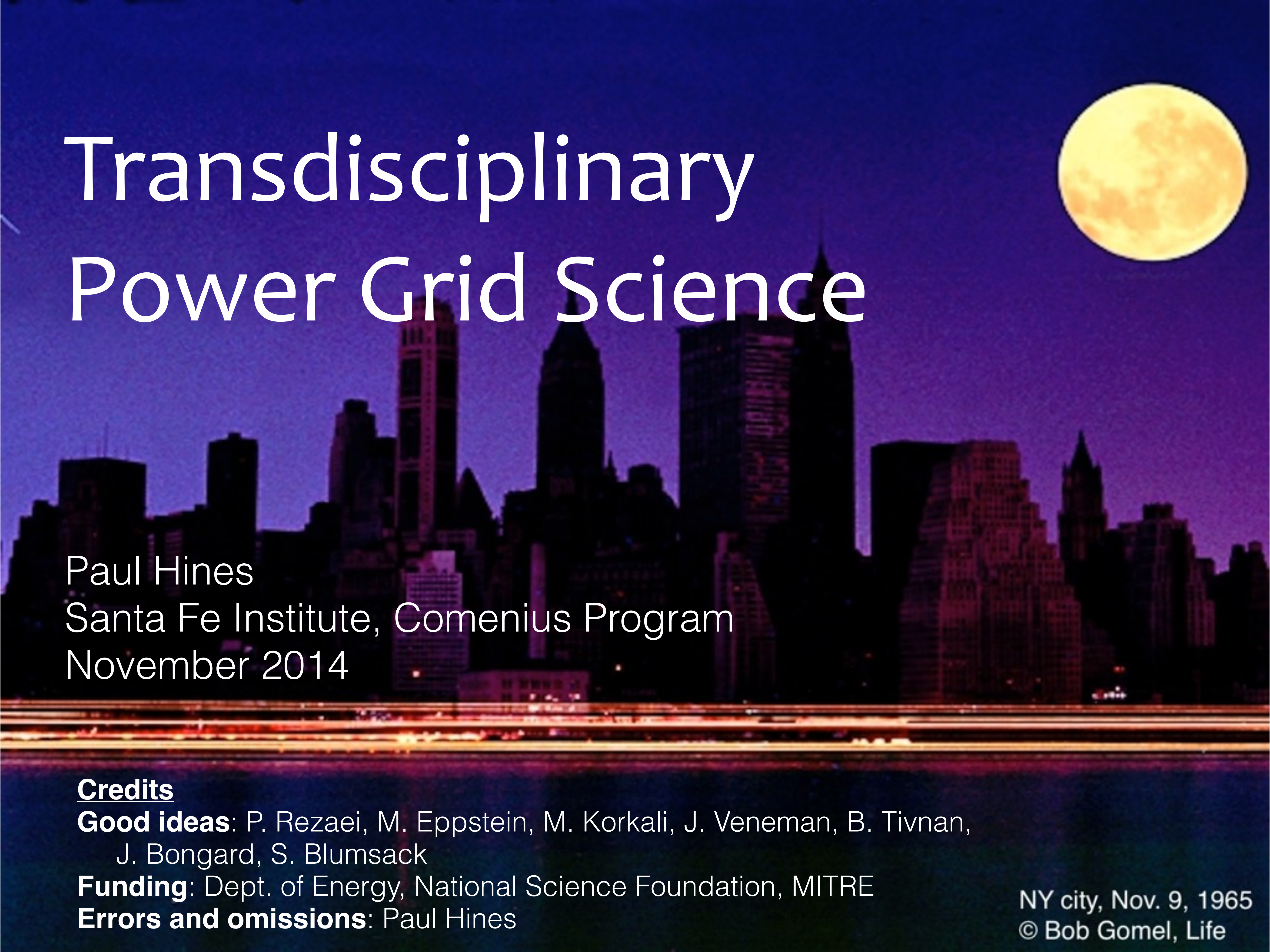

Transdisciplinary Power Grid Science

Paul Hines
Santa Fe Institute, Comenius Program
November 2014

Credits
Good ideas: P. Rezaei, M. Eppstein, M. Korkali, J. Veneman, B. Tivnan, J. Bongard, S. Blumsack
Funding: Dept. of Energy, National Science Foundation, MITRE
Errors and omissions: Paul Hines

NY city, Nov. 9, 1965

Outline

Outline

- Why I am a power grid scientist/engineer

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- Why I am a power grid scientist/engineer

- What is the power grid and what makes it “complex”

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- Why I am a power grid scientist/engineer
- What is the power grid and what makes it “complex”
  - What is transdisciplinary power grid science?

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  - What is transdisciplinary power grid science?
- Cascading failures in power grids

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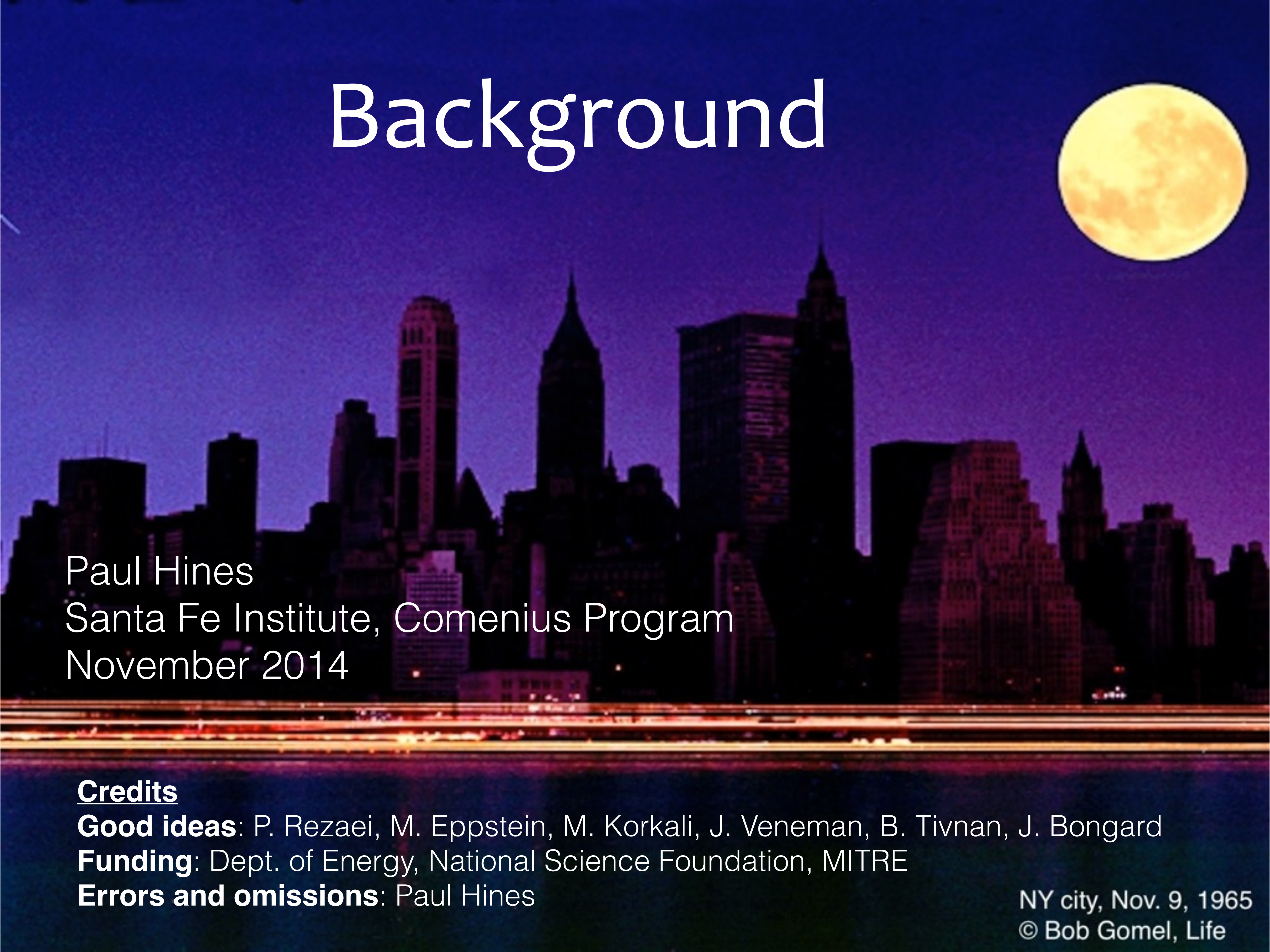
- Why I am a power grid scientist/engineer
- What is the power grid and what makes it “complex”
  - What is transdisciplinary power grid science?
- Cascading failures in power grids
- Smart Grid: Will it make blackouts better or worse?

Outline

- Why I am a power grid scientist/engineer
- What is the power grid and what makes it “complex”
    - What is transdisciplinary power grid science?
- Cascading failures in power grids
- Smart Grid: Will it make blackouts better or worse?
- Carrots vs. Sticks: Smart Grid and human behavior



Background

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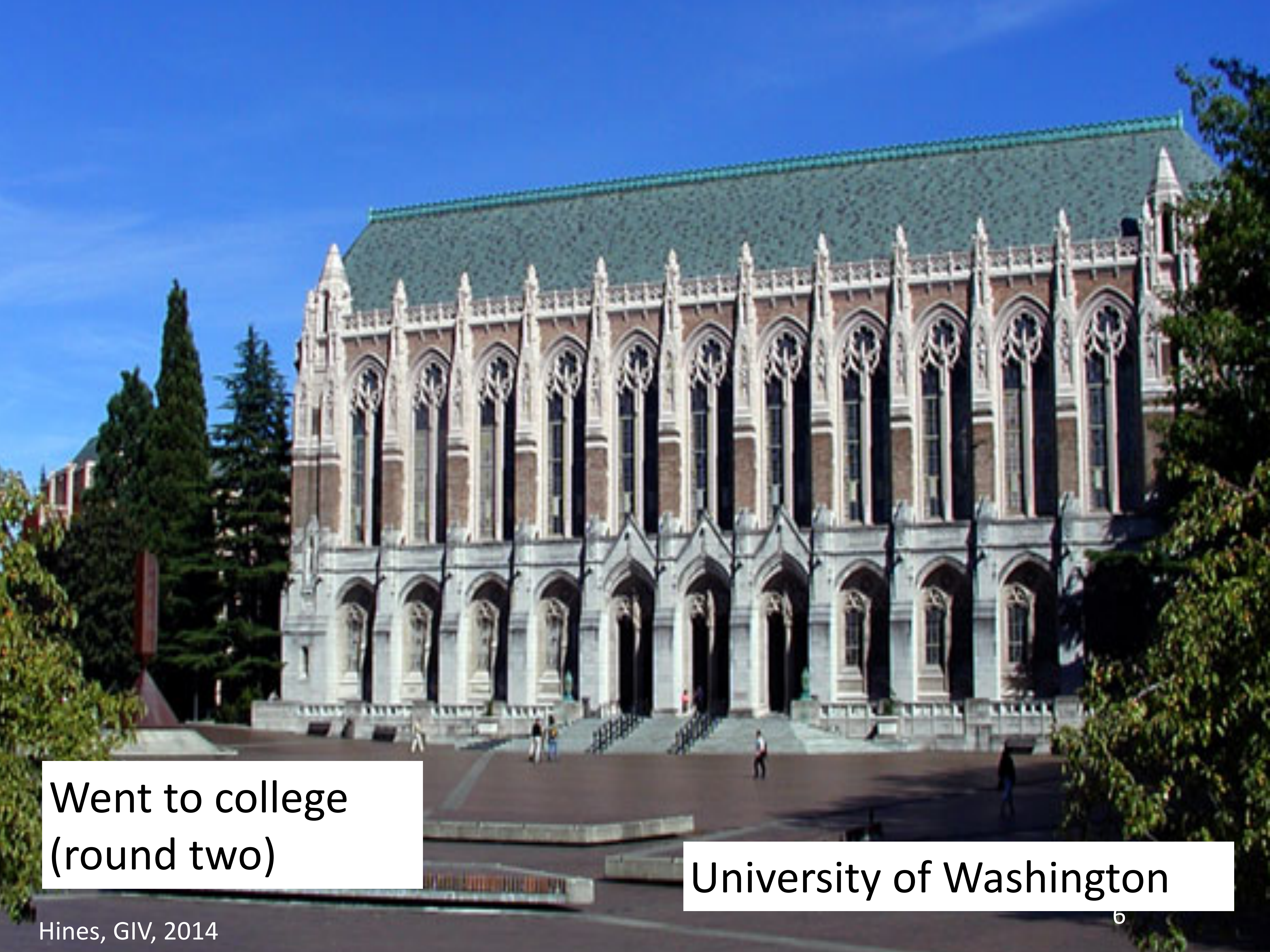
Errors and omissions: Paul Hines

NY city, Nov. 9, 1965

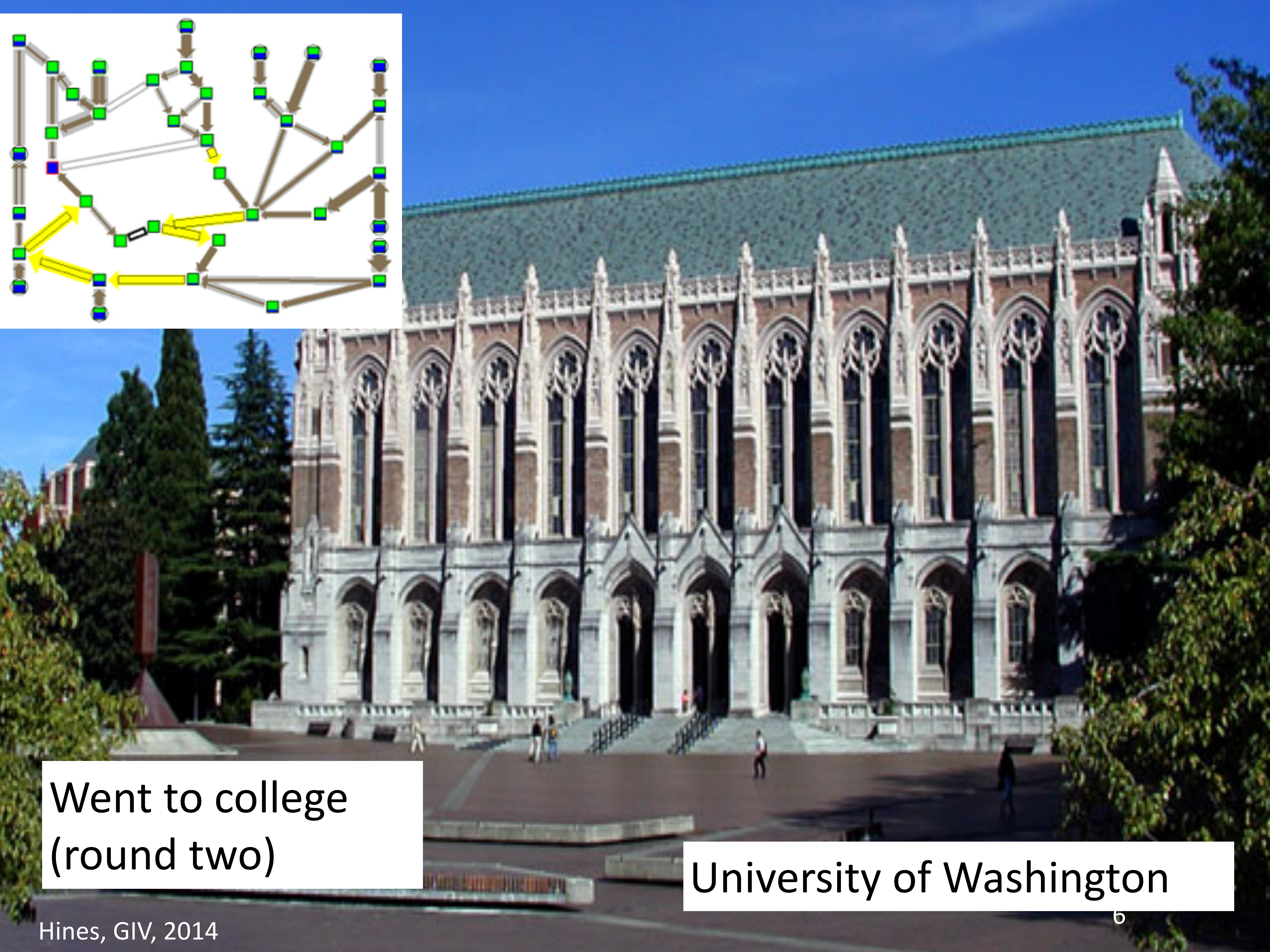
Went to College (the first time),
power engineering

Went to work,
got a bit bored



Went to college
(round two)

University of Washington



Went to college
(round two)

University of Washington

CONTACT US

INMA FOUNDATION

Building Bridges Across Cultural Borders

Learned Arabic

BLOG

ABOUT

FAITH

PROJECTS

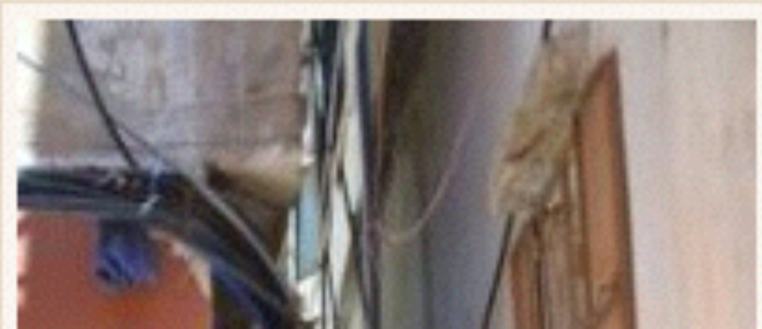
PHOTOS

VIDEOS

The INMA Volunteer Experience

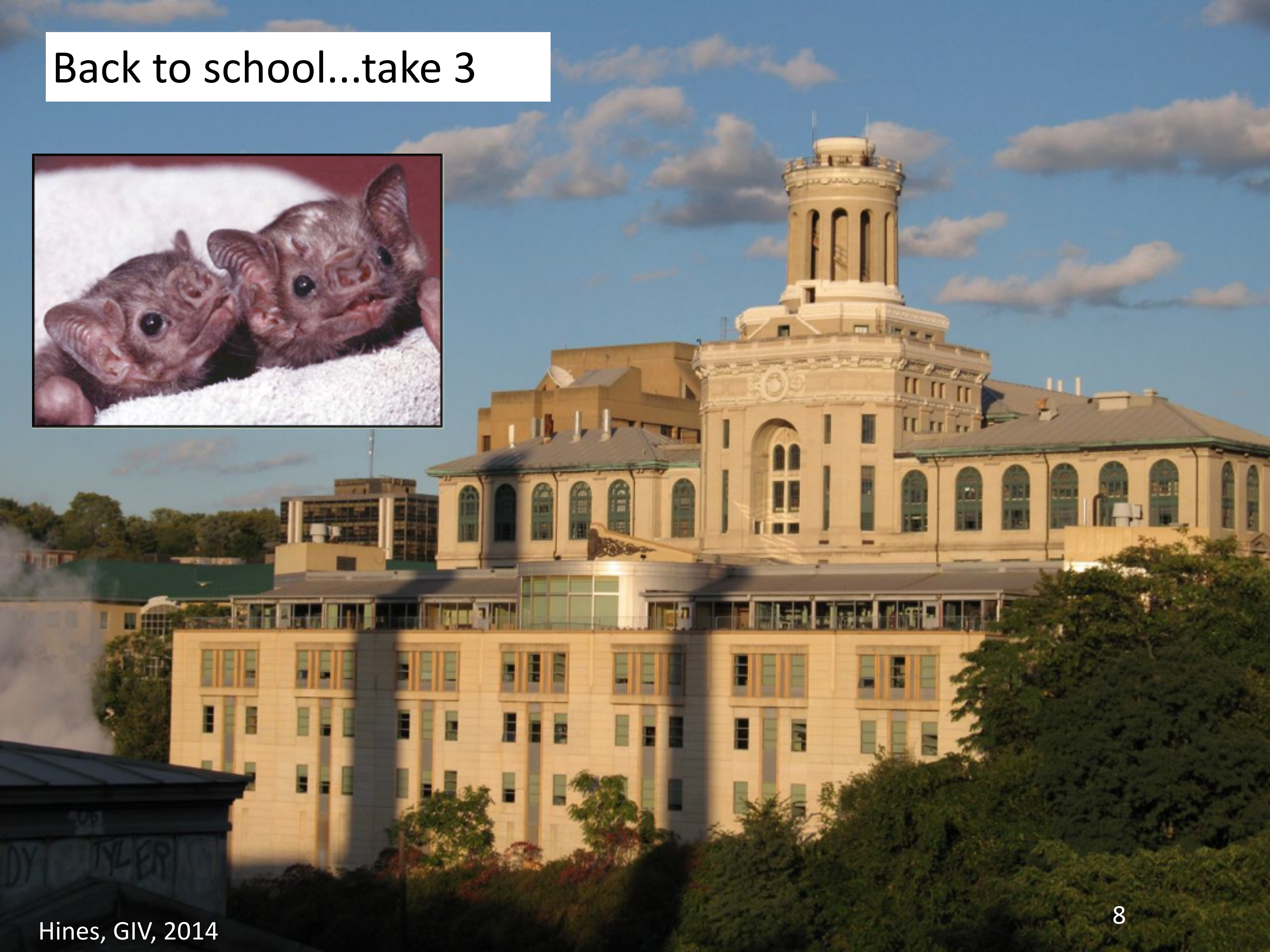
When we arrived in Beirut we were still not sure what to expect. We knew we would be working with kids in a Palestinian refugee camp - but that was about it.

The first impression as we walked into the camp was of an incredible web of electrical wires and water pipes haphazardly



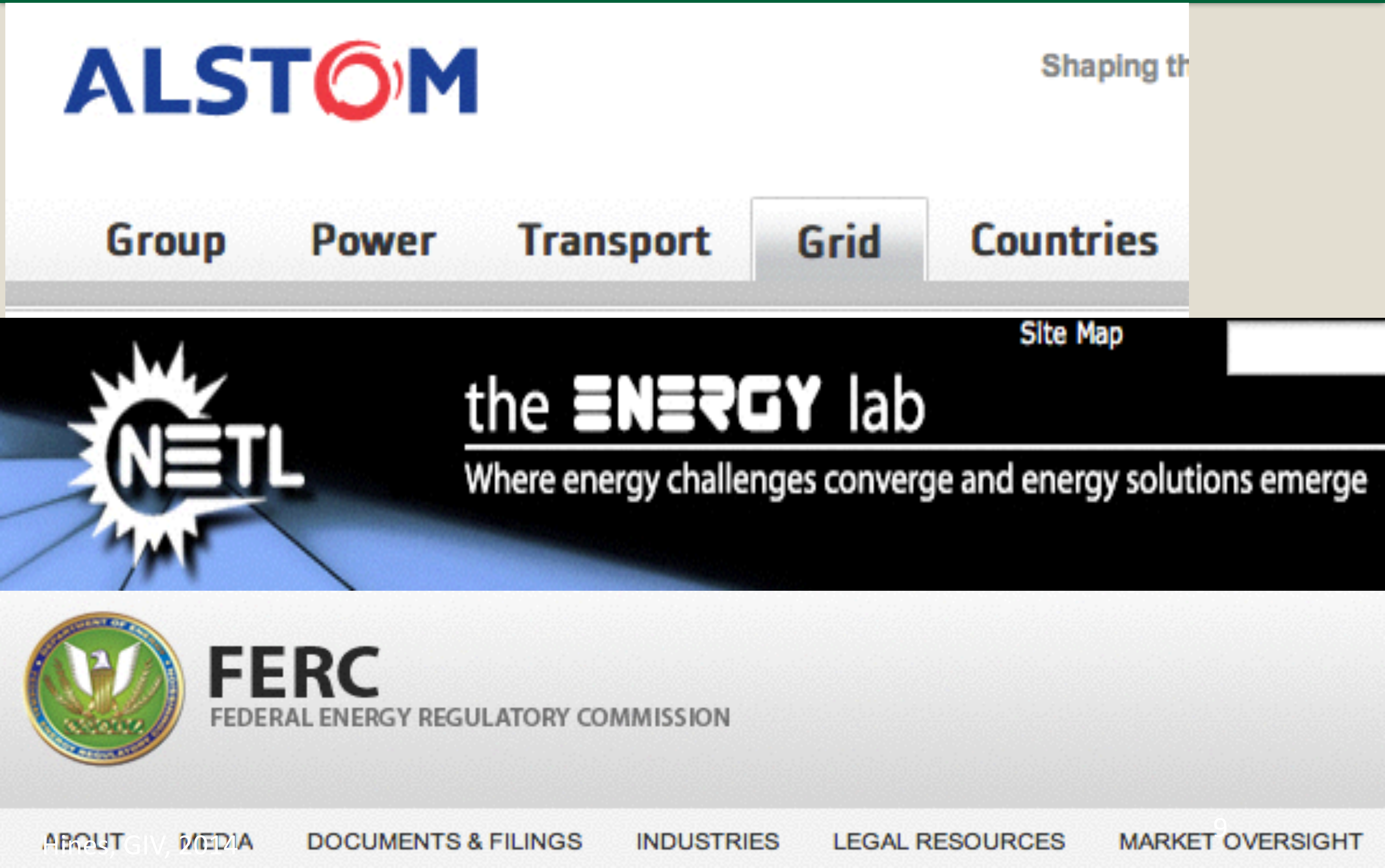
Back to school...take 3

Back to school...take 3



Hines, GIV, 2014

After a few other detours



Back to college...4th time is the charm?

Why I'm an engineer

Why I'm an engineer

In order to make the

Why I'm an engineer

In order to make the

IEEE

Advancing Technology for Humanity

Why I'm an engineer

In order to make the world a better place

IEEE

Advancing Technology for Humanity

Why I'm an engineer

In order to make the world a better place (cultivate the universe)

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"IEEE's core purpose is to foster technological innovation and excellence for the benefit of humanity."

Why I'm a scientist

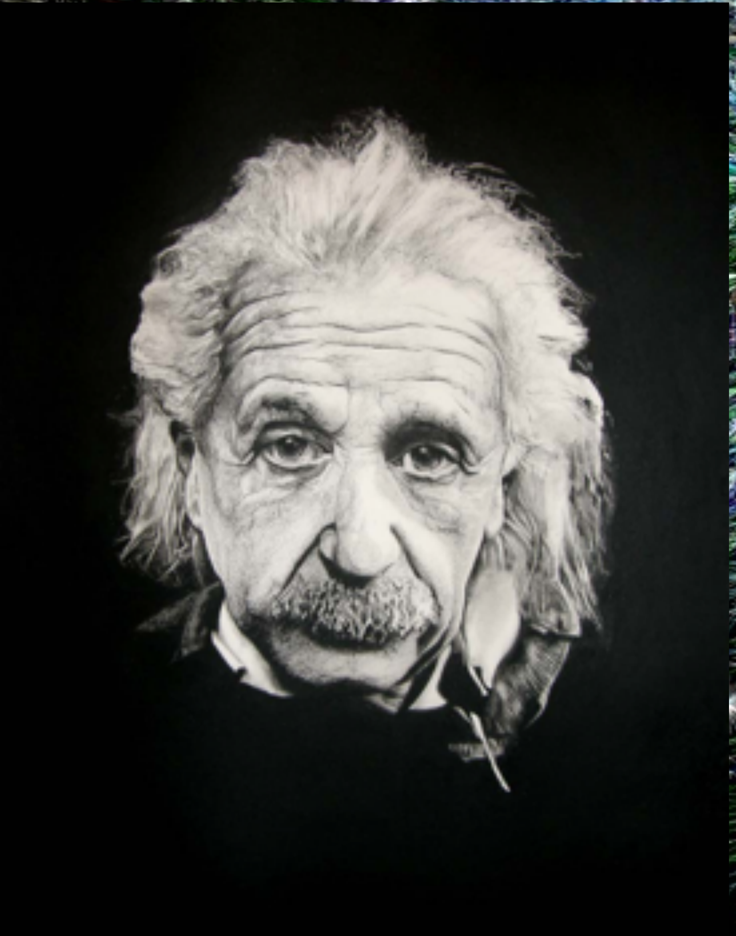
Why I'm a scientist

Because it is good

Why I'm a Scientist

Because it is good

to understand the universe.



Hines, GIV, 2014

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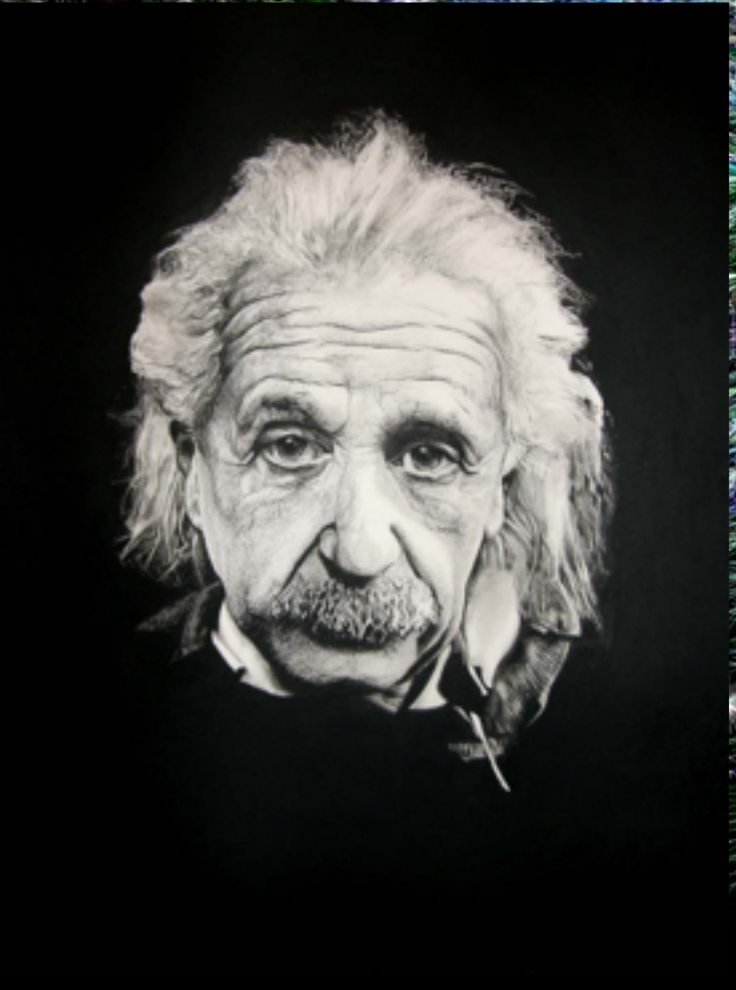

Hines, GIV, 2014

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Hines, GIV, 2014

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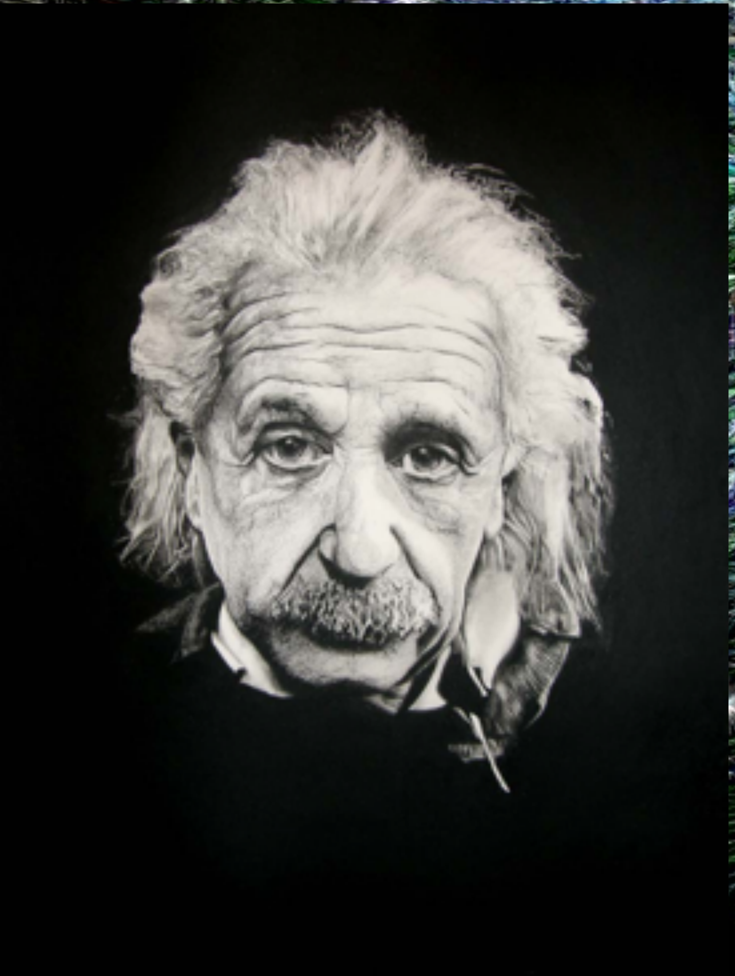
"I want to know God's thoughts –



Hines, GIV, 2014

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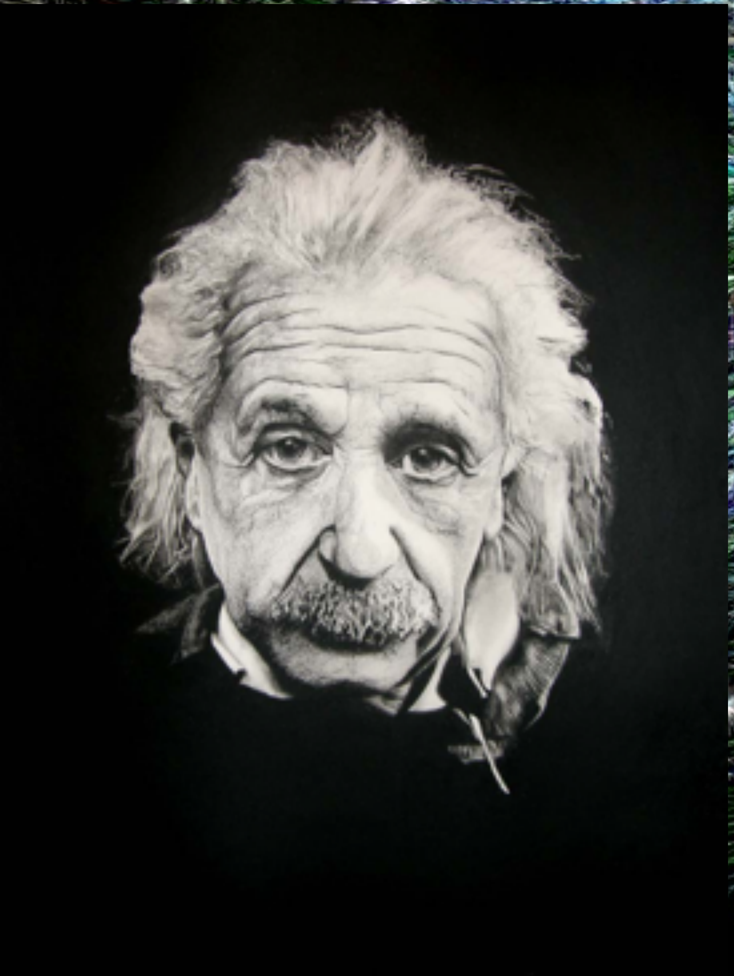

"I want to know God's thoughts –
the rest are mere details"

