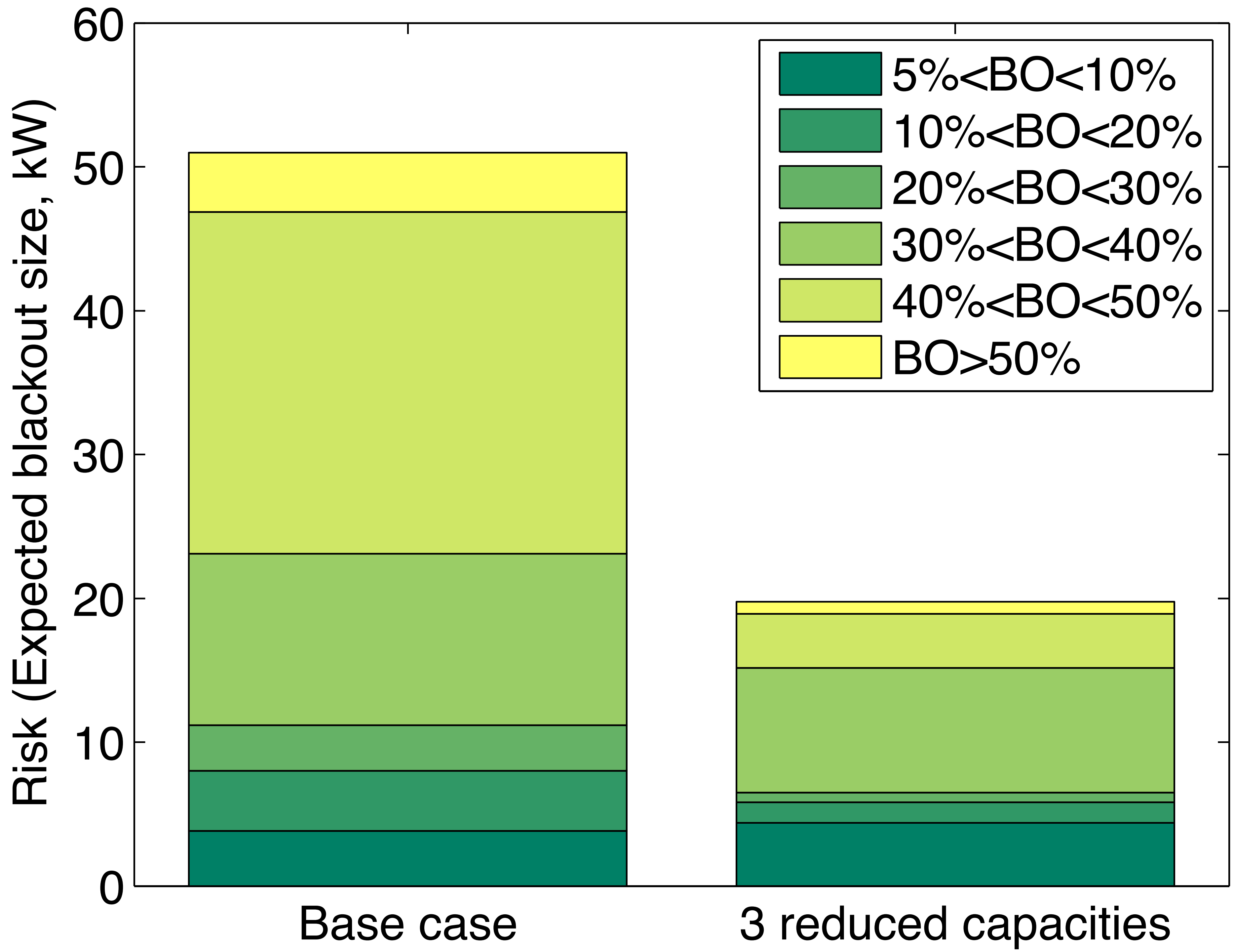


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Pr(Sensitivity) ≥ z
10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5
Branch Sensitivity (z, kW)
Some components contribute
orders of magnitude more
to blackout risk than the average