Hines, GIV, 2014

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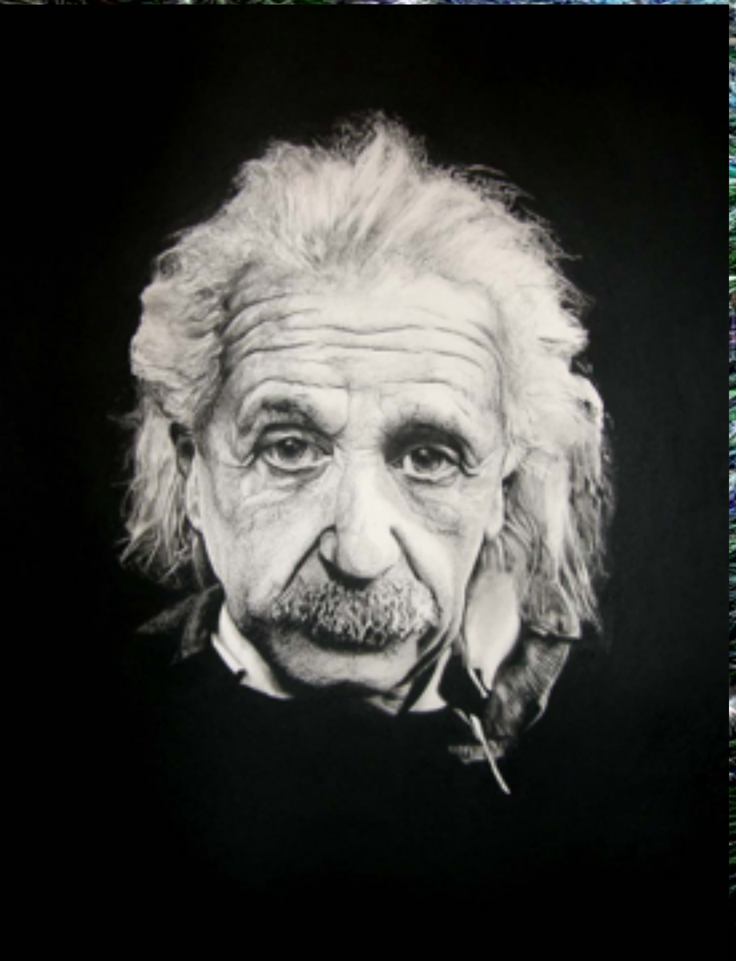
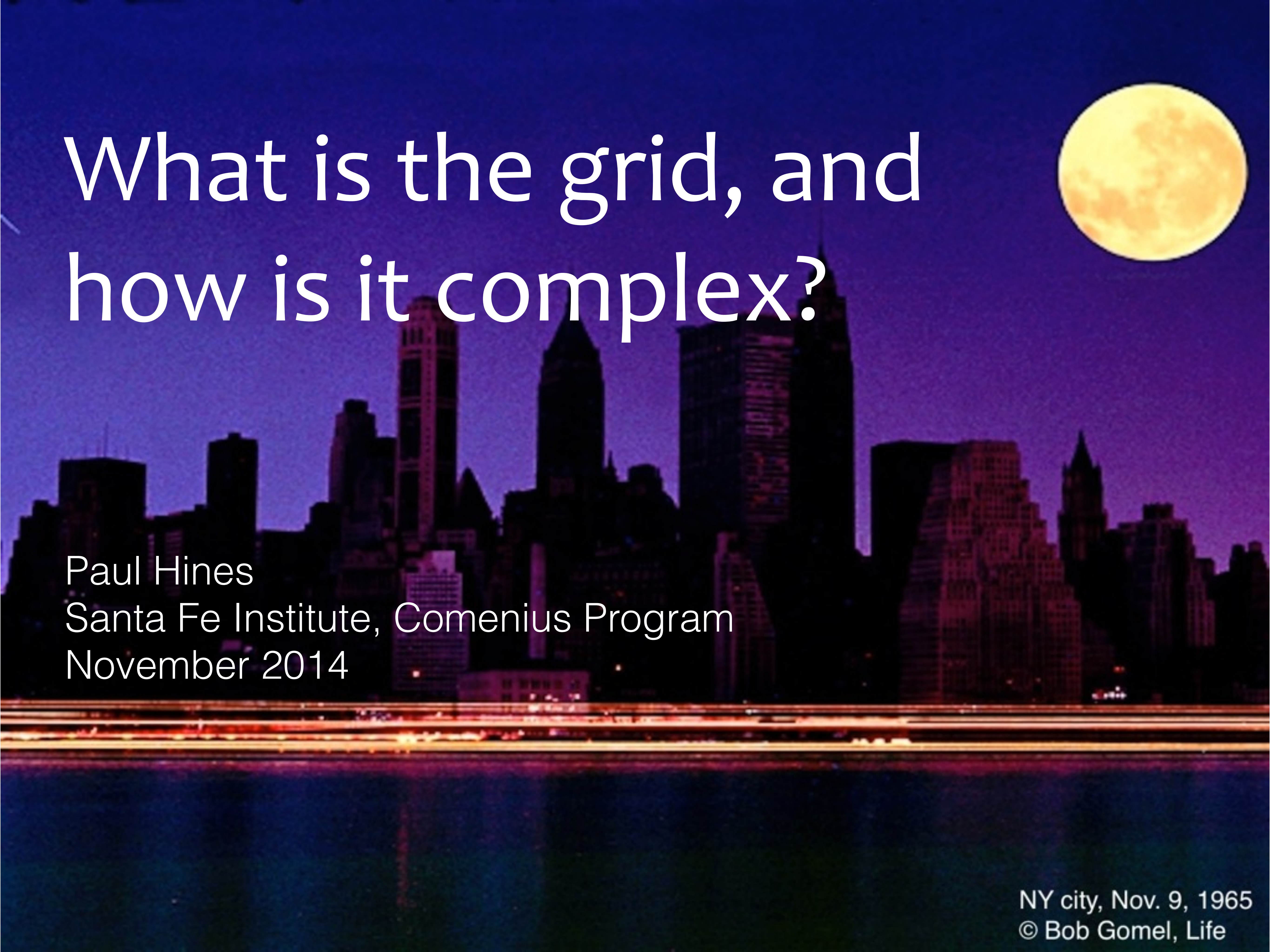


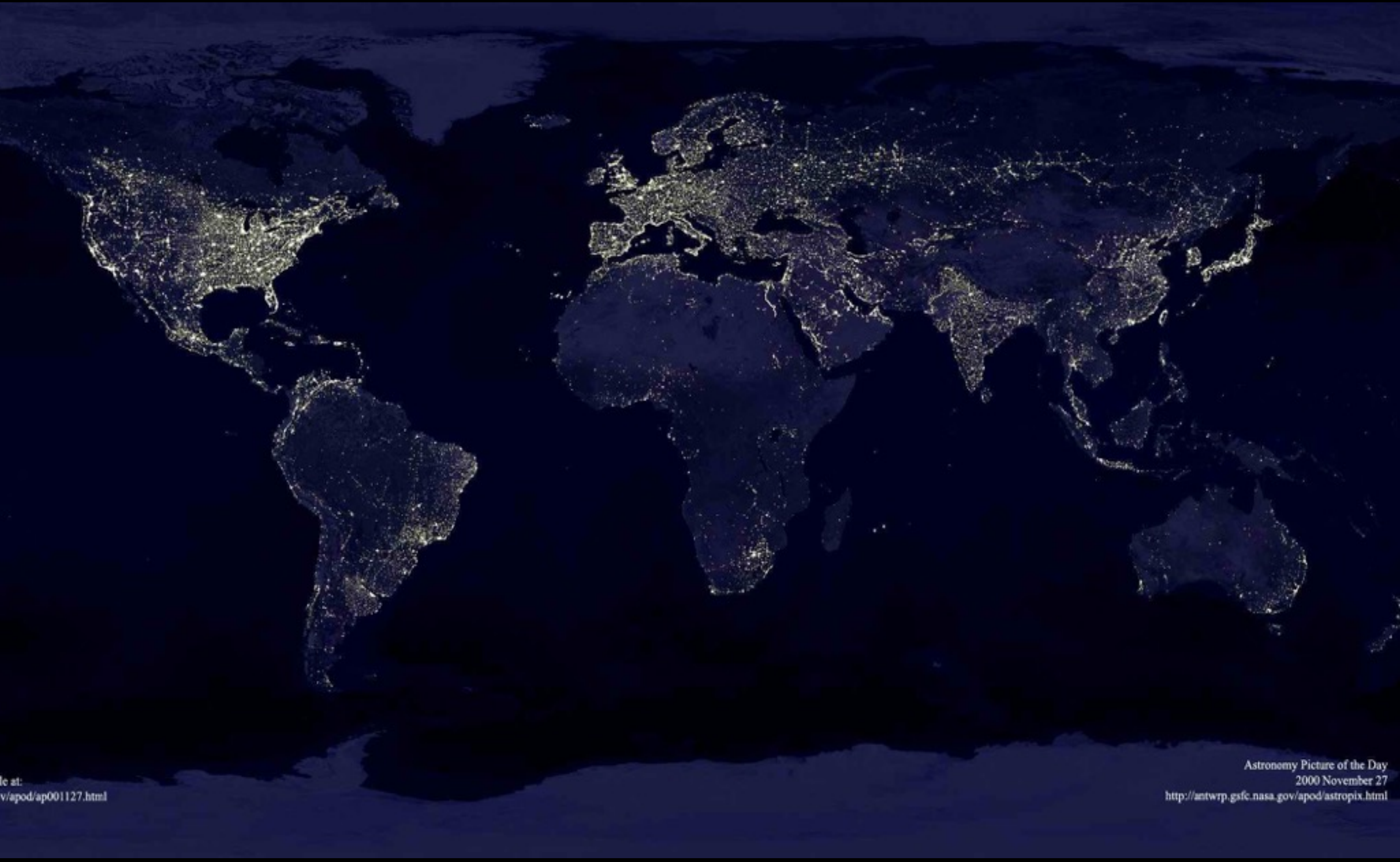
"I want to know God's thoughts –
the rest are mere details"
Albert Einstein

What is the grid, and how is it complex?

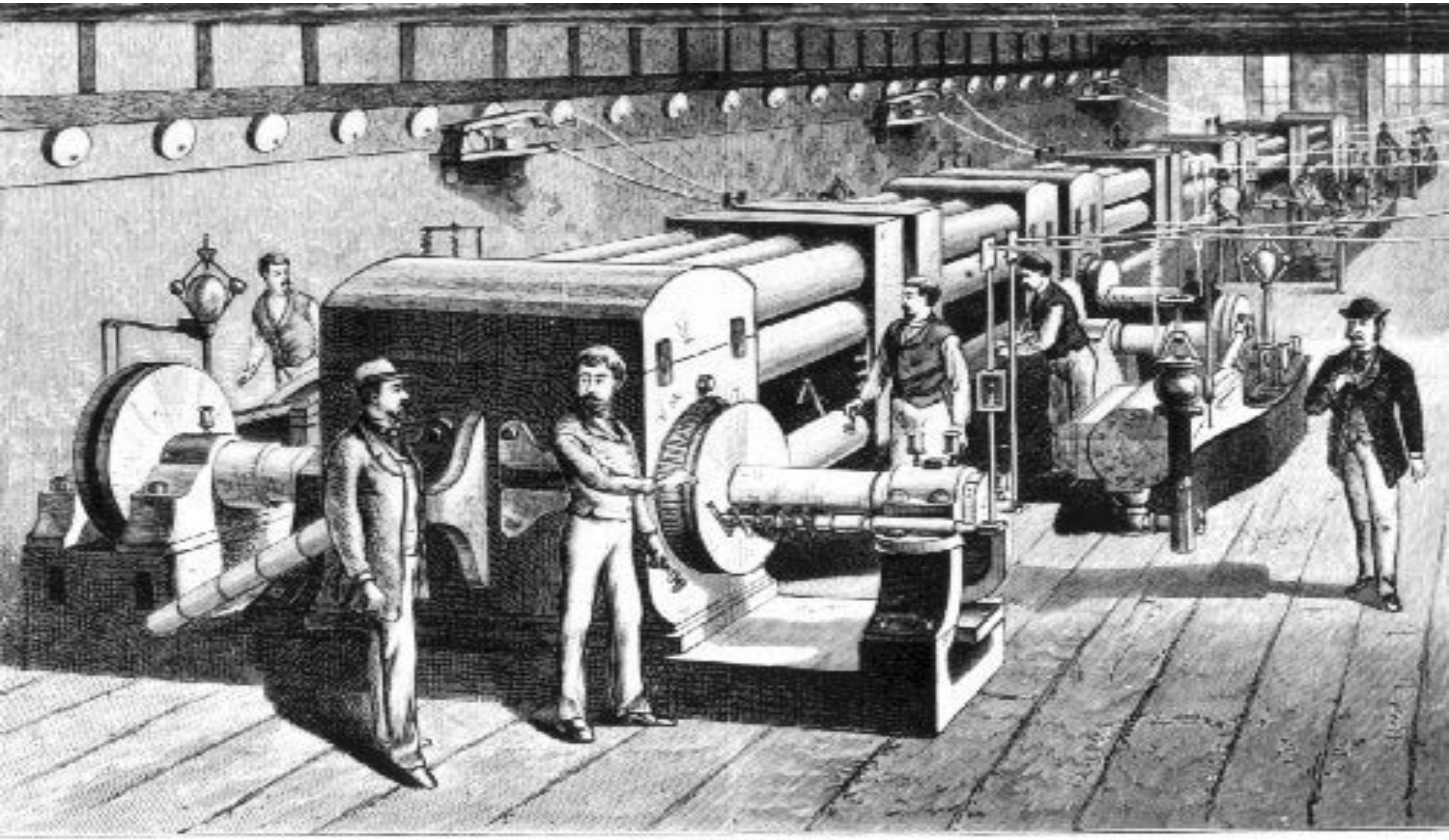
Paul Hines
Santa Fe Institute, Comenius Program
November 2014



NY city, Nov. 9, 1965


le at:
v/apod/ap001127.html
Astronomy Picture of the Day
2000 November 27
http://antwrp.gsfc.nasa.gov/apod/astropix.html

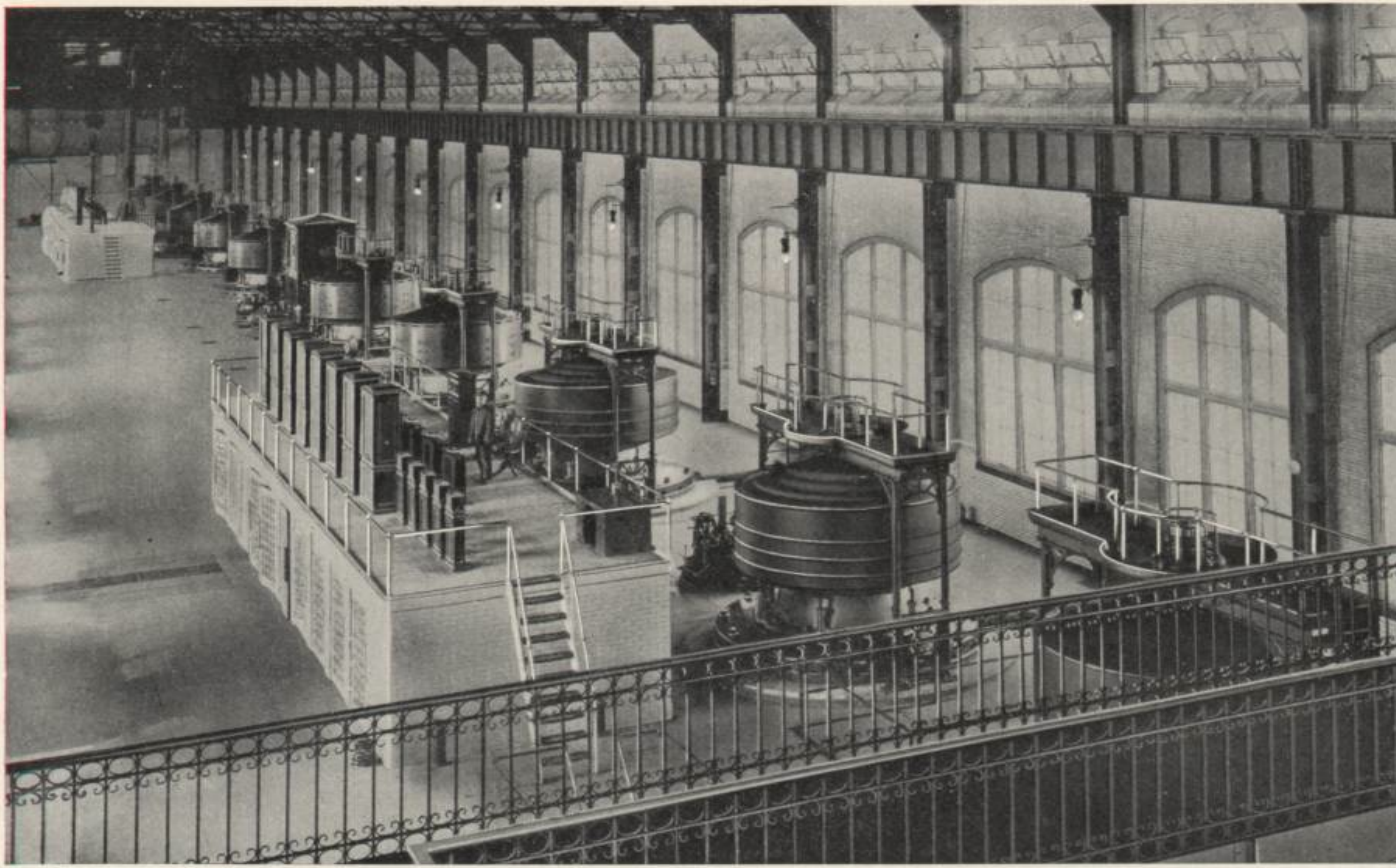
Pearl street station



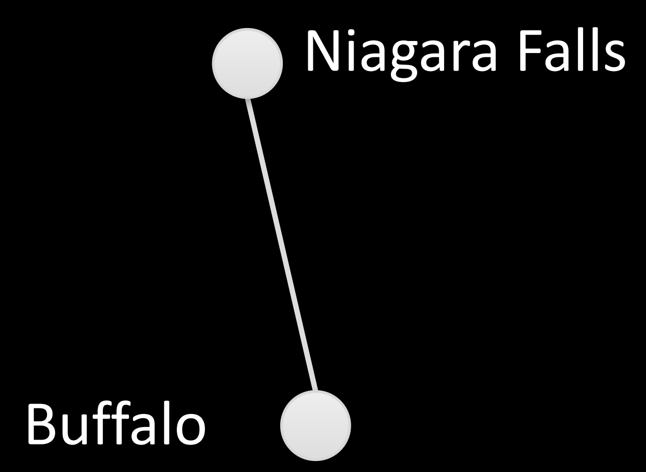
THE DYNAMO ROOM.
FIRST EDISON ELECTRIC LIGHTING STATION IN NEW YORK.

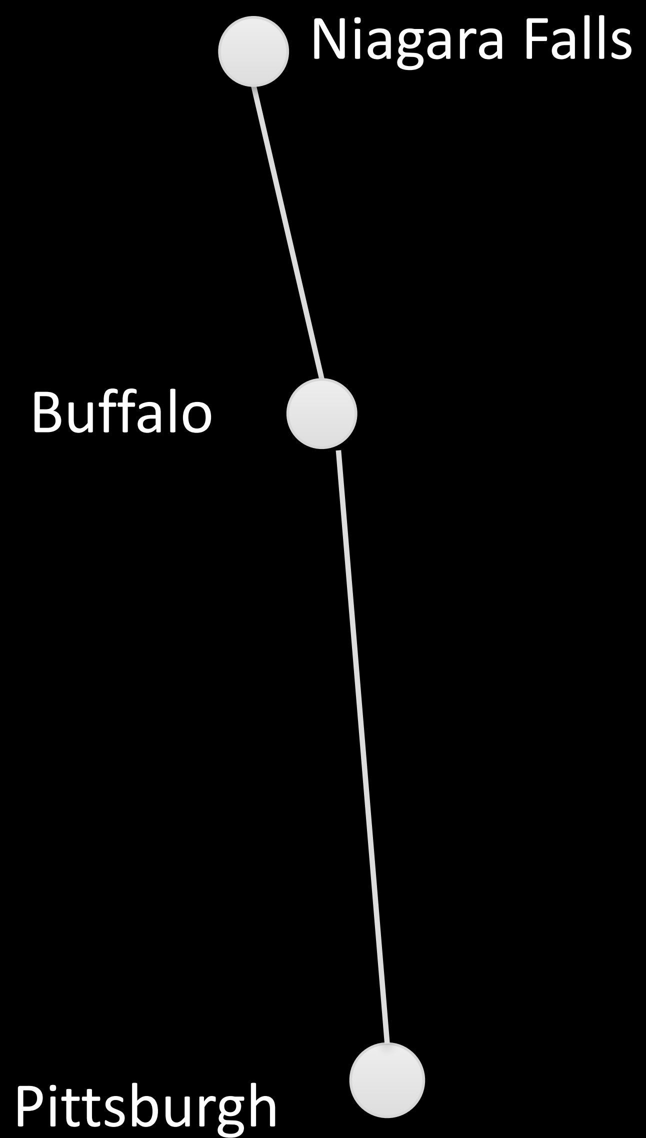
U.S. DEPARTMENT OF THE INTERIOR, NATIONAL PARK SERVICE, EDISON NATIONAL HISTORIC SITE

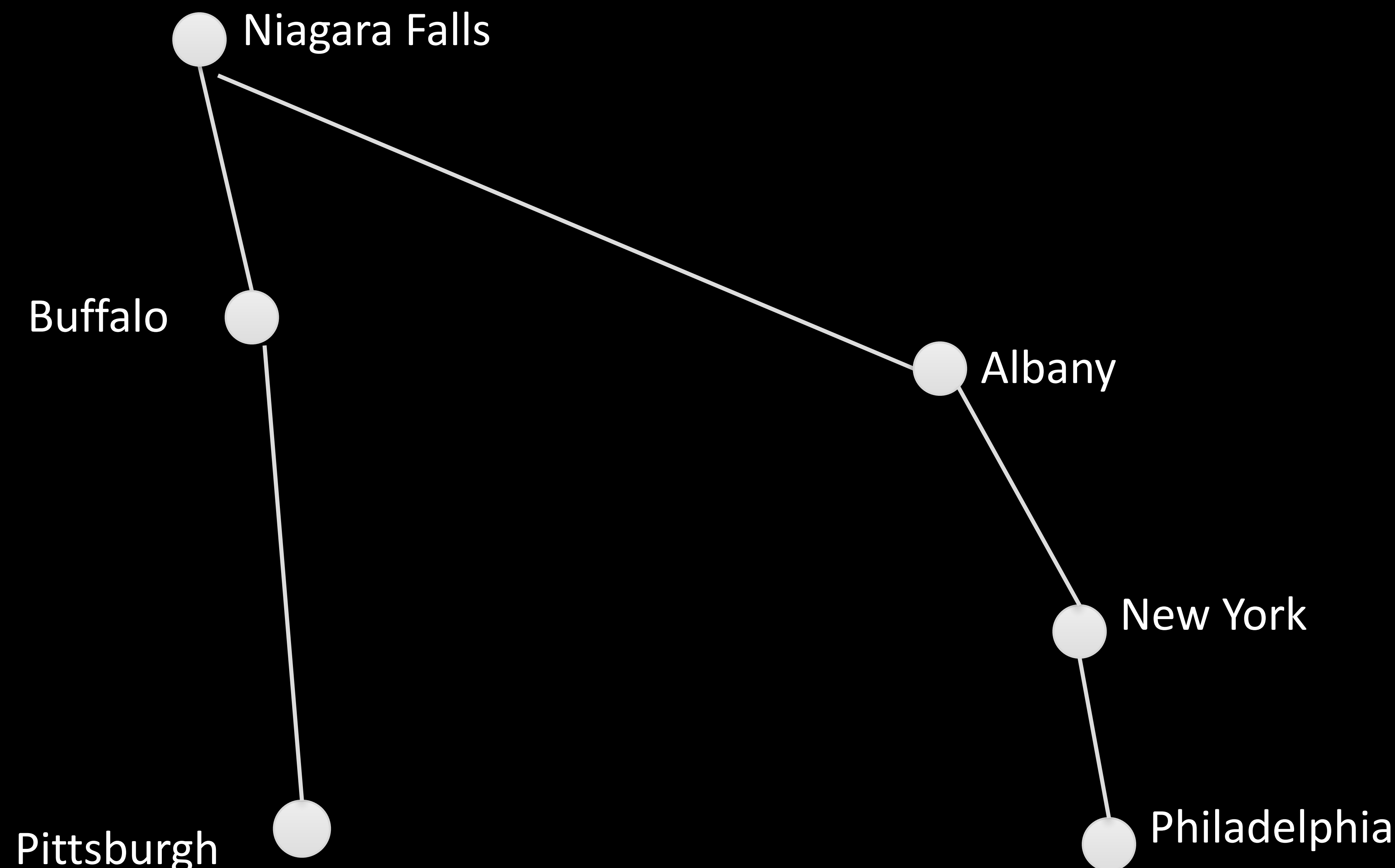
1895: Niagara Falls to Buffalo

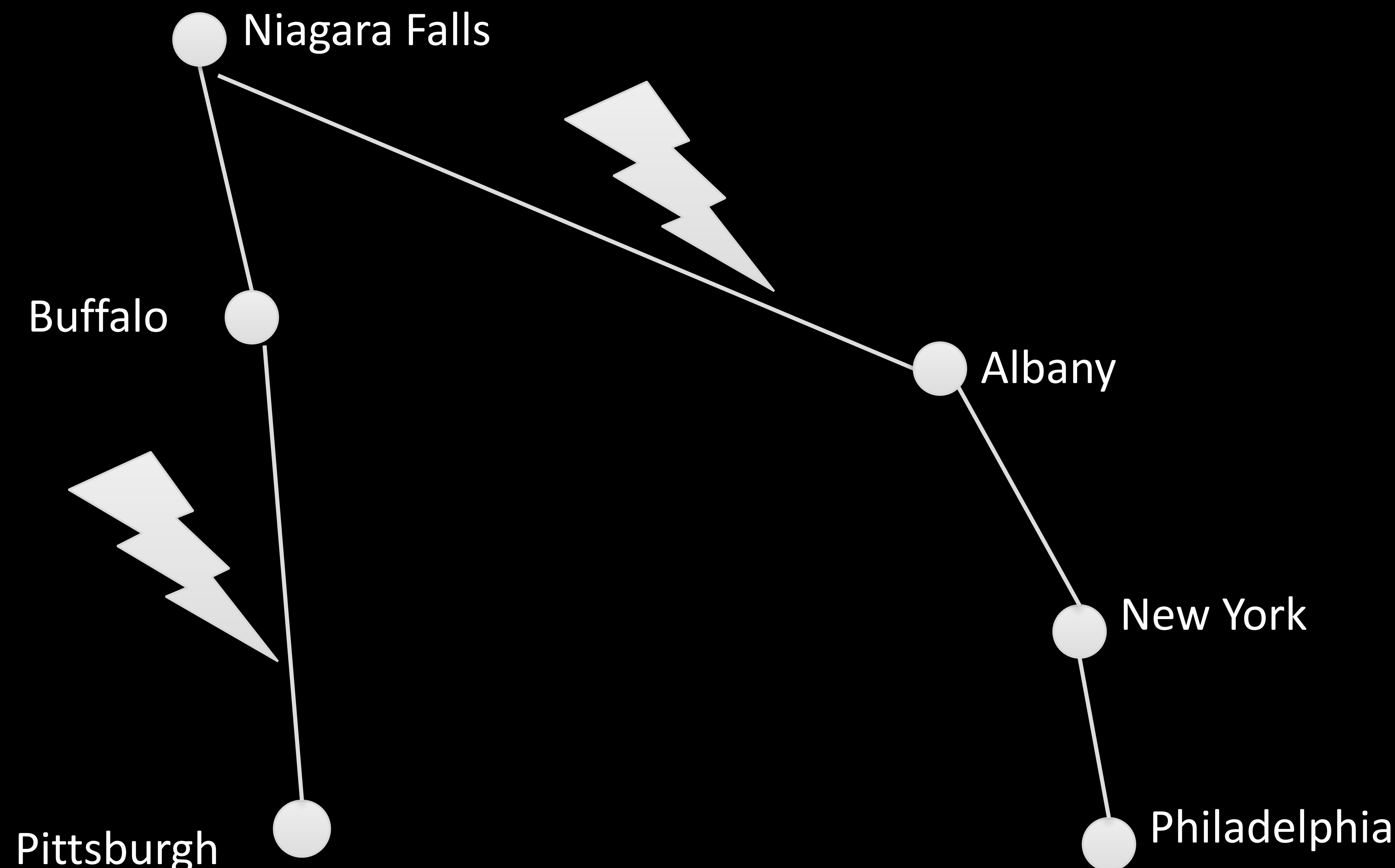


GENERATING STATION OF THE NIAGARA FALLS POWER COMPANY, SHOWING THE TEN 5,000 H. P. GENERATORS


Niagara Falls
Buffalo


Niagara Falls
Buffalo
Pittsburgh


Niagara Falls
Buffalo
Albany
New York
Pittsburgh
Philadelphia


Niagara Falls
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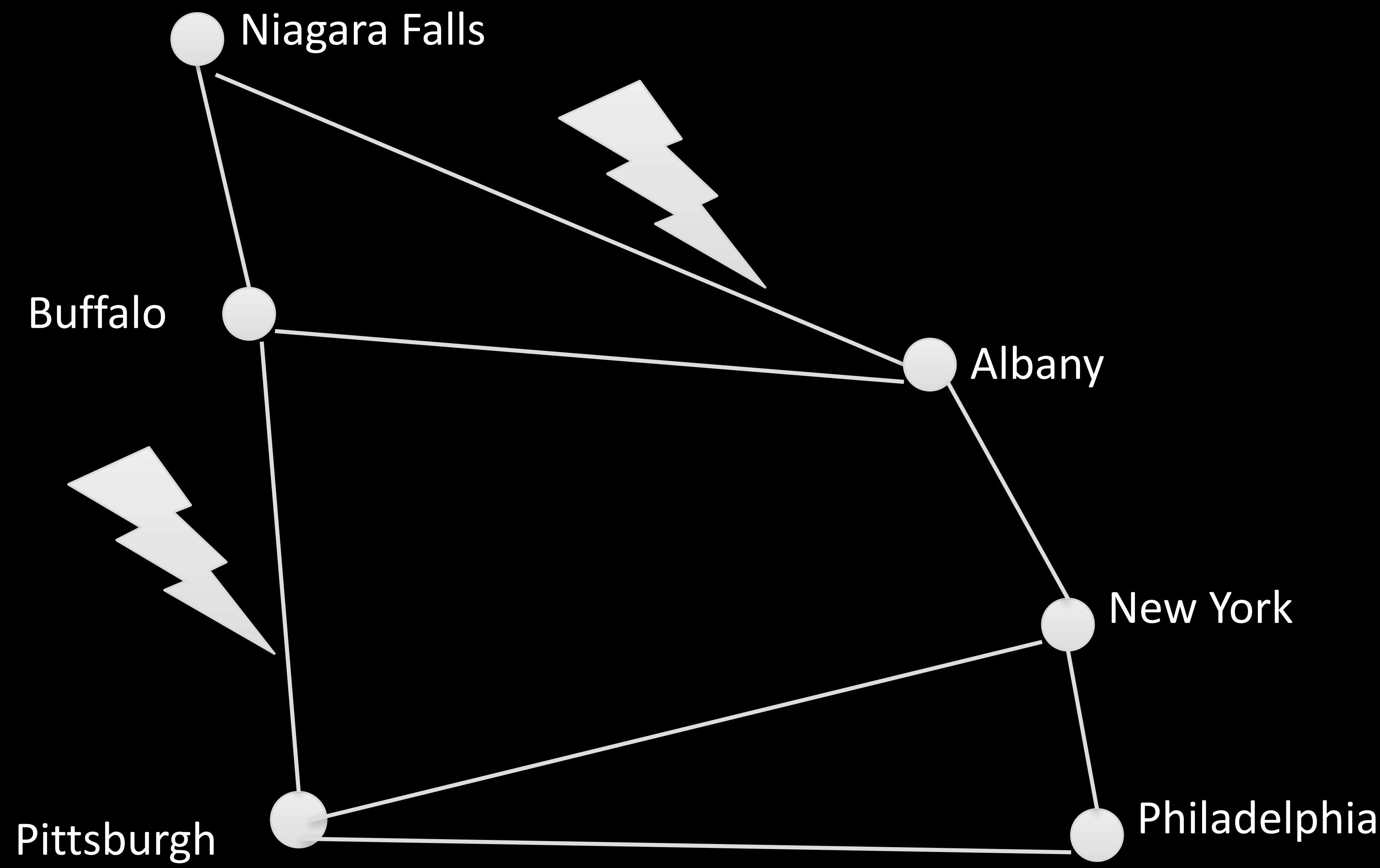

Niagara Falls
Buffalo
Albany
New York
Pittsburgh
Philadelphia

US Northeast and Canada
August 14, 2003
50 million people

California, Arizona, Mexico
September 8, 2011
5 million people

Photo: Bikas Das/AP Photo
IEEE Spectrum, Oct. 2012

Bangledesh. 1 November 2014

Officials said it would take at least 12 hours to repair the system and restore power to the capital Dhaka [AP]

Things we know about power grids

Things we know about power grids

The physics
of generation

Things we know about power grids

The physics
of generation

The physics of
transmission

Things we know about power grids

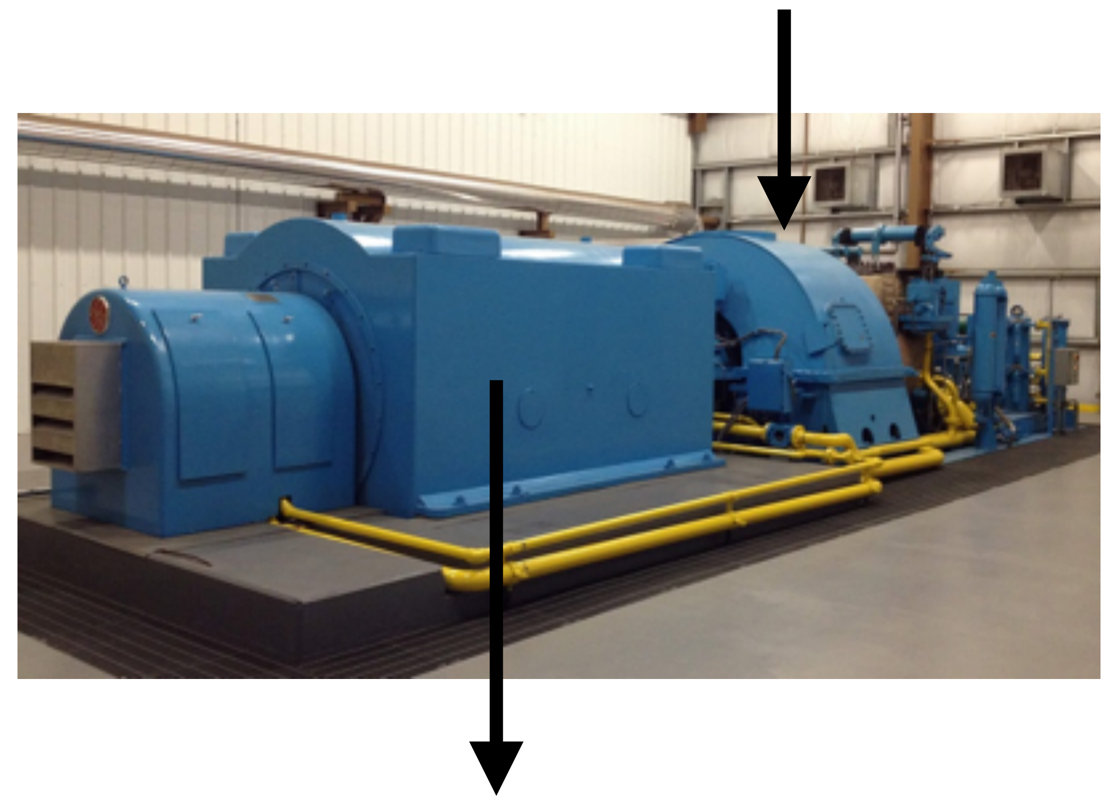
The physics of generation

The physics of transmission

That they mostly work

(note the simple interface)

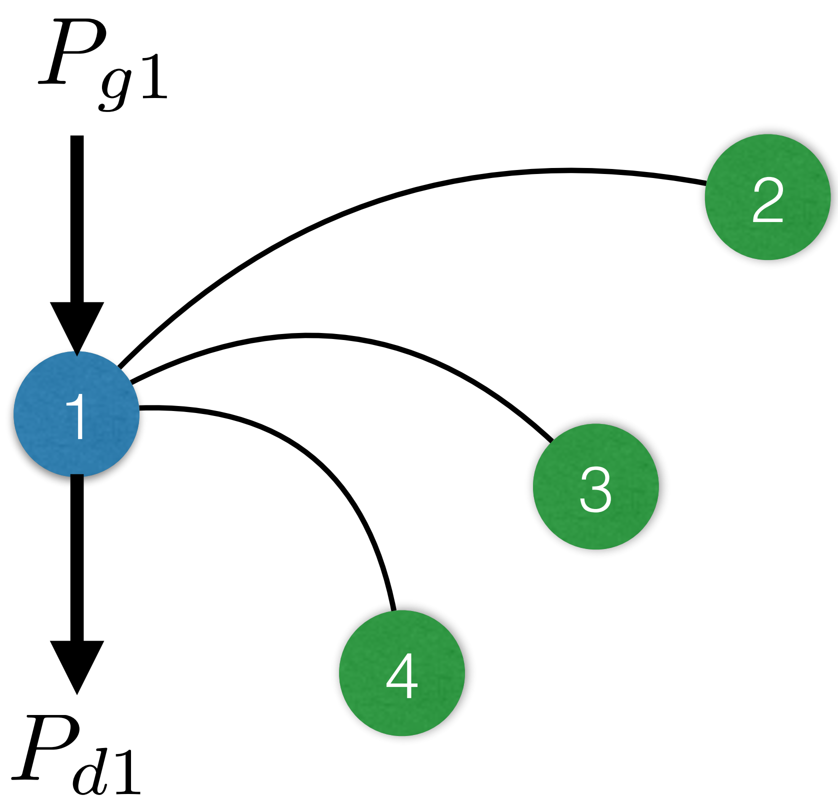
Two key principles



What goes in, must come out
(there is no storage)

If what goes out is not
equal to what goes in
generators speed up/down

Two key principles



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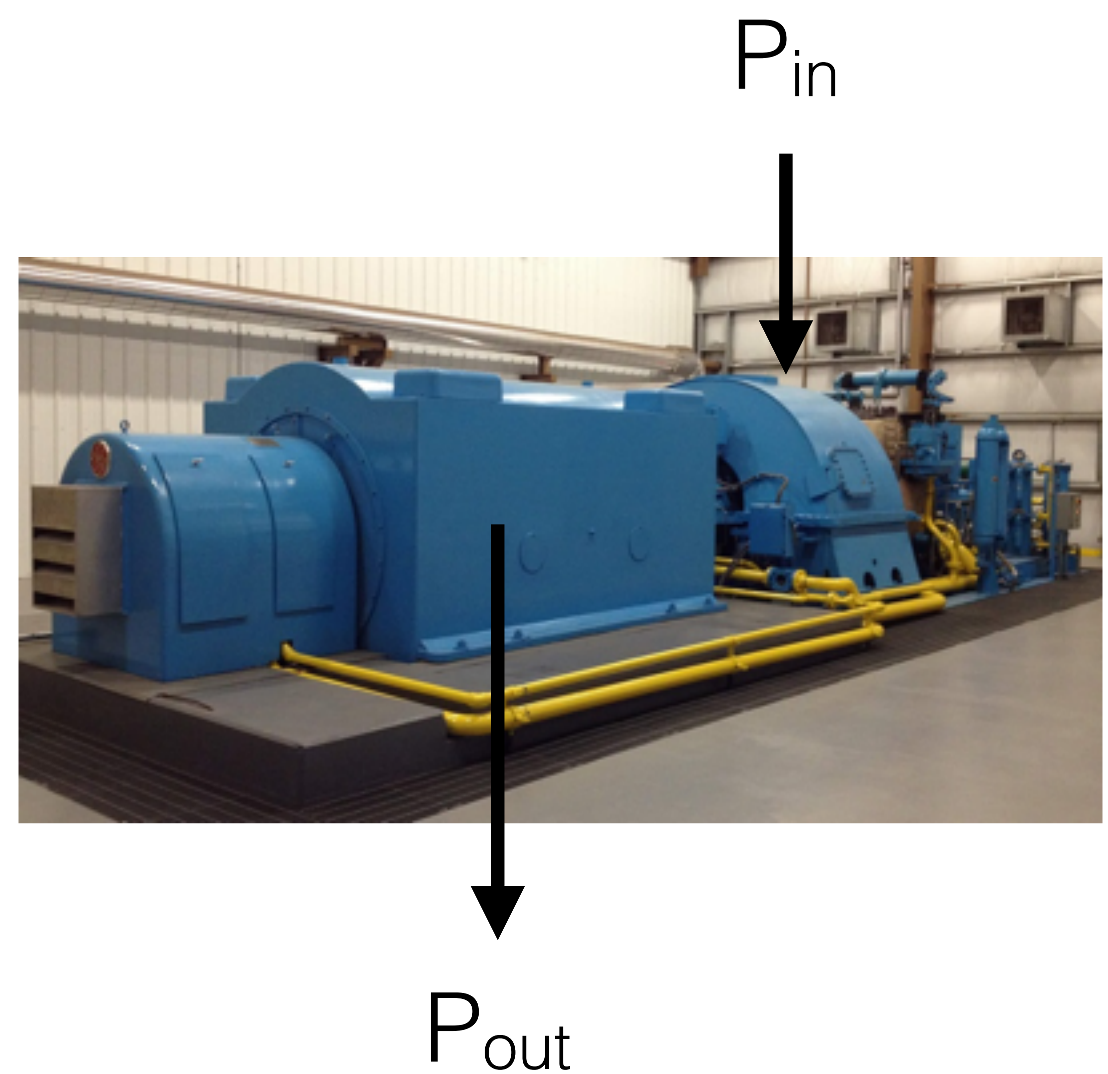

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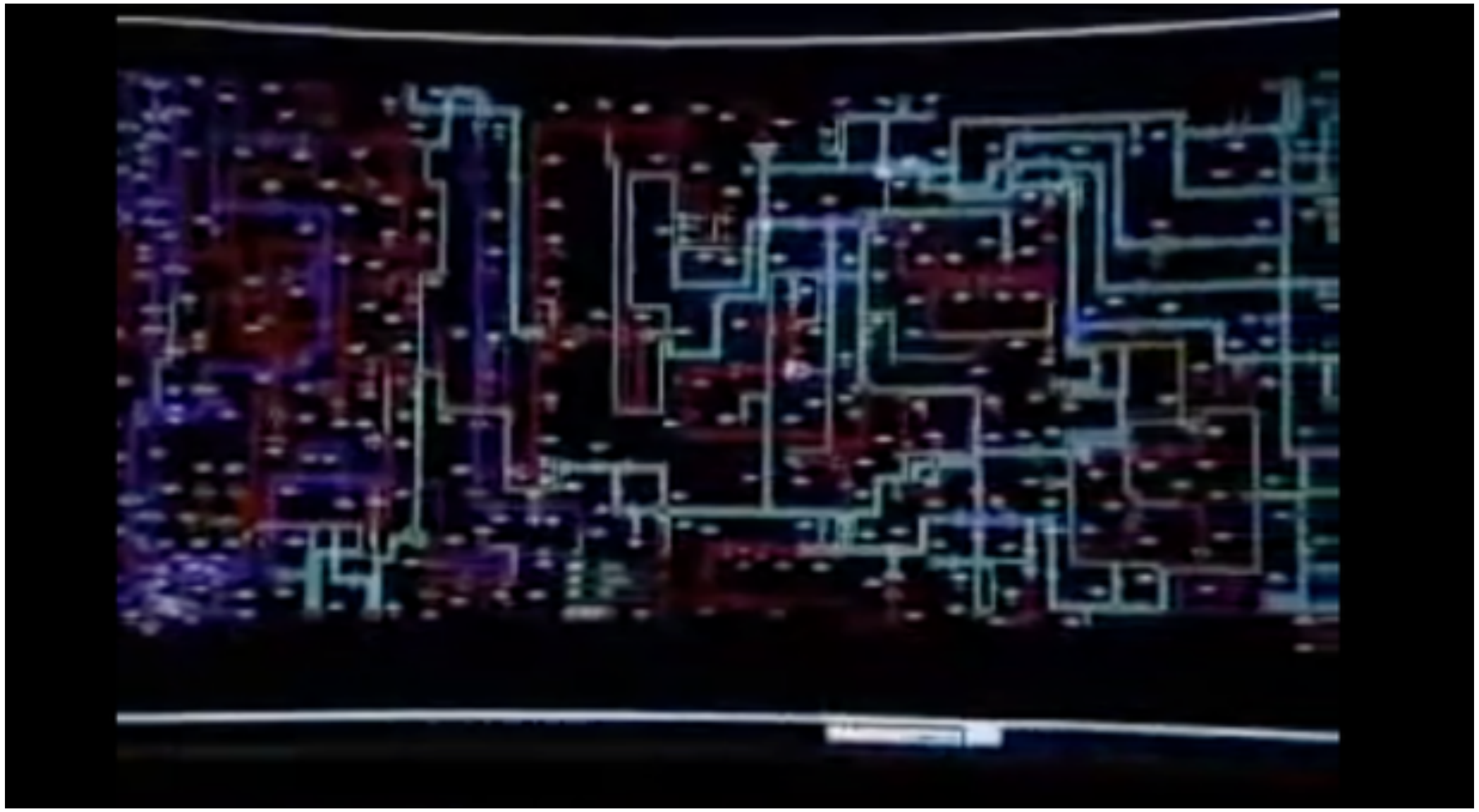
Illustration of this process

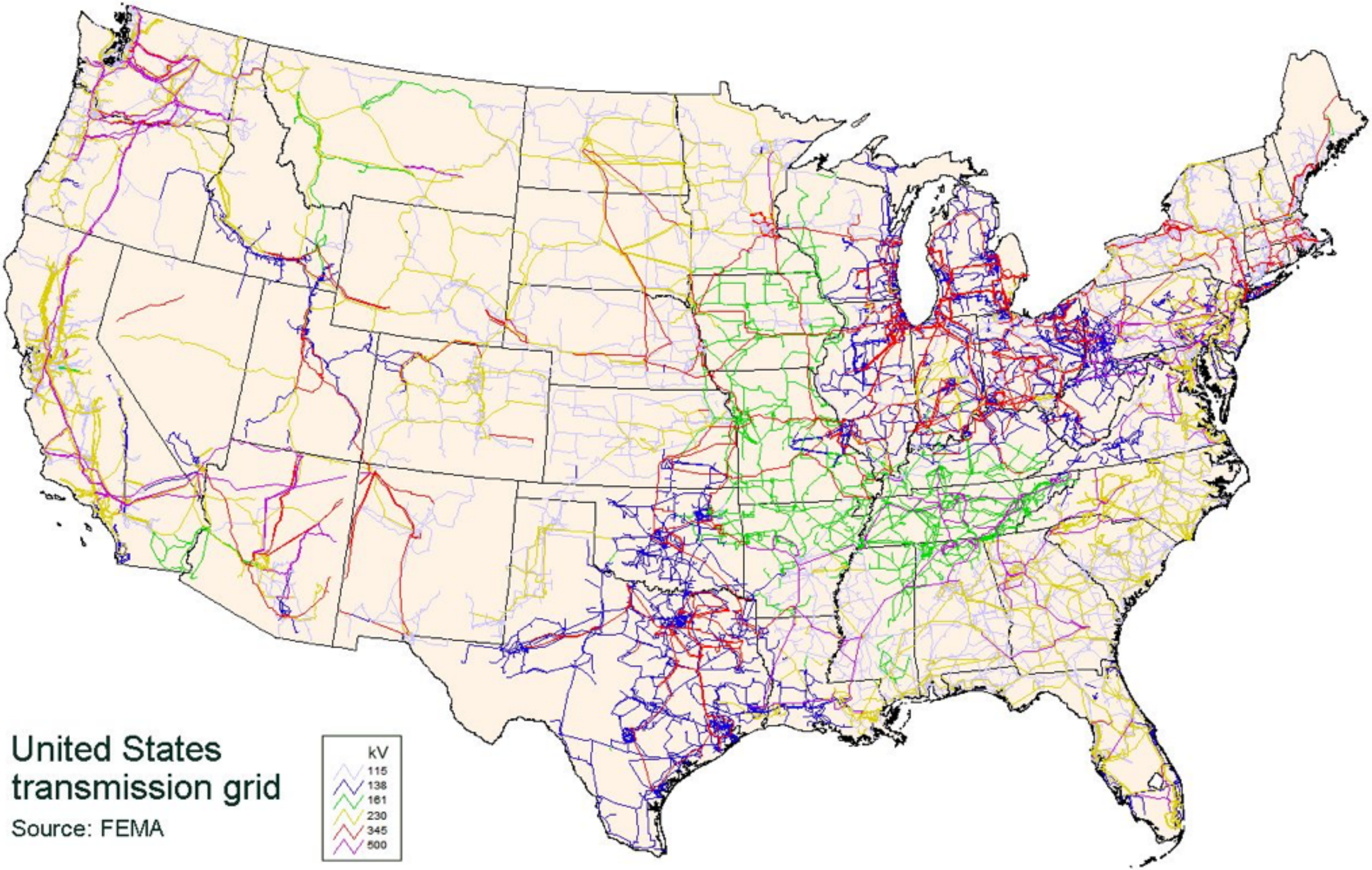


http://youtu.be/UTM2Ck6XWHg

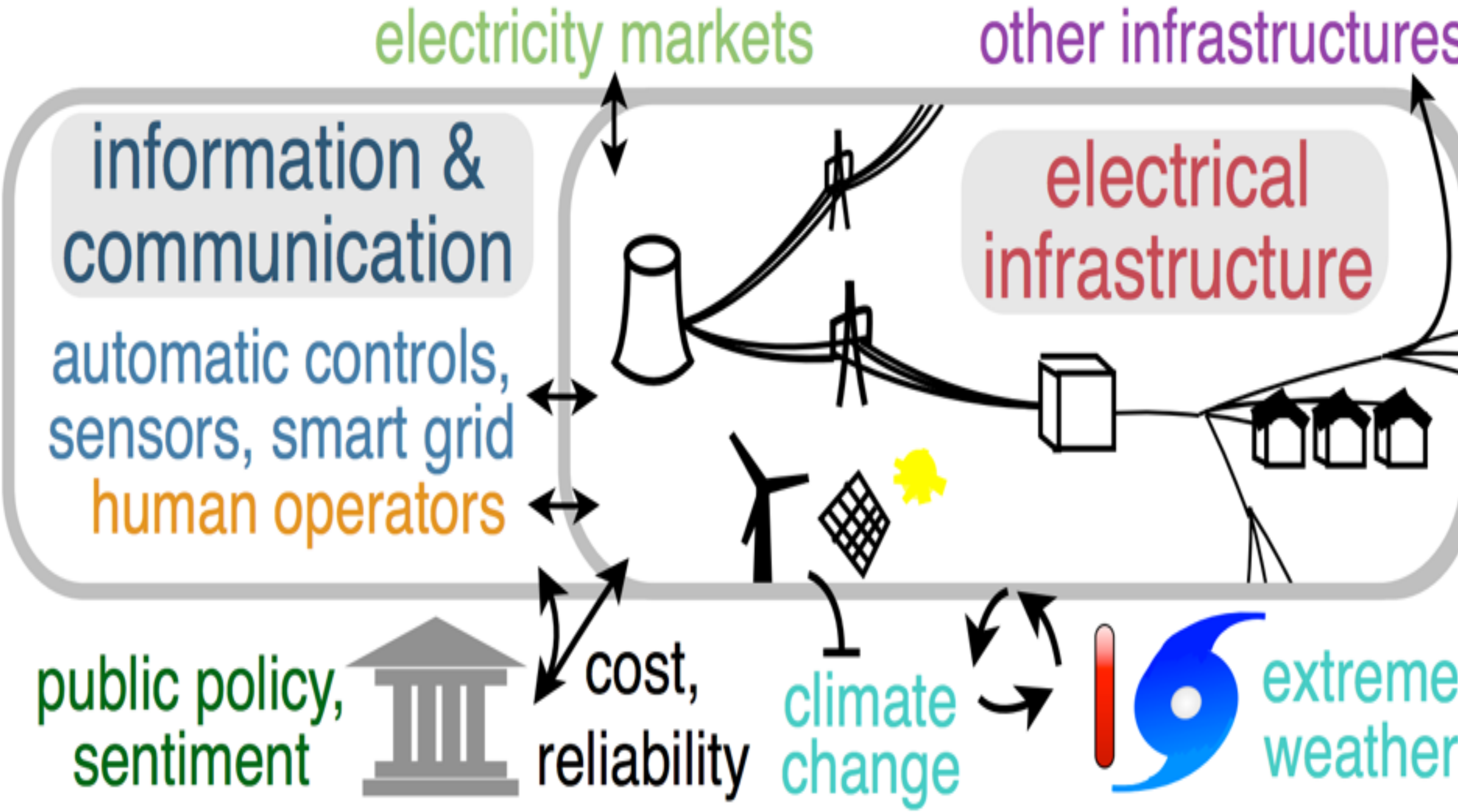
Things that we don’t know

- Exactly why cascades happen
- How to make them not happen
- How to incorporate intermittent wind and solar at very large scales without adding risk to this fragile system
- (and especially) How to coordinate the actions of millions of devices and people (and the weather) to improve reliability, efficiency and sustainability

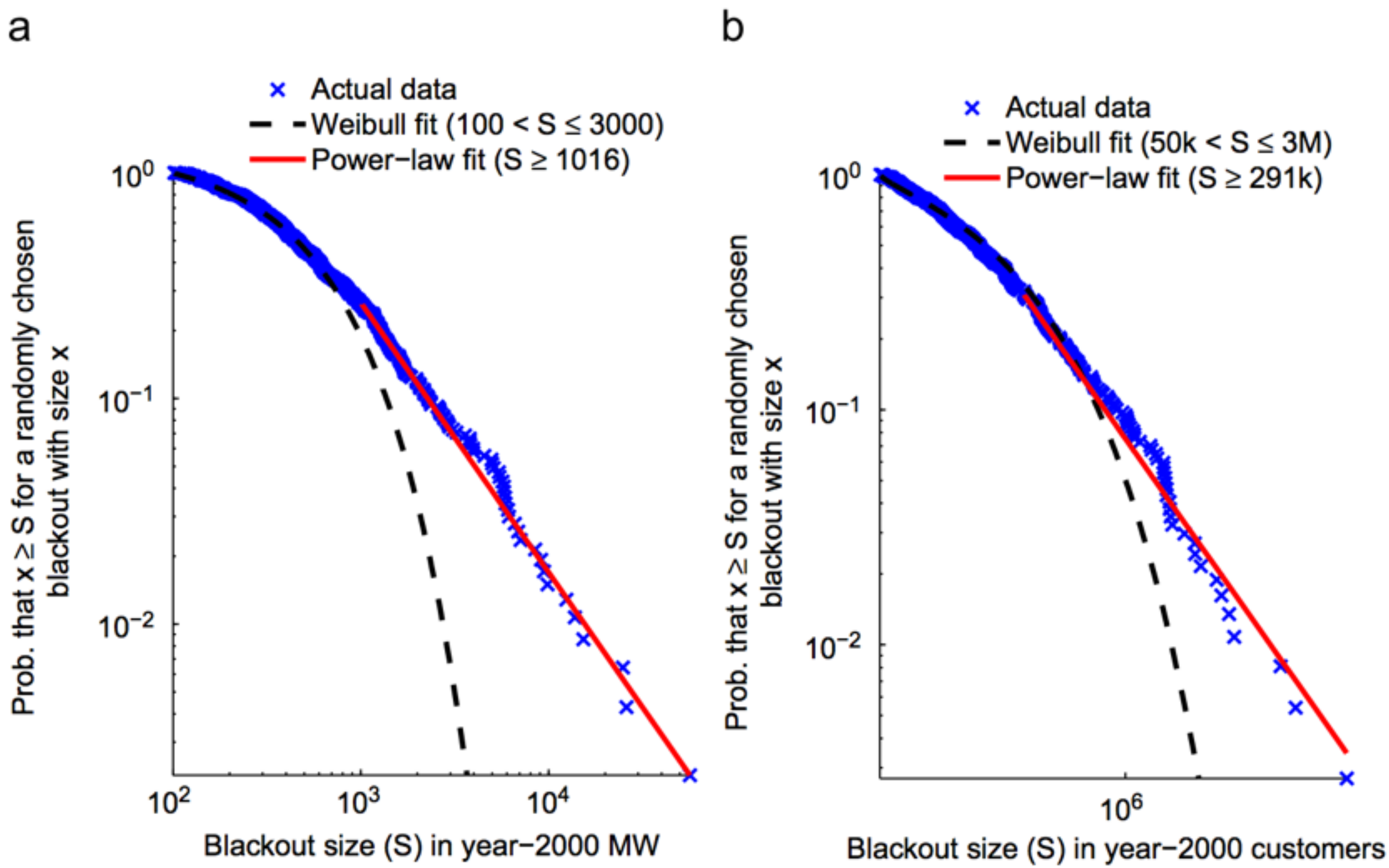
The US Power Grid



The more important picture…



Because of complex interactions among nature, components and people we get power laws in in blackout sizes



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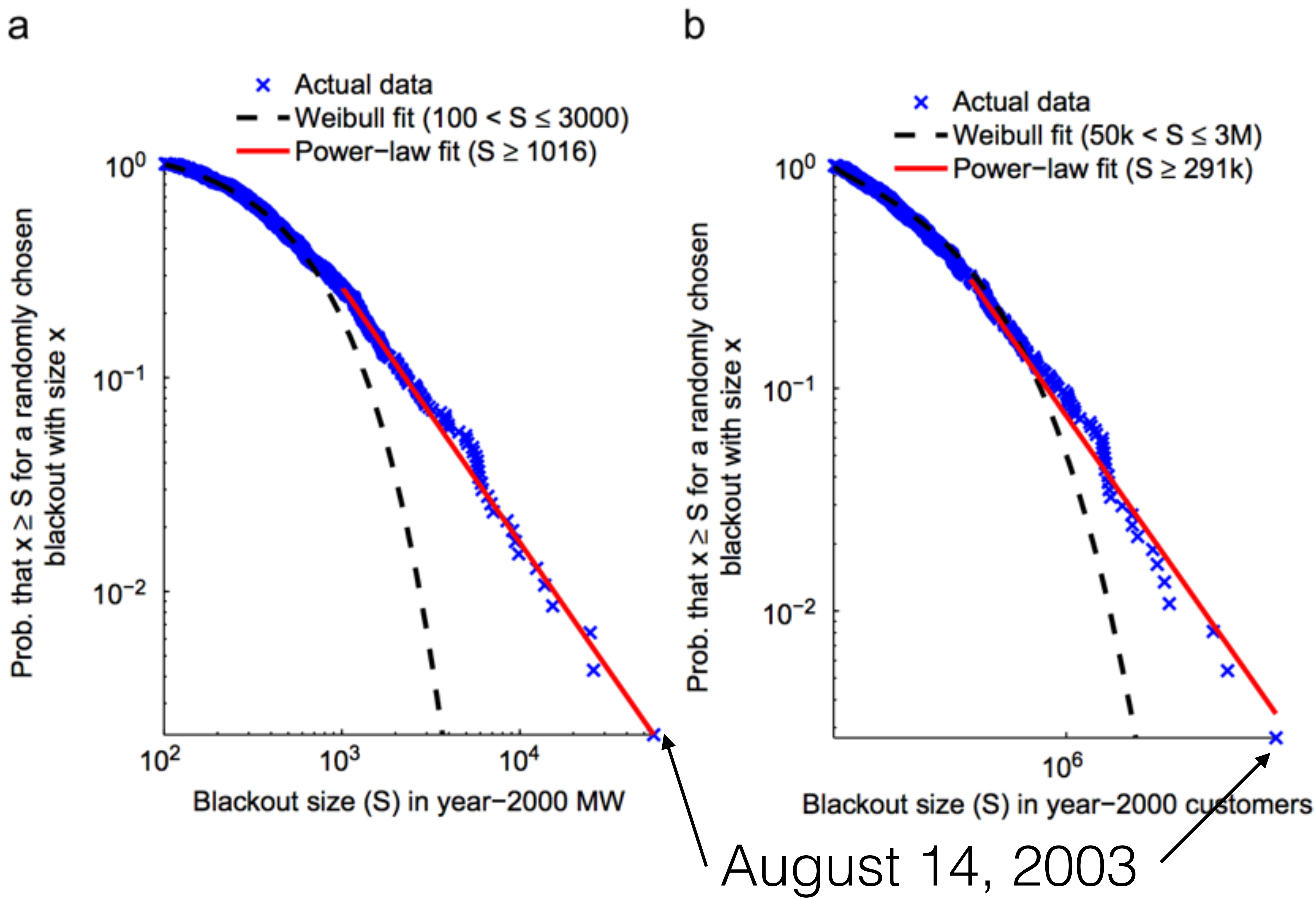

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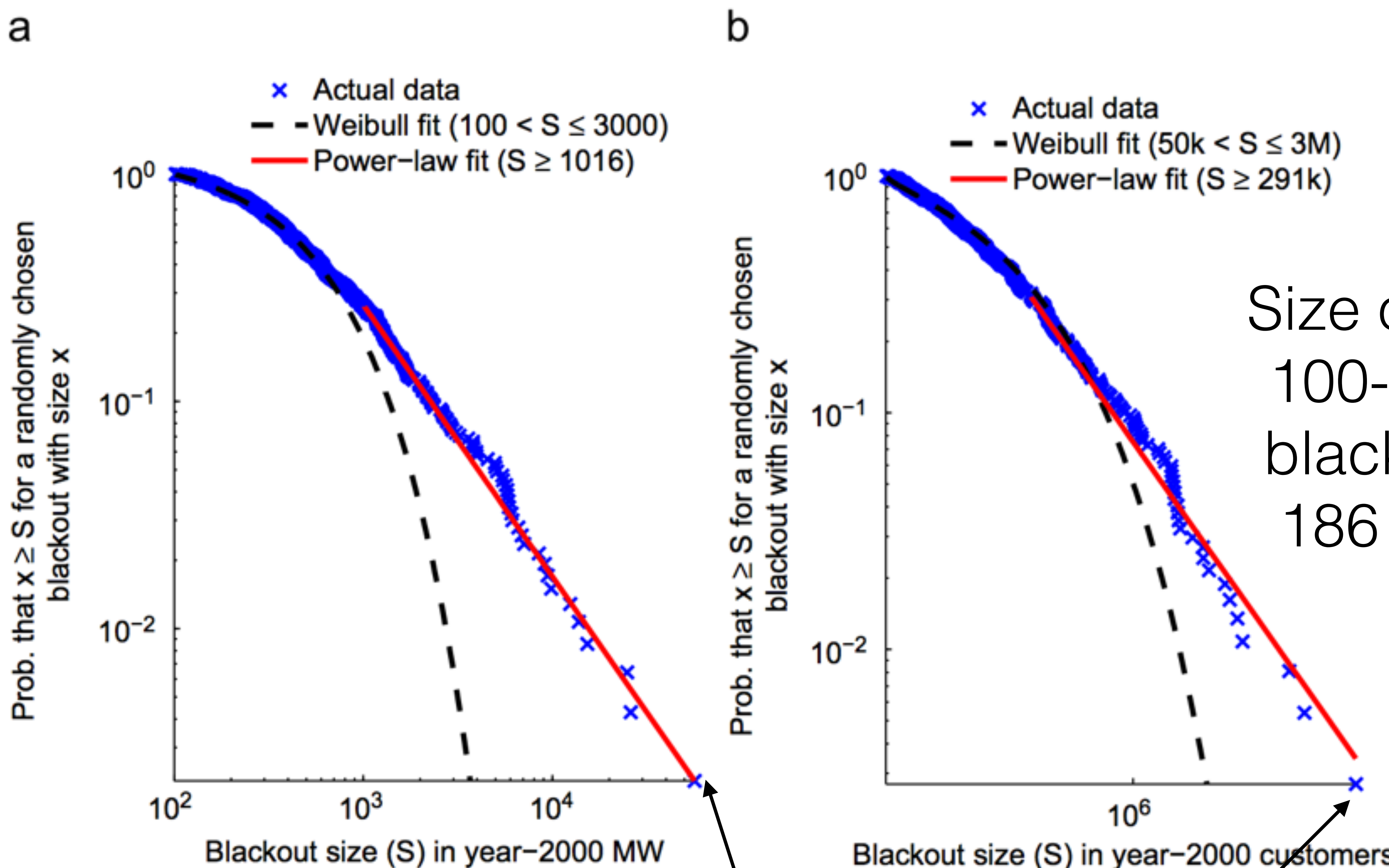


Size of the 100-year blackout: 186 GW

August 14, 2003

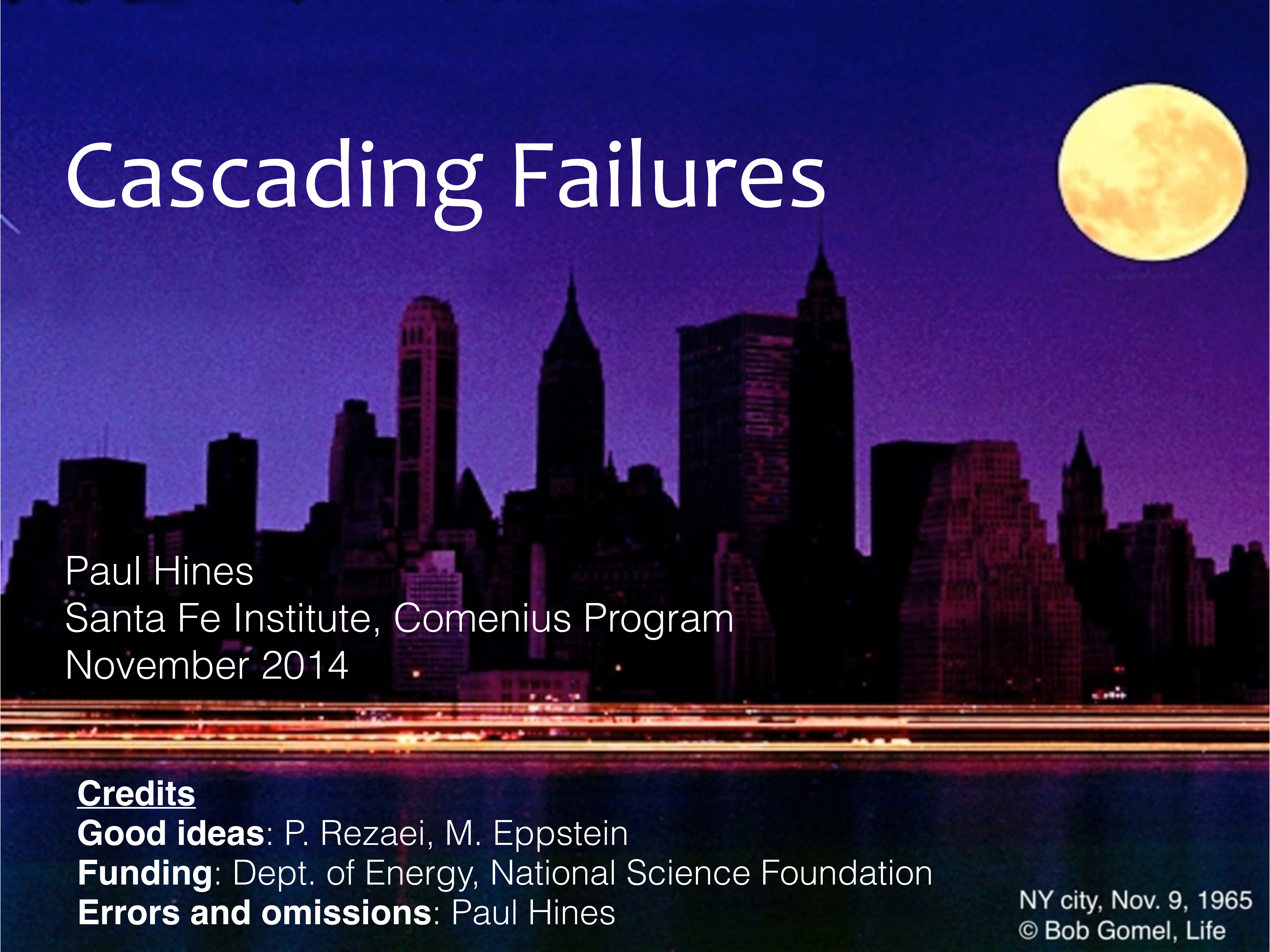
Key points about power laws and risk

- Risk is probability times cost
- If event cost is distributed as a power law, and the slope is shallow (-1), then risk is infinite, and very hard to measure

Cascading Failures

Paul Hines
Santa Fe Institute, Comenius Program
November 2014

Credits
Good ideas: P. Rezaei, M. Eppstein
Funding: Dept. of Energy, National Science Foundation
Errors and omissions: Paul Hines