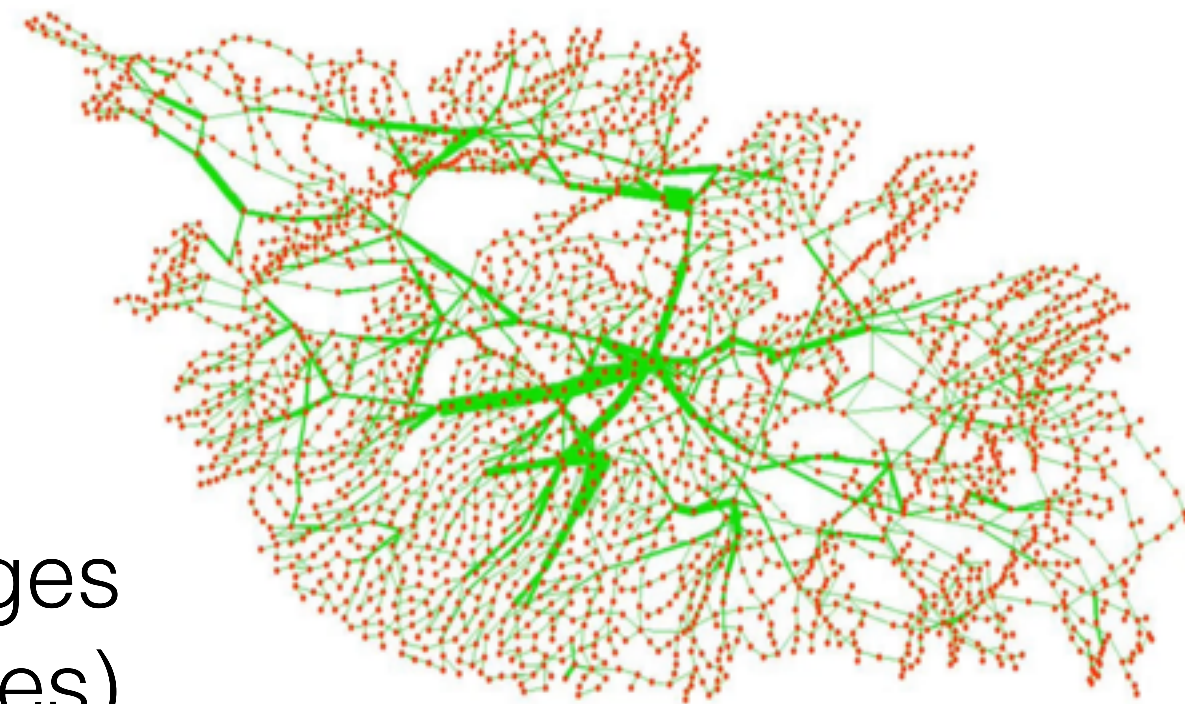
Can we use this insight to reduce risk?

- Take the 3 lines that contribute most to blackout risk
- Re-dispatch generators to leave more margin between the flow on these lines and the limit (cut the limit in half)
- Fuel costs increase by 1.6%
- Large (S>5%) blackout risk decreases by 61%
- Very large (S>40%) blackout risk decreases by 83%
- Perhaps we would be better off without these lines?

Before and after

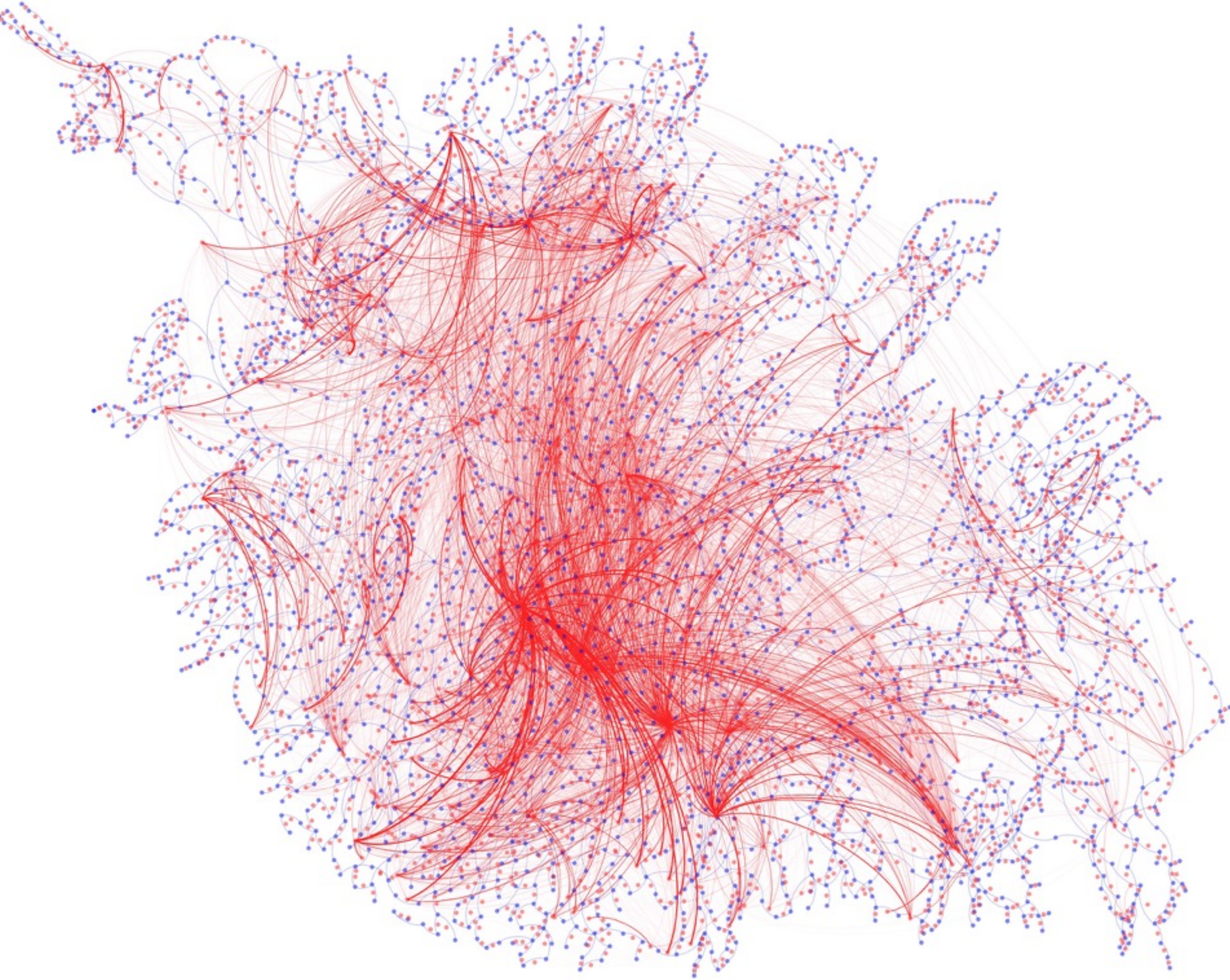


Visualizing influences, and finding critical components



- Take data from many cascades
- Count the rates at which outages produce “child” outages (element-wise propagation rates)
- Find which outages tend to follow particular outages
- Build a matrix of conditional probabilities:

$$h_{ij} = \Pr[\, j \text{ fails} \mid i \text{ fails} \,]$$



Conclusions

- It is possible to estimate **cascading failure risk** in reasonable time (e.g., overnight) for practically sized systems
- The data that result lead to **practical insight**:
  - Some components contribute **hundreds of times** more to risk, relative to the average.
  - **Reducing flows** on these components reduces risk
  - Some components **propagate cascades** (within the cascade) much more than others. (Mitigation schemes in progress)

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