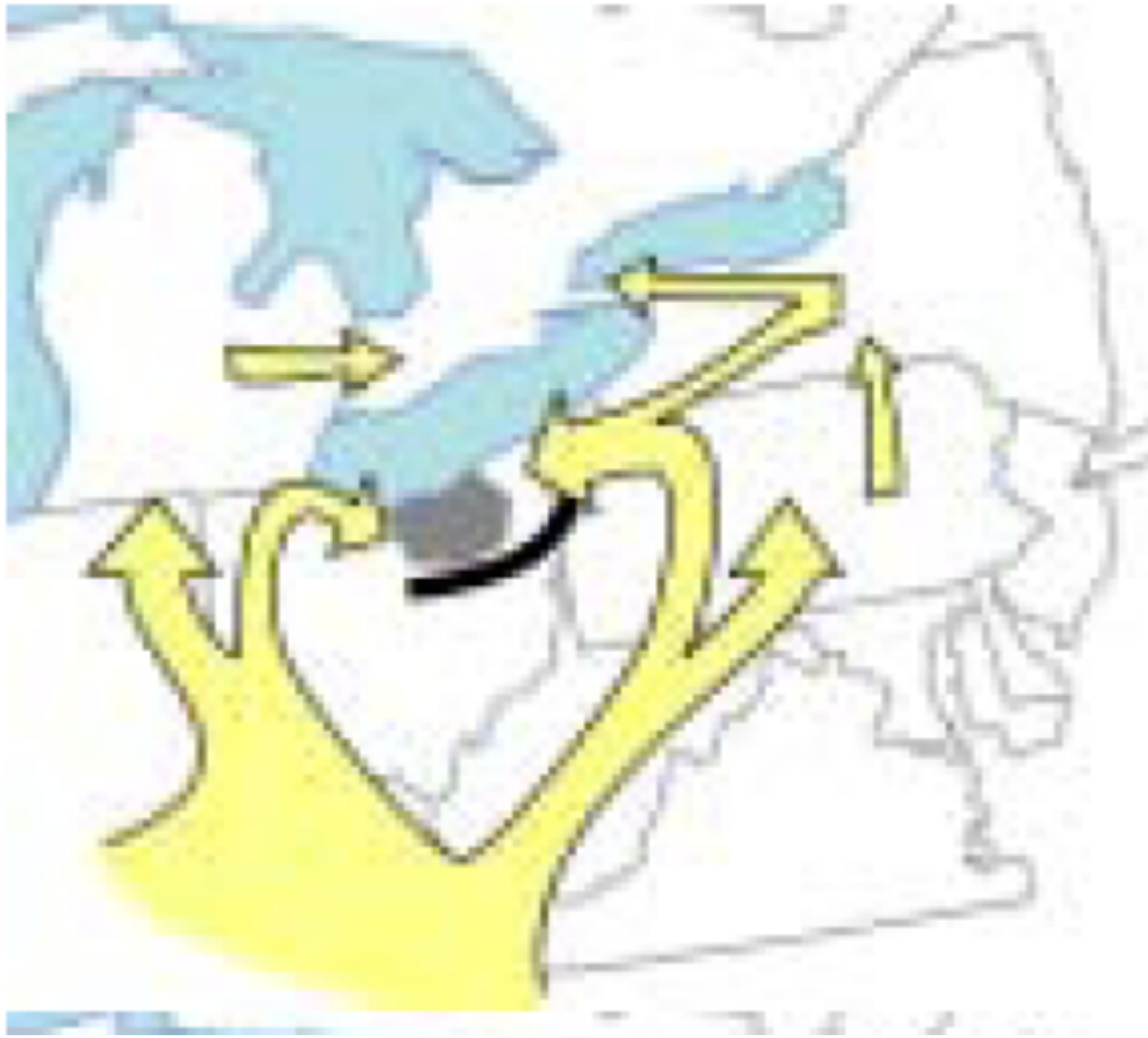
NY city, Nov. 9, 1965

August 14, 2003

1. 16:05:57

Hines, GIV,

2.
16:05:58



Hines, GIV,
2014

3.
16:09:25

Hines, GIV,
2014

4.
16:10:37

Hines, GIV, 2014

5.
16:10:39

Hines, GIV,
2014

6.
16:10:40

Hines, GIV, 2014

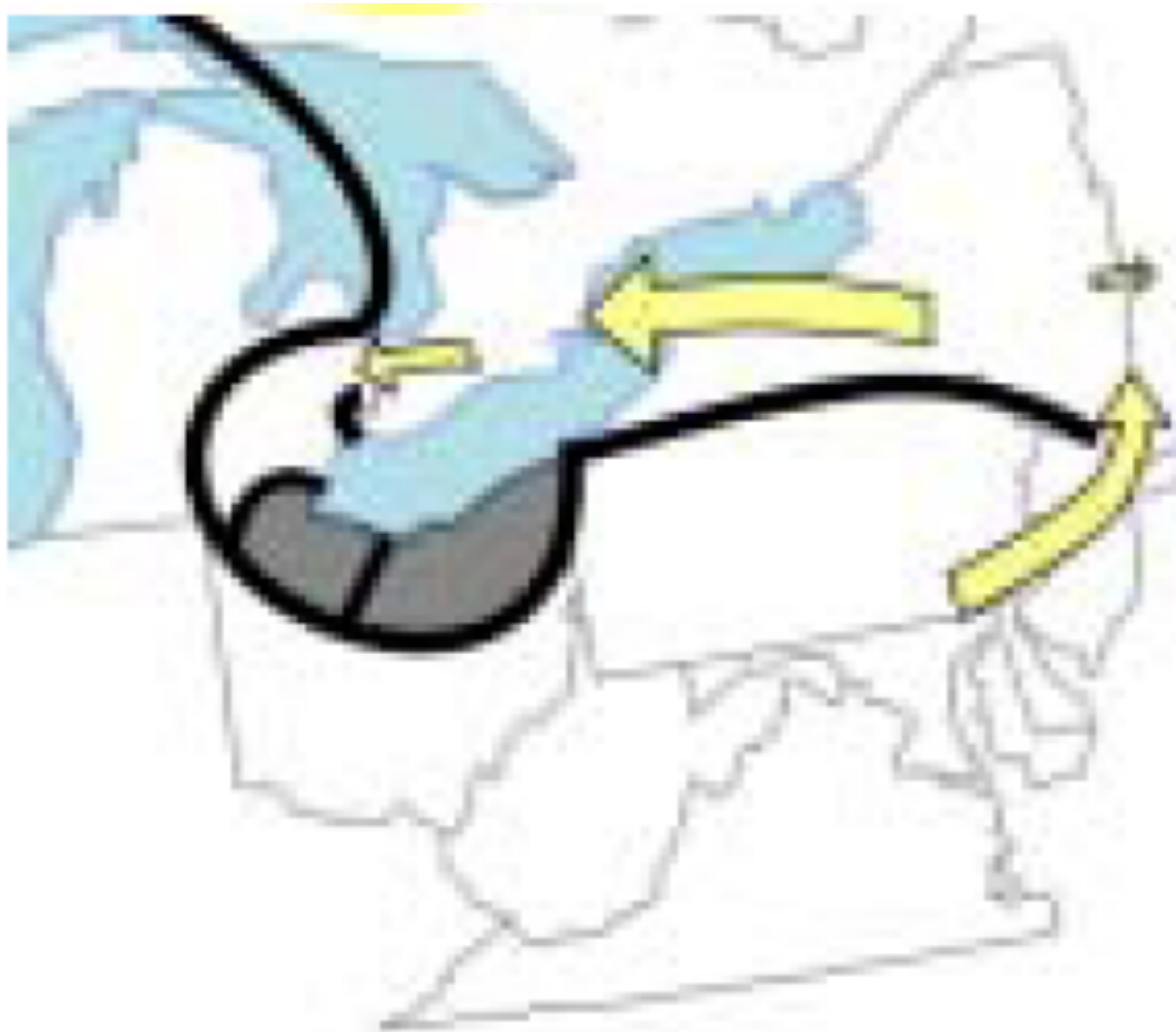
7. 16:10:41

Hines, GIV, 2014

8.
16:10:44

Hines, GIV,
2014

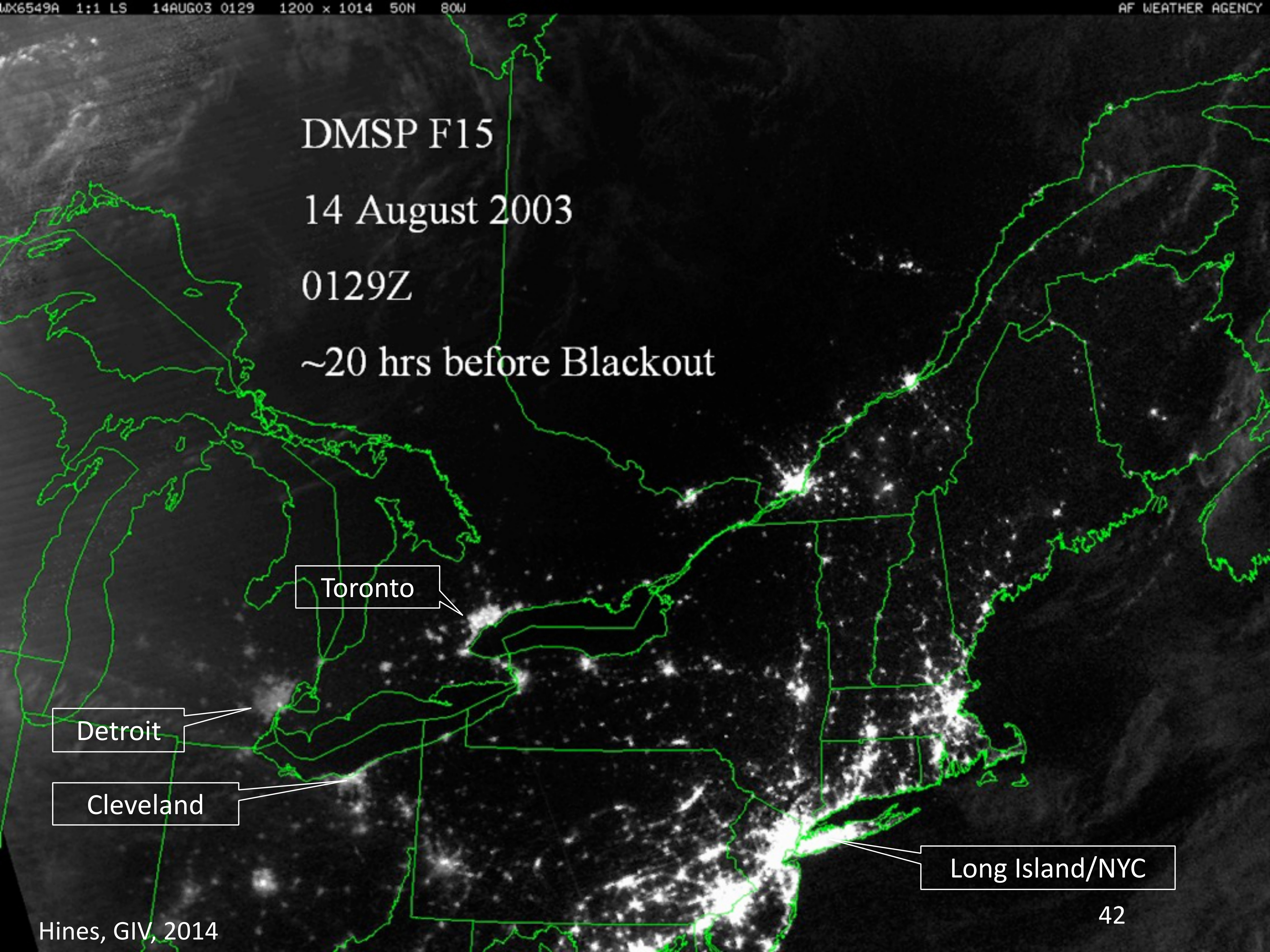
9.
16:10:45



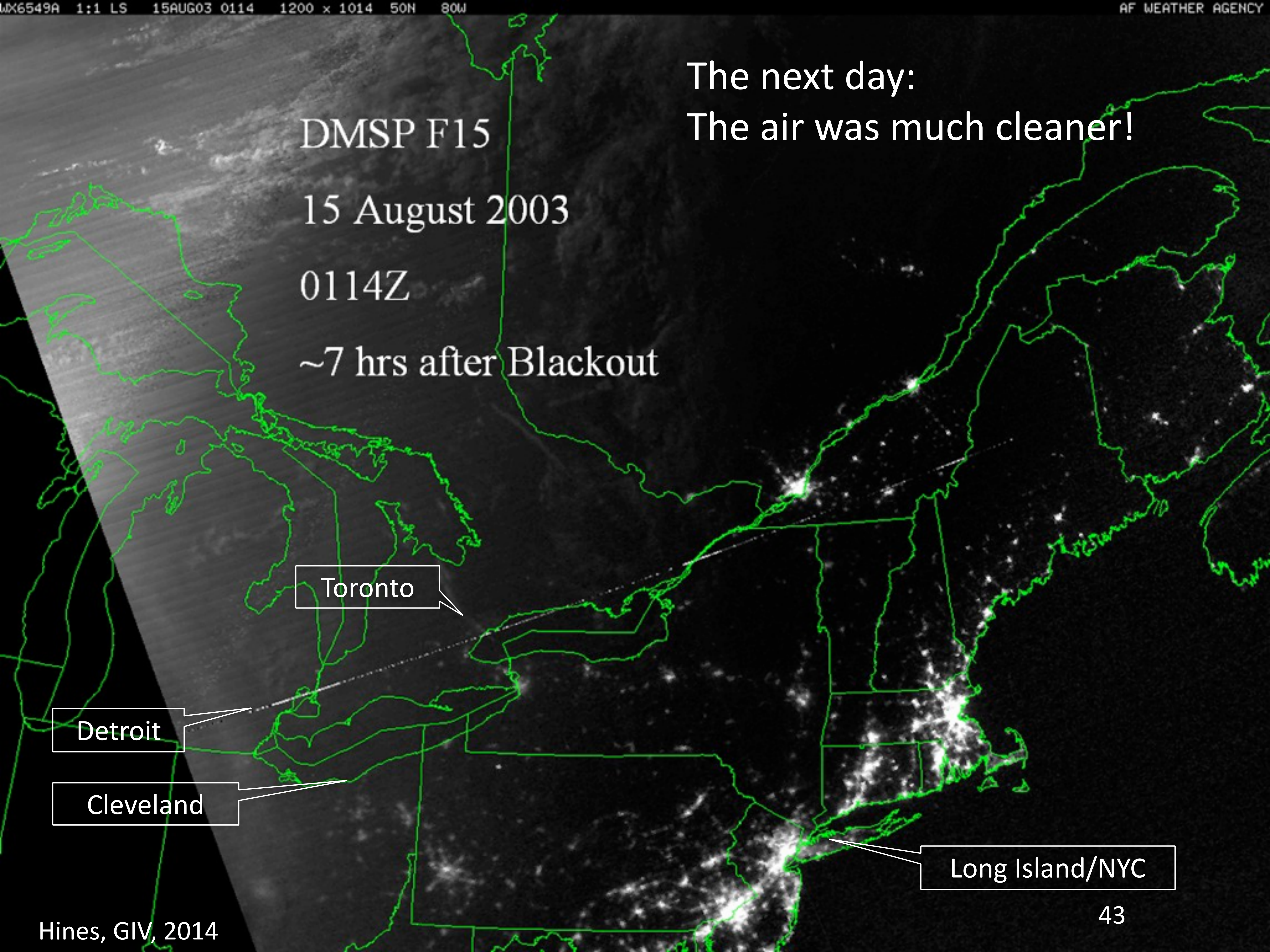
Hines, GIV,
2014

10.
16:13:00

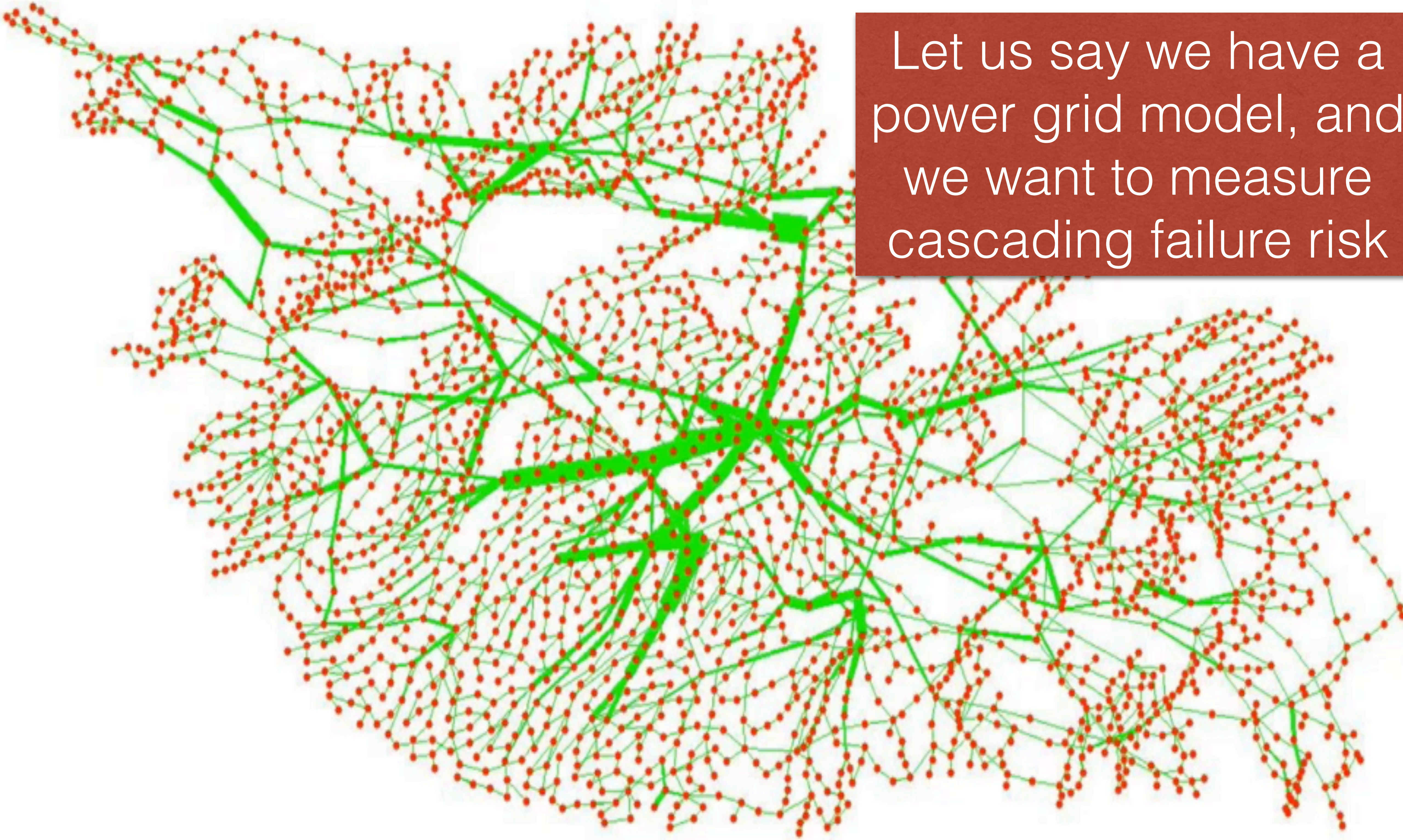
Hines, GIV,

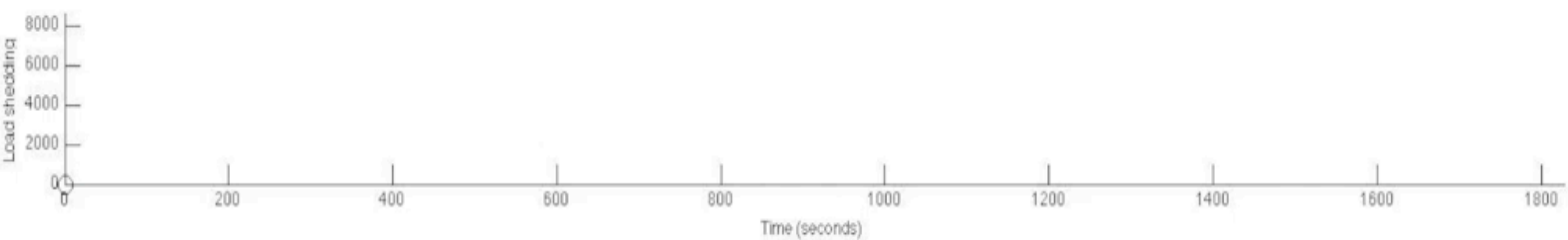


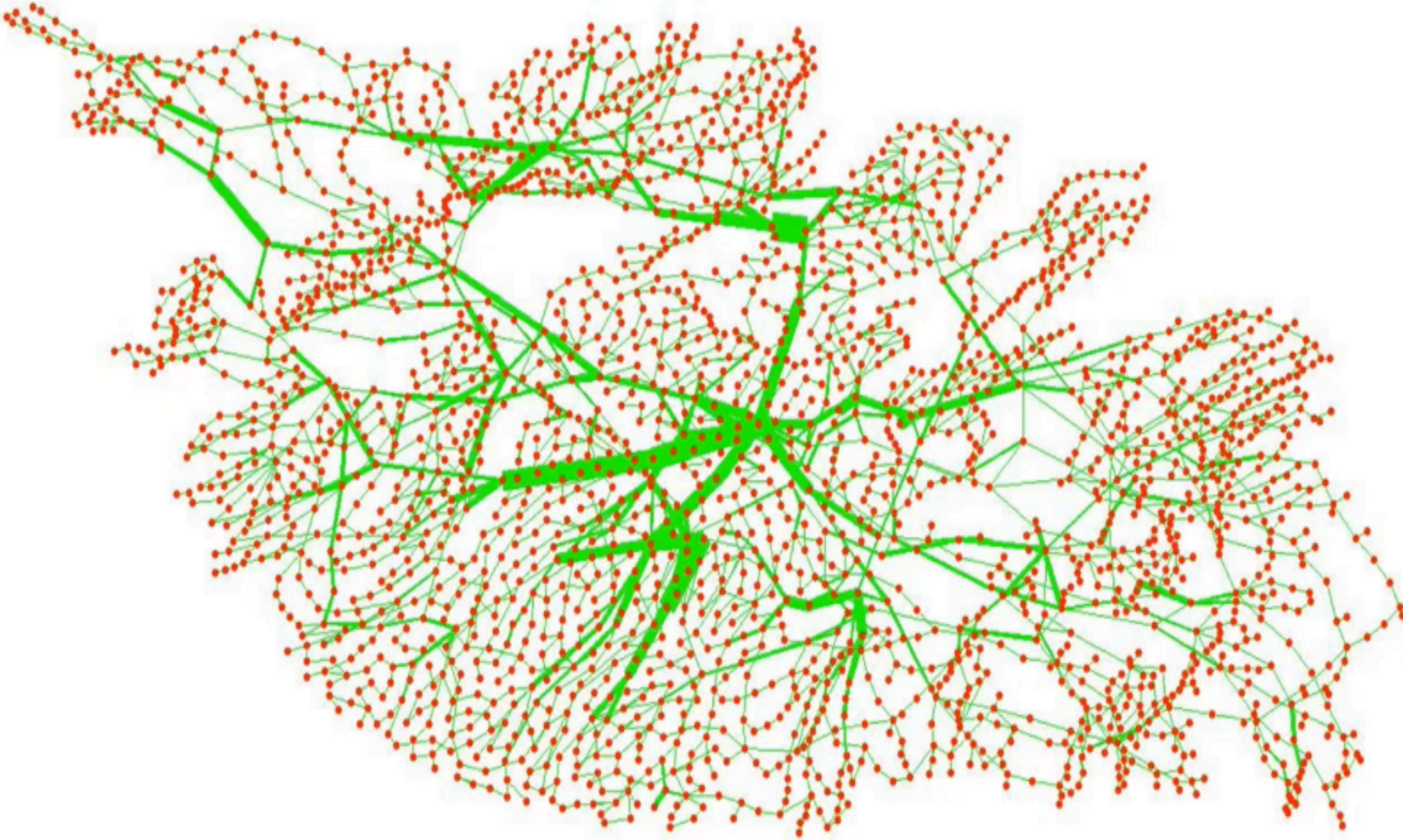
Hines, GIV, 2014

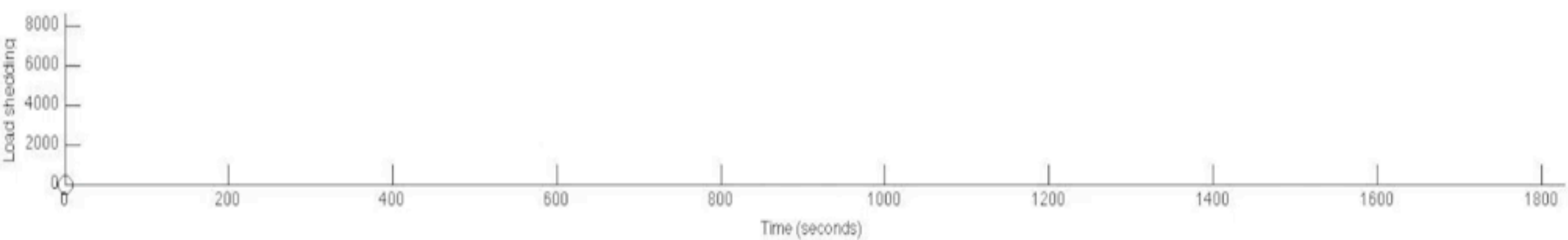

WX6549A 1:1 LS 15AUG03 0114 1200 x 1014 50N 80W
AF WEATHER AGENCY
The next day:
The air was much cleaner!
DMSP F15
15 August 2003
0114Z
~7 hrs after Blackout
Toronto
Detroit
Cleveland
Long Island/NYC
Hines, GIV, 2014

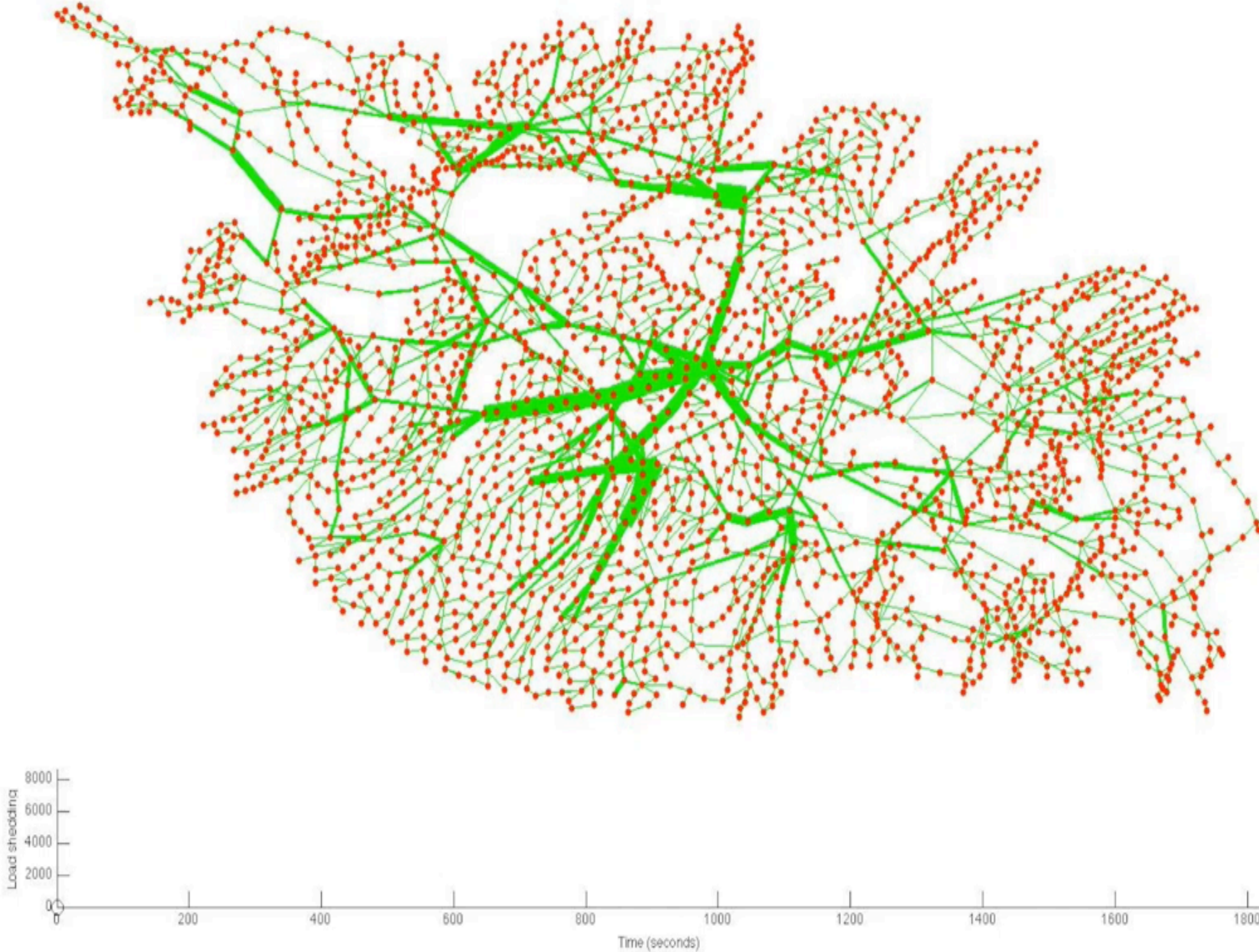
Let us say we have a power grid model, and we want to measure cascading failure risk








8000
6000
4000
2000
0
Load shedding
0
200
400
600
800
1000
1200
1400
1600
1800
Time (seconds)



Load shedding
8000
6000
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The risk analysis challenge

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- 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

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- ~1970s, Monte Carlo methods were developed for probabilistic reliability analysis

The risk analysis challenge

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- 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 3-4 orders of magnitude

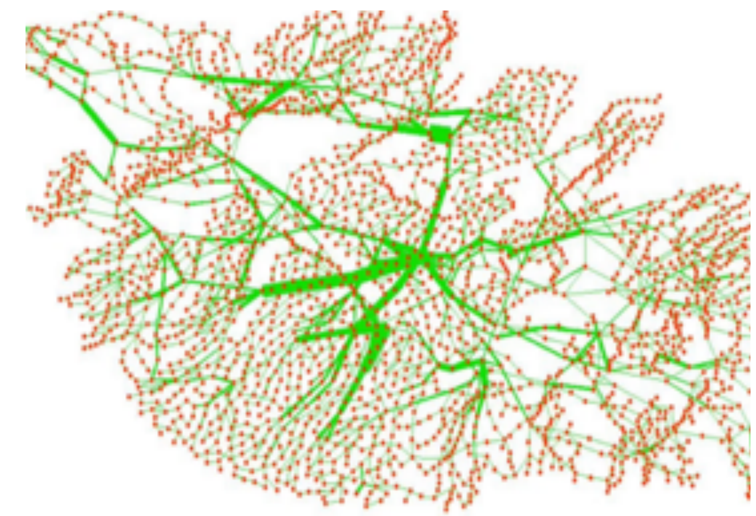
But most combinations are benign, only a few are “malignant”

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.



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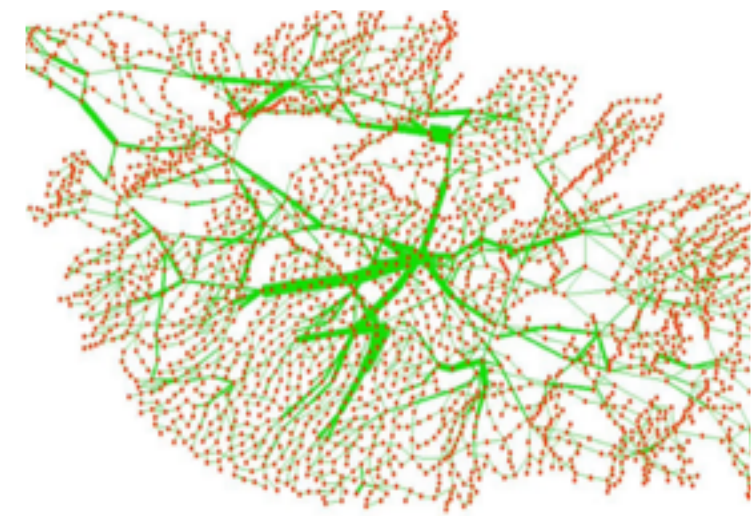
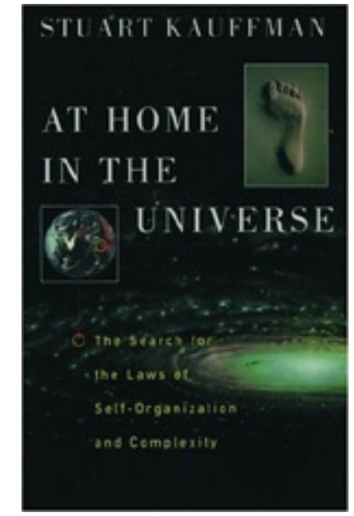
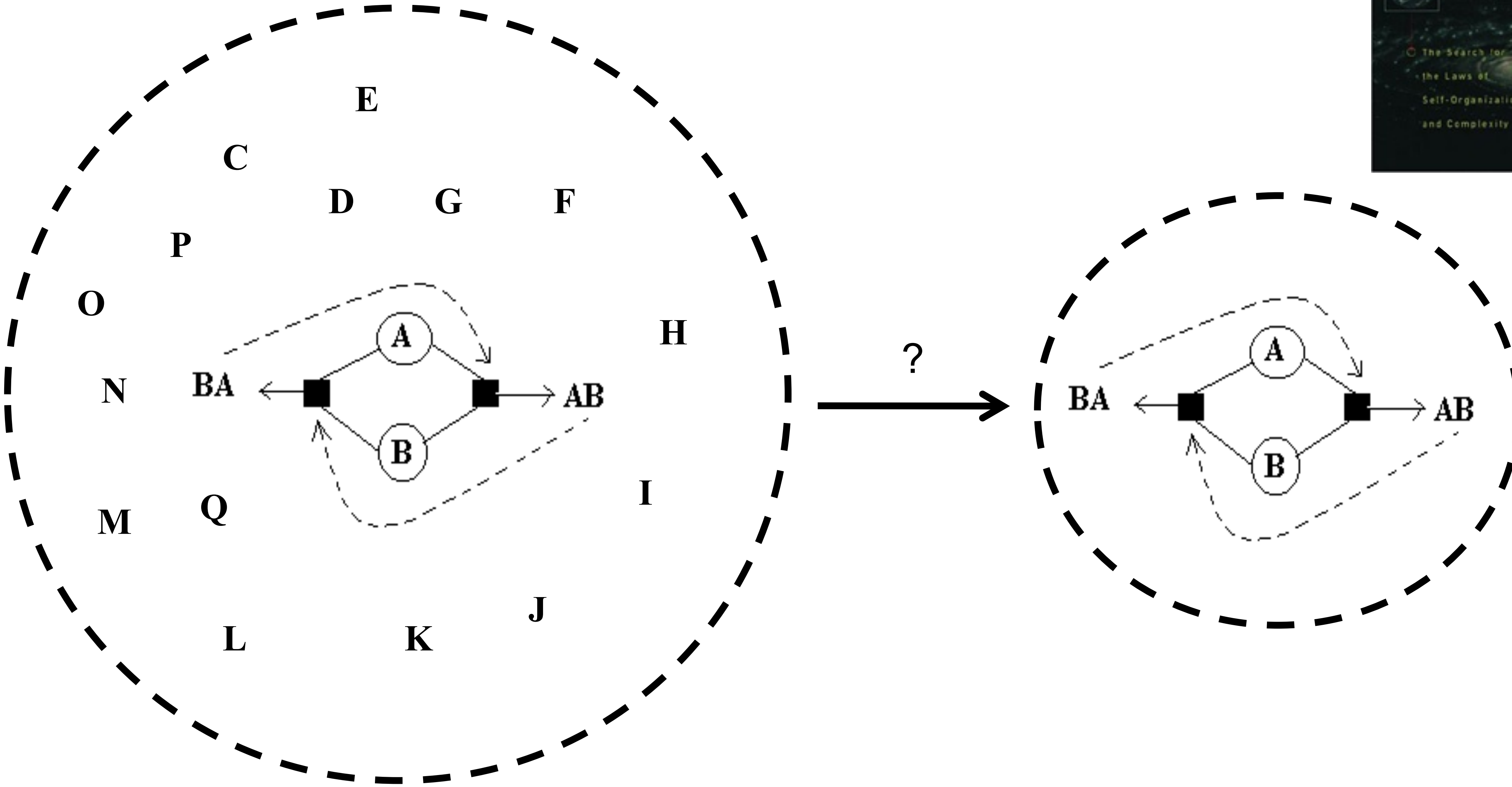


Can we somehow quickly find the malignant combinations, and then use their probabilities to estimate risk?

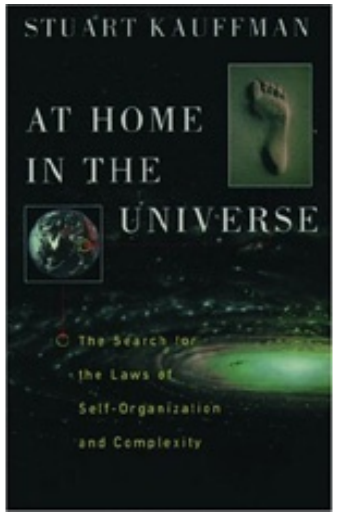
Stuart A. Kauffman, *At Home in the Universe*, 1996

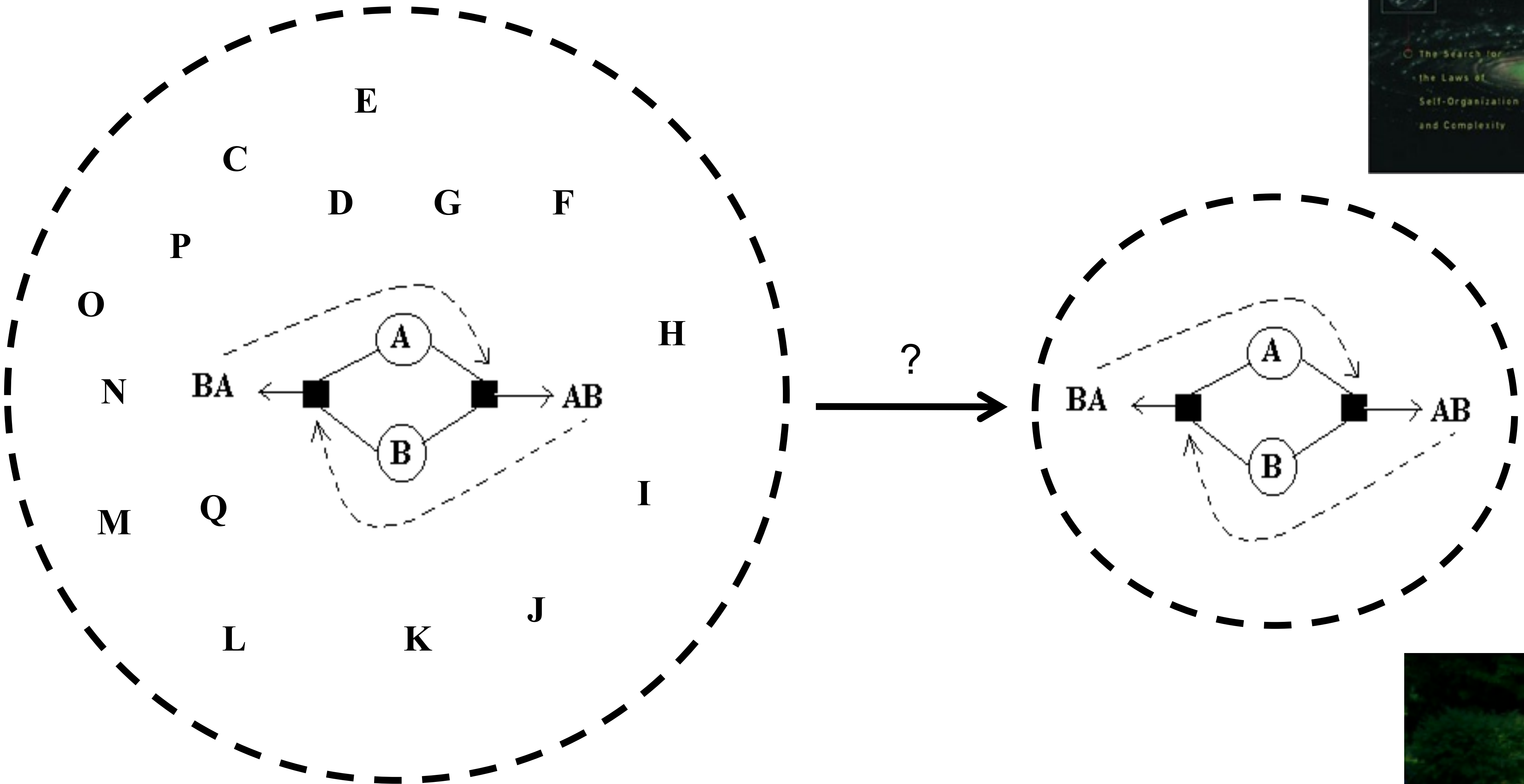




Searching for Autocatalytic Sets from among a large collection of molecules

Stuart A. Kauffman, *At Home in the Universe*, 1996

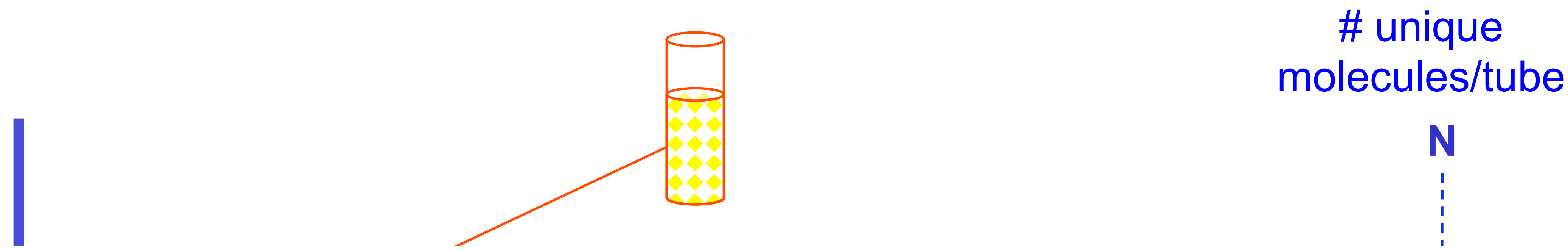




Searching for Autocatalytic Sets from among a large collection of molecules

M. Eppstein

The Random Chemistry algorithm



Credit: M. Eppstein

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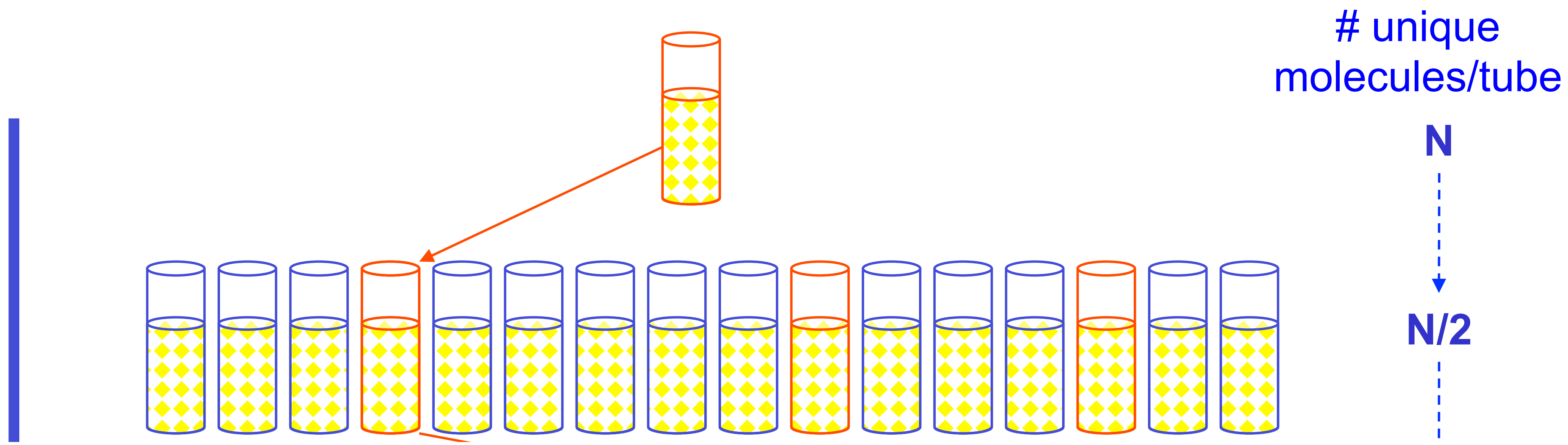

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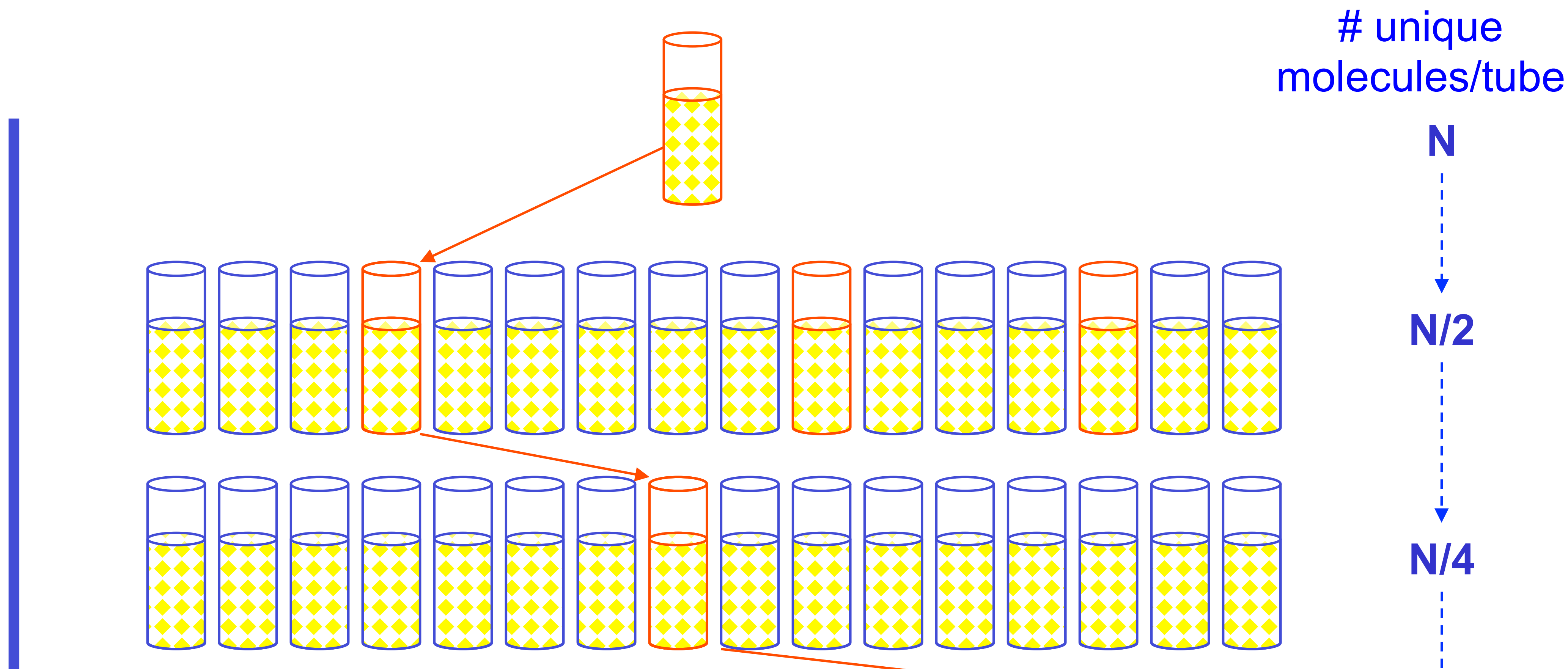

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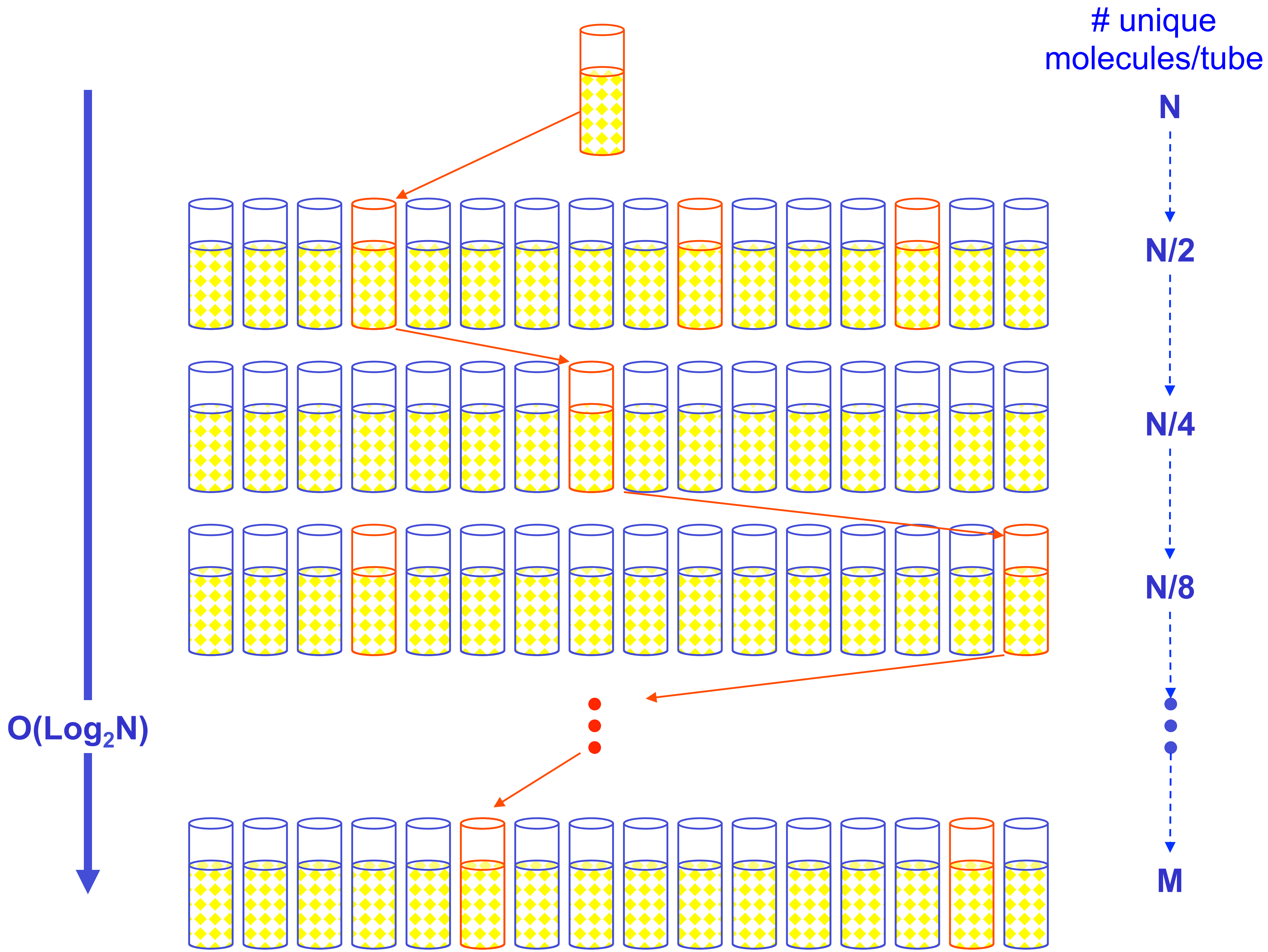

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Estimating risk from RC (1)

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

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The estimated number of malignancies of size k

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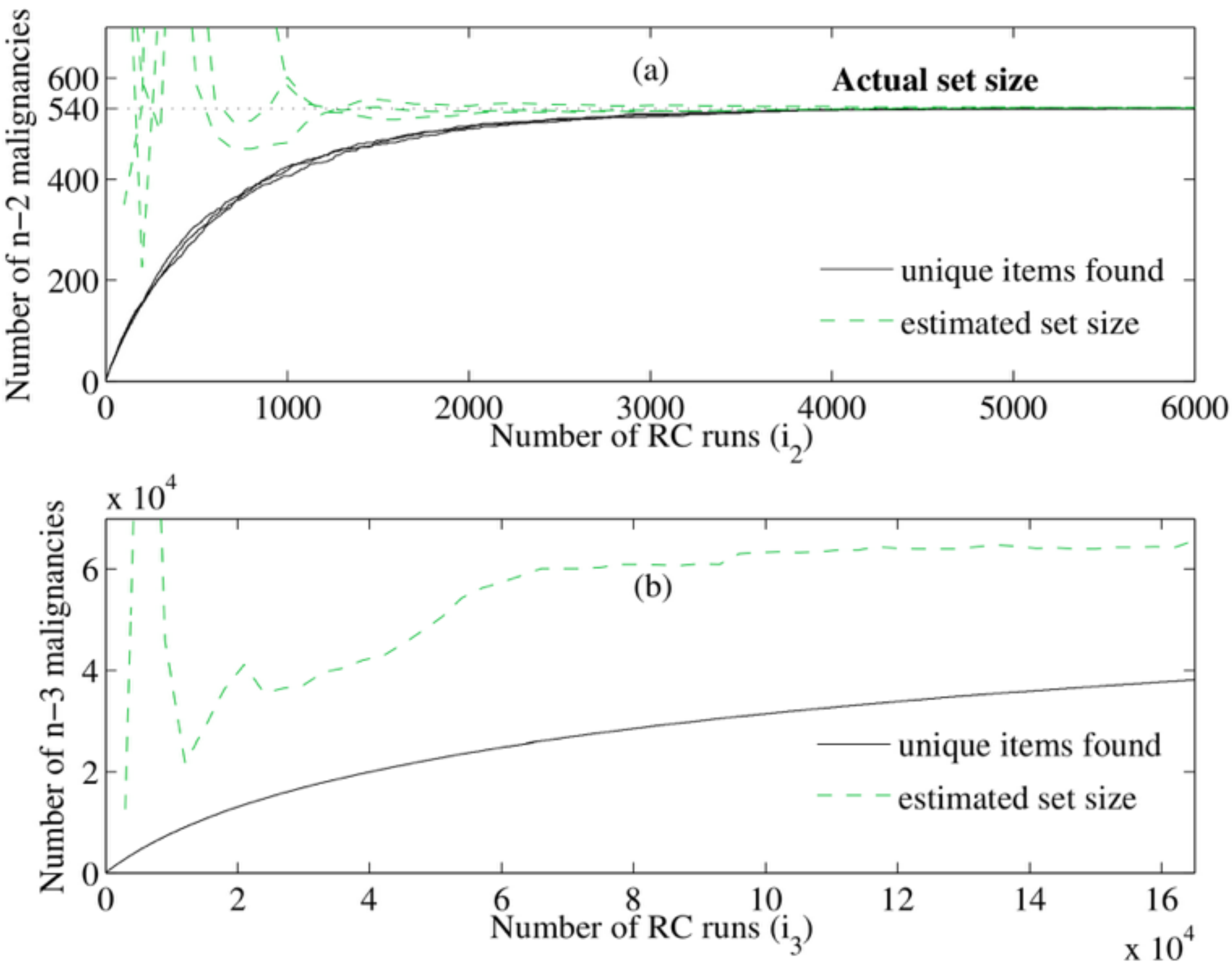
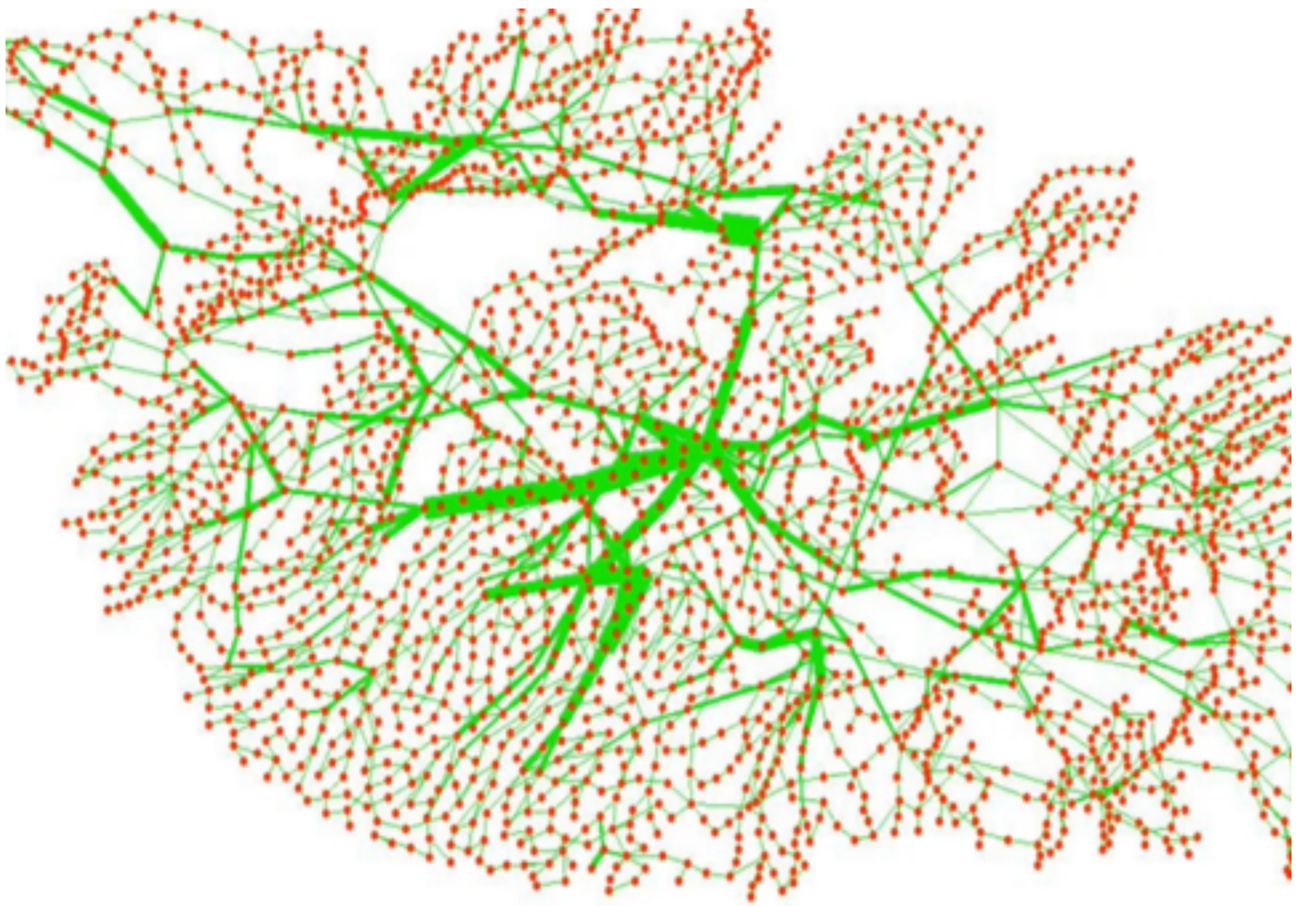
Combined probability

The number of malignancies of size k found by RC

Estimating the set size



Comparing RC to Monte Carlo



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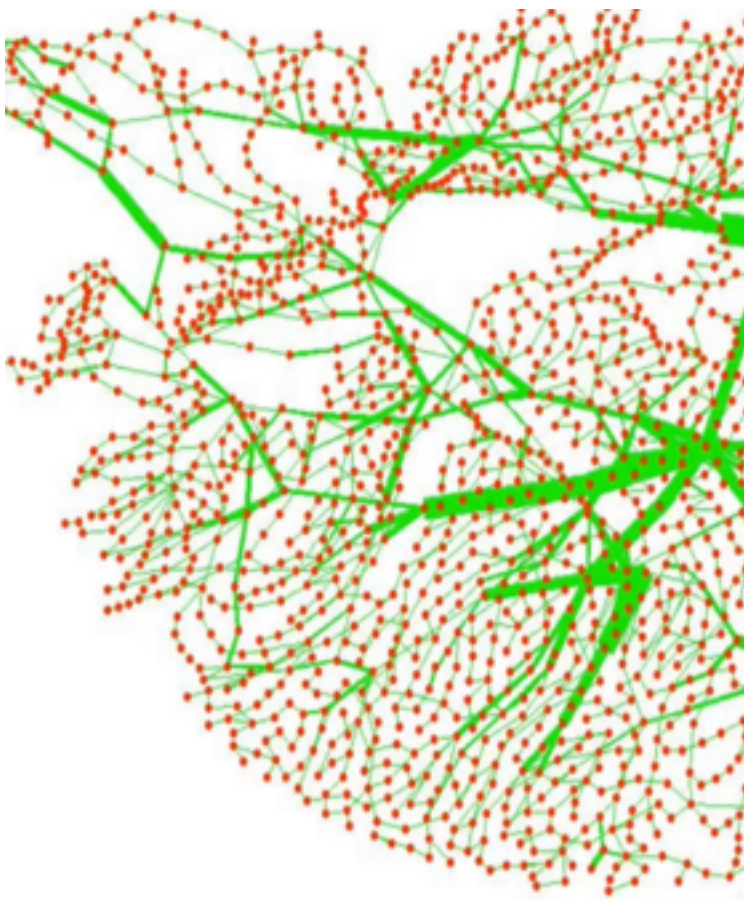
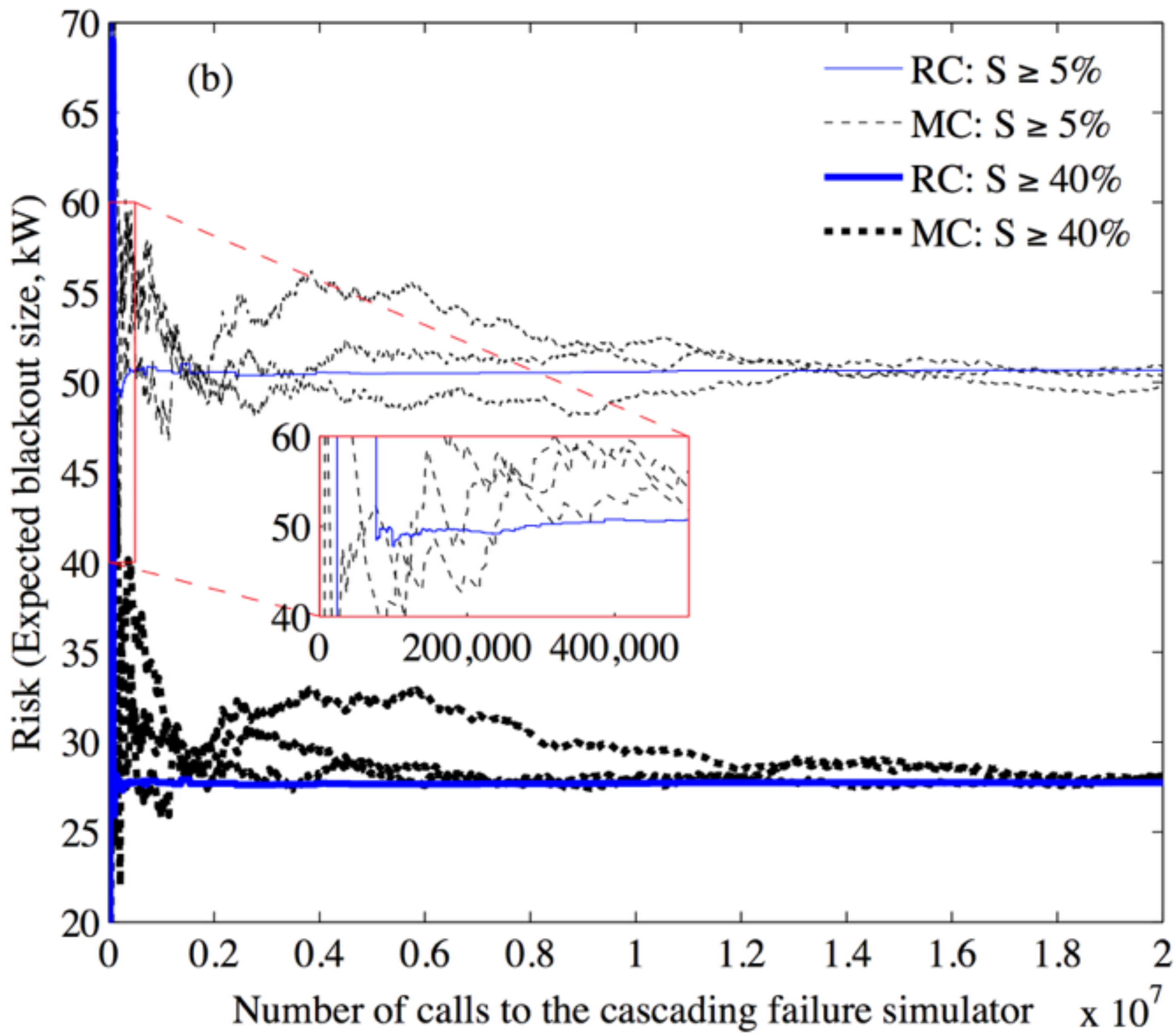
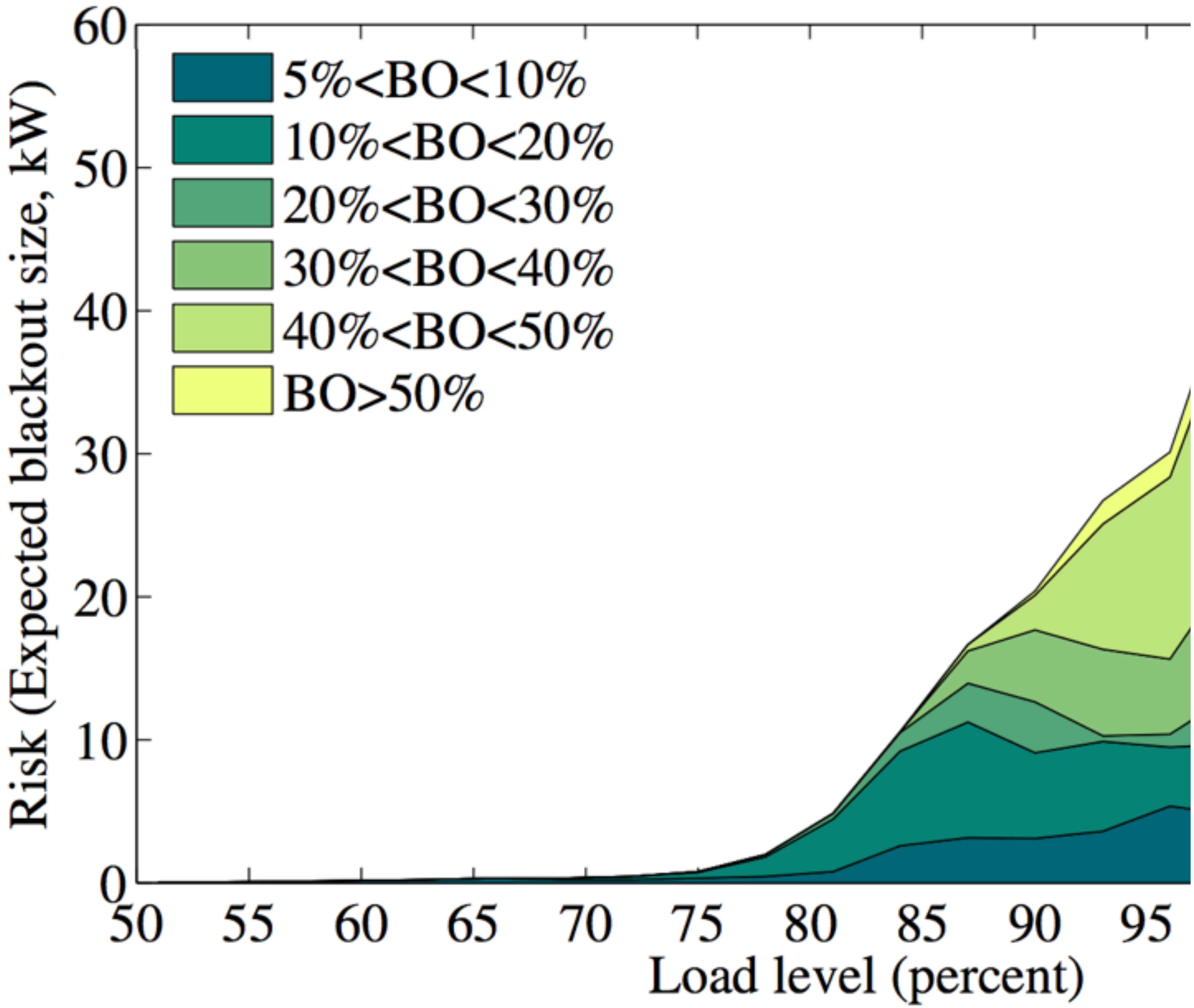


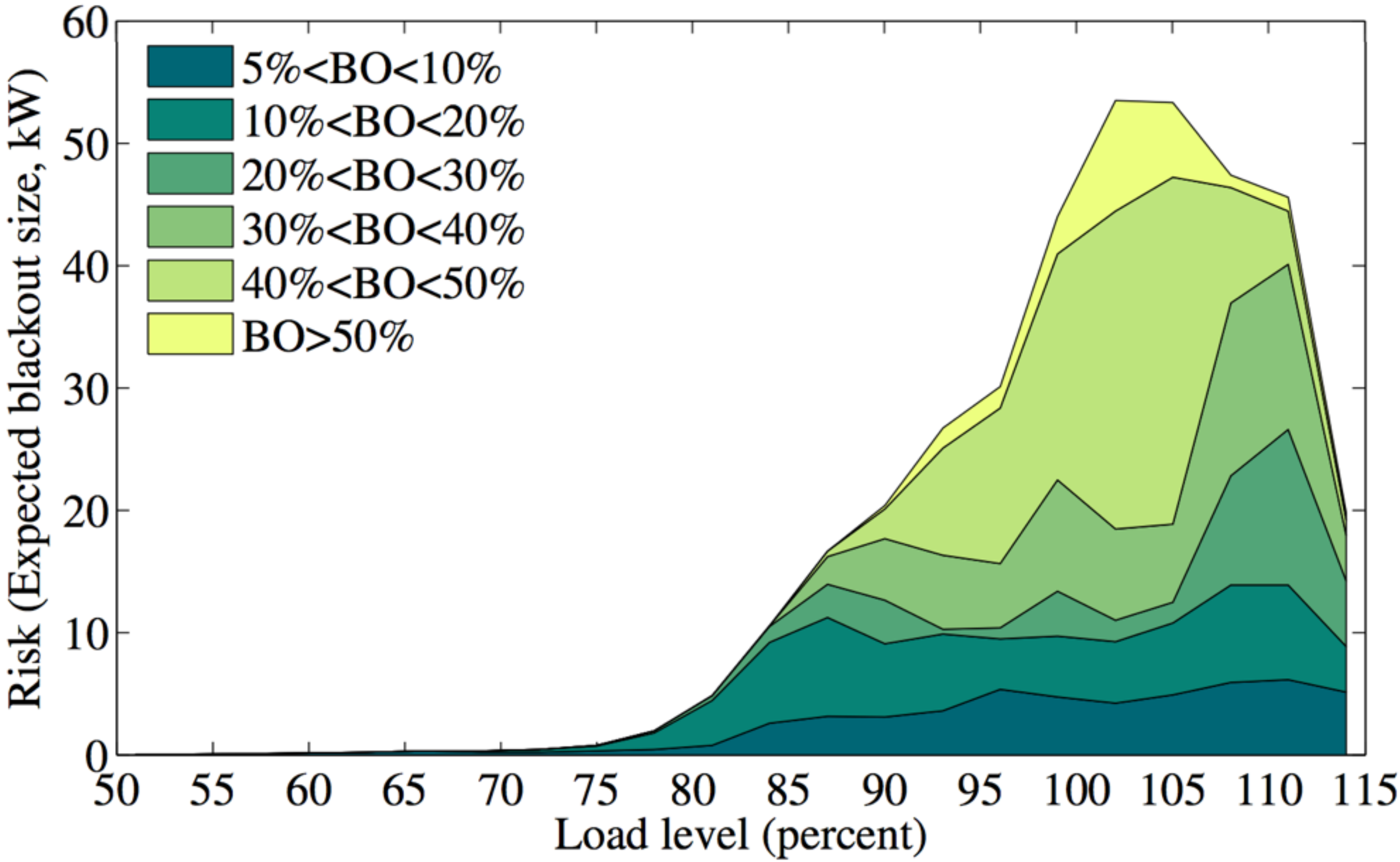


Risk vs. load



5%<BO<10%
10%<BO<20%
20%<BO<30%
30%<BO<40%
40%<BO<50%
BO>50%
Risk (Expected blackout size, kW)
0
10
20
30
40
50
60
50
55
60
65
70
75
80
85
90
95
Load level (percent)

Risk vs. load



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85
90
95
100
105
110
115
Load level (percent)

After many simulations, differentiate (1) to get the sensitivity of Risk to outage probabilities…

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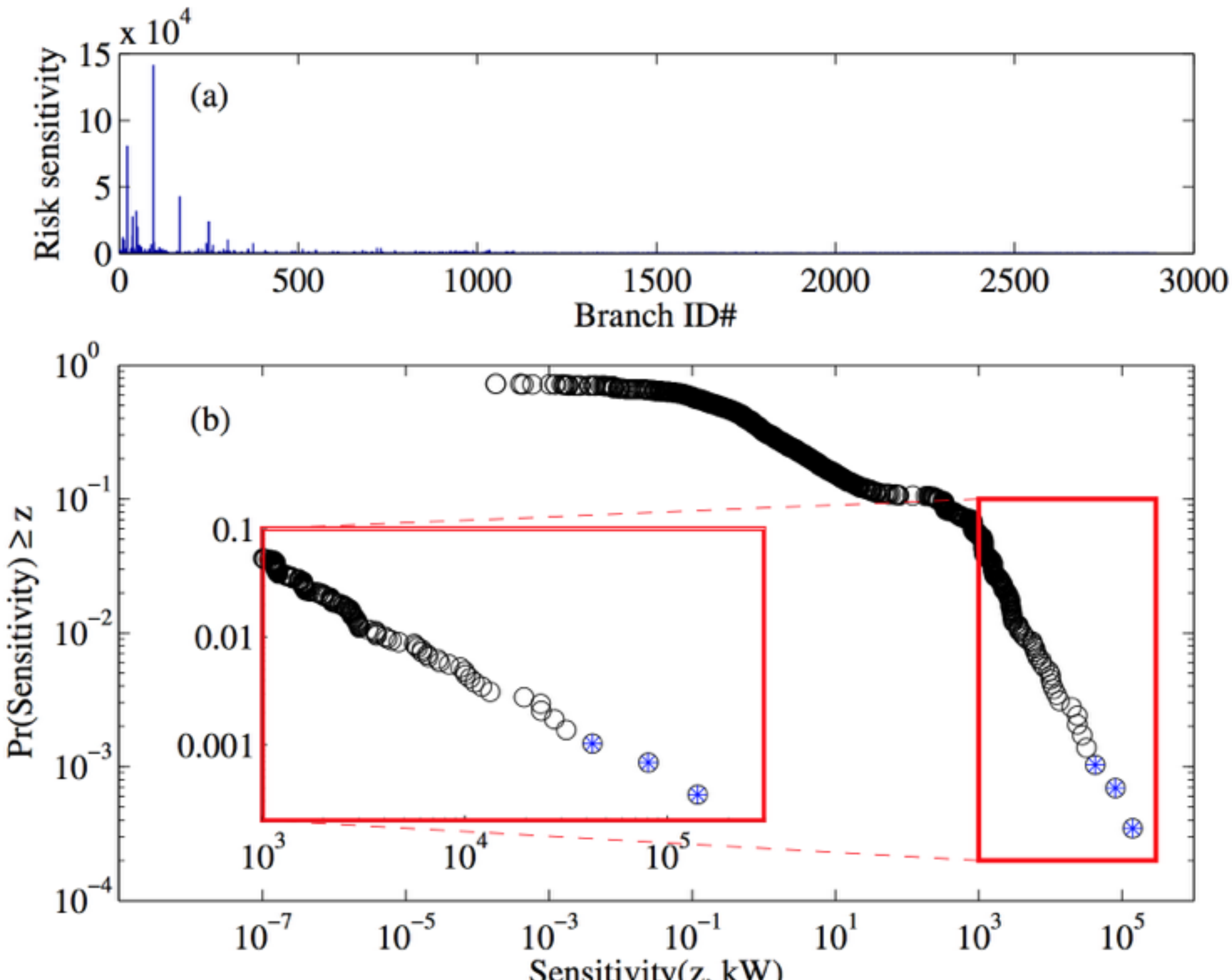

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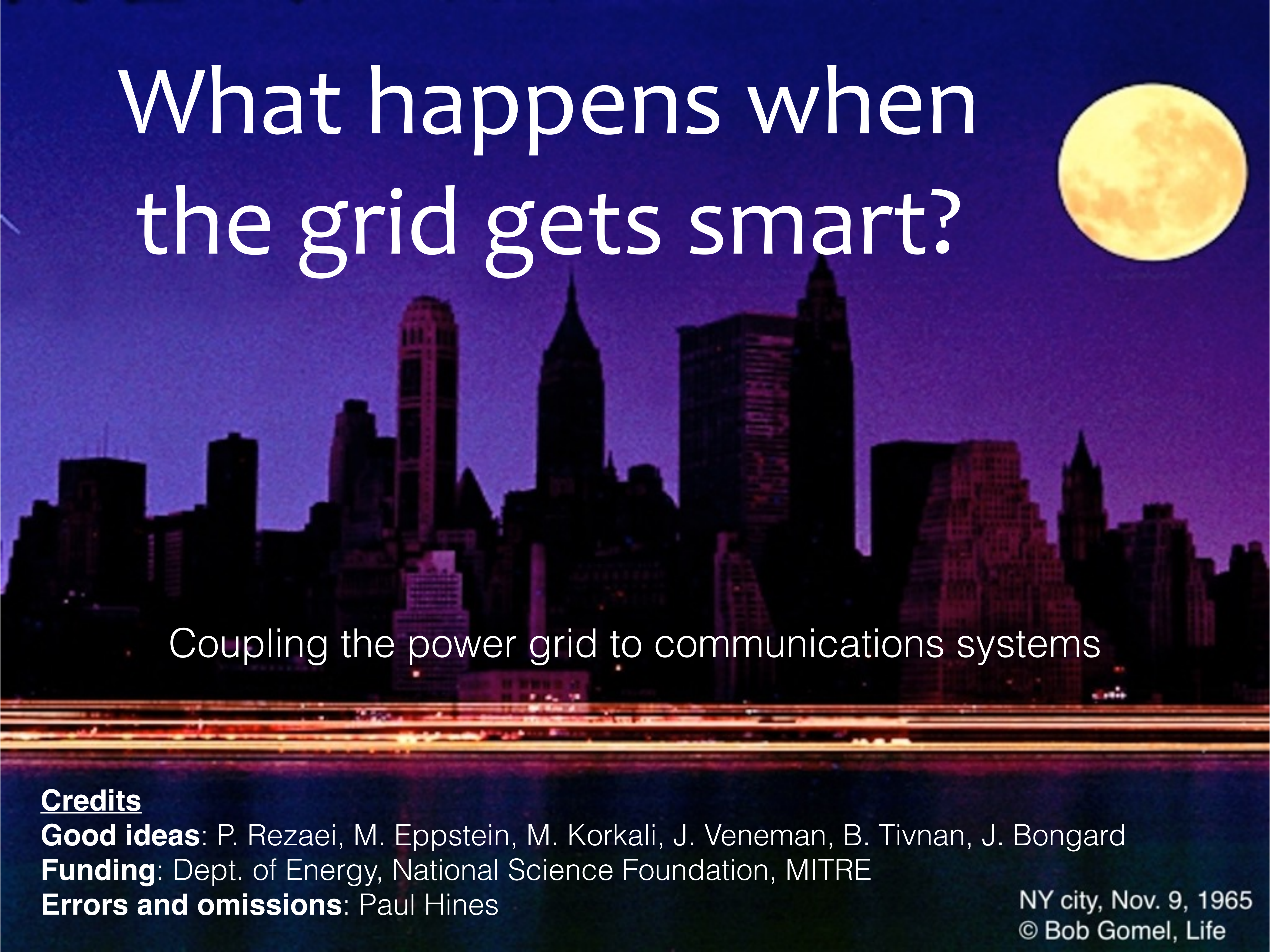
- Very large (S>40%) blackout risk decreases by 83%



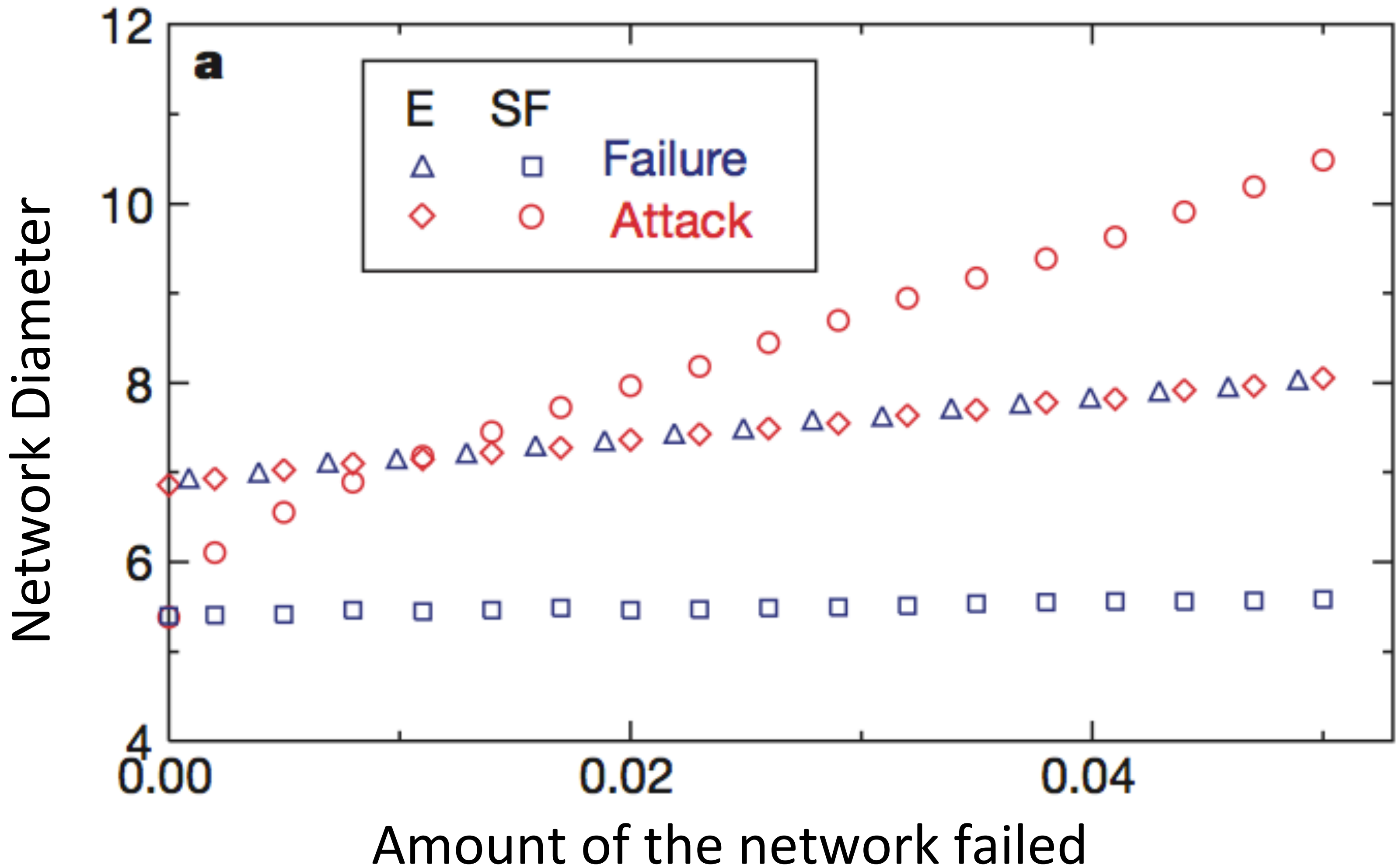
What happens when the grid gets smart?

Coupling the power grid to communications systems

Credits
Good ideas: P. Rezaei, M. Eppstein, M. Korkali, J. Veneman, B. Tivnan, J. Bongard
Funding: Dept. of Energy, National Science Foundation, MITRE
Errors and omissions: Paul Hines

NY city, Nov. 9, 1965

A key result in network science



Key question

If we couple the power grid to communications systems will risk increase or decrease?

Perhaps coupling will cause risk to increase?

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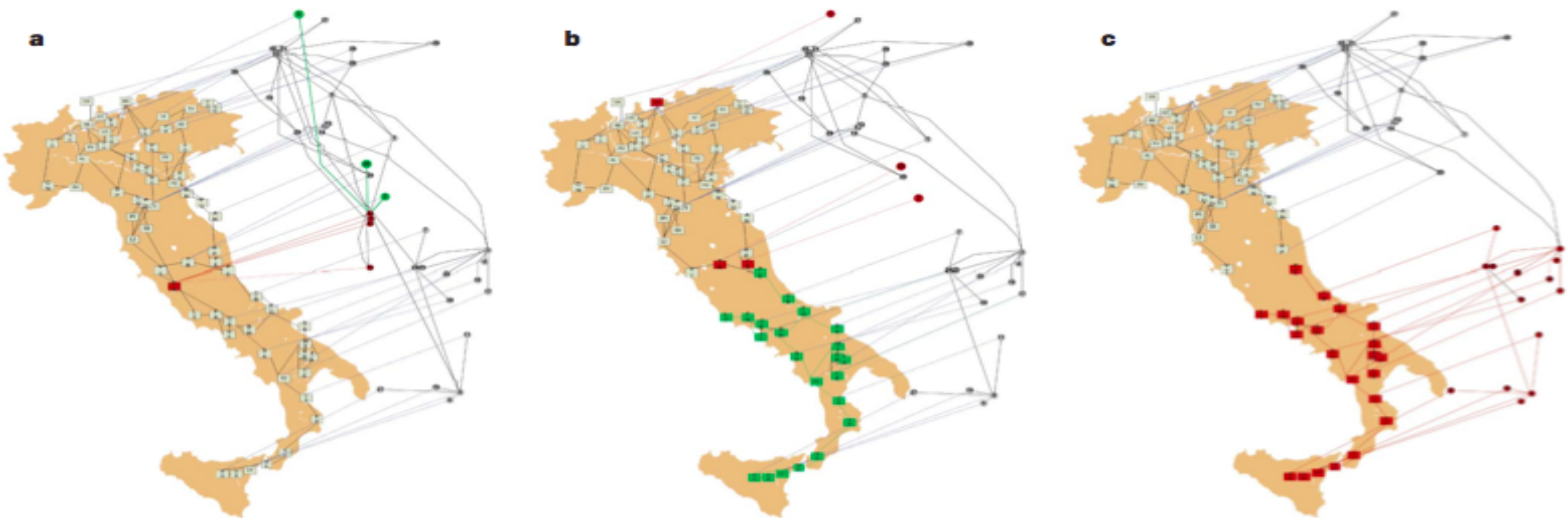
Vol 464 | 15 April 2010 | doi:10.1038/nature08932 nature

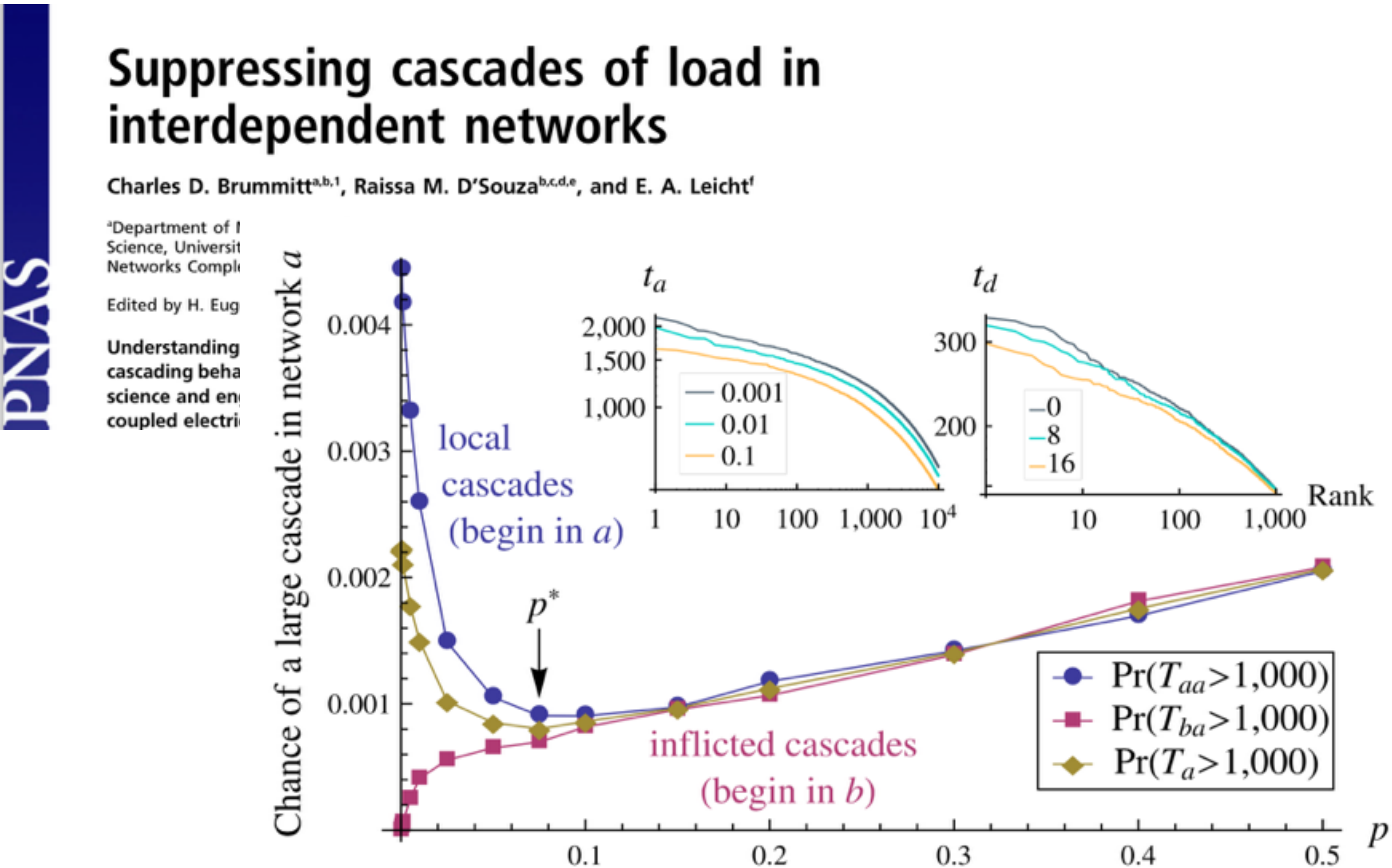
LETTERS

Catastrophic cascade of failures in interdependent networks

Sergey V. Buldyrev[1,2], Roni Parshani[3], Gerald Paul[2], H. Eugene Stanley[2] & Shlomo Havlin[3]



Perhaps coupling will cause risk to go down, and then up?


PNAS

Suppressing cascades of load in interdependent networks

Charles D. Brummitt[a,b,1], Raissa M. D'Souza[b,c,d,e], and E. A. Leicht[f]

[a]Department of I
Science, Universit
Networks Compl

Edited by H. Eug

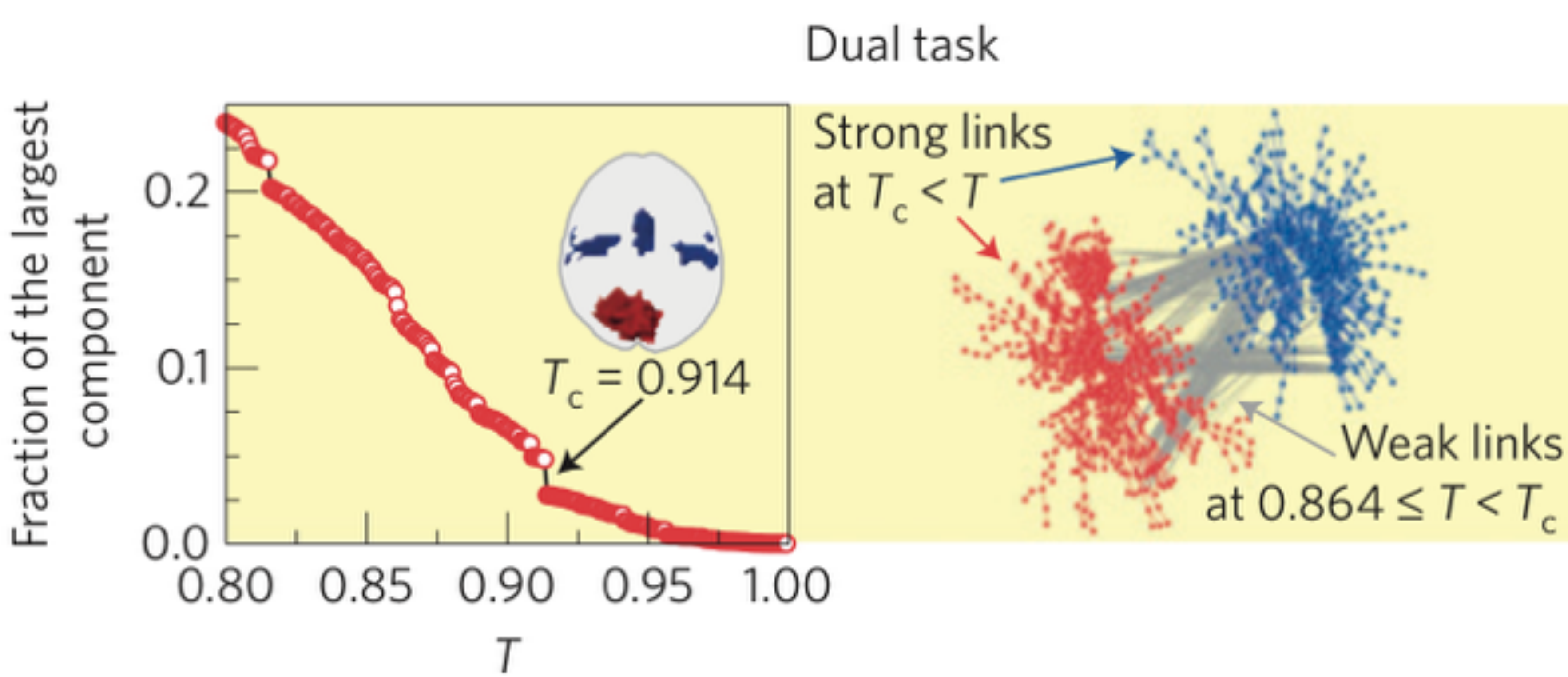
Understanding
cascading beha
science and en
coupled electri

Or maybe coupling is useful?

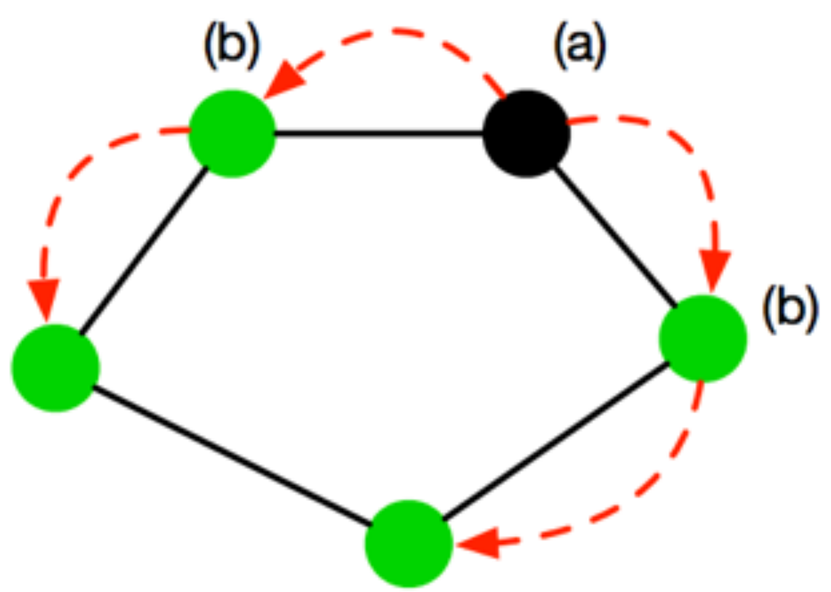
Avoiding catastrophic failure in correlated networks of networks

Saulo D. S. Reis[1,2], Yanqing Hu[1], Andrés Babino[3], José S. Andrade Jr[2], Santiago Canals[4], Mariano Sigman[3,5] and Hernán A. Makse[1,2,3★]

nature physics



However the mechanics of cascading in the grid differ from contagion models



Conventional models of contagion

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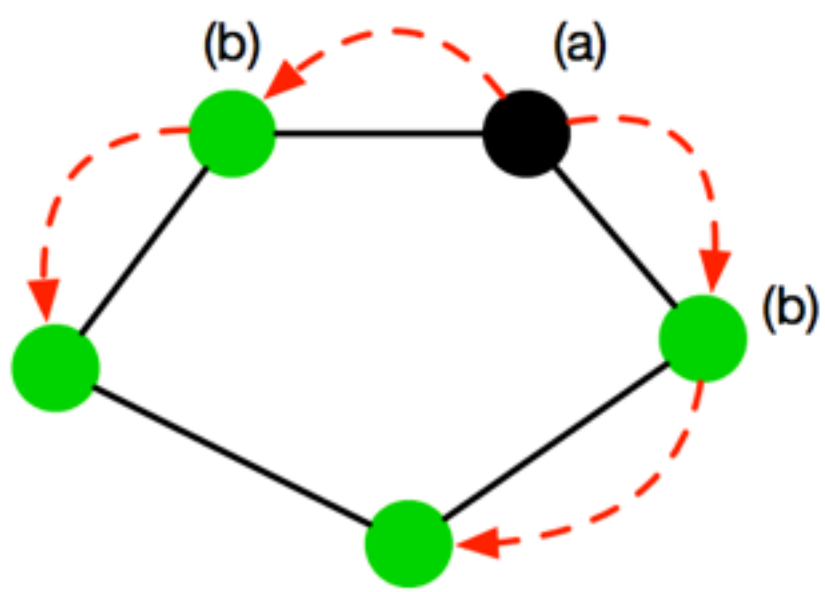

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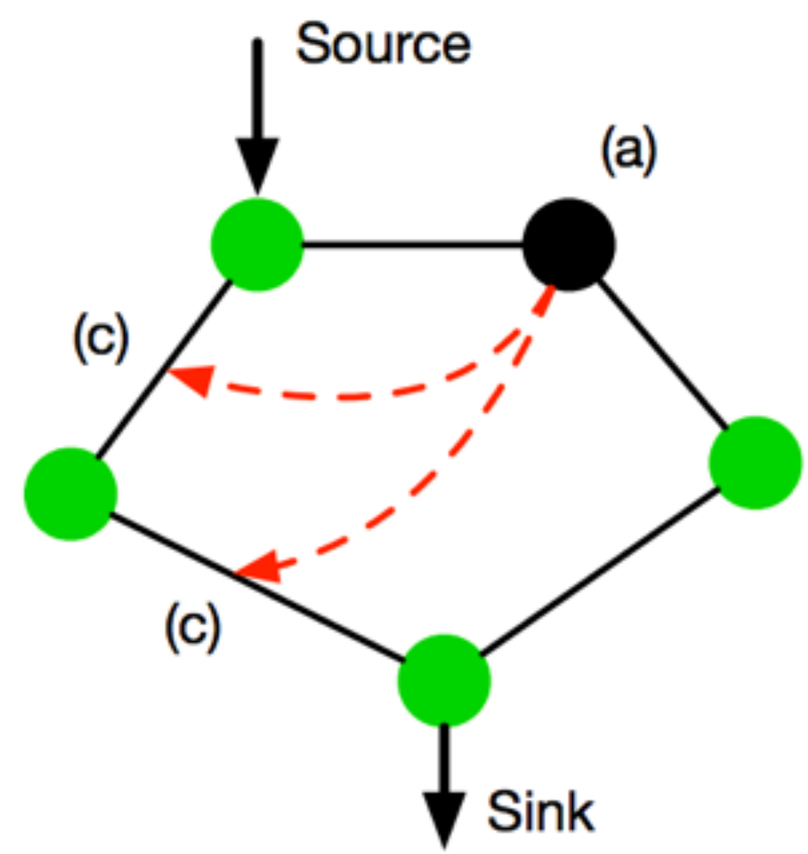

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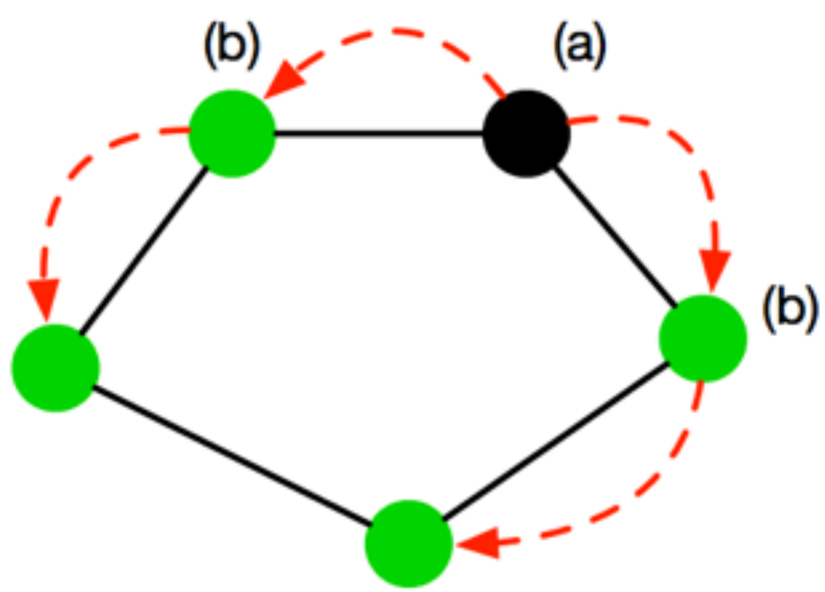

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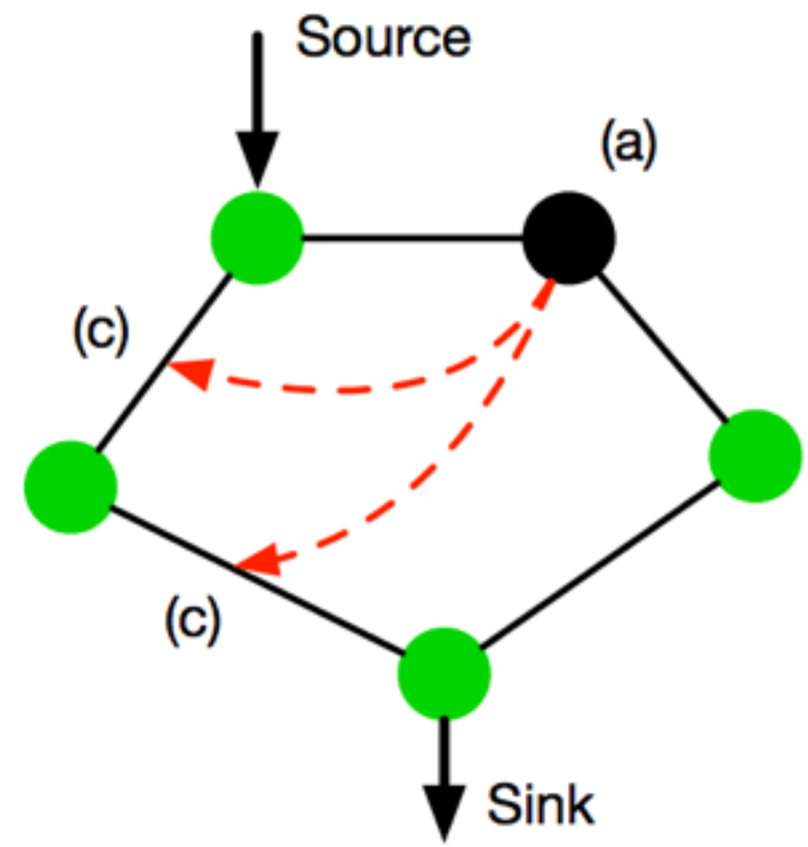
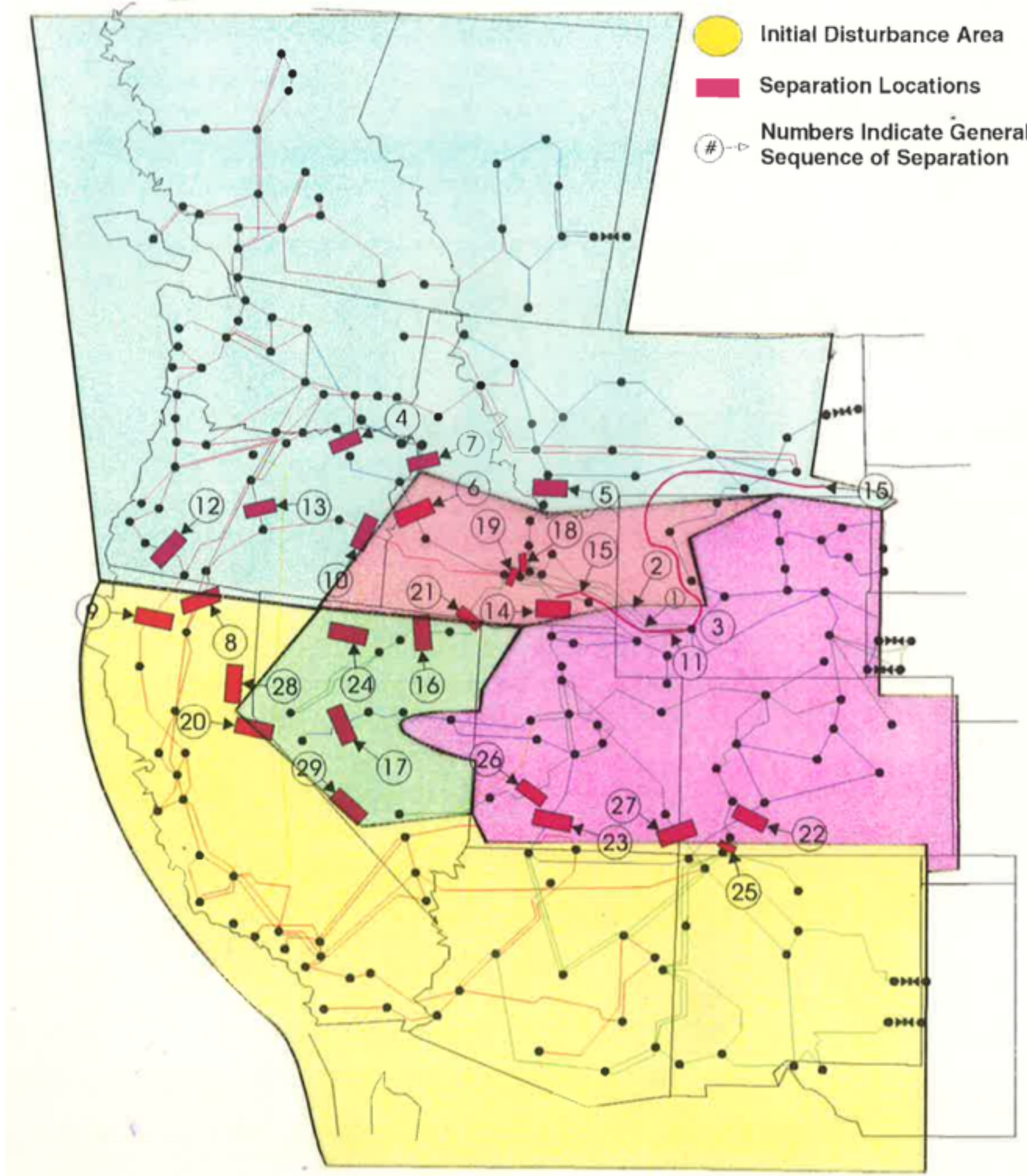


Cascading in power grids

Just in case you think this is just in my silly toy model



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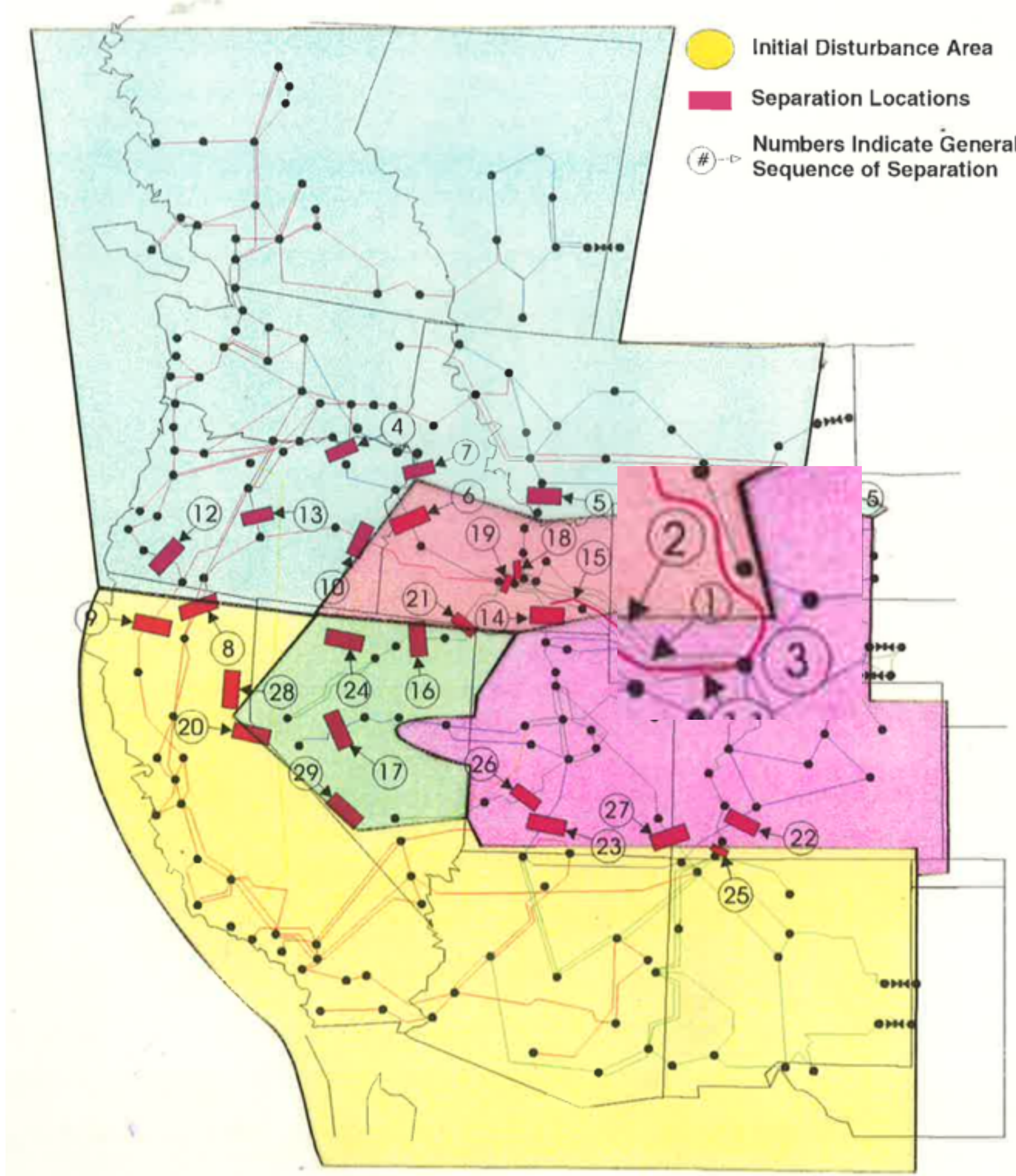

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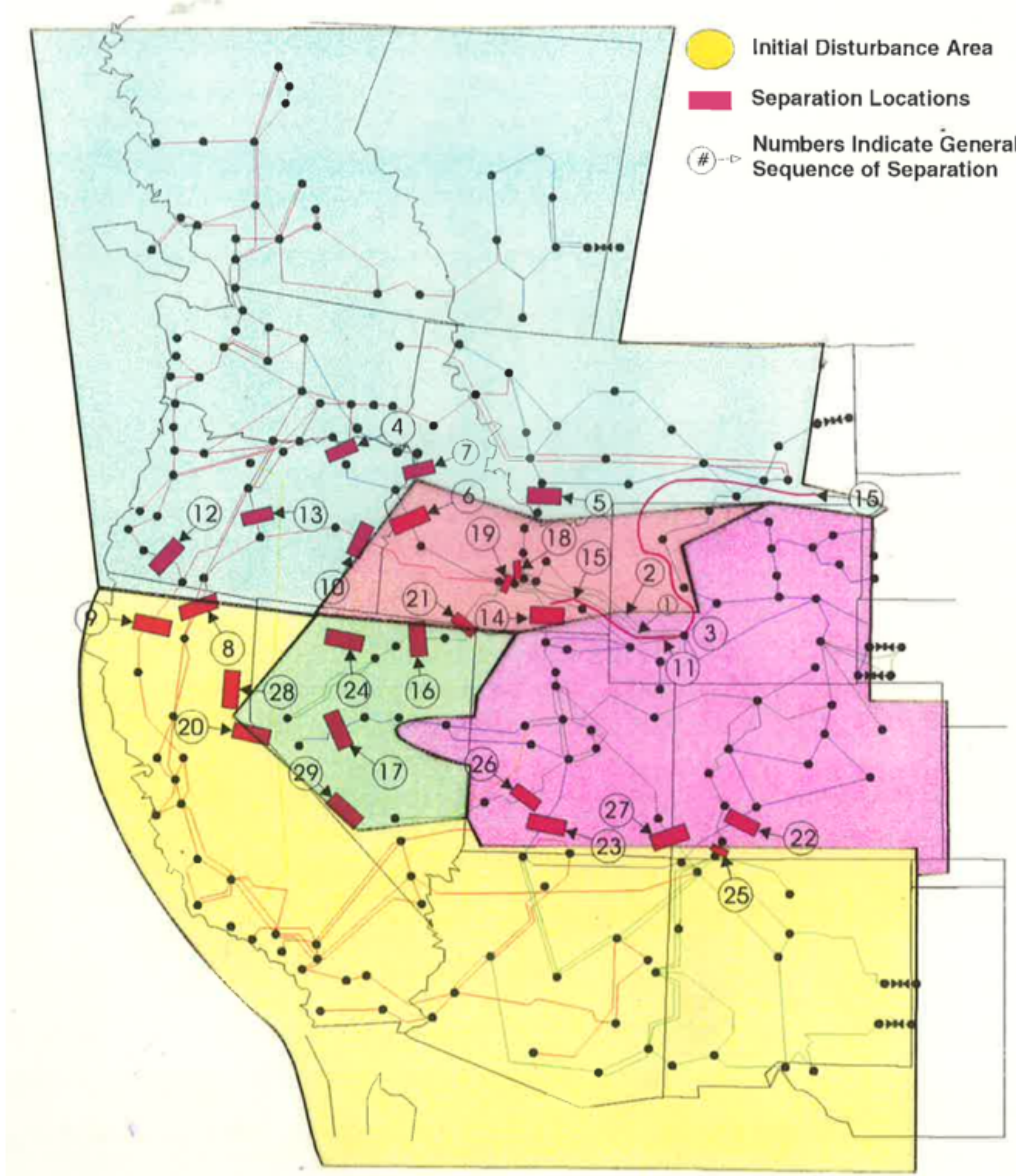

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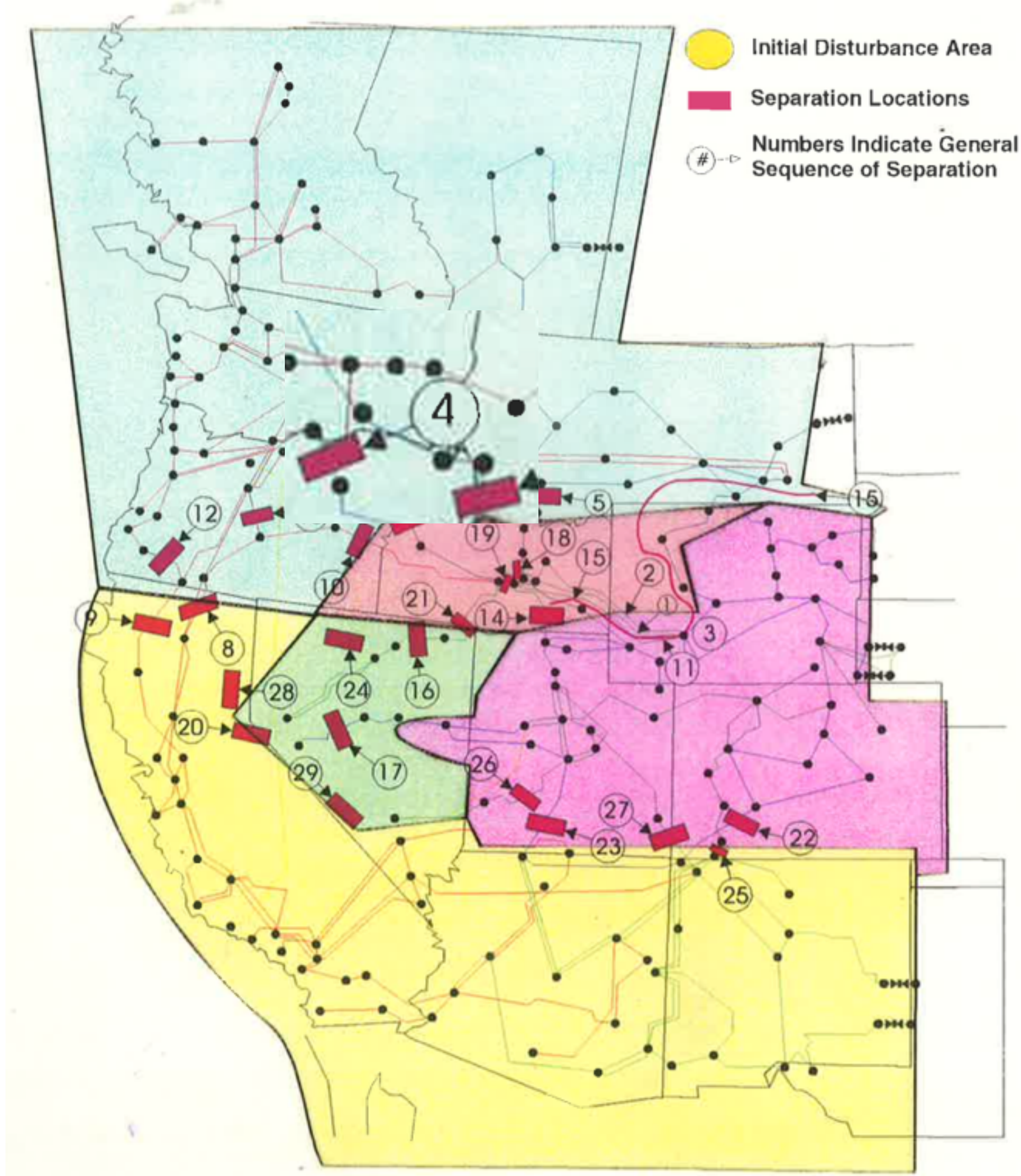

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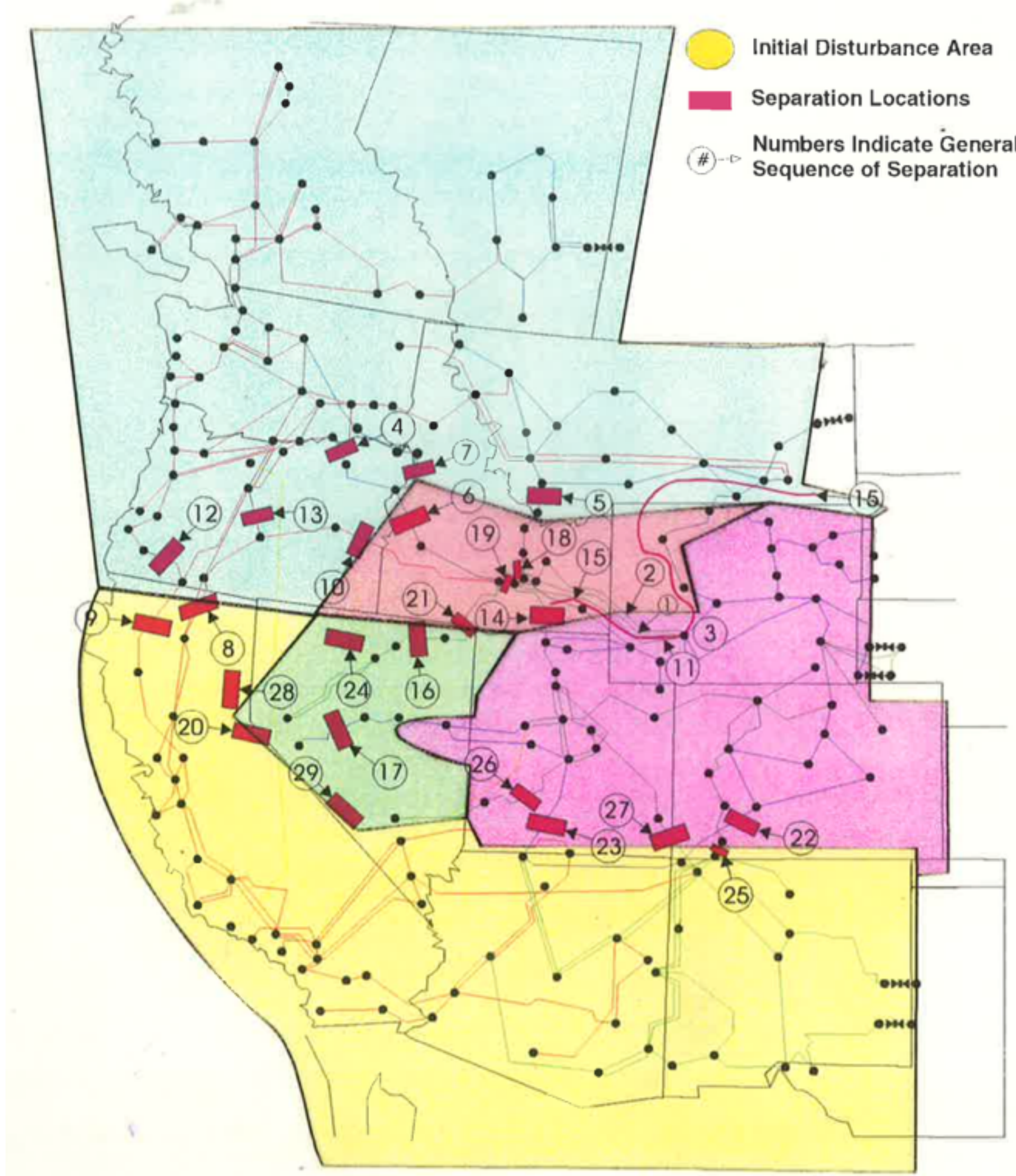

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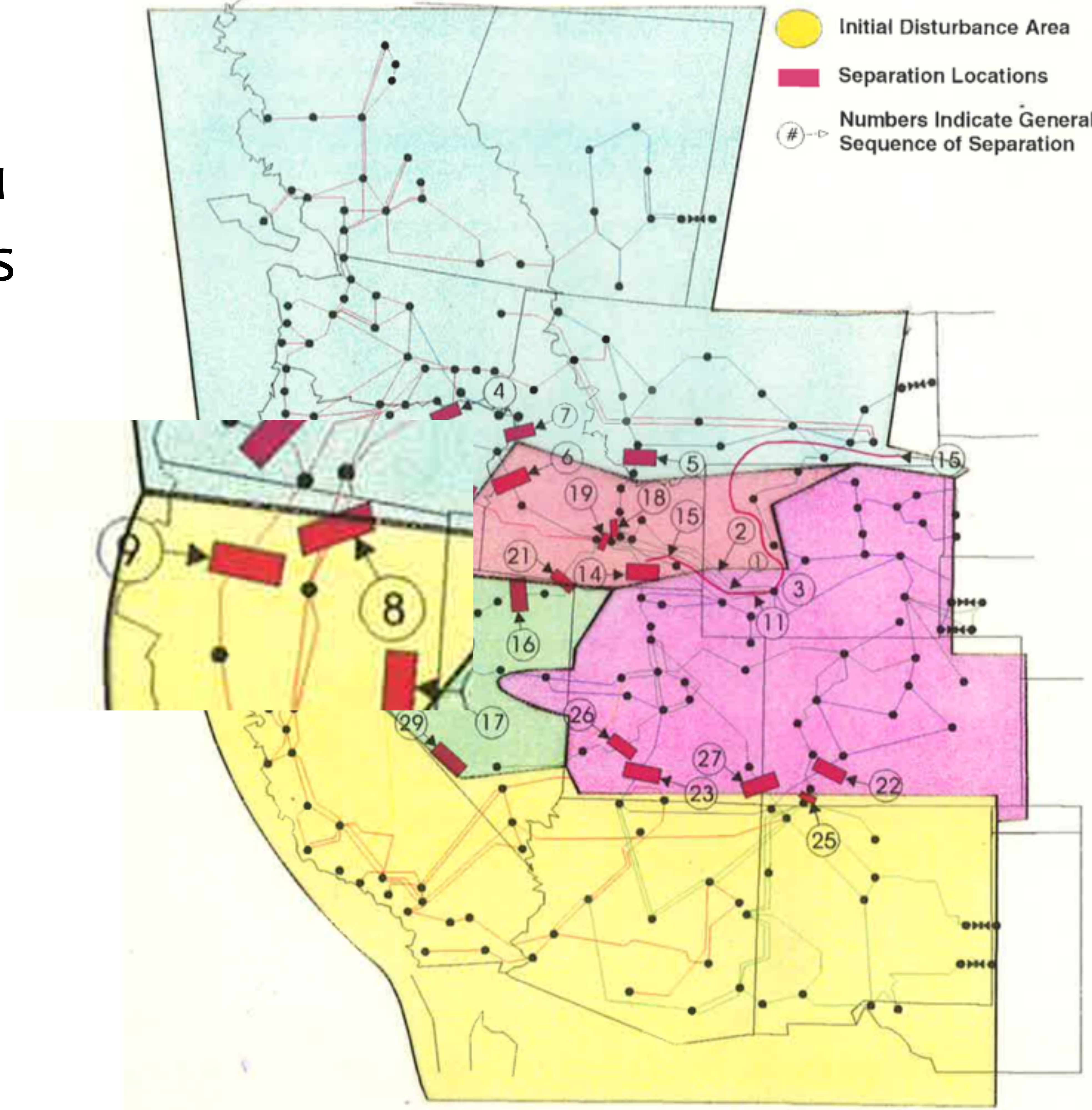

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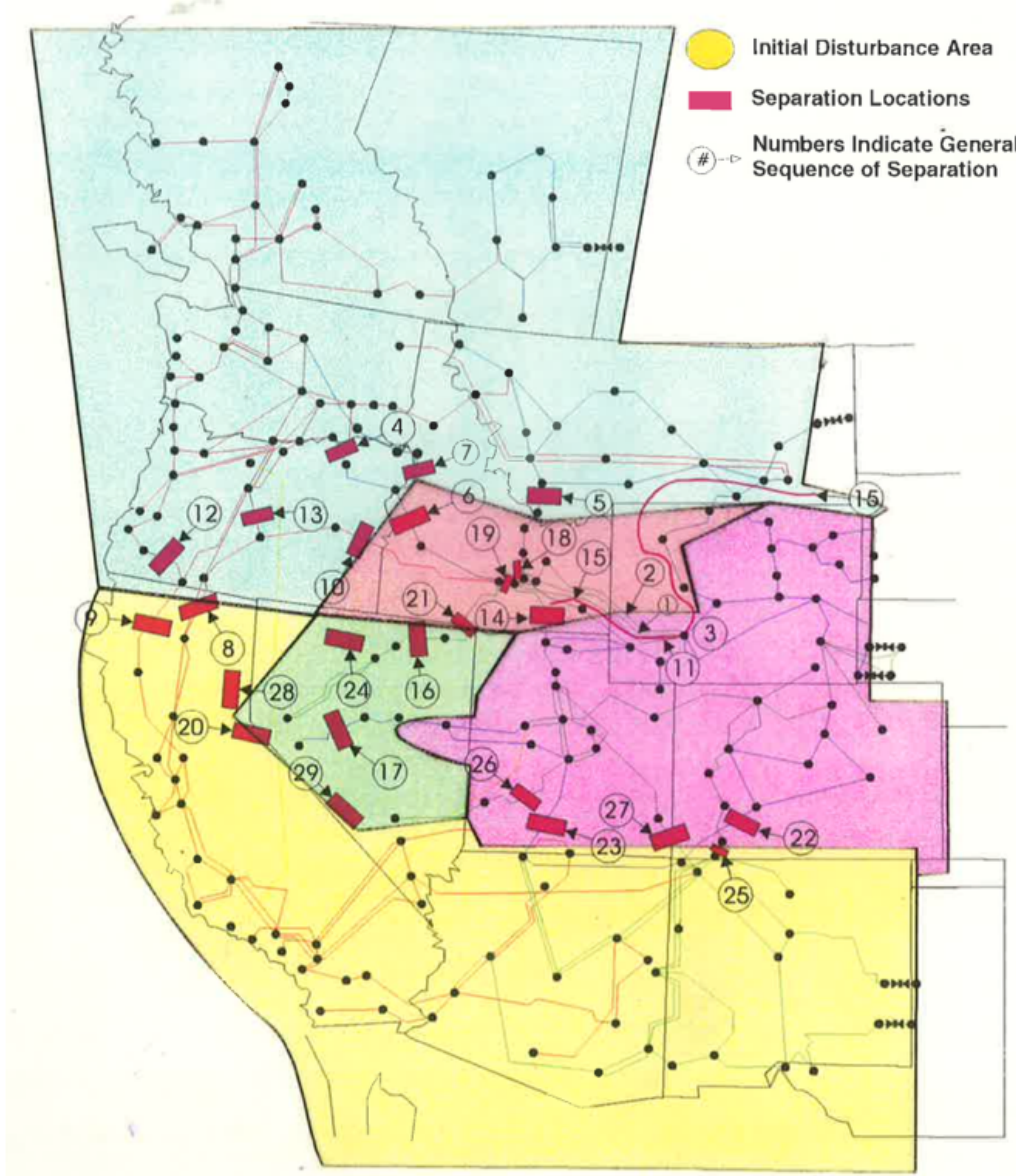
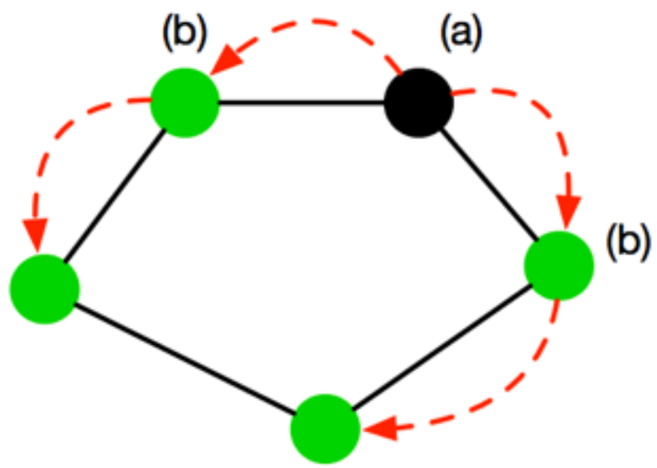


If you model power grids this way, you can get dramatically erroneous answers



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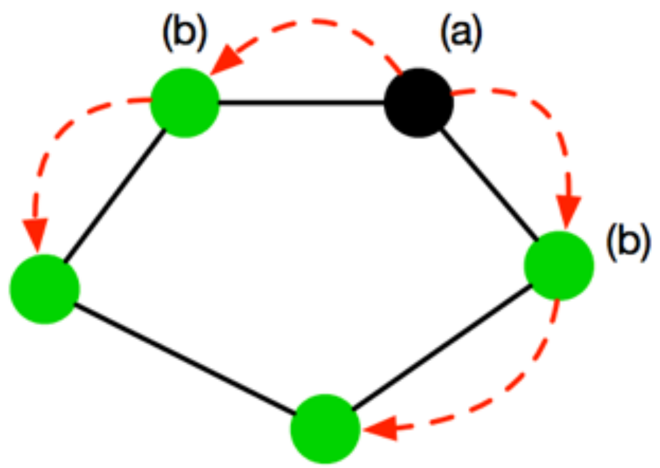


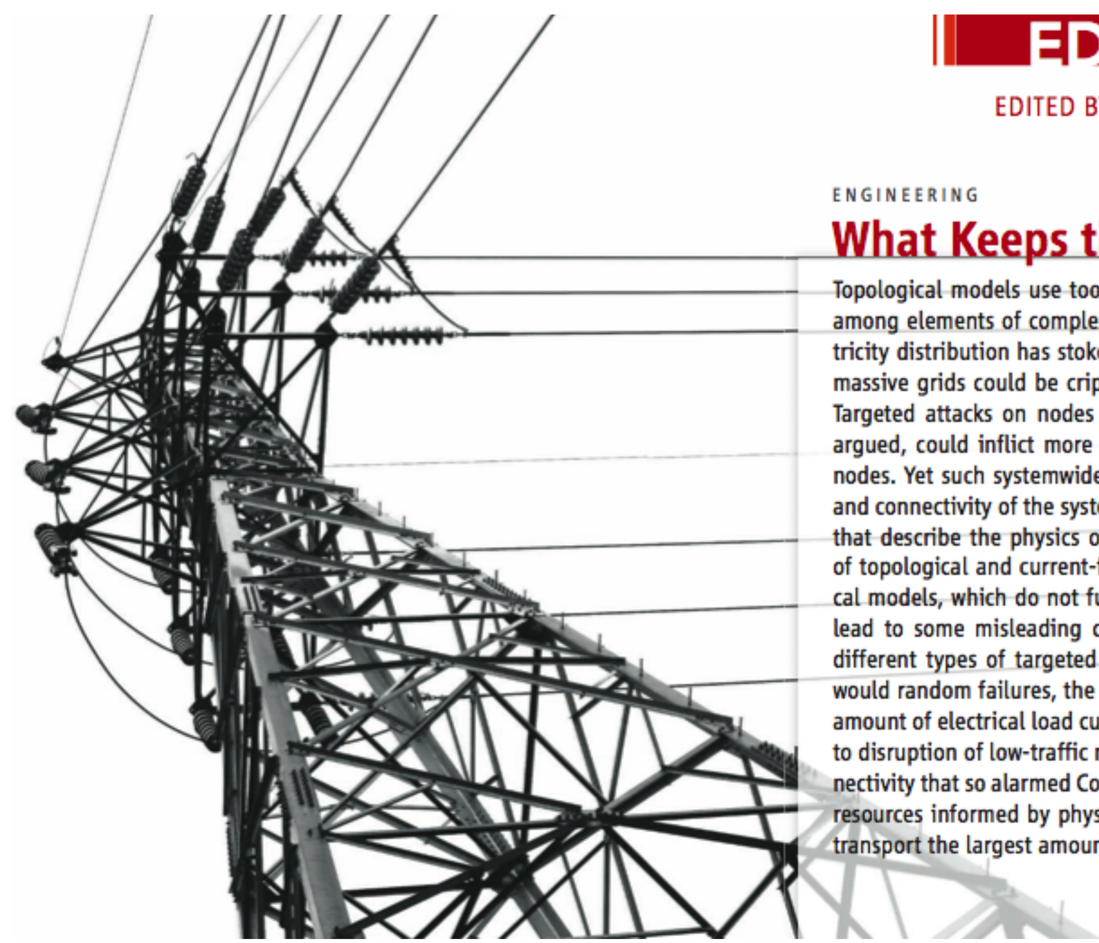
Conventional models of contagion

Do topological models provide good information about electricity infrastructure vulnerability?

Paul Hines,[1,a)] Eduardo Cotilla-Sanchez,[1,b)] and Seth Blumsack[2,c)]

[1]*School of Engineering, University of Vermont, Burlington, Vermont 05405, USA*

[2]*Department of Energy and Mineral Engineering, Pennsylvania State University, University Park, Pennsylvania 16802, USA*



EDITORS' CHOICE

EDITED BY KRISTEN MUELLER AND JAKE YESTON

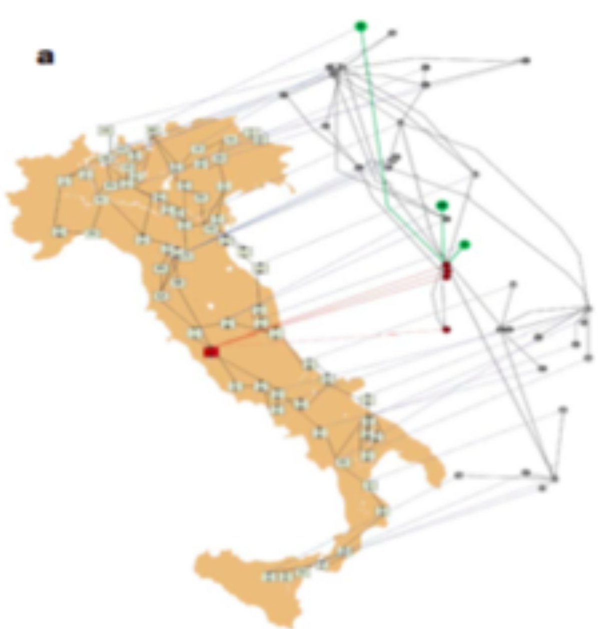
ENGINEERING

What Keeps the Power On?

Topological models use tools from graph theory to explore connections among elements of complex systems. Recently their application to electricity distribution has stoked fears, including in the U.S. Congress, that massive grids could be crippled by seemingly minor initial disruptions. Targeted attacks on nodes with low loads but high connectivity, some argued, could inflict more damage than attacks on the highest-loaded nodes. Yet such systemwide failures are dictated not only by the nodes and connectivity of the system but also by the laws of Ohm and Kirchhoff that describe the physics of electrical flow. In a systematic comparison of topological and current-flow models, Hines *et al.* show that topological models, which do not fully capture the effects of electrical flow, can lead to some misleading conclusions. Though all models showed that different types of targeted disruption would inflict more damage than would random failures, the physics-based measure of blackout size—the amount of electrical load curtailed—did not show the same susceptibility to disruption of low-traffic nodes as did the topological measures of connectivity that so alarmed Congress. Allocation of infrastructure protection resources informed by physics-based models would focus on nodes that transport the largest amounts of power. — BW

Chaos **20**, 33122 (2010).

Let's use *reasonably* accurate grid models, and then couple them to a very simple comm. model



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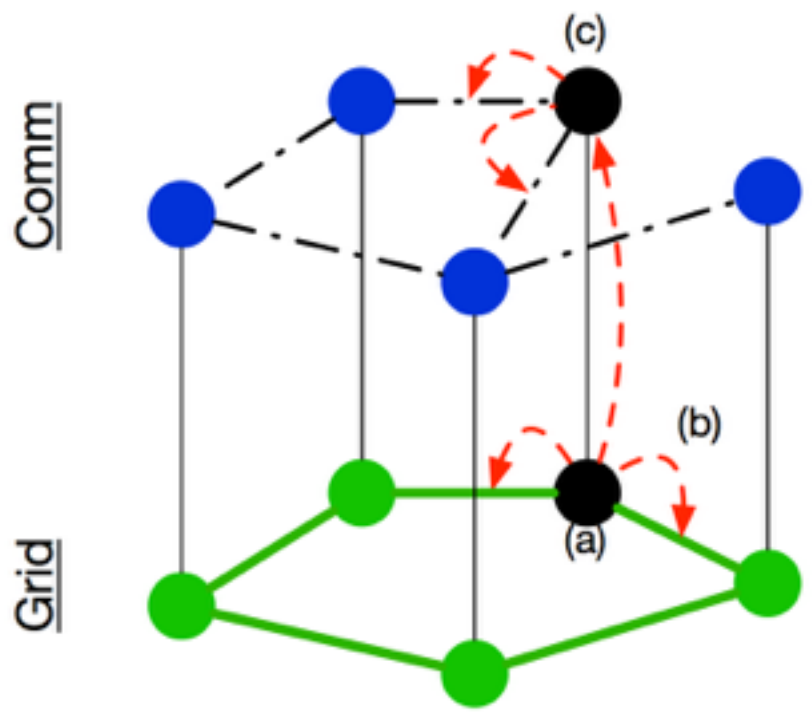

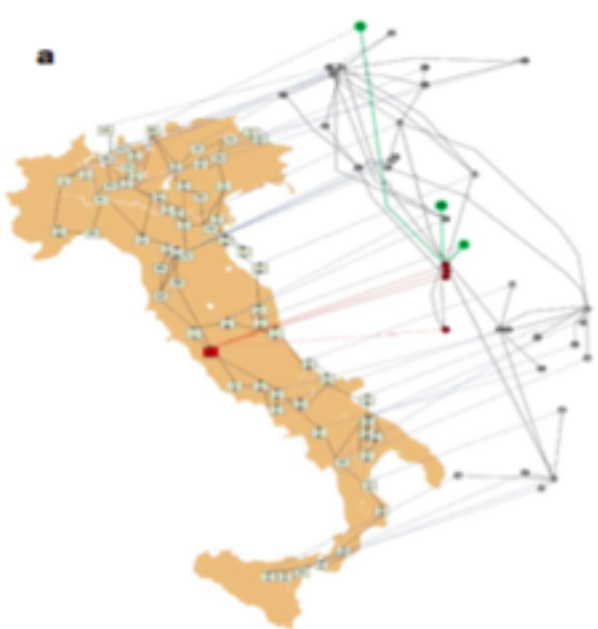

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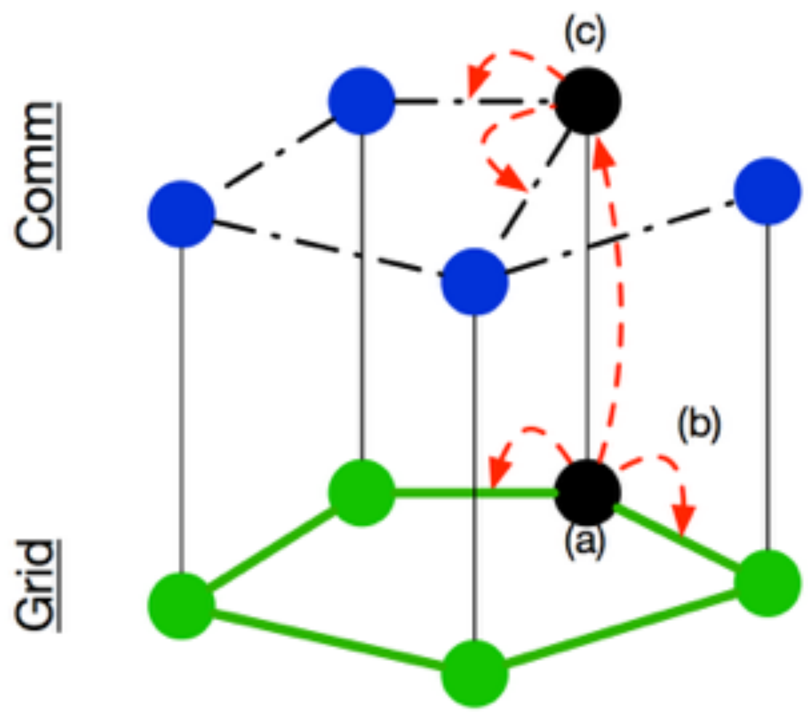

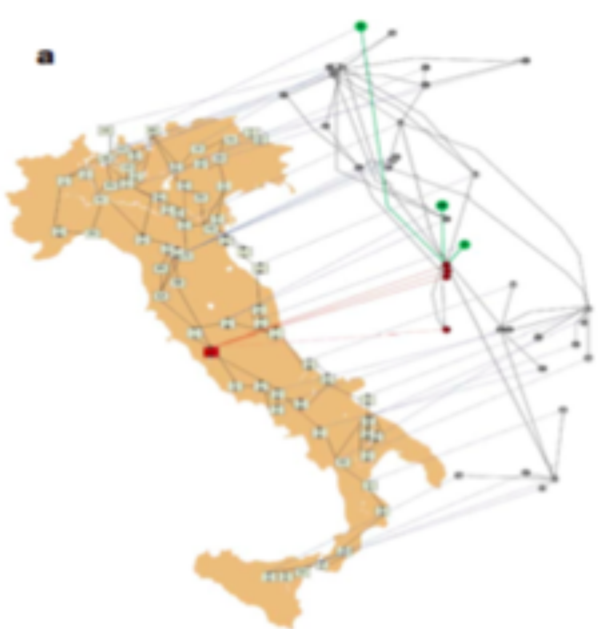

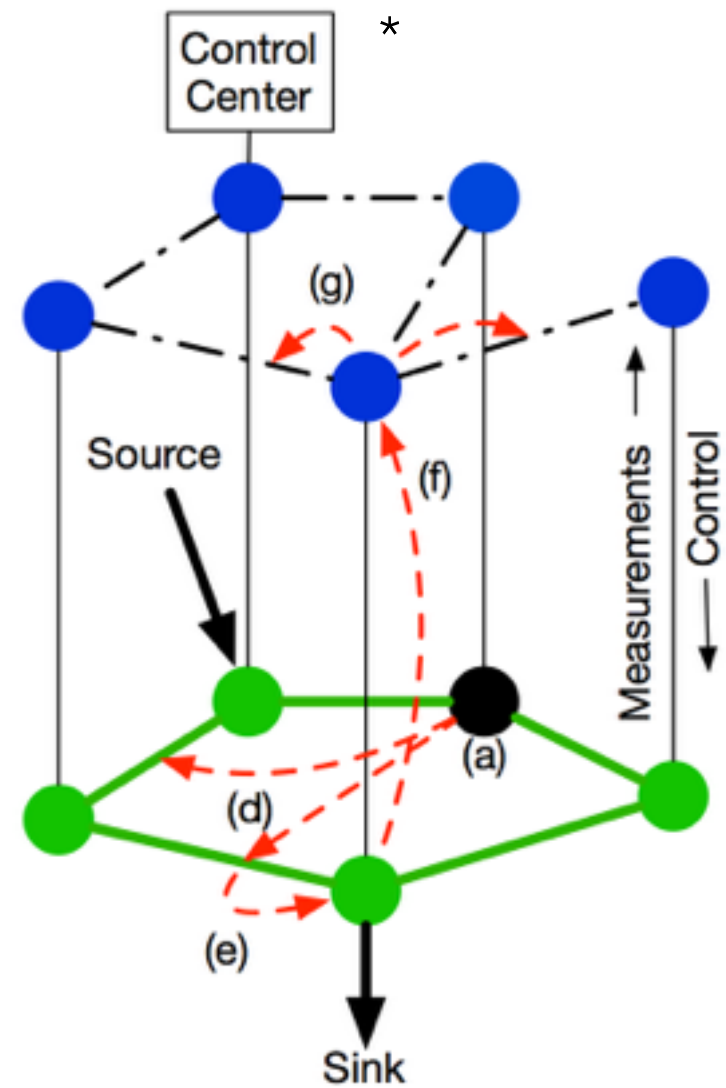

*Model is very similar to work by Parandehgheibi, Modiano & Hay

How does robustness change with the level of coupling? *Comparison result*

Coupled topological model with Polish grid coupled to Comm. network (10% rewired copy of grid)

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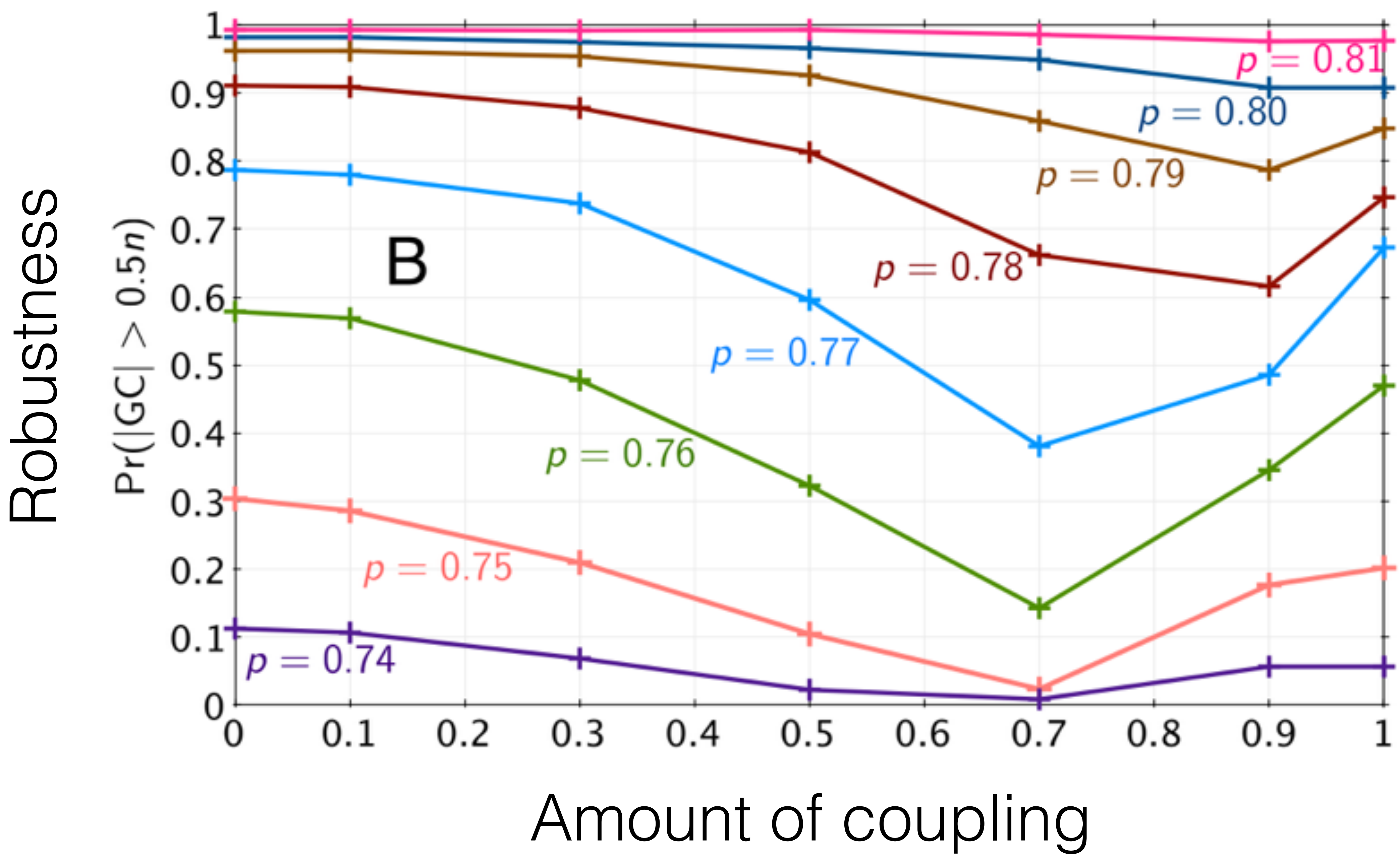

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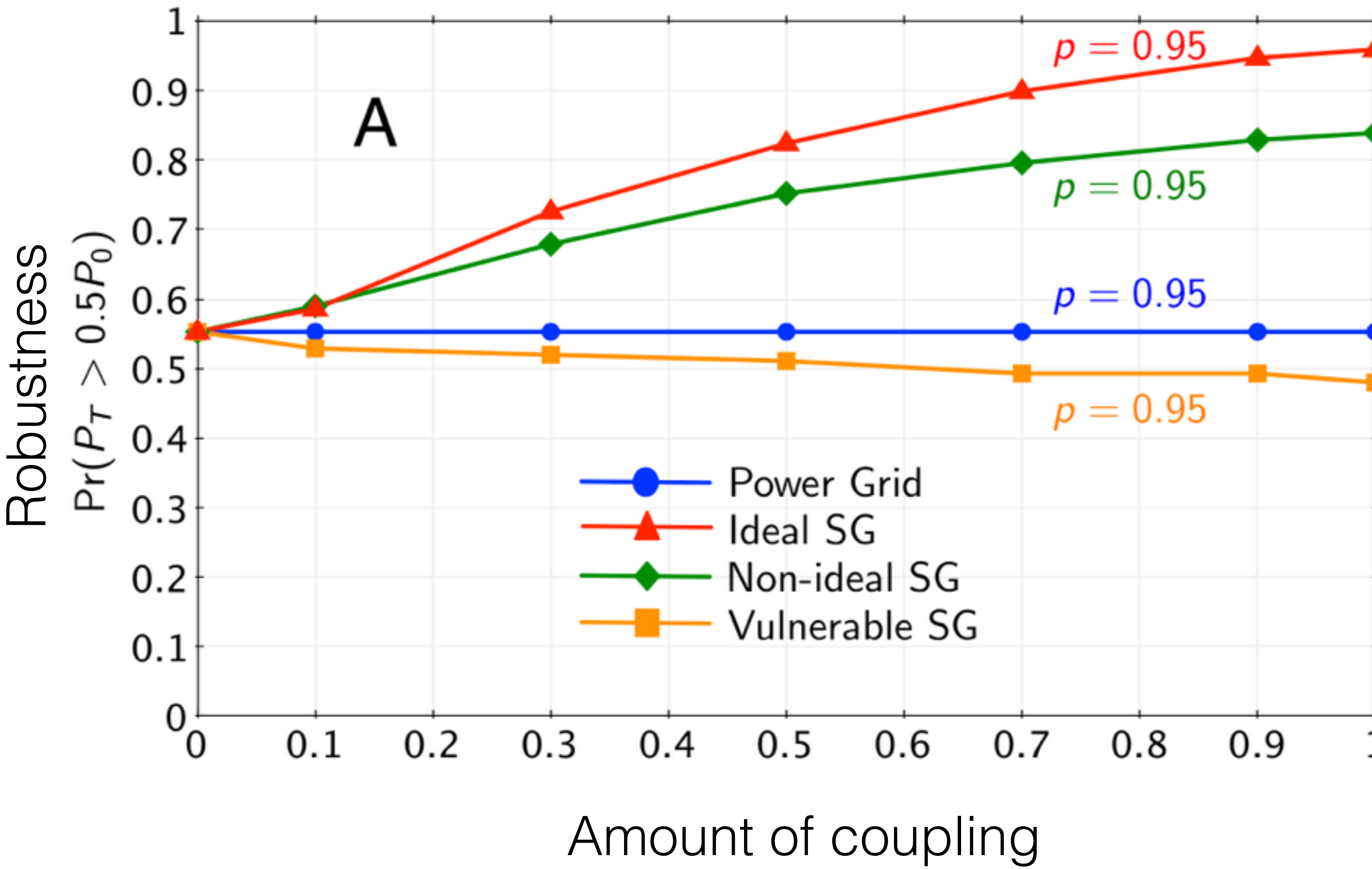
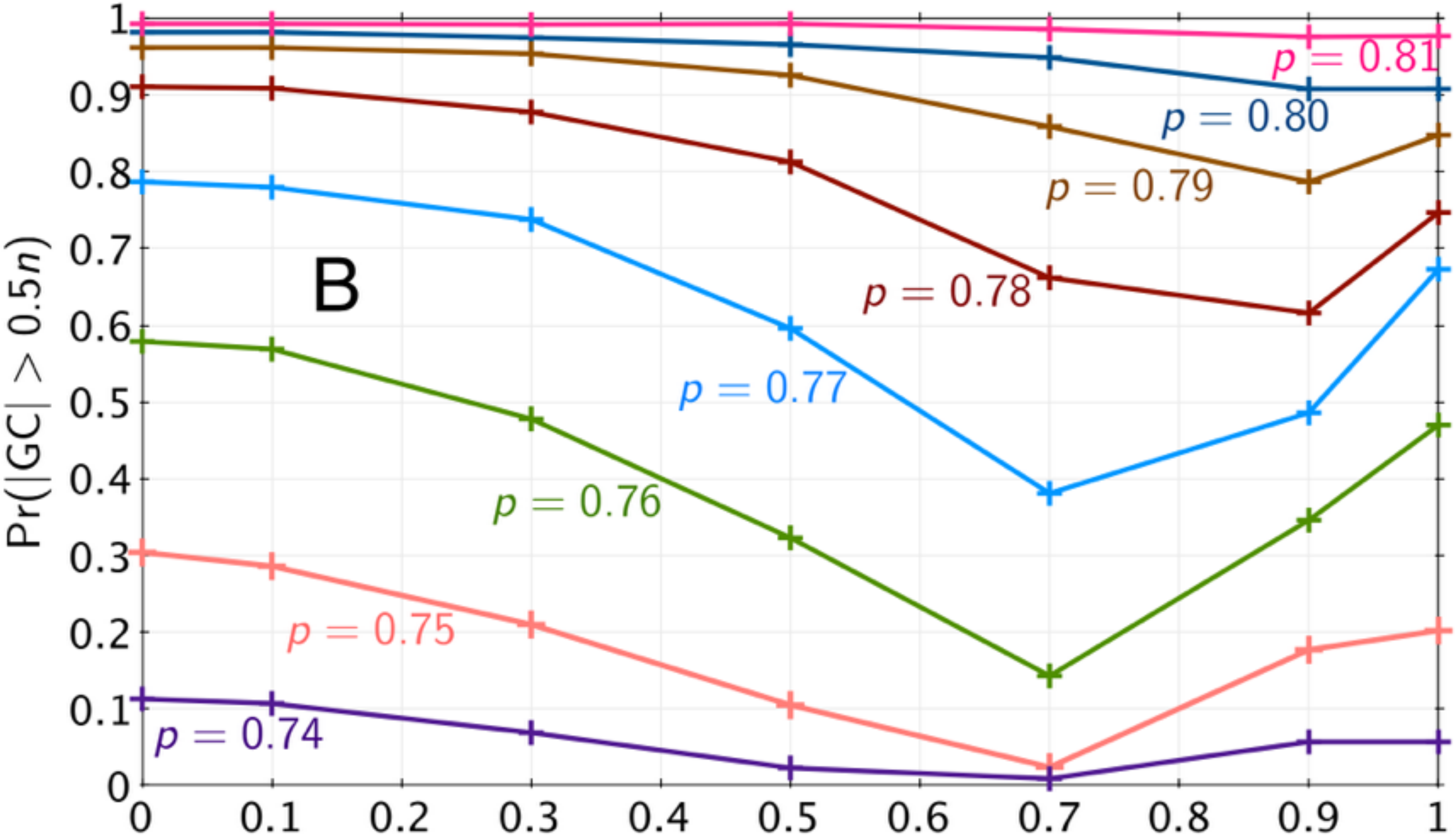


Optimal coupling



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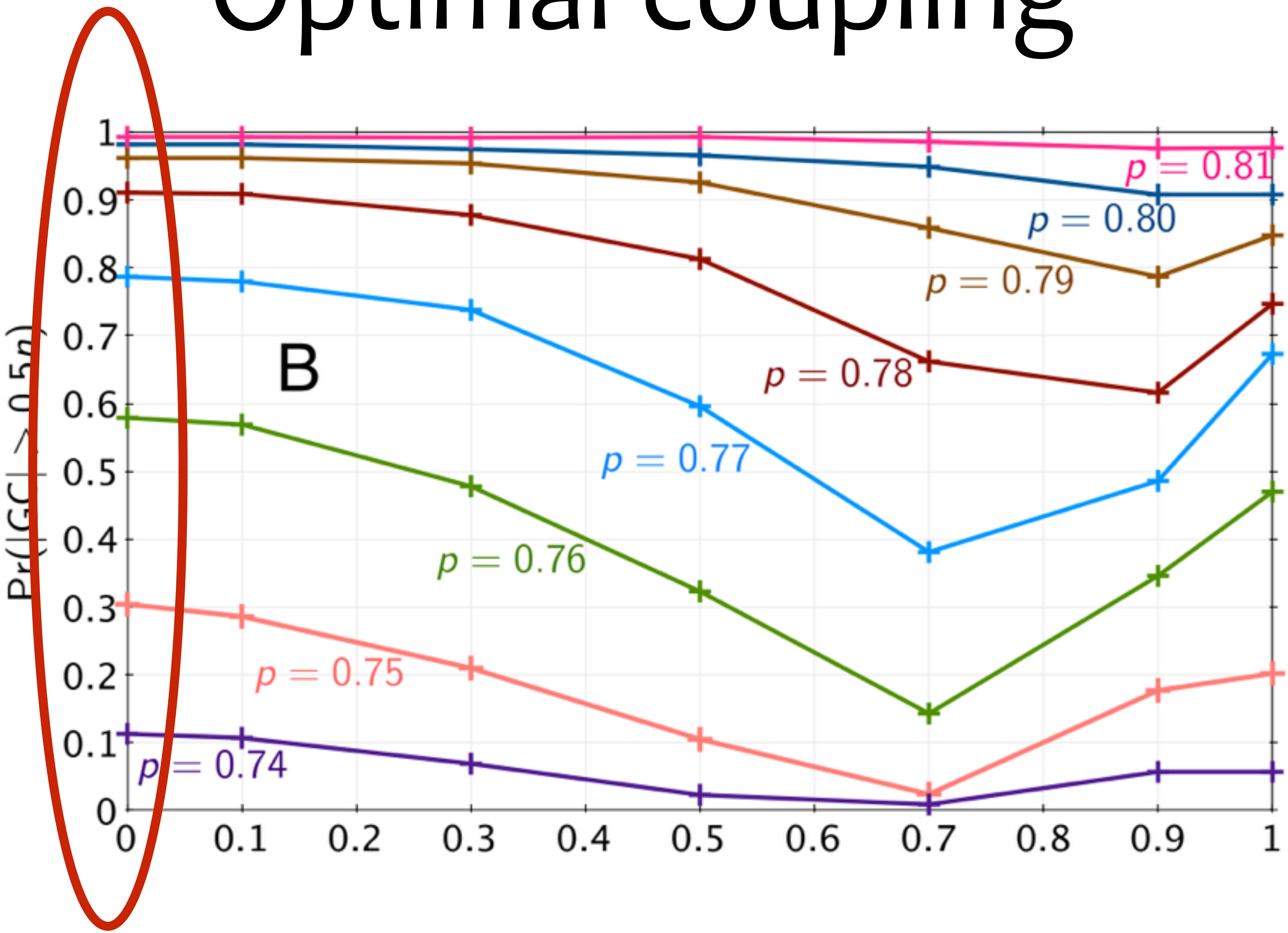

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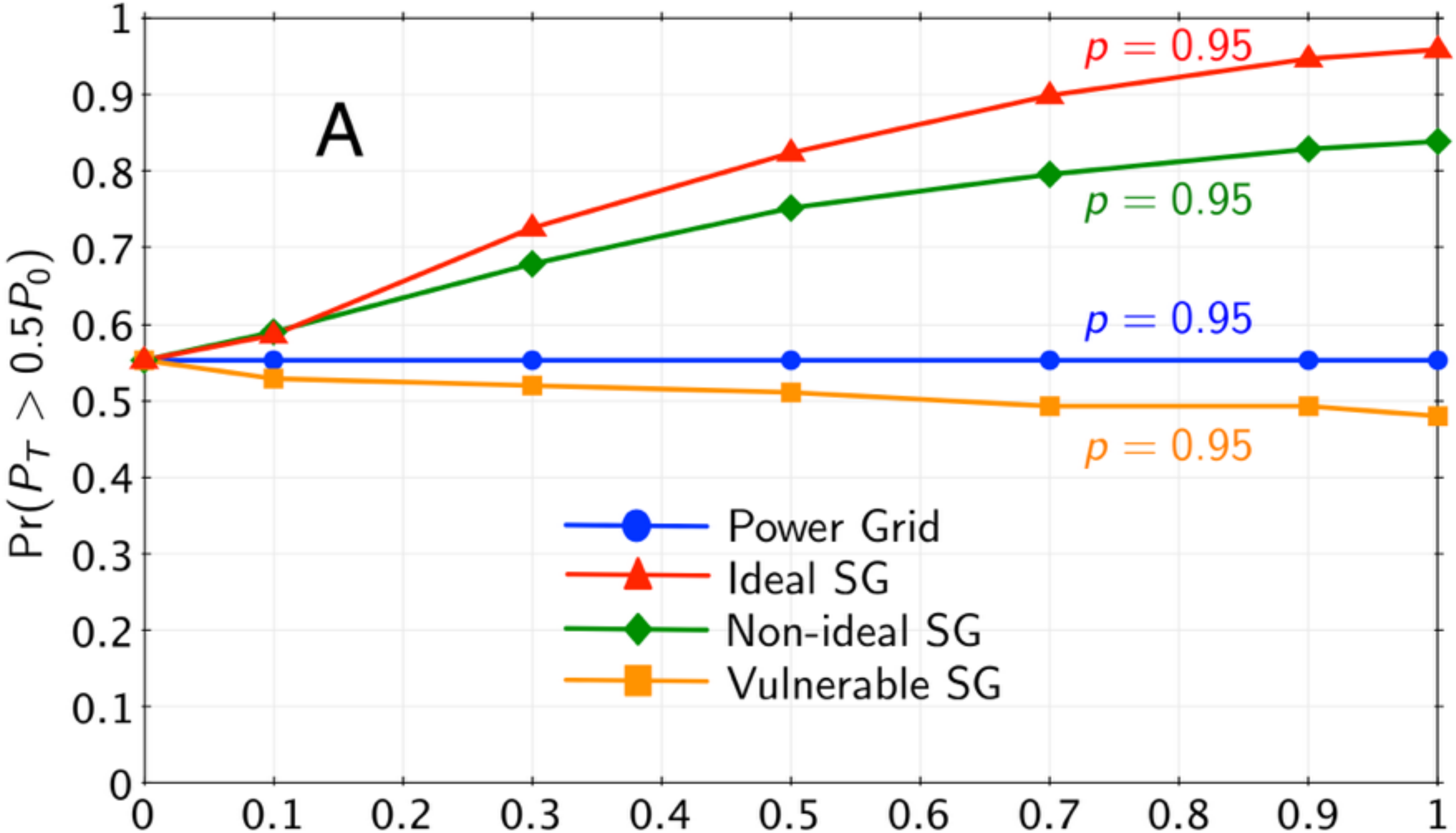

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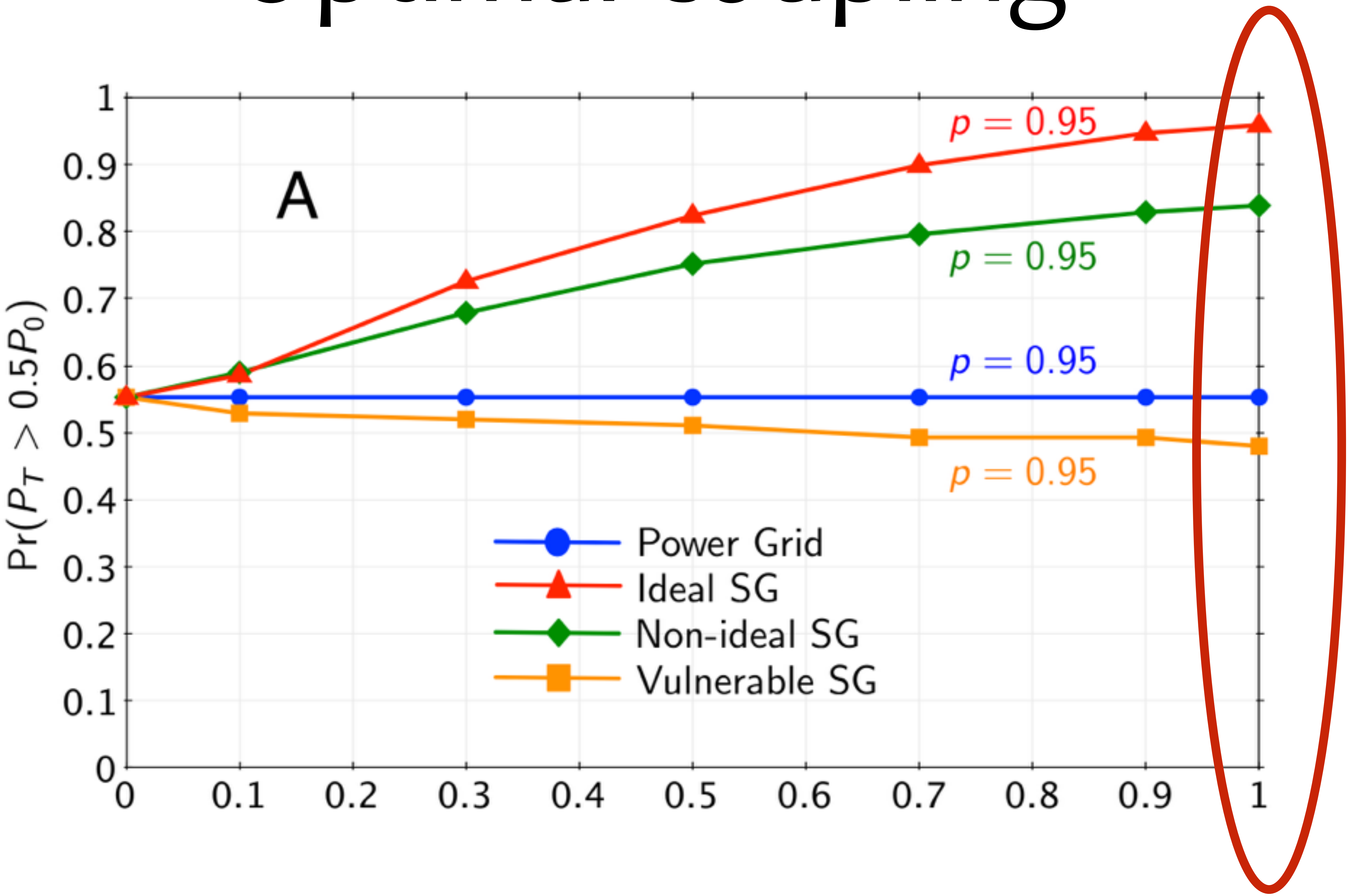

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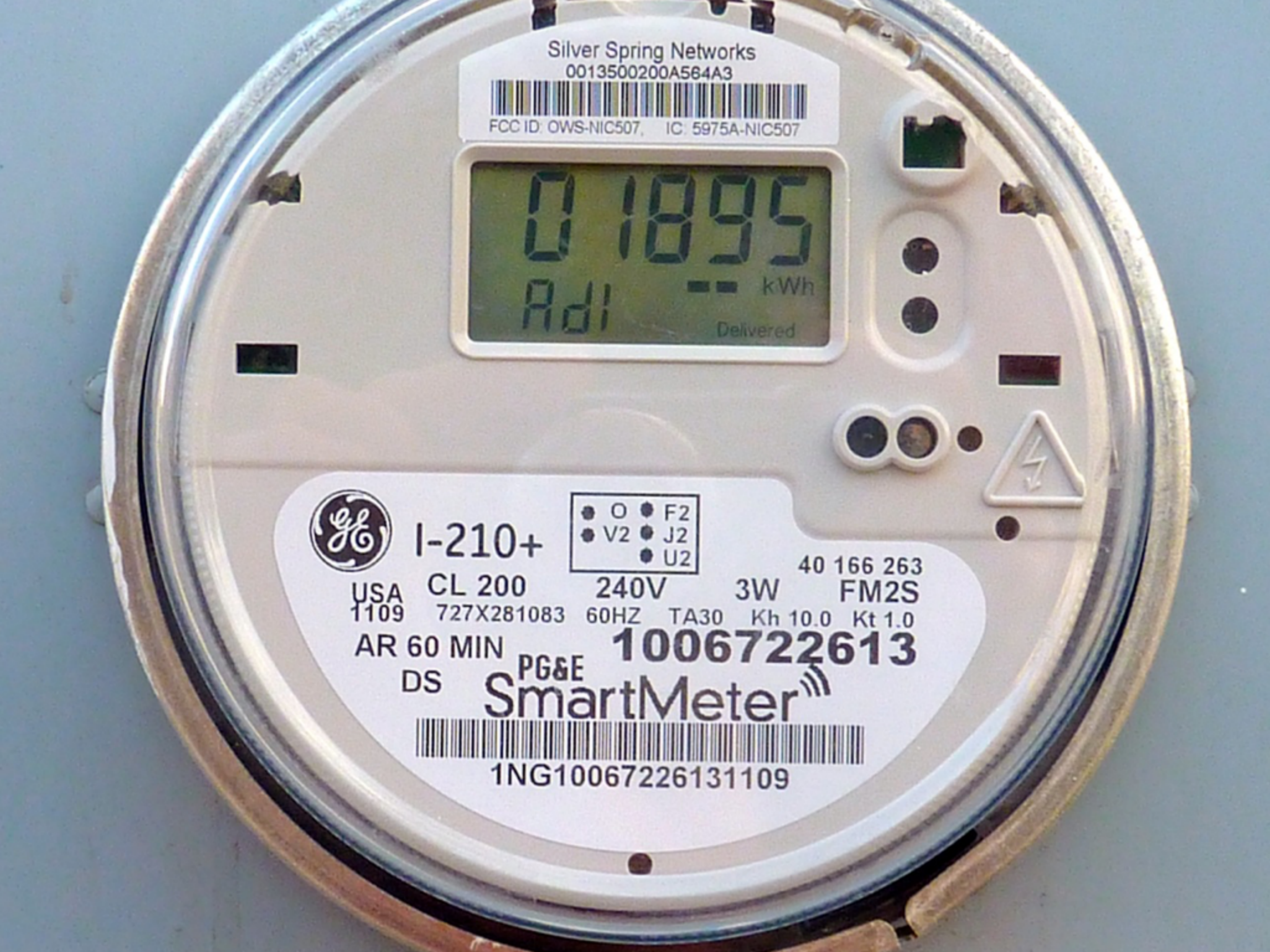
Consumer Behavior
Carrots vs. Sticks

Paul Hines
Santa Fe Institute, Comenius Program
November 2014

Credits
Good ideas: Seth Blumsack
Funding: Dept. of Energy, Green Mountain Power
Errors and omissions: Paul Hines

NY city, Nov. 9, 1965



Silver Spring Networks
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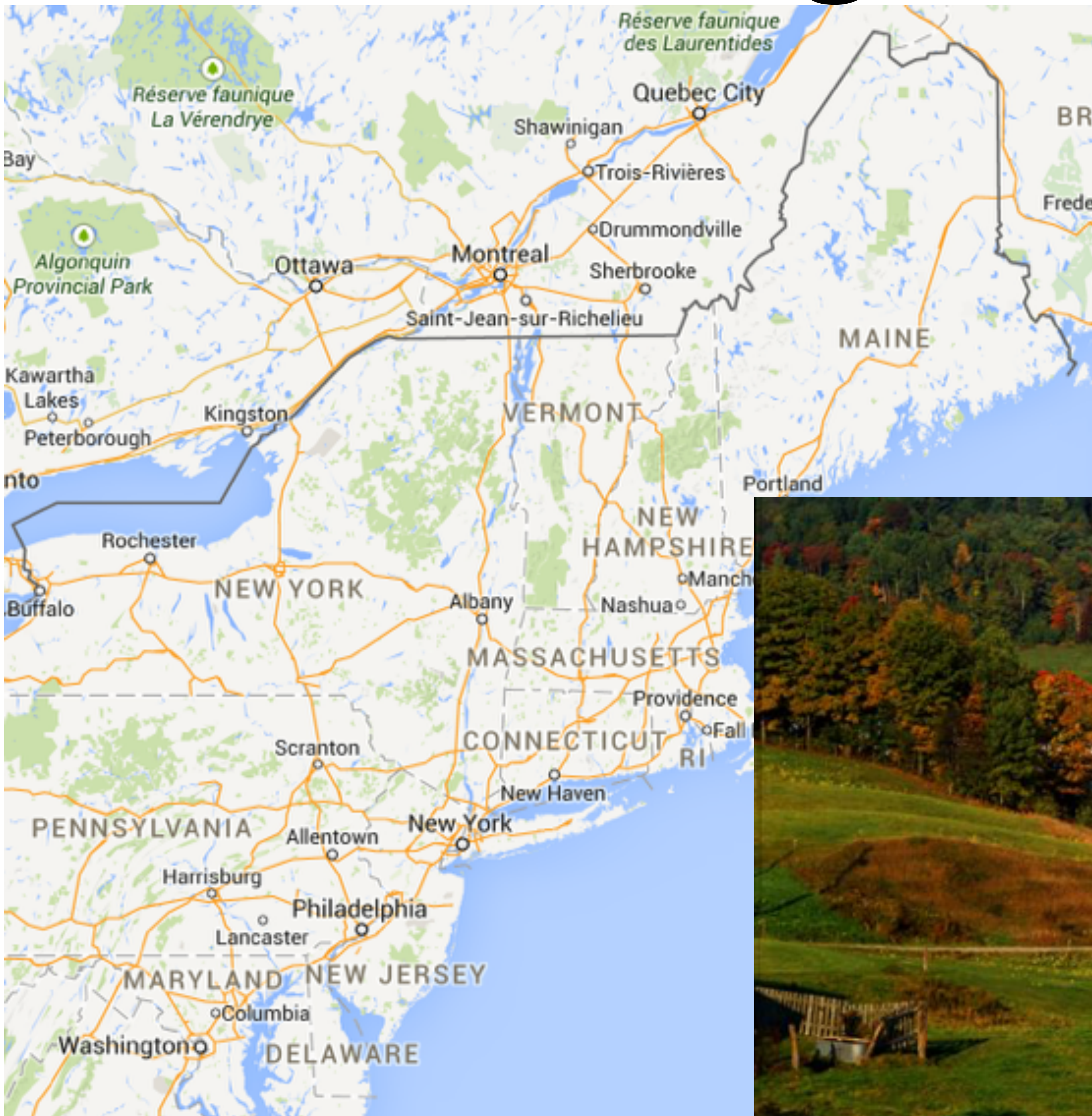
FCC ID: OWS-NIC507, IC: 5975A-NIC507
01895
Adl
kWh
Delivered
I-210+
O F2
V2 J2
U2
40 166 263
USA
1109
CL 200
727X281083
240V
60HZ
3W
TA30
FM2S
Kh 10.0
Kt 1.0
AR 60 MIN
1006722613
DS
PG&E
SmartMeter
1NG10067226131109

How do we get better results without this?

Different types of electricity prices

- Real time pricing
- Time-of-use
- **Critical Peak Pricing (stick)**
- **Critical Peak Rebate (carrot)**

eEnergy Vermont



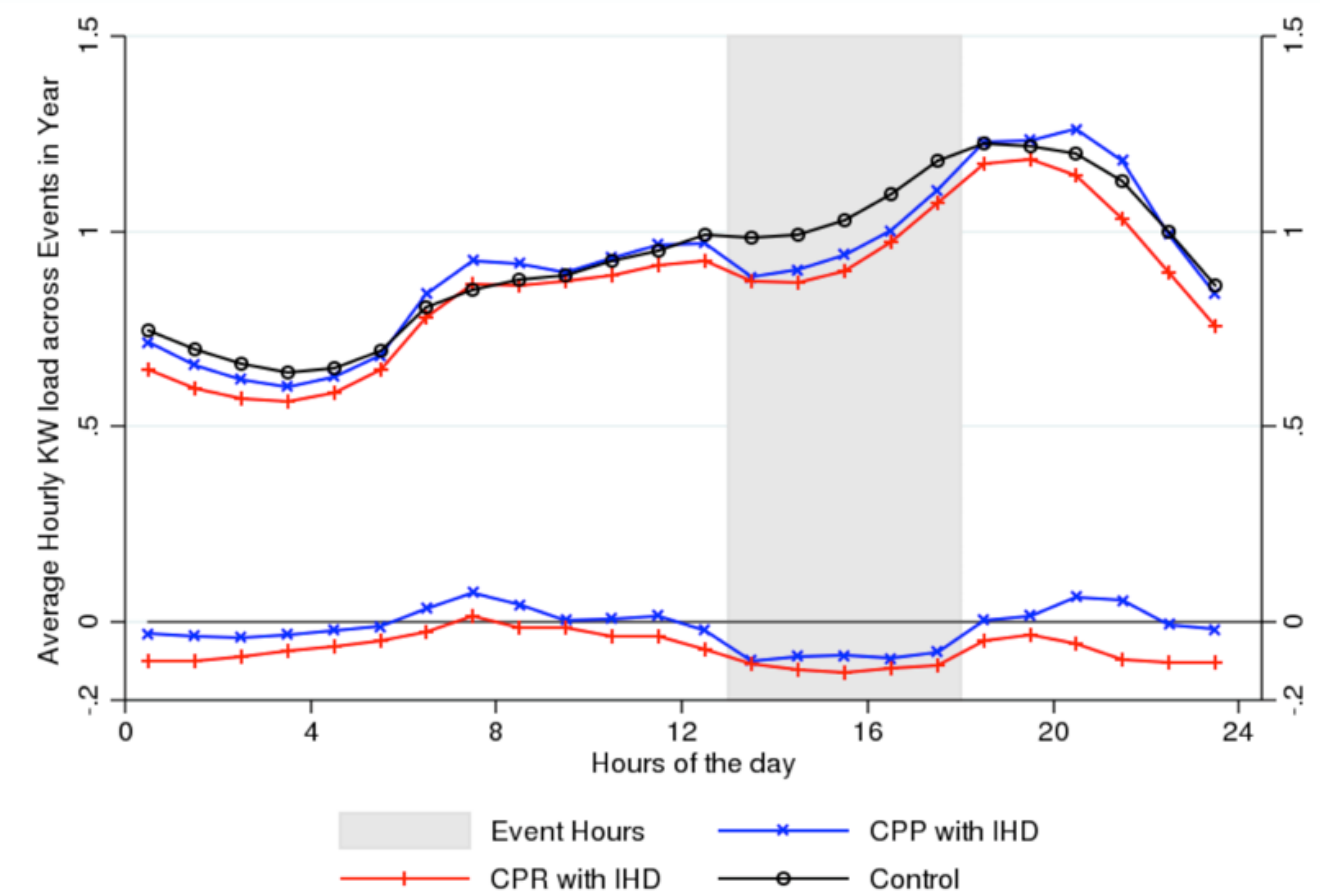
Experimental setup

Group No	Group Name	Survey	Year 1	Year 2	IHD	Notification	Required sample size
1	CPR	X	CPR	CPR		X	390
2	CPR+IHD	X	CPR	CPR	X	X	195
3	CPP	X	CPP	CPP		X	390
4	CPP+IHD	X	CPP	CPP	X	X	195
5	CPR-CPP	X	CPR	CPP		X	390
6	CPR-CPP+IHD	X	CPR	CPP	X	X	195
7	Flat+Notification	X	Flat	Flat		X	390
C1	Flat w/o Notification (Control)	X	Flat	Flat			390
C2	Control, No Survey		Flat	Flat			1200
Totals							3735

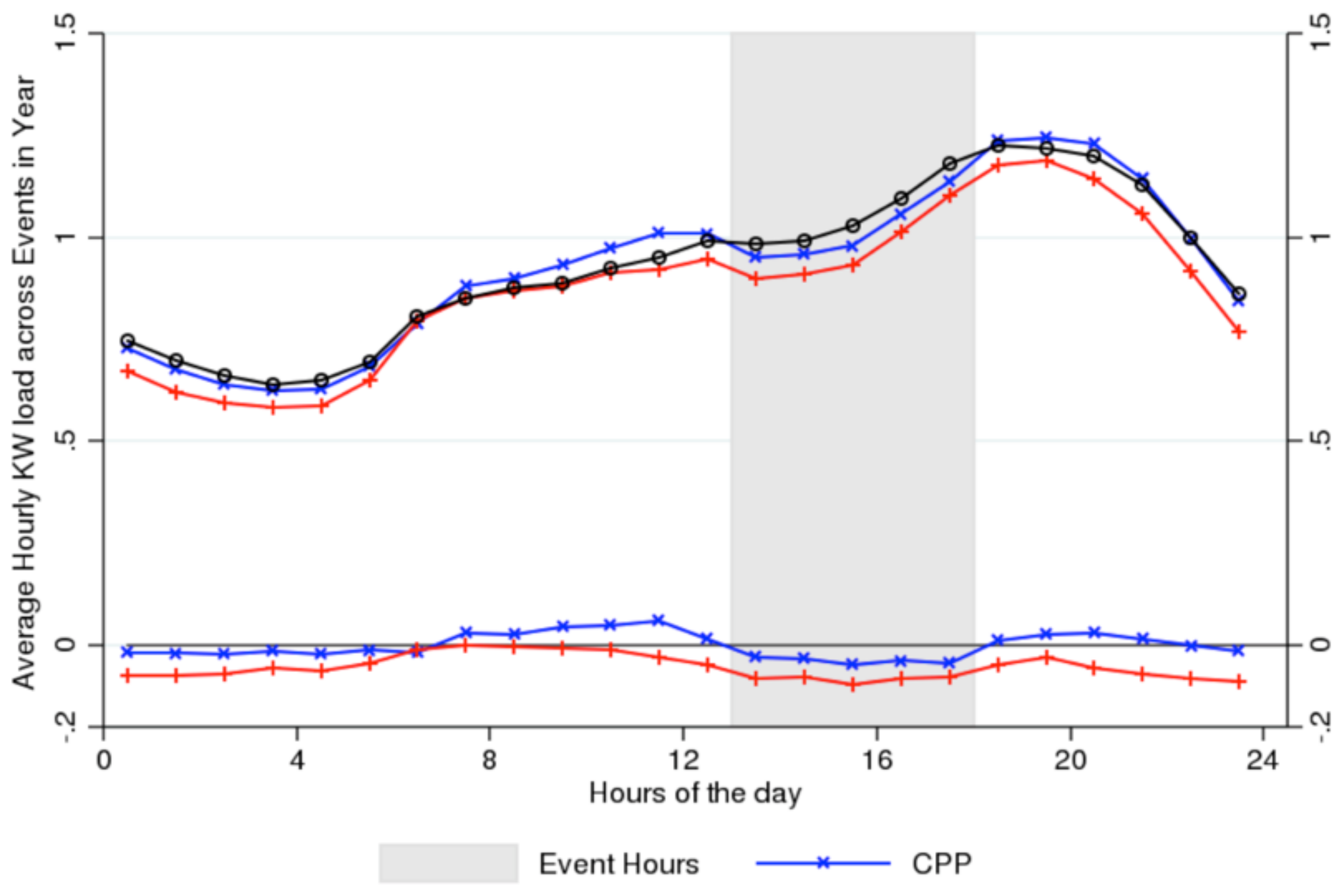
Predictions…

- Classical economic theory assumes that
  - people react about the same to losing money and winning money
  - people will gather the information needed to make rational decisions
- Thus, we would expect the carrot and the stick to work about equally as well, and the additional information would be only marginally helpful

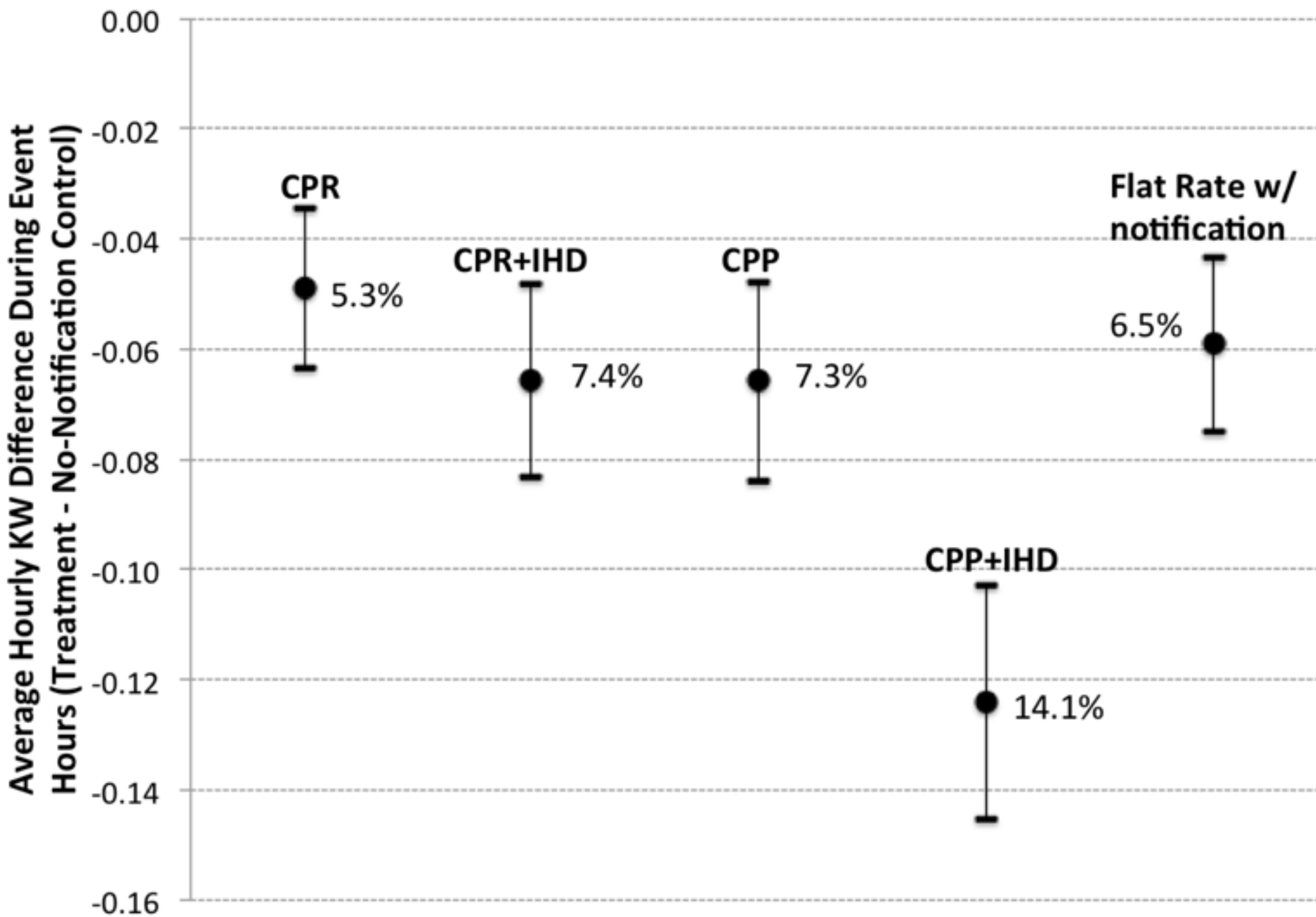
Event day behavior with IT



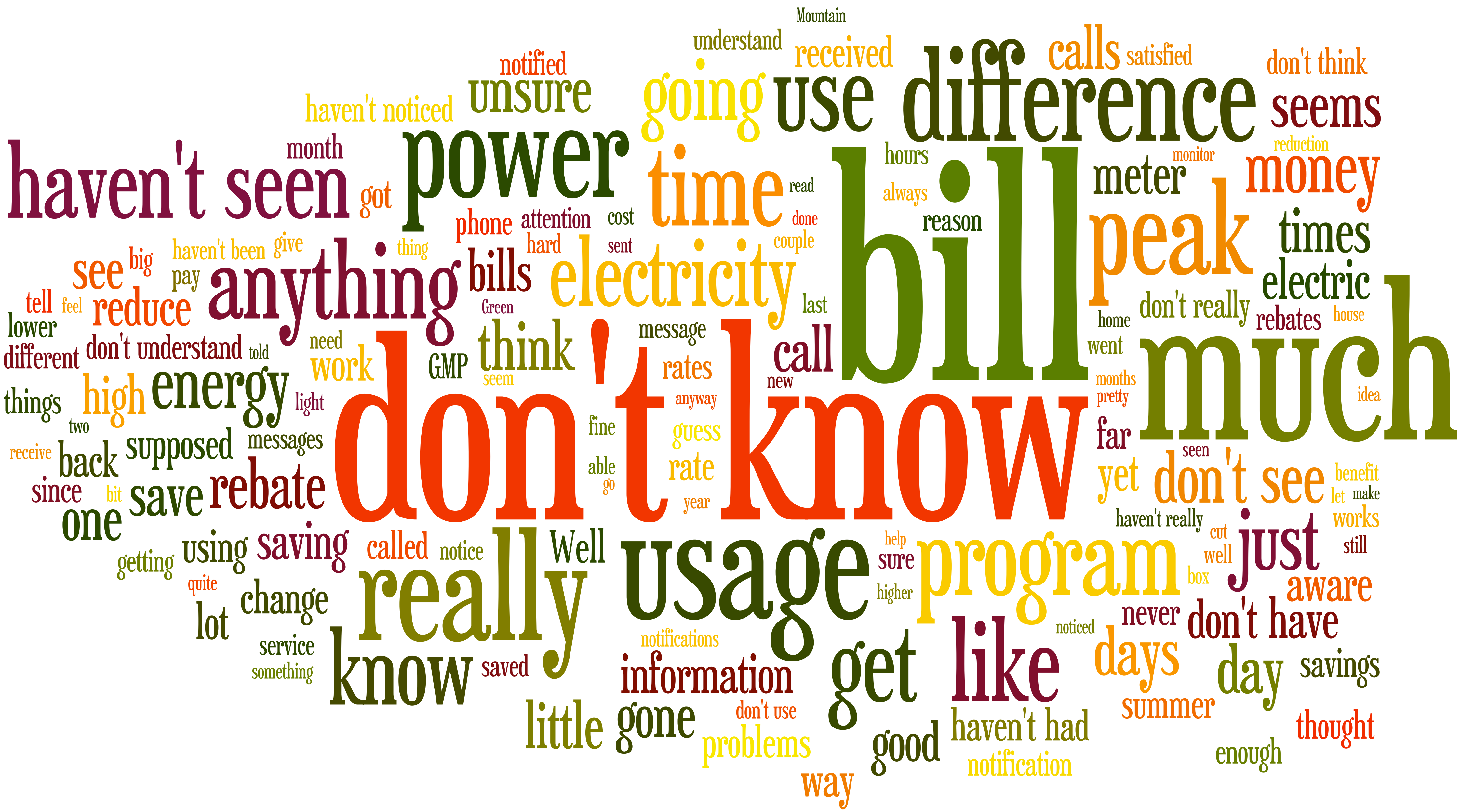
Event day behavior without IT



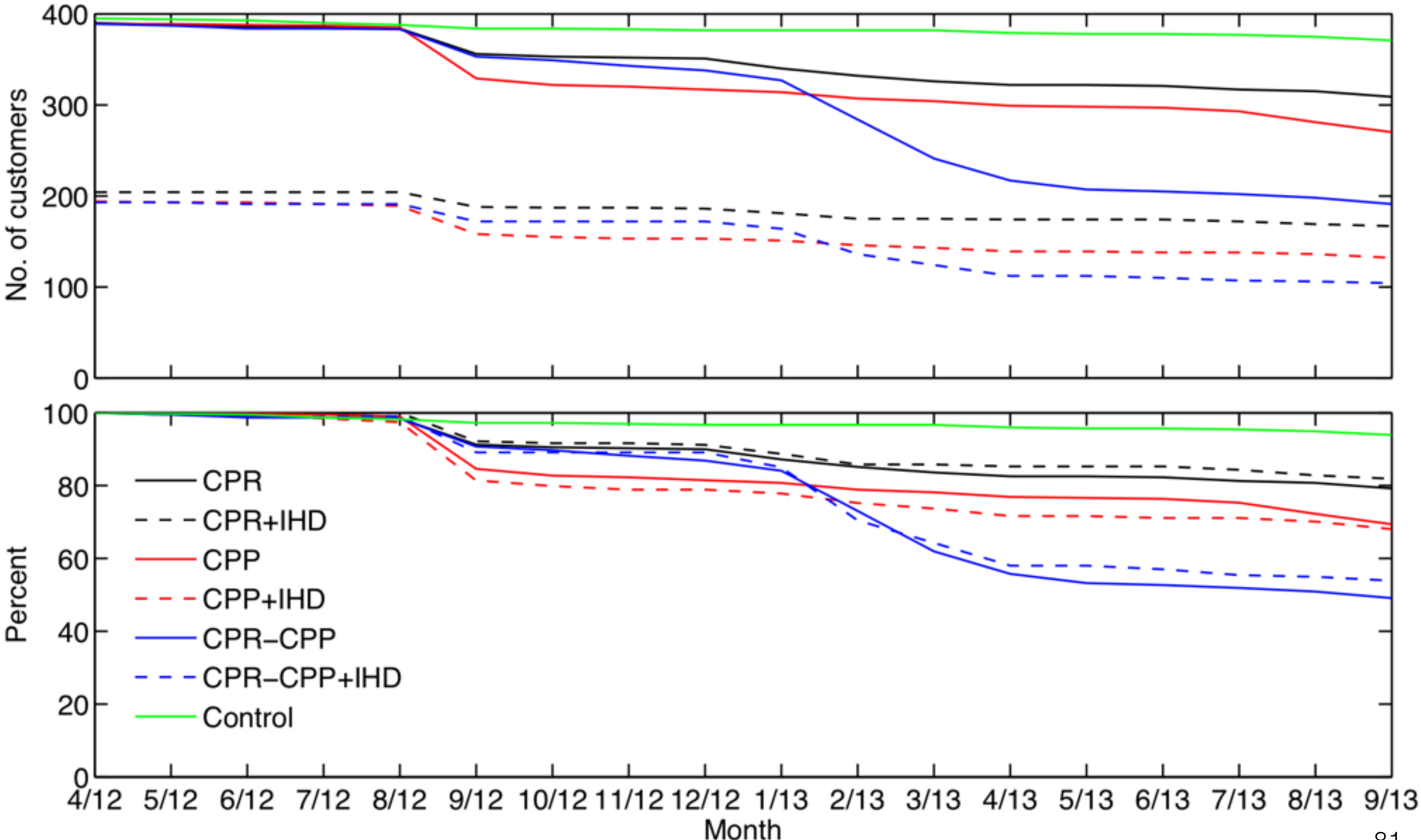
Overall results



Perhaps more importantly, from survey results:



Customer Endurance



Conclusions

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- In some cases, people respond about as well to simple notification as they do to small financial incentives

- People respond well to penalties, but they don’t like them

Transdisciplinary Power Grid Science

Paul Hines
Santa Fe Institute, Comenius Program
November 2014

Credits
Good ideas: P. Rezaei, M. Eppstein, M. Korkali, J. Veneman, B. Tivnan, J. Bongard, S. Blumsack
Funding: Dept. of Energy, National Science Foundation, MITRE
Errors and omissions: Paul Hines

NY city, Nov. 9, 1965